

Galactic Sources

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High-energy (HE) gamma rays

> 100 MeV



Very-high-energy (VHE) gamma rays

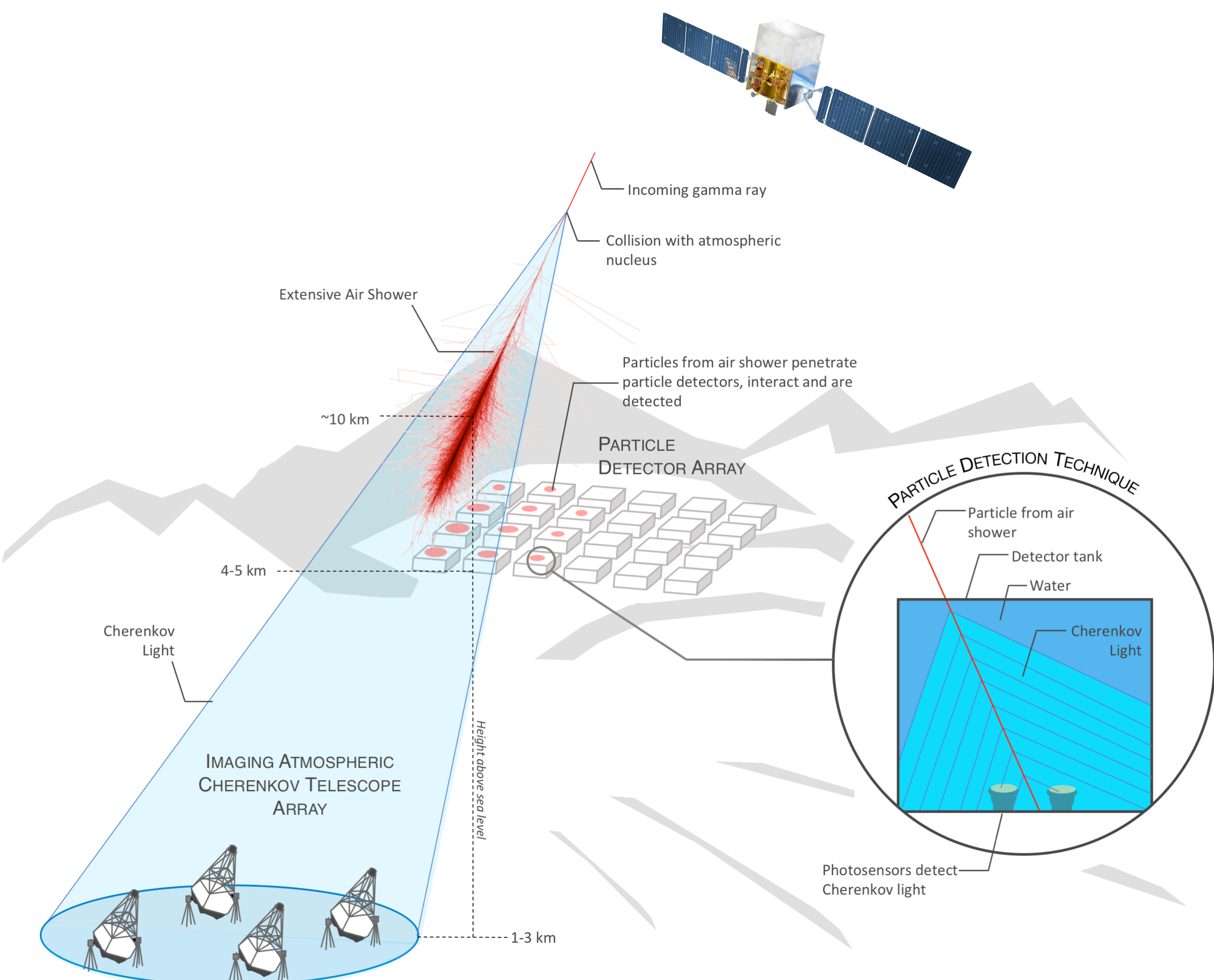
> 0.1 TeV



Ultra-high-energy (UHE) gamma rays

> 100 TeV





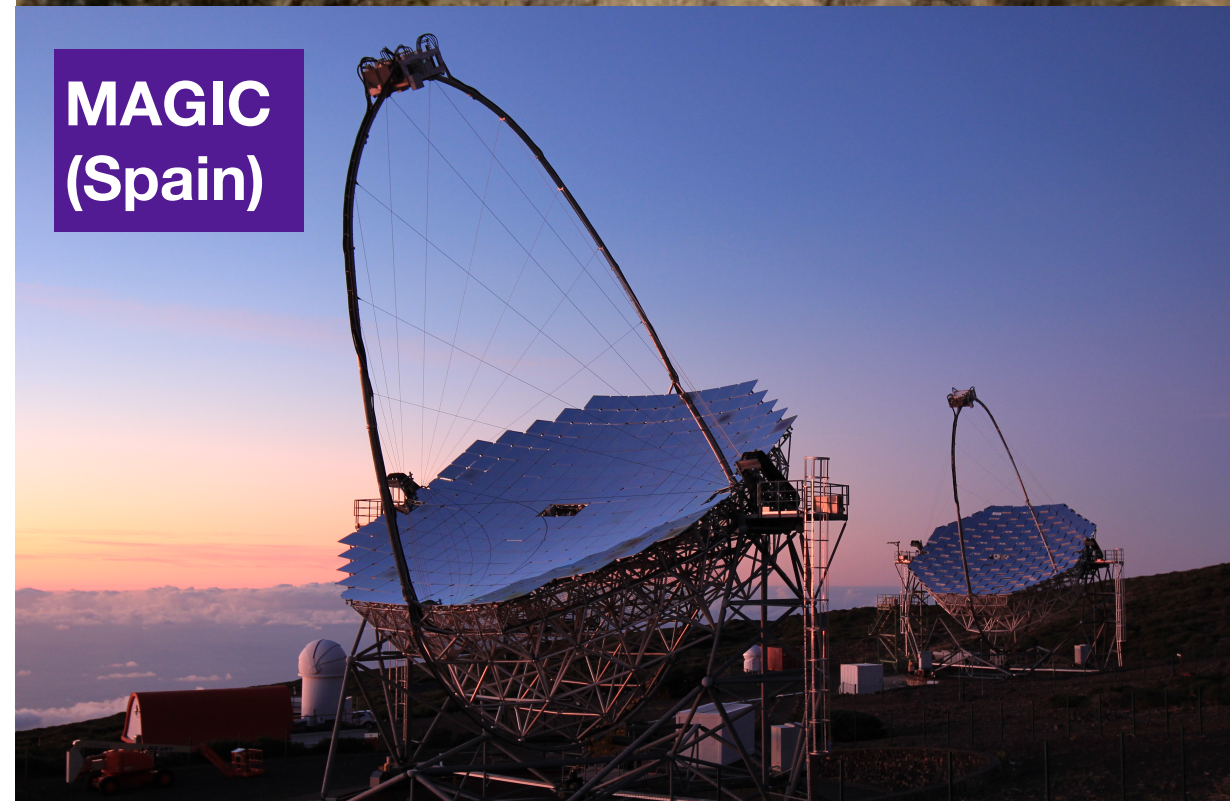
	IACS	Particle detectors
Energy range	tens GeV - tens TeV	> tens TeV
Background rejection	Excelent	Moderate
Angular and energy resolution	Better than particle detectors	Worse than IACTs
Duty cycle	Dark time - moderate moonlight	>99%
FoV	Small	Big

Shower image, 100 GeV γ -ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, <https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html>

Not to scale

Detecting gamma rays with ground-based experiments

- Imaging Air Cherenkov Telescopes (IACTs)
 - Very-high-energy (VHE, $E > 100$ GeV) regime



- Detectors:
 - Ultra-high-energy (UHE, TeV-PeV) regime



Detecting gamma rays with ground-based experiments

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SWGO
(Chile)



- Detectors:
 - Ultra-high-energy (UHE, TeV-PeV) regime

Current experiments

Future*

Detecting gamma rays with ground-based experiments

- Imaging Air Cherenkov Telescopes (IACTs)
 - Very-high-energy (VHE, $E > 100 \text{ GeV}$) regime
- Detectors:
 - Ultra-high-energy (UHE, TeV-PeV) regime

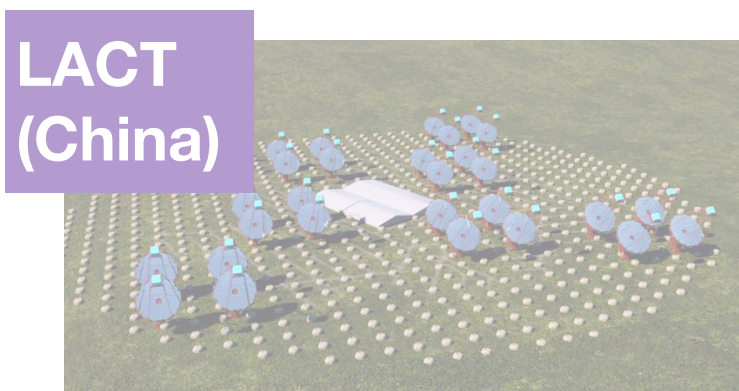
Current experiments



More details on these topics
Gamma-ray Astronomy (Anita Reimer)
Gamma rays from ground (Gabrijela Zaharijas)
+many talks in the GA session

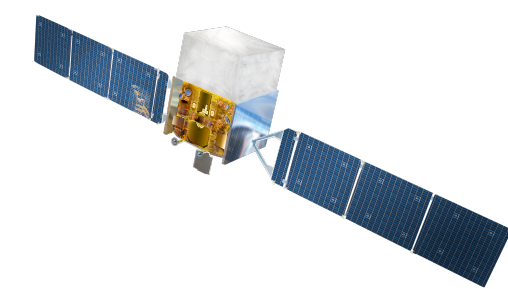


Future*

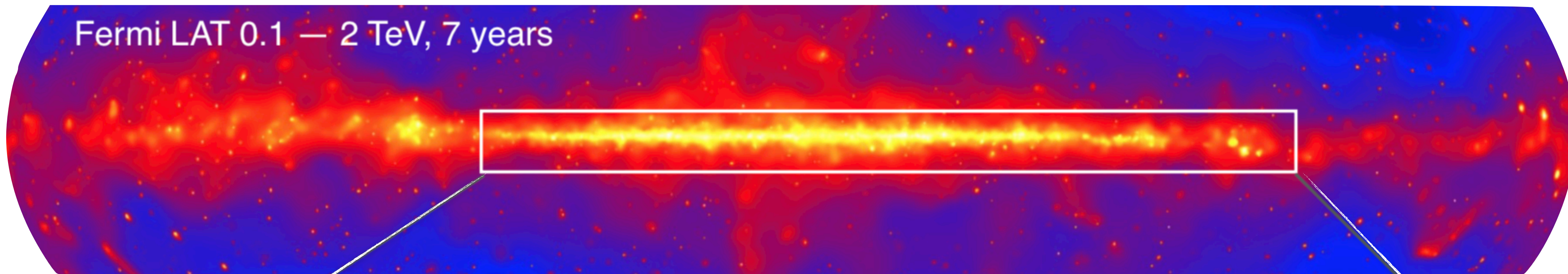


SWGO
(Chile)

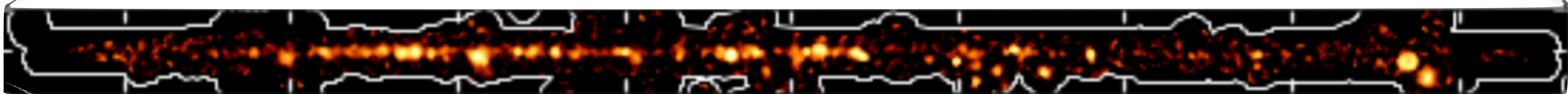




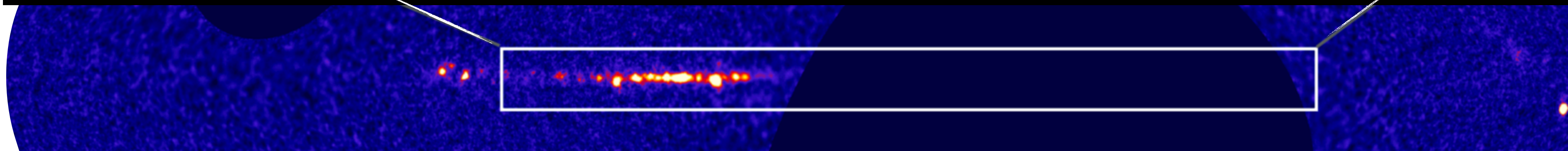
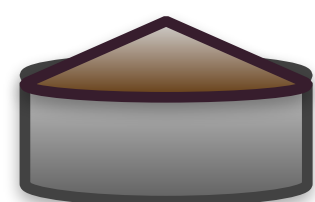
Fermi LAT 0.1 — 2 TeV, 7 years



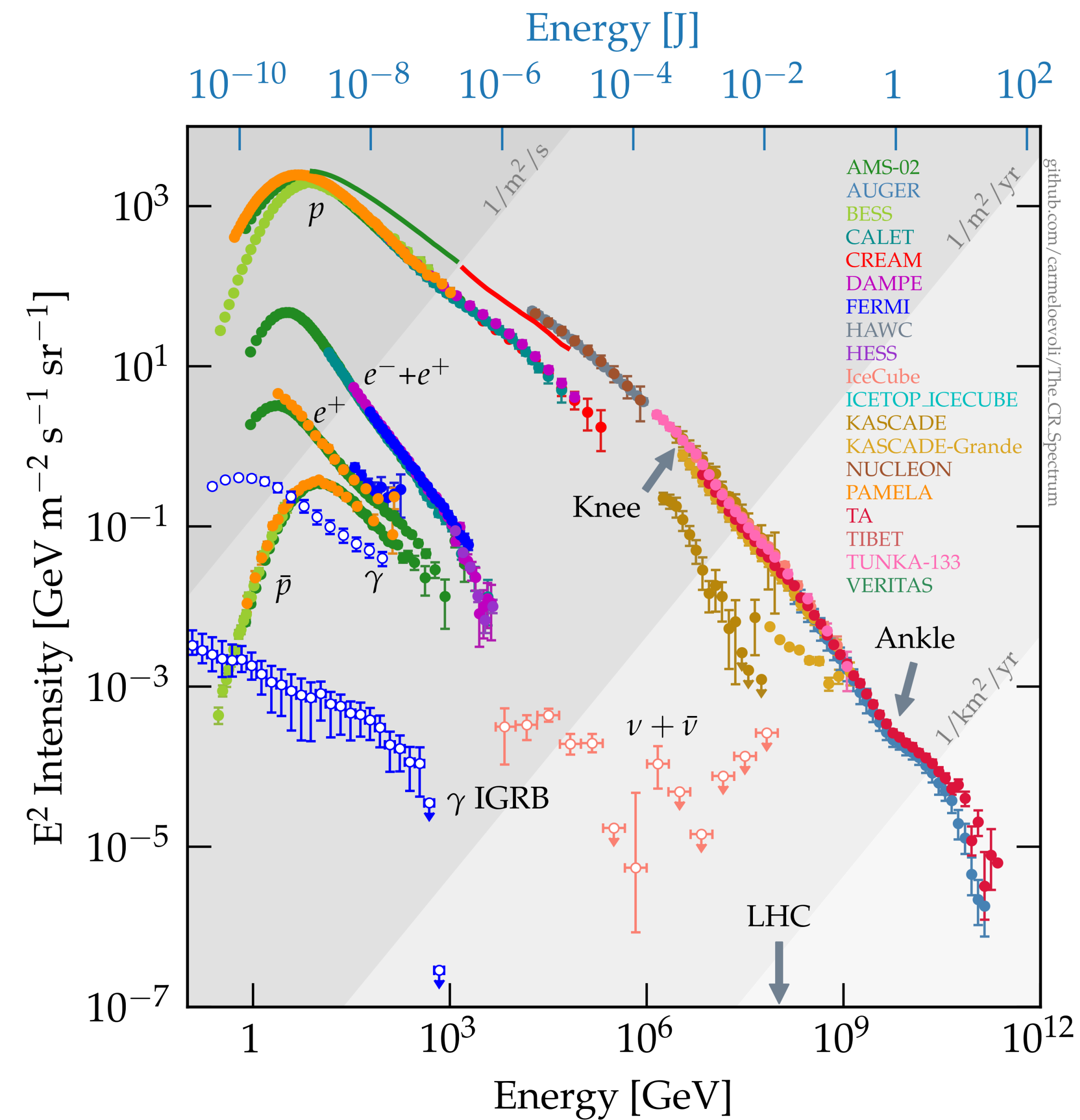
H.E.S.S., 1 TeV, 10 years



HAWC, <100 TeV, 1.5 years

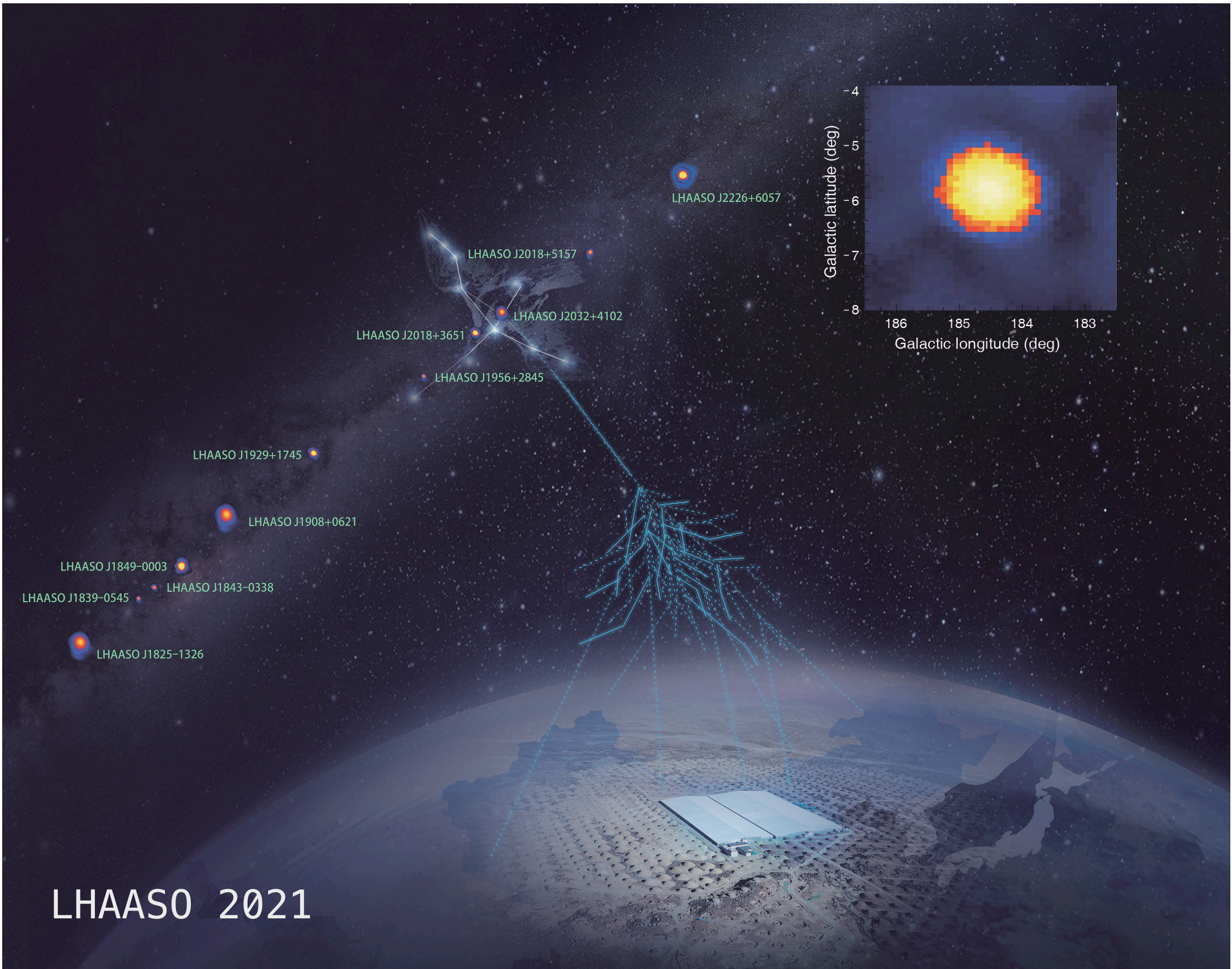


Connection to Cosmic Rays



Evoli 2025 (<https://zenodo.org/records/14635074>)

- Which are the sources of CRs around the knee?
- **PeVatrons**
 - **Produce ~100 TeV photons**

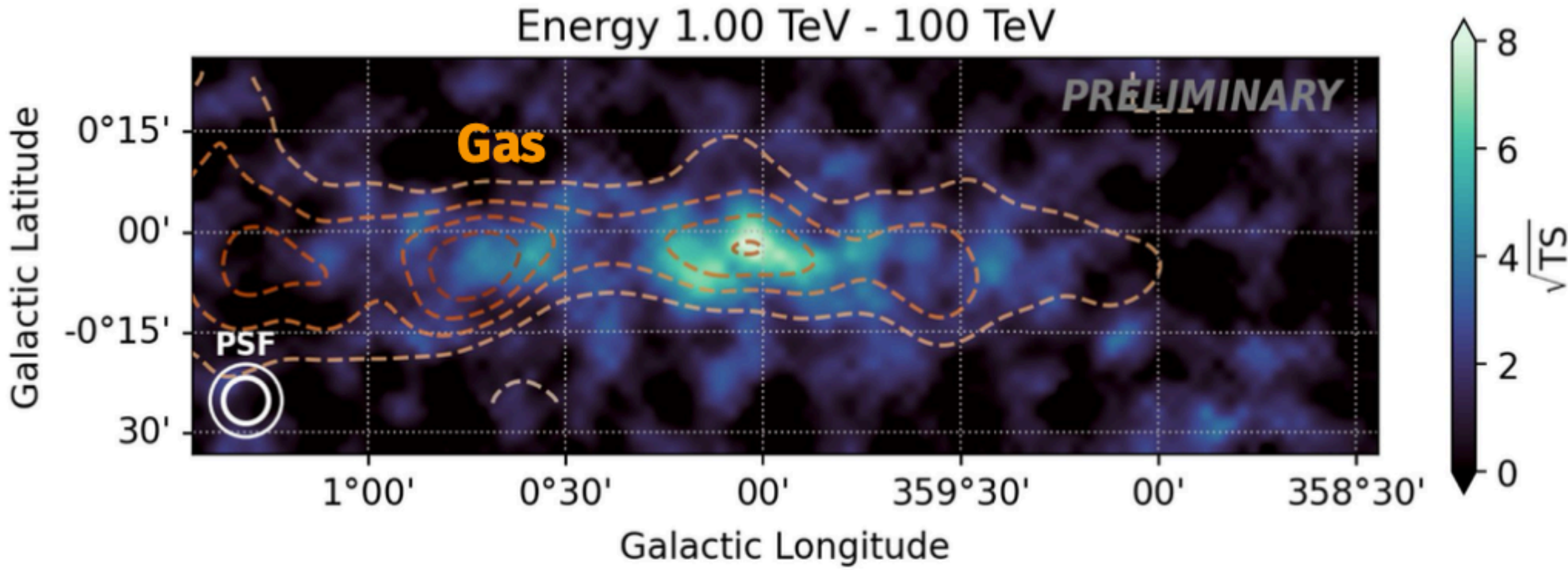


Galactic Center

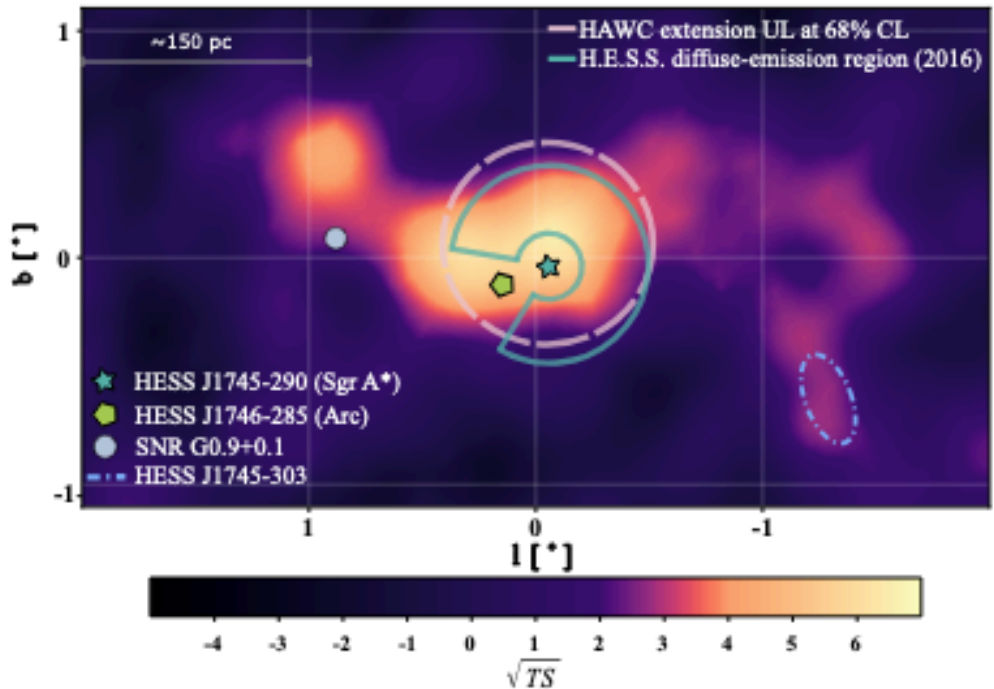
- First hadronic PeVatron in the Galaxy H.E.S.S. (Science 2016)
- Quasi continuous p+ injection
- No evidence of a spectral cutoff up to 100 TeV (HAWC 2024)

