On superbubbles and cosmic rays

Measurements of high-energy γ-ray emission from young massive star cluster environments

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Anton Pannekoek Institute Colloquium

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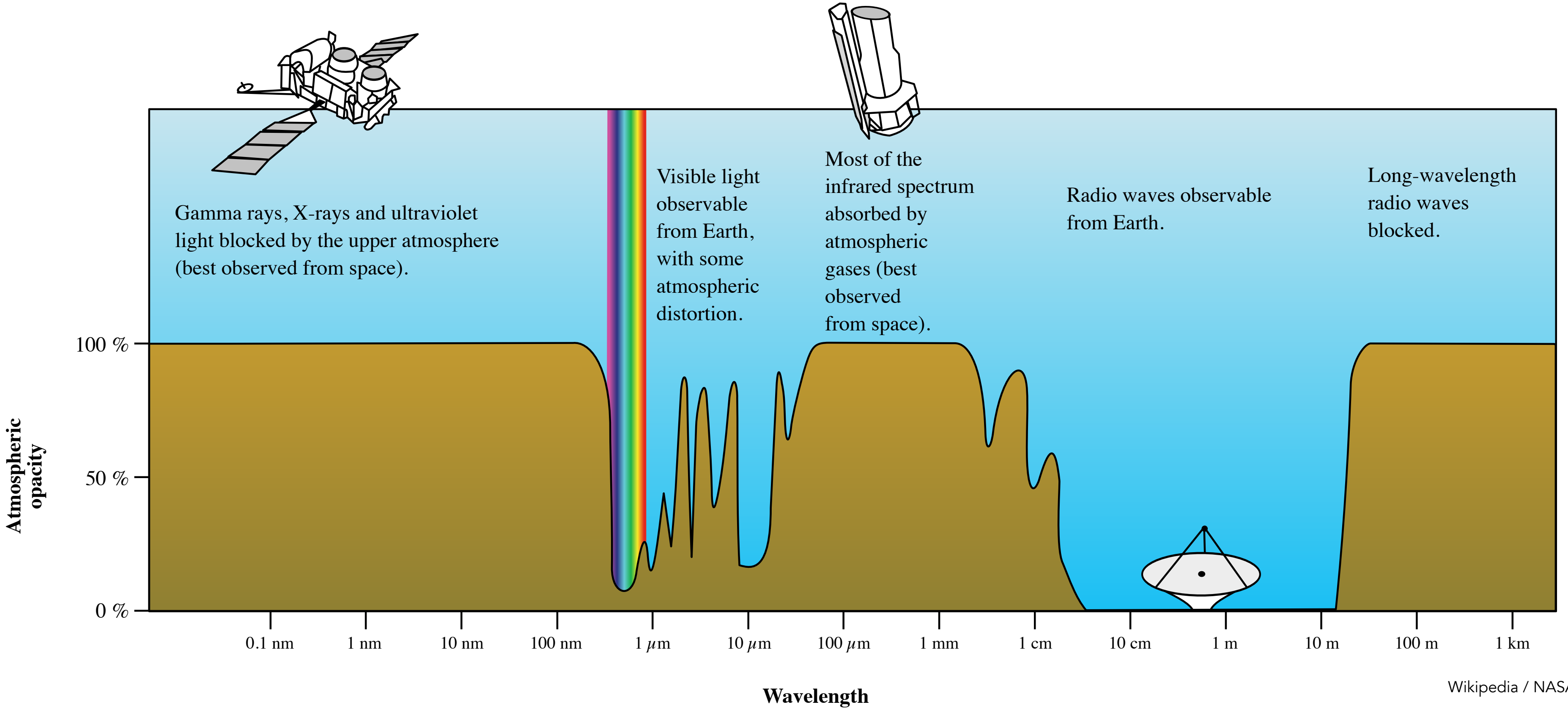
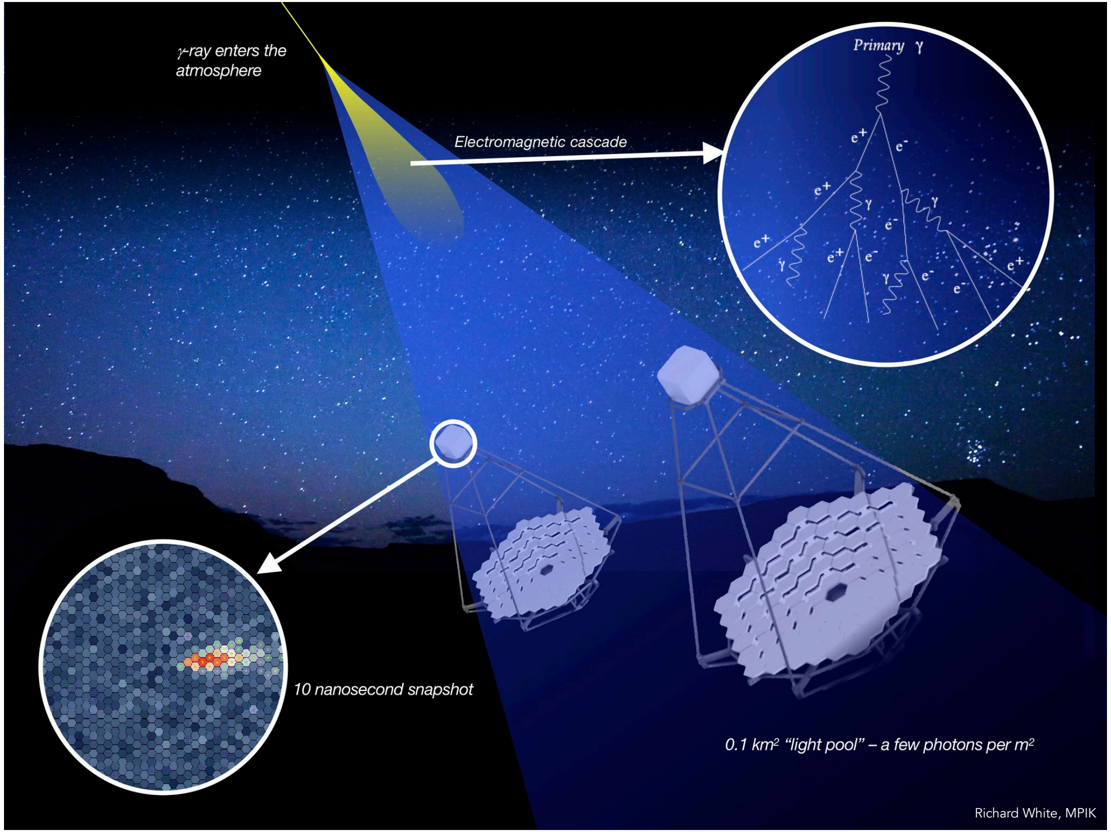
Observing the electromagnetic spectrum



Wikipedia / NASA

Imaging Atmospheric Cherenkov Telescopes

- Detect **Cherenkov light** from secondary particles in air shower
- Requires telescopes with **large mirrors** and **fast cameras**
- **High resolution** (energy ~20%, direction ~0.1°)
- **Restricted to dark nights** (~1,300 hours per year)
- **Limited field of view** (~5°×5°)



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

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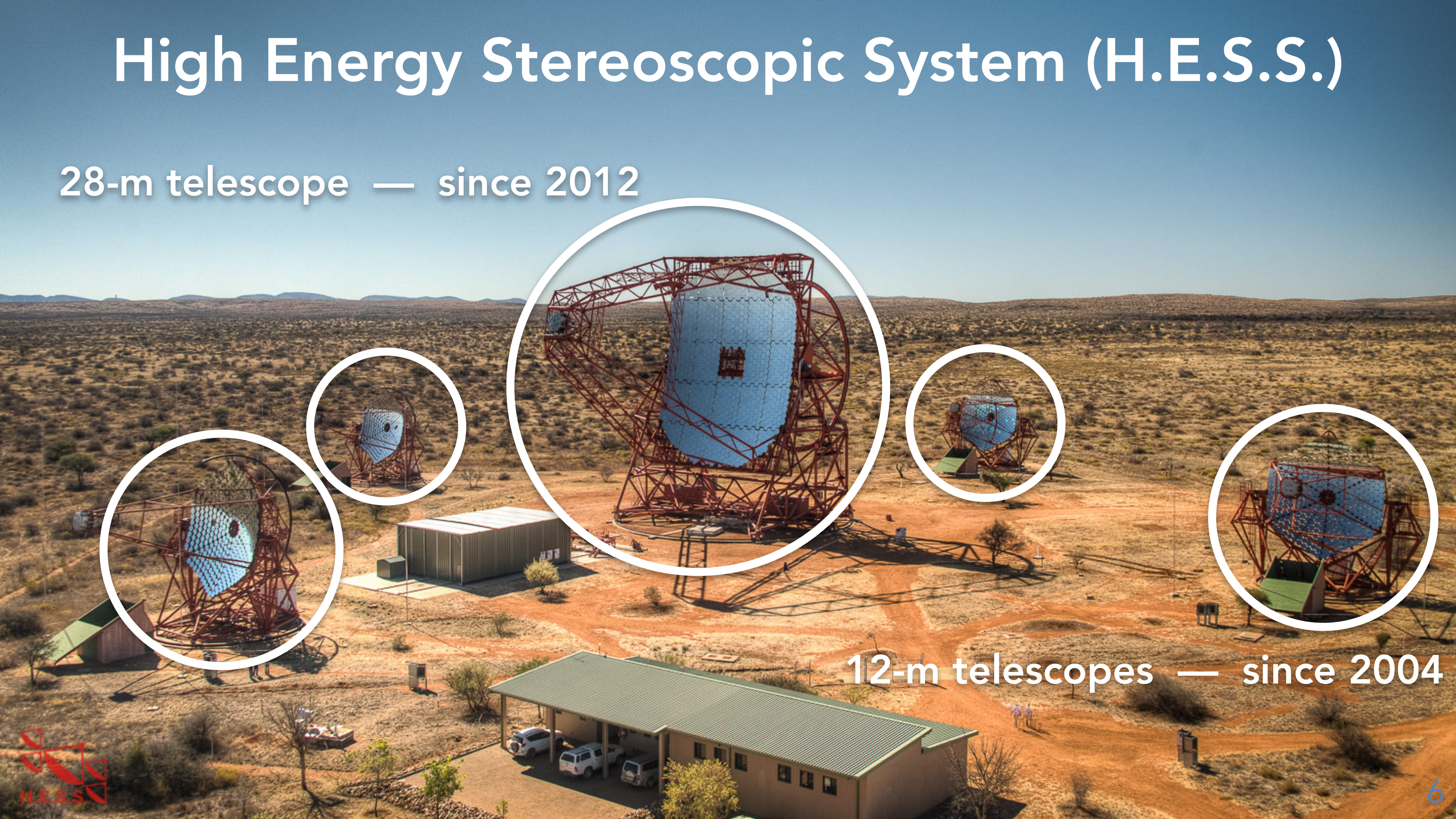
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28-m telescope — since 2012
12-m telescopes — since 2004
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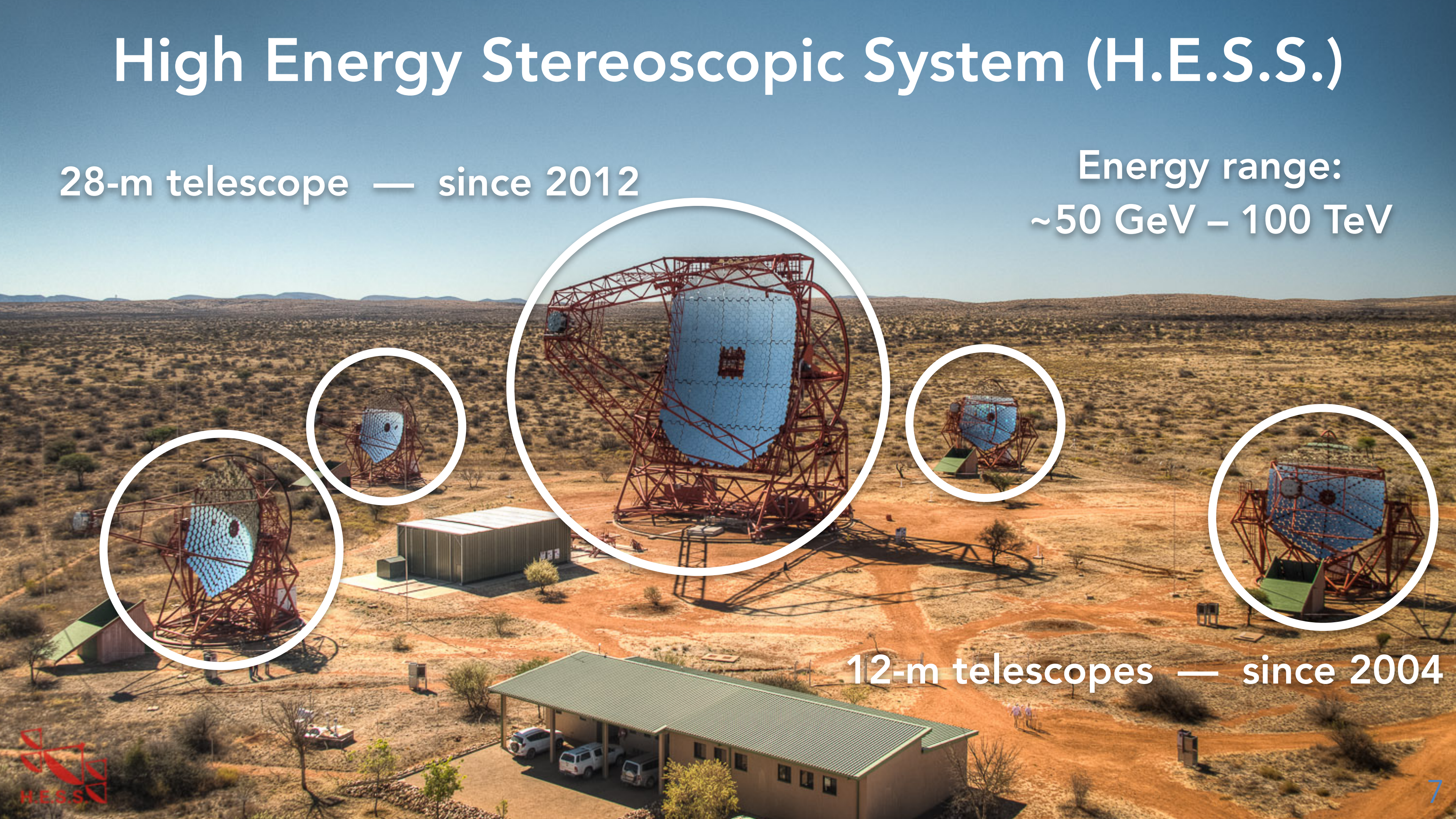
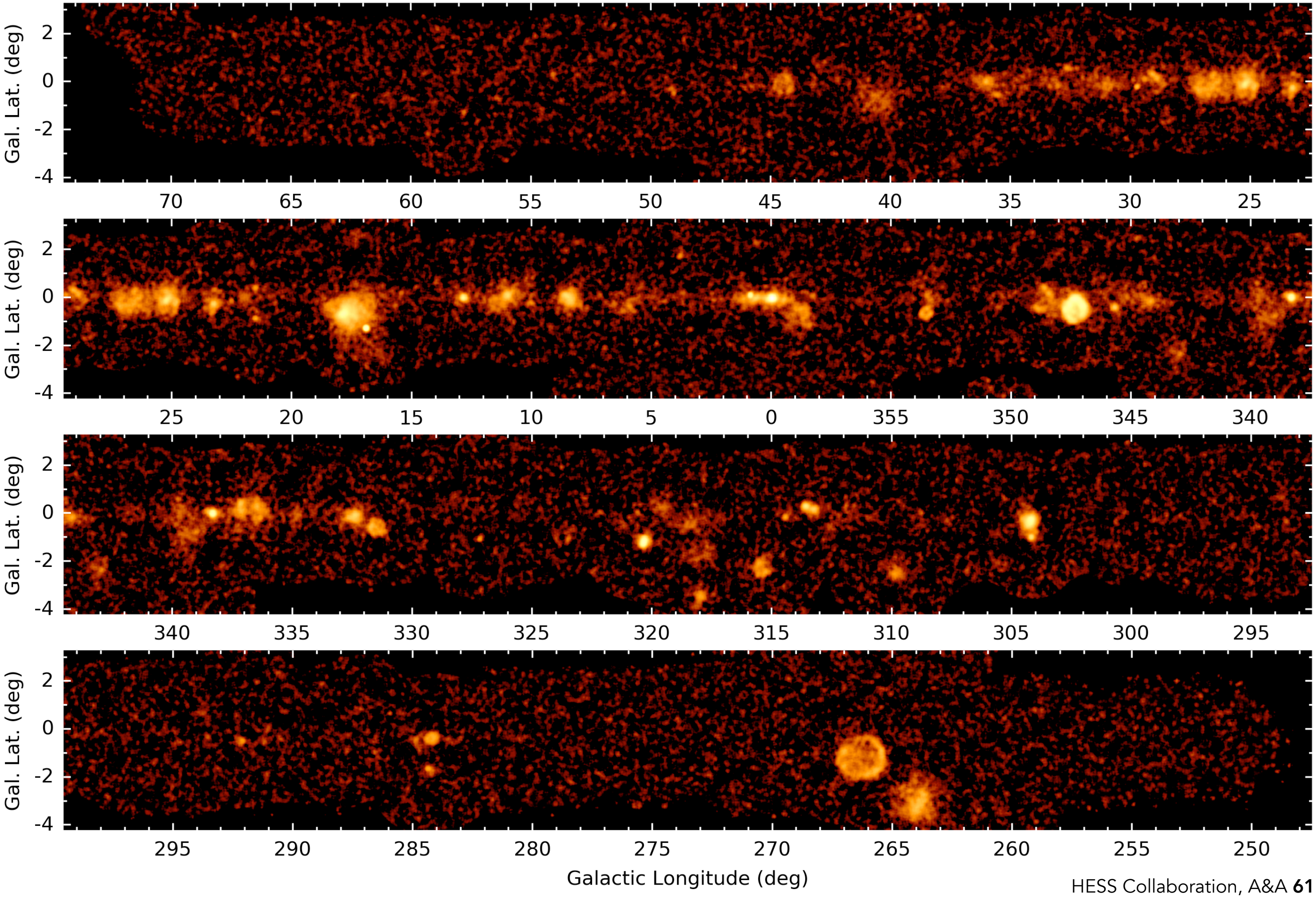


