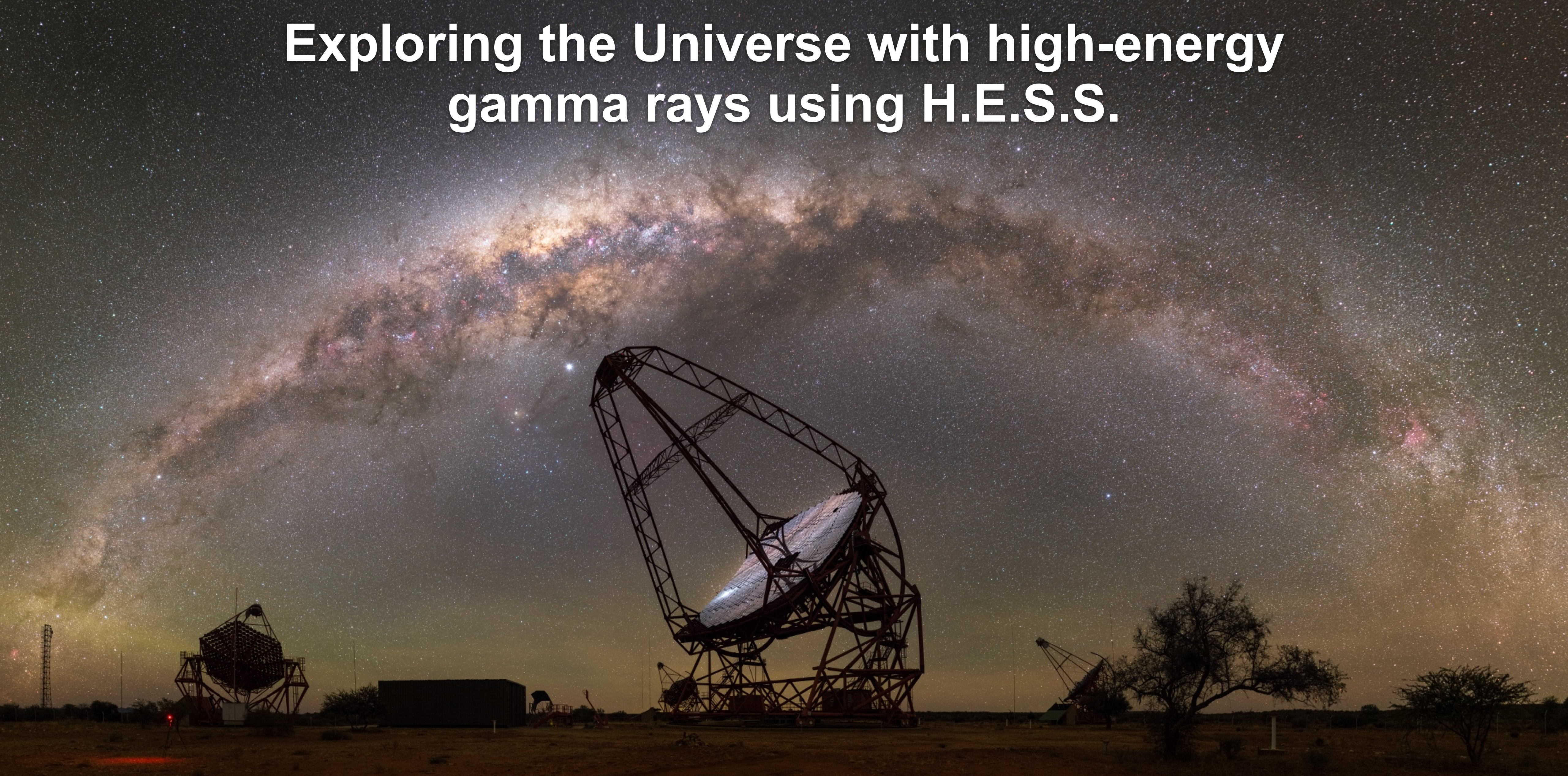


Exploring the Universe with high-energy gamma rays using H.E.S.S.



Lars Mohrmann ■ Max-Planck-Institut für Kernphysik

Heidelberg Joint Astronomical Colloquium ■ Heidelberg, January 13, 2026

Exploring the Universe with high-energy gamma rays using H.E.S.S.

Outline

- Introduction
- Results
 - ▶ overview
 - ▶ young massive star clusters
 - ▶ microquasars
 - ▶ the Crab Nebula
- Brief outlook

Lars Mohrmann ■ Max-Planck-Institut für Kernphysik

Heidelberg Joint Astronomical Colloquium ■ Heidelberg, January 13, 2026

The electromagnetic spectrum

The Crab Nebula across the electromagnetic spectrum:

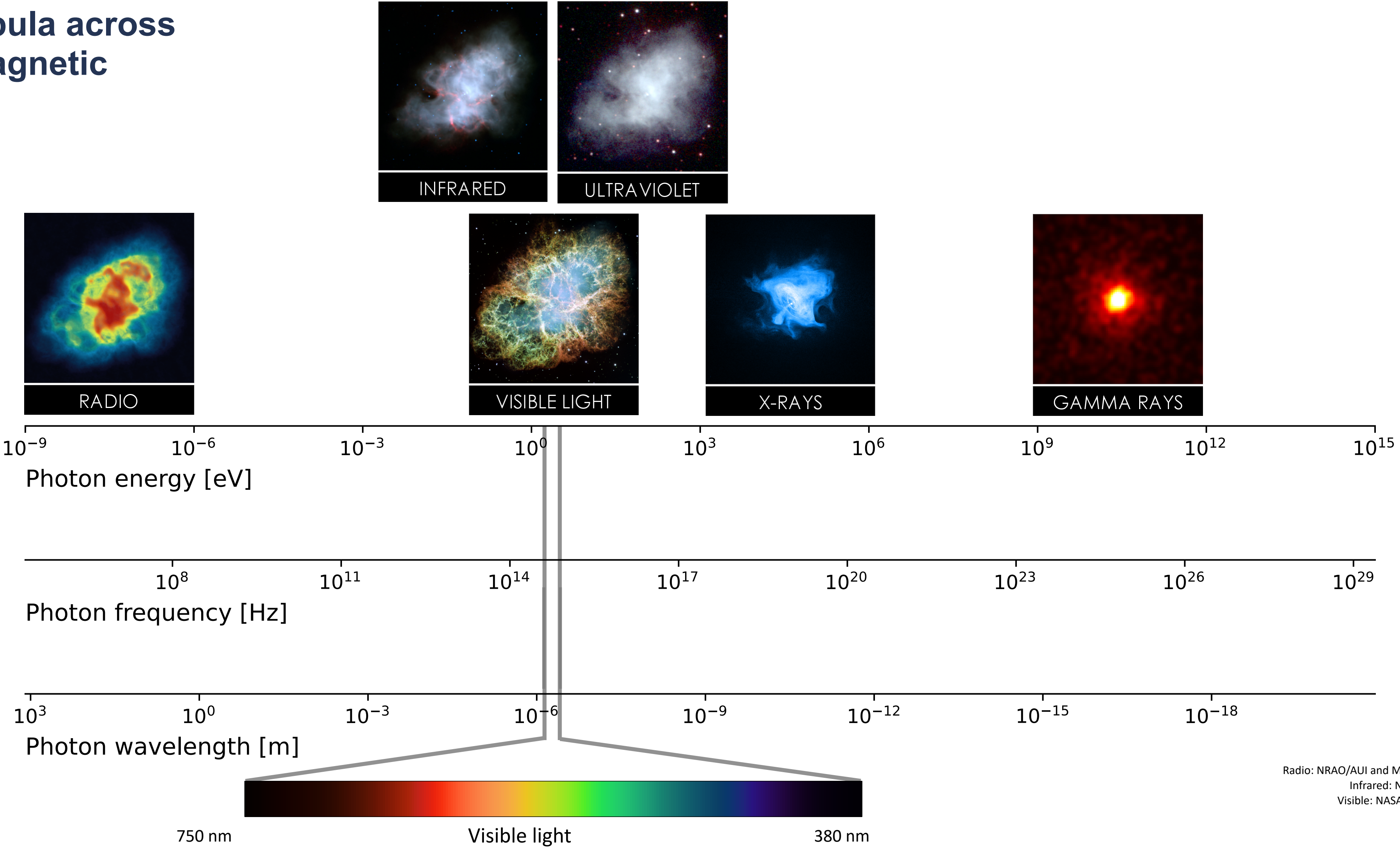


Image references:
Radio: NRAO/AUI and M. Bietenholz; NRAO/AUI and J.M. Uson, T.J. Cornwell
Infrared: NASA/JPL-Caltech/R. Gehrz (University of Minnesota)
Visible: NASA, ESA, J. Hester and A. Loll (Arizona State University)
Ultraviolet: NASA/Swift/E. Hoversten, PSU
X-ray: NASA/CXC/SAO/F.Seward et al.
Gamma: NASA/DOE/Fermi LAT/R. Buehler

The electromagnetic spectrum

The Crab Nebula across the electromagnetic spectrum:

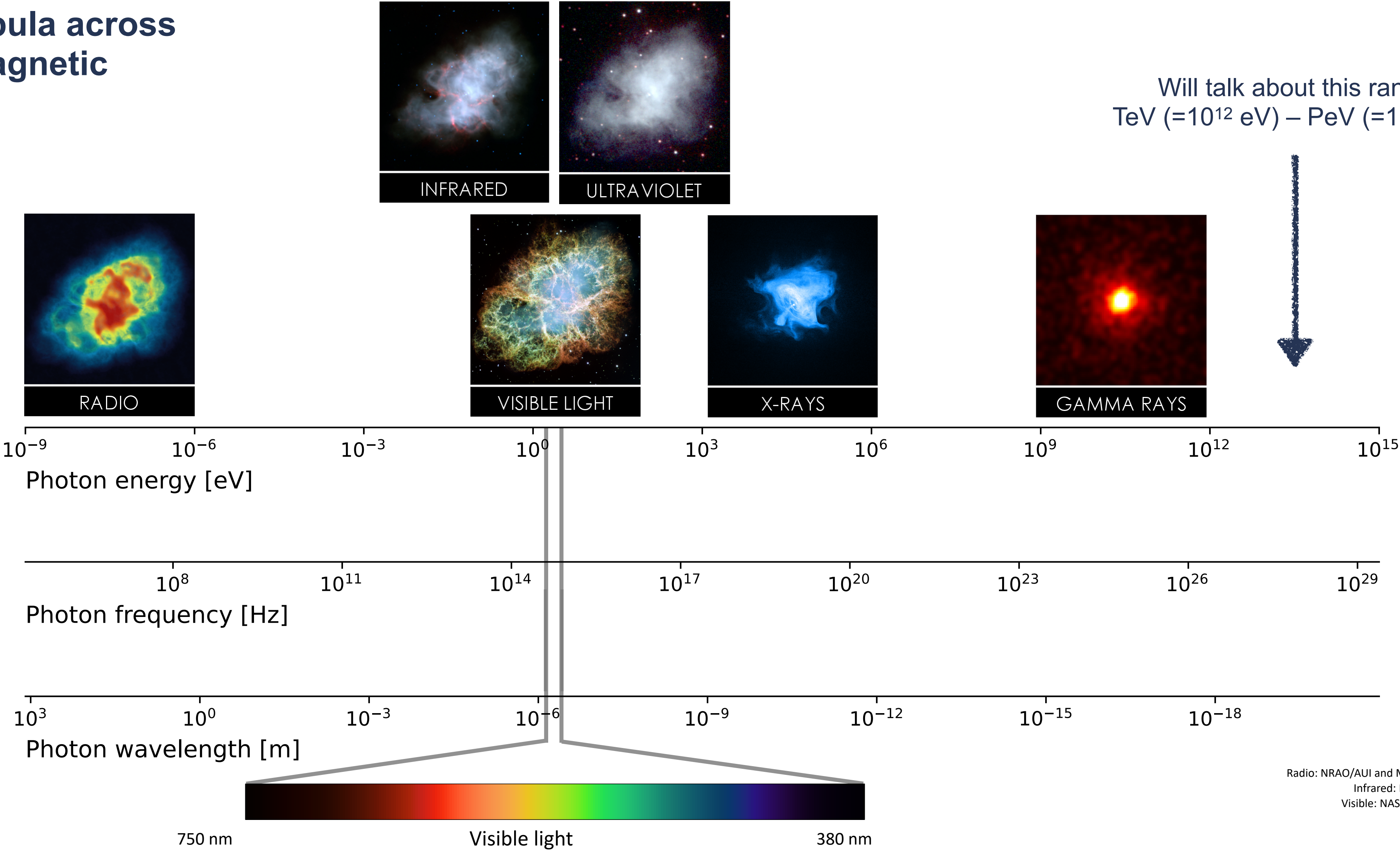


Image references:
Radio: NRAO/AUI and M. Bietenholz; NRAO/AUI and J.M. Uson, T.J. Cornwell
Infrared: NASA/JPL-Caltech/R. Gehrz (University of Minnesota)
Visible: NASA, ESA, J. Hester and A. Loll (Arizona State University)
Ultraviolet: NASA/Swift/E. Hoversten, PSU
X-ray: NASA/CXC/SAO/F.Seward et al.
Gamma: NASA/DOE/Fermi LAT/R. Buehler

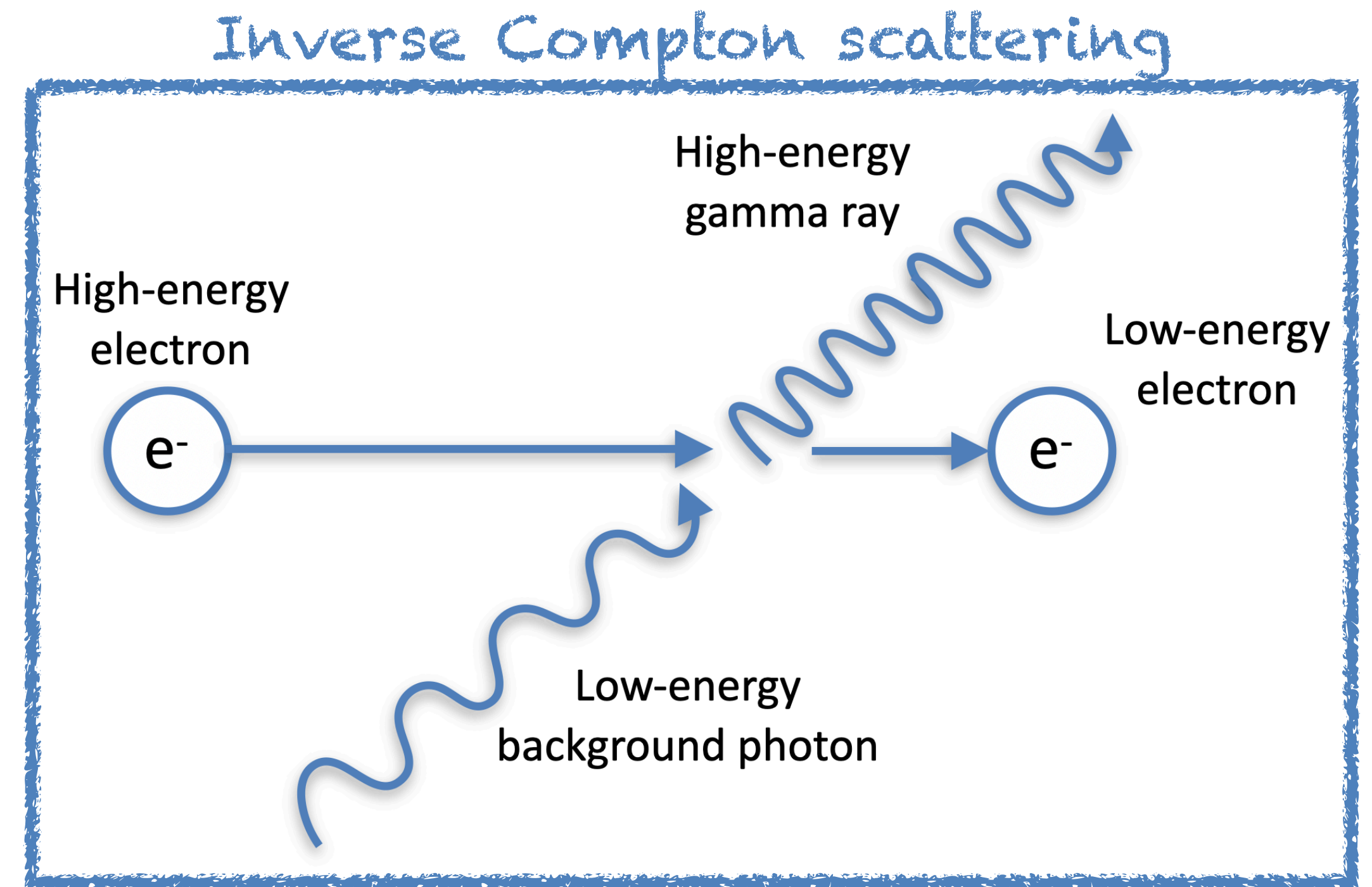


Why γ -ray astronomy?

- High-energy γ -rays are produced *non-thermally*

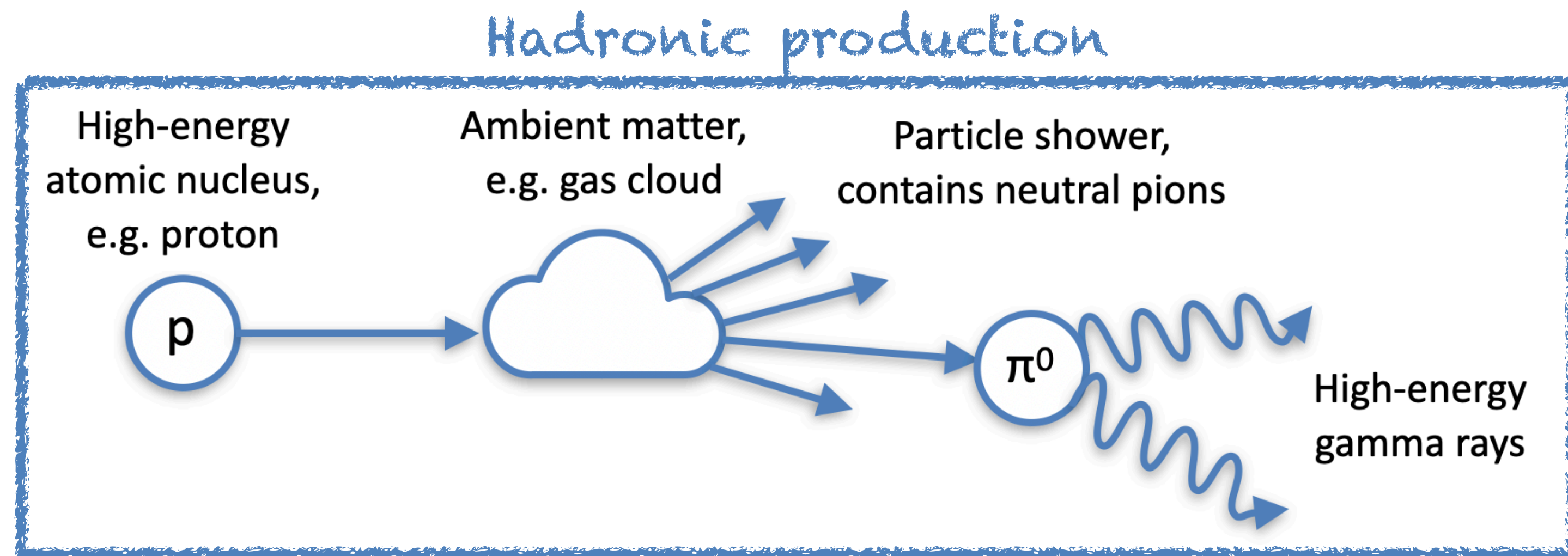
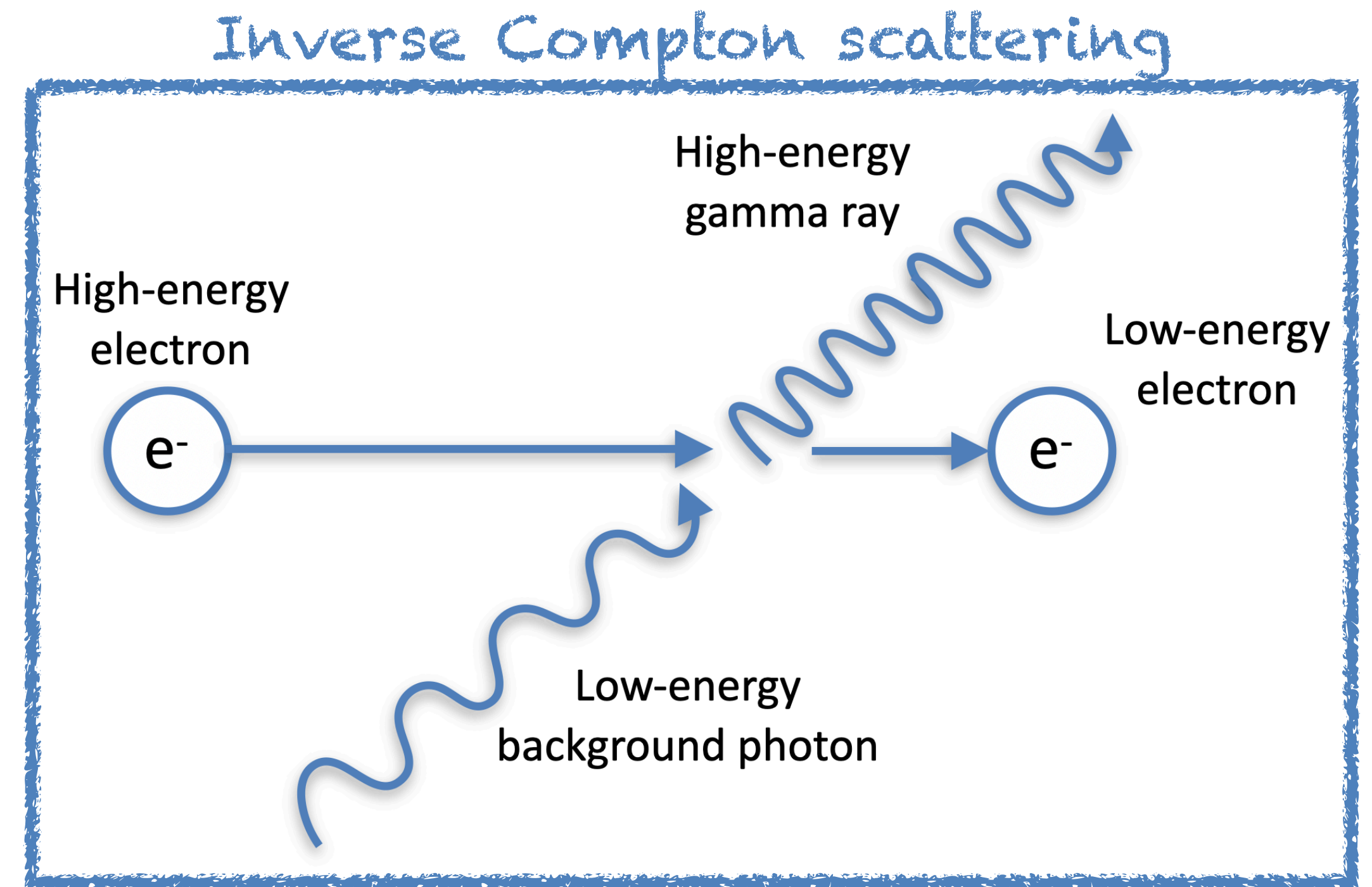
Why γ -ray astronomy?

- High-energy γ -rays are produced *non-thermally*
- Inverse Compton scattering
 - up-scattering of low-energy photons by high-energy electrons



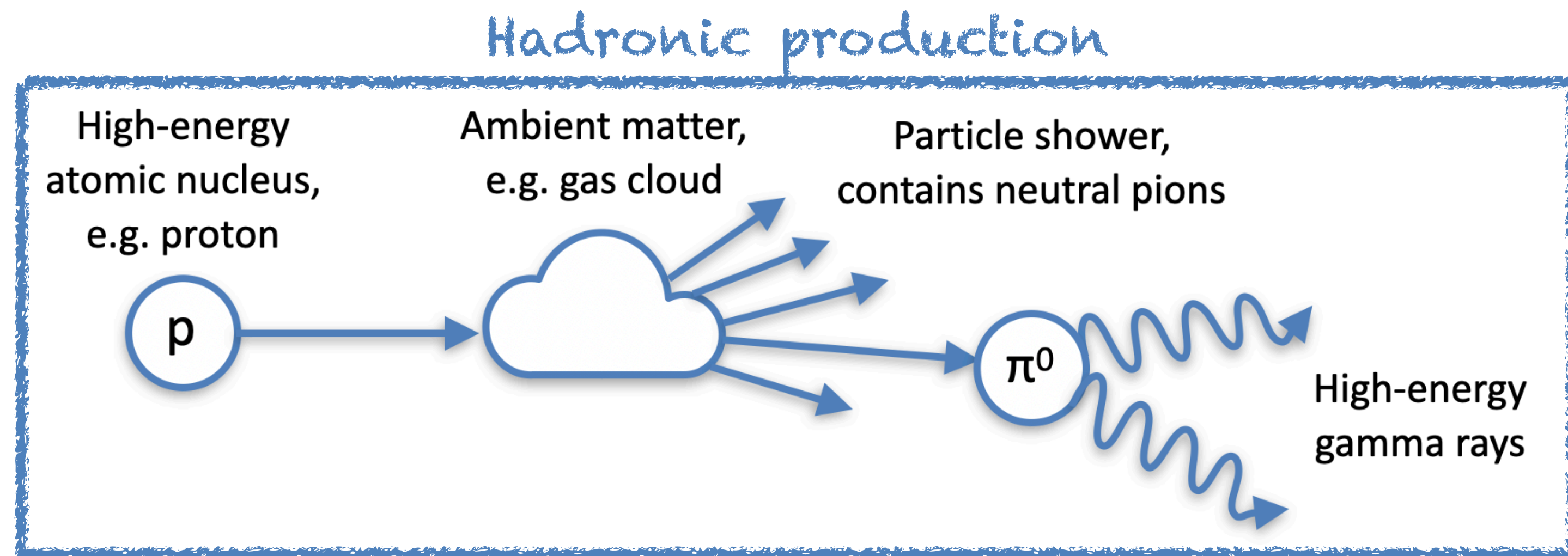
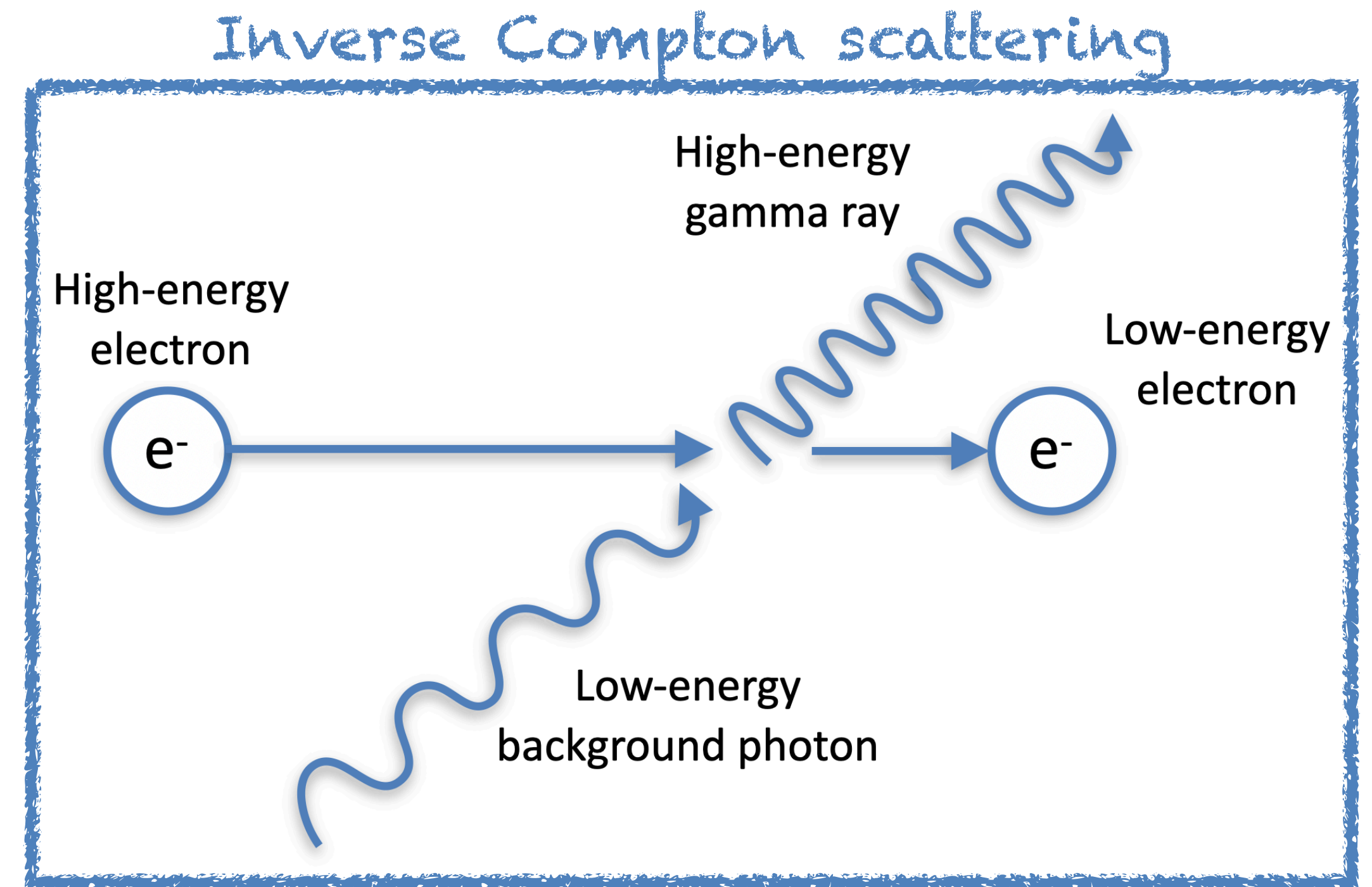
Why γ -ray astronomy?

- High-energy γ -rays are produced *non-thermally*
- Inverse Compton scattering
 - up-scattering of low-energy photons by high-energy electrons
- Hadronic production
 - γ -rays from interactions of high-energy atomic nuclei



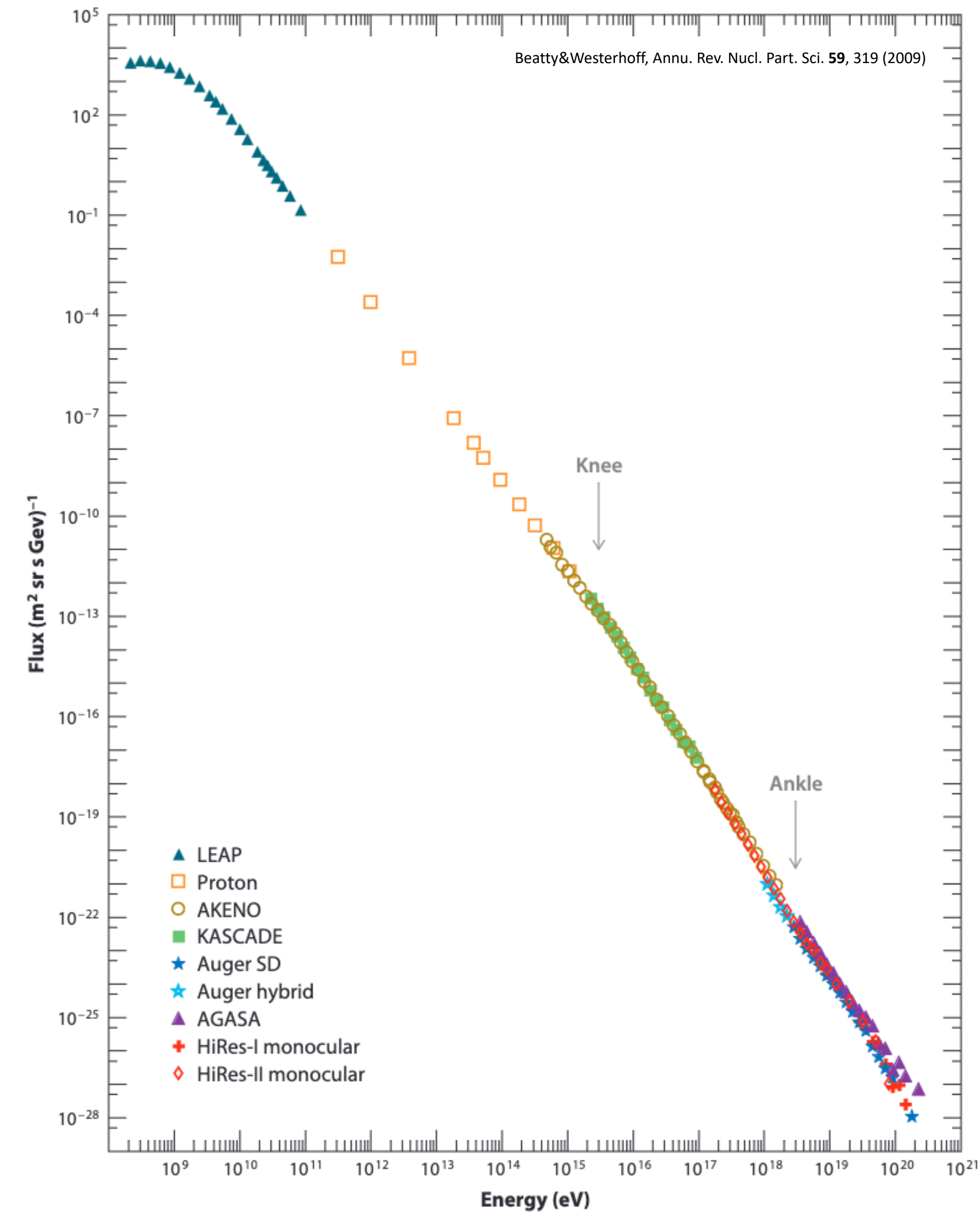
Why γ -ray astronomy?

- High-energy γ -rays are produced *non-thermally*
- Inverse Compton scattering
 - up-scattering of low-energy photons by high-energy electrons
- Hadronic production
 - γ -rays from interactions of high-energy atomic nuclei
- Can use γ -rays to study acceleration of cosmic rays!



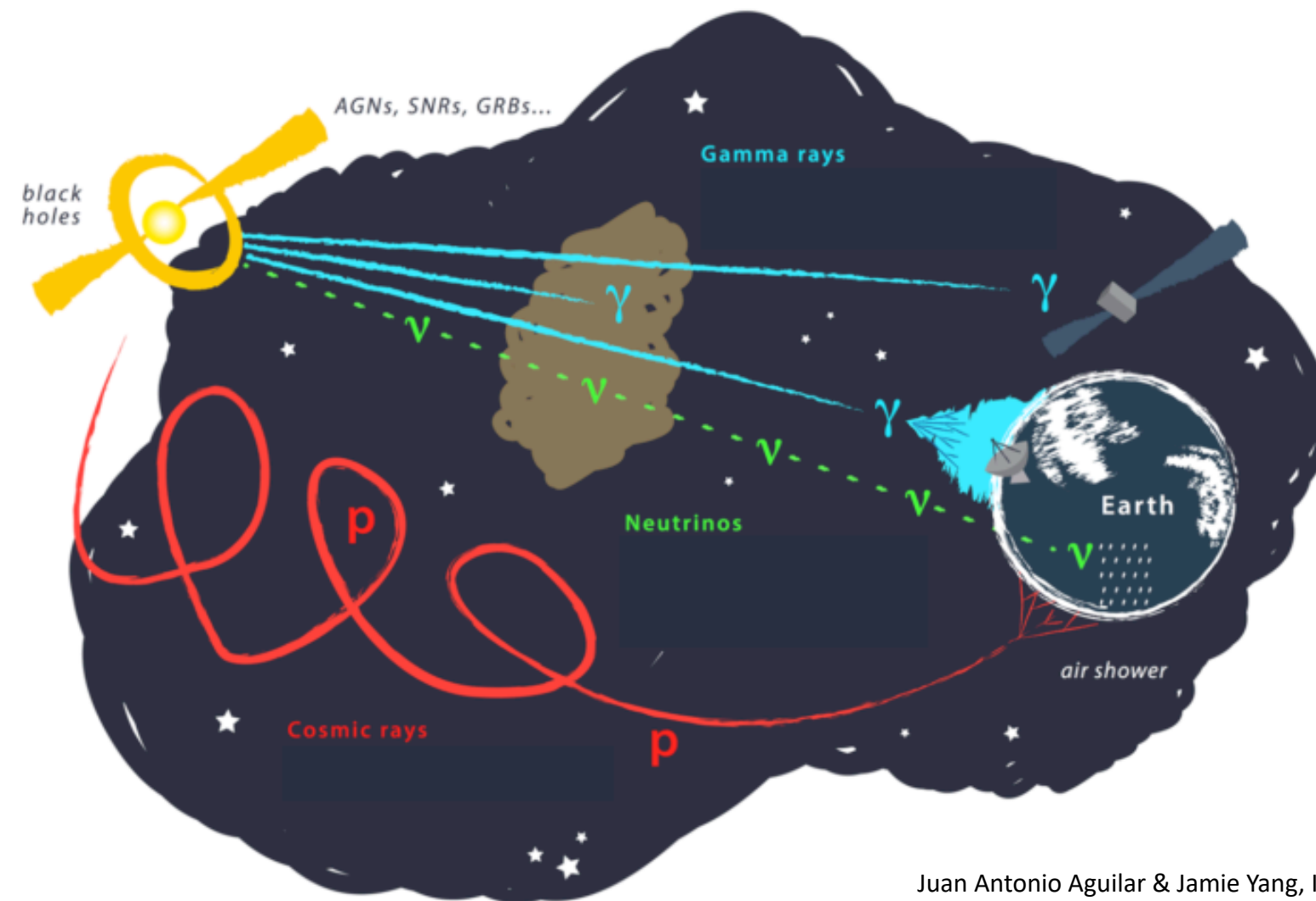
The origin of cosmic rays

- The Universe accelerates particles to **unimaginably high energies**
- Finding their **origin** is a more than 100 yr old **mystery**

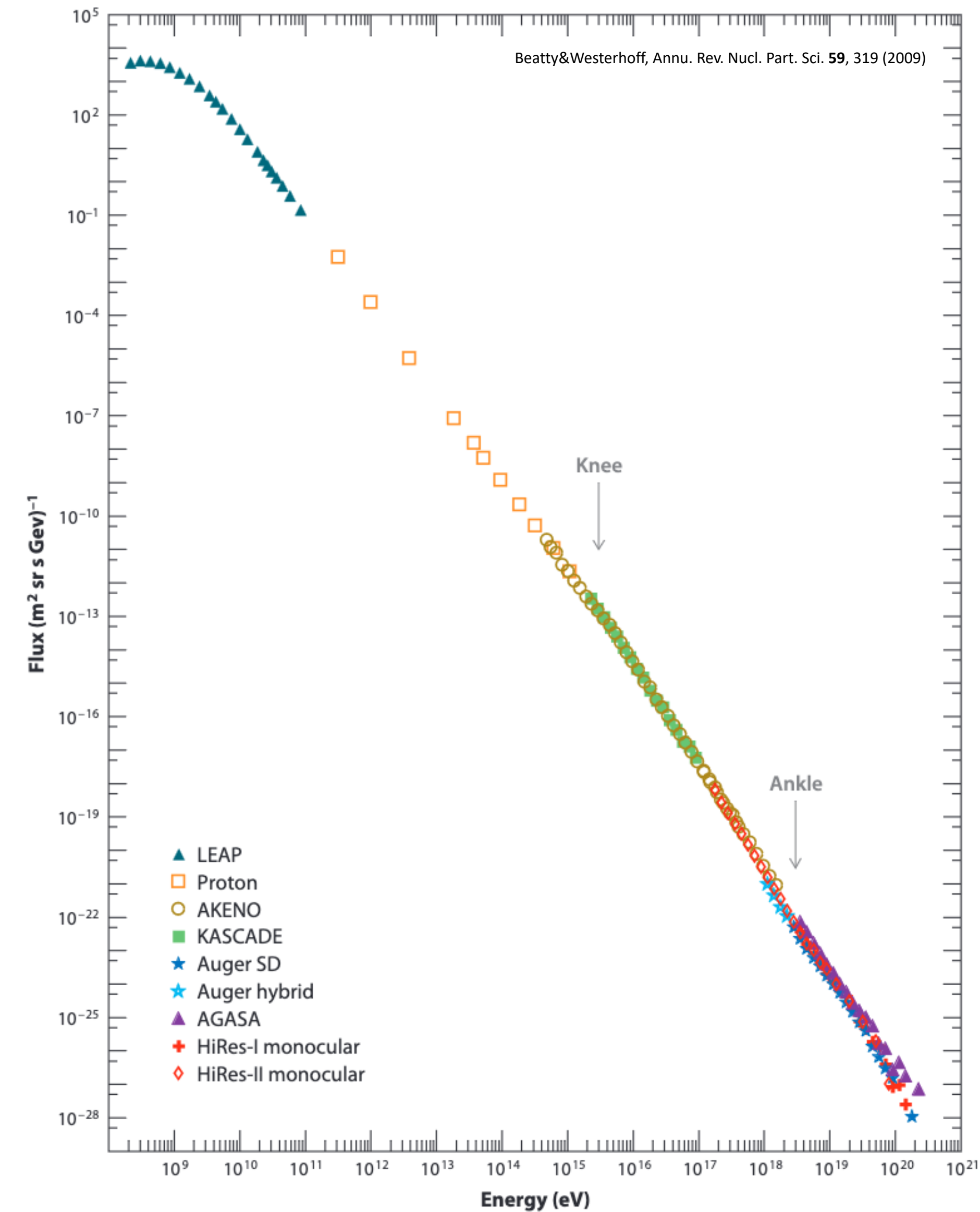


The origin of cosmic rays

- The Universe accelerates particles to **unimaginably high energies**
- Finding their **origin** is a more than 100 yr old **mystery**
- Cosmic rays are **deflected** in cosmic **magnetic fields!**
- Need **neutral** messengers:
 - ▶ photons
 - ▶ neutrinos
 - ▶ gravitational waves

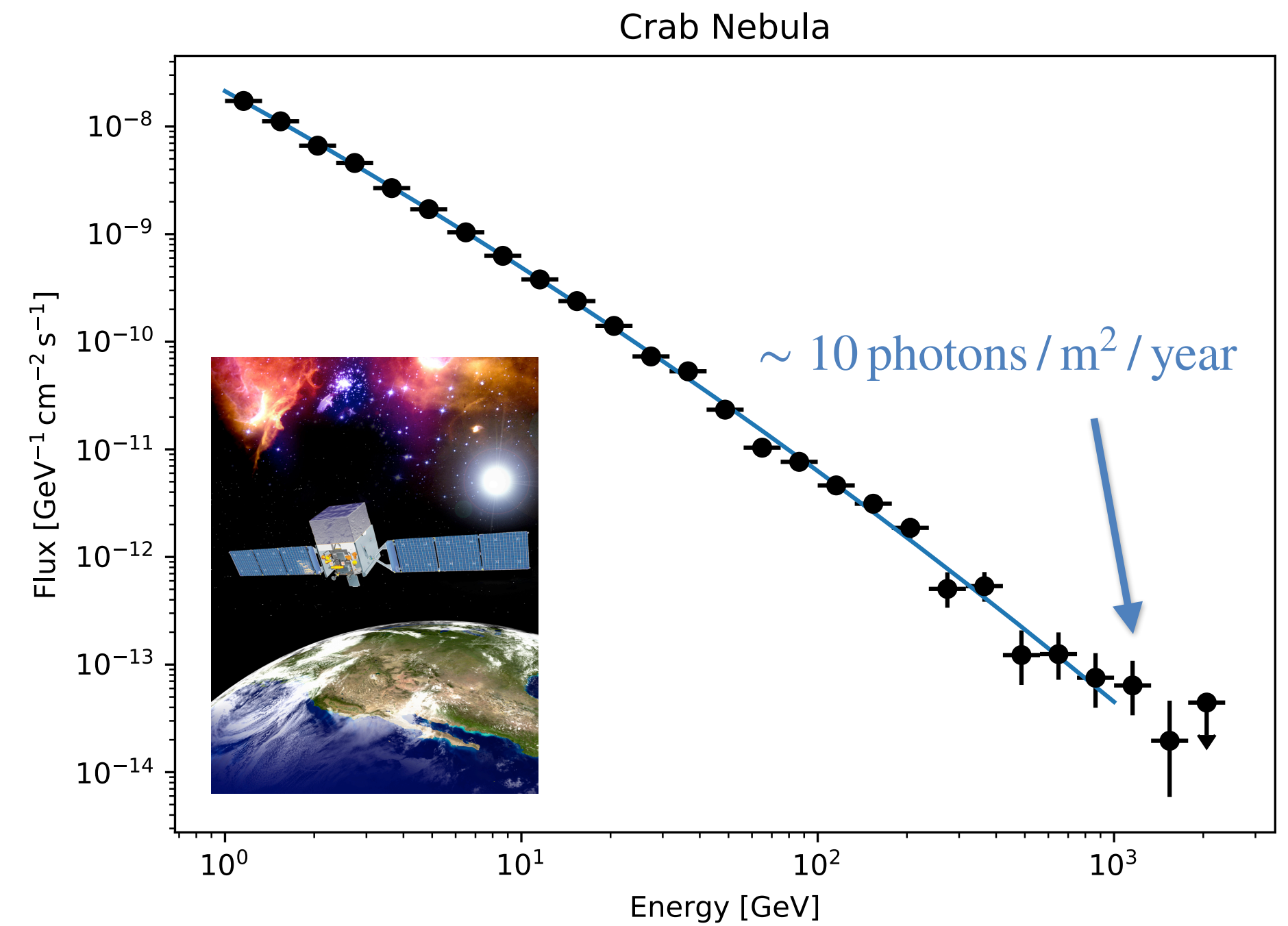


Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC



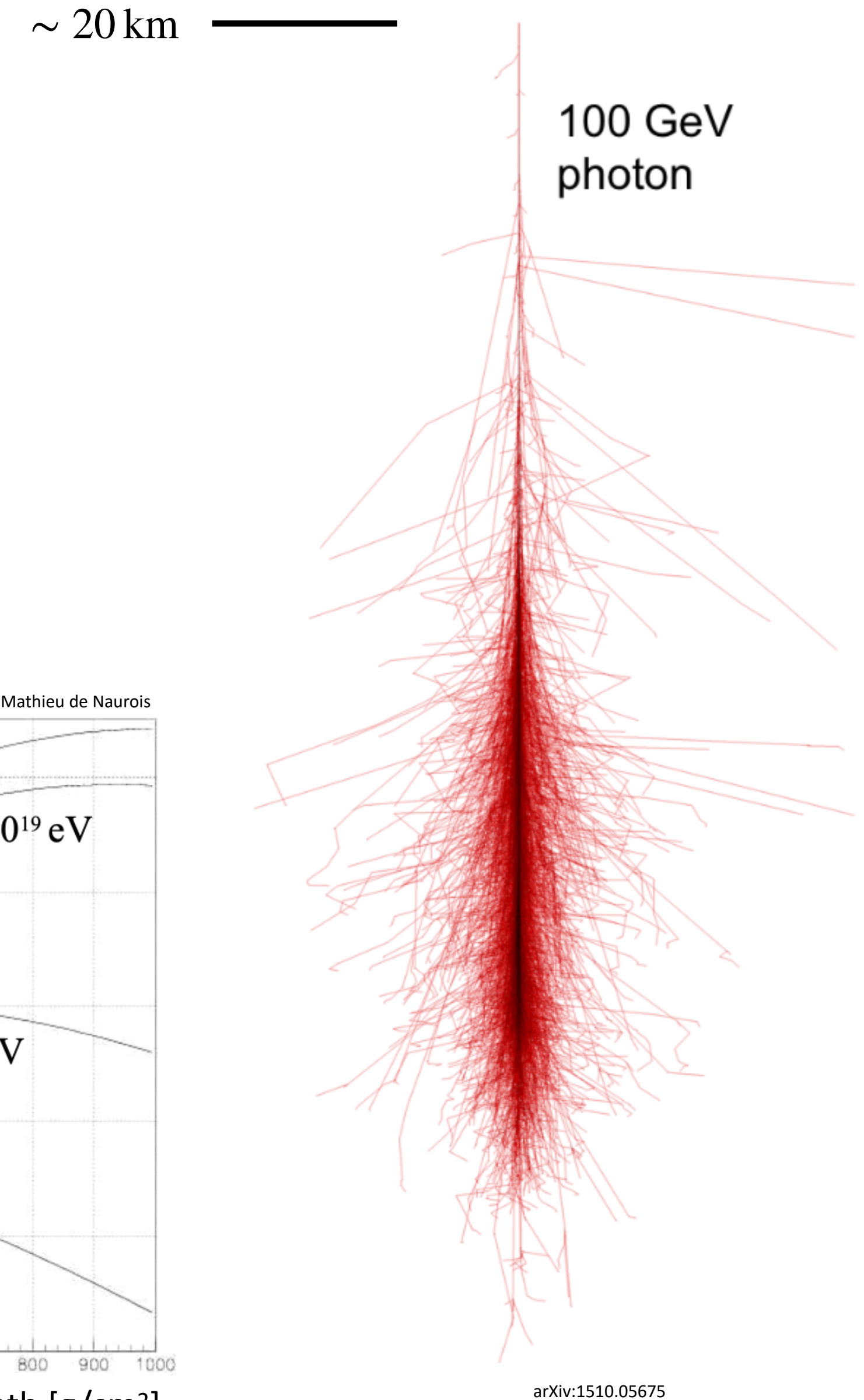
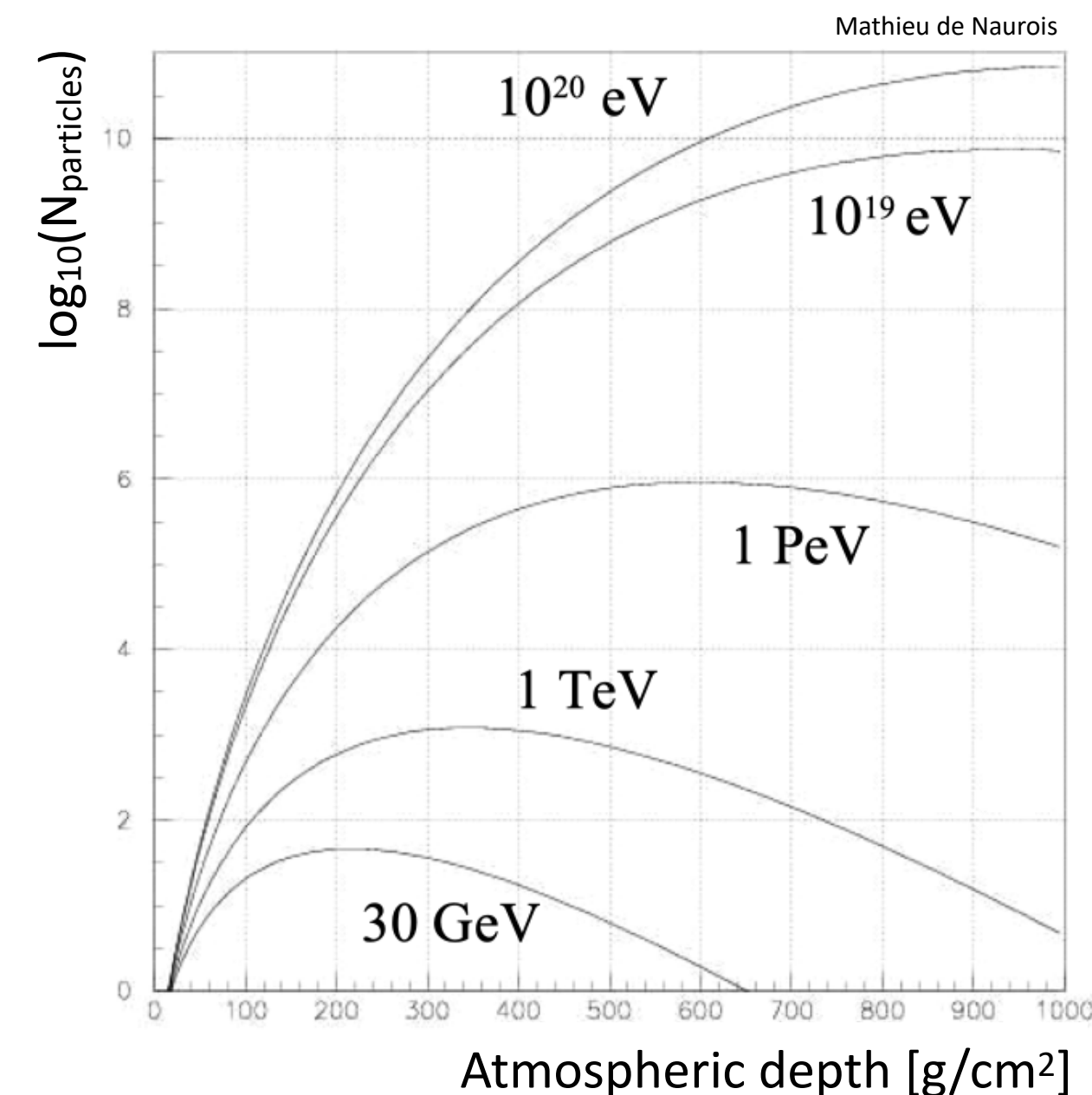
Detection of gamma rays from the ground

- High-energy gamma rays are **scarce**
 - ▶ need **large detection areas**
 - ▶ impossible in space – need to observe gamma rays from the **ground** to do TeV astronomy



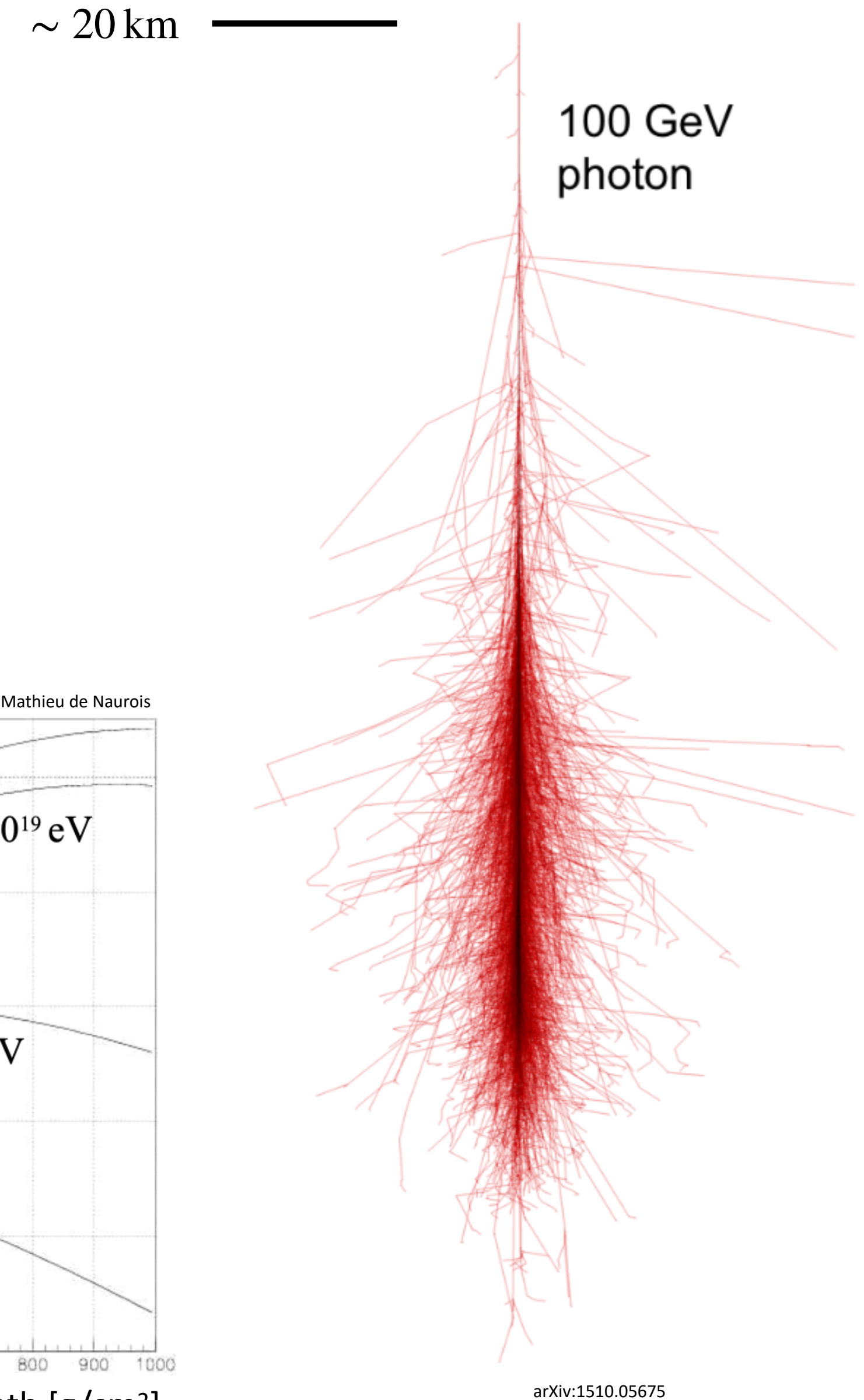
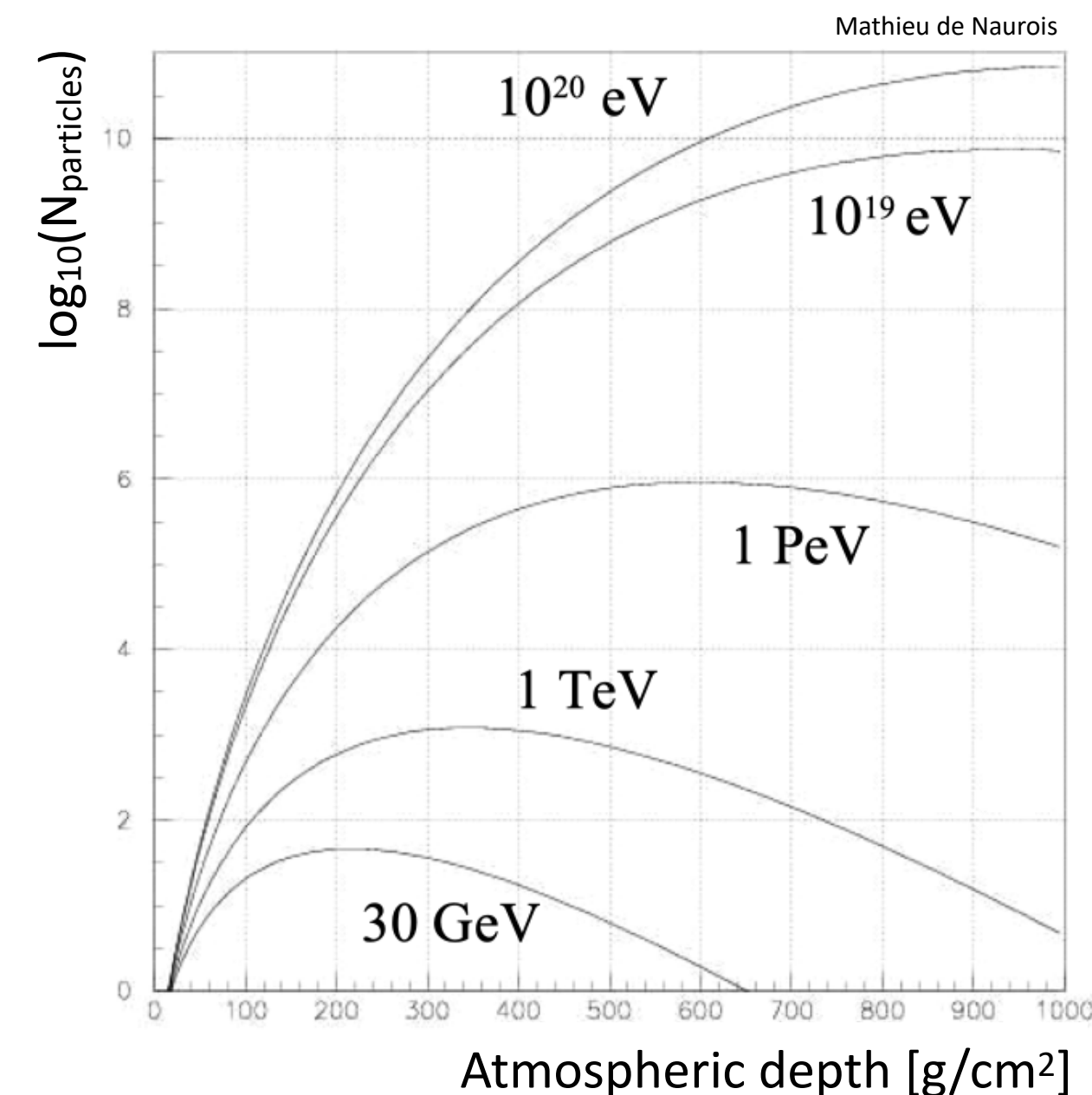
Detection of gamma rays from the ground

- High-energy gamma rays are **scarce**
 - ▶ need **large detection areas**
 - ▶ impossible in space – need to observe gamma rays from the **ground** to do TeV astronomy
- **Extensive air showers**
 - ▶ particle cascade developing in the atmosphere
 - ▶ number of secondary particles proportional to primary particle energy
 - ▶ shower axis closely aligned with primary particle direction



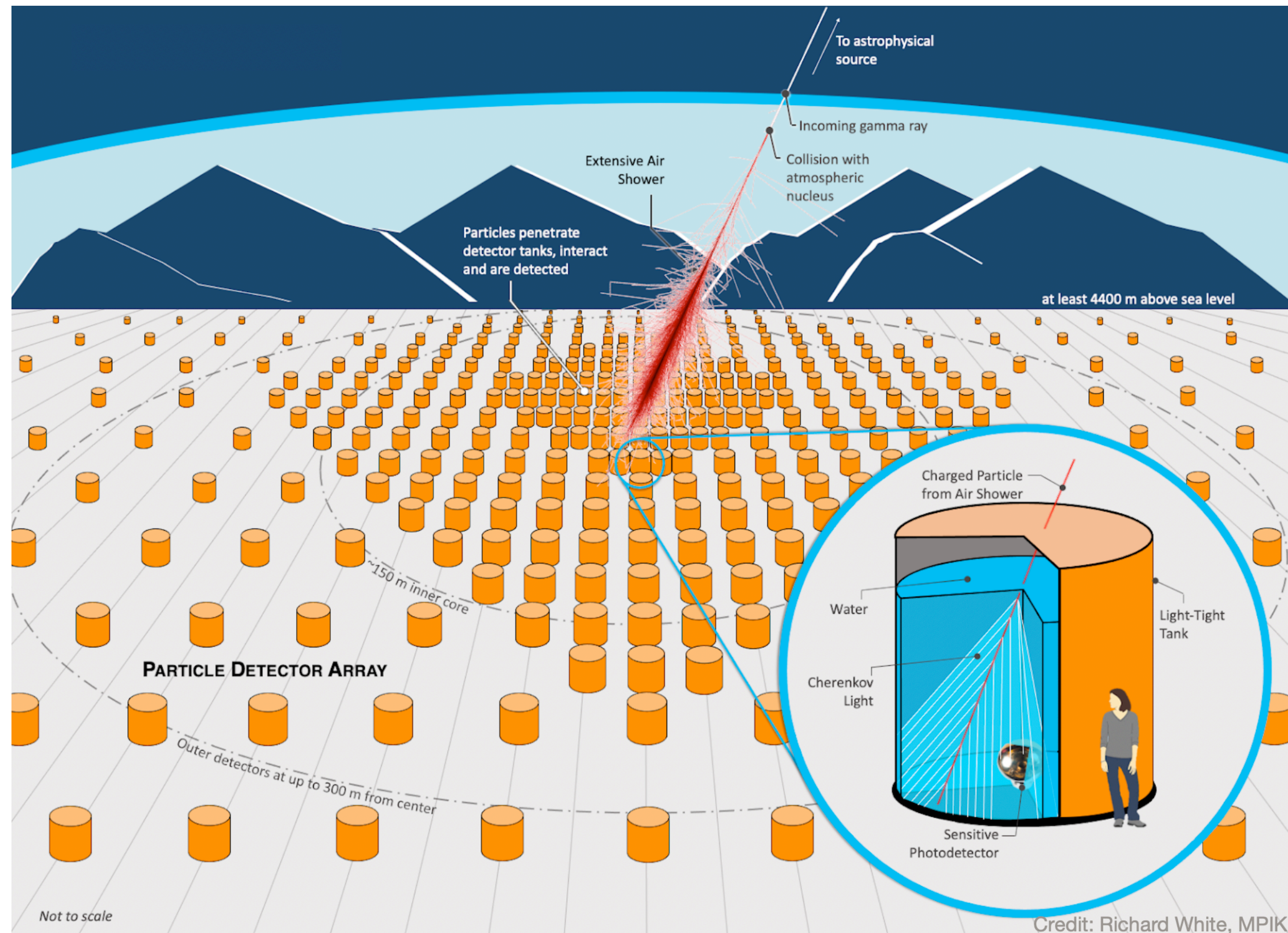
Detection of gamma rays from the ground

- High-energy gamma rays are **scarce**
 - ▶ need **large detection areas**
 - ▶ impossible in space – need to observe gamma rays from the **ground** to do TeV astronomy
- **Extensive air showers**
 - ▶ particle cascade developing in the atmosphere
 - ▶ number of secondary particles proportional to primary particle energy
 - ▶ shower axis closely aligned with primary particle direction
- → Can observe high-energy gamma rays **indirectly** from the ground by measuring the **atmospheric air showers** they initiate



Ground-level particle detector arrays

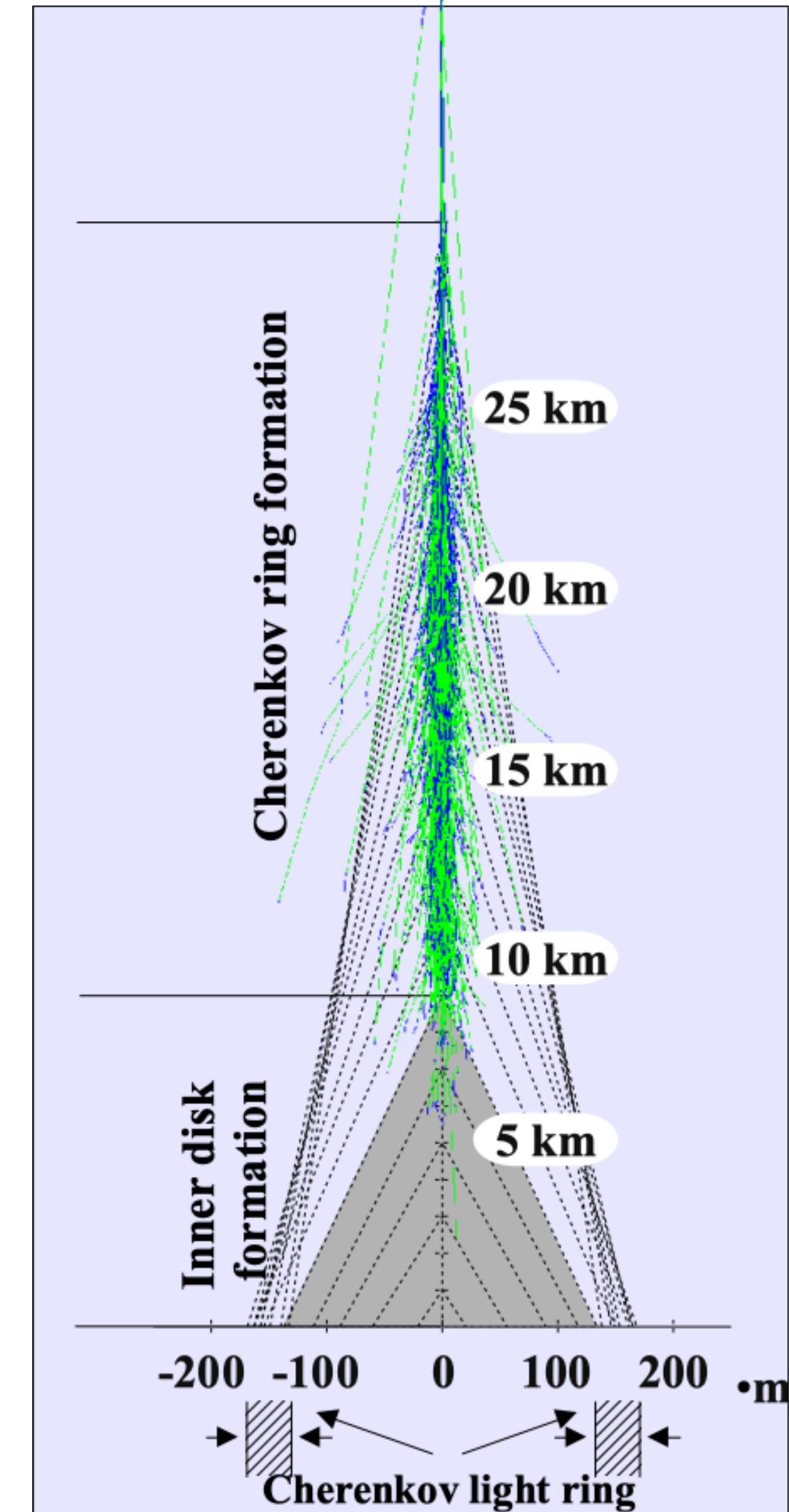
- Detect secondary particles when they **reach the ground**
 - ▶ e.g. with water Cherenkov tanks
- Sensitivity in TeV regime requires **high altitude** (> 4000 m)
- **Advantages**
 - ▶ large instantaneous field of view
 - ▶ $\sim 100\%$ duty cycle
- **Disadvantages**
 - ▶ modest resolution (only “footprint” of shower measured)
 - ▶ need many detectors to cover large area



