VHE Galactic Physics

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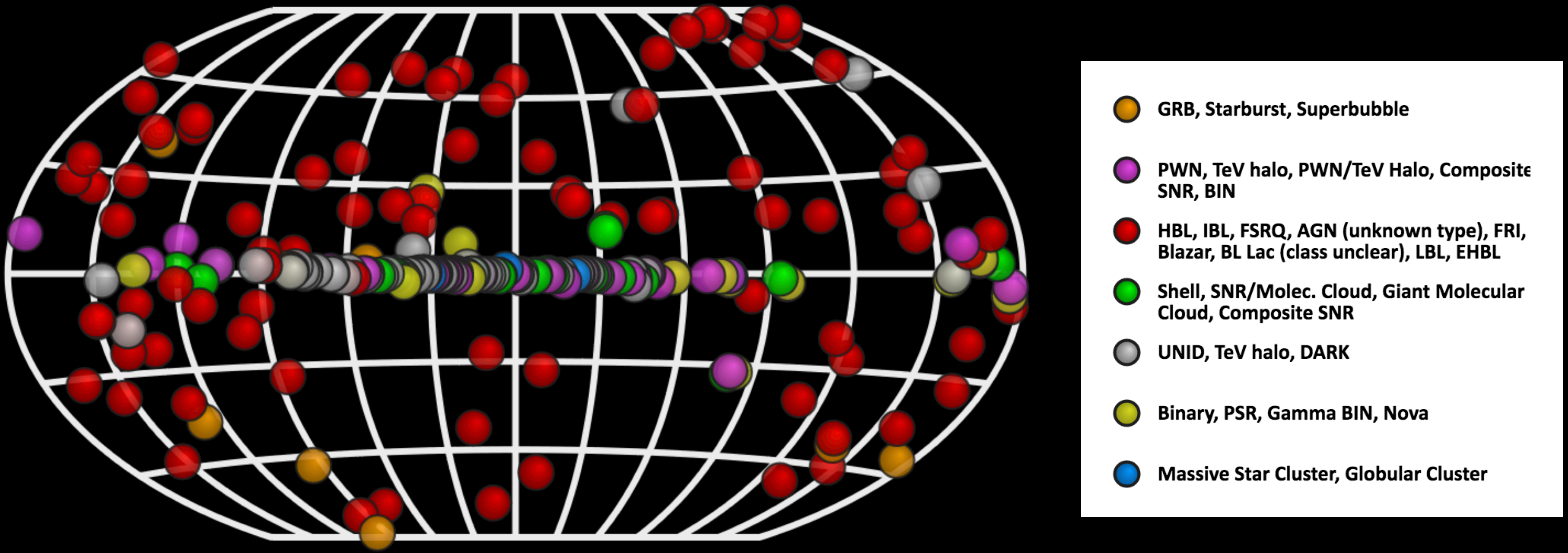
Instituto de Astrofísica de Canarias

São Paulo Advanced School on Multi-Messenger Astrophysics 2023

VHE Galactic Sources



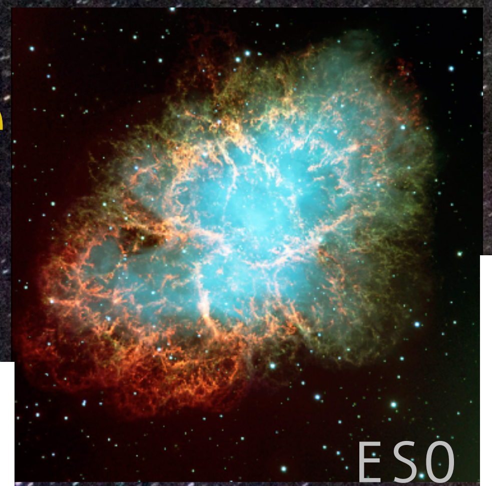
- **252* sources of VHE gamma rays** (http://tevcat2.uchicago.edu/)
  - Blazars are the largest population (~80)
  - Followed by SNRs and PWNe (63)

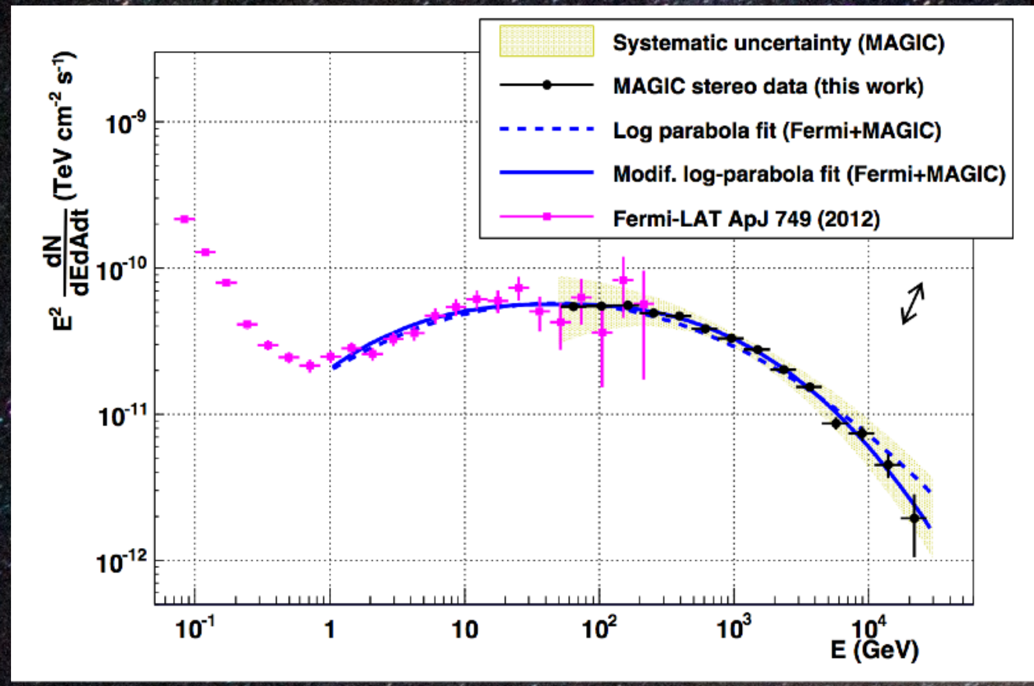
* March 30, 2023

VHE Galactic Sources

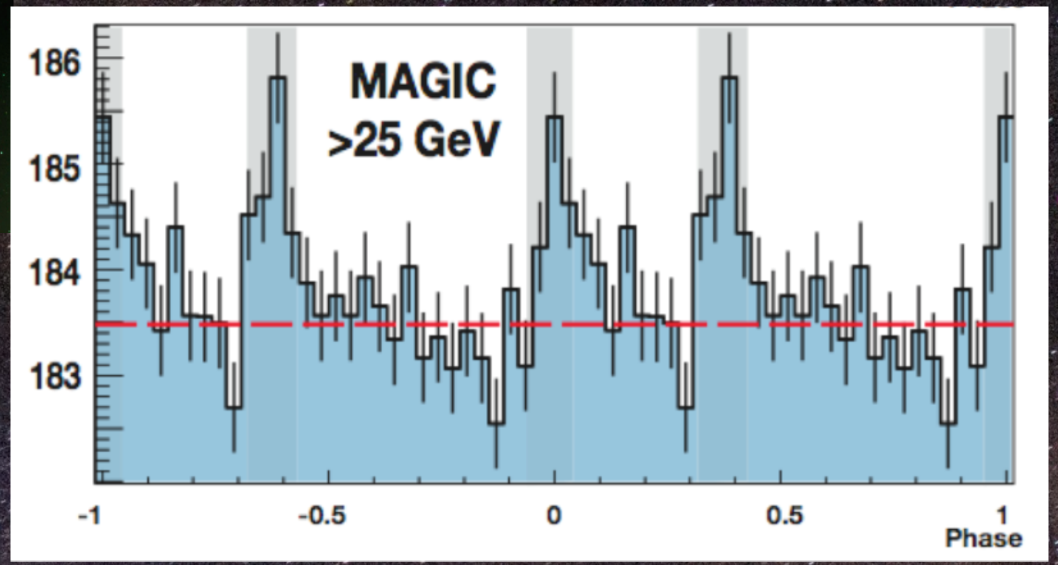
~100 VHE Galactic sources (TeVCat)

Pulsar-wind nebulae & Crab Nebula

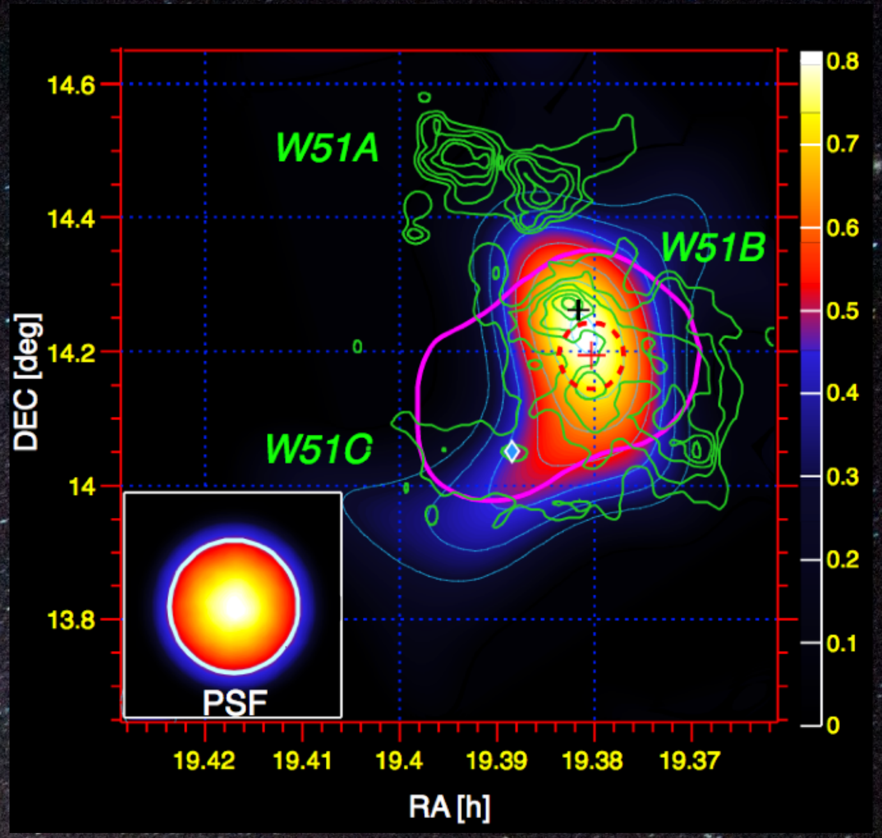




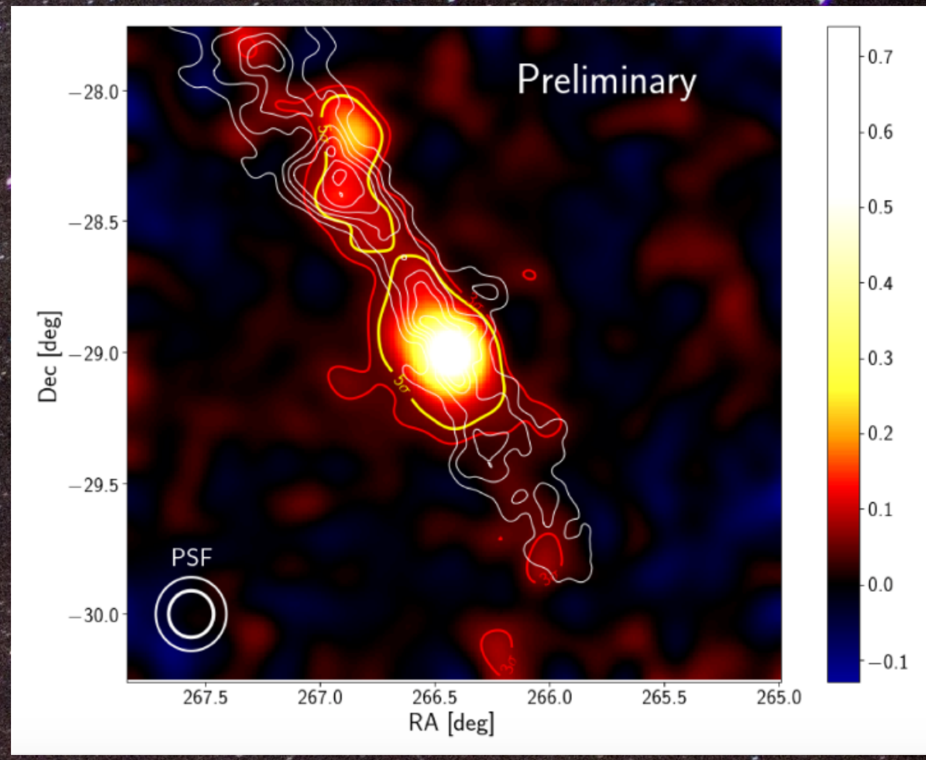
Pulsars



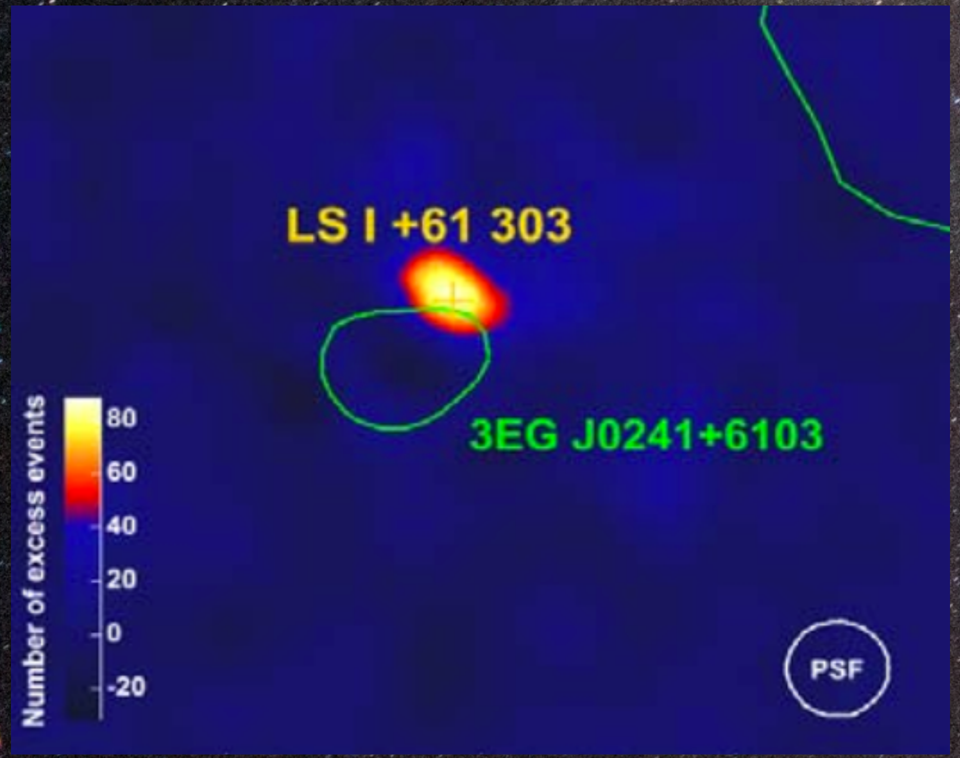
SNRs



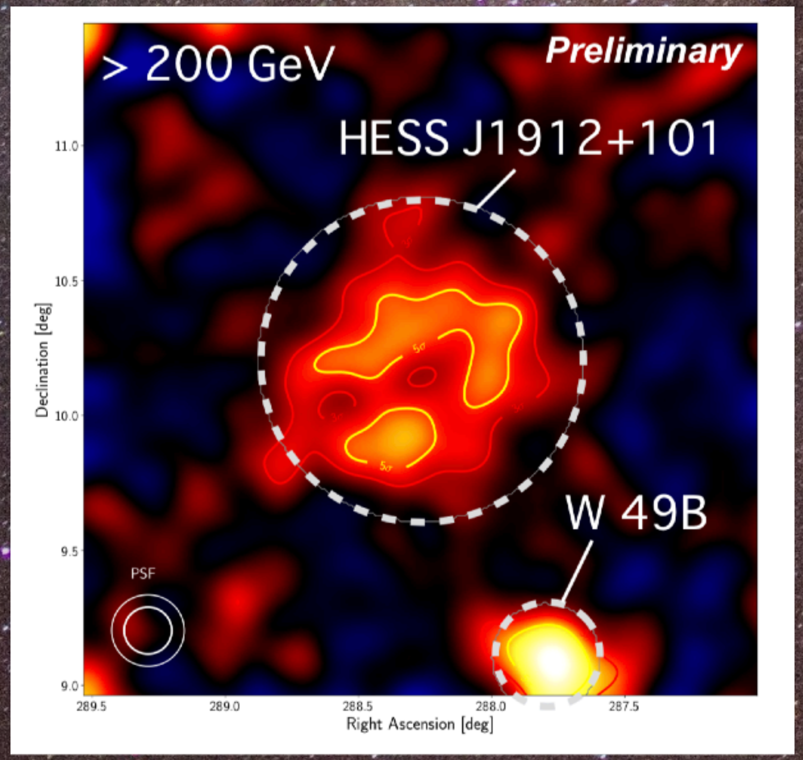
Galactic Center



Binaries

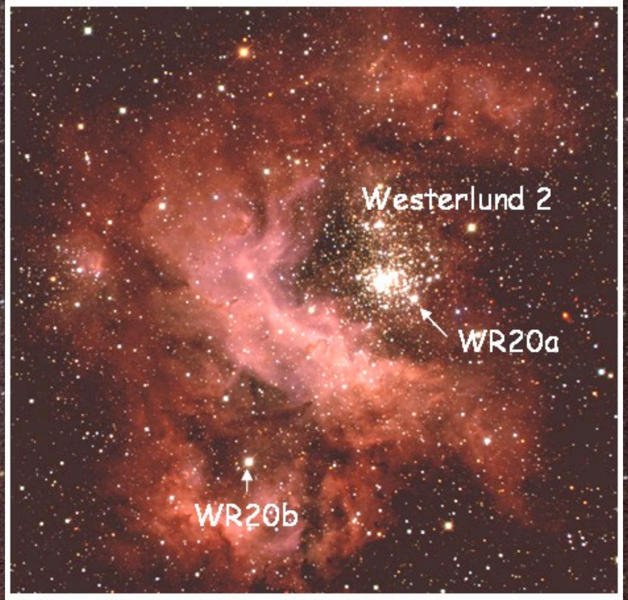


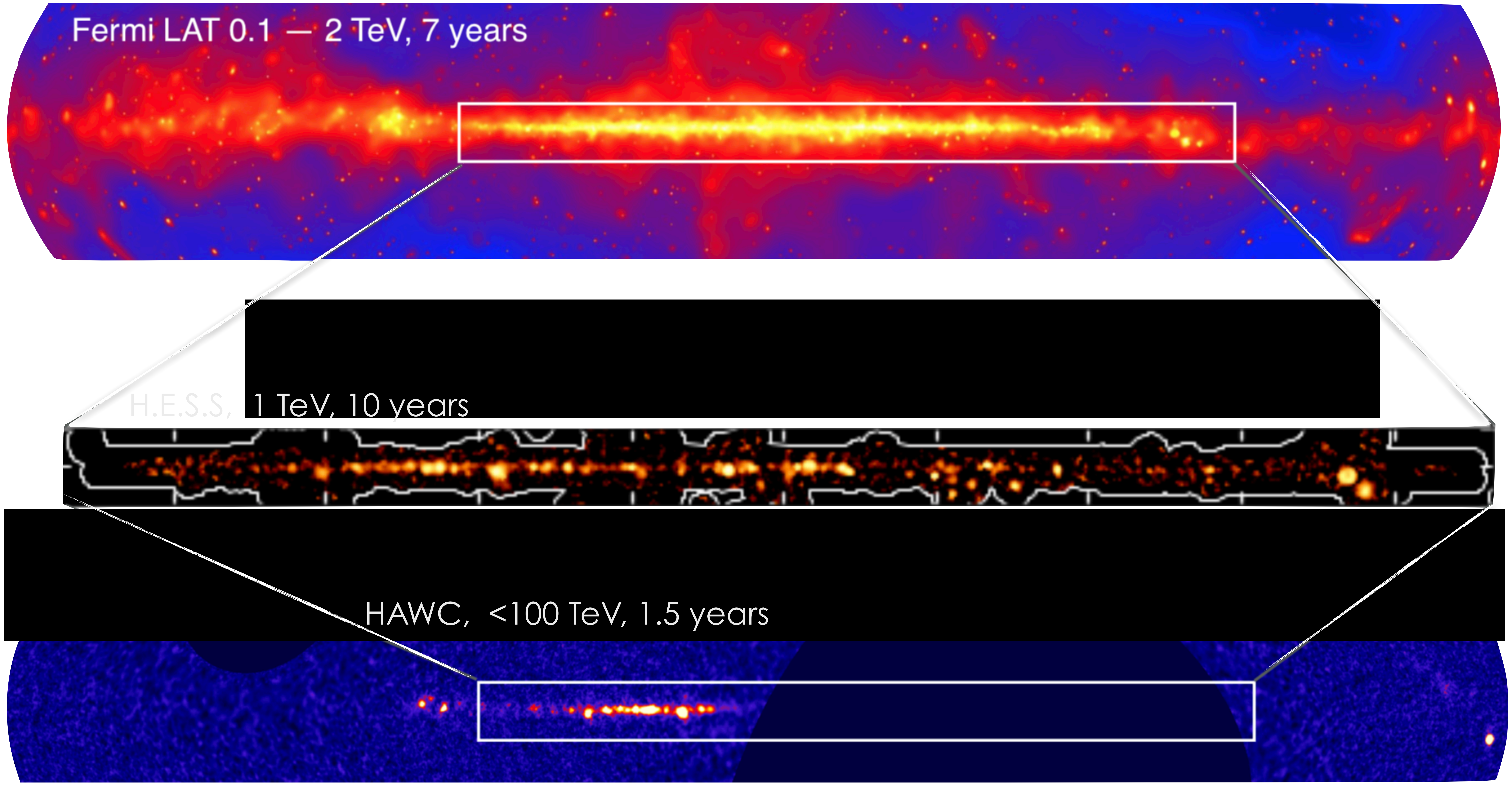
Extended/unidentified sources



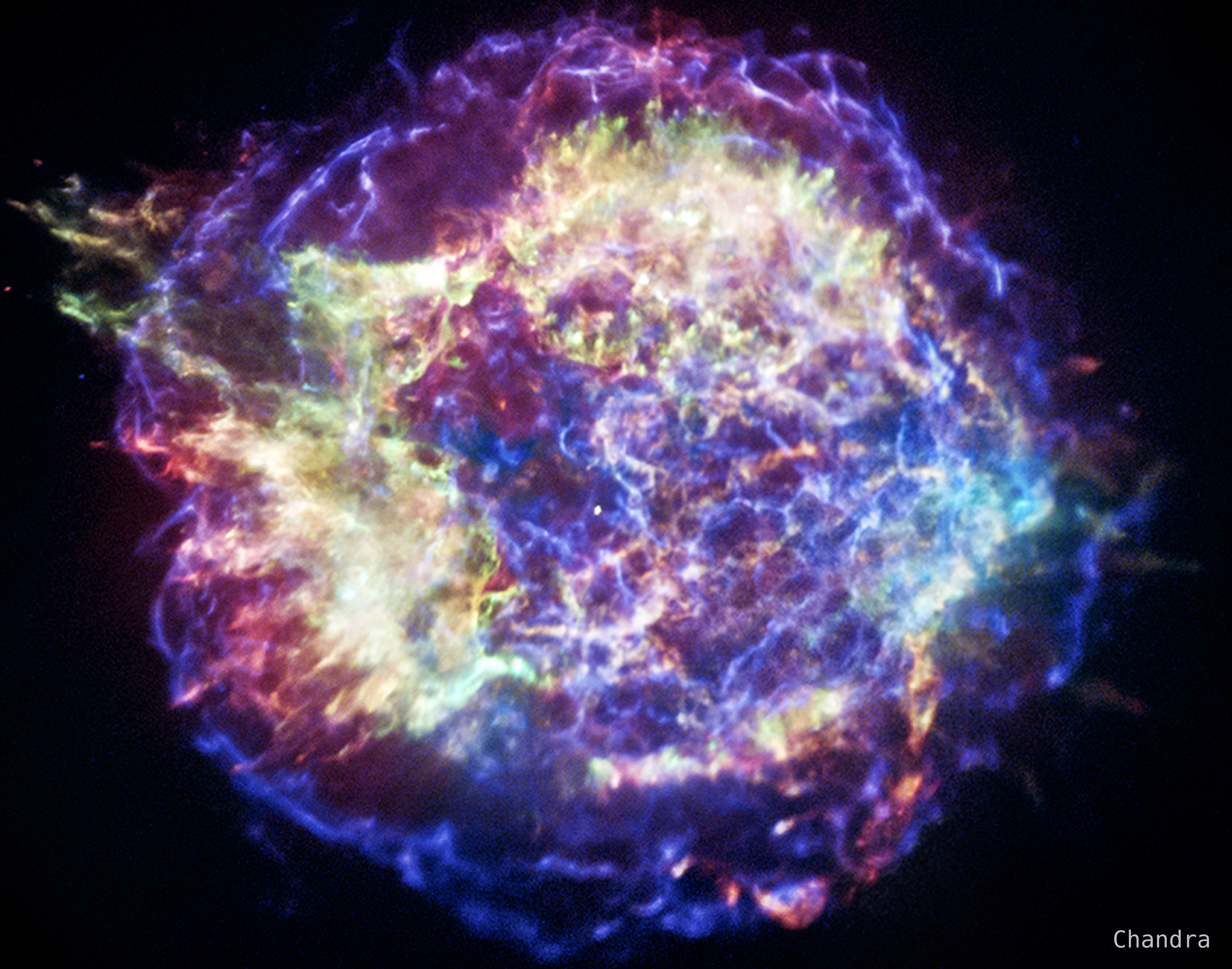
Transient phenomena

Star-forming regions




Fermi LAT 0.1 — 2 TeV, 7 years
H.E.S.S, 1 TeV, 10 years
HAWC, <100 TeV, 1.5 years

Supernova Remnants (SNRs)

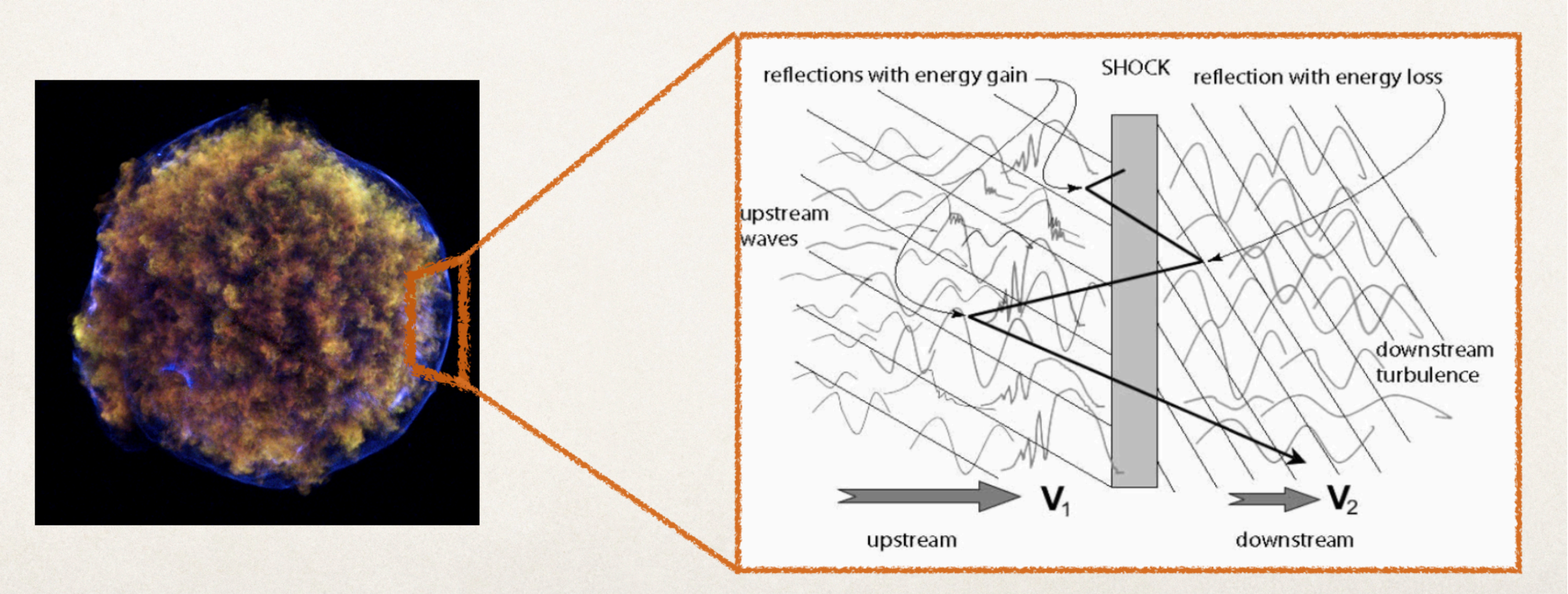


Chandra

SNRs: cosmic accelerators

NASA/Goddard

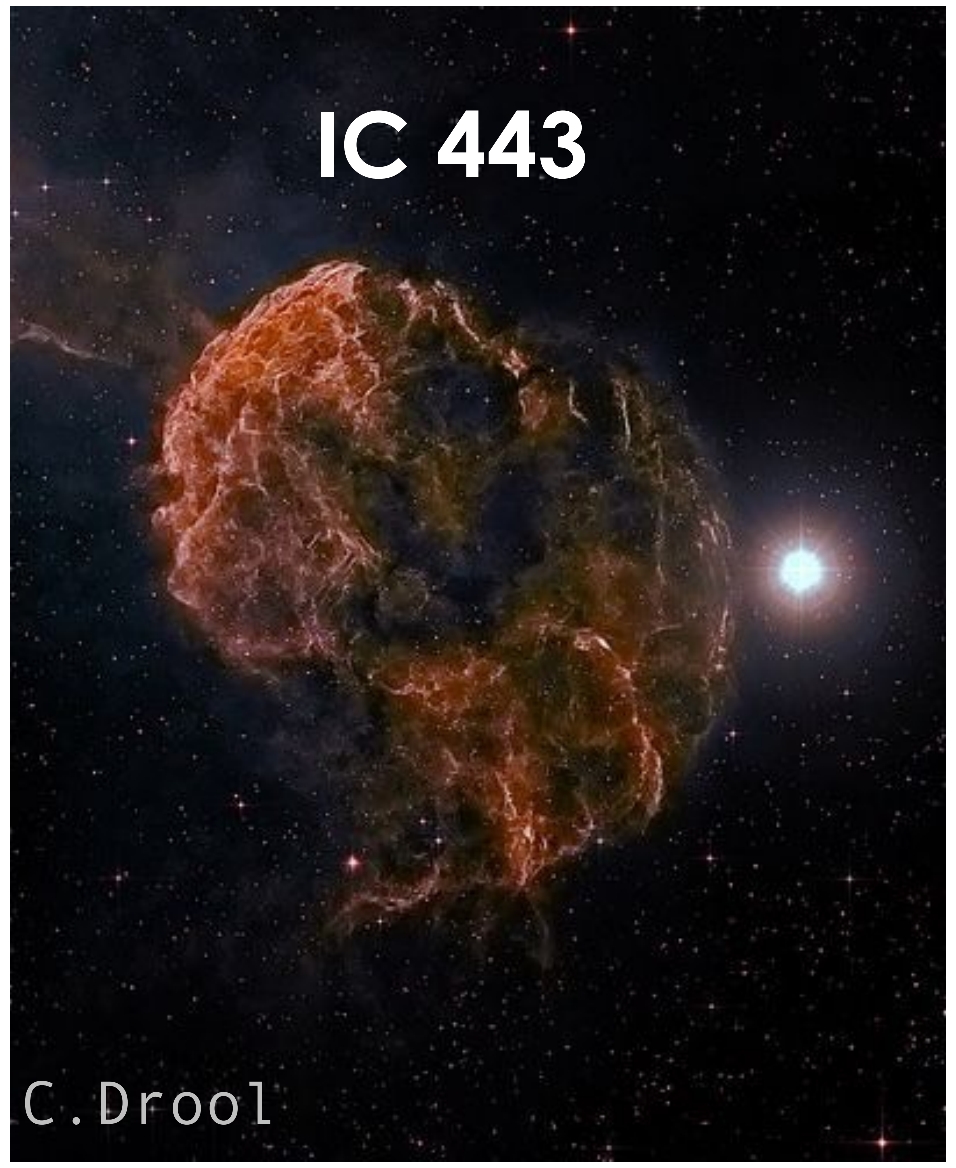
- **Diffusive shock acceleration mechanism**
  - Repeated multiple scatterings with magnetic turbulence produce small energy gain at each shock crossing (I order Fermi acceleration)

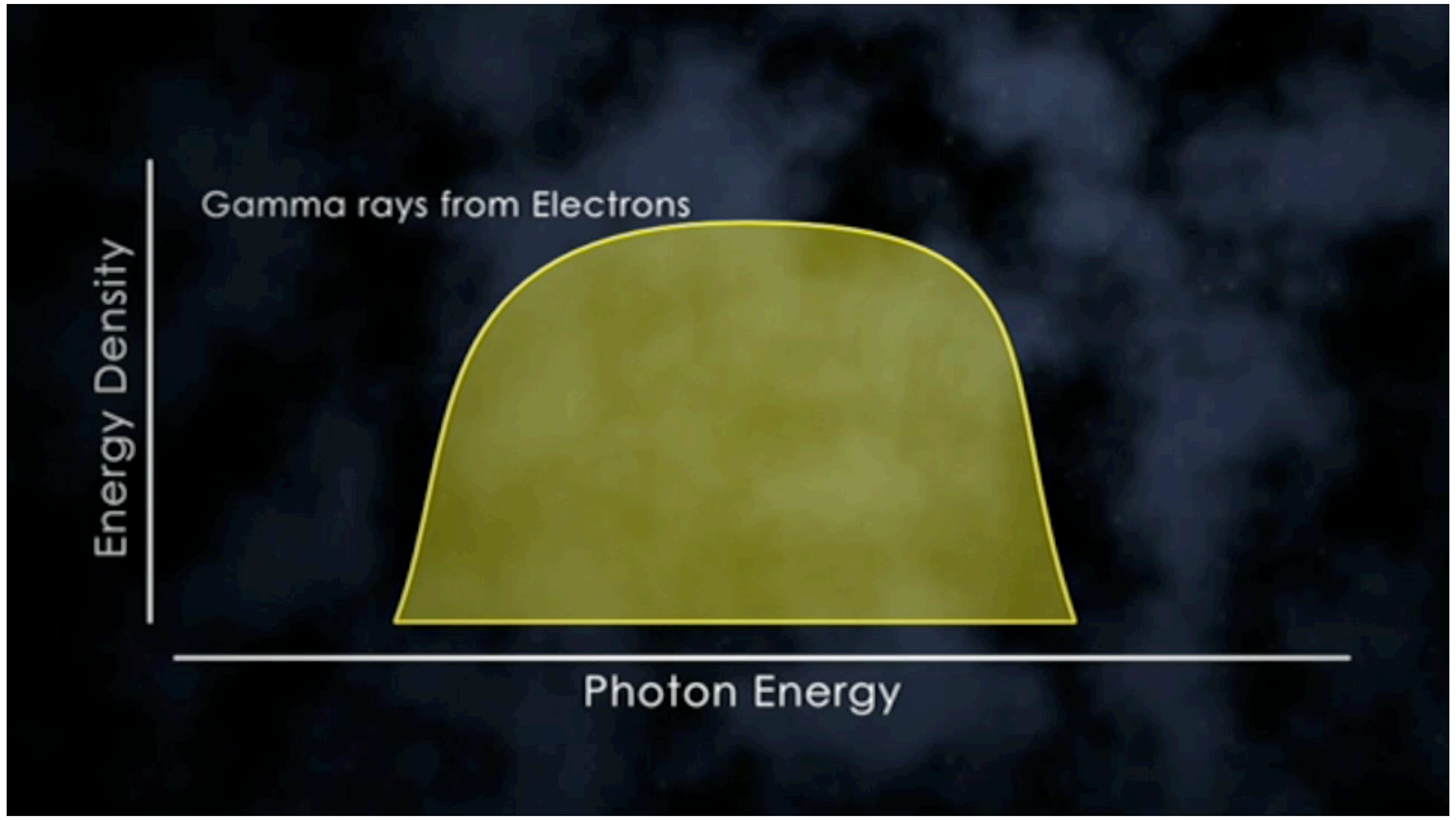


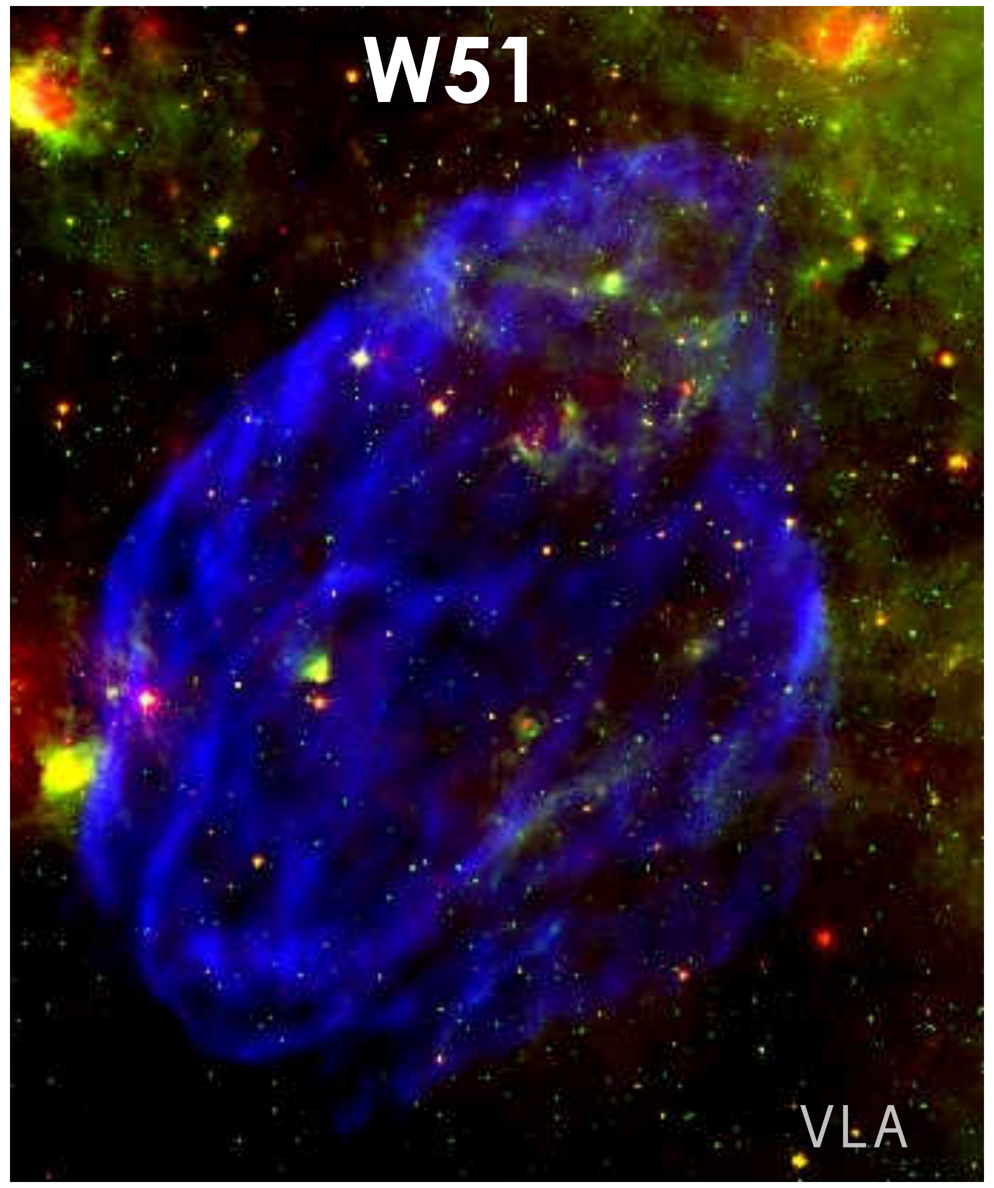
SNRs: cosmic accelerators

NASA/Goddard

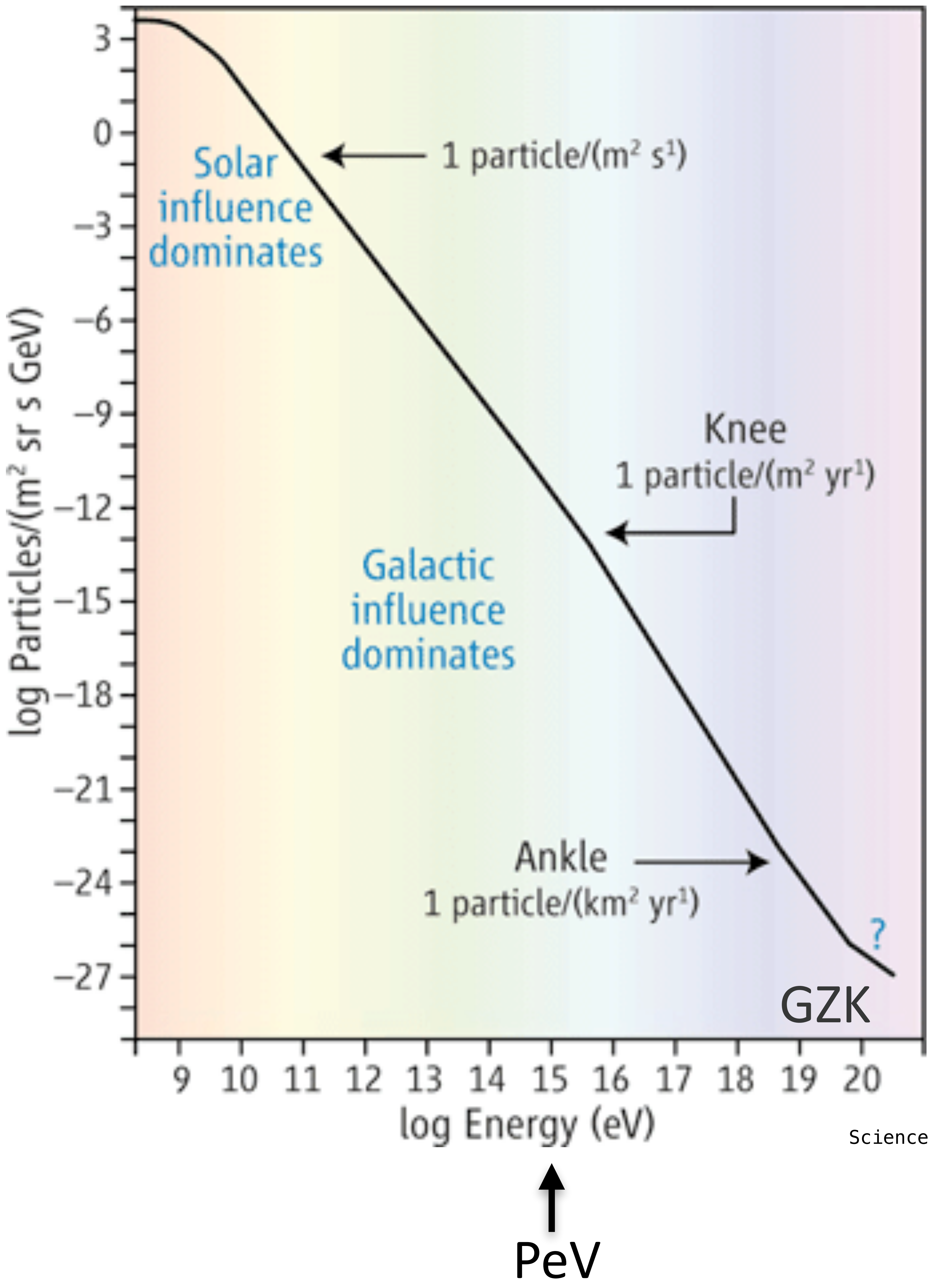
- **Diffusive shock acceleration mechanism**
  - Repeated multiple scatterings with magnetic turbulence produce small energy gain at each shock crossing (I order Fermi acceleration)
  - Two direct evidences in gamma raysas a signature for sources of Galactic CRs:
    - the 'pion bump' below 100 MeV, due to the $\pi0$ decay
    - and γ-ray emission at E > 100 TeV



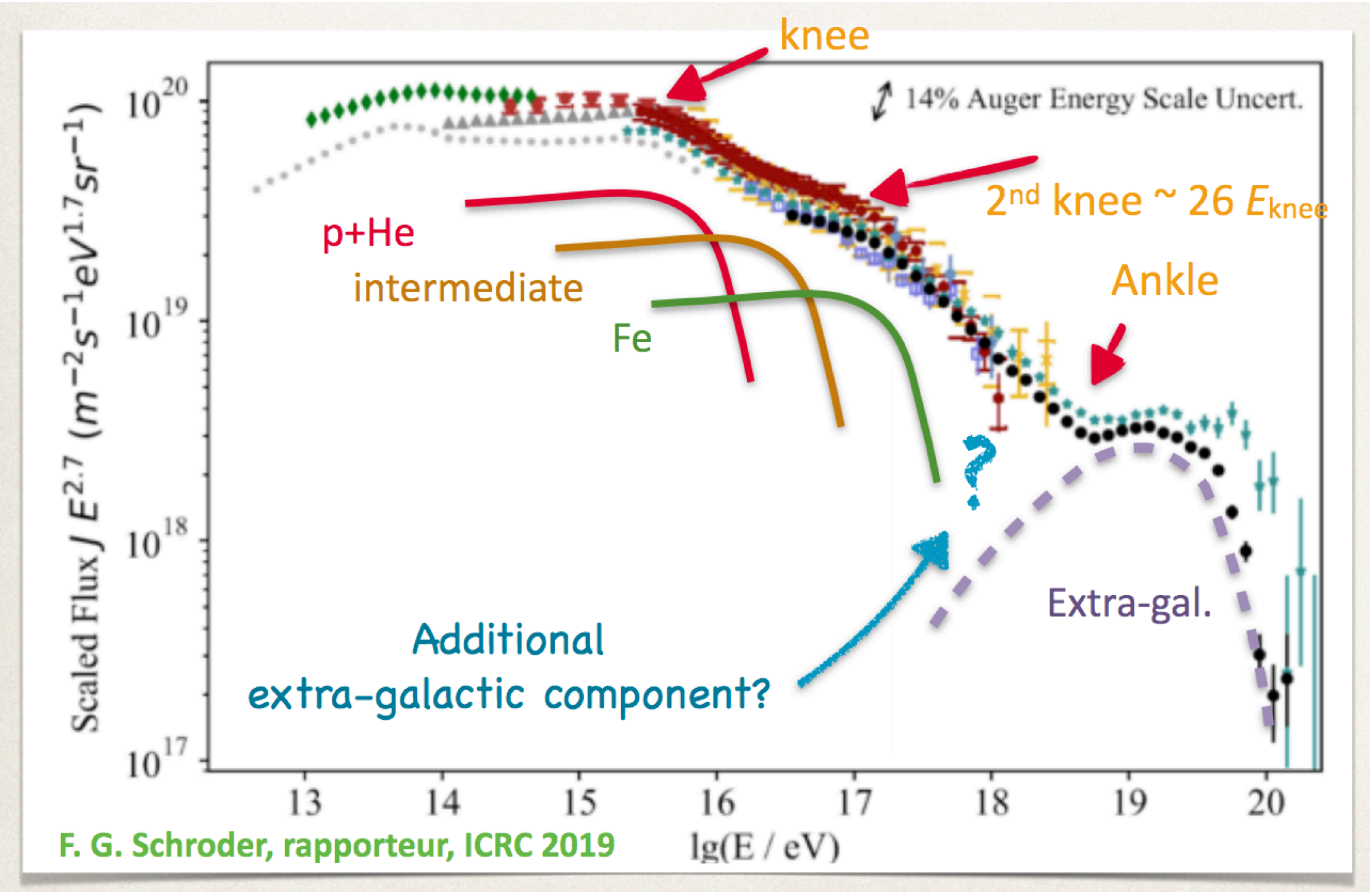




SNRs: cosmic accelerators

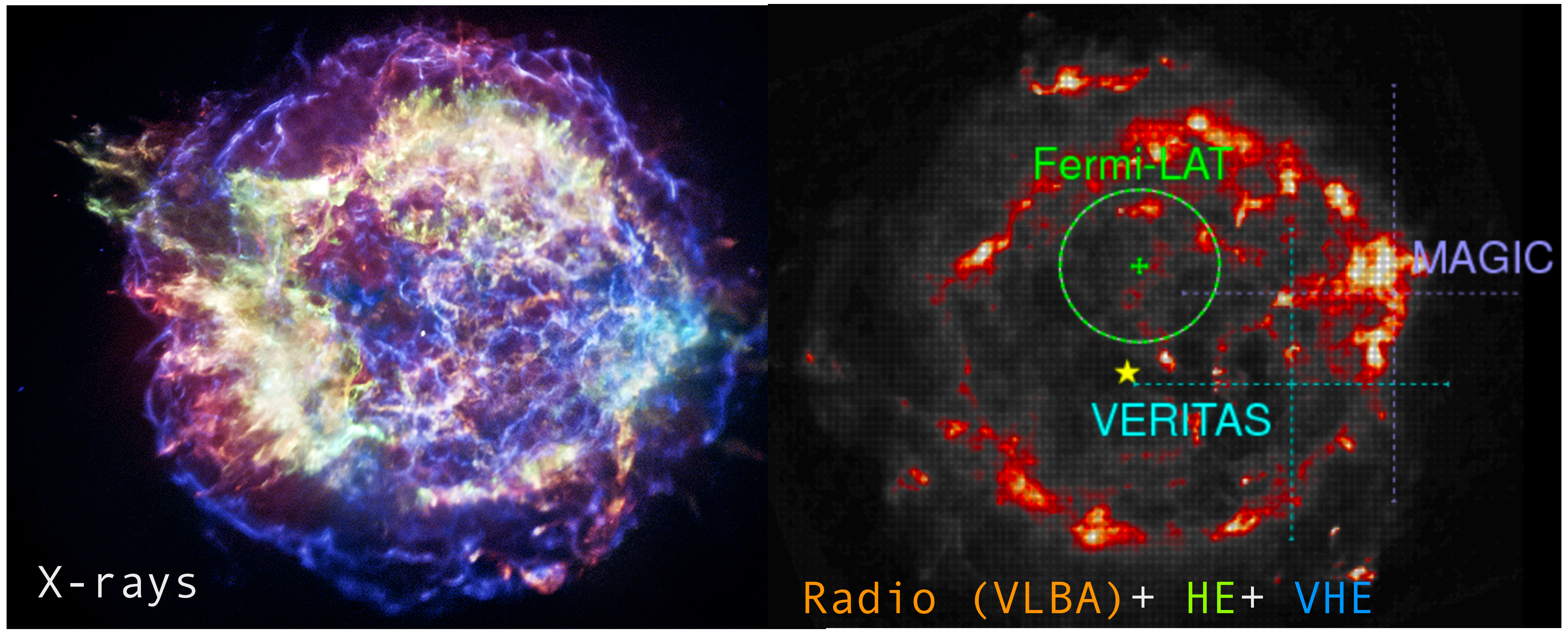


- **PeVatrons**?
  - Protons need to be accelerated **at least up to ~ 1PeV**
    - Different experiments provide different values between 0.5-3 PeV
  - **Produce ~100 TeV photons**
  - B amplification needed and good acceleration efficiency (10%)



from G: Morlino

Cassiopea A: a hadronic PeVatron?



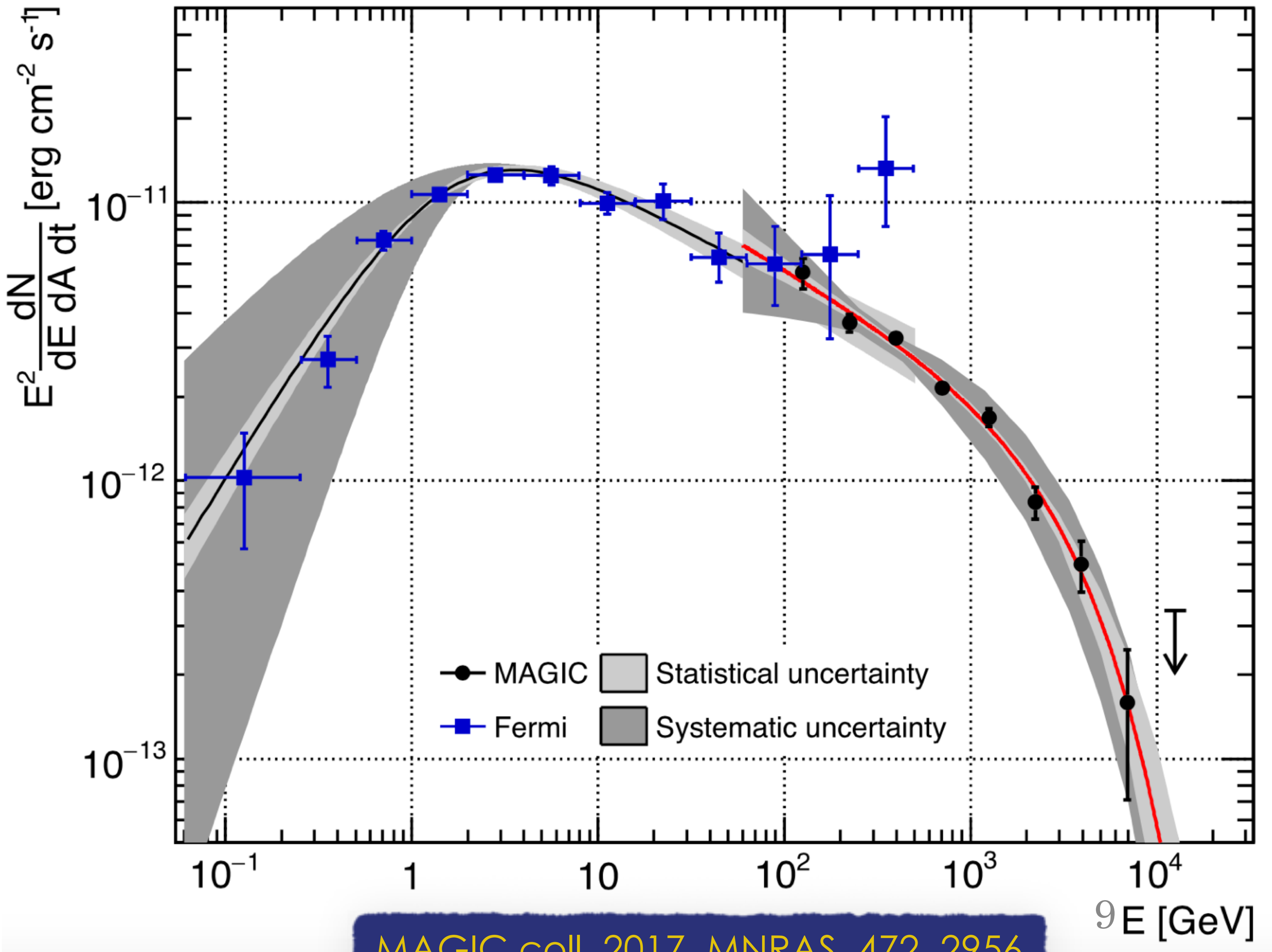
- Relatively young (~300 yr) SNR
- GeV/TeV point-like emission: Fermi, HEGRA, VERITAS and MAGIC

Latest results

- MAGIC: ~160 hr of data
- SED measured until 8 TeV: **EPWL**, with **cut-off at ~3.5 TeV**

Explanation

- MWL emission not explained with single population of electrons nor protons, although **protons likely dominate TeV emission**
- but Cas A **is not PeVatron** at present time



MAGIC coll. 2017, MNRAS, 472, 2956

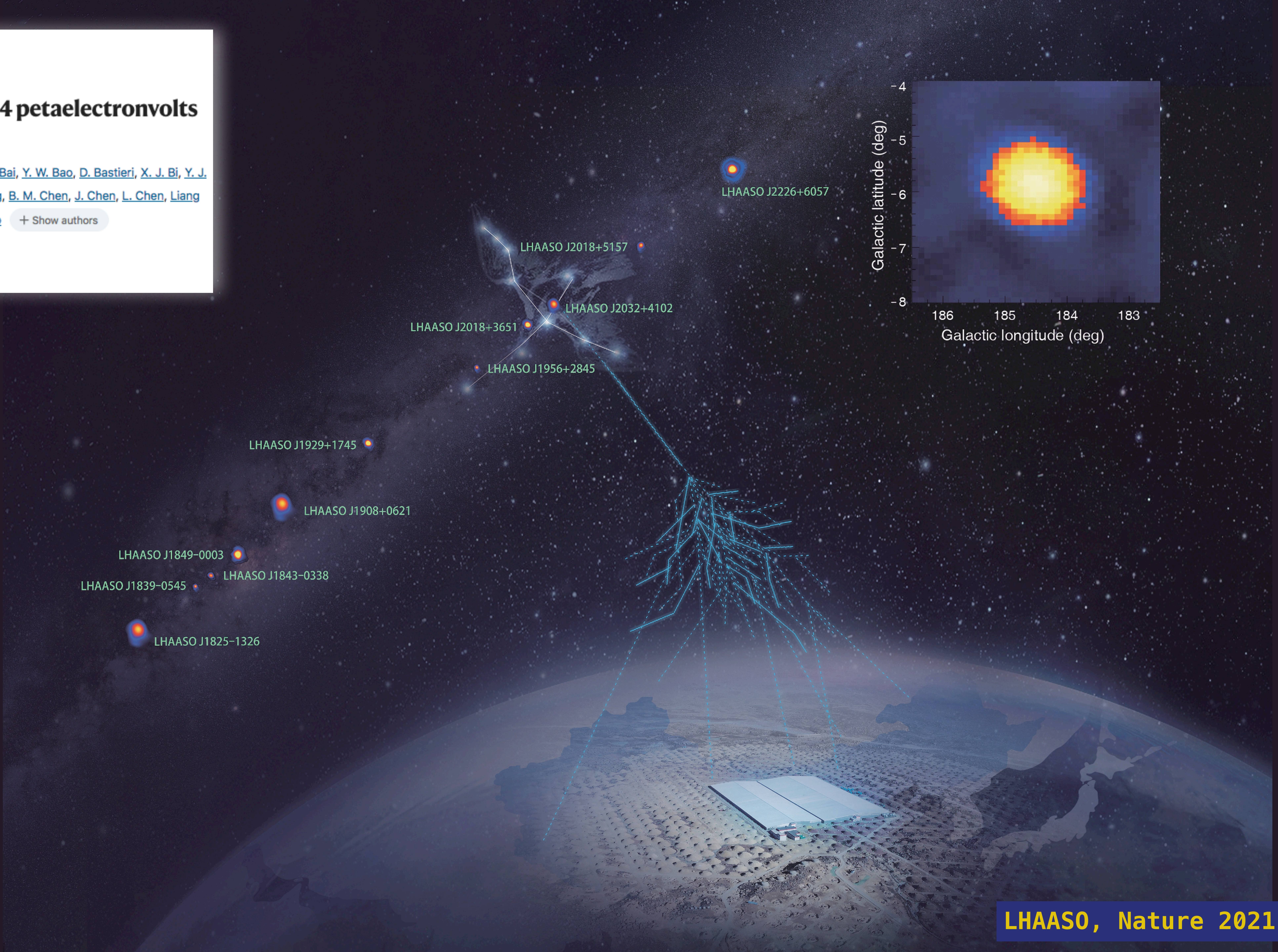
nature > articles > article

Article | Published: 17 May 2021

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, Q. An, Axikegu, L. X. Bai, Y. X. Bai, Y. W. Bao, D. Bastieri, X. J. Bi, Y. J. Bi, H. Cai, J. T. Cai, Zhe Cao, J. Chang, J. F. Chang, X. C. Chang, B. M. Chen, J. Chen, L. Chen, Liang Chen, Long Chen, M. J. Chen, M. L. Chen, Q. H. Chen, ... X. Zuo + Show authors

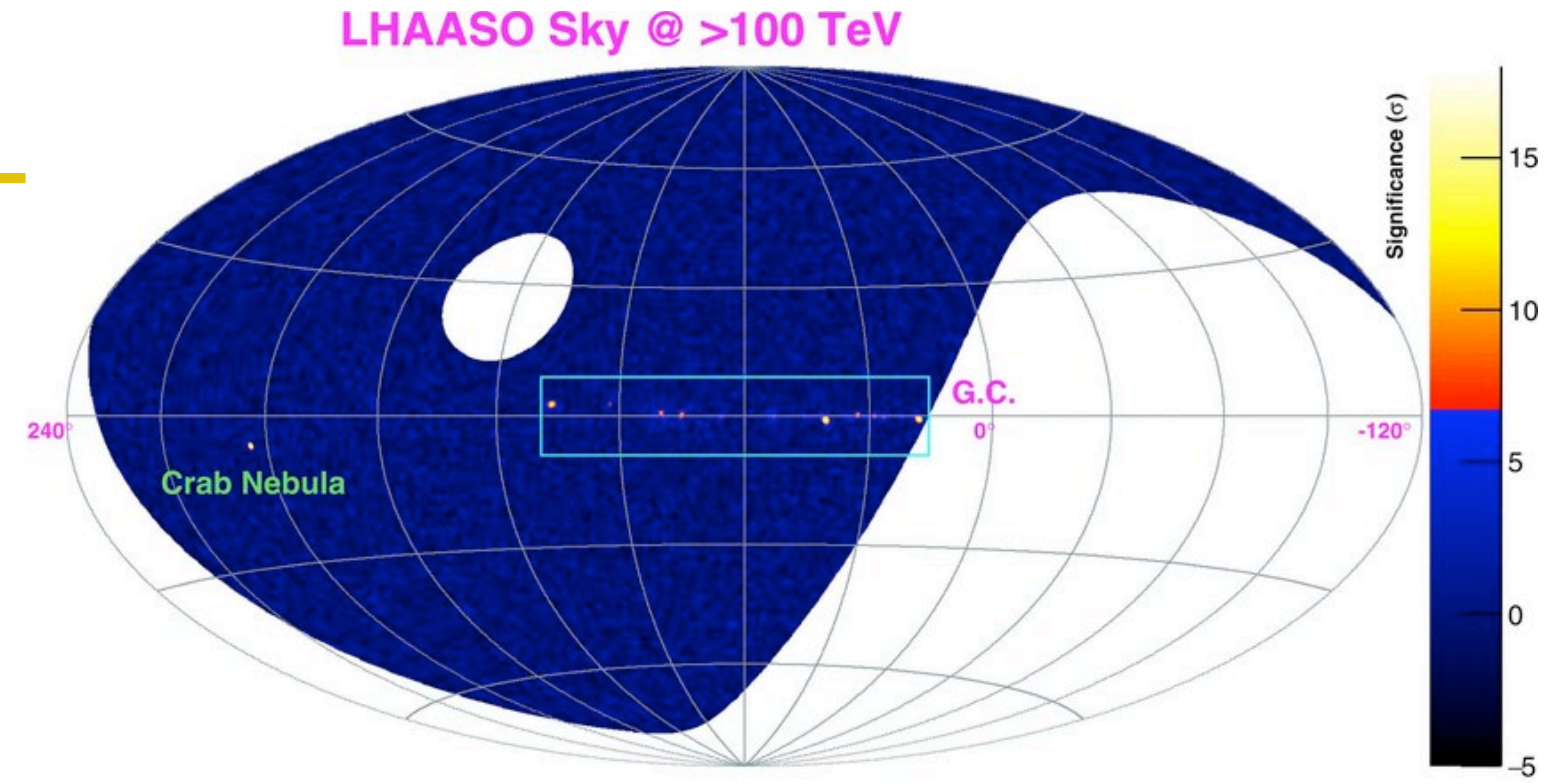
Nature 594, 33–36 (2021) | Cite this article

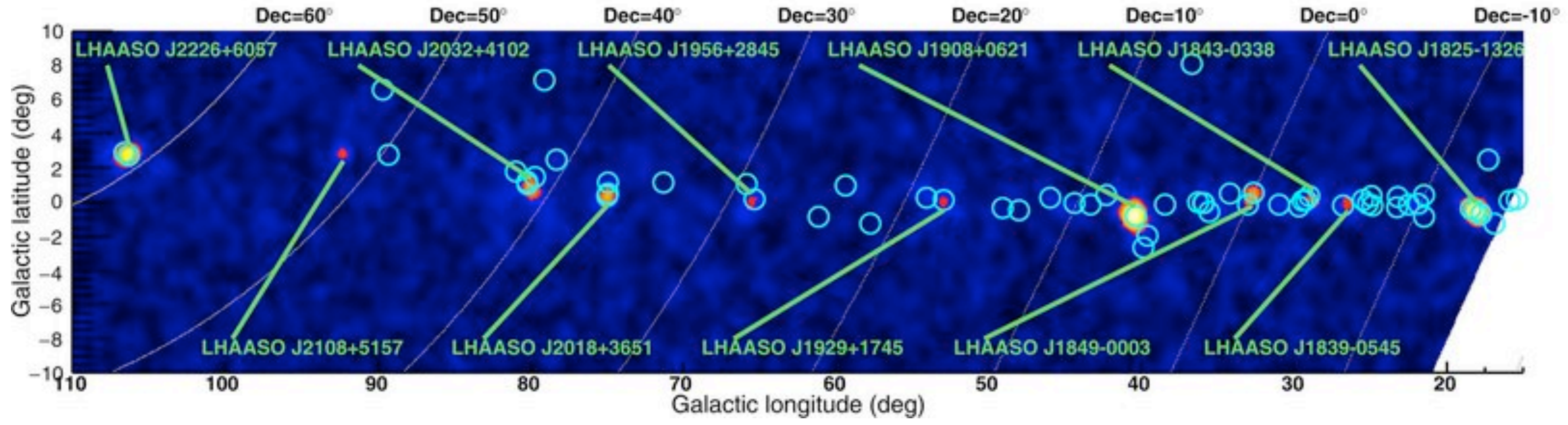


LHAASO, Nature 2021

LHAASO: 12 PeVatrons

- Detection of **more than 530 photons** at **E > 100 TeV - 1.4 PeV** from **12 γ-ray sources**





source	Number of on-source events	number of background events	exposure (hr)
LHAASO J0534+2202	67	5.5	2236.4
LHAASO J1825-1326	61	3.2	1149.3
LHAASO J1839-0545	26	4.2	1614.5
LHAASO J1843-0338	30	4.3	1715.4
LHAASO J1849-0003	36	4.8	1865.3
LHAASO J1908+0621	74	5.1	2058.0
LHAASO J1929+1745	29	5.8	2282.6
LHAASO J1956+2845	34	6.1	2461.5
LHAASO J2018+3651	42	6.3	2610.7
LHAASO J2032+4102	45	6.7	2648.2
LHAASO J2108+5157	30	6.4	2525.8
LHAASO J2226+6057	60	6.2	2401.3

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26-0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71-0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Sources associated mainly with PWNe, pulsars… leptonic PeVatrons

LHAASO, Nature 2021

LHAASO: 12 PeVatrons

- Here we report the detection of **more than 530 photons** at energies **> 100 TeV - 1.4 PeV** from **12 ultrahigh-energy γ-ray sources** with a statistical significance greater than seven standard deviations

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2[d]	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3[e]	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3[f]	< 2[f]	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7[g]	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5[h]	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	$\sim 10 - 20$[j]	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}$[d]	$1.8 - 3.3$[k]	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2[d]	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}$[l]	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	3.3 ± 0.3[m]/4.0 ± 0.5[n]	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08[o]	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08[o]	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8[p]	~ 10[p]	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8[p]	~ 10[p]	2.2×10^{37}	

γ-rays with E slightly higher than 0.1 PeV have been reported from a few objects in the Galactic plane by Tibet and HAWC (Amenomori et al. 2019, Abeysekara et al. 2020, Abeysekara et al. 2021, Amenomori et al. 2021)

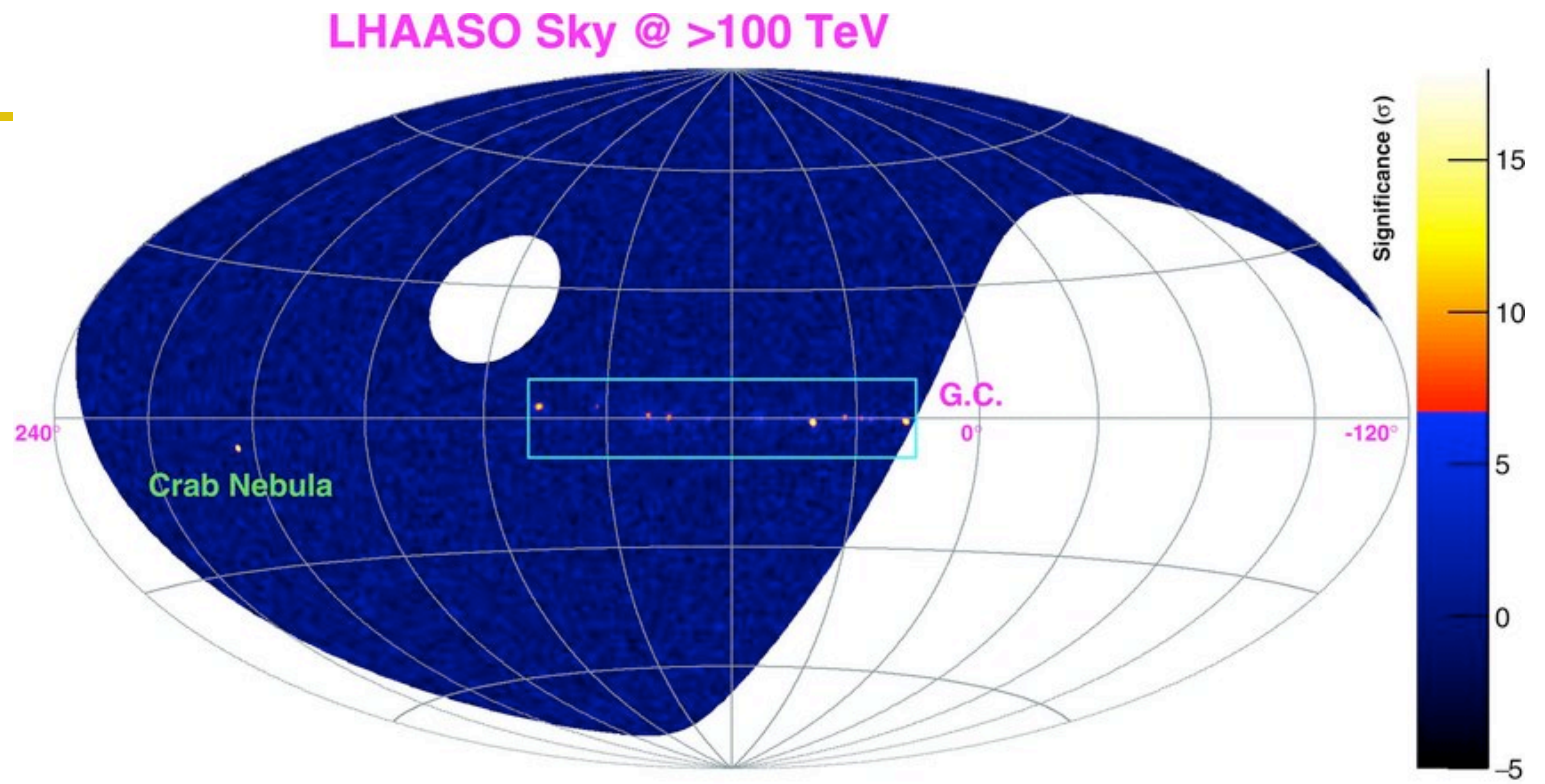
LHAASO, Nature 2021

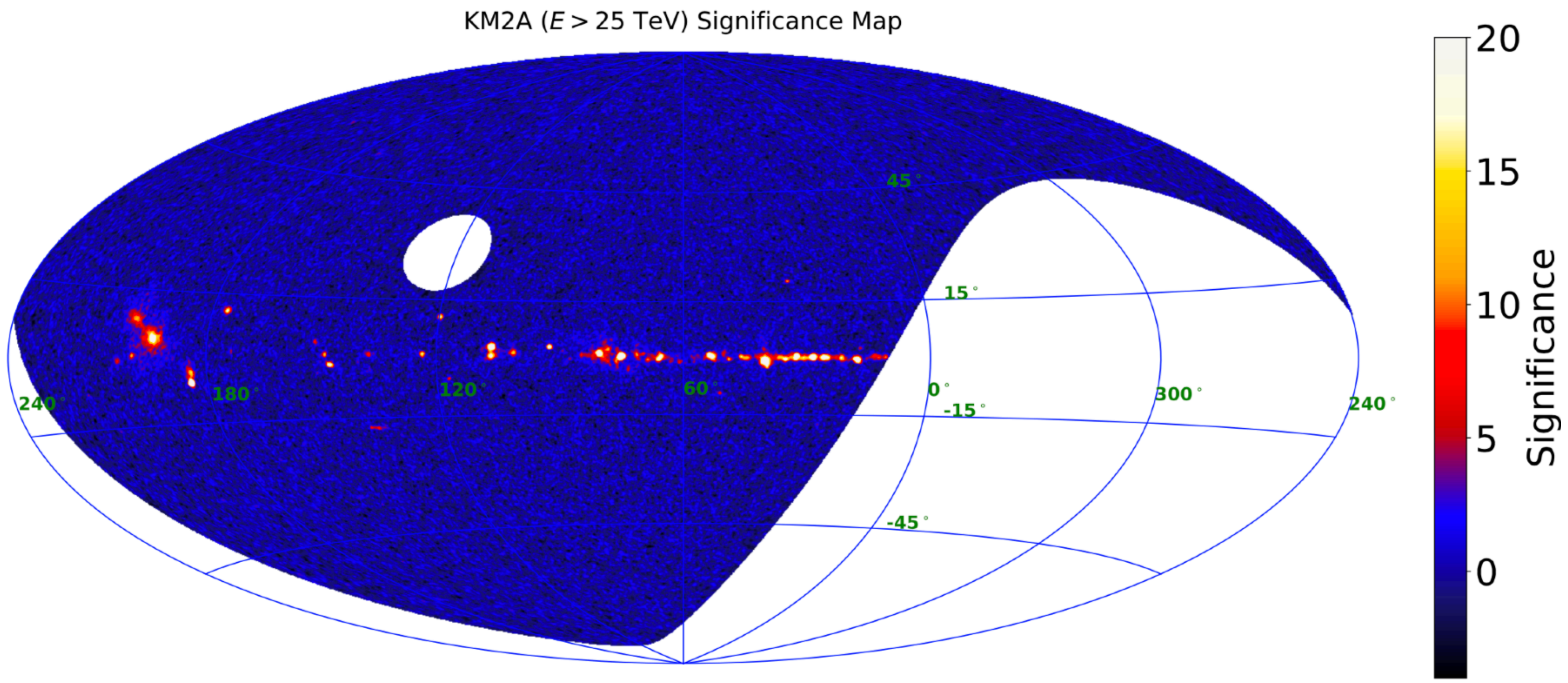
LHAASO: 42 PeVatrons!