HAWC

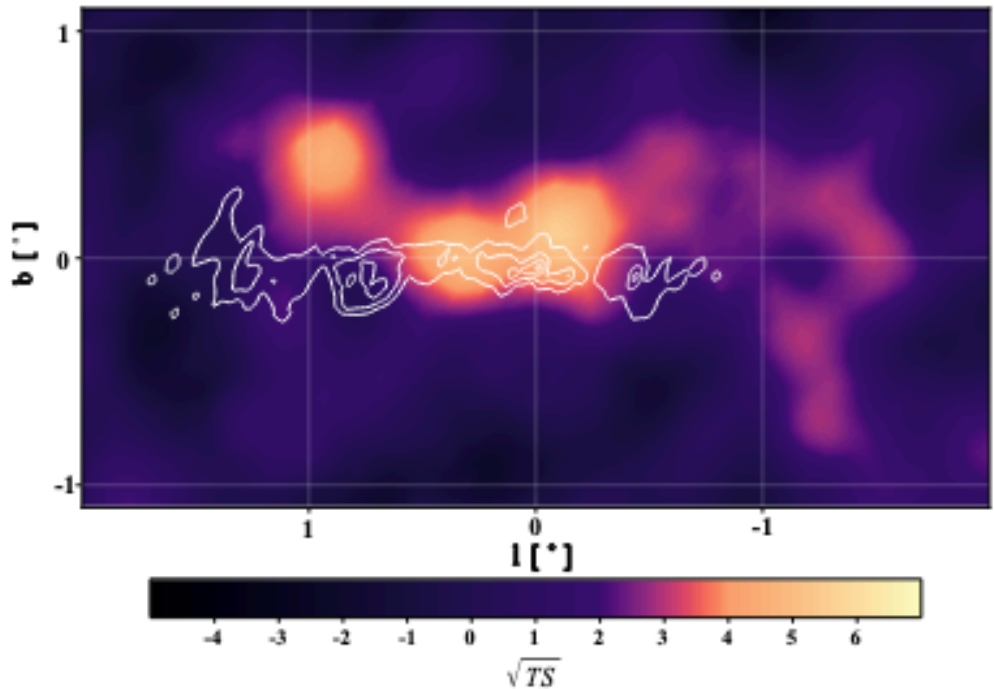
LST-1



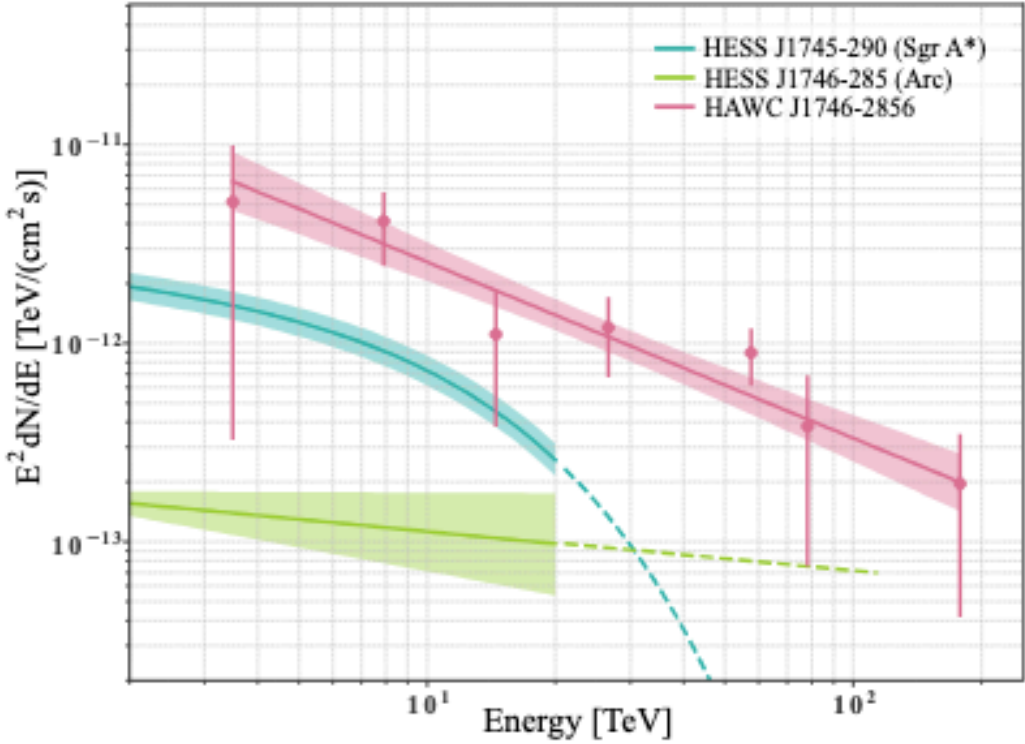
S. Abe (ICRC 2025)



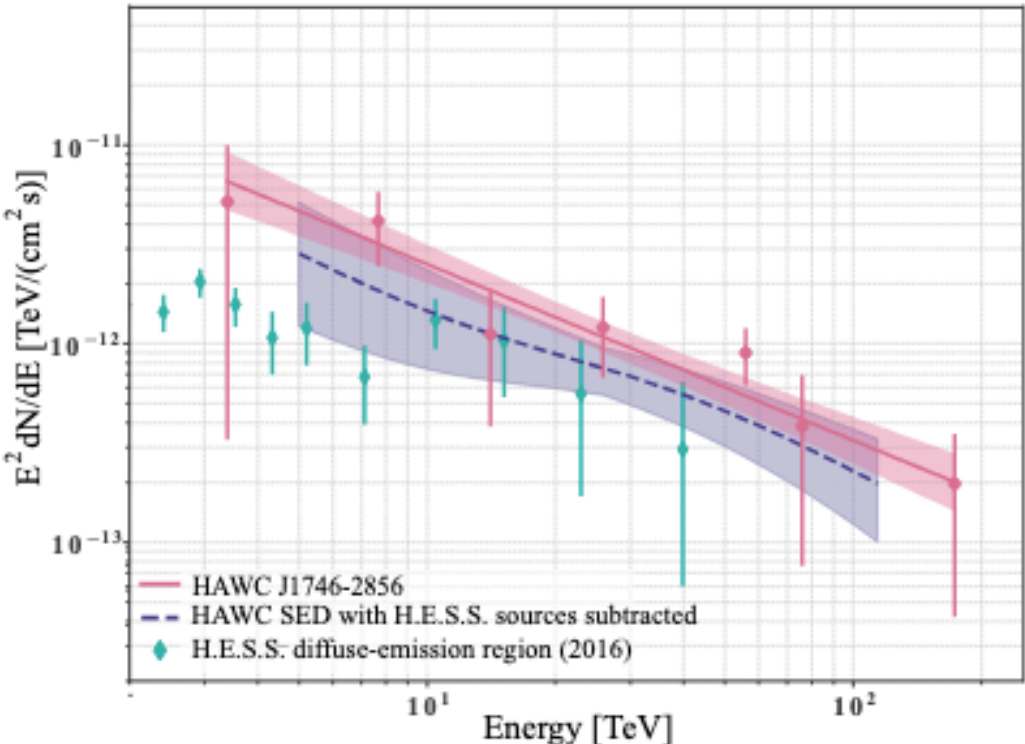
(a)



(c)



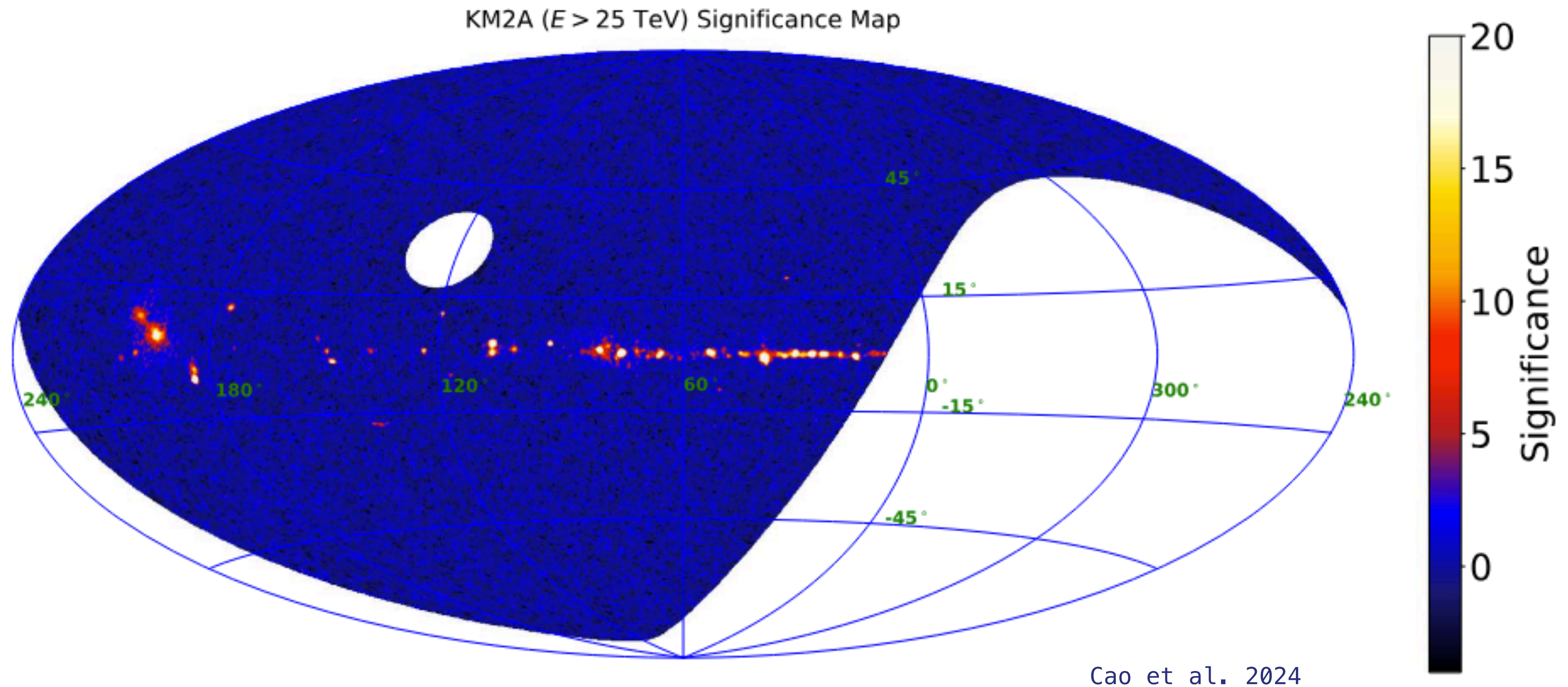
(b)



(d)

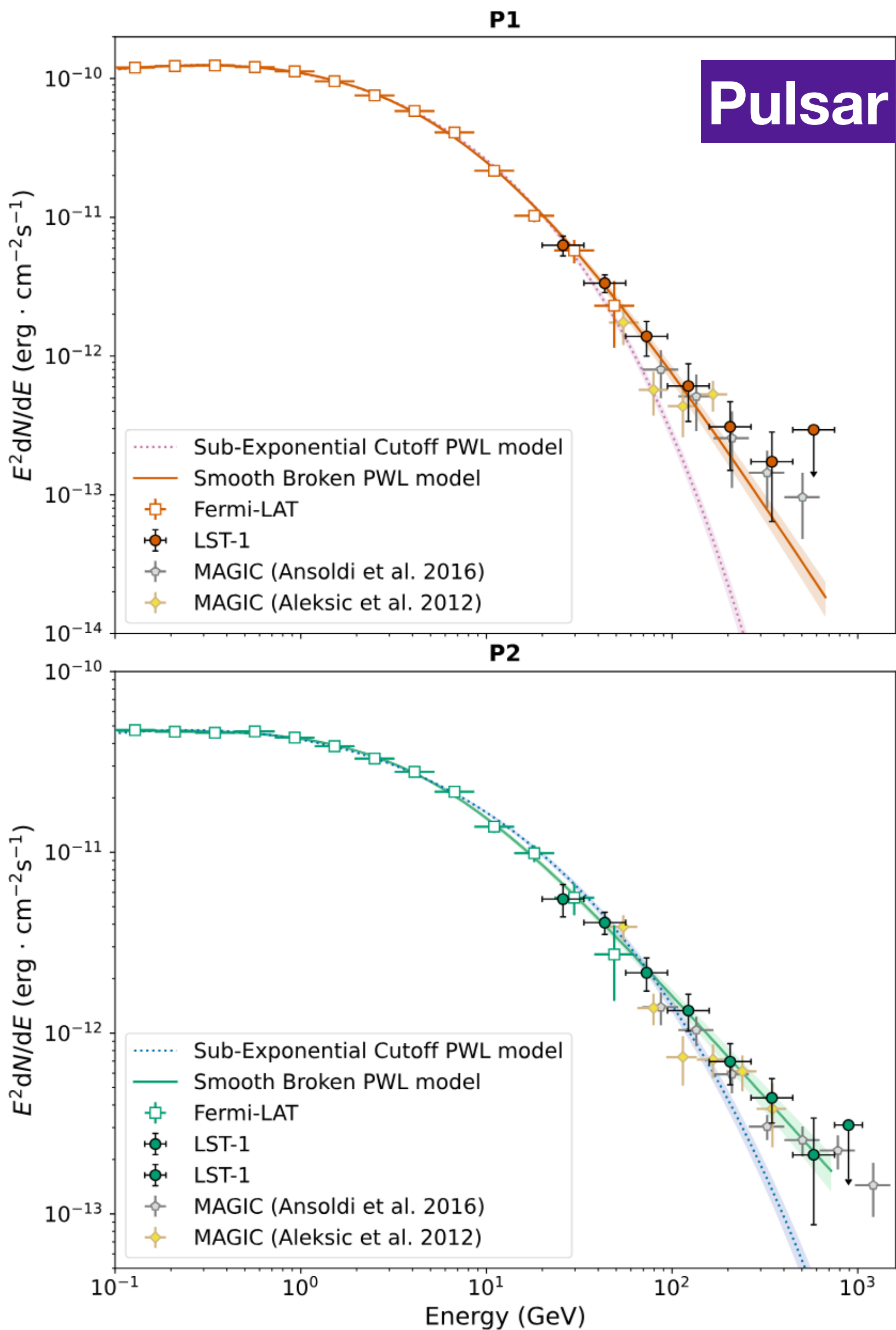
HAWC 2024

PeV sources



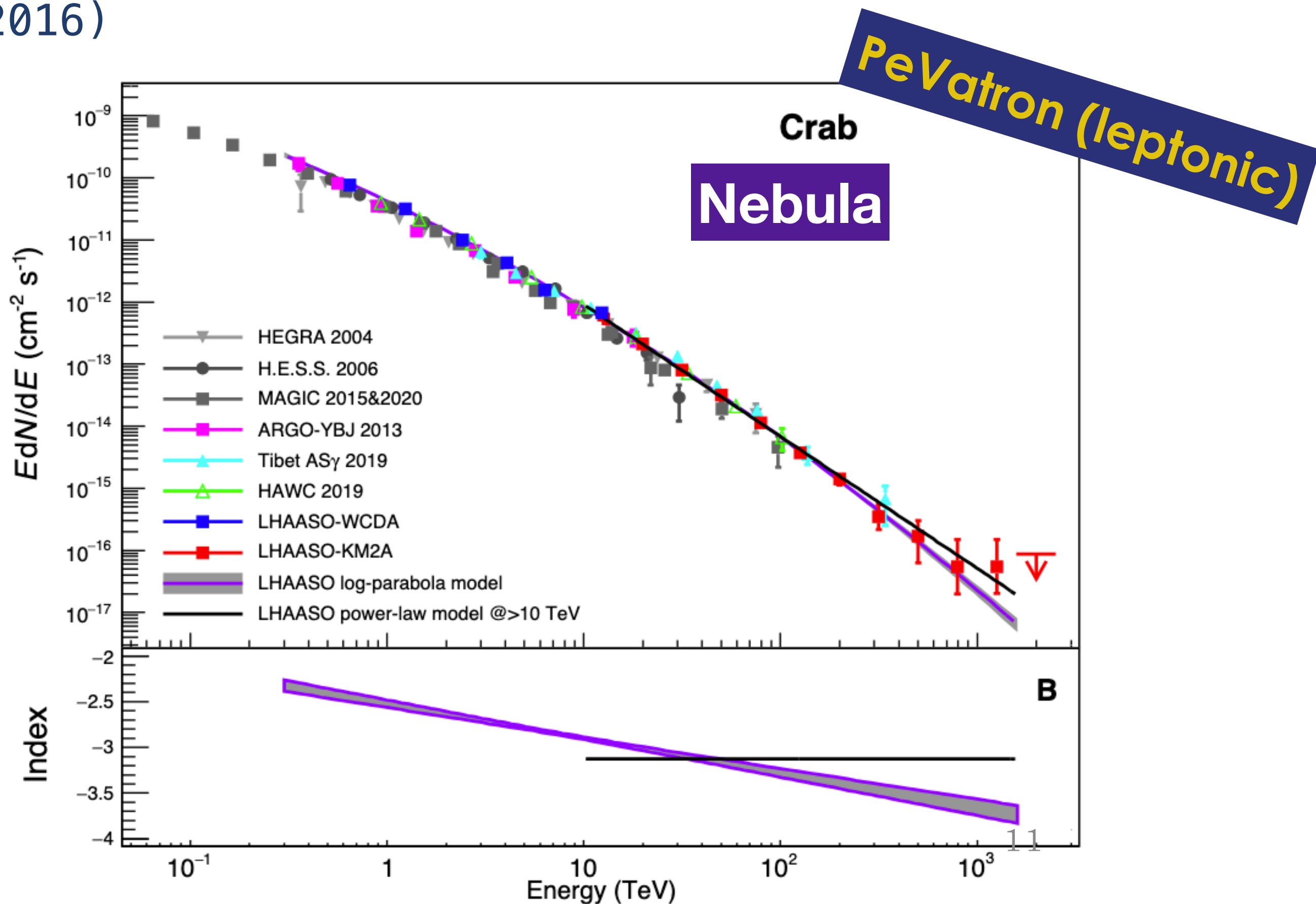
- 1st LHAASO source catalog (Cao et al. 2024)
- Total of **90 sources**
- **43 sources detected at UHE > 100 TeV** (at $> 4\sigma$)
 - mostly associated to pulsars/PWNe (**leptonic** origin)
- Some sources do not have any counterpart

The Crab Nebula & pulsar



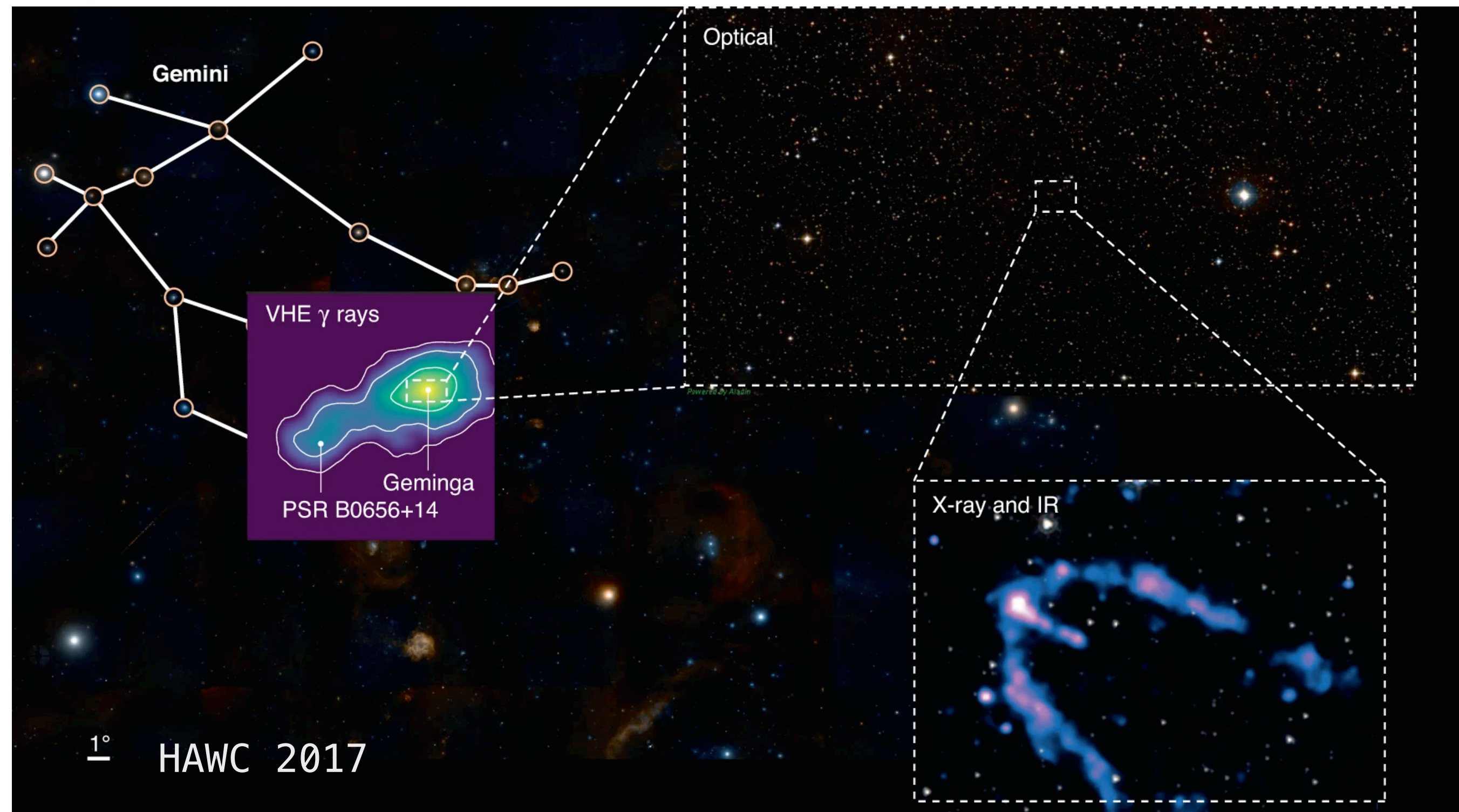
Abe et al. 2025

- Nebula SED measured until ~100 TeV by IACT (MAGIC 2020)
- Identification as a **(leptonic) PeVatron** (LHAASO 2021) with photons up to 1.1 PeV
- **Pulsed emission** from Crab spectrum extending up to 1.5 TeV (MAGIC 2016)