28-m telescope — since 2012

Energy range:
~50 GeV – 100 TeV

12-m telescopes — since 2004



HESS Collaboration, A&A **612**, A1 (2018)

Production of γ-rays

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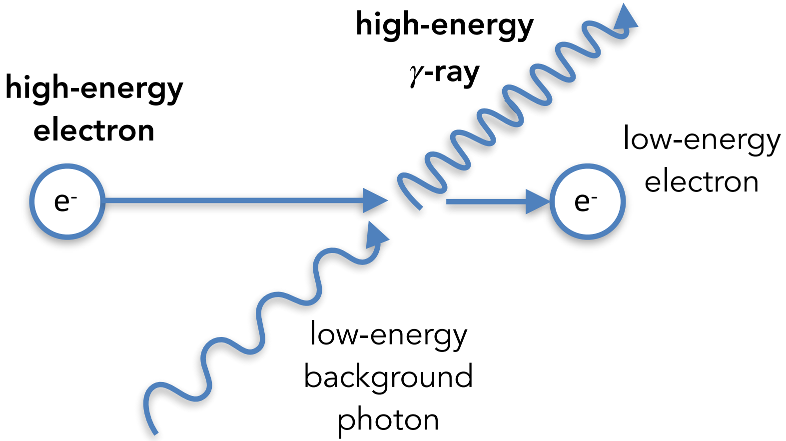

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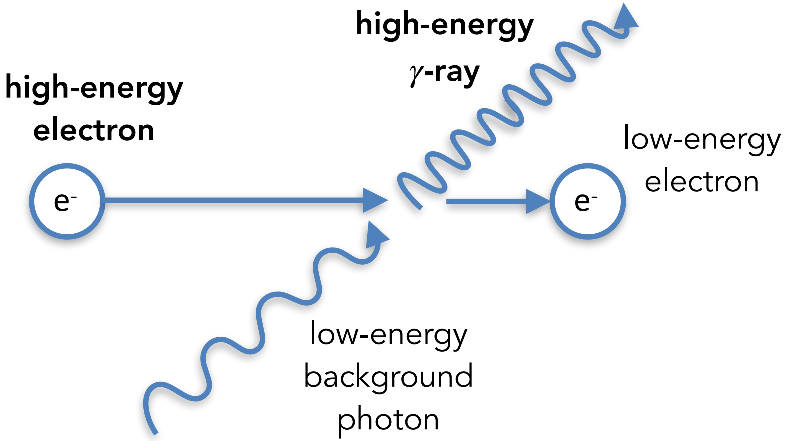
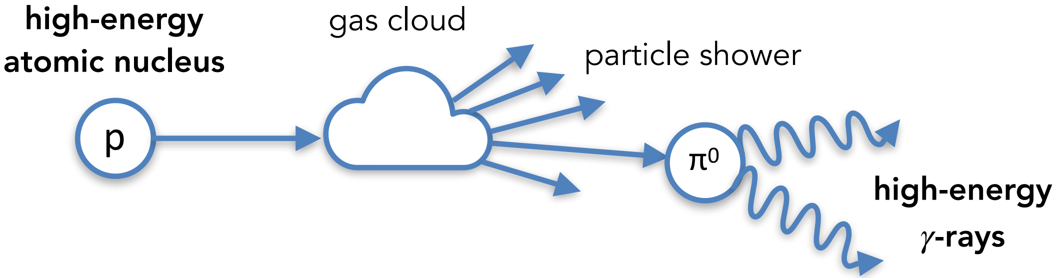


- **Hadronic production**



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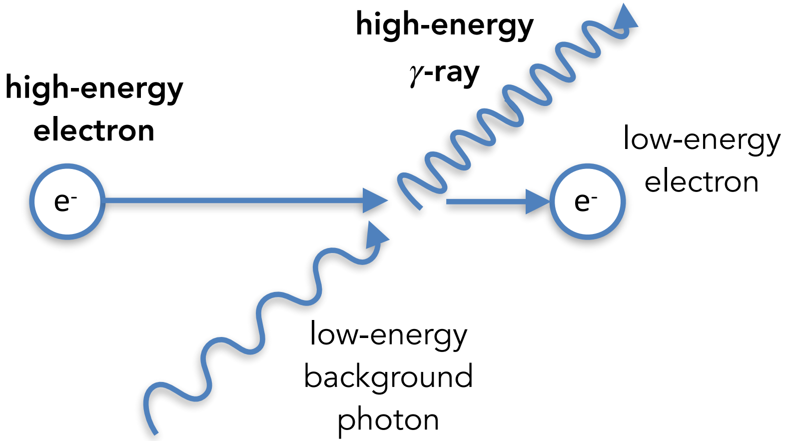

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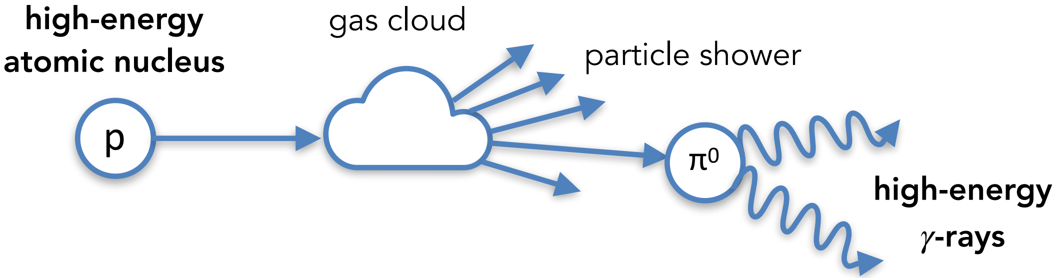
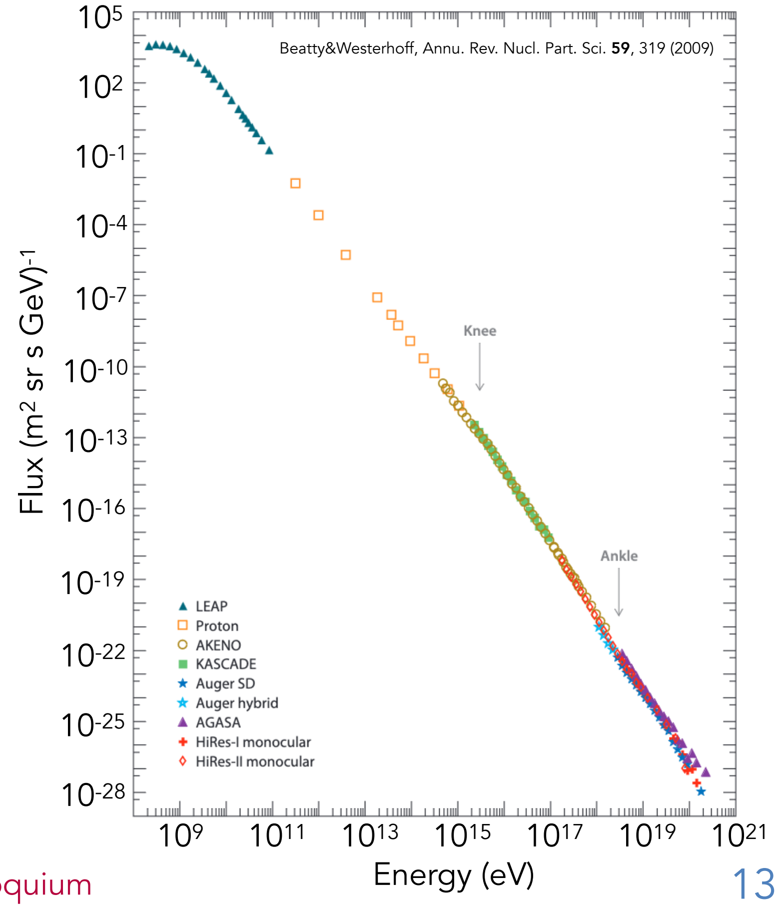


- We can use **γ-rays** to study the acceleration of **cosmic rays**!