New results!!!

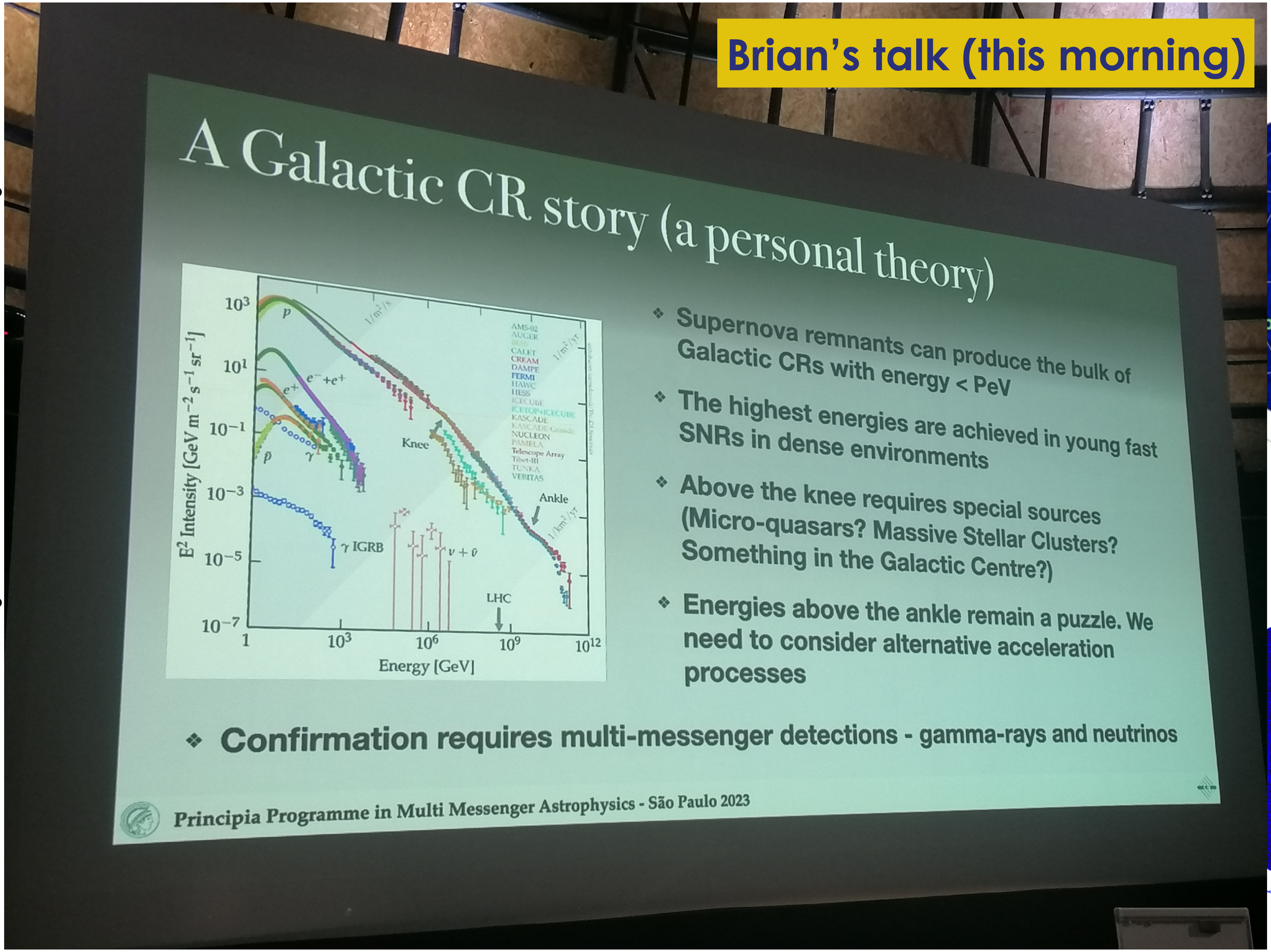
- Detection of 90 sources:
  - 32 new TeV sources
    - 7 do not have any associations
    - 8 GeV counterparts only
    - 16 pulsar or PWN/SNR associations
    - 1 extragalactic

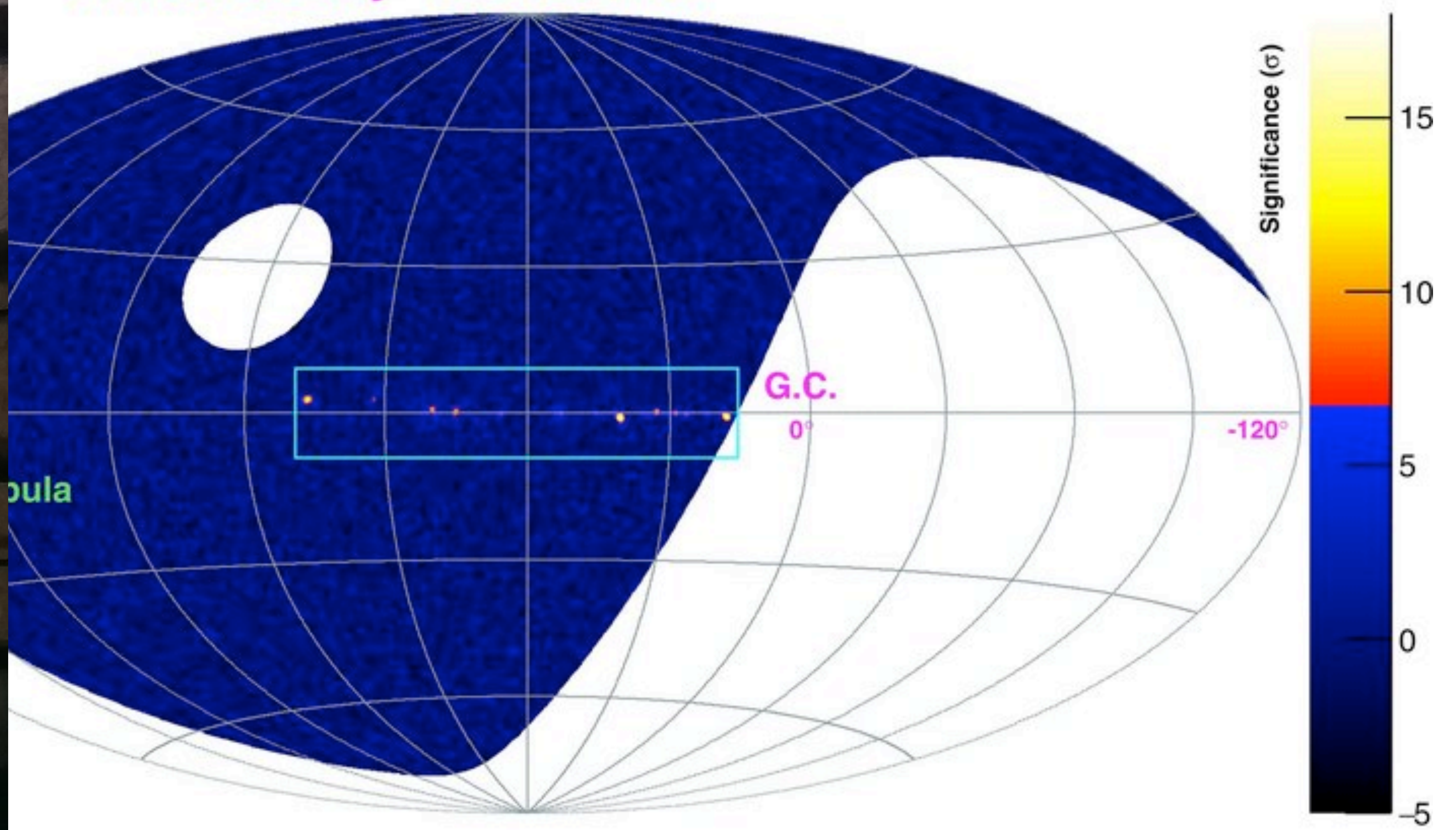
- 43 sources are detected at E > 100 TeV at > 4σ
  - 8 are not detected by WCDA at energies 1–25 TeV, which would represent a new class of gamma-ray sources with dominant gamma-ray emission at energies around tens of TeV or E > 100 TeV (Cao et al. 2023)

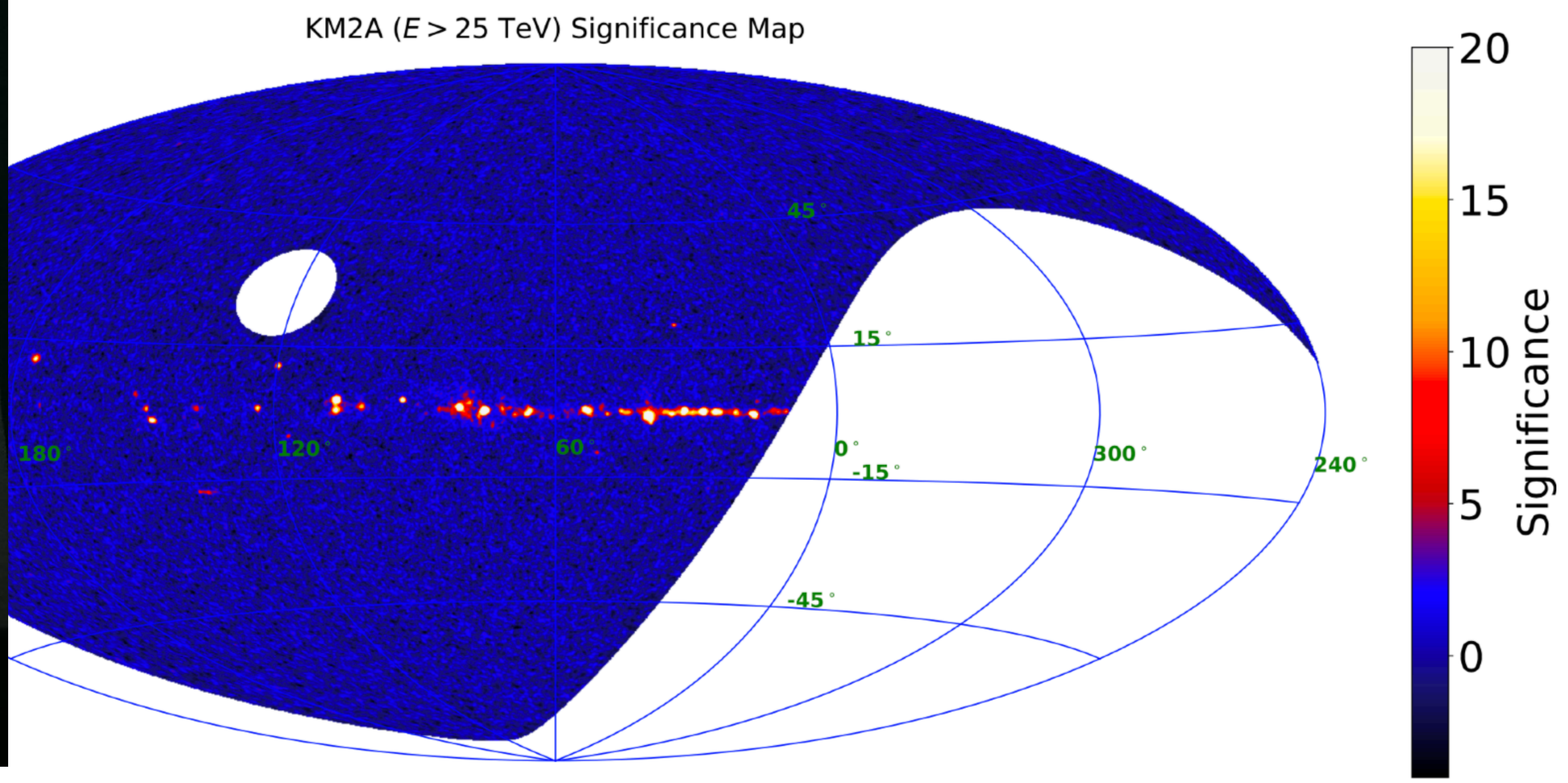




Cao et al. 2023

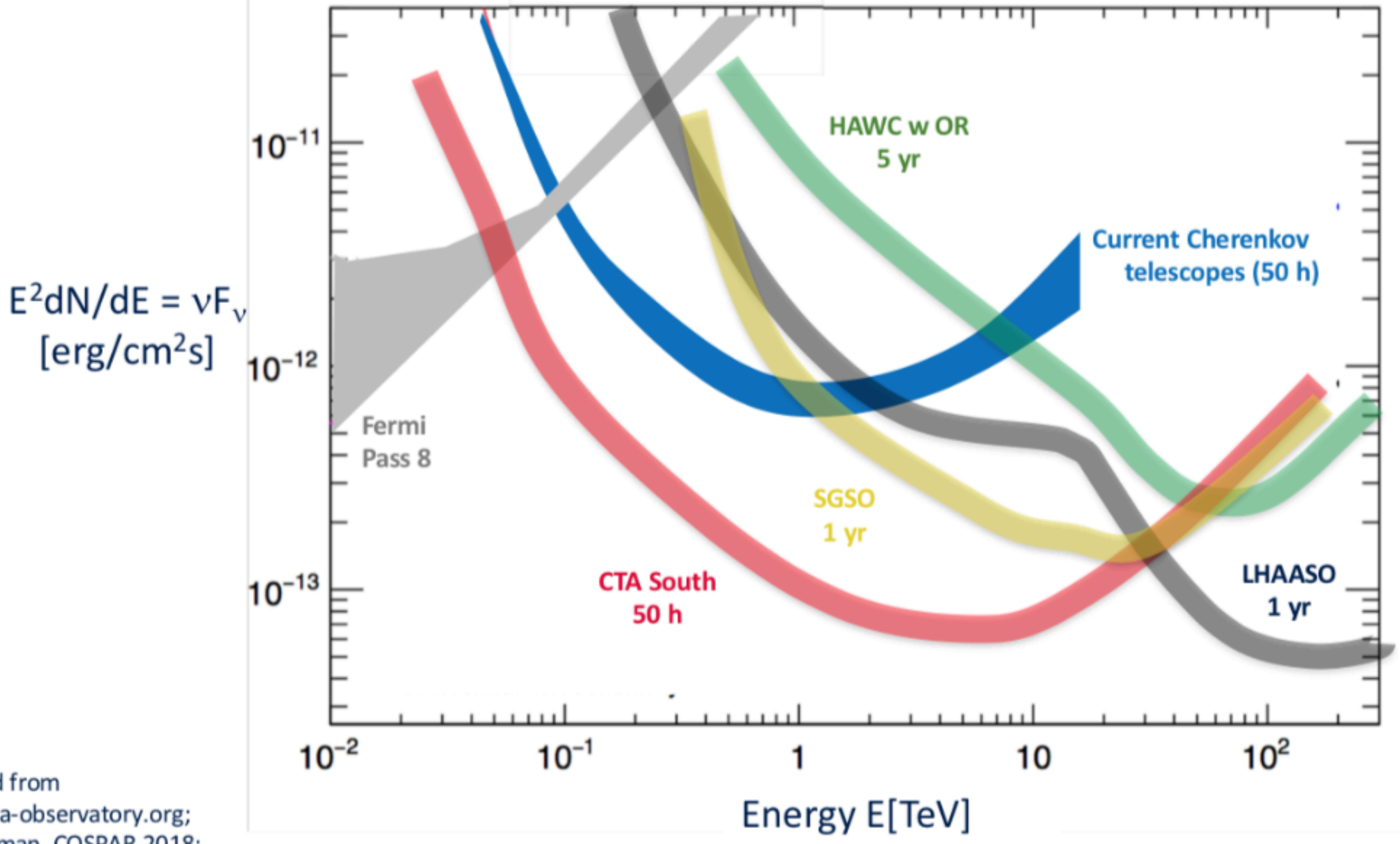






Sources associated mainly with PWNe, pulsars… : leptonic PeVatrons
some associations with SNRs likely: hadronic origin?
massive star clusters?

current and future detectors

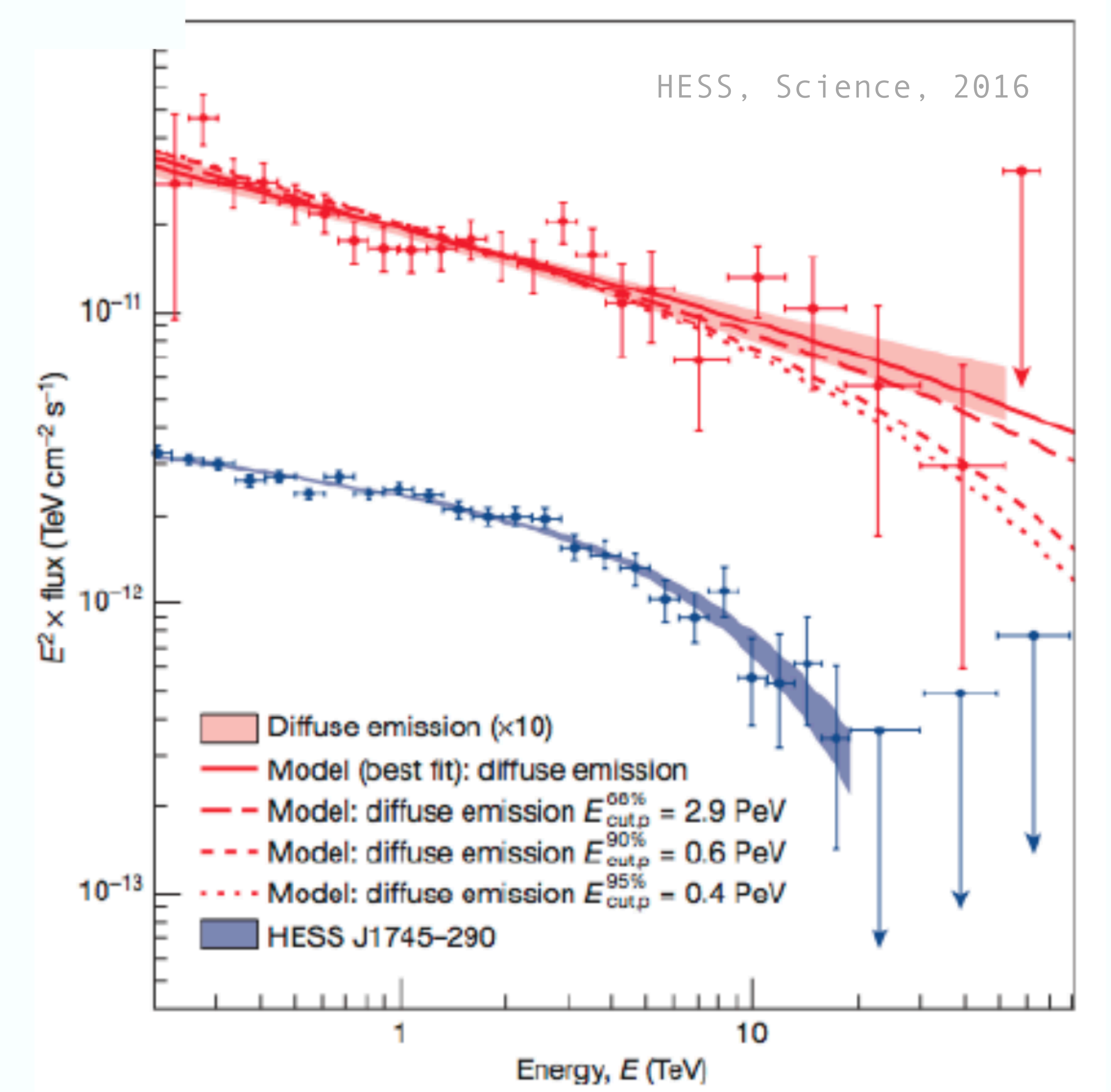


adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

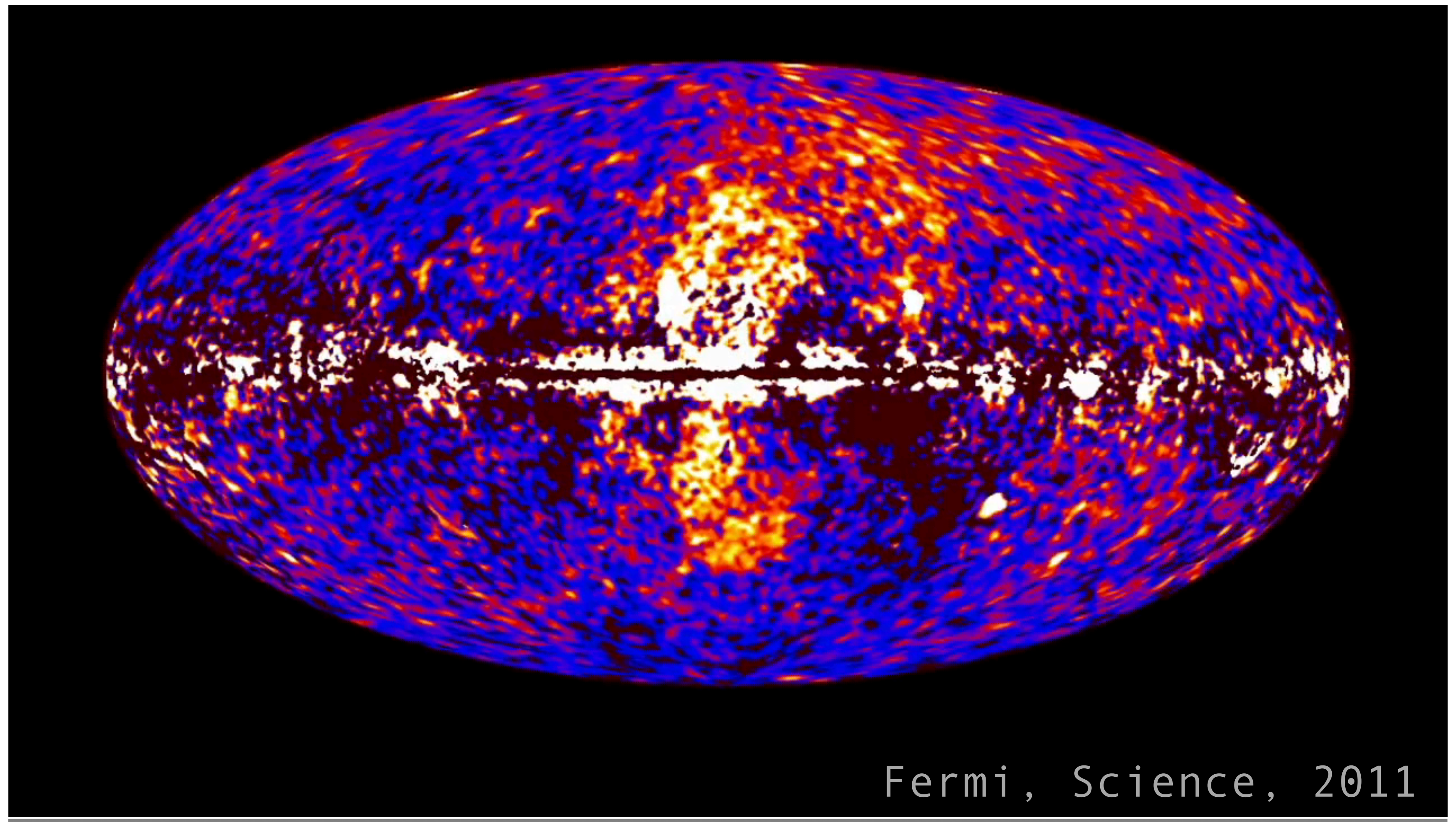
plot from Aharonian’s presentation 20202


Galactic
Center
NASA/Spitzer

Galactic Center: a PeVatron



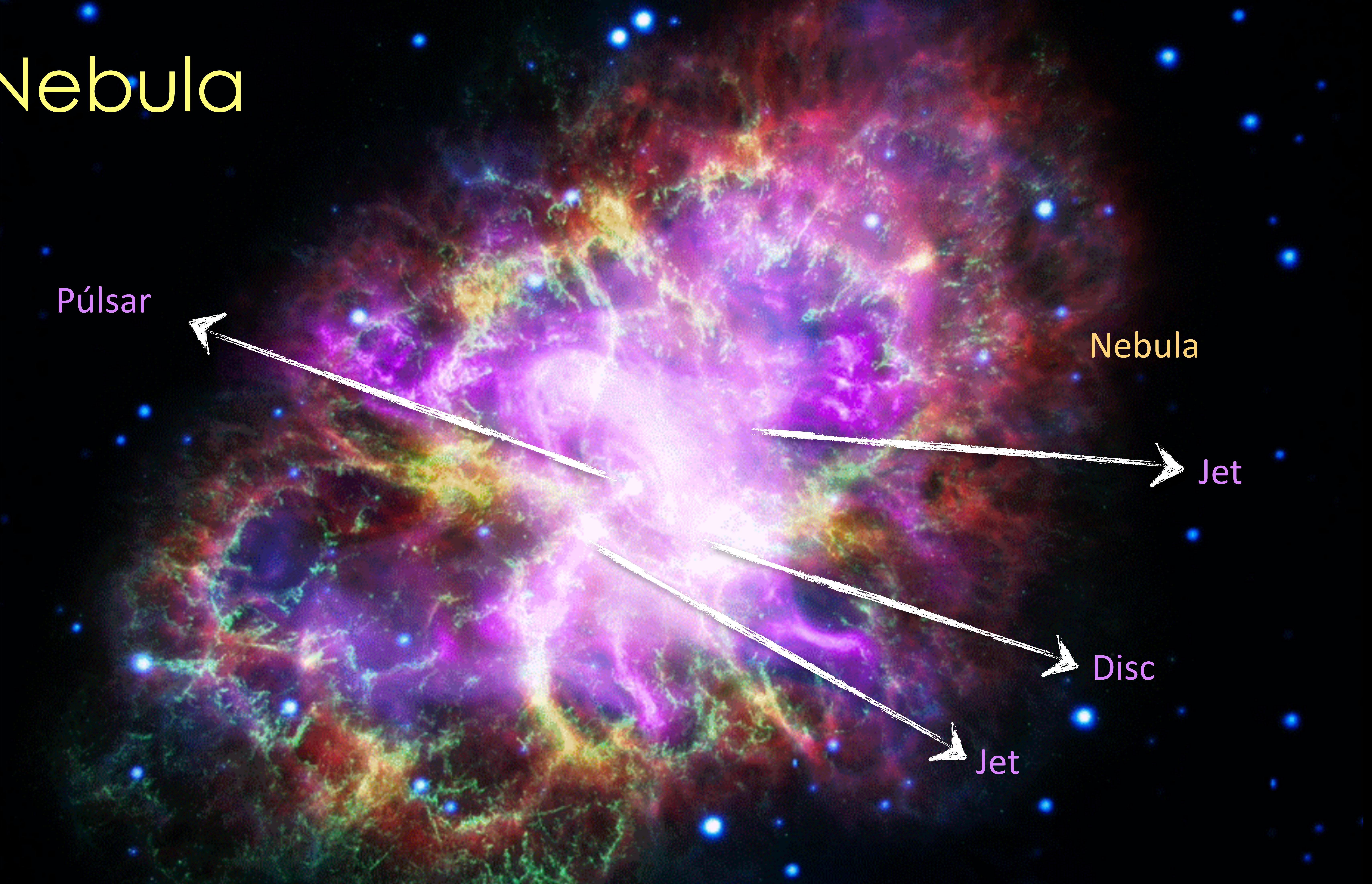
- H.E.S.S (Science 2016):
  Sgr A* first PeVatron in the Galaxy! -> hadronic PeVatron
- Origin of diffuse emission:
  - **Interaction of CRs** (from central BH) **with ISM**?
  - **CR acceleration in CMZ** (and in particular star forming regions) ?
  - Emission profile consistent with propagation of protons accelerated continuously **from a region < 10 pc from GC**



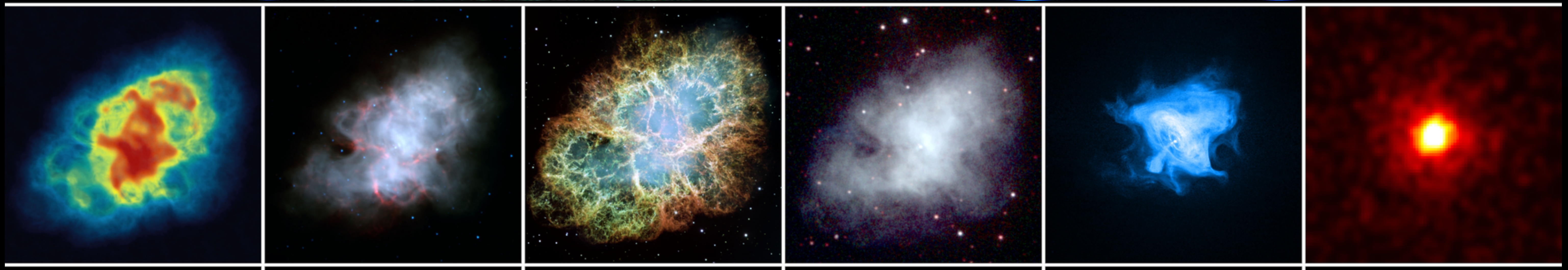
- **Fermi bubbles: SgA* remnants?**
- Hadrons? IC on CMB photons?

Crab Nebula (PWN)

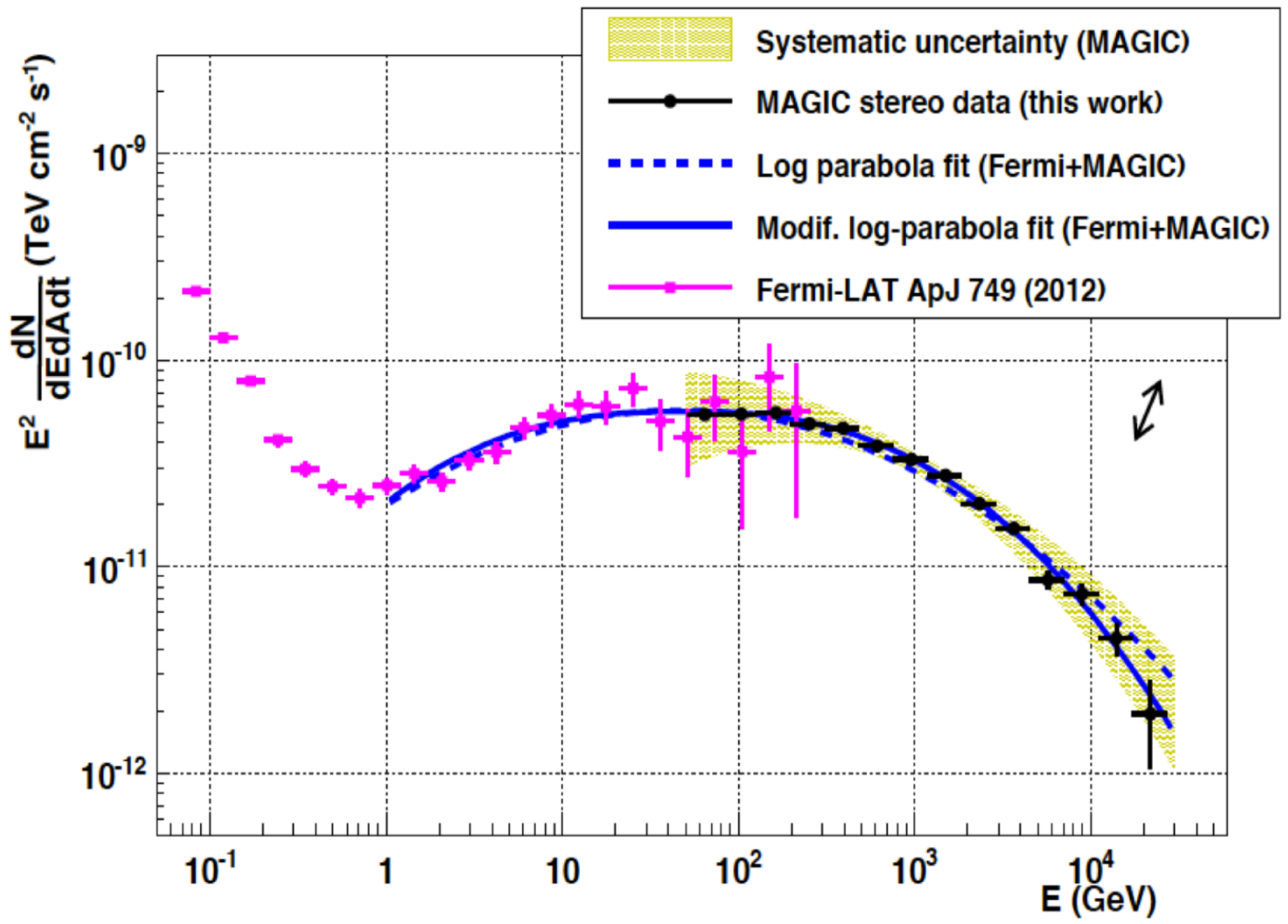
Year: 1054



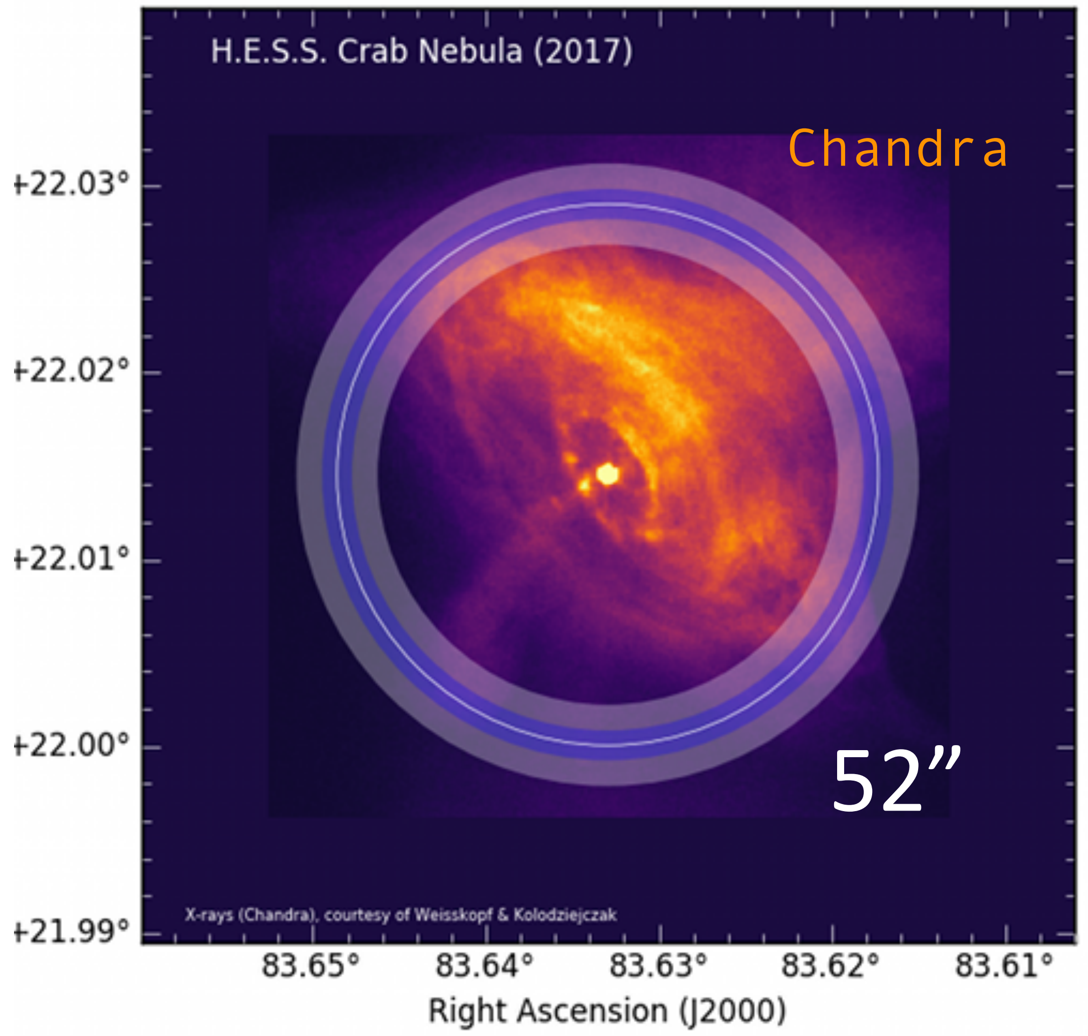
NASA: VLA+Spitzer+HST+XMM-Newton+Chandra



The Crab Nebula



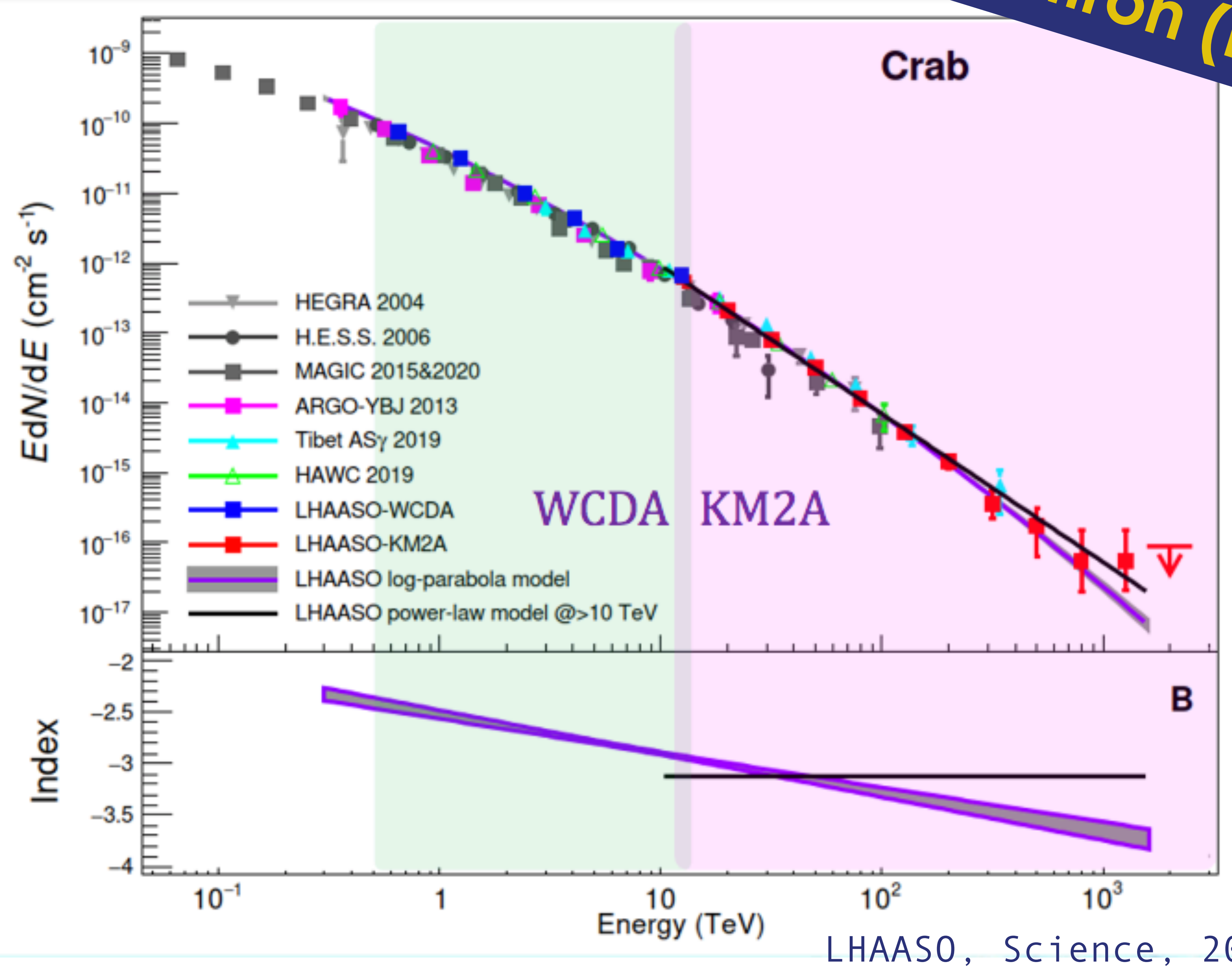
MAGIC, 2015, JHEAP 5



HESS, Nature, 2019

- **Standard candle for TeV astronomy**
- Fermi-MAGIC: **IC peak** at 53 GeV (Aleksić et al. 2015)
- MAGIC: very large zenith angle observations (ZA>70°): spectrum **measured until ~100 TeV**!!!
- LHAASO SED up to
  - Careful monitoring of atmosphere
- **No evidence of cut-off**

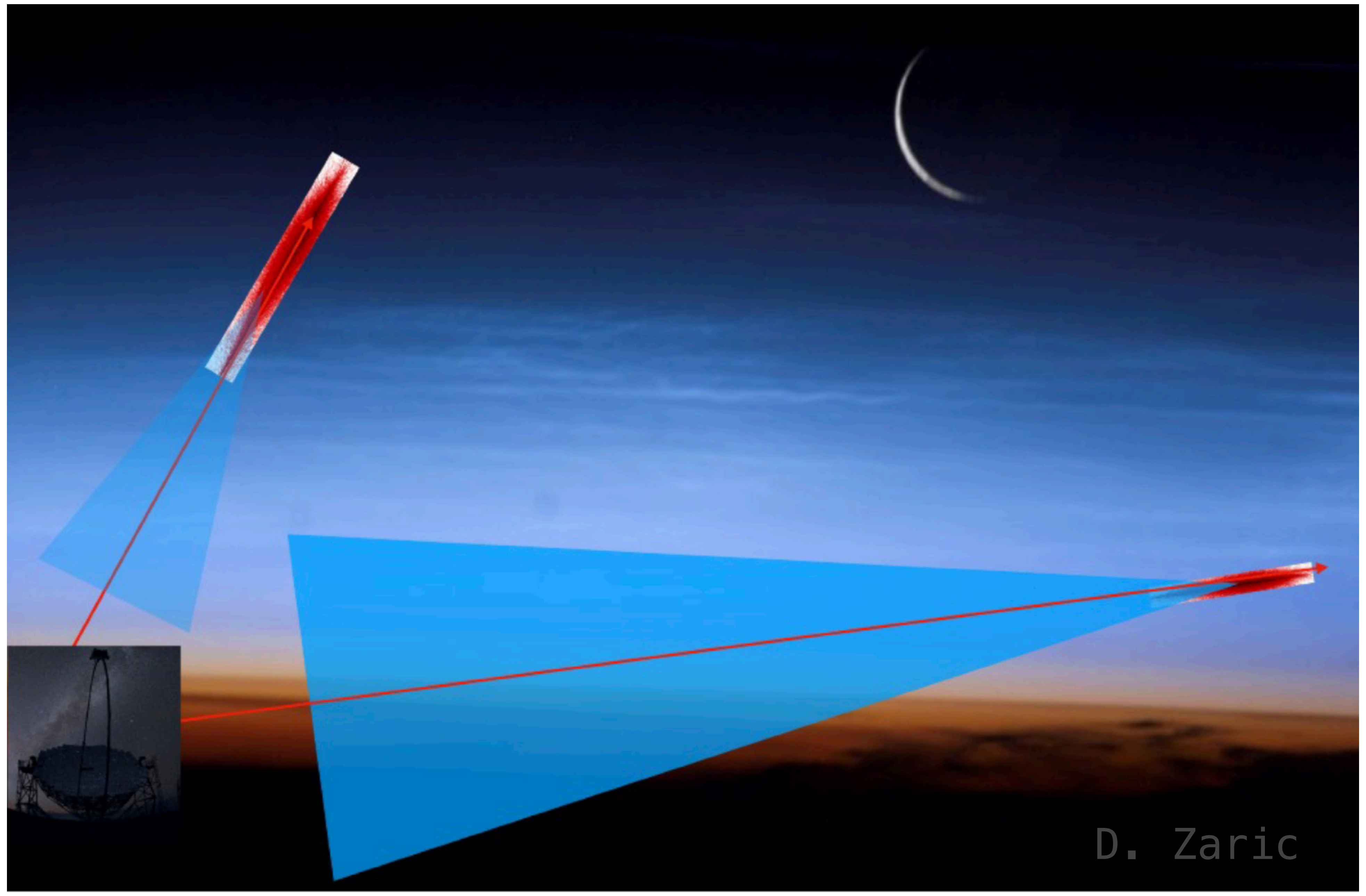
PeVatron (leptonic)

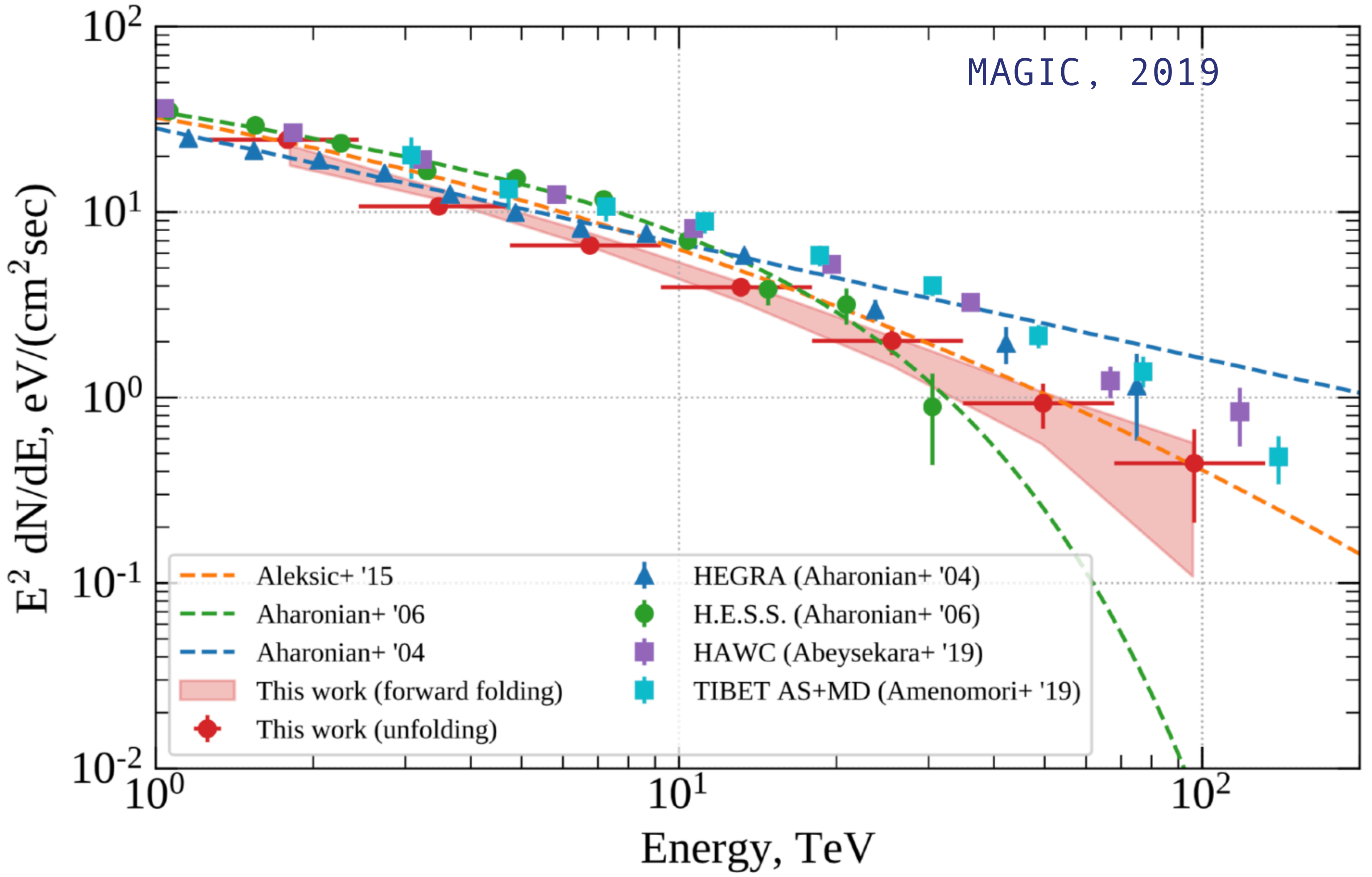


LHAASO, Science, 2021

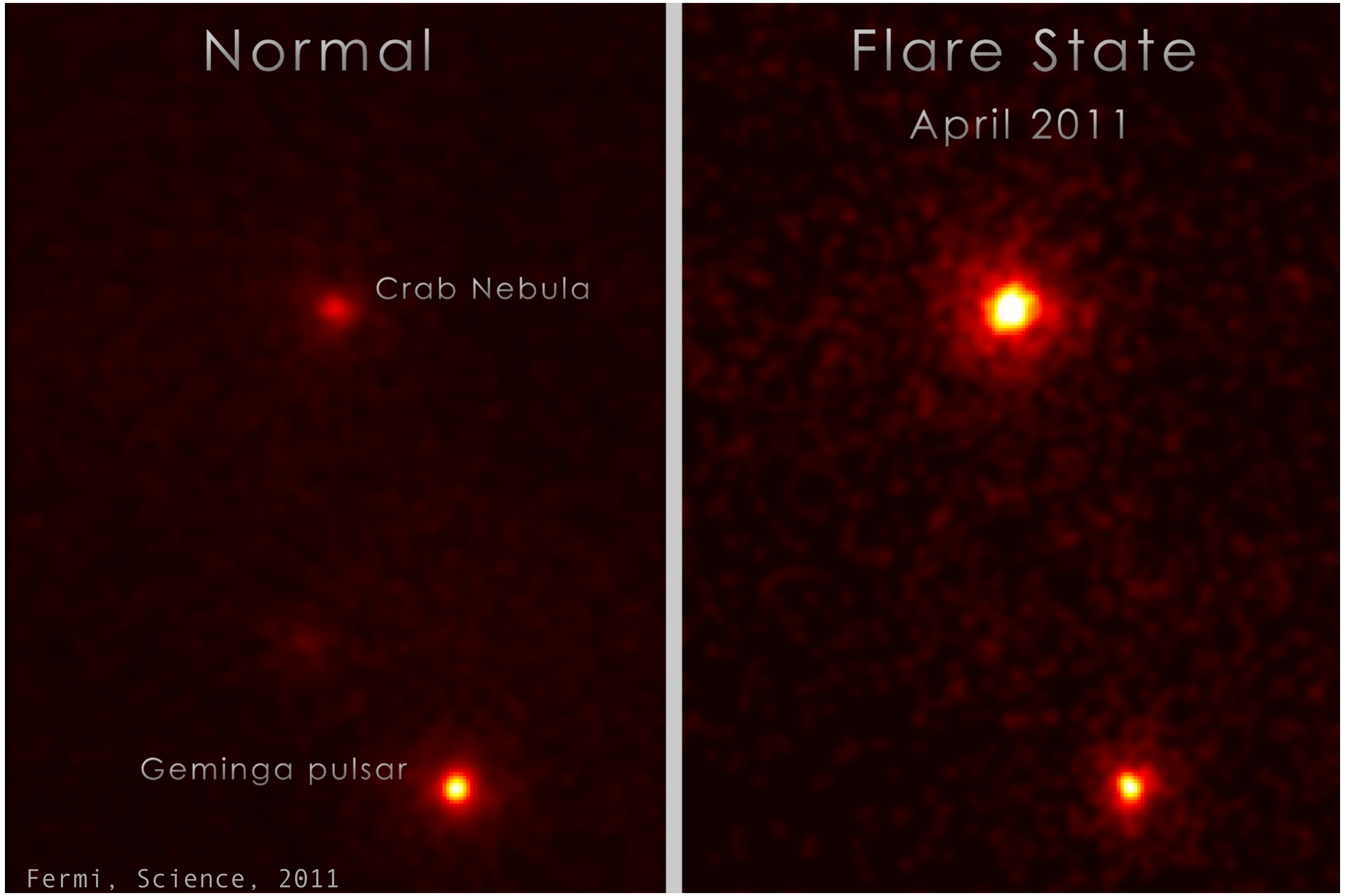
The Very Large Zenith Angle (VLZA) technique

- To detect gamma rays > several tens of TeV
  - Flux decreases rapidly → low count rates
- Solution:
  - increase observation time ✗
  - increase the collection area ✓
    - Build larger telescope arrays -> future CTA
    - Observe at Very Large Zenith Angles > 70° zenith
- MAGIC @VLZA
  - MAGIC collection area @zenith: ~ 0.05 km²
  - MAGIC collection area: ~ 2 km²
    - **unprecedented gamma-ray collection area**
  - MAGIC VLZA performance is impacted by the limited reconstruction of the shower parameters
    - remoteness of shower
    - small shower in camera (3-4 pixels)



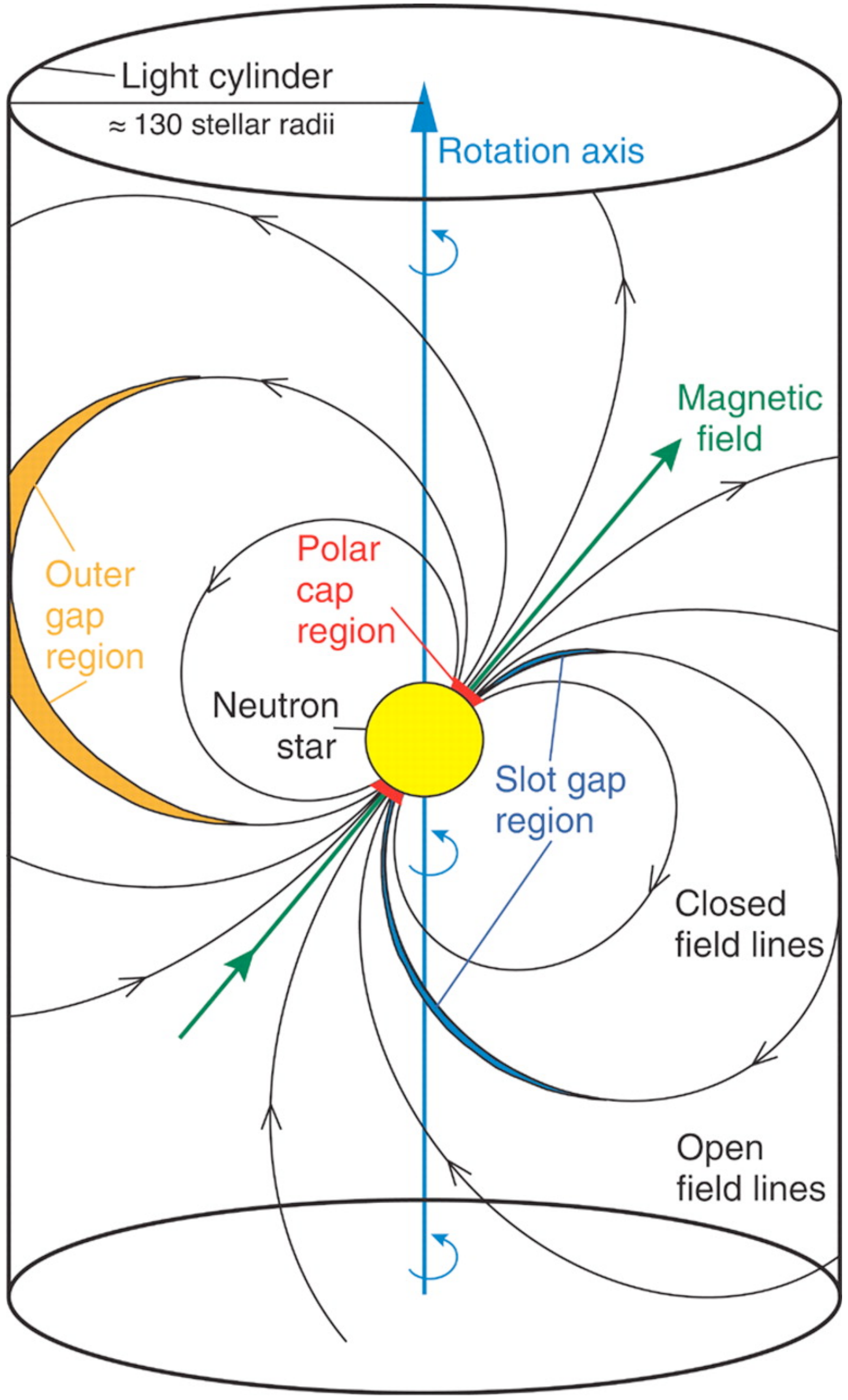


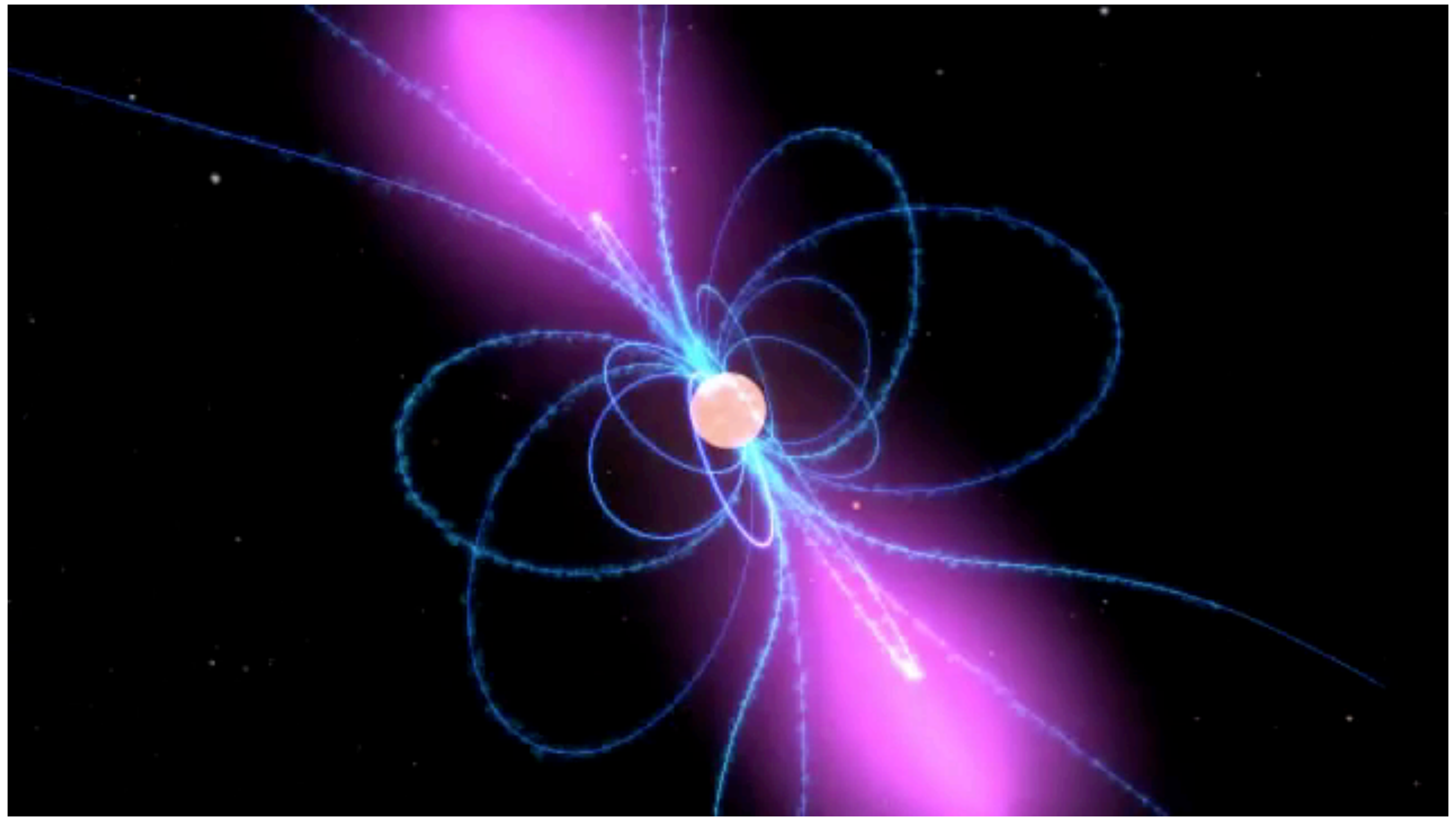
Crab Nebula: standard candle?

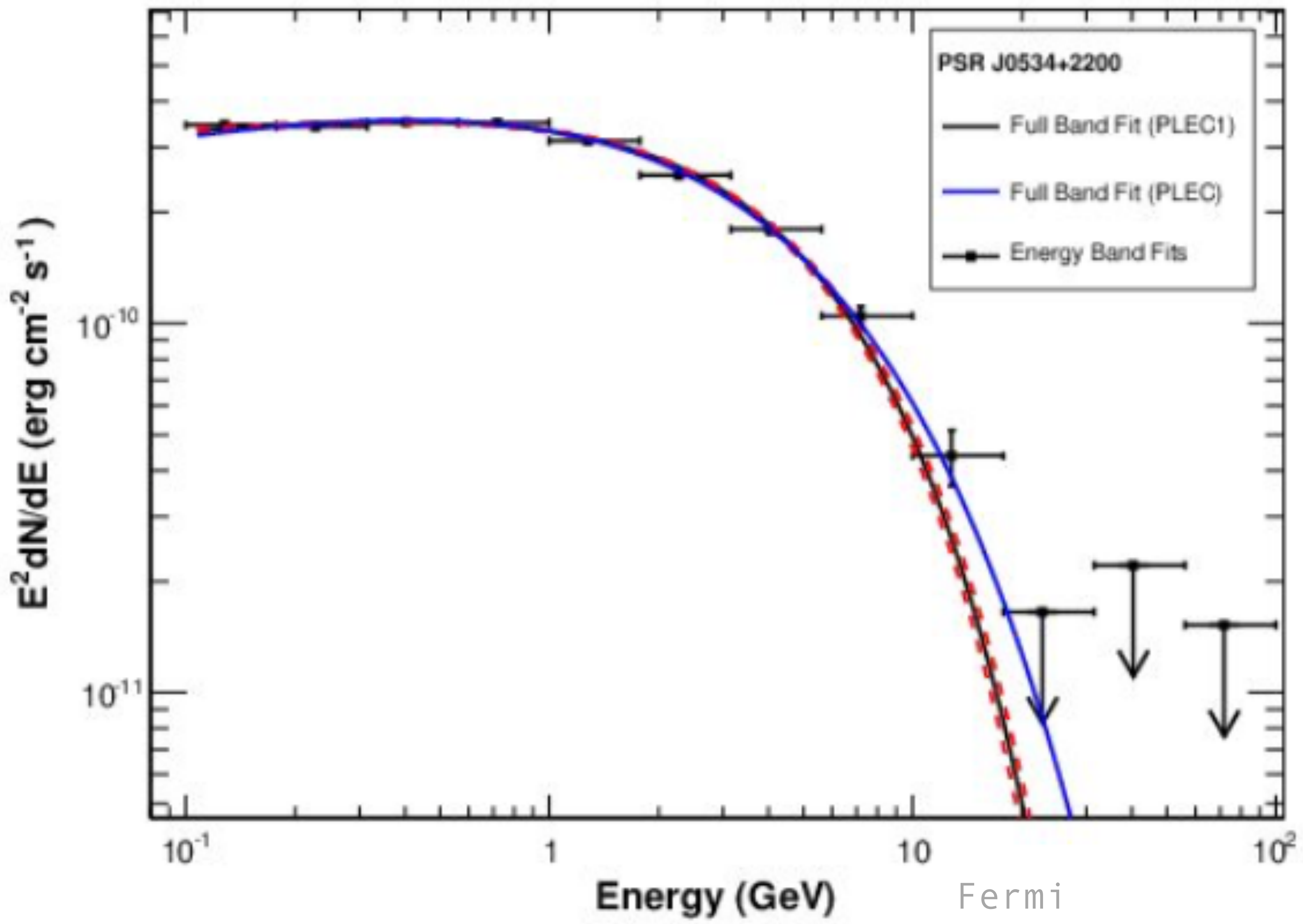


- **Fermi-LAT detects increase in the Crab Nebula emission x30 !**
  - What is the mechanism at work? PeV electrons rapidly cooling?
- No variability at X-rays (Chandra, INTEGRAL) -> two populations of e^-?
- Not yet detected at VHE

Gamma-ray **Pulsars**







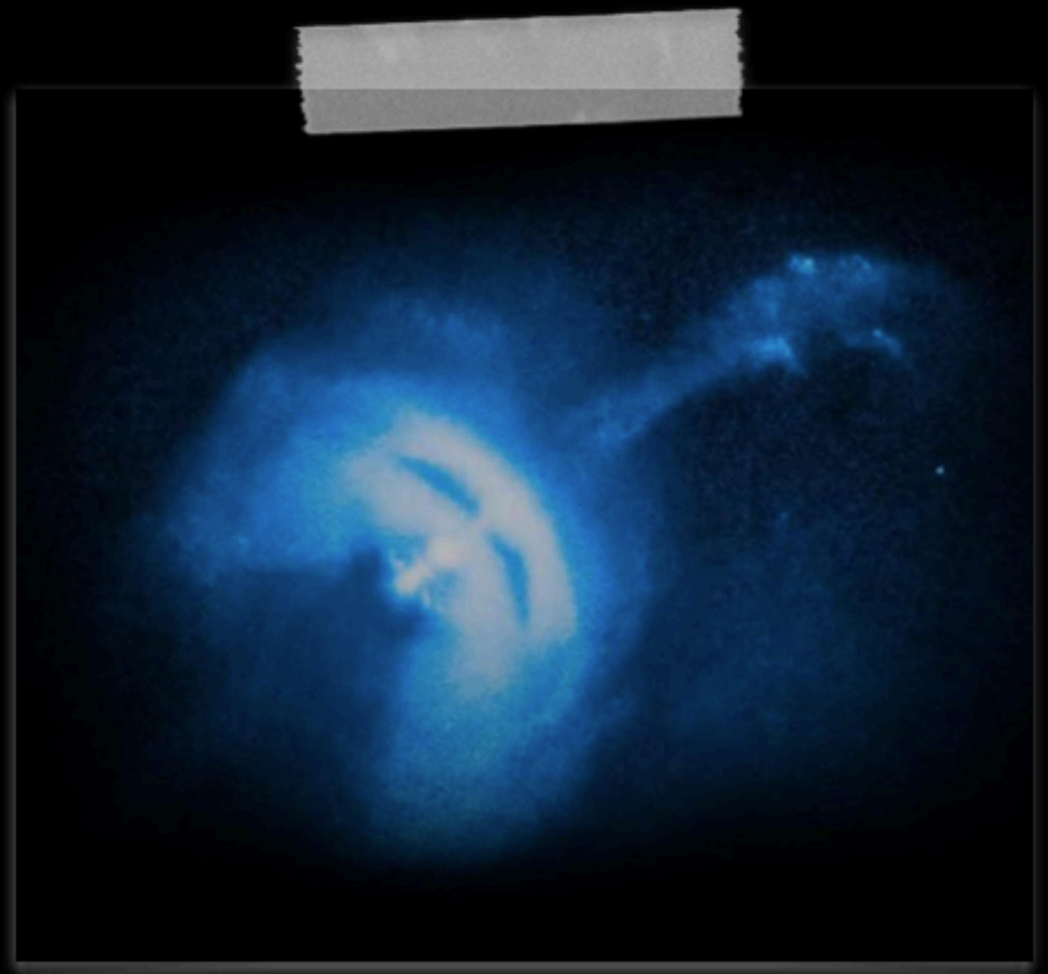
2200 radio pulsars
300 HE pulsars (Fermi)
3 pulsars at VHE (Crab, Vela, Geminga)

Famous pulsars at VHE

Crab

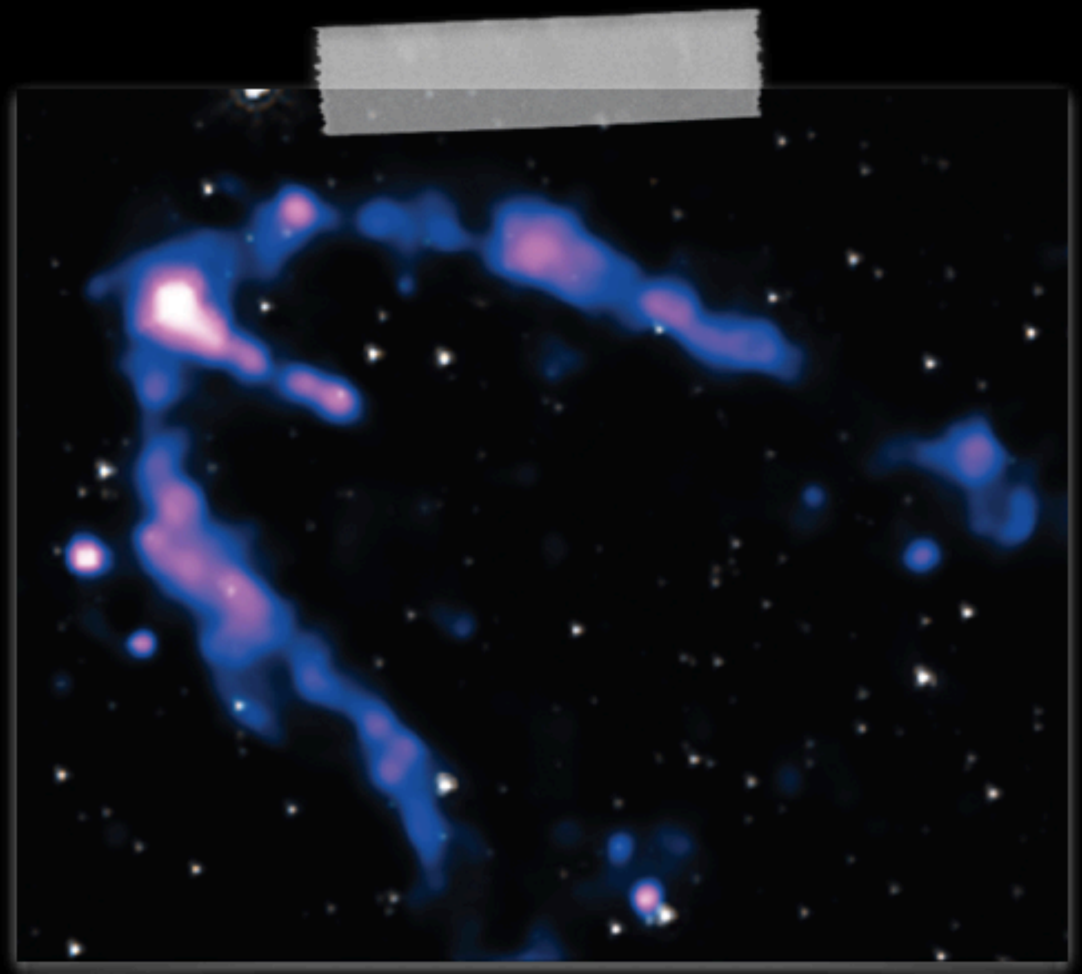
SN explosion:
1054 AC
Pulsar rotation:
30 times per second
33 msec

Vela



SN explosion:
110 000 - 123 000 years ago
Pulsar rotation:
12 times per second
83 msec

