Extragalactic and MM physics at VHE

NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN
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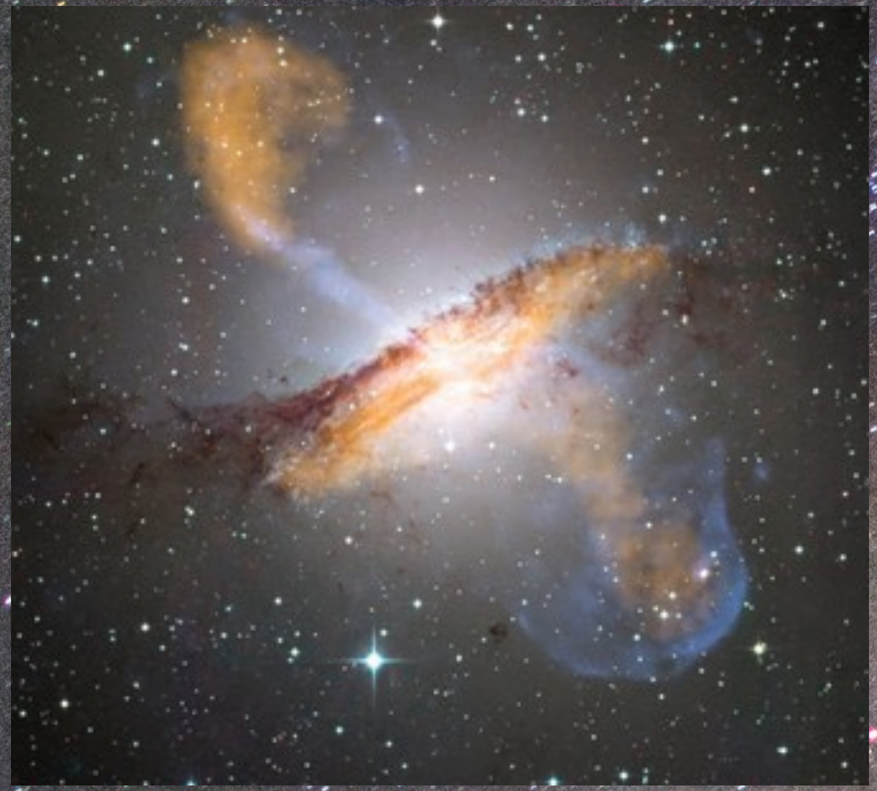
Instituto de Astrofísica de Canarias

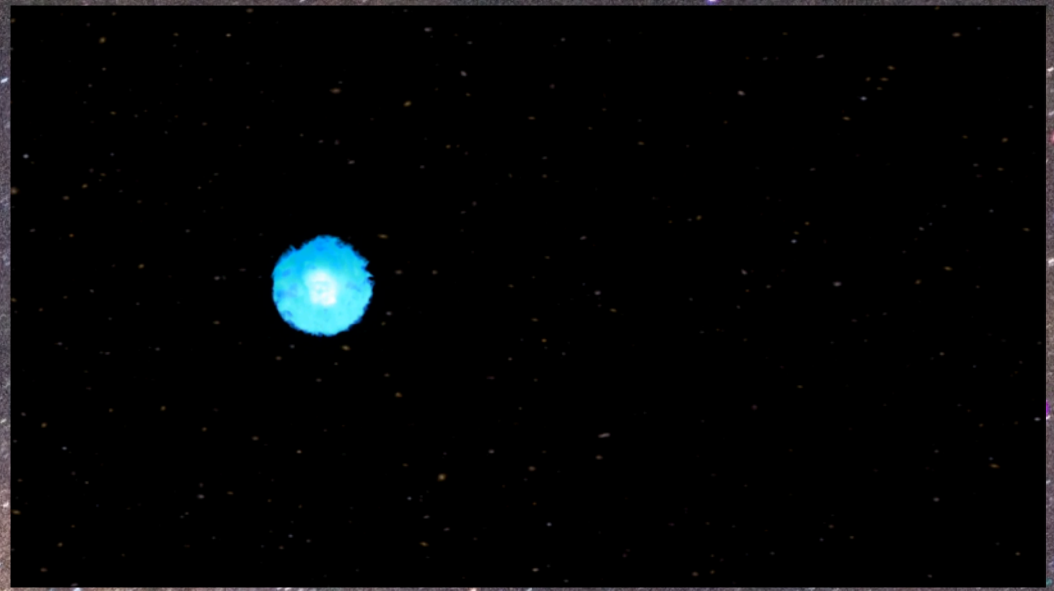
São Paulo Advanced School on Multi-Messenger Astrophysics 2023

Extragalactic and fundamental physics

AGNs



GRBs

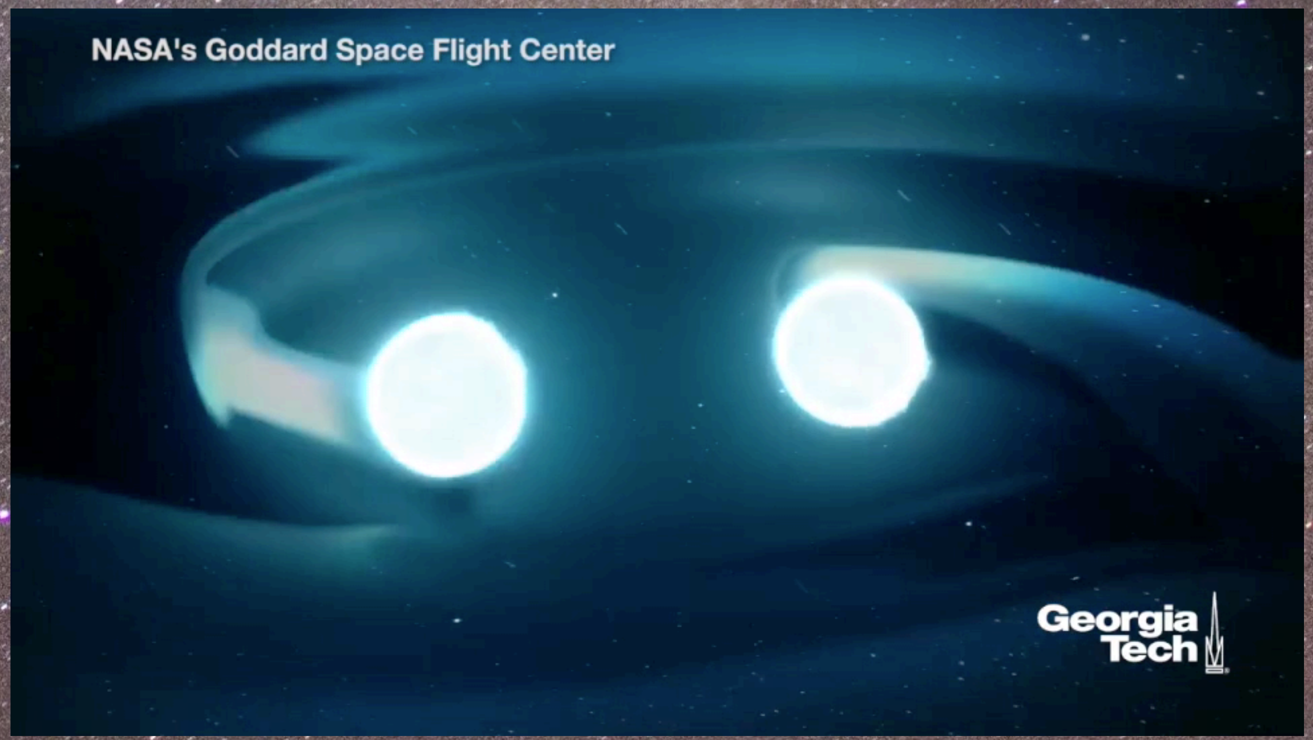


Fundamental Physics

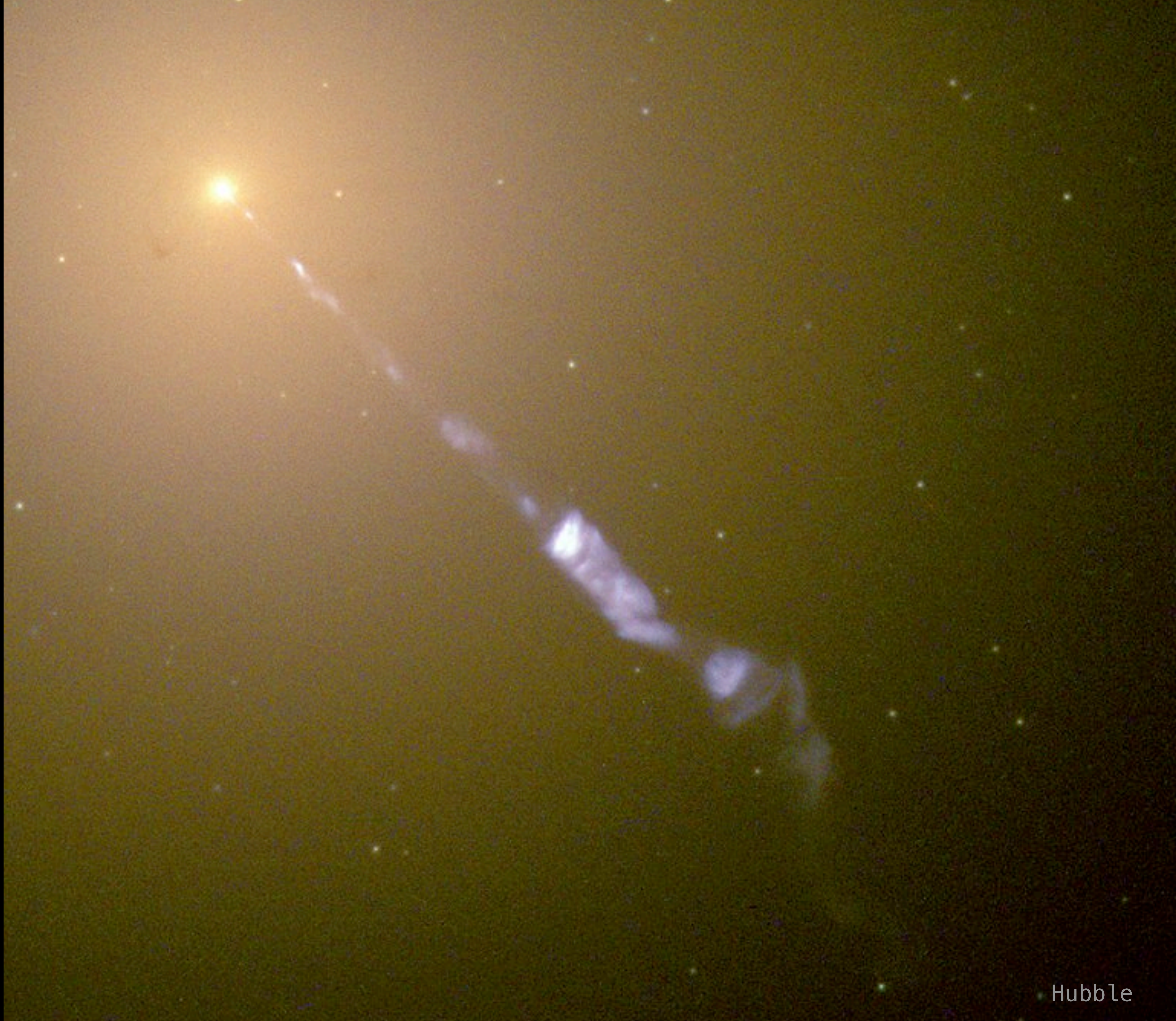
Dark Matter
Lorentz Invariance

Neutrino search

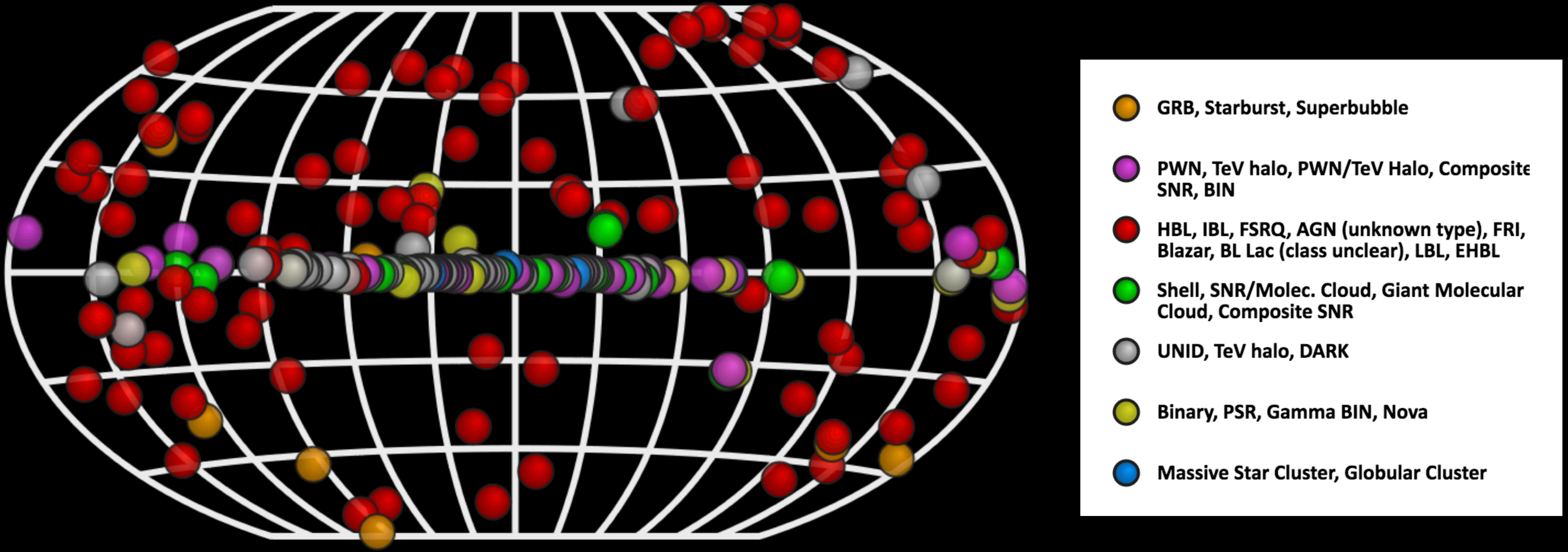
GW counterparts



Active
Galactic
Nuclei


Hubble

VHE Galactic Sources

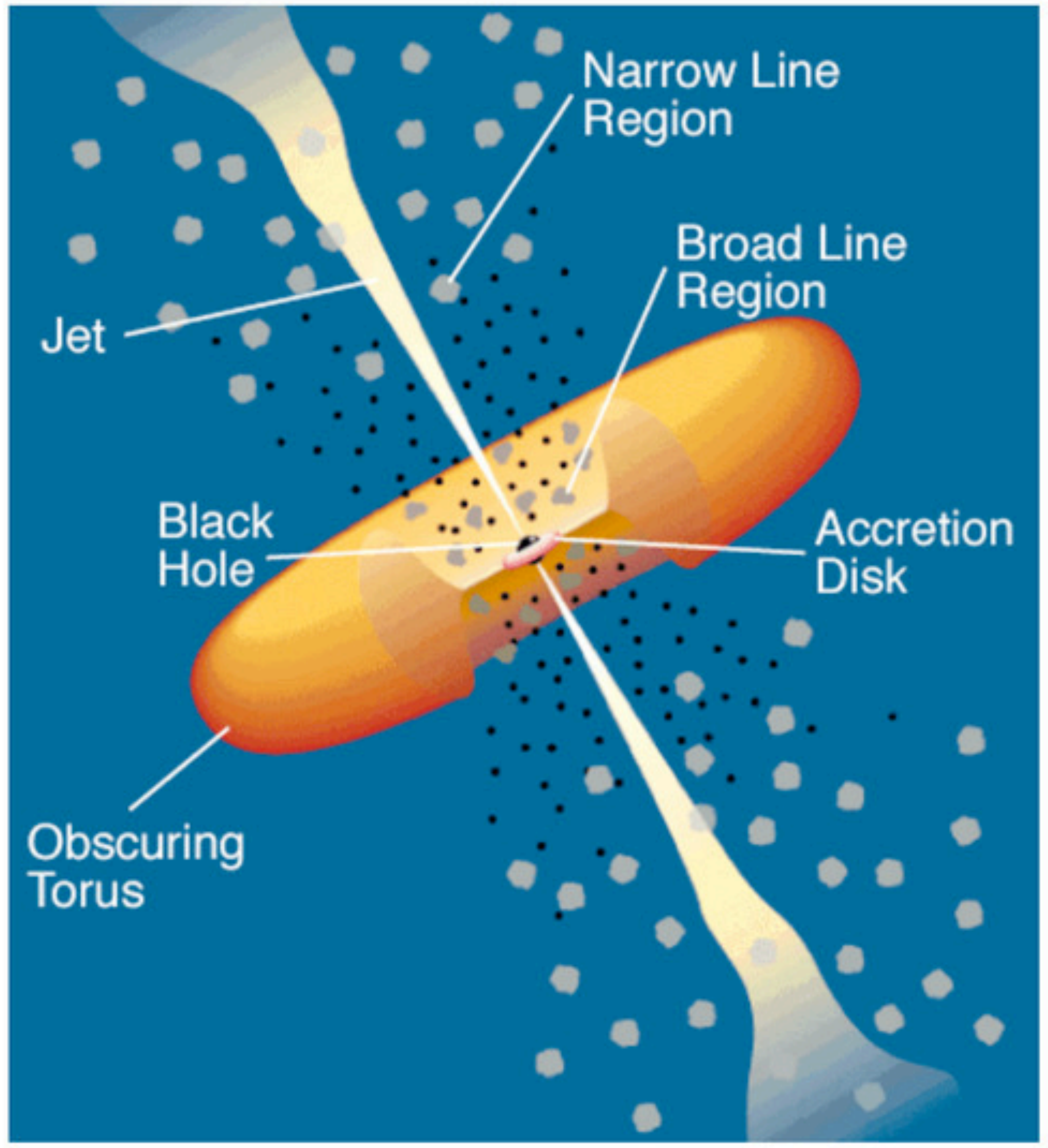


- **252* sources of VHE gamma rays** (http://tevcat2.uchicago.edu/)
  - Blazars are the largest population: ~81
  - Radio galaxies: 4
  - Starbursts: 2

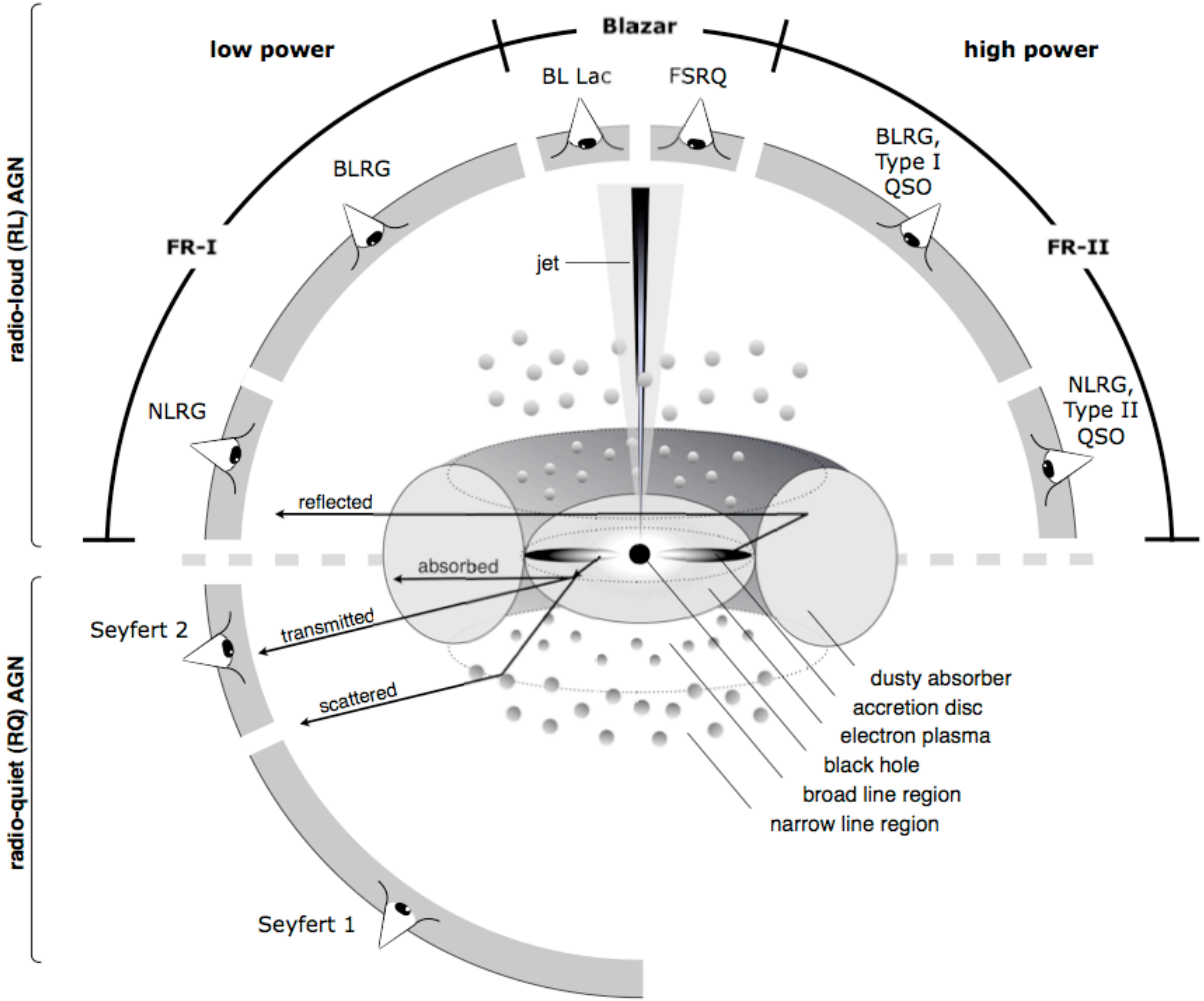
Jetted AGNs

Blazars can be classified as:

- **Flat Spectrum Radio Quasars (FSRQs)**: exhibit lines with an equivalent width of >5 Å
- **BL Lac objects**: fainter lines or even absent

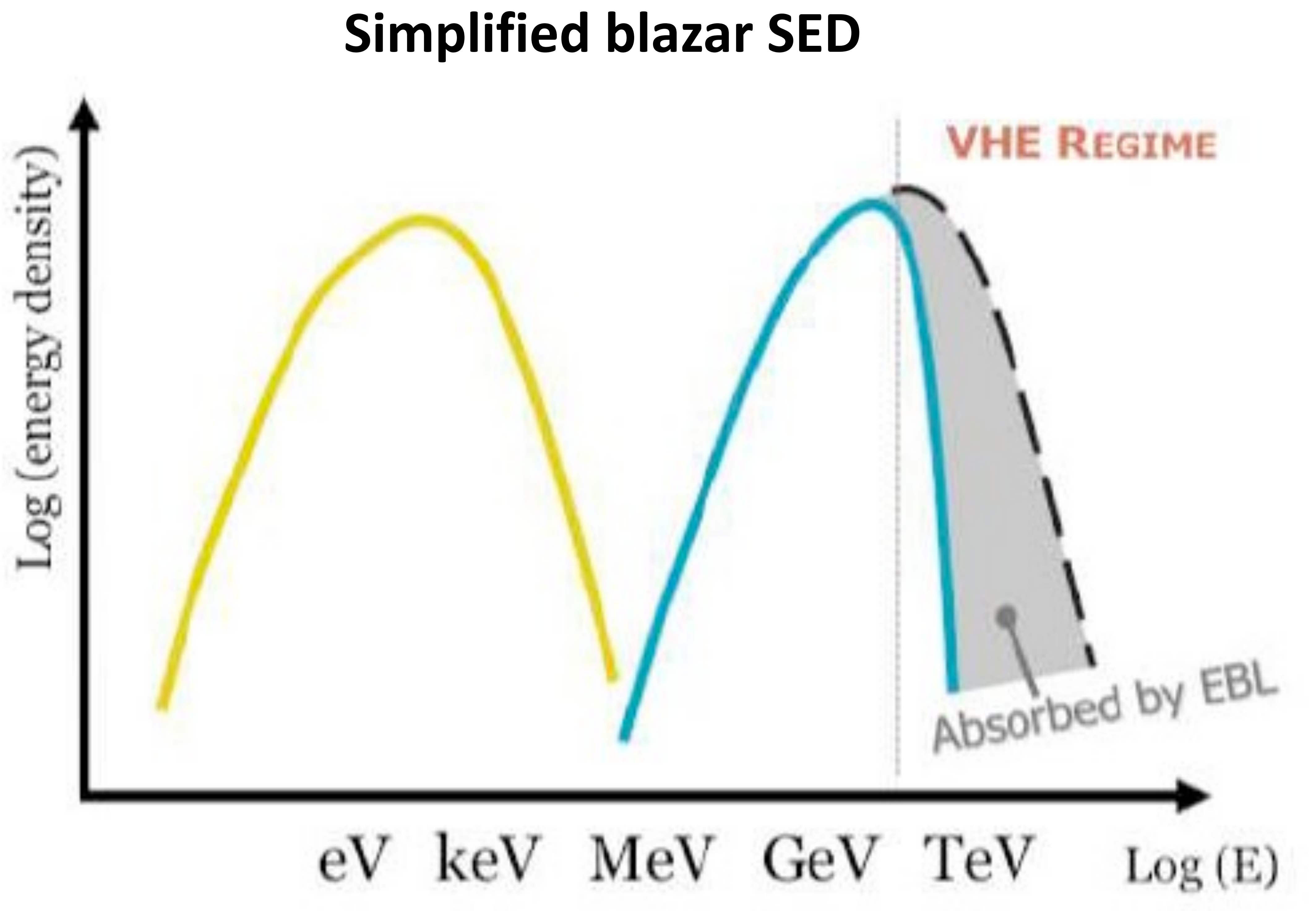


simplified scheme from Urry & Padovani 1995



Sketch of the basic ideas of the unified AGN model. Credit: Beckmann & Shrader (2012).

Blazars

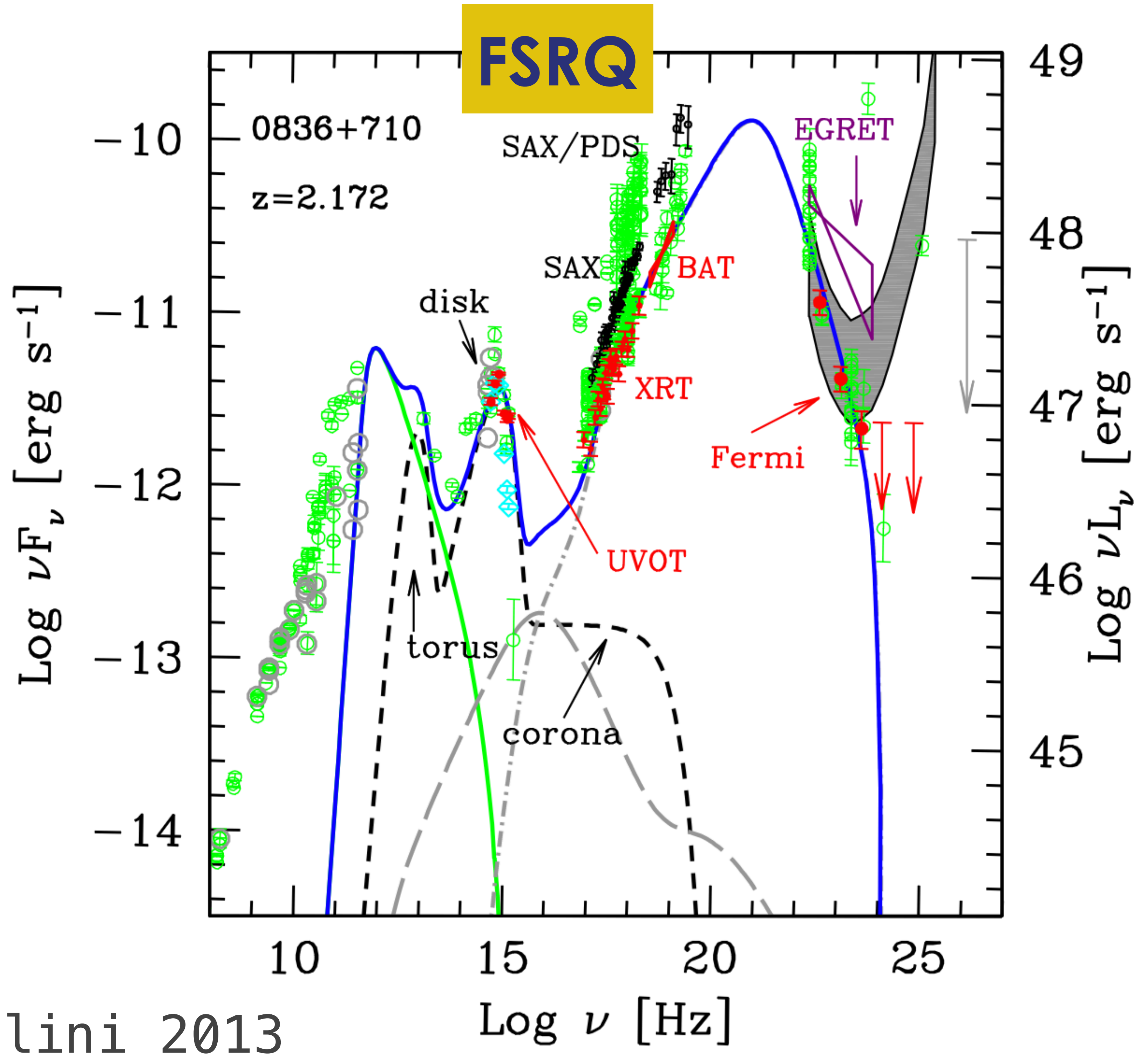


Prandini et al. 2011

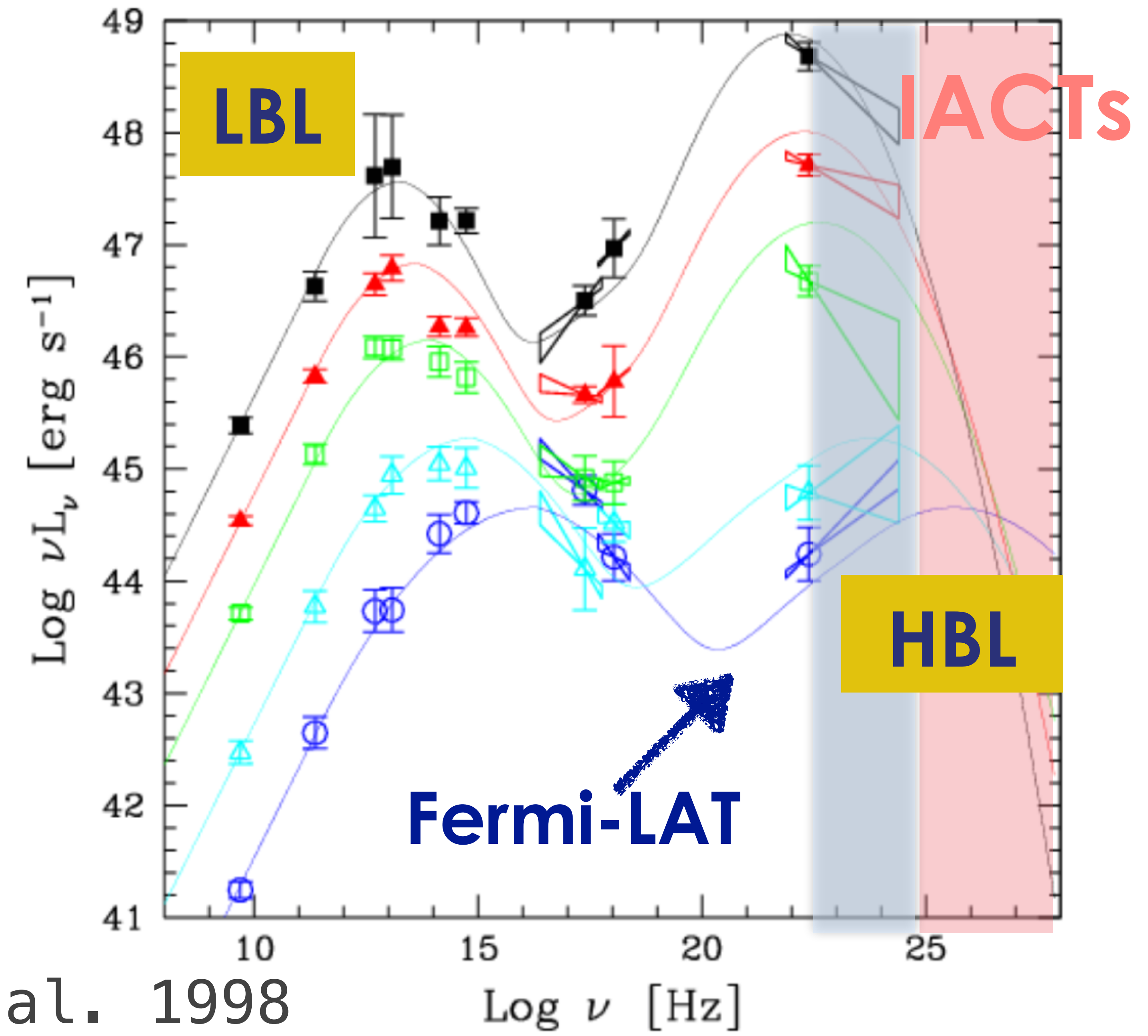
Blazars can be classified as:

- **Flat Spectrum Radio Quasars (FSRQs)**
- **BL Lac objects**

Most popular models to interpret the blazar emission:
- One zone, leptonic
- One zone, hadronic
- Multi zone, either leptonic or hadronic

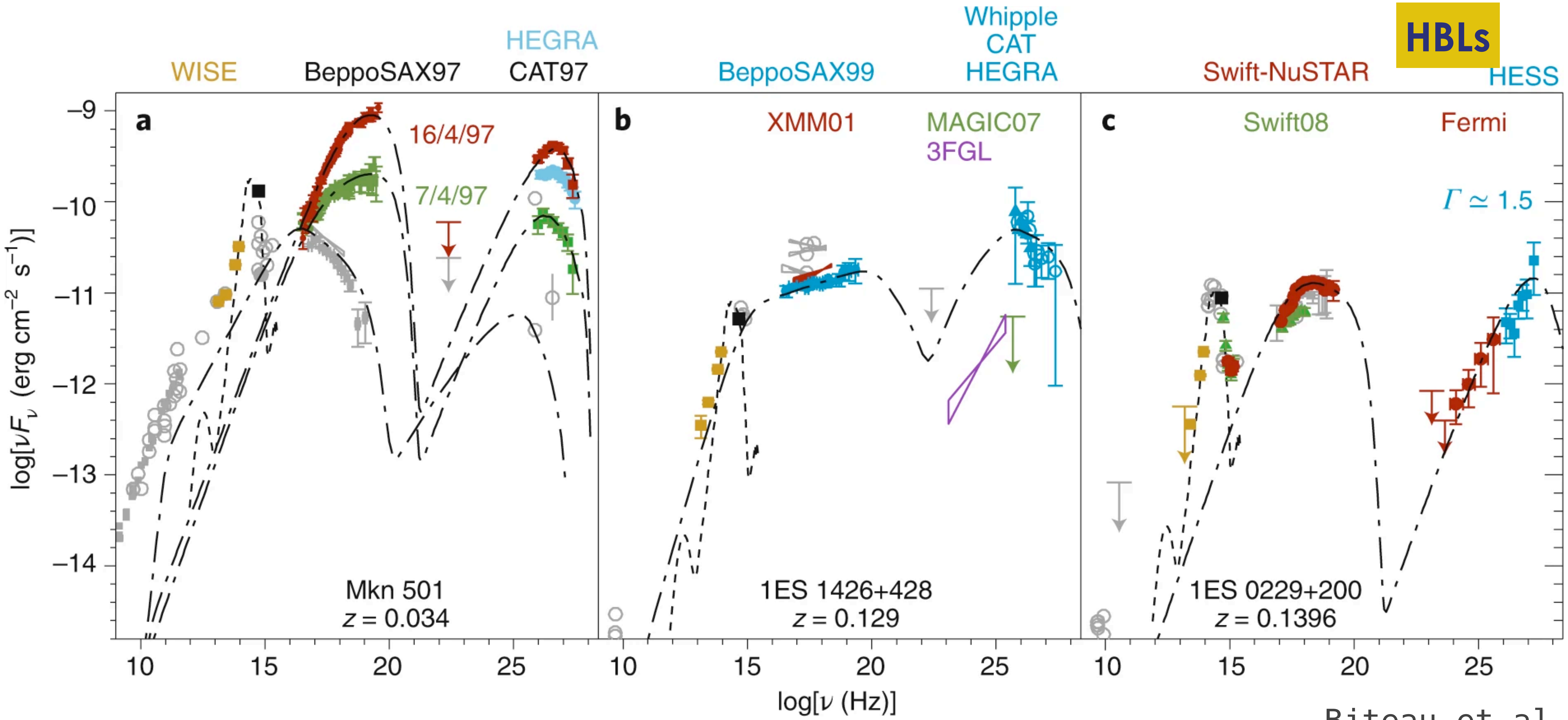


Ghisellini 2013

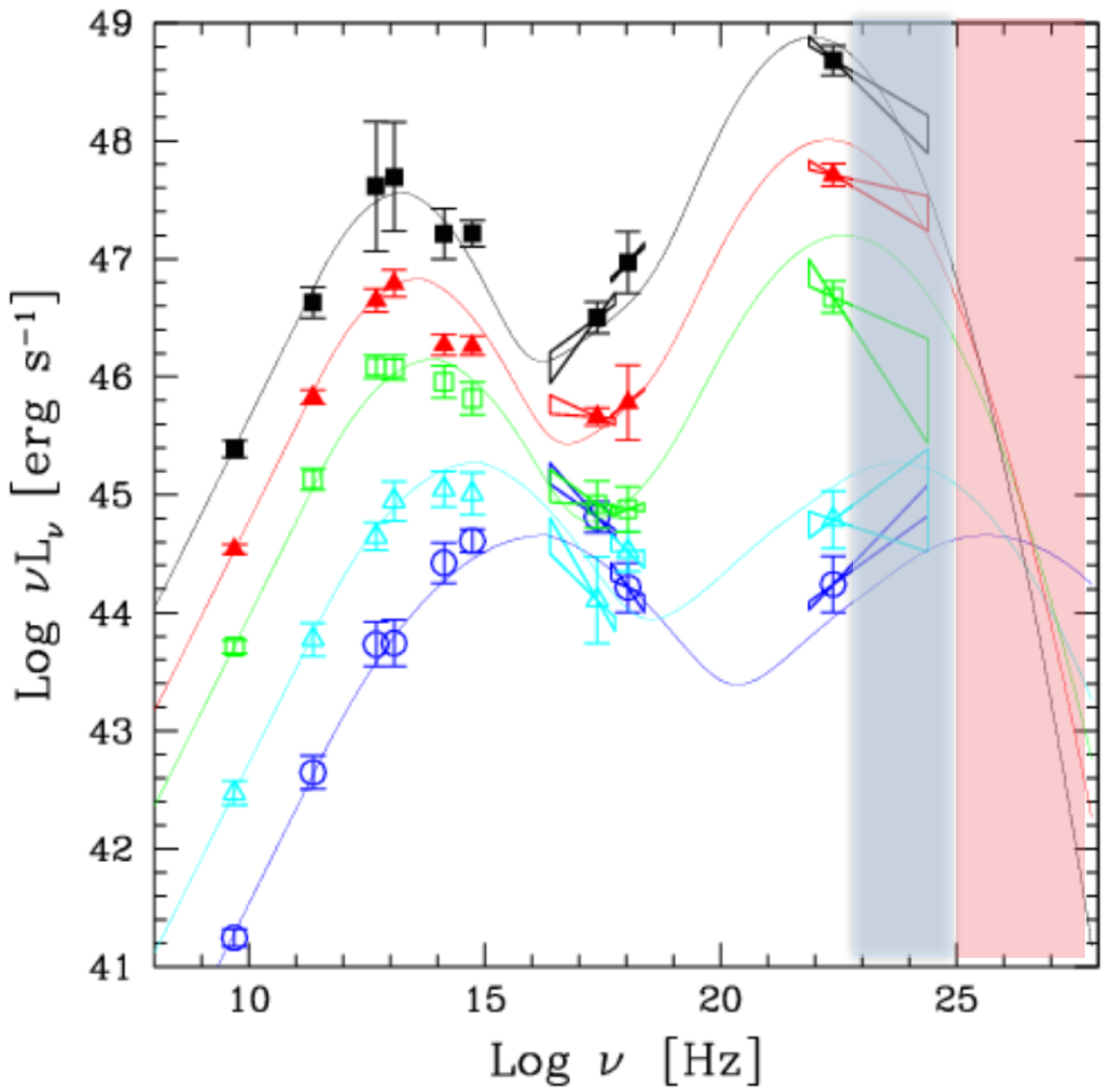


Fossati et al. 1998

Blazars



HBLs



Fossati et al. 1998

Biteau et al. 2020

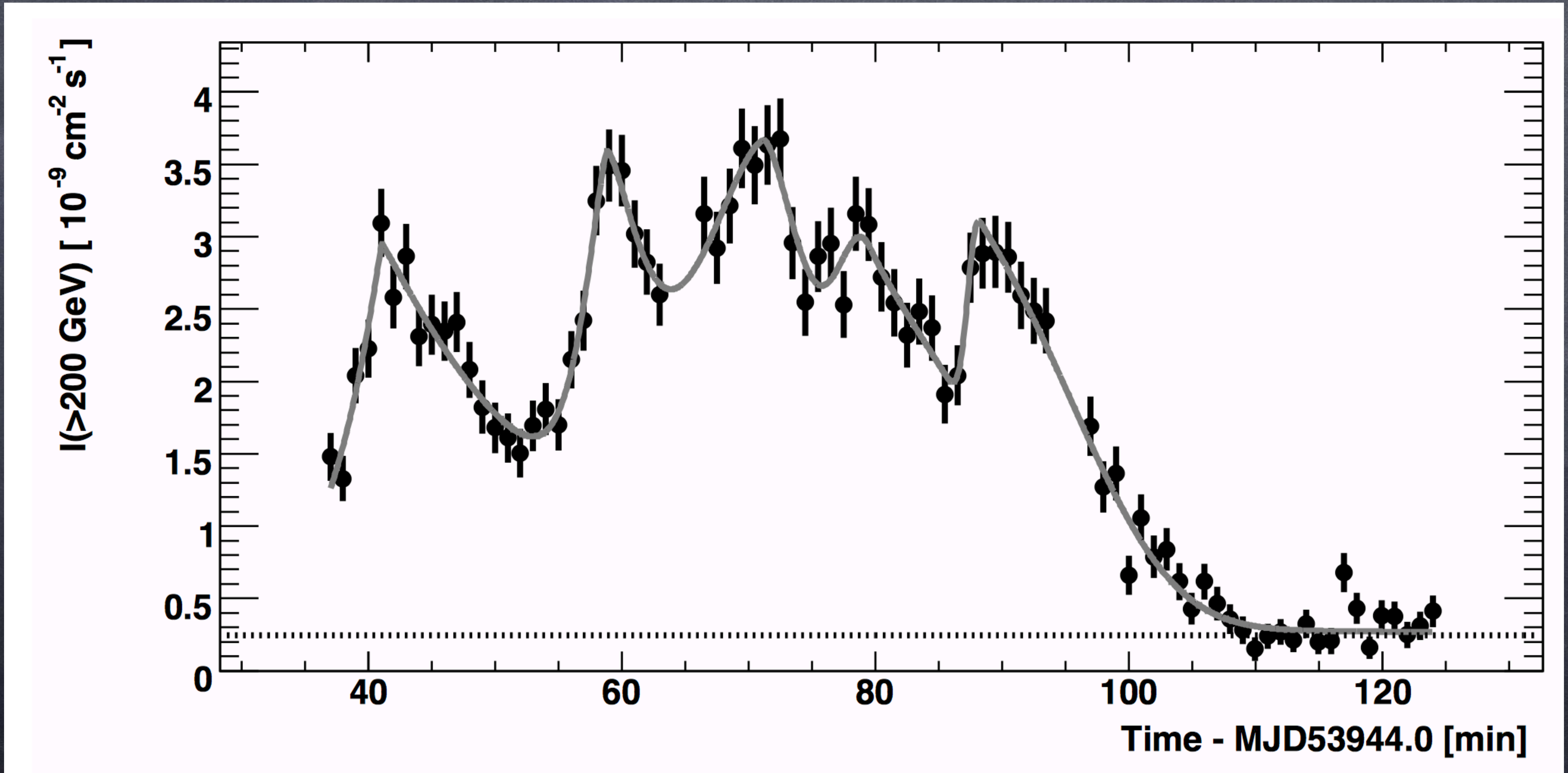
- The most successful leptonic models applied to **extreme-TeV blazars thus appear to be simple SSC models** that involve electron distributions with either a large minimimum Lorentz factor, $\gamma_{min} >> 1$, or hard particle spectra, $p < 2$, as well as a magnetic field strength well below equipartition
- (Lepto-)hadronic models: Typical hadronic scenarios for extreme blazars are based on the **co-acceleration of protons and electrons** and attribute the TeV emission to proton synchrotron radiation or to the decay of pions from proton–photon interactions, possibly mixed with SSC emission from secondary pairs

Jet structure

- Some multi-wavelength light curves points to the need of structure jets, showing more complex behaviours than expected from simple one-zone emitting regions, including also fast variability
- First hint of an spectral narrow feature in the VHE band from Mrk 501
- CTA will bring better resolution and MWL campaigns will be key

Slide from J. Becerra González

Extreme variability PKS 2155-304

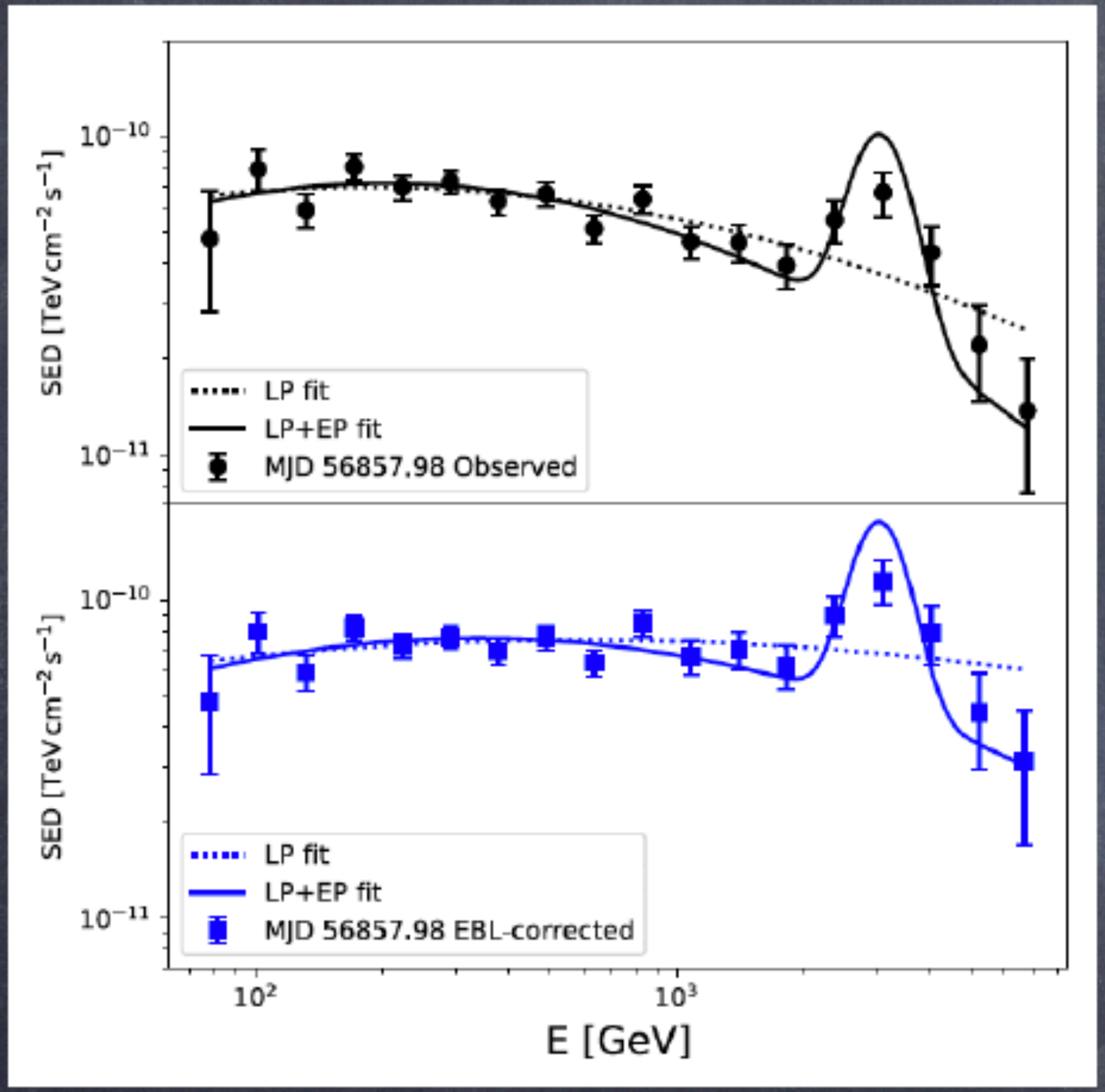


HESS coll. 2007, ApJ, 664, L71

Slide from J. Becerra González

Hint of a narrow VHE spectral feature

Likelihood Ratio Test



2014 July 19-20

(MJD 56857.98)

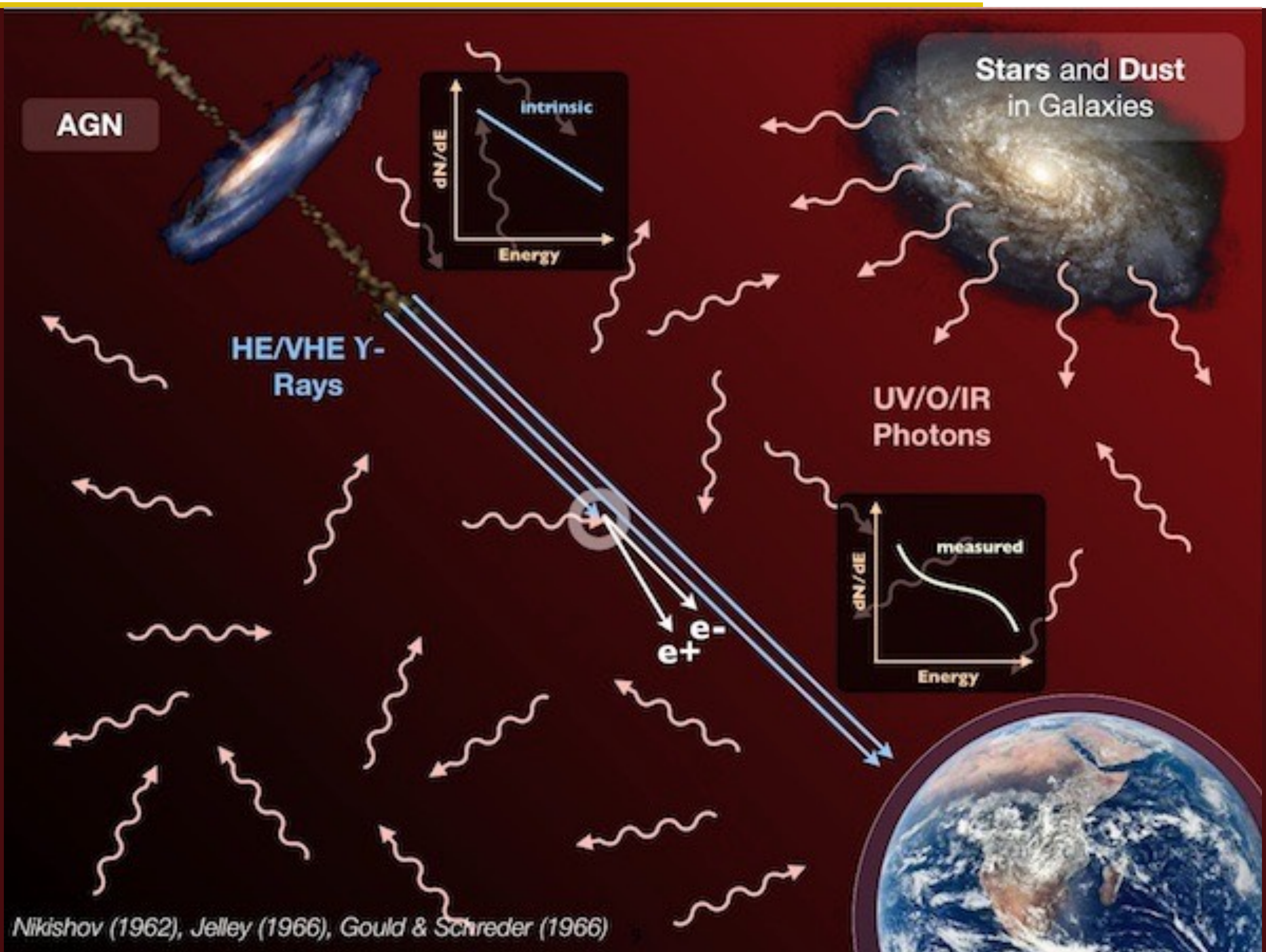
	Fit	$f_0 \cdot 10^{10}$ [TeV^{-1}cm^{-2}s^{-1}]	Γ	b	$K \cdot 10^5$ [TeV^{-1}cm^{-2}s^{-1}]	β	Ep [TeV]	χ^2/df	LRT
Observed	LP	2.56 ± 0.09	-2.16 ± 0.03	0.08 ± 0.02	-	-	-	39.8/19	
Observed	LP+EP	2.54 ± 0.10	-2.26 ± 0.04	0.14 ± 0.03	7.7 ± 1.7	9.1 ± 3.2	3.04 ± 0.10	13.5/16	4.5σ
EBL-corr	LP	3.00 ± 0.11	-1.99 ± 0.03	0.04 ± 0.02	-	-	-	35.4/19	
EBL-corr	LP+EP	2.99 ± 0.11	-2.08 ± 0.04	0.10 ± 0.03	13.0 ± 3.0	10.0 ± 3.6	3.03 ± 0.10	14.6/16	3.9σ

MAGIC Coll. (JBG, DP) 2020, A&A, 637, A86

[redacted]

Slide from J. Becerra González

Extragalactic Backgroun Light (EBL)

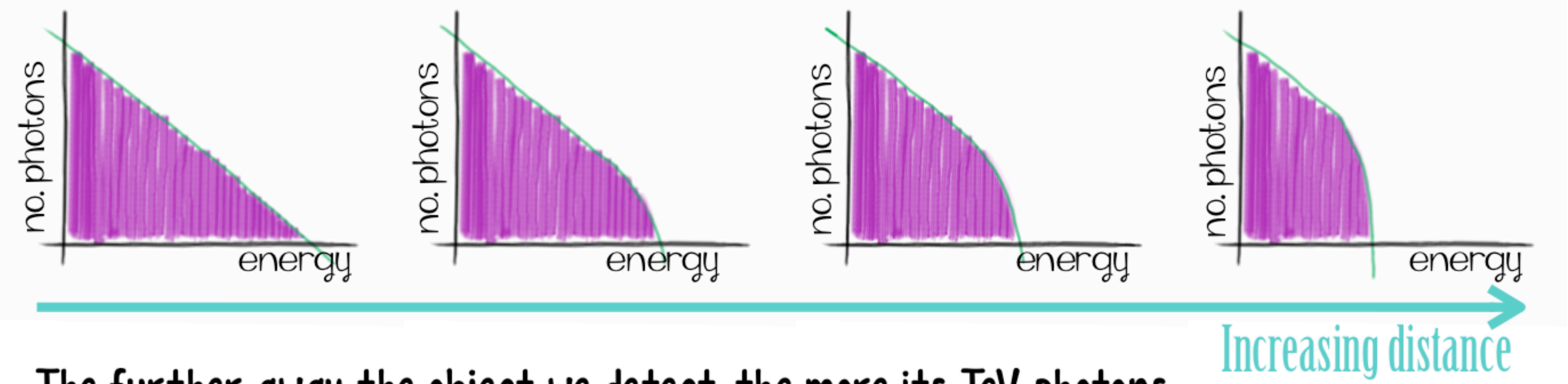


Slide from M. Raue

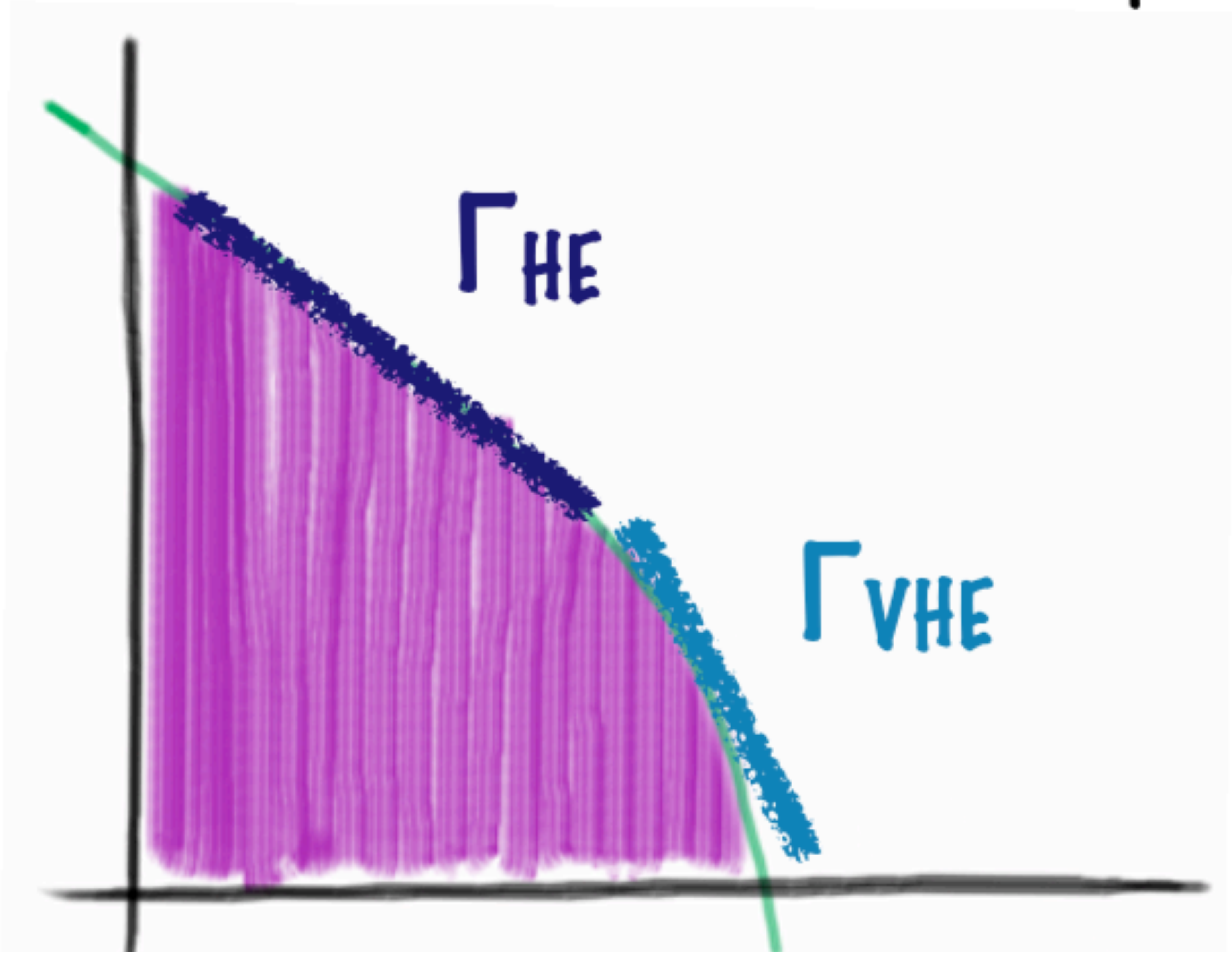
Extragalactic Backgroun Light (EBL)