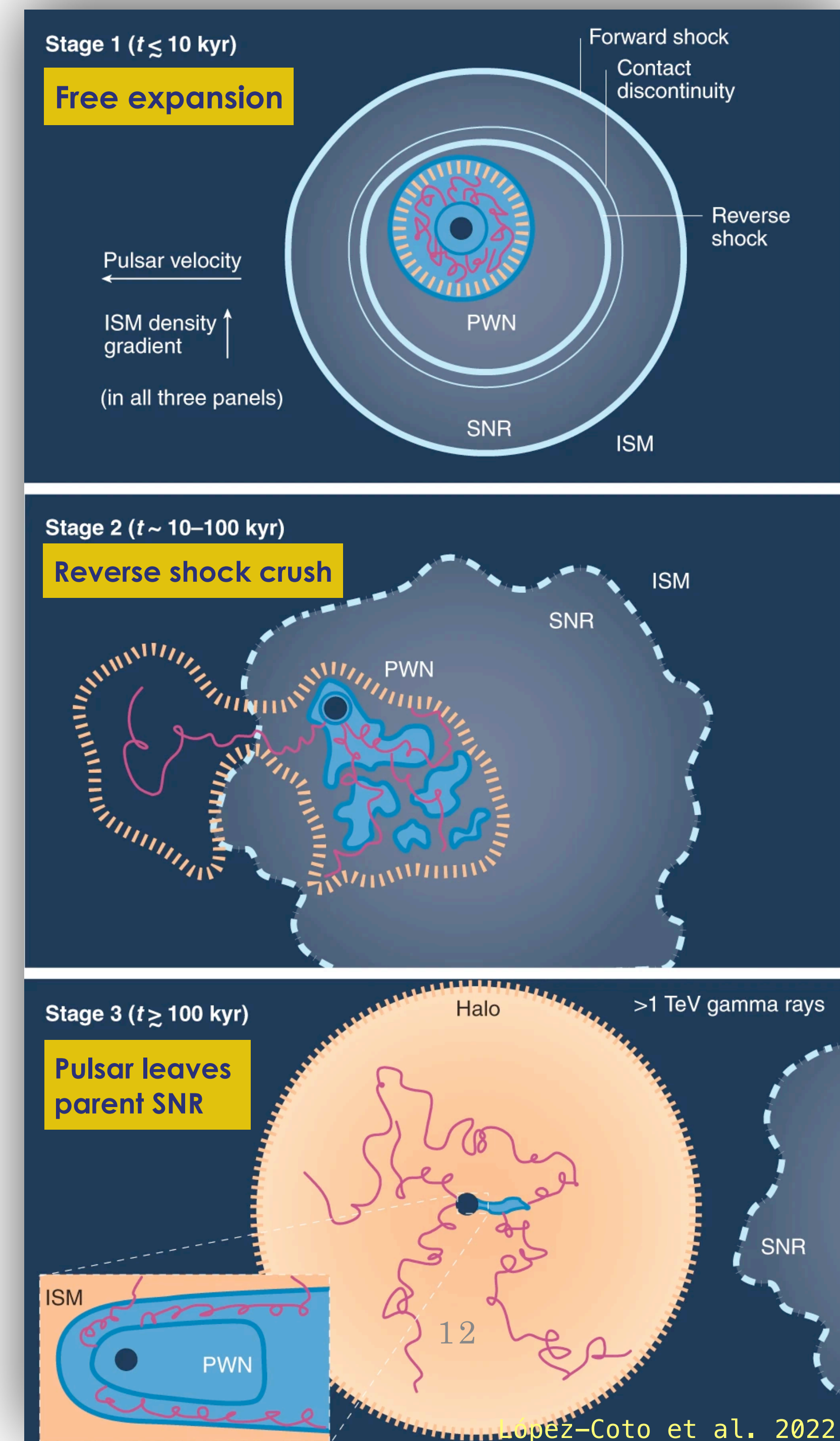


LHAASO 2021

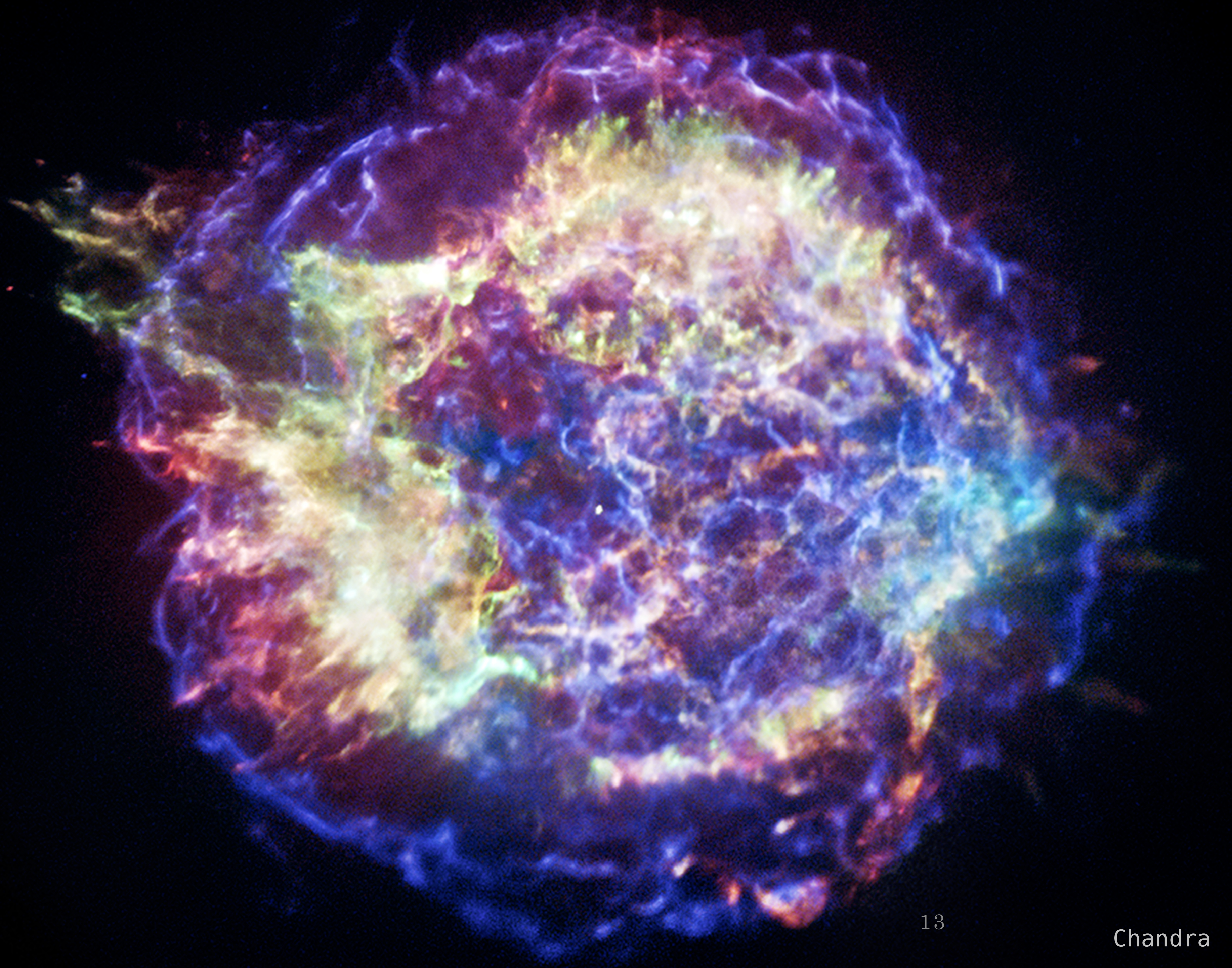
TeV halos



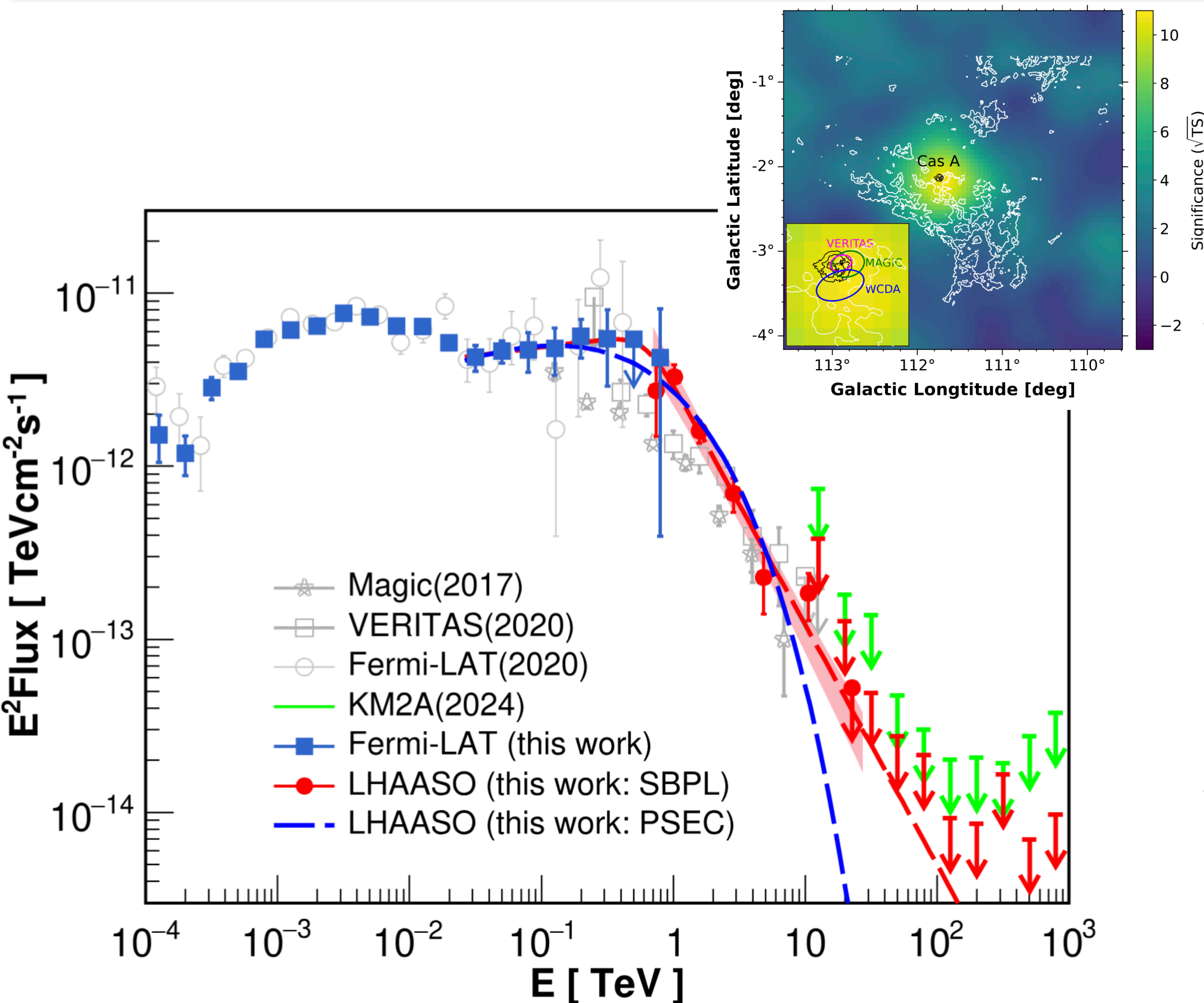
- HAWC detected two very extended gamma-ray sources coincident with Geminga and PSR B0656+14 (Abeysekara et al. 2017)
- **TeV halo produced by electrons diffusing into the ISM** (see e.g. López-Coto et al. 2022)
- 35 sources from LHAASO 1st catalog associated to pulsars
 - Possibly some TeV halos (Cao et al. 2024)



Supernova Remnants (SNRs)



Sub-PeV: Cassiopeia A



Cao et al. 2024b

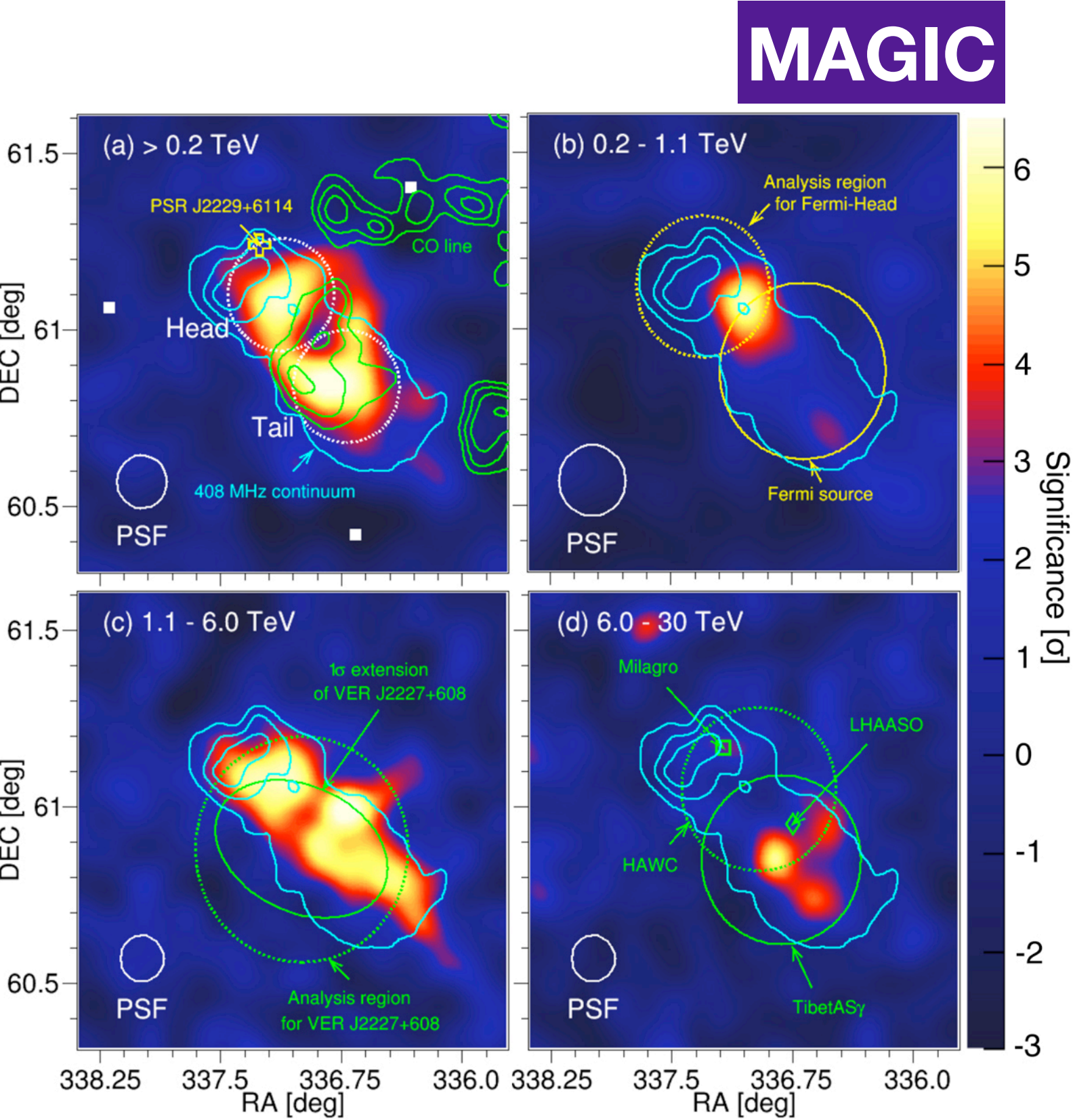
Young SNR (350 years)

- MAGIC (Anhen et al. 2017) : with cut-off at ~ 3.5 TeV -> **Cas A is not PeVatron at present time**
- MWL emission not explained with single population of electrons nor protons, although **protons likely dominate** the VHE emission
 - Pion bump
- **Bump spectral feature** above 30 GeV (Cao et al. 2024b) with soft spectrum of > 1 TeV

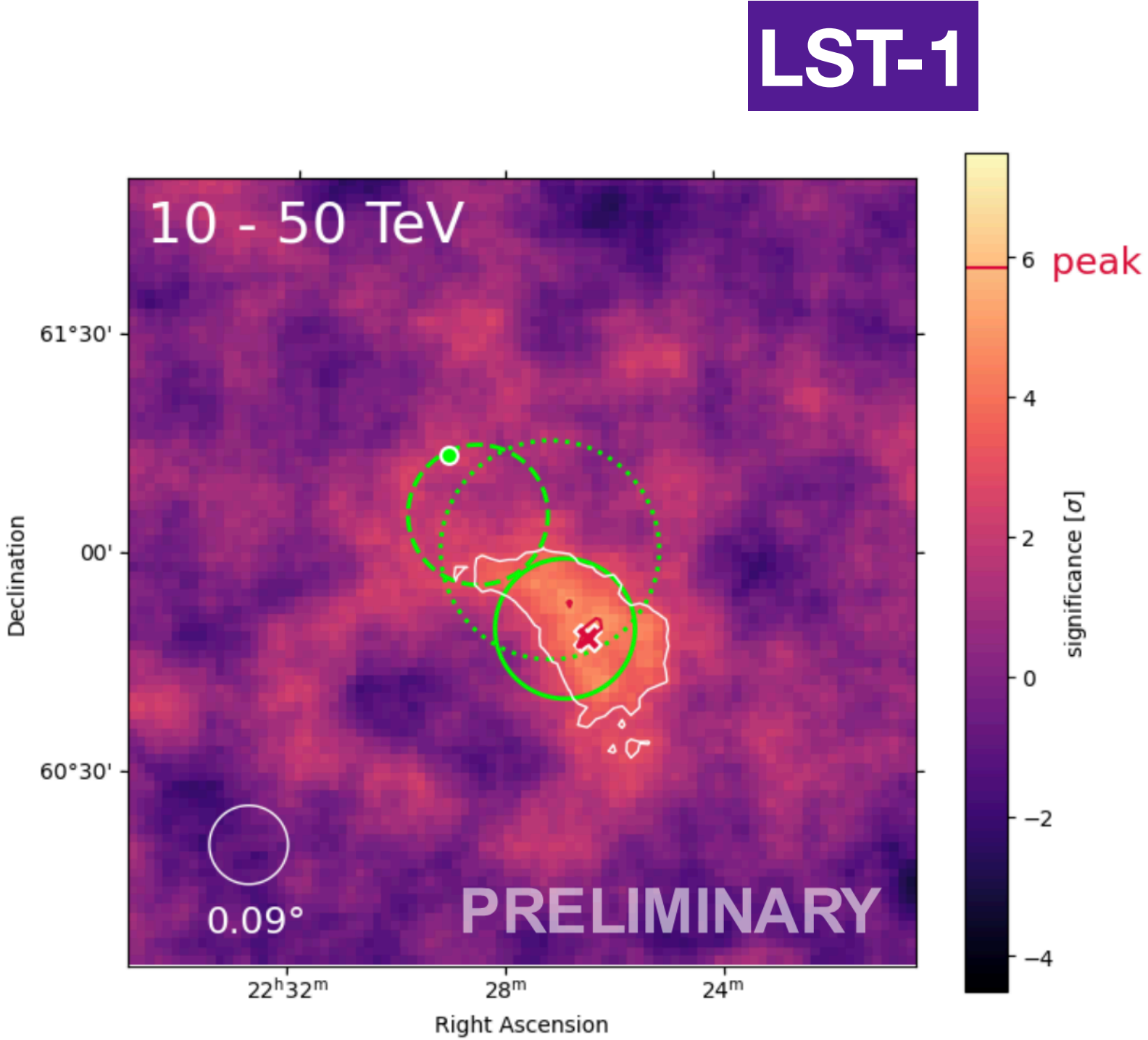
Evidence of
proton acceleration

Boomerang PWN & SNR G106.3+2.7

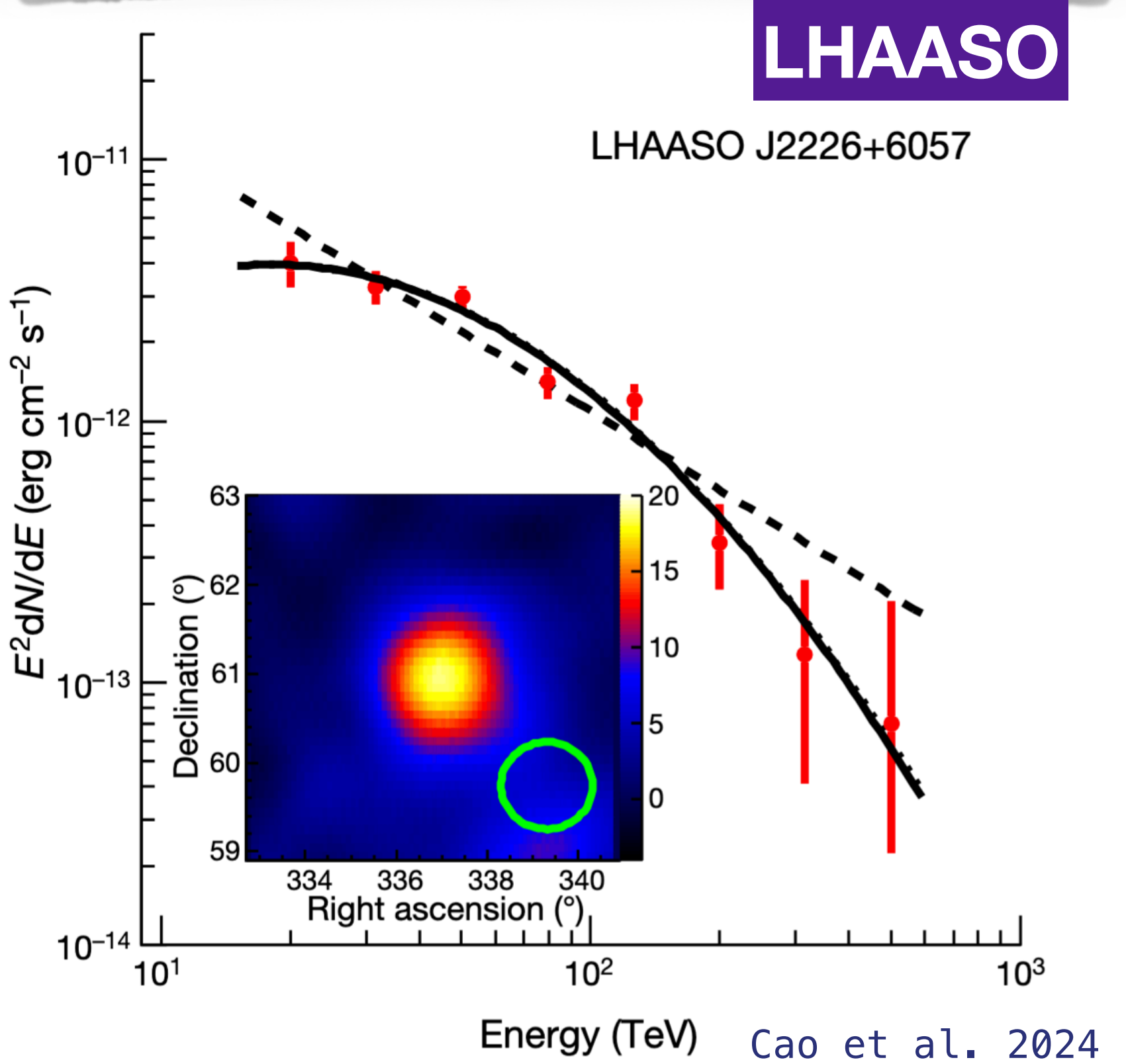
Letter | Published: 01 March 2021
Potential PeVatron supernova remnant G106.3+2.7 seen in the highest-energy gamma rays
The Tibet ASy Collaboration
Nature Astronomy (2021) | Cite this article



Acciari et al. 2023



M.S.. Carrasco, ICRC 2024



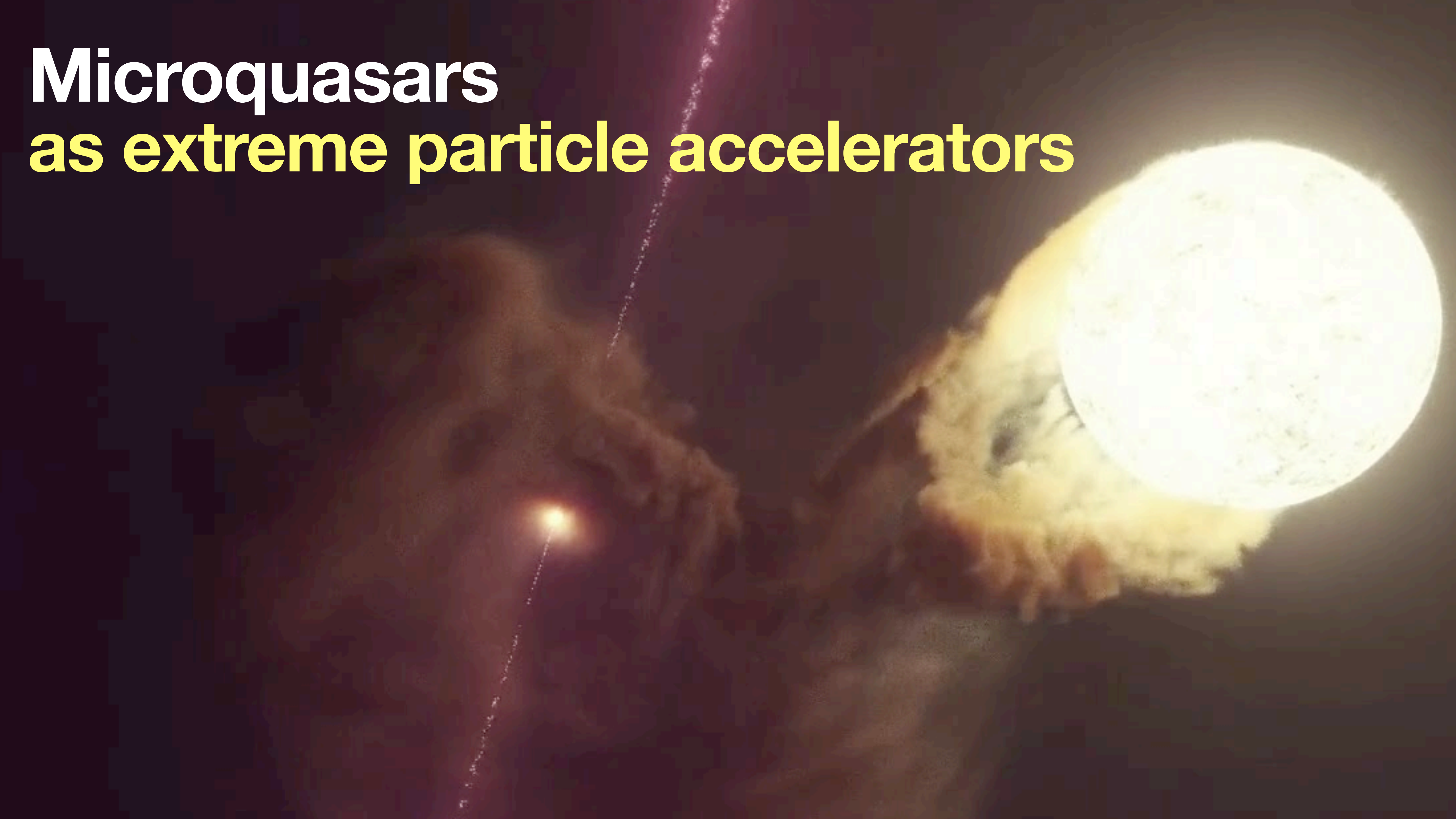
- Middle-aged SNR (4–10 kyr),
- **PeVatron candidate** (HAWC 2020, Tibet 2021, MAGIC 2023, LHAASO 2024...)
- Head: pulsar + PWN: leptonic PeVatron?
- **Tail**: expanding in cavity + dense molecular cloud
 - **Proposed hadronic origin** (MAGIC 2023)
 - p+ spectrum with Ecutoff of ~1 PeV

**Evidence of
proton acceleration**

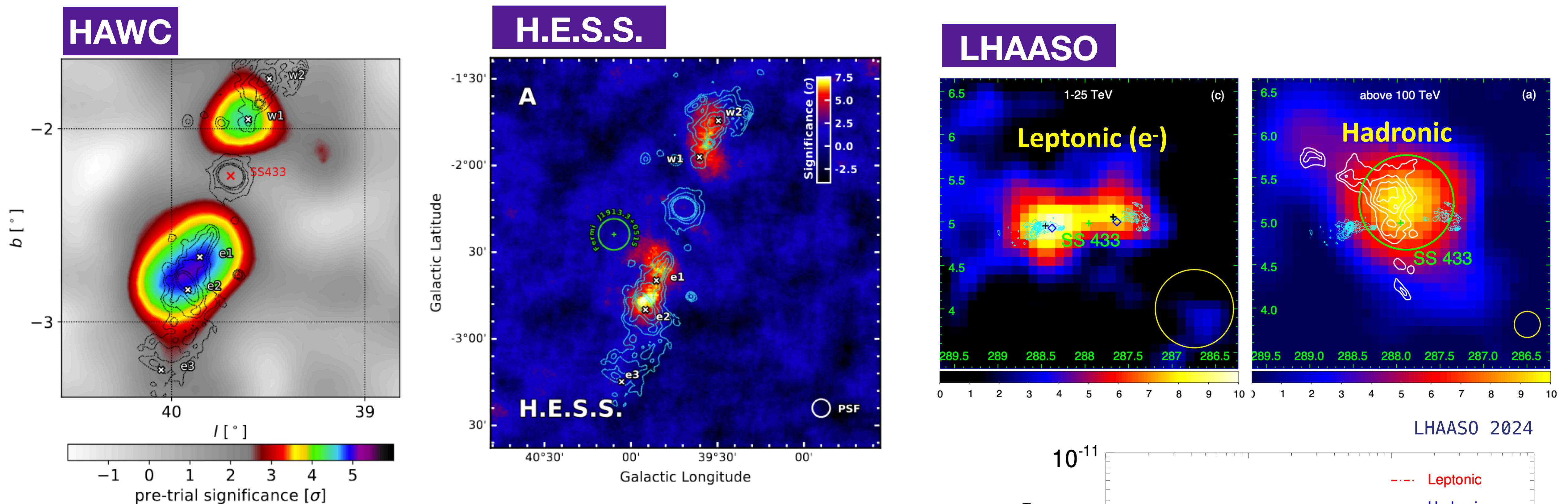
SNR contribution to LHAASO sources : passively illuminated clouds?