Geminga



SN explosion:
300 000 years ago
Pulsar rotation:
4.2 times per second
238 msec

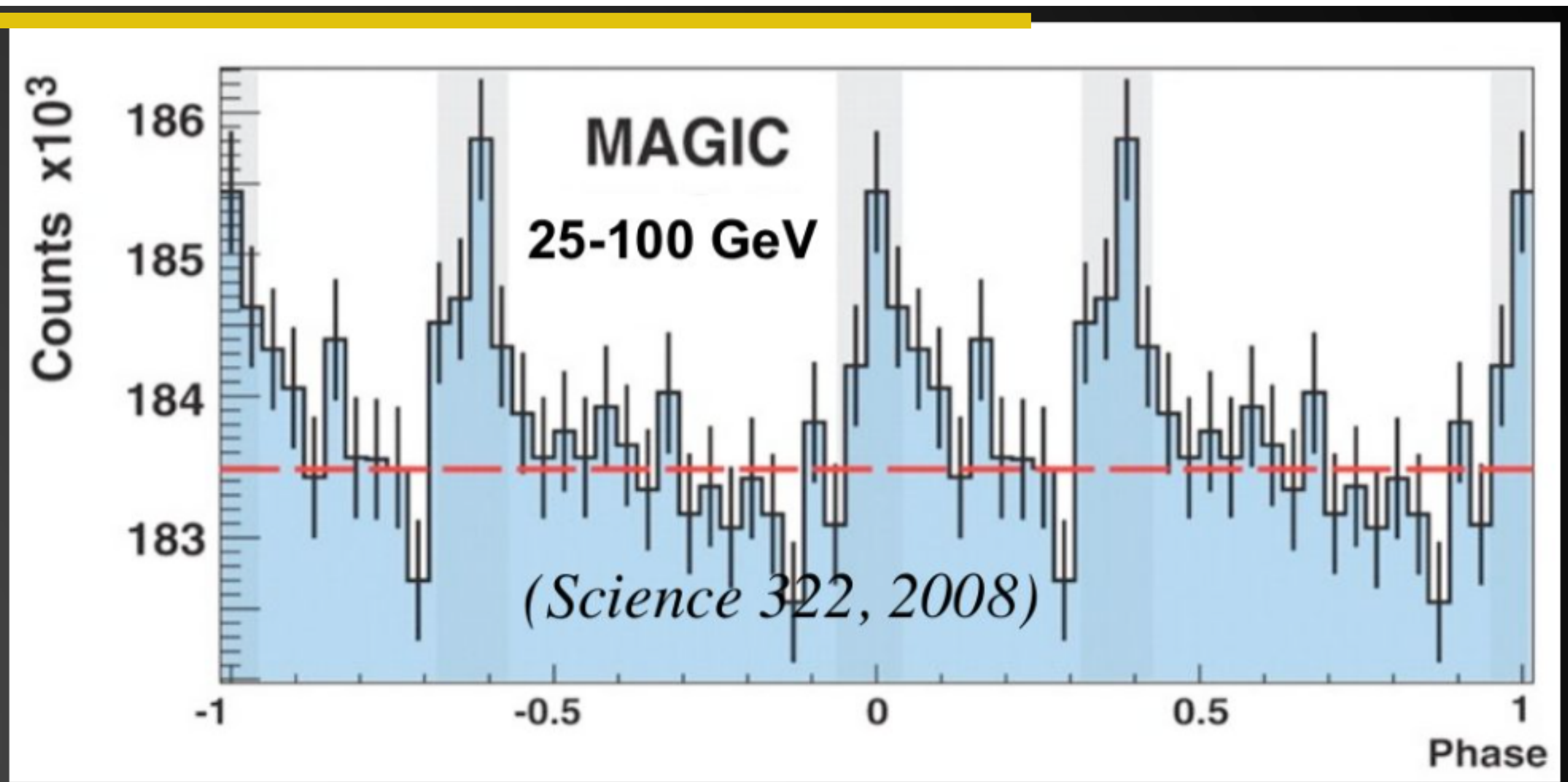
Pulsars at TeV energies

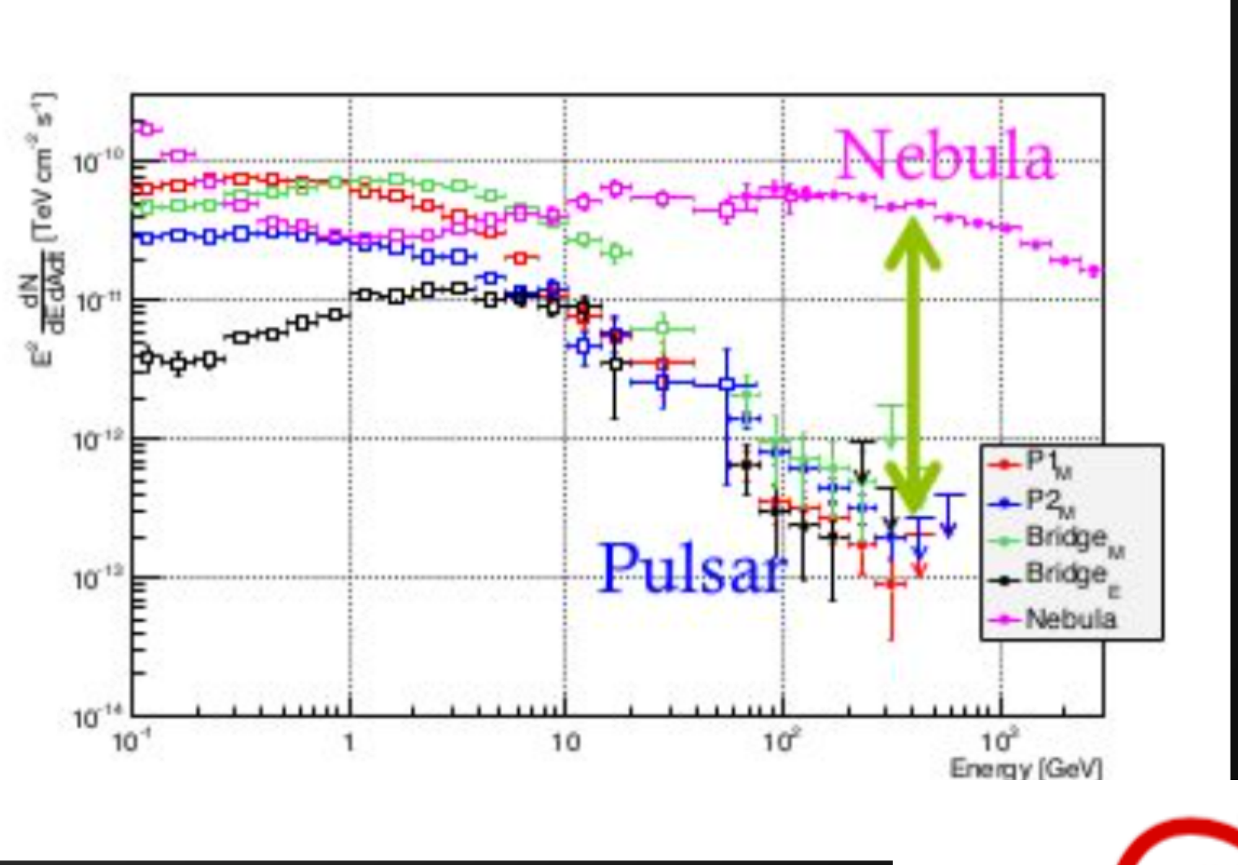
- **2008: Crab Pulsar VHE Discovery, Ruled out polar cap model.** *Aliu E. et al.(MAGIC Collab.) Science(2008) 322, 1218*

- **2011: Detection up to 100 GeV. Excluded the cutoff at more than 6σ.** *Aleksic et al. (MAGIC Collab.) ApJ 742 (2011) 43; Aliu E. et al. (VERITAS Collab.) Science(2011) ,334, 6052*

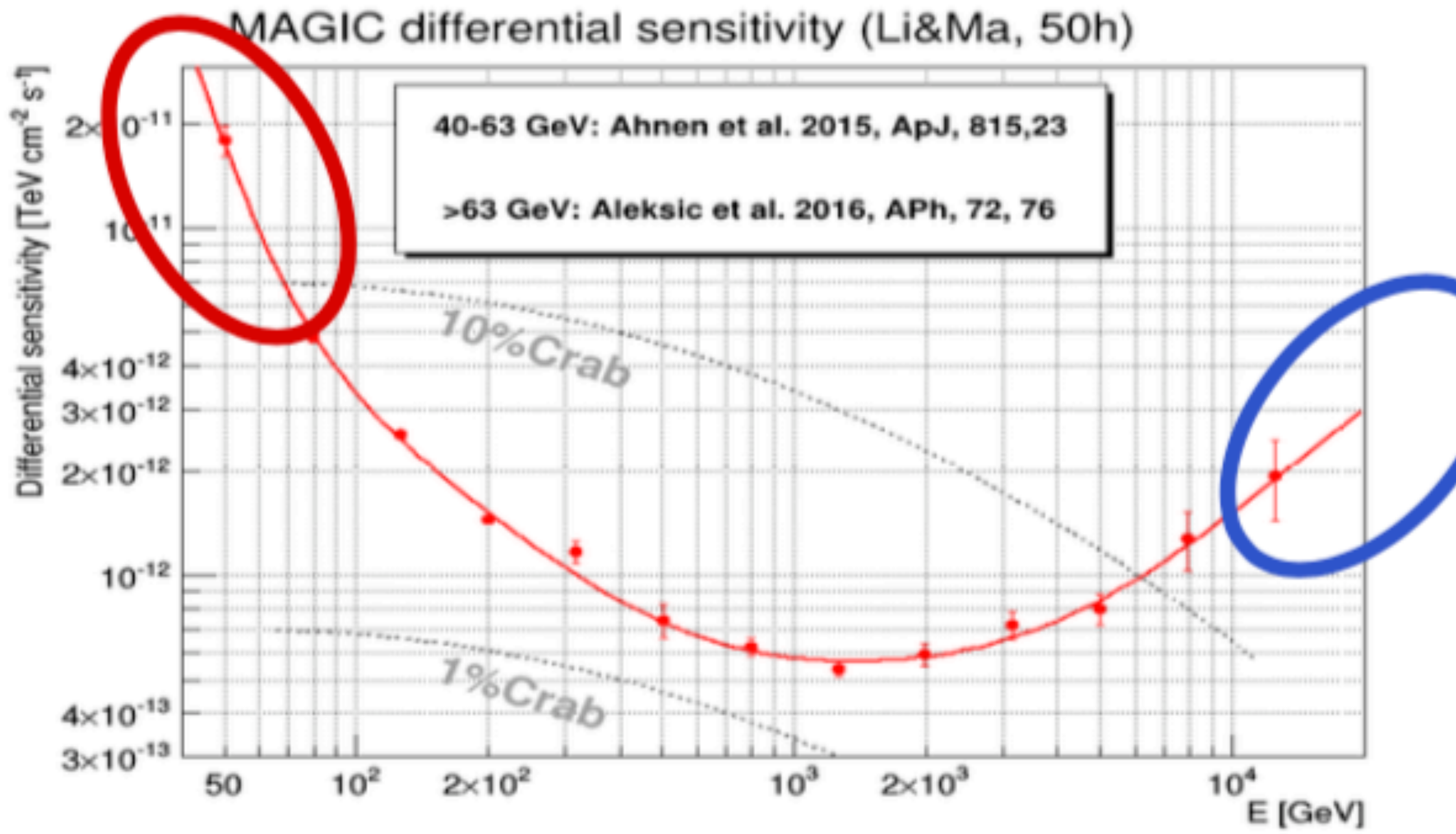
- **2012: Detection up to 400 GeV. Existence of a hard component.** *Aleksic et al. (MAGIC Collab.) A&A 540 (2012) A69*

- **2014: Detection of the Bridge emission.** *Aleksic et al. (MAGIC Collab.) A&A 565 (2014) 12)*



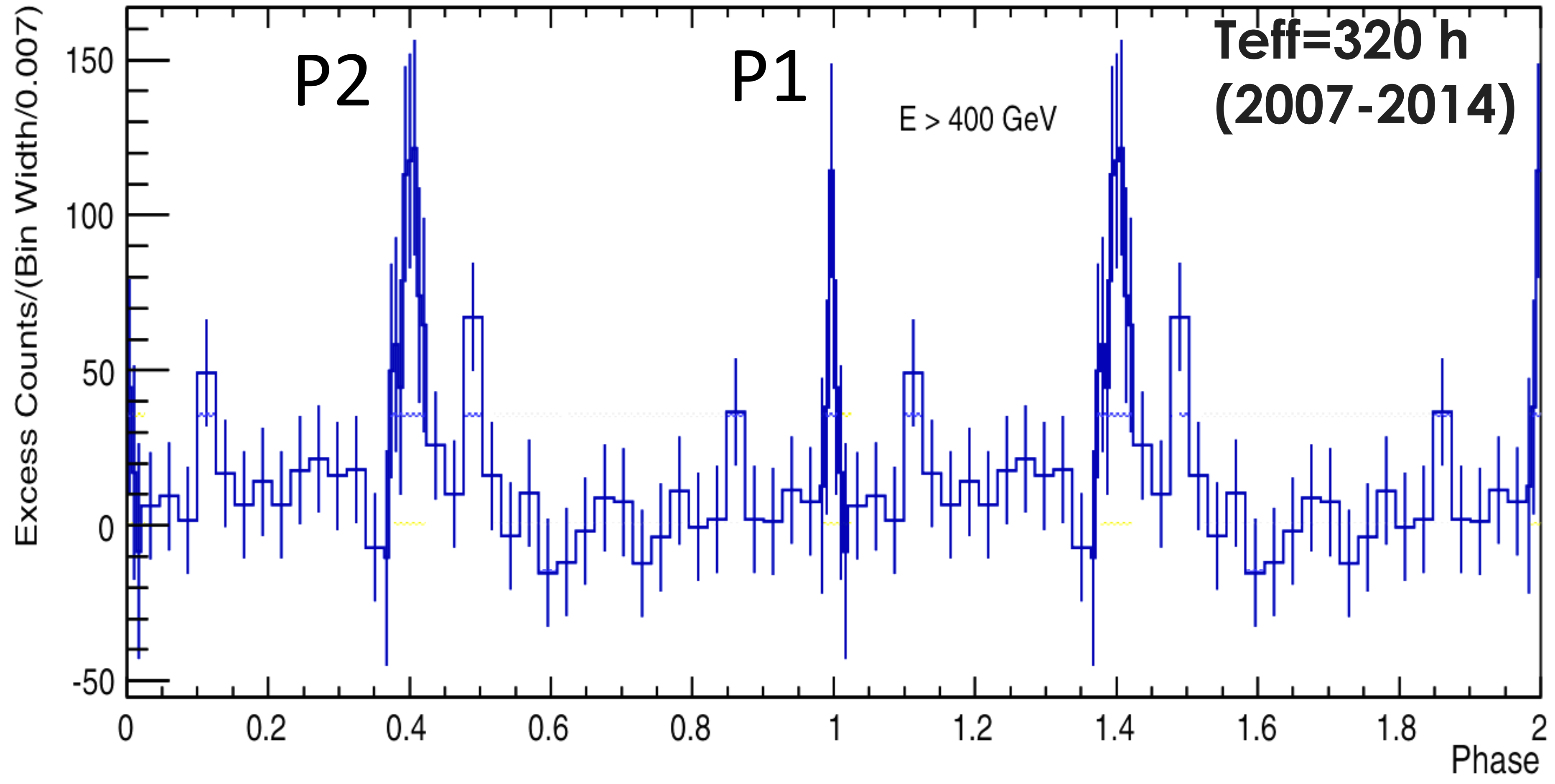


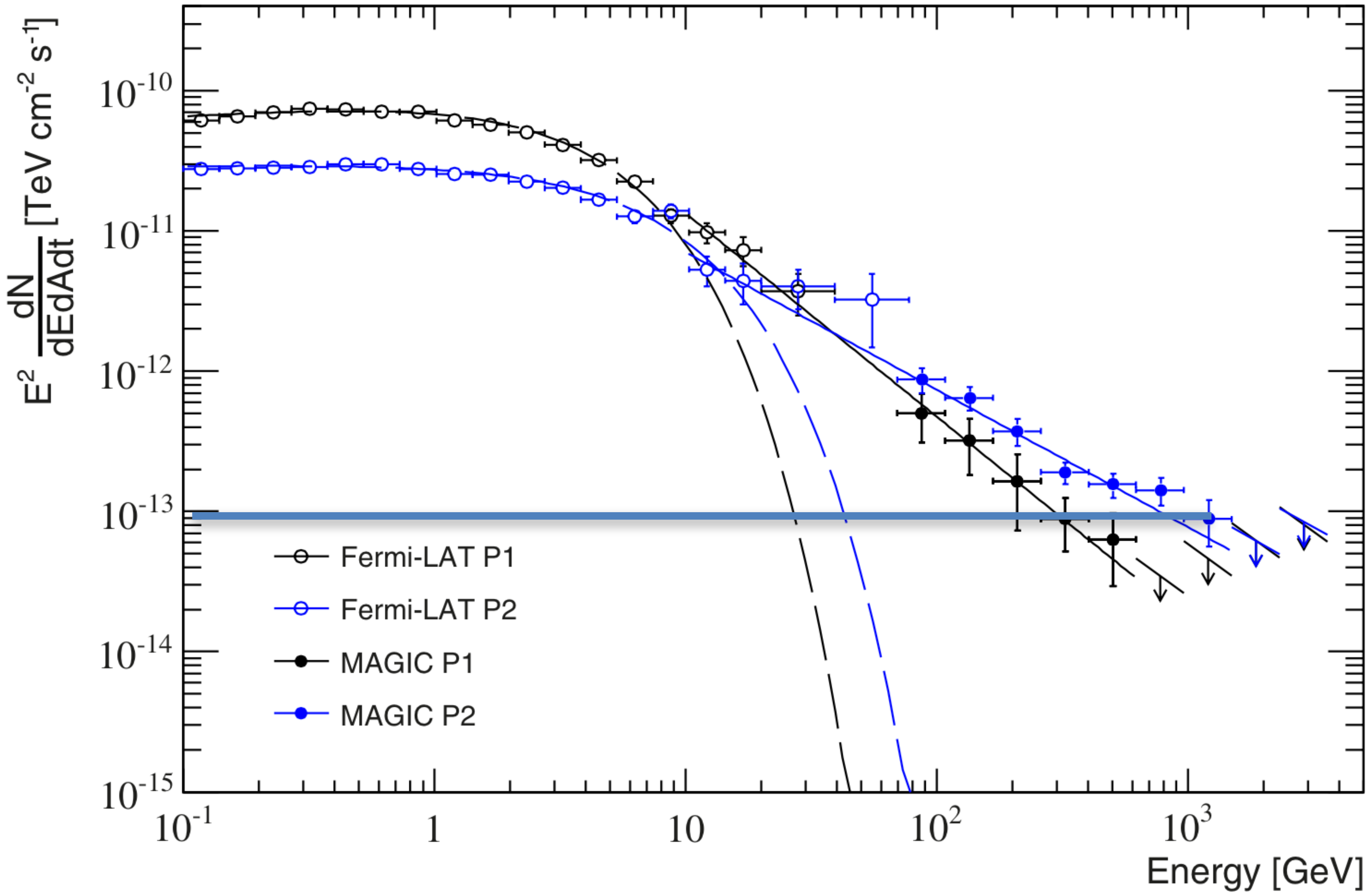
Slide from Jezabel R. @ TeVPa 2017



Crab Pulsar at TeV energies

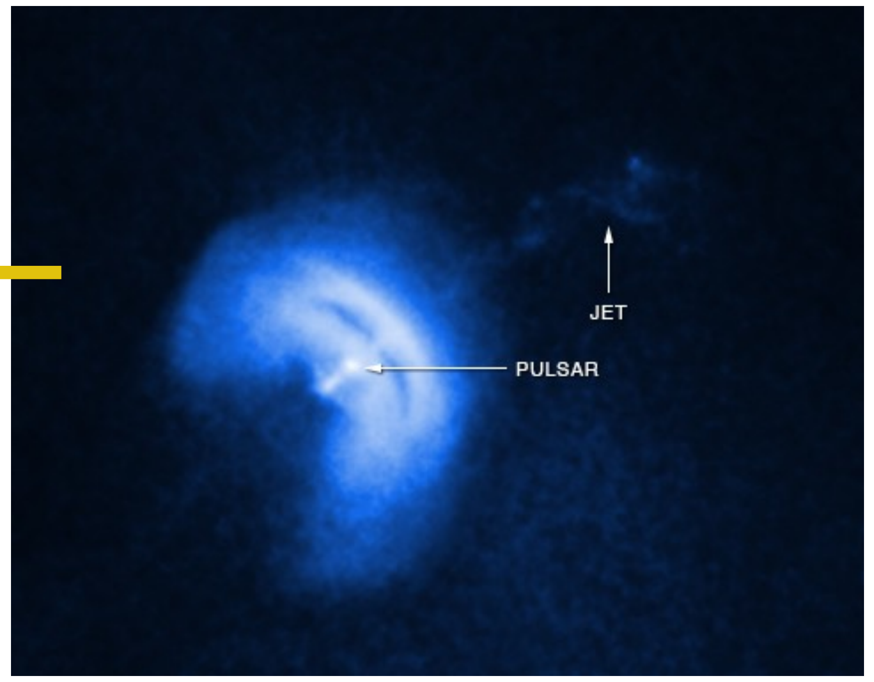
MAGIC, 2016, A&A, 585, A33

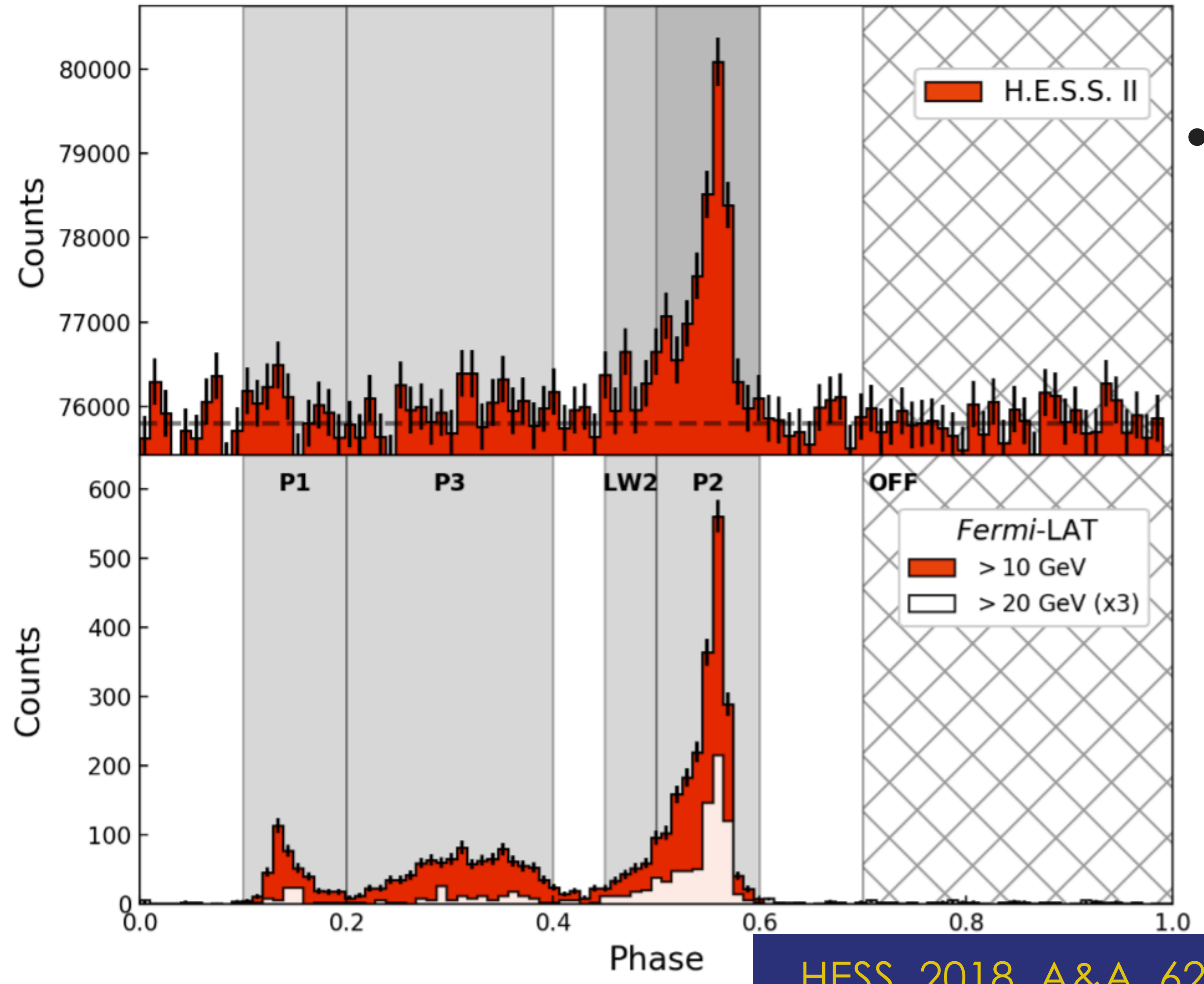




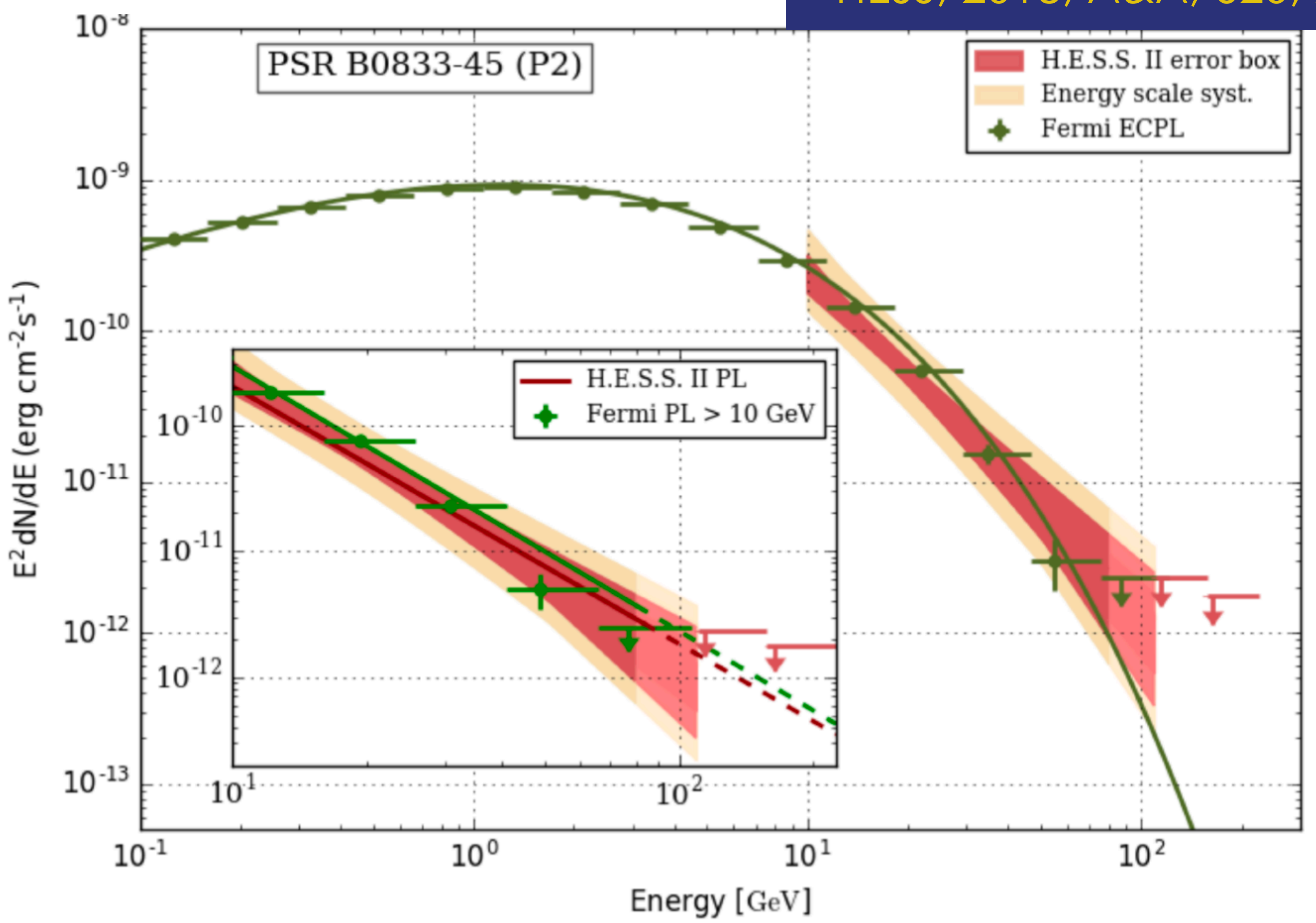
- MAGIC discovered **pulsed emission** from Crab spectrum extending **up to 1.5 TeV**
- Spectra of both peaks extending as PWLs far beyond the expected cutoffs:
  - **P1** detected up to **0.6 TeV** (Γ=3.5 ± 0.1)
  - **P2 detected up to 1.5 TeV** (Γ=3.0 ± 0.1)
- **Model implications** of detection of TeV photons:
  - Synchrotron-curvature ruled out (It would require unrealistic curvature radii) but **IC required**
  - Emission from **outer magnetosphere** via IC
  - Magnetospheric synchrotron-self-Compton
  - However **no model can fully explain presence of TeV pulsations**

Vela pulsar at TeV energies



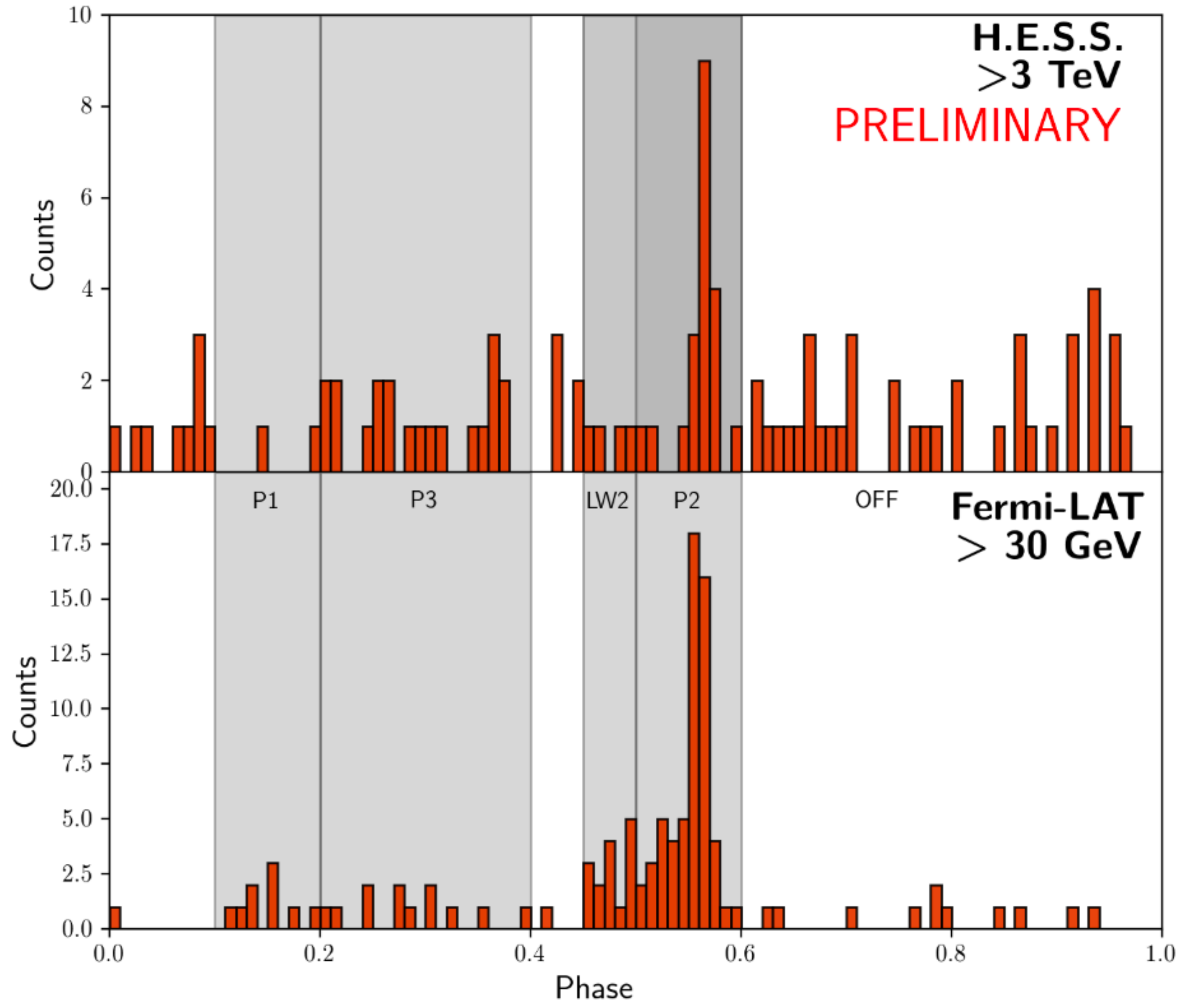


HESS, 2018, A&A, 620, A66



- H.E.S.S detection of the Vela pulsar at **20-80 GeV** with H.E.S.S. II telescope

HESS, Texas symposium 2017



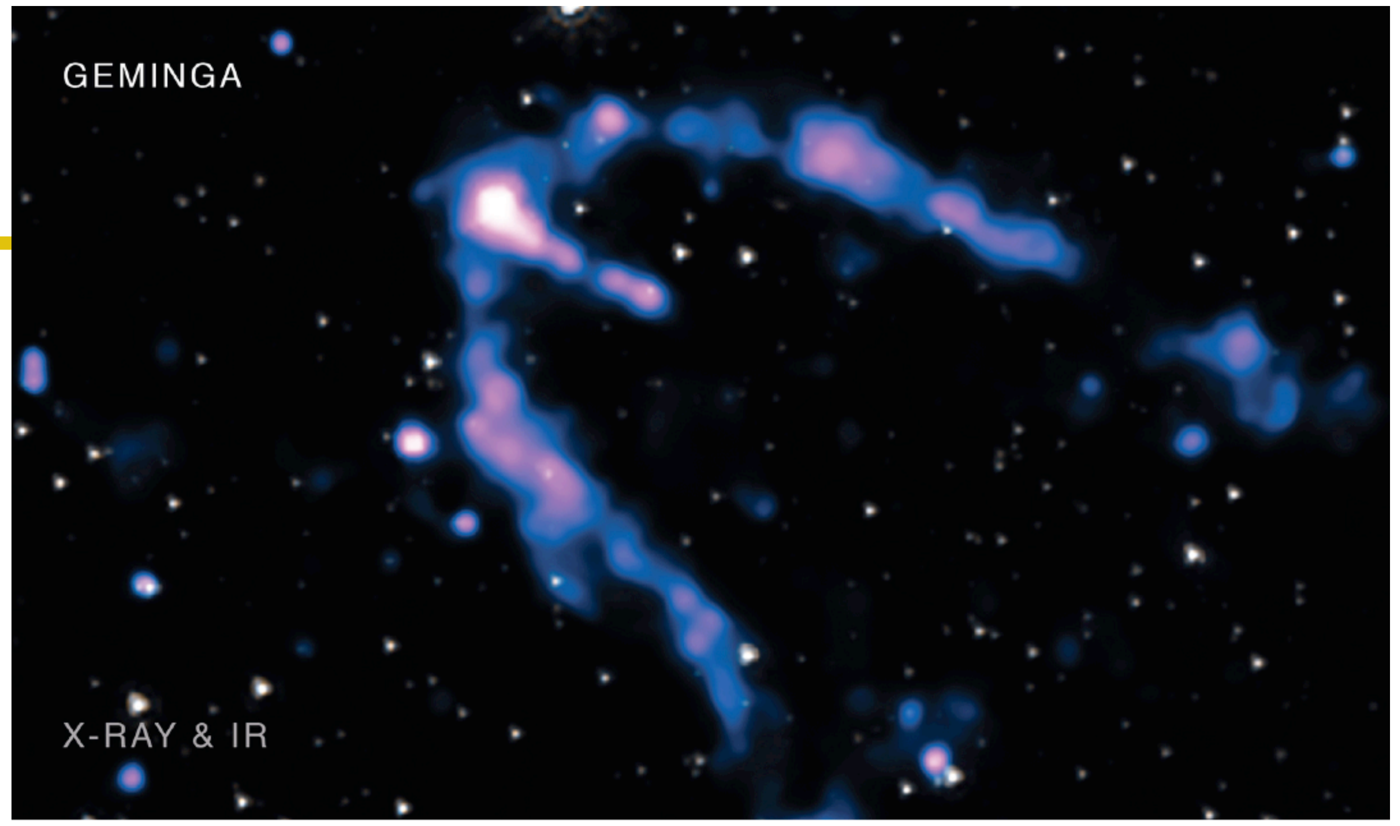
- Data from 2004-2016 observations
- 60 hours in stereoscopic mode: at least 2 telescopes among CT1-CT4

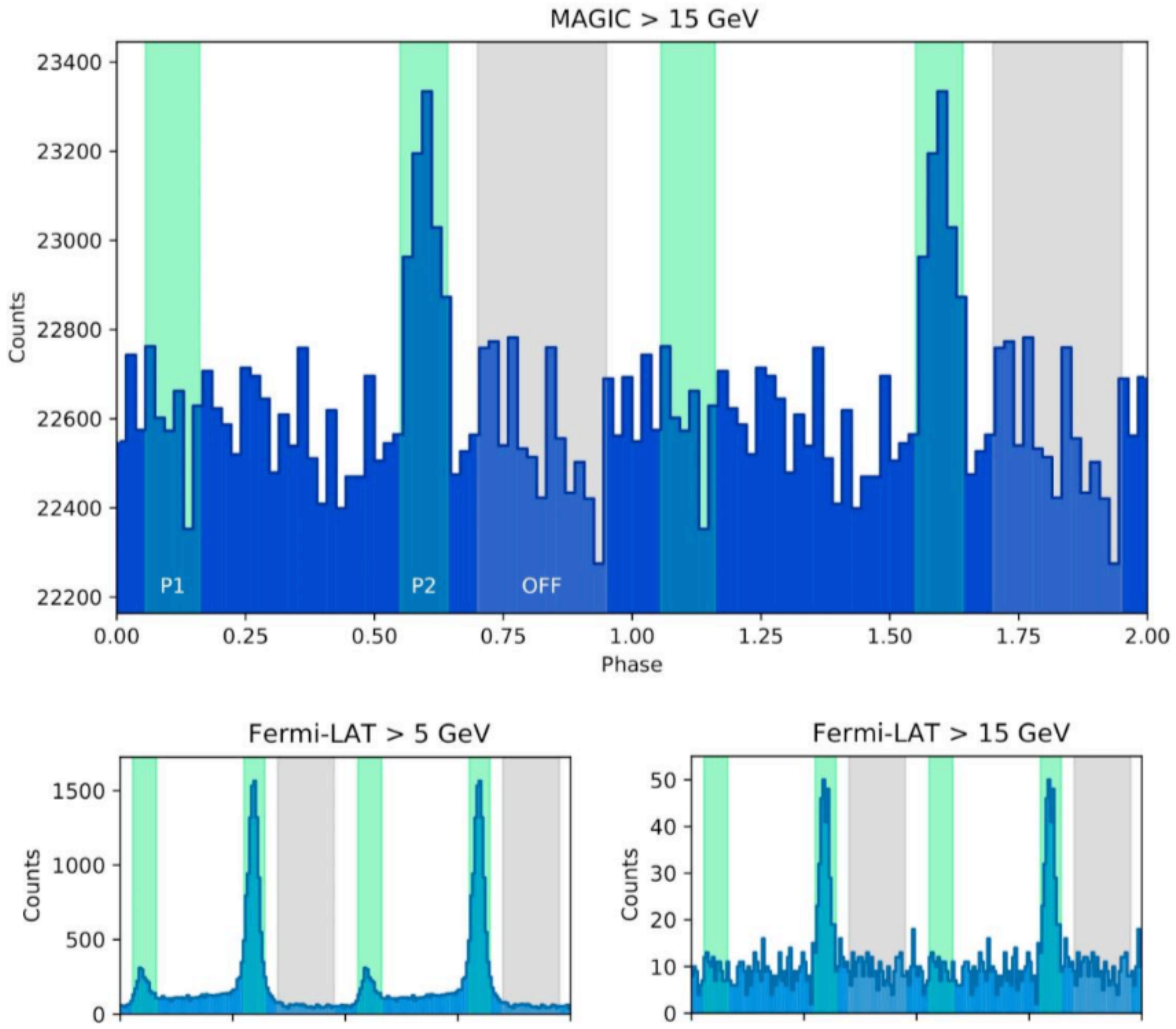
- Significance of the signal, ***Cm* test**:
  - > 3 TeV: **5.3σ**
  - > 7 TeV: **5.6σ**
- **H-test** > 7 TeV: **4.5σ**

- Also claimed detection at TeV energies in Texas 2017, but no more information since then

Geminga

- Detection by MAGIC at **15-80 GeV** (Acciari et al. 2020)
  - **Third known pulsar**
  - **First middle-aged one**
- The power-law tail emission detected by MAGIC is interpreted as the **transition from curvature radiation to Inverse Compton Scattering** of particles accelerated in the northern outer gap.





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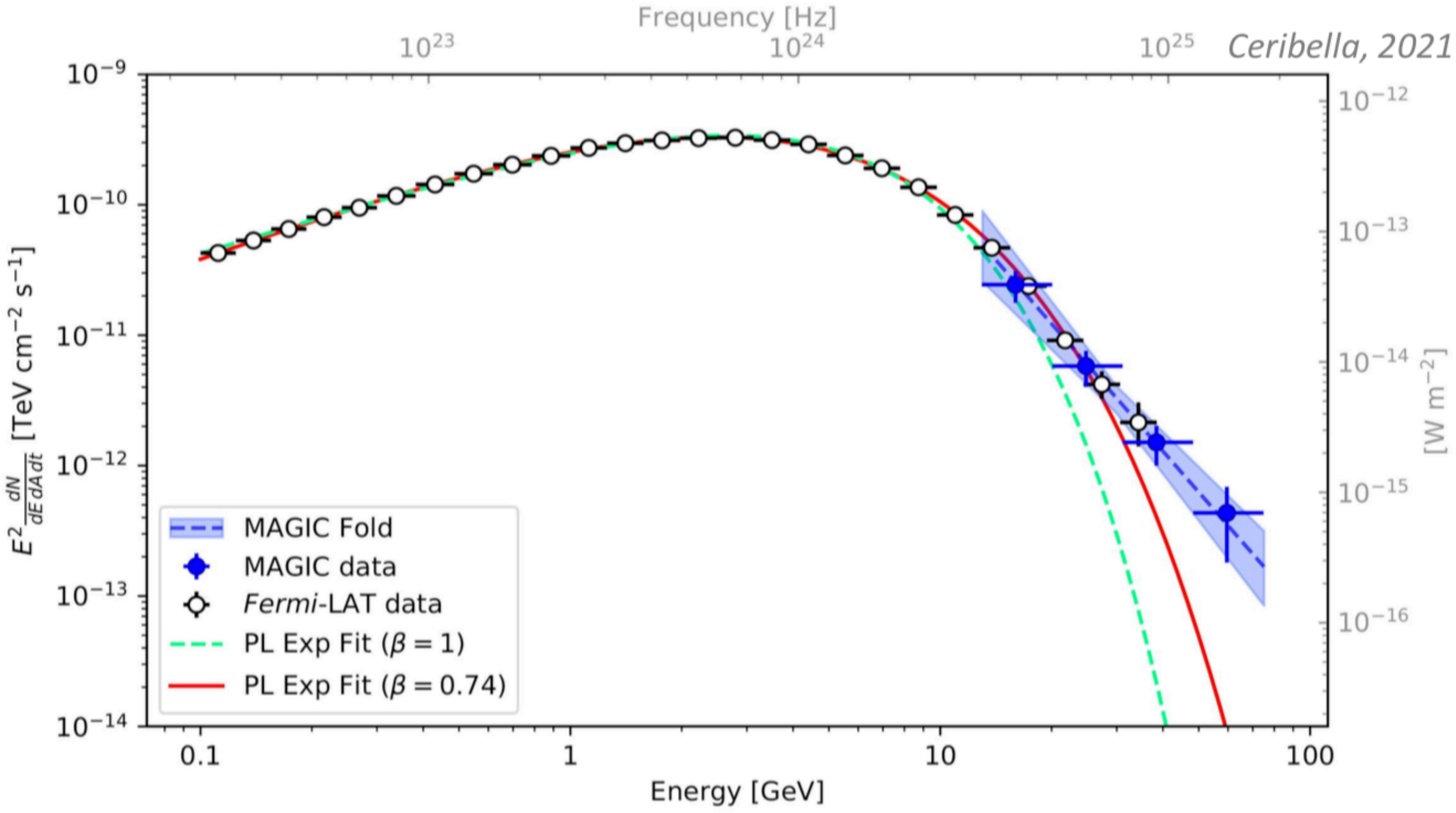
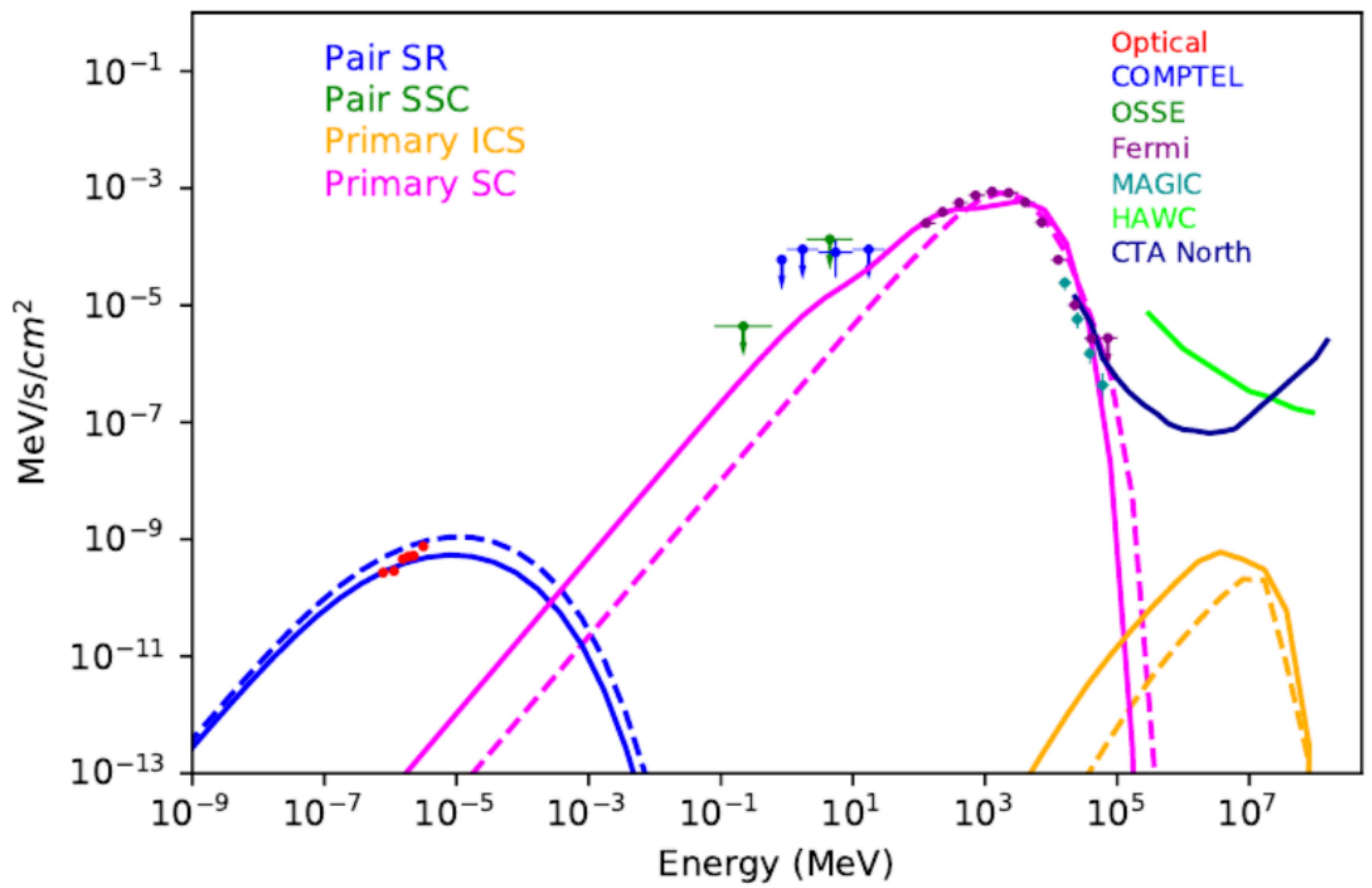


MAGIC, A&A 2020

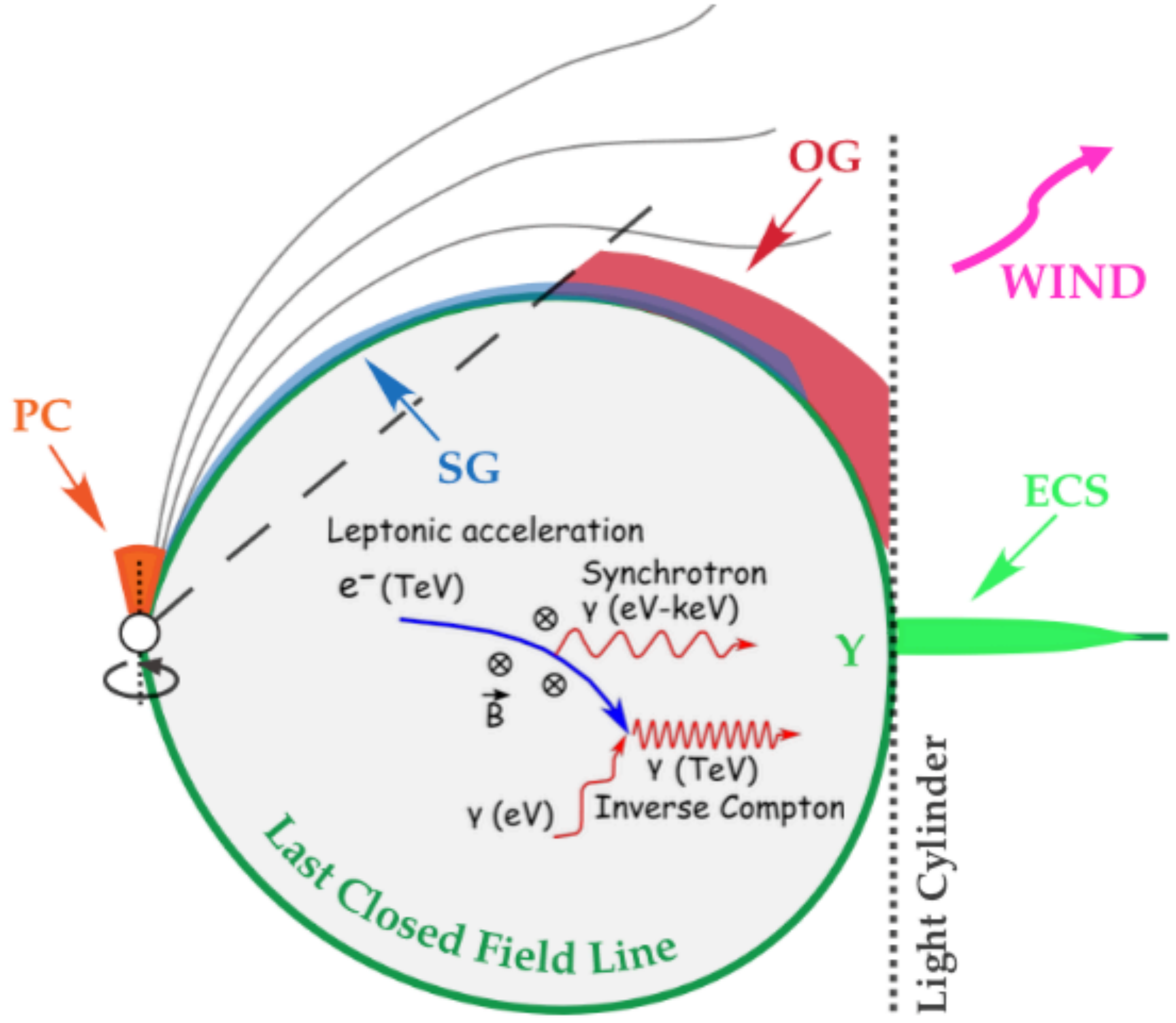
Which scenario?

- Harding et al. 2021 predict **three distinct VHE components**:
  - **SC** from primaries whose **high-energy tail can extend to 100 GeV**
    - HE tail of the primary SC that produces the Fermi spectrum in **Vela & Geminga**
  - **SSC** from pairs that can extend **to several TeV**
    - Detected in **Crab** by MAGIC
  - **ICS** from primary particles accelerated in the current sheet that scatter pair synchrotron radiation, which **appears beyond 10 TeV**
    - ICS component peaking above 10 TeV from **Vela** by H.E.S.S

From *Harding et al., 2021*

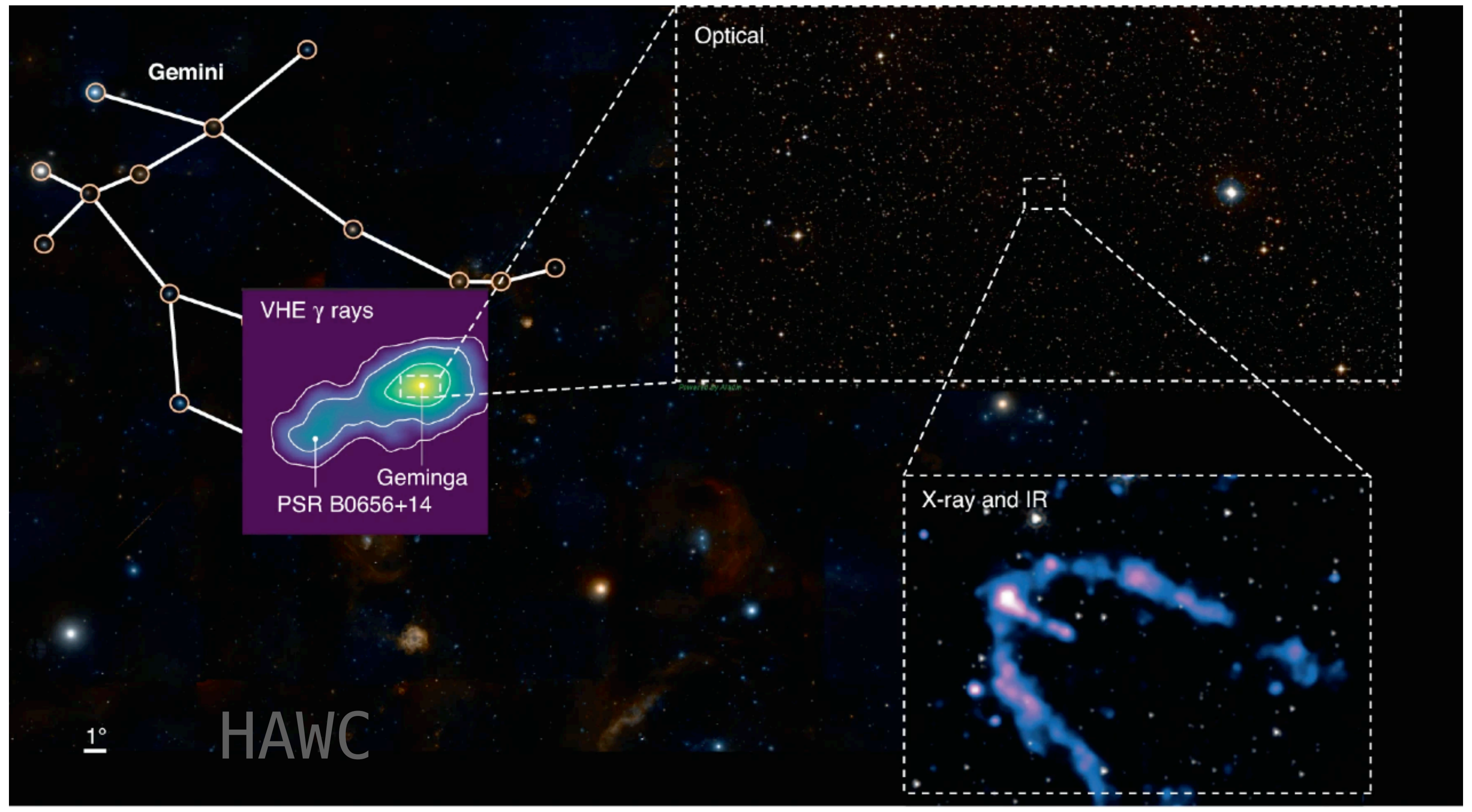


Adapted from *Hirotani, 2008*

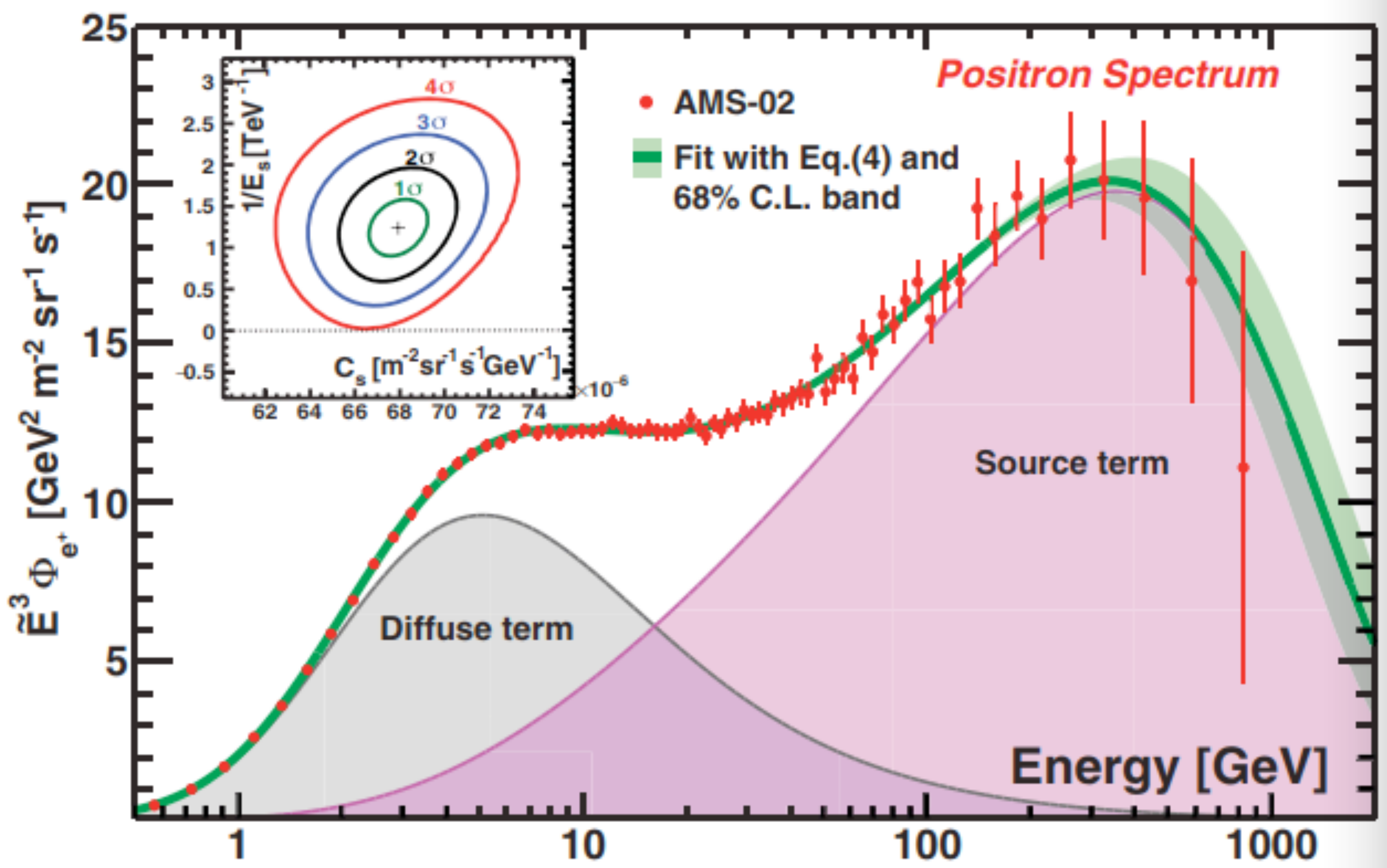


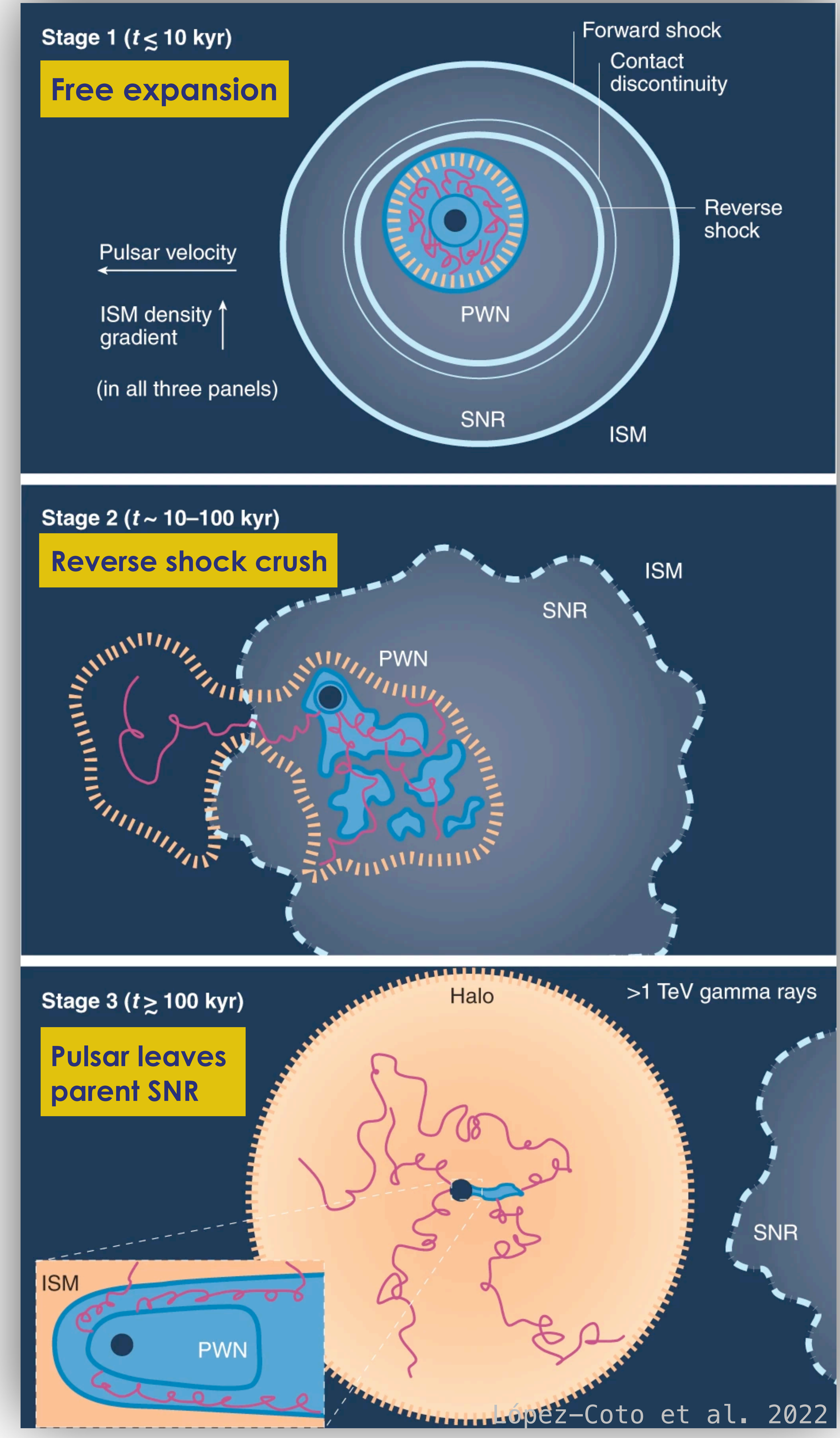
from G. Ceribella, Bonn 2023

PWNe/TeV halos



AMS coll.





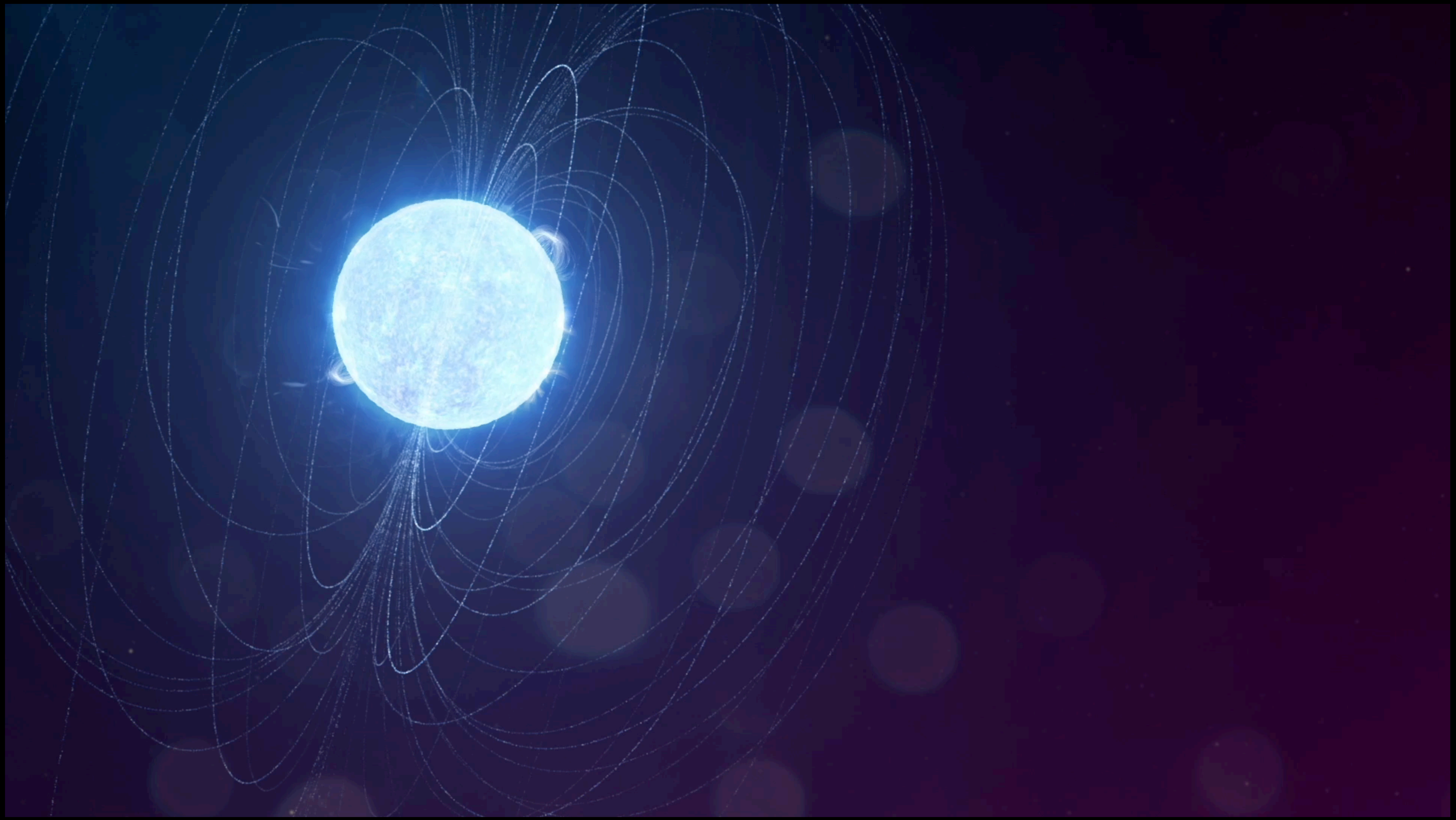
López-Coto et al. 2022

- HAWC detected two very extendd gamma-ray sources coincident with Geminga and PSR B0656+14 (Abeysekara et al. Science 2017)
  - Single PWL 8-40 TeV
  - Electrons (100 TeV): IC upscaterring CMB
    - Not a substantial contribution to the electron and positron spectra at the Earth by these two pulsars (assumption of a uniform (one-zone) diffusion coefficient to the Earth)
    - Still debated in the community (see Hooper et al. 2017)
- **TeV halo produced by electrons diffusing into the ISM**
  - halo: population of particles freem from their parent PWN
- 35 1LHAASO sources are found with one associated pulsar each and 2 1LHAASO sources (Cao et al. 2023)-> PSR J0218+4232 tMSP association?