Cherenkov radiation from air showers

Order-of-magnitude estimates for a 1 TeV gamma-ray shower:

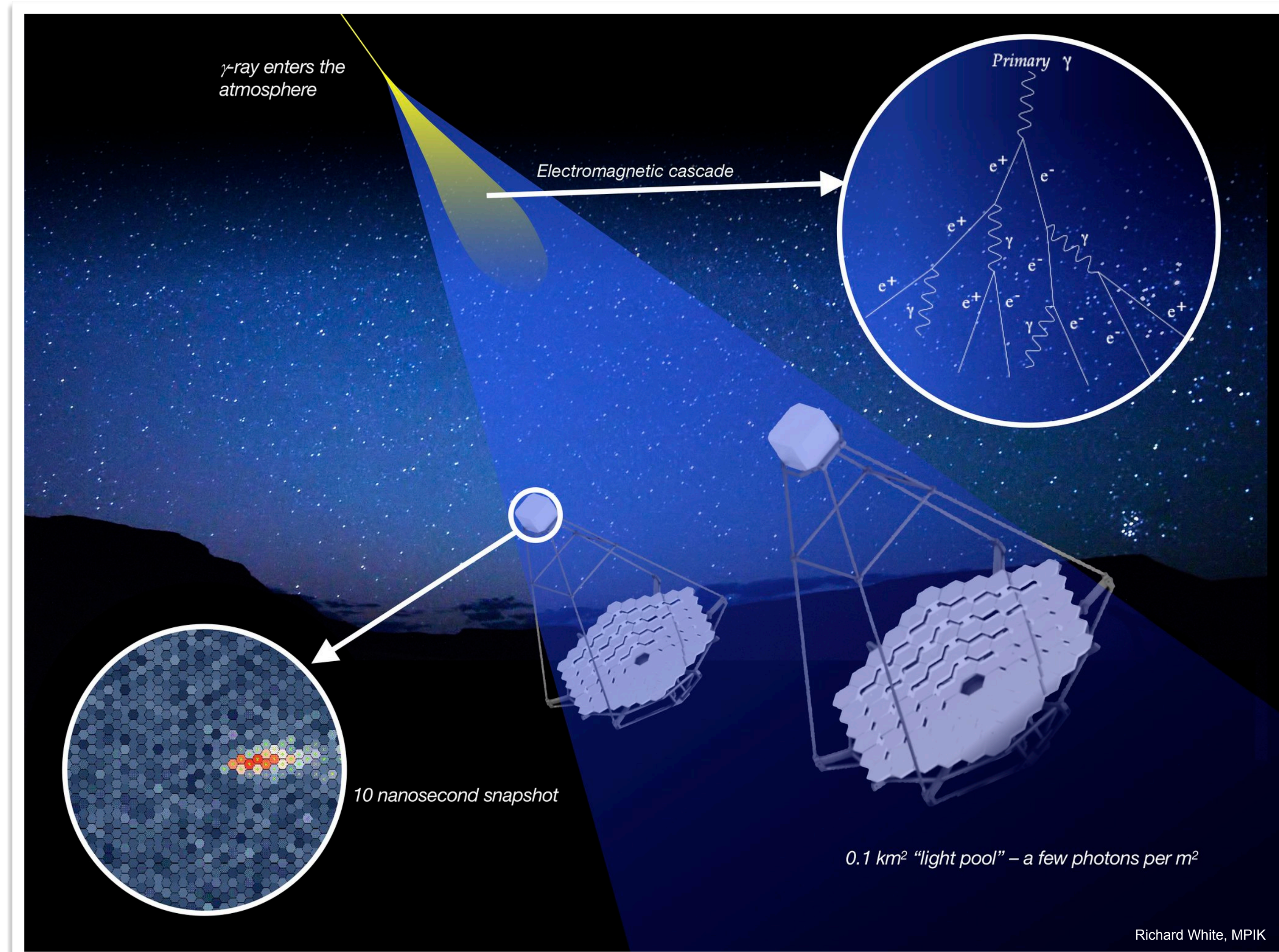
- **Shower maximum**
 - ▶ altitude $\sim 10\text{km}$
 - ▶ $\sim 10^3$ charged particles
- **Cherenkov radiation**
 - ▶ opening angle $\sim 1^\circ$
 - ▶ ~ 10 photons / m / particle
- **Cherenkov light pool**
 - ▶ radius $\sim 100\text{m}$
 - ▶ ~ 1000 photons / m^2
 - ▶ total duration of signal < 10 ns



Mathieu de Naurois, LLR

Imaging Atmospheric Cherenkov Telescopes (IACTs)

- Detect **Cherenkov light** from secondary particles in air shower
- Requires **large mirrors** and **fast cameras**
- **Advantages**
 - high resolution (energy $\sim 20\%$, direction $\sim 0.1^\circ$)
 - high instantaneous sensitivity due to large effective collection area
- **Disadvantages**
 - restricted to dark, moonless nights
→ $\sim 15\%$ duty cycle
 - limited field of view ($\sim 5^\circ \times 5^\circ$)
→ need to point the telescopes



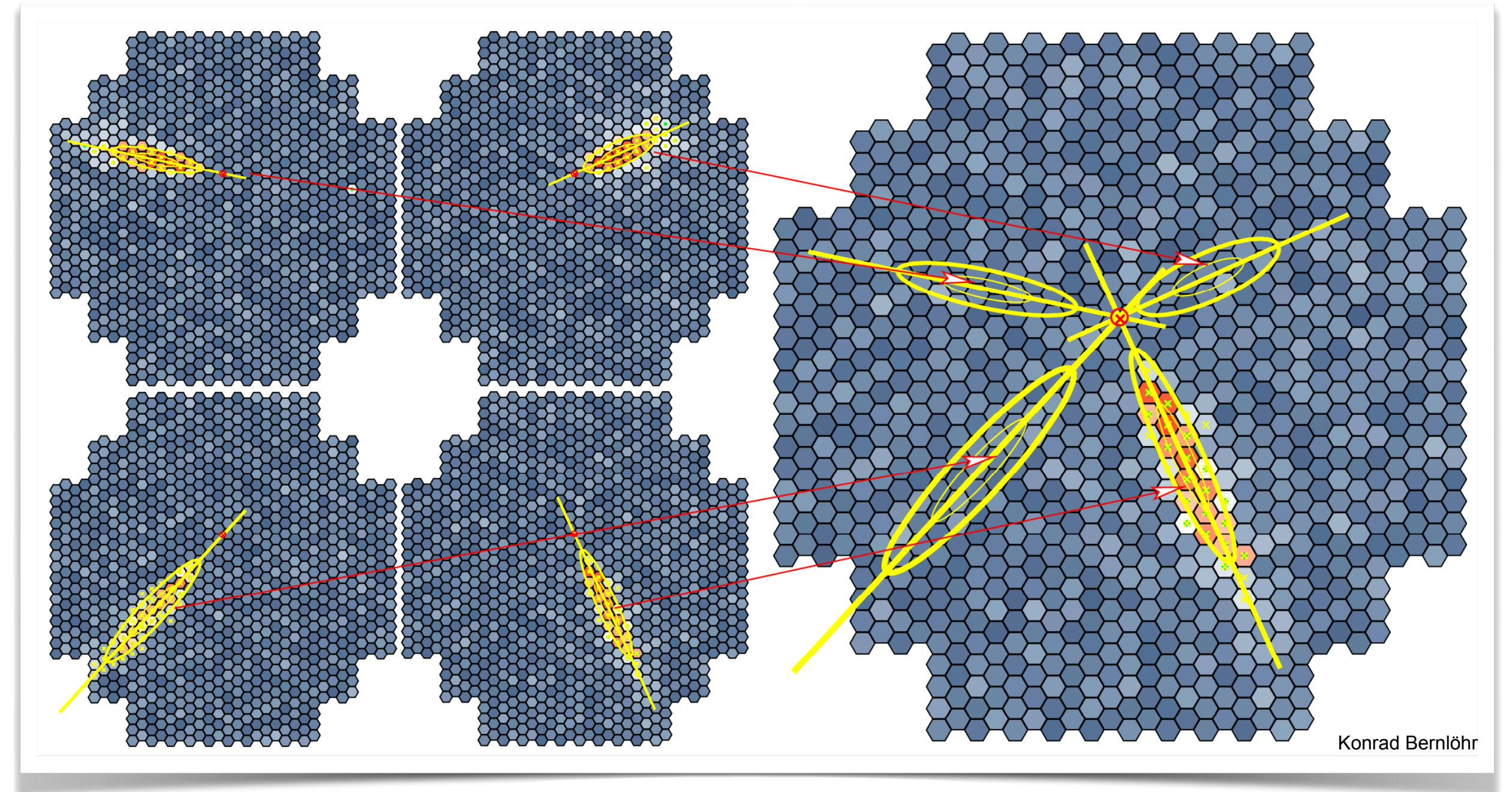
High Energy Stereoscopic System (H.E.S.S.)

- Khomas Highland, Namibia
- Sensitive to γ -rays with energies 100 GeV – 100 TeV
- 4 telescopes with 12-m mirrors (since 2004)
- 1 telescope with 28-m mirror (since 2012)



Stereoscopy and hybrid arrays

- Why does it help to have **multiple telescopes**?
 - ▶ “stereoscopy” enables triangulation
 - ▶ greatly improves accuracy of reconstruction
 - ▶ sketch illustrates a simple analytical reconstruction algorithm
 - ▶ more sophisticated, likelihood-based algorithms also in use



Stereoscopy and hybrid arrays

- Why does it help to have **multiple telescopes**?
 - ▶ “stereoscopy” enables triangulation
 - ▶ greatly improves accuracy of reconstruction
 - ▶ sketch illustrates a simple analytical reconstruction algorithm
 - ▶ more sophisticated, likelihood-based algorithms also in use
- Why does it help to have **telescopes of different sizes**?
 - ▶ size of telescope dish determines minimum detectable gamma-ray energy
→ main driver for low-energy sensitivity
 - ▶ instrumented area determines amount of detected air showers
→ main driver for high-energy sensitivity



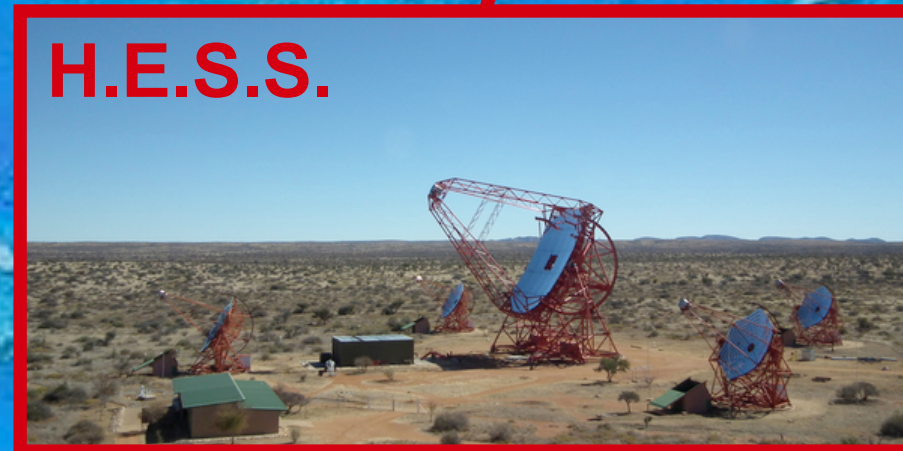
H.E.S.S. in the landscape of gamma-ray observatories



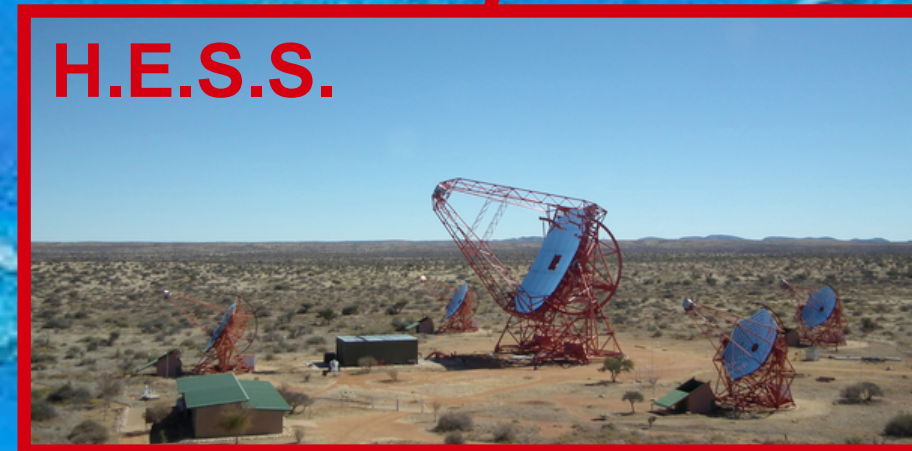
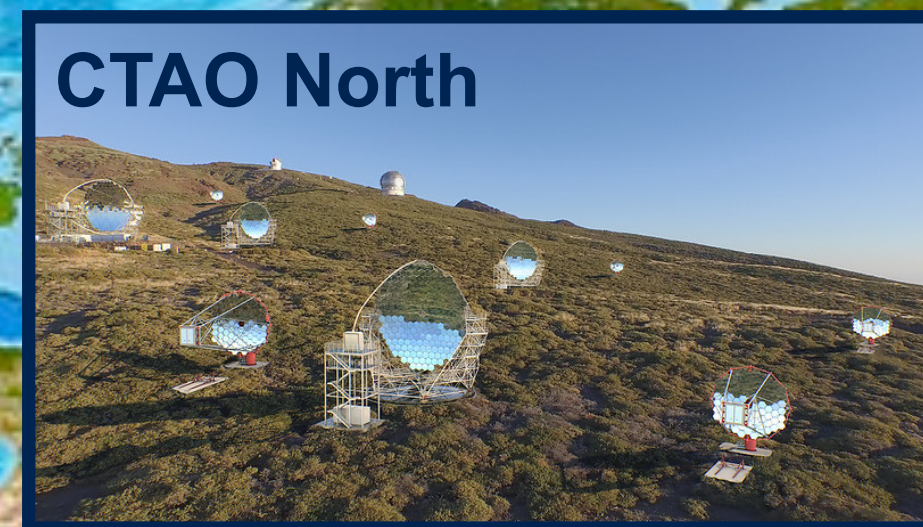
H.E.S.S. in the landscape of gamma-ray observatories



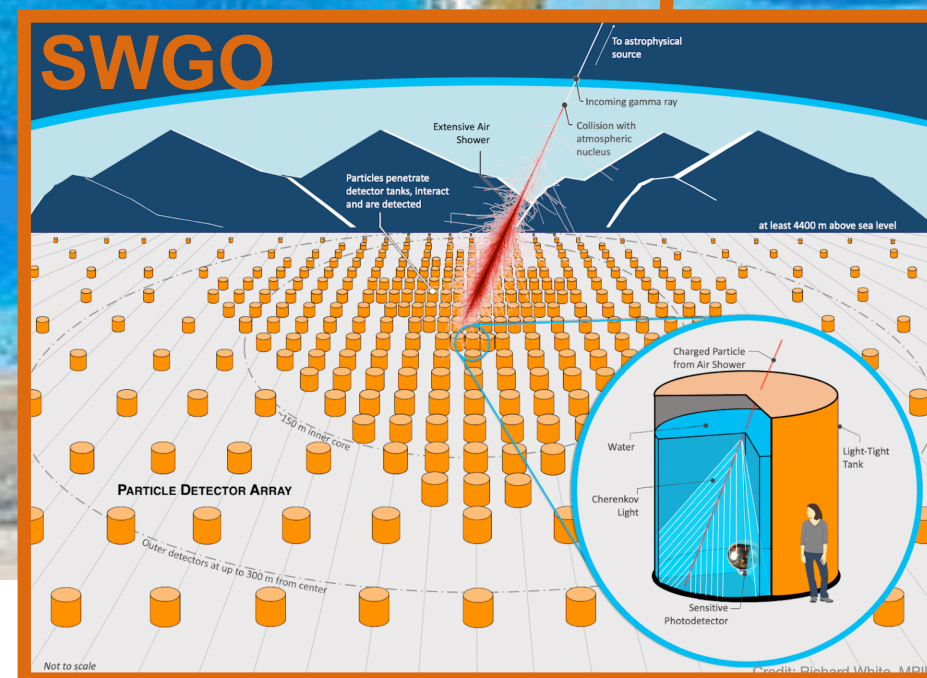
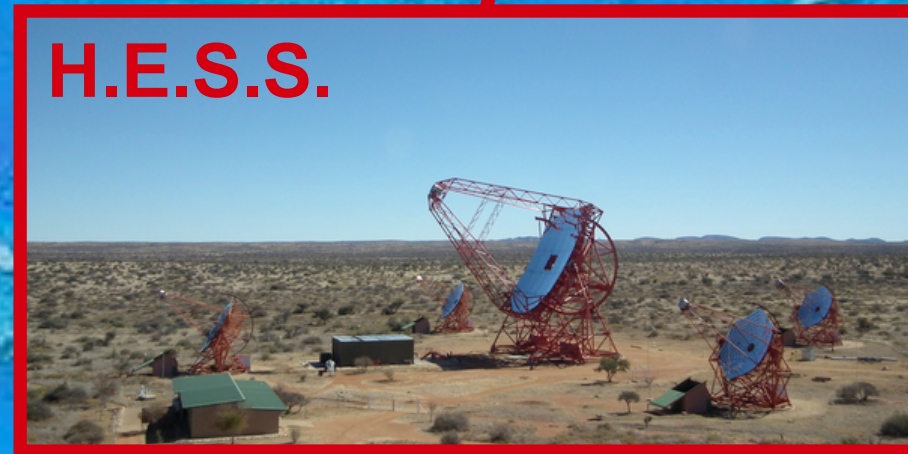
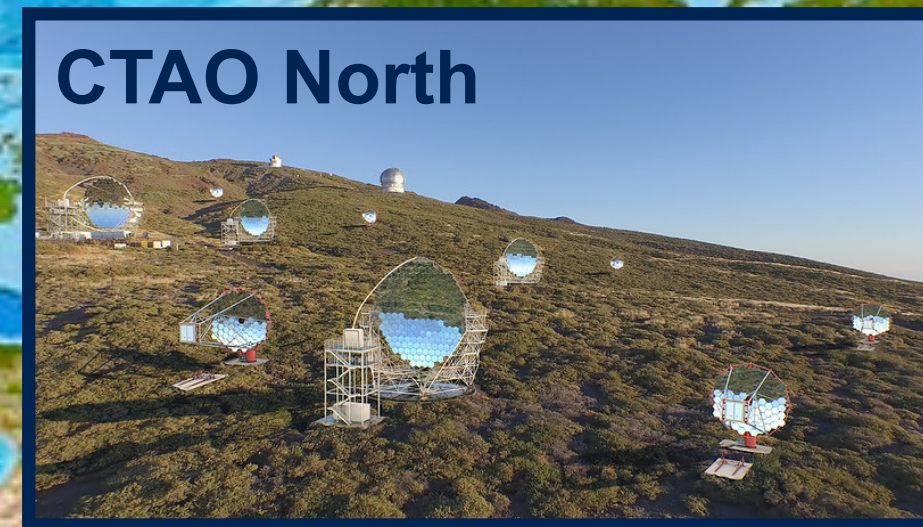
H.E.S.S. in the landscape of gamma-ray observatories



H.E.S.S. in the landscape of gamma-ray observatories



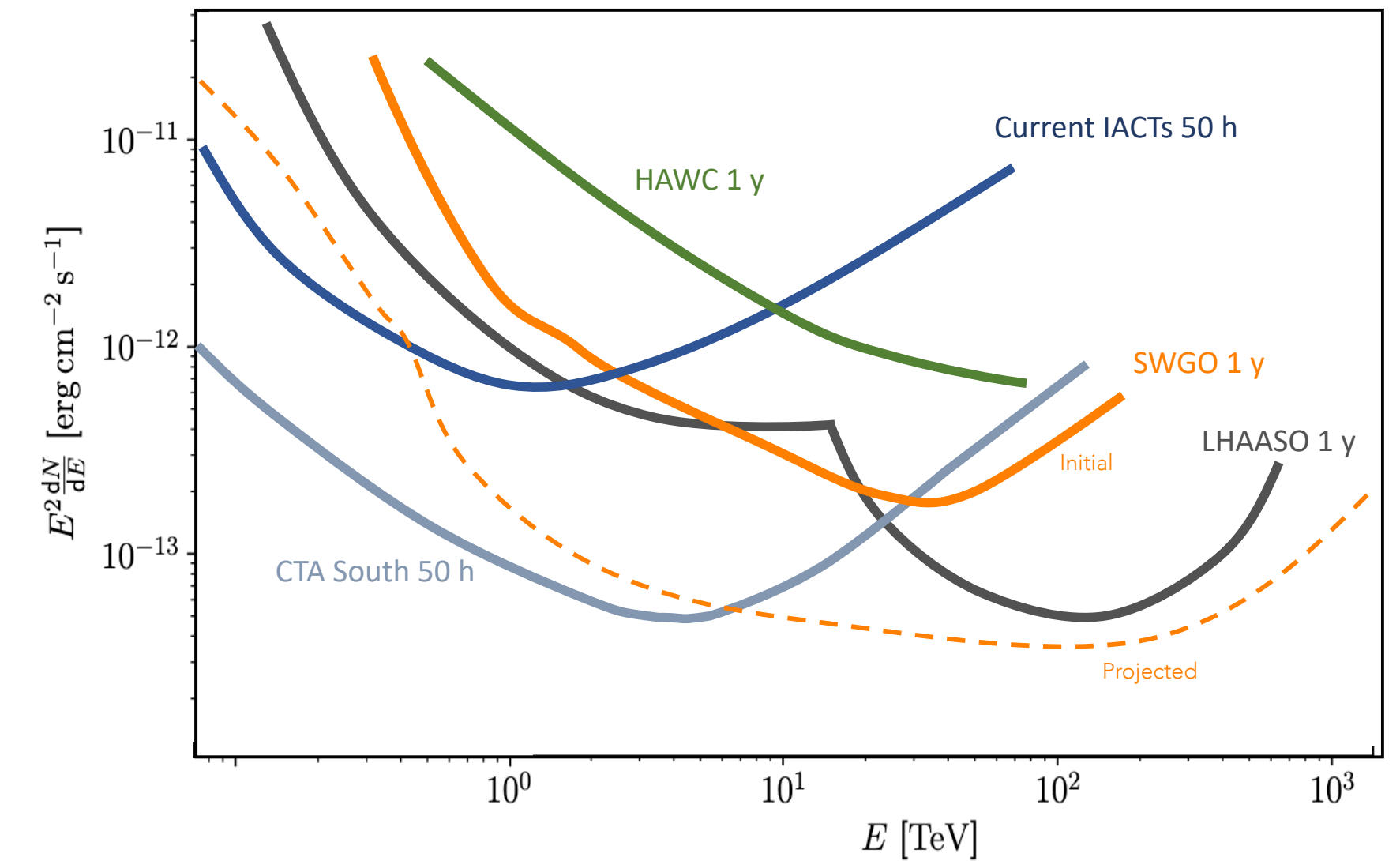
H.E.S.S. in the landscape of gamma-ray observatories



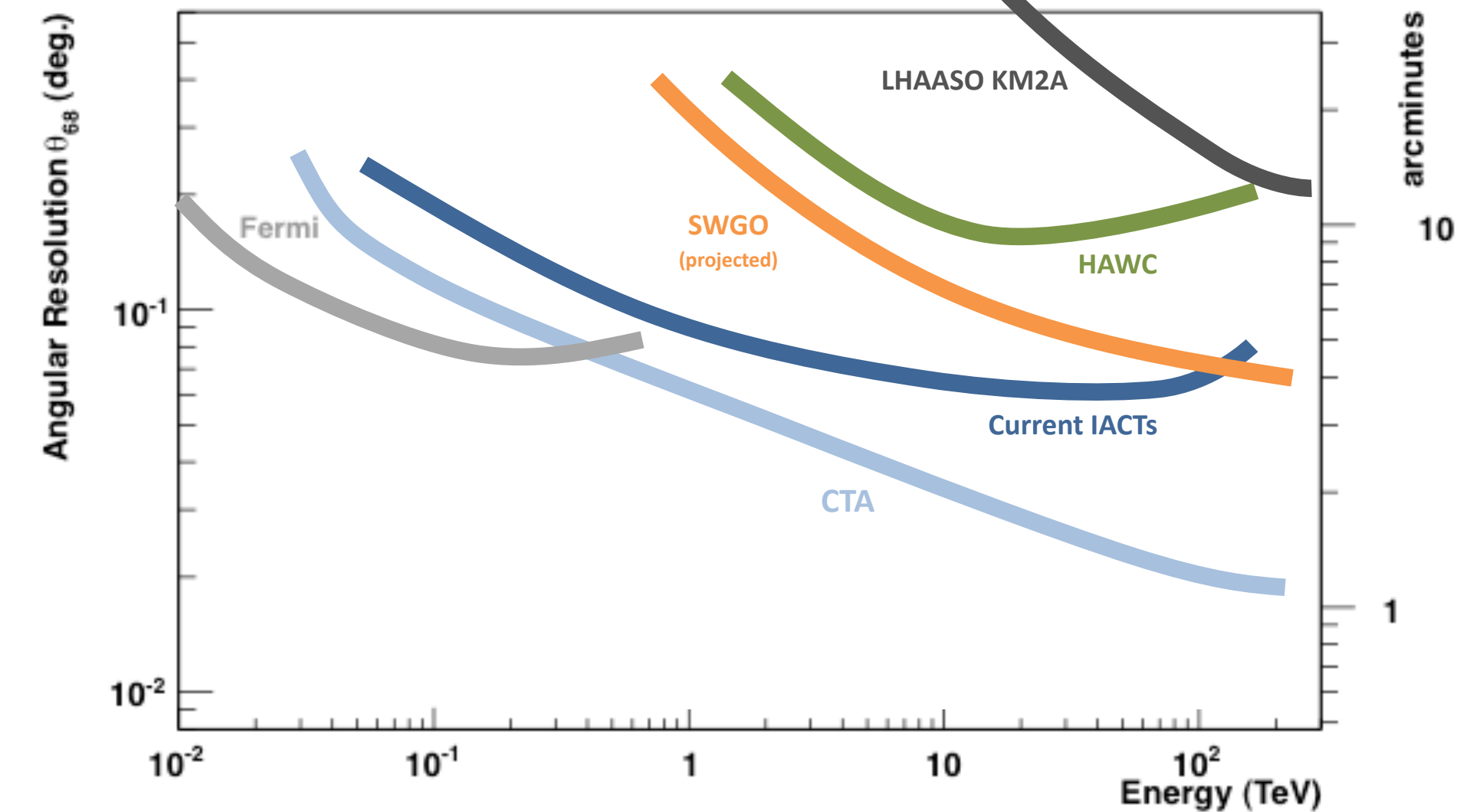
Sensitivity and Resolution

- **Ground-level particle detector arrays** are more sensitive than IACTs at high energies
- However, they provide a **worse angular resolution**
→ **detailed morphological studies** require IACTs
- So do **short-time transient events**
(e.g. gamma-ray bursts, novae, AGN flares...)

Differential sensitivity (point-like source)

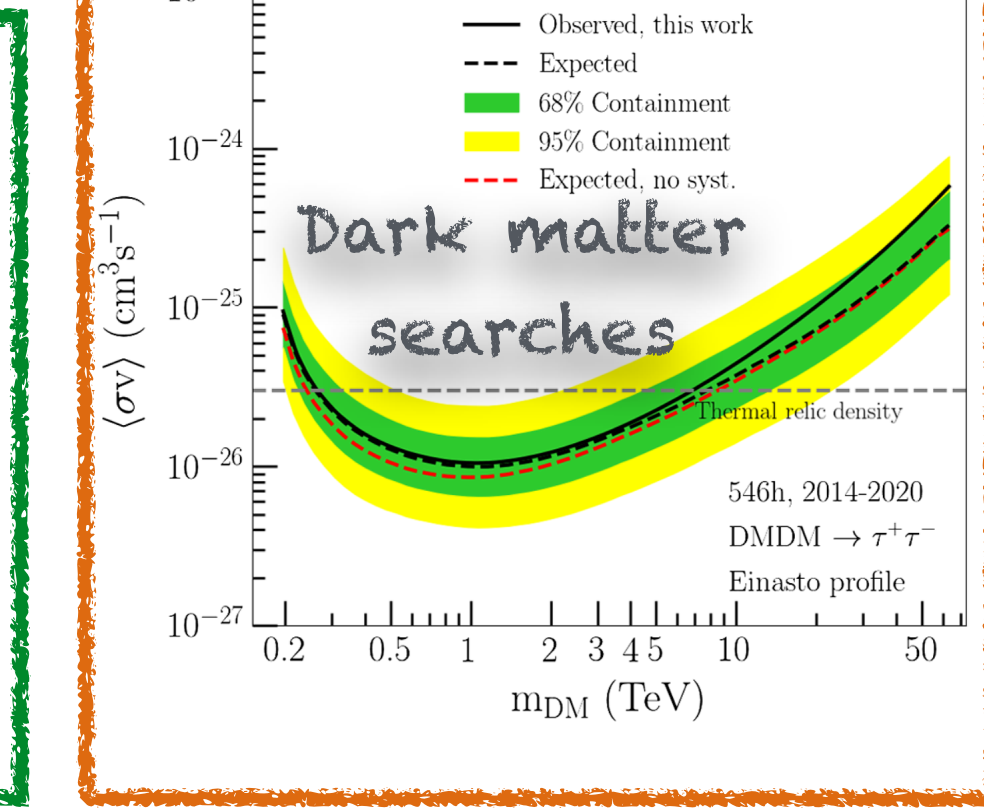
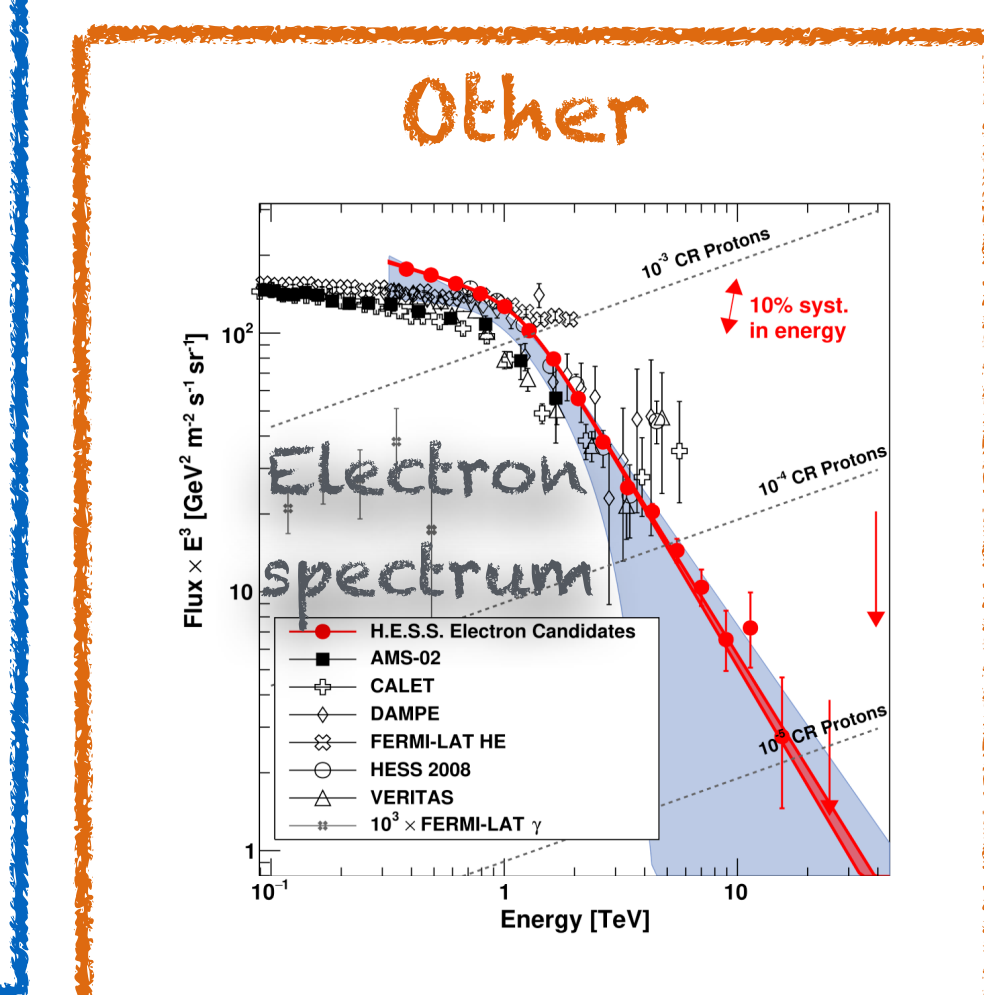
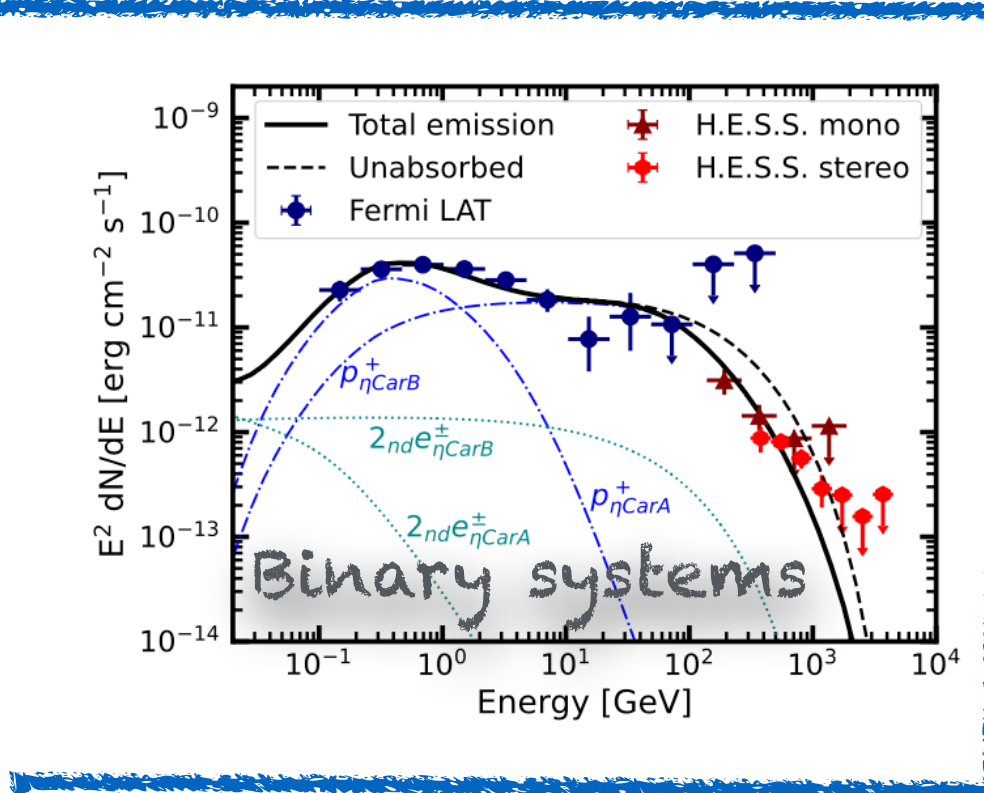
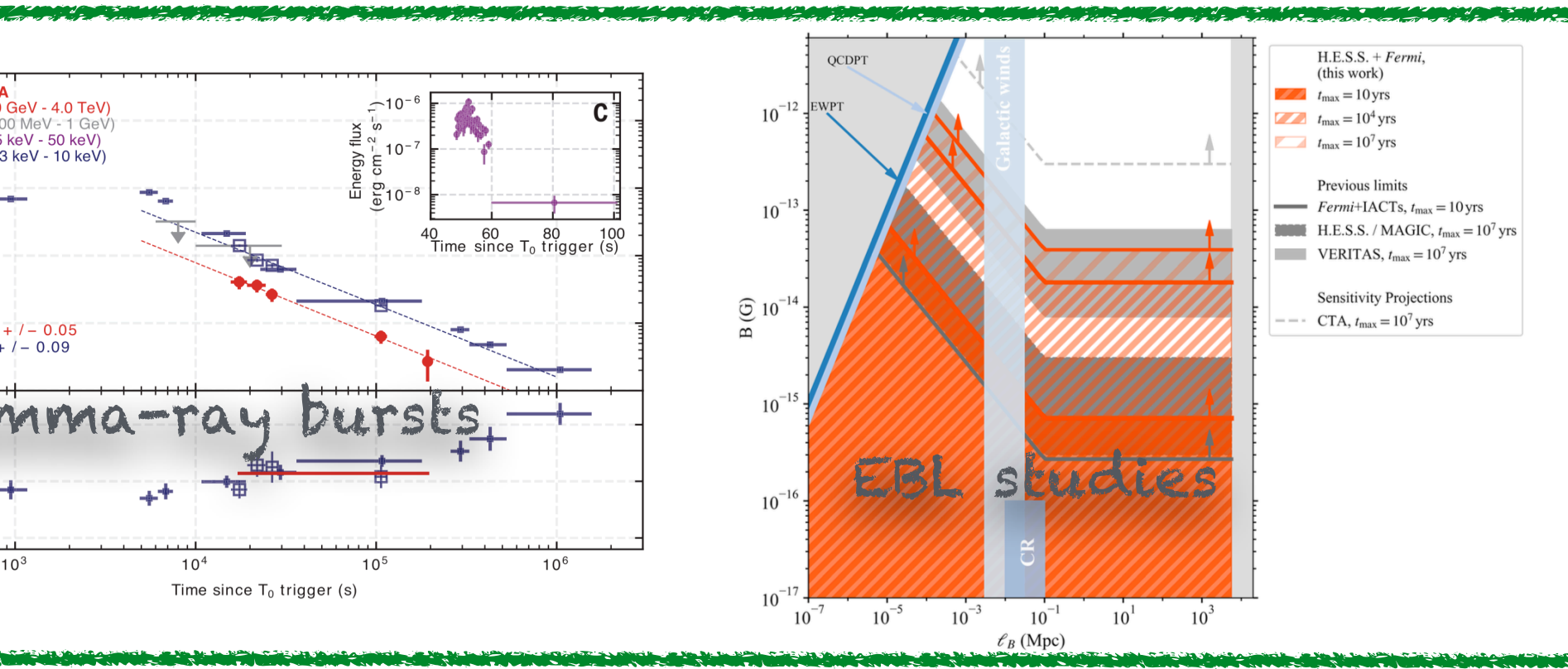
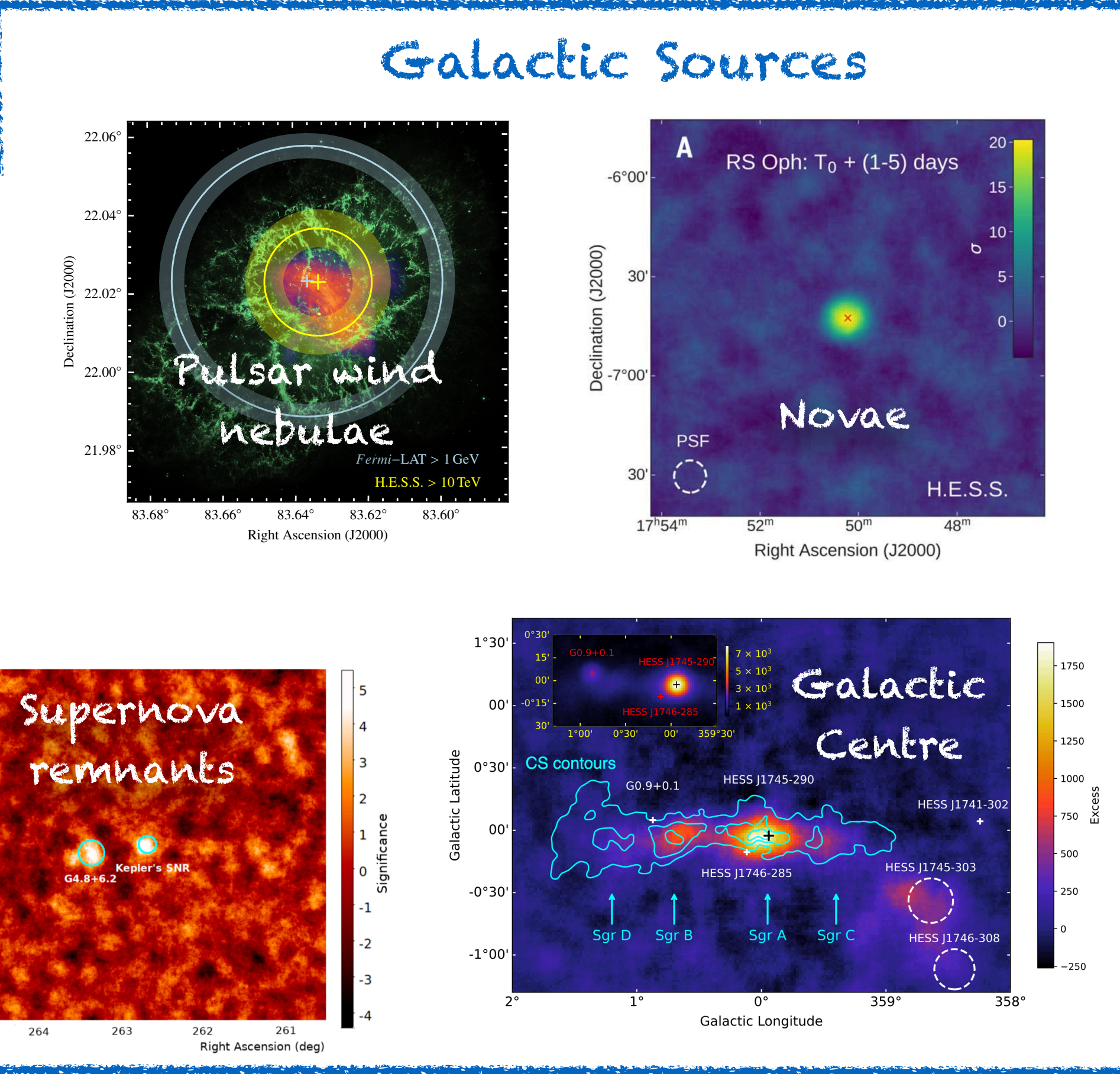
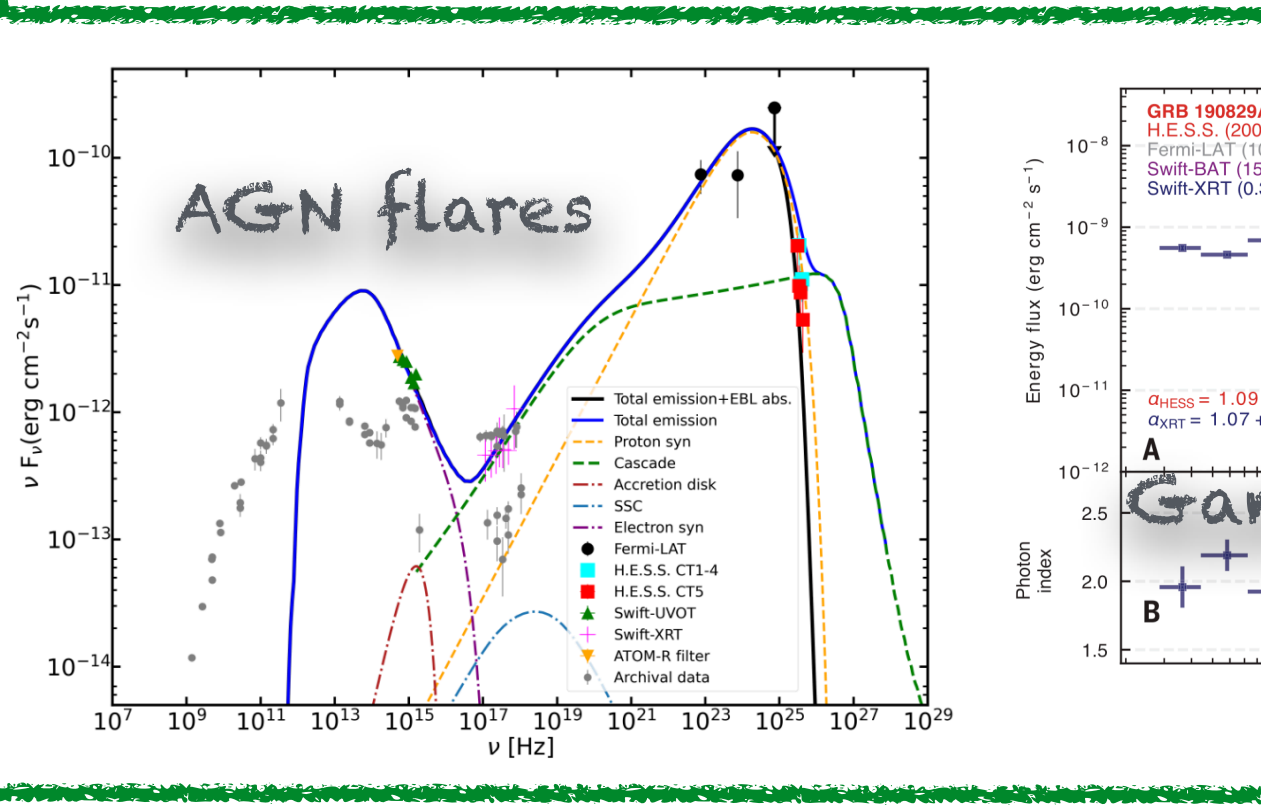
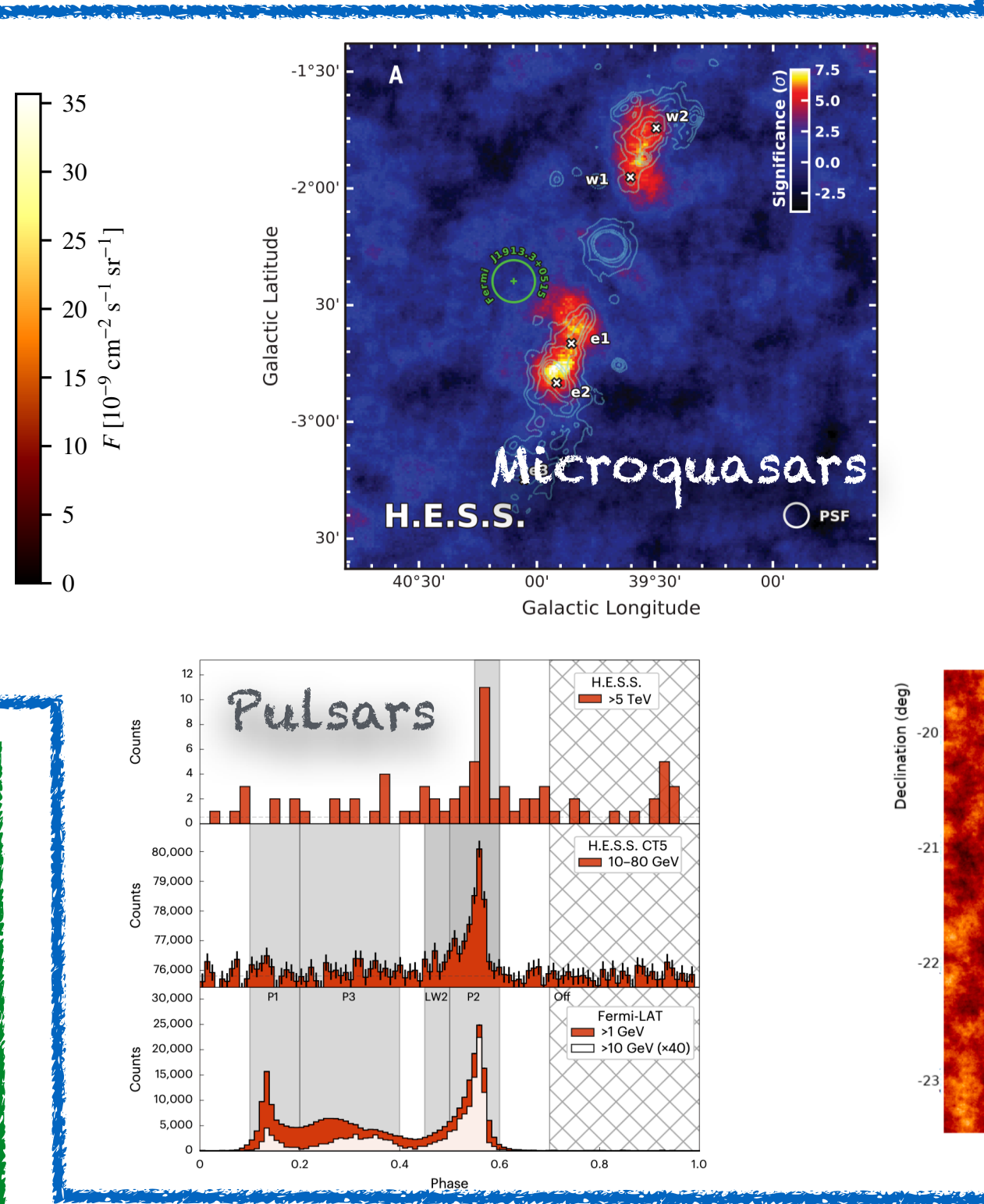
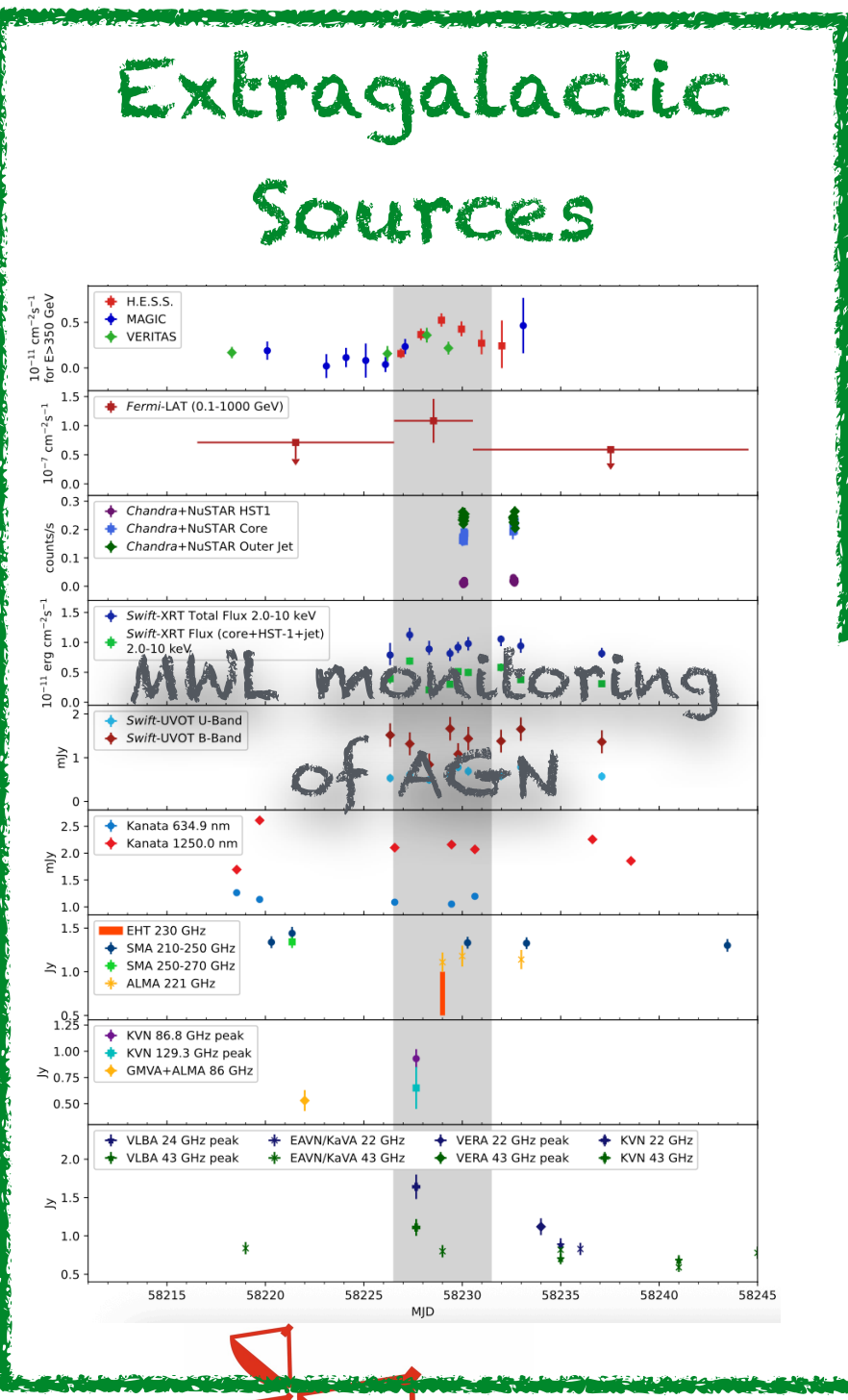
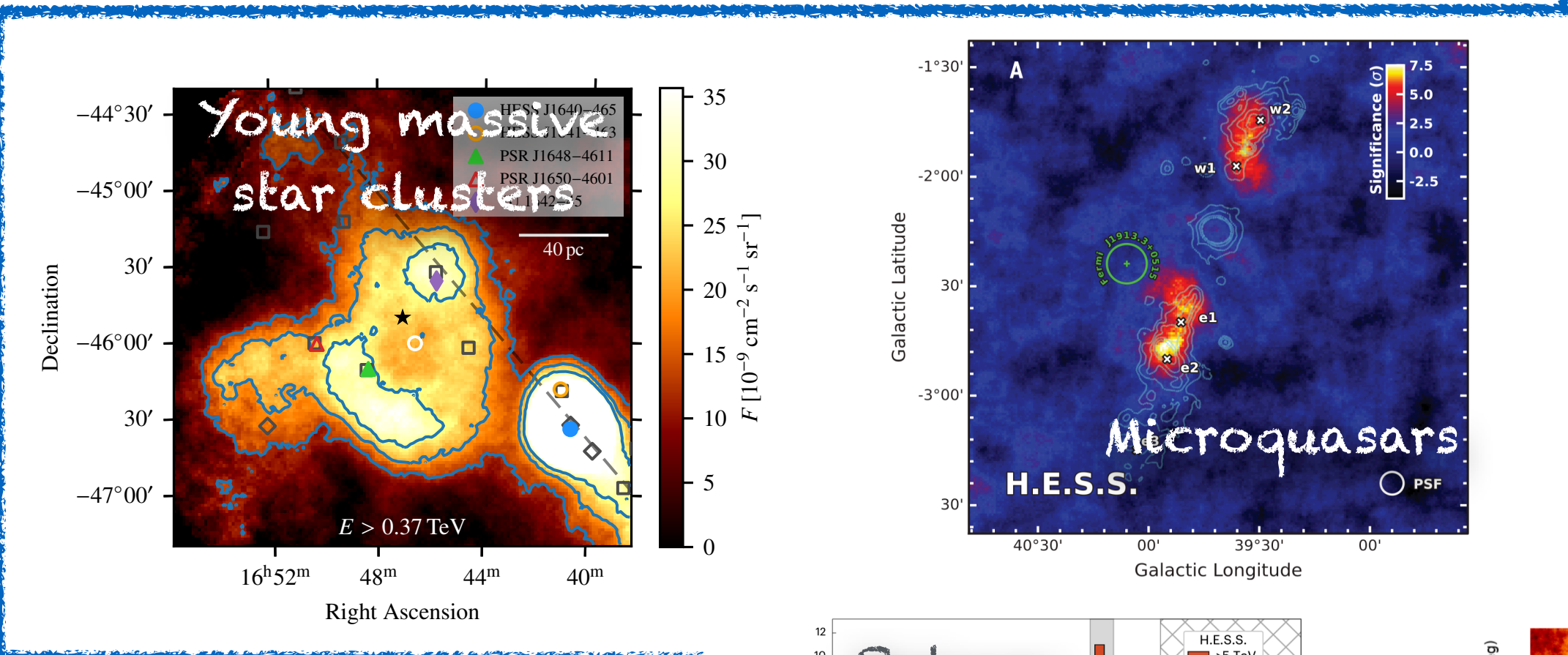