Slide from M. Raue

EBL



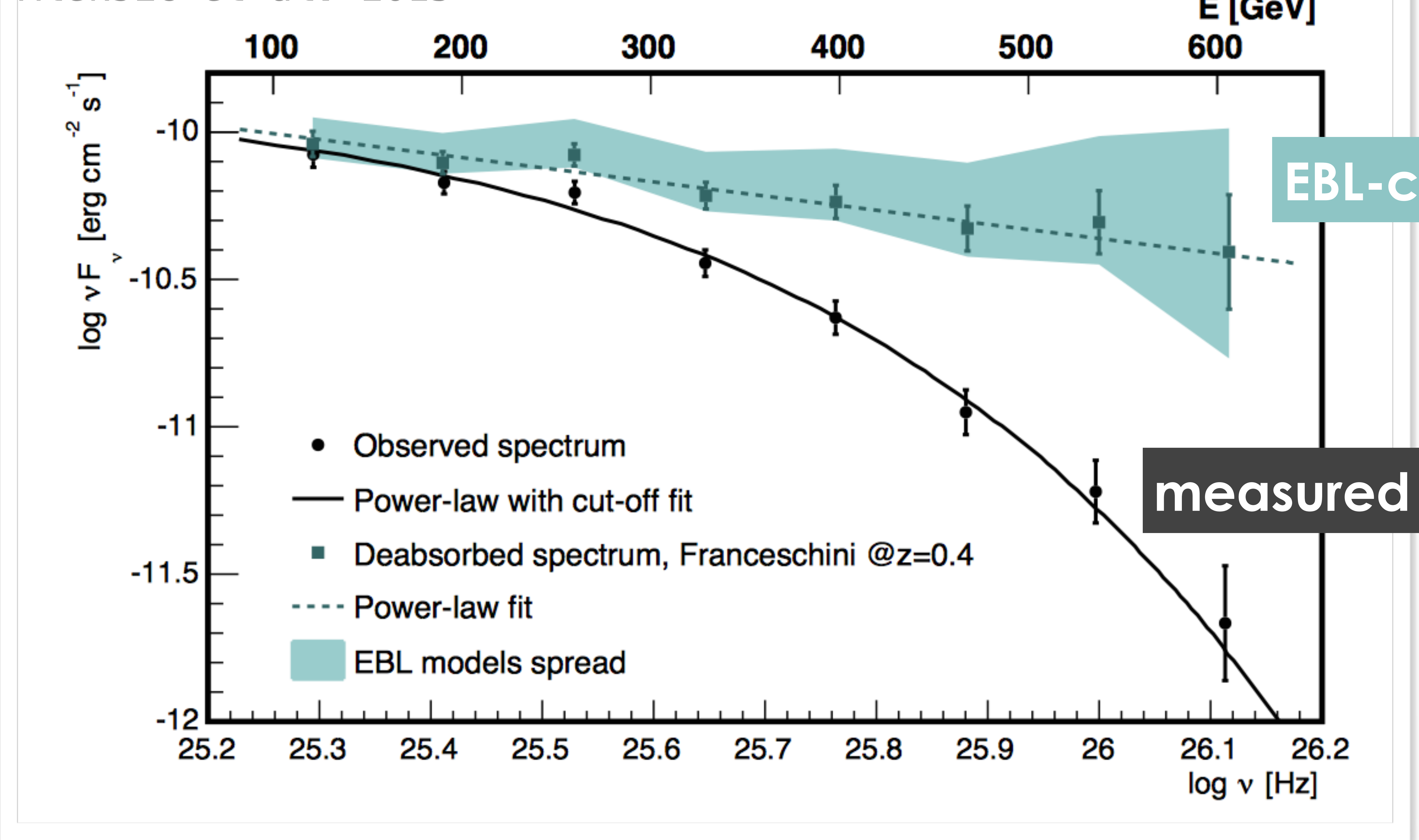
The further away the object we detect, the more its TeV photons are absorbed by the EBL – this results in a break in the spectrum



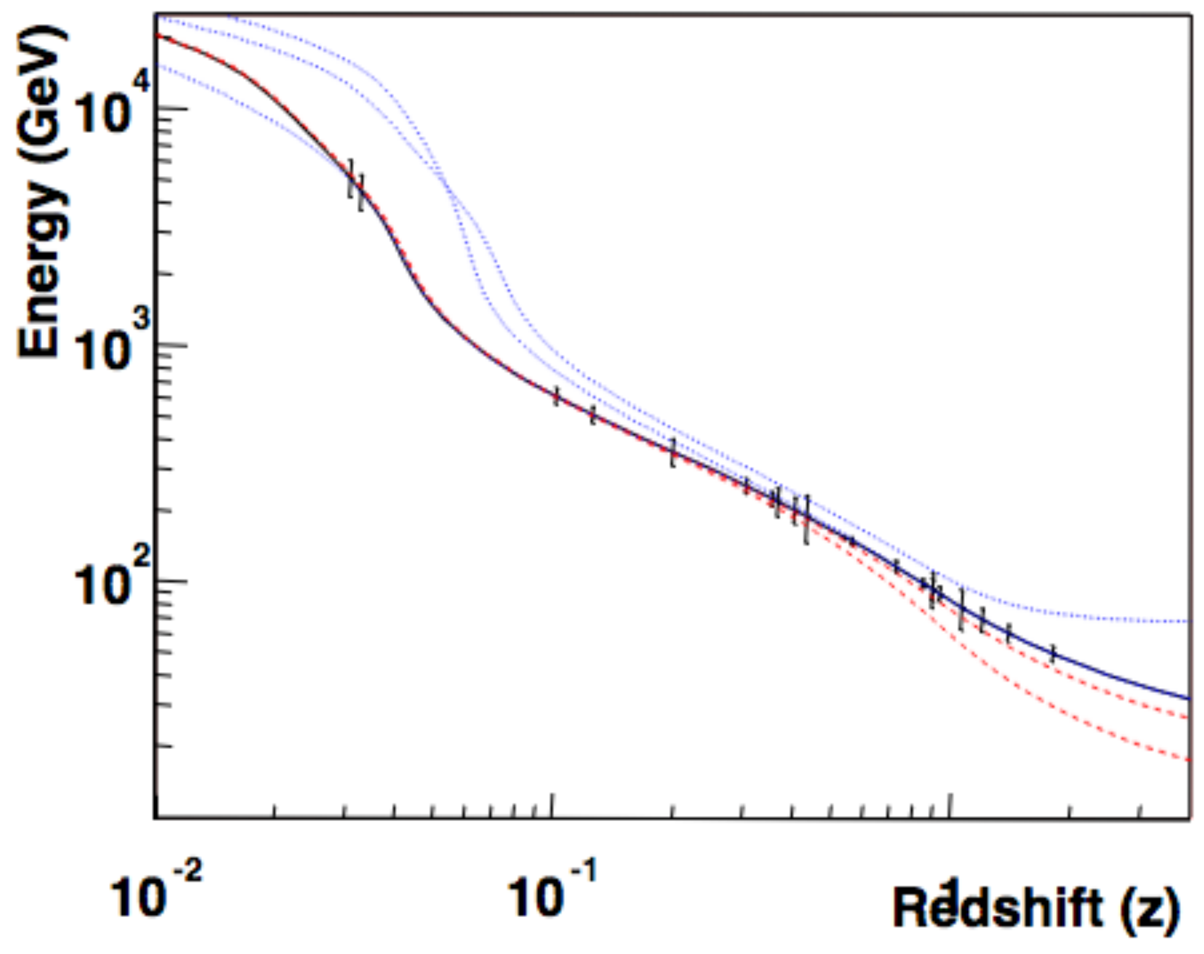
Slide from D. Horan

EBL

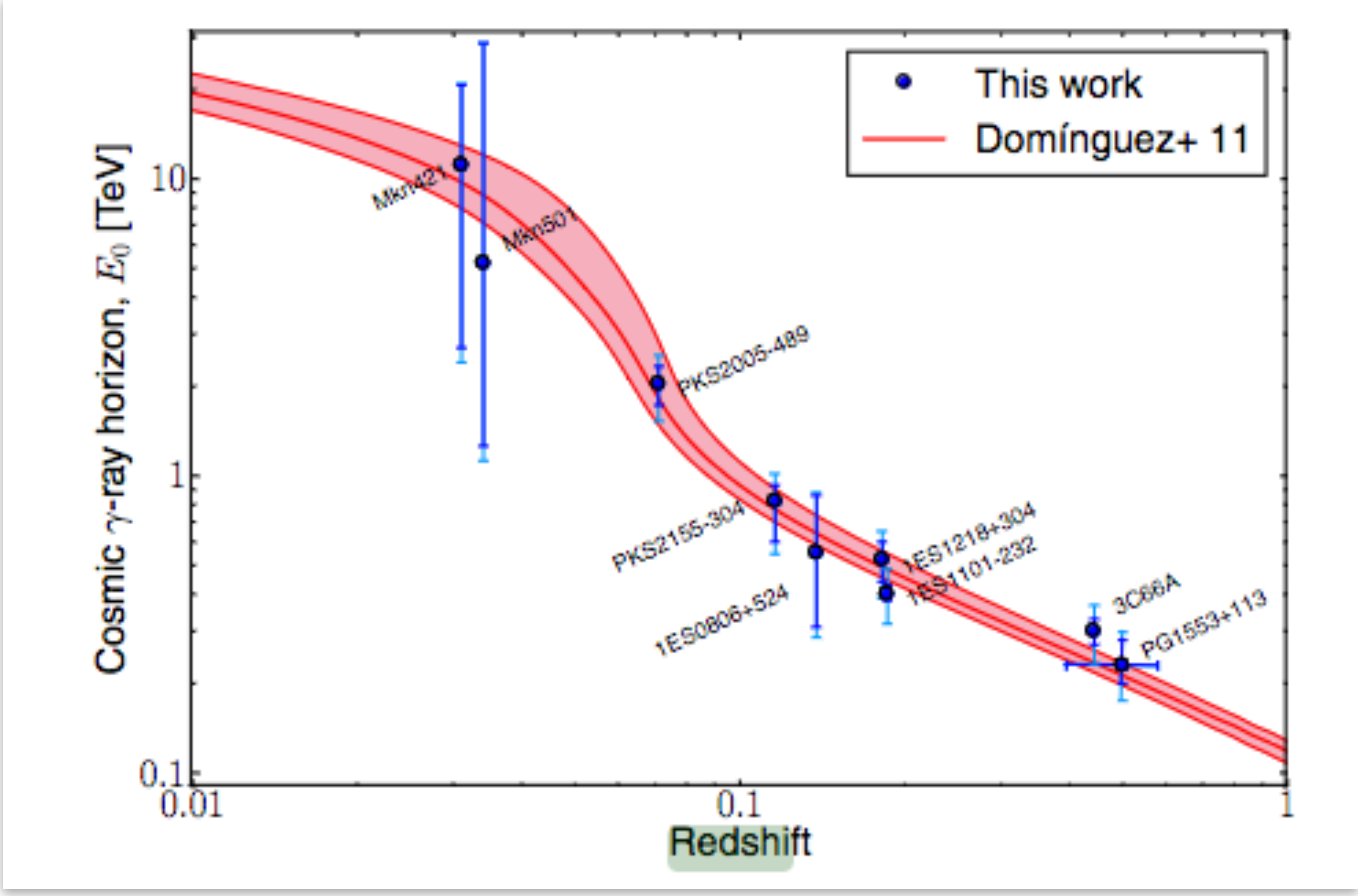
PG 1553+113(z~0.4)



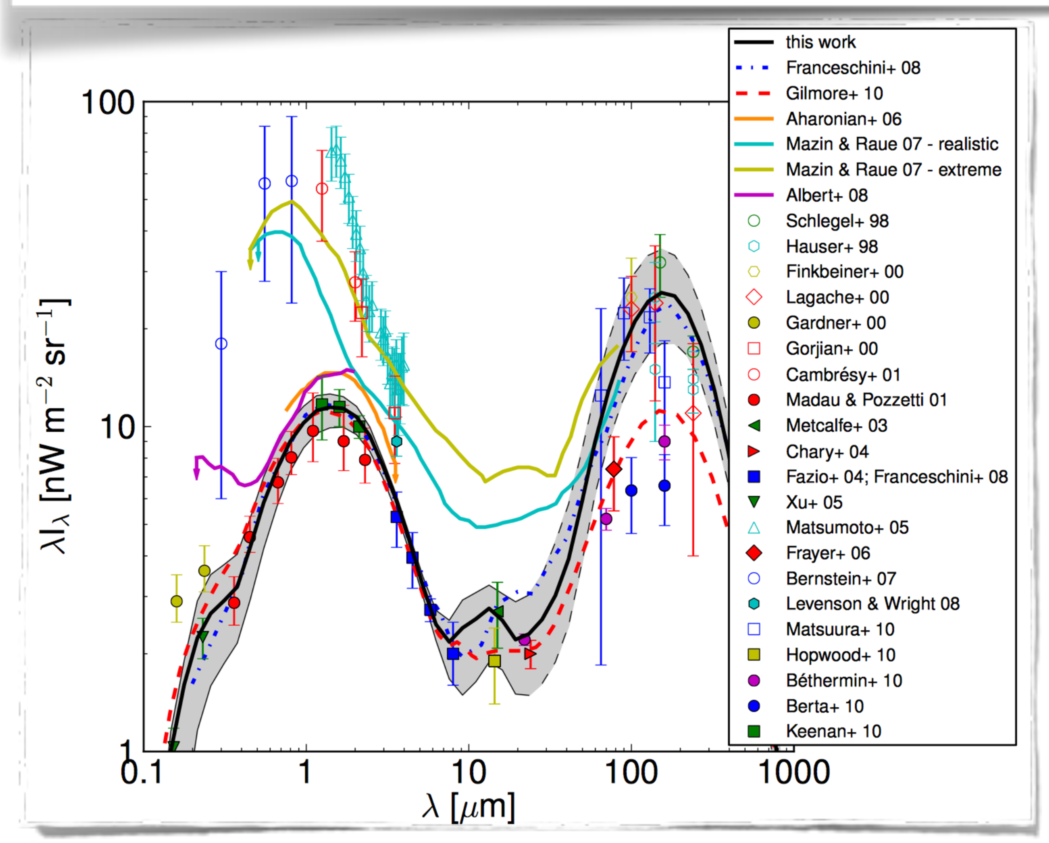
Aleksic et al. 2015



O. Blanch 2055

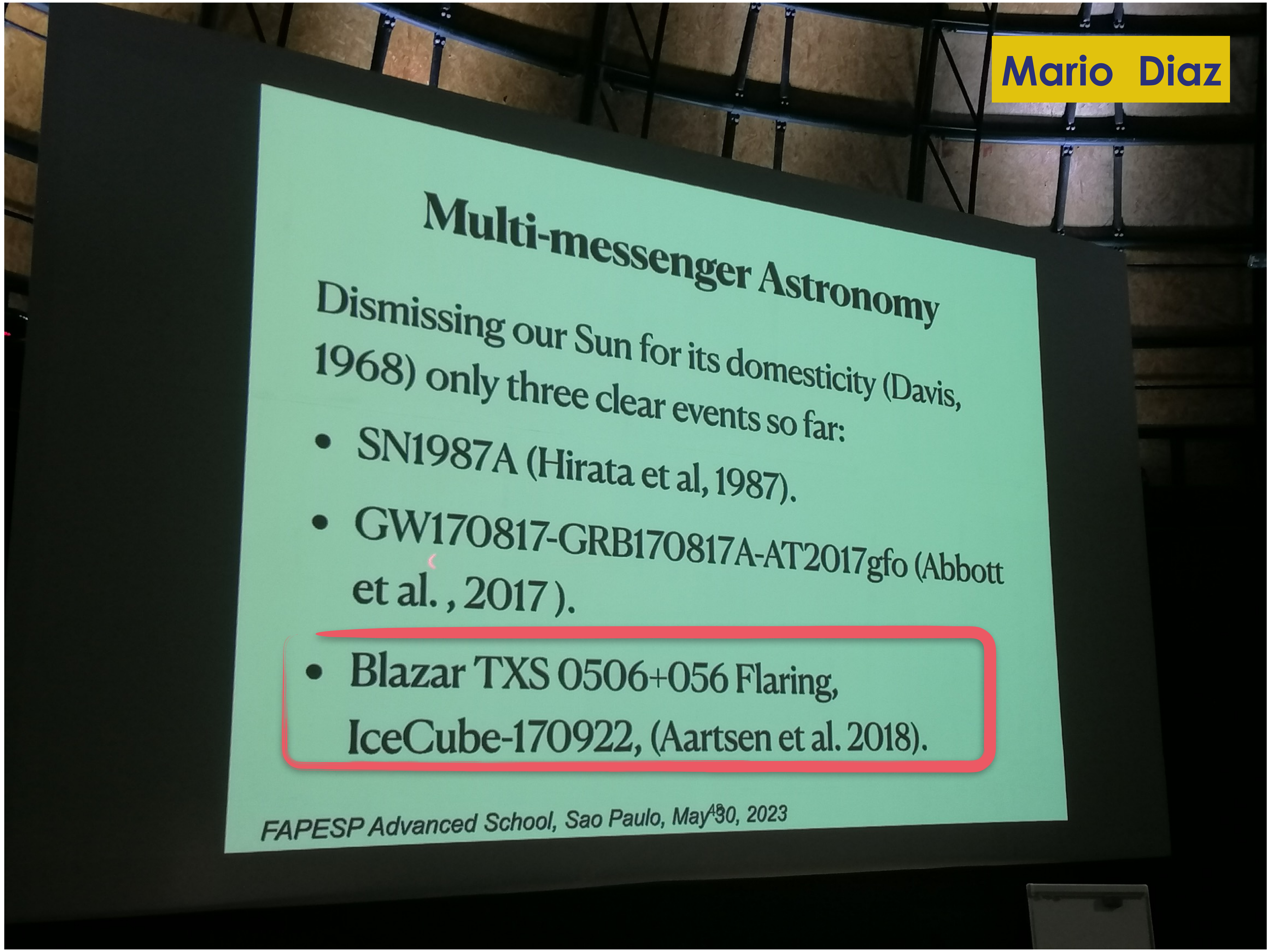


Dominguez et al. 2011



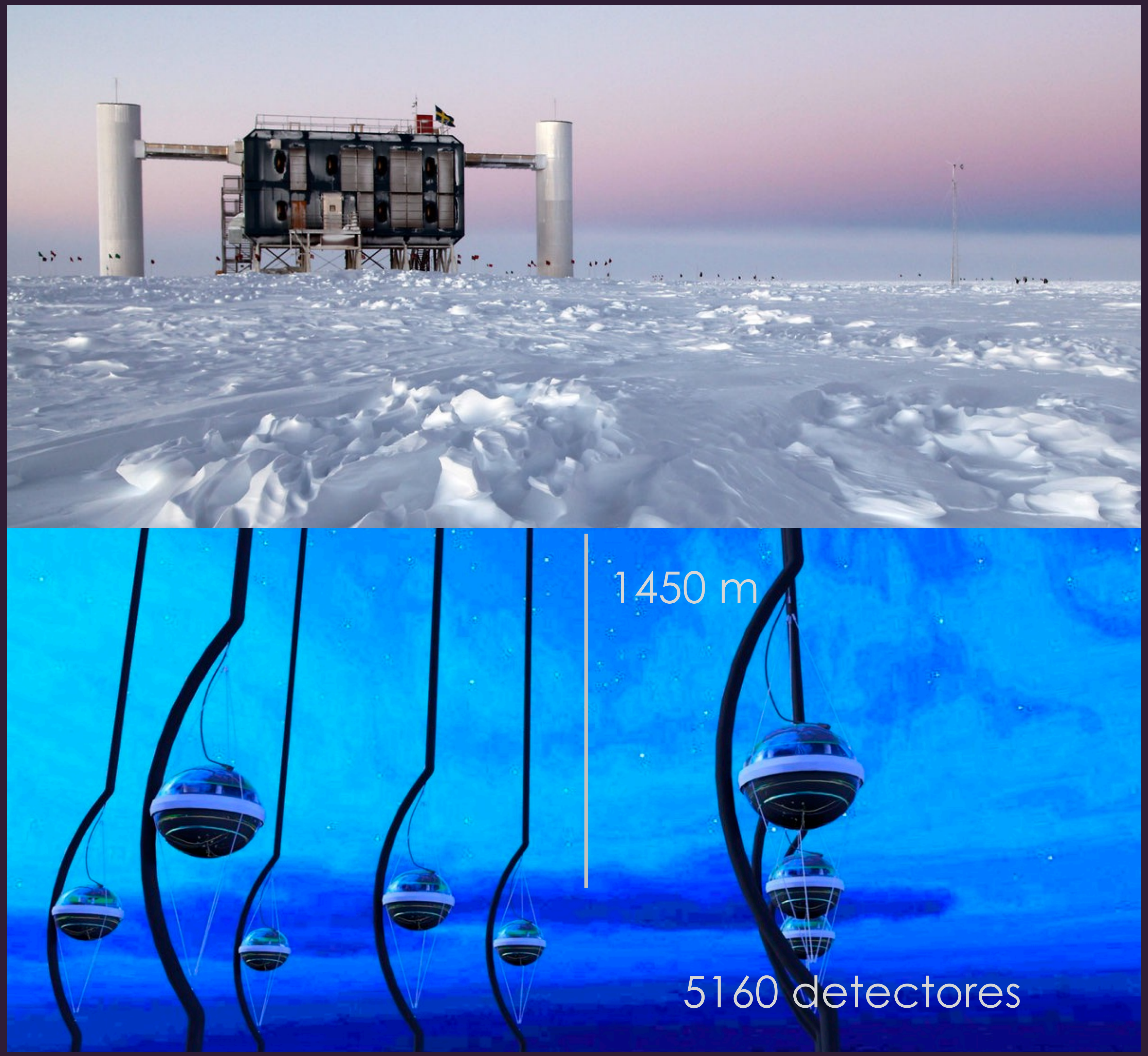
- **Gamma-ray horizon**
  - Most distant source GRB201216C at **z=1.1** (MAGIC 2020)
    - most distant blazar PKS 0346-27 at z=0.991 (HESS 2021)

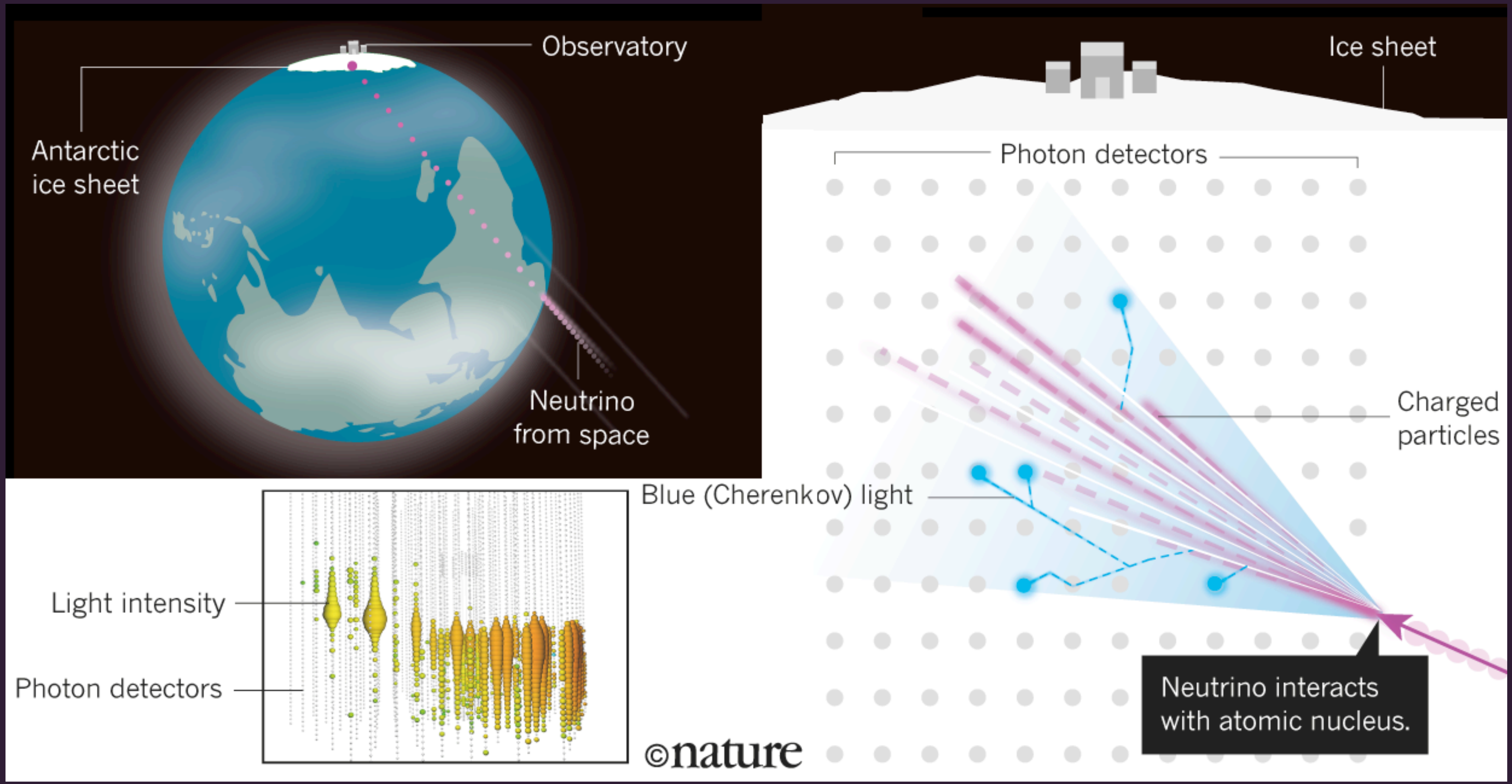
→ **pushing the limits!**



Mario Diaz
Multi-messenger Astronomy
Dismissing our Sun for its domesticity (Davis, 1968) only three clear events so far:
• SN1987A (Hirata et al, 1987).
• GW170817-GRB170817A-AT2017gfo (Abbott et al. , 2017).
• Blazar TXS 0506+056 Flaring, IceCube-170922, (Aartsen et al. 2018).
FAPESP Advanced School, Sao Paulo, May 30, 2023

High-energy neutrinos





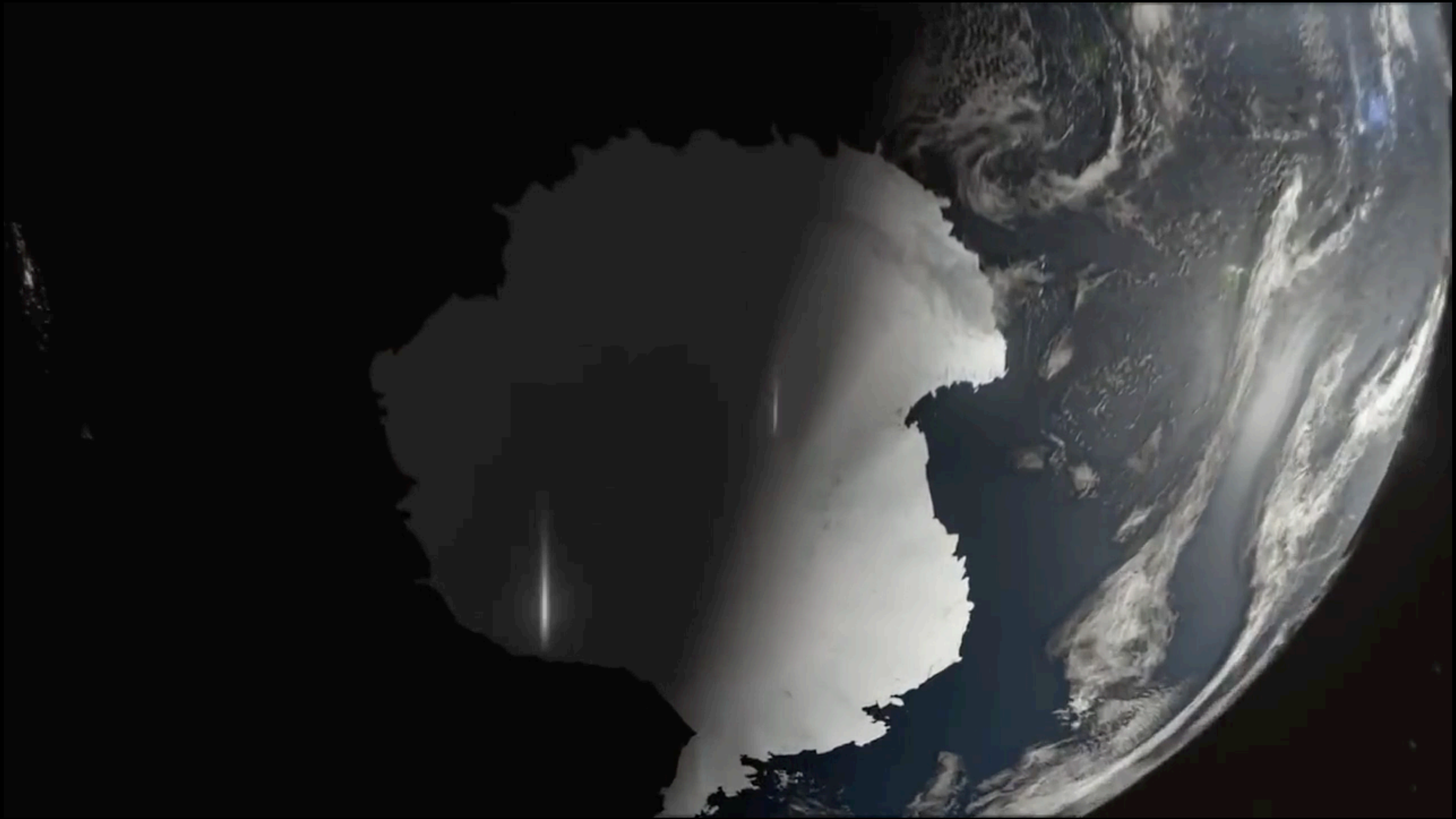
Few dozens of highly energetic neutrinos : TeV-PeV (10^{12-15} eV)

7-year data set:

- total of 60 neutrino events with E: 60 TeV to 10 PeV (from Halzen & Kheirandish 2022)

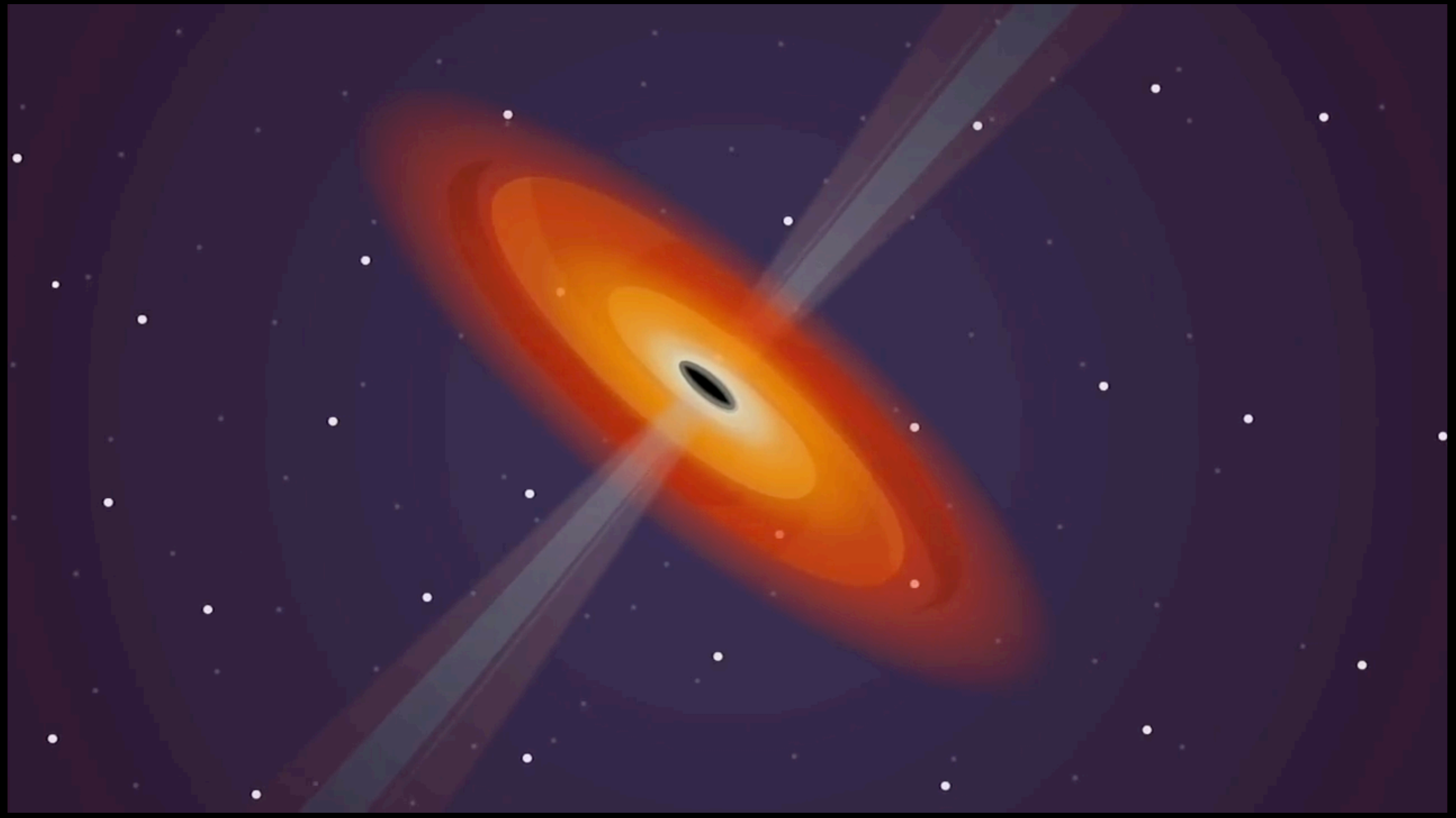
September 22, 2017

IC170922A : neutrino with E: 290 TeV

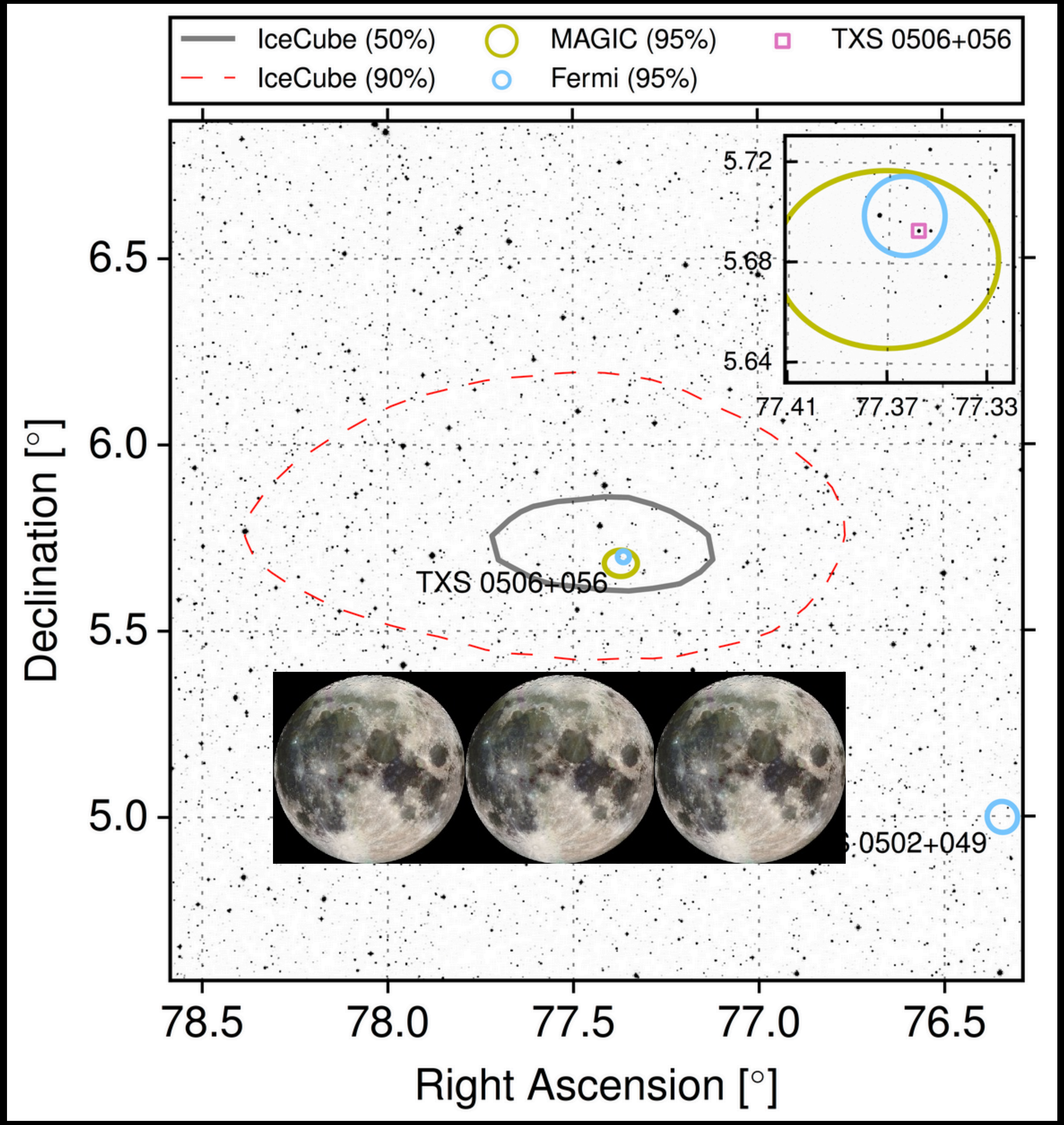


First confirmed cosmic/extragalactic neutrino

Galaxy **TXS 0506+056** : a blazar in Orion



z = 0.34 (Paiano et al. 2018)



First confirmed cosmic/extragalactic neutrino

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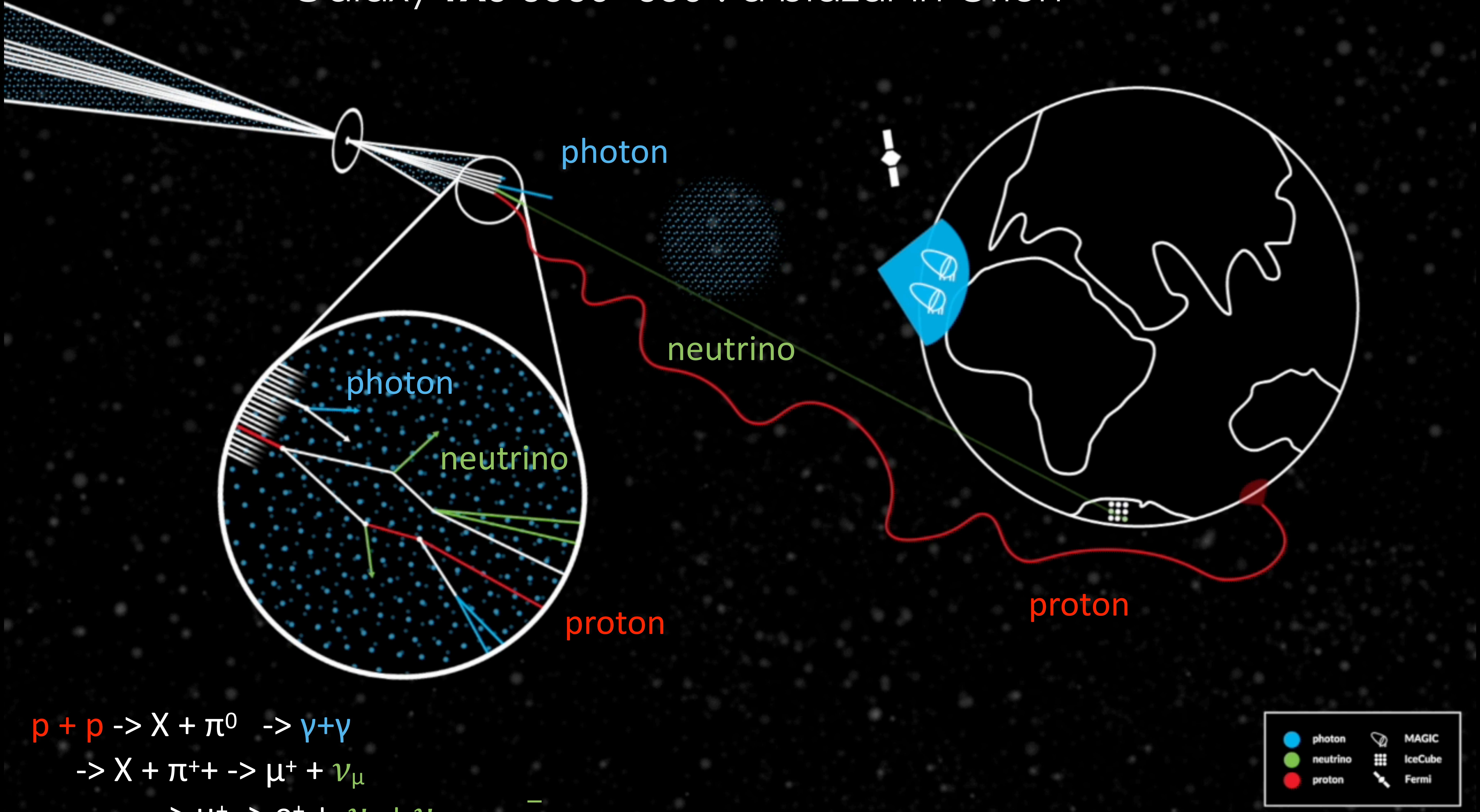


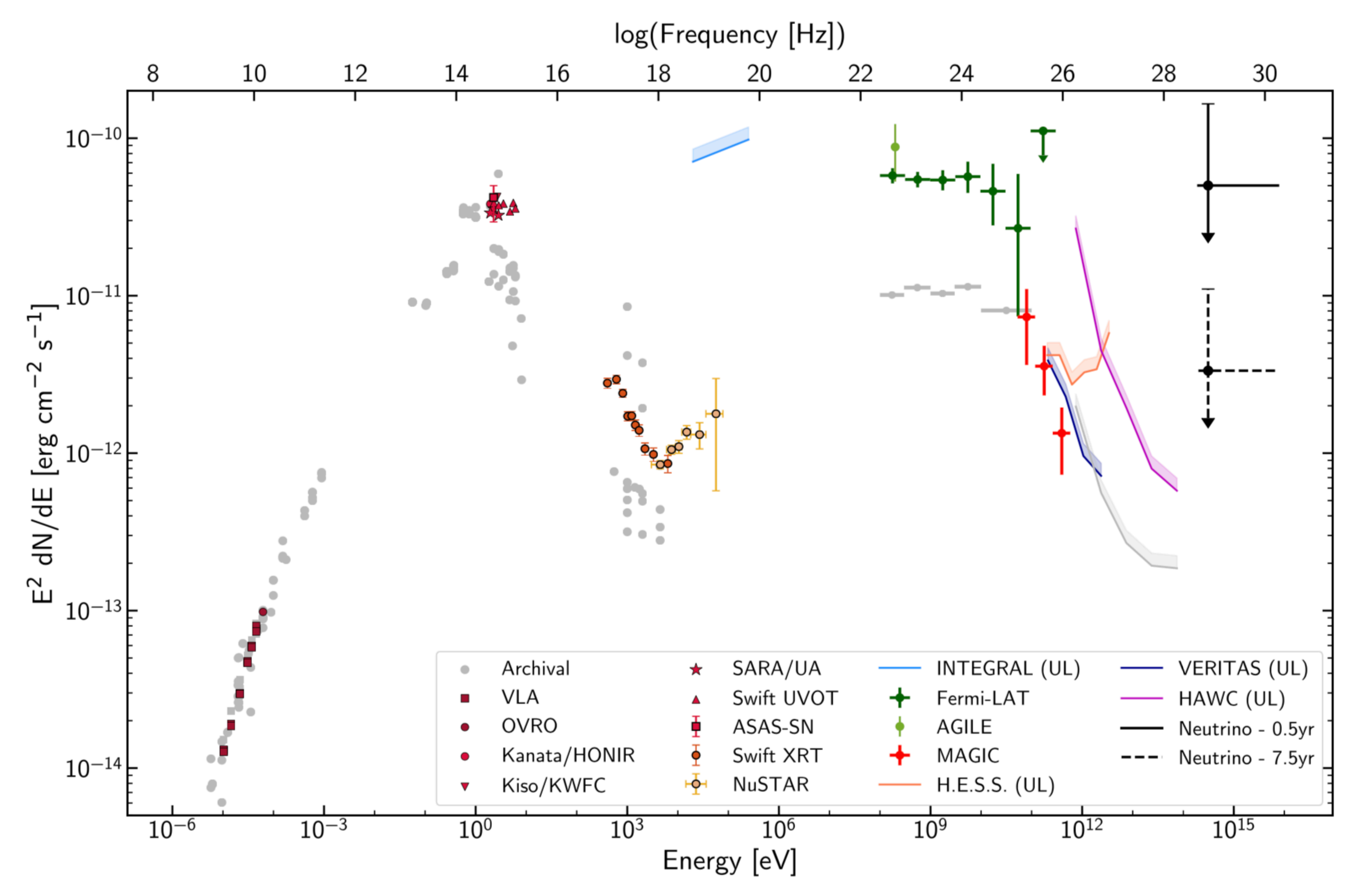
$p + p \rightarrow X + \pi^0 \rightarrow \gamma + \gamma$

$\rightarrow X + \pi^{+}+ \rightarrow \mu^+ + \nu_\mu$

$\rightarrow \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Aartsen et al. (ICECUBE, Fermi, MAGIC+), Science, 2018

First confirmed extragalactic neutrino of identified origin



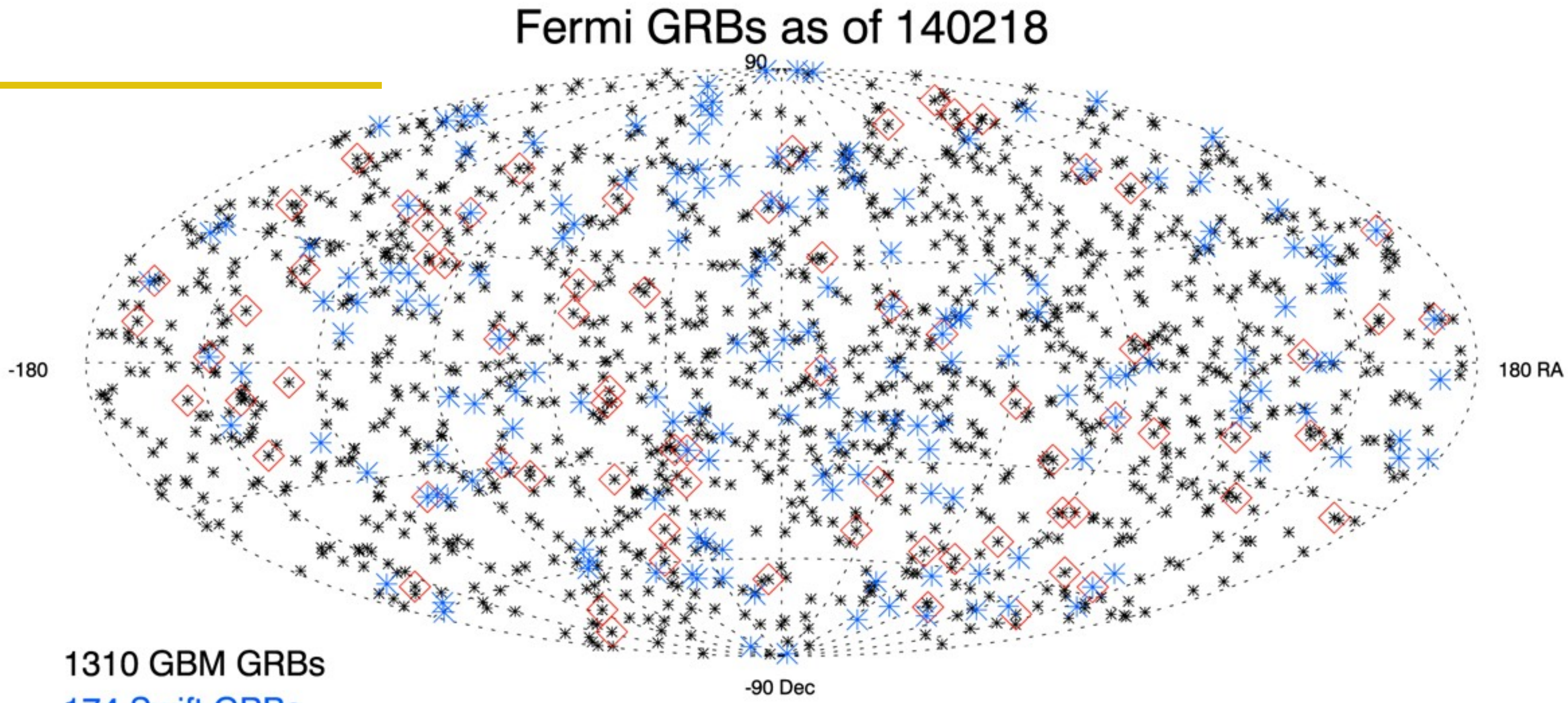
More interesting results released by ICECUBE in the past years

Science Magazine 2018 Breakthrough:
2º Editor's Choice
3º People's choice

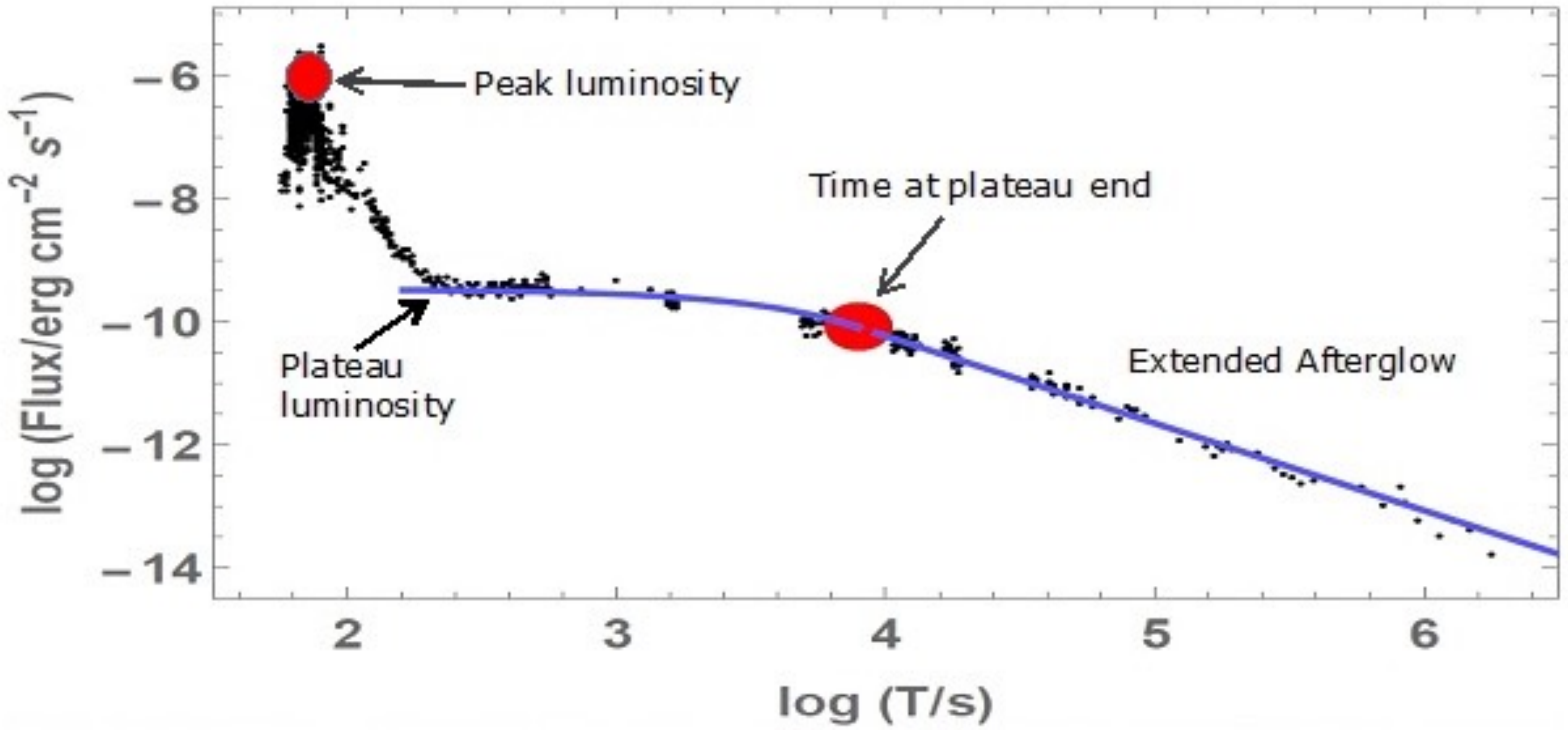
Aartsen et al. (ICECUBE, Fermi, MAGIC+), Science, 2018

