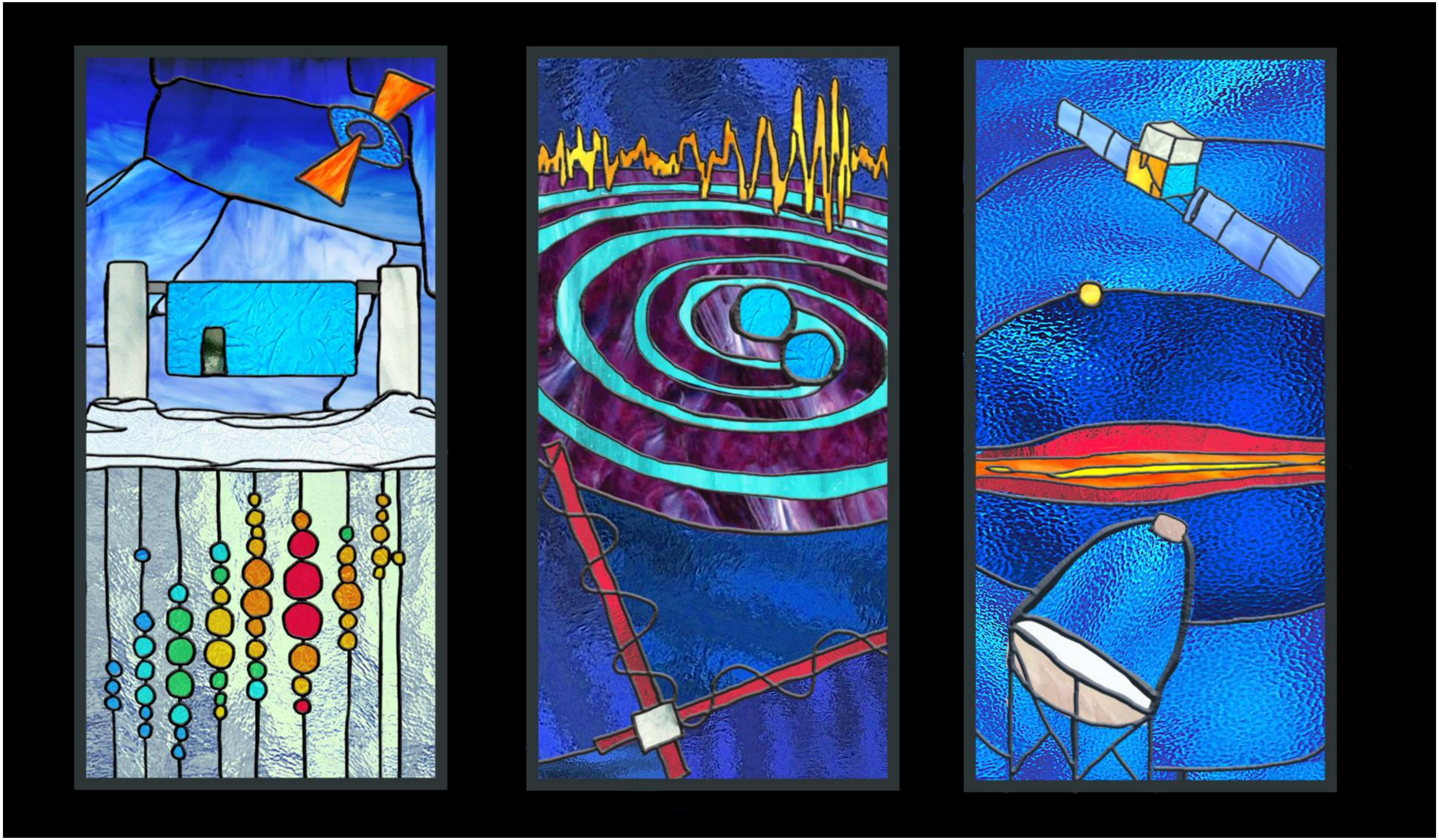
Neutrino Astronomy: detectors, techniques, and status

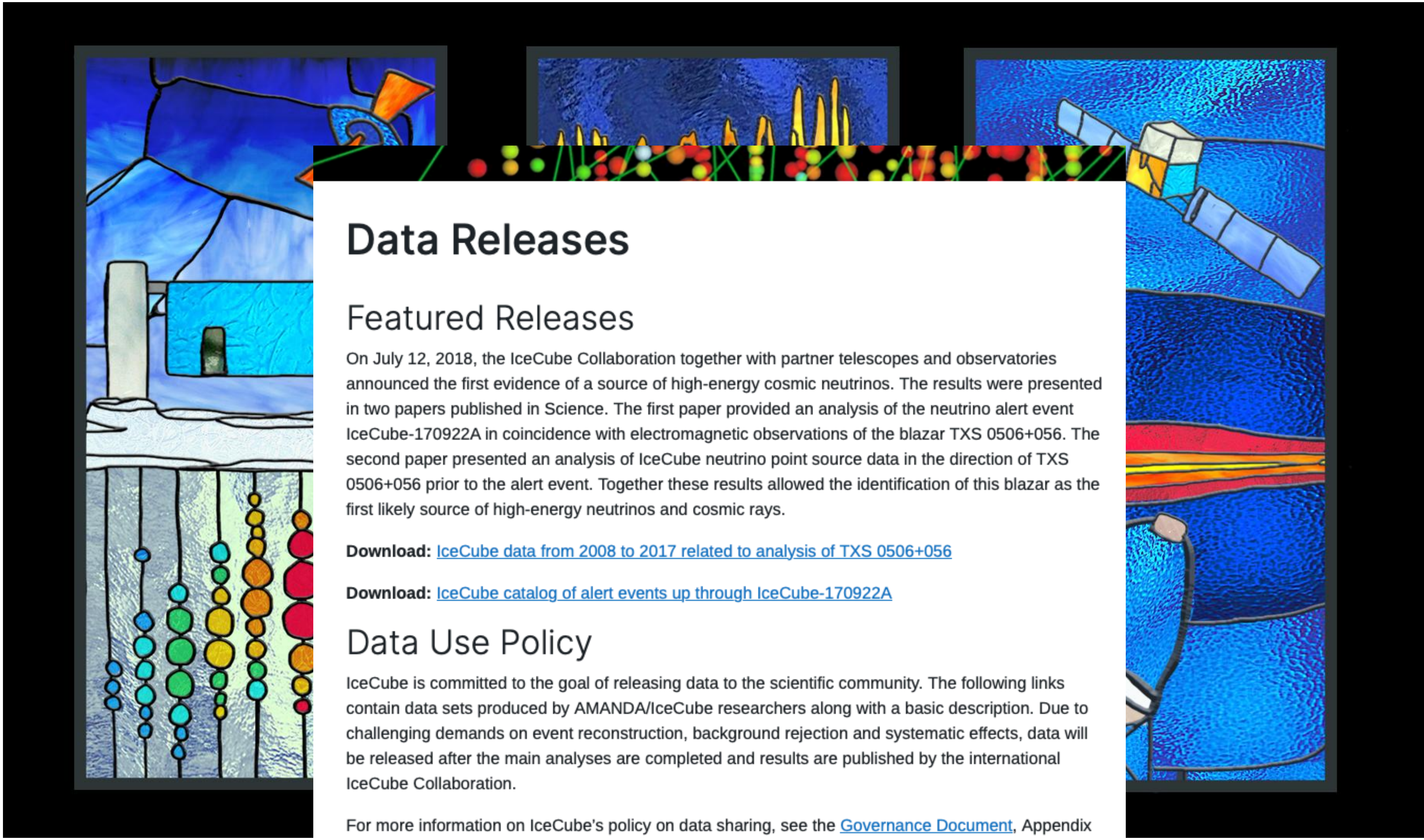
Carlos Argüelles

São Paulo Advanced School on
Multi-Messenger Astrophysics
Instituto Principia

The objective of this lecture series



The objective of this lecture series



Data Releases

Featured Releases

On July 12, 2018, the IceCube Collaboration together with partner telescopes and observatories announced the first evidence of a source of high-energy cosmic neutrinos. The results were presented in two papers published in Science. The first paper provided an analysis of the neutrino alert event IceCube-170922A in coincidence with electromagnetic observations of the blazar TXS 0506+056. The second paper presented an analysis of IceCube neutrino point source data in the direction of TXS 0506+056 prior to the alert event. Together these results allowed the identification of this blazar as the first likely source of high-energy neutrinos and cosmic rays.

Download: IceCube data from 2008 to 2017 related to analysis of TXS 0506+056

Download: IceCube catalog of alert events up through IceCube-170922A

Data Use Policy

IceCube is committed to the goal of releasing data to the scientific community. The following links contain data sets produced by AMANDA/IceCube researchers along with a basic description. Due to challenging demands on event reconstruction, background rejection and systematic effects, data will be released after the main analyses are completed and results are published by the international IceCube Collaboration.

For more information on IceCube's policy on data sharing, see the Governance Document, Appendix E: Dissemination and Sharing of IceCube Research Results and Data.

Download Data Sets

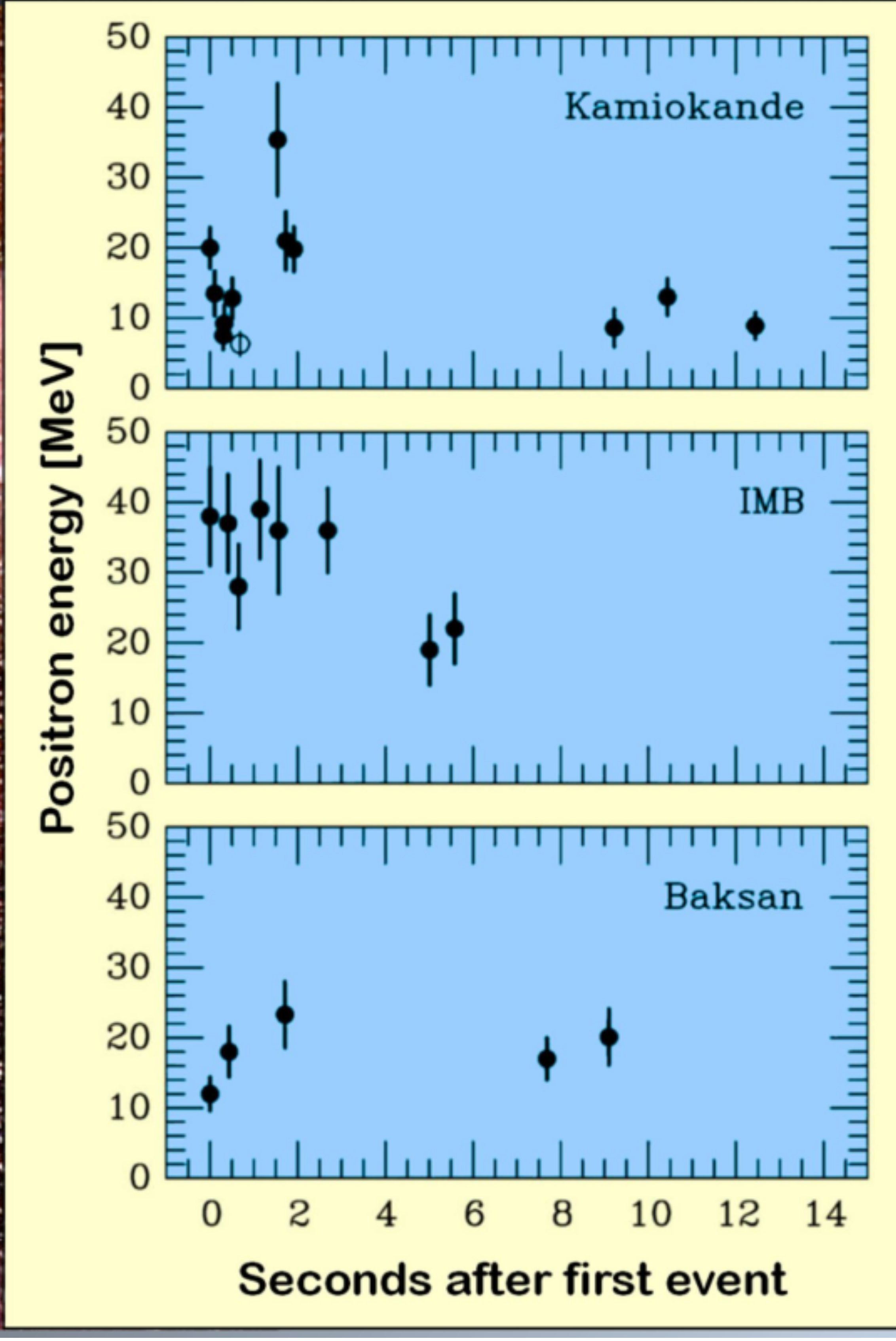
The pages below contain information about the data that were collected and links to the data files.

Cardápio

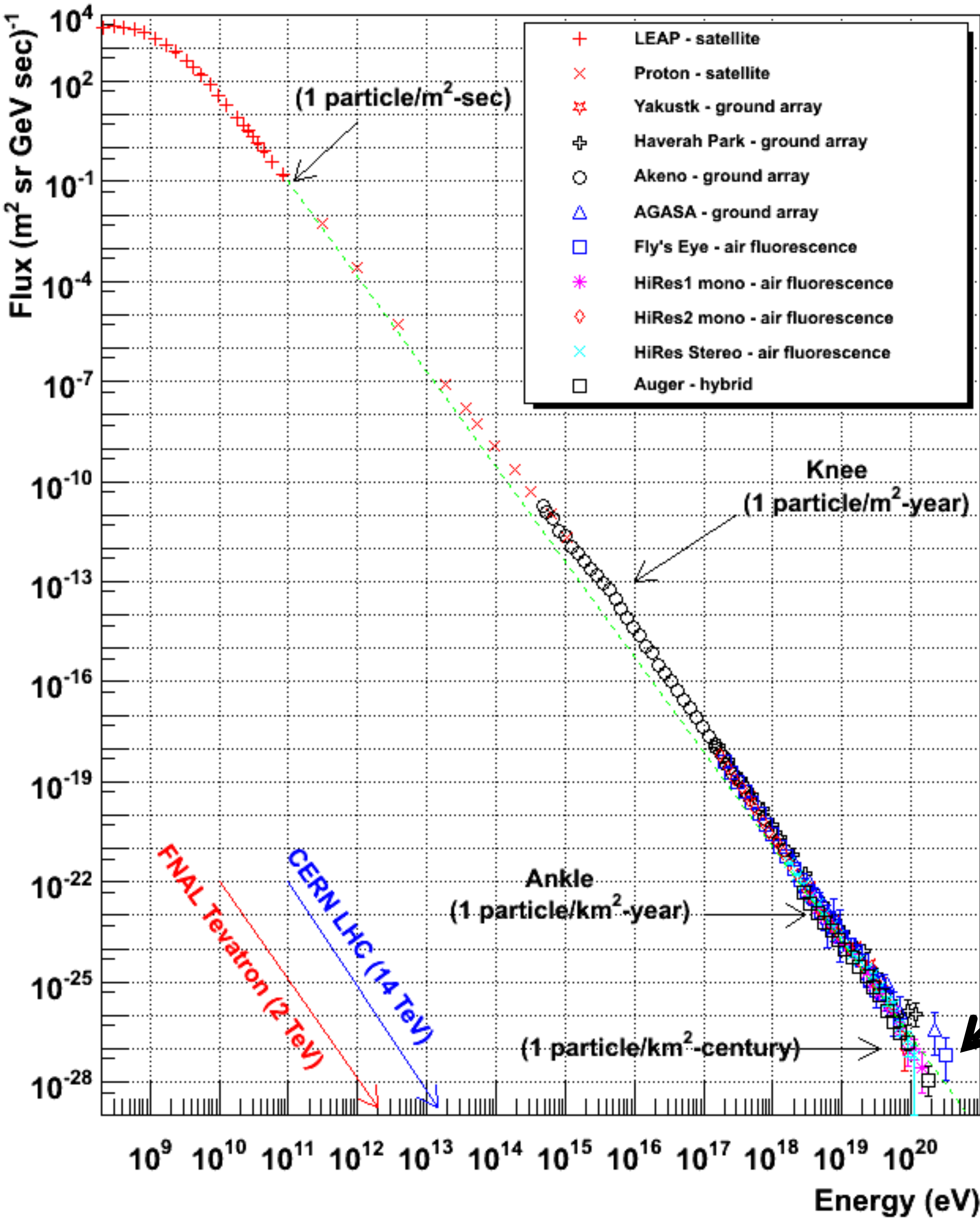
1. Why high-energy neutrino astrophysics?
2. Some history: the road to discovery
3. Signature, backgrounds, and particle physics
4. Discovery of high-energy astrophysical neutrinos
5. *Statistics interlude*
6. What do we know about neutrino sources?
7. *Neutrino oscillation interlude*
8. Particle physics with high-energy neutrinos
9. Near future and final remarks

Motivation

the birth of neutrino astronomy: supernova 1987A



origin of cosmic rays: oldest problem in astroparticle physics



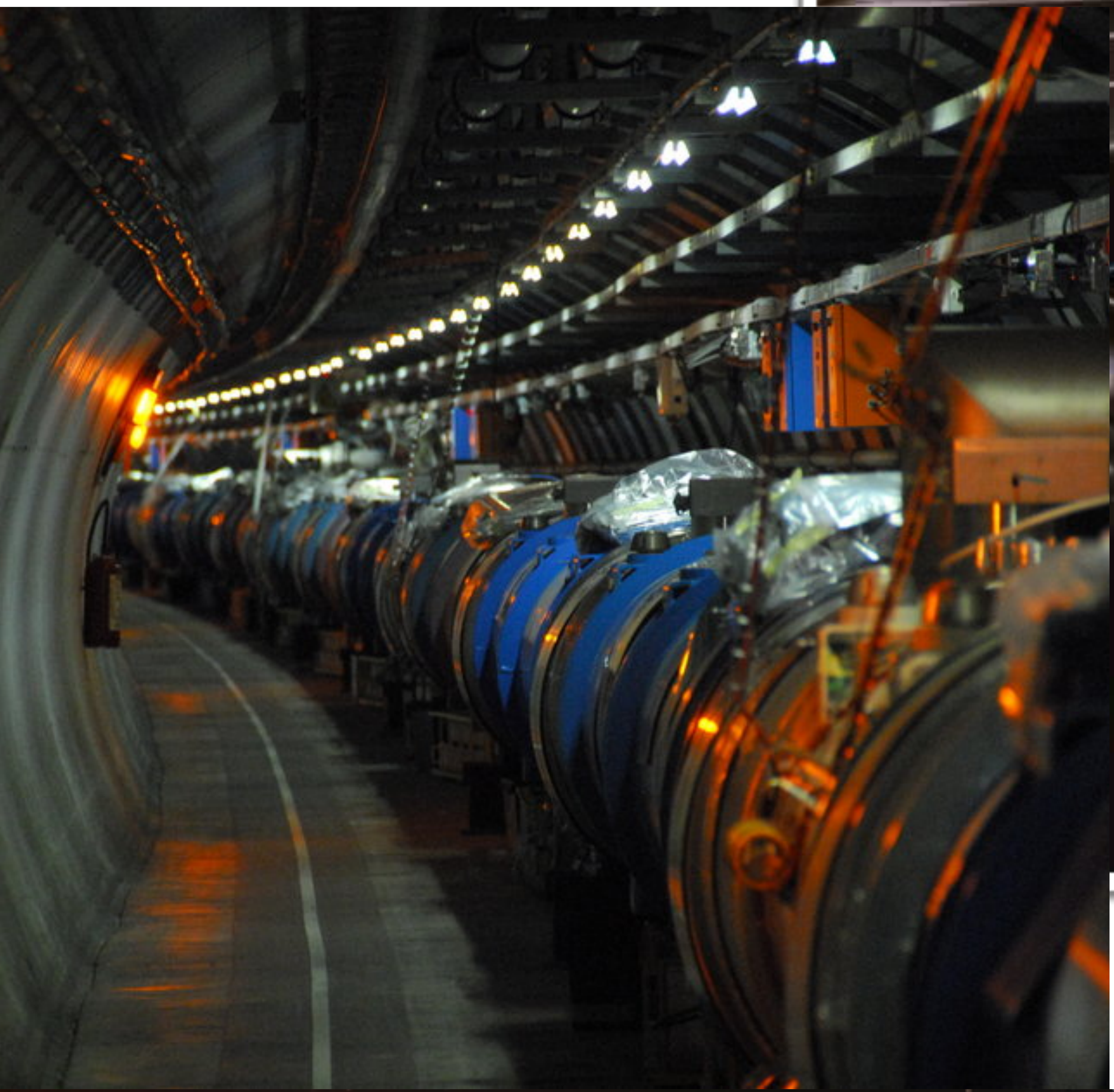
cosmic-ray challenge

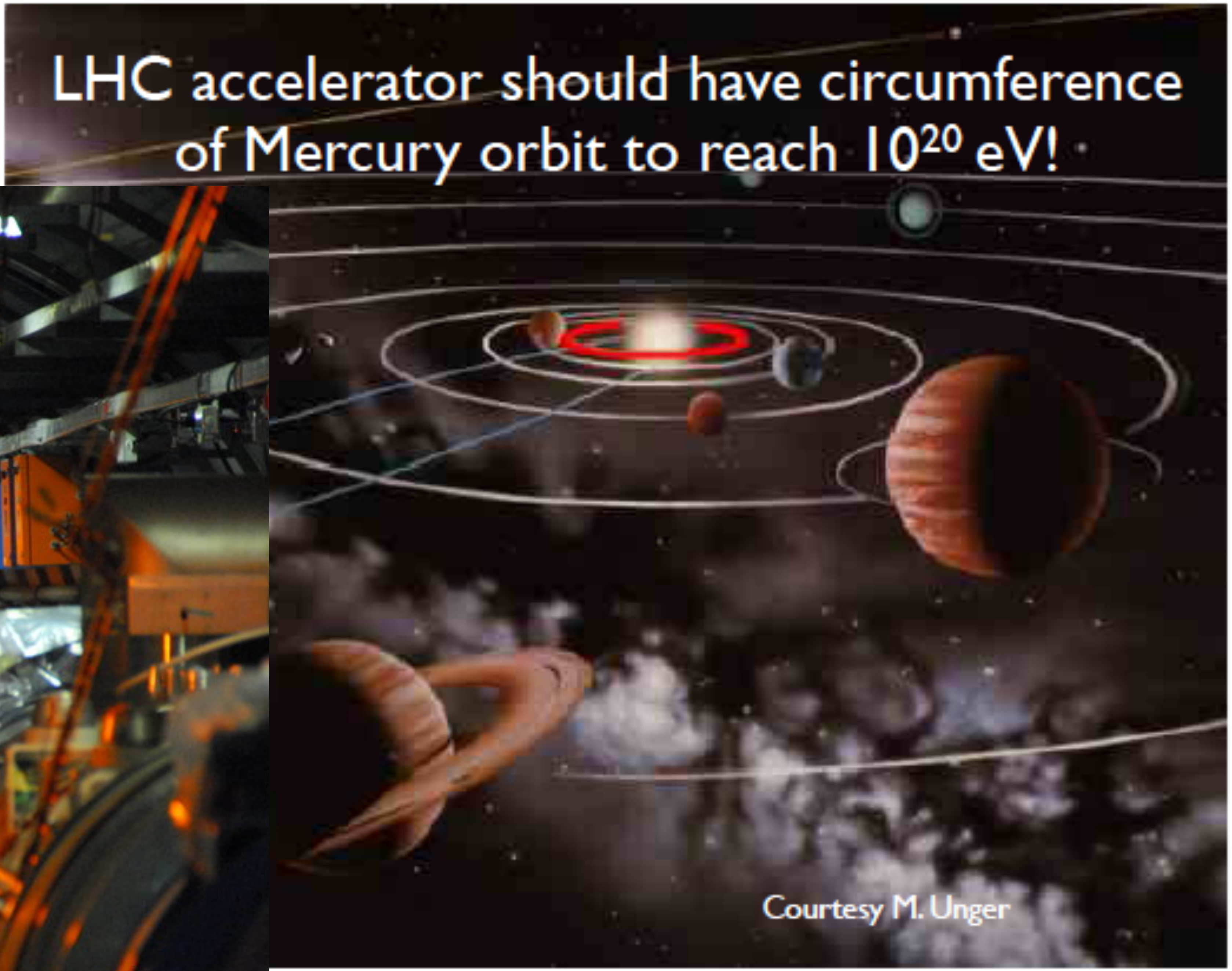
both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

highest energy radiation from the Universe: protons!

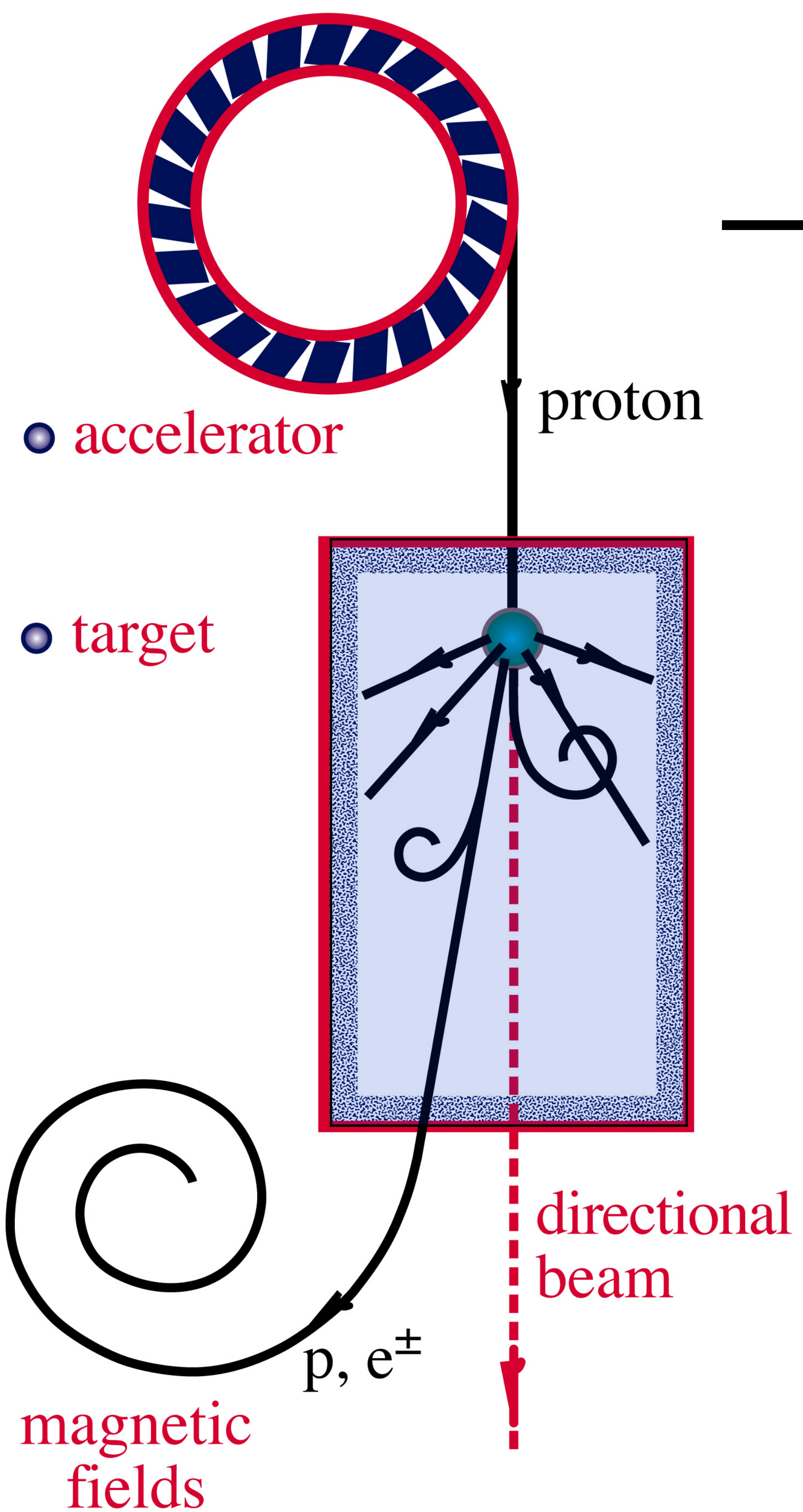
high energy
high luminosity





Fly's Eye 1991
300,000,000 TeV

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

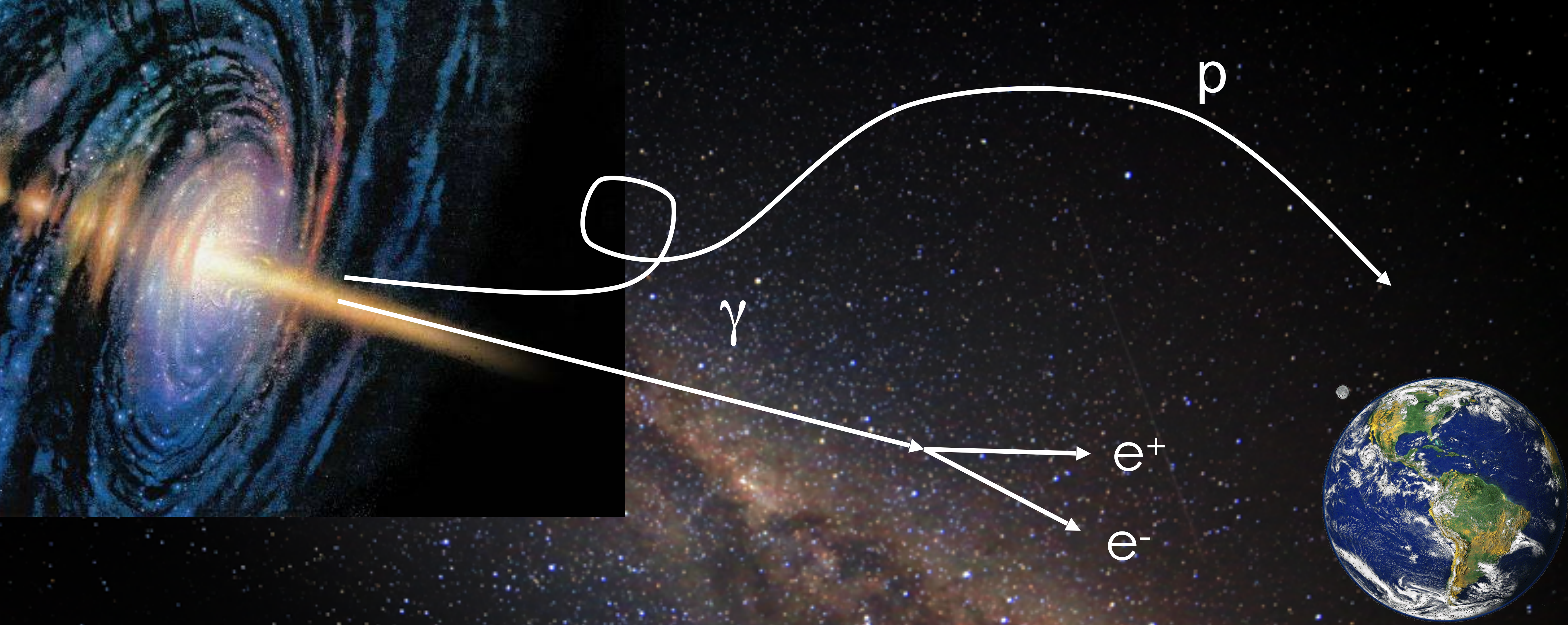
$p + \gamma \rightarrow n + \pi^{+}$

~ cosmic ray + neutrino

$\rightarrow p + \pi^{0}$

~ cosmic ray + gamma

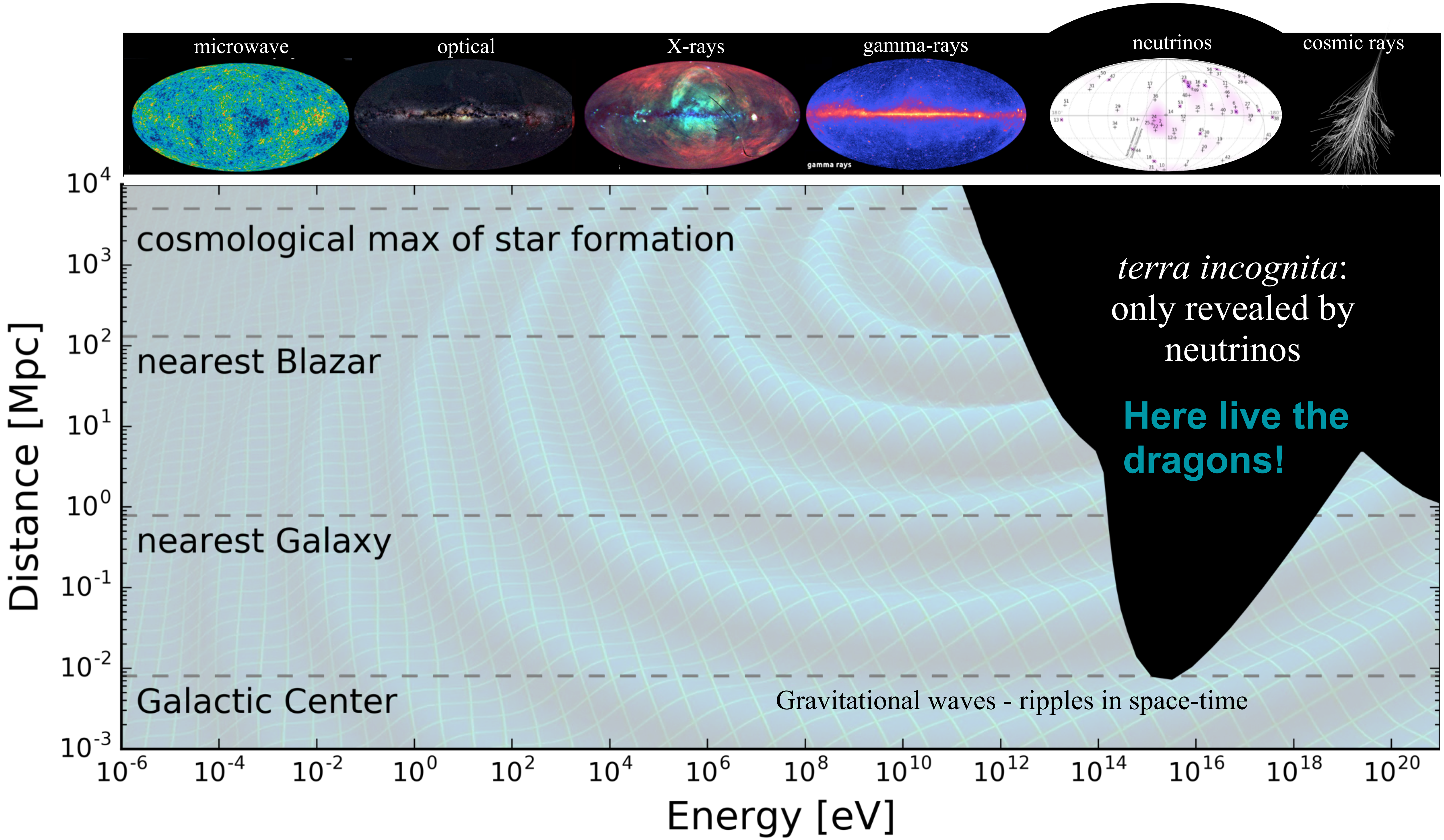
The opaque Universe



$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

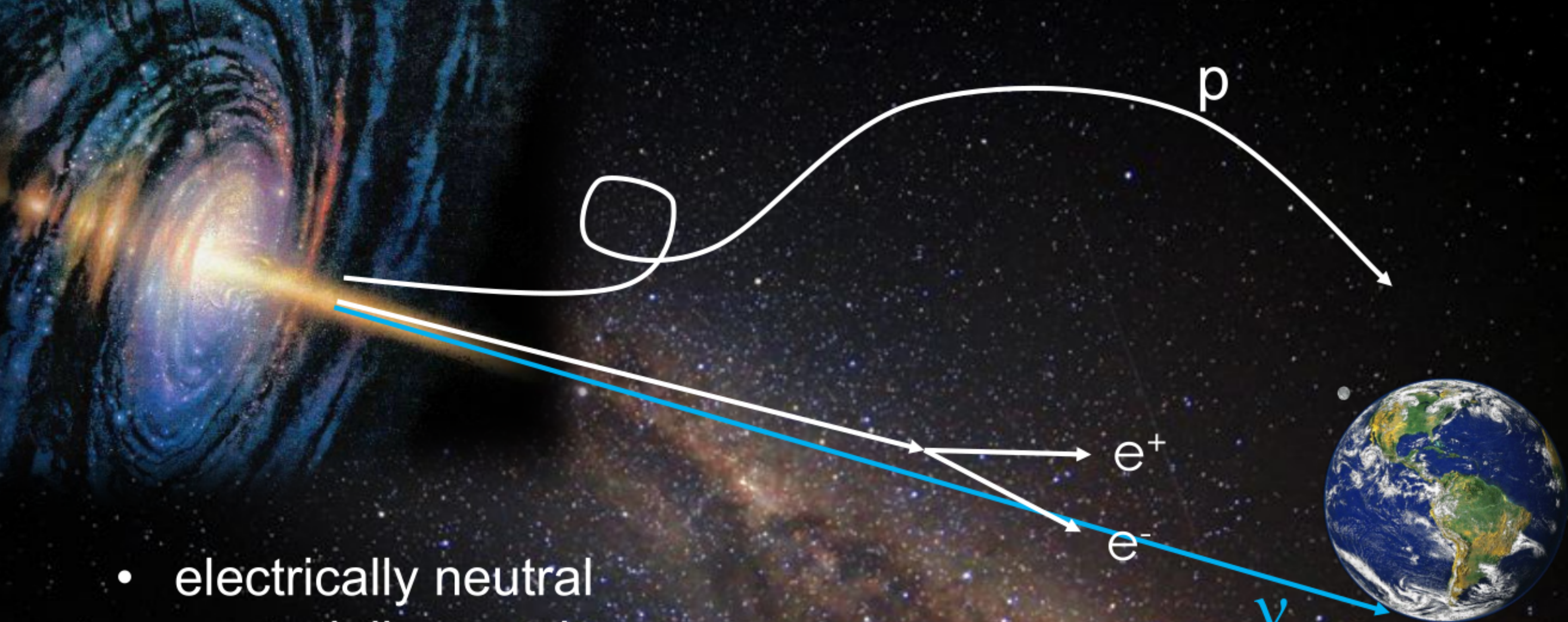
PeV photons interact with microwave photons (411/cm^3)
before reaching our telescopes
enter: neutrinos

highest energy "radiation" from the Universe: neutrinos and cosmic rays



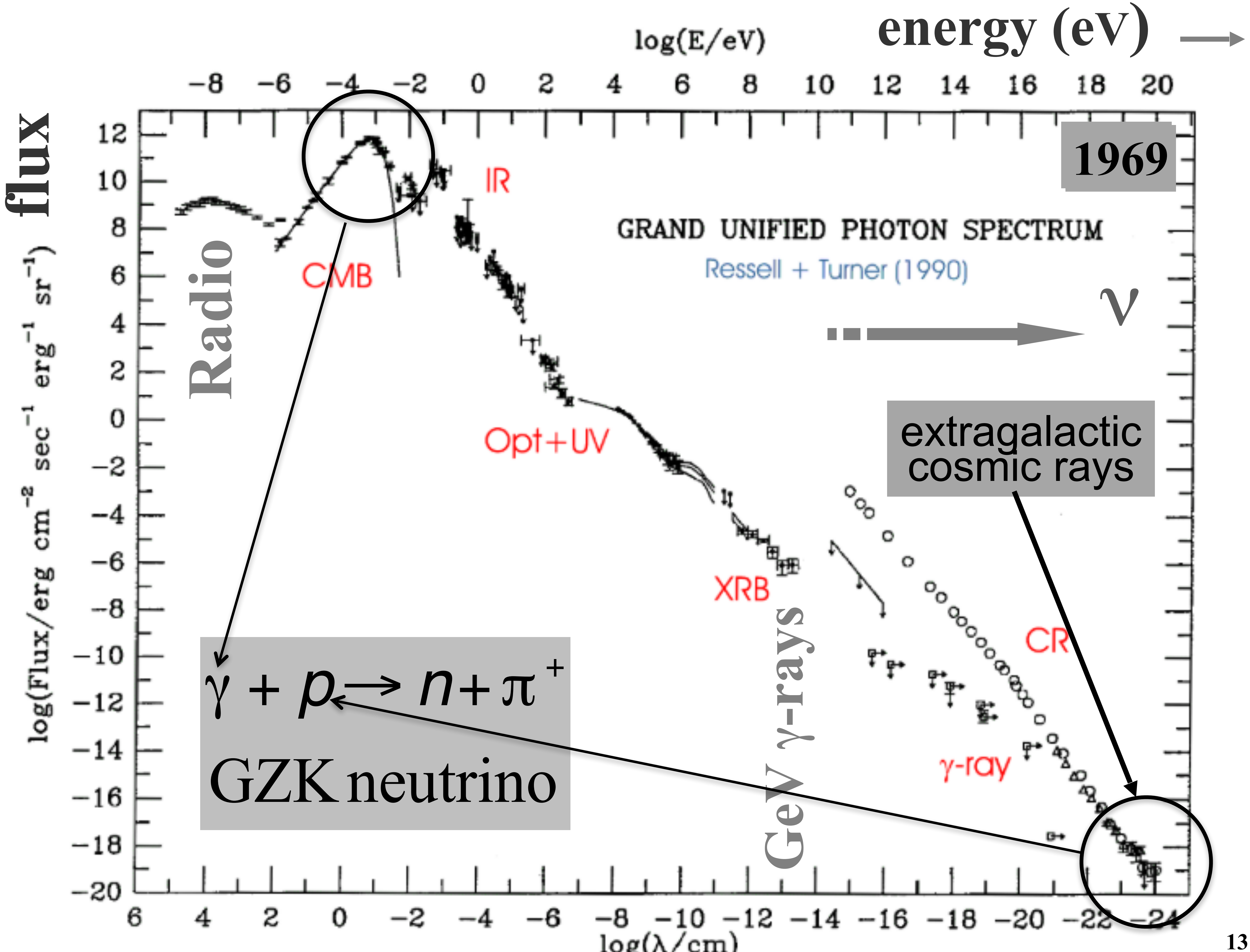
Universe is opaque above ~100 TeV energy

Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector?


energy (eV)
log(E/eV)
flux
1969
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
log(Flux/erg cm^-2 sec^-1 erg^-1 sr^-1)
log(λ/cm)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
CR
γ-ray
ν
extragalactic cosmic rays
γ + p → n + π+
GZK neutrino

cosmic-rays interact with the microwave background

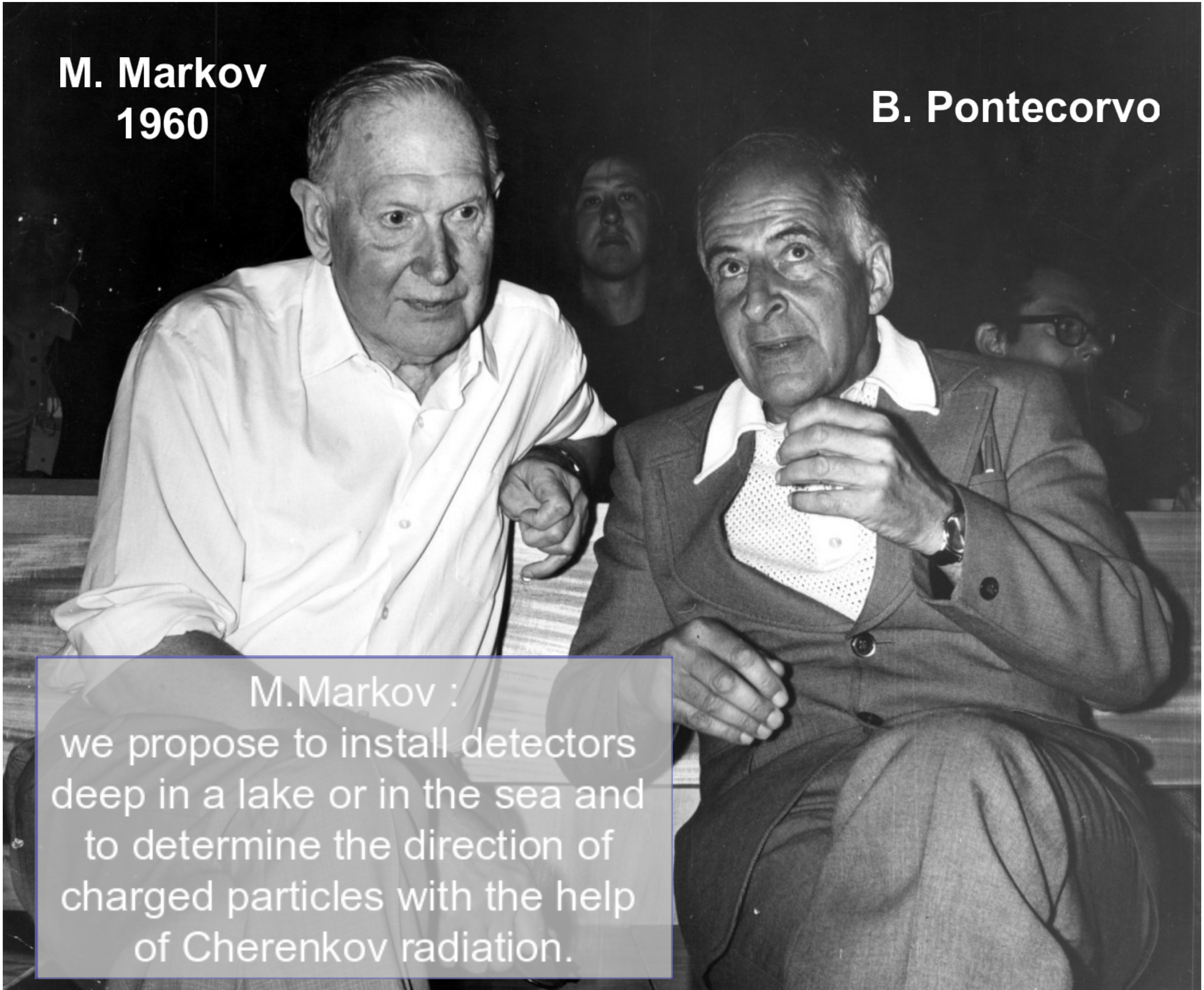
$$p+\gamma \rightarrow n+\pi^{+} \ \textit{and} \ p+\pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy **appear**

$$\pi \rightarrow \mu+\upsilon_{\mu} \rightarrow \{e+\overline{\upsilon_{\mu}}+\upsilon_{e}\}+\upsilon_{\mu}$$

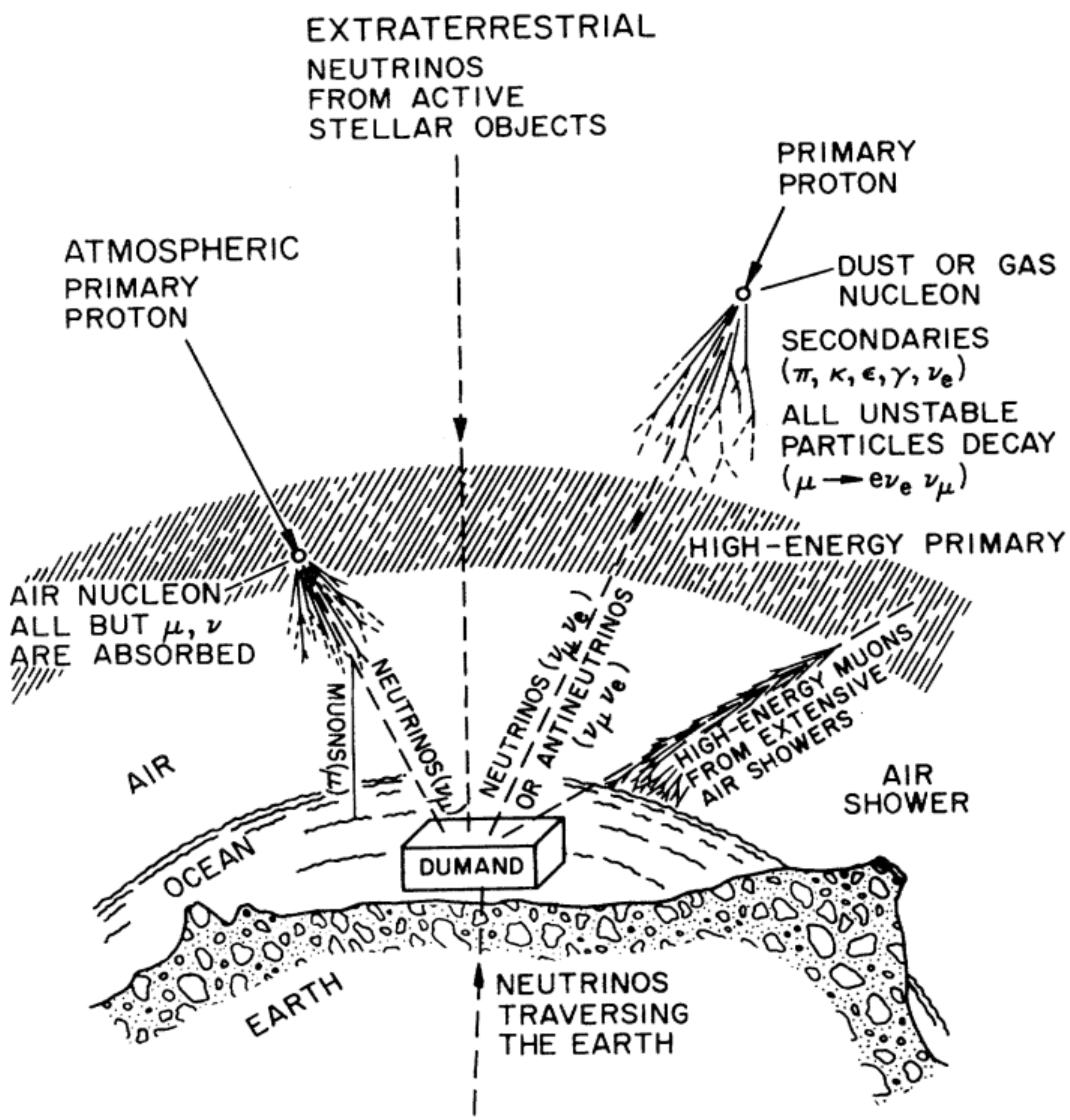
1 event per cubic kilometer per year

...but it points at its source!


M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

Pioneers

DUMAND: Deep Underwater Muon and Neutrino Detector (1973-1995)



Art Roberts, Rev.Mod.Phys. 64 (1992) 259-312
Christian Spiering and Uli Katz, Prog.Part.Nucl.Phys. 67 (2012) 651-704

DUMAND: Deep Underwater Muon and Neutrino Detector (1973-1995)

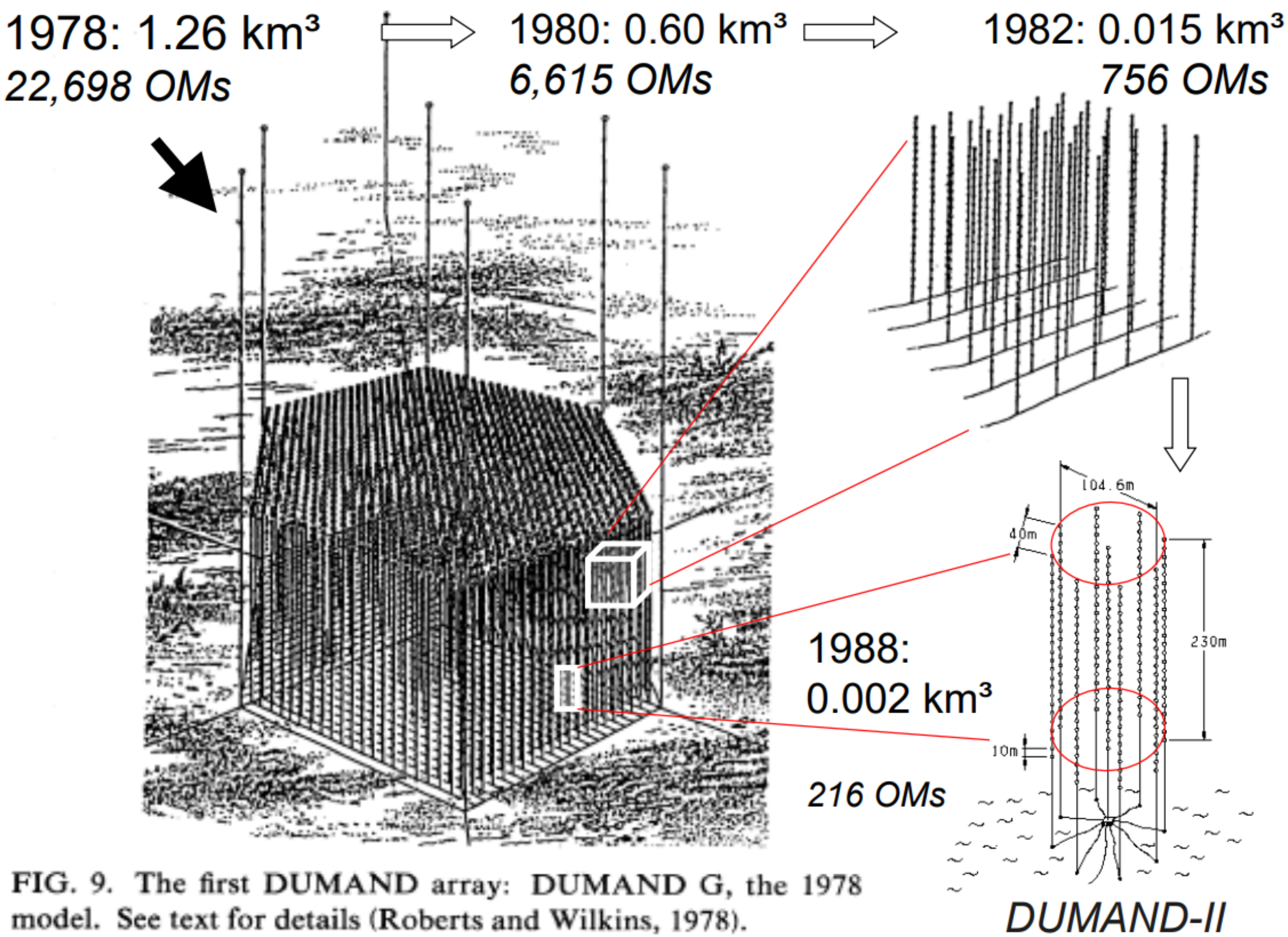
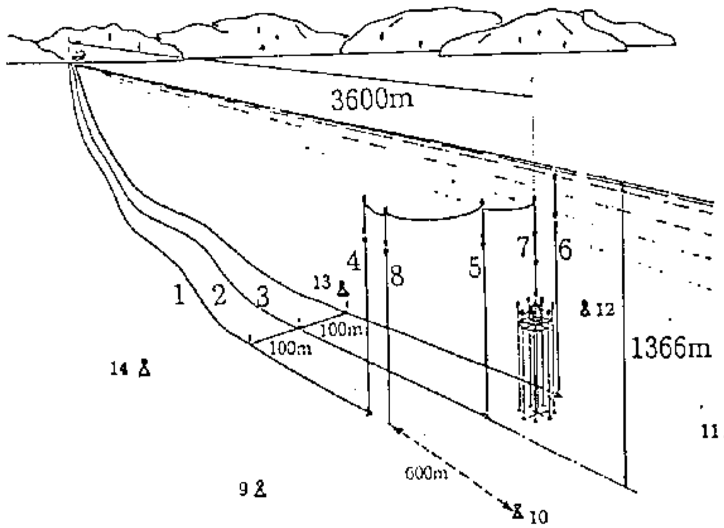
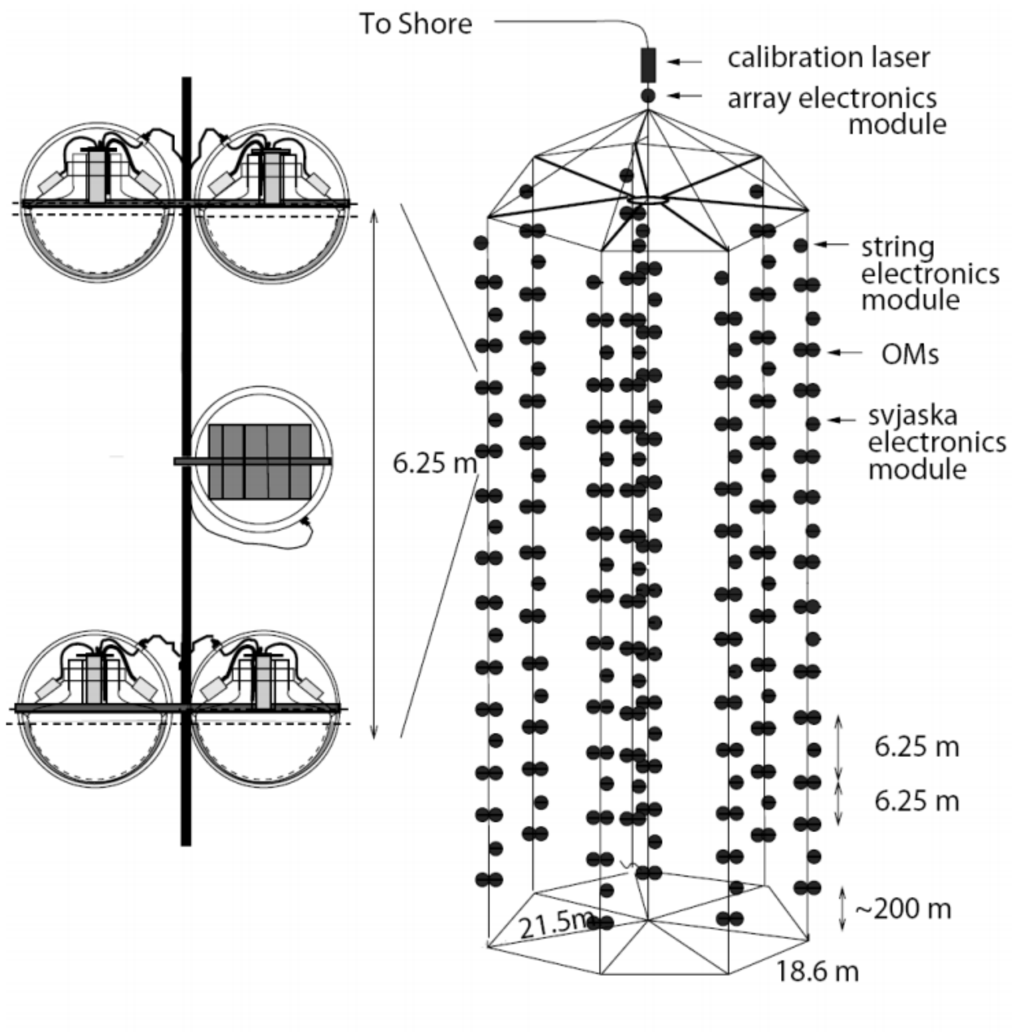


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

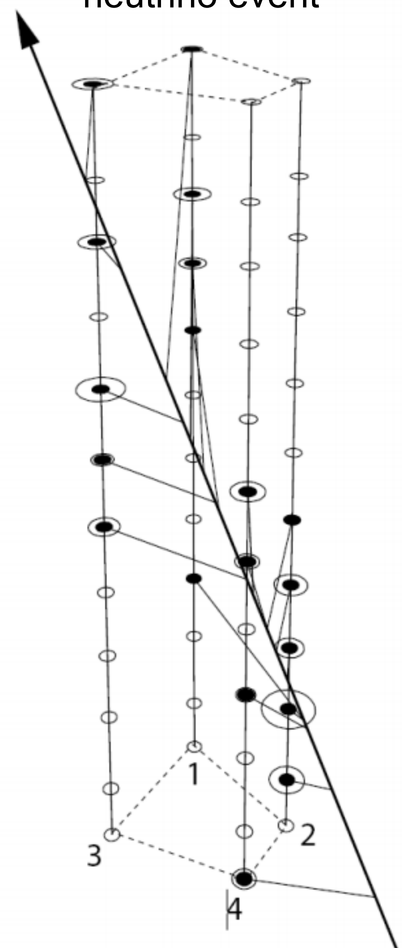
Art Roberts, Rev.Mod.Phys. 64 (1992) 259-312
Christian Spiering and Uli Katz, Prog.Part.Nucl.Phys. 67 (2012) 651-704

Baikal Neutrino Telescope (1993-1996)



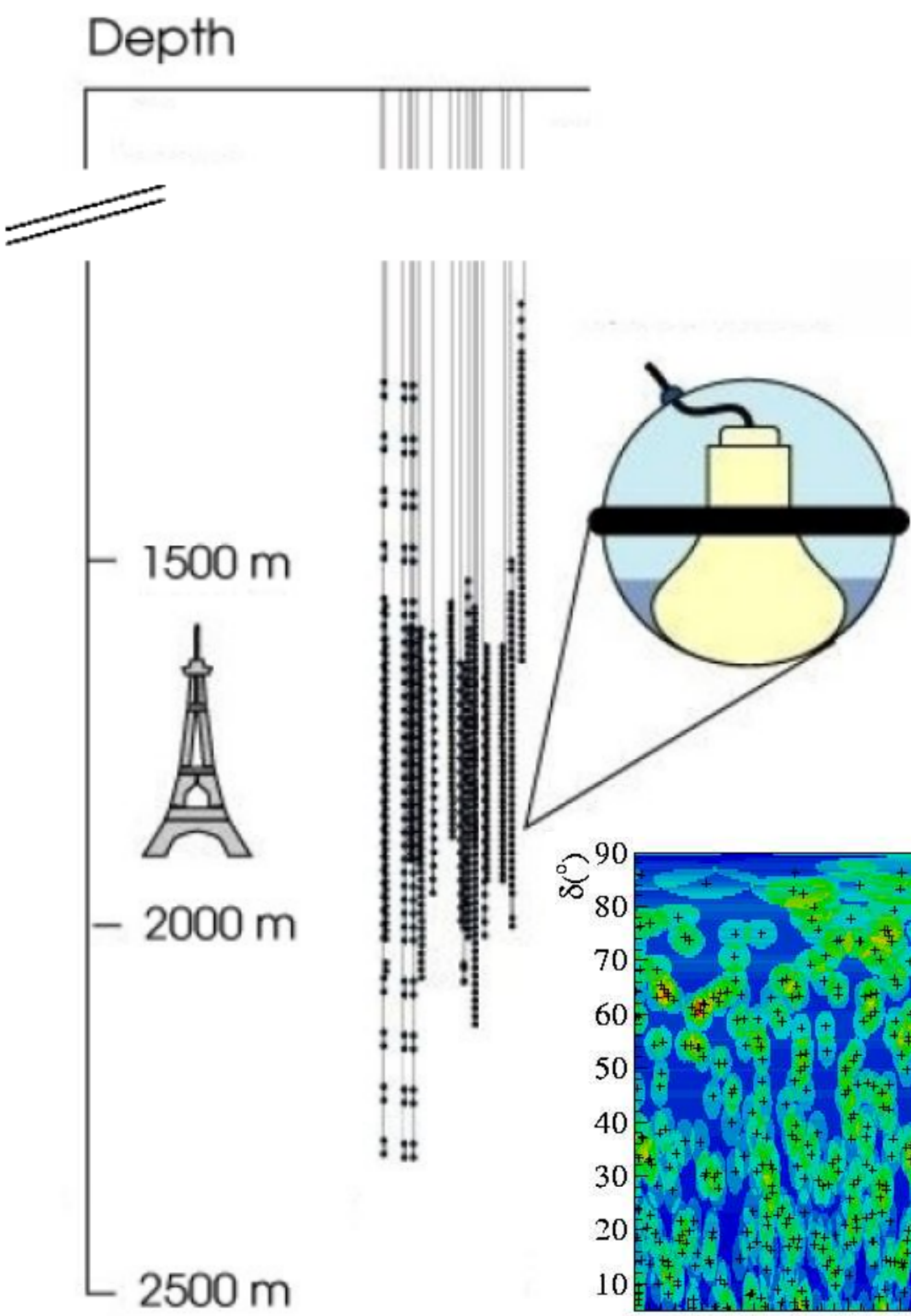


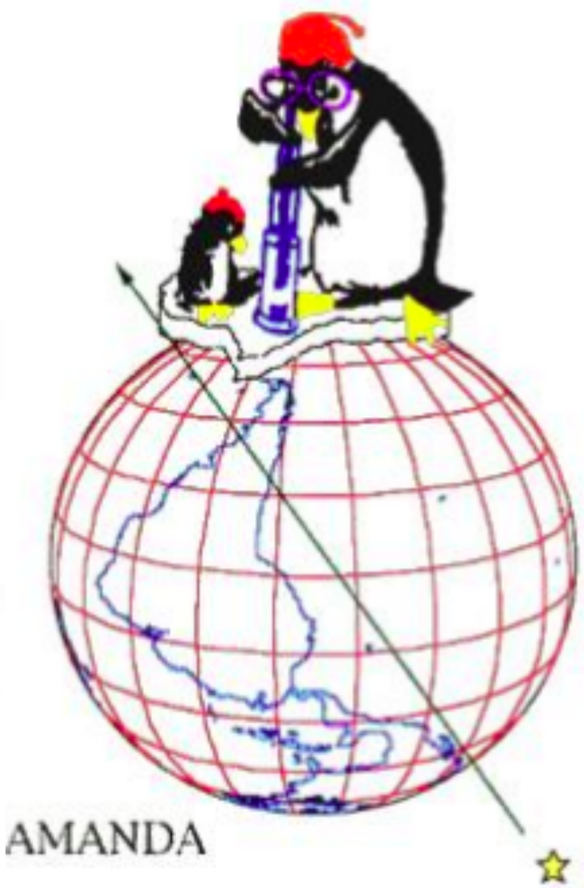
1996 first up-going muon neutrino event

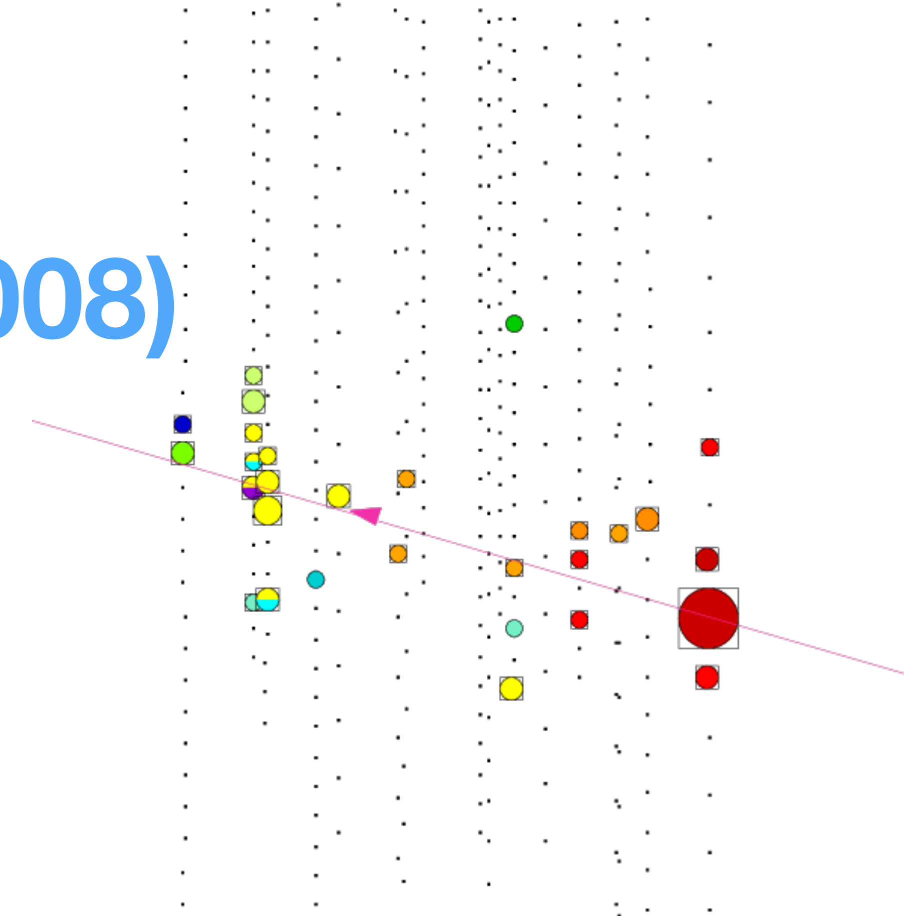


Art Roberts, Rev.Mod.Phys. 64 (1992) 259-312
Christian Spiering and Uli Katz, Prog.Part.Nucl.Phys. 67 (2012) 651-704

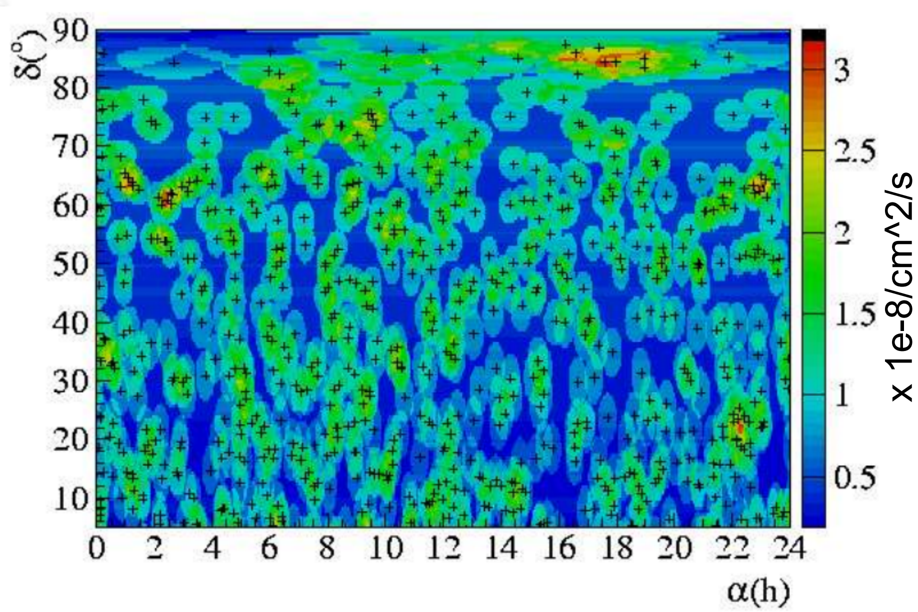
AMANDA: Antarctic Muon And Neutrino Detection Array (1993-2008)



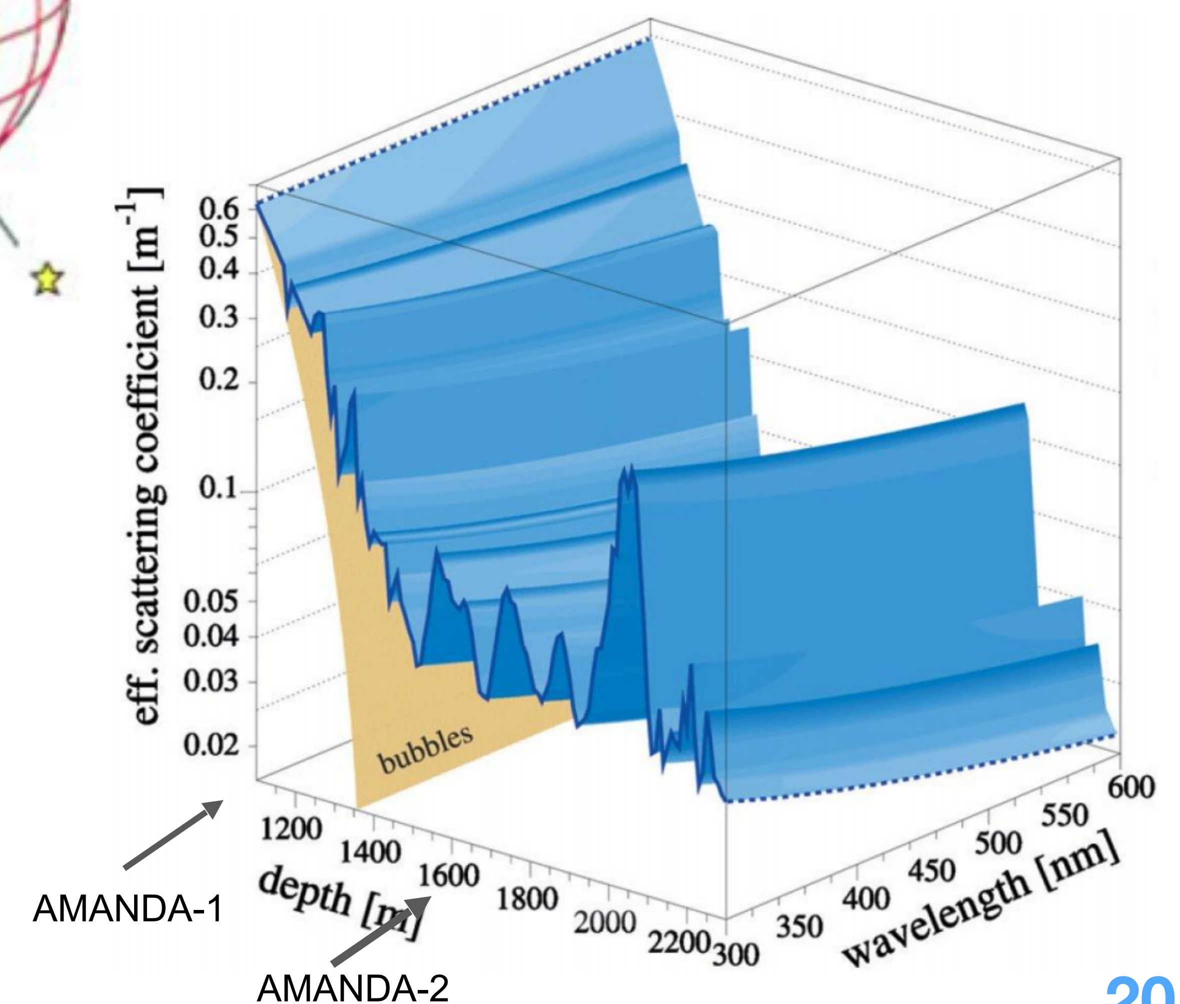




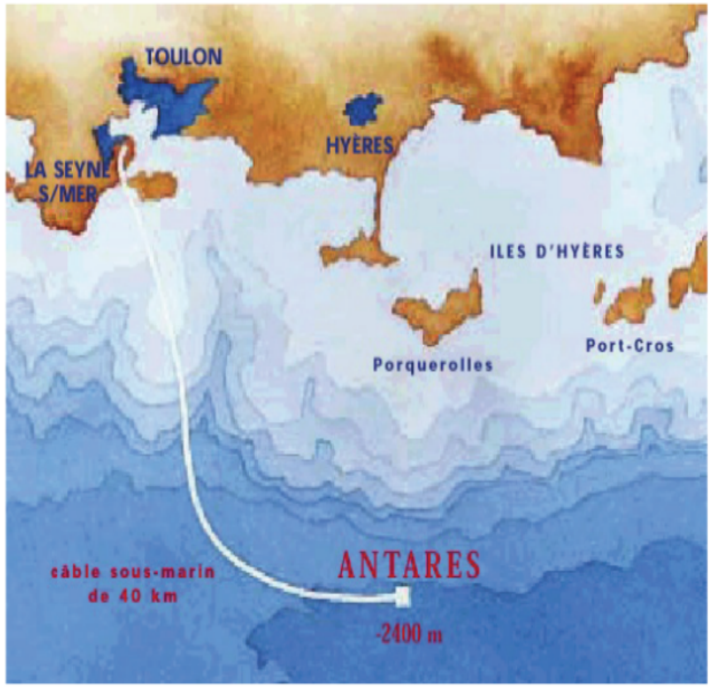
Atmospheric neutrino event candidate observed by AMANDA-2

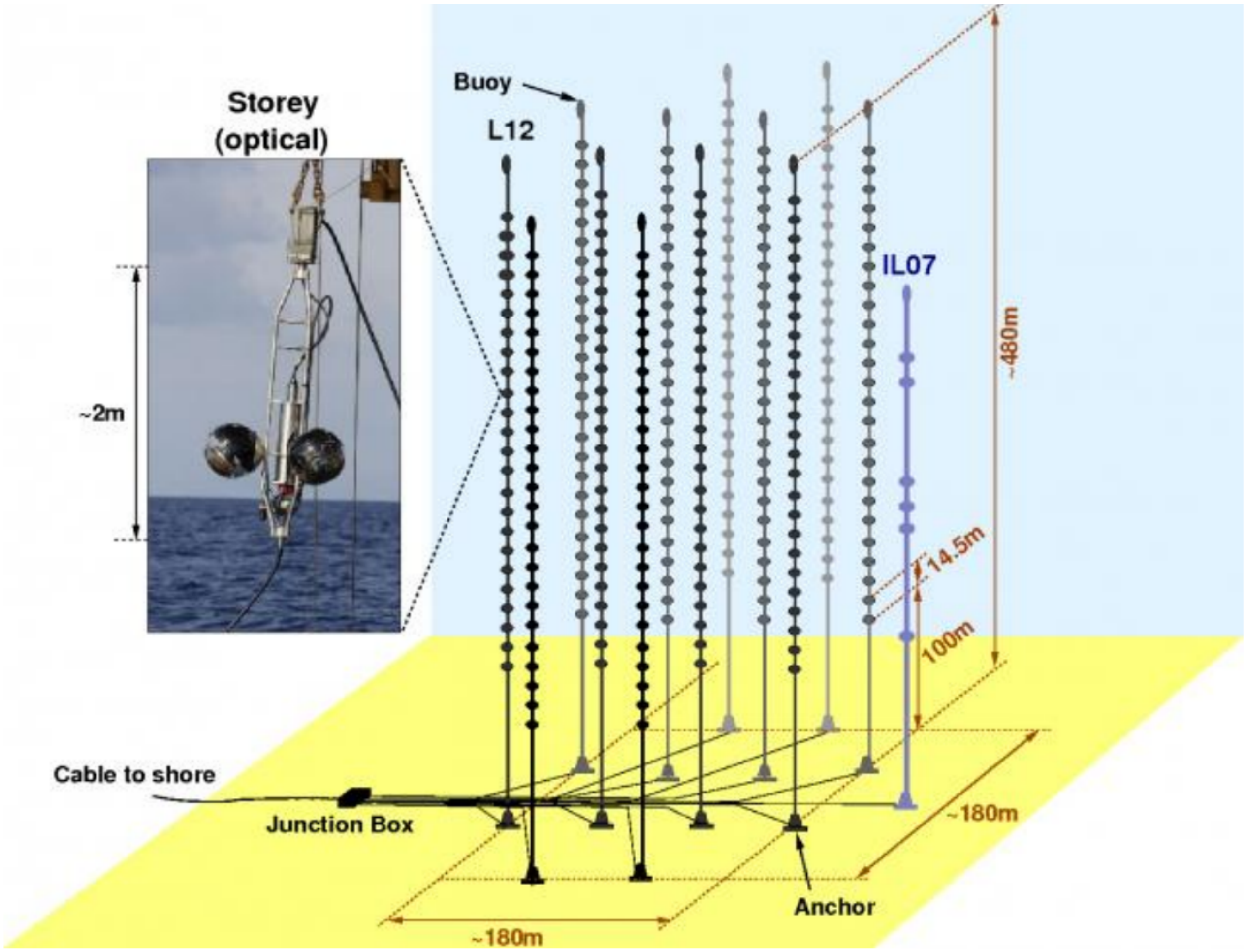


AMANDA Collaboration Phys.Rev.D71:077102,2005

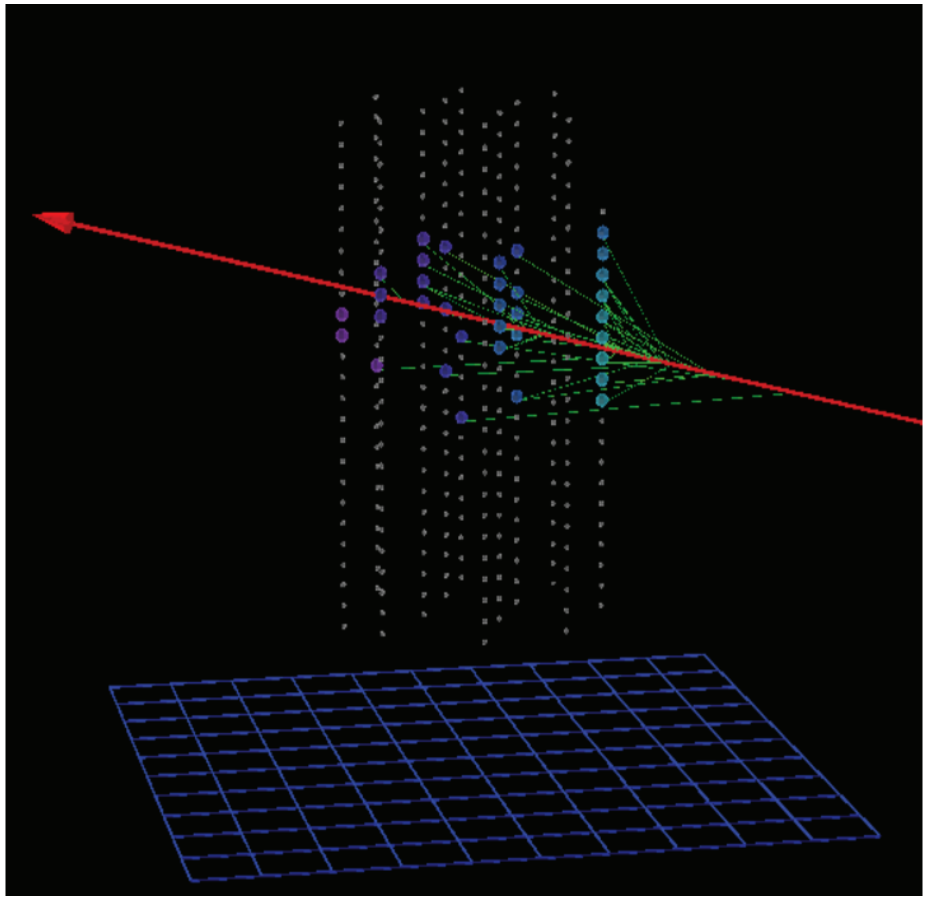


ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch (2002 - present)



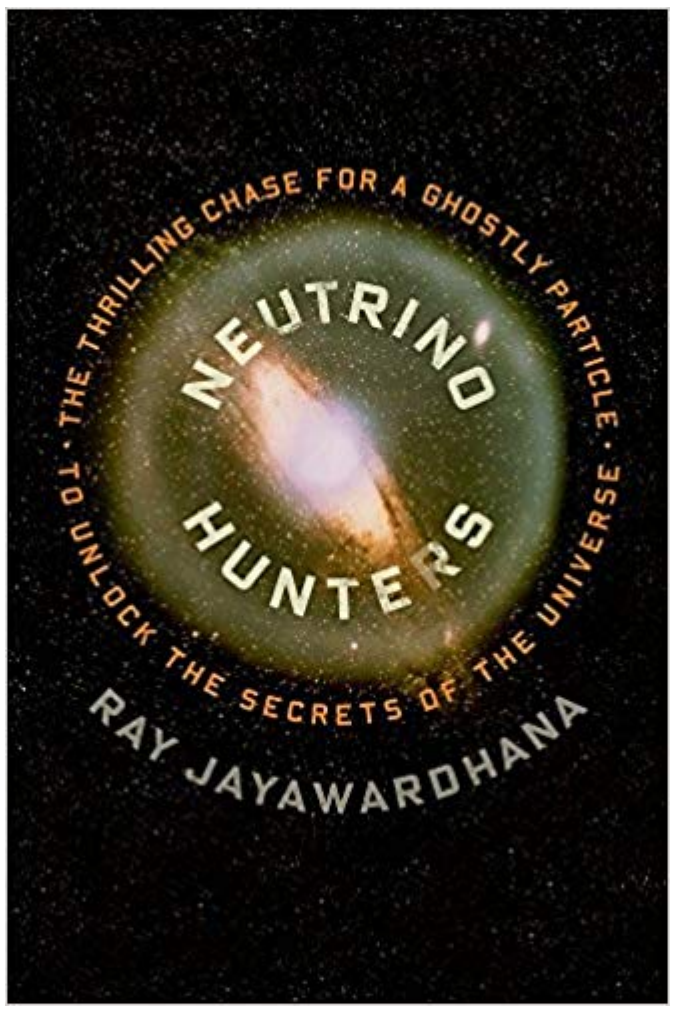


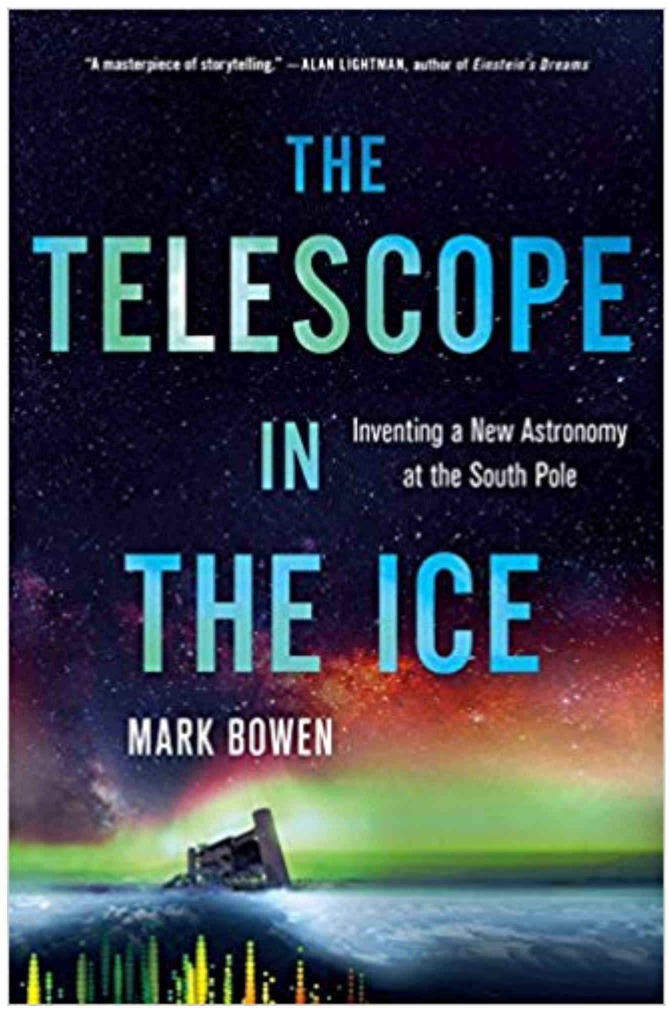
Candidate neutrino event display



That is all the history I am going to cover, but these are nice and fun reads

Art Roberts, Rev.Mod.Phys. 64 (1992) 259-312
Christian Spiering and Uli Katz, Prog.Part.Nucl.Phys. 67 (2012) 651-704
Christian Spiering European Physics Journal H, 2012





Towards High-Energy Neutrino Astronomy

A Historical Review

Christian Spiering[a]

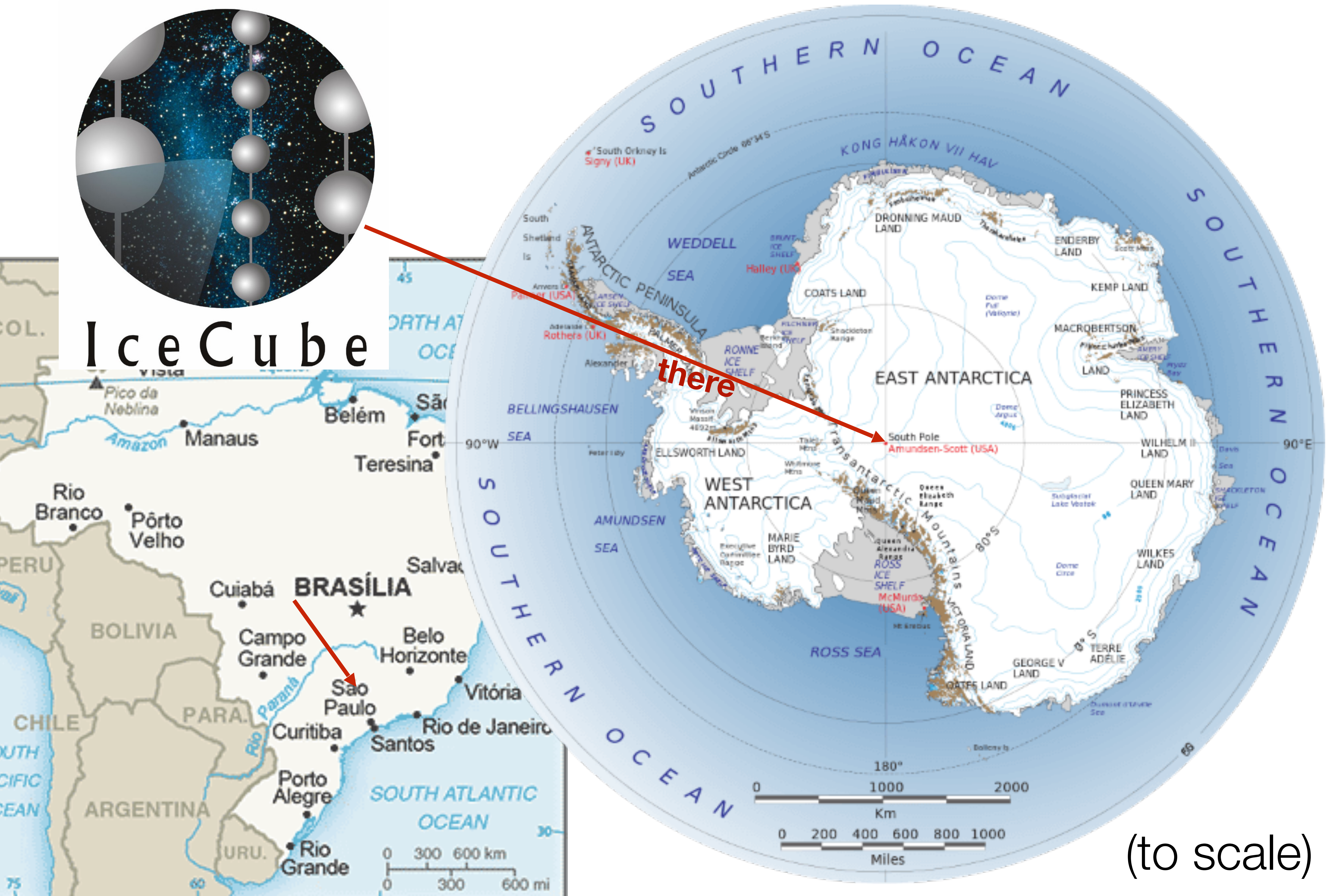
DESY, Platanenallee, D-15738 Zeuthen

Abstract. The search for the sources of cosmic rays is a three-fold assault, using charged cosmic rays, gamma rays and neutrinos. The first conceptual ideas to detect high energy neutrinos date back to the late fifties. The long evolution towards detectors with a realistic discovery potential started in the seventies and eighties, with the pioneering works in the Pacific Ocean close to Hawaii and in Lake Baikal in Siberia. But only now, half a century after the first concepts, such a detector is in operation: IceCube at the South Pole. We do not yet know whether with IceCube we will indeed detect extraterrestrial high energy neutrinos or whether this will remain the privilege of next generation telescopes. But whatever the answer will be: the path to the present detectors was a remarkable journey. This review sketches its main milestones.

http://neutrinohistory2018.in2p3.fr/

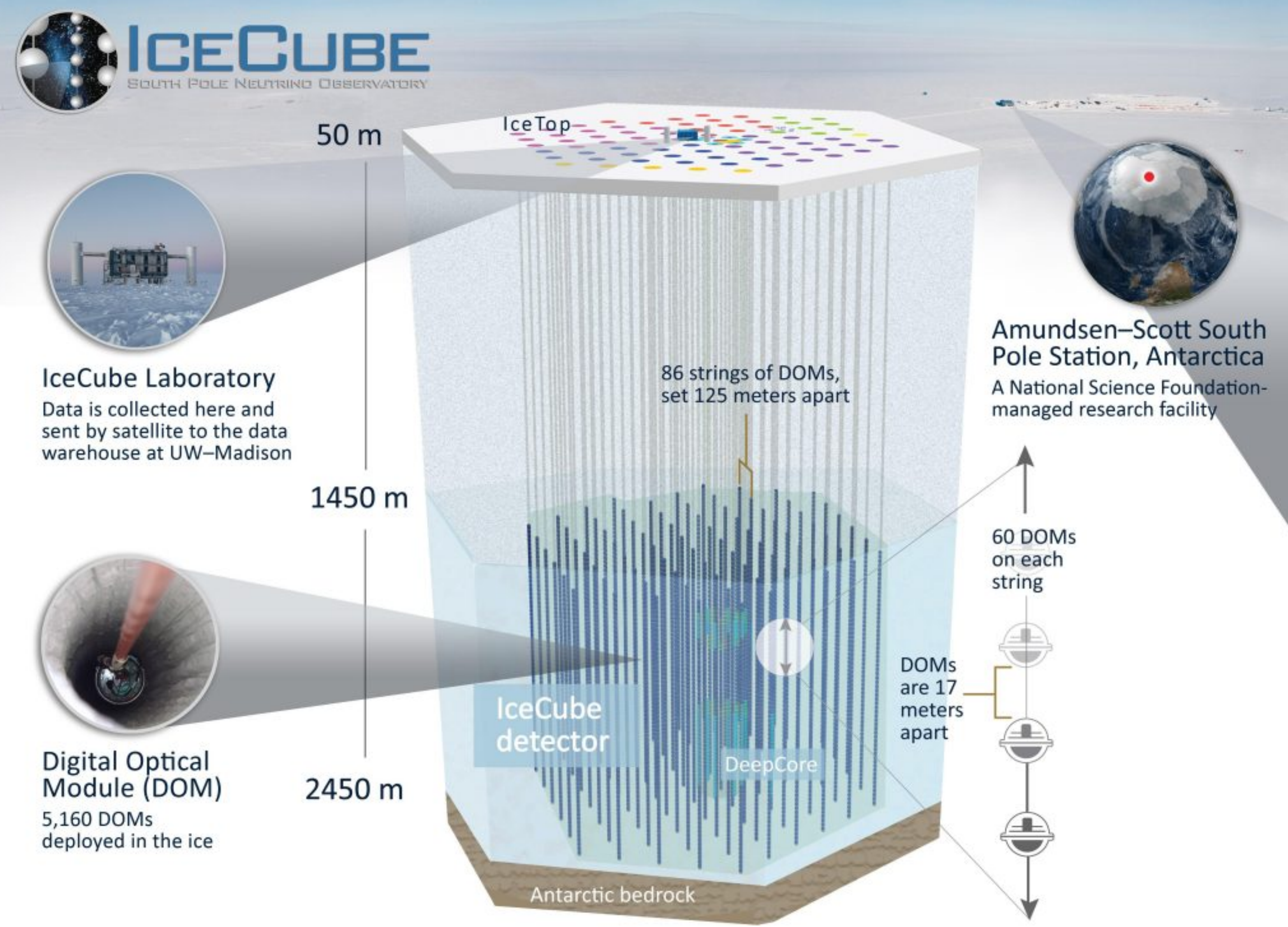
IceCube detection principles and reconstruction techniques

The IceCube experiment

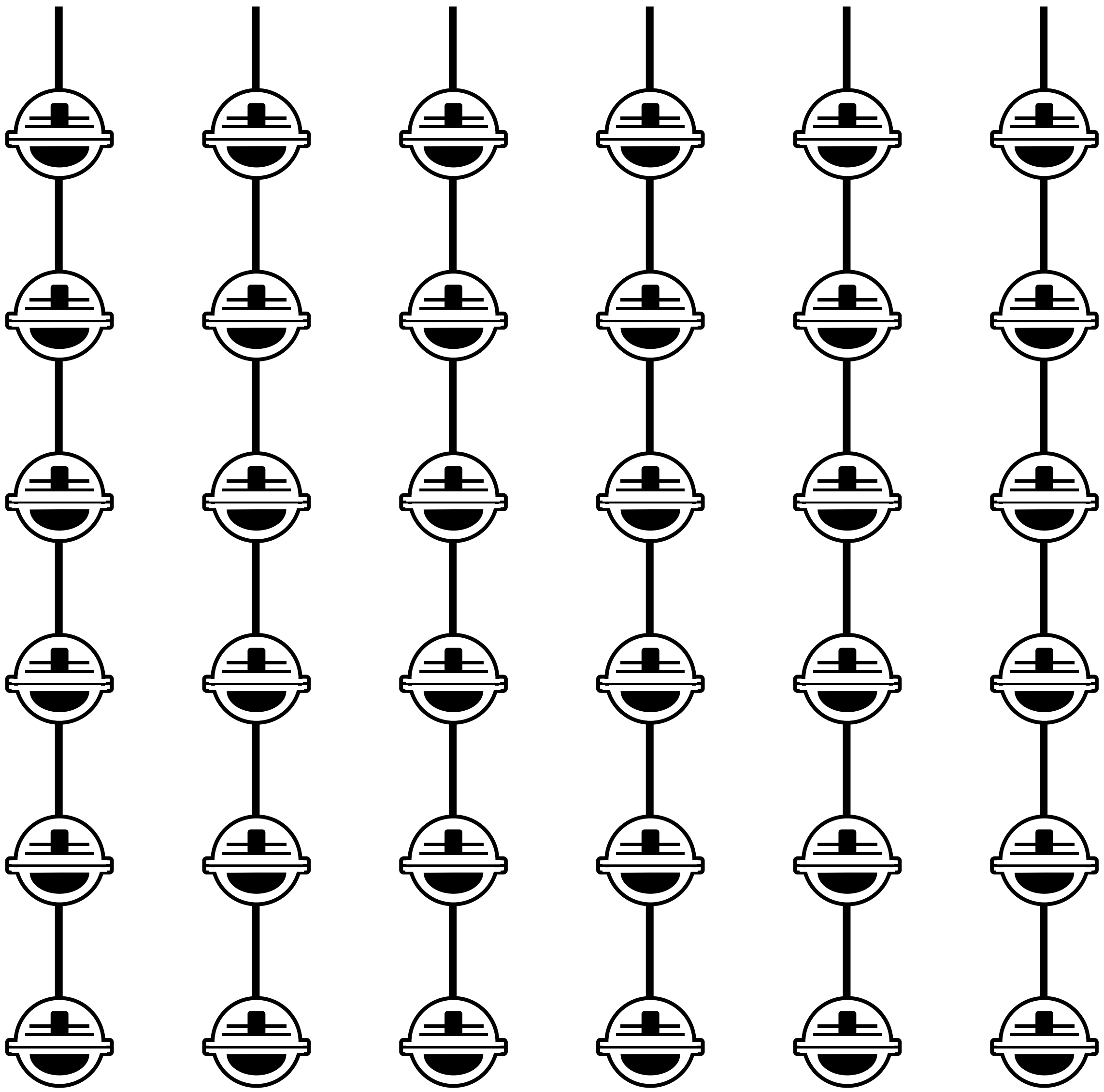


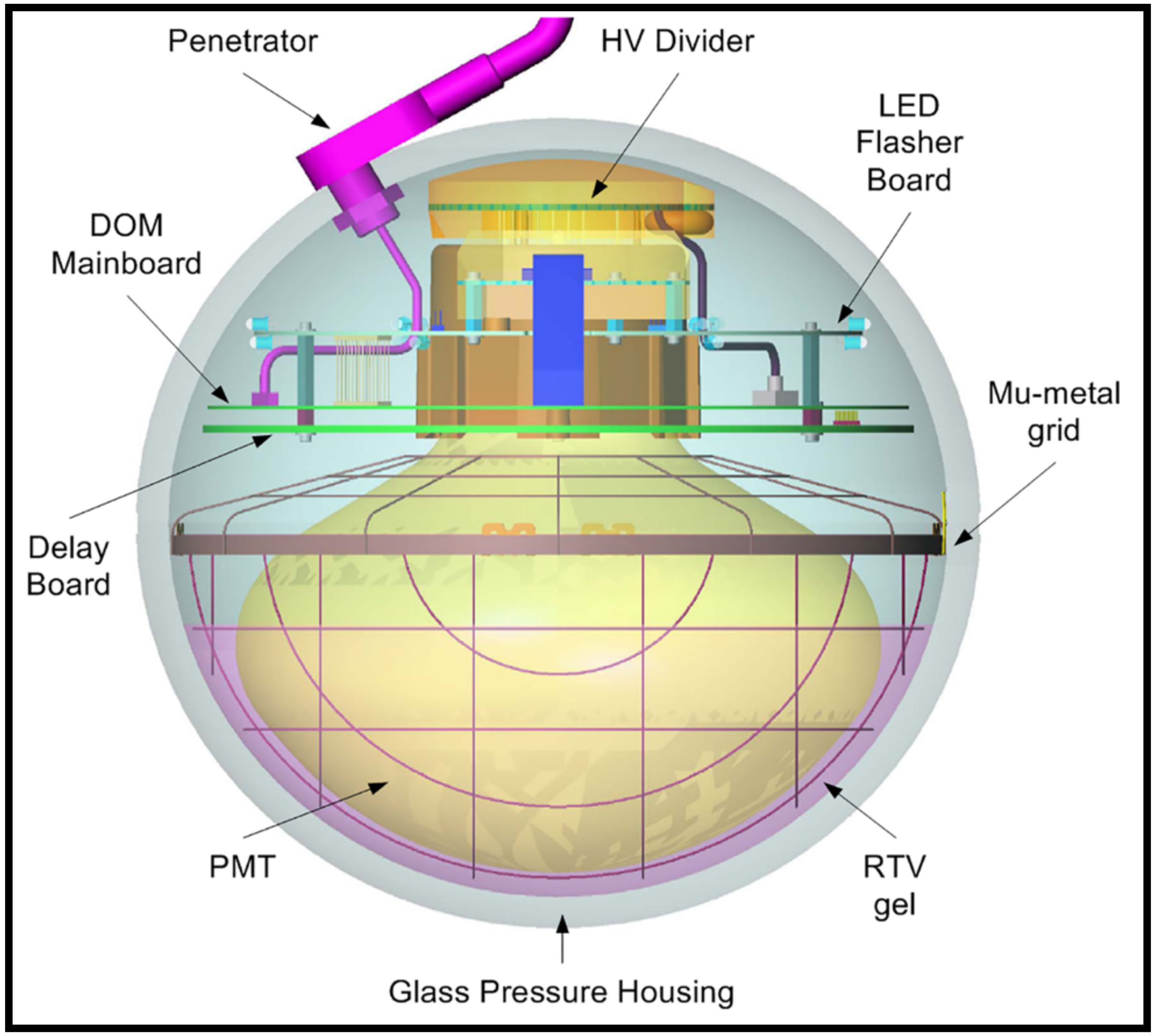
(to scale)


TWRT

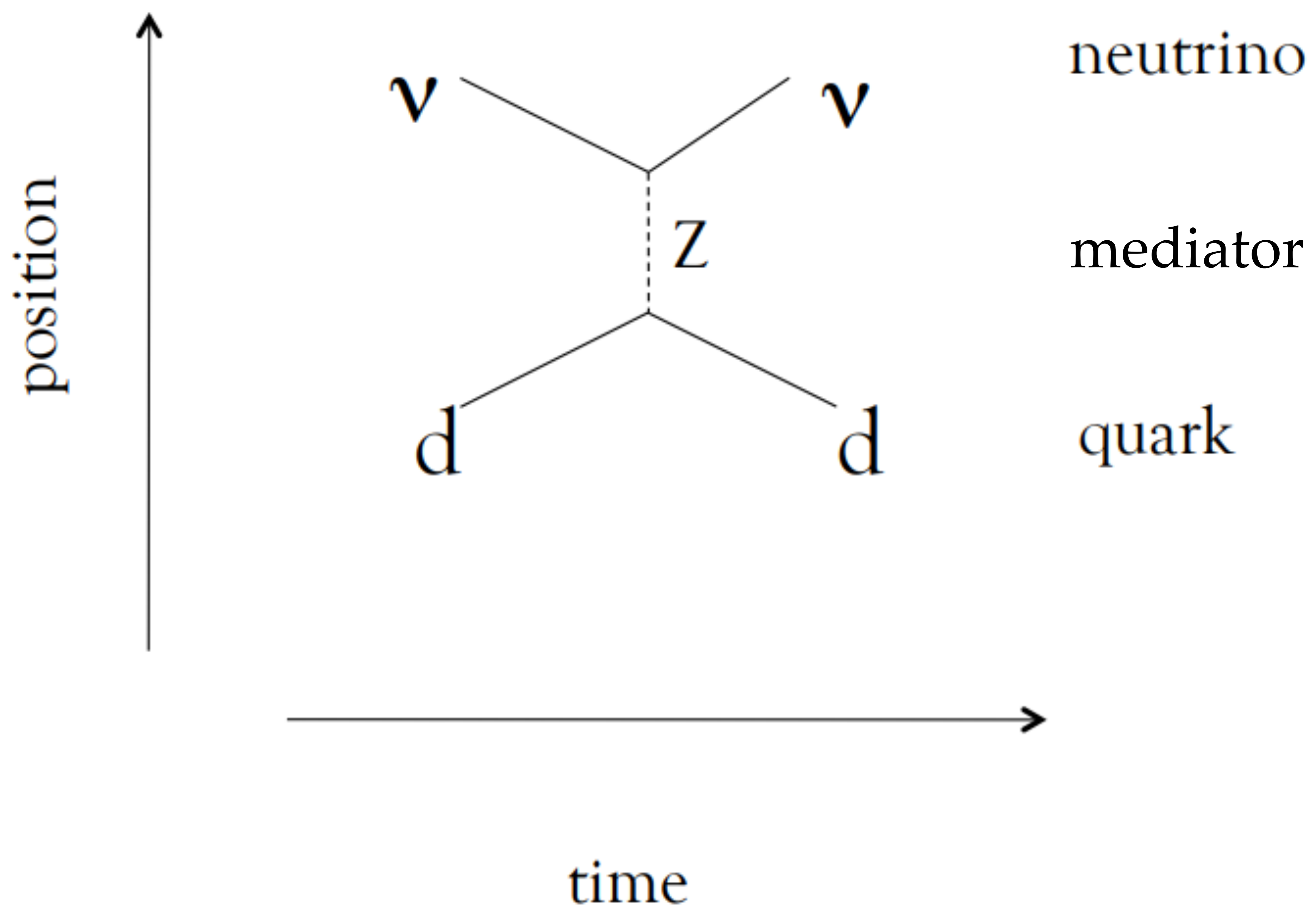

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

Digital Optical Module (DOM)

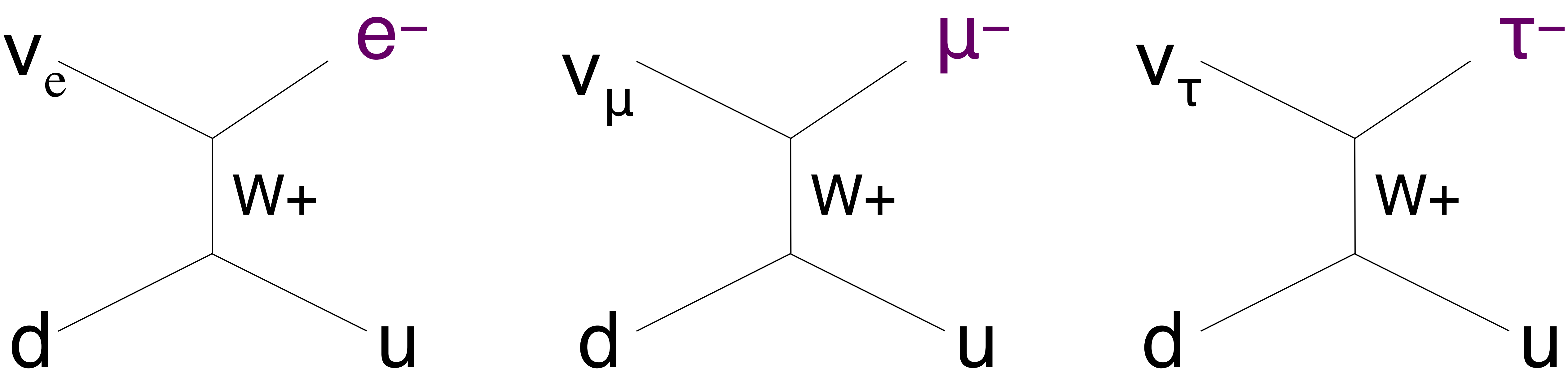


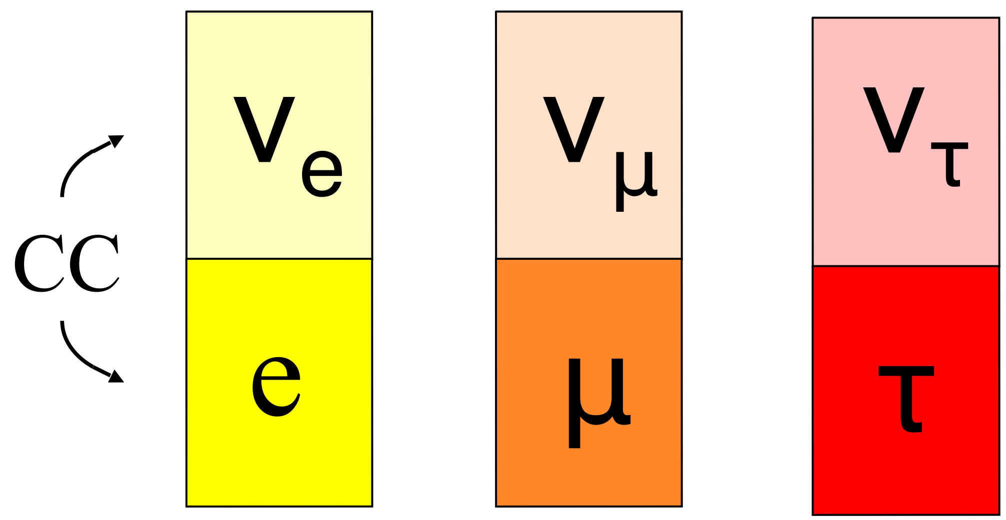


We describe interactions in terms of "exchange particles"

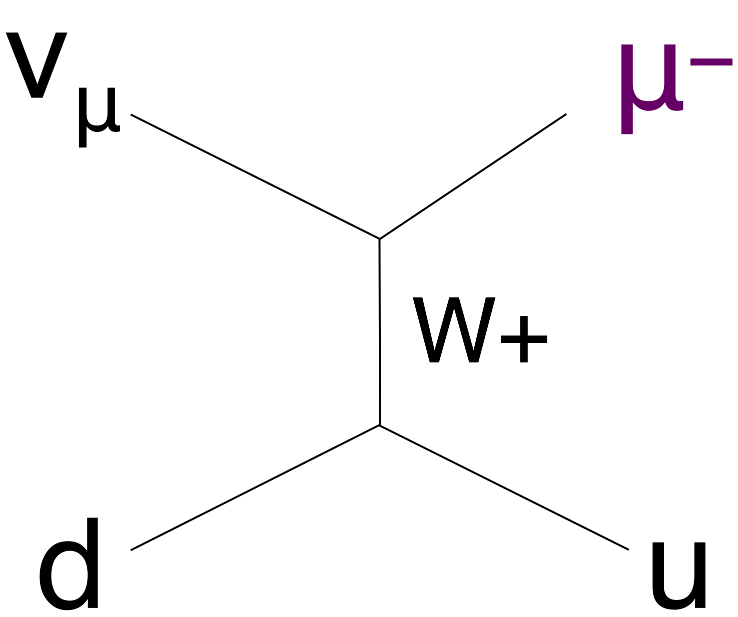


We use the outgoing particle to classify the neutrino. We term this neutrino “flavor.”

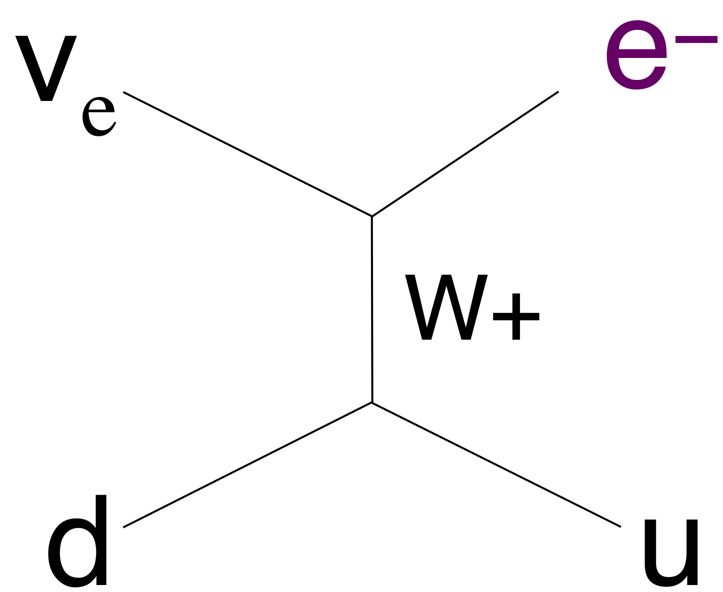




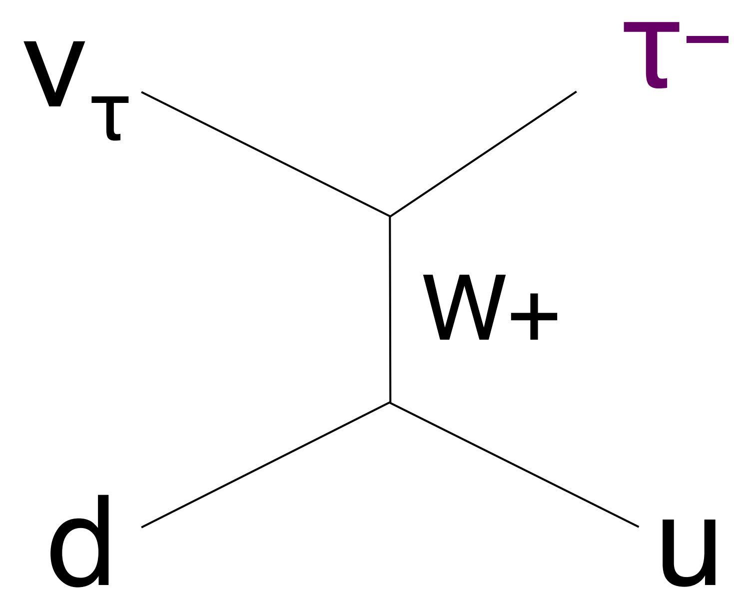
All charge-current Interactions



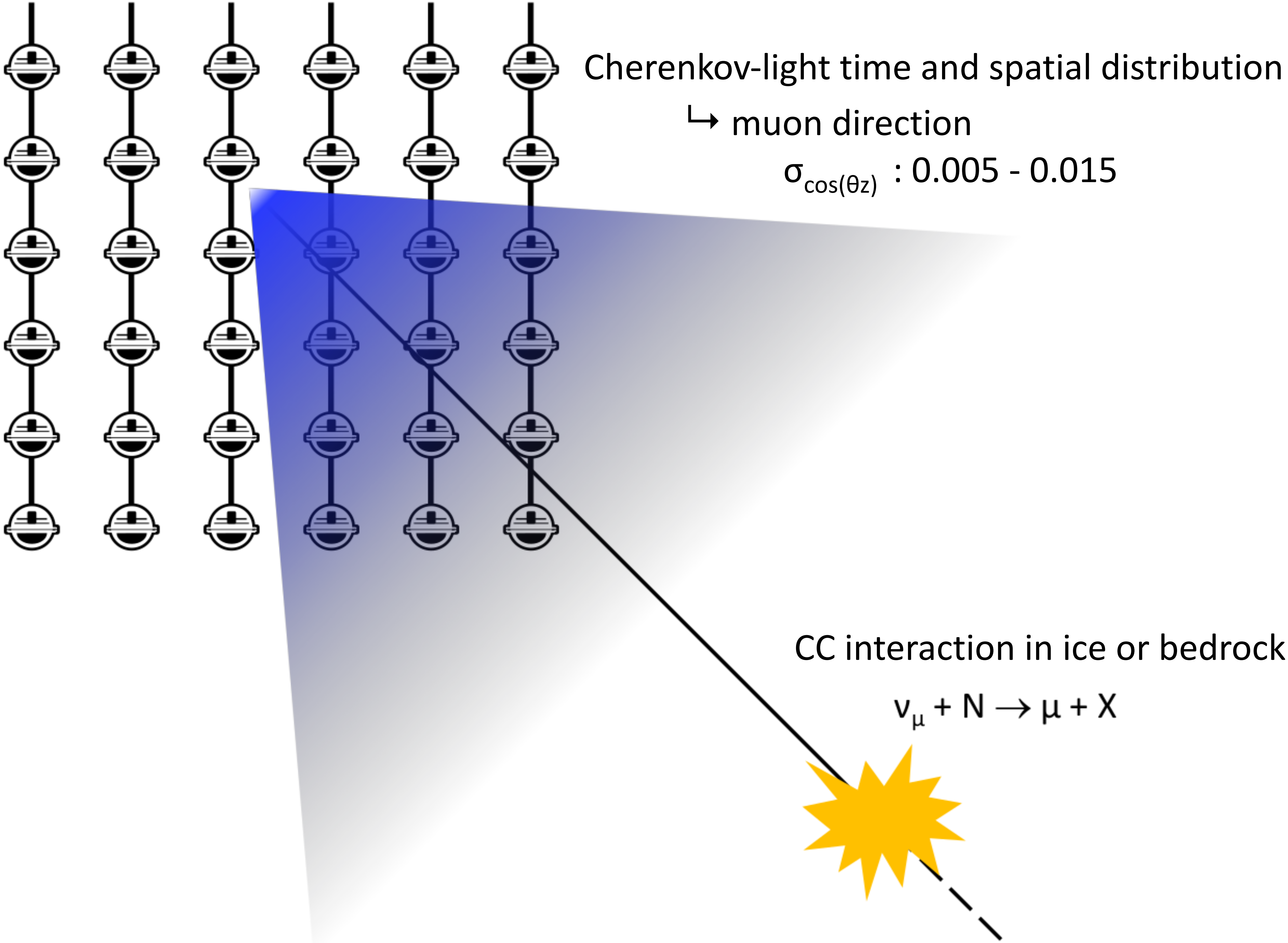
Events can start in the detector or below it (throughgoing).



Events must be contained or partially contained in the detector.

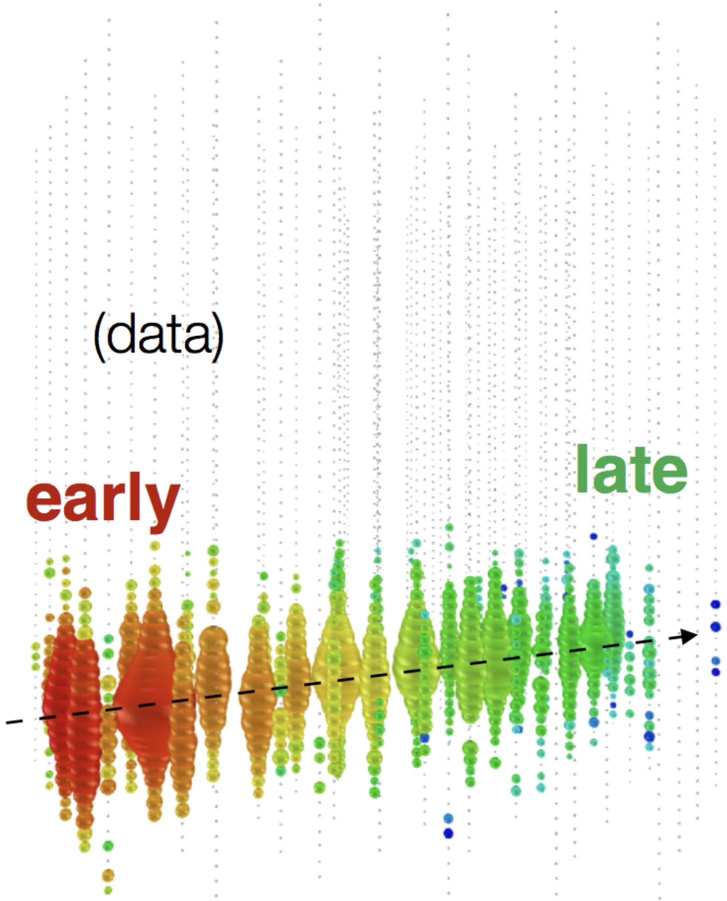


Events must be contained in the detector.


Cherenkov-light time and spatial distribution
↳ muon direction
$\sigma_{\cos(\theta z)}$: 0.005 - 0.015
CC interaction in ice or bedrock
$\nu_\mu + N \rightarrow \mu + X$

All event morphologies

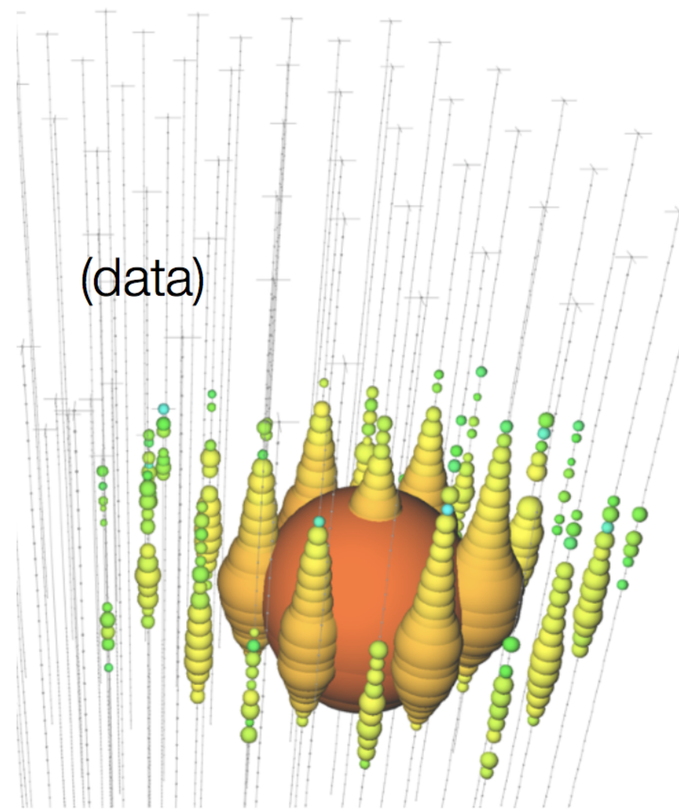
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

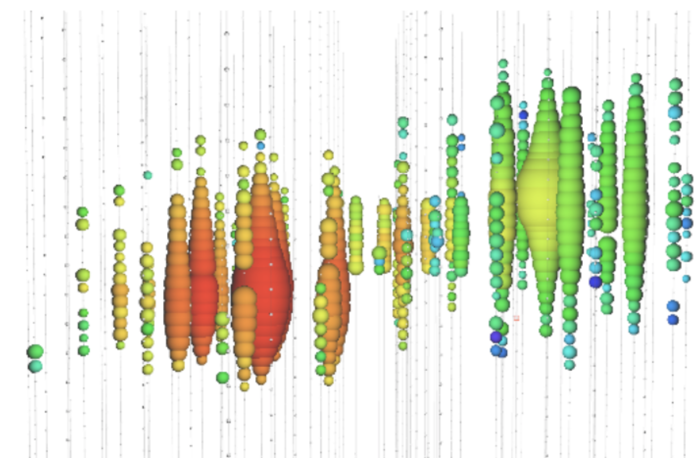


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

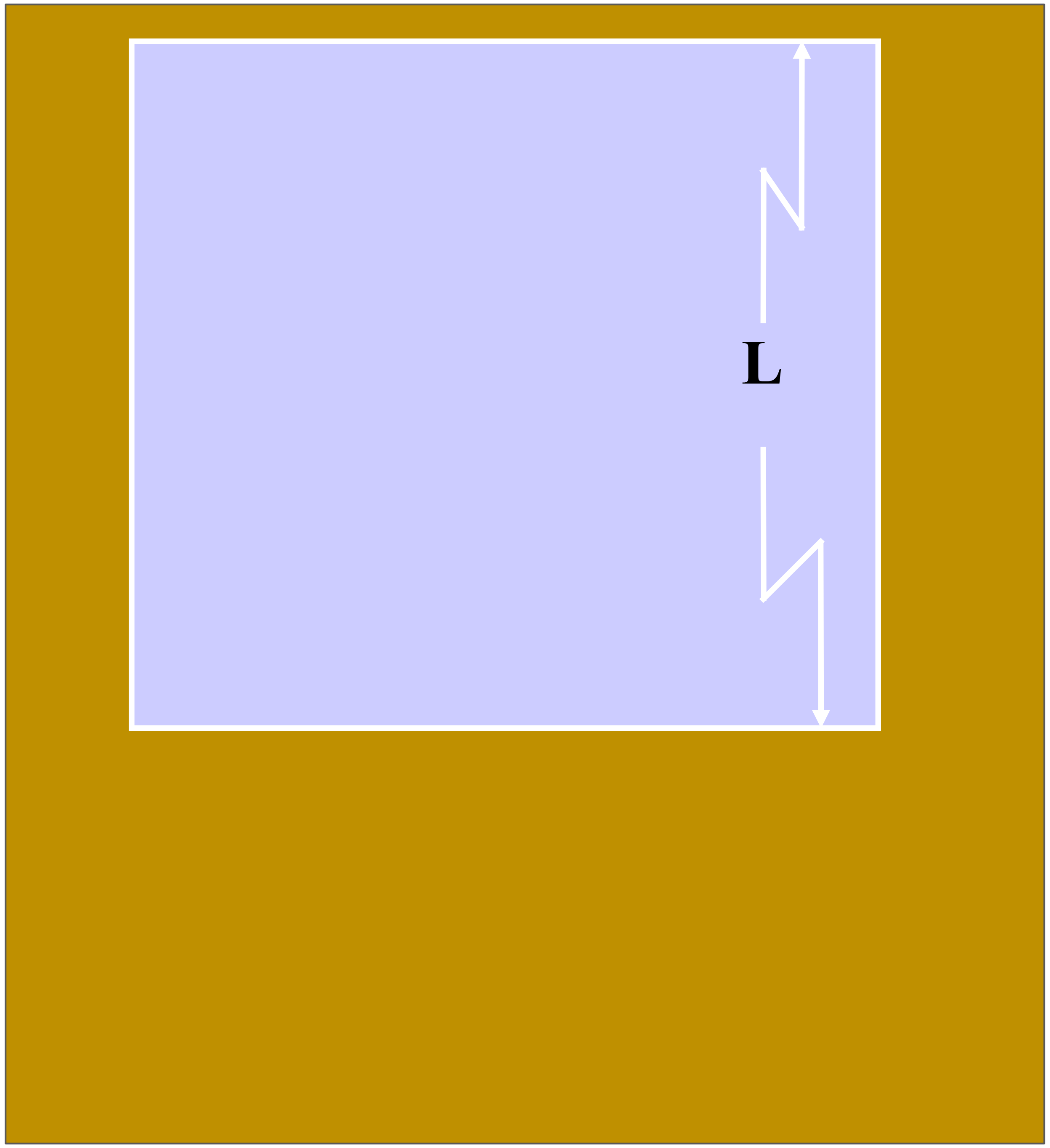
(simulation)



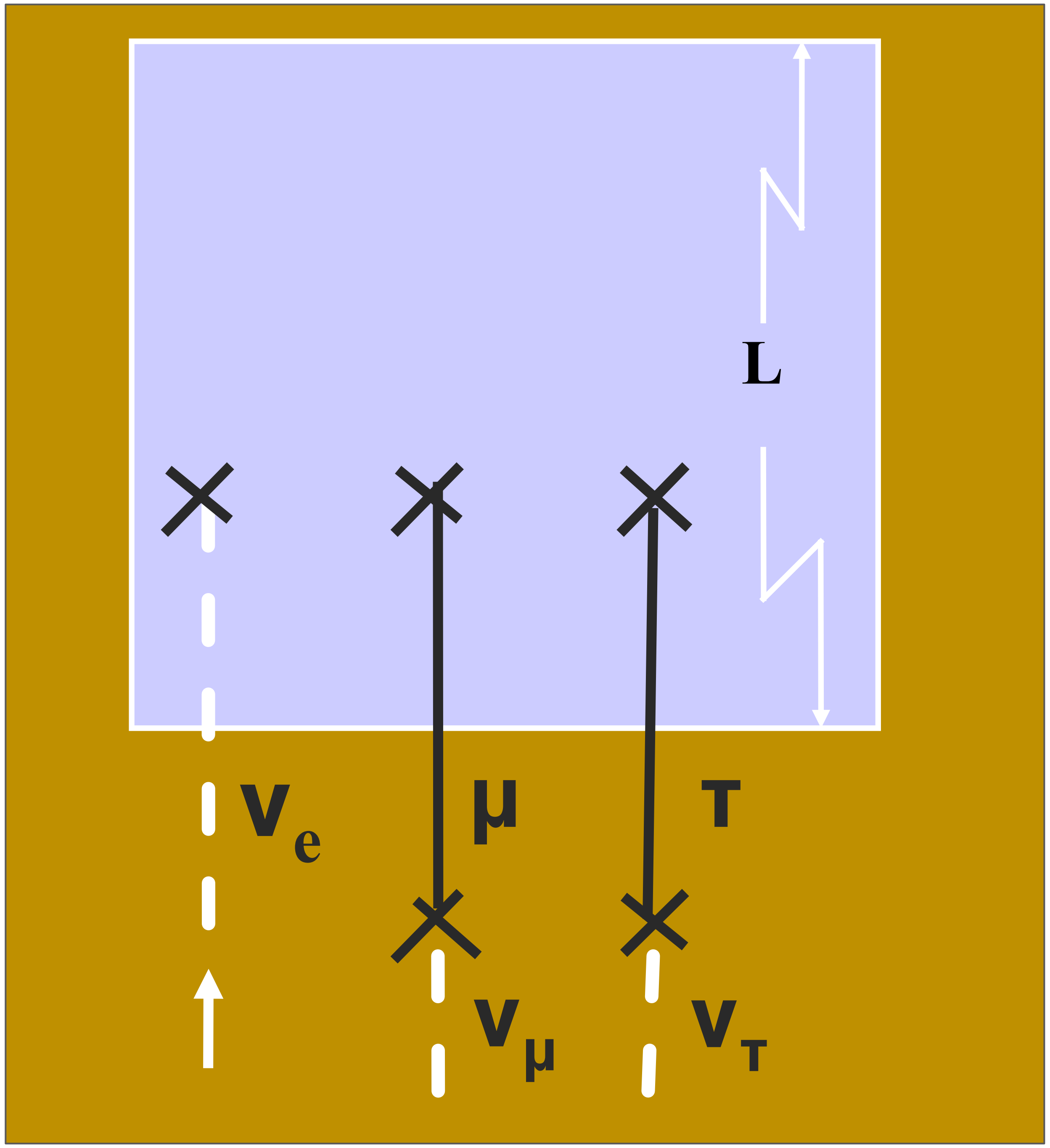
Double cascade

(resolvable above ~100 TeV deposited energy)

neutrino detection probability



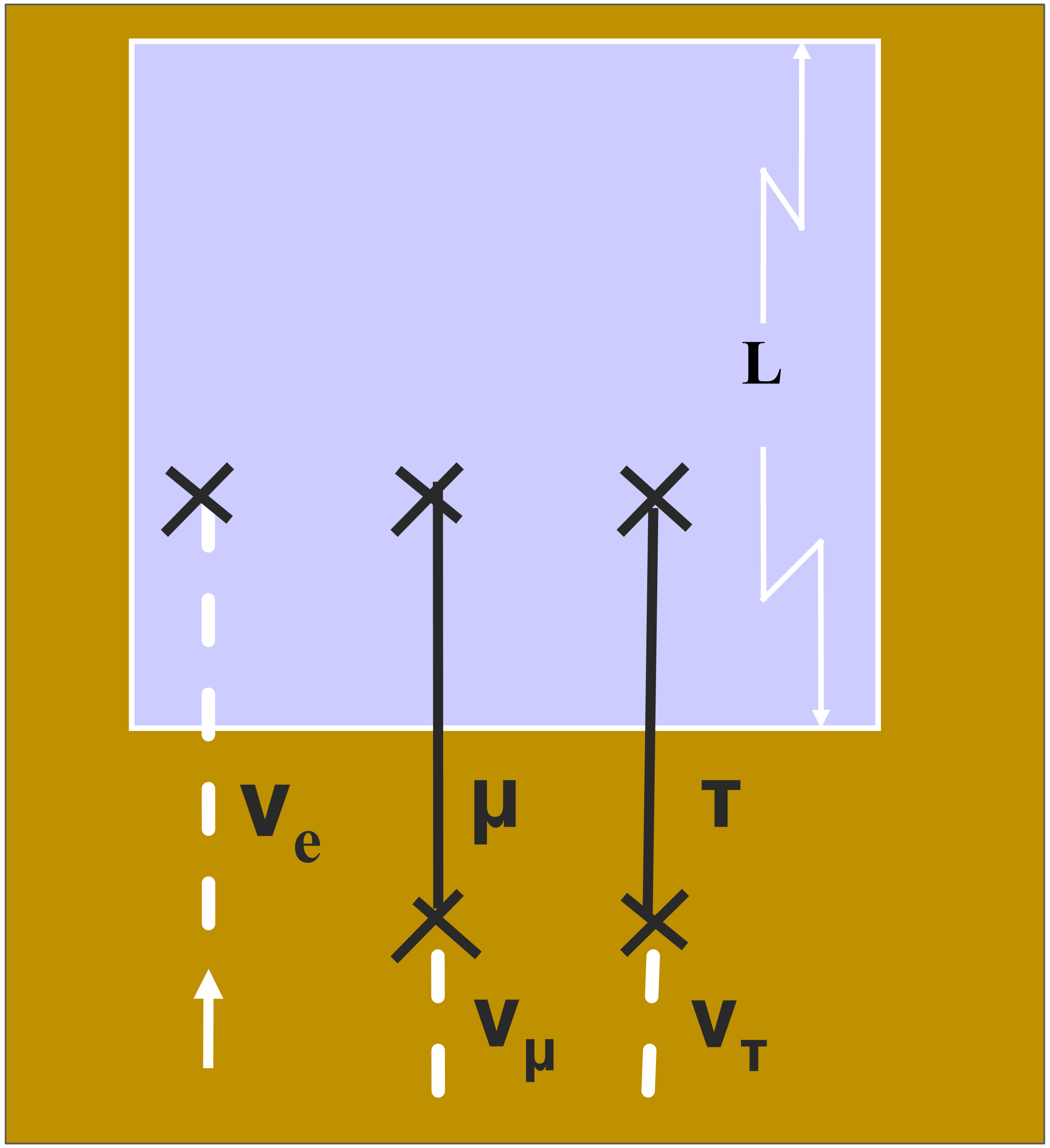
neutrino detection probability



neutrino detection probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

$$1-e^{-\frac{L}{\lambda_\nu}}$$

$$\simeq\frac{L}{\lambda_\nu}$$

$$for\ \ \nu_\mu\quad L\rightarrow R_\mu\left[E_\mu=(1-y)E_\nu\right]$$

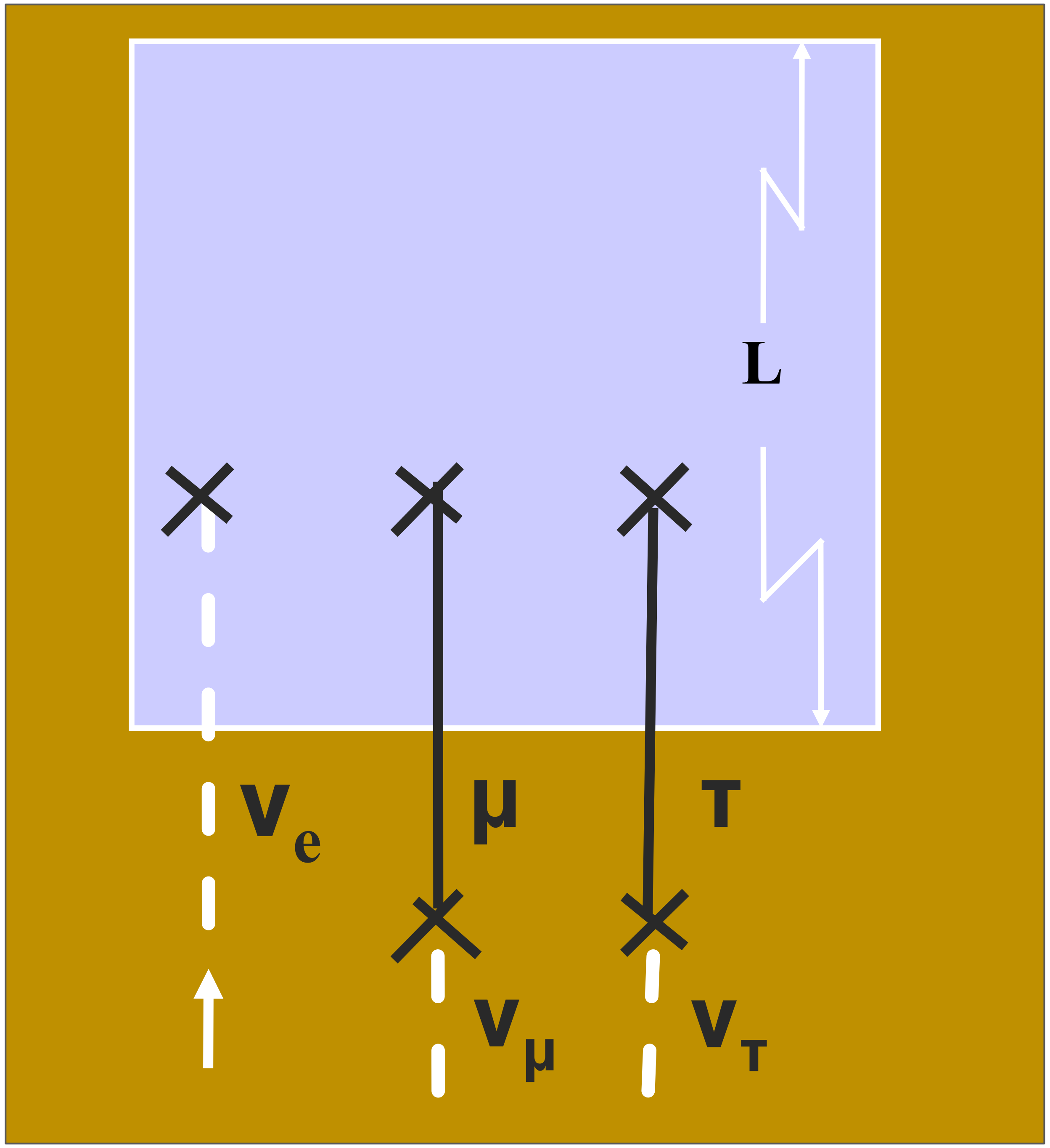
$$for\ \ \nu_\tau\quad L\rightarrow\left(E_\tau/m_\tau\right)c\tau_\tau$$

$$P_{\mathrm{det}}=n\sigma_\nu L$$

neutrino detection probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

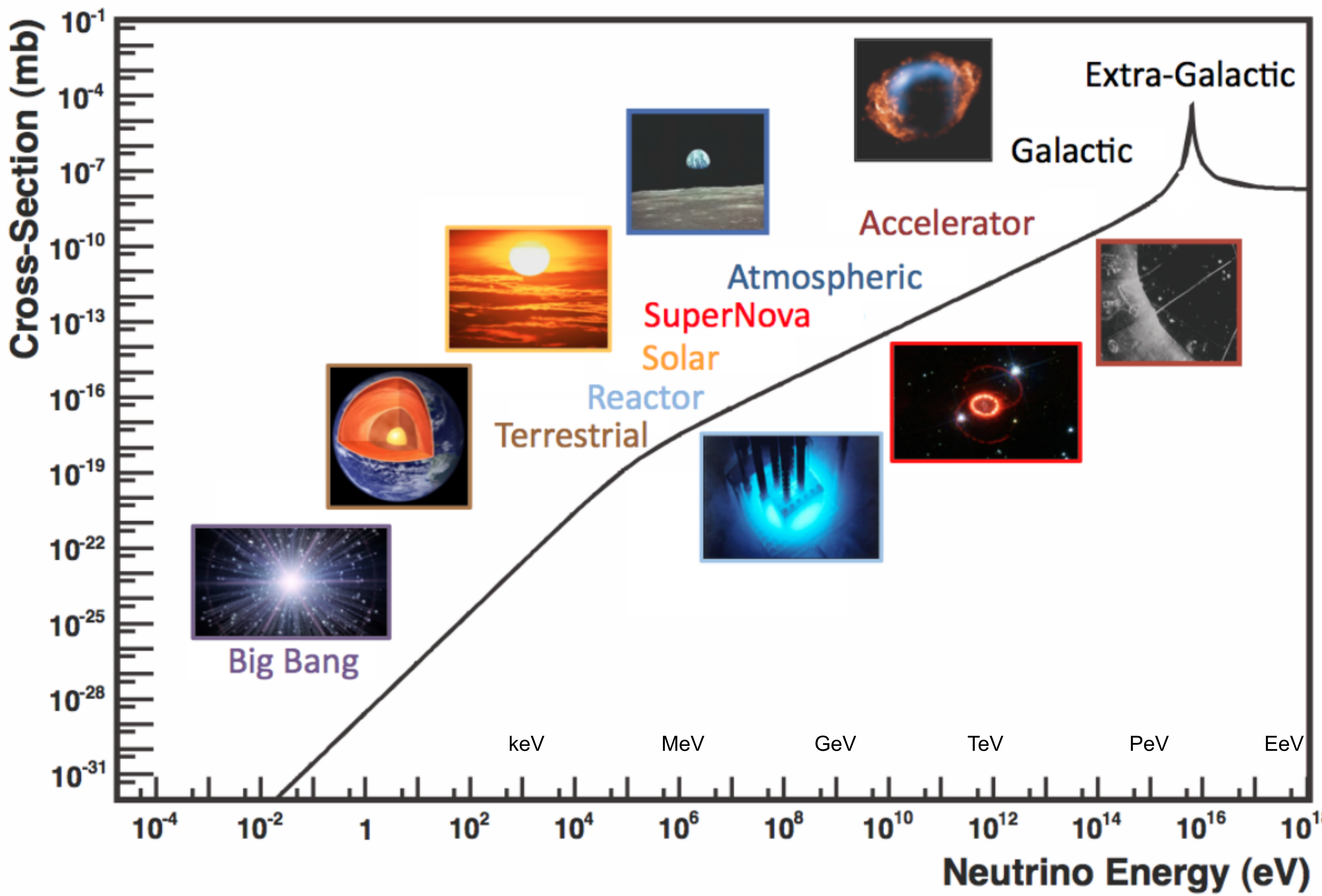
$$\simeq 1 - e^{-\frac{L}{\lambda_\nu}} \simeq \frac{L}{\lambda_\nu}$$

$$\text{for } \nu_\mu \quad L \rightarrow R_\mu [E_\mu = (1-y) E_\nu]$$

$$\text{for } \nu_\tau \quad L \rightarrow (E_\tau / m_\tau)\, c\tau_\tau$$

$$P_{\text{det}} = n \sigma_\nu L$$

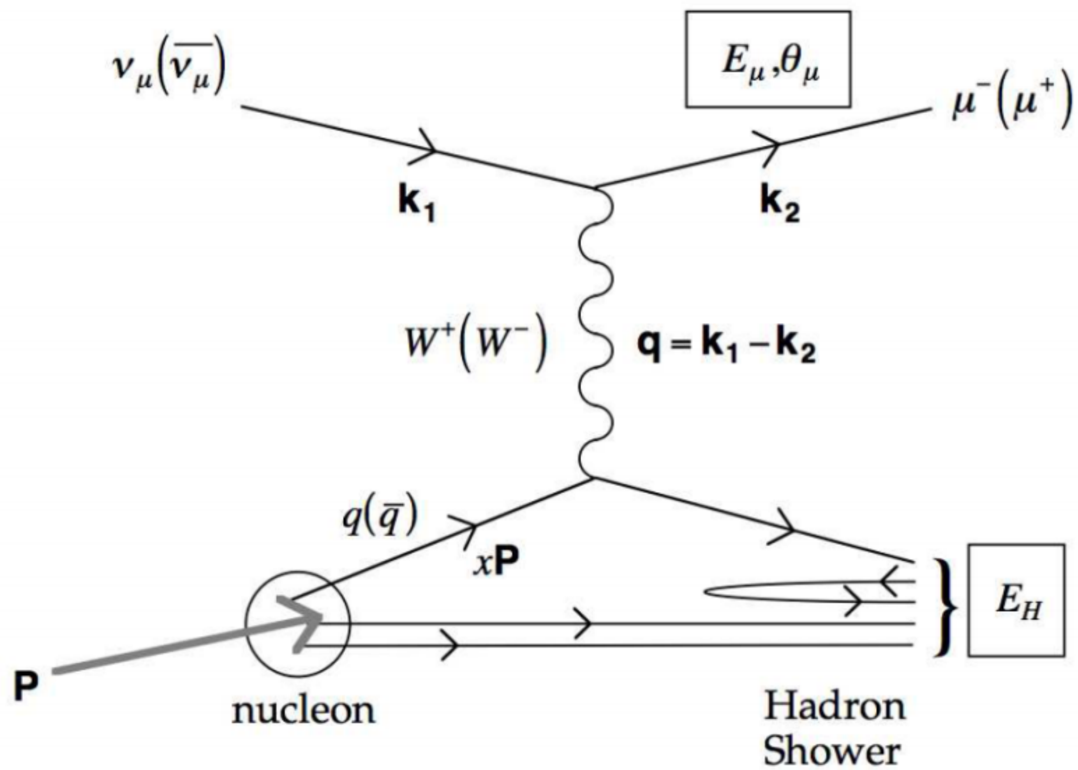
Total neutrino cross section



J. Formaggio 1305.7513

Relevant neutrino interactions

Neutrino-nucleon scattering at these energies is dominated by “deep inelastic scattering” (DIS) where the neutrino interacts with a parton in the nucleon.



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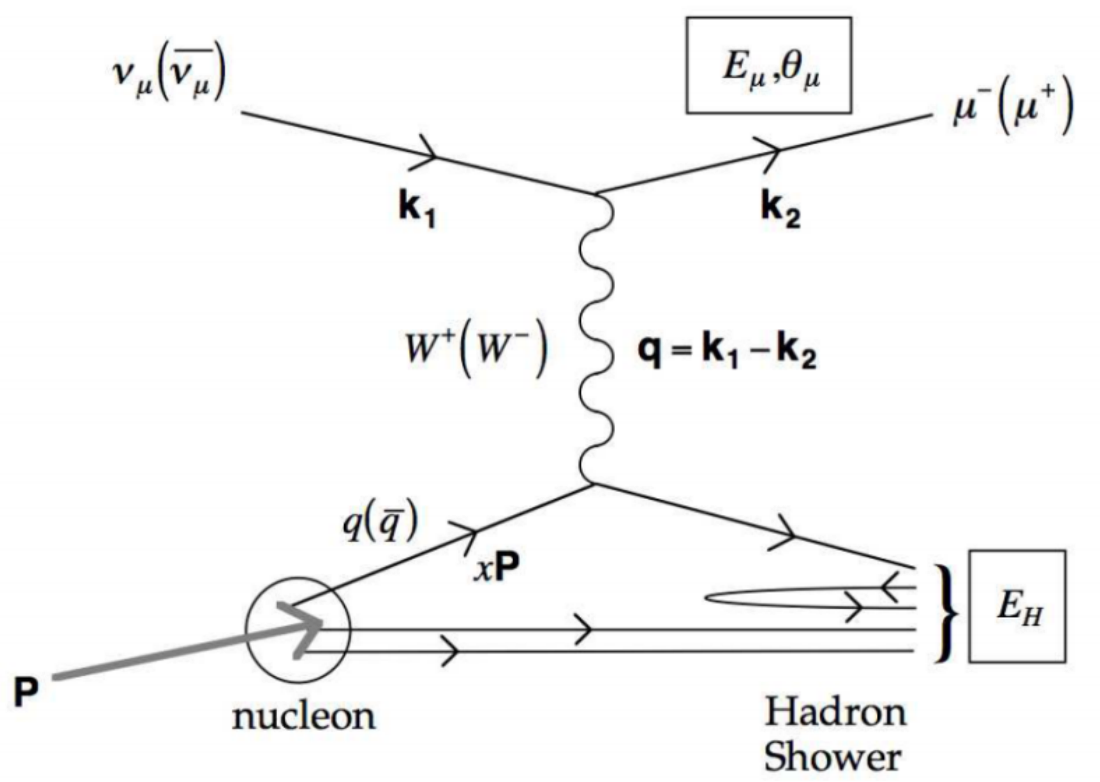
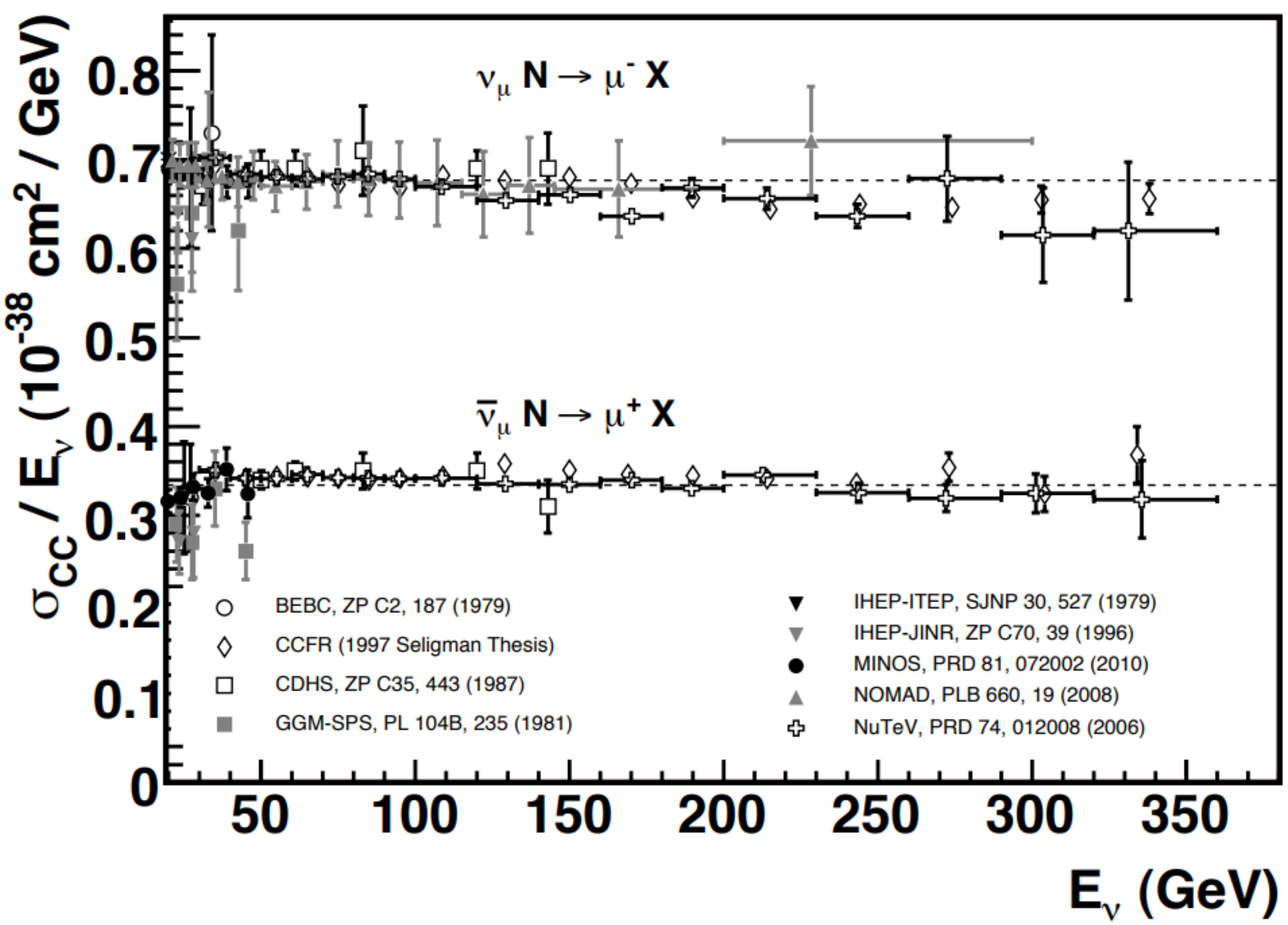
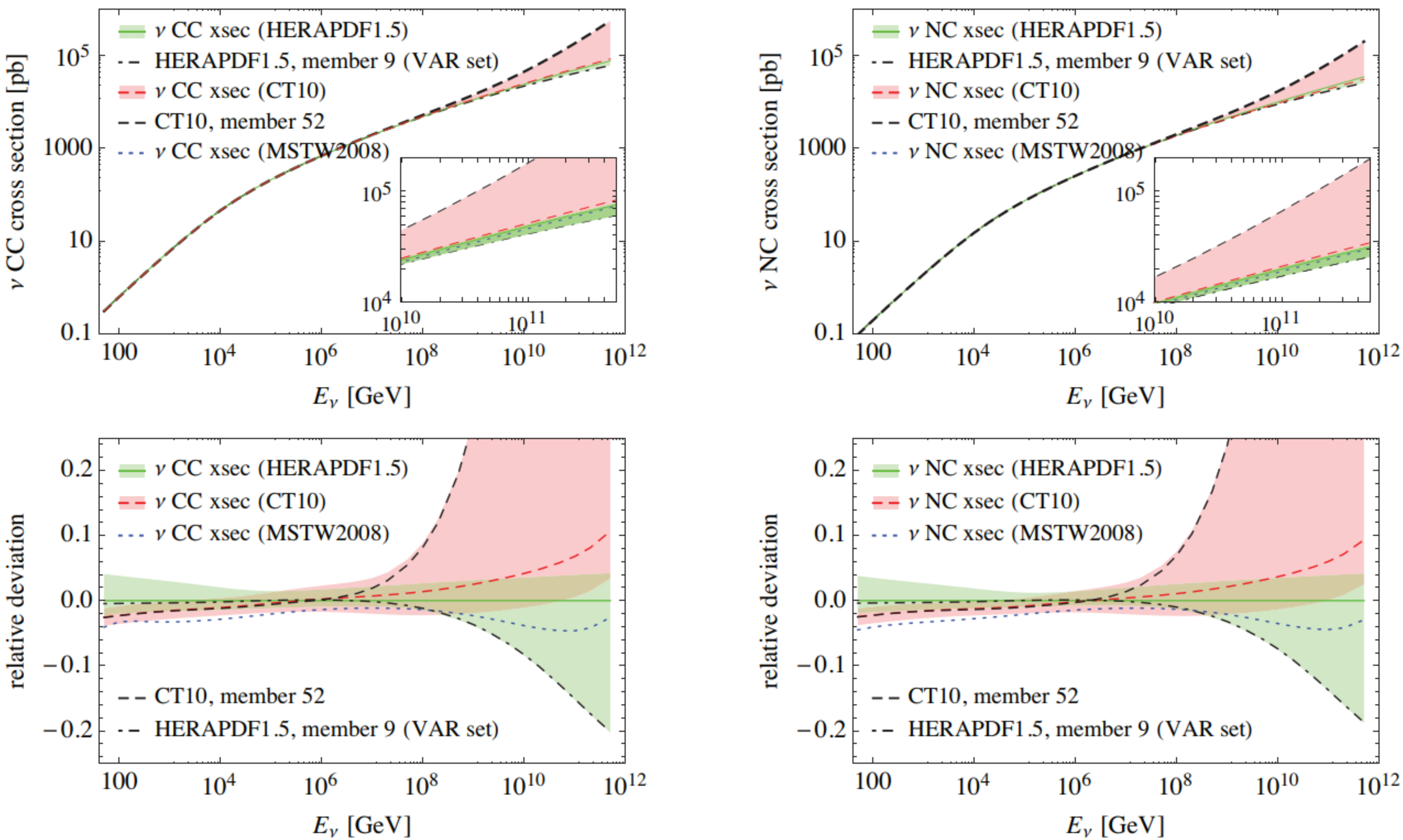




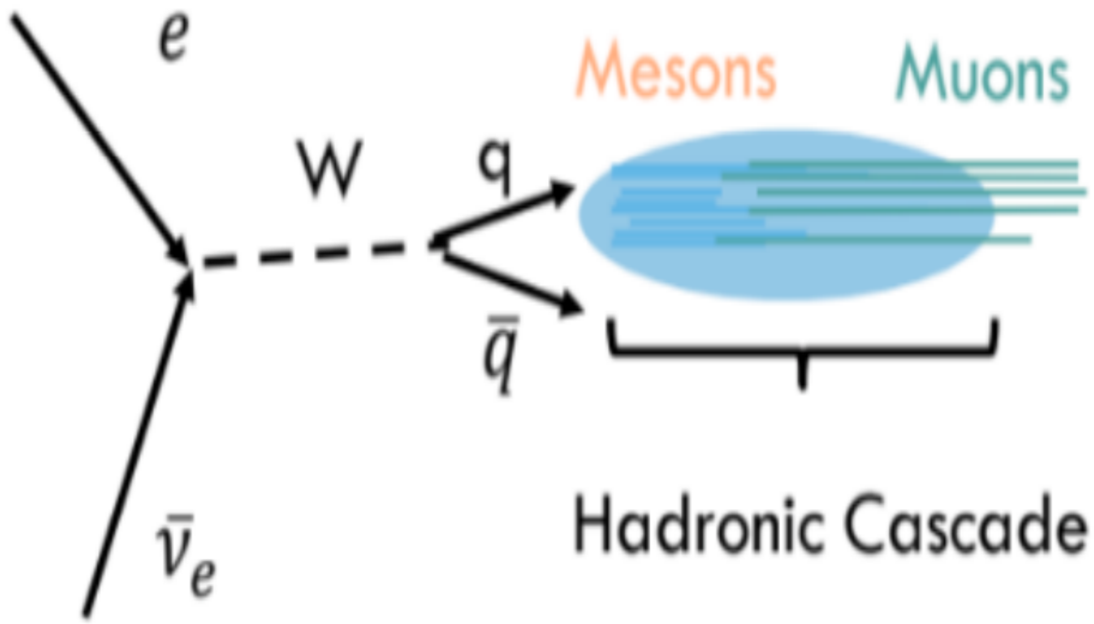
$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi\,(1+Q^2/M_{W,Z}^2)^2}\left[\begin{array}{c}\frac{y^2}{2}2xF_1(x,Q^2)+\left(1-y-\frac{Mxy}{2E}\right)F_2(x,Q^2)\\ \pm y\left(1-\frac{y}{2}\right)xF_3(x,Q^2)\end{array}\right]$$

Uncertainties on DIS interactions



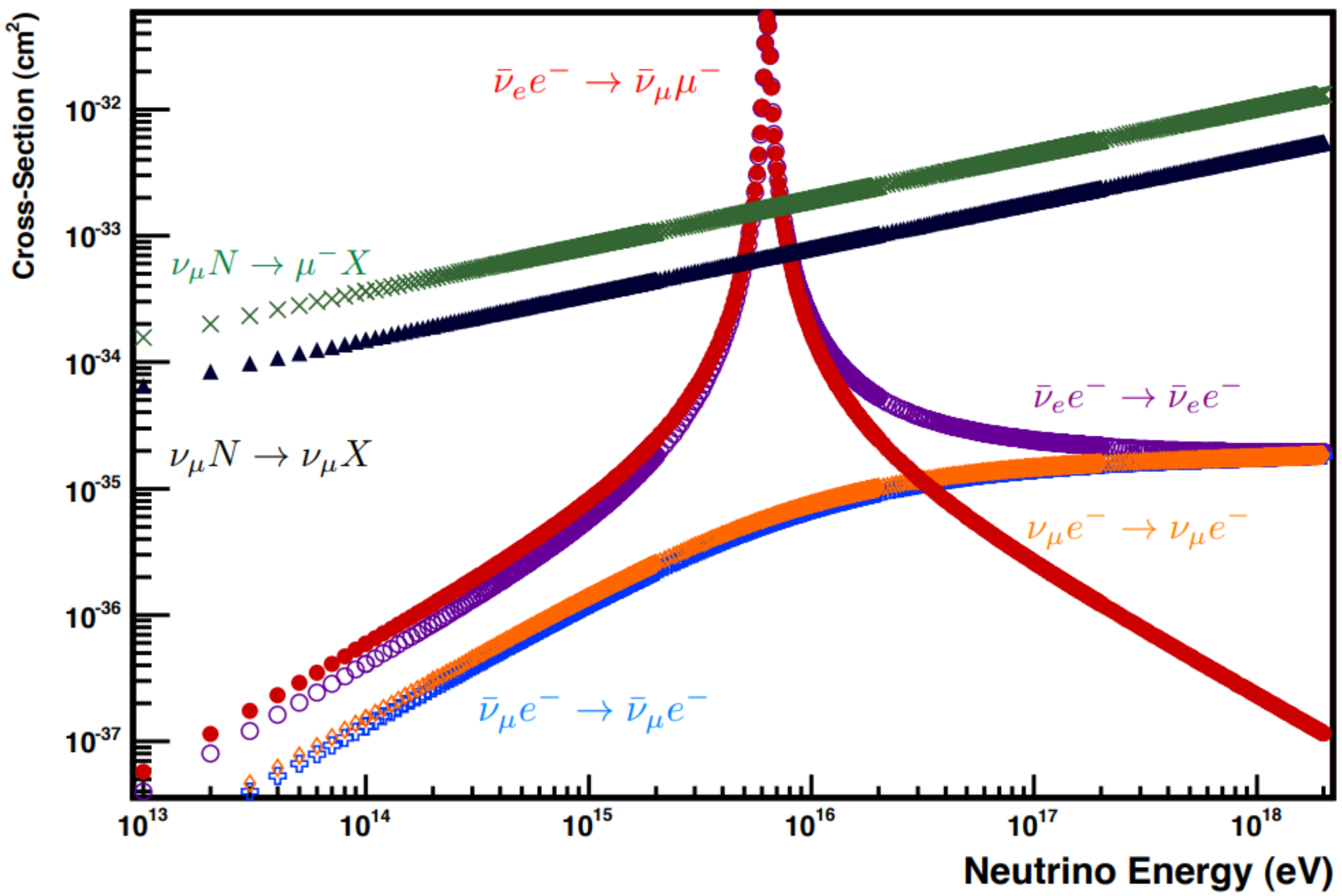
In the region of interest uncertainties below the 4 % level

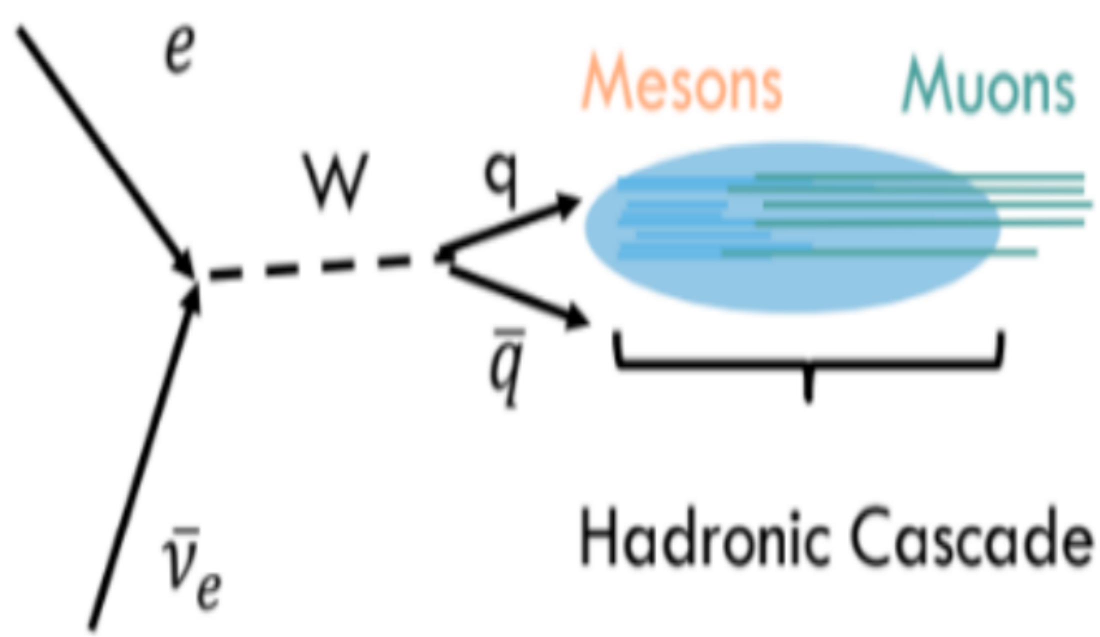
Resonant-W production *aka* Glashow resonance



Resonant-W production *aka* Glashow resonance

$\bar{\nu}_e e \rightarrow$ anything $\quad 5.02 \times 10^{-31}$





$$\frac{d\sigma(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-)}{dy} = \frac{2G_F^2 m_e E_\nu}{\pi}\left[\frac{g_R^2}{(1+2m_e E_\nu y/M_Z^2)^2} + \left|\frac{g_L}{1+2m_e E_\nu y/M_Z^2} + \frac{1}{1-2m_e E_\nu/M_W^2 + i\Gamma_W/M_W}\right|^2\right]$$

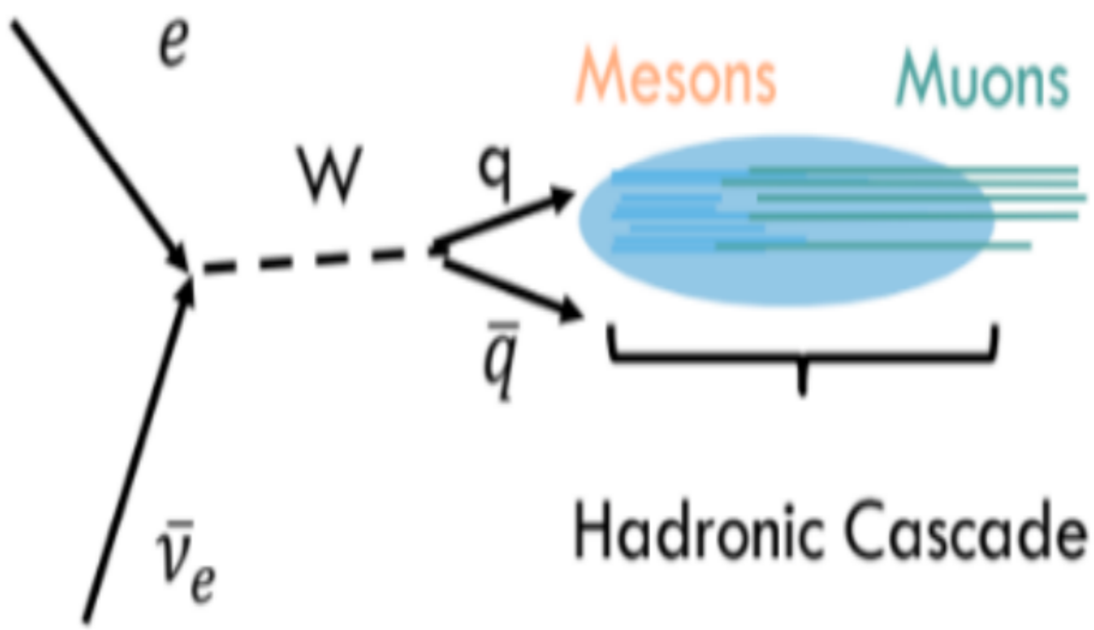
In the Earth only present for anti-electron neutrinos:
this process is important for flavor identification and nu to nubar ratio

Resonant-W production *aka* Glashow resonance

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

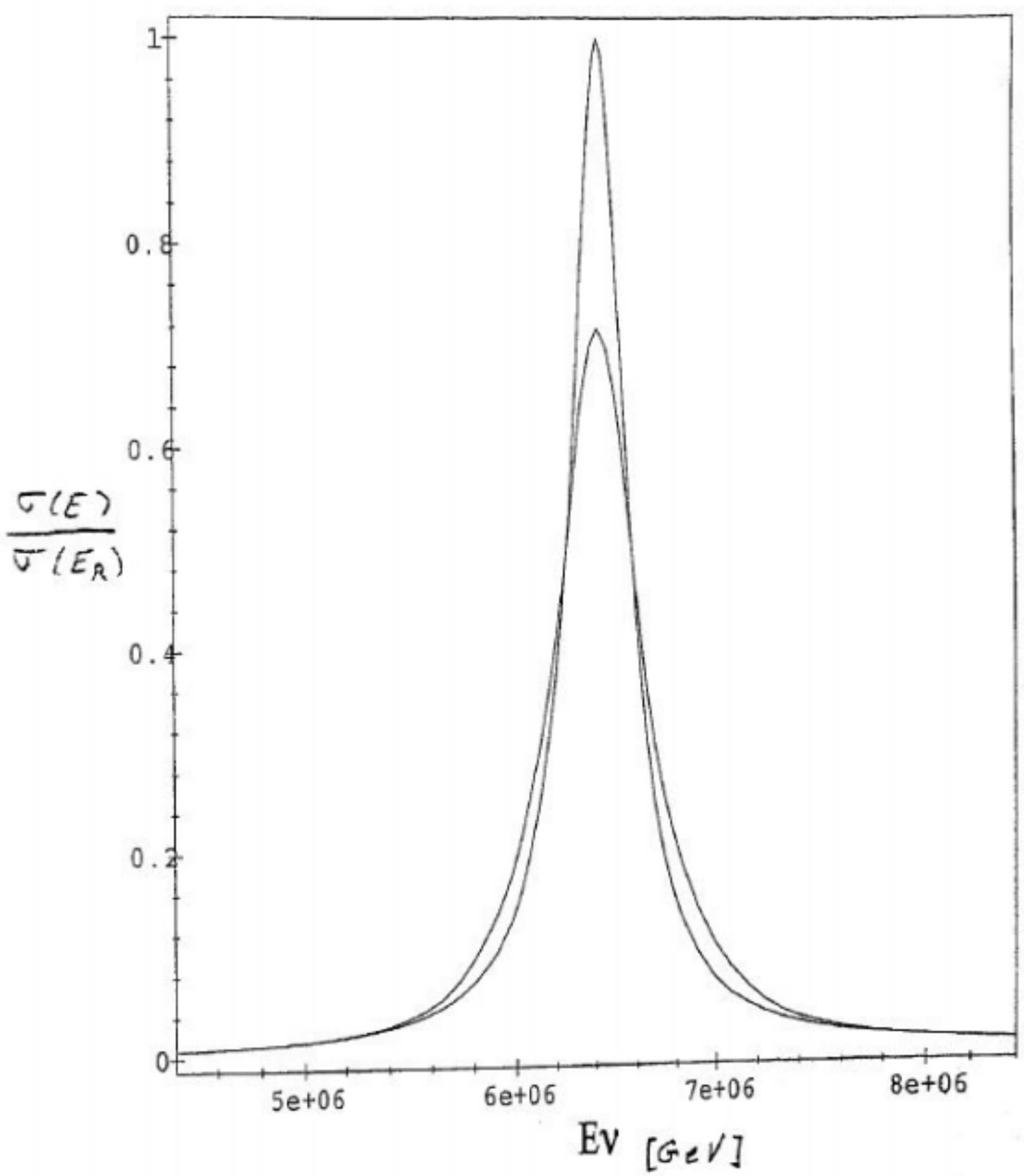
	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.80 ± 0.09) %	
Γ_2	$e^+\nu$		(10.75 ± 0.13) %	
Γ_3	$\mu^+\nu$		(10.57 ± 0.15) %	
Γ_4	$\tau^+\nu$		(11.25 ± 0.20) %	
Γ_5	hadrons		(67.60 ± 0.27) %	
Γ_6	$\pi^+\gamma$		$< 8 \times 10^{-5}$	95%
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%
Γ_8	$c\,X$		(33.4 ± 2.6) %	
Γ_9	$c\,\bar{s}$		$(31 {}^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	



$$\frac{d\sigma(\bar{\nu}_e e^- \to \bar{\nu}_e e^-)}{dy} = \frac{2G_F^2 m_e E_\nu}{\pi}\left[\frac{g_R^2}{(1+2m_eE_\nu y/M_Z^2)^2} + \left|\frac{g_L}{1+2m_eE_\nu y/M_Z^2} + \frac{1}{1-2m_eE_\nu/M_W^2 + i\Gamma_W/M_W}\right|^2\right]$$

In the Earth only present for anti-electron neutrinos:
this process is important for flavor identification and nu to nubar ratio

Technical note:
electrons are not in empty space

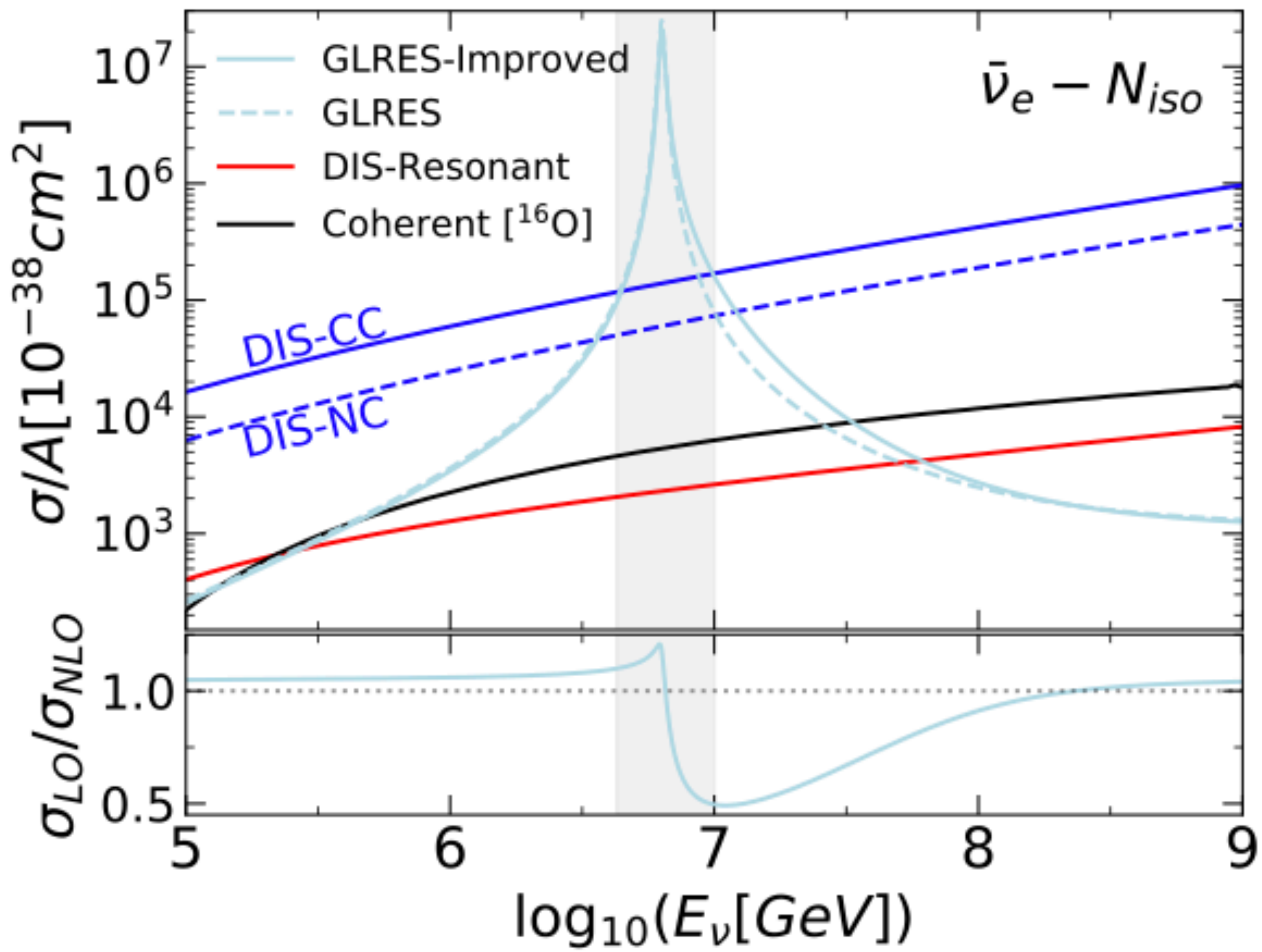


Z	$\sigma(E_R)/\sigma^{(0)}(E_R)$
8	0.85
12	0.83
14	0.78
20	0.76
26	0.73

Figure 1: Scaled cross sections of the WR on electrons at rest and electrons in $Z = 26$.