The origin of cosmic rays

- The Universe accelerates cosmic rays to **unimaginably high energies**
- Finding their origin is a **>100 yr old mystery**
- Cosmic rays have **profound impact** e.g. on **Galaxy evolution**



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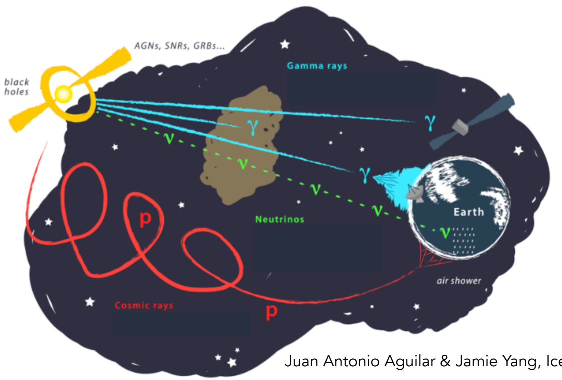
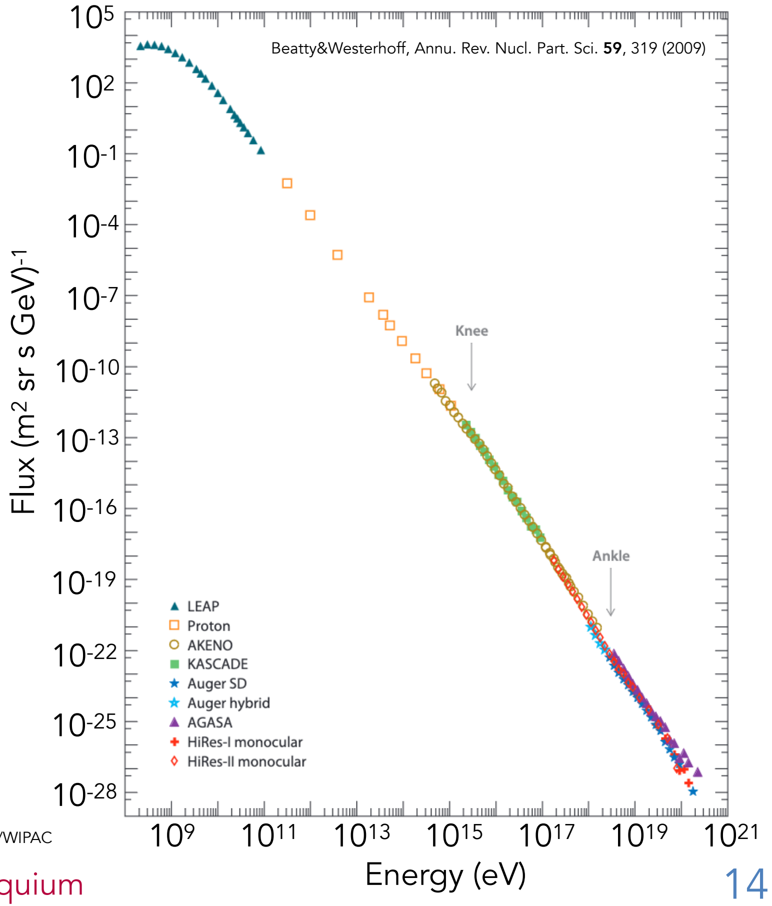
- Cosmic rays are **deflected** in cosmic magnetic fields!
- Need **neutral messengers**



Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC



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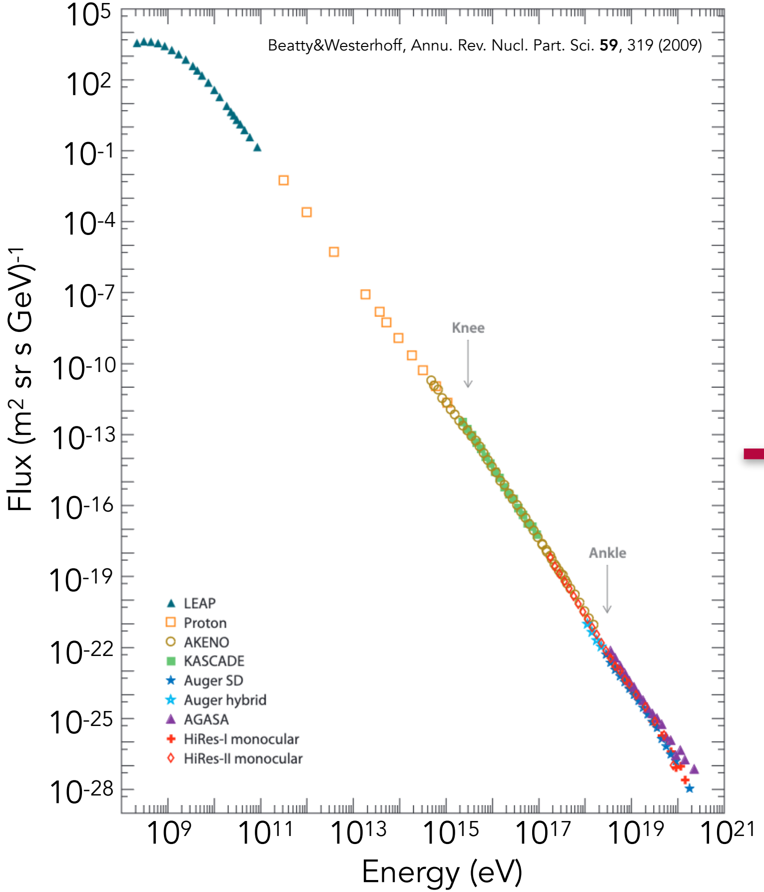
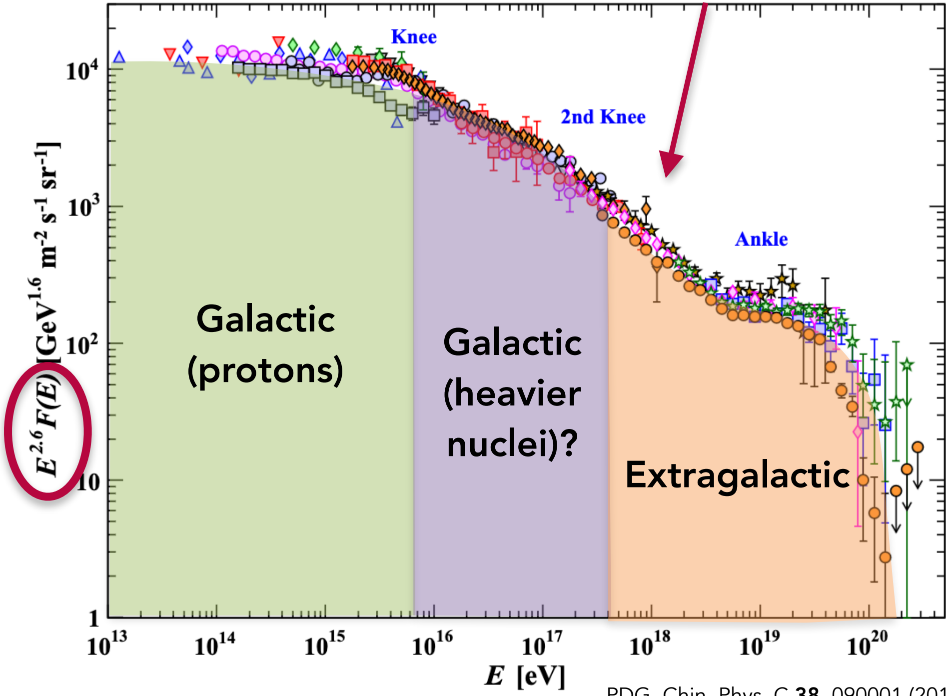


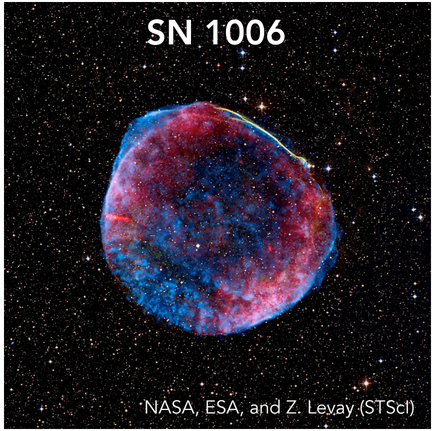
Not clear where exactly the transition from Galactic to extragalactic happens!



PDG, Chin. Phys. C **38**, 090001 (2014)

The supernova remnant paradigm

- **Bulk of Galactic cosmic rays** accelerated by **supernova remnants**



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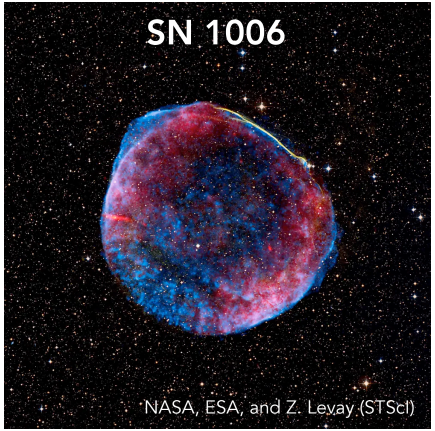
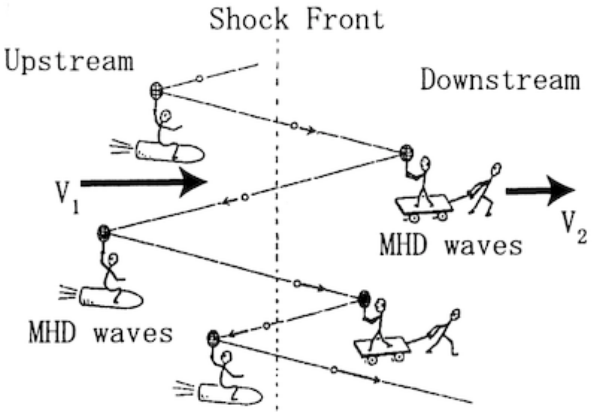
- **Bulk of Galactic cosmic rays** accelerated by **supernova remnants**
- SNRs expel **fast shocks → diffuse shock acceleration**
  - cosmic rays gain energy through multiple shock crossings
  - average gain per crossing proportional to particle energy
  - naturally leads to power-law spectra





Manfred Scholer

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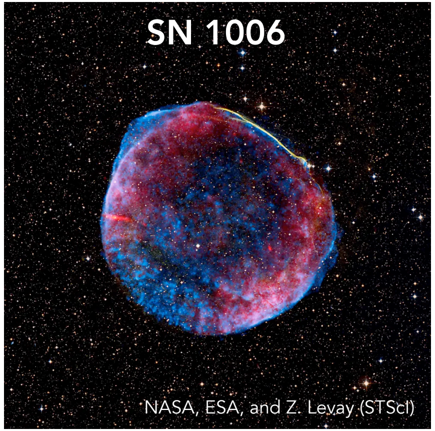

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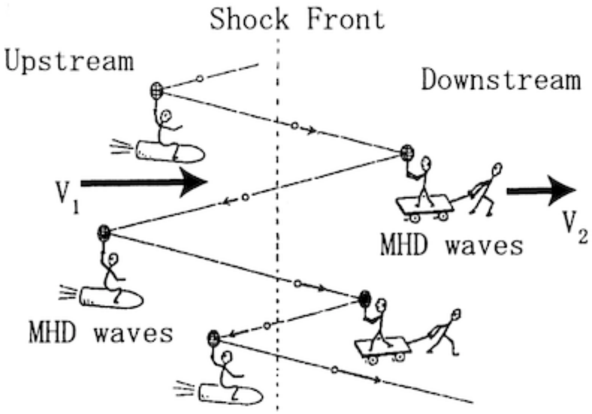
- Only SNRs **provide enough power** to sustain the cosmic-ray flux
  - already realised by Baade & Zwicky (1934), later Ginzburg (1961)
  - few SN per century, each ~10^{51} erg
  - can sustain measured flux if ~10% of kinetic energy is transformed into cosmic rays



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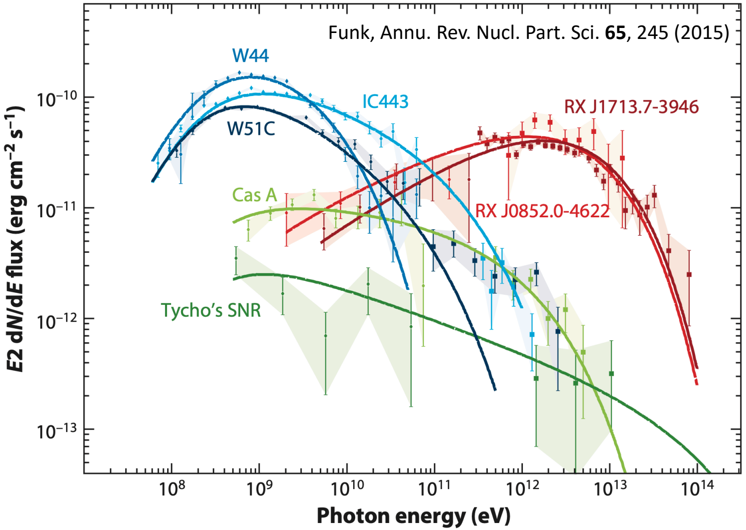
- γ**-ray spectra** of known SNRs **cut off too early**
  - efficient acceleration to highest energies only in the first 100 years?