Angular Resolution

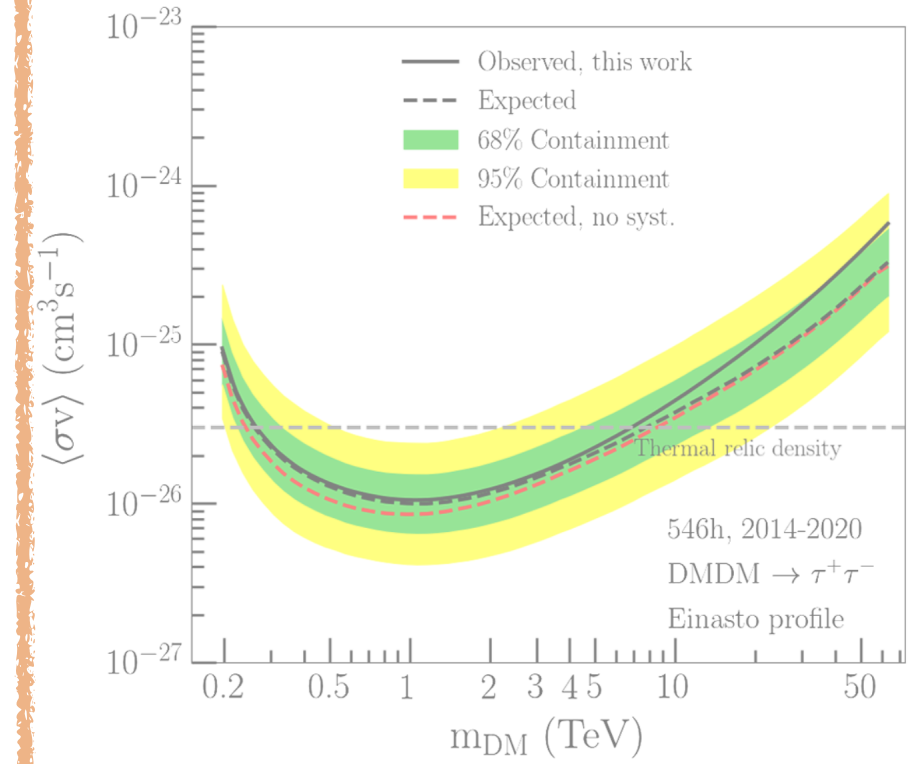
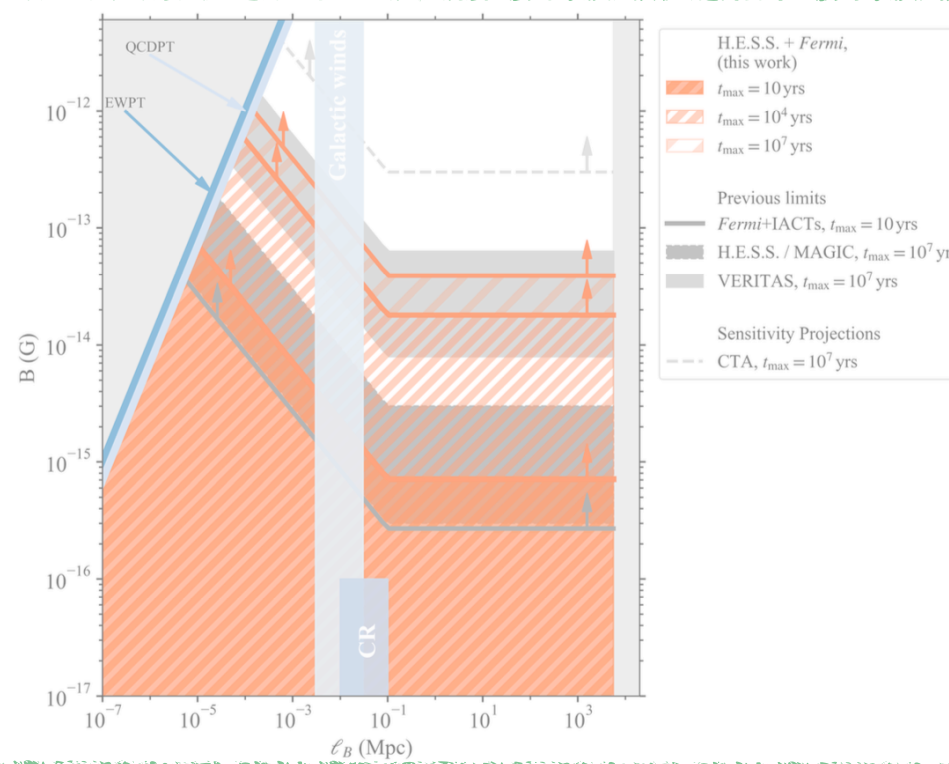
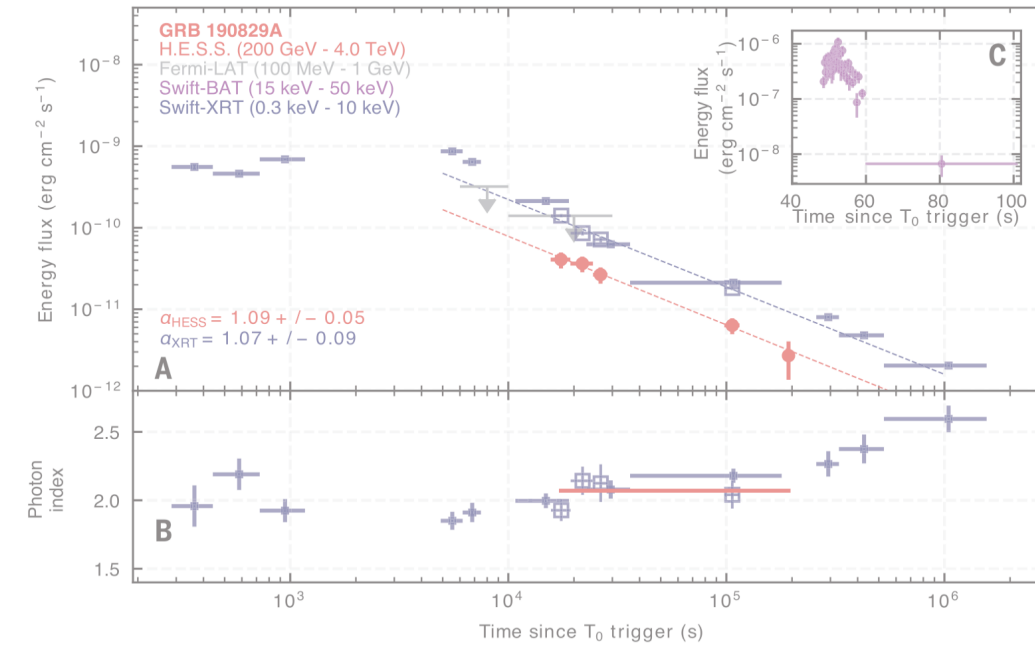
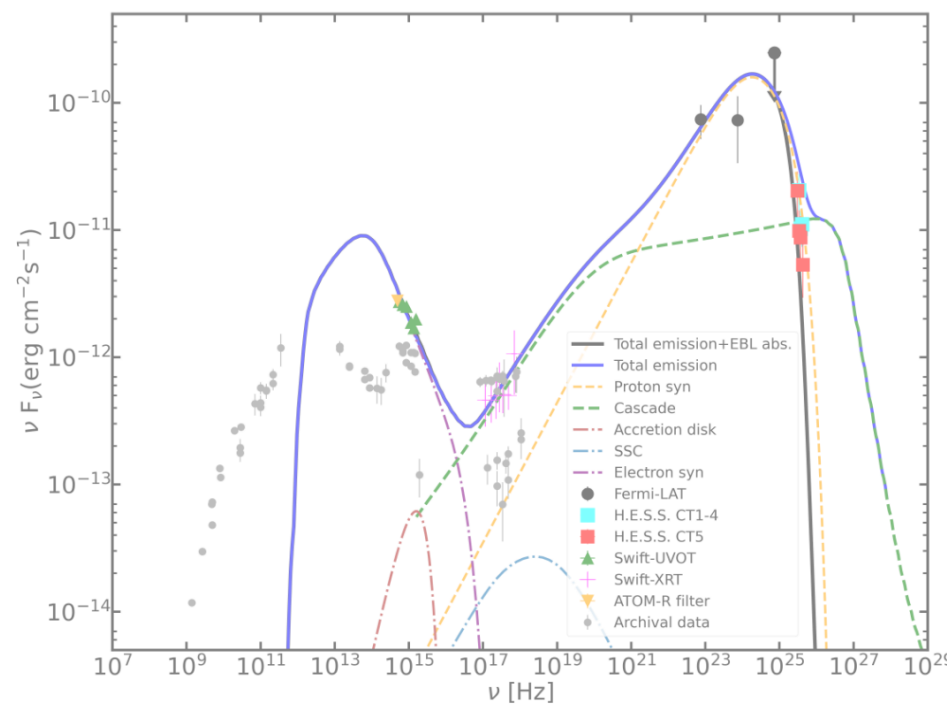
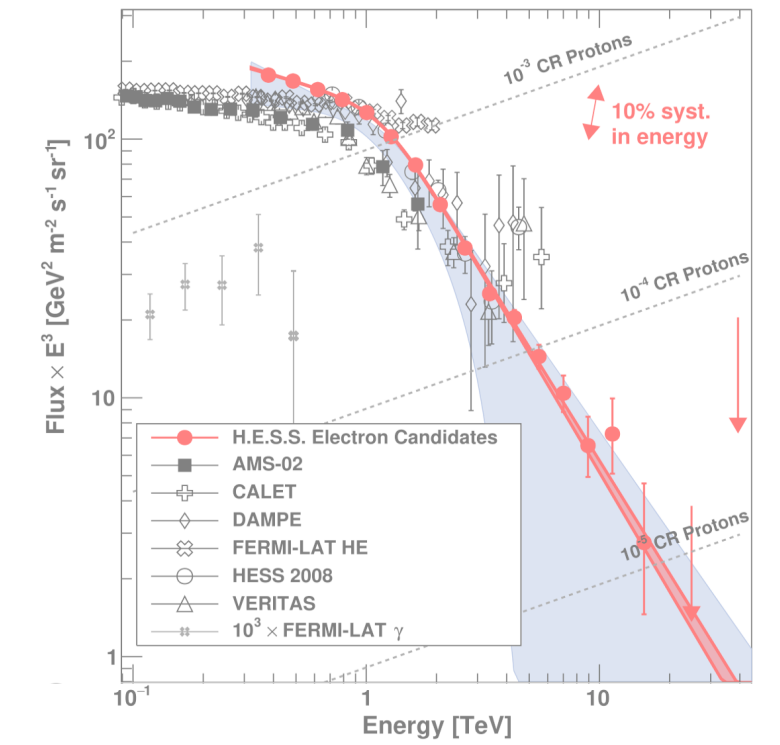
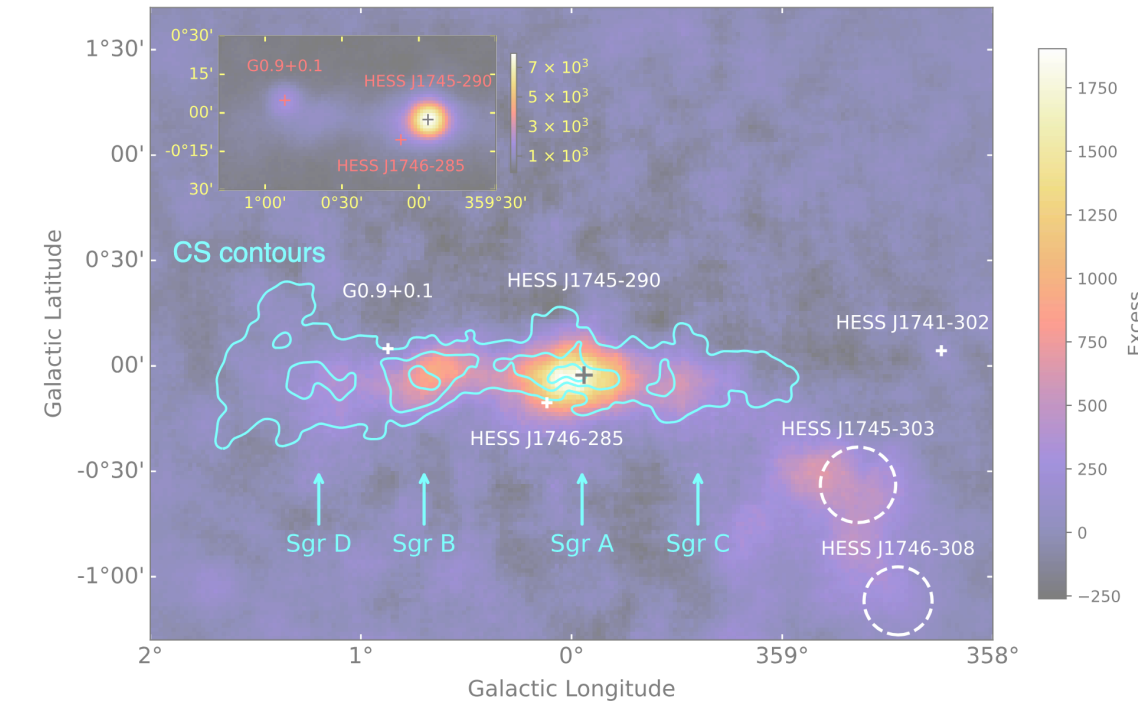
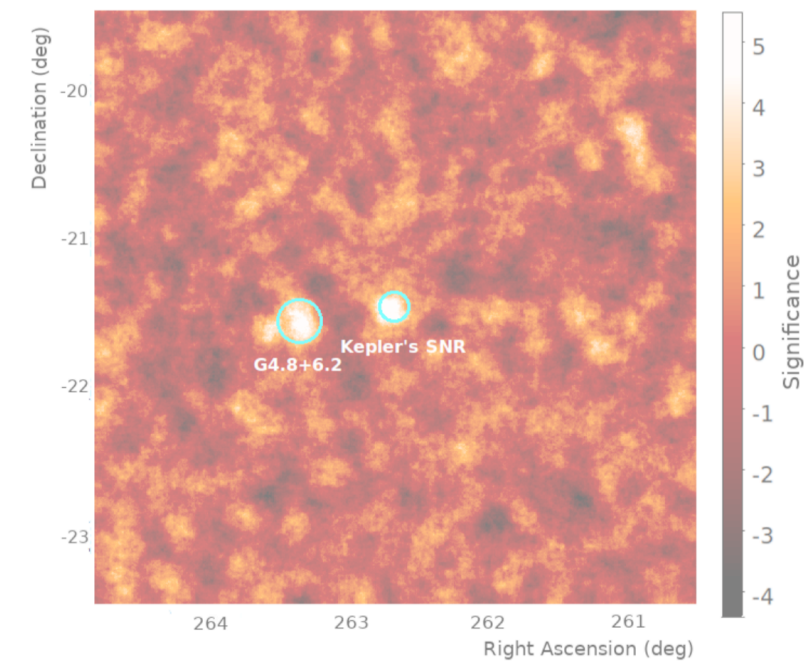
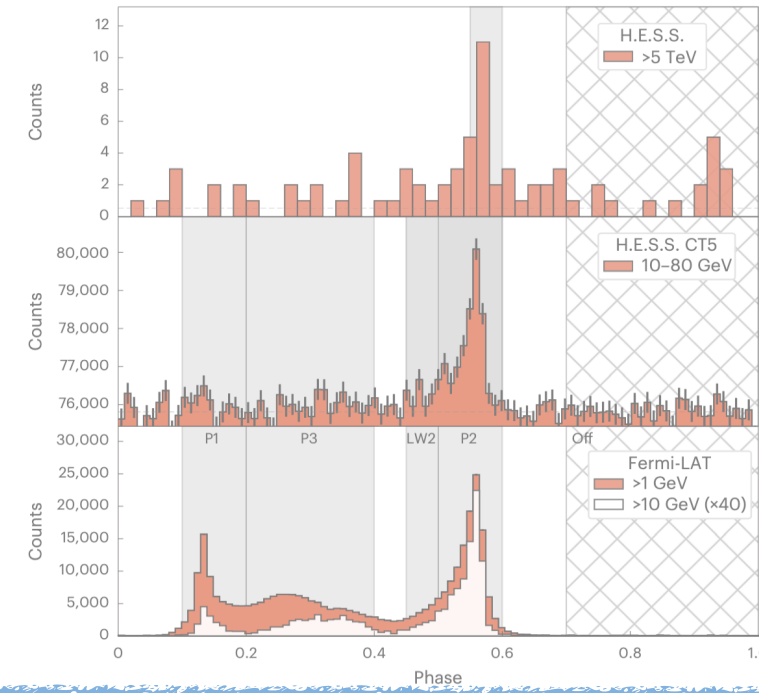
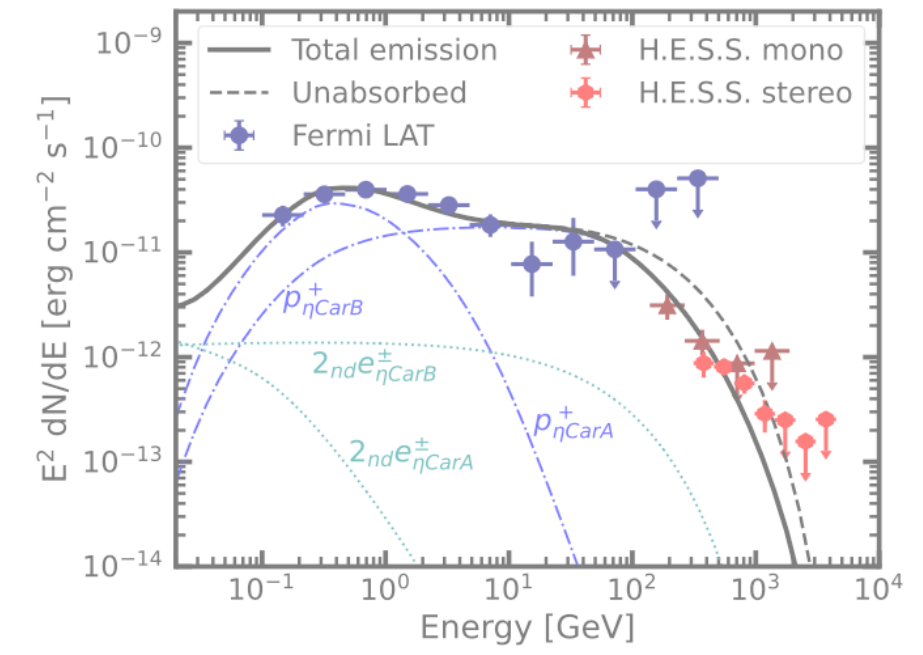
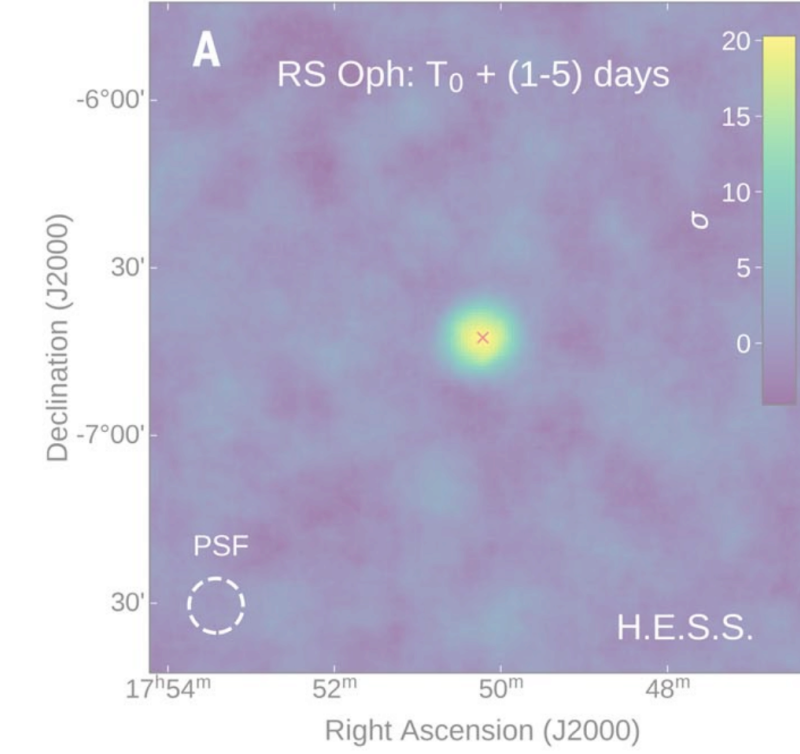
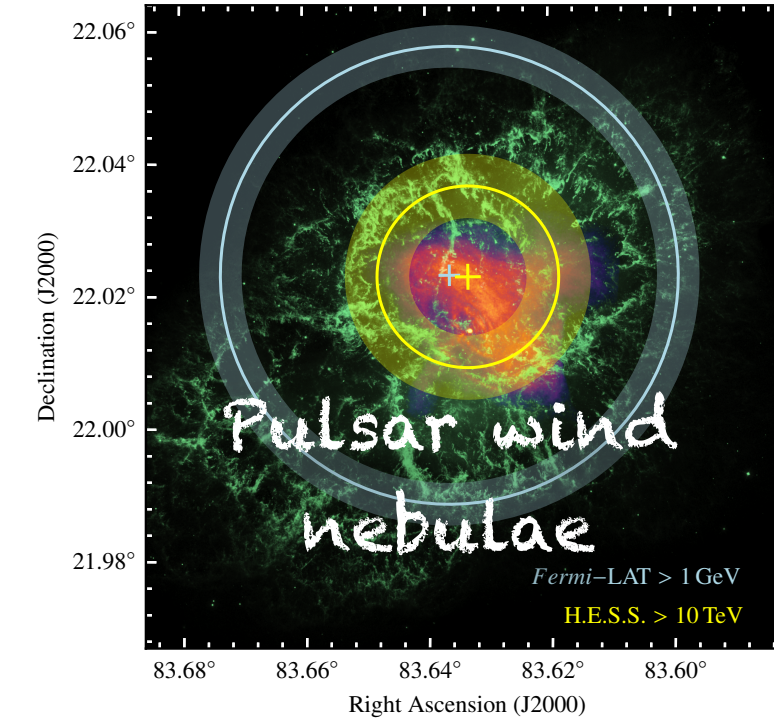
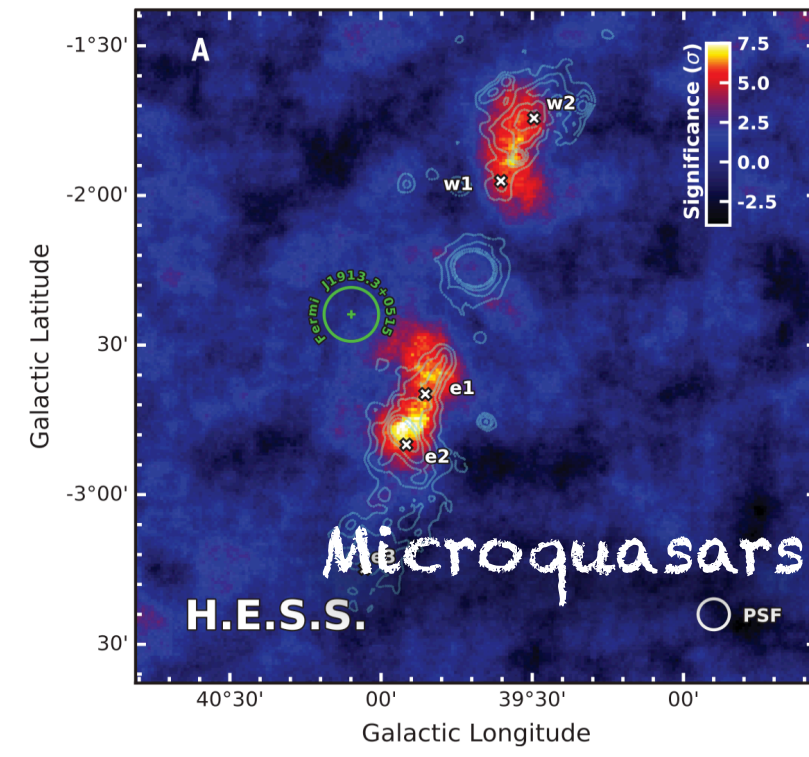
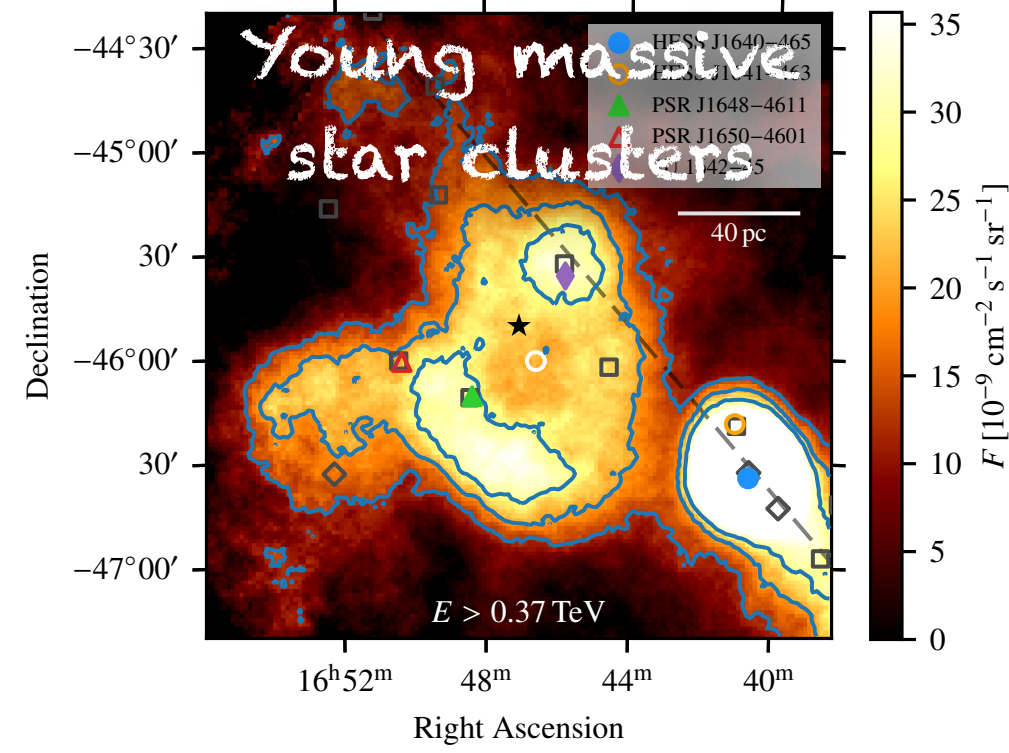


Jim Hinton

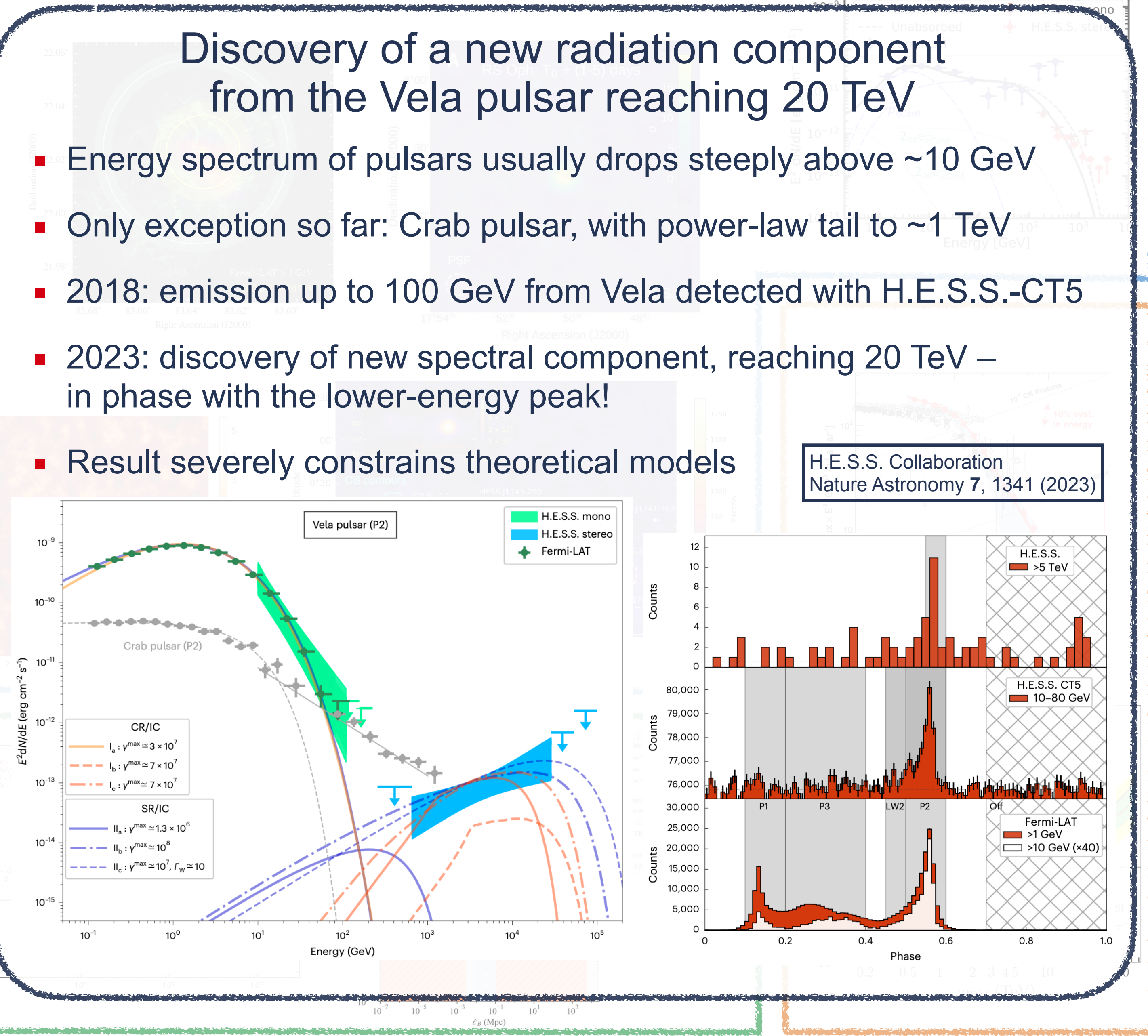
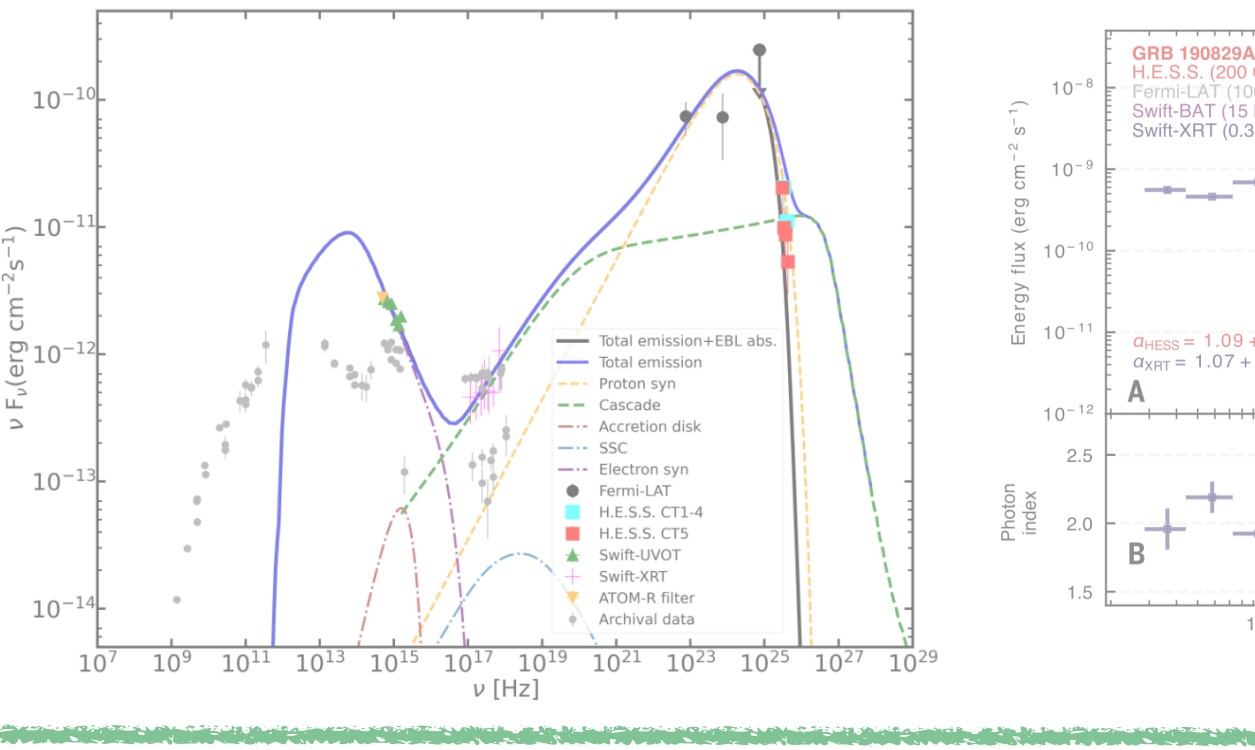
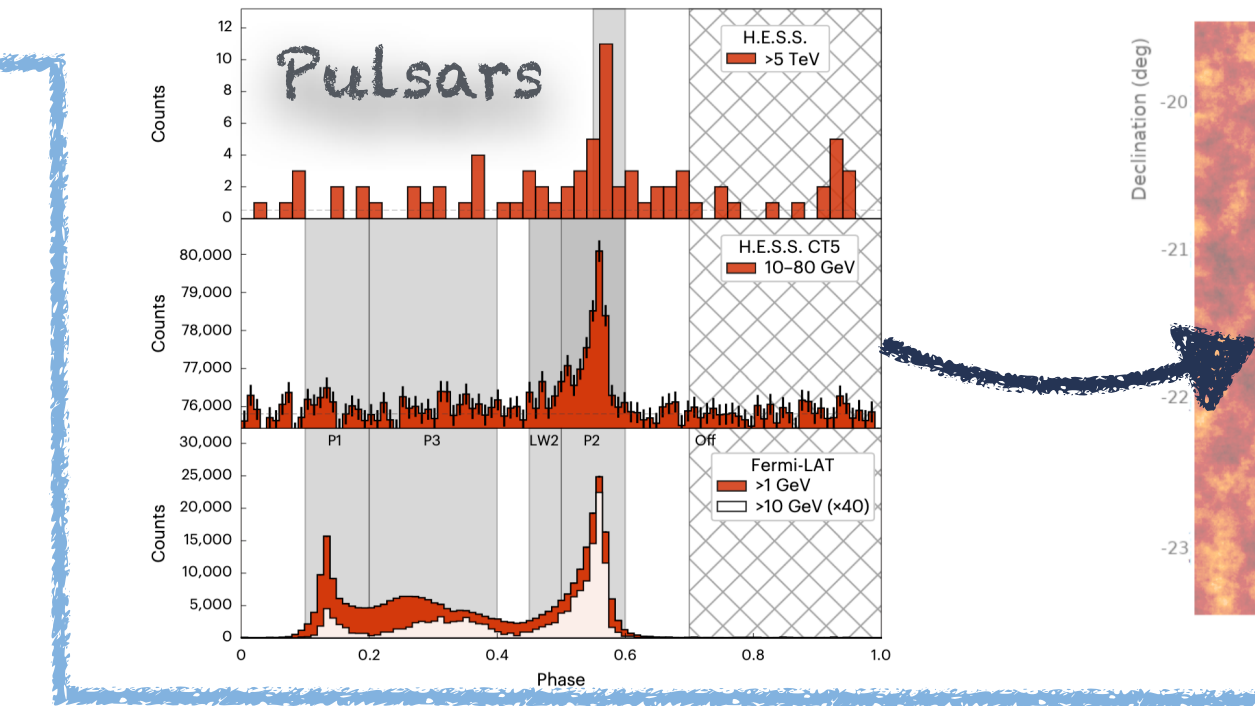
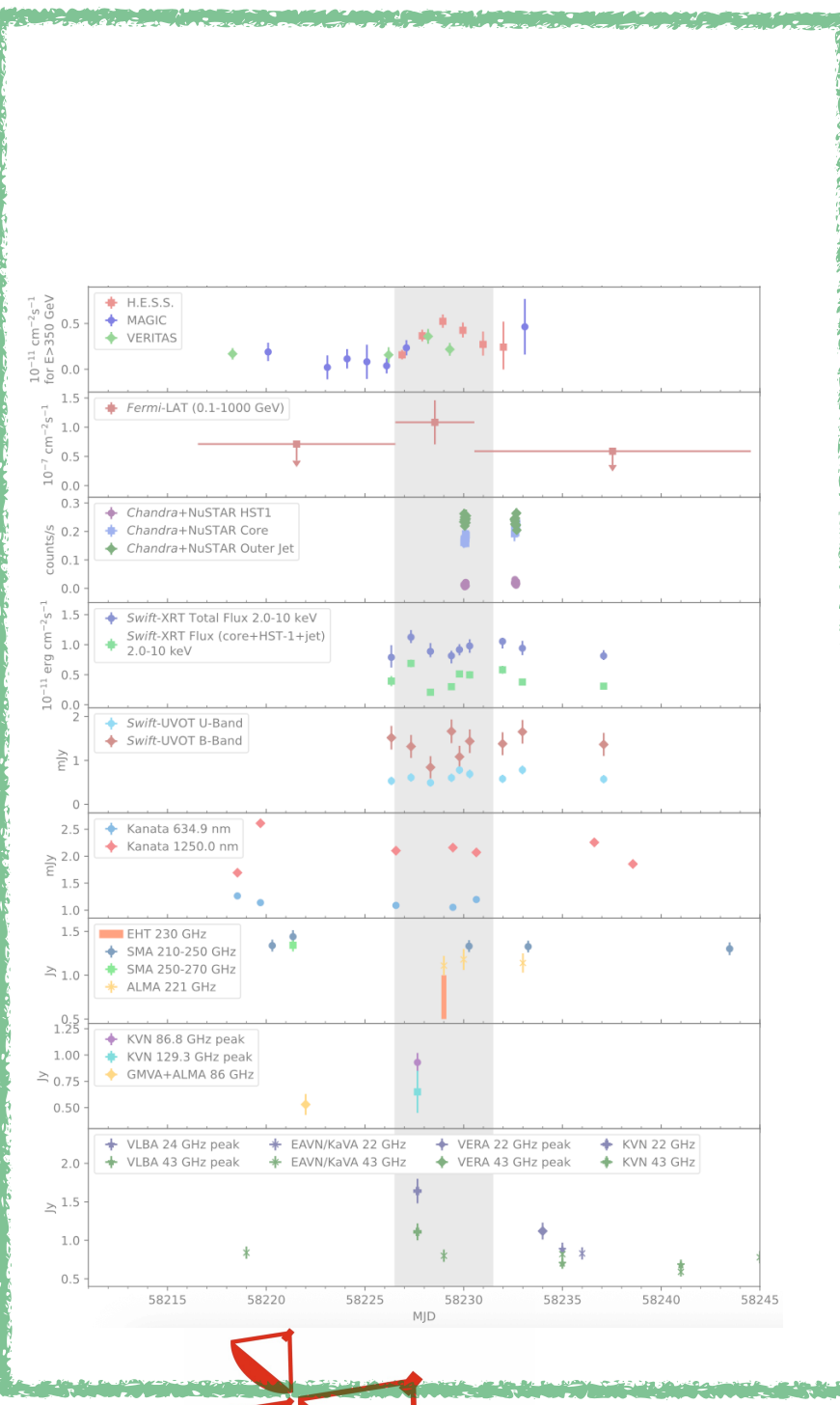
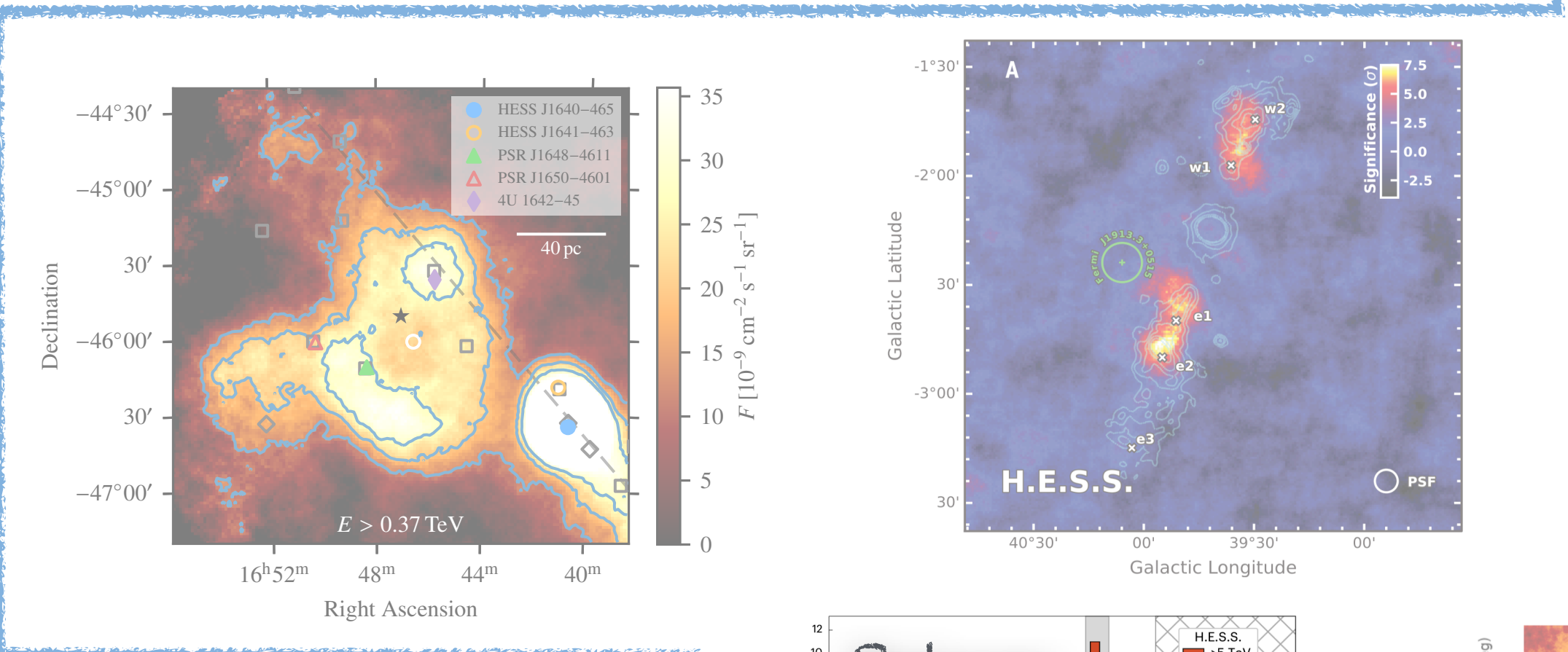
H.E.S.S. Science Coverage



H.E.S.S. Science Coverage



H.E.S.S. Science Coverage



- Discovery of a new radiation component from the Vela pulsar reaching 20 TeV
- Energy spectrum of pulsars usually drops steeply above ~10 GeV
- Only exception so far: Crab pulsar, with power-law tail to ~1 TeV
- 2018: emission up to 100 GeV from Vela detected with H.E.S.S.-CT5
- 2023: discovery of new spectral component, reaching 20 TeV – in phase with the lower-energy peak!
- Result severely constrains theoretical models

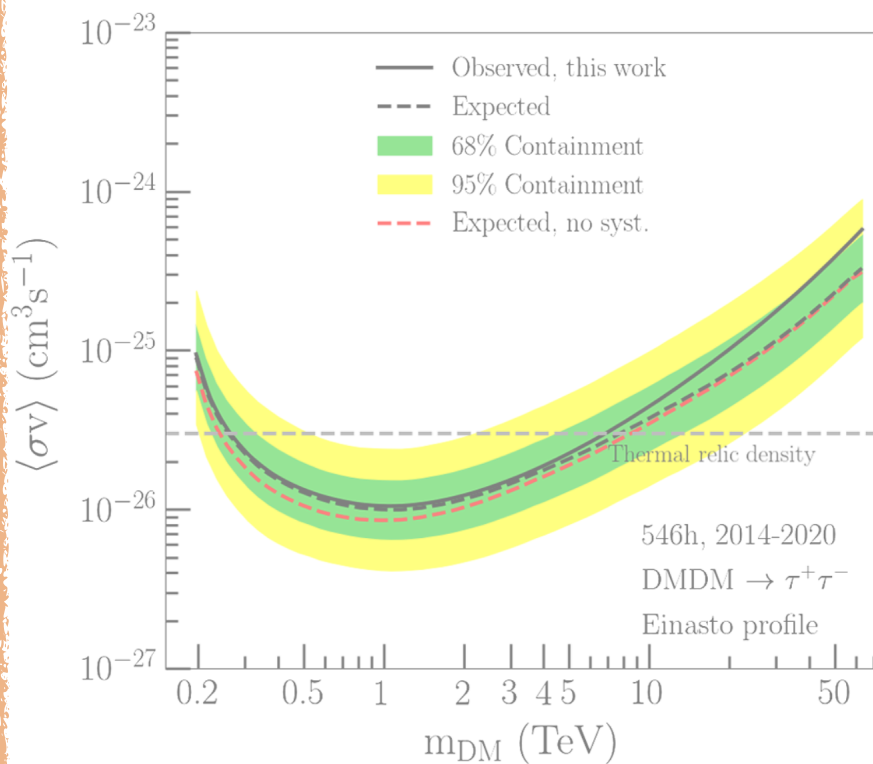
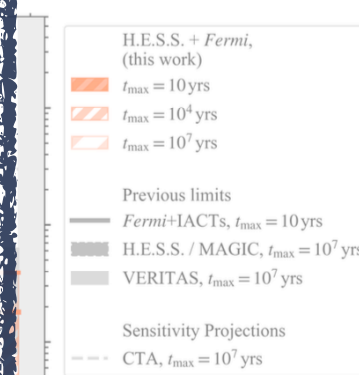
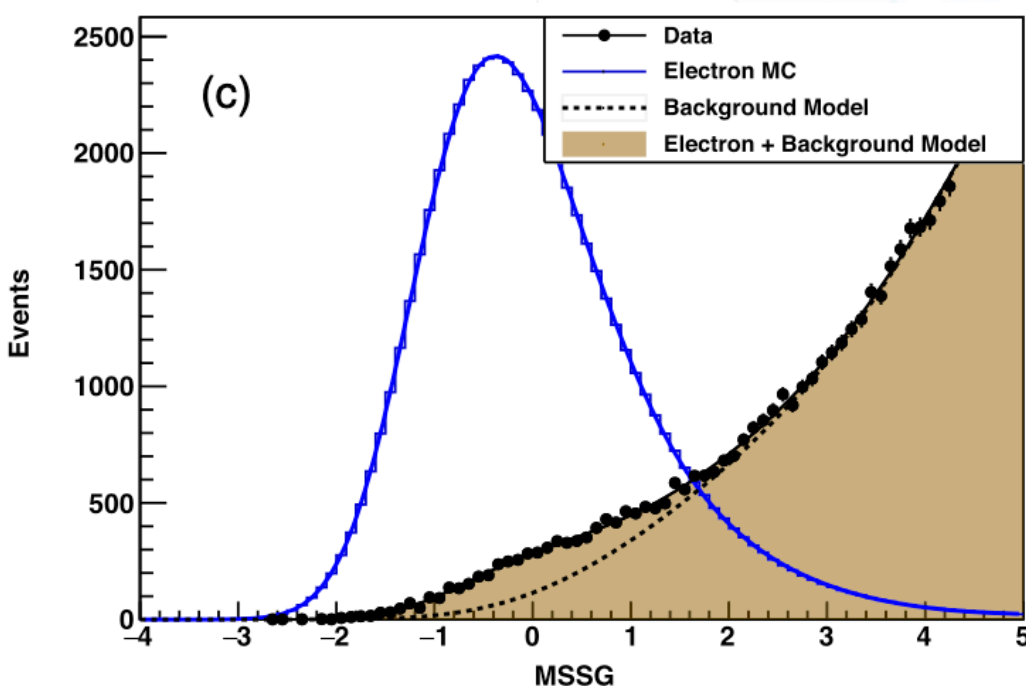
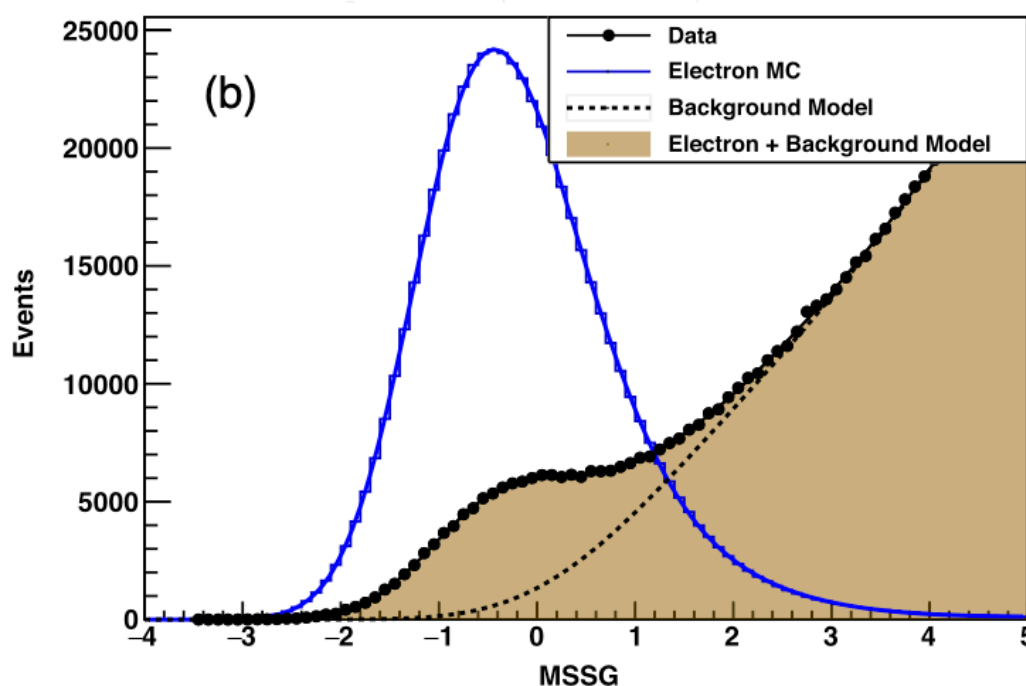
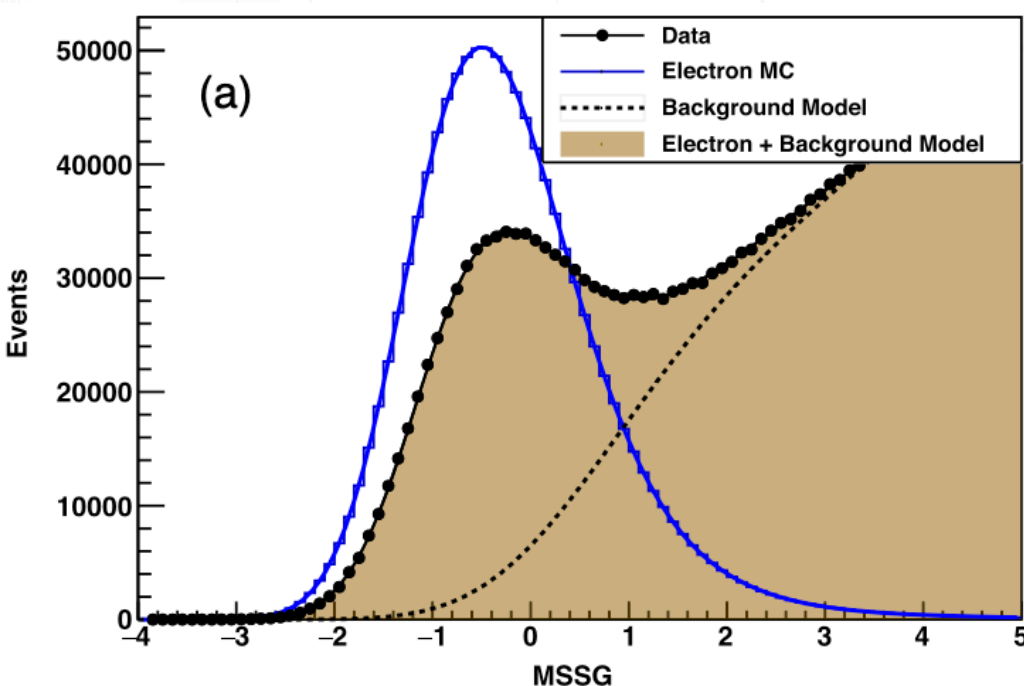
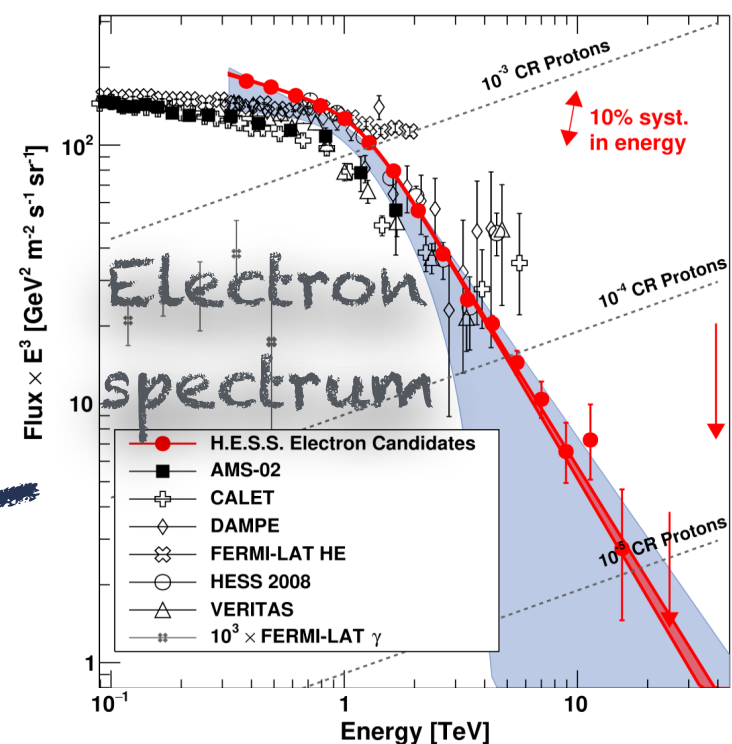
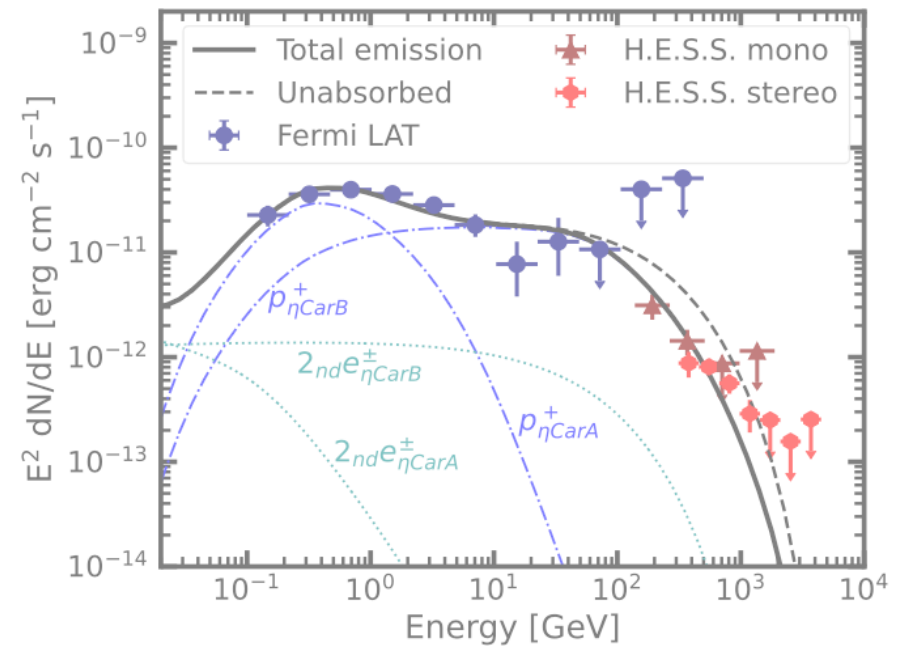
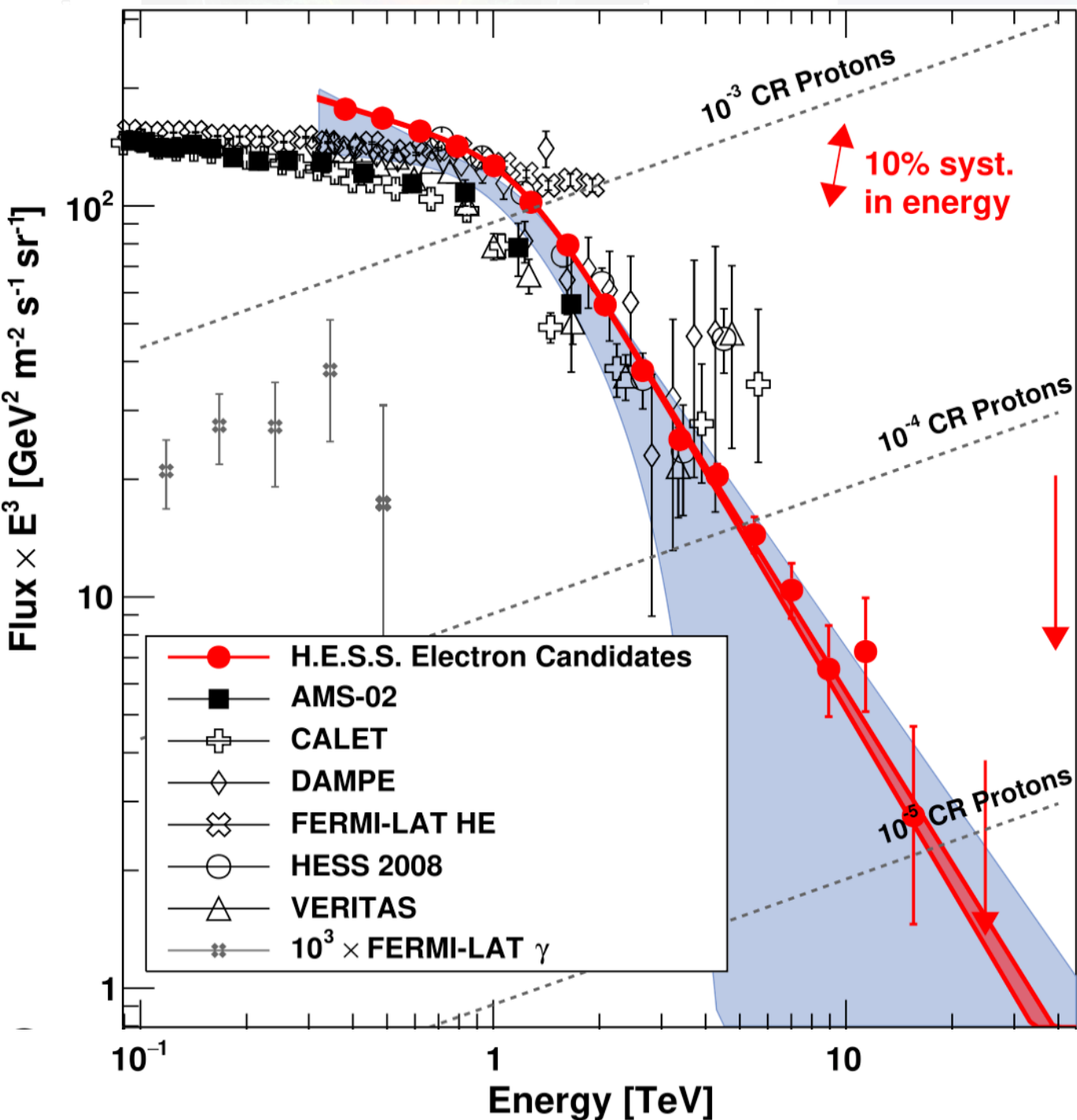


H.E.S.S. Science Coverage

High-statistics measurement of the cosmic-ray electron spectrum

- Electron-initiated air showers closely resemble gamma-ray initiated air showers
- Need very strong rejection of hadronic background
- Confirmation of spectral break at ~ 1 TeV
- Extension of spectrum to beyond 10 TeV
- No sign of an up-turn at high energies (would be expected from a nearby electron source)

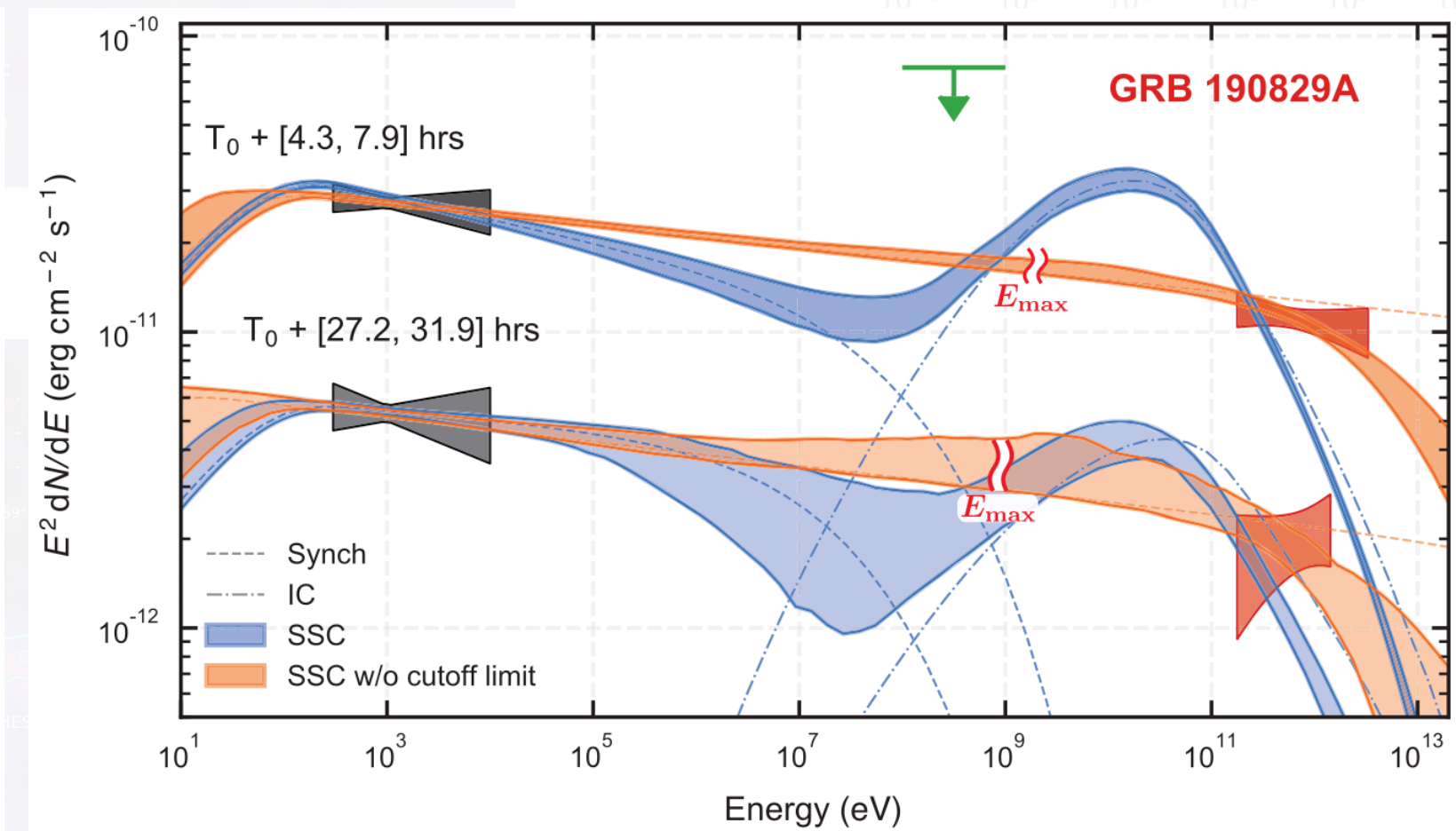
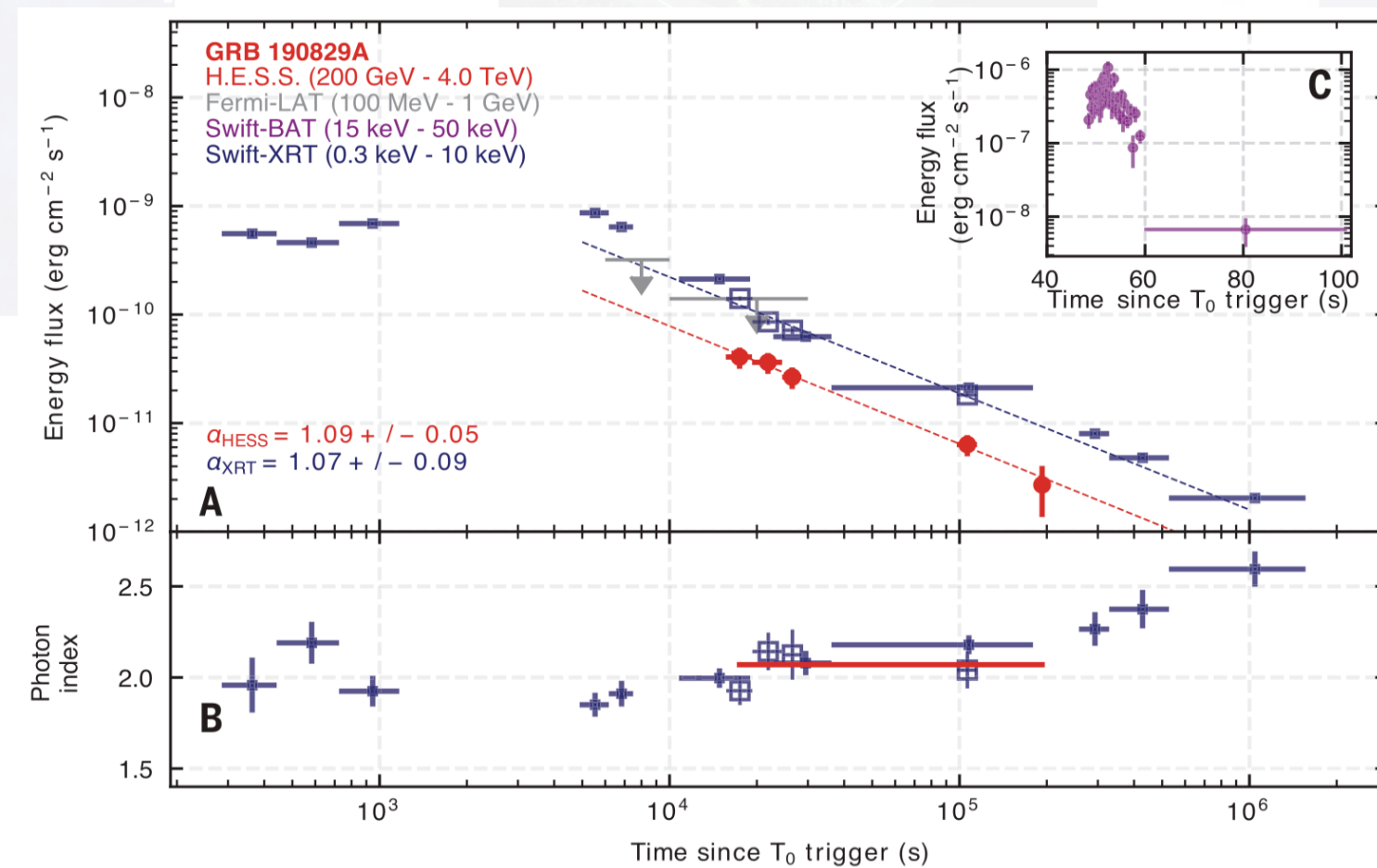
H.E.S.S. Collaboration
PRL 133, 221001 (2024)



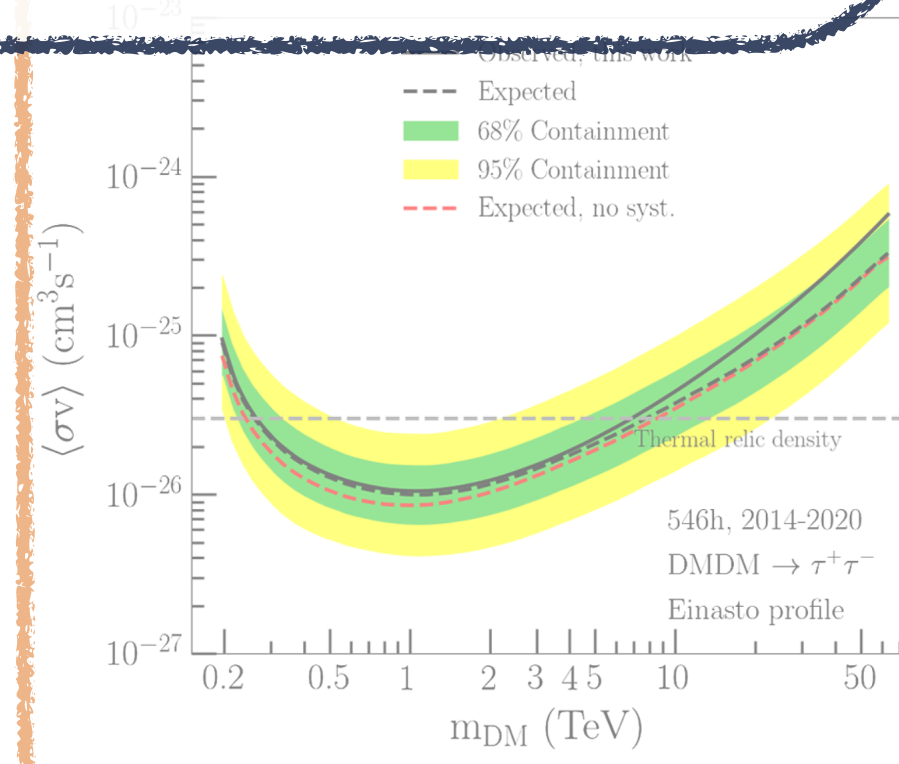
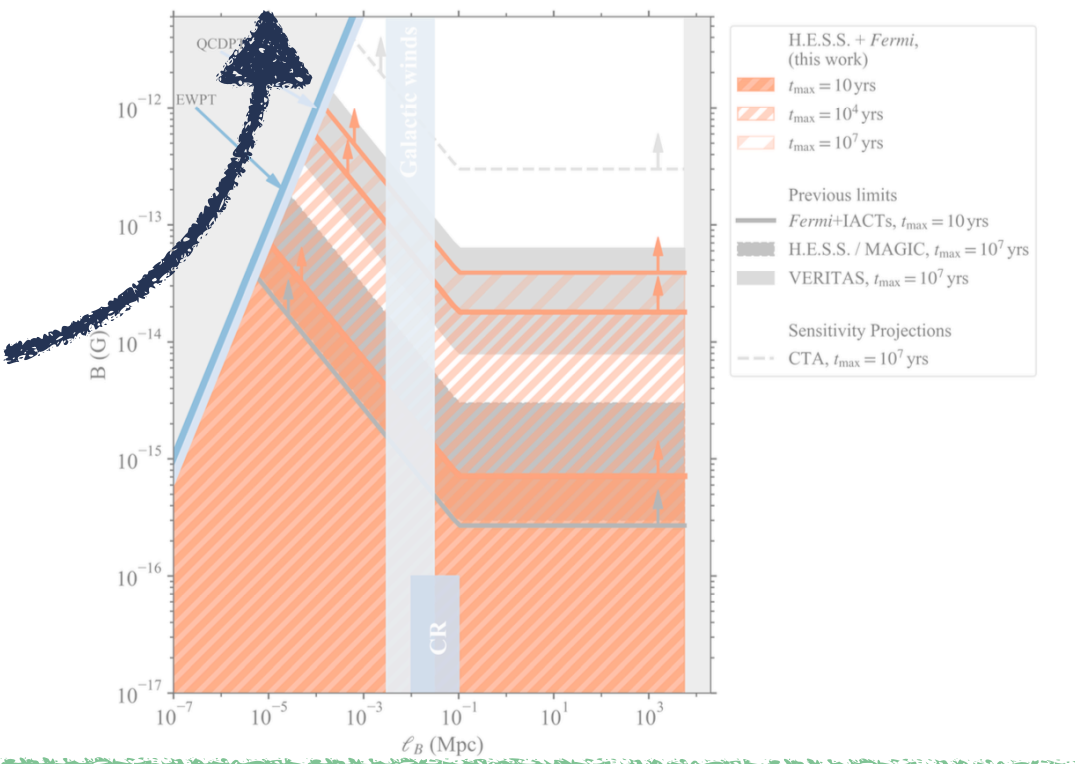
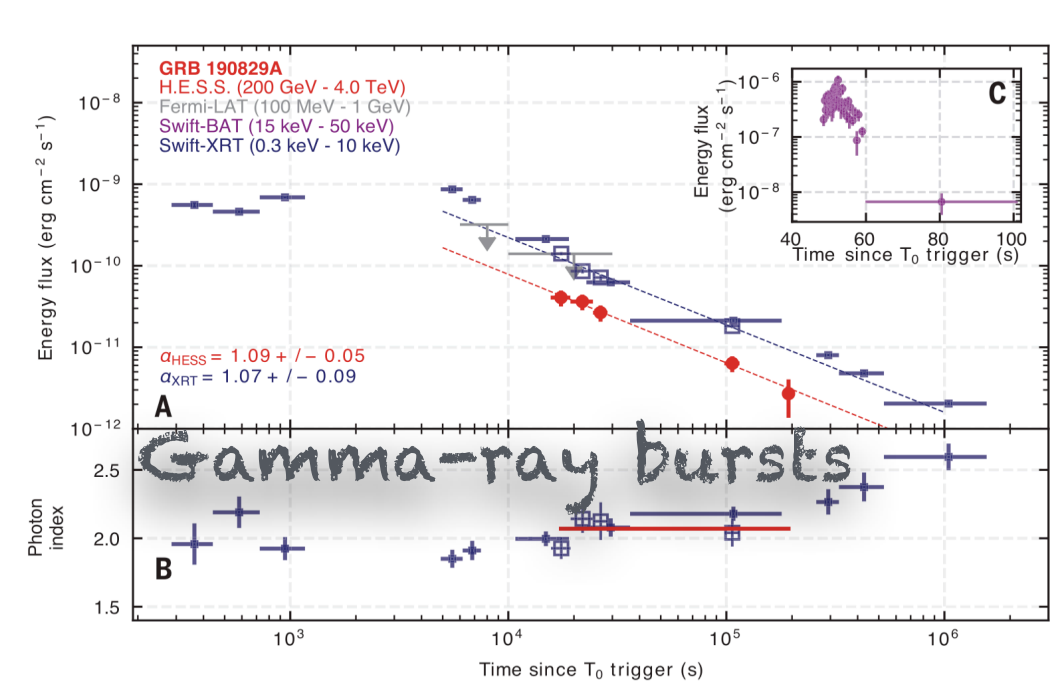
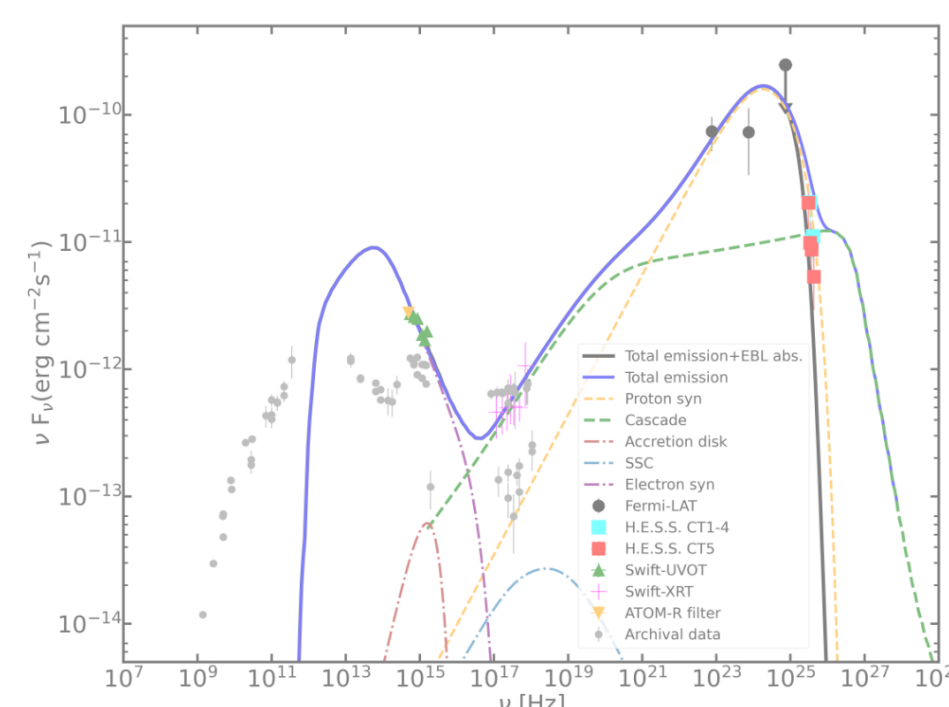
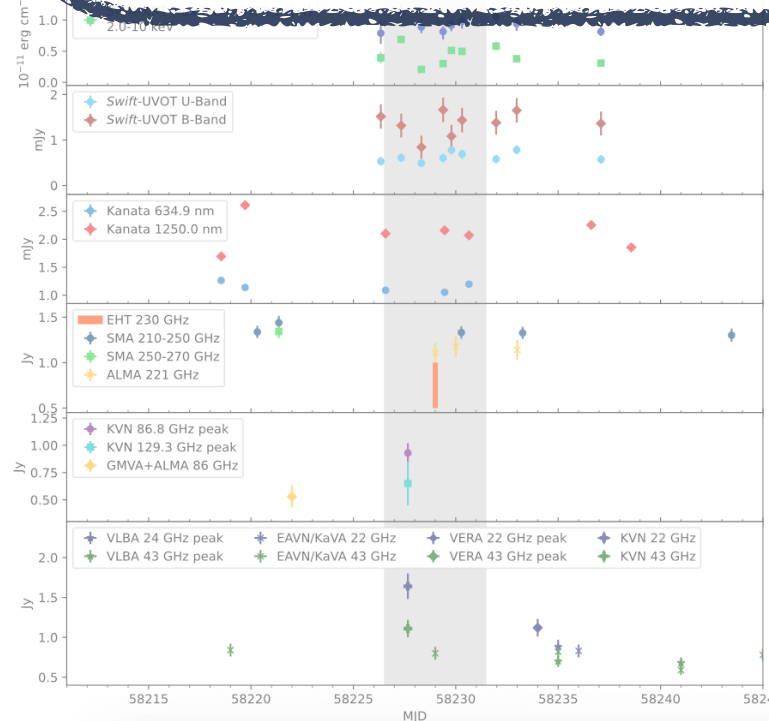
H.E.S.S. Science Coverage

Detection of GRB afterglow emission up to 56 hours after the burst

- GRB 180720B: first GRB detection with IACTs (after decades of searching)
- GRB 190829A: extremely nearby GRB (redshift $z = 0.0785$)
- Detection of afterglow emission in three consecutive nights
- Striking similarity in temporal and spectral behaviour of gamma-ray and X-ray signal
- Difficult to model with standard one-zone synchrotron self-Compton (SSC) model



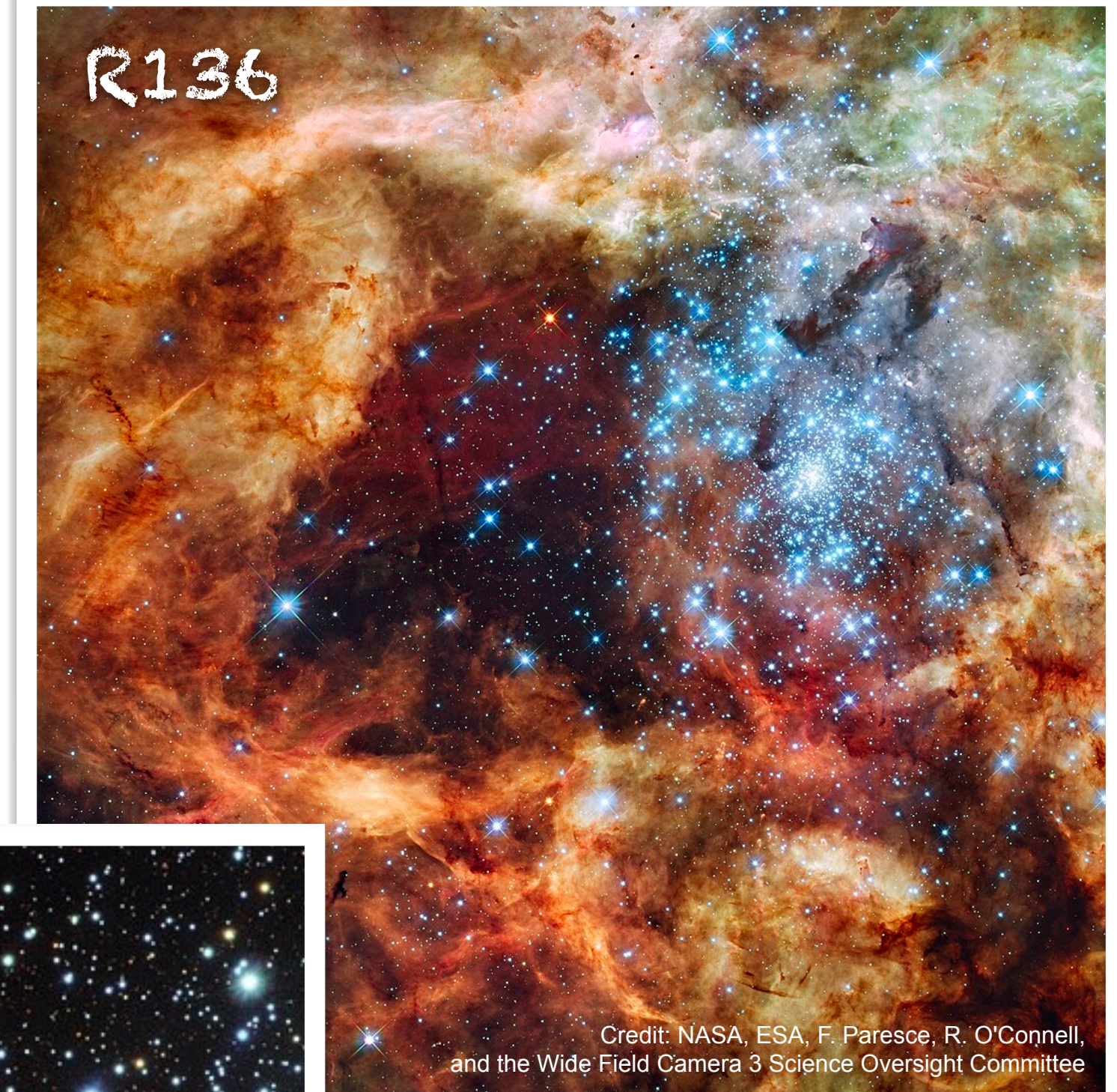
H.E.S.S. Collaboration
Science **372**, 1081 (2021)



Young massive star clusters

■ What are they?