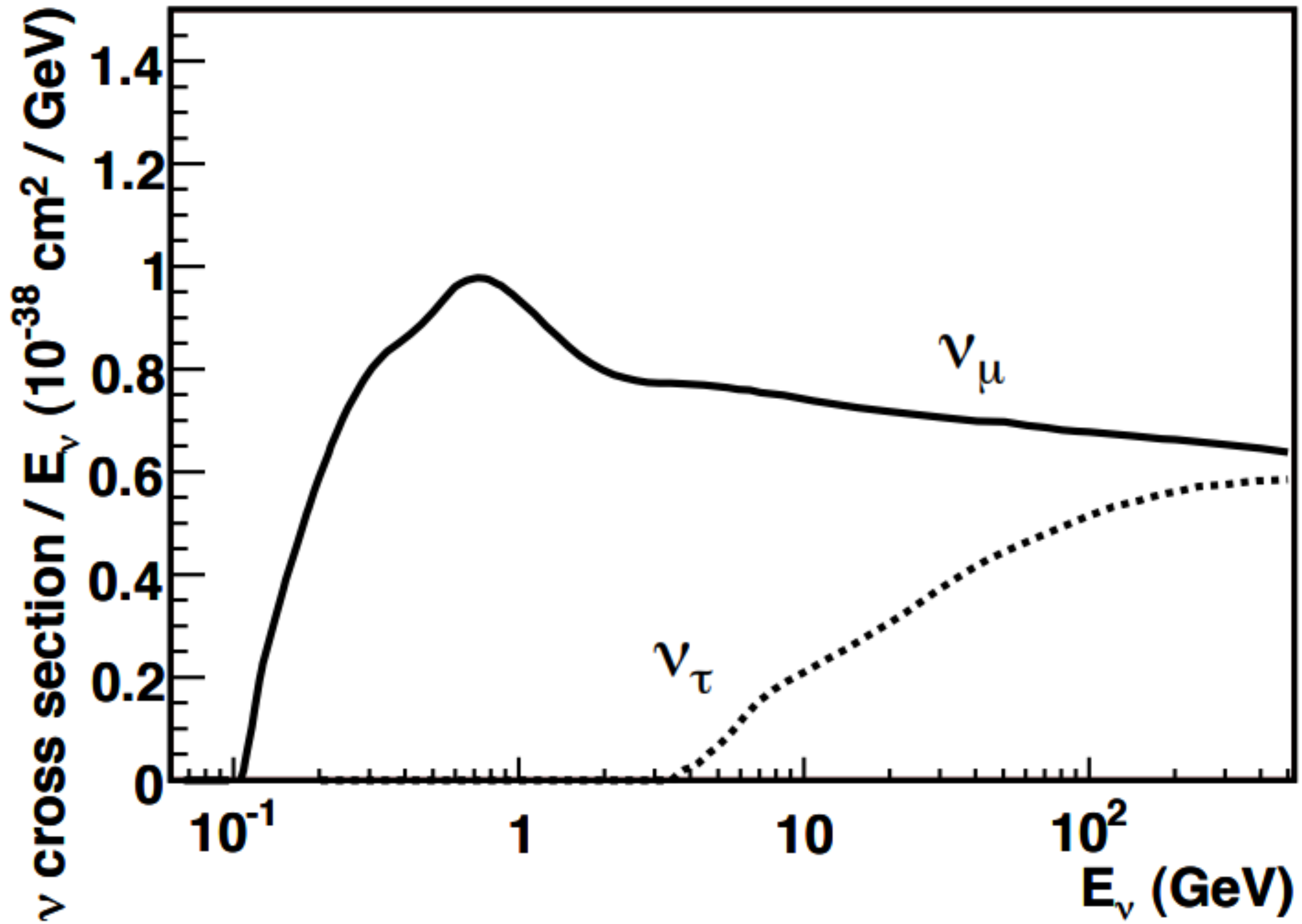
Loewy et al. arXiv:1407.4415

Technical note:
other corrections to the GR cross section

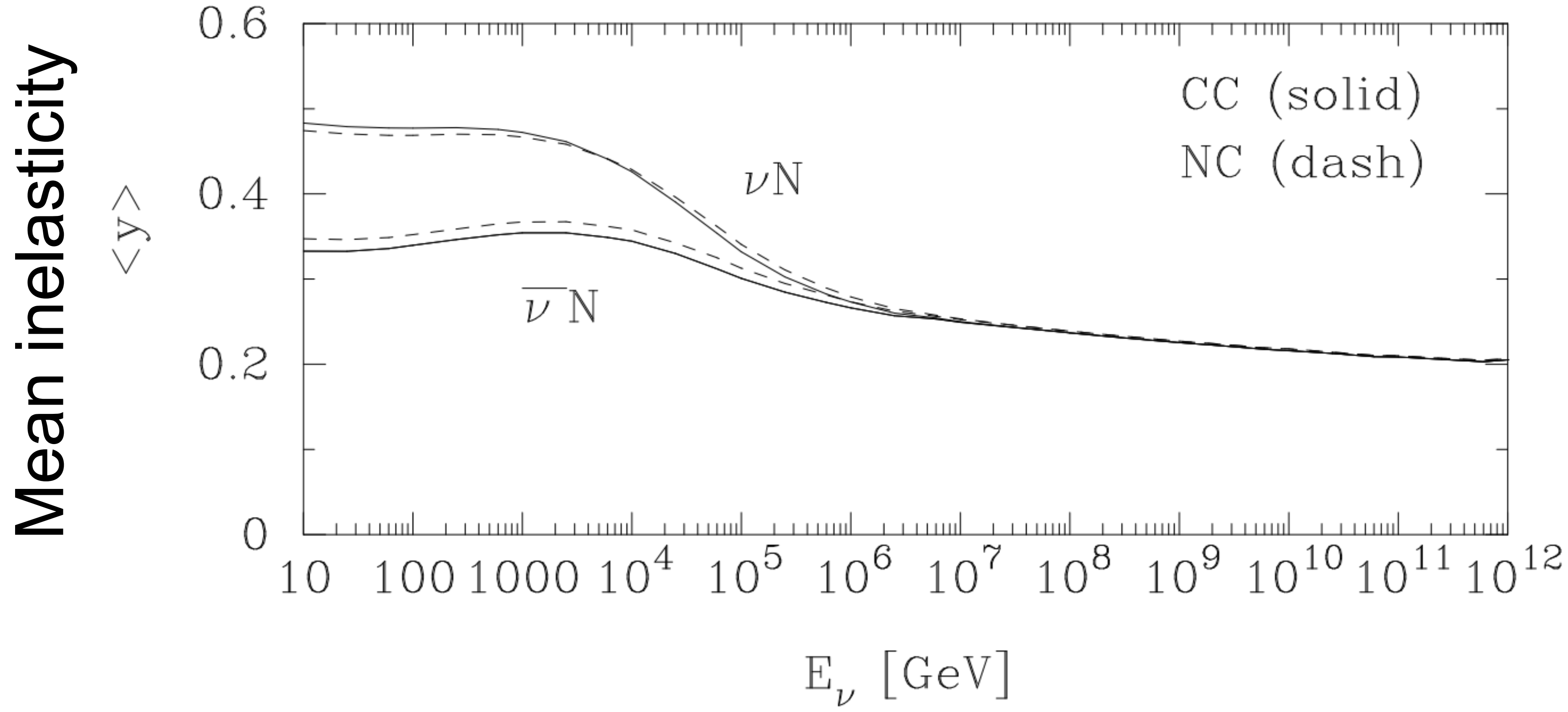


Alfonso Garcia Soto et al arXiv:2004.04756

What about flavor dependence?



High-energy DIS approximations



$$\sigma_{\nu N}^{CC} = 5.53 \times 10^{-36}\ \mathrm{cm}^2 (\frac{E_\nu}{1\ \mathrm{GeV}})^{\alpha},$$

$$\sigma_{\nu N}^{NC} = 2.31 \times 10^{-36}\ \mathrm{cm}^2 (\frac{E_\nu}{1\ \mathrm{GeV}})^{\alpha}$$

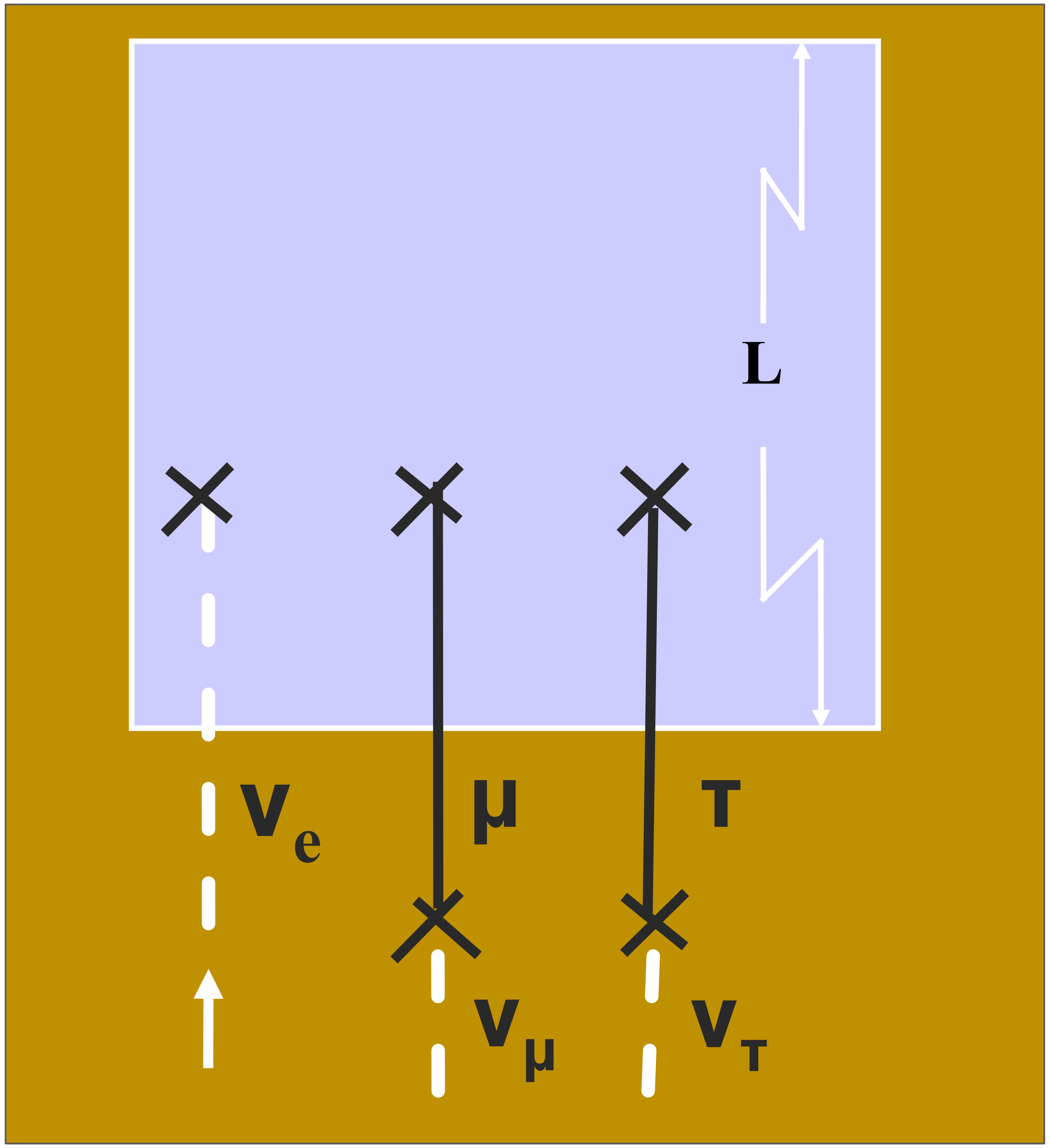
$$\alpha \simeq 0.363$$

$$10^{16}\ \mathrm{eV} \leq E_\nu \leq 10^{21}\ \mathrm{eV}$$

neutrino detection probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

$$1-e^{-\frac{L}{\lambda_\nu}} \simeq \frac{L}{\lambda_\nu}$$

$$for\ \ \nu_\mu \quad L \rightarrow R_\mu \left[E_\mu = (1-y) E_\nu \right]$$

$$for\ \ \nu_\tau \quad L \rightarrow (E_\tau / m_\tau)\, c\tau_\tau$$

$$P_{\det} = n\sigma_\nu L$$

In-class exercise

Given the neutrino cross section is approximately

$$\sigma_{\nu N}^{CC} = 5.53 \times 10^{-36}\ \mathrm{cm}^2 (\frac{E_\nu}{1\ \mathrm{GeV}})^\alpha,$$

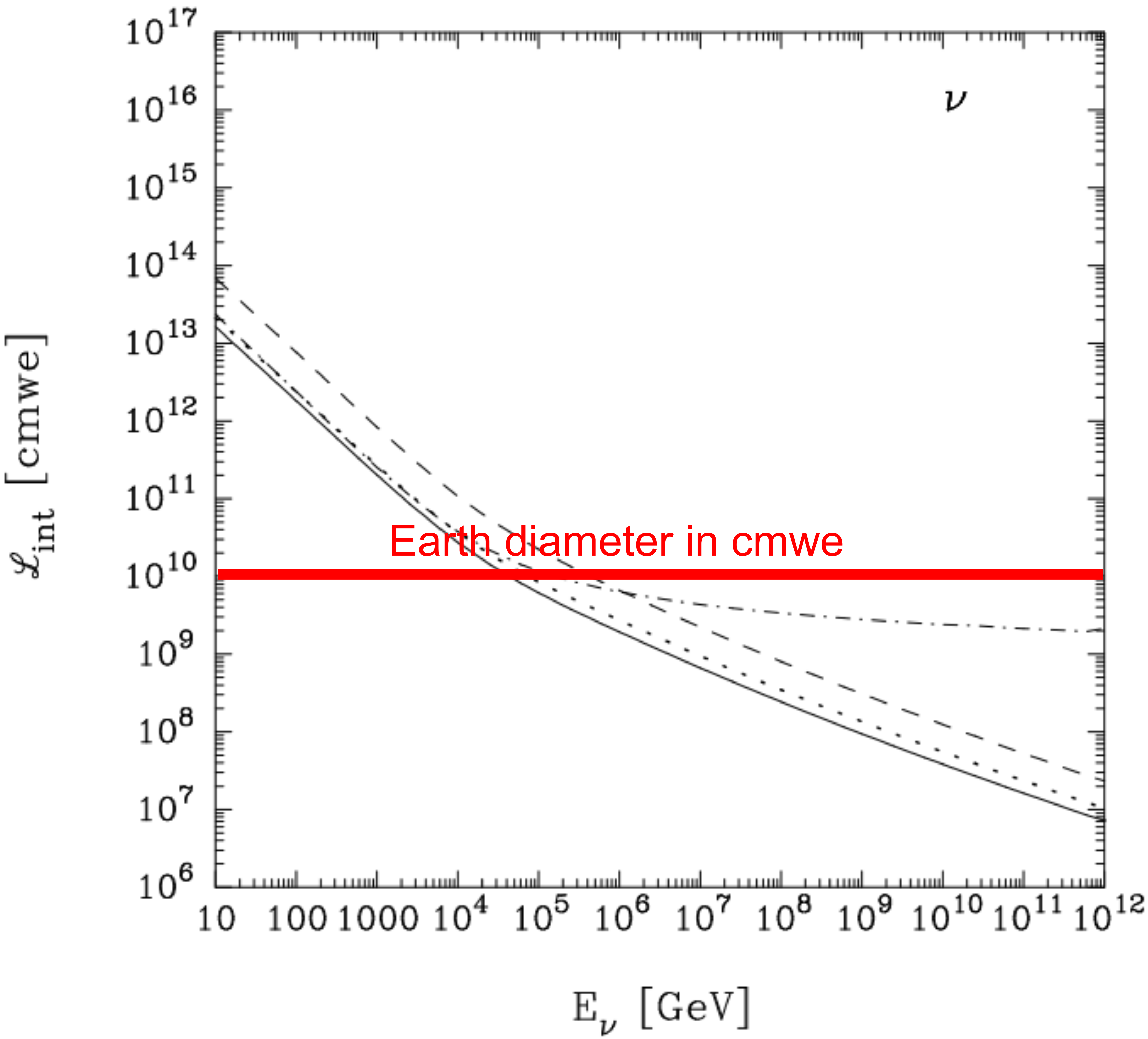
$$\sigma_{\nu N}^{NC} = 2.31 \times 10^{-36}\ \mathrm{cm}^2 (\frac{E_\nu}{1\ \mathrm{GeV}})^\alpha$$

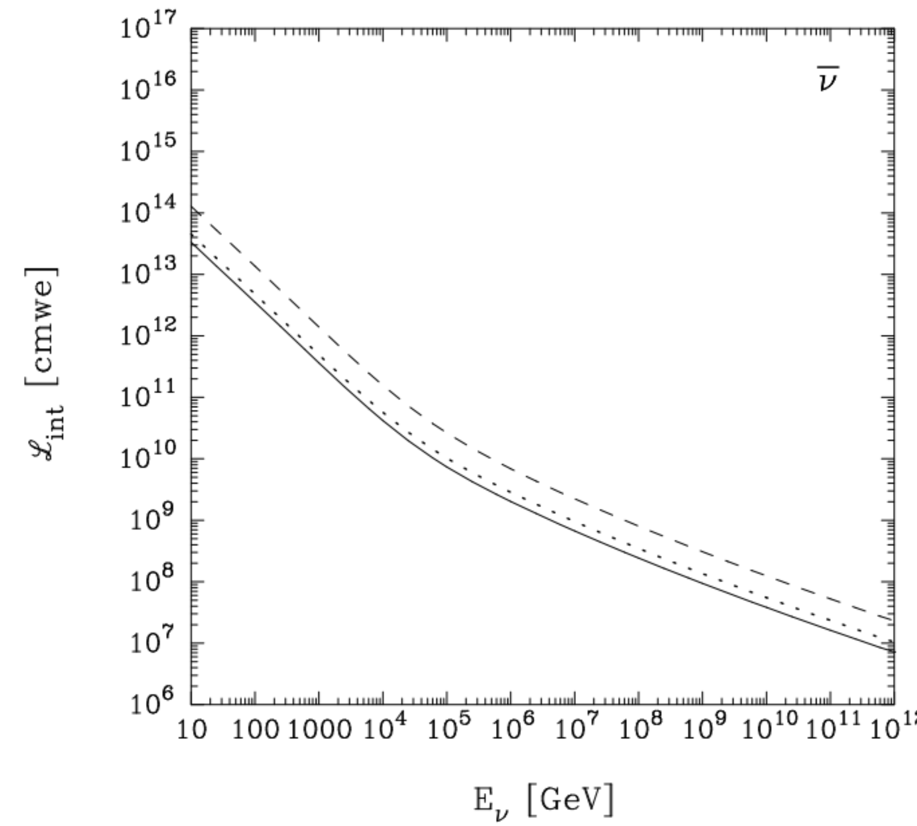
$$\alpha \simeq 0.363$$

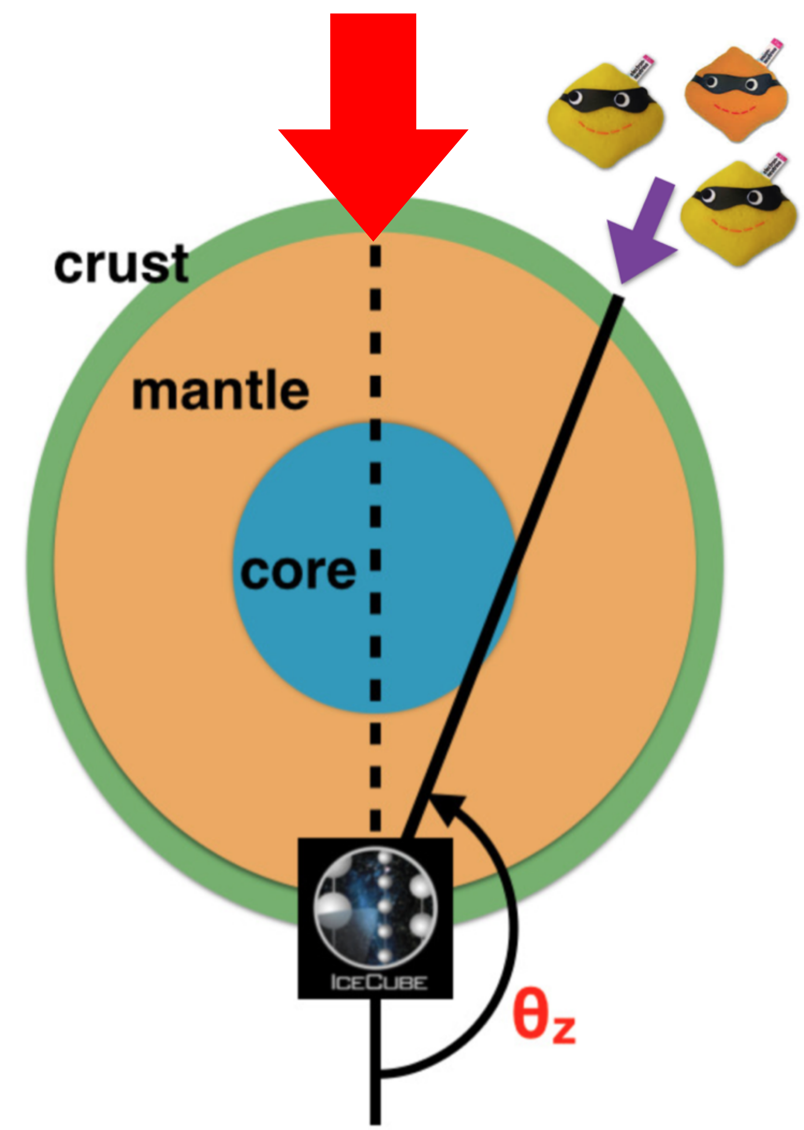
$$10^{16}\ \mathrm{eV} \leq E_\nu \leq 10^{21}\ \mathrm{eV}$$

Assuming that the Earth mean density is 5 g/cm^3, what is the neutrino interaction length at 100 TeV?

Neutrino interaction length



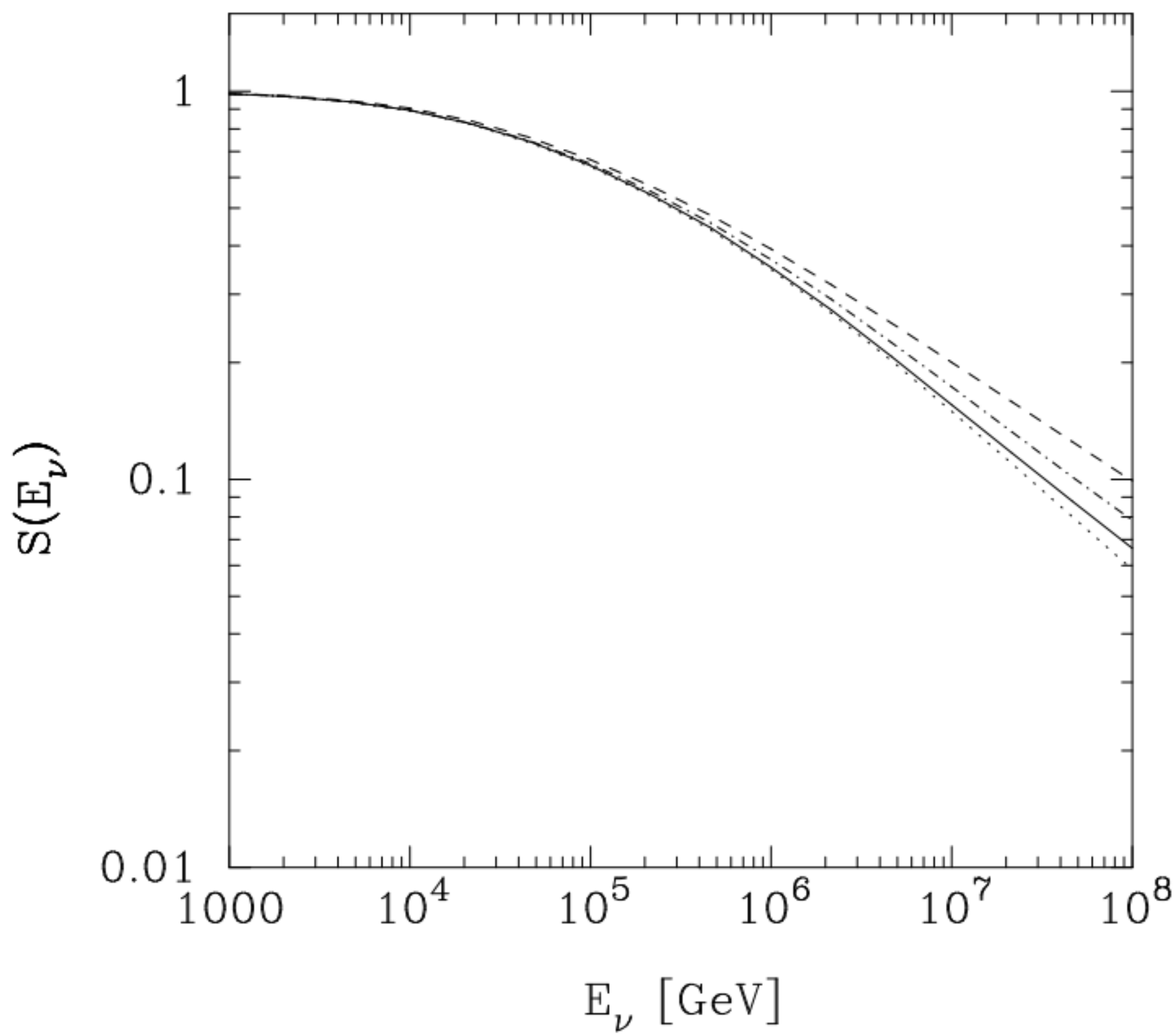


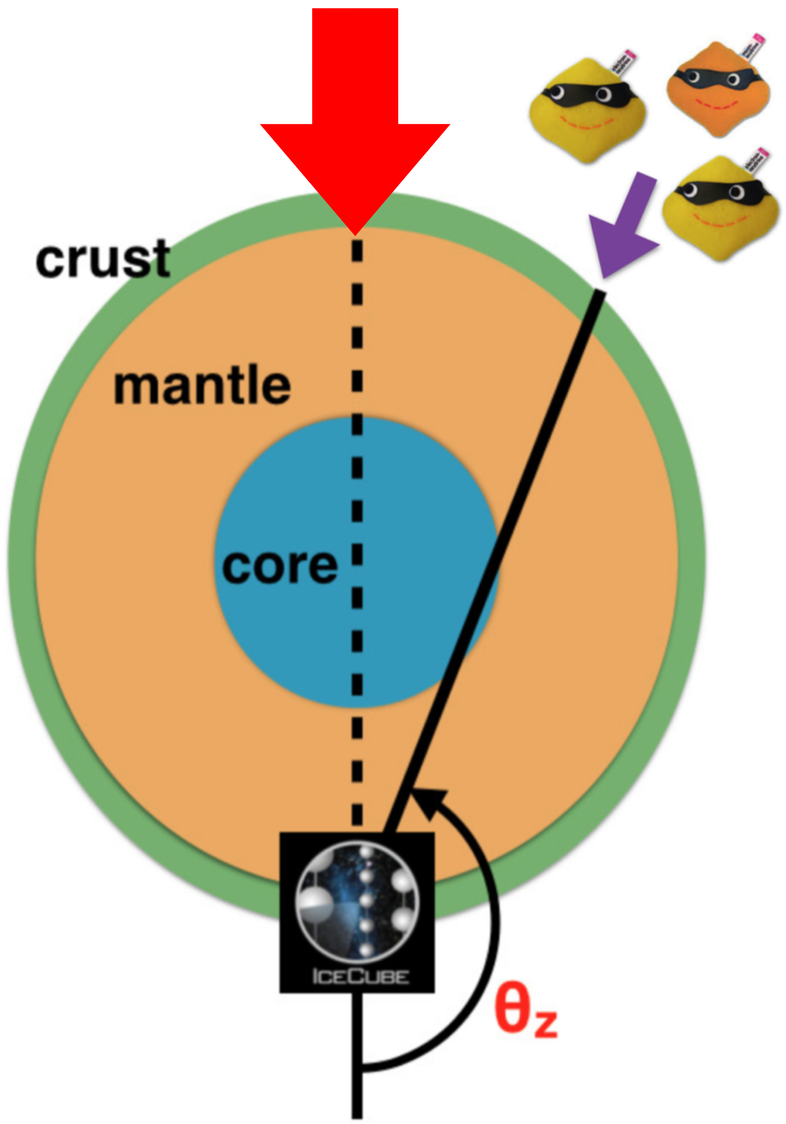


Earth is transparent to neutrinos below ~ 40 TeV.

Shadow factor

$$S(E_\nu) = \frac{1}{2\pi}\int_{-1}^{0} d\cos\theta \int d\phi \exp\left[-z(\theta)/\mathcal{L}_{\rm int}(E_\nu)\right]$$





For isotropic astrophysical neutrino fluxes the “zenith-averaged” attenuation is more relevant.

A story of neutrinos through the Earth

How to account for neutrinos cascading down

$$\frac{\partial}{\partial x}\left(\frac{d\phi_{\nu_\ell}(E_\nu, x)}{dE_\nu}\right) = -\left(\sigma_{\nu_\ell}^{\mathrm{NC}}(E_\nu) + \sigma_{\nu_\ell}^{\mathrm{CC}}(E_\nu)\right)\frac{d\phi_{\nu_\ell}(E_\nu, x)}{dE_\nu}$$

$$x(\theta) \equiv N_a \int_{l.o.s.} \rho_\oplus[r(x,\theta)]dx$$

How to account for neutrinos cascading down

contribution from neutrinos cascading down

$$\frac{\partial}{\partial x}\left(\frac{d\phi_{\nu_\ell}(E_\nu, x)}{dE_\nu}\right) = -\left(\sigma^{\rm NC}_{\nu_\ell}(E_\nu) + \sigma^{\rm CC}_{\nu_\ell}(E_\nu)\right)\frac{d\phi_{\nu_\ell}(E_\nu, x)}{dE_\nu} + \int_E^\infty d\tilde{E}\, \frac{d\sigma^{\rm NC}_{\nu_\ell}(E_\nu, \tilde{E}_\nu)}{dE_\nu}\frac{d\phi_{\nu_\ell}(\tilde{E}_\nu, x)}{d\tilde{E}_\nu}$$

$$x(\theta) \equiv N_a \int_{l.o.s.} \rho_\oplus[r(x,\theta)]dx$$

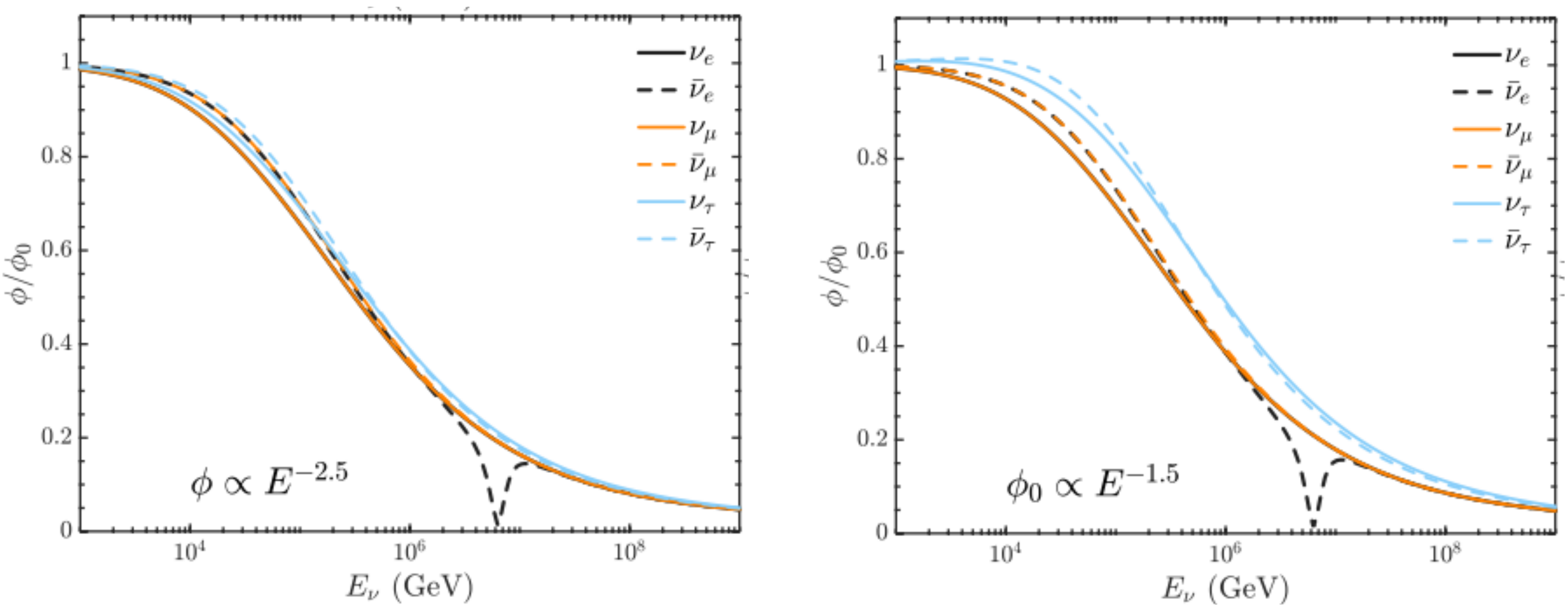
How to account for neutrinos cascading down

contribution from neutrinos cascading down

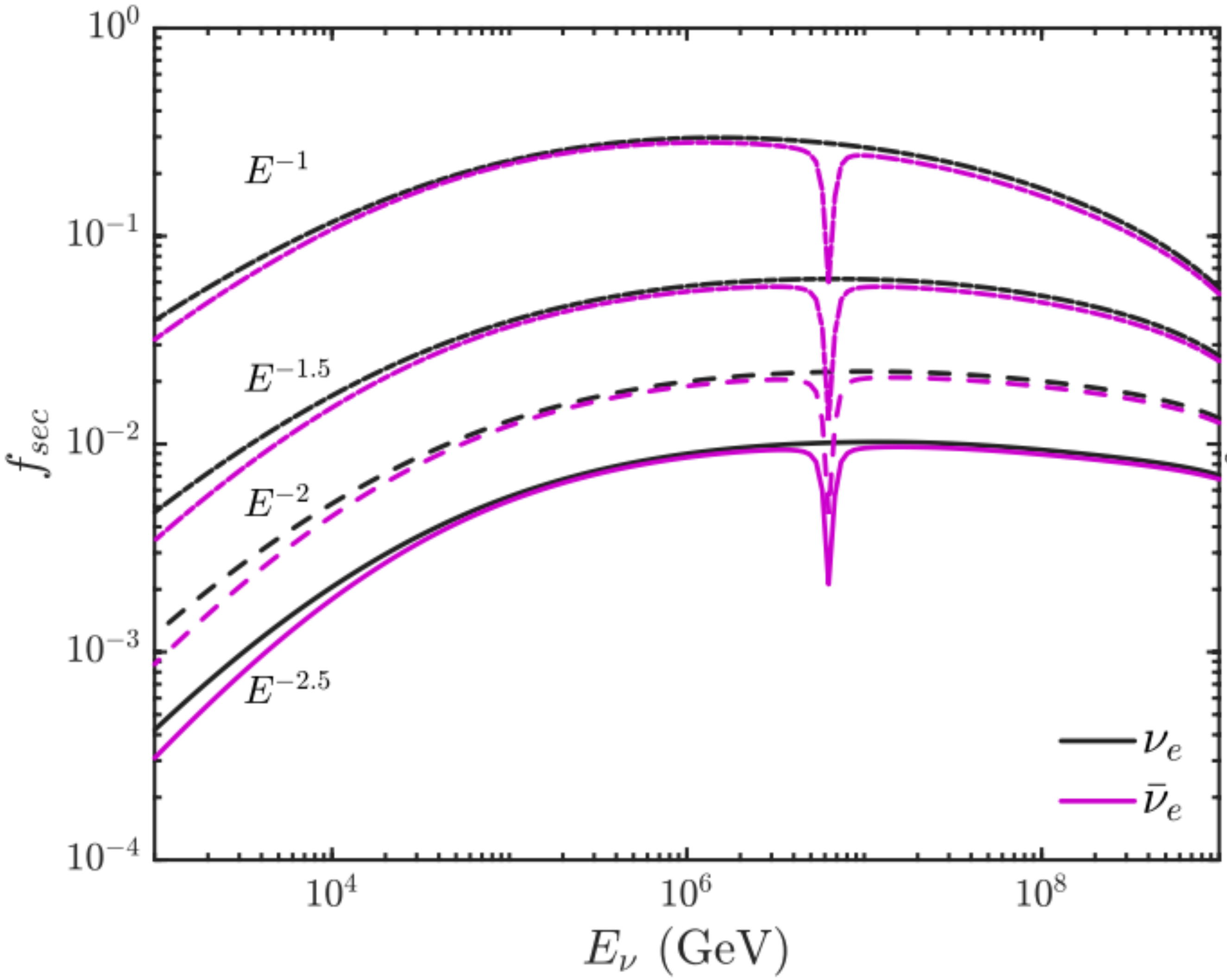
$$\frac{\partial}{\partial x}\left(\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu}\right) = -\left(\sigma^{\rm NC}_{\nu_\ell}(E_\nu)+\sigma^{\rm CC}_{\nu_\ell}(E_\nu)\right)\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu} + \int_E^\infty d\tilde{E}\,\frac{d\sigma^{\rm NC}_{\nu_\ell}(E_\nu,\tilde{E}_\nu)}{dE_\nu}\,\frac{d\phi_{\nu_\ell}(\tilde{E}_\nu,x)}{d\tilde{E}_\nu}$$

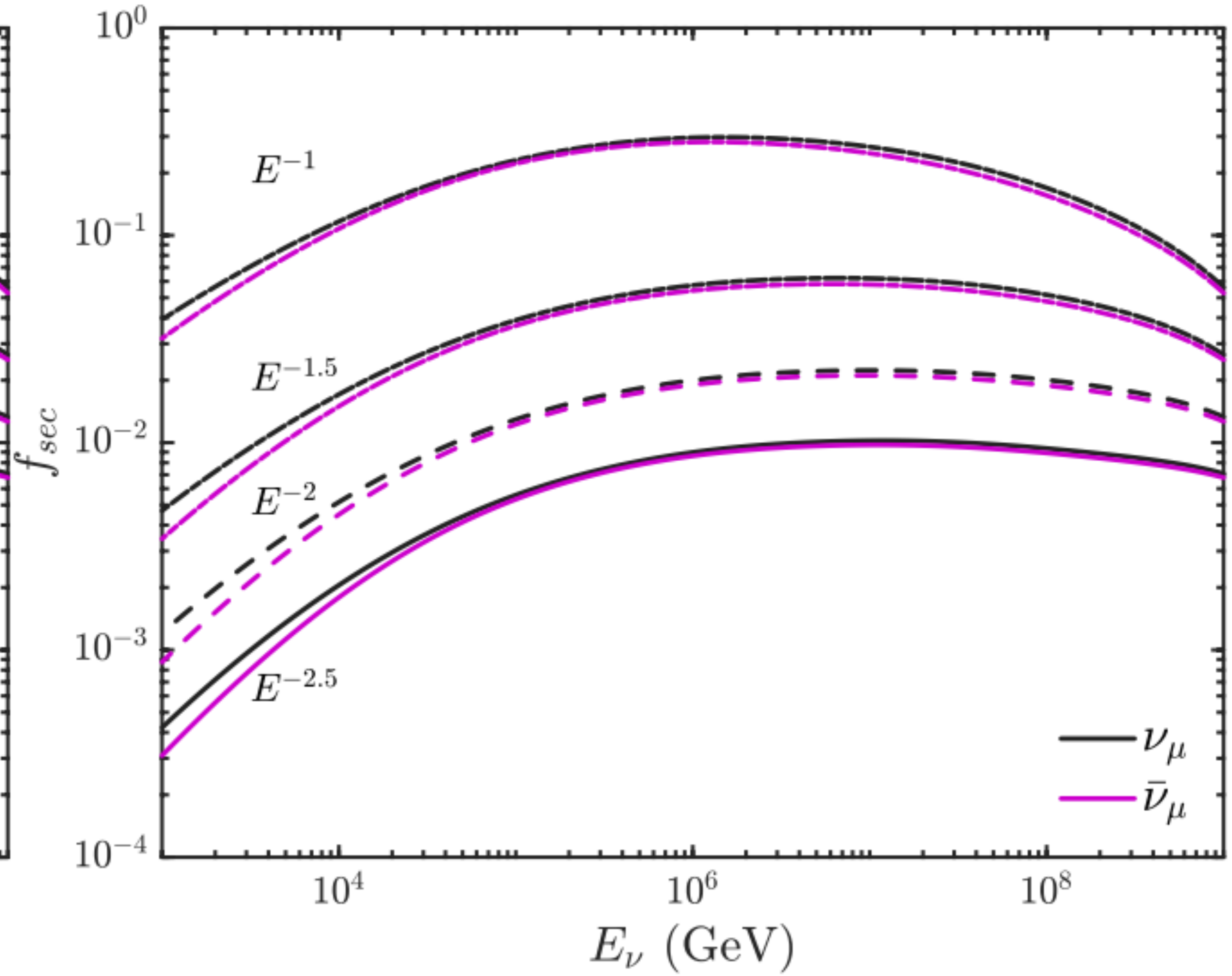
$$x(\theta) \equiv N_a \int_{l.o.s.} \rho_\oplus[r(x,\theta)]dx$$

$$I_\tau = \int_E^\infty d\tilde{E}\int_0^1 dy\,\frac{z}{E}\,\frac{dn}{dz}\,\frac{d\sigma^{CC}_{\nu_\tau}(\tilde{E},y)}{dy}\,\frac{d\phi_{\nu_\tau}(\tilde{E},x)}{d\tilde{E}}.$$

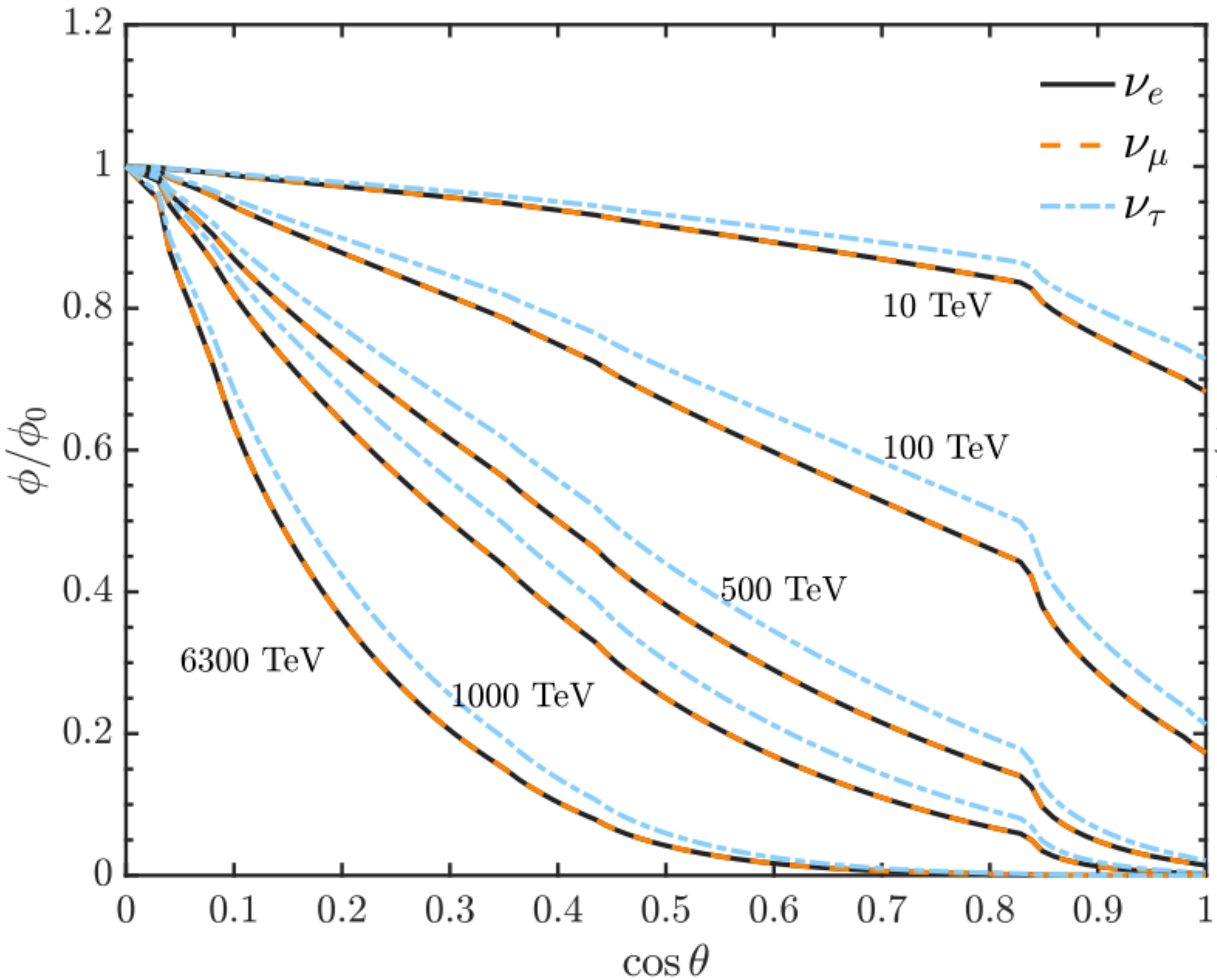


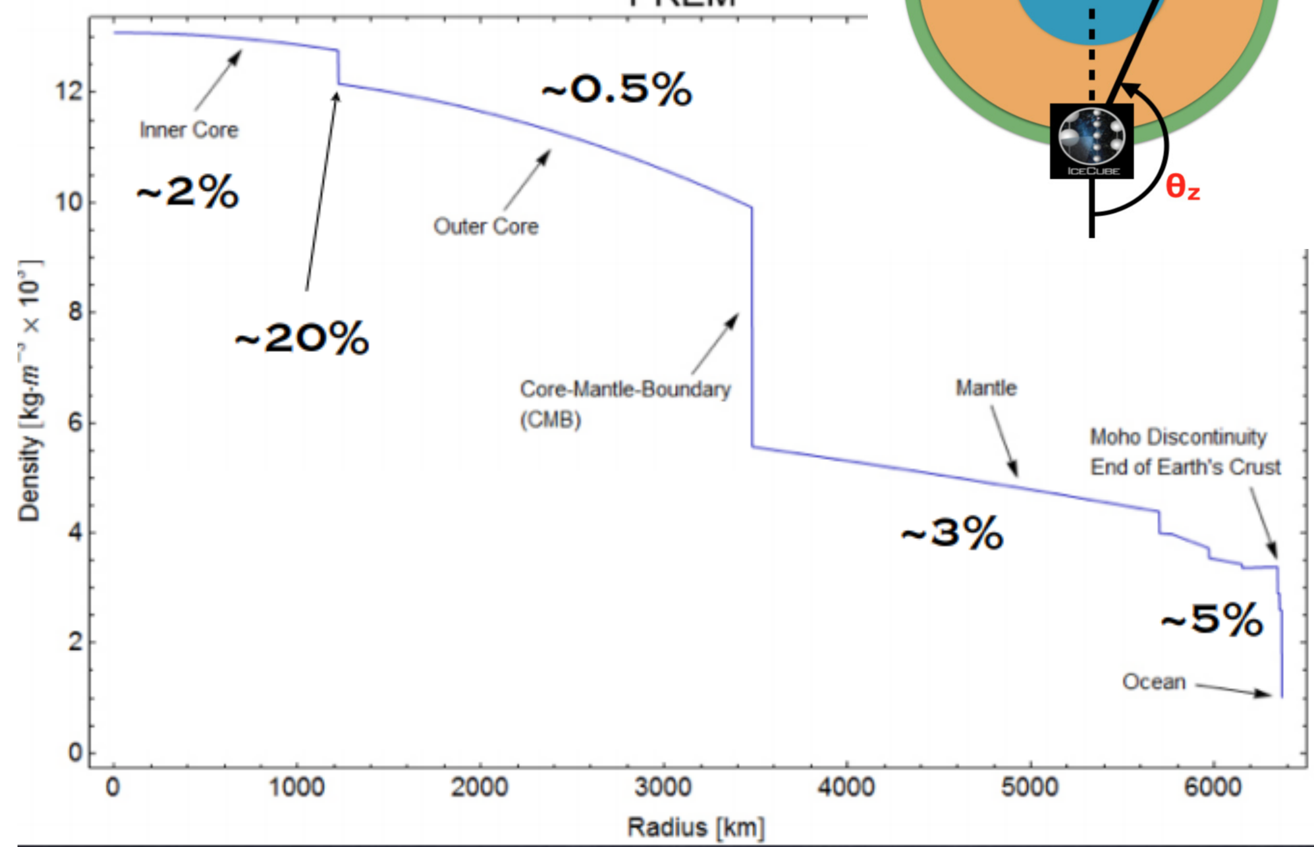
Effect of secondaries is small unless you have a very hard spectrum

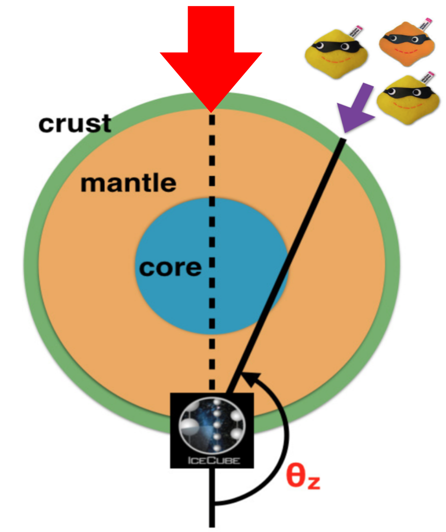




Angular view of Earth absorption

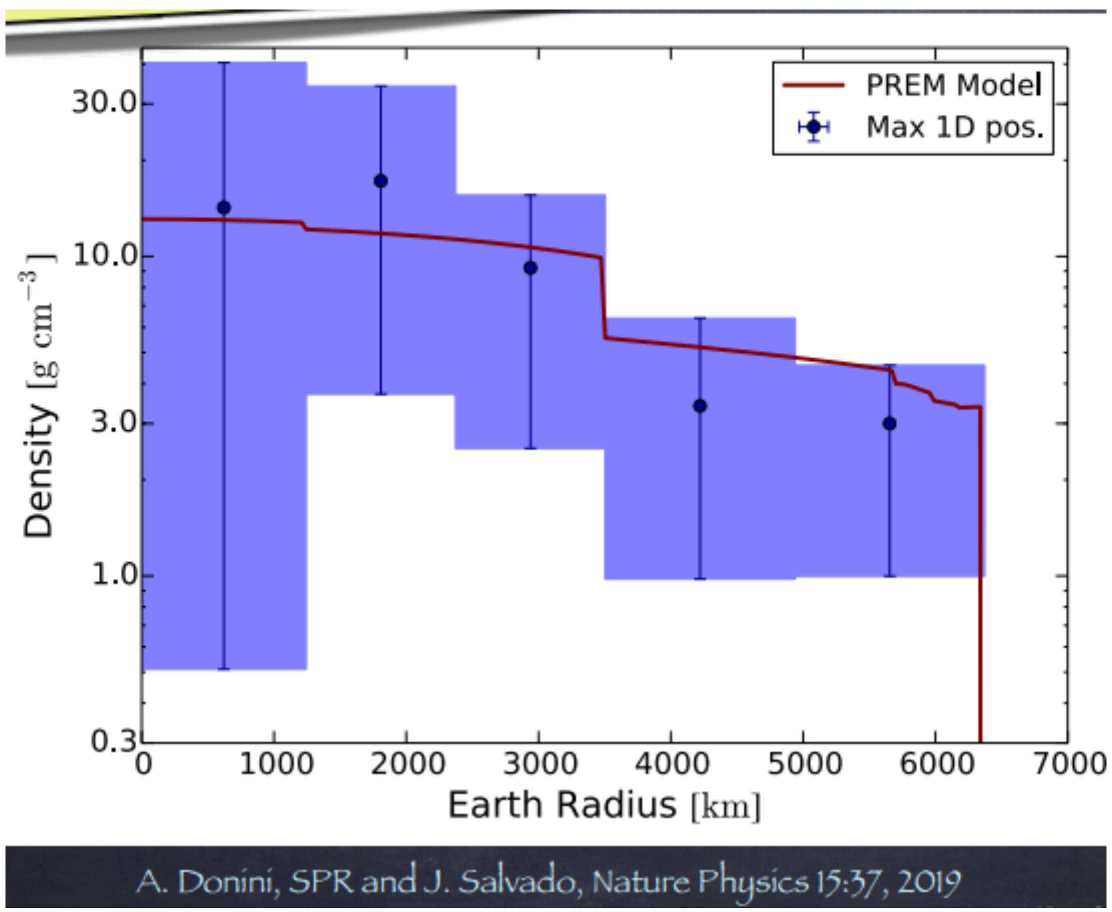


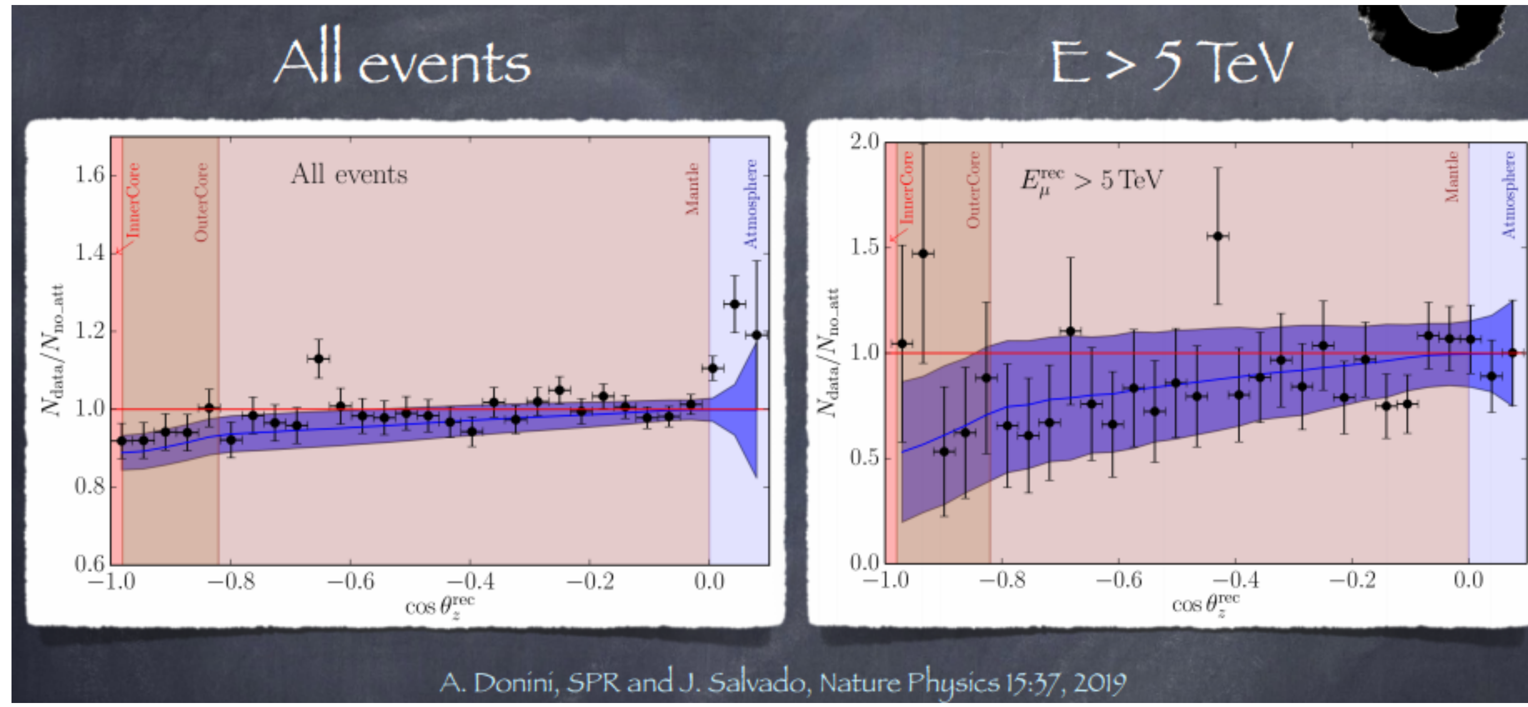


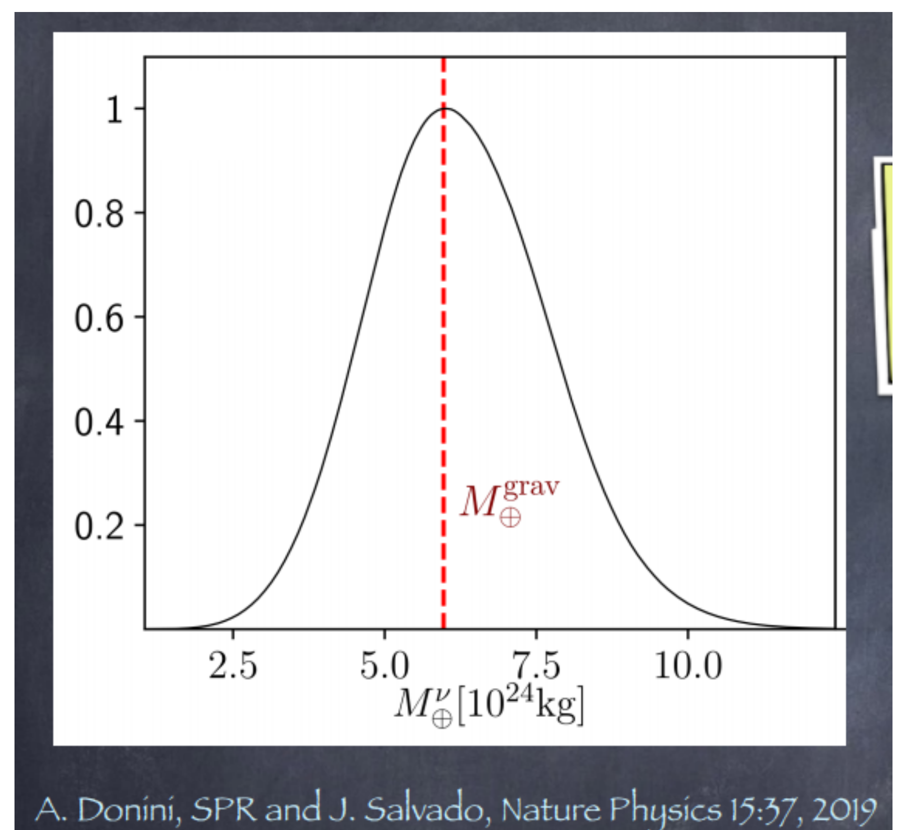


Could you measure the Earth using this effect?

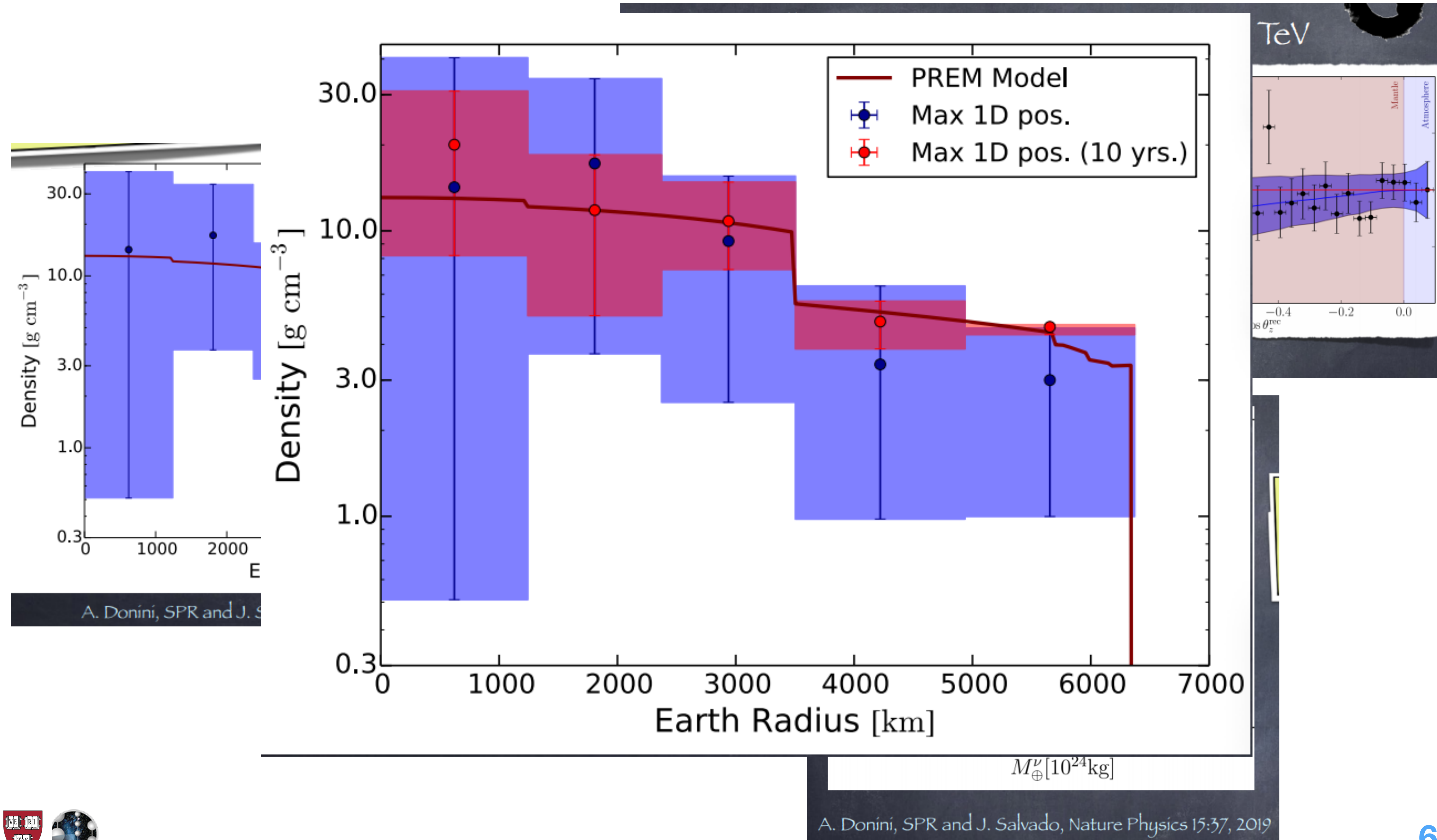
Yes, you can measure the Earth mass and profile with neutrinos







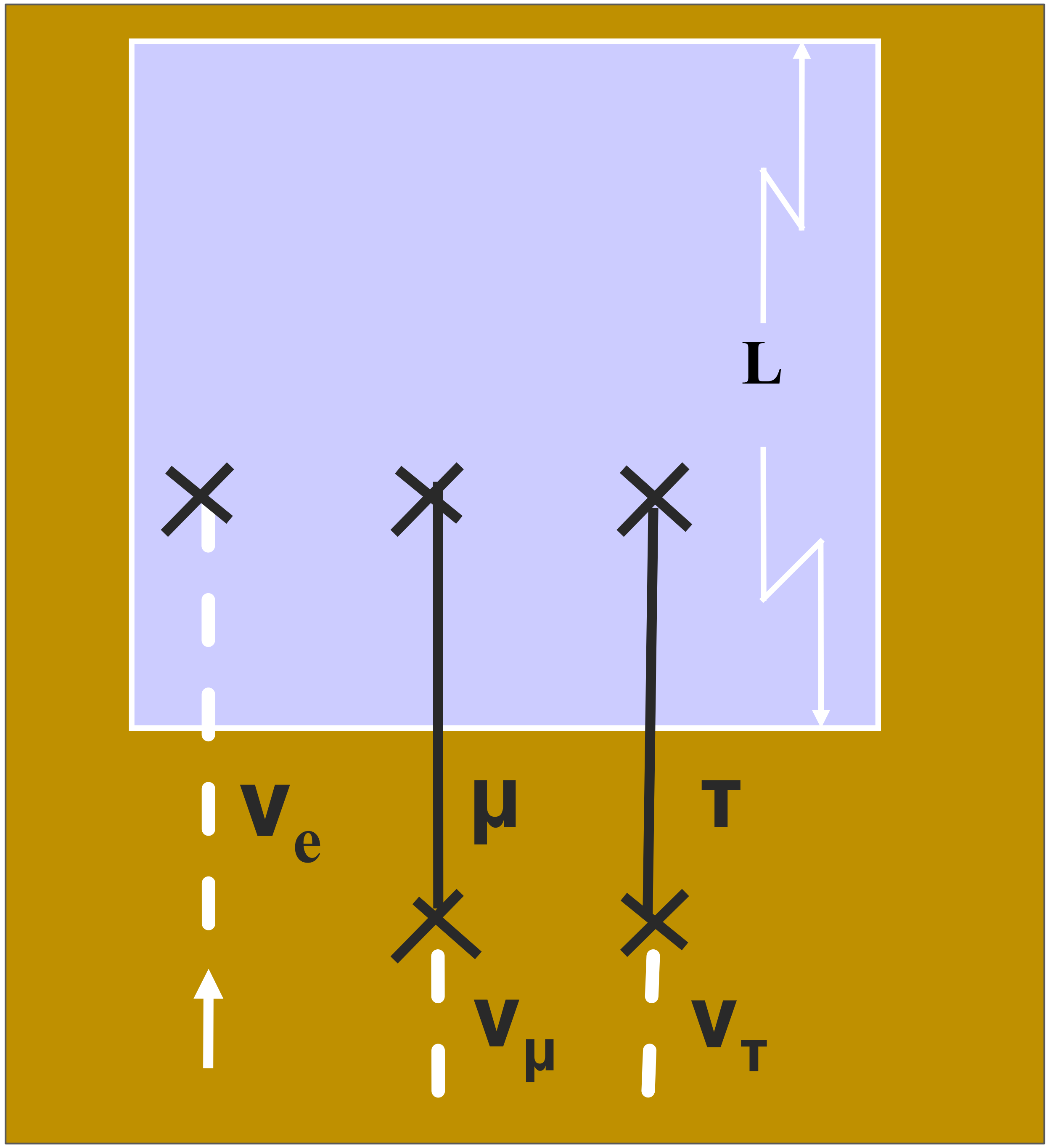
Yes, you can measure the Earth mass and profile with neutrinos



neutrino detection probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

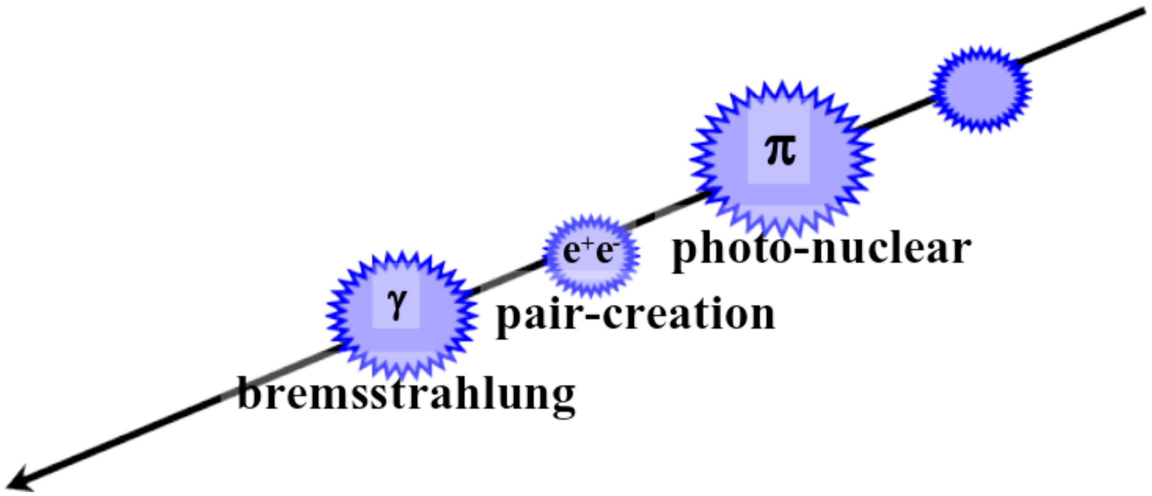
$$\simeq 1 - e^{-\frac{L}{\lambda_\nu}} \simeq \frac{L}{\lambda_\nu}$$

$$for \quad \nu_\mu \quad L \to R_\mu \left[E_\mu = (1-y) E_\nu \right]$$

$$for \quad \nu_\tau \quad L \to (E_\tau / m_\tau)\, c\tau_\tau$$

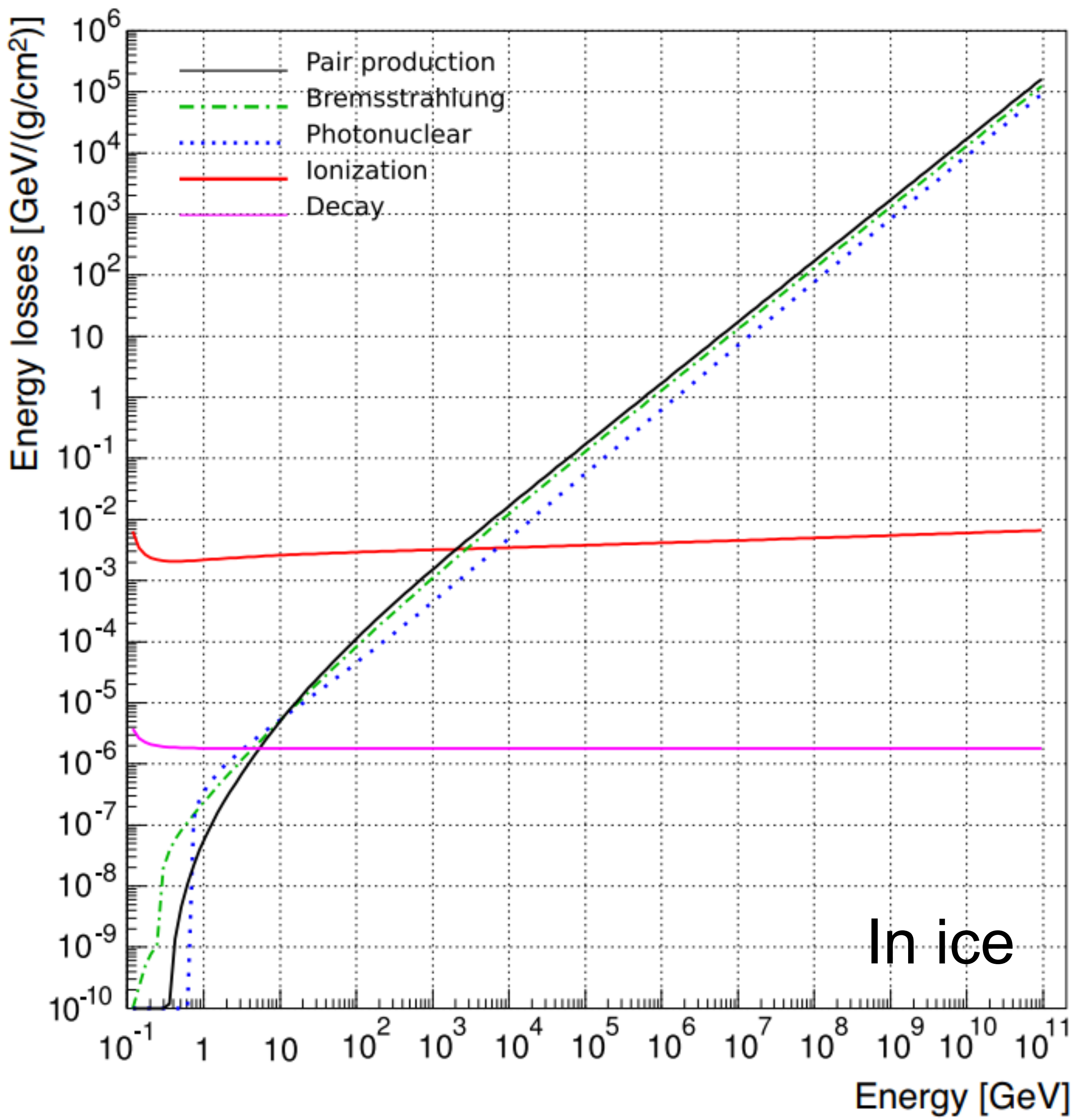
$$P_{\det} = n \sigma_\nu L$$

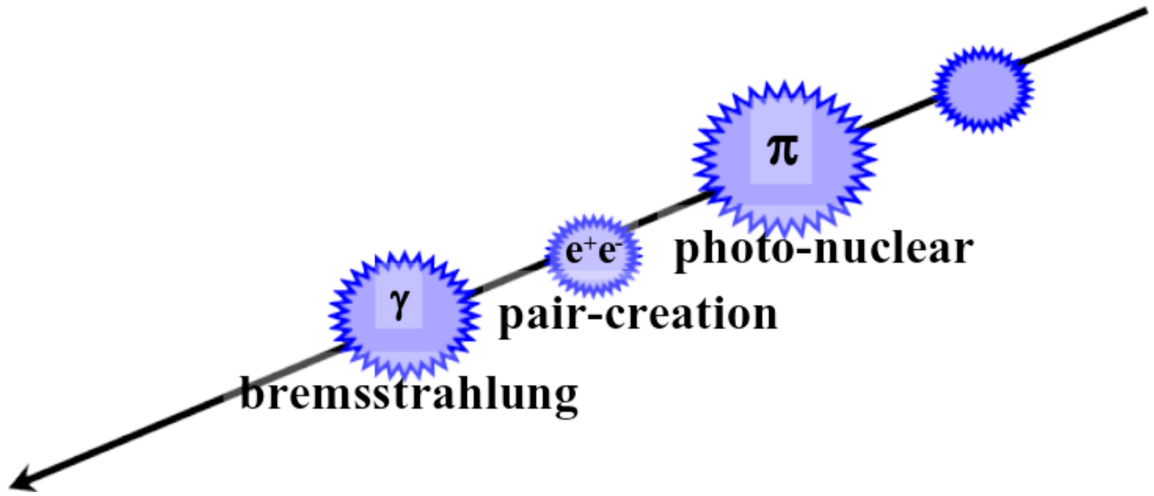
Muon losses and ranges



Mean energy losses are
well described by

Muon losses and ranges





Mean energy losses are well described by

$$-\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_I + \left(\frac{dE}{dx}\right)_B + \left(\frac{dE}{dx}\right)_P + \left(\frac{dE}{dx}\right)_N$$

$$-\frac{dE}{dx} = a_I(E) + b(E) \cdot E$$

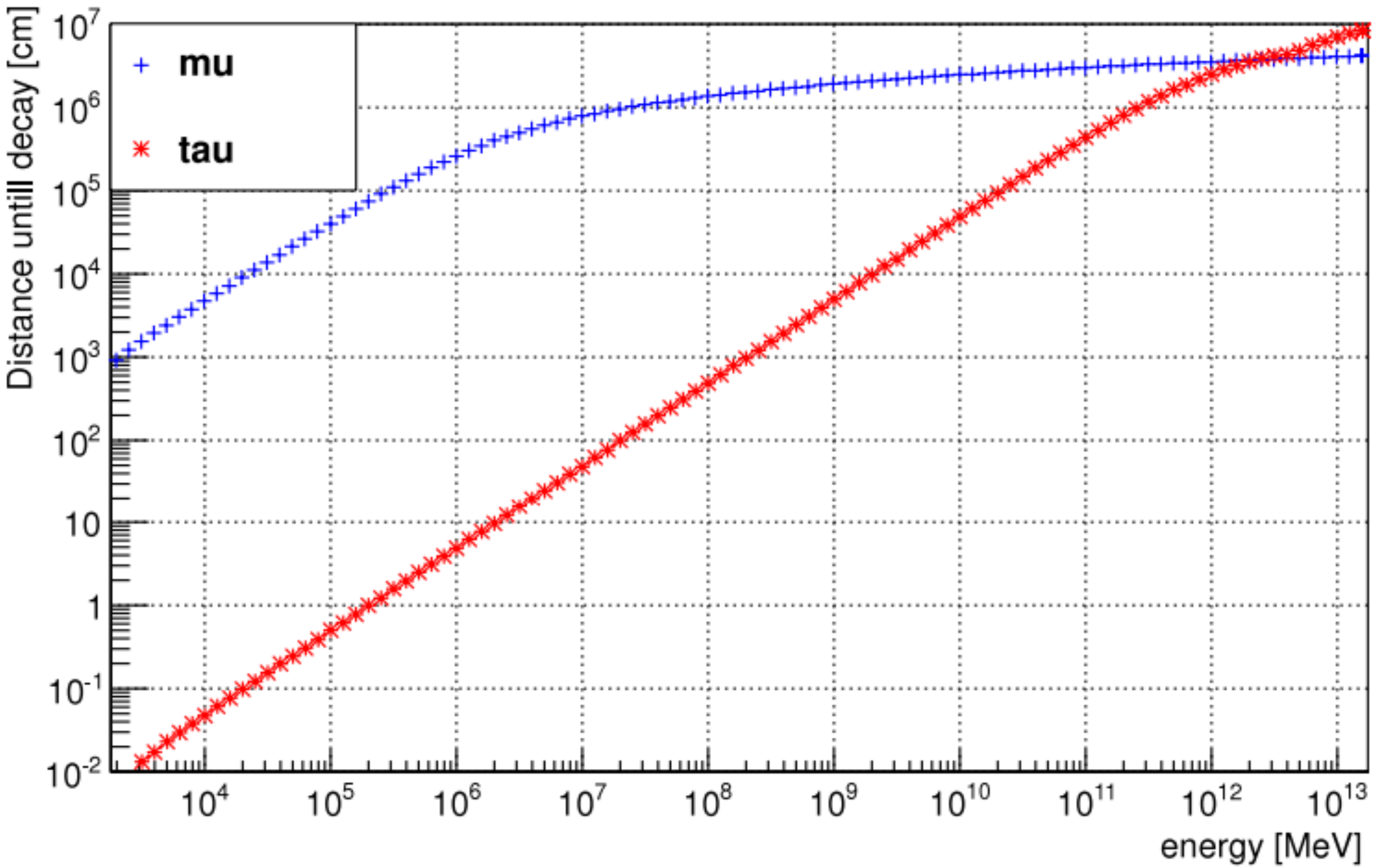
$$\text{with} \quad b(E) = b_B(E) + b_P(E) + b_N(E)$$

Mean muon range

$$x_f = \log(1 + E_i \cdot b/a)/b$$

medium	$a, \frac{\text{GeV}}{\text{mwe}}$	$b, \frac{10^{-3}}{\text{mwe}}$
ice	0.268	0.470

Tau vs muon ranges



Putting everything together: the neutrino and muons effective area

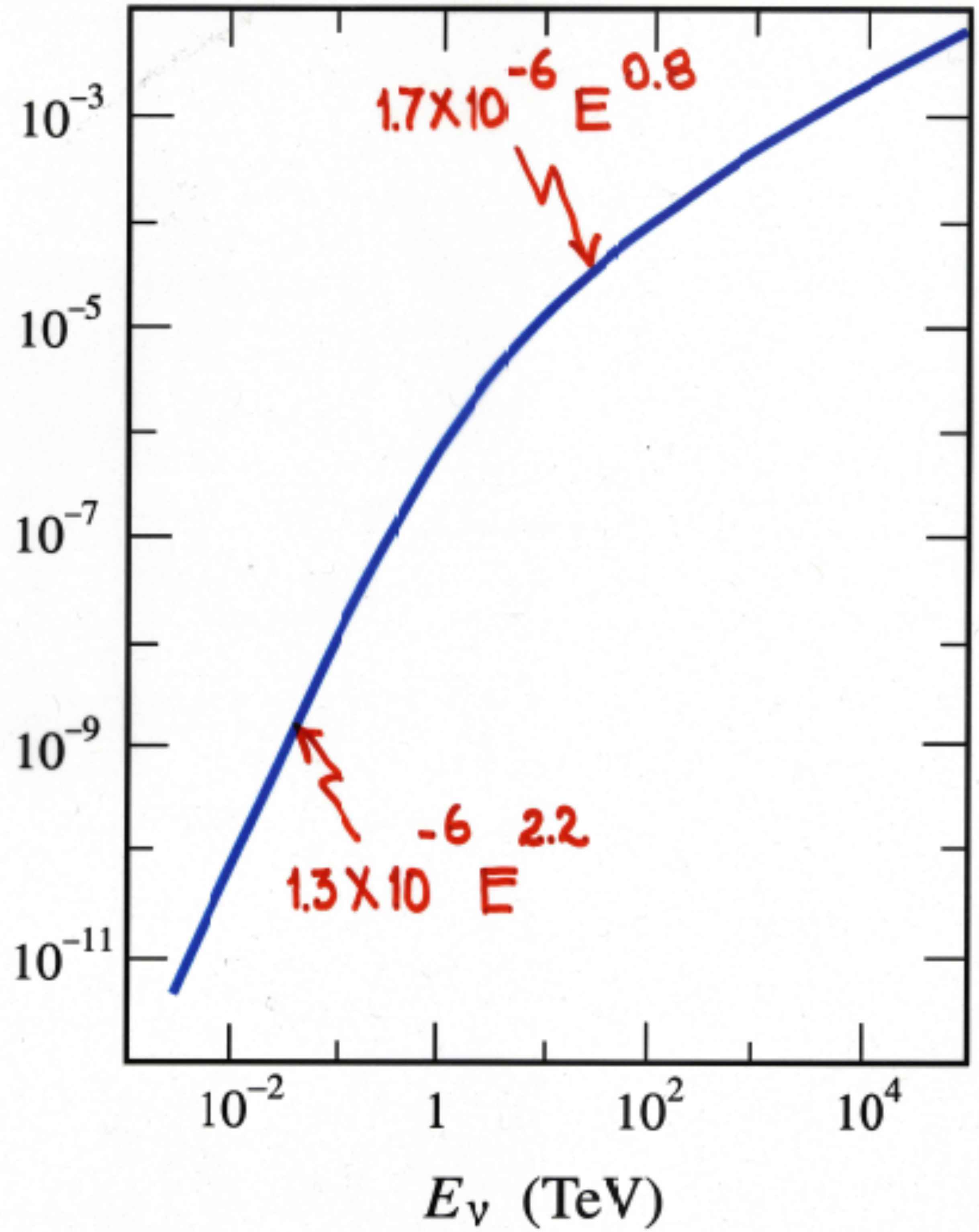
$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu\to\mu} \times \Phi_\nu$$

$$P_{\nu\to\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \simeq 10^{-6} E_{TeV}$$

$$A_\nu \to A_\nu = P_{\nu\to\mu}\, P_{survival}\, A_\mu$$

- $P_{\nu\to\mu} = \text{density} \cdot \sigma_\nu(E) \cdot R_\mu(E)$



- $N_{events} = \text{AREA} \int \frac{dN_\mu}{dE} P_{\nu\to\mu}\, dE$

Neutrino telescope effective area at 100 TeV

$$area \times P_{\mu\rightarrow\nu} (= \frac{\lambda_{\mu}}{\lambda_{\nu}} = nR_{\mu}\sigma_{\nu} \simeq 10^{-6}\ E_{TeV})$$

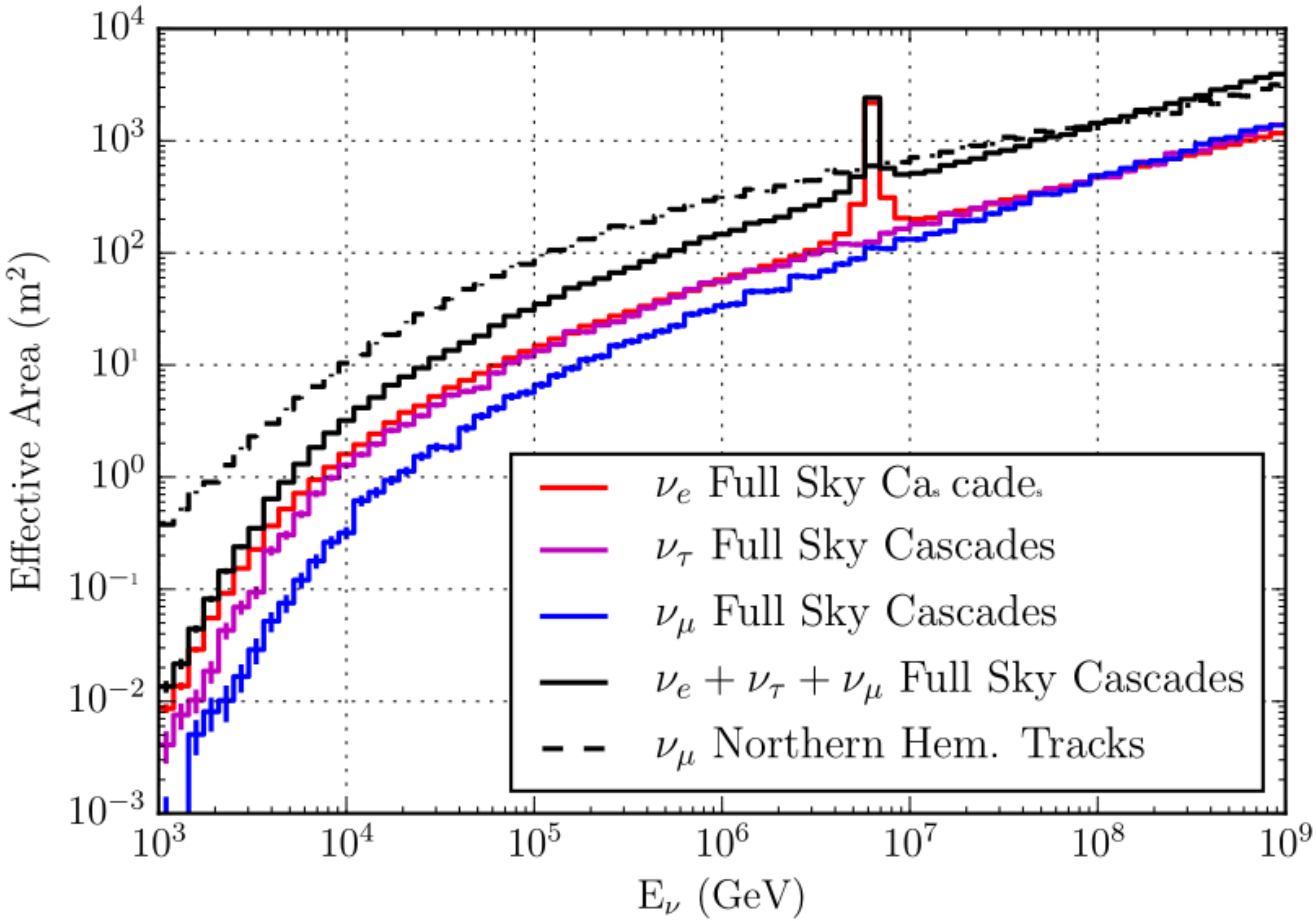
- AMANDA ~ ANTARES ~ (1- 5) m^2
- IceCube 86 strings ~ 100 m^2

The neutrino effective area is the size of the neutrino telescope

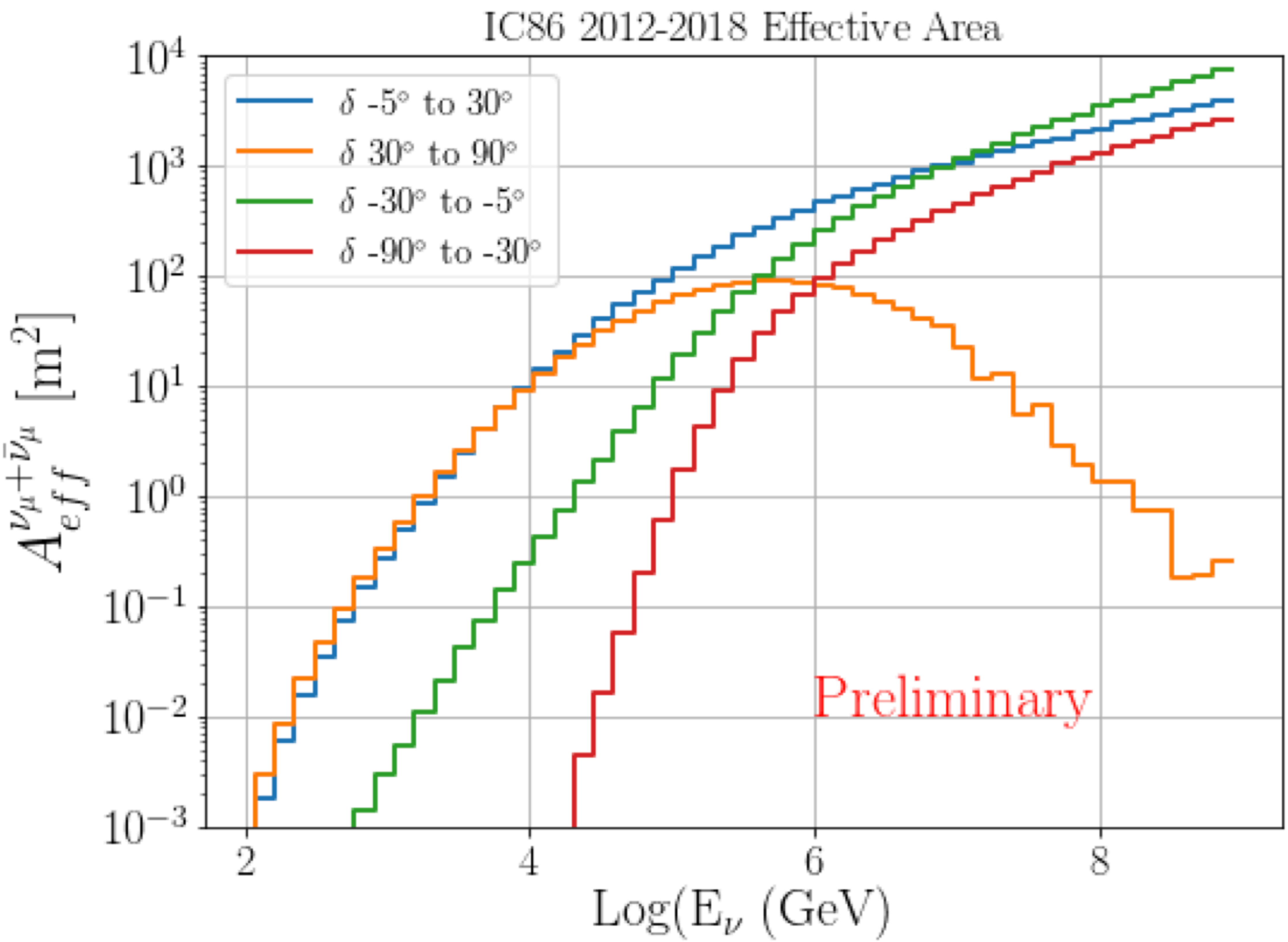
SAO director Fred Lawrence Whipple (middle) at the 10-m Gamma Ray Reflector on the day the 'Mount Hopkins Observatory' opened its doors in 1968

IceCube is comparable to a 10 m gamma-ray telescope

Typical IceCube's All-sky effective areas



Typical IceCube's Differential effective areas



In-class exercise: Event Rate Estimation

Assuming that the effective area is given by

$$A_{eff}(E_\nu) = 10\mathrm{m}^2 \left(\frac{E}{10\mathrm{TeV}}\right)^{0.8}$$

And the astrophysical flux is given by

$$\phi_{astro}(E_\nu) = 10^{-18} \left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-2} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}\mathrm{sr}^{-1}$$

How many (all-sky) events do you expect from 10 TeV to 10 PeV in 10 years?

Reconstructing events in the ice (or in water)

Cherenkov cone and track reconstruction

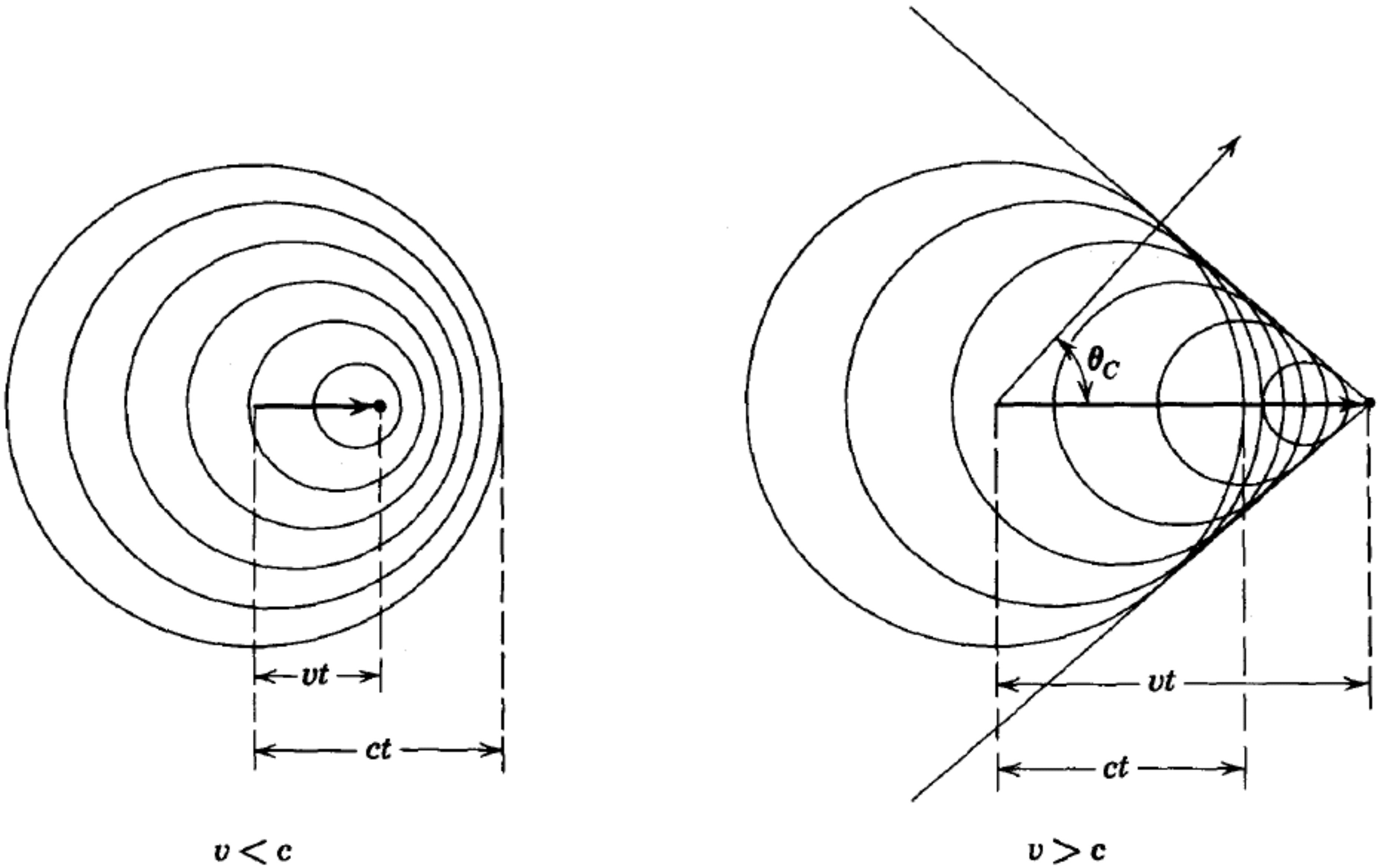


Fig. 14.14 Cherenkov radiation. Spherical wavelets of fields of a particle traveling less than, and greater than, the velocity of light in the medium. For $v > c$, an electromagnetic "shock" wave appears, moving in the direction given by the Cherenkov angle θ_c.

$$\cos\theta_c = (n \cdot \beta)^{-1} \qquad n \simeq 1.32 \qquad \theta_c \approx 41^\circ$$

Cherenkov cone and track reconstruction

$$\cos\theta_c = (n \cdot \beta)^{-1} \qquad n \simeq 1.32 \qquad \theta_c \approx 41^\circ$$

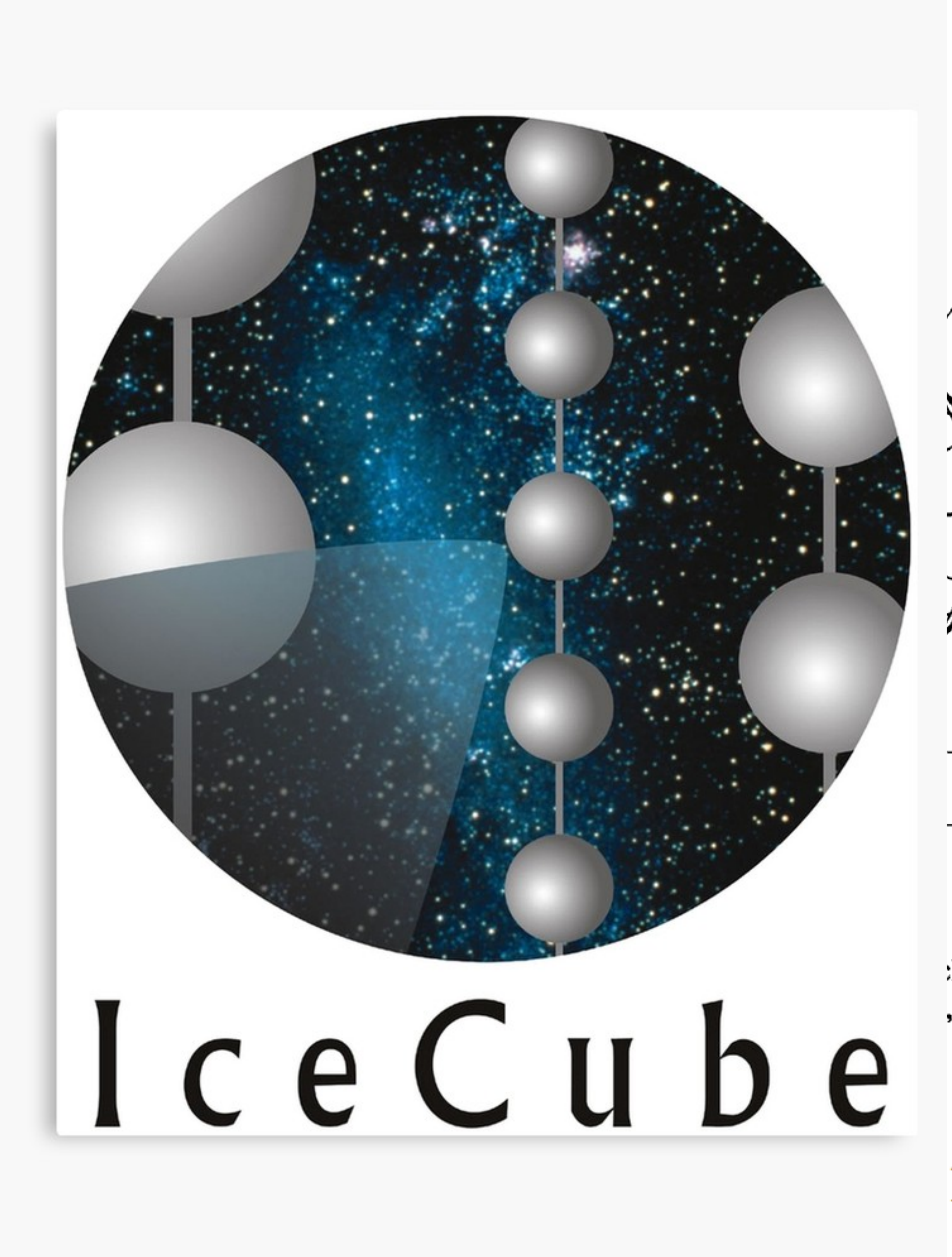
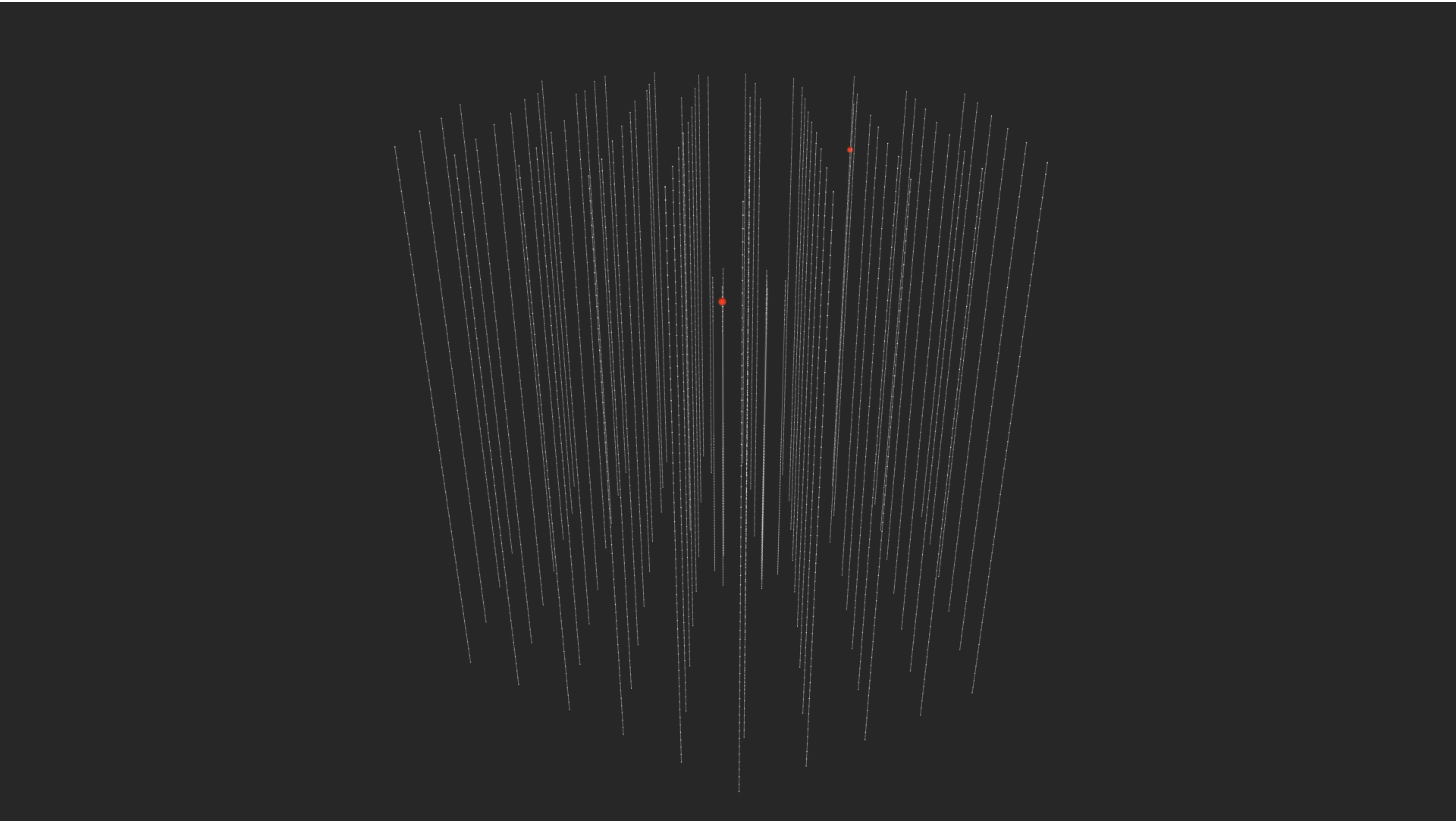


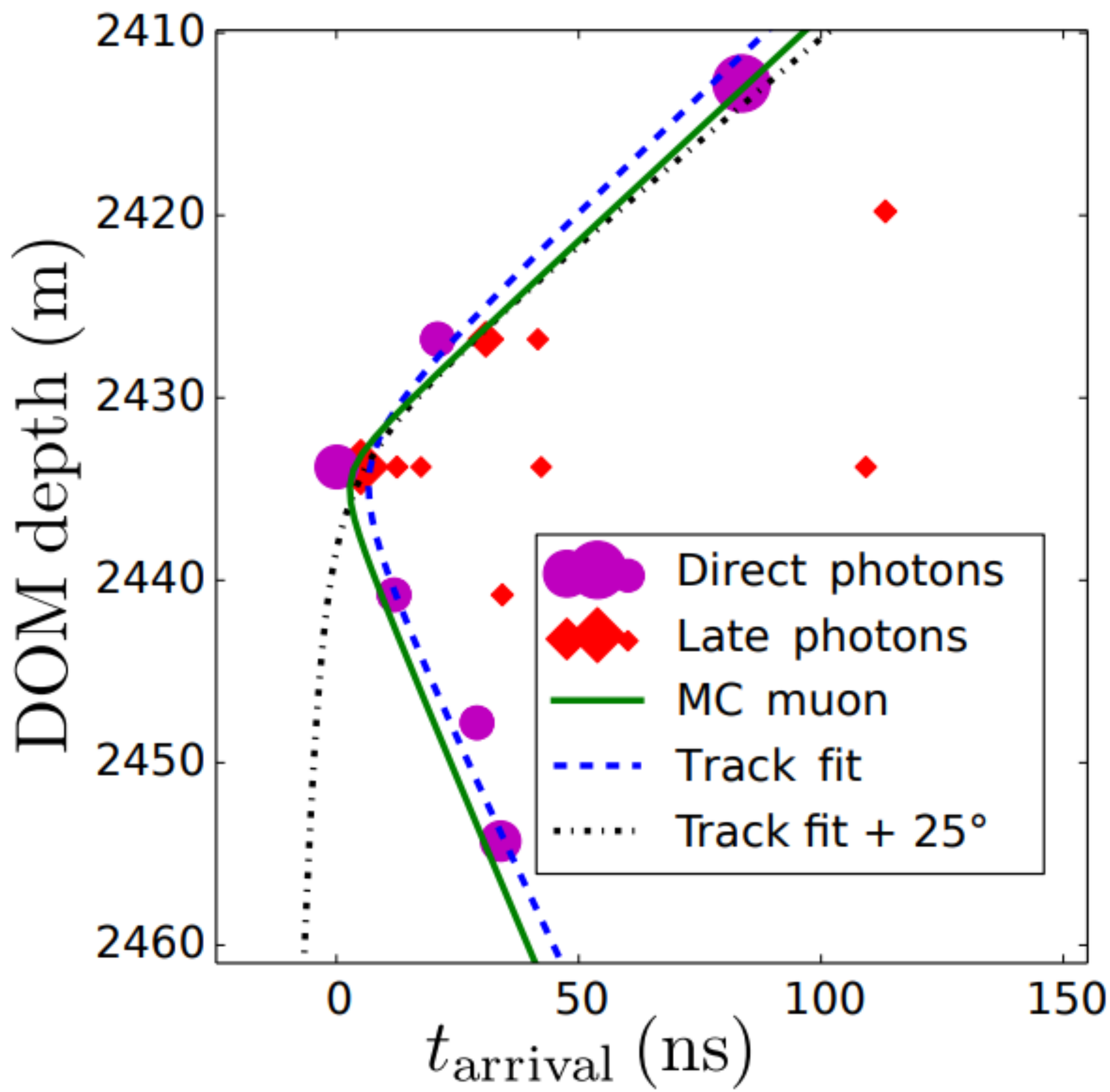
Fig. 14 … le traveling
less tha… , an electro-
magne… Cherenkov

cos … 1°

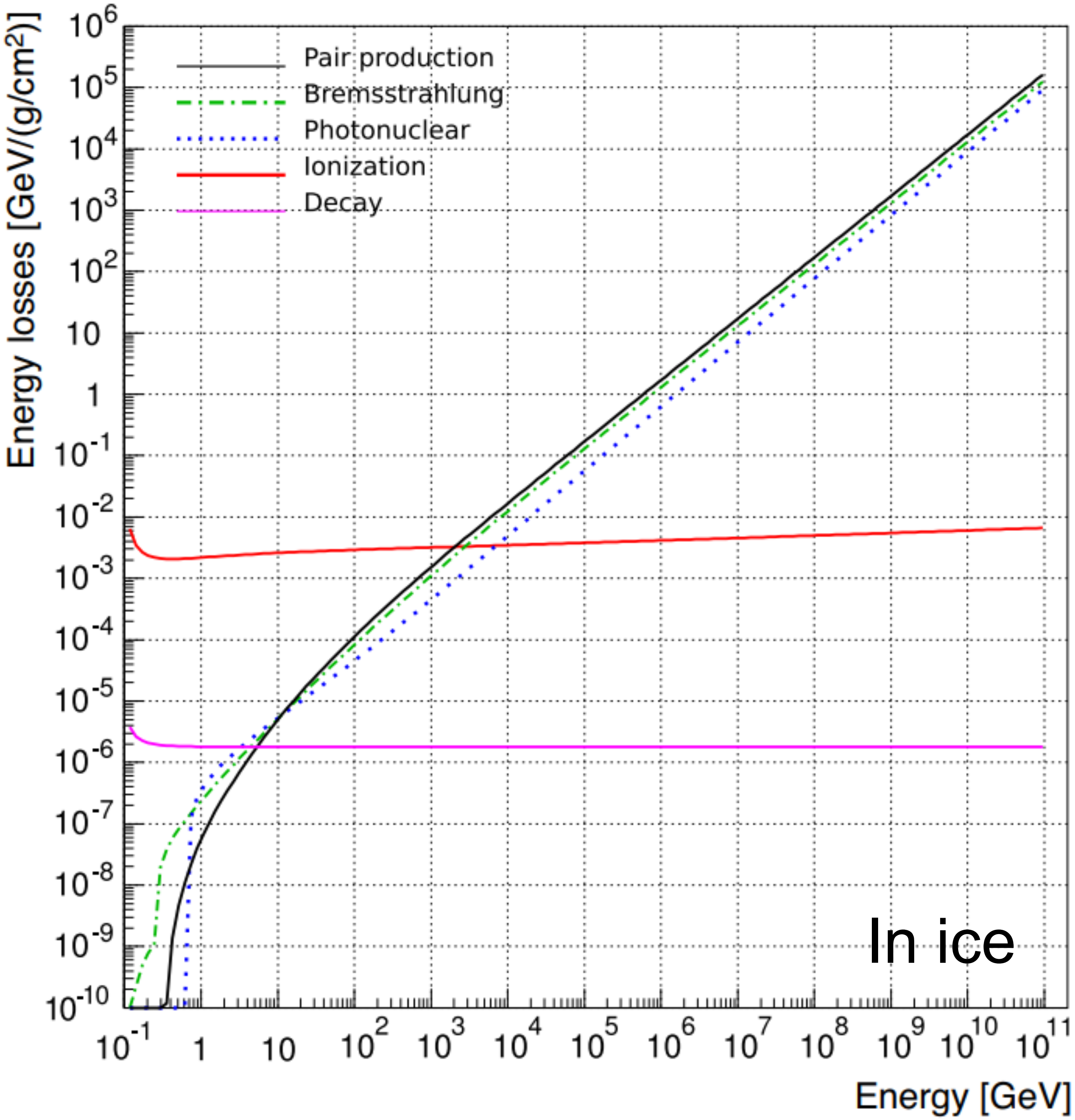
Muon with Cherenkov cone

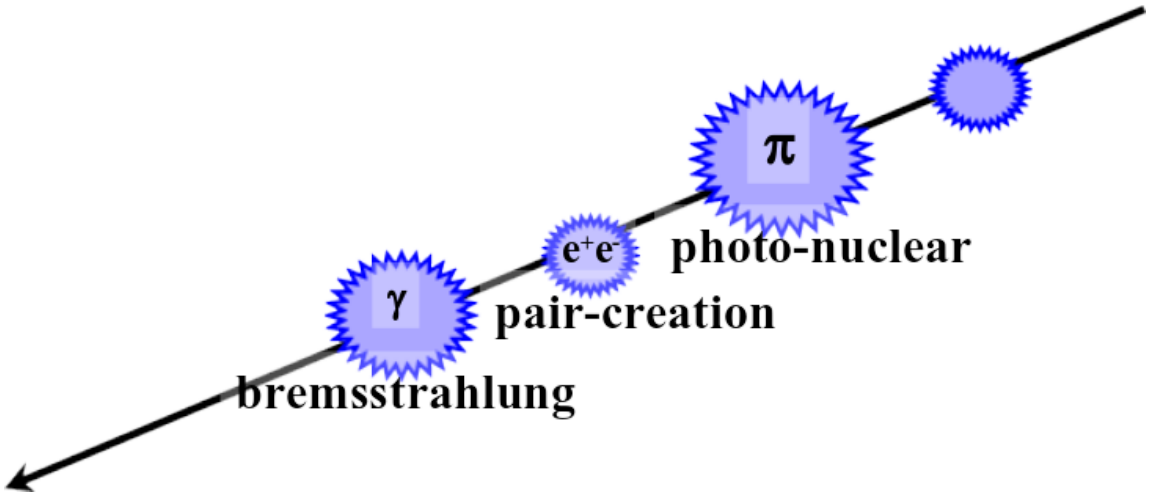


Muon reconstruction with direct photons



Remember our muon losses discussion





Losses are dominated by *stochastic* process…

what does that imply?

Stochastic behavior of muon losses

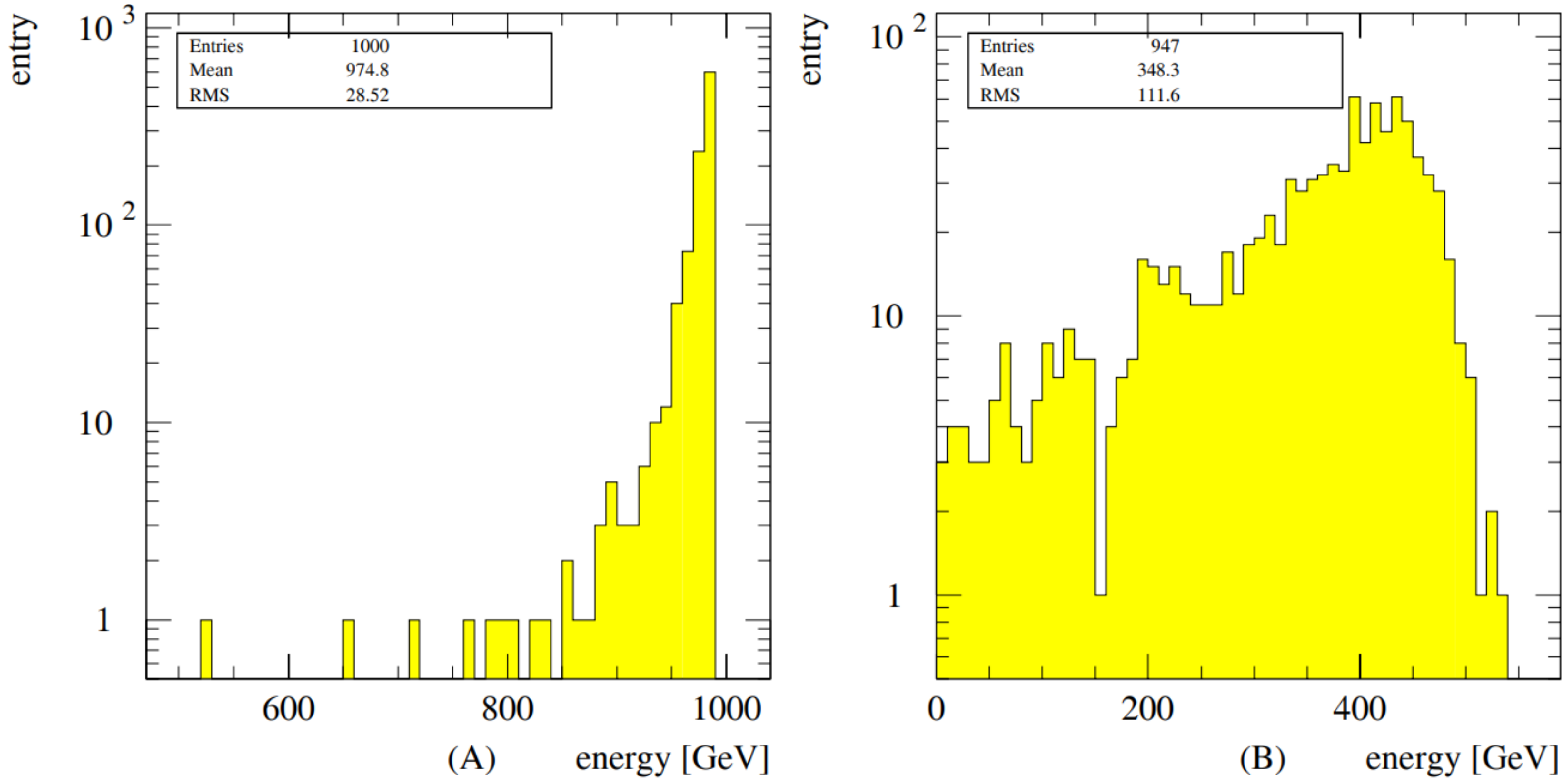


Figure 3.12: Stochastic character of muon energy loss The picture shows distributions of the final energy of 1000 simulated muons (initial energy $1TeV$) after passing (A) $50m$ and (B) $1500m$ of fresh water, simulated with GEANT (section 6.2)

From C. Wiebusch (1995)

Muon tracks with charged secondaries

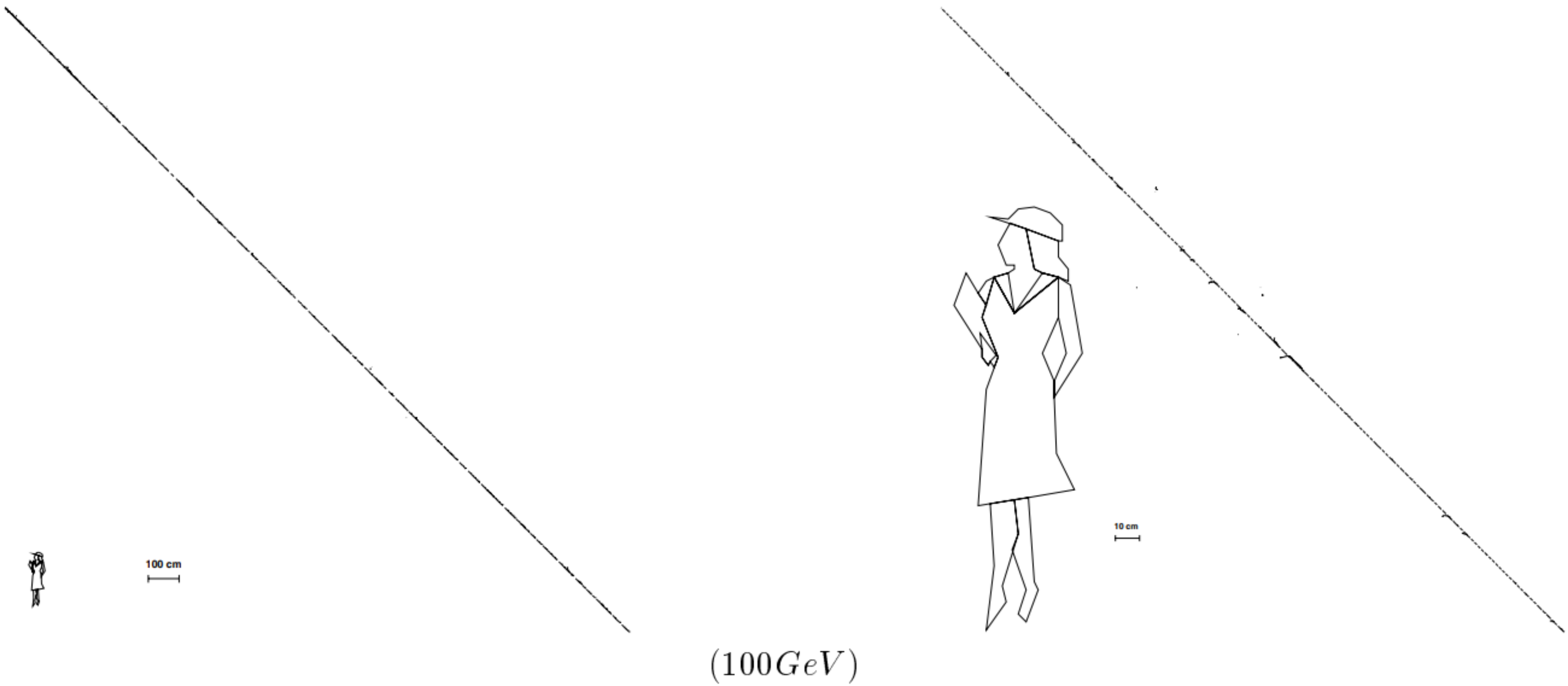
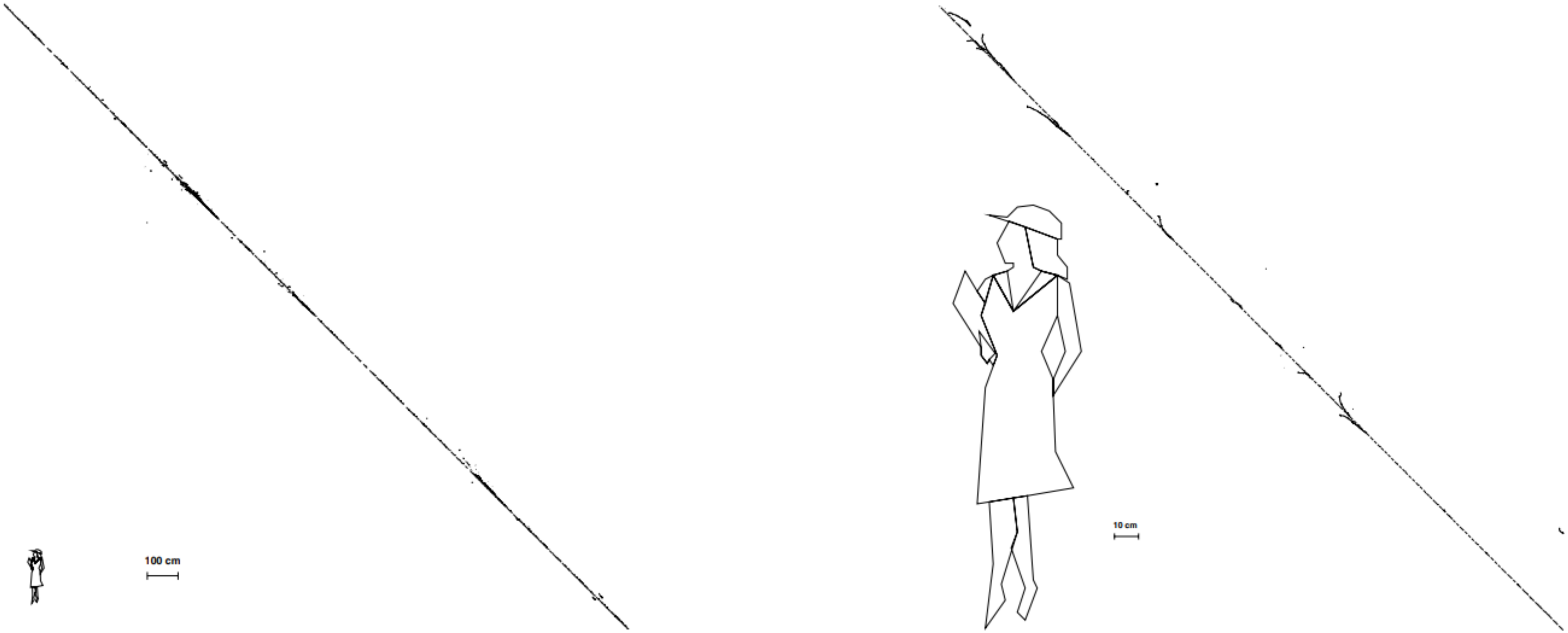


Figure 3.13: Typical muon tracks and charged secondaries above the Čerenkov threshold for different energies in two zoom levels.

From C. Wiebusch (1995)

Muon tracks with charged secondaries



$(1TeV)$

Figure 3.13: Typical muon tracks and charged secondaries above the Čerenkov threshold for different energies in two zoom levels.

From C. Wiebusch (1995)

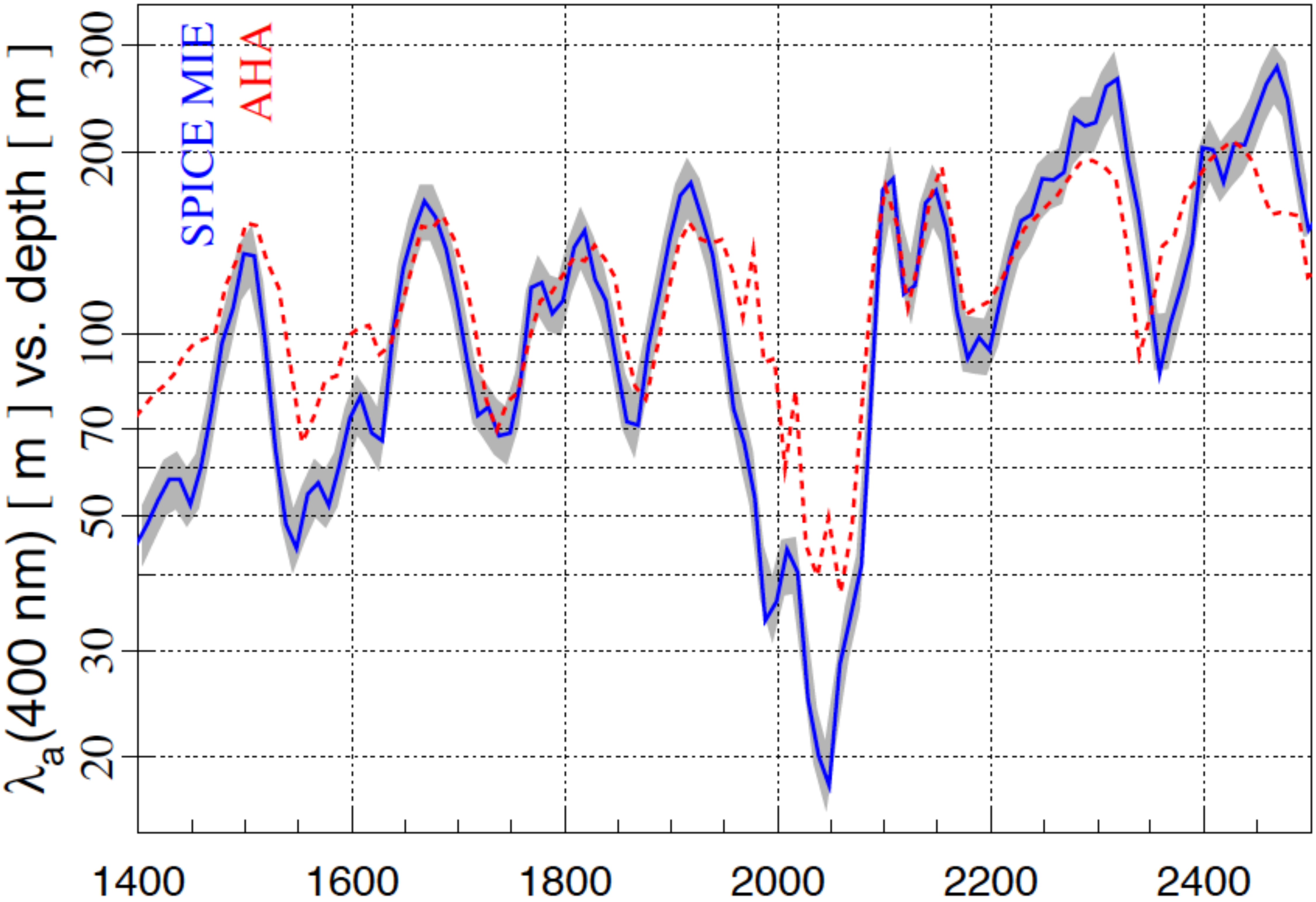
Muon tracks with charged secondaries

$(10TeV)$

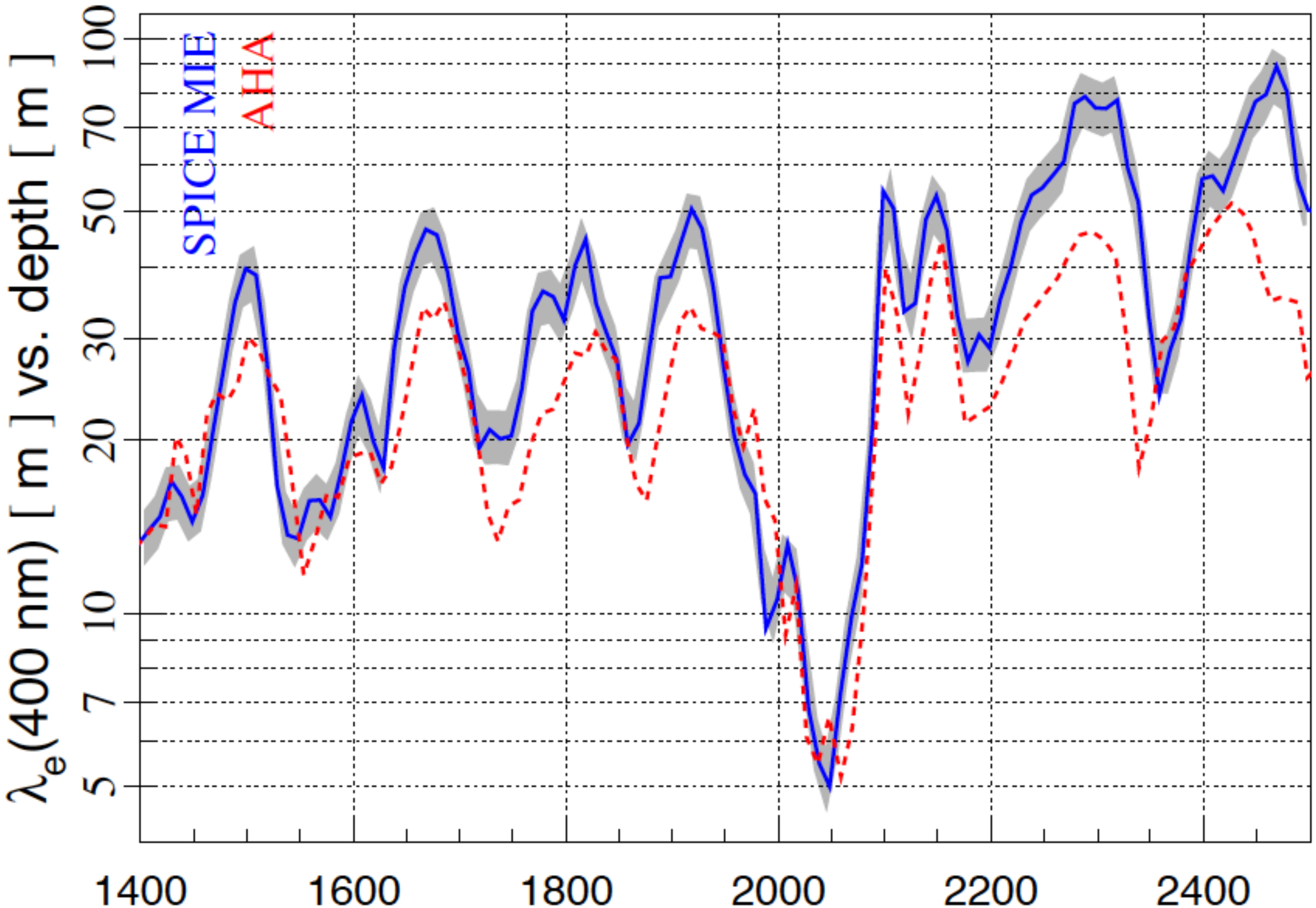
Figure 3.13: Typical muon tracks and charged secondaries above the Čerenkov threshold for different energies in two zoom levels.

From C. Wiebusch (1995)

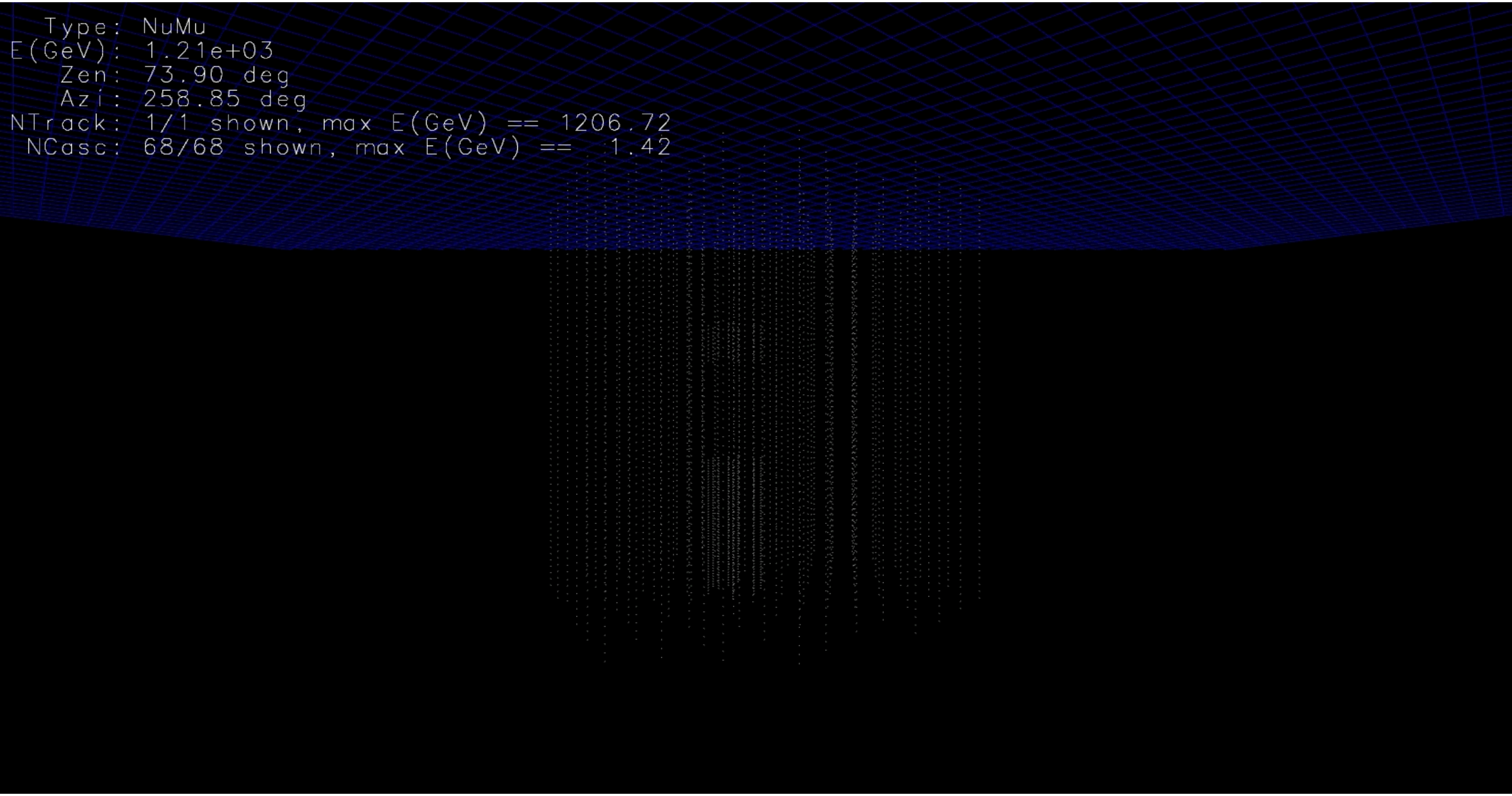
Absorption length in ice



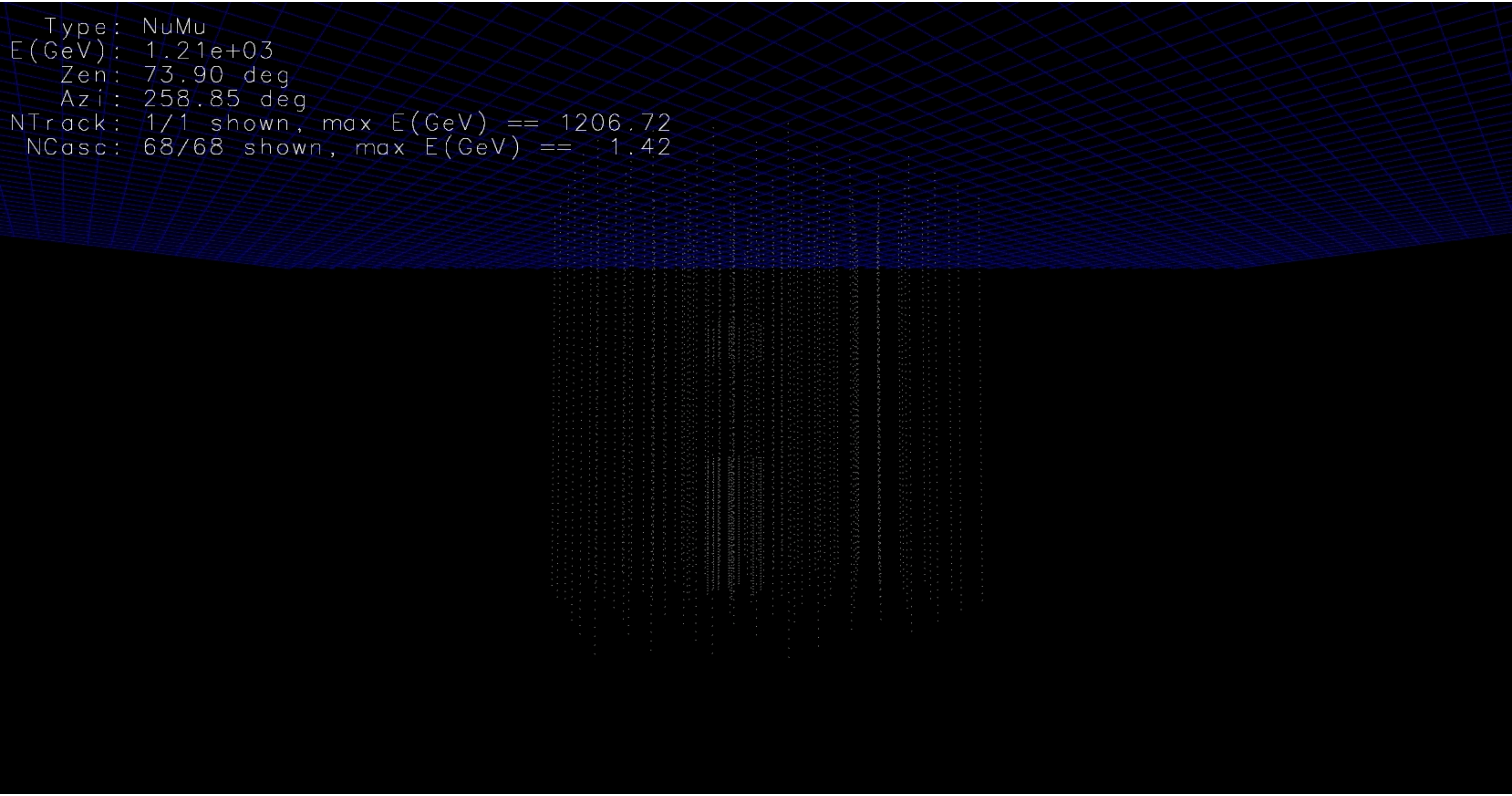
Scattering length in ice



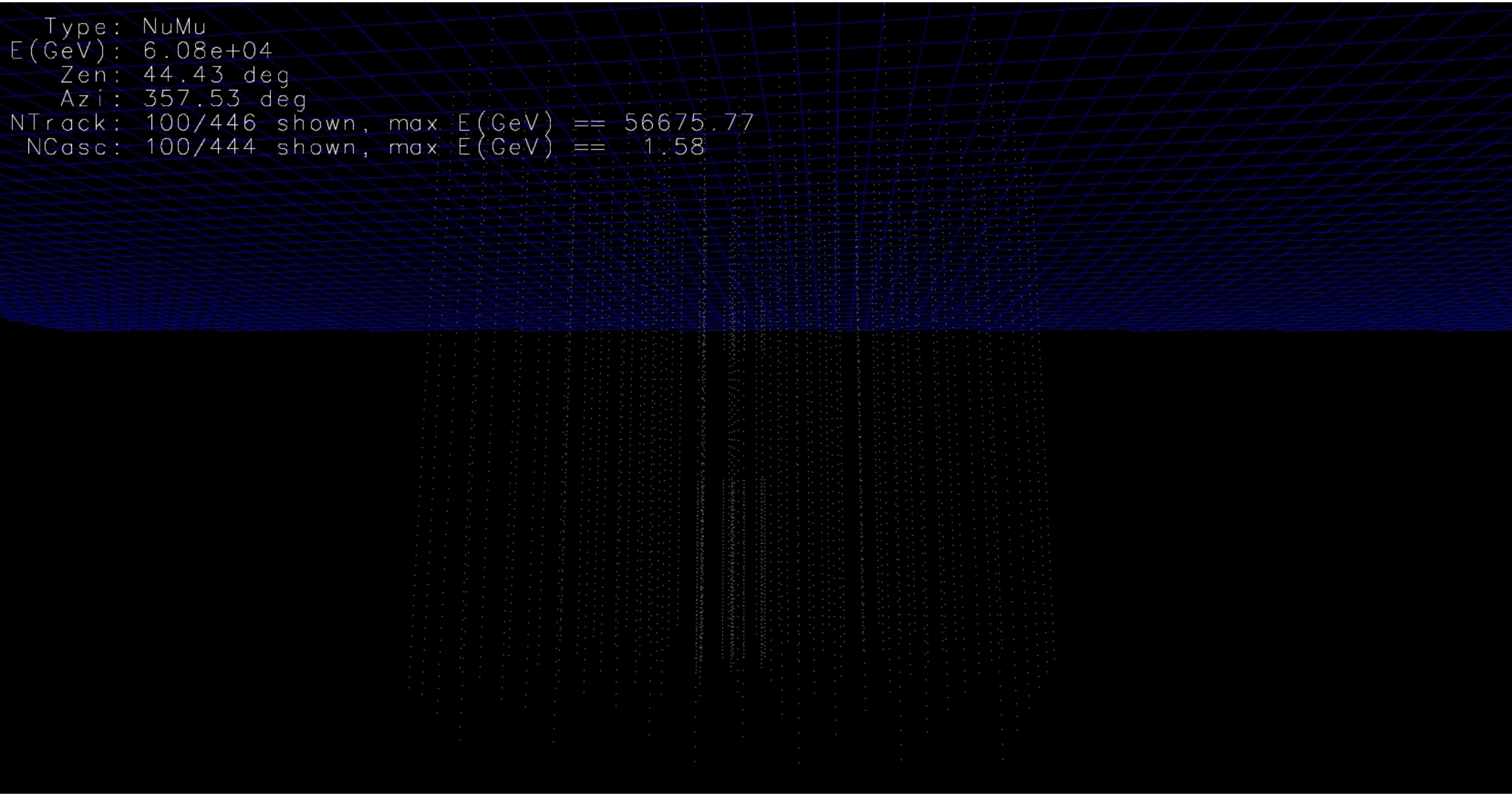
Muon in ice


Type: NuMu
E(GeV): 1.21e+03
Zen: 73.90 deg
Azi: 258.85 deg
NTrack: 1/1 shown, max E(GeV) == 1206.72
NCasc: 68/68 shown, max E(GeV) == 1.42

Muon in sea water

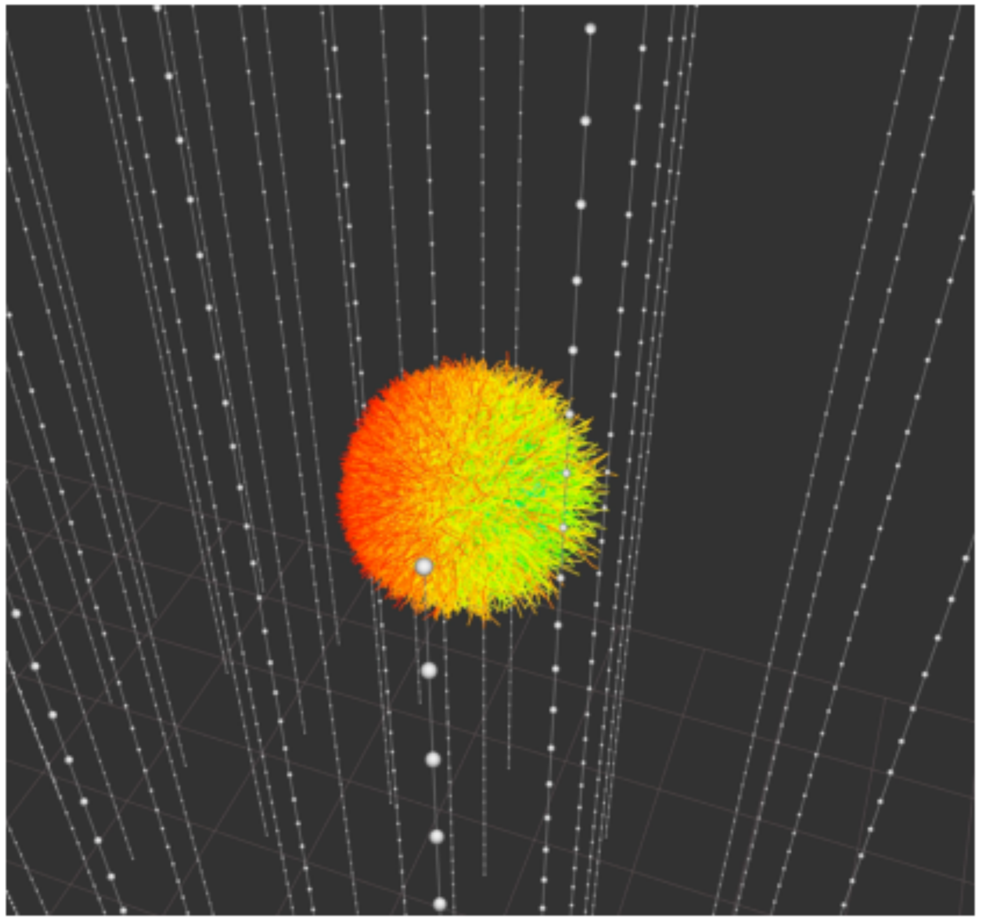


Why is this a difficult problem?