Gamma
Ray
Bursts

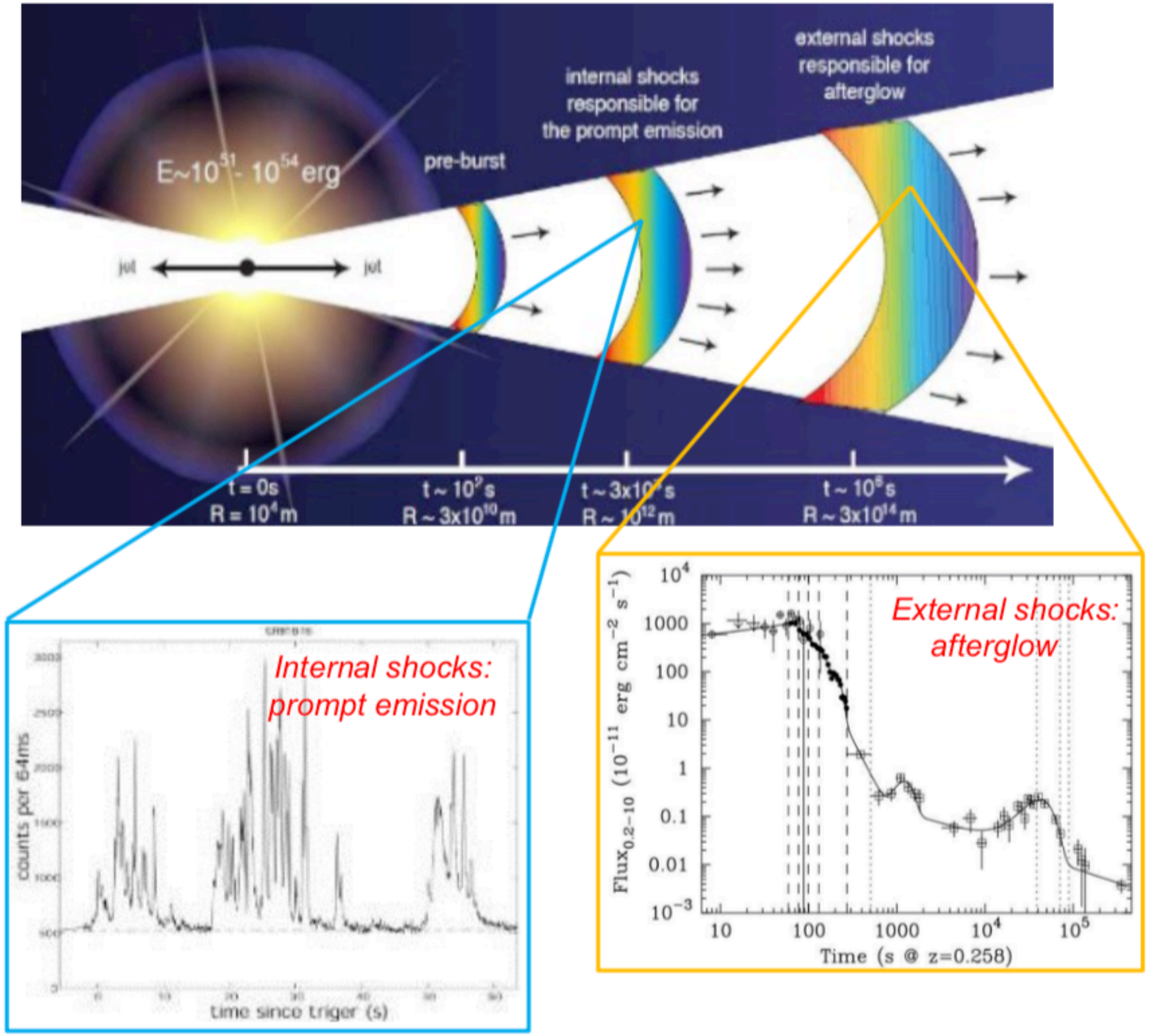
GRBs



1310 GBM GRBs
174 Swift GRBs
73 LAT GRBs

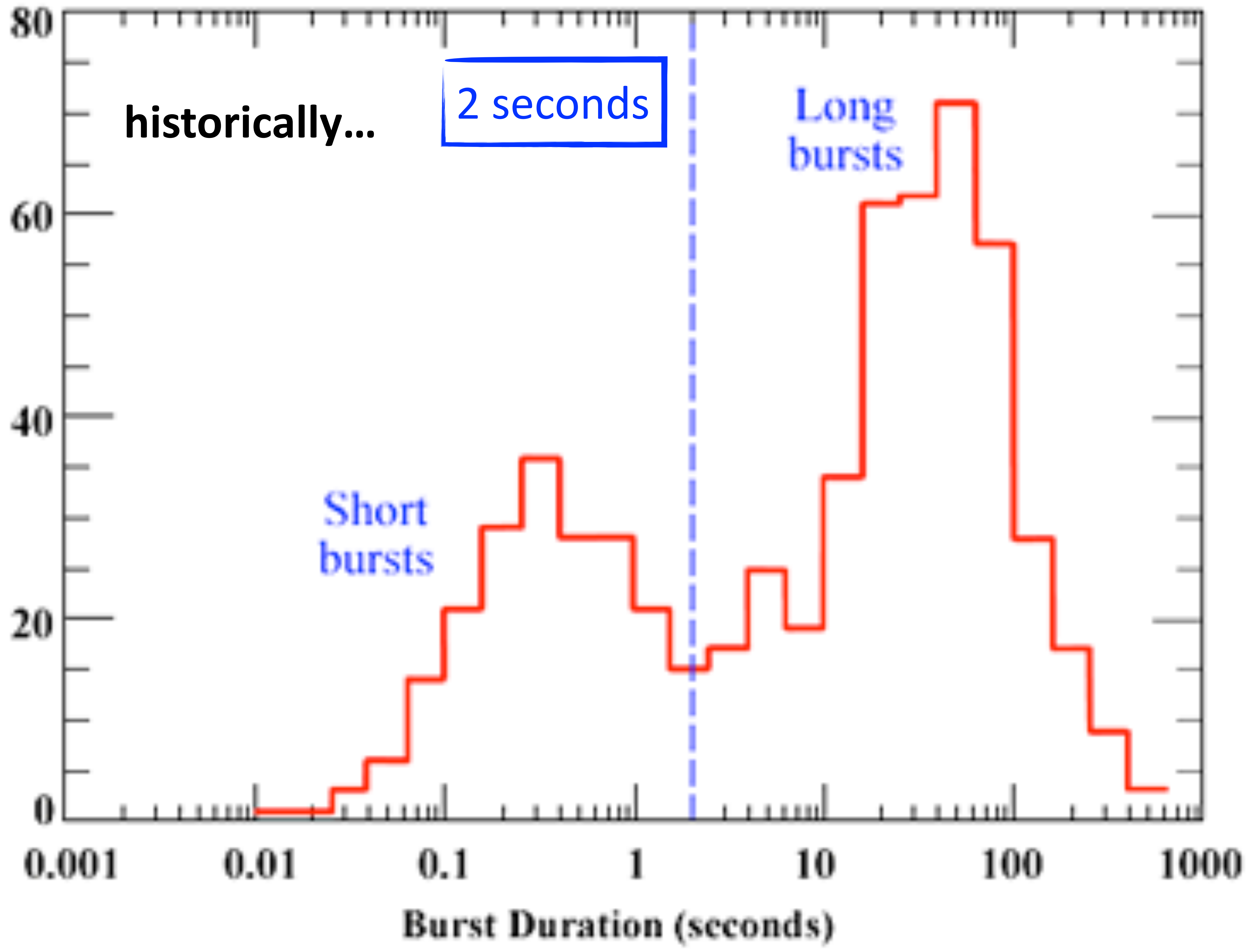


GRBs



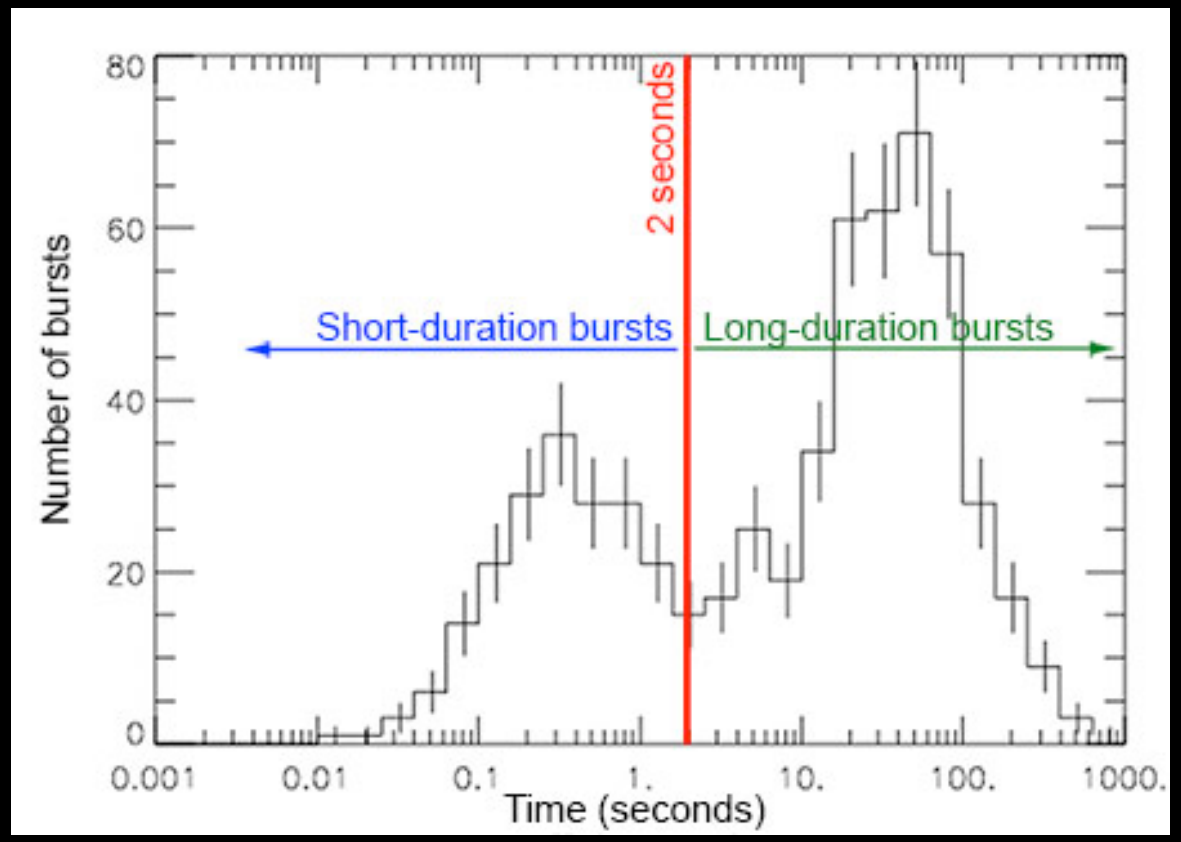
from A. Carosi

- Transient events with **10^{52} - 10^{54} erg** energy release



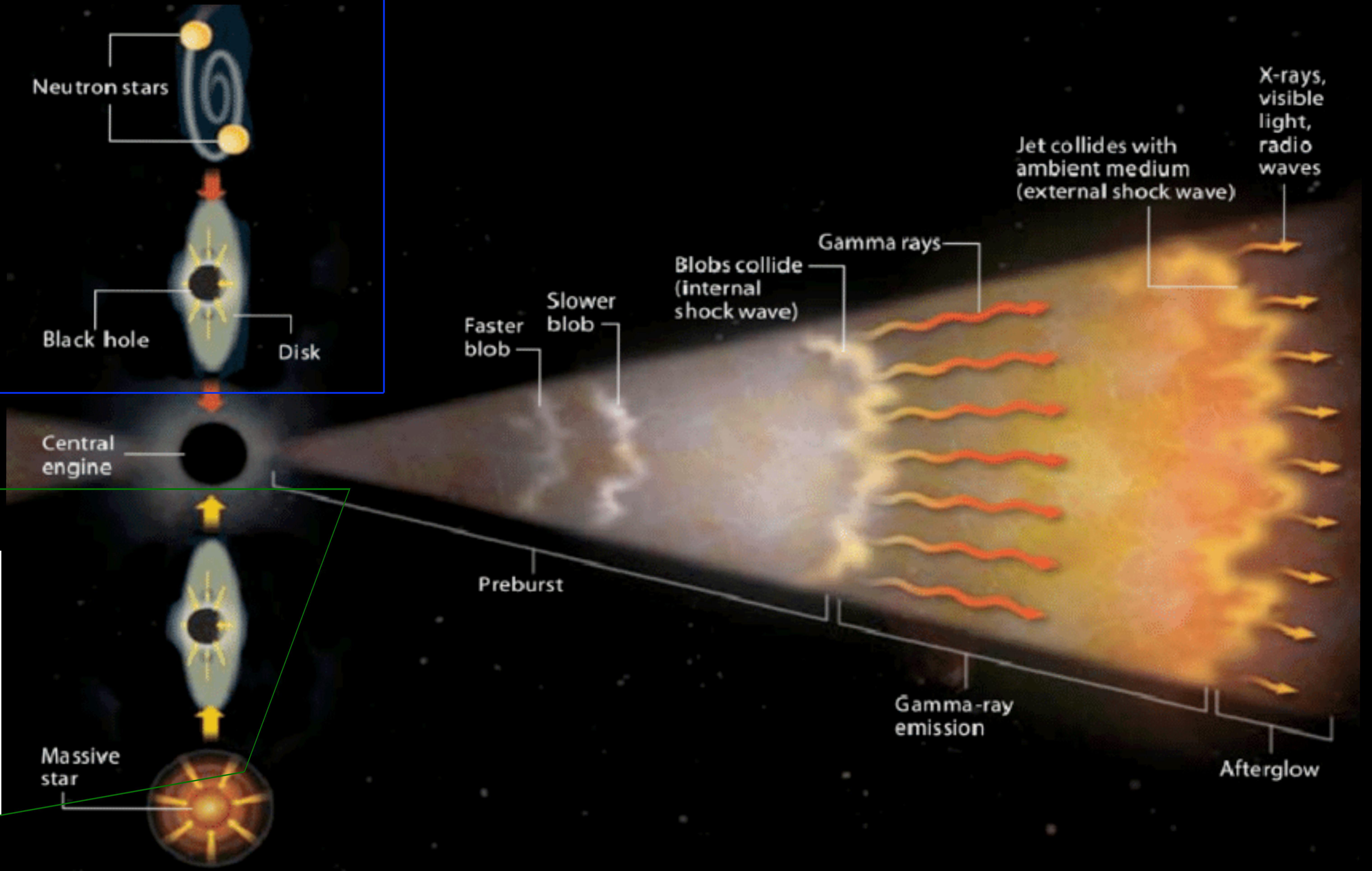
* see Amati 2021 for a review

Different origin



Short GRBs
Binary Neutron Star mergers

Long GRBs
Collapsar Massive Star

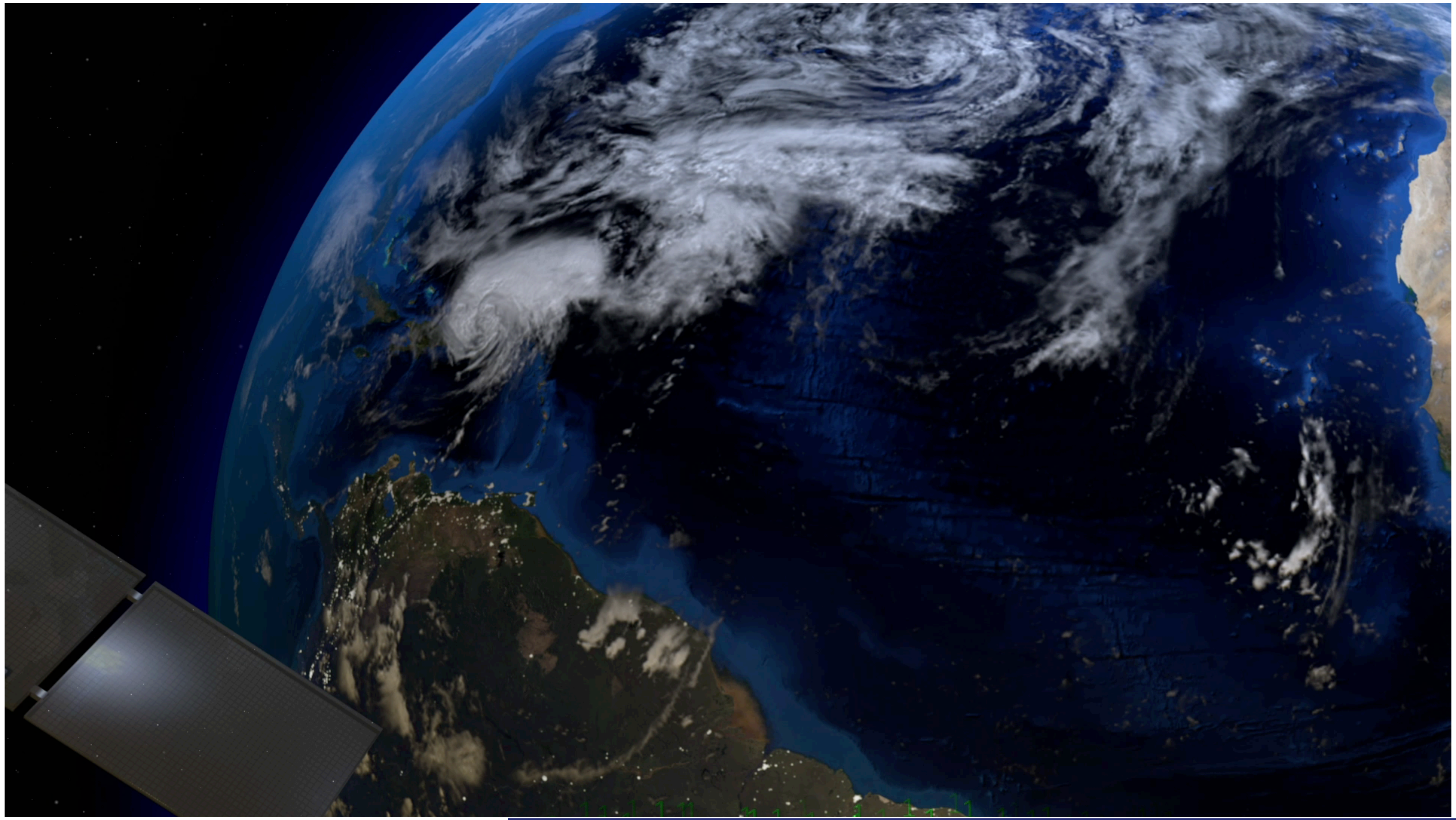


MAGIC: designed for GRB hunting

MAGIC: **17 m de diámetro**
64 T de peso
25 segundos

GTC: 10.4 m de diámetro
400 T de peso

GRB190114C: 1st GRB at VHE!

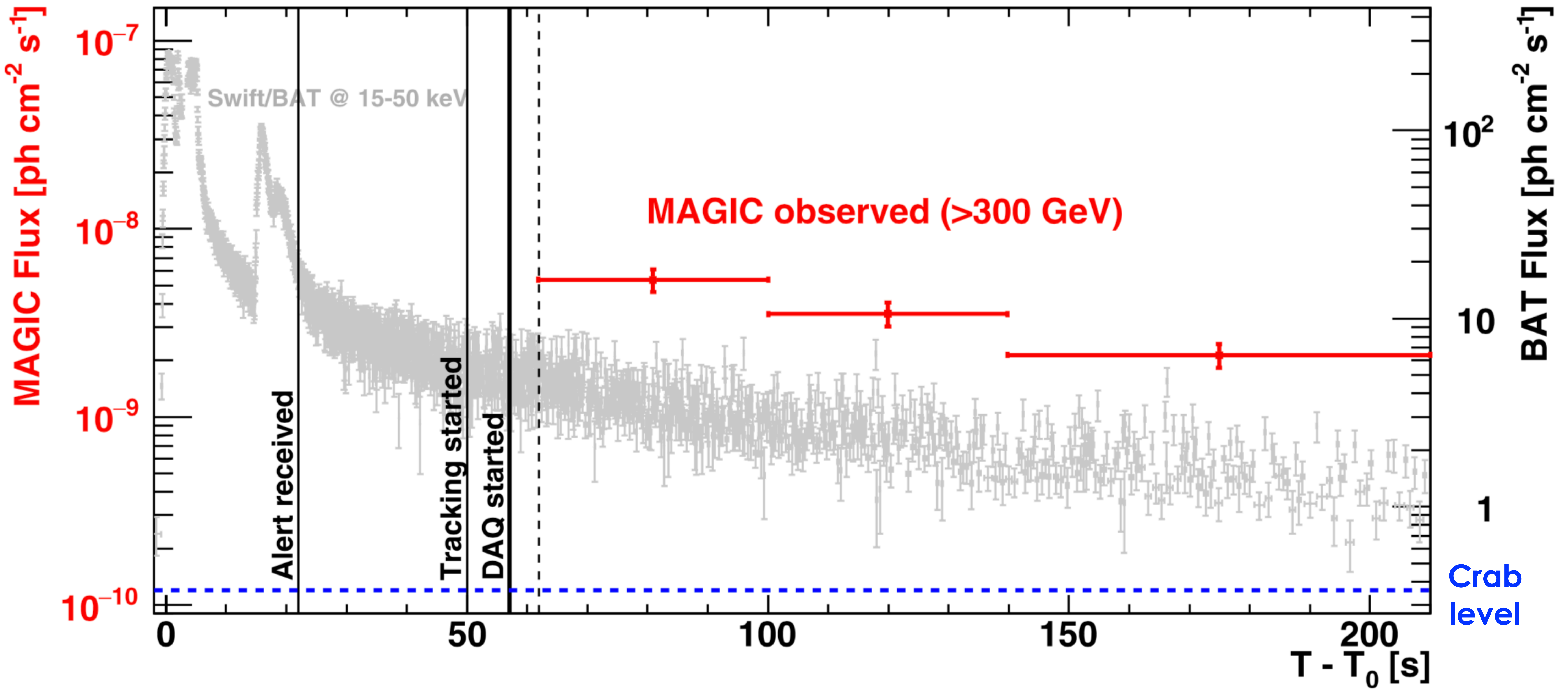


The MAGIC collaboration, Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)

T0+22 sec: Swift & Fermi alert issued
T0+50 sec: MAGIC started observations -> **MAGIC VHE detection**
T0+20 min: no more VHE signal

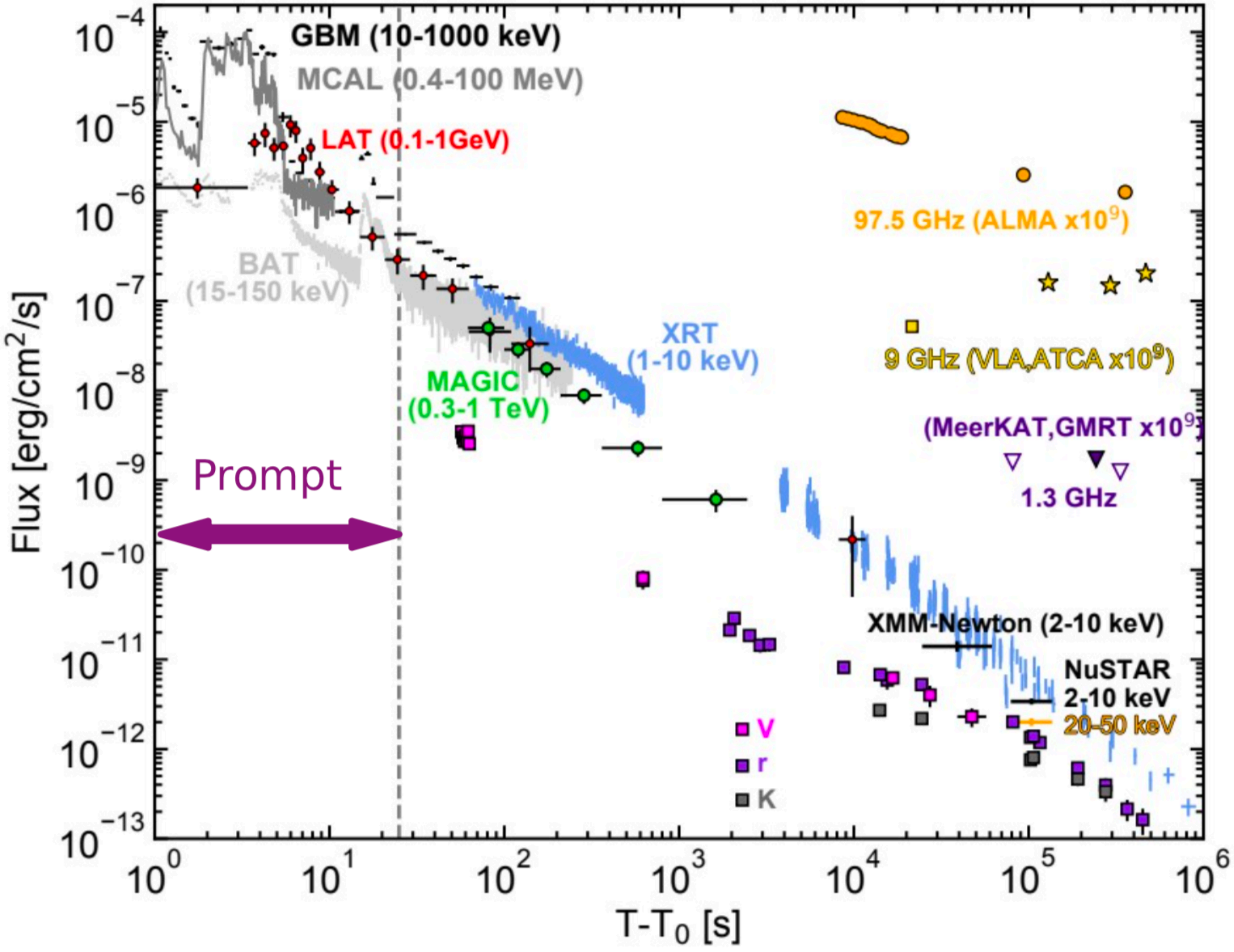
GRB190114C: 1st GRB at VHE!

The MAGIC Collaboration, Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)



1st GRB in the VHE domain (200 GeV-1 TeV)
It took MAGIC only **28 seg to repositing and start datataking**
VHE emission **vanished after 20min**
New era starts!

GRB190114C: 1st GRB at VHE!

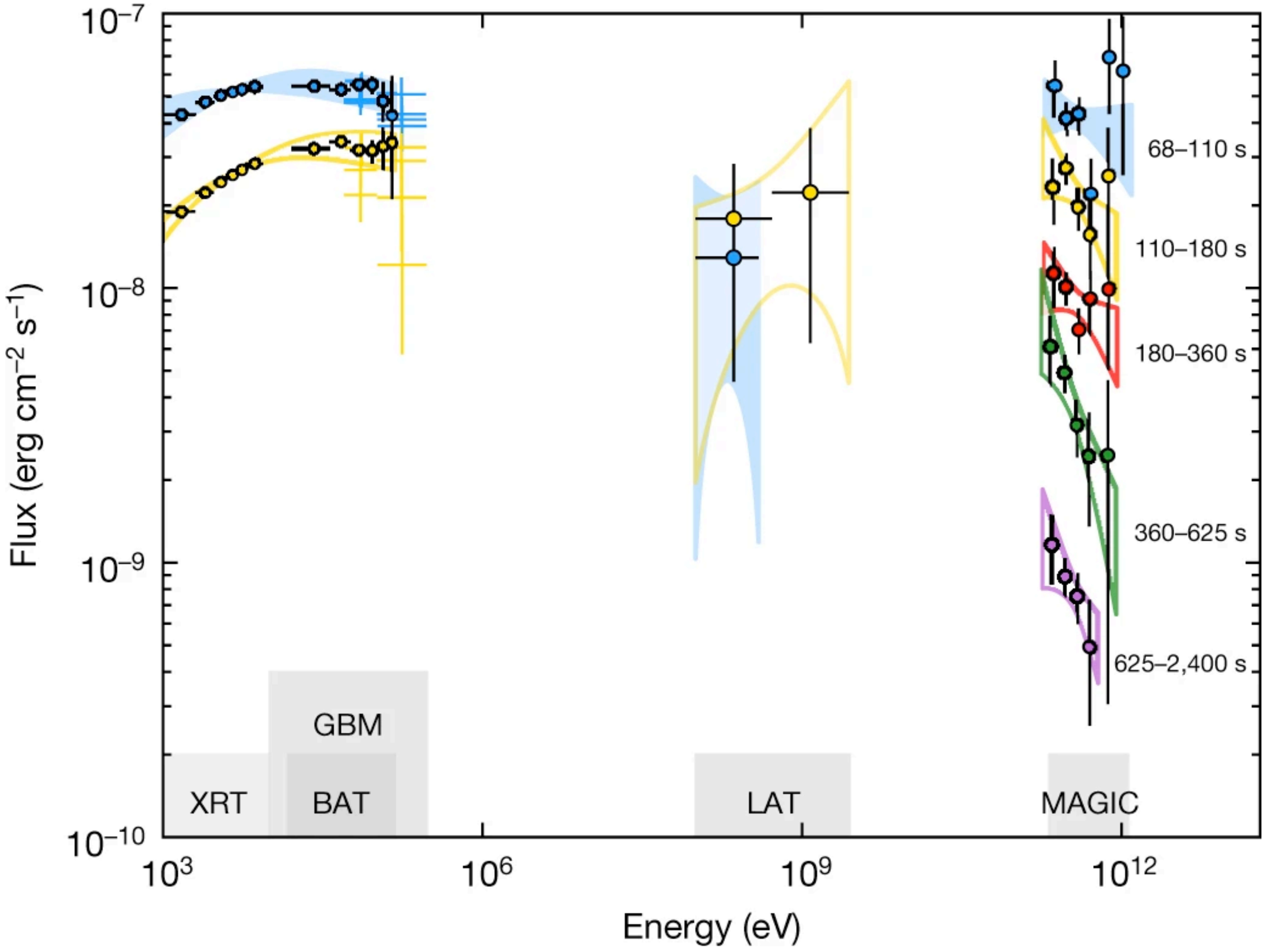


- z = 0.4245 ± 0.0005 (Paiano et al. 2019)
- MAGIC detects the **afterglow emission**

The MAGIC Collaboration,
Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)

GRB190114C: 1st GRB at VHE!

The MAGIC Collaboration, Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)



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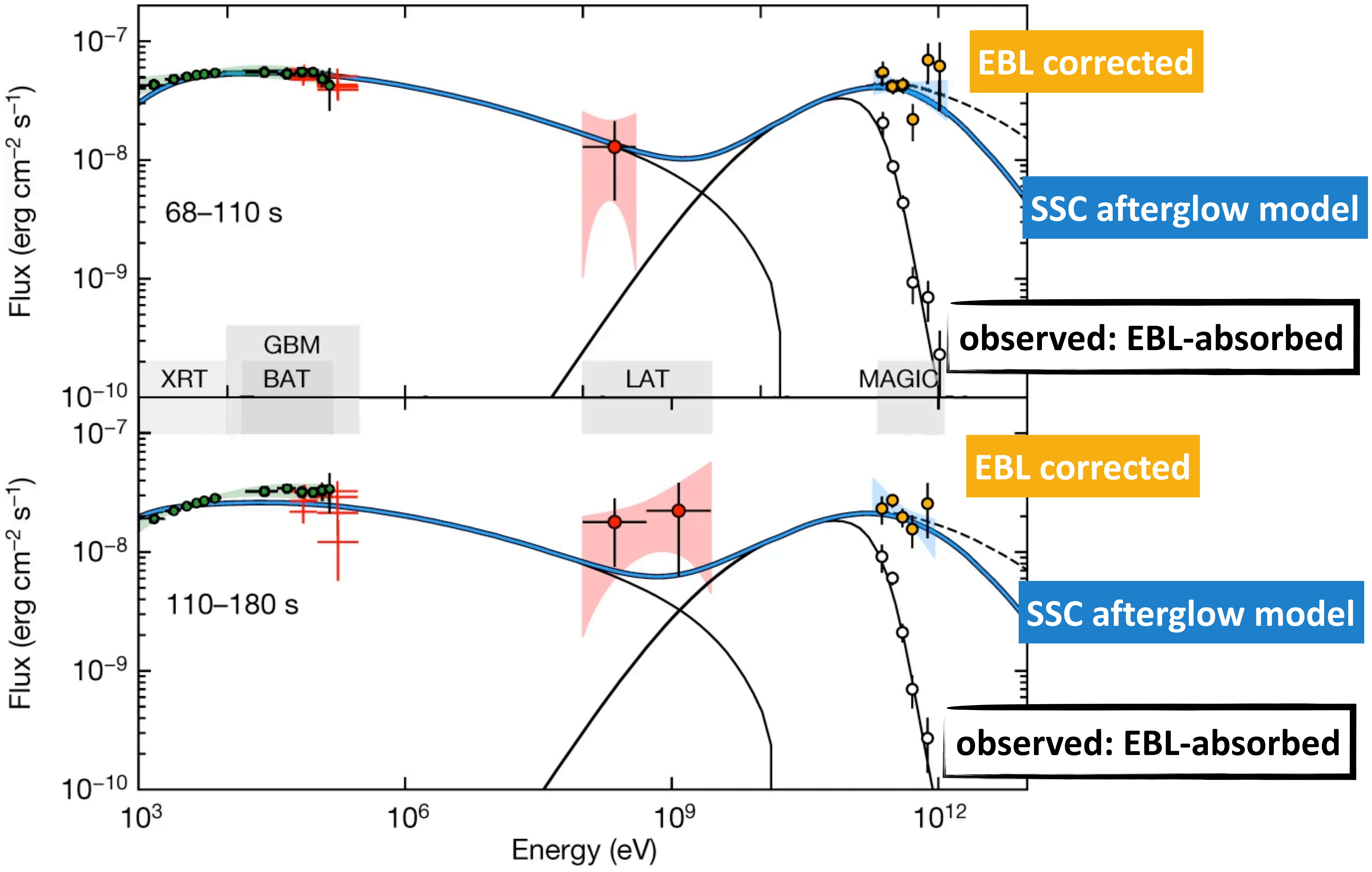
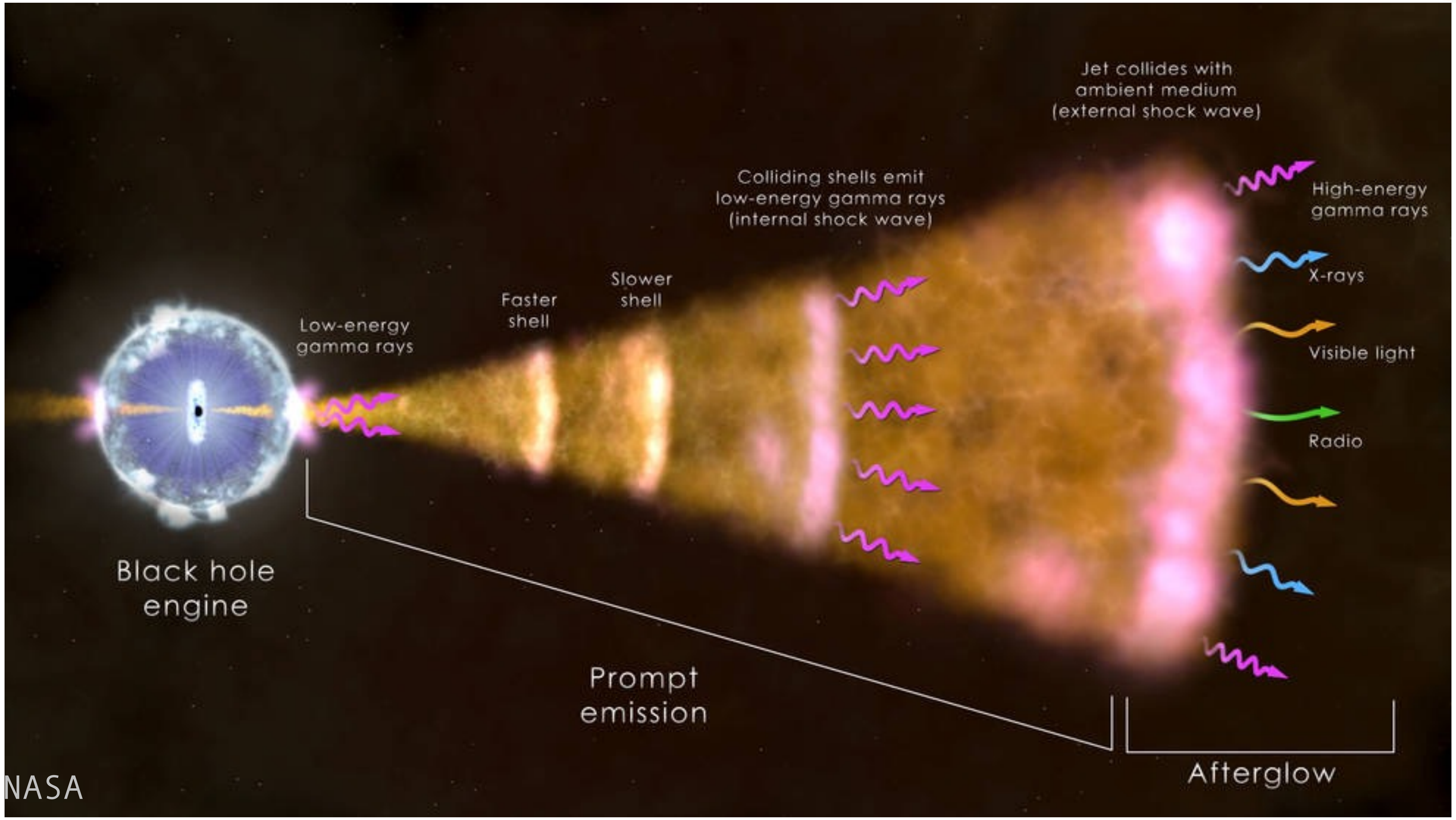
Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)



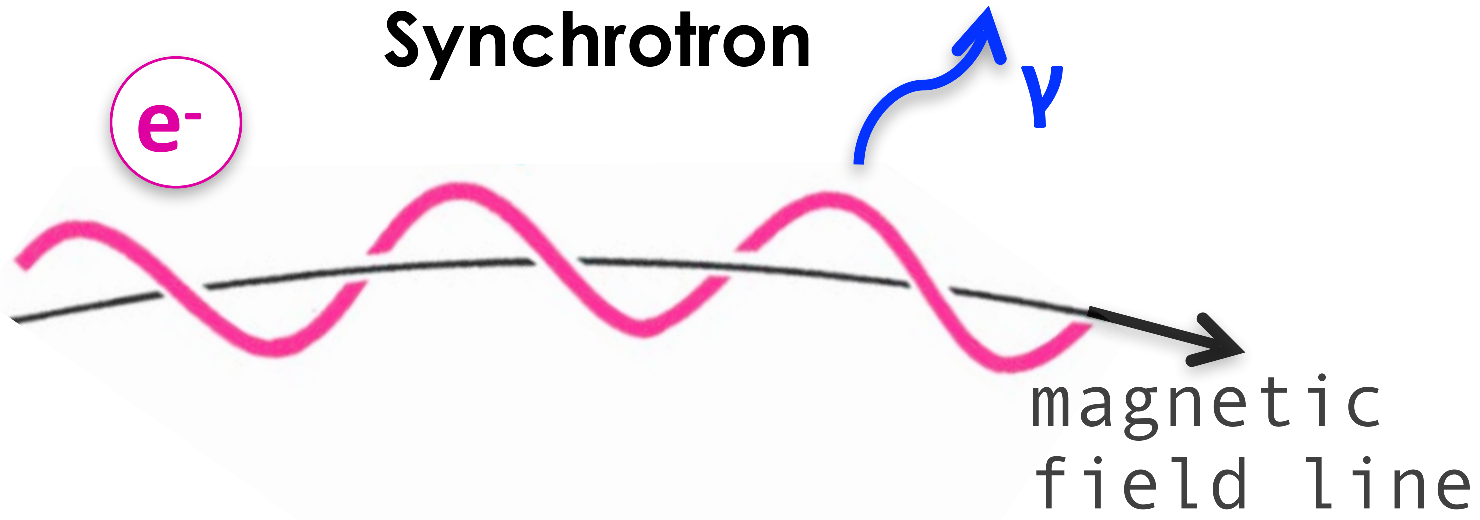
First clear evidence of a second emission component (SSC - blazar-like)

GRB190114C: 1st GRB at VHE!

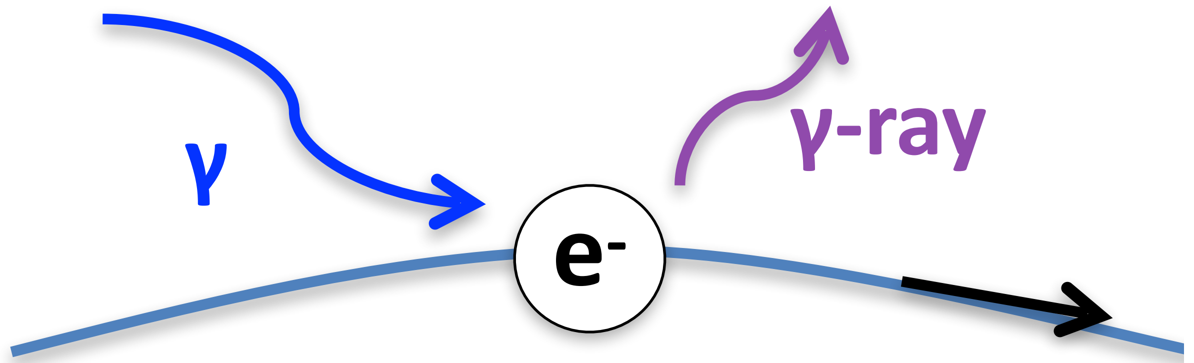


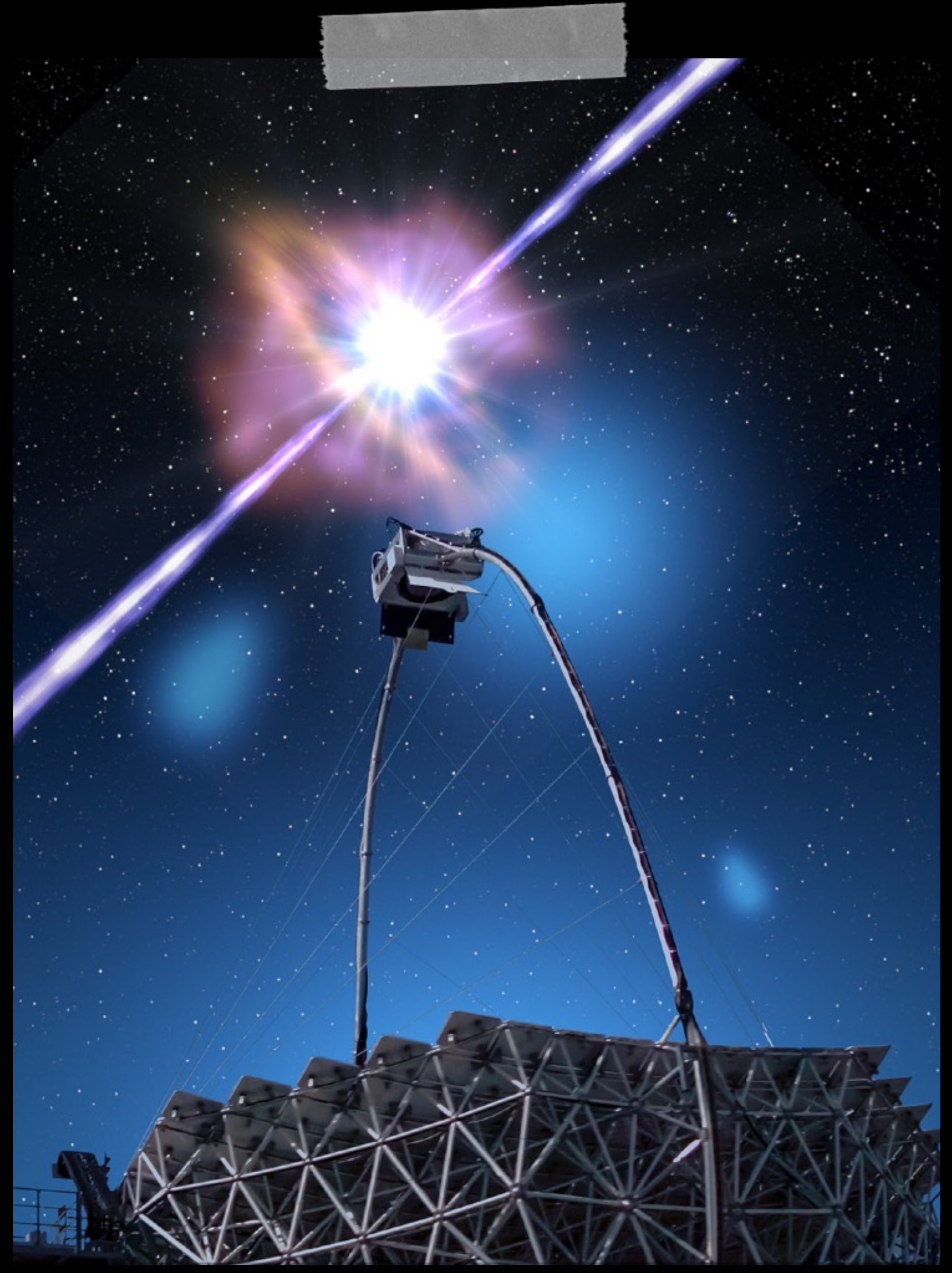
Synchrotron Self-Compton

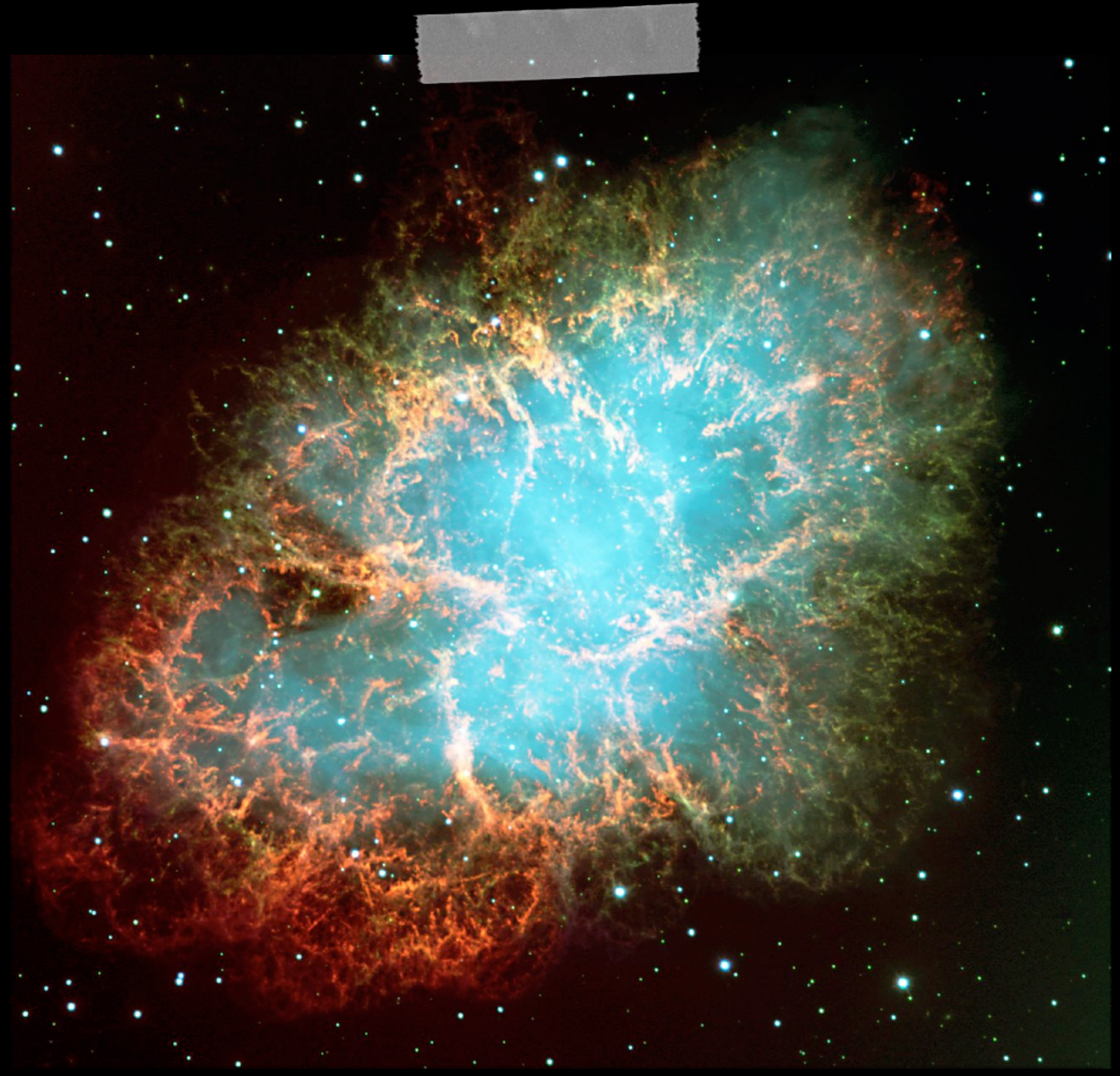
Synchrotron

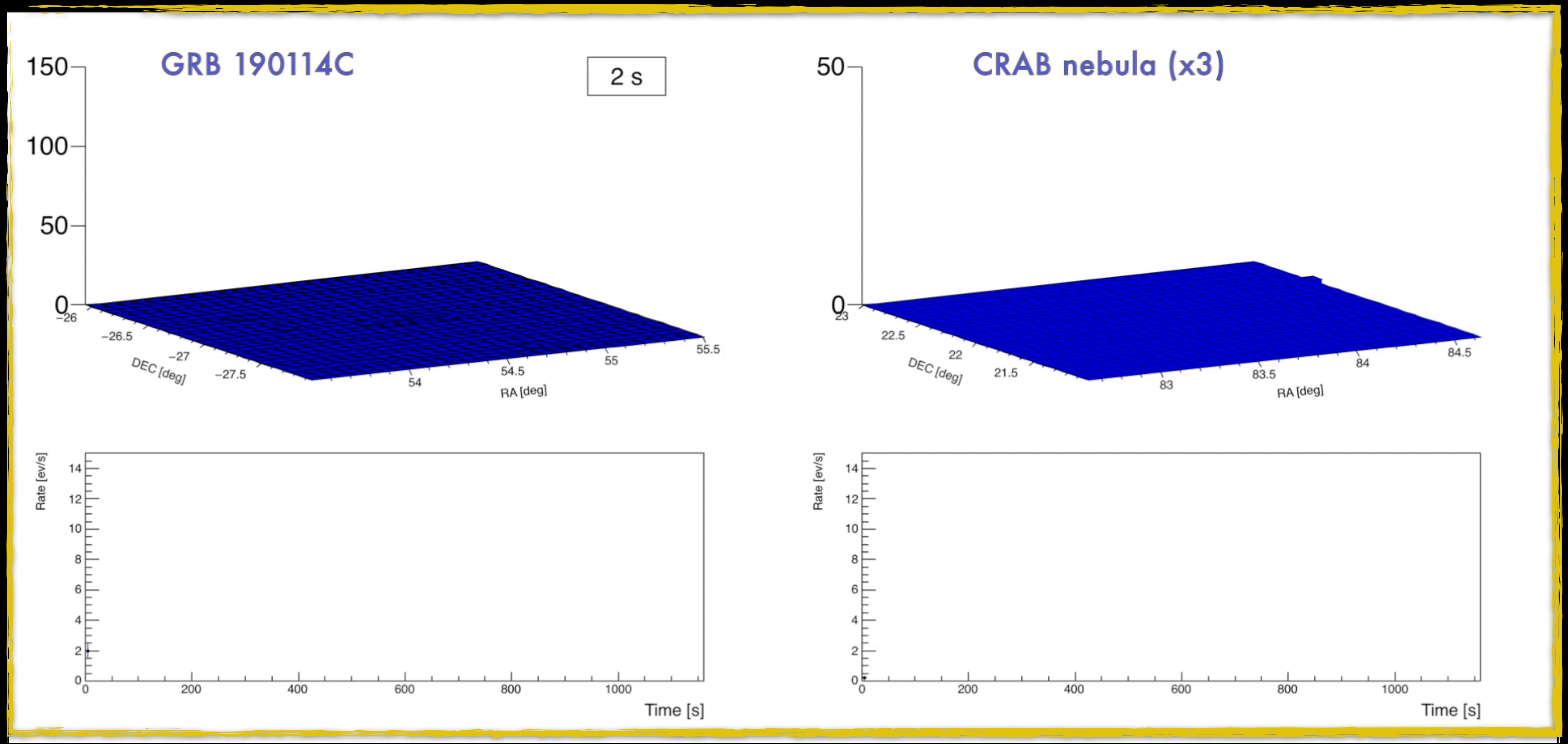


Inverse Compton







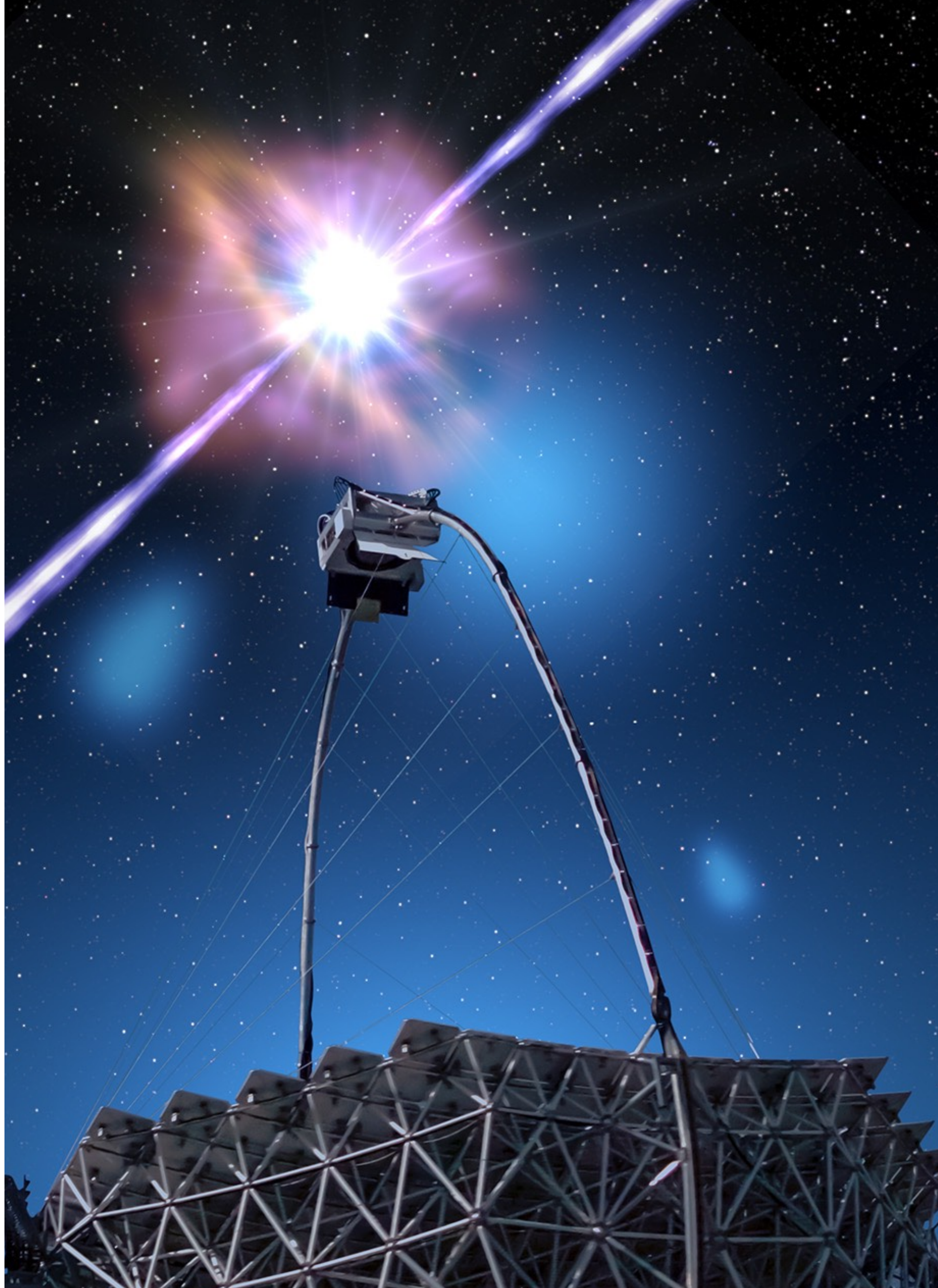


GRB 190114C es la fuente más brillante detectada en rayos gamma: x1000 Crab!

GRB190114C

- 1st GRB unambiguous detection at TeV energies
- 1st GRB observed over 20 orders of magnitude in energy
- 1st GRB with unambiguous detection of a new energetic emission component distinct from synchrotron
- 1st single broad-band modeling of a GRB including both components
- Brightest TeV source ever detected (>~ 100 crab) *

from A. Carosi



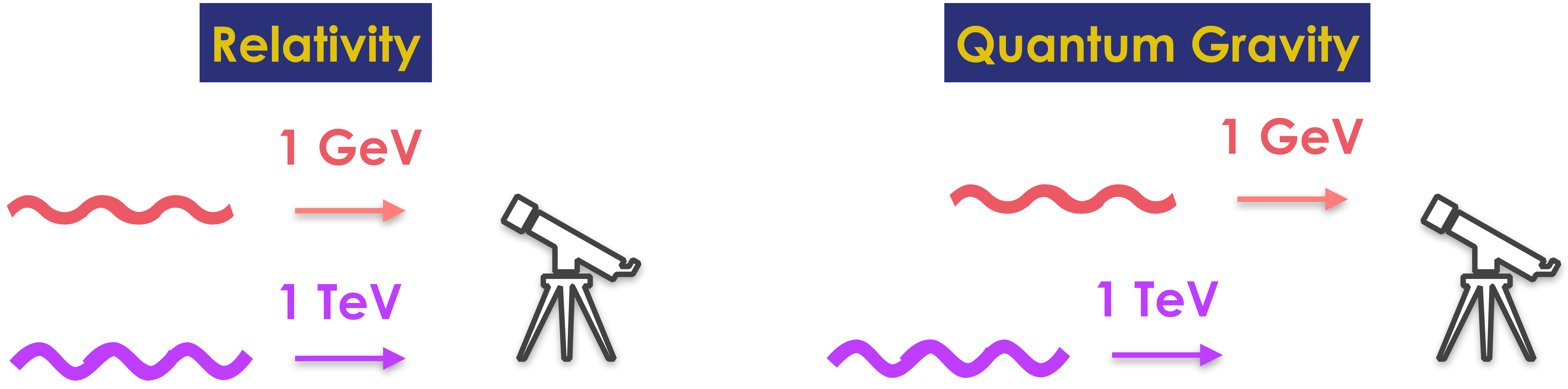
L

I

V

Lorentz Invariance Violation

- Einstein's theory of Relativity postulates: the **speed of light in a vacuum is a constant** independent of the energy of photons
- Quantum theories of gravity: speed of light might be energy dependent -> **Lorentz invariance violation (LIV)**
  - **Best measured over long distances**
  - **Difference greater at higher energies**



VHE gamma ray telescopes can be especially competitive in the search for LIV effects

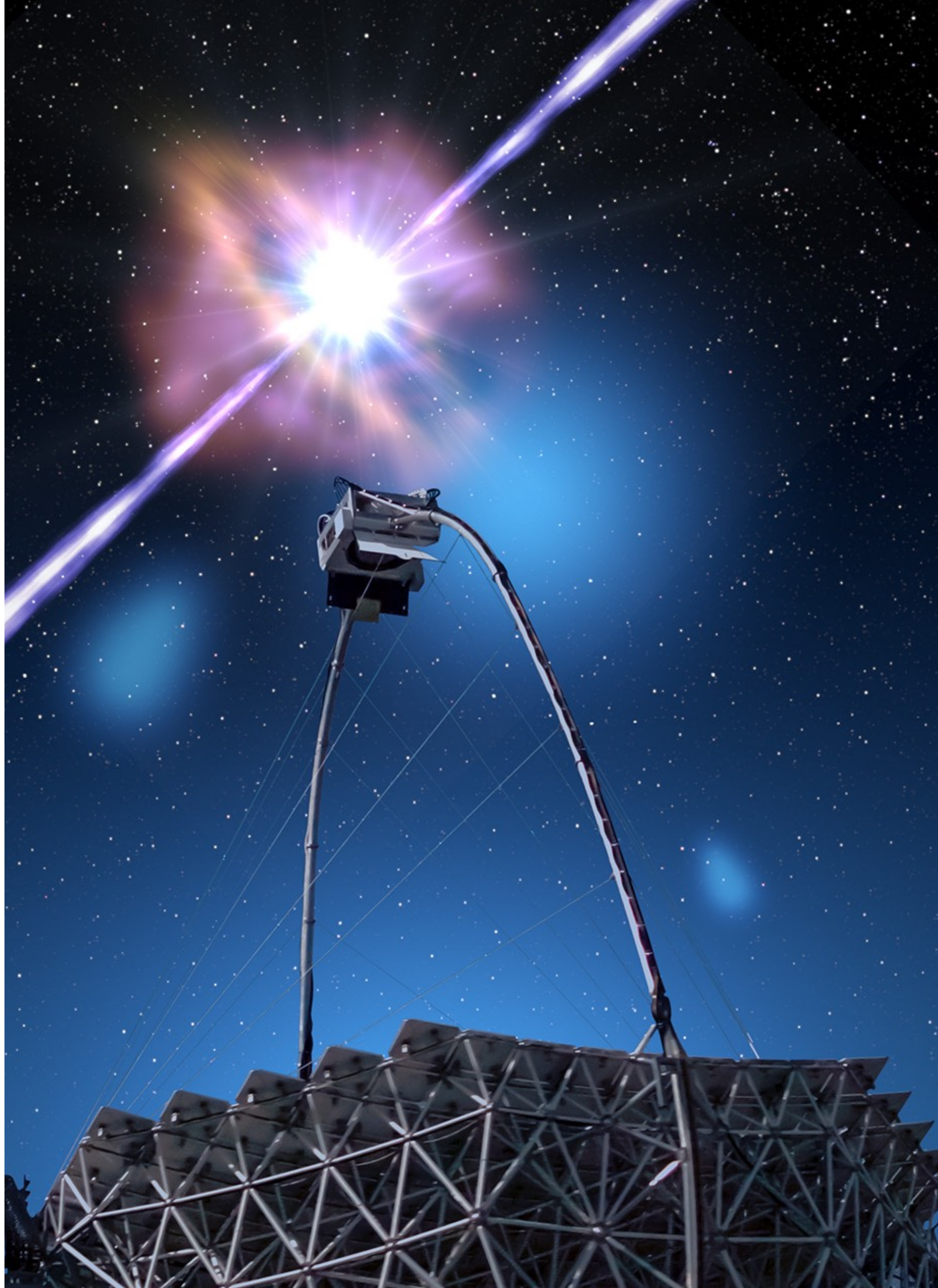
LIV tests with GRB190114C

- Measured the **arrival times and energies of photons**
- Models to describe the temporal evolution of the emission
- **No energy-dependent time delay in arrival times of gamma rays**
  - strong constraints on some quantum gravity theories

First LIV studies with a GRB at VHE (Acciari et al. 2020)

- LIV also measured with blazars (Albert et al. 2008, Abramowski et al. 2011, Abdalla et al. 2019..) and pulsars (Ahnen et al. 2017, Zitzer et al. 2013)

….now coming back to GRBs at VHE …



GRB 180720B

GBM trigger at 14:21:39 UTC

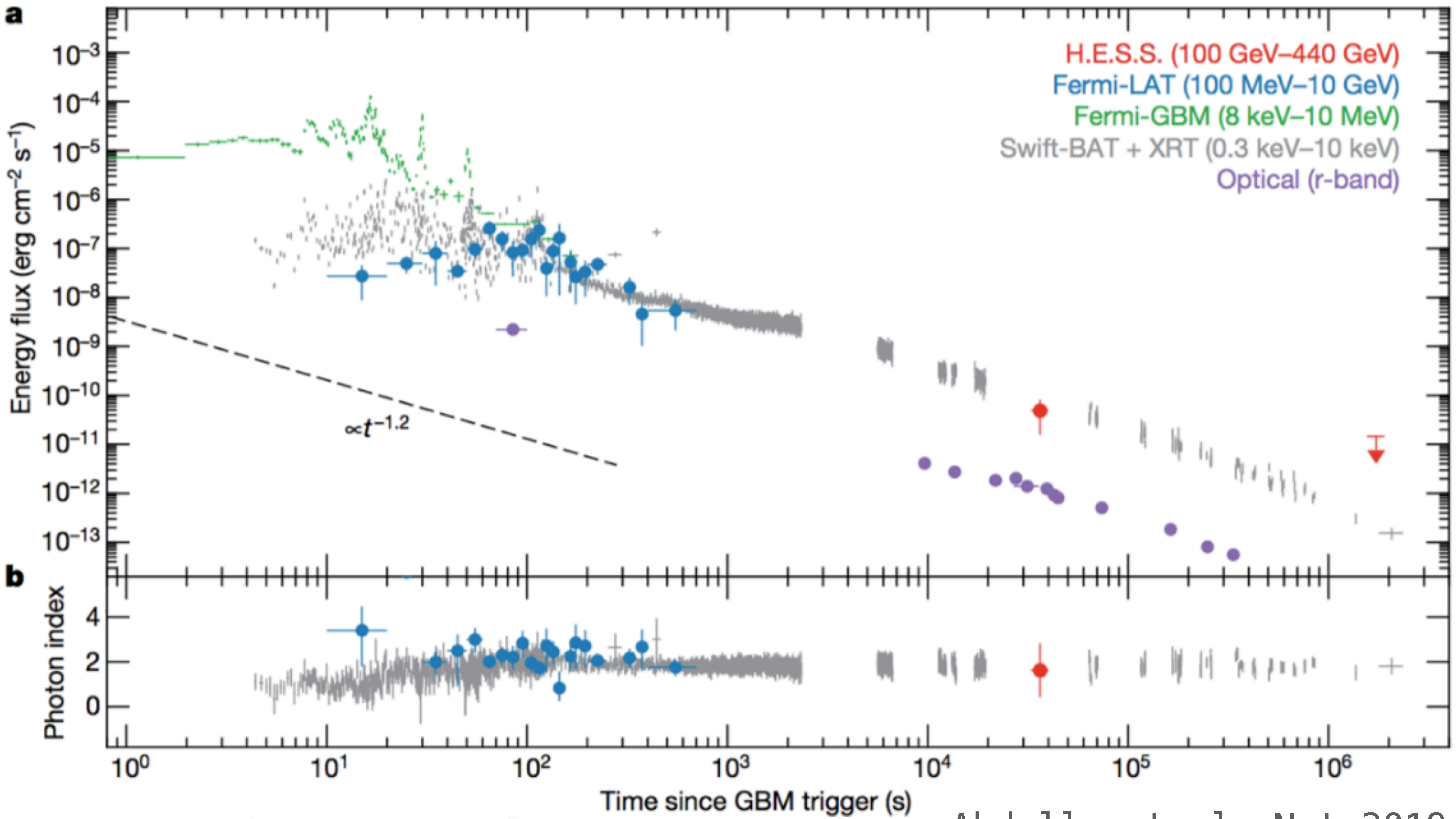
- ❑ $z = 0.653$ (VLT/X-shooter)
- ❑ LAT: detected up to $T_0 + 700$ s
- ❑ Emax = 5 GeV, $T_0 + 142$ s
- ❑ $T_{90} = 48.9 \pm 0.4$ s
- ❑ $E_{iso} \sim 6 \times 10^{53}$ erg (50-300 keV)

(6th brighter GBM event)
(2nd highest 11 hr flux in XRT)

H.E.S.S. follow up:

- ❑ start at T_0+10 hr
- ❑ Total exposure: 2 hr

A very high energy component deepin the Gamma-Ray Burst afterglow, H. Abdalla et al. (H.E.S.S. Coll.), Nature, 575, 464



Abdalla et al. Nat 2019

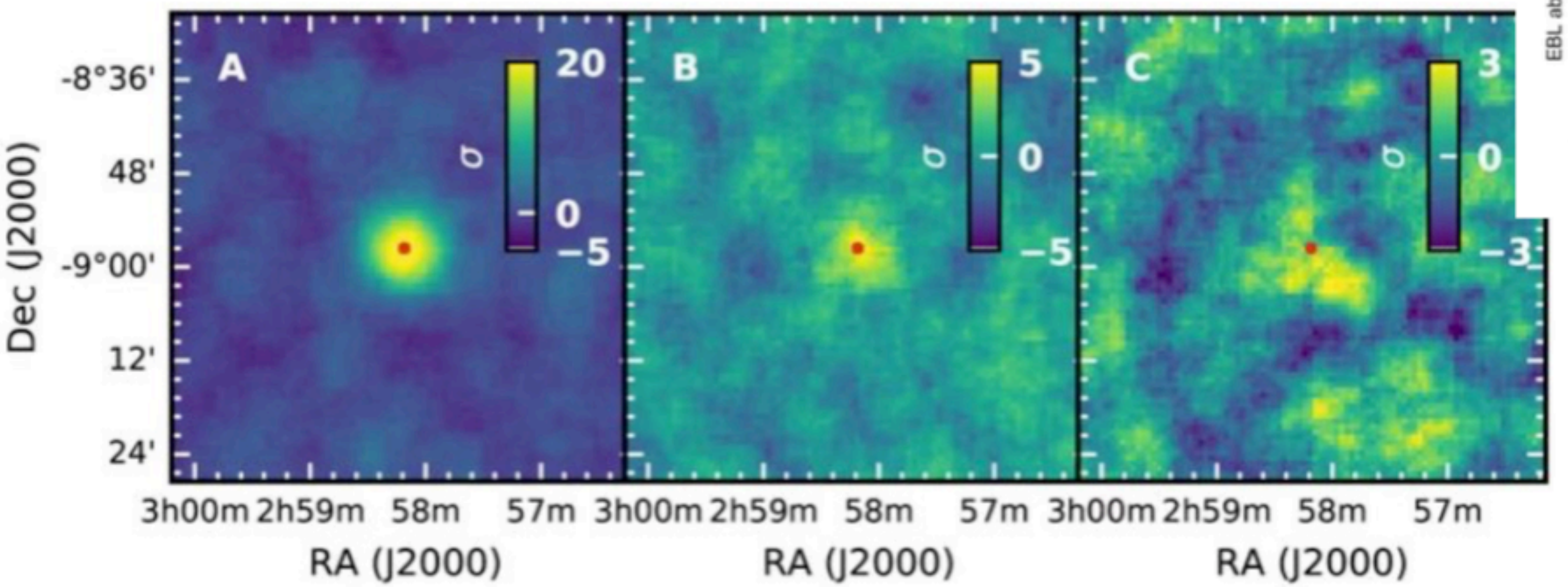
Slide from A. Carosi

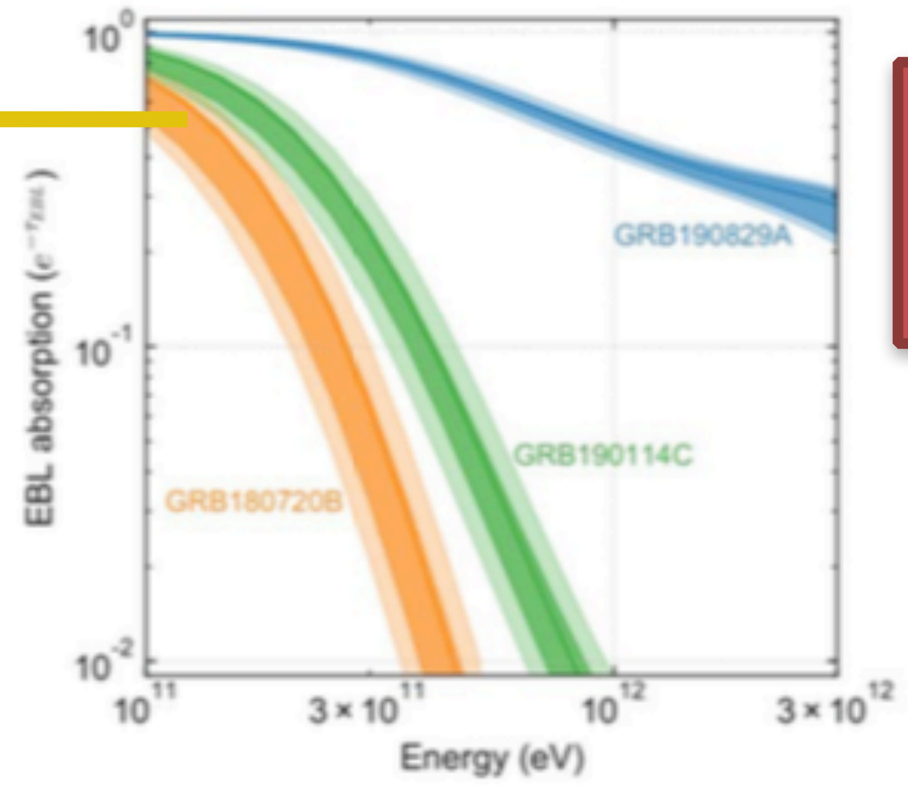
VHE emission deep in the afterglow

GRB 190829A

Synchrotron emission extending to VHE?