- Molecular cloud located close to a SNR can provide an effective target for production of gamma rays (e.g. Aharonian 1991; Aharonian & Atoyan 1996; Gabici et al. 2007, Galicia & Aharonian 2021, Mitchell et al. 2021)
- SNRs still remain candidate PeV accelerators, as they might be producing particles at PeV energies in short time intervals, namely during their early evolution.
 - self-amplification of the magnetic field
- **SNR-illuminated clouds in coincidence with UNID sources** detected in the first LHAASO catalogue (Mitchell & Celli 2025) -> **new population of gamma-ray sources?**

Microquasars as extreme particle accelerators



Persistent TeV emission from microquasars: SS433

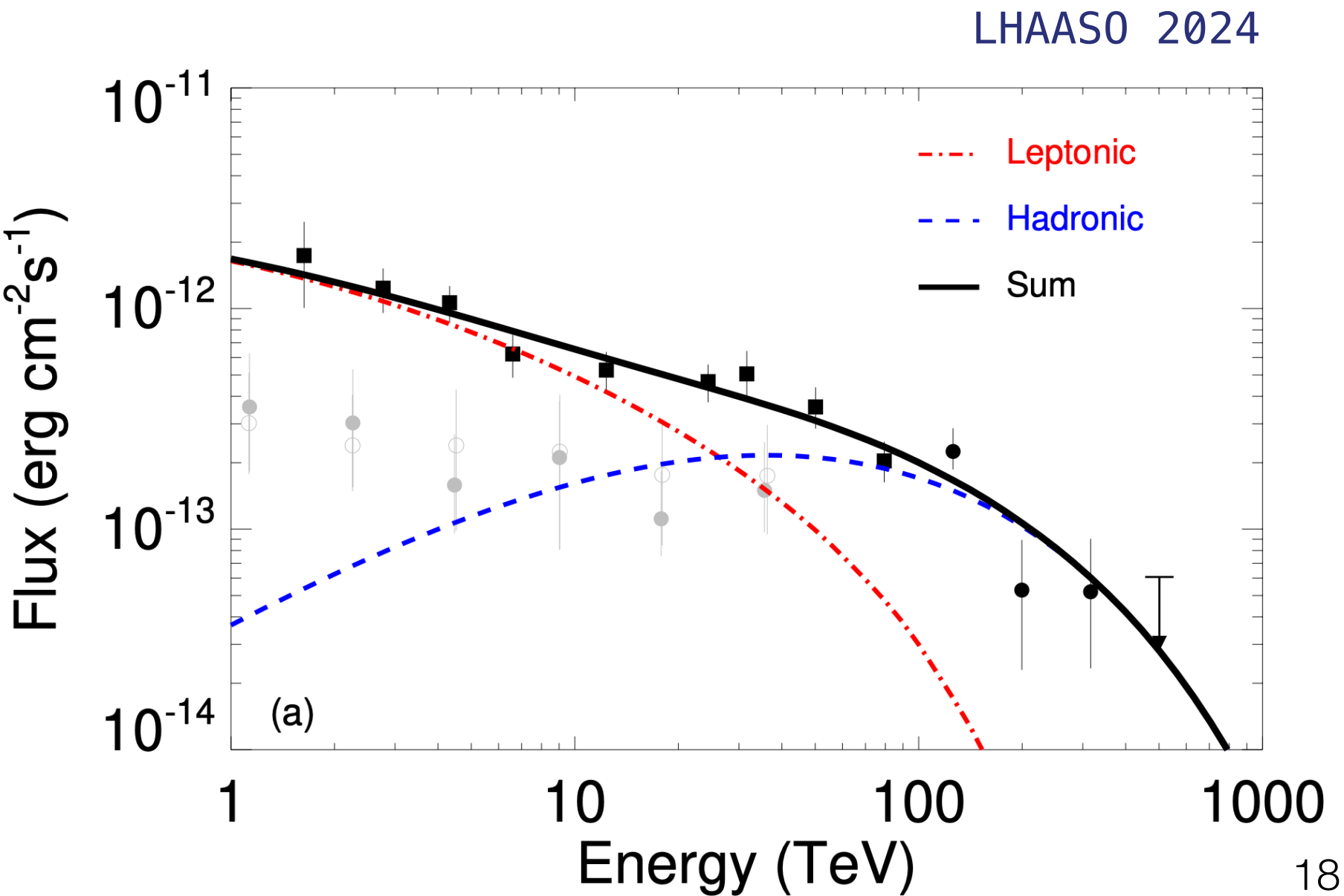


HAWC Coll. 2023

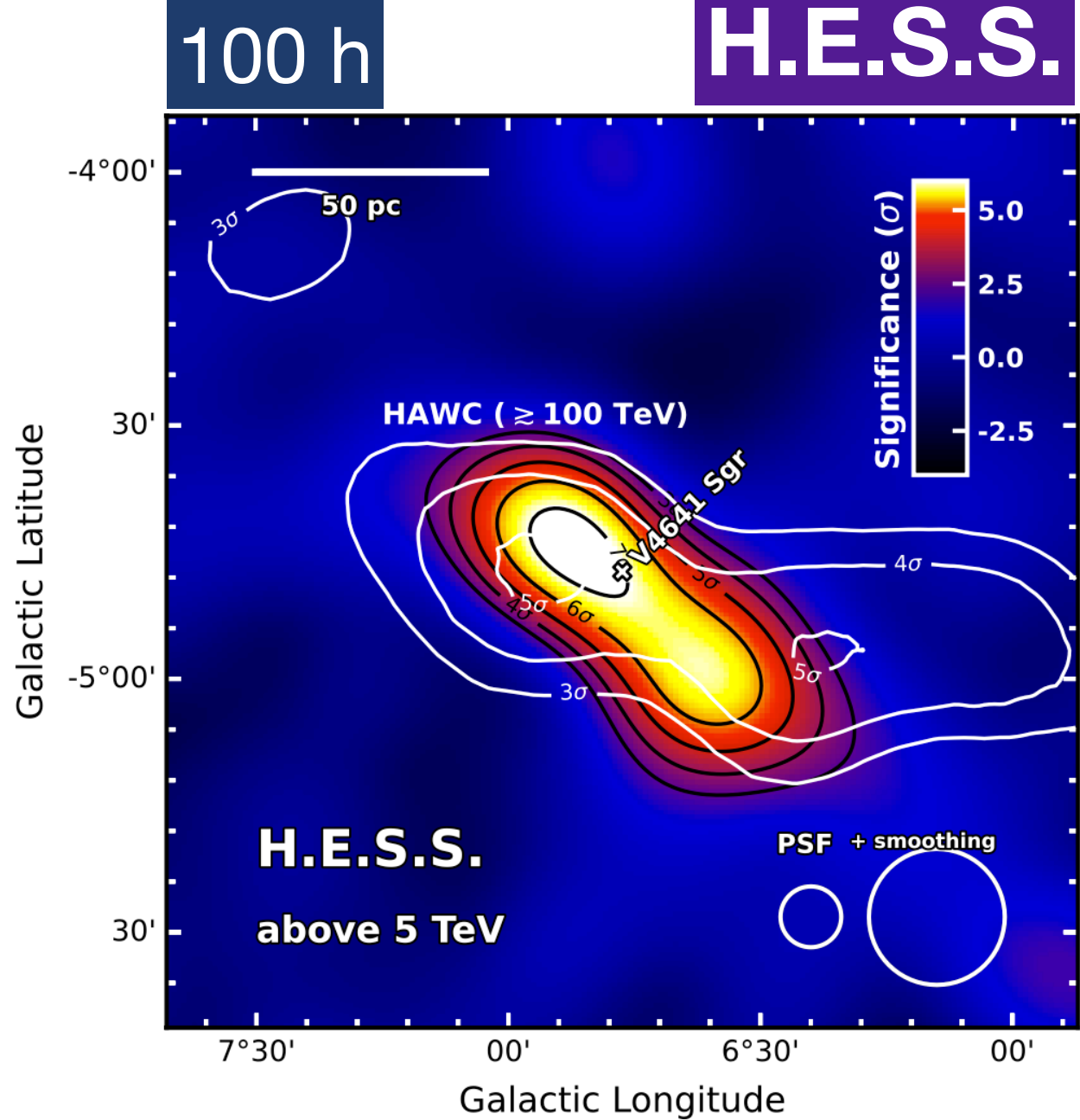
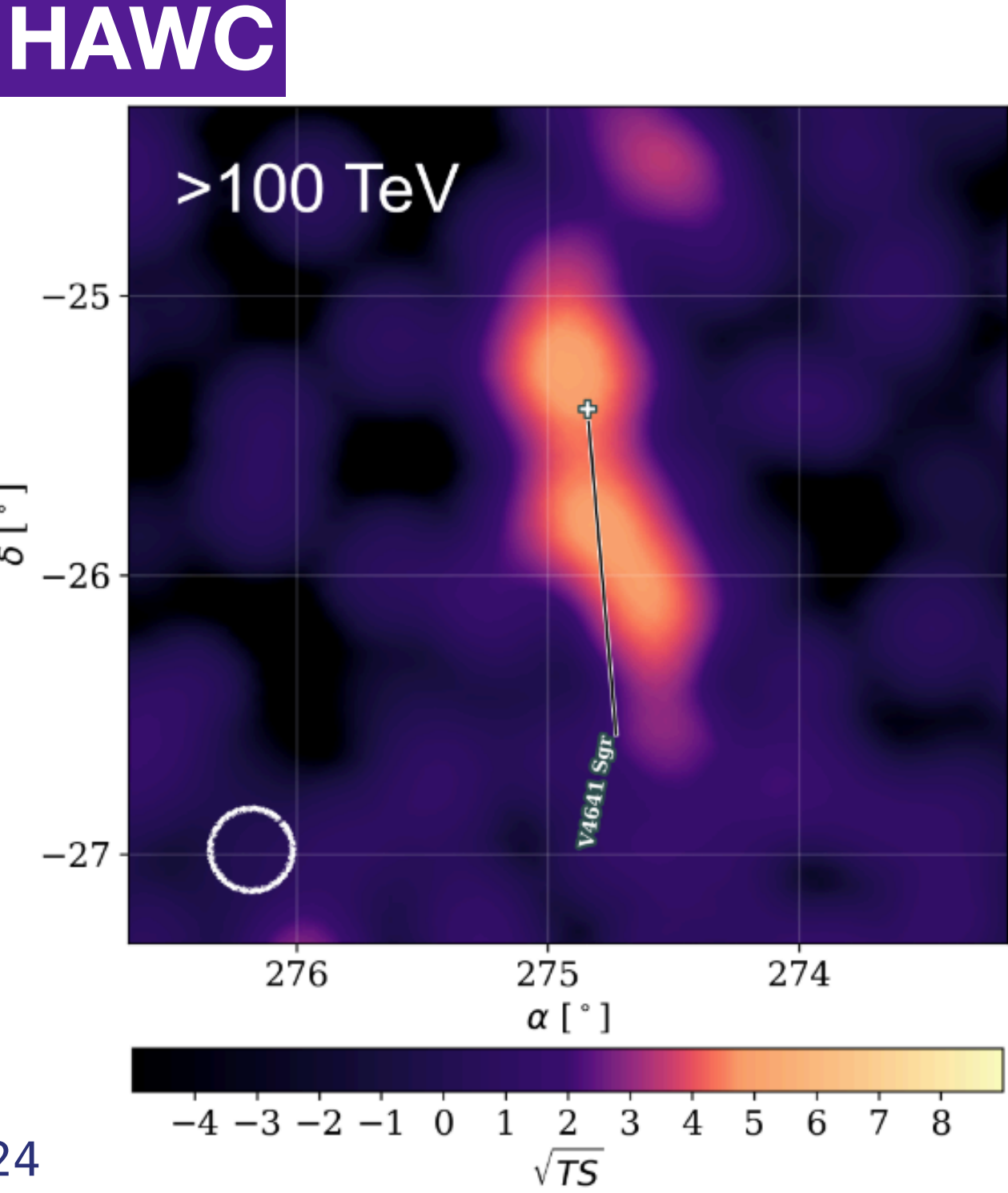
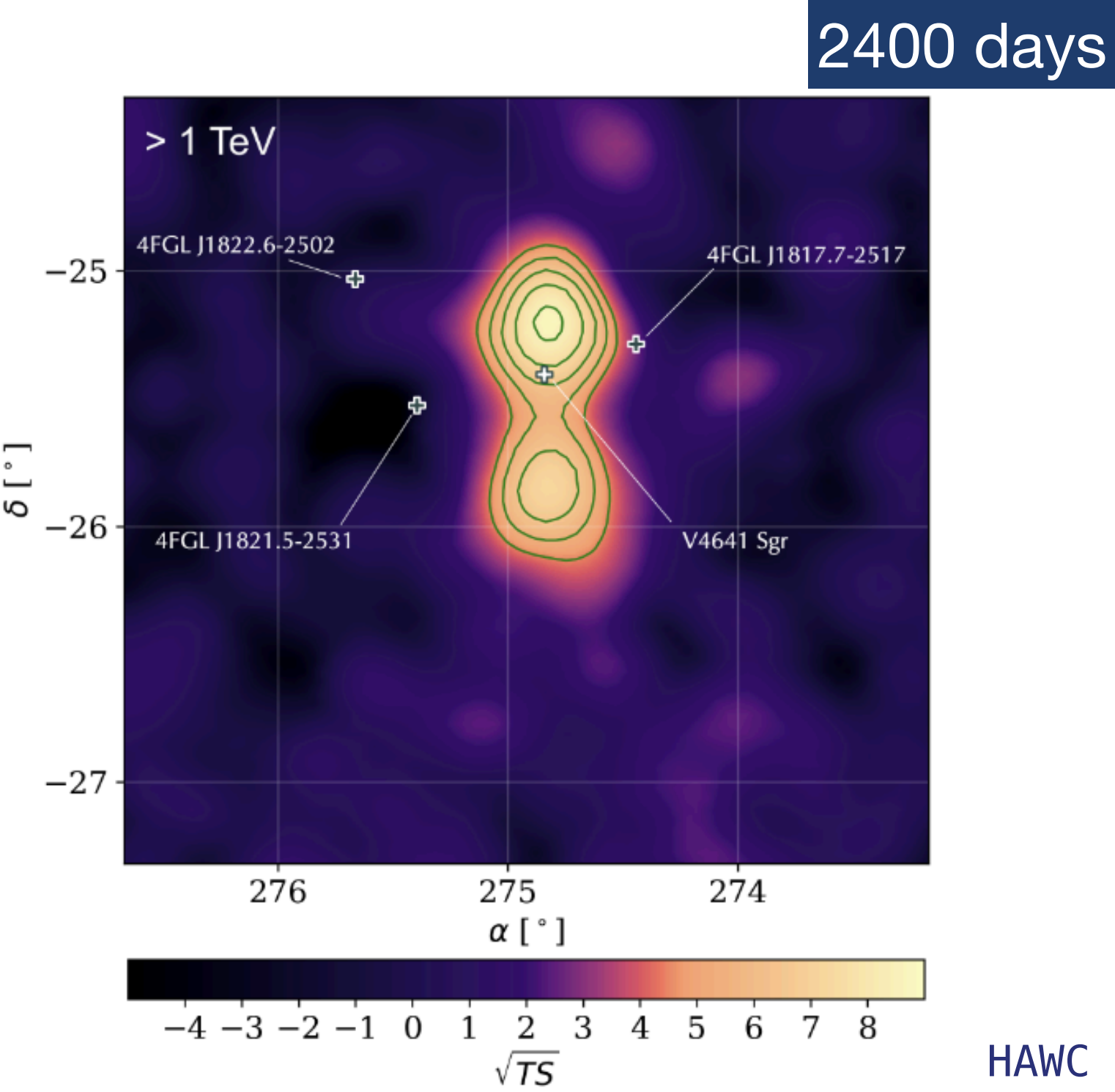
H.E.S.S. Coll. 2024

- HAWC discovery of **TeV emission at interaction regions** (Abeysekara et al. 2023)
- Confirmation by H.E.S.S. **up to 50 TeV** (HESS coll. 2024)
- **Leptonic** scenario proposed, acceleration of electrons up to 200 TeV
- Detection **above 100 TeV** by LHAASO (LHAASO 2024)
- **hadronic** origin of UHE emission from the central region (coincident with atomic cloud)

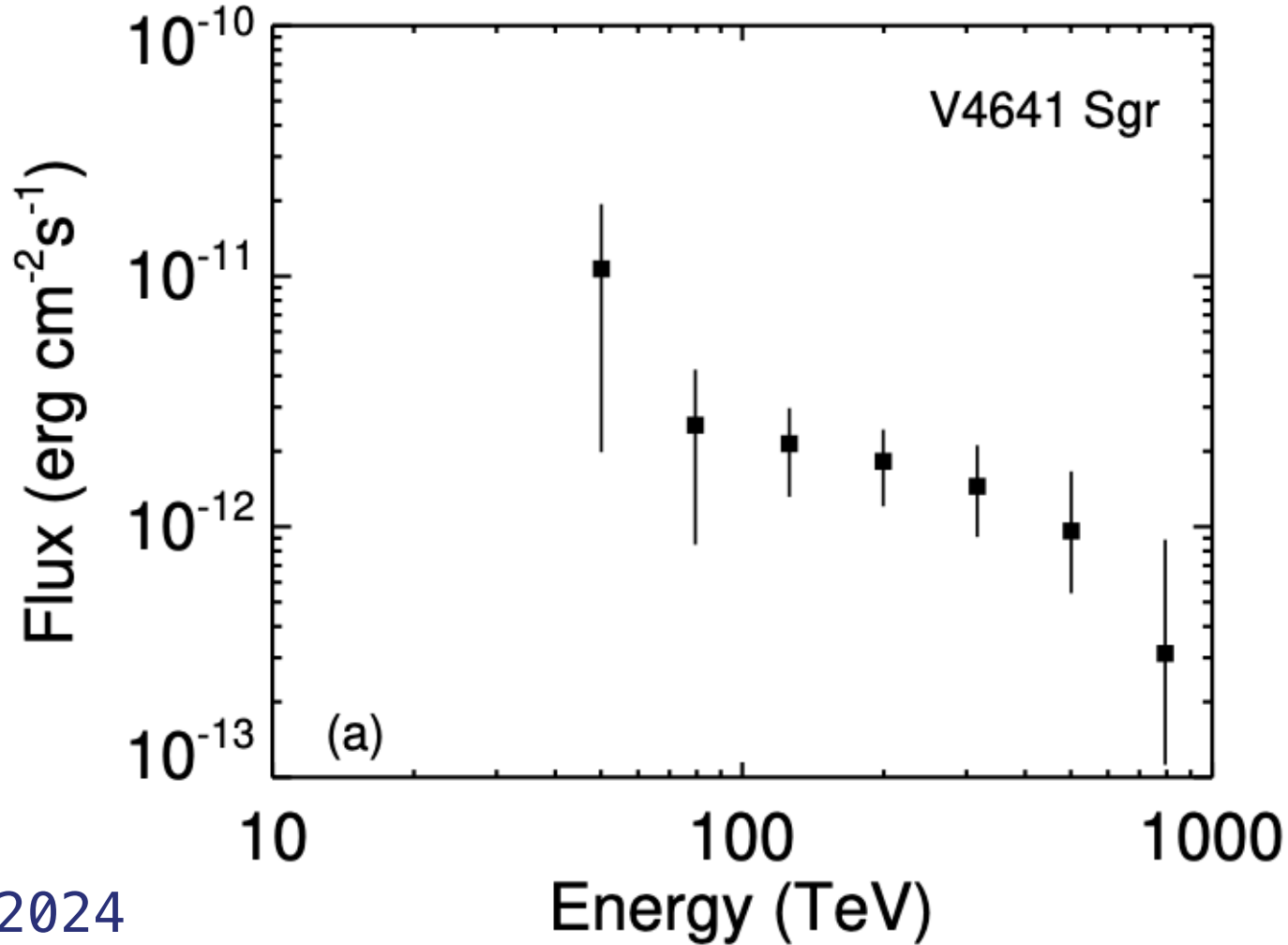
**First microquasar
detected in the TeV regime**



Persistent TeV emission from microquasars: V4641 Sgr



L. Olivera-Nieto (ICRC 2025)



- The highest **energy of photons: 0.8 PeV (LHAASO 2024)**
 - IC cannot reproduce such a hard spectrum (due to the KN effect)
 - Reasonable spectrum of protons
- **V4641 Sgr is most likely a so-called super-PeVatron that energizes protons up to energies at least ~ 10 PeV (LHAASO 2024)**
- H.E.S.S. emission most likely of leptonic origin (Olivera-Nieto 2025)

Persistent TeV emission from microquasars

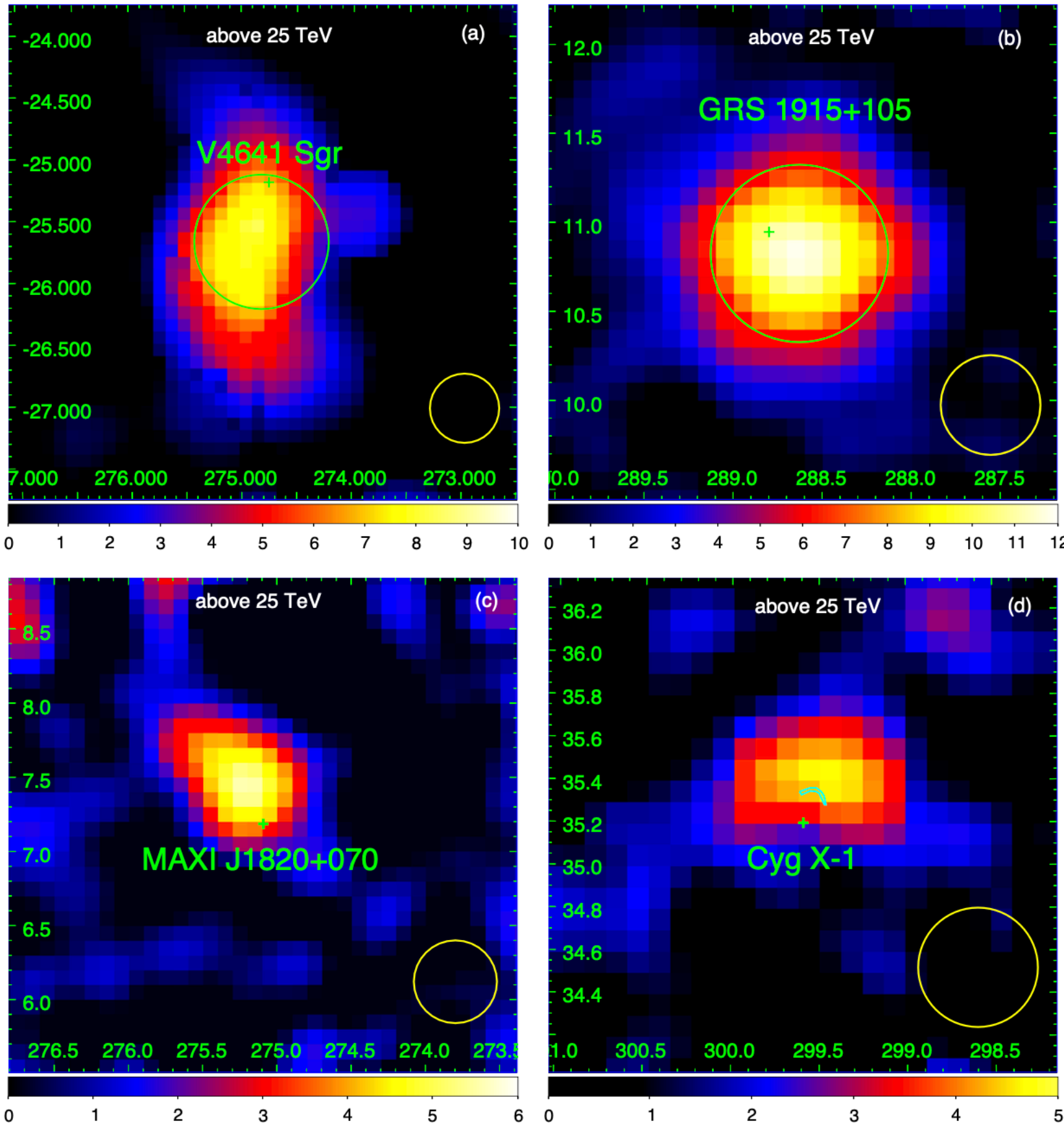
Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension ^a	Flux ^b (Crab Unit)
SS 433 E.		J1913+0457	9.7 ^c	2.78 ± 0.19	25 – 100		0.10
SS 433 W.	4.6 ± 1.3^{33}	J1910+0509	8.6 ^c	2.92 ± 0.21	25 – 100	0.70°	0.082
SS 433 central		J1911+0513	9.8	4.03 ± 0.29	100 – 400	0.32°	0.32
V4641 Sgr	6.2 ± 0.7^{34}	J1819-2541	8.1	2.67 ± 0.27	40 – 1000	0.36°	3.9
GRS 1915+105	9.4 ± 0.6^{35}	J1914+1049	6.1	3.07 ± 0.15	25 – 400	0.33°	0.17
MAXI J1820+070	2.96 ± 0.33^{36}	J1821+0726	5.9	3.19 ± 0.29	25 – 400	$< 0.28^\circ$	0.13
Cygnus X-1	2.2 ± 0.2^{37}	J1957+3517	4.0	4.07 ± 0.35	25 – 100	$< 0.22^\circ$	< 0.01
XTE J1859+226	4.2 ± 0.5^{38}	–	1.9	–	–	–	< 0.03
GS 2000+251	2.7 ± 0.7^{39}	–	1.7	–	–	–	< 0.04
CI Cam	$4.1^{+0.340}_{-0.2}$	–	1.4	–	–	–	< 0.03
GRO J0422+32	2.49 ± 0.3^{41}	–	0.8	–	–	–	< 0.01
V404 Cygni	2.39 ± 0.14^{42}	–	0.5	–	–	–	< 0.02
XTE J1118+480	1.7 ± 0.1^{43}	–	0	–	–	–	< 0.01
V616 Mon	1.06 ± 0.1^{44}	–	0	–	–	–	< 0.01

^a separation between two point-like sources of SS 433 below 100 TeV; 39% containment radius for SS 433 central, V4641 Sgr and GRS 1915+105; one-tailed 95% confidence upper limit for the source size for MAXI J1820+070 and Cygnus X-1.

^b at 100 TeV, 1 CrabUnit $\simeq 10^{-12}$ erg cm⁻²s⁻¹

^c the combined detection significance for the two point-like sources is 12.9 σ .

Table 1: LHAASO’s measurement of Galactic BH-jet systems in the field of view.