An incomplete information challenge

Emitted

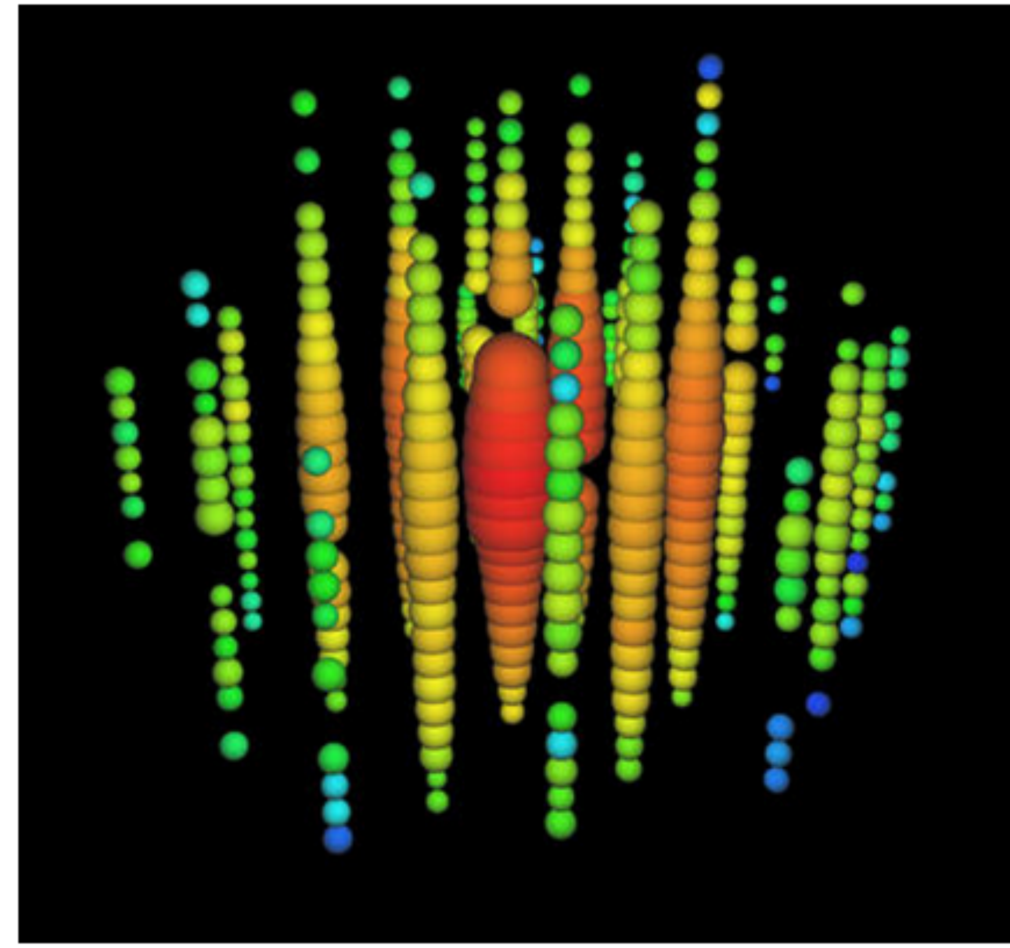


Asymmetry in photon emission helps with directional reconstruction

Information loss

$$\nu_e + N \rightarrow e + X$$
$$\nu_l + N \rightarrow \nu_l + X$$

Detected



$$\boldsymbol{\Theta} = (x, y, z, \theta, \phi, E, t)$$

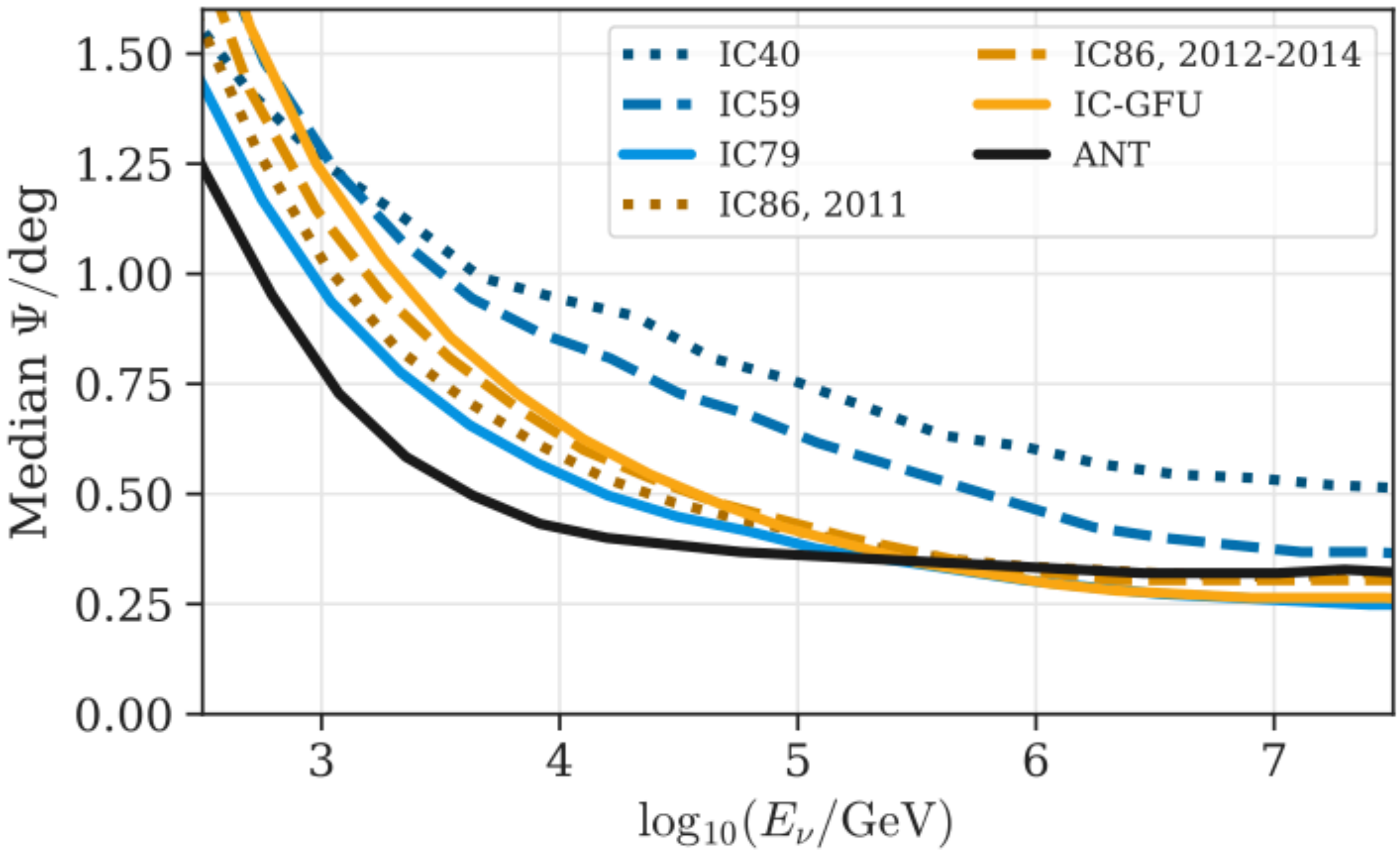
Physics model (emission, absorption, scattering)

$$X = q_{DOM}(t)$$

Maximize $\mathcal{L}(\boldsymbol{\Theta} | X_{\mathrm{Data}})$

Muon angular resolution

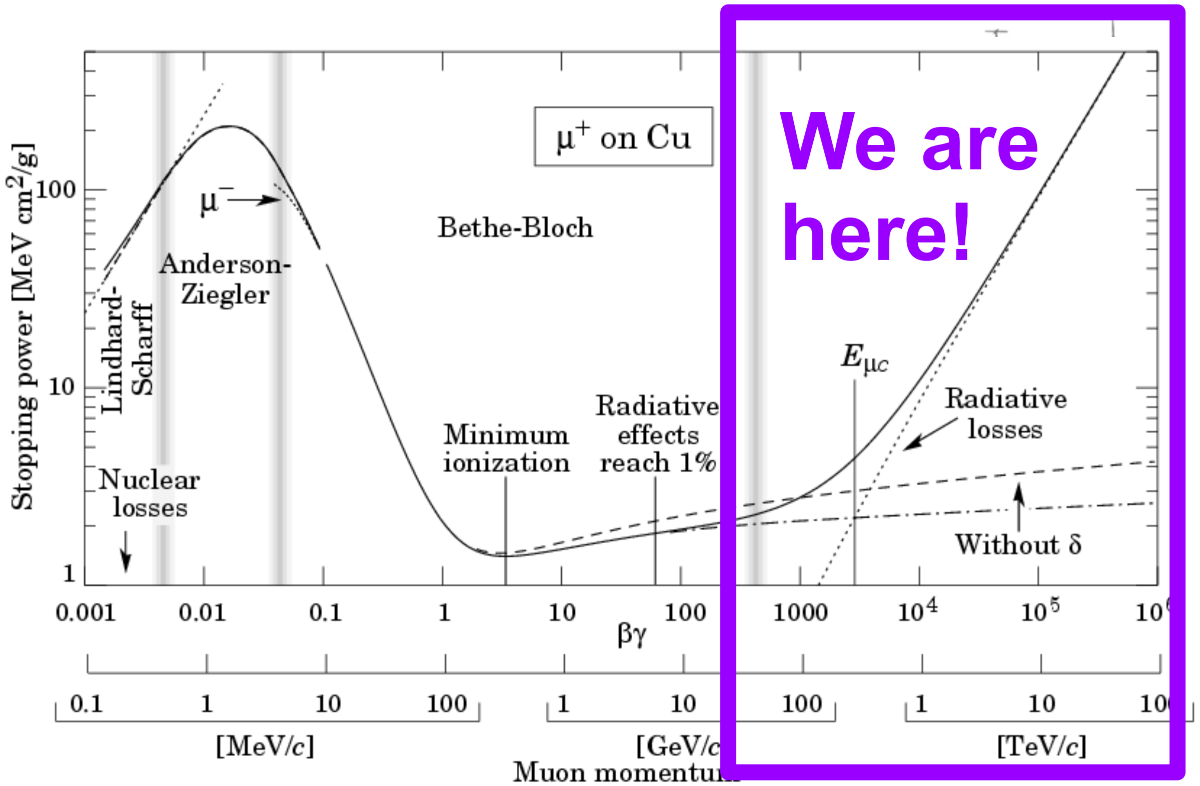
ANTARES, IceCube, Auger, and TA, arXiv:2201.07313

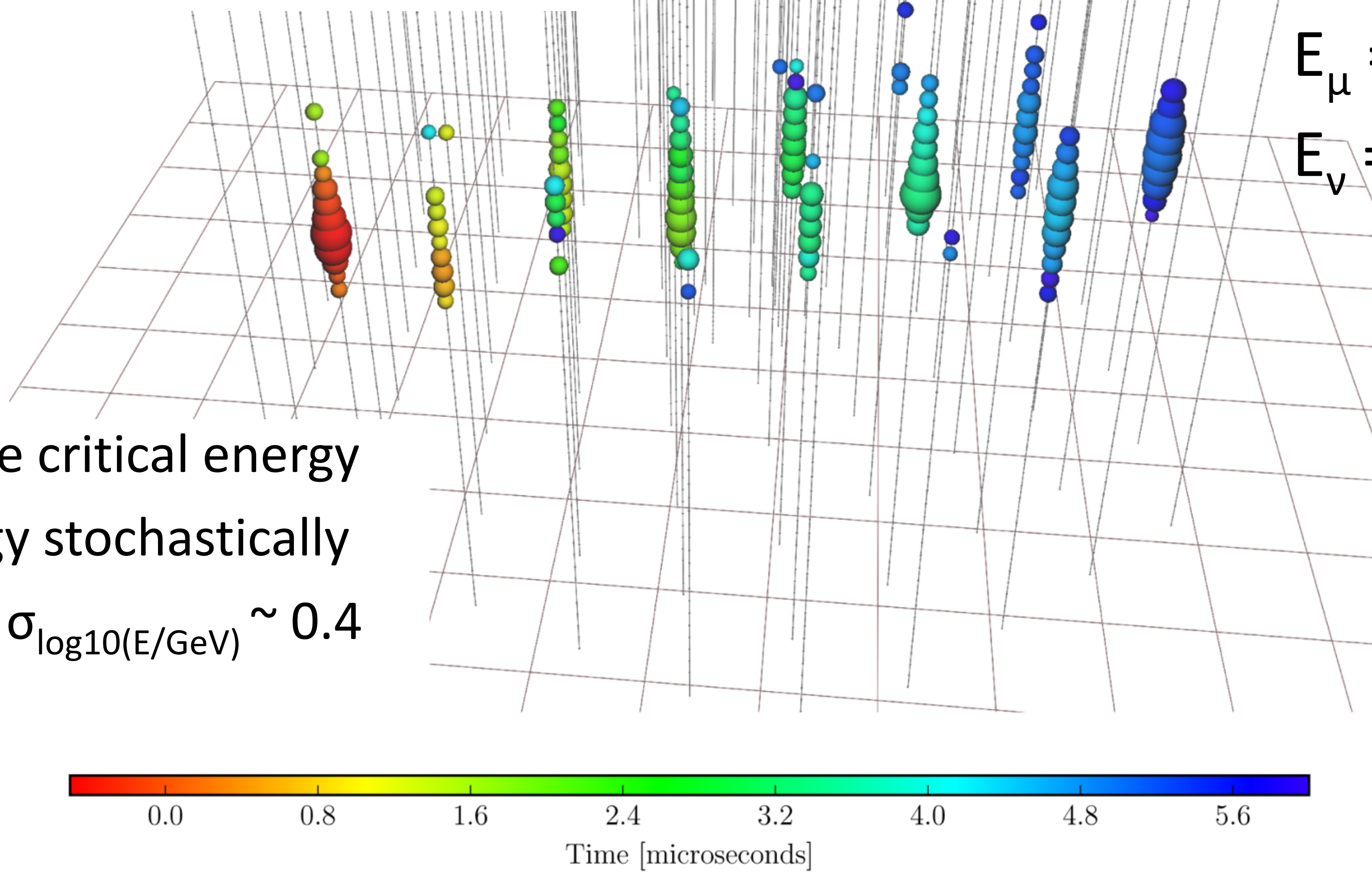


The Floor

Mean deviation angle between
muon and neutrino

$$\psi = 0.7^\circ \times (E_\nu/\mathrm{TeV})^{-0.7}$$



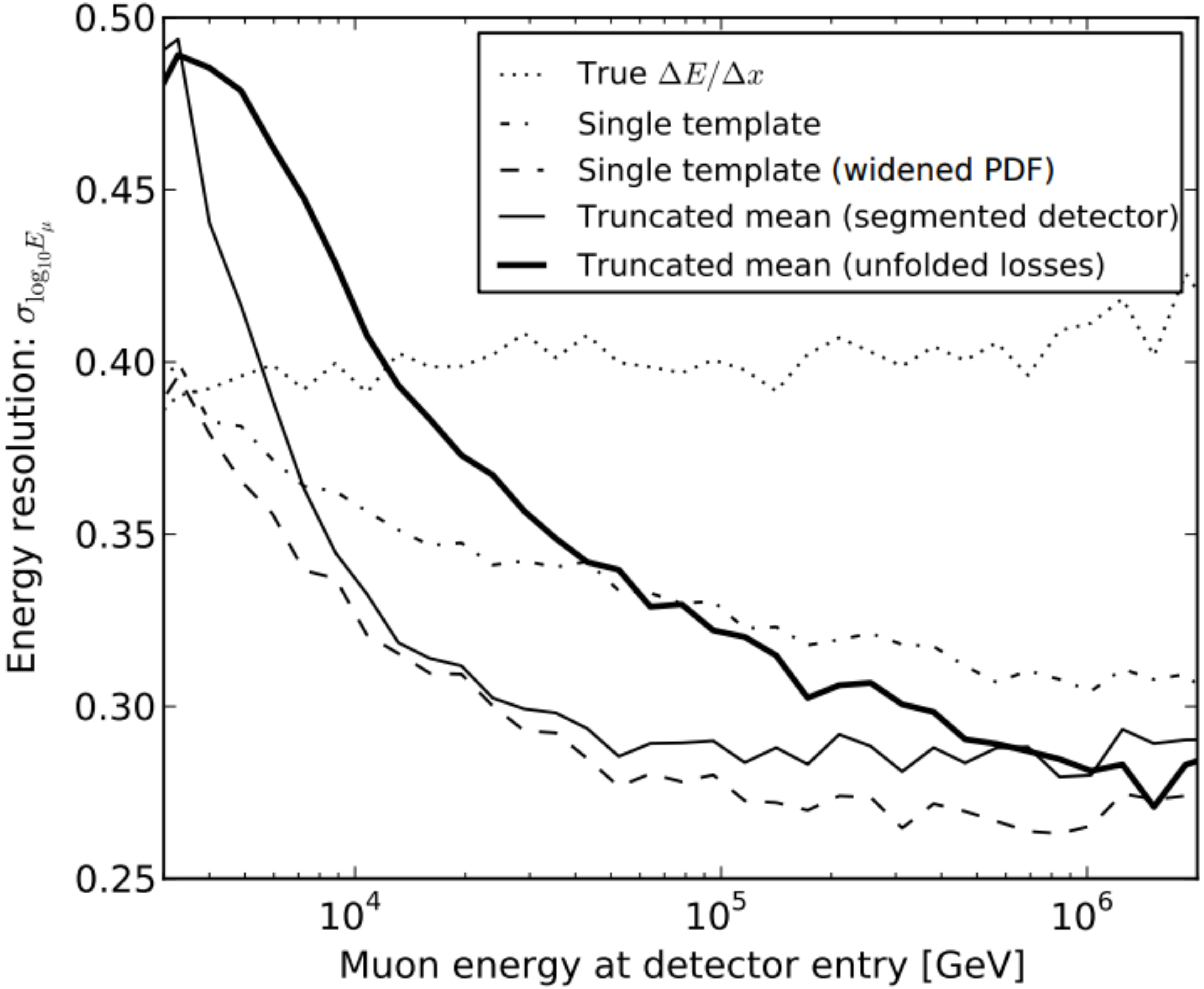


E_μ = 139 TeV

E_ν = 179 TeV

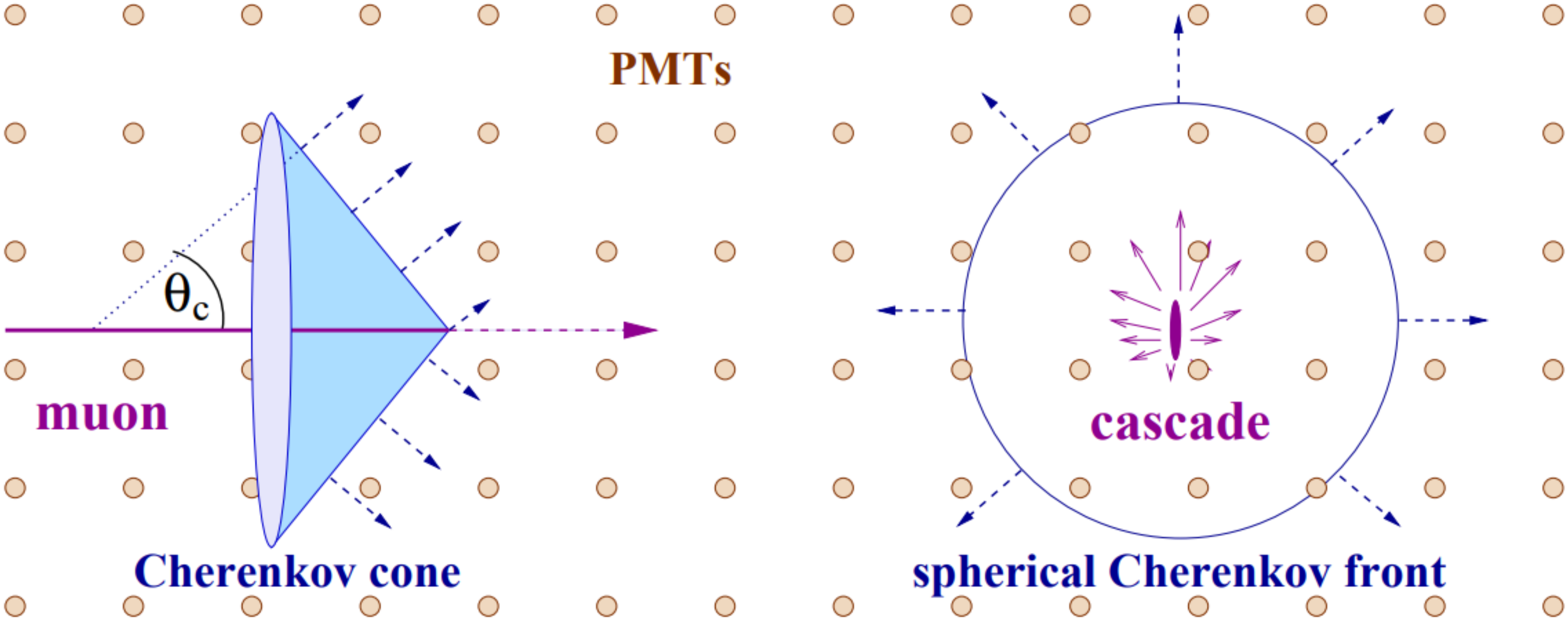
- Muon above critical energy
- Loses energy stochastically
- Resolution: $\sigma_{\log10(E/GeV)}$ ~ 0.4

Muon energy resolution

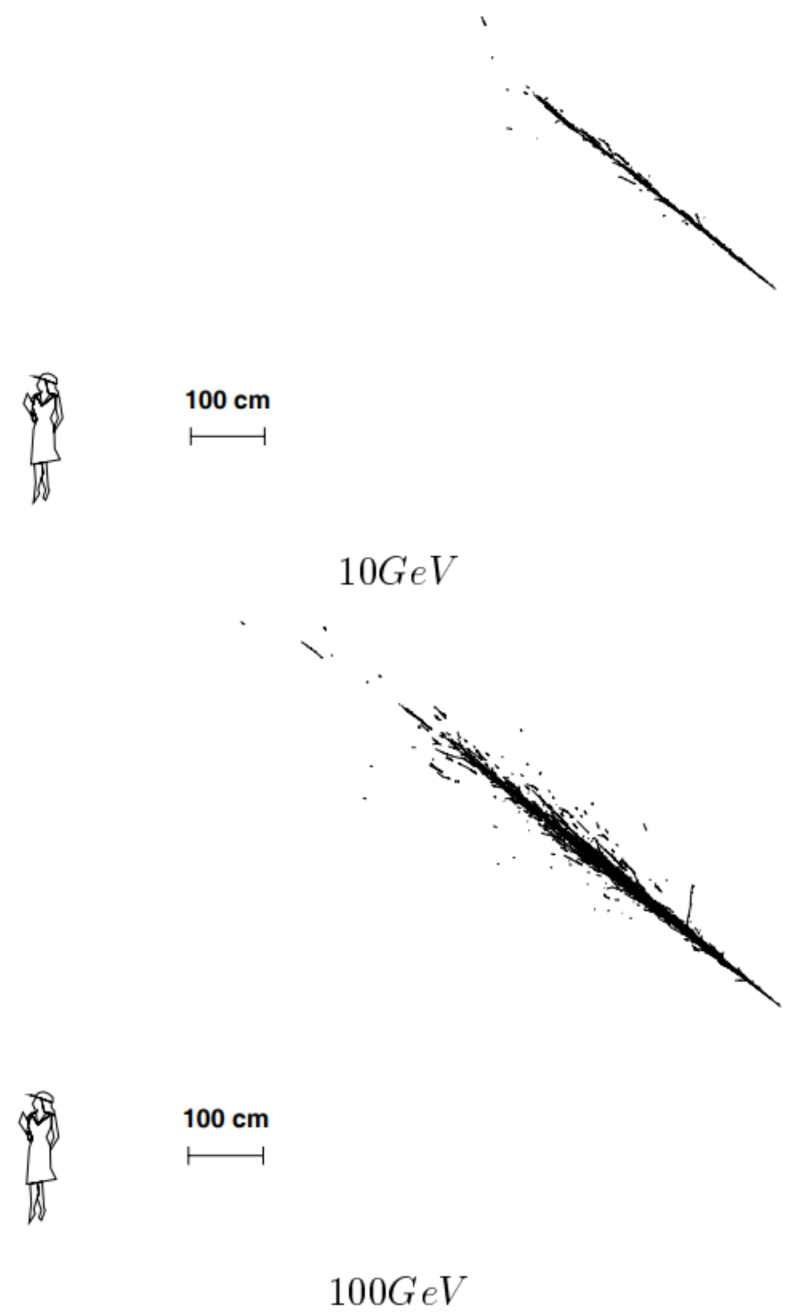


Why is this so bad?
Can we improve?

Cherenkov front and cascade reconstruction



Electromagnetic cascades longitudinal



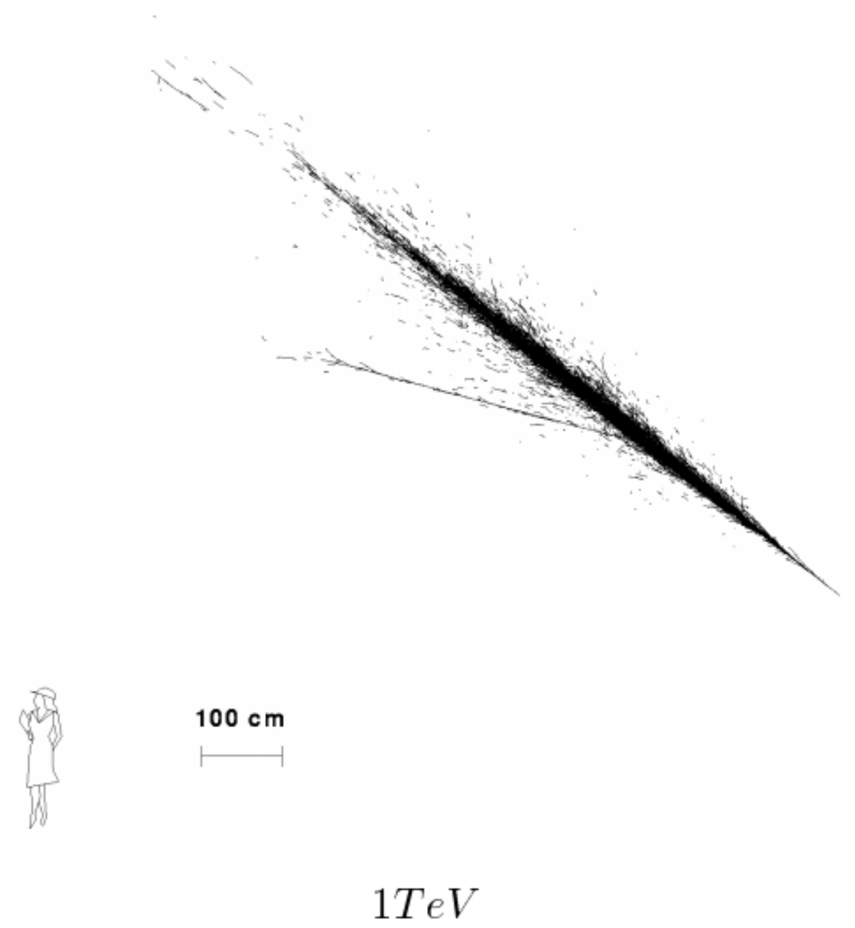


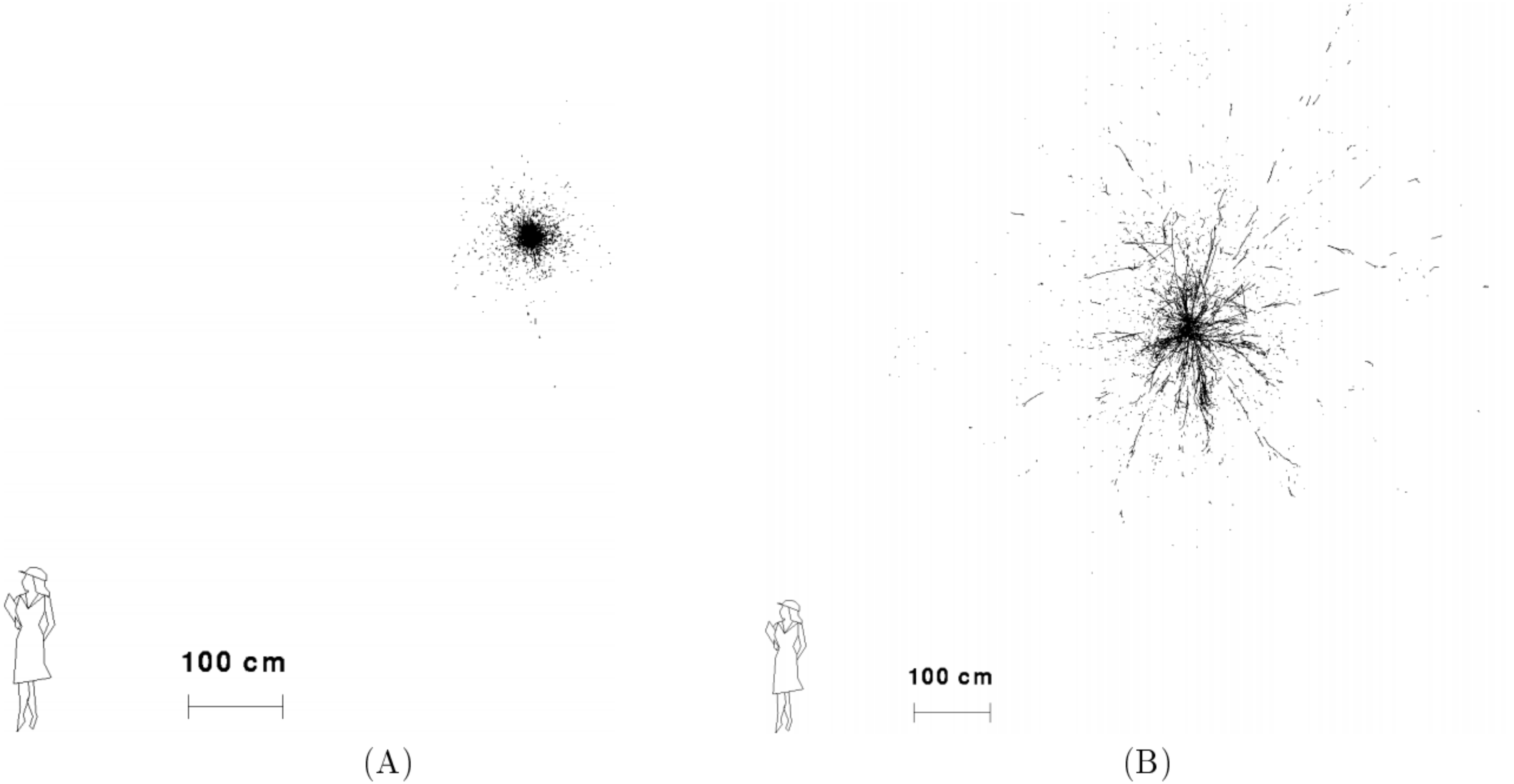
Figure 3.14: Typical electromagnetic cascades in fresh water for three different initial energies. Plotted are only charged tracks above the Čerenkov threshold. Though the longitudinal size of the shower does not change largely, the number of particles increases strongly with the energy. The pictures are postscript graphics, which sizes increase as follows: $85kB$, $466kB$, $4000kB$!

From C. Wiebusch (1995)

Cascades transverse

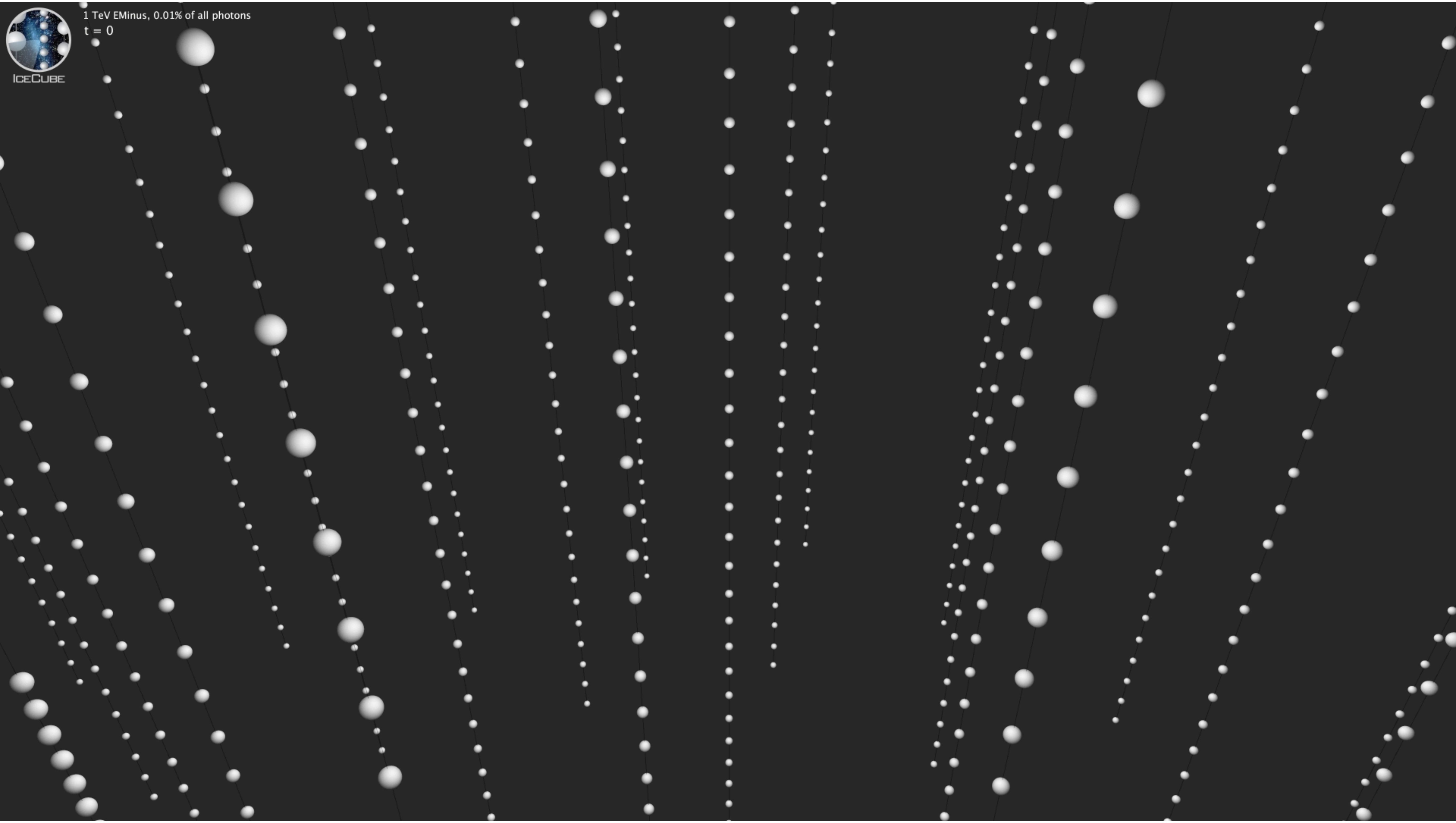
Electromagnetic cascade

Hadronic cascade



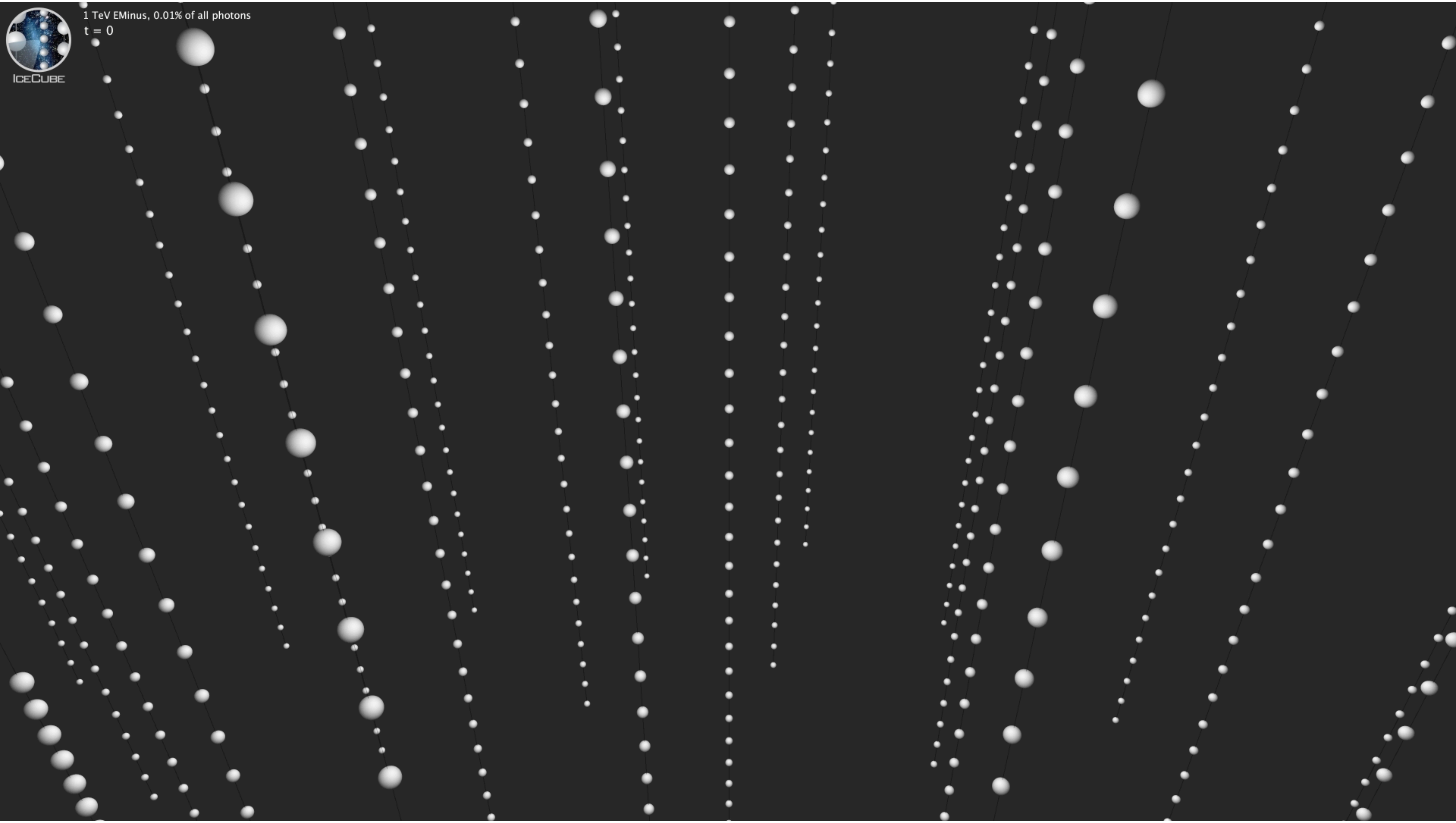
From C. Wiebusch (1995)

Cascade in ice

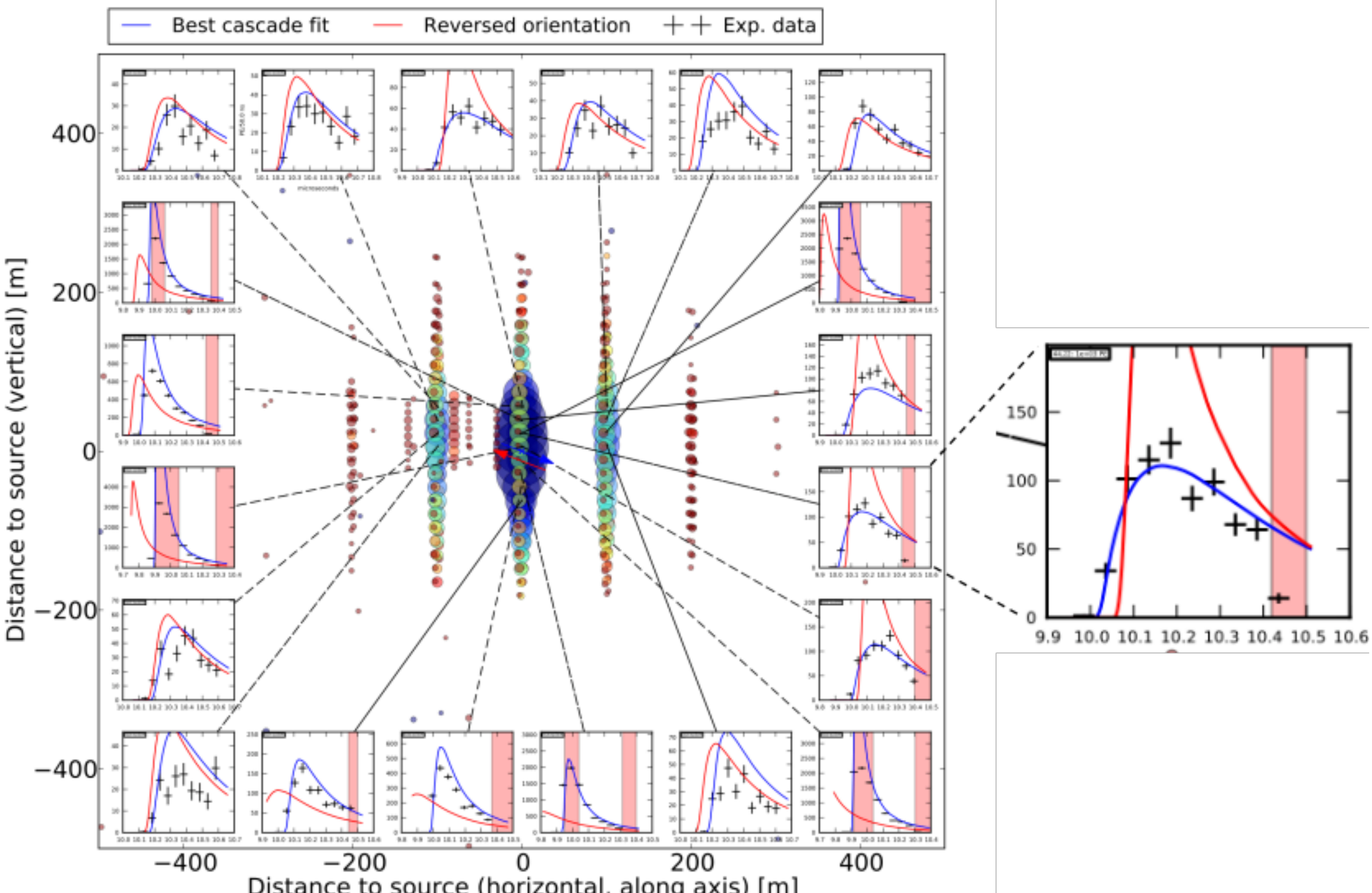


1 TeV

Cascade in water



1 TeV



Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
150
100
50
0
9.9
10.0
10.1
10.2
10.3
10.4
10.5
10.6

AMANDA holeice camera

Subtle local ice effects are important

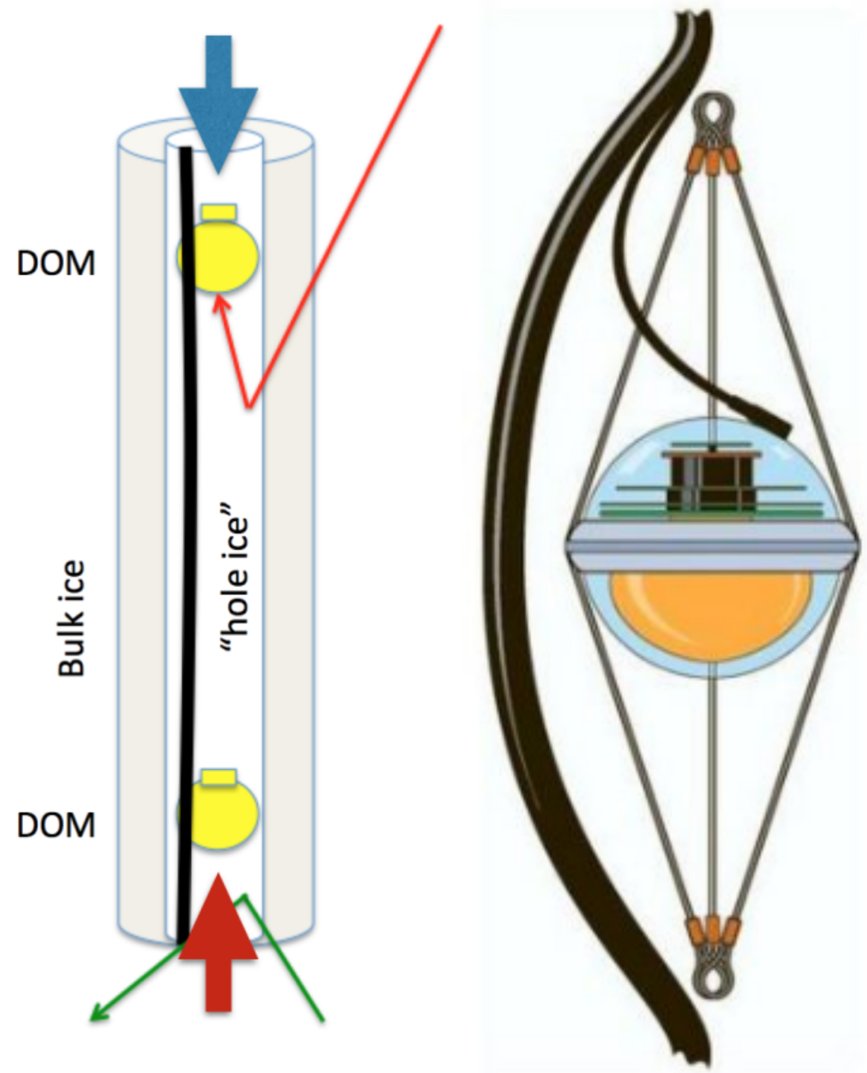
Hole-ice

- Refrozen central column with high scattering

DOM orientation

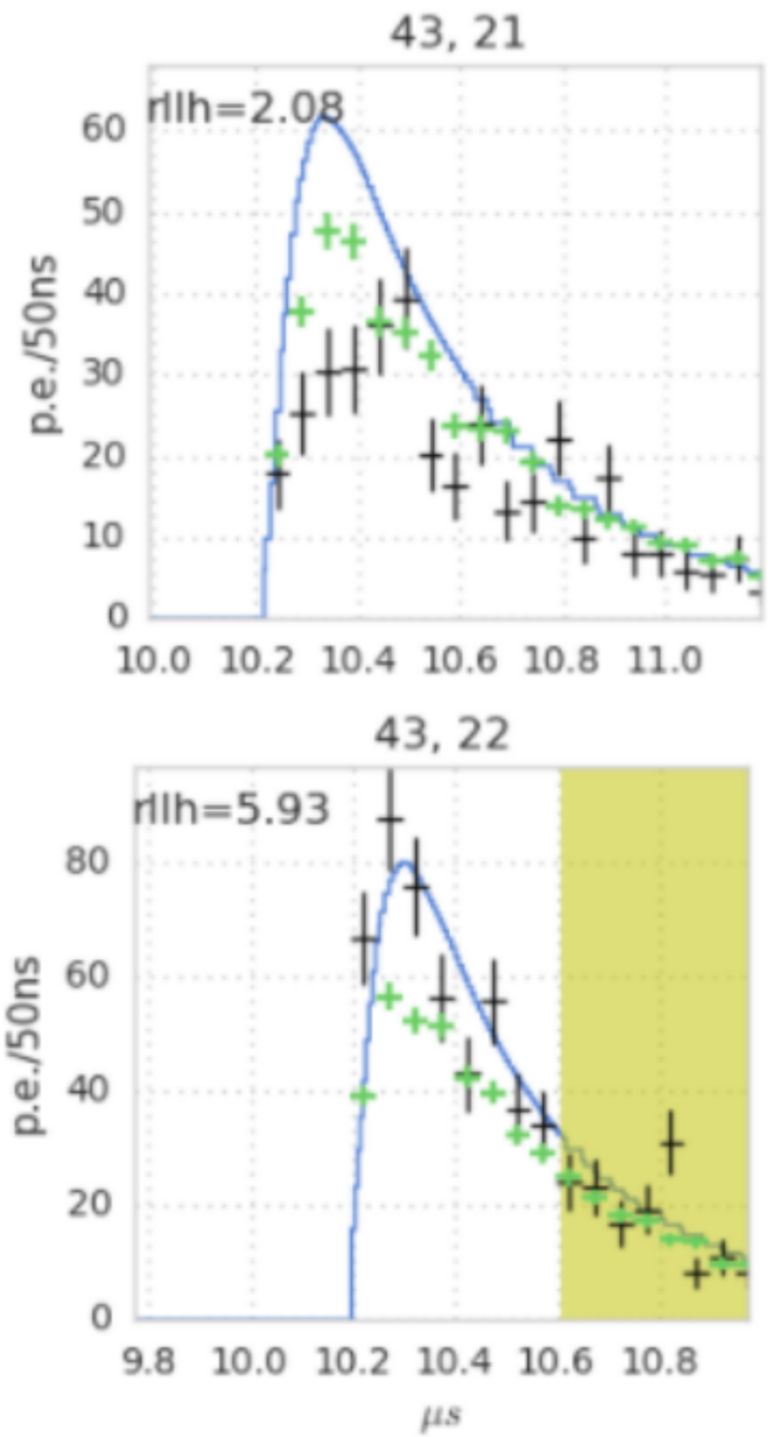
- Thick, support cable may impede direct photons if vertex is nearby
- A few DOMs may not be perfectly horizontal

Looking up the string



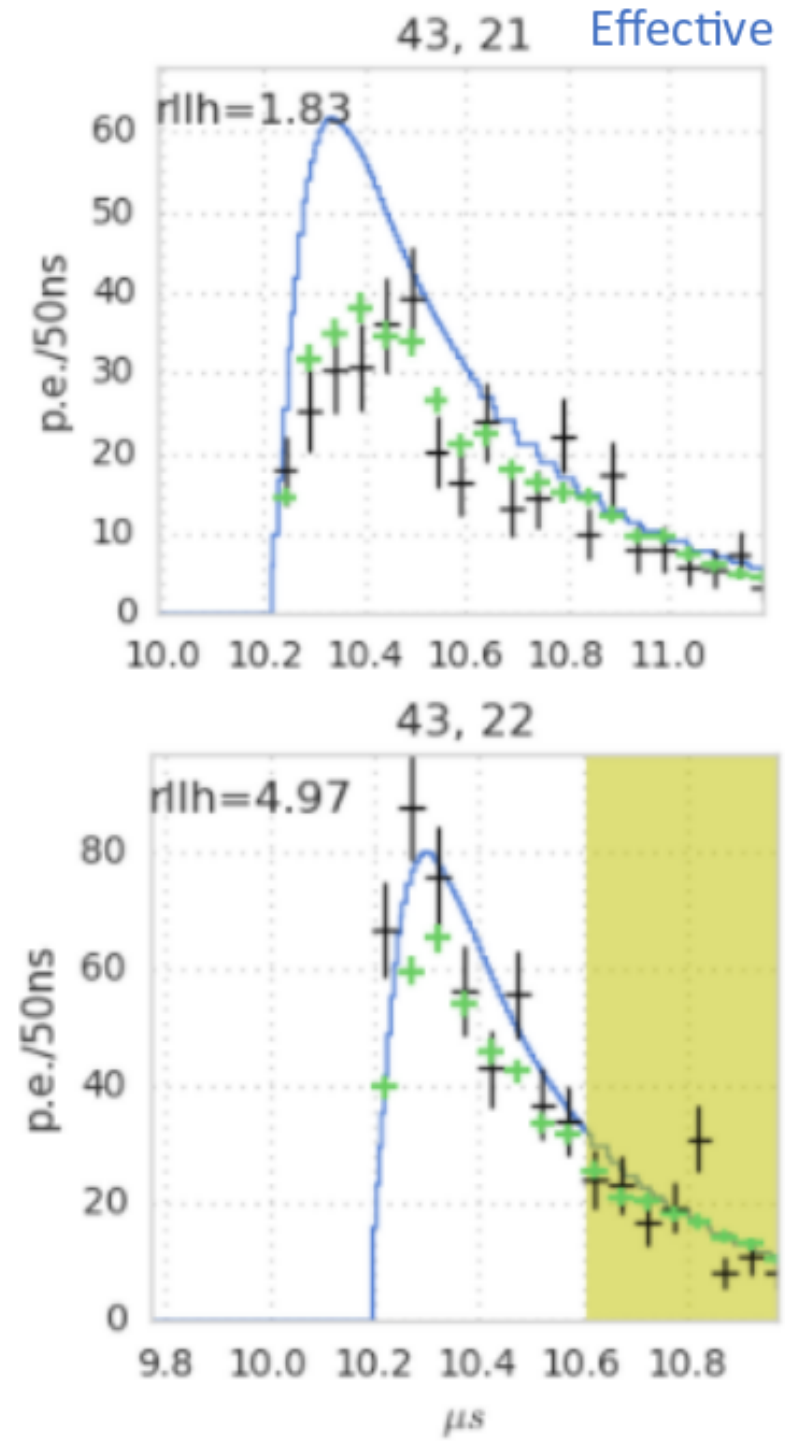
Subtle local ice effects are important

Without local effects

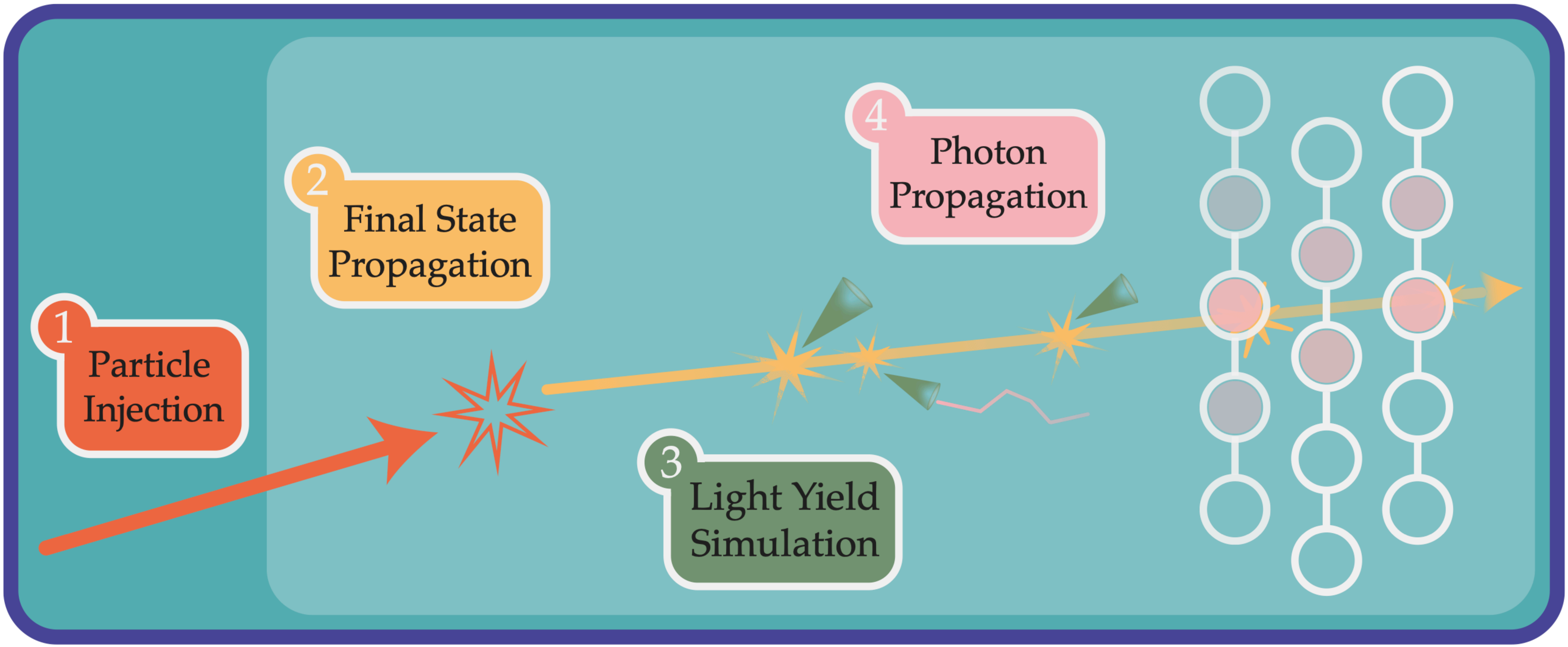


With local effects

Bert data
Direct photon MC
Effective photon MC

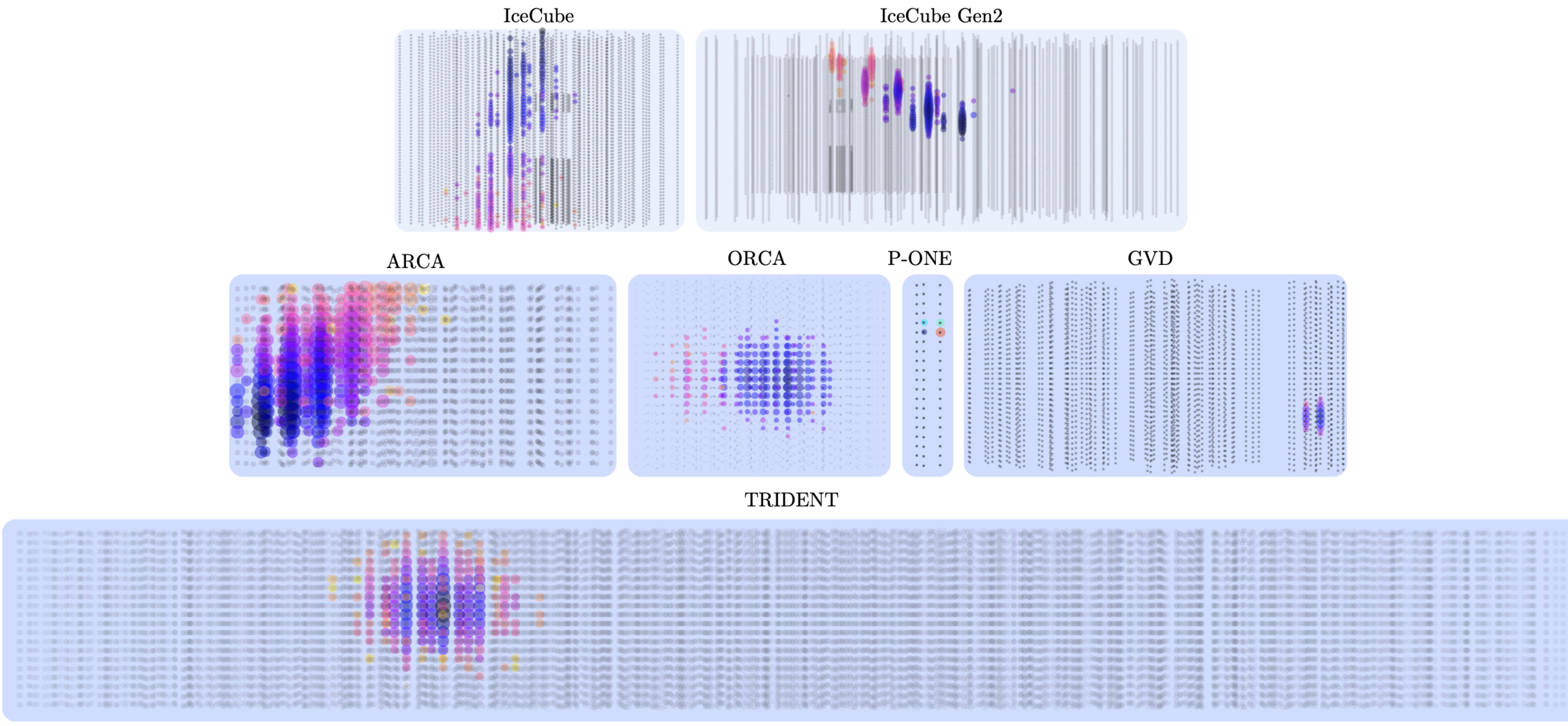


Prometheus: An Open-Source Solution to Neutrino Telescope Simulation



https://github.com/Harvard-Neutrino/prometheus

J. Lazar, S. Meighen-Berger, C. Haack, D. Kim, S. Giner, and CA arXiv:2304.14526



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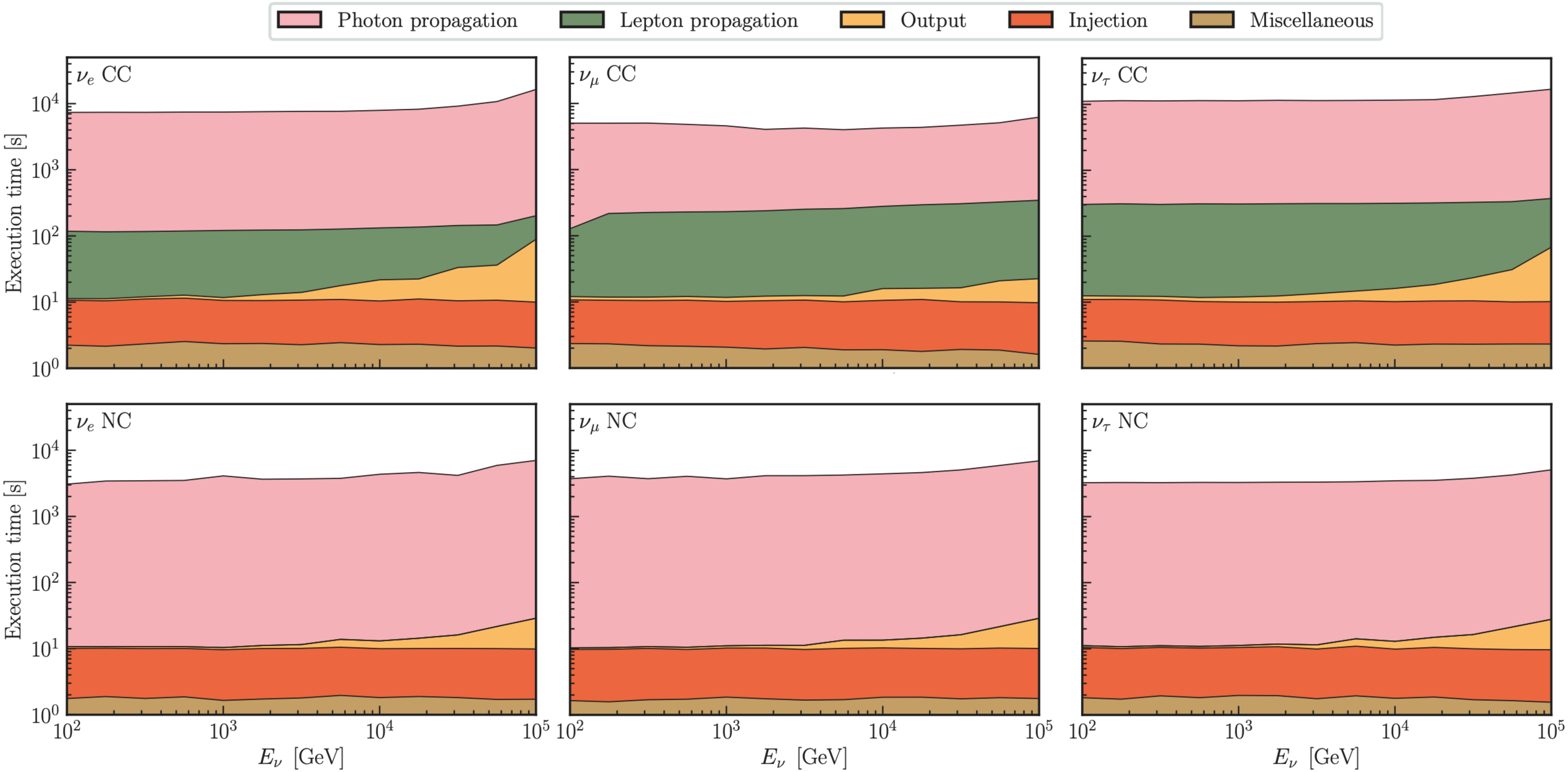
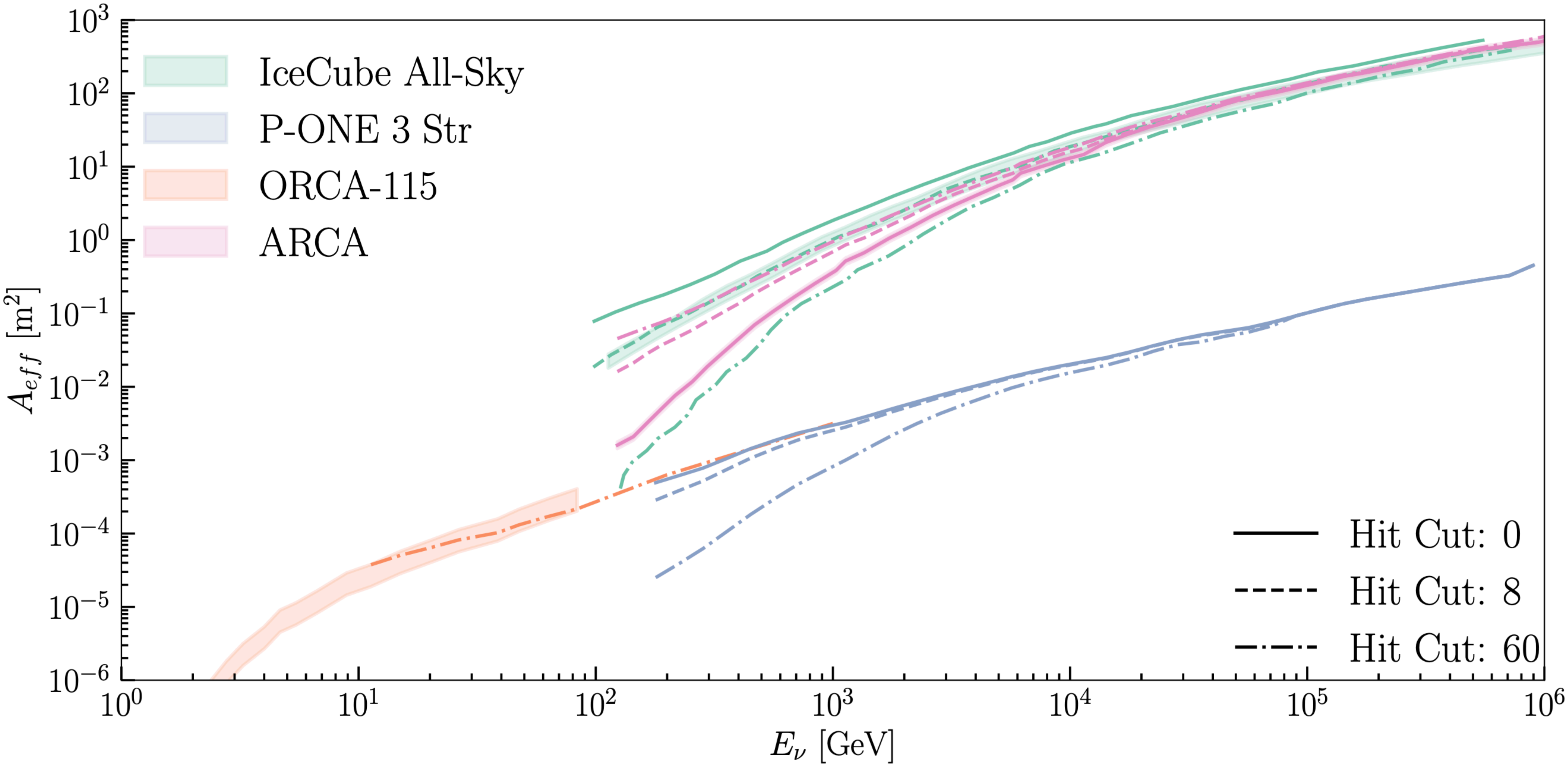


https://github.com/Harvard-Neutrino/prometheus

J. Lazar, S. Meighen-Berger, C. Haack, D. Kim, S. Giner, and CA arXiv:2304.14526



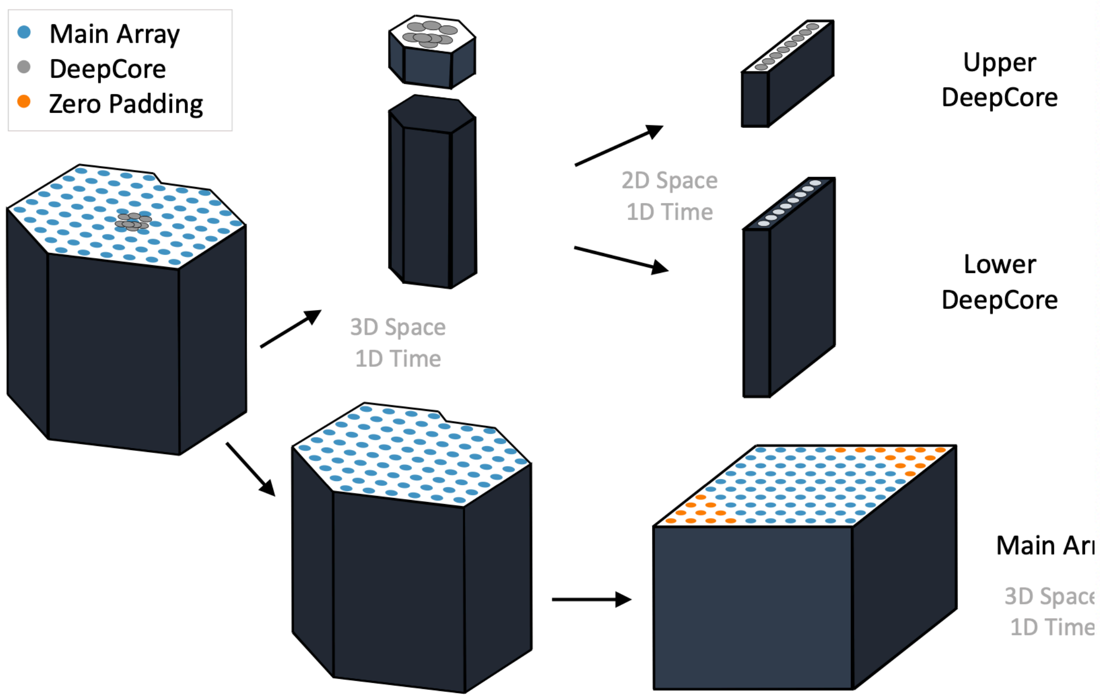
https://github.com/Harvard-Neutrino/prometheus

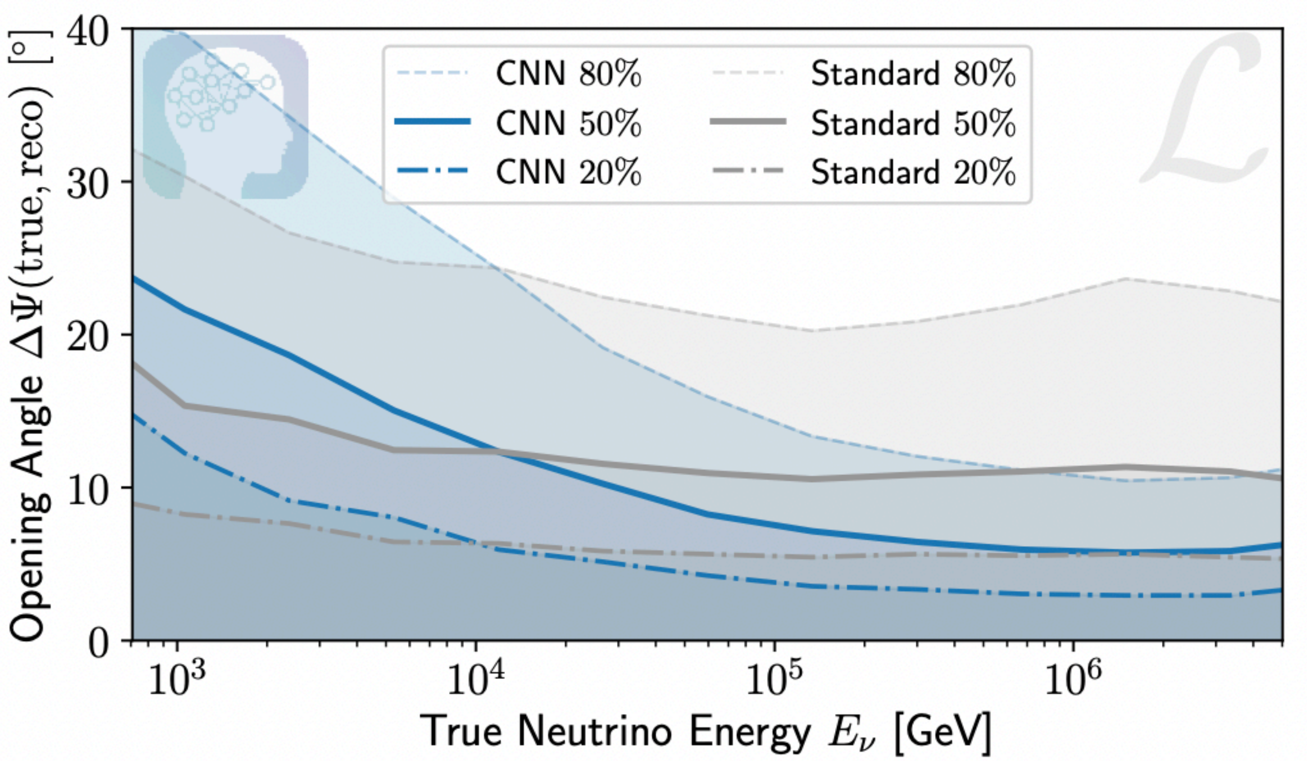
J. Lazar, S. Meighen-Berger, C. Haack, D. Kim, S. Giner, and CA arXiv:2304.14526

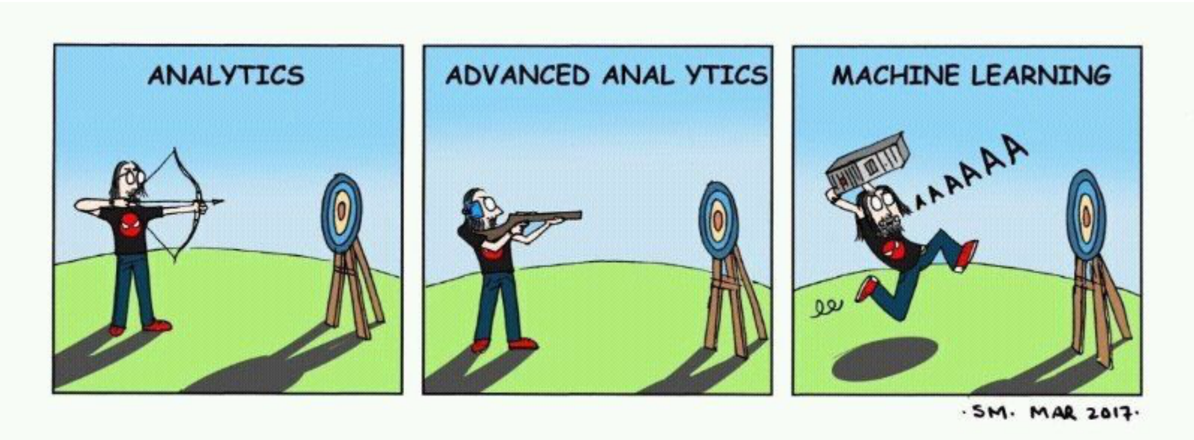
Improvements with Machine Learning

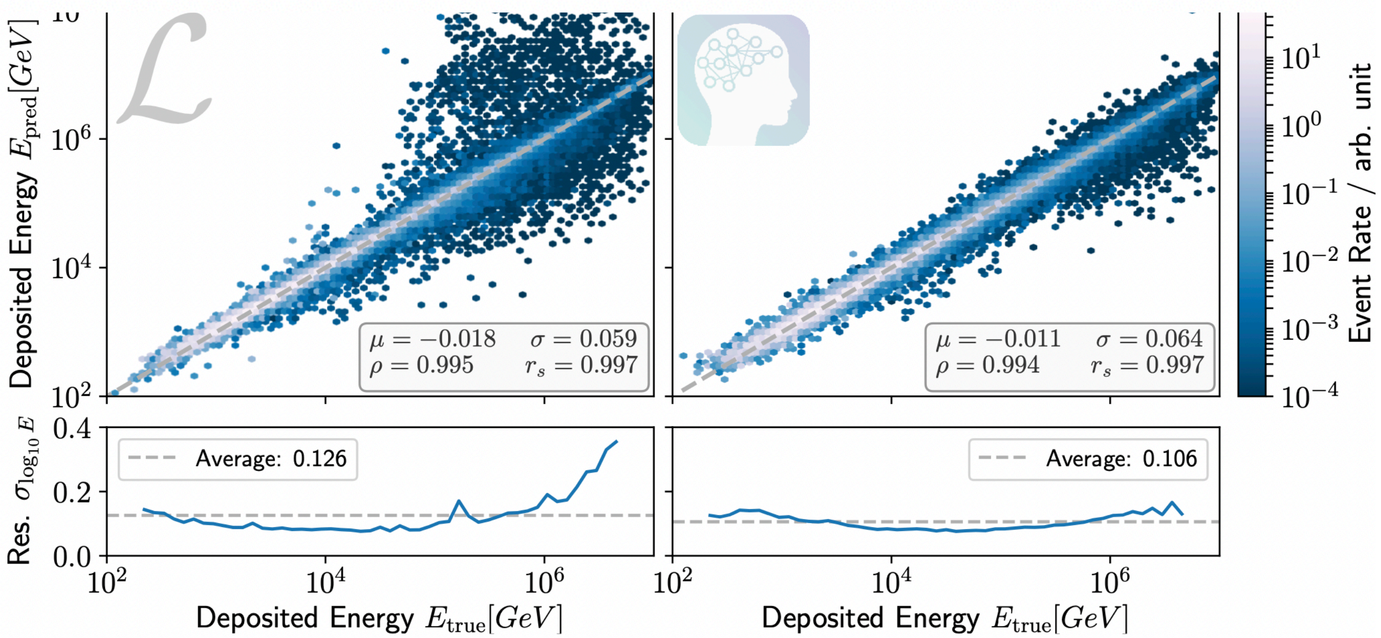
Examples from IceCube, but true across the board

IceCube Collaboration arXiv:2101.11589



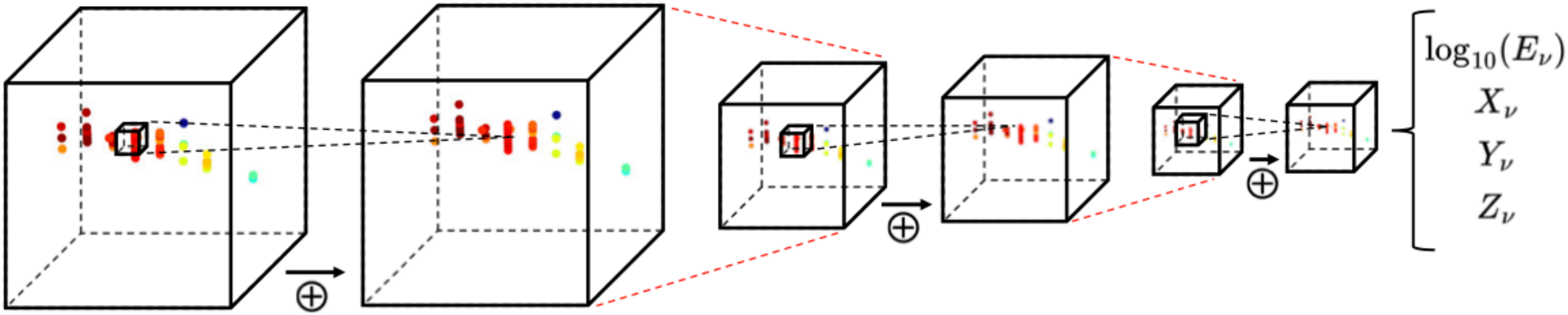


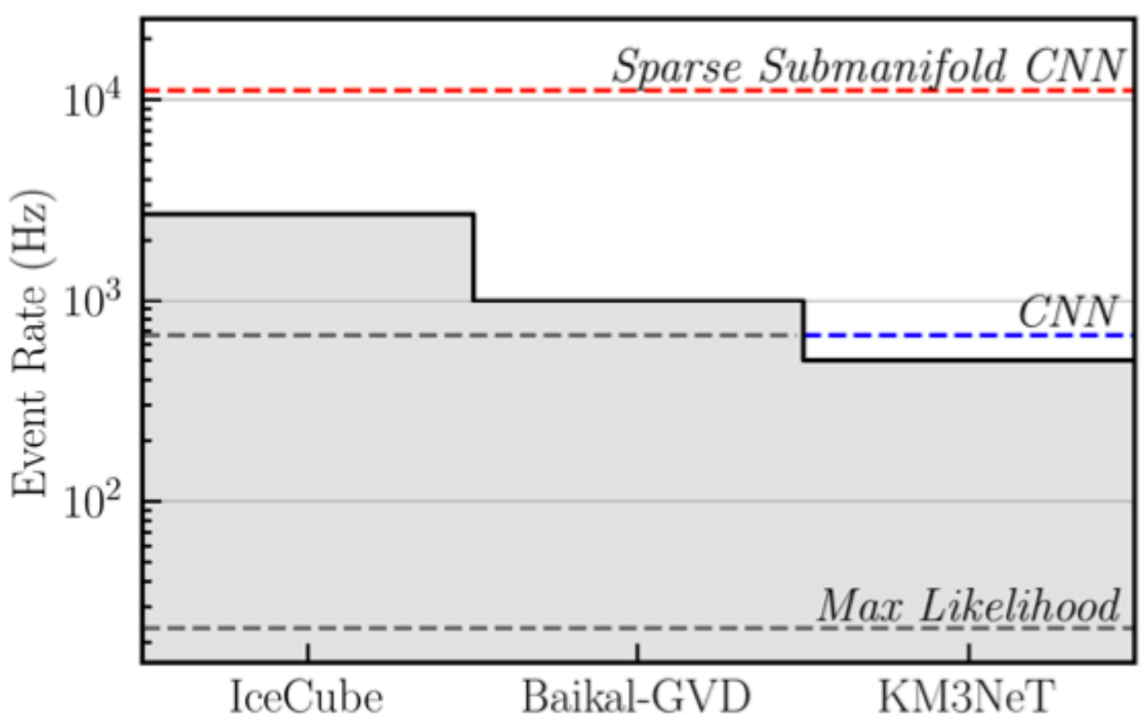


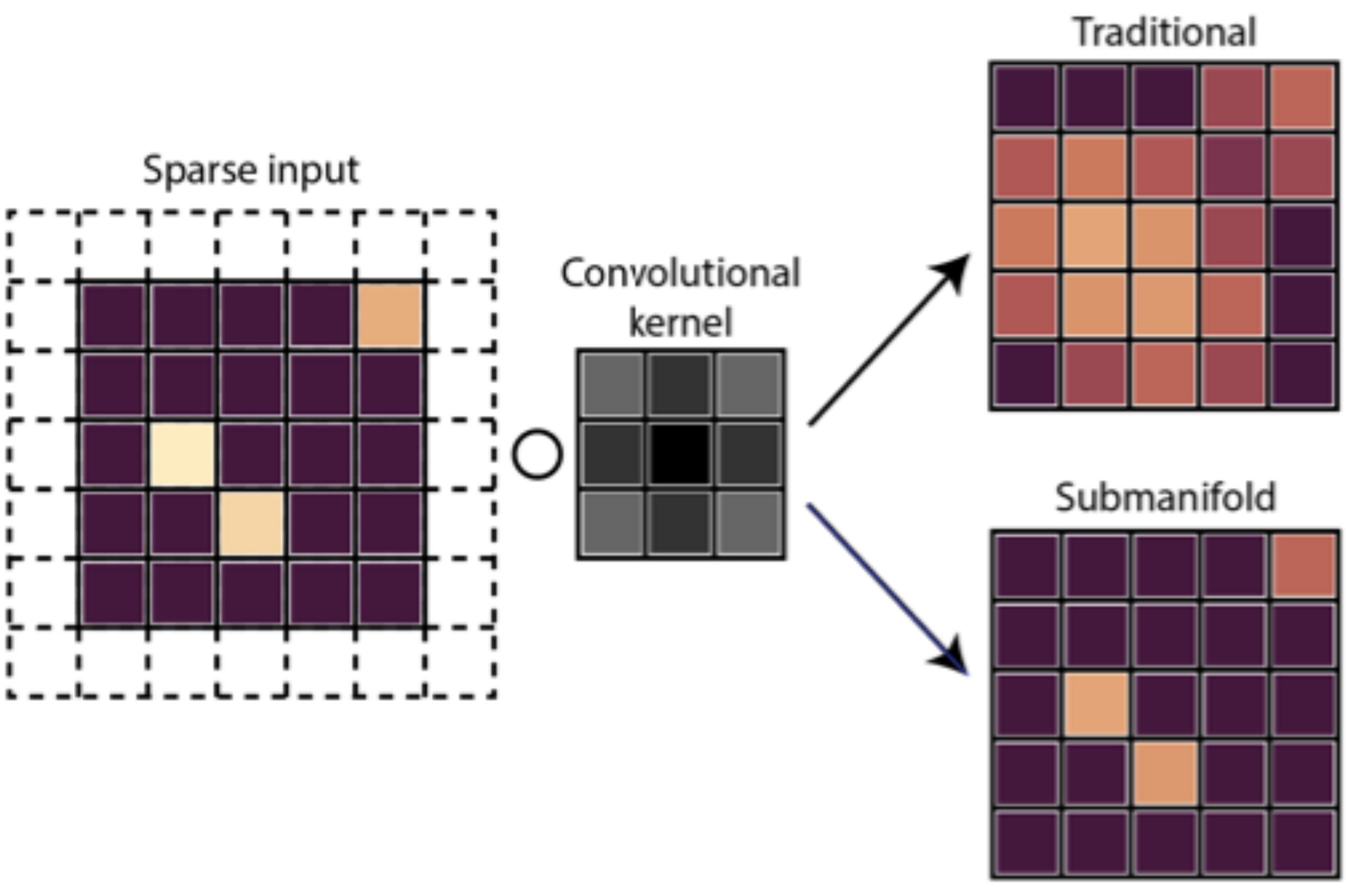



Felix Yu Jeffrey Lazar

That potential is growing: New Reconstructions



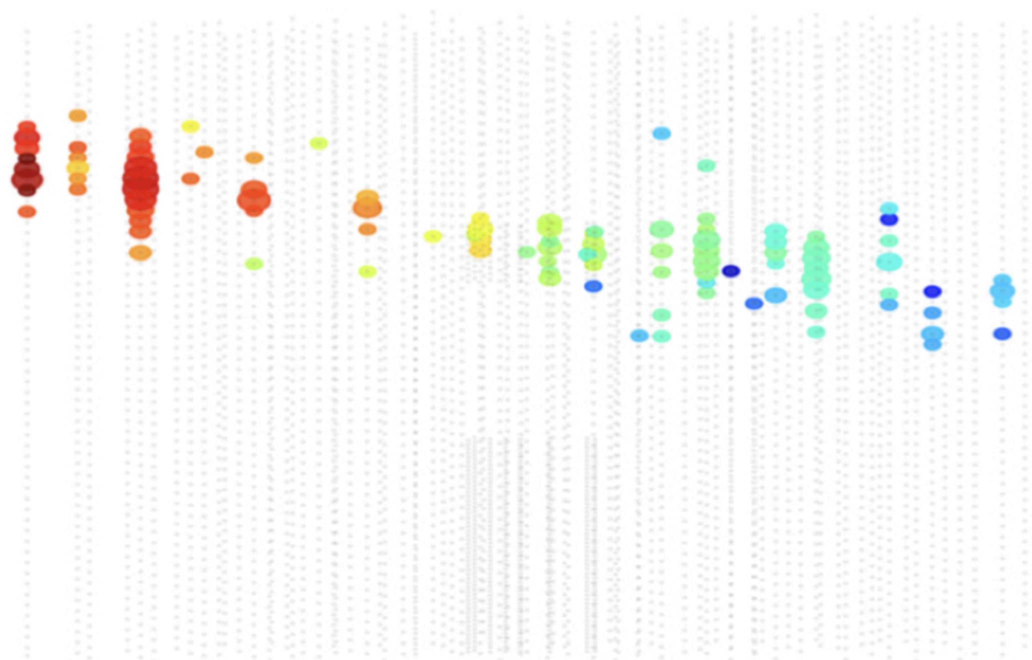


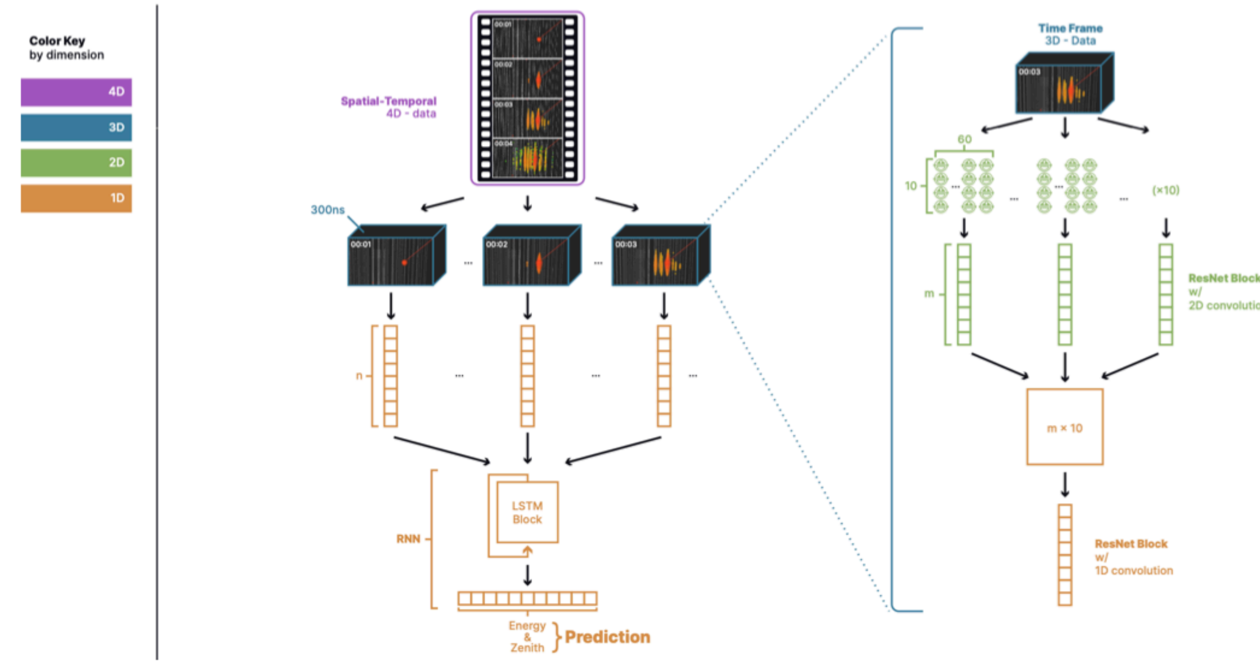


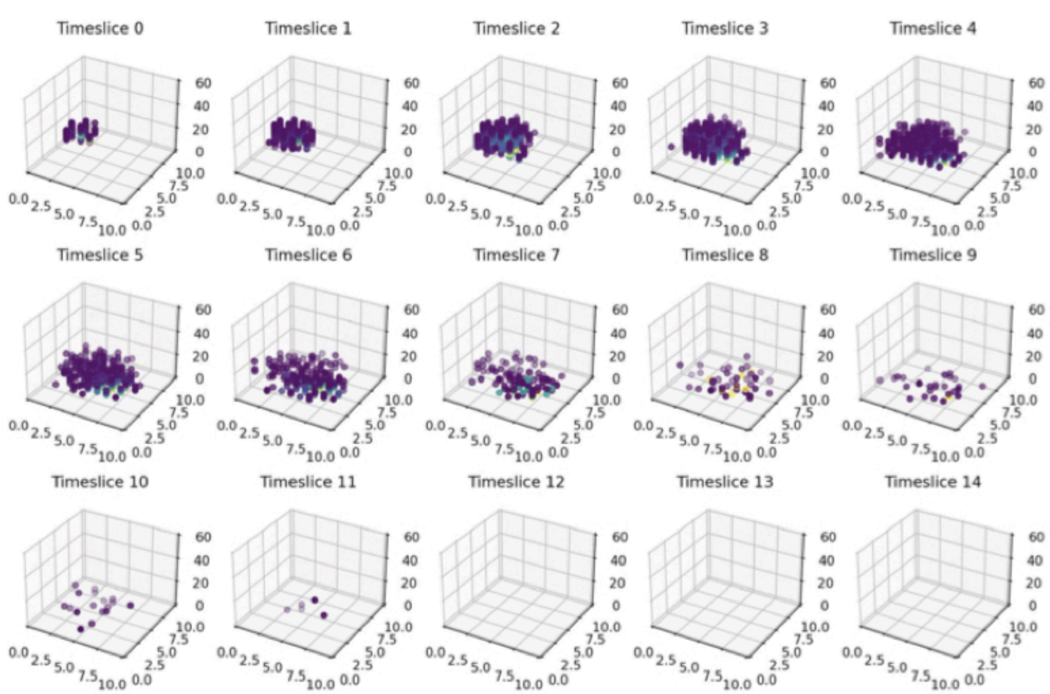
F. J. Yu, J. Lazar, and CA arXiv:2303.08812

Miaochen (Andy) Jin

That potential is growing: New Reconstructions





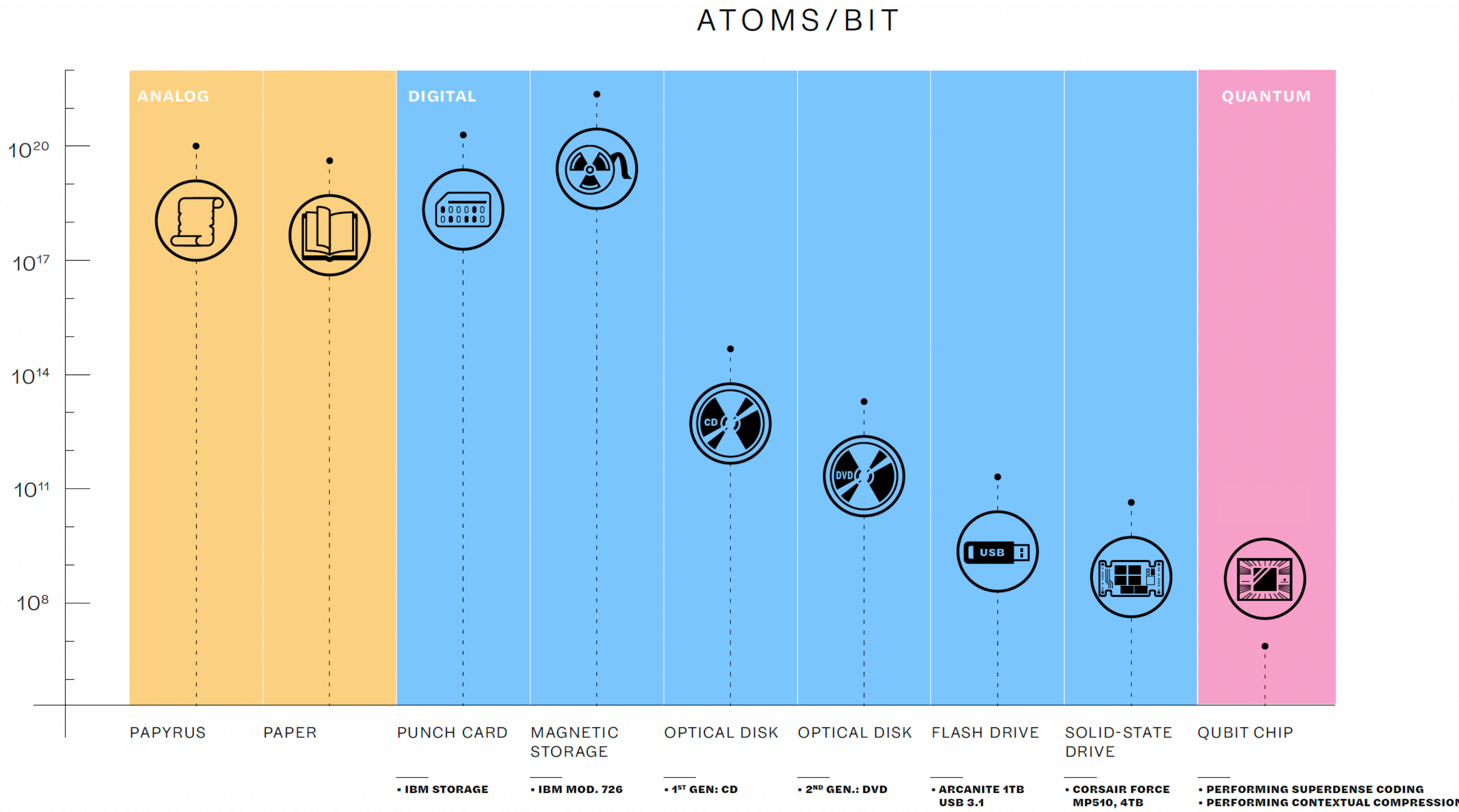


If all the IceCube data were processed by GPUs, they would use, on average, the power of **18 households**, whereas a TPU would use **only 1% of this energy.**

Google Edge TPU

M. Jin, Y. Hu, CA to appear soon

Neutrino Telescopes In the Quantum Computer Era

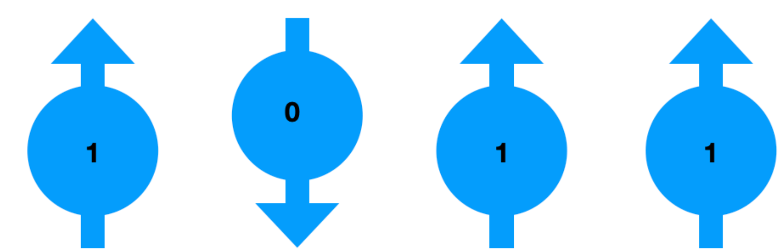


Current number encoding e.g.:

Int32	00000000000000000000000000000101
UInt32	00000000000000000000000000000101
Float32	01000000101000000000000000000000

Quantum digital encoding:

Store the information in the correlation between spins (parity states):



bit	1	1	1	1	1	0	1	0	0
$\mathcal{O}$	XX	XY	XZ	YX	YY	YZ	ZX	ZY	ZZ
λ	-1	1	-1	1	-1	1	-1	1	-1

- Quantum encoding allows for compression (16qbits).
- Can store a typical IceCube event in 8 qubits and all google drive contents in 44 qubits.
- Protocol allows for contextual access to the data: can retrieve the relevant parts of information efficiently.

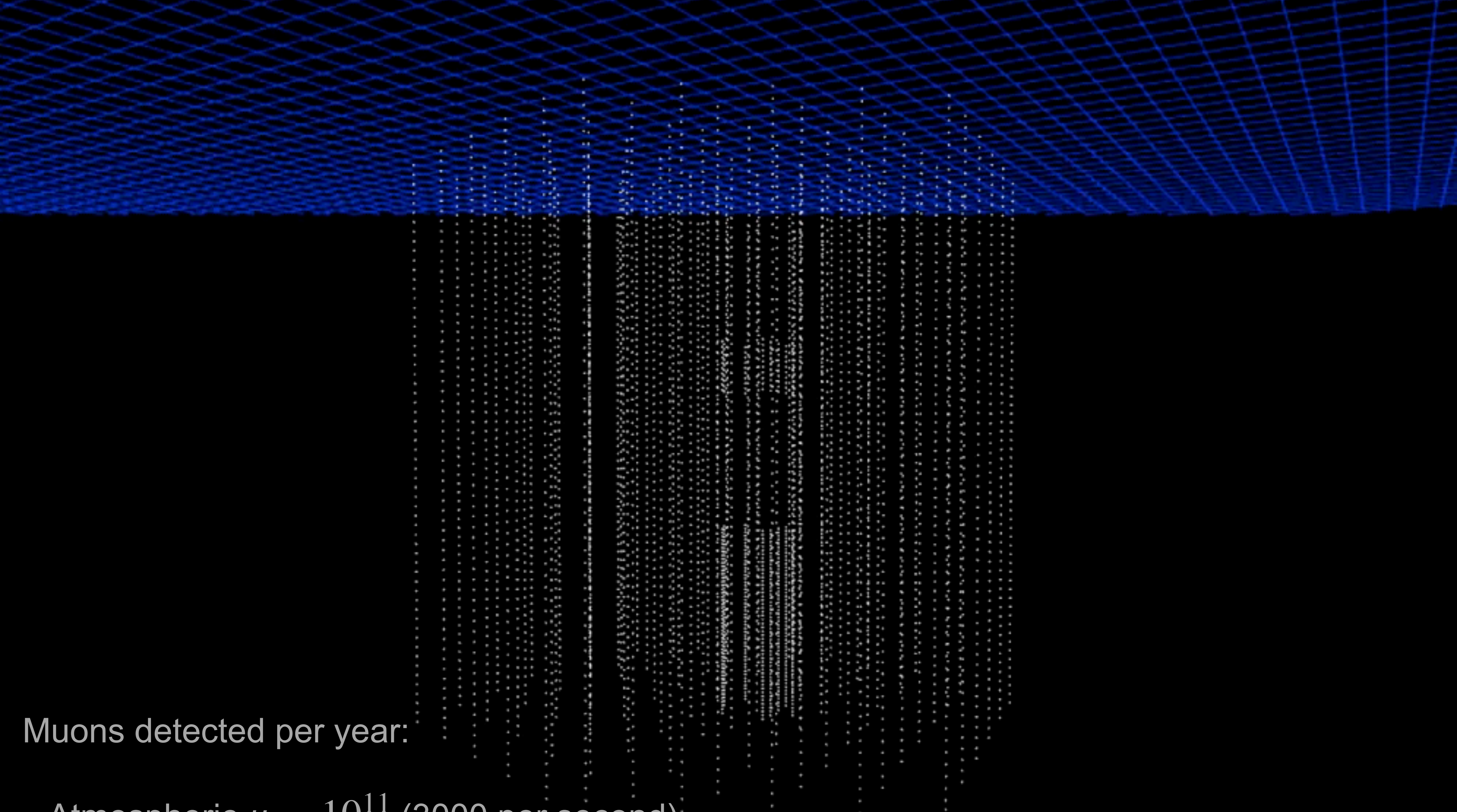
J. Lazar, S. Giner, G. Gatti, CA, and M. Sanz (2022) *in preparation*

Let's think how this technology will help us ten years down the road!

See A. Delgado *et al. 2203.08805* for recent review on Quantum Computing used in HEP data analysis.

Atmospheric backgrounds

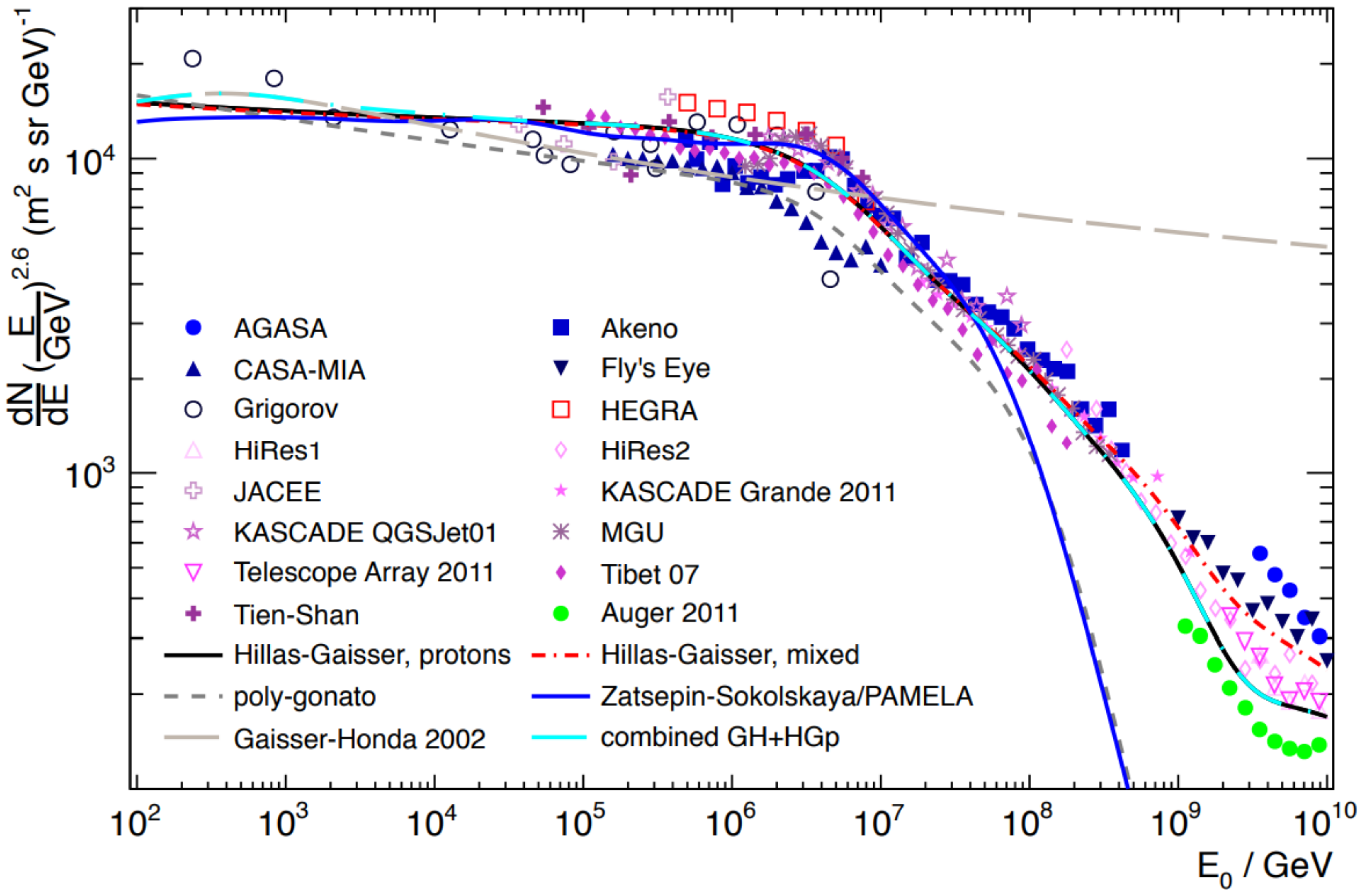
10 msec of IceCube data

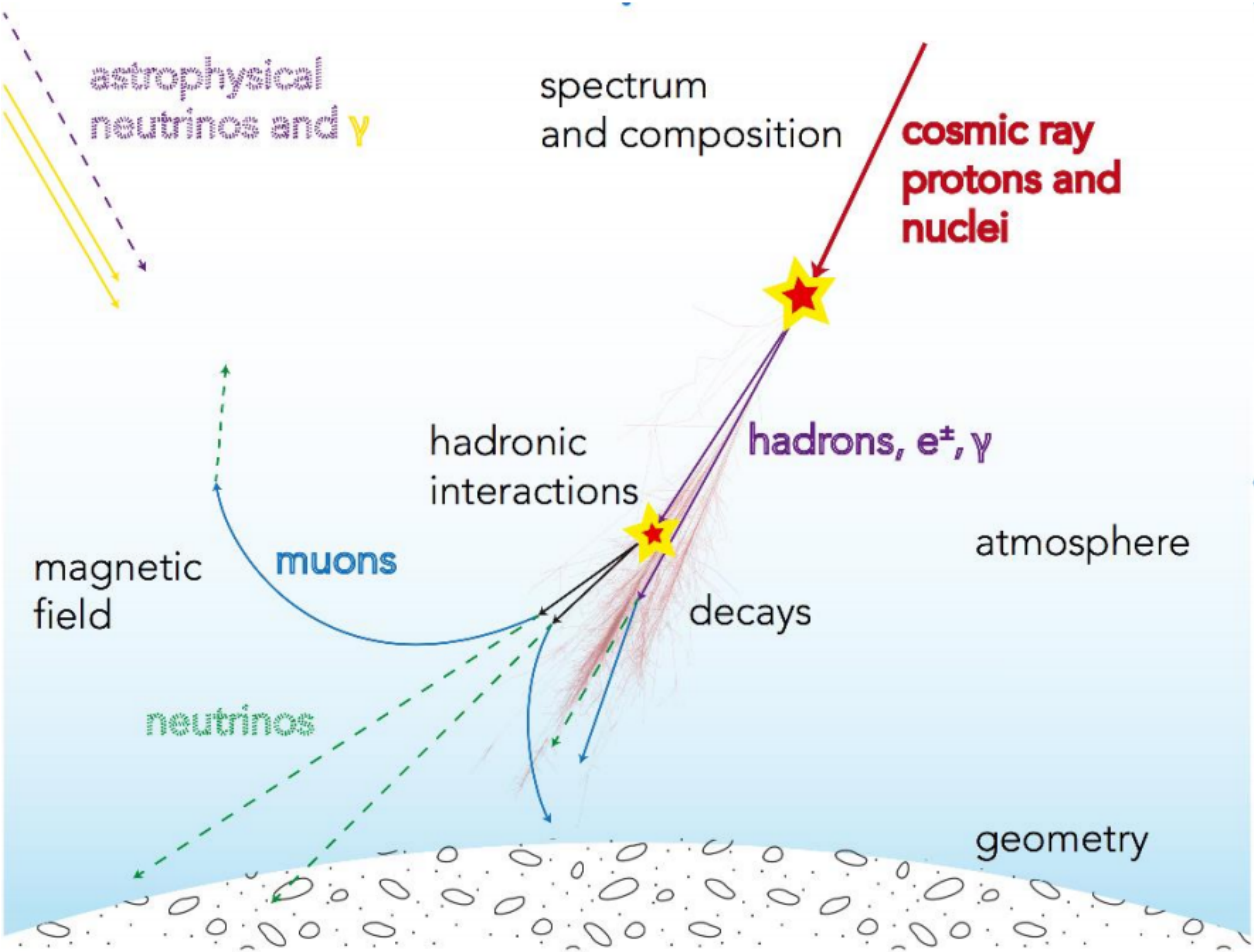


Muons detected per year:

- Atmospheric $\mu \sim 10^{11}$ (3000 per second)
- Atmospheric* $\nu \rightarrow \mu \sim 10^{5}$ (1 every 6 minutes)
- Cosmic** $\nu \rightarrow \mu \sim 10^{2}$

The Cosmic-Ray Spectra




astrophysical
neutrinos and γ
spectrum
and composition
cosmic ray
protons and
nuclei
hadronic
interactions
hadrons, e±, γ
atmosphere
magnetic
field
muons
decays
neutrinos
geometry

Atmospheric neutrinos production

conventional (from longer-lived hadrons)

$$p, A + \mathrm{air} \rightarrow \pi^{\pm}, \pi^{0}, \mathrm{K}^{\pm}, \mathrm{K}^{0}_{\mathrm{S,L}}$$

muons and muon neutrinos

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$

electron neutrinos

$$K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$

prompt (from rare short-lived hadrons)

$$p, A + \mathrm{air} \rightarrow \mathrm{D}, \Lambda_{\mathrm{C}} \rightarrow \nu_{\mu}, \nu_{e}, \mu$$

Subset of dominant decay channels

decay channel	branching ratio (BR)
$\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}$	100 %
$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$	99.9877 %
$K^{0}_{e3} : K^{0}_{L} \rightarrow \pi^{\pm}e^{\mp}\nu_{e}$	40.55 %
$K^{0}_{\mu 3} : K^{0}_{L} \rightarrow \pi^{\pm}\mu^{\mp}\nu_{\mu}$	27.04 %
$K^{+} \rightarrow \mu^{+}\nu_{\mu}$	63.55 %
$K^{+}_{e3} : K^{+} \rightarrow \pi^{0}e^{+}\nu_{e}$	5.07 %
$K^{+}_{\mu 3} : K^{+} \rightarrow \pi^{0}\mu^{+}\nu_{\mu}$	3.353 %
$D^{+} \rightarrow \overline{K}^{0}\mu^{+}\nu_{\mu}$	9.2 %
$D^{0} \rightarrow K^{-}\mu^{+}\nu_{\mu}$	3.3 %

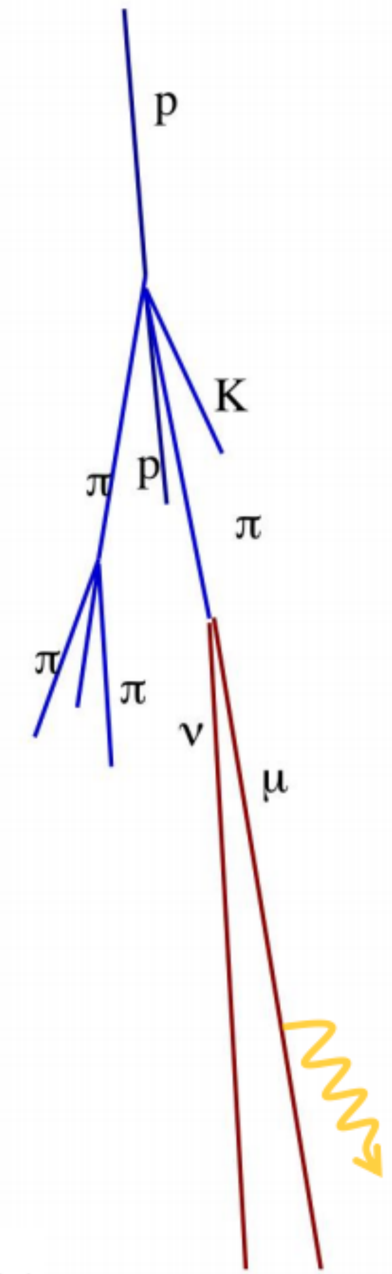
+ charge conjugates

http://pdg.lbl.gov

Cascade equations

System of coupled non-linear PDE for each particle species *h* :

$$
\begin{aligned}
\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = &-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} && \text{Interactions with air} \\
&-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} && \text{Decays} \\
&-\frac{\partial}{\partial E}\left(\mu(E)\Phi_h(E,X)\right) && \text{Continuous losses} \\
&+\sum_k \int_E^{\infty} \mathrm{d}E_k \, \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} && \text{Re-injection from interactions} \\
&+\sum_k \int_E^{\infty} \mathrm{d}E_k \, \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)} && \text{Re-injection from decays}
\end{aligned}
$$



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell \; \rho_{\mathrm{air}}(\ell)$$

Cascade equations

System of coupled non-linear PDE for each particle species *h* :

$$
\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}\left(\mu(E)\Phi_h(E,X)\right) + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}
$$

cosmic ray physics

Interactions with air

Decays

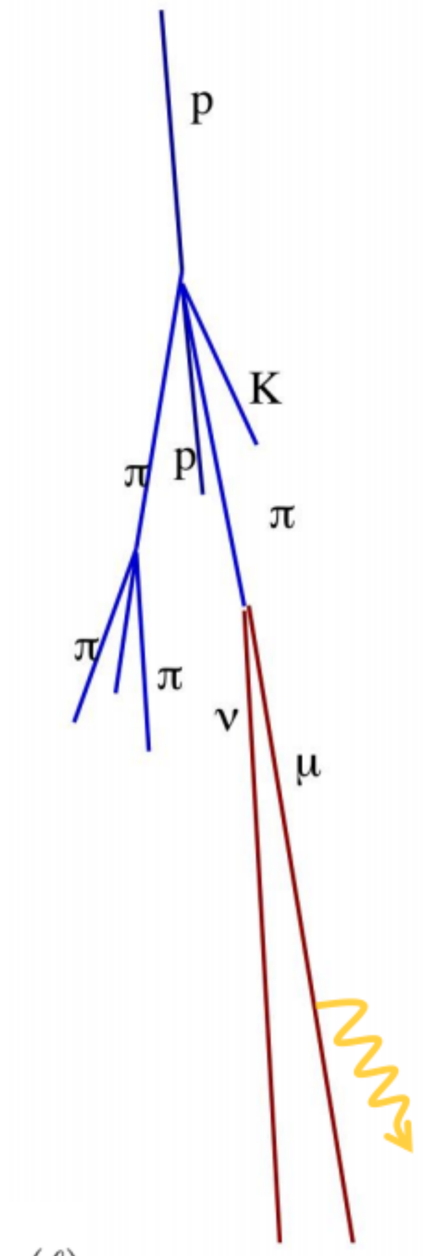
atmospheric physics

Continuous losses

Re-injection from interactions

Re-injection from decays

particle physics



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell \; \rho_{\mathrm{air}}(\ell)$$

Cascade equations

System of coupled non-linear PDE for each particle species *h* :

$$
\begin{aligned}
\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = & -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} \\
& -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} \\
& -\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) \\
& +\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} \\
& +\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X}
\end{aligned}
$$

cosmic ray physics

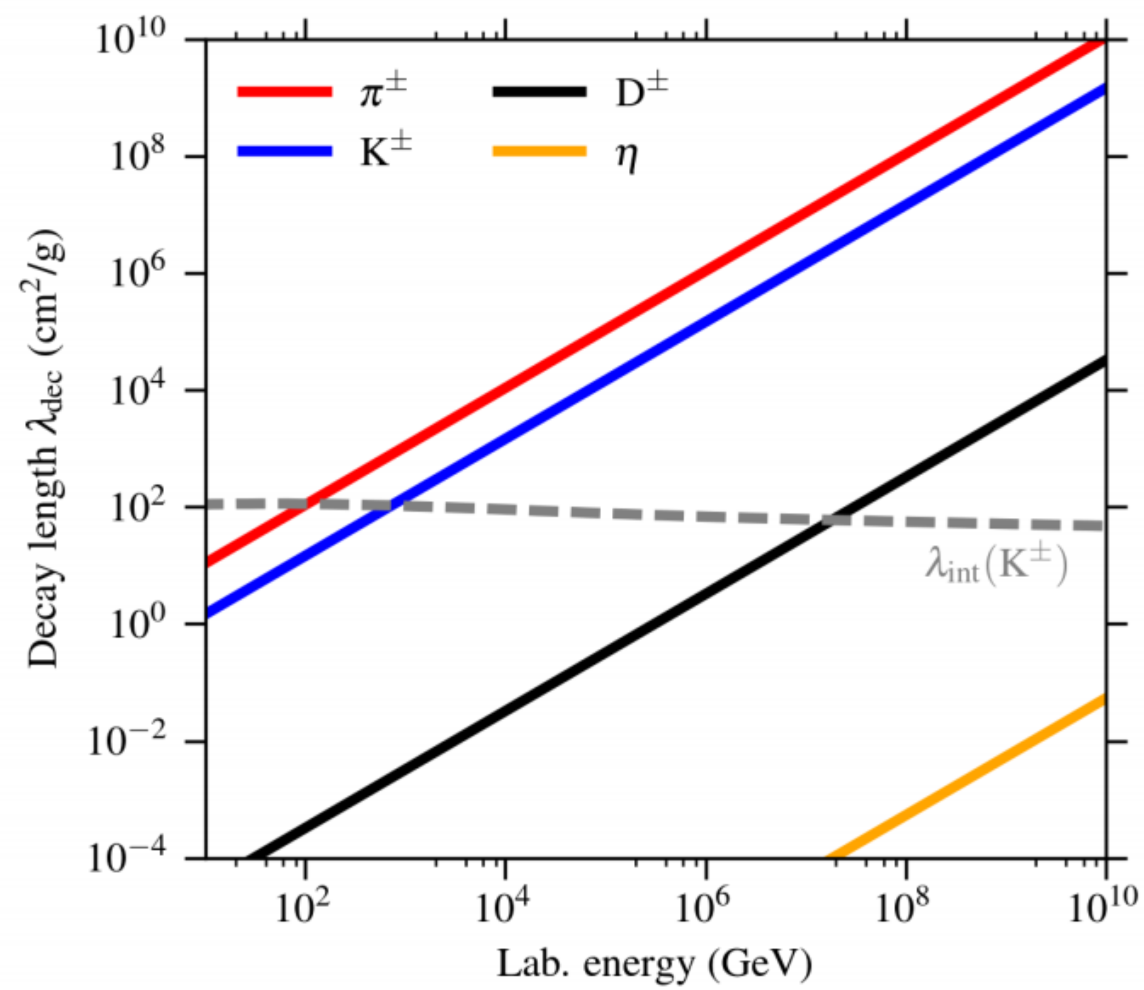
Interactions with air

atmospheric physics

Decays

Continuous losses

particle physics



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell\ \rho_{\mathrm{air}}(\ell)$$

Cascade equations

System of coupled non-linear PDE for each particle species *h* :

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X}$$

cosmic ray physics

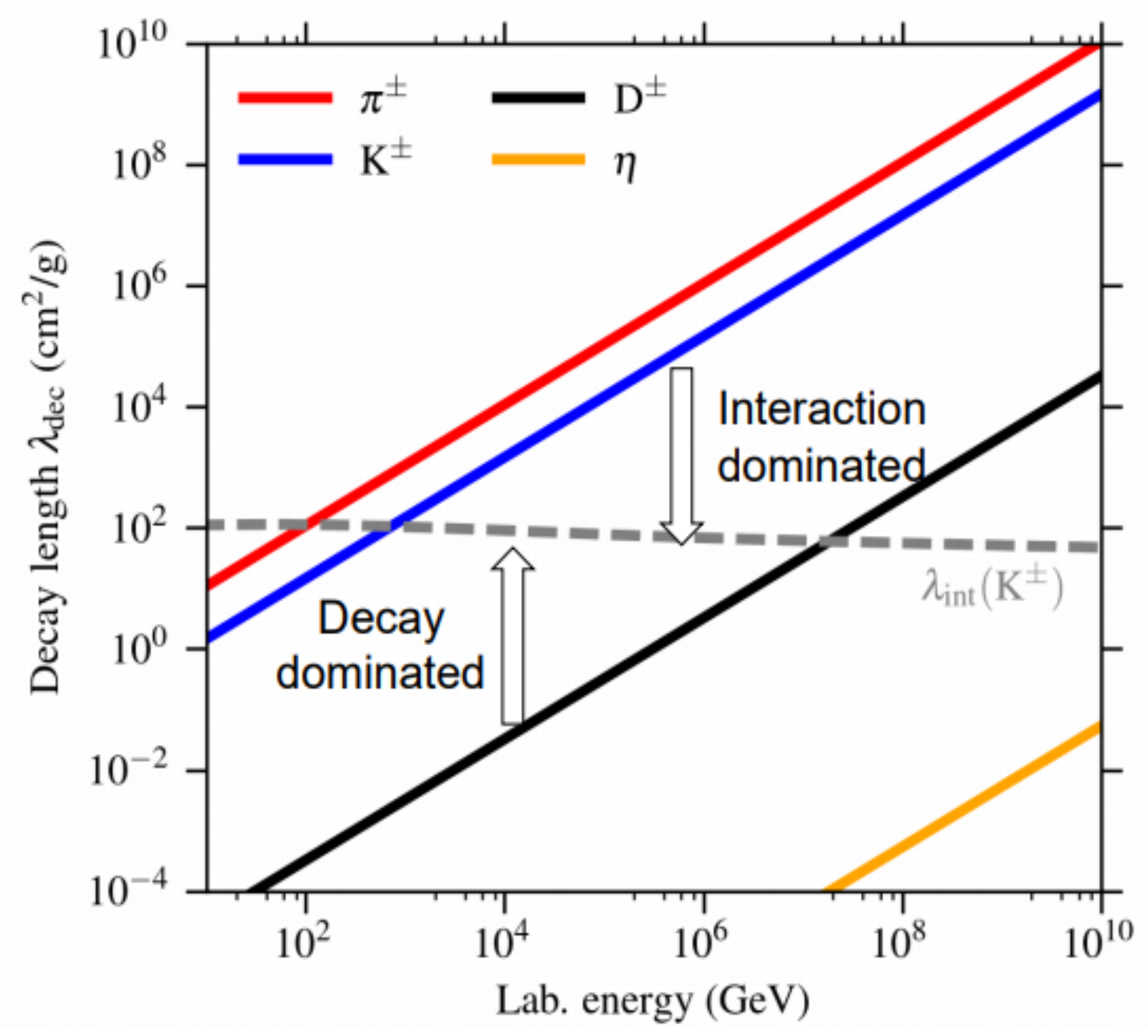
Interactions with air

Decays

atmospheric physics

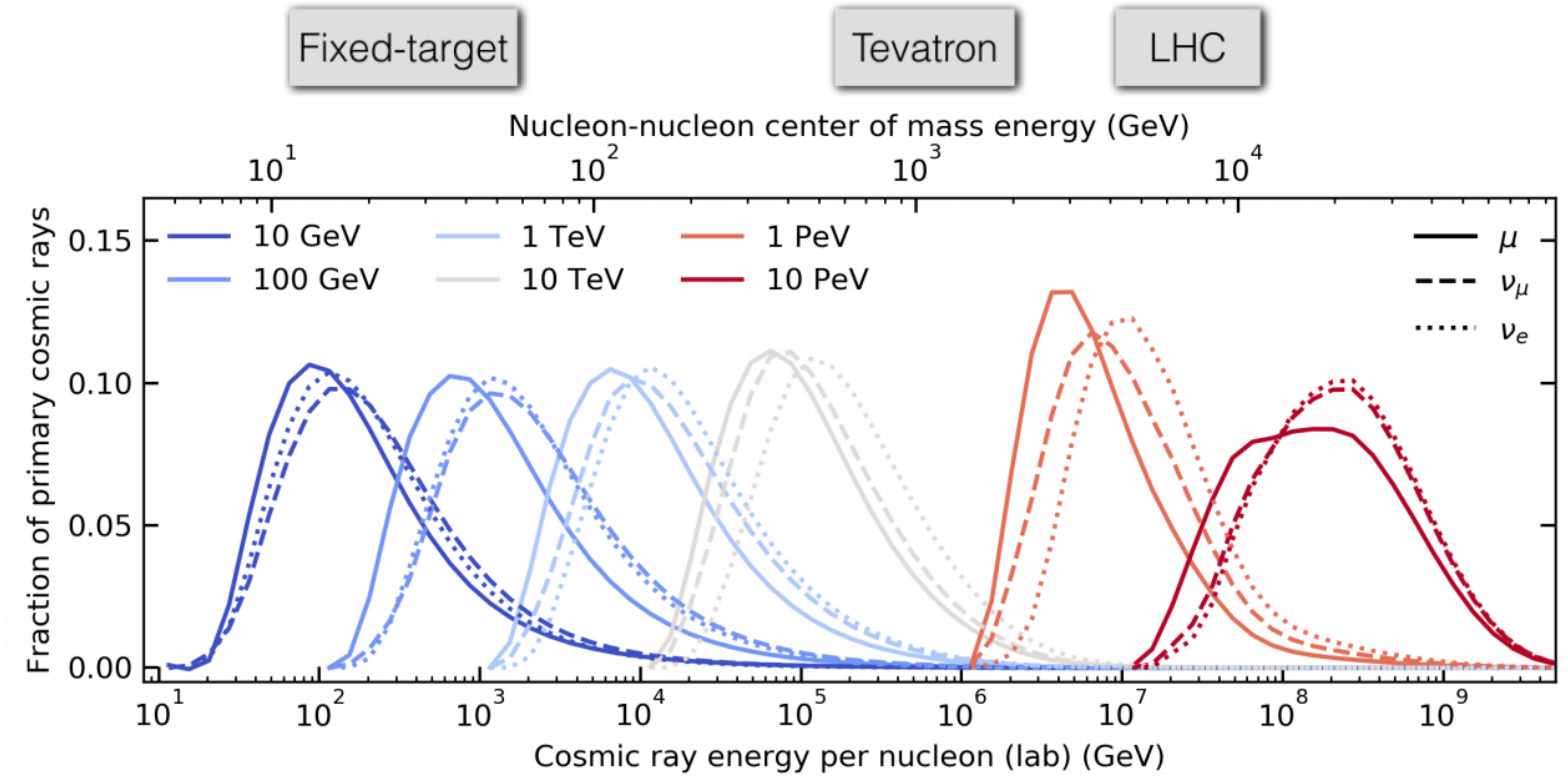
Continuous losses

particle physics

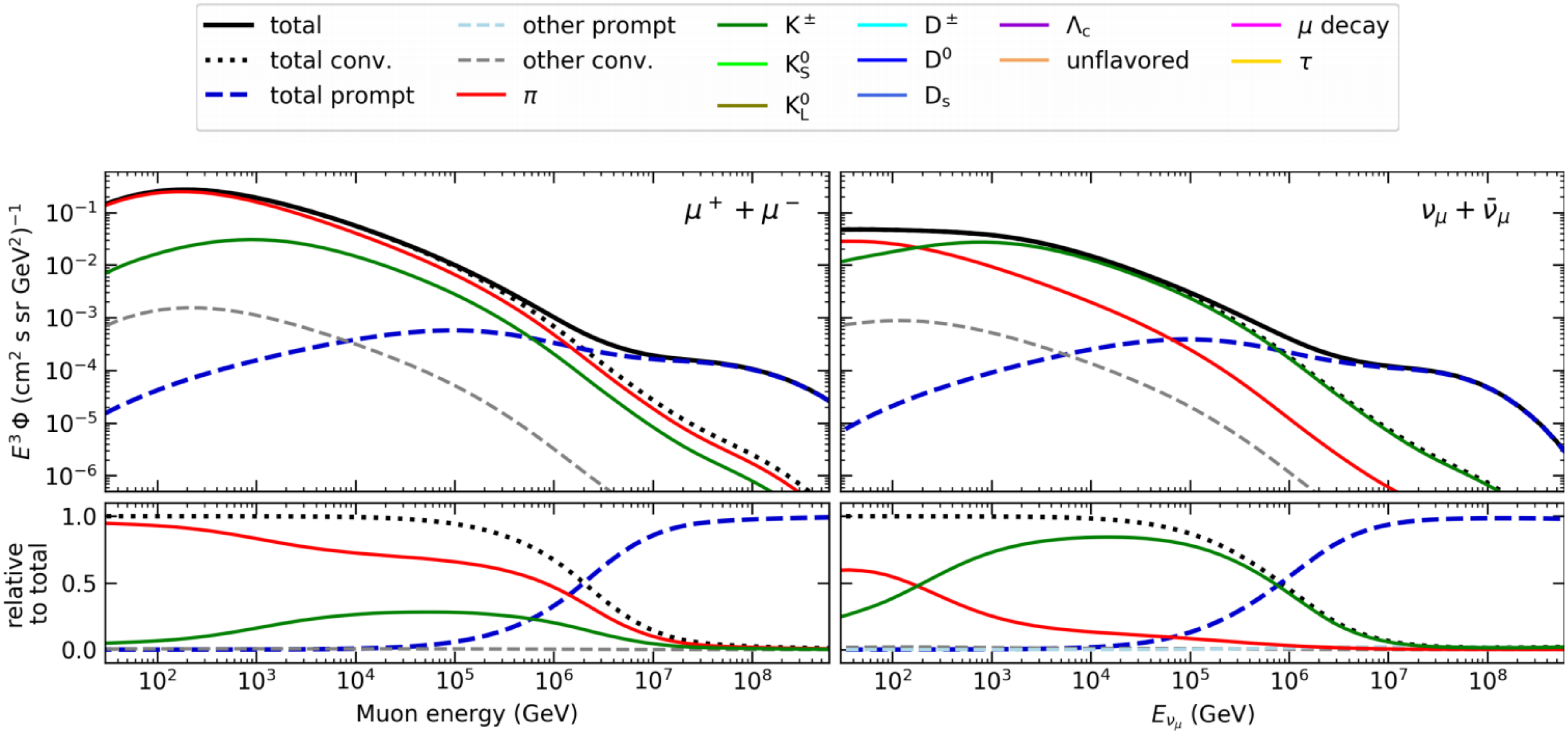


$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell\ \rho_{\mathrm{air}}(\ell)$$

Relationship between primary and secondary particles



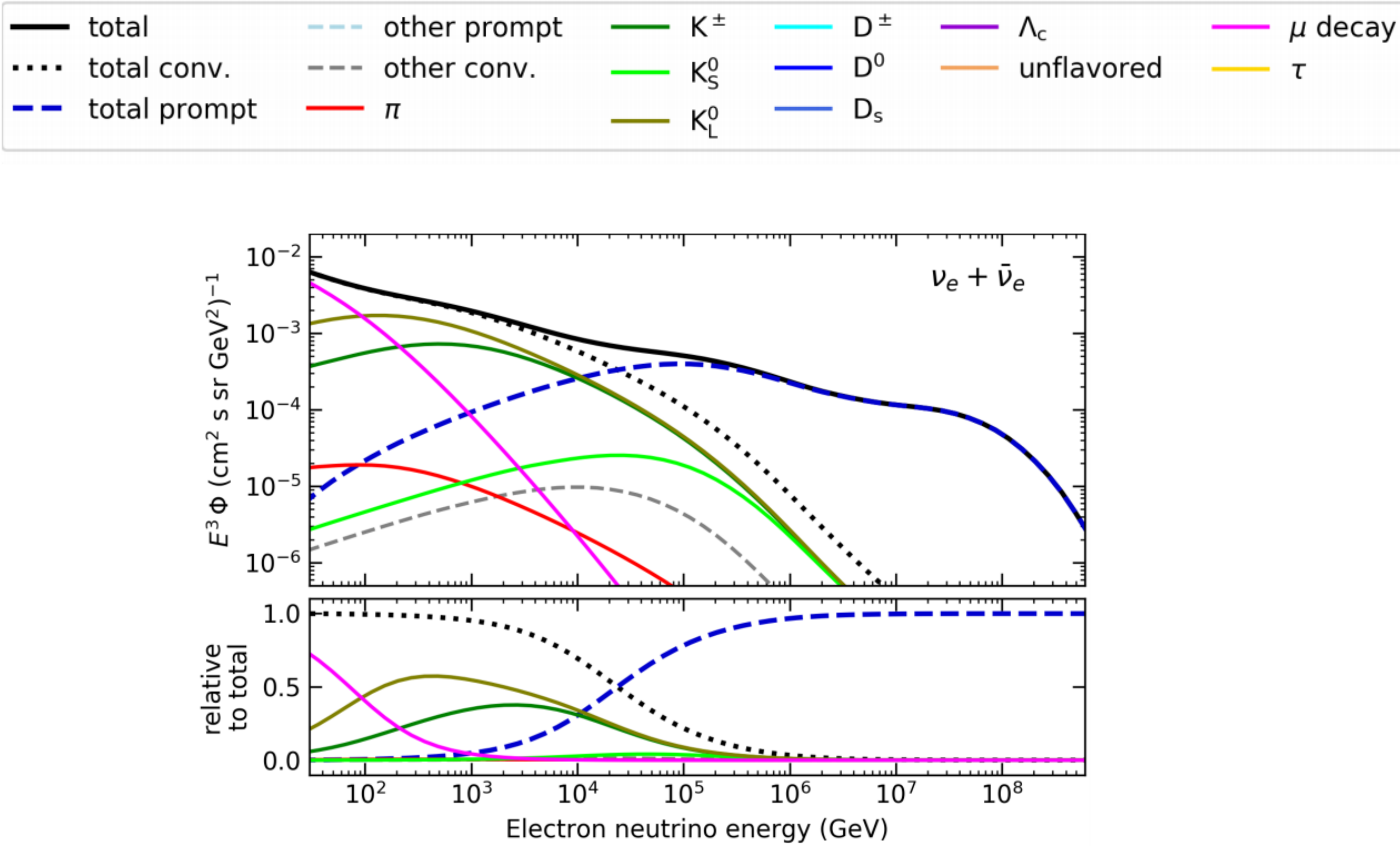
Muon-neutrino flux



https://github.com/afedynitch/MCEq

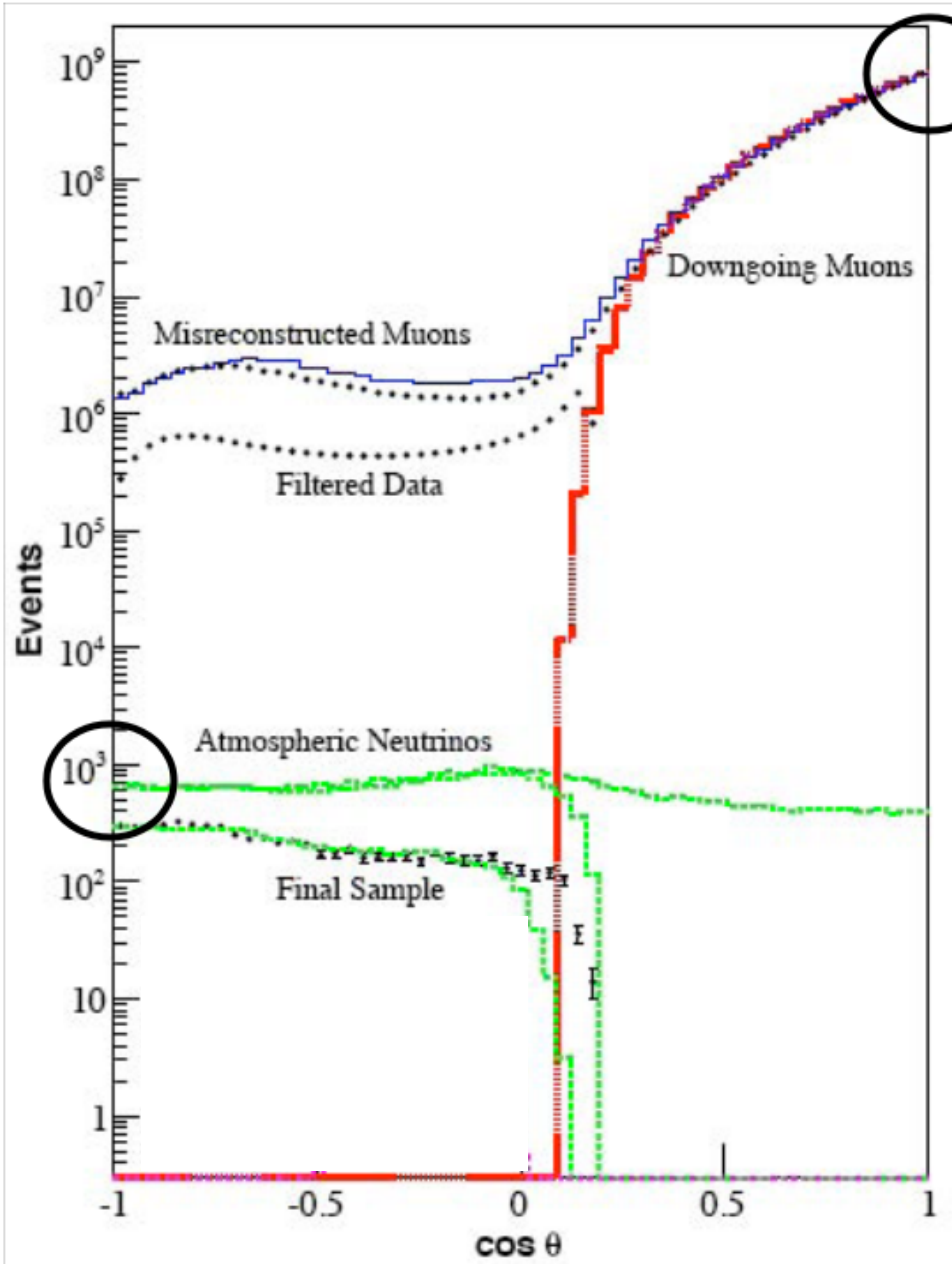
CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129
MCEq: Code paper, AF, R. Engel, in prep. for submission

Electron-neutrino flux

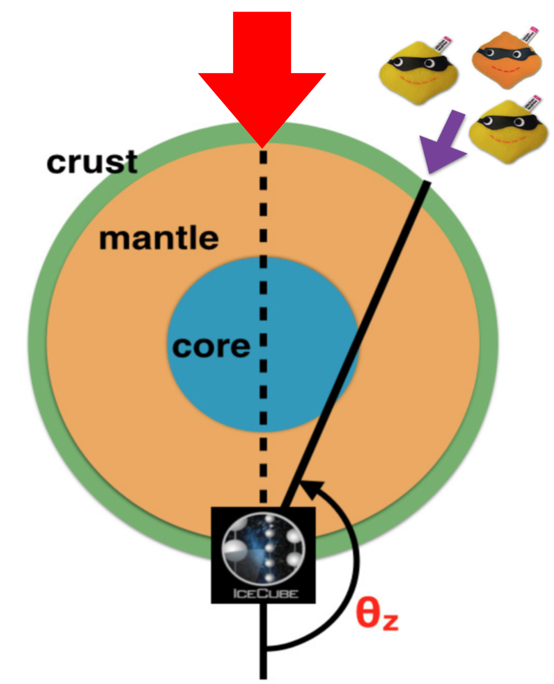


https://github.com/afedynitch/MCEq

CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129
MCEq: Code paper, AF, R. Engel, in prep. for submission



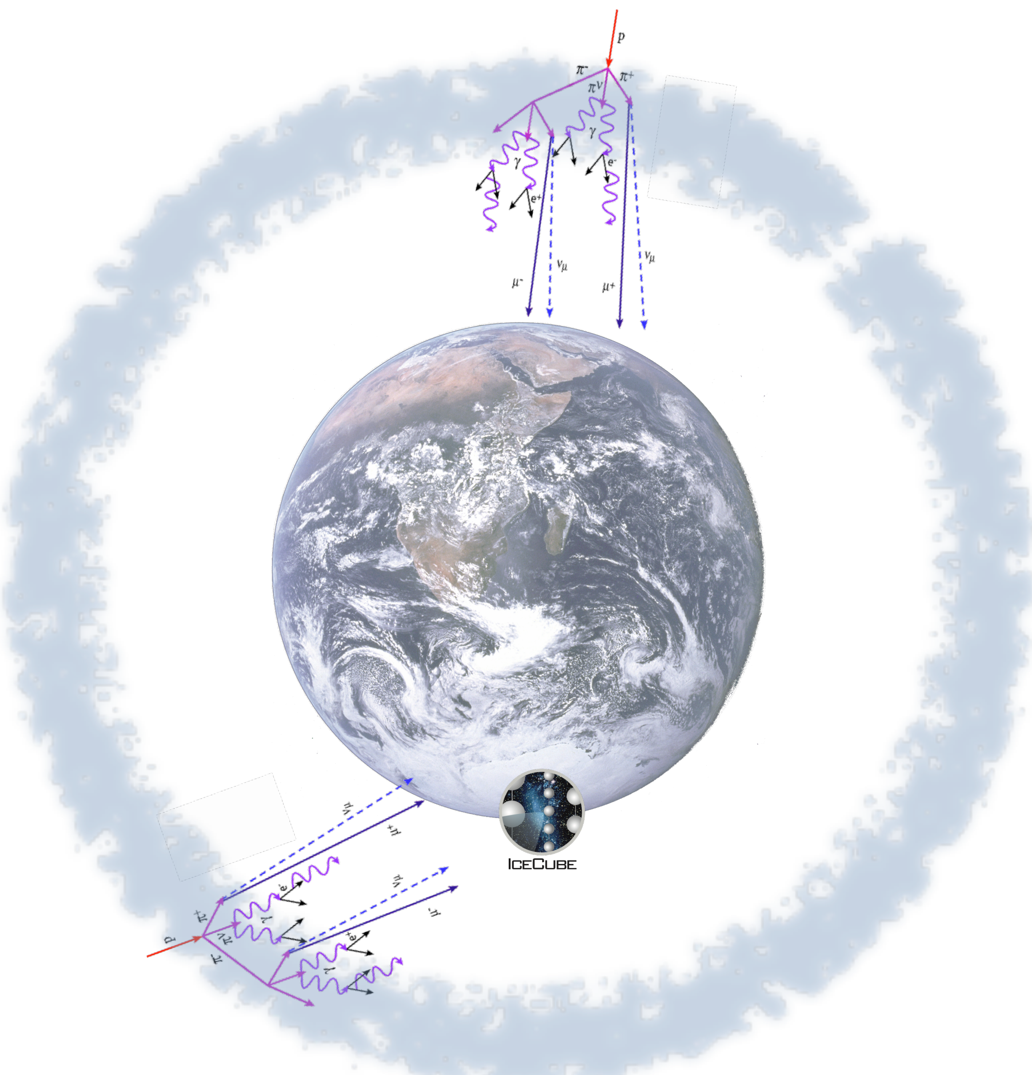
Downgoing Muons
Misreconstructed Muons
Filtered Data
Atmospheric Neutrinos
Final Sample
Events
cos θ

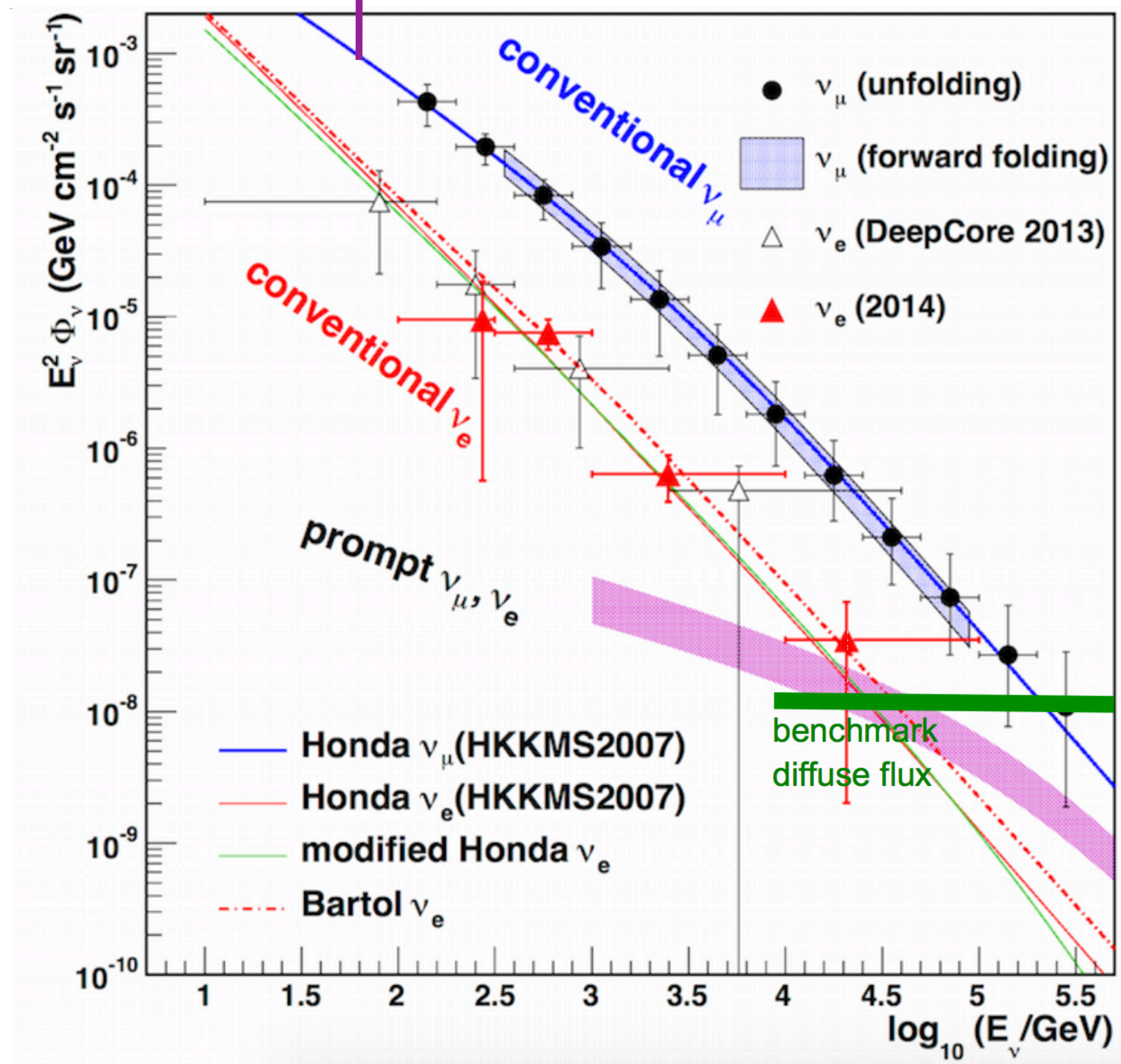


crust
mantle
core
θz

Two prone hunt of astrophysical neutrinos

10^6 atmospheric μ
per atmospheric ν

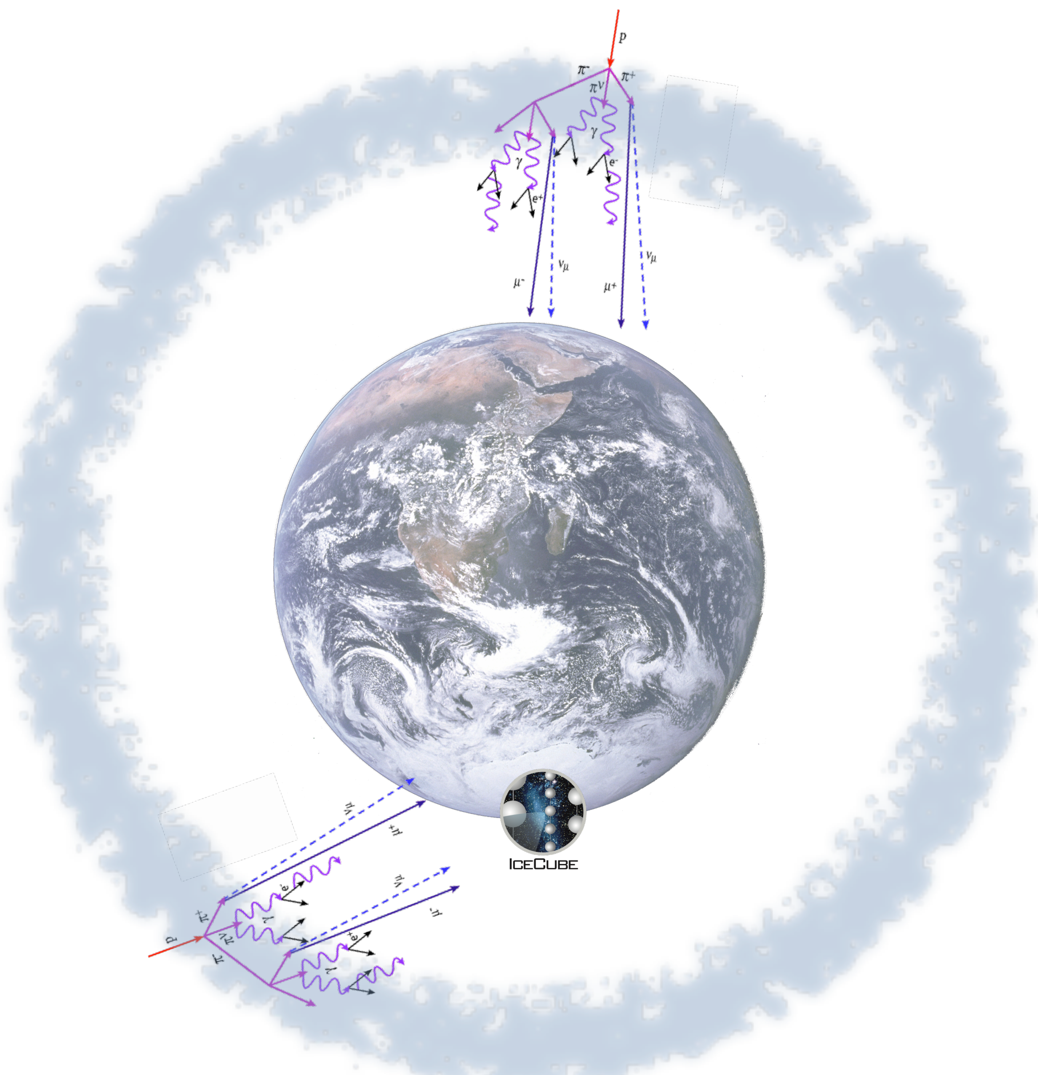


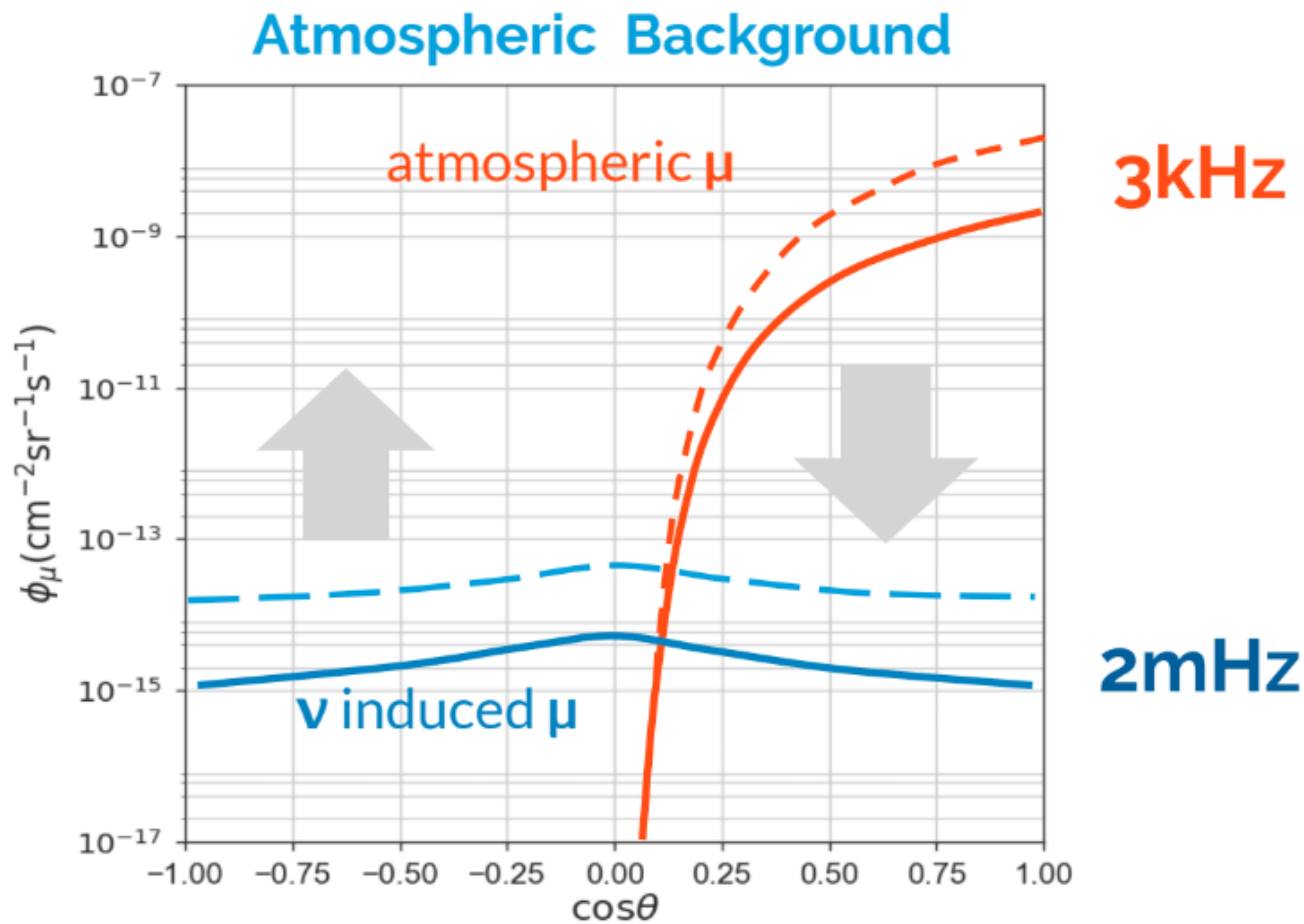


Challenges:

Astrophysical neutrino flux is very small

Large atmospheric neutrino and muon backgrounds



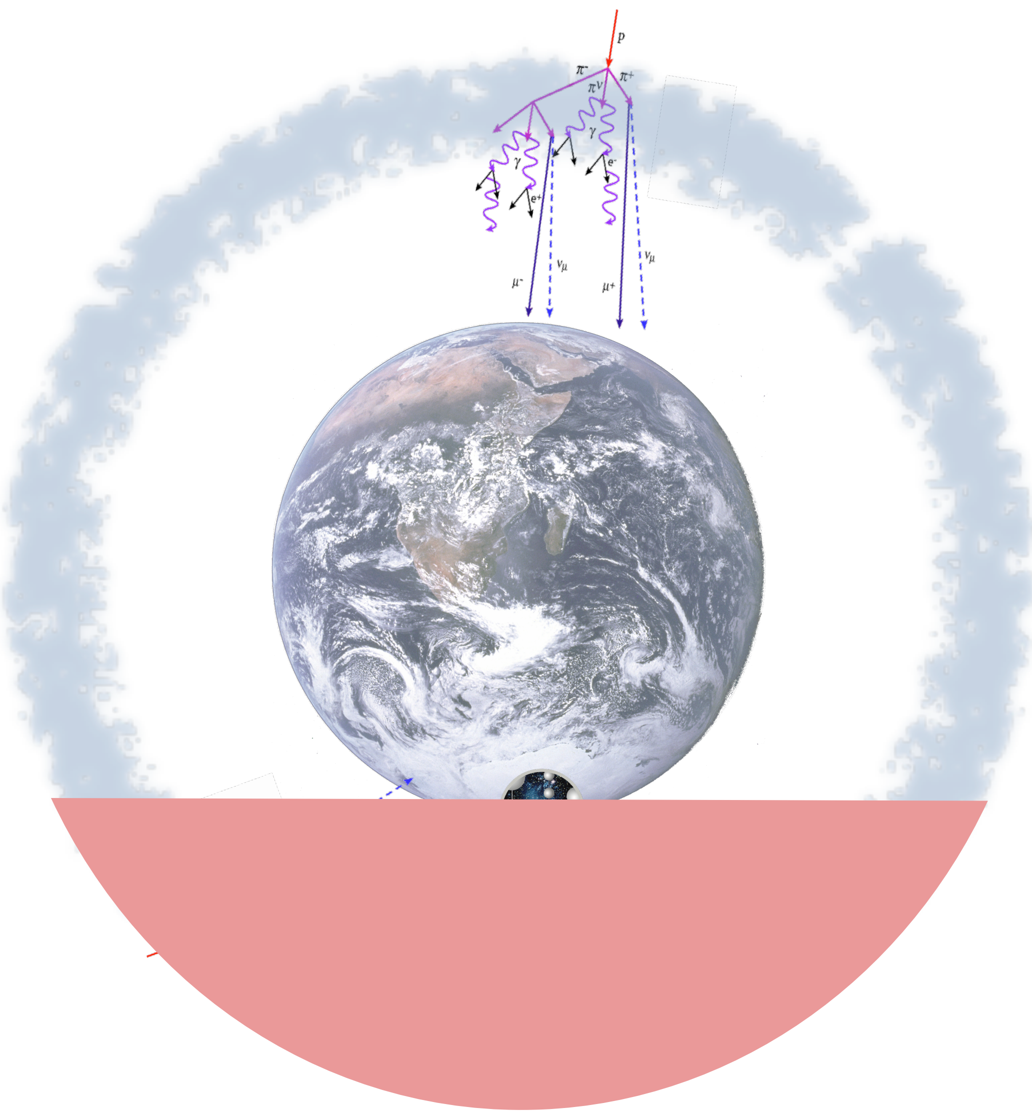


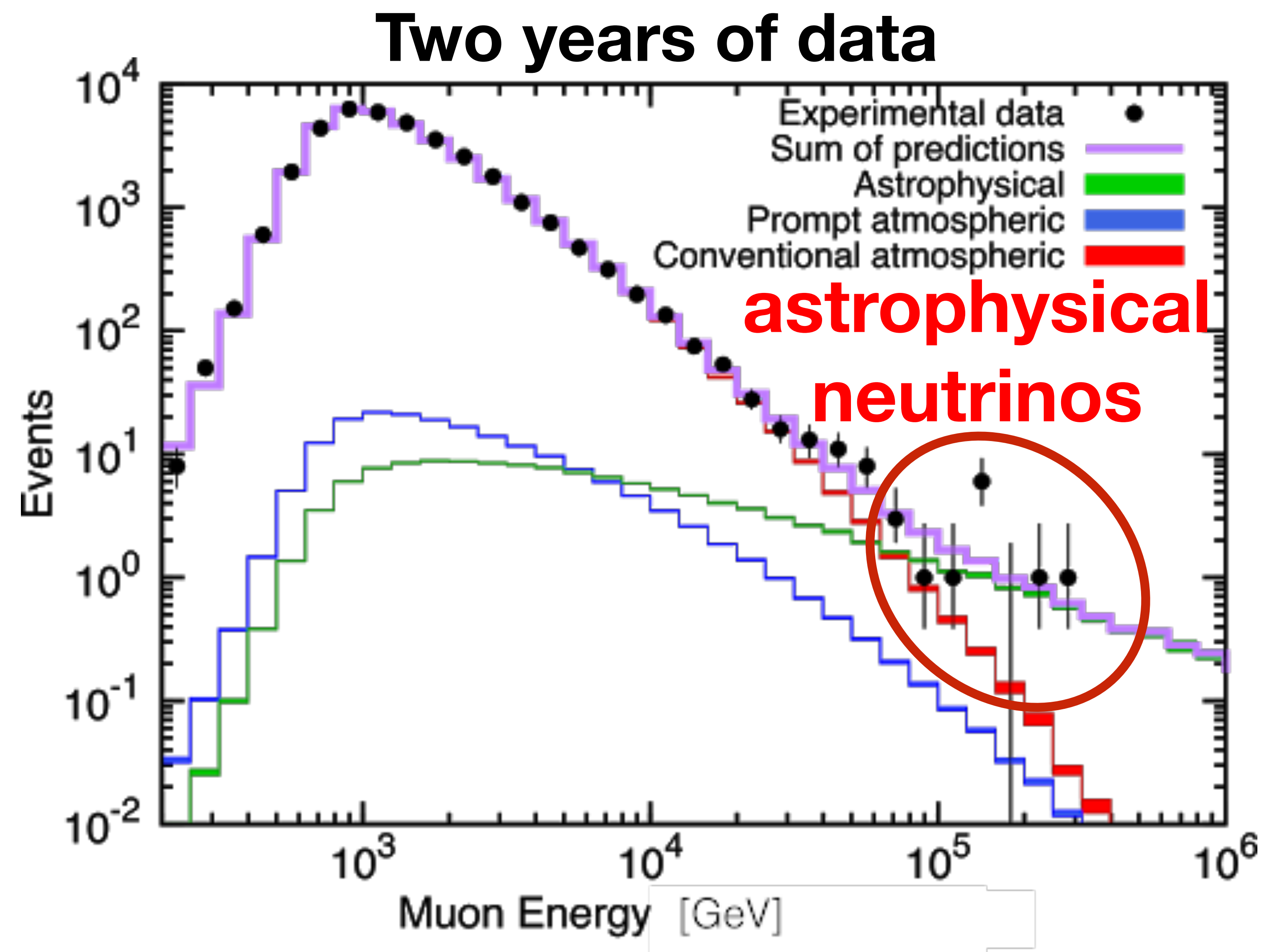
Challenges:

Astrophysical neutrino flux is very small

Large atmospheric neutrino and muon backgrounds

Strategy One: look at the Northern Sky

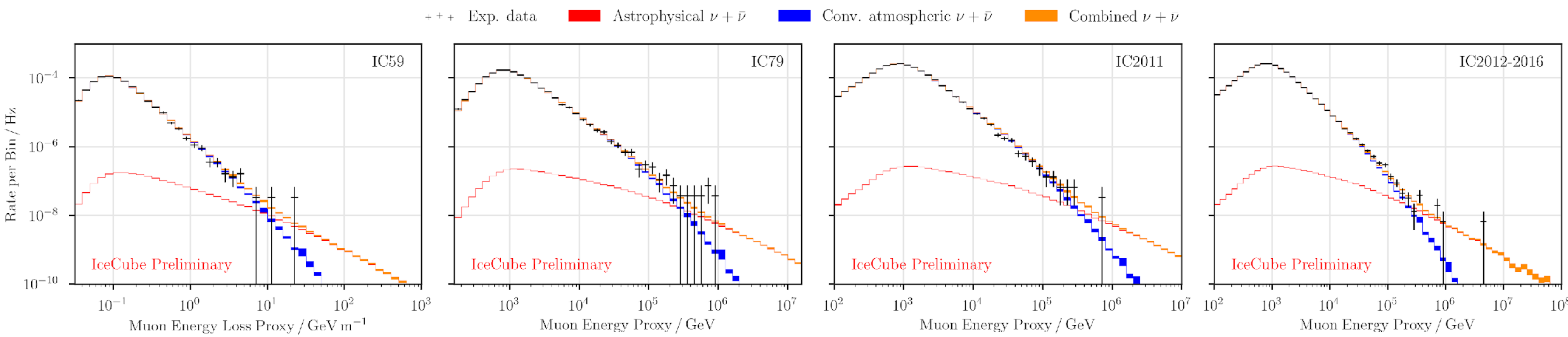




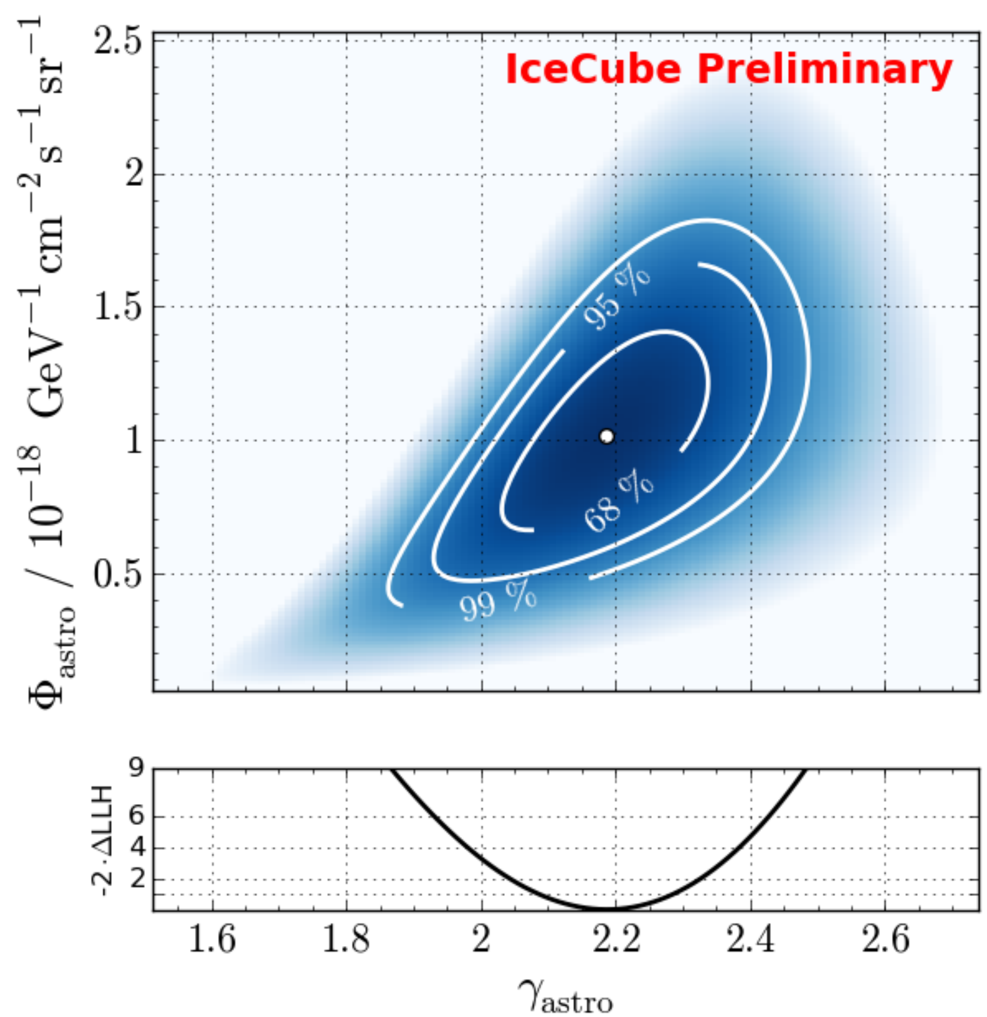
Strategy:

- Use the Earth to block the large atmospheric muon flux
- Look at the highest energy where the atmosphric neutrino flux is smallest

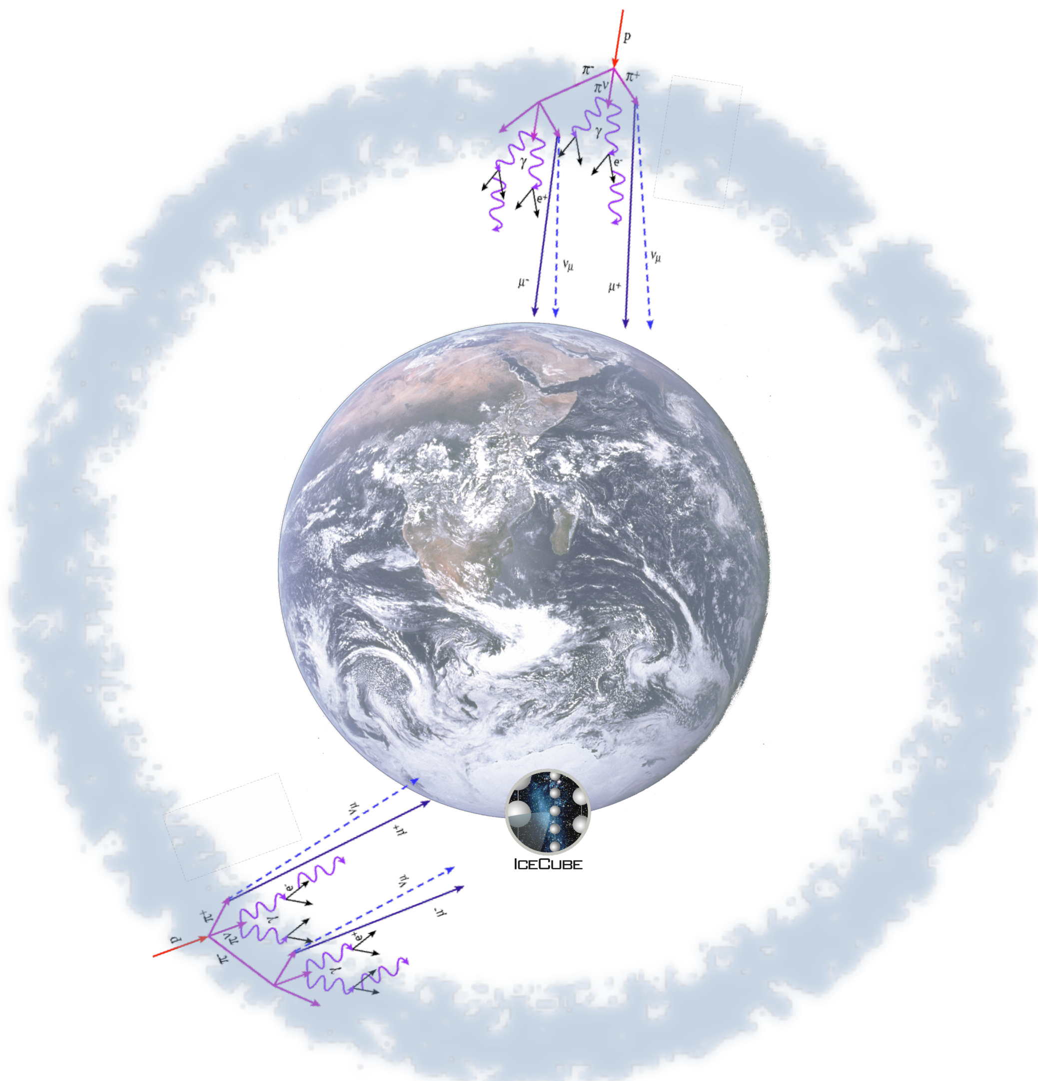
8 years of northern-sky neutrinos show consistent excess over atmospheric background

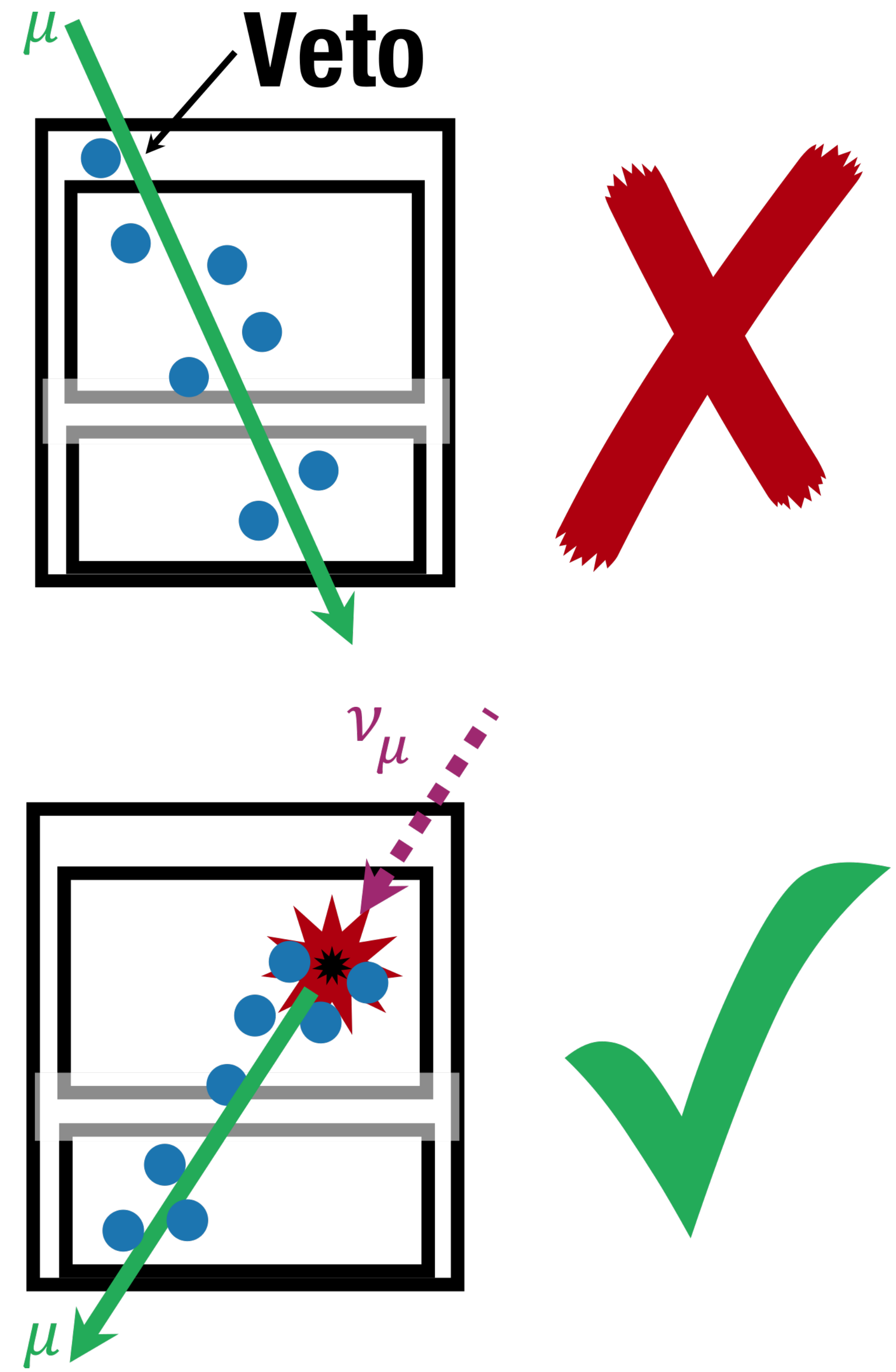


Northern-sky astrophysical neutrino flux is well characterized by single power-law with spectral index: 2.19±0.10



Strategy Two: Use the other detector as a veto



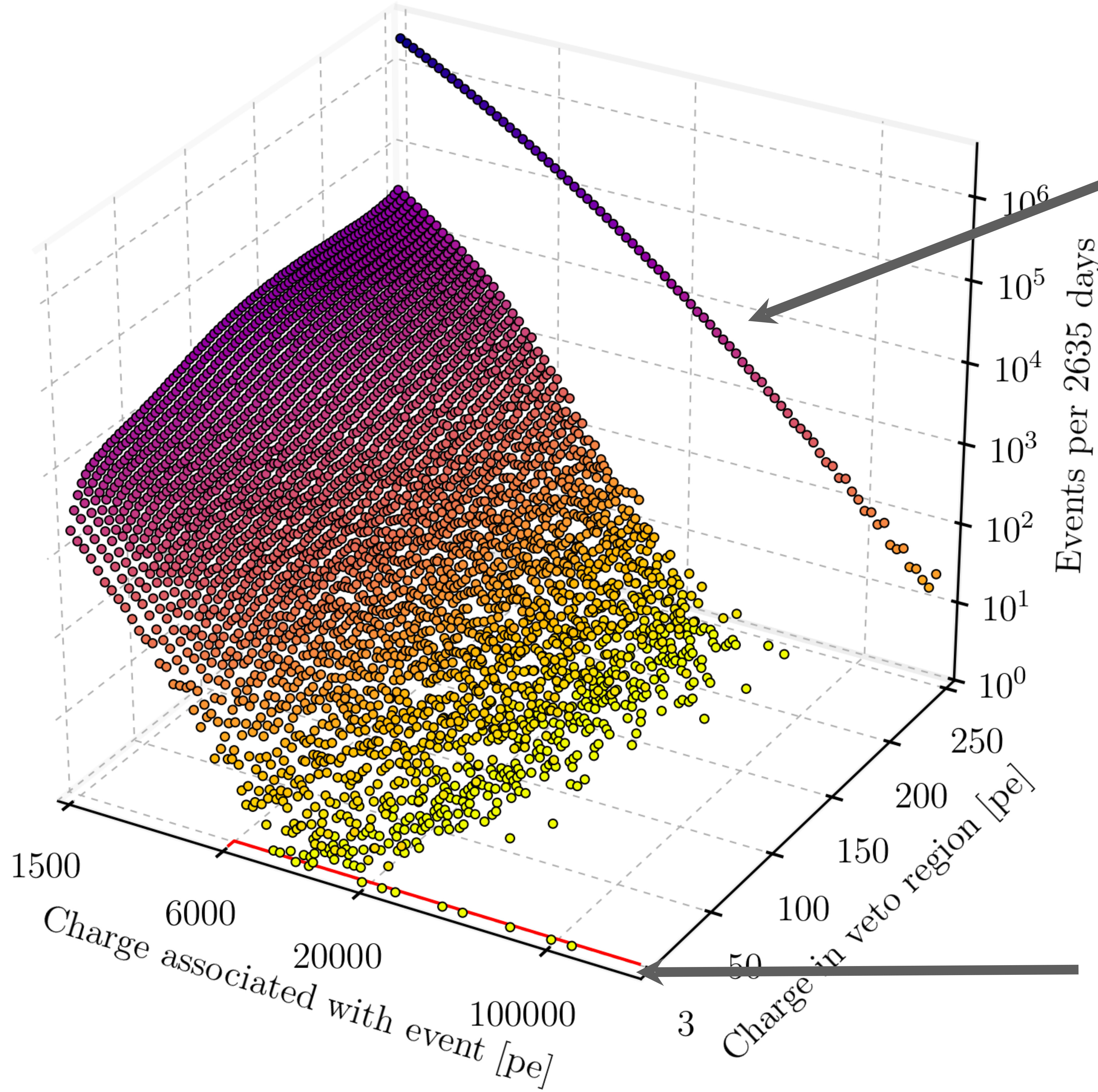


Strategy:

- Define a veto region in the detector to supress the atmospheric background,

Advantage: All-sky vision

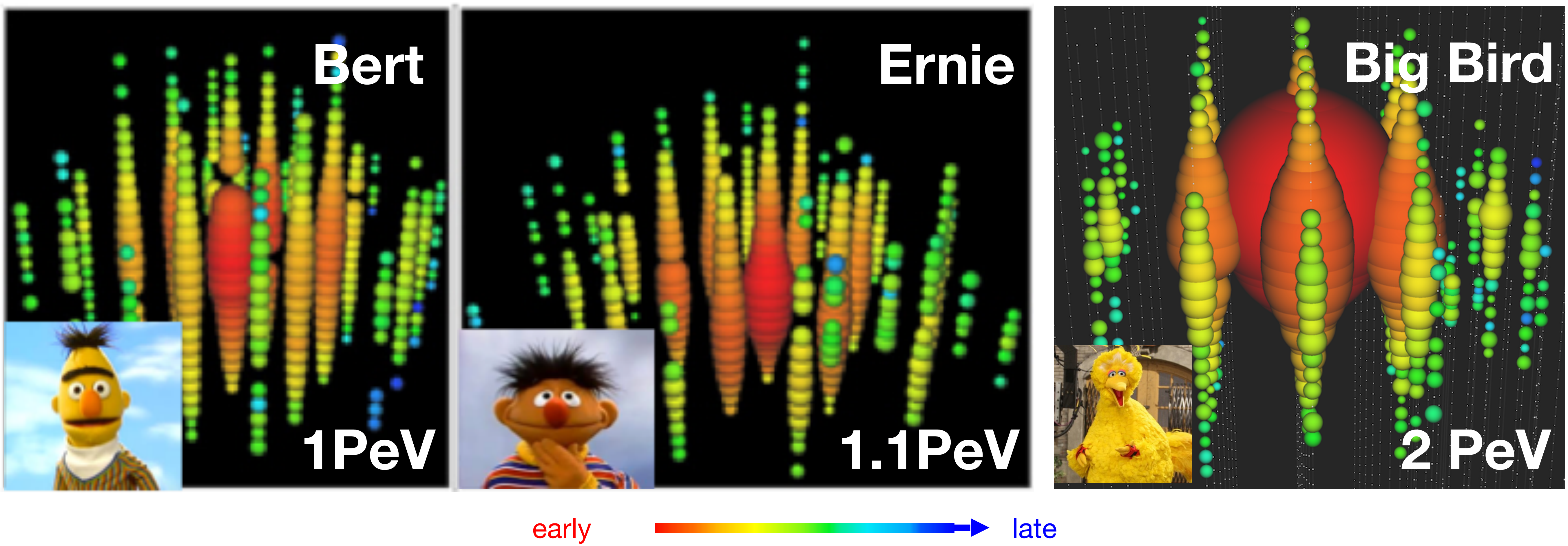
High-Energy Starting Events (HESE)



Large muon background that is well-separated

Astrophysical neutrinos candidates!