Other authors suggest SSC /EIC (Salafia et al. 2022, Sato et al. 2022, Zhang et al. 2021)

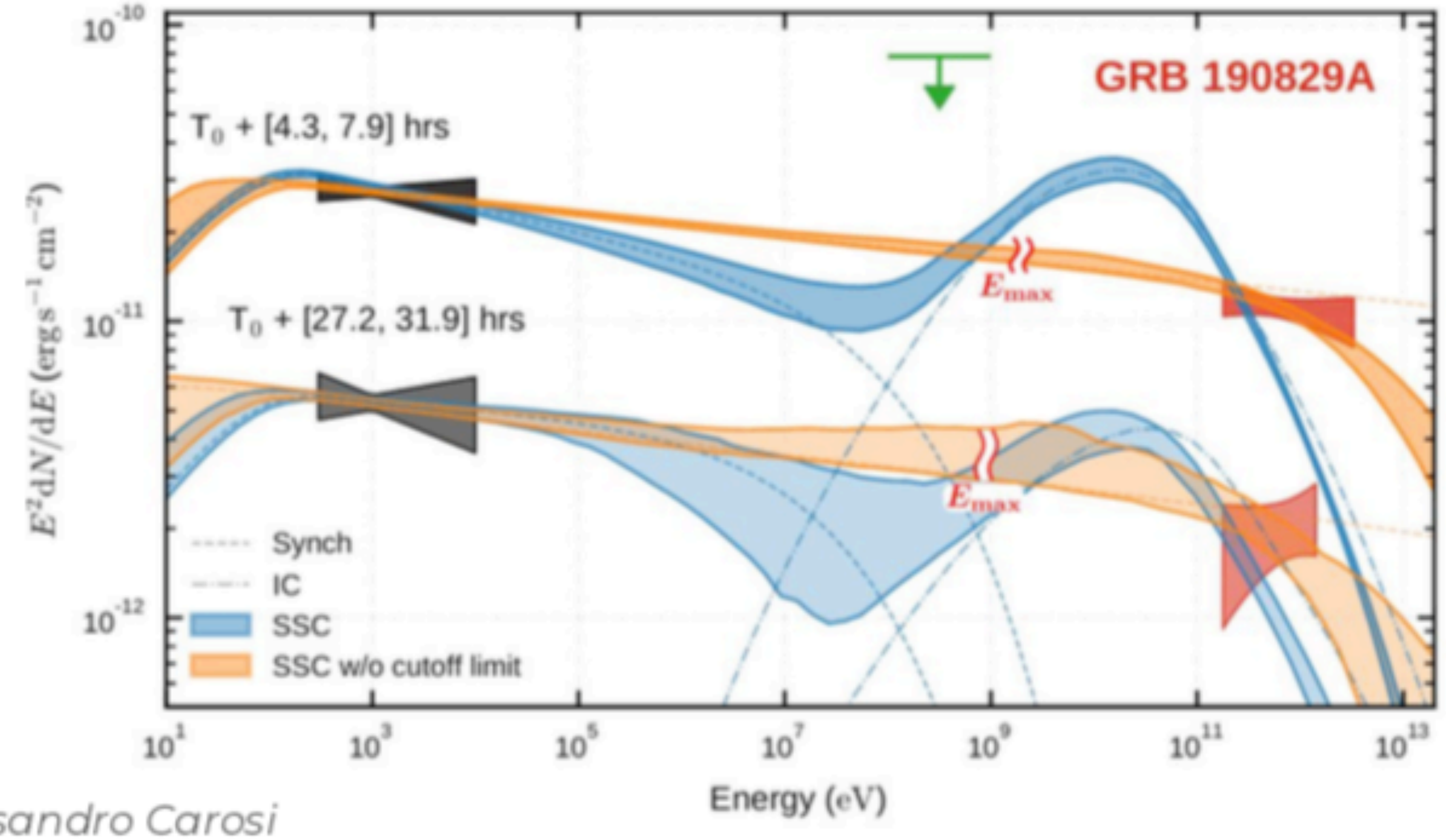




- SSC model unlikely
- challenging the the synchrotron burnoff limit → acceleration mechanisms?

H.E.S.S.

Revealing X-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow, H. Abdalla et al. (H.E.S.S. Coll.), Science, 372, 6546



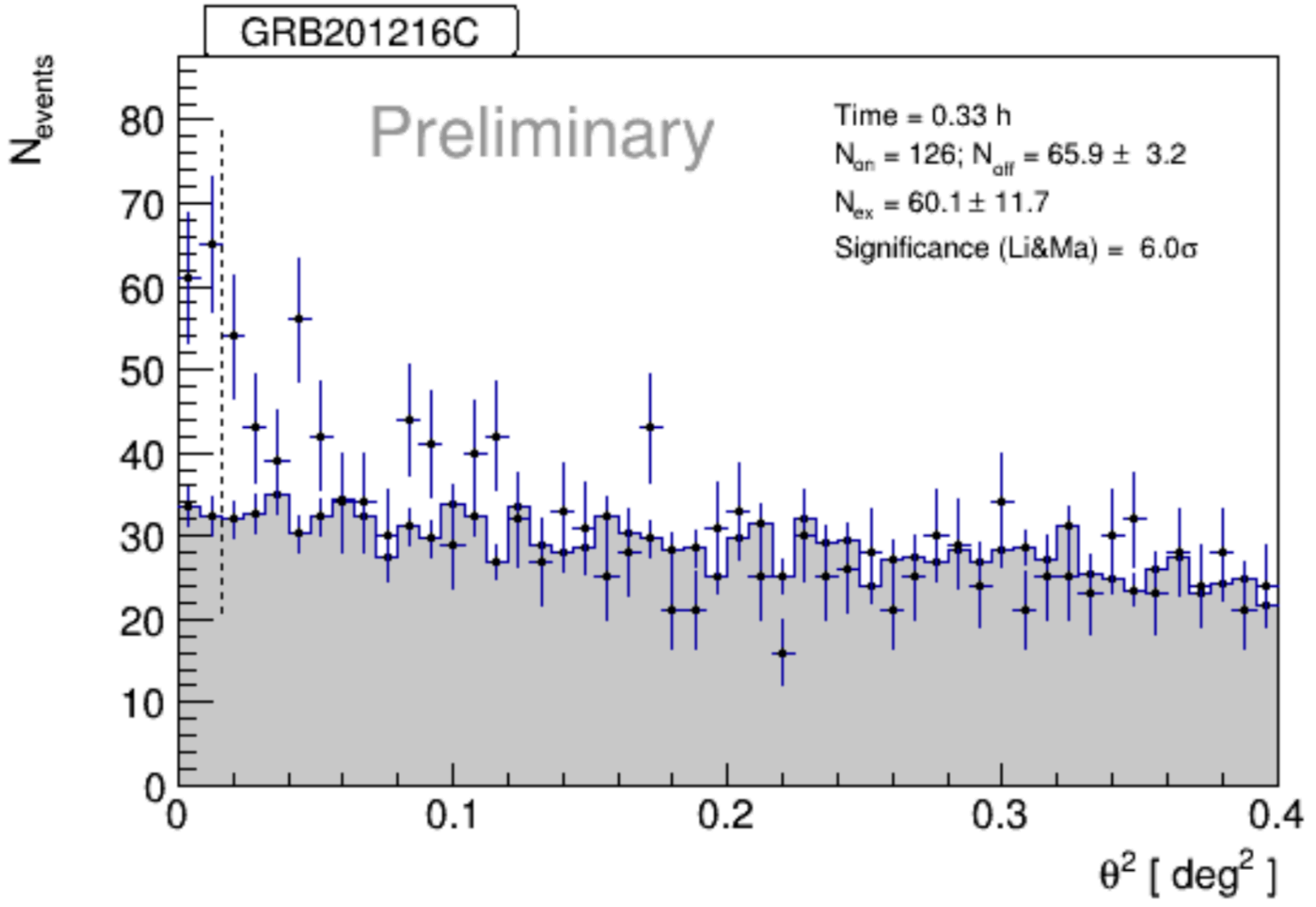
Detected by Swift and Fermi-GBM on 2019/08/29 at 19:56:44 UTC (swift T_0)

- very low-luminosity (E_{iso}~ 2 x 10^{50} erg) & nearby (z~0.08) event
- Not detected by Fermi-LAT (~ 100 MeV - 100 GeV)
- Prompt emission (T_{90}) <~ 1 min;
- low value of E_{peak} ~ 11 keV but harder precursor
- Beside a large flare at $T=T_0+103$ s, quite normal X-ray afterglow behaviour

Slide from A. Carosi

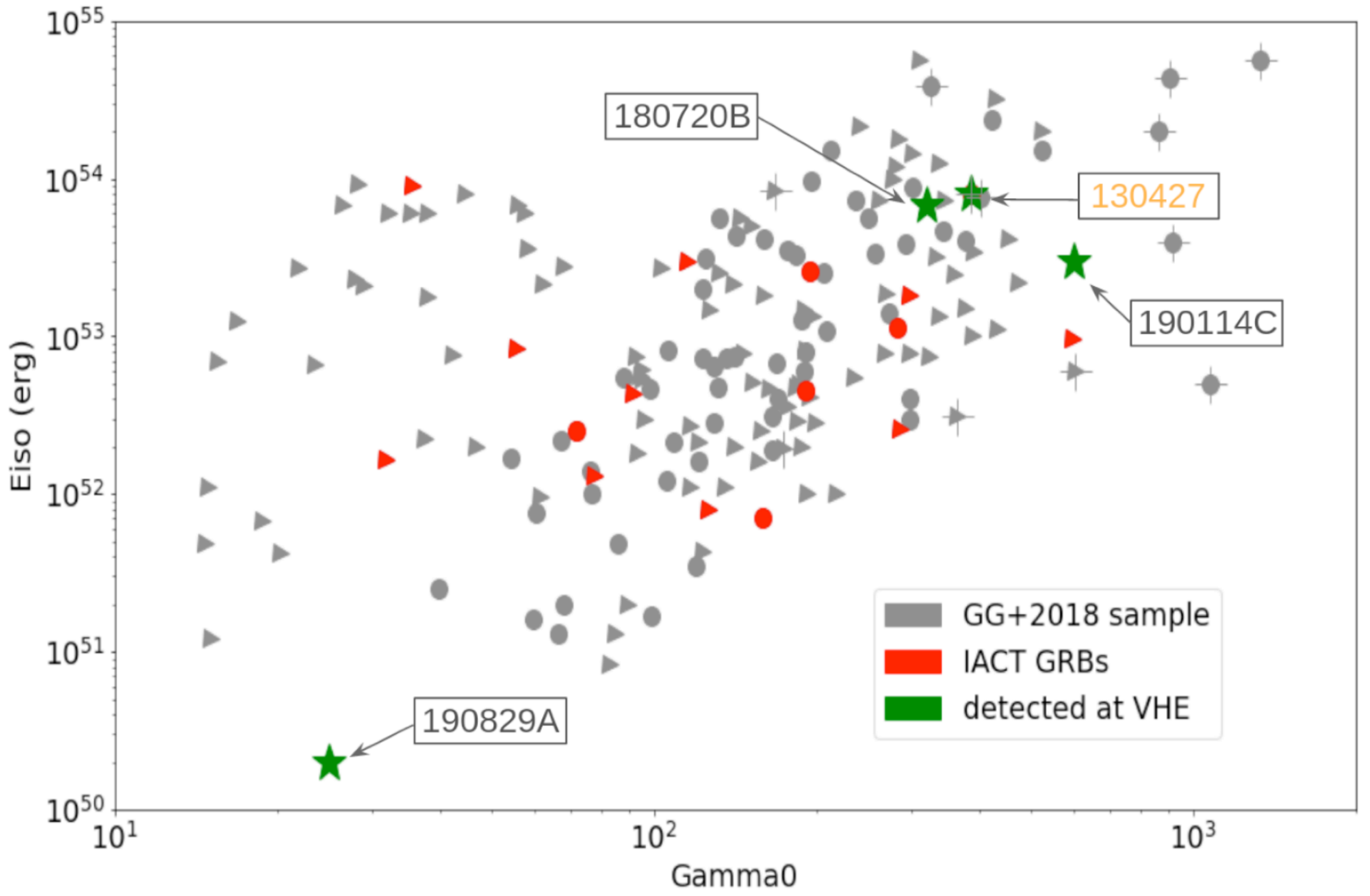
GRB 201216C

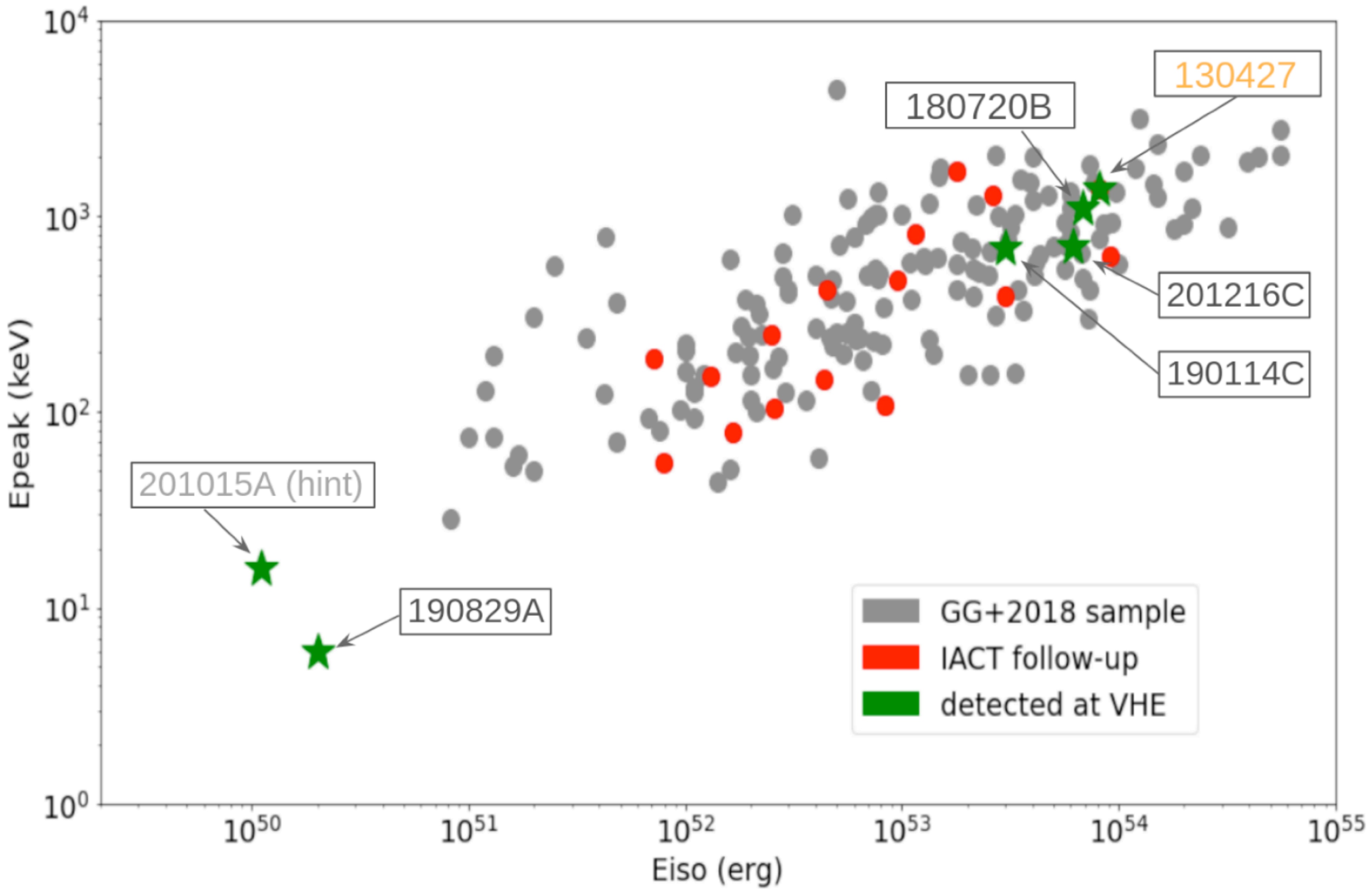
- **Most distant VHE source: z=1.1**
- Discovered by MAGIC (GCN 29075, Fukami et al. 2021)
  - Observations T0+56 seconds after Swift/BAT alert
  - Due to the strong absorption effect by EBL a very steep power-law decay was found for the observed spectrum
  - The intrinsic spectrum, corrected for the EBL absorption was found to be consistent with a flat single power-law until 200 GeV
  - After 50 min only upper limits on the emitted flux have been derived since no significant emission was found after this time.



Fukami et al. 2021

GRBs at VHE





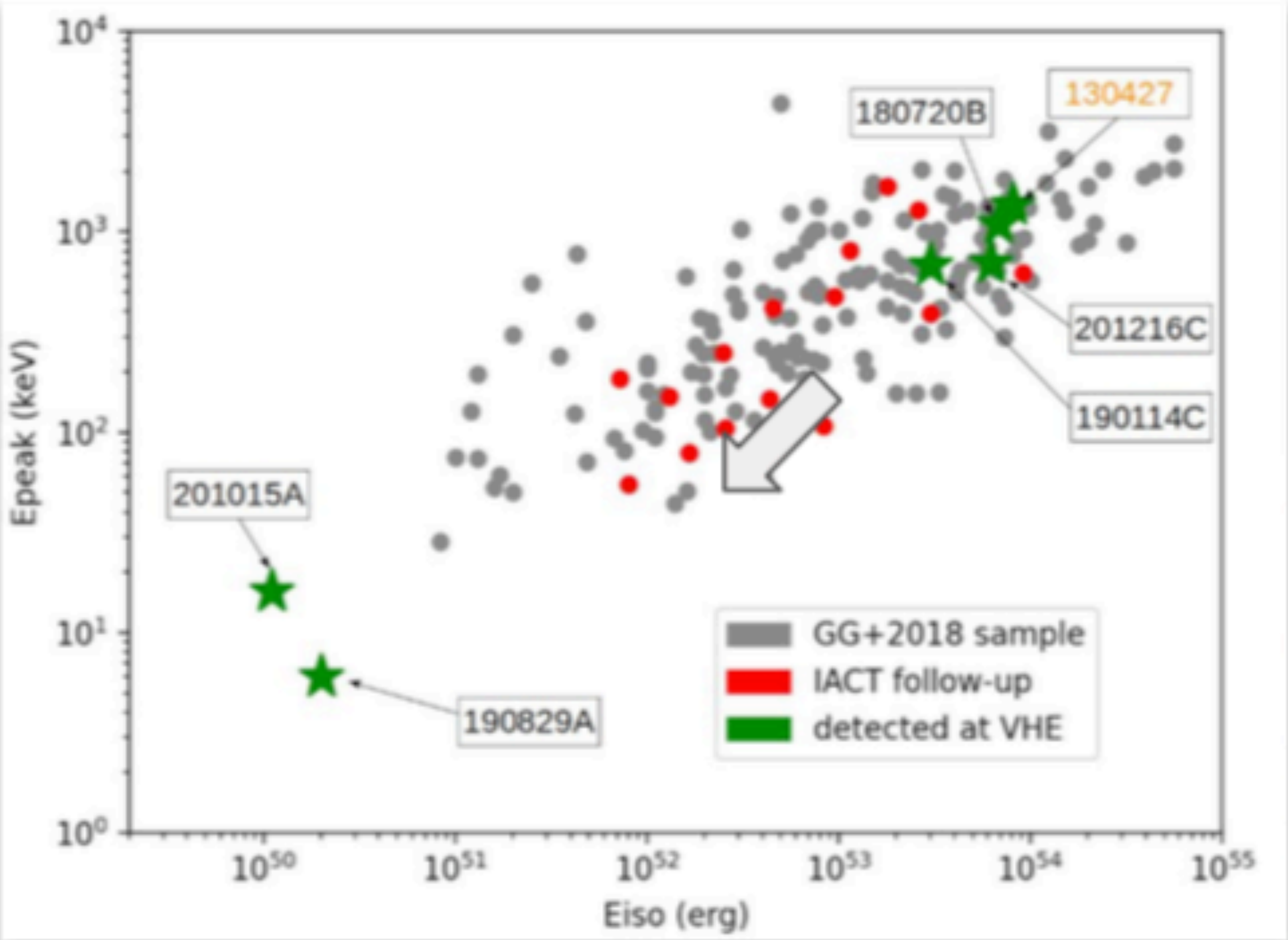
Berti & Carosi 2022

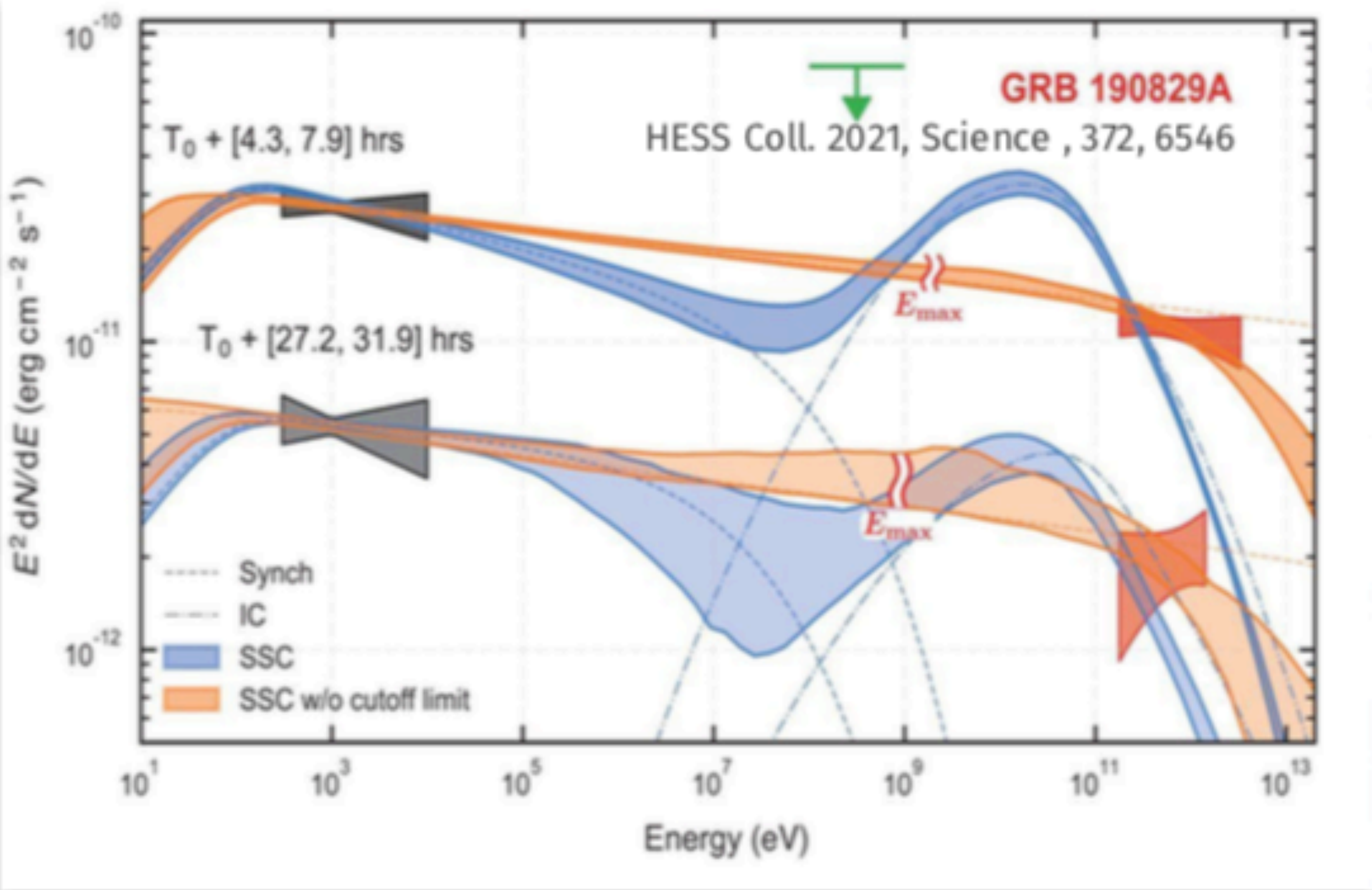
Name	T_{90} [s]	Redshift	E_{iso} [erg]	IACT	α_{obs}	E_{max}
180720B	48.9	0.653	6 × 10^{-53}	H.E.S.S.	3.7 ± 1.0	440 GeV
190114C	362	0.4245	3 × 10^{-53}	MAGIC	5.43 ± 0.22	1 TeV
190829A	58.2	0.0785	2 × 10^{-50}	H.E.S.S.	2.59 ± 0.08	3.3 TeV
201216C	48	1.1	5 × 10^{-53}	MAGIC	-	-
201015A	9.8	0.423	10^{-50}	MAGIC	-	-

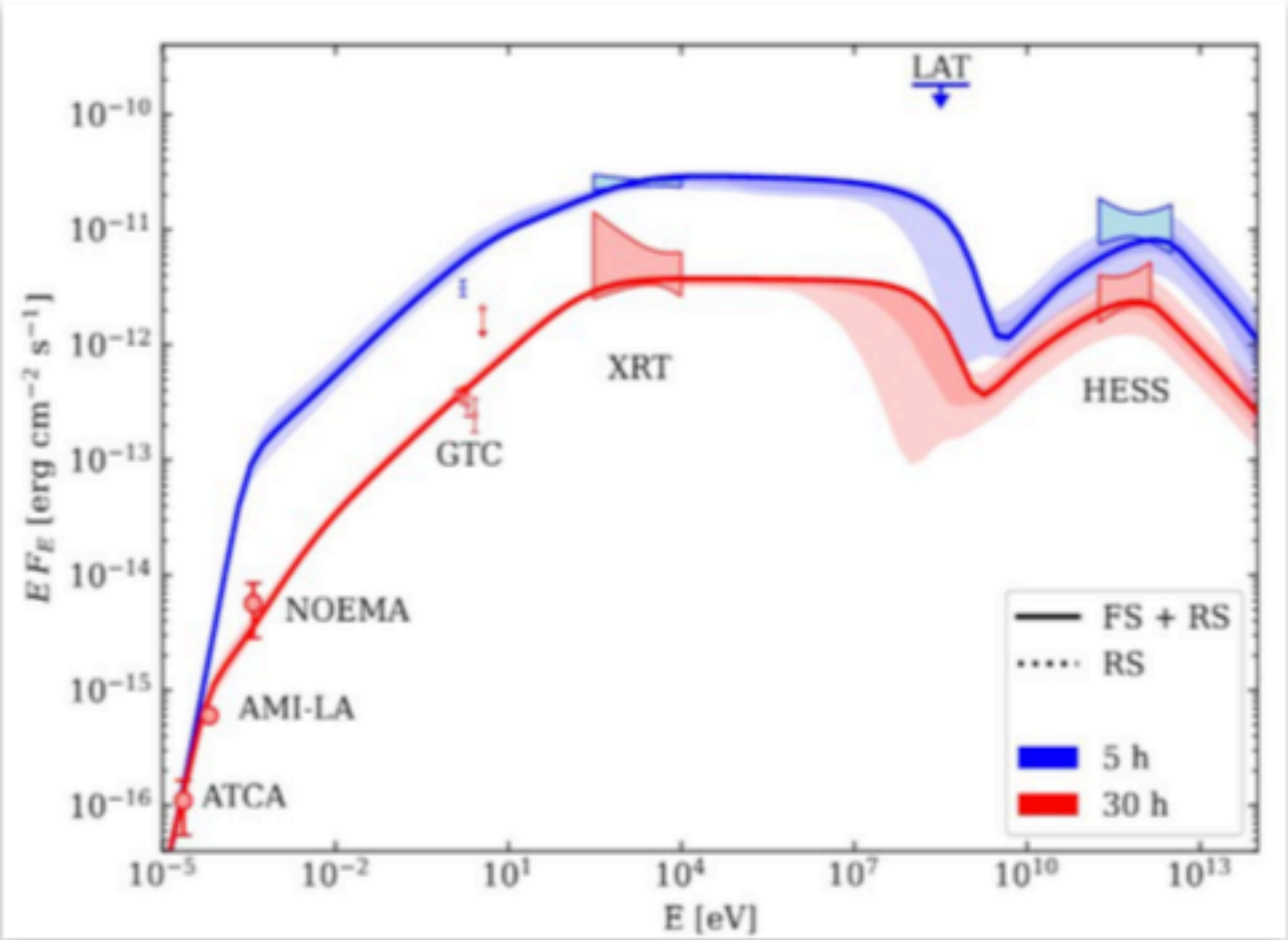
GRBs at VHE

Although the quest for the first detection is over, we are now moving to the phase of physics interpretation and, possibly, populations studies

- ❑ Which are the emission mechanisms? VHE during afterglow and/or prompt? ***Do all GRB have a VHE component?*** Why haven't we detected GRB before ?
- ❑ We now had few detections (like GRB 180720B and GRB 190114C) that were somehow 'expected' (bright, powerful etc). However, we also have something that is (apparently) different. Are we observing the first (or one of the first) event of a new GRB population? Or do we just have to think that the parameters space of the possible VHE-emitter GRB is much larger than we thought in the past?







- prompt?

Slide from A. Carosi

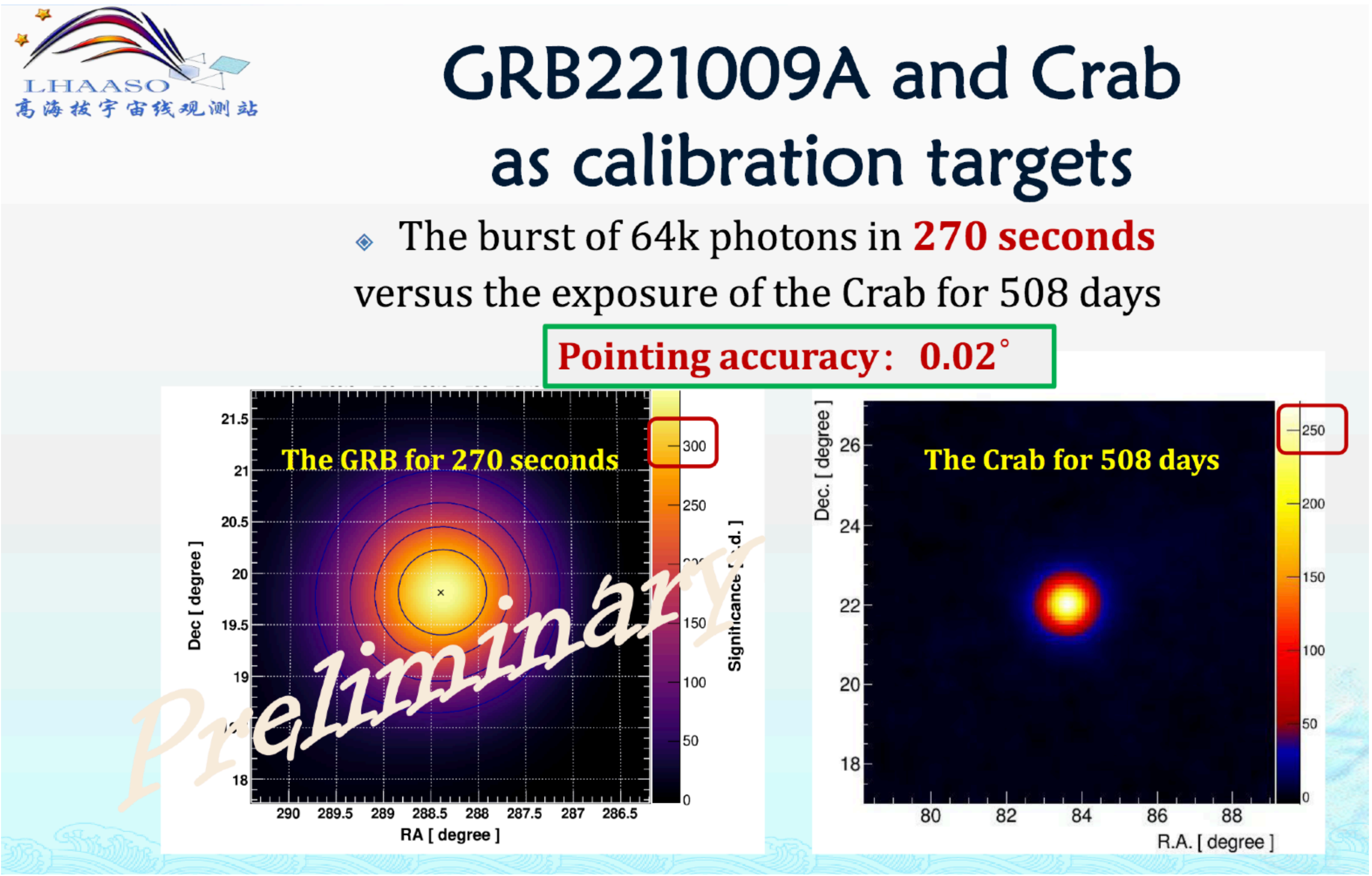
GRB 221009A: Brighest of all times (BOAT)

- **Unusually bright and long-lasting** discovered by Swift (GCN 32635), Fermi-GBM (GCN 32636) and Fermi-LAT (GCN 32637)
  - 1 in 10000 year event! (Laskar et al. 2023)
    - E~10^{55} erg (An et al 2023)
    - z=0.151 (GCN 32648)
    - LAT emission lasted for 2 days
    - Probably detectable with radio telescopes for years (Laskar et al. 2023)

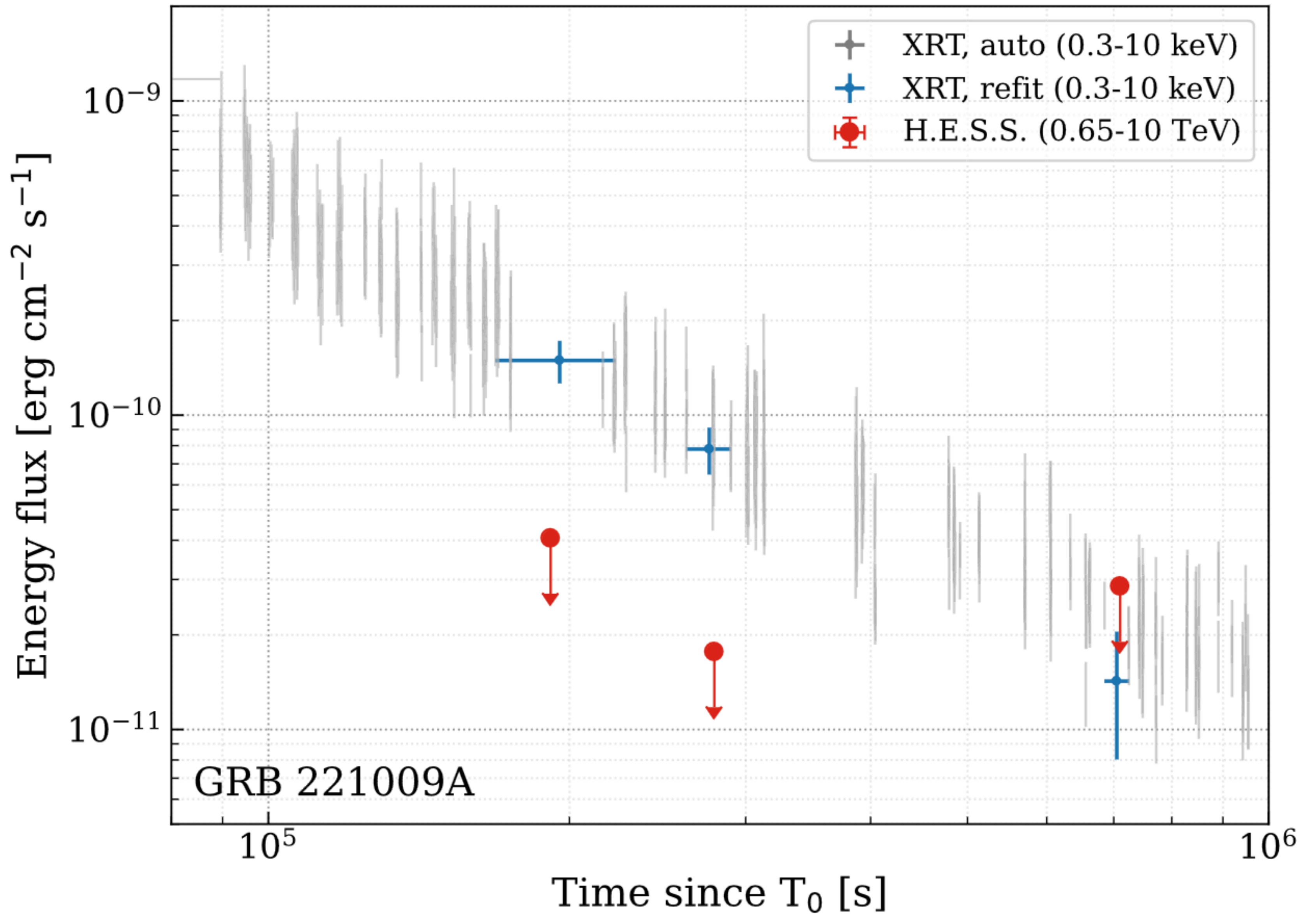
- **Detection by LHAASO** (GCN 32677):
  - **more than 5000 photons up to 18 TeV**!!
  - T0+2000 seconds (>100 sd) -> **no prompt emission**!

- **No IACT detection** claimed (Aharonian et al. 2023)

- **No neutrino** found across event samples ranging from MeV to PeV energies (Abbasi et al. 2023)



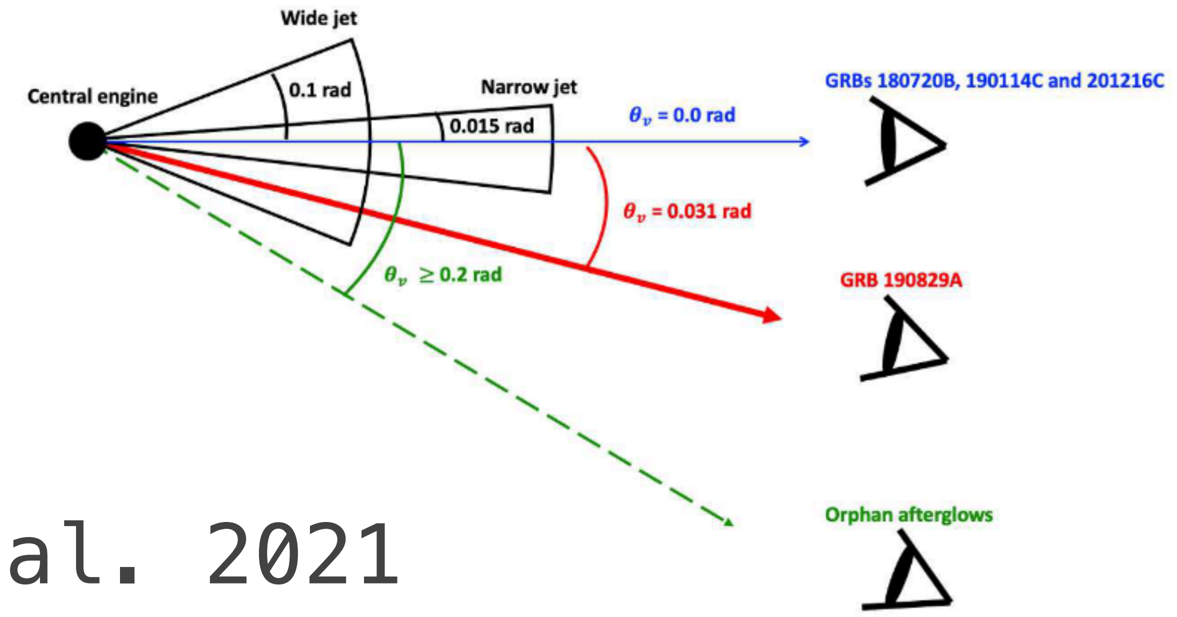
Slide from Z. Cao



Aharonian et al. 2023

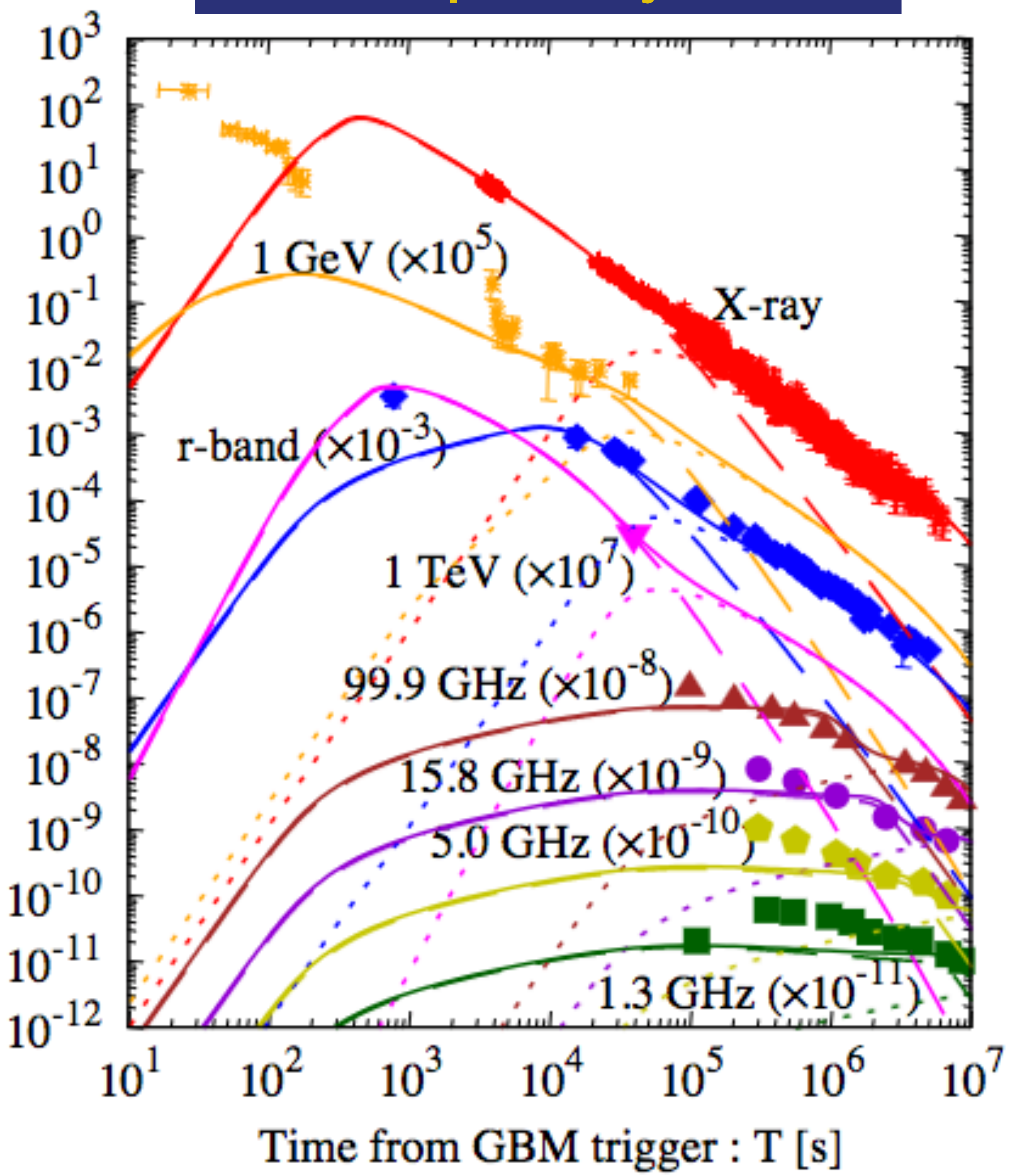
GRB 221009A: Brighest of all times

- The physics:
  - GRB 221009A and other energetic GRBs:
    - same energy function and luminosity function as normal lGRBs
    - statistical properties are consistent with normal lGRBs suggest that there is nothing special for these bursts except their apparent brightness (Lan et al. 2023)
      - they **likely share the similar progenitor systems** and experience similar energy dissipation processes and radiation mechanisms as normal lGRBs
      - Differences due to the jet viewing angle?
    - **Structured jet** (O'Connor et al. 2023)
    - Two component jet: wide+narrow (Sato et al. 2023):
      - **gamma-ray photons from the SSC component of the narrow jet**



Sato et al. 2021

Two-component jet model

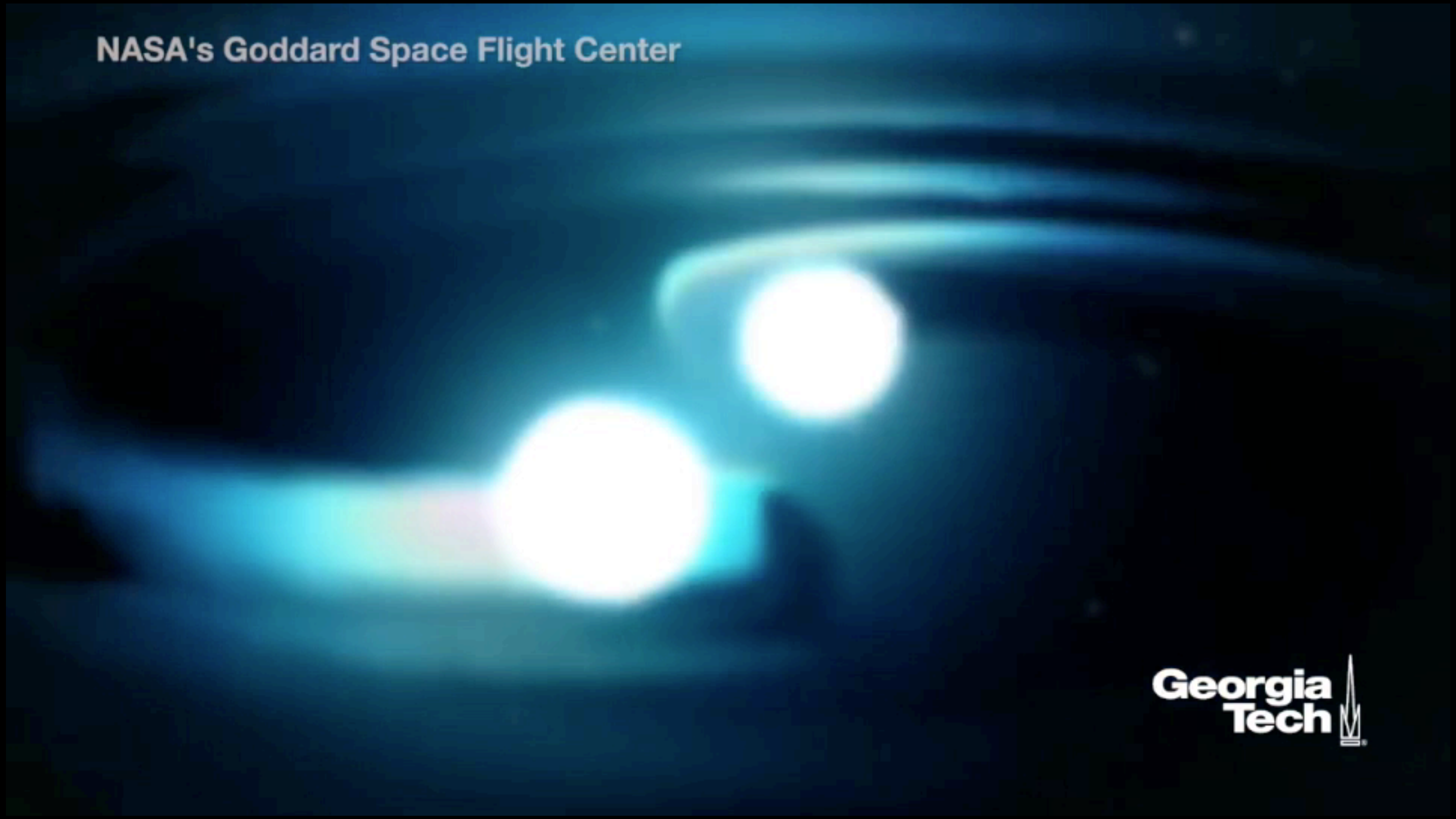


Sato et al. 2023

SSC to explain VHE ?