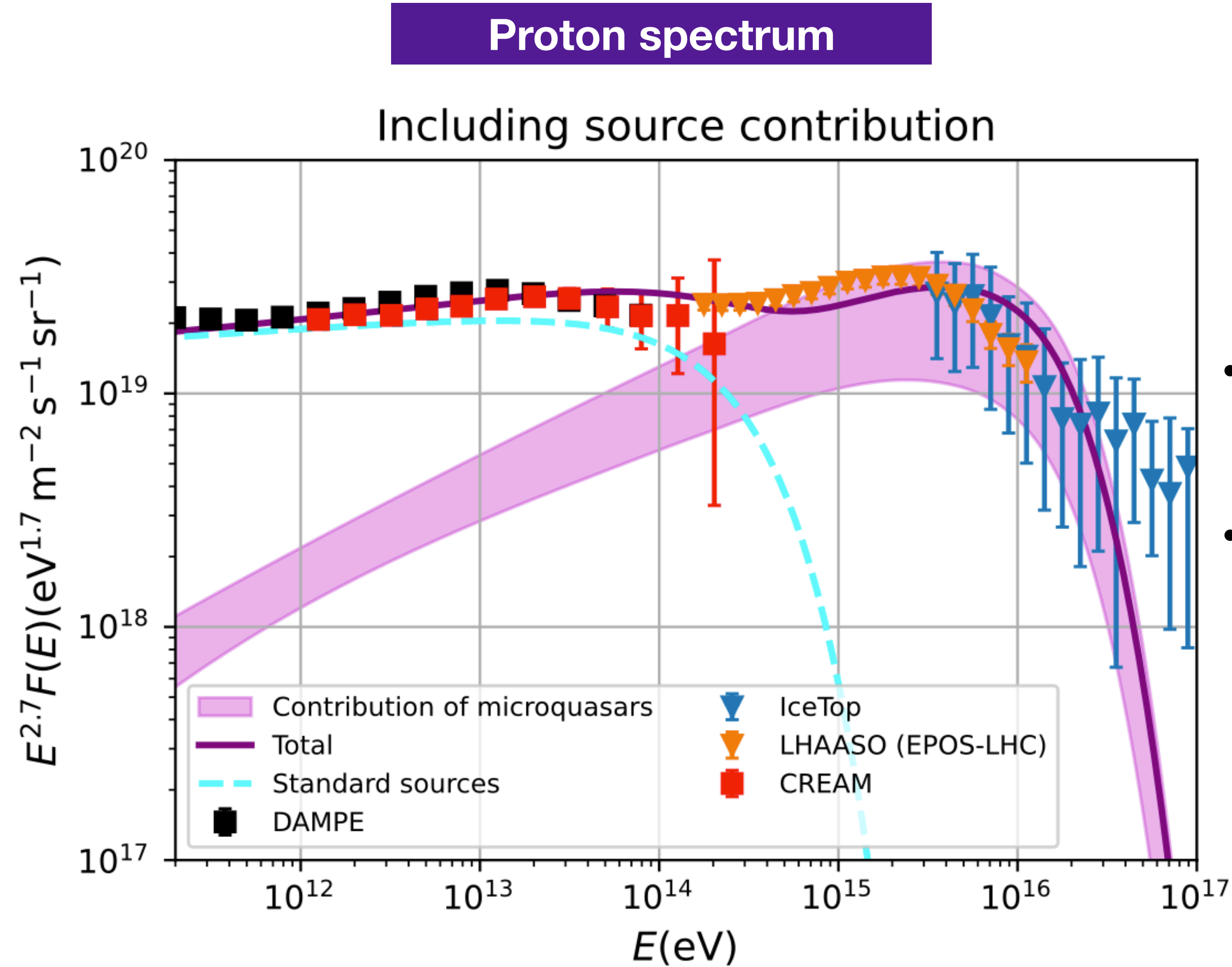


(LHAASO 2024 arxiv: 2410.08988)

- Galactic BH-jet systems can be potentially important **factories of CRs around and above the knee** (LHAASO 2024)

**BH-jet binaries
are efficient particle
accelerators**

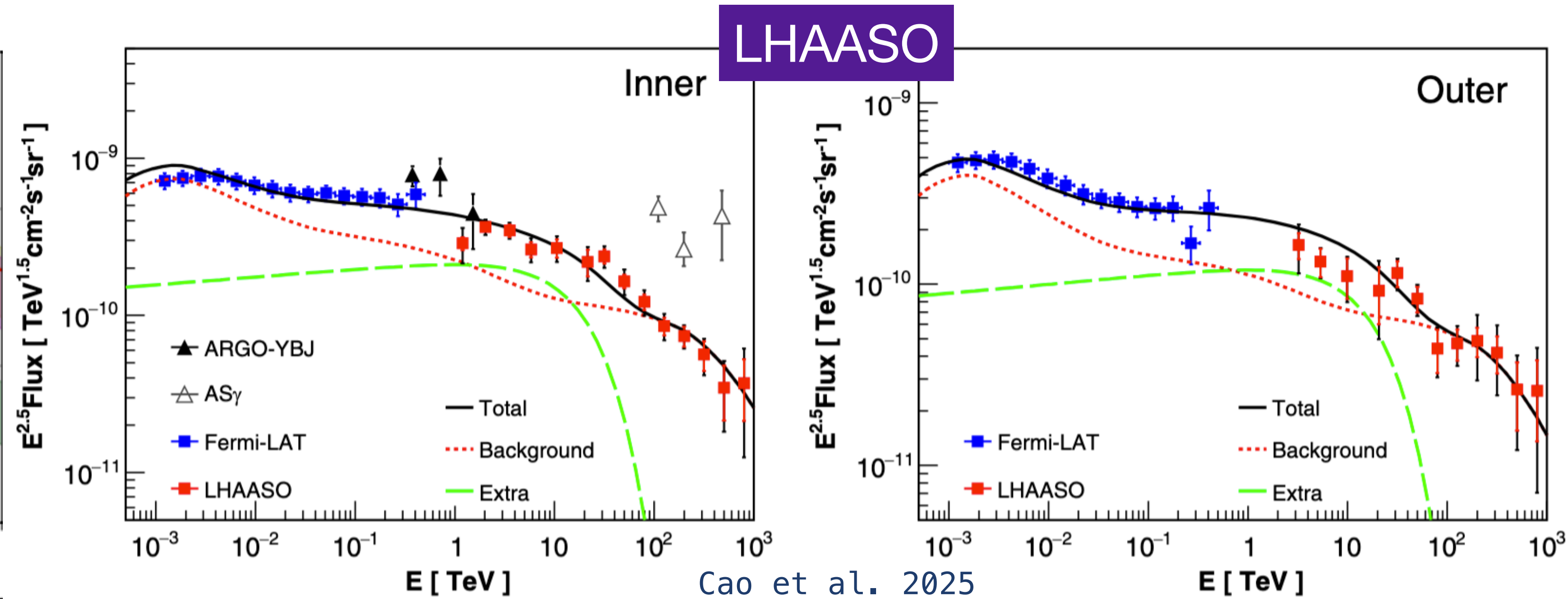
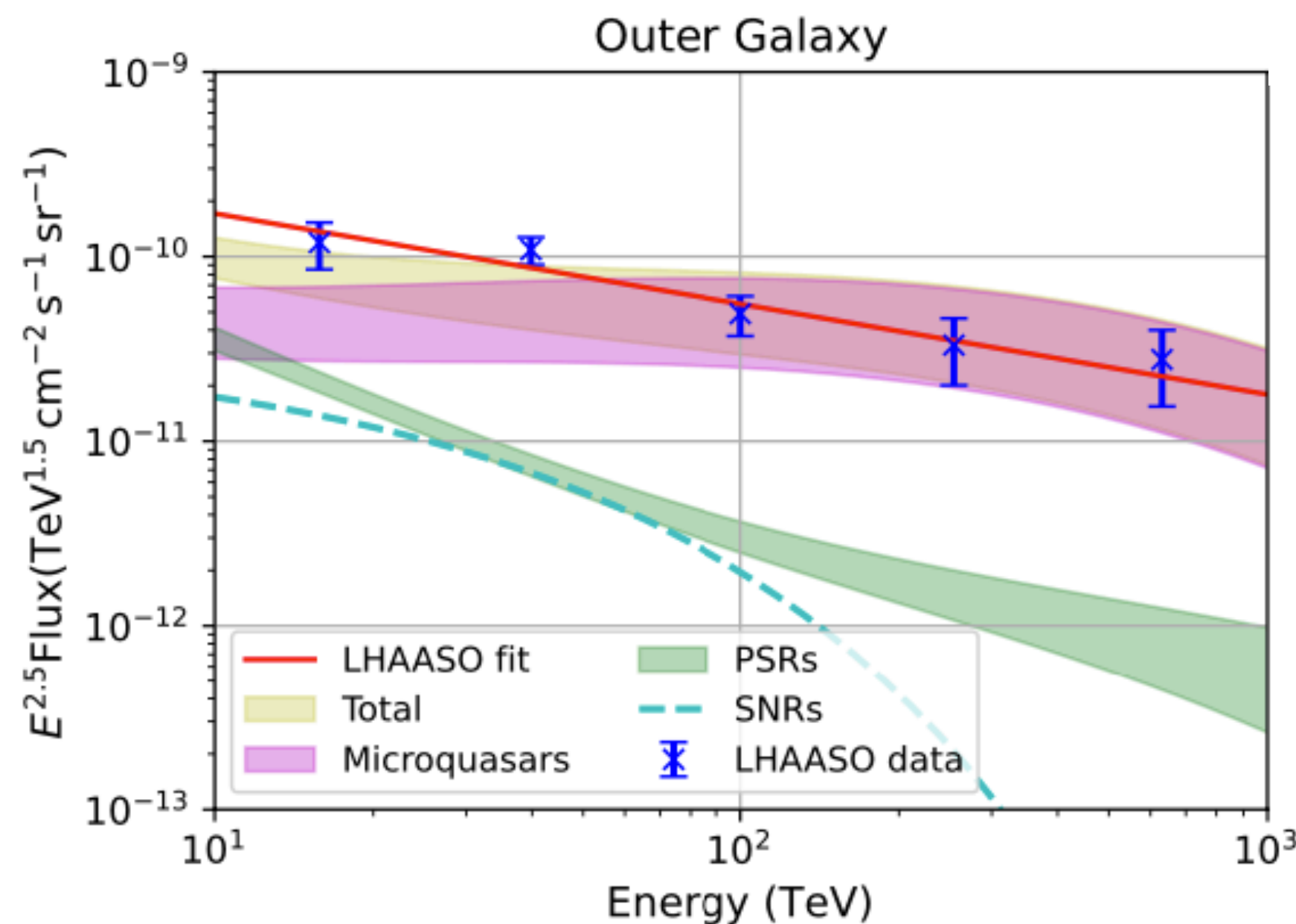
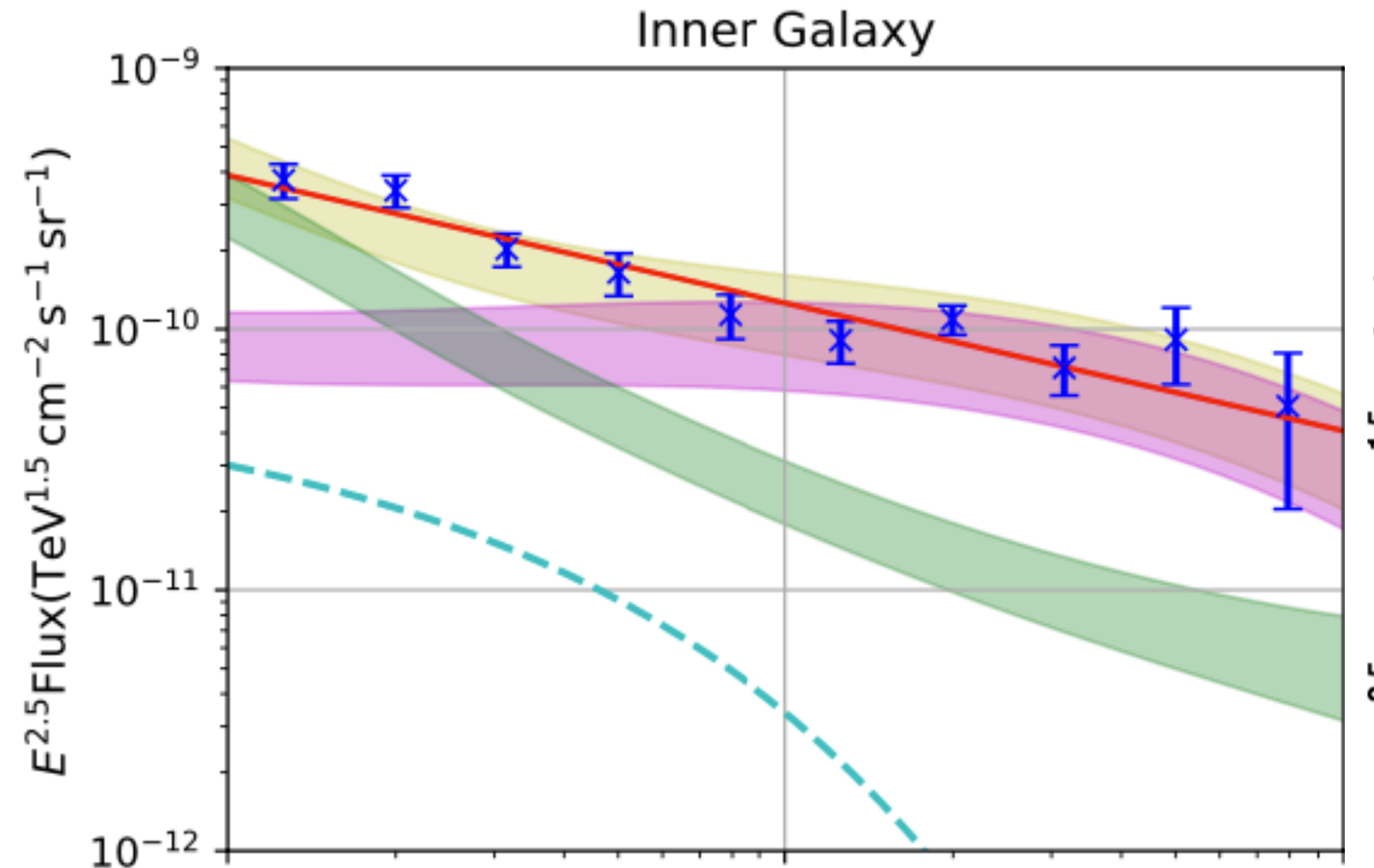
Microquasars as CR accelerators?



Kaci et al. 2025

- Microquasars can potentially account for the CR flux around and above the knee (Kaci et al. 2025)
- Bump @10 TeV and hardening @300 TeV naturally arise

Diffuse gamma-ray emission: microquasar contribution



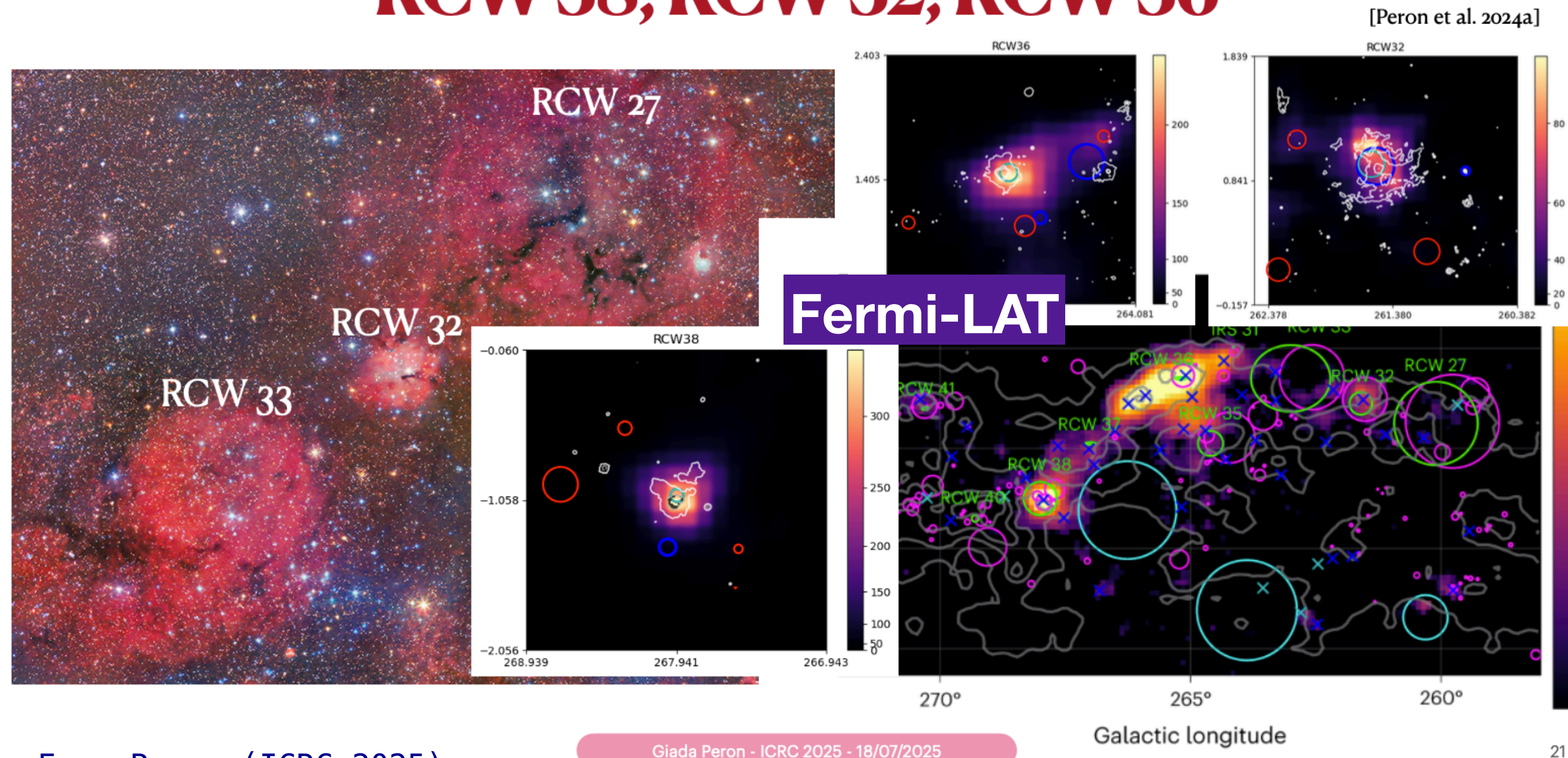
- Diffuse emission widely reported MILAGRO 2008, H.E.S.S. 2014, ARGO-YBJ 2015, Tibet AS γ 2021, HAWC 2024, LHAASO 2025
- From Kaci et al. 2025
 - Inner galaxy: microquasars can account almost entirely for the total diffuse emission
 - Outer galaxy: microquasars as main contributors with minimal contribution from unresolved pulsars



Star clusters & star-forming regions

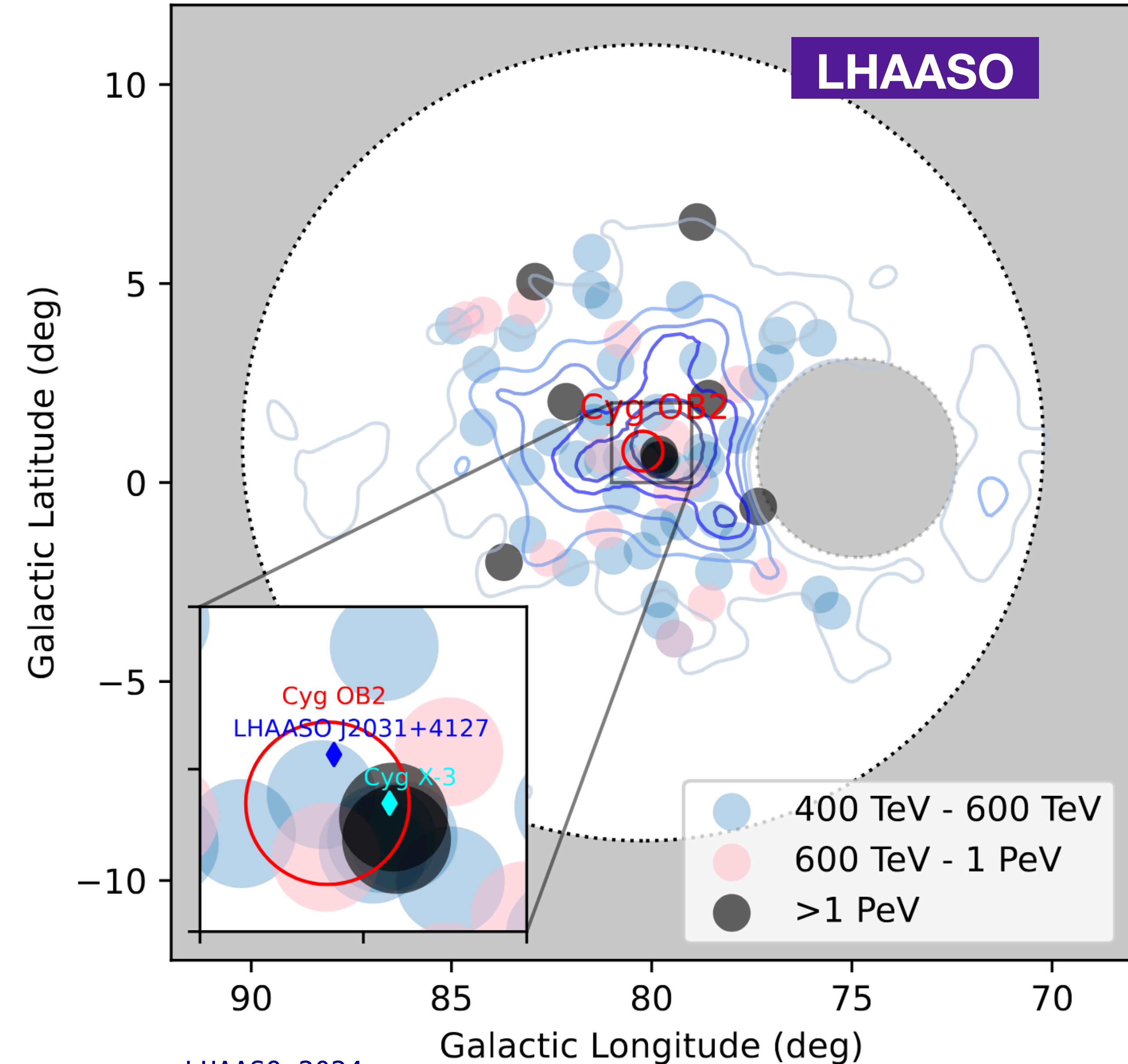
(Young) stellar clusters

RCW 38, RCW 32, RCW 36



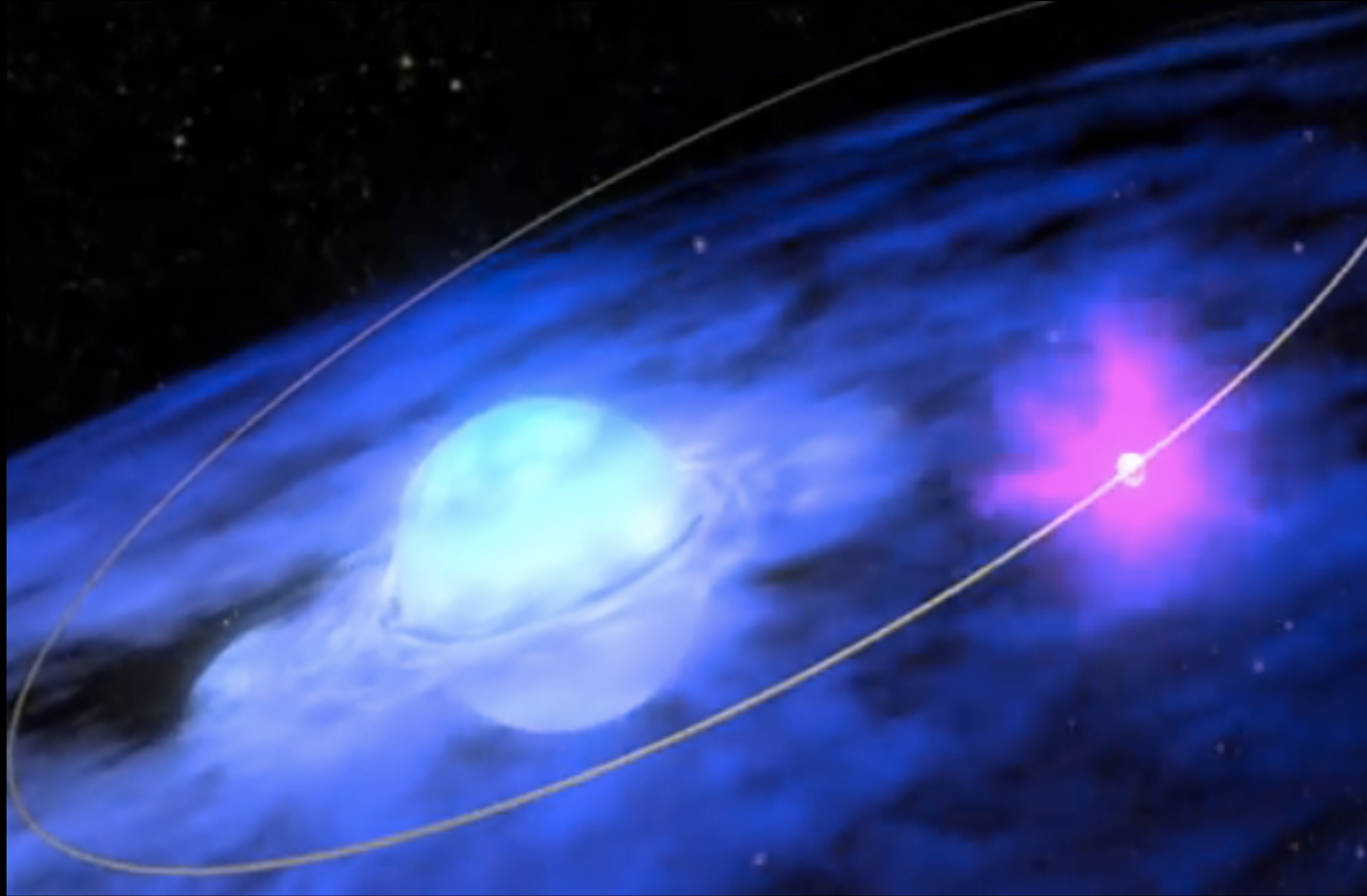
- **Young stellar clusters are expected to be gamma-ray sources** as the result of the interactions between the CRs accelerated at the wind termination shocks
- **Stellar wind termination shocks are CR accelerators** (Peron et al. 2024), ~1-10% of the CR population
- **Correlation between Fermi-LAT- unidentified sources and HII regions that trace young massive star clusters** -> massive star winds can alone accelerate particles and produce gamma-ray emission **at least up to GeV energies** (Peron et al. 2024b).

The Cygnus bubble

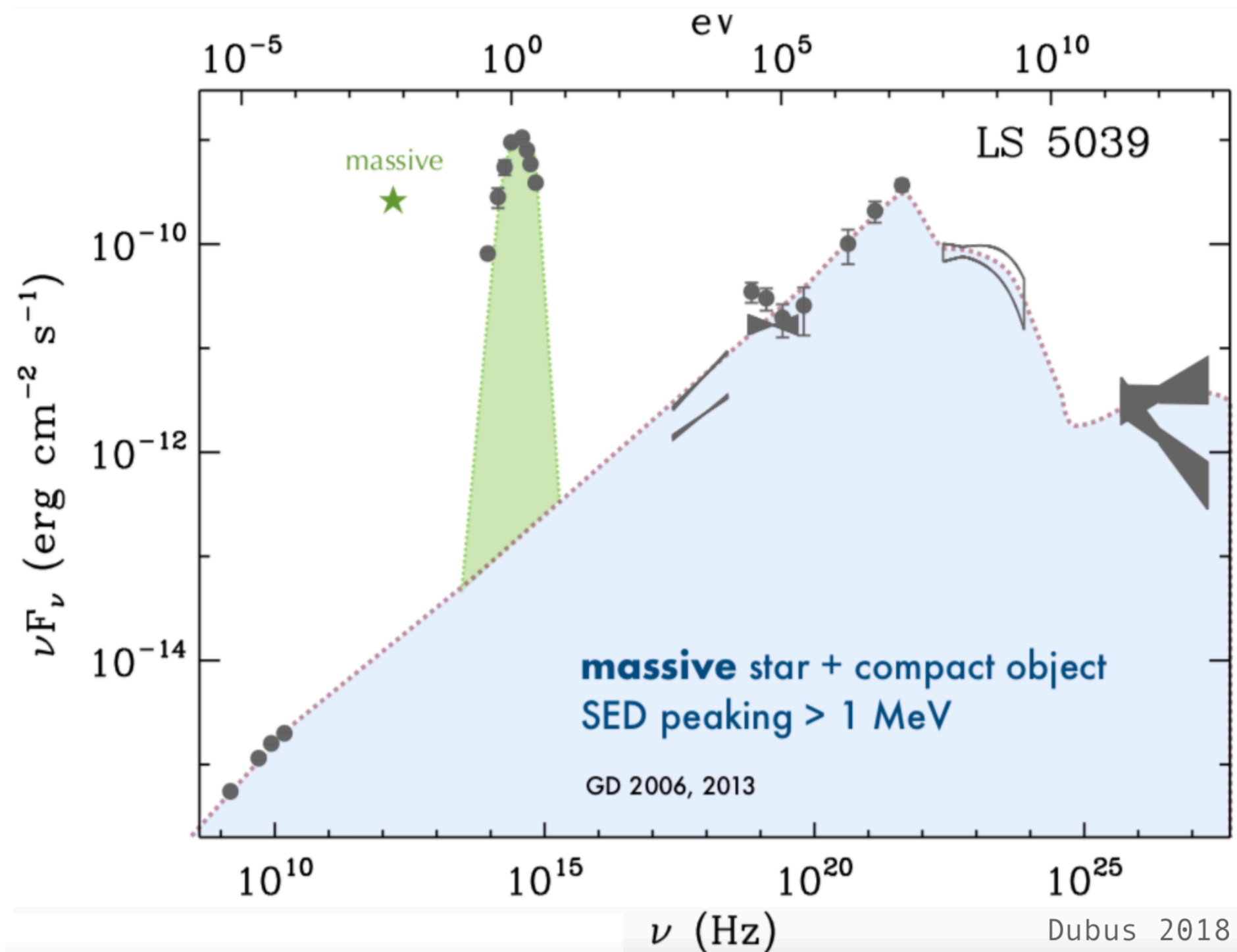


- **Star forming region:** many sources Cyg OB2, PSR J2032+4130, PSR J2032+4127/MT91, Cyg X-3...
- gamma-ray bubble spanning at least 100°
- **Hadronic emission up to PeV**
- What about **Cygnus X-3**?
 - **PeV photons coincident with its position** (and OB2)
 - ULs on a long-term campaign by MAGIC (see talk by L. Barrios-Jiménez, GA session)