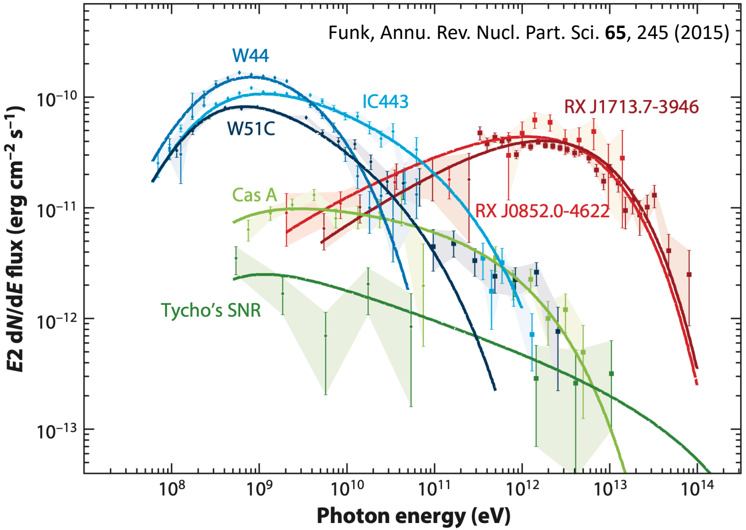


The supernova remnant paradigm

- γ**-ray spectra** of known SNRs **cut off too early**
  - efficient acceleration to highest energies only in the first 100 years?
- **Theory struggles** to explain acceleration to **PeV energies**
  - Hillas criterion:

$$E_{\max} \sim \frac{Z}{3} \left(\frac{R_{\rm sh}}{\rm pc} \right) \left(\frac{u_{\rm sh}}{1000\,{\rm km\,s^{-1}}} \right) \left(\frac{B}{\mu{\rm G}} \right) {\rm TeV}$$

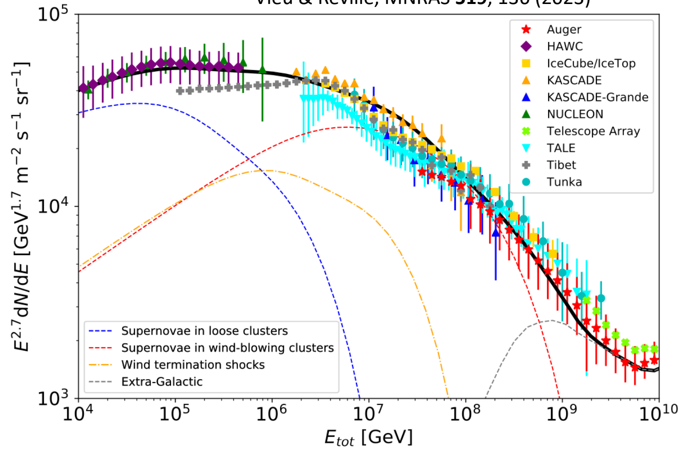
  - requires magnetic field amplification from feedback of cosmic rays and special conditions (very fast shocks, …)



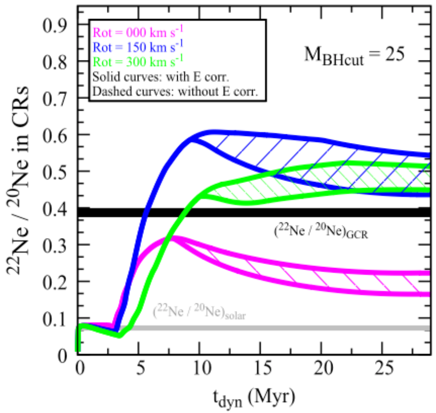
Young massive star clusters to the rescue

- **Young massive star clusters** proposed as favourable environments for cosmic-ray acceleration (Cesarsky 1983, Klepach 2000, Bykov 2001, Aharonian 2019, Gupta 2020, Morlino 2021, Tatischeff 2021, Vieu 2022, 2023, Härer 2025, …)
  - potentially provide conditions for **acceleration to PeV energies**
  - can explain **composition anomalies** (^{22}Ne/^{20}Ne)

Vieu & Reville, MNRAS **519**, 136 (2023)



Gupta et al., MNRAS **493**, 3159 (2020)



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  - potentially provide conditions for **acceleration to PeV energies**
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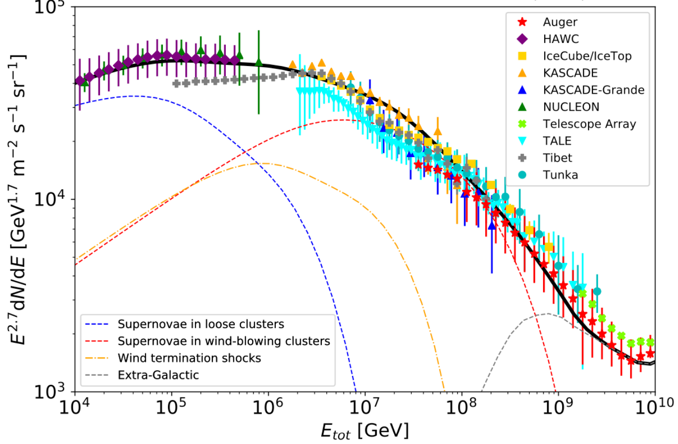
- **Details are extremely complex!**
  - compact vs. loose clusters
  - young vs. evolved clusters
  - stellar composition
  - …

Vieu & Reville, MNRAS **519**, 136 (2023)



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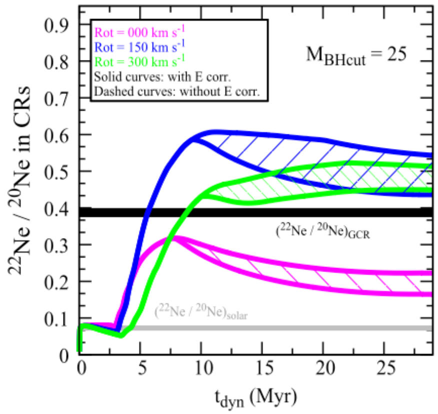
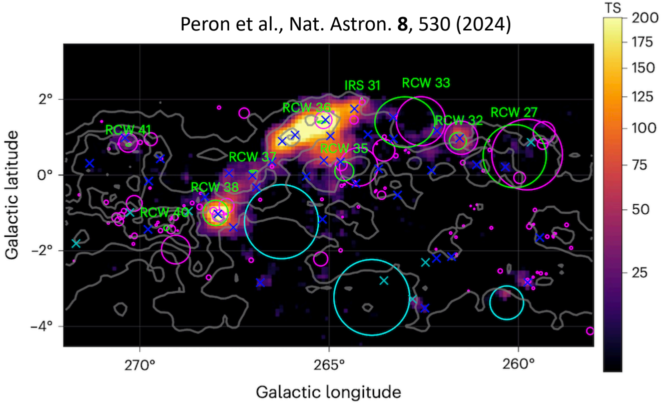
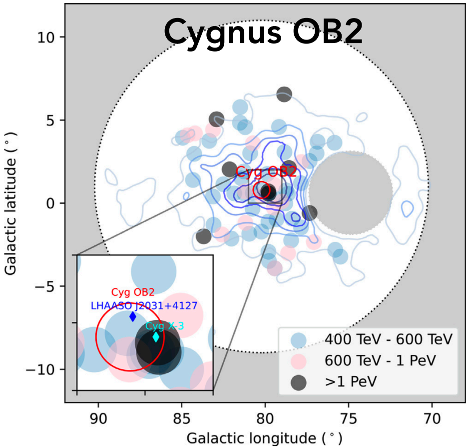


Young massive star clusters to the rescue

- γ**-ray emission** detected from numerous young massive star clusters
  - with *Fermi*-LAT at GeV energies
  - with ground-based instruments at TeV energies

Peron et al., Nat. Astron. **8**, 530 (2024)





LHAASO Collaboration, Science Bulletin **69**, 449 (2024)

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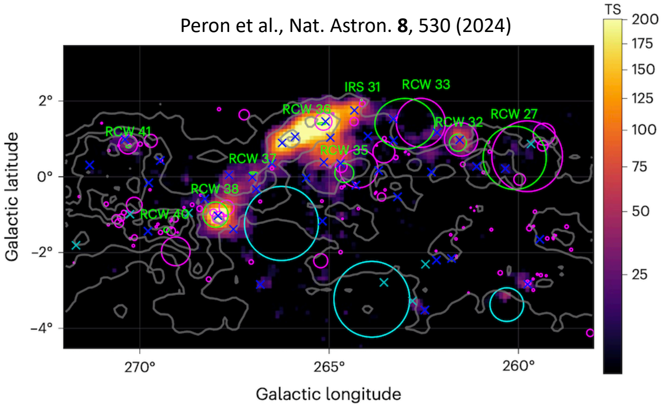
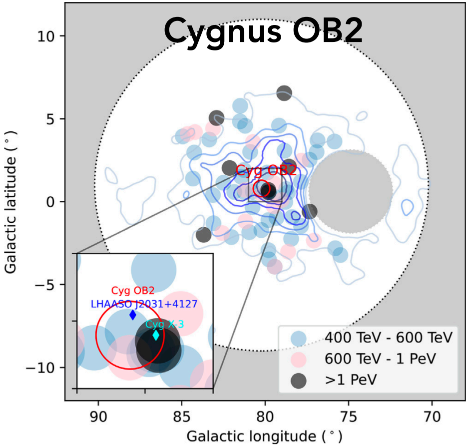


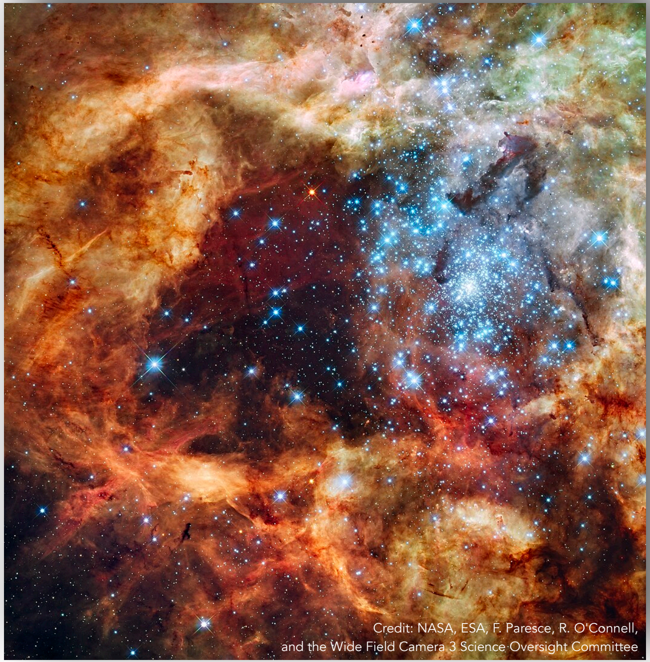
- Young massive star clusters are **cosmic-ray accelerators!**



LHAASO Collaboration, Science Bulletin **69**, 449 (2024)

Young massive star clusters

- **What are they?**
  - dense clusters of massive stars
    (O/B stars, supergiants, Wolf-Rayet stars, …)
  - age: $\lesssim$ few million years
  - total mass: $\gtrsim 10^4\ M_\odot$
  - compact clusters: $r \lesssim$ few pc


Credit: NASA, ESA, F. Paresce, R. O'Connell, and the Wide Field Camera 3 Science Oversight Committee

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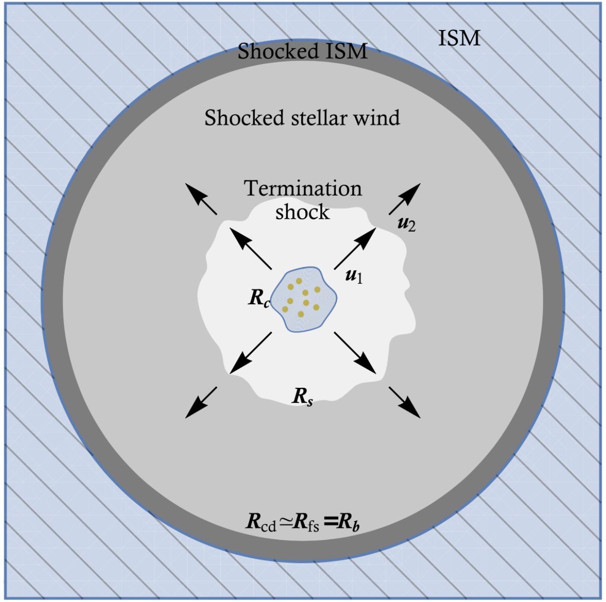

Morlino et al., MNRAS **504**, 6096 (2021)

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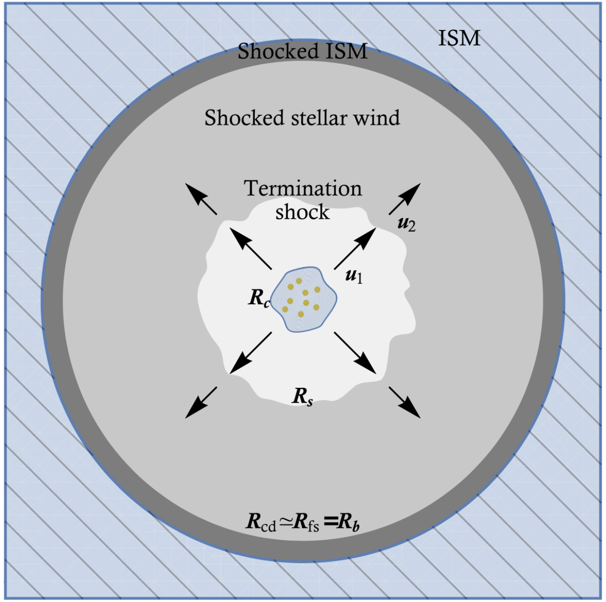
- **Cosmic-ray acceleration**
  - wind-wind interactions inside cluster
  - turbulence in superbubble
  - cluster wind termination shock



Morlino et al., MNRAS **504**, 6096 (2021)