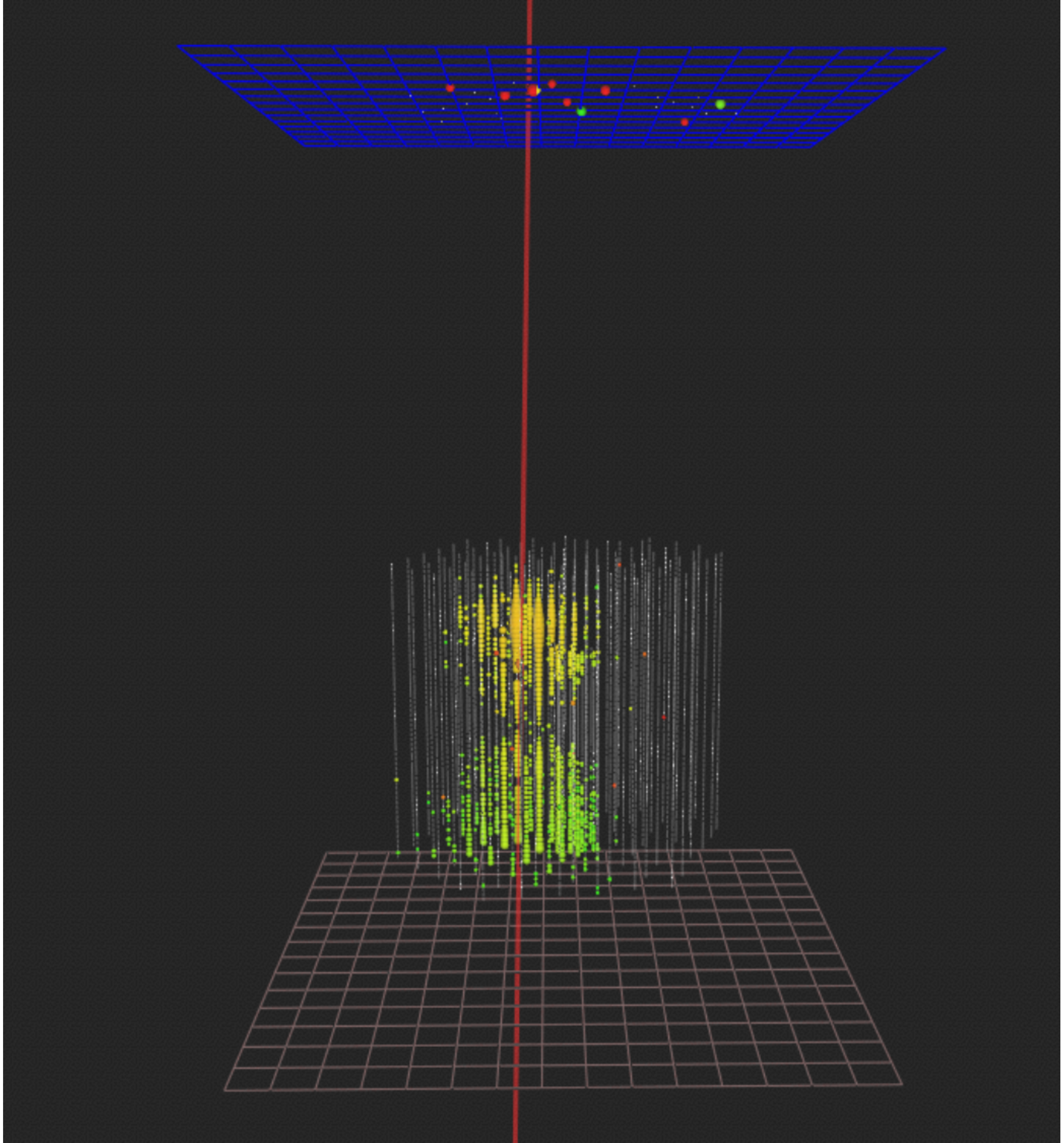
This event selection contains some of the highest energy neutrinos ever observed



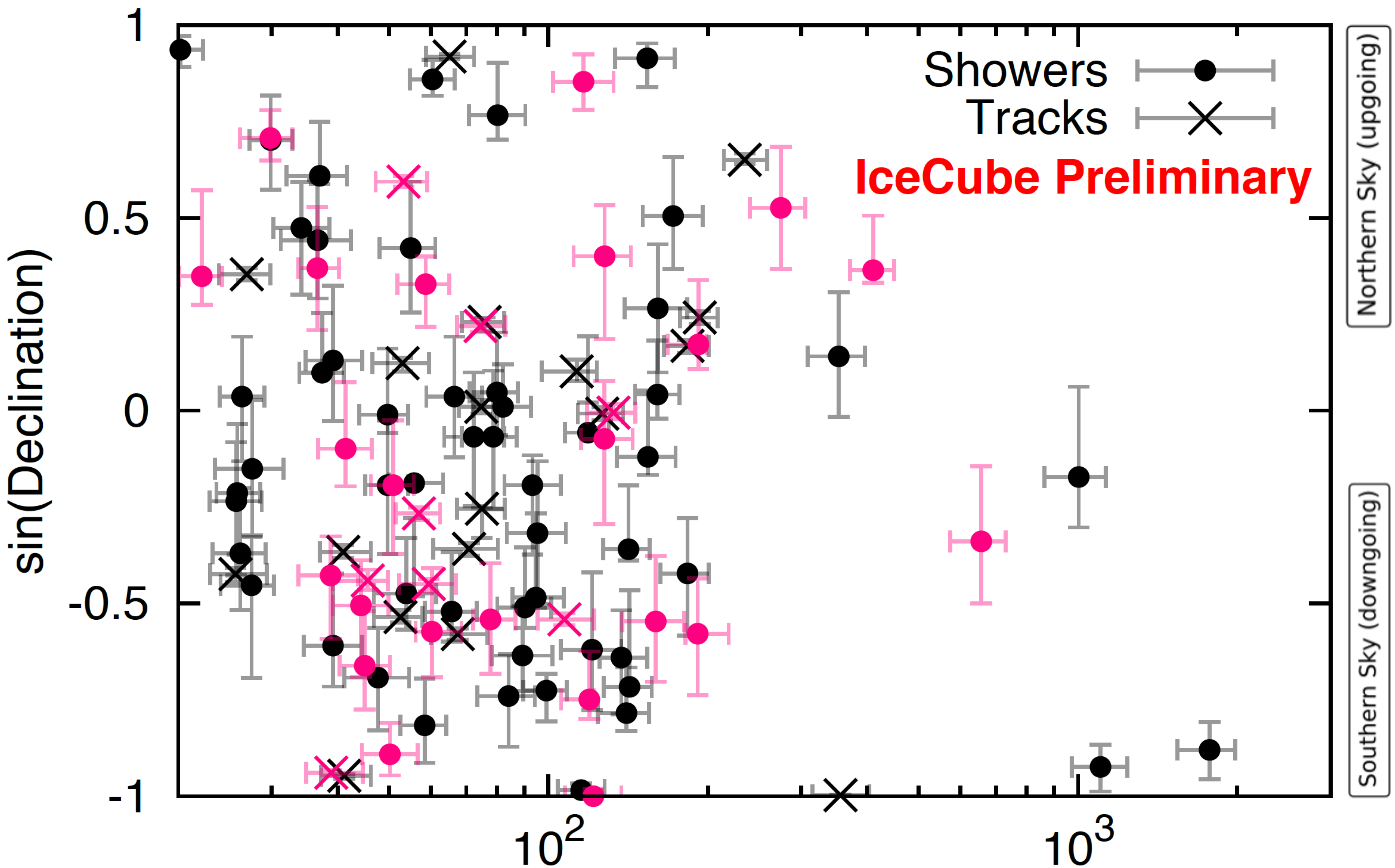
Color indicates time (red earlier, green later)
Sphere sizes indicate charge deposited.

430 TeV inside detector
PeV ν_μ
no air shower

all cosmic neutrinos are isolated by self-veto

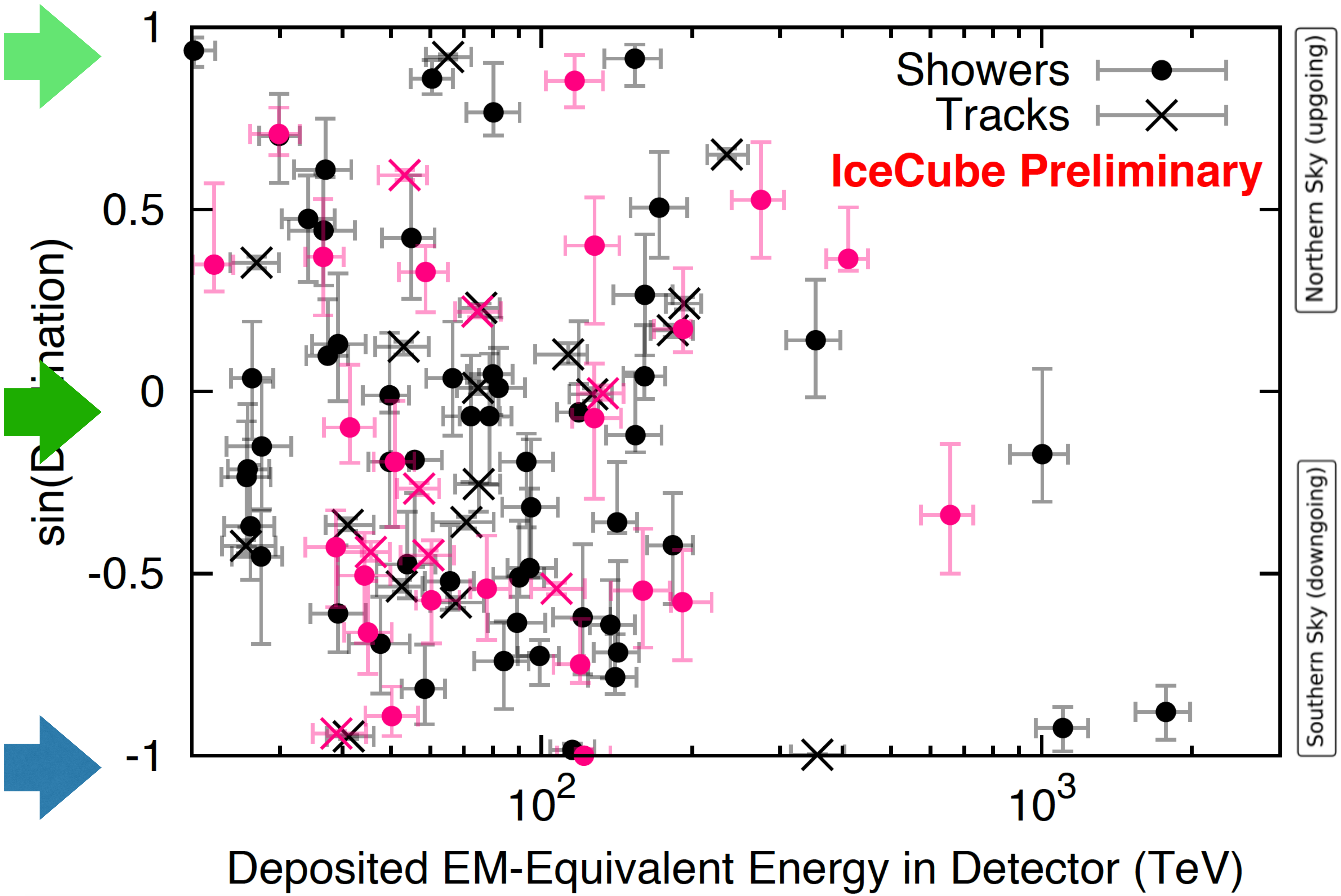


HESE-7.5 years distribution



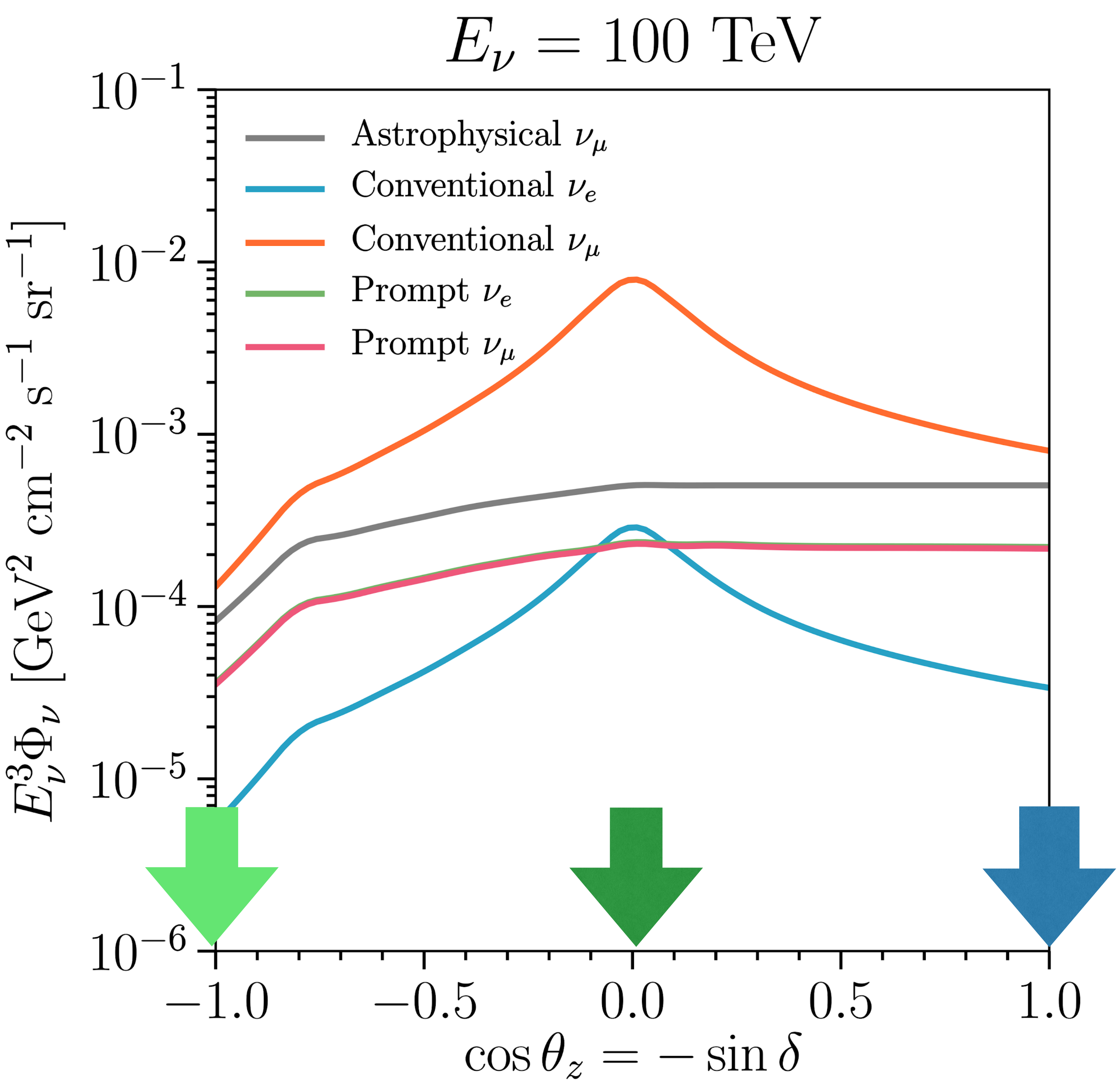
*HESE = high-energy starting events

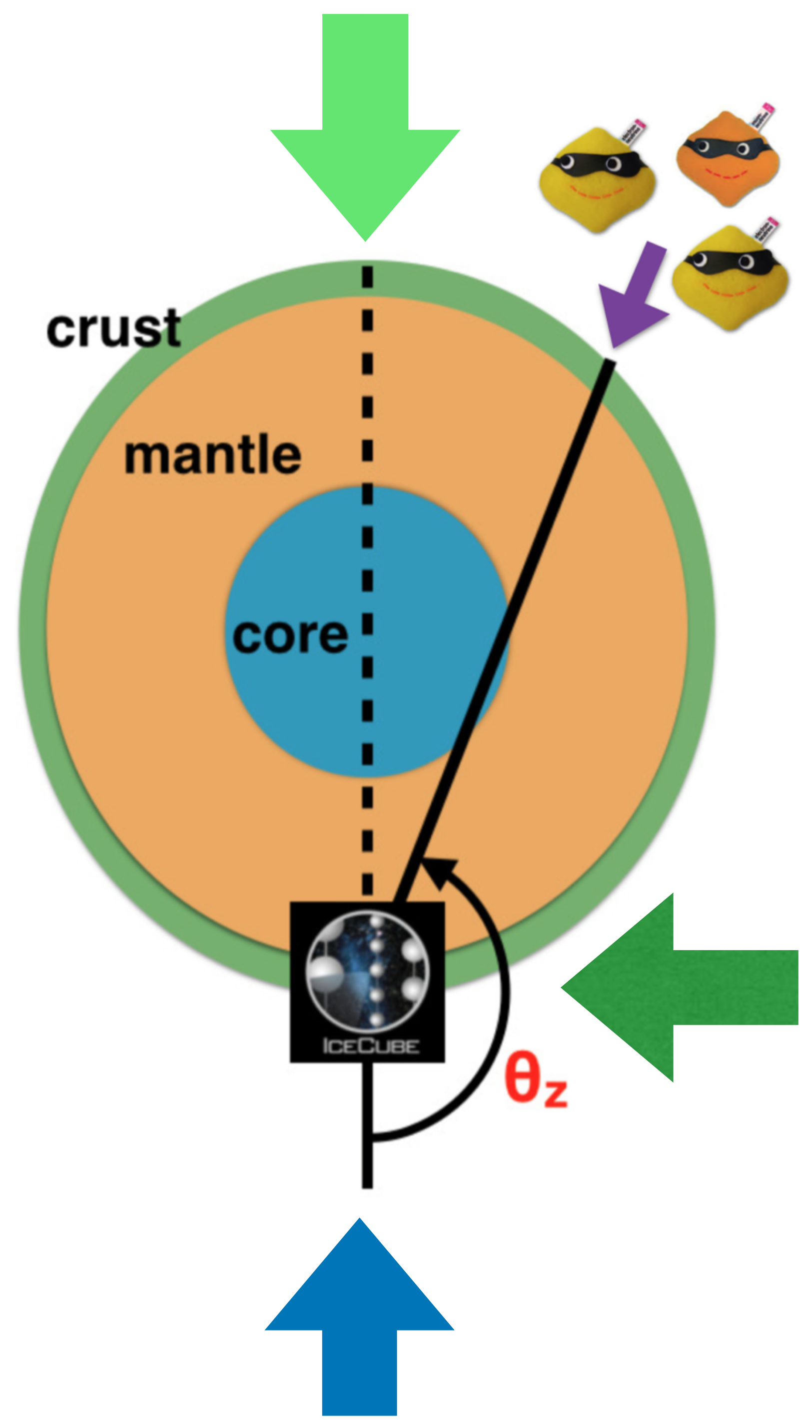
HESE-7.5 years distribution



***HESE = high-energy starting events**

Expected angular distributions





How to look in the downgoing direction?

What is the passing fraction?

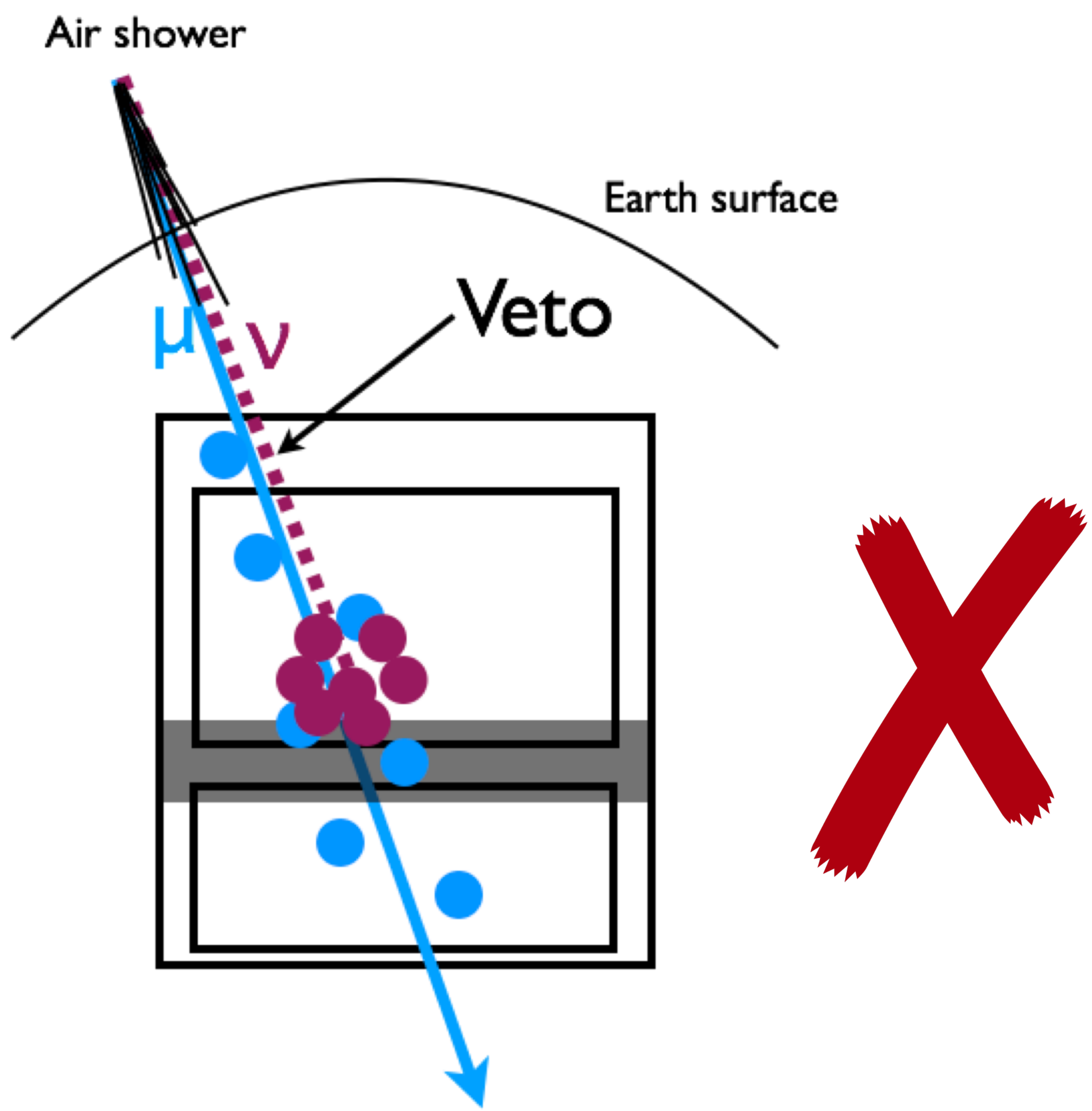
Passing Fraction =

Cosmic Ray Flux *

Shower Development *

Muon Energy Loss *

Detector Response



Passing fraction: probability that all accompanying muons of the shower pass the cuts (veto) given a neutrino interaction in the detector

Revisiting the passing fraction

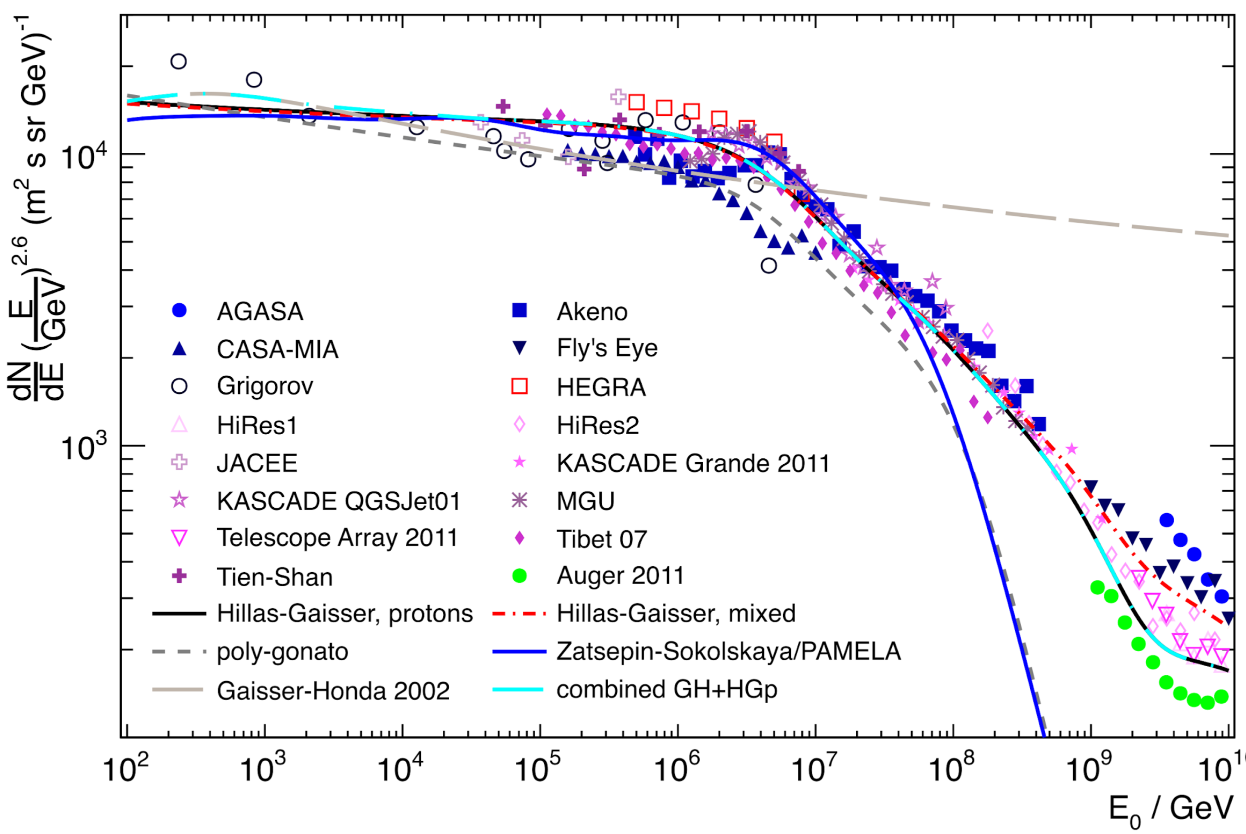
Passing Fraction =

Cosmic Ray Flux *

Shower Development *

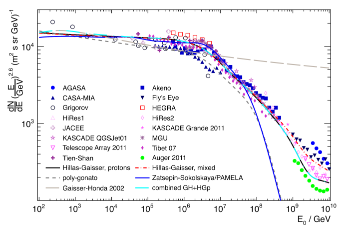
Muon Energy Loss *

Detector Response



Revisiting the passing fraction

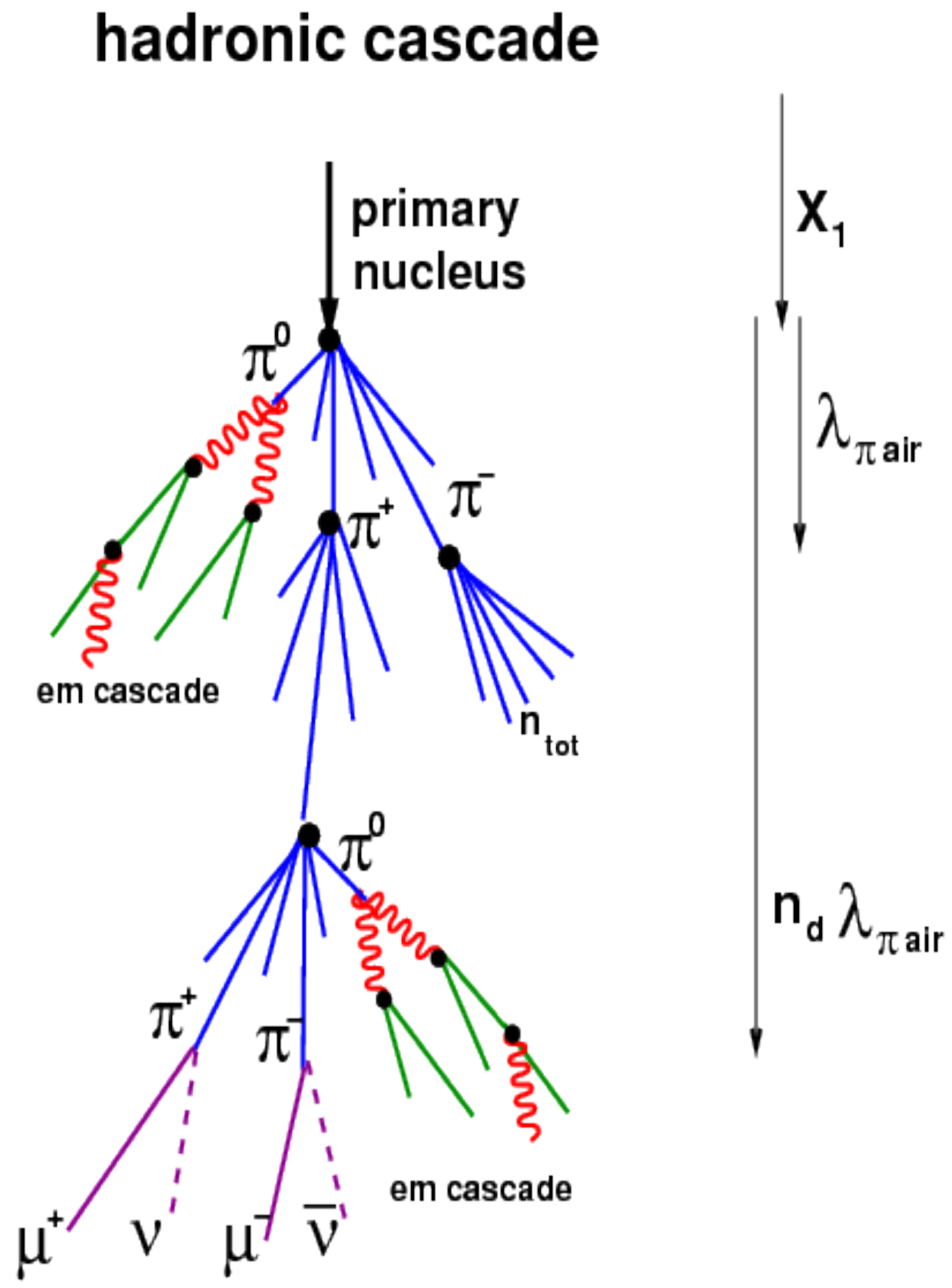
Passing Fraction =

Cosmic Ray Flux * 

Shower Development *

Muon Energy Loss *

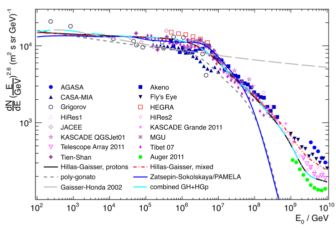
Detector Response



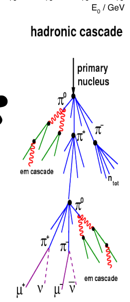
Revisiting the passing fraction

Passing Fraction =

Cosmic Ray Flux *

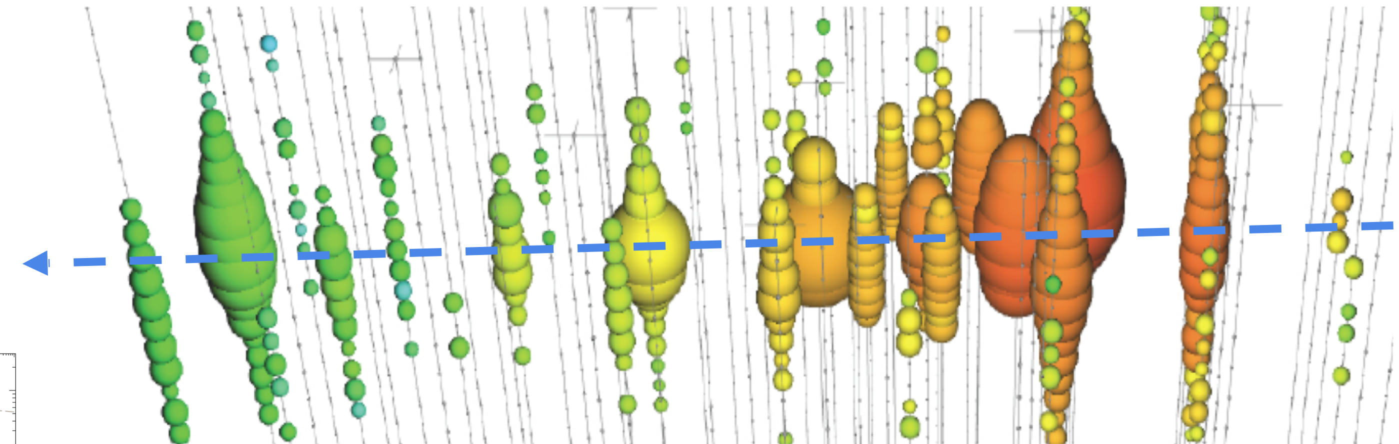


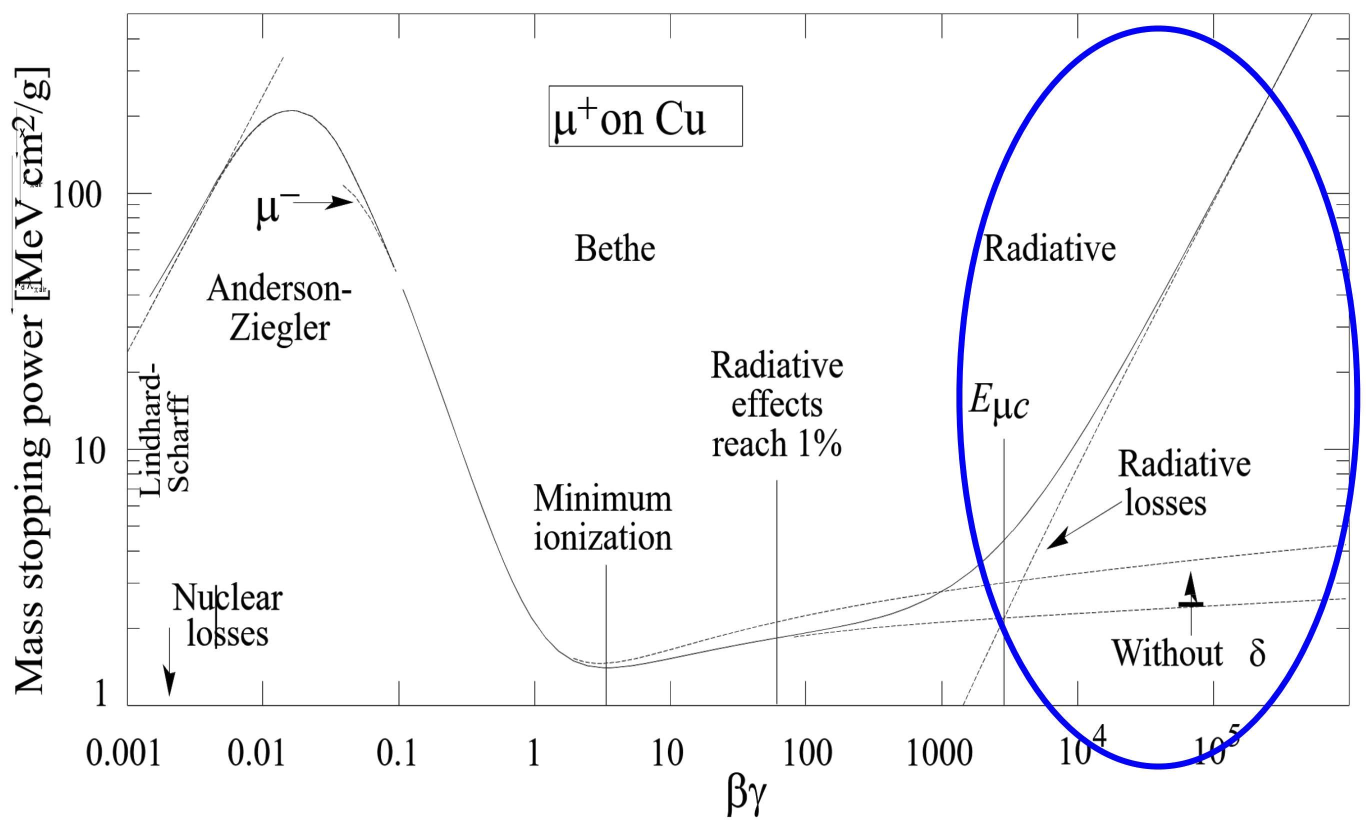
Shower Development *



Muon Energy Loss *

Detector Response

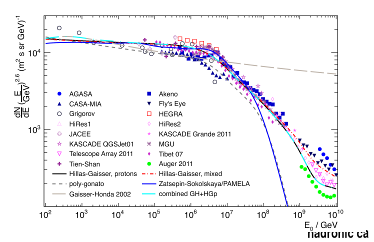




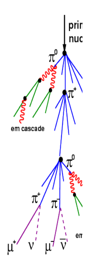
Revisiting the passing fraction

Passing Fraction =

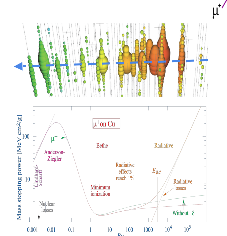
Cosmic Ray Flux *



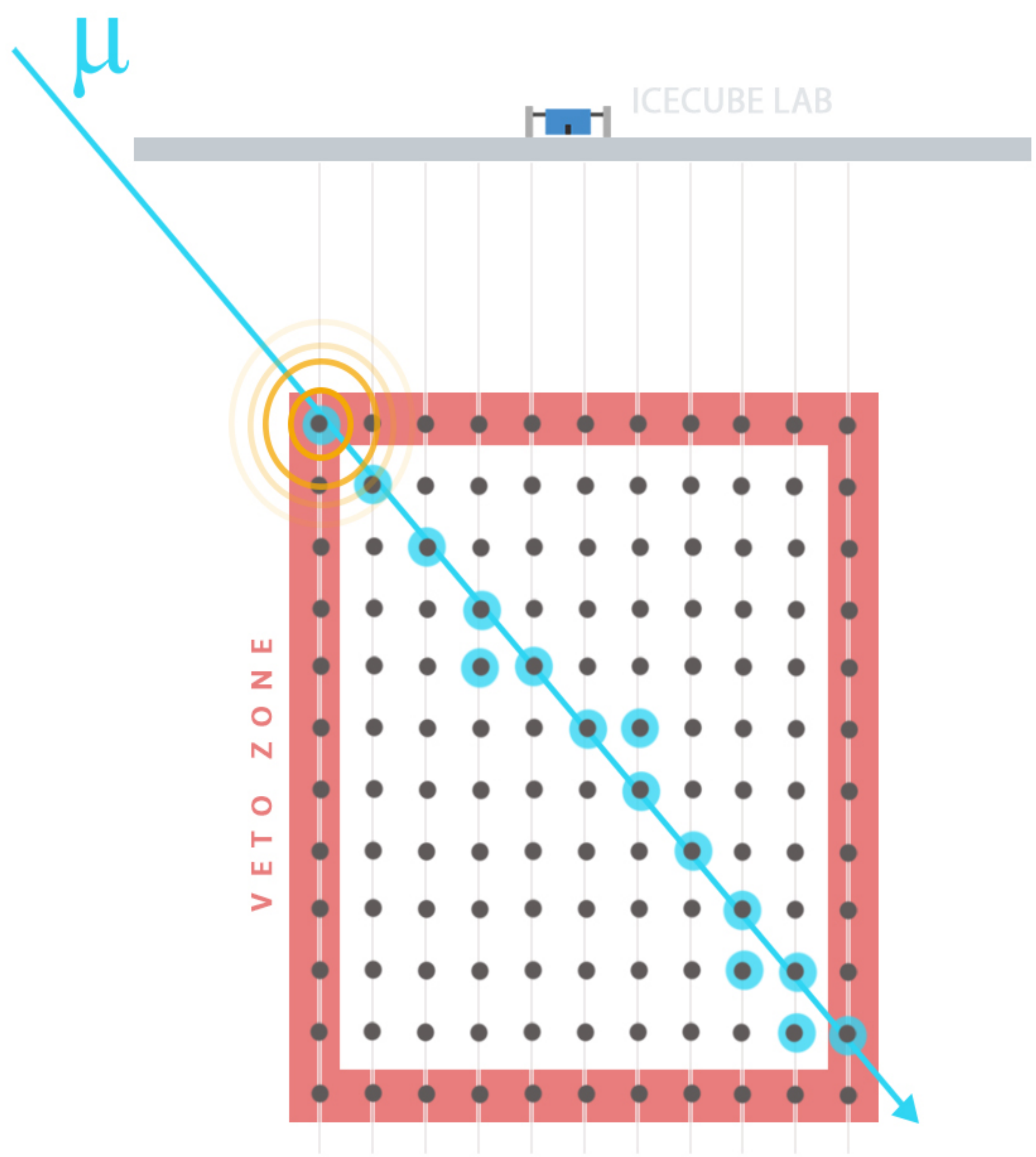
Shower Development *



Muon Energy Loss *

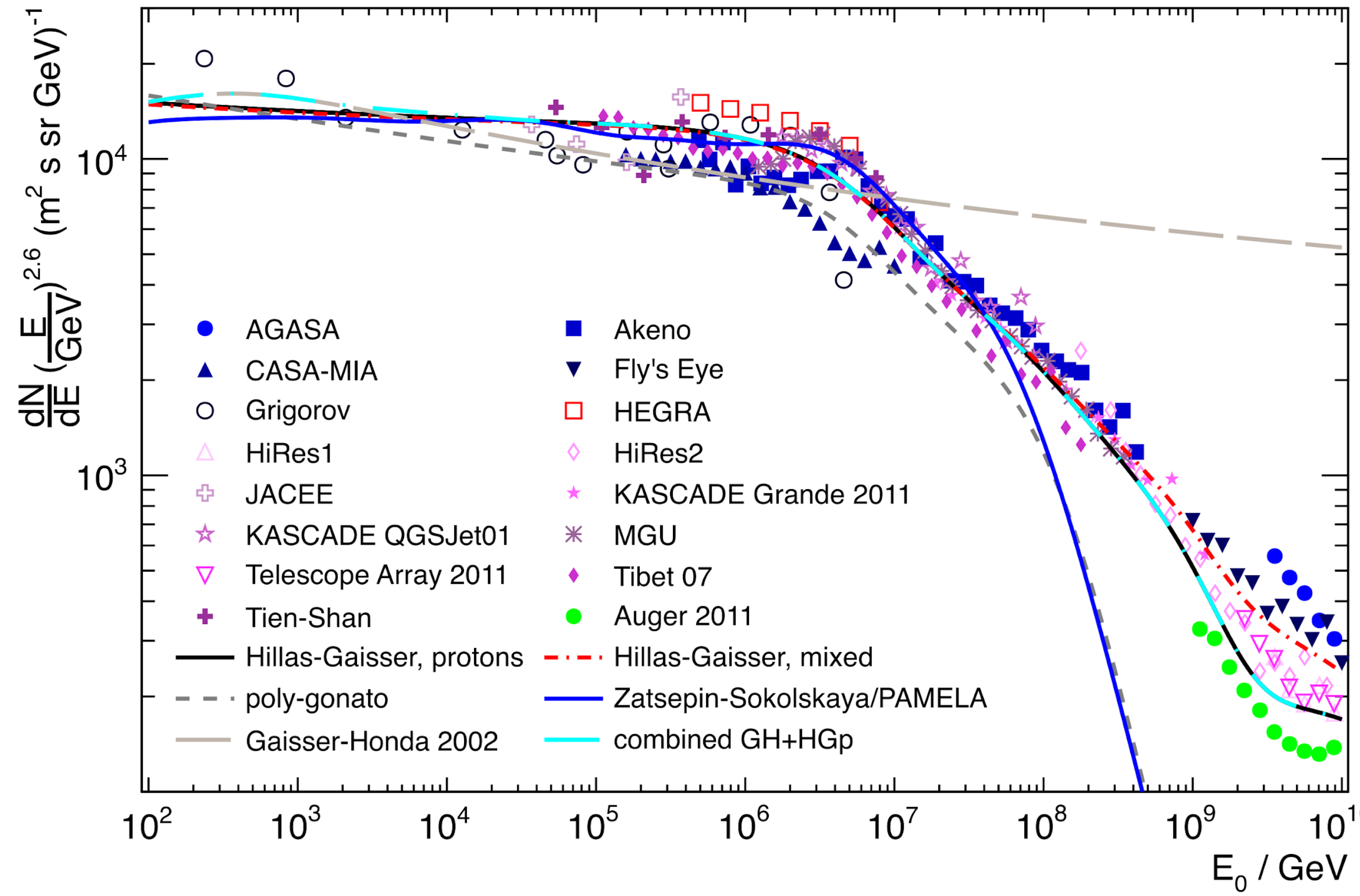


Detector Response



CA, Palomares-Ruiz, Schneider, Wille, Yuan arXiv:1805.11003

Start with the cosmic-rays



Total Flux

Column Density

Parent Energy

Cosmic Ray Energy

$$\mathcal{P}_{\rm pass}(E_\nu,\theta_z) = \frac{1}{\phi_\nu(E_\nu,\theta_z)} \sum_A \sum_p \int dE_p \int \frac{dX}{\lambda_p(E_p,X)} \int dE_{\rm CR}$$

Cosmic Ray Type

Parent Type

CR->meson->(neutrino+muon)

Cosmic ray flux

Yield of parent meson from cosmic ray

Yield of neutrino from parent meson

$$\mathcal{P}_{\rm pass}(E_\nu,\theta_z) = \frac{1}{\phi_\nu(E_\nu,\theta_z)} \sum_A \sum_p \int dE_p \int \frac{dX}{\lambda_p(E_p,X)} \int dE_{\rm CR} \boxed{\frac{dN_{p,\nu}}{dE_\nu}(E_p,E_\nu)\, \frac{dN_{A,p}}{dE_p}(E_{\rm CR},E_p,X)\,\phi_A(E_{\rm CR})}$$

$$\times \underbrace{\boxed{\mathcal{P}^{\rm sib}_{0\text{-}\mu}(\theta_z|E_p,E_\nu)}}_{\text{Correlated, sibling muon}} \underbrace{\mathcal{P}^{\rm shower}_{0\text{-}\mu}\left(N_\mu=0;\boxed{\bar{N}_{\mu,A}(E_{\rm CR}-E_p,\theta_z)}\right)}_{\text{Uncorrelated, proto. shower muons; Poisson}},$$

Coupling via E_p subtraction

CA, Palomares-Ruiz, Schneider, Wille, Yuan arXiv:1805.11003

Adding correlated and uncorrelated muons

Muon and neutrino from same interaction

N-body decay governs products

Muon from separate shower branch

Product governed by “average shower”

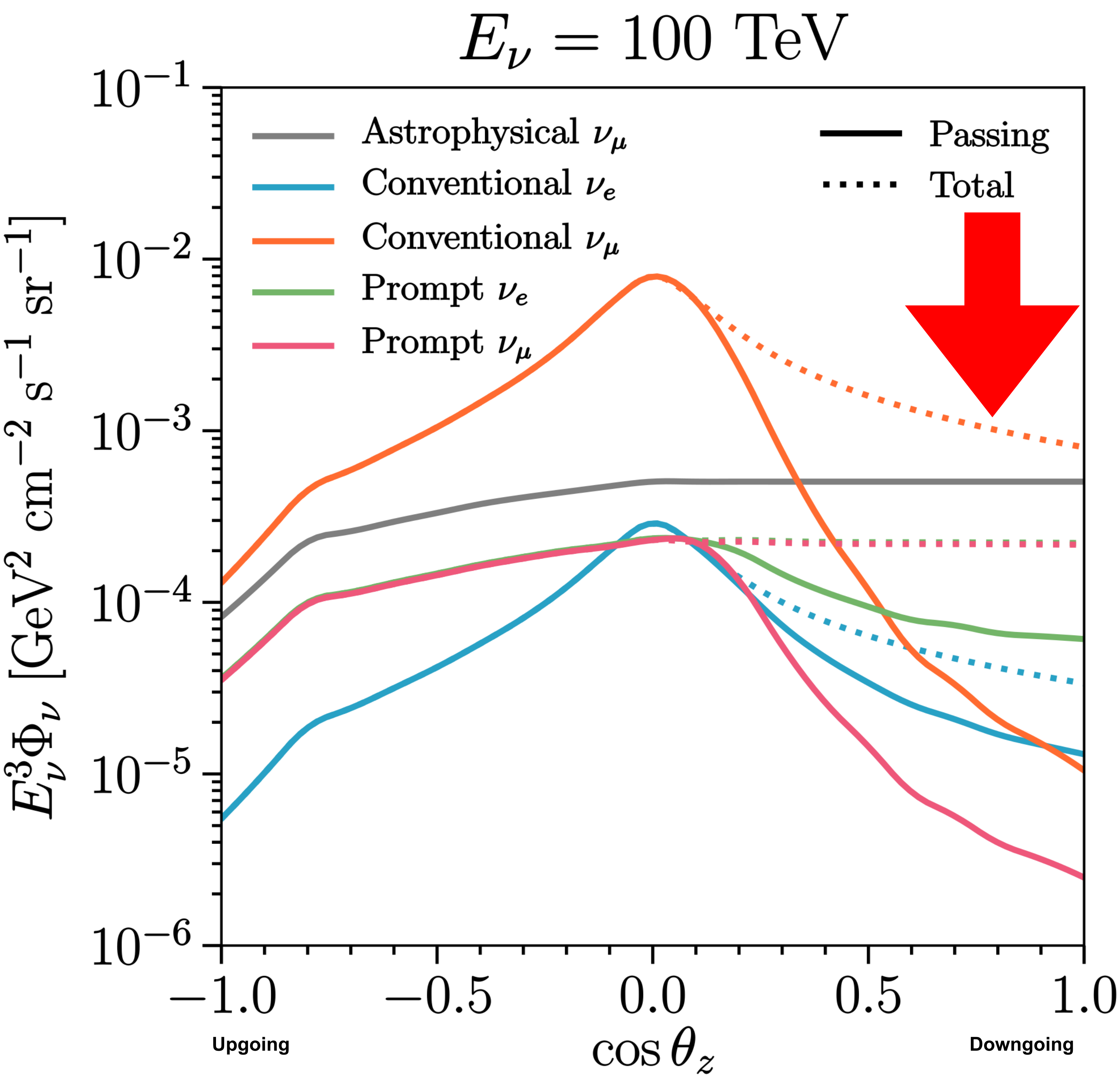
Cosmic ray shower with parent energy subtracted

$$\mathcal{P}_{\text{pass}}(E_\nu, \theta_z) = \frac{1}{\phi_\nu(E_\nu, \theta_z)} \sum_A \sum_p \int dE_p \int \frac{dX}{\lambda_p(E_p, X)} \int dE_{\text{CR}} \boxed{\frac{dN_{p,\nu}}{dE_\nu}(E_p, E_\nu)\, \frac{dN_{A,p}}{dE_p}(E_{\text{CR}}, E_p, X)\, \phi_A(E_{\text{CR}})}$$

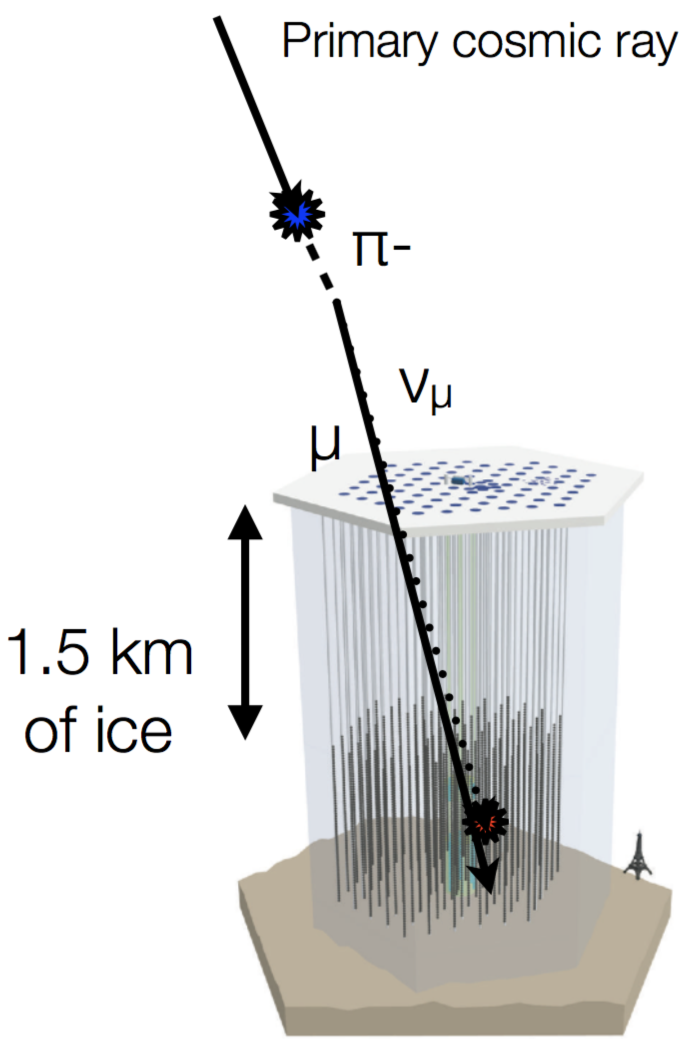
$$\times \boxed{\underbrace{\boxed{\mathcal{P}^{\text{sib}}_{0\text{-}\mu}(\theta_z | E_p, E_\nu)}}_{\text{Correlated, sibling muon}} \underbrace{\mathcal{P}^{\text{shower}}_{0\text{-}\mu}\left(N_\mu = 0; \boxed{\bar{N}_{\mu,A}(E_{\text{CR}} - E_p, \theta_z)}\right)}_{\text{Uncorrelated, proto. shower muons; Poisson}}},$$

Coupling via E_p

Coincident muons supress neutrino flux!

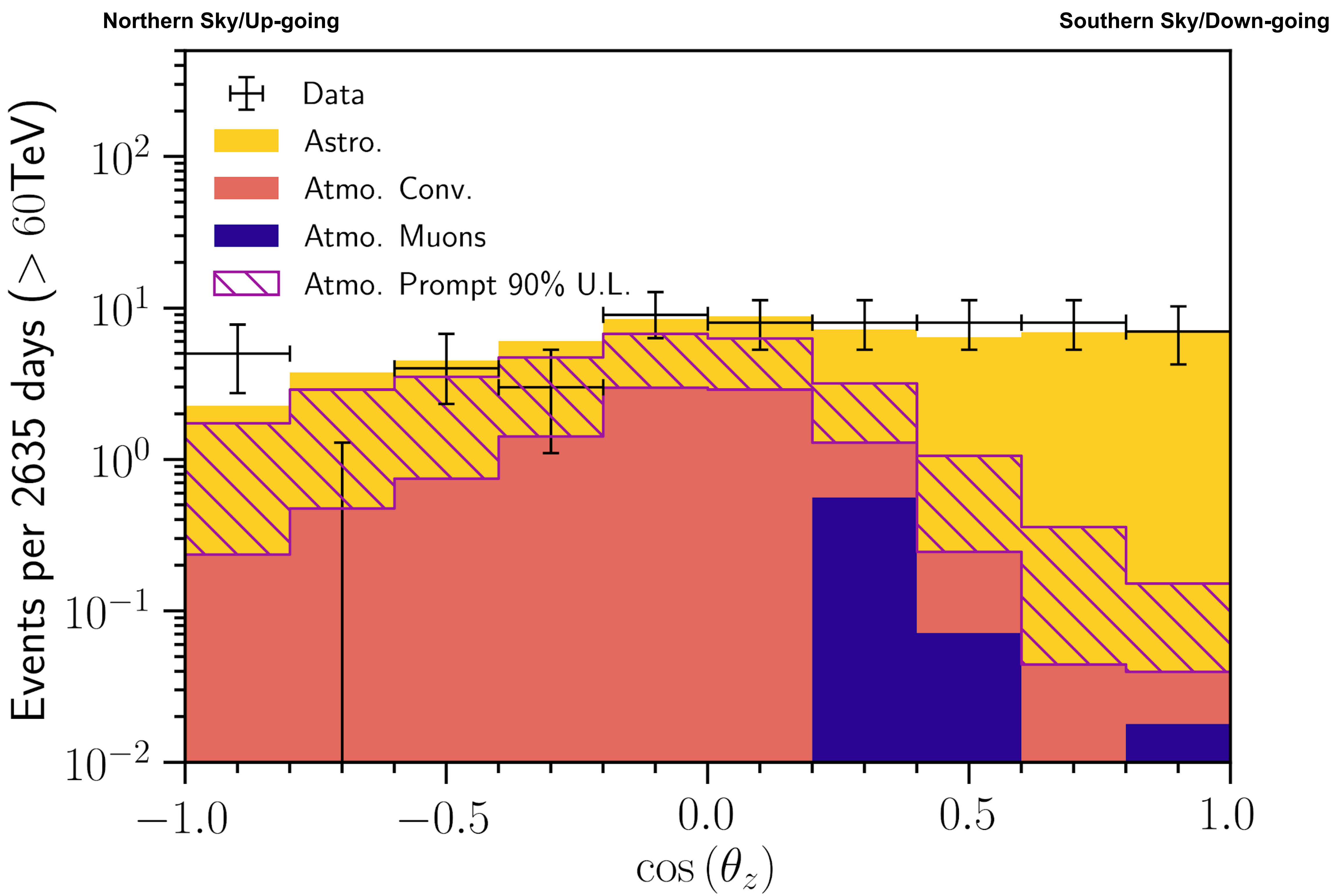


An active muon veto removes down-going atmospheric neutrinos.

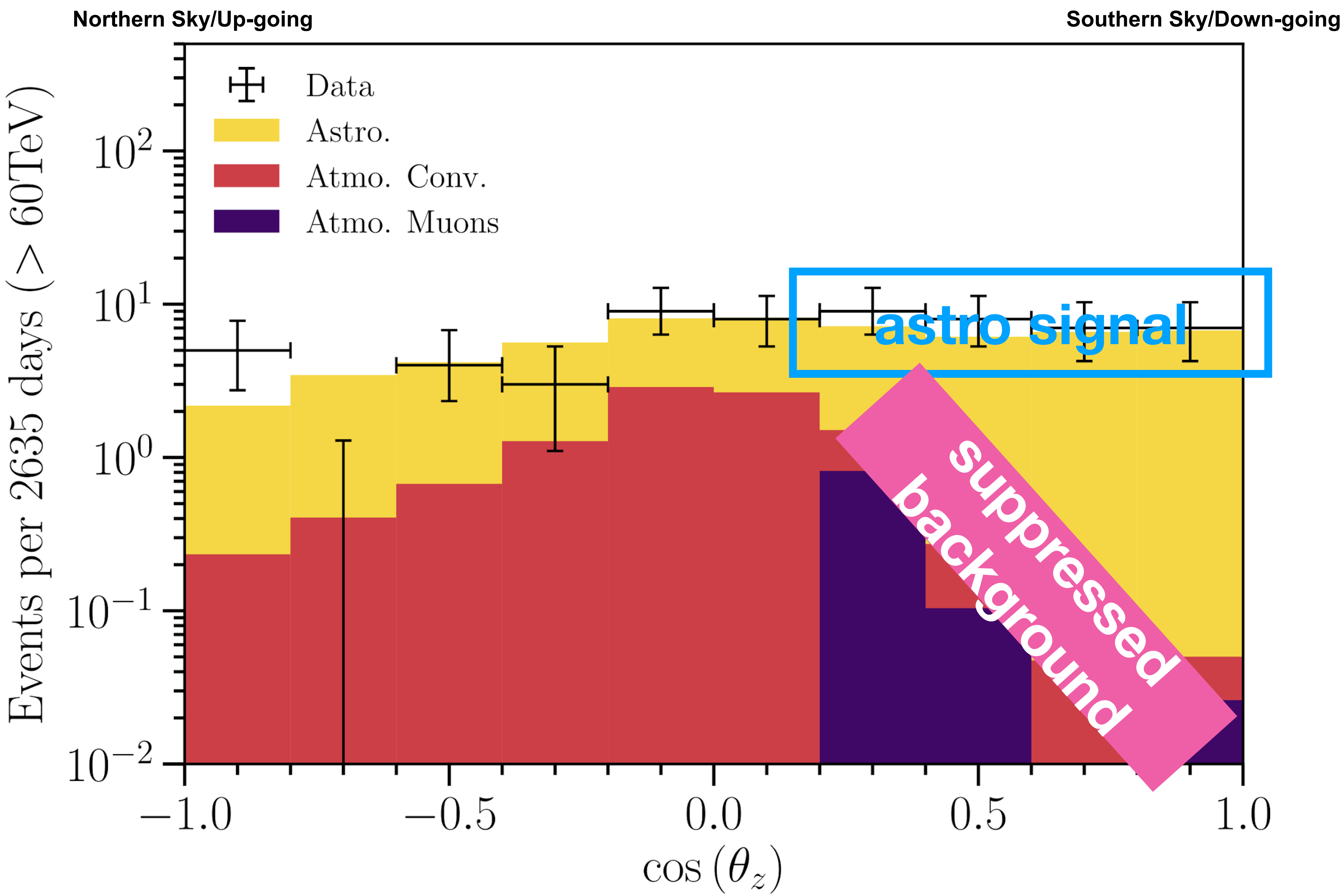


https://github.com/tianluyuan/nuVeto

HESE-7.5 years angular distribution

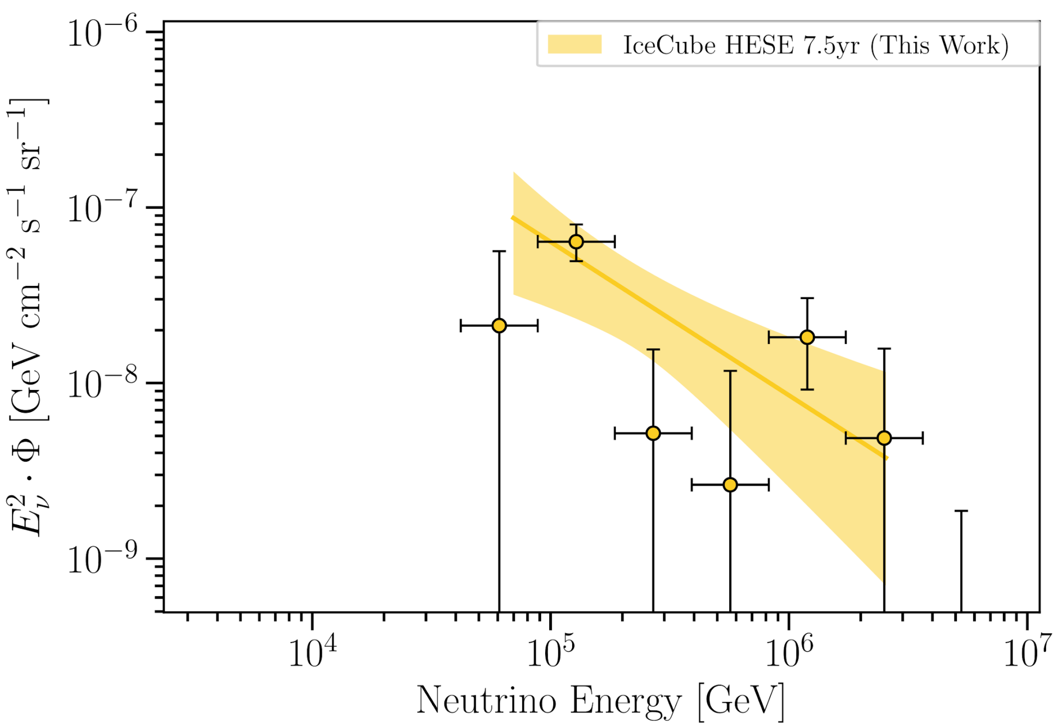


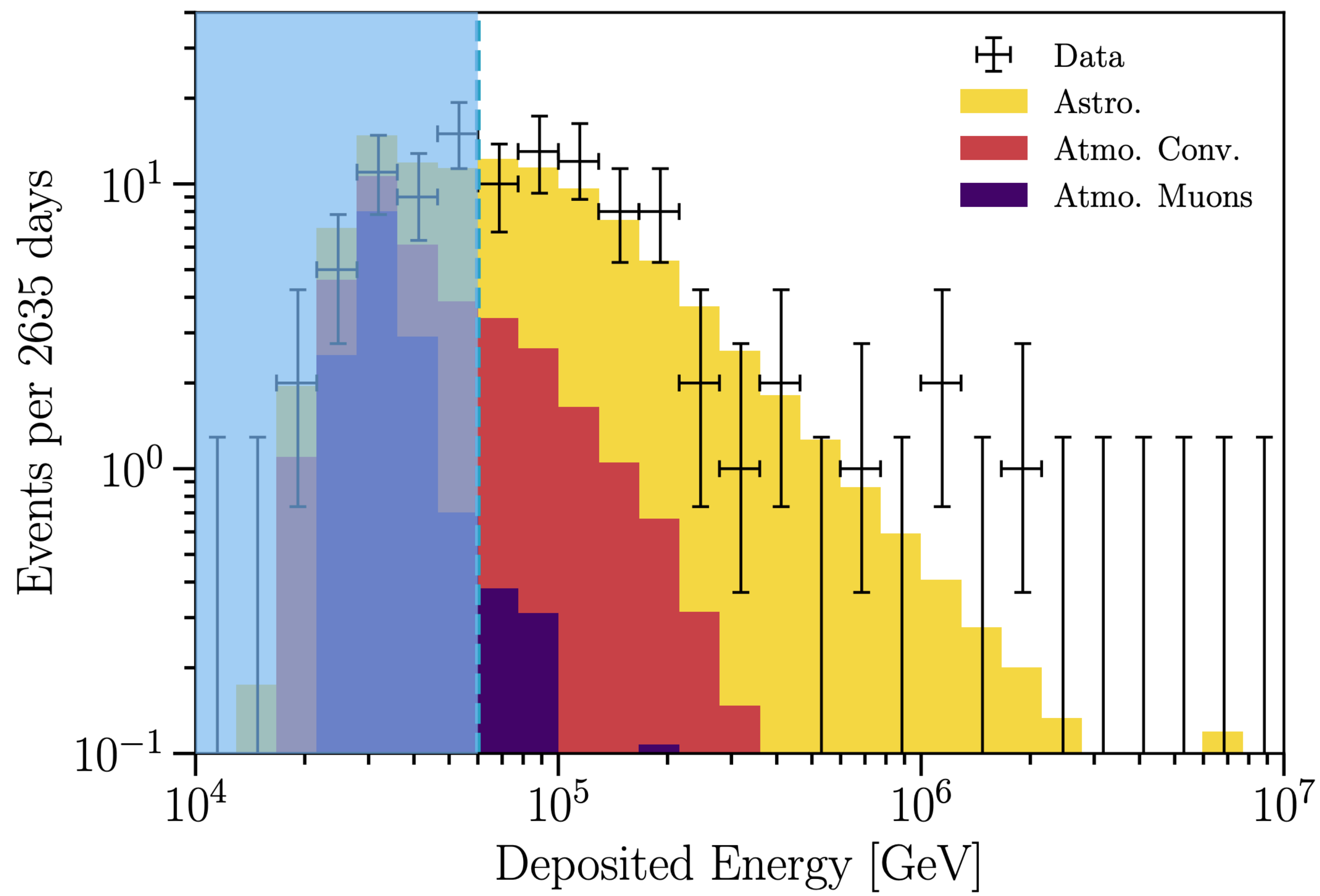
HESE-7.5 years angular distribution



Starting Events Energy Distribution And Inferred Spectrum

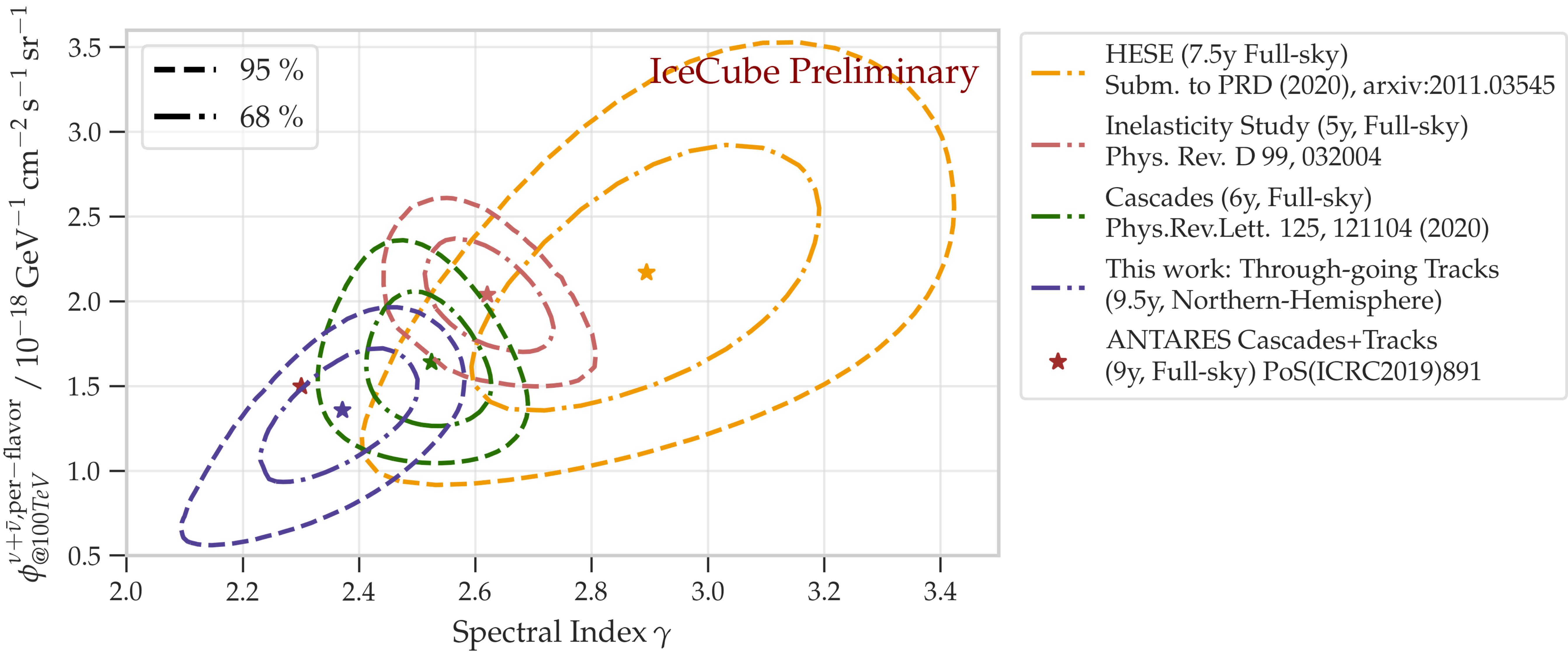
$\gamma = 2.9 \pm 0.2$





High-Energy Starting Events energy distribution is well described by a single power-law, but with a spectral index softer than the northern tracks!

Comparison of different single power-law spectra

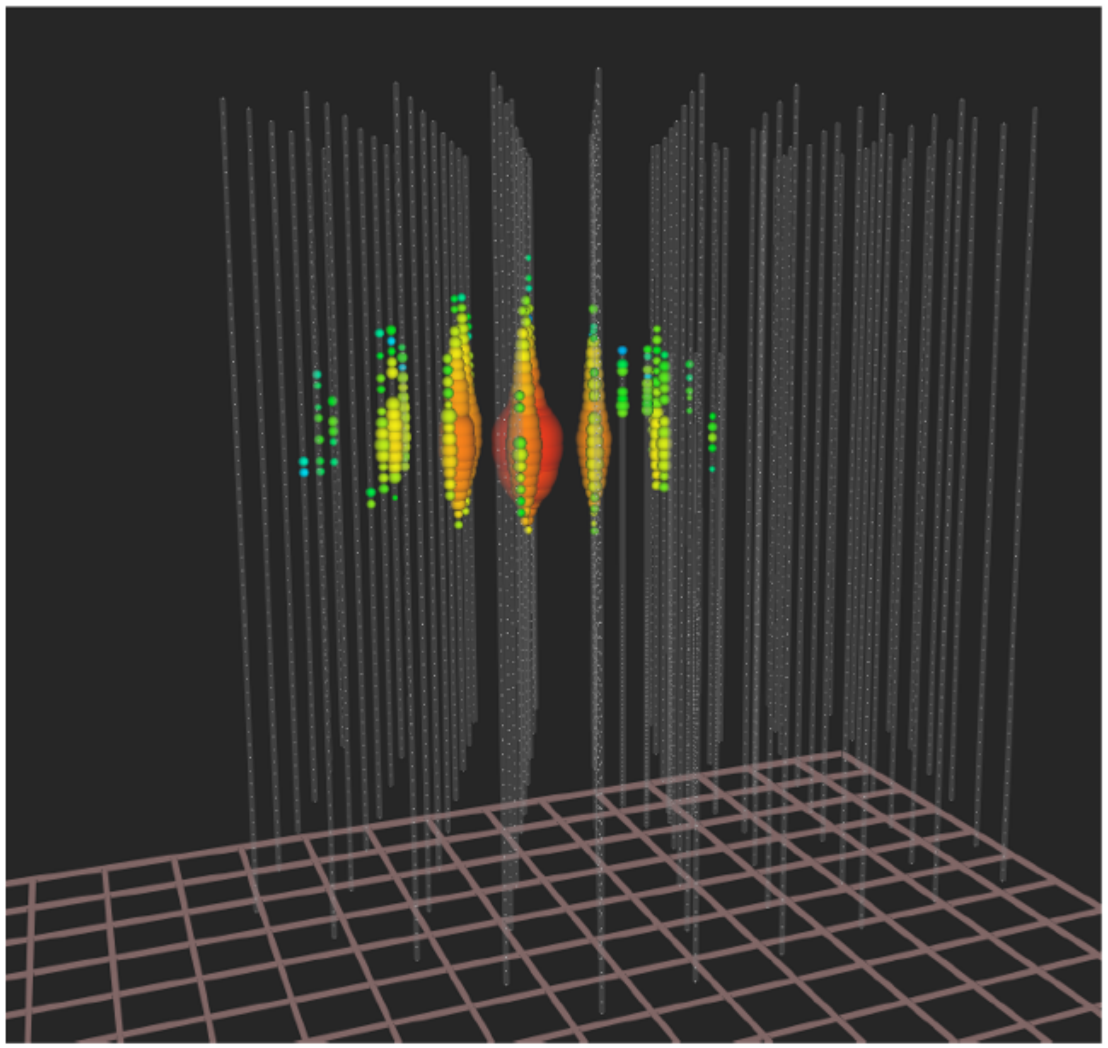


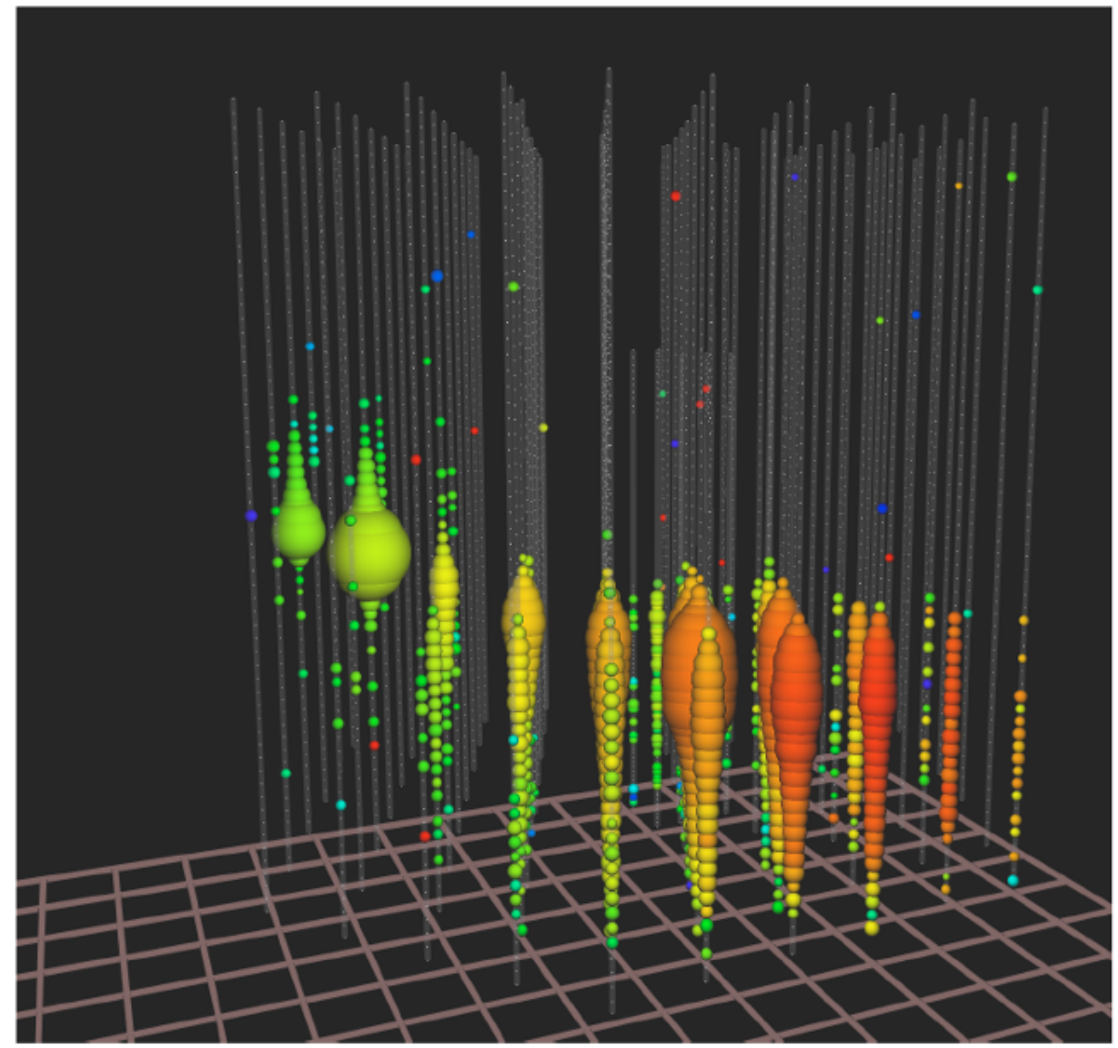
- ❖Shower power (hep-ph/0409046): Cascade-only event selections also produce very pure astrophysical neutrino samples!
- ❖Multiyear cascade analysis extends to TeV energies, yields a harder spectrum. Restricting this above 60 TeV, HESE spectrum is recovered.
- ❖First hints of a diffuse component in the ANTARES data!

Summary: complementary search strategies

Neutrinos interacting inside the detector

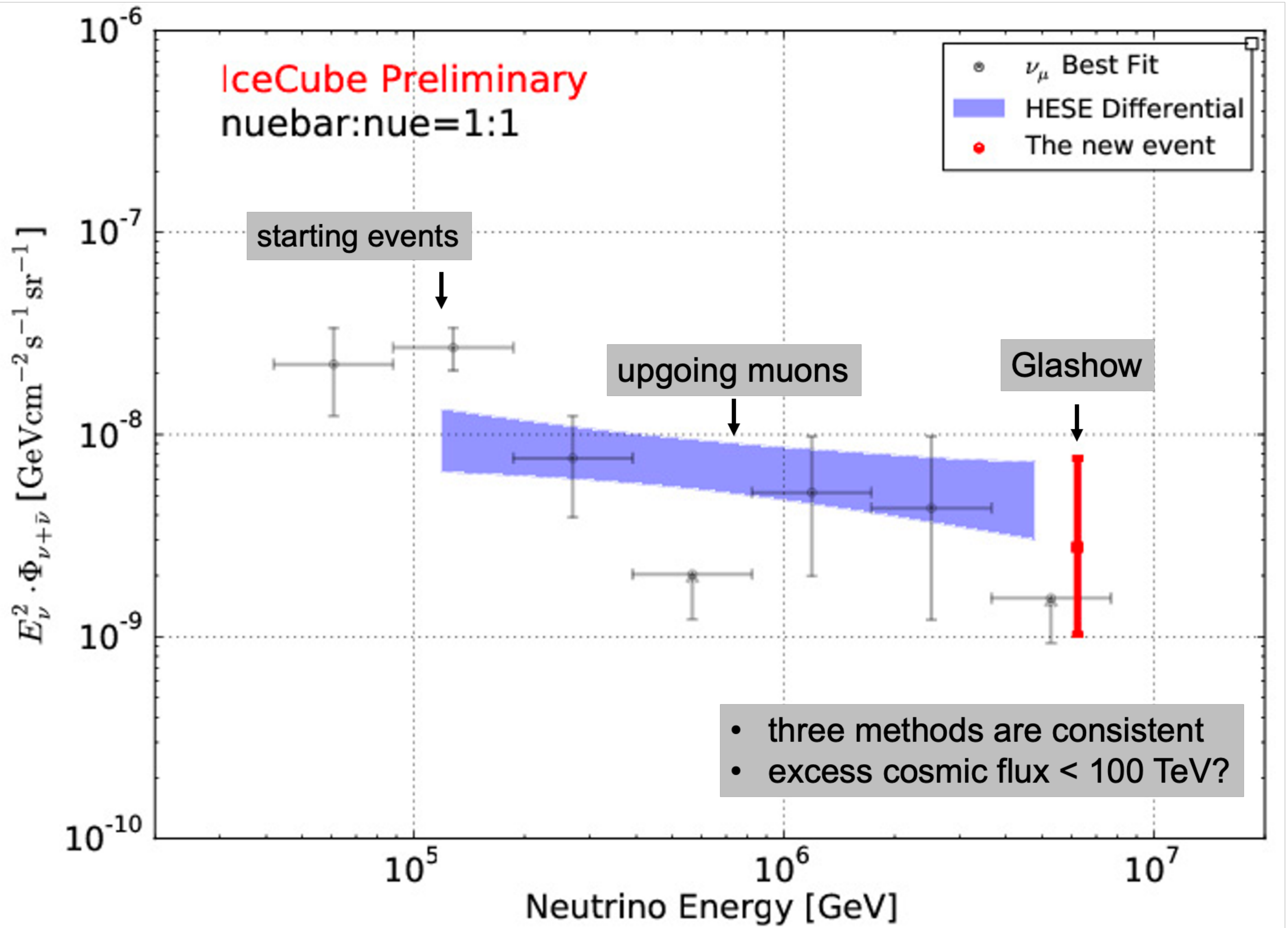
Muon neutrinos filtered by Earth



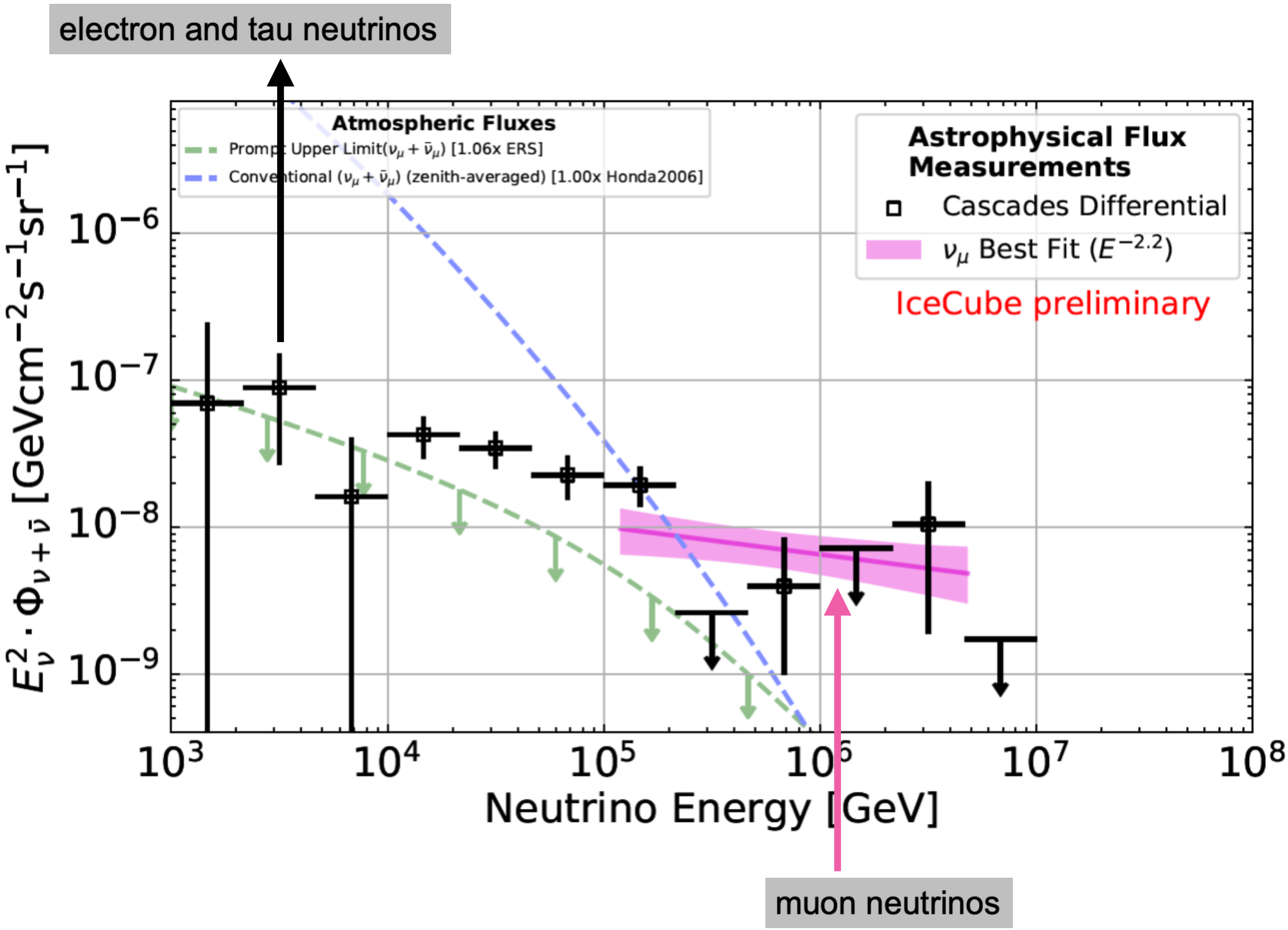


Total energy measurement all flavors, all sky

Astronomy: angular resolution superior (<0.4 degrees)

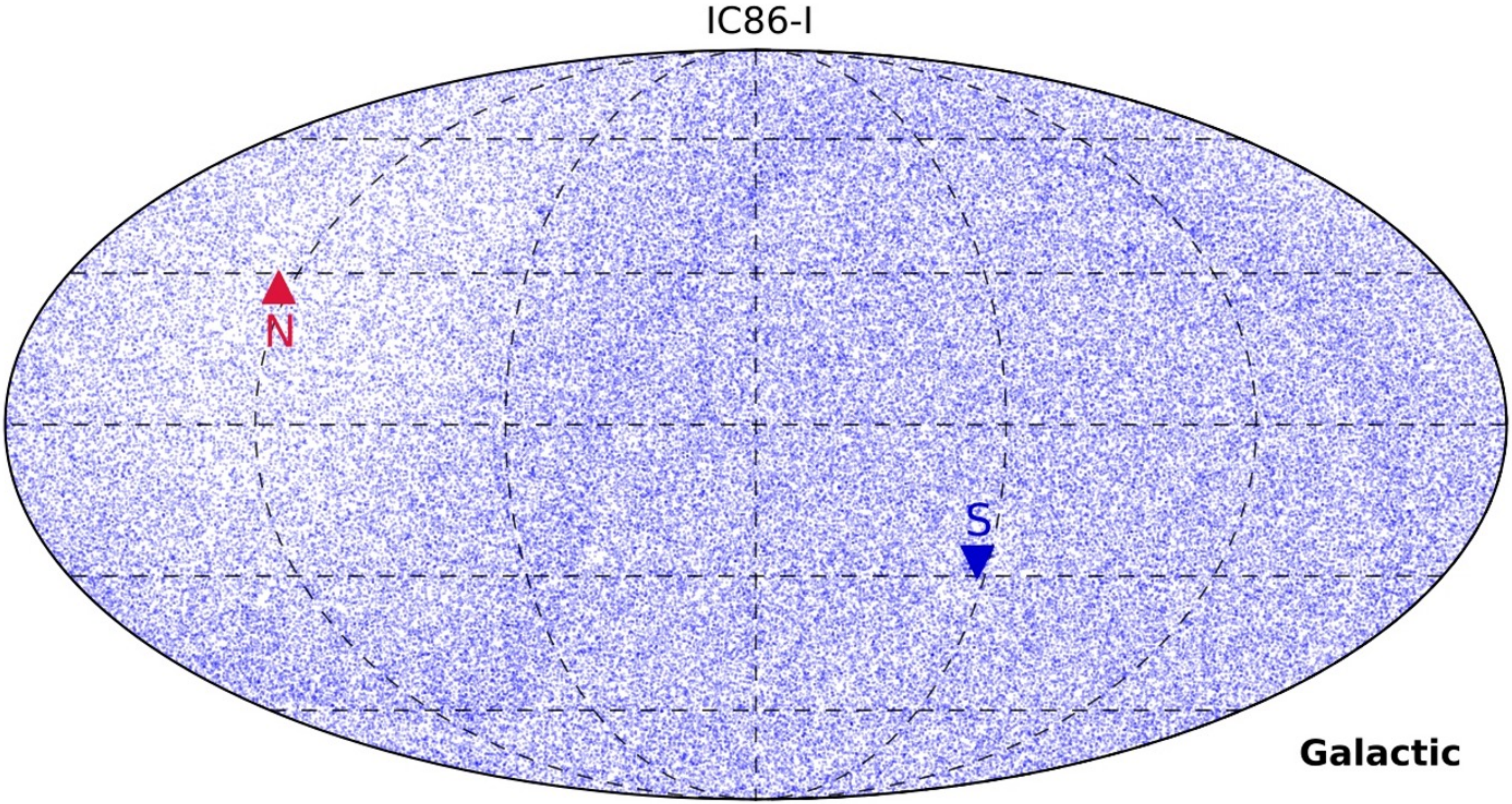


IceCube Preliminary
nuebar:nue=1:1
ν_μ Best Fit
HESE Differential
The new event
starting events
upgoing muons
Glashow
• three methods are consistent
• excess cosmic flux < 100 TeV?
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^5
10^6
10^7



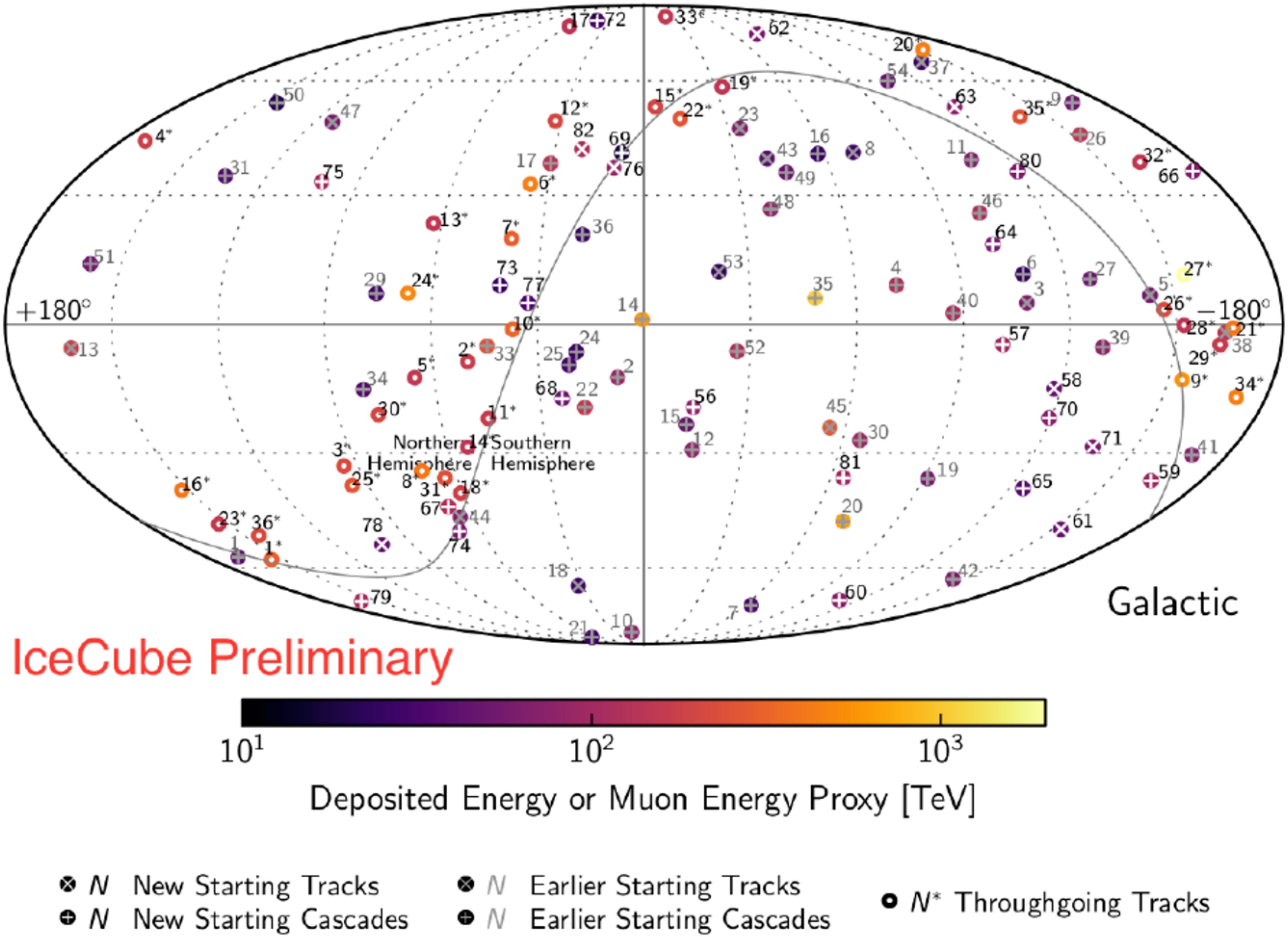
electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]
muon neutrinos

Search for Neutrino Sources



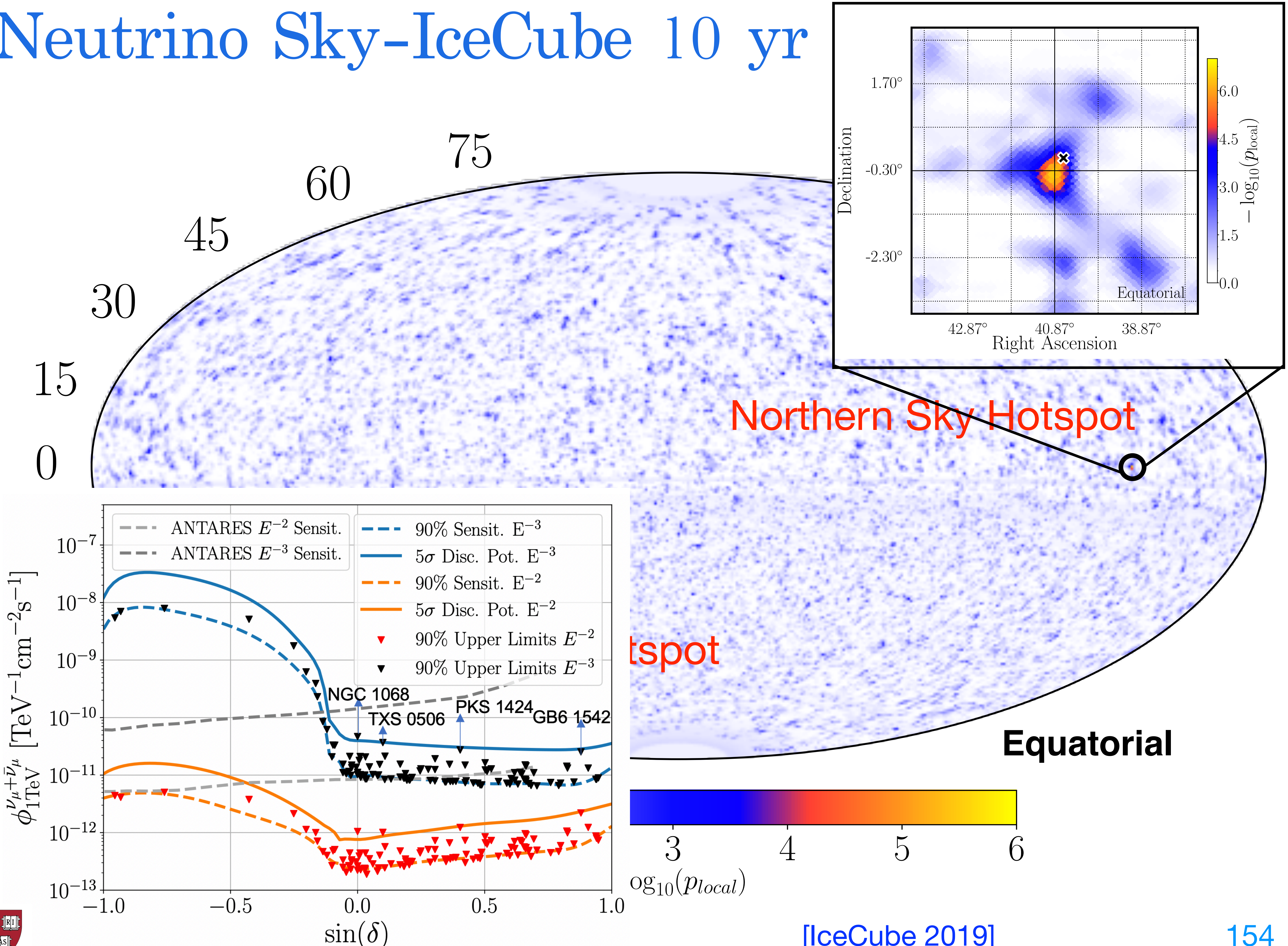
138322 neutrino candidates in one year

120 cosmic neutrinos
~12 separated from atmospheric background with E>60 TeV
structure in the map results from neutrino absorption by the Earth



+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

Neutrino Sky-IceCube 10 yr

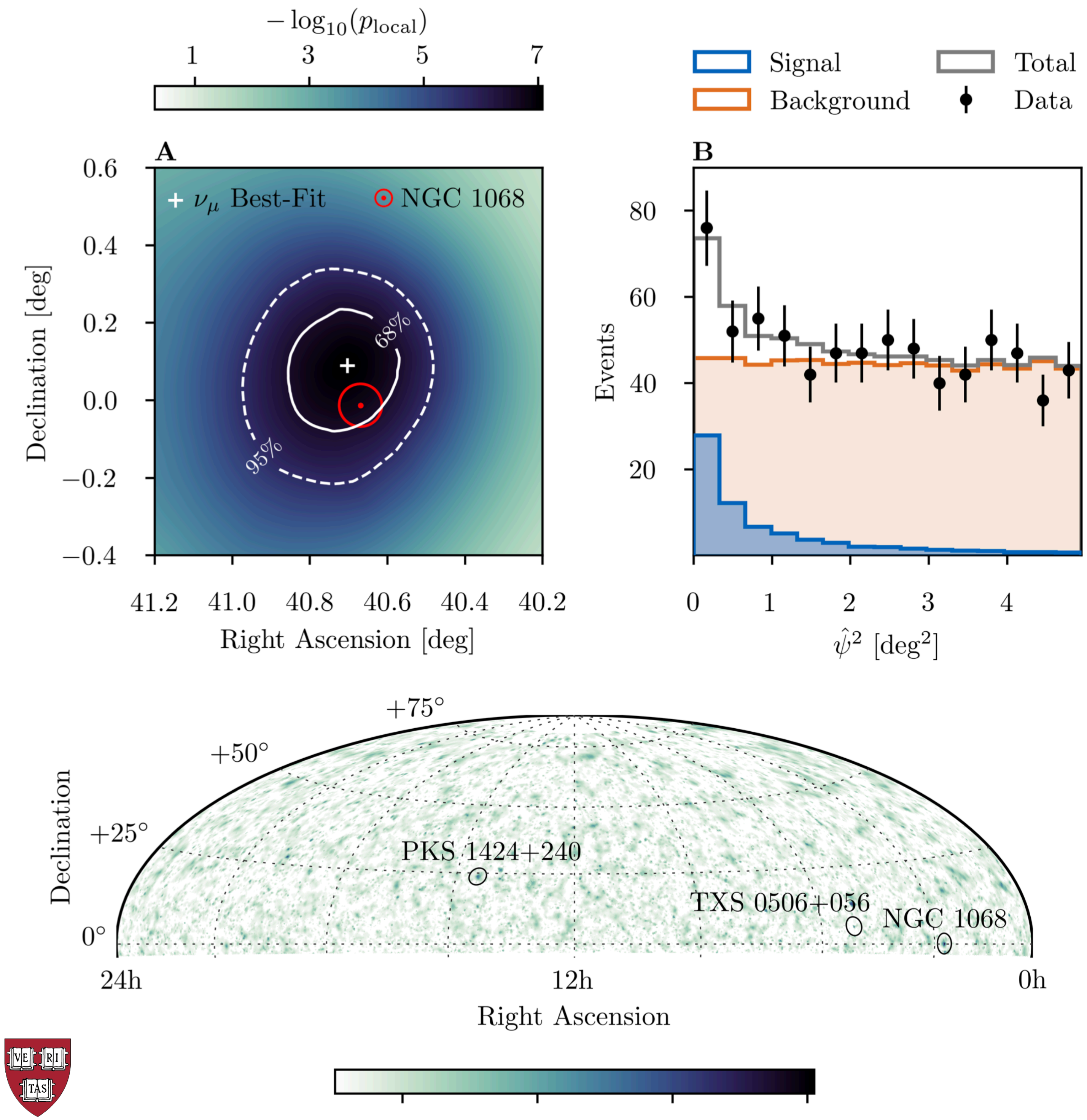


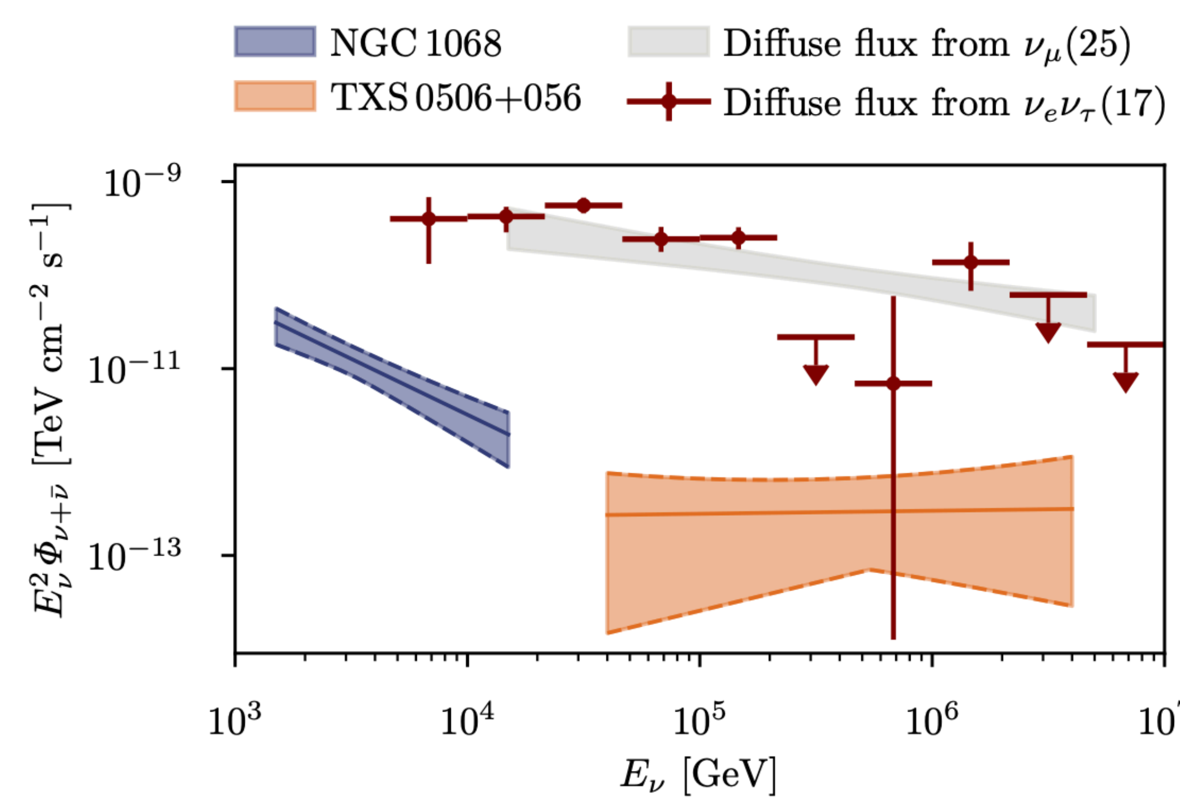
[IceCube 2019]

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

Recent News! NGC1068 is a high-energy neutrino source



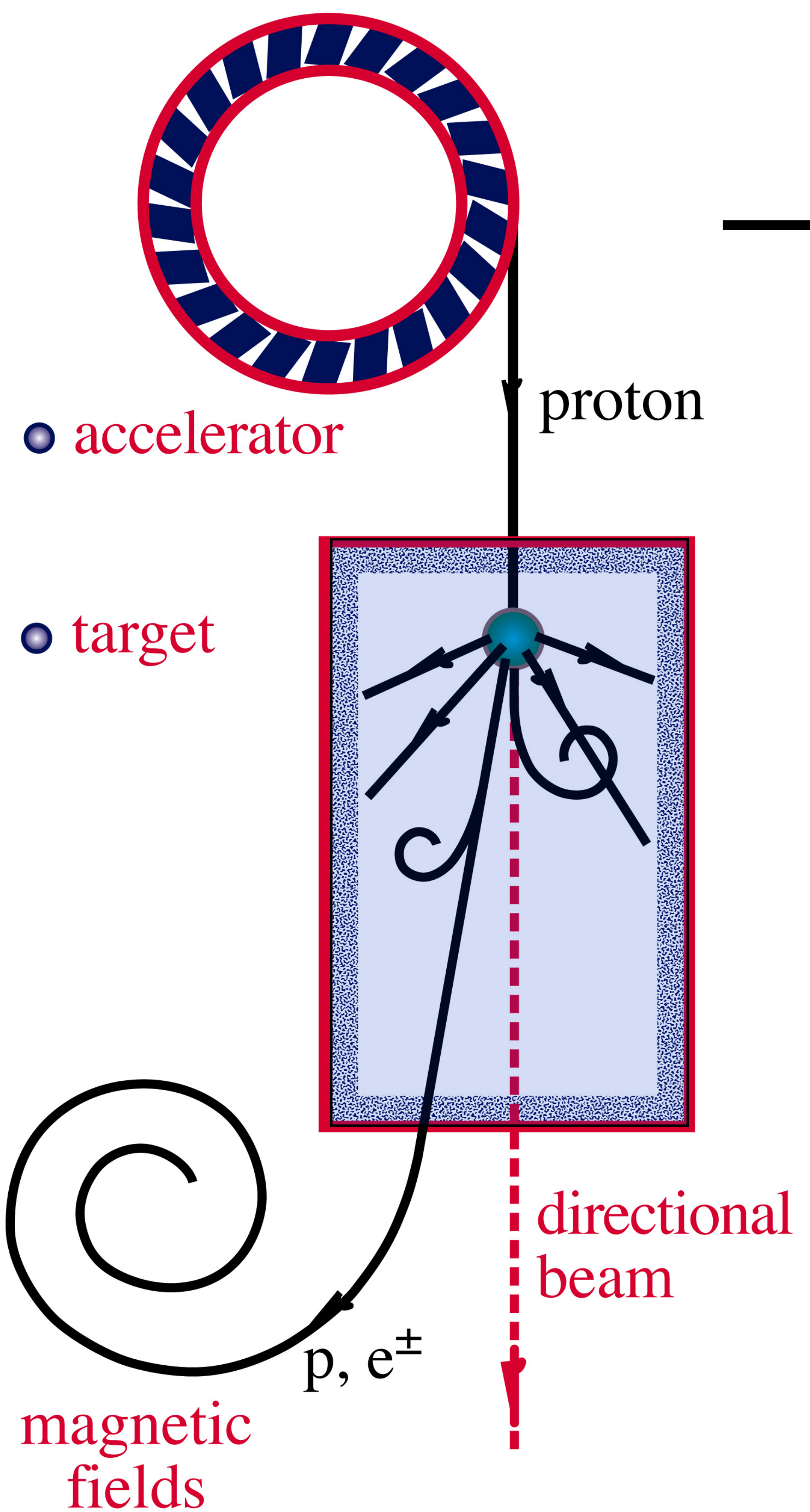


- we observe a diffuse flux of neutrinos from extragalactic sources

- a subdominant Galactic component cannot be excluded

- where are the PeV gamma rays that accompany PeV neutrinos?

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

$$p + \gamma \rightarrow n + \pi^{+}$$

~ cosmic ray + neutrino

$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma

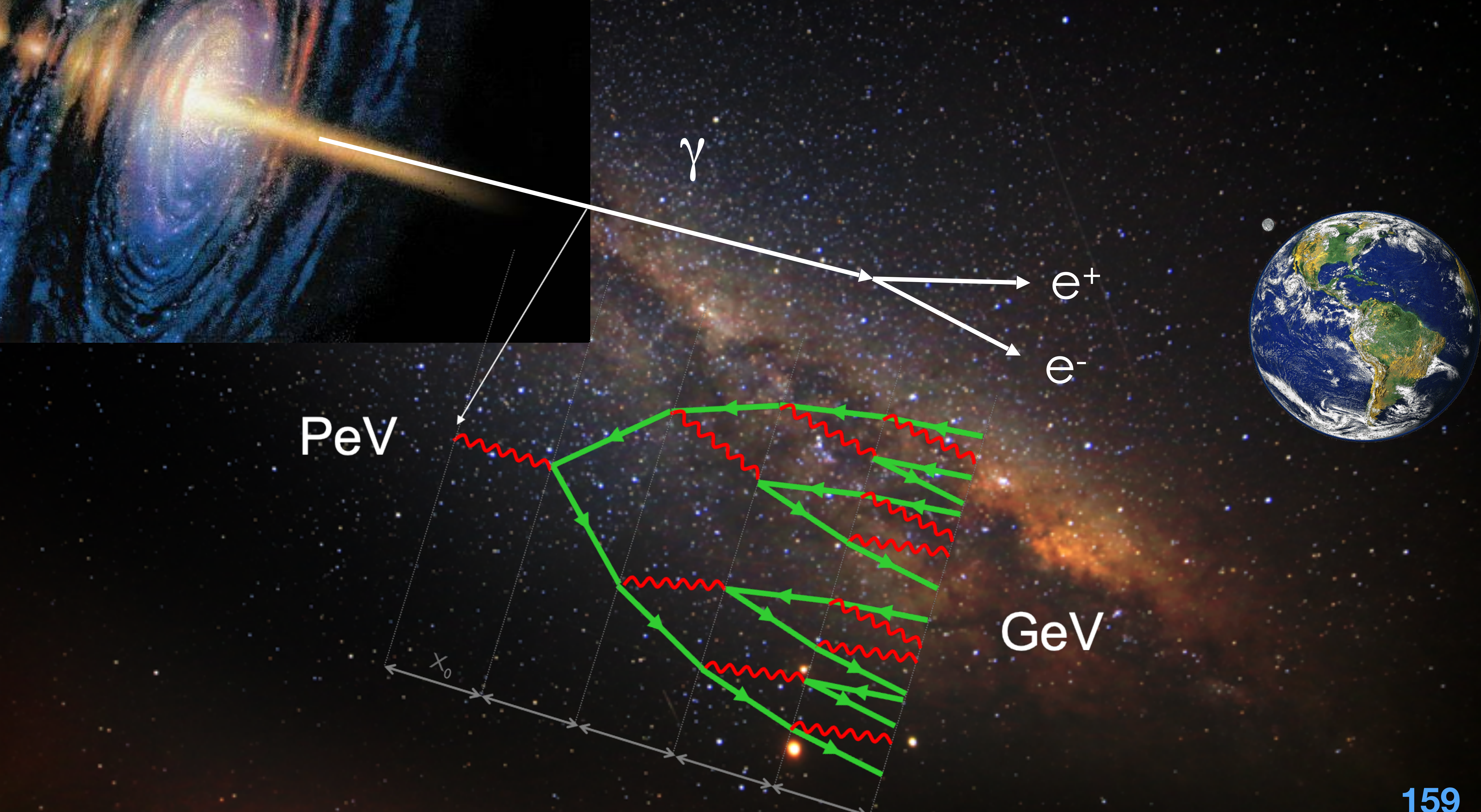
The opaque Universe

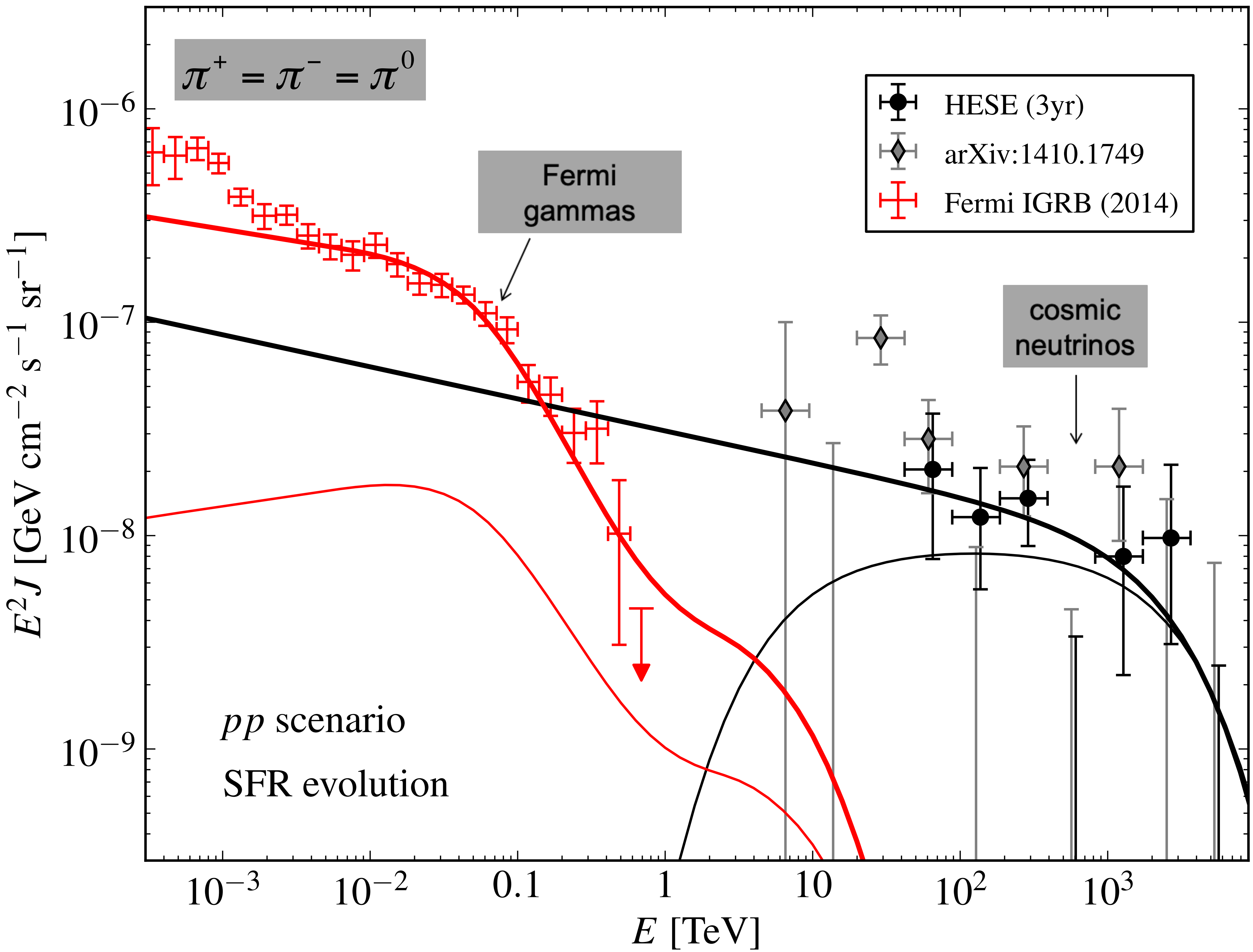
$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

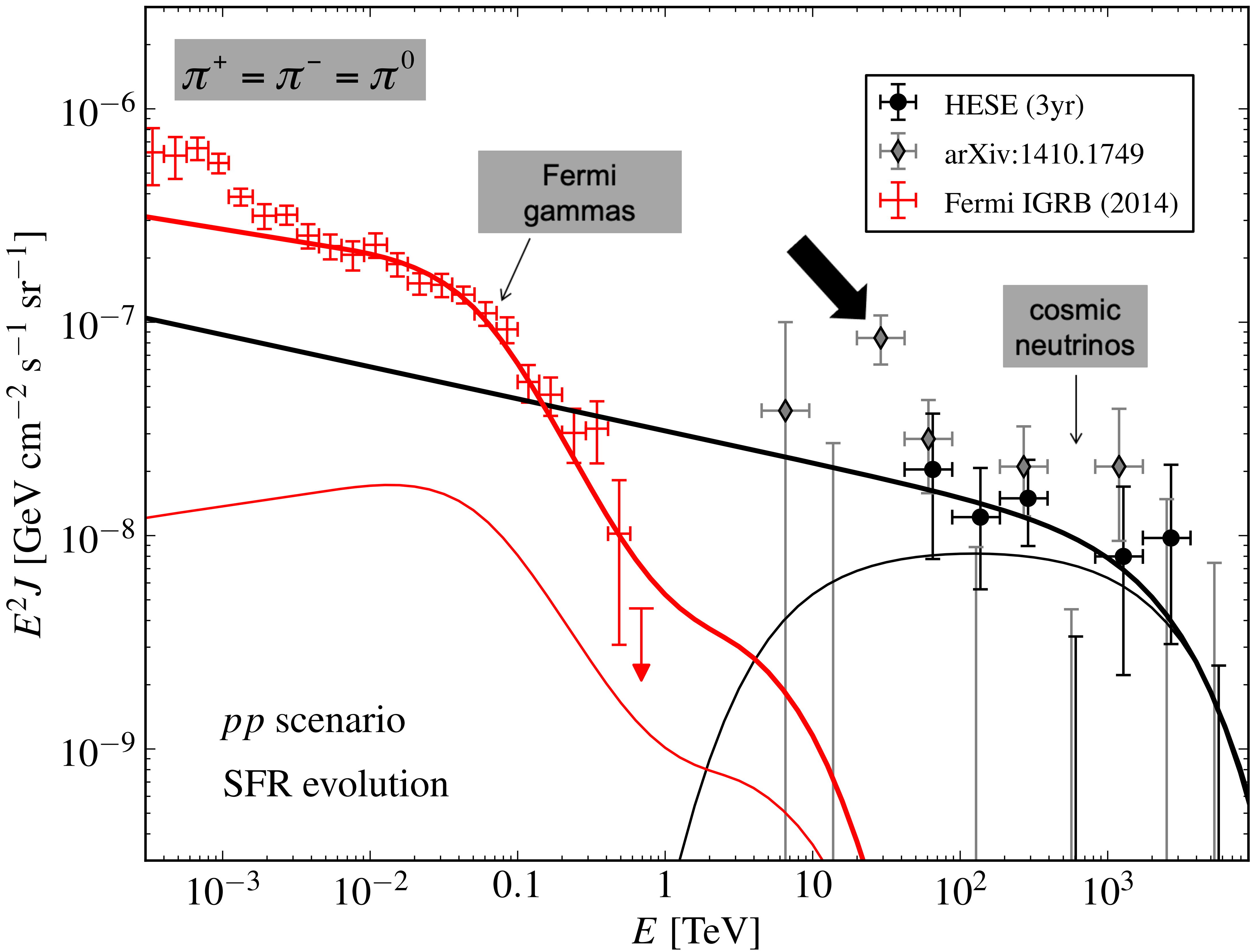
The opaque Universe

$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

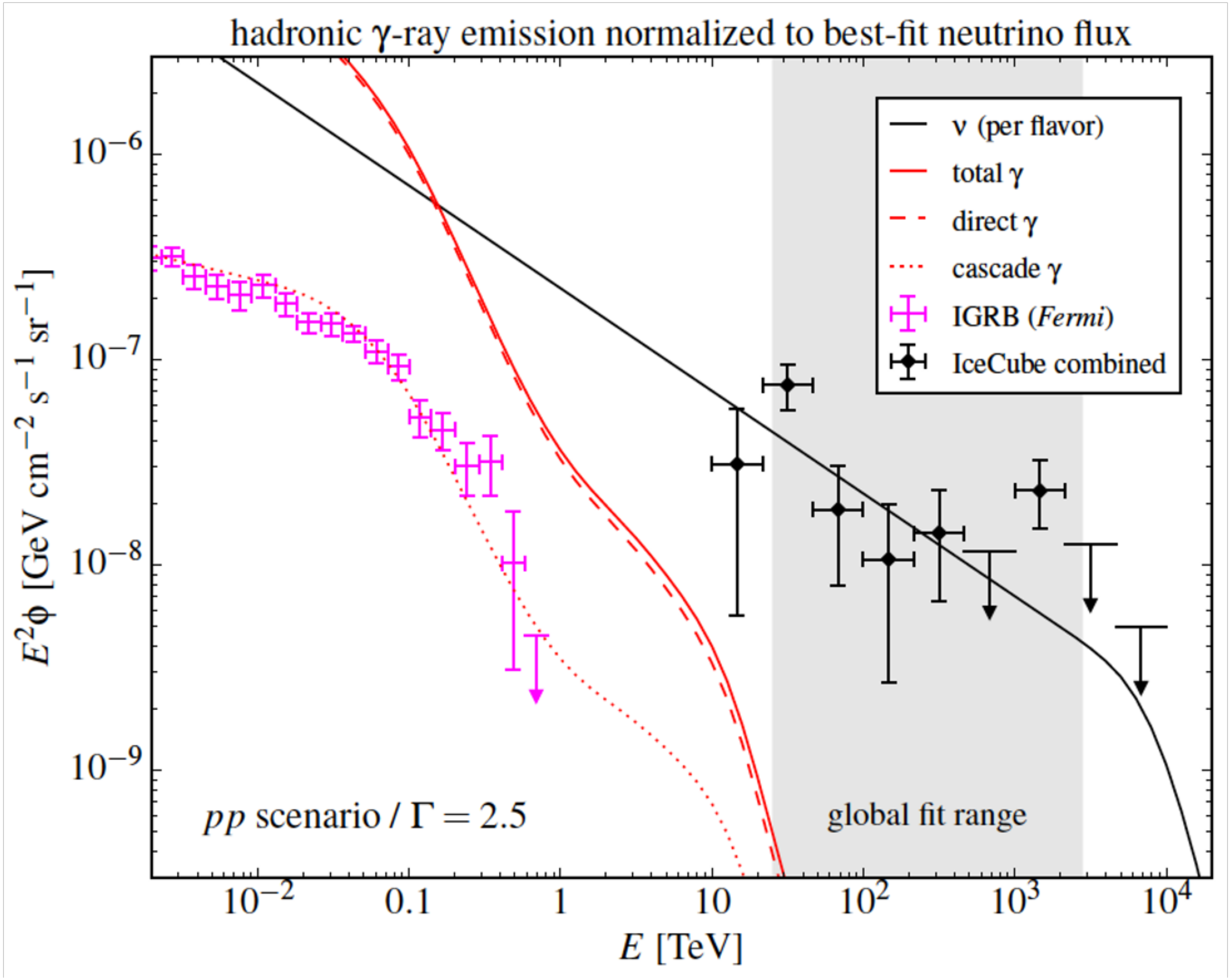




$\pi^+ = \pi^- = \pi^0$
Fermi gammas
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
cosmic neutrinos
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

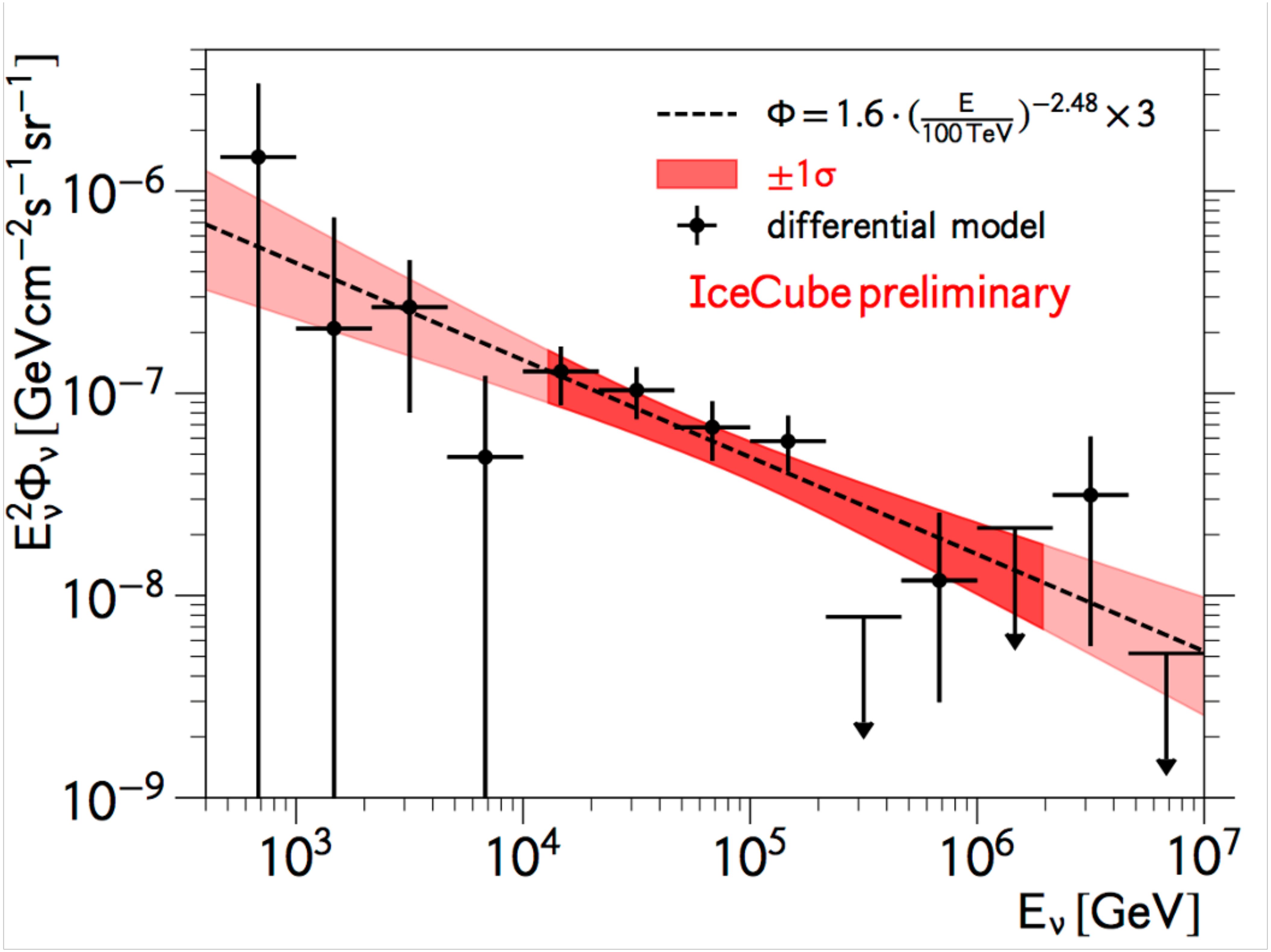


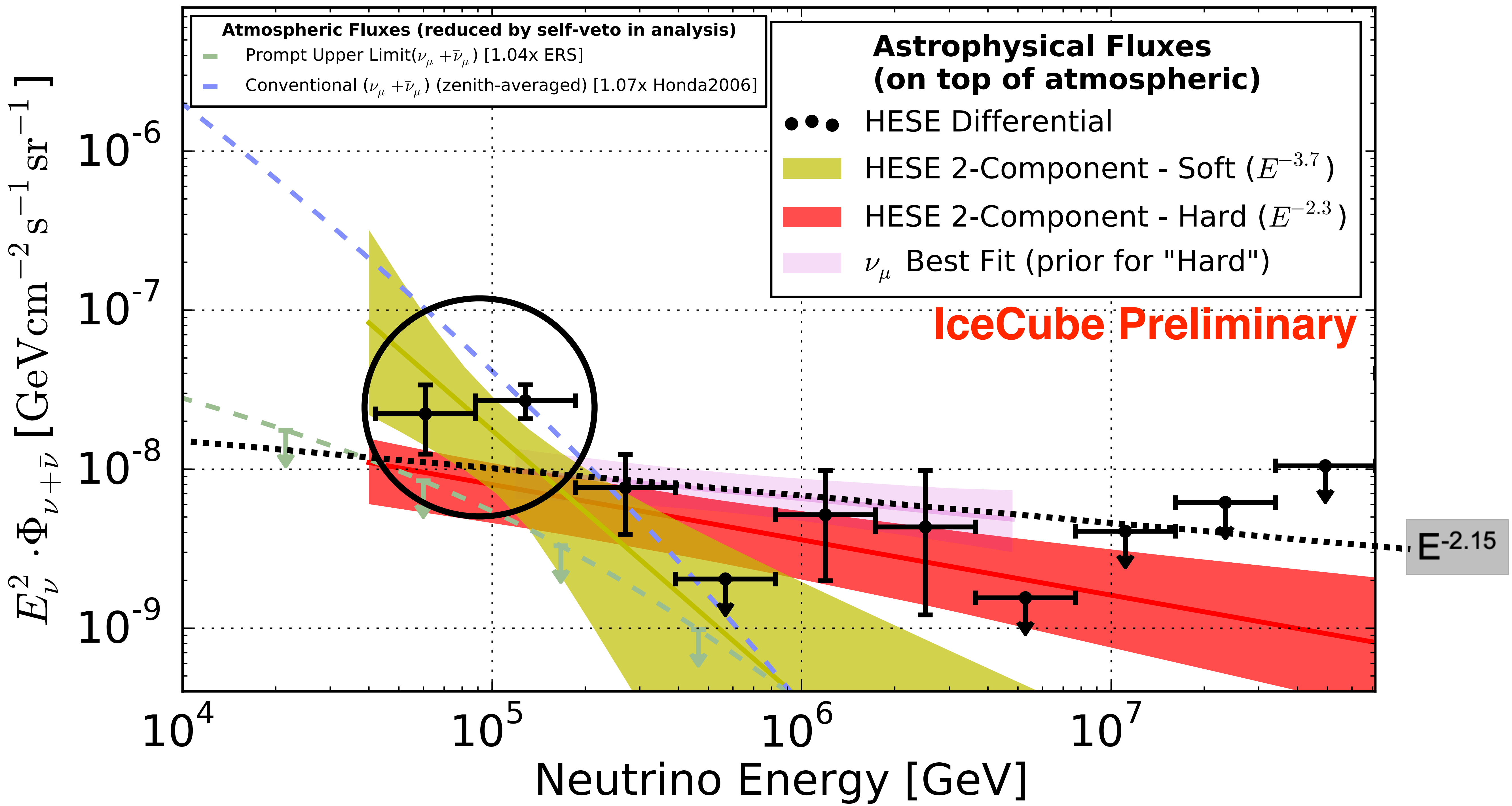
$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3



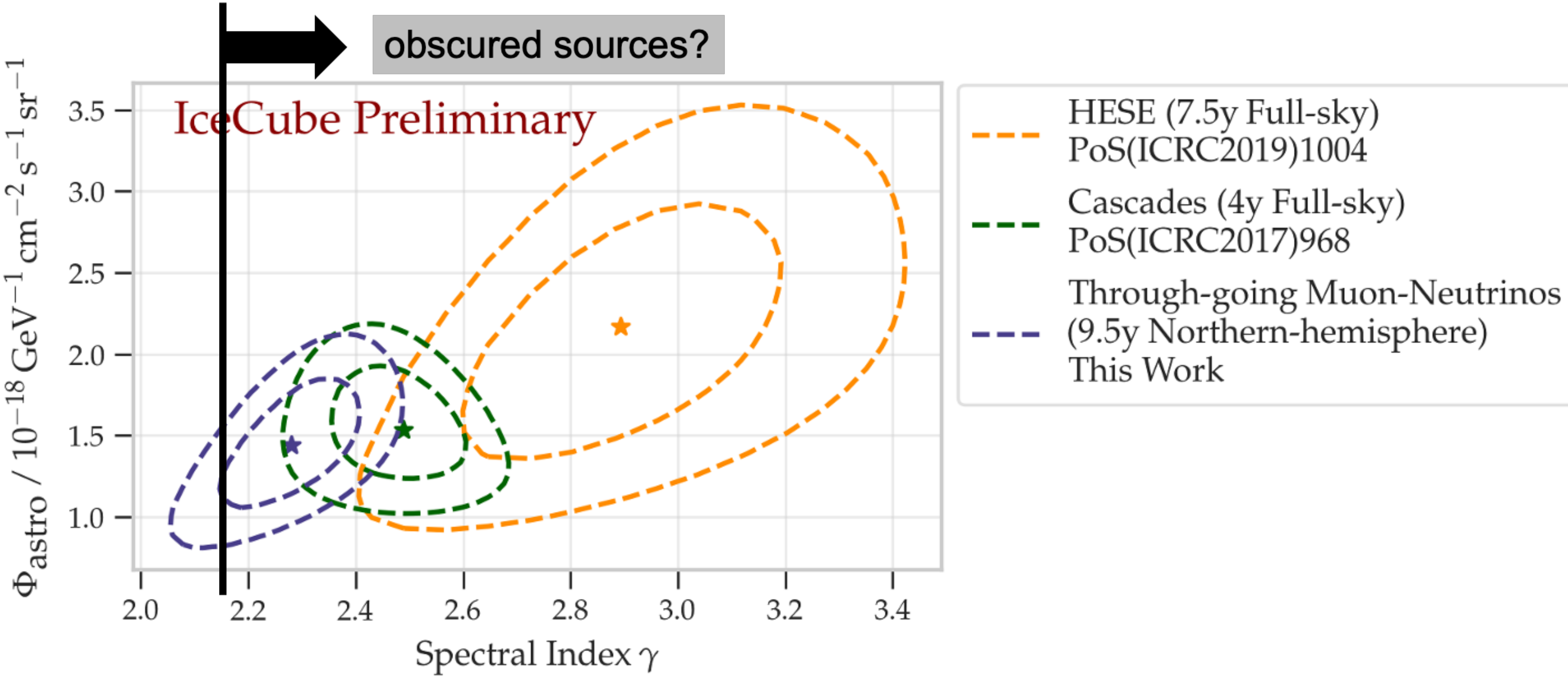
dark sources below 100 TeV not seen in γ's ?
gamma rays cascade in the source to lower energy

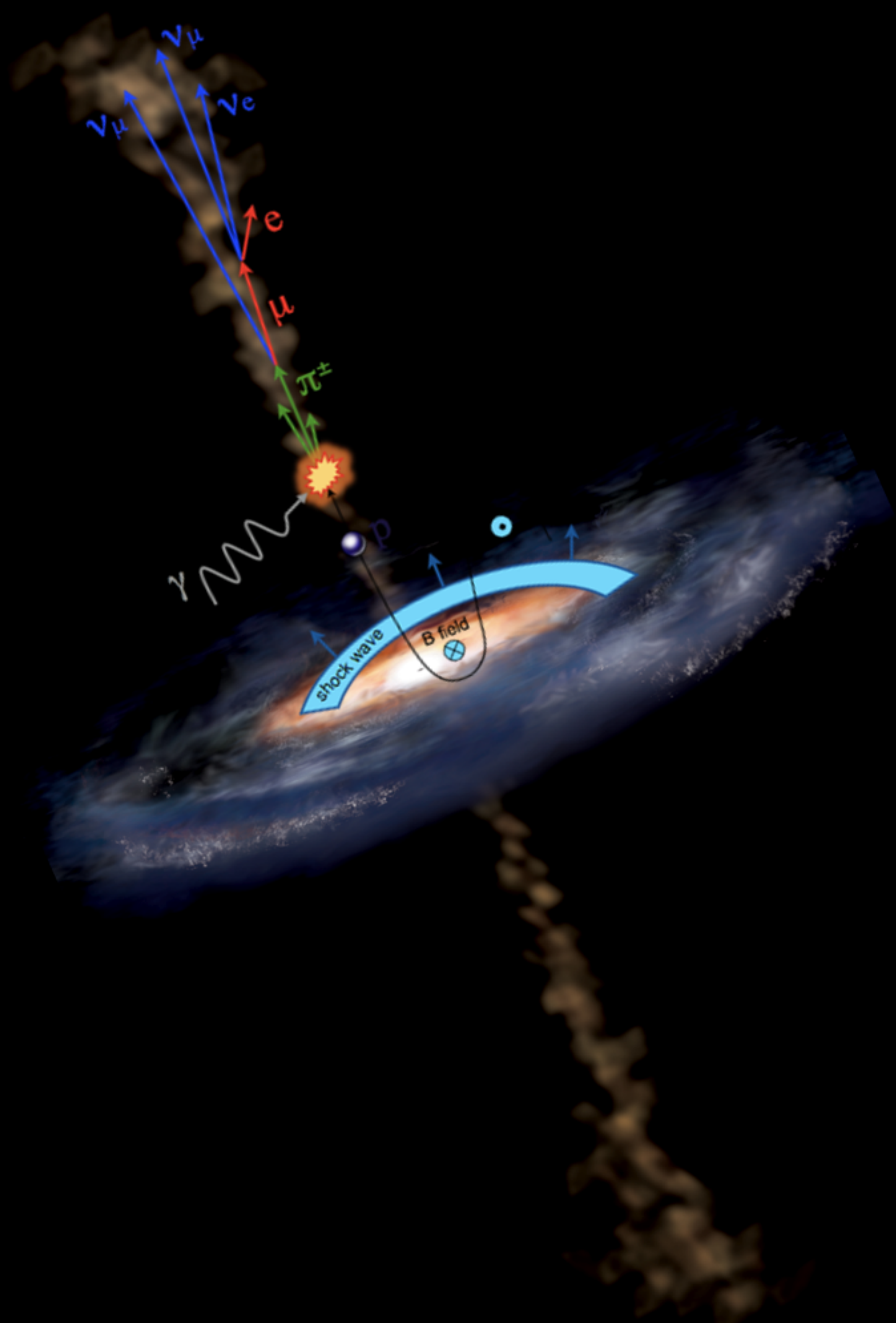
Multi-year cascade ($\nu_e+\nu_\tau$) analysis: dark sources ?





excess gamma rays relative to Fermi flux? Obscured sources?


obscured sources?
IceCube Preliminary
HESE (7.5y Full-sky) PoS(ICRC2019)1004
Cascades (4y Full-sky) PoS(ICRC2017)968
Through-going Muon-Neutrinos (9.5y Northern-hemisphere) This Work
Φ_{astro} / 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
Spectral Index γ
3.5
3.0
2.5
2.0
1.5
1.0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4

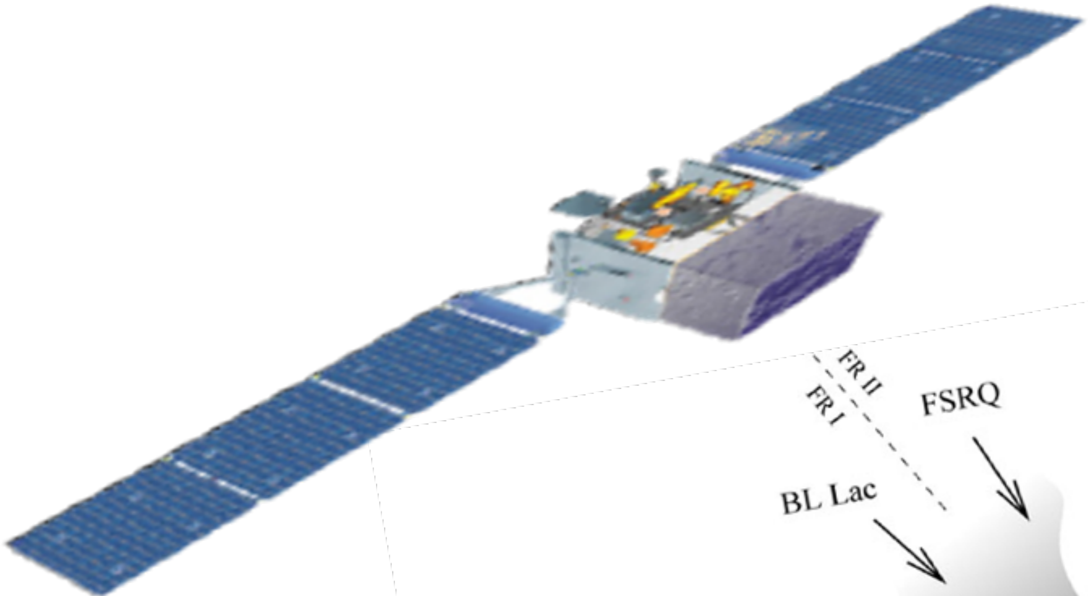


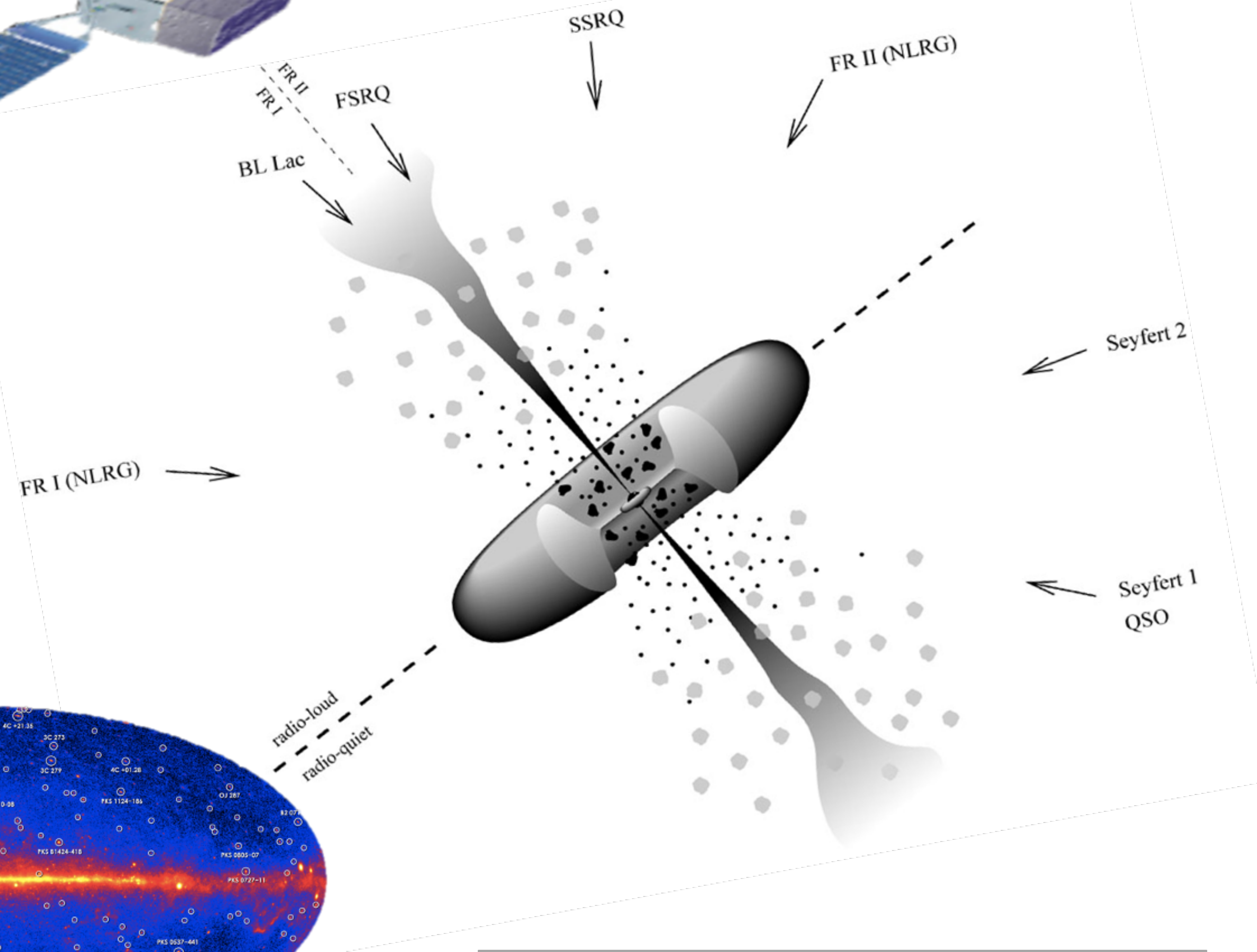
Fermi sources
are mostly
blazars

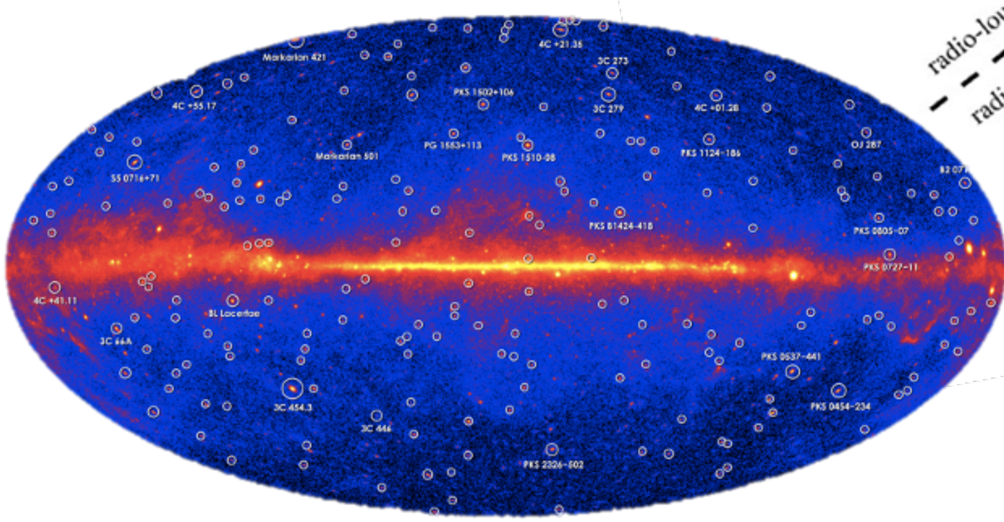
common sources?

→

multimessenger
astronomy

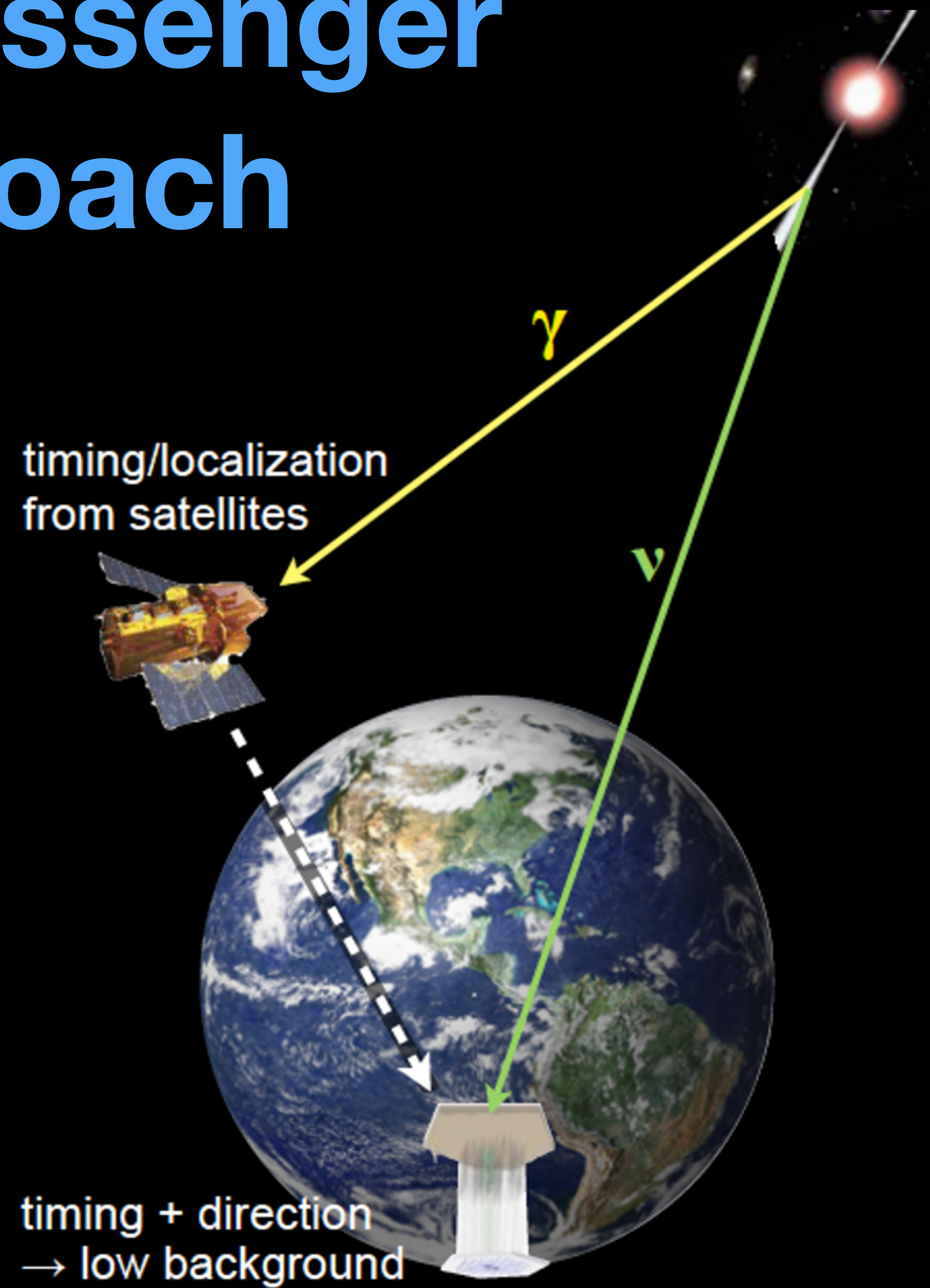






Fermi sky: mostly blazars

Multimessenger approach



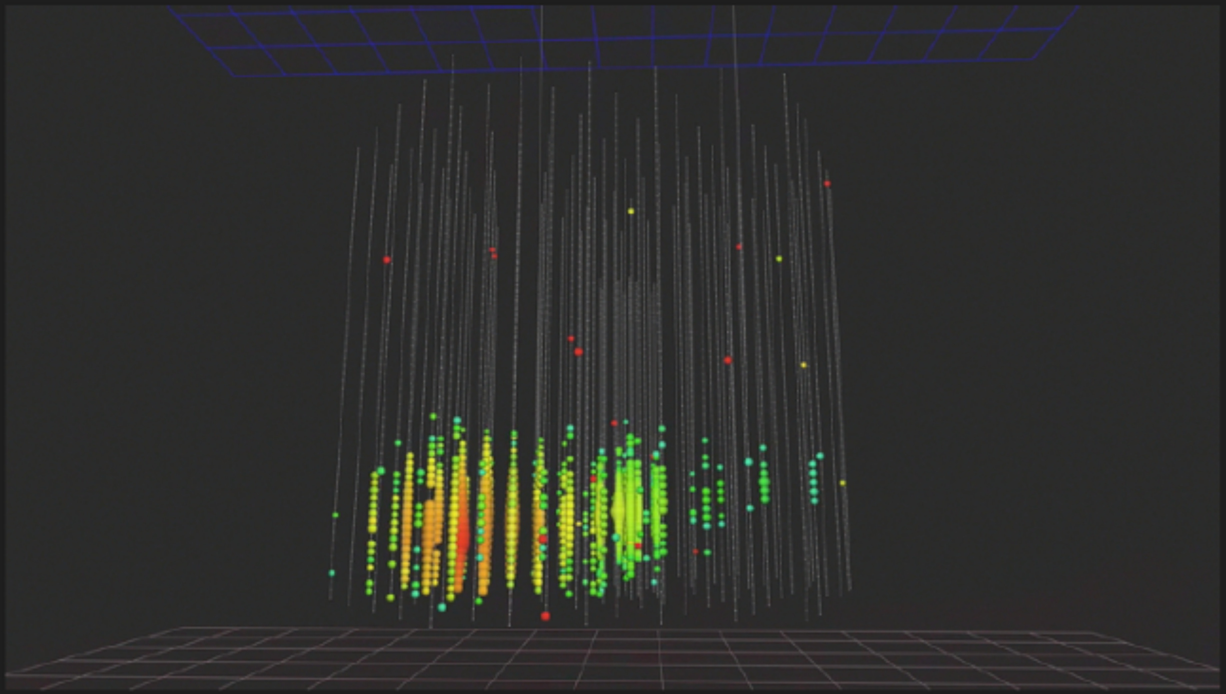
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

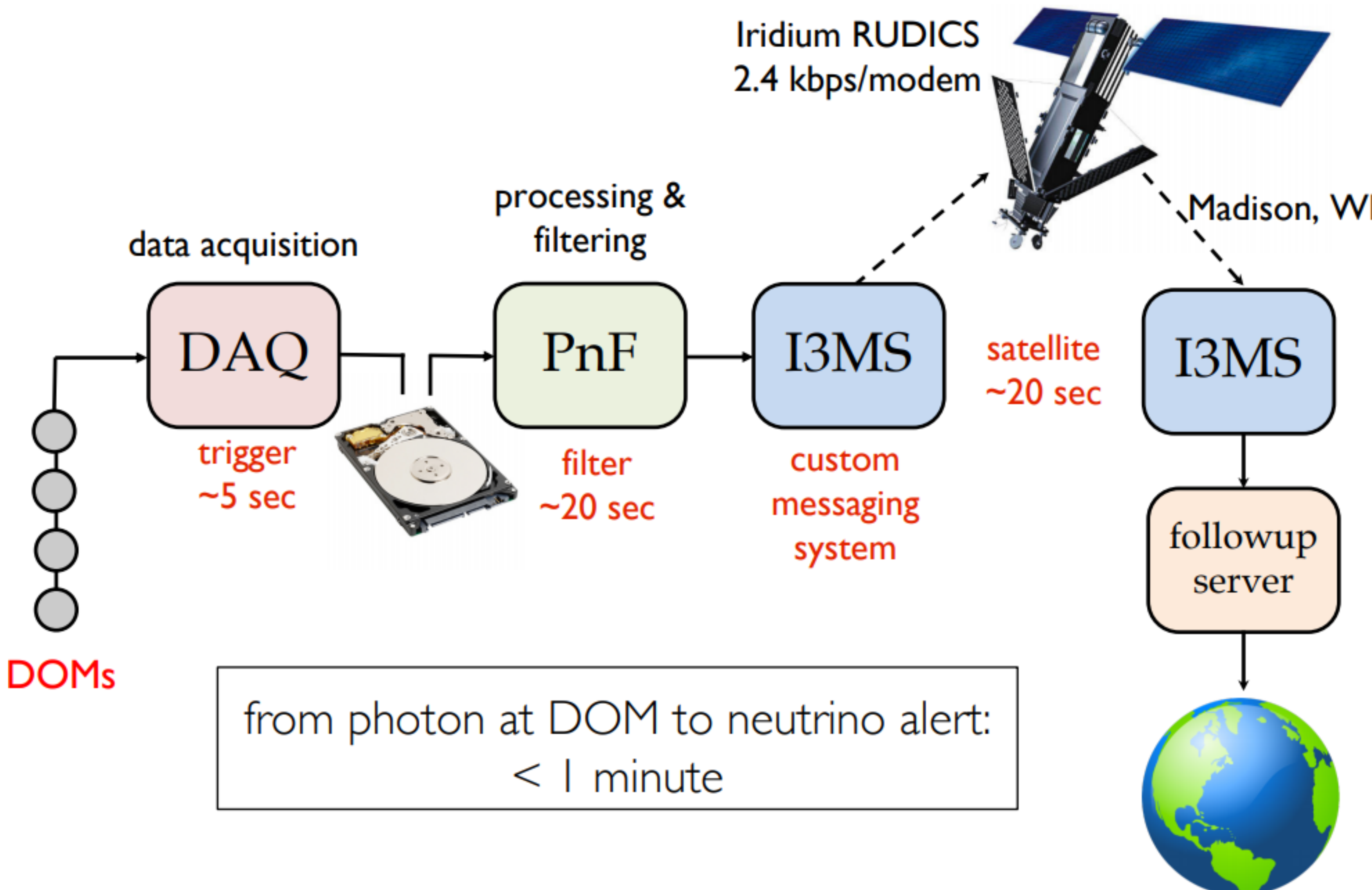

```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                  +9.2972d {+09d 17' 50"} (current),
                  +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;    118 DOY;    16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
```

GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them.**



Real time system up and running!