- ▶ dense clusters of massive stars (O/B stars, Wolf-Rayet stars)
- ▶ total mass: $\gtrsim 10^4 M_{\odot}$
- ▶ compact clusters: $r \lesssim \text{few pc}$
- ▶ superimposed stellar winds + supernovae
→ can blow “superbubble” into the interstellar medium



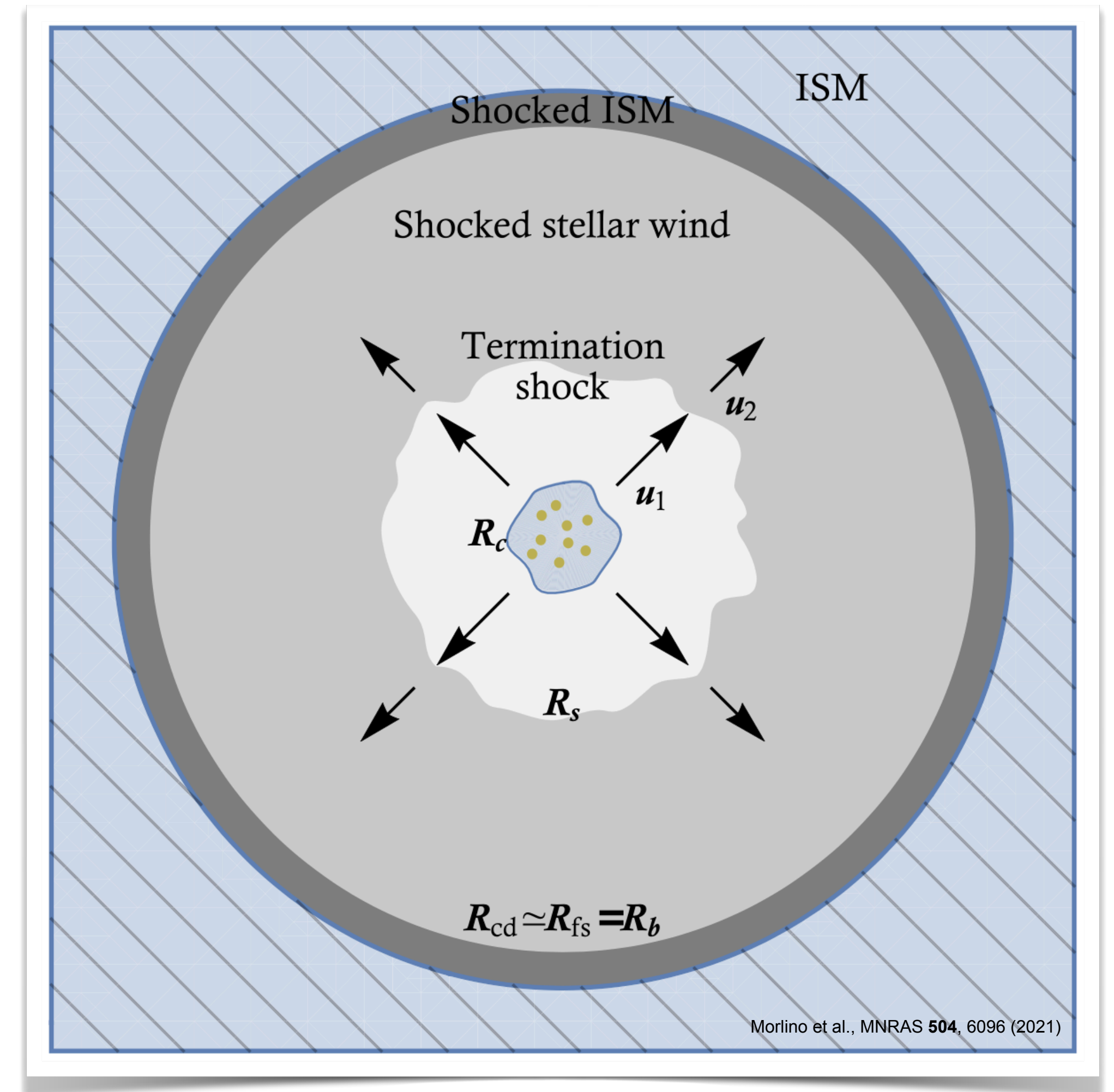
Young massive star clusters

■ What are they?

- ▶ dense clusters of massive stars (O/B stars, Wolf-Rayet stars)
- ▶ total mass: $\gtrsim 10^4 M_\odot$
- ▶ compact clusters: $r \lesssim \text{few pc}$
- ▶ superimposed stellar winds + supernovae
→ can blow “superbubble” into the interstellar medium

■ Why are they interesting for us?

- superbubble environments potentially are great for cosmic-ray acceleration
- ▶ wind/wind interactions inside cluster
- ▶ turbulence in shocked medium
- ▶ collective wind termination shock



"A deep spectromorphological study of the γ -ray emission surrounding the young massive stellar cluster Westerlund 1"

Astronomy & Astrophysics 666, A124 (2022)

A deep spectromorphological study of the γ -ray emission surrounding the young massive stellar cluster Westerlund 1

F. Aharonian^{1,2}, H. Ashkar³, M. Backes^{4,5}, V. Barbosa Martins⁶, Y. Becherini^{7,8}, D. Berge^{6,9}, B. Bi¹⁰, M. Böttcher⁵, M. de Bony de Lavergne¹¹, F. Bradascio¹², R. Brose¹, F. Brun¹², T. Bulik¹³, C. Burger-Scheidlin¹, F. Cangemi¹⁴, S. Caroff¹⁴, S. Casanova¹⁵, M. Cerruti⁷, T. Chand⁵, S. Chandra⁵, A. Chen¹⁶, O. Chibueze⁷, P. Cristofari¹⁷, J. Damascene Mbarubucyeye⁶, A. Djannati-Atai⁷, J.-P. Ernenwein¹⁸, K. Feijen¹⁹, G. Fichtel de Clairfontaine¹⁷, G. Fontaine³, S. Funk²⁰, S. Gabici⁷, Y. A. Gallant²¹, S. Ghafourizadeh²², G. Giavitto⁶, L. Giunti^{7,12}, D. Glawion²⁰, J. F. Glicenstein¹², P. Goswami⁵, M.-H. Grondin²³, L. K. Härer², M. Haupt⁶, J. A. Hinton², M. Hörbe²⁴, W. Hofmann², T. L. Holch⁶, M. Holler²⁵, D. Horns²⁶, M. Jamroz²⁷, V. Joshi²⁰, I. Jung-Richard²⁰, E. Kasai⁴, K. Katarzyński²⁸, U. Katz²⁰, B. Khélifi⁷, W. Kluźniak²⁹, Nu. Komin¹⁶, K. Kosack¹², D. Kostunin⁶, G. Kućek Mezek⁸, R. G. Lang²⁰, S. Le Stum¹⁸, A. Lemièr⁷, M. Lemoine-Goumard²³, J.-P. Lenain¹⁴, F. Leuschner¹⁰, T. Lohse⁹, A. Luashvili¹⁷, I. Lypova²², J. Mackey¹, J. Majumdar⁶, D. Malyshev²⁰, V. Marandon², P. Marchegiani¹⁶, A. Marcowith²¹, G. Martí-Devesa²⁵, R. Marx²², G. Maurin¹¹, M. Meyer²⁶, A. Mitchell^{20,2}, R. Moderski²⁹, L. Mohrmann^{2,*}, A. Montanari¹², E. Moulin¹², J. Müller³, T. Murach⁶, K. Nakashima²⁰, M. de Naurois³, A. Nayerhoda¹⁵, J. Niemiec¹⁵, S. Ohm^{6,*}, L. Olivera-Nieto², E. de Ona Wilhelmi⁶, M. Ostrowski²⁷, S. Panny²⁵, M. Panter², R. D. Parsons⁹, G. Peron², D. A. Prokhorov³⁰, G. Pühlhofer¹⁰, M. Punch^{7,8}, A. Quirrenbach²², R. Rauth^{25,*}, P. Reichherzer¹², A. Reimer²⁵, O. Reimer²⁵, M. Renaud²¹, B. Reville², F. Rieger², G. Rowell¹⁹, B. Rudak²⁹, E. Ruiz-Velasco², V. Sahakian³¹, H. Salzmann¹⁰, D. A. Sanchez¹¹, A. Santangelo¹⁰, M. Sasaki²⁰, F. Schüssler¹², H. M. Schutte⁵, U. Schwanke⁹, J. N. S. Shapopi⁴, A. Specovius^{20,*}, S. Spencer²⁴, Ł. Stawarz²⁷, R. Steenkamp⁴, S. Steinmassl², C. Steppa³², I. Sushch⁵, H. Suzuki³³, T. Takahashi³⁴, T. Tanaka³³, R. Terrier⁷, C. Thorpe-Morgan¹⁰, M. Tsirou², N. Tsuji³⁵, R. Tuffs², T. Unbehaun²⁰, C. van Eldik²⁰, B. van Soelen³⁶, M. Vecchi³⁰, J. Veh²⁰, C. Venter⁵, J. Vink³⁰, S. J. Wagner²², R. White², A. Wiercholska¹⁵, Y. Wun Wong²⁰, M. Zacharias^{17,5}, D. Zargaryan¹, A. A. Zdziarski²⁹, S. J. Zhu⁶, S. Zouari⁷, N. Żywucka⁵ (H.E.S.S. Collaboration), R. Blackwell¹⁹, C. Braiding³⁷, M. Burton³⁸, K. Cubuk³⁸, M. Filipović³⁹, N. Tothill³⁹, and G. Wong³⁹

(Affiliations can be found after the references)

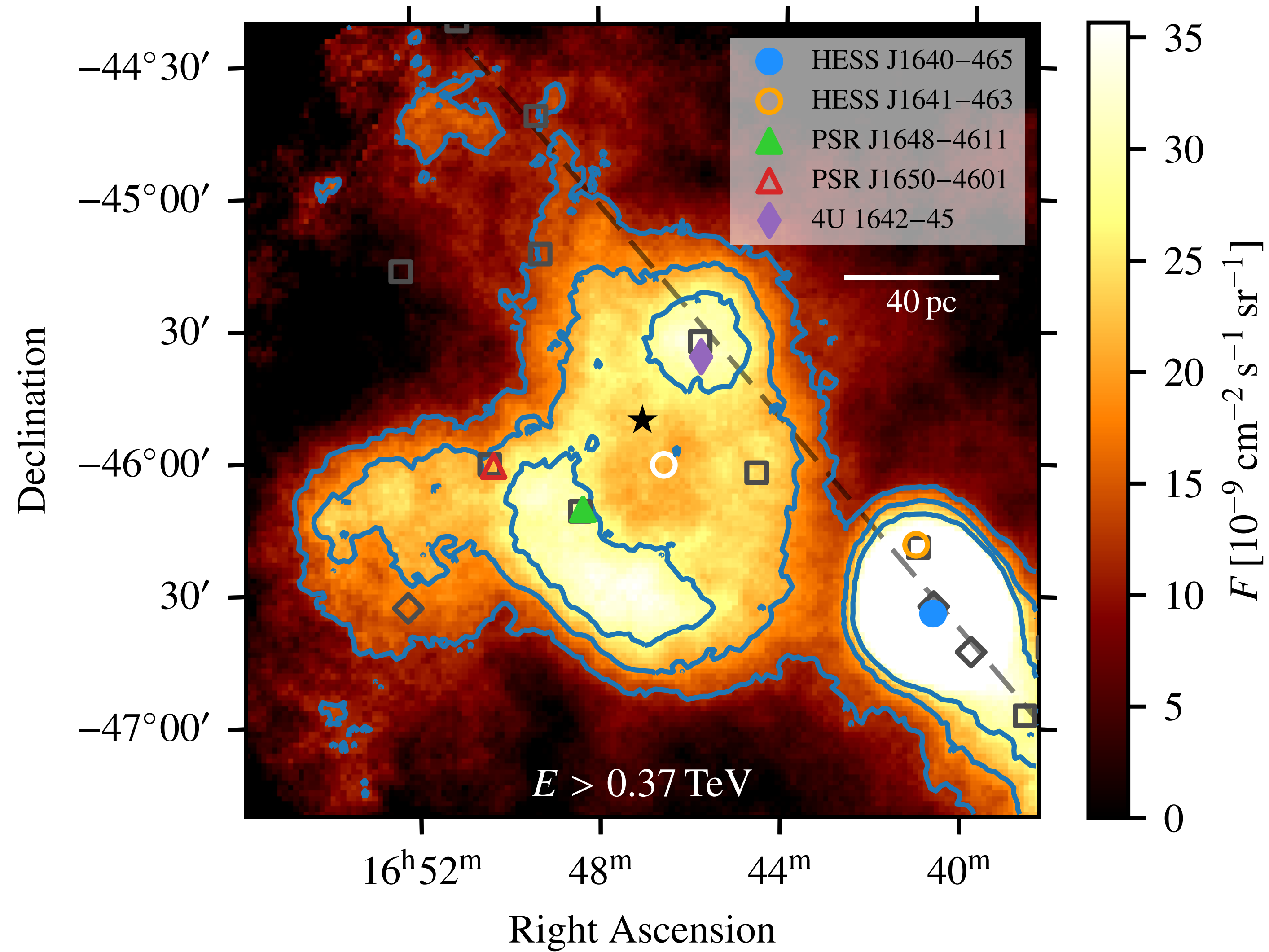
Received 22 June 2022 / Accepted 21 July 2022

ABSTRACT

Context. Young massive stellar clusters are extreme environments and potentially provide the means for efficient particle acceleration. Indeed, they are increasingly considered as being responsible for a significant fraction of cosmic rays (CRs) that are accelerated within the Milky Way. Westerlund 1, the most massive known young stellar cluster in our Galaxy, is a prime candidate for studying this hypothesis. While the very-high-energy γ -ray source HESS J1646–458 has been detected in the vicinity of Westerlund 1 in the past, its association could not be firmly identified. **Aims.** We aim to identify the physical processes responsible for the γ -ray emission around Westerlund 1 and thus to understand the role of massive stellar clusters in the acceleration of Galactic CRs better. **Methods.** Using 164 h of data recorded with the High Energy Stereoscopic System (H.E.S.S.), we carried out a deep spectromorphological study of the γ -ray emission of HESS J1646–458. We furthermore employed H I and CO observations of the region to infer the presence of gas that could serve as target material for interactions of accelerated CRs. **Results.** We detected large-scale ($\sim 2^\circ$ diameter) γ -ray emission with a complex morphology, exhibiting a shell-like structure and showing no significant variation with γ -ray energy. The combined energy spectrum of the emission extends to several tens of TeV, and it is uniform across the entire source region. We did not find a clear correlation of the γ -ray emission with gas clouds as identified through H I and CO observations. **Conclusions.** We conclude that, of the known objects within the region, only Westerlund 1 can explain the majority of the γ -ray emission. Several CR acceleration sites and mechanisms are conceivable and discussed in detail. While it seems clear that Westerlund 1 acts as a powerful particle accelerator, no firm conclusions on the contribution of massive stellar clusters to the flux of Galactic CRs in general can be drawn at this point. **Key words.** acceleration of particles – radiation mechanisms: non-thermal – shock waves – stars: massive – gamma rays: general – galaxies: star clusters: individual: Westerlund 1

* Corresponding authors; e-mail: contact.hess@hess-experiment.eu

Westerlund 1

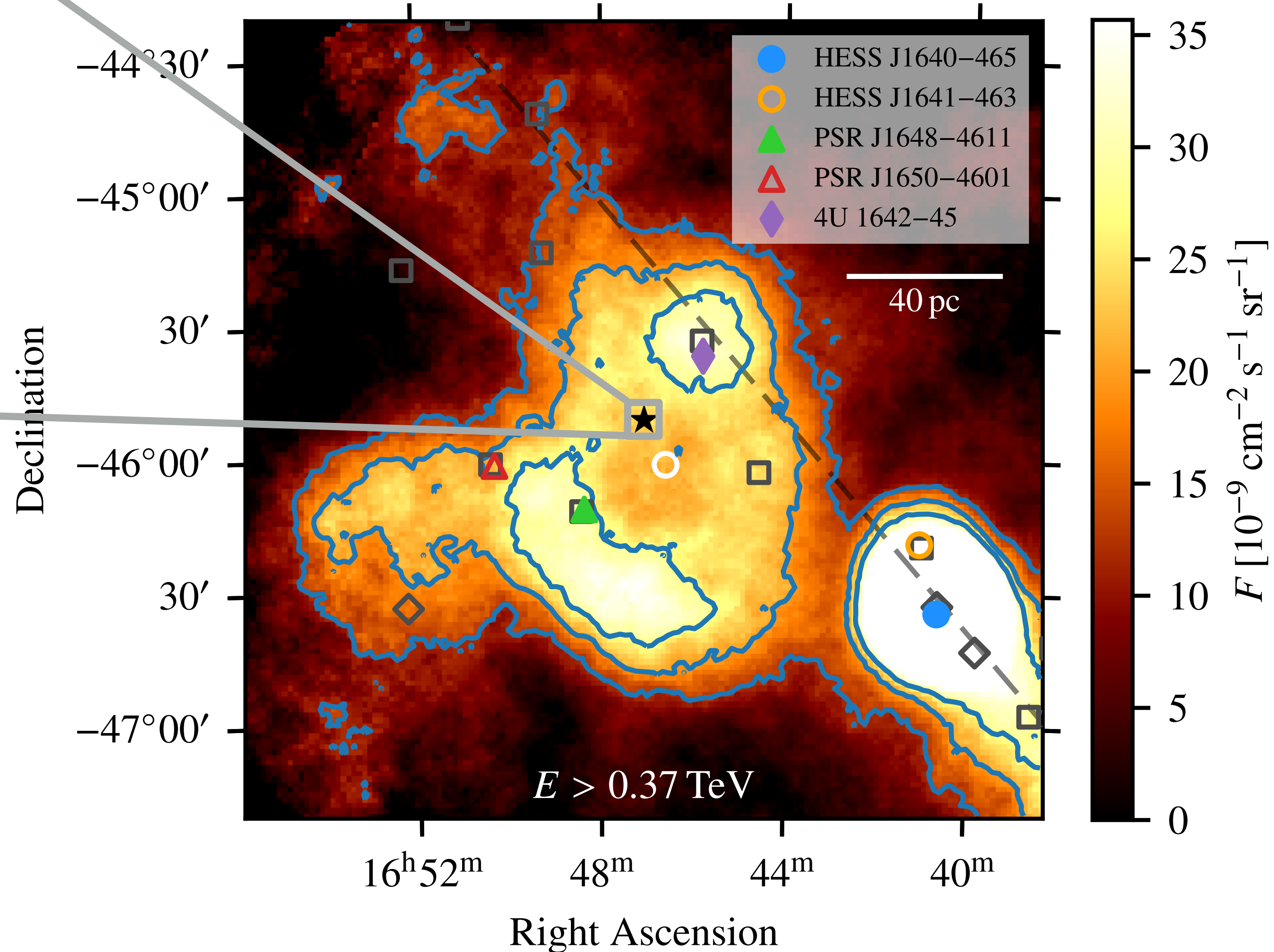


Westerlund 1



■ Westerlund 1

- ▶ most massive young star cluster in Galaxy
- ▶ $M \sim 10^5 M_{\odot}$
- ▶ half-mass radius ~ 1 pc
- ▶ age $\sim 3 - 5$ Myr
- ▶ distance ~ 4 kpc

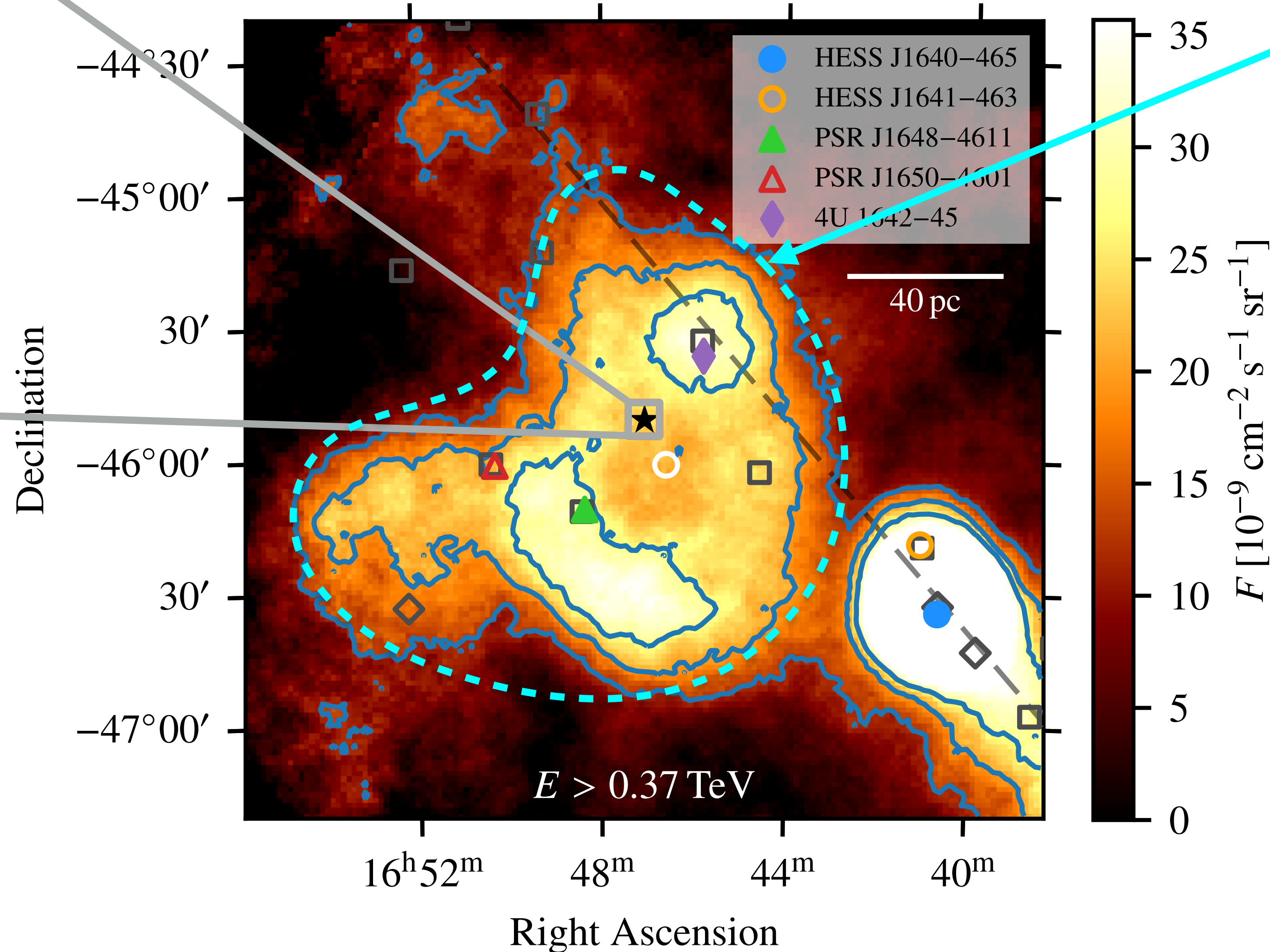


Westerlund 1



■ Westerlund 1

- ▶ most massive young star cluster in Galaxy
- ▶ $M \sim 10^5 M_{\odot}$
- ▶ half-mass radius ~ 1 pc
- ▶ age $\sim 3 - 5$ Myr
- ▶ distance ~ 4 kpc



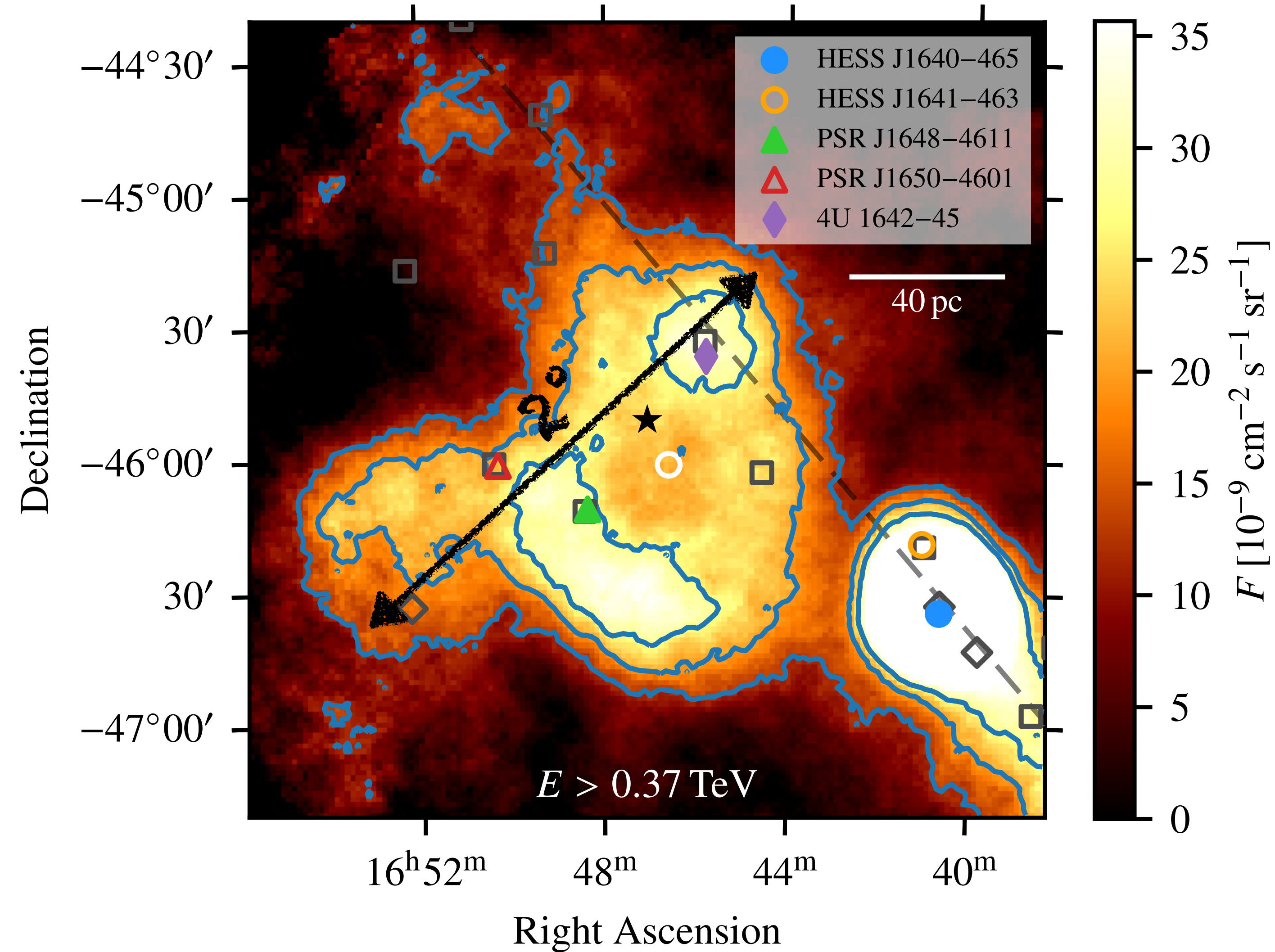
■ HESS J1646-458

- ▶ largely extended γ -ray source
- ▶ very likely associated with Westerlund 1

Westerlund 1

■ Source extent

- ▶ diameter $\sim 2^\circ$ (140 pc)
- ▶ 100 $\times$ larger than cluster itself!



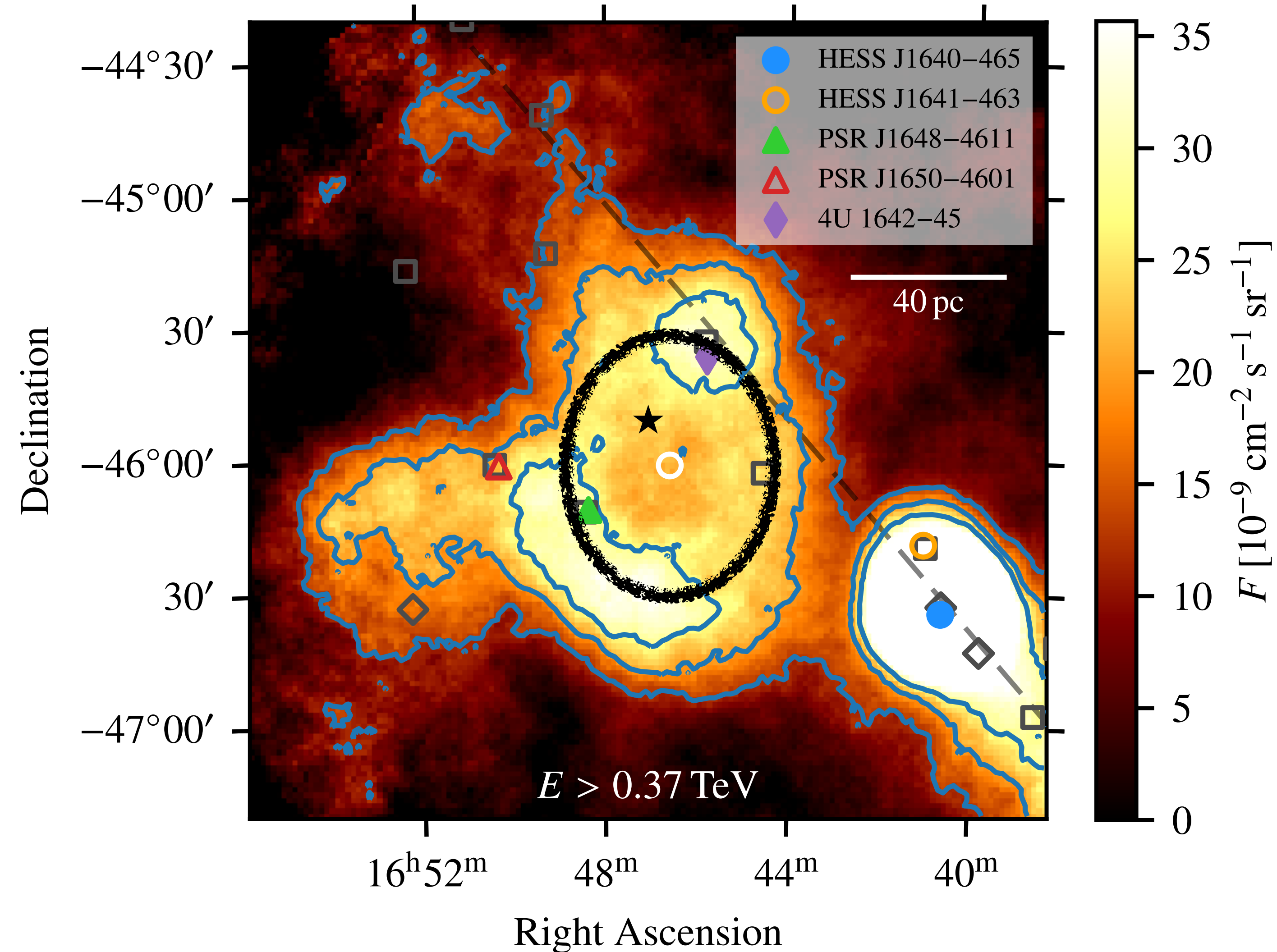
Westerlund 1

■ Source extent

- ▶ diameter $\sim 2^\circ$ (140 pc)
- ▶ 100 $\times$ larger than cluster itself!

■ Source morphology

- ▶ γ -ray emission does not peak at cluster position
- ▶ ring-like structure with Westerlund 1 near centre!
- ▶ several bright spots along the ring



Westerlund 1

■ Source extent

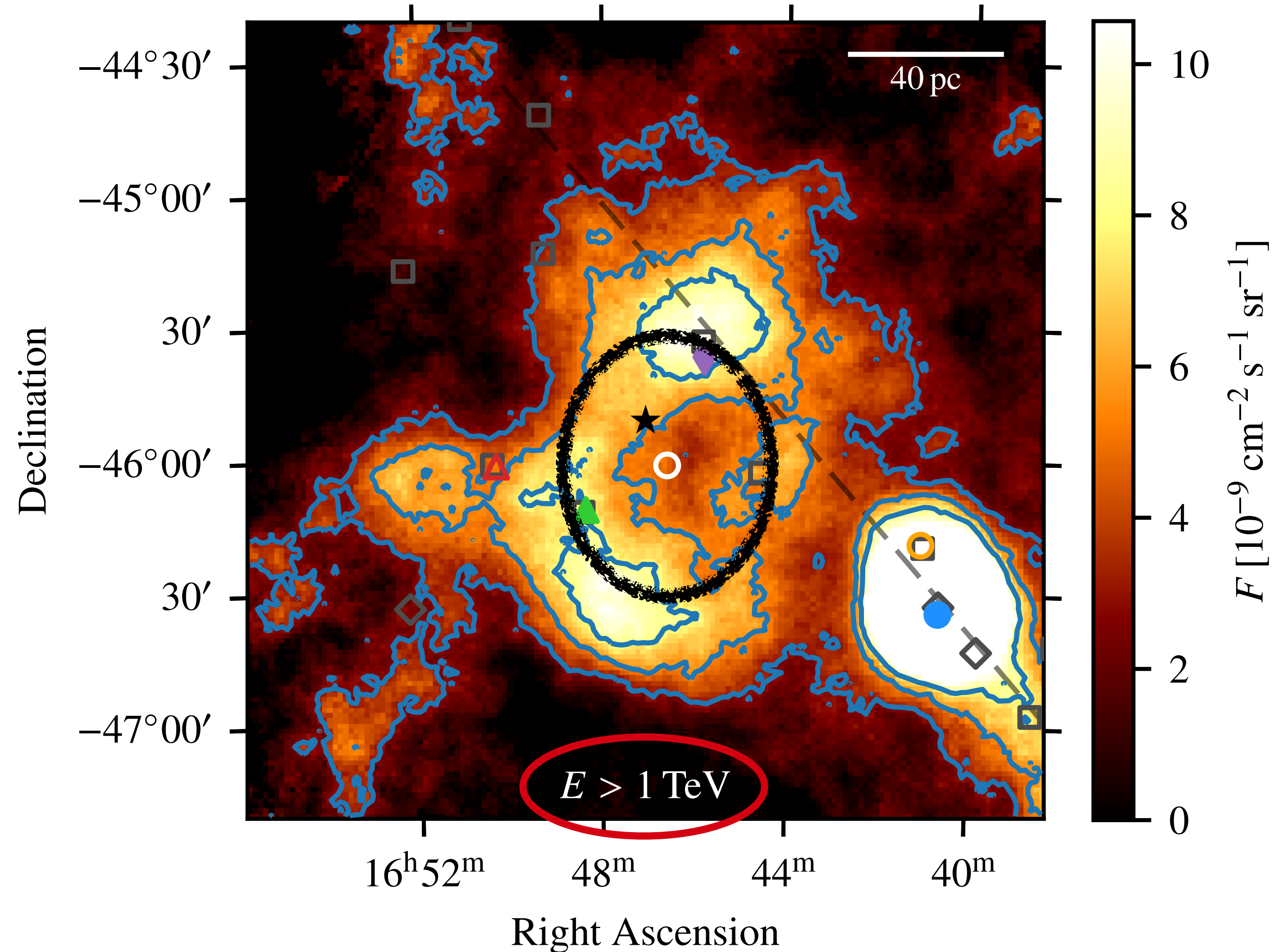
- ▶ diameter $\sim 2^\circ$ (140 pc)
- ▶ 100 $\times$ larger than cluster itself!

■ Source morphology

- ▶ γ -ray emission does not peak at cluster position
- ▶ ring-like structure with Westerlund 1 near centre!
- ▶ several bright spots along the ring

■ Energy dependence?

- ▶ bright spots remain
- ▶ ring-like structure persists!



Westerlund 1

■ Source extent

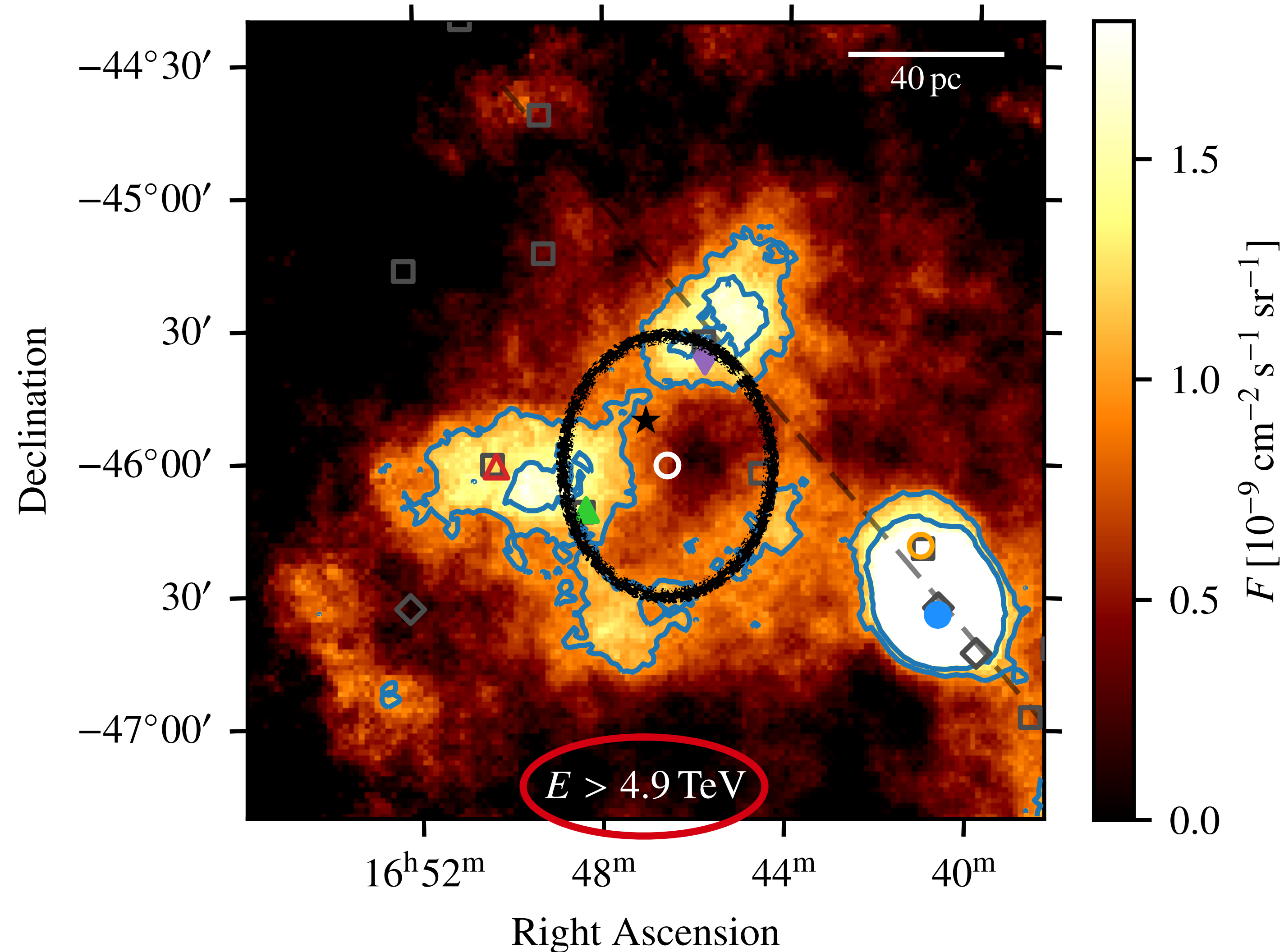
- ▶ diameter $\sim 2^\circ$ (140 pc)
- ▶ 100 $\times$ larger than cluster itself!

■ Source morphology

- ▶ γ -ray emission does not peak at cluster position
- ▶ ring-like structure with Westerlund 1 near centre!
- ▶ several bright spots along the ring

■ Energy dependence?

- ▶ bright spots remain
- ▶ ring-like structure persists!



Westerlund 1

■ Source extent

- ▶ diameter $\sim 2^\circ$ (140 pc)
- ▶ 100 $\times$ larger than cluster itself!

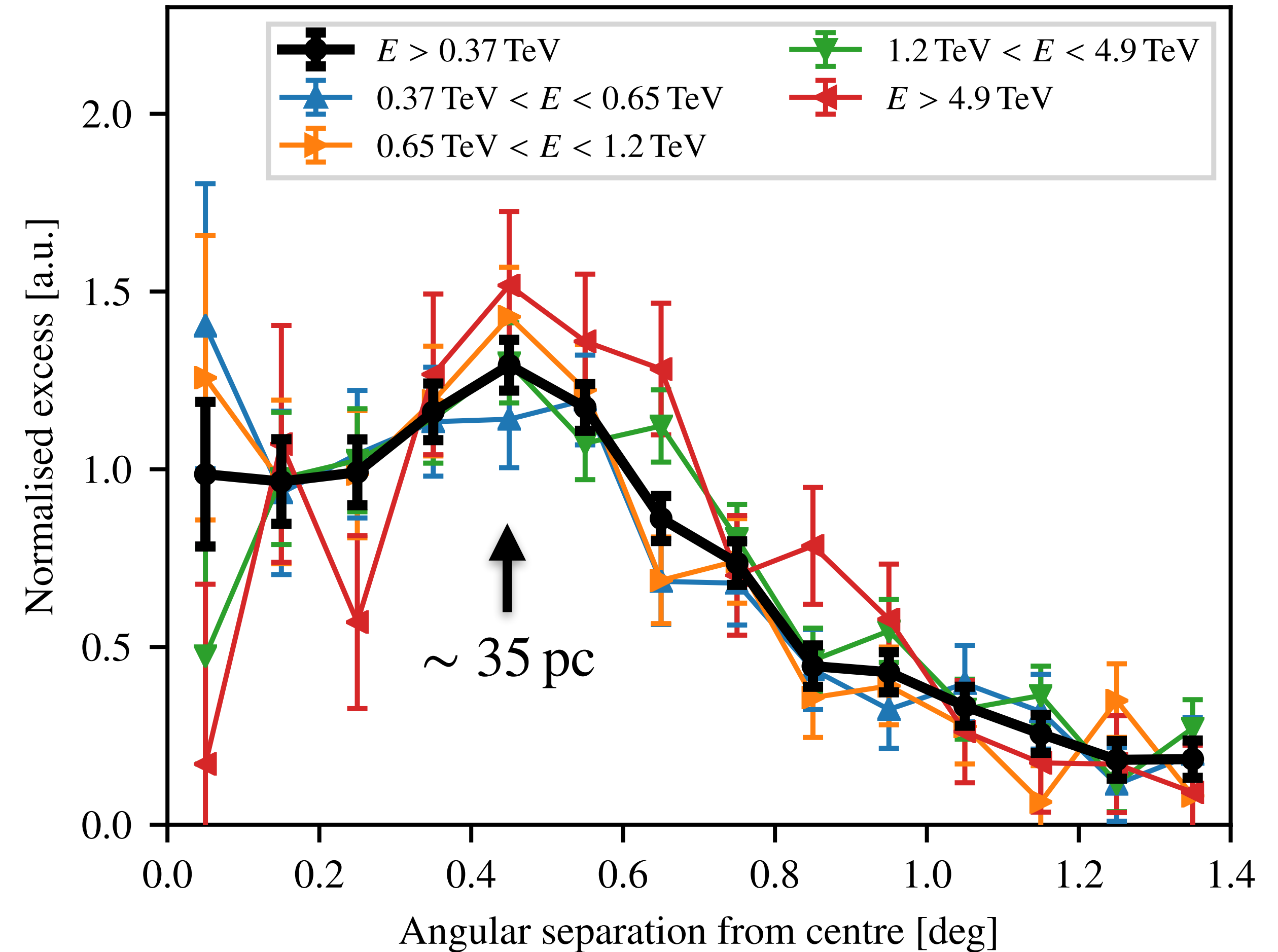
■ Source morphology

- ▶ γ -ray emission does not peak at cluster position
- ▶ ring-like structure with Westerlund 1 near centre!
- ▶ several bright spots along the ring

■ Energy dependence?

- ▶ bright spots remain
- ▶ ring-like structure persists!

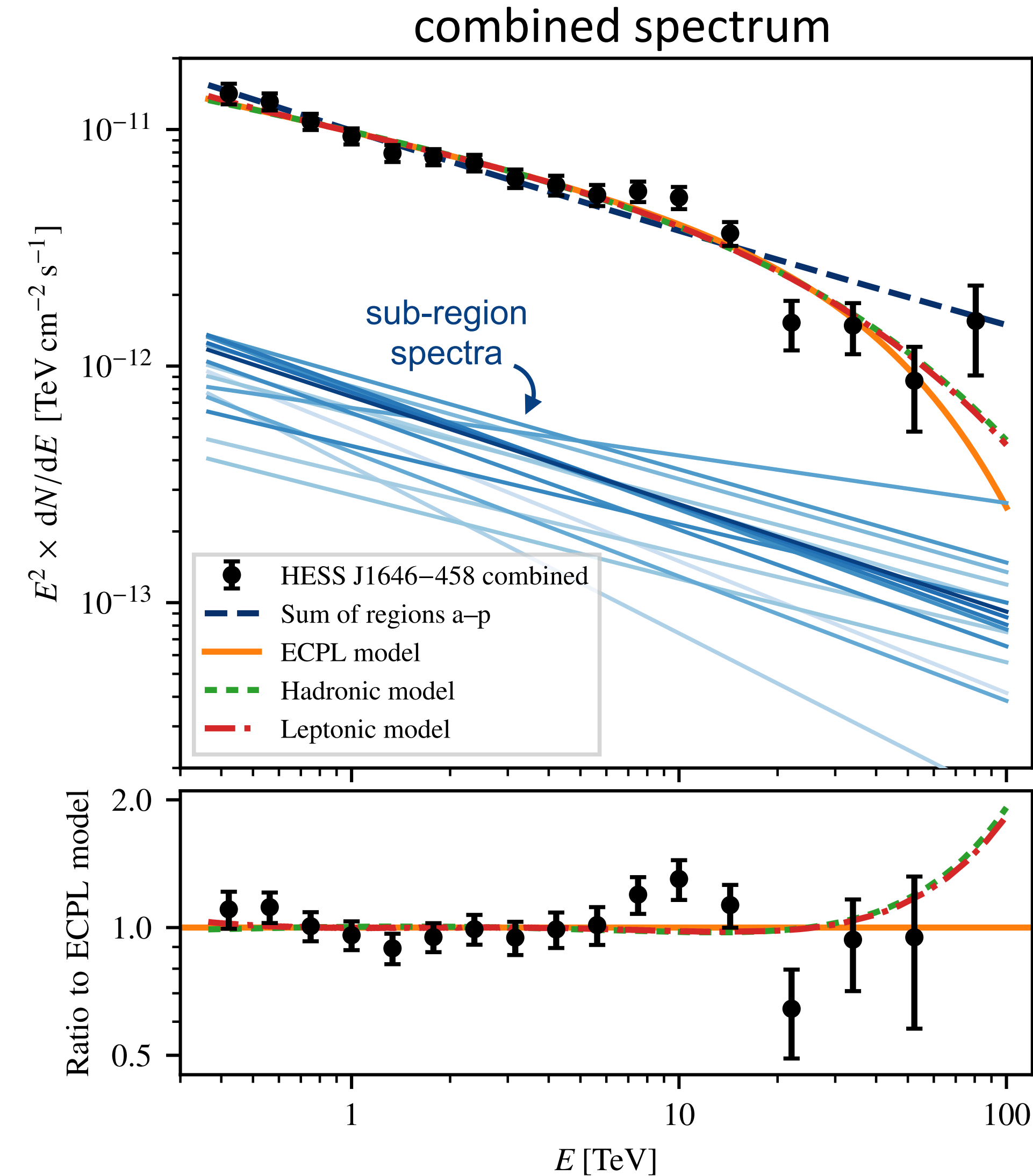
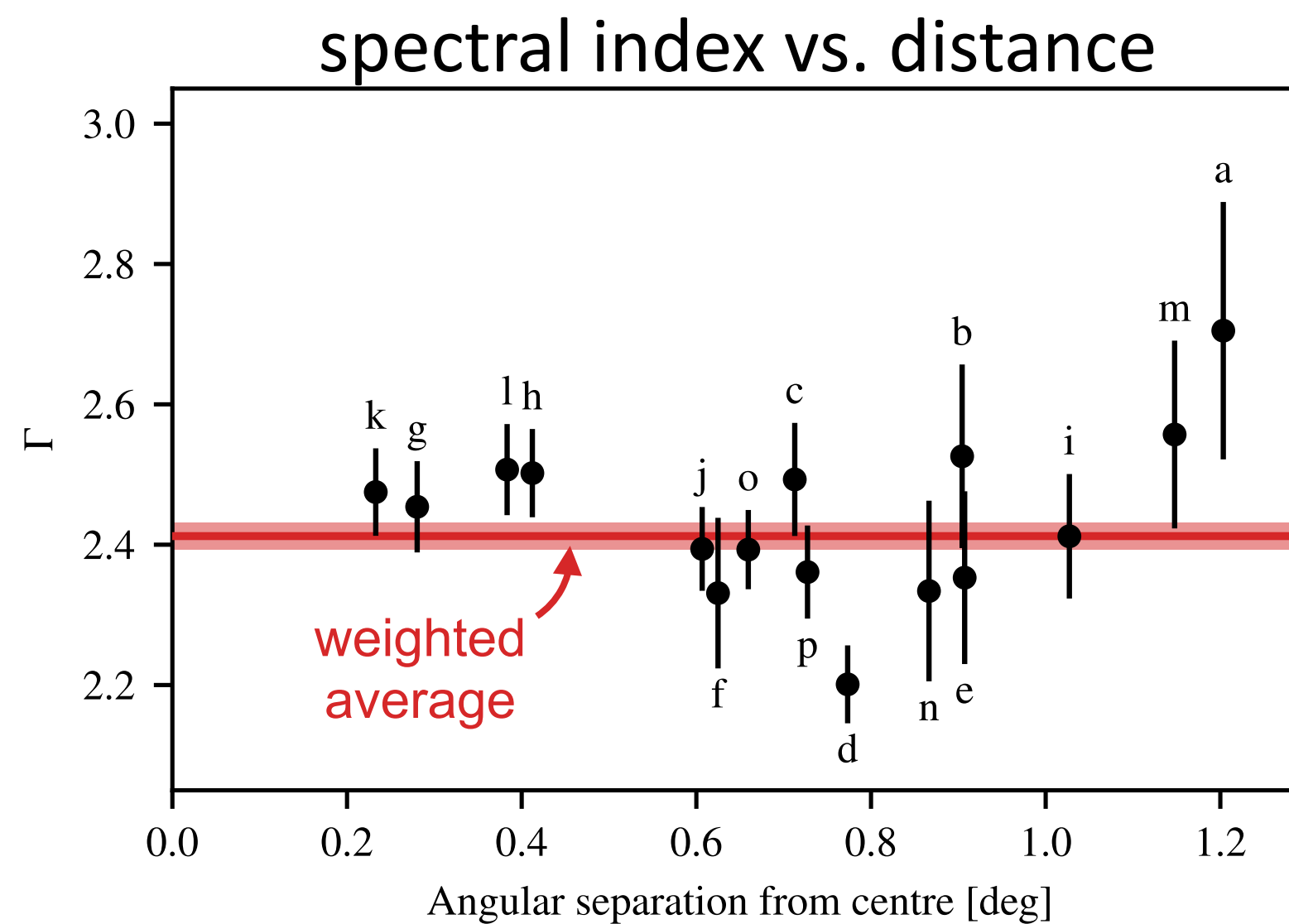
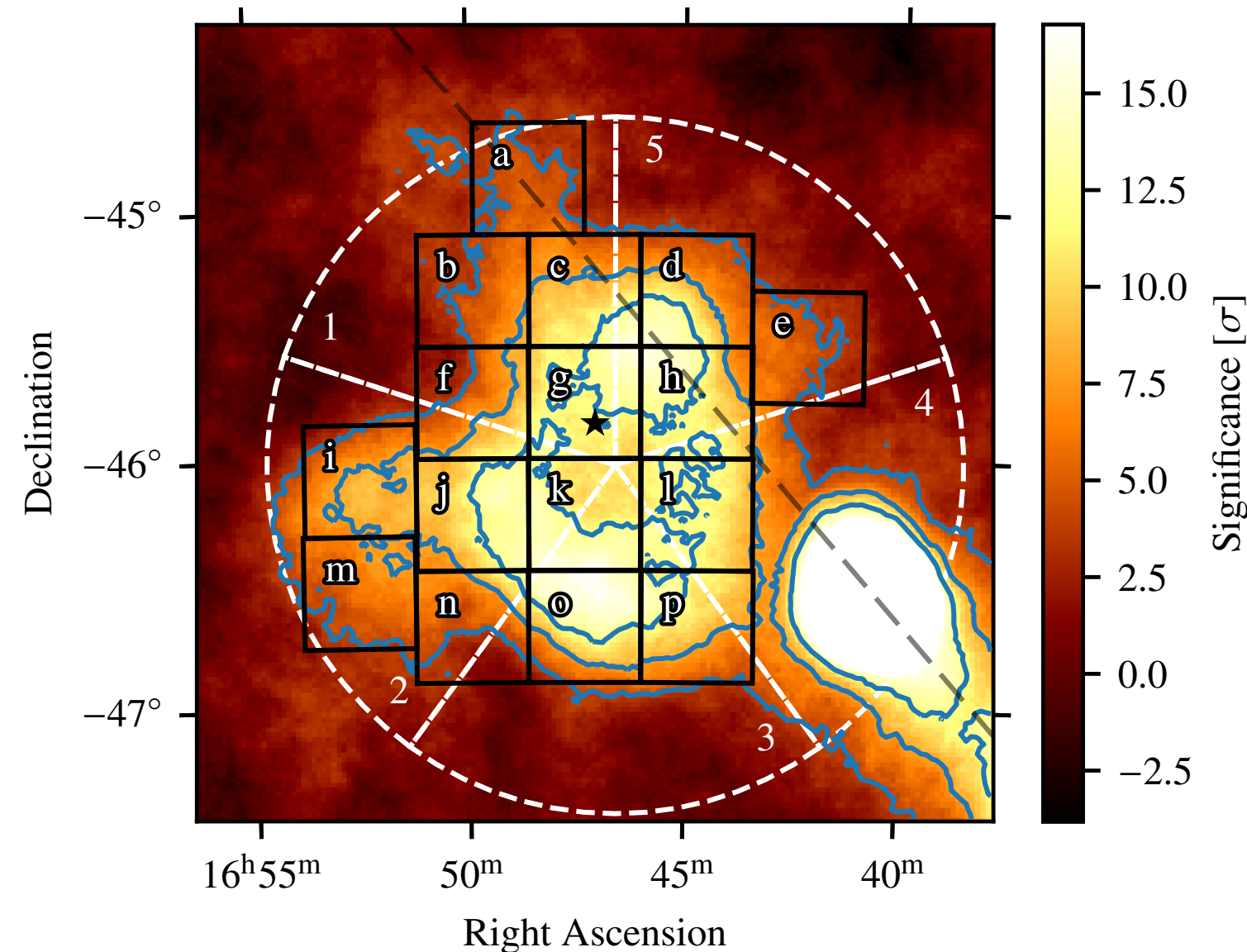
■ Confirmed by radial profiles



Westerlund 1

■ Energy spectrum

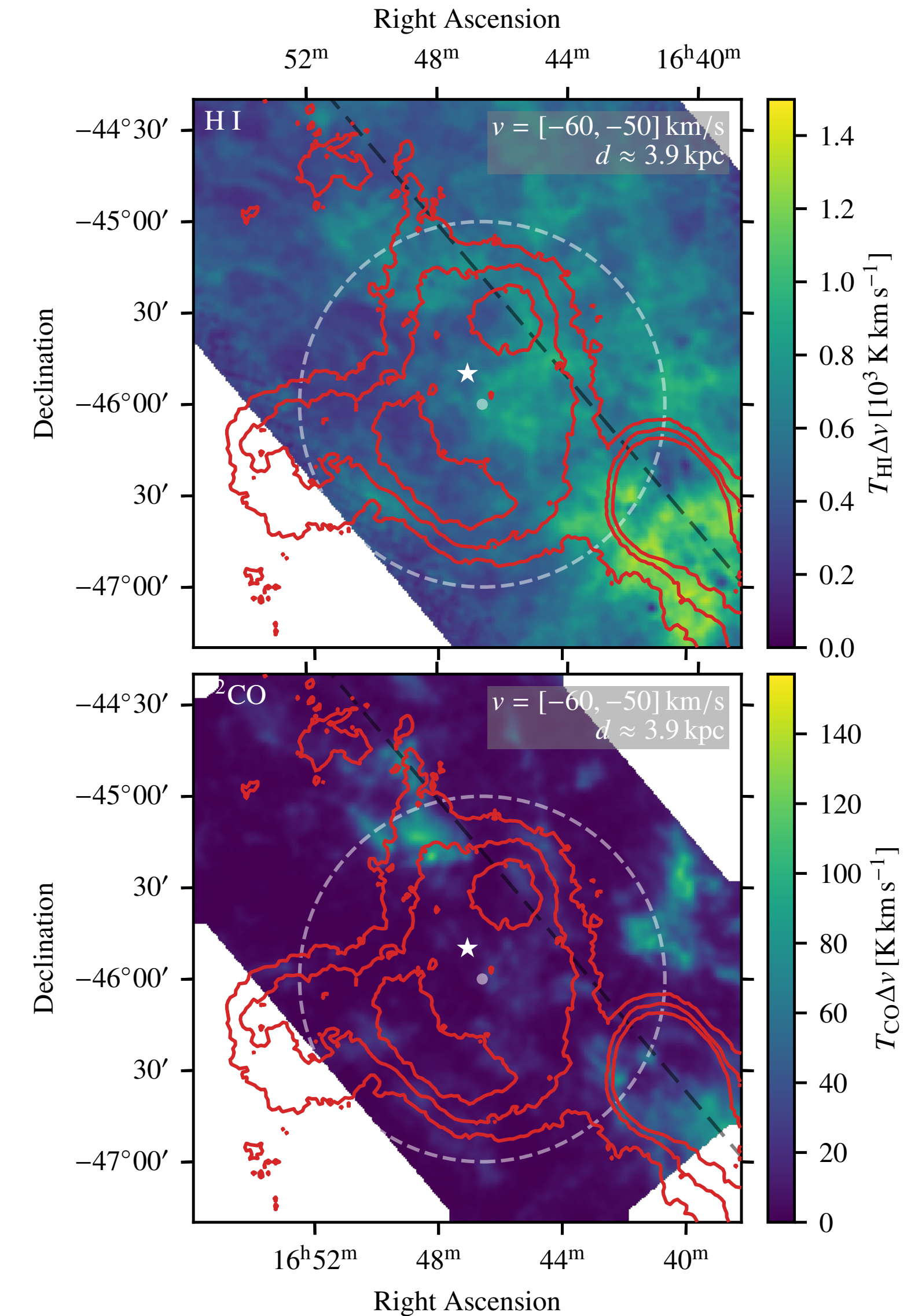
- ▶ extracted in 16 signal regions
- ▶ individual spectra remarkably similar
- ▶ add up region spectra → combined spectrum
- ▶ extends to several ten TeV!
- ▶ $\Gamma = 2.30 \pm 0.04$, $E_c = (44^{+17}_{-11})$ TeV



Westerlund 1

■ Correlation with gas tracers

- ▶ hadronic production scenario requires target material
- ▶ comparison with **HI** ($\rightarrow$ atomic hydrogen) and ^{12}CO ($\rightarrow$ molecular hydrogen) line emission
- ▶ **low gas density** in regions with bright gamma-ray emission



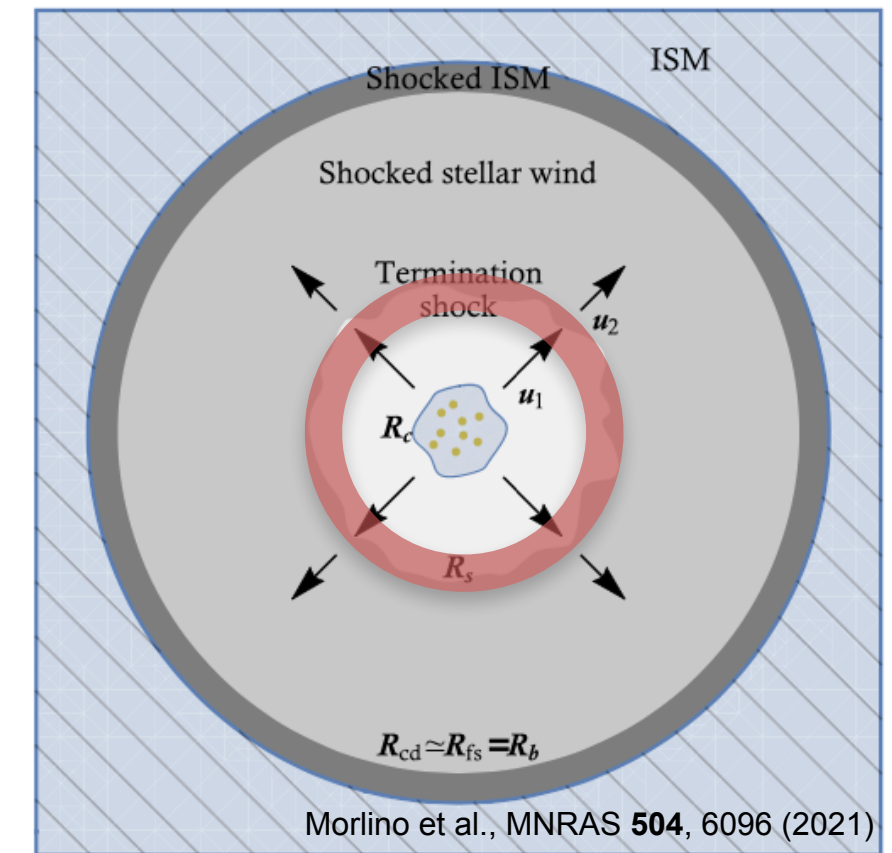
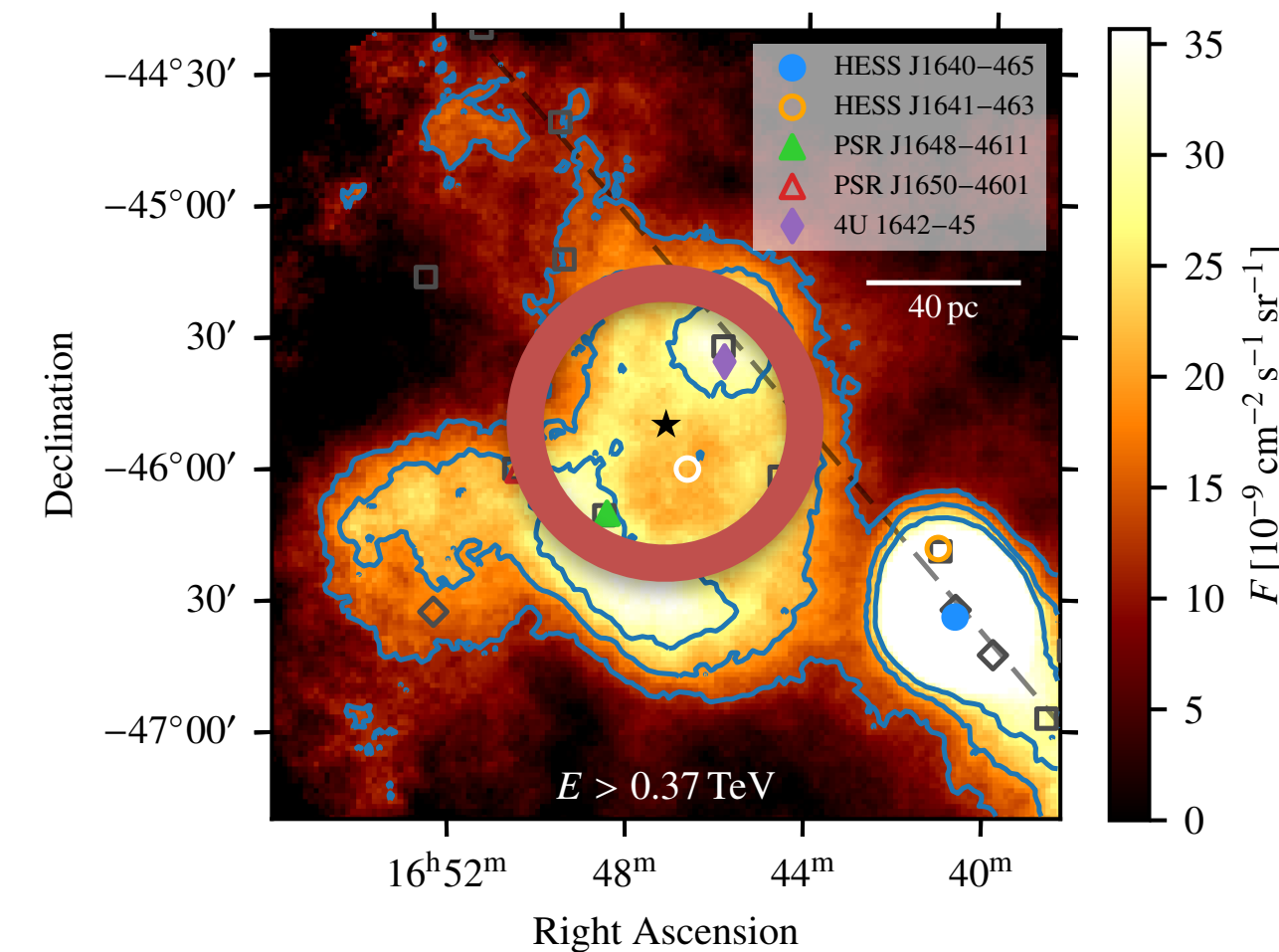
Westerlund 1