Magnetars

- Extreme magnetic fields -> ~10^{14}-10^{15}G
- 10% SN explotions-> magnetars (Popov & Prokhorov 2006)
- **Slower rotation than pulsars**: 0.3-10 segundos
- ~ **30 known magnetars** in the Milky Way

STRONGEST MAGNETIC FIELDS IN THE UNIVERSE

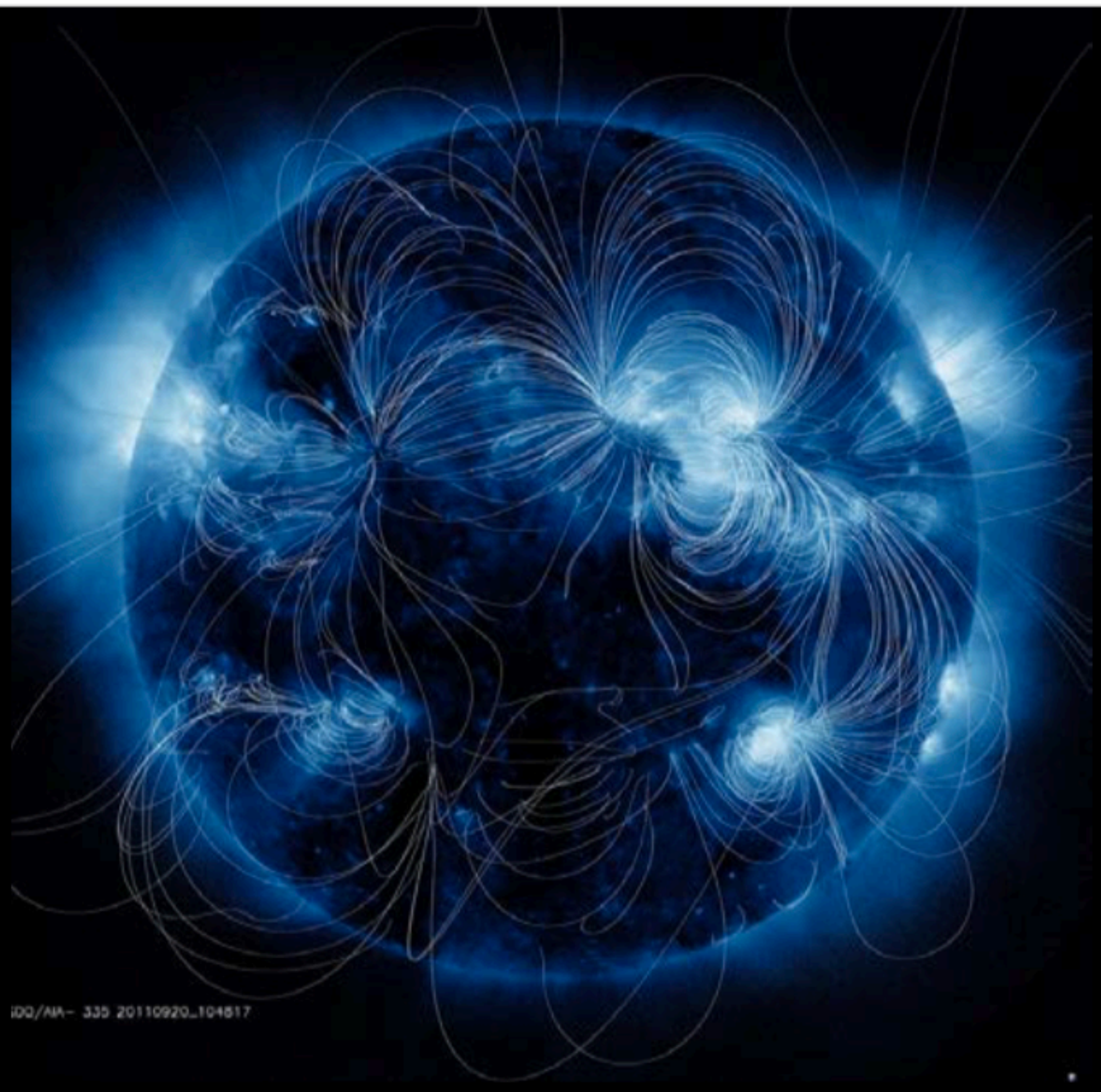


NASA

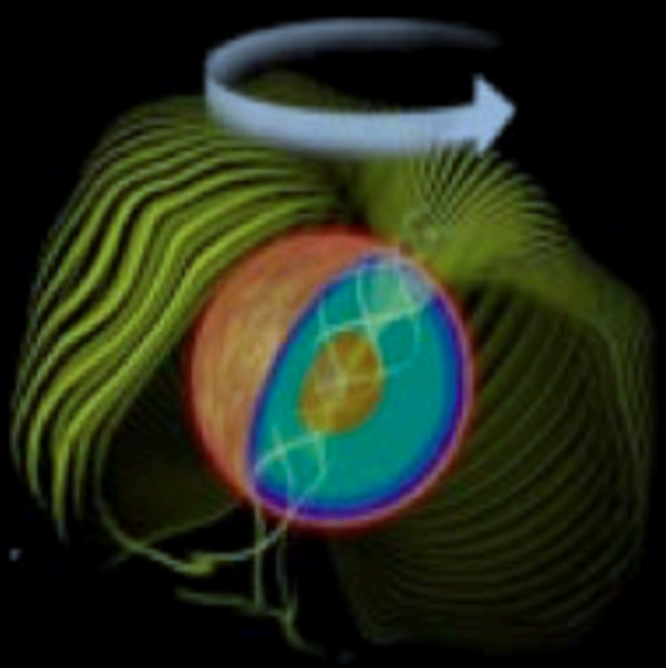
- **Magnetars have highly twisted and complex magnetic field morphologies, both inside and outside the star. The surface of young magnetars are so hot that they are bright in X-rays.**

- **Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.**

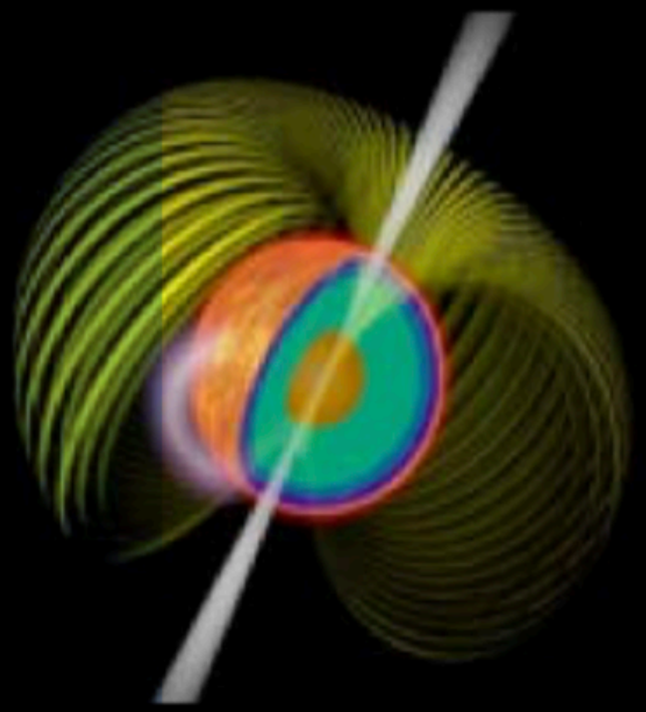
- **Twisted magnetic fields might locally (or globally) stress the crust (either from the inside or from the outside). Plastic motions and/or returning currents convert into crustal heating causing the outburst onset and evolution.**



Magnetars

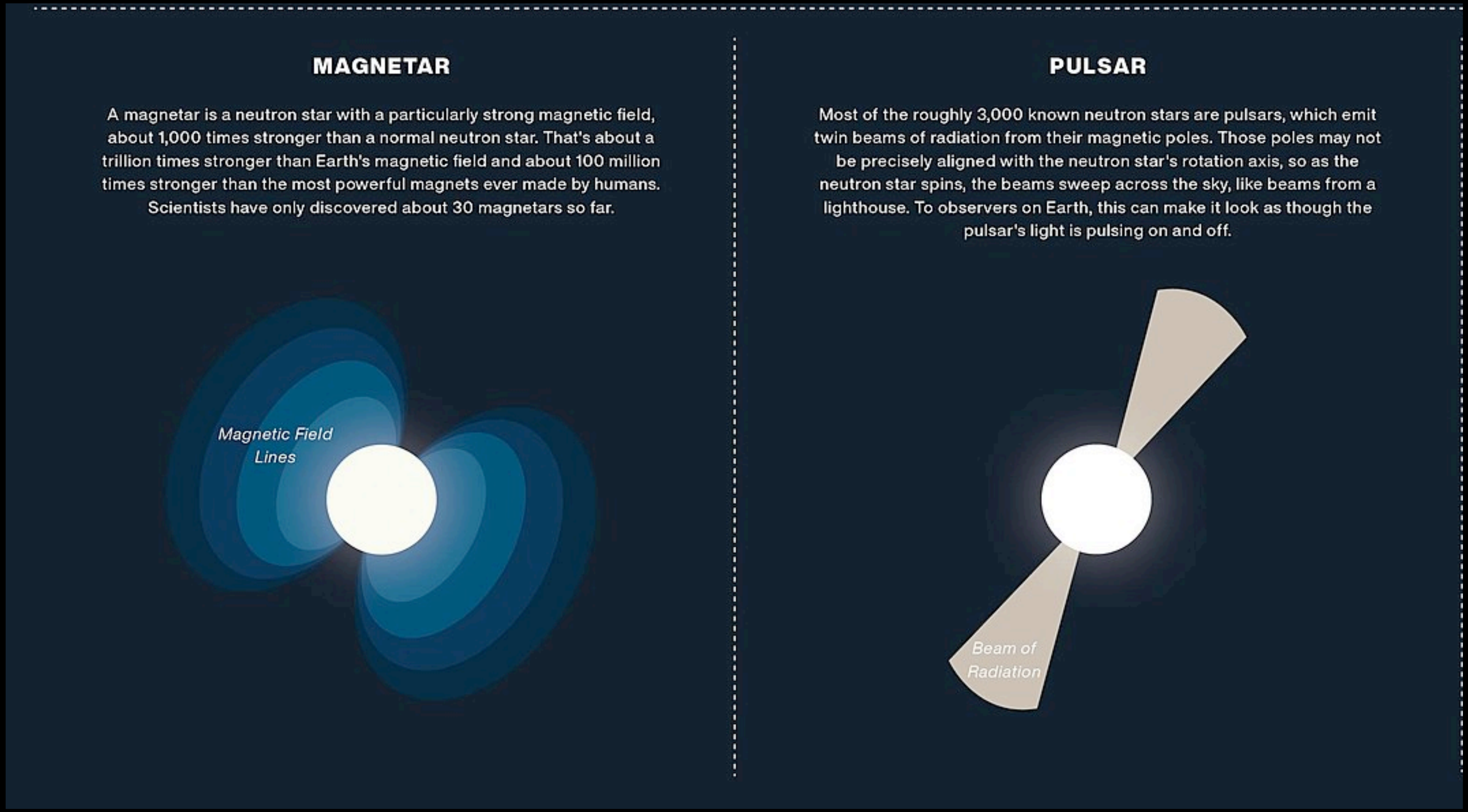


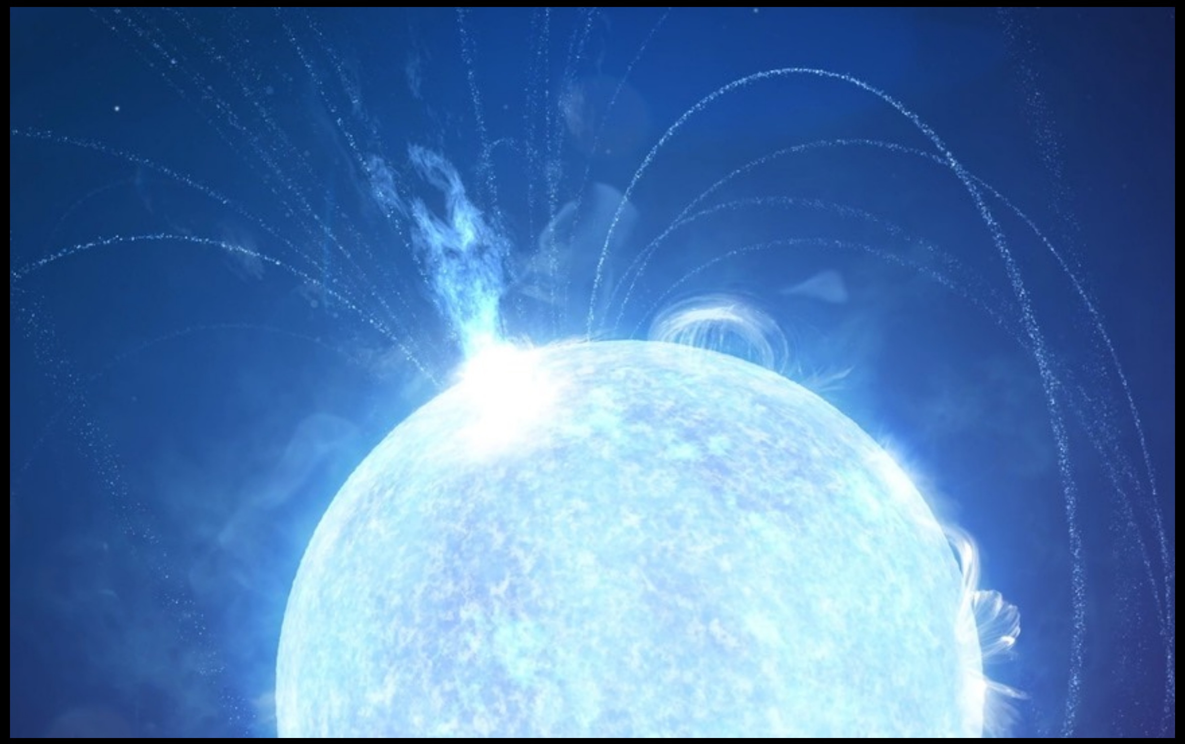
Normal Pulsars



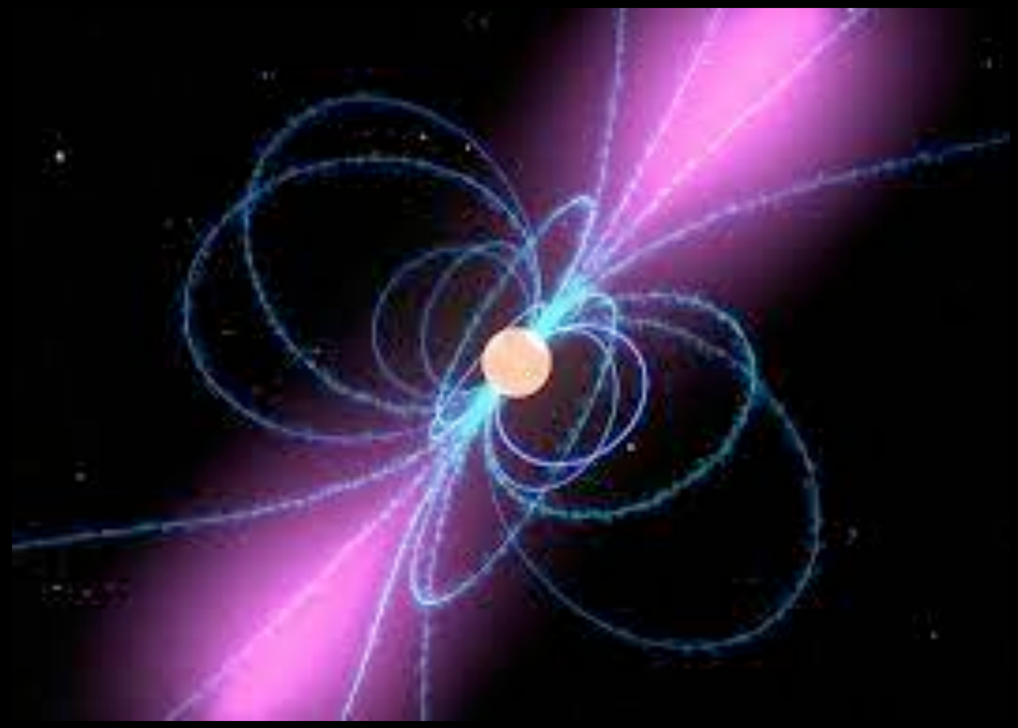
(Thompson & Duncan 1993; Thompson, Lyutikov & Kulkarni 2002; Fernandez & Thompson 2008; Nobili, Turolla & Zane 2008a,b)

slide from N. Rea





$\sim 10^{14}–10^{15}$G

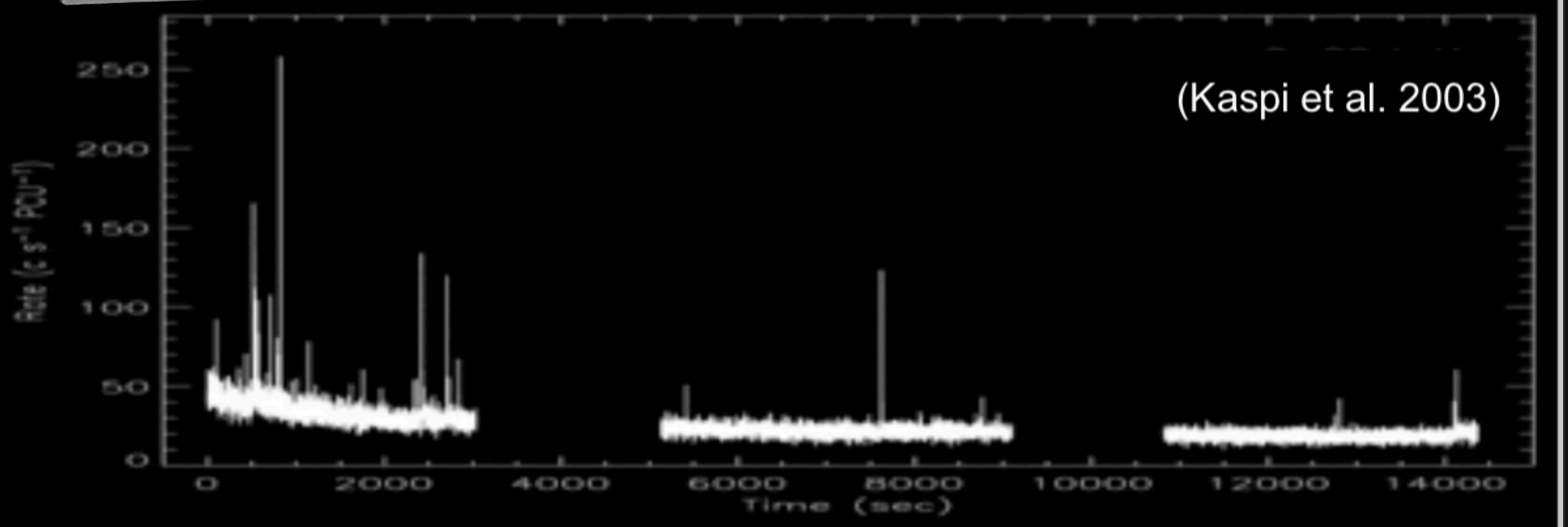


$\sim 10^{12}$ G

Types of bursts

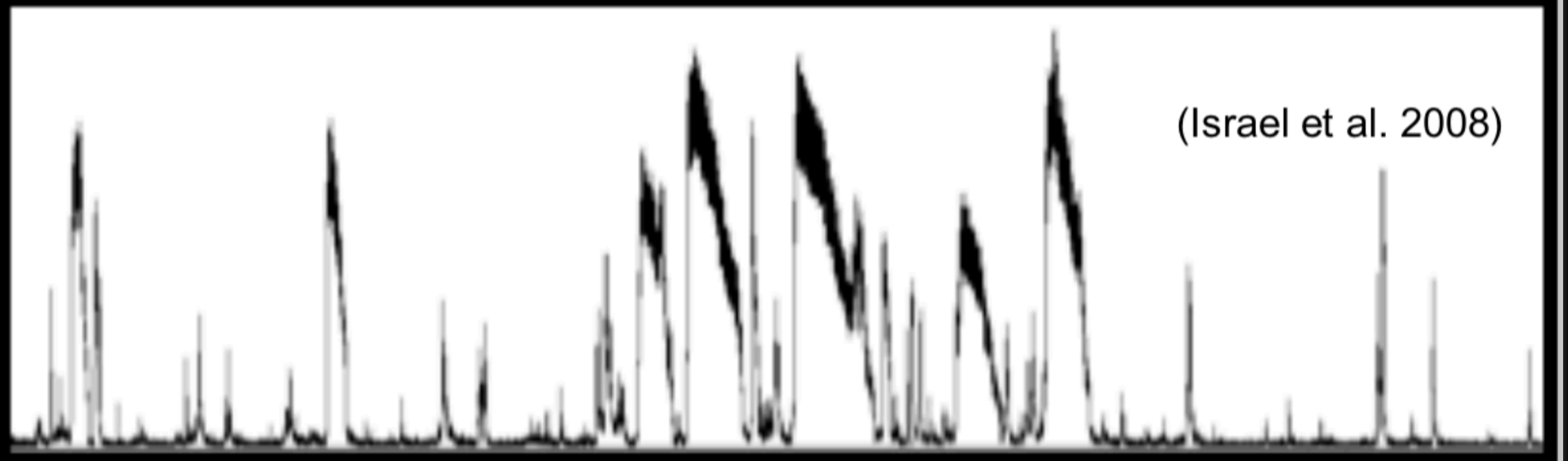
Short bursts

- the most common
- they last ~0.1s
- peak ~10^{41} ergs/s
- soft γ-rays thermal spectra



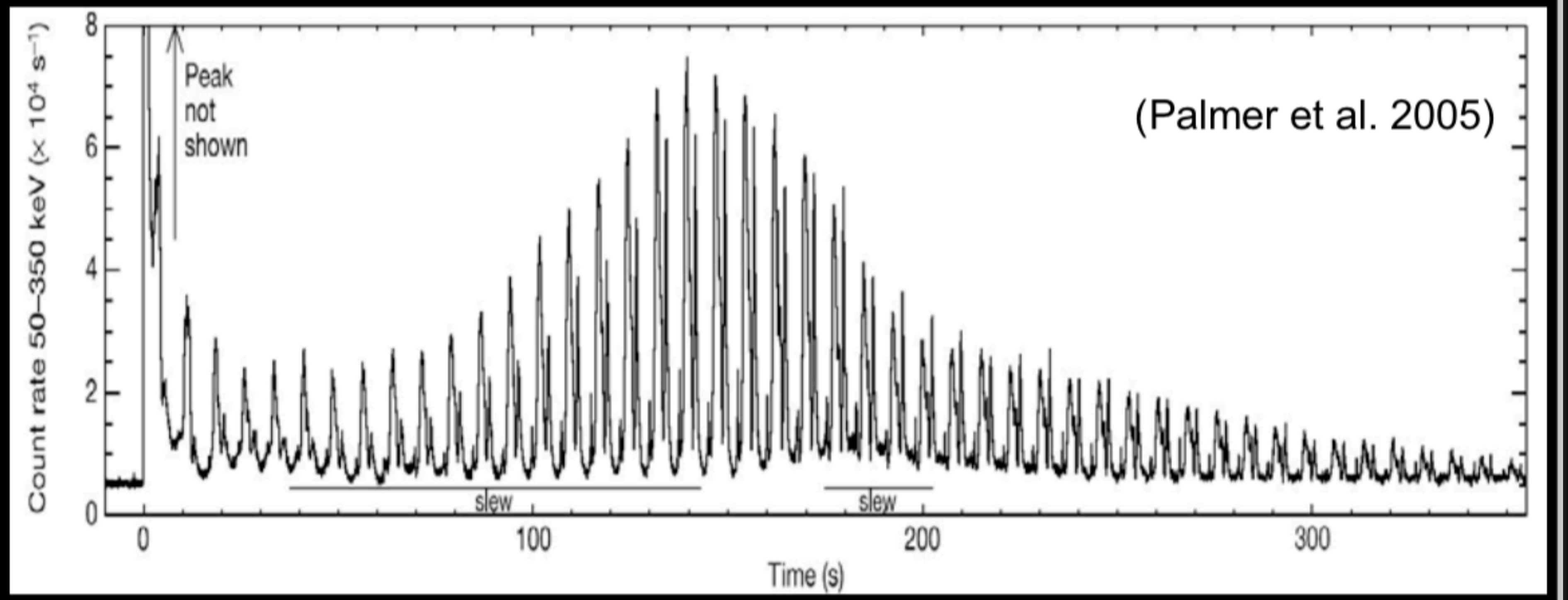
Intermediate bursts

- they last 1-40 s
- peak ~10^{41}-10^{43} ergs/s
- abrupt on-set
- usually soft γ-rays thermal spectra



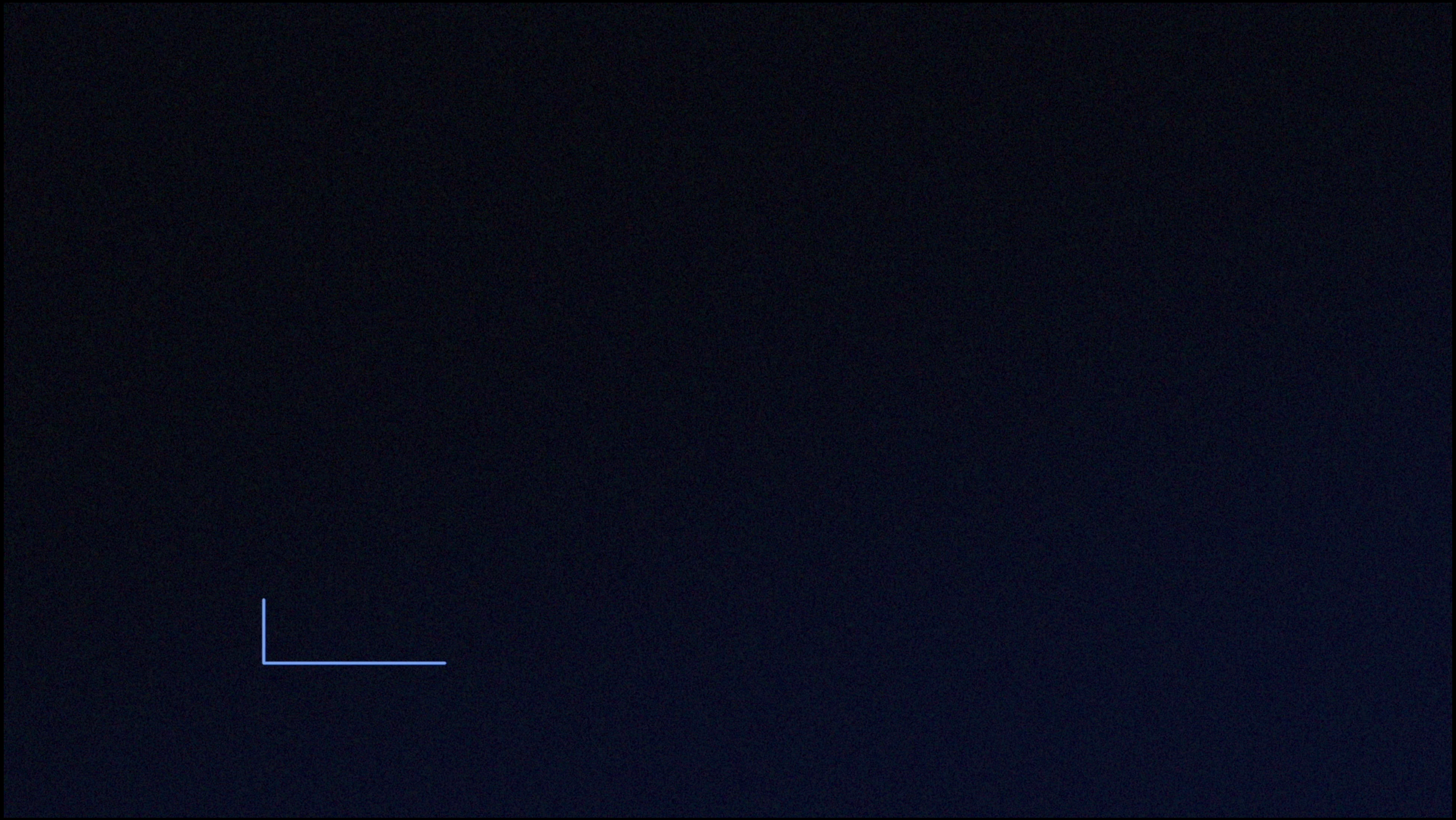
Giant Flares

- their output of high energy is exceeded only by blazars and GRBs
- peak energy > 3×10^{44} ergs/s
- <1 s initial peak with a hard spectrum which rapidly become softer in the burst tail that can last > 500s, showing the NS spin pulsations, and quasi periodic oscillations (QPOs)



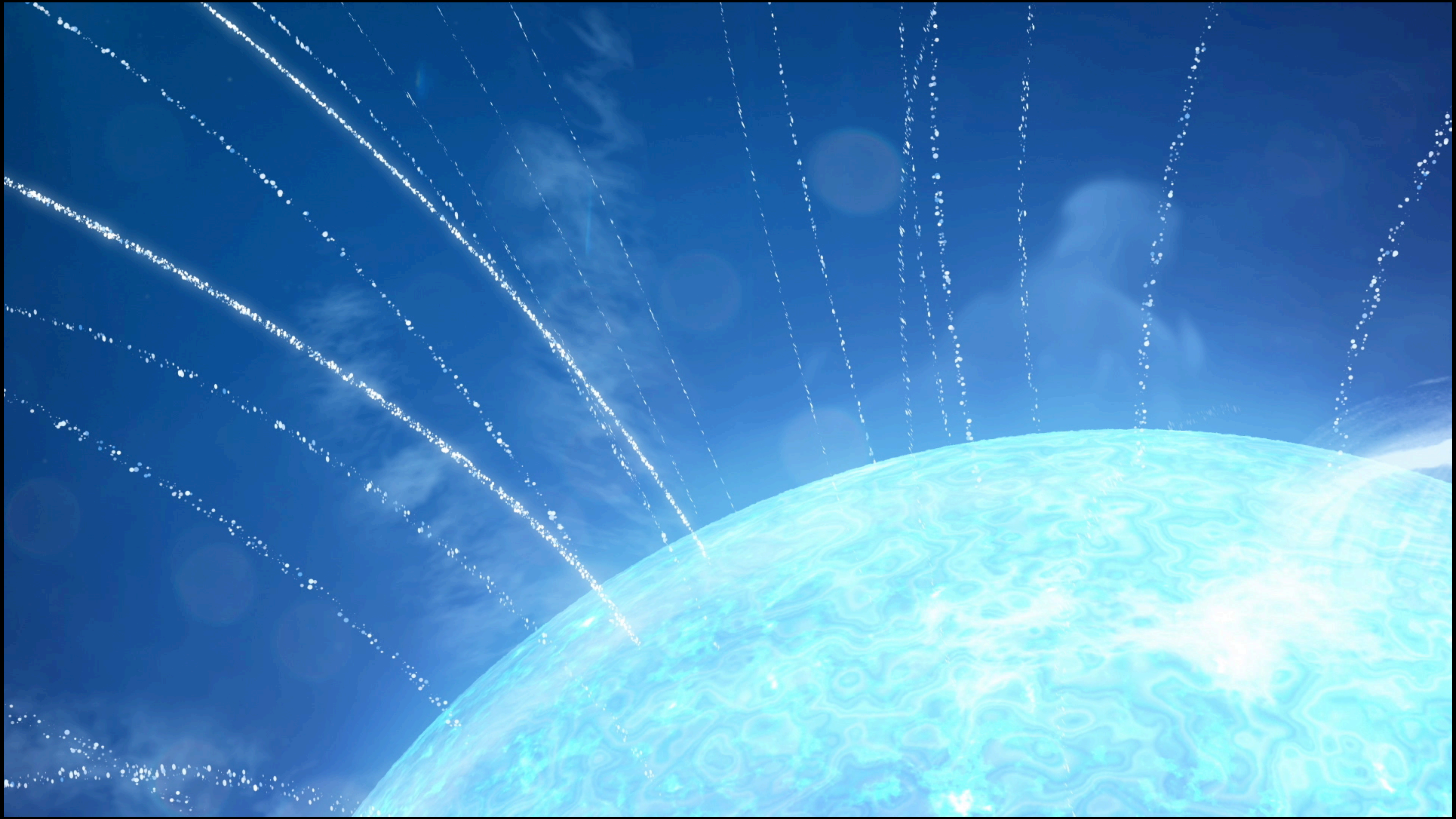
Slide from N. Rea

INTERMEDIATE FLARES



NASA/Fermi

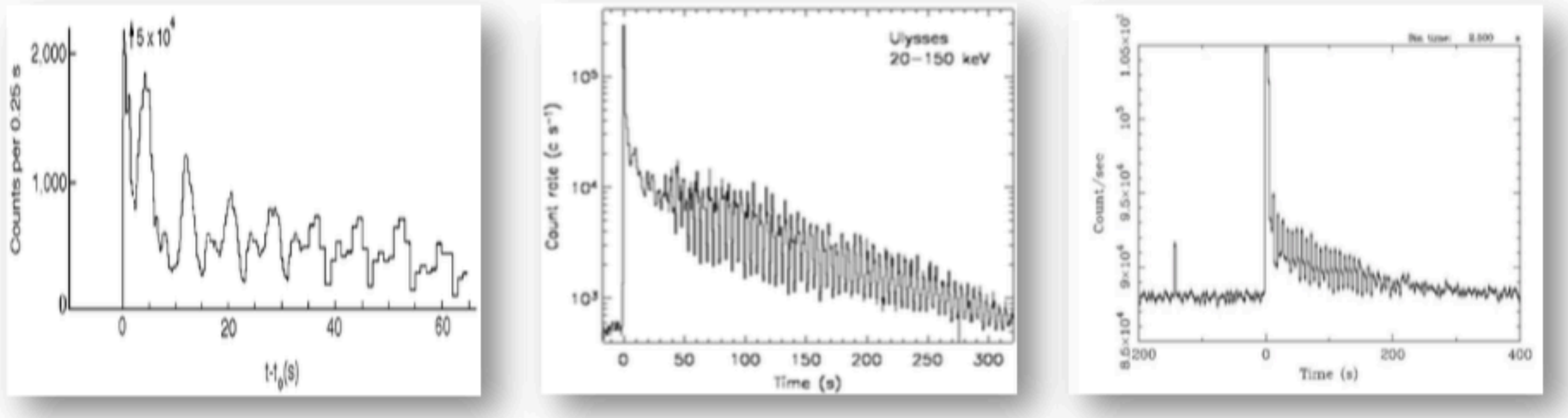
GIANT FLARES



Rare (1/decade) **short** (few min-1 h) **transient** events
Energy: ~ $10^{44} - 10^{47}$ erg s^{-1}

GIANT FLARES

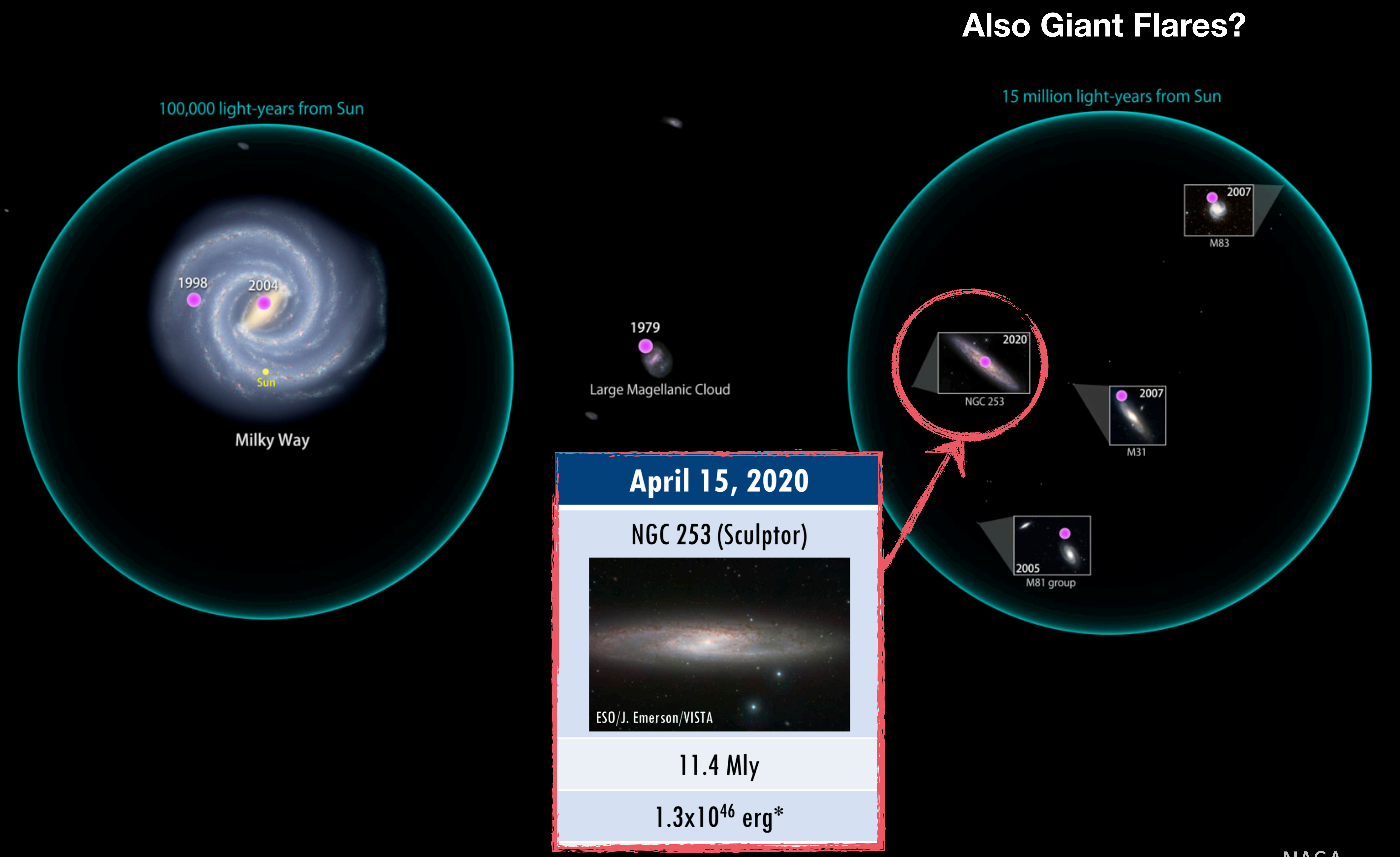
- **Most energetic explosions**(~ 10^{44} – 10^{47} erg s^{-1})
  - **3 detected in the last 40 years in the Galaxy**:
    - **Very luminous hard peak**, **lasting about a second** and with a luminosity of ~ 10^{47} erg s^{-1}
    - **Rapid decay into a softer tail lasting hundreds of seconds**
    - **Thermal afterglow** of <1h at hard x-rays



	1979 March 5 SGR 0626-66	1998 Aug 27 SGR 1900+14	2004 Dec 27 SGR 1806-20
Initial spike L_{peak} :	4 10^{44} erg/s	> 8 10^{44} erg/s	≈10^{47} erg/s
Tail energy:	4 10^{44} erg	10^{44} erg	10^{44} erg

Rare (1/decade) **short** (few min-1 h) **transient** events

GIANT FLARES



NASA

GIANT FLARES

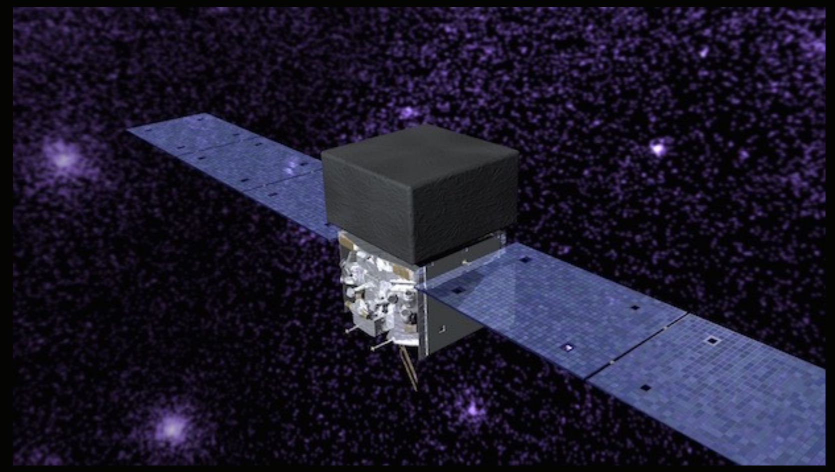
NASA

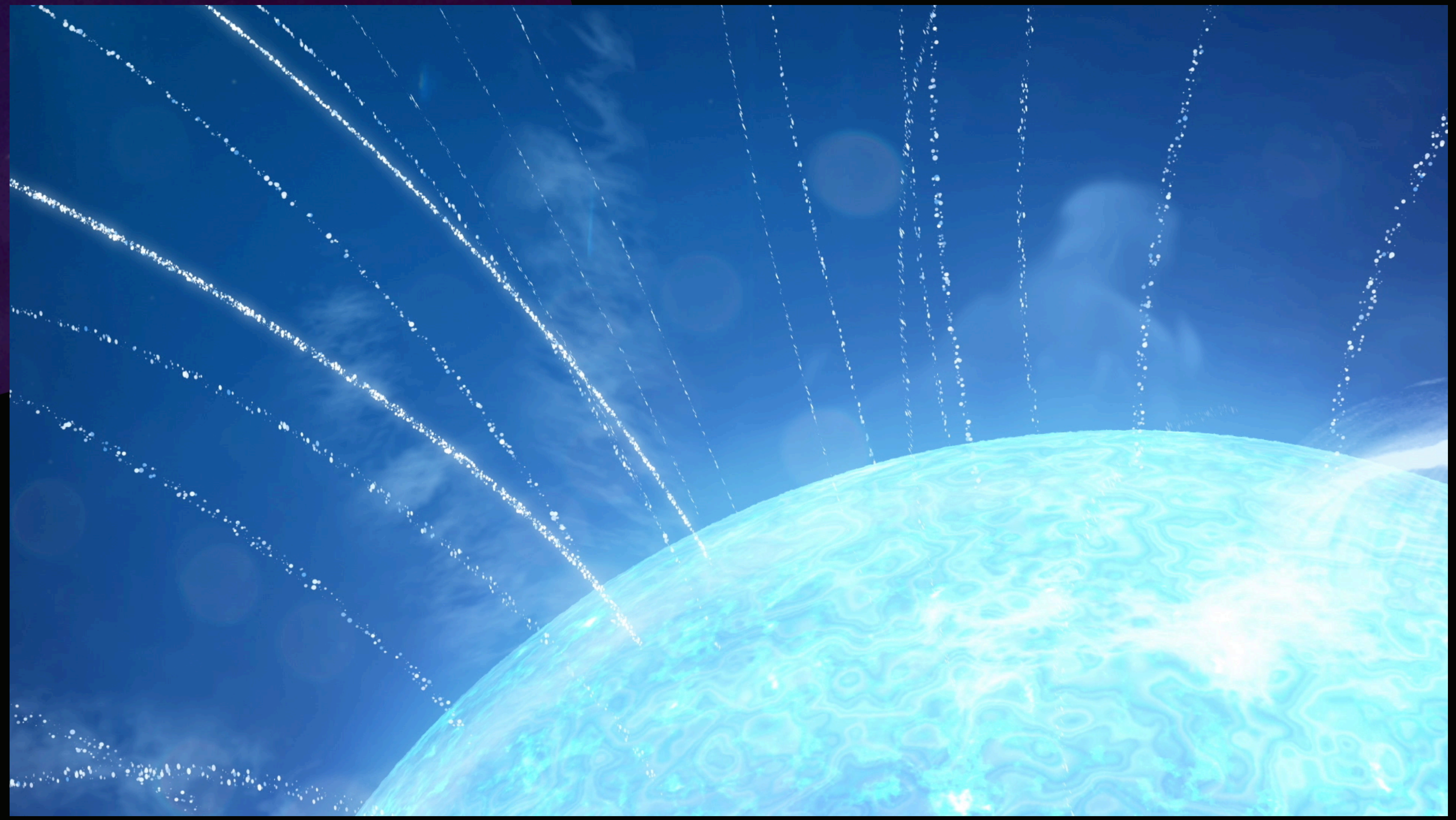
GIANT FLARE NGC253
15 abril 2020

- **Duration: 140 ms**
- Very rapid **flare risetime ~77 μs** (Fermi–GBM coll. 2021)

GIANT FLARE NGC253

Fermi-LAT: first GeV detection of a magnetar



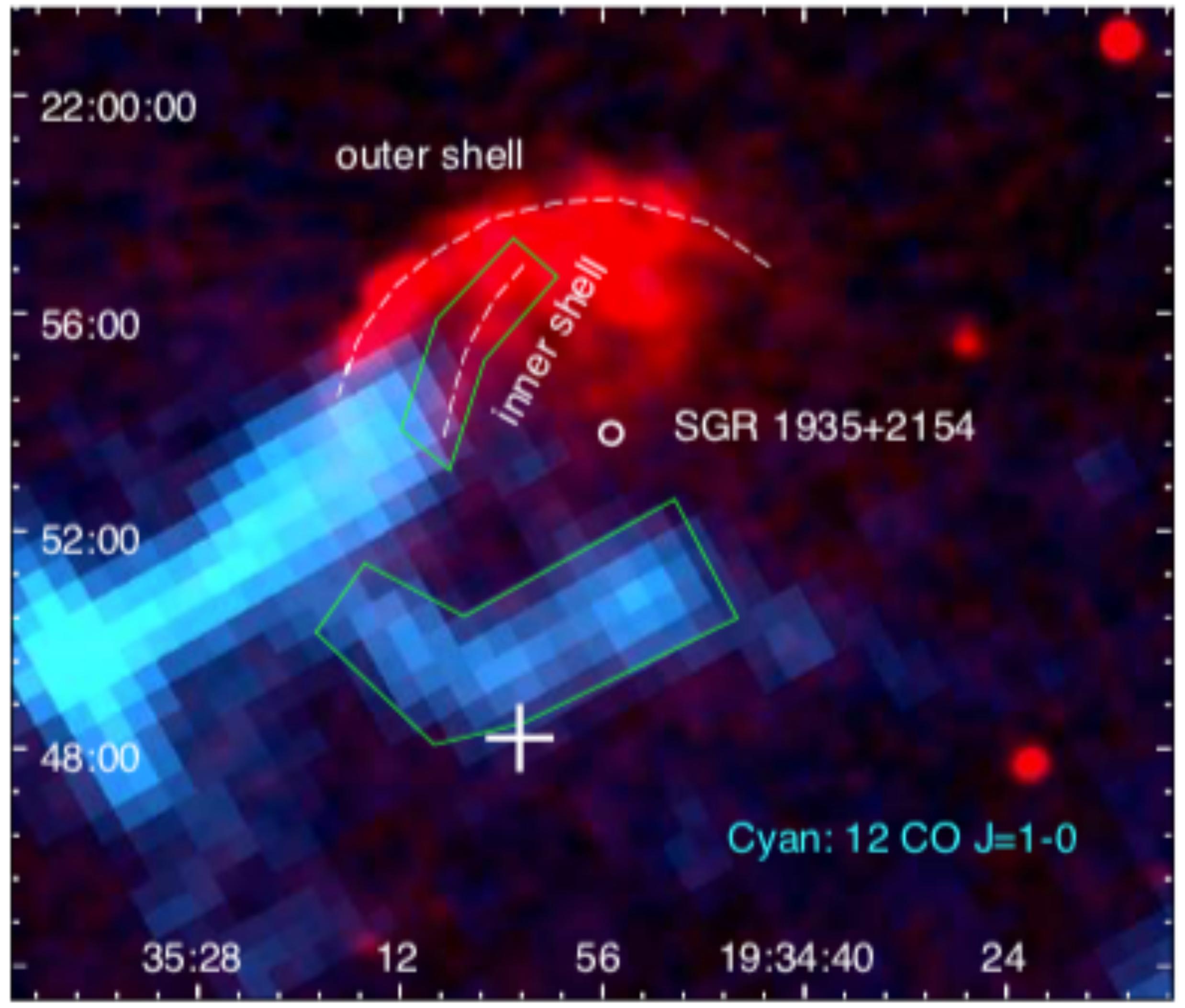


- **Only 3 HE photons:** 480 MeV, 1.3 GeV and 1.7 GeV (Fermi-LAT coll. 2021)
- GeV emission arises from dissipation associated with the collision between an ultra-relativistic outflow from the GF and an external shell of swept-up material

MAGIC as optical telescopes

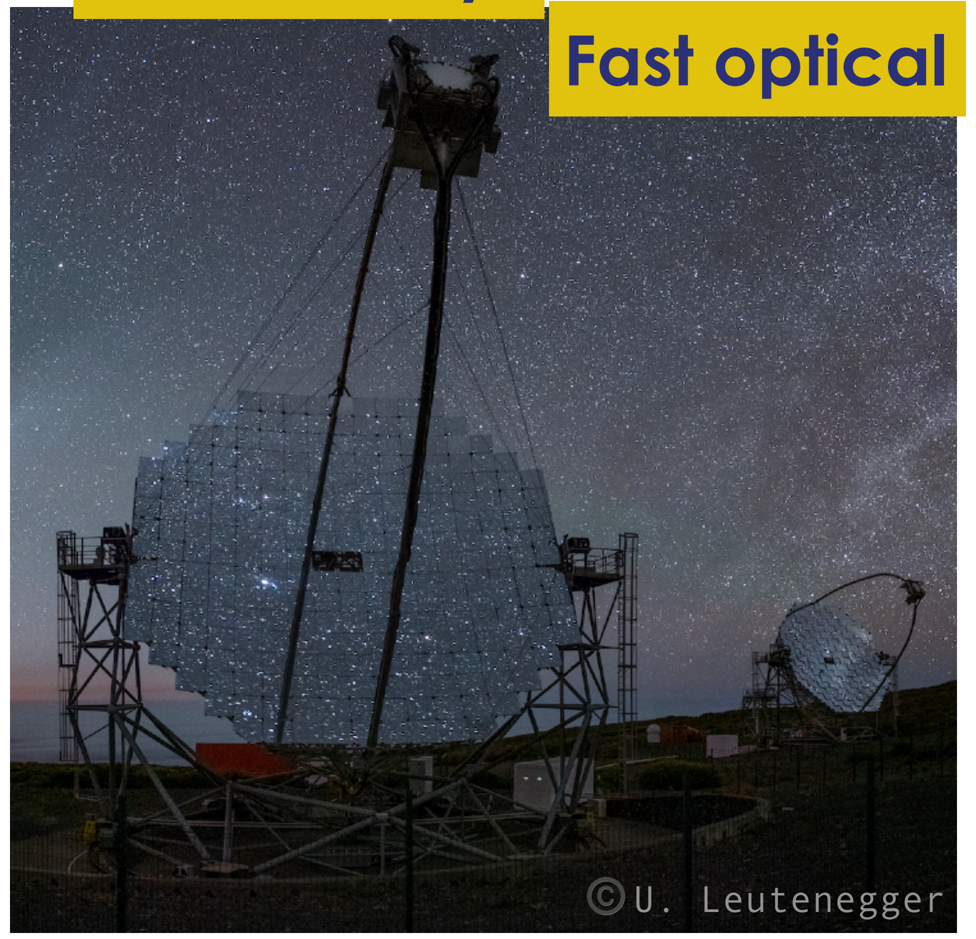
- **Magnetars can emit fast optical bursts (FOBs)** (Yang et al. 2019)
  - Spectral extension of the same radiation mechanism that generate FRBs
  - Inverse Compton upscattering
- The **MAGIC telescopes are able to operate simultaneously both as VHE and optical telescopes**
- The central pixel has been adapted to perform optical observations
  - Capable to detect **isolated 1-ms** optical flashes **as faint as ~ 8 mJy (13.4 mag)** with **maximum sensitivity at 350 nm** (Hassan et al. 2017)
- MAGIC central pixel is an optimal system to **search for short optical flares (FOBs)**

MWL collaboration: SGR 1935+2154

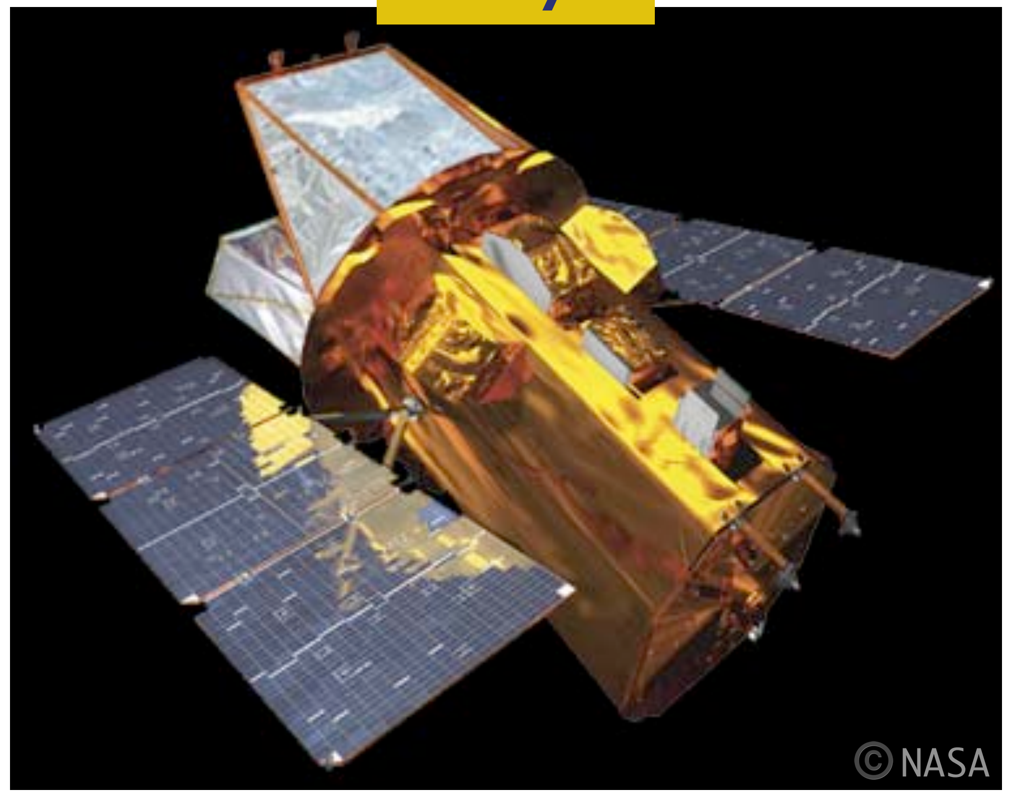


Gamma rays

Fast optical

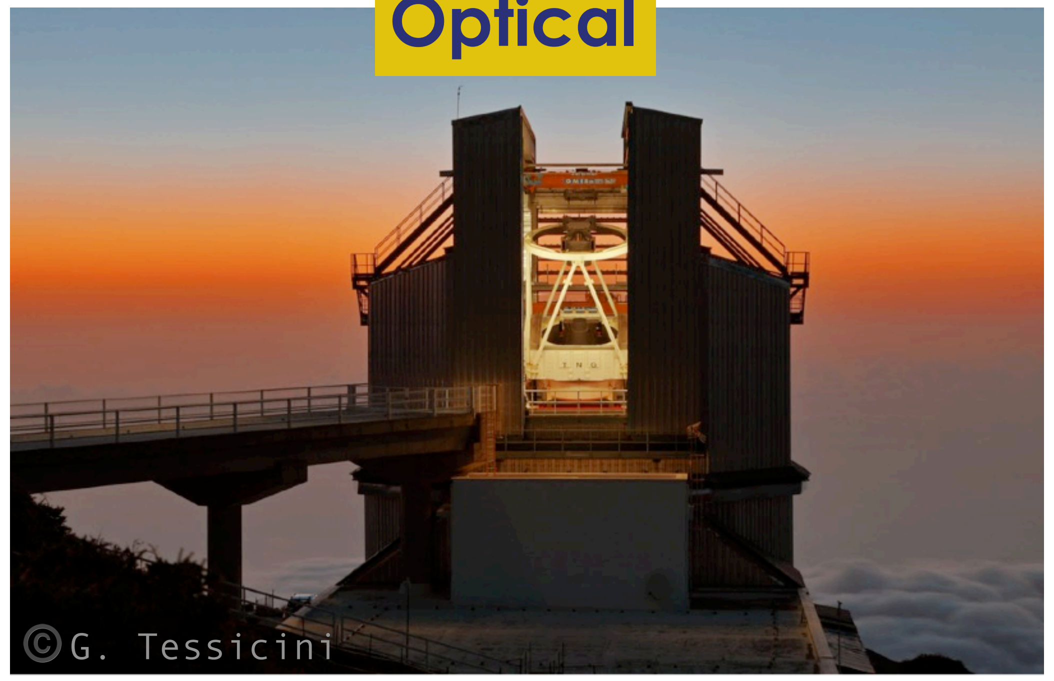


X-rays

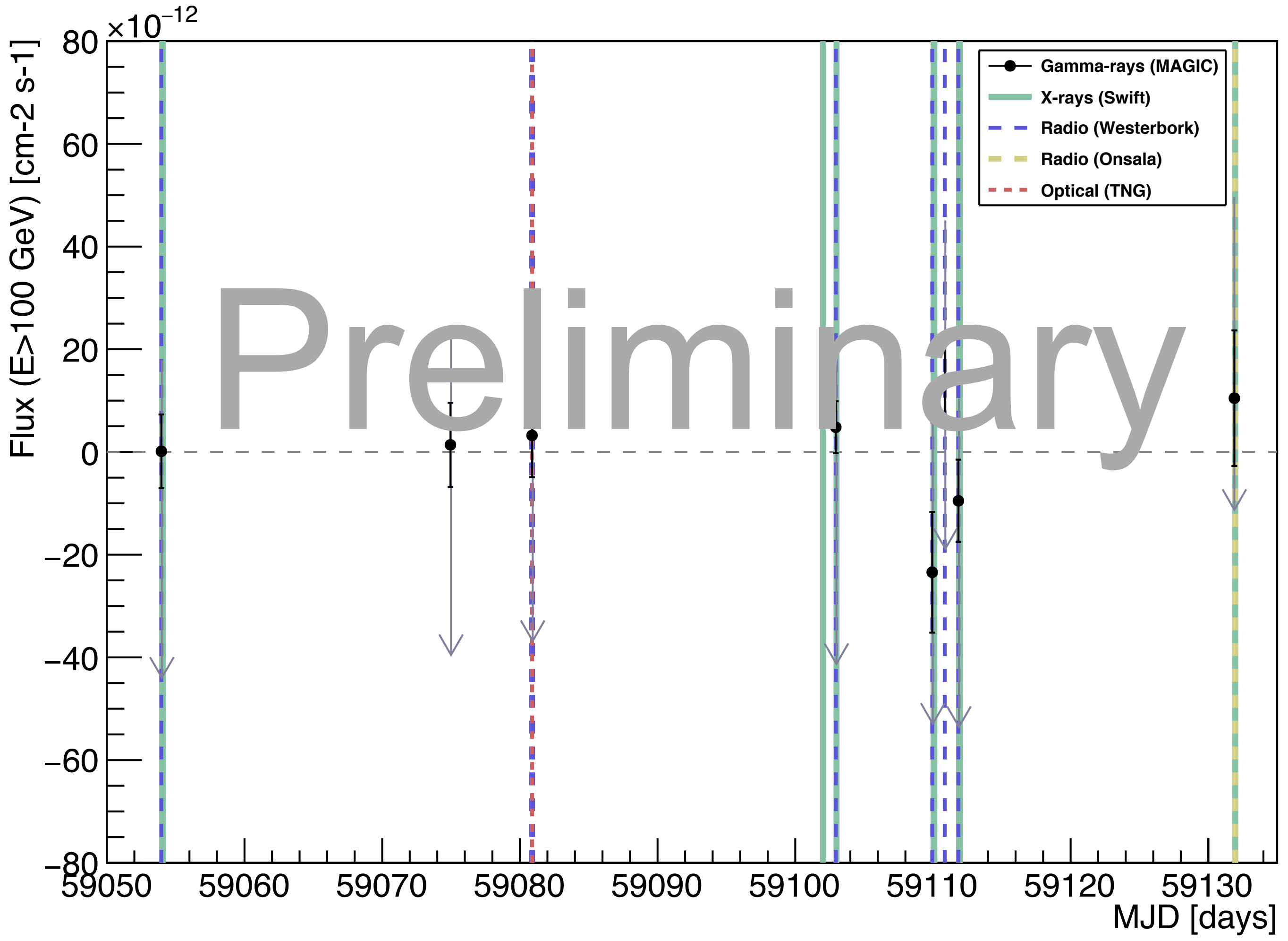


Radio

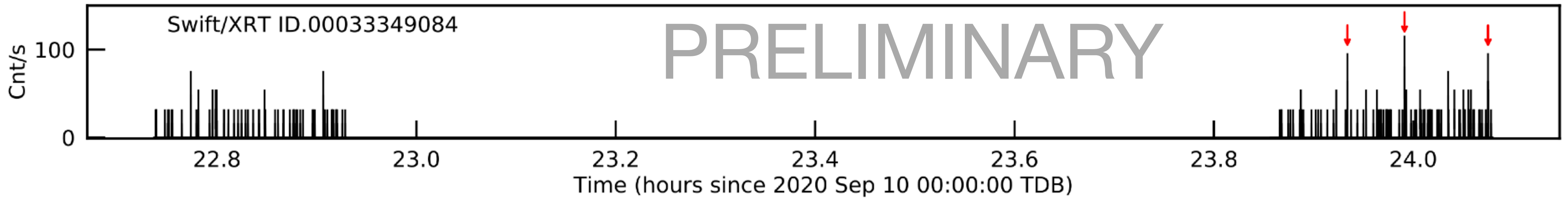
Optical



More info on SGR1935+2154 tomorrow! Stay tuned!



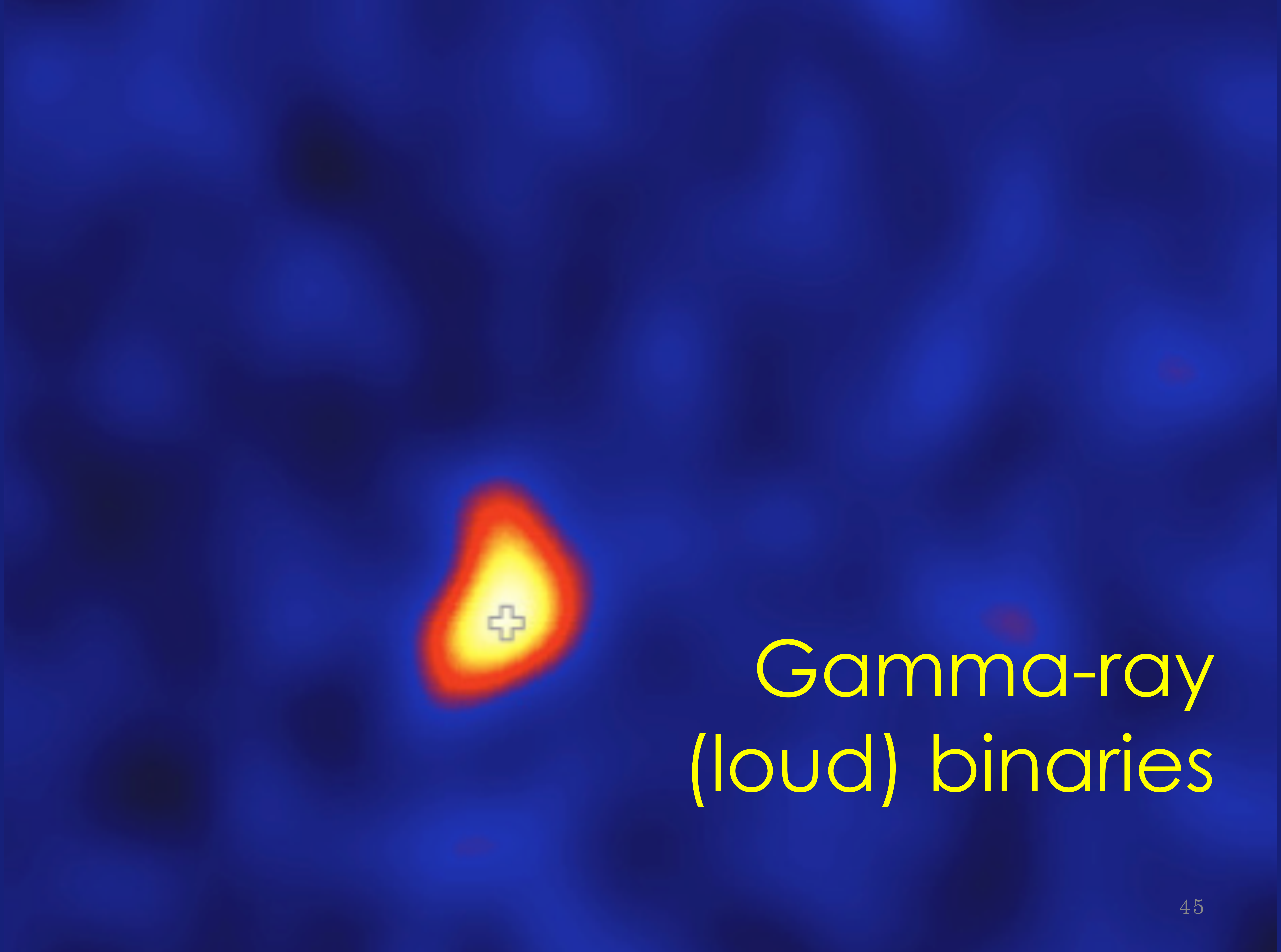
Example of bursts detected by **Swift/XRT**



López-Oramas et al. 2021

The hunt at VHE is still ongoing

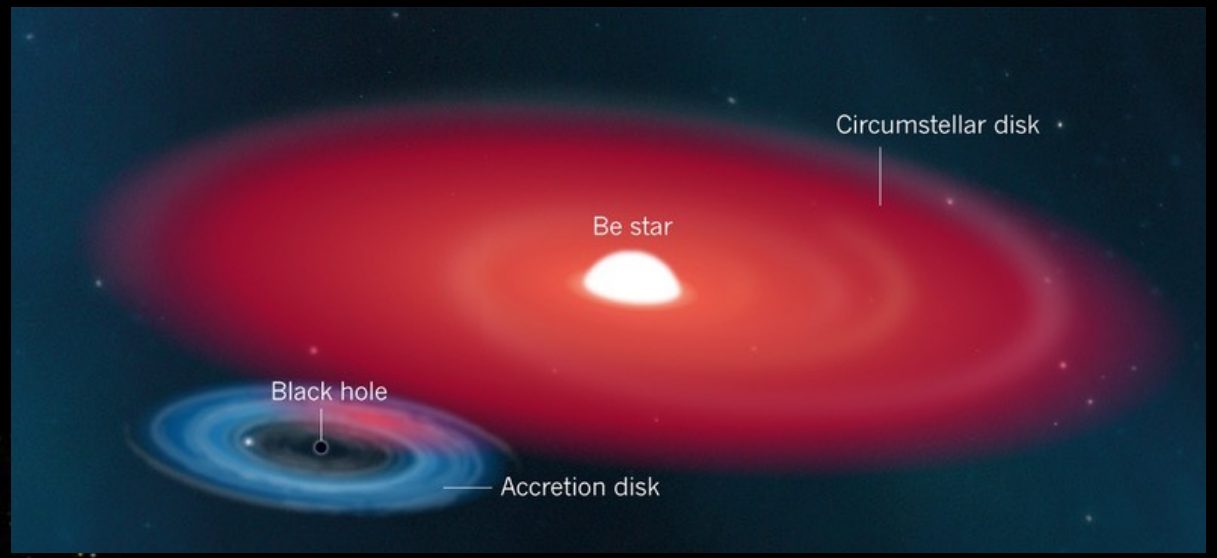
Gamma-ray (loud) binaries



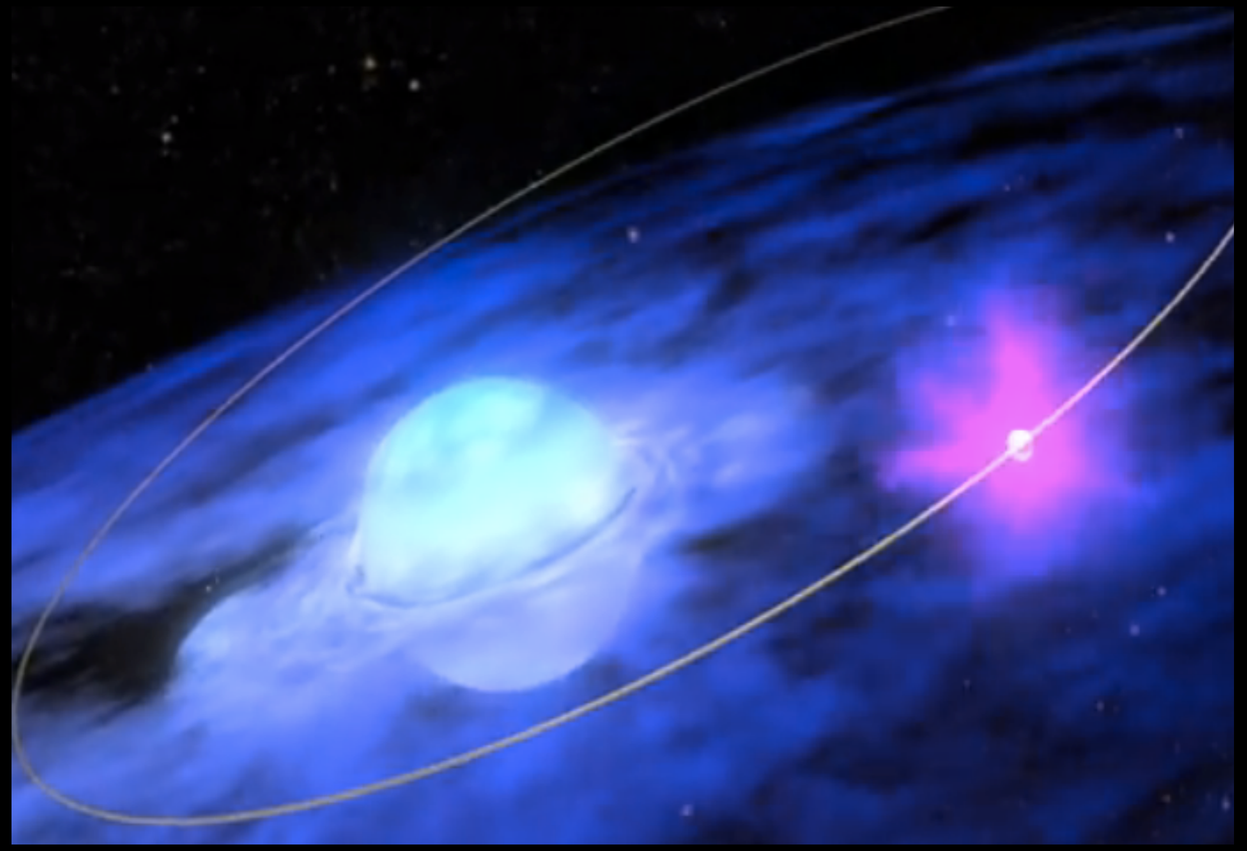
Massive microquasars

Microquasars

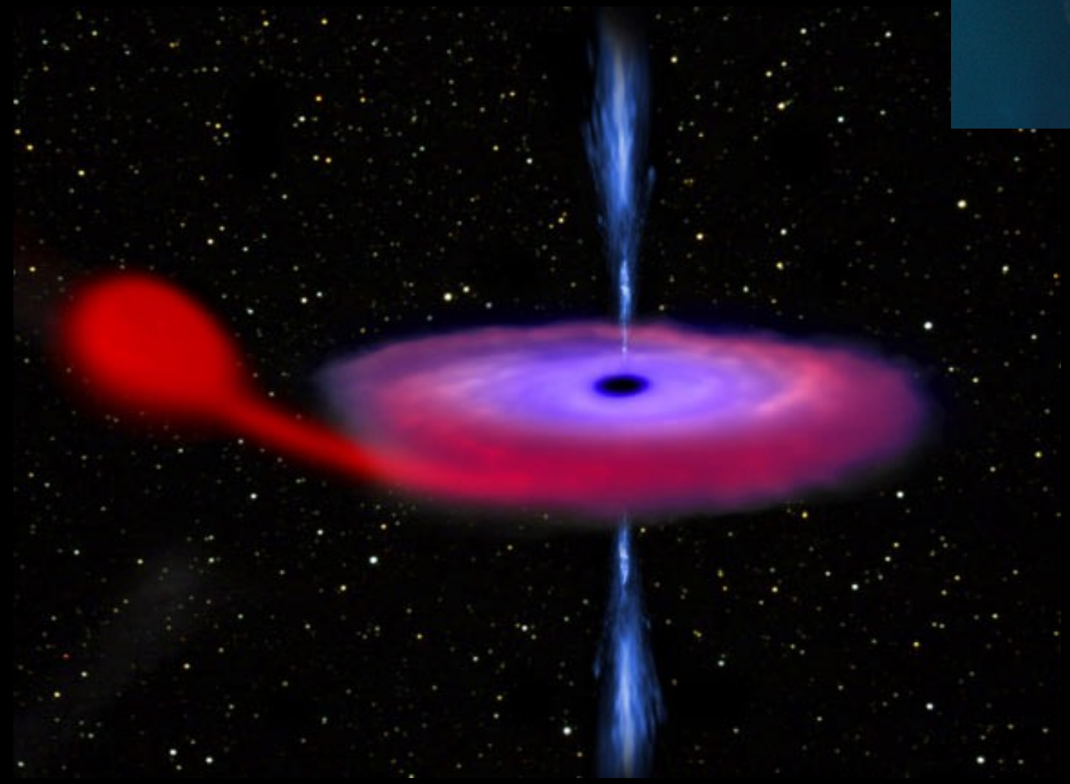
Be+BH



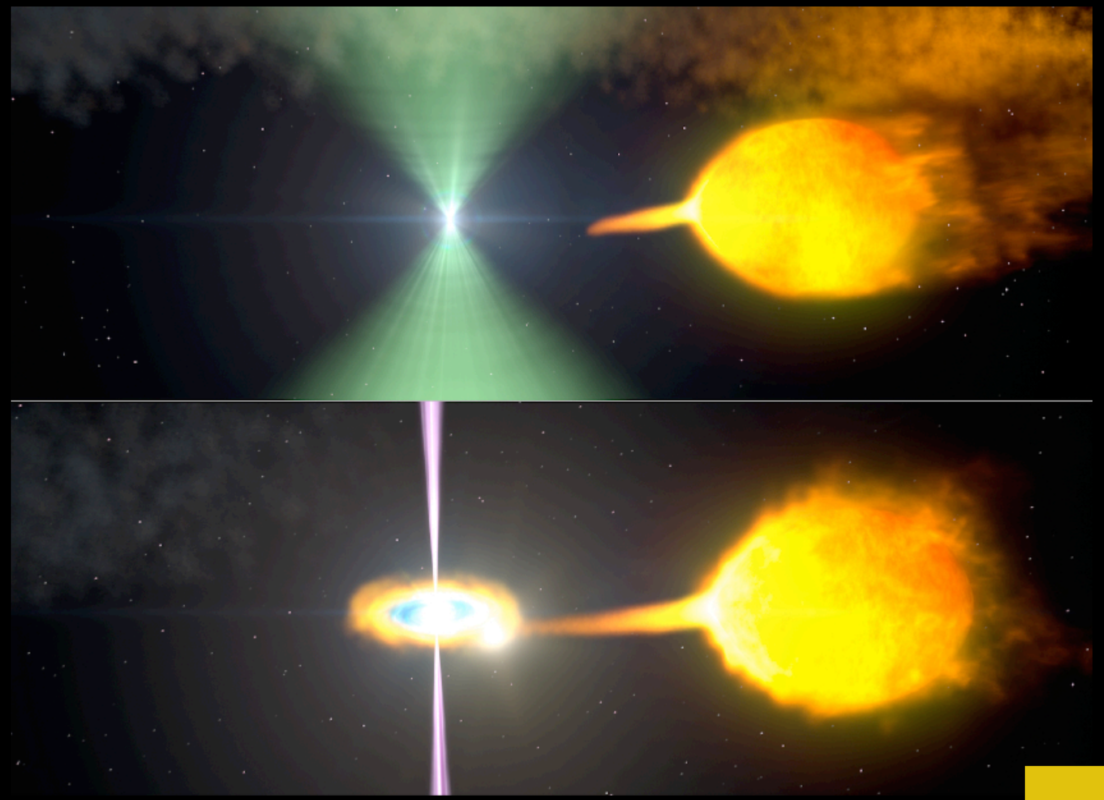
HMXBs (Pulsar-wind)



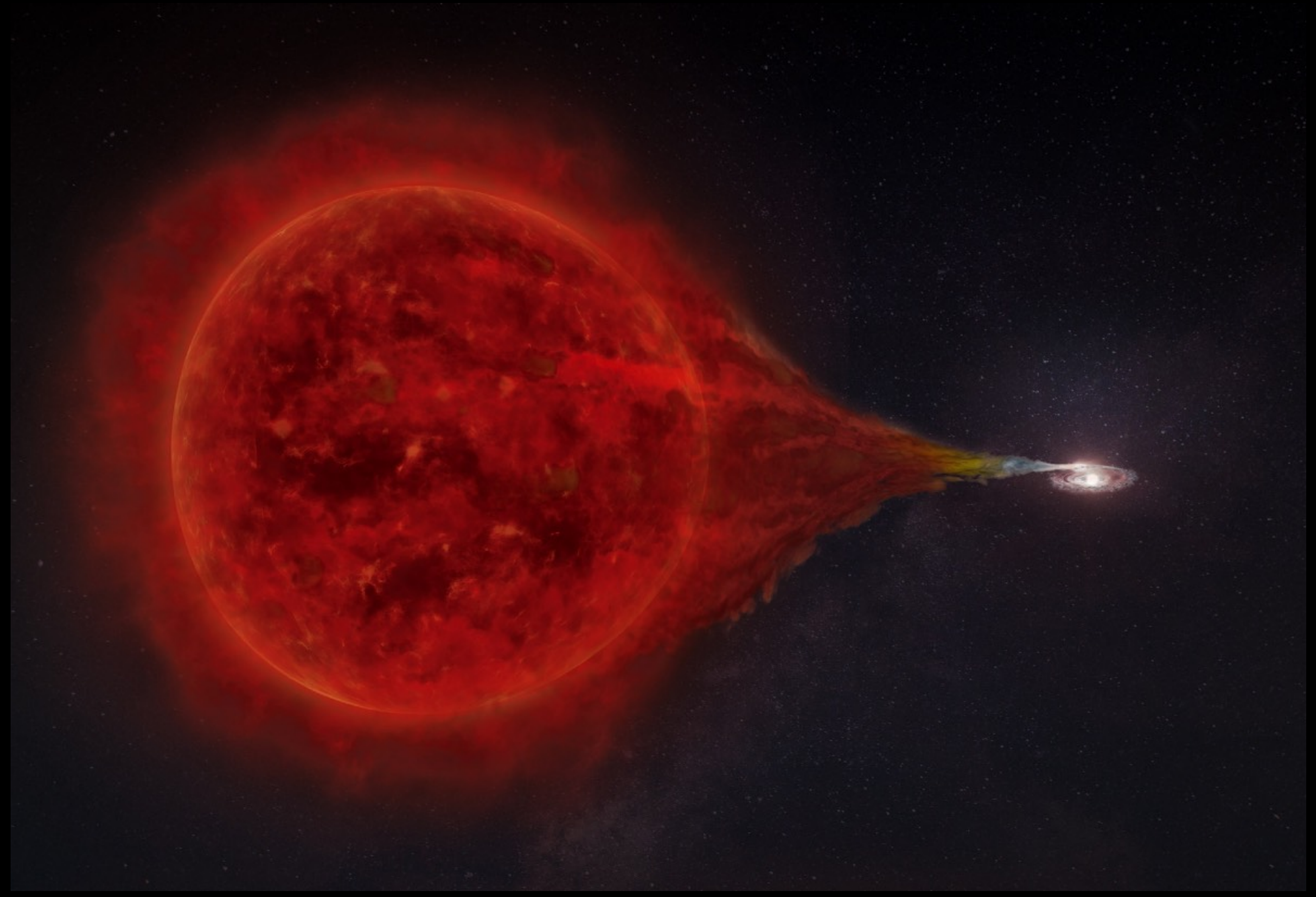
LMXBs



tMSPs

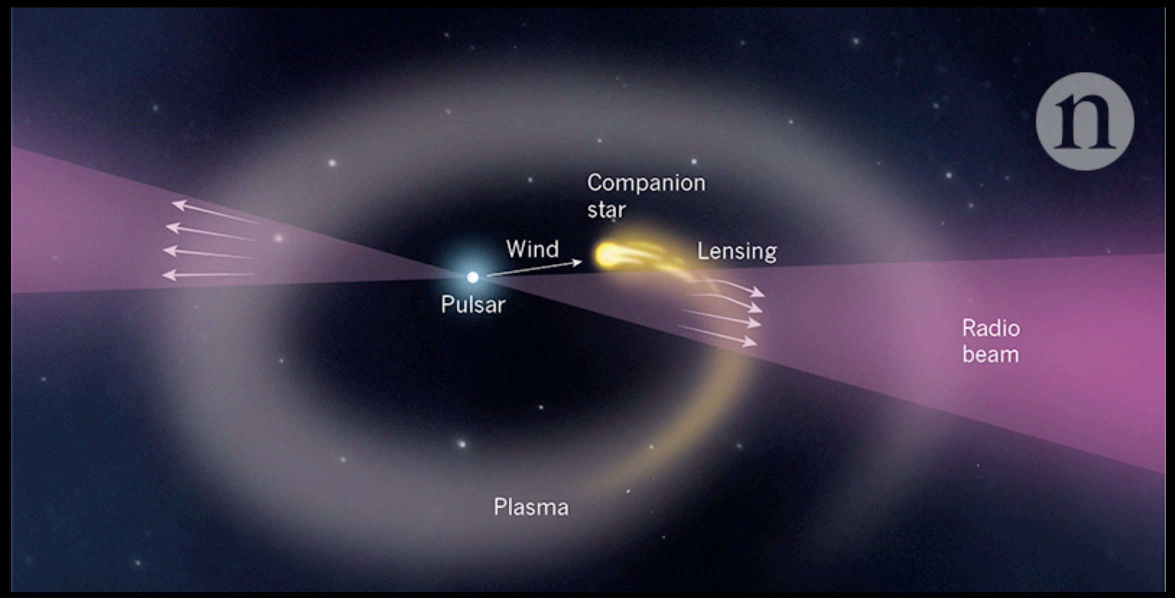


Novae

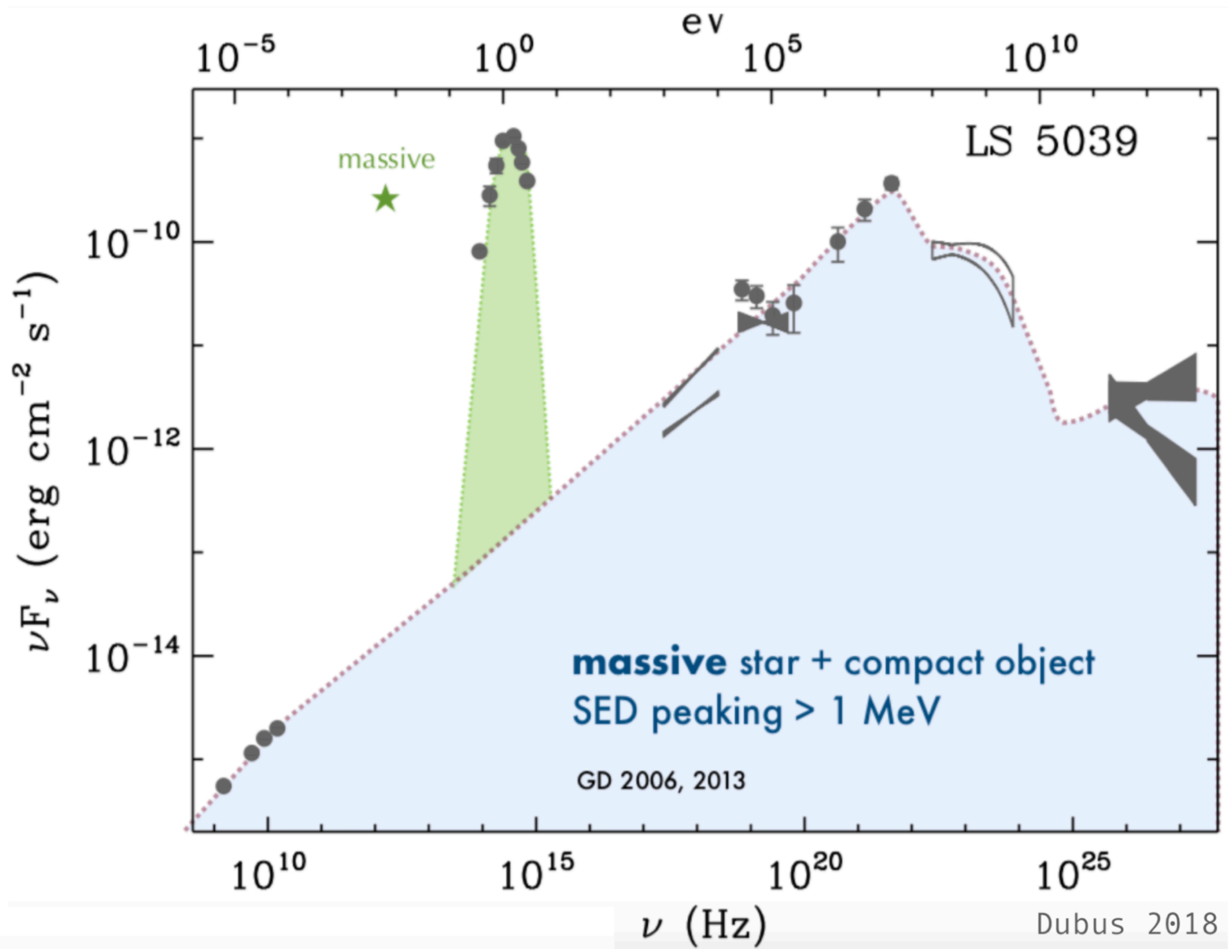


Colliding wind binary

Black widow



Gamma-ray binaries



- Compact binary: Star + compact object (NS/BH)
- **Bulk of the non-thermal emission in the γ-ray domain (E>1MeV)**
- **Only 7 known systems** (out of ~300 X-ray binaries)

Questions to answer:
Nature of compact object
Emission mechanisms?
Low-mass companion?
Why so few?