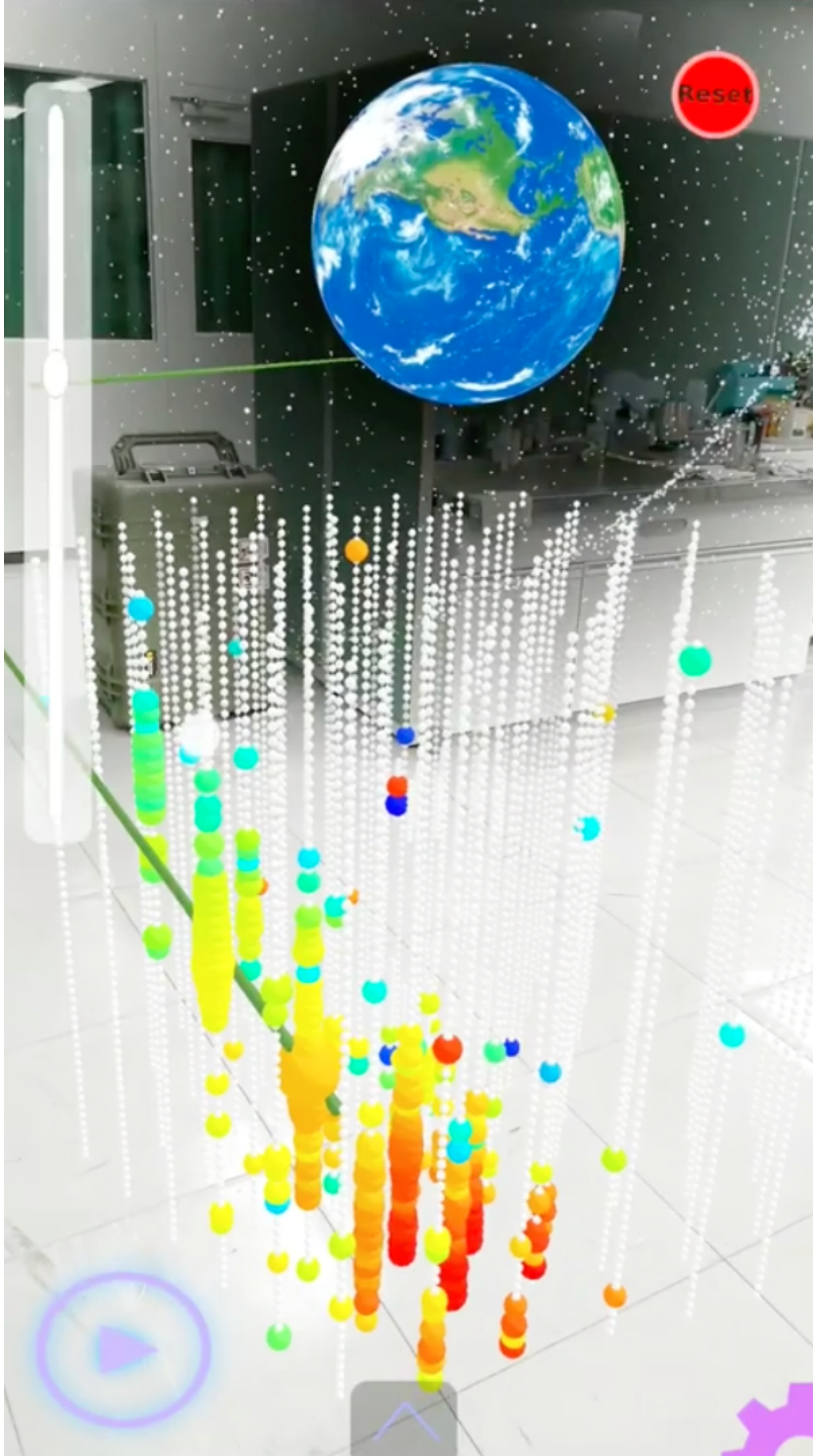


from photon at DOM to neutrino alert:
< 1 minute

Try the IceCube Augmented reality app to see our alert events!

Search for:

IceCubeAR



IceCube Trigger

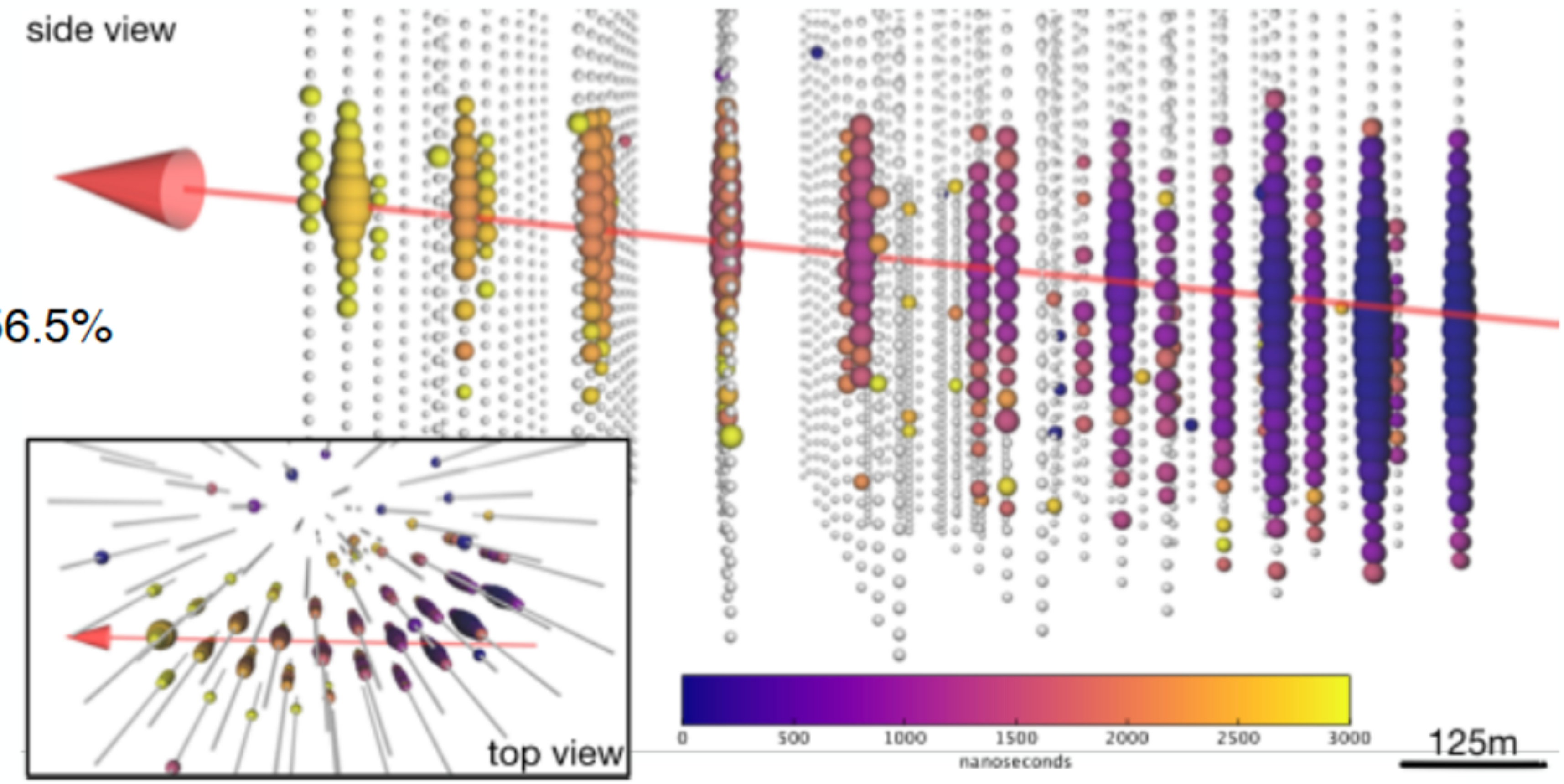
43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;    265 DOY;    17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

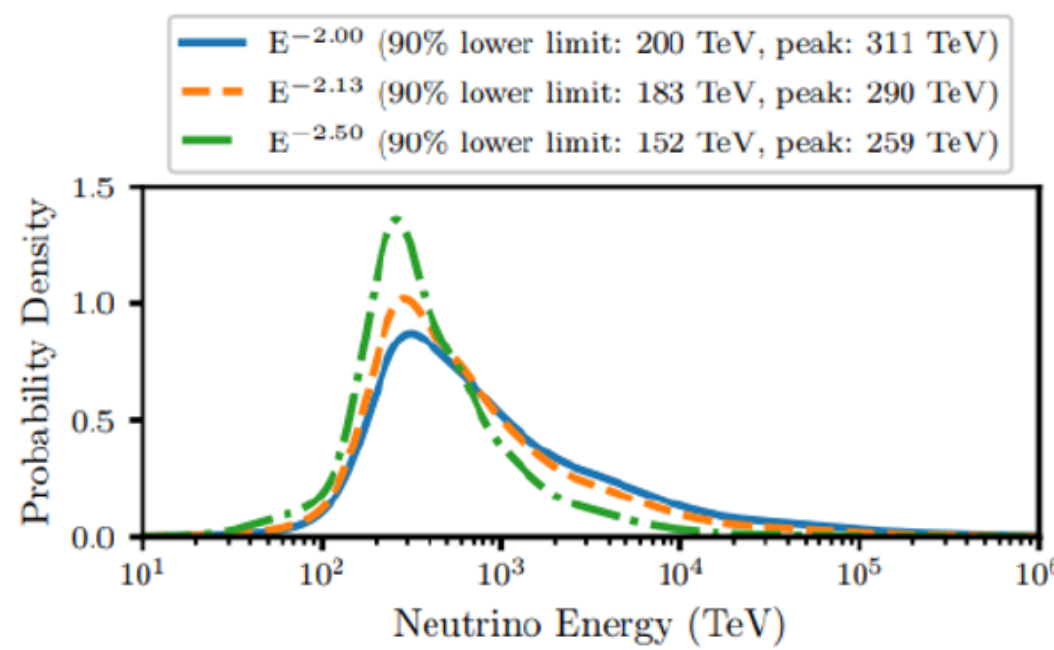
IC-170922A

23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

Signalness: 56.5%



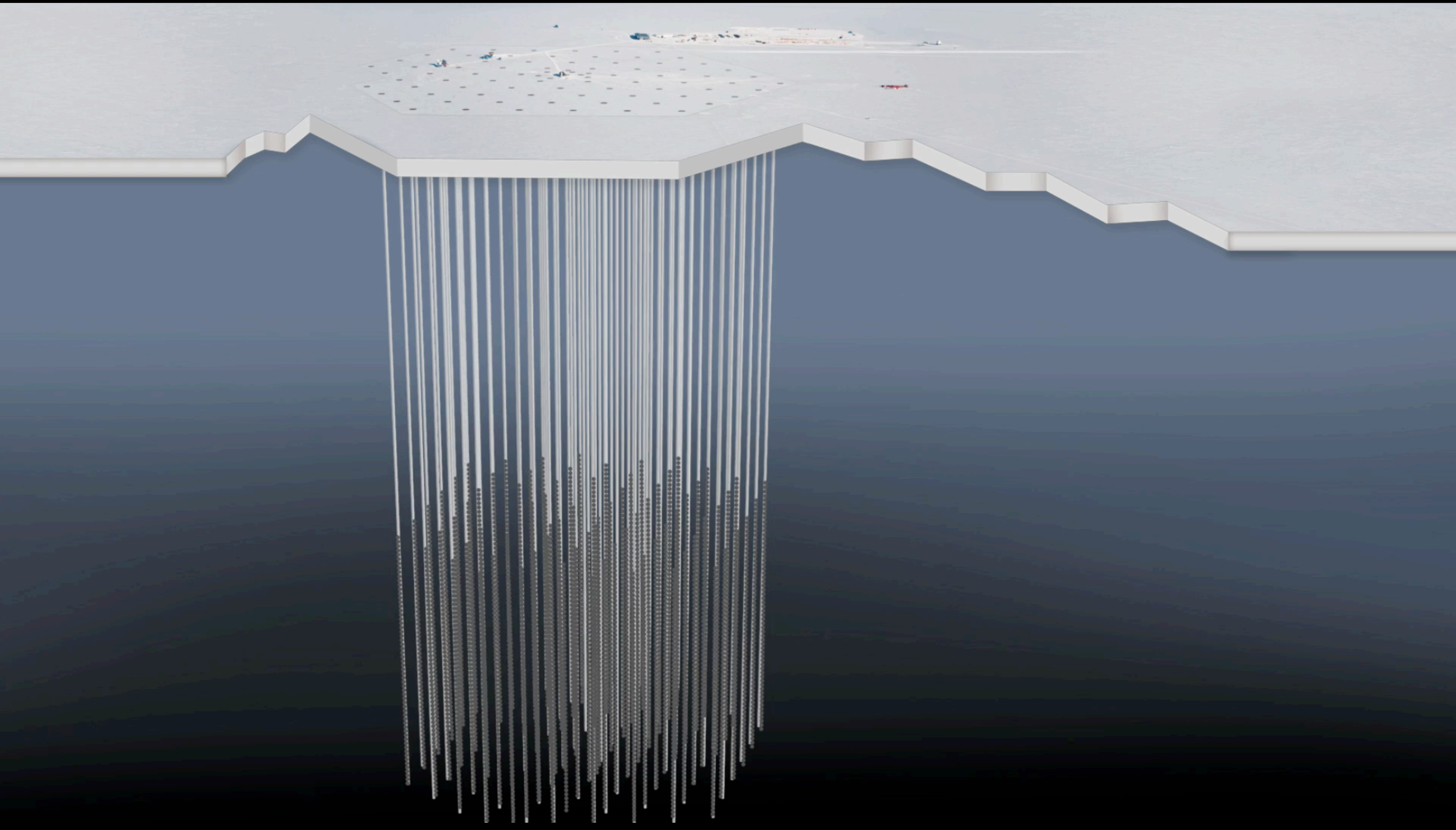
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).

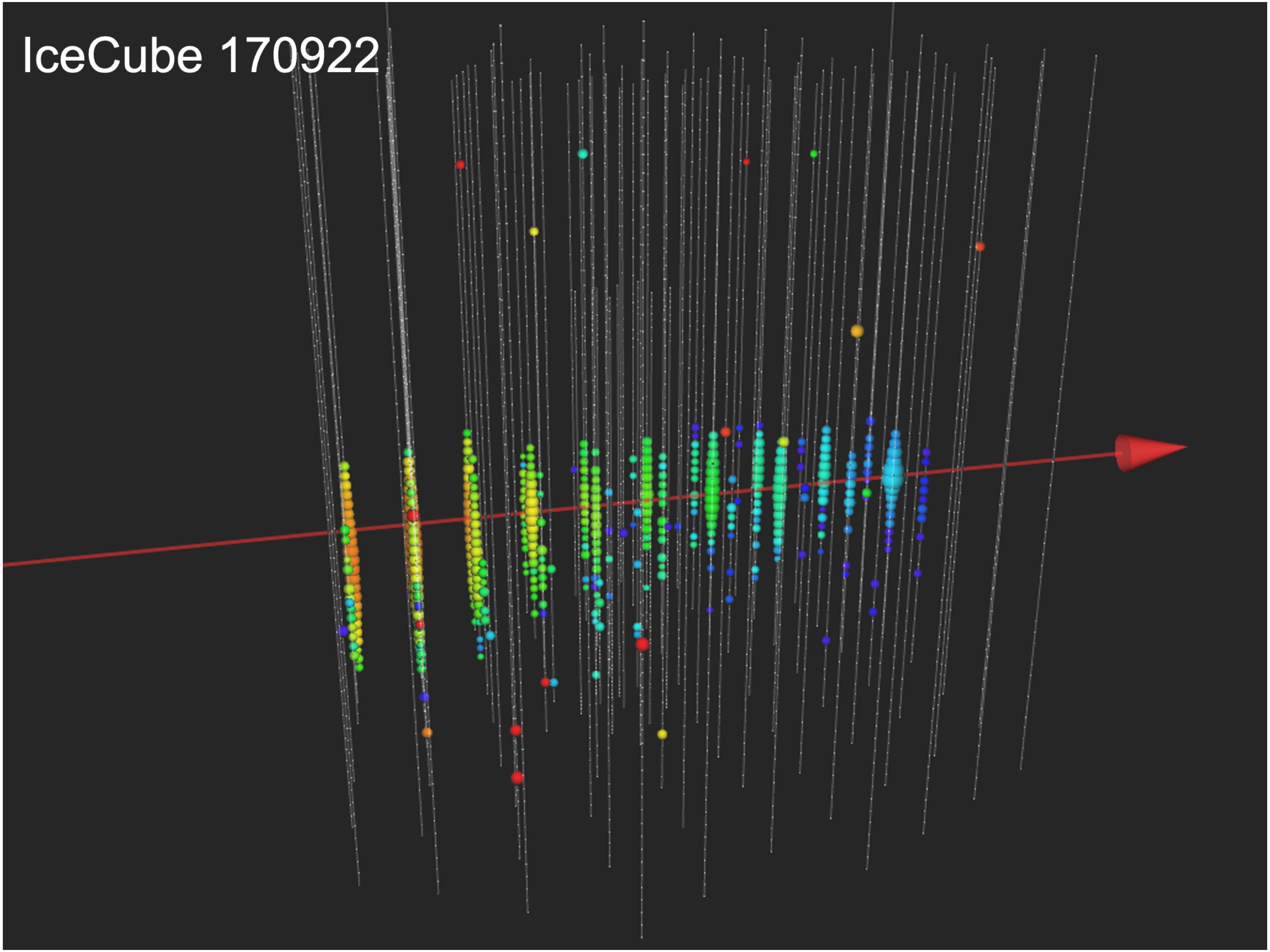


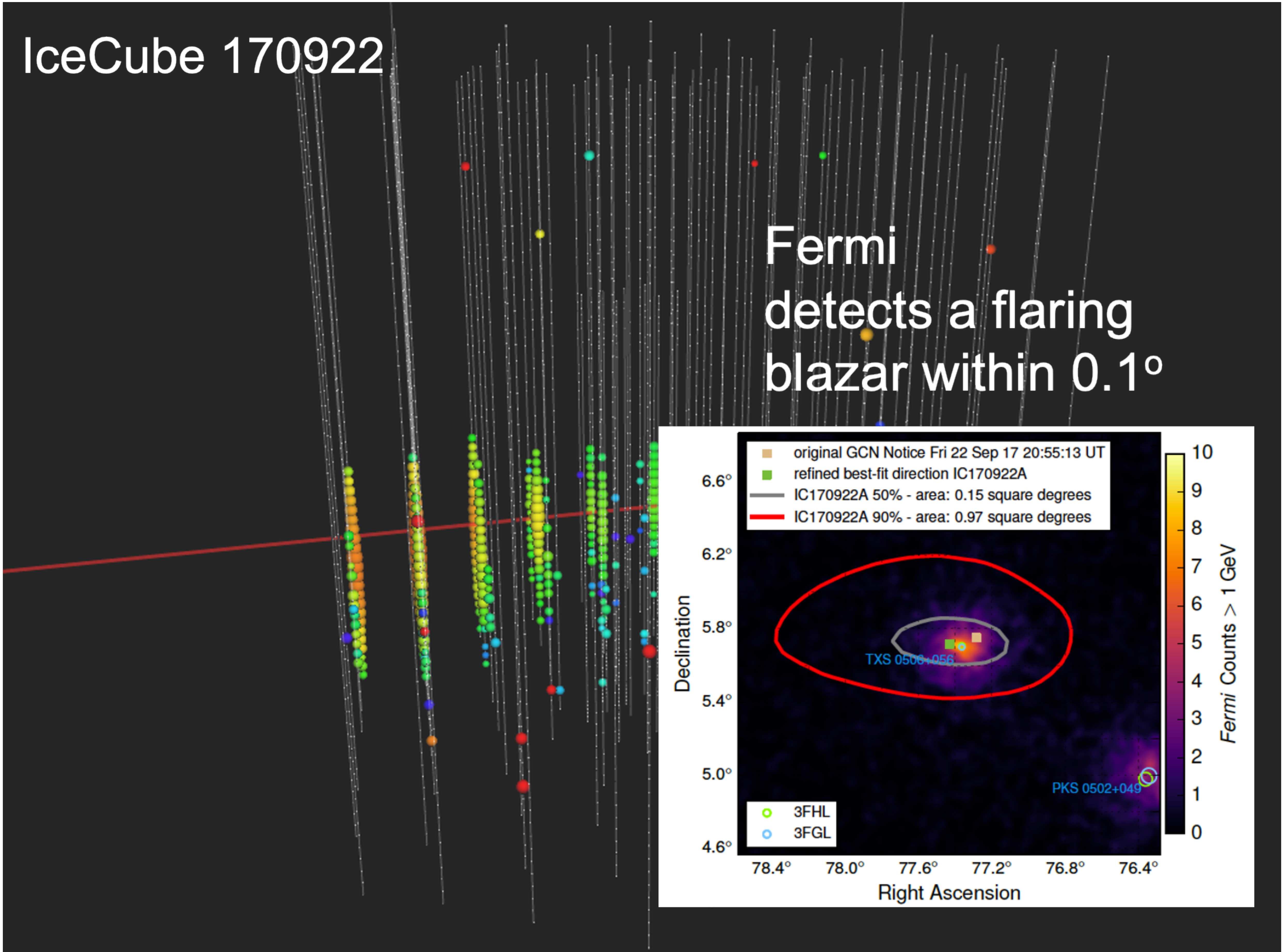
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

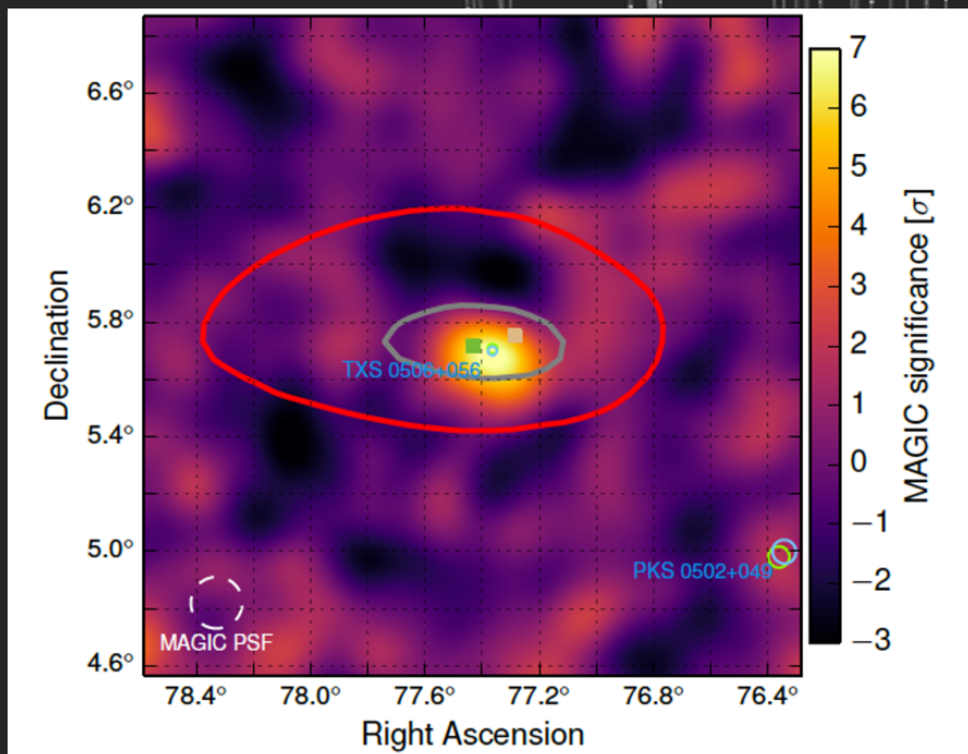
multimessenger neutrinos: a new class of sources and a new class of telescopes



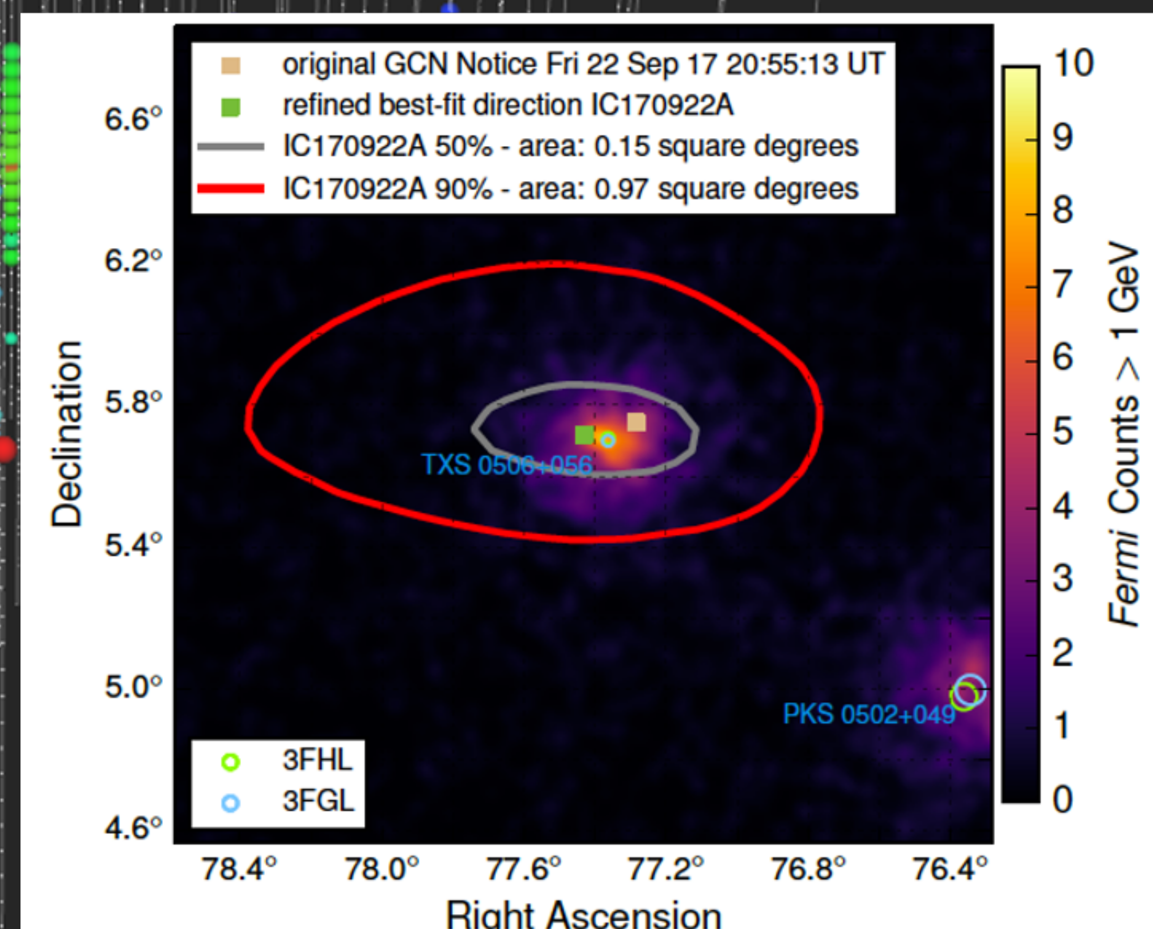

IceCube 170922


IceCube 170922
Fermi
detects a flaring
blazar within 0.1º
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
TXS 0506+056
PKS 0502+049
3FHL
3FGL
Declination
Right Ascension
Fermi Counts > 1 GeV
6.6°
6.2°
5.8°
5.4°
5.0°
4.6°
78.4°
78.0°
77.6°
77.2°
76.8°
76.4°
10
9
8
7
6
5
4
3
2
1
0

IceCube 170922



Fermi
detects a flaring
blazar within 0.1°



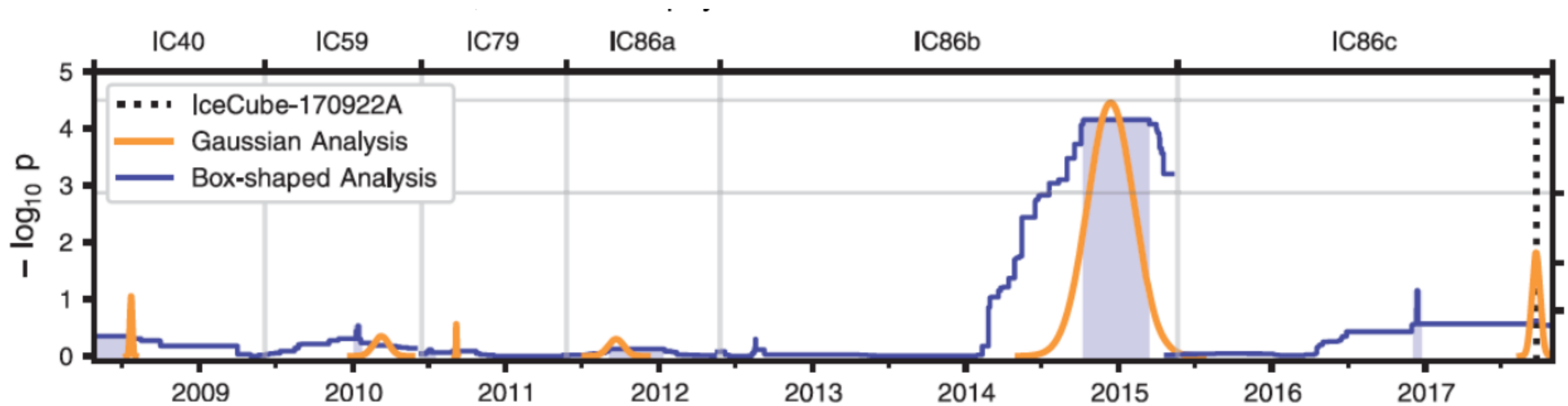
MAGIC
detects emission of
> 100 GeV gammas

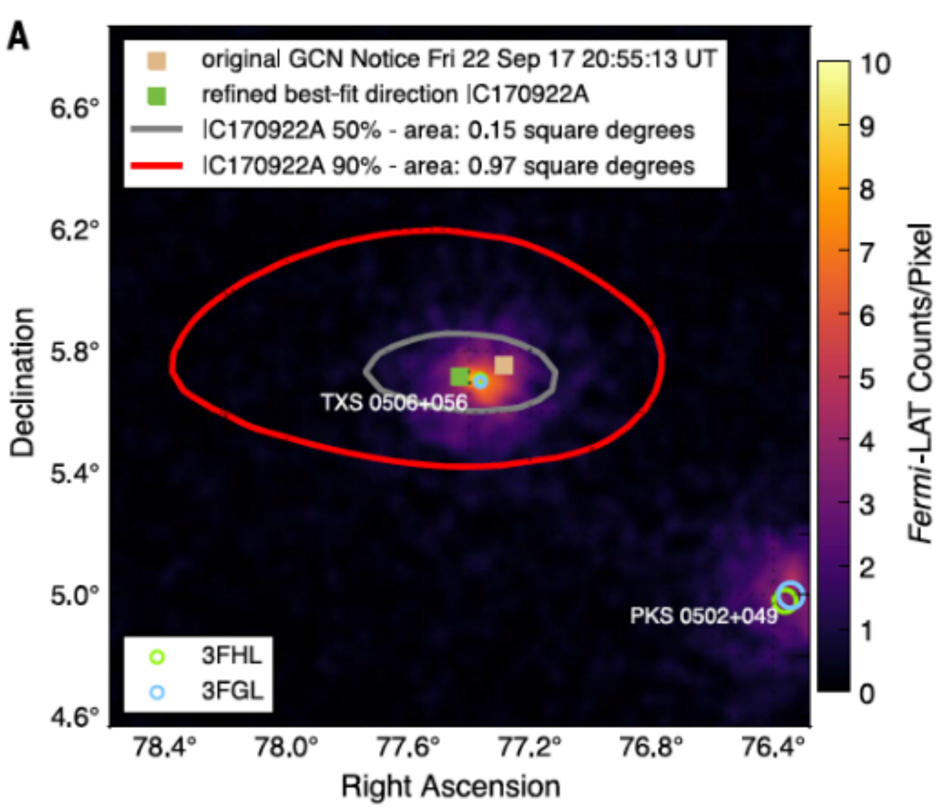
multiwavelength campaign launched by IC 170922

IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43° Dec 5.72°
- Fermi-LAT: flaring blazar within 0.1° (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

Looking at the archival data in the TXS direction



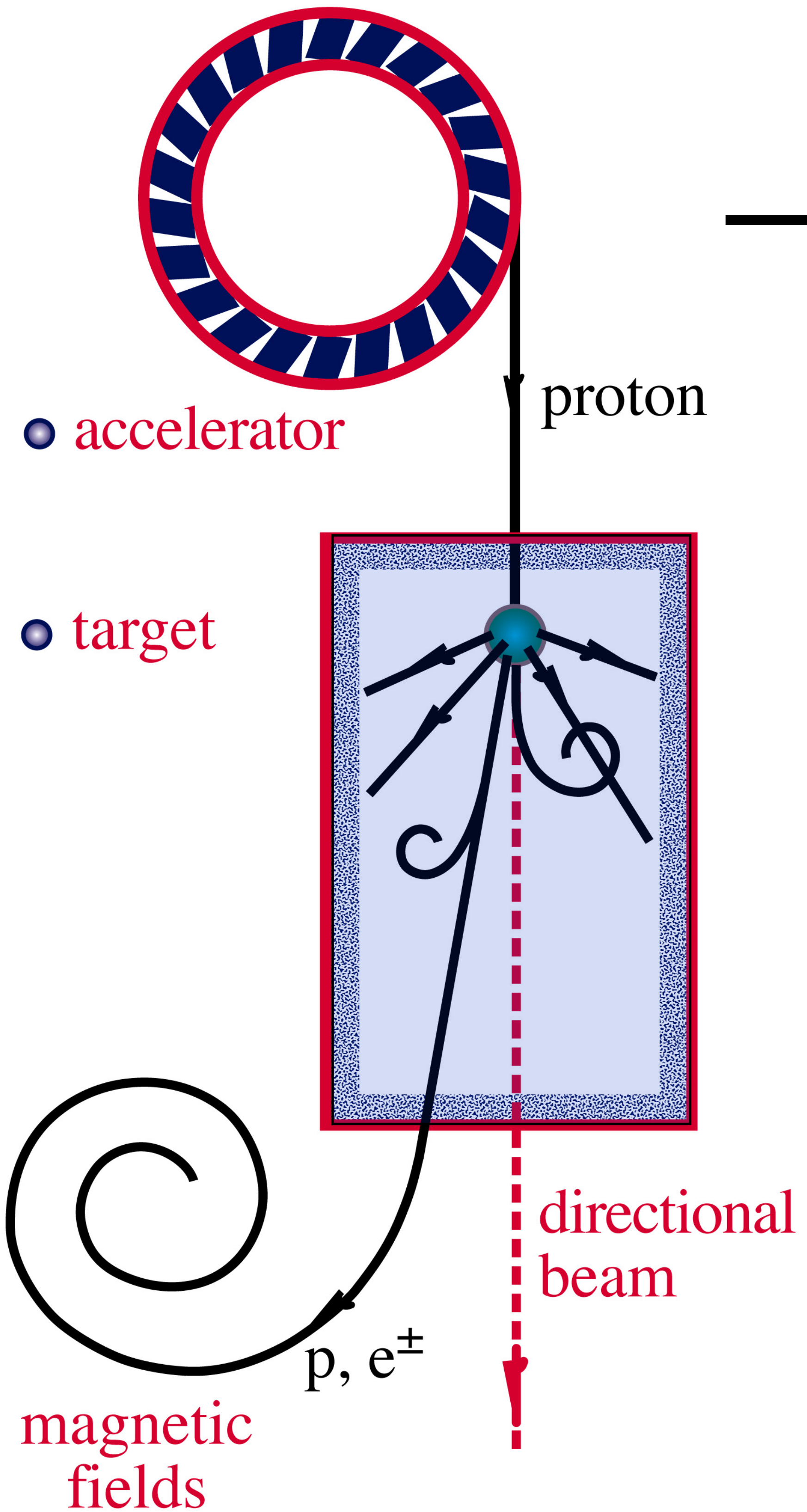


search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- 2.10^{-5} bkg. probability
- spectrum E$^{-2.1}$

No significant gamma-ray emission at flaring time!

ν and γ beams : heaven and earth



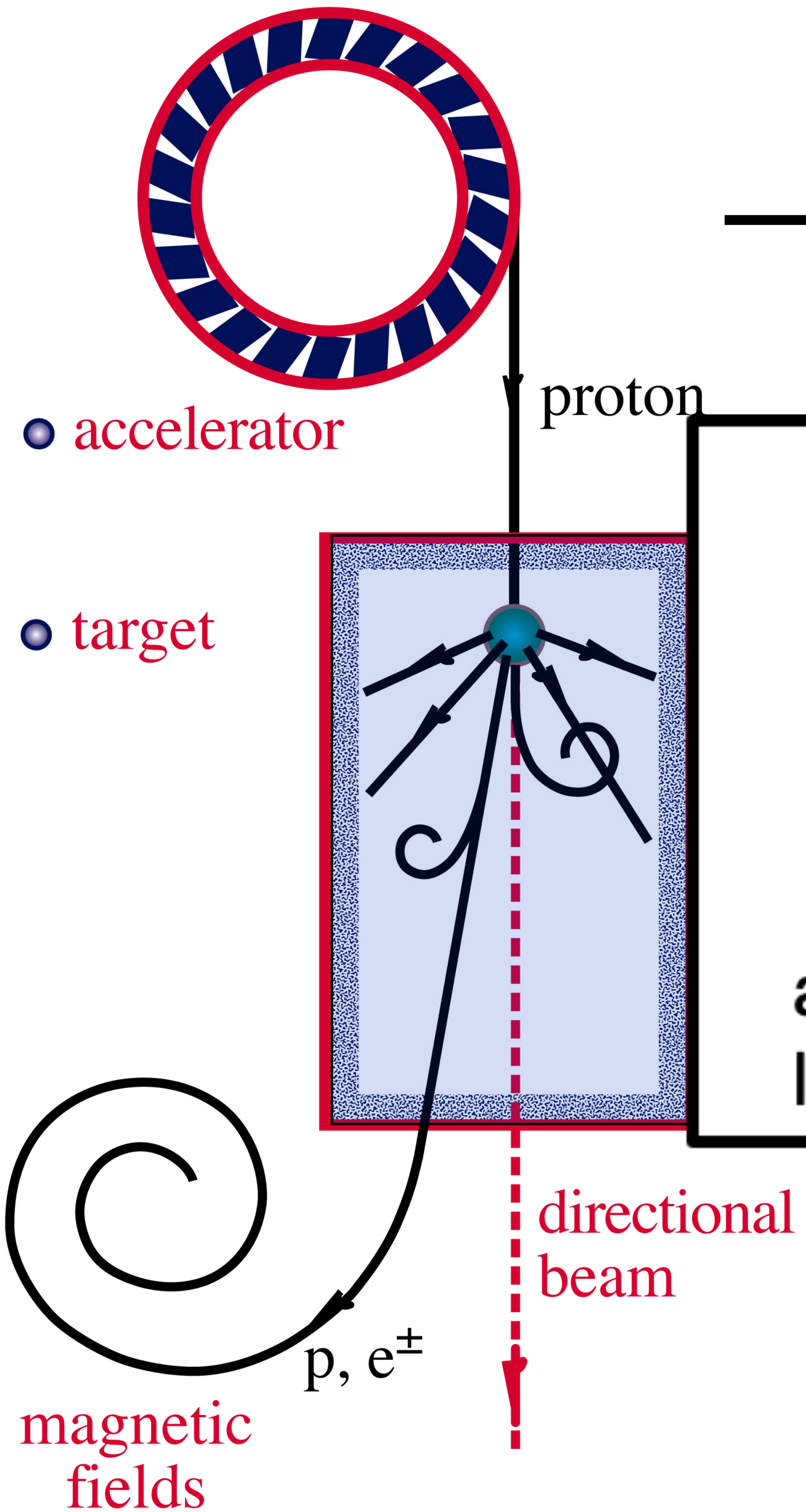
accelerator is powered by
large gravitational energy

supermassive black hole

nearby radiation

neutrino source
needs an accelerator
and
a target
source opacity?

ν and γ beams : heaven and earth



$$\tau_{\gamma\gamma} \propto \frac{\sigma_{\gamma\gamma}}{\sigma_{p\gamma}} \tau_{p\gamma}$$

the gamma rays that accompany the neutrinos lose energy in the source

accelerator is powered by large gravitational energy

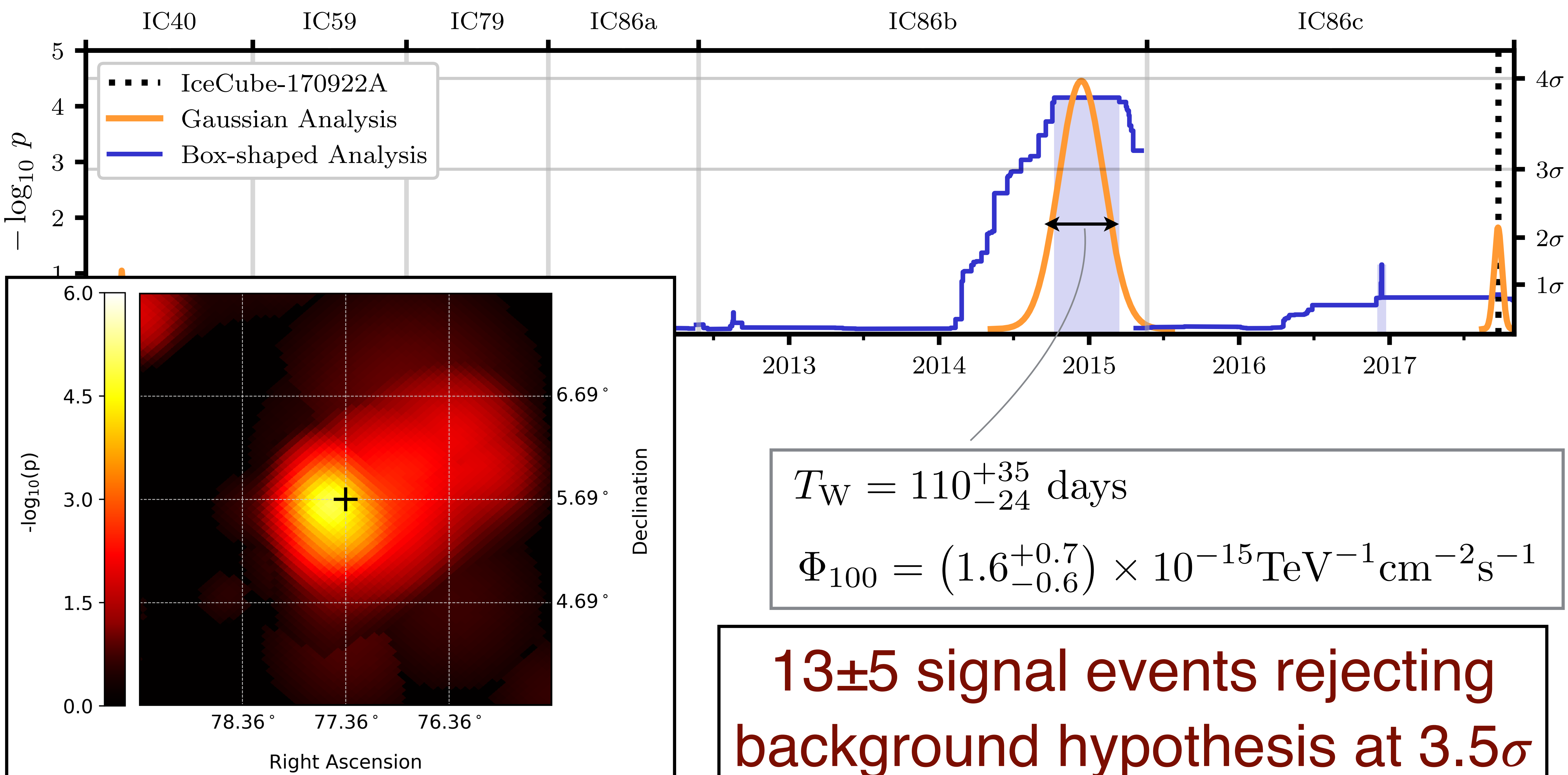
supermassive black hole

nearby
adiation

neutrino source needs an accelerator
and
a target
source opacity?

Neutrino Flare in 2014

Time-dependent search in the direction of TXS 0506+056 revealed a **neutrino flare** in December 2014.



$$T_{\mathrm{W}} = 110^{+35}_{-24}\ \text{days}$$

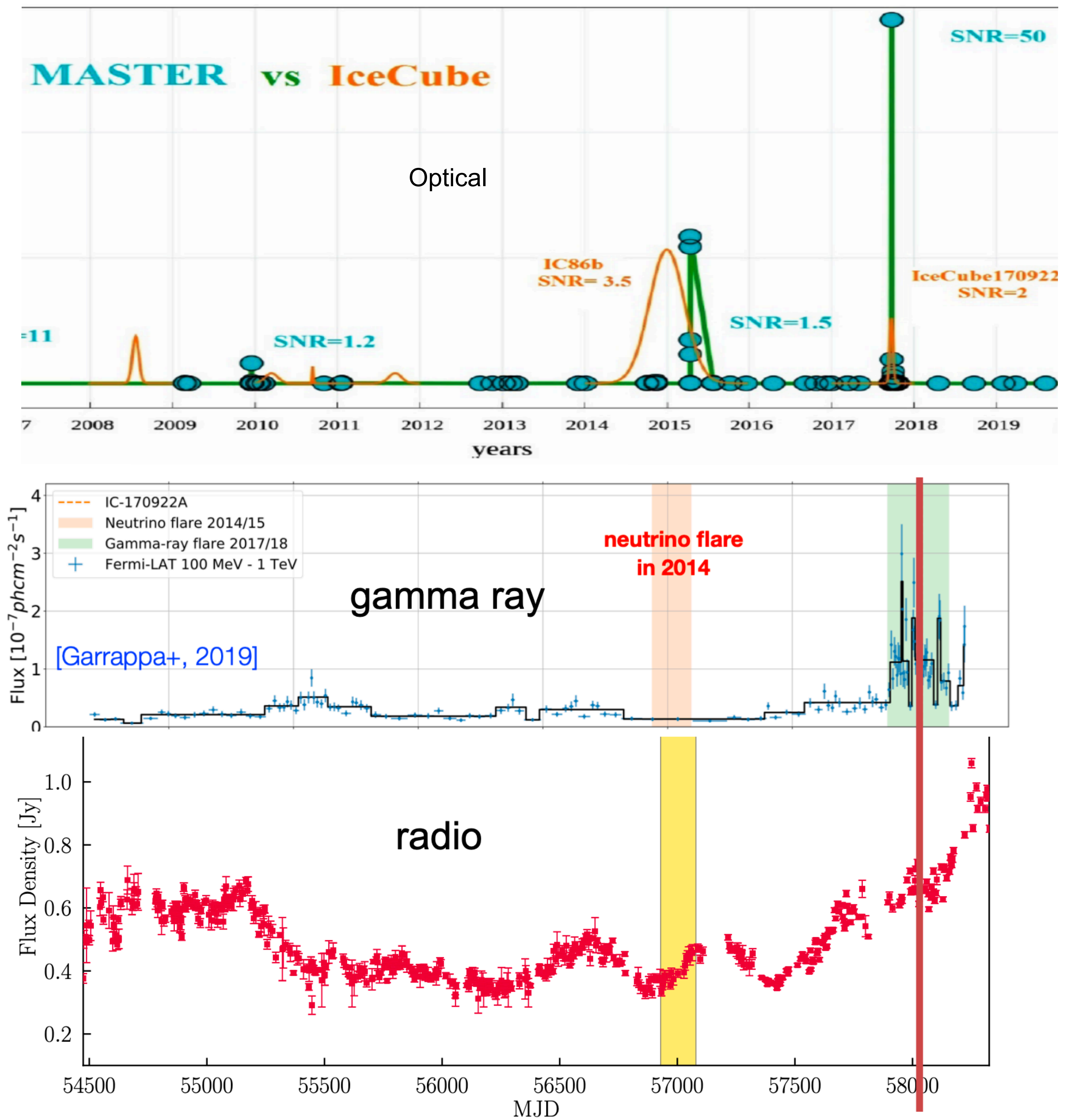
$$\Phi_{100} = \left(1.6^{+0.7}_{-0.6}\right) \times 10^{-15}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

13±5 signal events rejecting background hypothesis at 3.5σ

[IceCube, Science 2018]

Neutrino Flare in 2014

- Enhancement is seen around IC170922A in gamma-rays and radio, and a drop in optical.
- Neutrino flare in 2014-2015 is correlated with enhancement in radio and drop in optical flux, but *no change in gamma-rays.*



Gamma-neutrino anti-correlation?

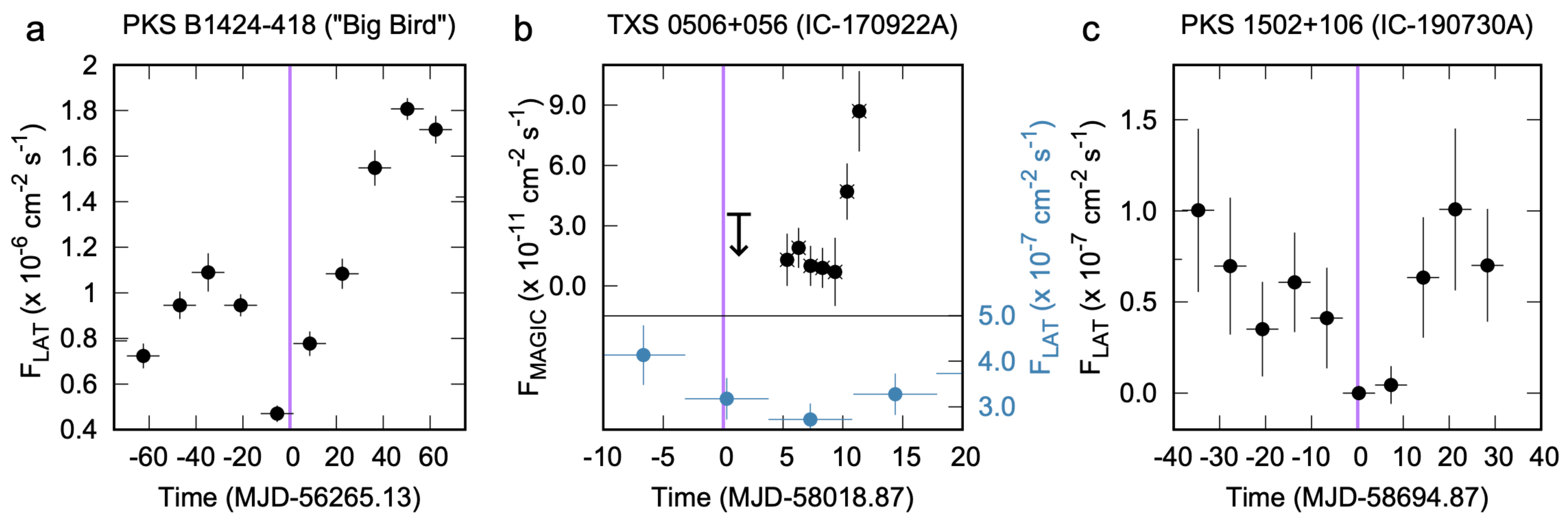
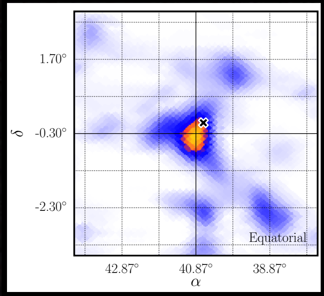


Figure 3. **γ-ray light curves for three blazars with coincident high-energy neutrinos.** **a**: PKS B1424-418 as mea-

E. Kun, I. Bartos, J. B. Tjus et al 2009.09792

The gamma-ray correlation is not so direct/obvious

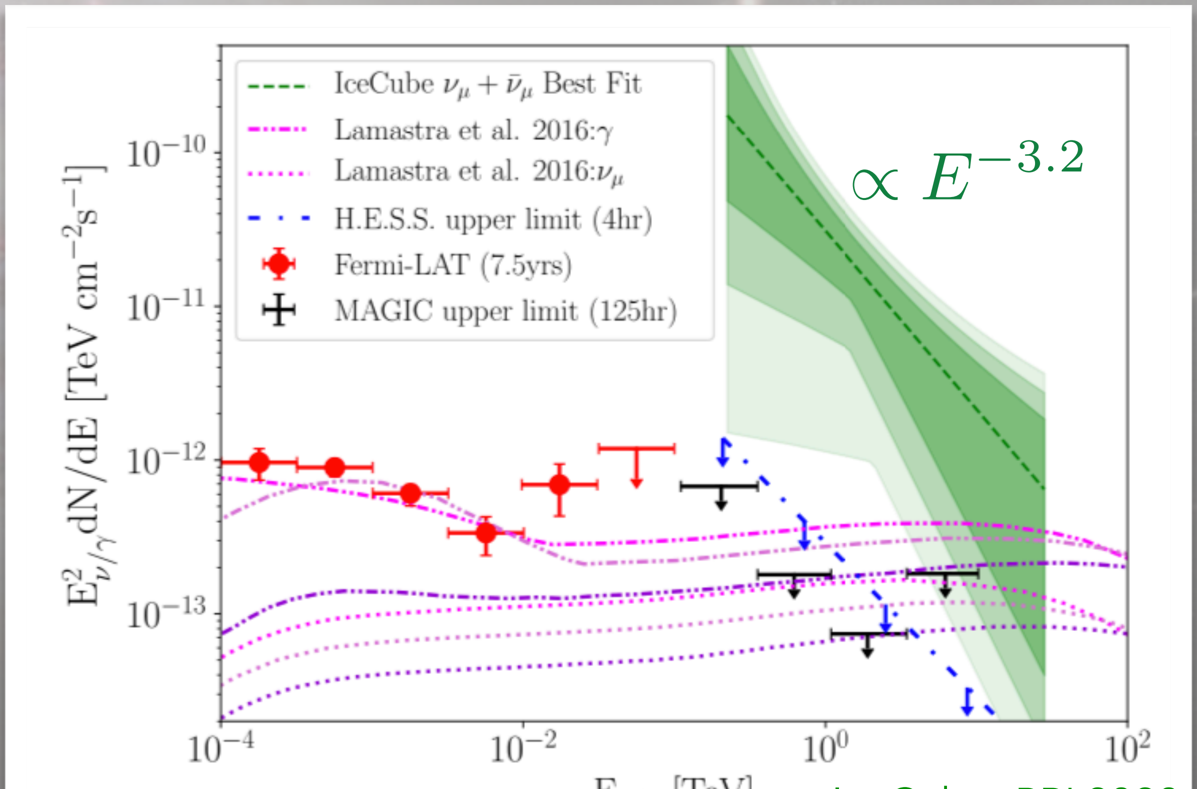
NGC 1068 & the Neutrino Signal



- NGC 1068, aka M77, is a Seyfert 2 galaxy with a heavily obscured nucleus
- One of the best studied AGN, which played a major role in AGN unification scheme
- Compton thick environment with Column density ~ 10^{25} cm^{-2}
- Bright in X-ray, and high infrared luminosity indicating high level of star formation

▸ *Historically considered as a promising cosmic-ray accelerator.*

- IceCube 10 yr time-integrated search found 51 neutrinos in the direction of NGC 1068, with a soft spectrum.
- The neutrino flux much higher than the observed γ-ray flux by *Fermi*.
- Models built on measured γ-ray flux by Fermi cannot accommodate the neutrino flux.
- **Obscuring** necessary to absorb the pionic γ-ray accompanying neutrinos.

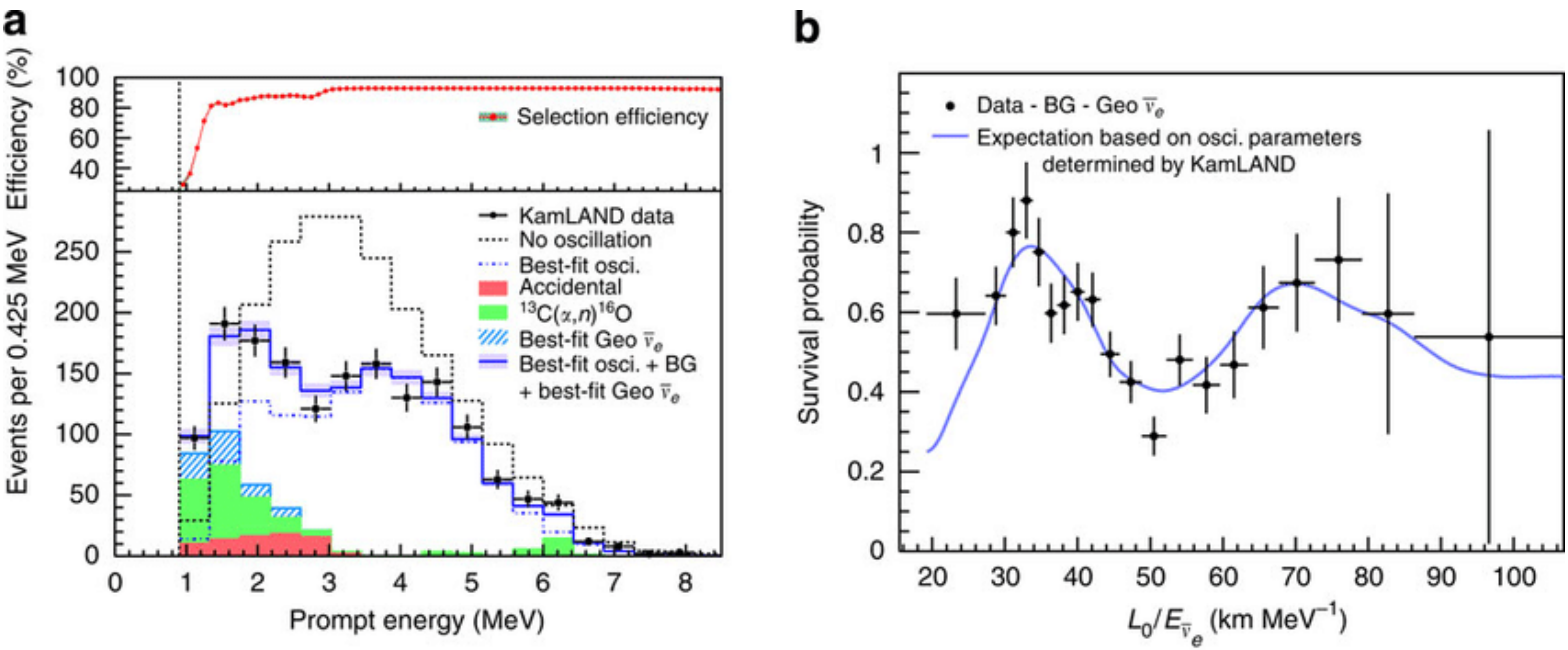


IceCube, PRL2020

Image Credit: NASA/HST

Interlude:
Review of neutrino oscillations

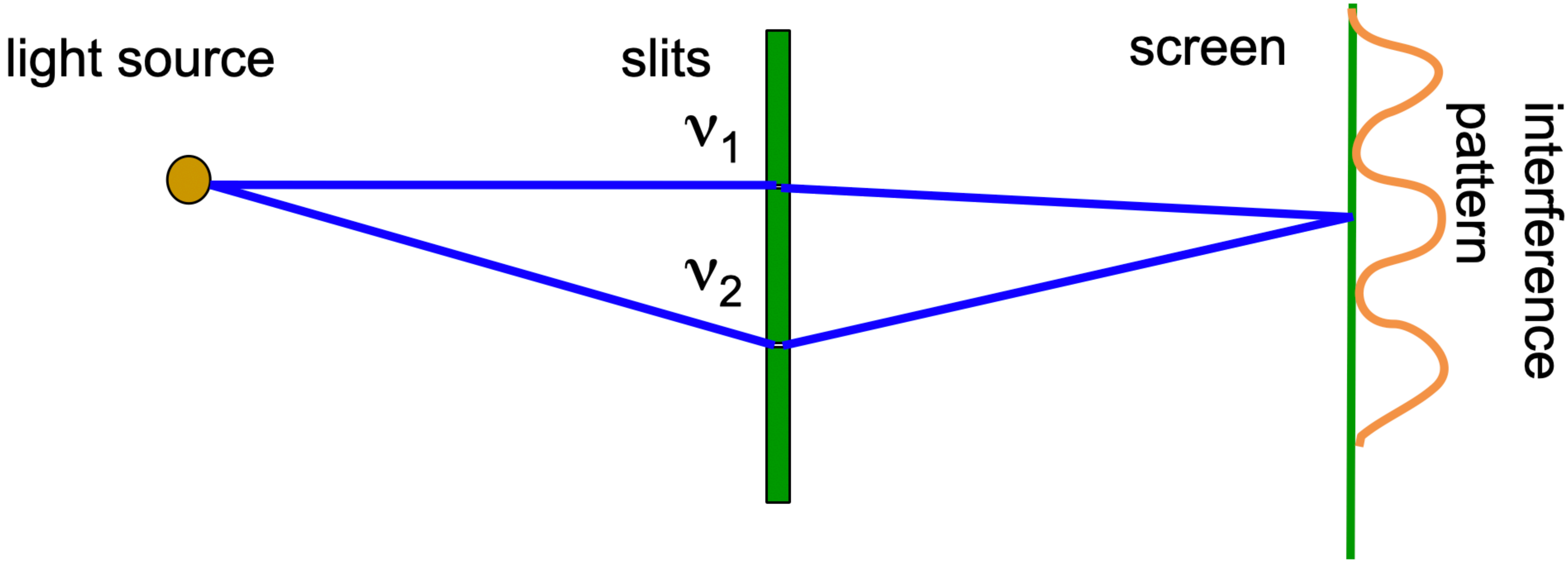
KamLAND sees the oscillation wiggle



High-energy astrophysical neutrino flavor composition

Neutrino oscillations: natural interferometers

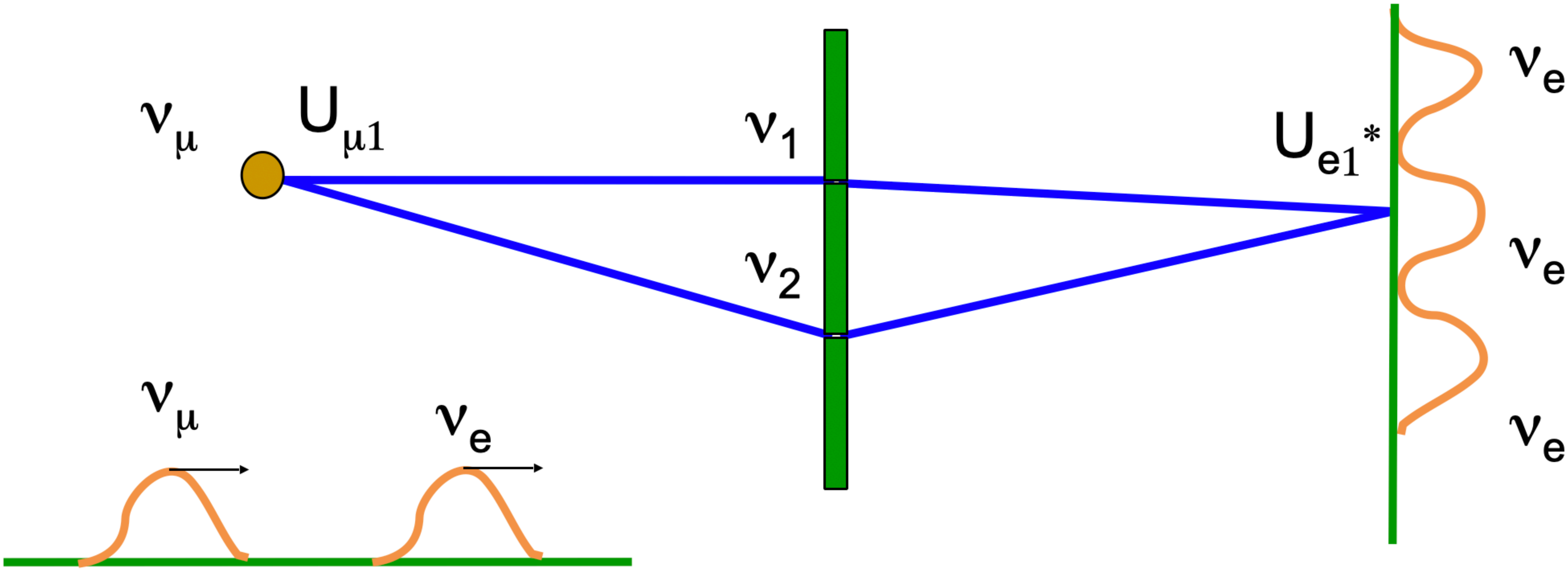
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

Neutrino oscillations: natural interferometers

Neutrino oscillation is an interference experiment (cf. double slit experiment)

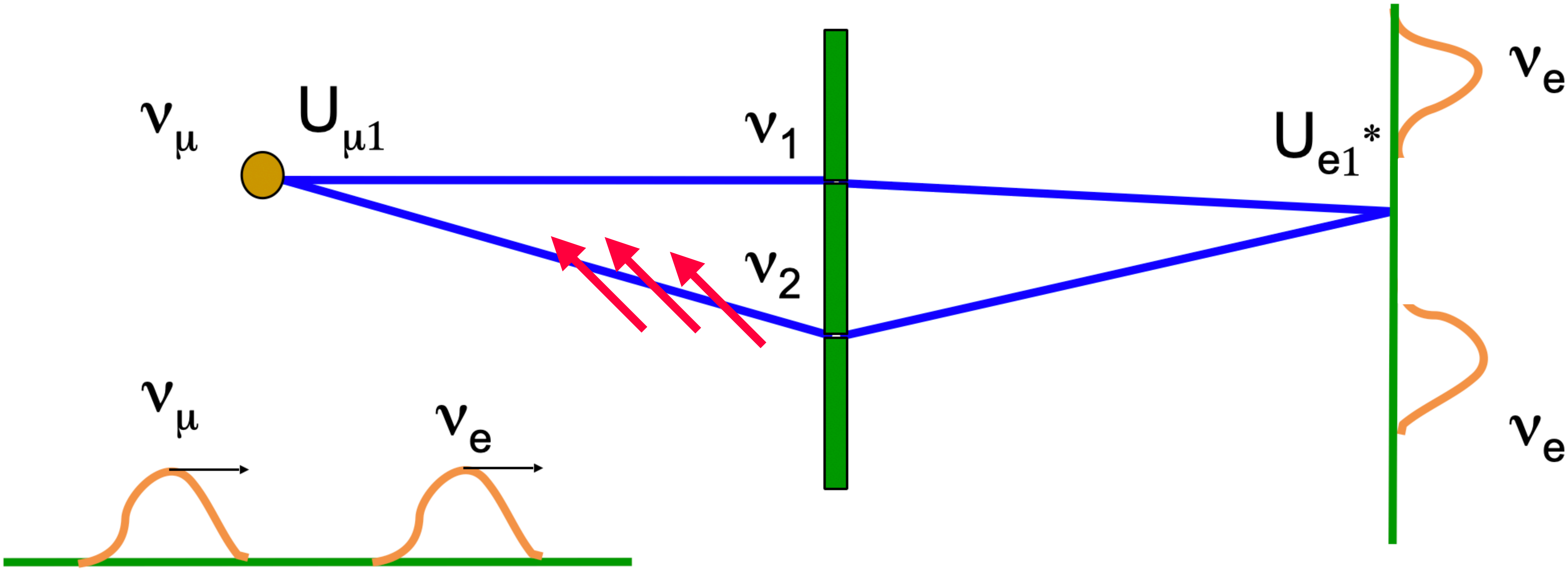


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

Neutrino oscillations: natural interferometers

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If ν_1 and ν_2 interact with anything along their way, they will produce new oscillation features!

For example: long-range neutrino forces, dark matter-neutrino interactions, neutrino decay, Lorentz violation, etc …

Flavor composition @ source

(GRBs, AGNs, blazars, pulsars…) $(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$$

(1:2:0)

Muon-damped

$$\pi^+ \to \cancel{\mu^+} + \nu_\mu$$

(0:1:0)

Neutron

$$n \to p + e^- + \bar{\nu}_e$$

(1:0:0)

Initial flavor



Flavor mixing

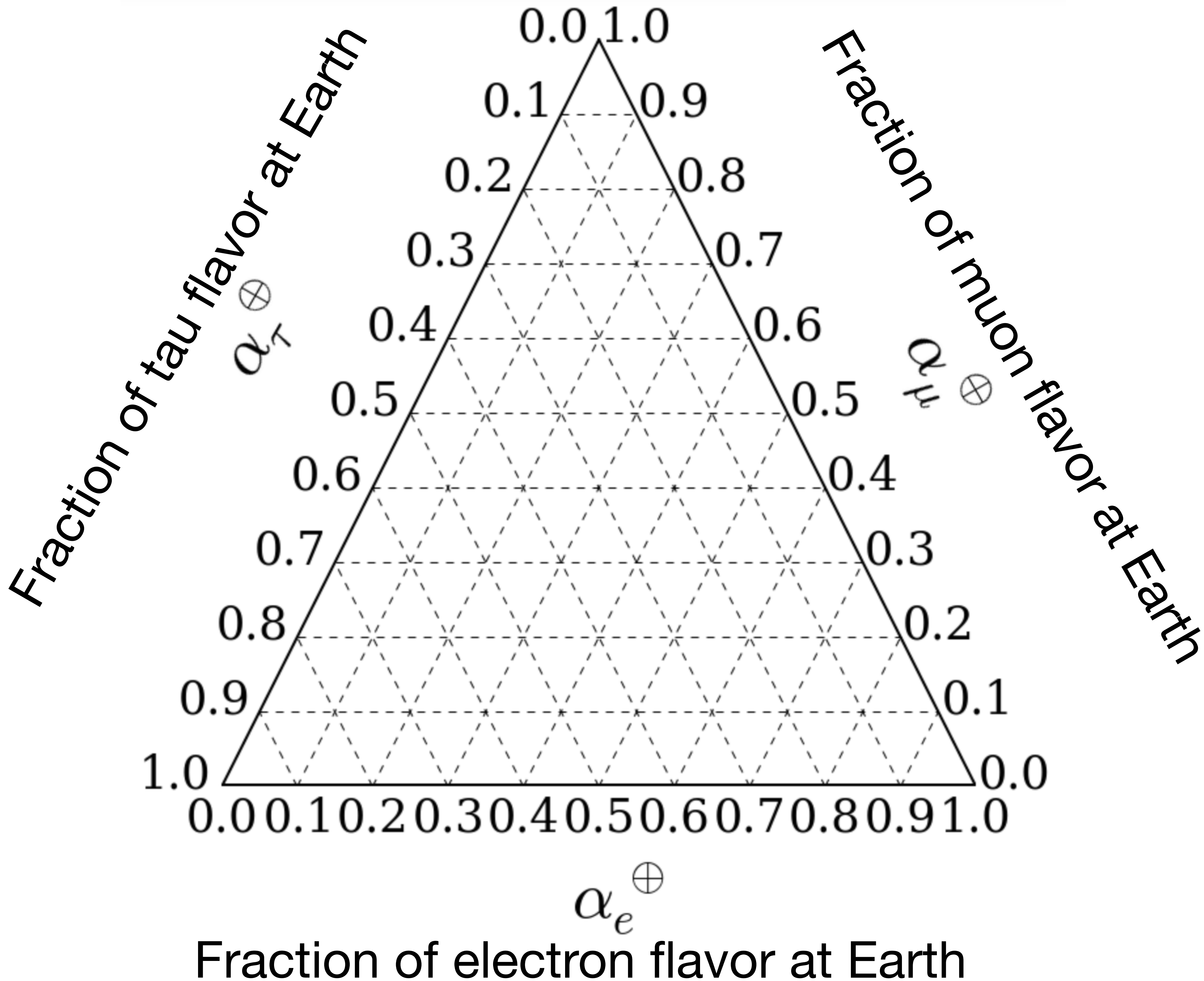
$$\phi_\beta^{\oplus}(E) = \sum_\alpha \bar{P}_{\nu_\alpha \to \nu_\beta}(E)\,\phi_\alpha^{p}(E)$$

Standard Expectation

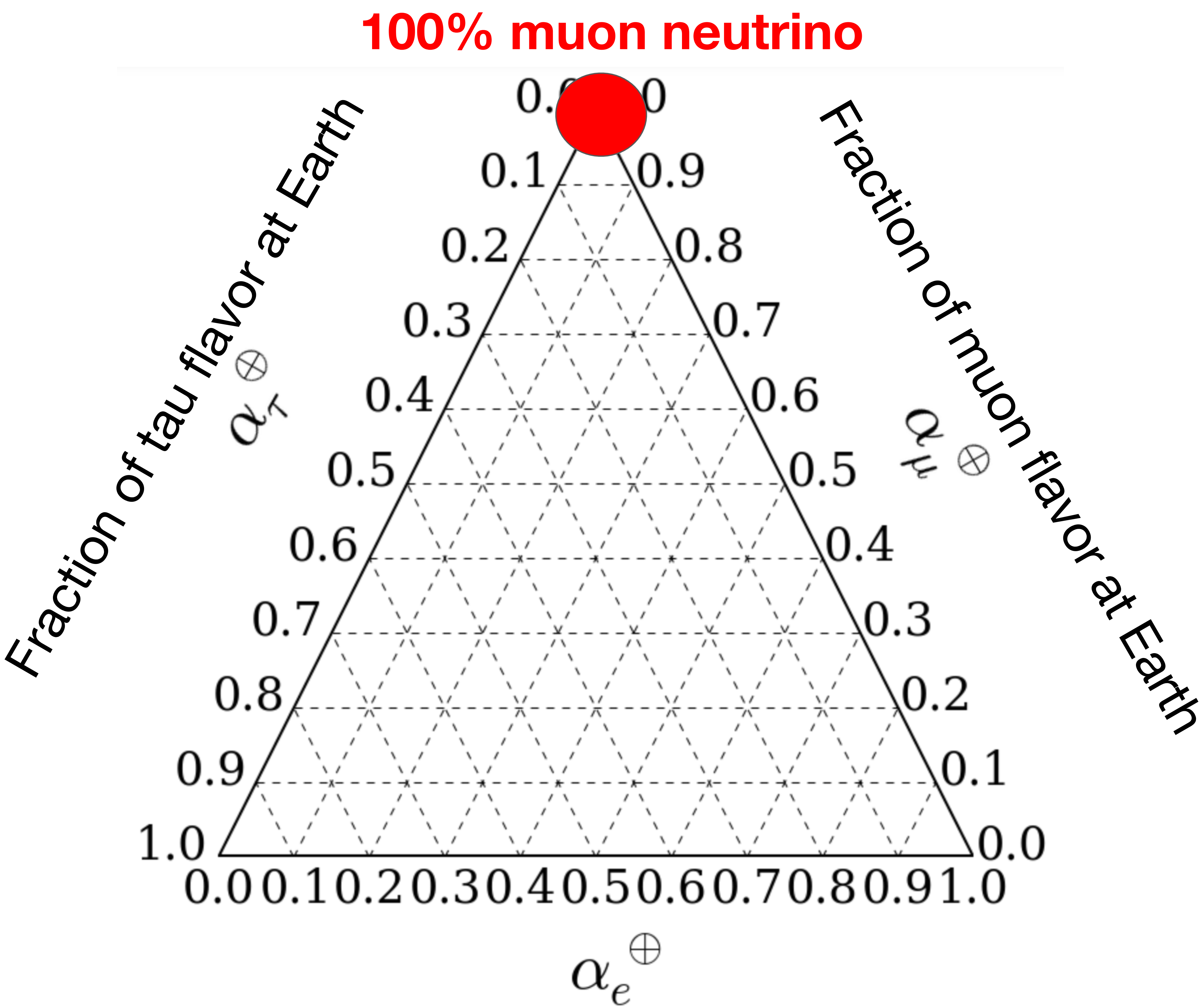
New Physics!



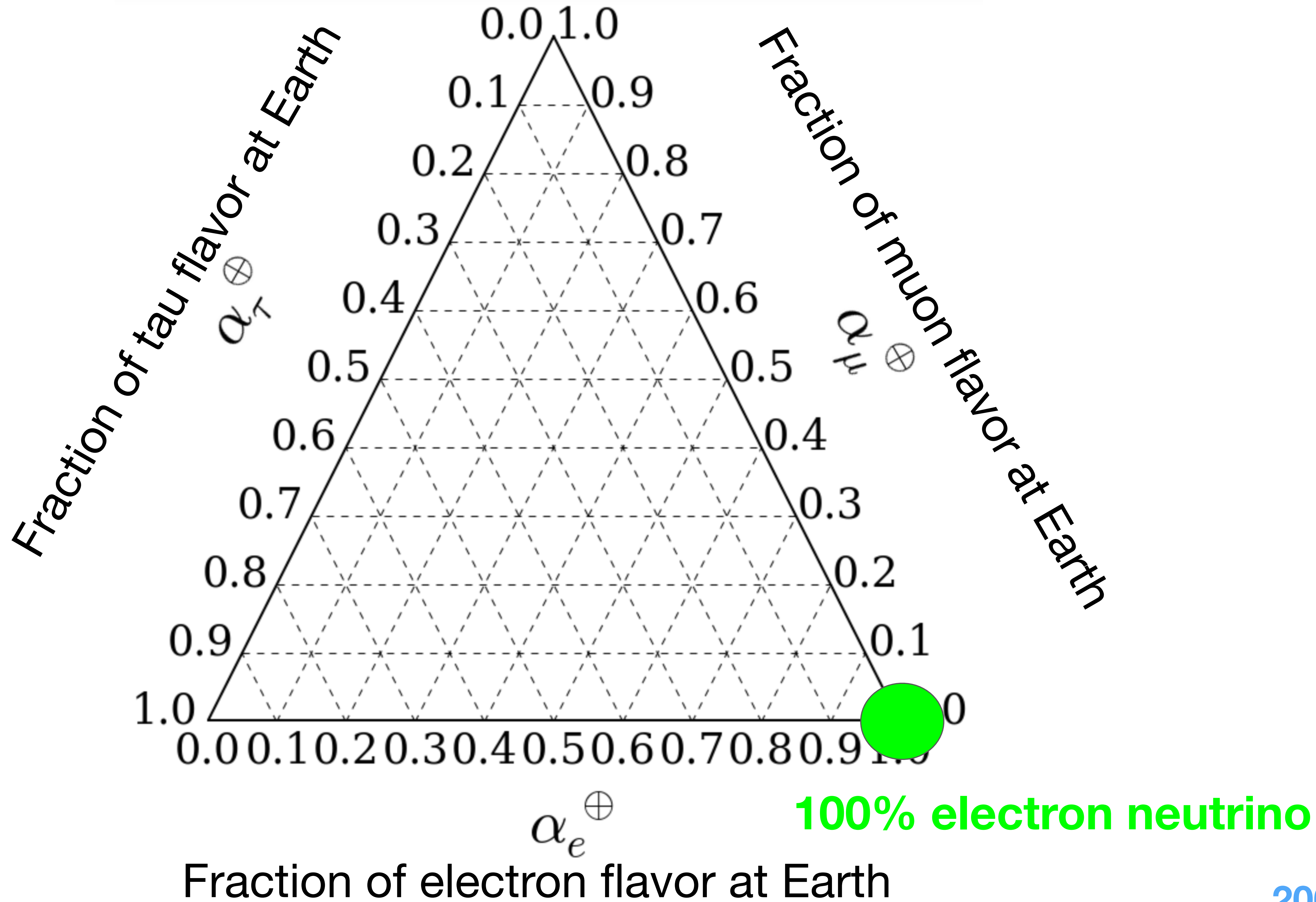
The flavor triangle



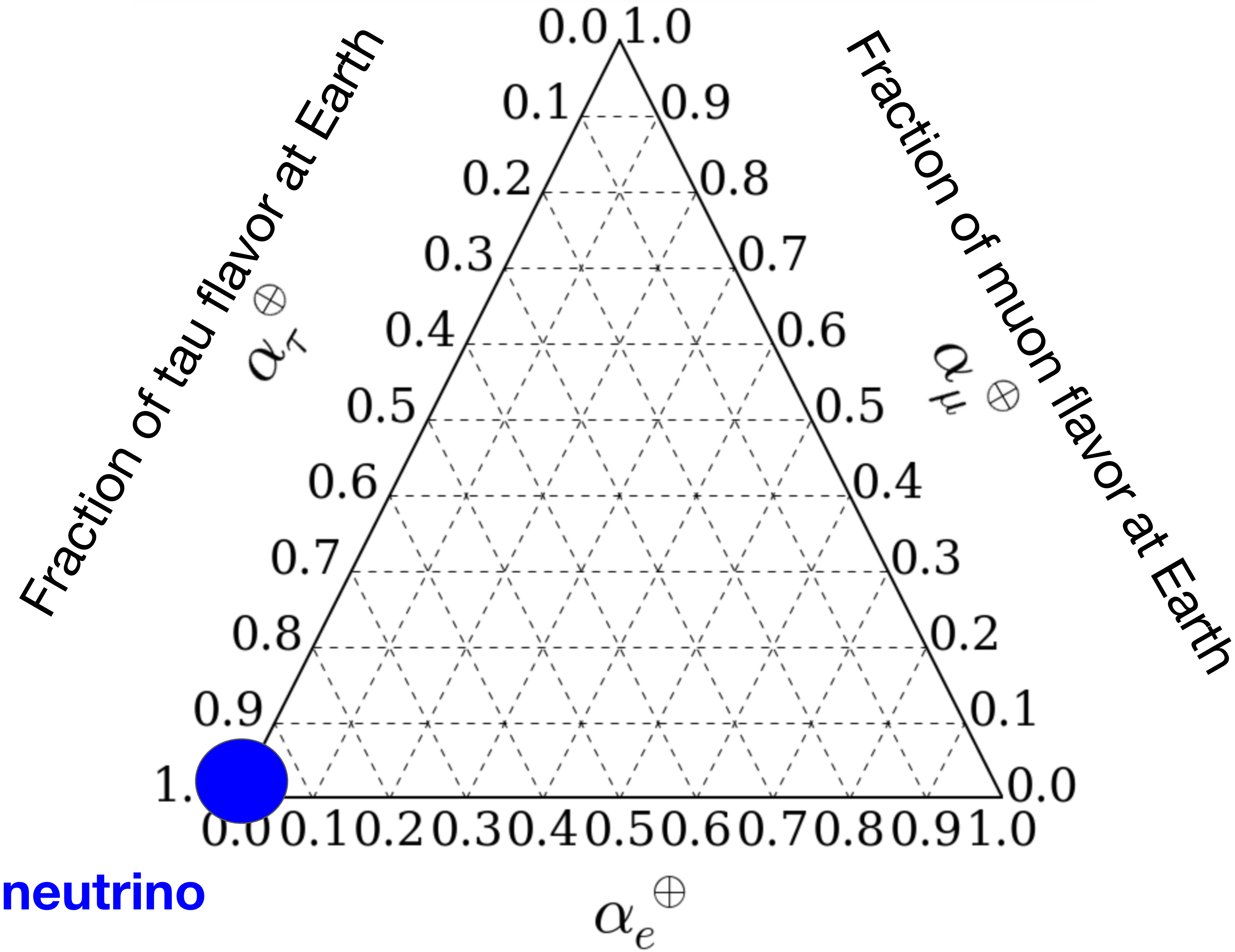
The flavor triangle



The flavor triangle

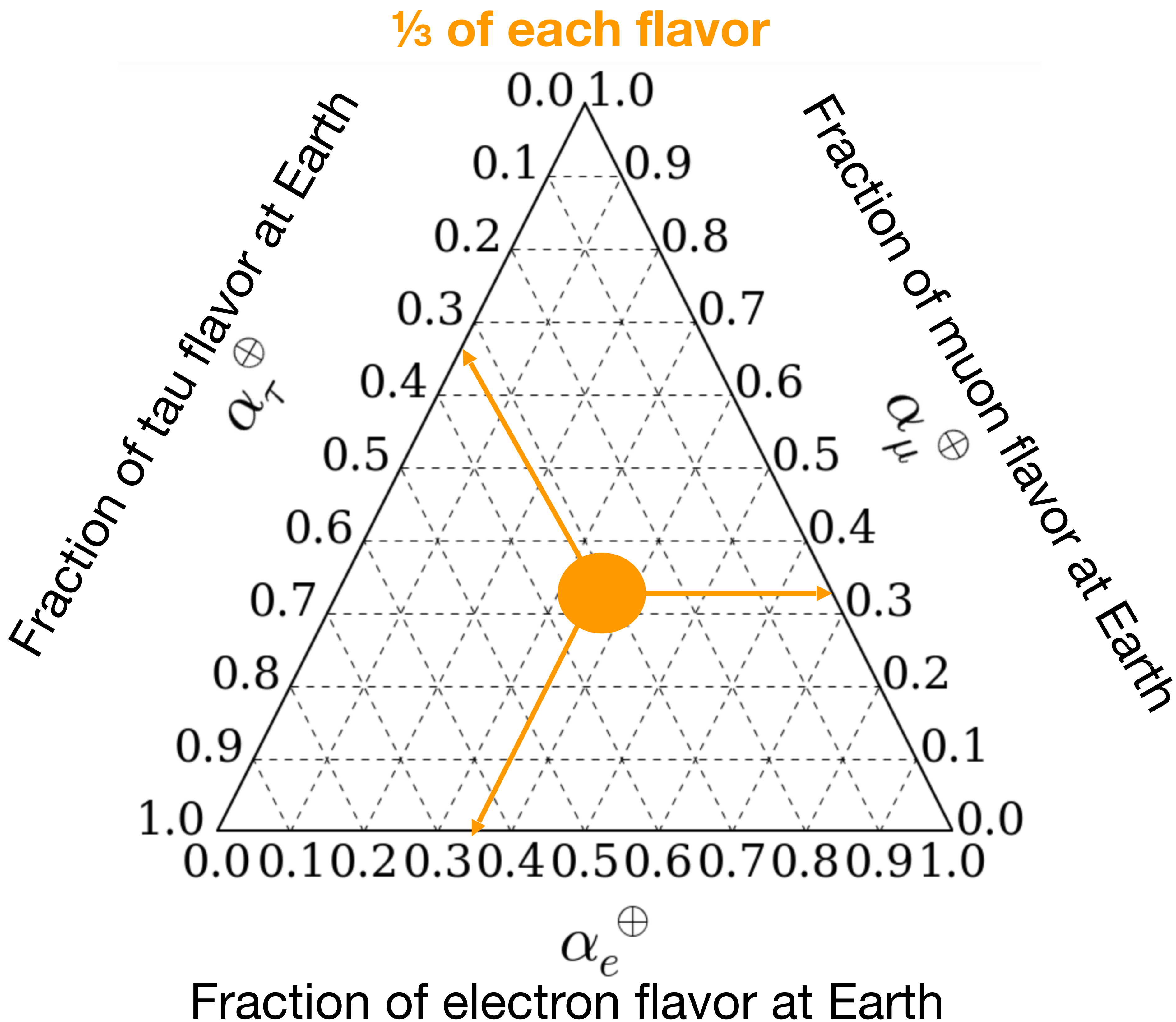


The flavor triangle

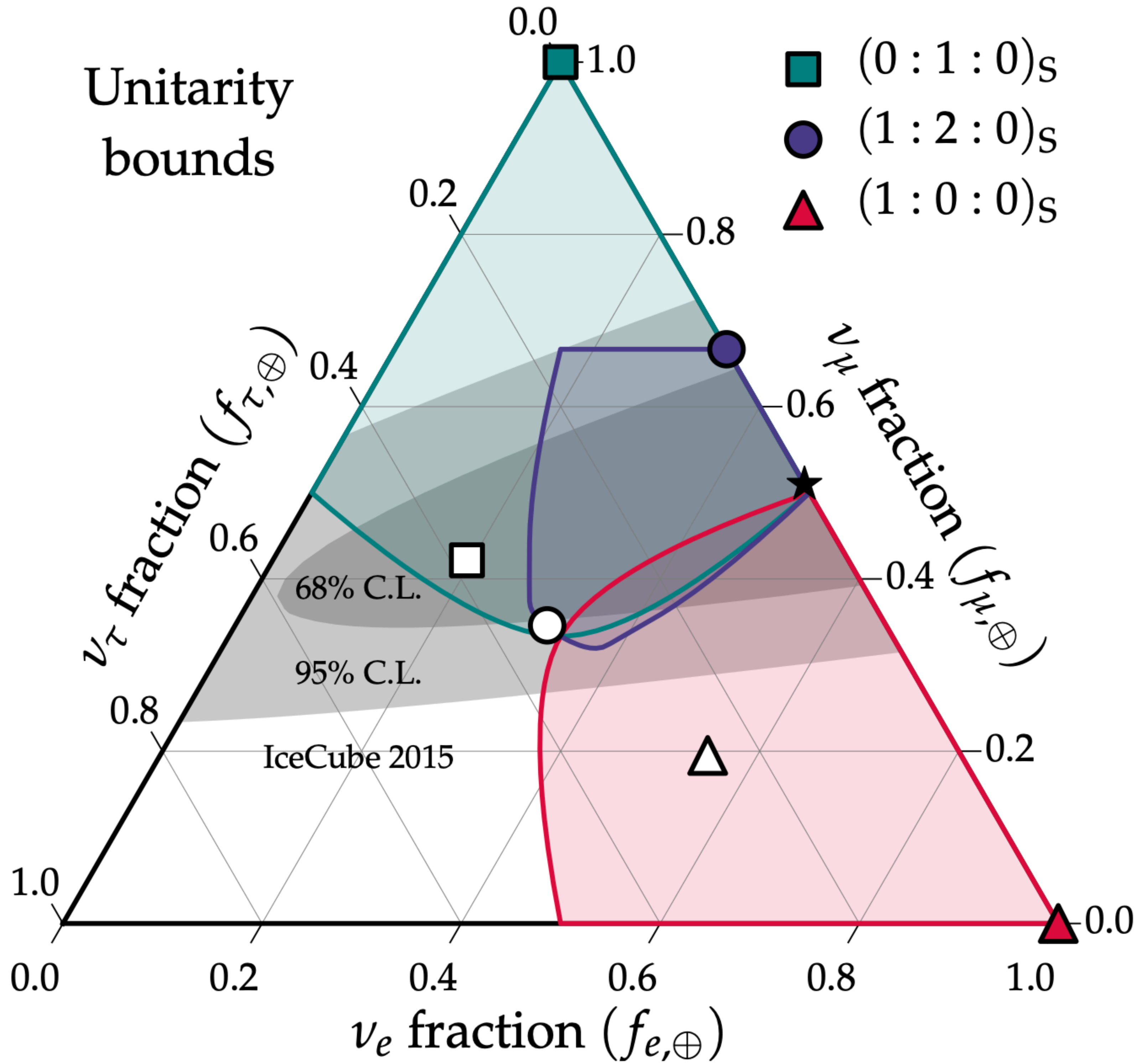


100% tau neutrino

The flavor triangle



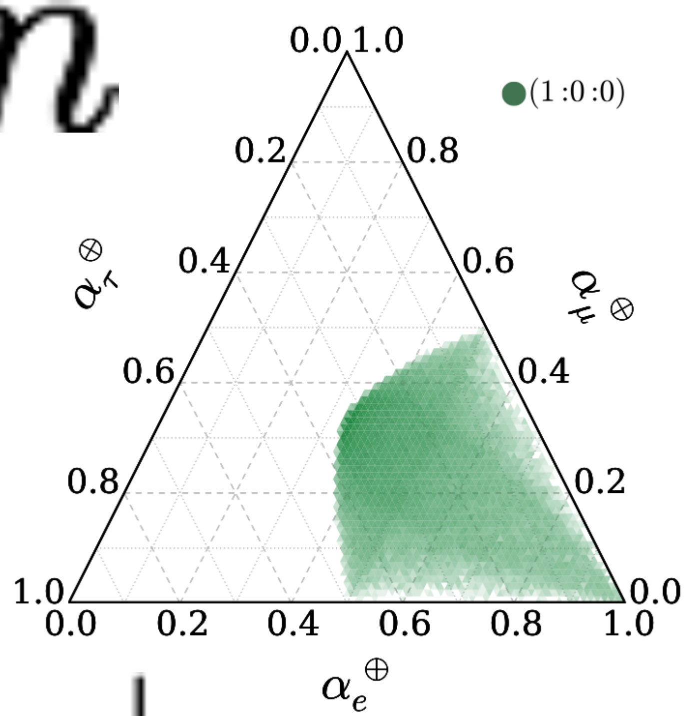
Unitarity



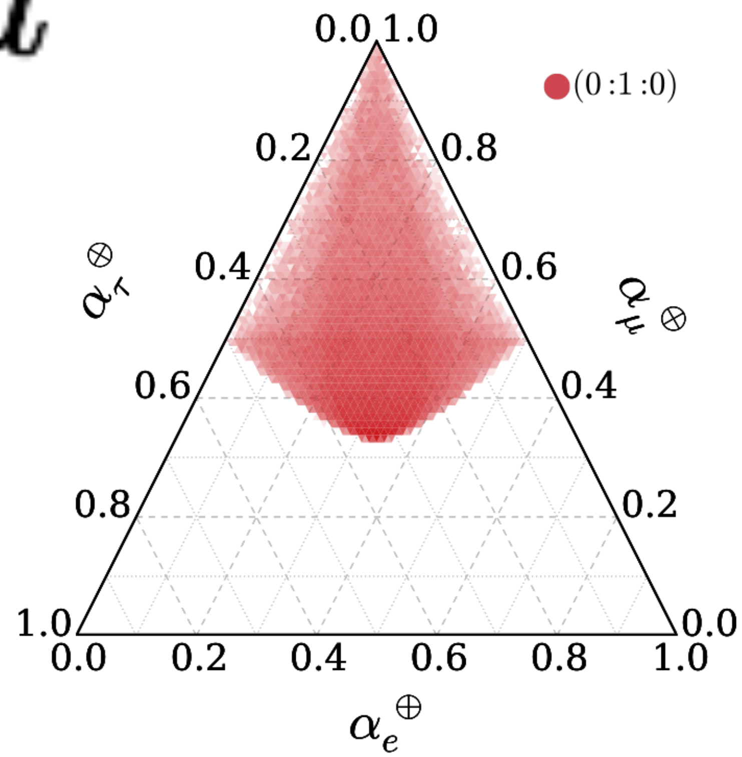
Ahlers, Bustamante, and Mu arXiv:1810.00893

Predicted flavor triangles given some initial flavor composition

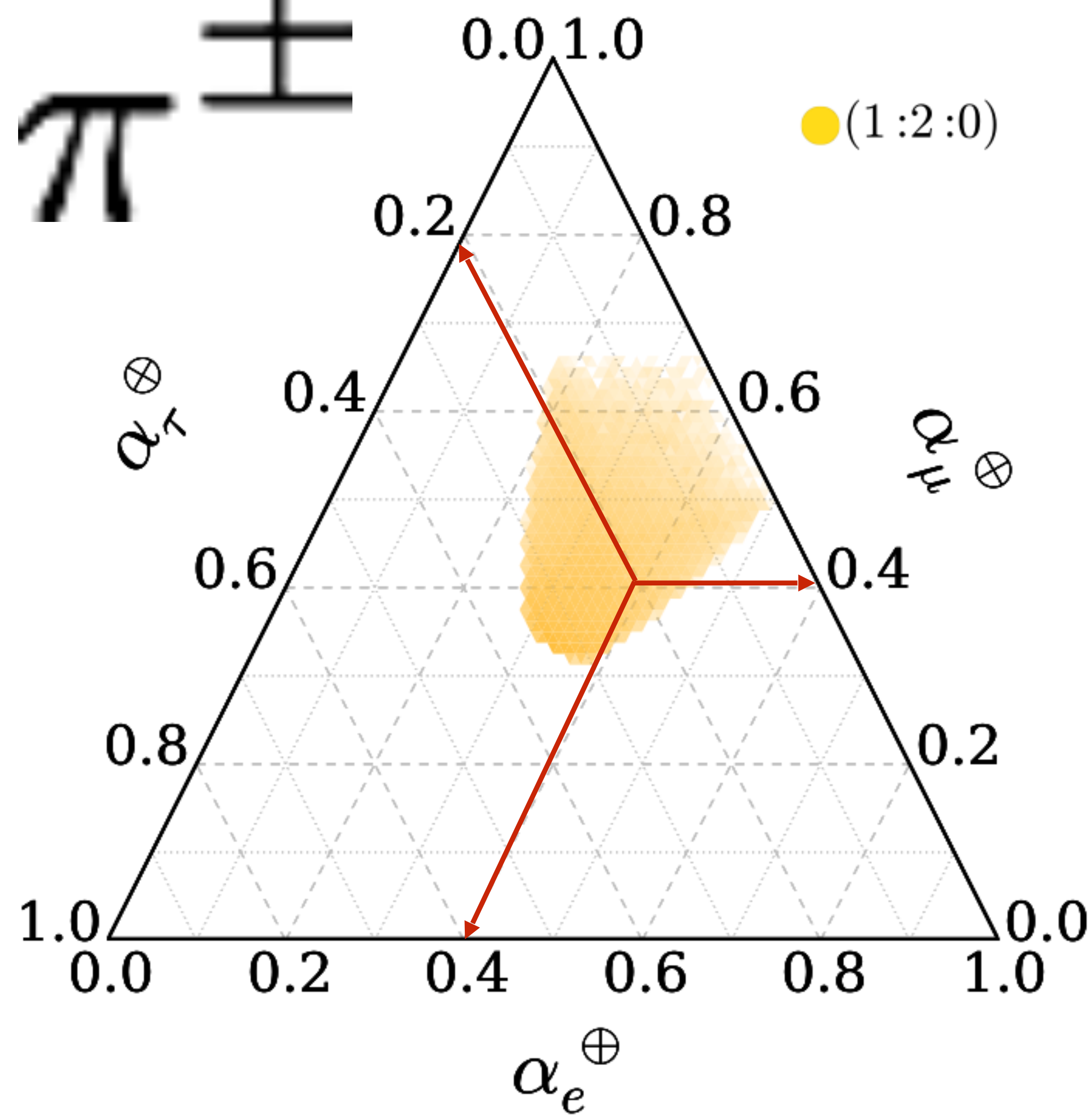
n



$\mu^\pm$



$\pi^\pm$



Due to unitarity, the possible Earth flavor ratios for a given initial flavor composition is confined.

Calculating $\bar{P}_{\nu_\alpha \to \nu_\beta}(E)$

The oscillation probability depends on the neutrino propagation hamiltonian

$$H(E) = V(E)^\dagger \begin{pmatrix} \Delta_1(E) & 0 & 0 \\ 0 & \Delta_2(E) & 0 \\ 0 & 0 & \Delta_3(E) \end{pmatrix} V(E)$$

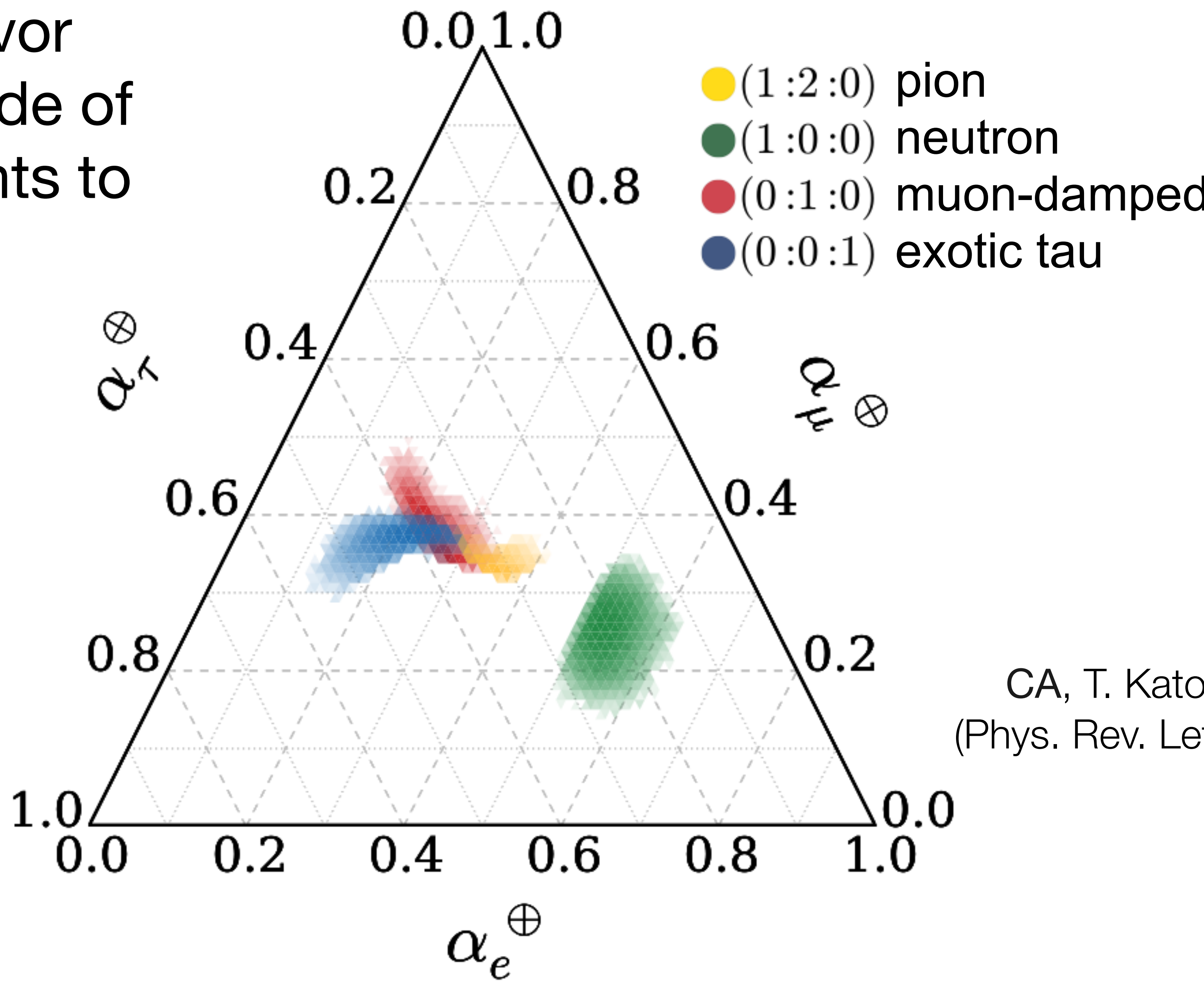
Since the oscillation length is much smaller than the distance of the sources

$$\bar{P}_{\nu_\alpha \to \nu_\beta}(E) = \sum_i |V_{\alpha i}|^2 \, |V_{\beta i}|^2$$

Oscillation probabilities depend only on the mixing elements!

After oscillations where will the different sources end up?

Measuring a flavor composition outside of these regions points to new physics!

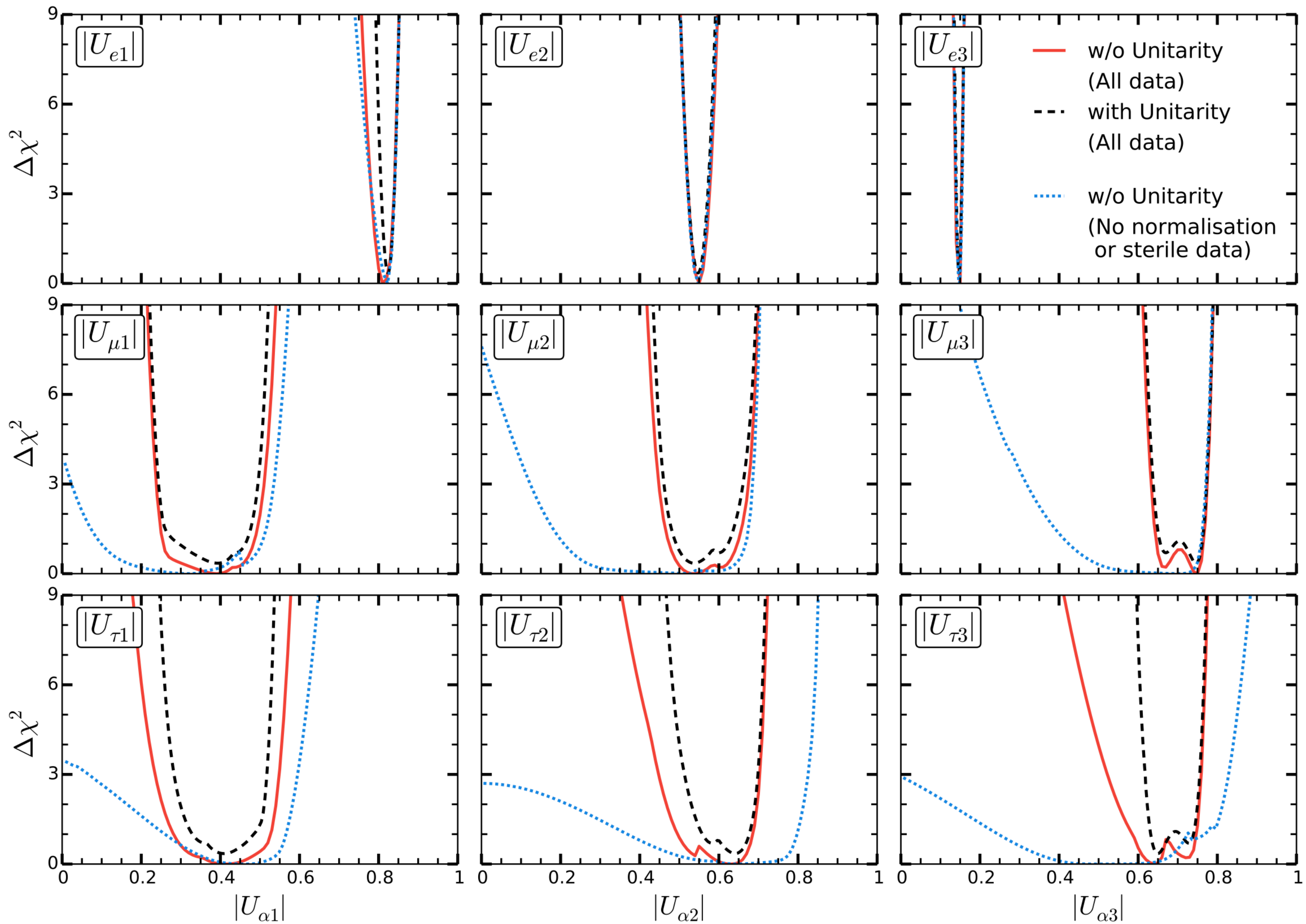


CA, T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

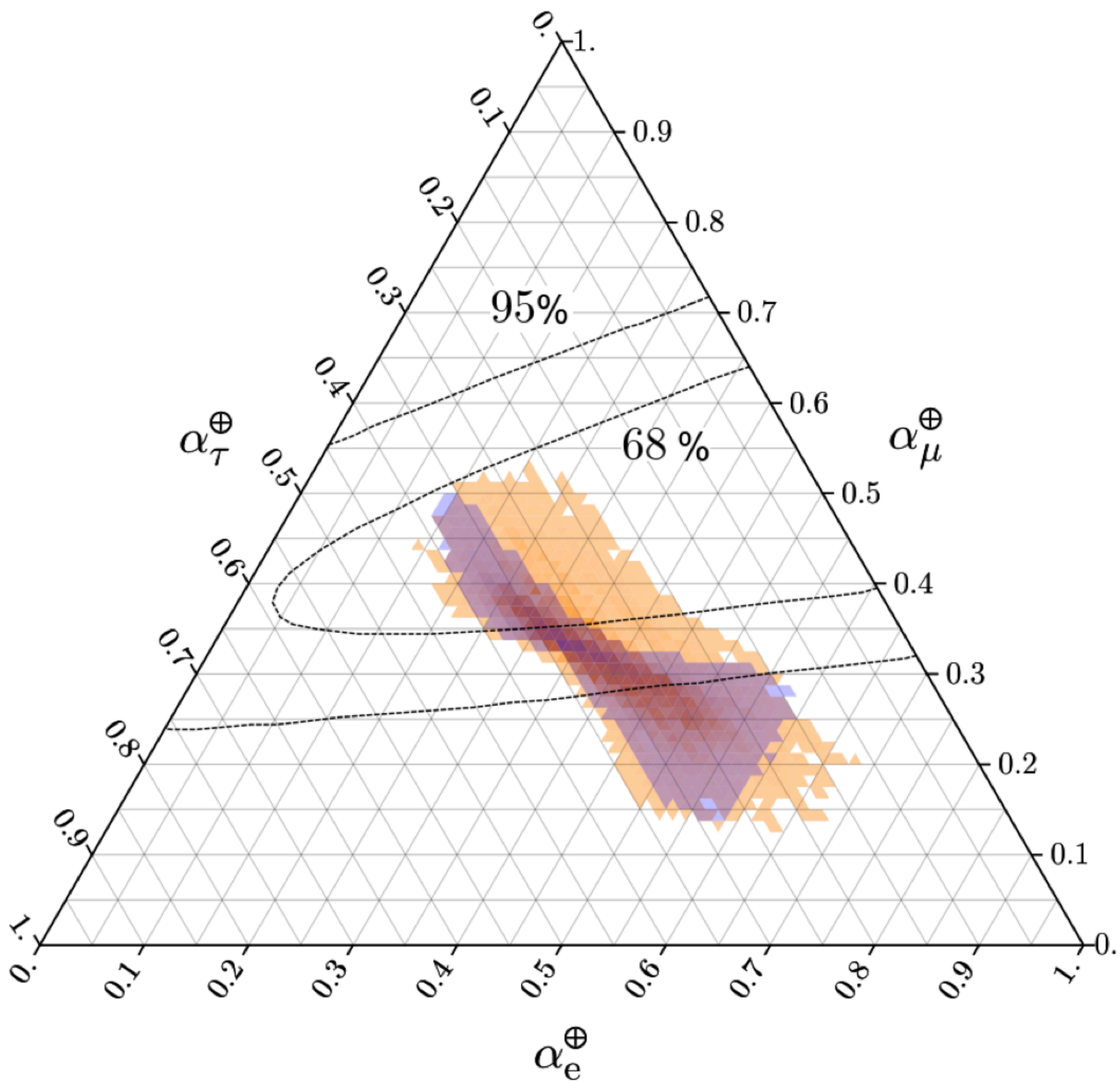
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

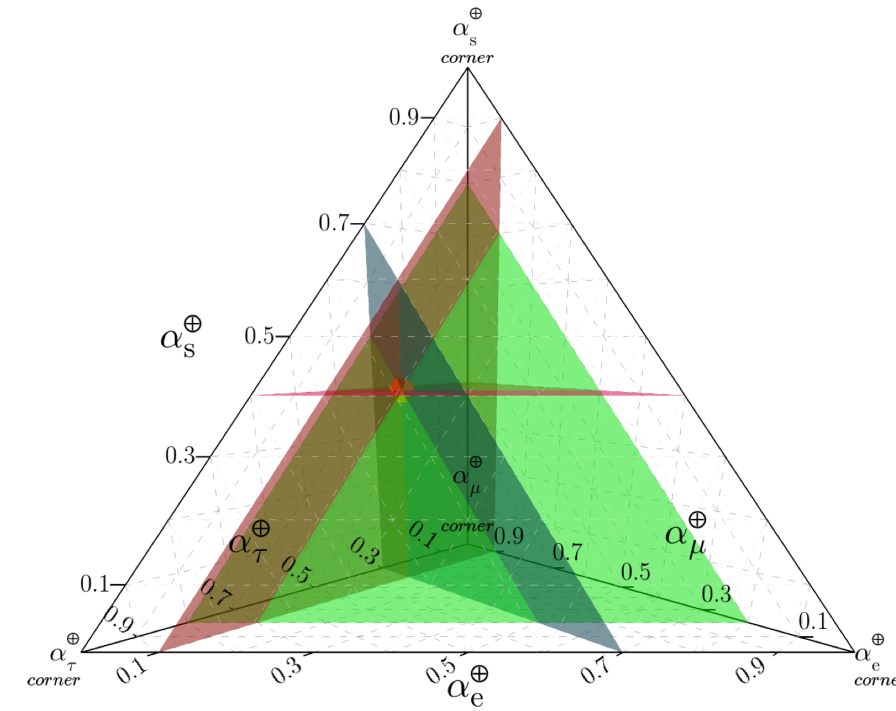
Non-unitarity

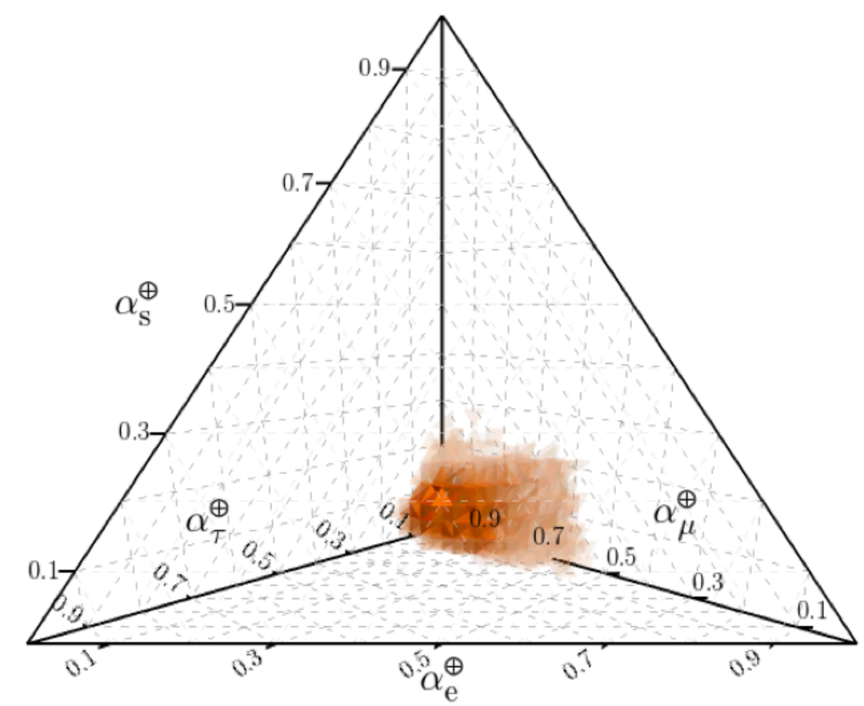
Parke & Ross-Lonergan 1508.05095



Non-unitarity

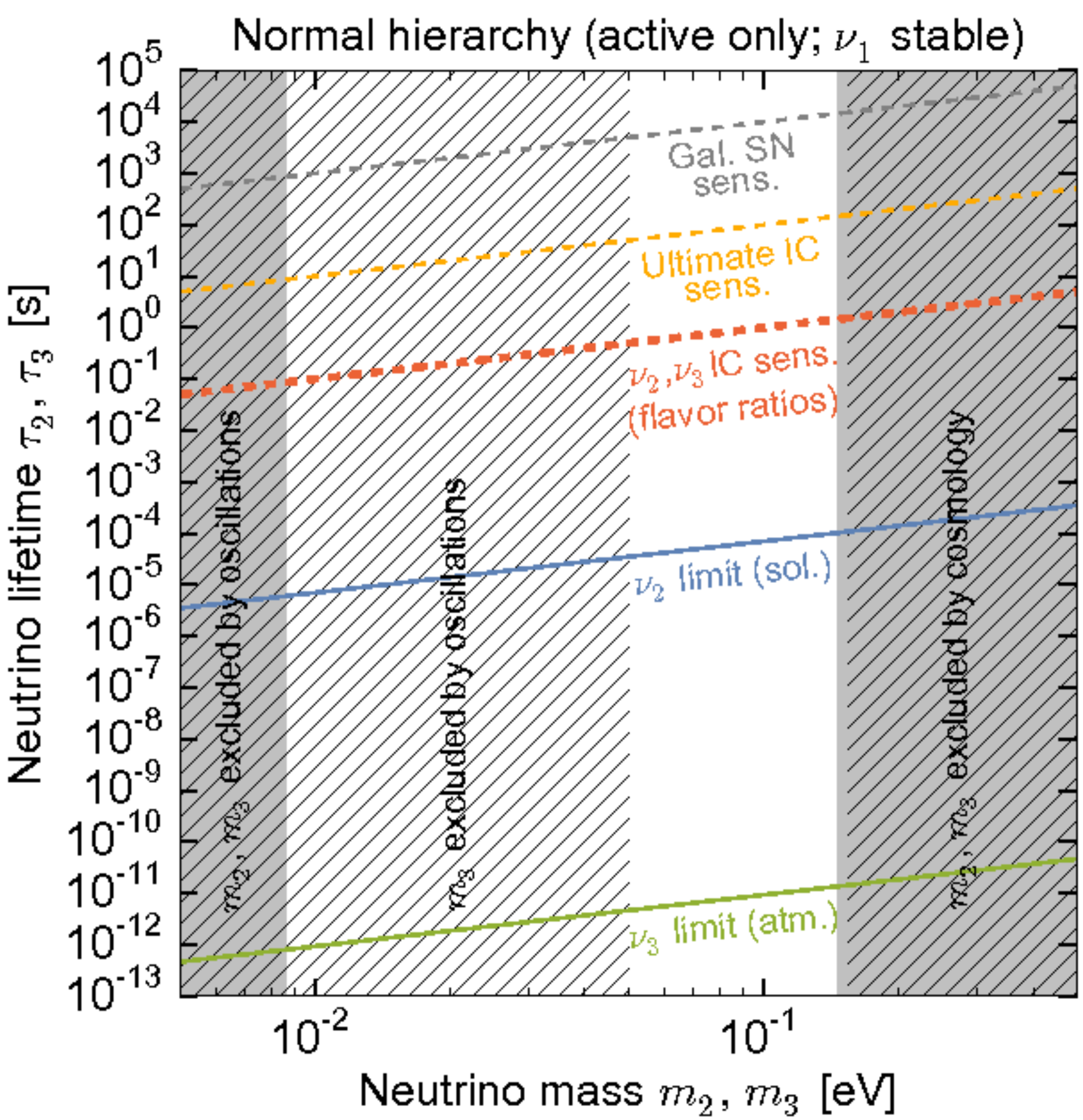


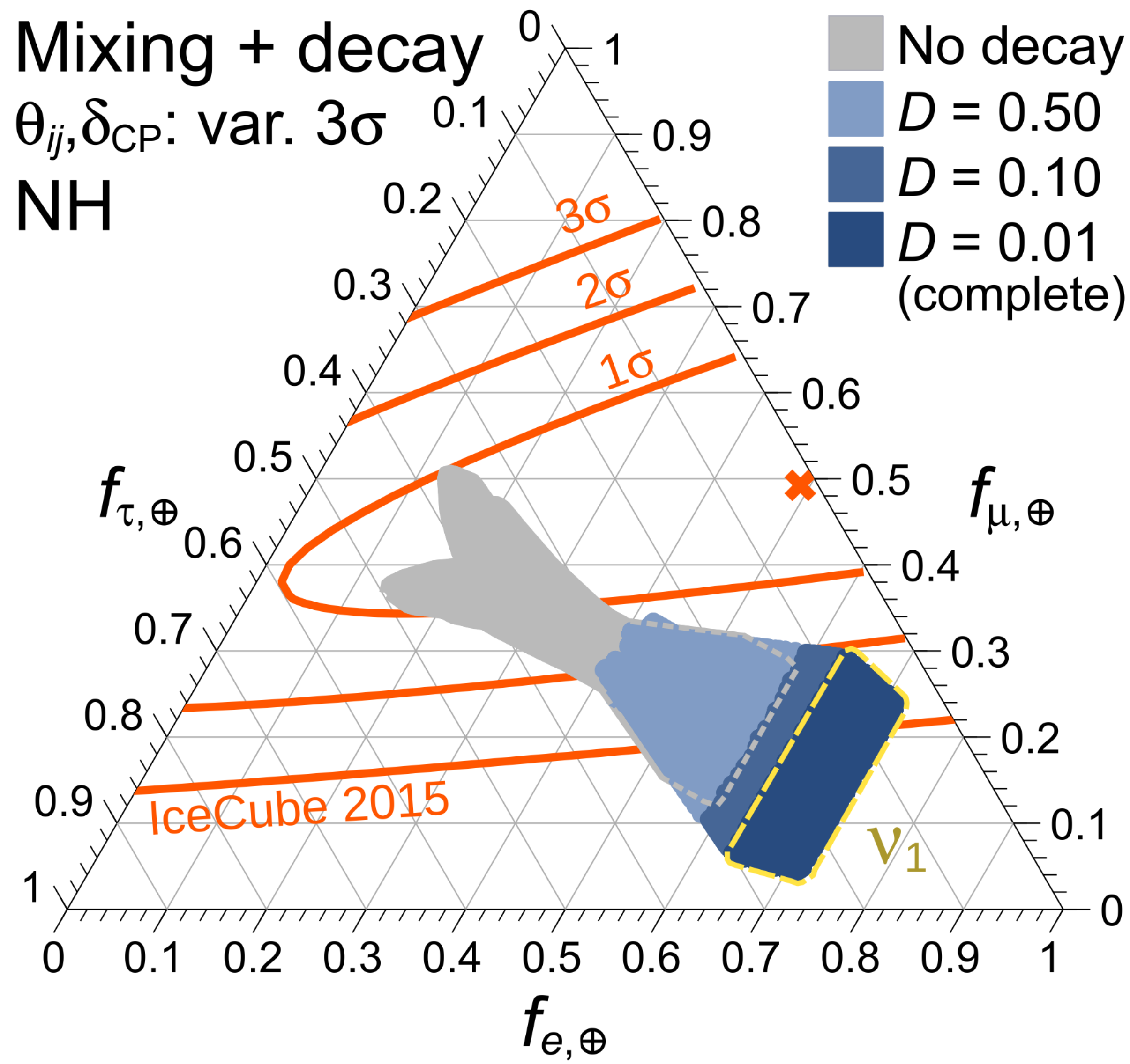




CA, Farrag, Katori, Khandelwal, Mandalia, Salvado arXiv:1909.05341

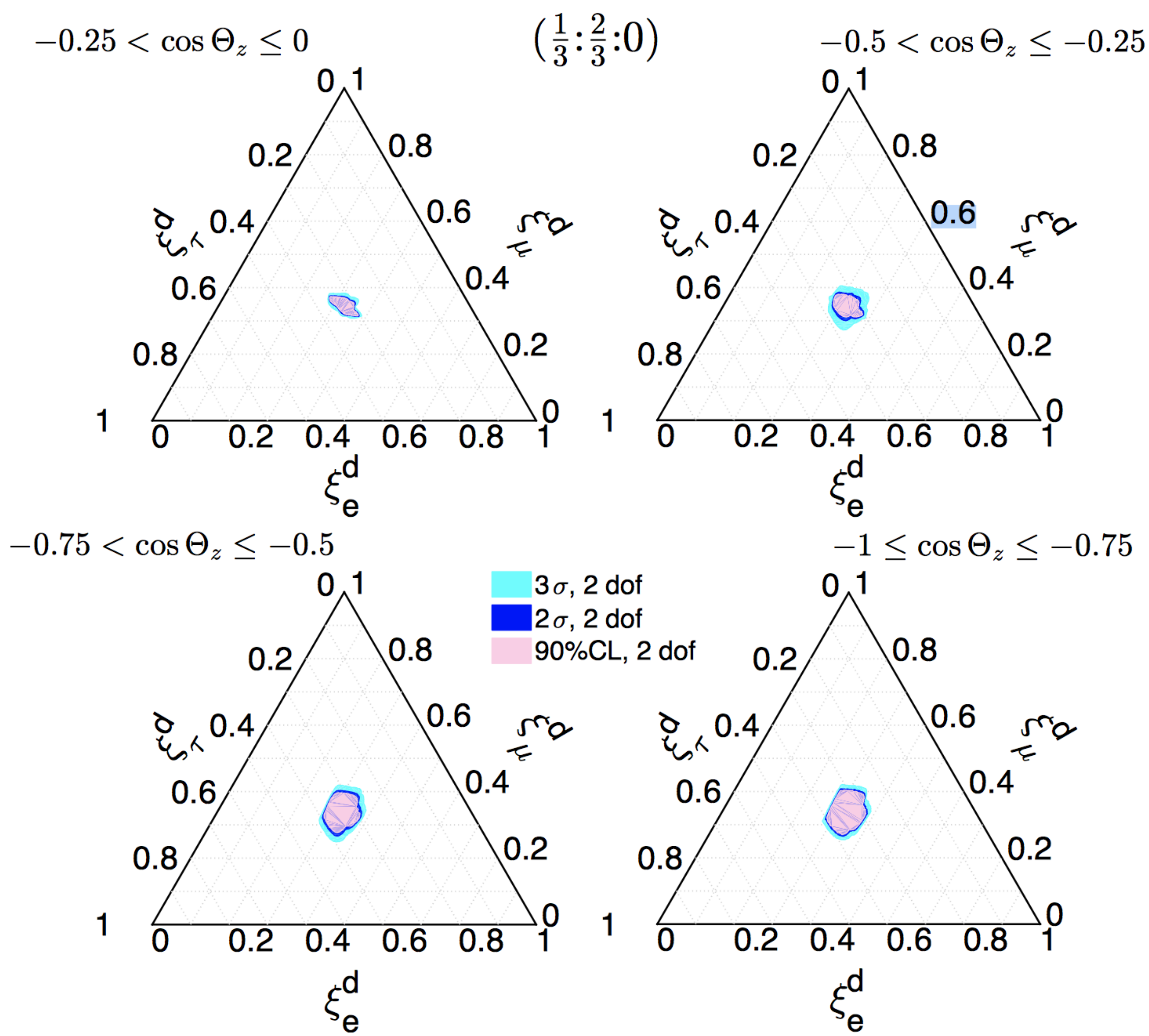
+Neutrino decay





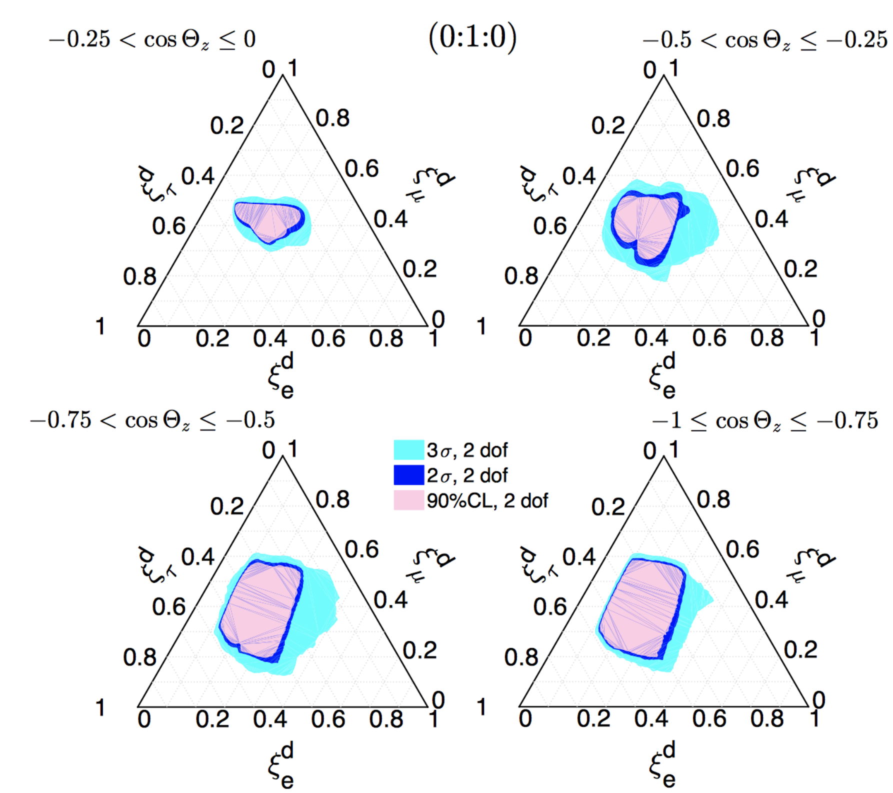
M. Bustamante, J. Beacom, K. Murase (1610.02096)

+ NSI@Earth



In the pion scenario NSI effects are small.

This is not the case for other initial flavor ratios.

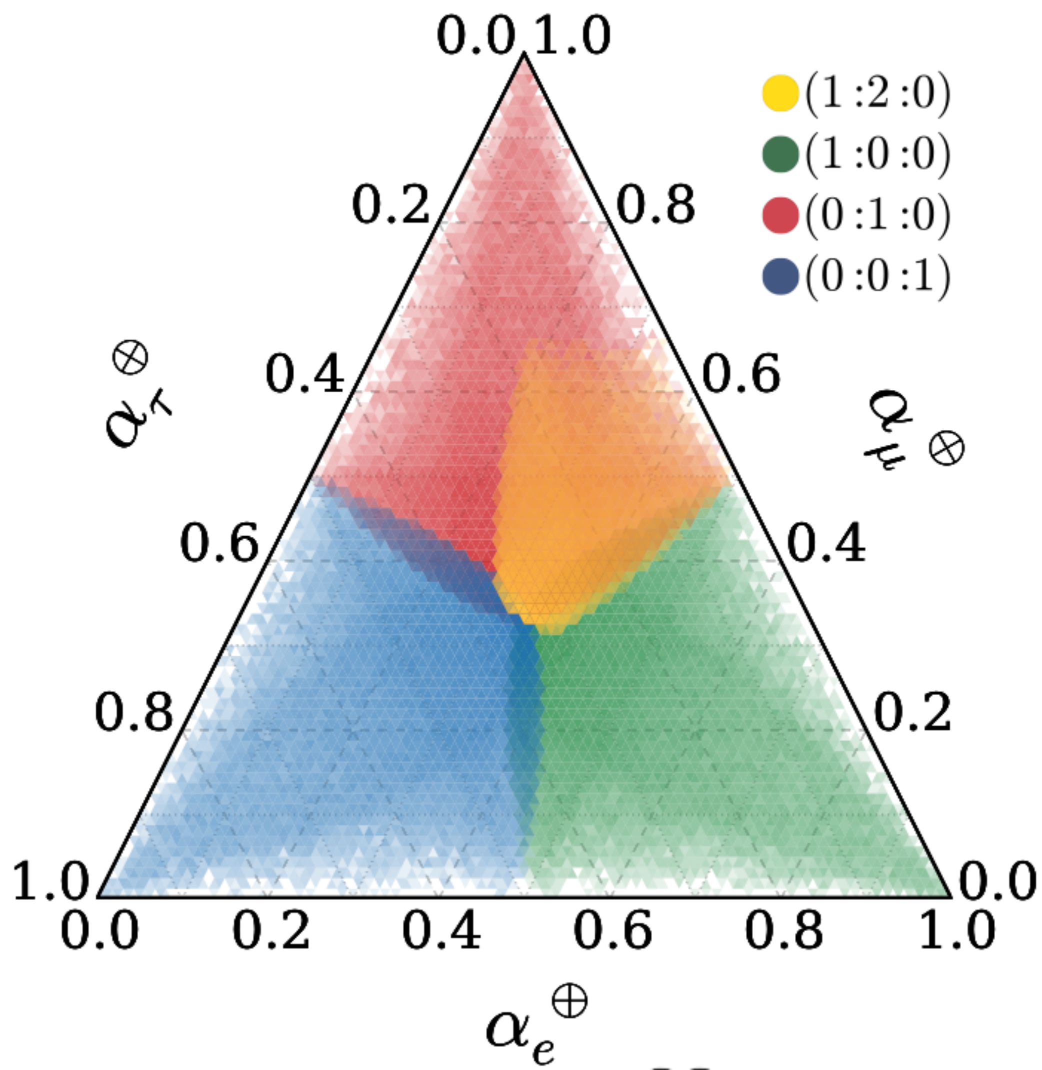


Gonzalez-Garcia et al. Astroparticle Physics 84 (2016) 15-22

+ New physics: effective operators

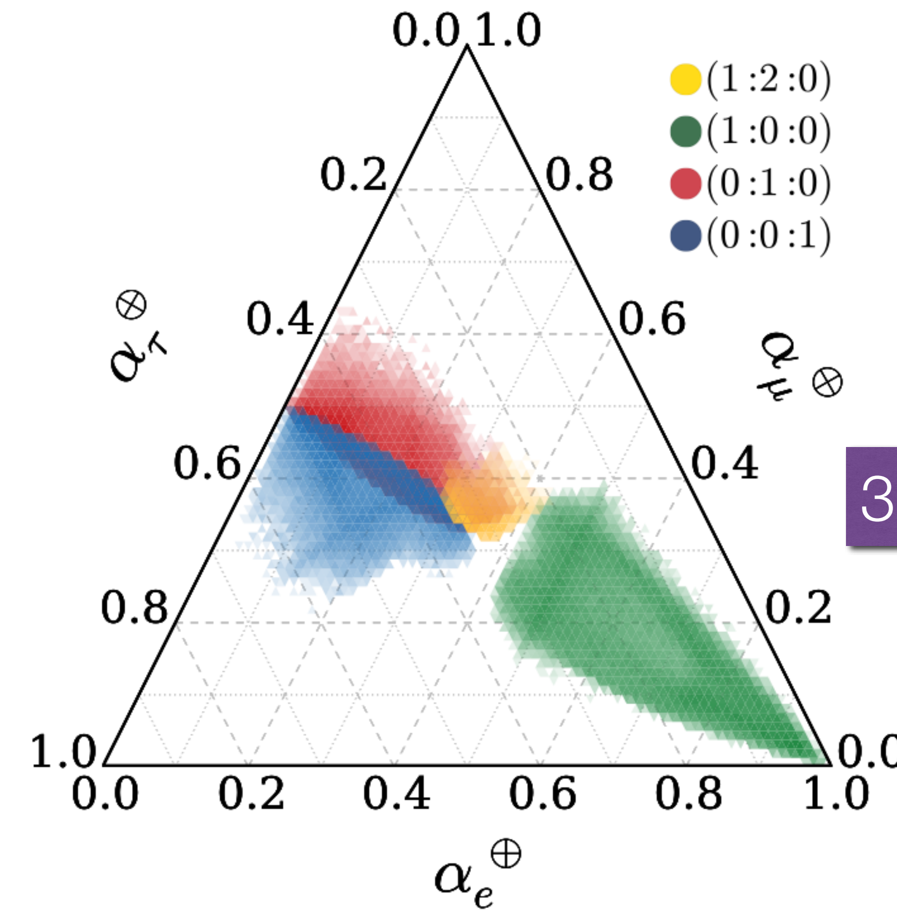
$$H = \frac{1}{2E} U M^2 U^\dagger + \boxed{\sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger}$$

(setting operators scales to current SK bounds)

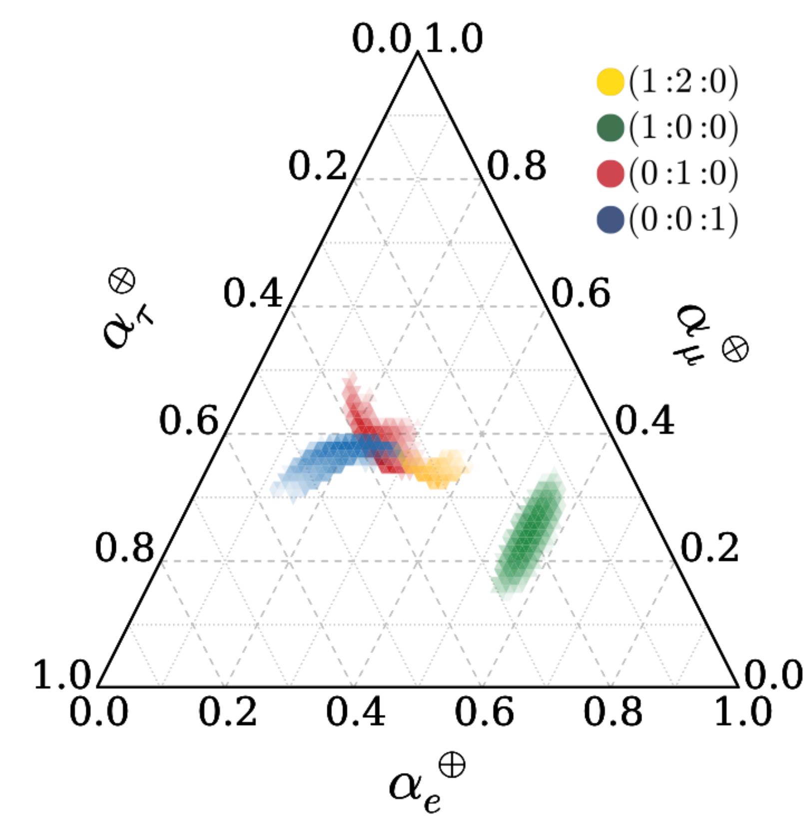


$O_0 \sim \mathrm{O}(10^{-23})$ GeV

$O_0 \sim \mathrm{O}(10^{-26})$ GeV



35 TeV

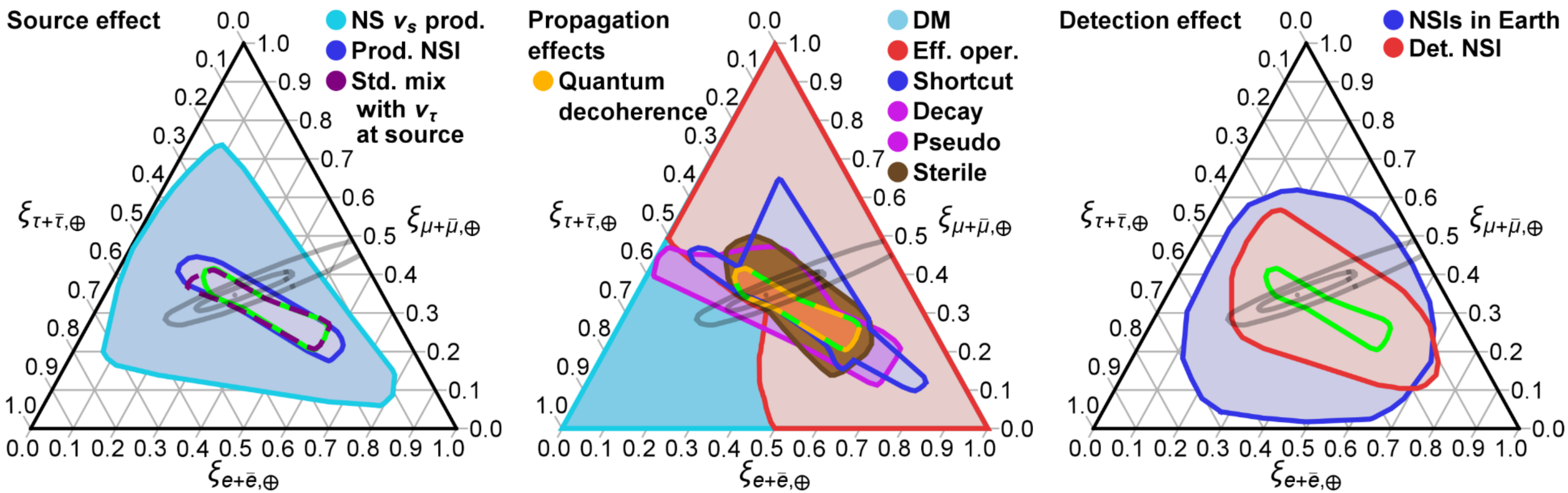


1 PeV

$O_0 \sim \mathrm{O}(10^{-29})$ GeV

Other New Physics Effects on the Flavor Triangle

Rasmussen et al arXiv:1707.07684

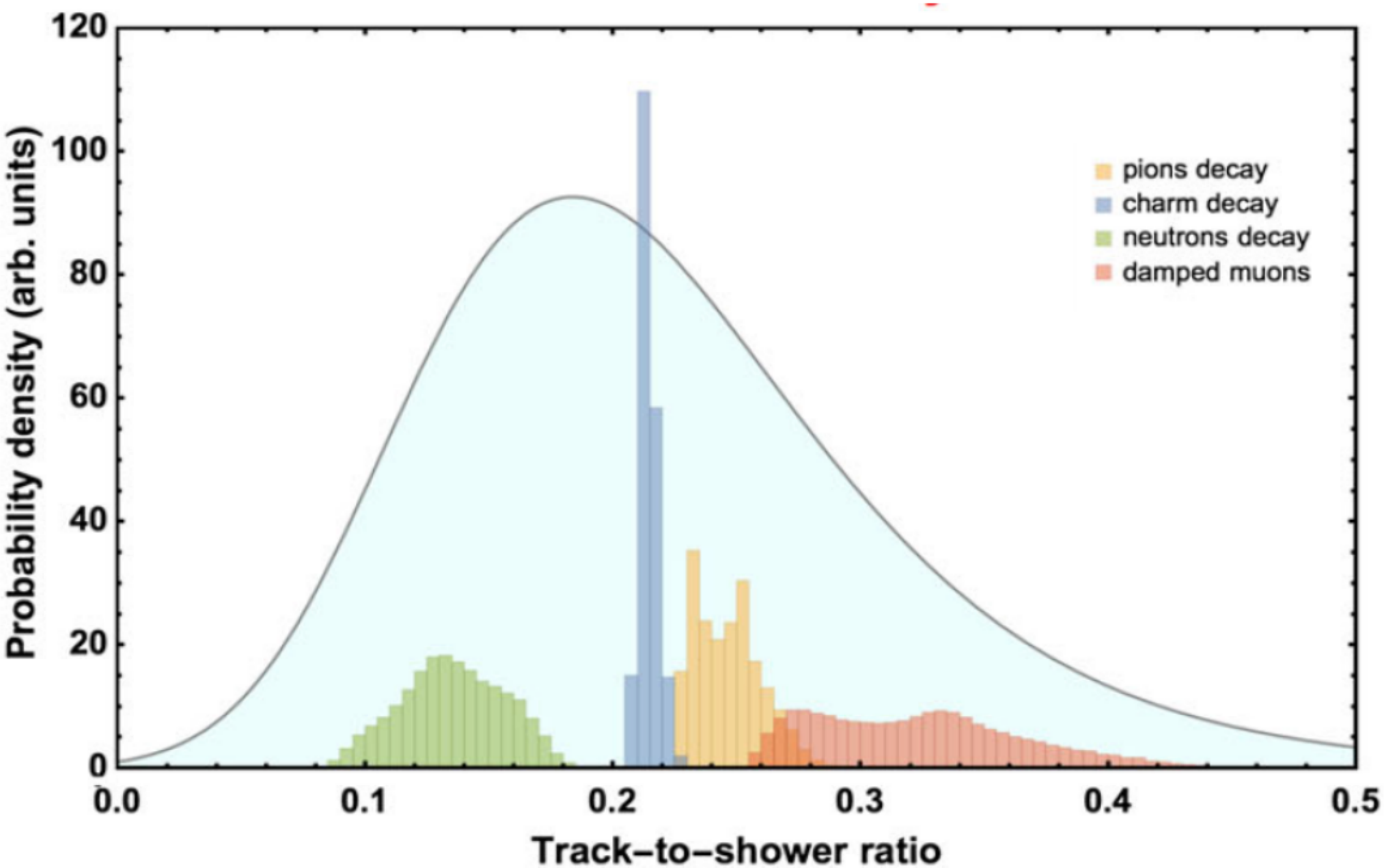


Learned & Pakvasa arXiv:hep-ph/9405296, Mena et al arXiv:1404.0017, CA et al arXiv:1506.02043, Bustamante et al arXiv:1506.02645, Brdar et al arXiv:1611.04598, Gonzalez-Garcia et al arXiv:1605.08055, Rasmussen et al arXiv:1707.07684, Etc

Folding in with the effective areas we can get expected track to cascade ratios

Palladino et al,PRL114(2015)171101

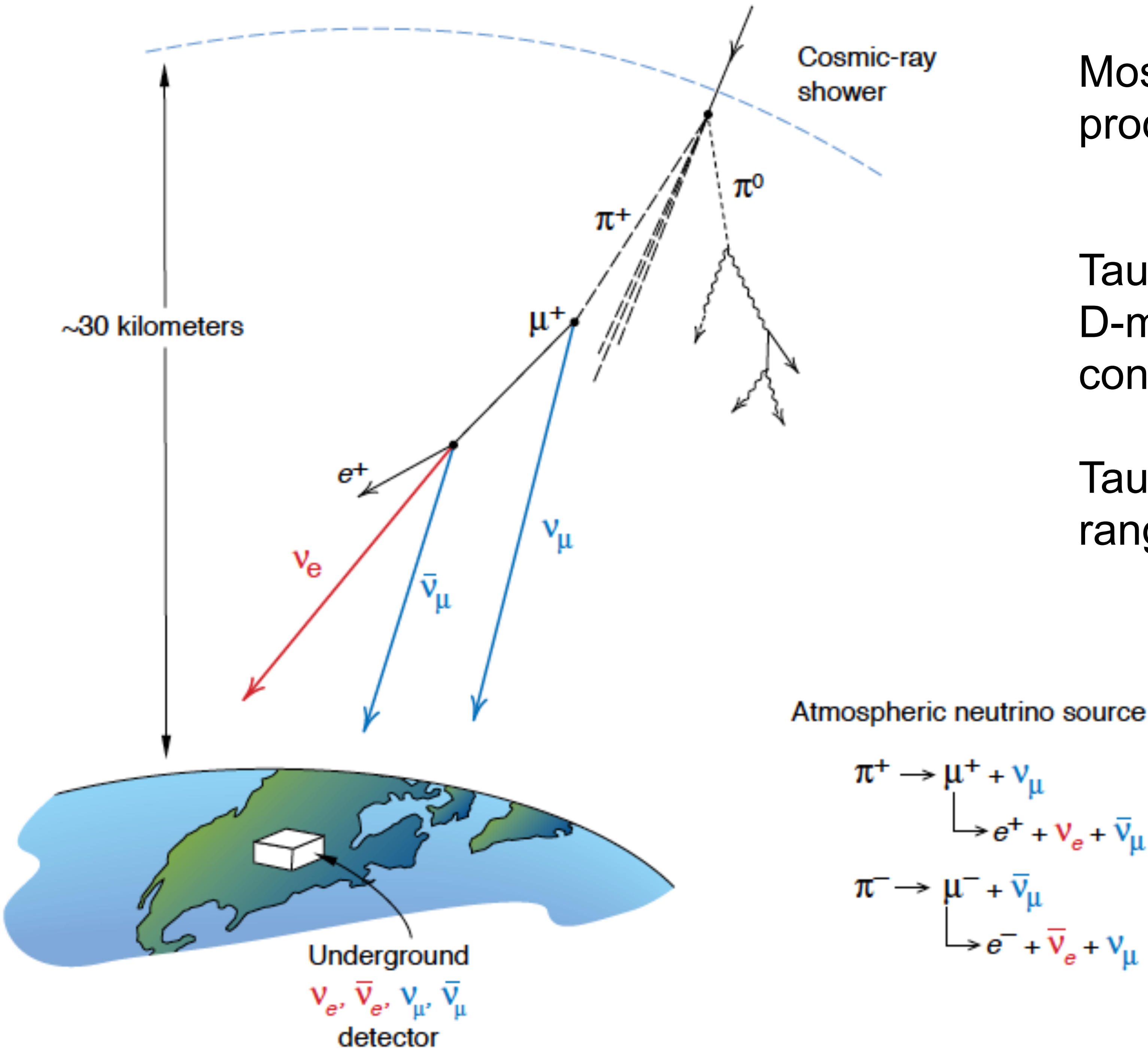
$$N_S = 8.4F_e + 0.9F_\mu + 6.3F_\tau, \qquad N_T = 3.7F_\mu.$$



Ternary classification

To tau or not to tau, that is the question.
Whether 'tis nobler underground to measure,
tracks and cascades of outrageous flavors,
or to hunt taus against a sea of troubles
and by good fortune get them.

Find tau neutrinos ~
Astrophysical neutrinos



Most atmospheric neutrinos are mostly produced by either pion or kaon decay.

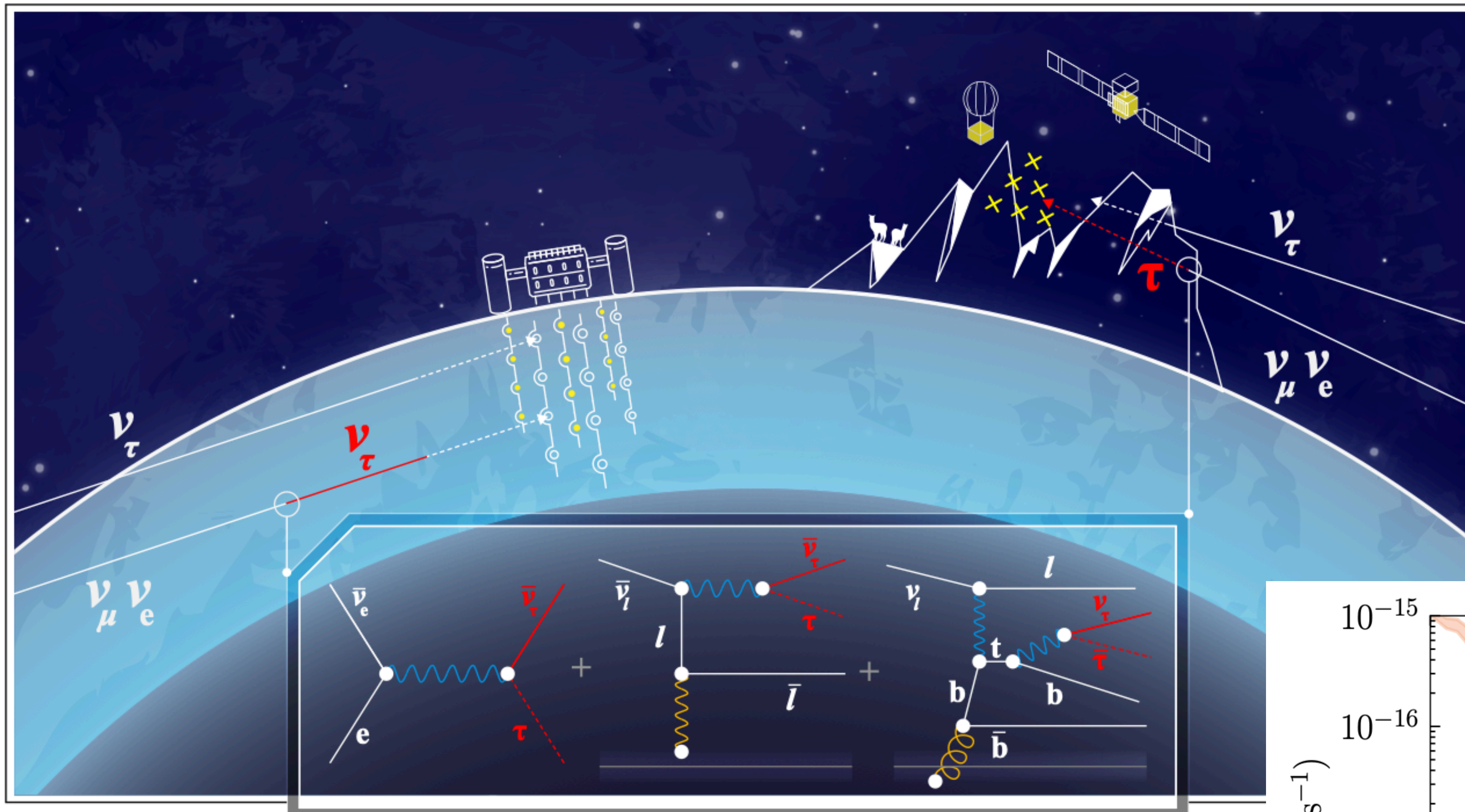
Tau neutrinos are predominantly produced by D-meson decay, which is a very small contribution.

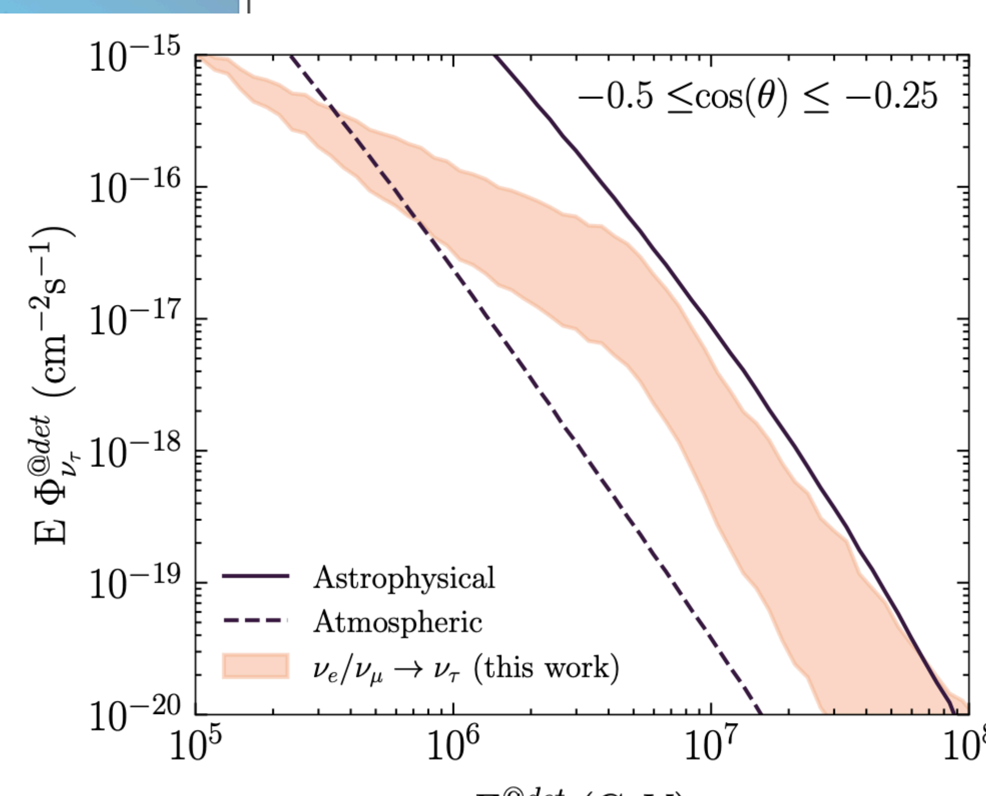
Tau neutrino contribution negligible in energy range of interest.