■ Correlation with gas tracers

- ▶ hadronic production scenario requires target material
- ▶ comparison with **HI** ($\rightarrow$ atomic hydrogen) and **^{12}CO** ($\rightarrow$ molecular hydrogen) line emission
- ▶ **low gas density** in regions with bright gamma-ray emission

■ Acceleration site

- ▶ expected radius of cluster wind termination shock: $\mathcal{O}(30\text{ pc})$
 $\rightarrow$ matches observed radius of gamma-ray shell!
- ▶ would be first demonstration of particle acceleration at a cluster wind termination shock



Westerlund 1

■ Correlation with gas tracers

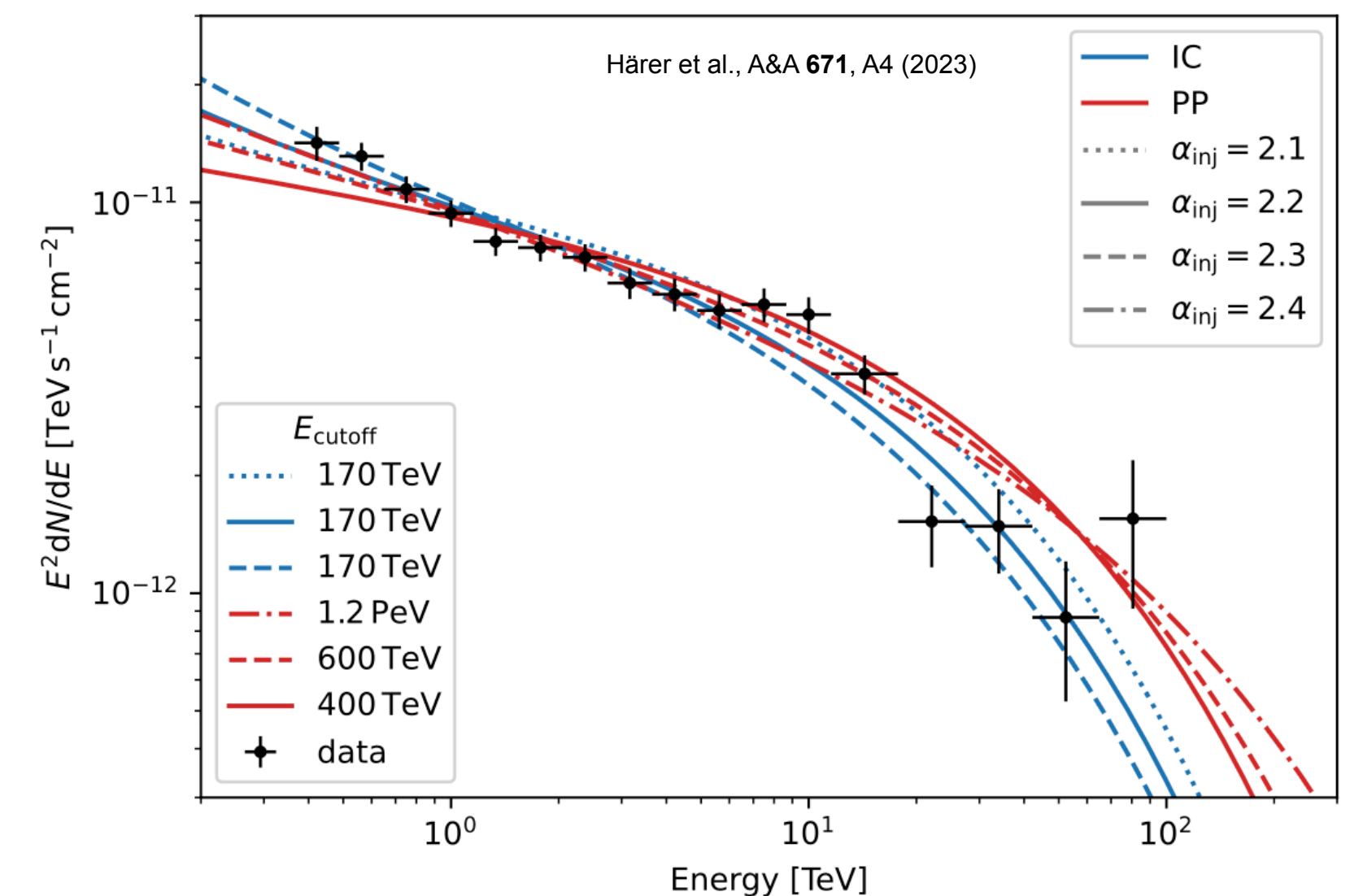
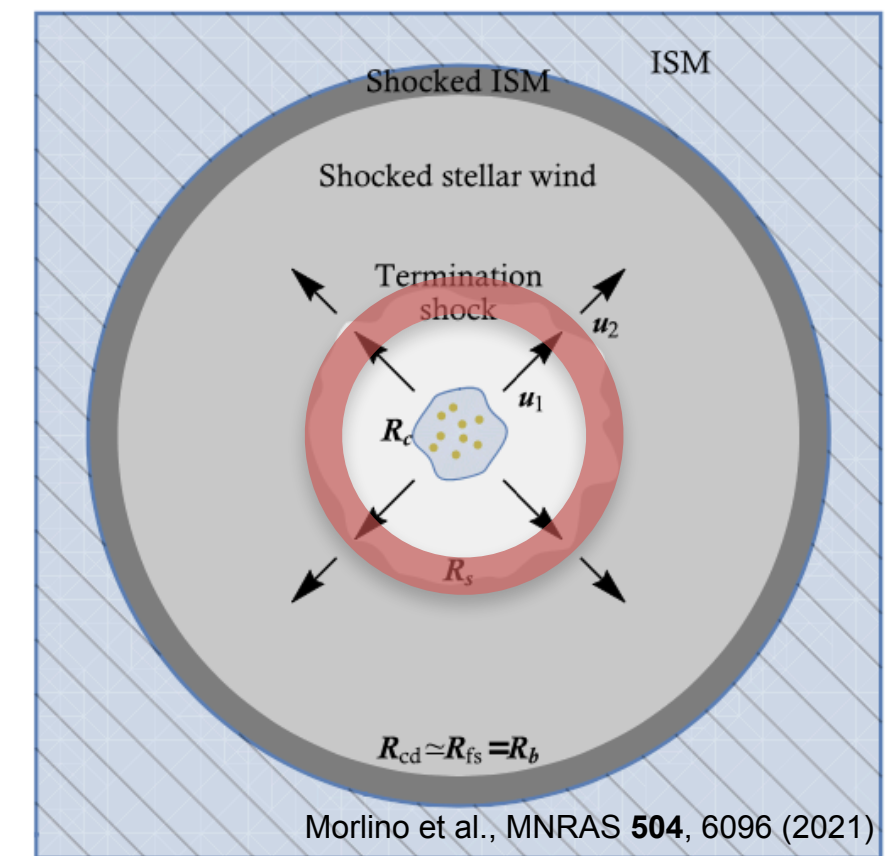
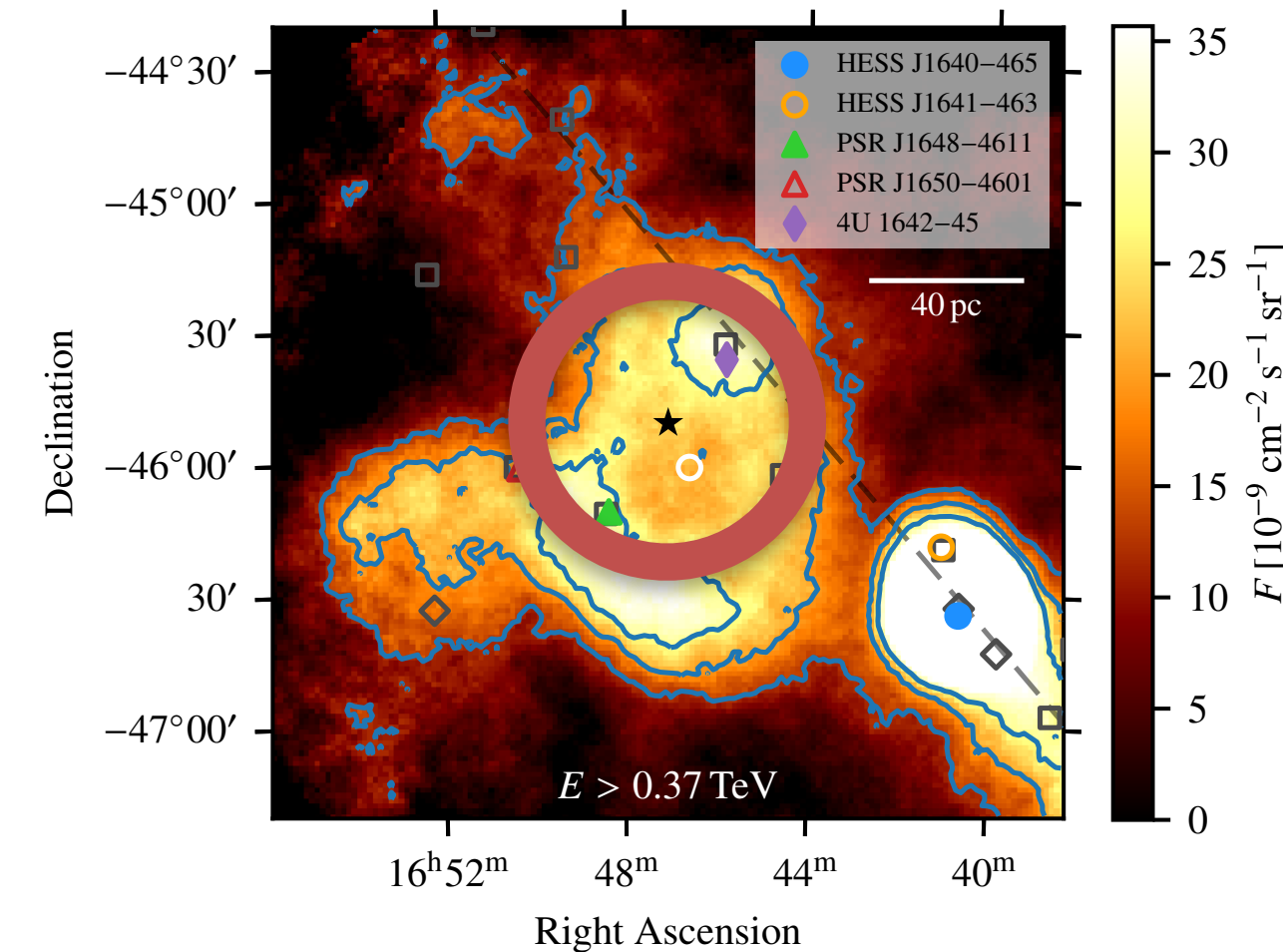
- ▶ hadronic production scenario requires target material
- ▶ comparison with **HI** ($\rightarrow$ atomic hydrogen) and **^{12}CO** ($\rightarrow$ molecular hydrogen) line emission
- ▶ **low gas density** in regions with bright gamma-ray emission

■ Acceleration site

- ▶ expected radius of cluster wind termination shock: $\mathcal{O}(30\text{ pc})$
 $\rightarrow$ matches observed radius of gamma-ray shell!
- ▶ would be first demonstration of particle acceleration at a cluster wind termination shock

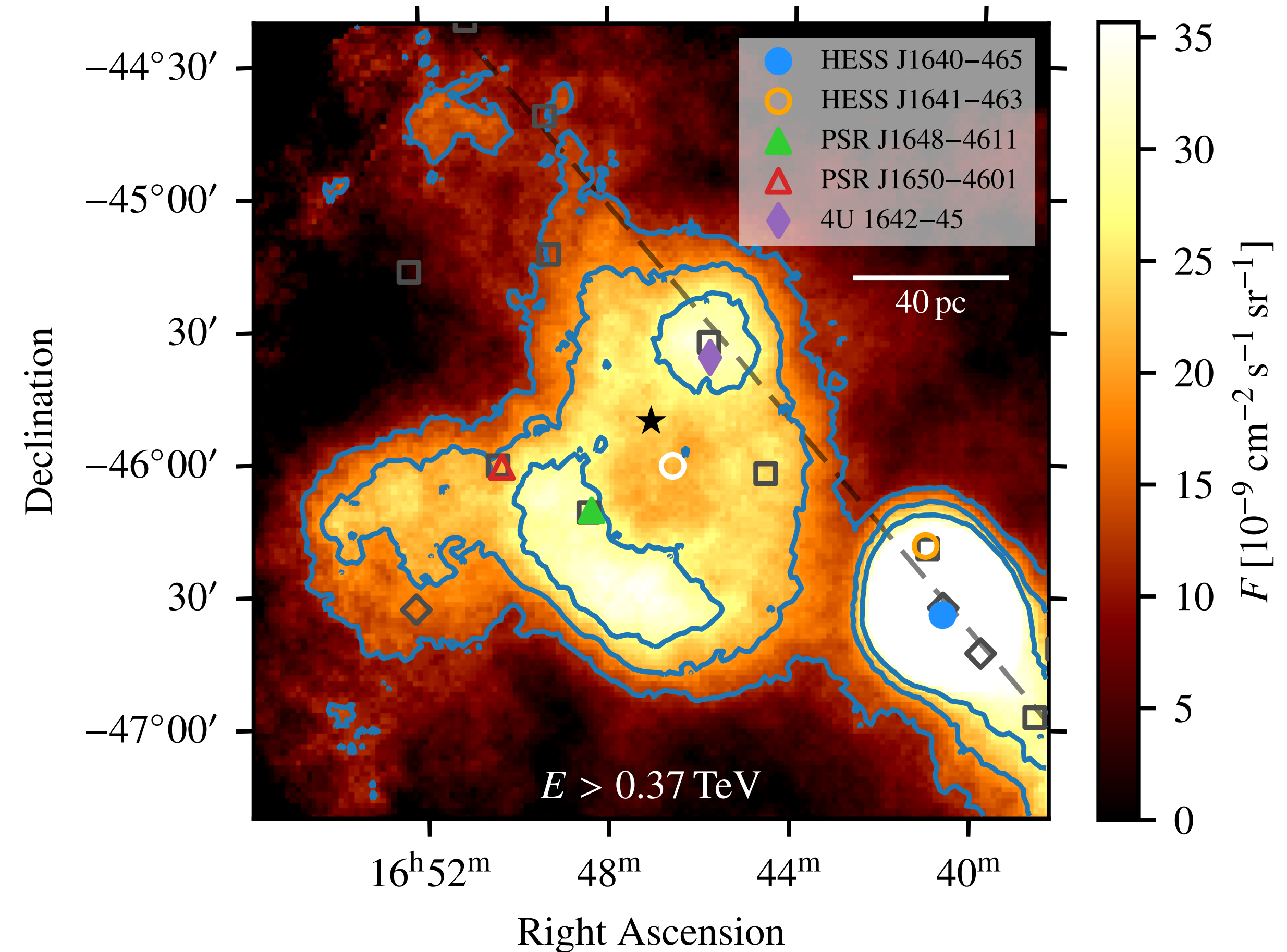
■ Emission mechanism

- ▶ in this scenario, leptonic (IC) origin of emission preferred
- ▶ however, expect also hadronic cosmic rays to be co-accelerated



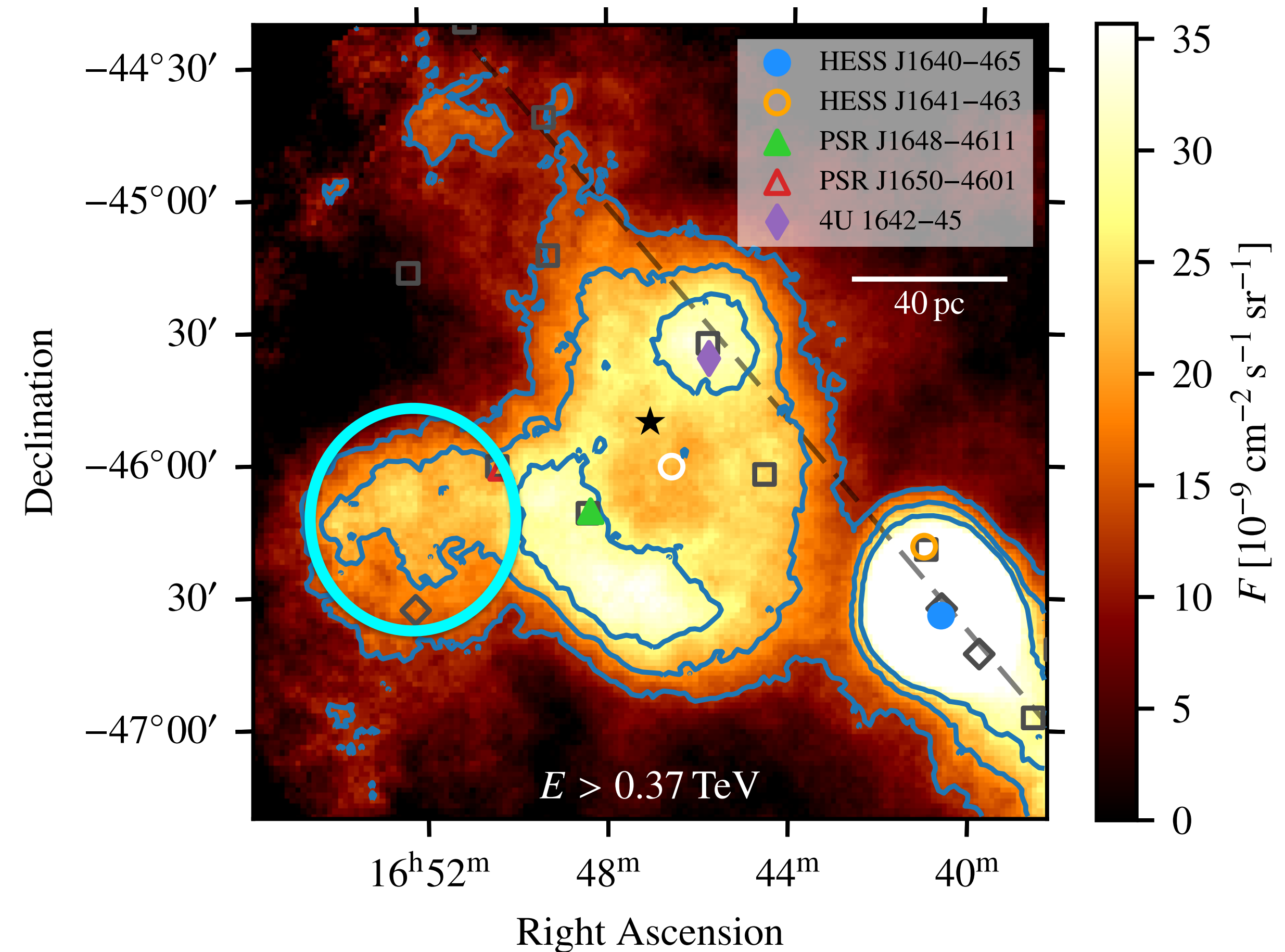
Westerlund 1 – summary

- **Westerlund 1 is a powerful cosmic-ray accelerator!**
- **Ring-like structure** indicates acceleration beyond the bounds of the cluster, possibly at the **cluster wind termination shock**
- **Low gas densities** – most of detected emission likely leptonic



Westerlund 1 – summary

- **Westerlund 1 is a powerful cosmic-ray accelerator!**
- **Ring-like structure** indicates acceleration beyond the bounds of the cluster, possibly at the **cluster wind termination shock**
- **Low gas densities** – most of detected emission likely leptonic
- ...but what is causing this “bulge”?!



"A cosmic-ray loaded nascent outflow driven by a massive star cluster"

Nature Communications 16, 10820 (2025)

A cosmic-ray loaded nascent outflow driven by a massive star cluster

Received: 21 March 2025

Accepted: 18 October 2025

Published online: 09 December 2025

 Check for updates

Marianne Lemoine-Goumard^{1,6,7} , Lucia Härer^{2,7} , Lars Mohrmann^{2,7} , Romain Bernet^{3,4}, Jim Hinton², Giada Peron⁵, Brian Reville², Luigi Tibaldo³ & Thibault Vieu²

Cosmic rays are widely held to drive outflows from star-forming galaxies and profoundly influence galaxy evolution. Direct evidence for cosmic-ray carrying outflows is however lacking. At the same time there is increasing awareness of the importance of massive star clusters in the acceleration of cosmic rays in galaxies. Here we report on the discovery of a nascent outflow driven by the massive star cluster Westerlund 1. Giga-electronvolt gamma-ray emission coincident with a cavity visible in atomic hydrogen traces the emergence of a population of relativistic electrons out of the Galactic Disc. The emission is offset from tera-electronvolt gamma-ray radiation surrounding the cluster, but connects to it smoothly spectrally and spatially. The implied energy density of co-accelerated protons and nuclei, assuming standard non-thermal electron/proton injection efficiencies, is at least an order of magnitude higher than that in the general interstellar medium. These particles therefore have the potential to dynamically influence the outflow. This discovery suggests that cosmic-ray loaded outflows may be a common feature of young massive star clusters, with implications for the transport of cosmic rays into the halo of the Galaxy.

Observations of nearby starburst galaxies suggest the presence of global cosmic-ray (CR) pressure driven winds¹. It is unclear however whether the CR content in the halo of the Milky Way is sufficient to accelerate such a wind. On the other hand, galaxy-scale simulations are in agreement that CR feedback at high latitudes succeeds in driving large-scale winds^{2–7}. Since these winds affect the nearby circumgalactic medium and, as a consequence, the Galactic star-formation rate, the CR content in the Galactic halo and the processes that regulate how CRs get there are critical components of any model of the interstellar medium (ISM)⁸.

Early fluid^{9,10} and kinetic^{11,12} models predicted the existence of Galactic winds driven by CRs in the halo. Modern simulations—encompassing stellar feedback, multiple supernovae, the resulting CR production and interaction with a multi-phase ISM—can now present a

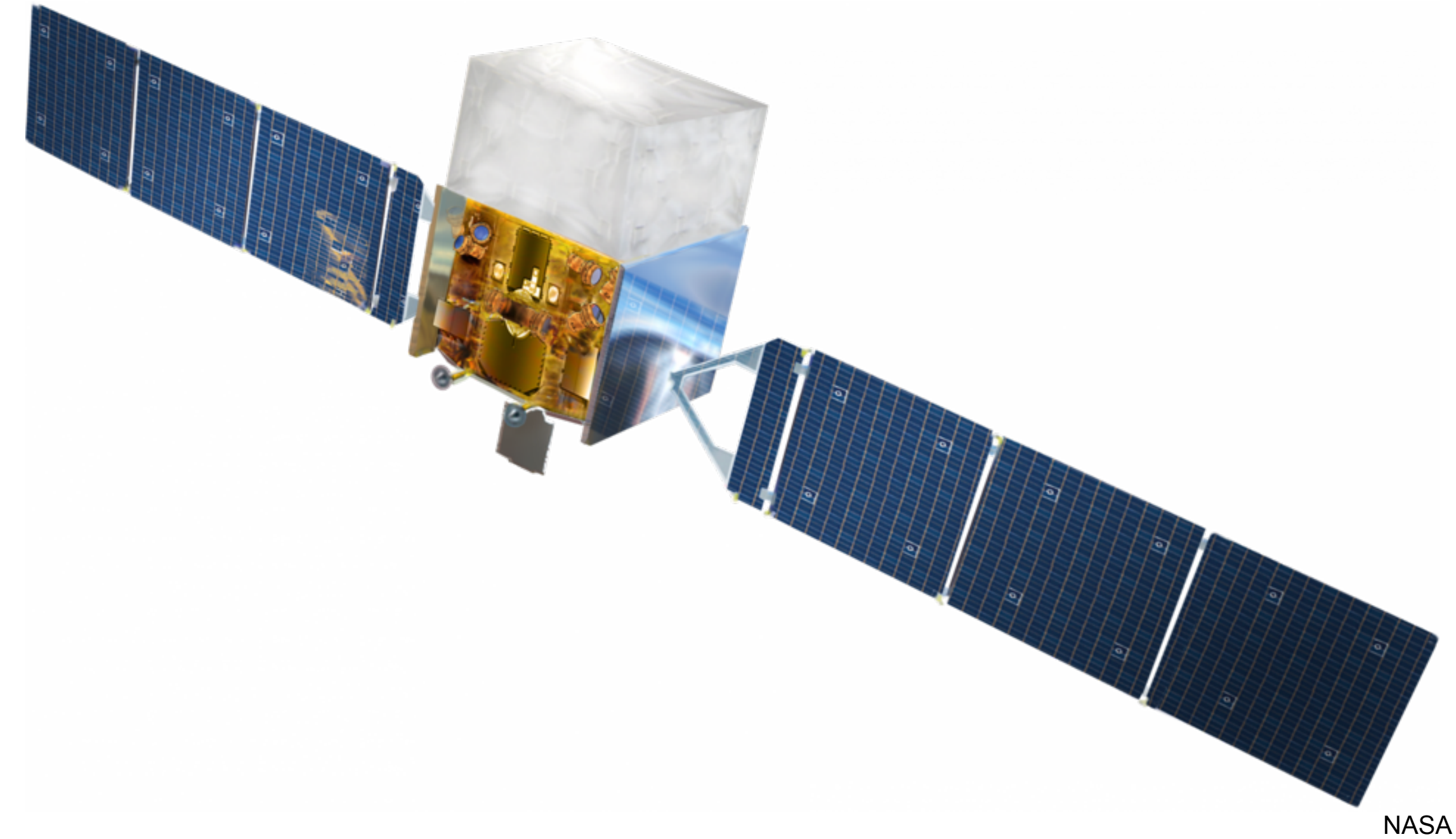
more consistent picture of this process e.g. ^{2–7}. These works find that the kpc-scale outflows are sensitive not only to the gas conditions in and around superbubbles, but also to the assumptions on CR transport and associated plasma effects. These effects, such as ion-neutral damping, depend upon the phase of the surrounding ISM and in particular that above and below the Galactic Plane.

The material feeding these halo winds originates from stellar activity, especially supernovae^{13,14}, which are unevenly distributed throughout the disk. To reach the halo, material must penetrate the diffuse warm ISM (WIM; see ref. ¹⁵ for further details). The WIM density falls off exponentially away from the mid-plane, with a scale-height of ≈ 1 kpc¹⁶, substantially longer than that of the thin disc of the Galactic Plane (≈ 100 pc¹⁷). Here, young massive star clusters (YMSCs) have a distinct advantage. The combined action of powerful winds and

¹Université Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, Gradignan, France. ²Max-Planck-Institut für Kernphysik, Heidelberg, Germany. ³IRAP, Université de Toulouse, CNRS, CNES, UPS, Toulouse, France. ⁴Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), Université de Toulouse, Toulouse, France. ⁵INAF Osservatorio Astrofisico Arcetri, Florence, Italy. ⁶Present address: Université Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, Gradignan, France. ⁷These authors contributed equally: Marianne Lemoine-Goumard, Lucia Härer, Lars Mohrmann. ✉ e-mail: mlemoine33@gmail.com; lucia.haerer@mpi-hd.mpg.de; lars.mohrmann@mpi-hd.mpg.de

Westerlund 1 (*Fermi*-LAT follow-up)

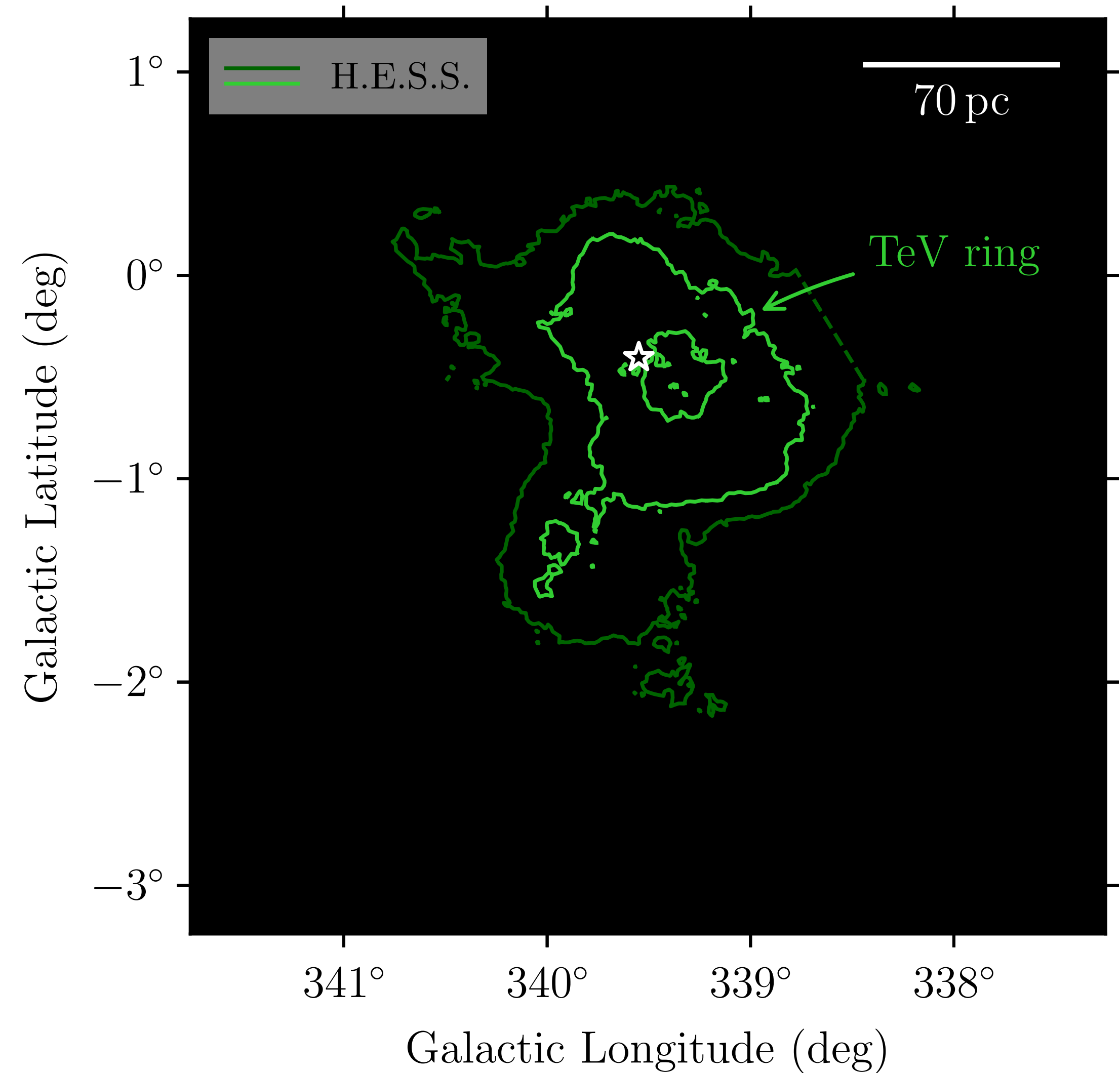
- New *Fermi*-LAT analysis
 - 15 years of data
 - energy range: 3 GeV – 3 TeV



Westerlund 1 (*Fermi*-LAT follow-up)

- **New *Fermi*-LAT analysis**

- ▶ 15 years of data
- ▶ energy range: 3 GeV – 3 TeV



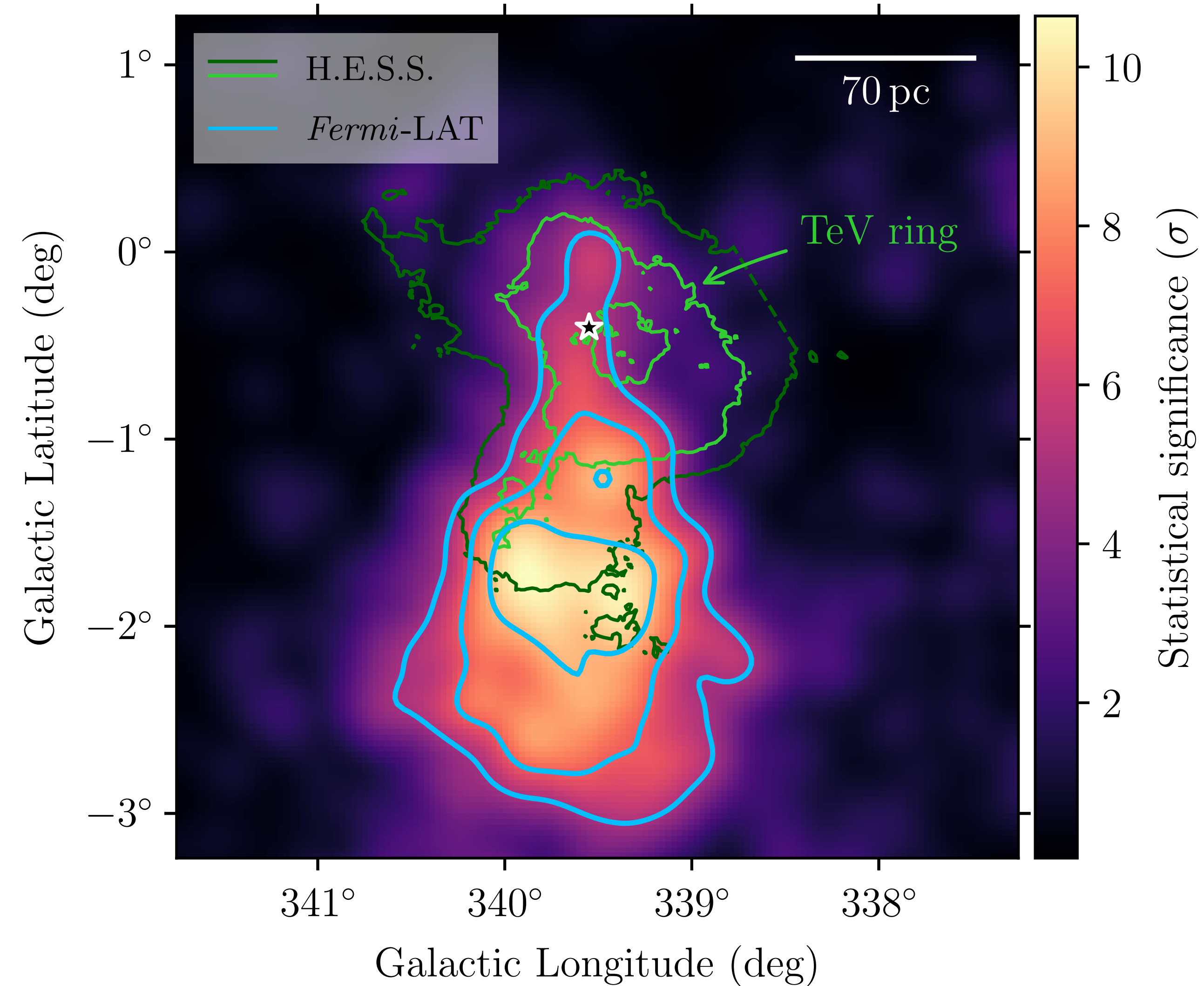
Westerlund 1 (*Fermi*-LAT follow-up)

■ New *Fermi*-LAT analysis

- ▶ 15 years of data
- ▶ energy range: 3 GeV – 3 TeV

■ Results

- ▶ extended emission region (> 100 pc)
- ▶ peak offset from TeV emission around Westerlund 1



Westerlund 1 (*Fermi*-LAT follow-up)

■ New *Fermi*-LAT analysis

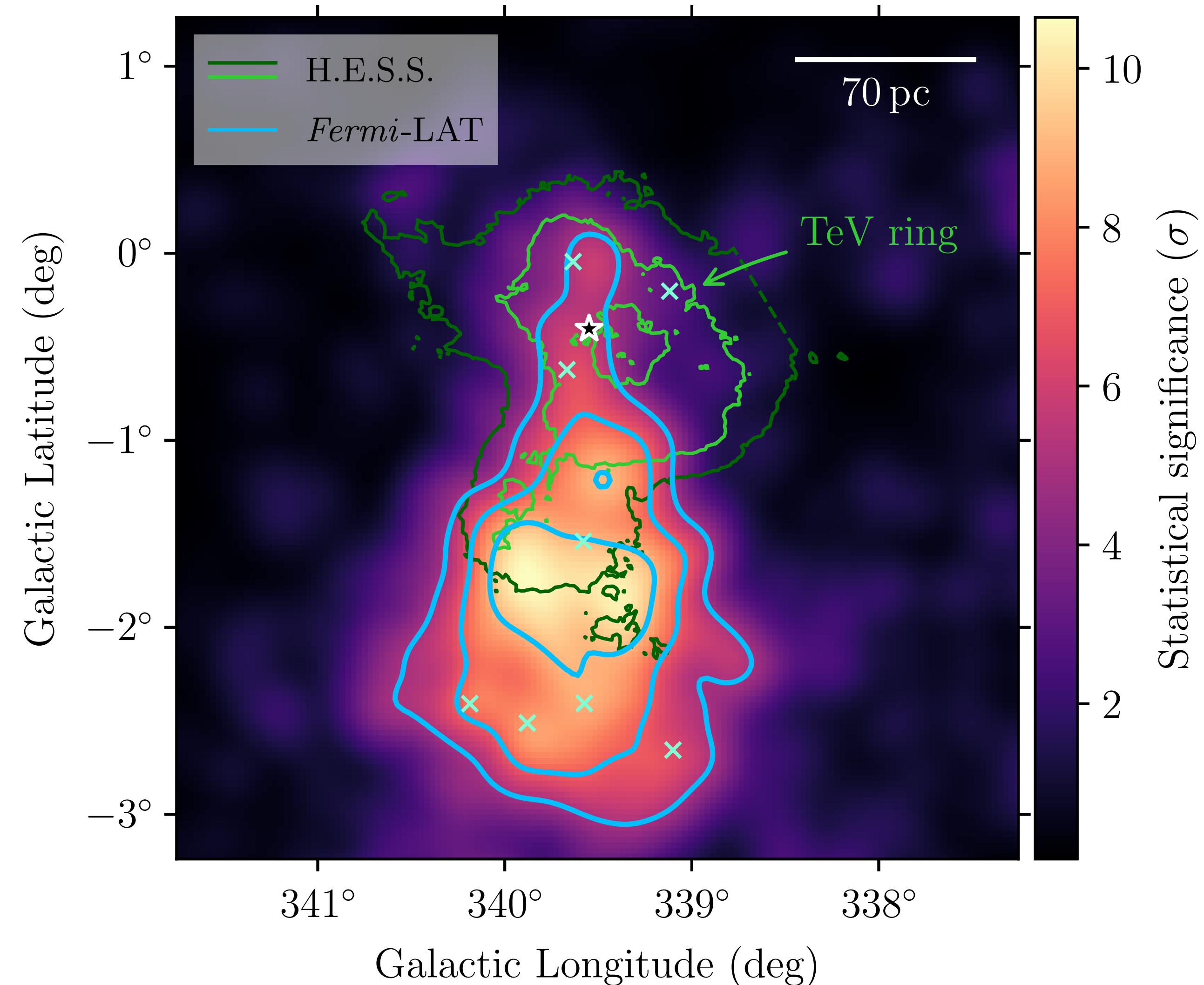
- ▶ 15 years of data
- ▶ energy range: 3 GeV – 3 TeV

■ Results

- ▶ extended emission region (> 100 pc)
- ▶ peak offset from TeV emission around Westerlund 1

■ Modelling

- ▶ *Fermi*-LAT catalog: 2 extended + 6 point-like sources!



Westerlund 1 (*Fermi*-LAT follow-up)

■ New *Fermi*-LAT analysis

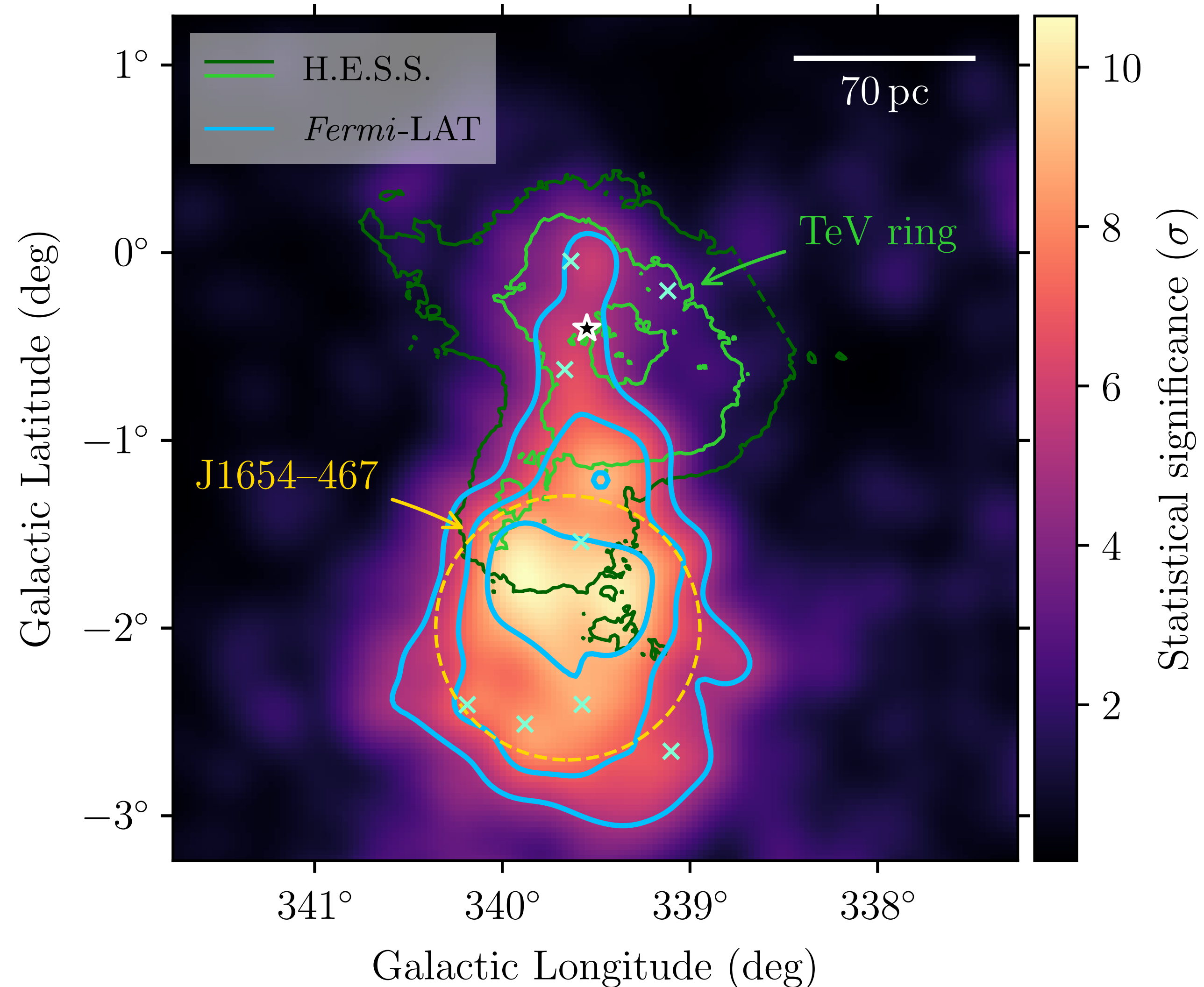
- ▶ 15 years of data
- ▶ energy range: 3 GeV – 3 TeV

■ Results

- ▶ extended emission region (> 100 pc)
- ▶ peak offset from TeV emission around Westerlund 1

■ Modelling

- ▶ *Fermi*-LAT catalog: 2 extended + 6 point-like sources!
- ▶ our best-fit model:
 - 1 Gaussian component (“J1654–467”) +
 - TeV template for emission near cluster
- ▶ statistically strongly preferred



Westerlund 1 (*Fermi*-LAT follow-up)

■ New *Fermi*-LAT analysis

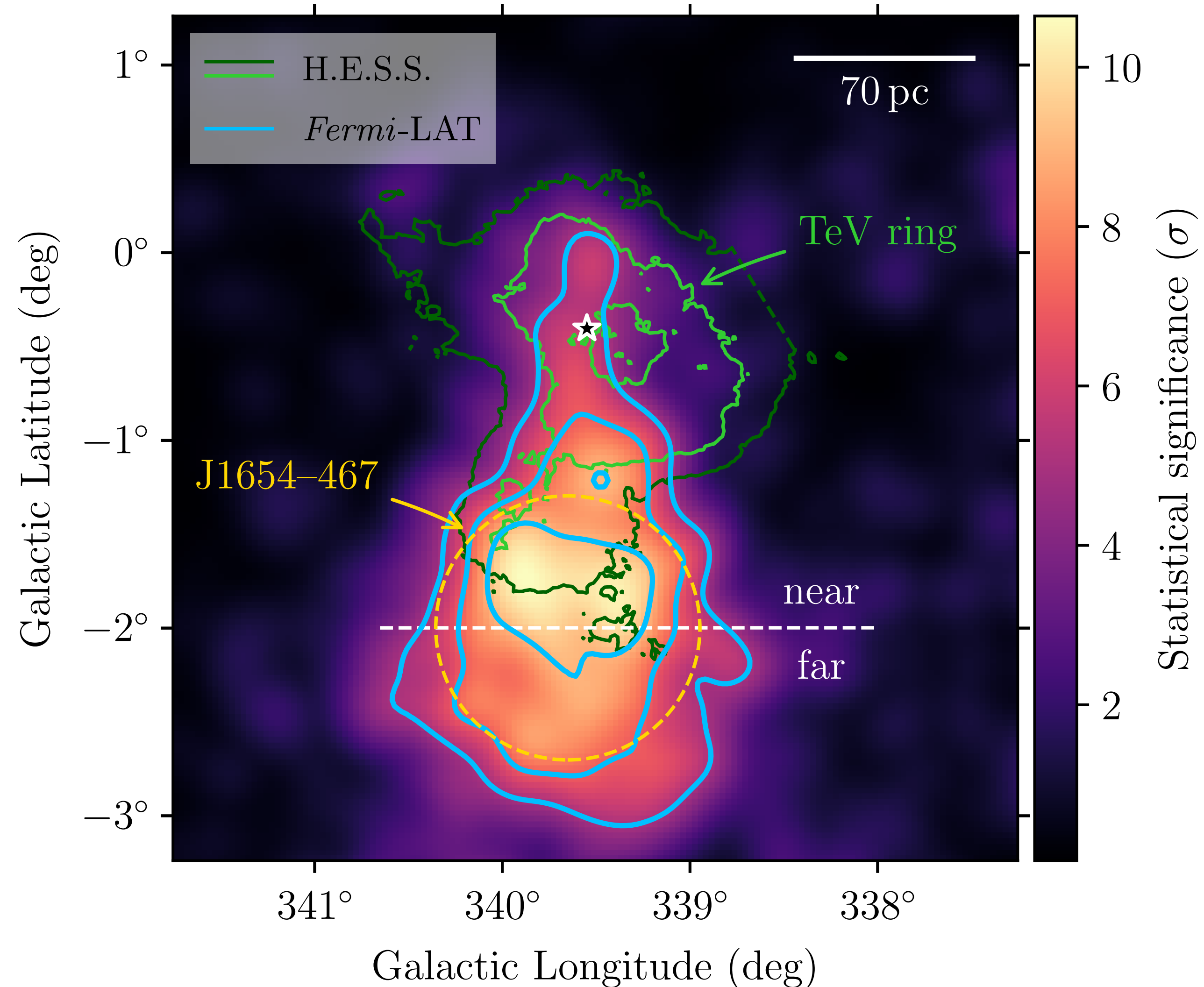
- ▶ 15 years of data
- ▶ energy range: 3 GeV – 3 TeV

■ Results

- ▶ extended emission region (> 100 pc)
- ▶ peak offset from TeV emission around Westerlund 1

■ Modelling

- ▶ *Fermi*-LAT catalog: 2 extended + 6 point-like sources!
- ▶ our best-fit model:
 - 1 Gaussian component (“J1654–467”) +
 - TeV template for emission near cluster
- ▶ statistically strongly preferred



Westerlund 1 (*Fermi*-LAT follow-up)

■ New *Fermi*-LAT analysis

- ▶ 15 years of data
- ▶ energy range: 3 GeV – 3 TeV

■ Results

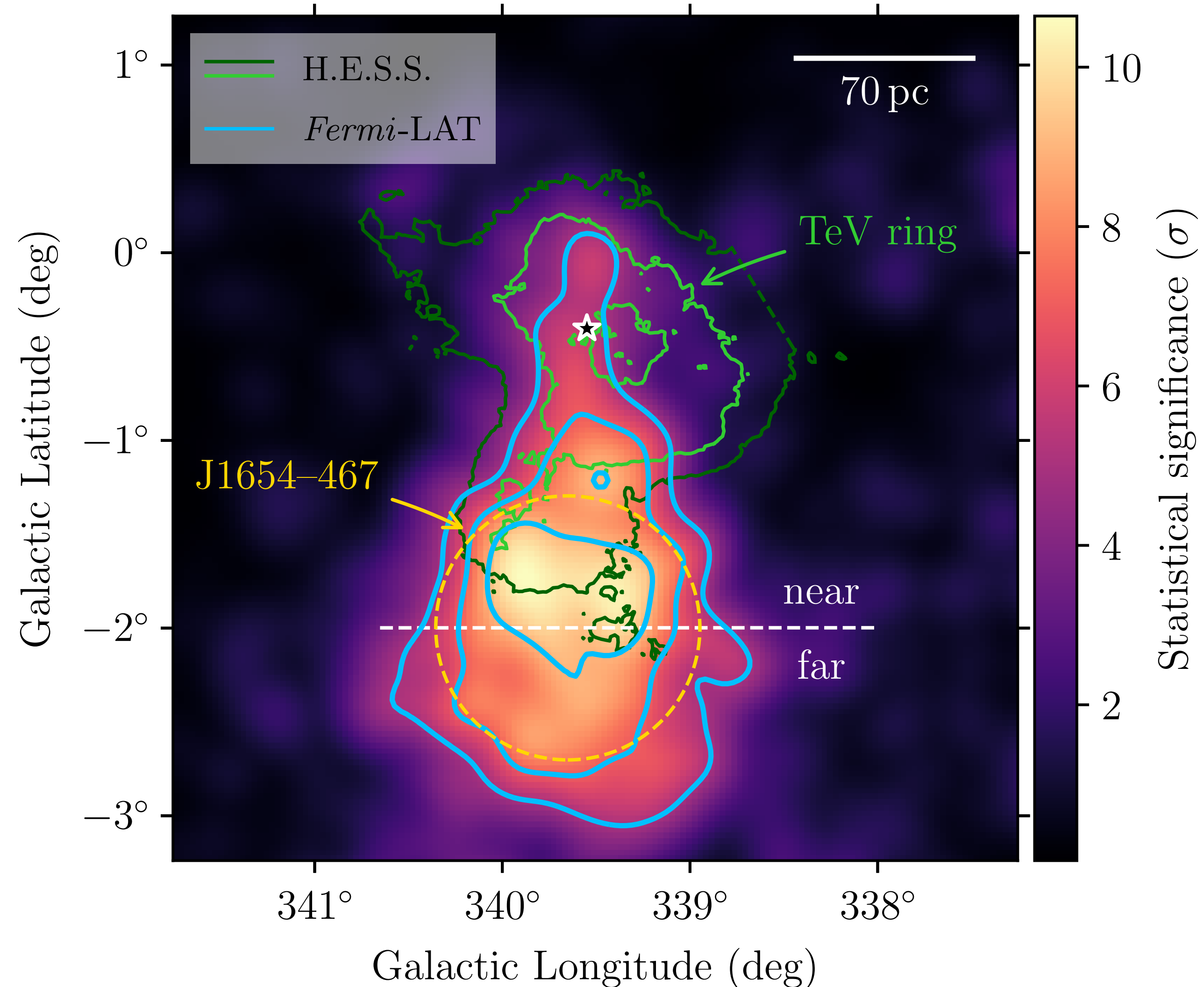
- ▶ extended emission region (> 100 pc)
- ▶ peak offset from TeV emission around Westerlund 1

■ Modelling

- ▶ *Fermi*-LAT catalog: 2 extended + 6 point-like sources!
- ▶ our best-fit model:
 - 1 Gaussian component (“J1654–467”) +
 - TeV template for emission near cluster
- ▶ statistically strongly preferred

■ J1654–467

- ▶ smoothly connected with TeV emission
- ▶ could this be cosmic rays escaping from Westerlund 1?

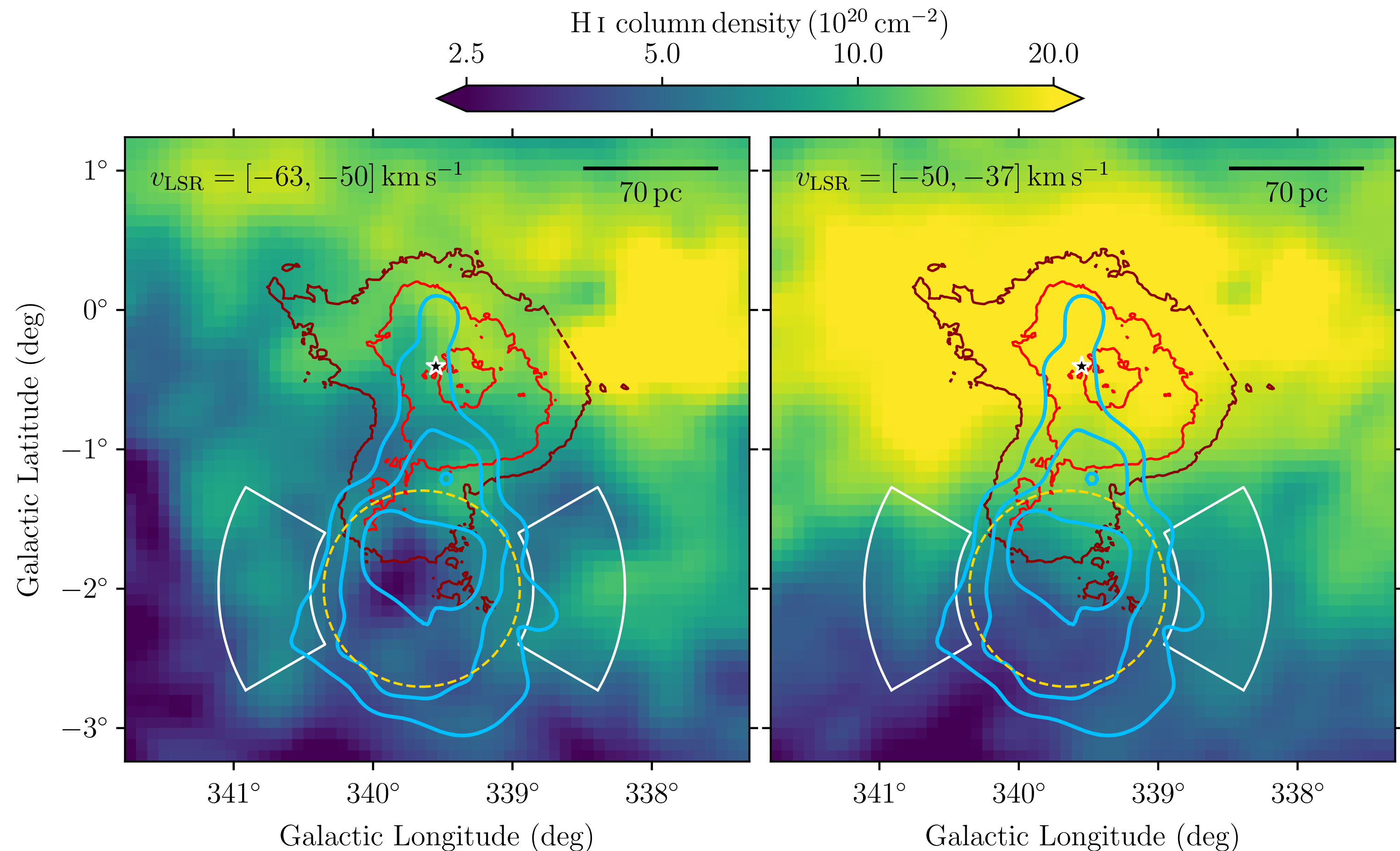


Westerlund 1 (*Fermi*-LAT follow-up)

■ HI column density maps

- ▶ velocity of gas near Westerlund 1 not well constrained
→ consider two adjacent intervals in velocity
- ▶ clear under-density coincident with new source J1654–467!
- ▶ difference to neighbouring lines of sight: $(0.7 - 1.5) \times 10^{20} \text{ cm}^{-2}$

■ A cavity created by an outflow from Westerlund 1?



Westerlund 1 (*Fermi*-LAT follow-up)

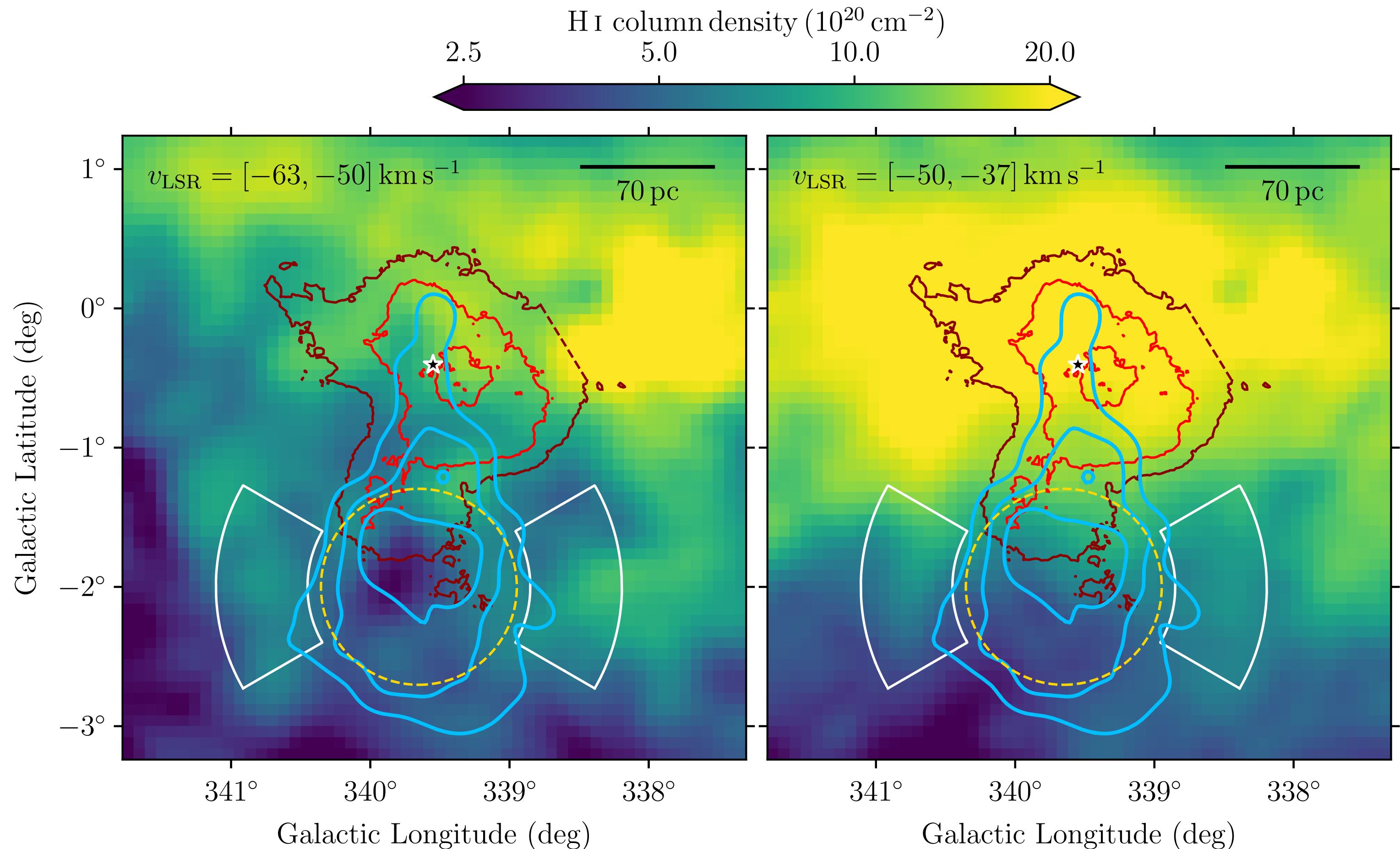
■ HI column density maps

- ▶ velocity of gas near Westerlund 1 not well constrained
→ consider two adjacent intervals in velocity
- ▶ clear under-density coincident with new source J1654–467!
- ▶ difference to neighbouring lines of sight: $(0.7 - 1.5) \times 10^{20} \text{ cm}^{-2}$

■ A cavity created by an outflow from Westerlund 1?

■ Properties of the cavity

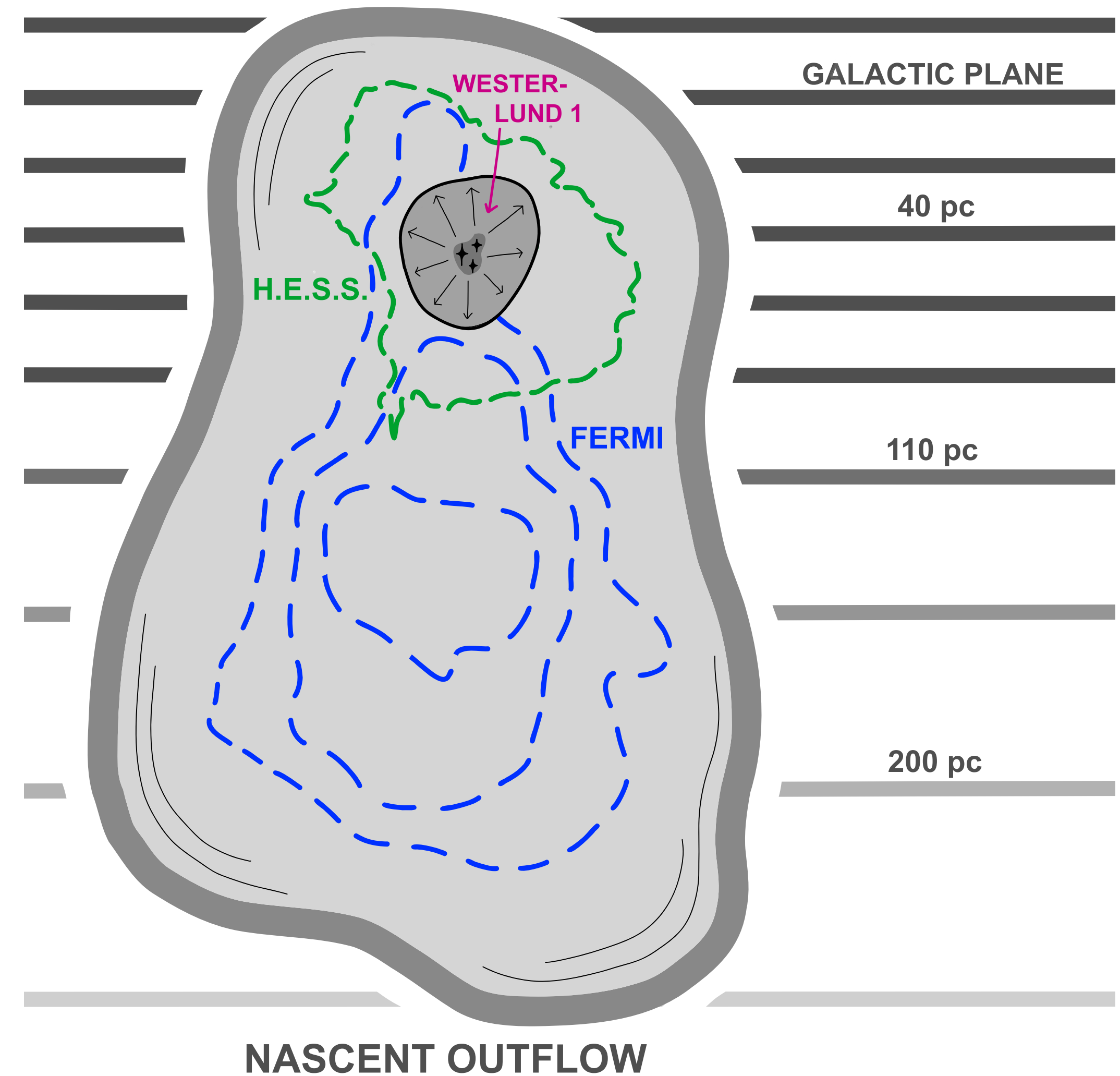
- ▶ extent $\sim (70 \text{ pc})^3$
- ▶ $0.3 - 0.7 \text{ atoms cm}^{-3}$ excavated
- ▶ energy requirement
 $\sim 10^{50} (T/10^4 \text{ K}) (n/1 \text{ cm}^{-3}) \text{ erg}$
→ within energy budget!