Common characteristics:

Massive companion star
Similar spectra & γ-ray emission variability
Non-thermal radio emission
Moderate X-ray emission

Situation in 2014

Known gamma-ray binaries

System	Star spectral type	Compact object	Star mass [$M_\odot$]	D [kpc]	Porb [days]	e	i	HE emission	VHE emission
PSR B1259-53	Be	48ms pulsar	31	2.3	1236.72	0.87	19-31	~P	P
LS 5039	O	-	23	2.5	3.91	0.35	13-64	~P	INFC
LS I +61 303	Be	-	12	2.0	26.49	0.54	10-60	~P	A
HESS J0632+057	Be	-	16	1.5	315.50	0.83	47-80	yes	A
FGL J1018.6-5856	O	-	31	5.4	16.58	-	-	yes	yes

Gamma-loud binaries: state-of-the-art

System	Star spectral type	Compact object	Porb [days]	HE emission	VHE emission
PSR B1259-53	Be	48ms pulsar	1236.72	yes	yes
LS 5039	O	magnetar? (Yoneda 2019)	3.91	yes	yes
LS I +61 303	Be	pulsar (magnetar?)	26.49	yes	yes
HESS J0632+057	Be	-	315.50	yes	yes
FGL J1018.6-5856	O	-	16.58	yes	yes
LMC P-3	O	-	10.2	yes	yes
PSR J2032+4127	Be	143 ms pulsar	50 years	yes	yes
Cygnus X-1	O	BH		yes	no (4σ hint once)
Cygnus X-3	WR	BH?		yes	no
SS 433	A	BH		yes	yes
4FGL J1405.1-6119	O	?		yes	no
V4641 Sgr	B9III	BH	2.8	no	yes? (HAWC)
eta Carinae	LBV	O/B star	5.5 years	yes	yes
RS Ophiuchi	red giant	white dwarf	454	yes	yes

microquasars (Cygnus X-1, Cygnus X-3, SS 433, 4FGL J1405.1-6119)

microblazar (V4641 Sgr)

colliding wind (eta Carinae)

nova (RS Ophiuchi)

Gamma-ray binaries

HE emitters

Gamma-ray Binaries : Scenarios

Pulsar-wind

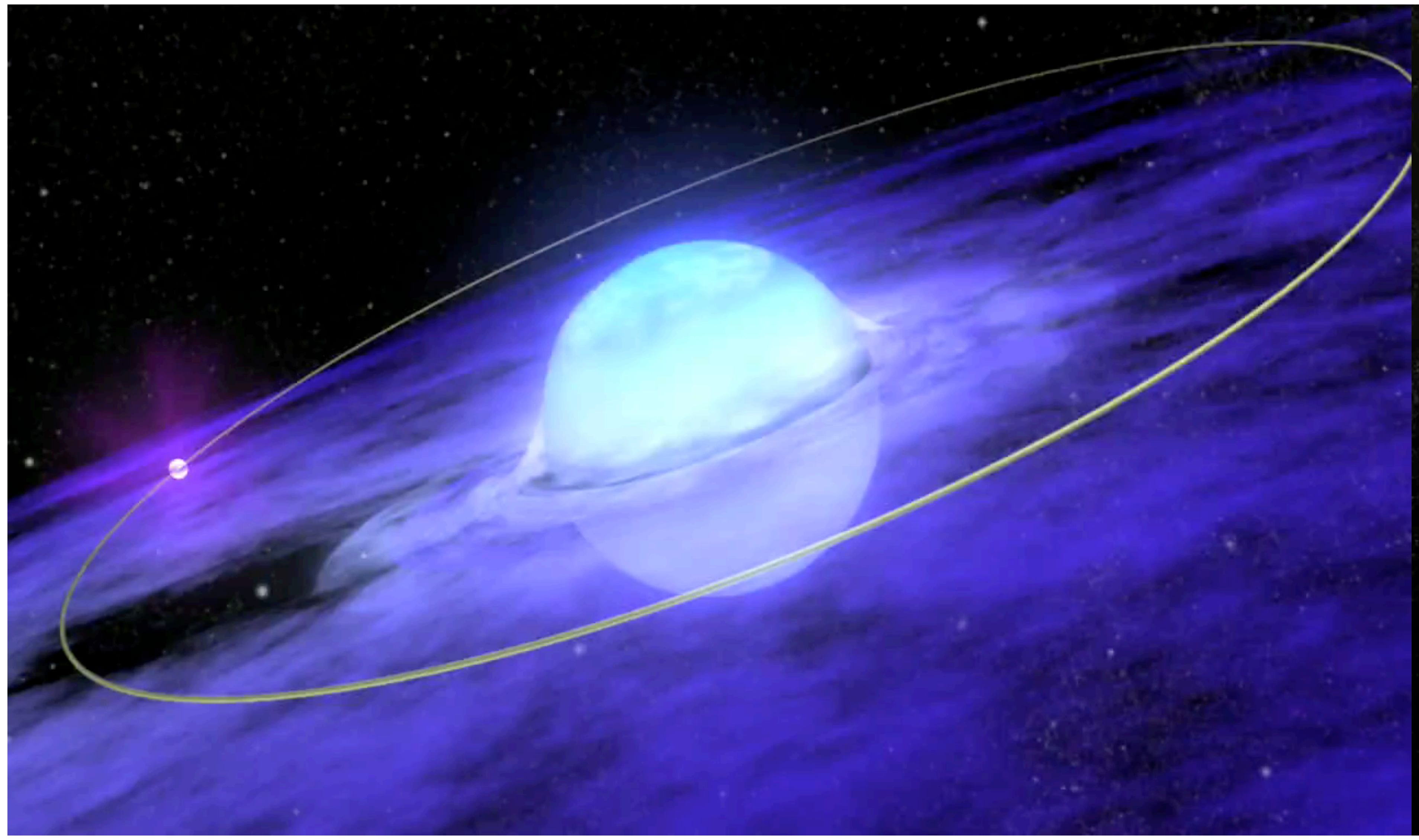
- Rotation-powered highly magnetized pulsar
- Pulsar wind+stellar wind
- IC: UV photons to gamma

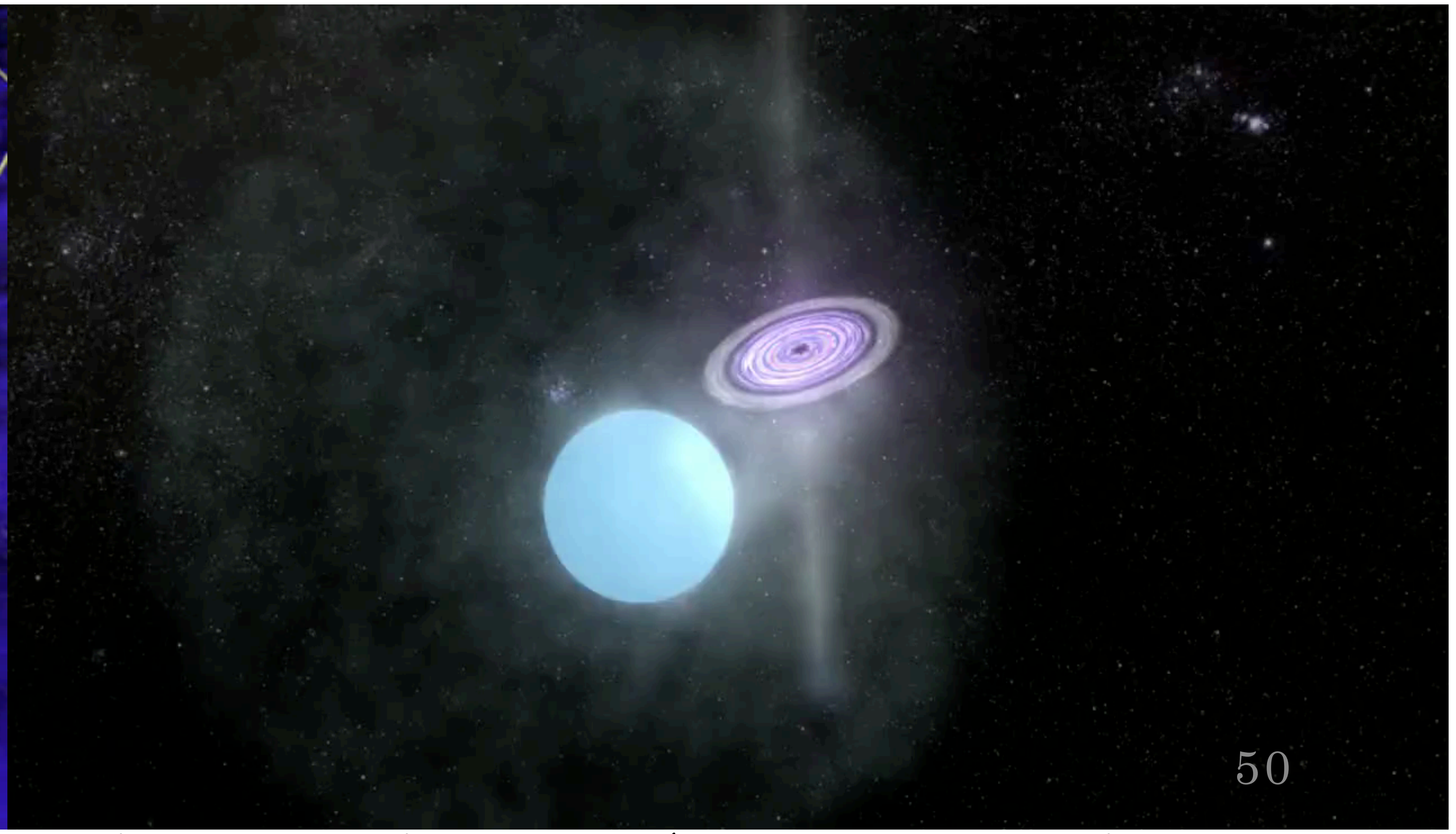
Microquasar

- Accretion onto compact object
- Ejection of plasma in jets
- IC or hadronic

NO PULSATIONS

NO JETS

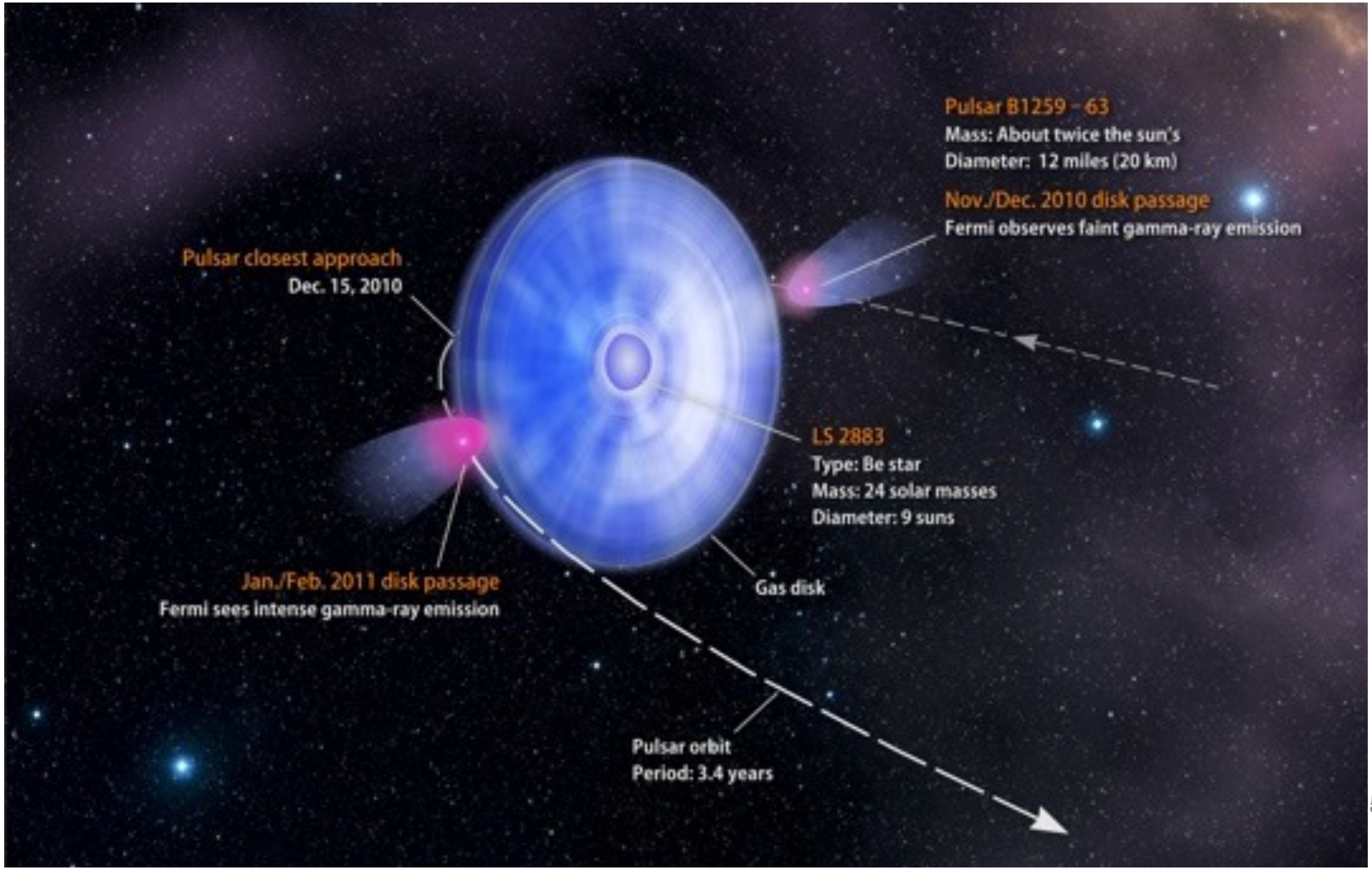




Credit: Walt Feimer, NASA/Goddard Space Flight Center

Gamma-ray binaries: discovery

- 2005: discovery of VHE from **PSR B1259-63** by HESS
- 3-year orbit
- Emission during periastron passage



PSR J2032+4127/MT91 213

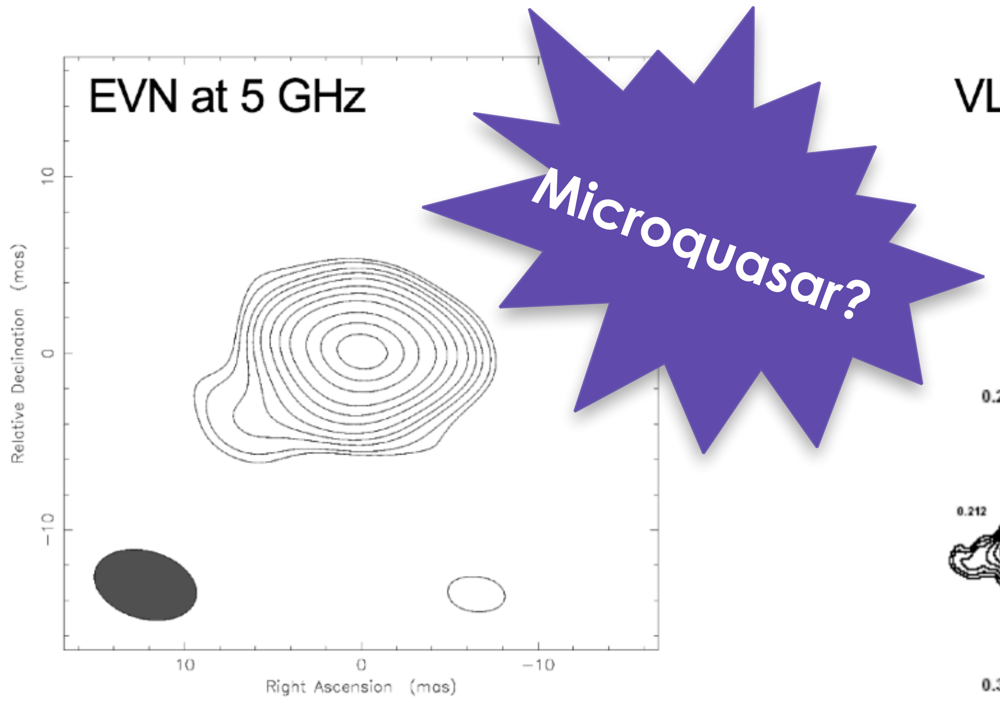
- **Pulsar + Be star**
- **Extremely eccentric binary:** Orbital period: ~50 years (Ho et al. 2017)
- Emission at VHE during **periastron passage: November 2017** (MJD 58070)

NASA

Pulsar-wind or microquasars?

MAGIC

LS I +61°303

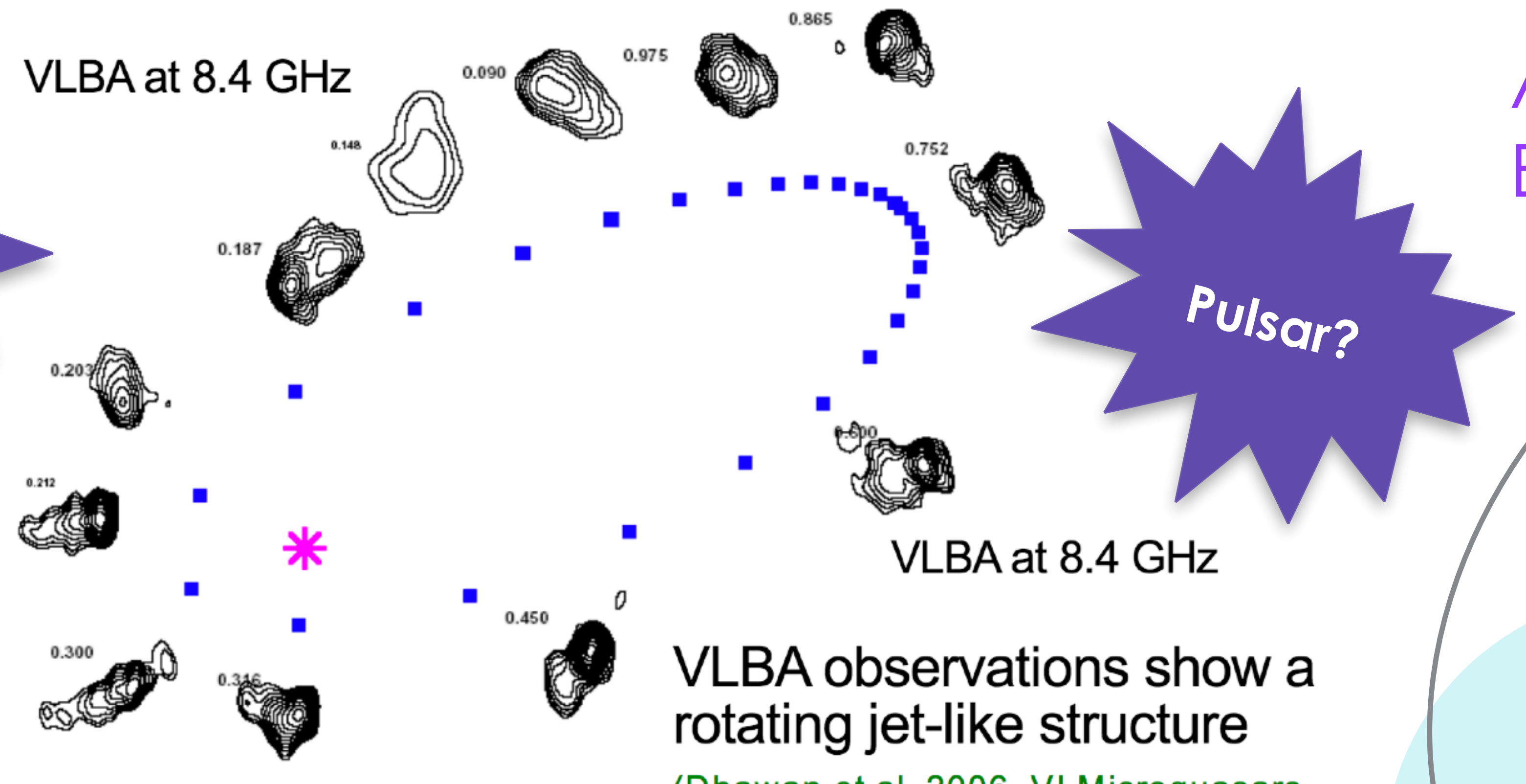


Resolved radio emission pointed towards the **microquasar** scenario (Massi et al. 2001 A&A 376, 217)

Accretion onto a compact object (NS or BH) embedded in mass outflow of the B-star

Taylor & Gregory 1982, ApJ 255, 210;
Taylor et al. 1992, ApJ 395, 268

(Slide from J.M- Paredes)

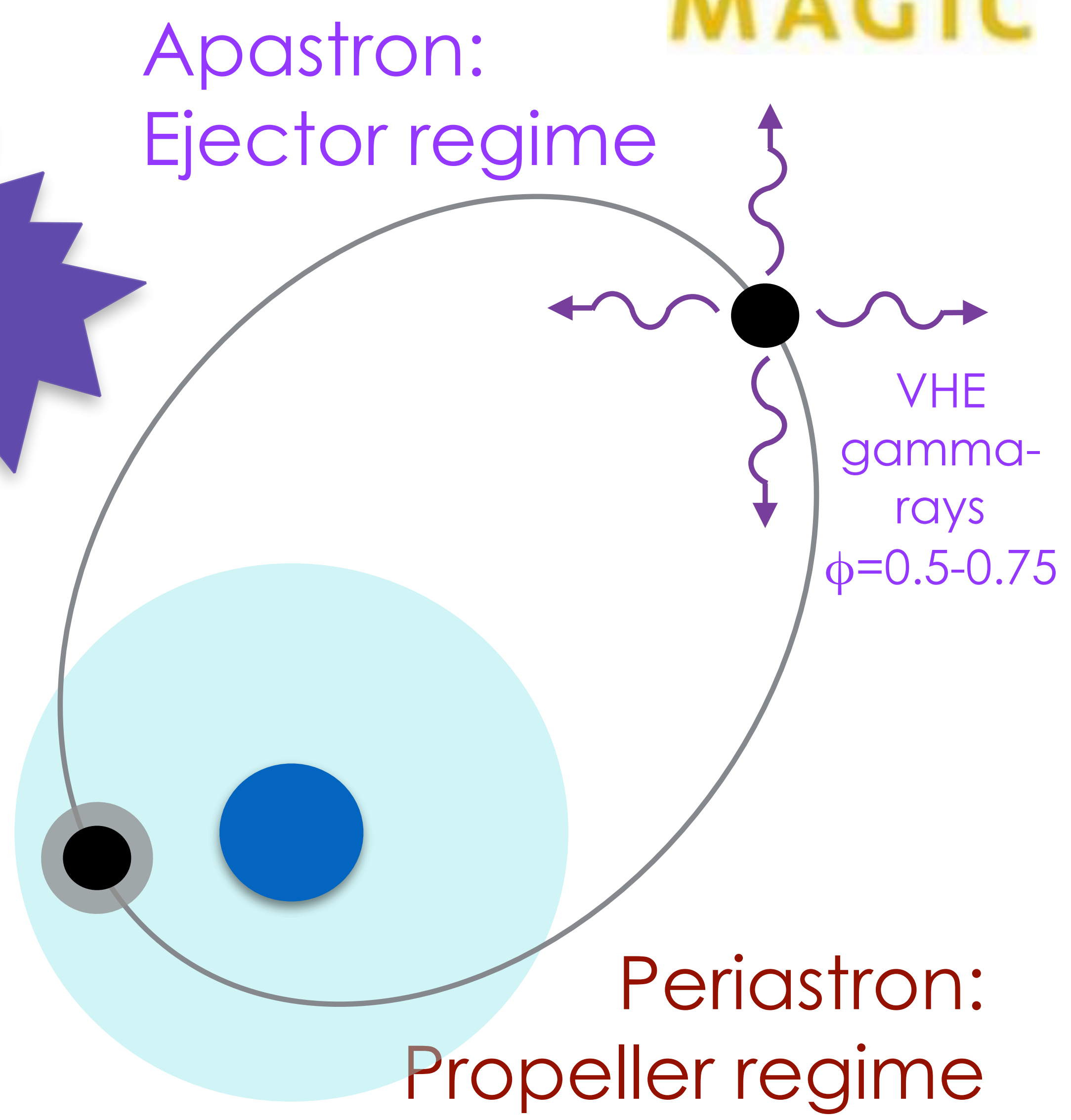


VLBA observations show a rotating jet-like structure

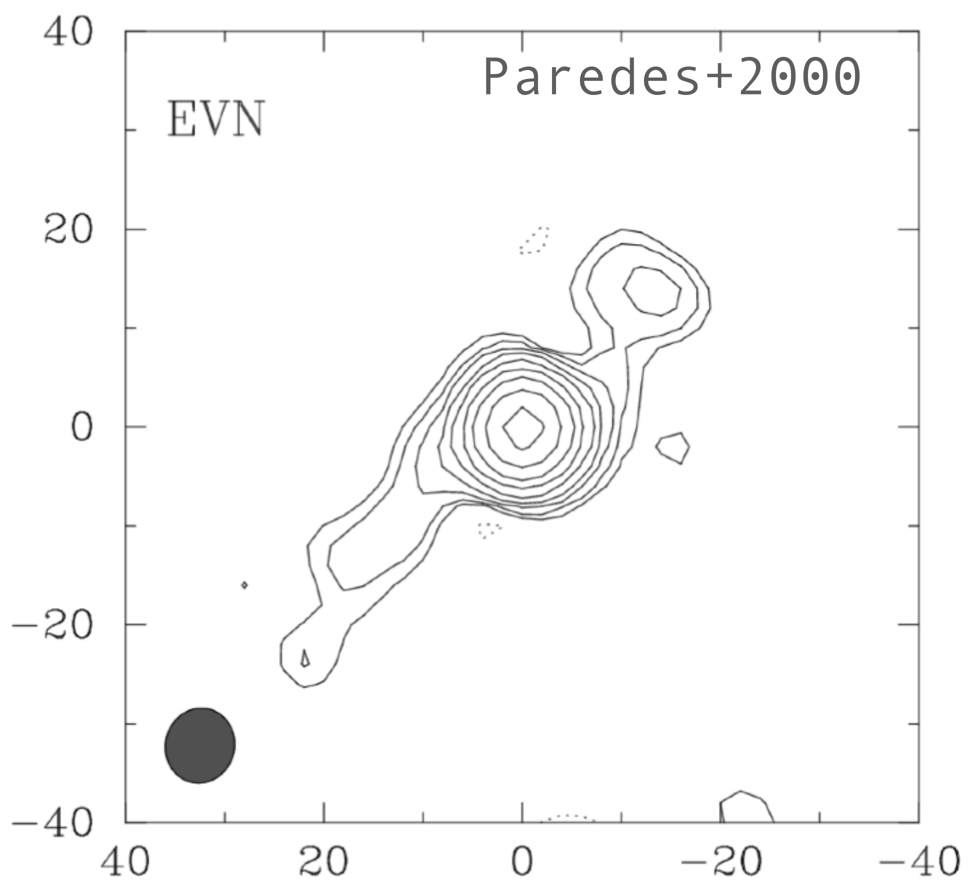
(Dhawan et al. 2006, VI Microquasars Workshop, Como)

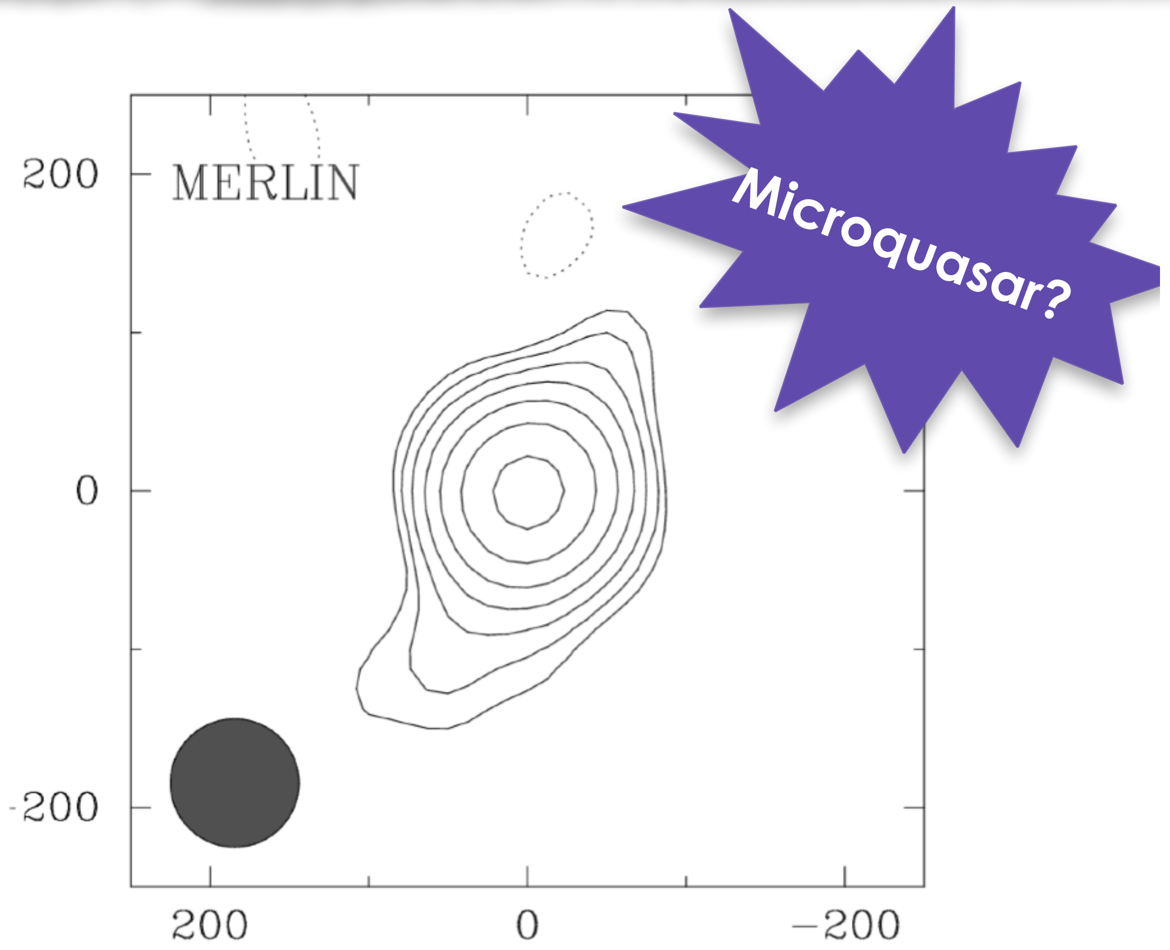
Non-accreting **young pulsar** in orbit around a mass-losing B star

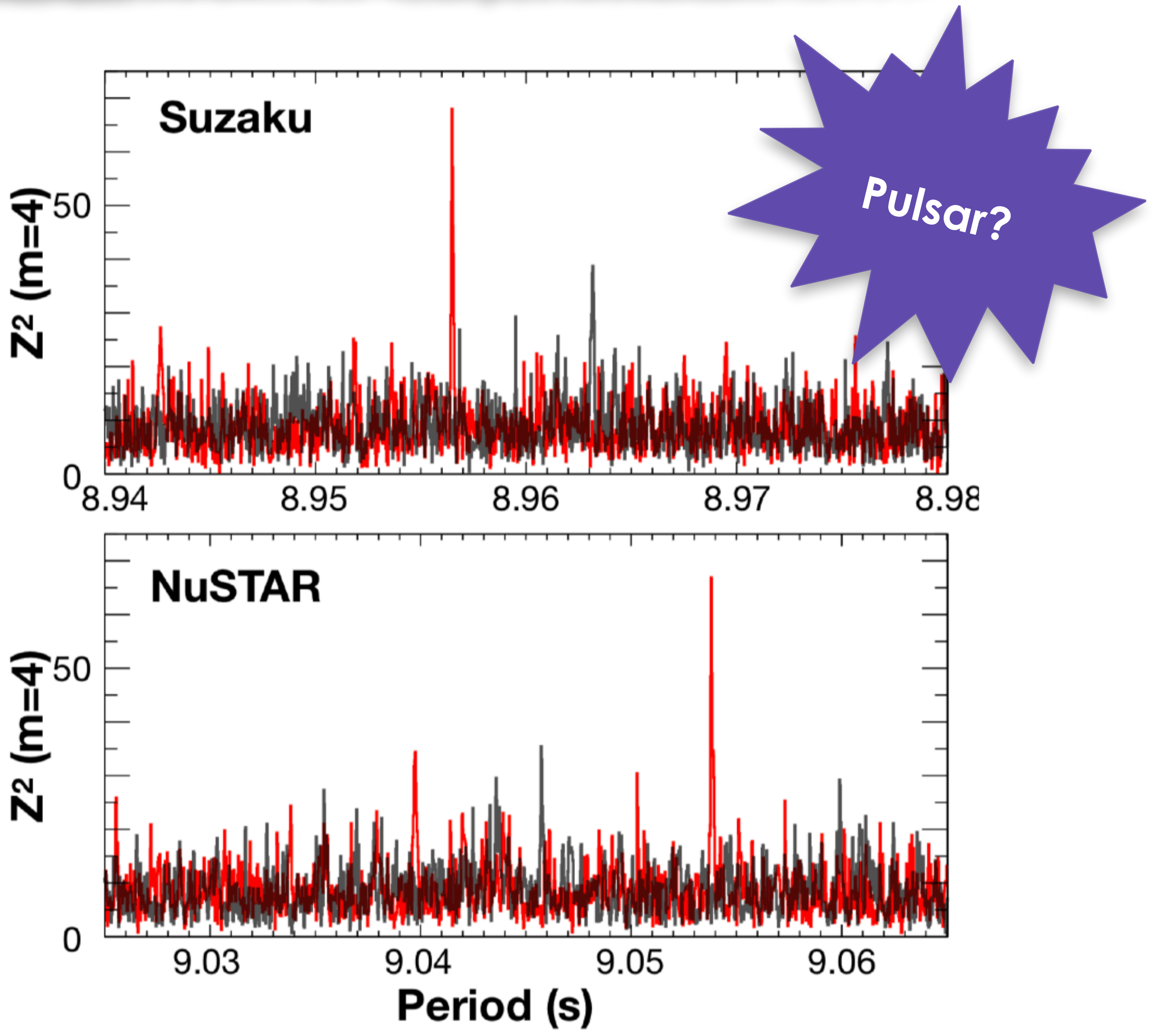
Maraschi & Treves 1981, MNRAS 194,1
Dubus 2006, A&A 456, 801



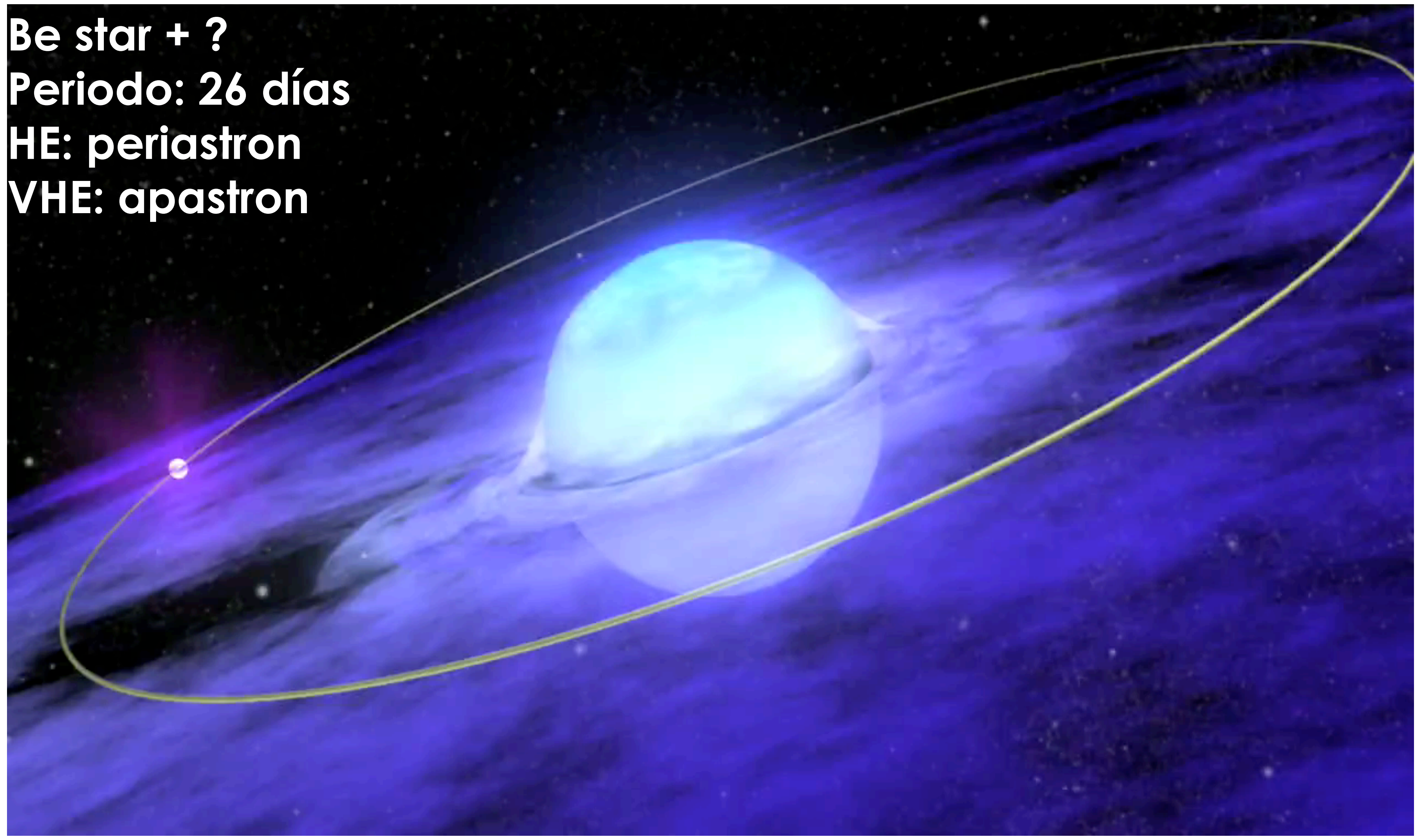
LS 5039

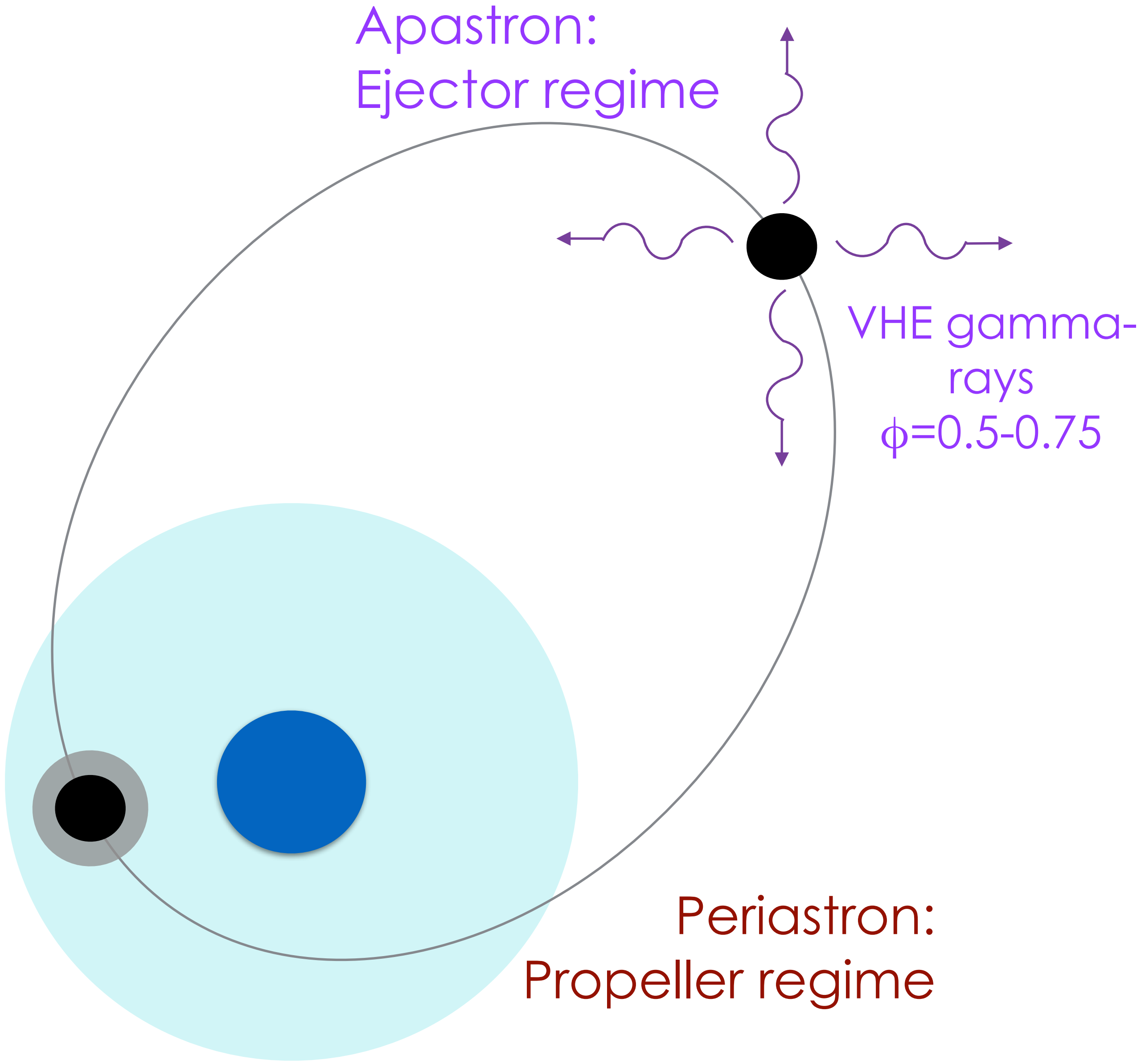


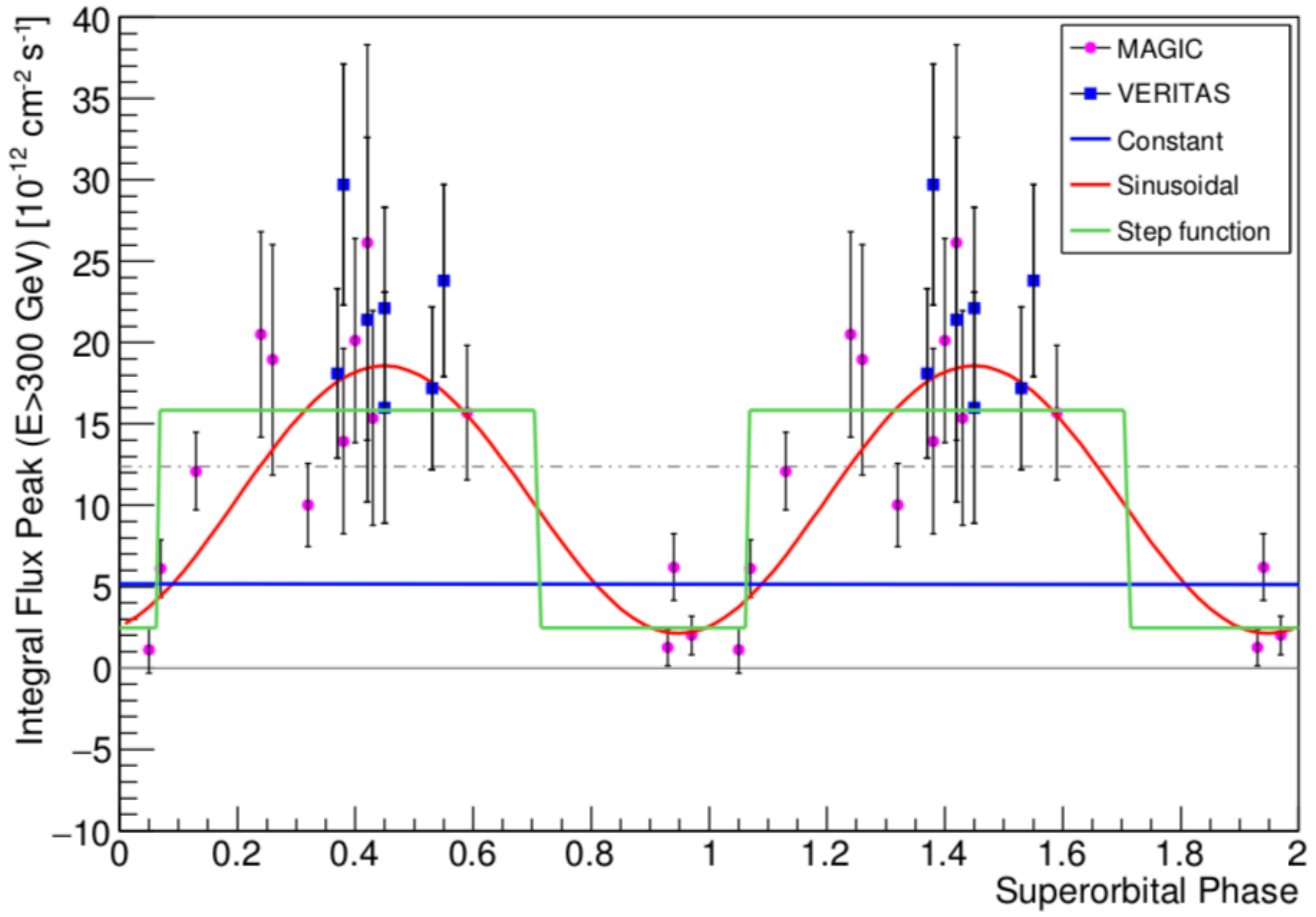


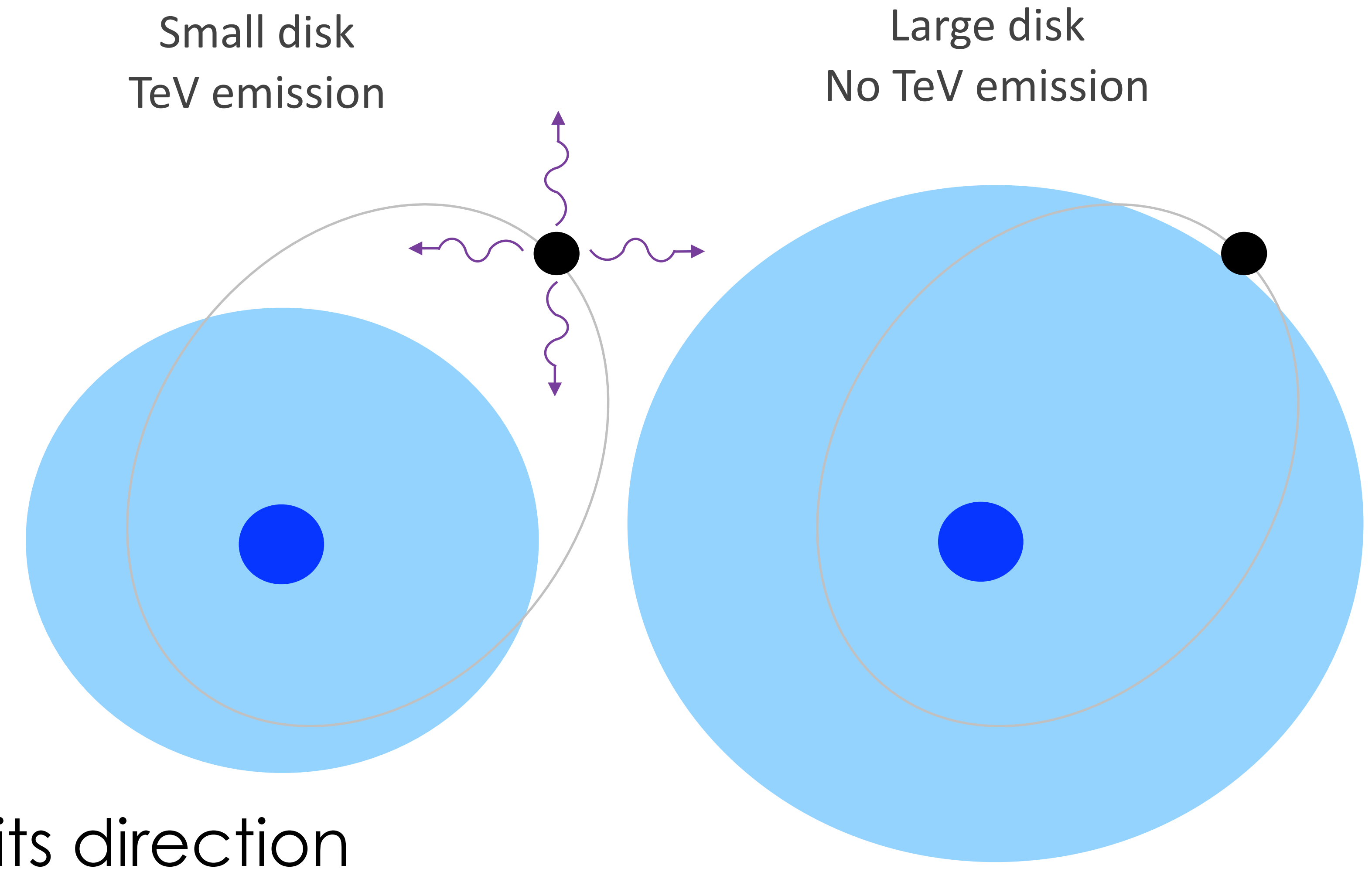


LS I +61°303





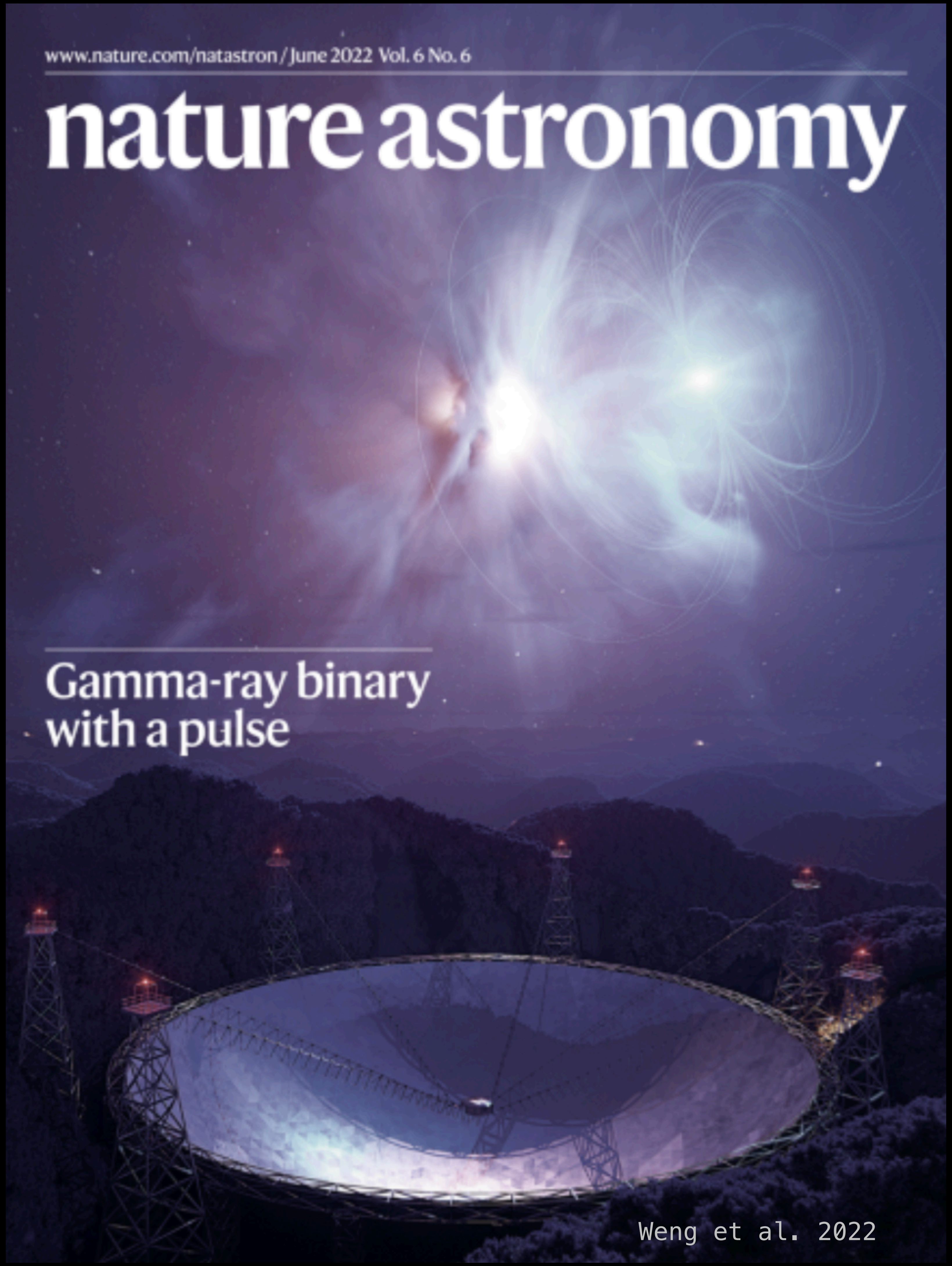




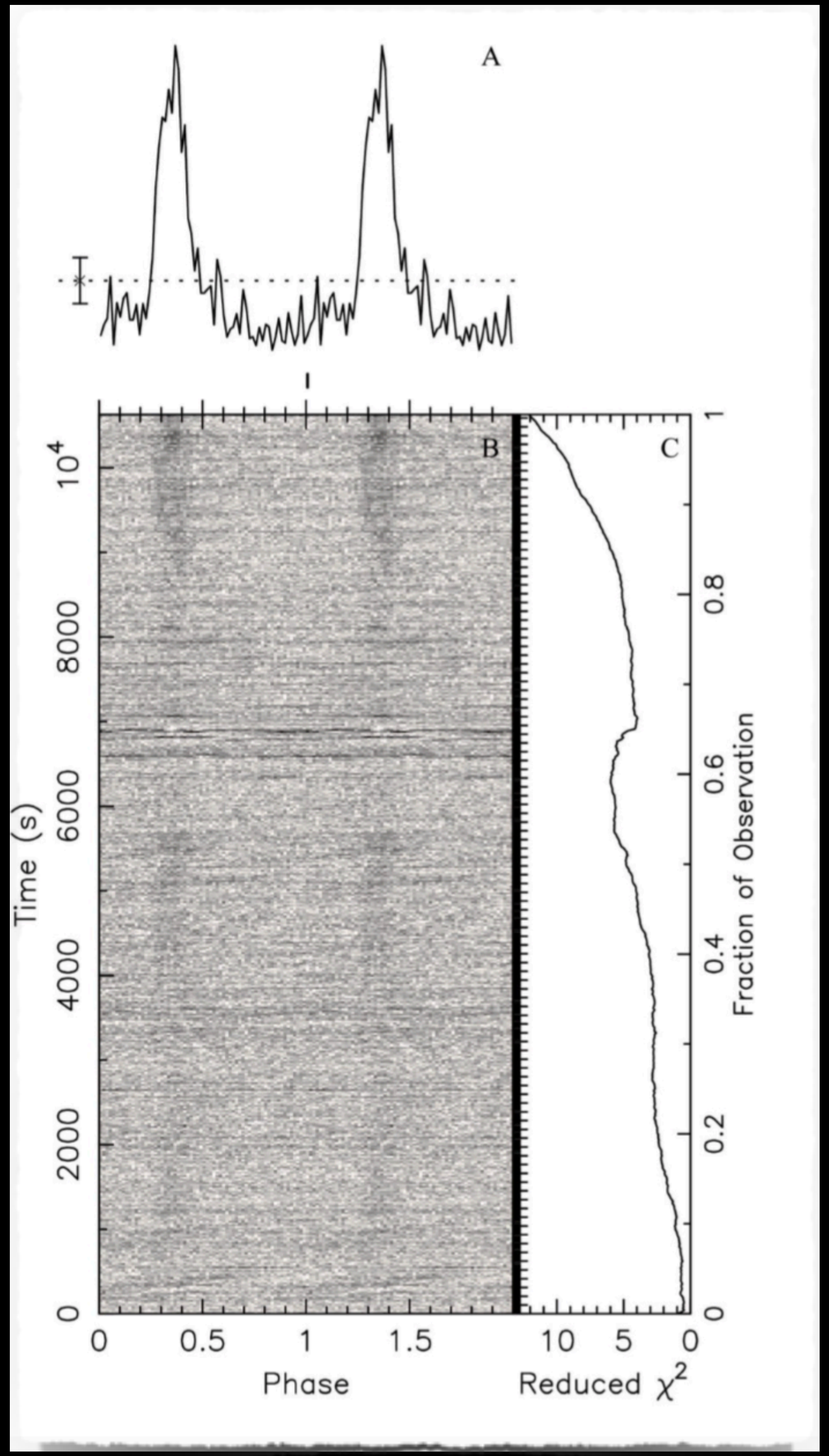
- **Be star+compact object**
- **Magnetar- like short burst (0,31 sec)** detected by Swift/BAT (Barthelmy et al. 2008) from its direction
- The **luminosity of this burst is on the lower end of the distribution of short bursts from magnetars**
- Magnetar in LSI (Bednarek 2009, Dubus 2010, Torres 2012)
- Flip-flop magnetar model (Torres 2012):
  - For ejector (apastron) to propeller (periastron)
  - Compatible with super-orbital modulation (Paredes 1987, Gregory 2002, Ahnen et al. 2016)

Super-orbital variability: changes in the **mass-loss rate** can set the propeller regime even at apastron

A pulsar in LS I +61° 303



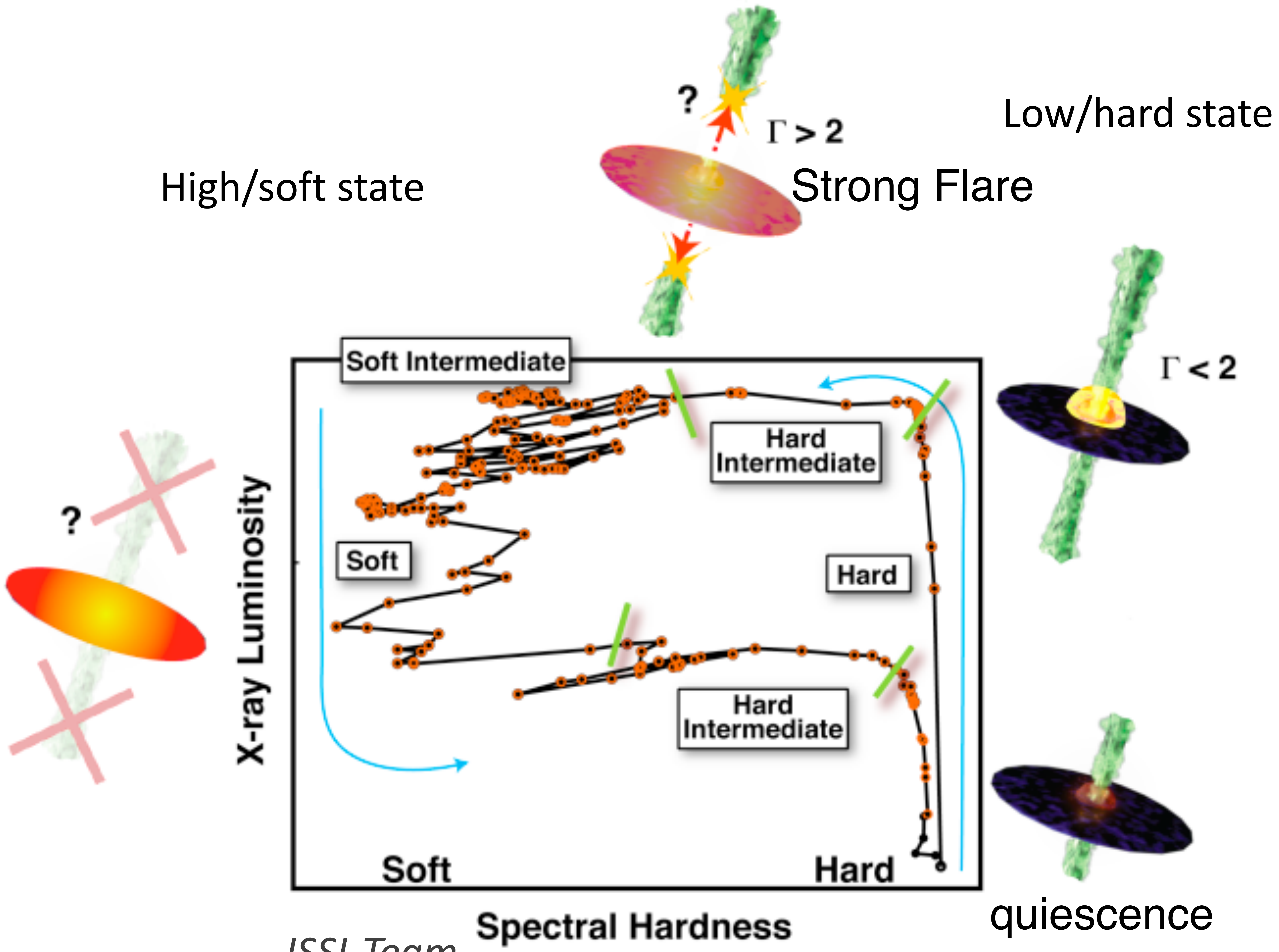
- **Pulsations 0.27 seg** detected with FAST (Weng et al. 2022)
- No periodicity in the signal
- "LS I 61 303 is the **first binary system containing a pulsar behaving as a magnetar**, probably one of the low-field magnetars class"



- "We find that 5–10% of the galactic magnetar population could plausibly have a bound companion" (Crimes et al. 2022)

Microquasars

Hardness Intensity Diagram (HID)