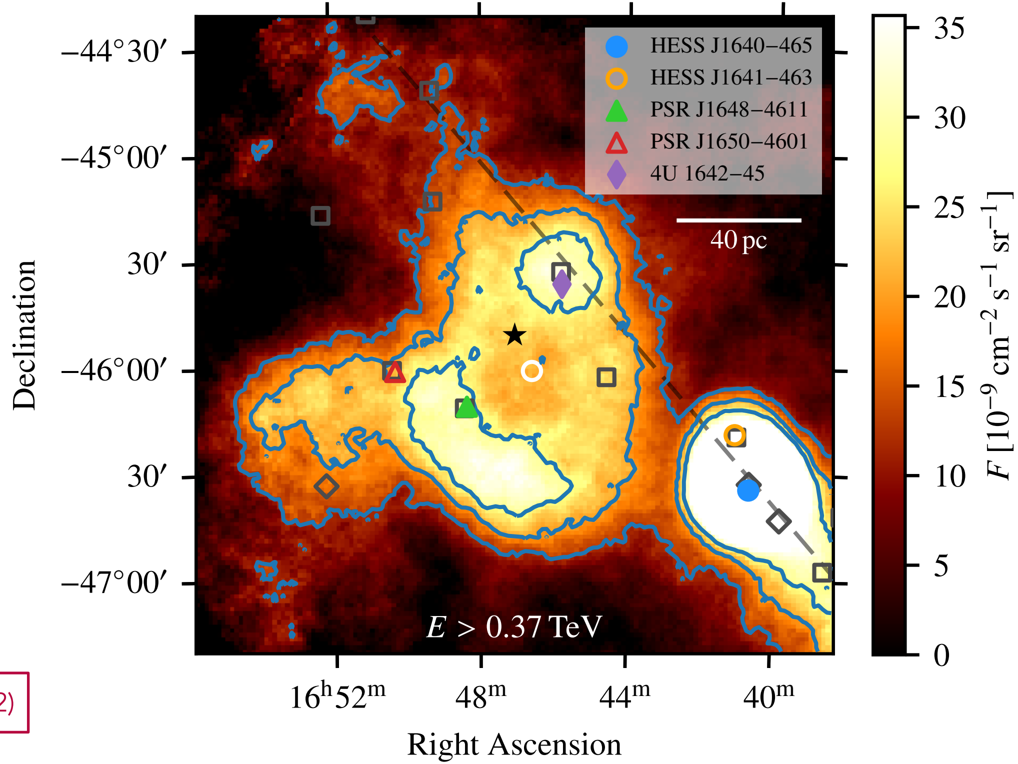
Westerlund 1

- **Most massive young star cluster** in the Milky Way
  - wealth of powerful stars
    (24 Wolf-Rayet stars, 4 red supergiants, 6 yellow hypergiants, 1 luminous blue variable, …)
  - total mass: 50,000–100,000 $M_\odot$
  - very compact: few pc across
  - relatively young: ~4 Myr

- Estimated **power of collective cluster wind:**
  - $L \approx 10^{39}$ erg s^{-1}

    (this corresponds to ~1% of the luminosity of **all** cosmic rays in the Galaxy)

Westerlund 1 seen with H.E.S.S.



H.E.S.S. Collaboration, *Astronomy & Astrophysics* **666**, A124 (2022)

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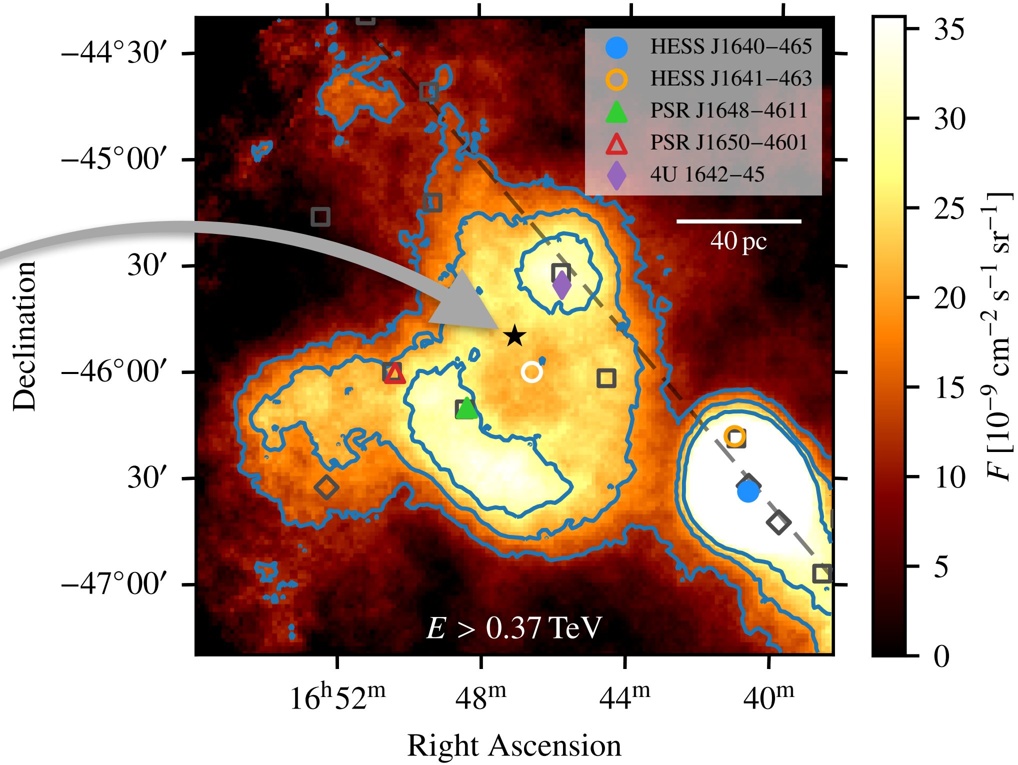

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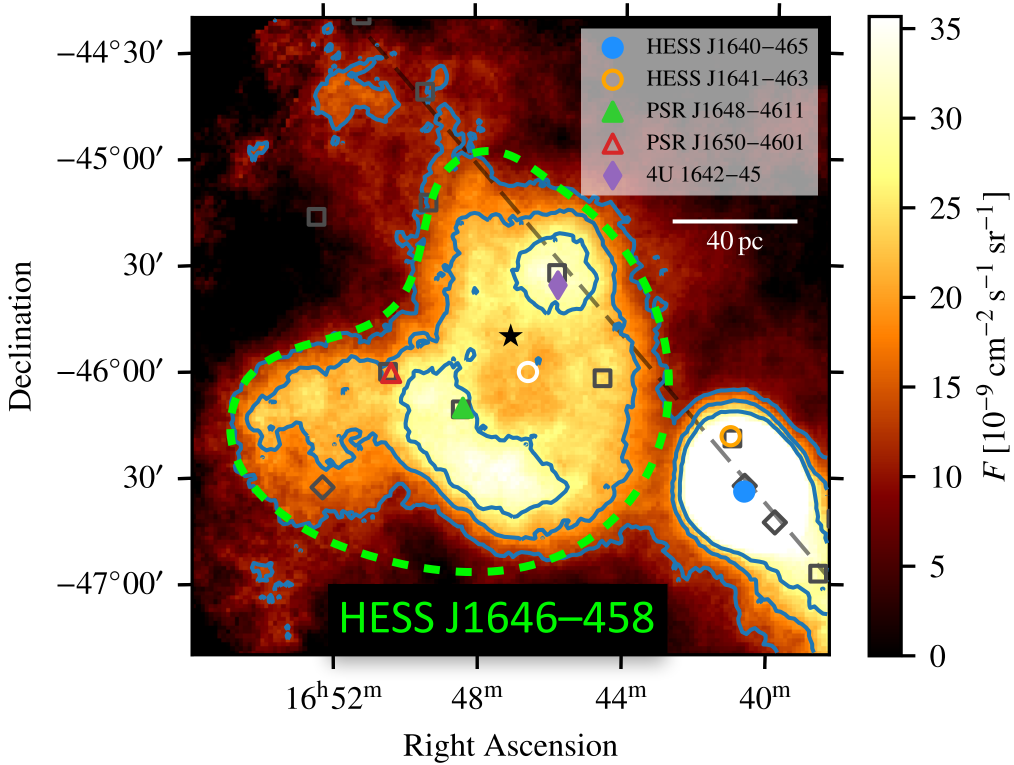
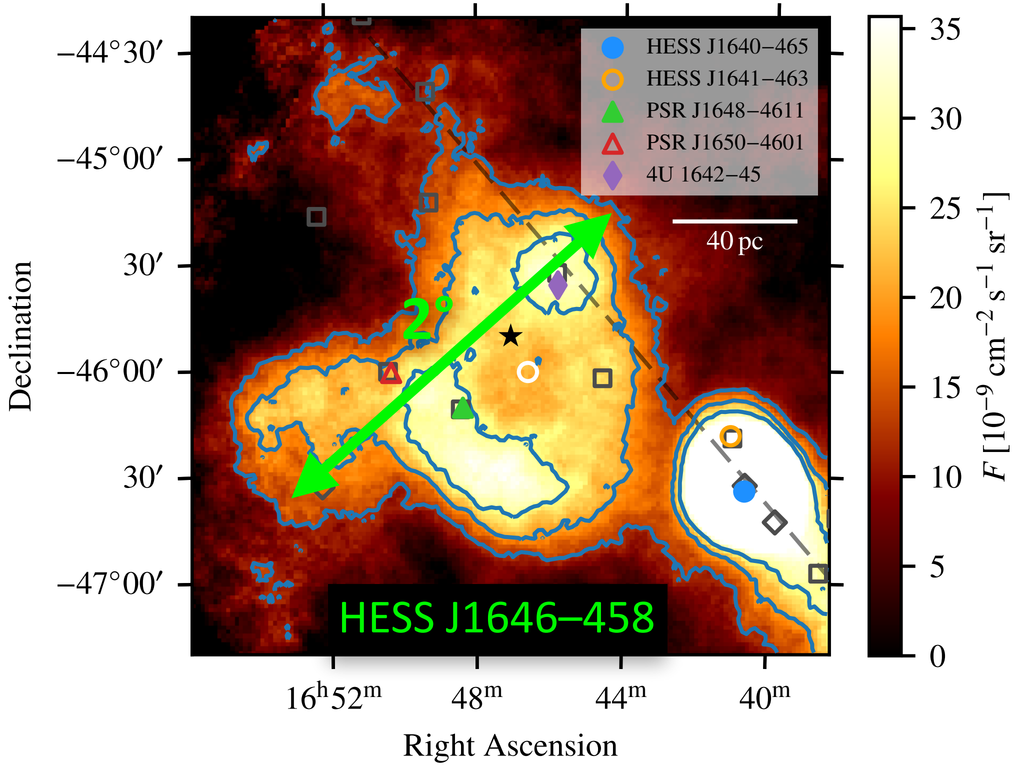


Westerlund 1 seen with H.E.S.S.

- **Source extent**
  - diameter ~2° (140 pc)
  - 100× larger than cluster itself!



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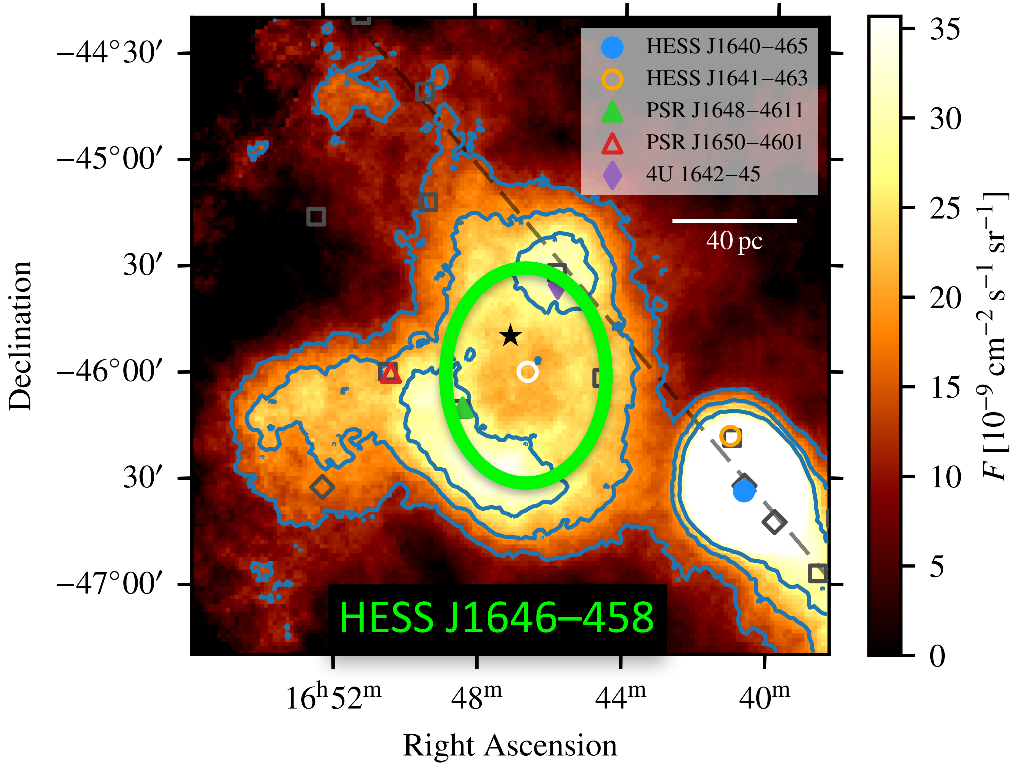
  - γ-ray emission does **not** peak at cluster position
  - **ring-like structure** with cluster near centre
  - several bright spots along the ring