Westerlund 1 (*Fermi*-LAT follow-up)

■ Proposed scenario: “nascent outflow”

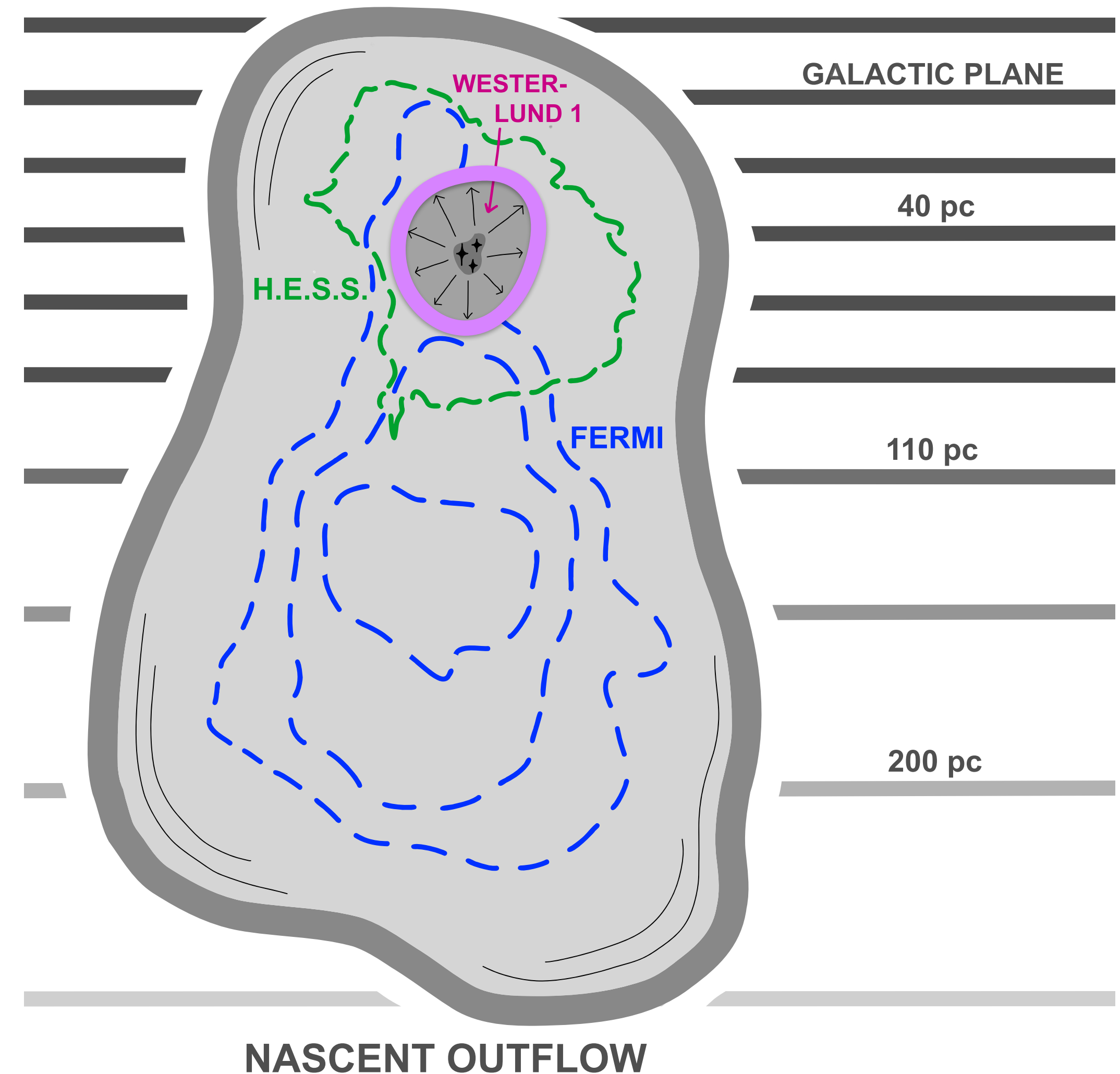
- ▶ **superbubble** expands asymmetrically due to ISM density gradient, but has not fully broken out of the Galactic disk yet



Westerlund 1 (*Fermi*-LAT follow-up)

■ Proposed scenario: “nascent outflow”

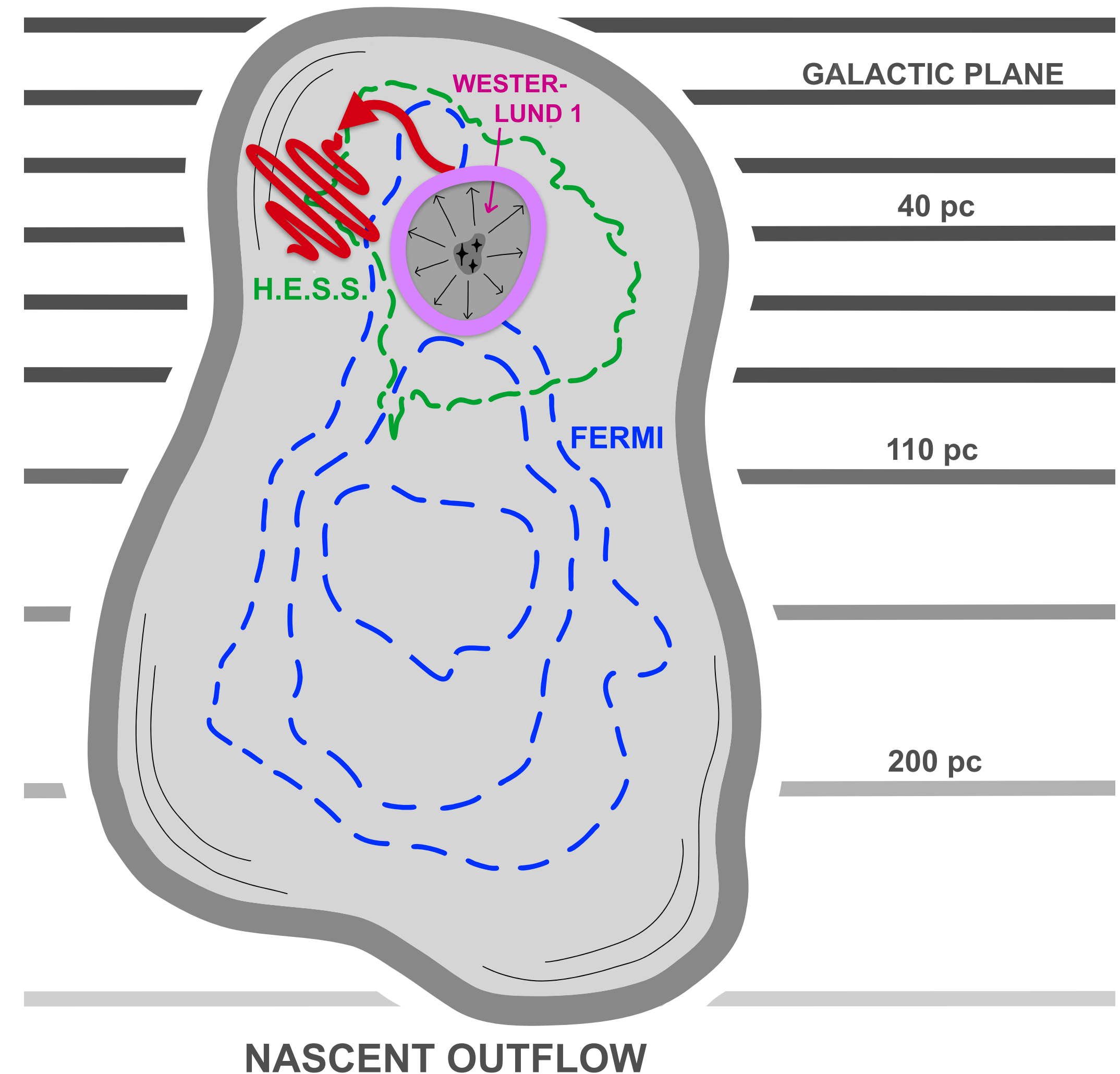
- ▶ **superbubble** expands asymmetrically due to ISM density gradient, but has not fully broken out of the Galactic disk yet
- ▶ cosmic rays accelerated at **cluster wind termination shock** (as in Härer et al. 2023)



Westerlund 1 (*Fermi*-LAT follow-up)

■ Proposed scenario: “nascent outflow”

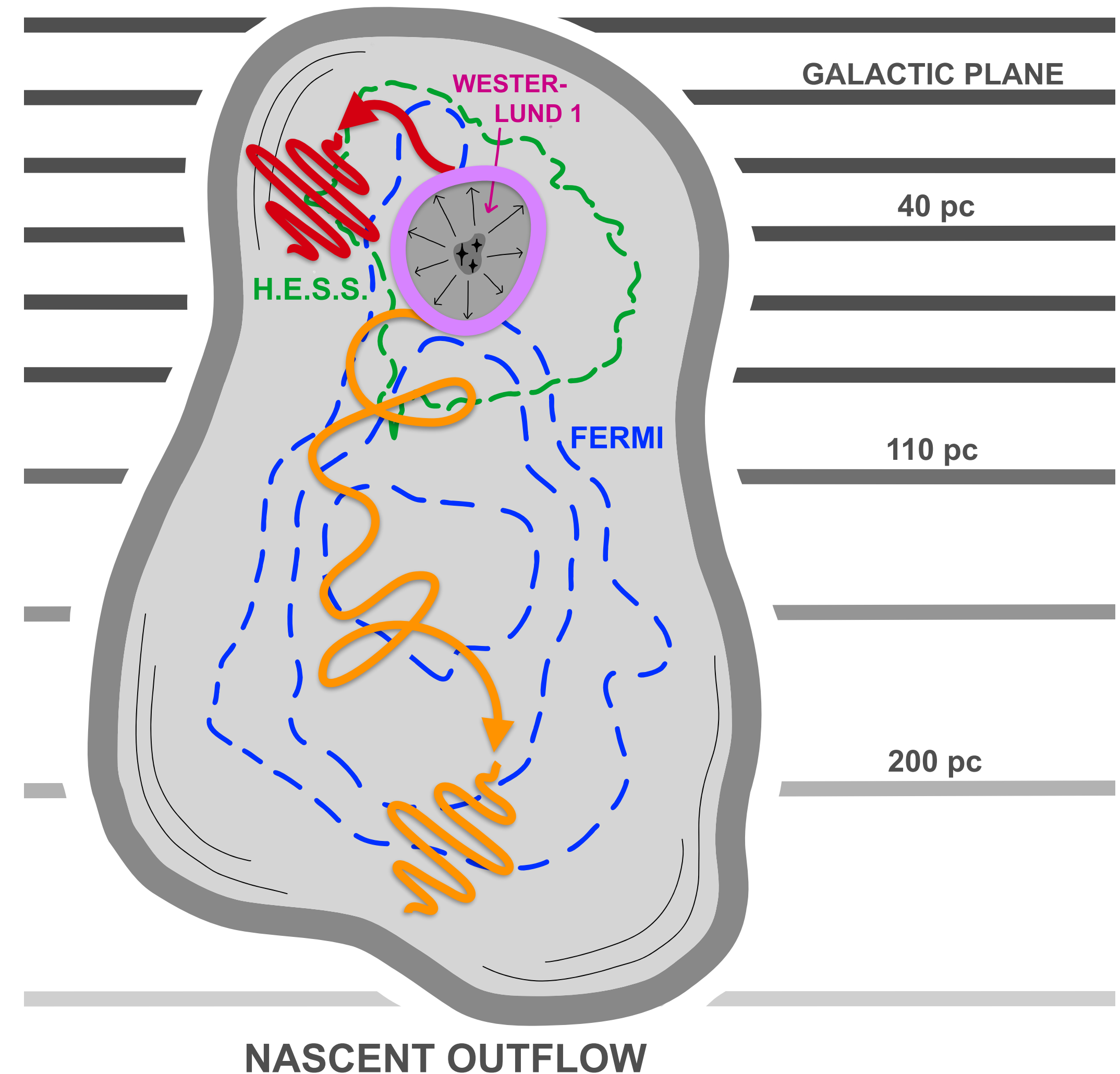
- ▶ **superbubble** expands asymmetrically due to ISM density gradient, but has not fully broken out of the Galactic disk yet
- ▶ cosmic rays accelerated at **cluster wind termination shock** (as in Härer et al. 2023)
- ▶ **high-energy electrons** lose energy quickly
→ produce TeV emission close to star cluster



Westerlund 1 (*Fermi*-LAT follow-up)

■ Proposed scenario: “nascent outflow”

- ▶ **superbubble** expands asymmetrically due to ISM density gradient, but has not fully broken out of the Galactic disk yet
- ▶ cosmic rays accelerated at **cluster wind termination shock** (as in Härer et al. 2023)
- ▶ **high-energy electrons** loose energy quickly
→ produce TeV emission close to star cluster
- ▶ **low-energy electrons** are transported along outflow
→ produce GeV emission far from star cluster



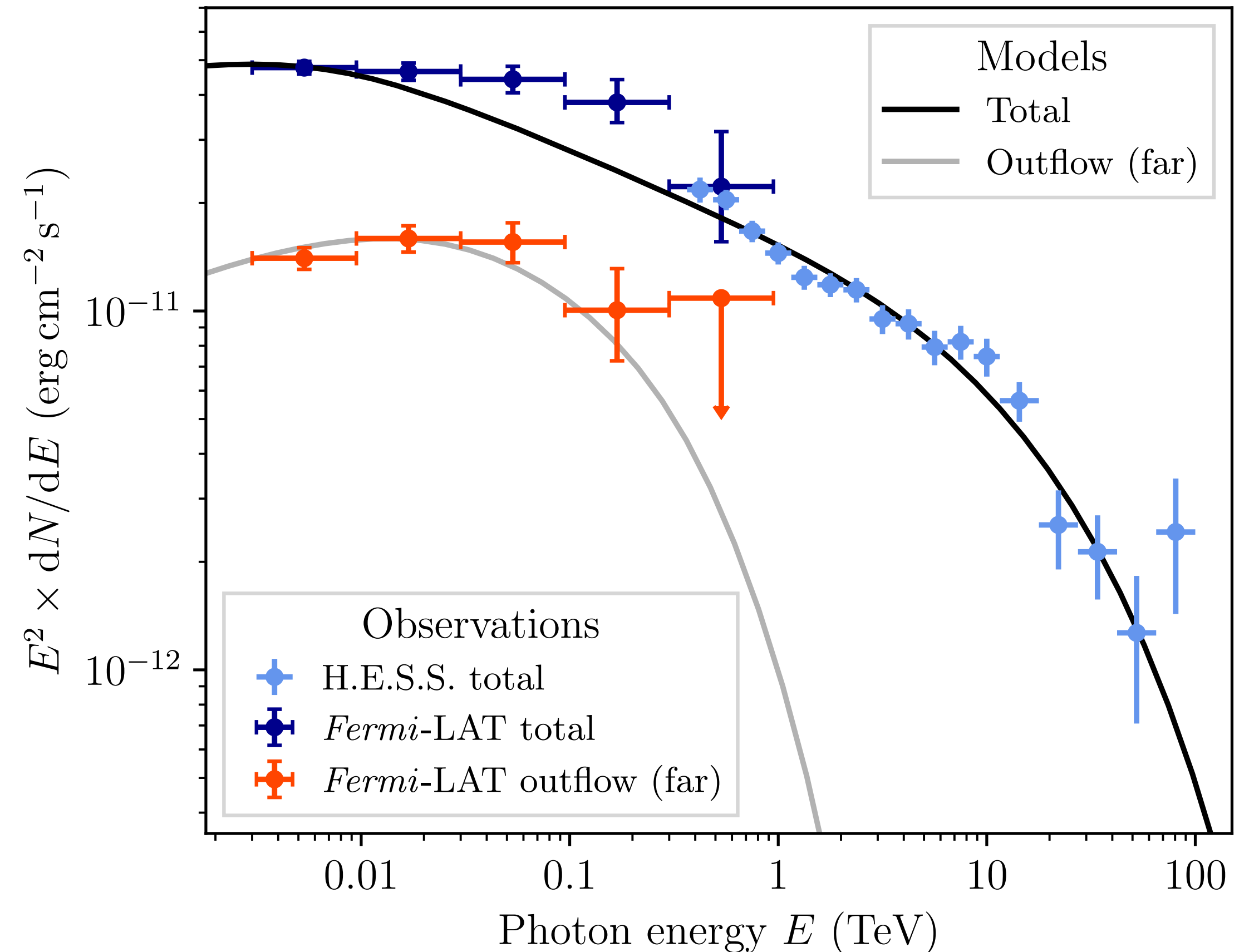
Westerlund 1 (*Fermi*-LAT follow-up)

■ Proposed scenario: “nascent outflow”

- ▶ **superbubble** expands asymmetrically due to ISM density gradient, but has not fully broken out of the Galactic disk yet
- ▶ cosmic rays accelerated at **cluster wind termination shock** (as in Härer et al. 2023)
- ▶ **high-energy electrons** lose energy quickly
→ produce TeV emission close to star cluster
- ▶ **low-energy electrons** are transported along outflow
→ produce GeV emission far from star cluster

■ Simple IC model

- ▶ electron acceleration efficiency: $\eta_e \approx 0.7\%$
- ▶ electron energy density in outflow: $U_e \sim (1 - 10) \text{ eV cm}^{-3}$



Westerlund 1 (*Fermi*-LAT follow-up)

■ Proposed scenario: “nascent outflow”

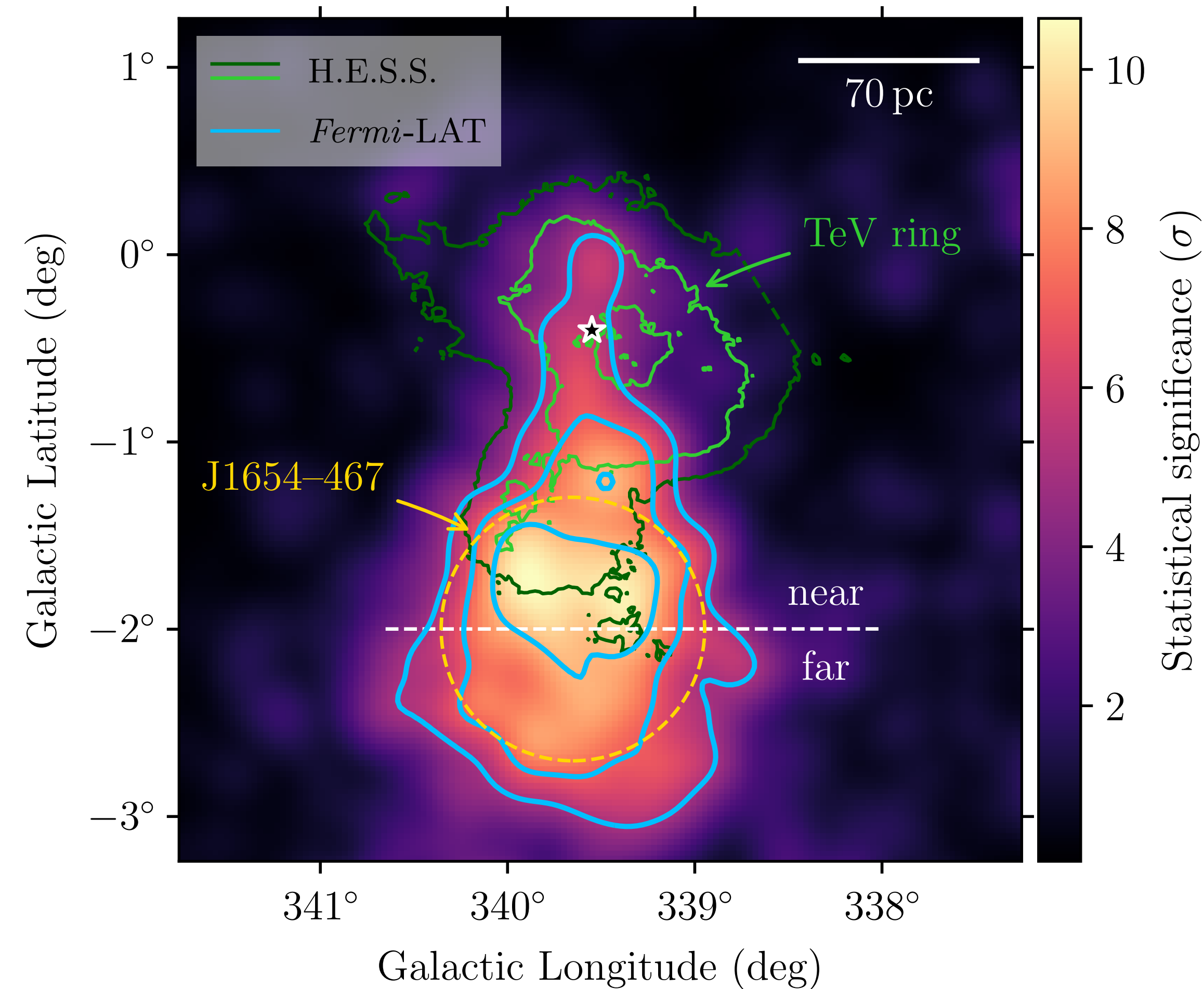
- ▶ **superbubble** expands asymmetrically due to ISM density gradient, but has not fully broken out of the Galactic disk yet
- ▶ cosmic rays accelerated at **cluster wind termination shock** (as in Härer et al. 2023)
- ▶ **high-energy electrons** lose energy quickly
→ produce TeV emission close to star cluster
- ▶ **low-energy electrons** are transported along outflow
→ produce GeV emission far from star cluster

■ Simple IC model

- ▶ electron acceleration efficiency: $\eta_e \approx 0.7\%$
- ▶ electron energy density in outflow: $U_e \sim (1 - 10) \text{ eV cm}^{-3}$

■ Implications

- ▶ expect $\eta_p > \eta_e$ and hence $U_p > U_e \rightarrow$ the outflow is loaded with cosmic rays!
- ▶ the outflow will eventually open a channel for cosmic ray transport into the halo!



"Acceleration and transport of relativistic electrons in the jets of the microquasar SS 433"

Science 383, 402-406 (2024)

RESEARCH

GAMMA-RAY ASTRONOMY

Acceleration and transport of relativistic electrons in the jets of the microquasar SS 433

H.E.S.S. Collaboration*†

SS 433 is a microquasar, a stellar binary system that launches collimated relativistic jets. We observed SS 433 in gamma rays using the High Energy Stereoscopic System (H.E.S.S.) and found an energy-dependent shift in the apparent position of the gamma-ray emission from the parsec-scale jets. These observations trace the energetic electron population and indicate that inverse Compton scattering is the emission mechanism of the gamma rays. Our modeling of the energy-dependent gamma-ray morphology constrains the location of particle acceleration and requires an abrupt deceleration of the jet flow. We infer the presence of shocks on either side of the binary system, at distances of 25 to 30 parsecs, and that self-collimation of the precessing jets forms the shocks, which then efficiently accelerate electrons.

SS 433 (also cataloged as V1343 Aql) is a binary system comprising a compact object, likely a black hole (1–3), and a type A supergiant star (4). Material from the supergiant is accreted onto the black hole, causing the latter to launch a pair of jets moving in opposite directions at approximately a quarter of the speed of light (5–7). The jets are orientated almost perpendicular to our line of sight from Earth (8) and precess with a half-opening angle of 20° and a period of 162 days (9–12). Adopting a distance measurement of 5.5 kpc (7), optical and radio observations have shown that the precessing jets extend to distances of $\sim 10^{-3}$ pc (13) and ~ 0.1 pc (7) from the black hole, respectively. X-ray emission reappears 25 pc from the binary (Fig. 1), indicating collimated flows (the outer jets) on larger scales, which emit x-ray photons through nonthermal processes (14–17).

The outer jets terminate ~ 100 pc from the black hole (14), where they deform the surrounding radio nebula (known as W 50 or SNR G039.7-02.0), which is thought to be the supernova remnant associated with the formation of the compact object in SS 433 (18). The morphology of W 50 indicates that the opening angle of the outer jets is considerably smaller than the 20° precession angle of the inner jets (19); the origin of this discrepancy is unknown (20). The lack of apparent change in the measured positions of radio filaments in the jet termination regions over a 33-year period provides an upper limit on their velocity of $< 0.023c$ (21, 22), although it is unclear whether the radio filaments trace the jets' flow. Bright x-ray knots emitting synchrotron radiation have been observed in the outer jets, but the temporal baseline and angular resolution were insufficient to determine their velocity (23). The dynamics of the outer jets and their termination process are poorly understood.

*Corresponding author: Laura Olivera-Nieto (laura.olivera-nieto@mpi-hd.mpg.de); Brian Reville (brian.reville@mpi-hd.mpg.de); Jim Hinton (jim.hinton@mpi-hd.mpg.de); Michelle Tsirou (michelle.tsirou@desy.de)

†H.E.S.S. Collaboration authors and affiliations are listed in the supplementary materials.

Several attempts have been made to use x-ray observations to probe the nonthermal emission mechanisms and internal dynamics of the eastern (16, 24) and western (17) outer jets. However, observations of the x-ray synchrotron emission alone cannot resolve variations in the distribution of accelerated particles. The intensity of synchrotron emission is approximately proportional to the number density of accelerated electrons and the energy density of the magnetic field; the latter is poorly constrained. X-ray-emitting electrons can also up-scatter low-energy photons to the gamma-ray regime through the inverse Compton scattering process. This process directly traces the population of high-energy electrons because the diffuse low-energy photon distribution in the Galaxy is expected to be smooth on the spatial scale of the outer jets (25, 26). Previous observations of tera-electron volt gamma rays emitted by the outer jets of SS 433 (27) indicate that the same energetic electrons responsible for the x-ray emission also produce gamma rays through inverse Compton scattering (28, 29). However, the angular resolution was insufficient to determine the emission regions and therefore the source of the energetic particles.

H.E.S.S. observations of SS 433

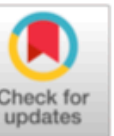
We imaged the outer jets of SS 433 at tera-electron volt energies using the High Energy Stereoscopic System (H.E.S.S.) array of imaging atmospheric Cherenkov telescopes. The observations totaled more than 200 hours of exposure time and were analyzed by using previously described methods, which were optimized for faint sources and the highest energies (30). The extended source HESS J1908+063 (also known as MGRO J1908+06) contaminates part of the SS 433 jet so was modeled then subtracted from the data (figs. S2 and S3).

The resulting gamma-ray image (Fig. 1A) shows two regions of gamma-ray emission at the previously known x-ray positions of the eastern and western jets, with peak statistical significances of 7.8σ and 6.8σ , respectively. No significant ($>5\sigma$) emission was detected from the central binary or the eastern termination region (Fig. 1A), which is as we expected because the x-ray emission from those regions predominantly has a thermal emission mechanism (14, 31). Fermi J1913+0515 (which has coordinates right ascension $288.28^\circ \pm 0.04$, declination $5.27^\circ \pm 0.04$) is a giga-electron volt gamma-ray source known to pulsate with a period consistent with the jet precession (32), indicating a potential connection with the SS 433 system. We detected no significant tera-electron volt emission from this source (26). The measured spectral energy distributions of each of the jets are shown in Fig. 1, B and C.

To investigate the energy dependence of the gamma-ray emission, we split the full H.E.S.S. energy range into three bands (0.8 to 2.5 TeV, 2.5 to 10 TeV, and >10 TeV), which were selected to have approximately the same gamma-ray excess counts over the background in each band. The significance maps for each band are shown in Fig. 2. We detected significant ($>5\sigma$) gamma-ray emission along both jets for the two highest-energy bands. In the lowest-energy band, we found lower-significance evidence of emission at 4.4σ and 4.7σ for the eastern and western jets, respectively. Gamma-ray emission >10 TeV appears only at the base of the outer jets (visible in x-rays) for both the eastern and western jets. By contrast, lower-energy gamma rays have their peak surface brightnesses at locations further along each jet, except for the lowest-energy band on the eastern side. In the latter case, no significant emission was detected inside the x-ray jet region, and evidence for emission appears close to the outer jet base (Fig. 2A). In the western jet, the best-fitting positions of the gamma-ray emission in each energy band have distances from the central binary (table S4) that differ from each other by 0.97σ and 2.6σ when comparing adjacent energy bands and by 5.3σ when comparing the lowest- and highest-energy band. The equivalent values for the eastern jet are 2.6σ , 3.3σ , and 0.1σ . Our significance calculations include both systematic and statistical sources of uncertainty and a trials factor correction (26).

Location of the particle acceleration

We interpret the offsets between the emission in different energy bands as indicating that transport of particles in the outer jets is dominated by advection (the bulk jet flow), not diffusion (random scattering of the particles by magnetic field fluctuations). The energy-dependent morphology then reflects an energy-dependent particle energy loss timescale. We infer that the emission arises from relativistic



The microquasar SS 433



The microquasar SS 433



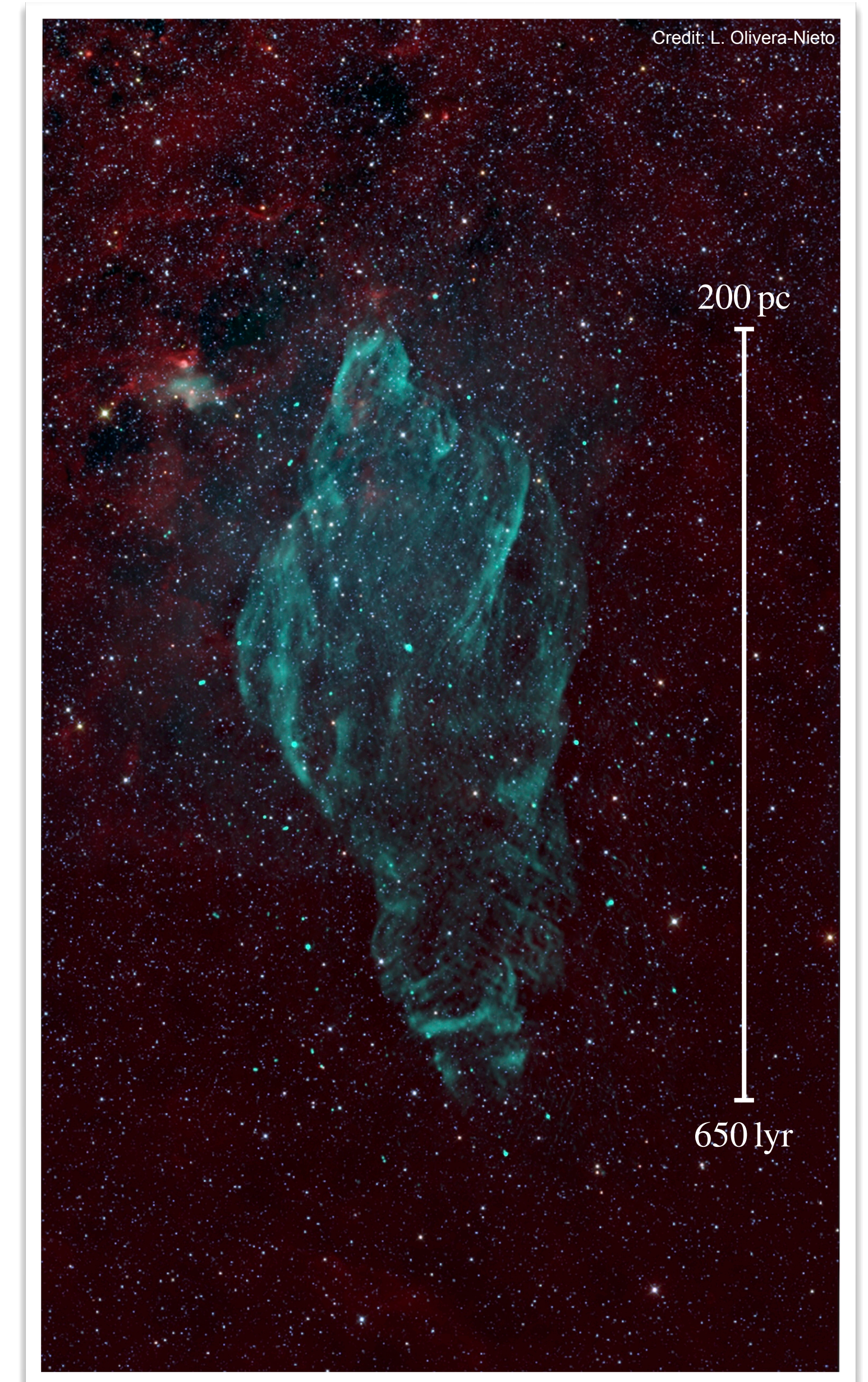
The microquasar SS 433



The microquasar SS 433

- **Supernova remnant W50**

- ▶ ~20,000 years old
- ▶ radio emission → synchrotron radiation from relativistic electrons



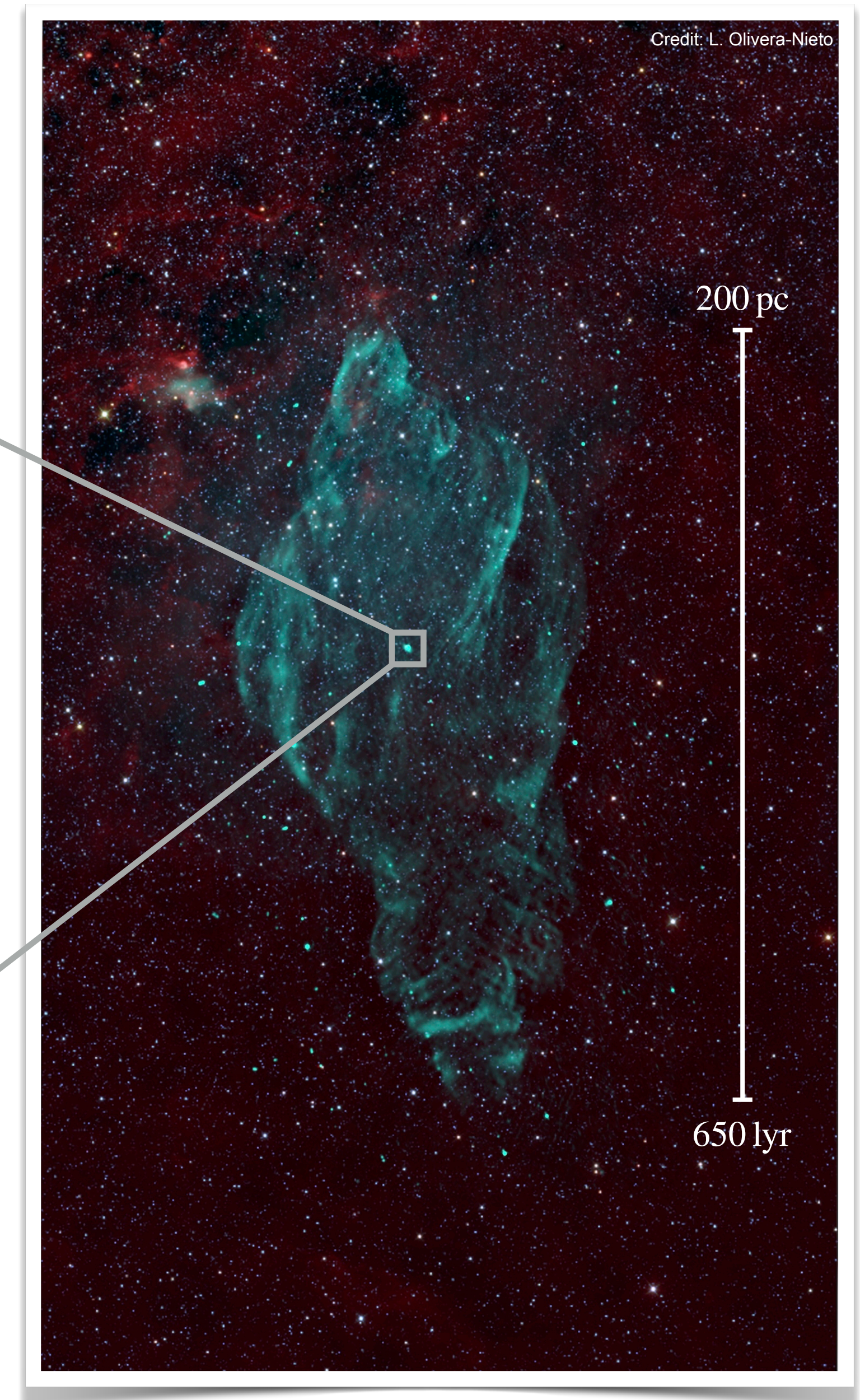
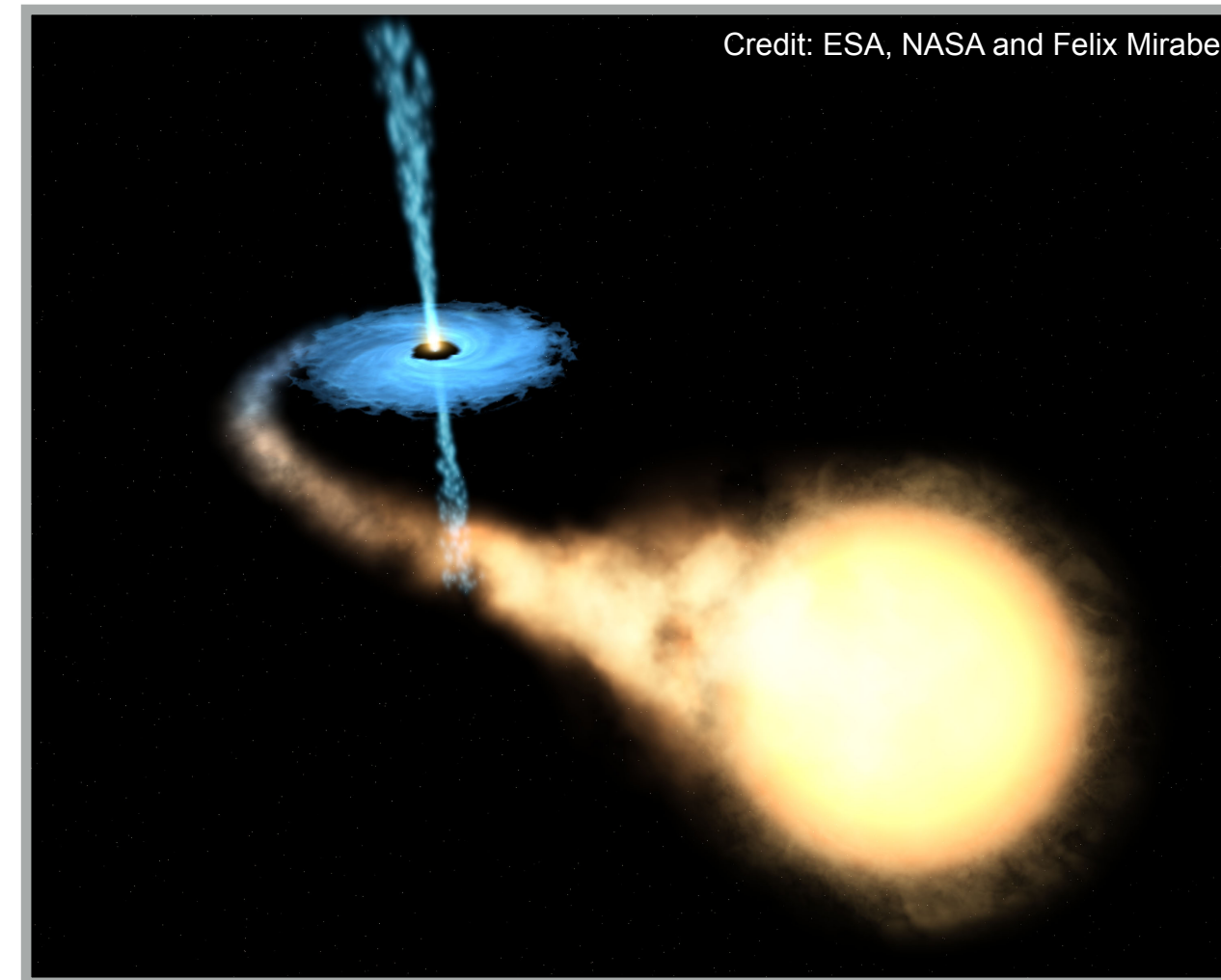
The microquasar SS 433

- **Supernova remnant W50**

- ▶ ~20,000 years old
- ▶ radio emission → synchrotron radiation from relativistic electrons

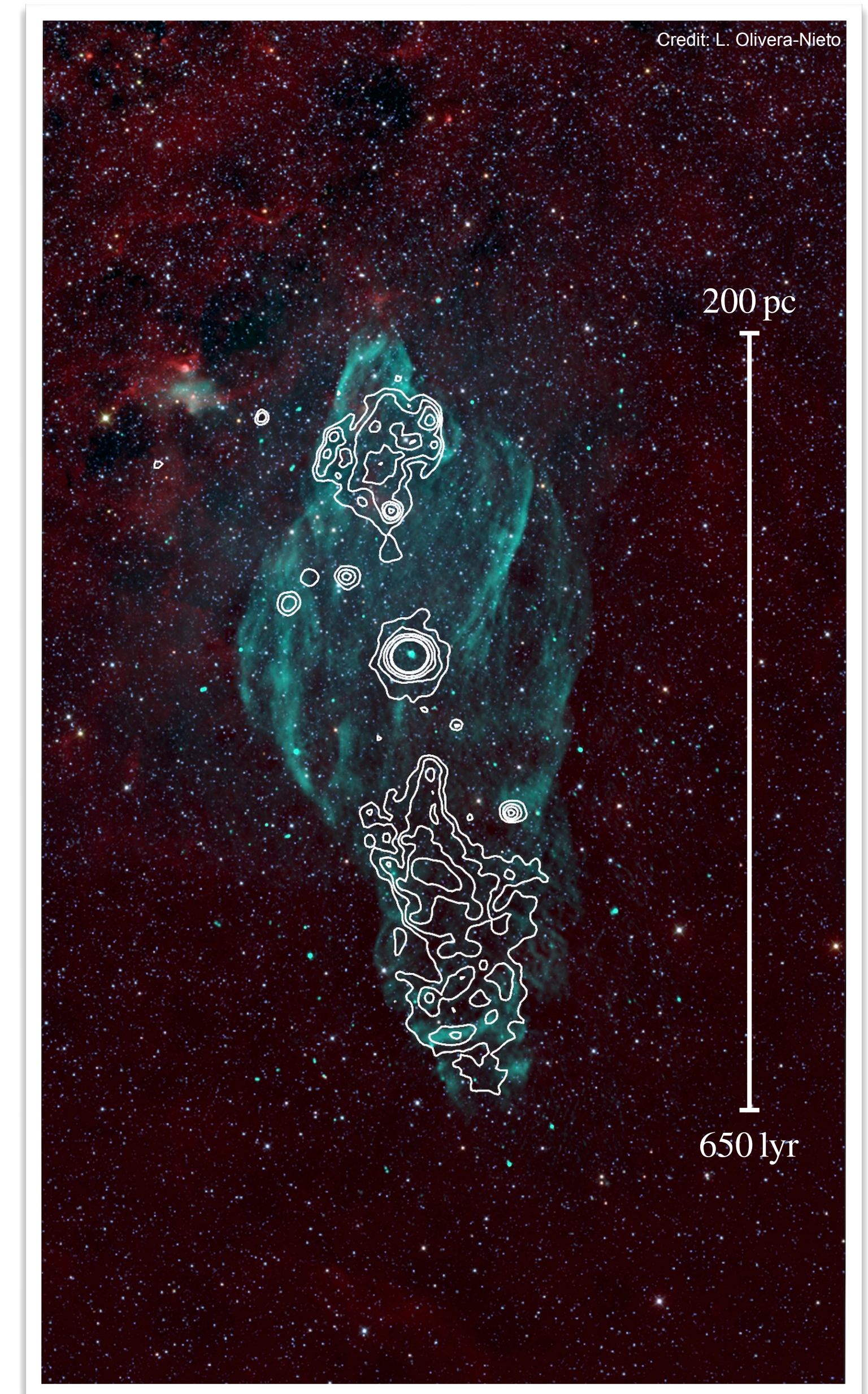
- **Microquasar SS 433**

- ▶ binary system: black hole + supergiant
- ▶ black hole accretes matter, launches jets



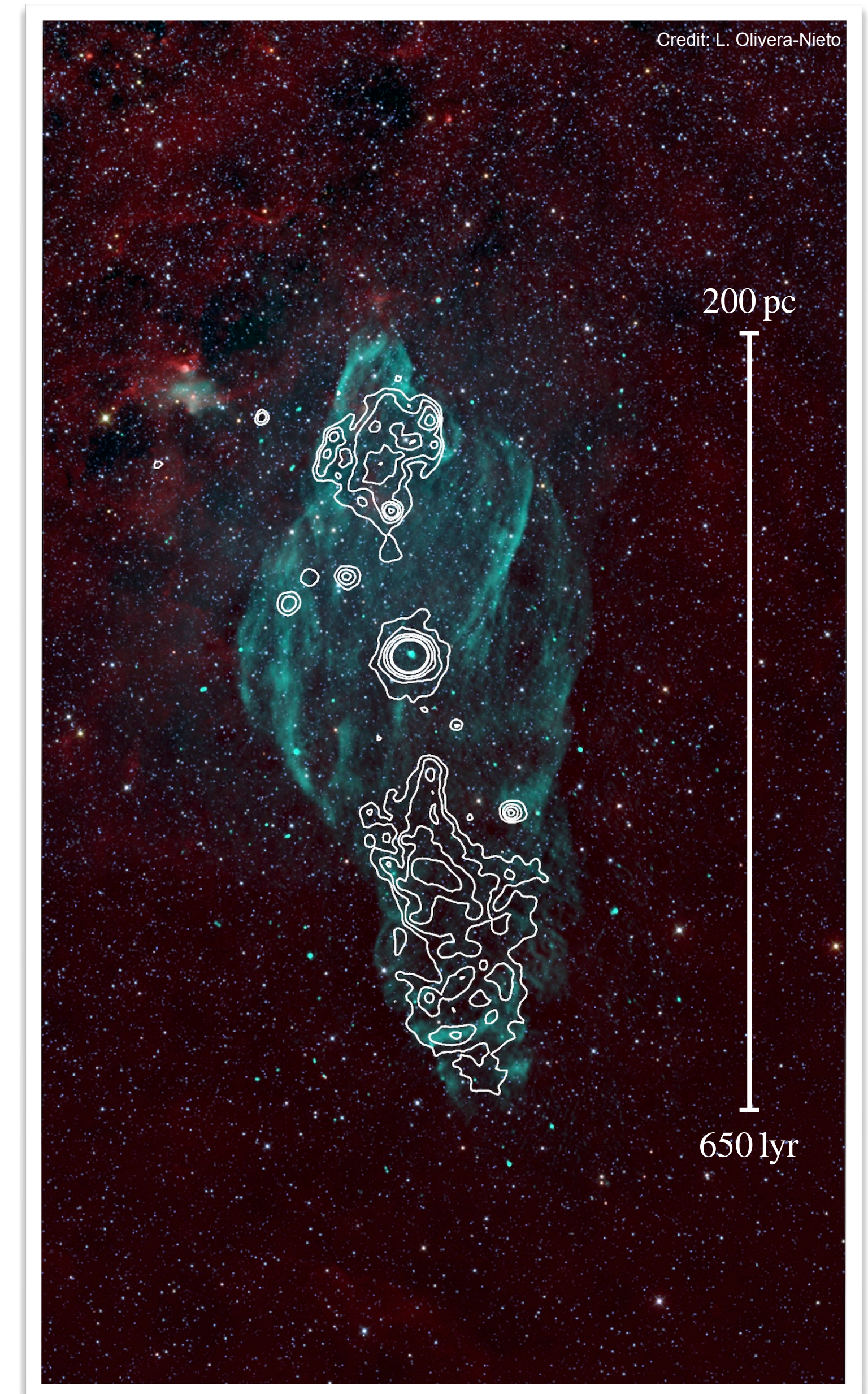
The microquasar SS 433

- **Supernova remnant W50**
 - ▶ ~20,000 years old
 - ▶ radio emission → synchrotron radiation from relativistic electrons
- **Microquasar SS 433**
 - ▶ binary system: black hole + supergiant
 - ▶ black hole accretes matter, launches jets
- **Non-thermal X-ray emission reveals presence of...**
 - ▶ ... large-scale jets
 - ▶ ... highly energetic electrons (> 100 TeV)



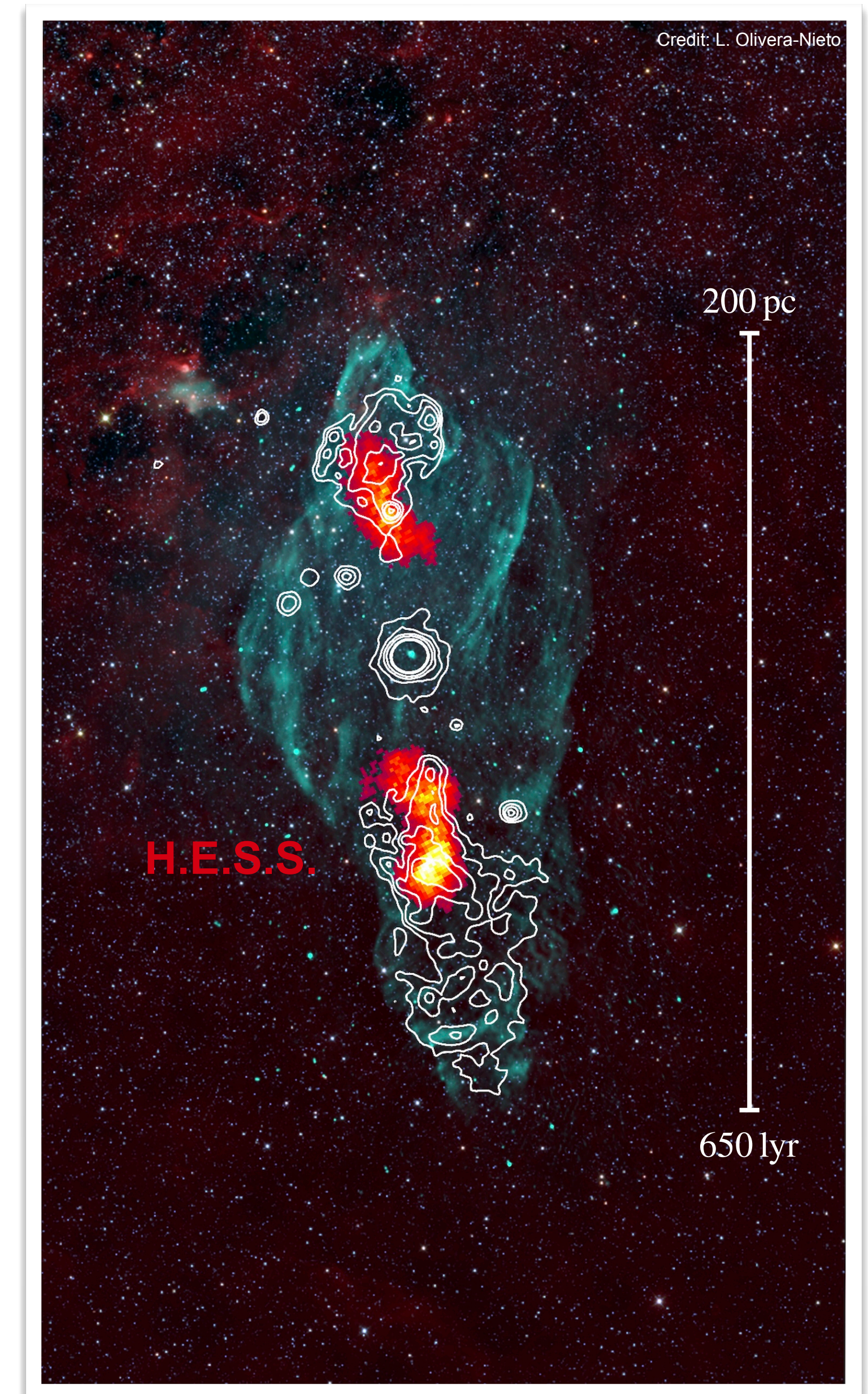
The microquasar SS 433

- **Supernova remnant W50**
 - ▶ ~20,000 years old
 - ▶ radio emission → synchrotron radiation from relativistic electrons
- **Microquasar SS 433**
 - ▶ binary system: black hole + supergiant
 - ▶ black hole accretes matter, launches jets
- **Non-thermal X-ray emission reveals presence of...**
 - ▶ ... large-scale jets
 - ▶ ... highly energetic electrons (> 100 TeV)
- **But we don't know:**
 - ▶ where are those electrons accelerated?
 - ▶ why do the jets “re-appear” at ~25 pc from the centre?



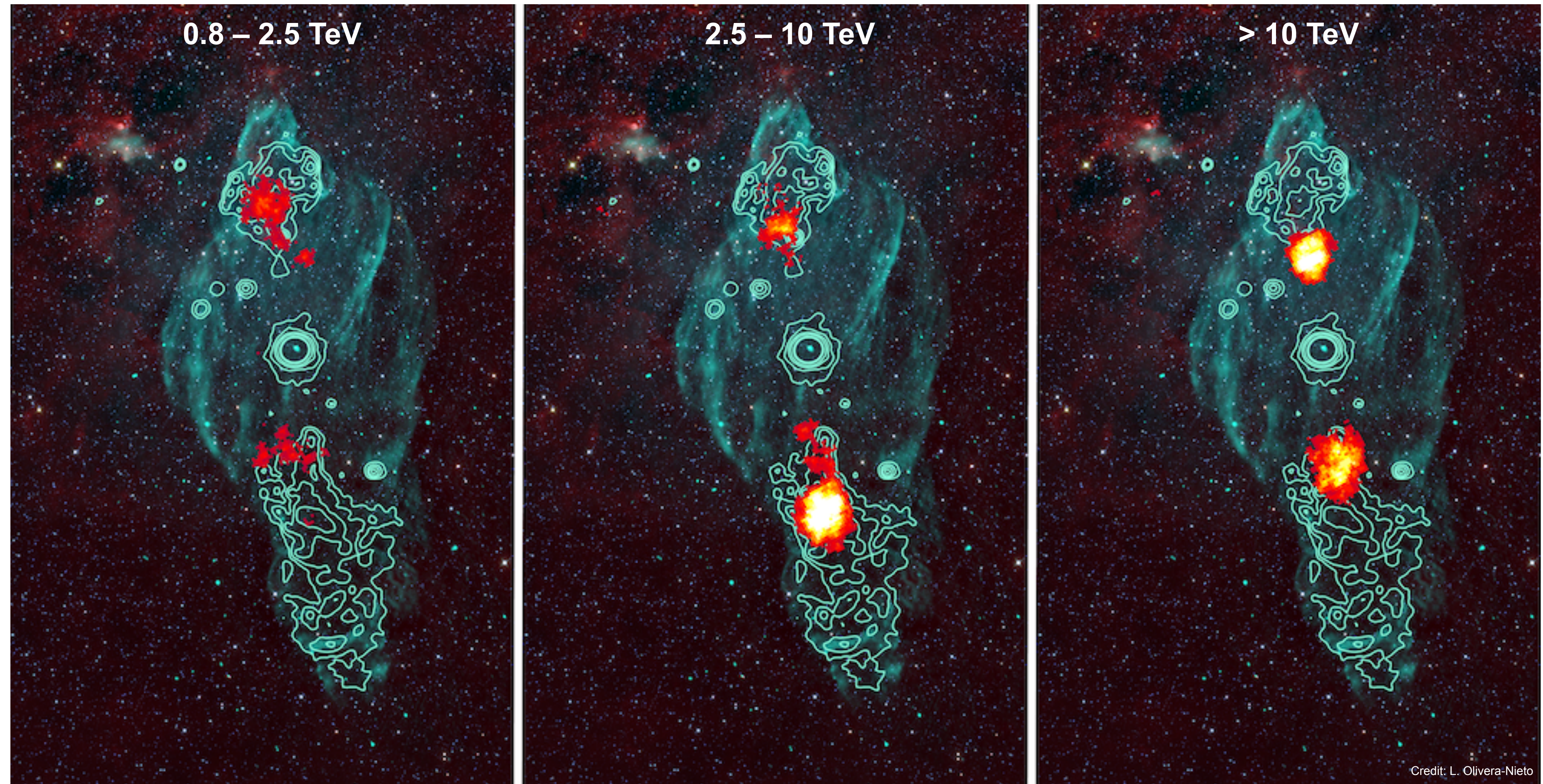
The microquasar SS 433

- **Supernova remnant W50**
 - ▶ ~20,000 years old
 - ▶ radio emission → synchrotron radiation from relativistic electrons
- **Microquasar SS 433**
 - ▶ binary system: black hole + supergiant
 - ▶ black hole accretes matter, launches jets
- **Non-thermal X-ray emission reveals presence of...**
 - ▶ ... large-scale jets
 - ▶ ... highly energetic electrons (> 100 TeV)
- **H.E.S.S. measurement**
 - ▶ TeV gamma-ray emission from jets



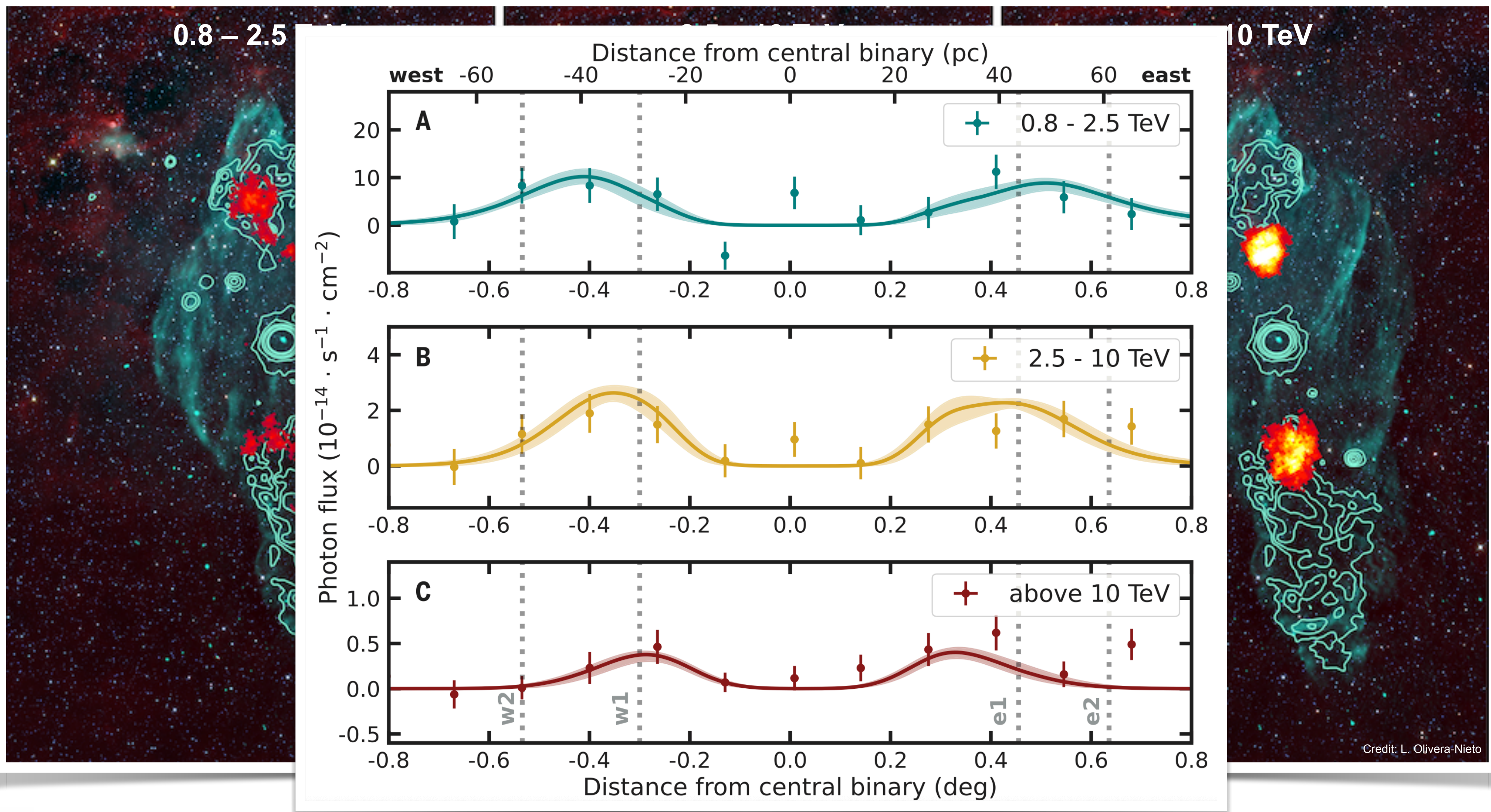
The microquasar SS 433

- **Supernova**
 - ▶ ~20,000 light years from Earth
 - ▶ radio emission
- **Microquasar**
 - ▶ binary system
 - ▶ black hole
- **Non-thermal emission**
 - ▶ ... large
 - ▶ ... high energy
- **H.E.S.S.**
 - ▶ TeV gamma rays



The microquasar SS 433

- **Supernova remnant**
 - ▶ ~20,000 years old
 - ▶ radio emission
- **Microquasar**
 - ▶ binary system
 - ▶ black hole
- **Non-thermal emission**
 - ▶ ... large
 - ▶ ... high energy
- **H.E.S.S.**
 - ▶ TeV gamma rays



The microquasar SS 433

- **Supernova remnant W50**

- ▶ ~20,000 years old
- ▶ radio emission → synchrotron radiation from relativistic electrons

- **Microquasar SS 433**

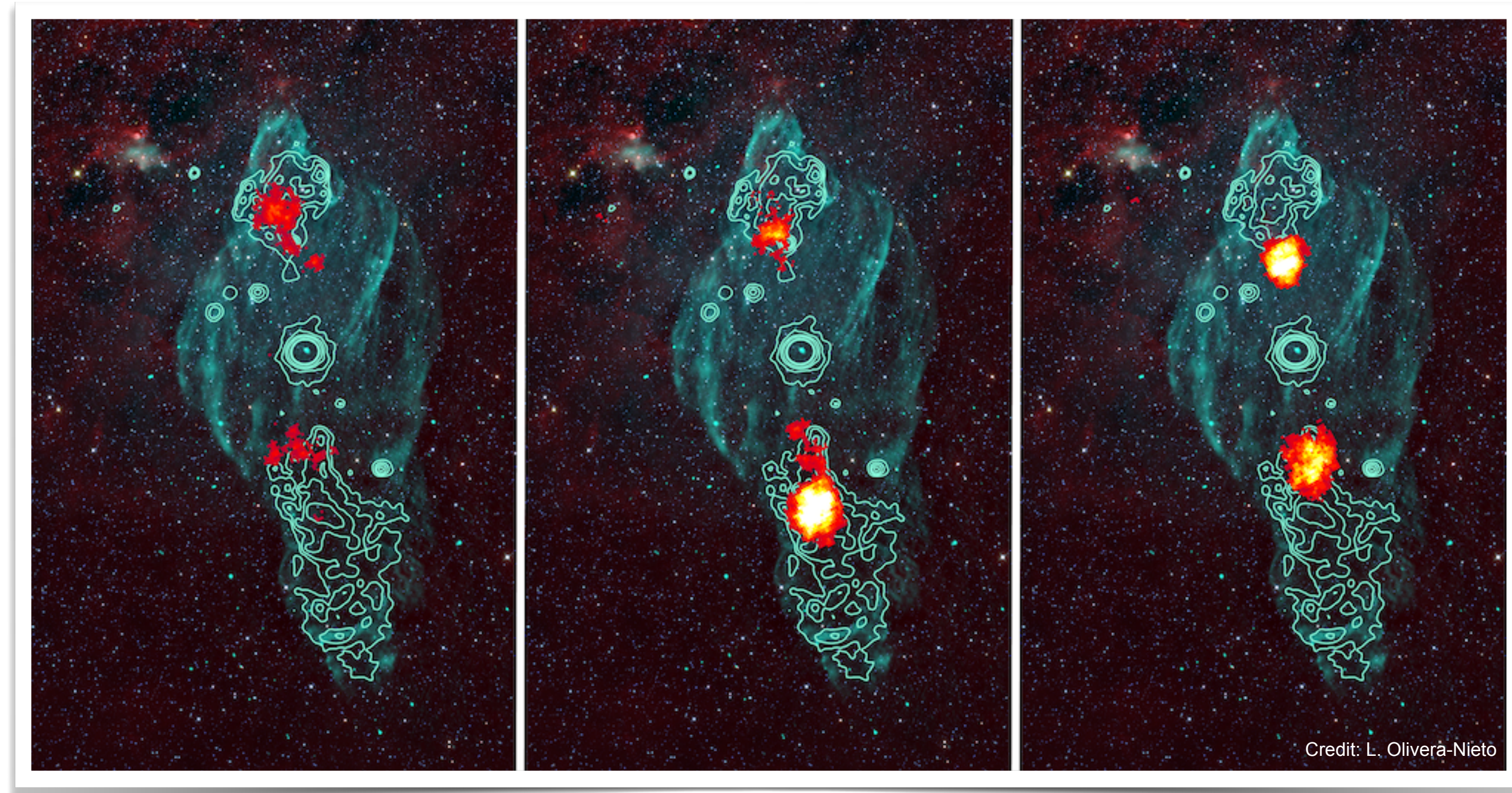
- ▶ binary system: black hole + supergiant
- ▶ black hole accretes matter, launches jets

- **Non-thermal X-ray emission reveals presence of...**

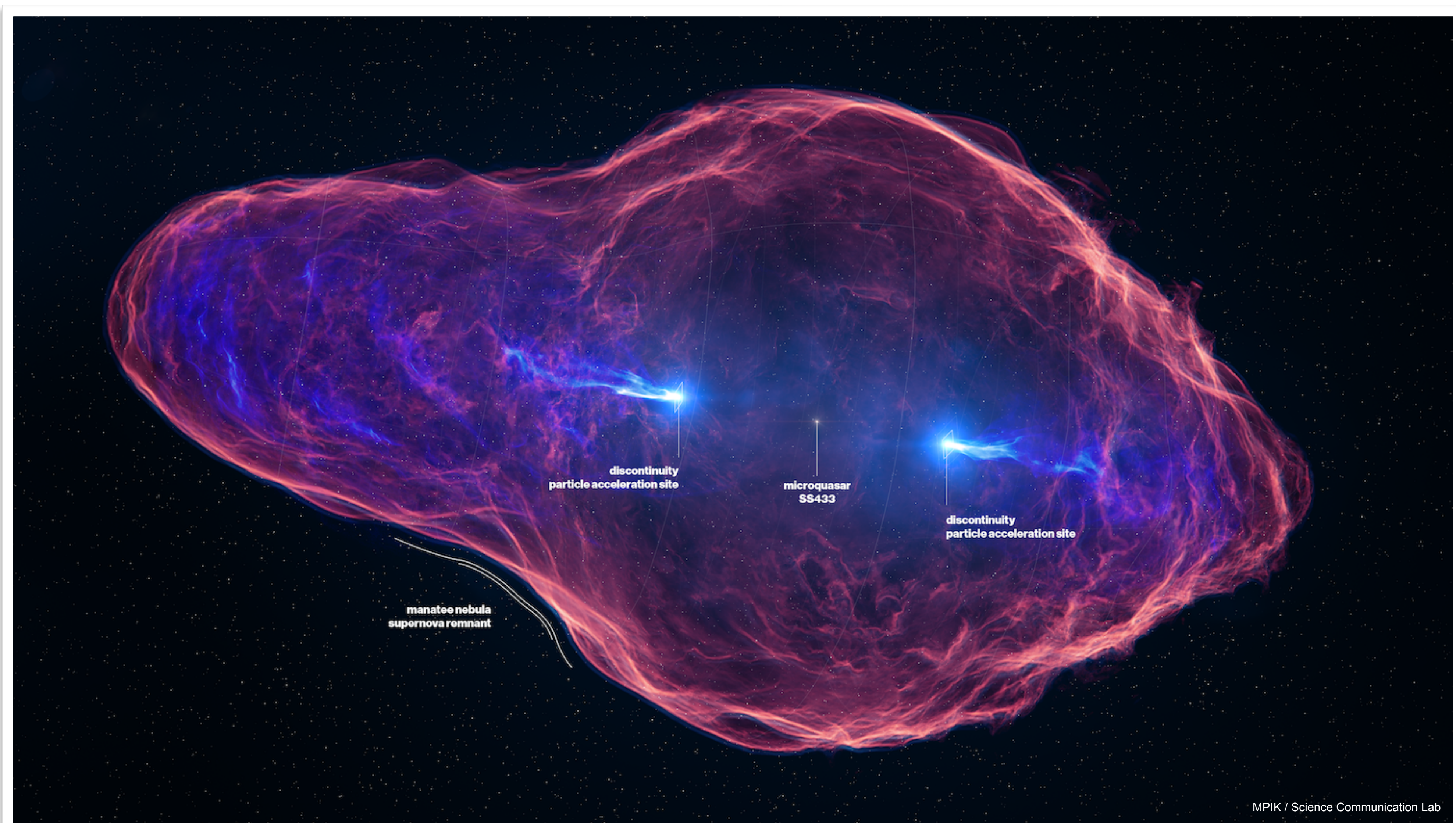
- ▶ ... large-scale jets
- ▶ ... highly energetic electrons (> 100 TeV)

- **H.E.S.S. measurement**

- ▶ TeV gamma-ray emission from jets
- ▶ energy-dependent morphology!
 - inverse-Compton emission from electrons
 - acceleration at base of large-scale jets
 - advection along the jet flow – with velocity $v_0 = (0.083 \pm 0.026_{\text{stat}} \pm 0.010_{\text{sys}}) c$



The microquasar SS 433



"Constraining the nature of the most extreme Galactic particle accelerator: H.E.S.S. observations of the microquasar V4641 Sgr"

Astronomy & Astrophysics, accepted (2025)

Constraining the nature of the most extreme Galactic particle accelerator. H.E.S.S. observations of the microquasar V4641 Sgr

A. Acharyya¹, F. Aharonian^{2,3}, H. Ashkar⁴, M. Backes^{5,6}, R. Batzofin⁷, D. Berge^{8,9}, K. Bernlöhr³, M. Böttcher⁶, C. Boisson¹⁰, J. Bolmont¹¹, F. Brun¹², B. Bruno¹³, C. Burger-Scheidlin¹⁴, T. Bylund¹⁵, S. Casanova¹⁴, J. Celic¹³, M. Cerruti¹⁵, A. Chen¹⁶, M. Chernyakova^{17,2}, J. O. Chibueze^{6,3}, O. Chibueze⁶, B. Cornejo¹², G. Cotter¹⁸, J. de Assis Scarpin⁹, M. de Bony de Lavergne^{12,19}, M. de Naurois⁴, E. de Oña Wilhelmi⁸, A. G. Delgado Giler⁹, J. Devin²⁰, A. Djannati-Atai¹⁵, A. Dmytriiev⁹, K. Egberts⁷, K. Egg¹³, J.-P. Ernenwein¹⁹, C. Escañuela Nieves³, P. Fauverge²¹, K. Feijen¹⁵, M. D. Filipovic²², G. Fontaine⁹, S. Funk¹³, S. Gabici¹⁵, Y.A. Gallant²⁰, J.F. Glicenstein¹², J. Glombitza¹³, P. Goswami²³, M.-H. Grondin²¹, L. Heckmann¹⁵, B. Heß²⁴, J.A. Hinton³, W. Hofmann⁹, T. L. Holch⁹, M. Holler²⁵, M. Jamroz²⁶, F. Jankowsky²³, A. Jardin-Blicq²¹, I. Jaroschewski¹², D. Jimeno⁸, I. Jung-Richardt¹³, K. Katarzyński²⁷, D. Kerszberg¹¹, B. Khélifi¹⁵, N. Komin^{20,16}, K. Kosack¹², D. Kostunin⁸, R.G. Lang¹³, S. Lazarević²², A. Lemièr¹⁵, M. Lemoine-Goumard²¹, J.-P. Lenain¹¹, P. Liniewicz²⁶, A. Luashvili⁹, J. Mackey⁷, D. Malyshev²⁴, V. Marandon¹², M. G. F. Mayer¹³, A. Mehta⁸, A.M.W. Mitchell¹³, R. Moderski²⁸, L. Mohrmann³, A. Montanari²³, E. Moulin¹², J. Niemiec¹⁴, L. Olivera-Nieto^{3,*,*}, M.O. Moghadam⁷, S. Panny²⁵, R.D. Parsons⁹, U. Pensec¹¹, P. Pichard¹⁵, T. Preis²⁵, G. Pühlhofer²⁴, M. Punch¹⁵, A. Quirrenbach²³, A. Reimer²⁵, G. Reimer²⁵, I. Reis¹², Q. Remy^{3,*,*}, H. X. Ren³, B. Reville^{3,*,*}, F. Rieger³, G. Roellinghoff¹³, G. Rowell³¹, B. Rudak²⁸, K. Sabri²⁰, S. Safi-Harb³⁰, V. Sahakian³², A. Santangelo²⁴, M. Sasaki¹³, F. Schüssler¹², J.N.S. Shapopi⁹, W. Si Said⁹, H. Sol¹⁰, L. Stawarz²⁶, S. Steinmass¹³, T. Tanaka³³, A.M. Taylor⁸, G. L. Taylor²¹, R. Terrier¹⁵, Y. Tian⁸, A. Timmermans³, M. Tsiros⁹, N. Tsuji^{34,*,*}, T. Unbehaun¹³, C. van Eldik¹³, M. Vecchi³⁵, C. Venter⁶, J. Vink²⁹, V. Voitsekhovskiy²⁹, S.J. Wagner²³, A. Wiercholska^{14,23}, M. Zacharias^{21,6}, A.A. Zdziarski²⁸, A. Zech¹⁰, W. Zhong⁴, S. Takekawa³⁶

(Affiliations can be found after the references)

November 13, 2025

ABSTRACT

Context. Microquasars have emerged as promising candidates to explain the cosmic-ray flux at petaelectronvolt energies. LHAASO observations revealed V4641 Sgr as the most extreme example so far. Its gamma-ray spectrum extends up to 800 TeV, which requires particles with multi-PeV energy. The TeV emission is highly extended, which challenges expectations given the reported low-inclination angle of the V4641 Sgr jets.