- Two proposed models: SSC (external IC) and synchrotron
- A simultaneous SED covering X-ray, HE and VHE range should be enough to discriminate:
  - hardening of the spectrum from GeV to TeV energies should be the smoking gun for the presence of a distinct component -> SSC
  - VHE emission as extension of synchrotron up to TeV-> synchrotron
  - **modeling suggest that the responsible VHE radiation mechanism is the SSC emission** although different mechanisms (e.g. synchrotron radiation, EIC) cannot be completely excluded and a conclusive answer cannot be given yet (Miceli & Nava 2022)
- More detections needed to clear out the emission mechanisms

Gravitational Wave counterparts

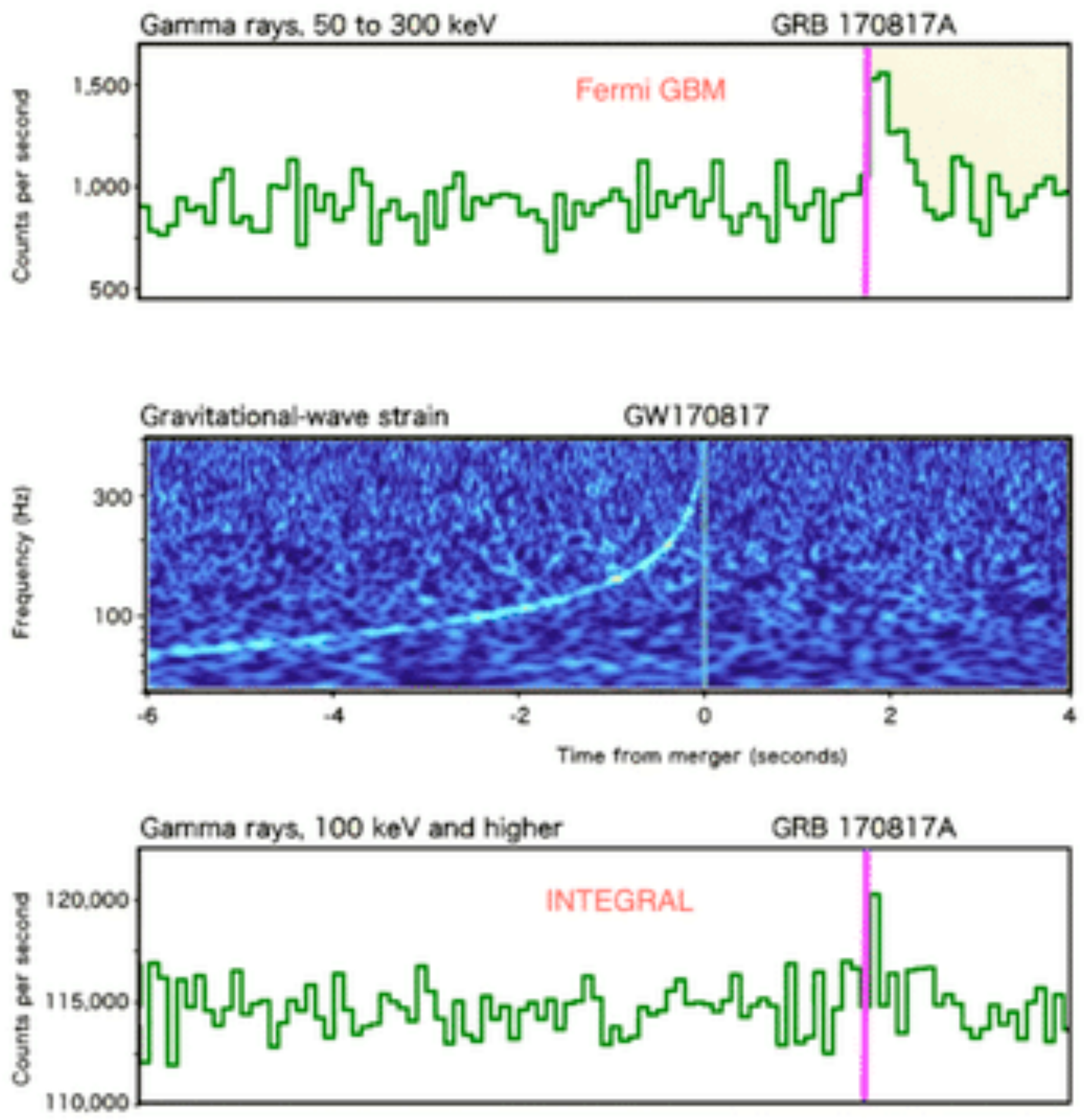


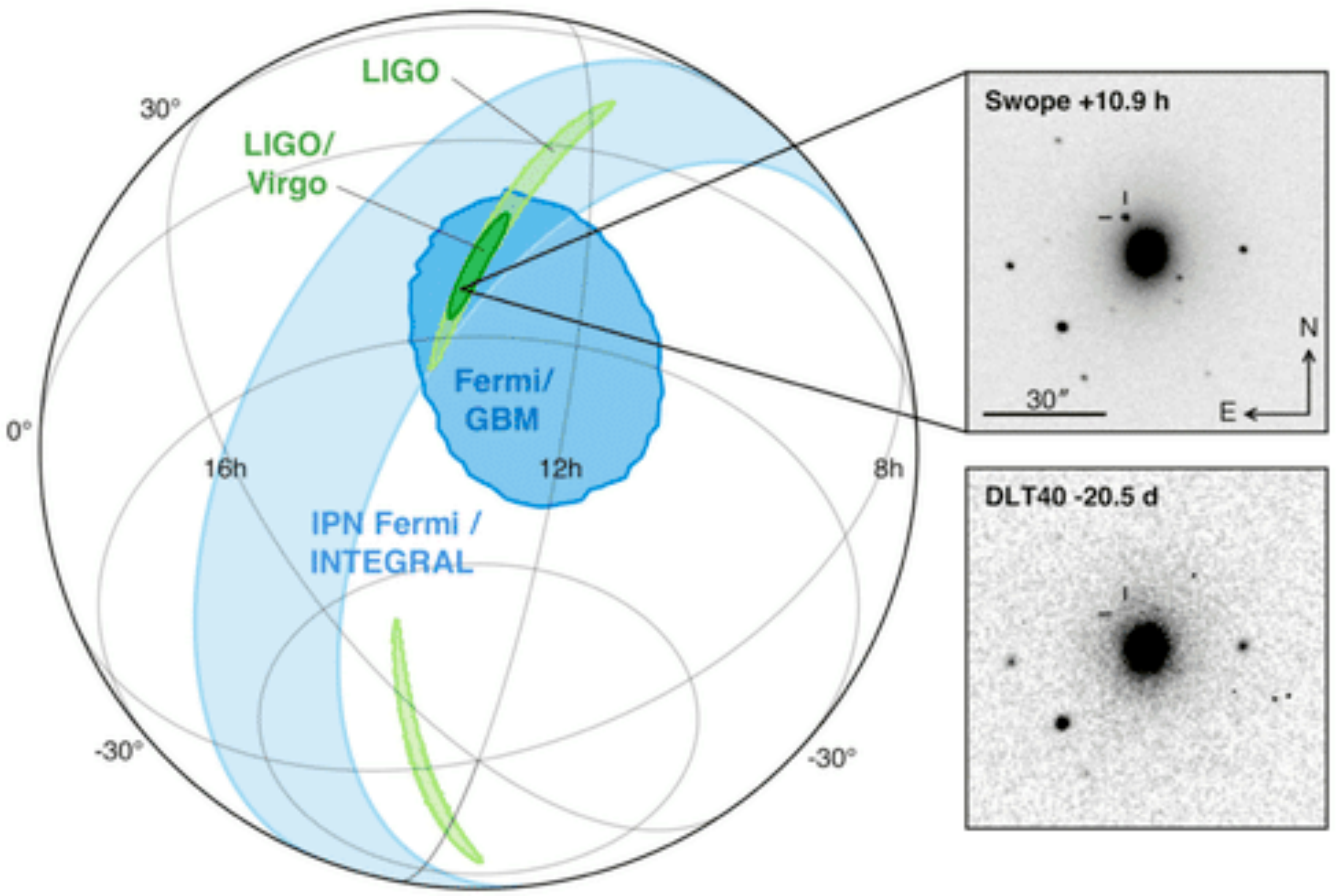
sGRBs: Binary neutron star (BNS) mergers

- **GW 170817 (On 2017 August 17, at 17:54:51 UTC): binary NS merger** detected by **LIGO/VIRGO** (Abbot et al. 2017)
    - **EM counterpart GRB170817: kilonova**
    - Result: BH (2.73 - 3.29 M⊙)

Birth of multi-messenger astronomy with GW

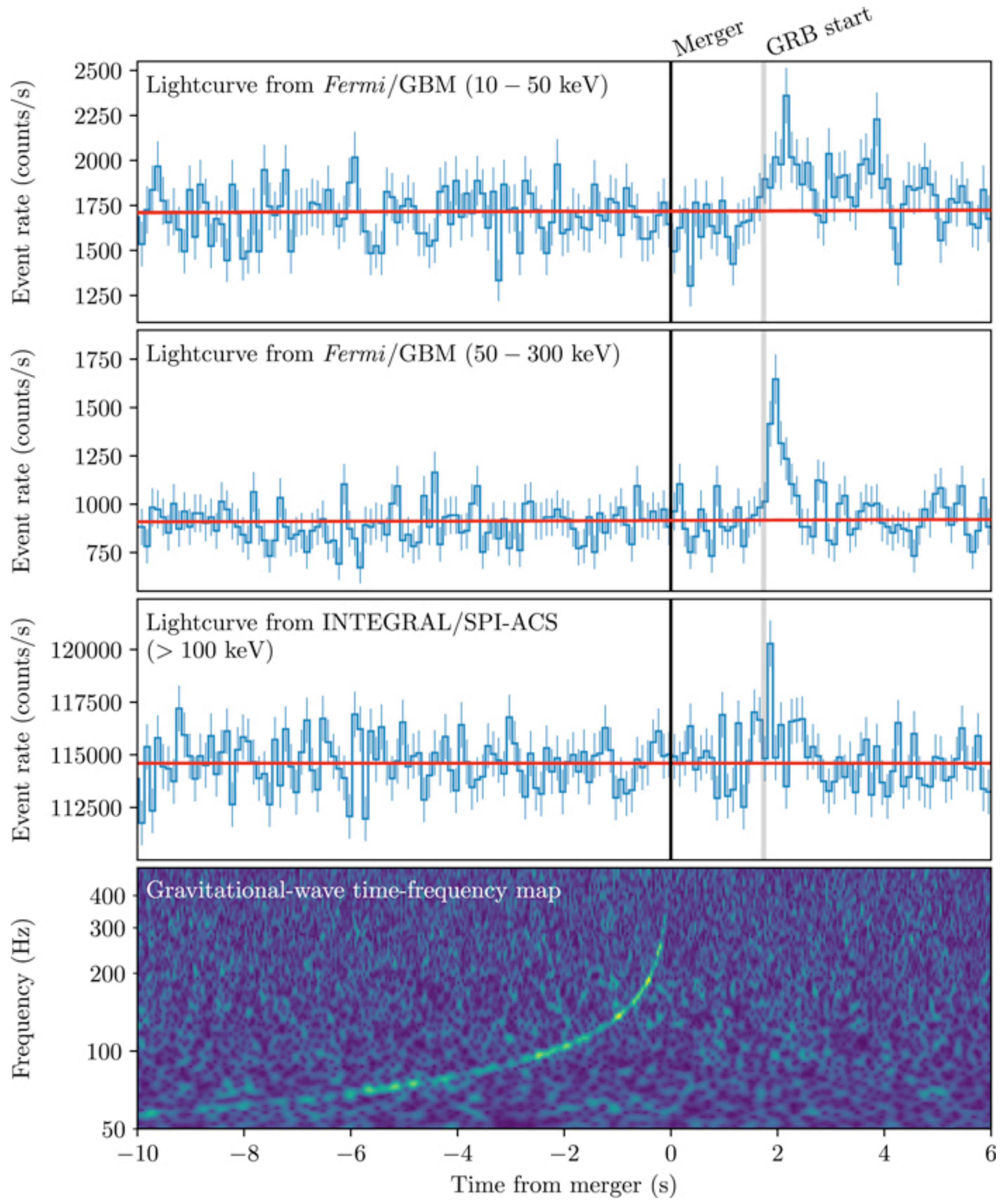
First evidence of BNS mergers as progenitors for sGRB



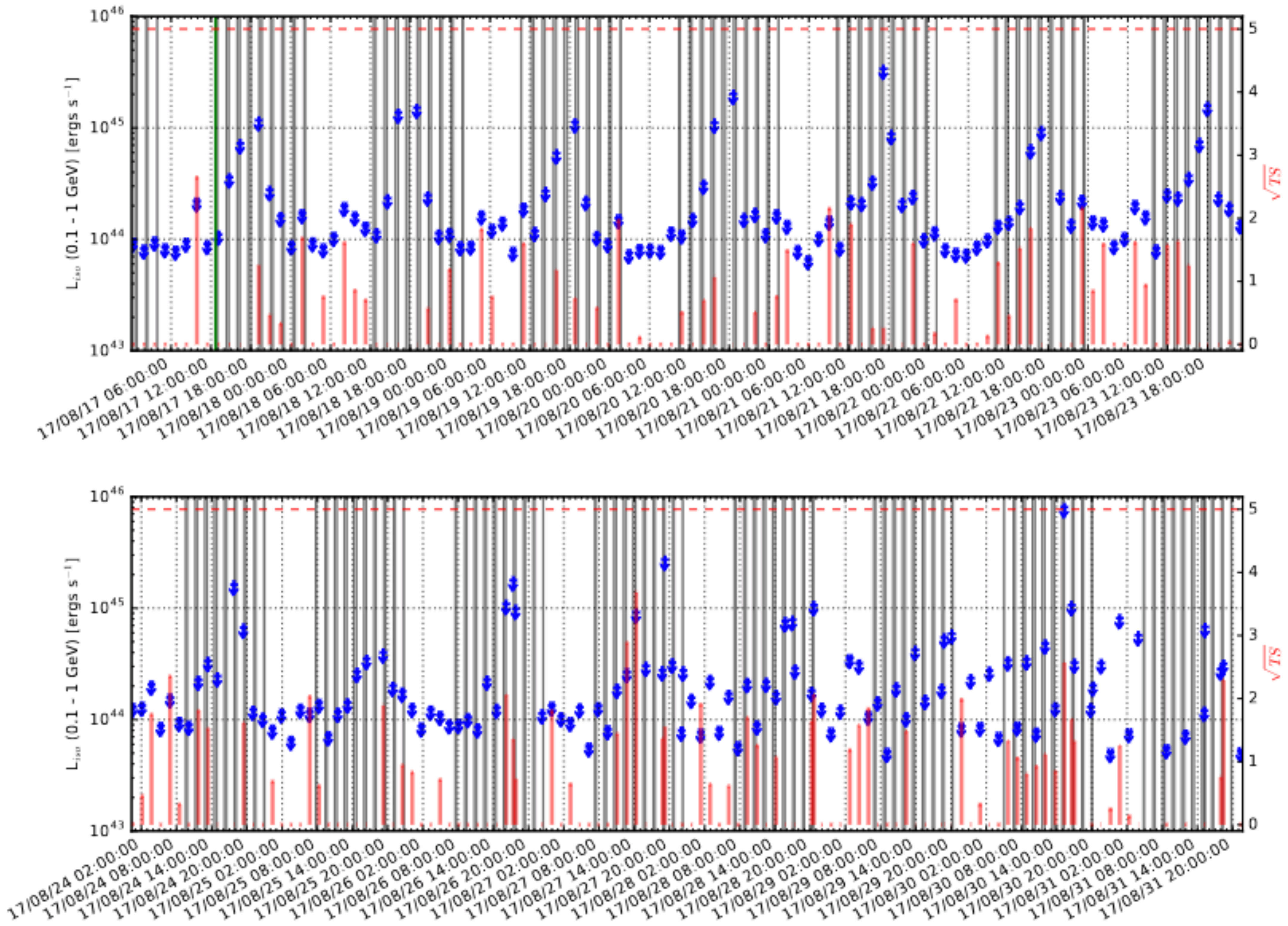


LIGO/VIRGO

GW 170817 at HE



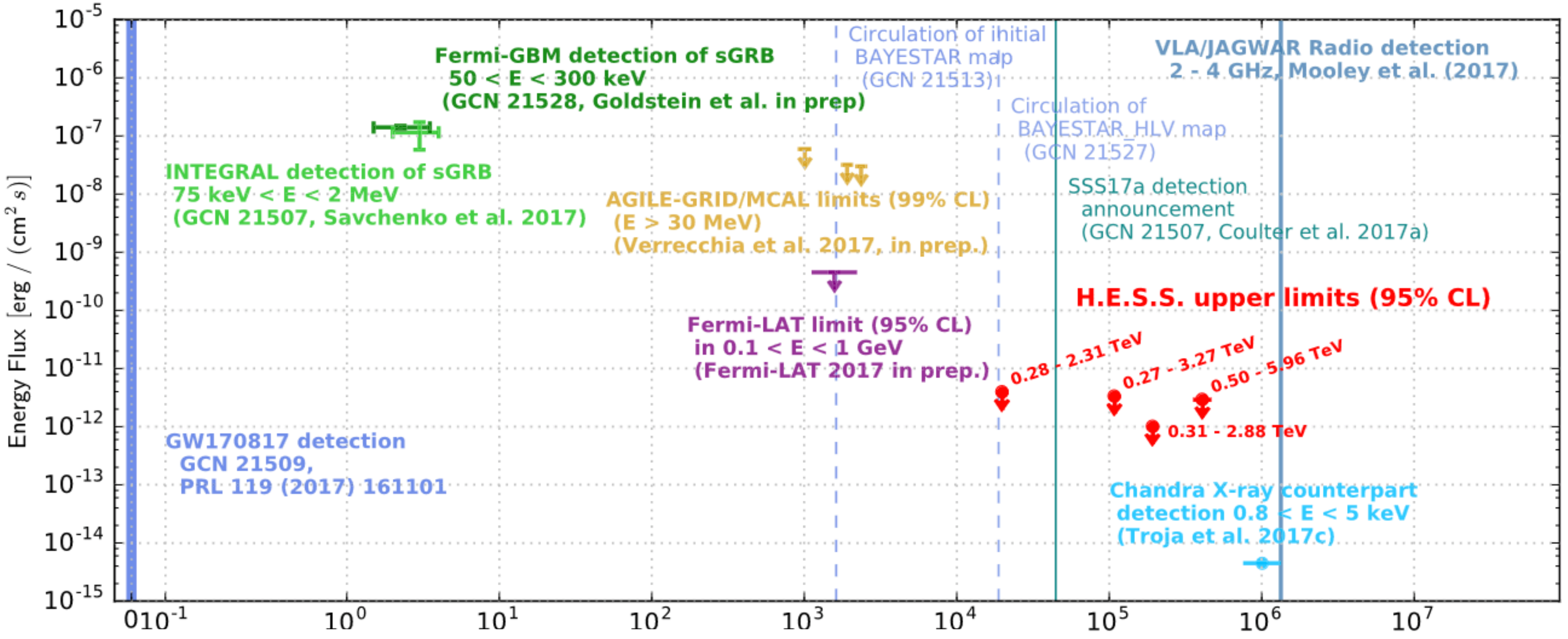
- **Fermi-GBM detected** the GRB right after the merger
- **No detection by Fermi-LAT**
  - LAT was not collecting data due to a passage through the South Atlantic Anomaly (SAA), and was thus unable to observe the prompt emission phase of the GRB
  - The LAT resumed collecting science data ~ 103 seconds later



Abbot et al. 2017

Fermi-LAT 2017

GW 170817 at VHE



- HESS Observations between Aug 17 - Aug 22
- No VHE detection (Abdalla et al. 2017)

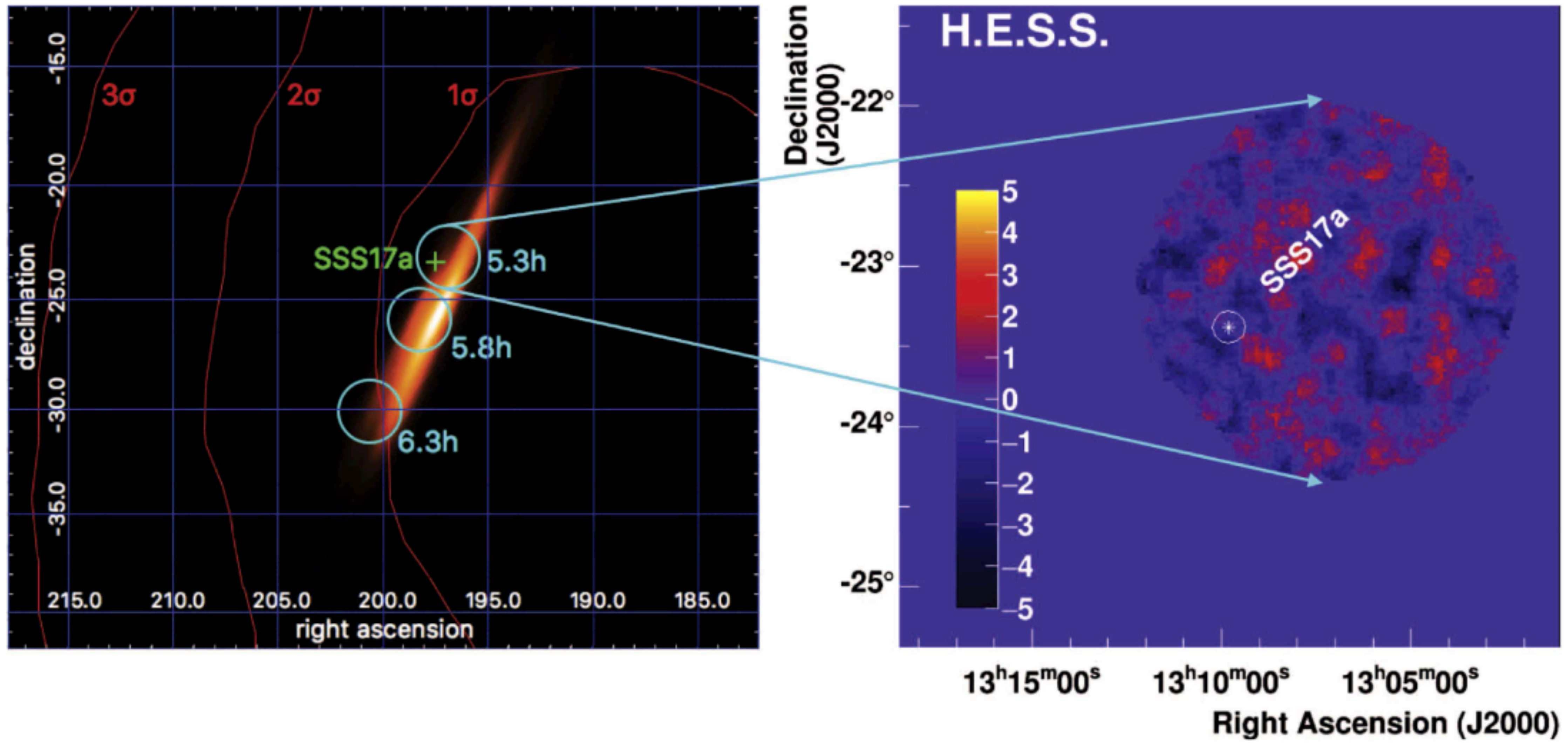


Table 2
Limits on the High-energy Gamma-Ray Flux at 95% C.L. and Assuming a E^{-2} Energy Spectrum Obtained During the Monitoring of SSS17a with H.E.S.S.

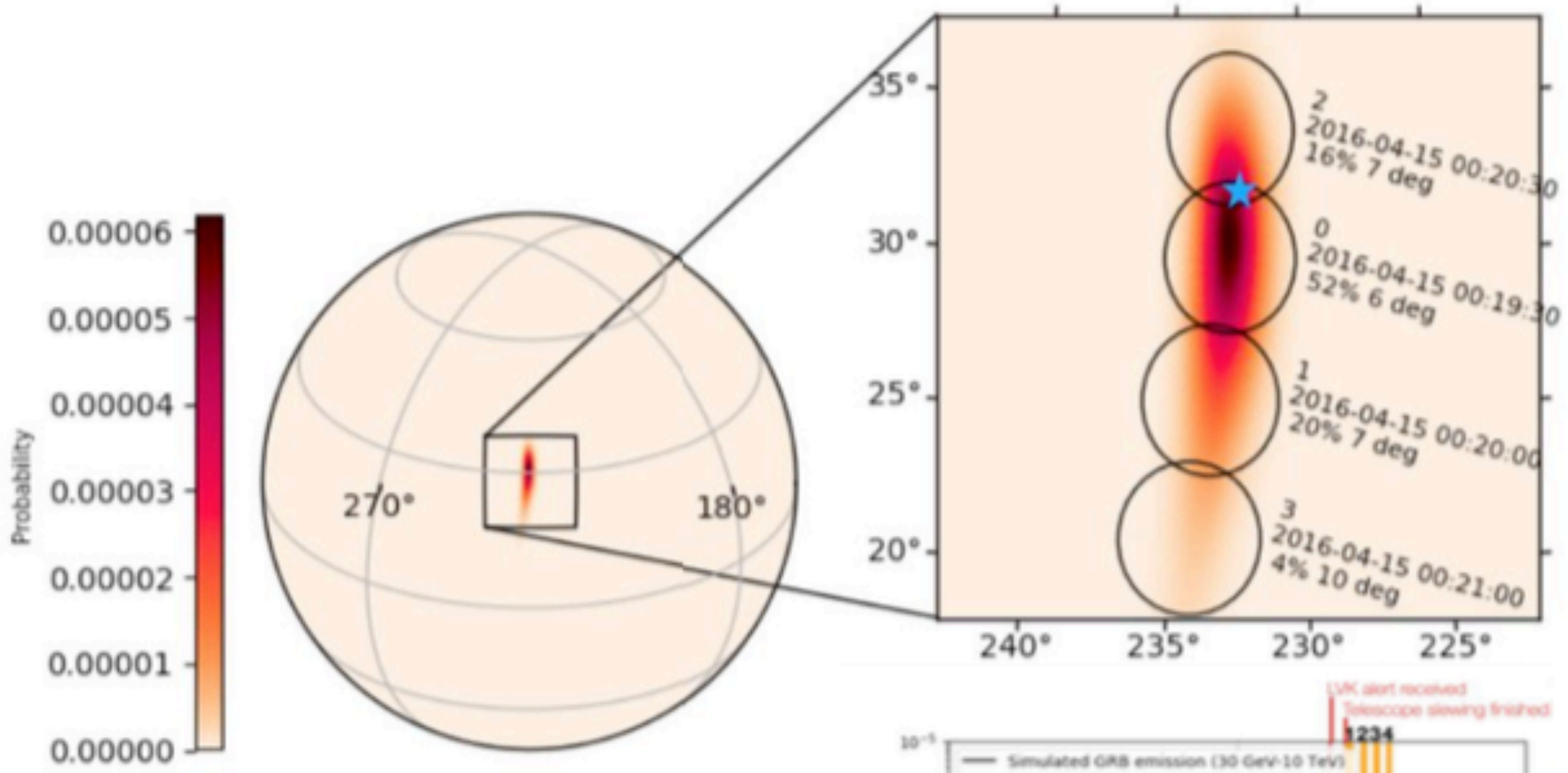
Pointings (See Table 1)	Time since GW170817 (days)	f_γ (erg cm^{-2} s^{-1})	Energy Band (TeV)
1a	0.22	$<3.9 \times 10^{-12}$	0.28–2.31
2a+2b	1.22	$<3.3 \times 10^{-12}$	0.27–3.27
3a+3b	2.22	$<1.0 \times 10^{-12}$	0.31–2.88
5a+6a	4.23, 5.23	$<2.9 \times 10^{-12}$	0.50–5.96
all	0.22—5.23	$<1.5 \times 10^{-12}$	0.27–8.55

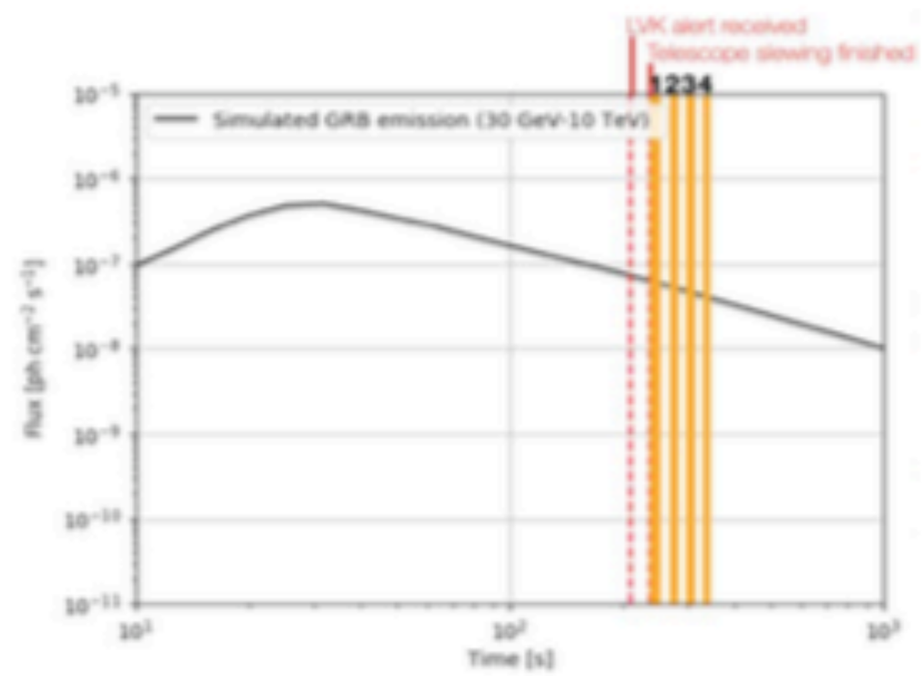
Abdalla et al. 2017

GW/sGRBs at VHE

We now know that GRBs are possible VHE emitter and we also have a good hint that sGRB can be too. However, few differences have to be considered wrt “standard” GRB case:

- ❑ GW emission is isotropic while GRB em emission is collimated within a jet → the viewing angle plays an important role
- ❑ The uncertainty in the sky location of the GW event requires the definition of an observational strategy for the search of the EM counterpart with pointed instruments through a scan of the sky map provided by the GW event.

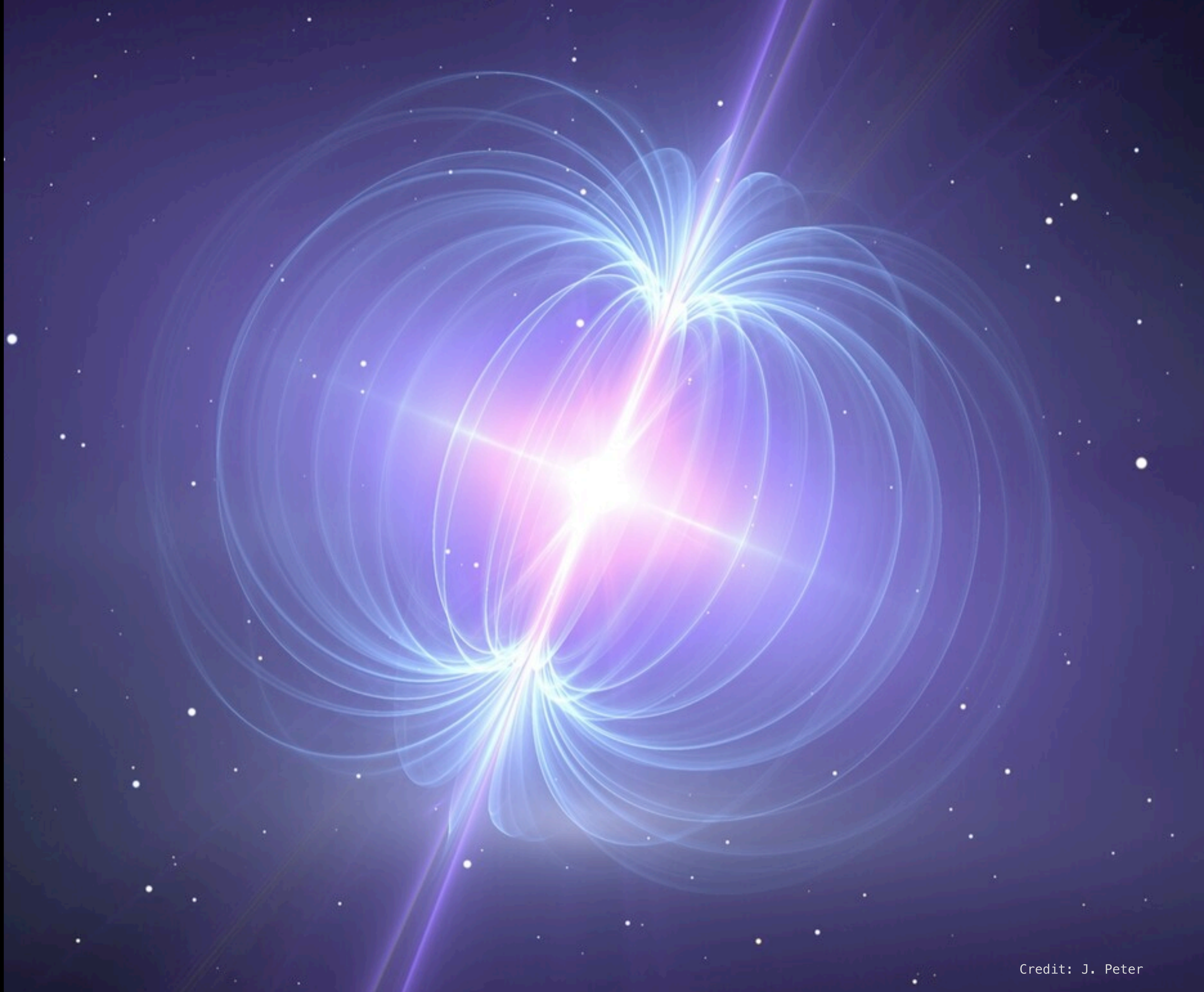




Patricelli+2021, Searching for very-high-energy electromagnetic counterparts to gravitational-wave events with the Cherenkov Telescope Array, ICRC 2021

Slide from A. Carosi

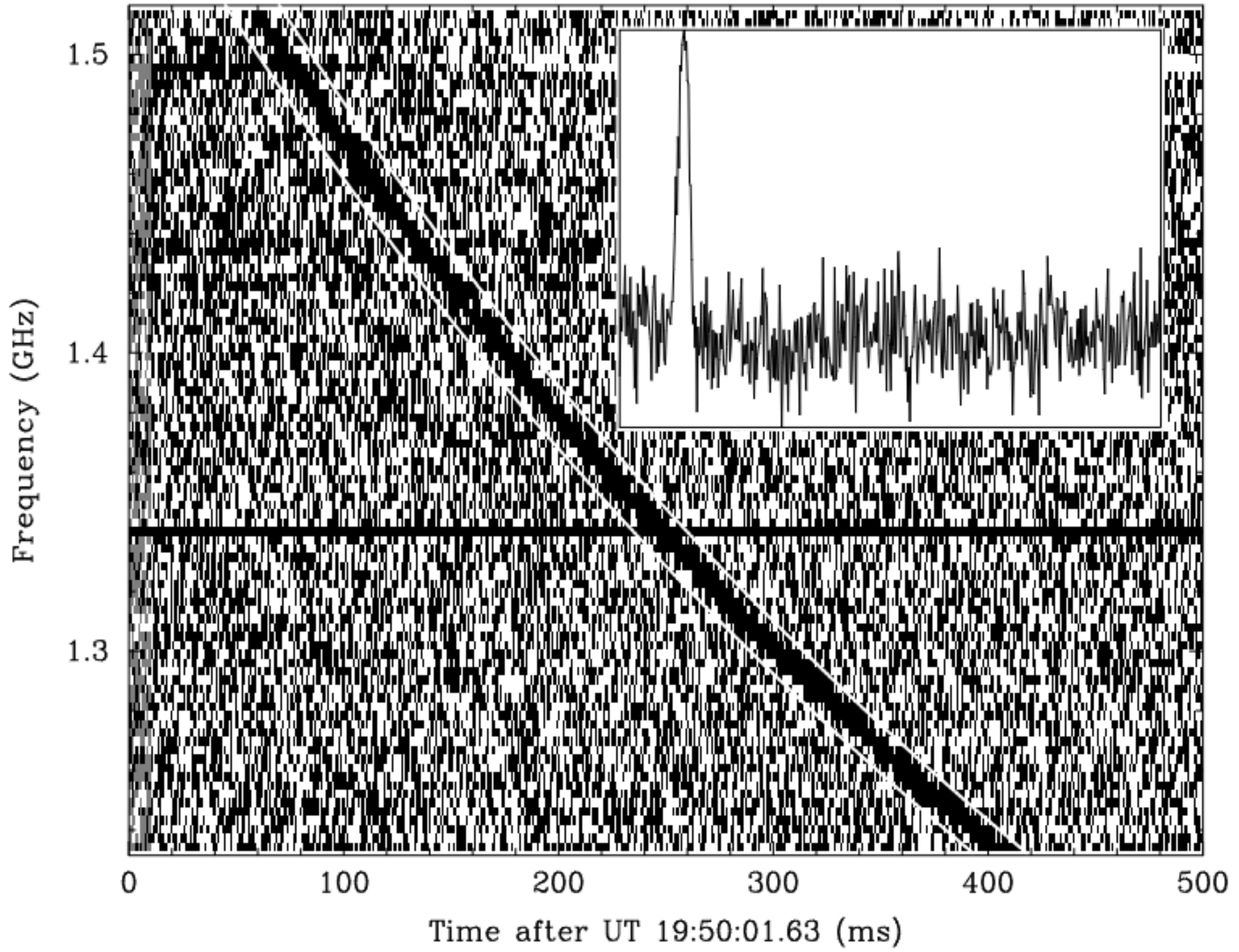
Fast Radio Bursts



Credit: J. Peter

The first FRB

- Radio flares of **millisecond duration**
- Short events that generate **as much energy in a thousandth of a second as the Sun does in an entire year**
- Discovered in 2007, extragalatic origin `(Lorimer et al. 2007)`
  - the Lorimer Burst FRB 010724 (Parkes Observatory, 2011)
  - a 30-Jy dispersed burst of **duration < 5 ms**
  - < 1 Gpc distance
- Most FRB are isolated signals



Science

REPORTS

A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. LORIMER, M. BAILES, M. A. MCLAUGHLIN, D. J. NARKEVIC, AND , F. CRAWFORD Authors Info & Affiliations

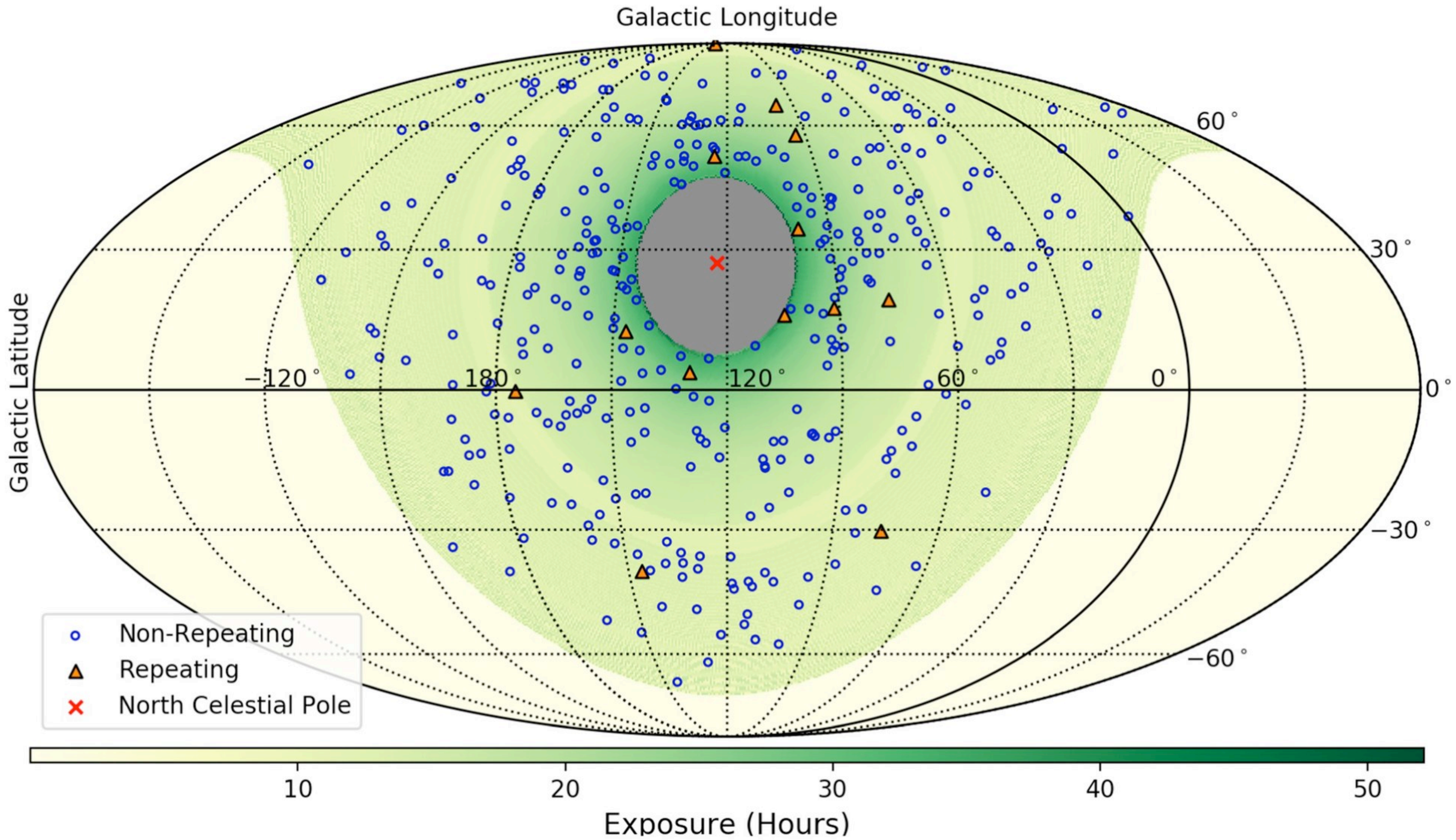
SCIENCE • 2 Nov 2007 • Vol 318, Issue 5851 • pp. 777-780 • DOI: 10.1126/science.1147532

FRBs

- **FRB 121102: first repeater** (Splitler et al. Nature 2016)
  - its localization in a dwarf star forming galaxy at redshift z = 0.19 (Chaterjee et al. 2017, Marcote et al. 2017, Tendulkar et al. 2017)

- Right now:
  - Total FRB count: 670 (April 2023)
  - Repeaters: 50
  - Host galaxies: 27

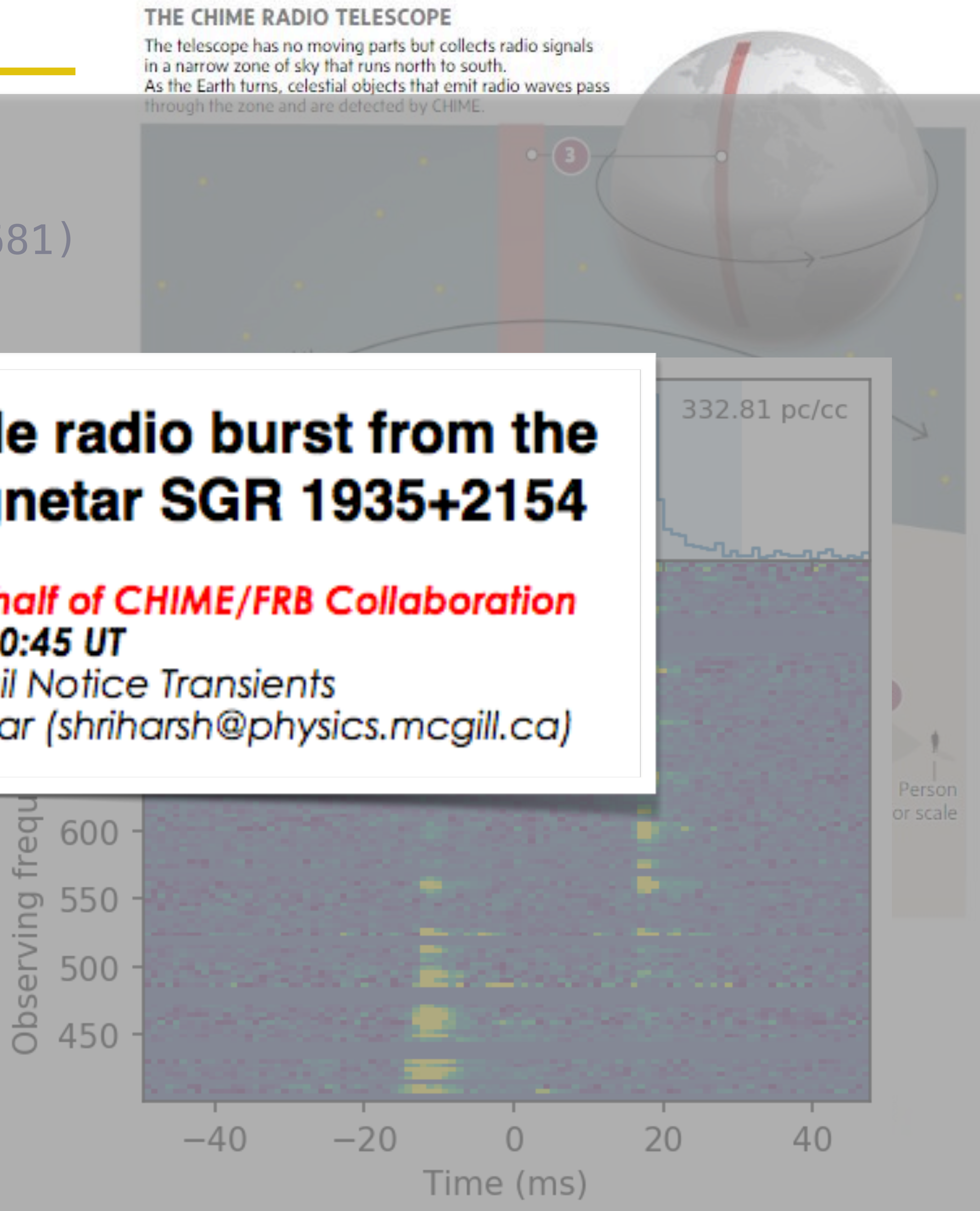
What is the nature of these FRBs?



Credit: CHIME/2019

FRB200428 : a unique case

- April 28, 2020: CHIME detects another FRB (ATel 13681)
- The burst had a **double-peak structure** with two components

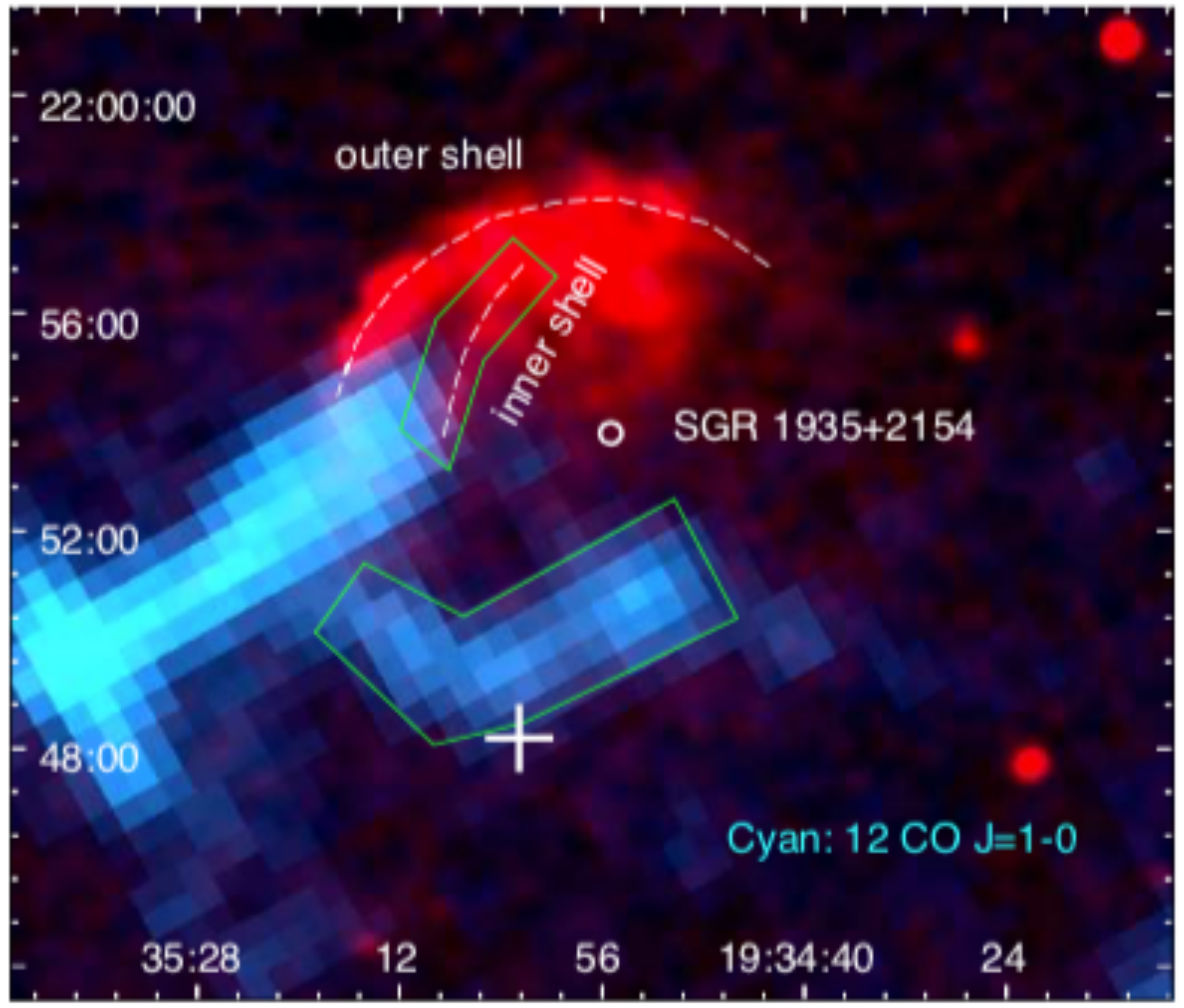


A bright millisecond-timescale radio burst from the direction of the Galactic magnetar SGR 1935+2154

ATel #13681; ***Paul Scholz (UToronto) on behalf of CHIME/FRB Collaboration***
on ***28 Apr 2020; 20:45 UT***
Distributed as an Instant Email Notice Transients
Credential Certification: Shriharsh Tendulkar (shriharsh@physics.mcgill.ca)

CHIME 2020

FRB200428 : SGR 1935+2154

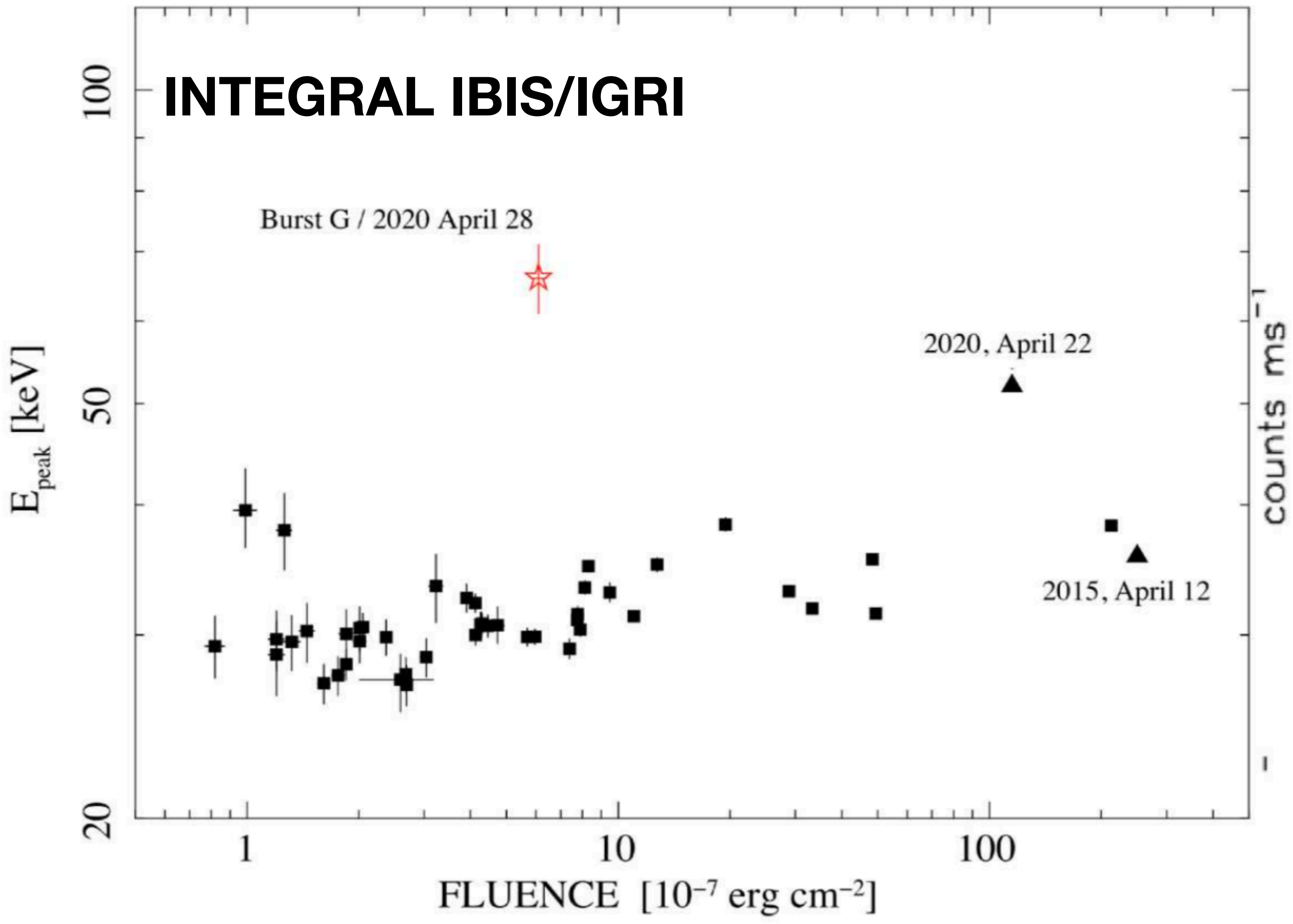


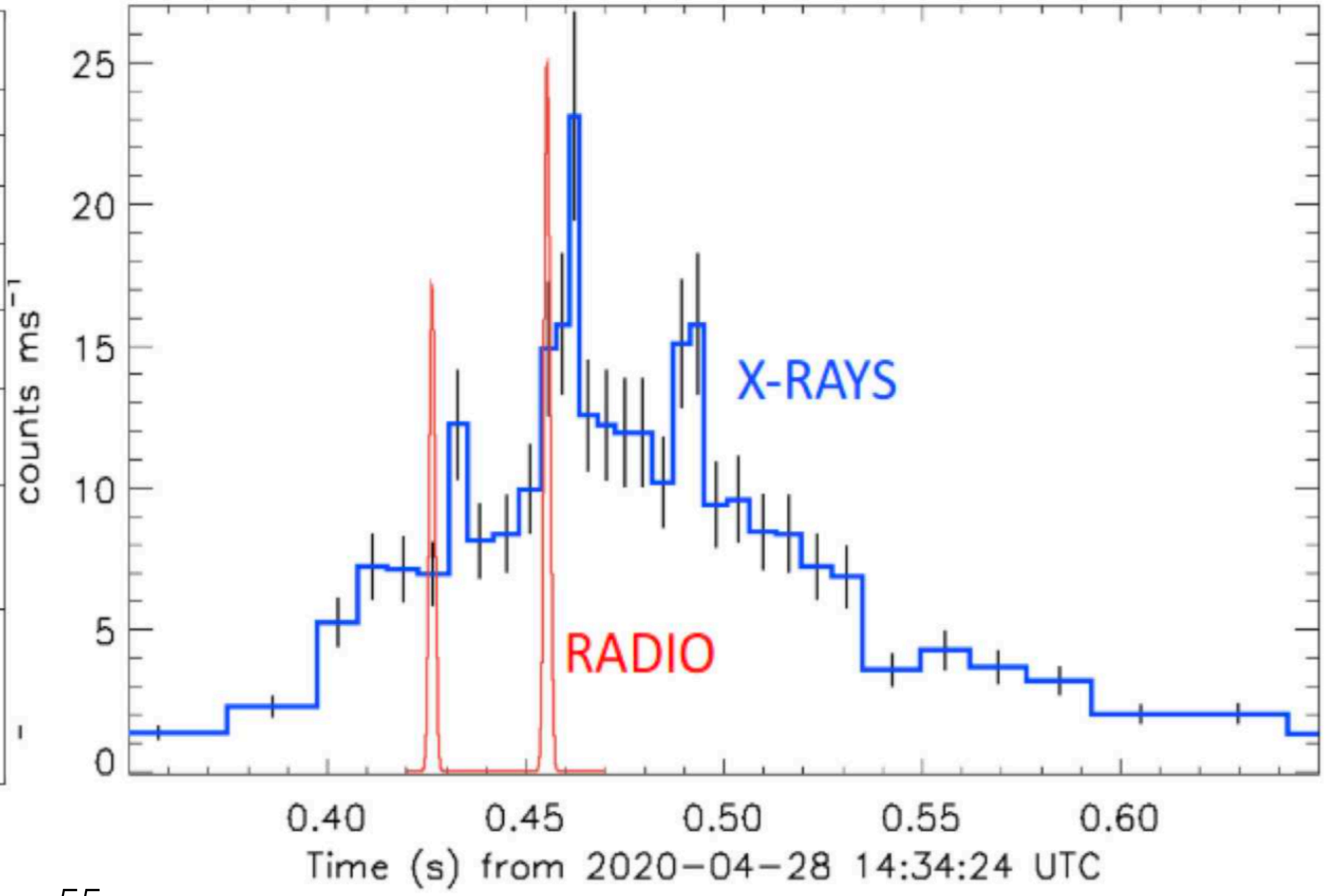
- Galactic magnetar located at 6.6 kpc (Zhou et al. 2020)
- **Hosted in an evolved SNR** (GG57.2+0.8) and (likely) interacting with a **surrounding molecular cloud**
  - April 2020: **a fast radio burst (FRB) is detected by CHIME/FRB** in coincidence with this magnetar (Andersen et al. 2020)
    - The burst had a **double-peak** structure with two components ~5 ms wide separated by ~30 ms
  - Confirmation by STARE2 (Bochenek et al. 2020) and European dishes: Westerbork, Onsala, Toruń (Kirsten et al. 2020)
  - **X-ray bursts** by Swift (Barthelmy et al. 2020), INTREGRAL (Mereghetti et al. 2020), AGILE (Tavani et al. 2021), Konus-Wind (Ridnaia et al. 2021),NICER (Younes et al. 2021), Insight HXMT (Li et al. 2021)
  - MAGIC could not observe due to pandemic lockdown

SGR 1935 +2154 is
the first FRB in the Galaxy and
the first identified FRB source

FRB200428 : SGR 1935+2154

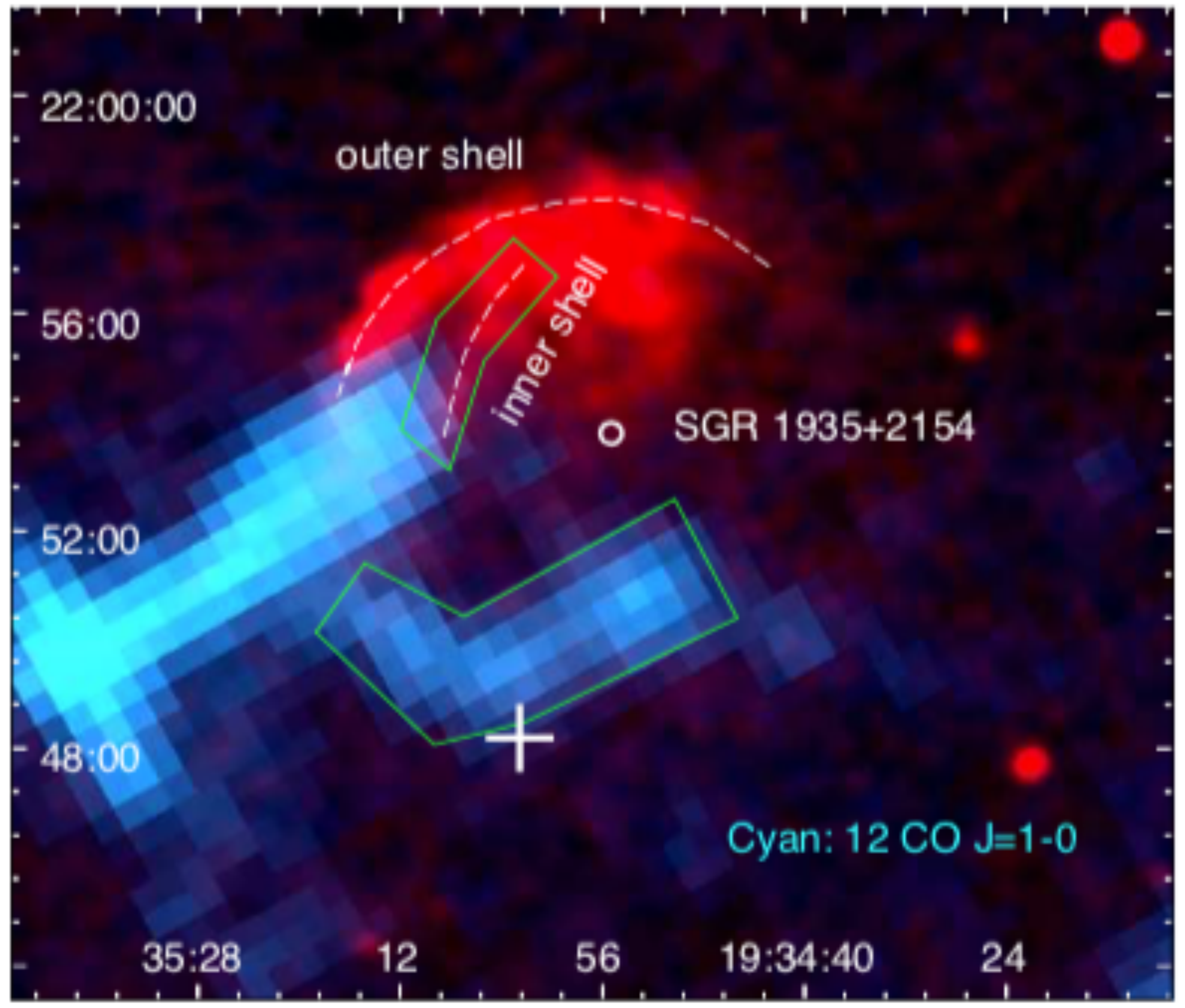
- It was not a giant flare but **intermediate**
- The X-ray burst was **not especially energetic but it was harder than other flares** (Mereghetti et al. 2020)
- Different models for the site of emission (see Zhang 2020 for a review):
    - inside magnetosphere
    - relativistic outflow interacting with surrounding ISM
- TeV emission can be expected according to theoretical models (Lyubarsky 2014, Murase et al. 2016, Metzger et al. 2020)