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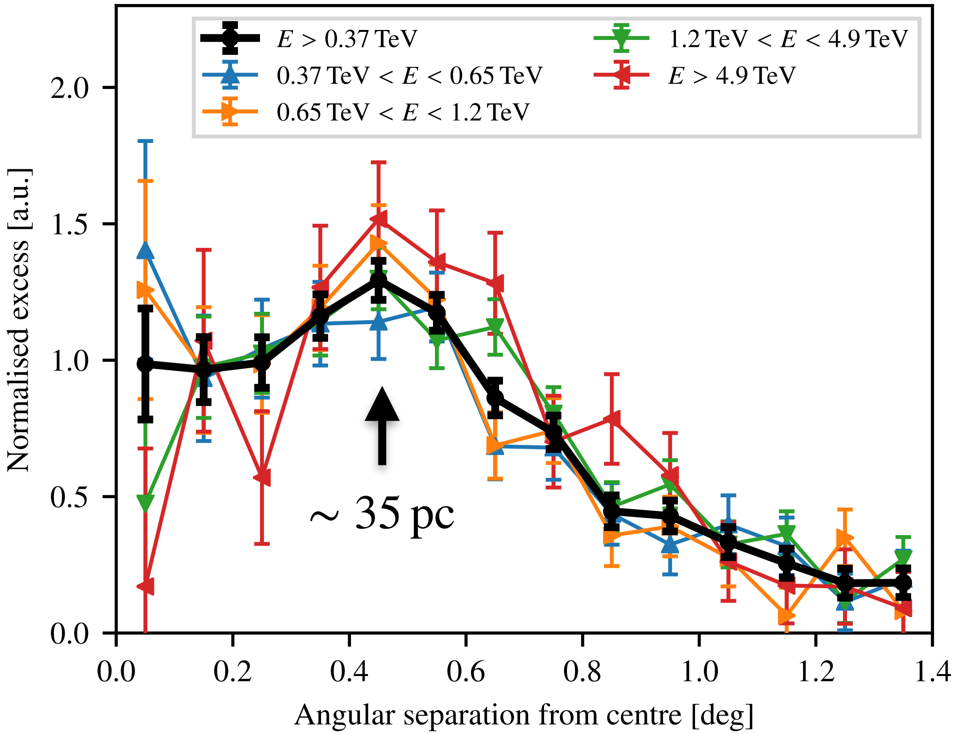
  - **ring-like structure** with cluster near centre
  - several bright spots along the ring
- **Radial emission profiles**
  - ring-like structure appears in all energy bands
  - radius of the ring is ~35 pc



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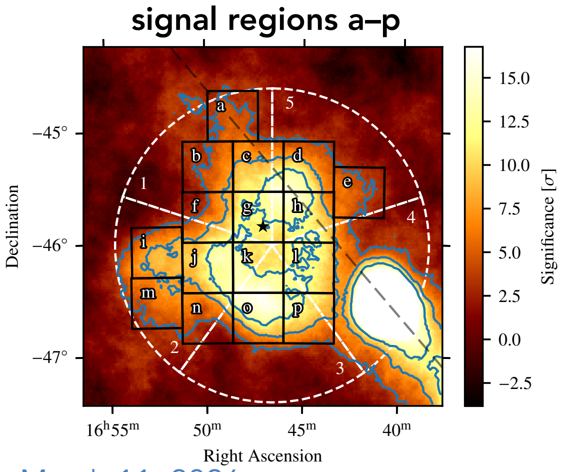
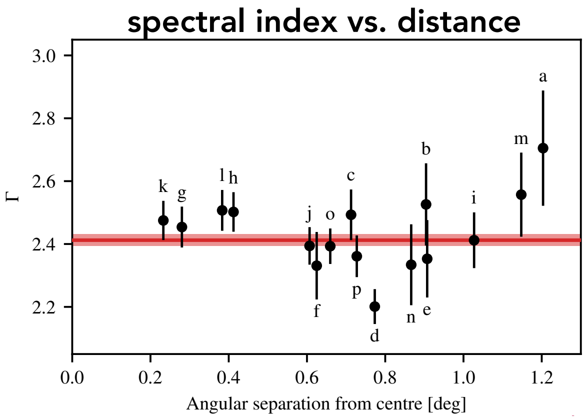
- **Energy spectrum**
  - extracted in 16 signal regions
  - individual spectra remarkably similar





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- **Energy spectrum**
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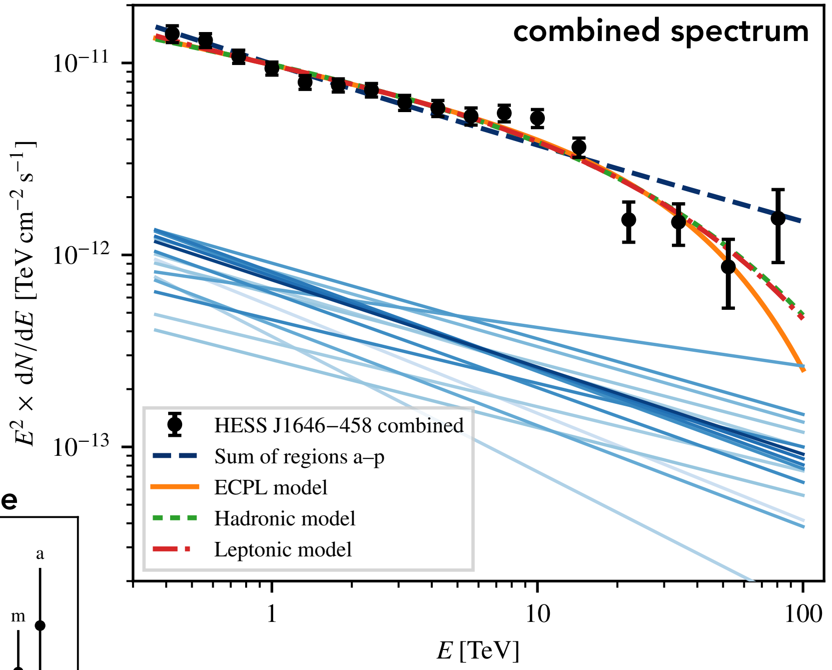
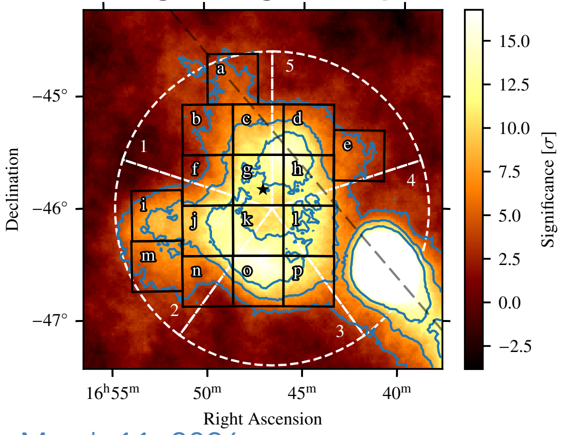
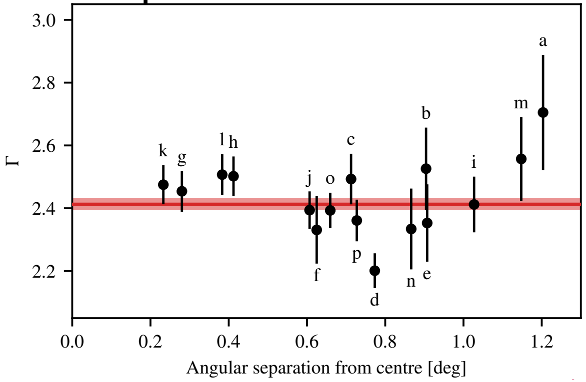
  - individual spectra remarkably similar
  - add up region spectra → combined spectrum
  - extends up to 100 TeV!



signal regions a–p



spectral index vs. distance

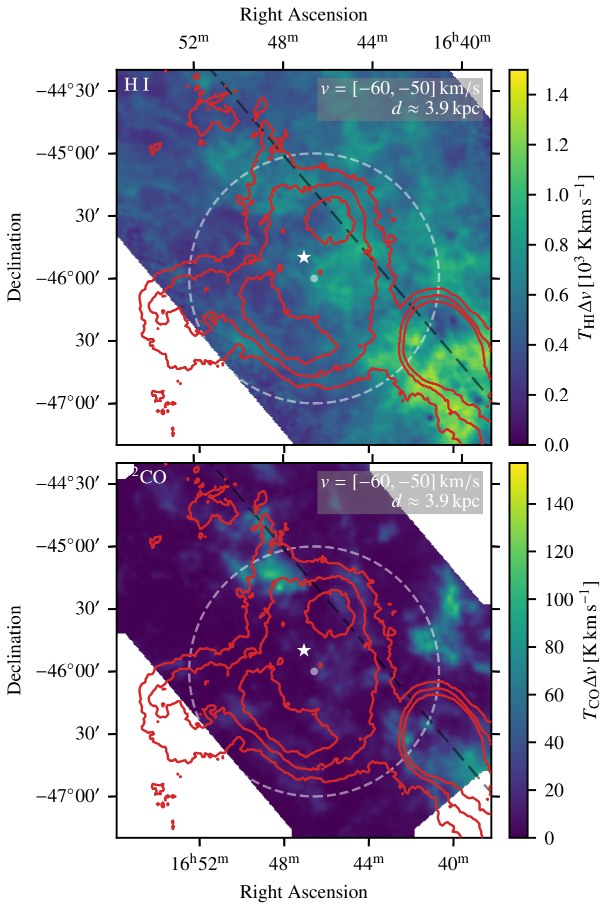


Interstellar medium density

- **Correlation with gas tracers**
  - comparison with **HI** (atomic hydrogen) and ^{12}CO (molecular hydrogen) line emission
  - **low gas density** in regions with bright gamma-ray emission

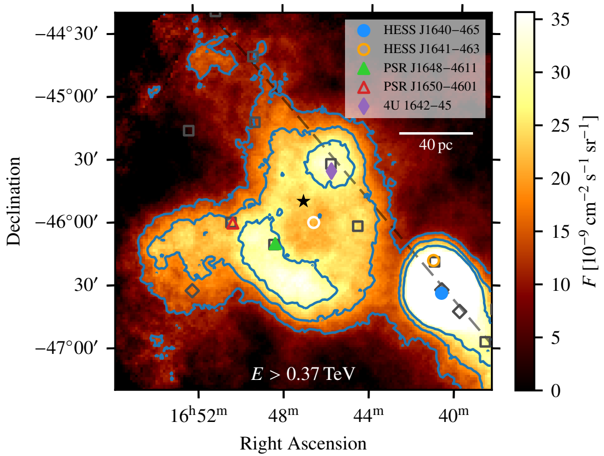
- Consistent with **superbubble** picture
  - expect low densities inside the bubble

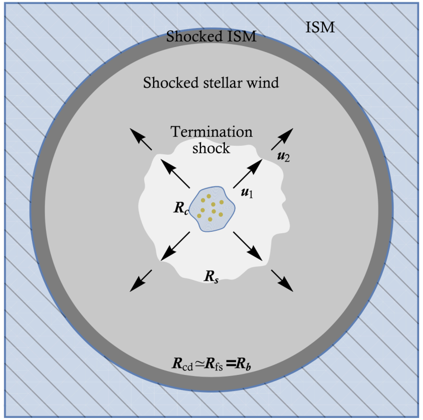
- TeV emission likely of **leptonic origin**
  - inverse-Compton emission
  - hadronic scenario also energetically disfavoured



Acceleration scenario

- **Large extent** + **ring-like structure** indicate that cosmic rays are **accelerated outside the cluster**