Strategy:

Search for high-energy double cascade deposition

Find tau neutrinos ~ Astrophysical neutrinos (caveat)



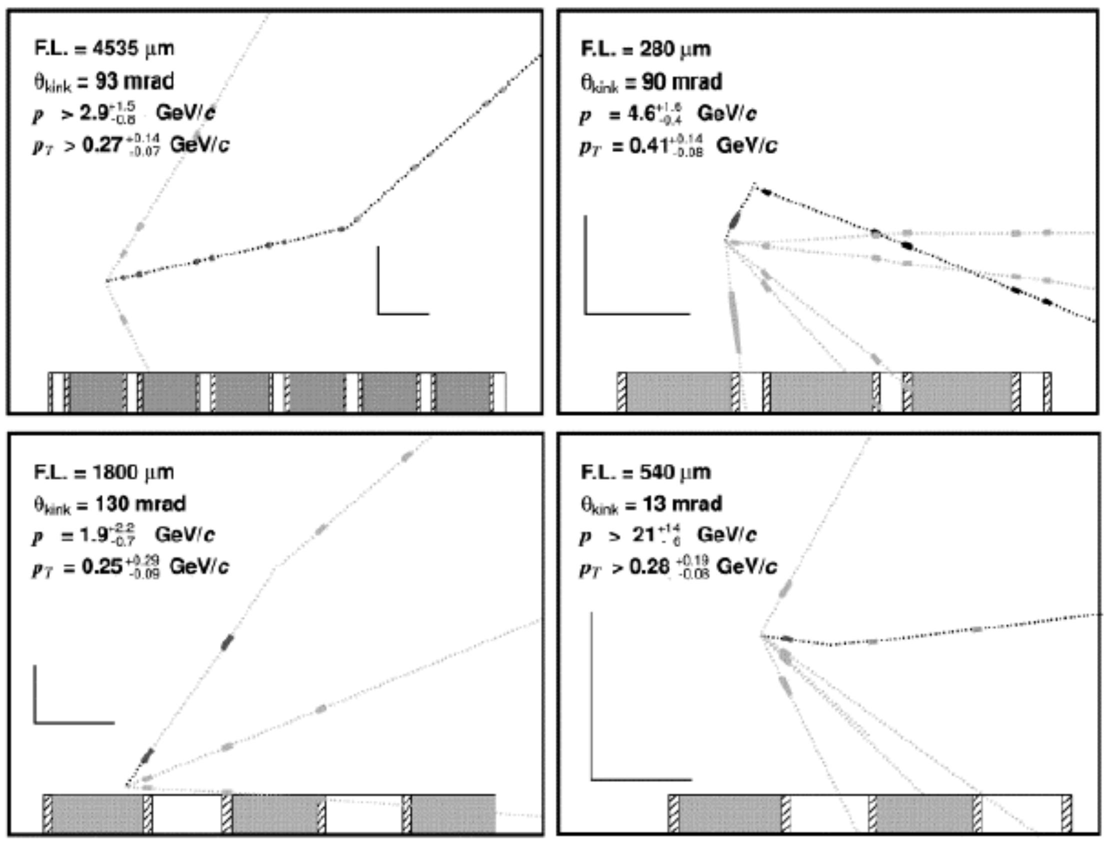


A. Garcia-Soto, P. Zhelnin, I. Safa, CA, arXiv:2112.06937

Strategy Three: Find tau neutrinos

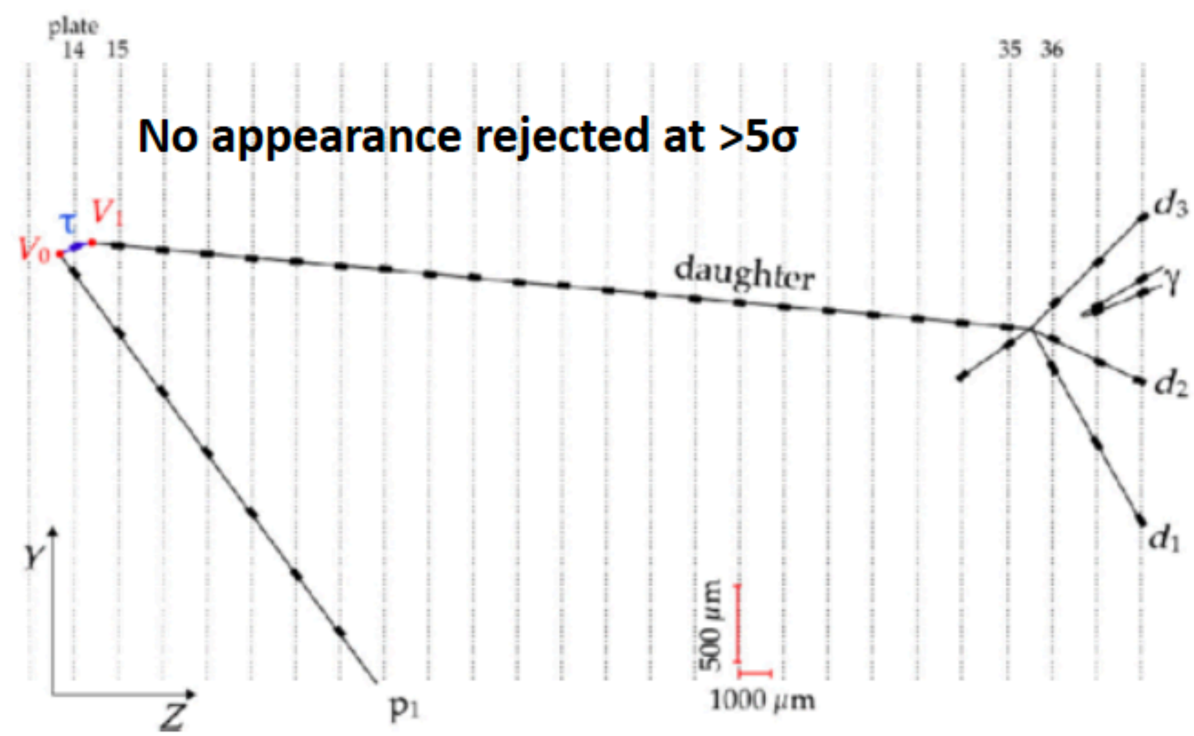
Detecting anthropogenic tau neutrinos at neutrino experiments

DONUT: charmed mesons (no oscillation) and emulsion



DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion

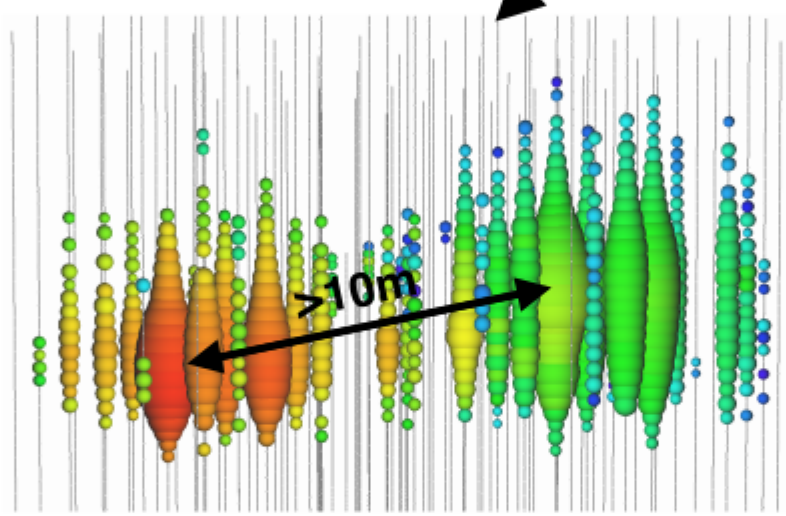


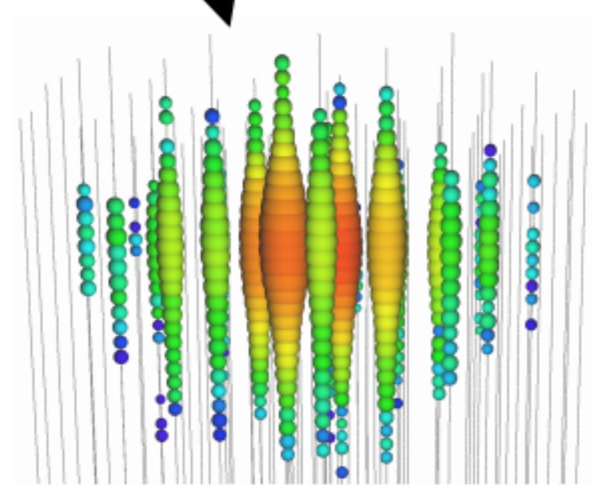
OPERA Phys. Rev. Lett. 115, 121802 (2015)

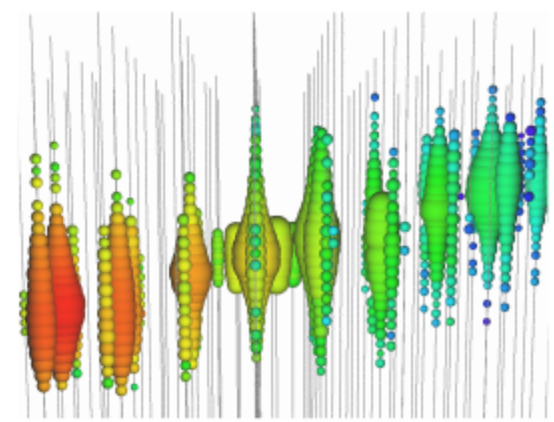
tau decay length = $\gamma\, c\, \tau$ = 50m per PeV

All HESE events in 7.5 years of data above 60 TeV

Observables from direct double-cascade reconstruction







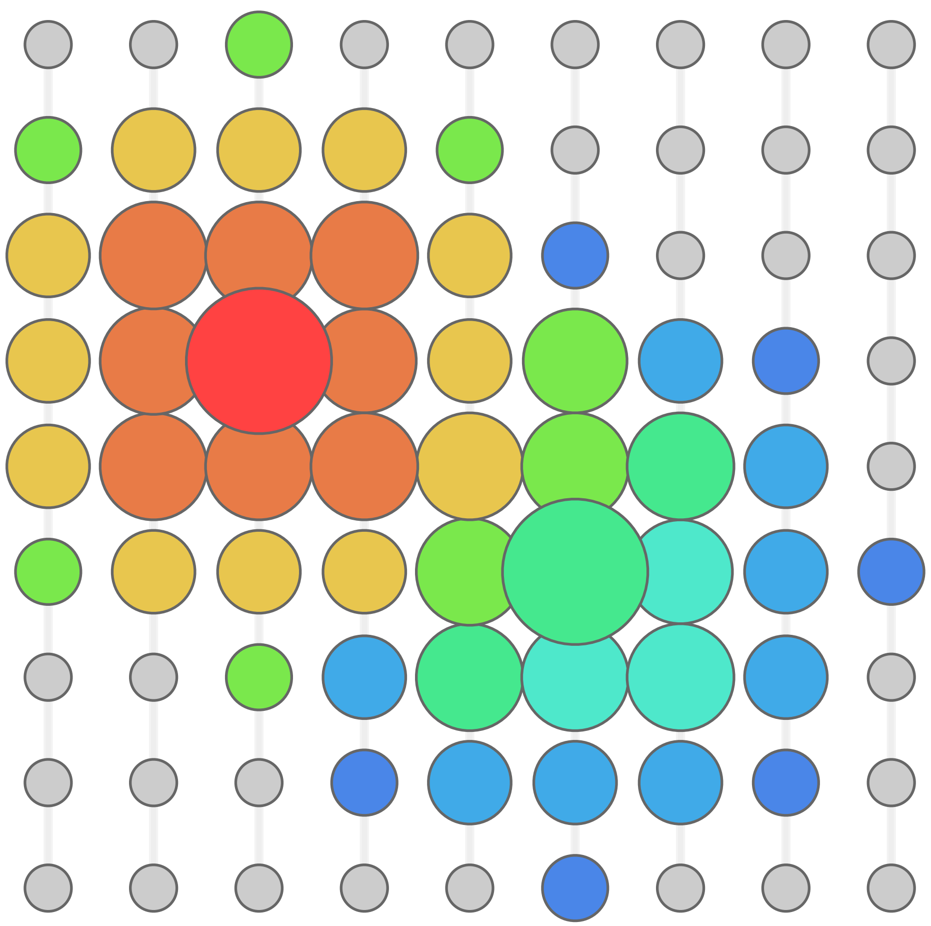
Double cascade sample:
ν_τ + N → τ + hadrons $\xrightarrow{>10m}$
hadrons / electrons

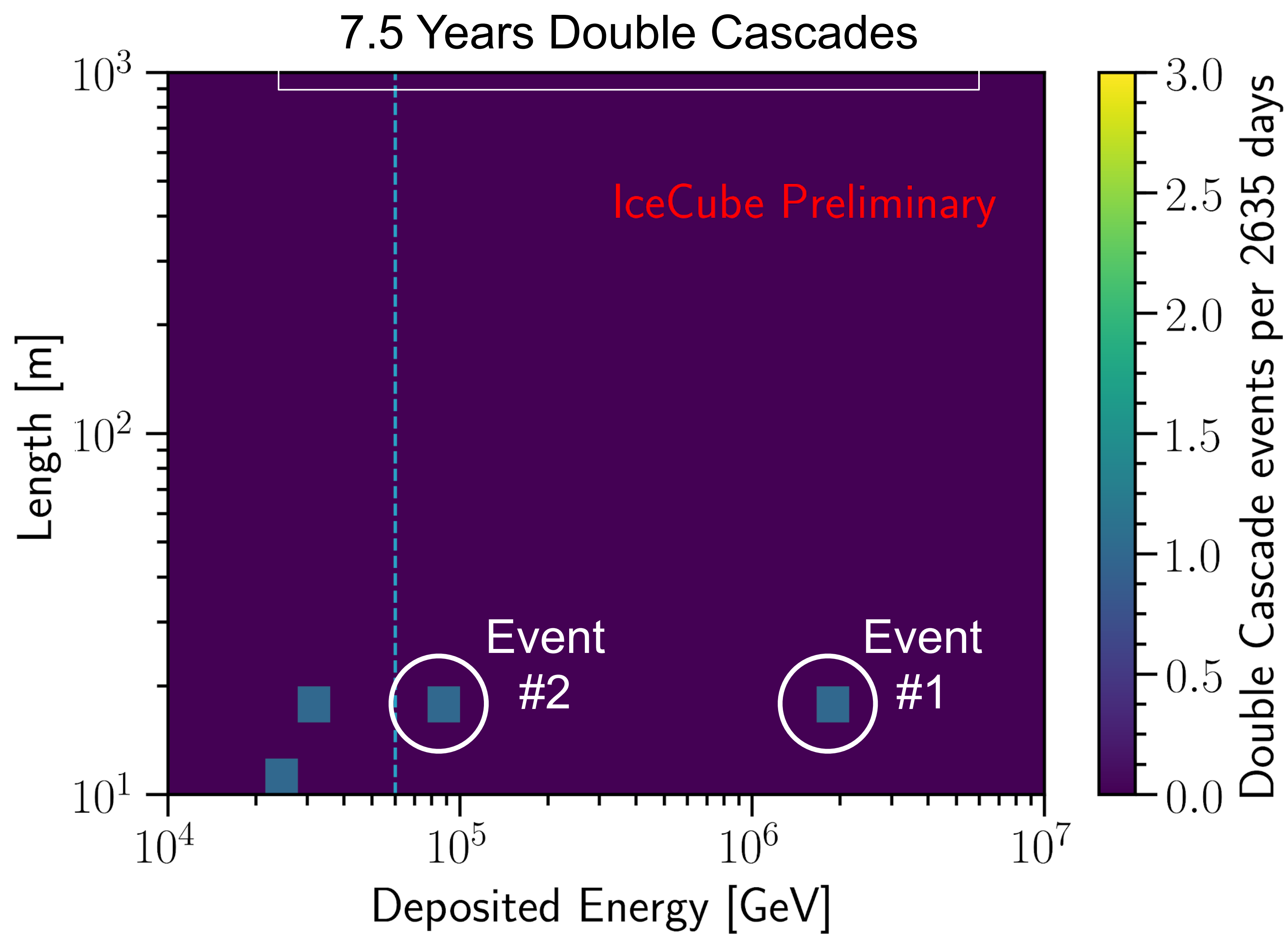
Single cascade sample with not well-reconstructable ν_τ – CC interactions, all other cascades

Track sample with ν_τ – CC interactions creating μ, ν_μ – and atm. μ – tracks

Flavor composition

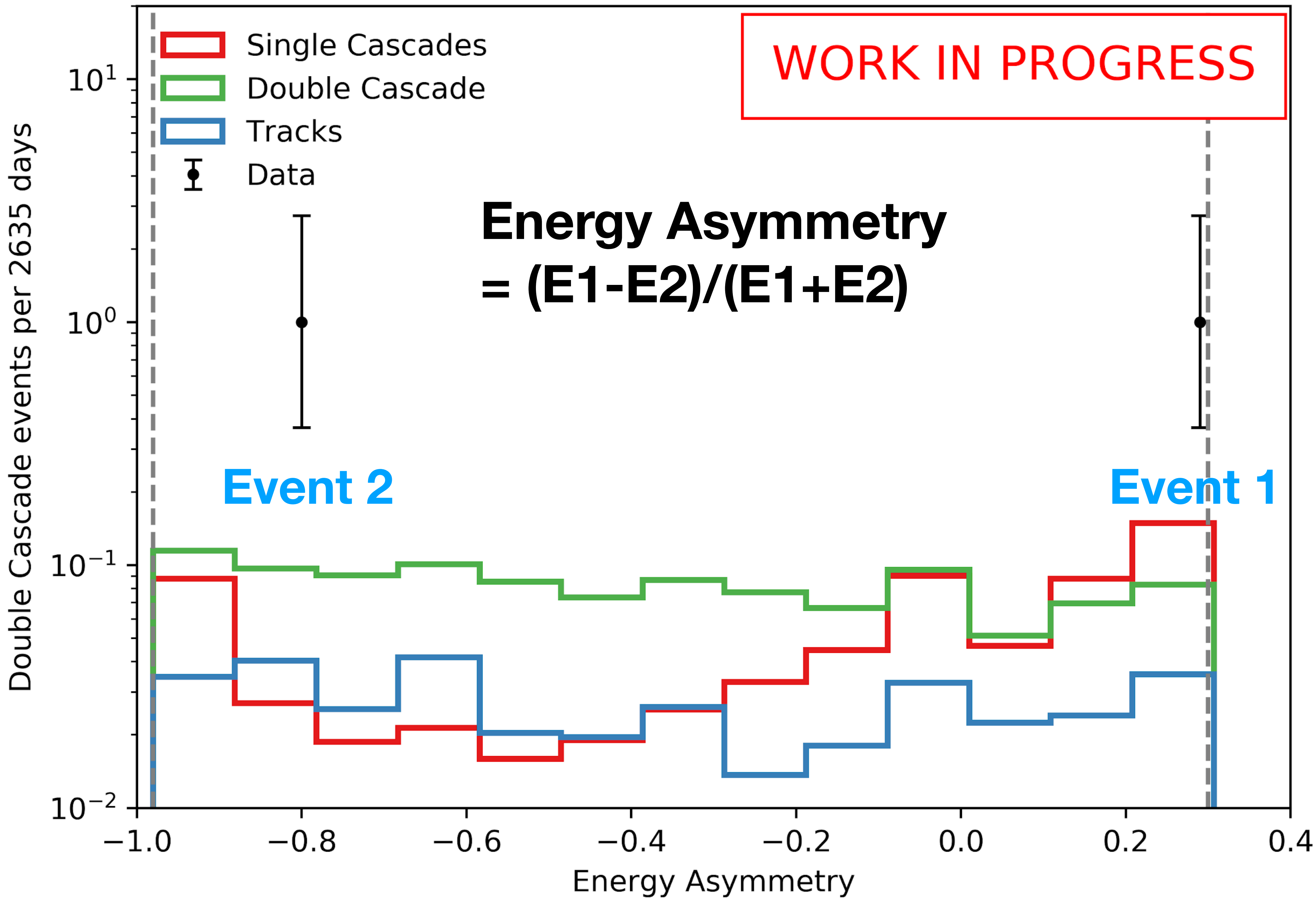
Two tau neutrino candidates observed in 7.5 HESE





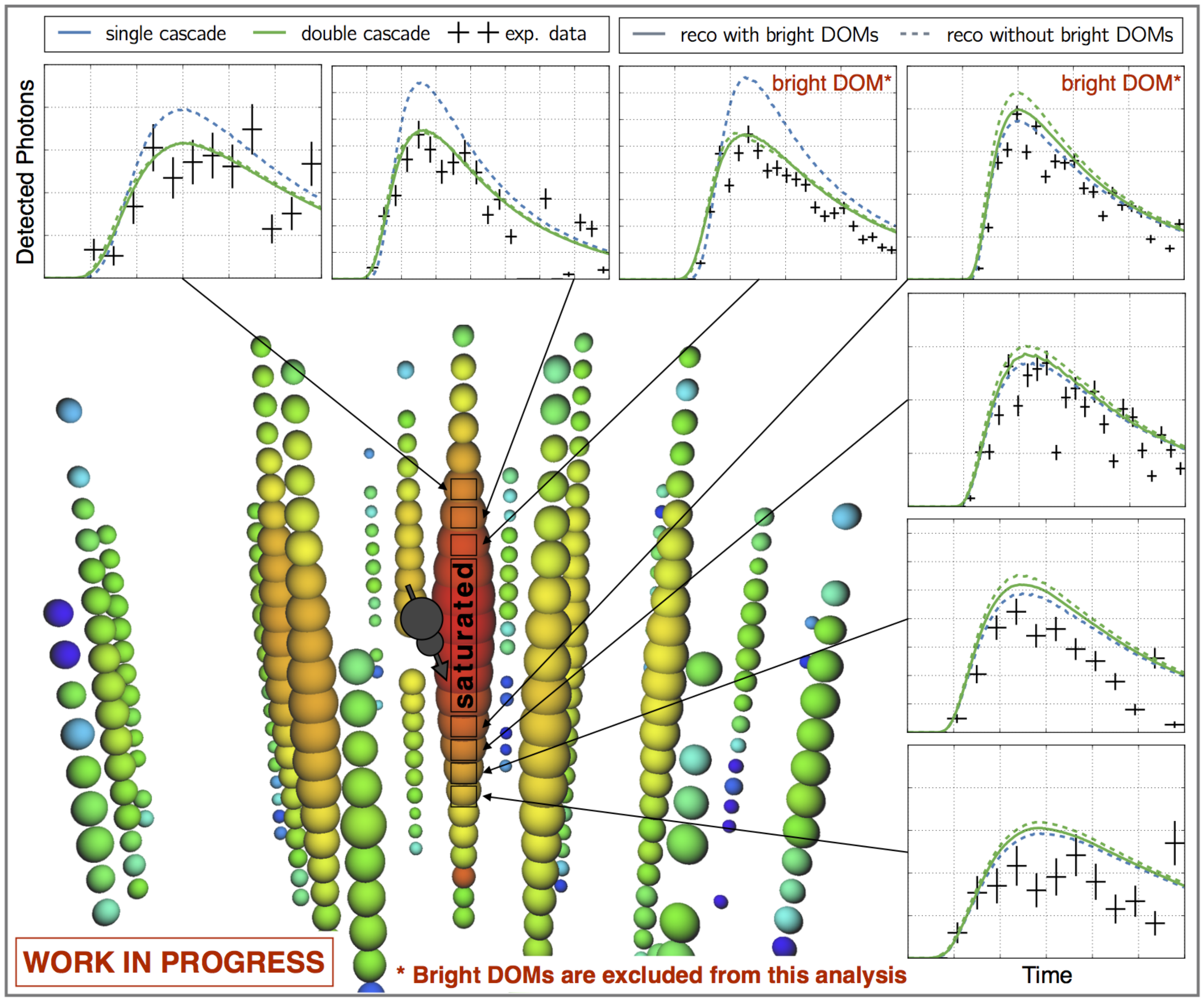
All energies: 4 events
0 new events in 2016 season
0 new events in 2017 season

Above 60TeV: 2 events
0 new events in 2016 season
0 new events in 2017 season



Event 2 is in a region where tau neutrinos are most likely to appear, event 1 is not.

Event 1 (Big bird): PeV event, does not show double bang characteristics on DOMs

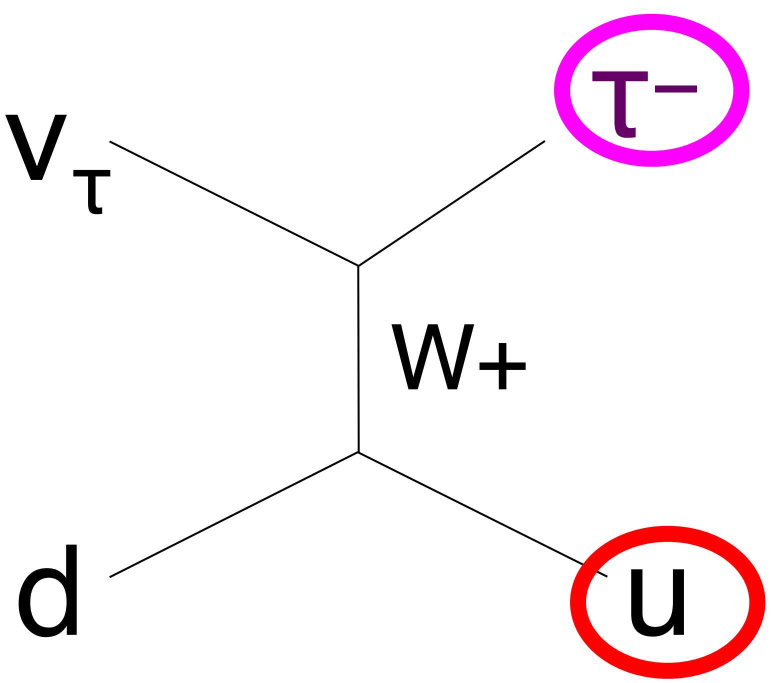


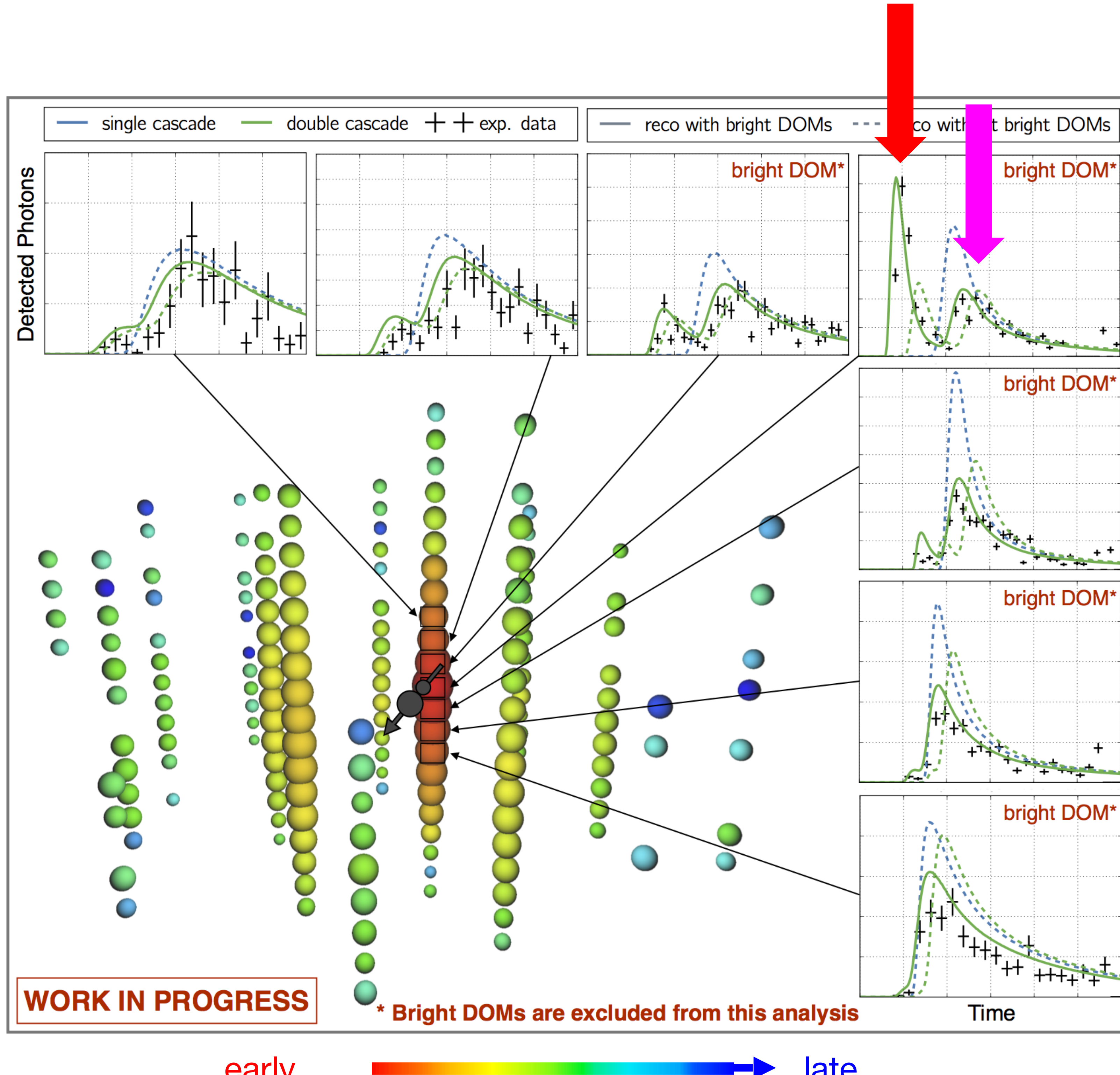
Event 2: First astrophysical ν_τ candidate identified!

Total deposited energy ~ 90 TeV.

First "bang" in time (shower)

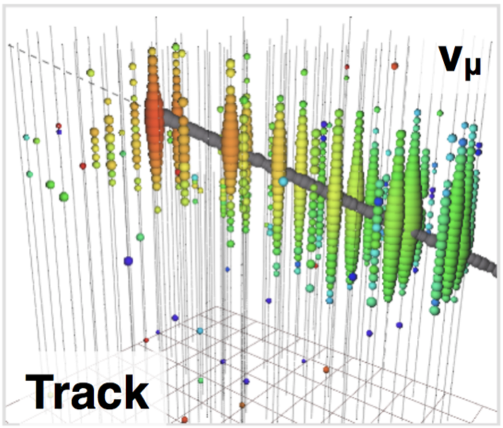
Second "bang" in time (tau decay)

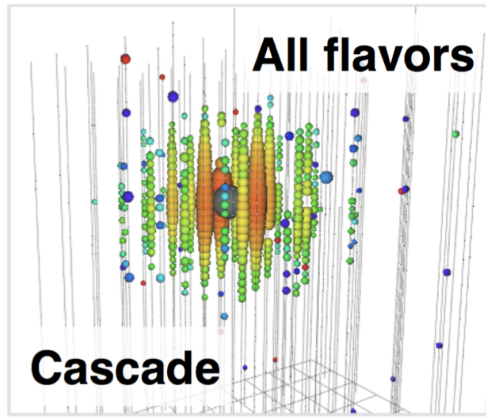


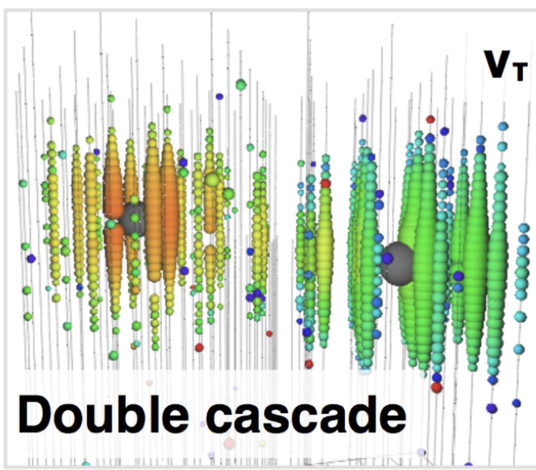


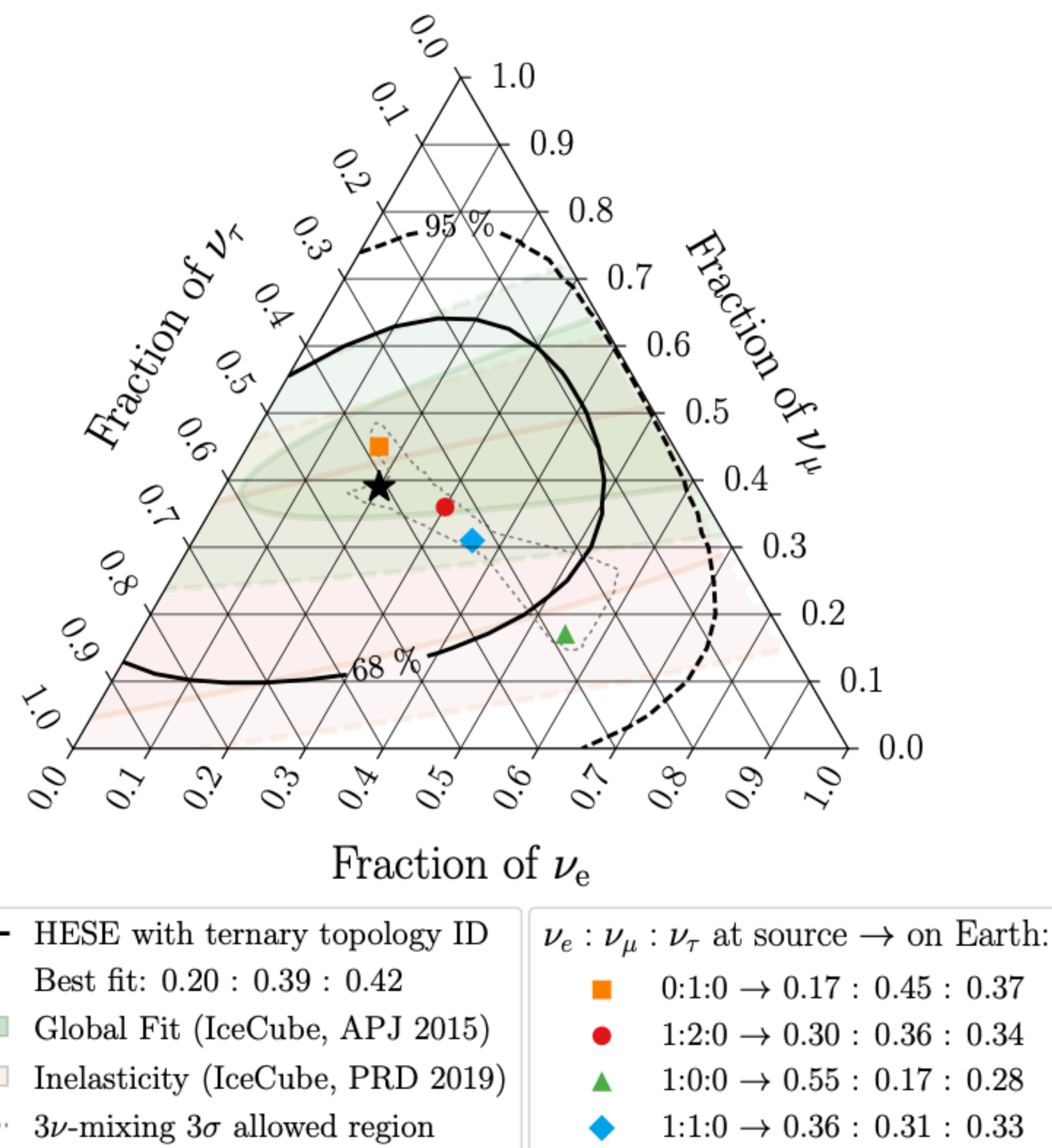
Separation between bangs ~17m,

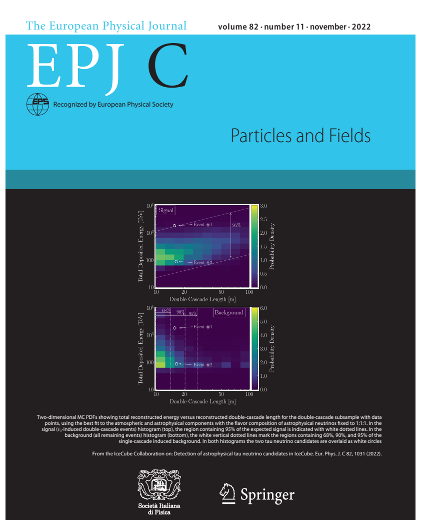
Latest Astrophysical Flavor Measurement





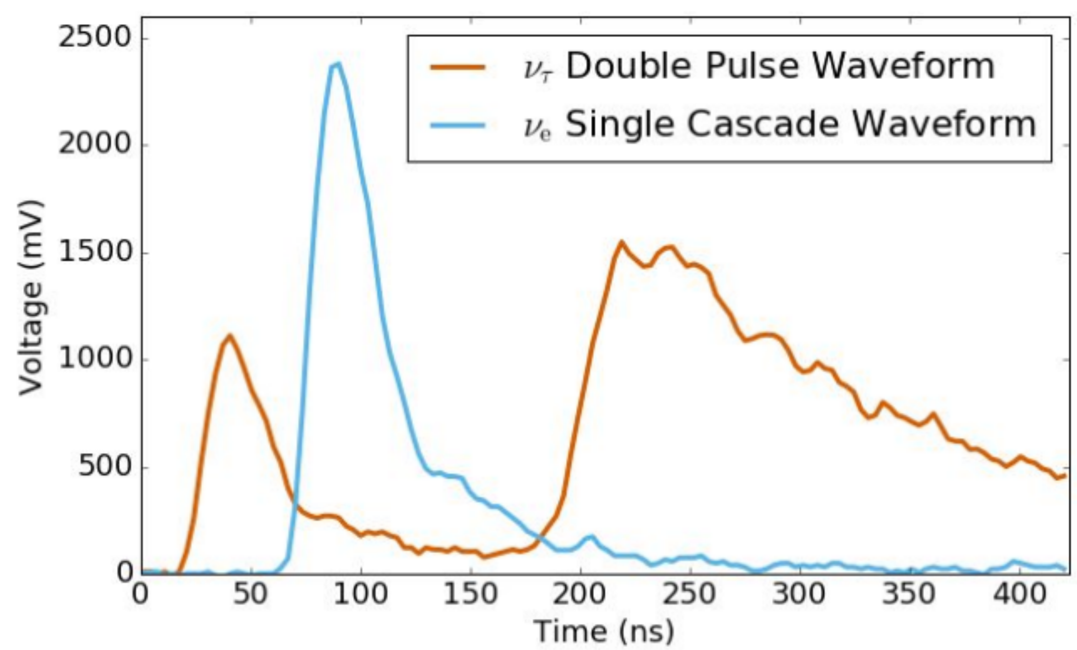




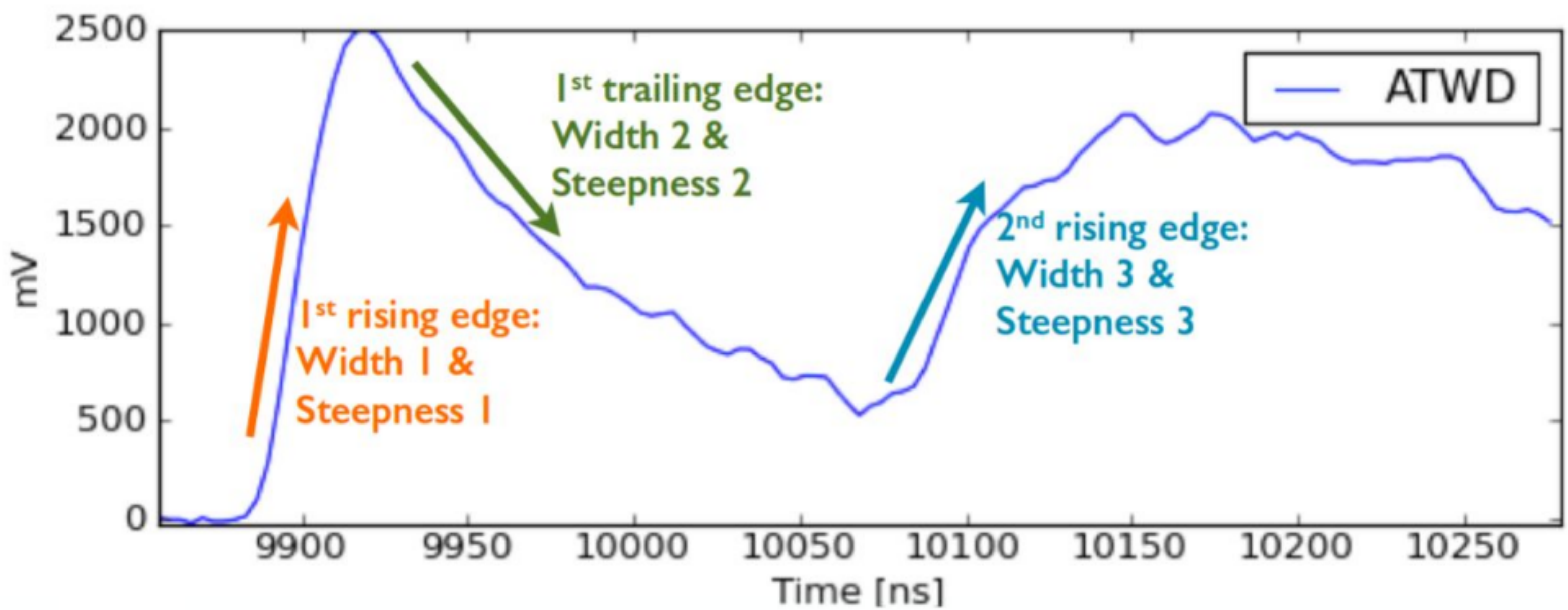


IceCube Collaboration
EPJ-C 82, 1031 (2022)

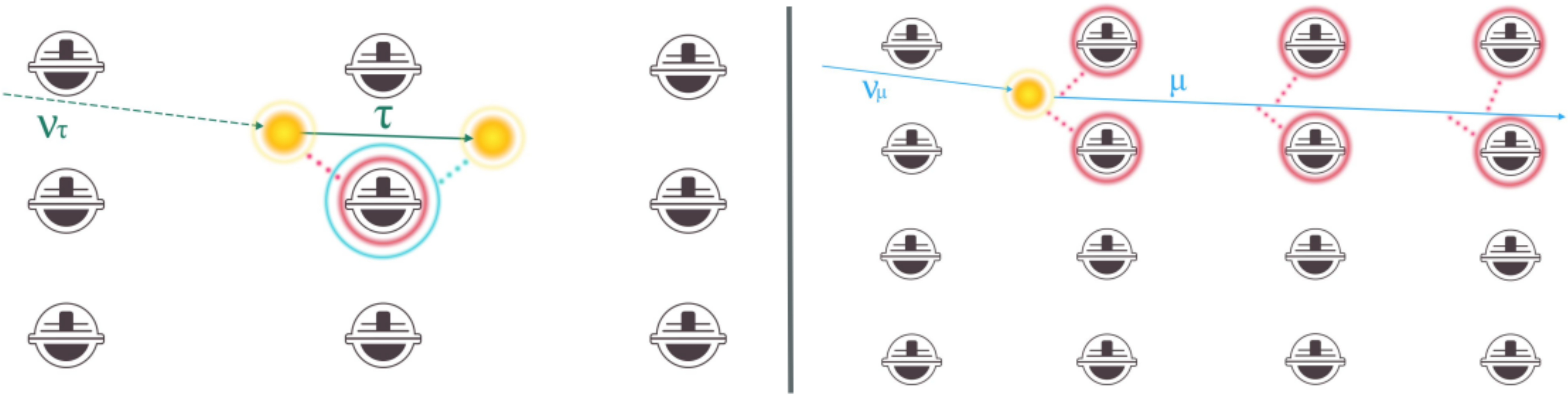
Tau Double Pulse Events



Double Pulse Algorithm (DPA)

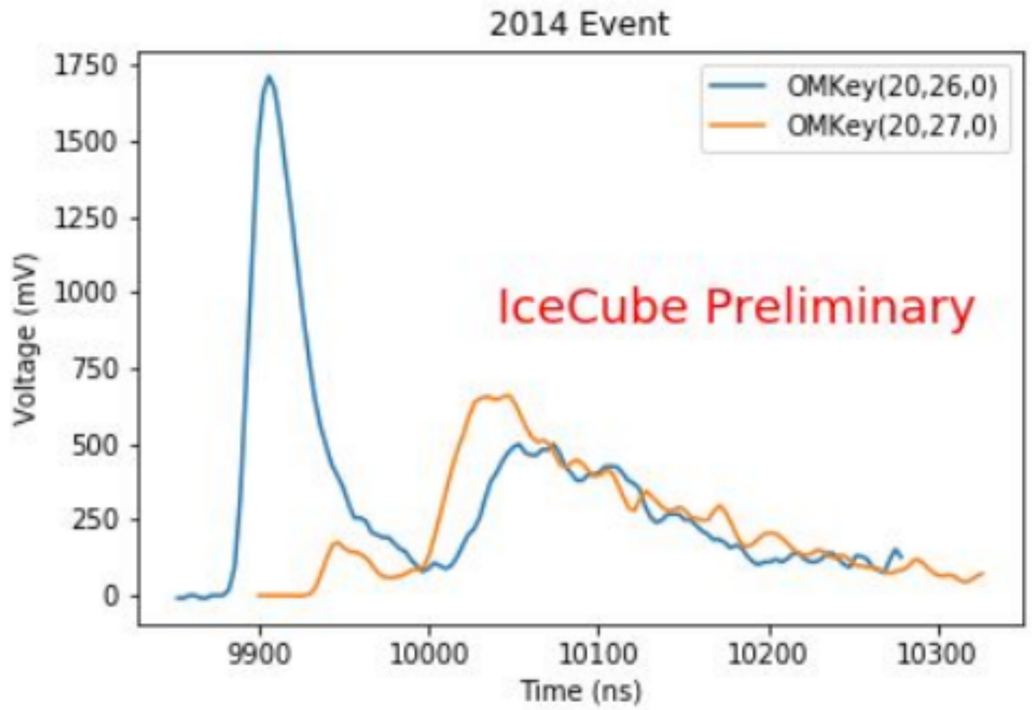


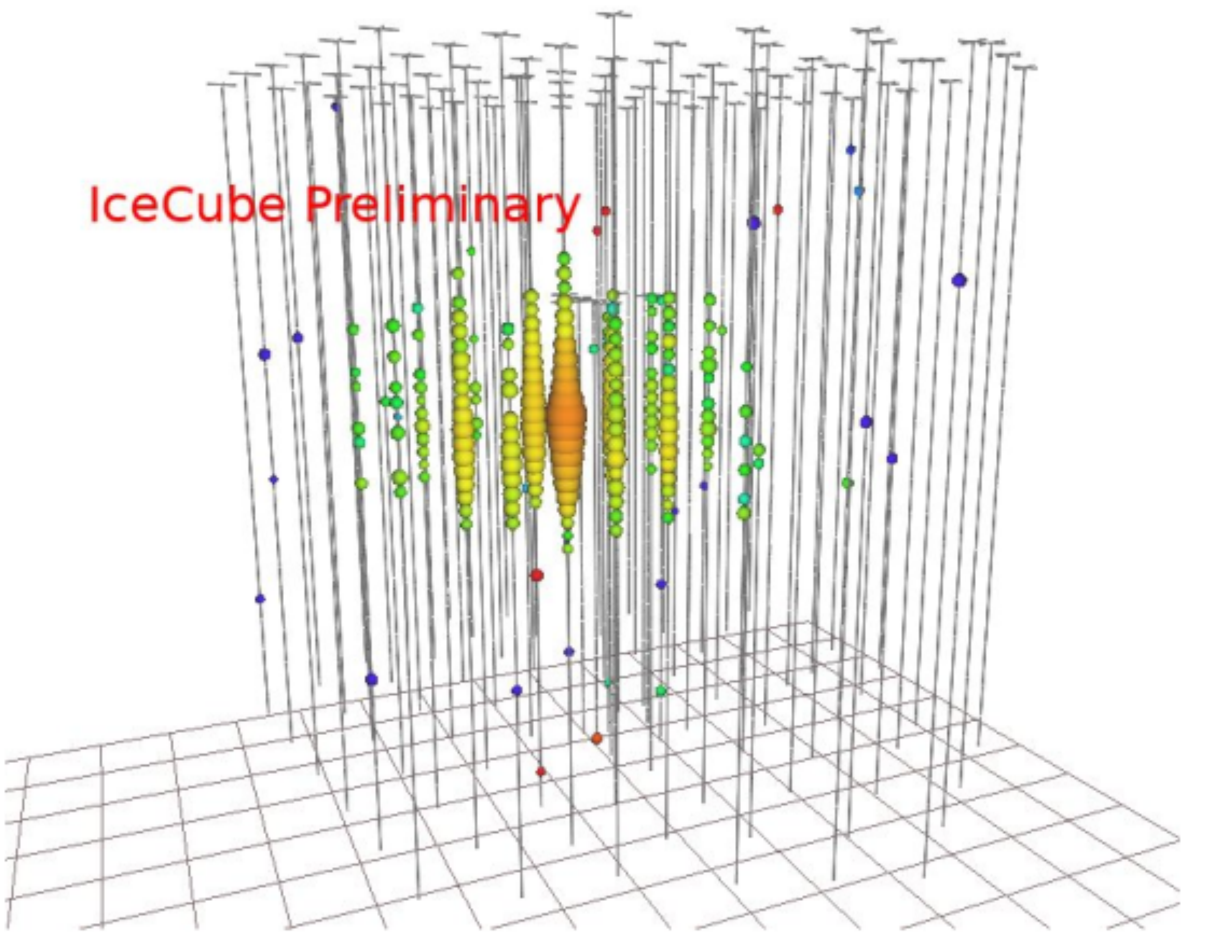
Cascade vs Track



Event #1 (2014)

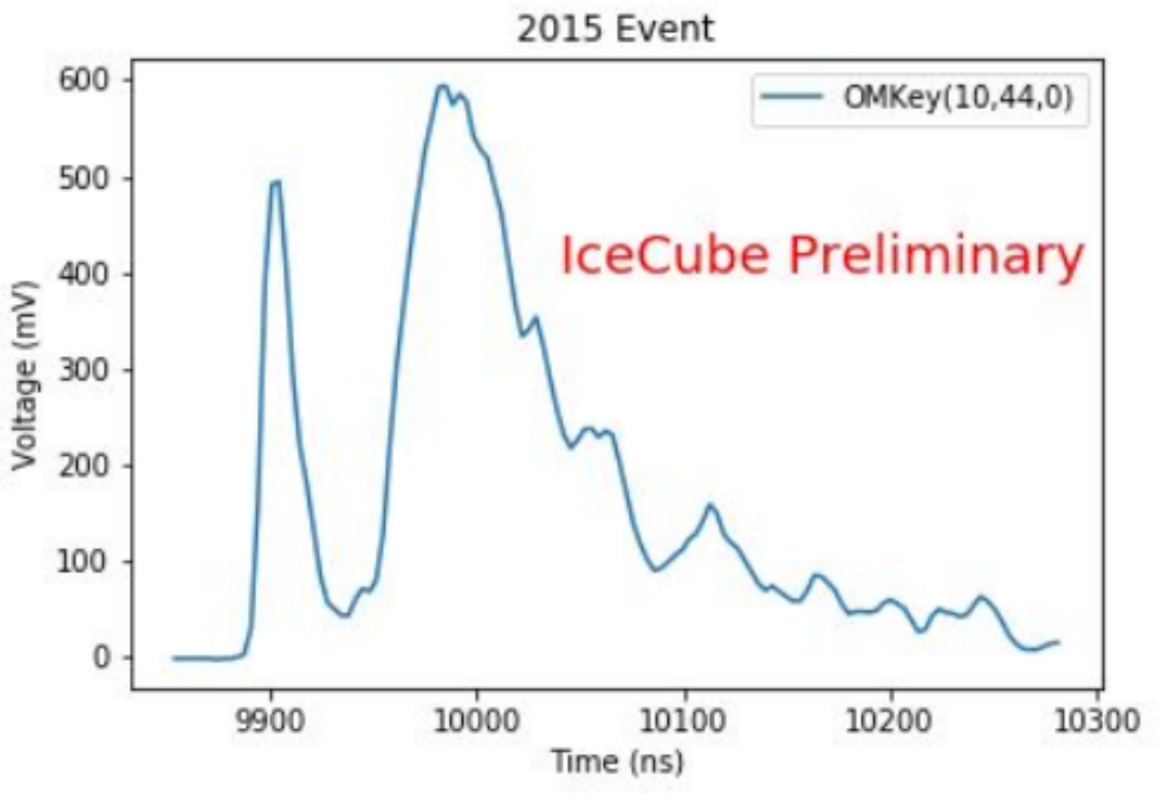
P-value: 0.196

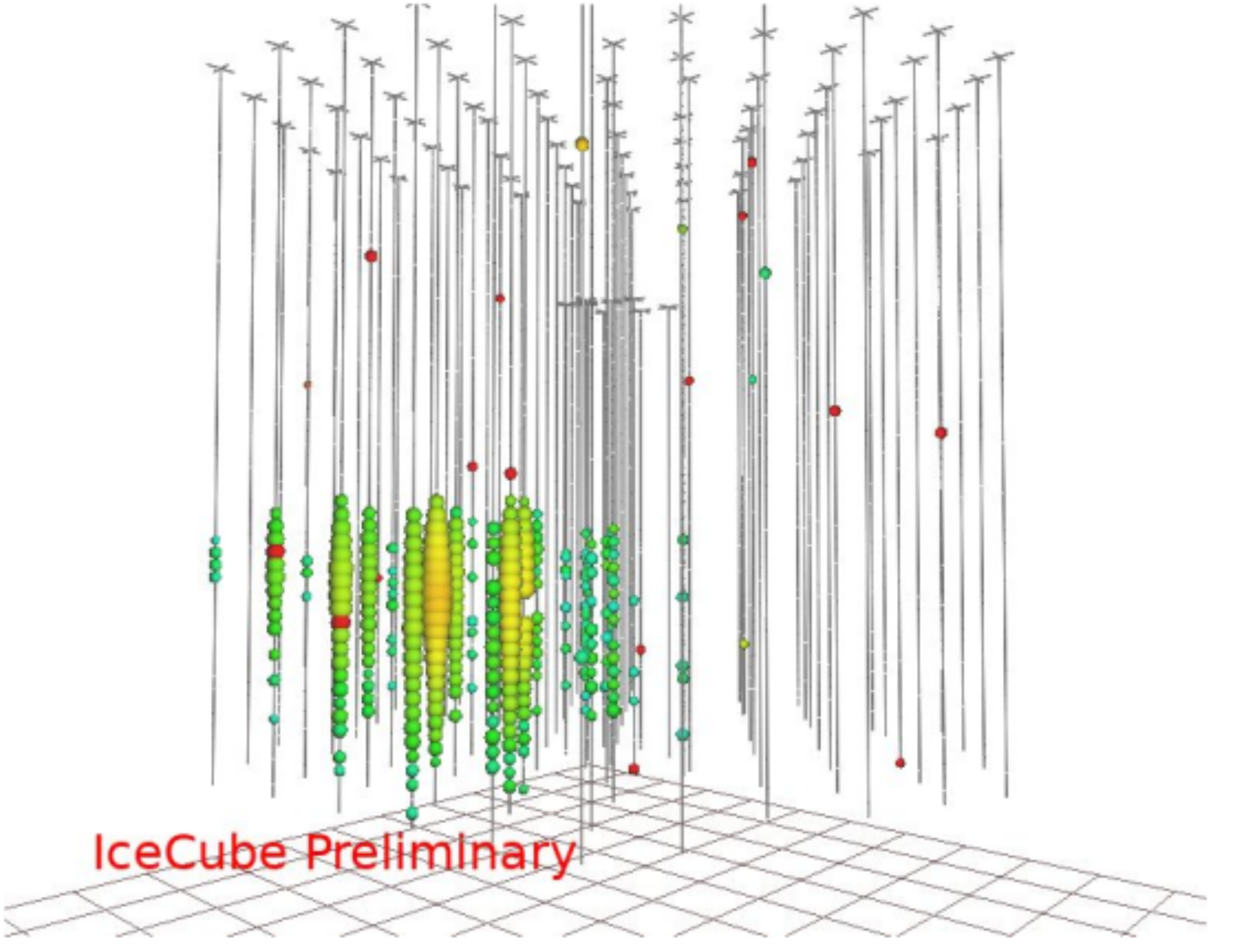




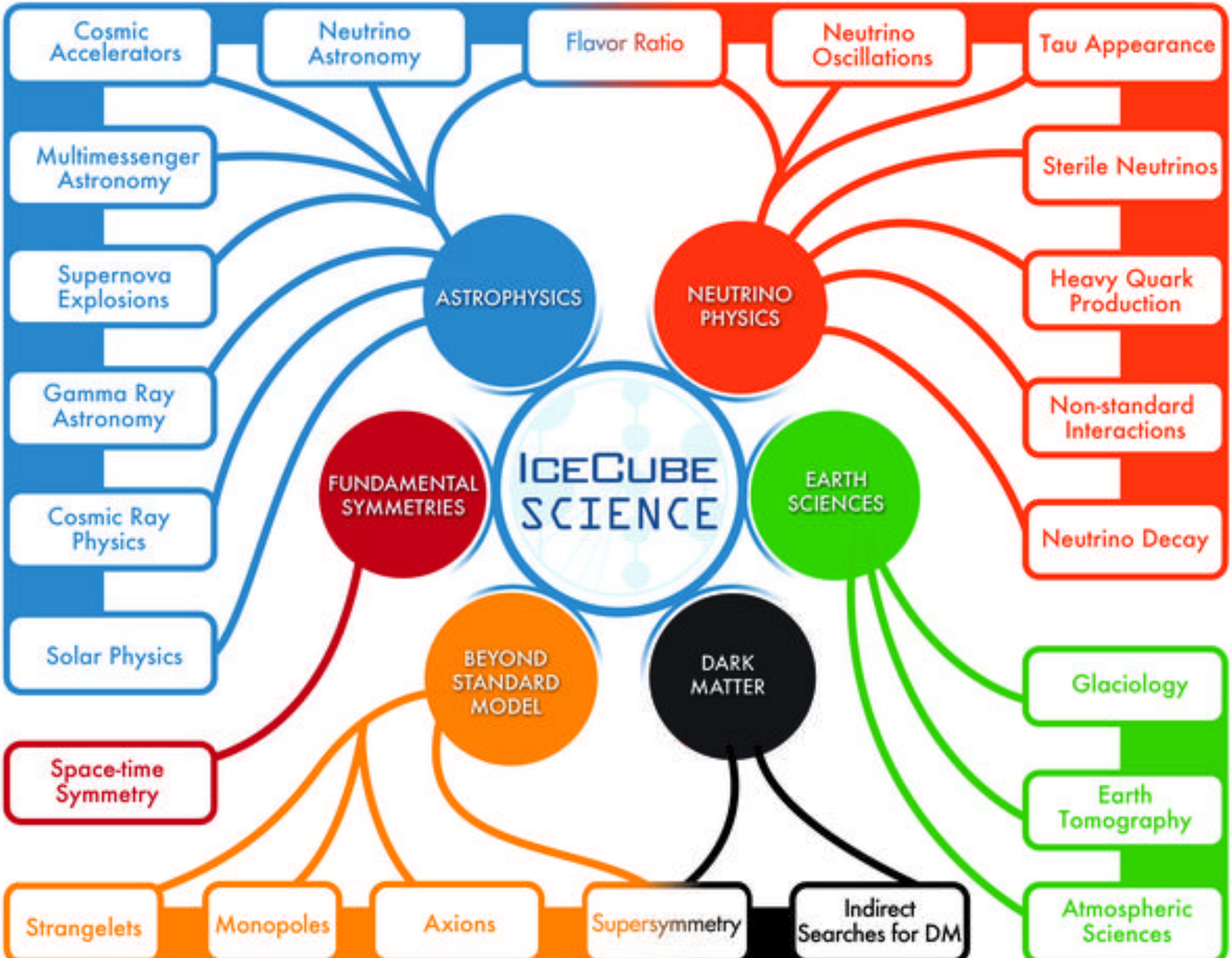
Event #2 (2015)

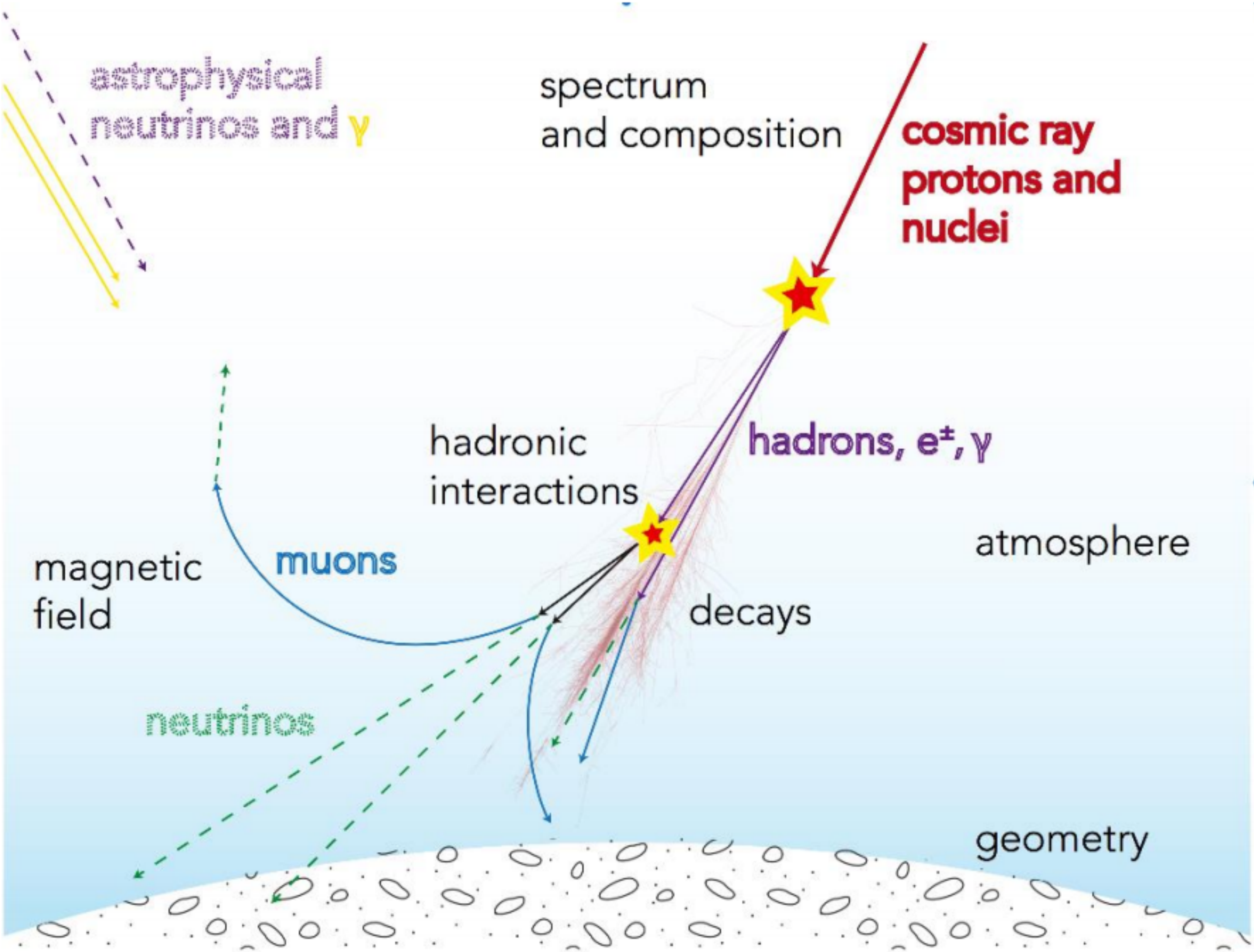
P-value: 1.0





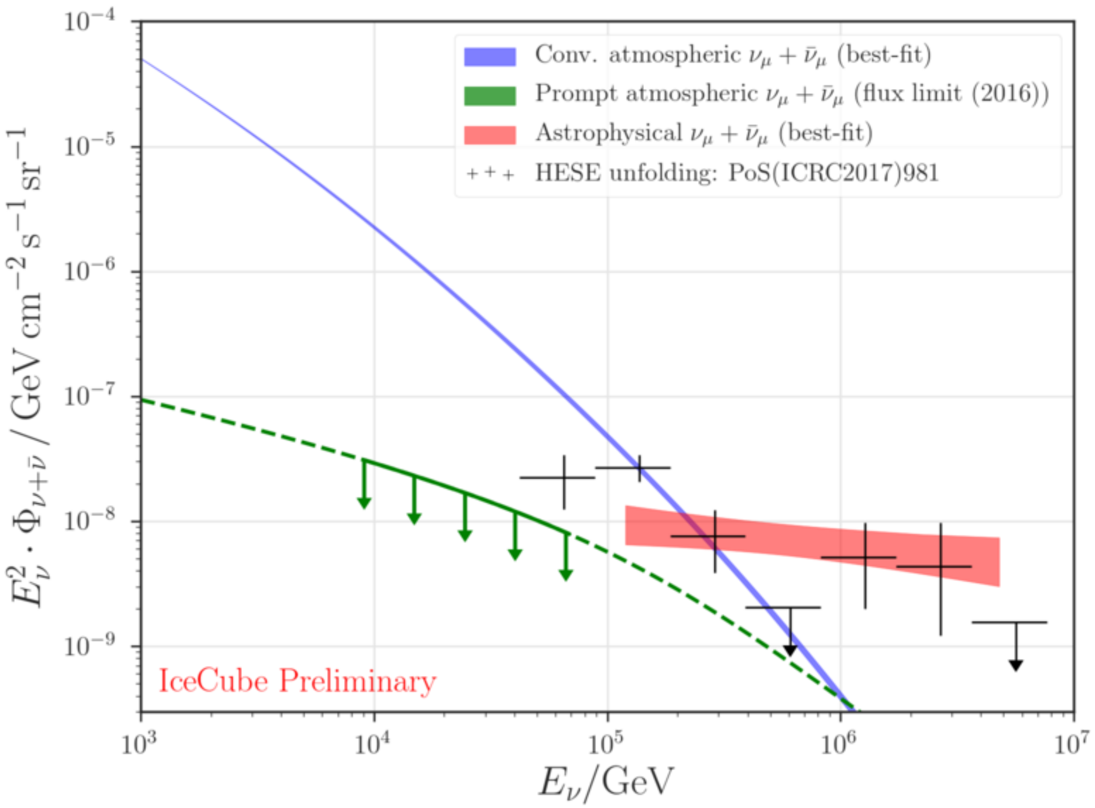
Particle Physics With High-Energy
&
Interesting open questions

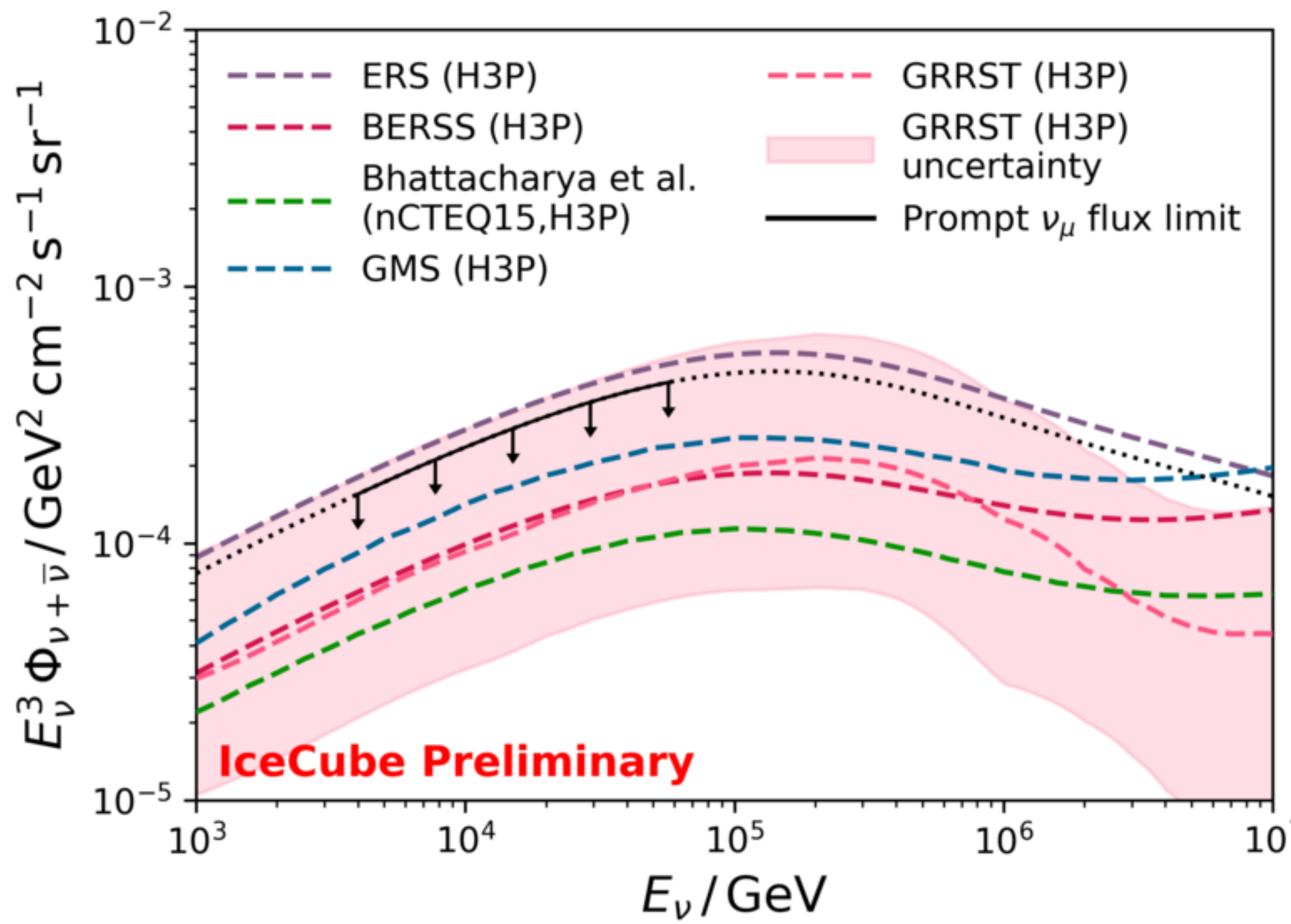

Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
Solar Physics
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Glaciology
Space-time Symmetry
Earth Tomography
Atmospheric Sciences
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM



astrophysical
neutrinos and γ
spectrum
and composition
cosmic ray
protons and
nuclei
hadronic
interactions
hadrons, e±, γ
magnetic
field
muons
atmosphere
decays
neutrinos
geometry

When will we measure the "prompt component"? Where are the neutrinos from D meson decay?

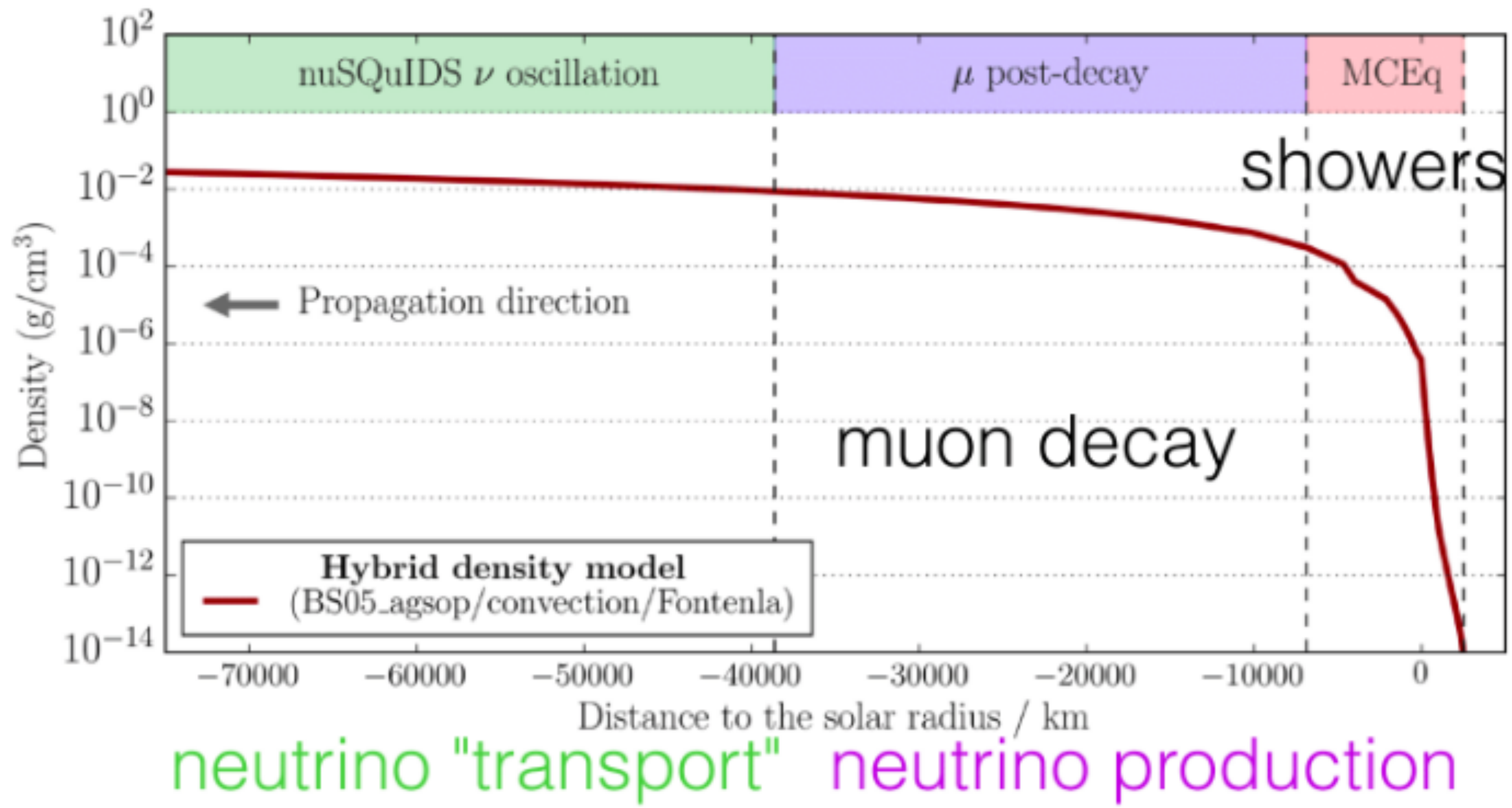




How about CR hitting the Sun?

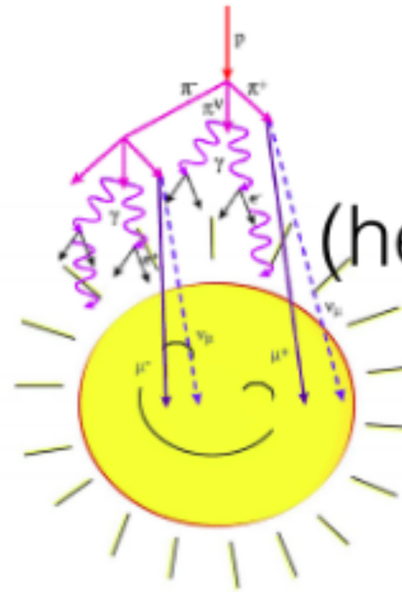
Like in the Earth the Sun is bombarded by CR, which shower in the solar atmosphere producing neutrinos

Where are the neutrinos produced?



- Showers occur in the outer part of the Sun.
- Very boosted muons decay in after shower region.

Neutrino transport



(here)

oscillations **absorption**

$$\frac{dF_\nu(E)}{dx} = -i[\mathrm{H}, \mathrm{F}_\nu(\mathrm{E})] - \sum_\alpha \frac{1}{2\lambda^\alpha(E)}\{\Pi_\alpha, F_\nu(E)\}$$

nc-"regeneration"

$$+\int_{E'} \frac{1}{\lambda_{\mathrm{NC}}(E')}\sum_\alpha \{\Pi_\alpha, F_\nu(E')\} NC(E', E)$$

$$+\int_{E'} \frac{1}{\lambda^\tau(E')} F_\tau(E') CC_\tau(E', E)\Pi_\tau$$

$$+\mathrm{Br}_\mu \int_{E'} \frac{1}{\lambda^\tau(E')} \bar{F}_\tau(E') CC_\tau(E', E)\Pi_\mu \,,$$

$$+\mathrm{Br}_e \int_{E'} \frac{1}{\lambda^\tau(E')} \bar{F}_\tau(E') CC_{\bar{\tau}}(E', E)\Pi_e$$

tau-"regeneration"

Neutrino propagation accounts for CC, NC, oscillations, and tau regeneration. Code is fast: 15-30 min per calculation.

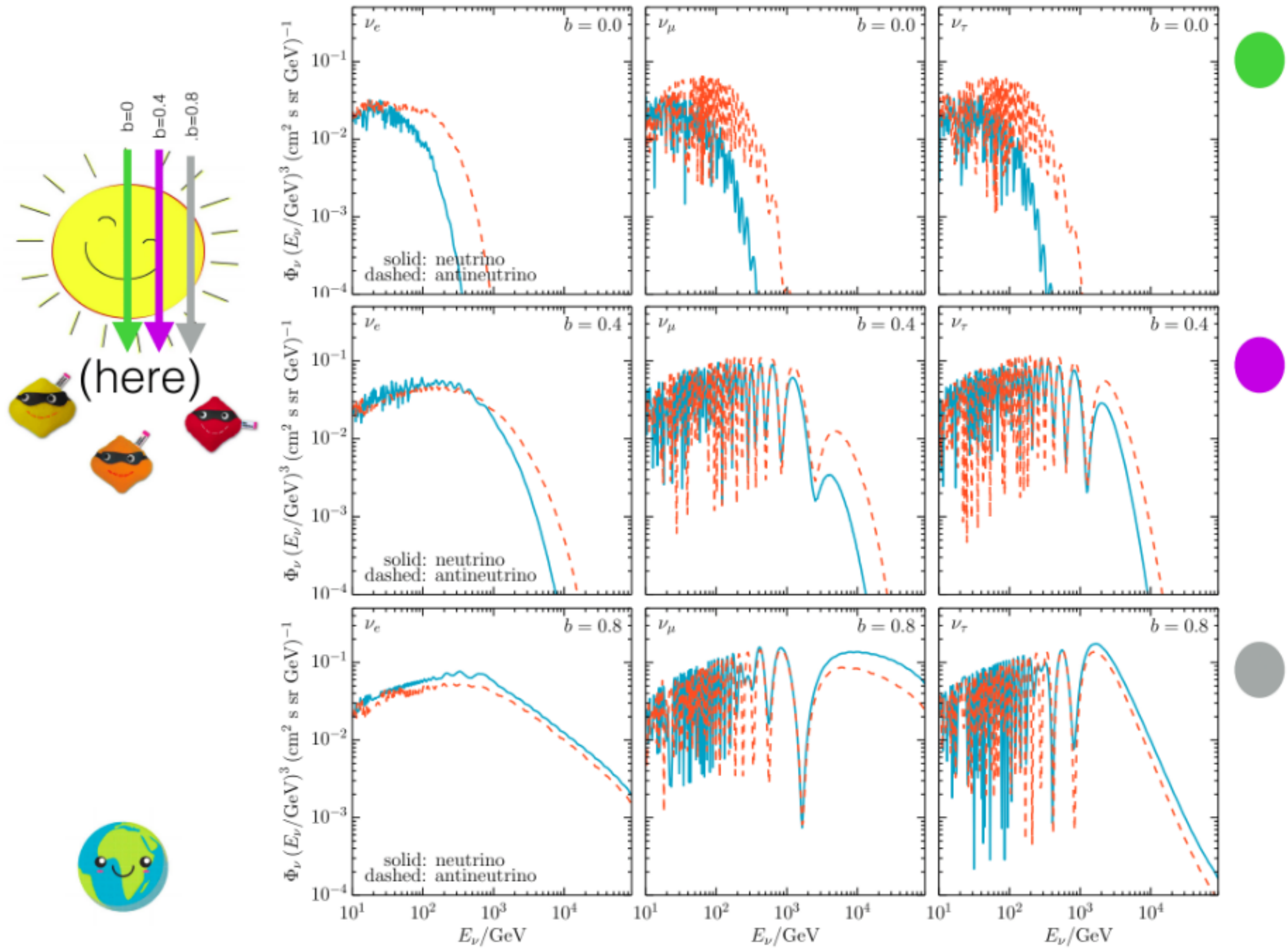
Get it here:

https://github.com/jsalvado/SQuIDS

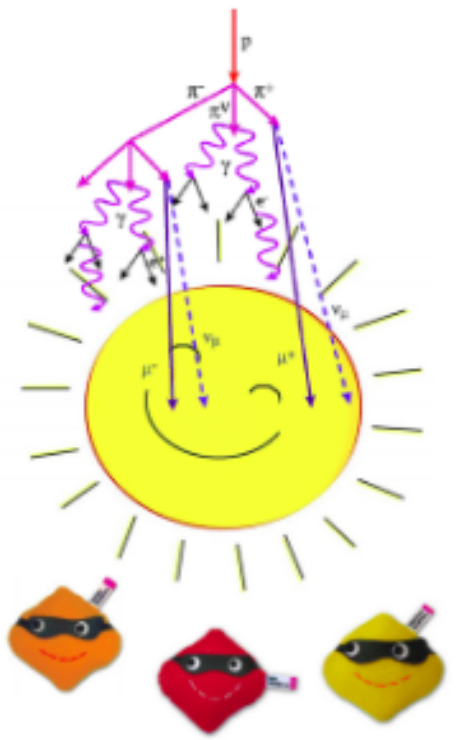
https://github.com/arguelles/nuSQuIDS

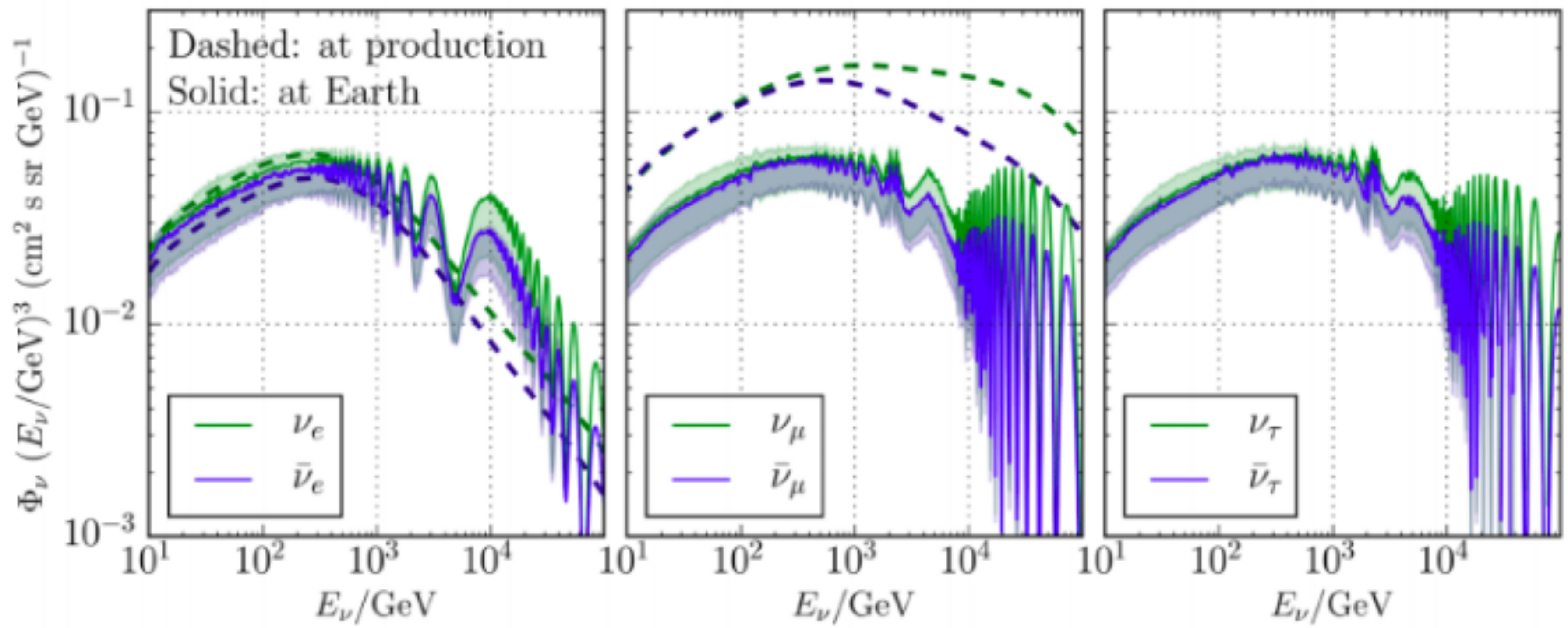
NU SQuIDS

SQuIDS


b=0
b=0.4
b=0.8
(here)
ν_e
ν_μ
ν_τ
$b = 0.0$
$b = 0.4$
$b = 0.8$
solid: neutrino
dashed: antineutrino
$\Phi_\nu\,(E_\nu/\mathrm{GeV})^3\,(\mathrm{cm}^2\ \mathrm{s\ sr\ GeV})^{-1}$
E_ν/GeV

Averaging Oscillations to Earth!





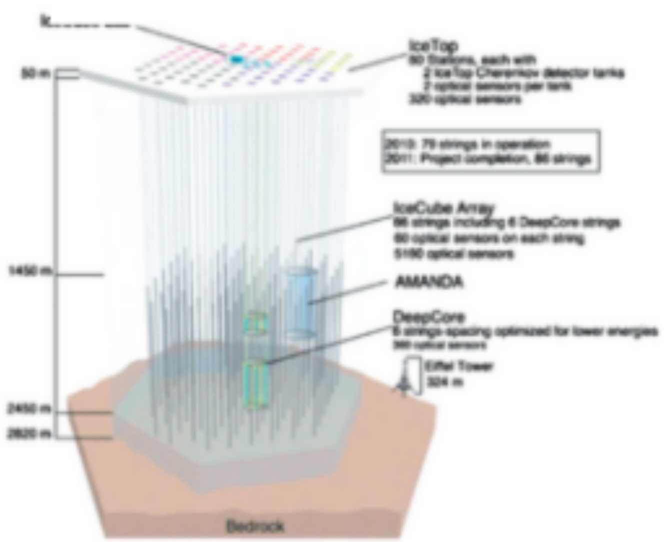
- At these high energies neutrino coherence is maintained.
- Low energy fast oscillation are average out due to vacuum oscillation through the year:
  - Aphelion to perihelion distance difference is ~ 4 million km.
  - Oscillation length at 100 GeV is ~ 1% of this distance.
  - Oscillation length is comparable at 10 TeV.

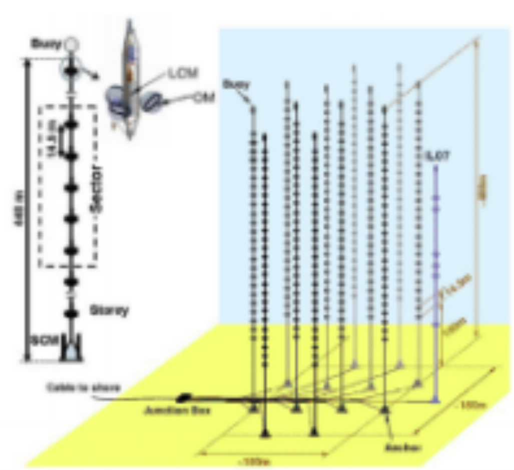
$$\bar{\Phi}_\alpha(E_\nu) = \frac{1}{T}\sum_\beta \int_0^T dt\ P_{osc}^{\beta,\alpha}(r(t), E_\nu)\Phi_{b,\beta}(E_\nu)$$

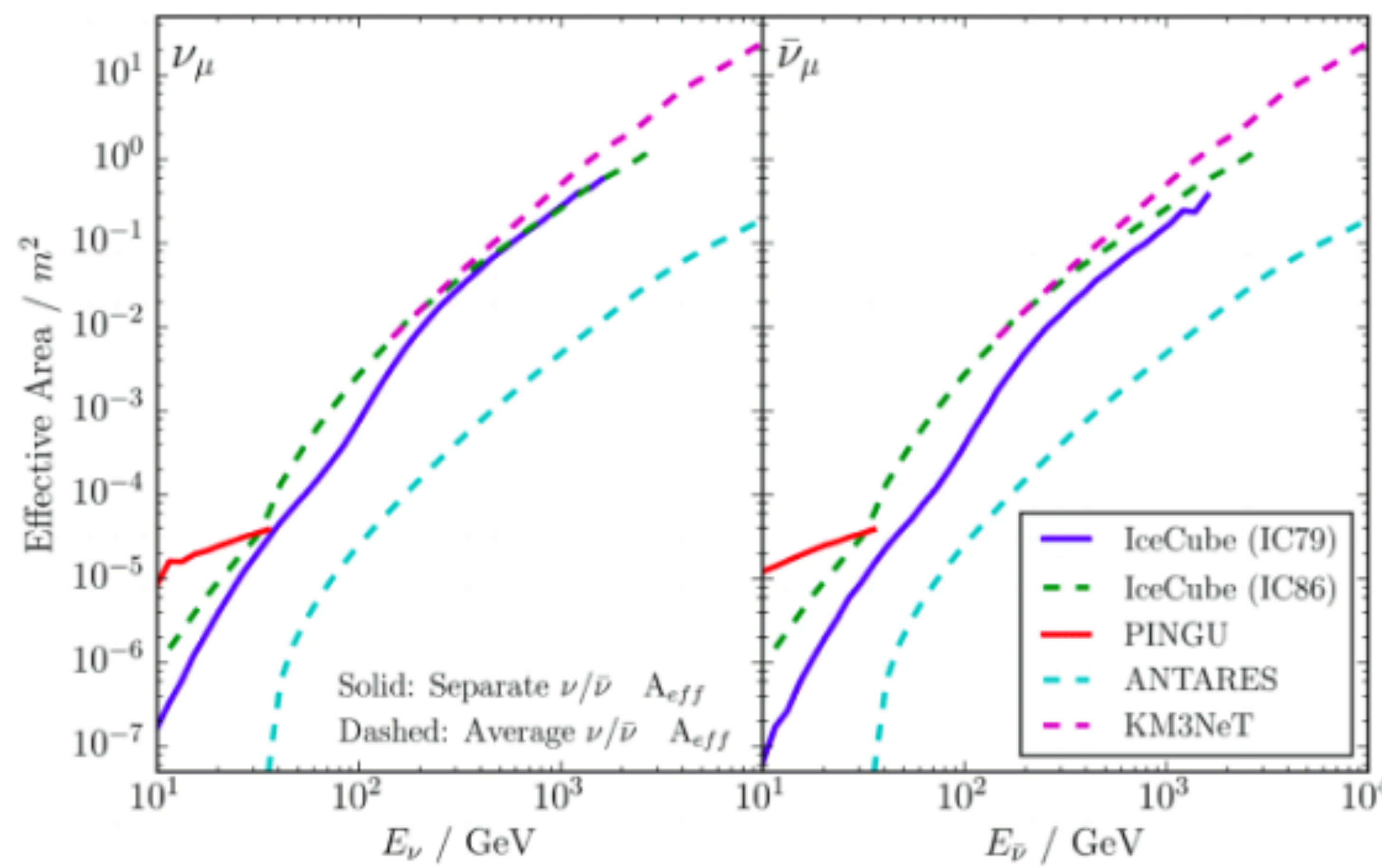
Rates!

(*used average nu+nubar effective area)

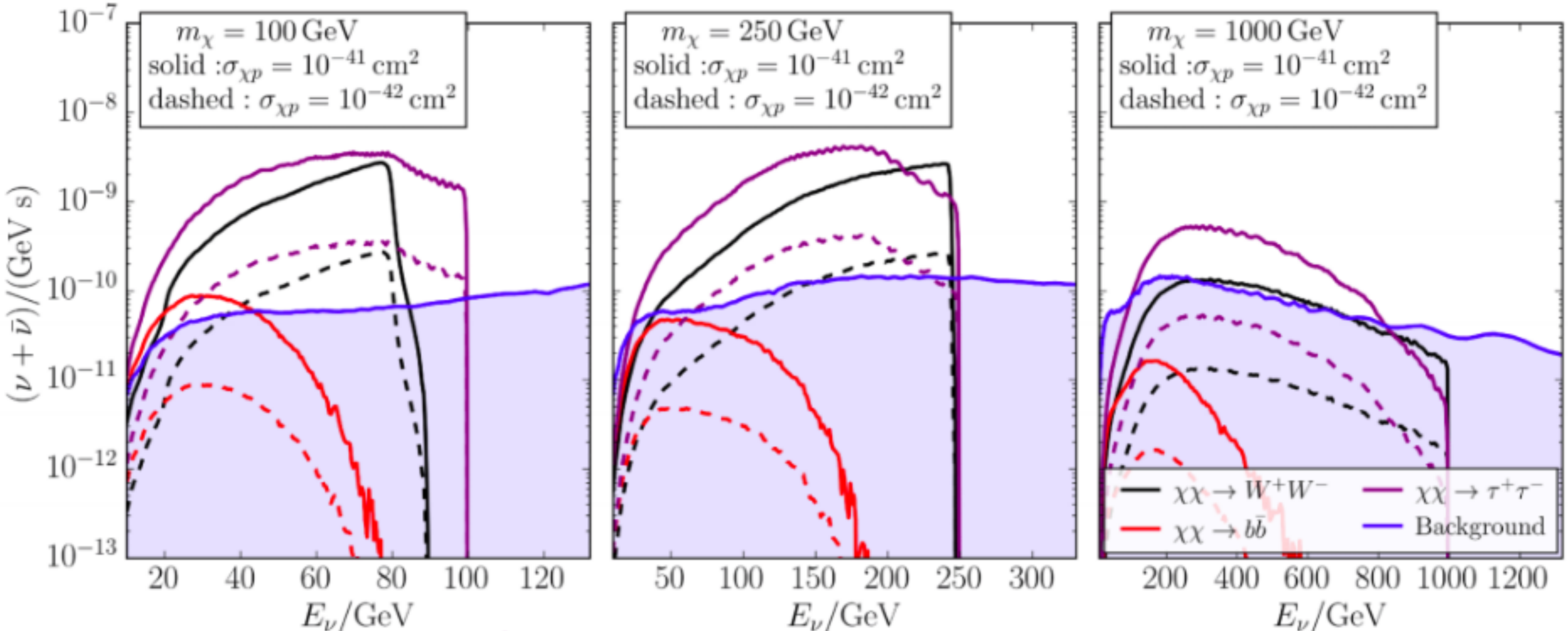
Experiment	Expected ν_μ rate R (evts / yr)	Expected $\bar{\nu}_\mu$ rate R (evts / yr)
IceCube (IC79)	$1.36 < R < 2.17$	$0.73 < R < 1.17$
IceCube (IC86)*	$2.05 < R < 3.29$	$1.97 < R < 3.16$
ANTARES*	$0.032 < R < 0.053$	$0.030 < R < 0.049$
IceCube+PINGU	$1.42 < R < 2.26$	$0.79 < R < 1.26$
KM3NeT*	$3.02 < R < 4.95$	$2.78 < R < 4.53$

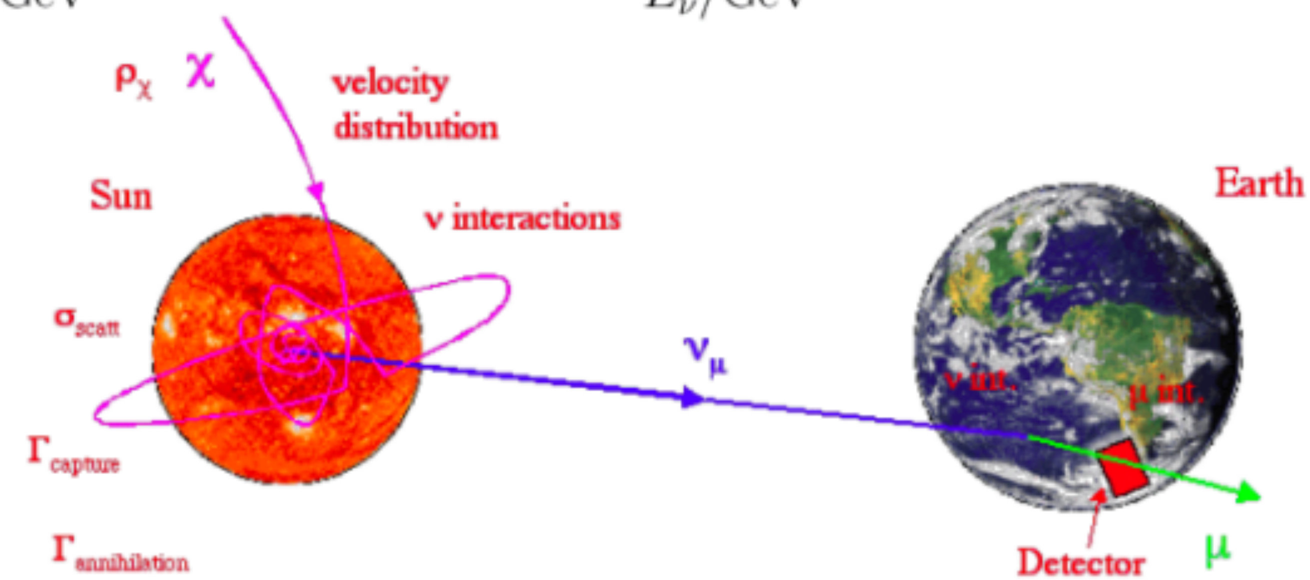






Solar-Atmospheric neutrinos as a DM background

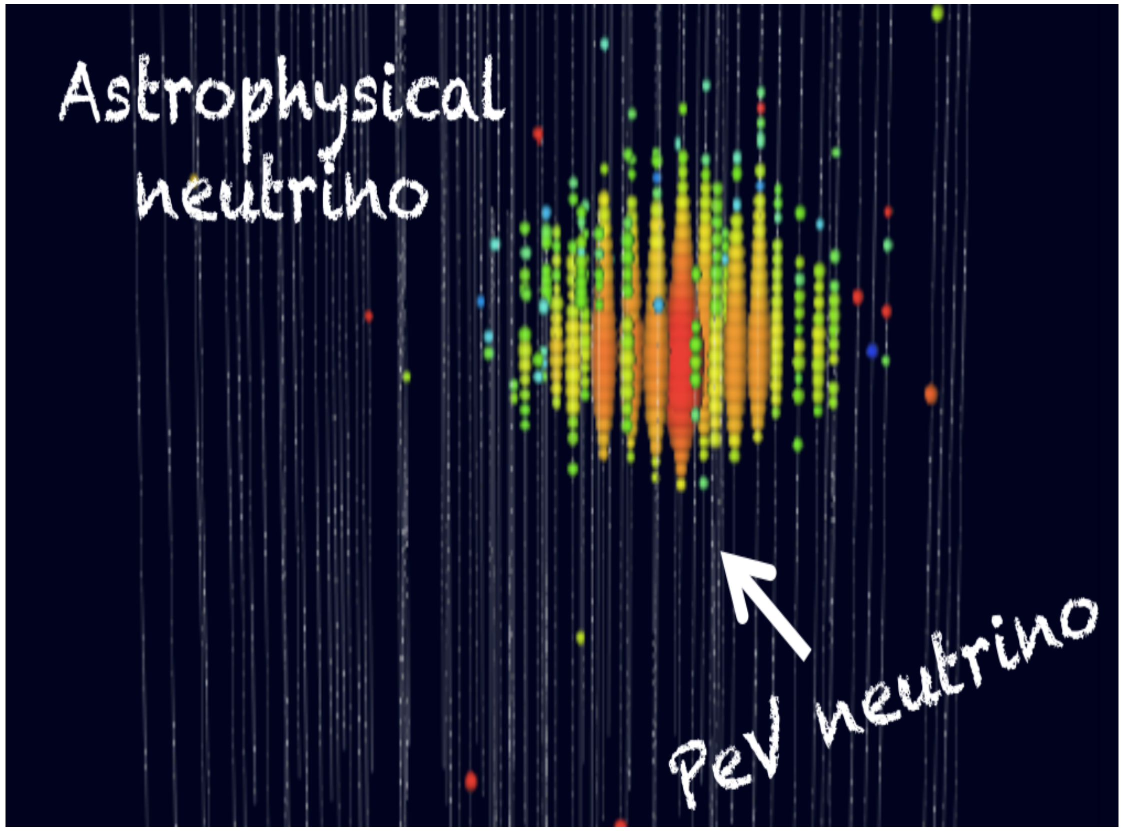


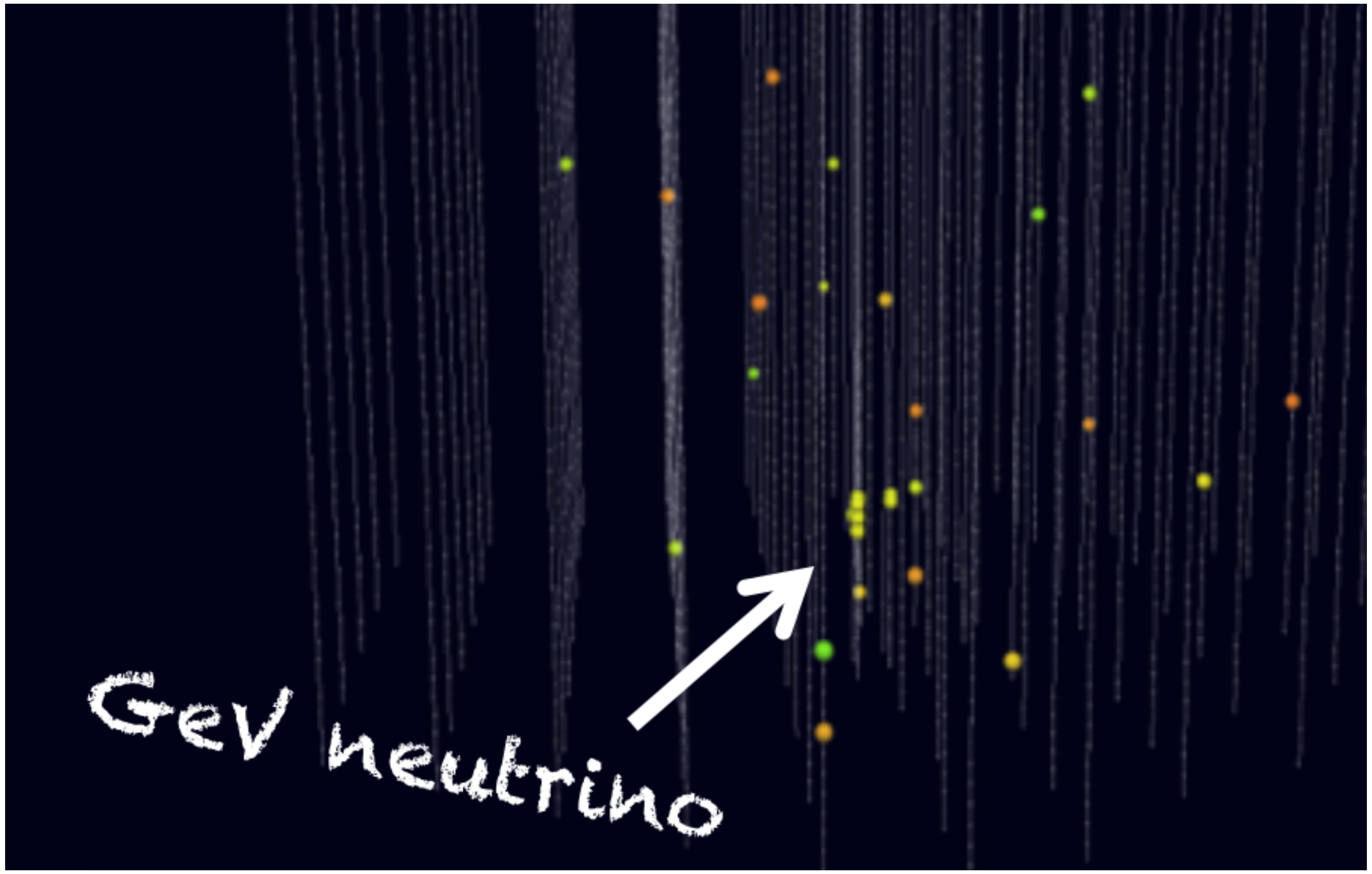


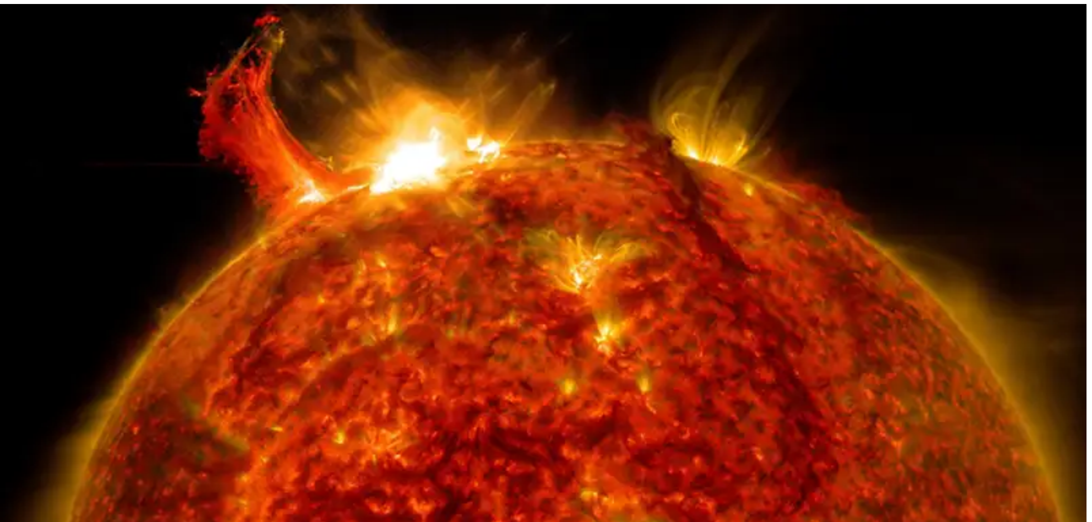
Maybe we wont find solar WIMPs, but these neutrinos are there for sure!

One persons background, becomes another one's signal!

There is also expected neutrino production from solar flares!

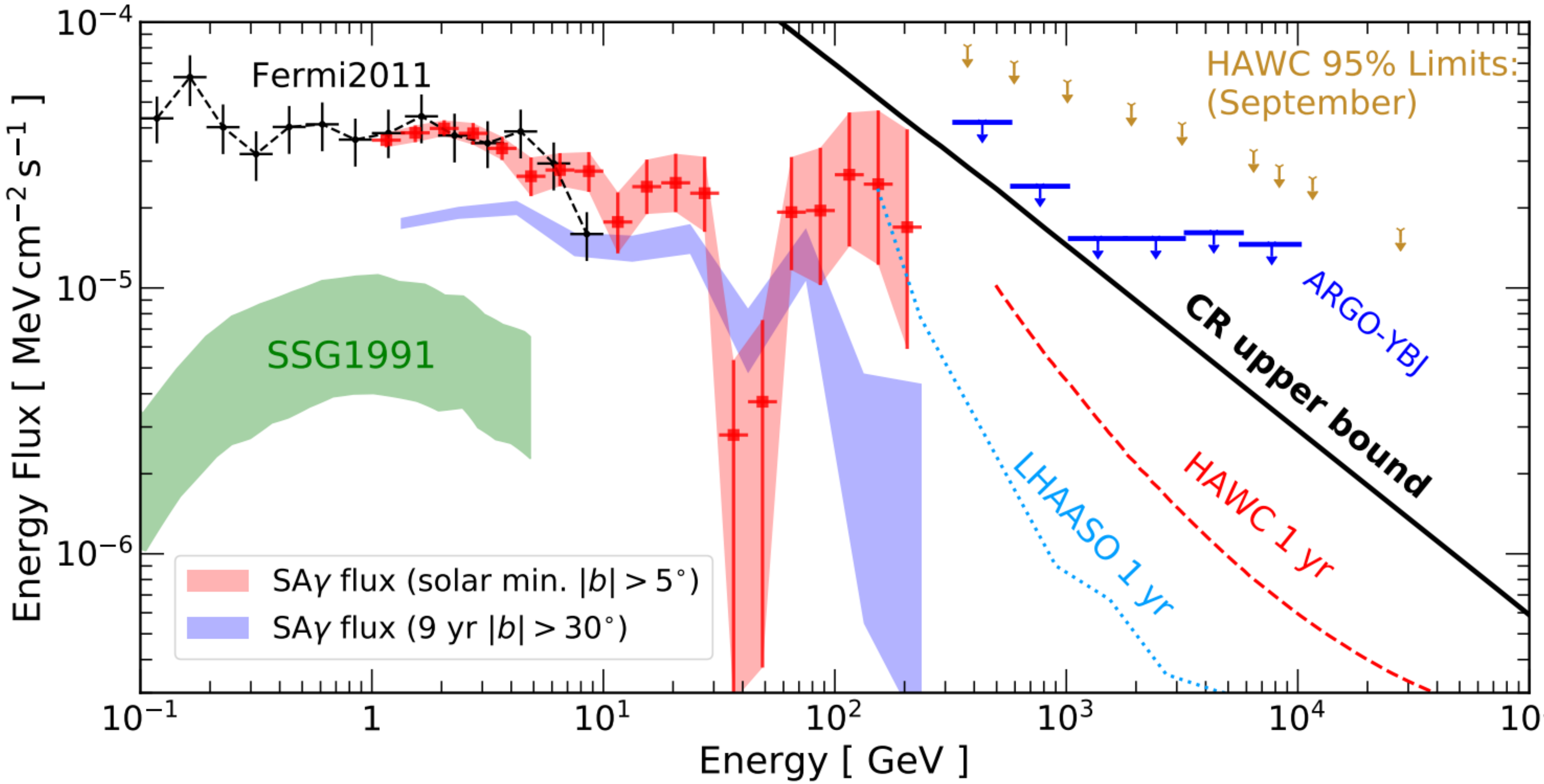






On going searches for temporal coincidence neutrino signature and solar flare.

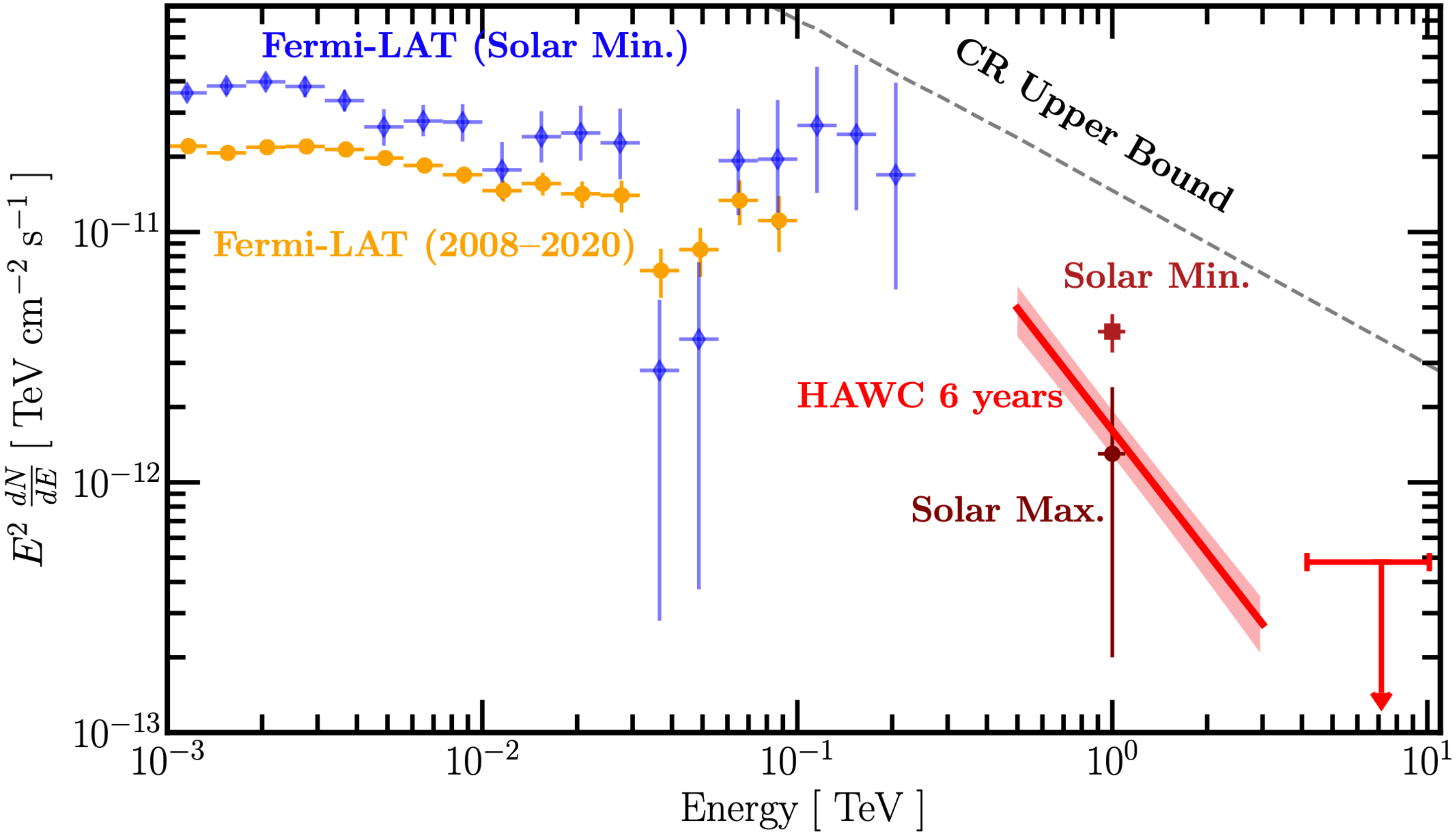
By the way … odd things are happening with the gamma-rays from the Sun



Unexpected Dip in the Solar Gamma-Ray Spectrum

Qing-Wen Tang, Kenny C. Y. Ng, Tim Linden, Bei Zhou, John F. Beacom, Annika H. G. Peter

The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC



The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC

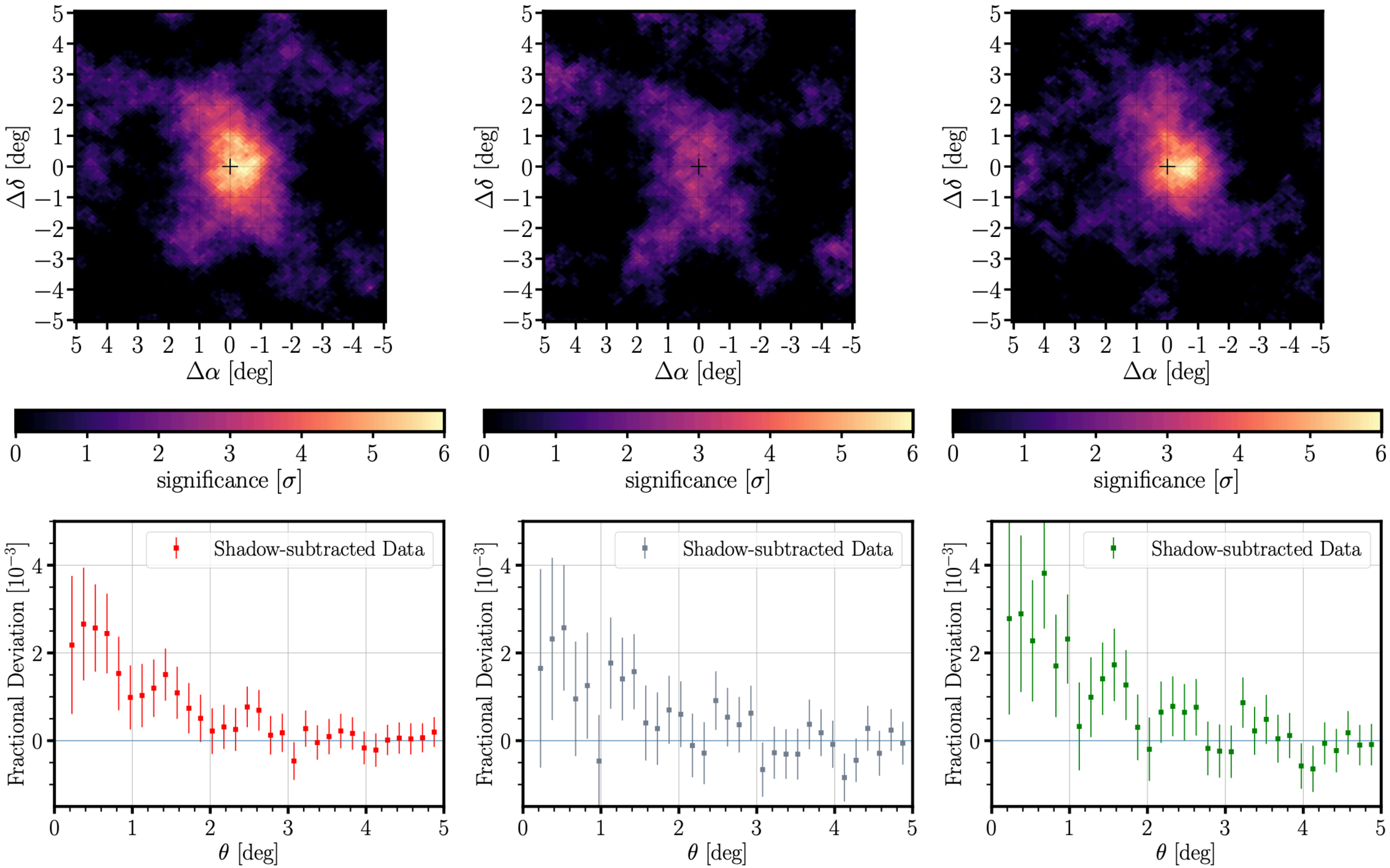
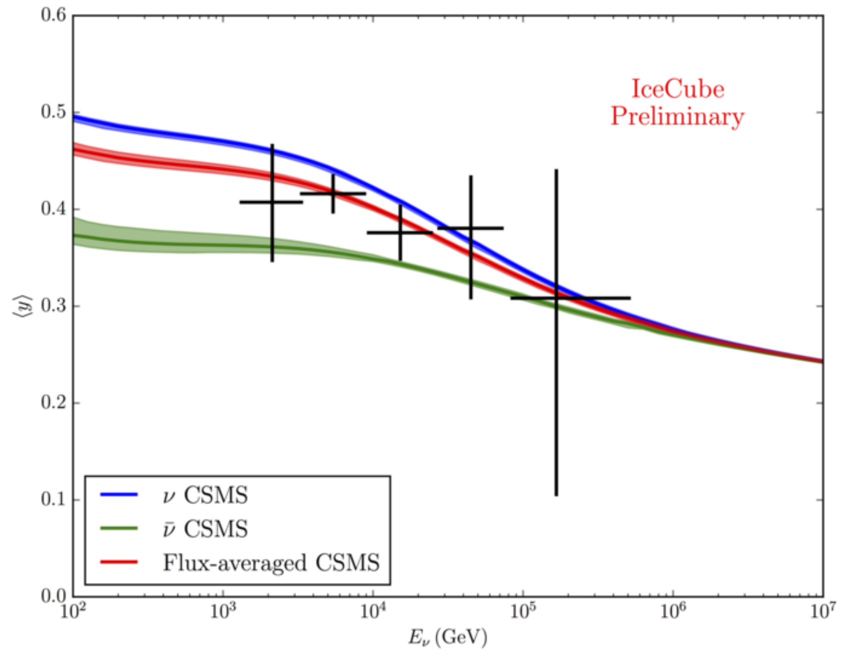
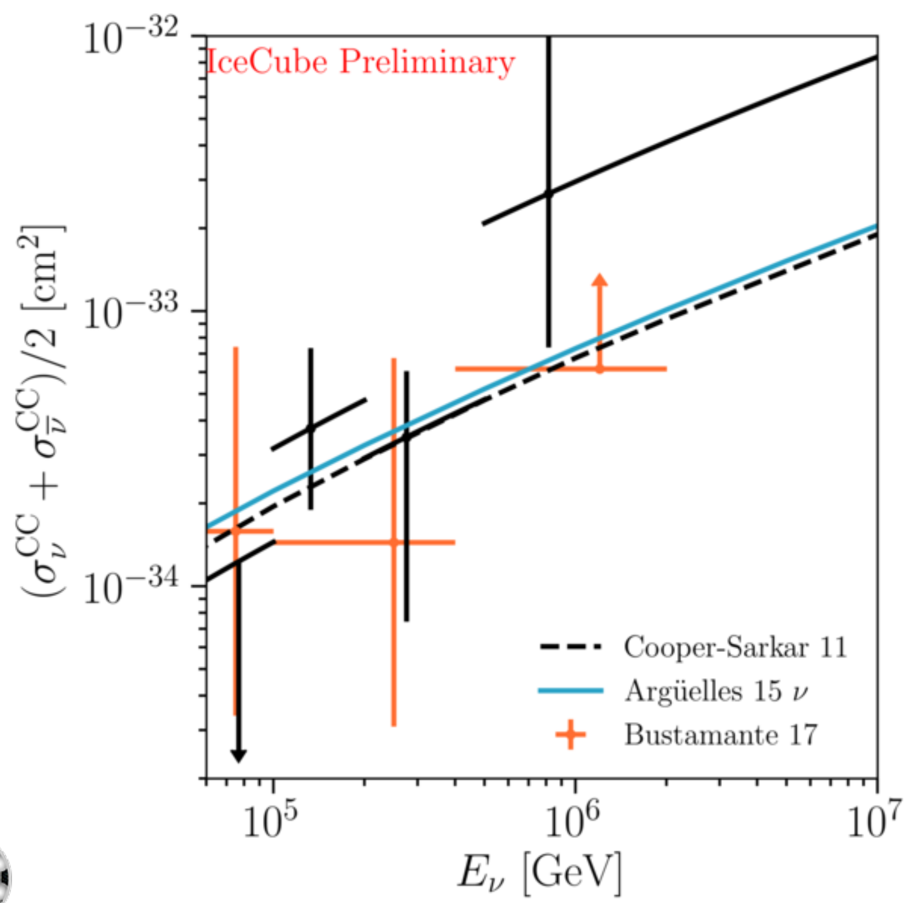
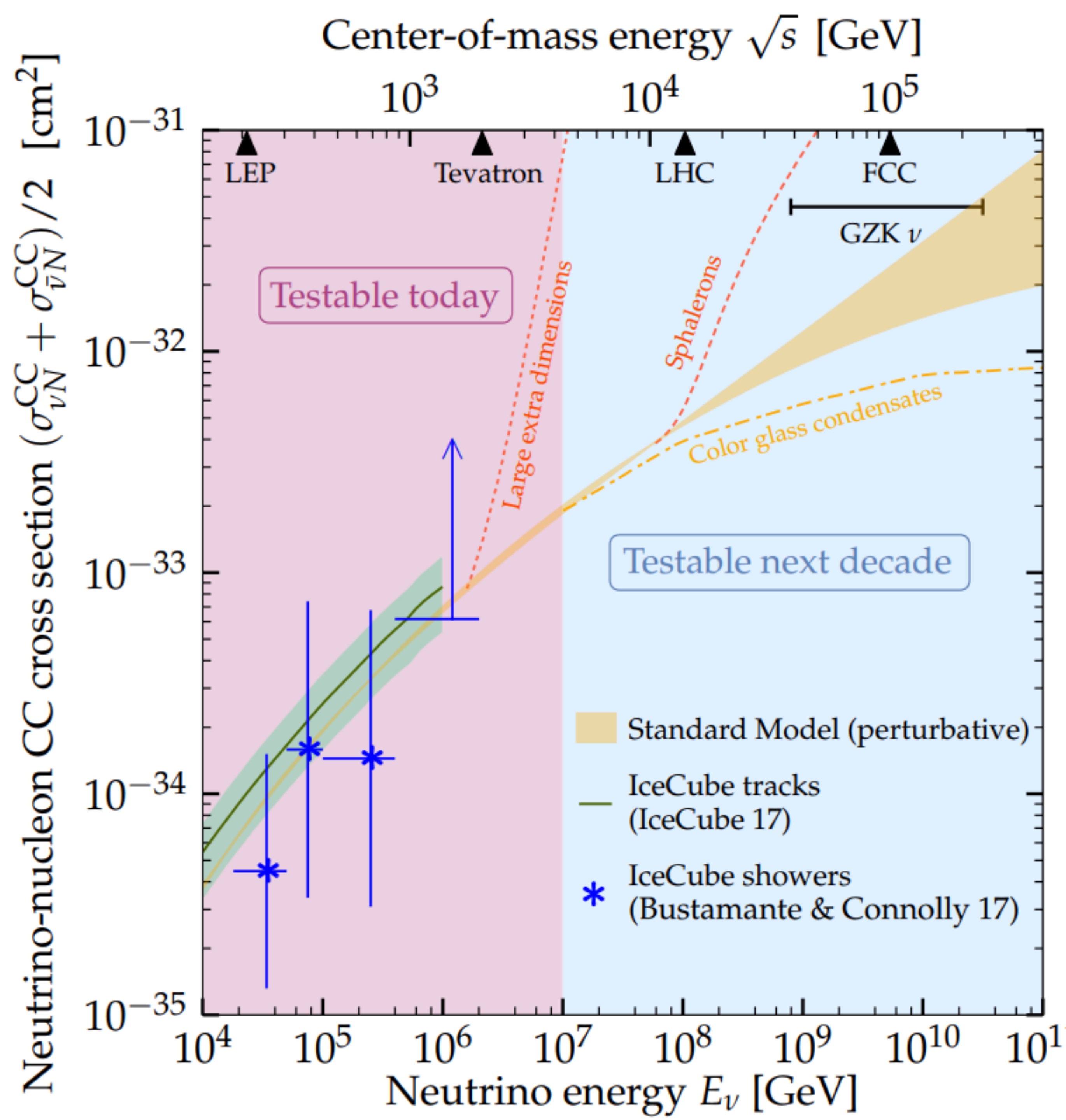


FIG. 2. Results for the combination of bins B2, B3, and B4, but otherwise as in Fig. 1. **Left:** The full 6.1-year data. **Middle:** Solar-maximum period. **Right:** Solar-minimum period.

Do we understand high-energy neutrino interactions? Will there be surprises?



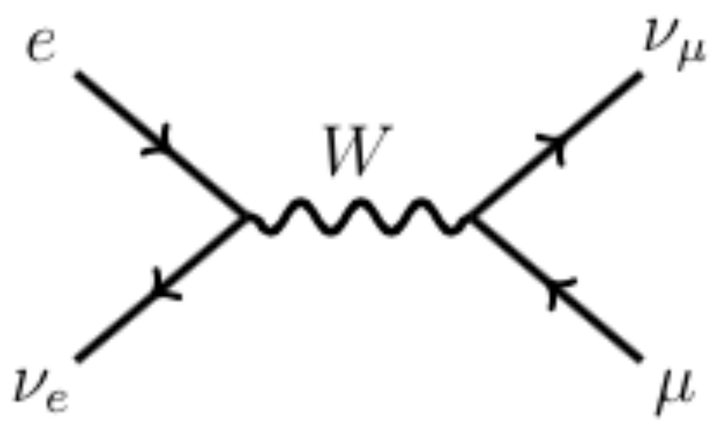


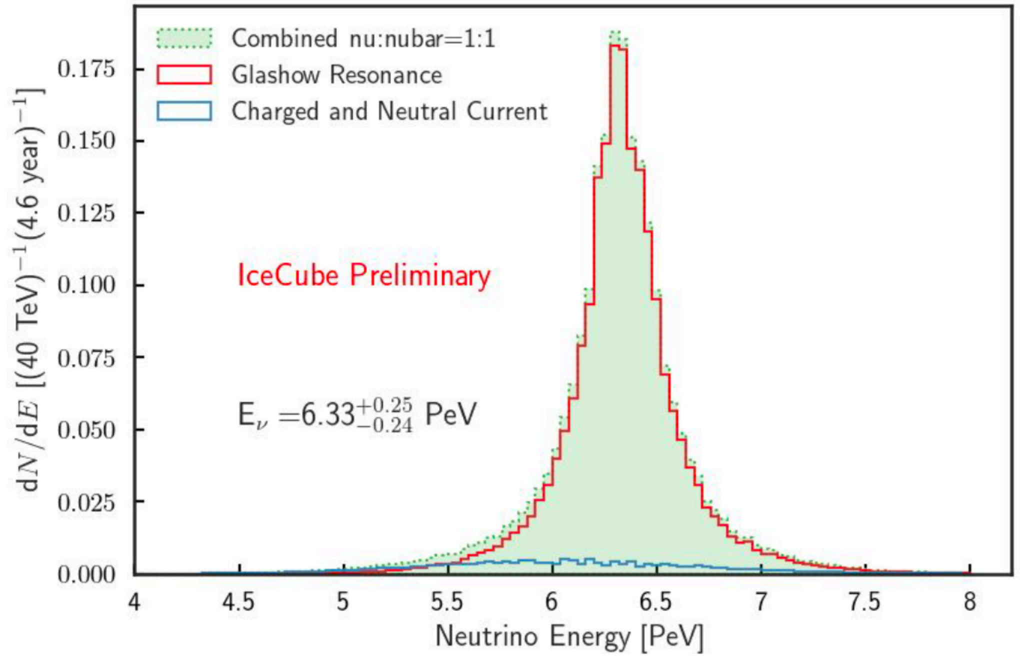


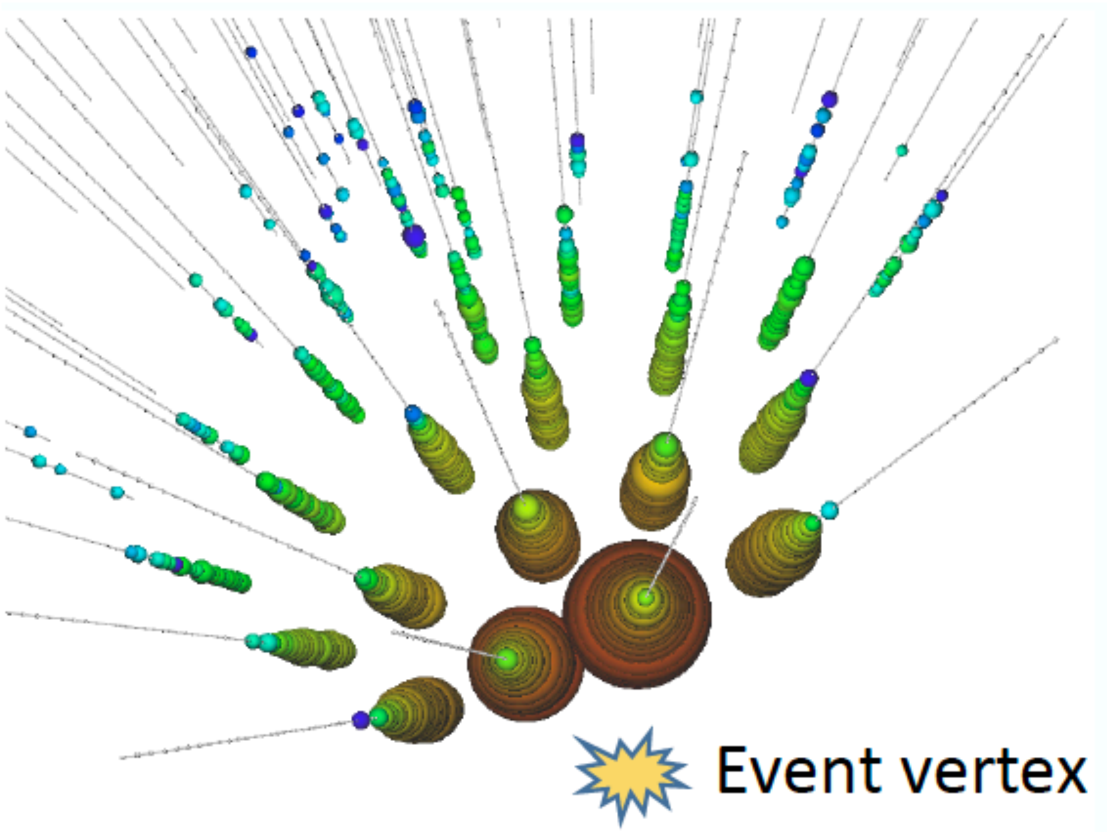
The first Glashow resonance event:

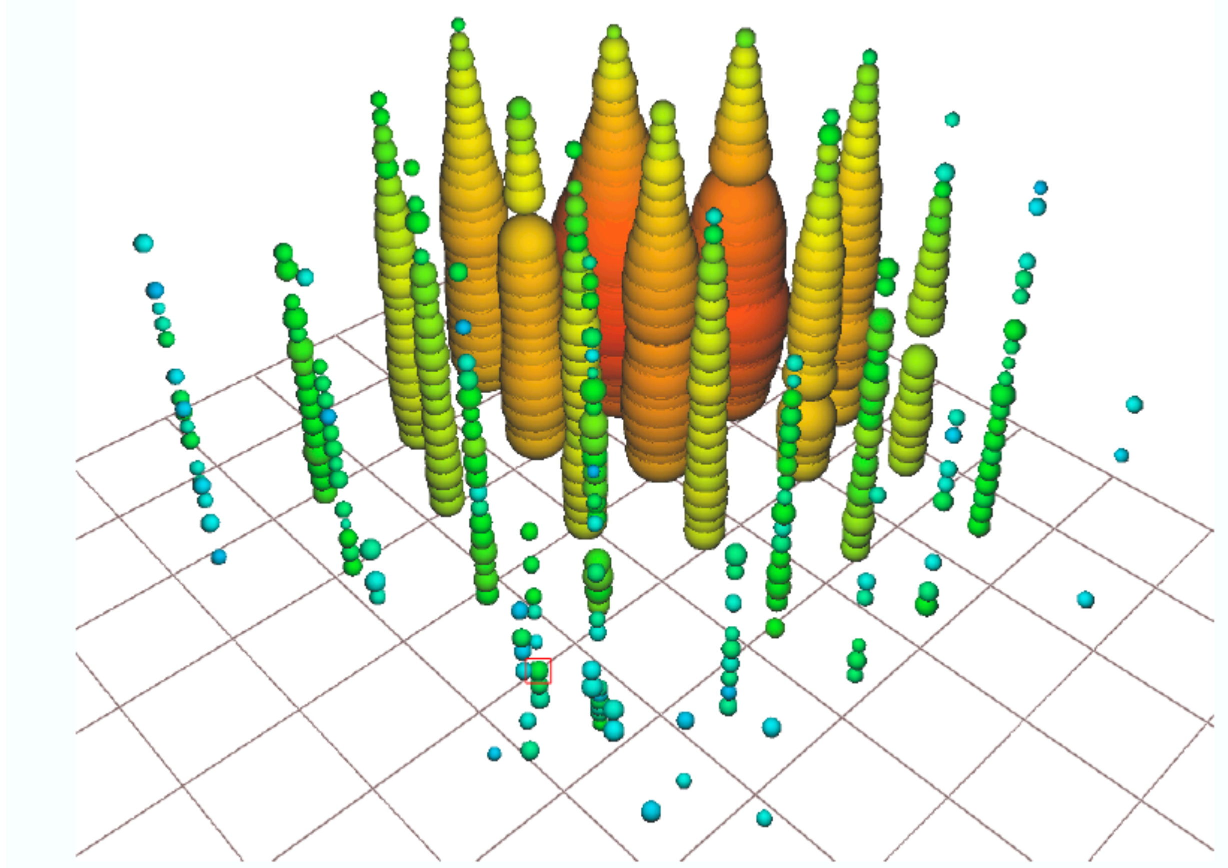
anti-ν_e + atomic electron → real W at 6.3 PeV

Resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron









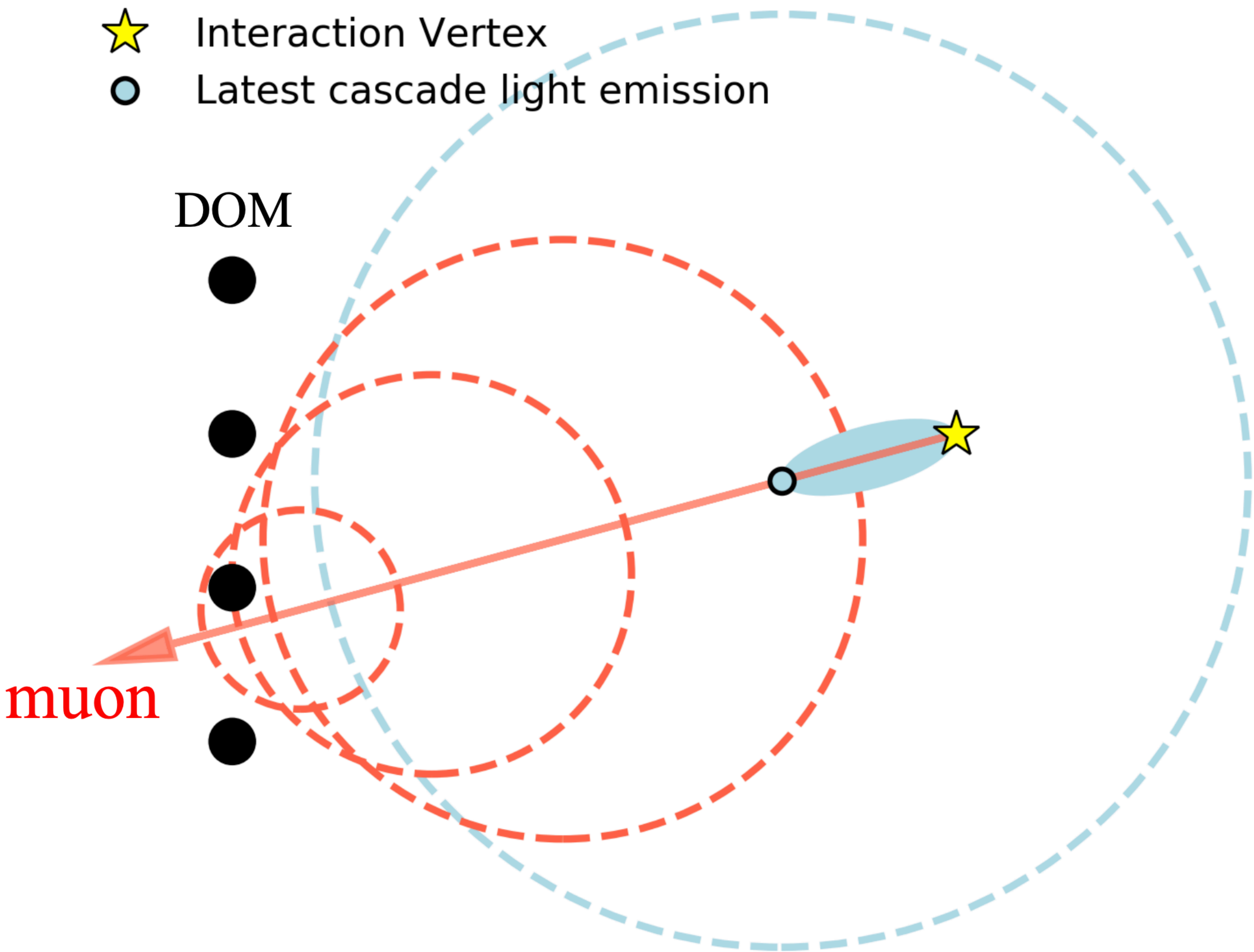
W production or background?

Signal:
hadronic (quark-antiquark decay of the W)

Or

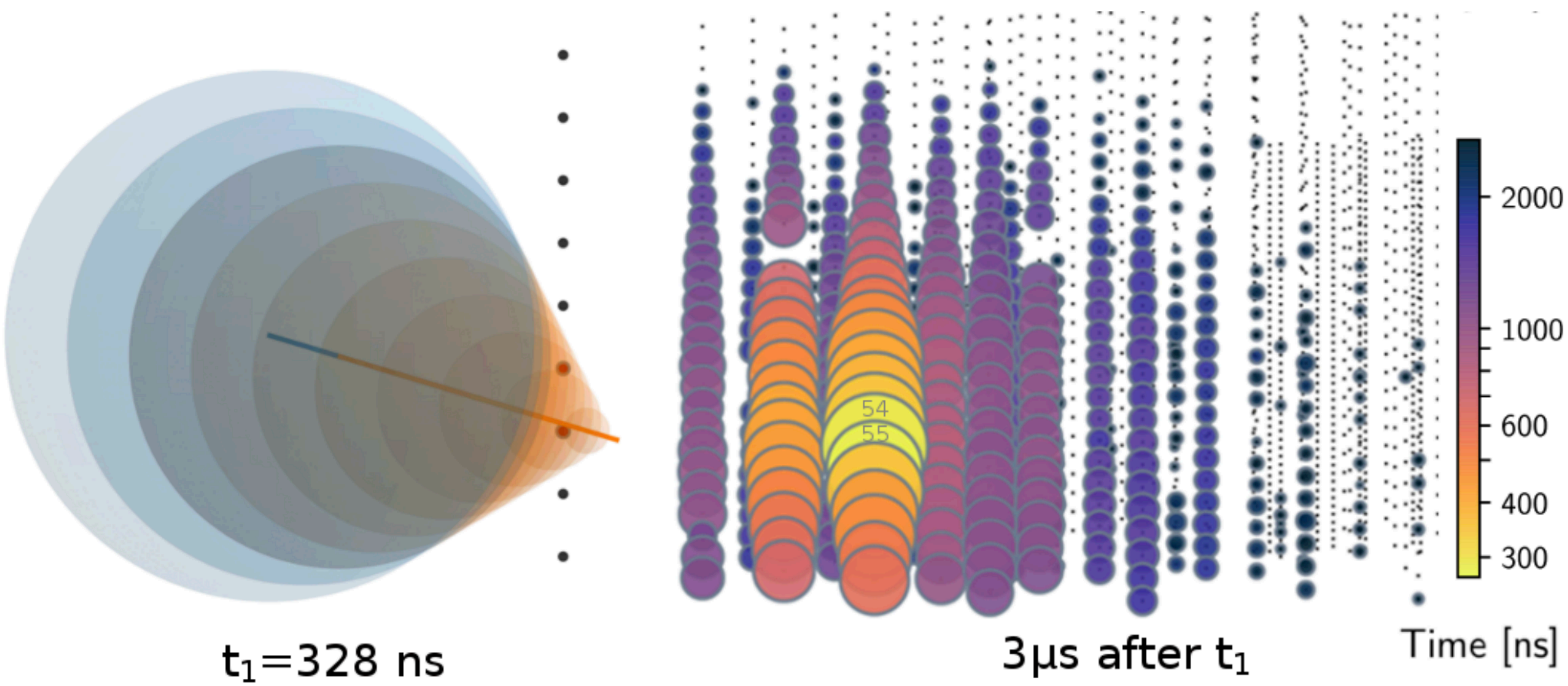
Background:
electromagnetic shower radiated by a high energy background cosmic-ray muon

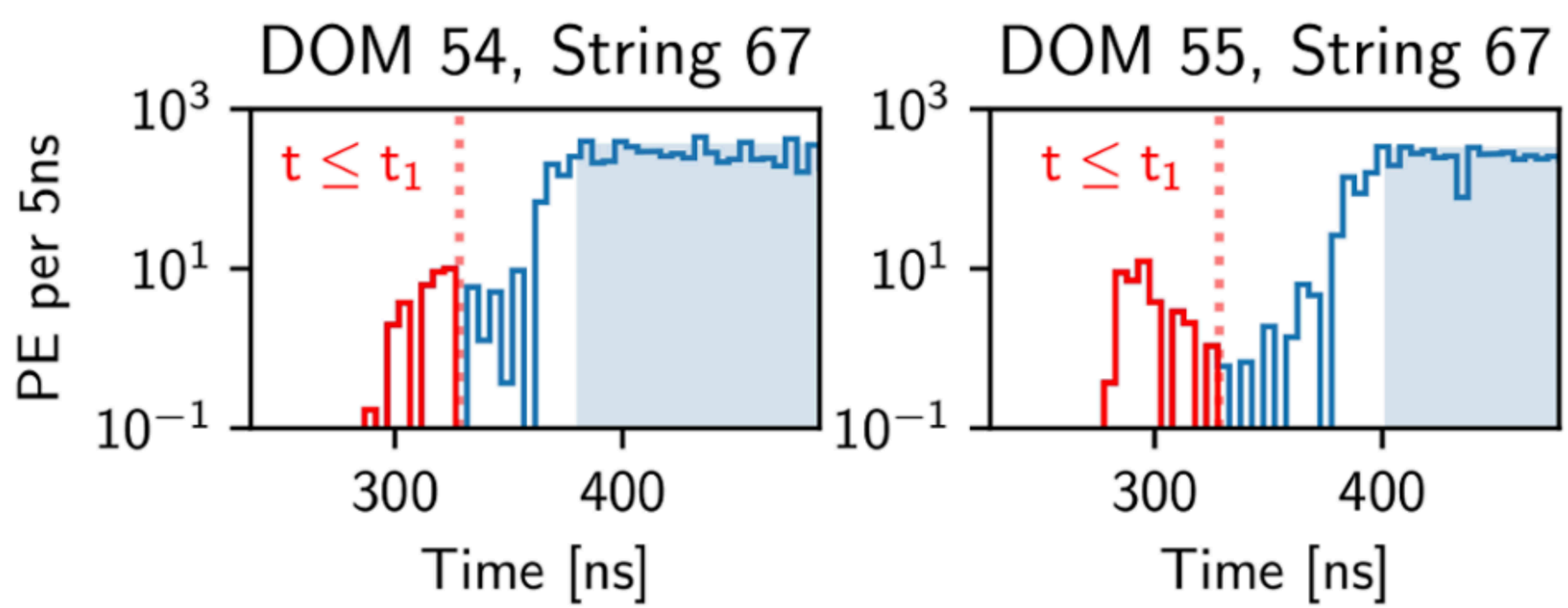
muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)



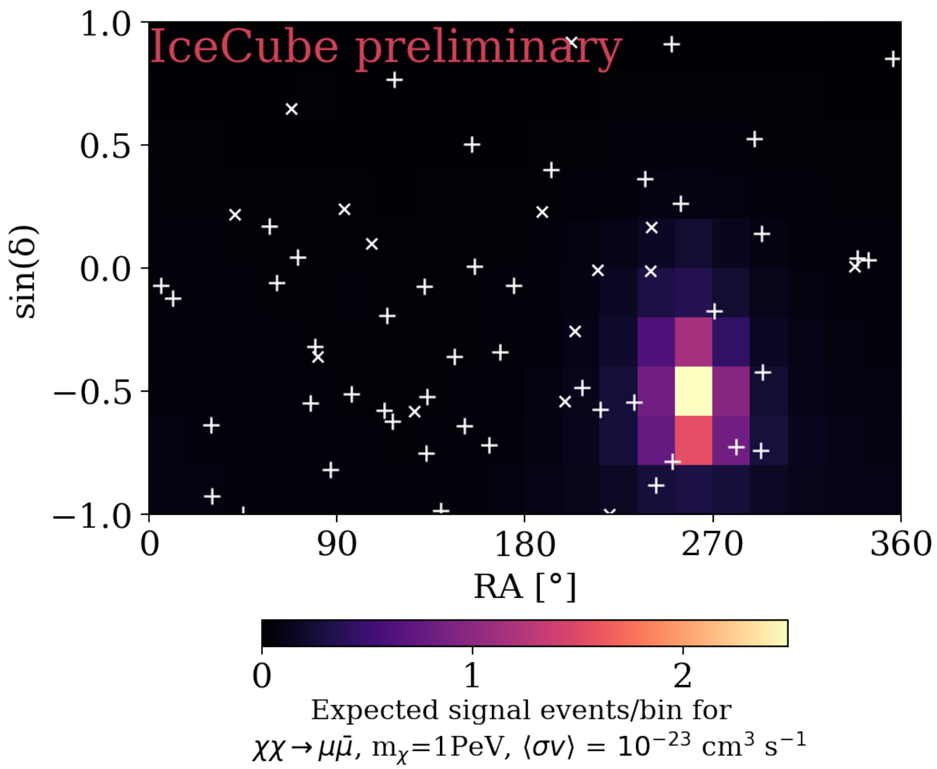
Hadronic shower from W-decay:

Early muons followed by electromagnetic shower

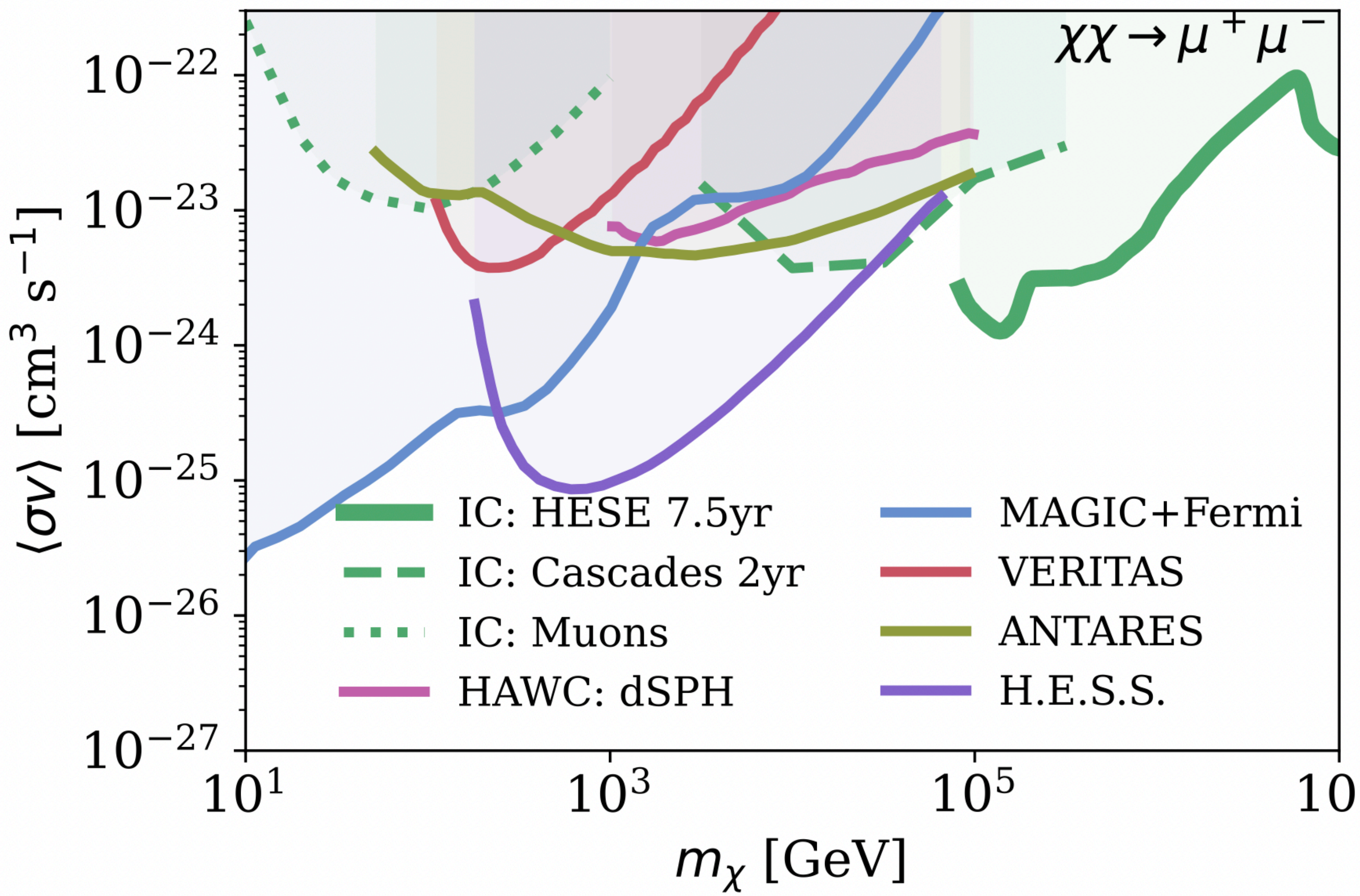


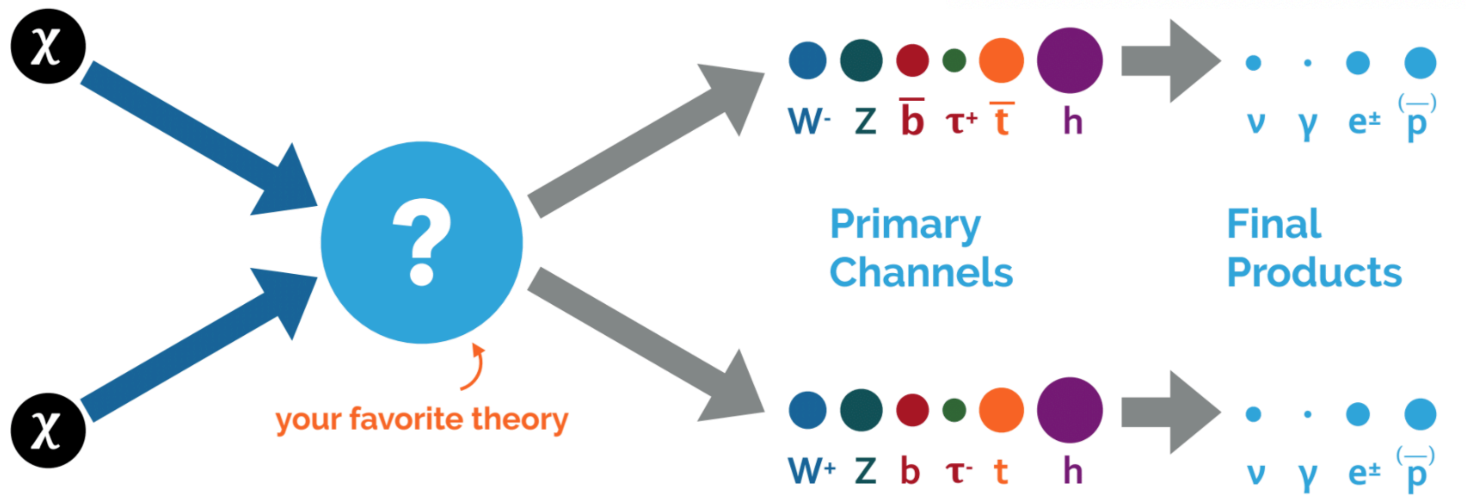


Dark matter annihilation



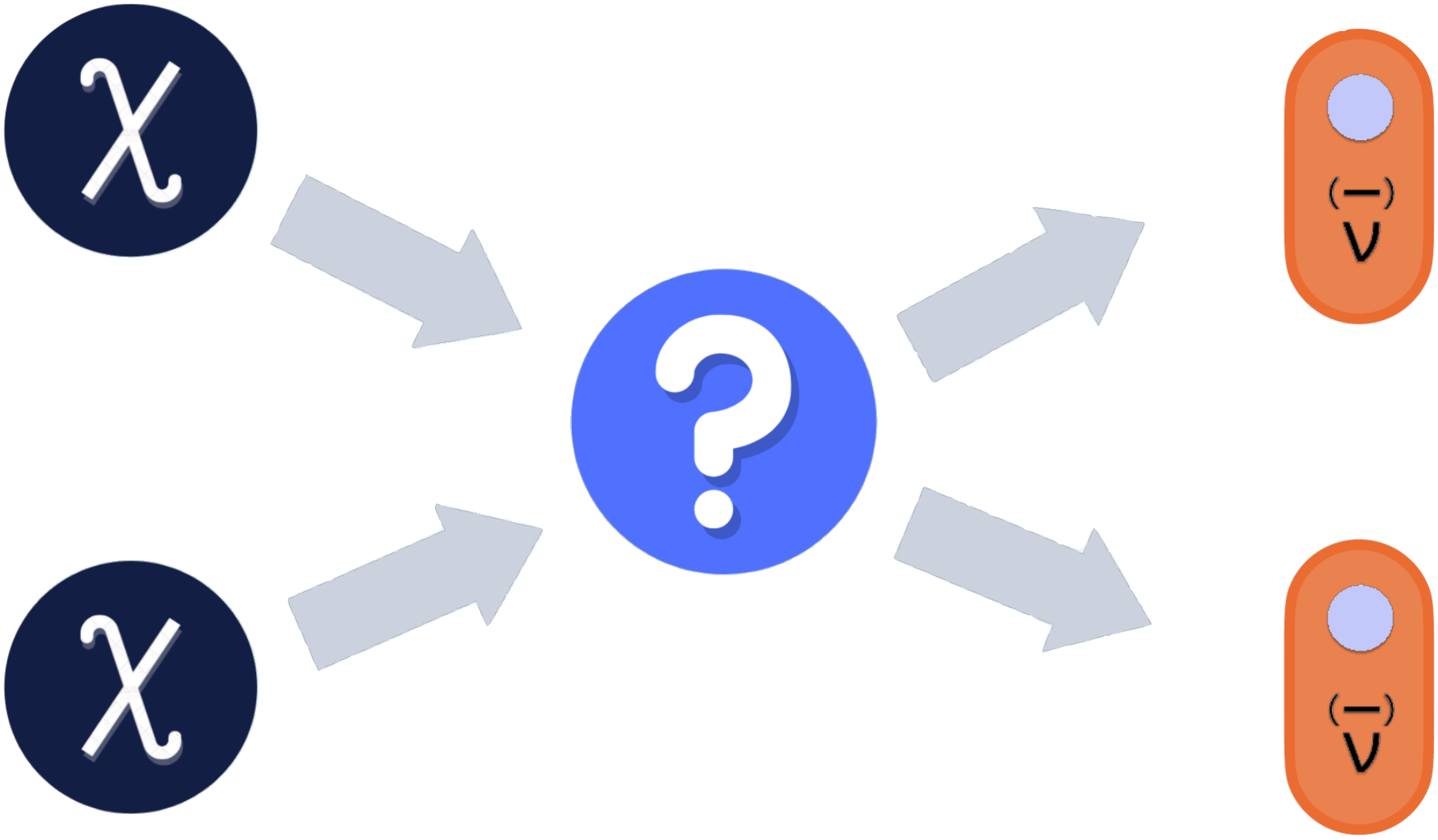
IceCube Collaboration, arXiv:2205.12950





IceCube Collaboration 2205.12950.
See also CA, H. Dujmovic arXiv 1907.11193, Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

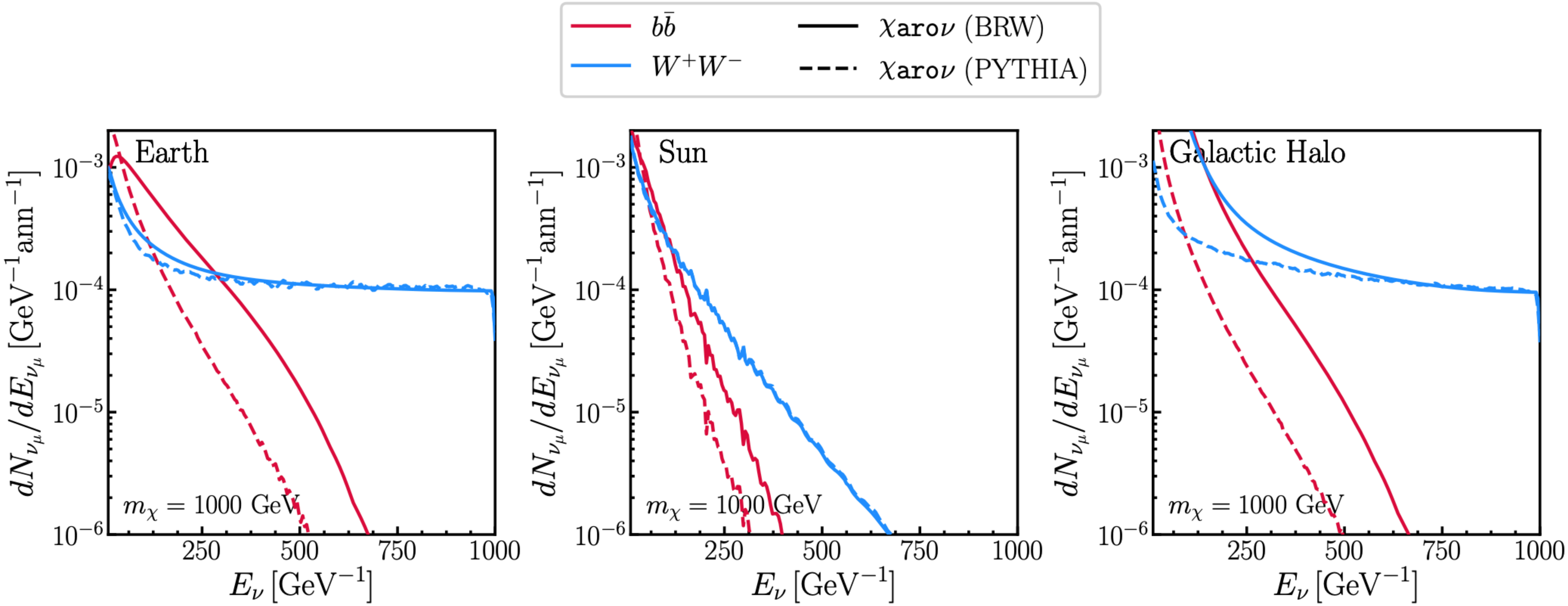
WIMP Miracle:
The final frontier



To rule out the WIMP miracle in a "model independent way" one needs to constraint all SM annihilation channels.

For good limits, we need good predictions!

https://github.com/IceCubeOpenSource/charon

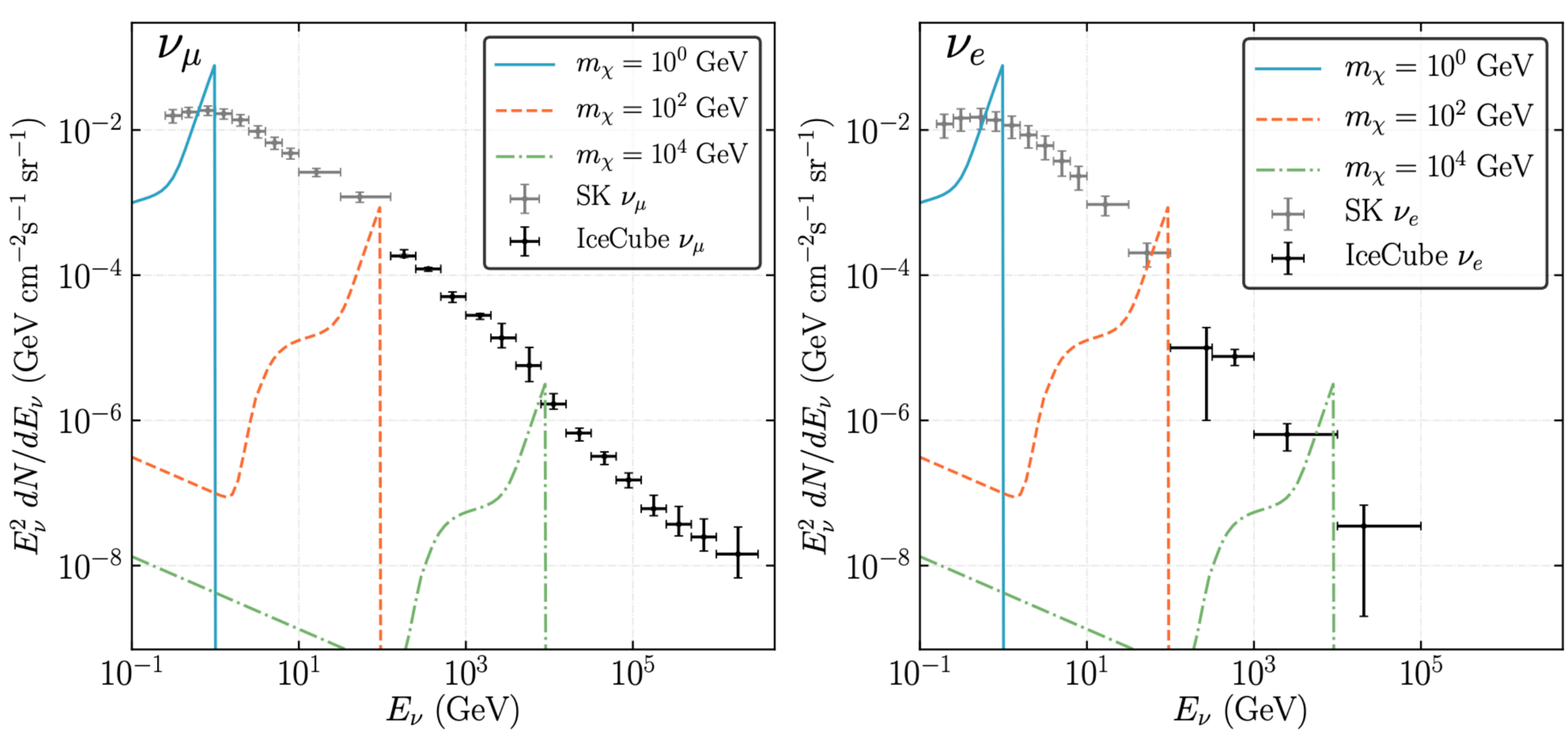


IceCube results with updated calculations to appear soon!

Q. Liu & J. Lazar *et al* 2007.15010

Bauer, Rodd & Webber *et al* 2007.15001

Background agnostic constraints on Dark matter making neutrinos



RICHARD, F., ET AL. (SUPER-KAMIOKANDE) PHYS. REV. D94 (5), 052001

AARTSEN, M. G., ET AL. (ICECUBE) (2015B), PHYS. REV. D91, 122004

ARGÜELLES, ET AL., REV. MOD. PHYS. 93, ARXIV:1912.09486

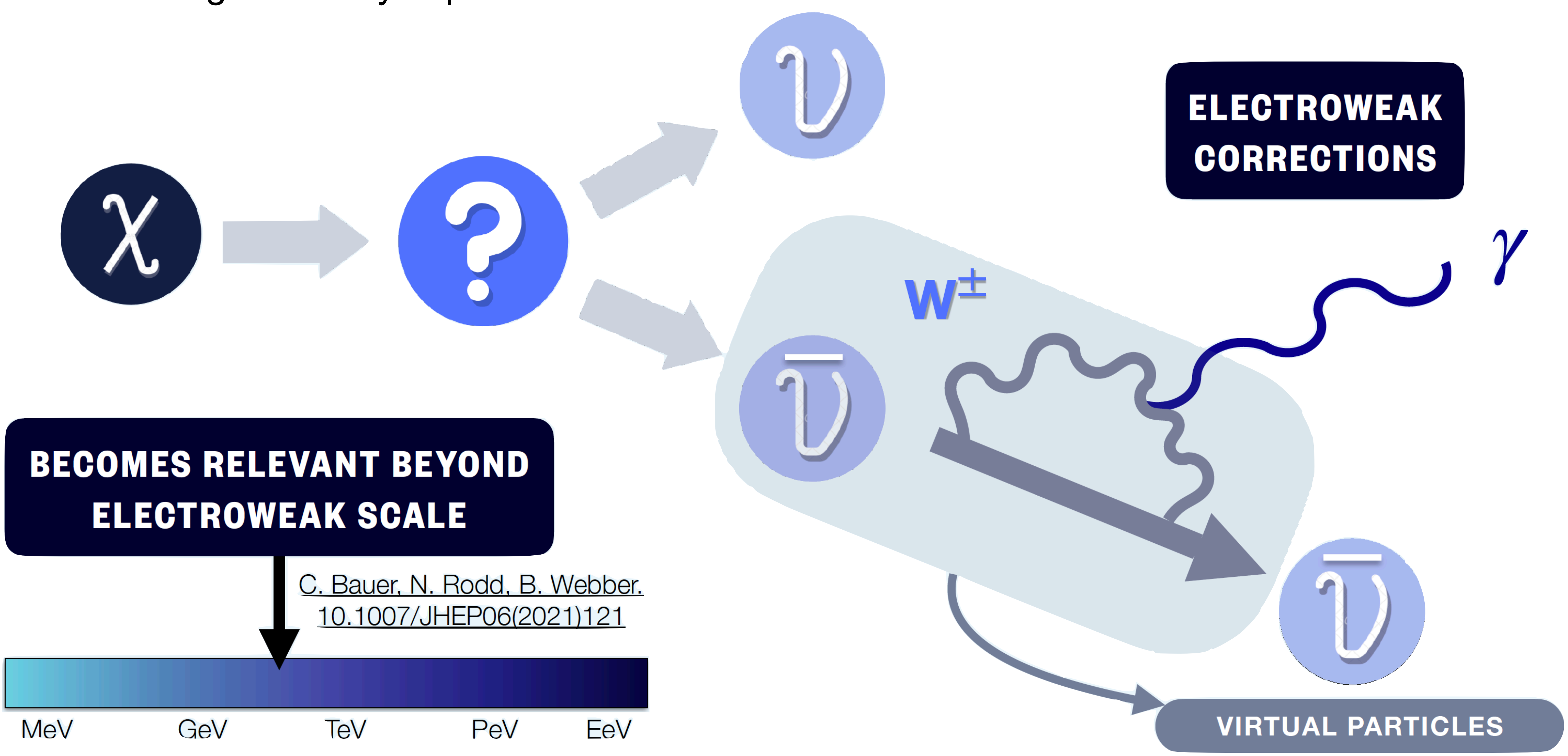
Background Agnostic $\Rightarrow \mathscr{L} = \begin{cases} \mathbb{P}(d\,|\,\mu) & (d < \mu), \\ 1 & (d \geq \mu) \end{cases}$

Flux of neutrinos from dark matter cannot overshoot measurements of the integrated neutrino flux.

$10^{-1} - 10^{2}$	Fermi-LAT [63]	γ
$10^{3} - 10^{9}$	*CTA* [64]	γ
$10^{4} - 10^{9}$	HAWC [65]	γ
$10^{5} - 10^{9}$	LHAASO [66]	γ
$10^{6} - 10^{9}$	IceTop [67]	γ
$10^{7} - 2 \times 10^{9}$	KASCADE [68]	γ
$10^{8} - 2 \times 10^{10}$	CASA-MIA [69]	γ
$10^{9} - 2 \times 10^{12}$	EAS-MSU [70]	γ
$10^{11.5} - 10^{14}$	TA-SD [71]	γ
$> 10^{12}$	Auger-SD [72]	γ

Gamma-ray experiments will have correlated signals

I will discuss these gamma-ray experiments too!