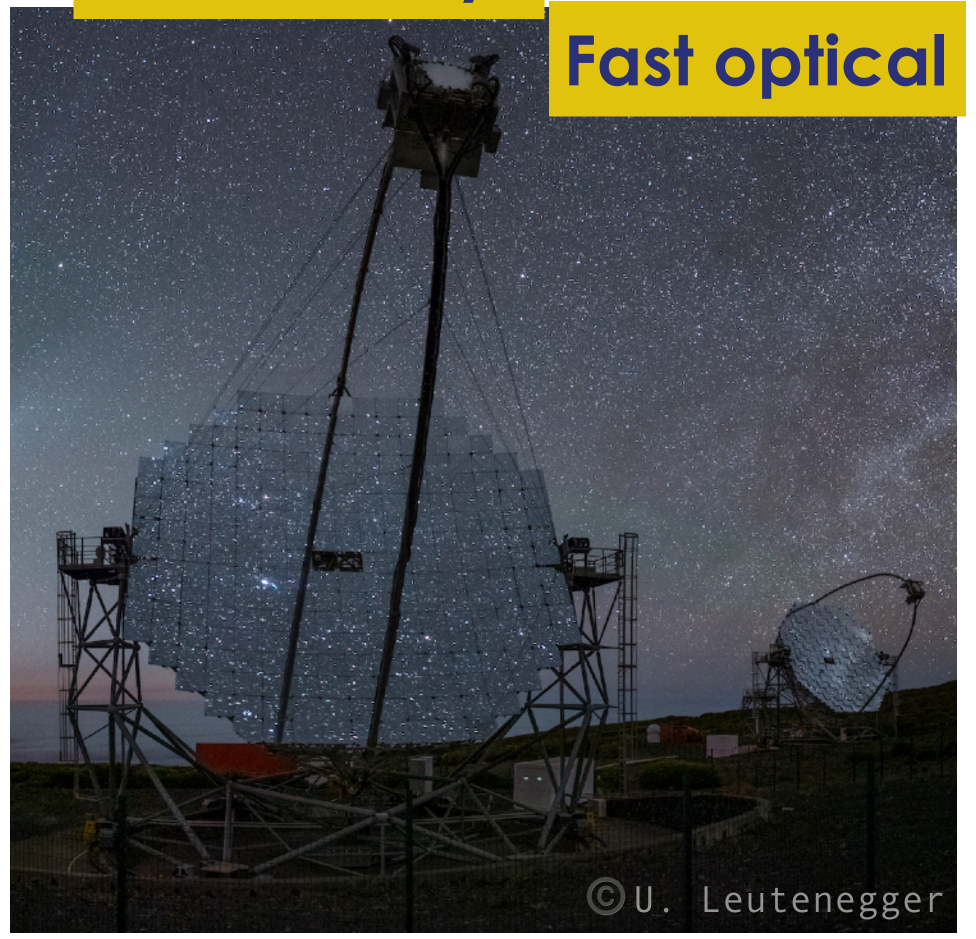
from Mereghetti et al. 2020

MWL collaboration: SGR 1935+2154

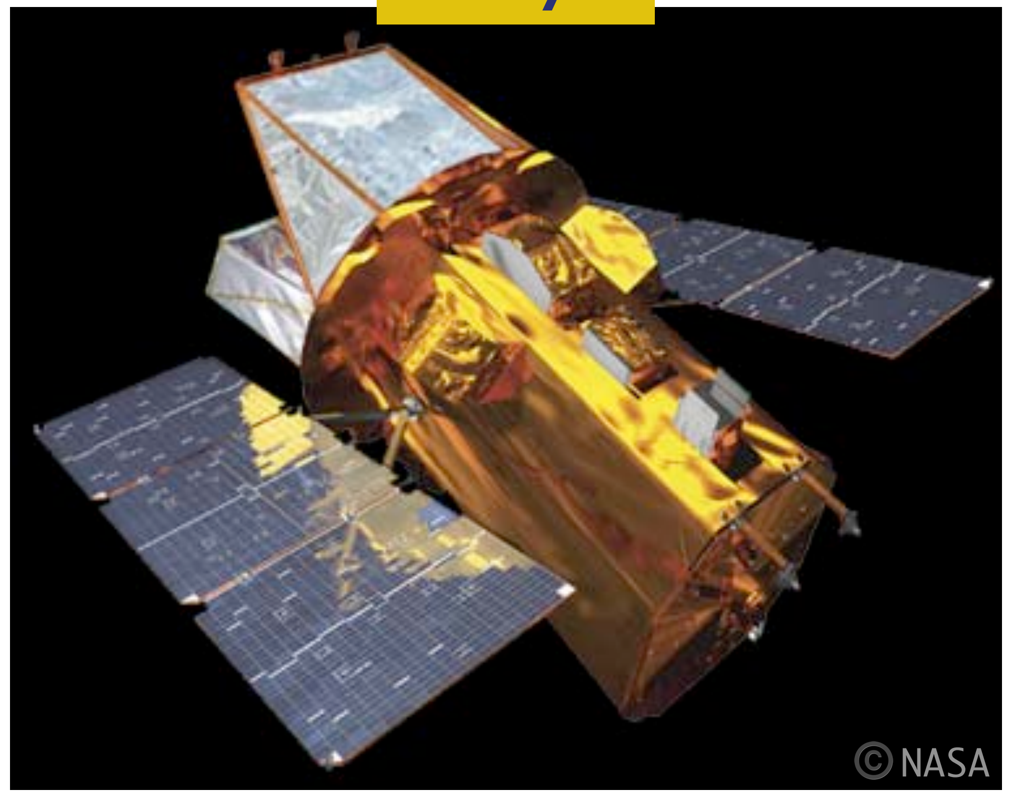


Gamma rays

Fast optical

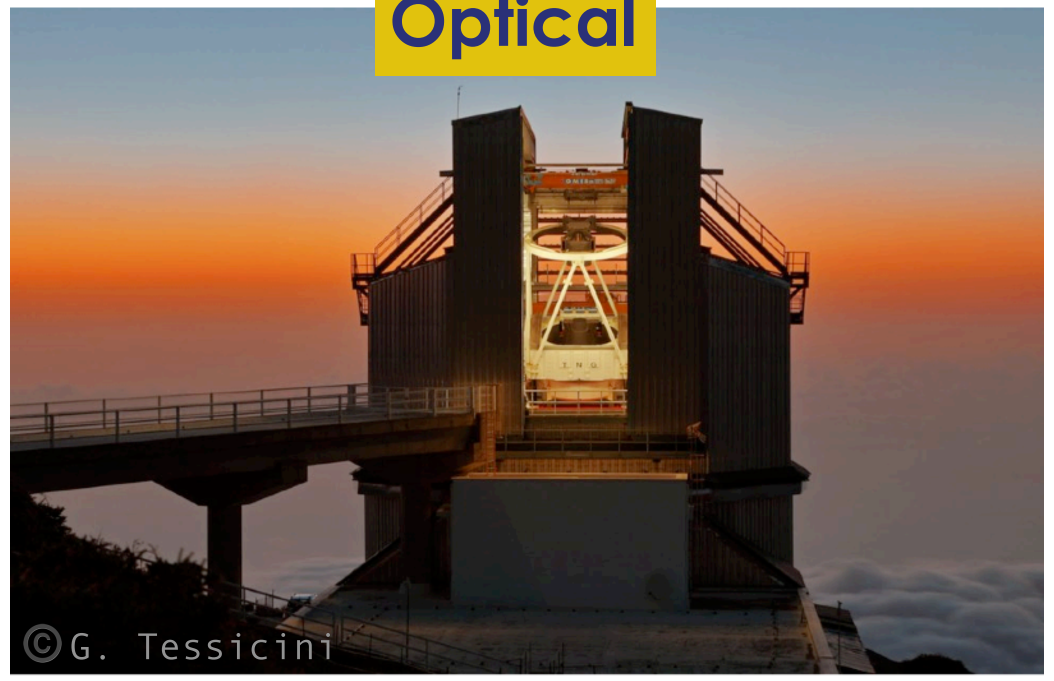


X-rays

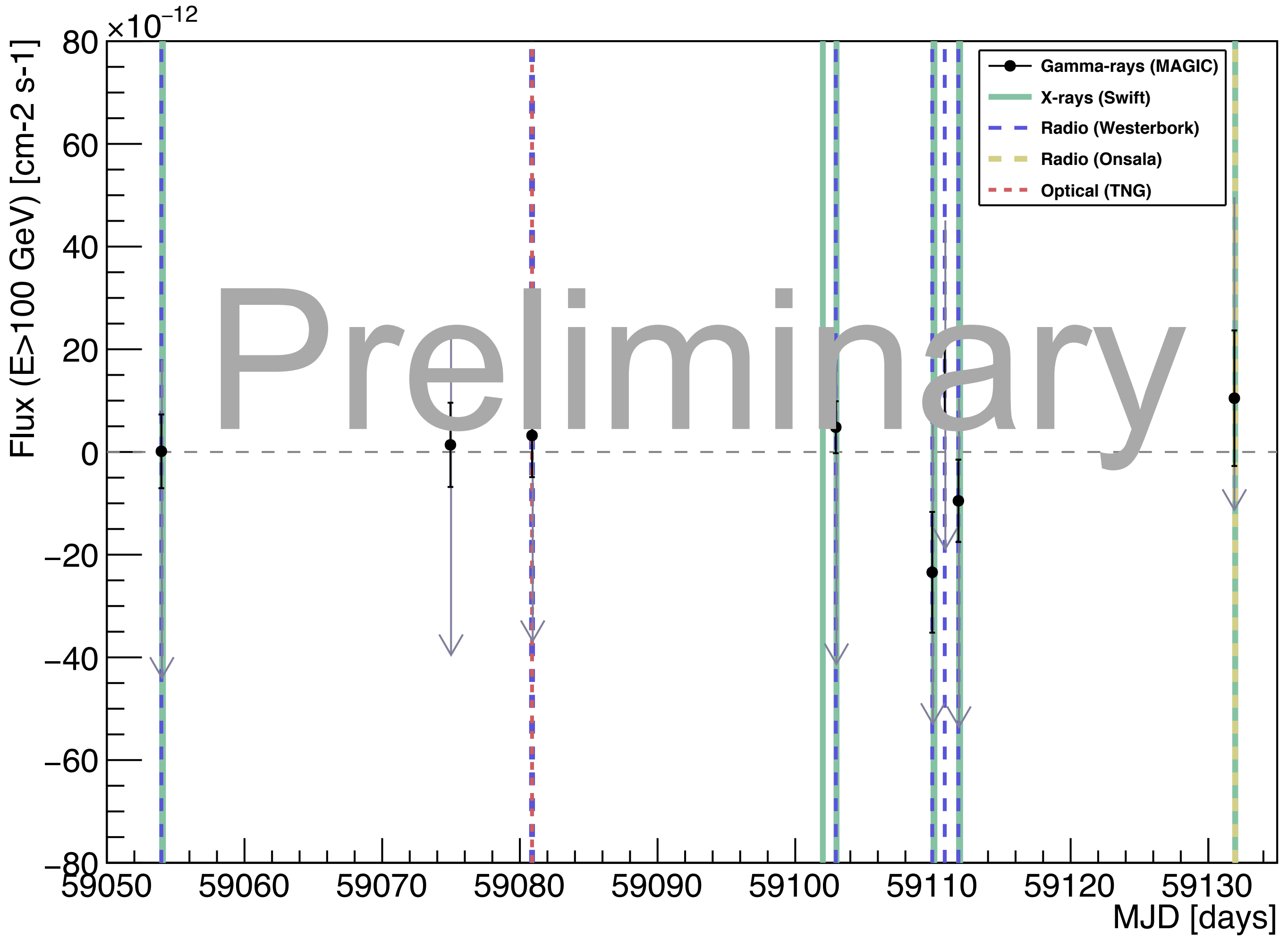


Radio

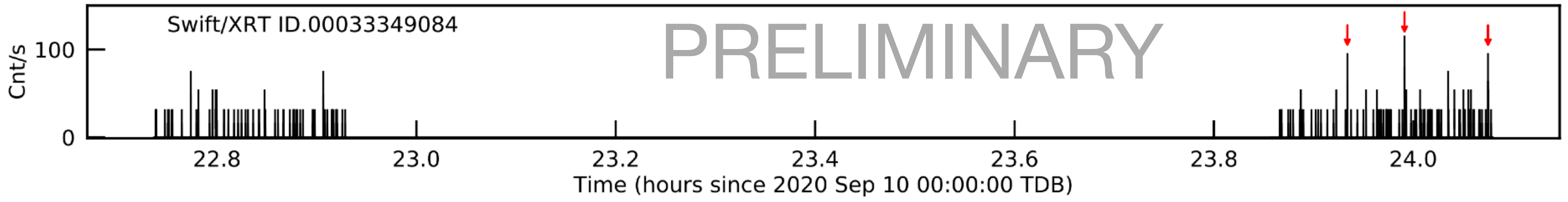
Optical



More info on SGR1935+2154 tomorrow! Stay tuned!

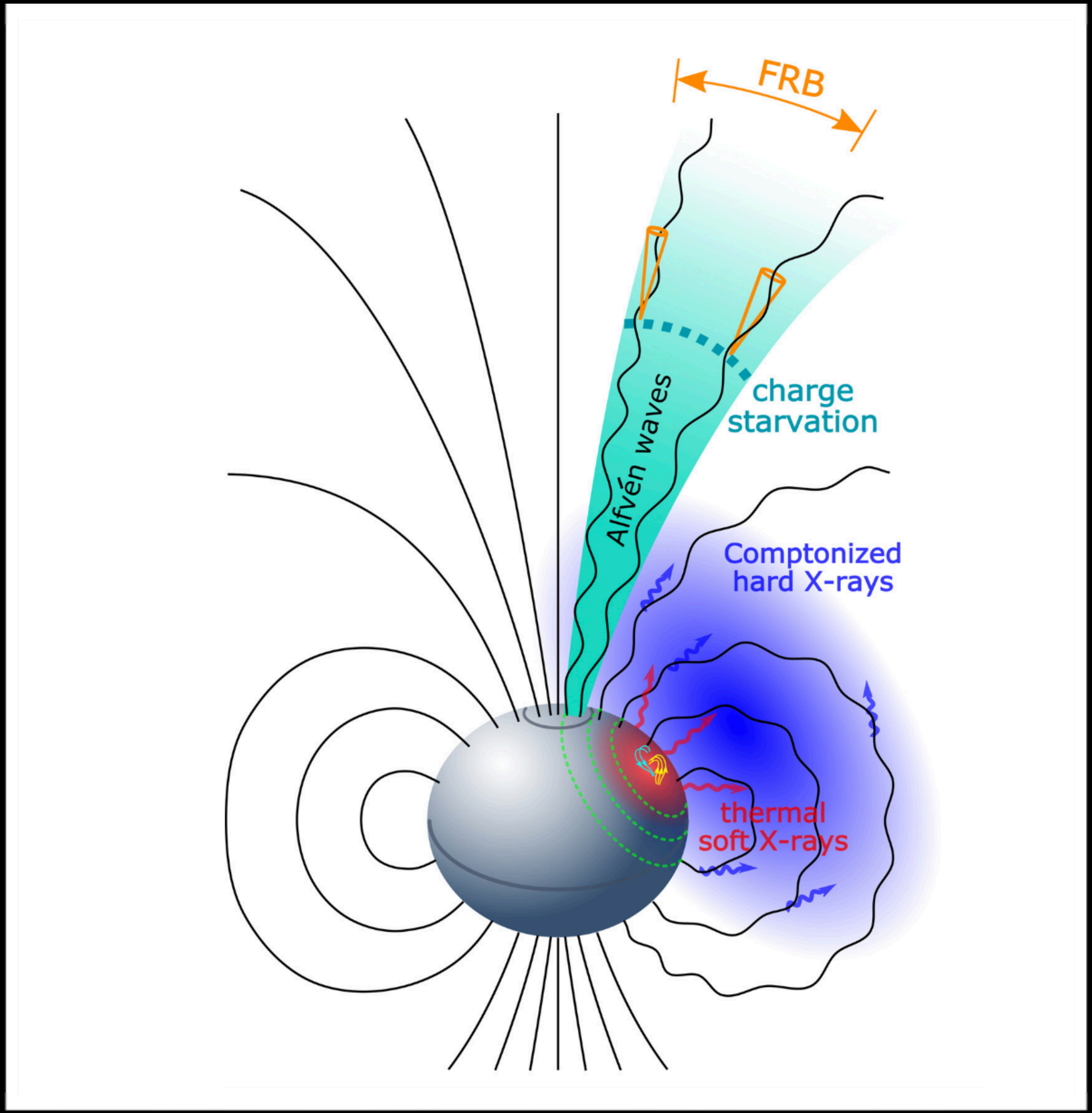


Example of bursts detected by **Swift/XRT**



López-Oramas et al. 2021

- **“FRBs are consistent with a population of magnetars** born through the collapse of giant, highly magnetic stars“(Bochenek et al. 2020)

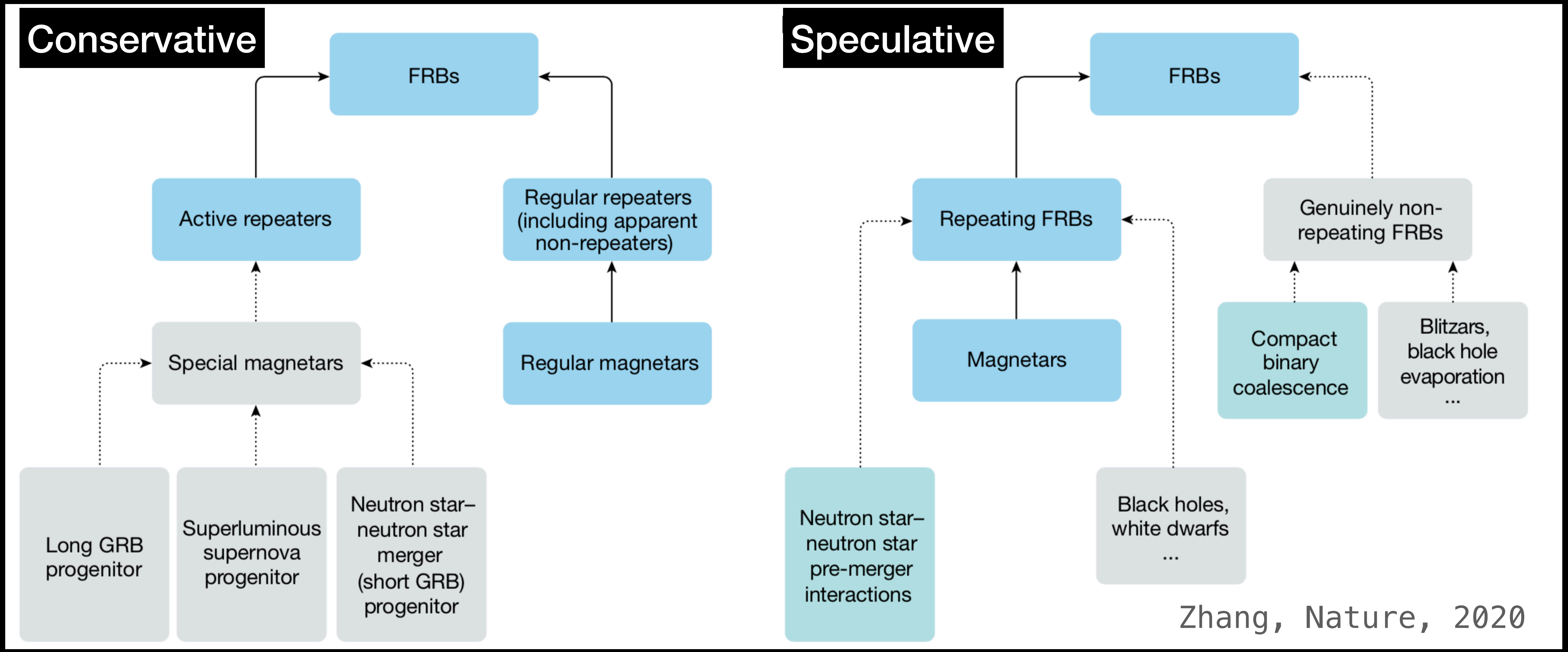


A unified picture of Galactic and cosmological fast radio bursts

Lu et al. 2020

A unified magnetar model for all FRBs?

- Galactic magnetars: SNe
- "Exotic" magnetars: extreme cosmic explosions such as long GRBs, superluminous SNe or even short GRBs (neutron star–neutron star mergers)
  - may give birth to extremely rapidly rotating magnetars
  - more active than Galactic ones
- **'Active magnetars' and SGR 1935+2154-like Galactic magnetars must be two distinct populations** (Margalit et al. 2020, Liu et al. 2020)



Open questions

Despite rapid progress in the field, there are still several open questions regarding the origin of FRBs, which will drive observational efforts and theoretical investigations in the field in years to come:

(1) Are there genuinely non-repeating FRBs? If so, what could be the plausible source(s)?

(2) Are there engines other than magnetars that could power repeating FRBs? If so, what could be the plausible sources?

(3) How is FRB emission generated, from magnetospheres (pulsar-like mechanism) or relativistic shocks (GRB-like mechanisms)? What is the mechanism that produces coherent emission from FRBs?

Zhang Nature 2020

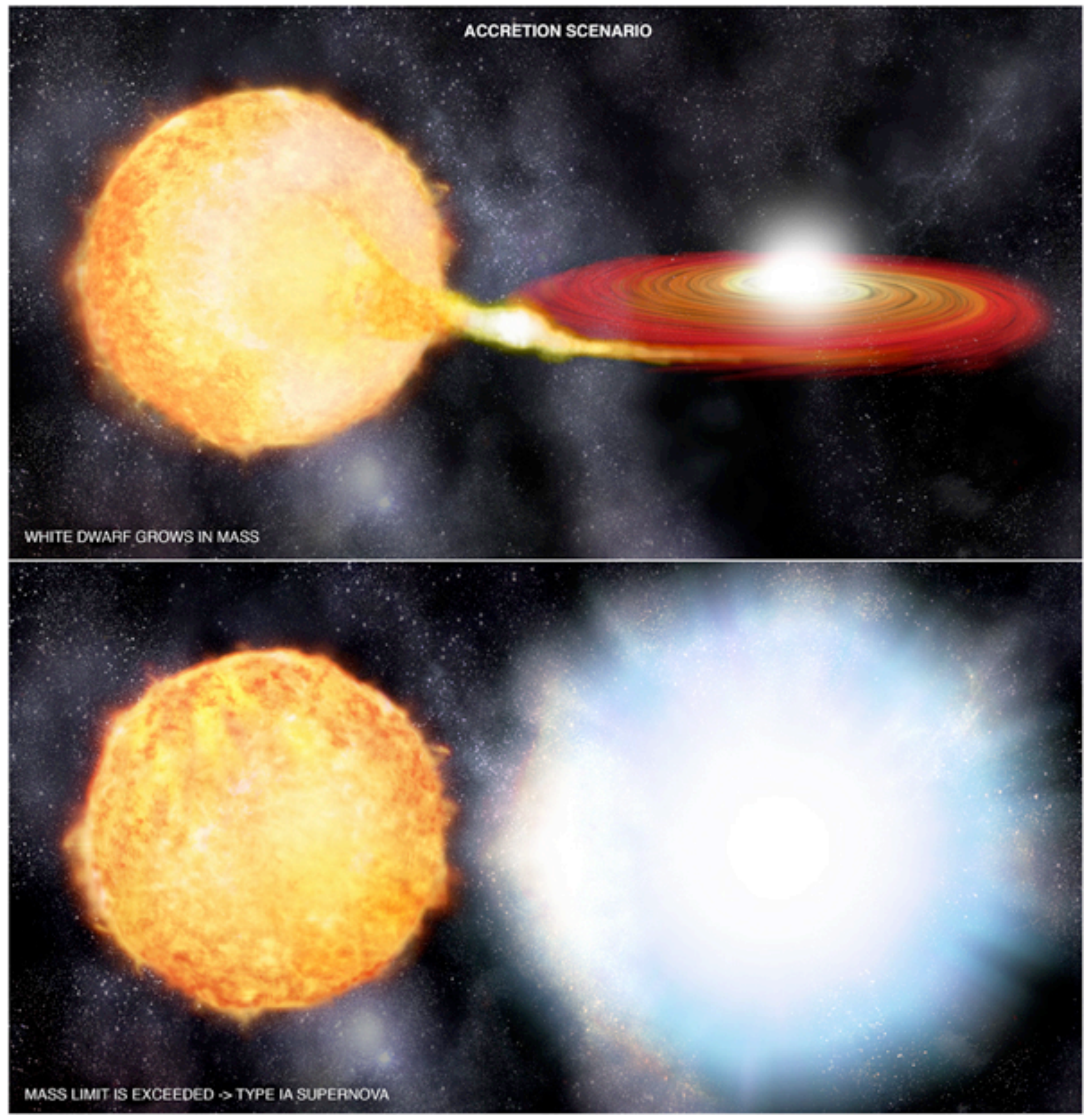
SuperNovae

SNe

SNe at VHE

- Campaigns on **extragalactic SNe**
- **MAGIC ULs on type Ia SN 2014J** (Ahnen et al. 2017), located at M82 (3.6 Mpc) -> nearest Type Ia SN in the last 50 years
- **H.E.S.S. ULs on 10 core-collapse SNe** observed within a year of the supernova event (Abdalla et al. 2019)
  - The lack of detection does not necessarily indicate that the early phase of SN evolution is not generally conducive to CR acceleration
  - The non-detection **suggests that the circumstellar mediums in this subsample are not likely to be dense enough for particle acceleration**

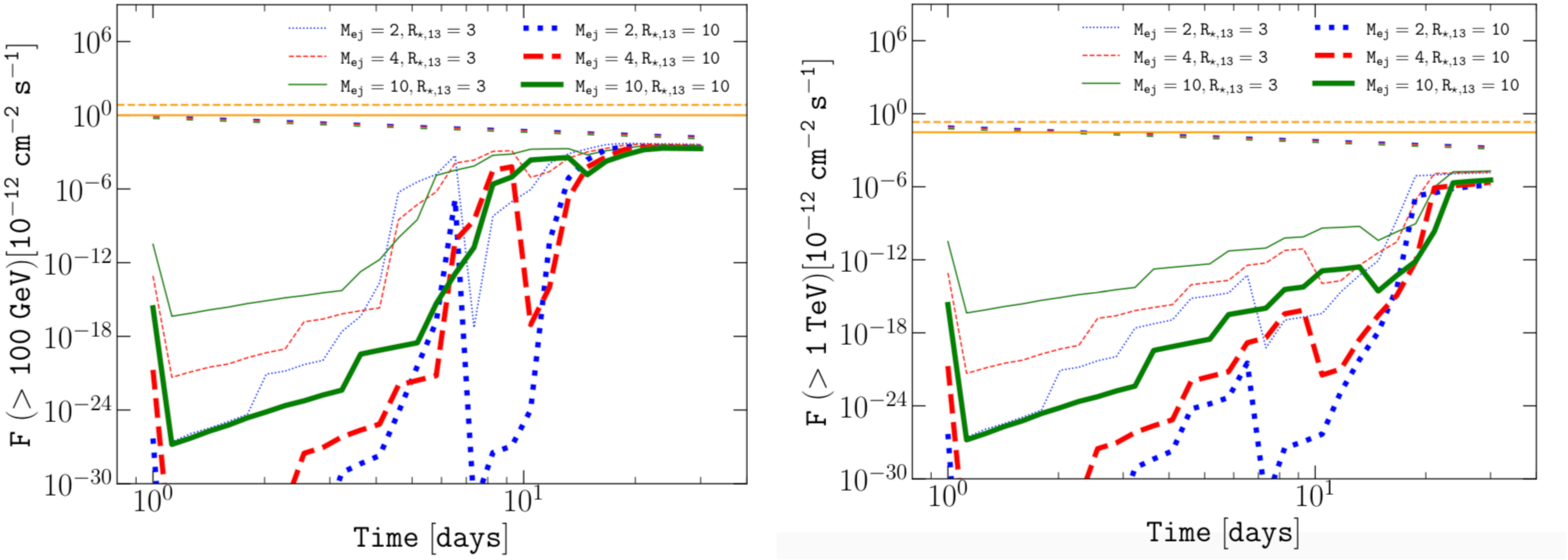
type Ia SN



type II SN (core collapse)

Core collapse SNe as TeV candidates

- CCSNe (type II) originating from (massive) stellar progenitors with dense winds can **fulfil the right conditions for CR acceleration** (Katz et al. 2011; Murase et al. 2011; Bell et al. 2013, Cristofari et al. 2022)
  - Detection at radio frequencies confirm the presence of relativistic electrons and shows that they could be efficient energetic particle accelerators
  - VHE emission is expected in Type II CC-SNe but the **gamma-ray signal can be attenuated in the first ~10 days** (Cristofari et al. 2022)
- In the case of **Galactic core-collapse SNe observations can be triggered by an observation of a prompt neutrino flare, since the EM signal is expected to be delayed** with respect to neutrinos by minutes to hours



Cristofari et al. 2022

SN 2023 ixf

- 2023ixf discovered 2023-05-19 07:45:07 UTC, MJD 60083.727 by Koichi Itagaki (Mag 14.4)
  - z= 0.000804 -> **~6.4 Mpc (M101)**
  - Type II SN -> exact type still not known
    - red supergiant star

MAXI/GSC upper limit of SN 2023ixf in M 101

ATel #16044; *N. Kawai (RIKEN), M. Serino (AGU), H. Negoro (Nihon U.), T. Mihara (RIKEN), M. Nakajima, K. Kobayashi, M. Tanaka, Y. Soejima, Y. Kudo (Nihon U.), T. Kawamuro, S. Yamada, T. Tamagawa, M. Matsuoka (RIKEN), T. Sakamoto, M. Serino, S. Sugita, H. Hiramatsu, H. Nishikawa, A. Yoshida (AGU), Y. Tsuboi, S. Urabe, S. Nawa, N. Nemoto (Chuo U.), M. Shidatsu (Ehime U.), I. Takahashi, M. Niwano, S. Sato, N. Higuchi, Y. Yatsu (Tokyo Tech), S. Nakahira, S. Ueno, H. Tomida, M. Ishikawa, S. Ogawa, T. Kurihara (JAXA), Y. Ueda, K. Setoguchi, T. Yoshitake, Y. Nakatani (Kyoto U.), M. Yamauchi, Y. Hagiwara, Y. Umeki, Y. Otsuki (Miyazaki U.), K. Yamaoka (Nagoya U.), Y. Kawakubo (LSU), M. Sugizaki (NAOC), W. Iwakiri (Chiba U.) report on behalf of the MAXI team:*

on 22 May 2023; 13:24 UT

Credential Certification: Tatehiro Mihara (mihara@crab.riken.jp)

Detection of candidate progenitor of SN 2023ixf in HST archival data

ATel #16050; *Monika Soraisam, Tom Matheson, Jen Andrews (NOIRLab), Gautham Narayan, Patrick Aleo (UIUC), ANTARES team*

on 23 May 2023; 22:16 UT

Credential Certification: Monika Soraisam (monika.soraisam@noirlab.edu)

Subjects: Optical, Star, Supernovae, Transient

Tweet

We searched the HST archival data for the progenitor of SN 2023ixf. A clear source can be seen at the SN position (https://antares.noirlab.edu/loci/ANT2023l4lgj6bhp4rt) in the F814W image from the HST program 9490 (PI: Kuntz), which was observed on UT 2002-11-16. The source is, however, not visible in the bluer bands (F435W and F555W). We measure a preliminary F814W magnitude of 24.39+/-0.08 for the source. Considering it as the candidate progenitor of SN 2023ixf and using a distance modulus of 29.05 for M101 (Shappee and Stanek, 2011, ApJ, 733), we obtain an approximate absolute magnitude (no extinction correction) of -4.66, which is in line with a supergiant progenitor.

NuSTAR detection of SN 2023ixf in M101

ATel #16049; *Brian Grefenstette (Caltech)*

on 23 May 2023; 16:32 UT

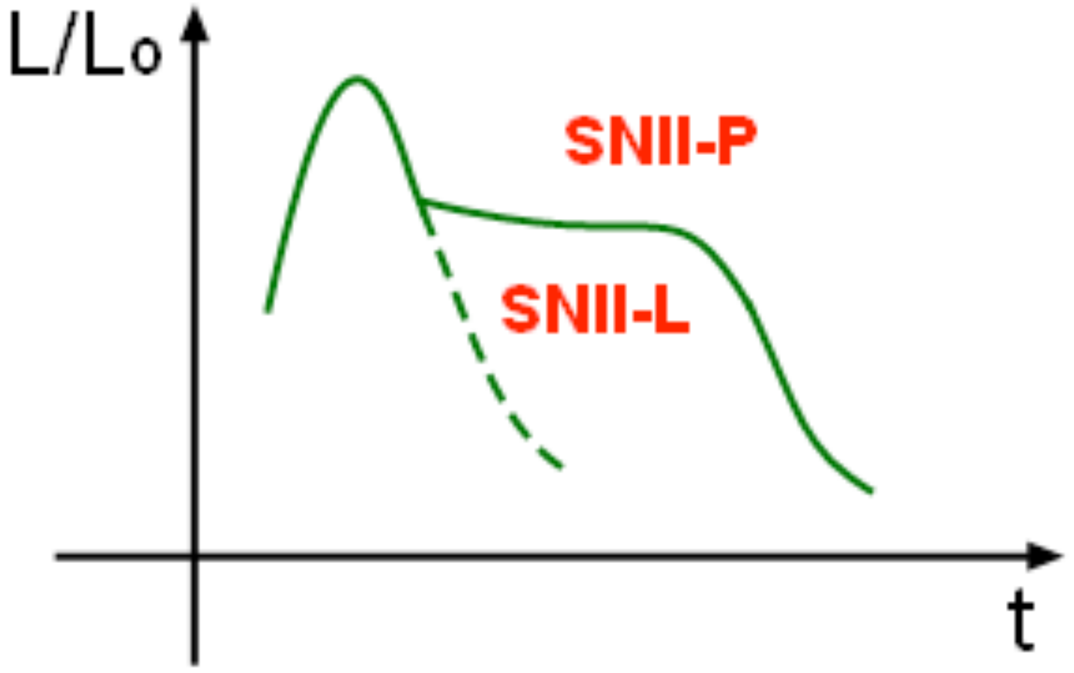
Credential Certification: Brian Grefenstette (Bwgref@srl.caltech.edu)

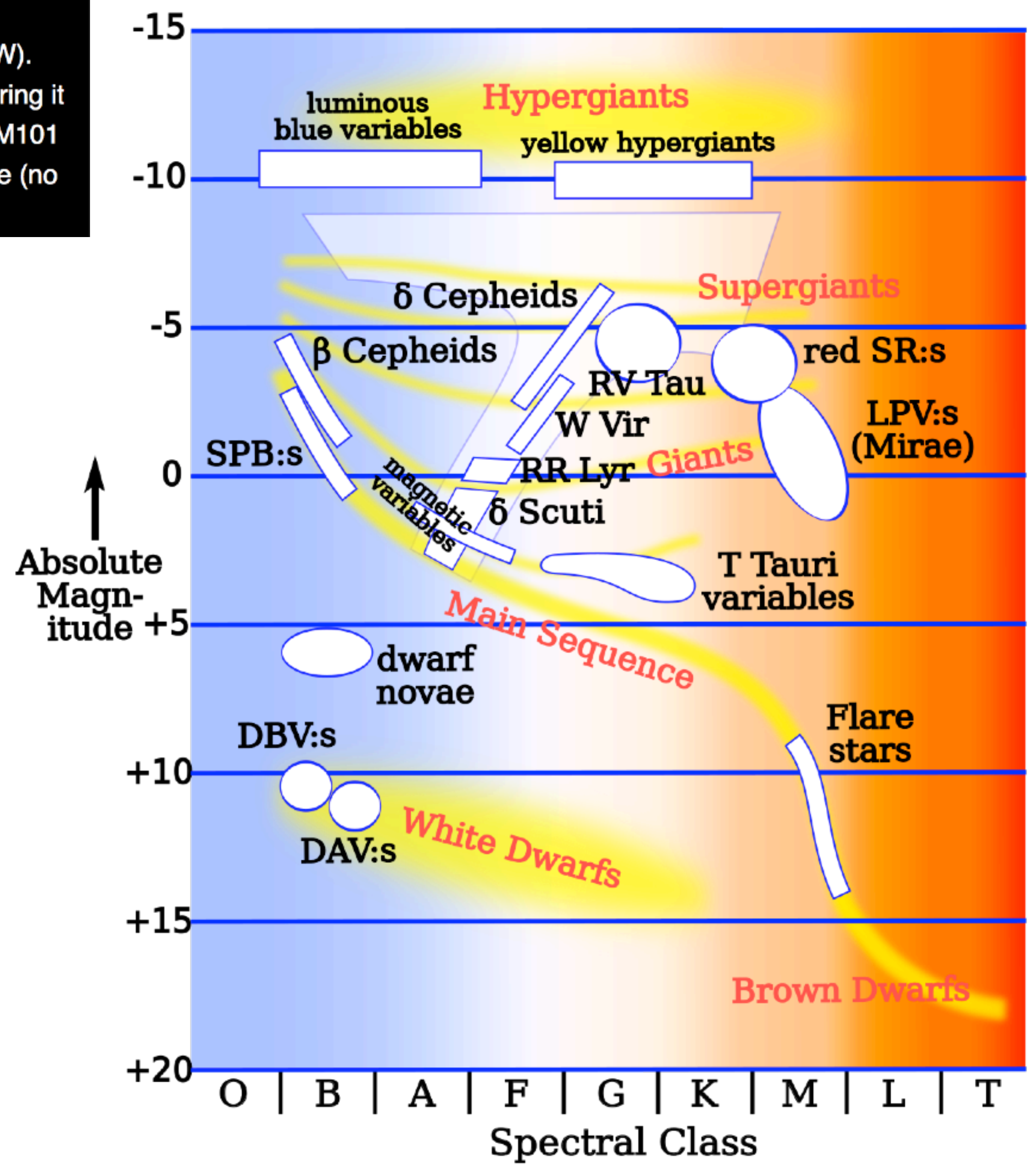
X-ray emission of SN 2023ixf and its progenitor

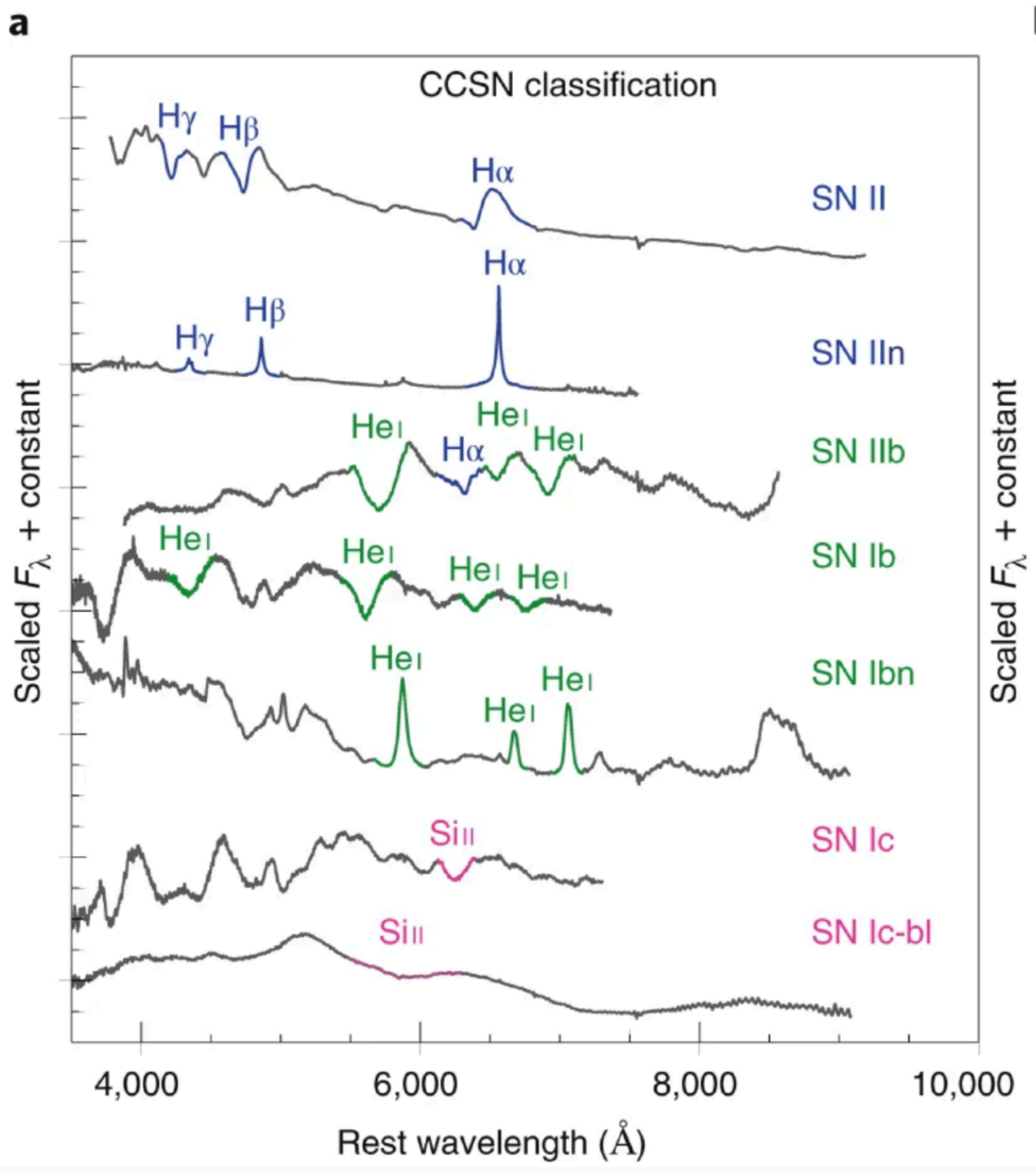
ATel #16051; *A. K. H. Kong (NTHU)*

on 24 May 2023; 08:58 UT

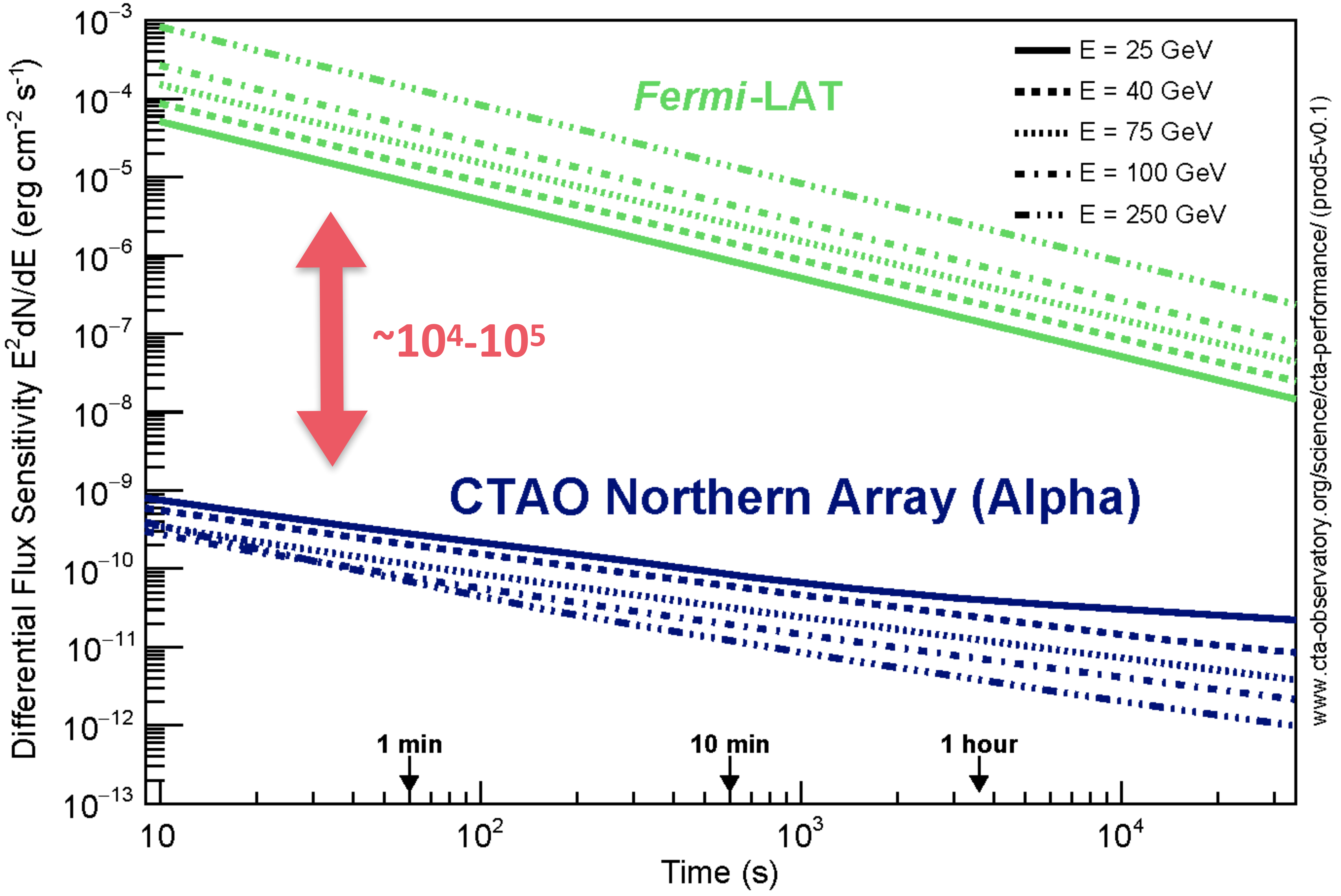
Credential Certification: Albert Kong (akong@phys.nthu.edu.tw)

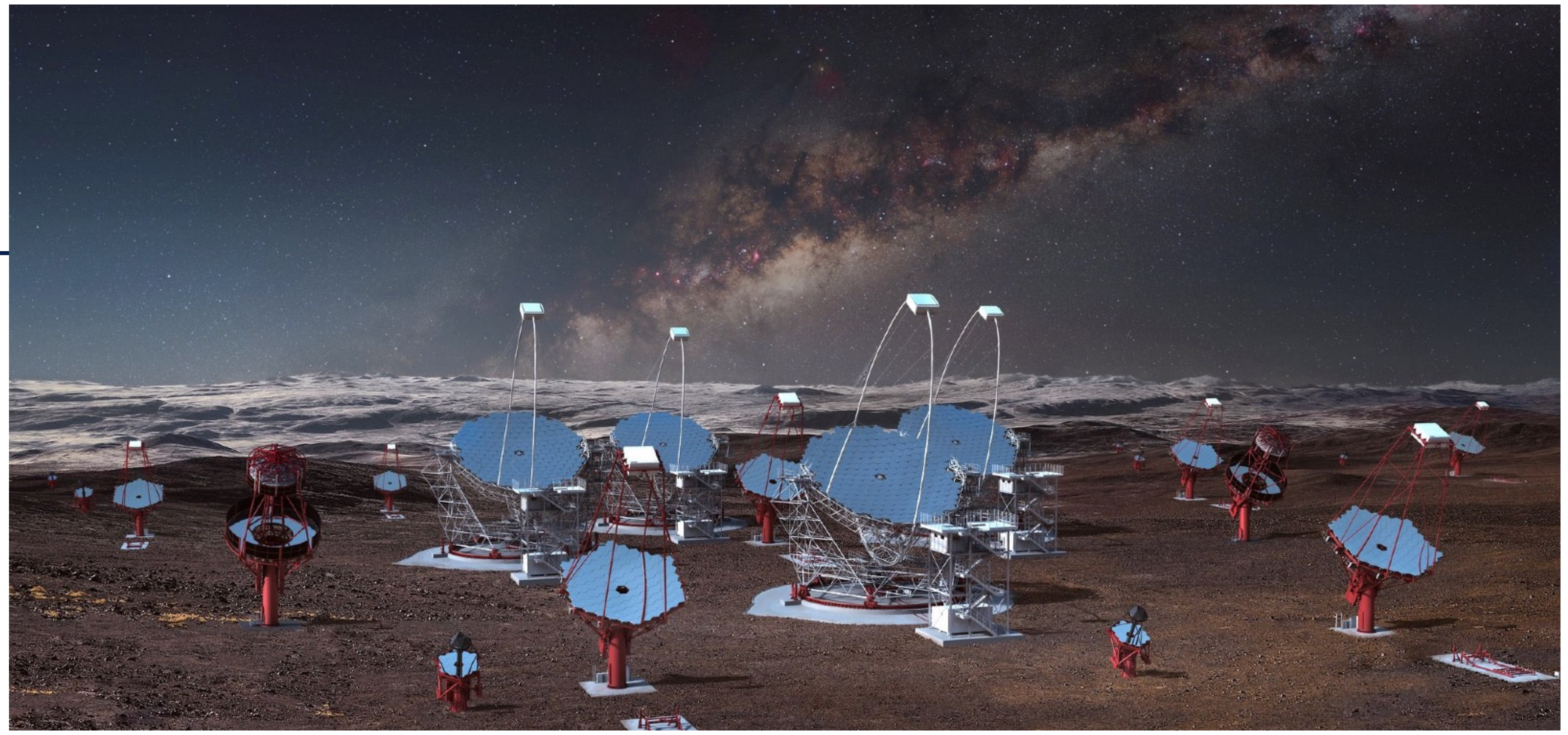






Short-time sensitivity





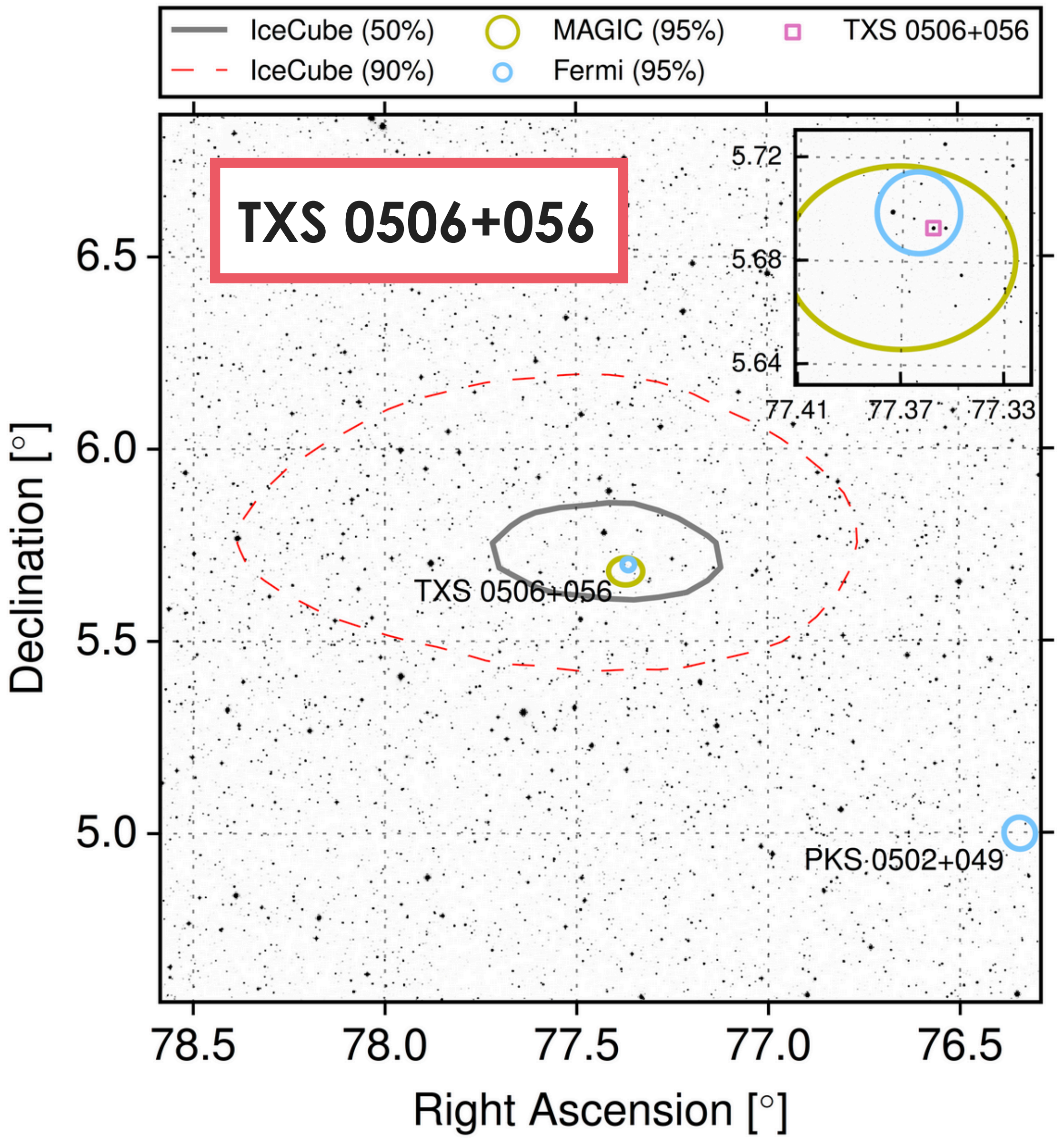
- Unprecedent **sensitivity at short timescales** -> **transient detection**
  - **Fast slewing** (LST: 20 sec)
  - **Low energy threshold** (20 GeV)

VHE transient astrophysics: state-of-the-art

Several types of **transient and multi-messenger sources**
discovered over the last five years
Exciting times for transient and multi-messenger astrophysics!