Aims. We spatially and spectrally resolved the gamma-ray emission from V4641 Sgr and investigated the particle acceleration in the system.

Methods. Using ≈ 100 h of H.E.S.S. data, we performed a spectro-morphological study of the gamma-ray emission around V4641 Sgr. We employed HI and dedicated CO observations of the region to infer the target material for cosmic-ray interactions.

Results. We detected multi-TeV emission around V4641 Sgr with a high significance. The emission region is elongated, and its major and minor axes are $0.34^{+0.04}_{-0.01}$ and $0.06^{+0.01}_{-0.01}$, respectively. We found a power-law spectrum with an index ≈ 1.8 , and together with results from other gamma-ray instruments, this reveals a spectral energy distribution (SED) that peaks at energies of ≈ 100 TeV for the first time. We found indications (3σ) of a two-component morphology, with indistinguishable spectral properties. The position of V4641 Sgr is inconsistent with the best-fit position of the single-component model and with the dip between the two components. We found no significant evidence of an energy-dependent morphology. No dense gas was found at any distance towards V4641 Sgr, which places an upper limit of $n_{\text{gas}} \lesssim 0.2 \text{ cm}^{-3}$ within the gamma-ray emission region.

Conclusions. The peak of the SED at ≈ 100 TeV identifies V4641 Sgr as a candidate cosmic-ray accelerator beyond the so-called knee. The absence of dense target gas places stringent energetic constraints on hadronic interpretations, however. The H.E.S.S. measurement requires an unusually hard (≈ 1.5) spectral index for the protons. A leptonic scenario faces fewer obstacles if the particle transport is fast enough to avoid losses and to reproduce the observed energy-independent morphology. The absence of bright X-ray emission across the gamma-ray emission region requires a magnetic field strength $\lesssim 3 \mu\text{G}$, however. Our findings favour a leptonic origin of the gamma-ray emission. This conclusion does not exclude hadron acceleration in the V4641 Sgr system.

Key words. Acceleration of particles – Radiation mechanisms: non-thermal – Gamma rays: stars – Stars: binaries – Stars: jets

1. Introduction

The origin of the cosmic-ray spectrum measured at Earth remains one of the largest mysteries in high-energy astrophysics. Precise measurements have revealed several spectral features that were interpreted as a result of differences in the produc-

tion processes or astrophysical source classes involved, and also cosmic-ray propagation through space. At energies of a few petaelectronvolts, a spectral break (usually referred to as the knee) was measured (Amenomori et al. 2008; Aartsen et al. 2019; LHAASO Collaboration et al. 2025). Below this energy, convincing theoretical arguments and experimental evidence have suggested that particles are predominantly accelerated in supernova remnants (SNRs, see e.g. Ginzburg & Syrovatskii 1964; Hillas 2005; Bell 2014). Because cosmic rays arriving at Earth

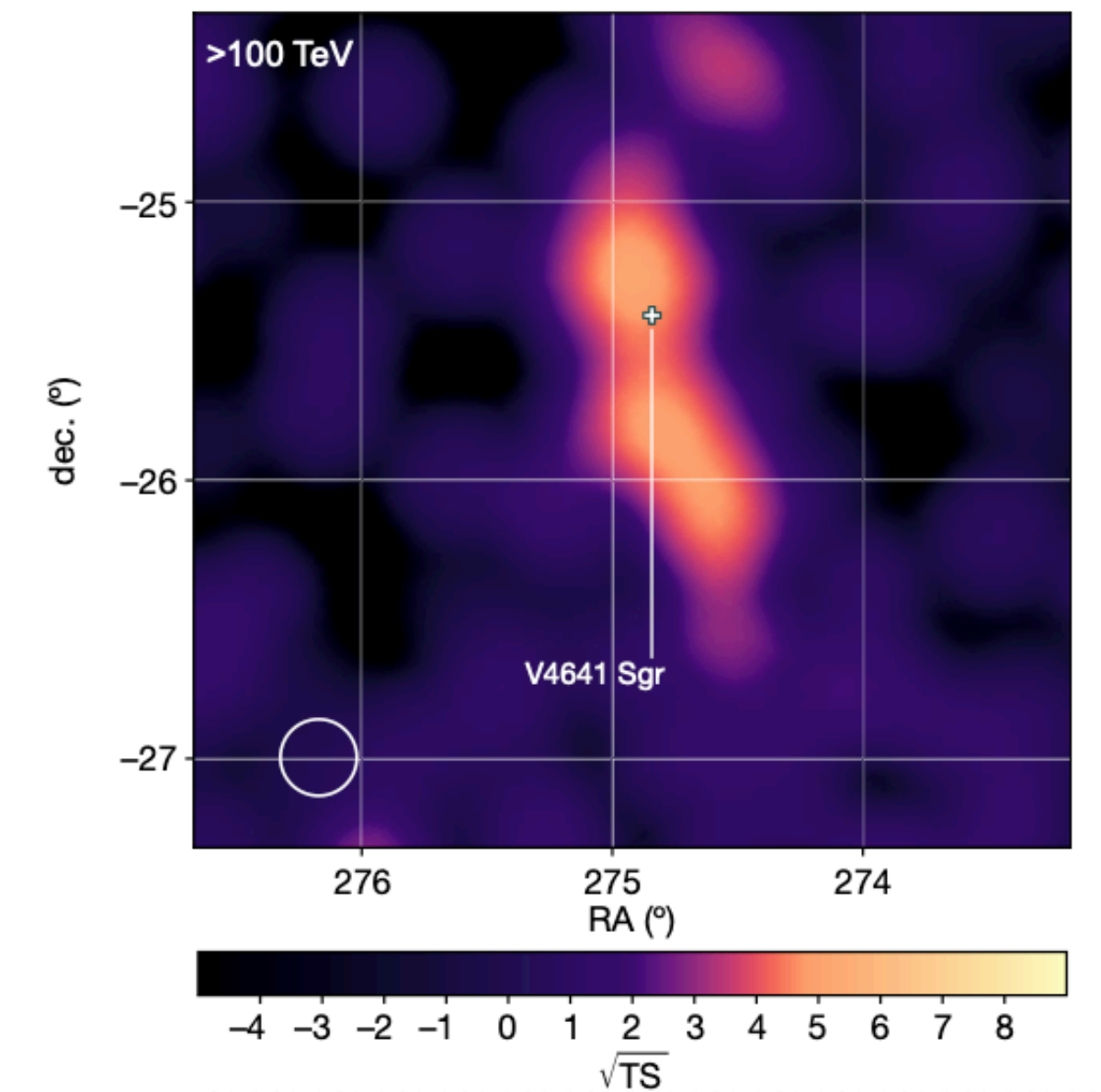
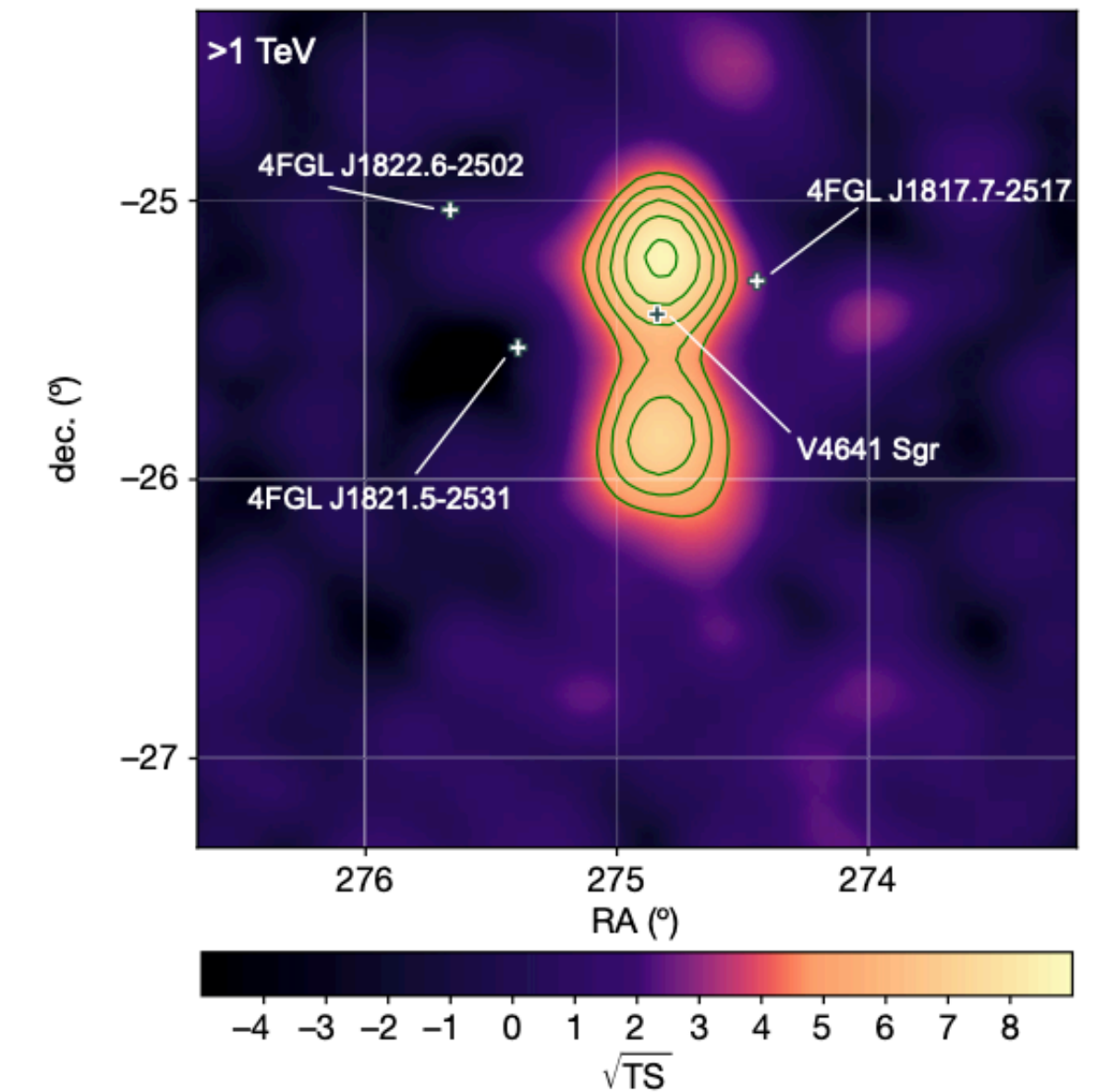
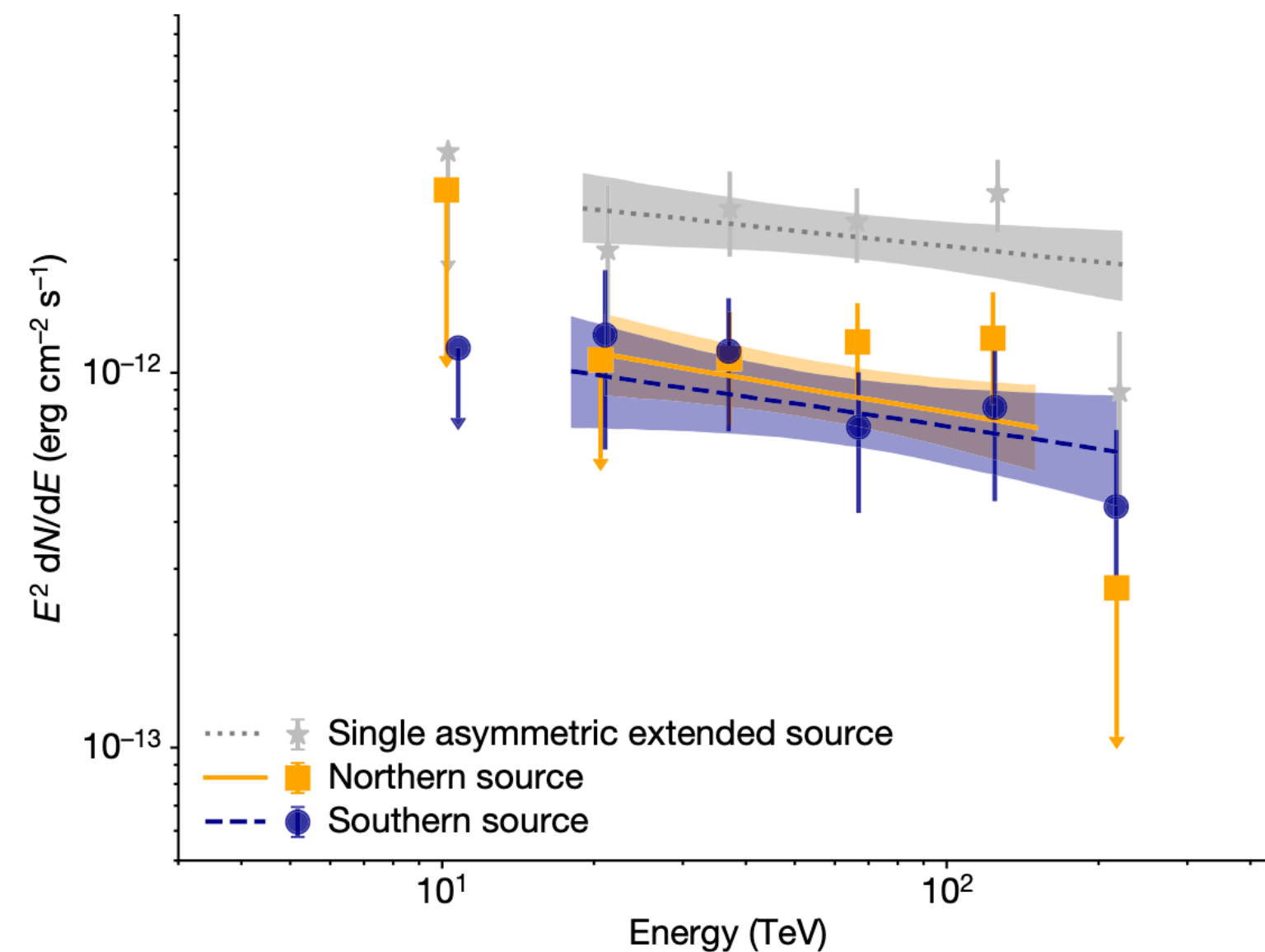
Send offprint requests to:
e-mail: contact.hess@hess-experiment.eu;
* Corresponding authors

V4641 Sgr

- **Off-plane ($b = -5^\circ$) microquasar**
 - not deemed very remarkable until recently...

V4641 Sgr

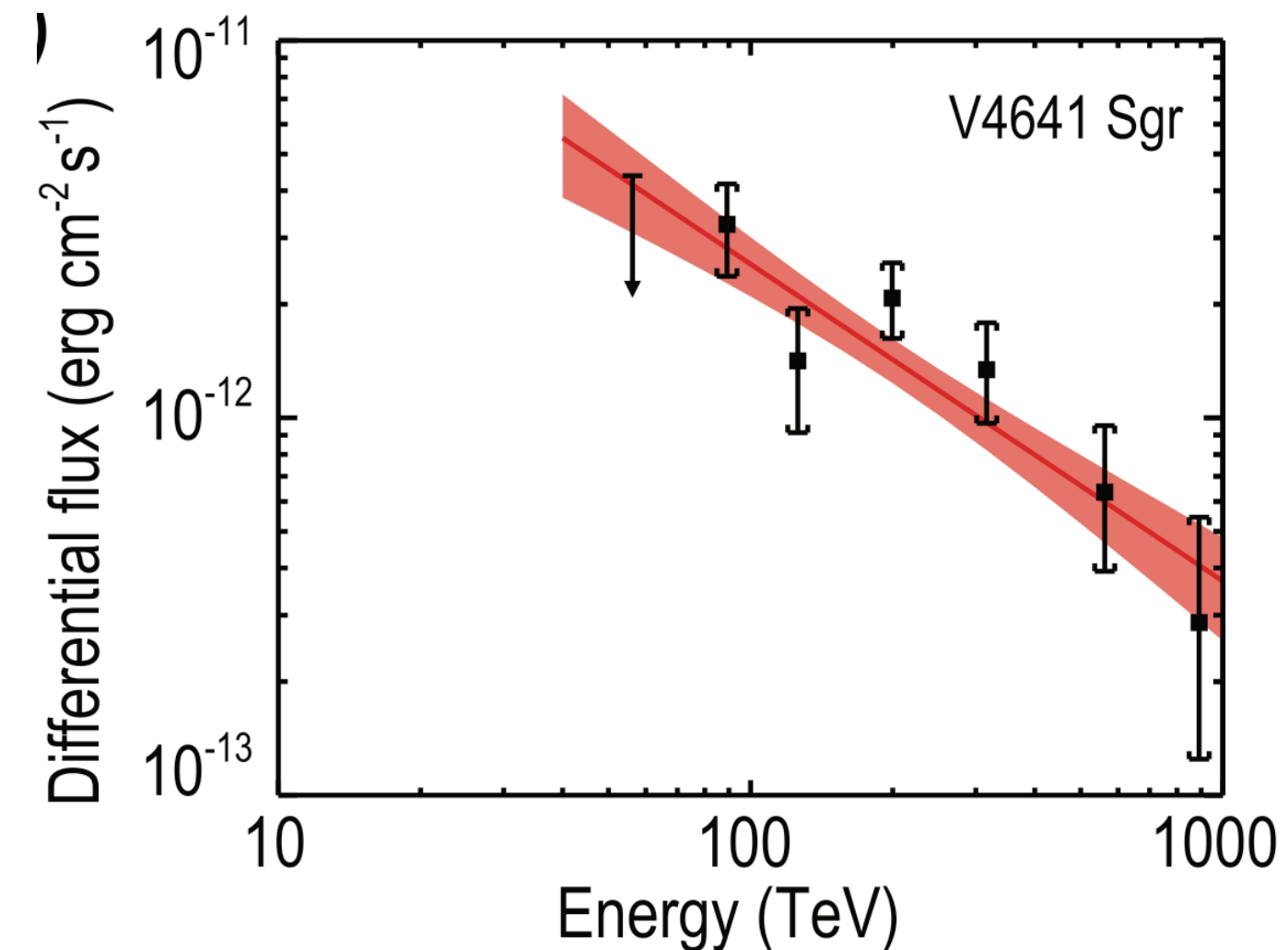
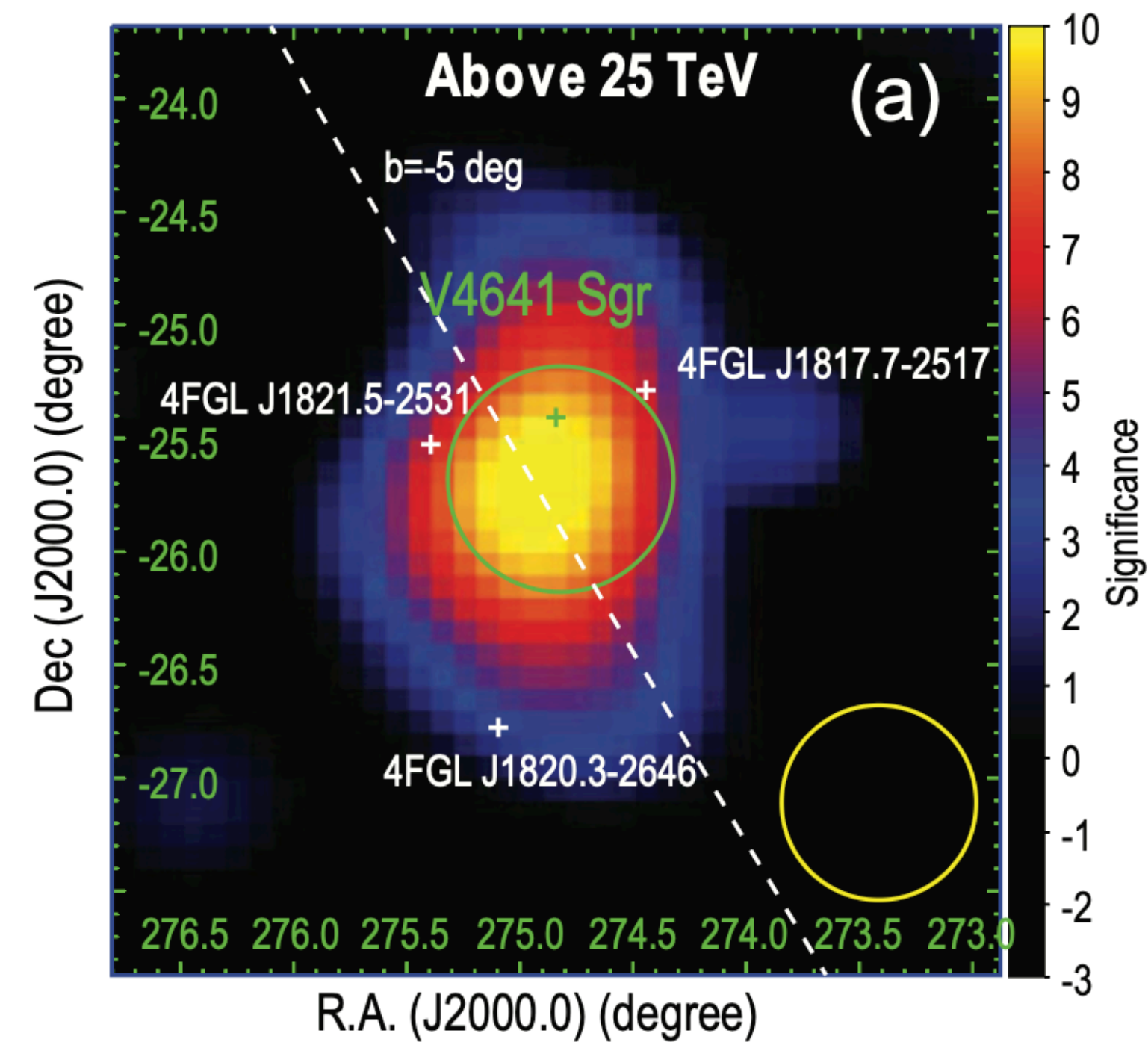
- **Off-plane ($b = -5^\circ$) microquasar**
 - ▶ not deemed very remarkable until recently...
- **Detection with HAWC**
 - ▶ energy range 18–217 TeV
 - ▶ hard spectral index ($\Gamma \approx -2.2$)
 - ▶ no clear preference between single elongated component or two point-like sources



HAWC Collaboration, Nature **634**, 557-560 (2024)

V4641 Sgr

- **Off-plane ($b = -5^\circ$) microquasar**
 - ▶ not deemed very remarkable until recently...
- **Detection with HAWC**
 - ▶ energy range 18–217 TeV
 - ▶ hard spectral index ($\Gamma \approx -2.2$)
 - ▶ no clear preference between single elongated component or two point-like sources
- **Detection with LHAASO**
 - ▶ energy range 40–800 TeV (!)
 - ▶ softer spectral index ($\Gamma \approx -2.8$)
 - ▶ morphology poorly constrained

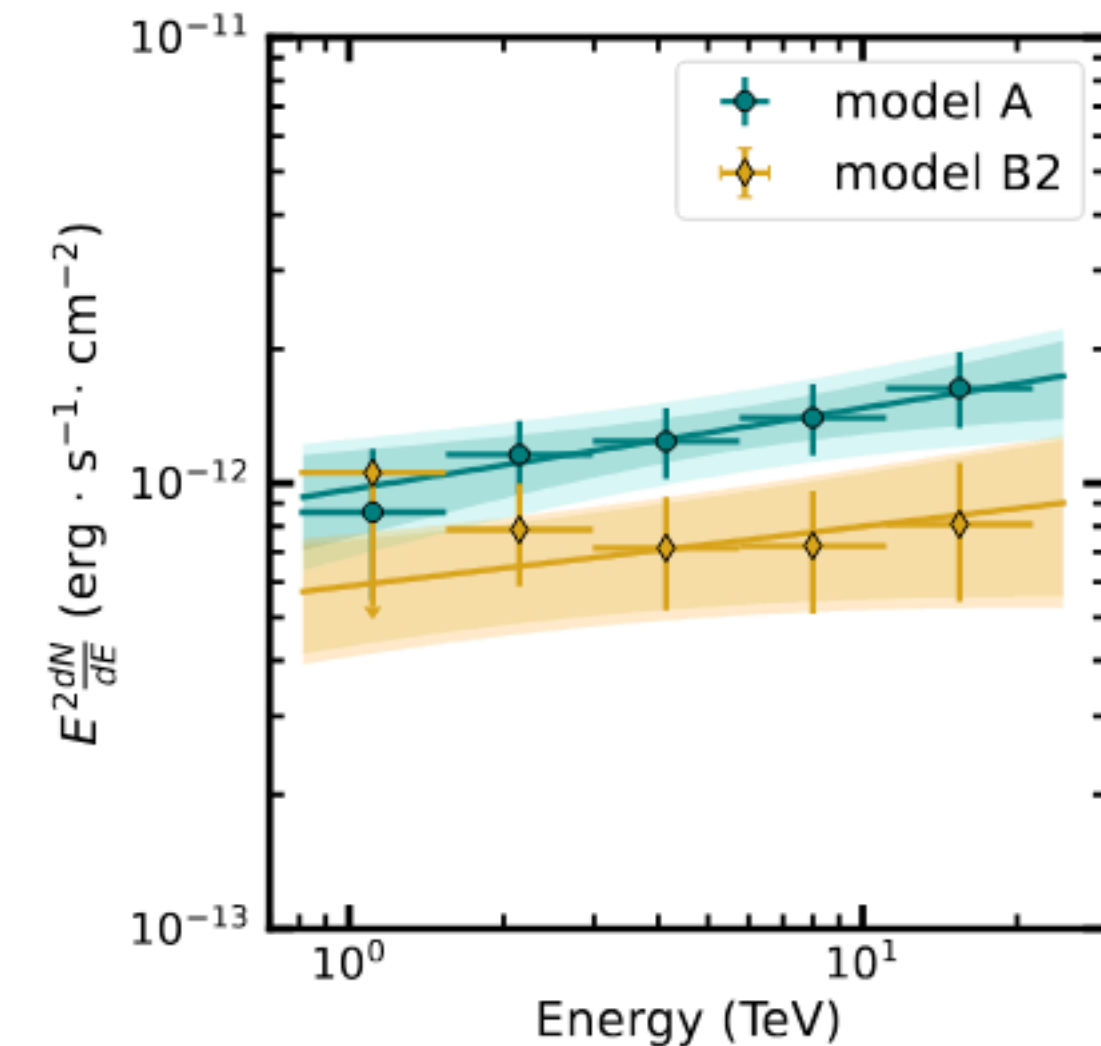
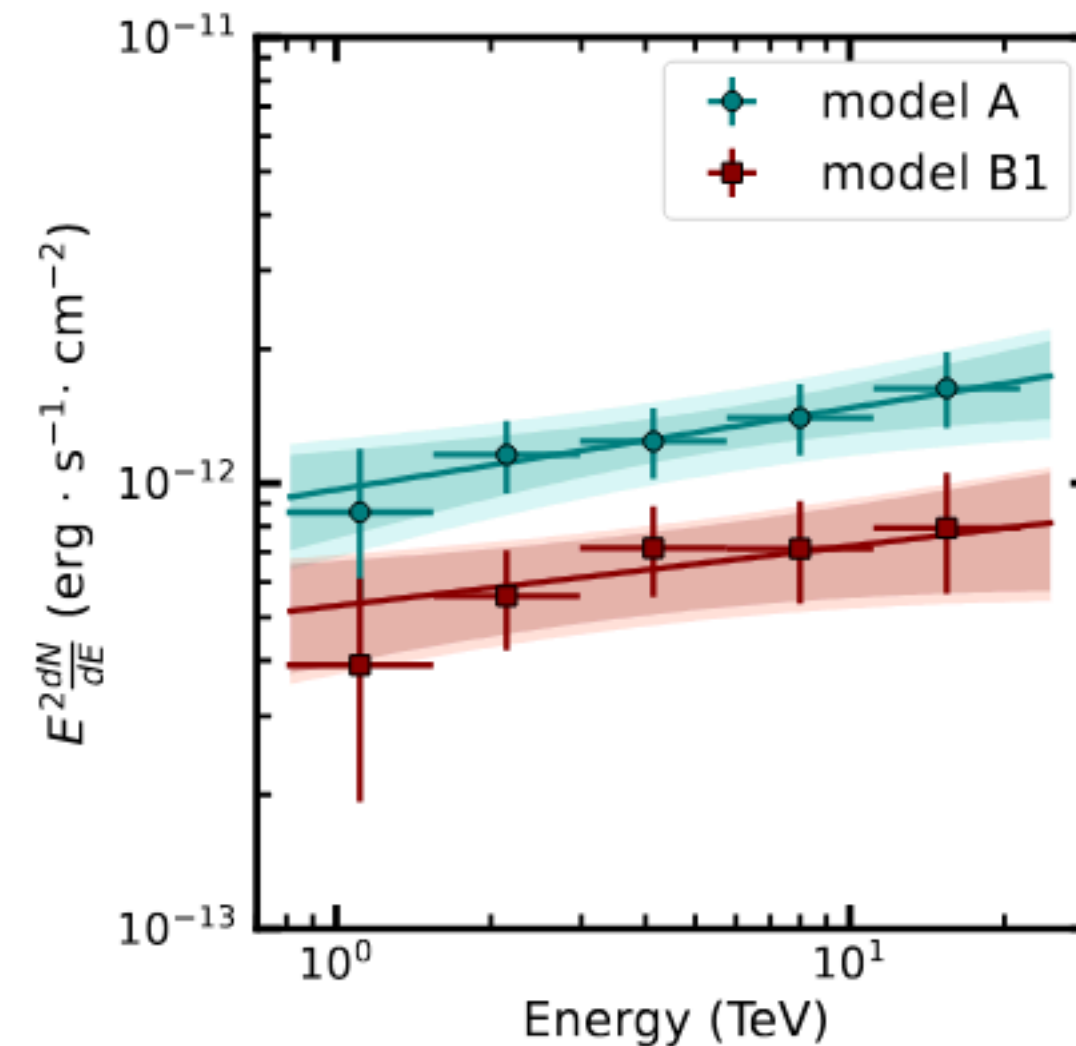
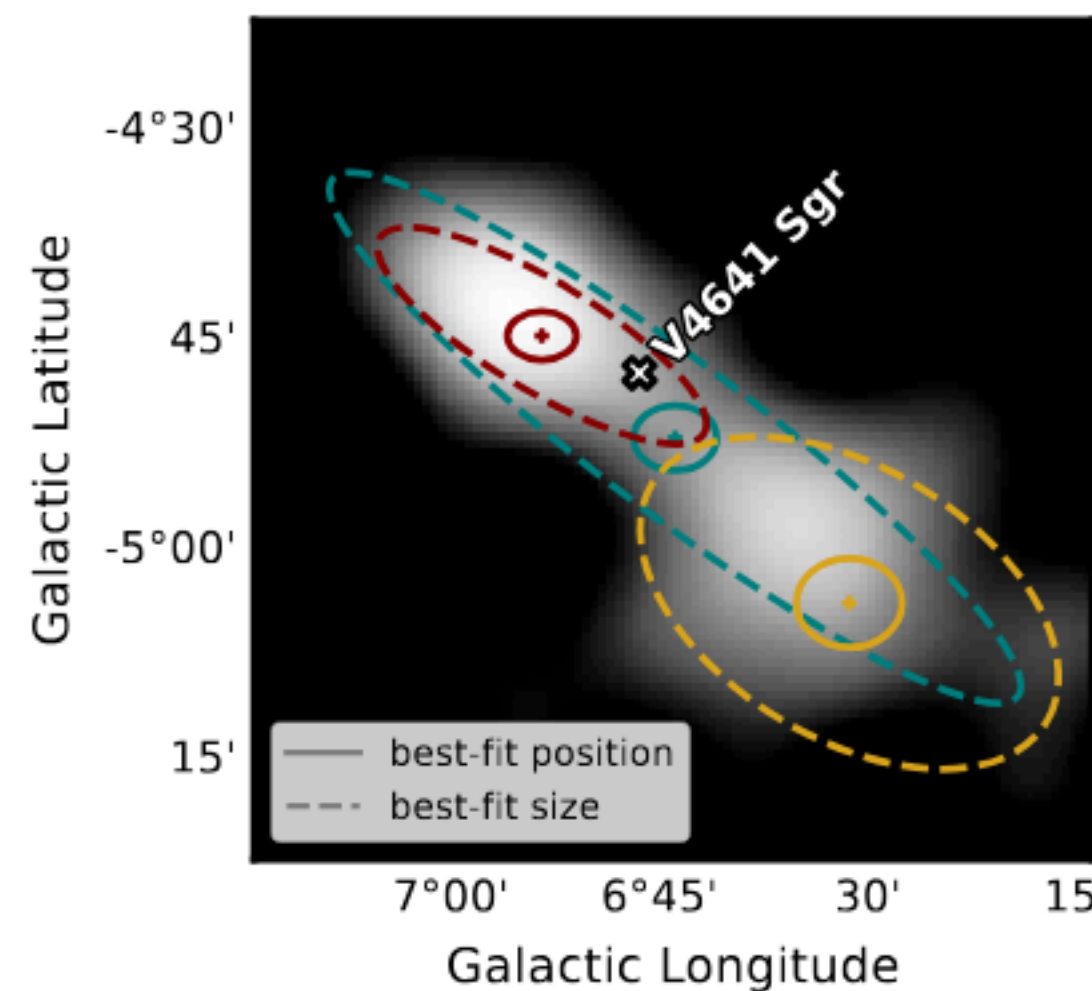
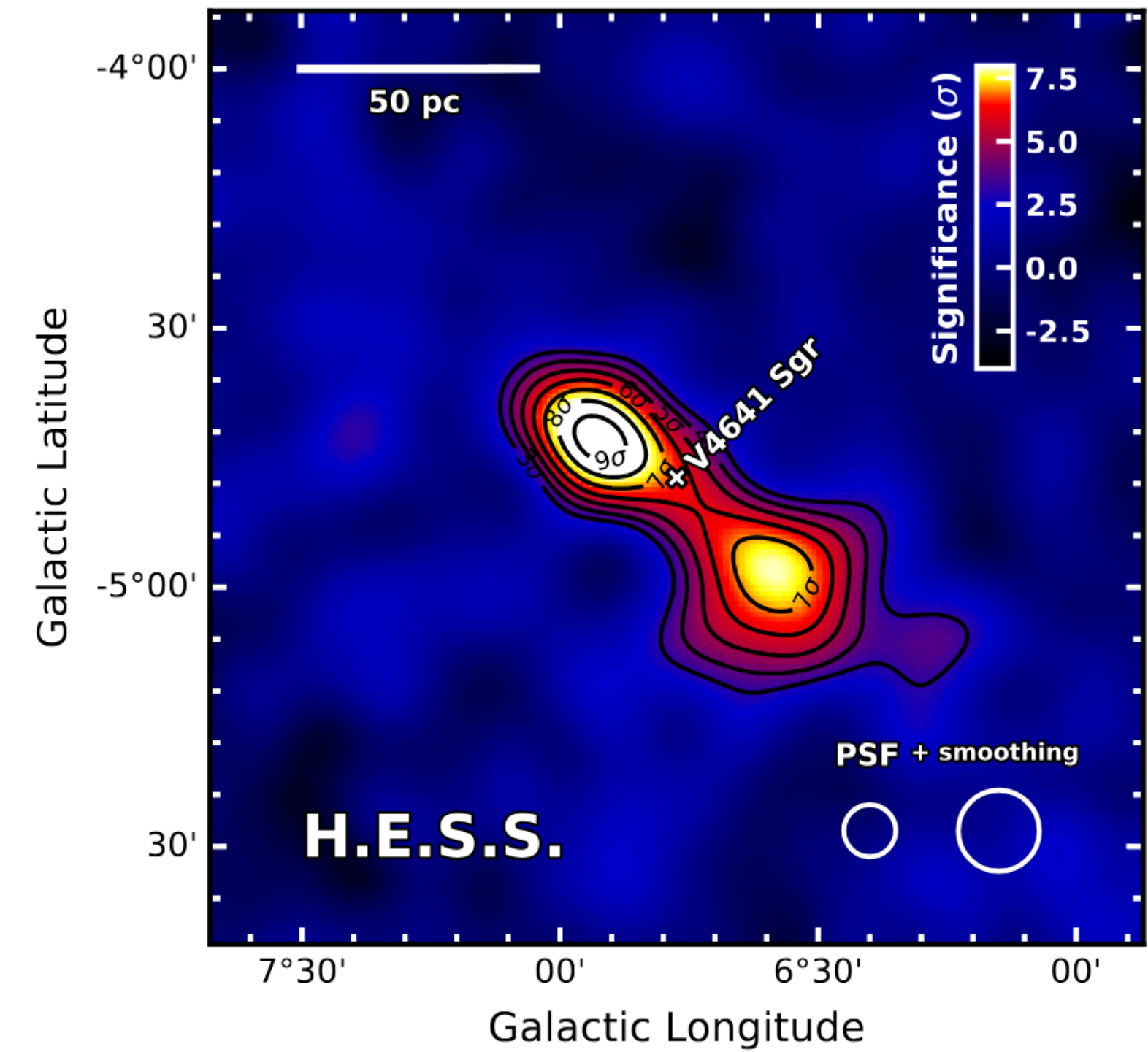


LHAASO Collaboration, Natl. Sci. Rev. **12**, nwaf496 (2025)

V4641 Sgr

■ H.E.S.S. measurement

- ▶ energy range 0.8–22 TeV
- ▶ very hard spectral index ($\Gamma \approx -1.8$)
- ▶ preference (3.2σ) for two separate components
- ▶ both components spatially resolved (i.e. not point-like)



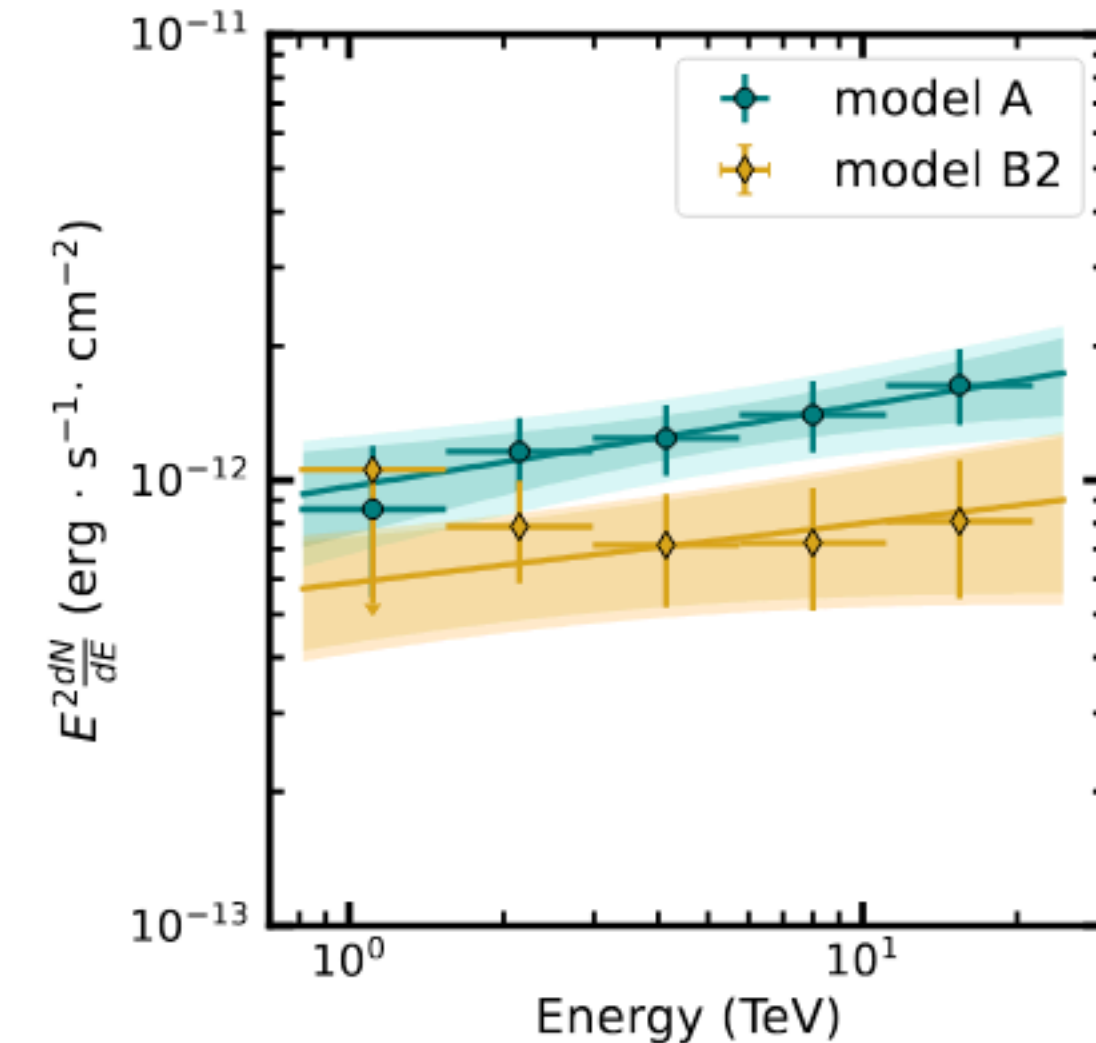
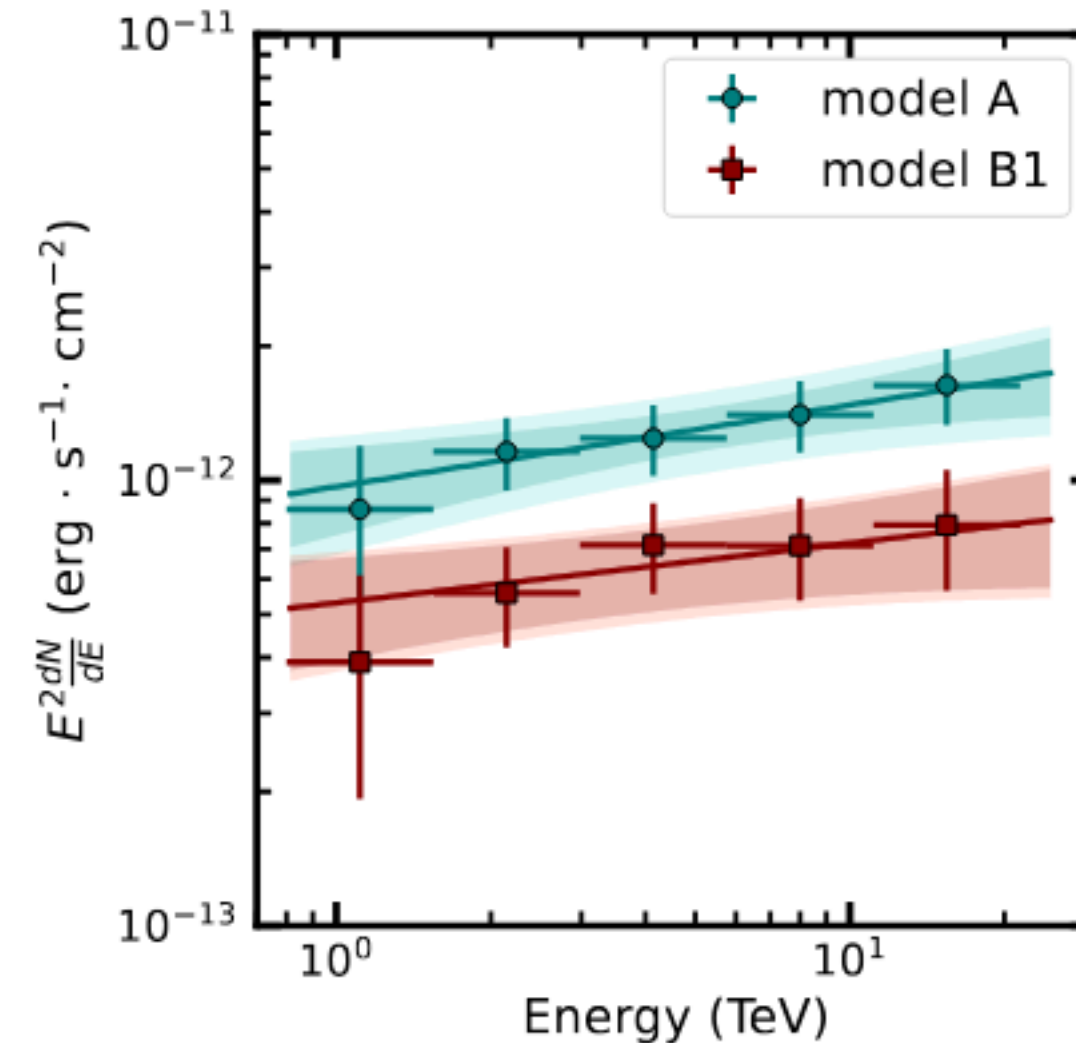
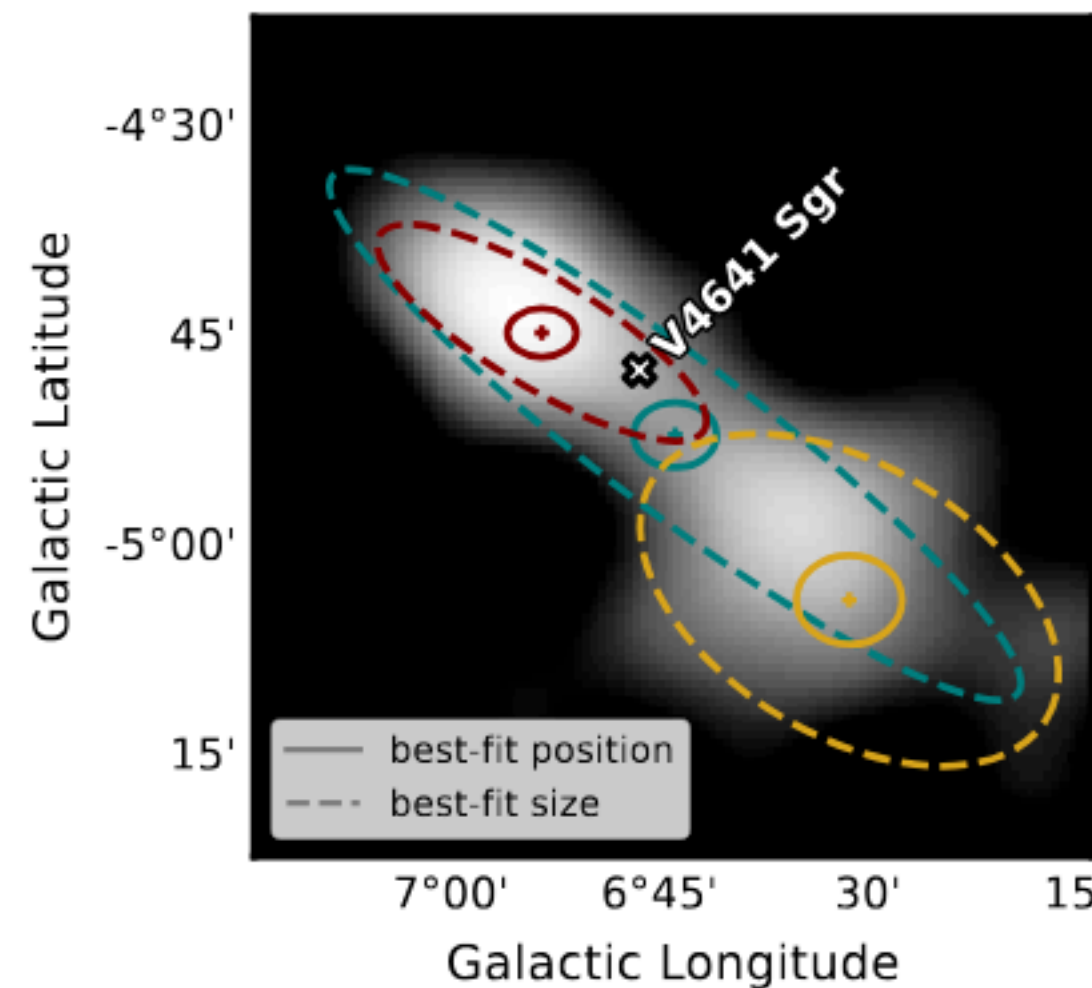
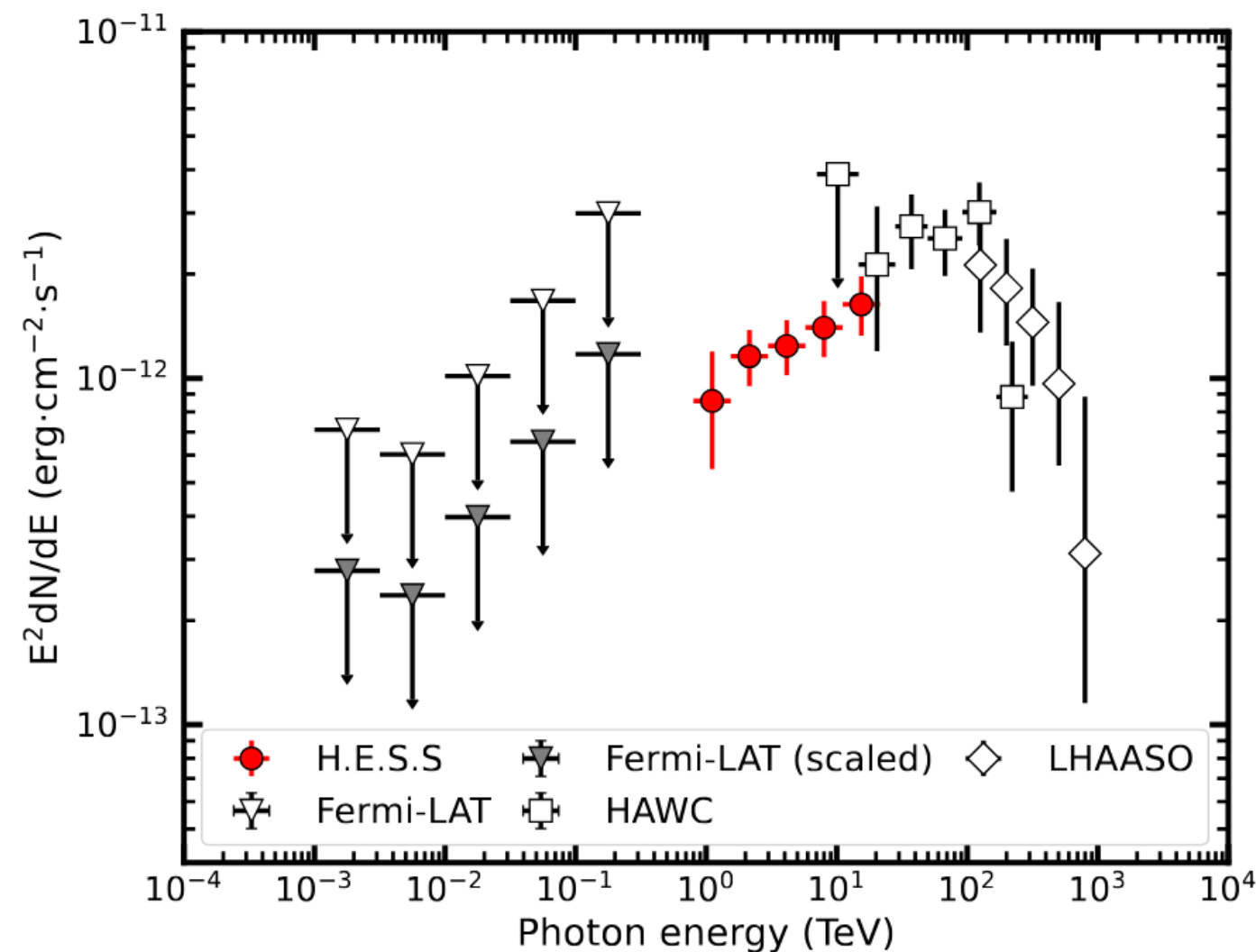
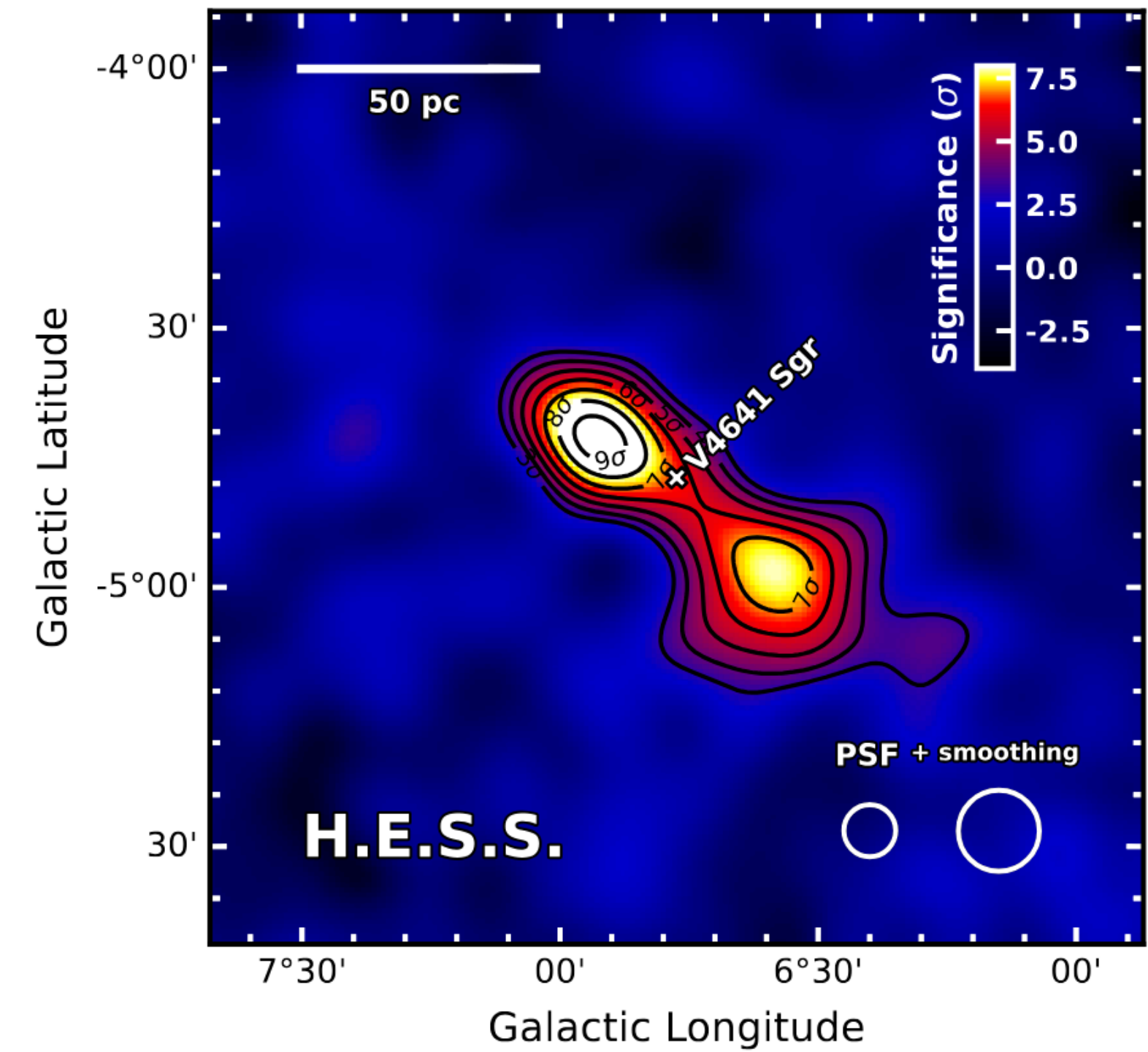
V4641 Sgr

■ H.E.S.S. measurement

- ▶ energy range 0.8–22 TeV
- ▶ very hard spectral index ($\Gamma \approx -1.8$)
- ▶ preference (3.2σ) for two separate components
- ▶ both components spatially resolved (i.e. not point-like)

■ Broad-band spectral energy distribution

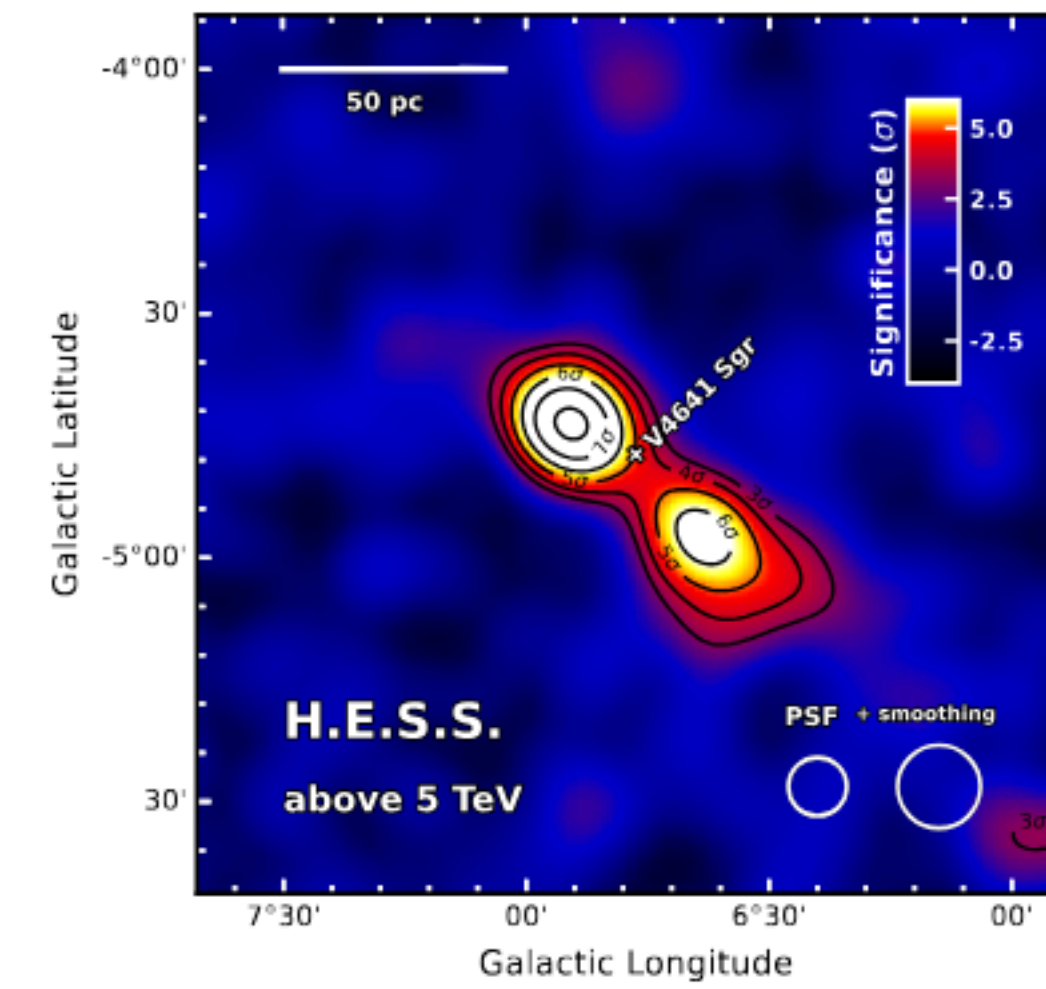
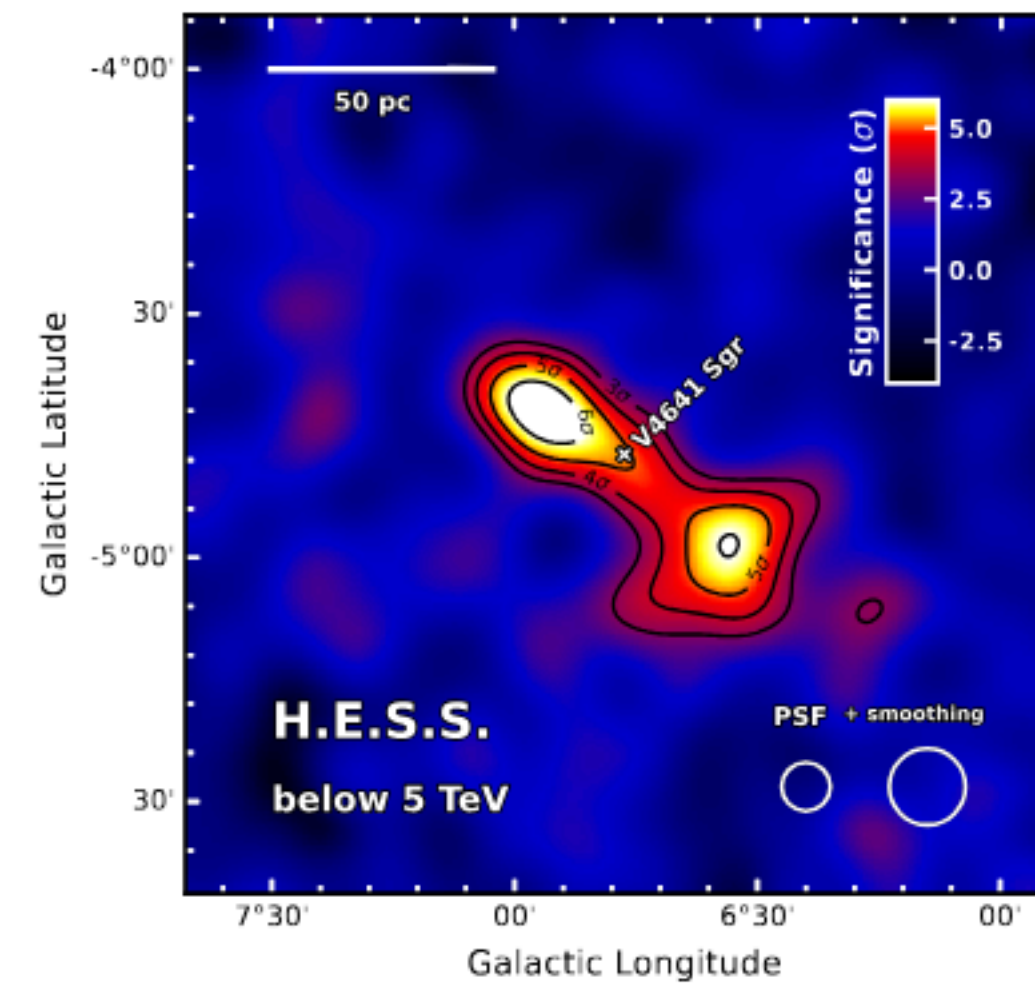
- ▶ peaked at ~ 100 TeV
- ▶ V4641 Sgr is an extremely powerful particle accelerator!



V4641 Sgr

■ Energy-dependent morphology?