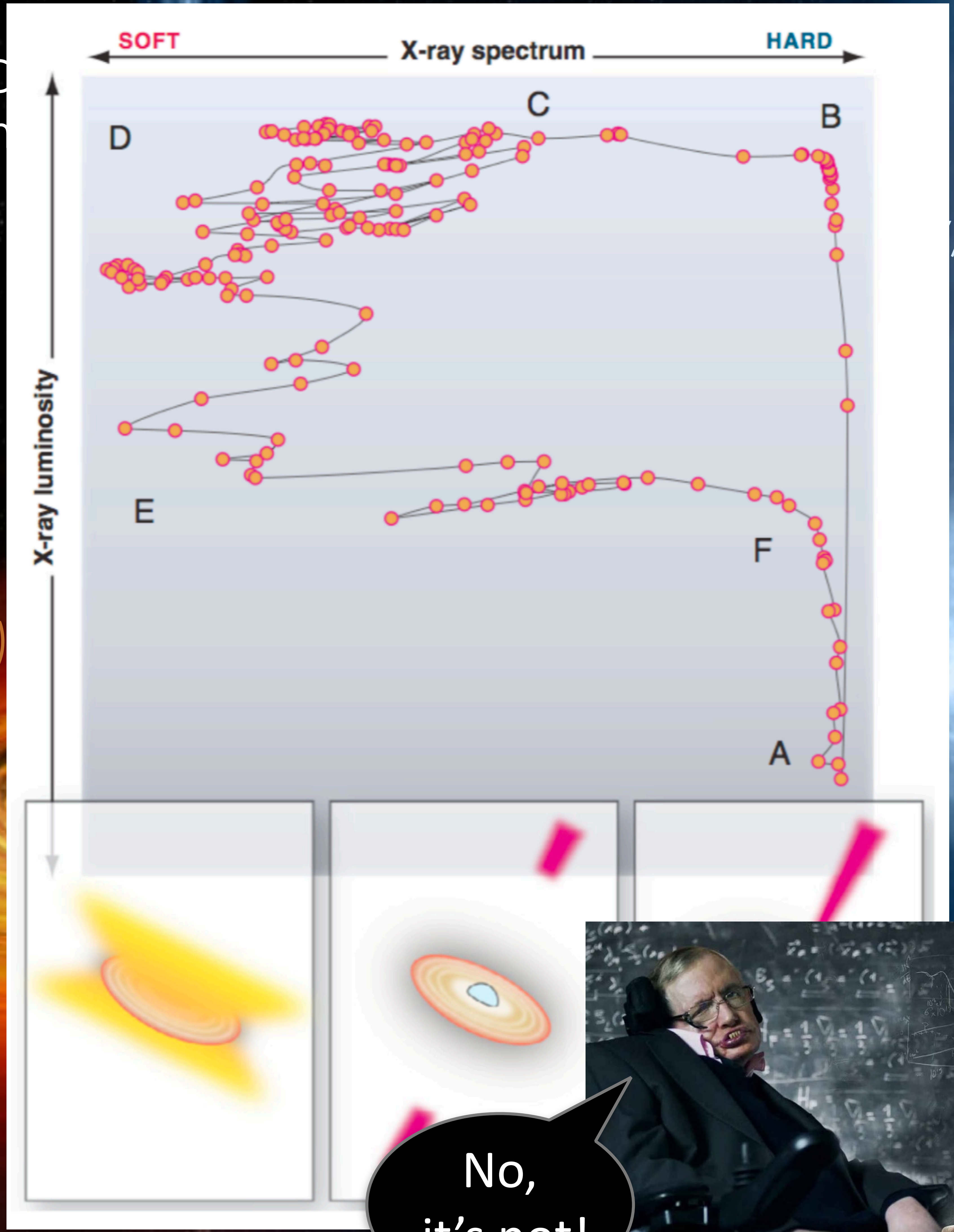


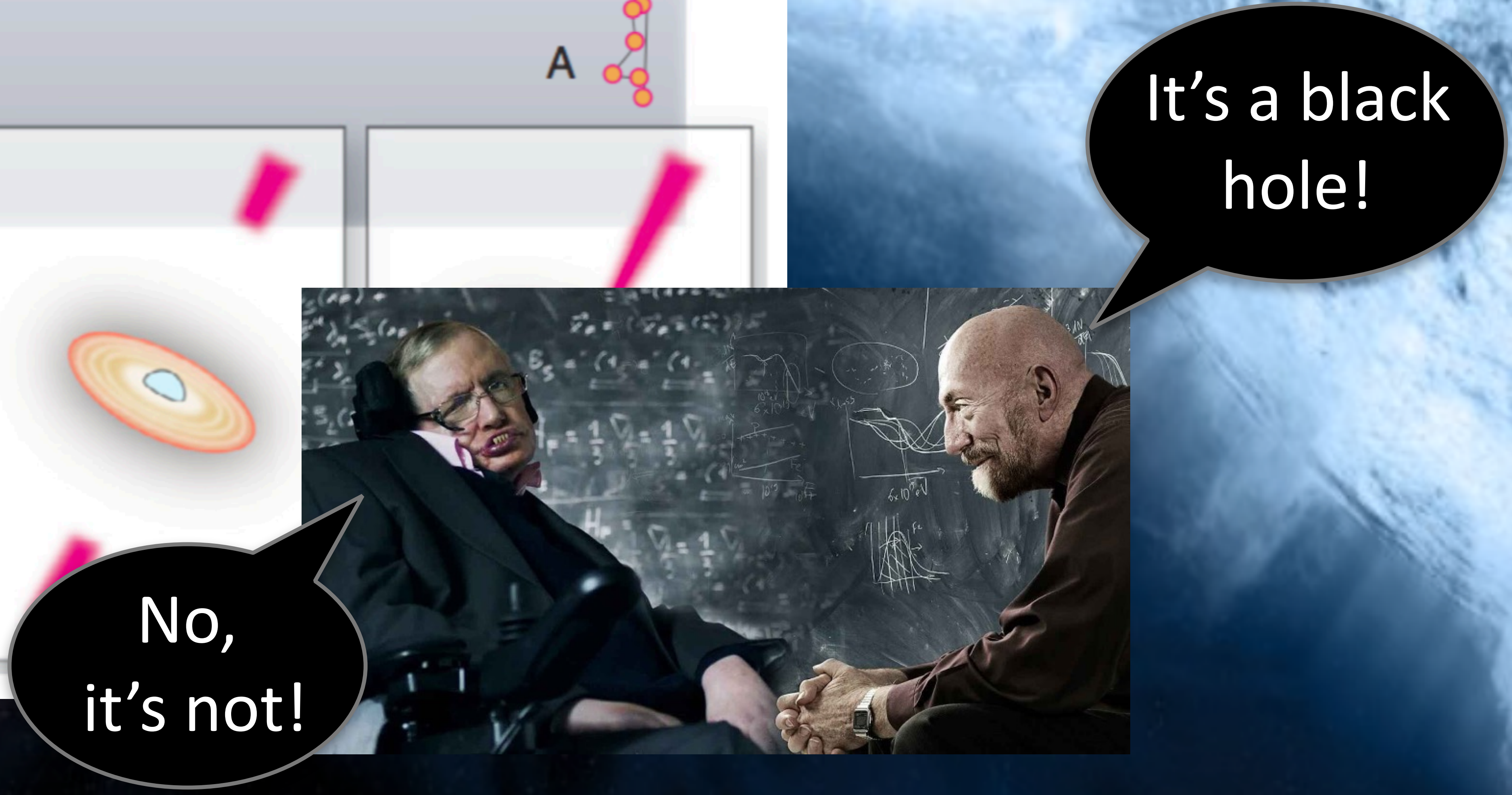
ISSI-Team

Jets
(radio, mm, O
X-rays, soft gamm

star
, IR)

Accretion disk
(optical, UV, soft X-rays)



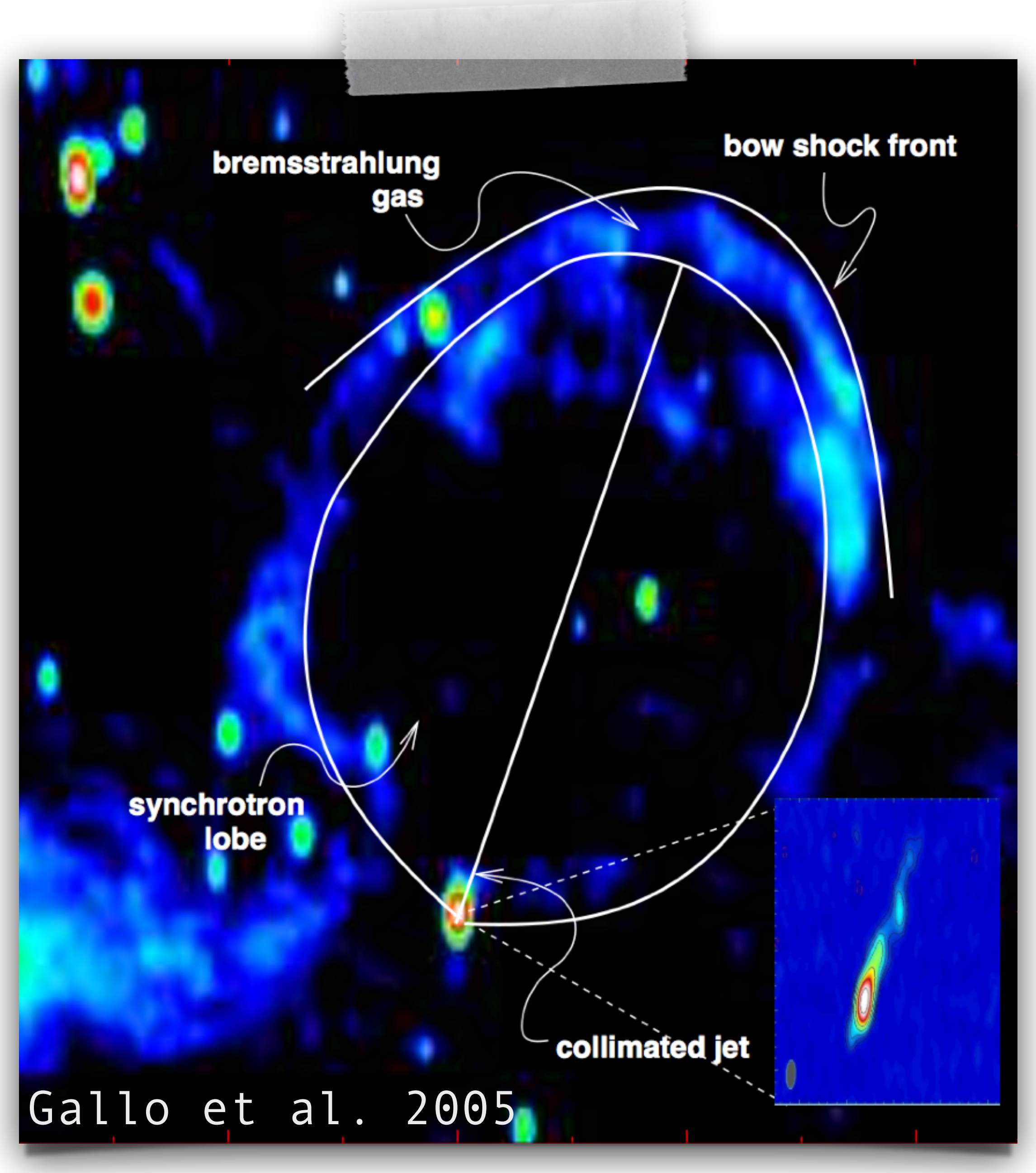


- **About 20 known Galactic microquasars,** possibly up to 150 (Paredes&Martí, 2015)

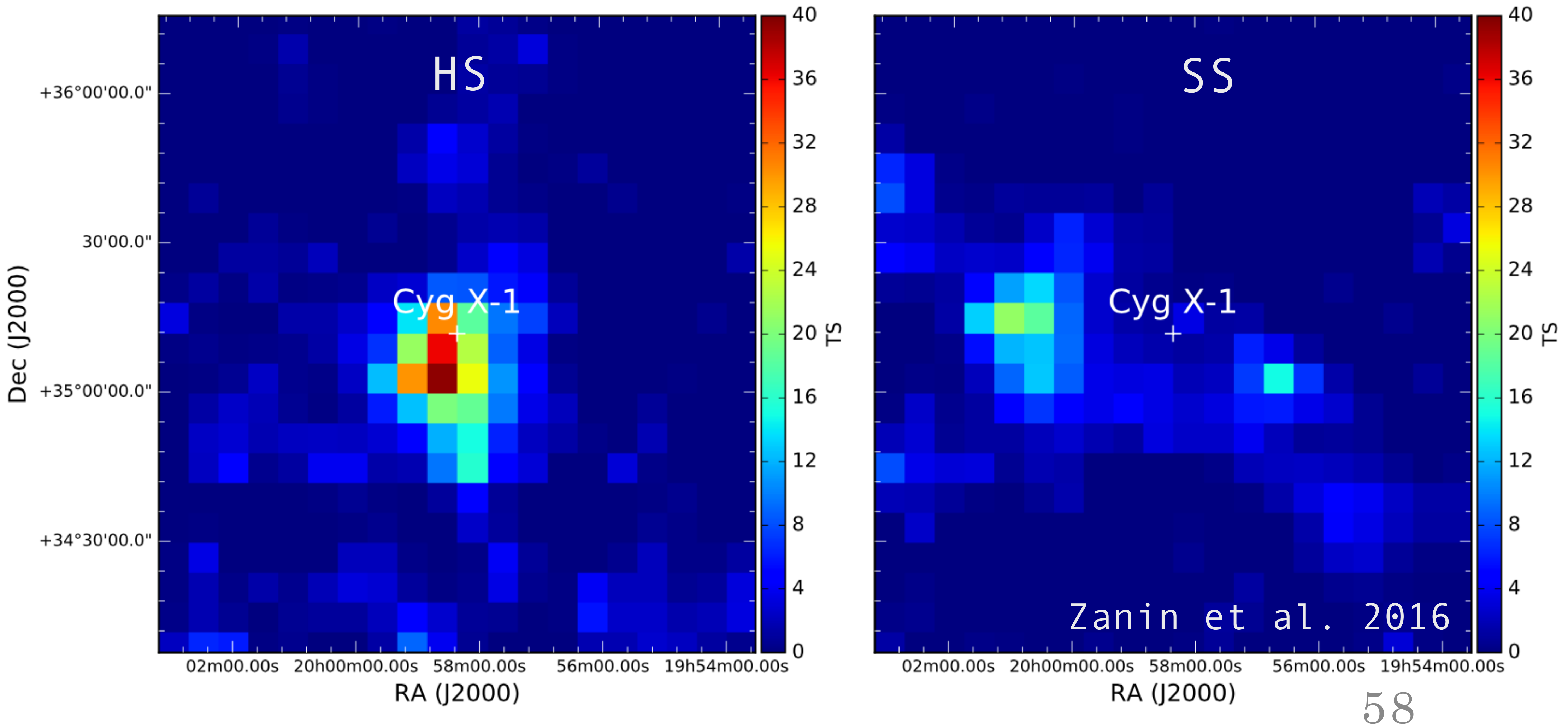
NASA/CXC/M.Weiss

Steady+transient emission: Cygnus X-1

- Massive O9.7 Iab star + BH
- **Highly collimated jet** (Stirling et al. 2001)
- Surrounded by radio/optical **nebula** (Gallo et al. 2005, Russell et al. 2007)
- Three transient episodes with AGILE during HS and IS (Bulgarelli et al. 2008, Sabatini et al. 2010, 2013)

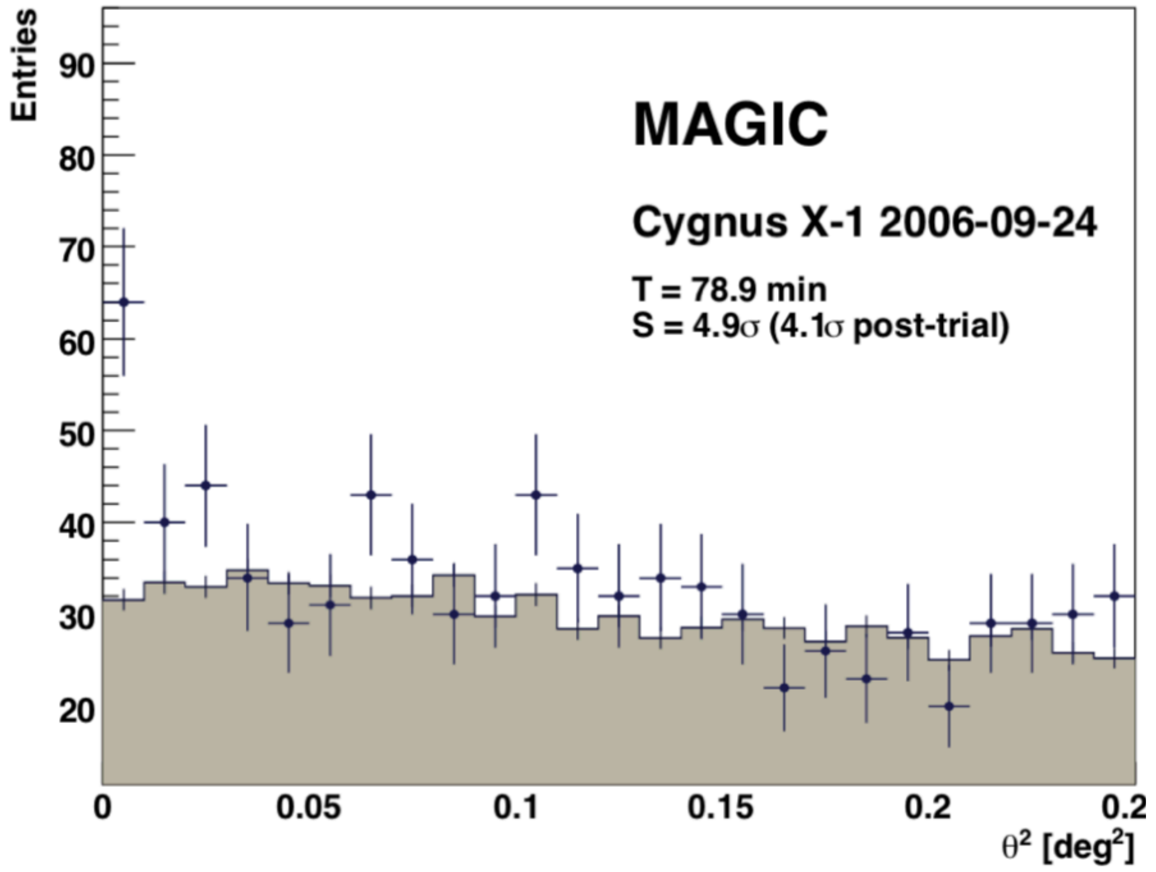


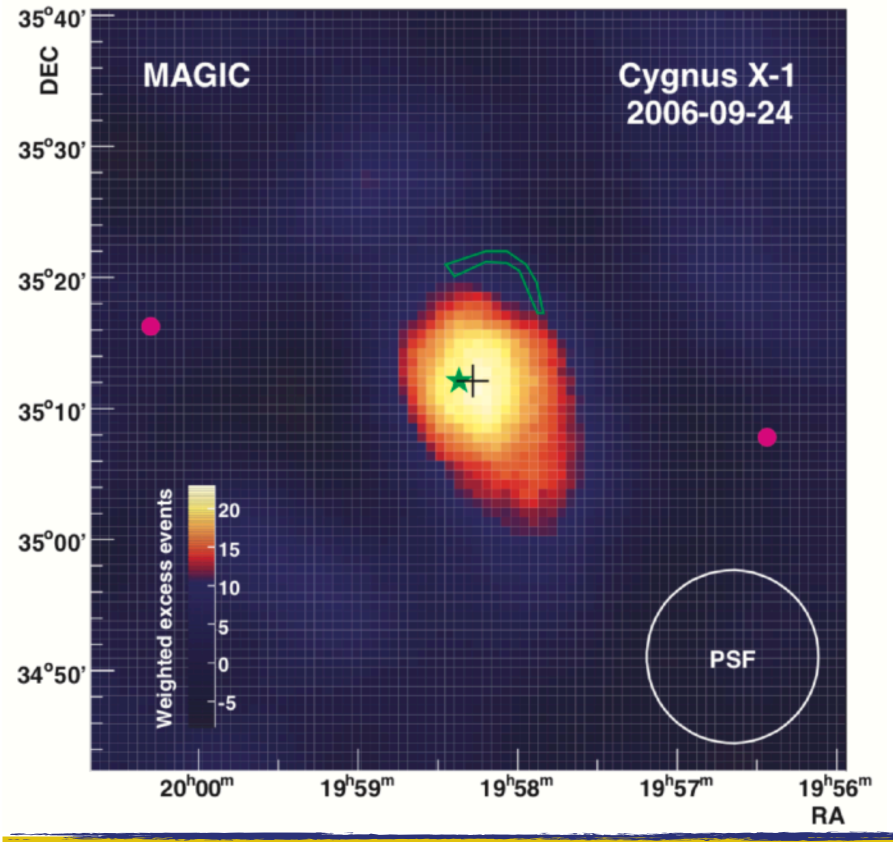
- **Detected at HE during HS**: **7.5yr** Fermi-LAT data (Zanin et al. 2016)
  - **Likely jet origin**
  - Evidence of flux orbital variability: anisotropic **inverse-Compton** on stellar photons as the mechanism at work
  - Different **hadronic component might exist** at higher energies



Cygnus X-1: results

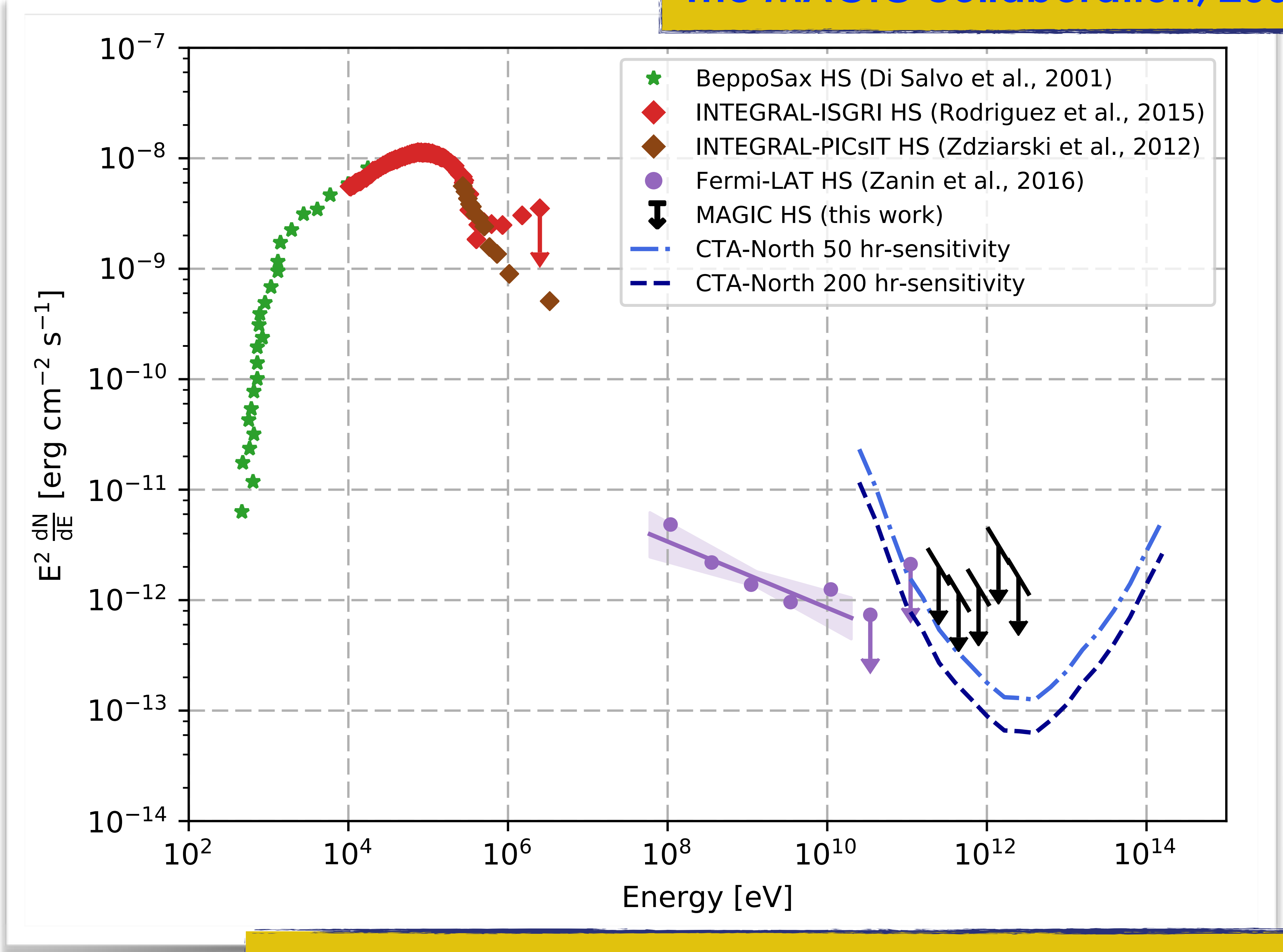
- **Hint of emission with MAGIC**: 4σ in 80 min (Albert et al. 2006)
  - Simultaneously with hard X-ray flare
  - During hard state (HS) and SUPC



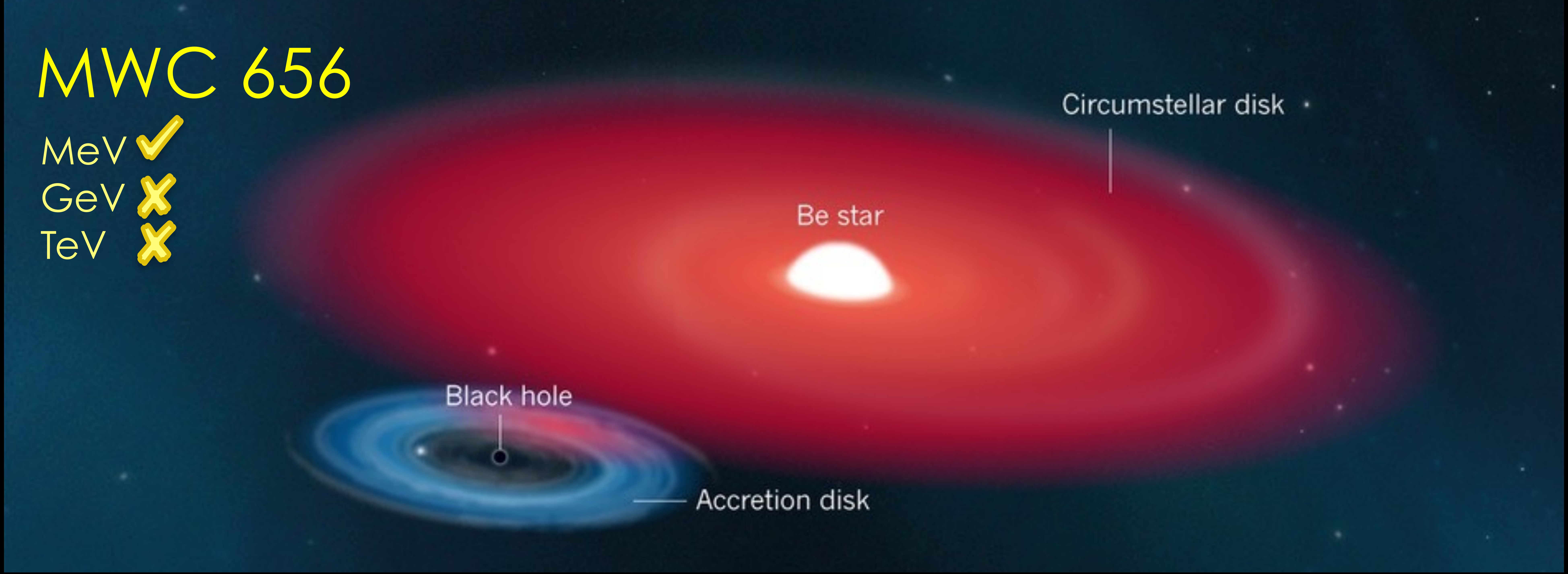


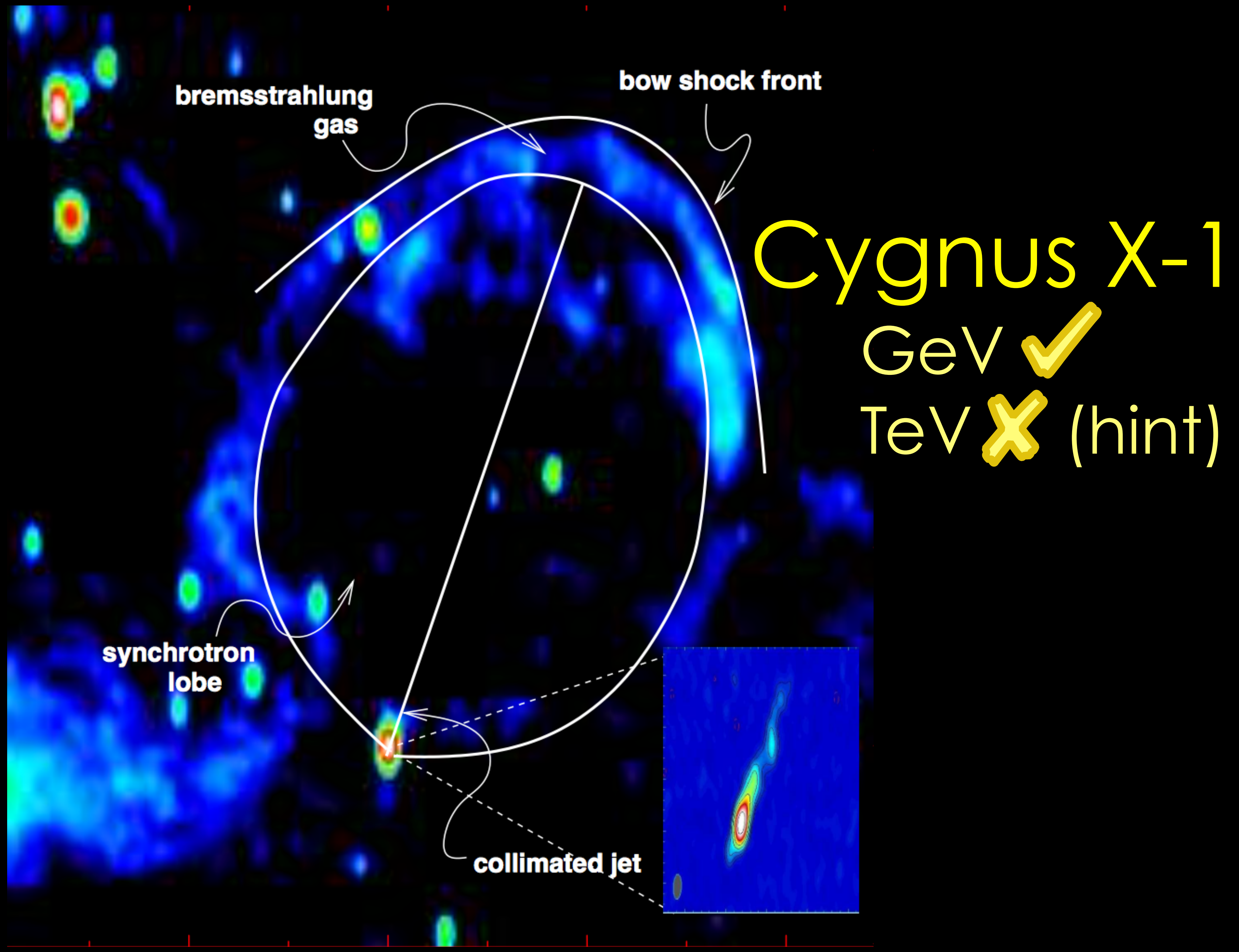
The MAGIC collaboration, 2006

- **100 h** (2007-2014) of MAGIC observations **mainly at HS** (83h)
- No significant excess at either X-ray state for steady, orbital or daily basis emission
- No emission above 200 GeV due to interaction between jet and ISM
  - **Jet-medium interaction discarded** as possible region for VHE emission above MAGIC sensitivity level: not affected by γ–γ absorption
- **Transient emission** (Albert et al. 2007) **still possible** at binary scale

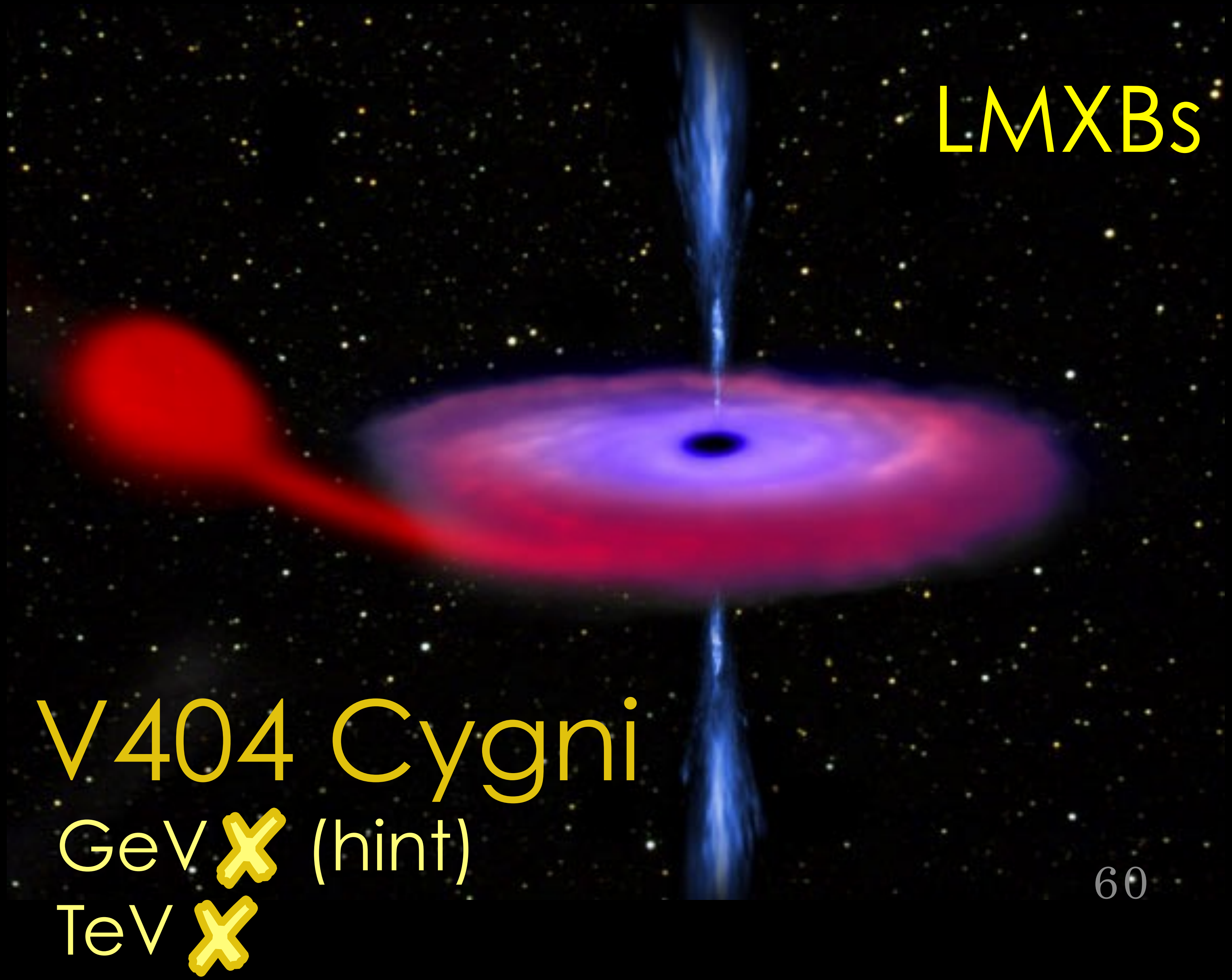


The MAGIC collaboration, 2017, MNRAS, 472, 3474

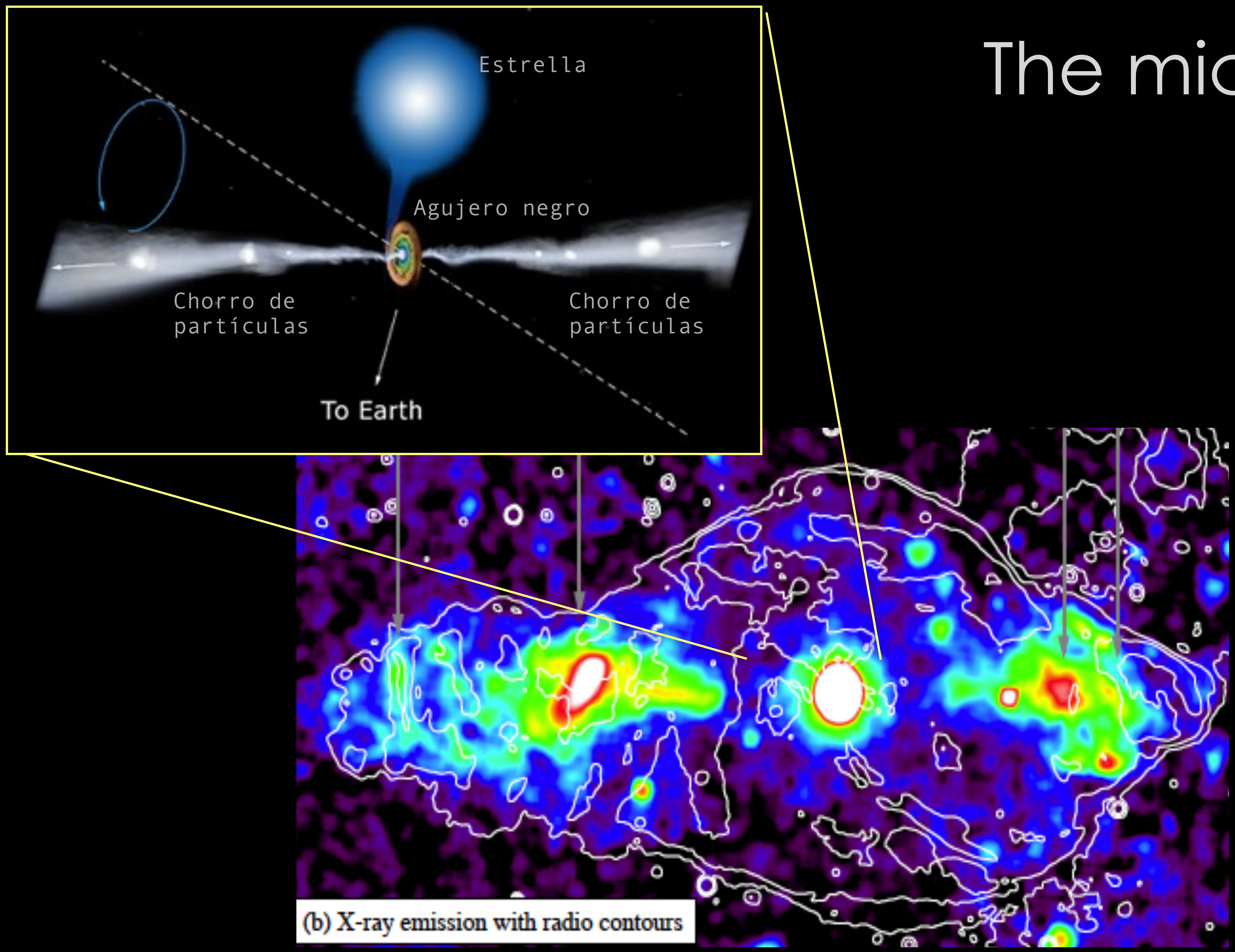




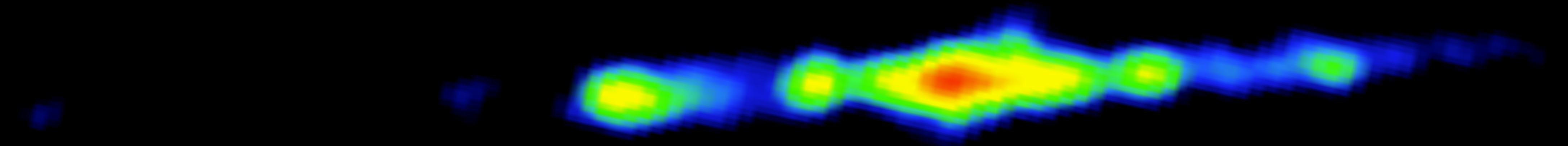
Gallo et al. 2005



The microquasar
SS433



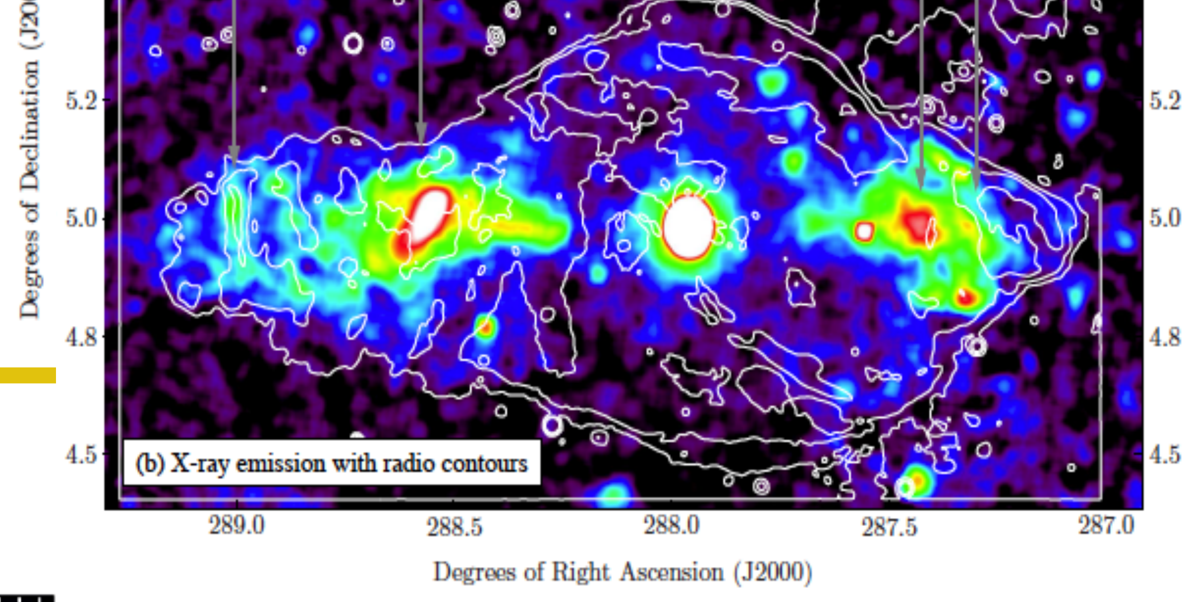
(b) X-ray emission with radio contours

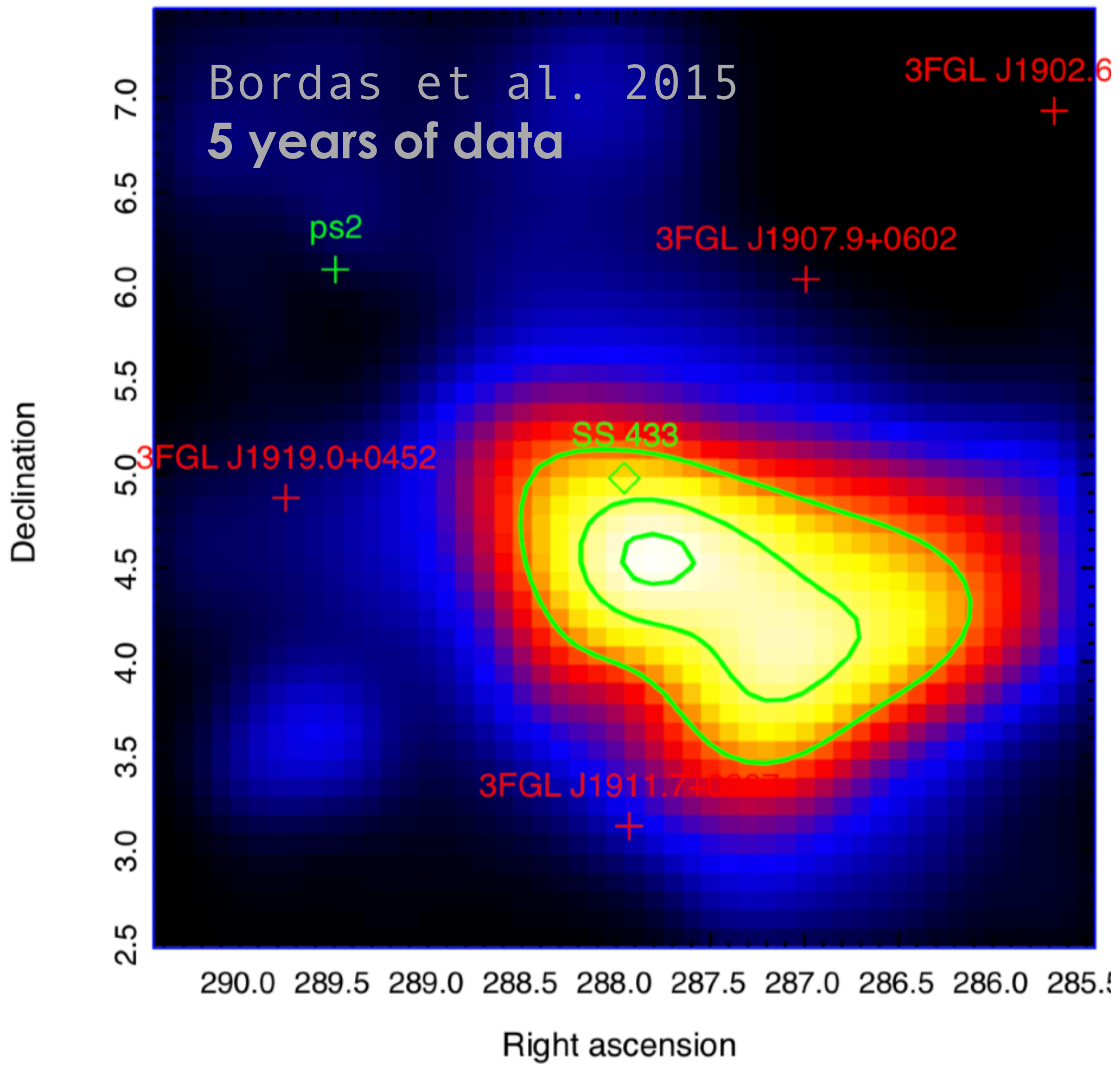


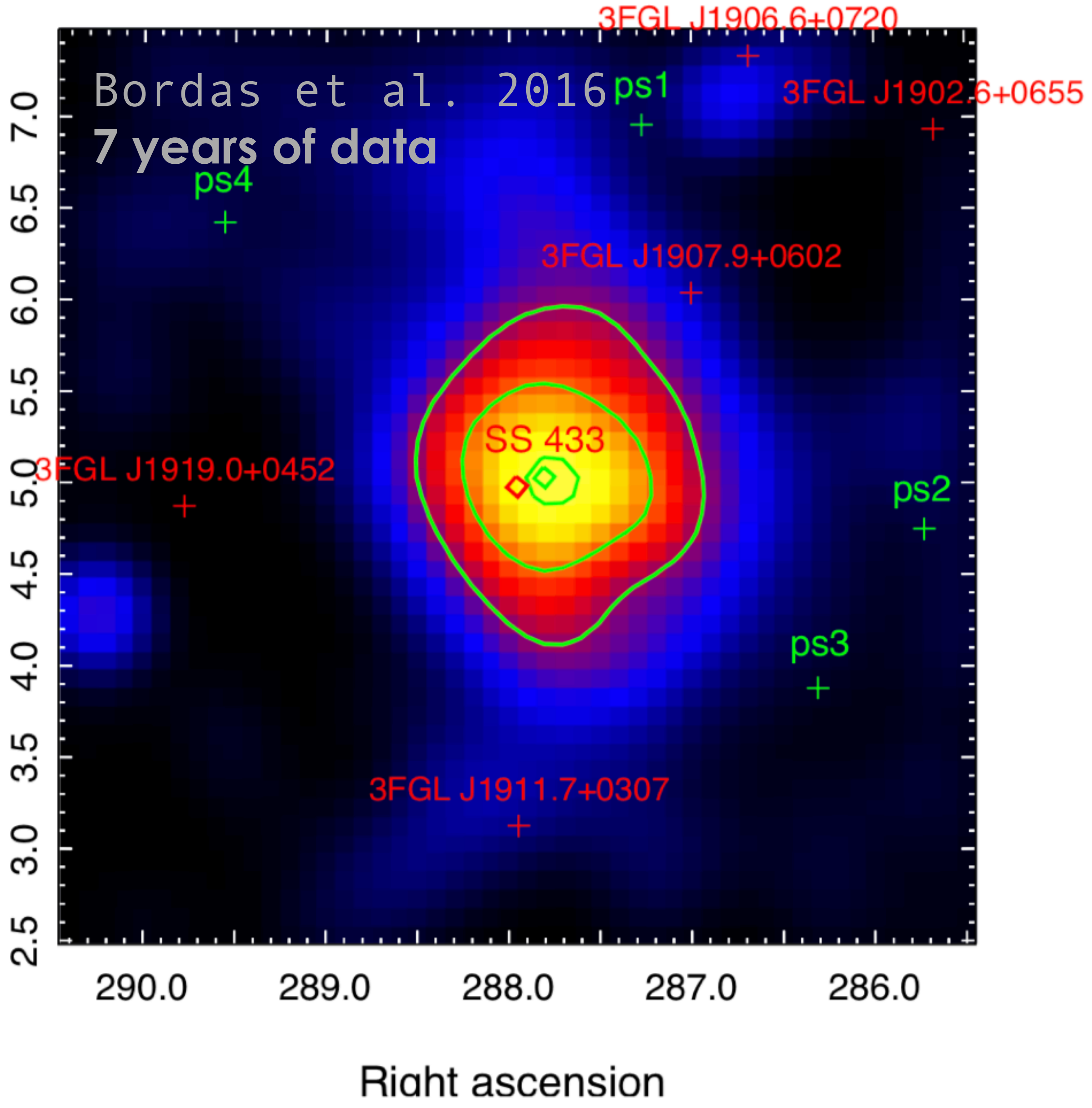
NASA/CXC/U.Amsterdam/S.Migliari et al // Goodall et a. 2011 /// NRAO

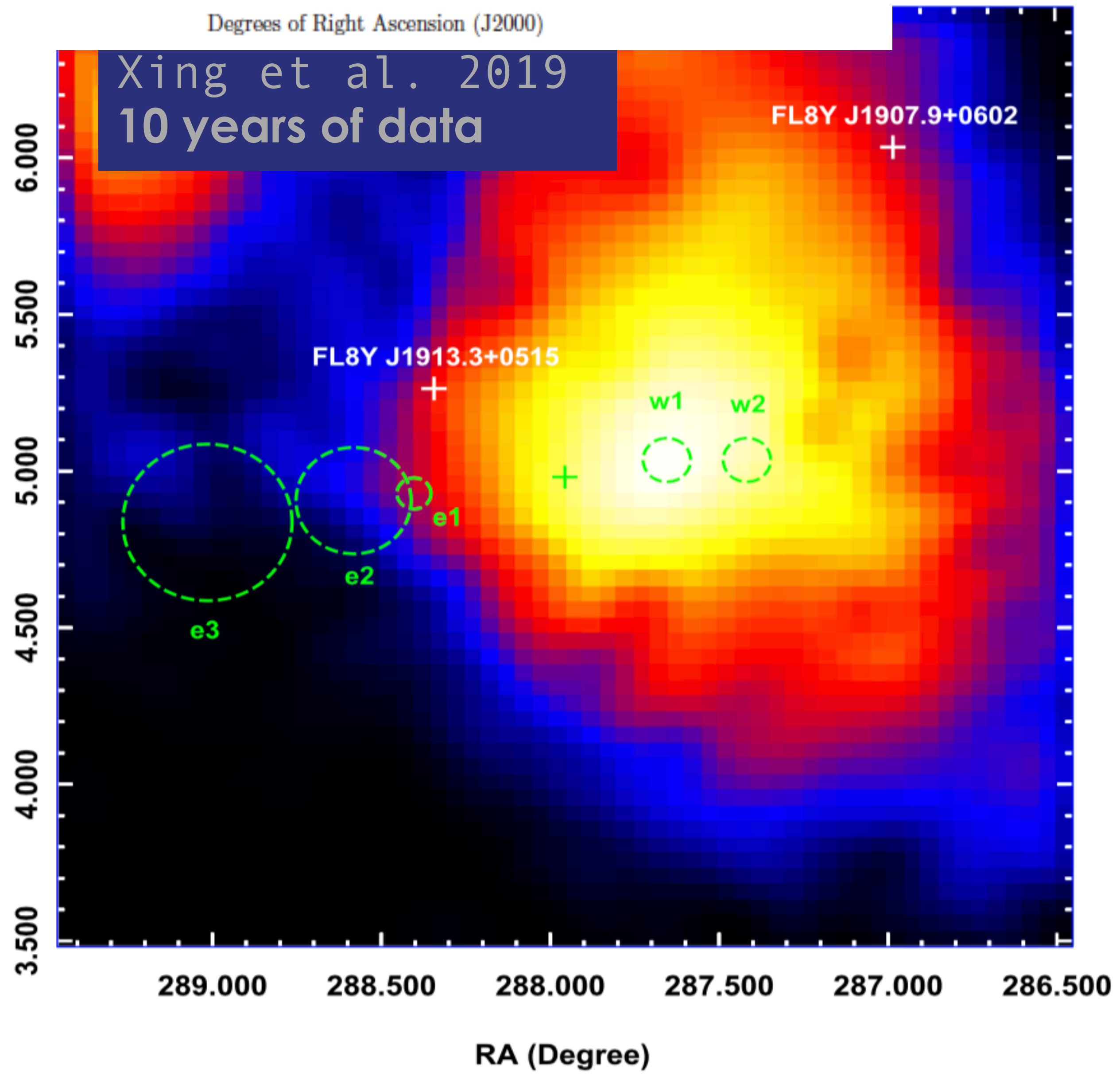
SS433 at **HE**: Fermi

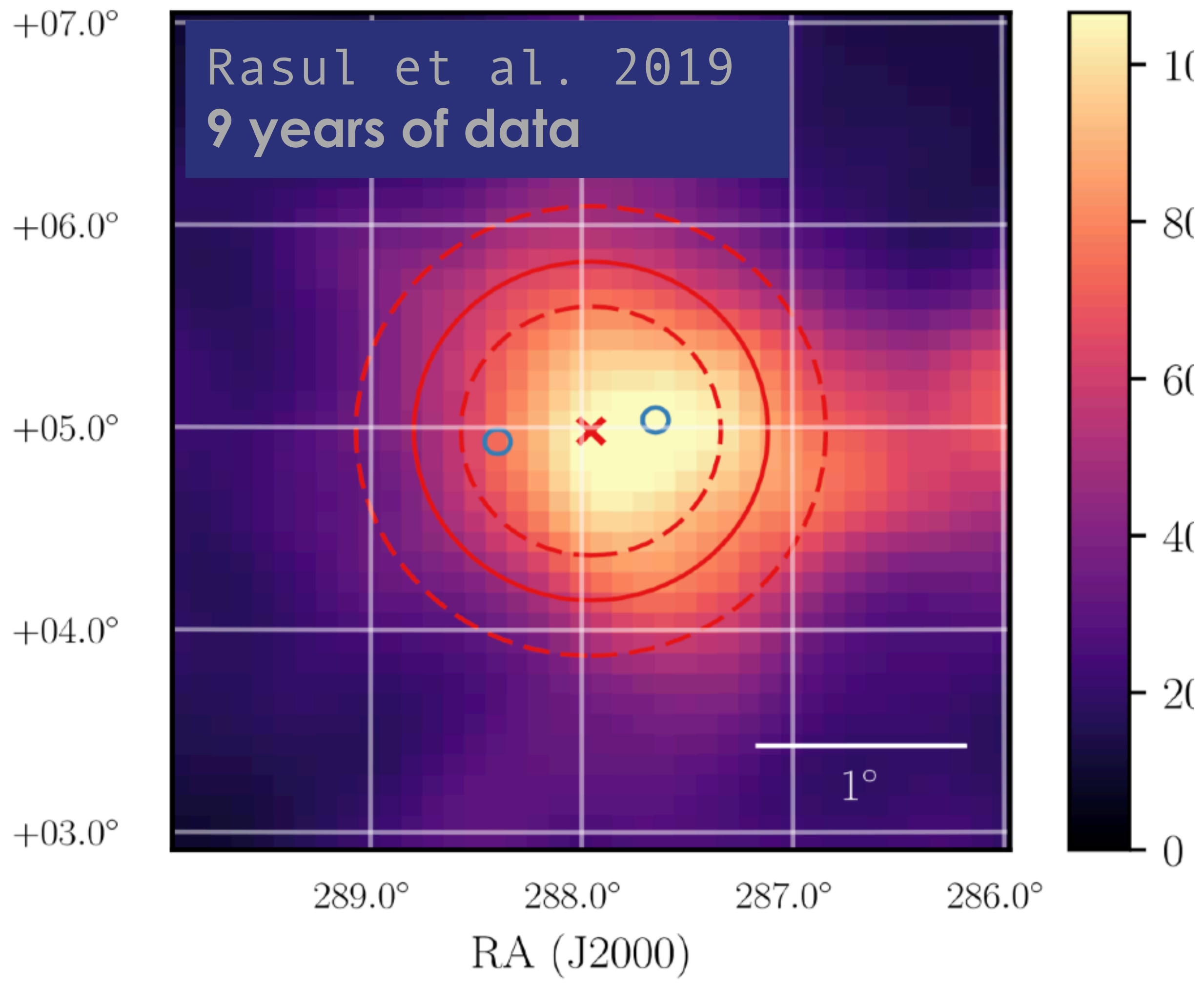
- Zona compleja, no hay acuerdo entre distintos análisis

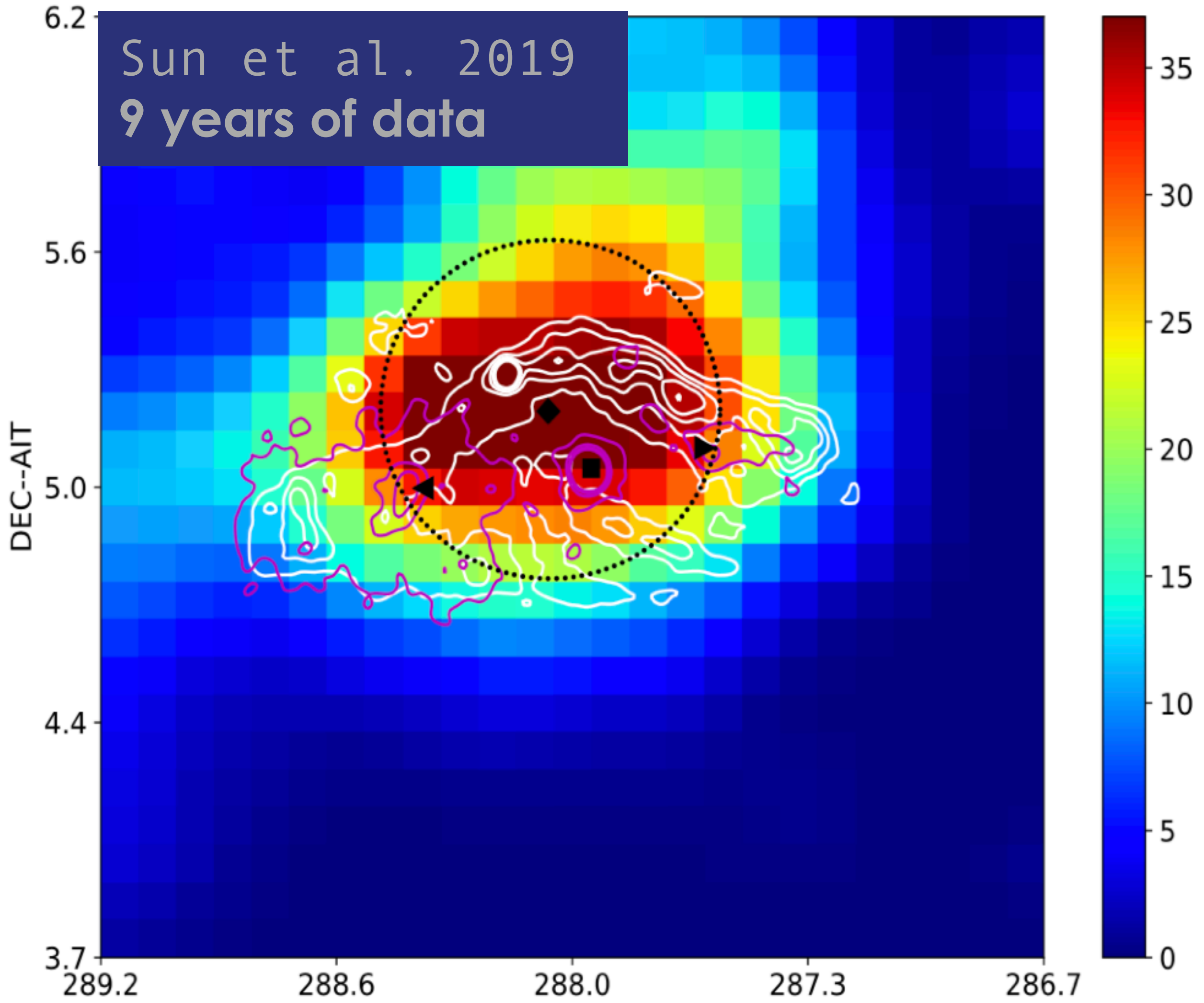


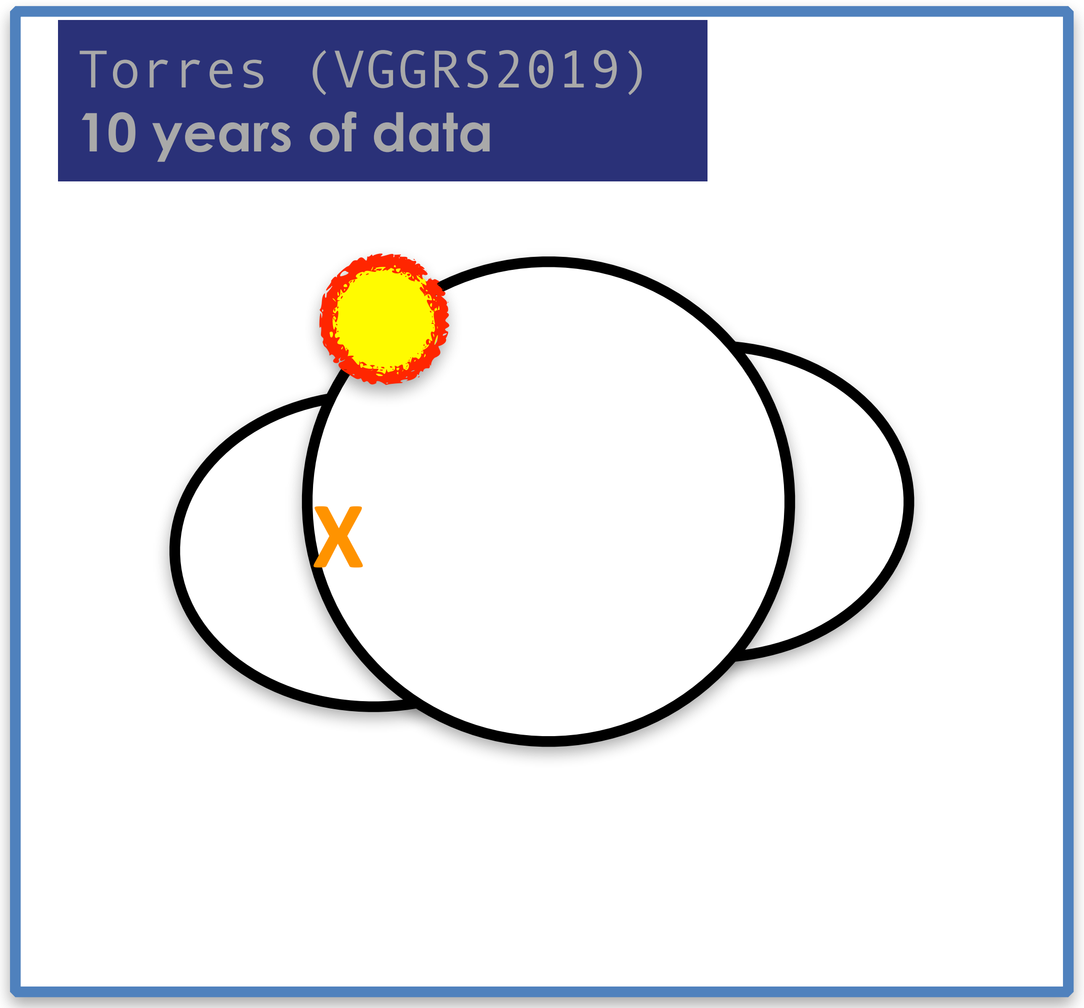






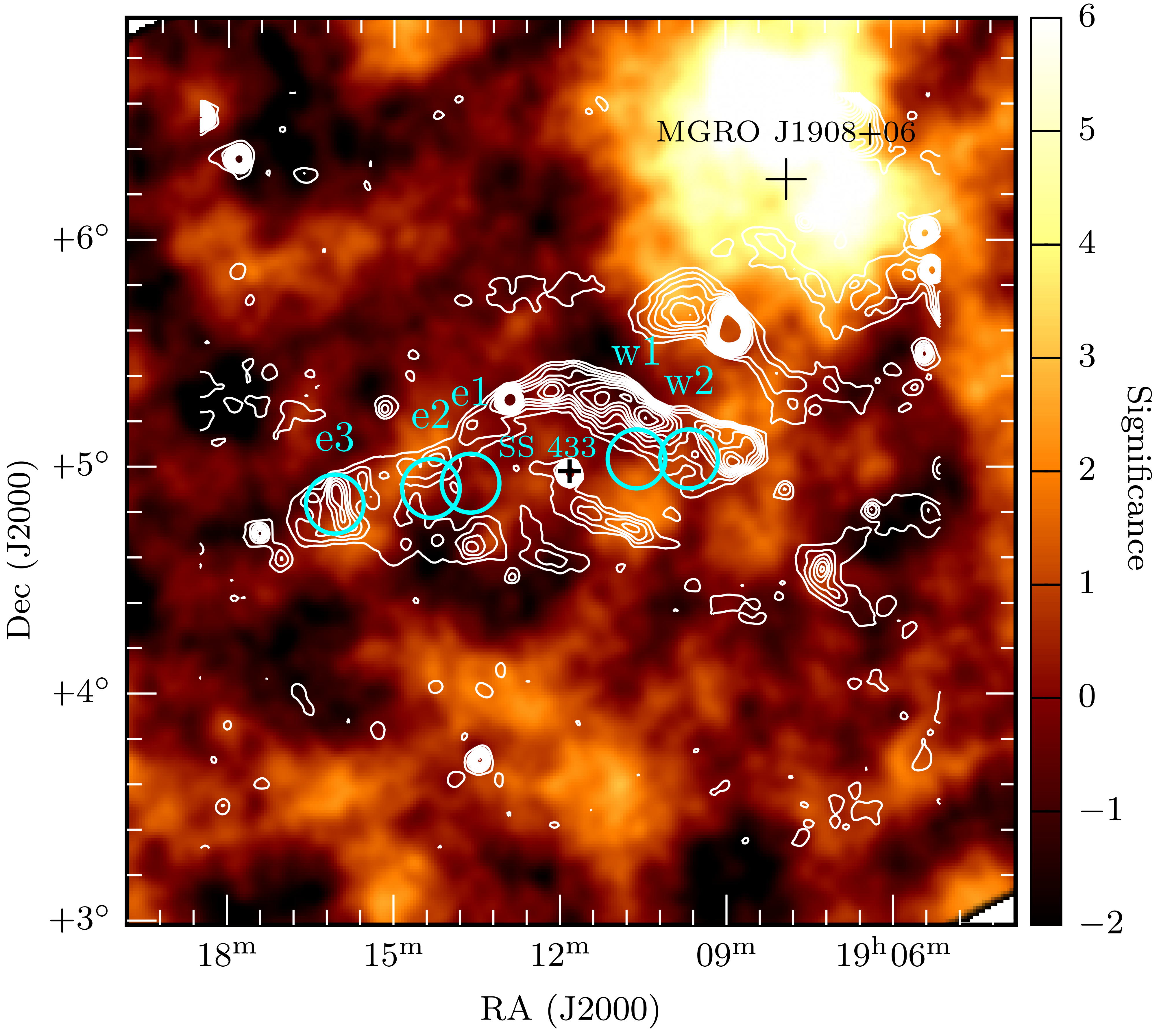






SS 433 at VHE

MAGIC and H.E.S.S.., 2017, A&A, 612, A14



MAGIC + H.E.S.S. campaign

- **No significant excess** detected
- Upper limits for central binary compatible with predictions (Reynoso et al. 2008)

Central binary

Hadronic scenario:

Flux prediction depends on efficiency in transferring jet kinetic power to relativistic p^+:

- We can **constrain**: $q_p \leq 2.5 \times 10^{-5}$

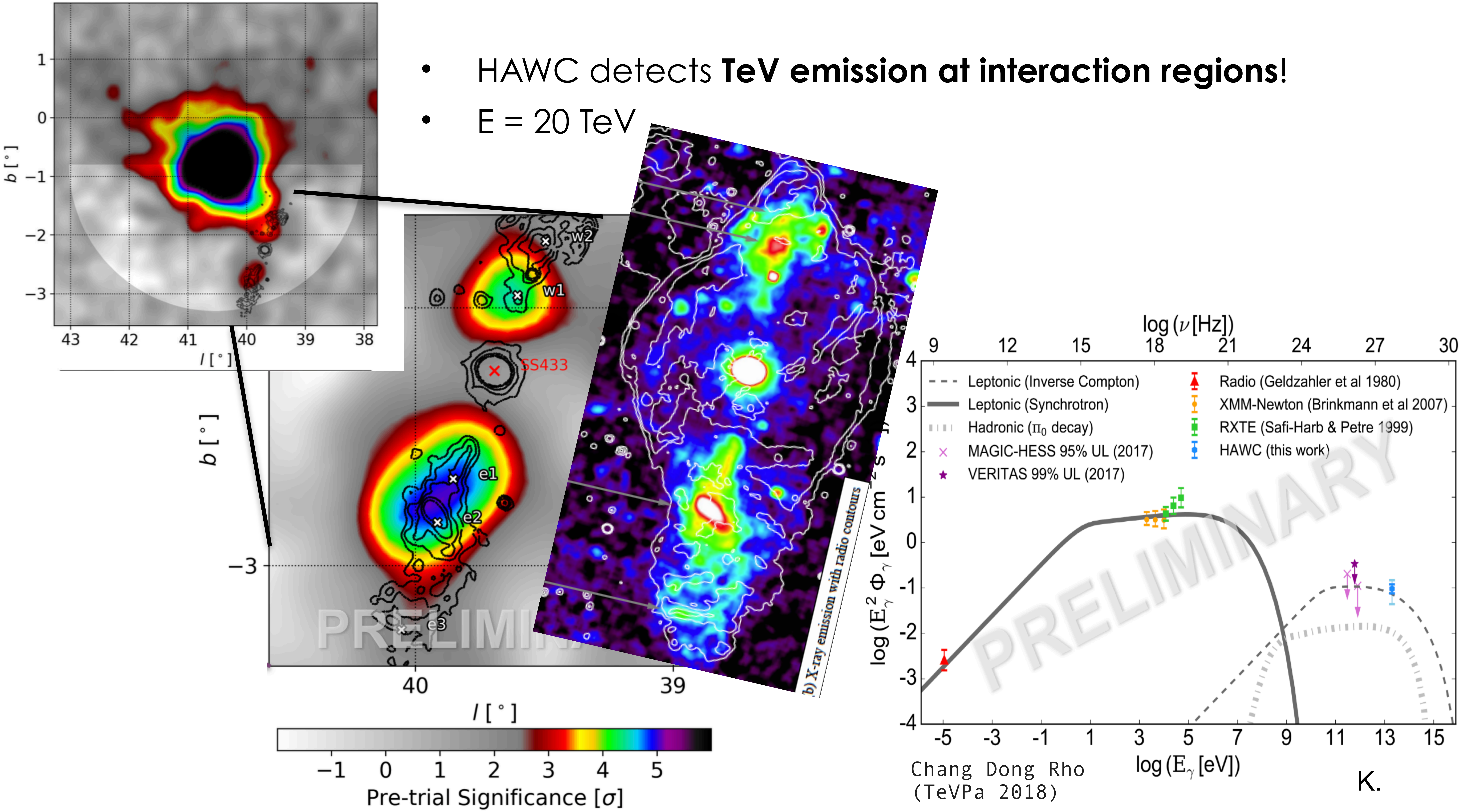
Interaction regions:

Leptonic scenario

- X-ray spectra of **synchrotron origin** -> presence of electrons up to ~50 TeV
  - Expected VHE fluxes (Bordas et al. 2009): **roughly at level of the reported ULs**
- Our **ULs**: constrains on the magnetic field in interaction regions: **lower limit of 20-25μG**

SS433 at **TeV** by HAWC

- HAWC detects **TeV emission at interaction regions**!
- E = 20 TeV



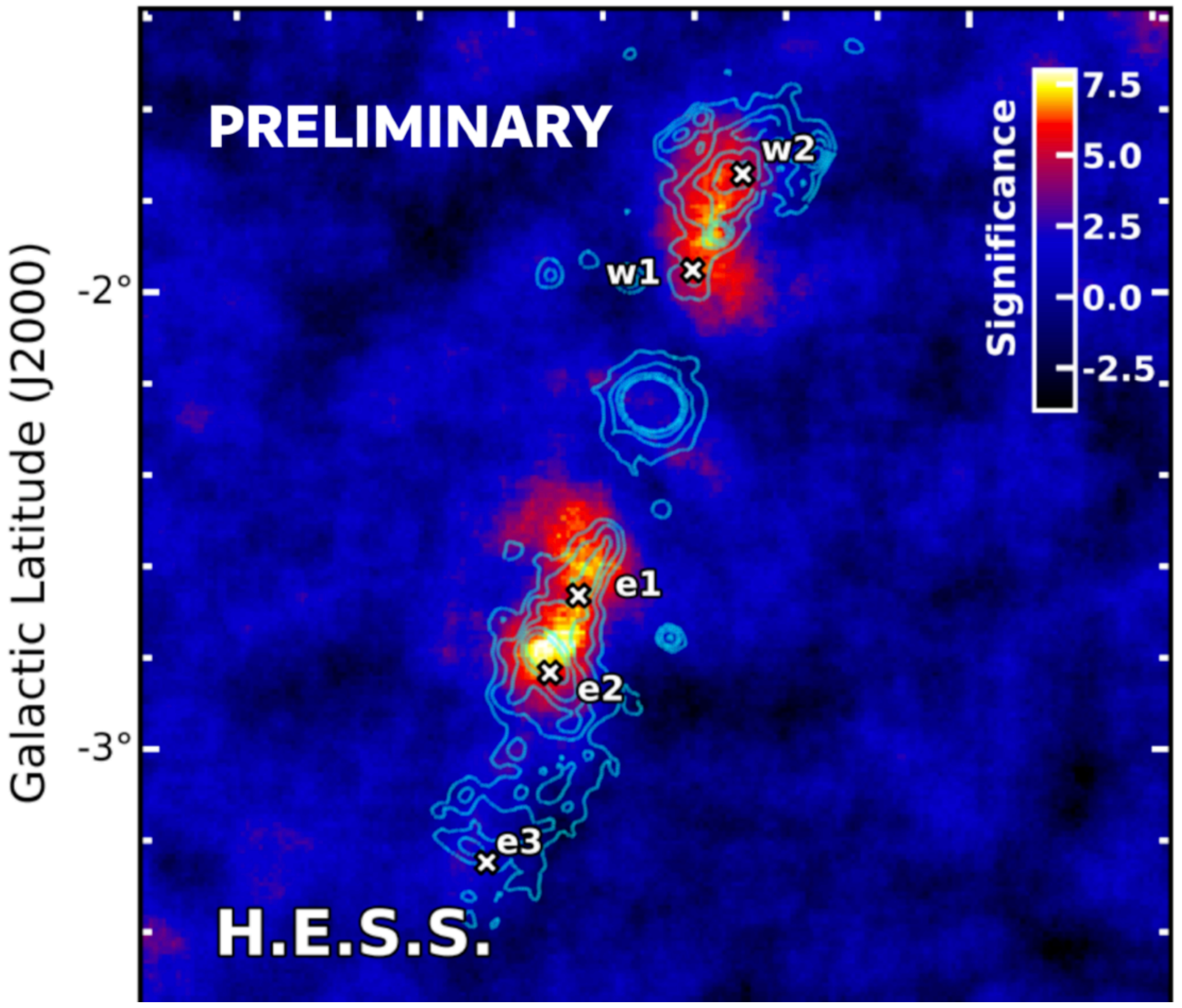
5.4σ (combined) detection **by HAWC** in e1 and w1 (HAWC coll., Nature, 2018)