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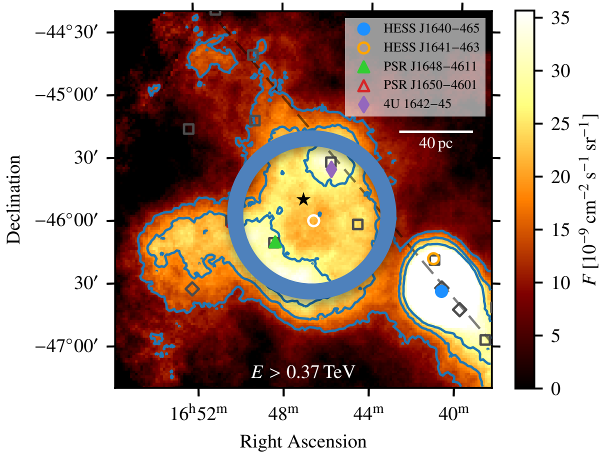
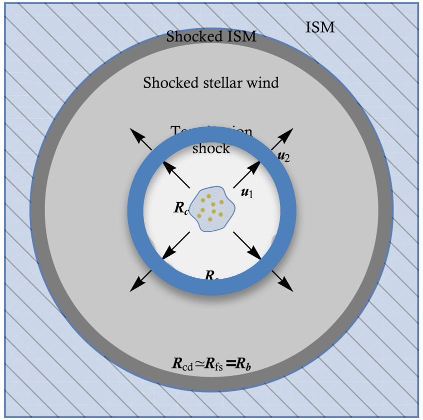
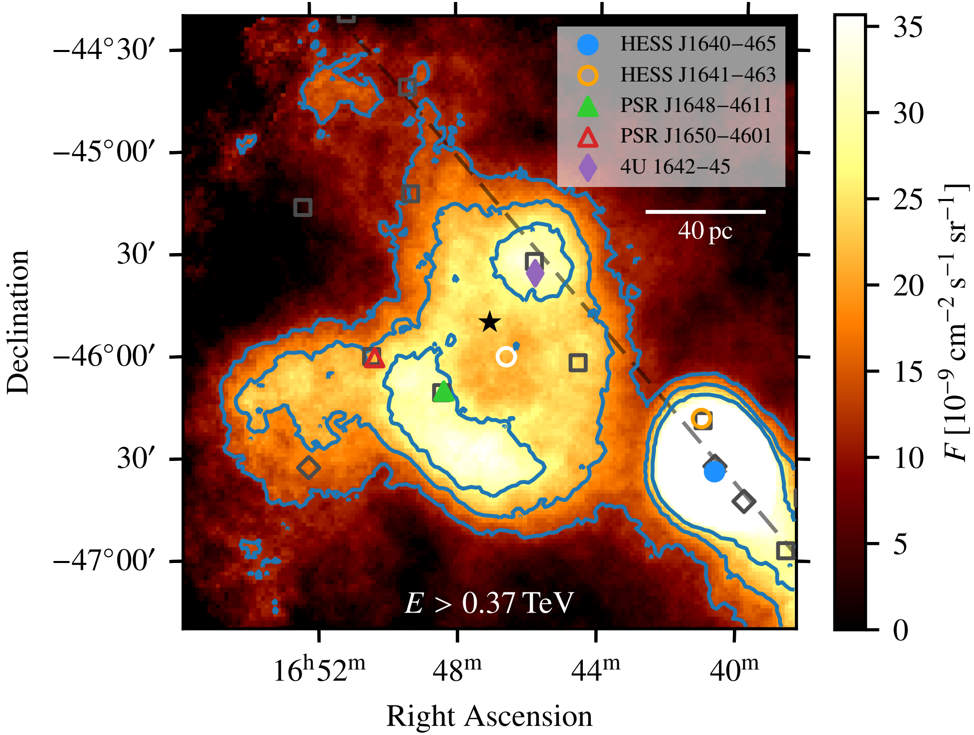
- **Ring-like structure** connected with cluster wind **termination shock?**
  - basic estimate suggests $R_{TS} \sim \mathcal{O}(30\ \mathrm{pc})$
    → matches radius of observed γ-ray ring!

- If confirmed, **first demonstration** of particle acceleration by a **collective wind** from a star cluster



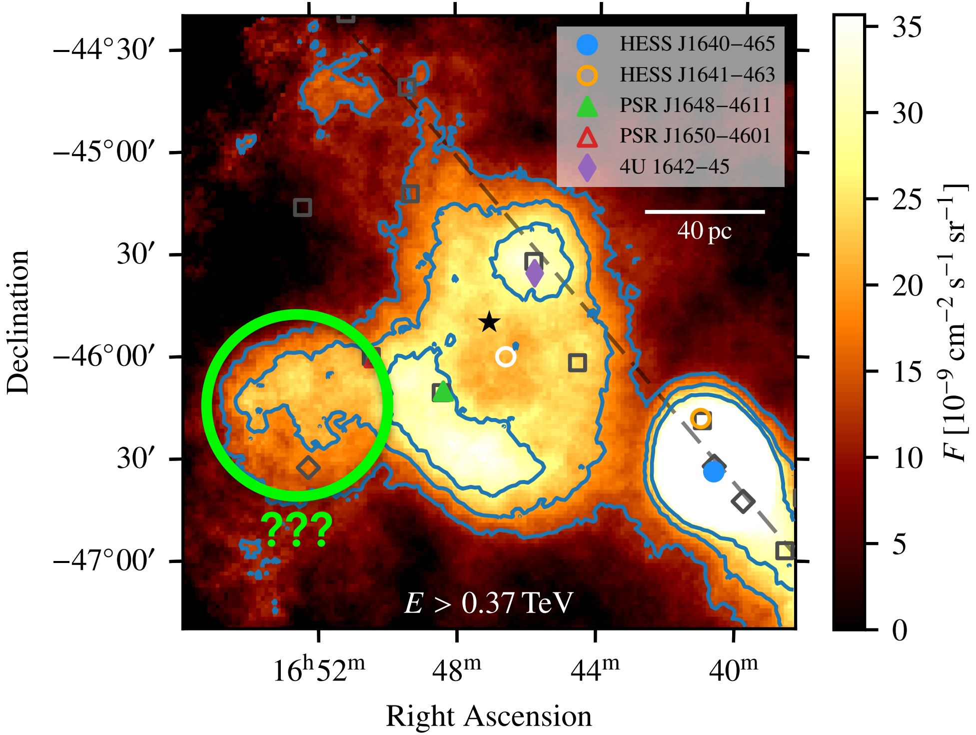


The “bulge”



HESS J1640−465
HESS J1641−463
PSR J1648−4611
PSR J1650−4601
4U 1642−45
40 pc
E > 0.37 TeV
−44°30′
−45°00′
30′
−46°00′
30′
−47°00′
Declination
16h52m
48m
44m
40m
Right Ascension
35
30
25
20
15
10
5
0
F [10−9 cm−2 s−1 sr−1]

The “bulge”


HESS J1640−465
HESS J1641−463
PSR J1648−4611
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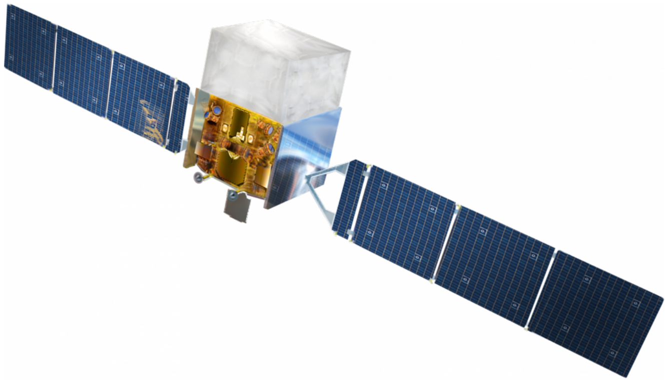
Westerlund 1 seen with *Fermi*-LAT

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



NASA

M. Lemoine-Goumard, L. Härer, **L. Mohrmann** et al., *Nature Communications* **16**, 10820 (2025)

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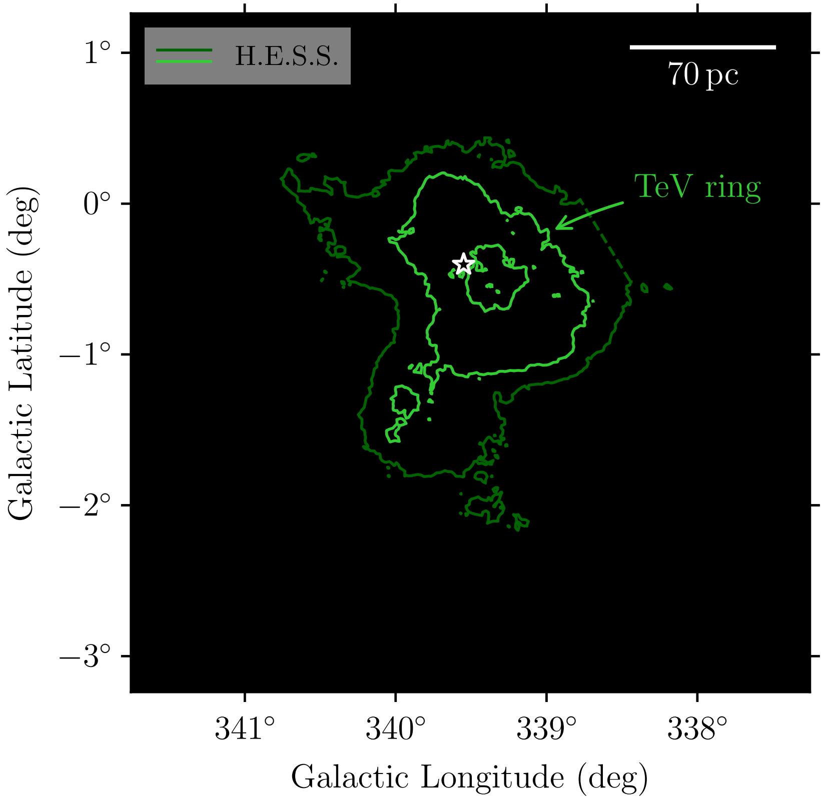

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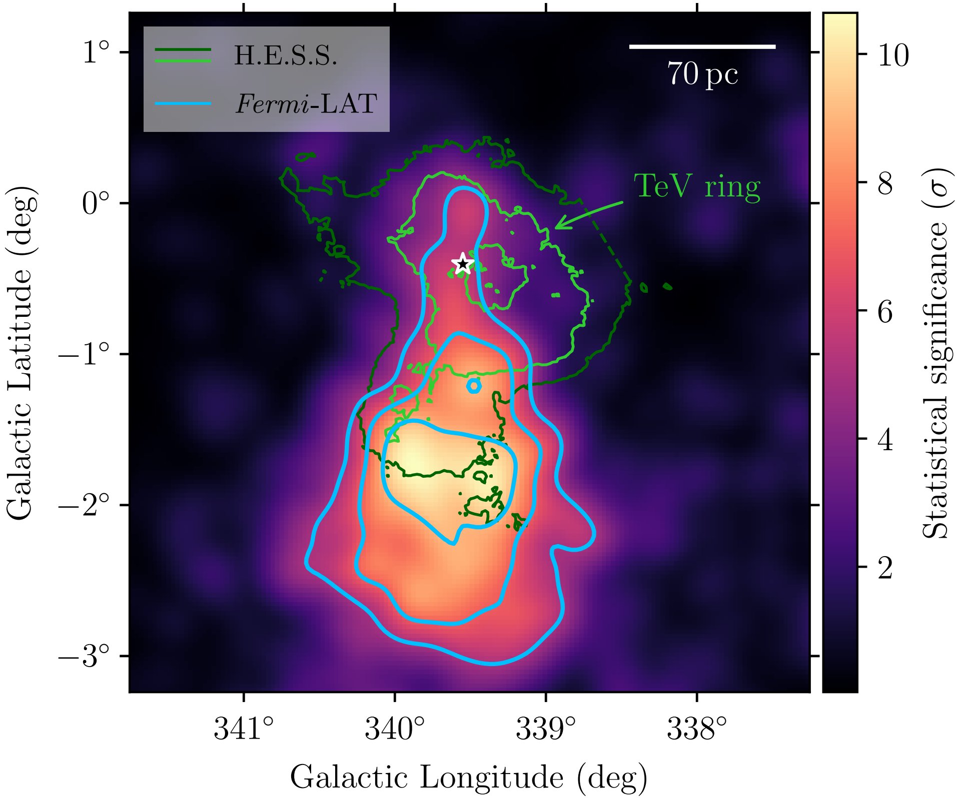

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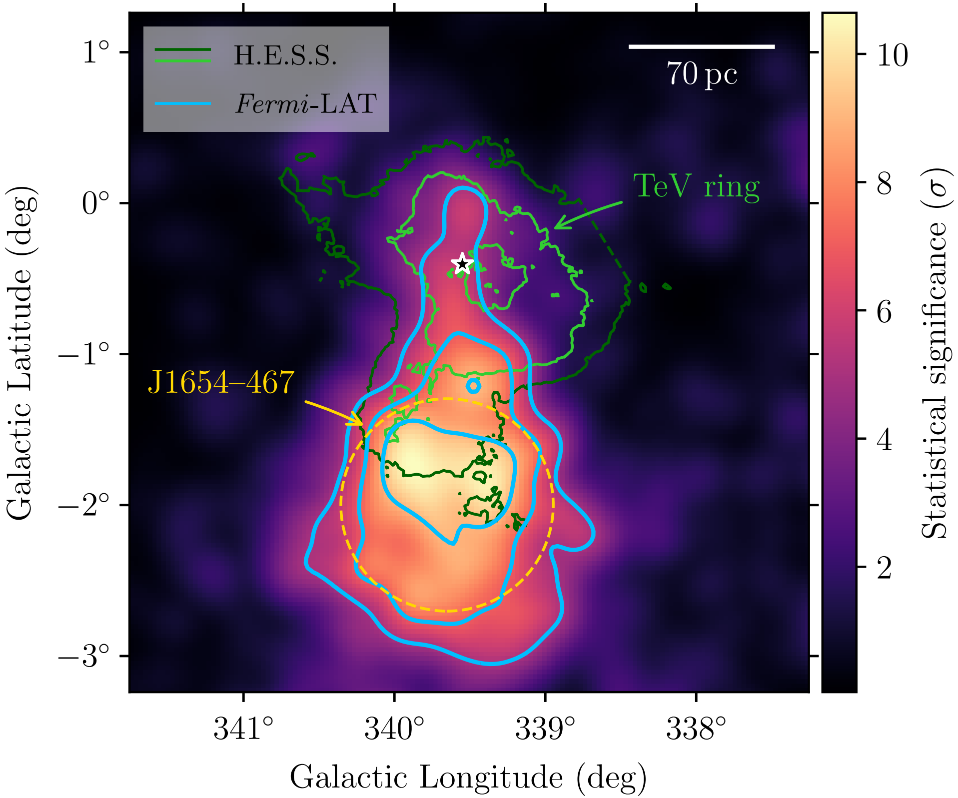
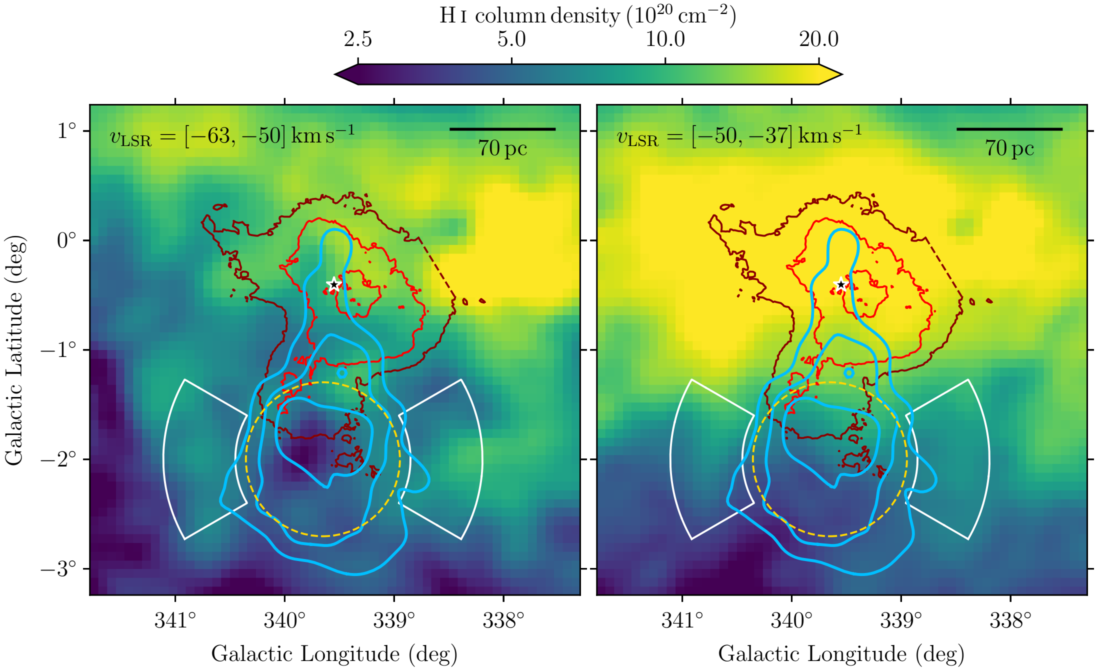
- **J1654–467**
  - smoothly connected with TeV emission
  - suggests common origin