Gamma-ray binaries

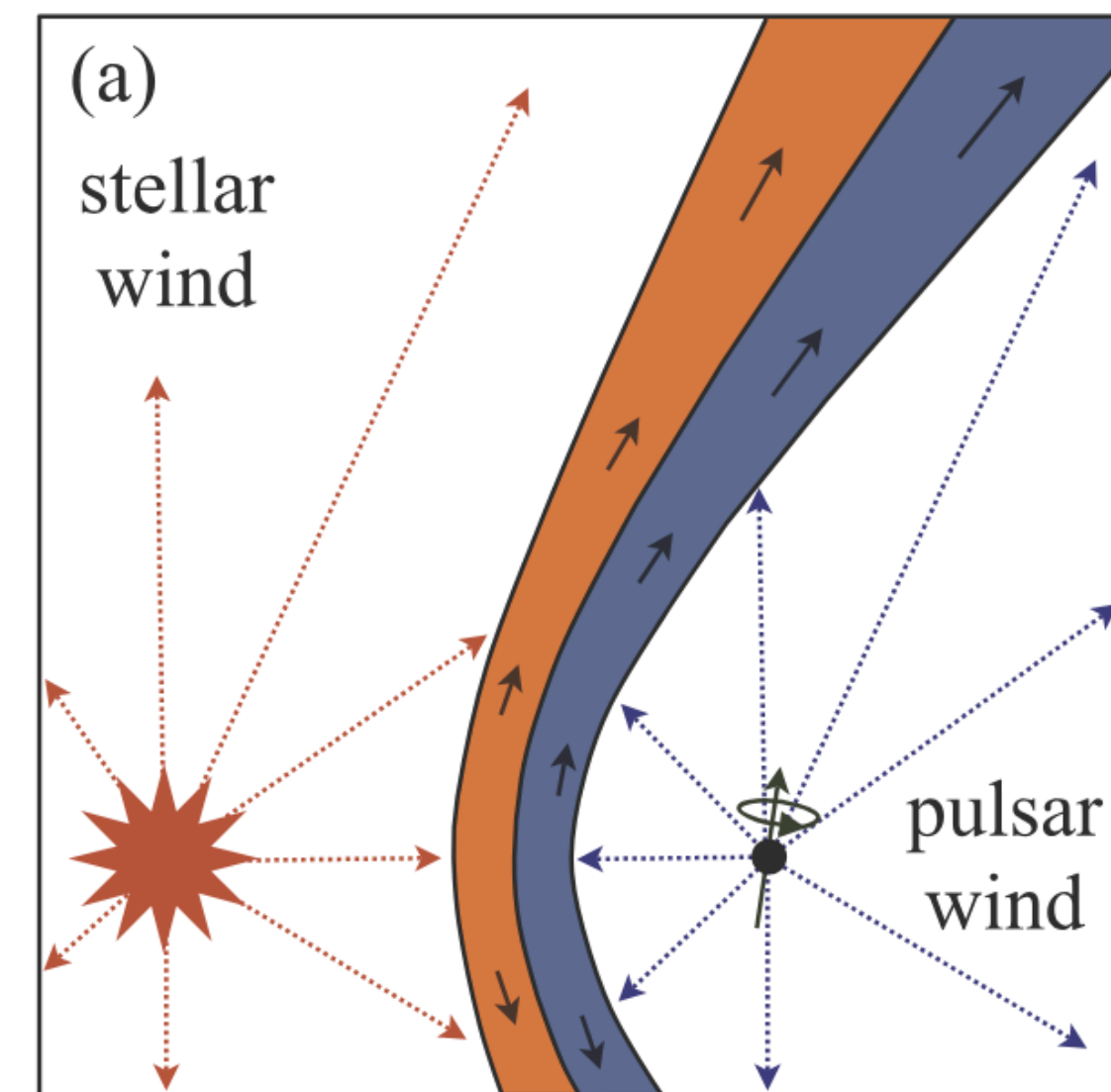
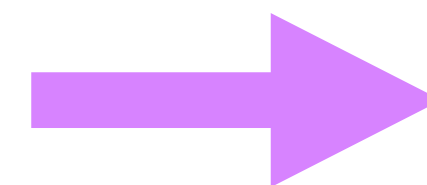
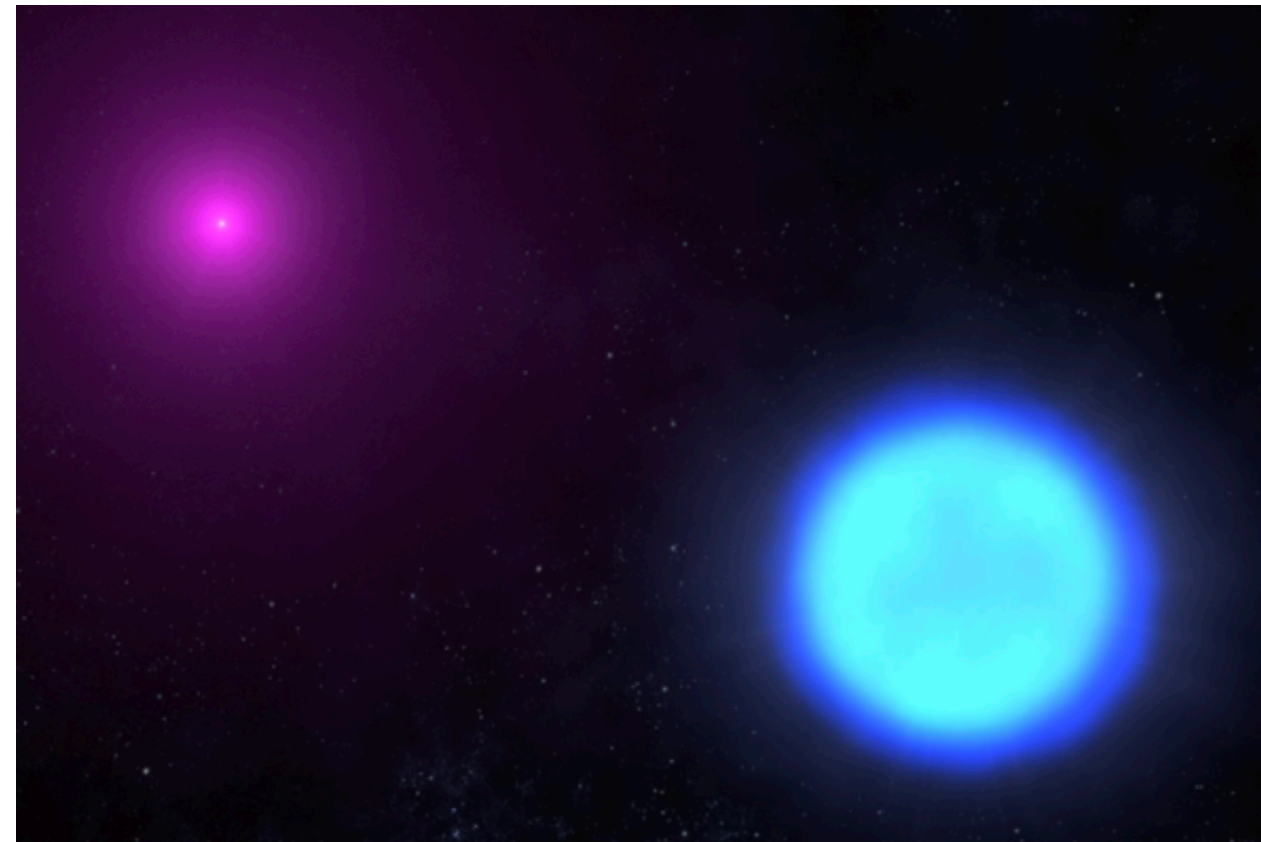
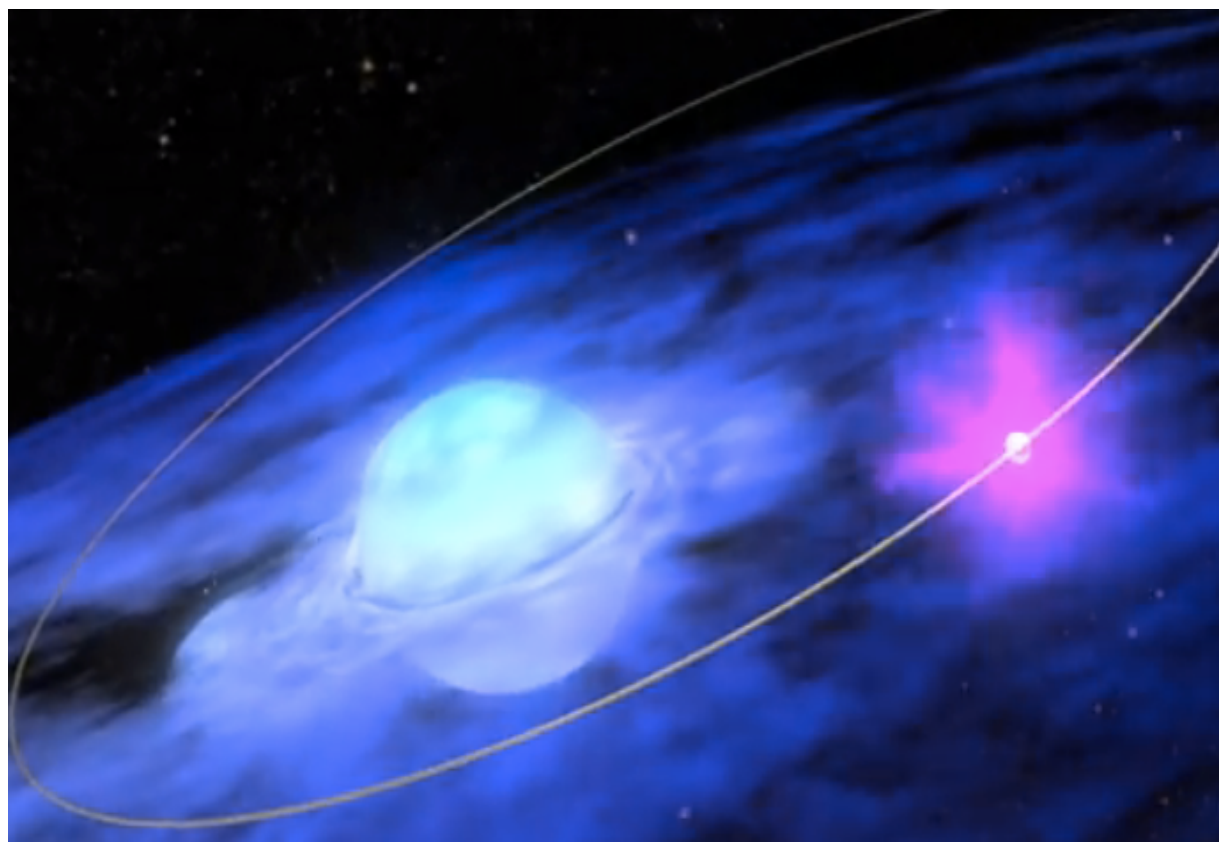


Gamma-ray binaries



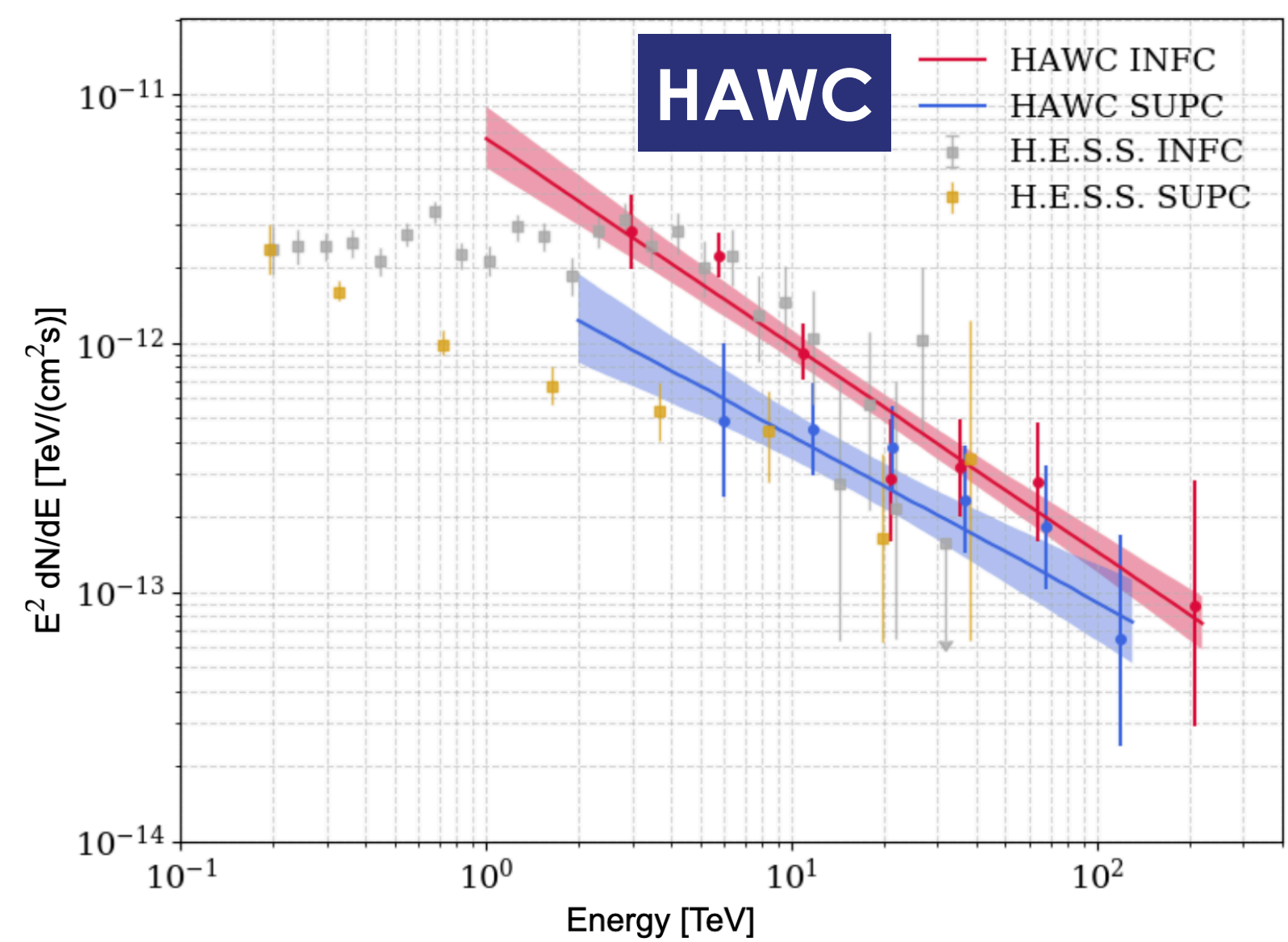
- Gamma-ray binaries in a nutshell:
 - Compact binary: O/Be Star + compact object
 - Bulk of the non-thermal emission in the γ -ray domain ($E > 1 \text{ MeV}$)
 - Only ~10 known systems** (out of ~300 X-ray binaries) **in the VHE domain**
 - 3 binaries detected at $E > 25 \text{ TeV}$ with HAWC/LHAASO**
 - Orbital variability

Gamma-ray binaries are likely non-accreting pulsar binaries

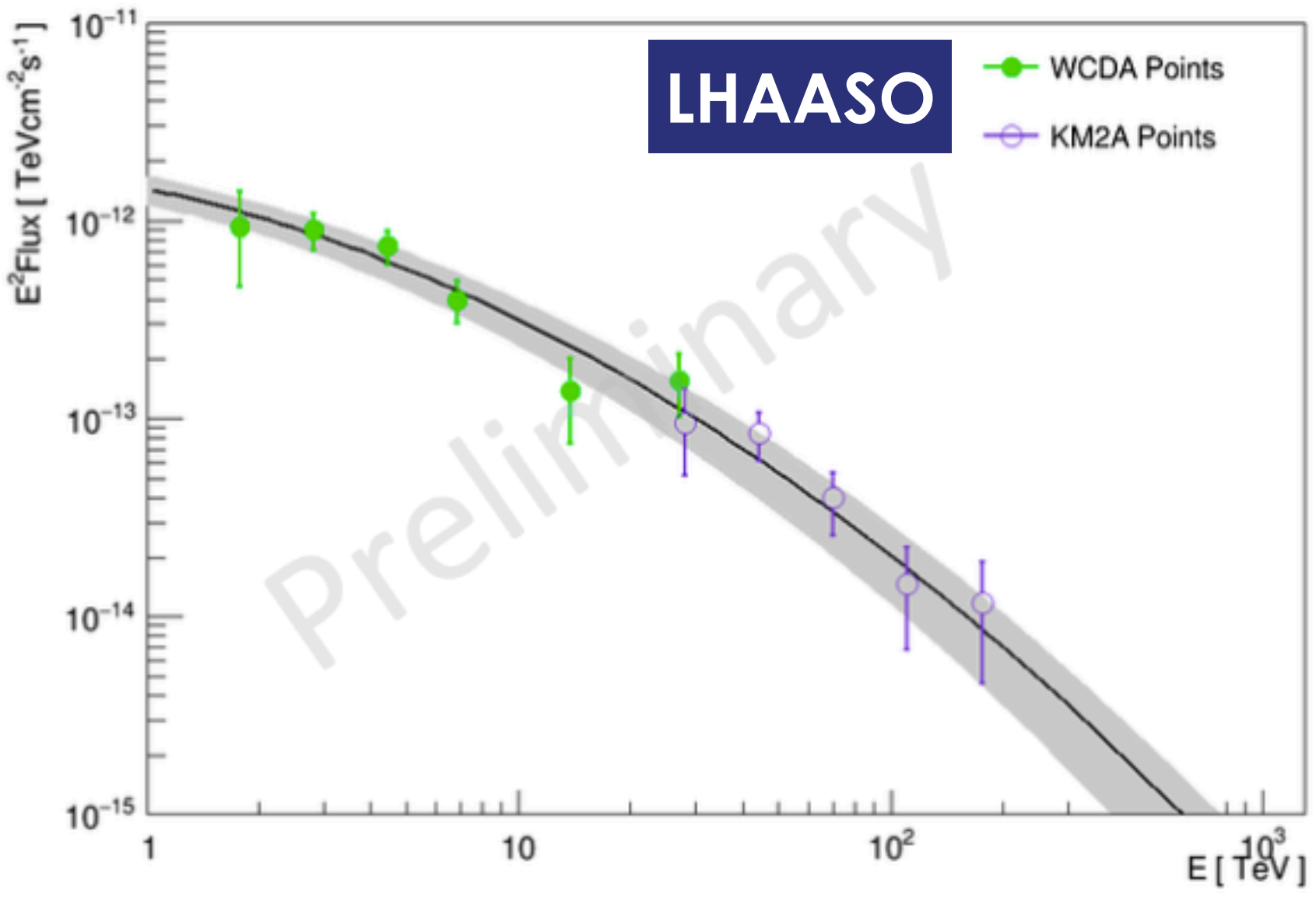


Gamma-ray binaries

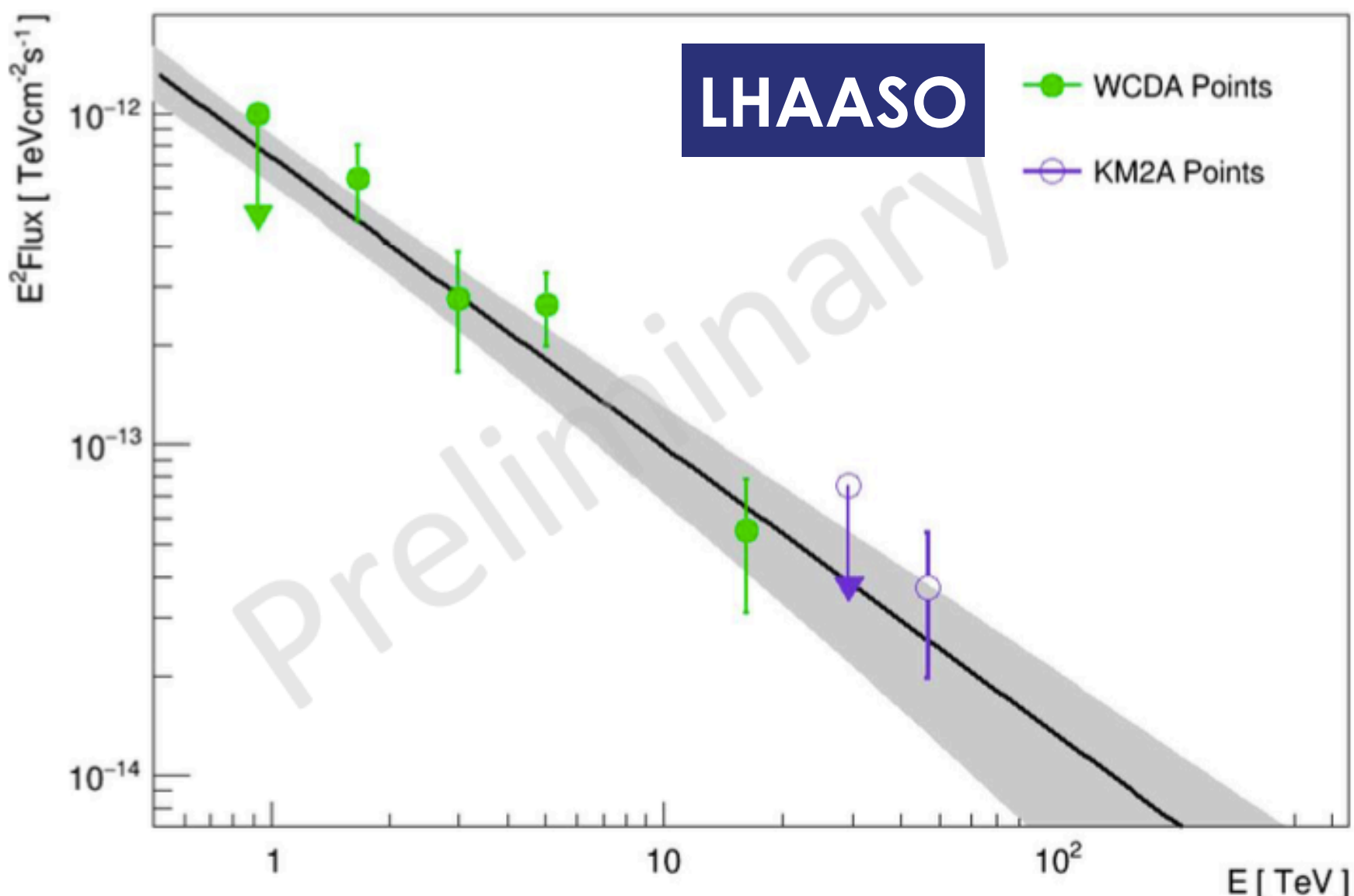
LS 5039



LS I +61 303



HESS J0632+057



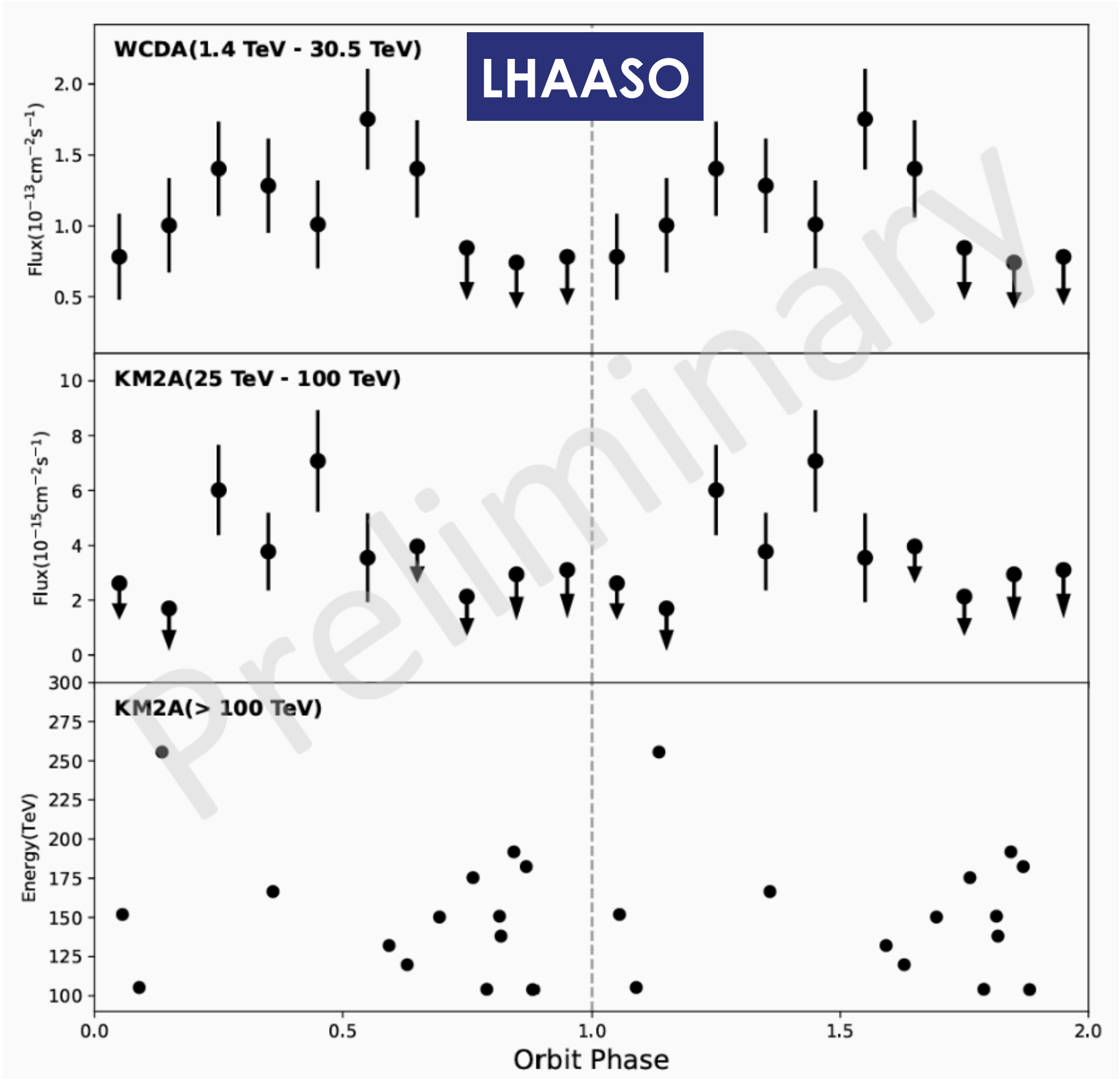
HAWC 2025

M. Hasan ICRC 2025

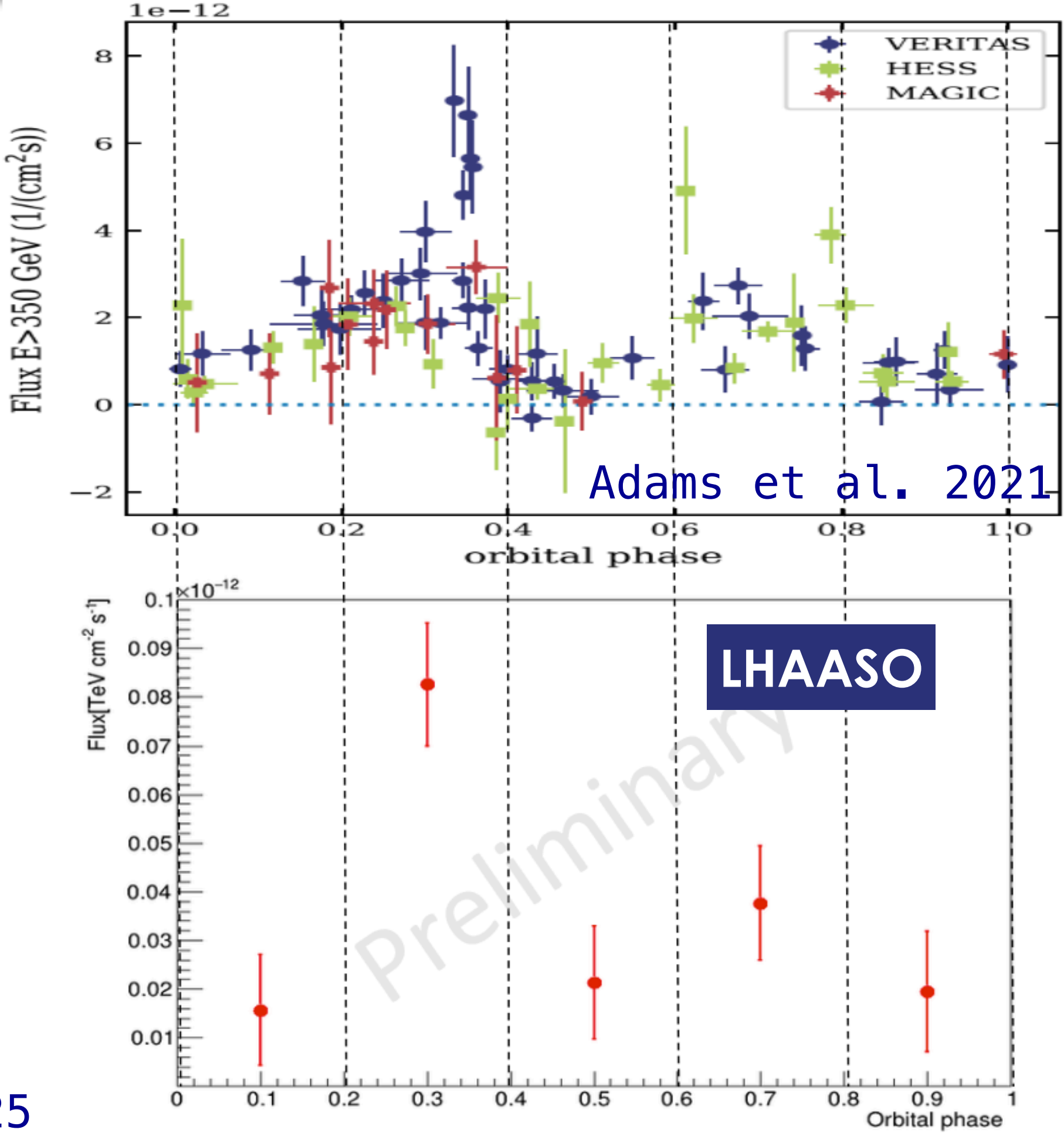
- Emission at tens of TeV with no apparent cut-off
- LS 5039 emission at 2-118 TeV modulated by the orbital motion (HAWC 2025)