VHE transient astrophysics: state-of-the-art

Neutrinos



TXS 0506+056 (IceCube, Fermi, MAGIC +others, Science 2018)

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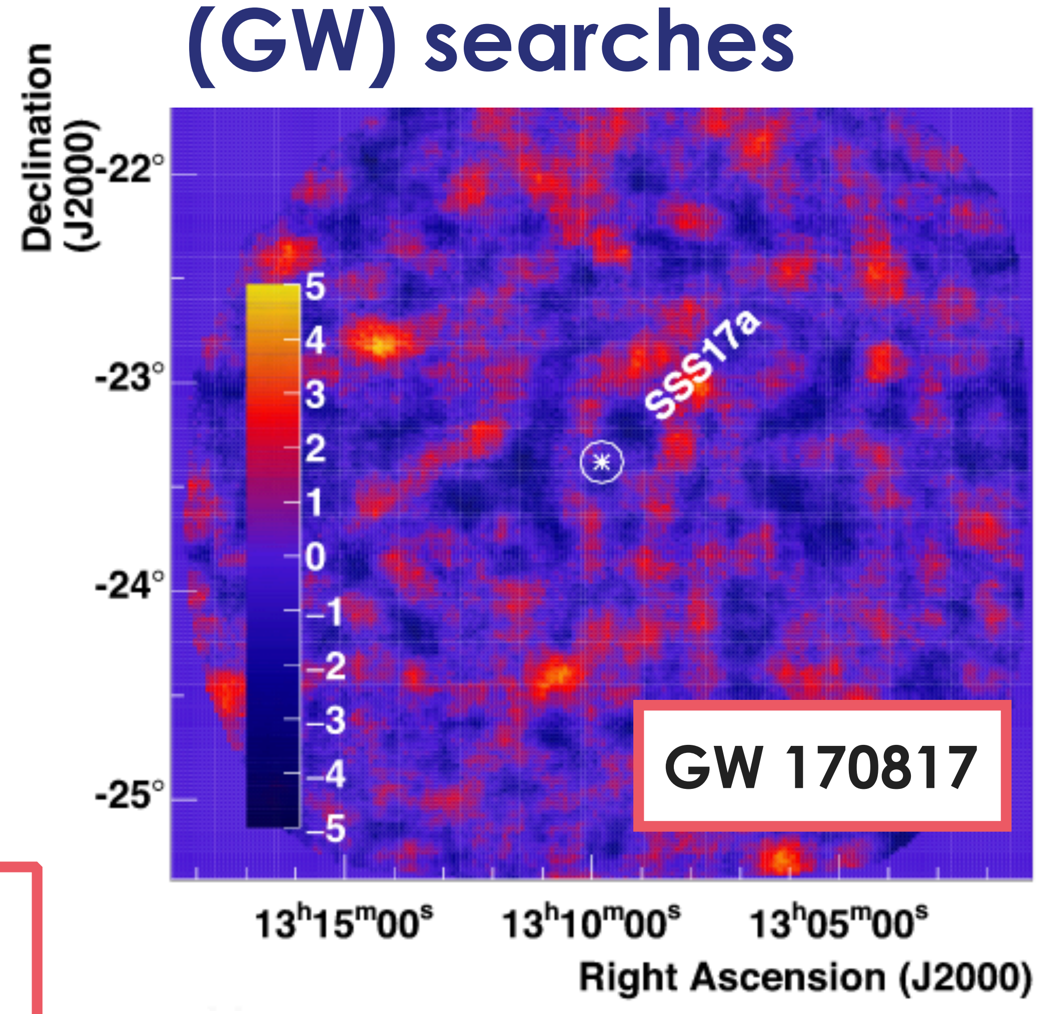
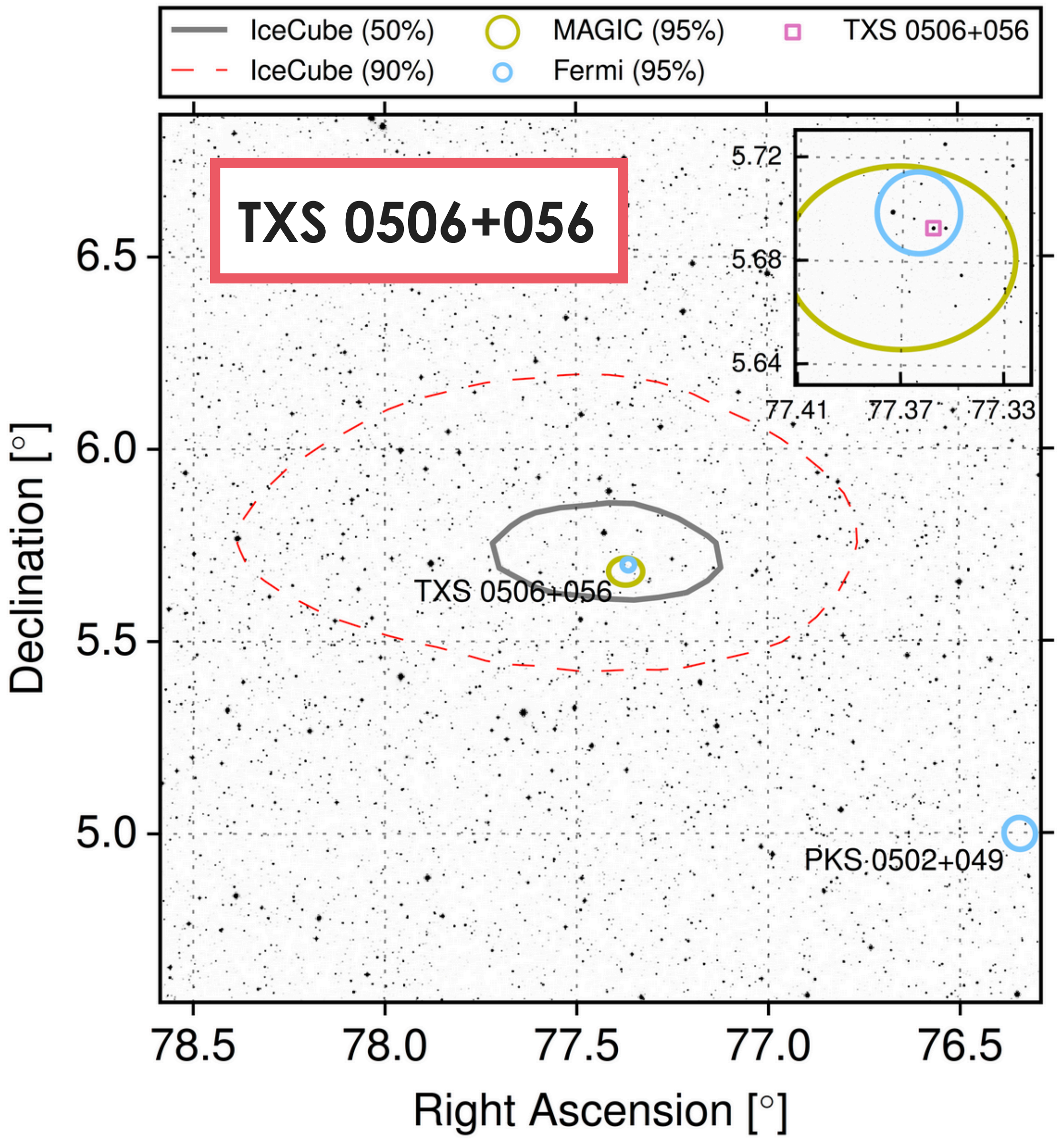
VHE transient astrophysics: state-of-the-art

Gravitational wave (GW) searches



GW 170817 (HESS. ApJL 2018)

Neutrinos



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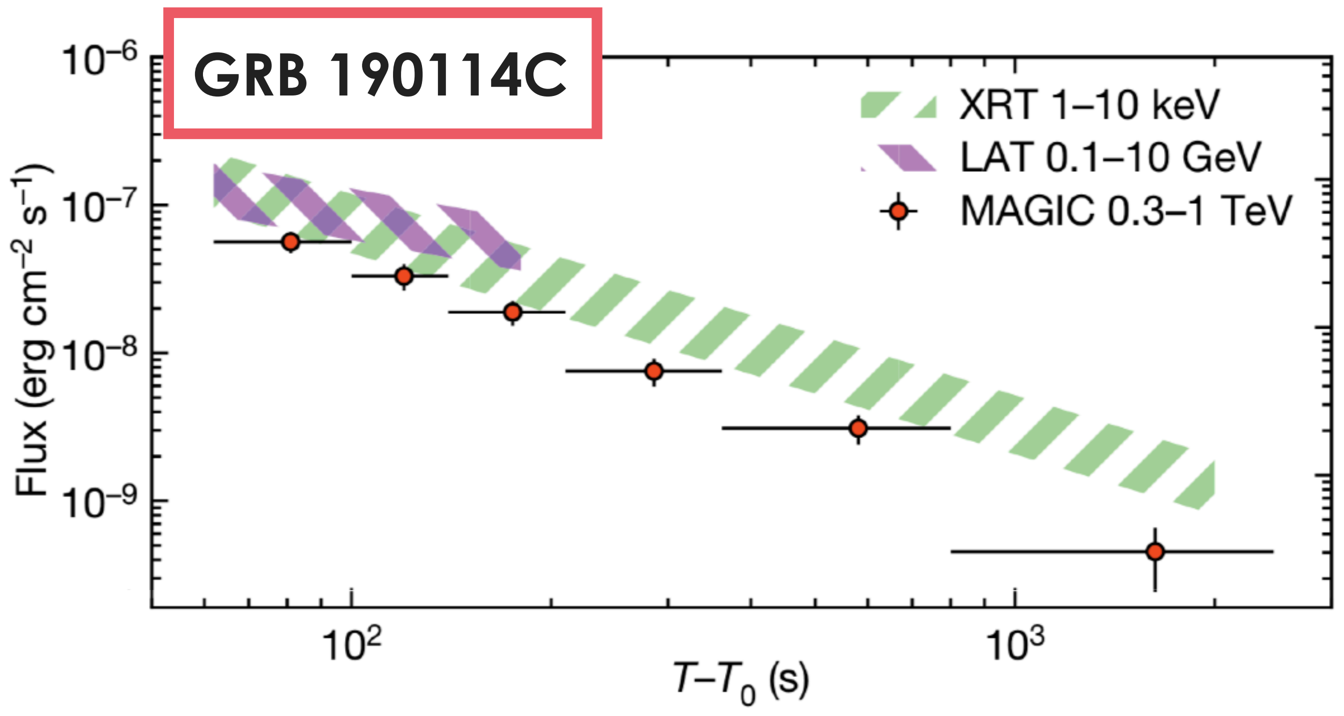

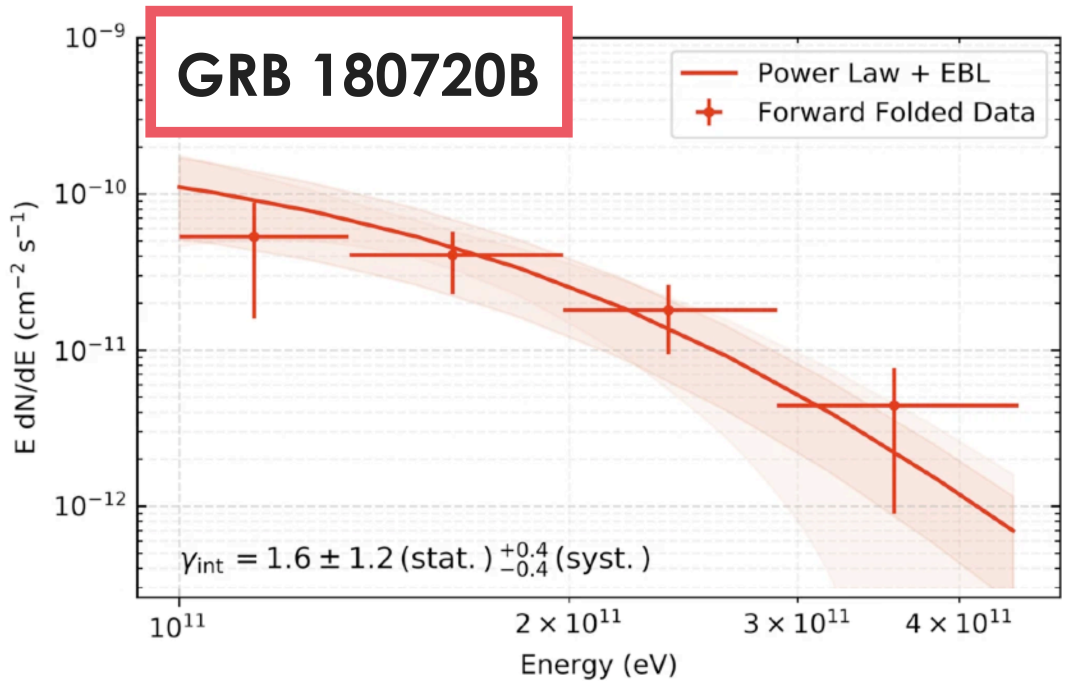

GRB 190114C (MAGIC, Nature 2019a, 2019b); GRB 180720B (H.E.S.S., Nature, 2019)
+ more

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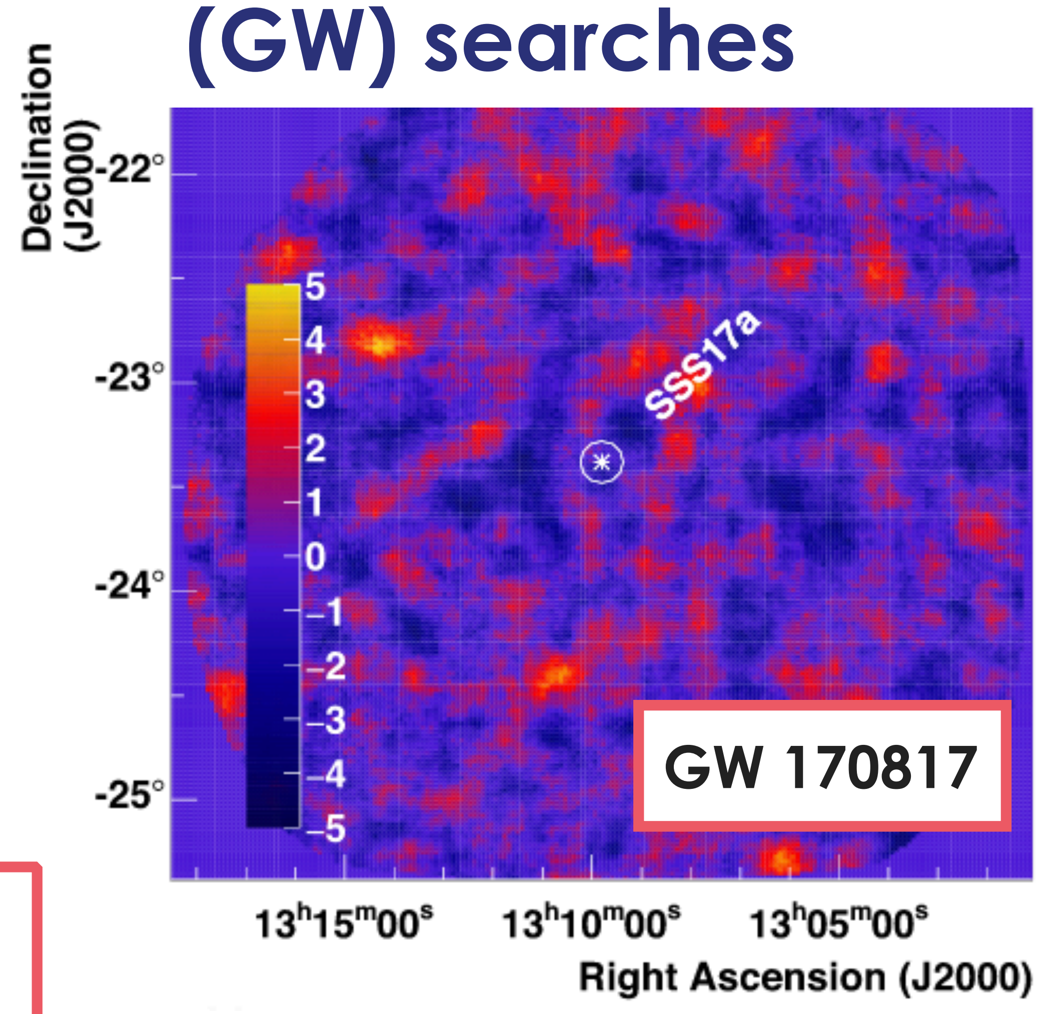

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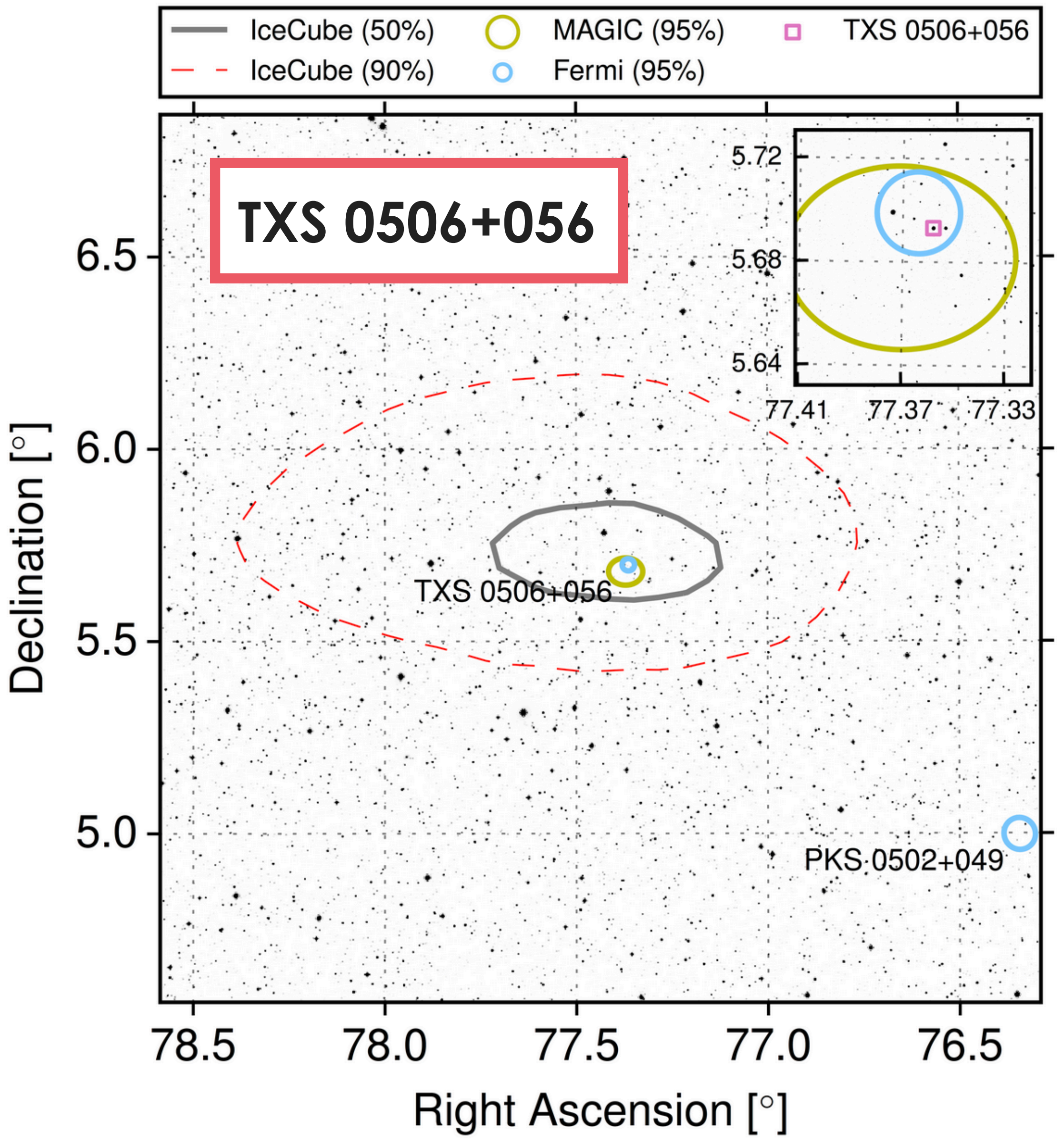

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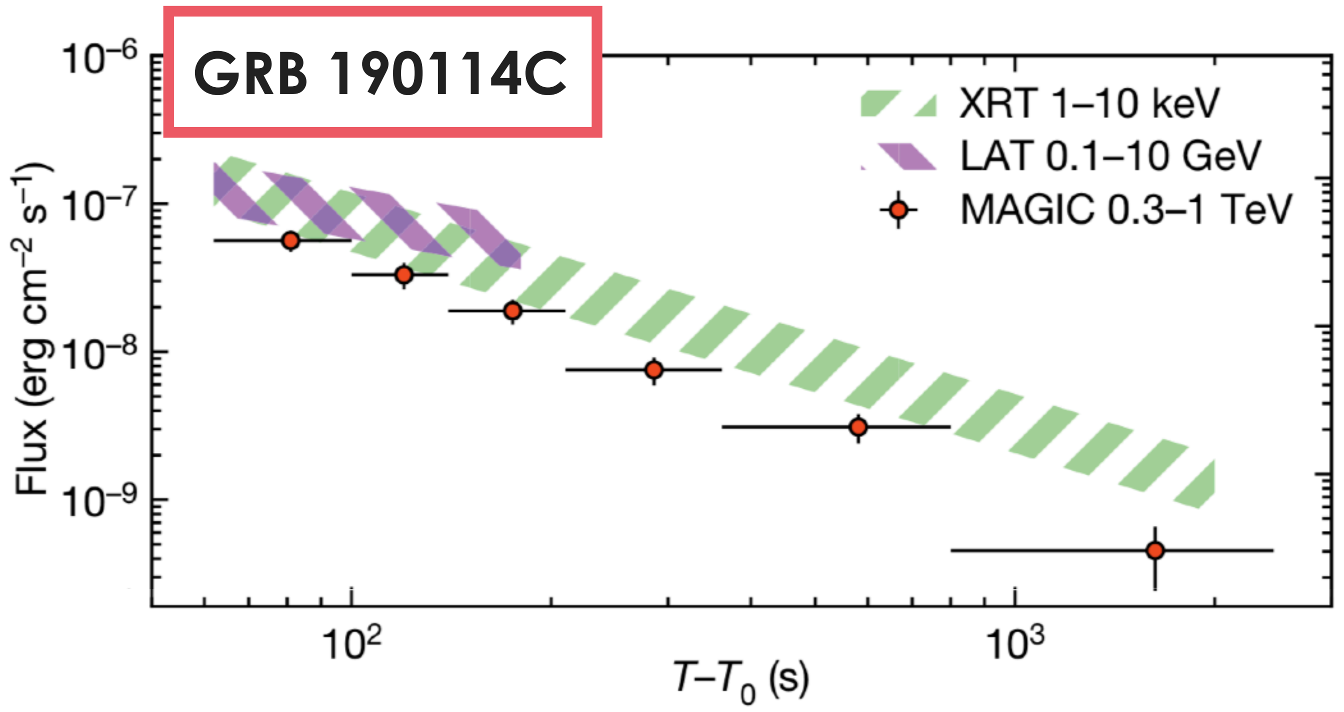

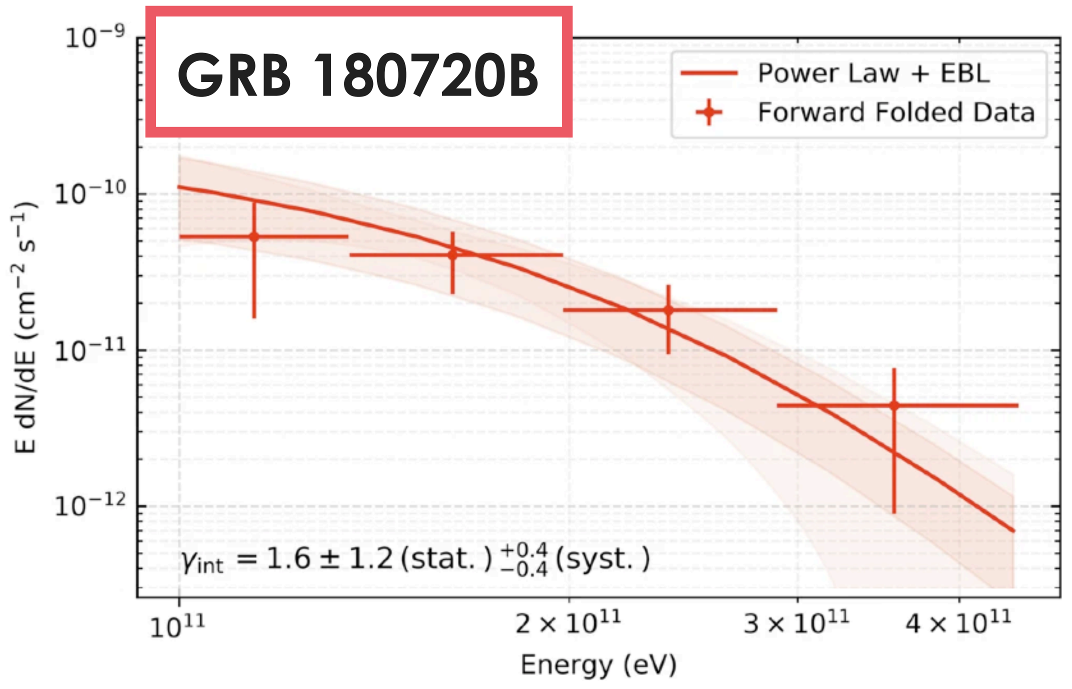

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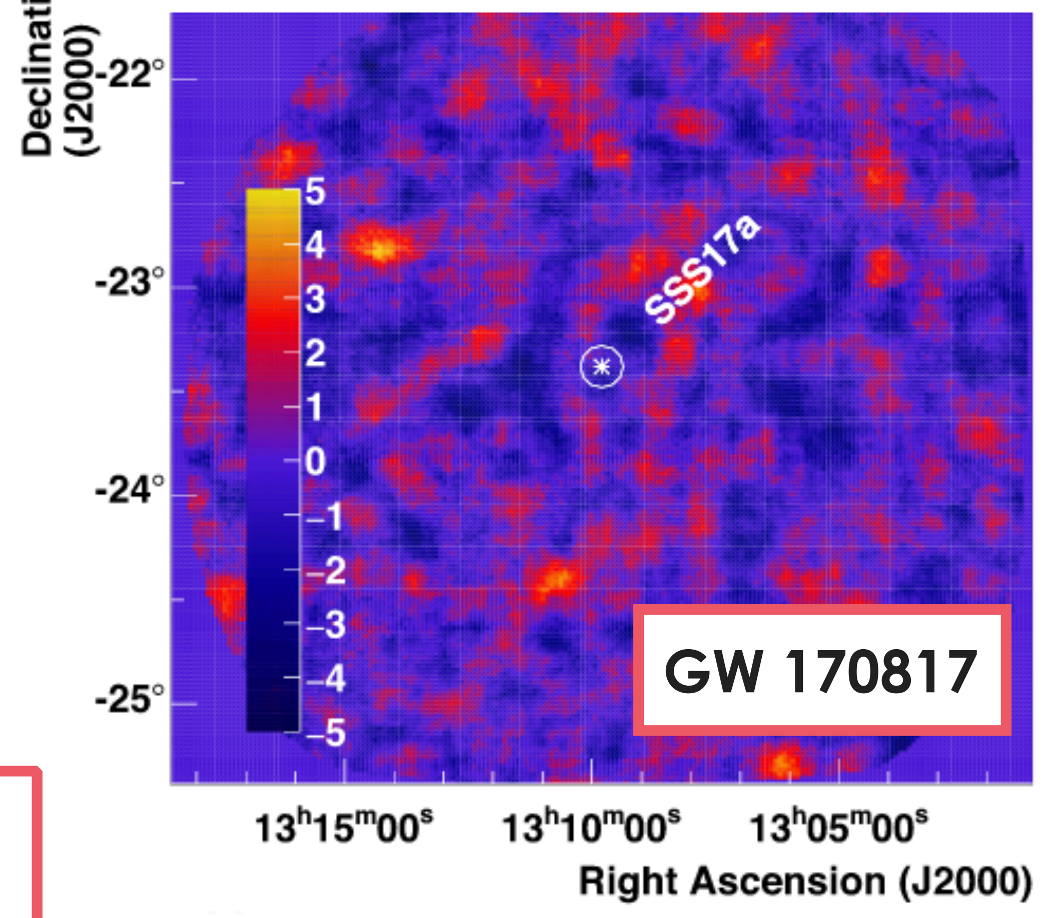

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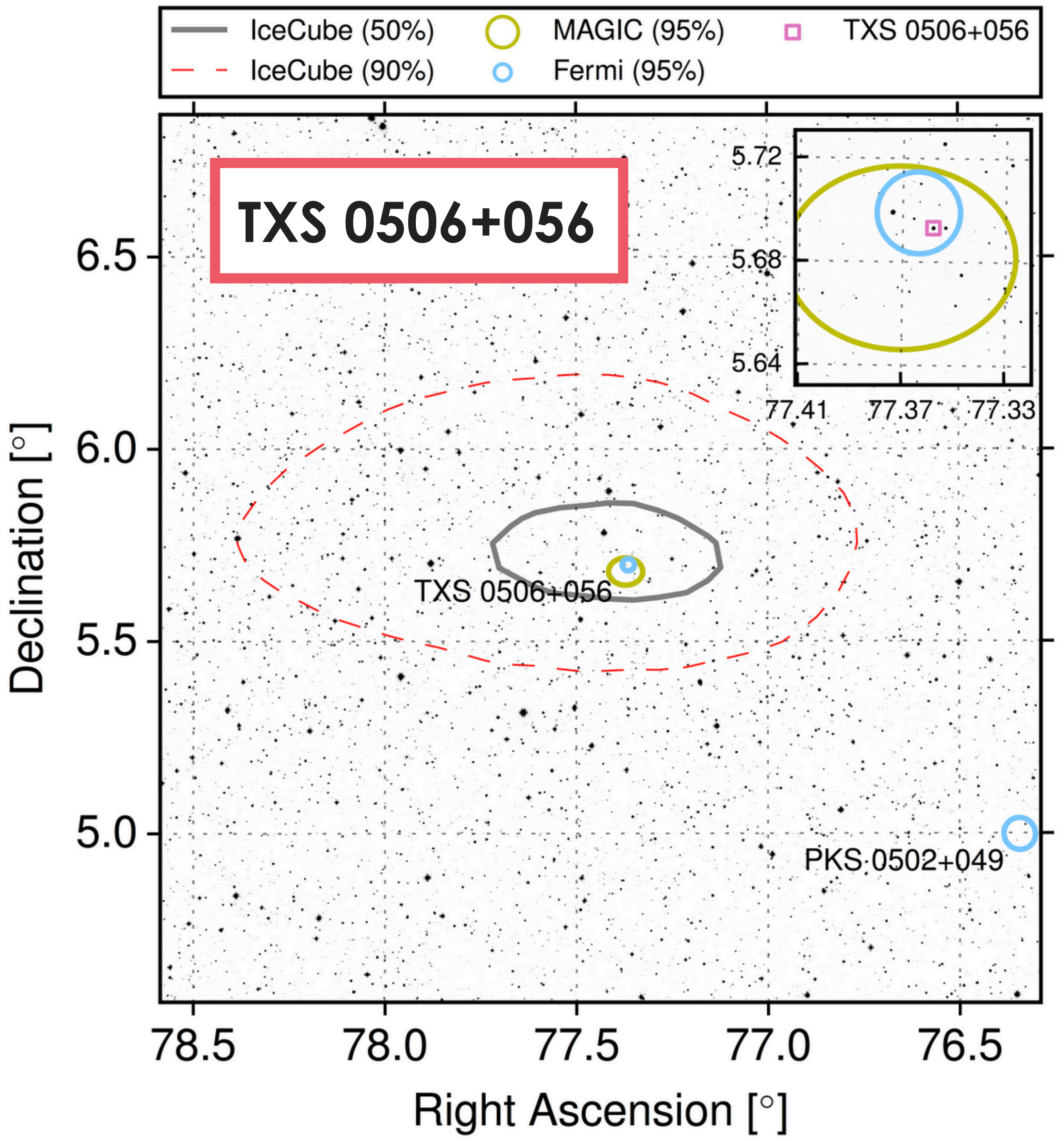

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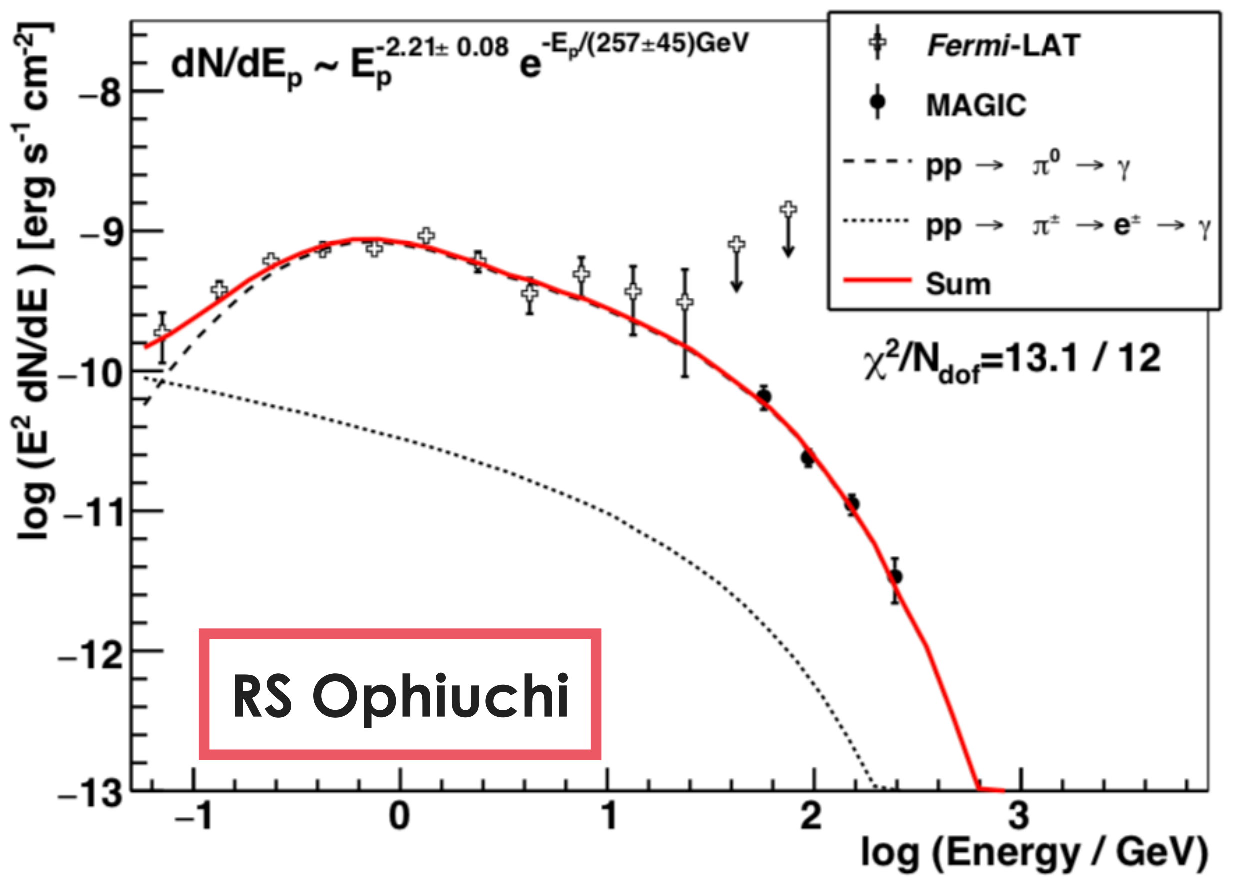
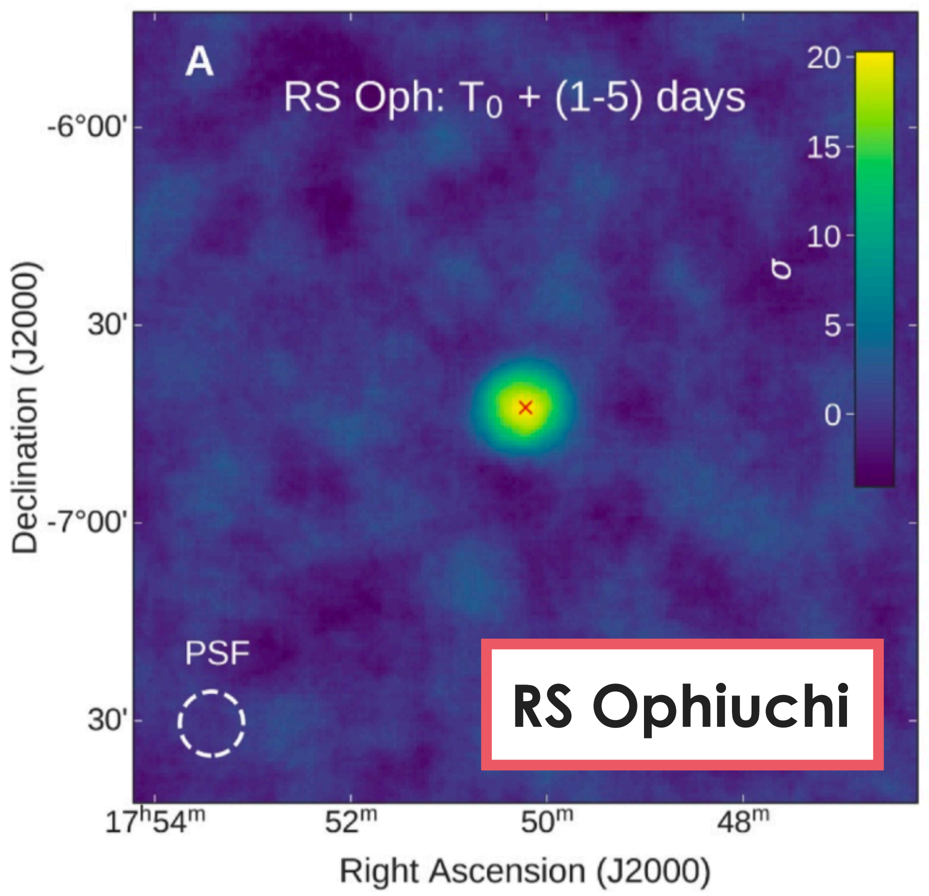
Novae



RS Oph (MAGIC, Nature Ast. 2022)



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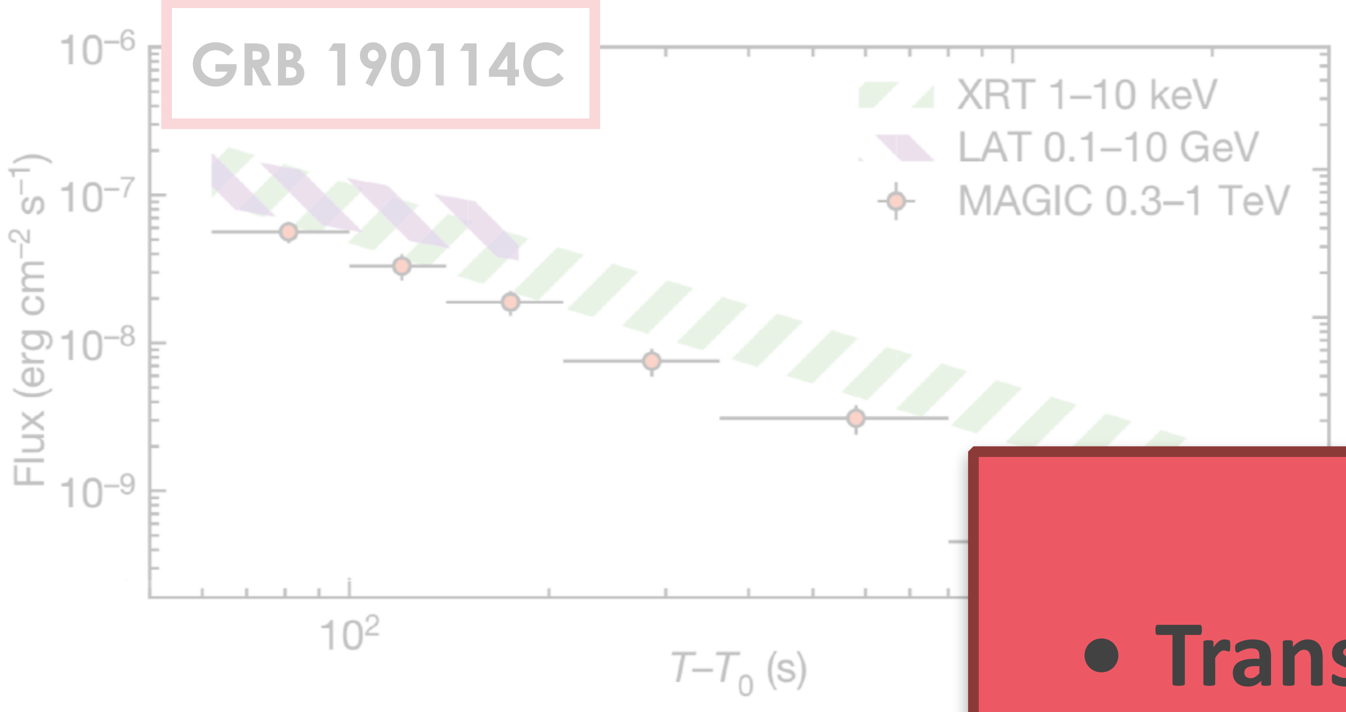
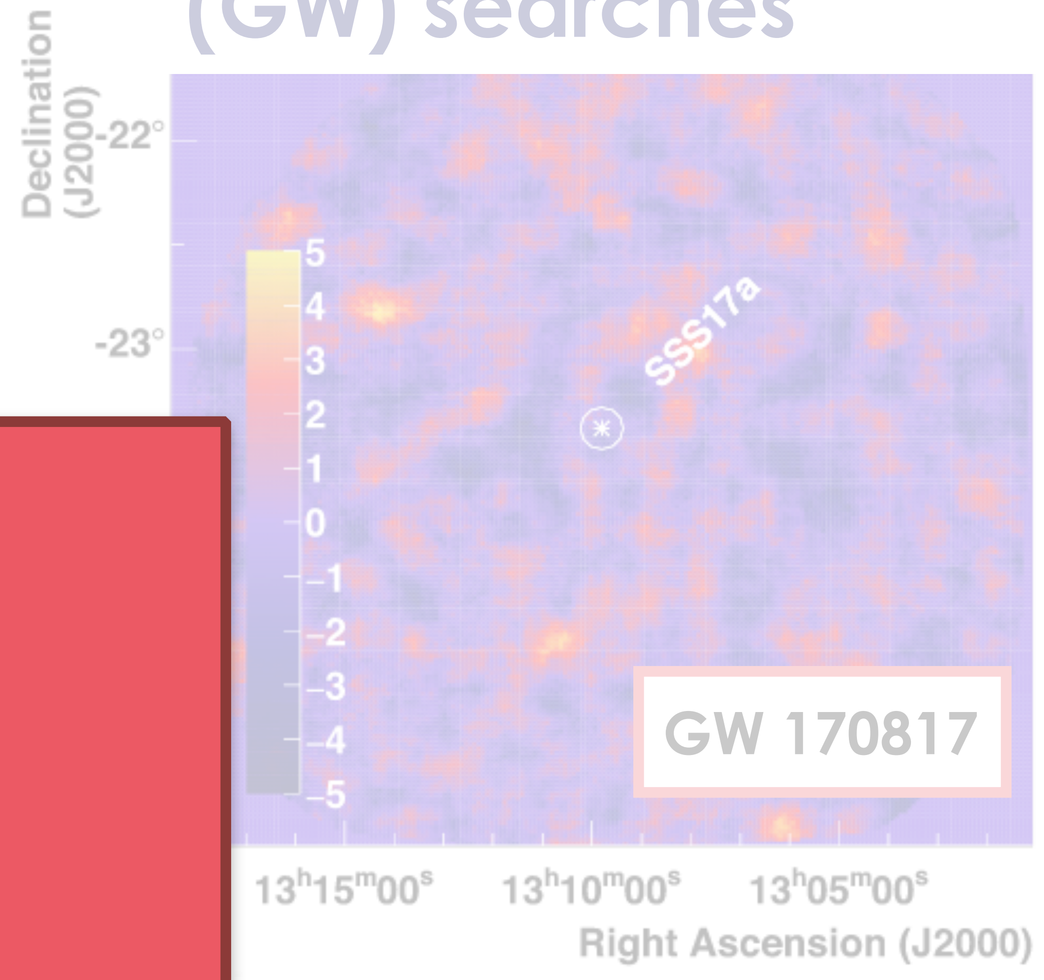


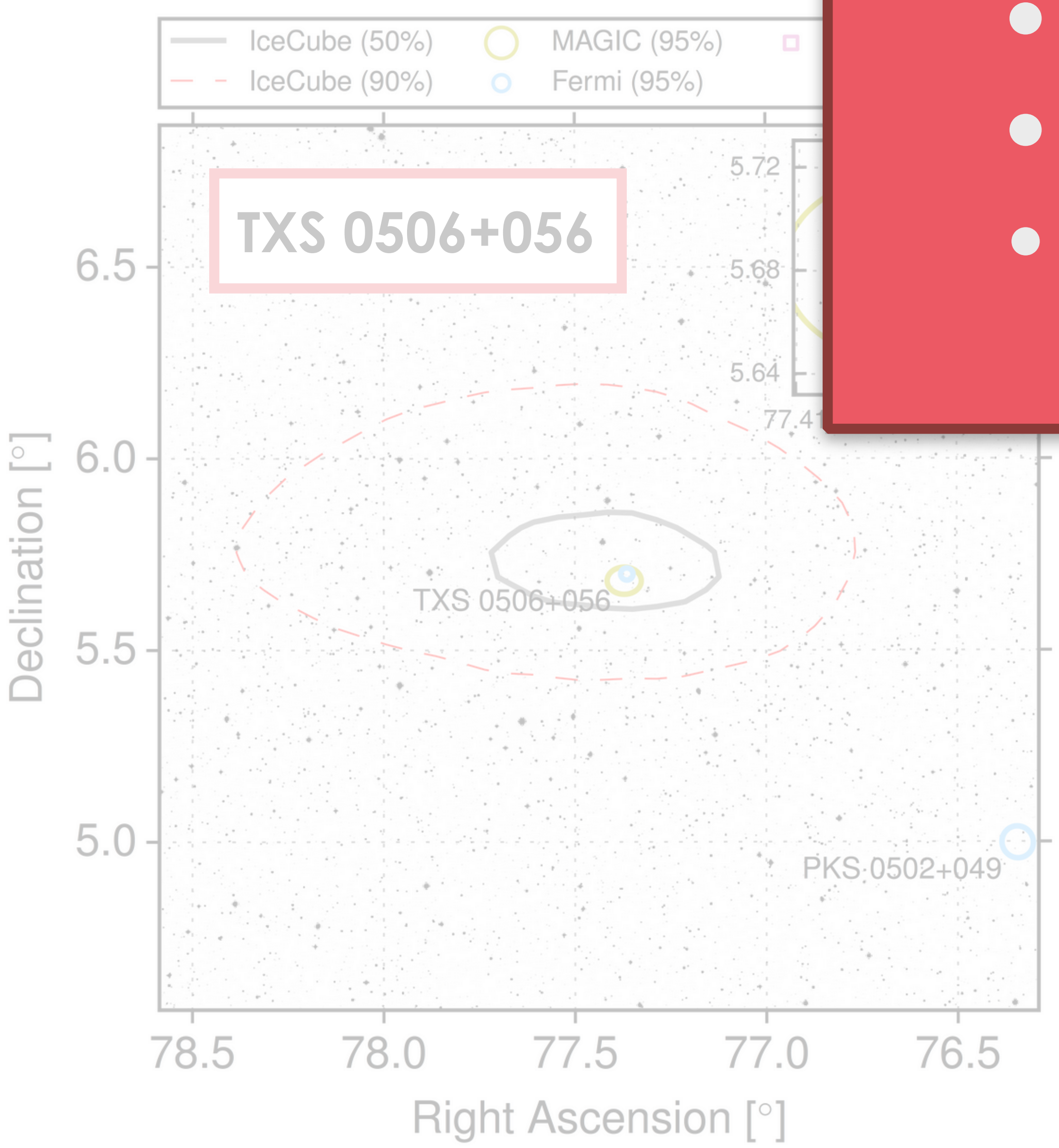
GRB 190114C (MAGIC, Nature 20
+ more

Gravitational wave (GW) searches



W 170817(HESS. ApJL 2018)

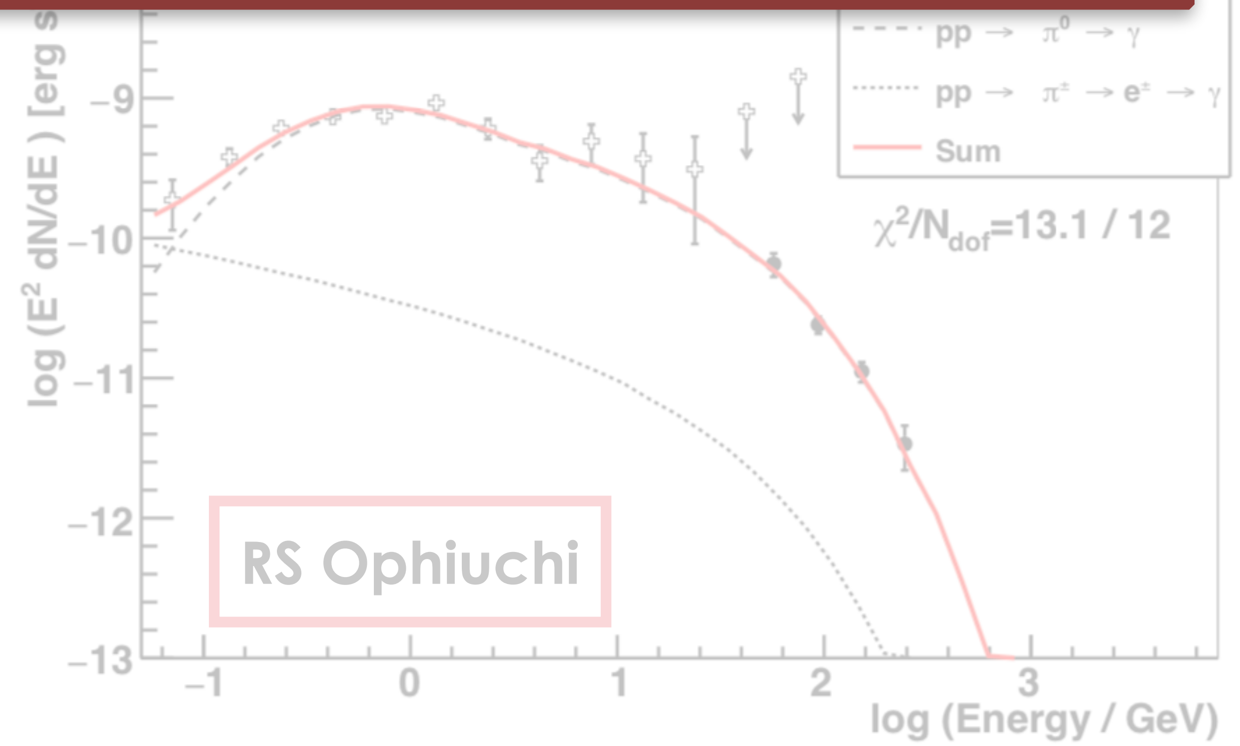
Neutrinos



TXS 0506+056 (IceCube, Fermi, MAGIC +others, Science 2018)

- **Transients Science Working Group (CTA Consortium)**
  - **Gamma-ray bursts (GRBs)**
  - **Gravitational waves (GWs)**
  - **Neutrinos**
  - **Galactic transients (microquasars, PWNe**, novae, tMSPs…)
  - Core-collapse supernovae

e



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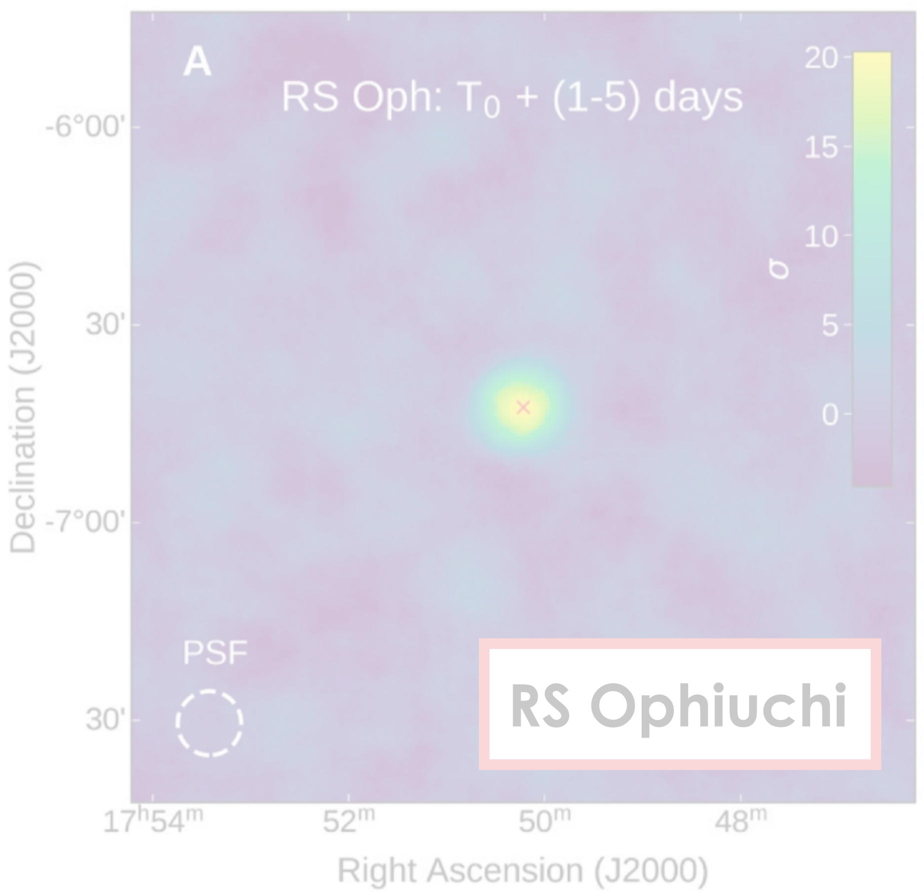


RS Oph (H.E.S.S., Science 2022)

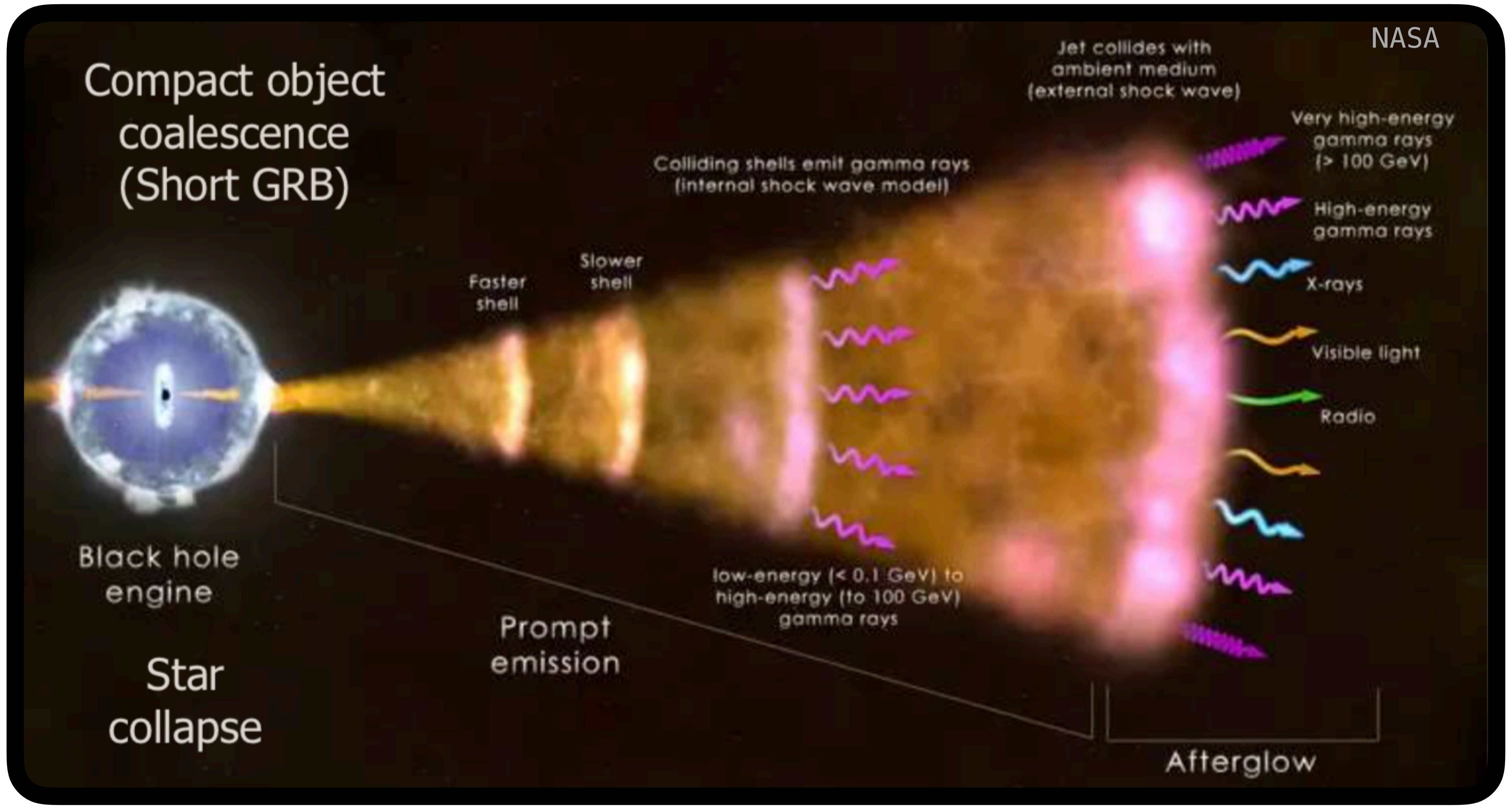
Gamma-ray Bursts (GRBs)

Population

Monte Carlo
Calibrated on Fermi-GBM & Swift data

1000 GRB – 44 yr

Swift bright GRBs, P(15–150 keV) > 2.6 γ cm^{-2} s^{-1}



Detection Analysis

SoHAPPy with

A Python package for gamma-ray astronomy

from ThStolarczyk

GRB population
Synthesis code
POSYTIVE
(Ghirlanda et al.2015)

→ Prompt emision → CTA detection

→ Afterglow emision → CTA detection

Gamma-ray Bursts (GRBs): afterglow

Reference simulation

- ✓ EBL model : Dominguez 2011
- ✓ IRF : Full Array (N, S)
  - Variable zenith (20°, 40°, 60°)
  - Variable observation time (100s, 30', 5h, 50 h)
  - Average azimuth
- ✓ Visibility
  - Moon veto whatever its phase (altitude < −0.25°)
  - GRB altitude > 24° (CTA requirements)
- ✓ Delays
  - ✓ Slewing : 30 s (LST)
    - MST additional delays neglected (<90 s)
  - ✓ Alert : 77 s

⇒ Total delay : 107 s

from ThStolarczyk

Preliminary

Rate		Total
Vis.	Counts	*611 ± 25*
	yr^{-1} @trig	**13.9 ± 0.6**
3σ	Counts	*96 ± 10*
	yr^{-1} @trig	**2.2 ± 0.2**
5σ	Counts	*81 ± 9*
	yr^{-1} @trig	**1.8 ± 0.2**

- Input: 1000 long GRB afterglows
  - Visibility above horizon, detection delays
  - Condition: detected if 90% of trials are successful
- **10% of the visible population are detected** (duty cycle)
- **Detection rate: 1.8** (± 0.2) **per year**
  - 1 event per year >20σ
  - 1 event every 2 years >50σ

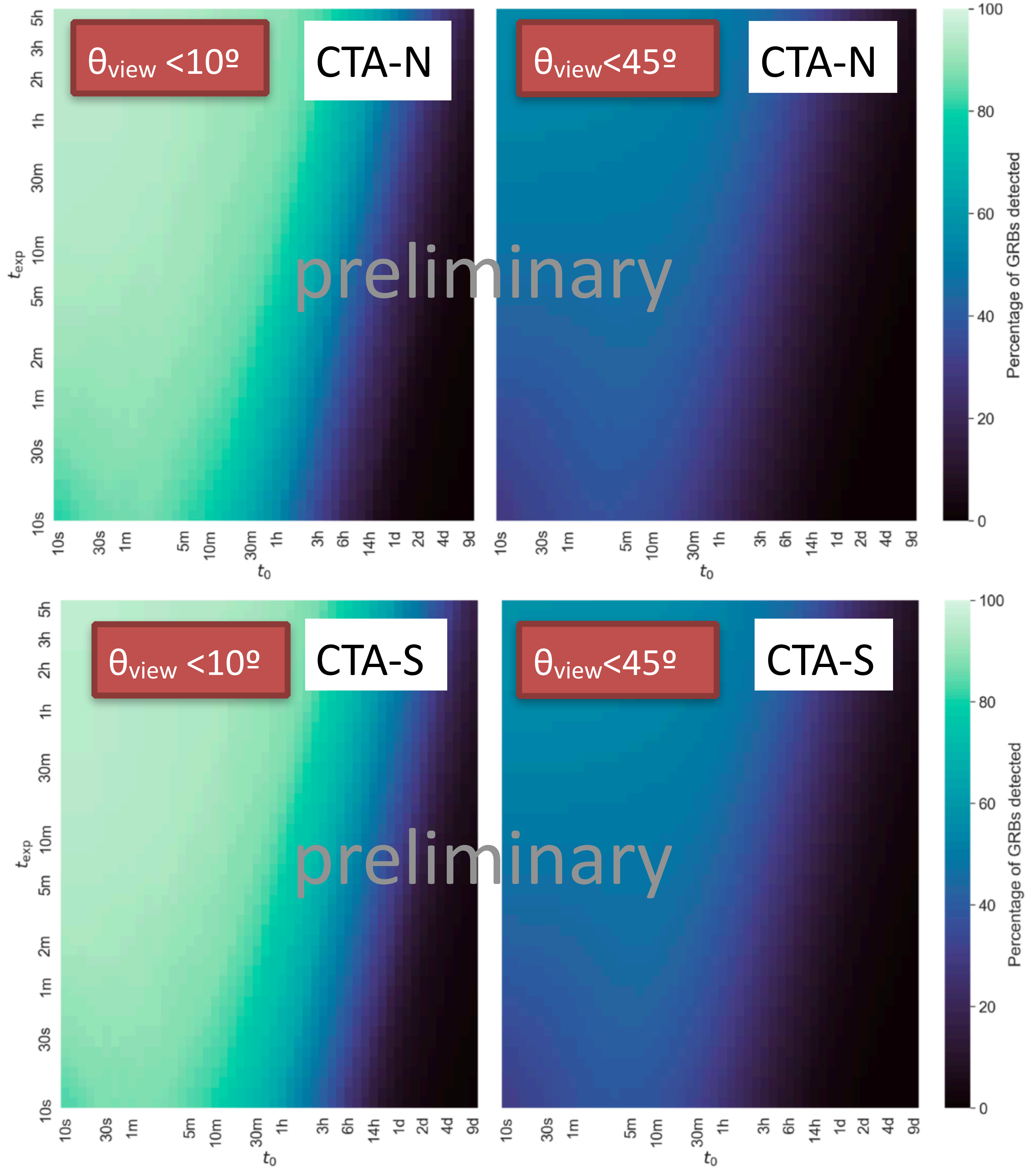
CTA will detect ~2 GRBs year (afterglow)

Gravitational Waves (GWs)

- The detection of **GW 170817 with LIGO-Virgo** and the corresponding detection and sky localization of GRB 170817:
  - **Birth of multi-messenger astronomy with GW**
  - First evidence of **binary neutron star (BNS) mergers as progenitors for short GRBs** (sGRBs)

- Follow-up GW transient events and **detect possible VHE counterpart**
- Simulations of **BNs mergers accompanied by short GRBs** GWCOSMoS database (Patricelli et al. 2016, 2018)

- CTA is sensitive enough to **detect** both **on-axis and off-axis GRBs with time delays up to ~10 min**



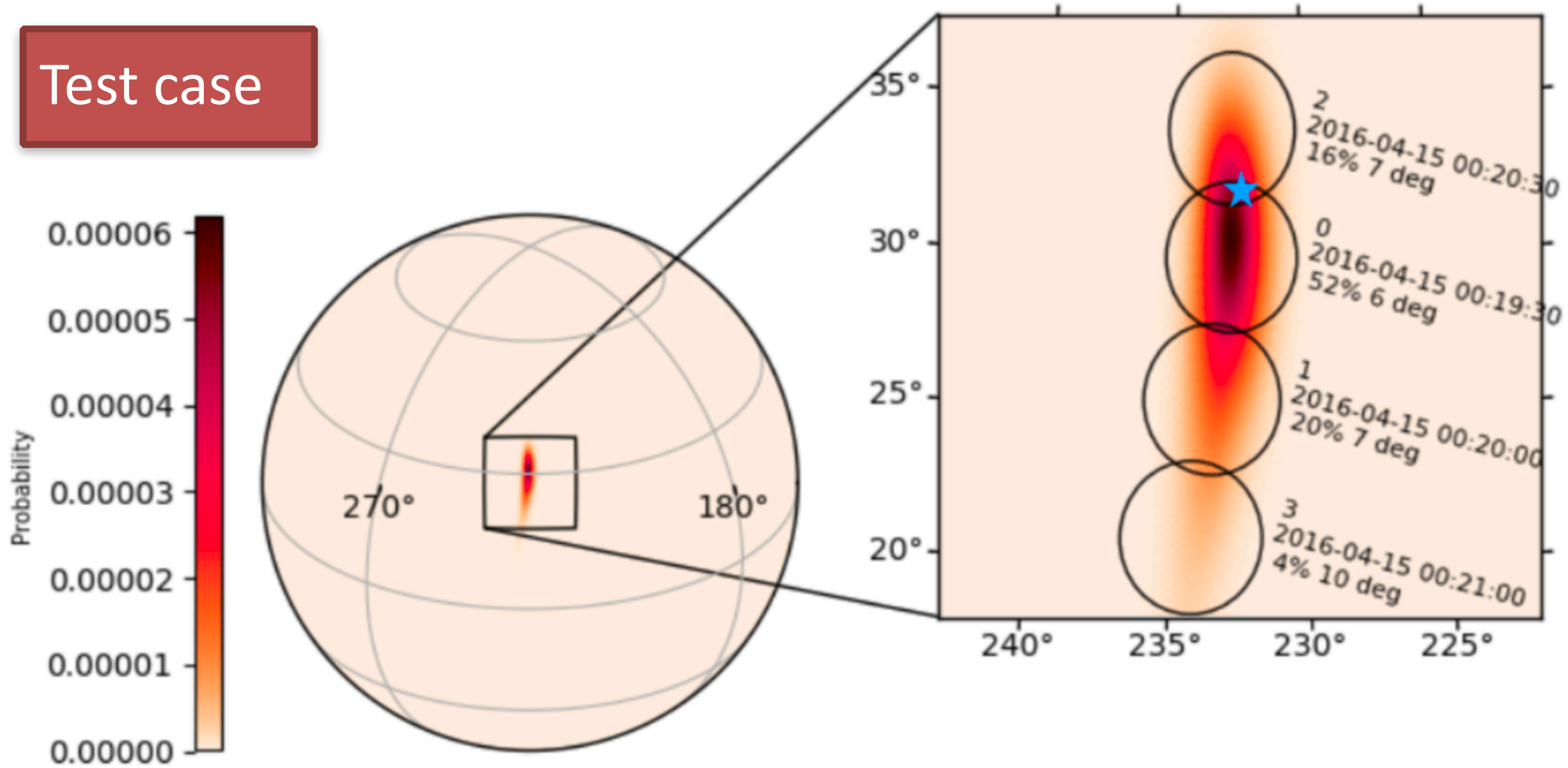
CTA will detect on/off-axis GW counterparts