Also in LHAASO catalog (Cao et al. 2023)

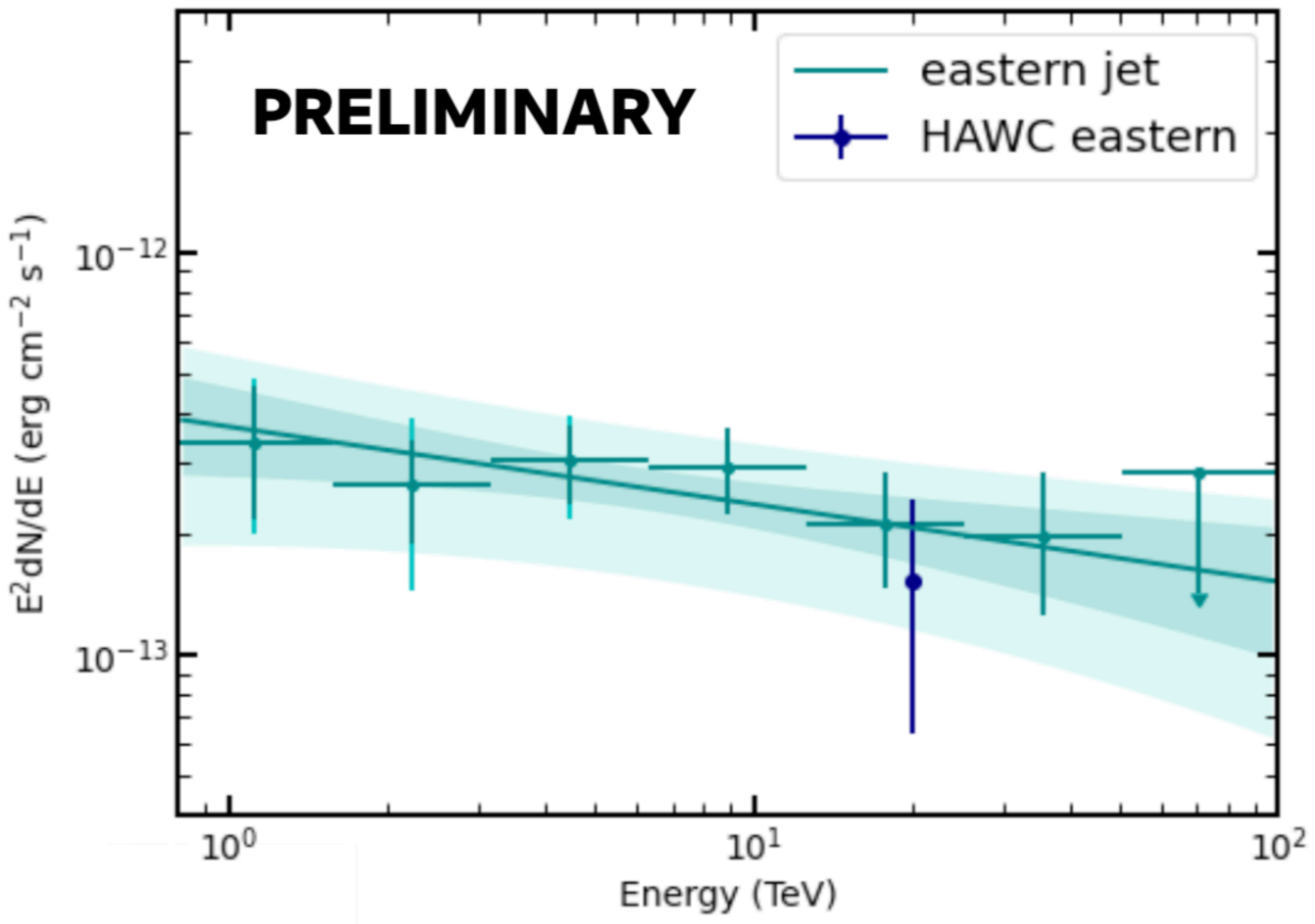
SS433 at **TeV** by HESS

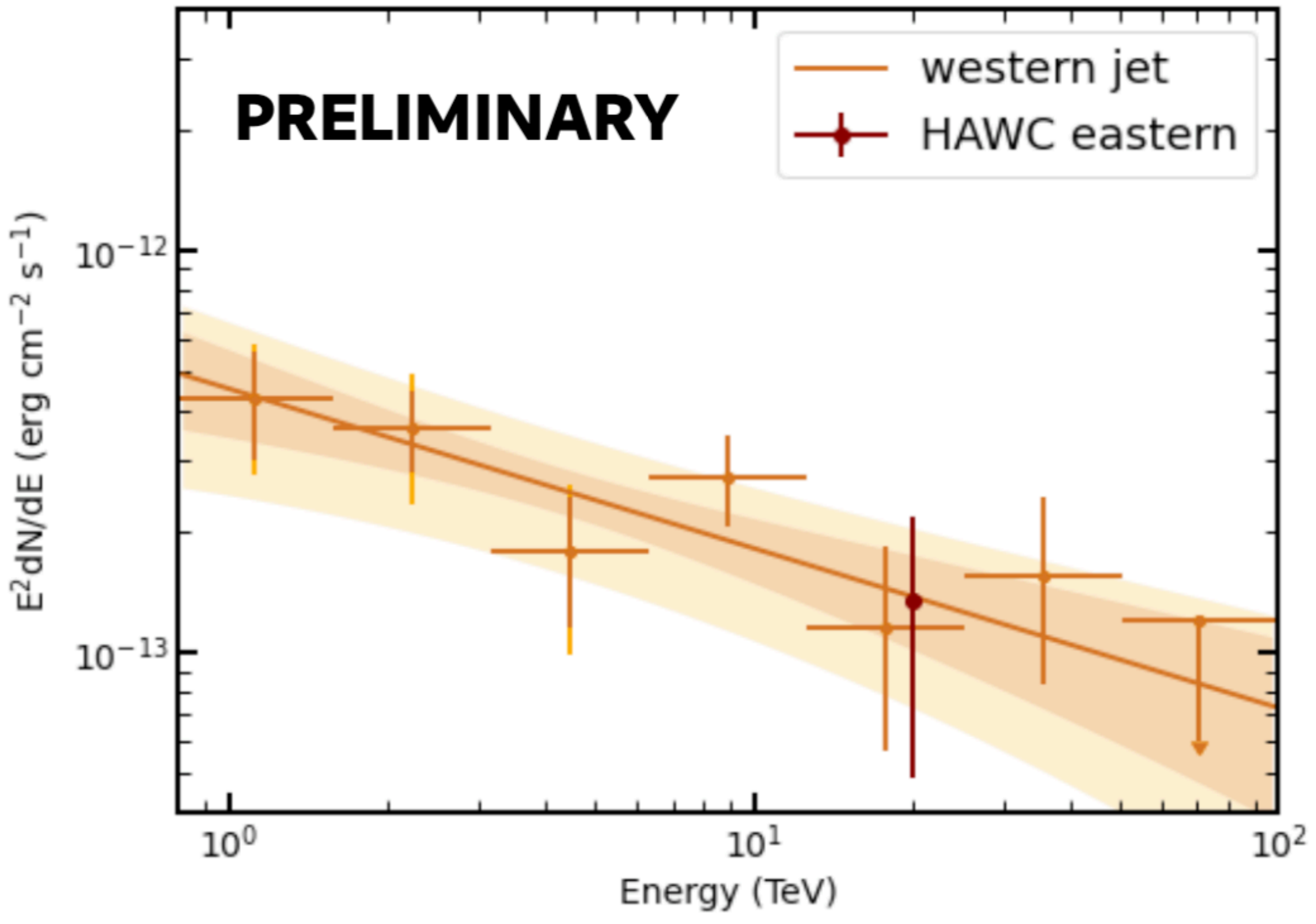
Zoom in to SS 433

- Two separate TeV excess consistent with each of the jets
- Western and eastern jet detected with 6.8σ and 7.8σ respectively
- No detectable emission from the central binary
- No detectable emission past the e2 region in eastern jet



- 300 h of data
- **TeV emission at interaction regions**
- Measured spectra between 800 GeV and 50 TeV
- First microquasar by an IACT



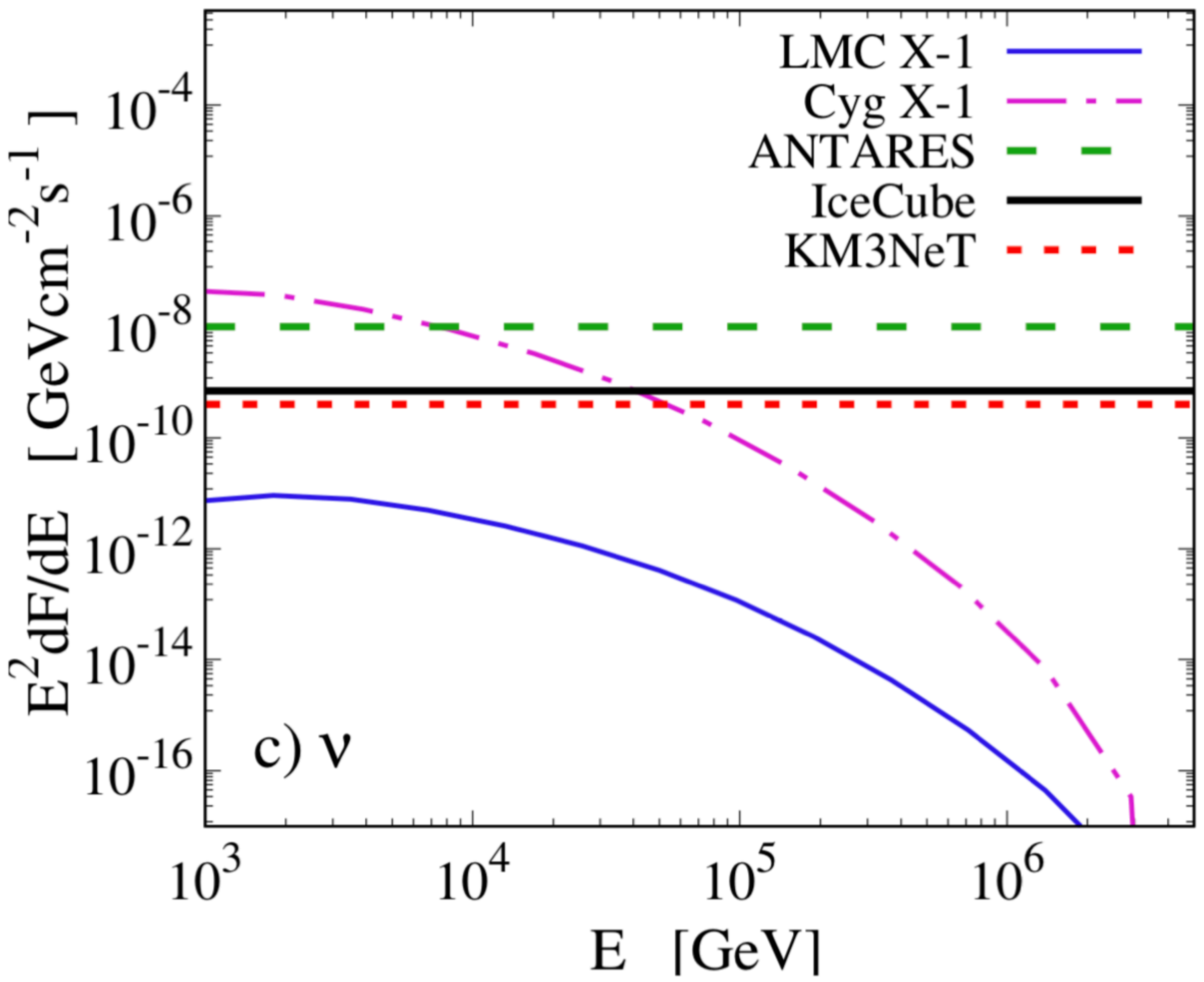


Slide from L. Olivera-Nieto, Gamma 2022

Connected gamma-neutrino emission in microquasars?

- **Protons can be accelerated in microquasar jets -> likely production of neutrinos**
- Neutrino and gamma-ray emissions are products of reaction chains that are caused by the p-p and p-γ interactions inside the jet (Papavasileiou et al. 2021)

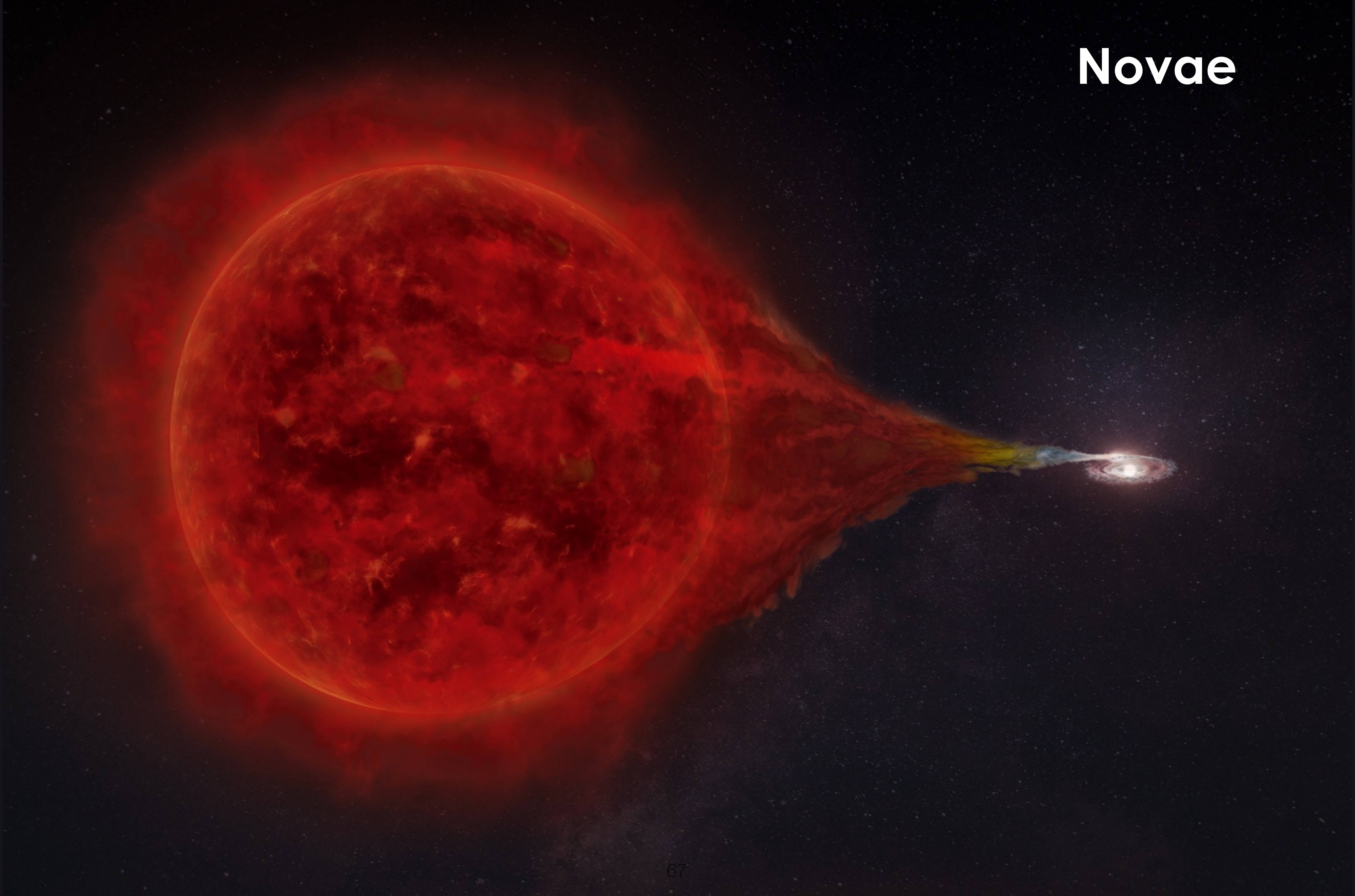
- Tests on **CygX1** and LMC X1 suggest **possible neutrino detection** associated to the former
- Hadronic dark jets of **SS433** could produce neutrino emission (Reynoso et al. 2008)
- Predicted neutrino flux at 1 TeV of $\phi_\nu = 2 \times 10^{-12}$ cm^{-2} s^{-1} (averaged over all precessional phases)
- **UL at 1 TeV** (8 years): $2.71 \cdot 10^{-13}$ TeV cm^{-2} s^{-1} (Aartsen et al. 2019), however it is spatially extended (angular size of up to several degrees >PSF_Icecube) -> analysis sensitivity is reduced.



Papavasileiou et al. 2021

- Icecube has set **ULs to the steady** neutrino flux of many high-mass microquasars such as SS433, CygX1, CygX3 (Aartsen et al. 2019) after 8 years of data-> **is transient emission still possible**?

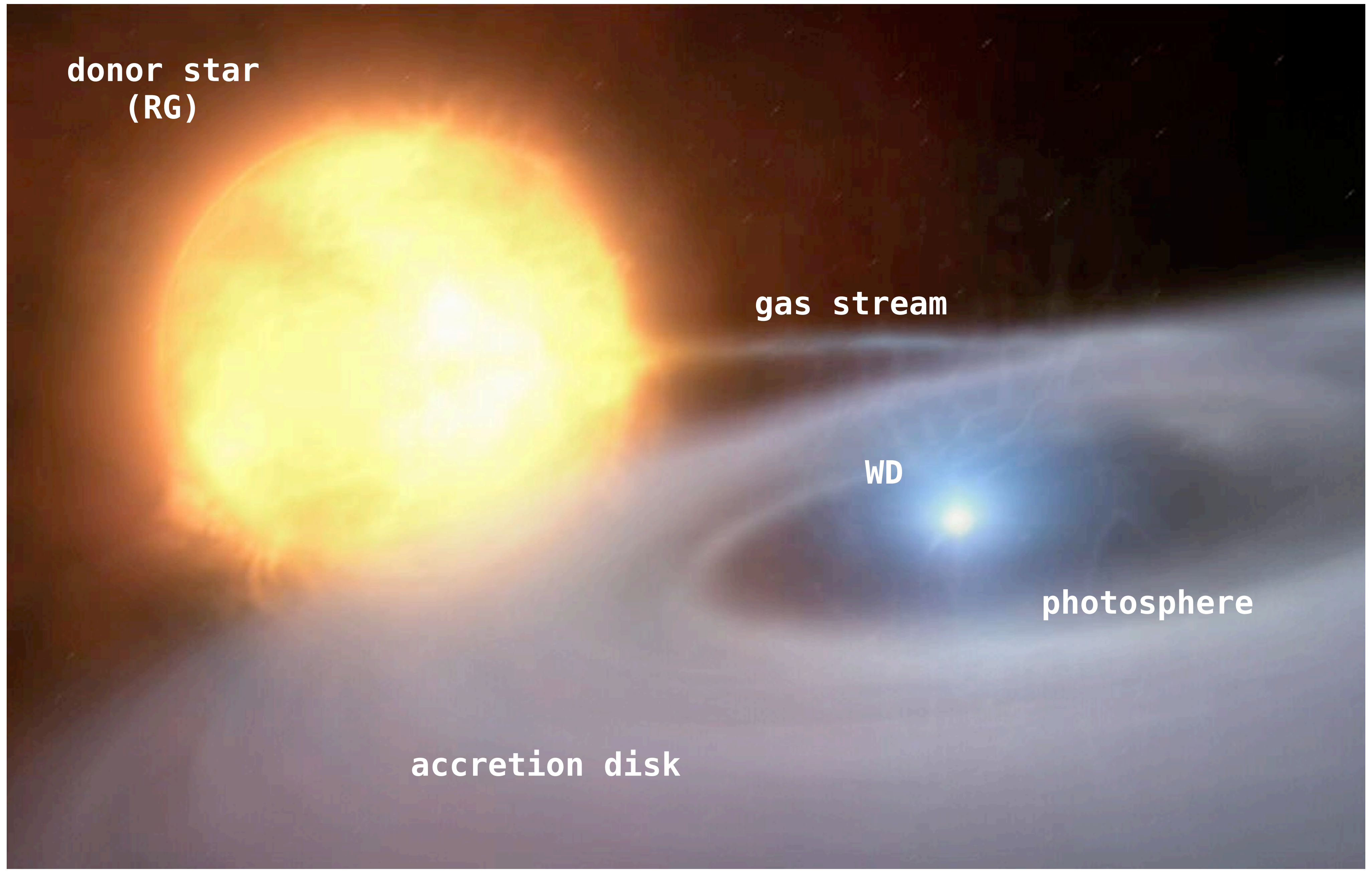
Novae



Novae

- Novae are **thermonuclear explosions** caused by accumulation of material from **donor star** on a surface of a **white dwarf (WD)**

- Classification depening on the donor star:
  - **Symbiotic binary:** the donor star is a **red giant (RG).** The **WD is immersed in the RG wind**
  - **Classical novae:** the donor is a low-mass star
- Novae outbursts usually last from weeks to months
- Some novae show repeated outbursts within a human lifetime: **recurrent novae (RN)**

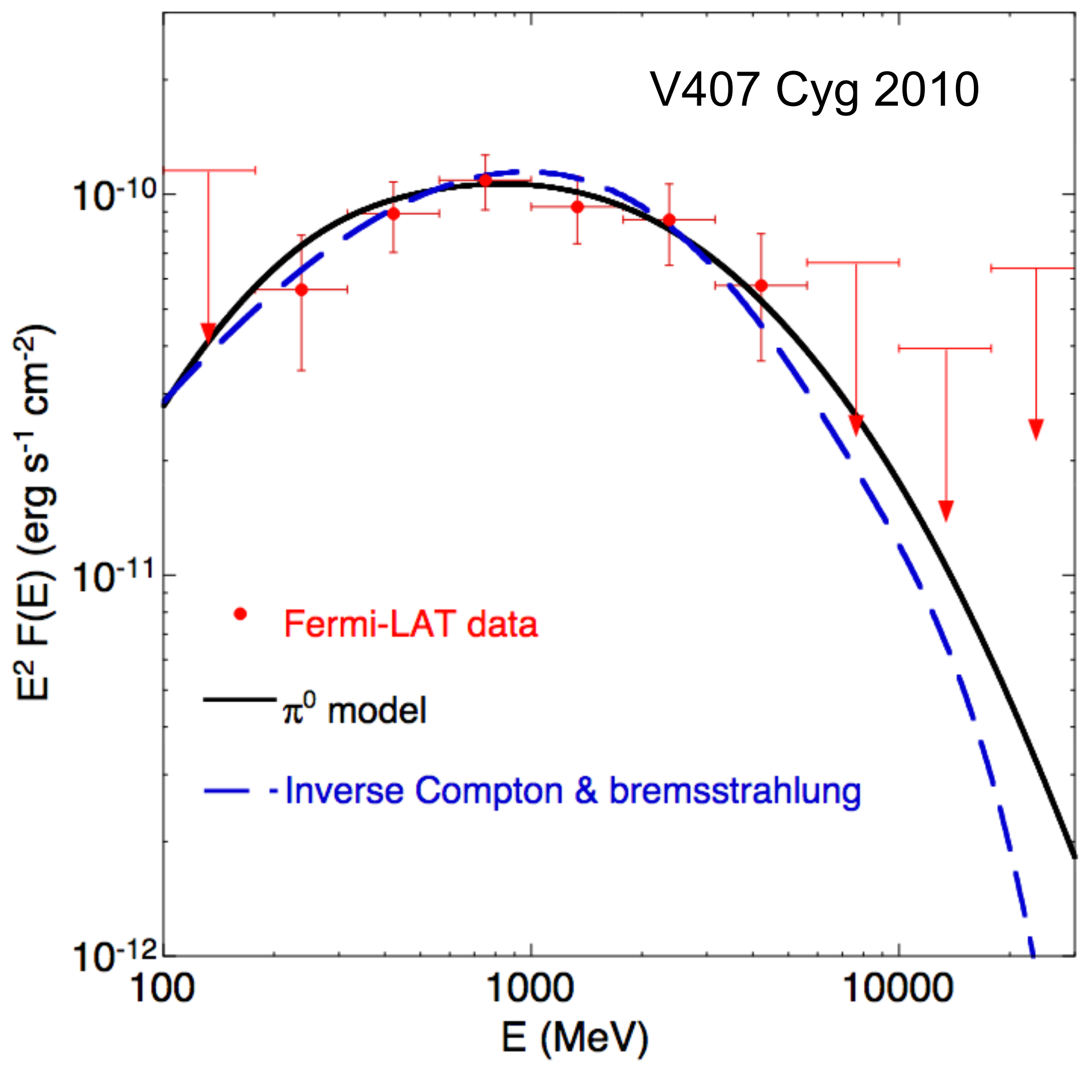


Credit: ESO / M. Kornmesser

Novae: sources of HE gamma rays

- The first nova to be detected by ***Fermi*-LAT** was the **symbiotic** system V407 Cyg (*Fermi*–LAT, Science, 2010)

- **Novae established as HE emitters (HE, E>100 MeV)**



Fermi–LAT, Science, 2010

Novae: sources of HE gamma rays

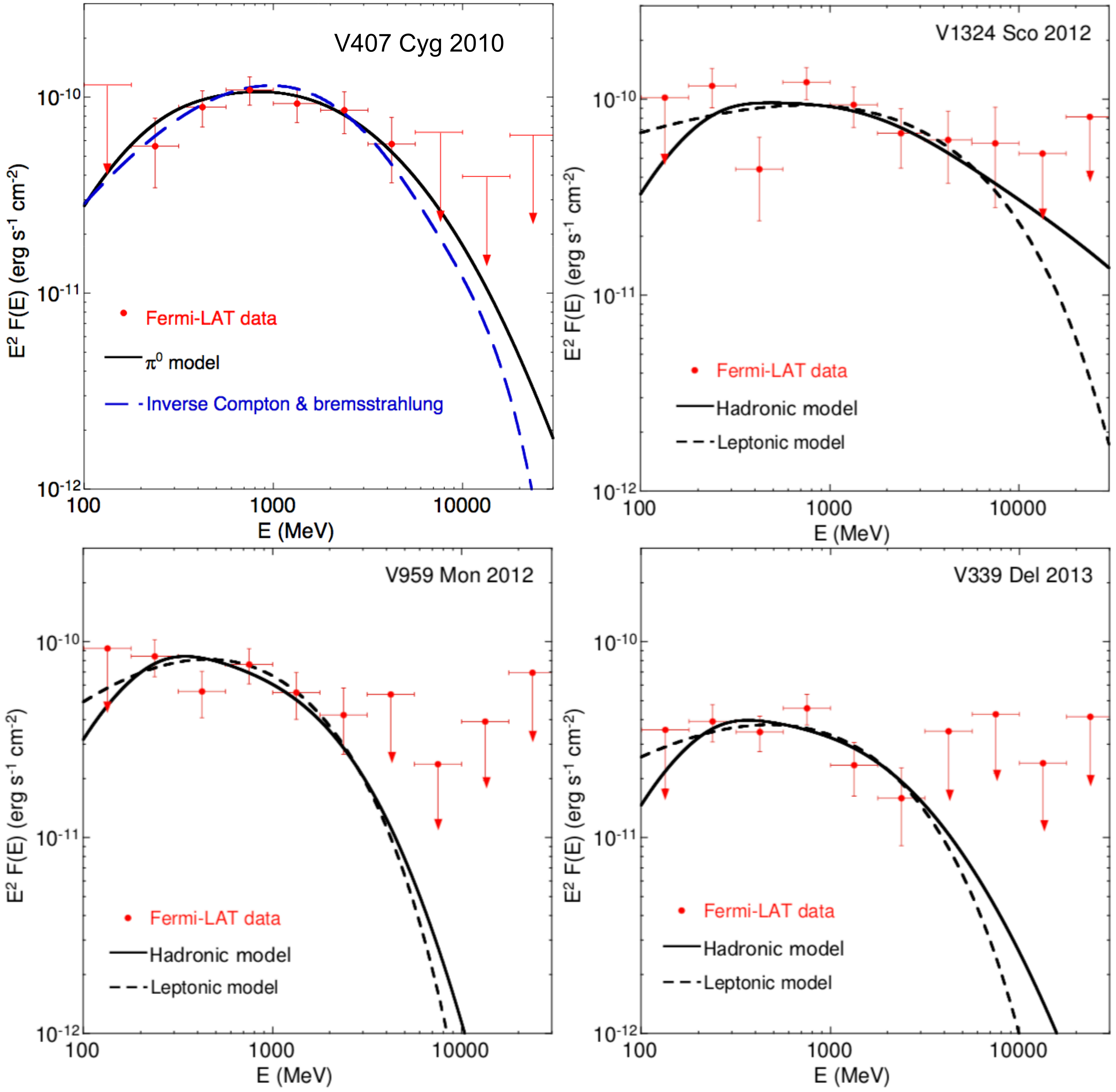
- The first nova to be detected by ***Fermi*-LAT** was the **symbiotic** system V407 Cyg (*Fermi*–LAT, Science, 2010)

- **Novae established as HE emitters (HE, E>100 MeV)**

- **Classical** novae (WD+low-mass star) are also **sources of HE gamma rays** (*Fermi*–LAT, Science, 2014)

- Emission could be explained with either **pp interaction** or **leptonic models** (IC+Brems.)

- SED measured up to 6 – 10 GeV

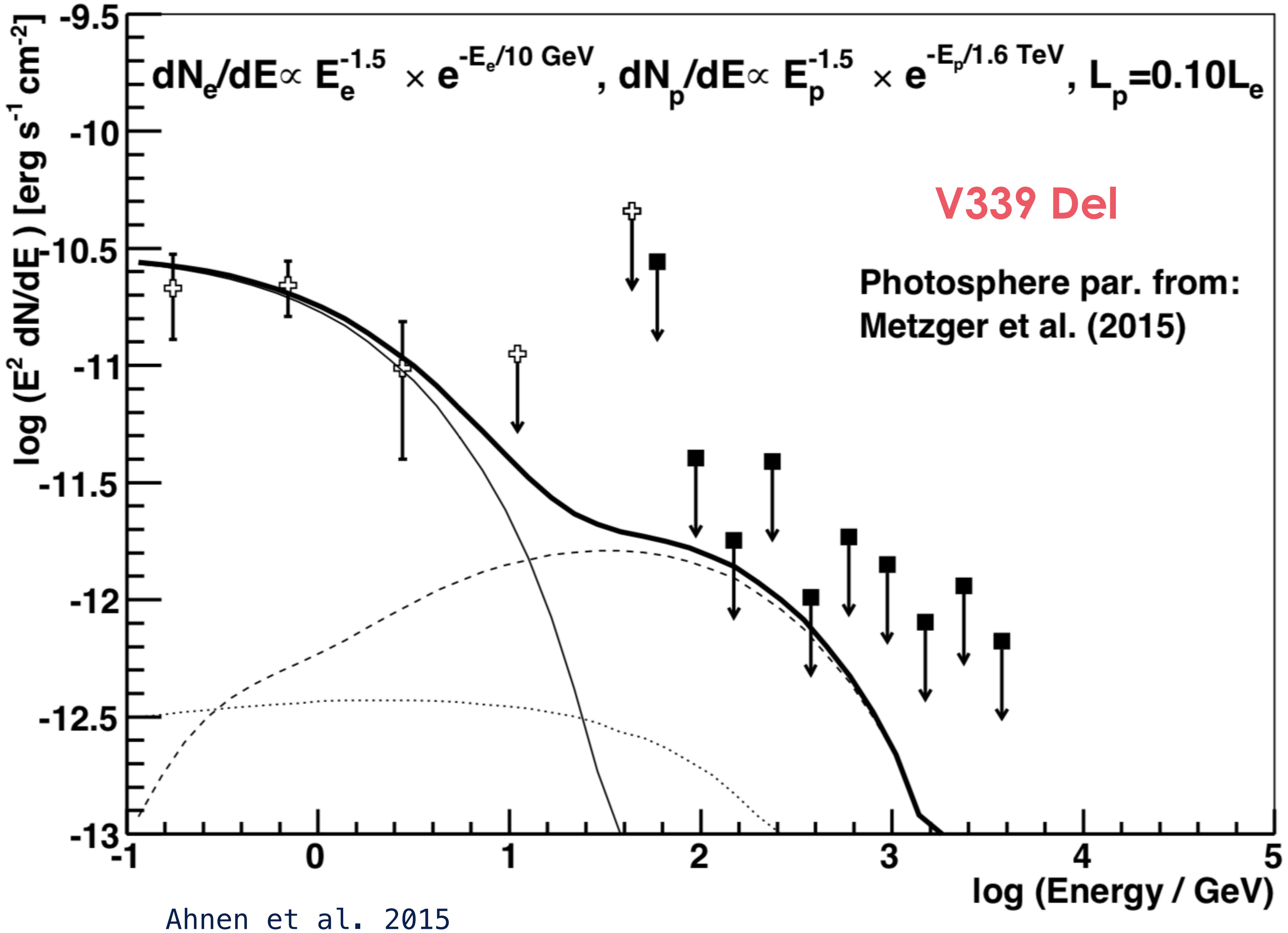


Fermi–LAT, Science, 2014

Are novae very-high-energy (VHE, E>100 GeV) emitters?

Searching for VHE emission

- **HE data alone is not enough** to disentangle electron and proton **acceleration models**
- Particles are accelerated in nova shock, **non-thermal processes** are at work
- **Protons can reach much higher energies due to lower energy losses** and thus possibly produce a second component detectable by IACTs
- IACTs had searched for a VHE component in novae for more than a decade (Aliu et al. 2012, Ahnen et al. 2015)

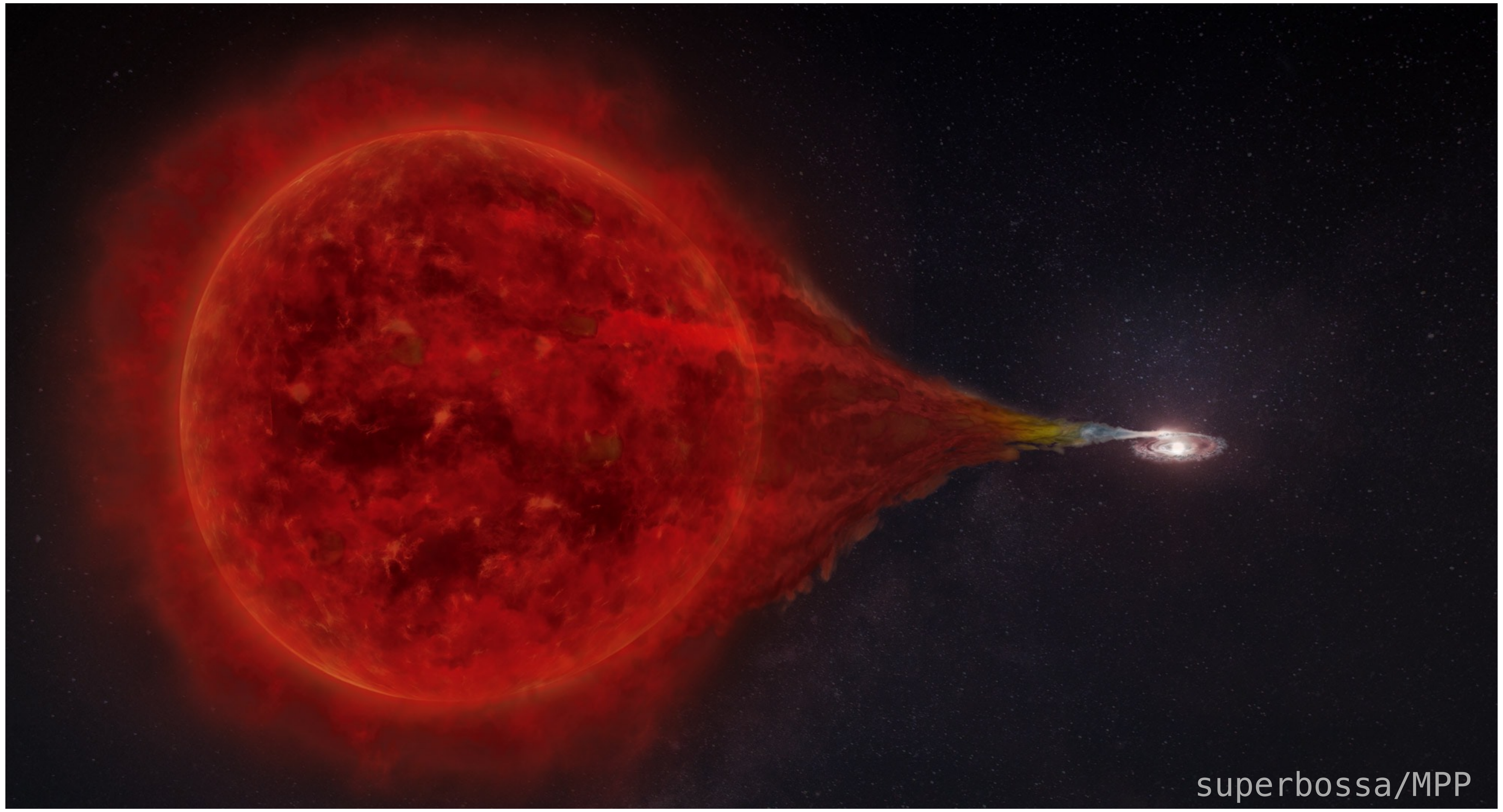


Ahnen et al. 2015

RS Ophiuchi

- RS Oph is a **recurrent symbiotic nova** which displays major **outbursts every ~15 years**
  - WD + M0-2 III RG star
    - M_{WD} = and M_{RG} = 0.68–0.80M⊙
  - Distance: 2.45 pc (Rupen et. al. 2008)
    - Recent Gaia DR3: parallax distance of 2.69 ± 0.18 kpc
  - Nine eruptions between 1898 and 2021
    - **Latest outburst: August 2021**

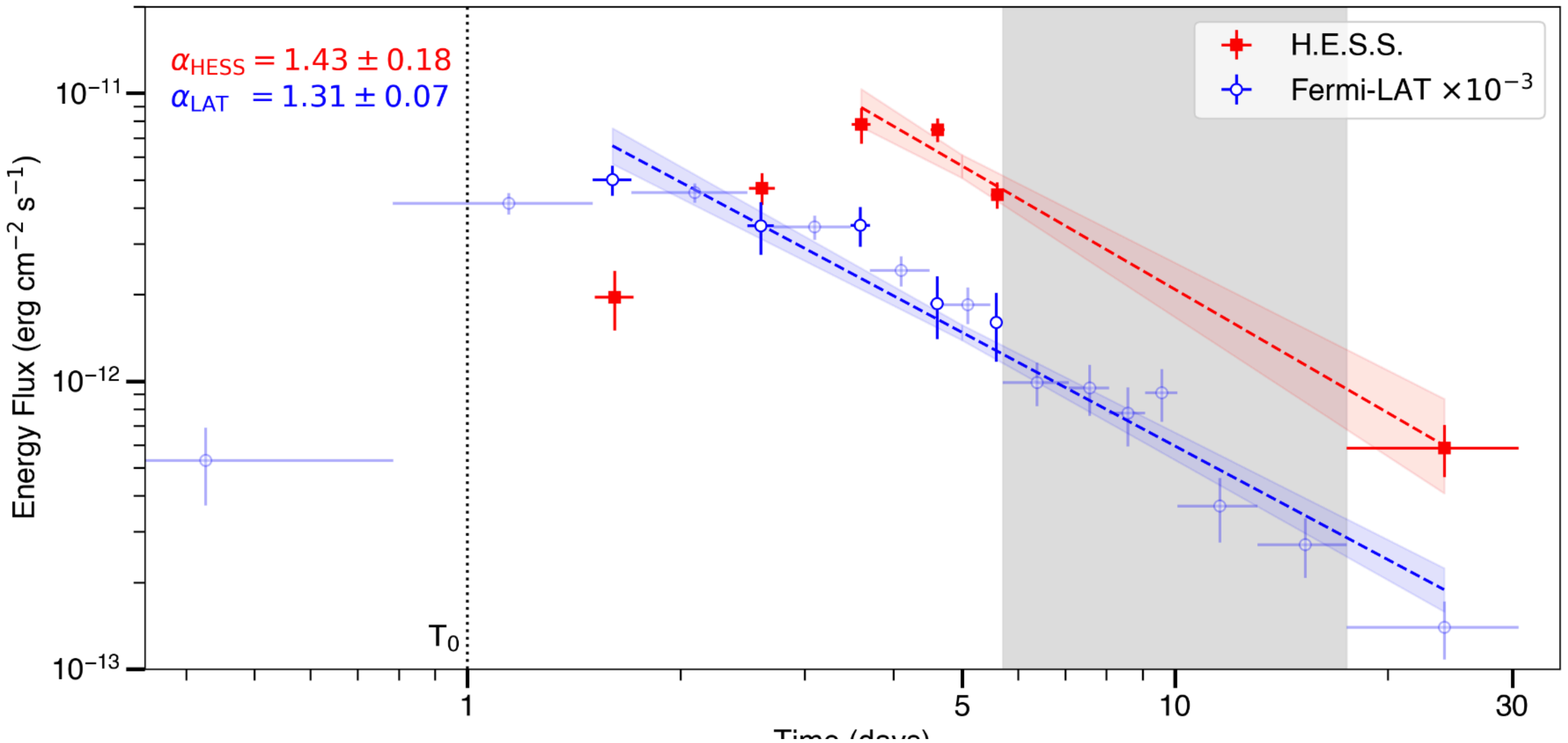
- **GeV emitter candidate:**
  - 2006 outburst of RS Oph detected by Swift/BAT could not be accounted by the decay of radioactive isotopes
  - Emission could be explained **via the production of non-thermal particles by diffuse shock acceleration** (Tatischeff et al. 2007)



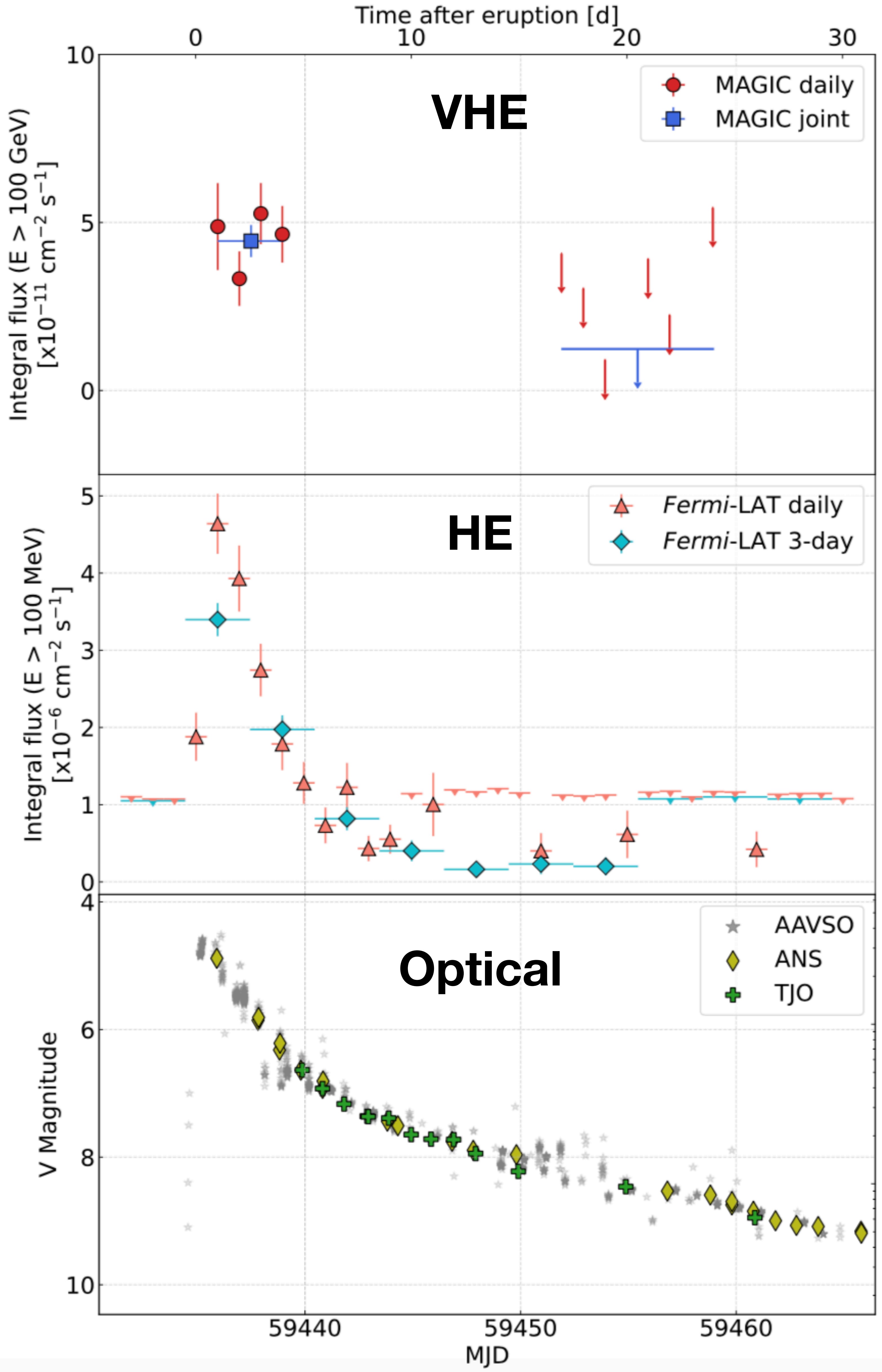
MWL view

- **First nova detected in the VHE regime** (HESS coll Science 2022, MAGIC coll Nature Astr. 2022)

Novae established as a new type of source of VHE gamma rays



- HESS coll Science 2022

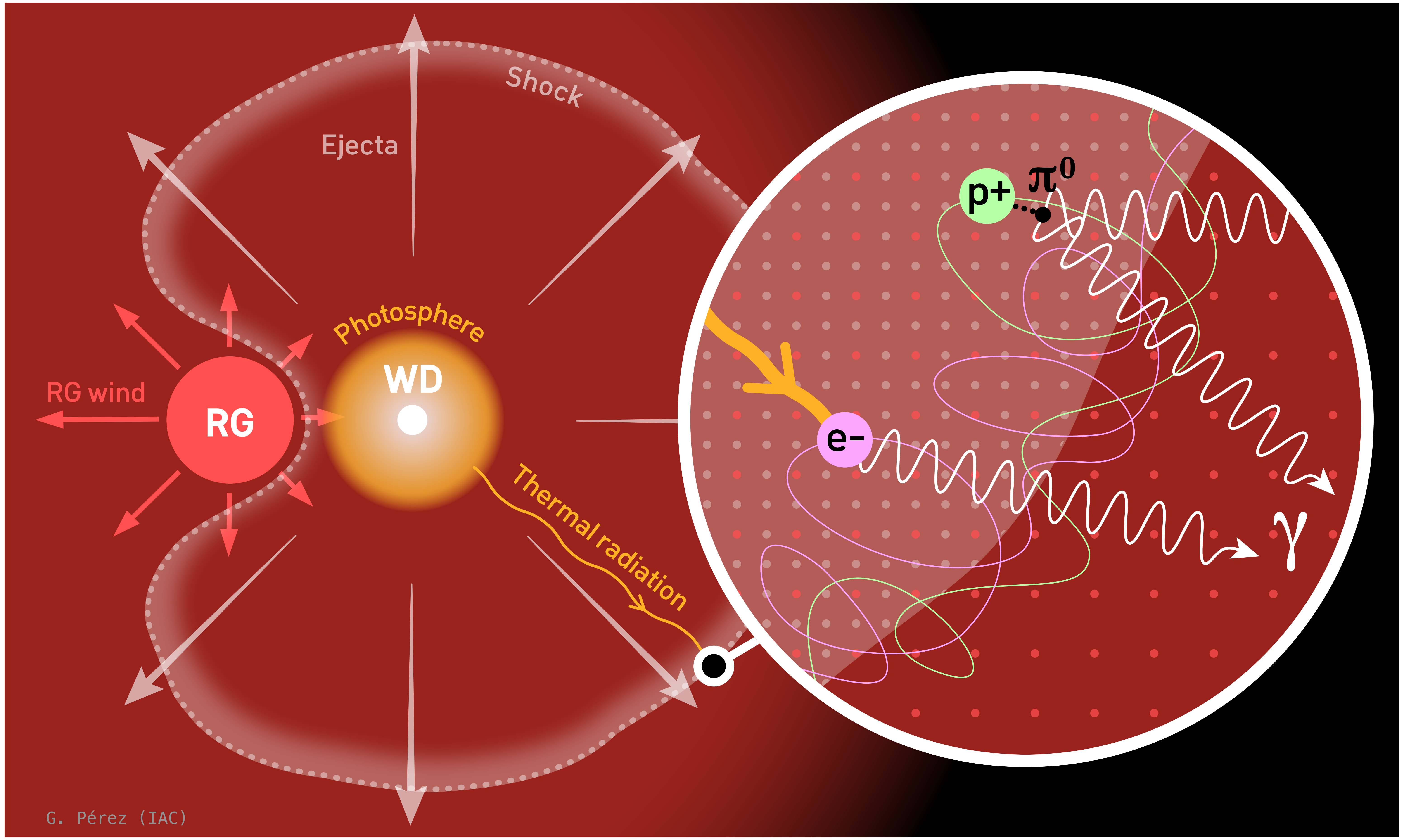


(Acciari et al. Nat. Astronomy, 2022)

RS Ophiuchi

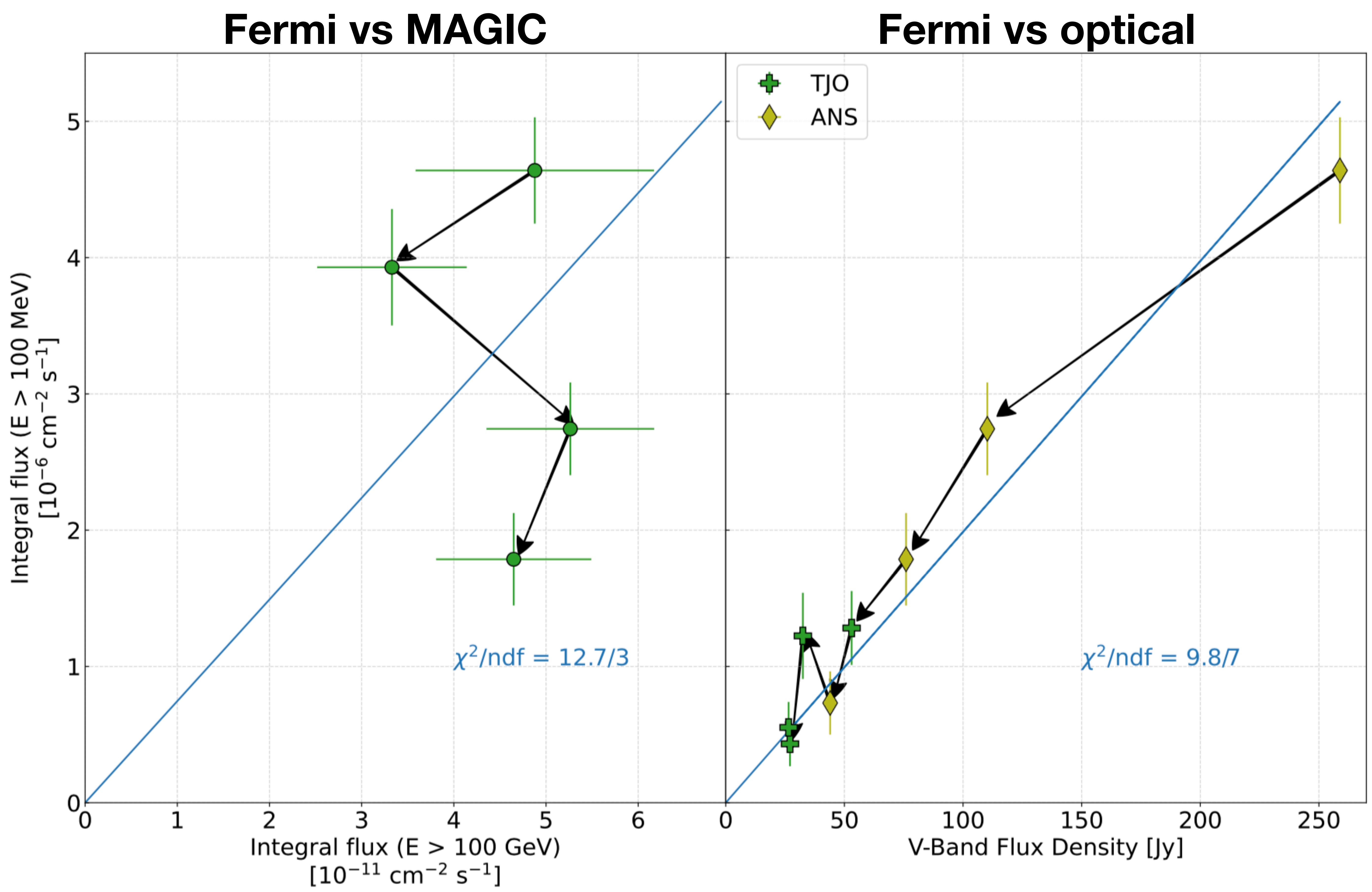
superbossa.com/MPP

What's going on?



- **Protons**: pp interaction on **nova ejecta** (with some contribution from RG wind)
- **Electrons**: IC on thermal radiation of the **WD photosphere**
- Modeling: particles are injected and either **cool down completely (electrons)** or we gather their emission during the **acceleration time (protons)**

MWL flux evolution

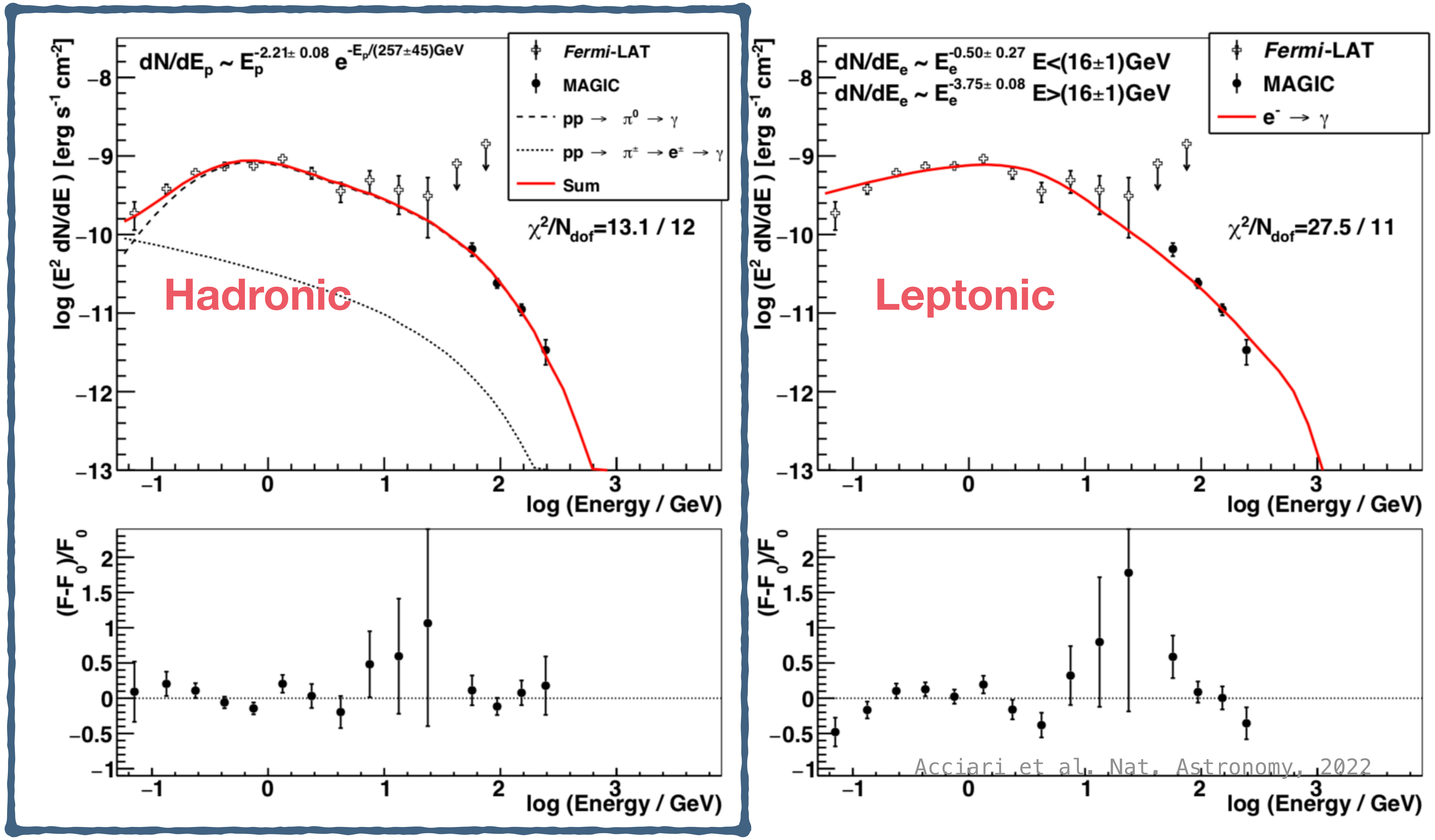


Acciari et al. Nat. Astronomy, 2022

- **VHE rougly flat, while HE decays faster**: can be explained as **hardening of the emission** during its decay
- **HE and optical** emission show **similar decay**: **not compatible with IC** model
  - IC emission should decay faster (due to increase of distance to photosphere)

- **Protons are favored**

Gamma-ray modelling



- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**
- **Hadronic scenario is favored**

Gamma-ray modelling: daily proton acceleration

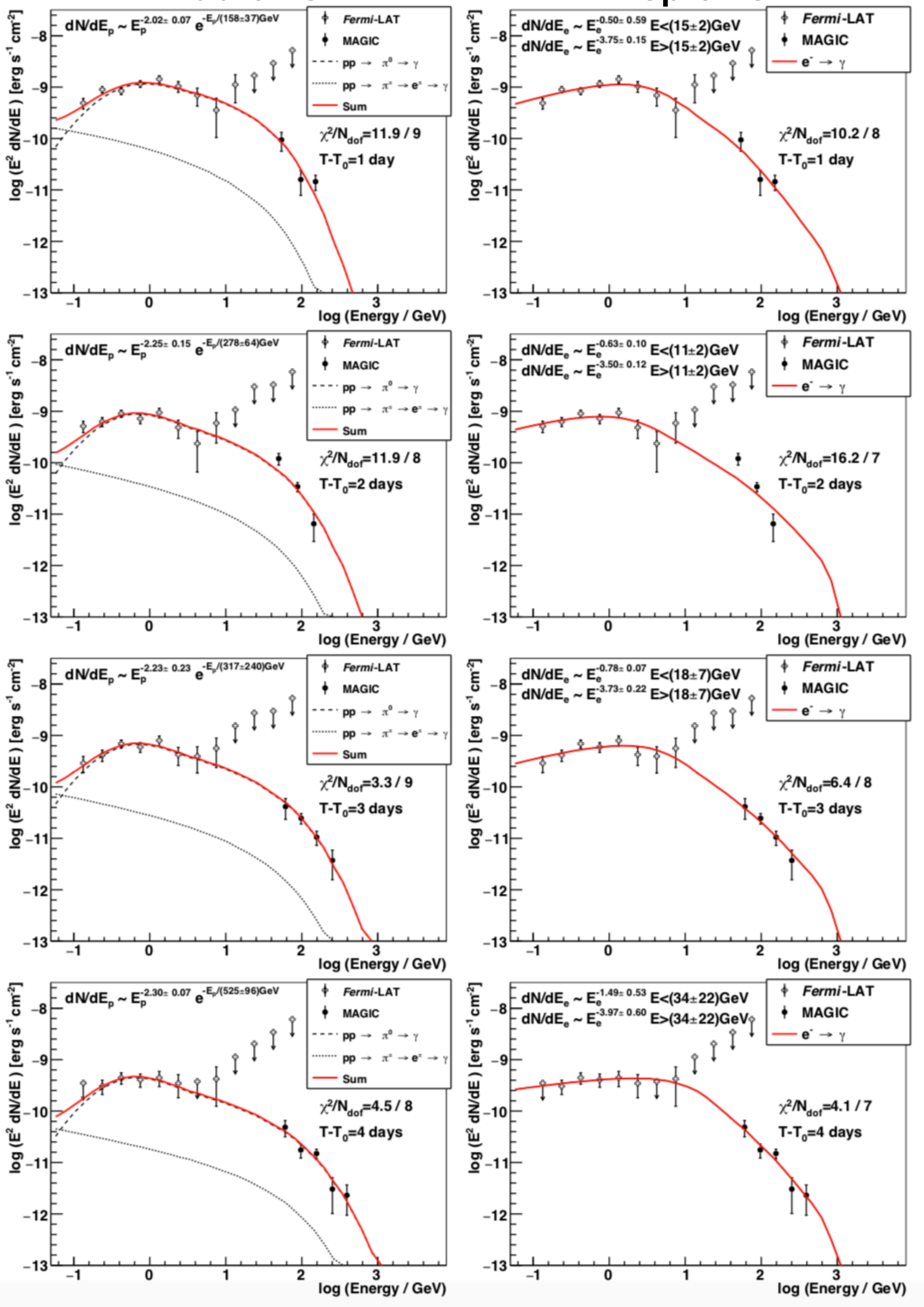
Hadronic | Leptonic

Aug 09

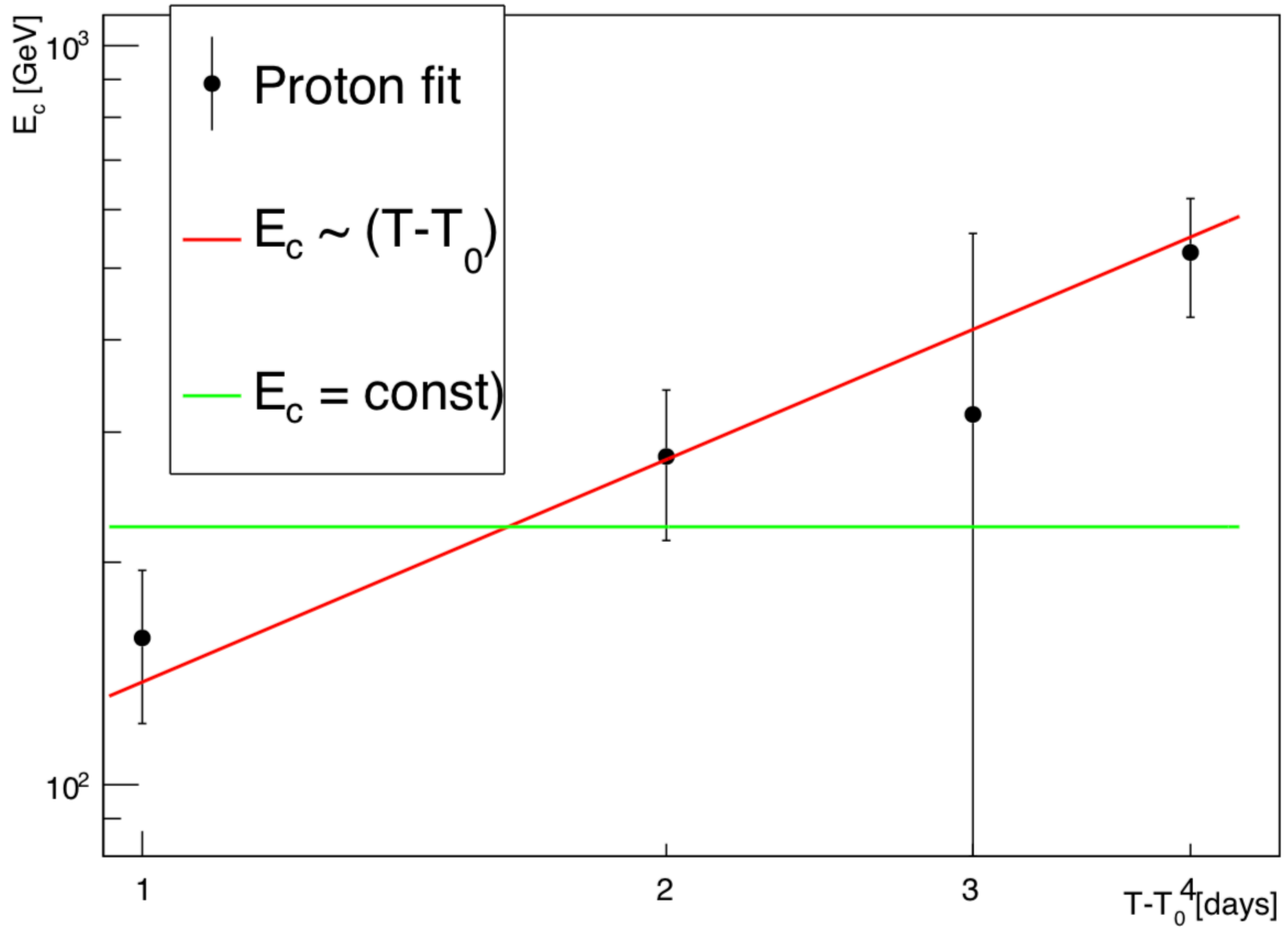
Aug 10

Aug 11

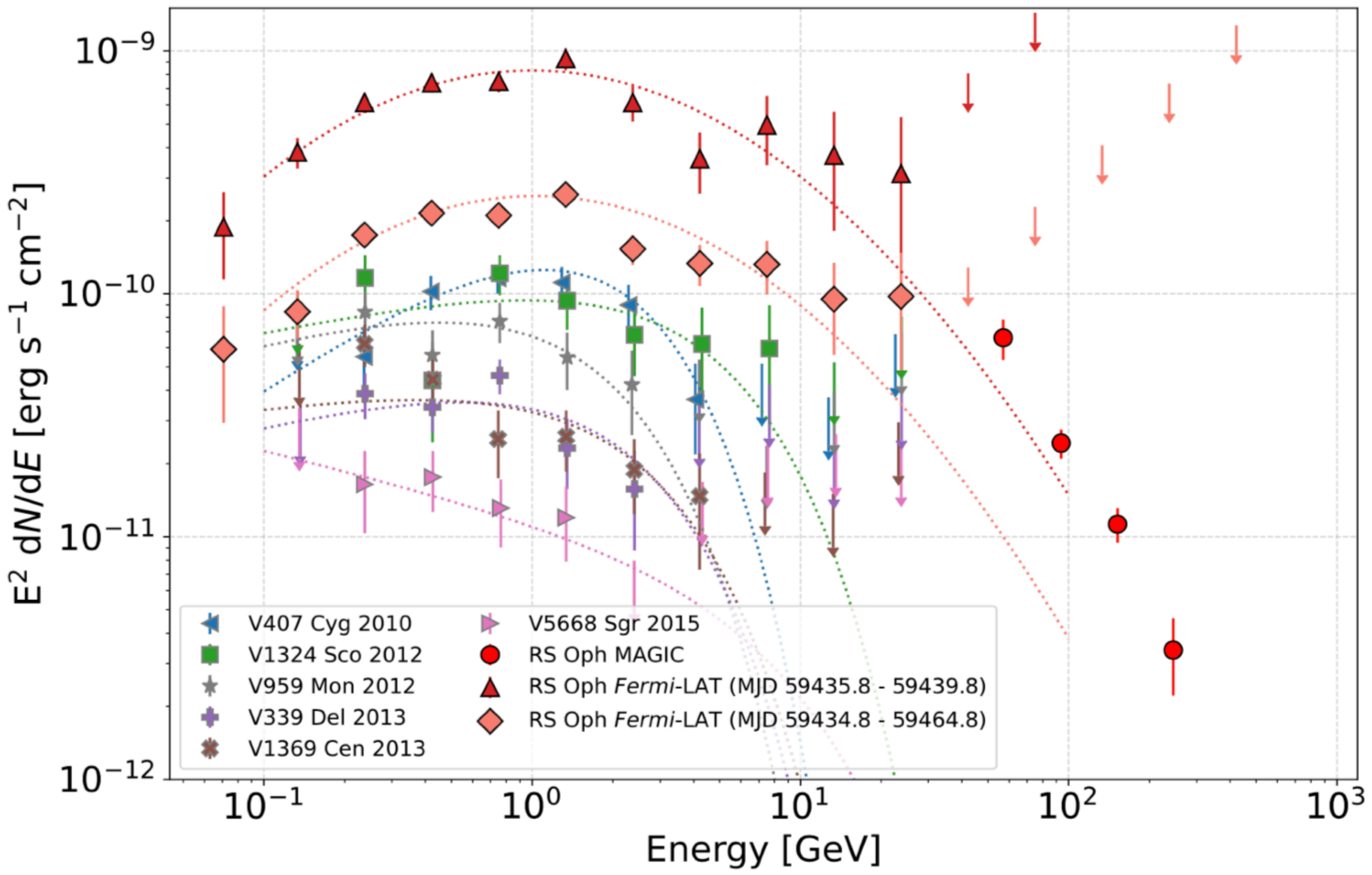
Aug 12

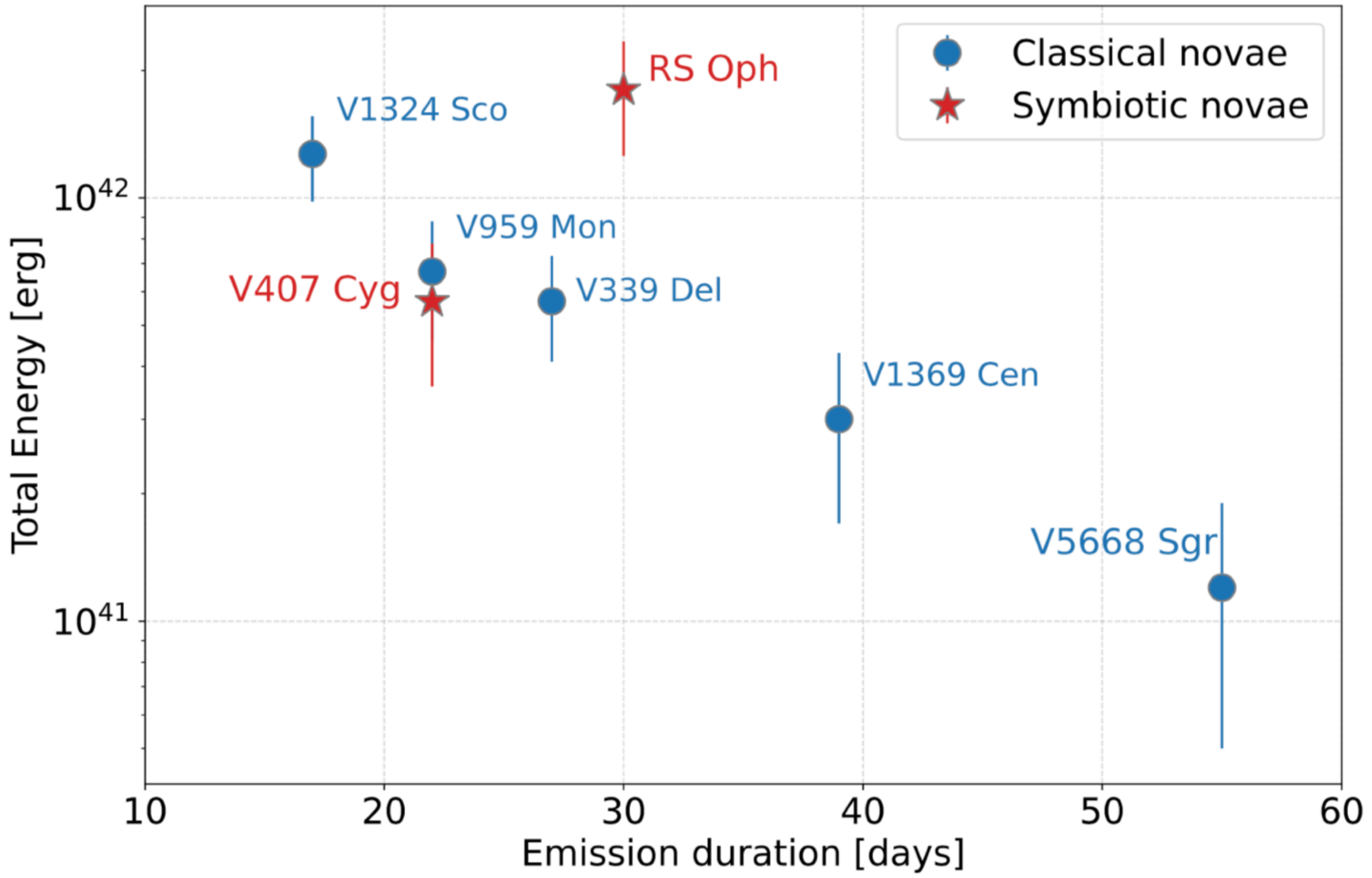


- **Daily SED**
  - **Hadronic scenario favored**
- **Increase of the cut-off energy with time:** hint of spectral hardening
  - In line with the expectations from the cooling and acceleration timescales
  - **Hadronic scenario favored**