C. Bauer, N. Rodd, B. Webber. 10.1007/JHEP06(2021)121

Background agnostic constraints on Dark matter making neutrinos

$10^{-1} - 10^{2}$	Fermi-LAT [63]
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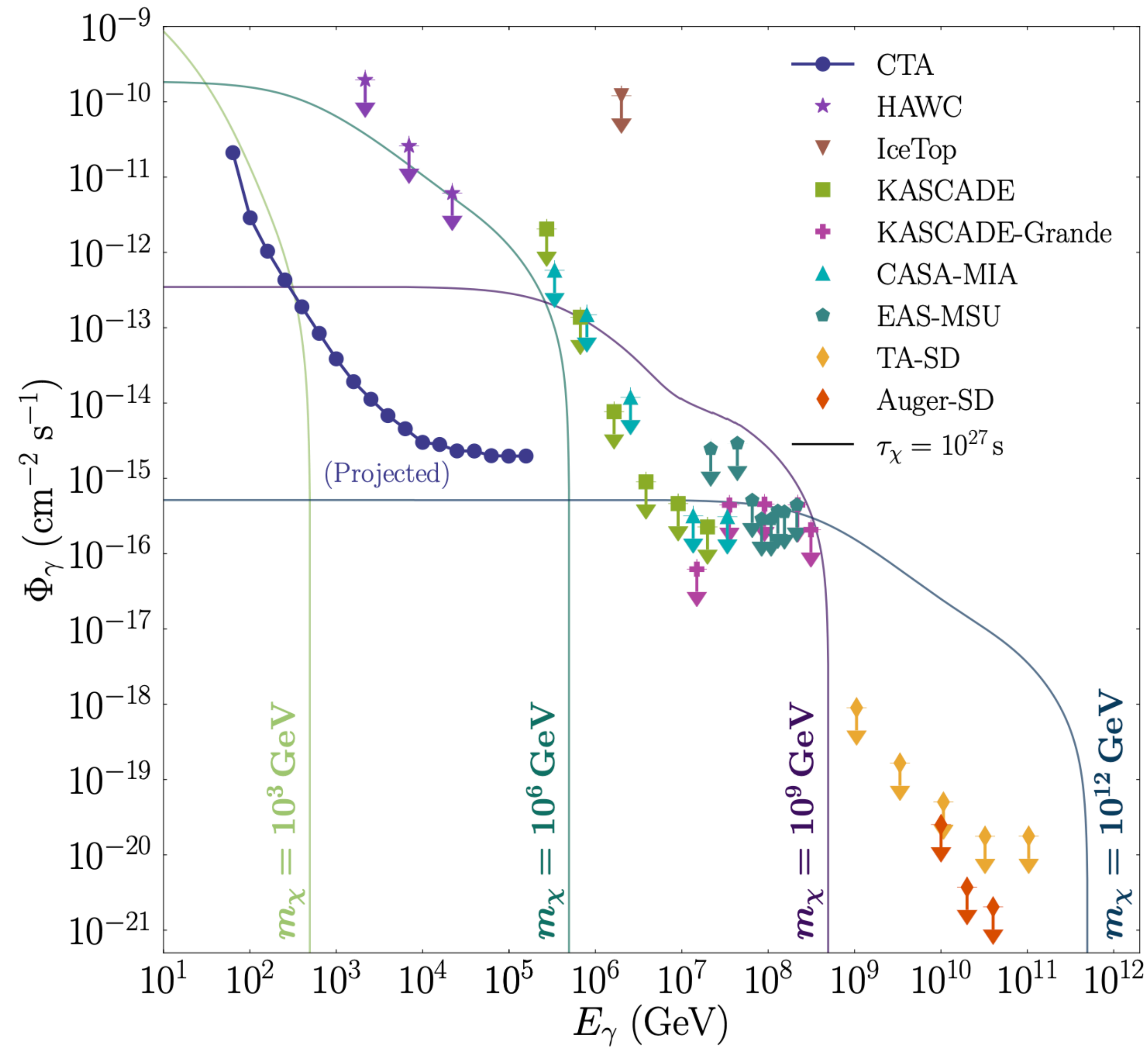
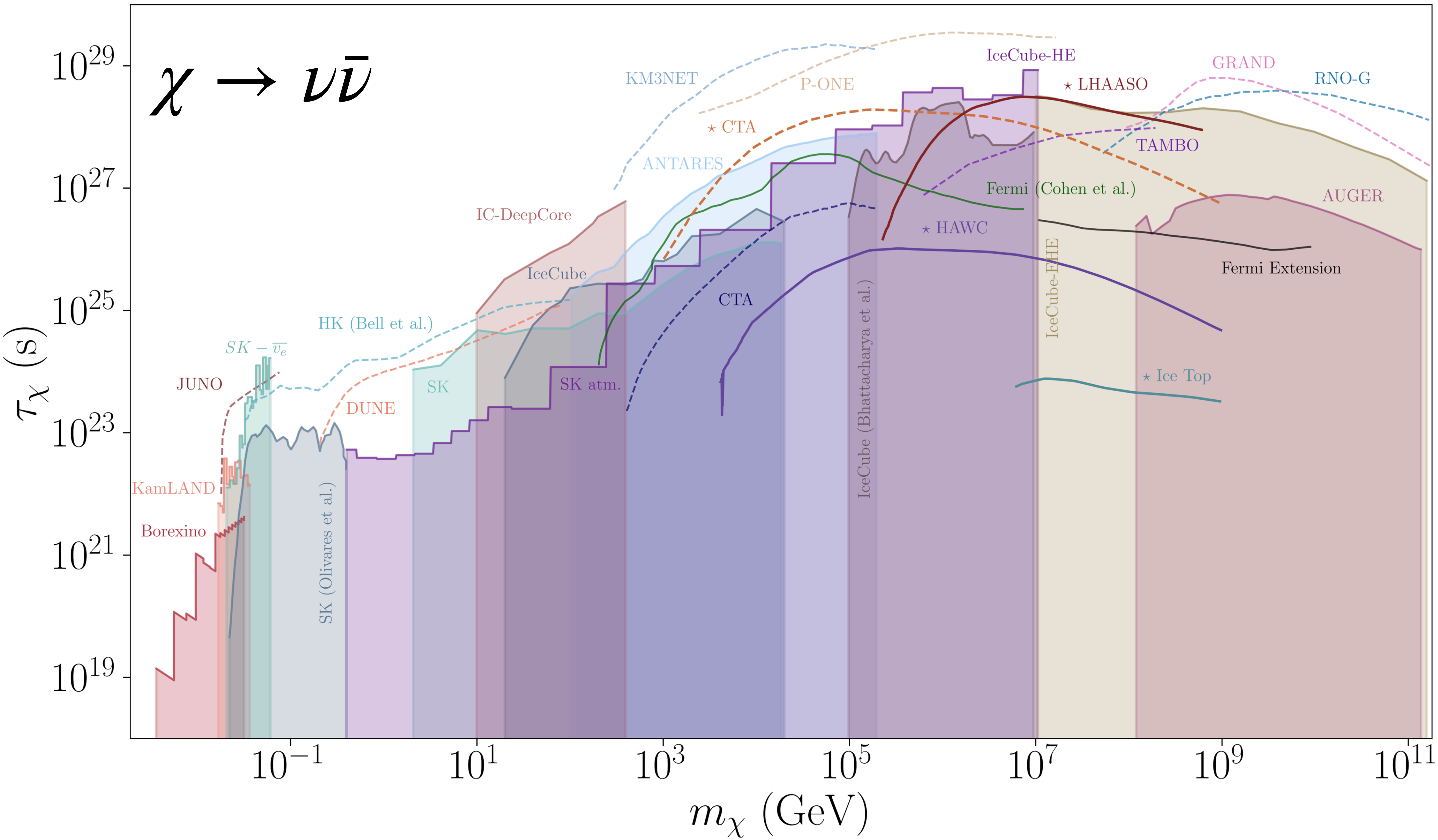


Associated gamma-ray flux should also not overshoot constraints

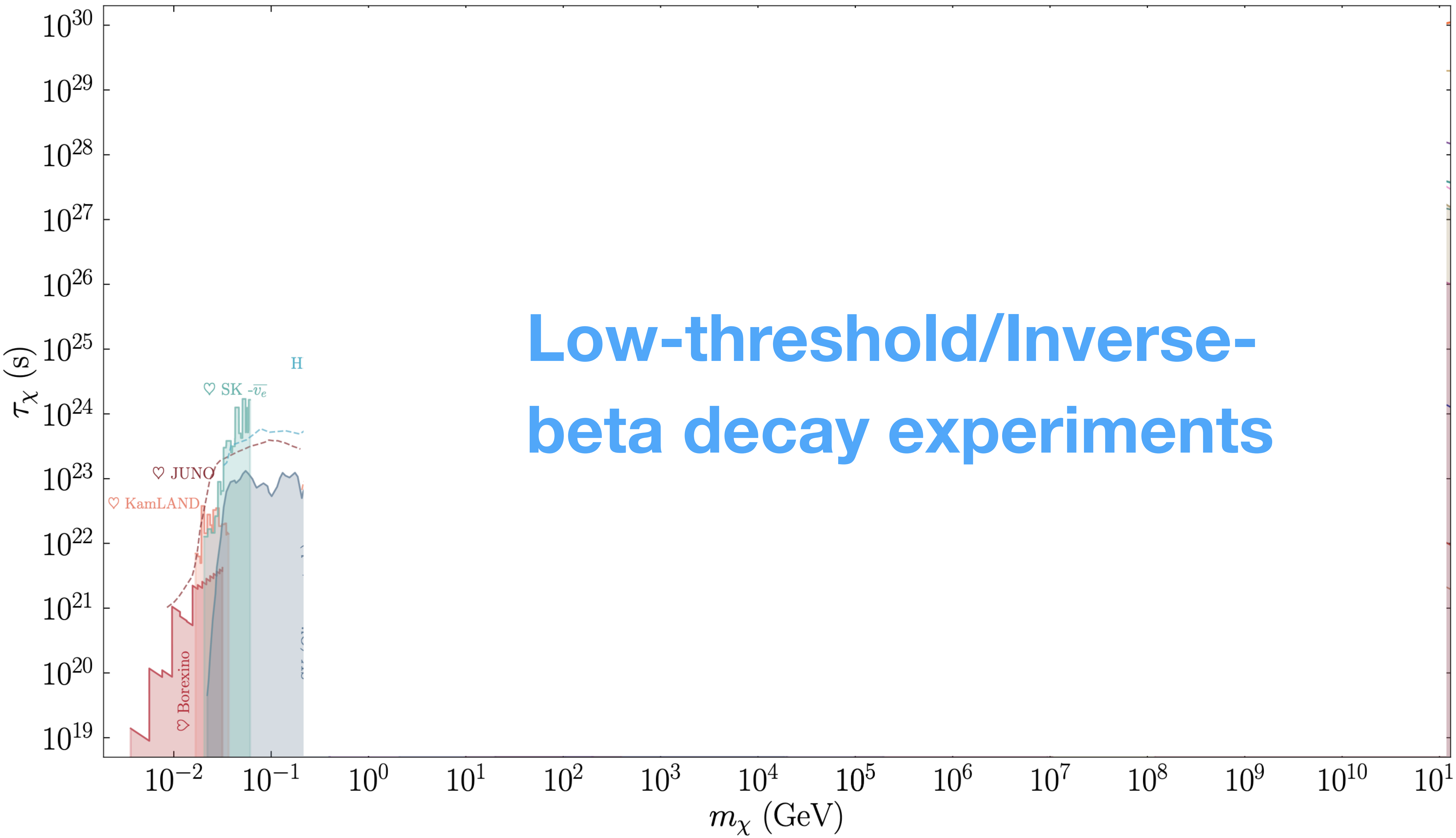
CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

And many more measurements ...



CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

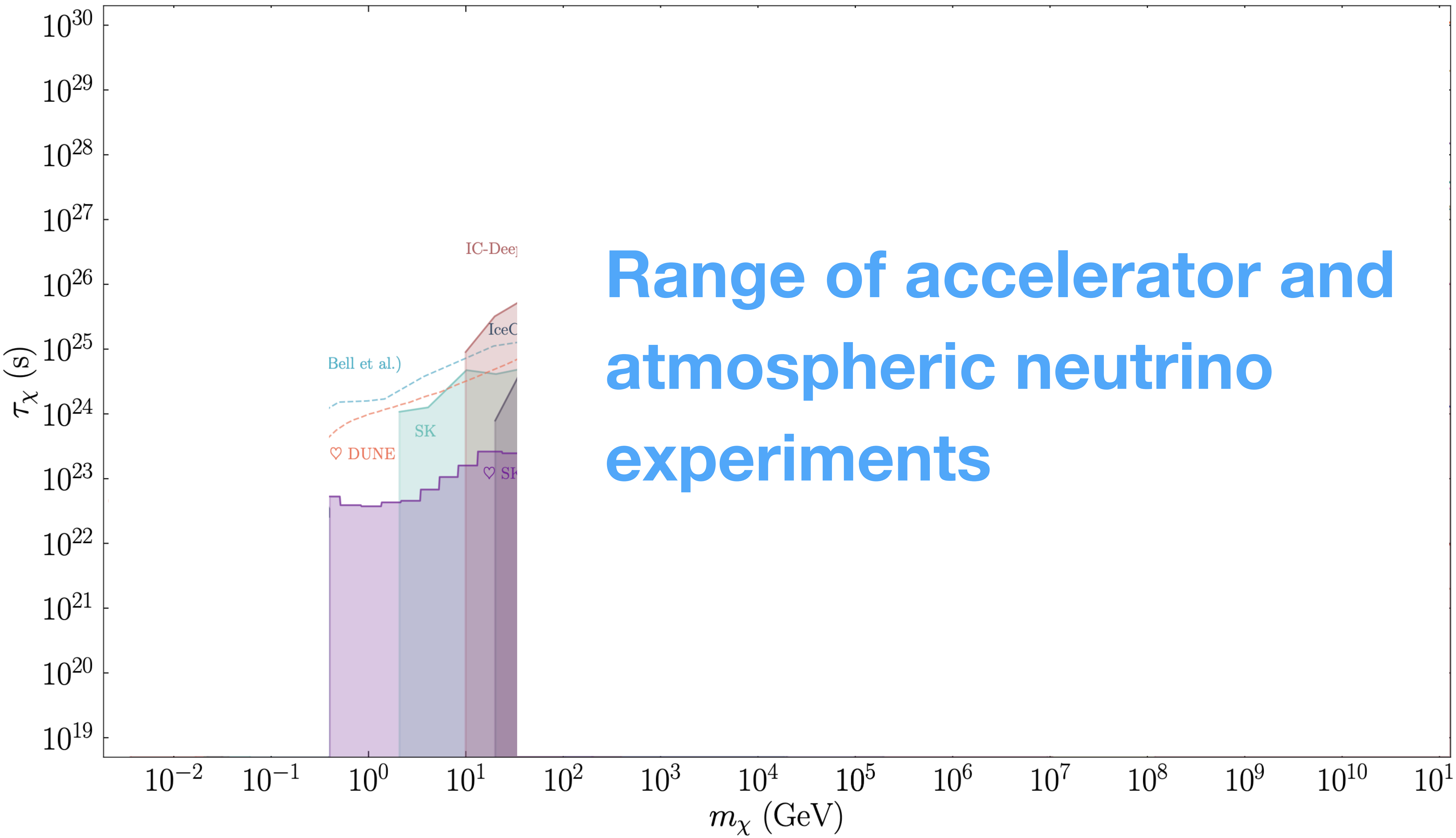
Constraints on dark matter decay to neutrinos



Low-threshold/Inverse-beta decay experiments

CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

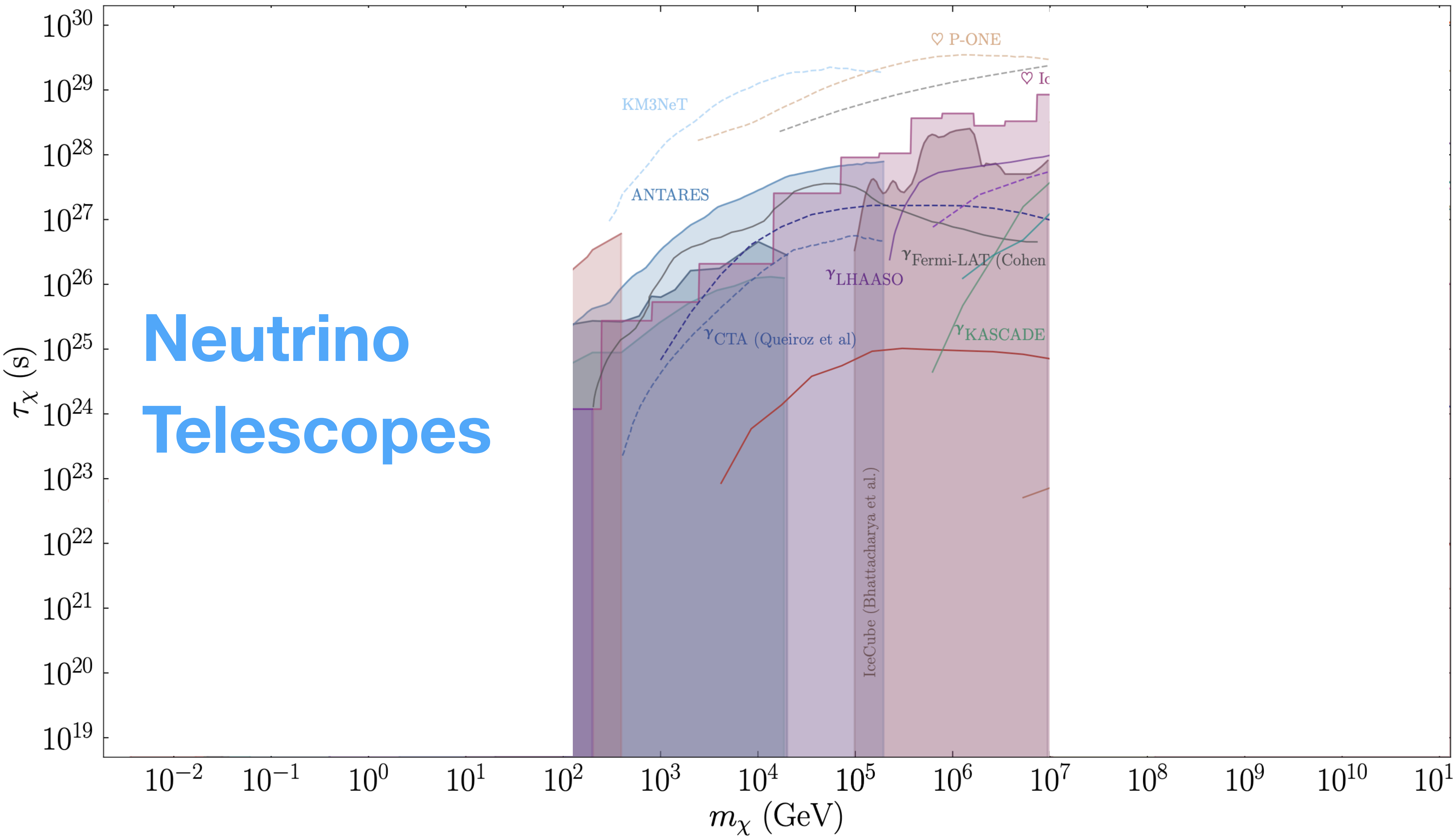
Constraints on dark matter decay to neutrinos



Range of accelerator and atmospheric neutrino experiments

CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

Constraints on dark matter decay to neutrinos



CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

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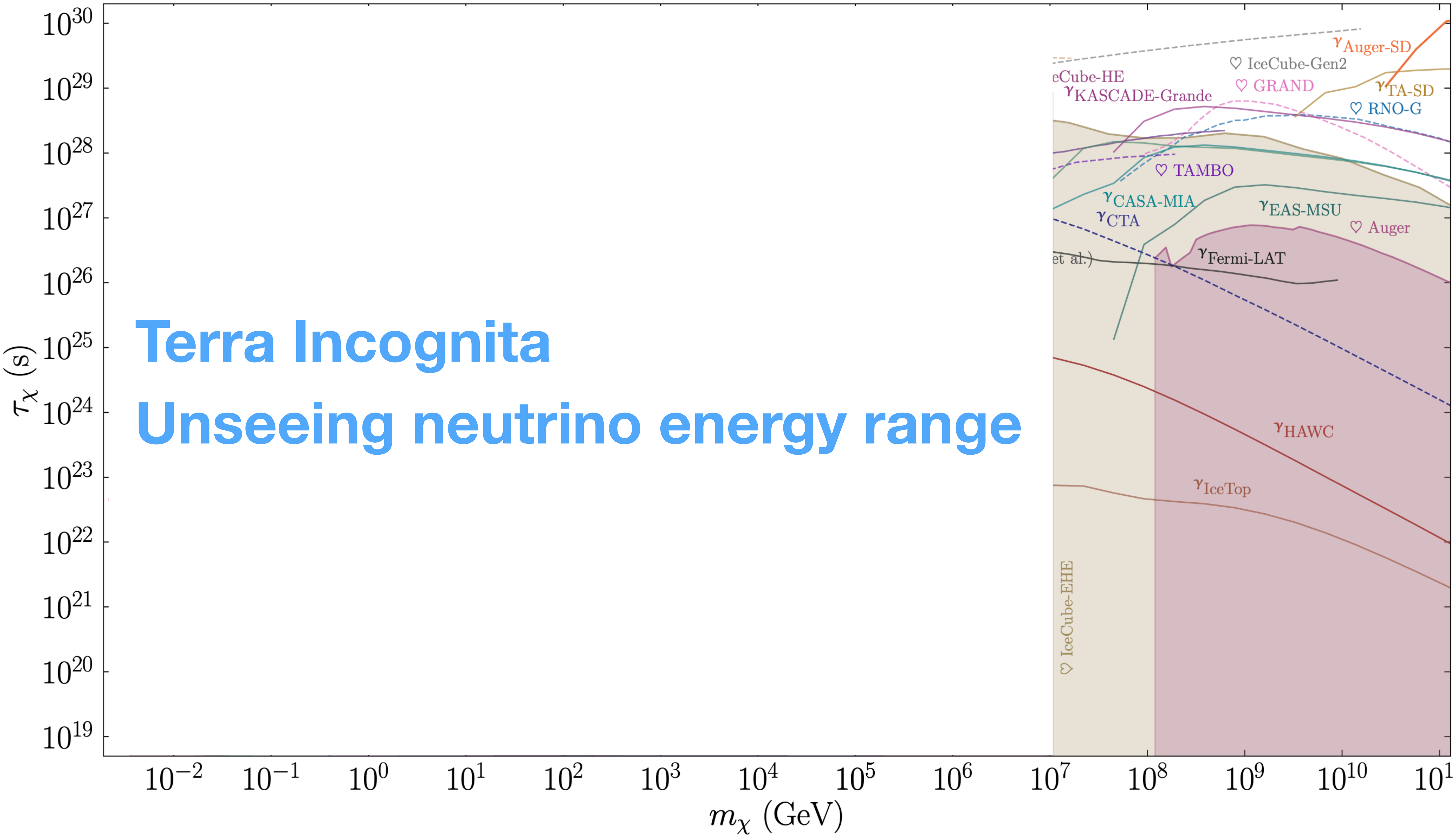

CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

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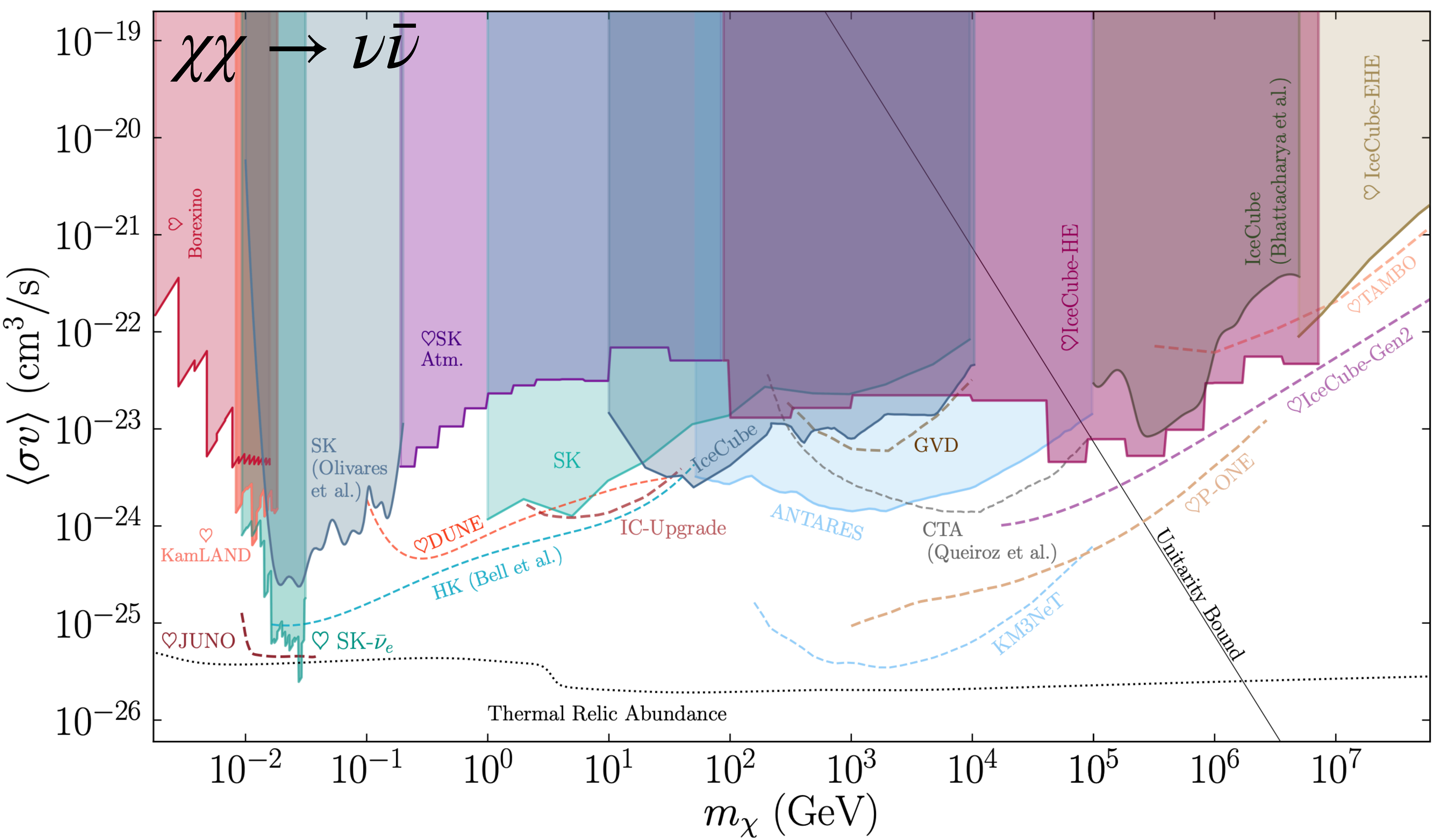
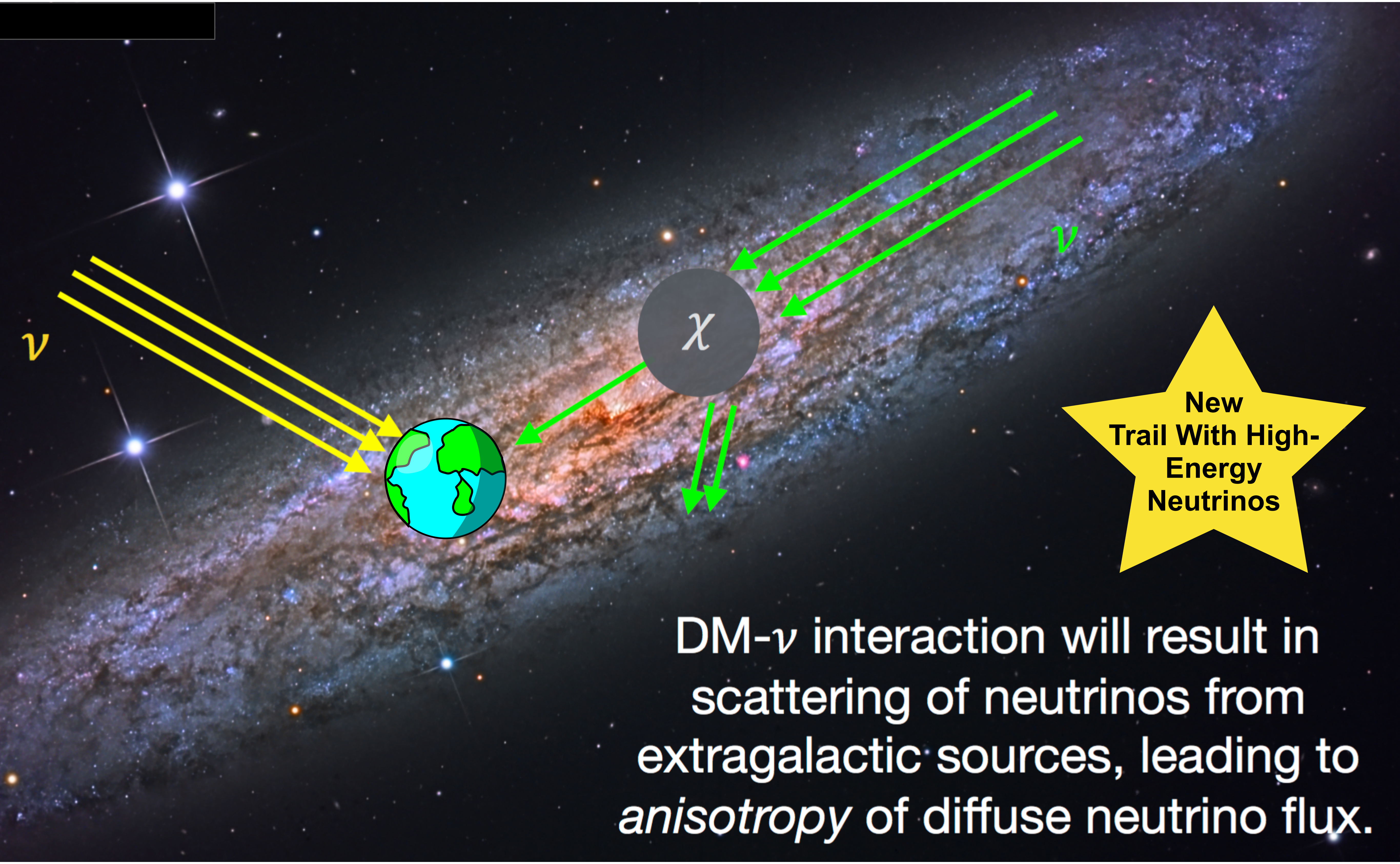


CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007.*

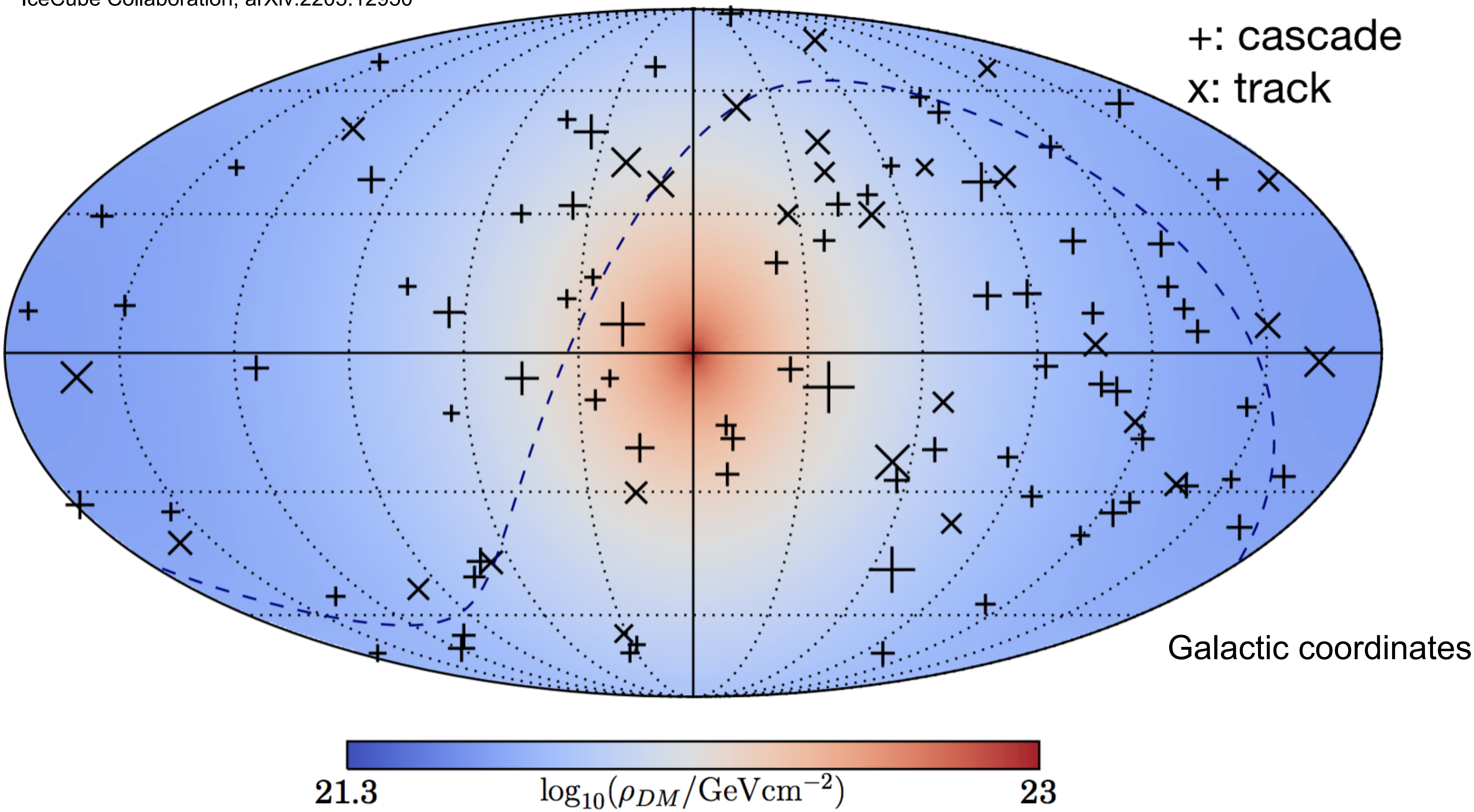
Dark matter neutrino incoherent **scattering**



CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

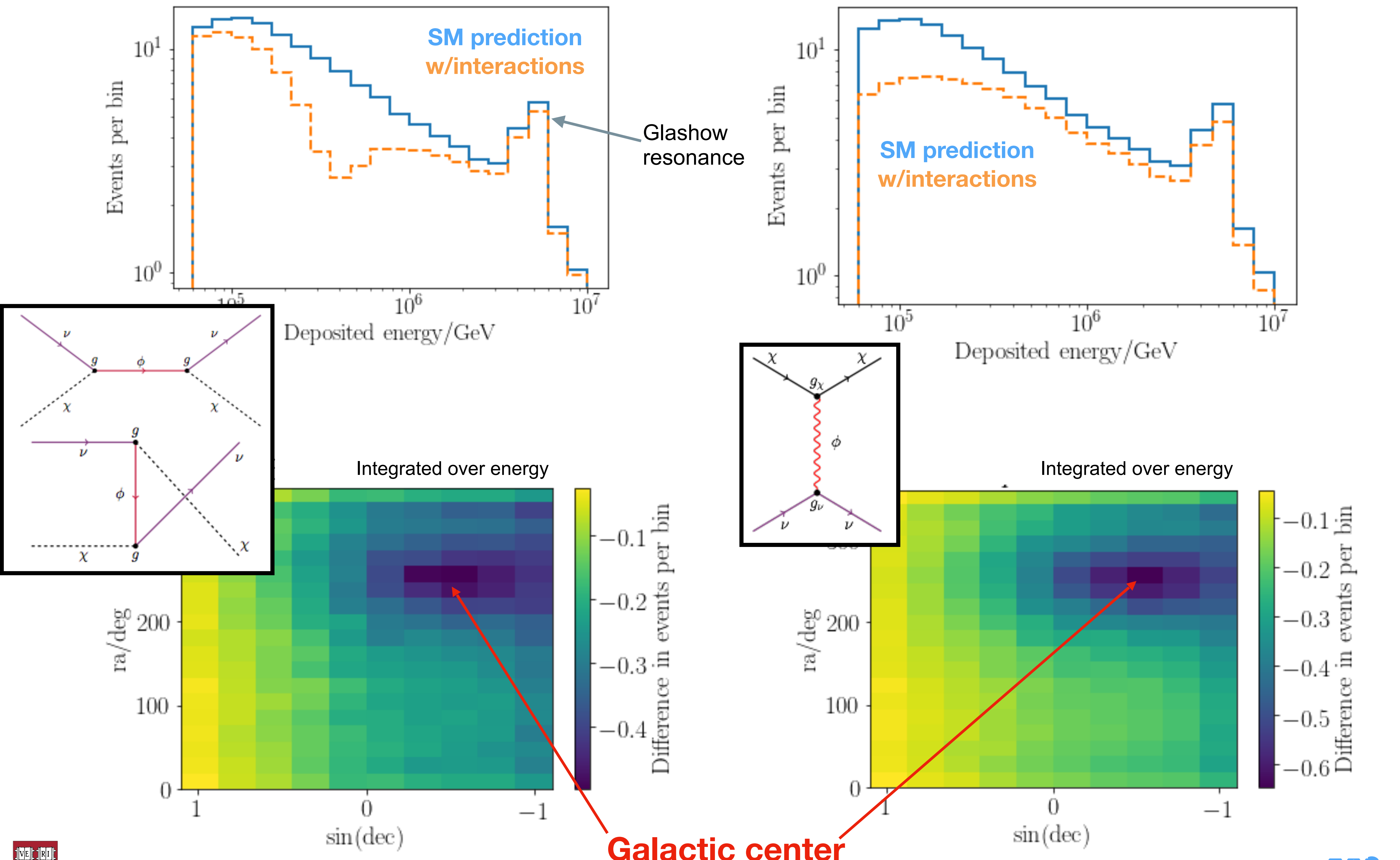
HESE Neutrino Skymap

HESE: high-energy starting events
IceCube Collaboration, arXiv:2205.12950

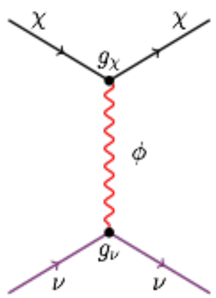


Events are compatible with an isotropic distribution: found no signal!

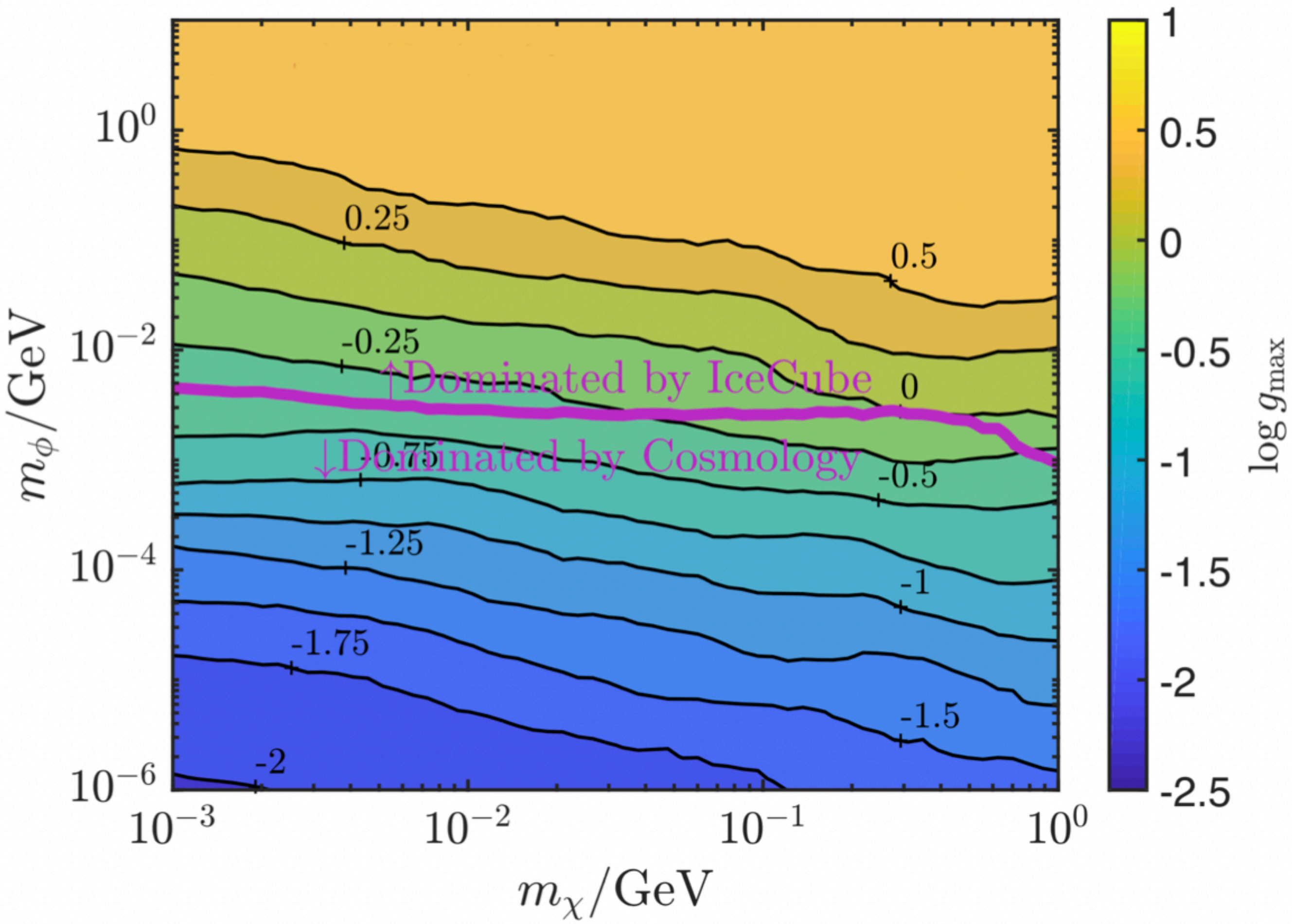
Also include effects in energy and direction

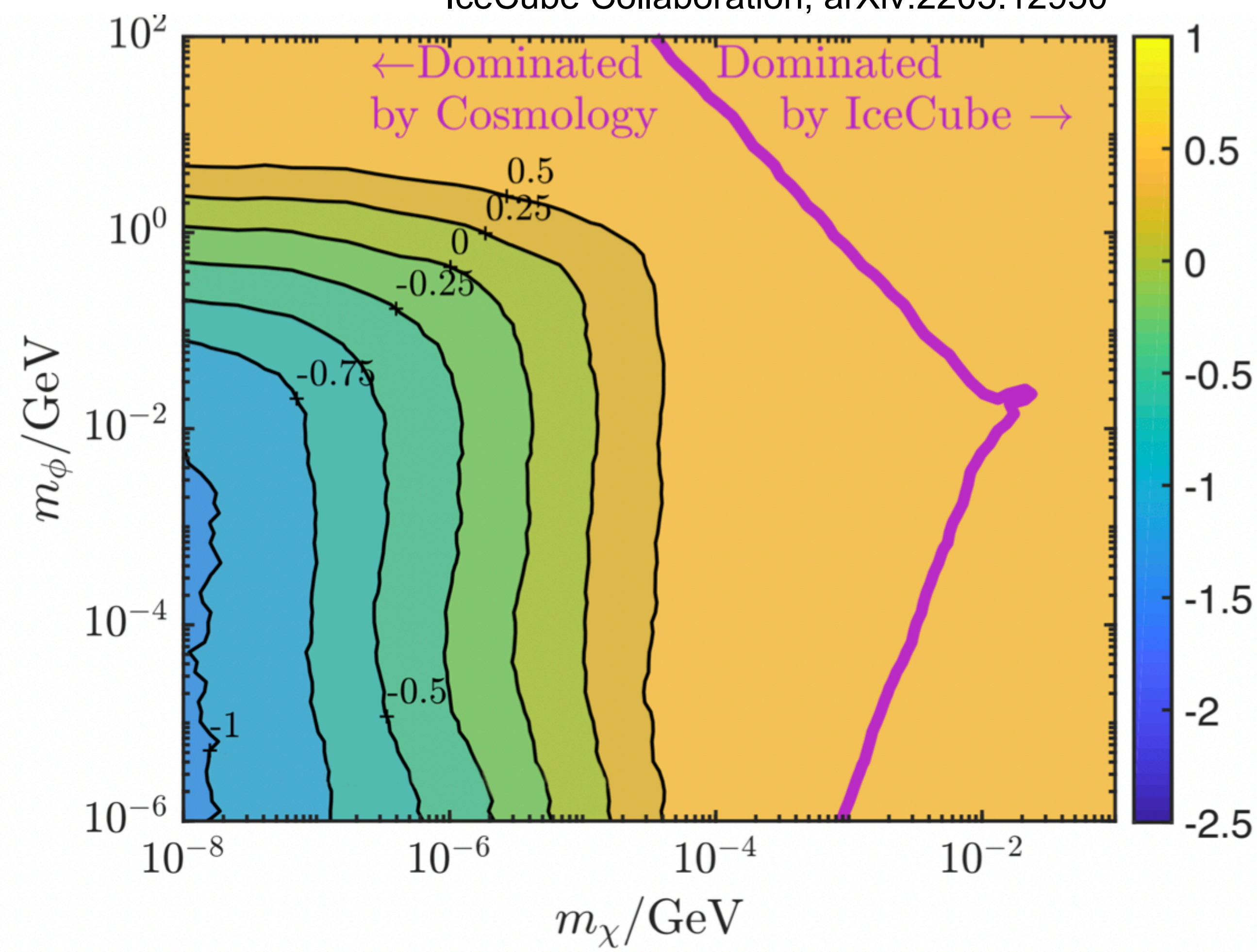


New constraints on neutrino-dark matter interactions



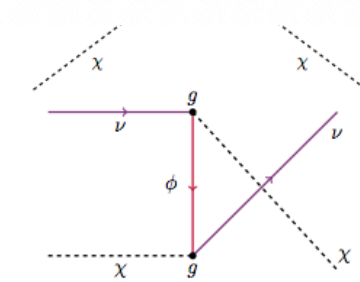
IceCube Collaboration, arXiv:2205.12950



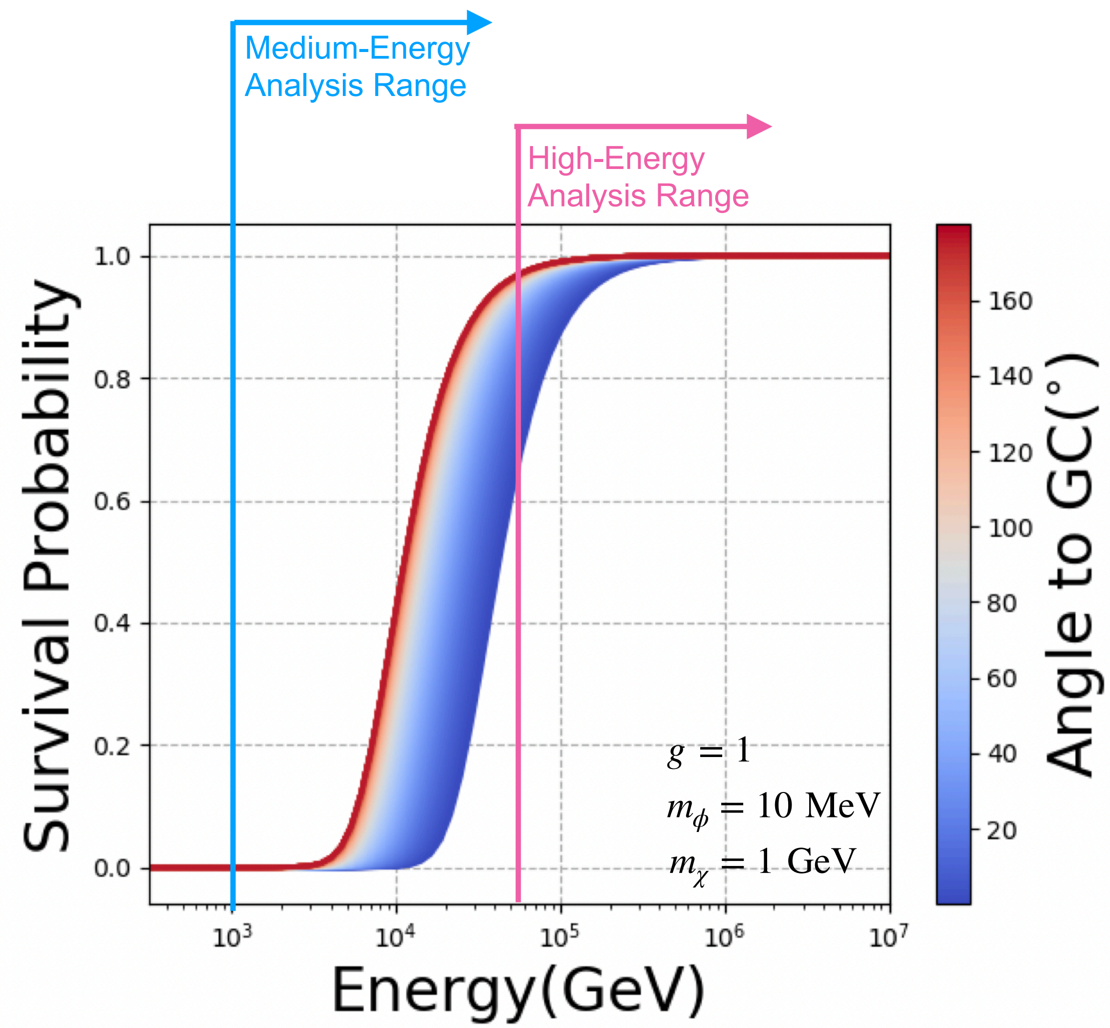


Color scale is the maximum allowed coupling.

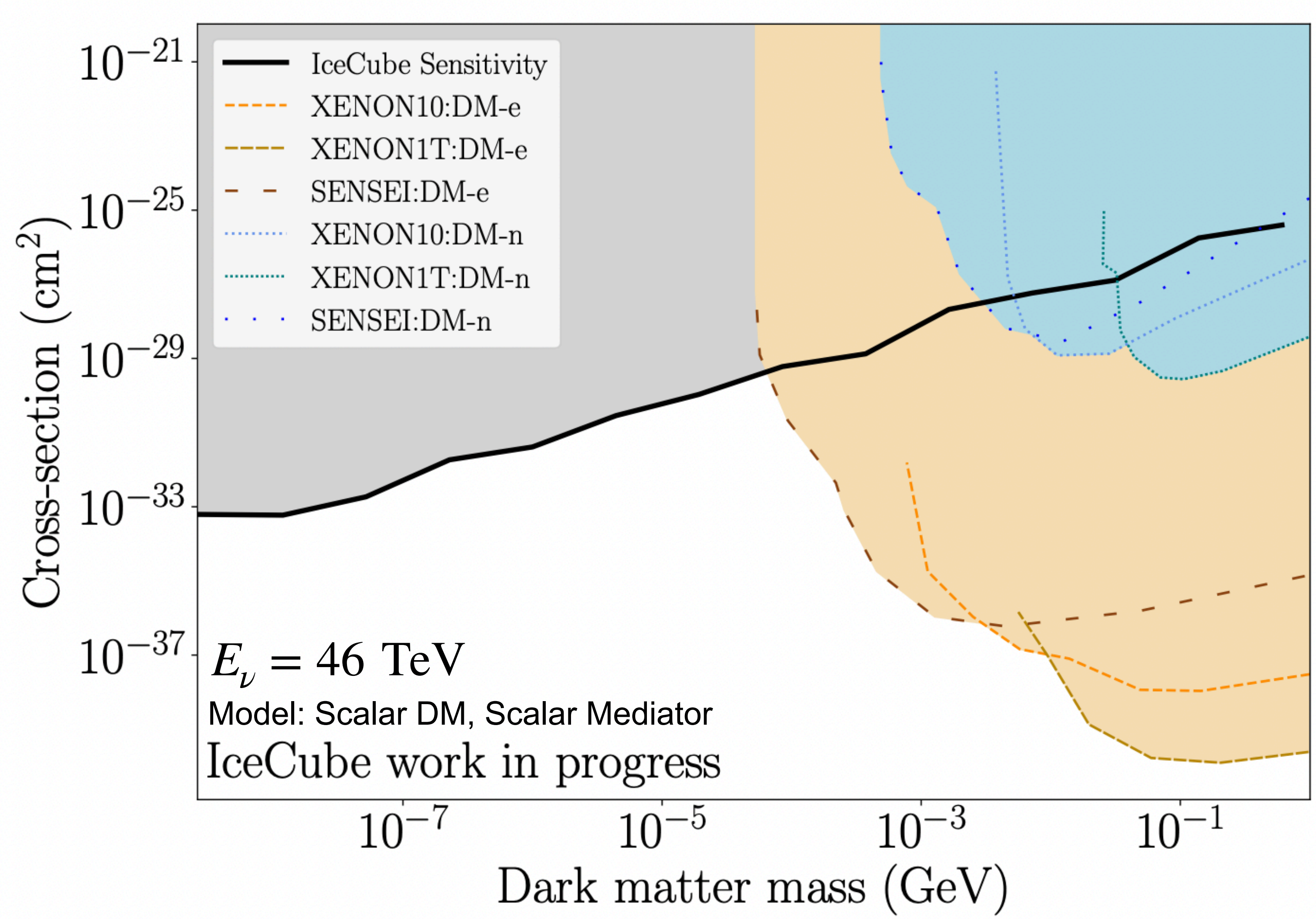
Cosmological bounds using Large Scale Structure from Escudero et al 2016



Second Generation Analyses Using Medium-Energy Starting Events



A. McMullen, A. Vincent, CA, A. Schneider arXiv:2107.11491

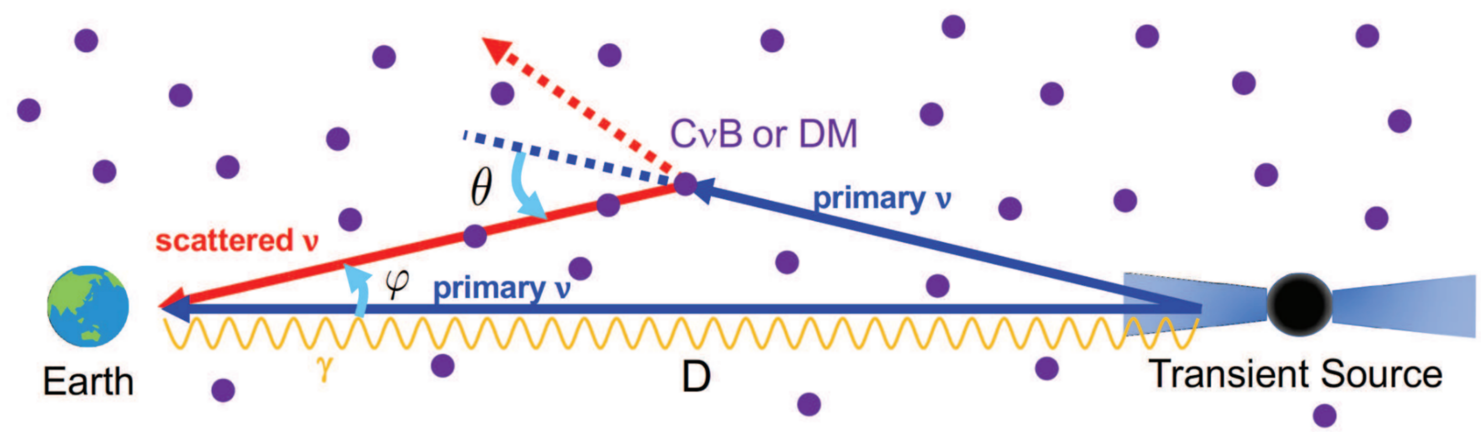


Larger sample sizes data sets yet to be used for these searches. Only IceCube's High-Energy Starting Events used so far.

Neutrino Time of Flight

Dark Matter-neutrino interactions
Murase & Shoemaker arXiv:1903.08607

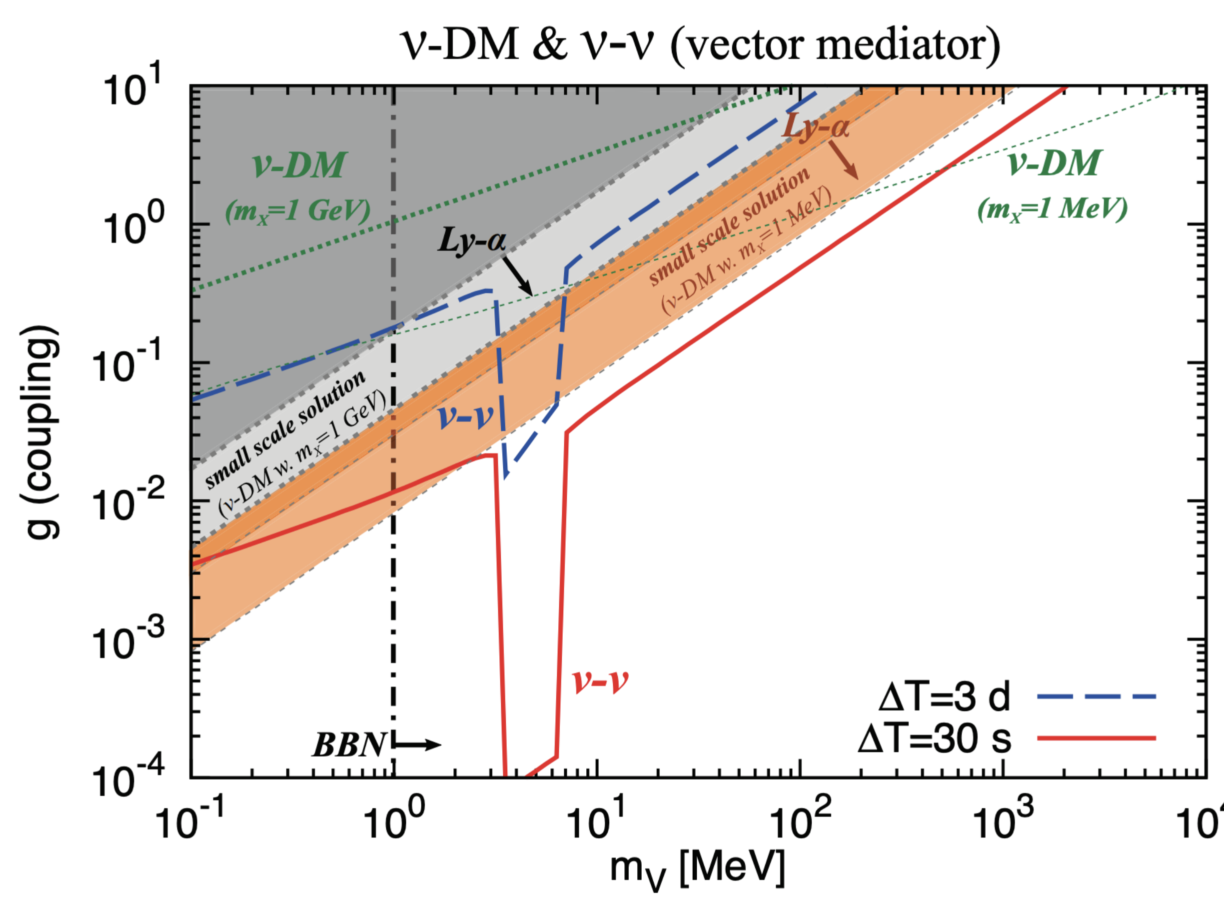
Time-of-flight constraints rely on assumption of flare emission window. Handle with care.



$$v(E) = c\left[1 - s_{\rm n}\frac{n+1}{2}\left(\frac{E}{E_{\rm LV,n}}\right)^n\right]$$

$$(\Delta v_{\nu\gamma}/c)_{TXS} \sim 10^{-11}$$

$$(\Delta v_{\nu\gamma}/c)_{SN1987A} \sim 3\cdot 10^{-9}$$

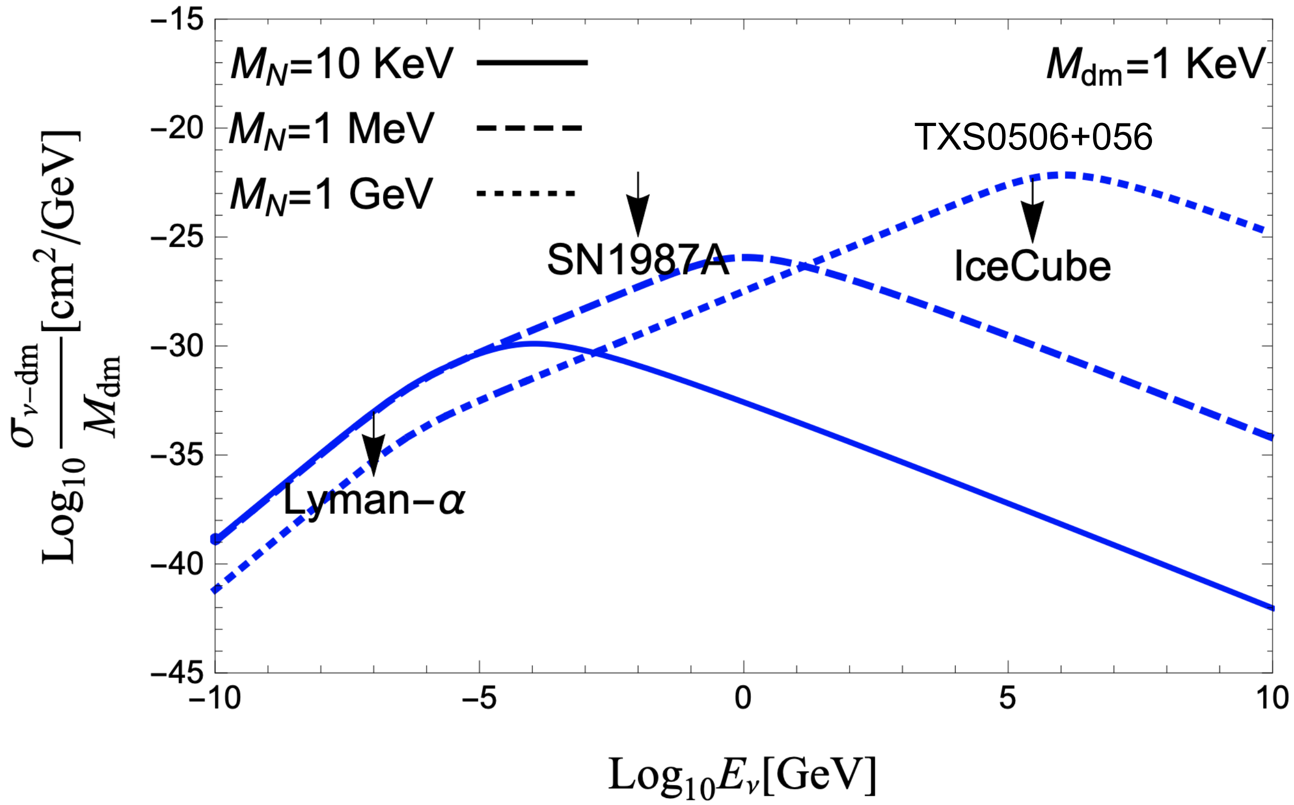


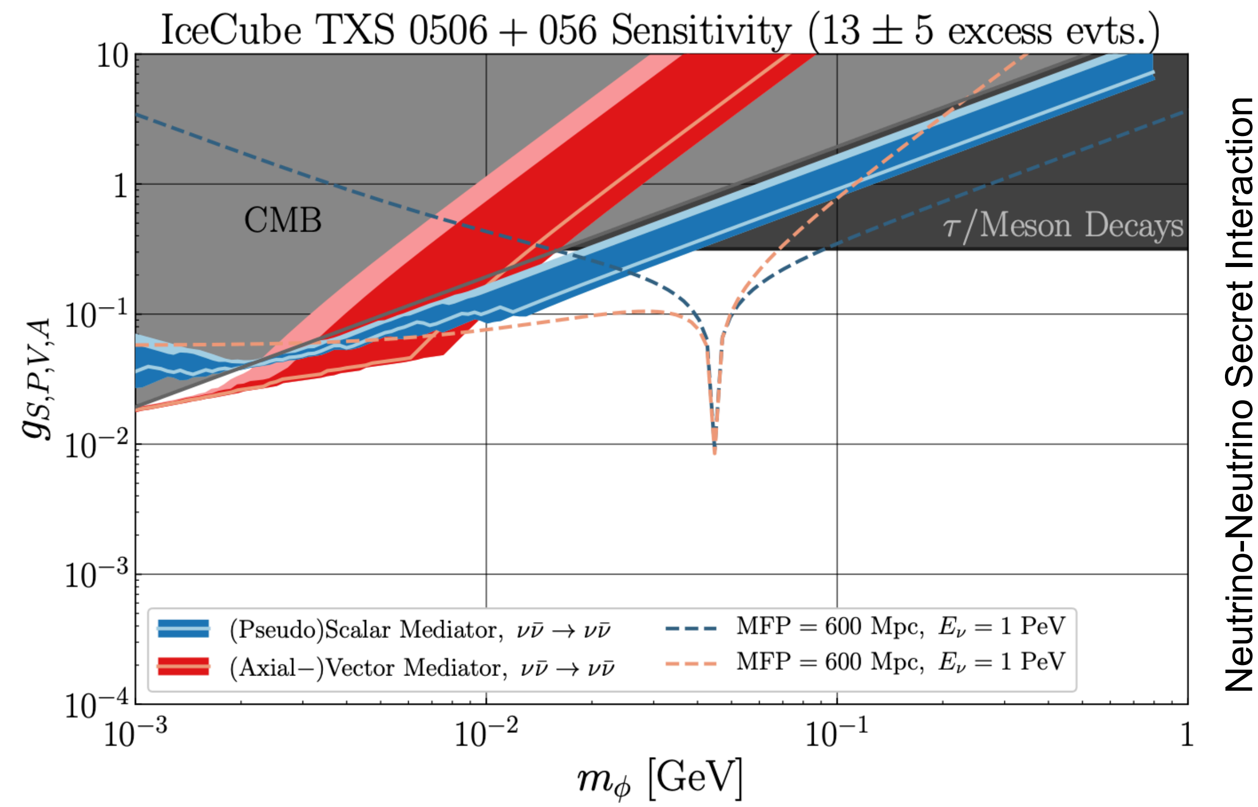
Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

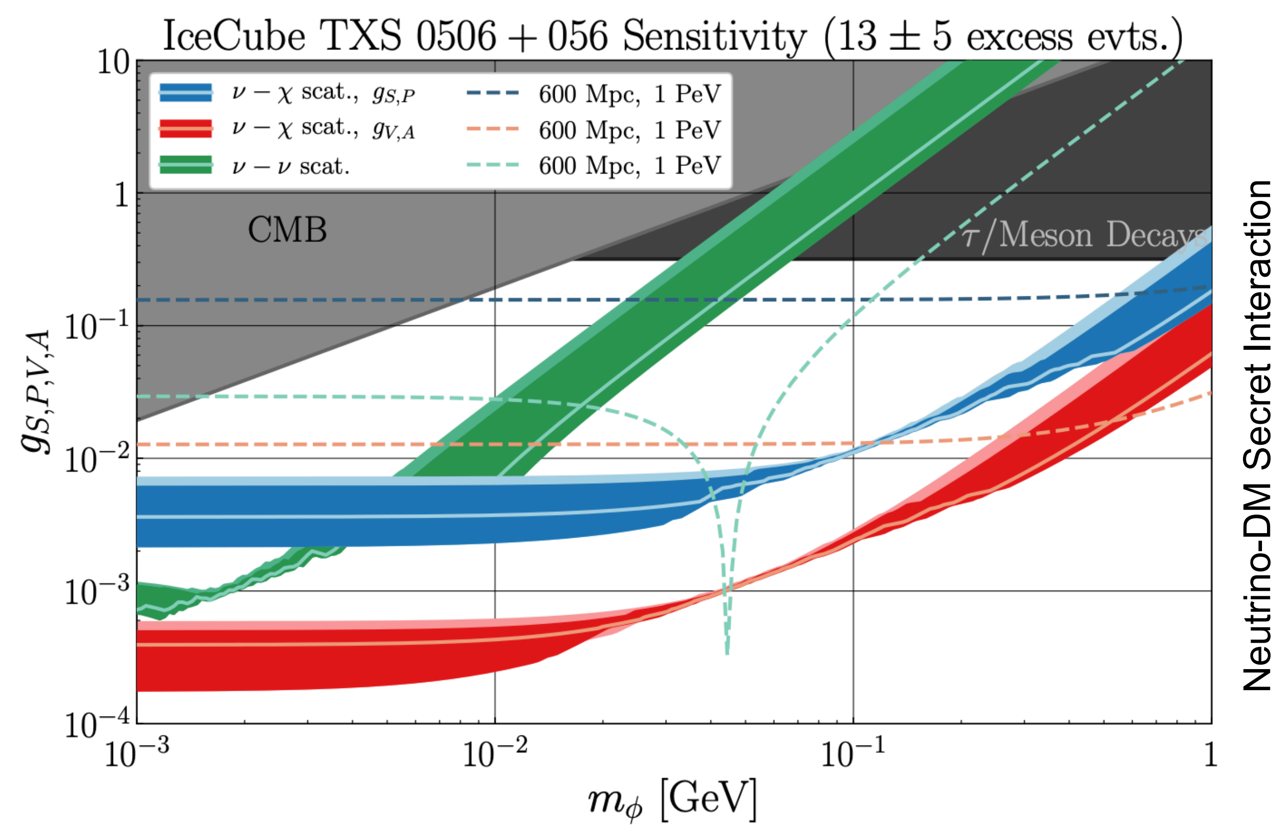
Opacity to Individual Sources

Kelly et al arXiv:1808.02889

Choi et al. arXiv:1903.03302







Opacity constraints rely on assumptions on the intrinsic source luminocity. Handle with care.

dark matter-neutrino couplings
CA et al. arXiv:1703.00451
Kelly et al arXiv:1808.02889
Choi et al. arXiv:1903.03302

neutrino-neutrino couplings
Kelly et al arXiv:1808.02889
CA et al. arXiv:2009.05201
Carpio et al. arXiv:2104.15136

Search for Lorentz Violation via Flavor Morphing

As neutrinos travel from their far away source they can interact with a Lorentz violating field.

Effects expected at the Planck Scale.

Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

Trajectories in the flavor triangle in the presence of Lorentz Violation (LV)

$$H_d = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{\frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger}$$

Dimension

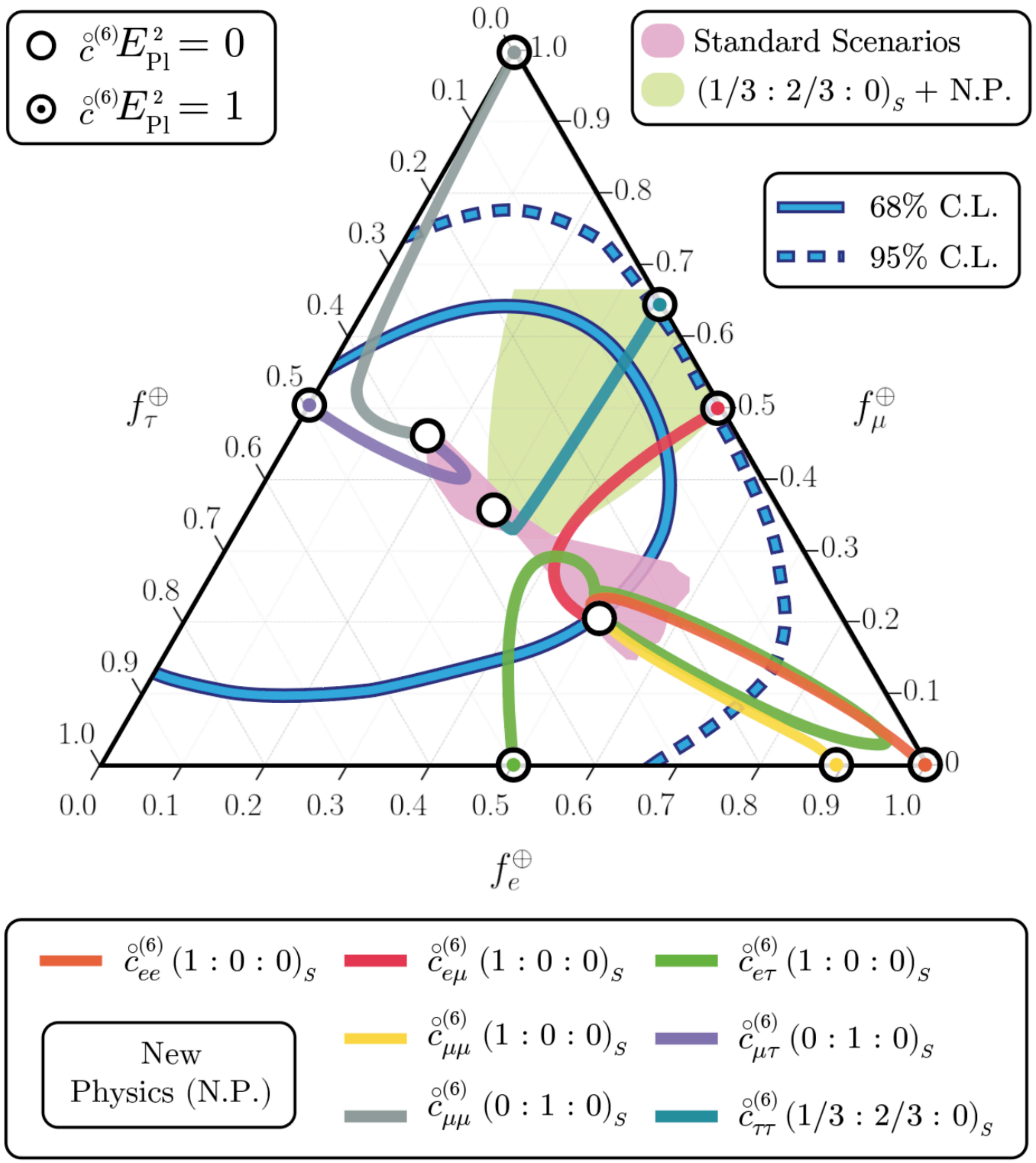
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

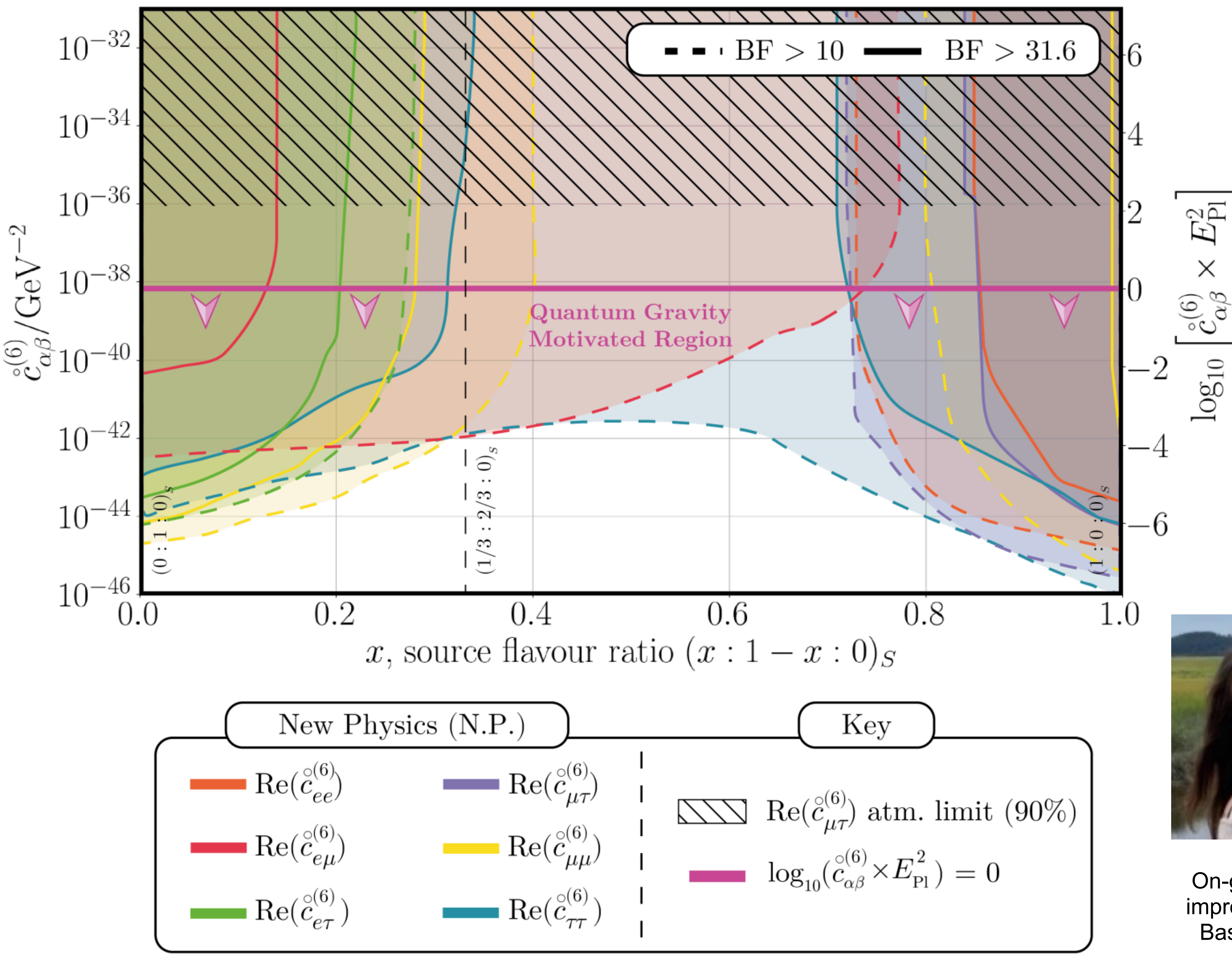
$(0:1:0)$ neutron

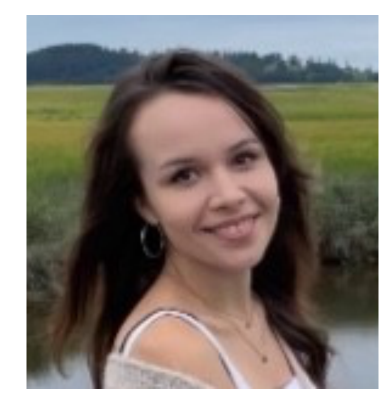
$(1:0:0)$ muon-damped



IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

Results on high-dimensional LV operators





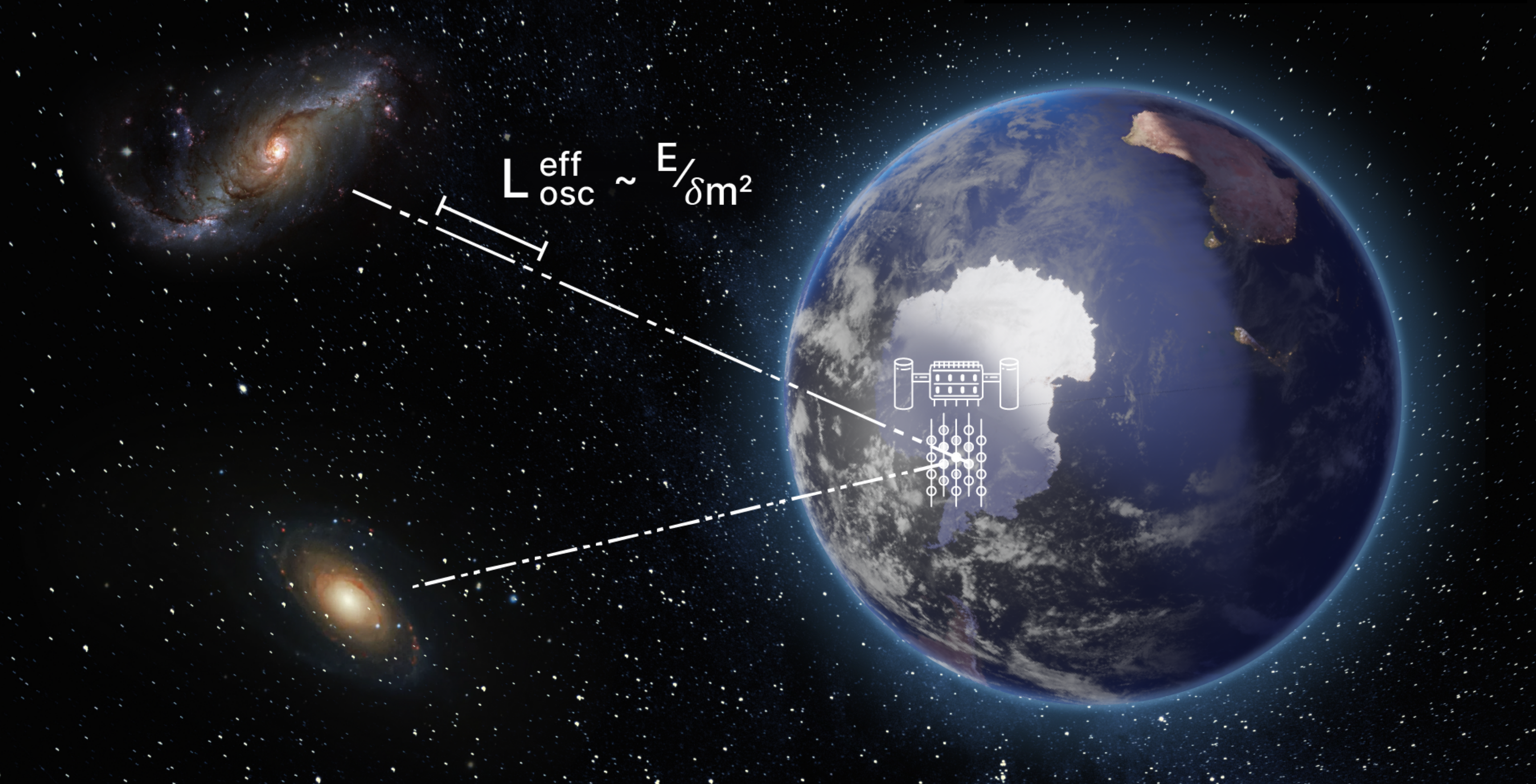
On-going work to improve on this by Basia Skrzypek

IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

Neutrino Oscillations At Cosmic Scales

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

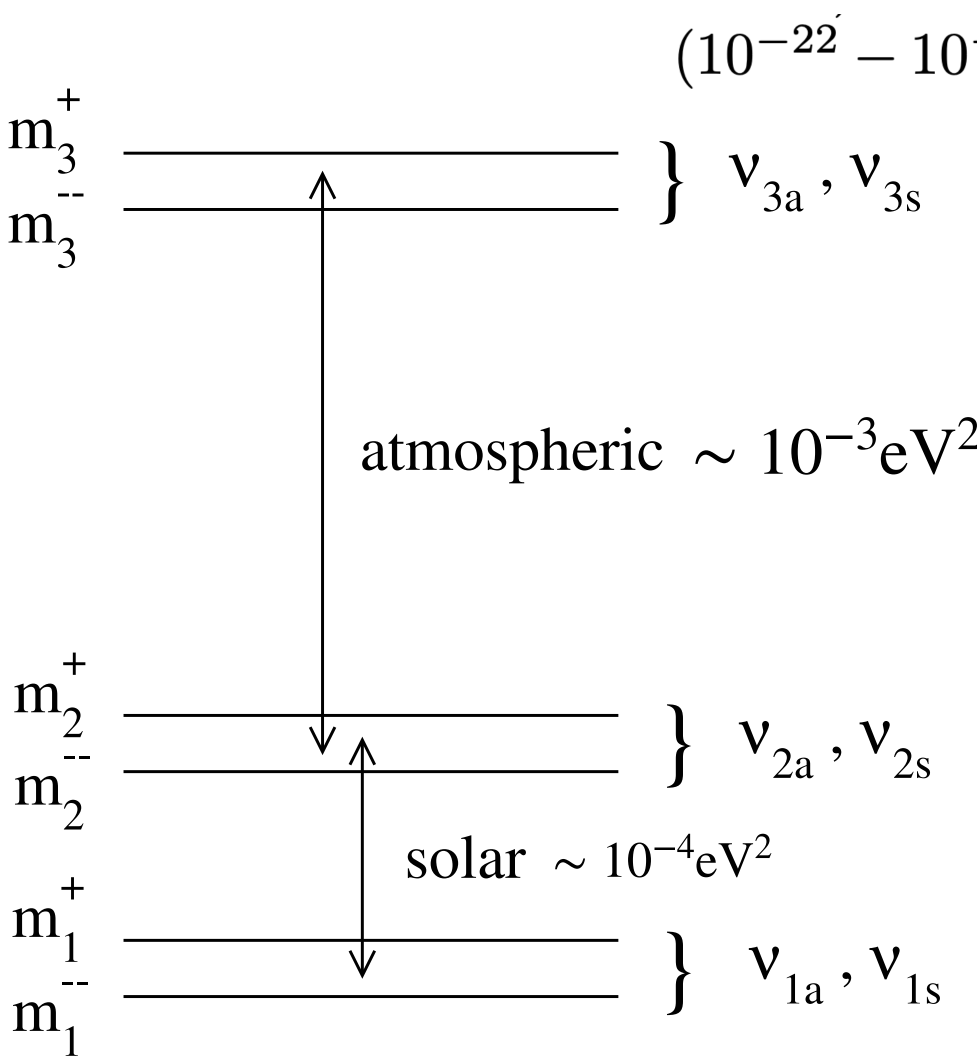
See also Beacom et al. hep-ph/0307151,
Esmaili arXiv:0909.5410, Esmaili & Farzan arXiv:1208.6012,
Rink & Sen arXiv:2211.16520

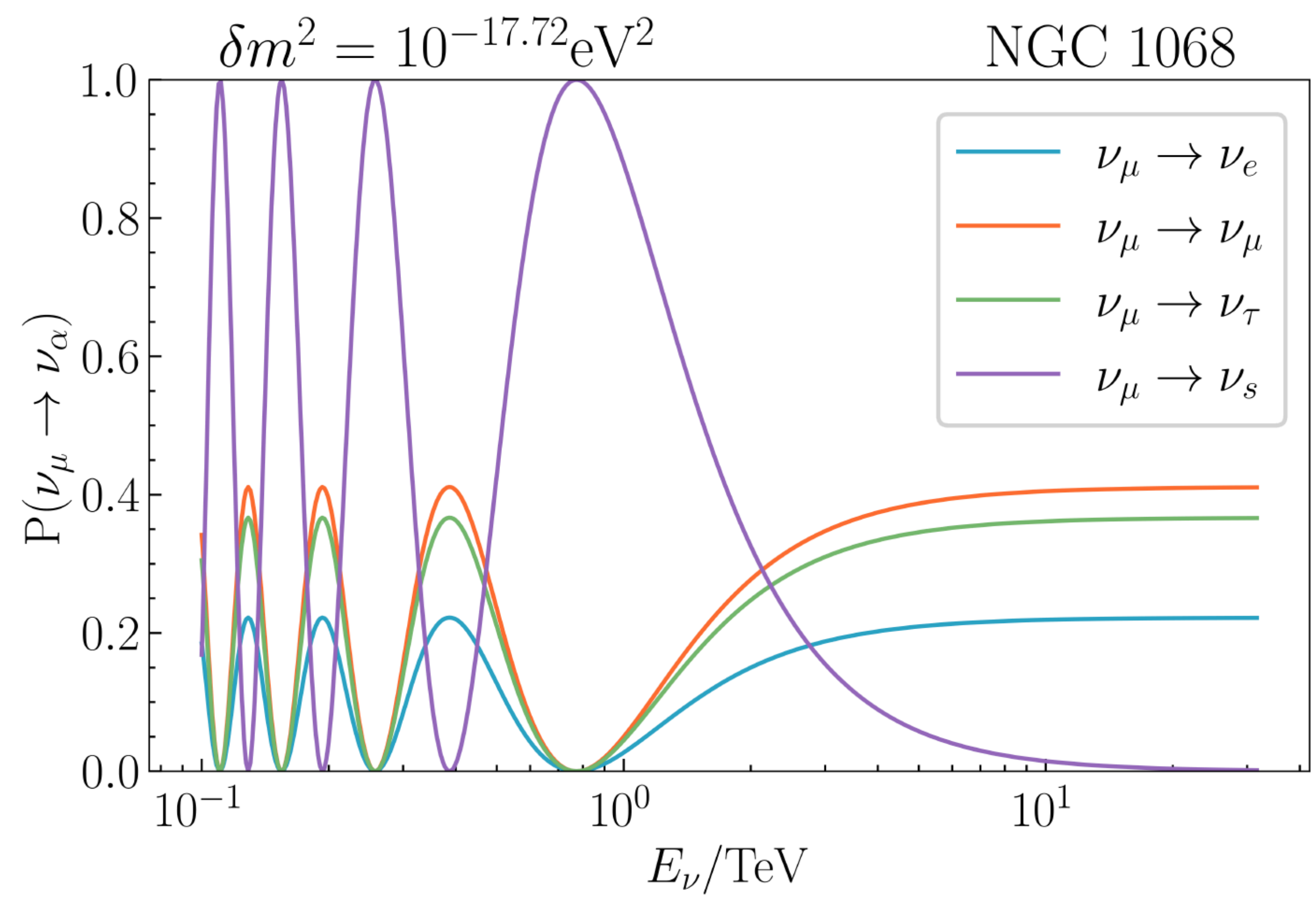


$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\rm eff}}{2E_\nu}\right)\right]$$

PseudoDirac Neutrinos

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737





$$\mathcal{L}_{\text{mass}} = \frac{1}{2}\Psi_L^t C M \Psi_L$$

$$\Psi_L = \begin{pmatrix} \nu_{\alpha L} \\ (\nu_{\alpha R})^c \end{pmatrix}$$

Dirac neutrinos $(M_R = 0)$

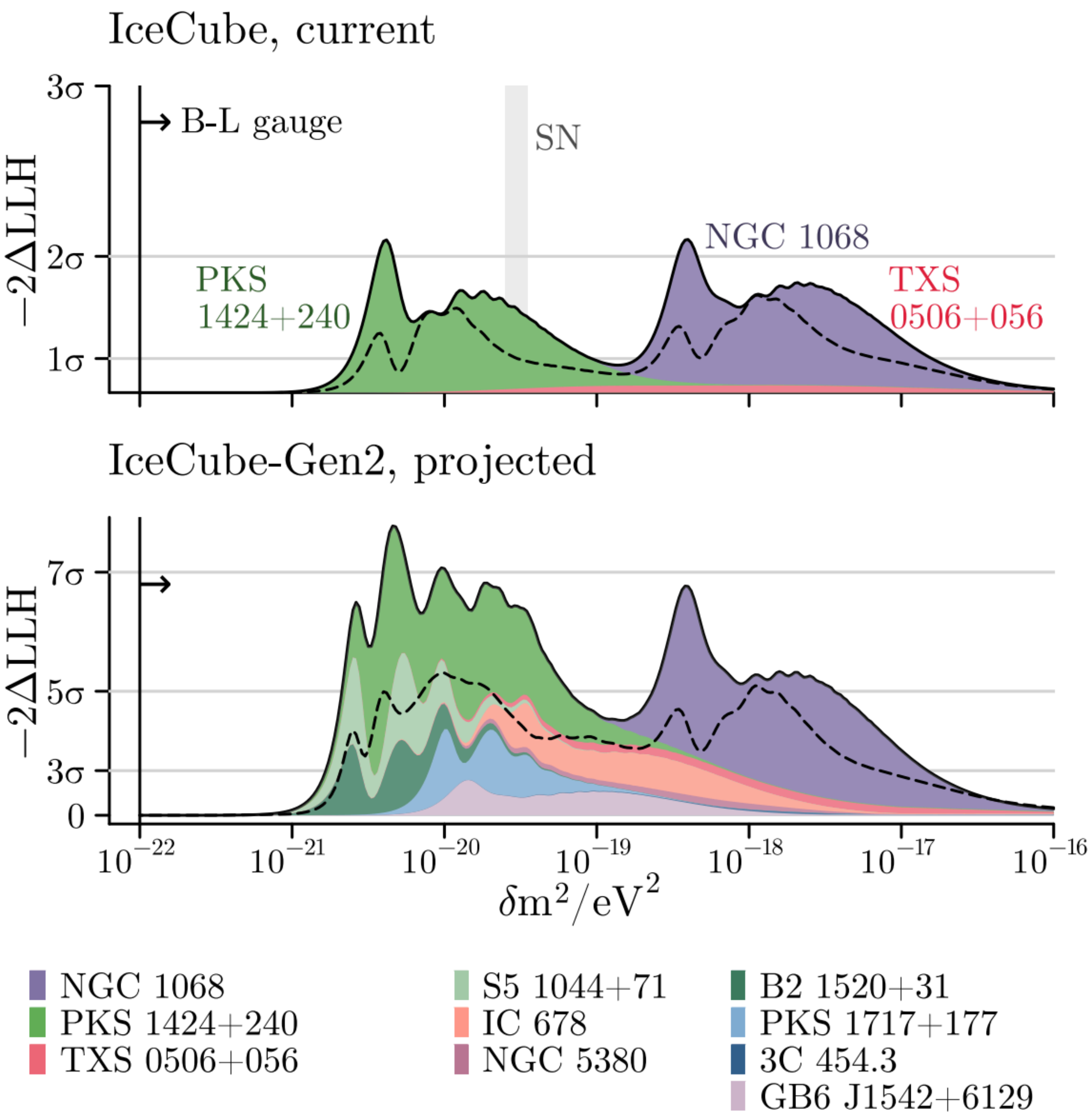
See-saw scenario $M_R >> M_D$

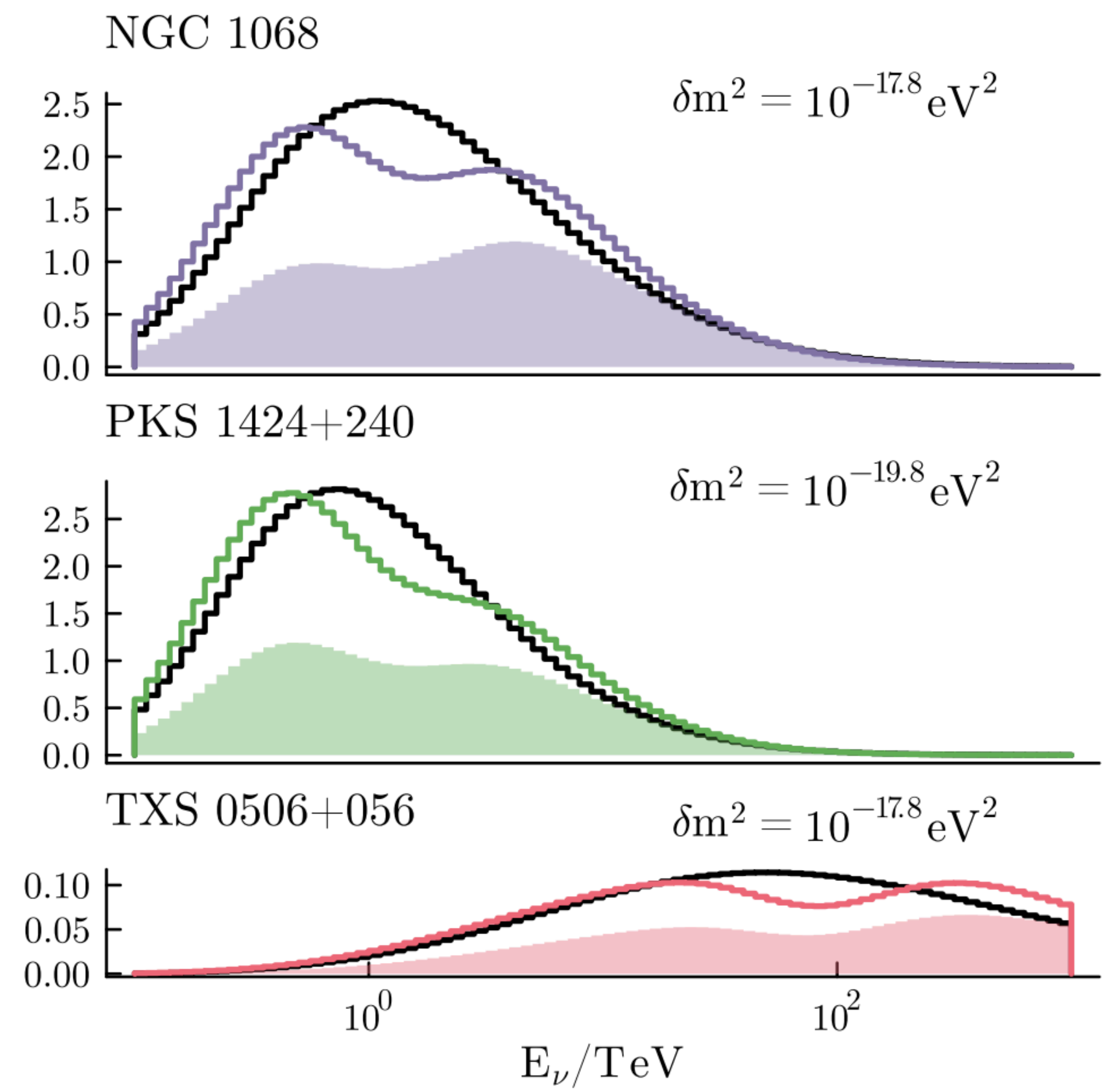
Pseudo-Dirac $M_R << M_D$

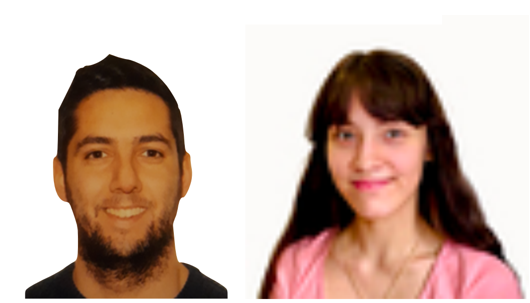
$$M = \begin{pmatrix} 0_3 & M_D \\ M_D & M_R \end{pmatrix}$$

J. W. Valle Phys.Rev.D 28 (1983) 540

Neutrino Oscillations At Cosmic Scales





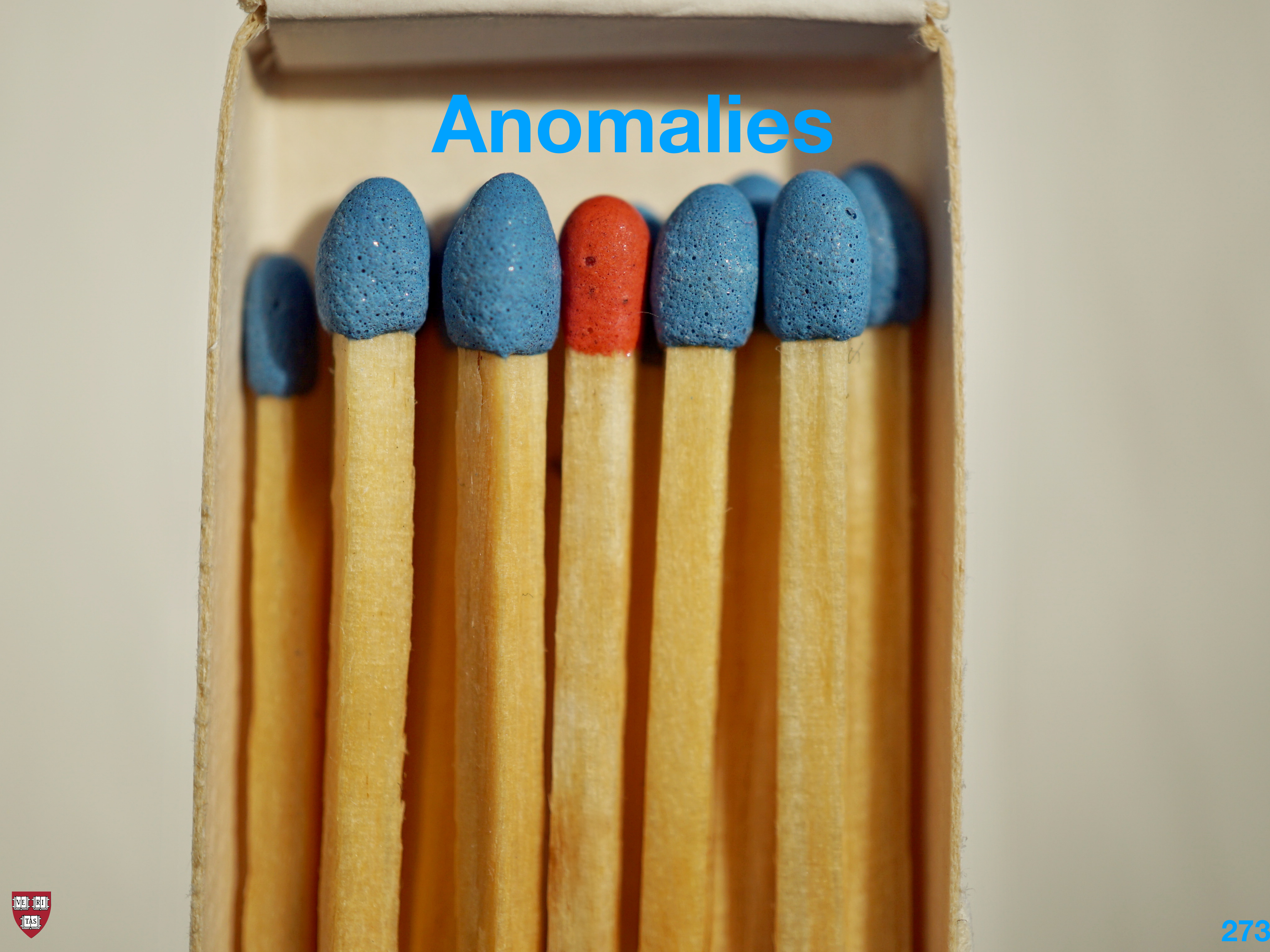


Work by Kiara Carloni and Ivan Martinez-Soler

Data analysis pending … fingers crossed!

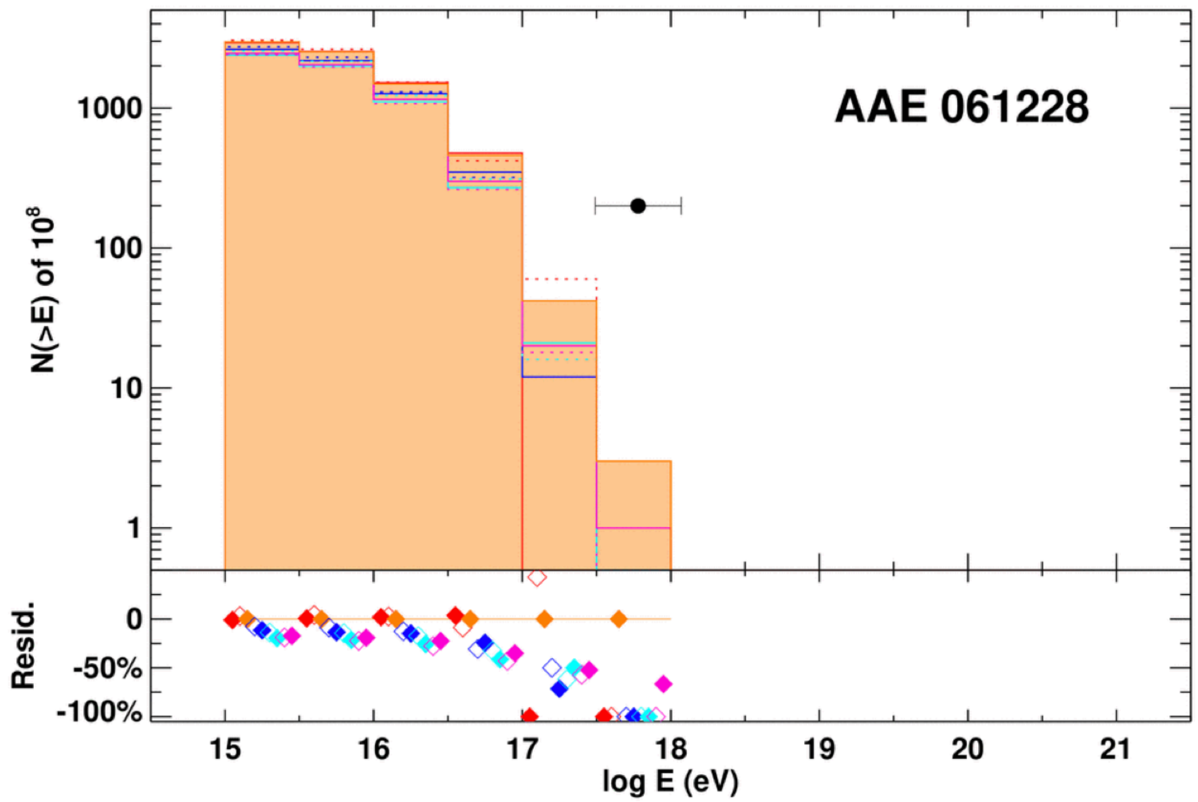
K. Carloni, I. Martínez-Soler, CA, KS Babu, PS Bhupal Dev arXiv:2212.00737

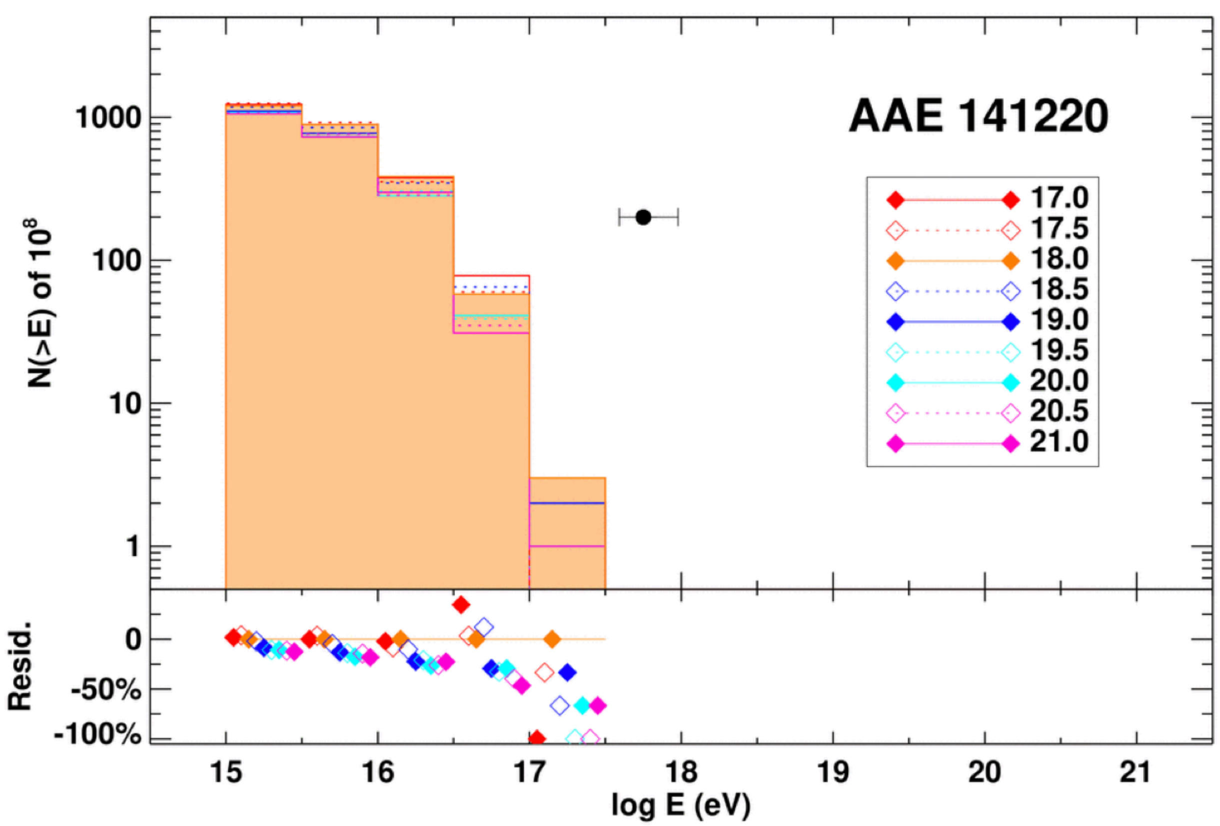
Anomalies



Unusual things

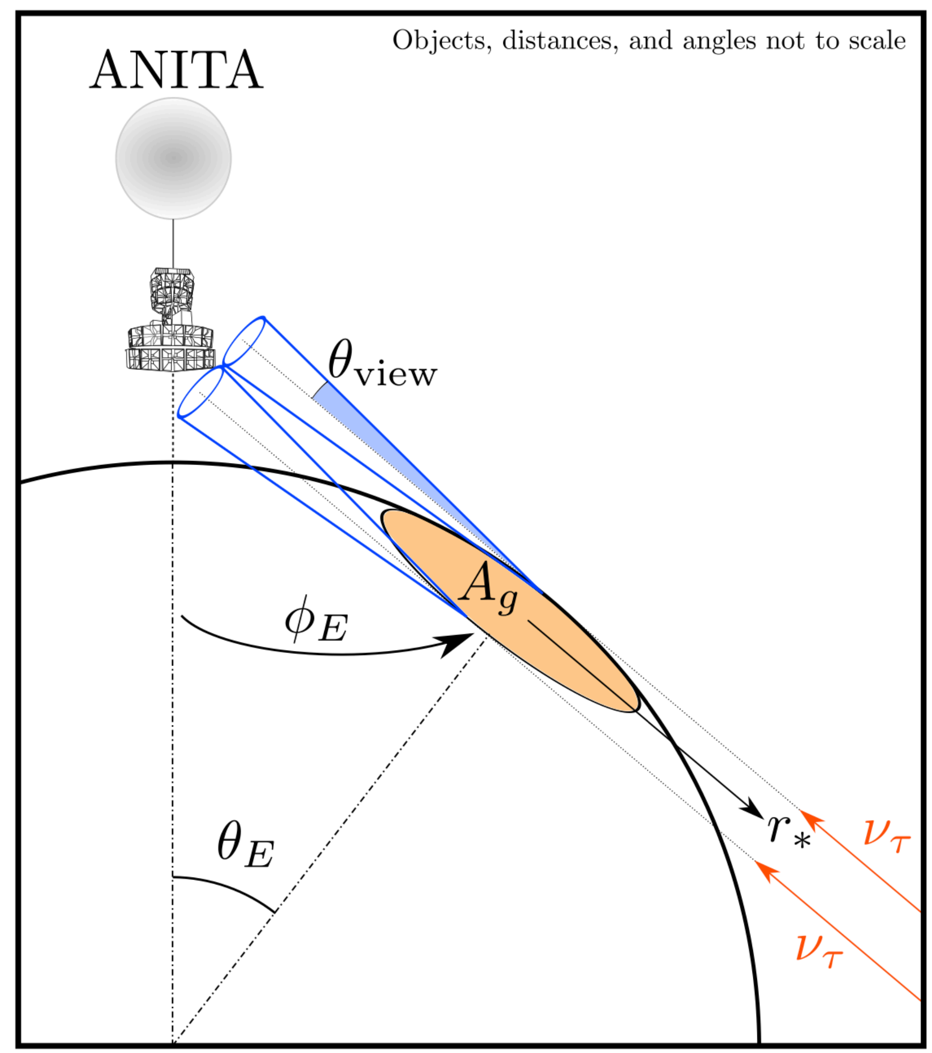
Fox et al arXiv:1809.09615





ANITA Collaboration arXiv:1803.05088

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.(1)	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec(2)	282.14064, +20.33043	50.78203, +38.65498
E_{shower} (3)	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

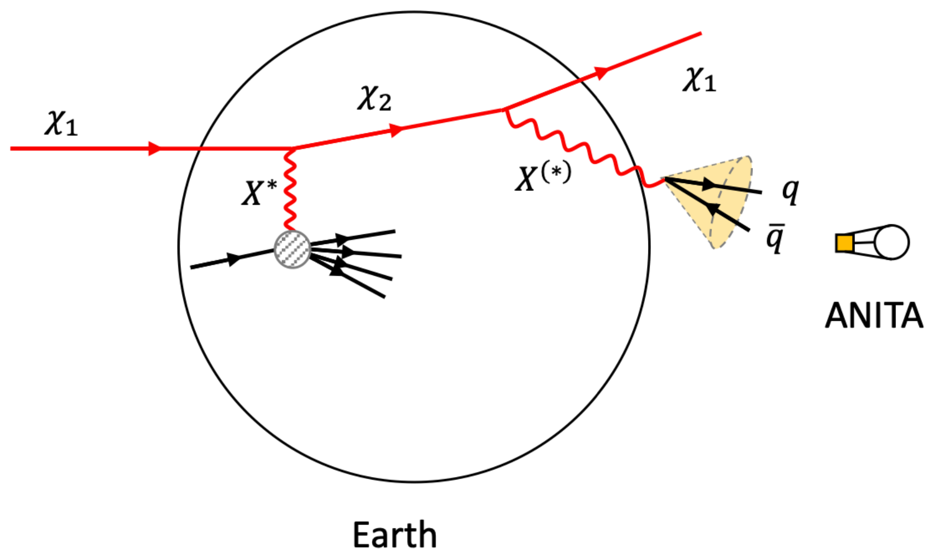


See also ANITA Coll. arXiv:2112.07069 for ANITA-IV results.
Four additional interesting events observed.

Unusual things

Explaining the ANITA Anomaly with Inelastic Boosted Dark Matter

Lucien Heurtier,[1,*] Doojin Kim,[1,†] Jong-Chul Park,[2,‡] and Seodong Shin[3,§]
[1]*Department of Physics, University of Arizona, Tucson, AZ 85721, USA*
[2]*Department of Physics, Chungnam National University, Daejeon 34134, Republic of Korea*
[3]*Department of Physics & IPAP, Yonsei University, Seoul 03722, Republic of Korea*



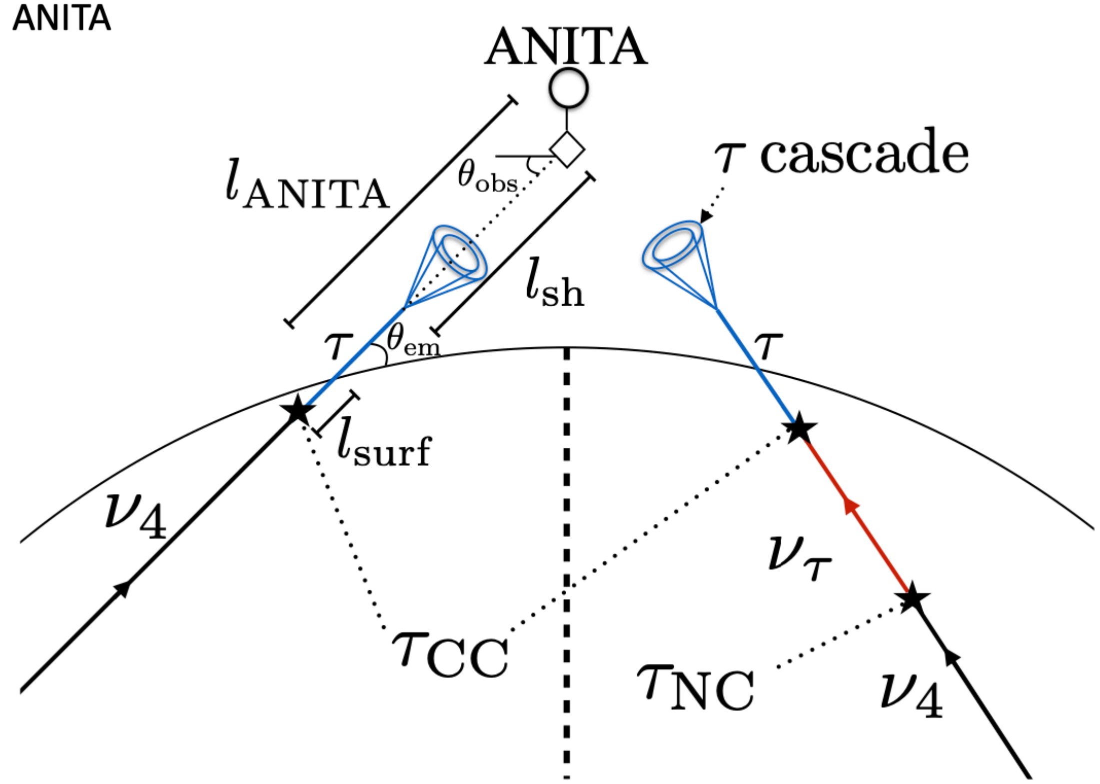
Looking at the Axionic Dark Sector with ANITA

I. Esteban[a,1], J. Lopez-Pavon[b,2], I. Martinez-Soler[c,3,4,5], J. Salvado[d,1]

See also …

Reflections On the Anomalous ANITA Events: The Antarctic Subsurface as a Possible Explanation

Ian M. Shoemaker,[1] Alexander Kusenko,[2,3] Peter Kuipers Munneke,[4] Andrew Romero-Wolf,[5] Dustin M. Schroeder,[6] and Martin J. Siegert[7]

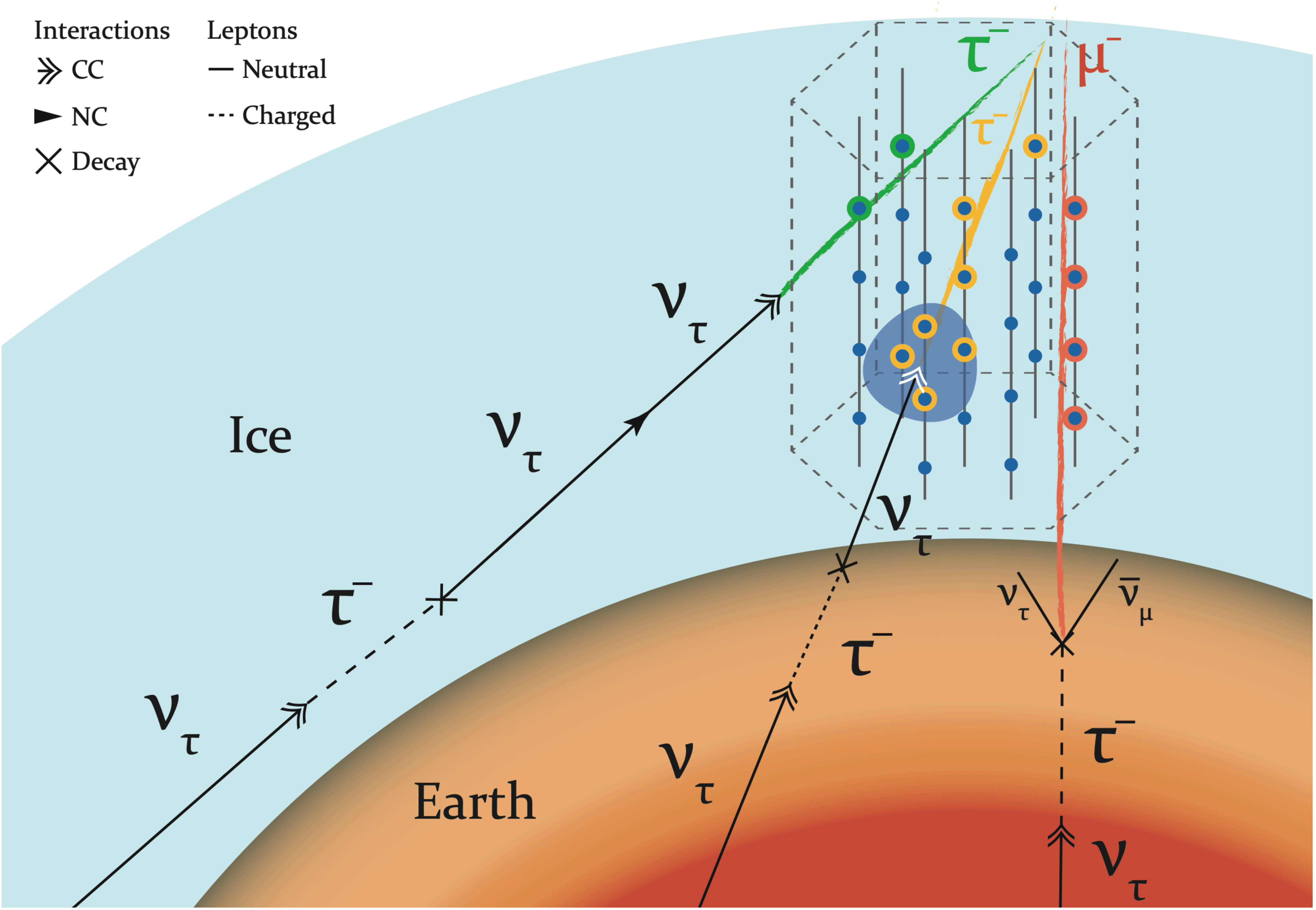


A Sterile Neutrino Origin for the Upward Directed Cosmic Ray Showers Detected by ANITA

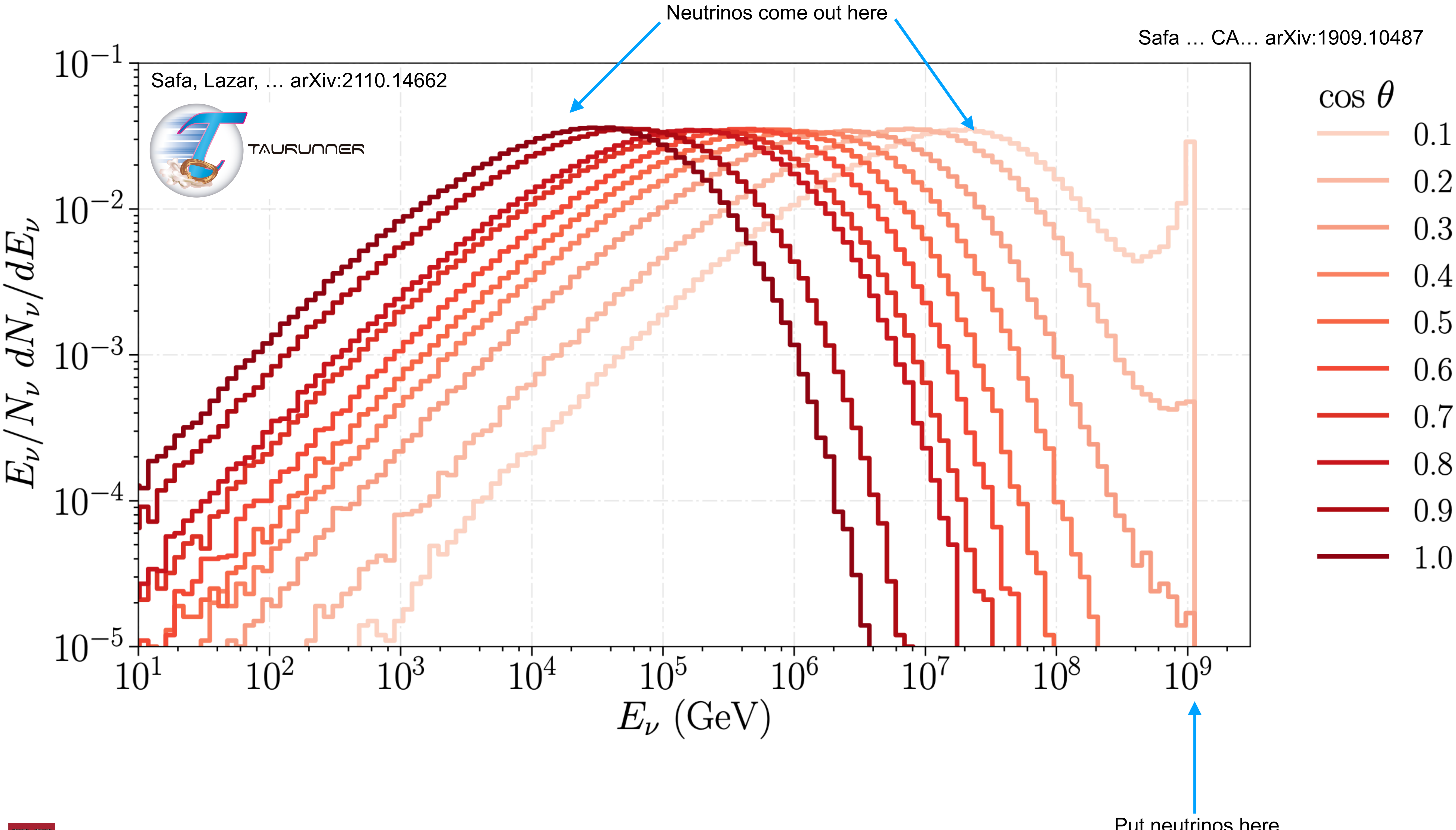
John F. Cherry[1] and Ian M. Shoemaker[1]
[1]*Department of Physics, University of South Dakota, Vermillion, SD 57069, USA*[*]
(Dated: 8-23-2018)

Tau Regeneration

Safa … CA… arXiv:1909.10487

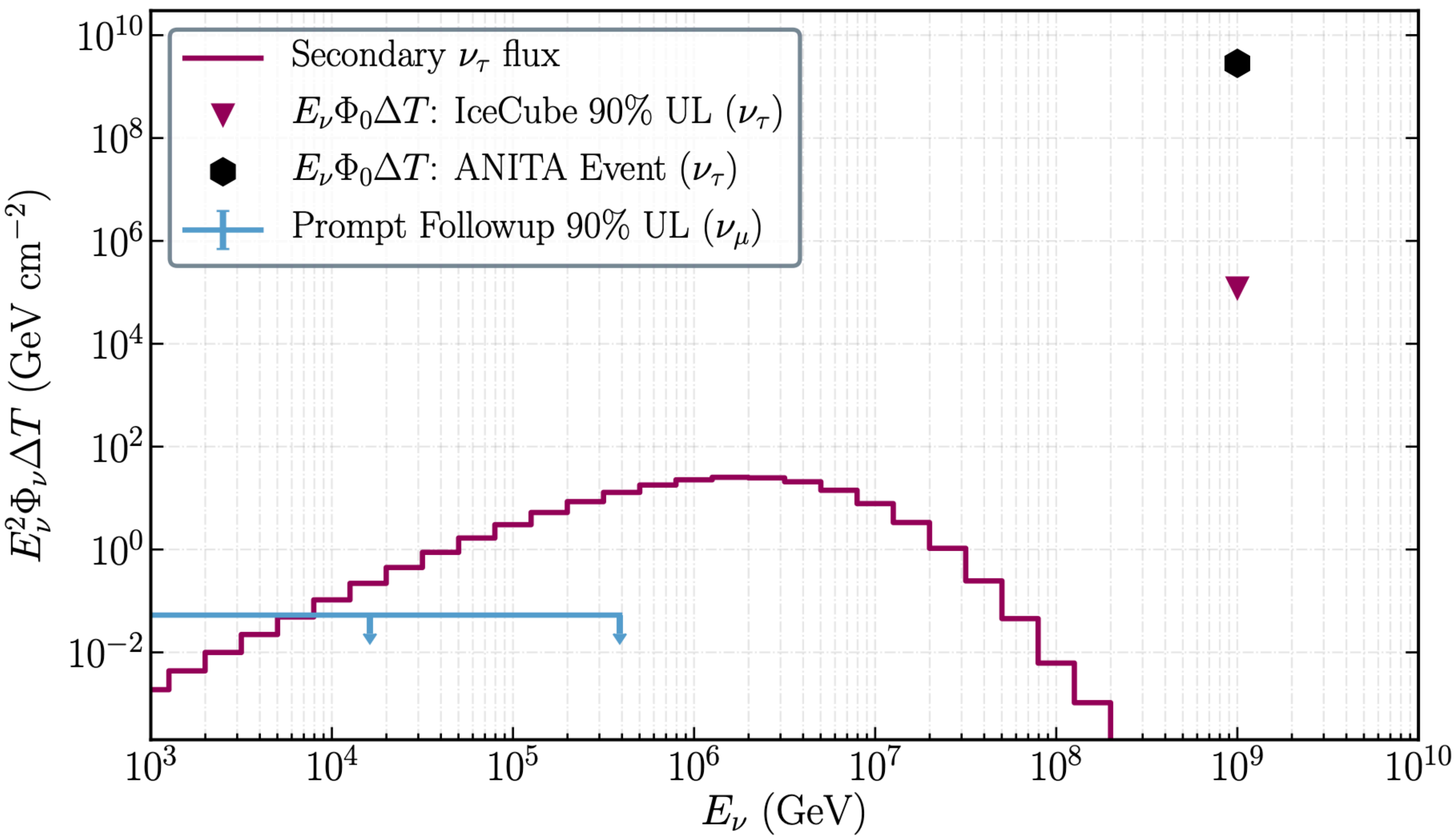


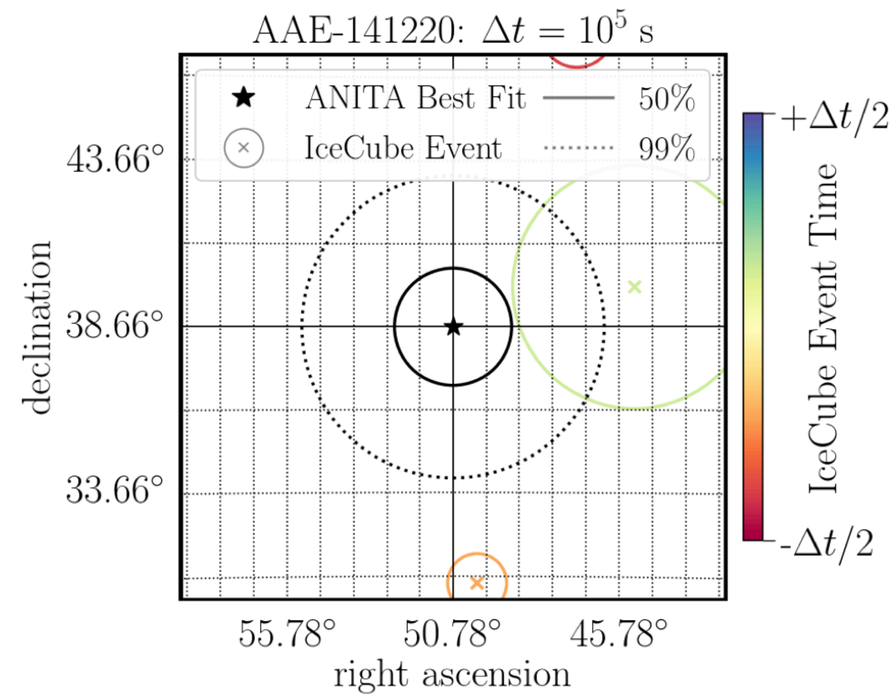
Intimate connection between PeV and ZeV energies

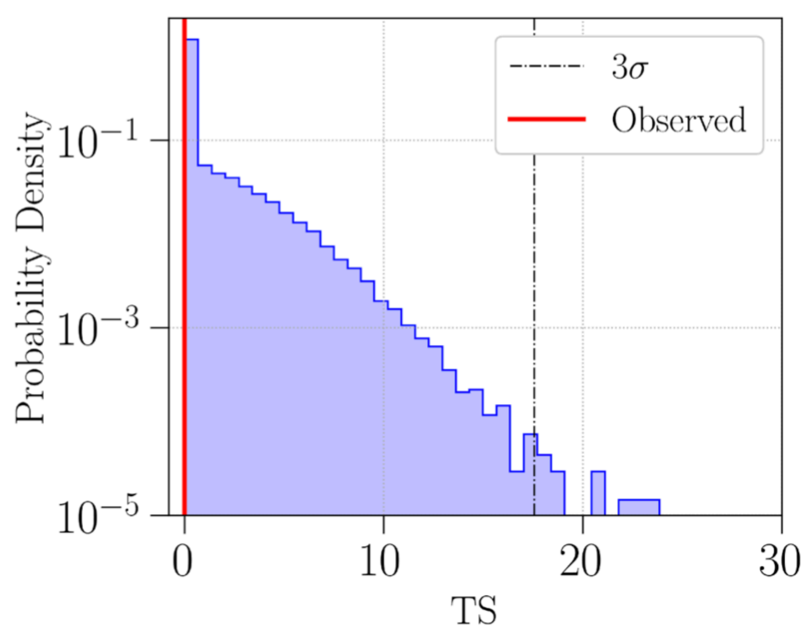


Get code here:
https://github.com/icecube/TauRunner

Ruling out ANITA Neutrino Interpretation

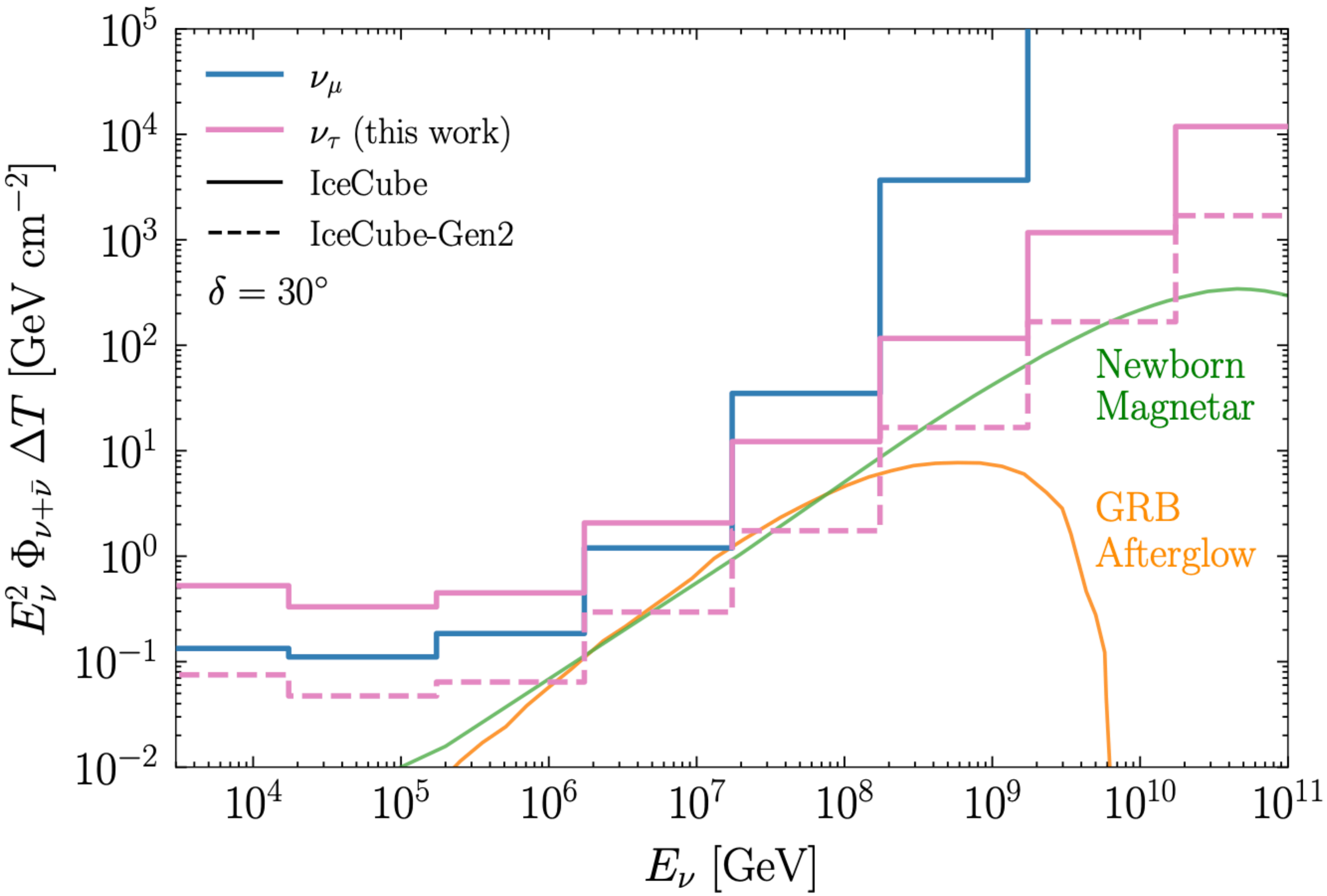


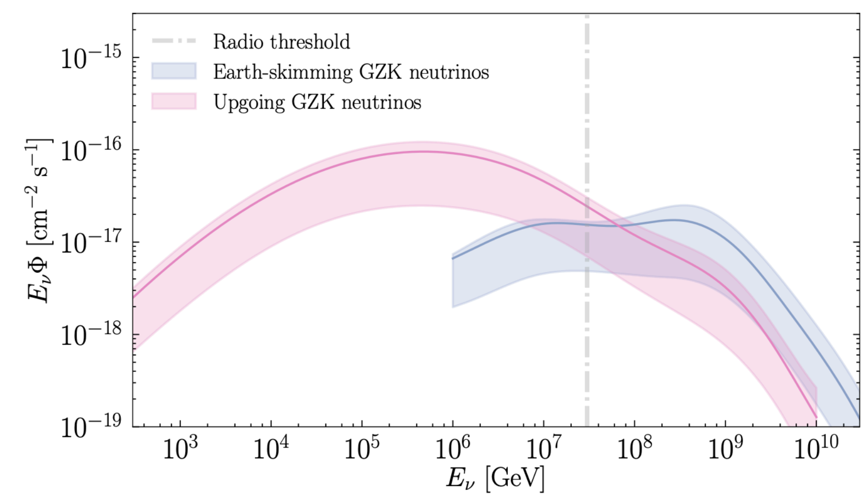




IceCube Collaboration arXiv:2001.01737

Constraints on EeV Fluxes From PeV Measurements





PeV Tau Neutrinos to Unveil Ultra-High-Energy Sources

Carlos A. Argüelles,[1,*] Francis Halzen,[2,†] Ali Kheirandish,[3,‡] and Ibrahim Safa[1,2,§]

arXiv:2203.13827

What other signatures of new physics could find?

Note: Not an exhaustive list

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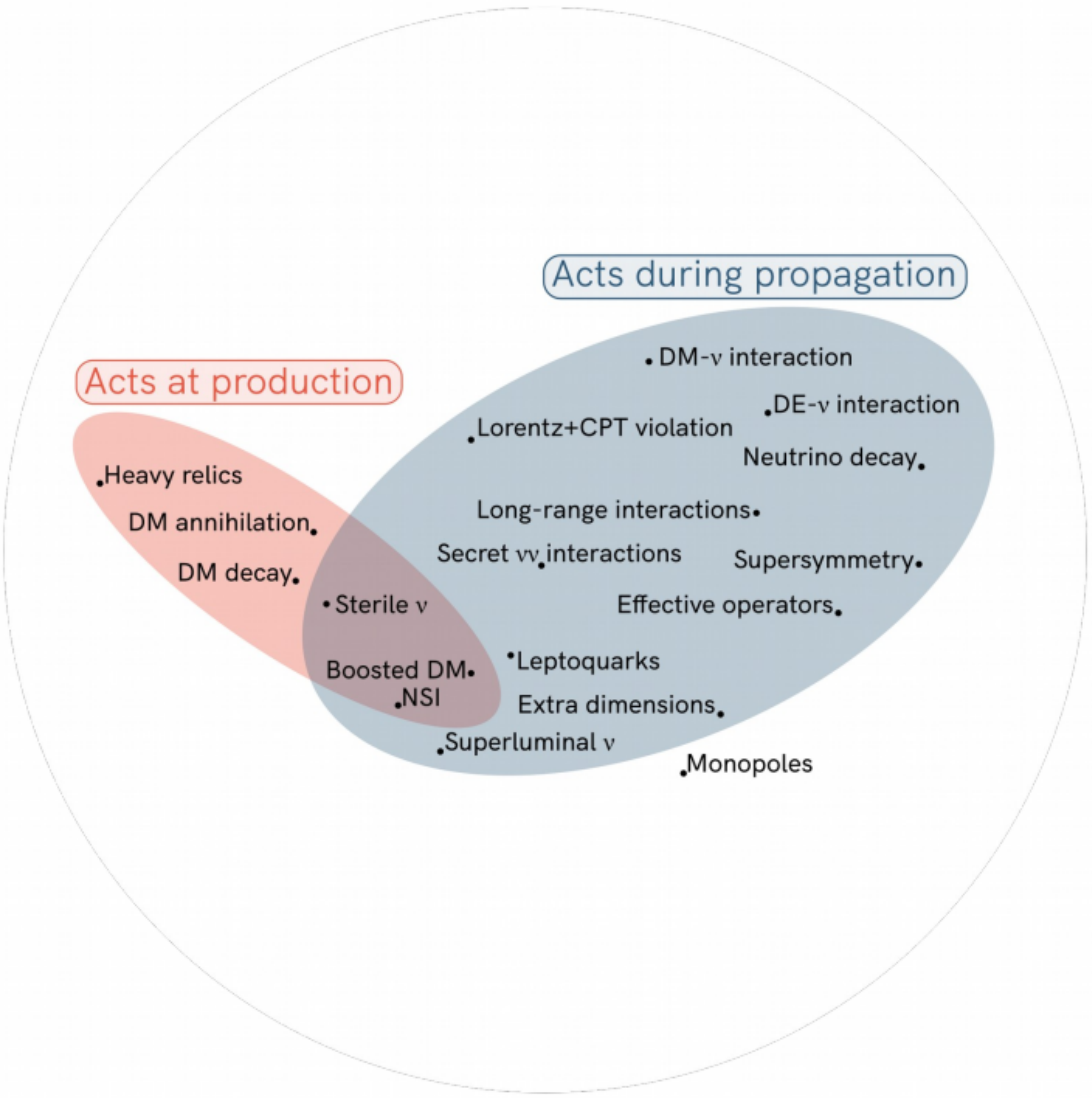
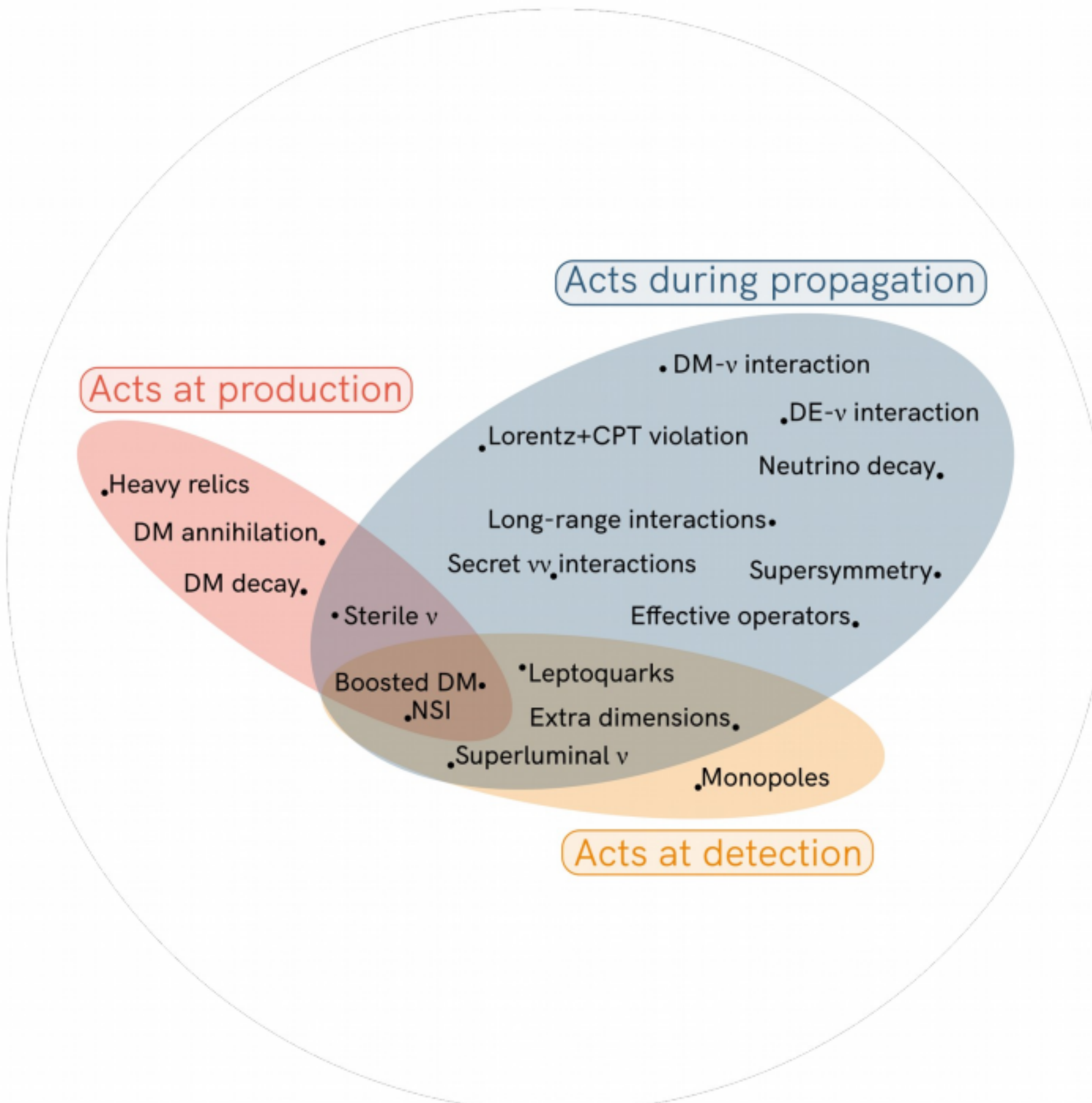


Note: Not an exhaustive list

What other signatures of new physics could find?

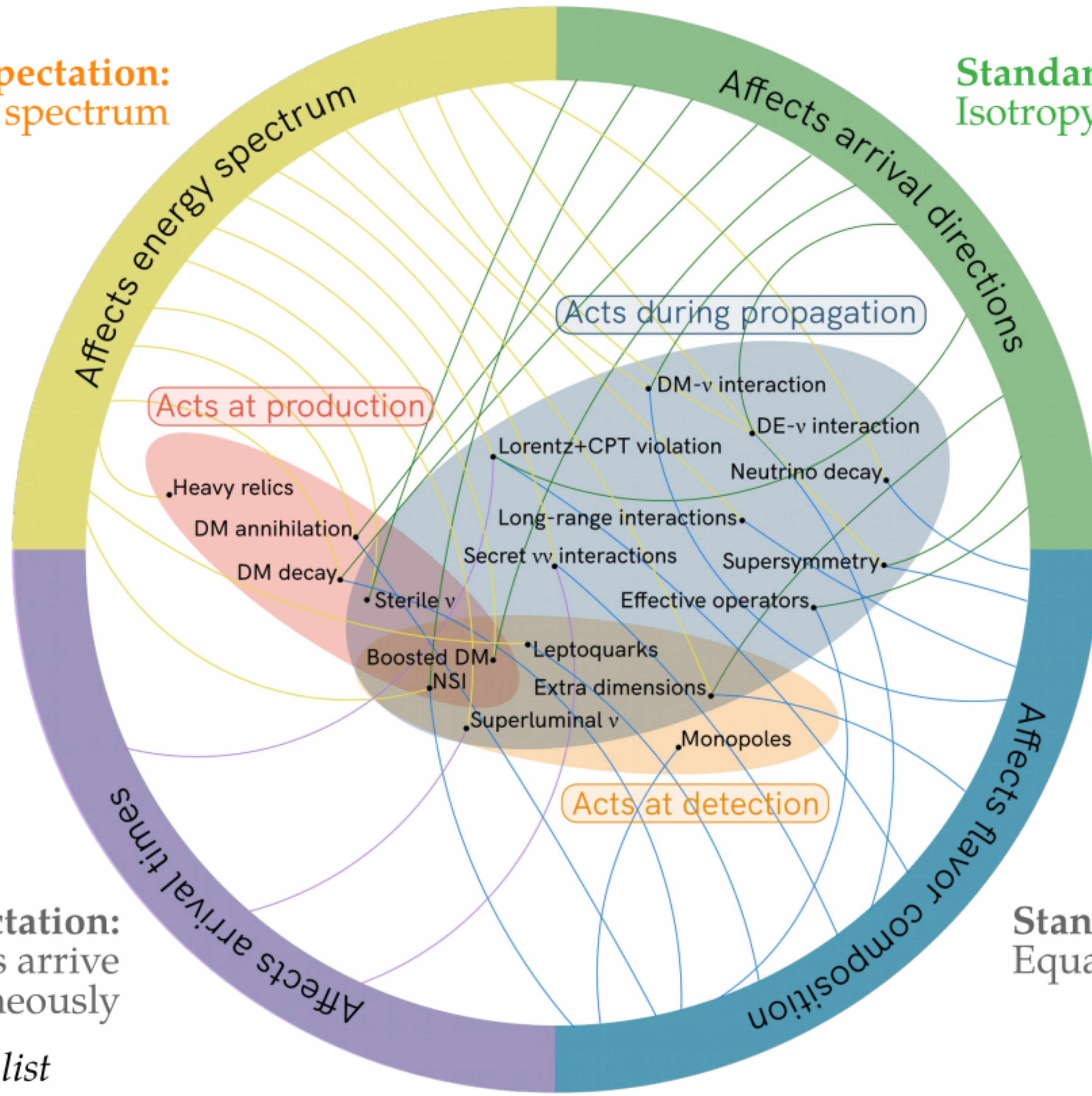


Note: Not an exhaustive list

What other signatures of new physics could find?

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

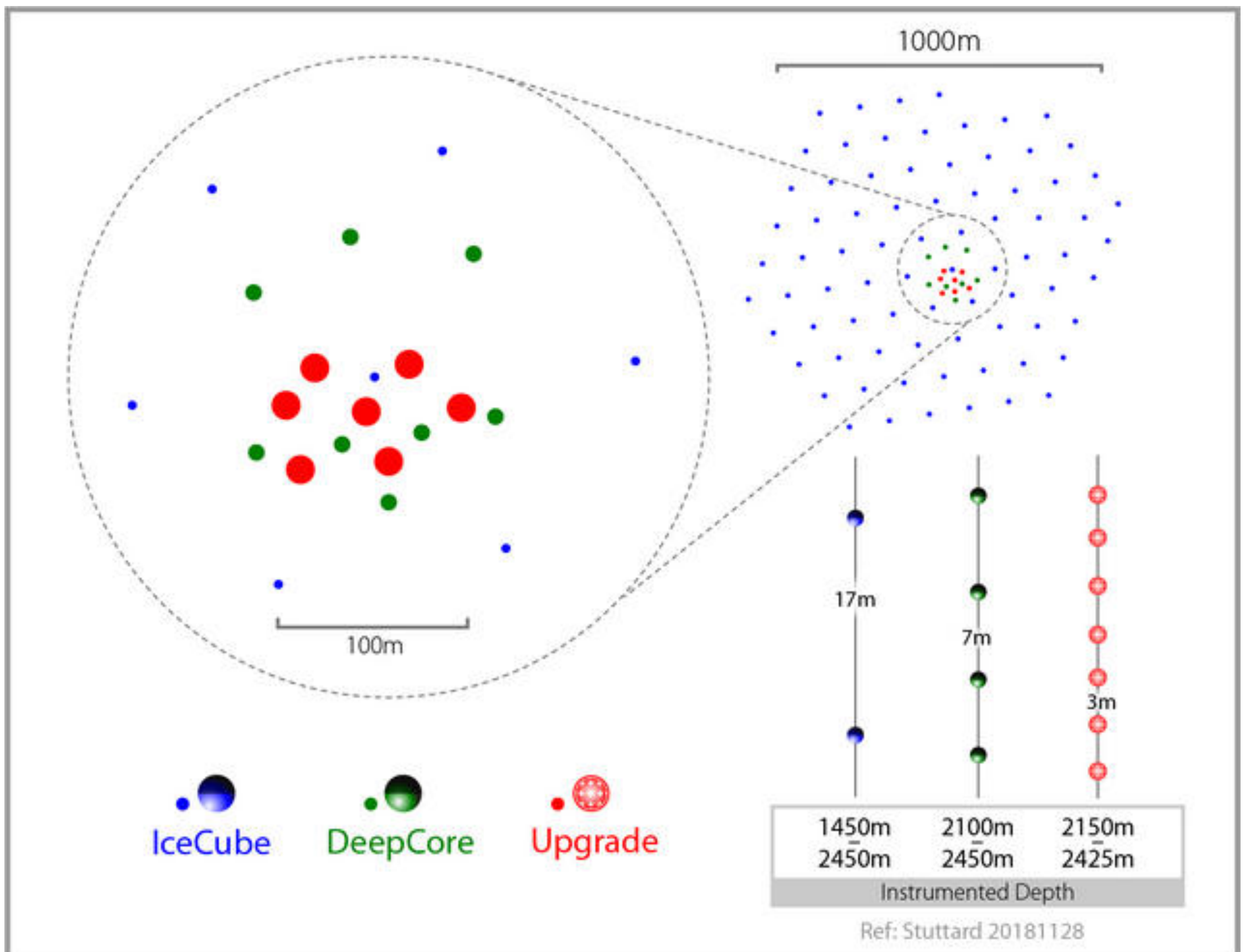
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

See CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvado, and Vincent arXiv:1907.08690 for more details

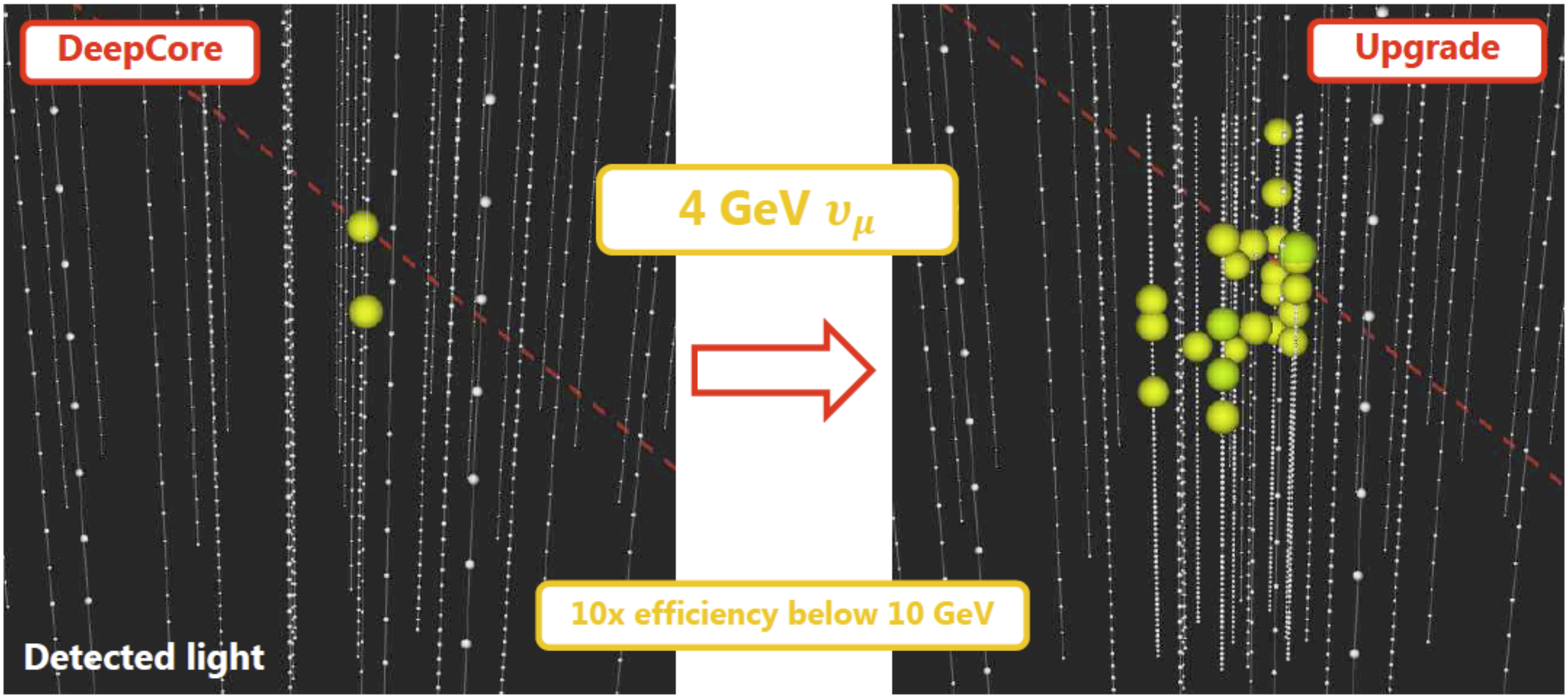
That potential is growing: The Upgrades

Phase 1: 7 new, high-precision strings in the central, densely instrumented region. Funded, installation in 2025.



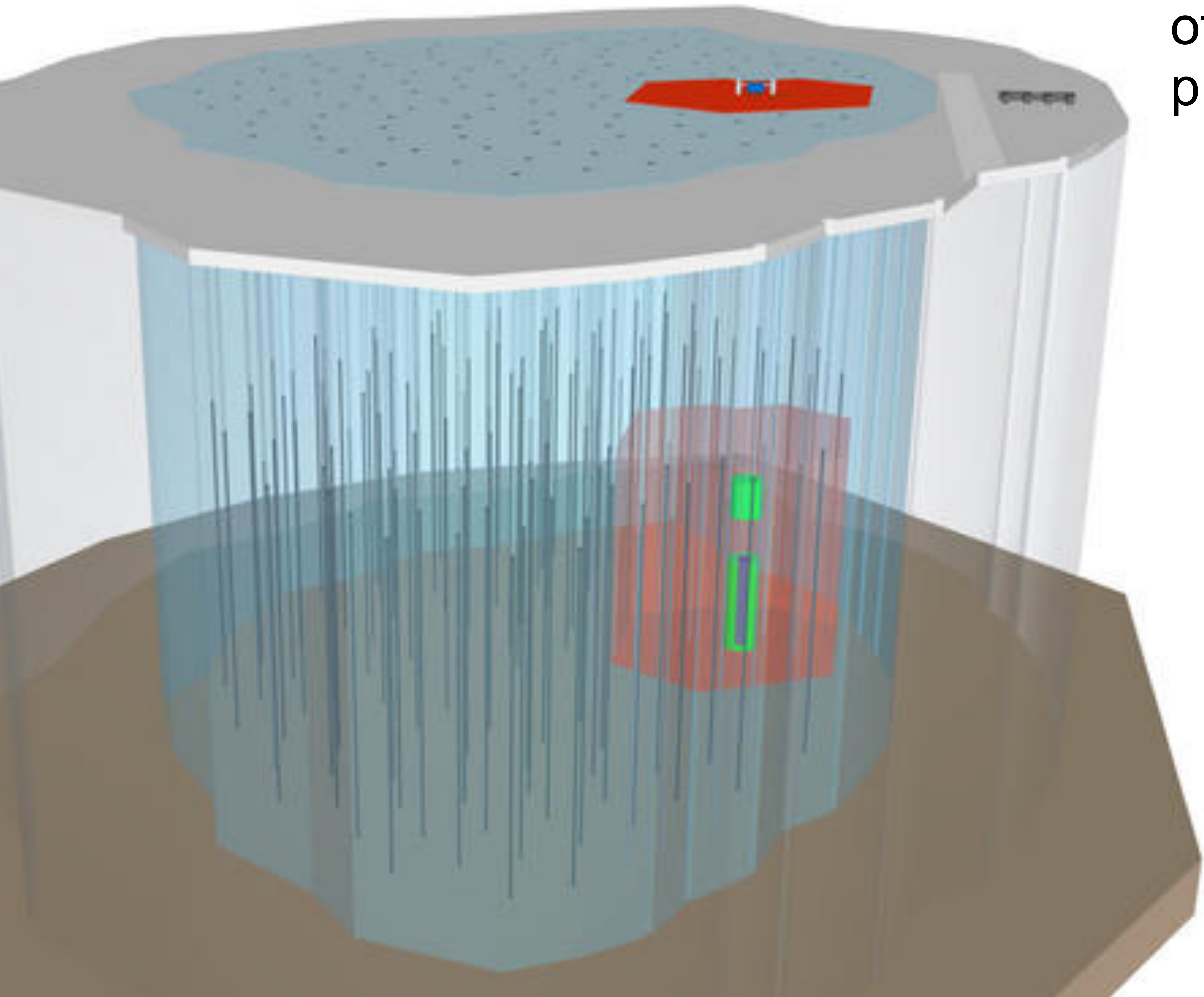
New detector technologies.
Better low energy reconstruction.
Improved flavor identification.

Improved light-collection for low-energy events



*DeepCore (shown on the left) is the current low-energy extension of IceCube

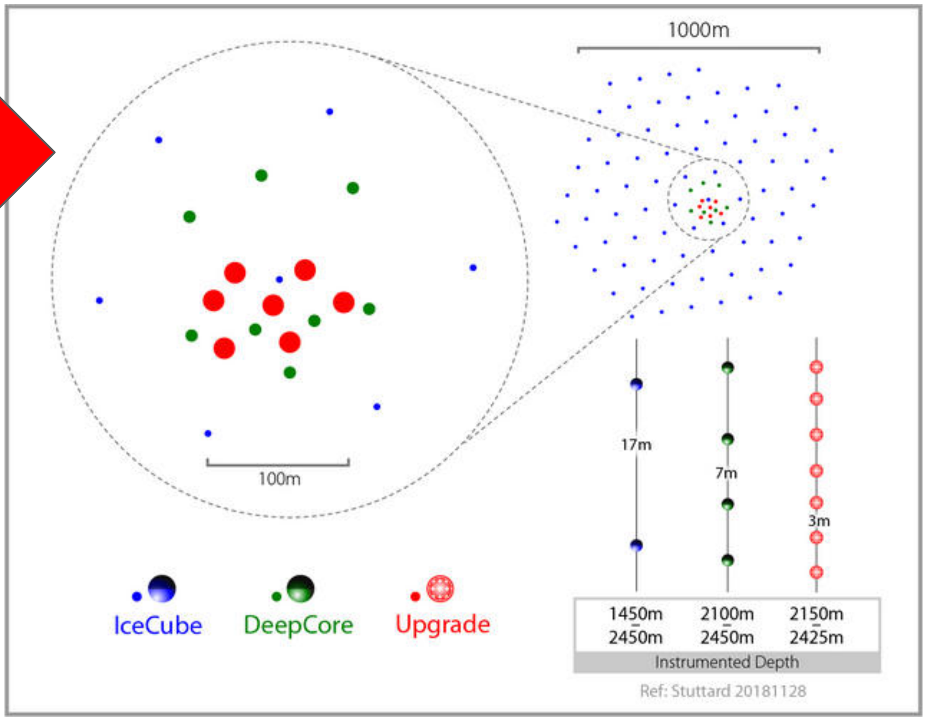
That potential is growing: The Upgrades

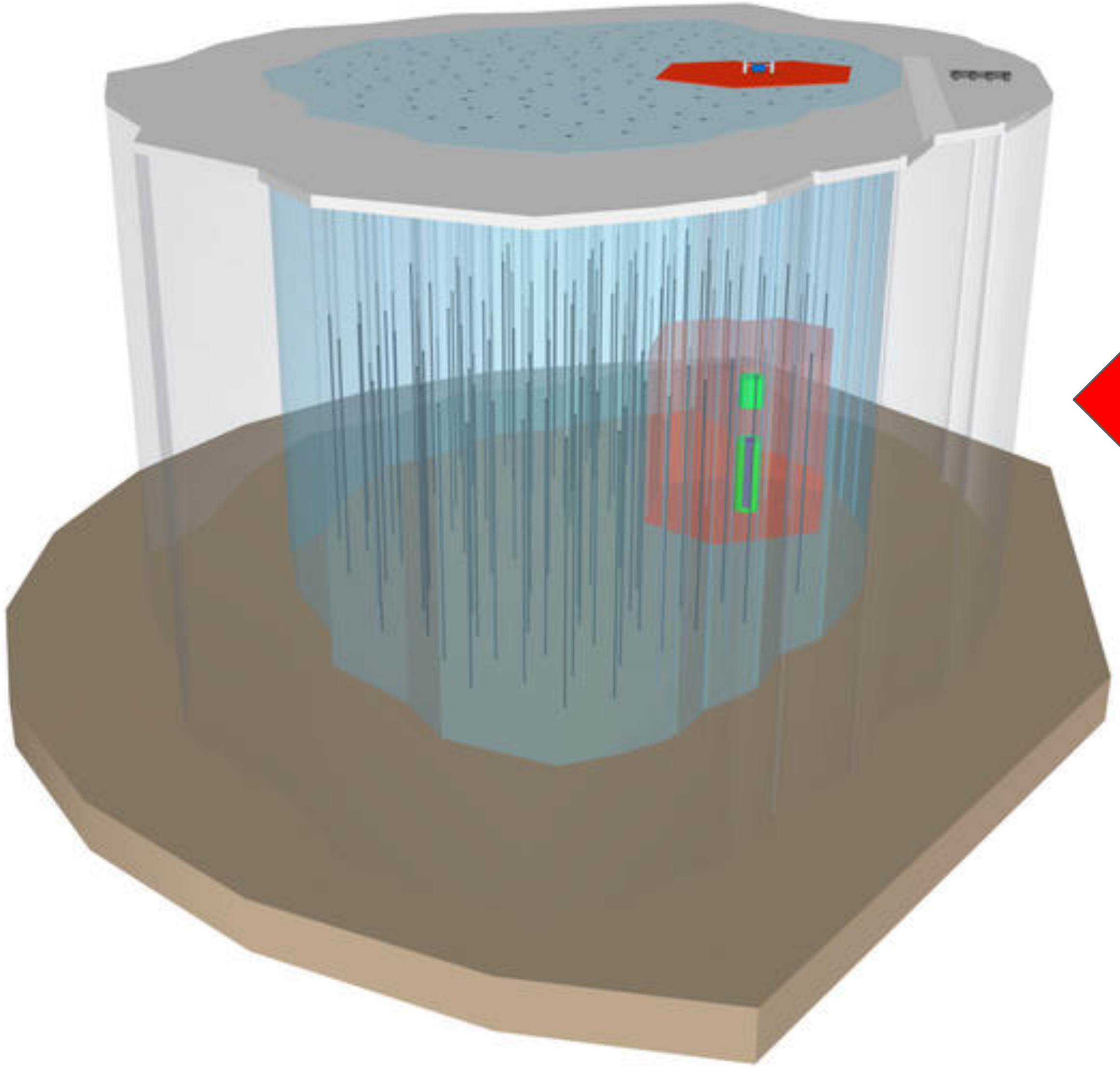


Phase 2: x10 the volume
of present IceCube,
plus additional detectors.

The Future of IceCube: The Upgrades

Phase 1: 7 new, high-precision strings in the central, densely instrumented region. Funded, installation in 2022.