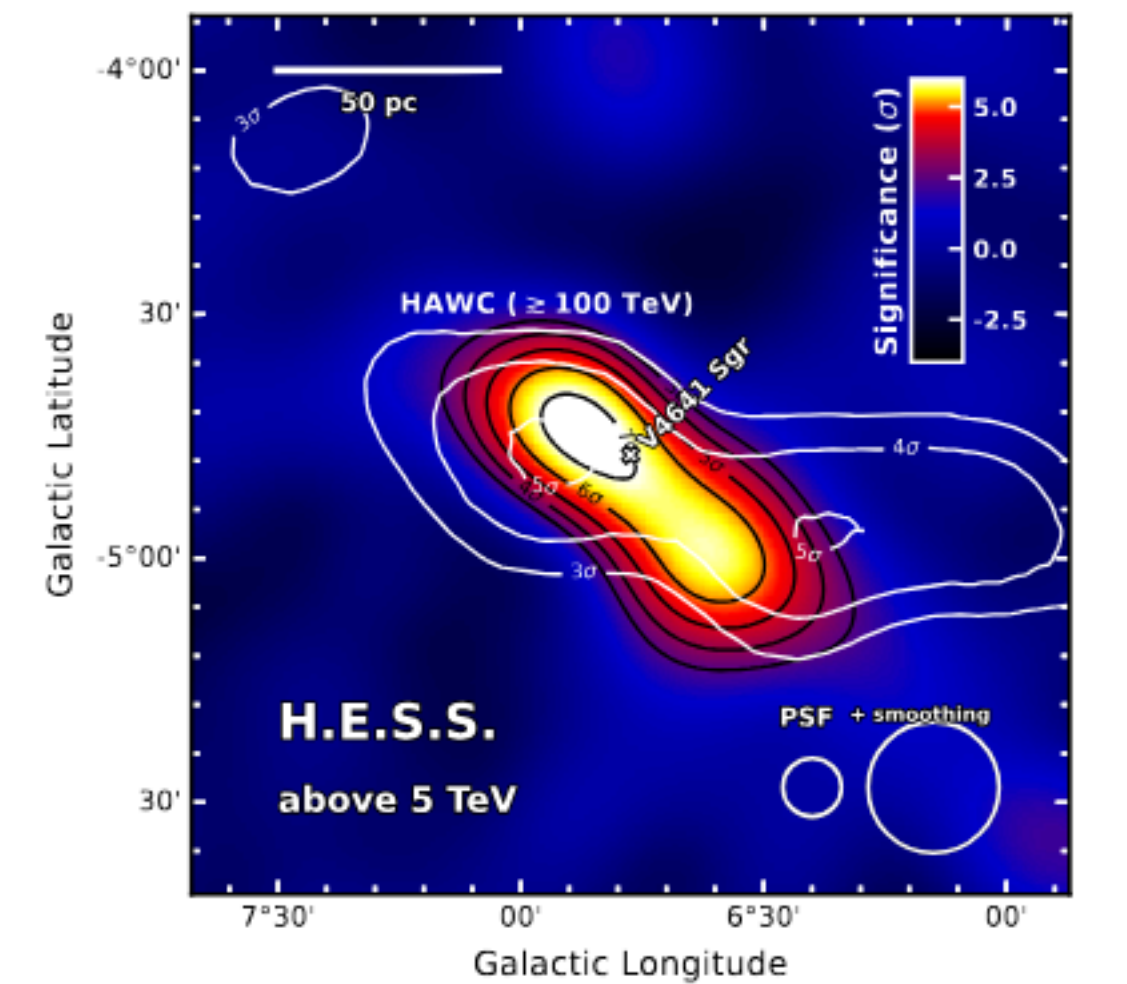
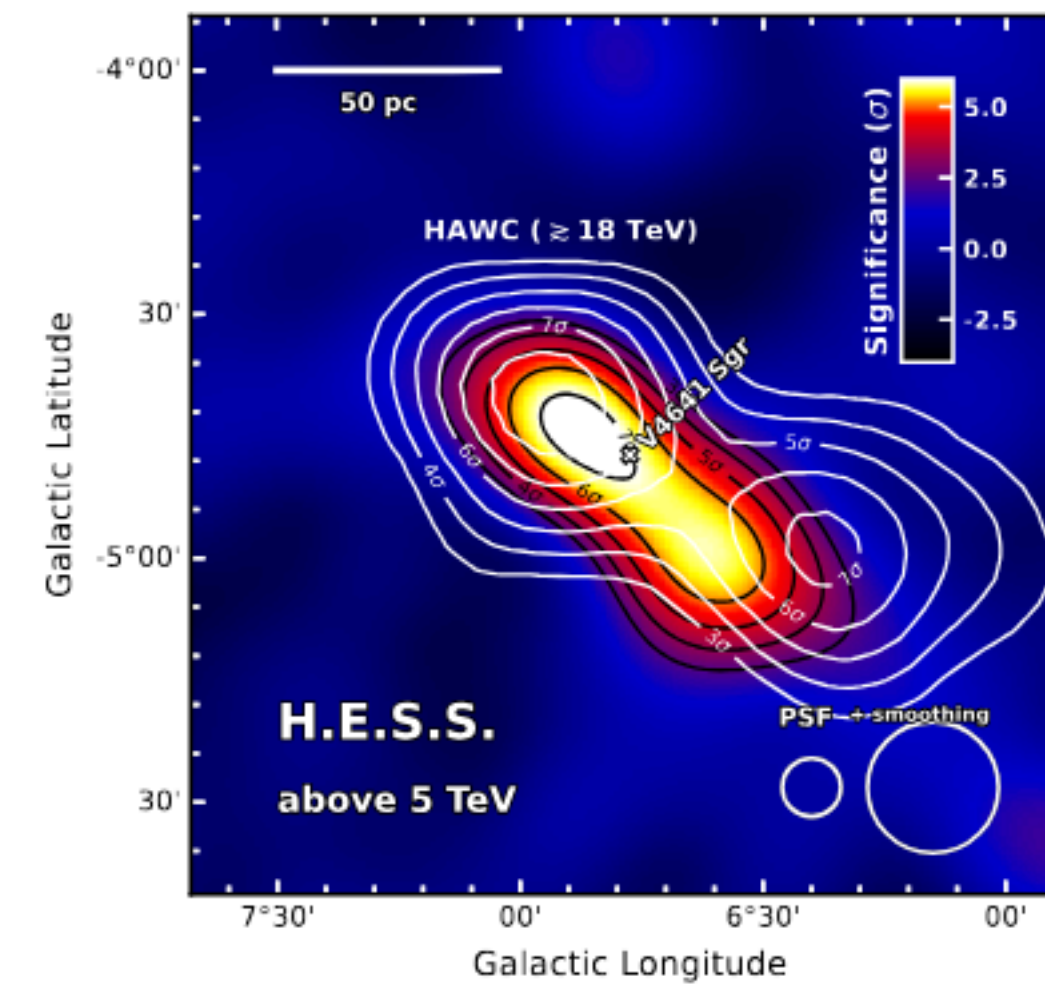
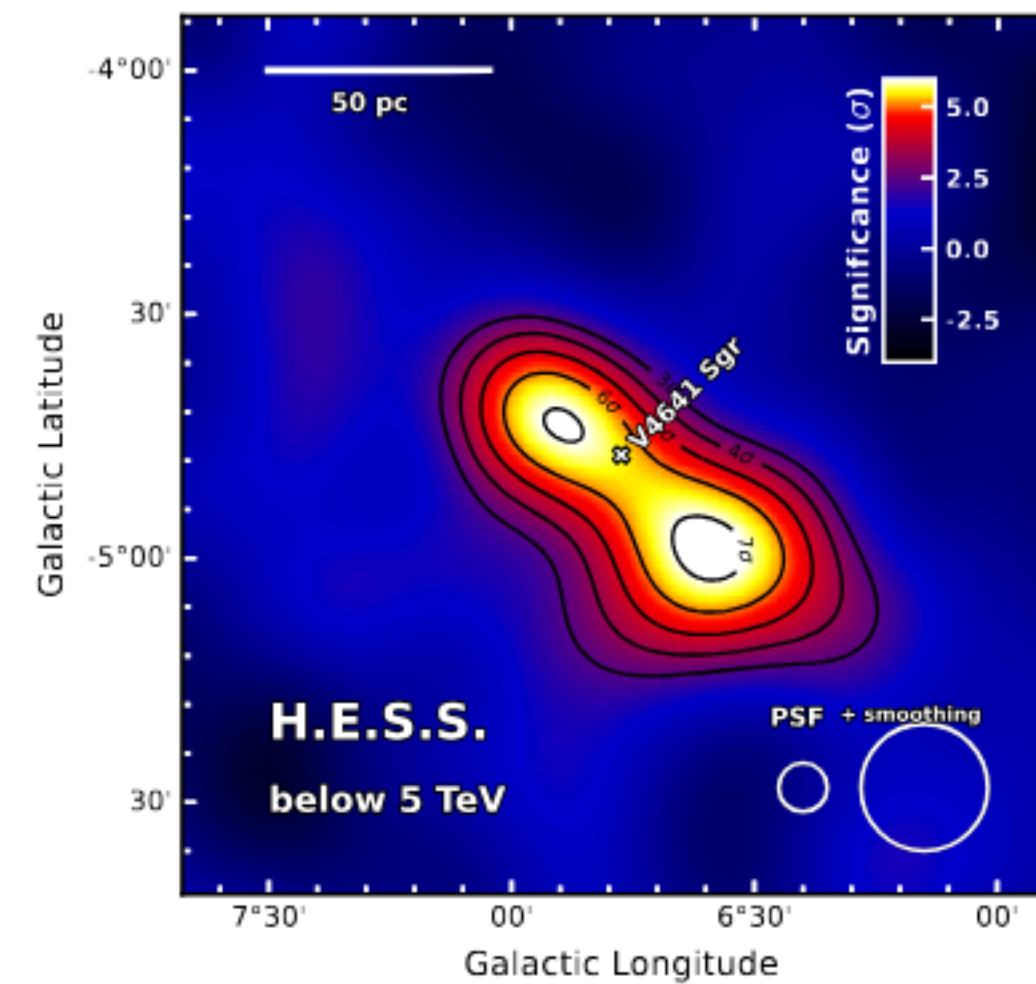
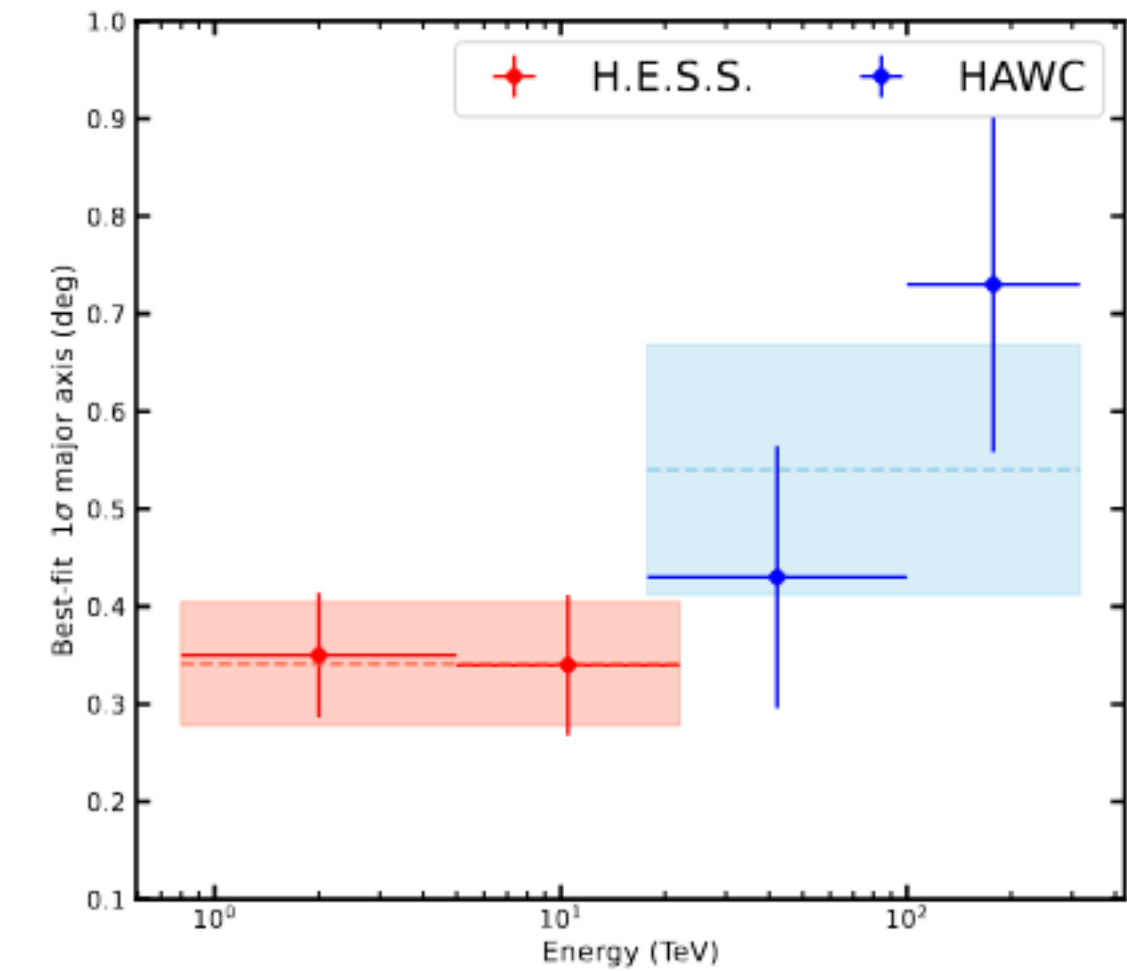
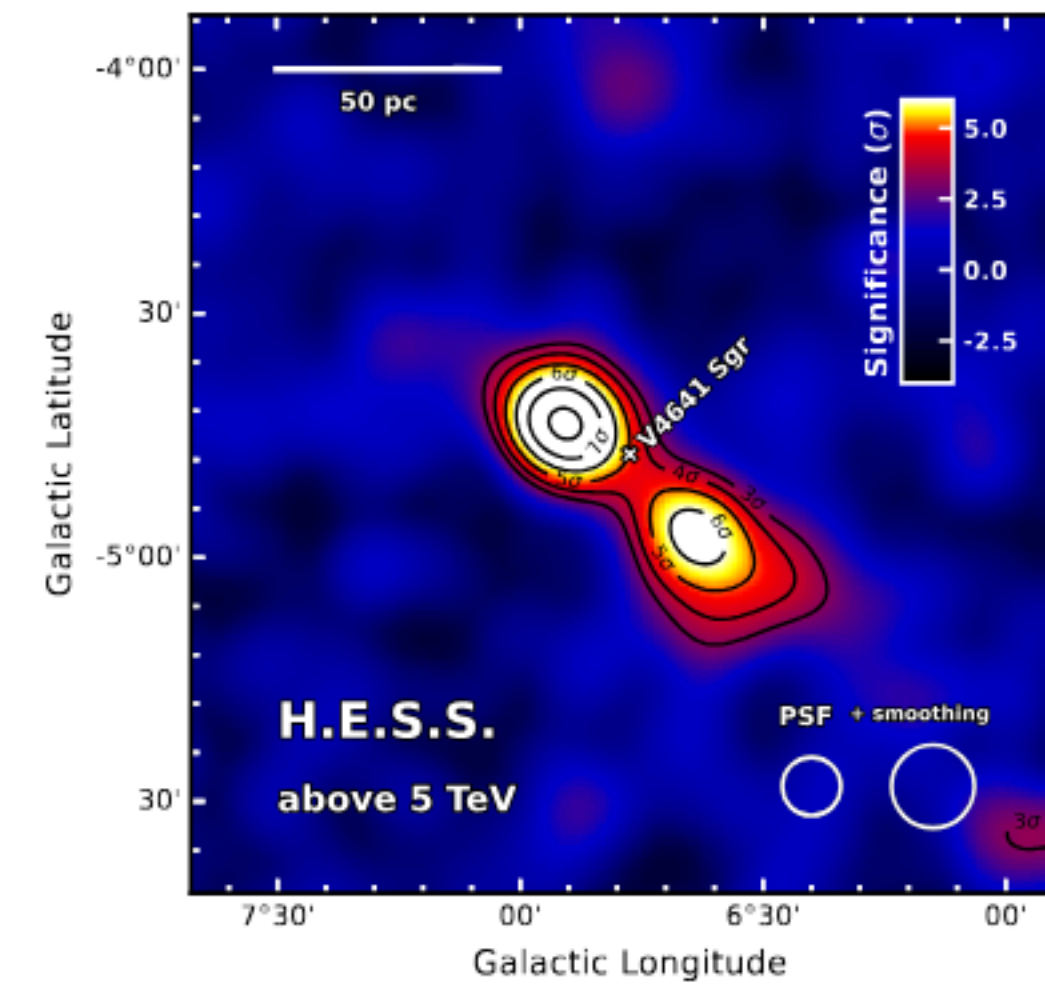
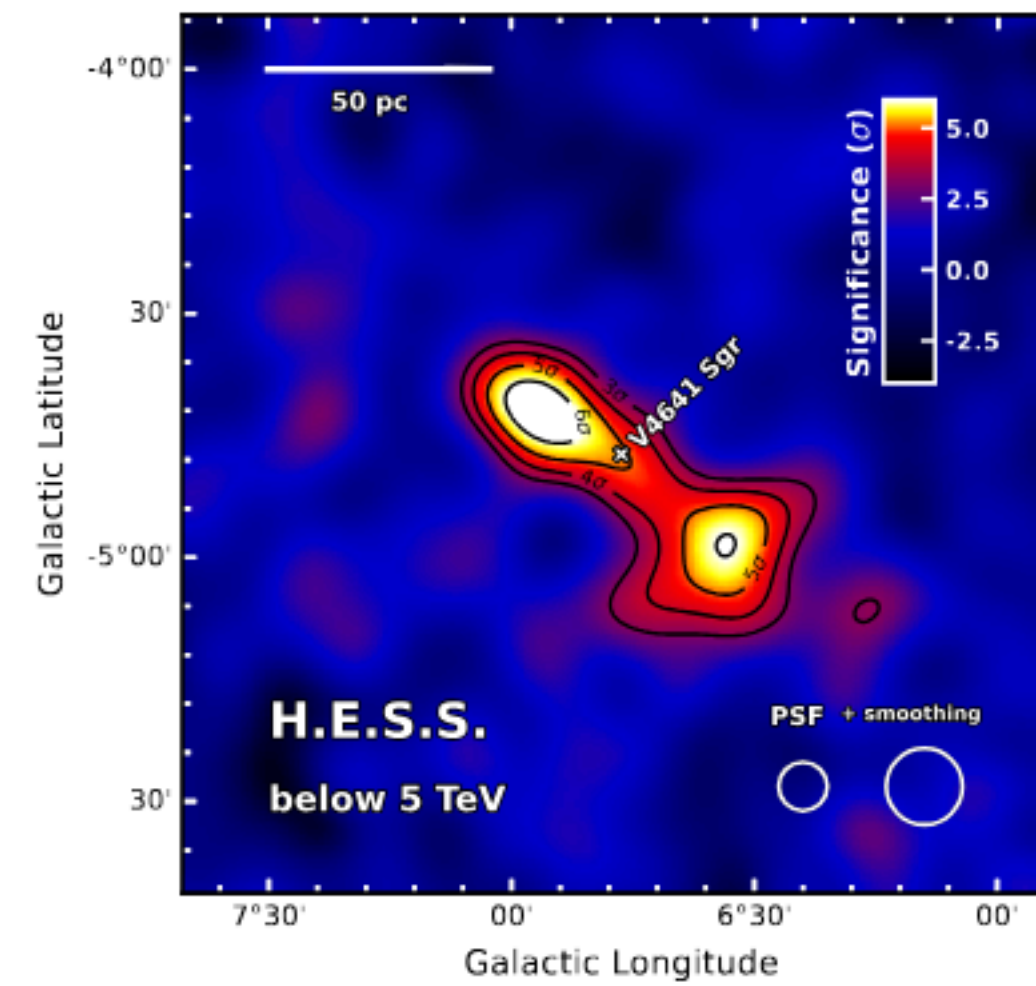
- ▶ no evidence from H.E.S.S. data alone



V4641 Sgr

■ Energy-dependent morphology?

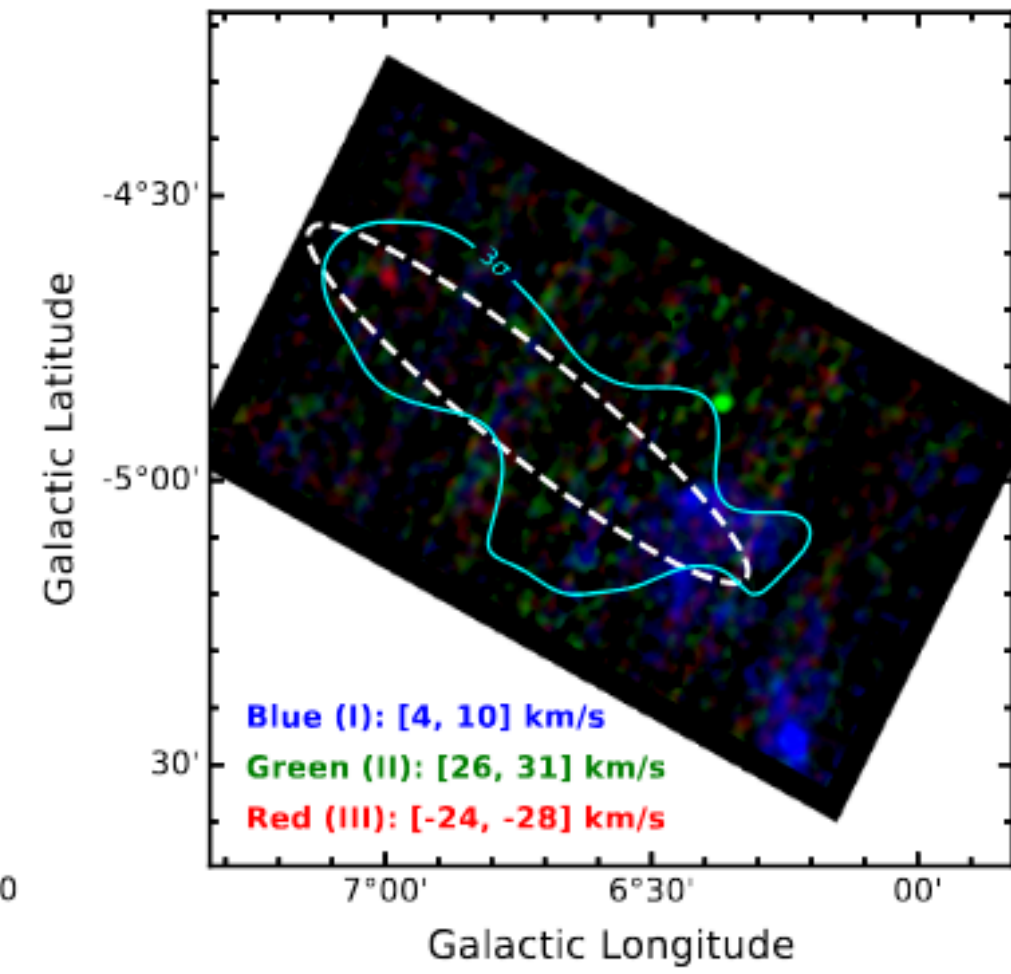
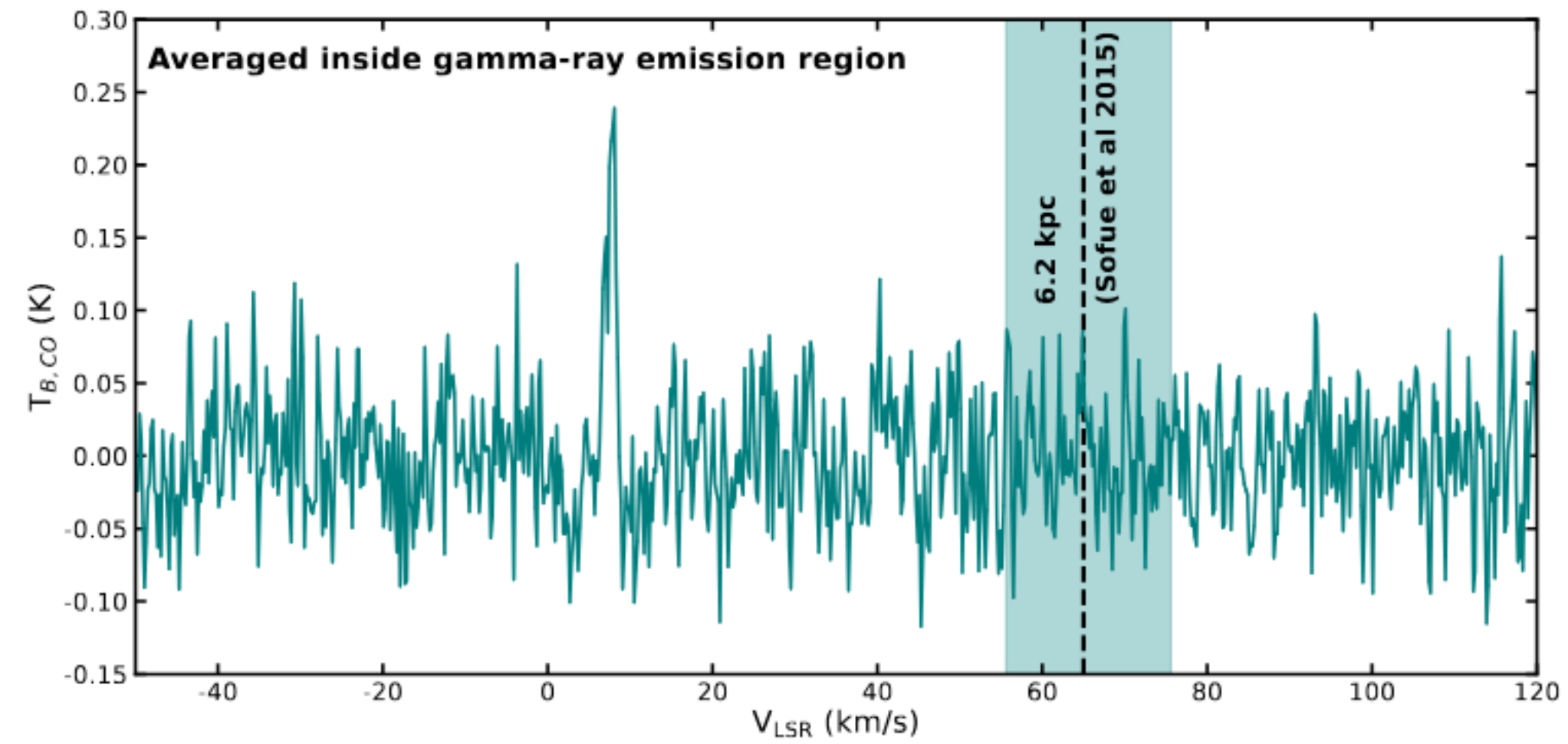
- ▶ no evidence from H.E.S.S. data alone
- ▶ indication of a trend when comparing to HAWC data
- ▶ not conclusive at this point



V4641 Sgr

■ Search for ambient gas

- ▶ densities very low
- ▶ molecular hydrogen (CO): $n_{\text{gas}} < 0.2 \text{ cm}^{-3}$
- ▶ atomic hydrogen (HI): $n_{\text{gas}} \approx 0.08 \text{ cm}^{-3}$



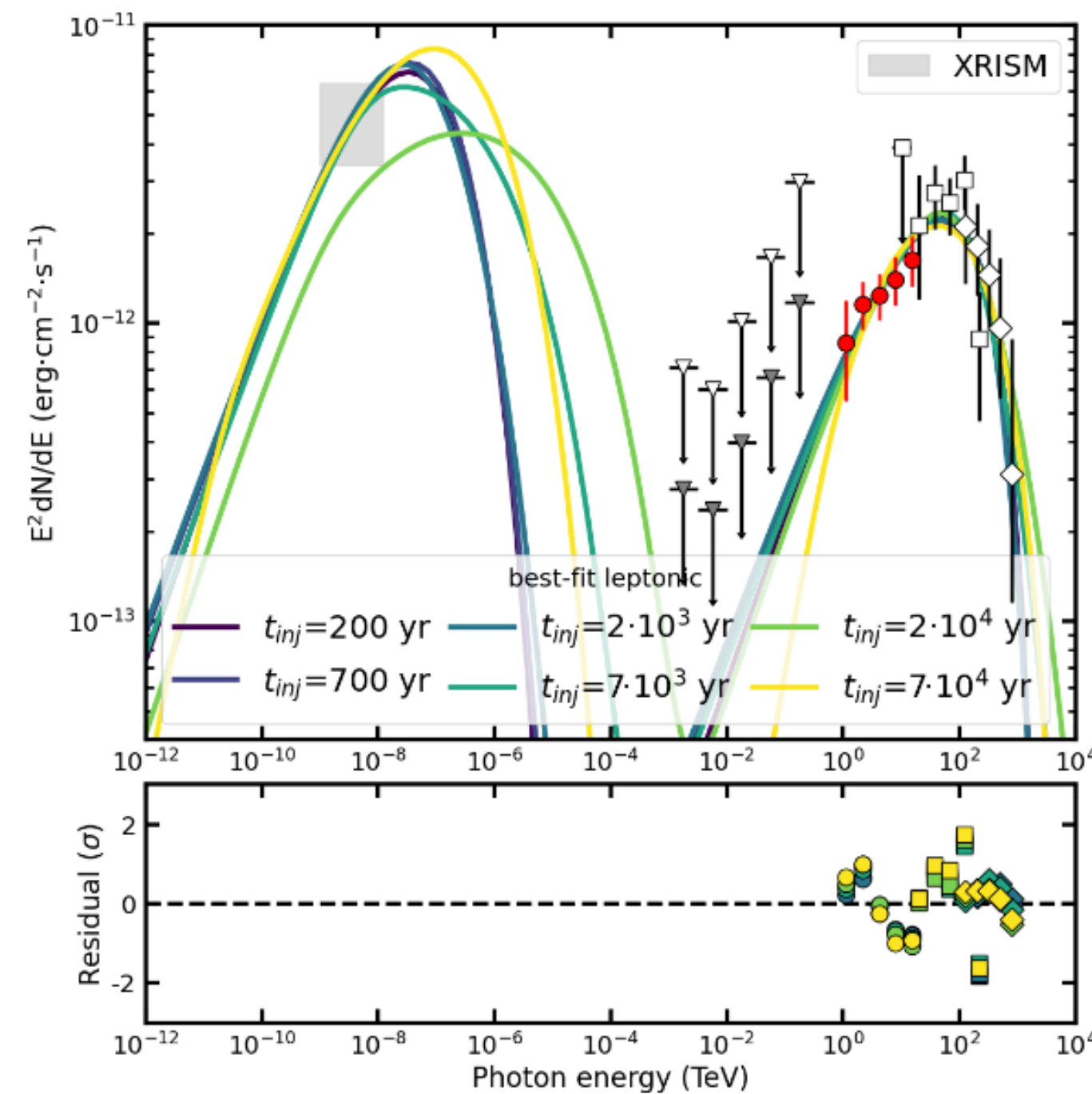
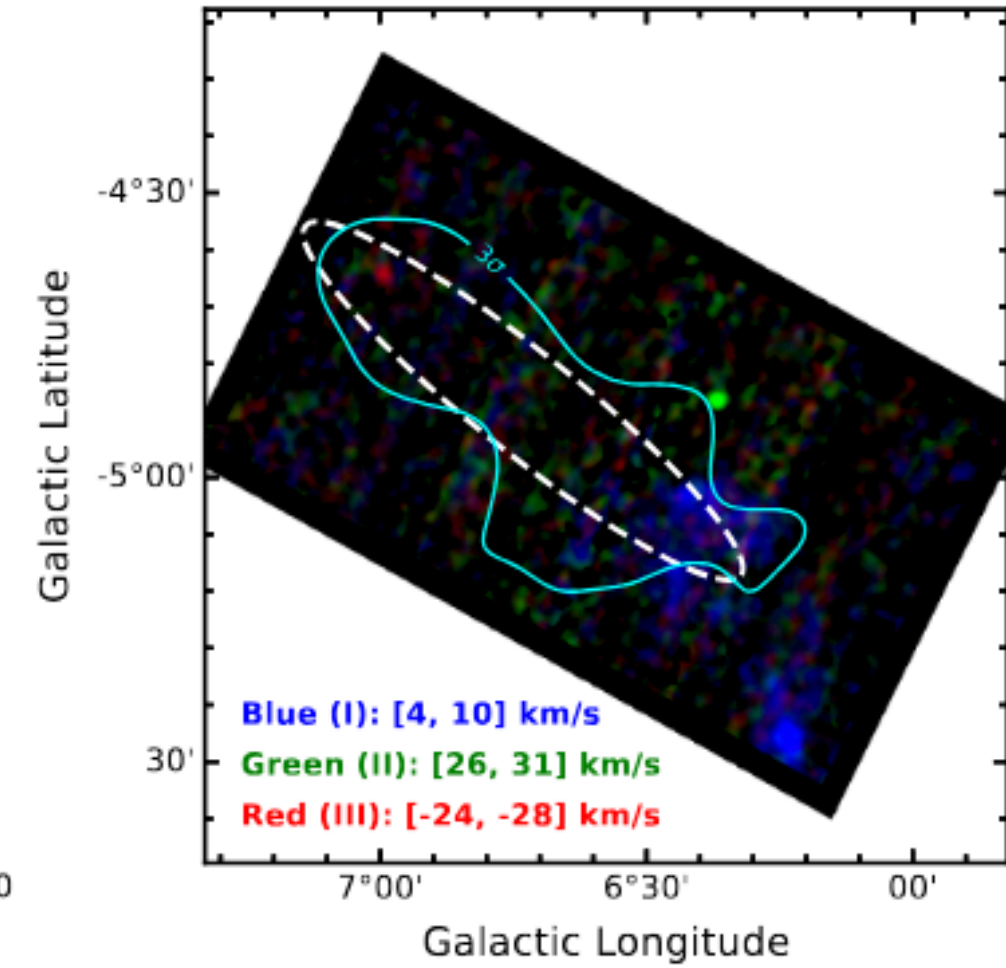
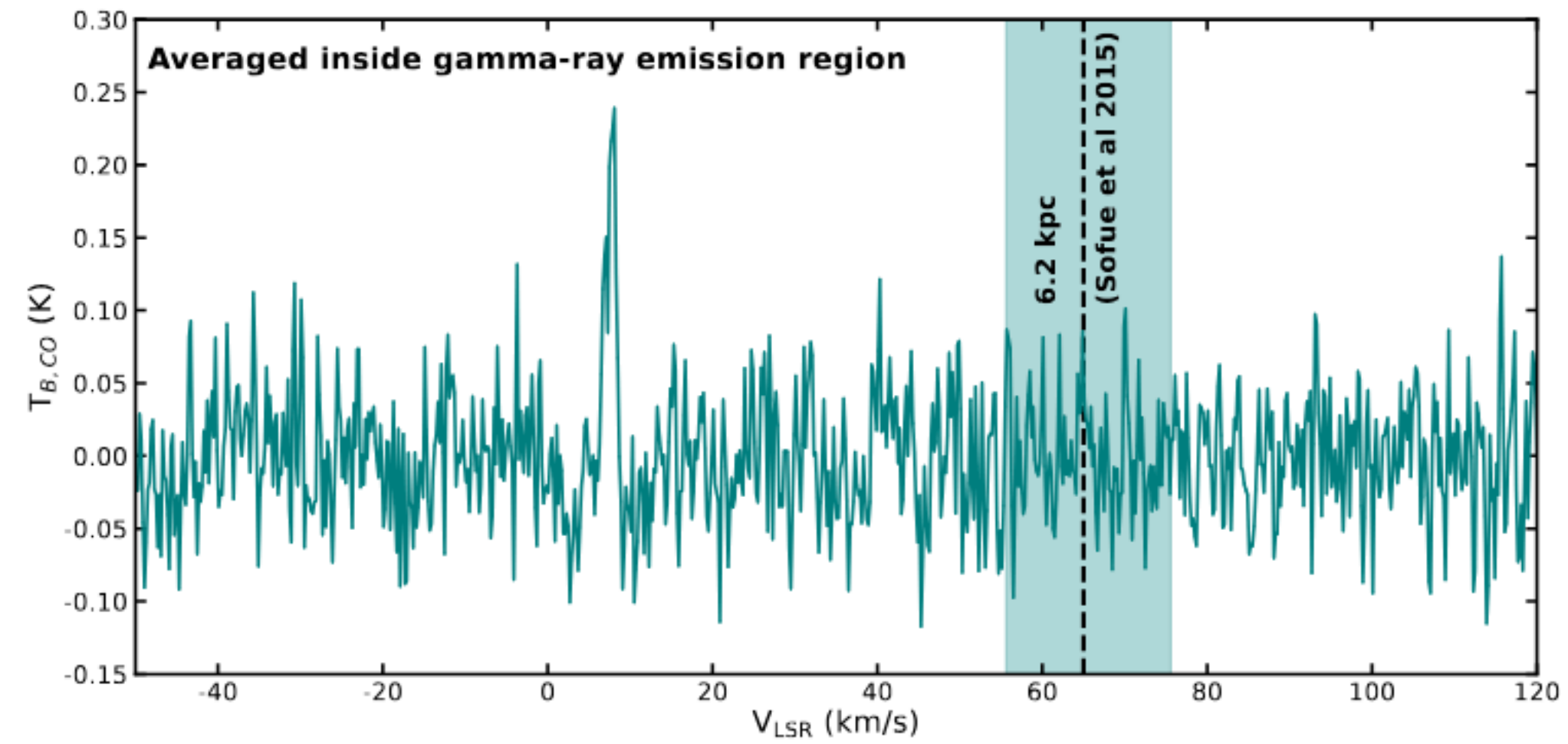
V4641 Sgr

■ Search for ambient gas

- ▶ densities very low
- ▶ molecular hydrogen (CO): $n_{\text{gas}} < 0.2 \text{ cm}^{-3}$
- ▶ atomic hydrogen (HI): $n_{\text{gas}} \approx 0.08 \text{ cm}^{-3}$

■ Leptonic model

- ▶ suggests $B < 3 \mu\text{G}$ and $t_{\text{inj}} \lesssim 10 \text{ kyr}$
- ▶ requires mildly relativistic jet ($v \gtrsim 0.1c$) to explain morphology
- ▶ low B field implies large (pc-scale) acceleration site



V4641 Sgr

■ Search for ambient gas

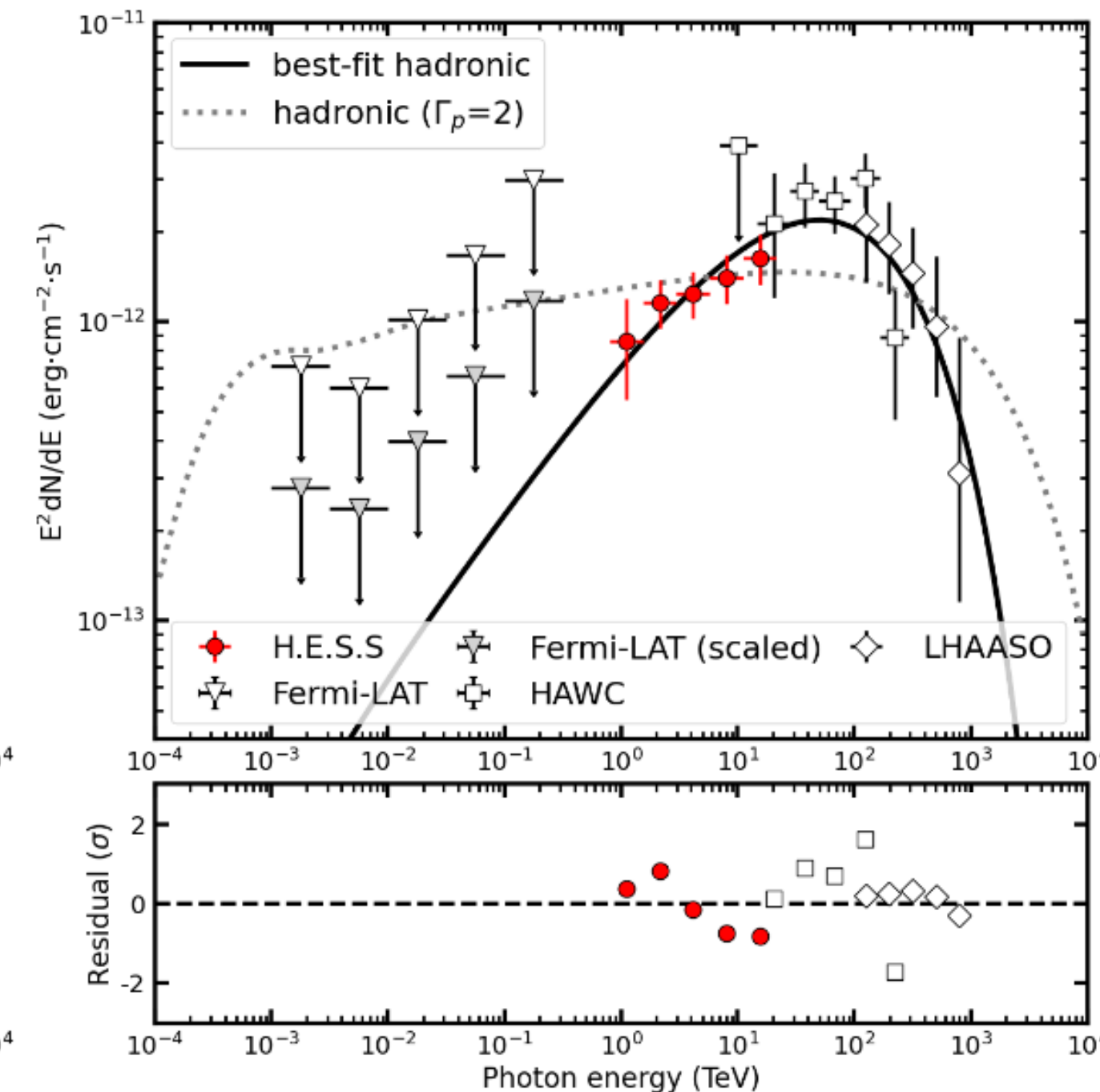
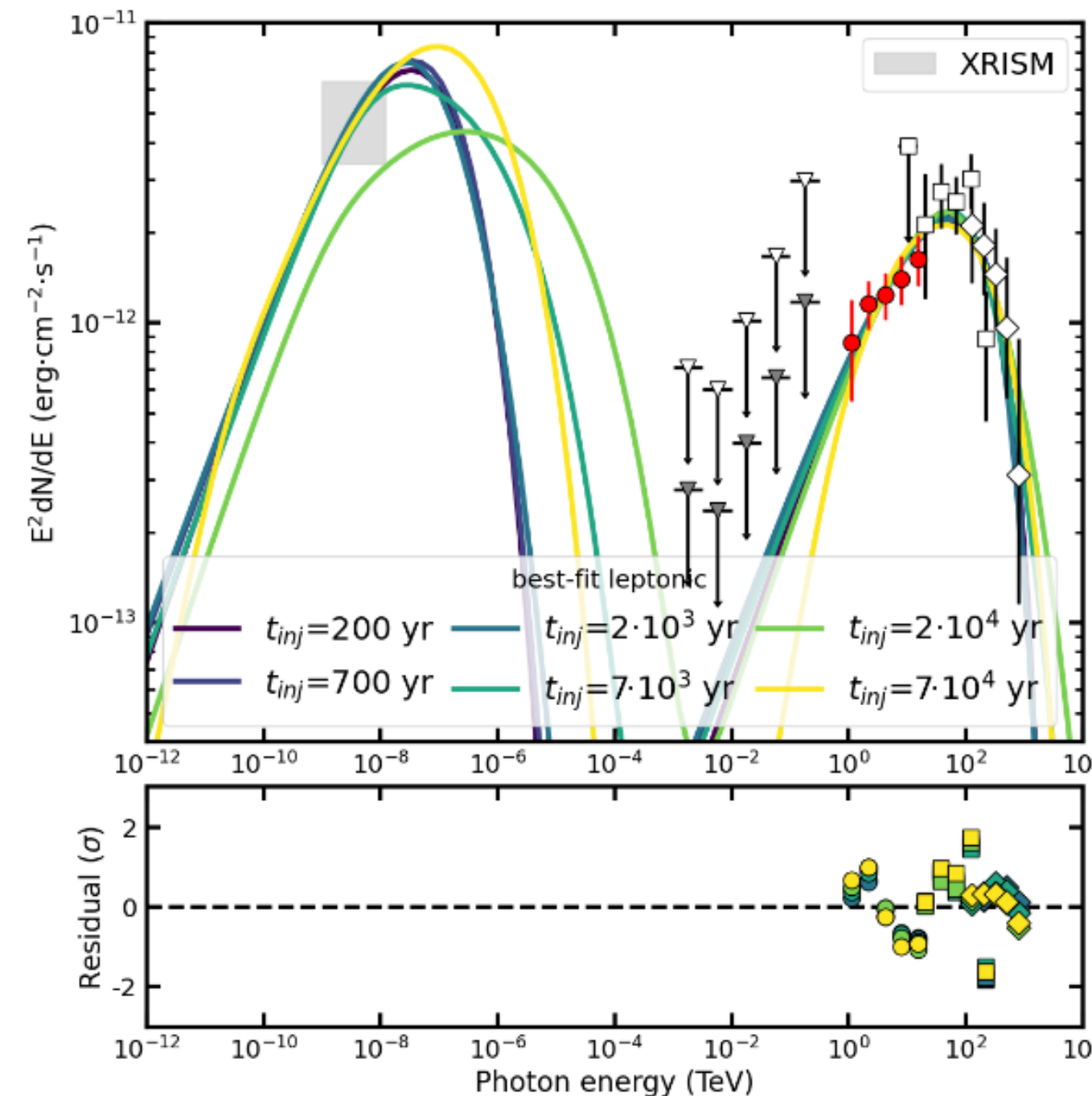
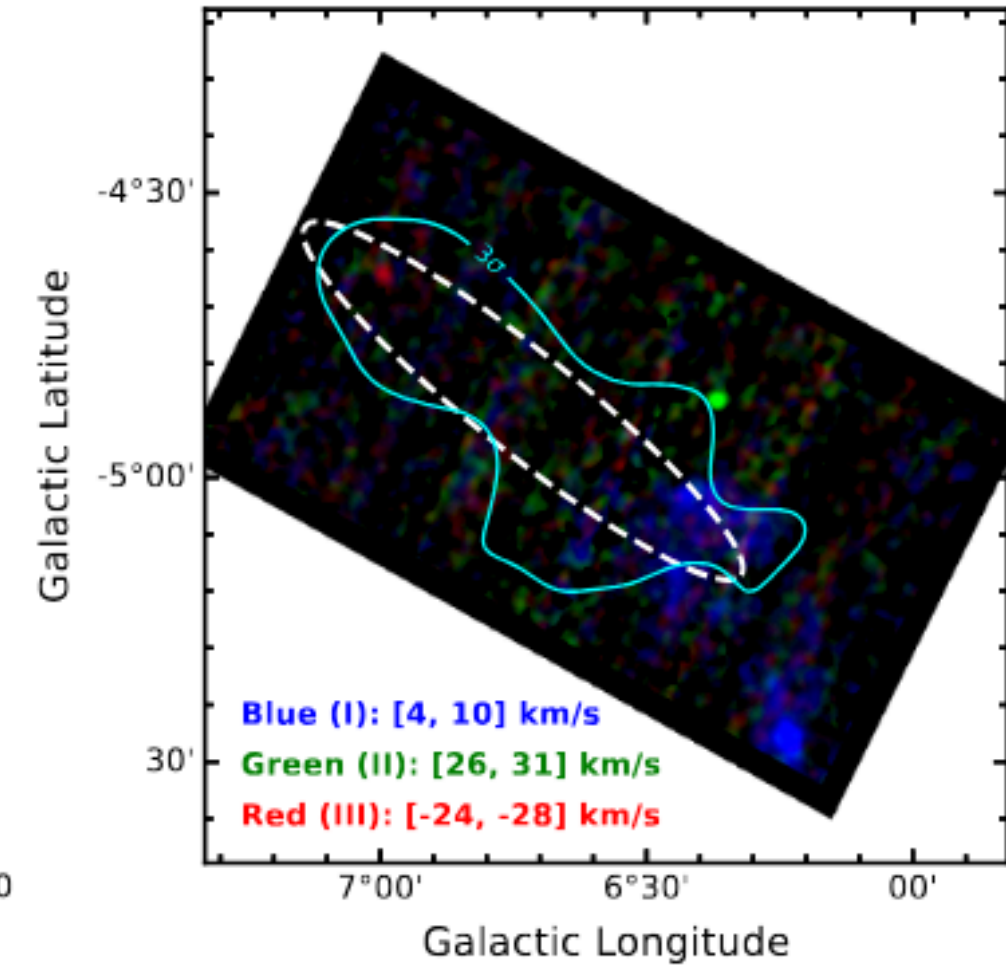
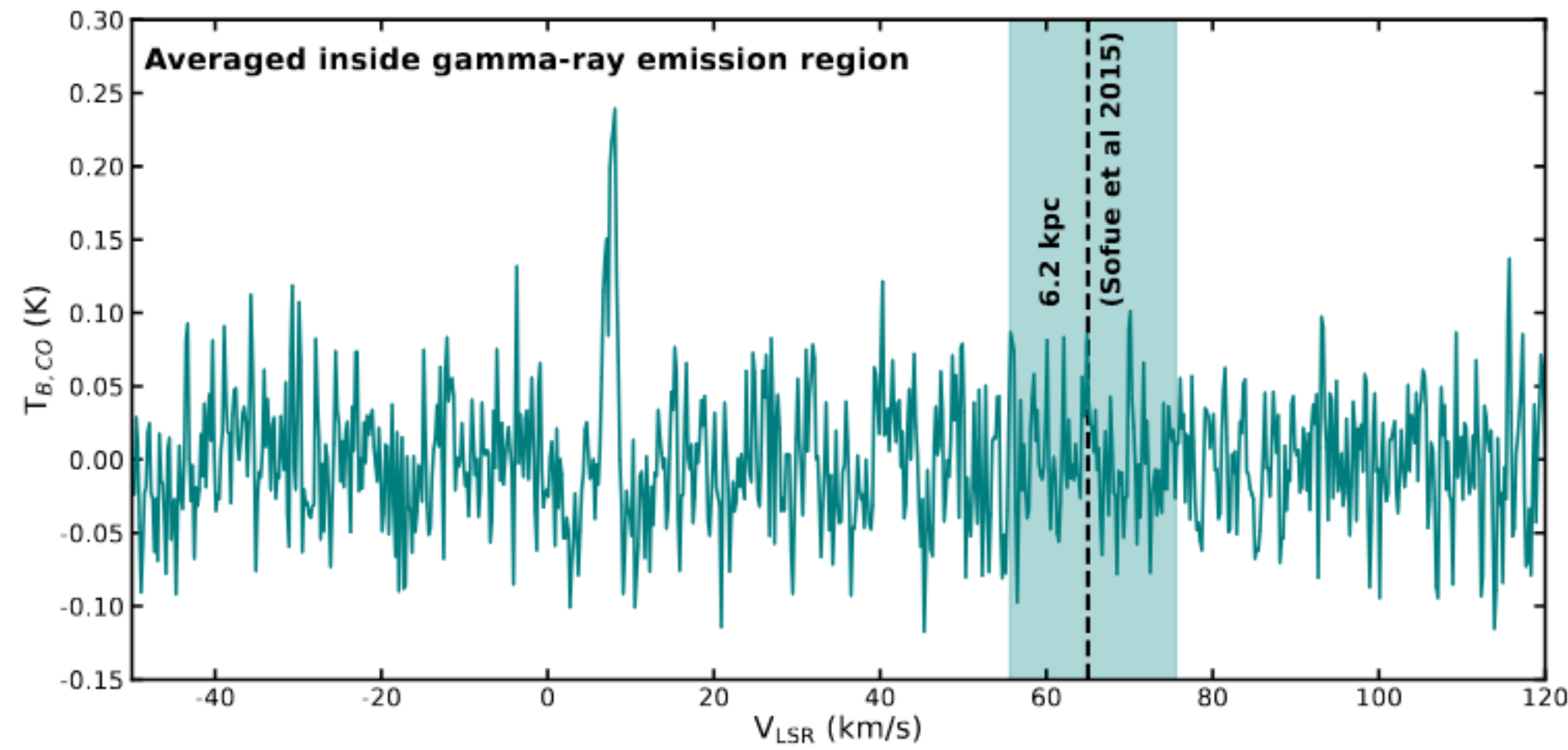
- ▶ densities very low
- ▶ molecular hydrogen (CO): $n_{\text{gas}} < 0.2 \text{ cm}^{-3}$
- ▶ atomic hydrogen (HI): $n_{\text{gas}} \approx 0.08 \text{ cm}^{-3}$

■ Leptonic model

- ▶ suggests $B < 3 \mu\text{G}$ and $t_{\text{inj}} \lesssim 10 \text{ kyr}$
- ▶ requires mildly relativistic jet ($v \gtrsim 0.1c$) to explain morphology
- ▶ low B field implies large (pc-scale) acceleration site

■ Hadronic model

- ▶ requires proton spectrum with $\Gamma \approx -1.5$ and $E_{\text{cut}} \approx 2 \text{ PeV}$ (rather extreme!)
- ▶ furthermore, low gas densities imply $u_p \gtrsim 0.5 \text{ keV cm}^{-3}$ and $B > 100 \mu\text{G}$



V4641 Sgr

■ Search for ambient gas

- ▶ densities very low
- ▶ molecular hydrogen (CO): $n_{\text{gas}} < 0.2 \text{ cm}^{-3}$
- ▶ atomic hydrogen (HI): $n_{\text{gas}} \approx 0.08 \text{ cm}^{-3}$

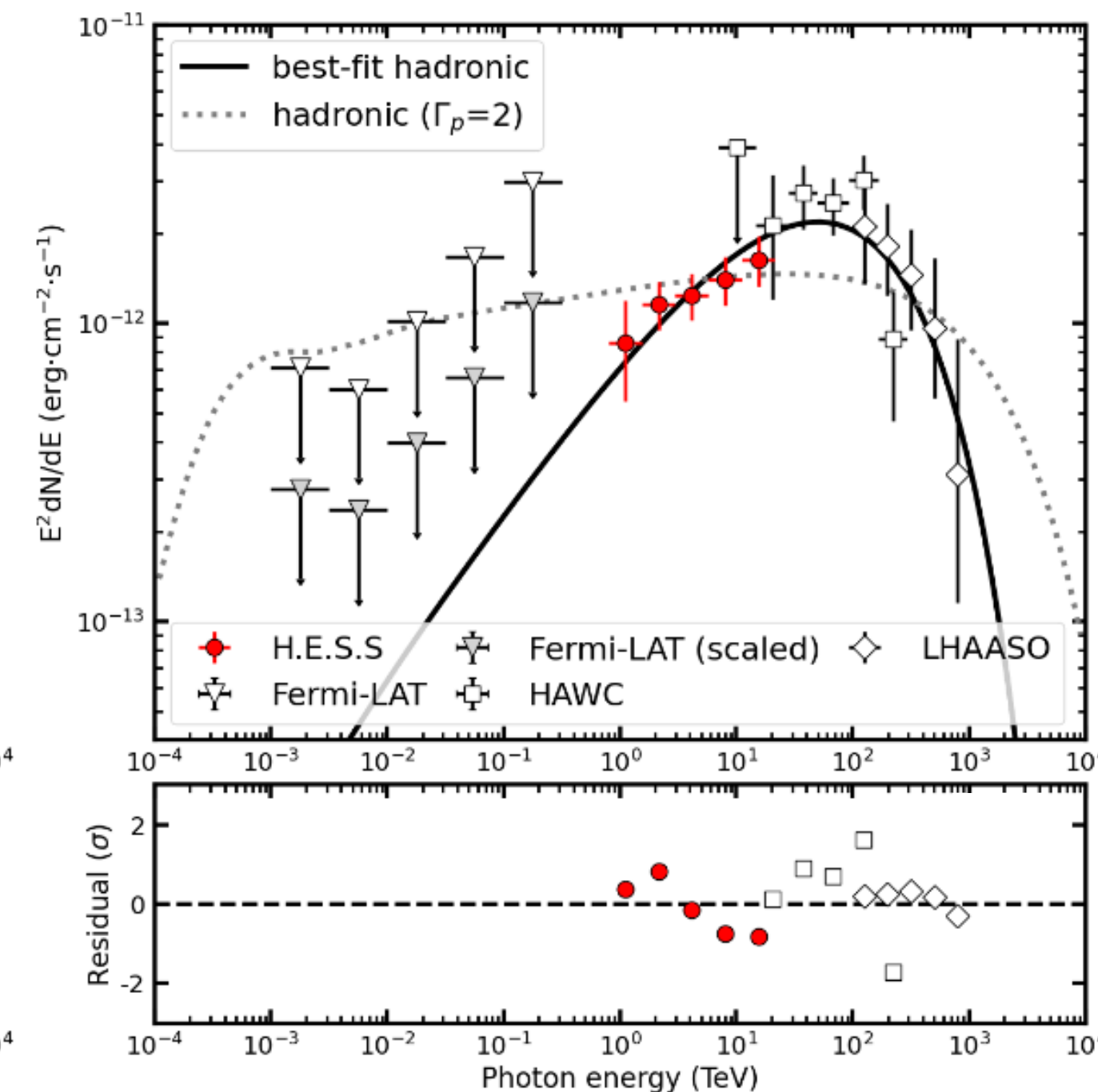
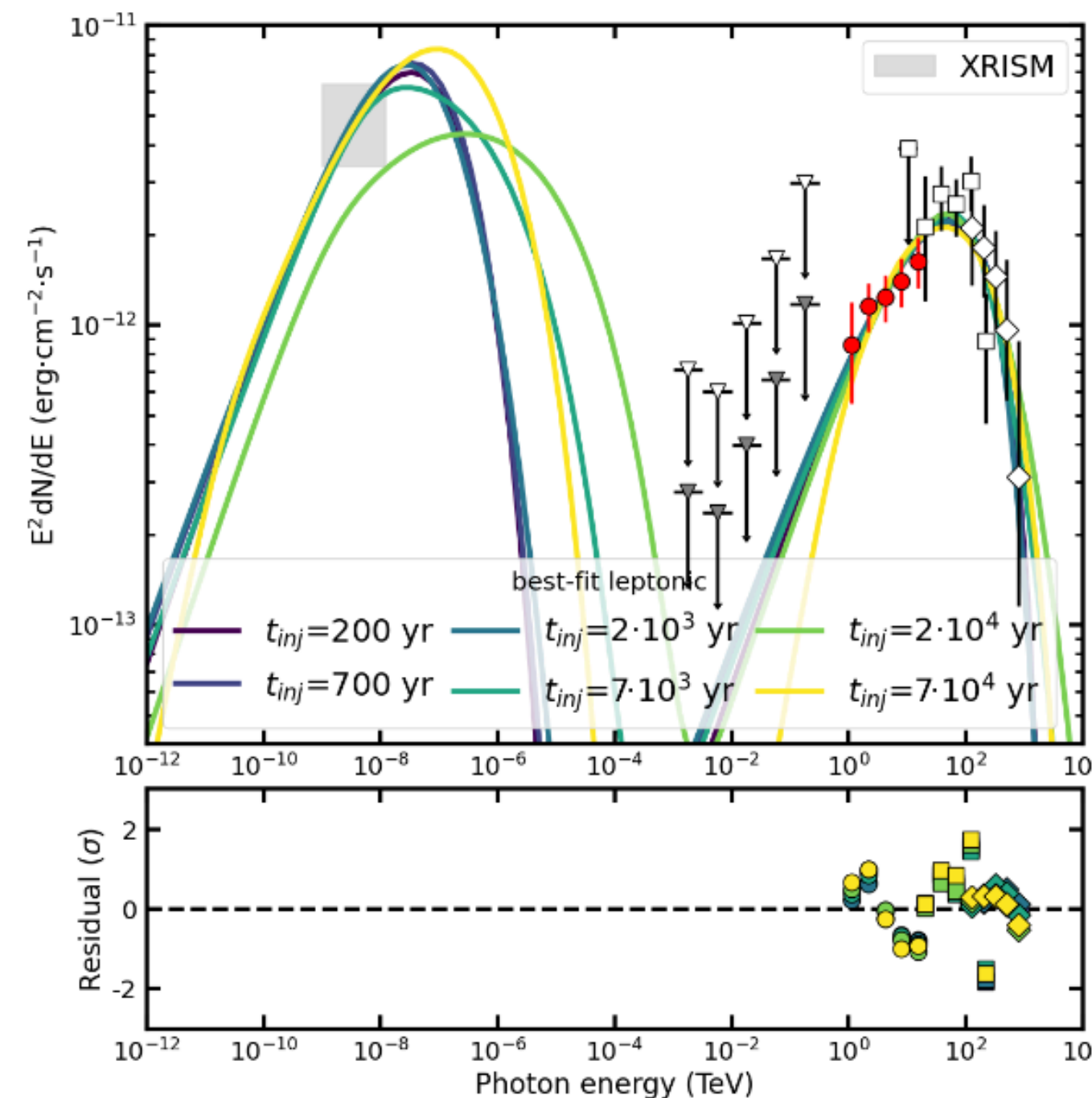
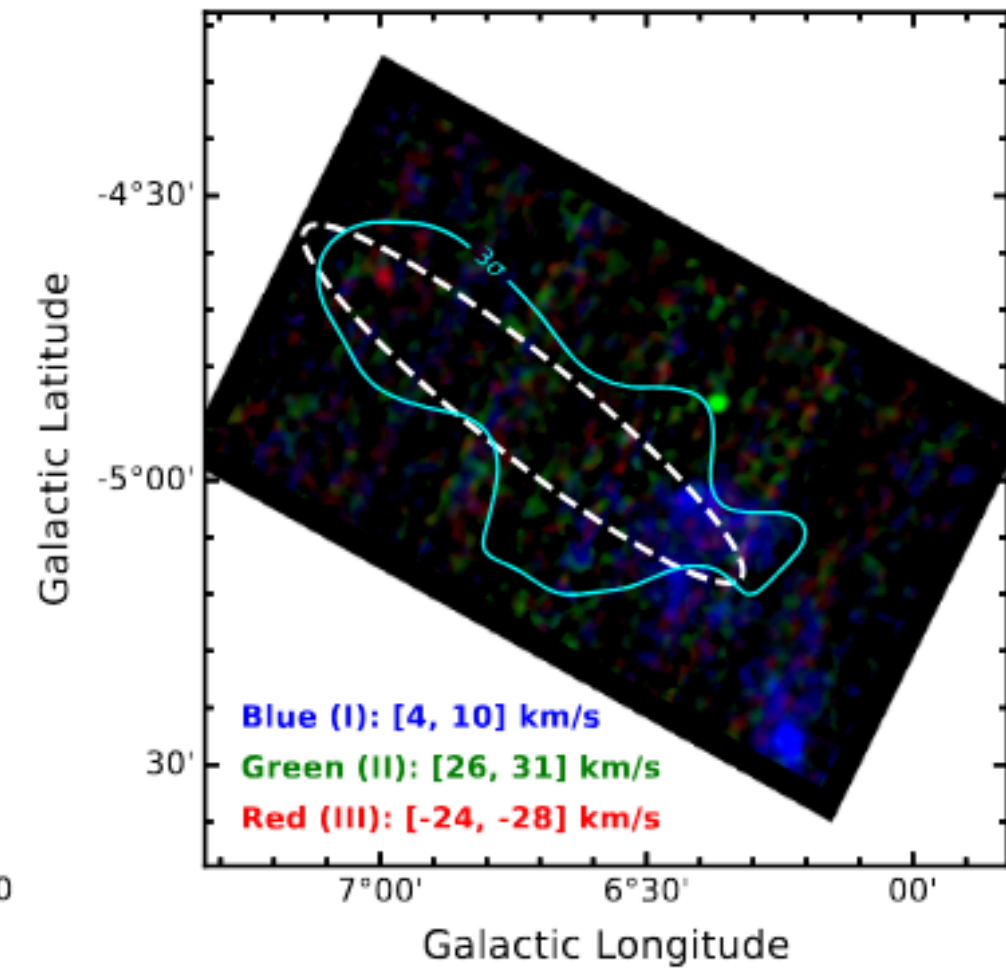
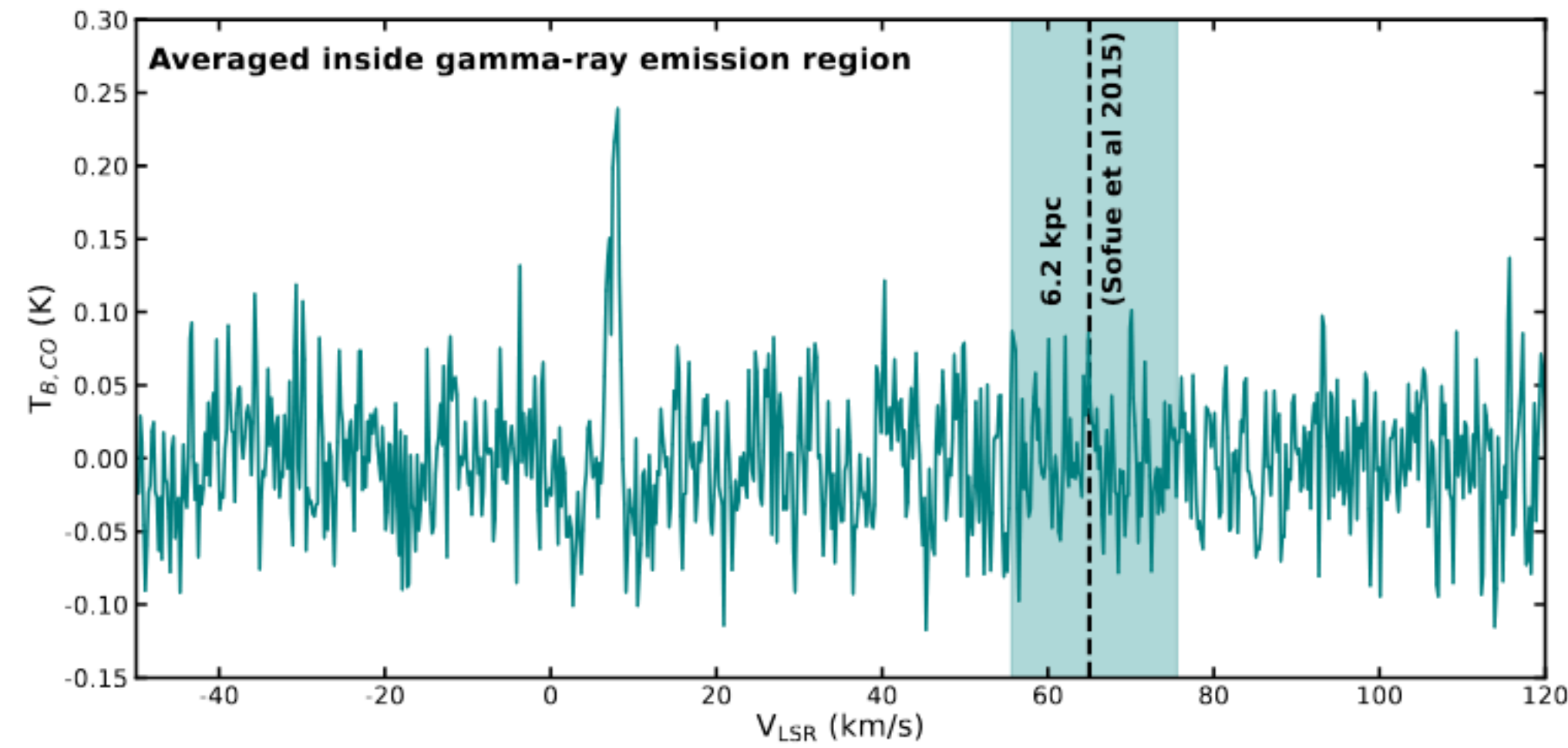
■ Leptonic model

- ▶ suggests $B < 3 \mu\text{G}$ and $t_{\text{inj}} \lesssim 10 \text{ kyr}$
- ▶ requires mildly relativistic jet ($v \gtrsim 0.1c$) to explain morphology
- ▶ low B field implies large (pc-scale) acceleration site

■ Hadronic model

- ▶ requires proton spectrum with $\Gamma \approx -1.5$ and $E_{\text{cut}} \approx 2 \text{ PeV}$ (rather extreme!)
- ▶ furthermore, low gas densities imply $u_p \gtrsim 0.5 \text{ keV cm}^{-3}$ and $B > 100 \mu\text{G}$

- → **Leptonic model preferred**
(but this does not preclude acceleration of protons!)



Outlook

- **H.E.S.S. will continue operating until at least September 2028**
 - ▶ exciting “legacy program” set in place
 - ▶ one strong focus: **time-domain science** (GRBs, novae, AGN flares, ...)
 - ▶ but also promising campaigns on **microquasars, star clusters, binaries...**
 - ▶ continuation beyond 2028 currently unclear



Outlook

- **H.E.S.S. will continue operating until at least September 2028**
 - ▶ exciting “legacy program” set in place
 - ▶ one strong focus: **time-domain science** (GRBs, novae, AGN flares, ...)
 - ▶ but also promising campaigns on **microquasars, star clusters, binaries...**
 - ▶ continuation beyond 2028 currently unclear
- **Public data archive**
 - ▶ aiming to prepare a comprehensive archive for 20+ years of H.E.S.S. data
 - ▶ analysis with CTAO science tool package (Gammapy)
 - ▶ a huge effort for the Collaboration
→ need to start the effort now!
 - ▶ hopefully a very valuable legacy for the community



Exploring the Universe with high-energy gamma rays using H.E.S.S.

<https://hess-experiment.eu>
<https://lmohrmann.github.io>

Lars Mohrmann ■ Max-Planck-Institut für Kernphysik

Heidelberg Joint Astronomical Colloquium ■ Heidelberg, January 13, 2026