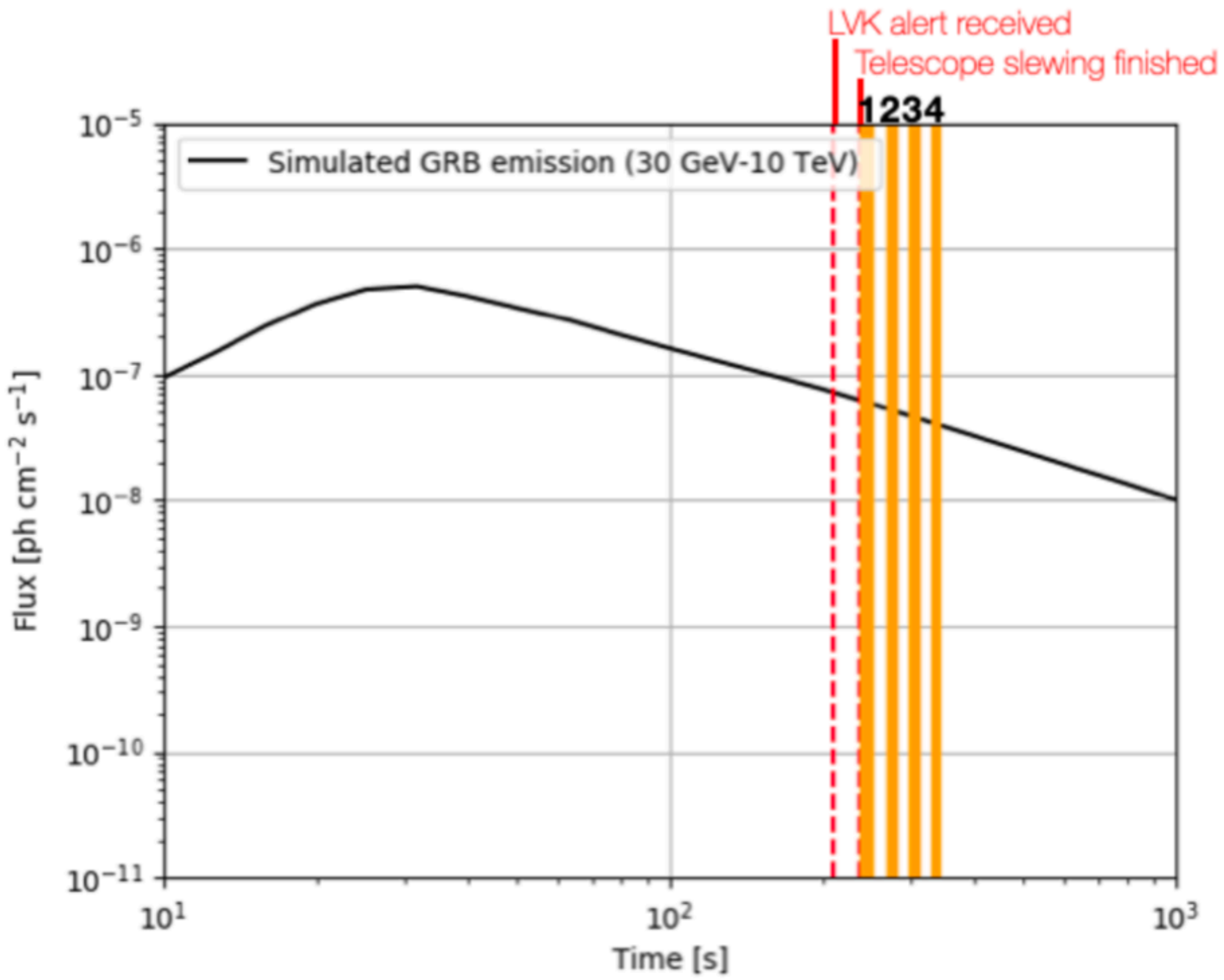
Patricelli et al. ICRC 2021

Gravitational Waves (GWs)

- Pointing strategy: observation **scheduling algorithm to derive optimal pointing to cover the GW error ellipse** area

Test case

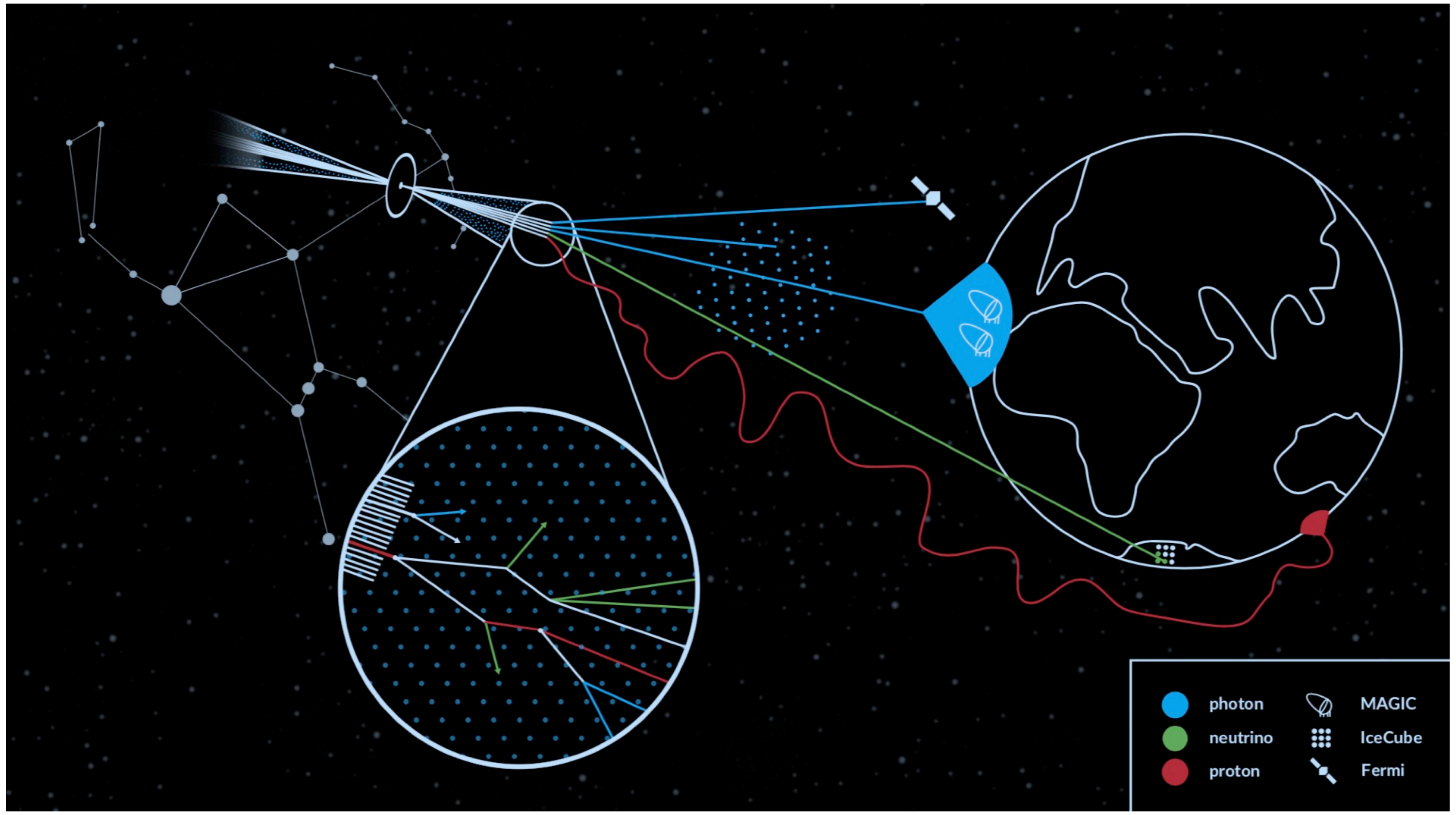




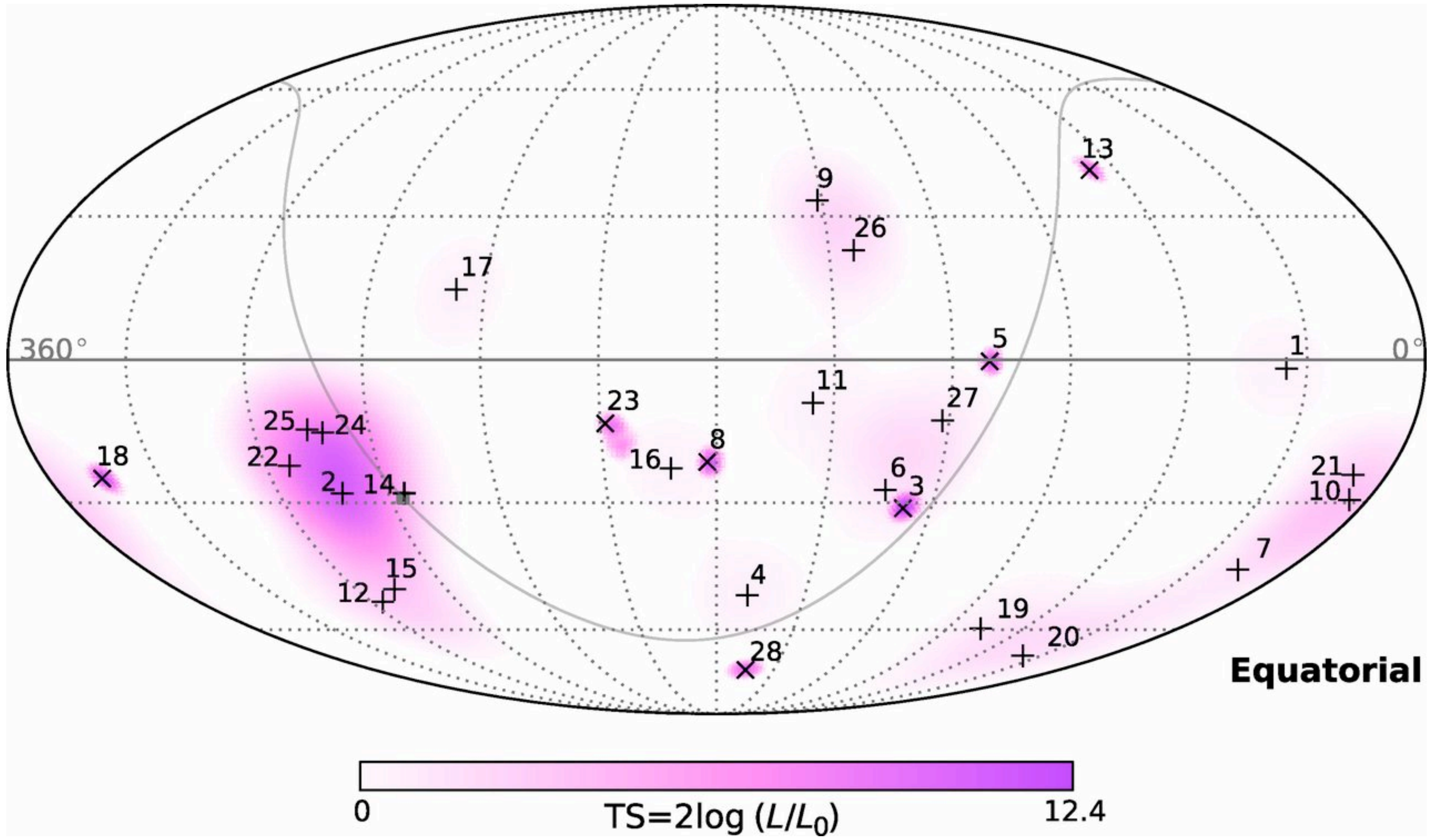
Patricelli et al. ICRC 2021

Neutrinos

- Detection of VHE counterpart of neutrino sources (populations with FIRESONG software)
- CTA will enable **counterpart detections to astrophysical neutrino events**
  - **Two source populations:**
    - **Transient: neutrino source alerts (blazars)**
    - **Steady: nu-cluster exceeding IceCube sensitivity** (following SFR evolution)

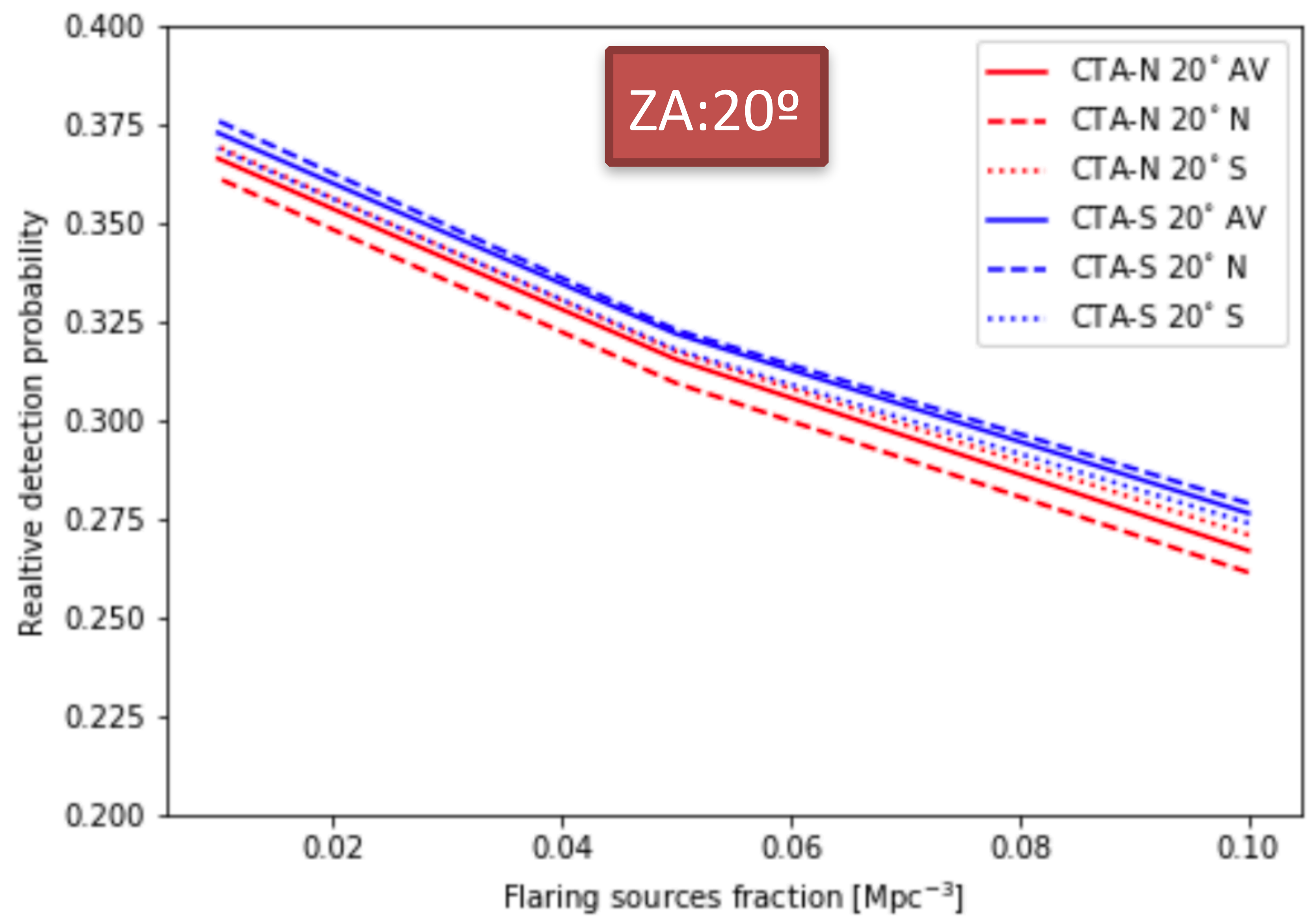


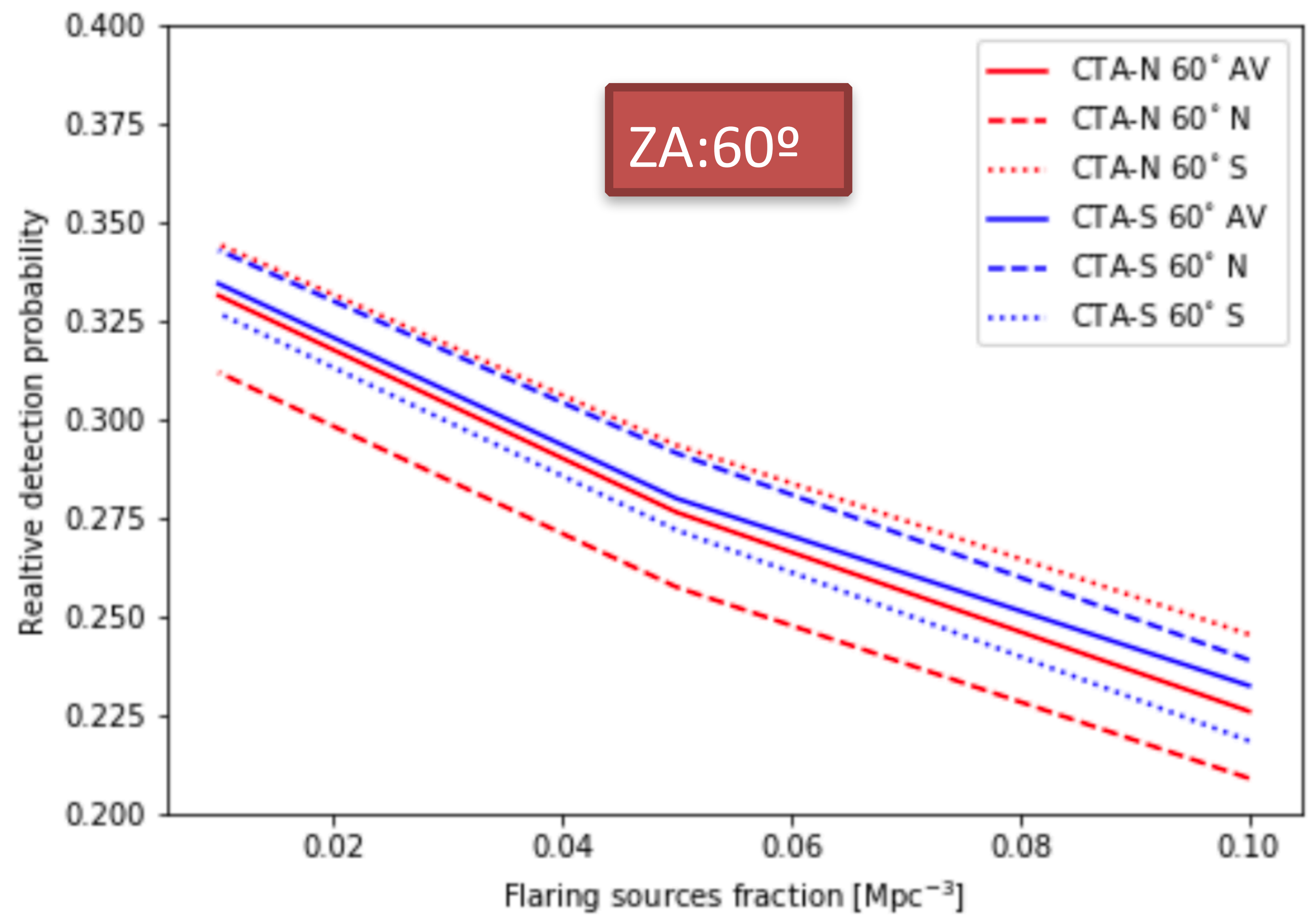
Credit: Elisa Bernardini, Konstancja Satalecka, Weronika Racz and Igor Rams



IceCube, Science 2013

Neutrinos: flaring sources





Sergijenko et al. ICRC 2021

FLARING SOURCES

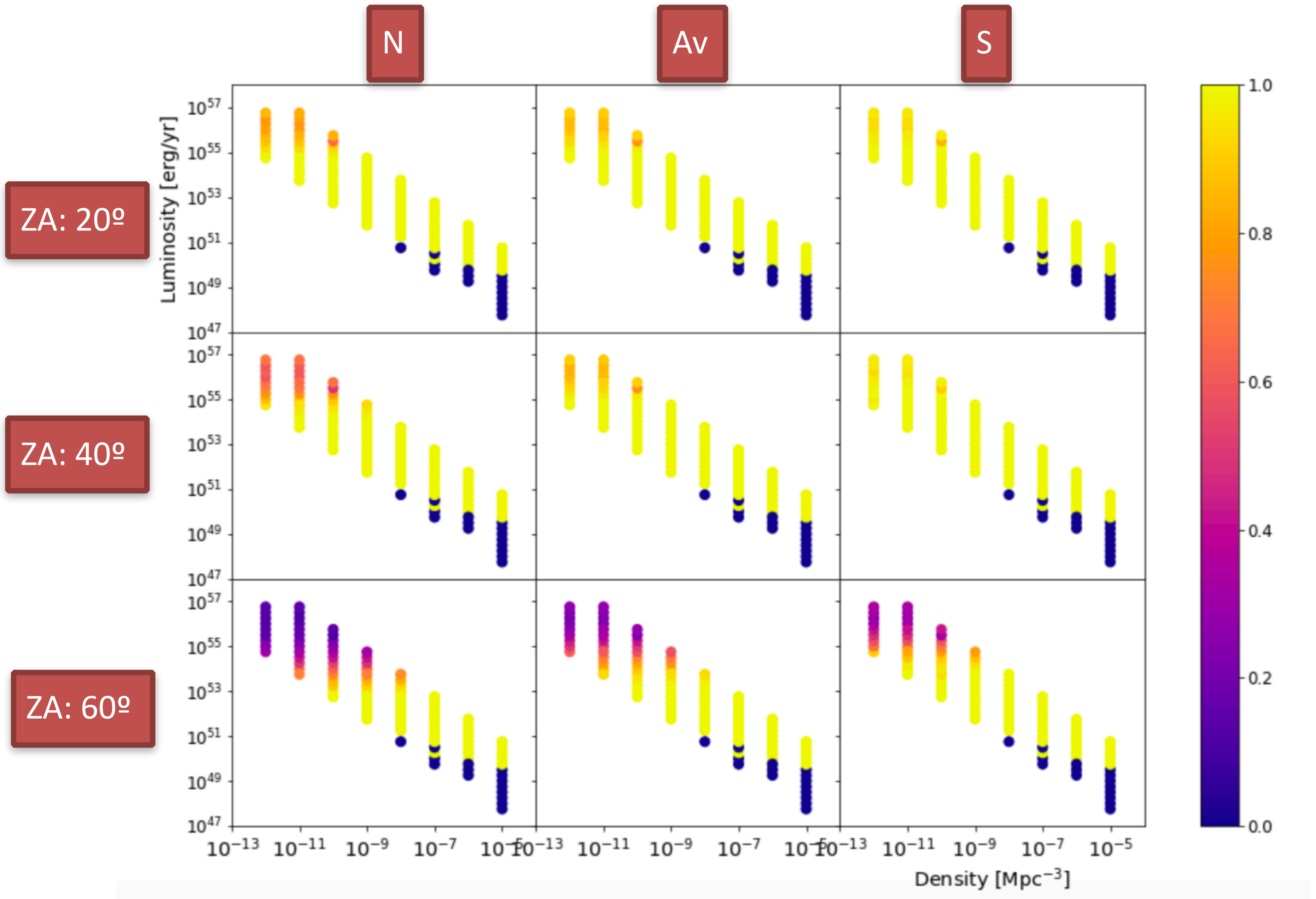
- Based on the neutrino flare model of TXS 0506+056 in 2014-2015
- Same flare duration (in the comoving) as TXS 0506
- Flat cosmological evolution and IC alerts always observable

- During **neutrino flares** from blazars **CTA will detect a counterpart for about one third of the cases after only 10 mins of observations**, with lower detection probabilities for steady neutrino sources.

CTA will detect flaring sources of neutrinos

Neutrinos

Steady sources: detection probability (CTA-N)



Sergijenko et al. ICRC 2021

STEADY SOURCES

- Local Density (source Mpc^{-3}) vs Luminosity (erg yr^{-1})
- SFR evolution of the nu population
- Assuming all the sources are always visible by CTA

- **Steady sources**: at low to mid zenith angle observations (20º-40º) **CTA-N will be able to detect all sources down to the density of ρ=10^{-9} Mpc^{-3} in 30 min**

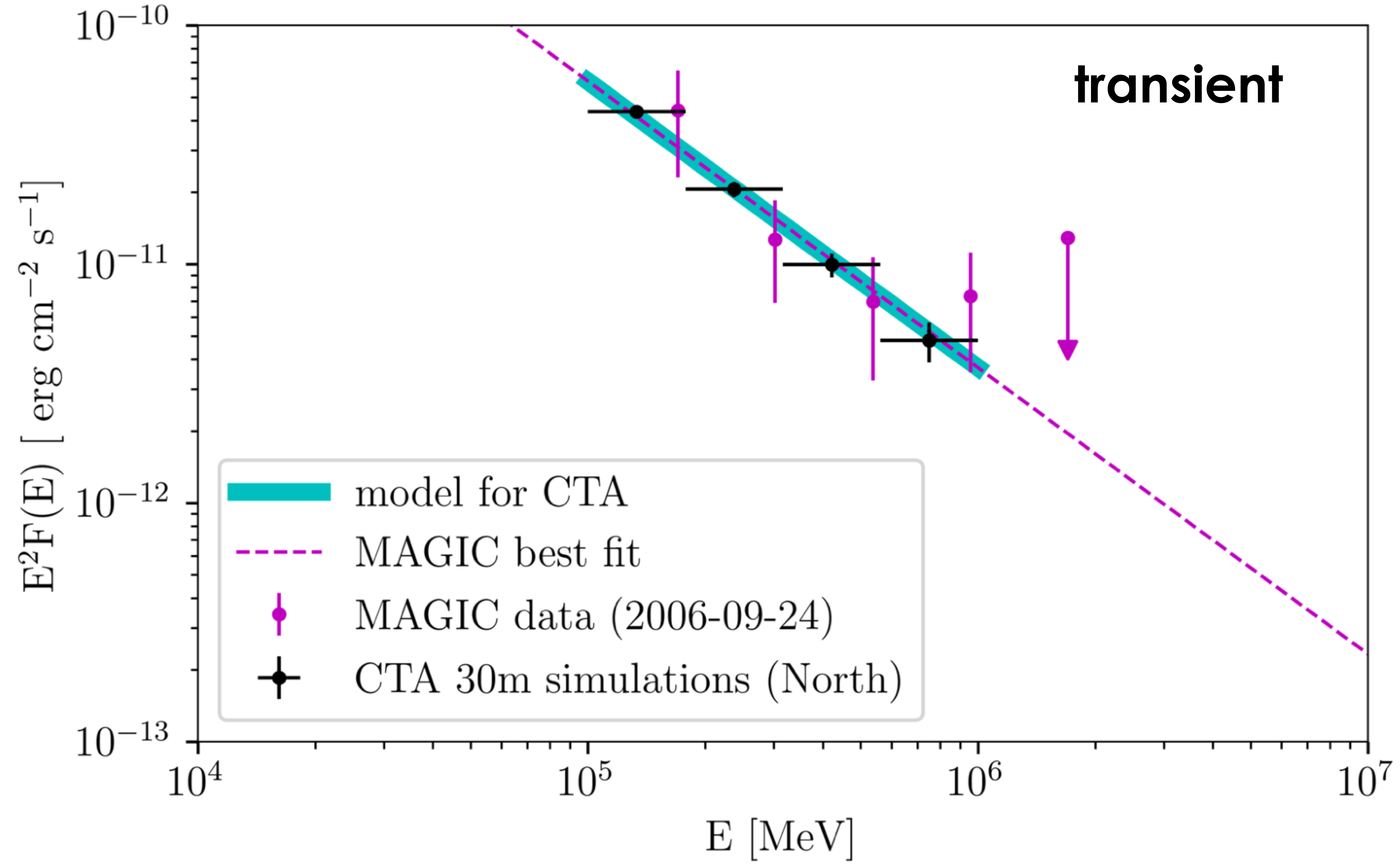
CTA will detect steady sources

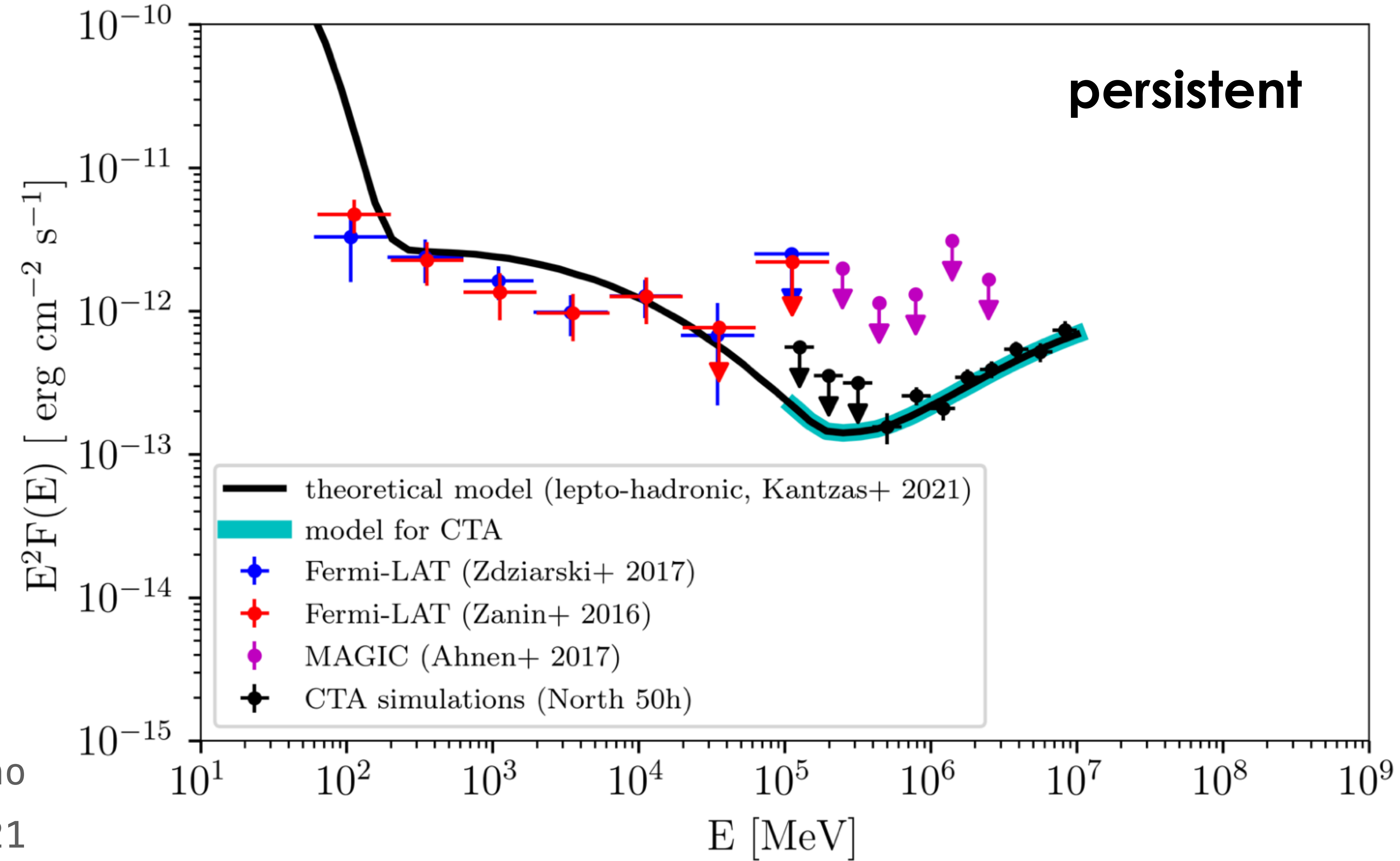
Galactic transients

Microquasars: Cygnus X-1

- Massive O star + black hole:
  - Transient: 4.9σ hint (80 min) at VHE by MAGIC (Albert et al. 2006)
  - Persistent: 7.5yr *Fermi*-LAT HE detection (Zanin et al. 2016)
- **CTA simulations** (100 GeV – 1 TeV) to search for:
  - Transient emission: 30-minute observation with MAGIC hint SED (Albert et al. 2006) as input
  - Persistent emission: lepto-hadronic model by Kantzas et al. 2021, assuming 50 h of observations
- **Detection of transient** (44σ) **and persistent emission** (39σ) **with CTA-North** (CTA Consortium in prep)

CTA will detect (some) microquasars





Plots by G. Piano

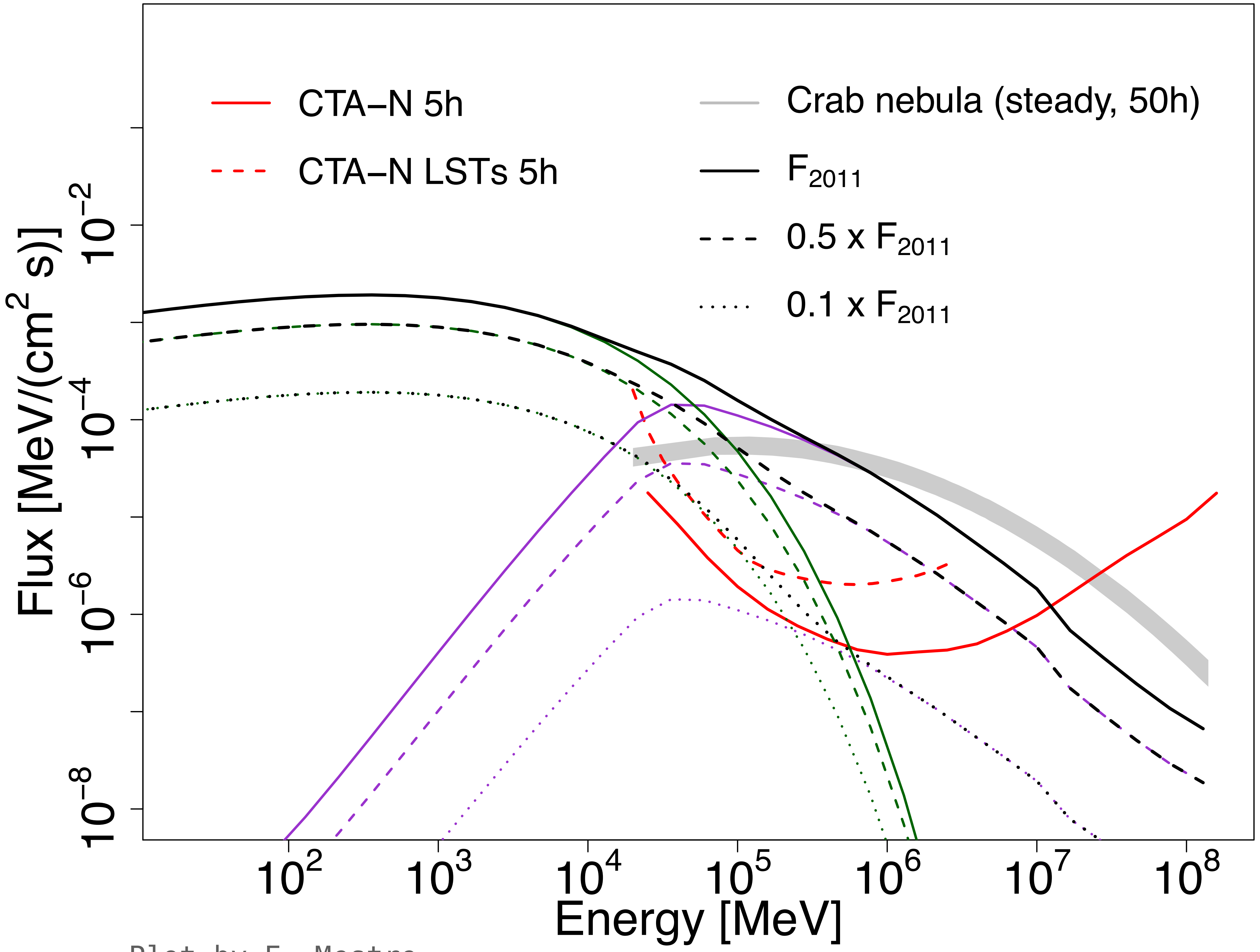
López-Oramas et al. ICRC 2021

Galactic transients

Crab Nebula Flares (PWNe)

- **Rapid and bright MeV flares** observed in Crab (Tavani et al. 2011, Abdo et al. 2011) with **timescales of hours**
  - **No TeV detection** with current IACTs
- Studying the capabilities of CTA to detect flares from the Crab Nebula (Mestre et al. 2021, CTA Consortium in prep)
- **Good prospects with CTA** and especially **LSTs**:
  - **VHE detection in < 5h** (CTA Consortium in prep)

CTA will detect flaring PWNe



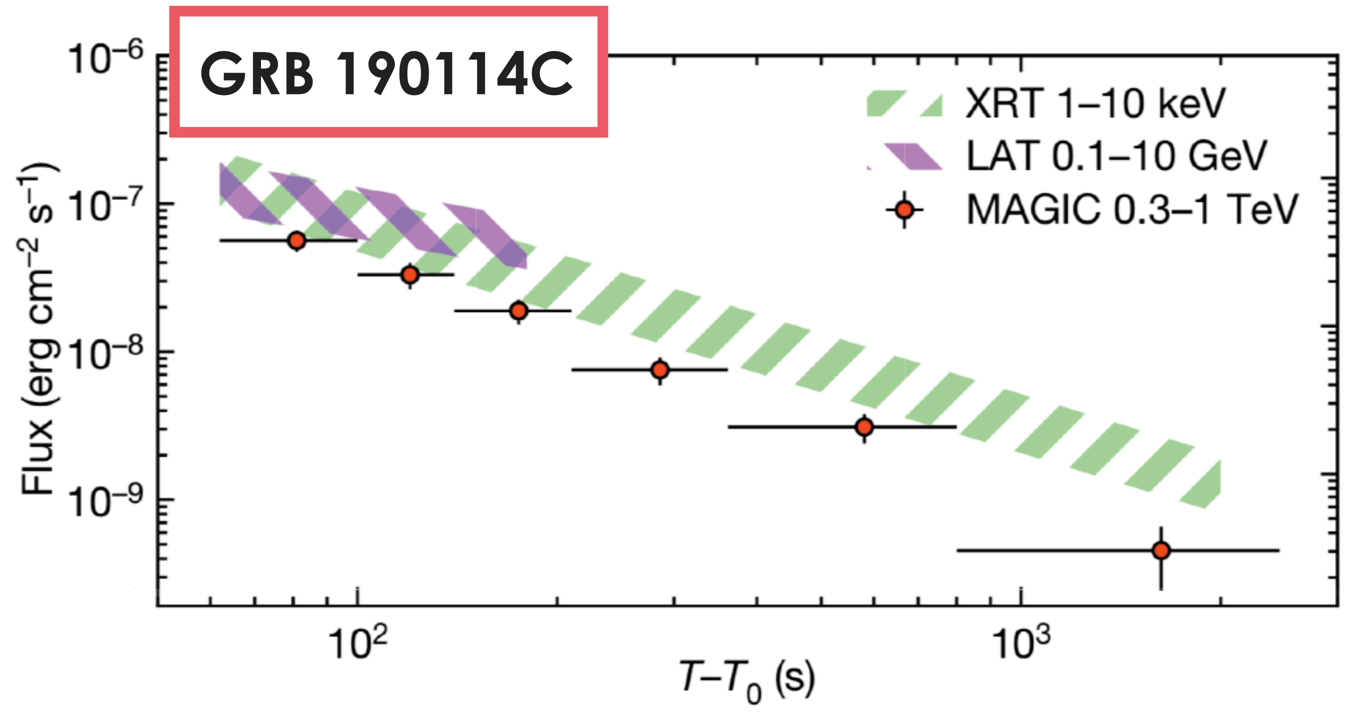
Plot by E. Mestre

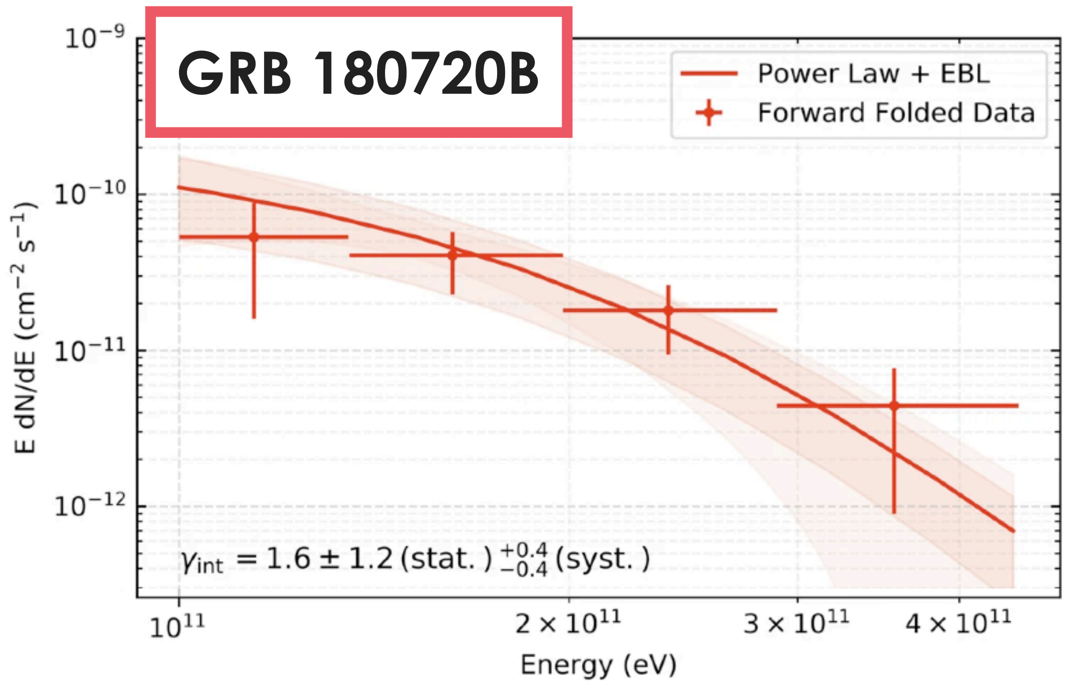
López-Oramas et al. ICRC 2021

DARK MATTER

Aion Viana's talk
later on

Gamma-ray bursts (GRBs)





GRB 190114C (MAGIC, Nature 2019a, 2019b); GRB 180720B (H.E.S.S., Nature, 2019)
+ more

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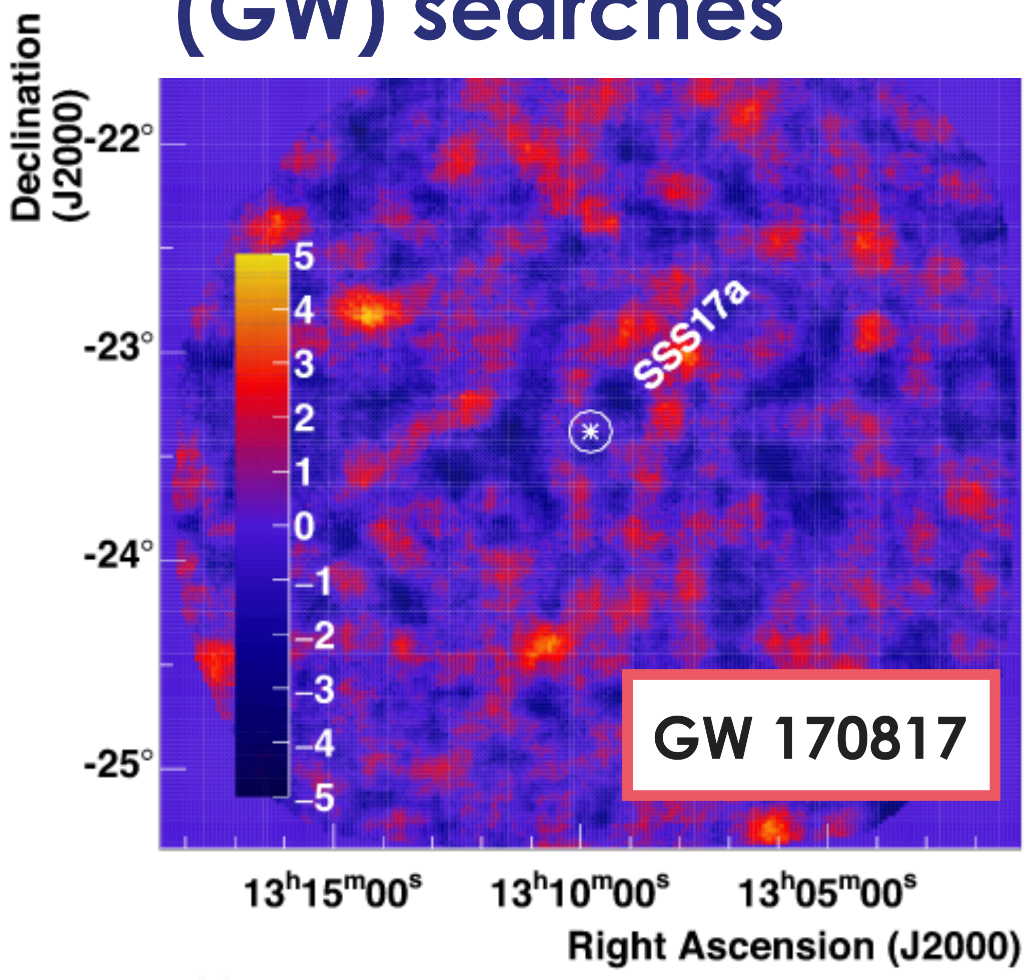

GW 170817 (HESS. ApJL 2018)

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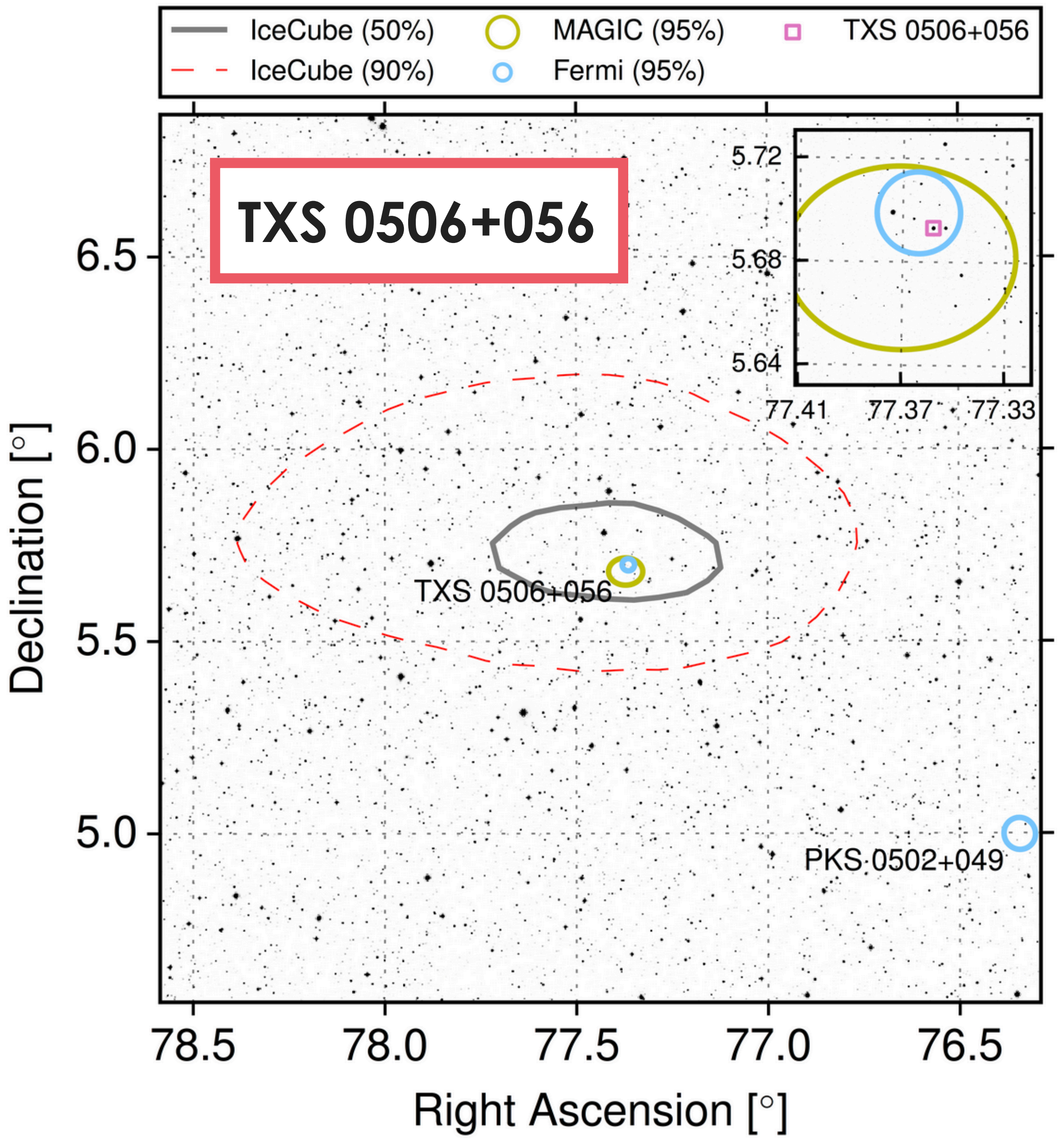

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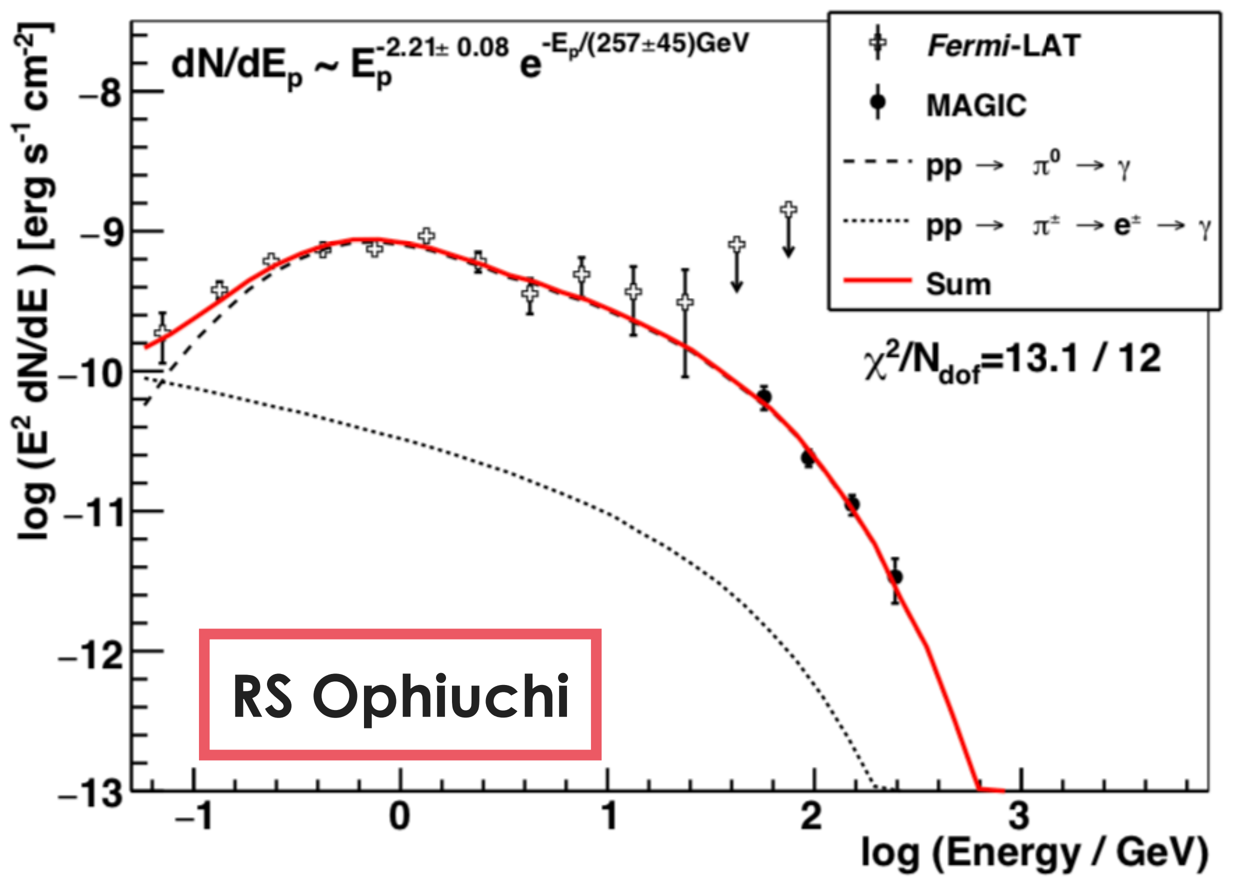
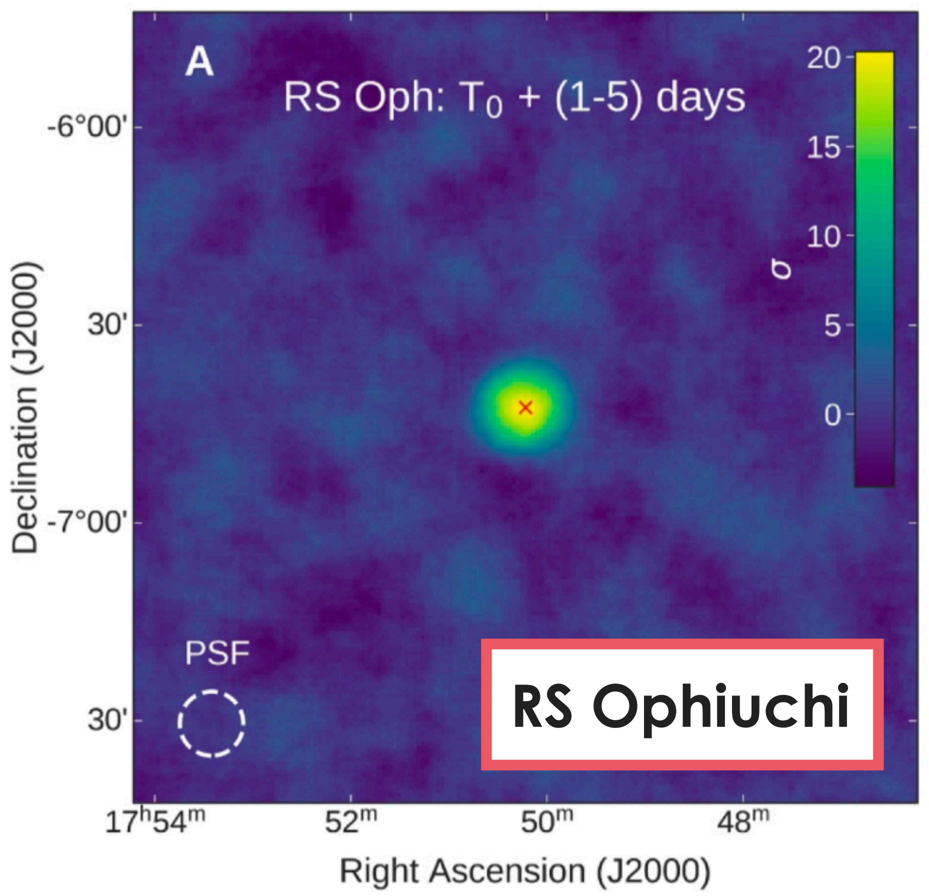
Novae

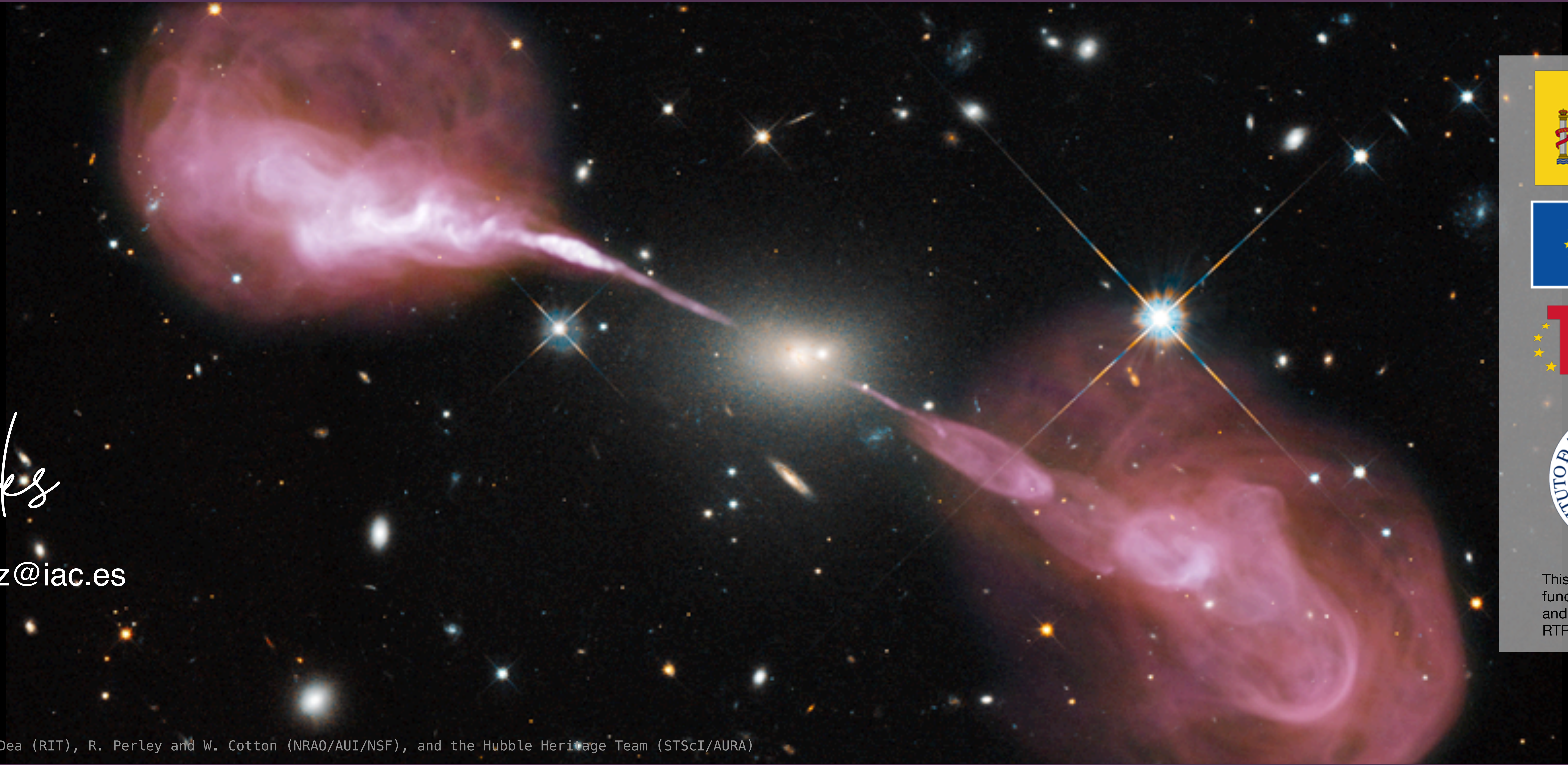


RS Oph (MAGIC, Nature Ast. 2022)



RS Oph (H.E.S.S., Science 2022)

Extragalactic and exotic physics at VHE



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