Gamma-ray binaries

LS I +61 303



HESS J0632+057



M. Hasan ICRC 2025

- Orbital modulation seen by LHAASO (M. Hasan ICRC 2025)

Novae



Novae

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

Classical novae
main sequence star+WD



Credit: ESO / M. Kornmesser

Symbiotic novae
red giant + WD



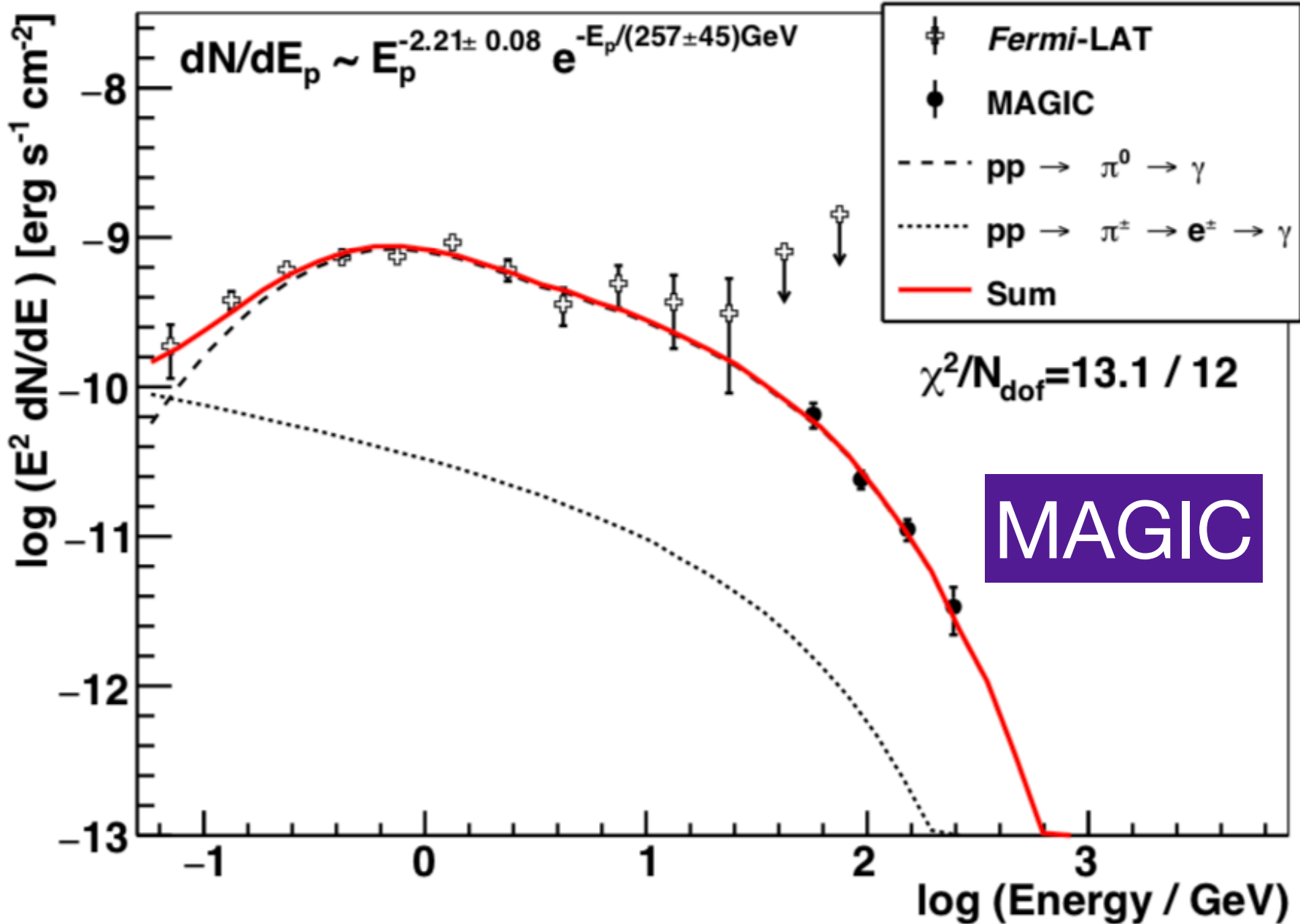
Credit: Hardy

- Roche-lobe overflow
- Long (no) recurrency : $> 10^4$ years

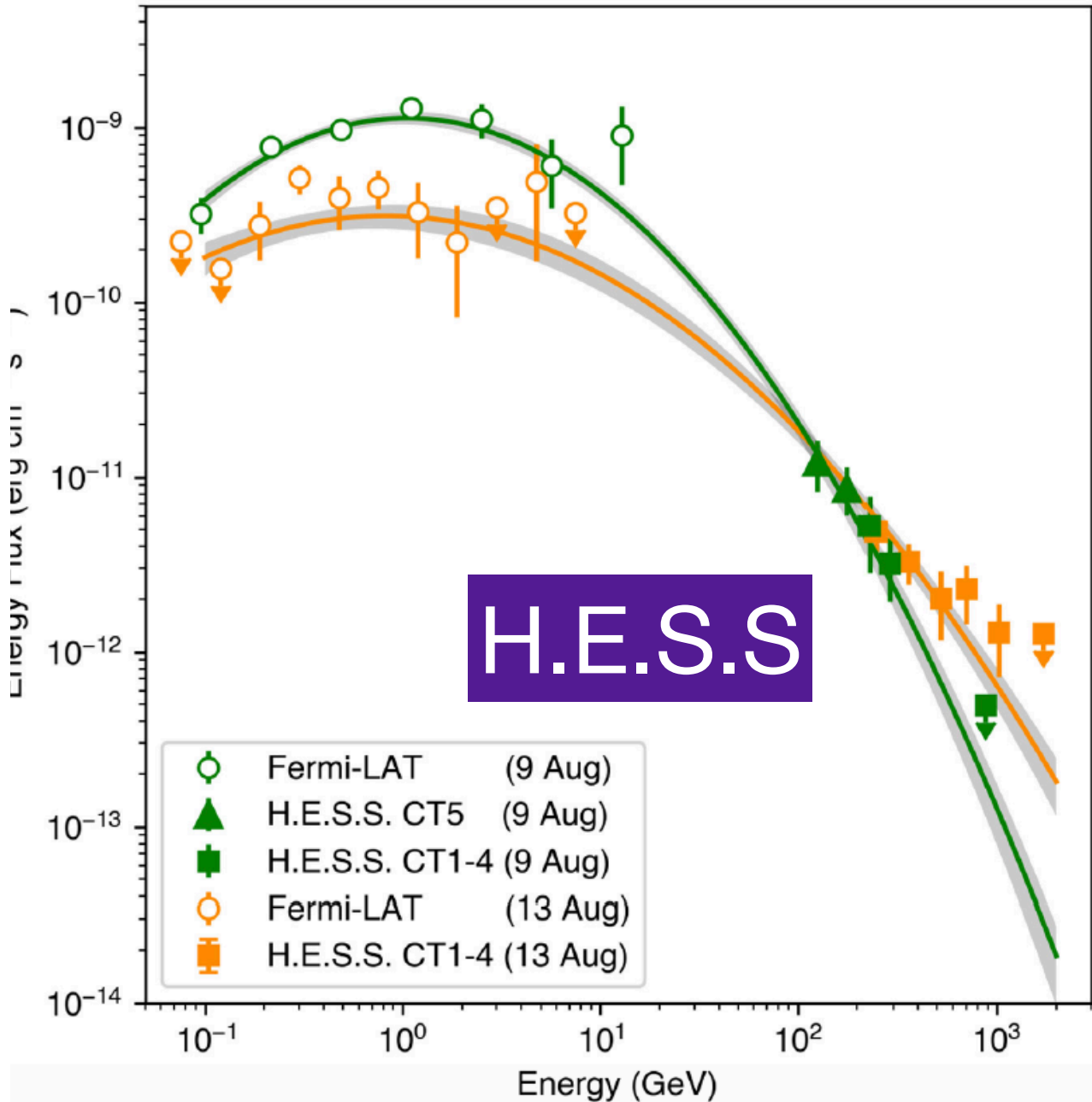
- Accretion from stellar wind
- Some novae show repeated outbursts within a human lifetime:
recurrent novae (RN)

- **Novae established as HE emitters (HE, $E > 100$ MeV)** (*Fermi*-LAT 2010, 2014)

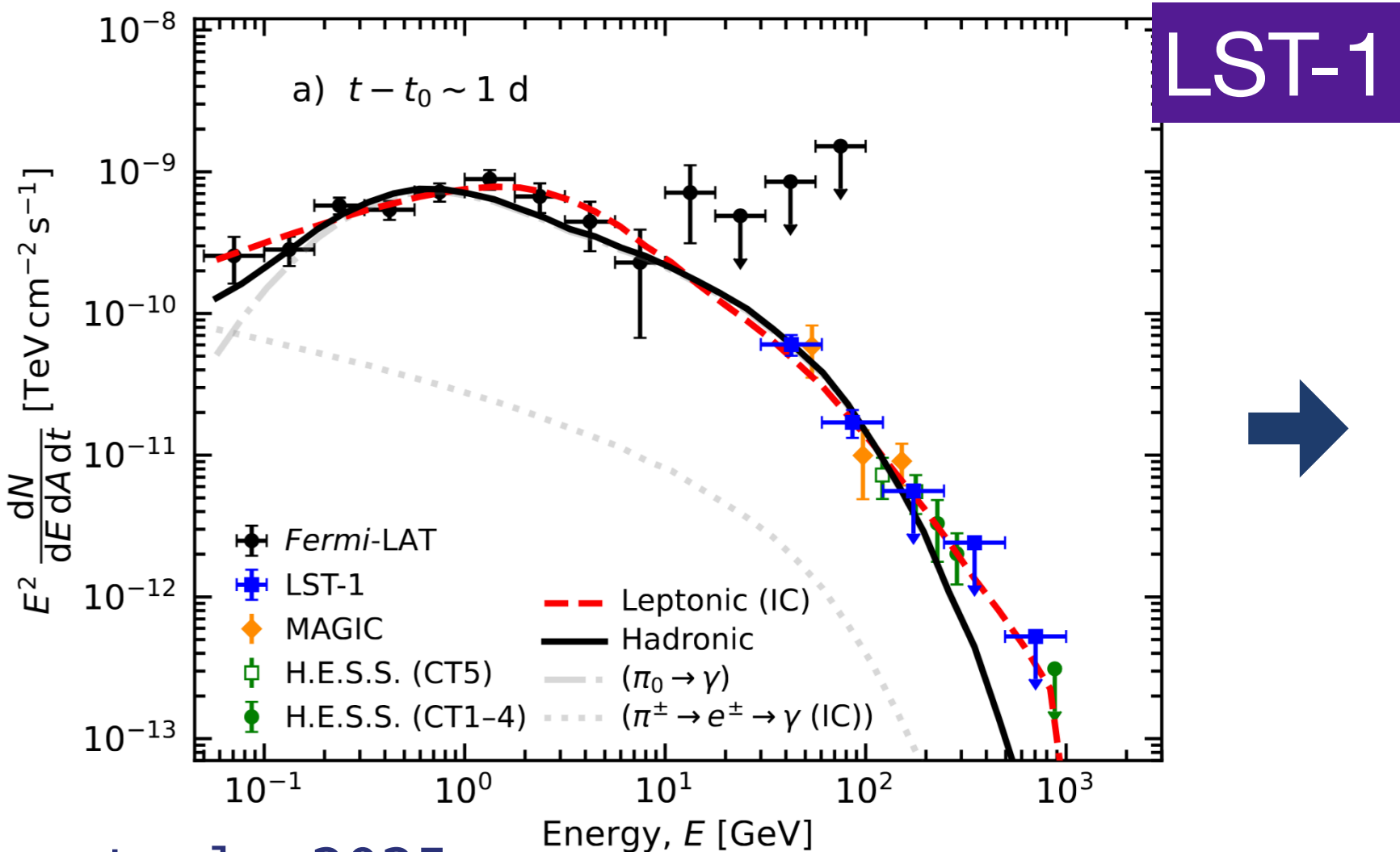
RS Ophiuchi: the first TeV nova



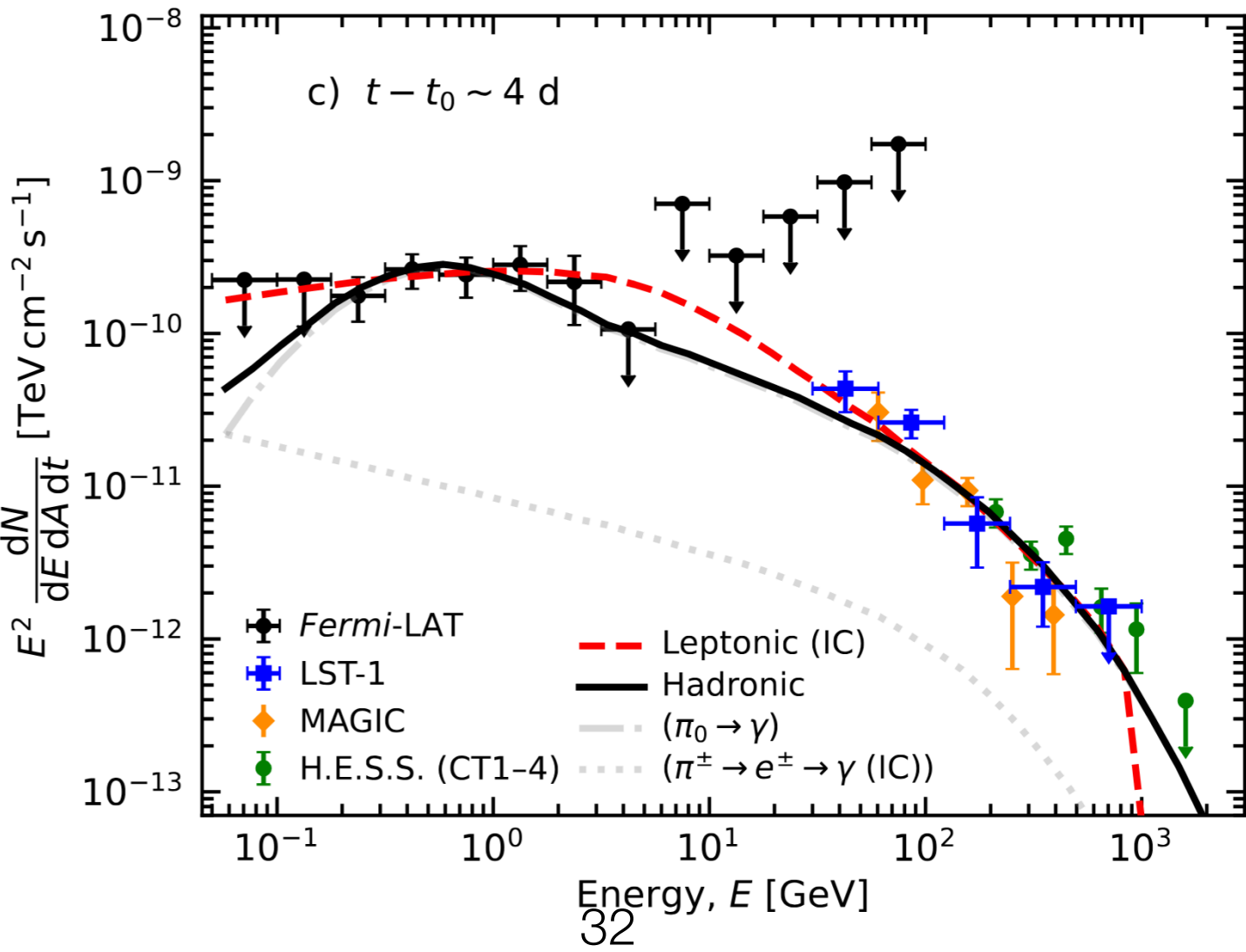
Acciari et al. 2022



HESS coll 2022



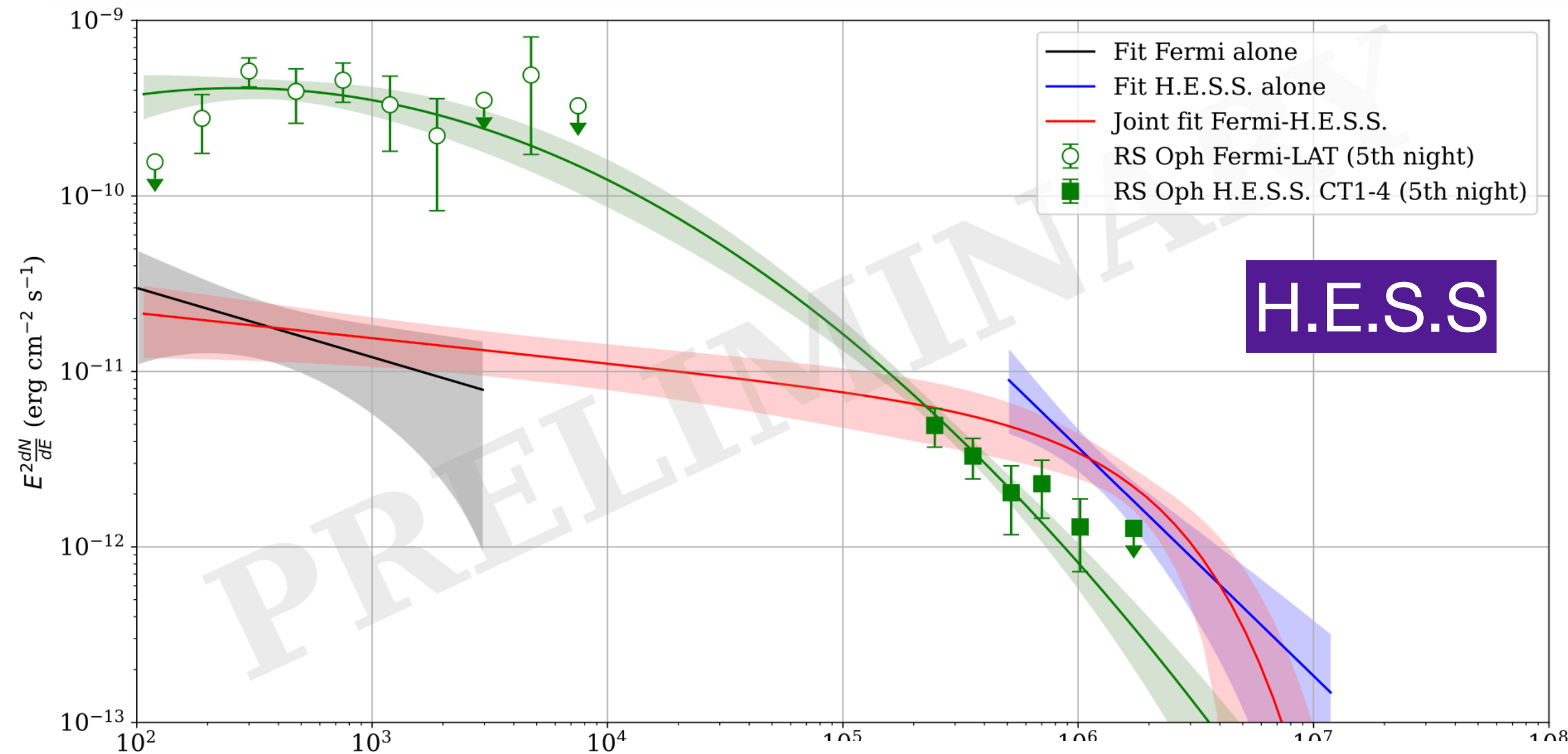
Abe et al. 2025



- Symbiotic recurrent nova, outburst in 2021
- **First and only nova detected in the VHE regime** (HESS 2022, MAGIC 2022, LST coll. 2025.)
- **Hadronic scenario favored**
- **Accelerated protons will eventually escape the nova shock**
- In the case of **recurrent novae**, **protons will accumulate in a ~10 pc bubble** with enhanced CR density

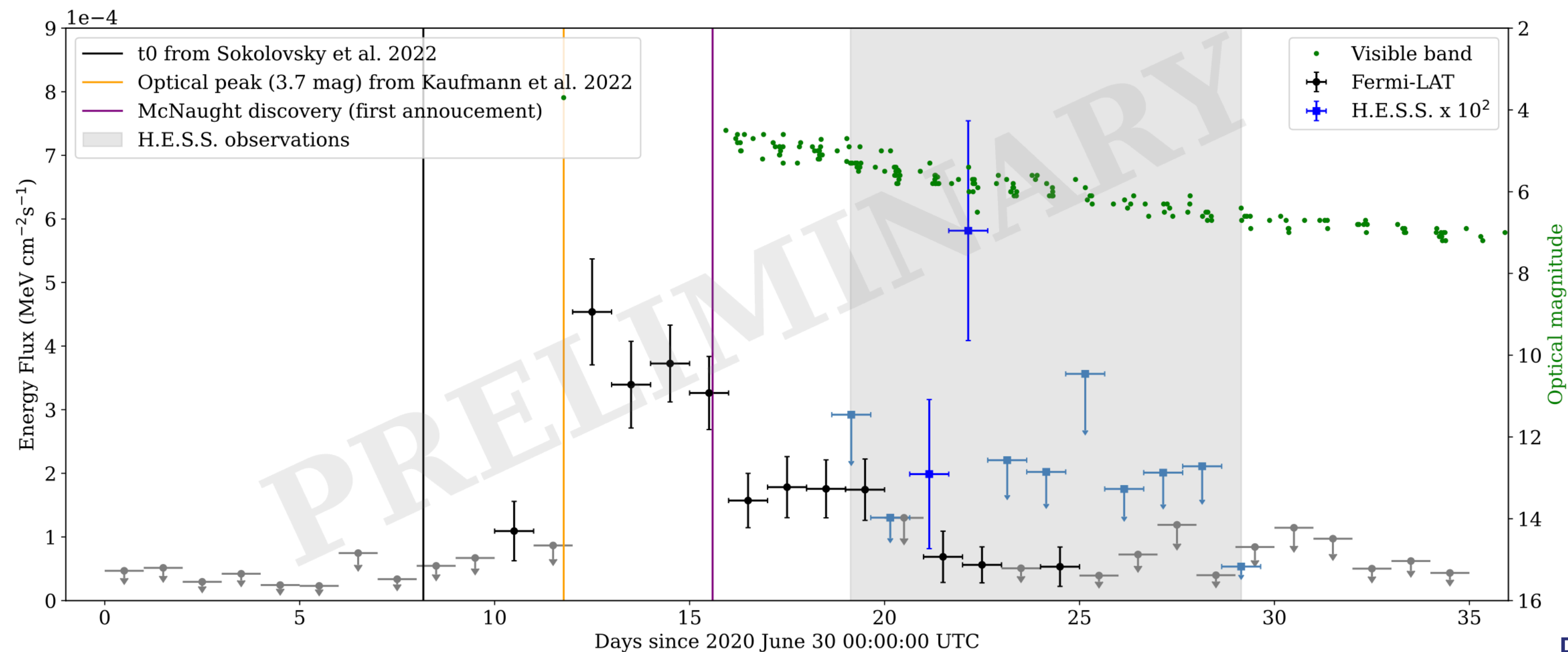
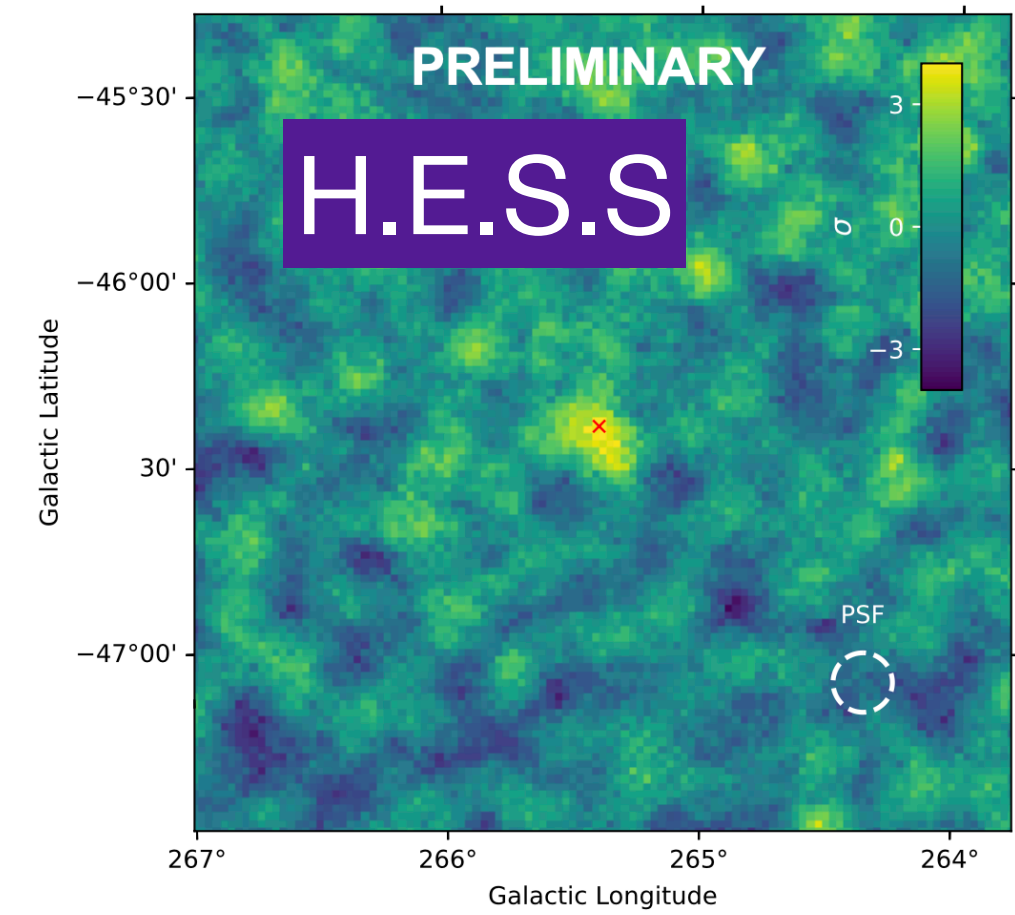
(Recurrent symbiotic) Novae are **proton accelerators**