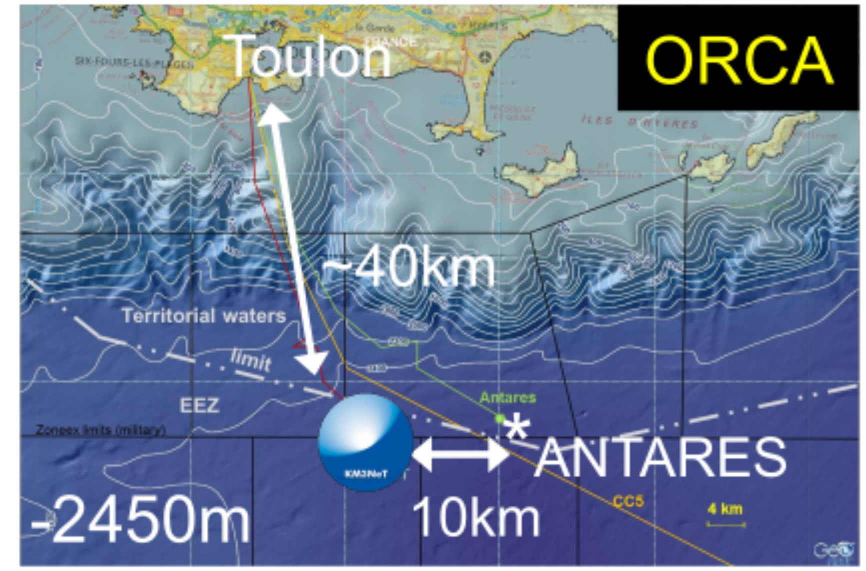
Phase 2: x10 the volume of present IceCube, plus additional detectors. Progressing through NSF Science Board approval.

Km3Net

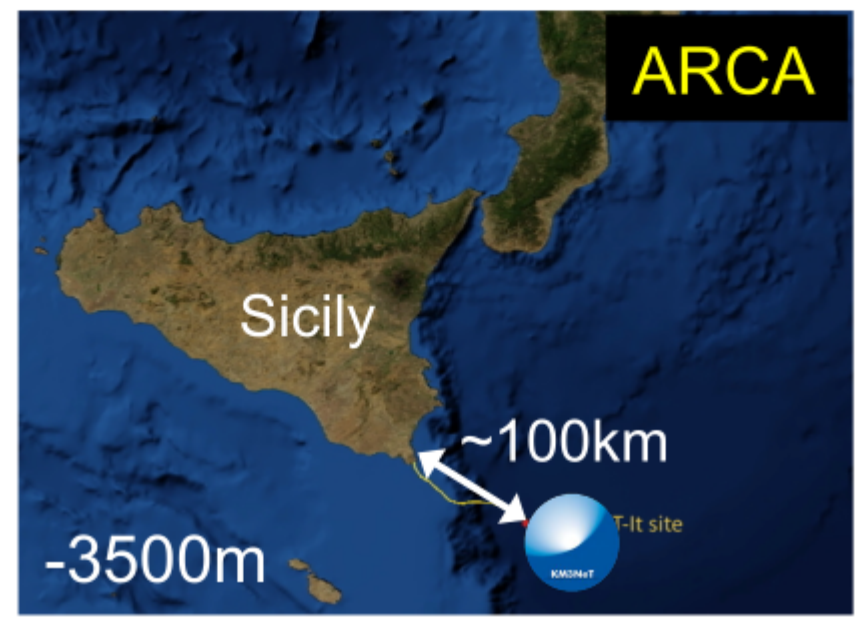
KM3NeT: ARCA & ORCA

ARCA → TeV-PeV neutrino astronomy

ORCA → neutrino mass ordering with few-GeV atmospheric neutrinos



ORCA: Oscillation **R**esearch with **C**osmics in the **A**byss



ARCA: Astroparticle **R**esearch with **C**osmics in the **A**byss

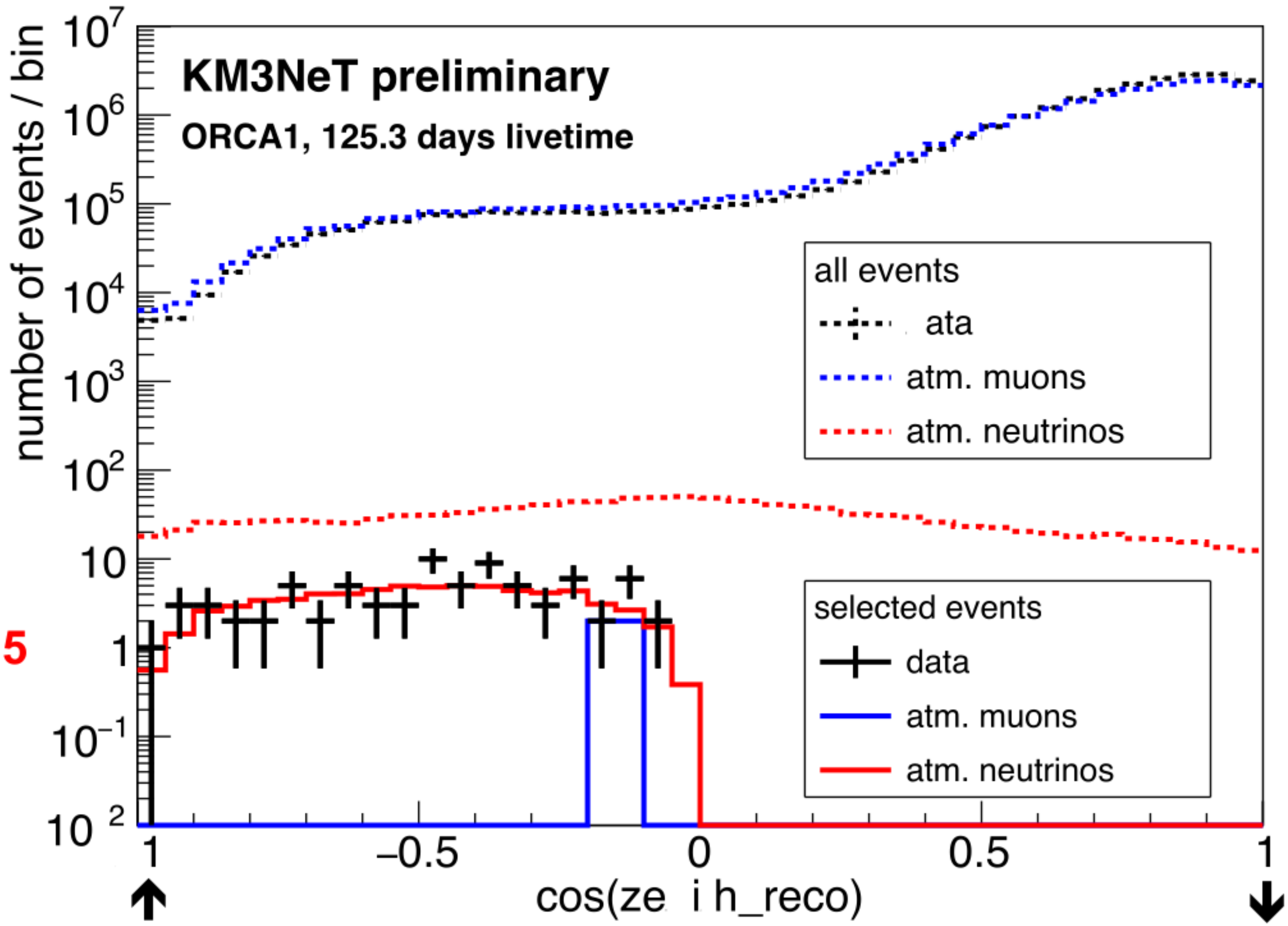
Km3Net

- ANTARES completed construction in 2008
  - ~2500m deep, 12 Vertical lines, each 350m high
  - Decommissioned May 2022

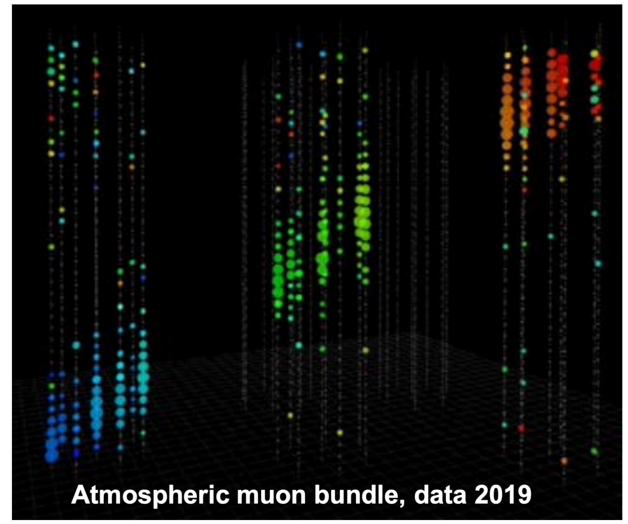
- KM3NET:
  - ORCA: 2500 m deep, 20m string spacing, 10 detection unites running
  - ARCA: 3500m deep, 90m string spacing, 19 detection units successfully deployed

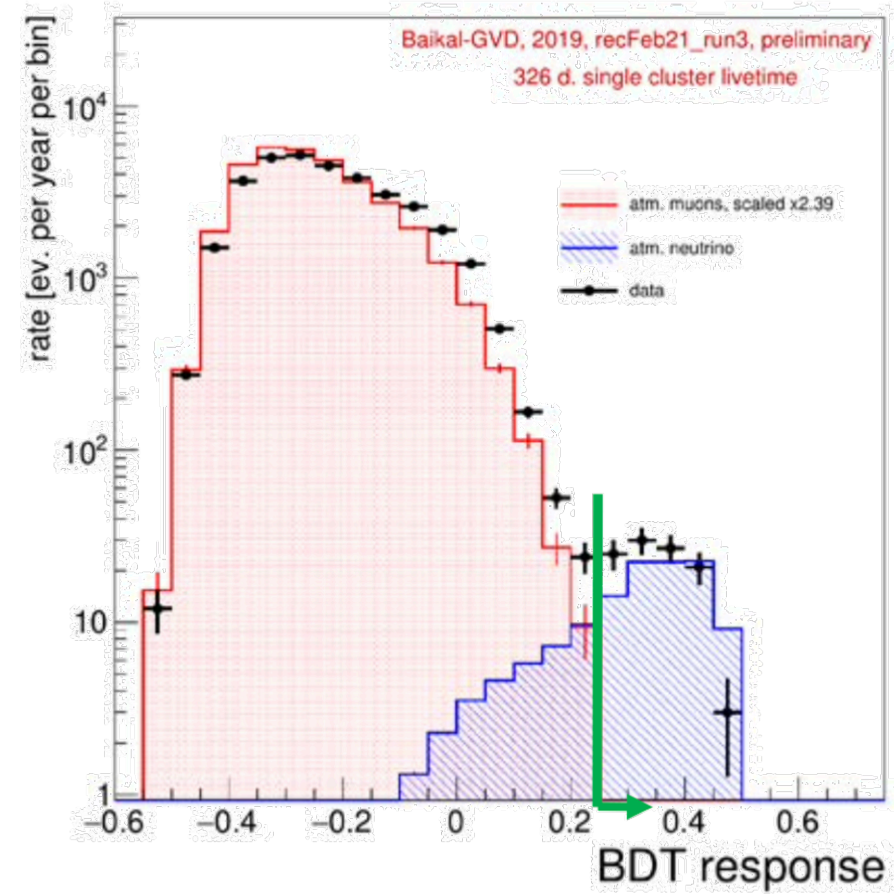
ORCA's first atm-nus!

Data: 77
ν MC: 67.5
μ MC: 4

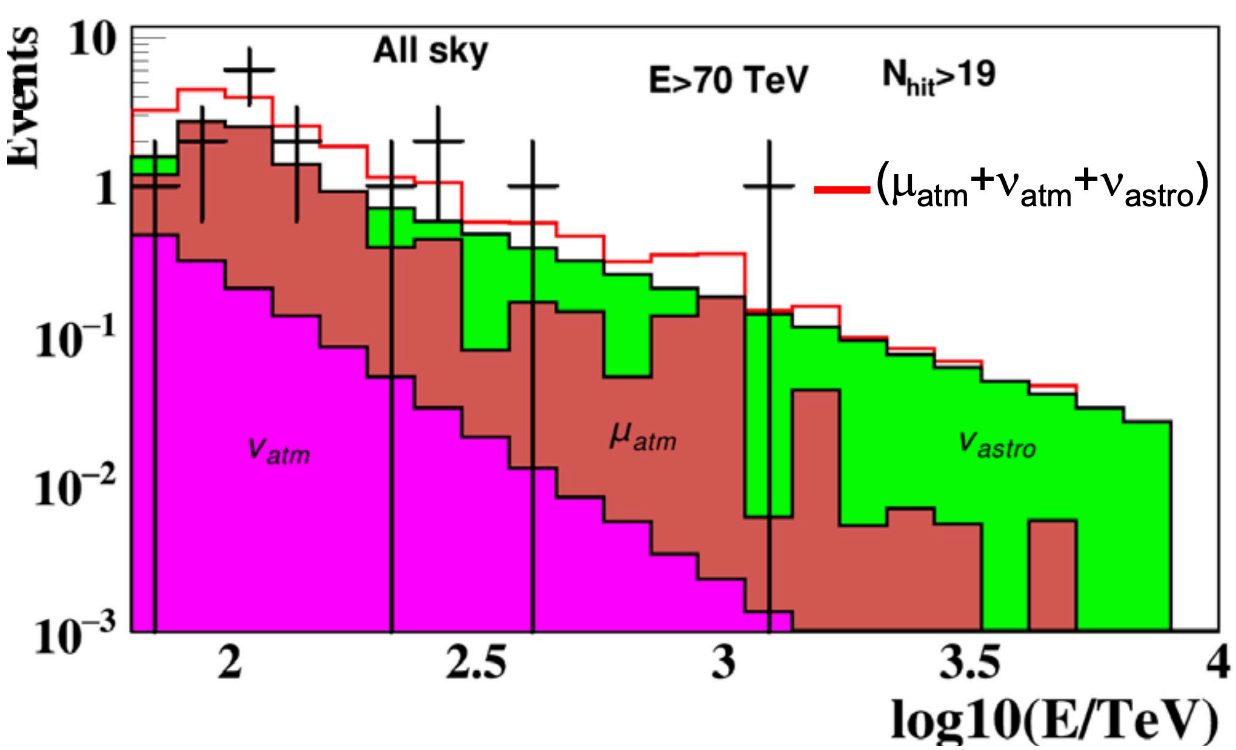


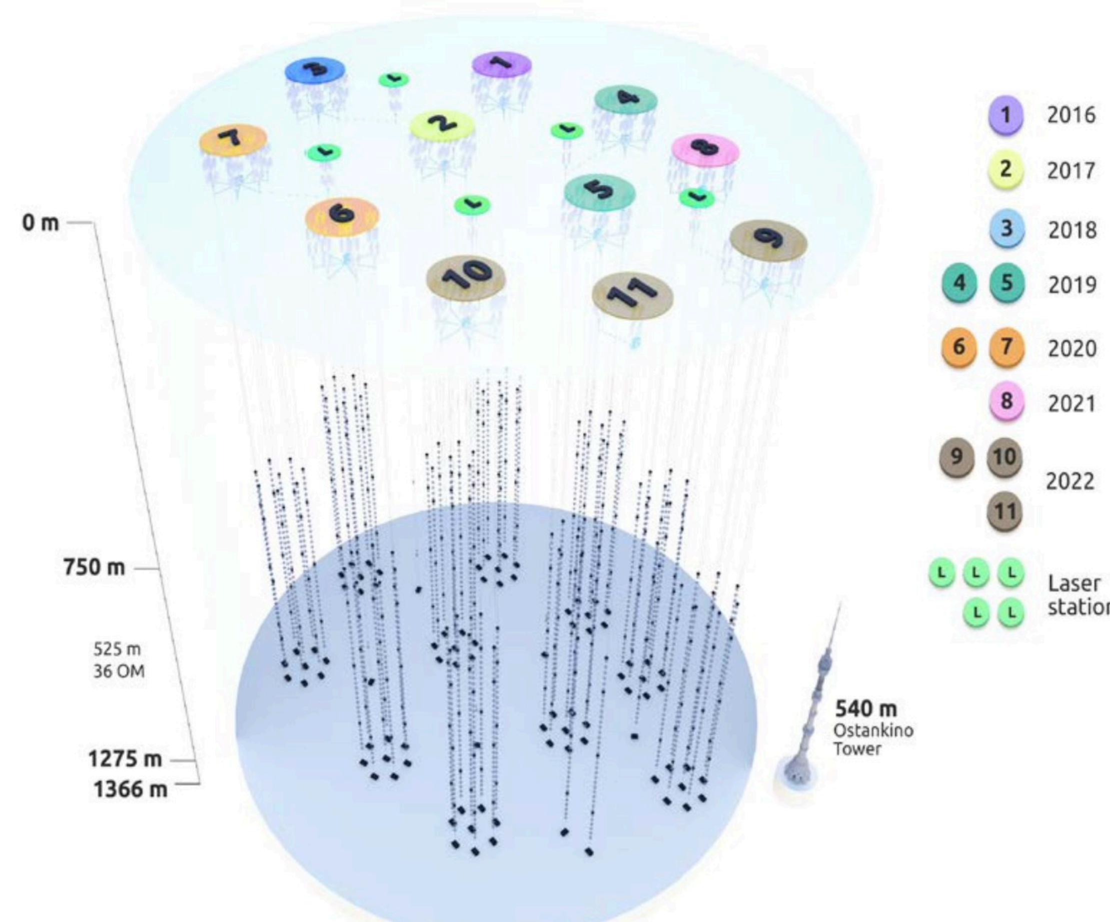
BAIKAL-GVD



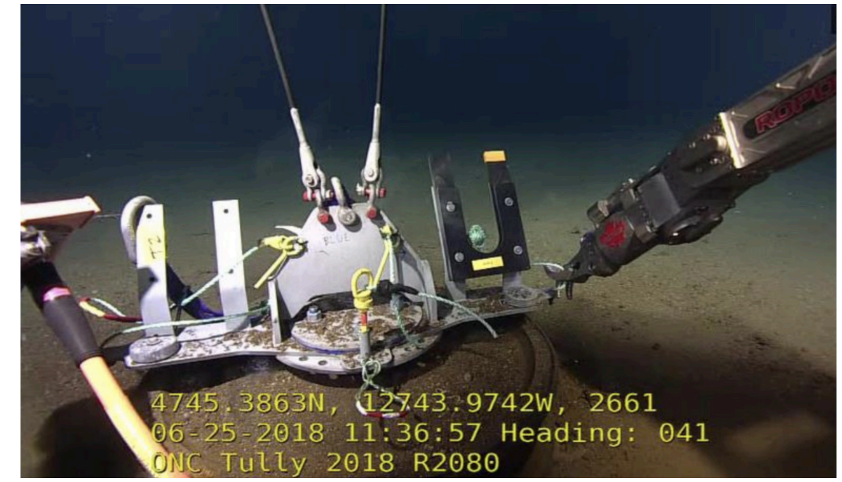


- 2022: Successfully deployed 10 clusters, 5 laser stations
- Each cluster has 288 OMs and depth 750-1275m
- 2025/2026 – ~ 1km3 GVD with total of 16-18 clusters
- 2022-2024 – "Conceptual Design Report" for next generation neutrino telescope in Lake Baikal

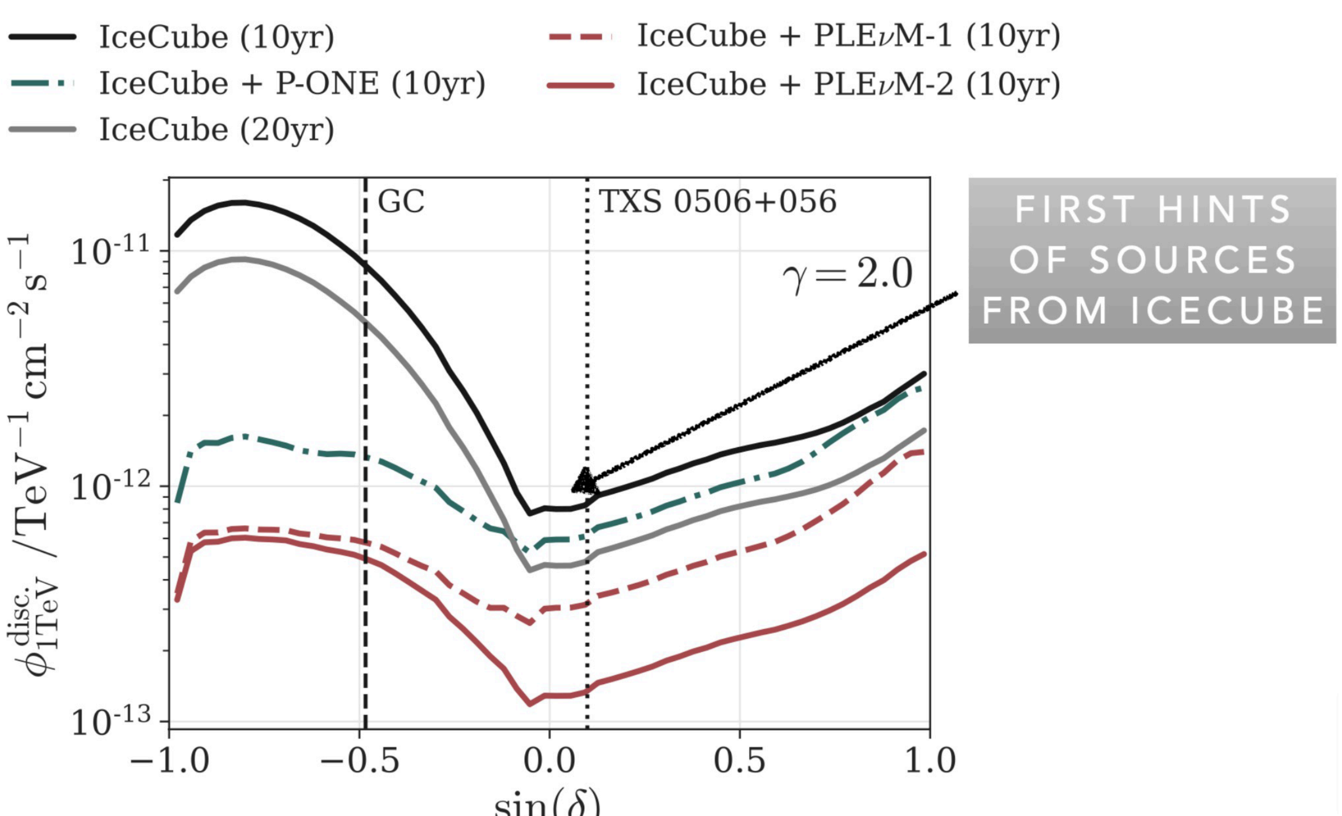


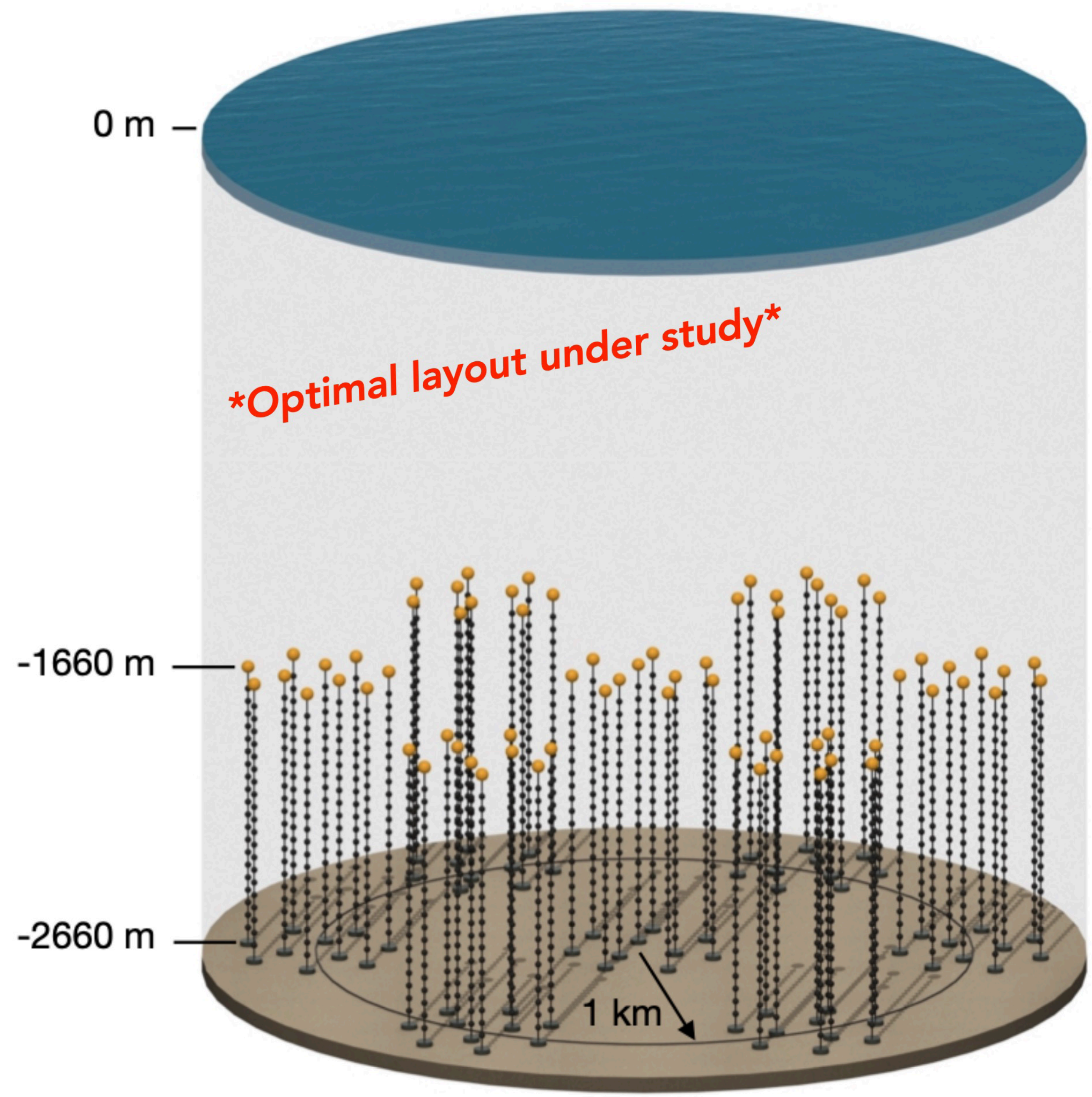


P-ONE



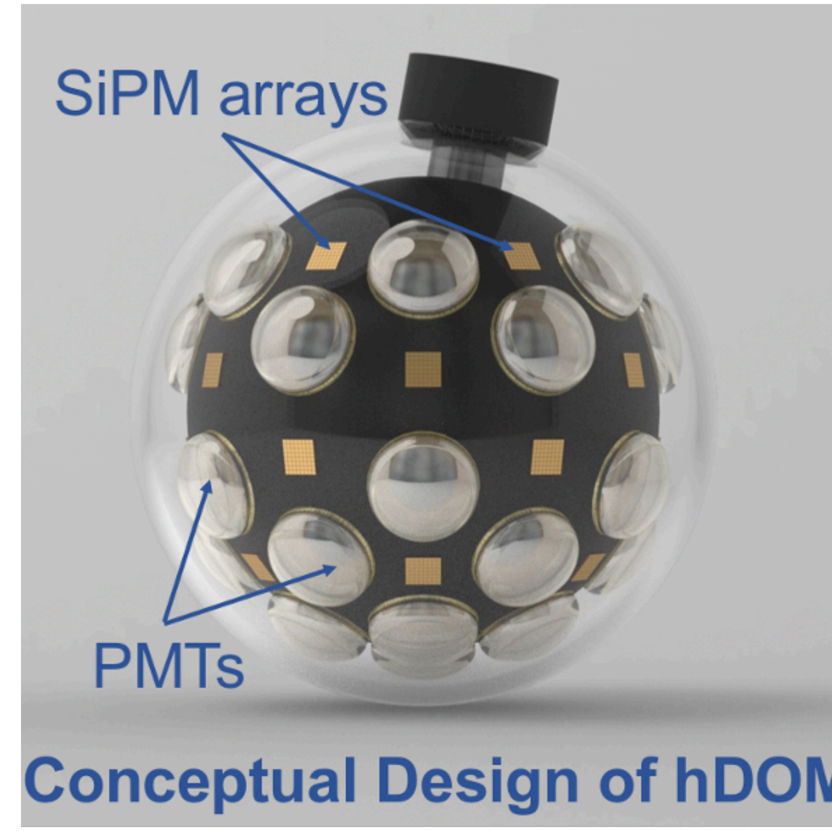
P-ONE Collaboration, Nature Astronomy (2020)

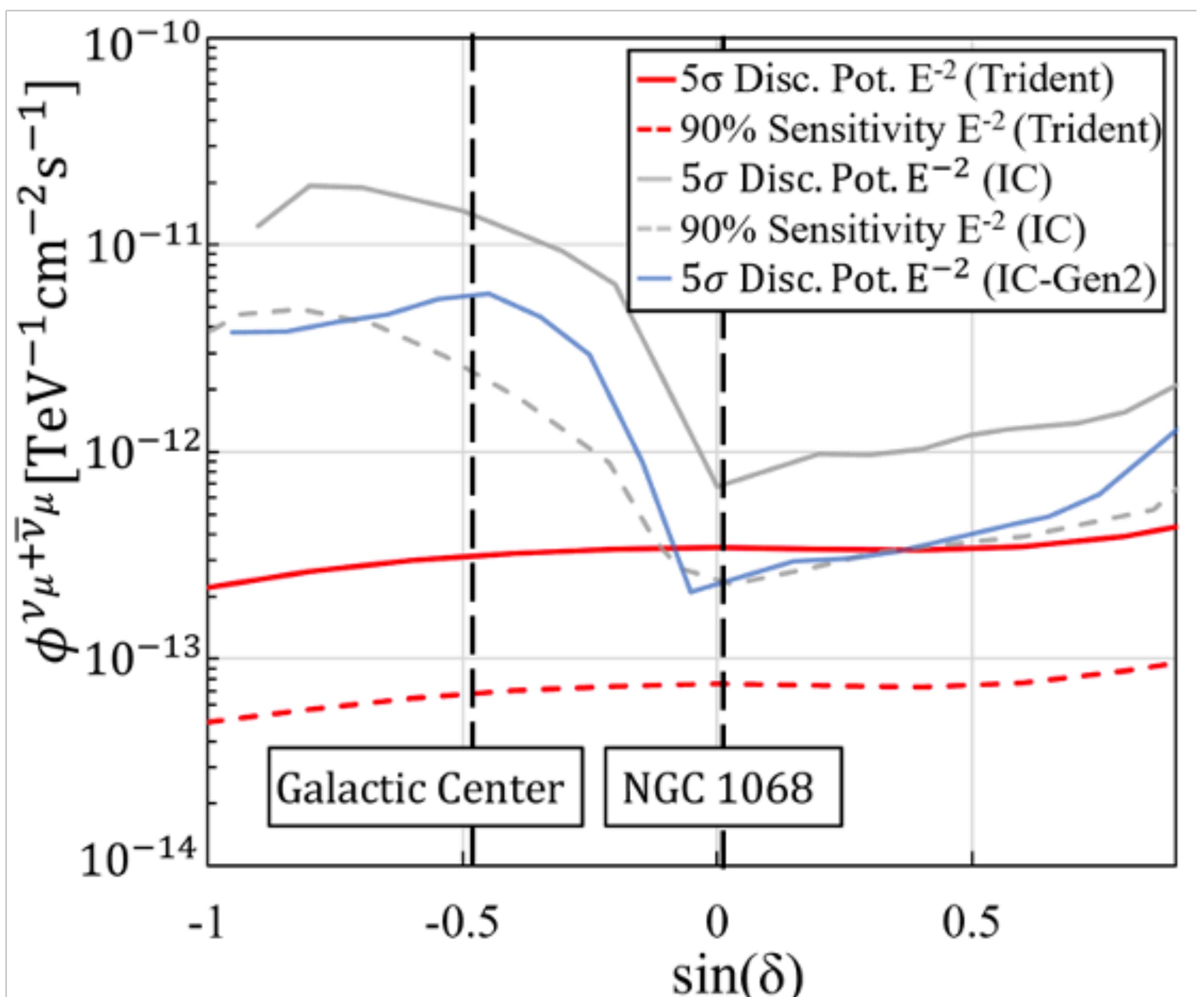


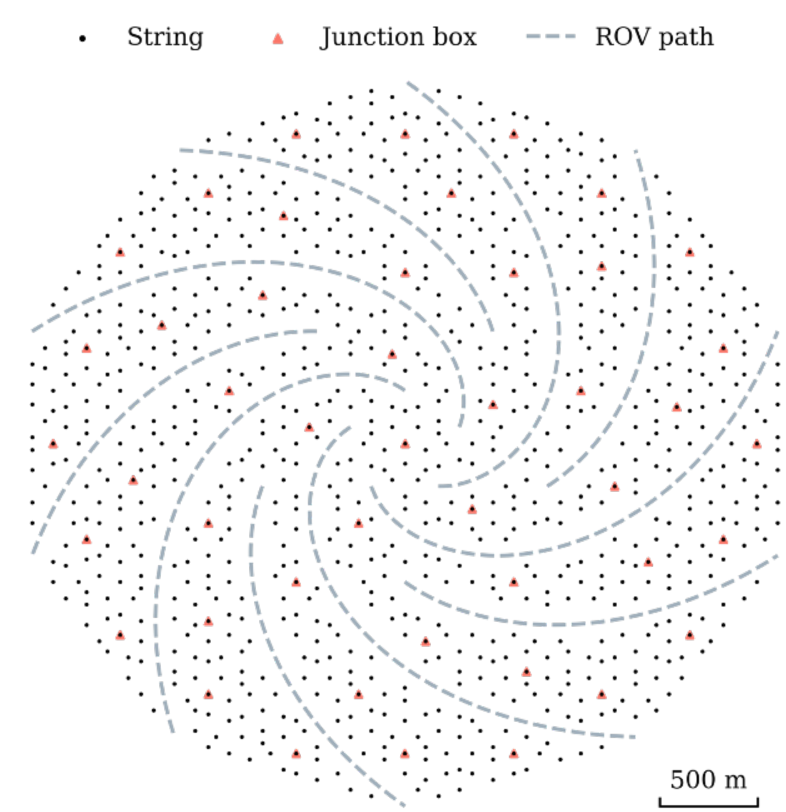


TRIDENT
海铃计划

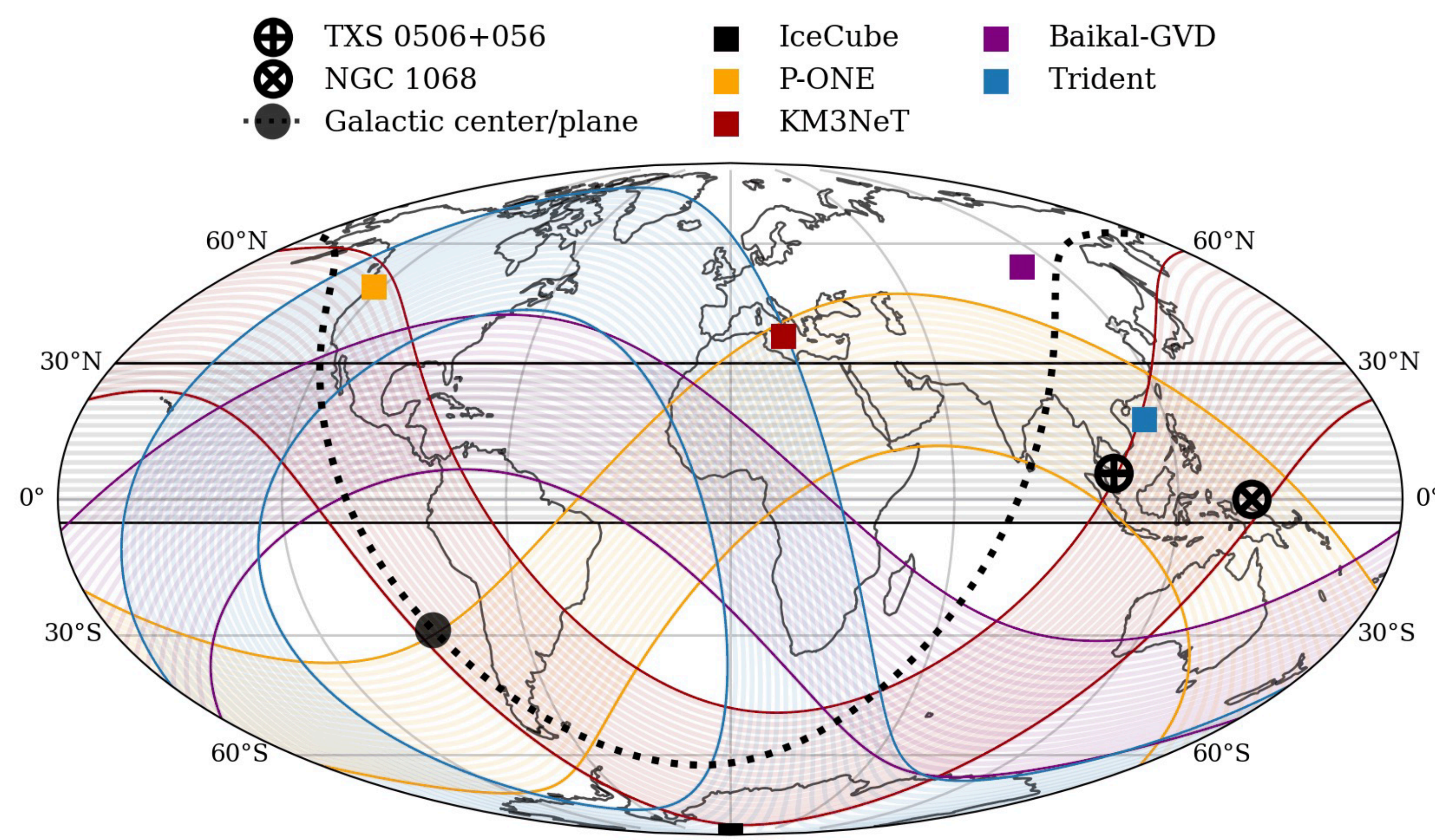
Envisioned full detector:
- 1211 strings
- 30 hDOM per string
- 7.5 km^3
- 3475m depth at South China Sea
- Underwater robots for deployment and maintena

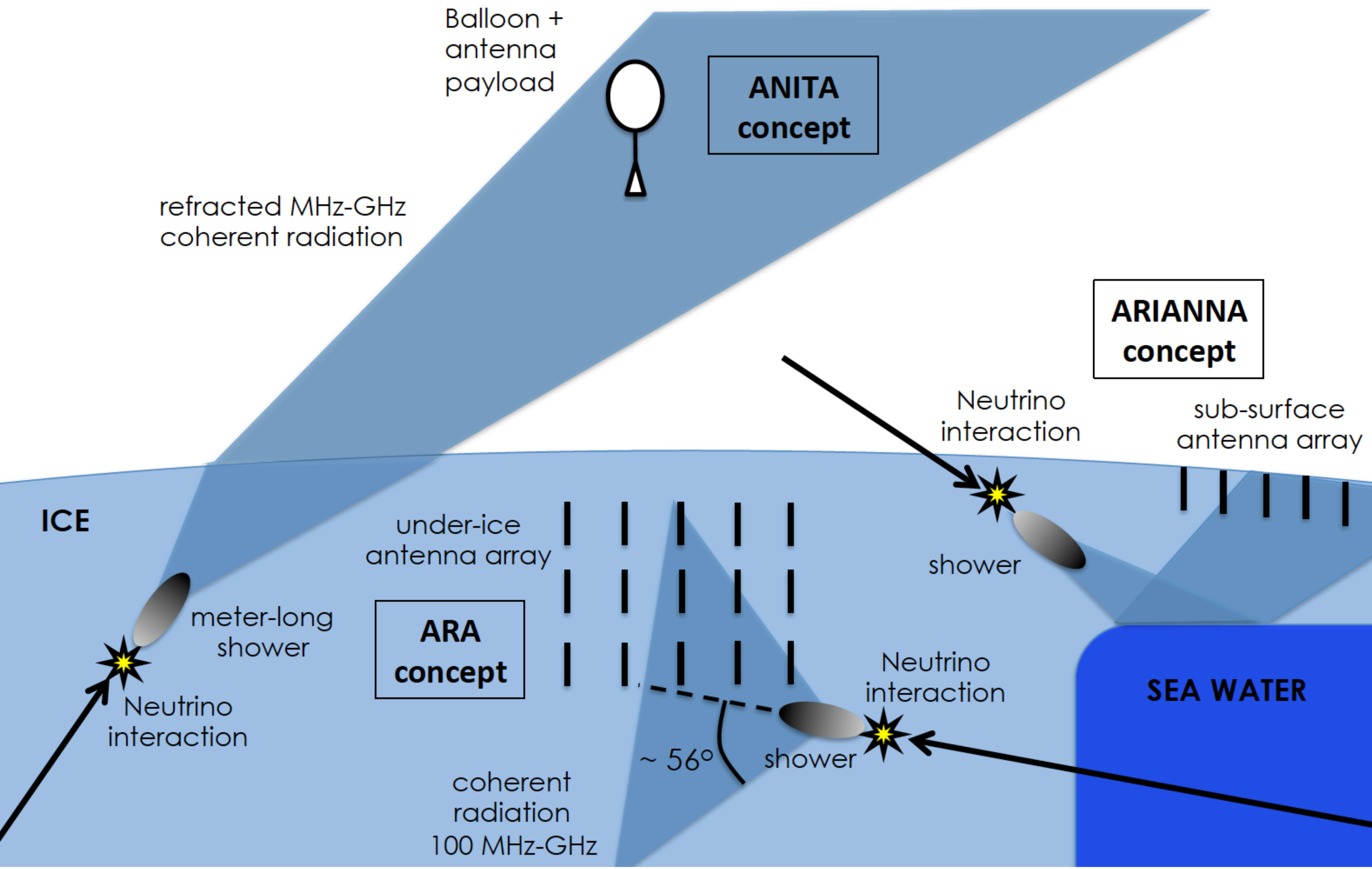




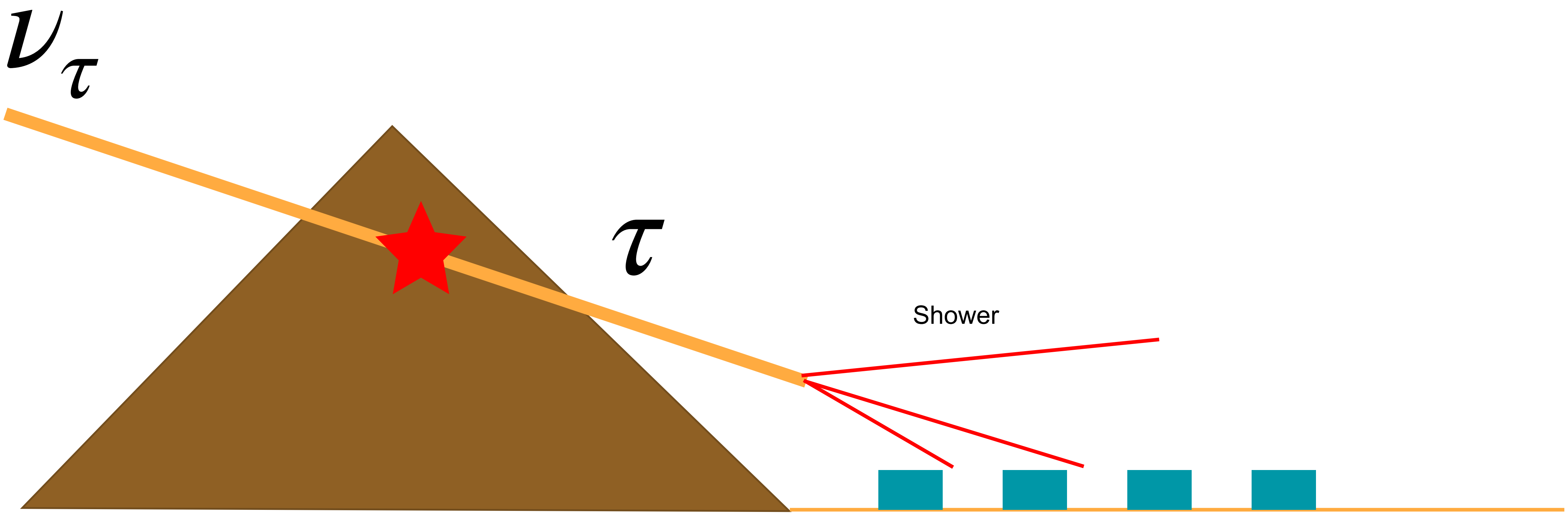


Future Neutrino Telescope Network



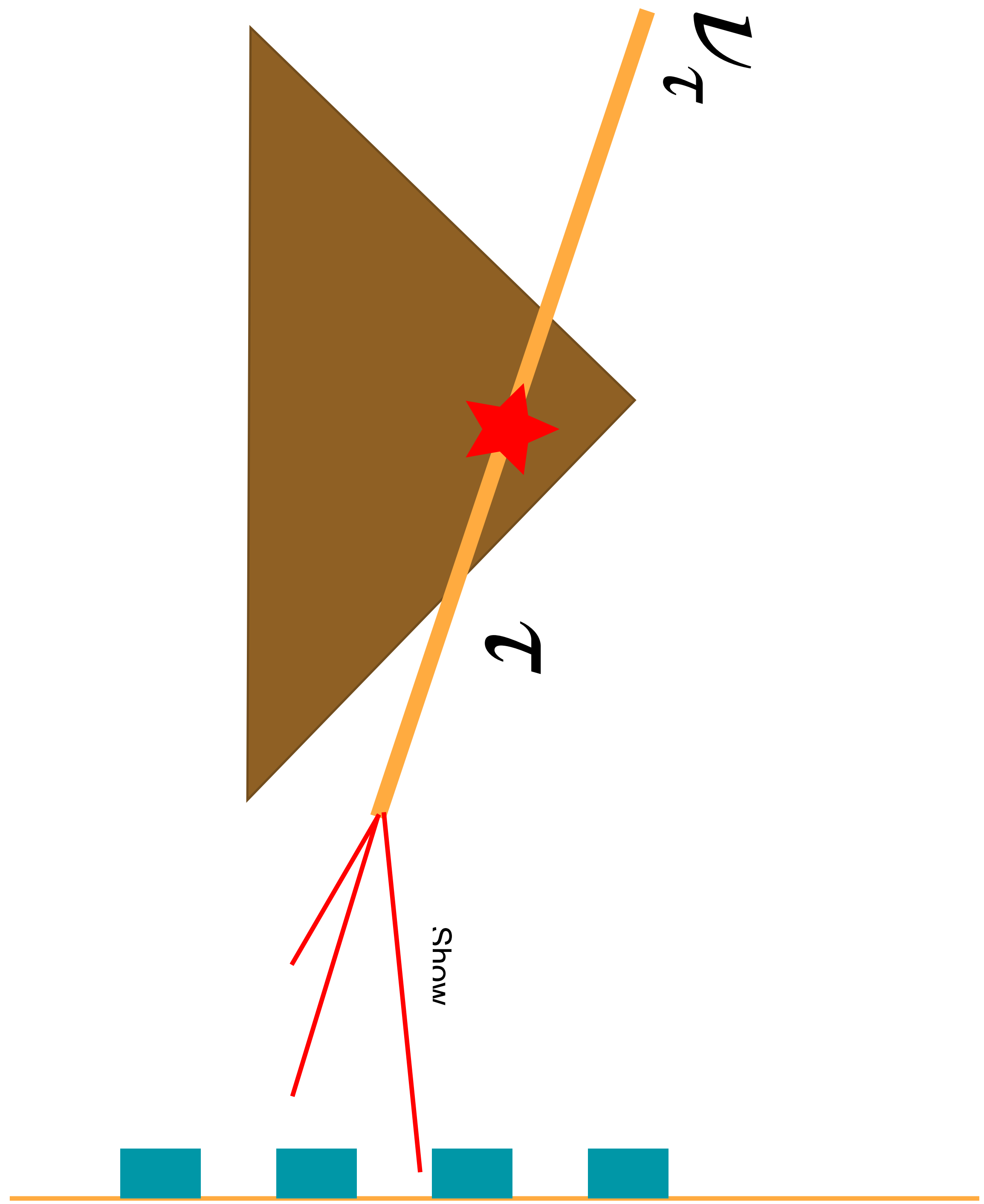

Balloon + antenna payload
ANITA concept
refracted MHz-GHz coherent radiation
ARIANNA concept
Neutrino interaction
sub-surface antenna array
ICE
under-ice antenna array
shower
meter-long shower
ARA concept
Neutrino interaction
SEA WATER
Neutrino interaction
~ 56º
shower
coherent radiation 100 MHz-GHz

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

This would be a more ideal scenario, but can't put mountain over detector

Pavel Zhelnin

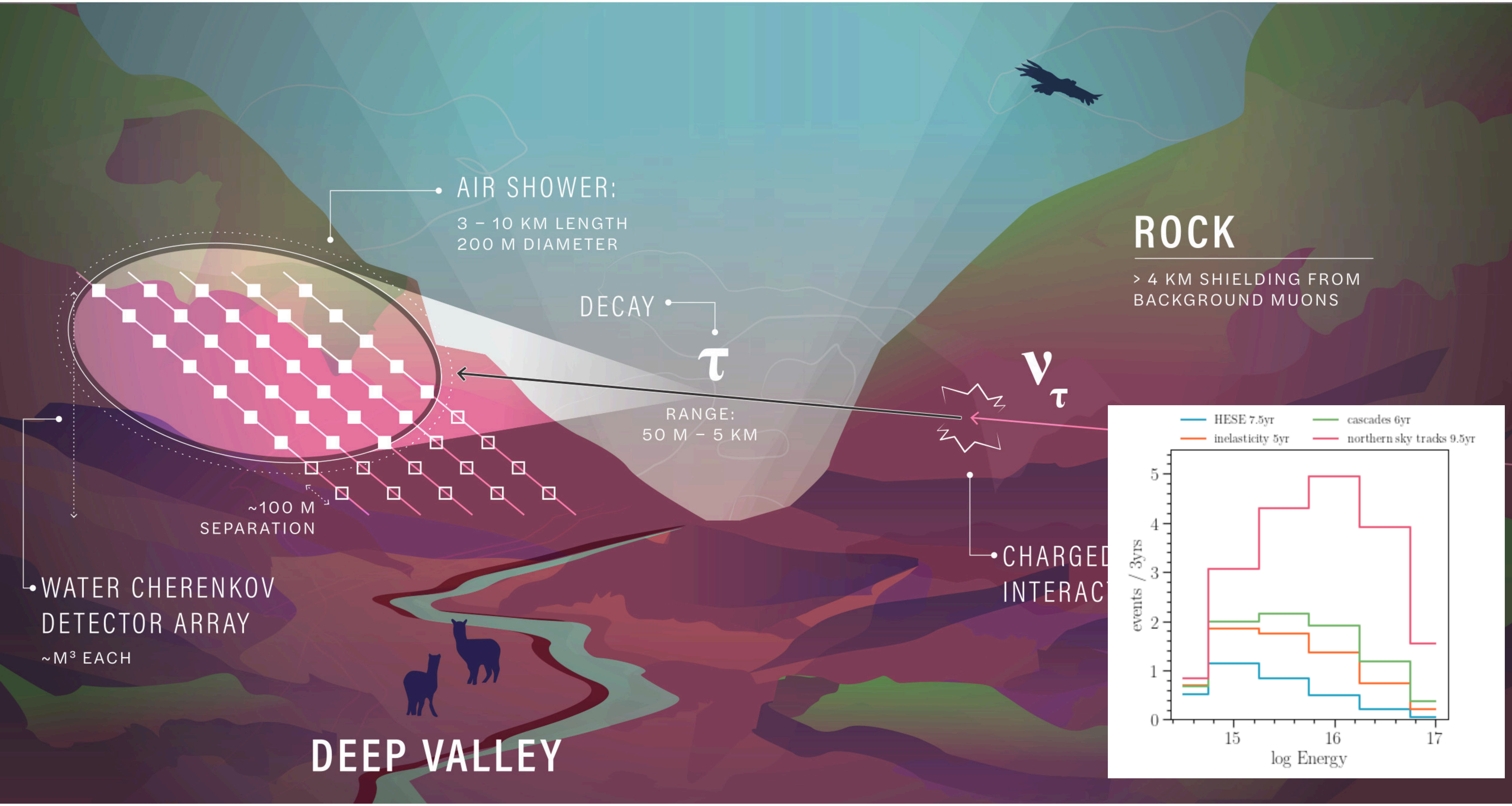
William Thomson

Diya Delgado

Jeffrey Lazar

Ibrahim Safa

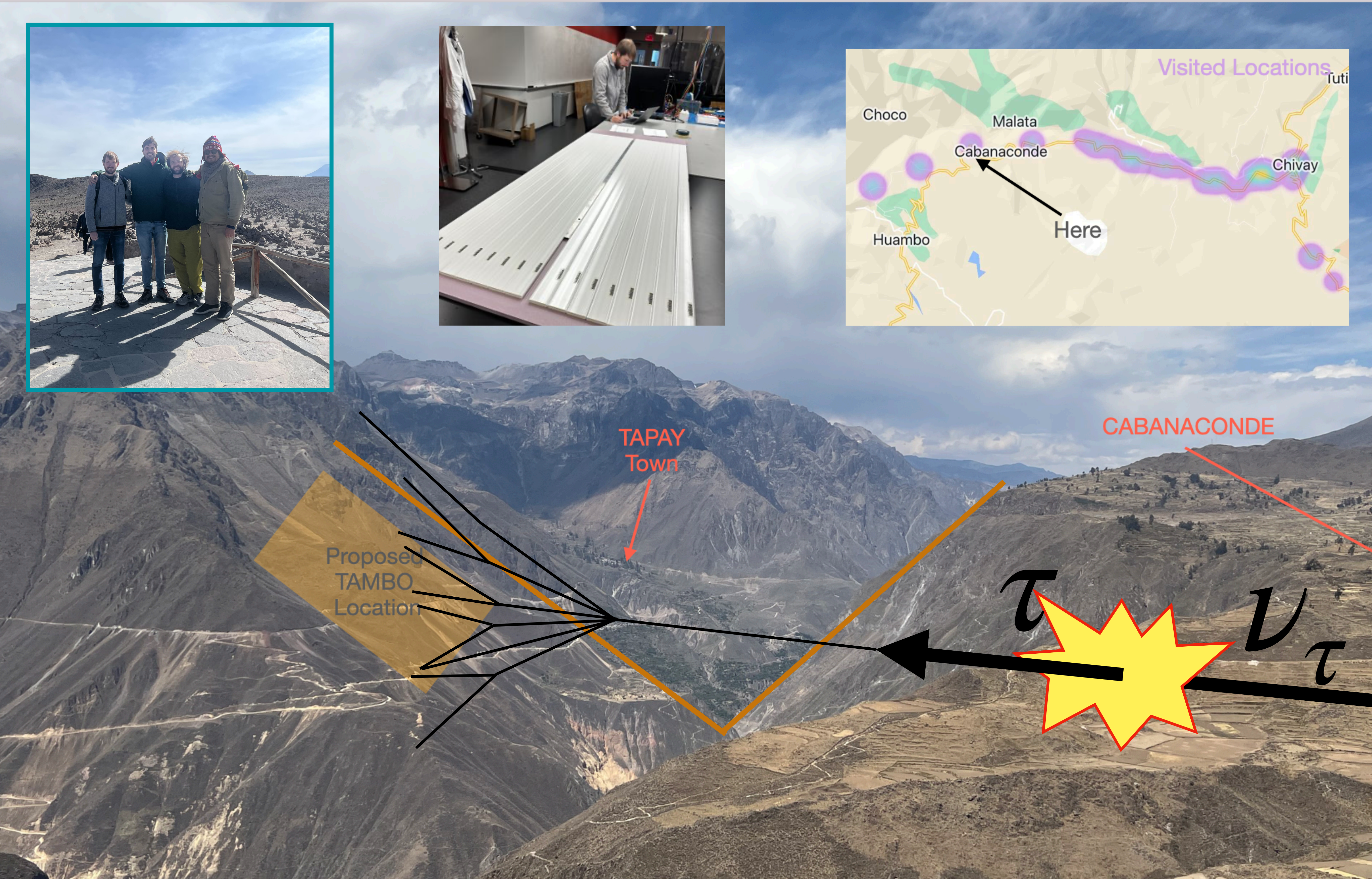
TAMBO



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

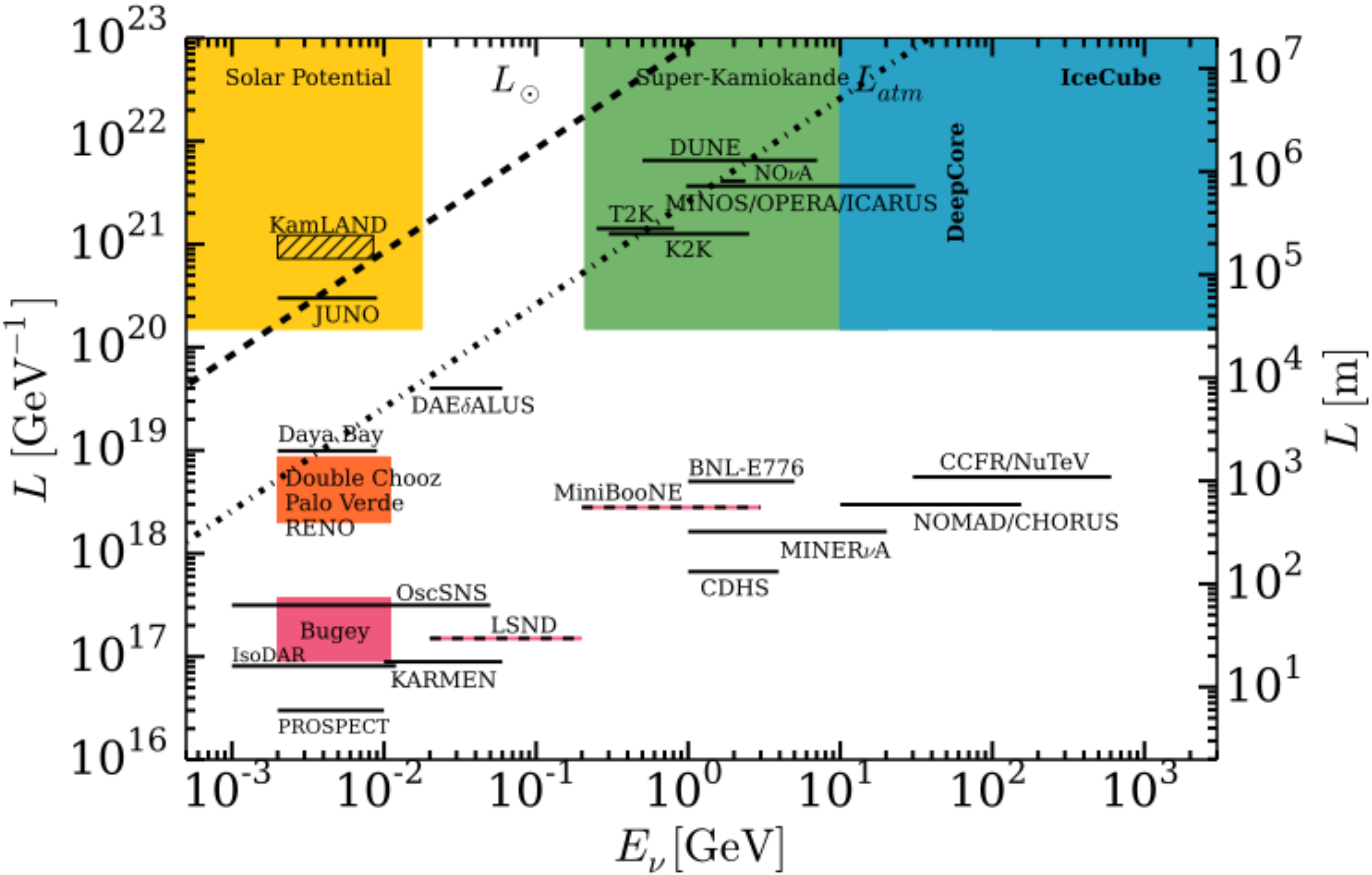
P. Zhelnin, I. Safa, A. Romero-Wolf and CA ICHEP2022

*TAMBO means house or inn in Quechua.

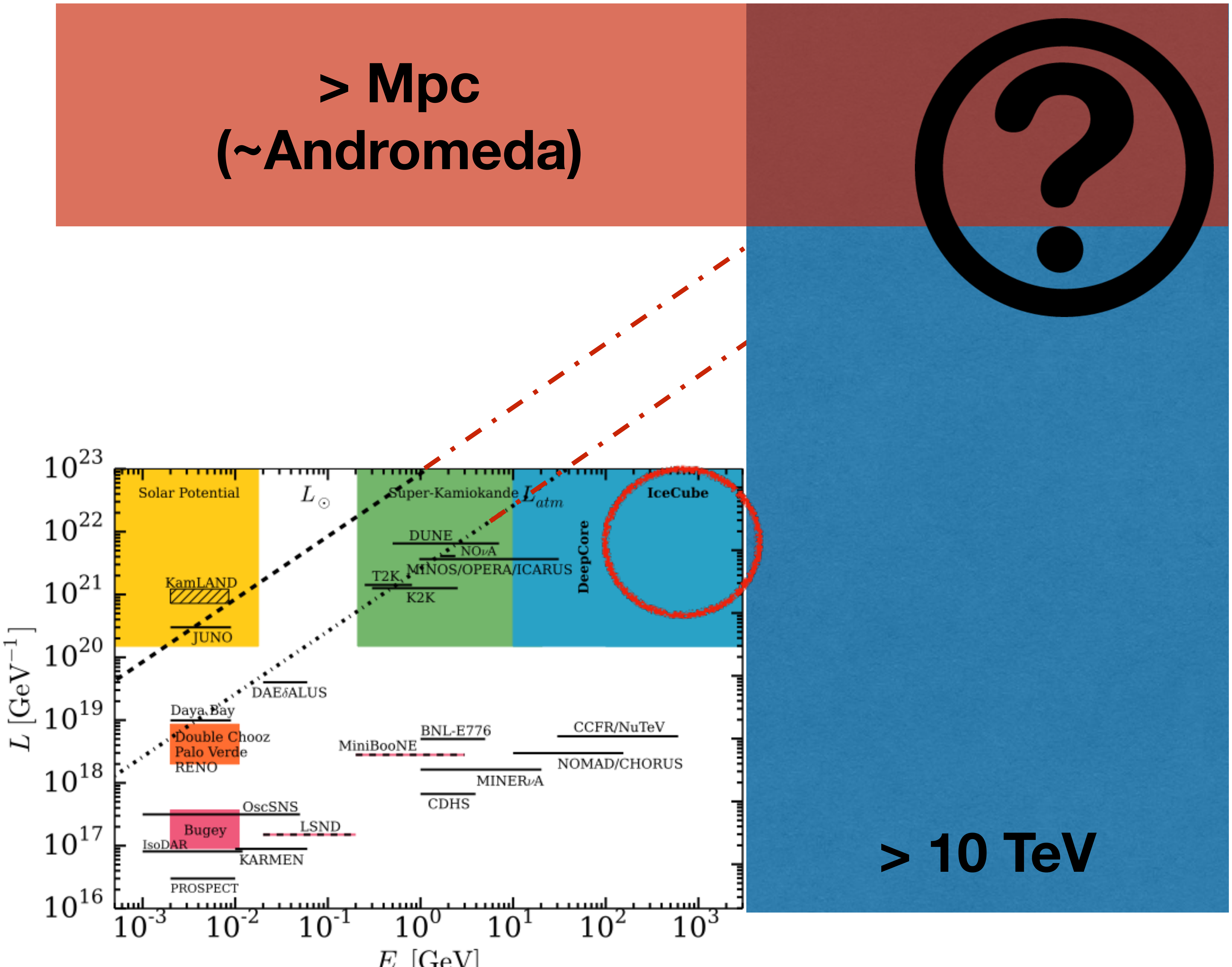


We went to Peru earlier last year and found a location for the experiment!
First prototype detectors are expected to be deployed next summer.

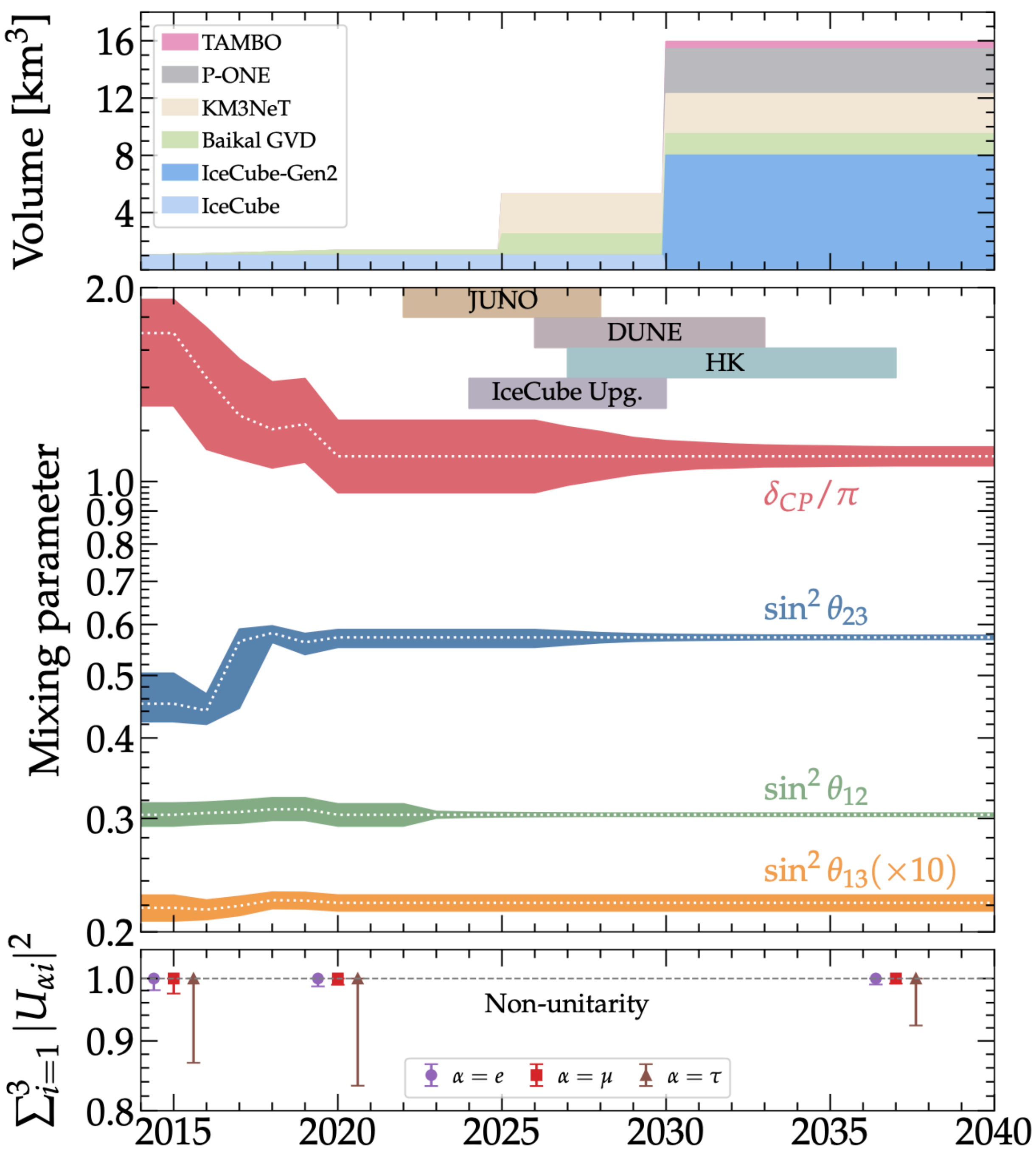
Terrestrial measurements

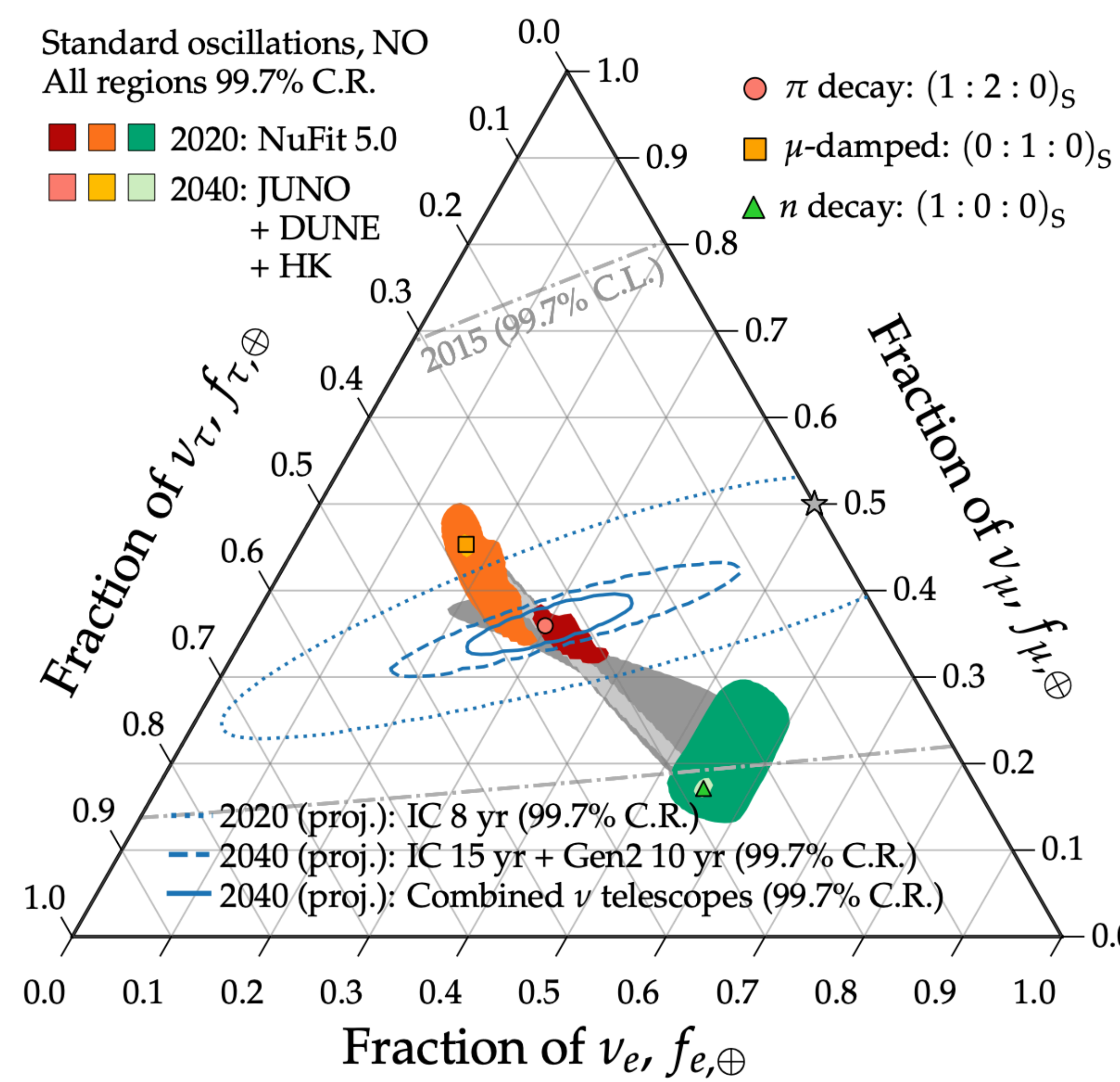


Terrestrial measurements ➡ *astrophysical* frontier

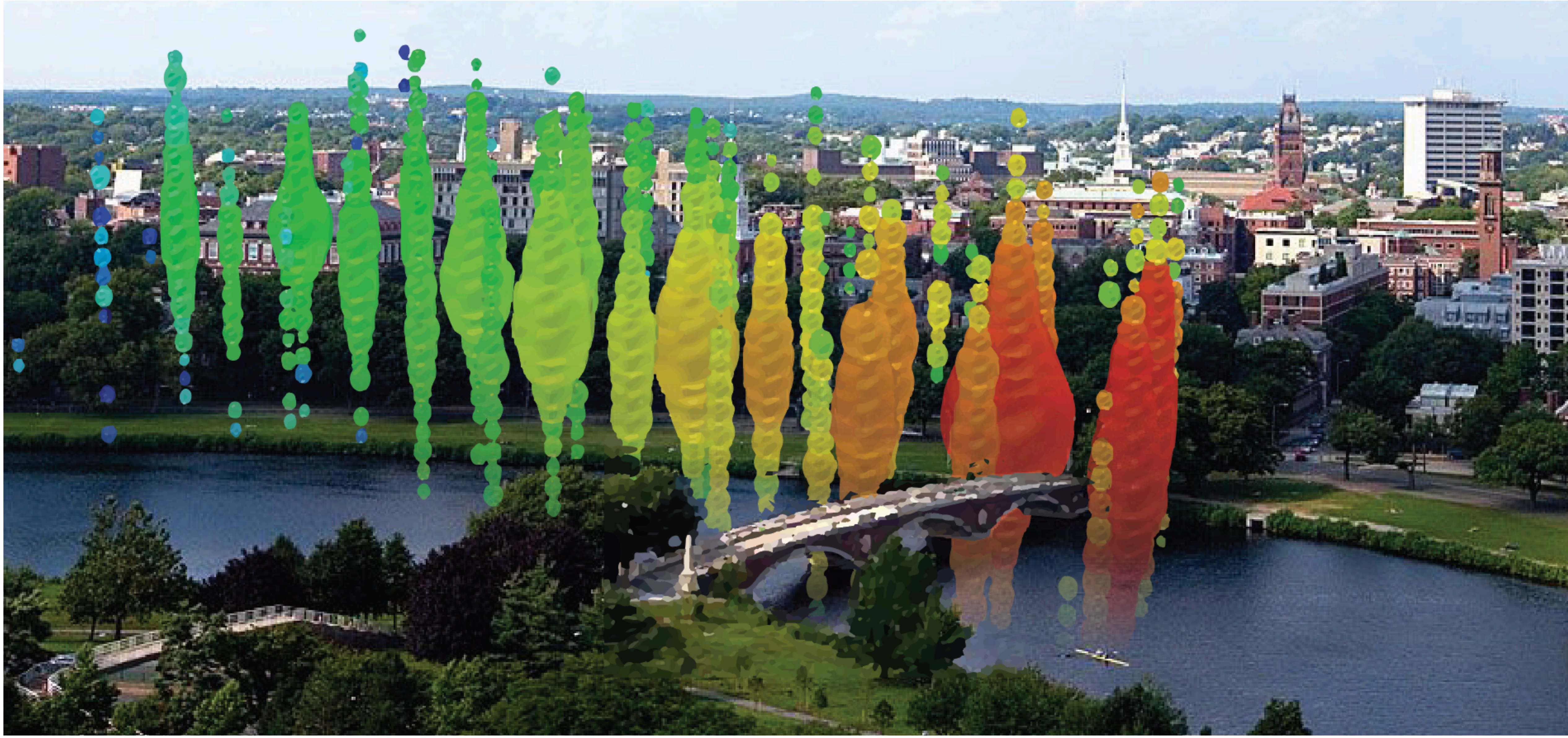


Projected Upgrade Flavor Measurement





N. Song, S. Li, CA, M. Bustamante, A. Vincent (arXiv:2012.12893)



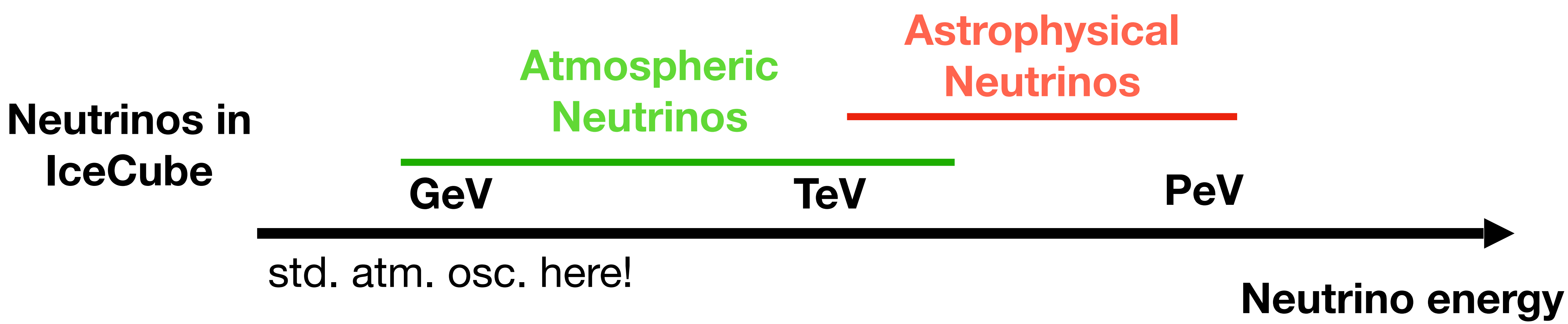
Obrigado!

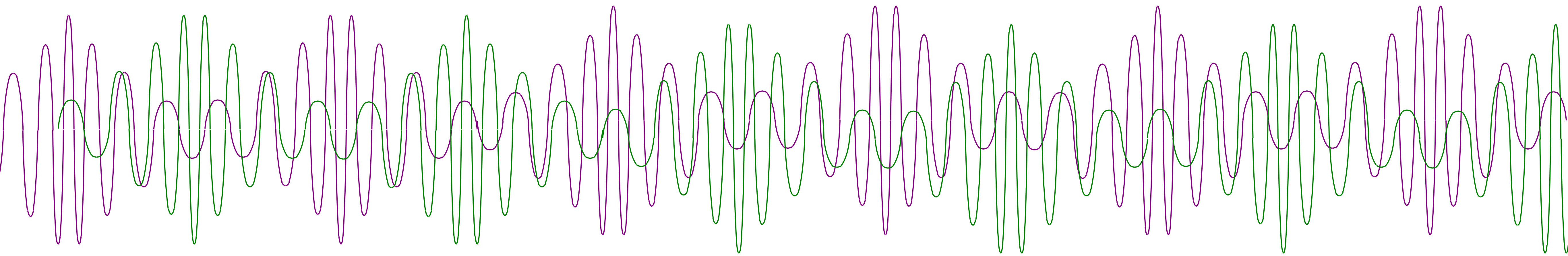
Why look for new physics with HE neutrinos?

- Standard neutrino oscillations term decreases with energy.
- High-energy atmospheric neutrinos: understood flux and flavor composition.
- Astrophysical neutrinos traverse the largest distances, small effects can accumulate.

Standard term | New physics term

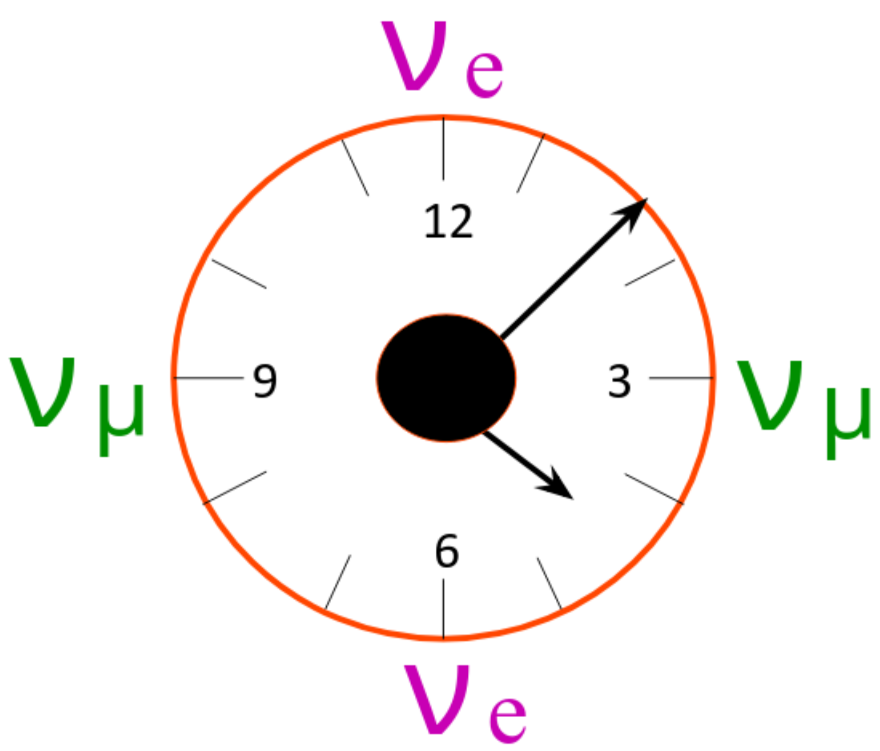
$$H = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{V_{\mathrm{new\ \ physics}}}$$





Because of oscillations, neutrinos are natural clocks.
As time passes, they change from one flavor to the other, and back.

$$|\nu(t)\rangle = e^{-iHt/\hbar}\,|\nu_\alpha\rangle$$

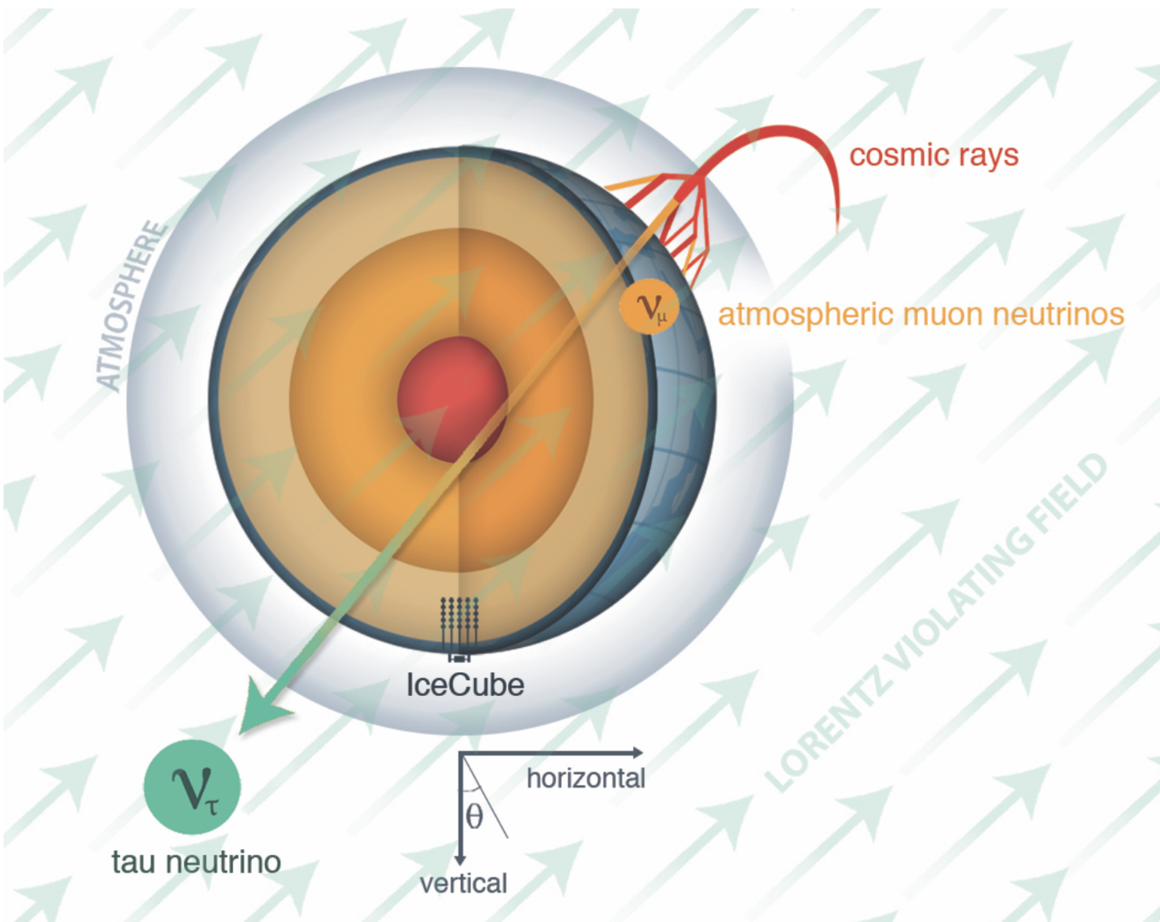


Lorentz violation will change the neutrino oscillation frequency producing **new flavor conversion**

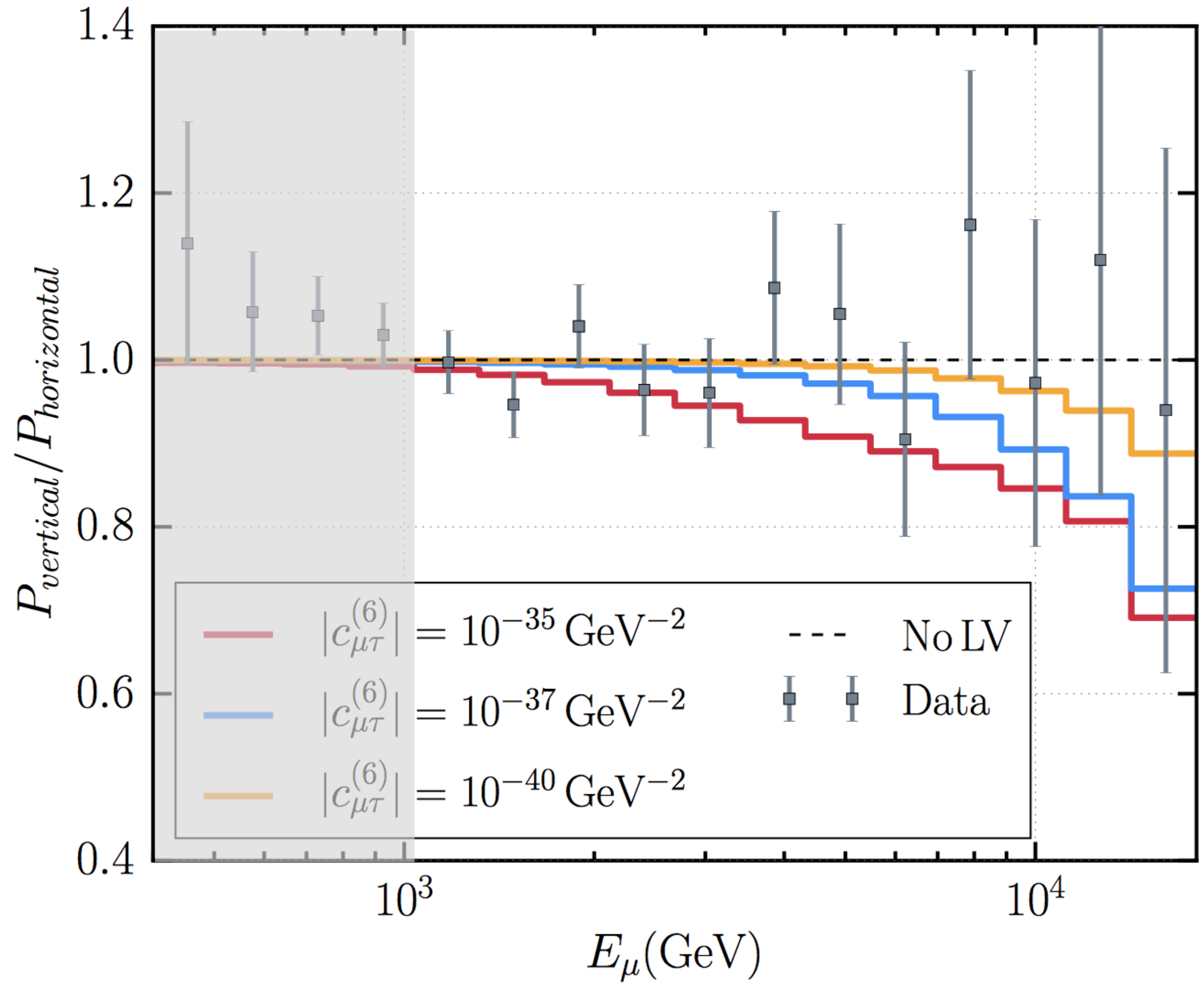
We have search for Lorentz Violation with high-energy Atmospheric Neutrinos

The analysis sensitivity, especially for high-dimensional operators, is dominated by the highest-energy events.

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots$$



$$P_{osc}(c^{(6)}_{\mu\tau} E_\nu L)$$



Lorentz violation changes the ratio of horizontal to vertical events.

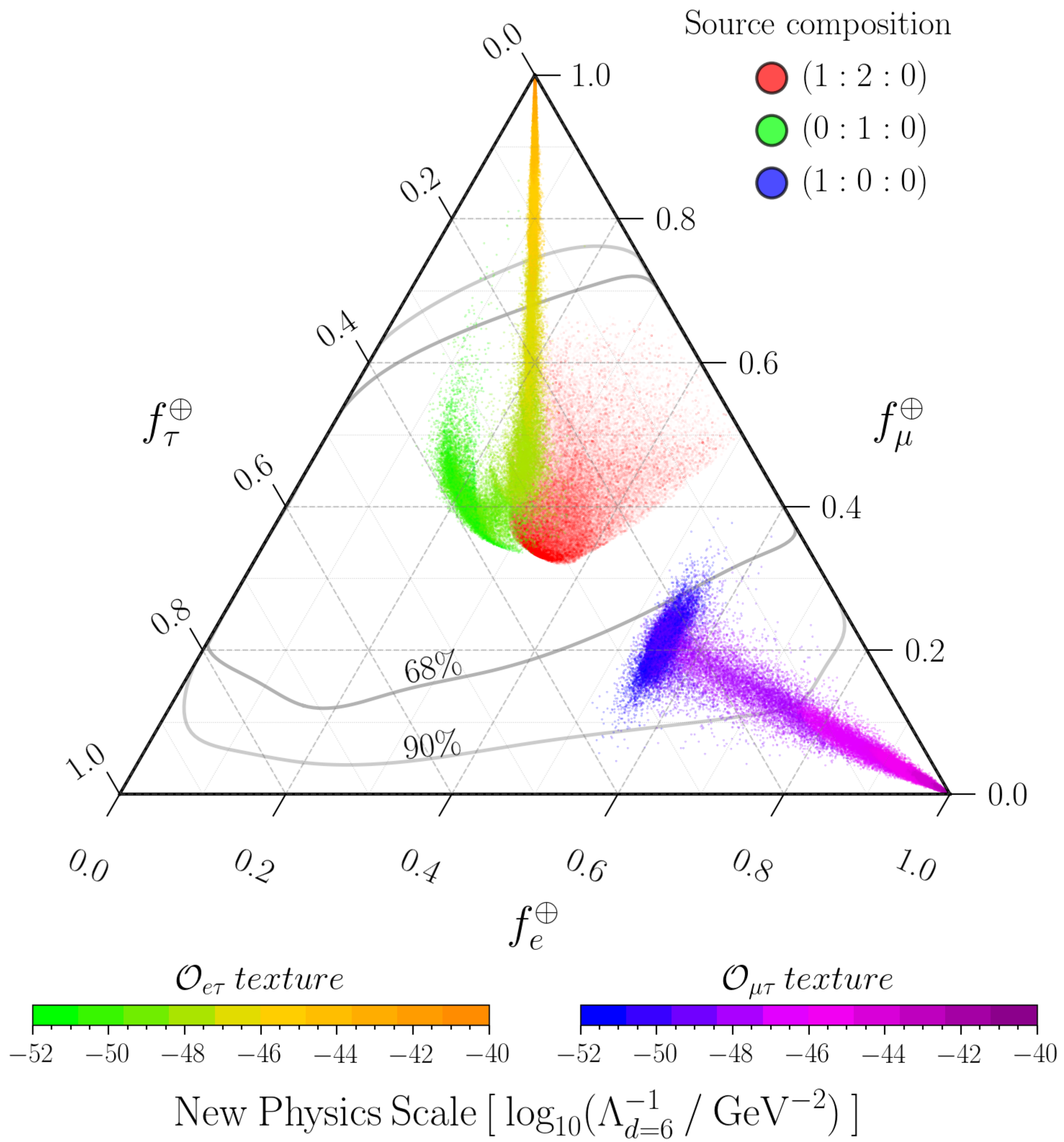
Leading constraints across several fields of physics

dim.	method	type	sector	limits		ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^+ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

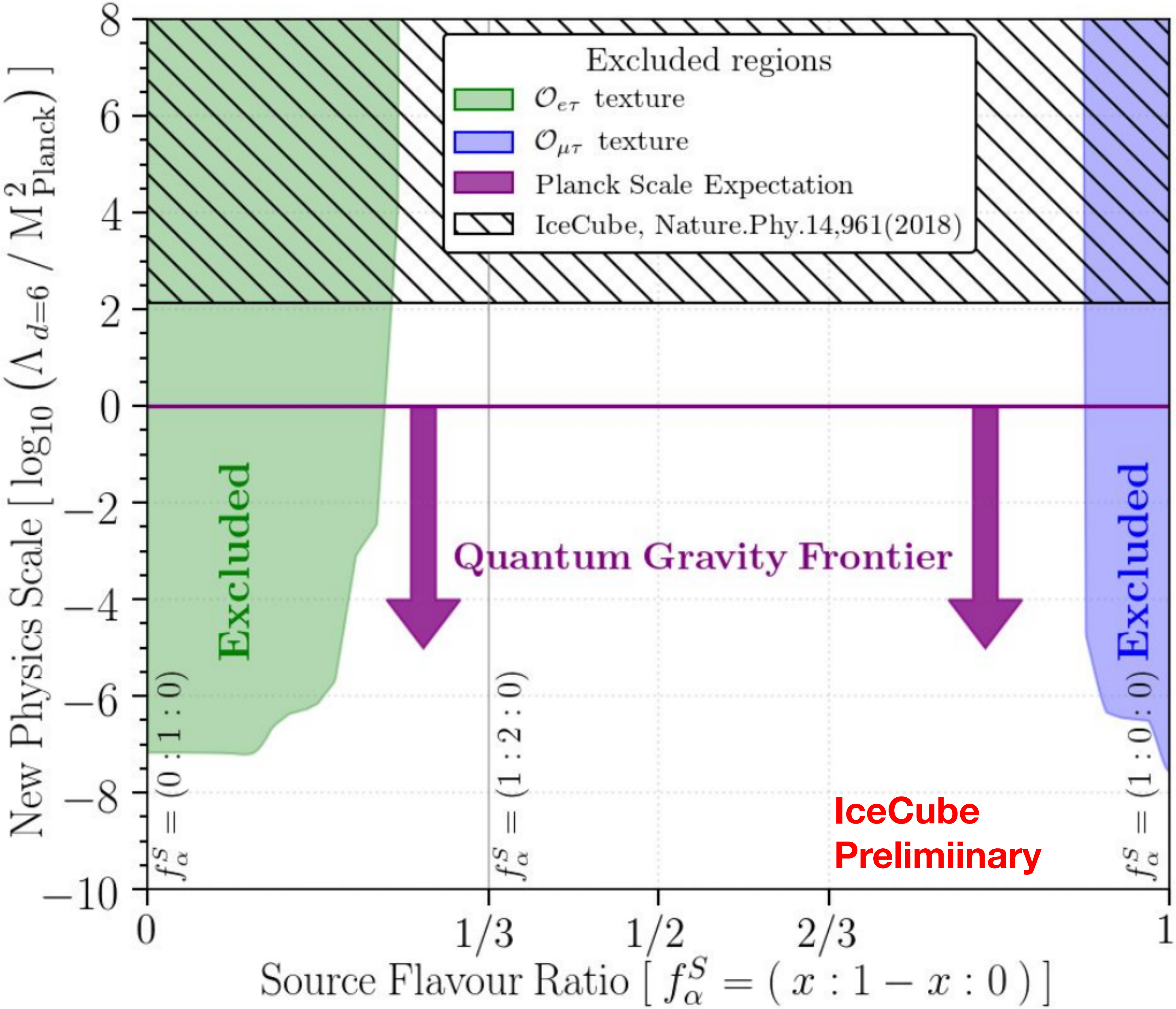
Very strong limits on Lorentz Violation induced by dimension-6 operators!

Nature Physics (2018) s41567-018-0172-2

Trajectories in the flavor triangle in the presence of Lorentz Violation (LV)



Results on high-dimensional LV operators



Beyond the Lorentz Violation interpretation

Our analysis is performed by introducing *effective terms*, which can be due to by other new physics beyond Lorentz Violation.

Standard term — New physics term

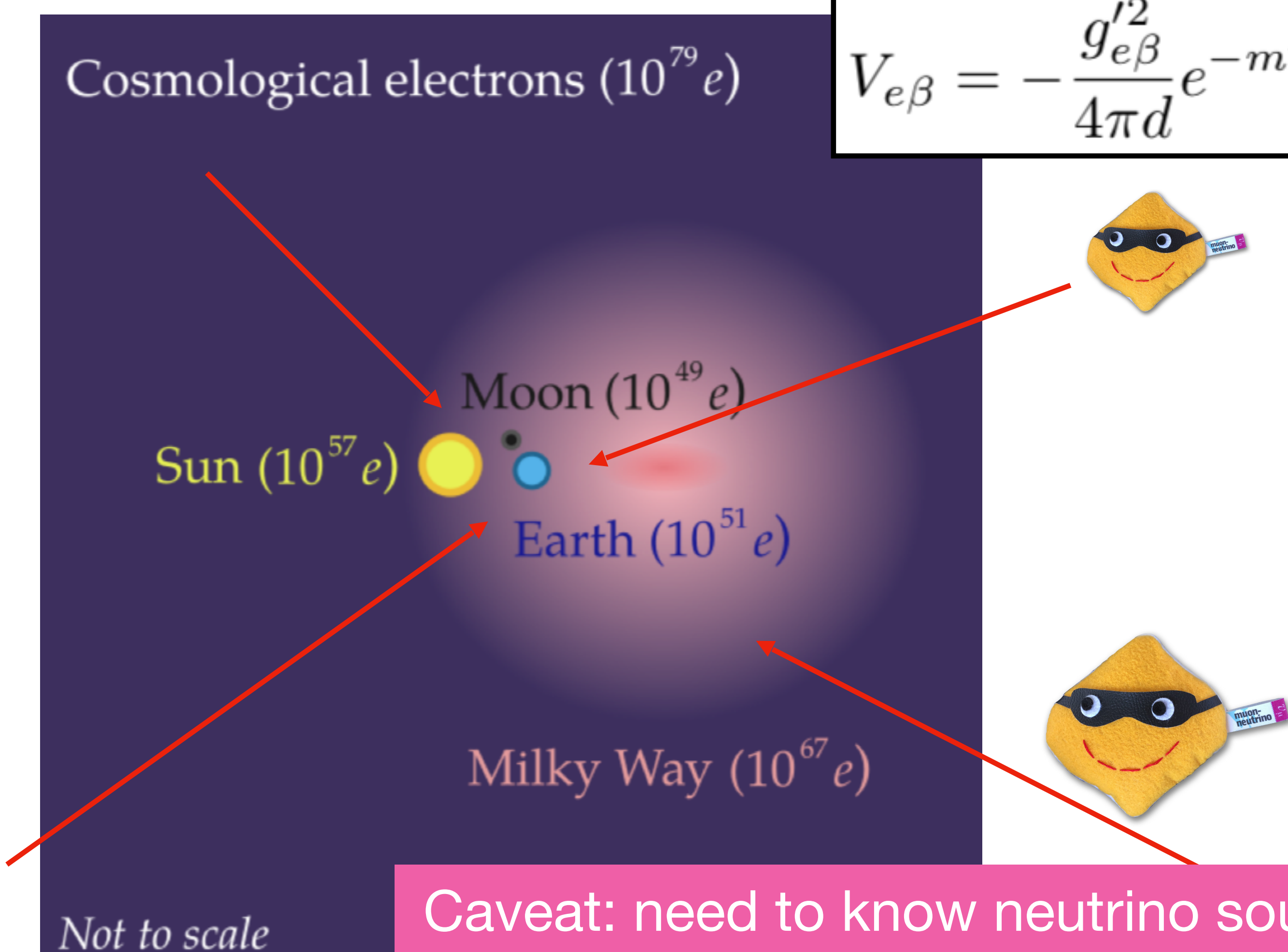
$$H = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{V_{\text{new physics}}}$$

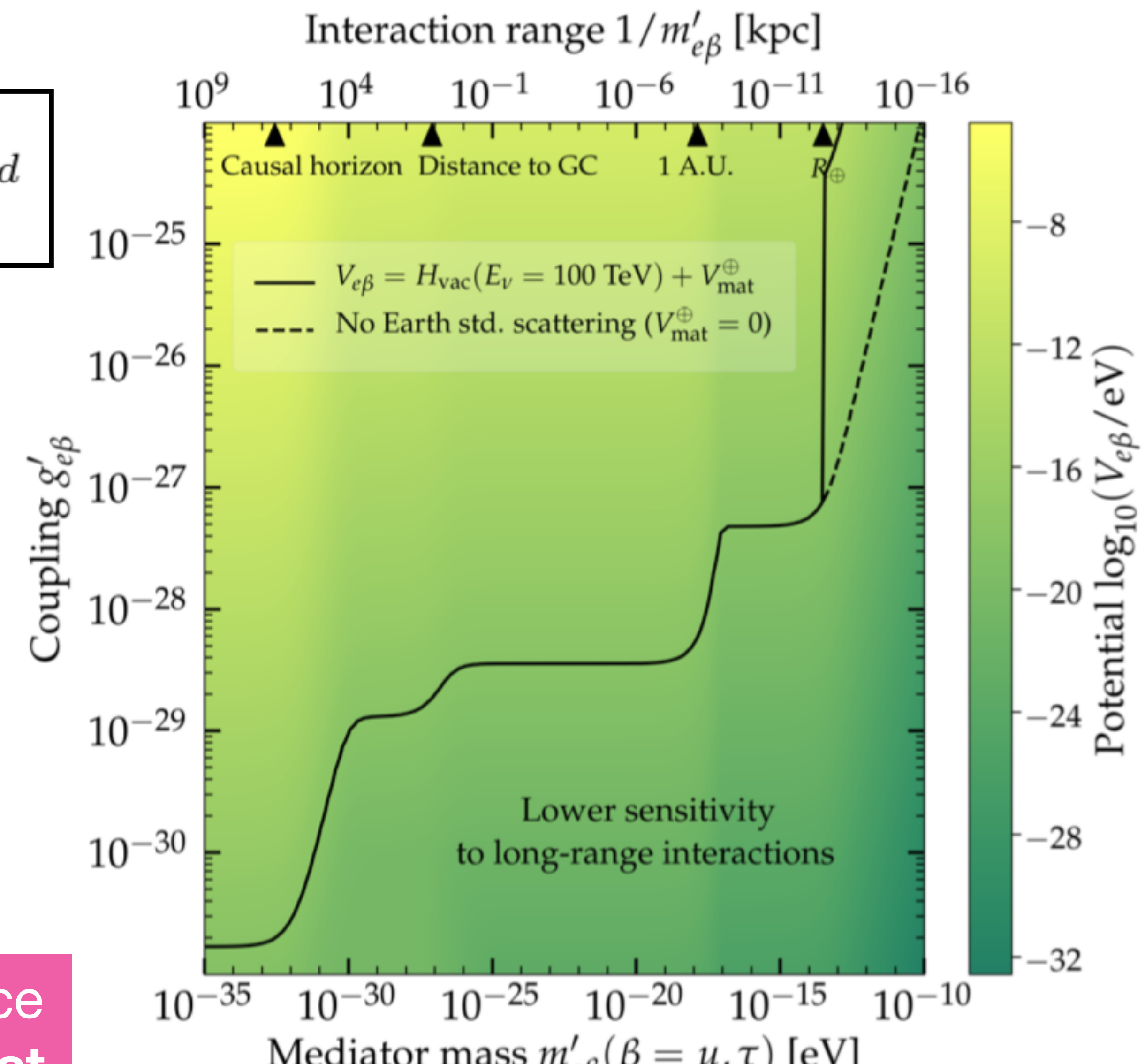
$V_{e\tau} < 10^{-27}\text{GeV}$ (0:1:0) source

$V_{\mu\tau} < 10^{-28}\text{GeV}$ (1:0:0) source

New long range forces gauged on $L_e - L_\alpha$

$$V_{e\beta} = -\frac{g'^2_{e\beta}}{4\pi d} e^{-m'_{e\beta} d}$$





Caveat: need to know neutrino source initial flavor composition to get **robust** bounds with current limits.

Bustamante et al. 1808.02042

Coherent **Dark Matter Scattering**

Standard term | New physics term

$$H = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{V_{\text{new physics}}}$$

$V_{e\tau} < 10^{-27}\mathrm{GeV}$

(0:1:0) source

$V_{\mu\tau} < 10^{-28}\mathrm{GeV}$

(1:0:0) source

Coherent scattering with dark cosmic background

Our analysis is performed by introducing *effective terms*, which can be due to by other new physics beyond Lorentz Violation.

$$V_D \sim G_D N_D$$

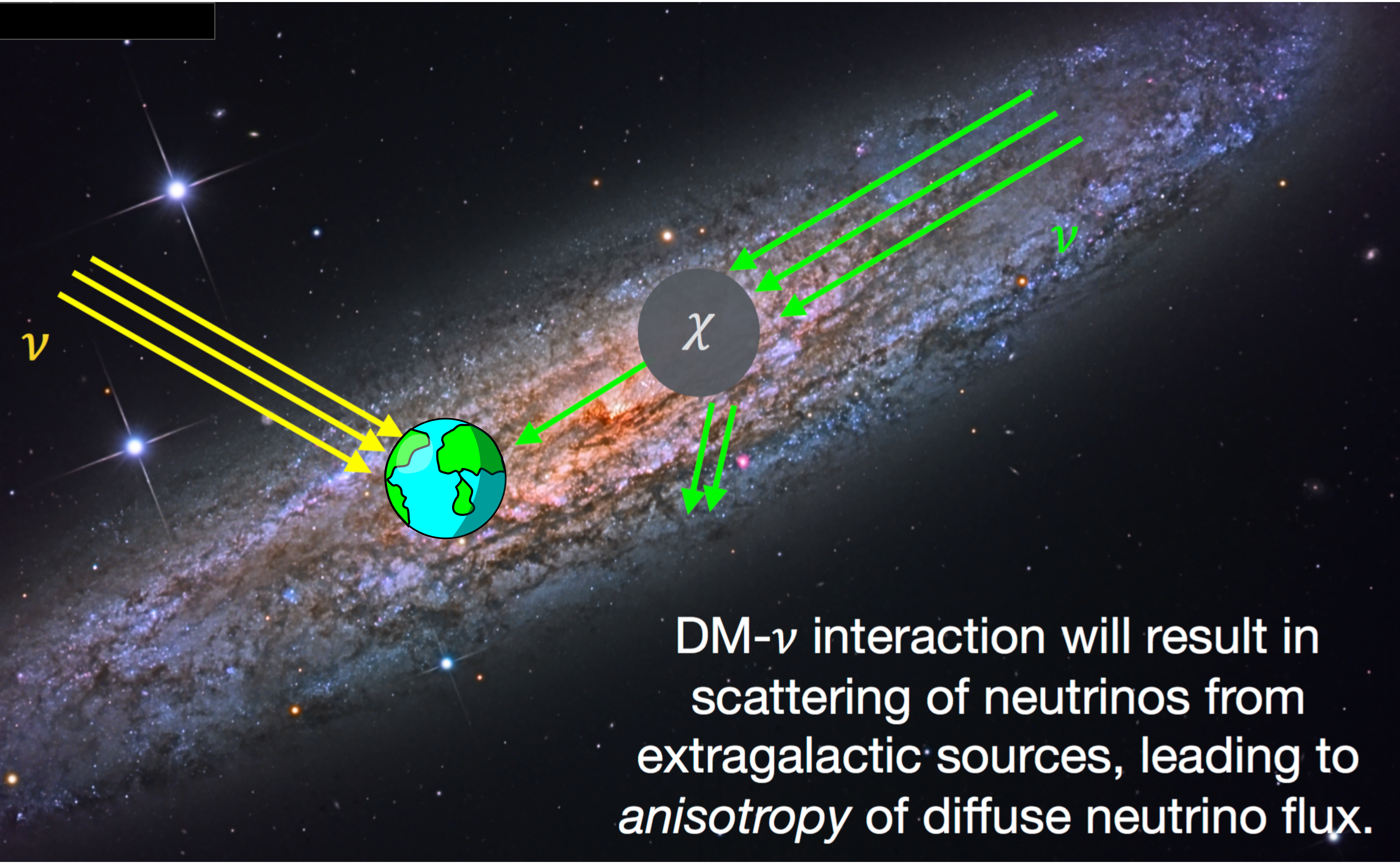
$$G_D \sim \frac{g_d^2}{M_D^2}$$

Caveat: need to know neutrino source initial flavor composition to get **robust** bounds with current limits.

de Salas, et al. Phys. Rev. D94 (2016) 123001

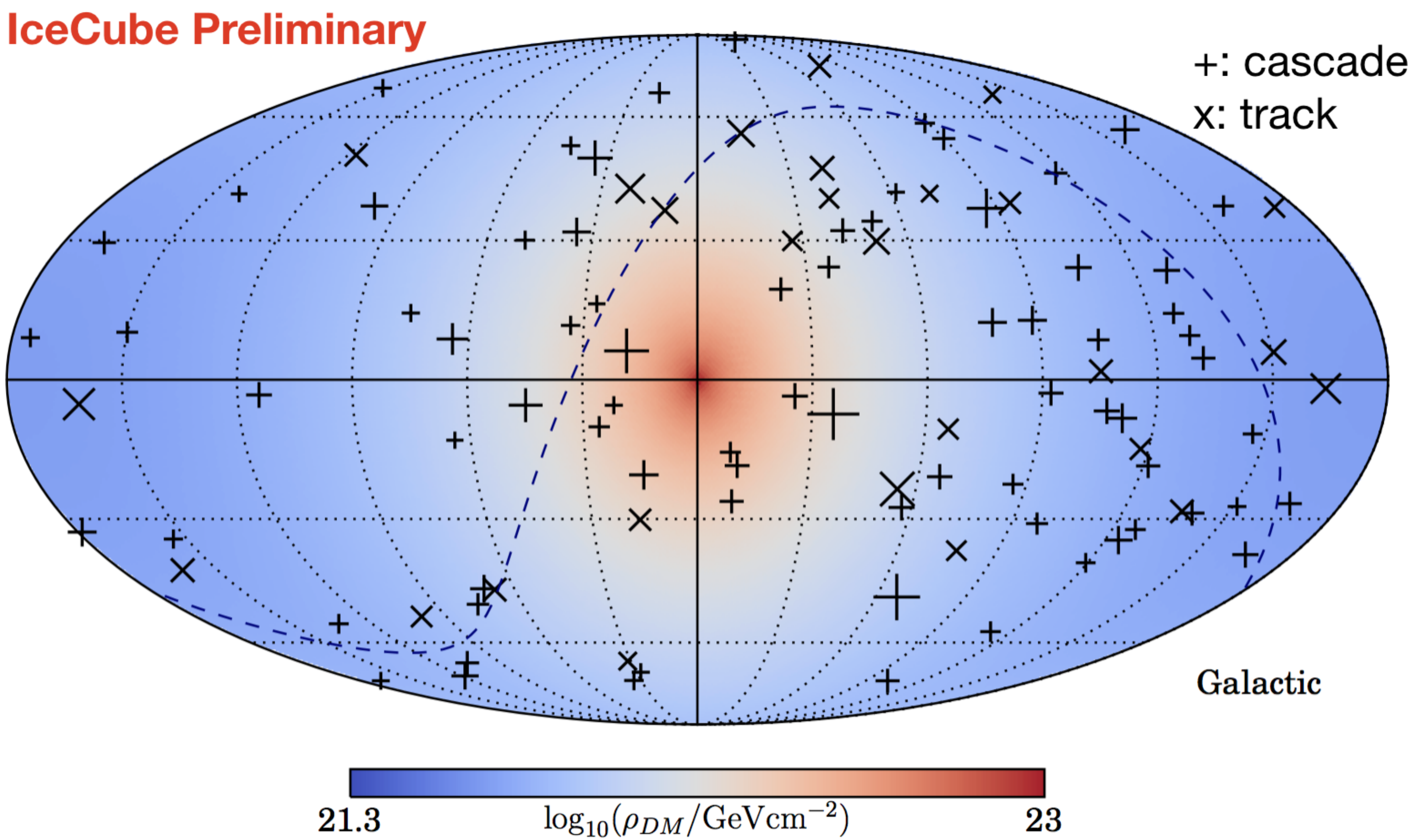
Capozzi et al. 1804.05117

Dark matter neutrino incoherent scattering



CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

Neutrino skymap

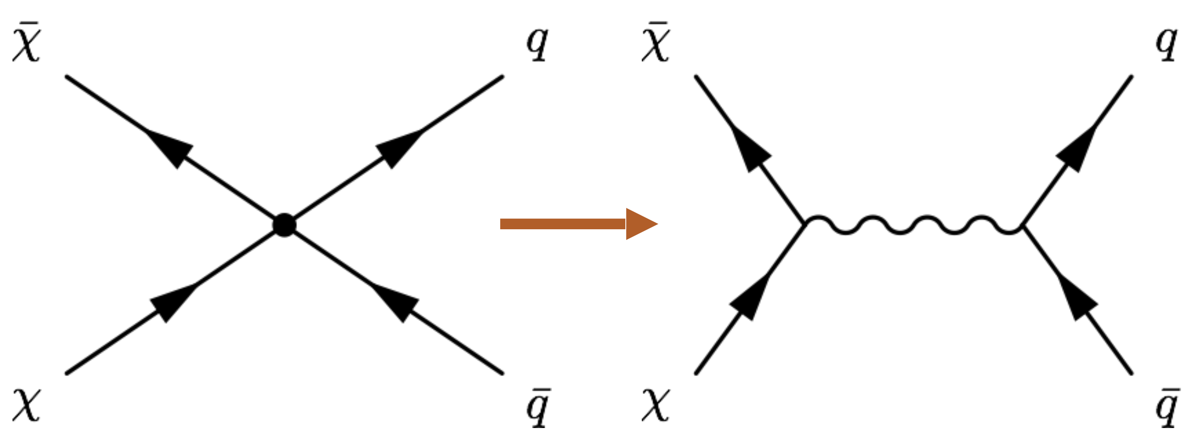


What about the cross section?

$$\sigma_{DM-\nu} \propto E_\nu^2 \xrightarrow[??]{} \left(\frac{\mathrm{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

No!

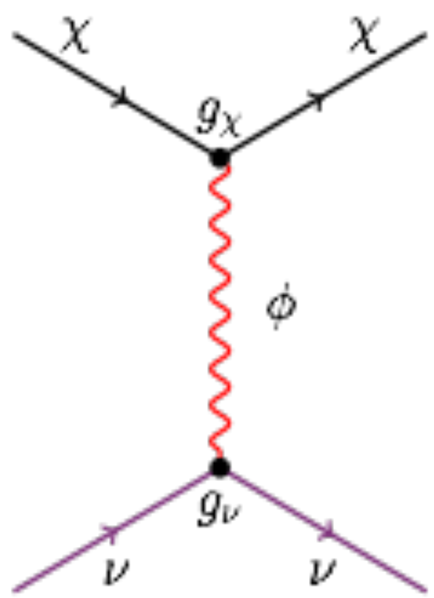
$$E \to \Lambda_{New\,physics}$$



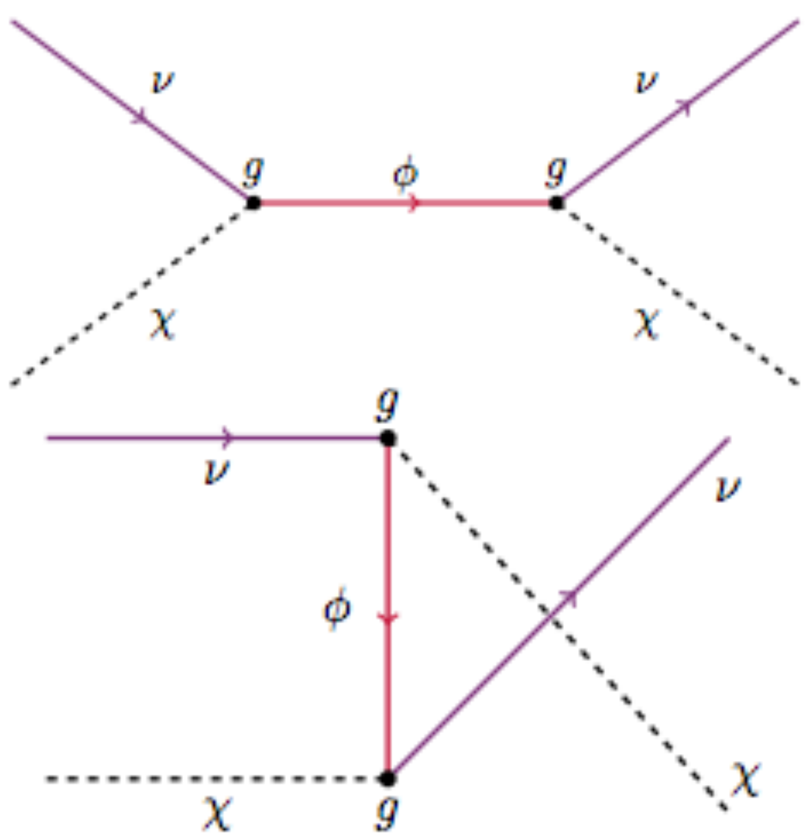
The low energy approximation does not work at a PeV!!

Begin to resolve microphysics: **need more concrete model**

Two Simplified Models

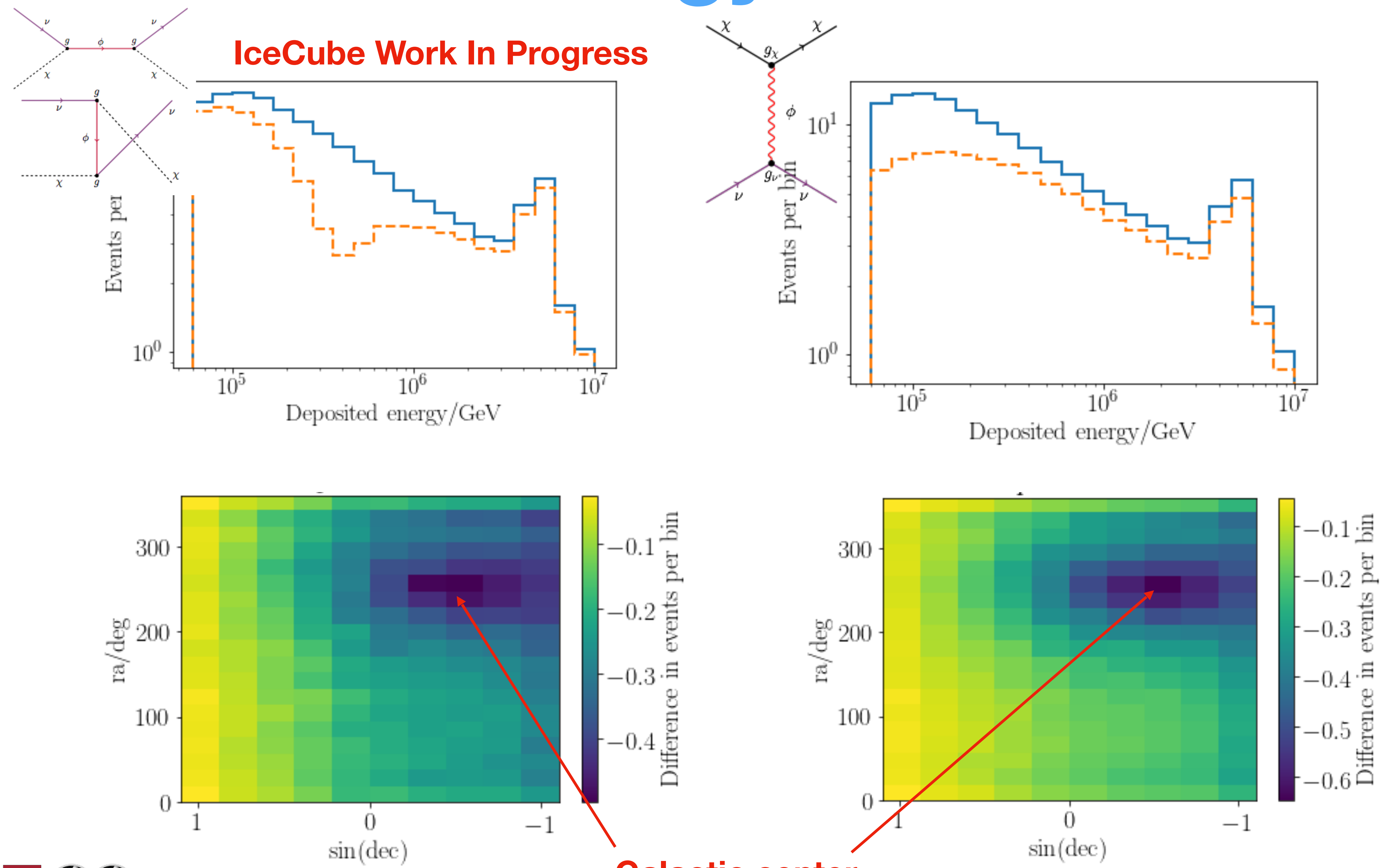


Fermion DM, **vector mediator**:
similar to a leptophillic Z' model



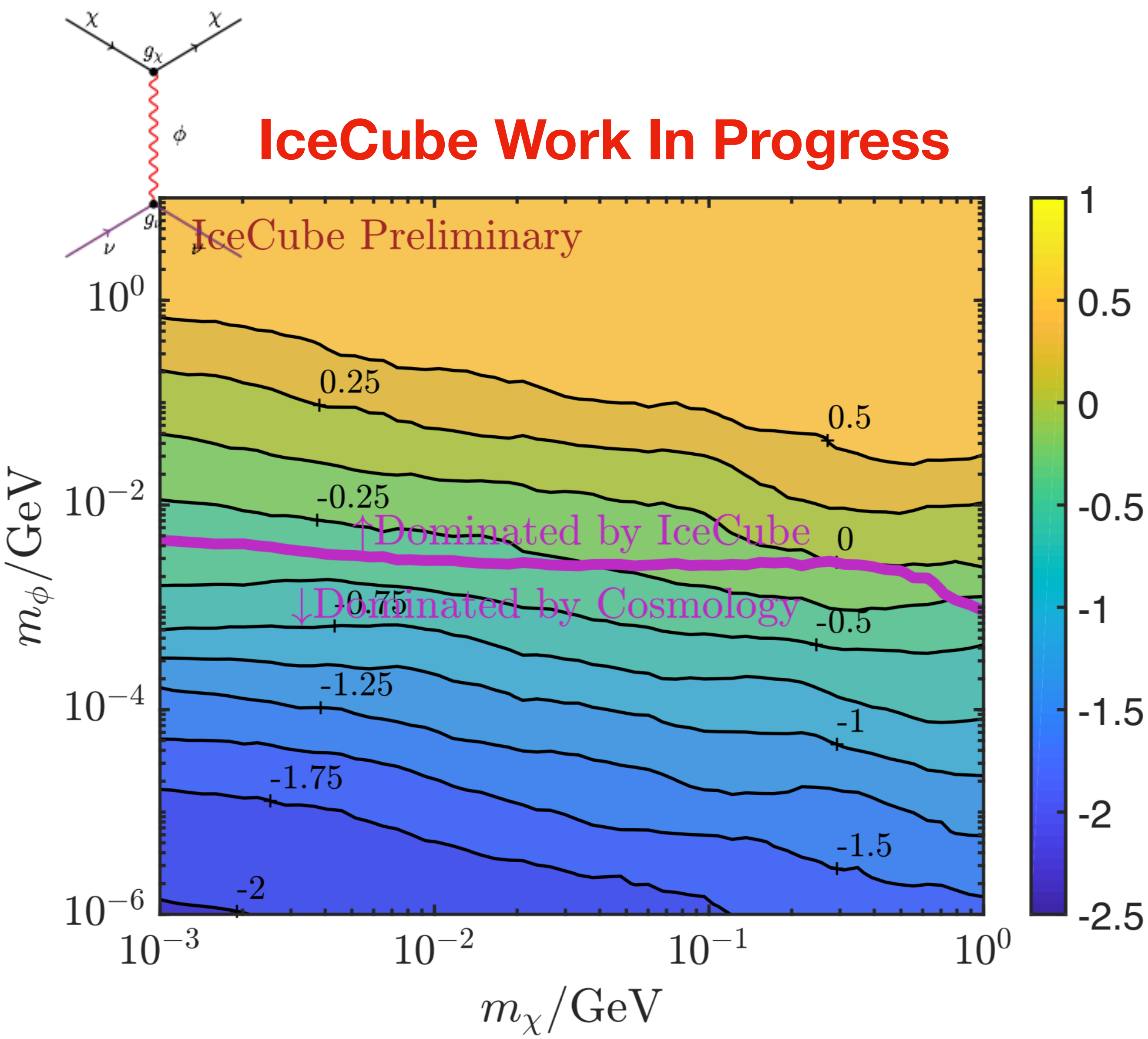
Scalar DM, **fermionic mediator**:
e.g. sneutrino dark matter,
neutralino mediator.
Resonant behavior (s-channel)

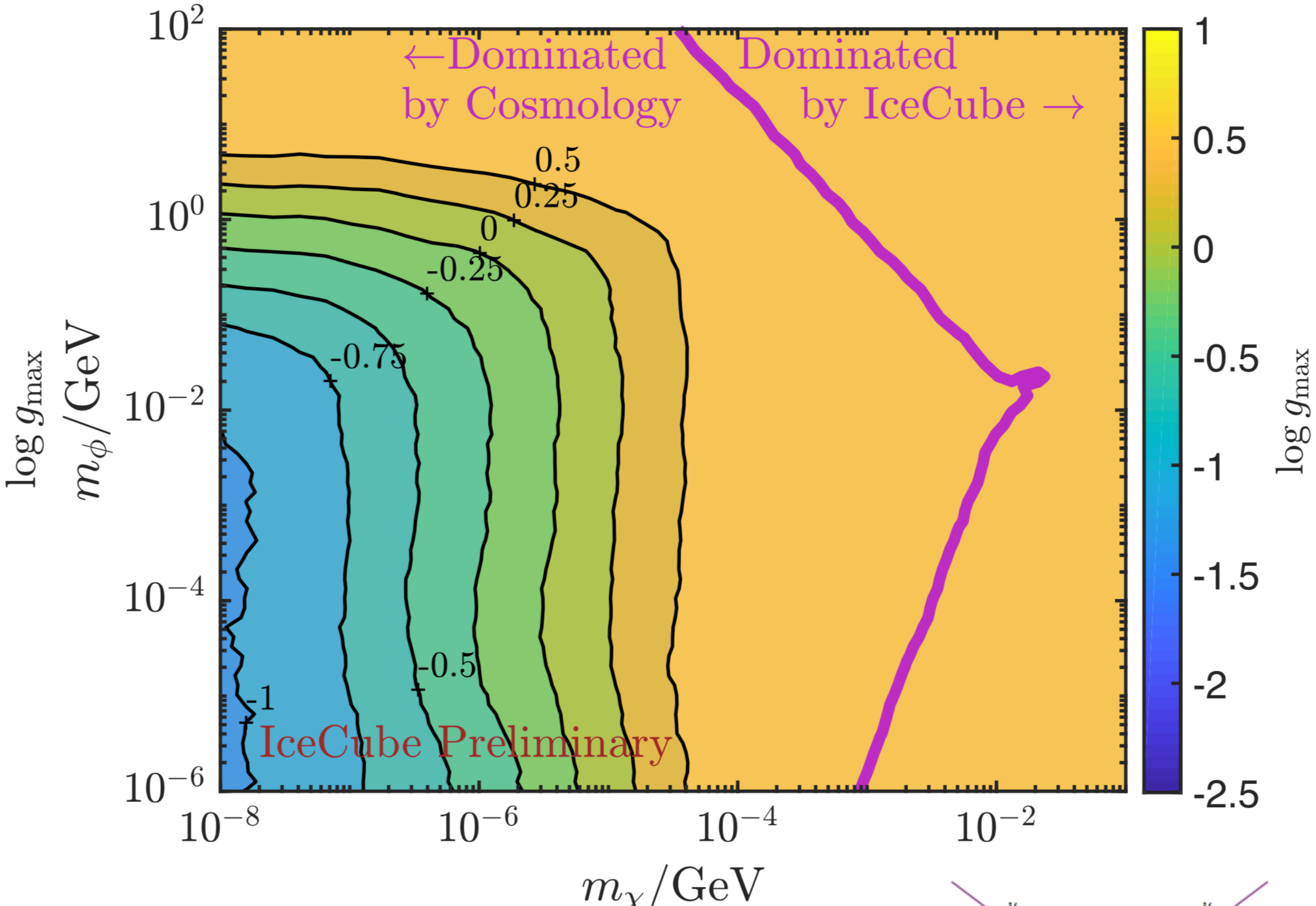
Effects in energy and direction

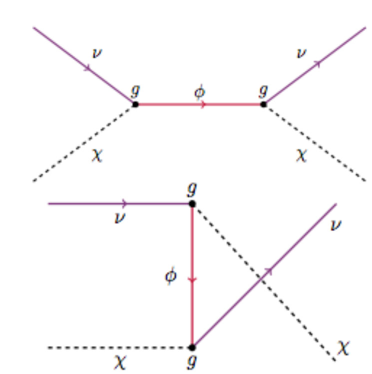


New constraints on neutrino-dark matter interactions

IceCube Work In Progress







Color scale is the maximum allowed coupling.

Cosmological bounds using Large Scale Structure from Escudero et al 2016

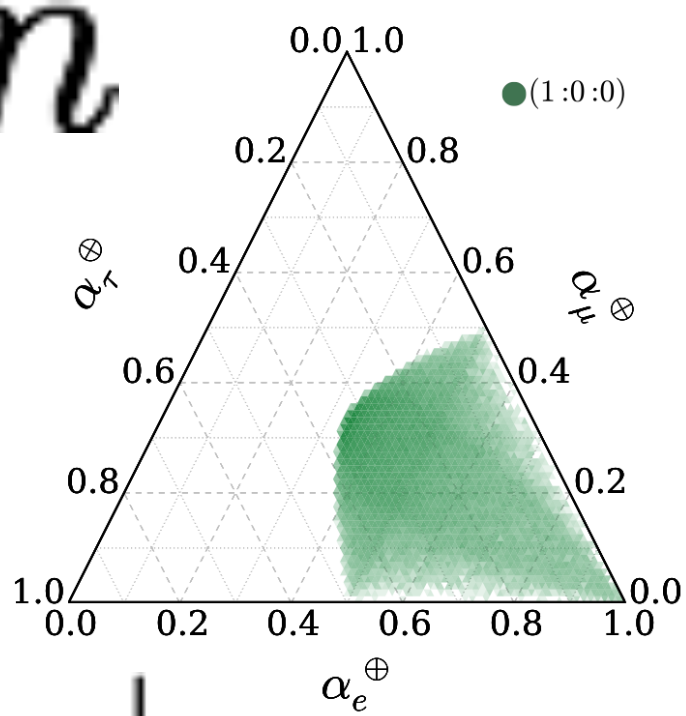
El fin

Thank
you!

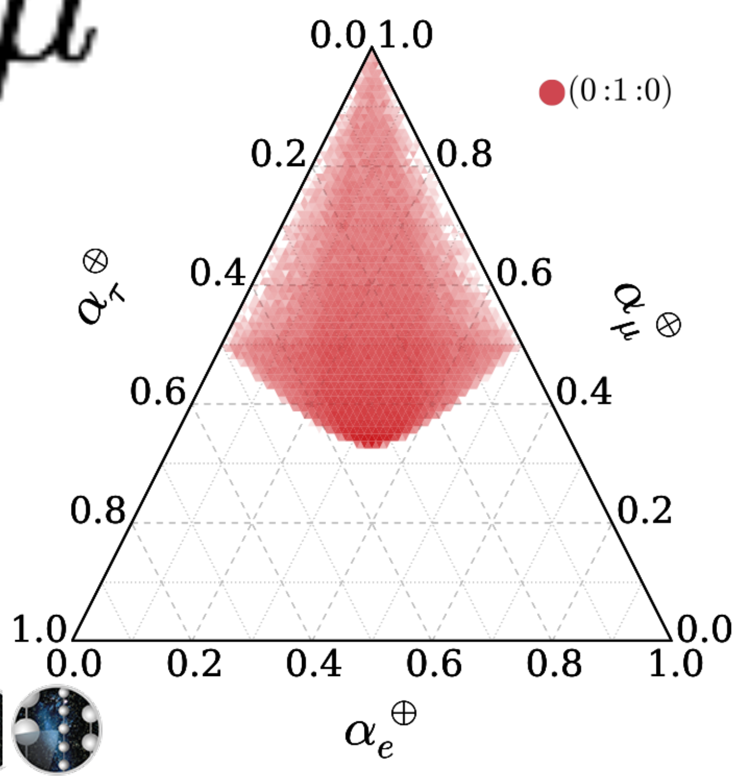
Bonus slides

Predicted flavor triangles given some initial flavor composition

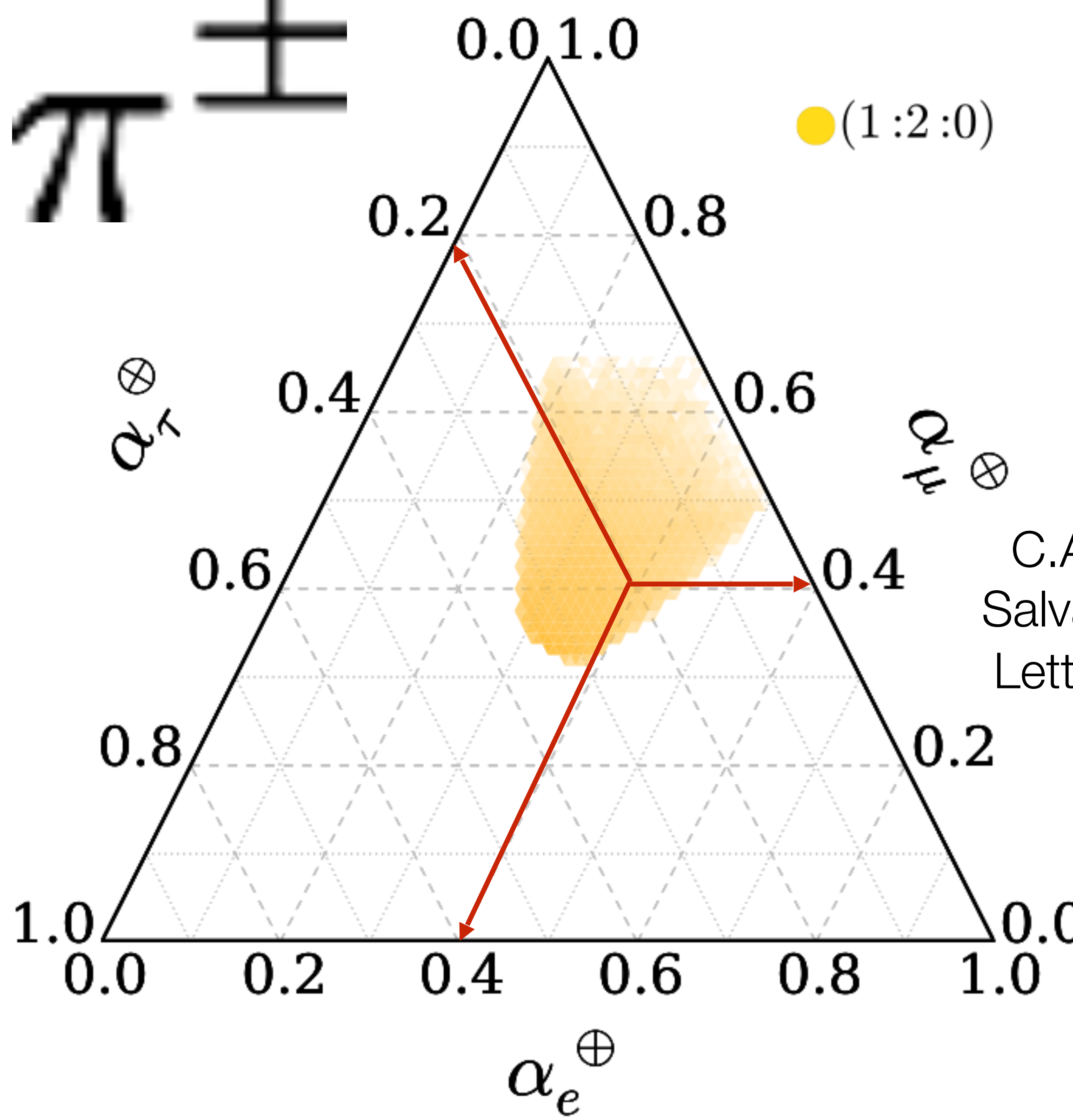
n



$\mu^{\pm}$



$\pi^{\pm}$



C.A., T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

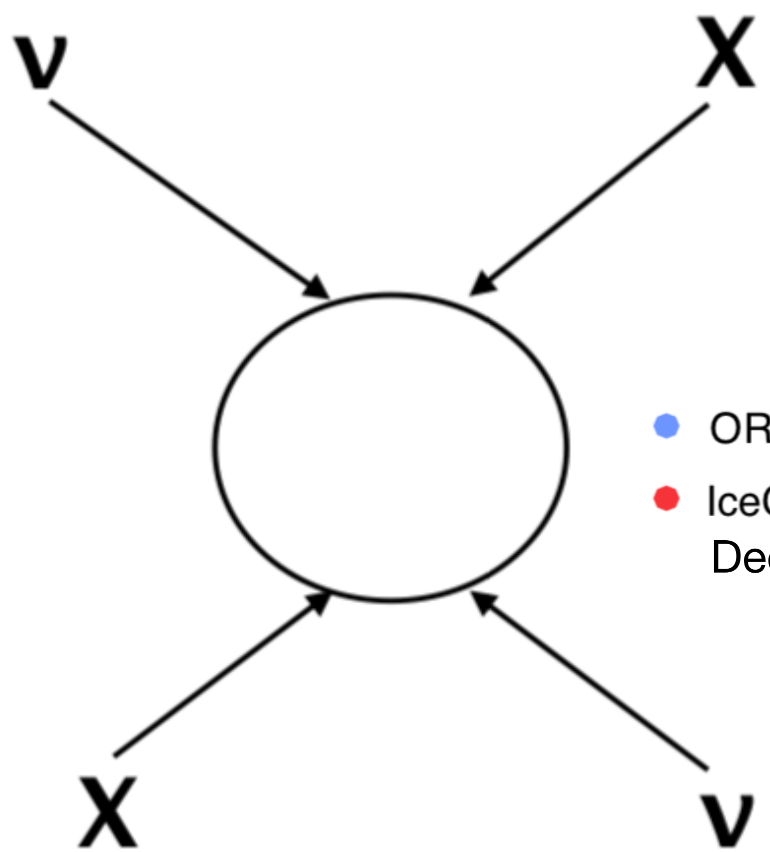
Due to unitarity, the possible Earth flavor ratios for a given initial flavor composition is confined.

Beyond the Lorentz Violation interpretation

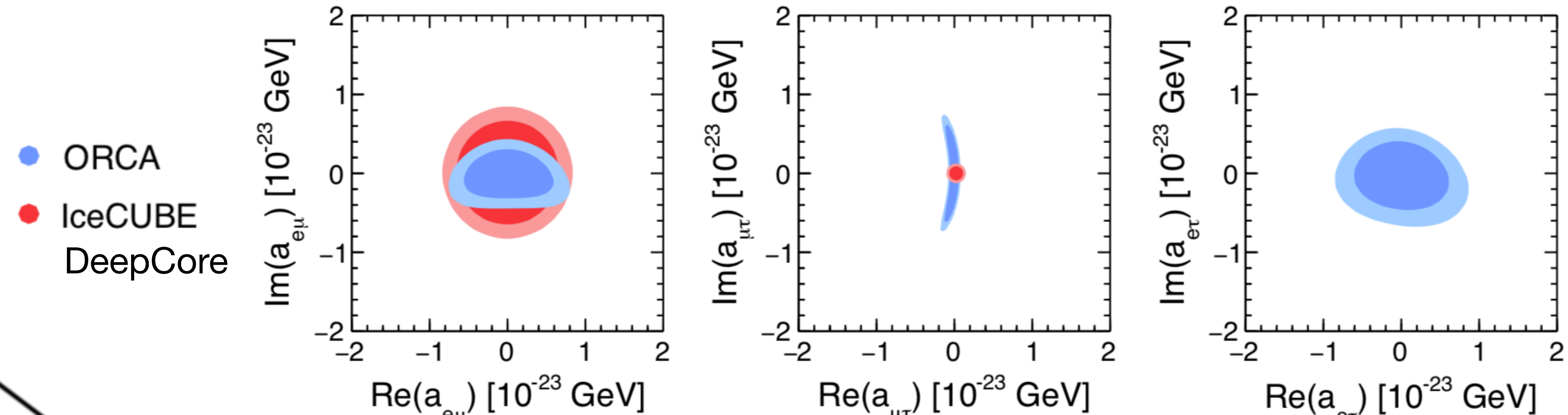
Induced by DM int.
Looks the same as the LV term

Coherent dark matter scattering with local DM

$$H_{\rm eff} = \begin{pmatrix} U\frac{mm^*}{2E}U^\dagger & 0 \\ 0 & U^*\frac{m^*m}{2E}U^T \end{pmatrix} + \begin{pmatrix} a(\hat{\mathbf{p}}) & b(\hat{\mathbf{p}}) \\ b^\dagger(\hat{\mathbf{p}}) & -a^*(\hat{\mathbf{p}}) \end{pmatrix}$$

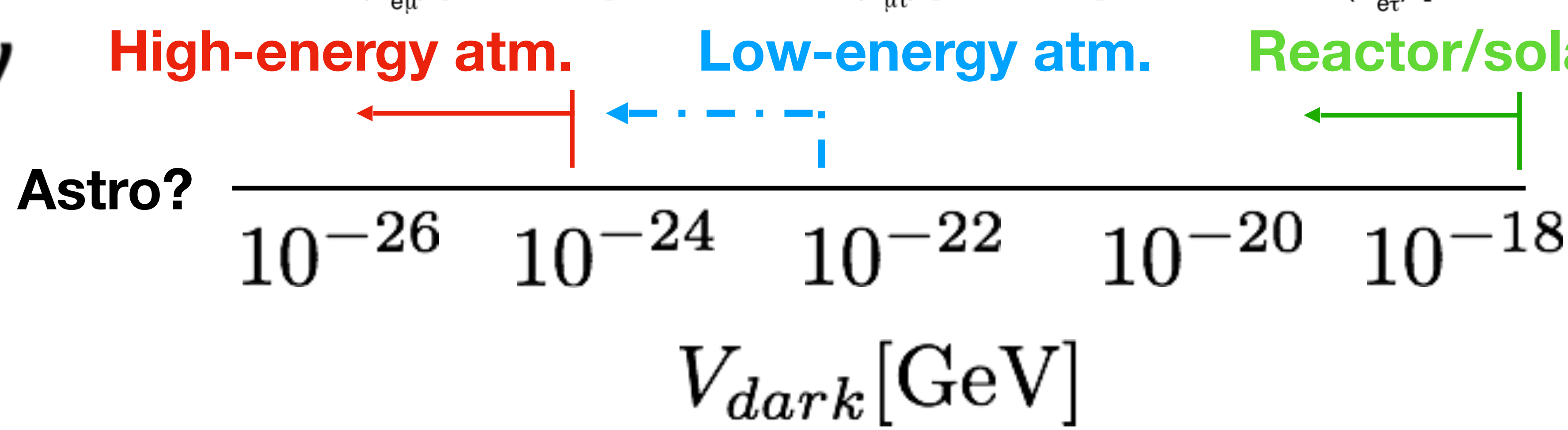


Projections to this kind of physics with 10 years of IceCube/ DeepCore.



$V_D \sim G_D N_D$

$G_D \sim g_D^2/m_D^2$

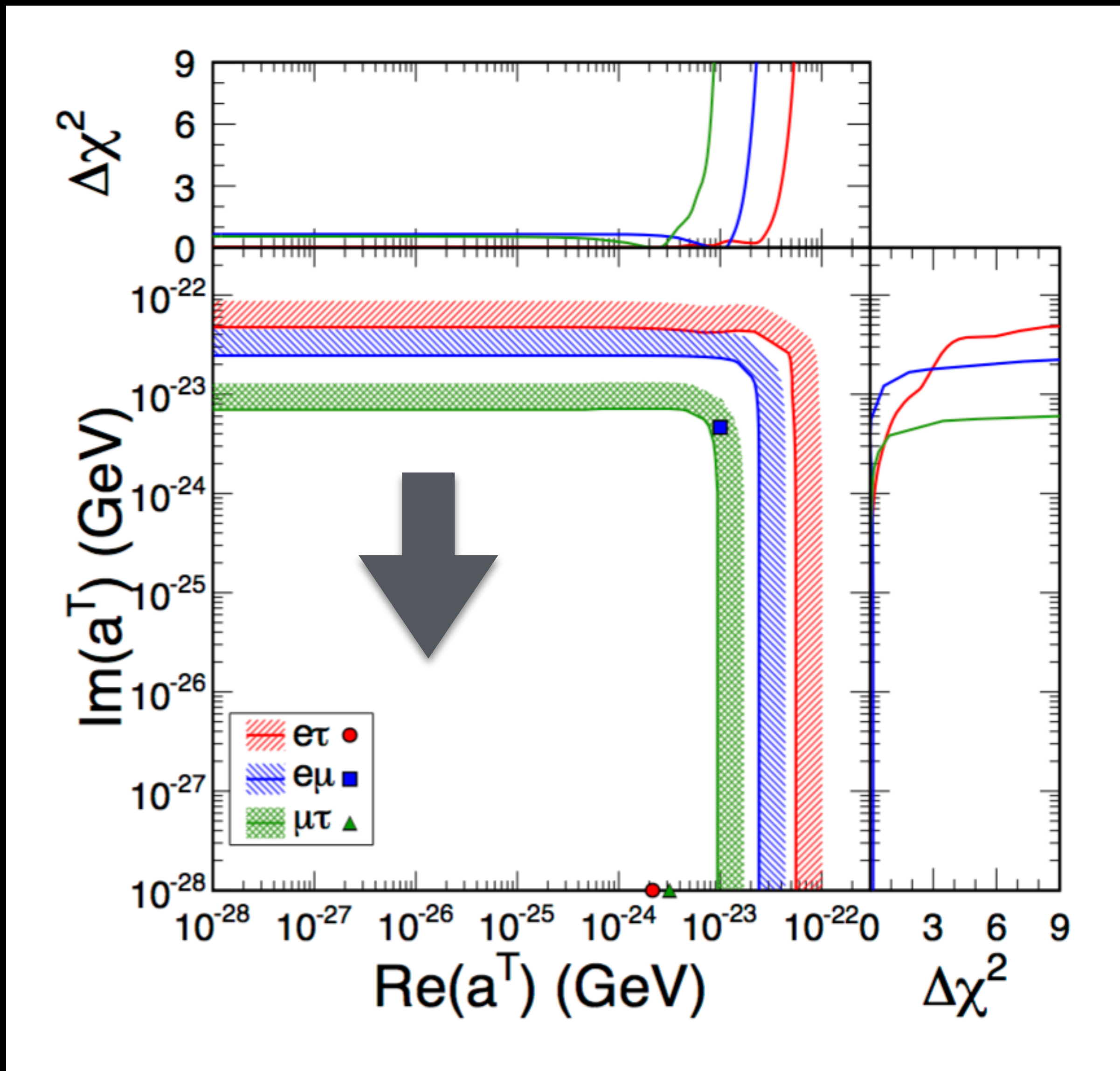


Reinterpret our LV limits in dark matter neutrino coherent scattering

Capozzi et al. 1804.05117

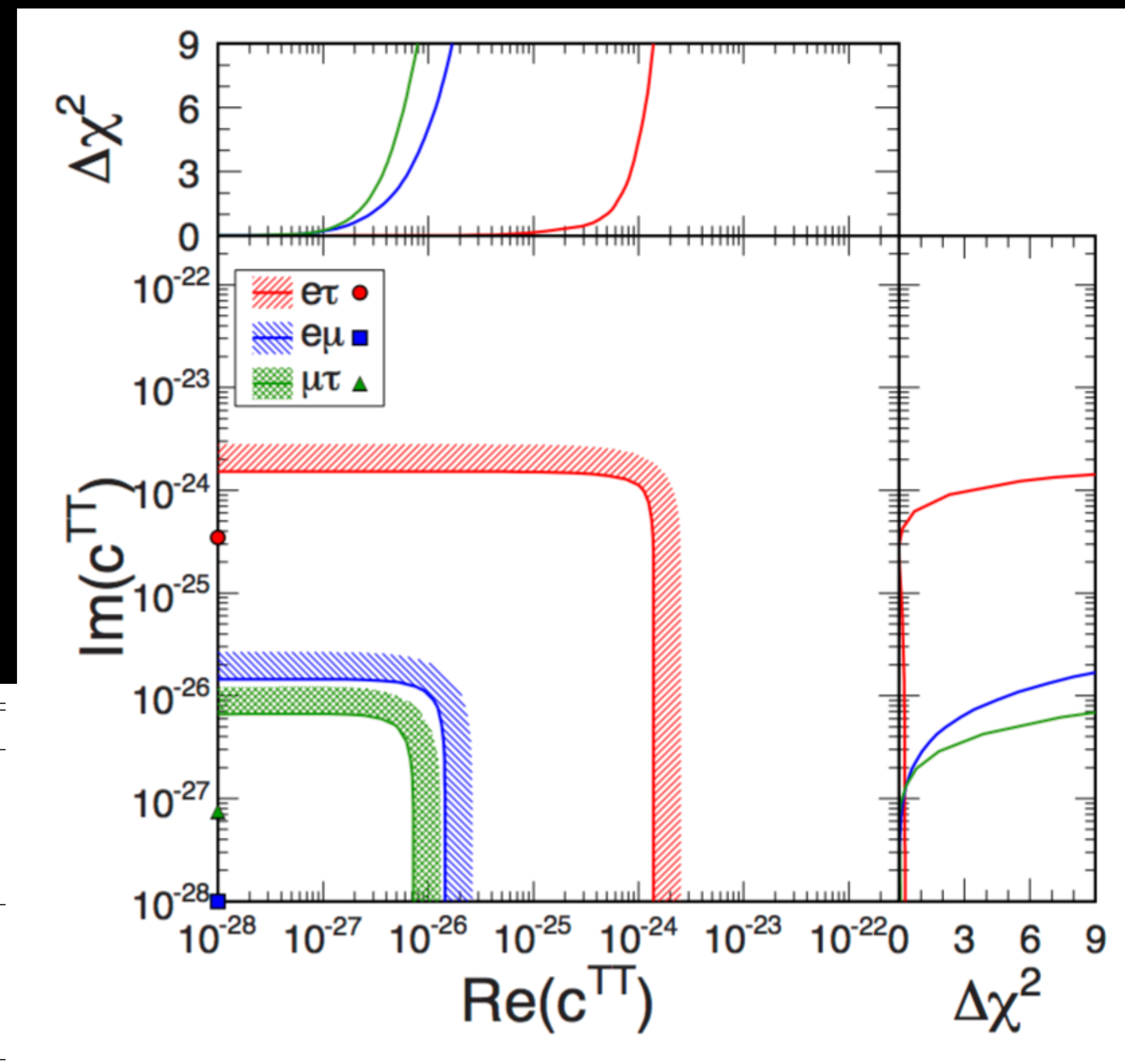
I'll come back to the astrophysical constraints soon…

Current bounds from SK

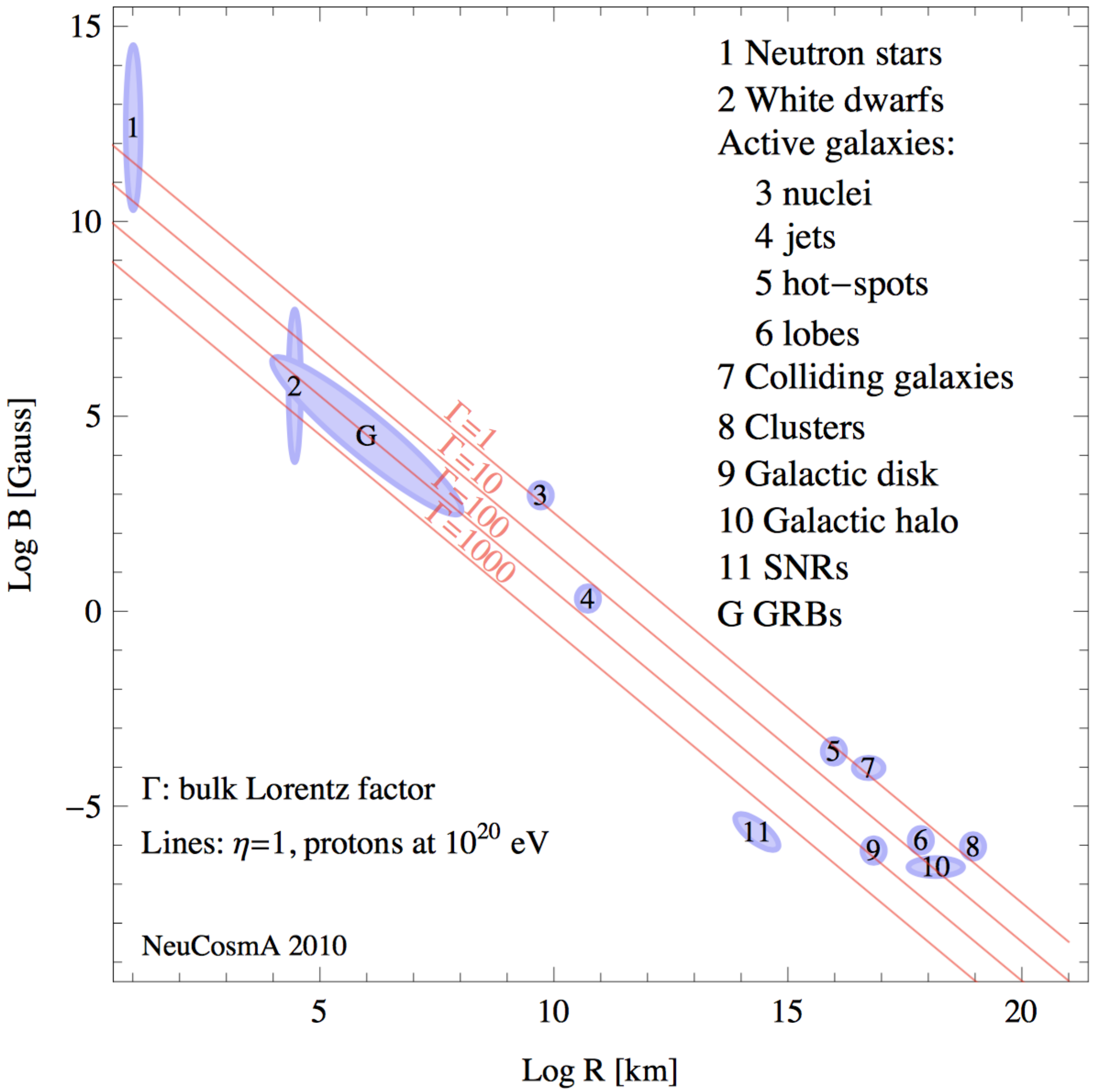


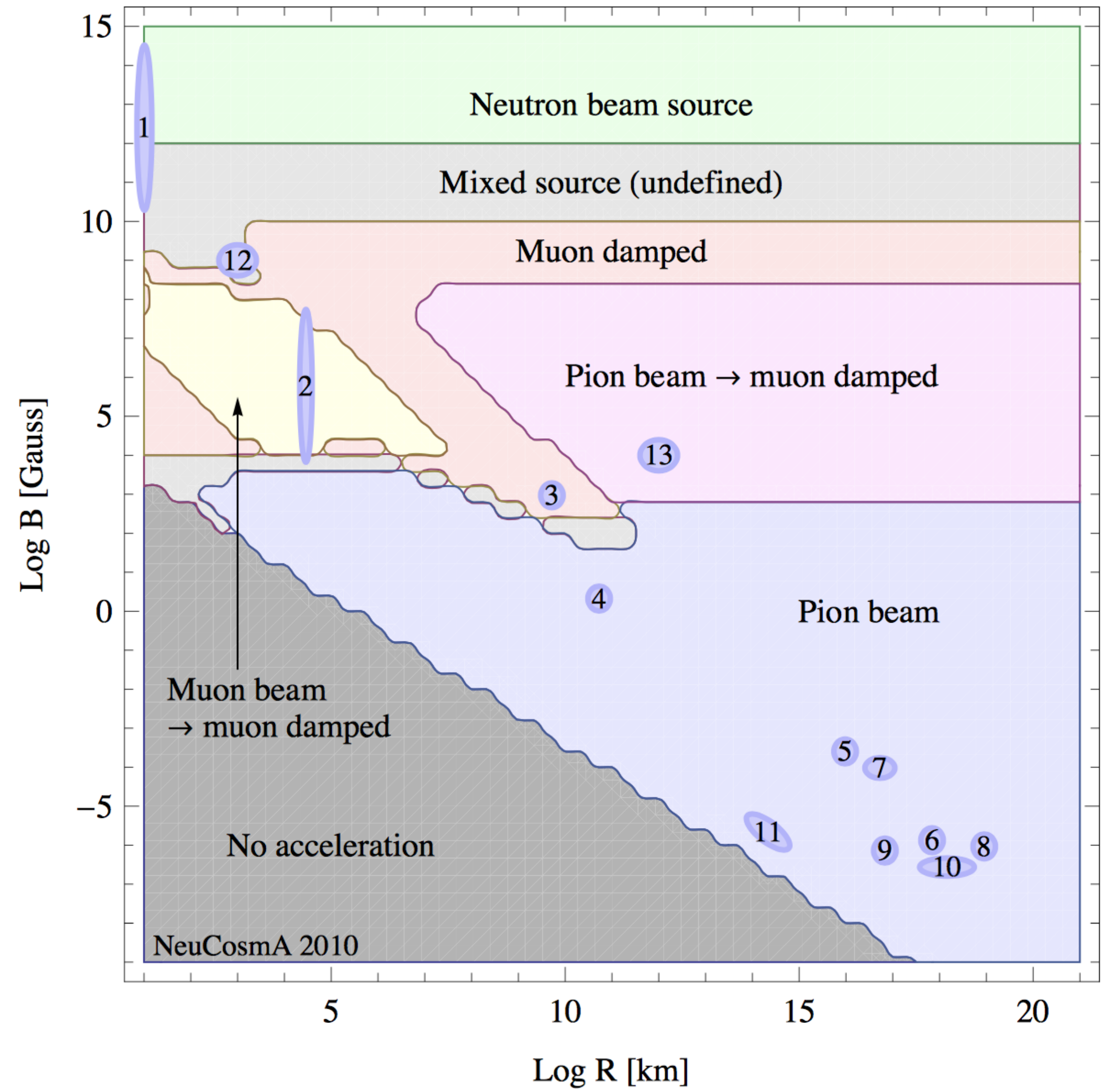
$$\begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ \left(a^T_{e\mu}\right)^* & 0 & a^T_{\mu\tau} \\ \left(a^T_{e\tau}\right)^* & \left(a^T_{\mu\tau}\right)^* & 0 \end{pmatrix}$$

$$\begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ \left(c^{TT}_{e\mu}\right)^* & 0 & c^{TT}_{\mu\tau} \\ \left(c^{TT}_{e\tau}\right)^* & \left(c^{TT}_{\mu\tau}\right)^* & 0 \end{pmatrix}$$



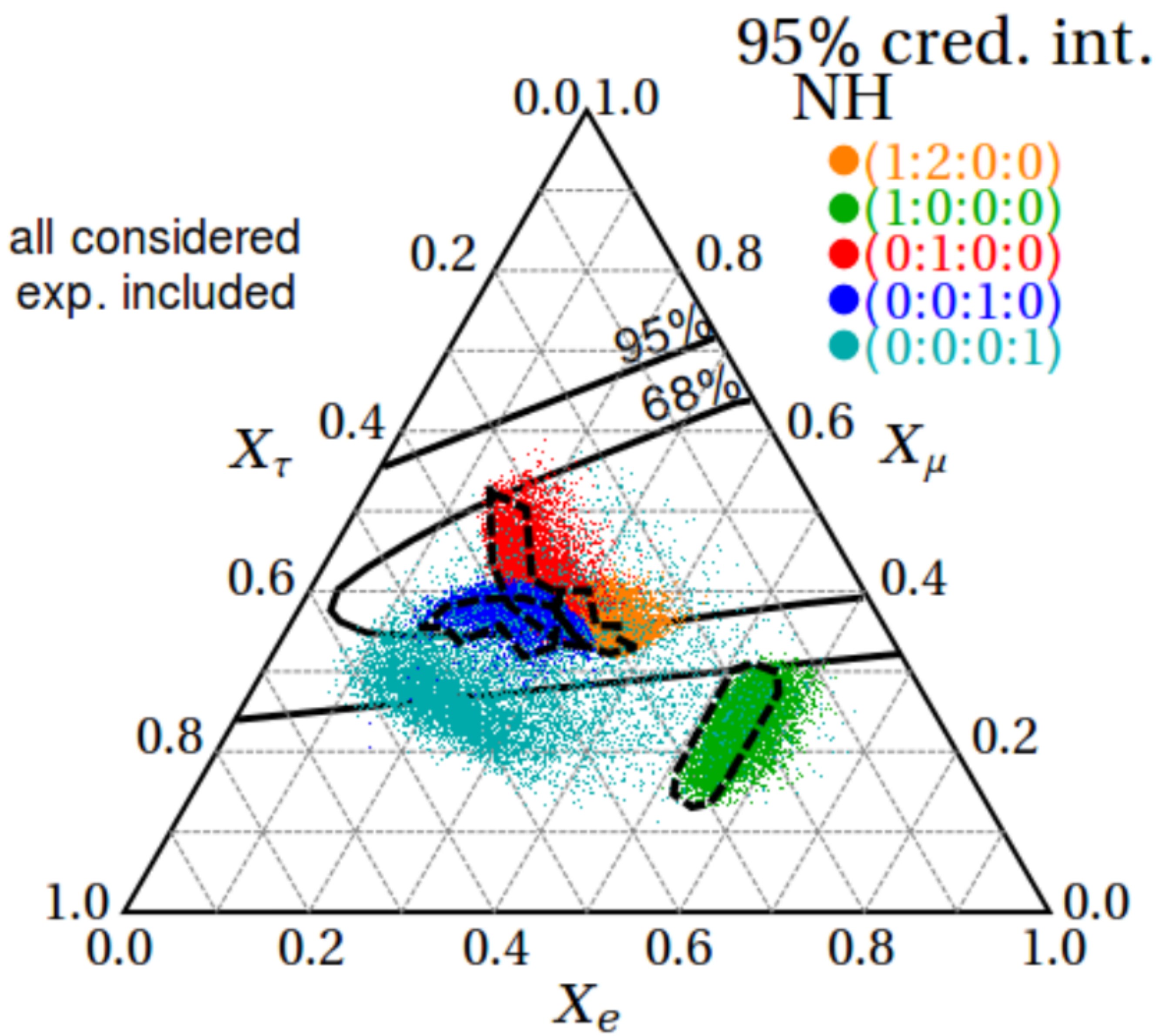
LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit	
$e\mu$	$\mathrm{Re}\left(a^T\right)$	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV	[58]
	$\mathrm{Im}\left(a^T\right)$	1.8×10^{-23} GeV	4.6×10^{-24} GeV			
	$\mathrm{Re}\left(c^{TT}\right)$	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20}	[58]
	$\mathrm{Im}\left(c^{TT}\right)$	8.0×10^{-27}	1.0×10^{-28}			
$e\tau$	$\mathrm{Re}\left(a^T\right)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV	[59]
	$\mathrm{Im}\left(a^T\right)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV			
	$\mathrm{Re}\left(c^{TT}\right)$	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17}	[59]
	$\mathrm{Im}\left(c^{TT}\right)$	1.0×10^{-24}	3.5×10^{-25}			
$\mu\tau$	$\mathrm{Re}\left(a^T\right)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	–	
	$\mathrm{Im}\left(a^T\right)$	5.1×10^{-24} GeV	1.0×10^{-28} GeV			
	$\mathrm{Re}\left(c^{TT}\right)$	4.4×10^{-27}	1.0×10^{-28}	0.1	–	
	$\mathrm{Im}\left(c^{TT}\right)$	4.2×10^{-27}	7.5×10^{-28}			





(arXiv:1007:0006)

+ (eV) sterile neutrino



- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

Brdar et al. JCAP 1701 (2017) no.01, 026