Comparison with other novae

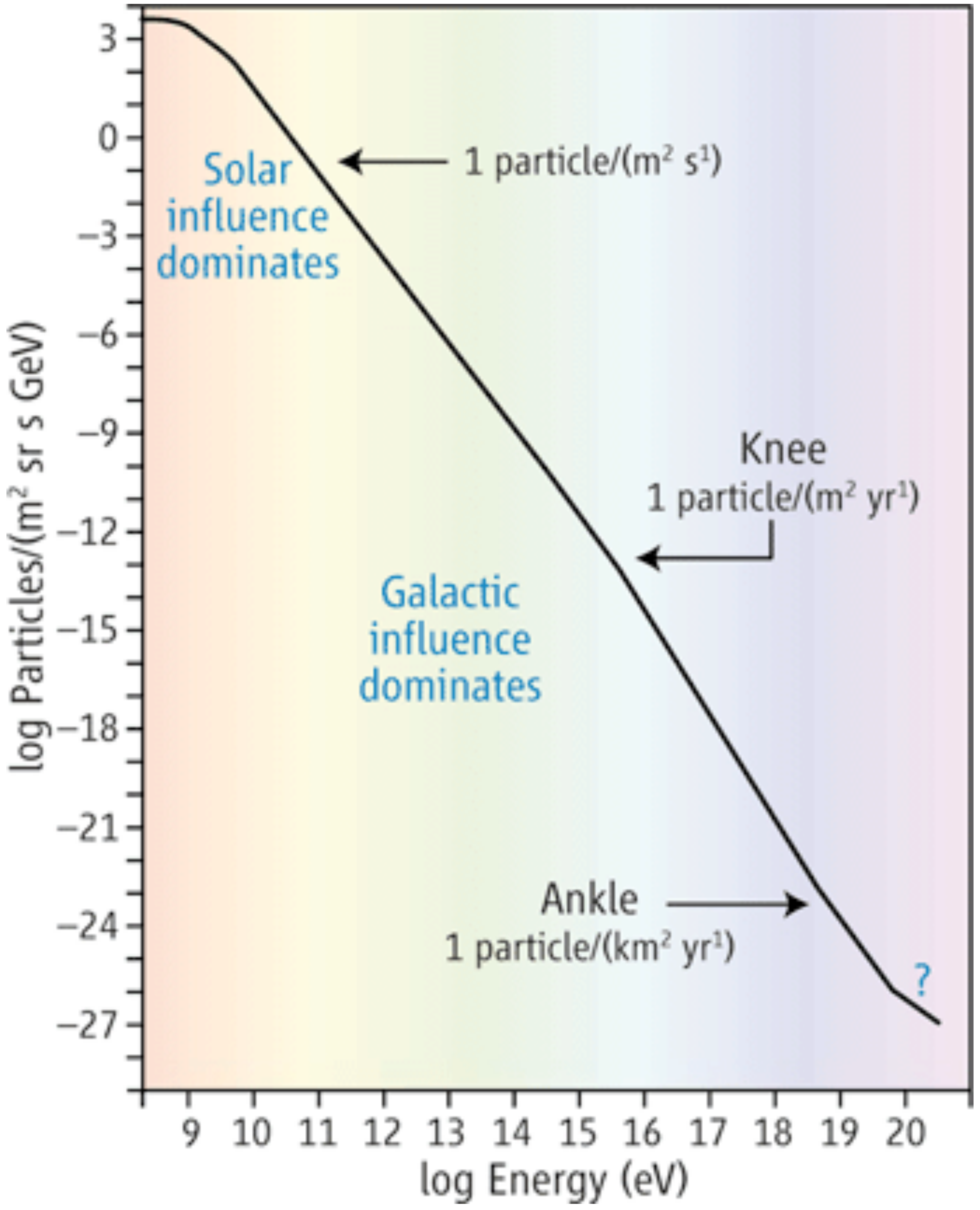




- RS Oph is the nova with the **highest flux** and **brightest nova**
  - Almost two orders of magnitude larger than previously-detected eruptions
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness

Galactic novae and cosmic rays

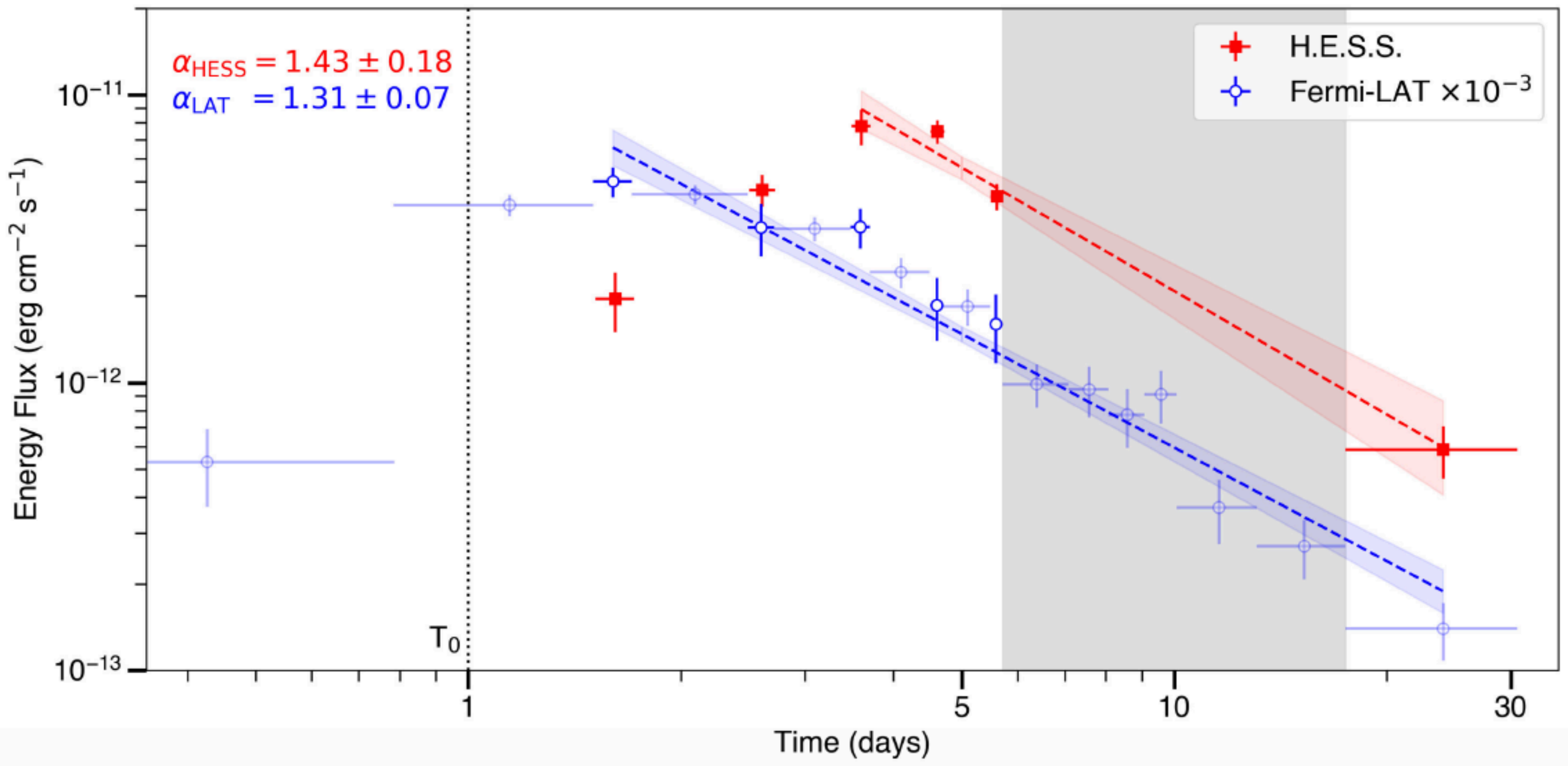
- **Accelerated protons will eventually escape the nova shock** carrying away most of their obtained energy. Such protons can **contribute to the Galactic Cosmic Ray sea**
- Using the CR energetic derived for RS Oph (~ 4.4×10^{43} erg): **<0.2% of the contribution from supernovae**
- Despite the small contribution to the overall CR sea, **novae would significantly increase the CR density in its close environment**: E_density(nova)>E_density(CR)
- In the case of **recurrent novae, protons will accumulate in a ~10 pc bubble with enhanced CR density**



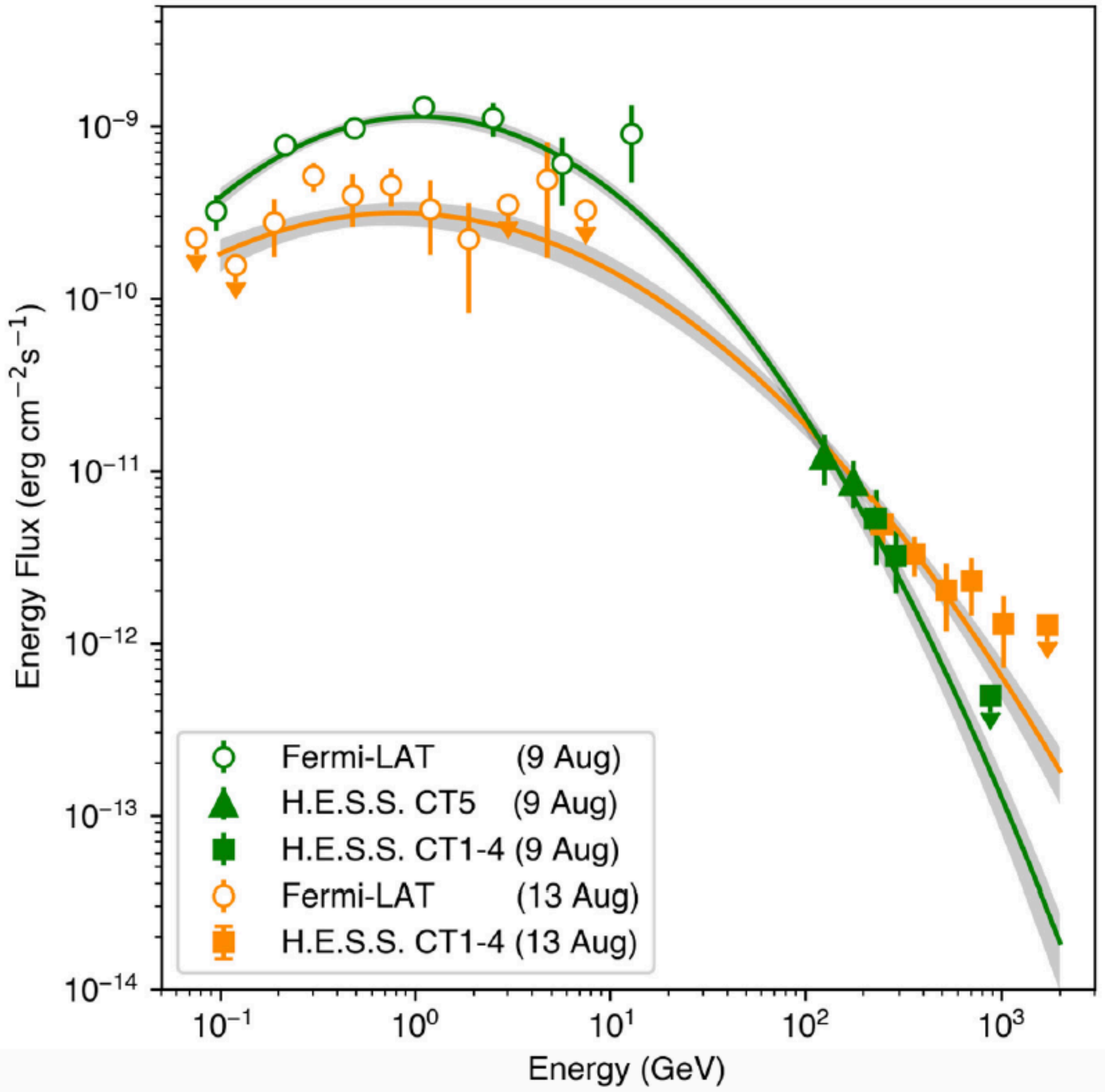
Extracted from Dulgig, Science 2020

RS Oph at gamma rays: H.E.S.S.

- Fermi-LAT & H.E.S.S. combined analysis
  - Finite acceleration of VHE protons (delayed VHE peak)
  - Single γ-ray component (similar temporal profiles & spectra)
- Hadronic scenario is preferred
  - Efficient acceleration up to $E_{p,max} \approx 10$ TeV



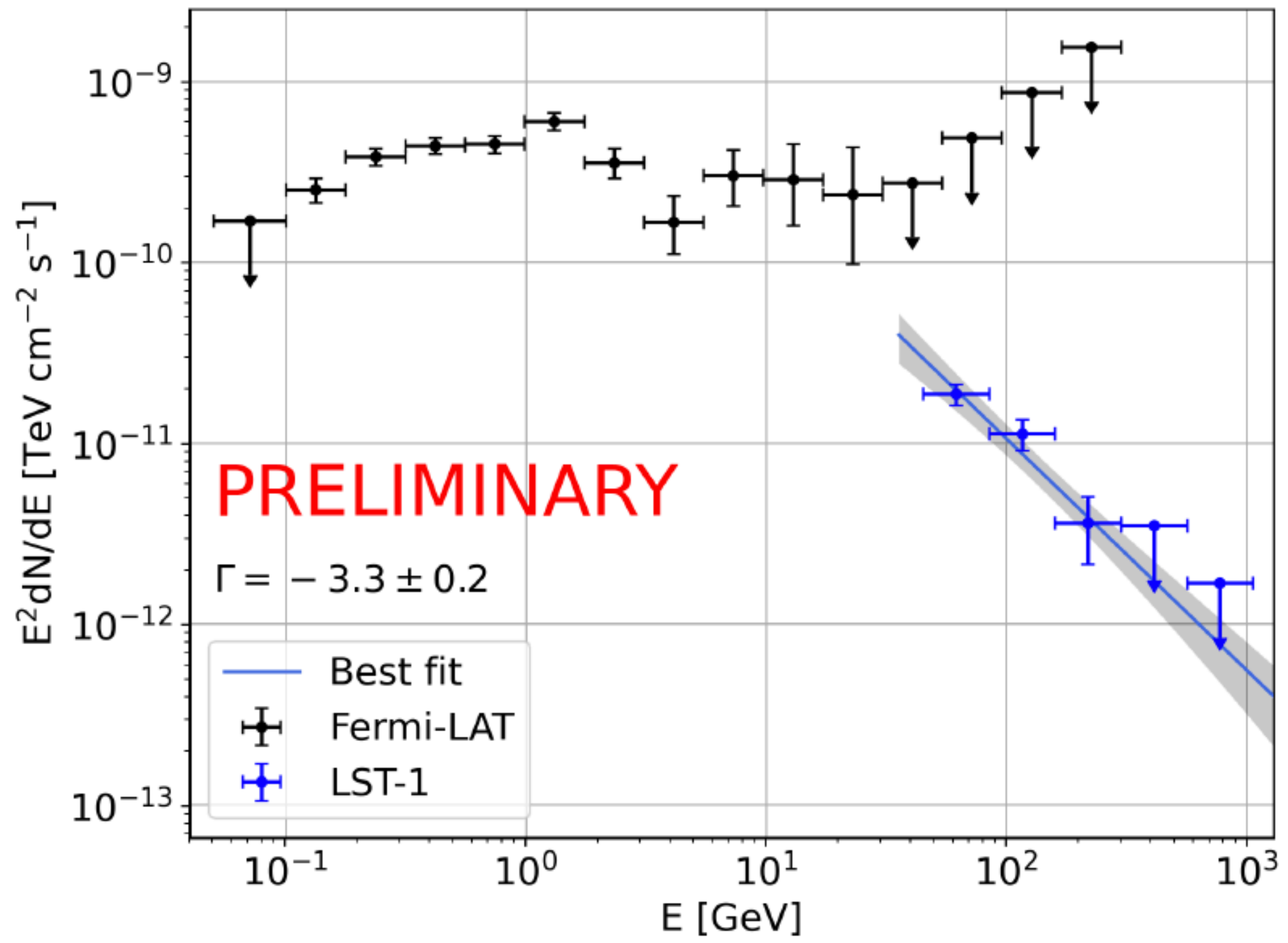
Source: H.E.S.S. Collaboration 2022



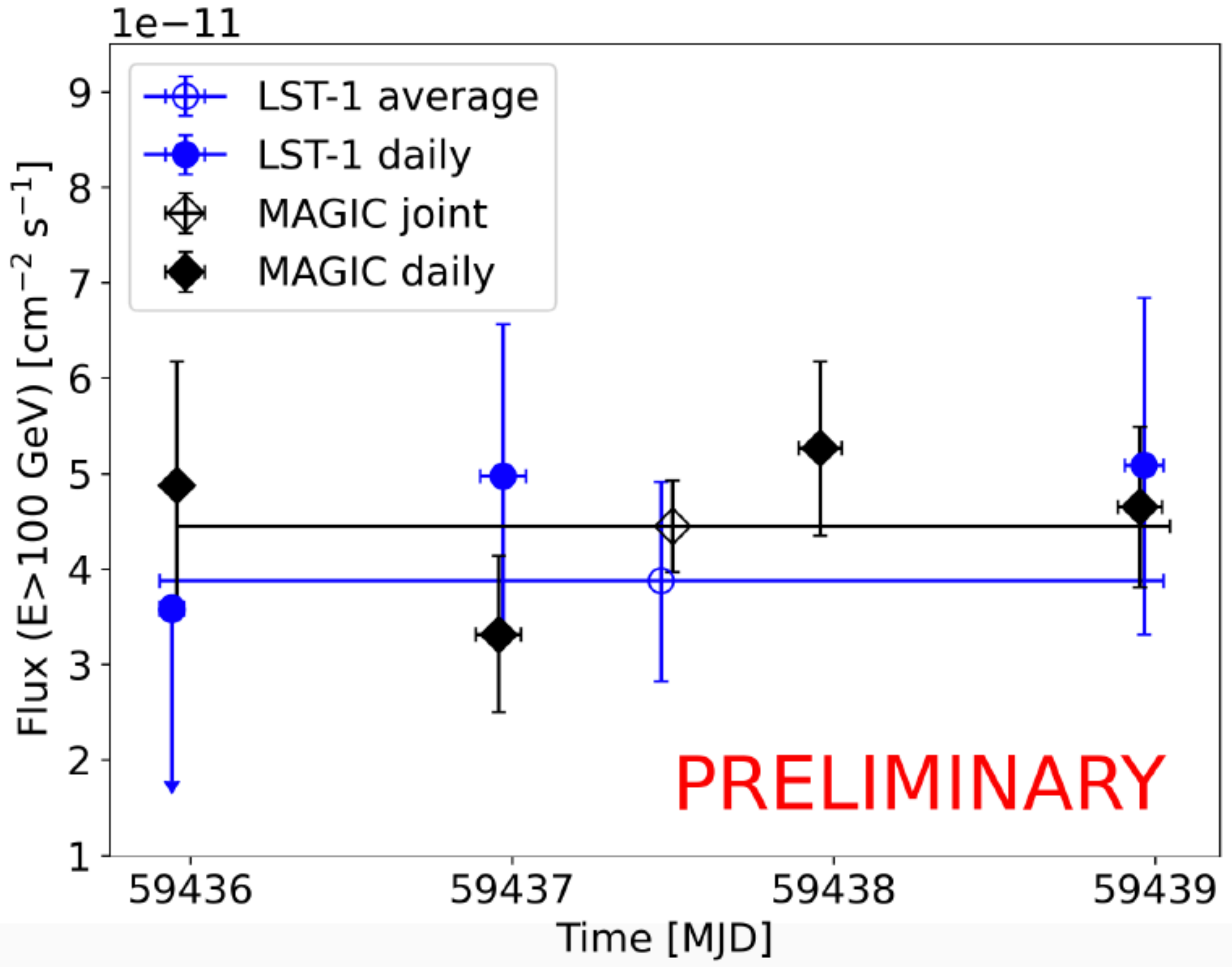
Slide from Aguasca-Cabot, VGGRS-VI

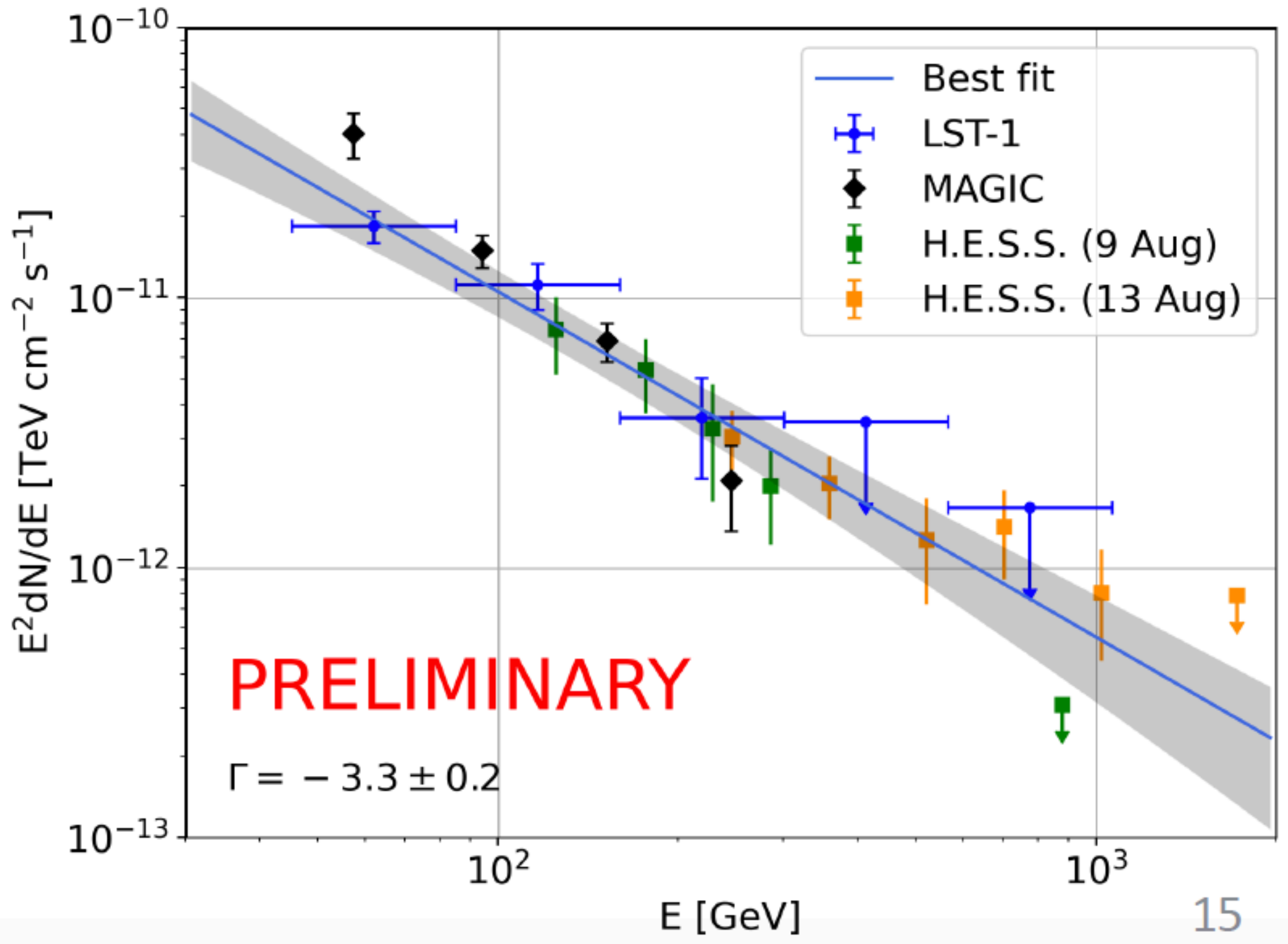
RS Oph at gamma rays: LST-1

- Clear detection of RS Oph with LST-1 (6.4 h)
  - Significance of ~ 7.5σ & S/N ratio of ~ 4.8%
- ~Smooth transition from HE to VHE range
  - Spectral analysis down to ~ 45 GeV
- Preliminary results compatible with other IACT facilities



New analysis with improved MC is ongoing





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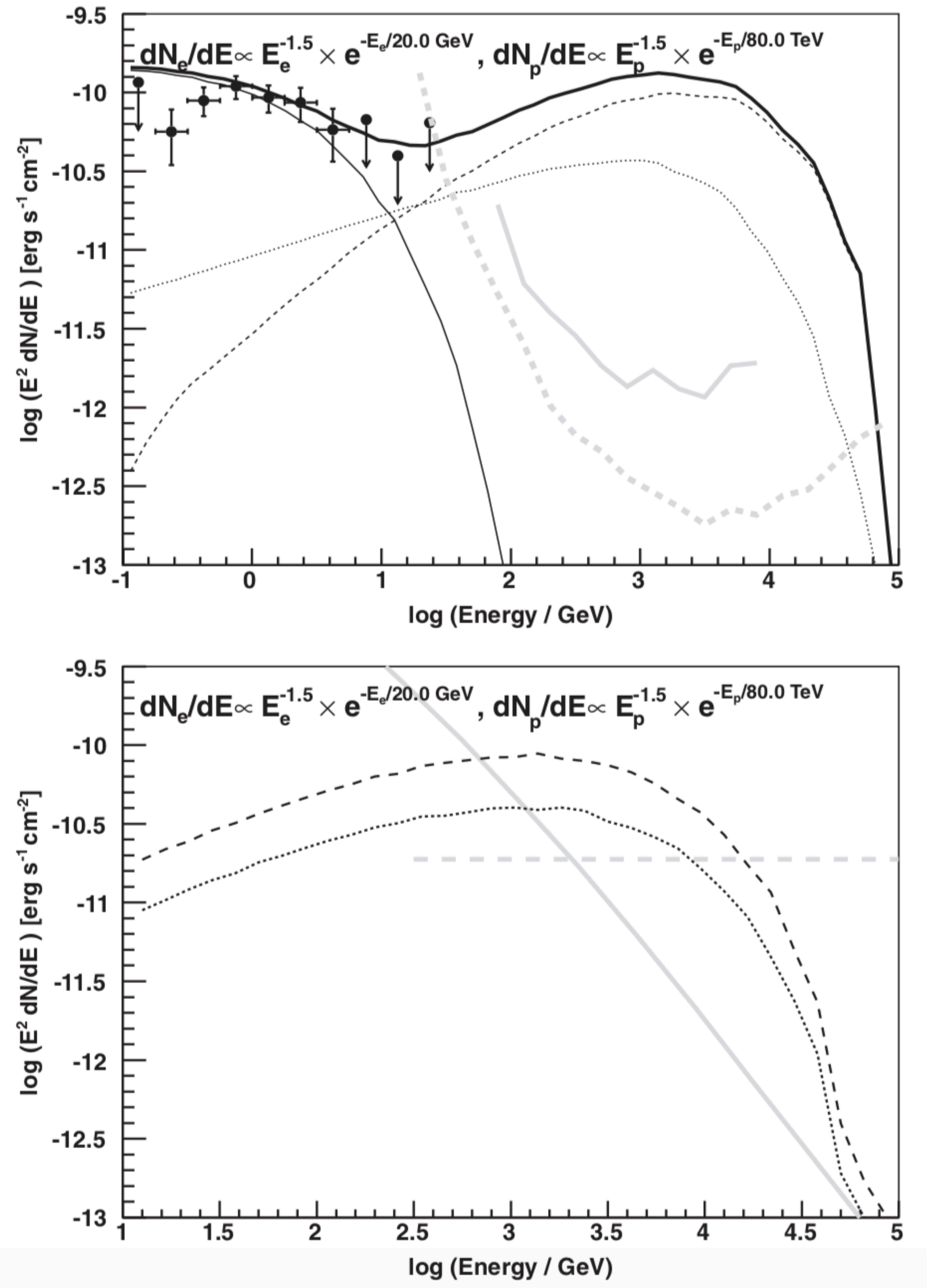
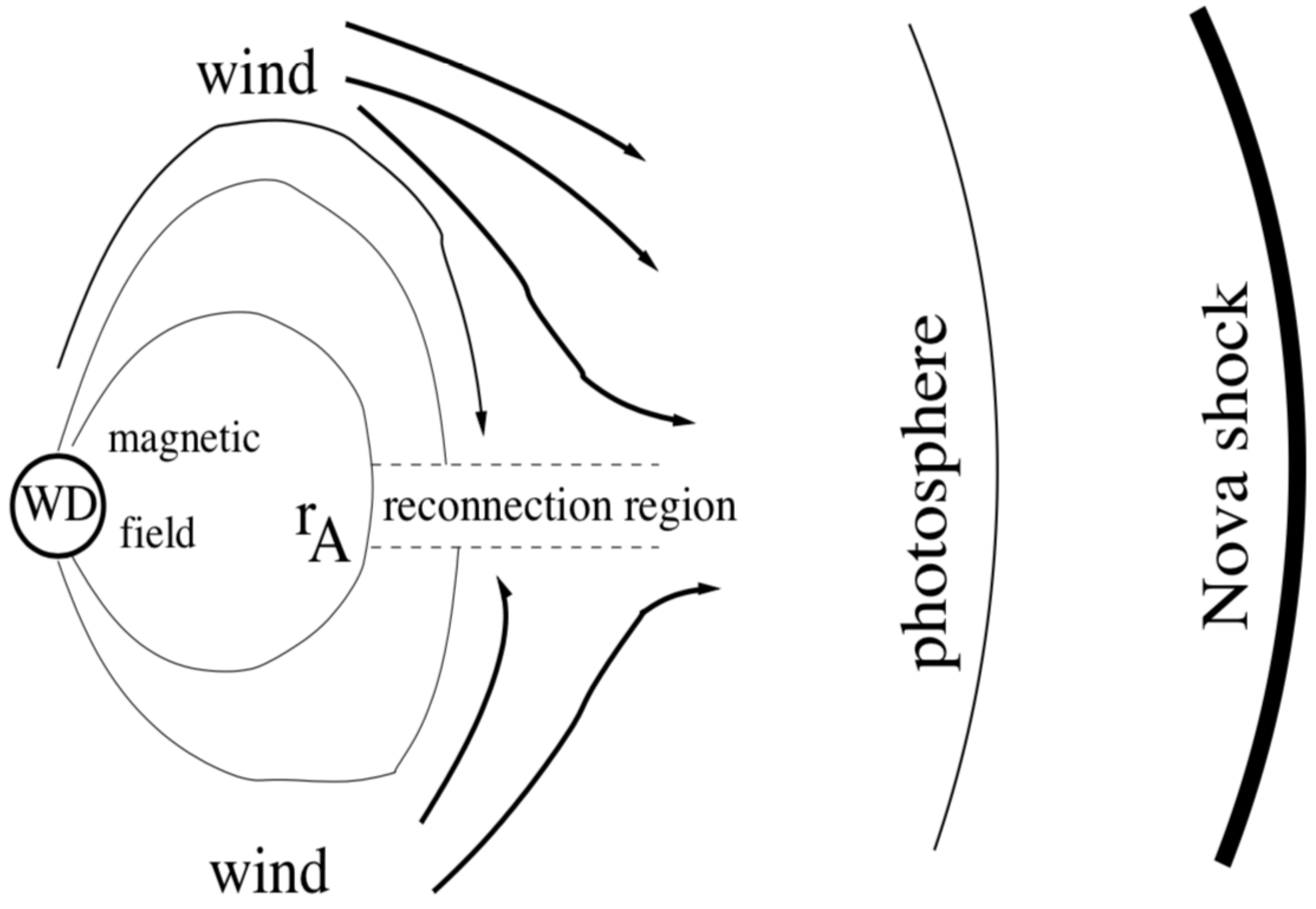
Slide from Aguasca-Cabot, VGGRS-VI

Neutrinos prediction in novae



Sitarek & Bednarek 2012



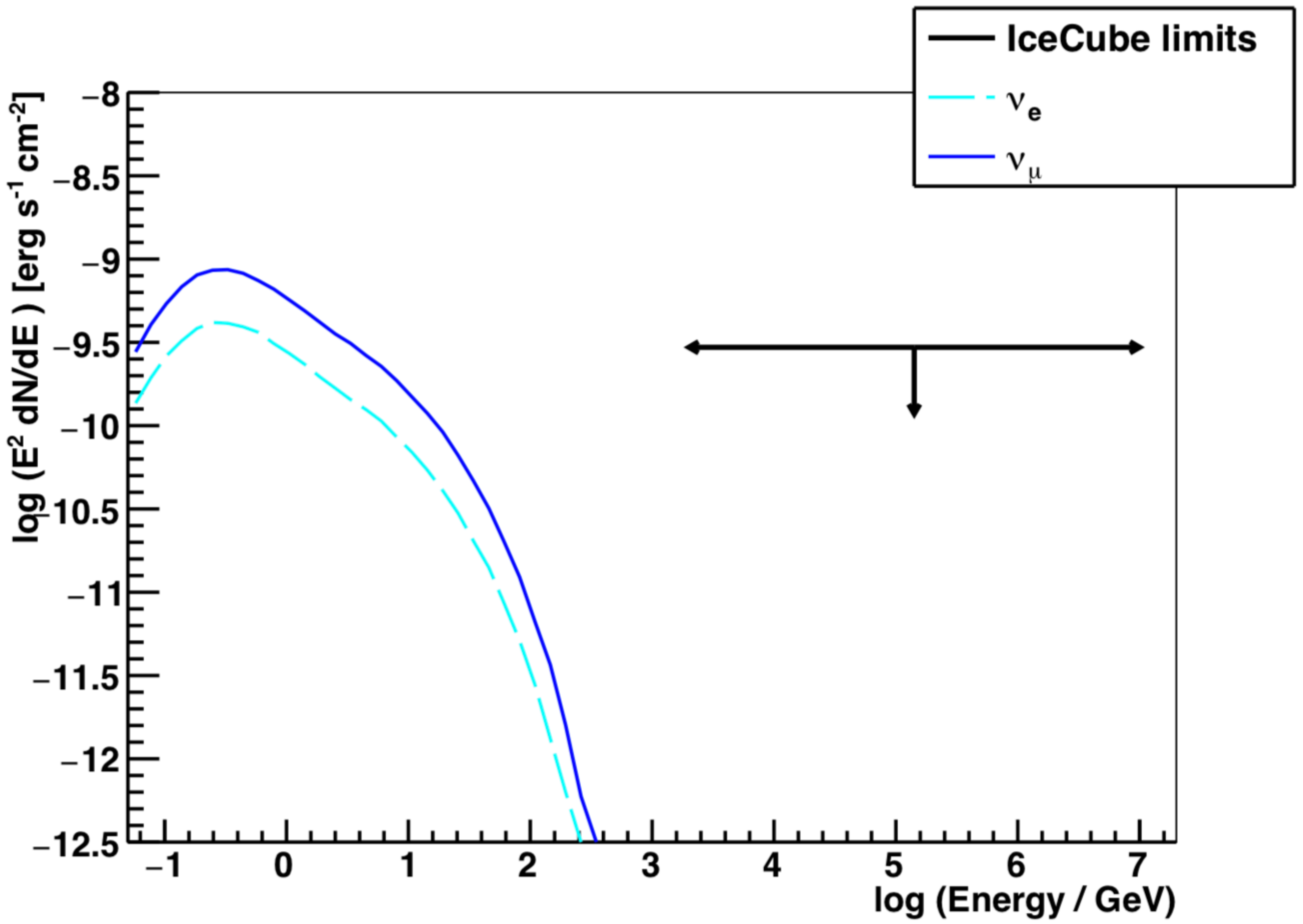
Bednarek & Smialkowski 2022

- Prediction **VHE and neutrino emissions from symbiotic nova** explosions (V407Cygni-like)`(Sitarek & Bednarek 2012)`

- Production of **neutrinos in collisions of relativistic protons with the matter of the fast wind from the WD** `(Bednarek & Smialkowski 2022)`

Neutrinos from RS Oph?

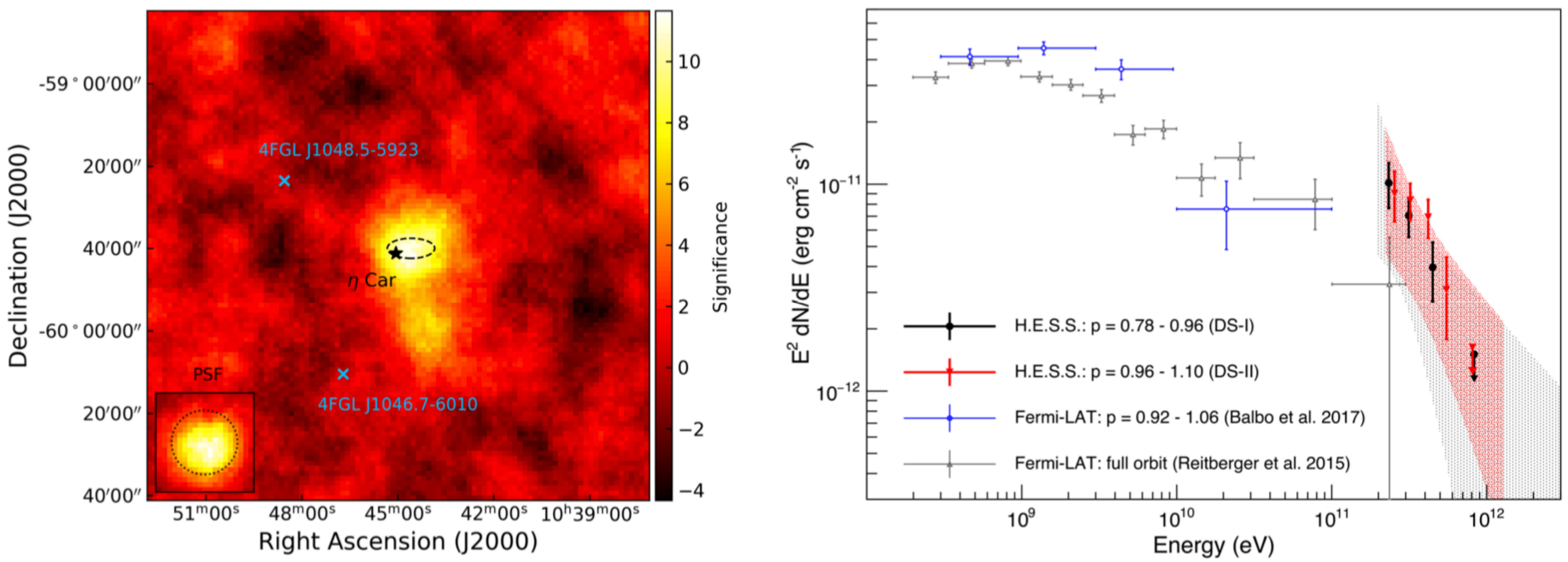
- **No signal detected by IceCube** in the 3 first days (Pizzuto et al. ATel #14851)
- We calculated the neutrino emission corresponding to the proton model and compared it with limits from the IceCube Collaboration
  - Protons reach only sub-TeV energies-> the **predicted neutrino emission does not reach energies higher than those of protons** and these limits cannot constrain the model



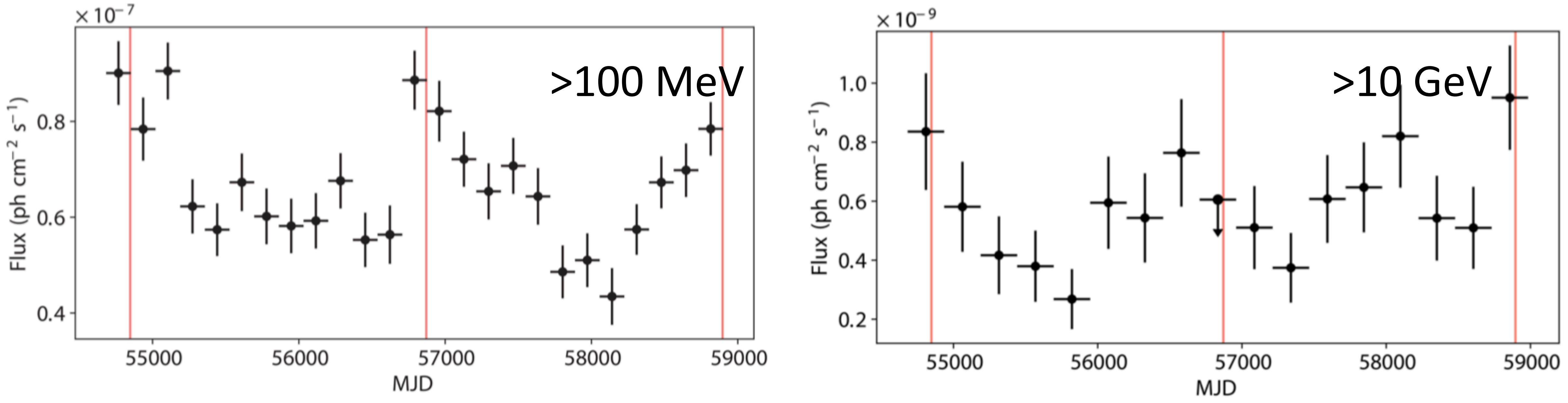
- Could SuperKamiokande have detected neutrino emission from RS Oph?
  - No: low collection area at the GeV energies the expected number of events is only of the order of 5 × 10^{-7}.

Colliding wind binaries (CWB)

Colliding wind binaries

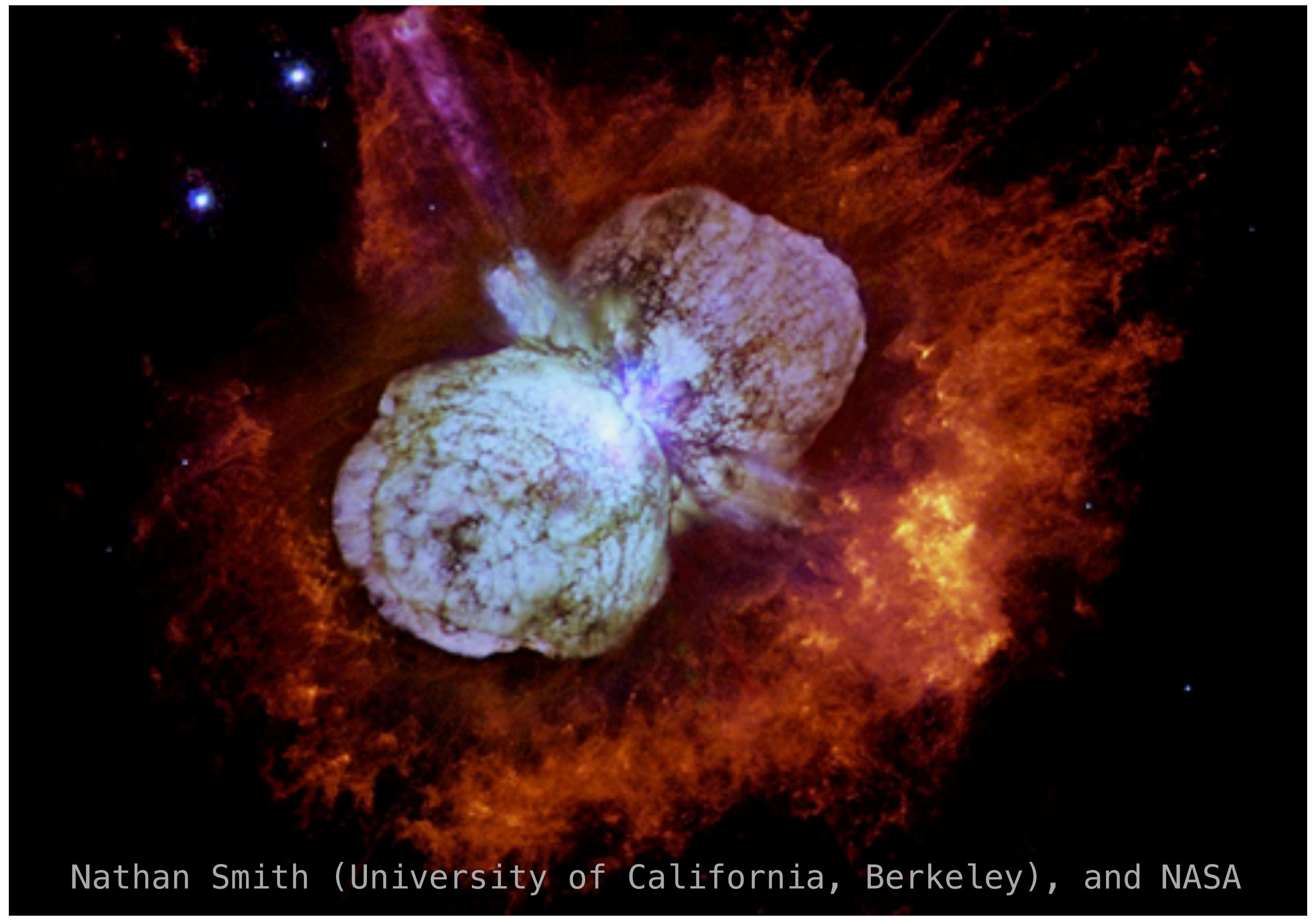


(H.E.S.S. Coll. 2020)

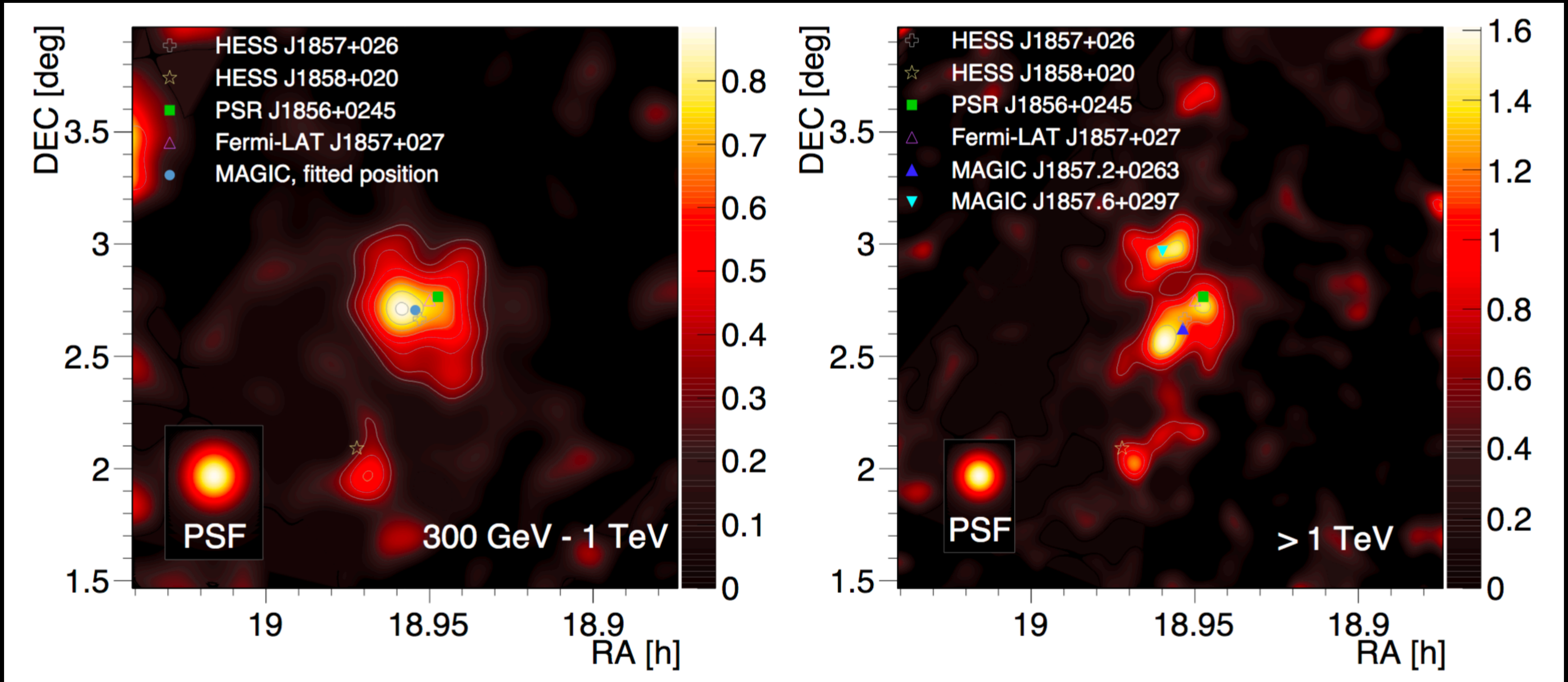


(Martí-Devesa et al. 2021)

Slide from P.Bordas, Gamma 2022

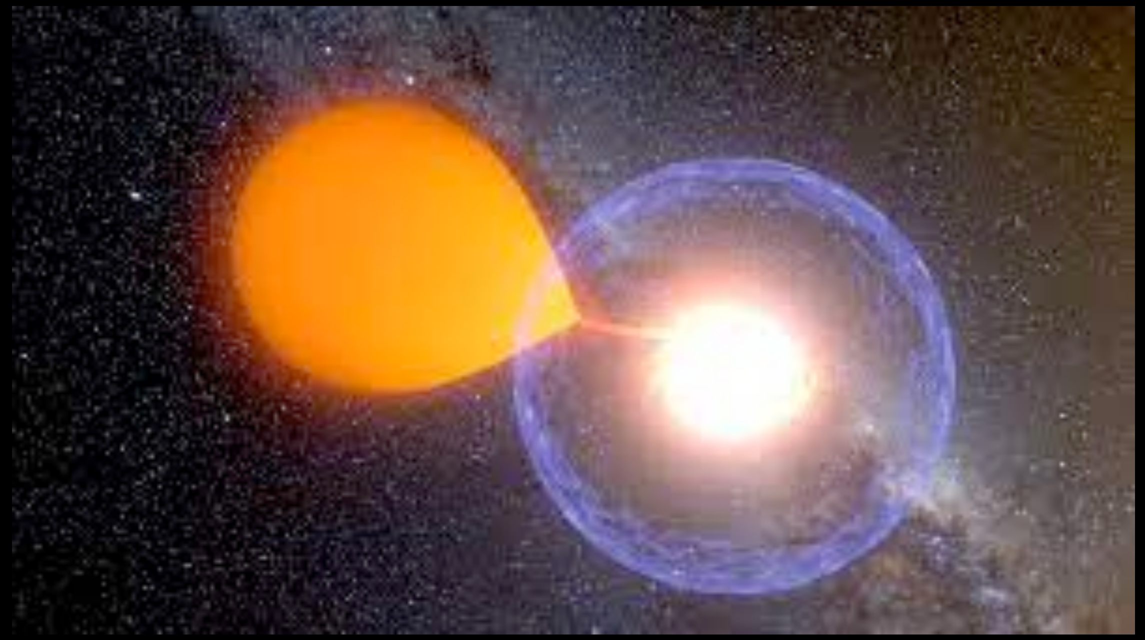


- Detected at HE by AGILE and *Fermi*-LAT in 2009 (Tavani et al. 2009; Abdo et al. 2009a)
- Composed of a **luminous blue variable primary star** of ~100 $M_\odot$ and an **O- or B-type companion** of ~30 $M_\odot$
- very eccentric orbit (e ~ 0.9) with a period of ~2023 days (~5.5 years)
- **strong and dense supersonic stellar winds**
  - colliding wind region (CWR) at the locations of ram-pressure balance
  - contact discontinuity and a strong shock on either side of it.
  - **high mass-loss rates**: $2\times10^{-4}\,M_\odot$/yr (500km/s) and $2\times10^{-5}\,M_\odot$/yr (3000 km/s)
  - wind material is shock-heated to 50 MK and gives rise to soft X-ray emission



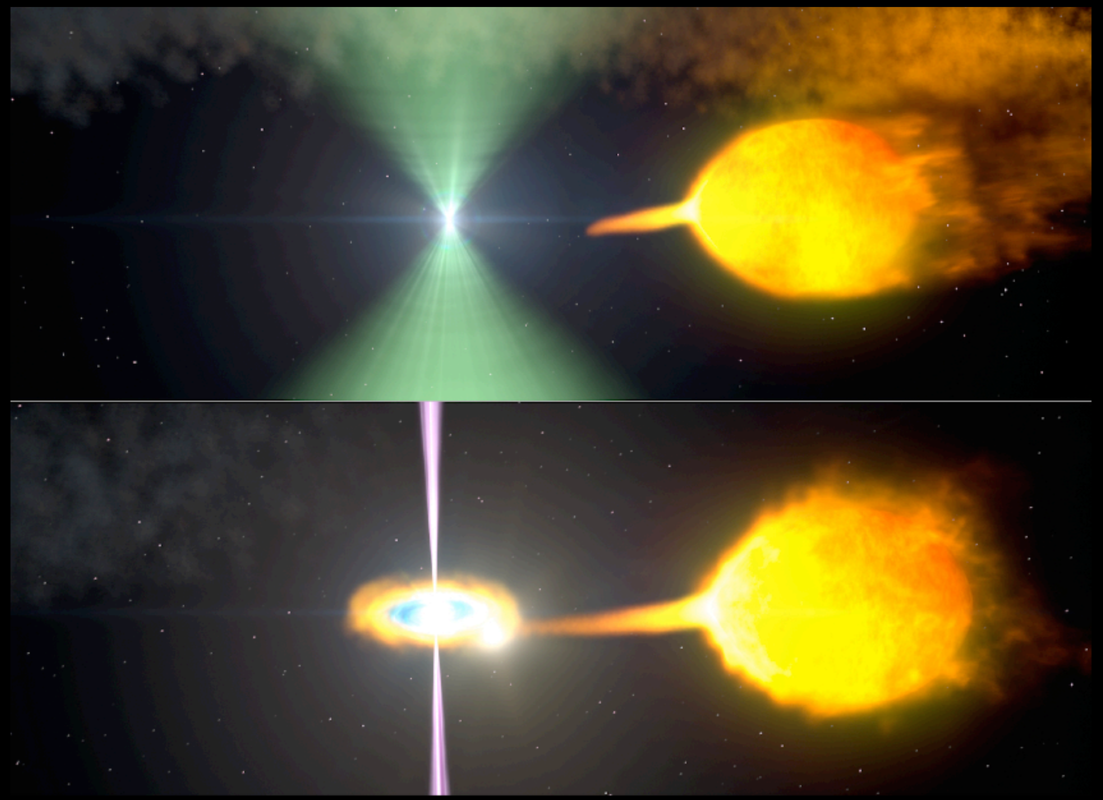
Unidentified extended sources

Still searching at VHE

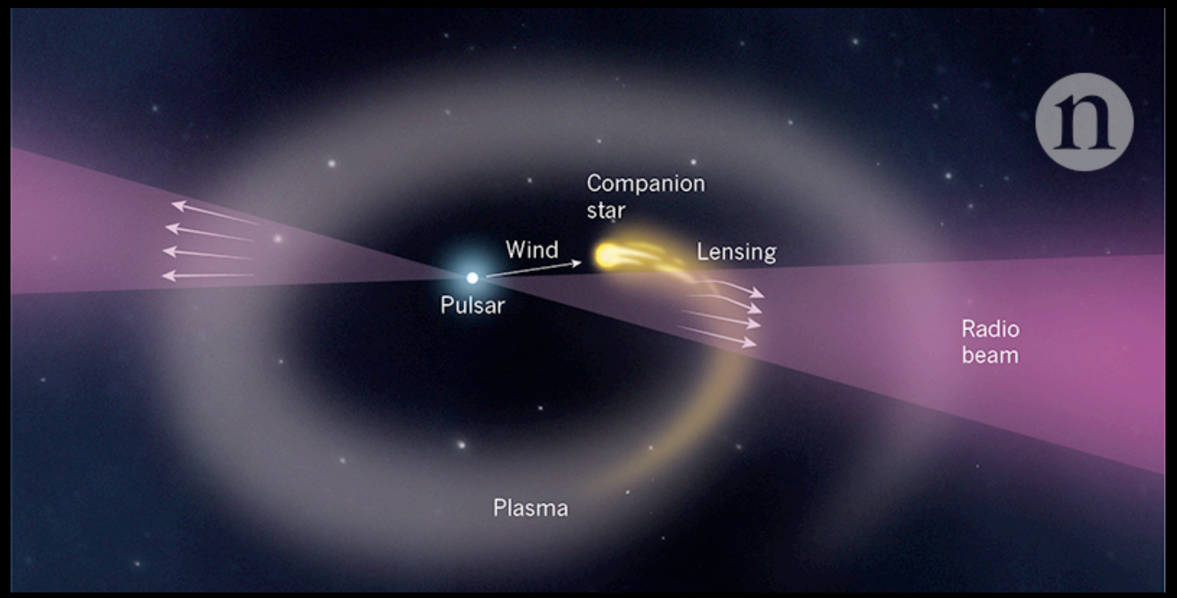


Classical novae

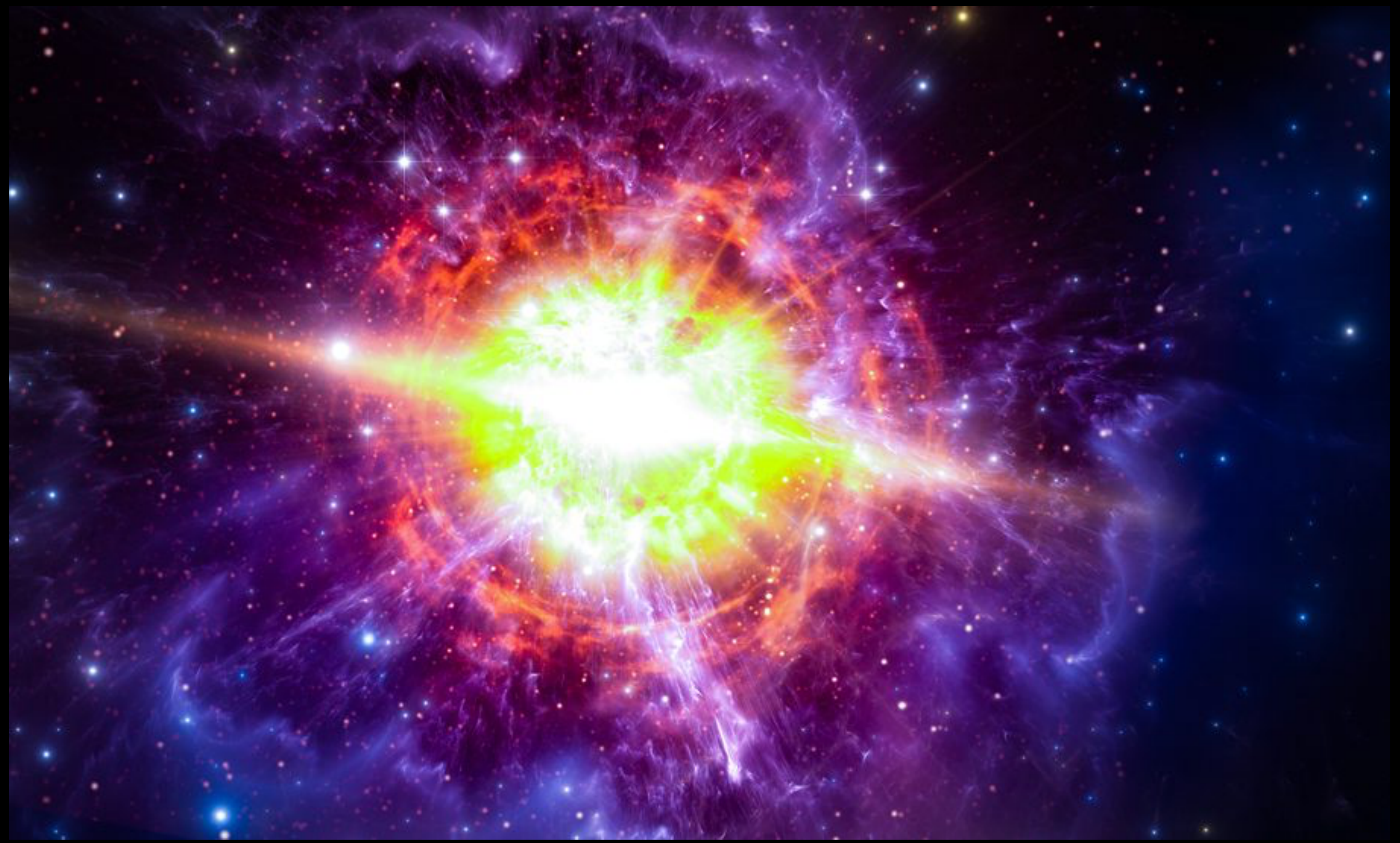
tMSPs



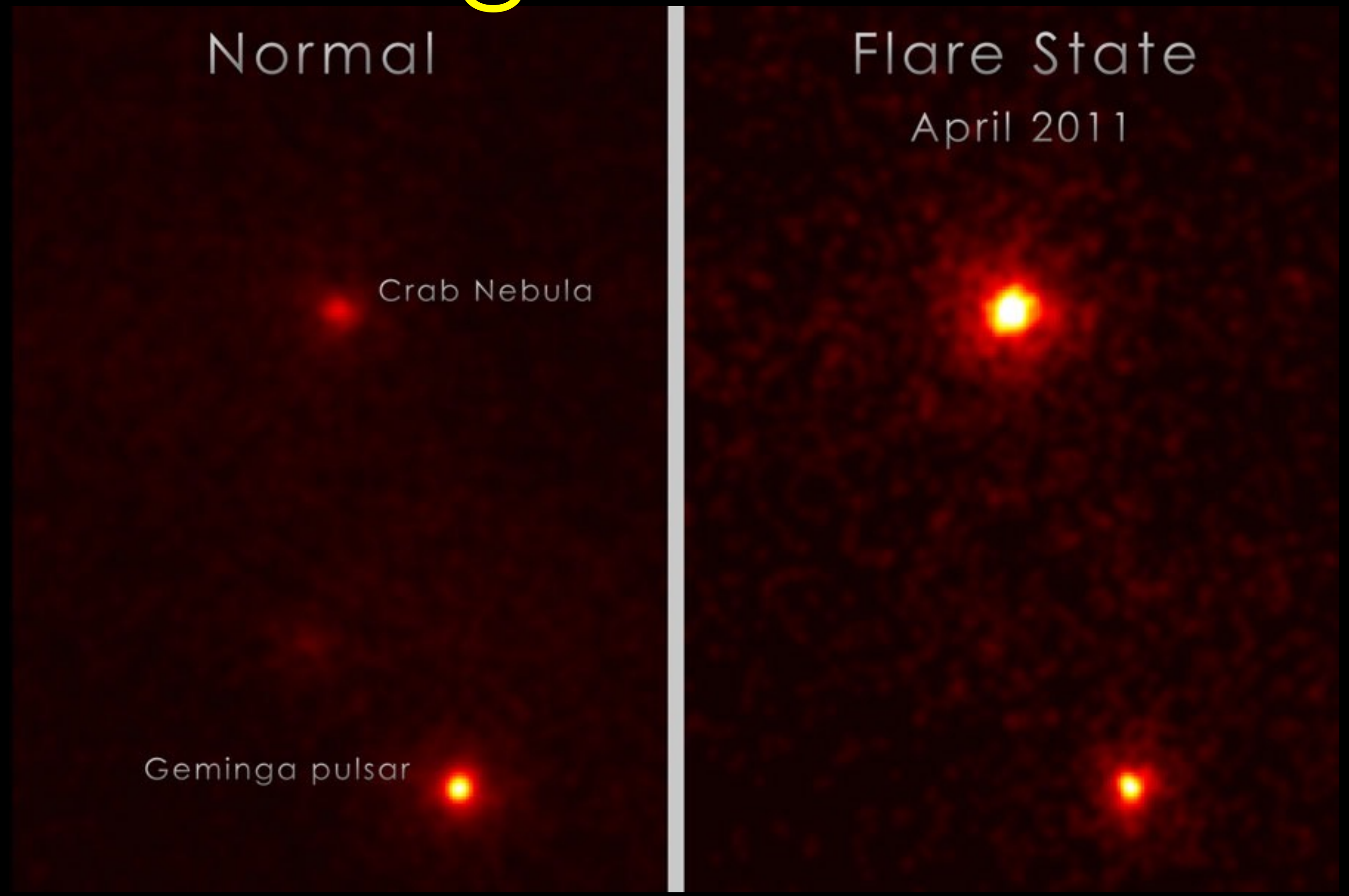
Black widow

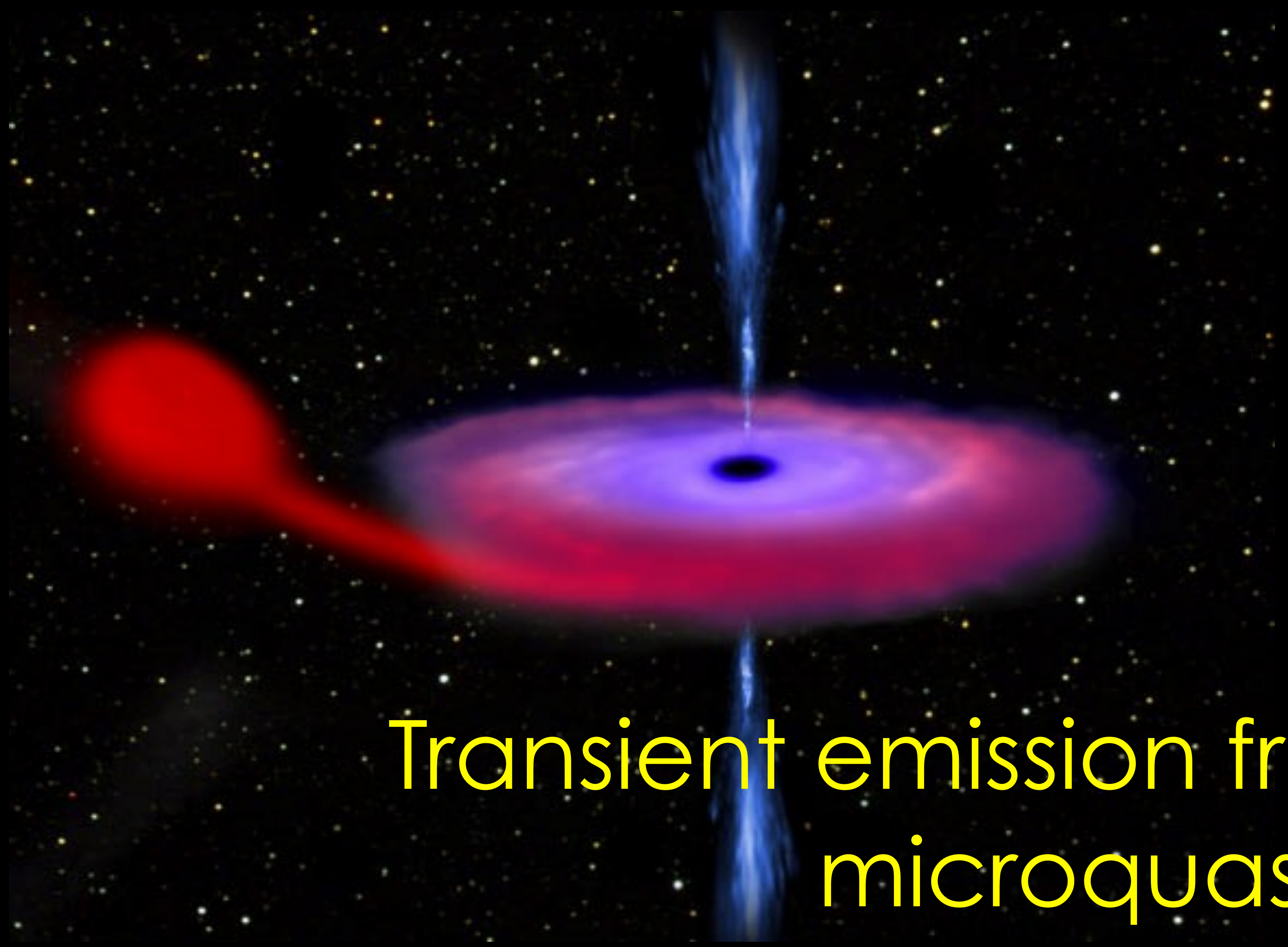


Supernovae



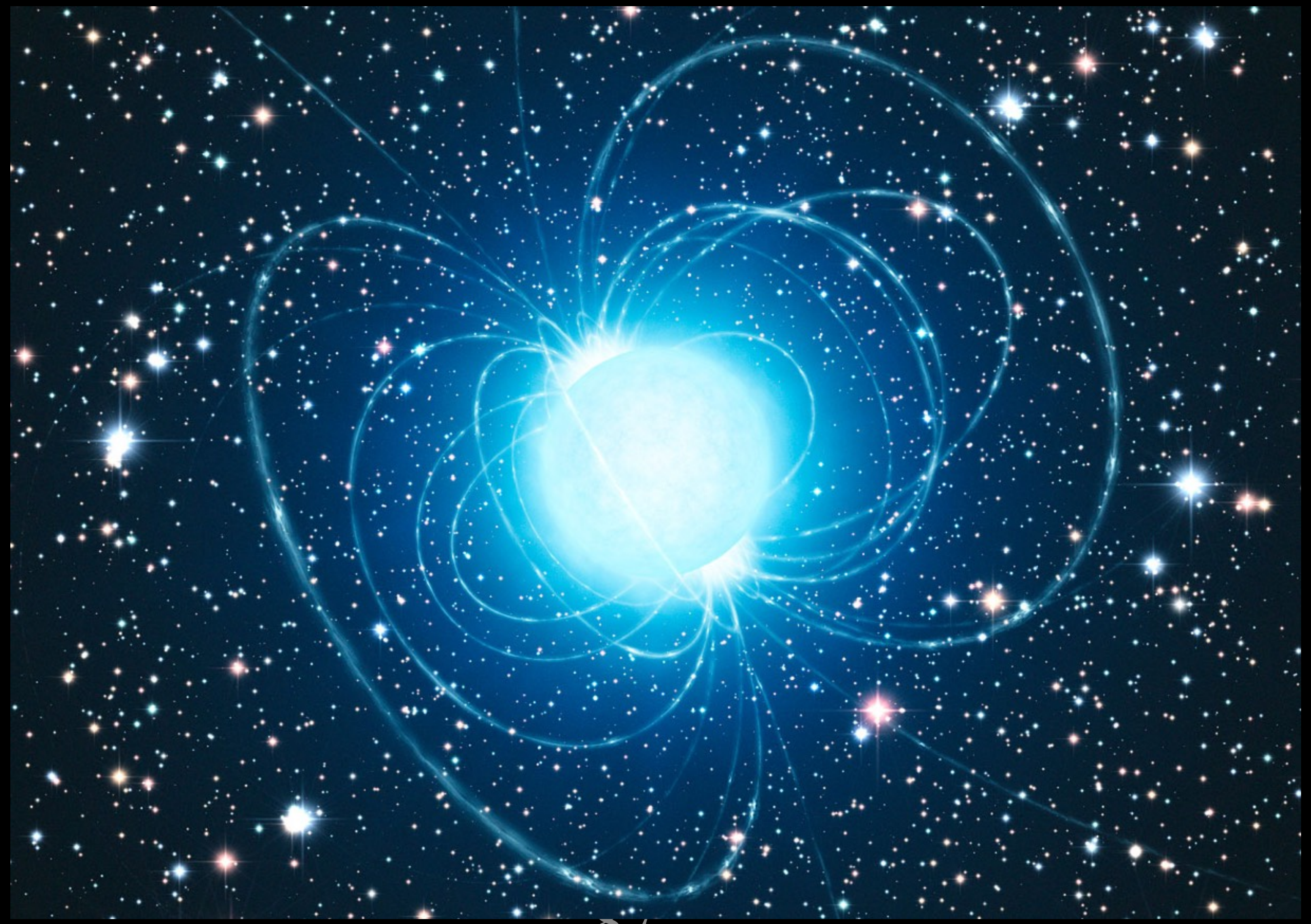
Flaring PWNe





Transient emission from microquasars

Magnetars



VHE Galactic Physics

NASA/JPL–Caltech/ESA/CXC/STScI

Thanks

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AGENCIA ESTATAL DE INVESTIGACIÓN

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