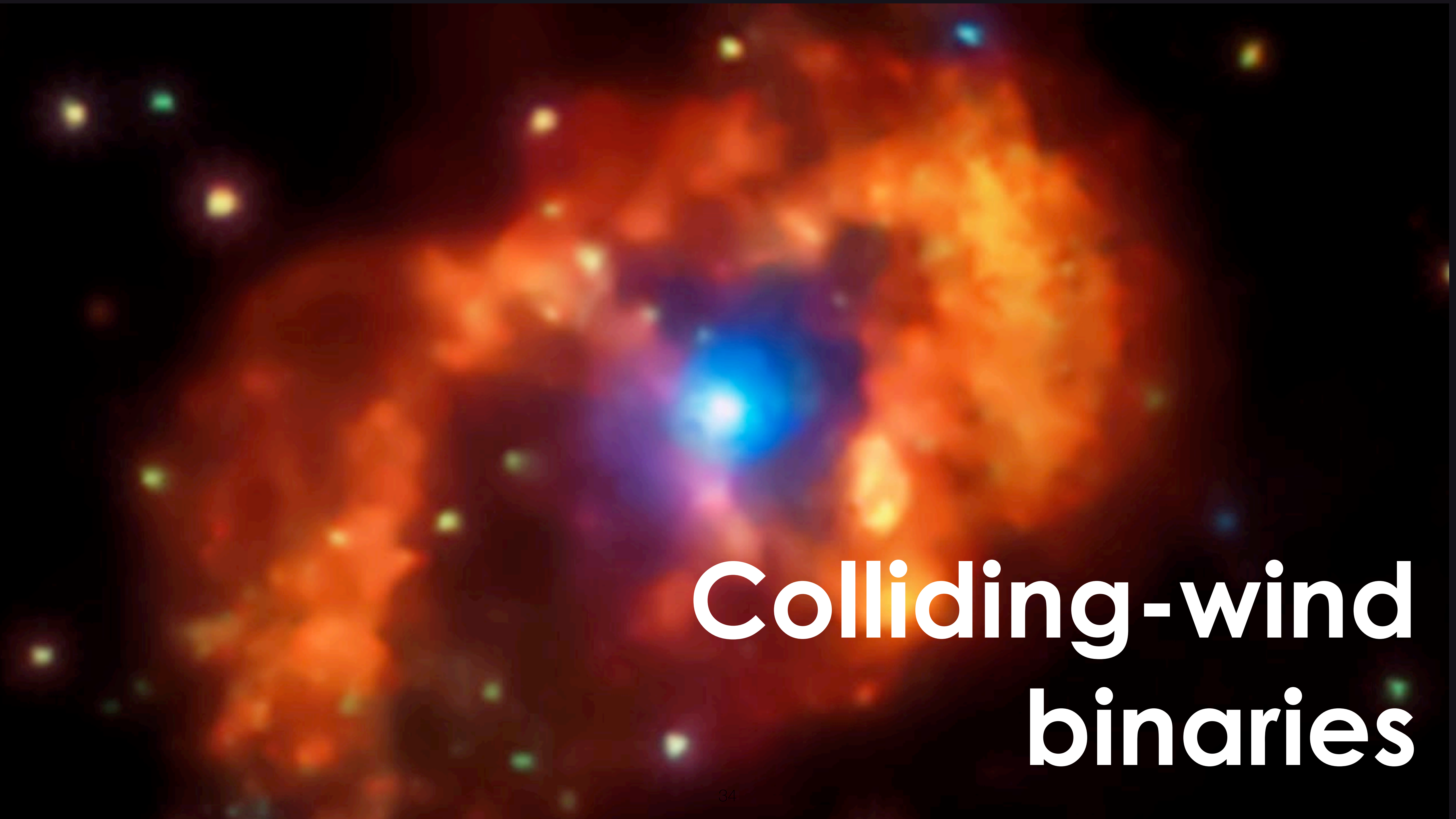
Classical novae as TeV sources?



• MGAB-V207 (YZ Reticuli) -> classical

- Outburst in July 2020
- Fermi-LAT signal
- H.E.S.S. observations: t0+8 nights
- **Hint of emission (3.7 σ post-trial) during two nights (Fauverge et al. ICRC 2025)**
- Reverse shock expanding into the wind of the hot shocked white dwarf -> internal shocks

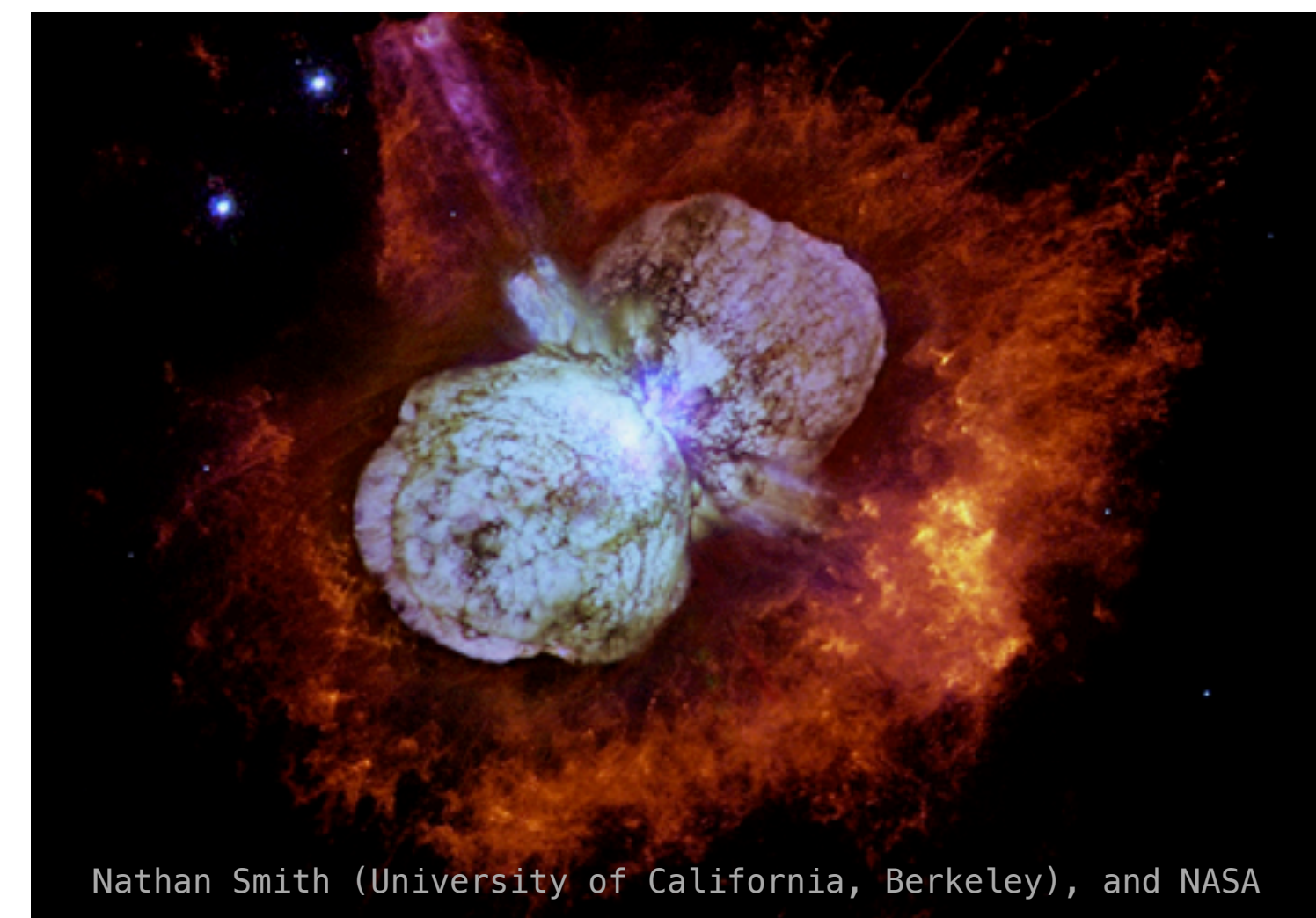




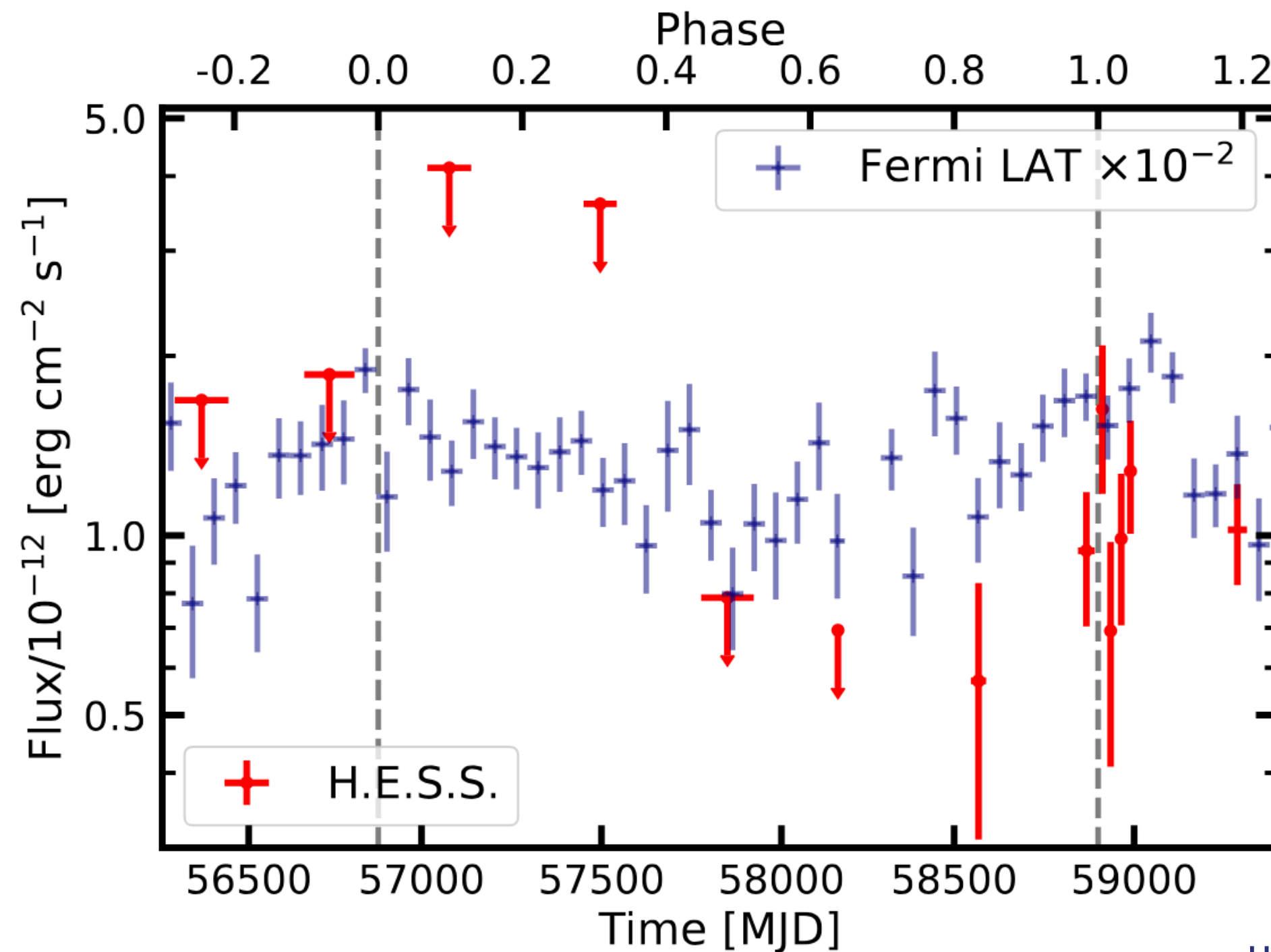
Colliding-wind binaries

Colliding wind binary: eta Car

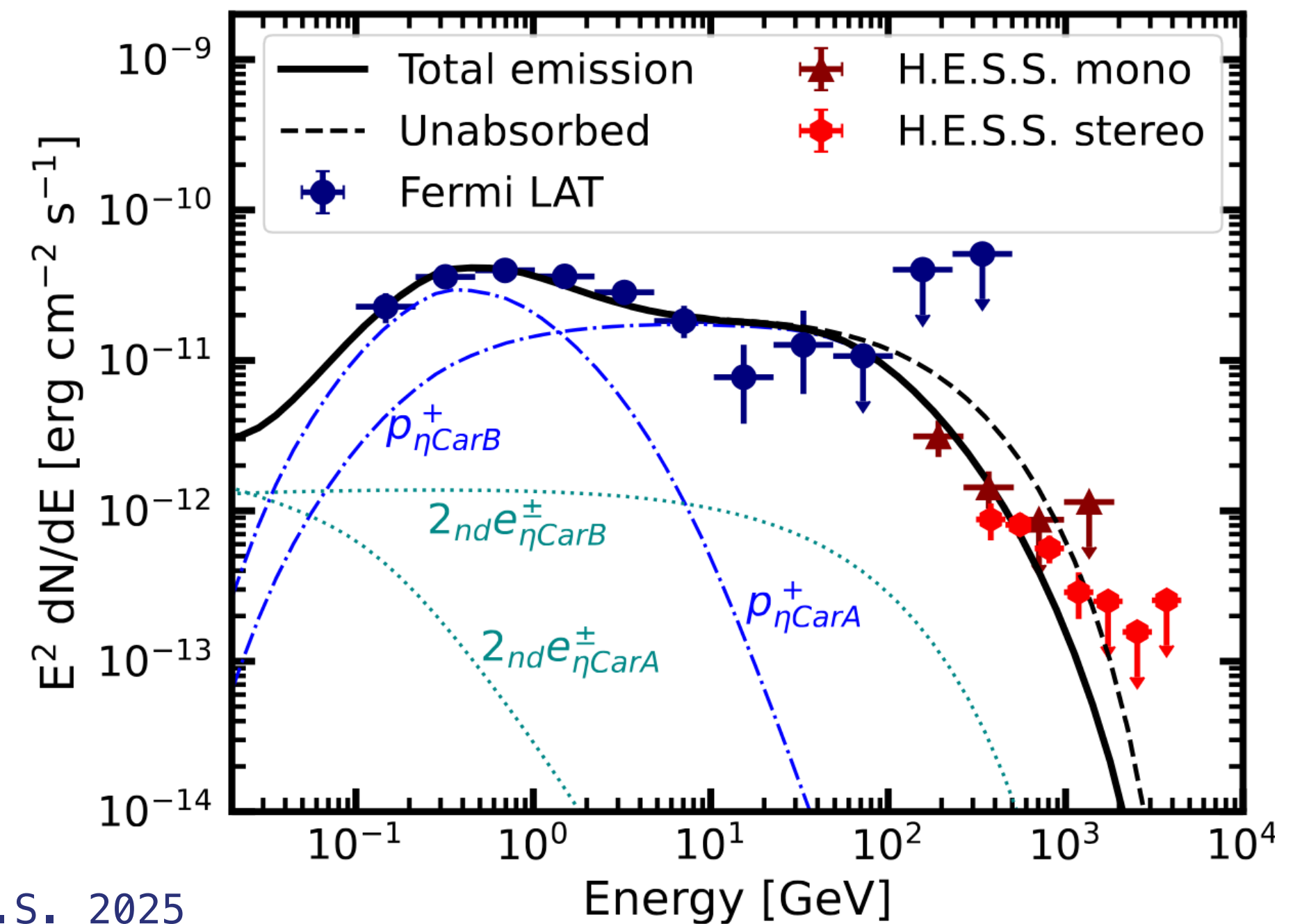
- LBV $\sim 90\text{-}100 M_{\odot}$ + **O- or B-type** $\sim 30 M_{\odot}$
 - orbit ($e \sim 0.9$) with a ~ 5.5 yr period
 - high mass-loss rates and supersonic winds
- **VHE emission** detected during **periastron passage** (H.E.S.S. 2020)
 - **2020 passage**: detected at energies 0.14 TeV up to above 1 TeV (H.E.S.S. 2025)
 - **Hadronic scenario**



2020



H.E.S.S. 2025



Cherenkov Telescope Array Observatory

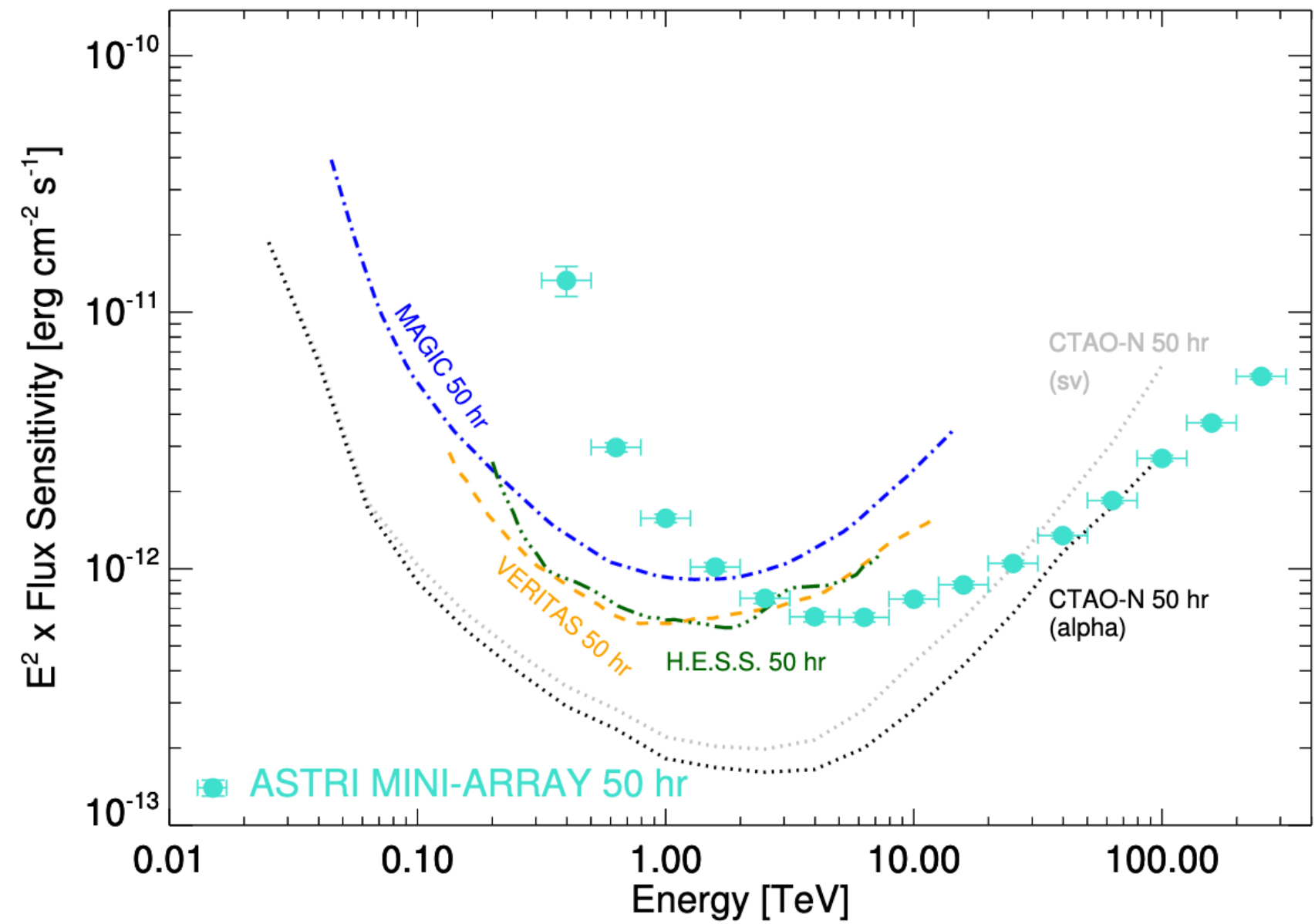
Next-generation ground-based gamma-ray observatory

One observatory, two sites, three types of telescopes

**Most sensitive Cherenkov array
worldwide by end of 2026**



ASTRI Mini-Array



- **Array of 9 Cherenkov telescopes** at Observatorio del Teide (Tenerife, Spain) (see e.g. [Vercellone 2024](#) and references therein)
 - **1 – 300 TeV** energy band
 - Schwarzschild-Couder type
 - primary 4.3m, secondary 1.8m
- **ASTRI-1 already operational**
 - Crab Nebula SED up to 20 TeV
- **Starting of stereoscopic observations** by the end 2025/beginning 2026

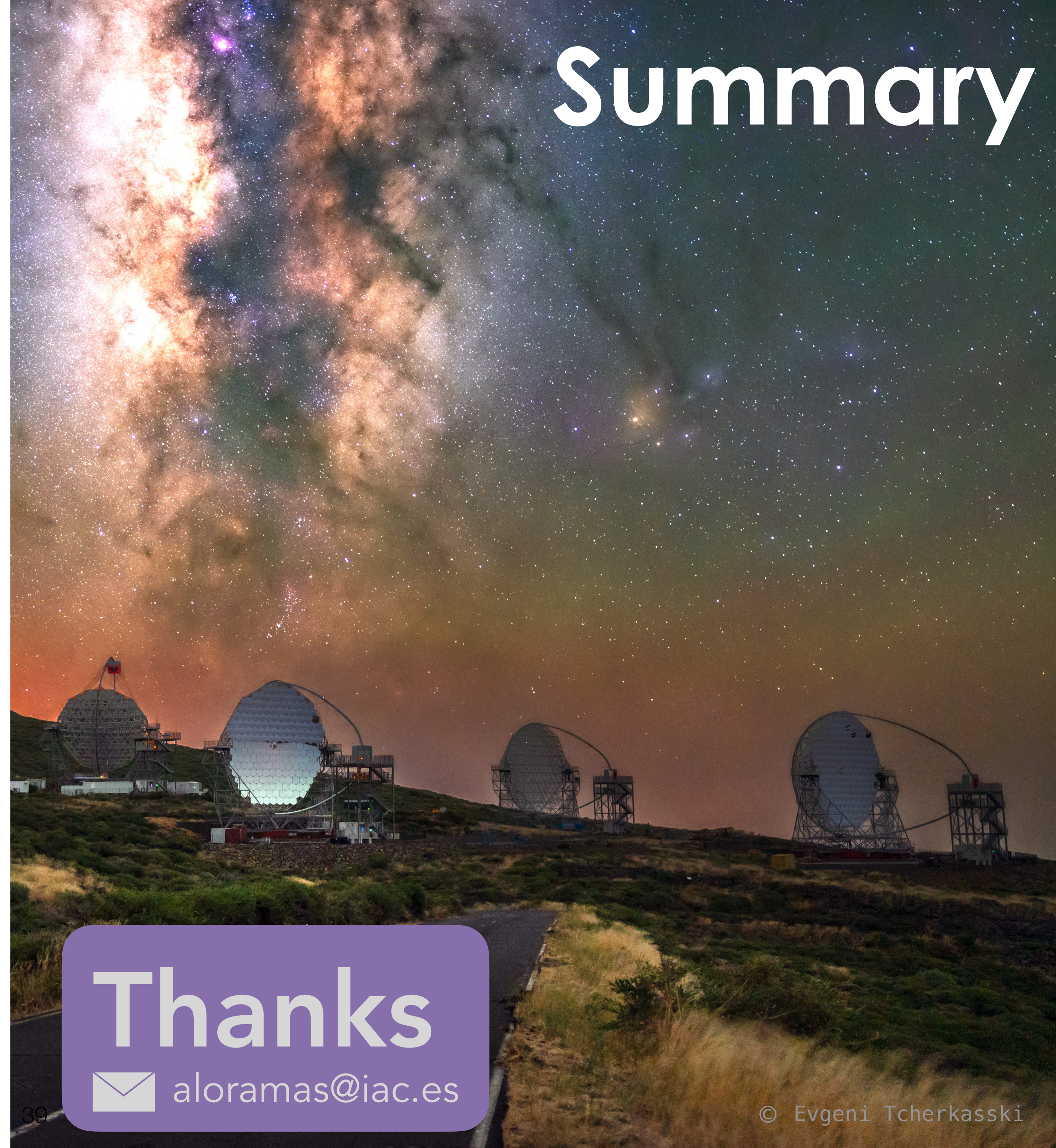


See talks by A. Carosi, E. Molina, A. Sunny (GA session)



Summary

- Plethora of **different types of Galactic systems** emitting in the gamma-ray regime
 - PWNe and SNRs largest VHE population
 - Newest Galactic populations: TeV halos, novae, microquasars, star clusters
- **Tens of PeVatrons** identified over the past few years
 - Mostly of **leptonic** origin (associated to pulsars and PWNe)
- **Binary systems**
 - **Microquasars:**
 - Recently **confirmed as TeV-PeV emitters**
 - **Persistent** emission
 - Responsible for CRs around and above the knee?
 - **Gamma-ray binaries**
 - Massive stars with compact object -> **likely non-accreting pulsars**
 - Emission **up to even 100 TeV** without cutoff
 - Orbital modulation in some sources in the whole gamma-ray domain
 - **Novae:**
 - **(Symbiotic) novae established as VHE emitters**
 - Emission of **hadronic origin**
 - Classical novae as TeV sources? Hint of emission by H.E.S.S.
 - **Colliding-wind binaries**
 - Eta carina up to 1 TeV
 - **Hadronic** origin of the VHE emission



Thanks



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Thanks

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Galactic Sources

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Instituto de Astrofísica de Canarias



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