A cavity in the interstellar medium

- **HI** (21 cm) emission line → **atomic hydrogen gas**



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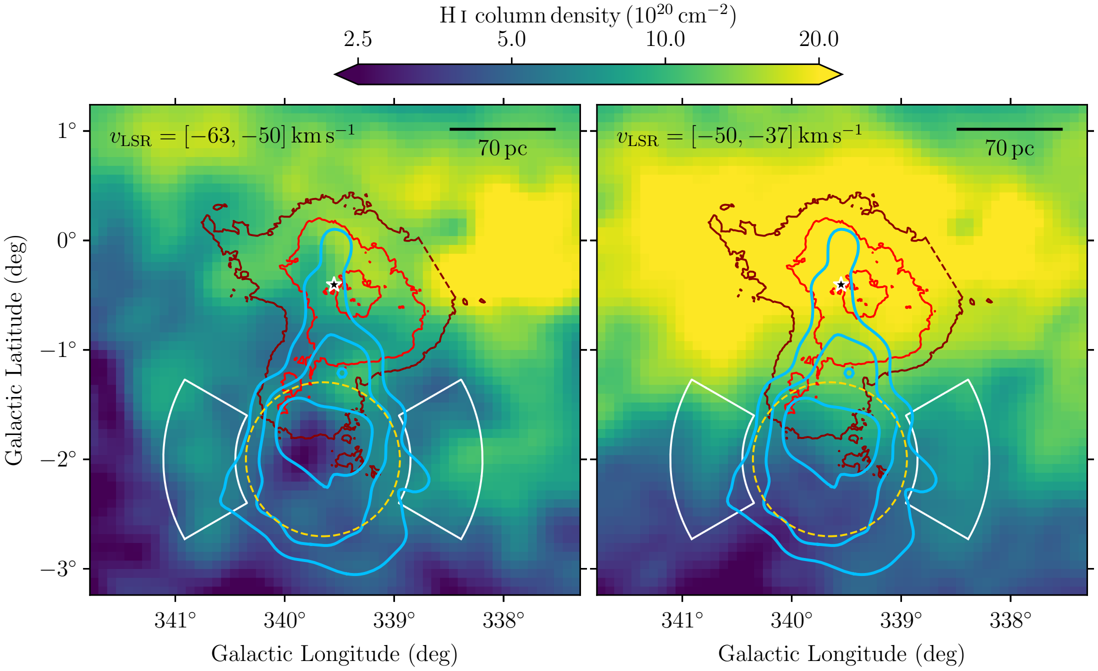


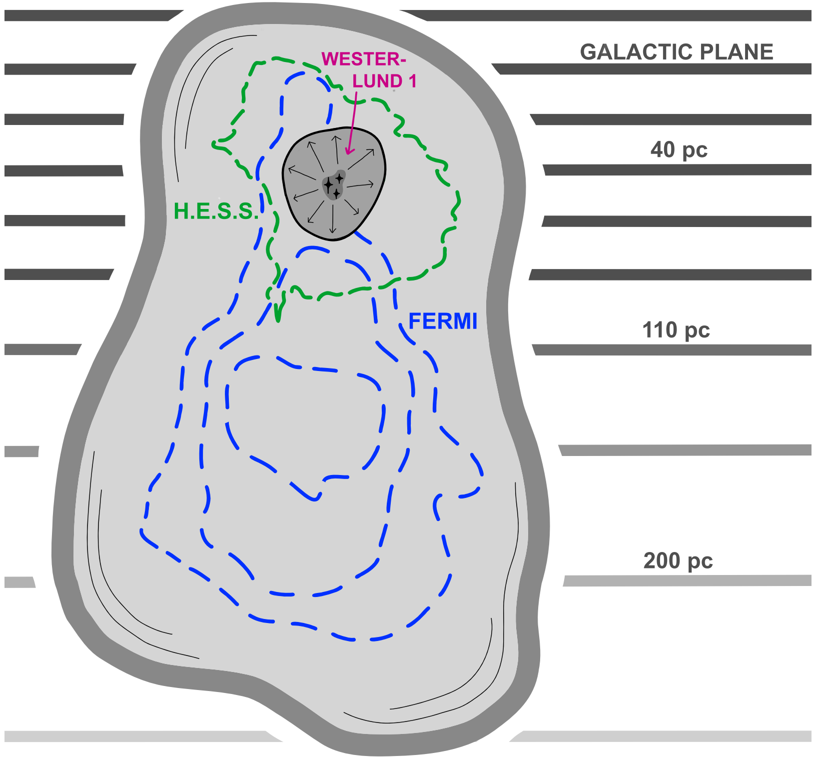
- **Cavity** coincident with J1654–467!

- **Properties**
  - volume ~(70pc)^3
  - less dense by 0.3–0.7 atoms cm^{-3}
  - energy requirement
    10^{50} (T/10^4 K) (n / 1 cm^{-3}) erg

- Plausibly excavated by **collective cluster wind** from Westerlund 1

A nascent outflow

- Proposed scenario: **“nascent outflow”**
  - **superbubble** expands asymmetrically due to density gradient in surrounding medium



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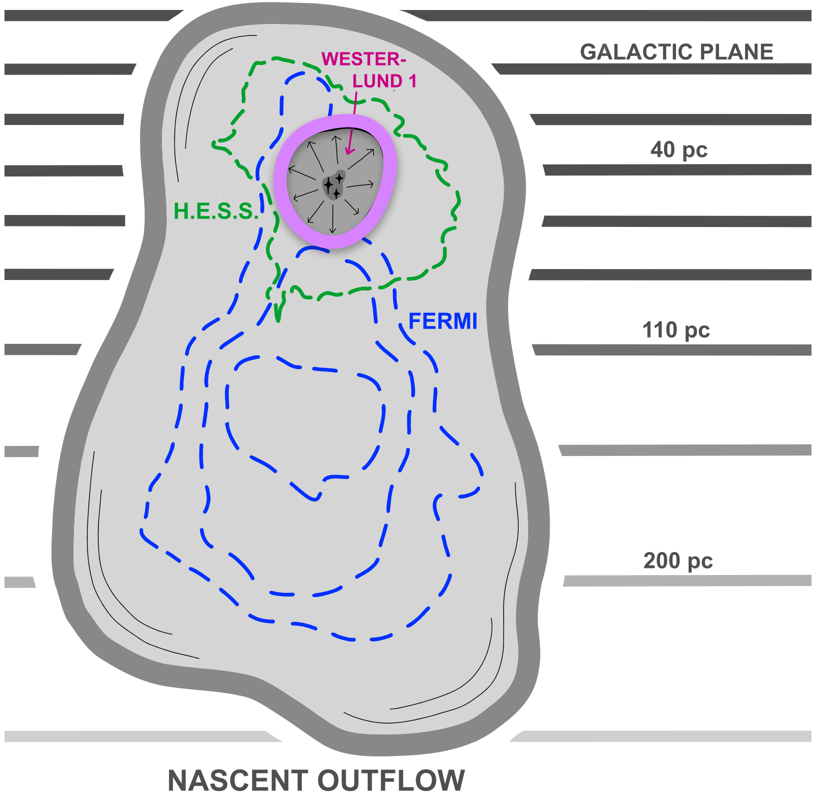

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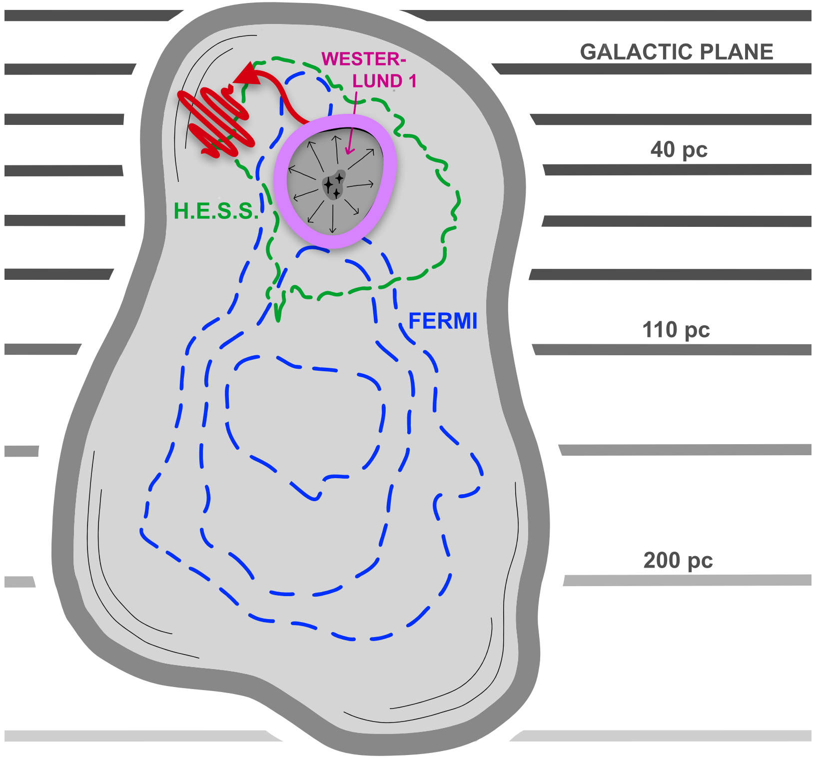

NASCENT OUTFLOW

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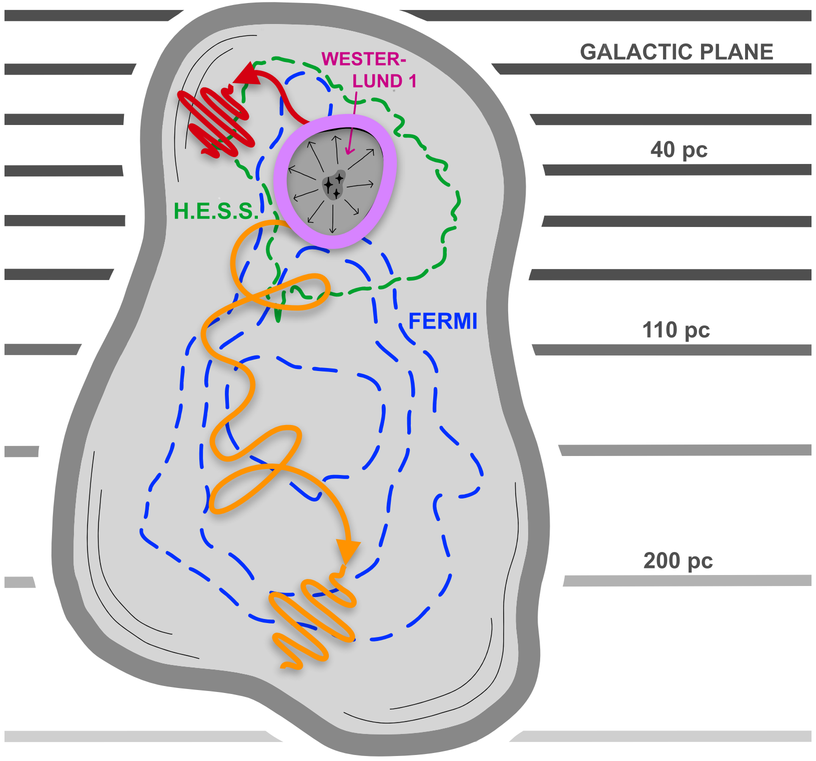

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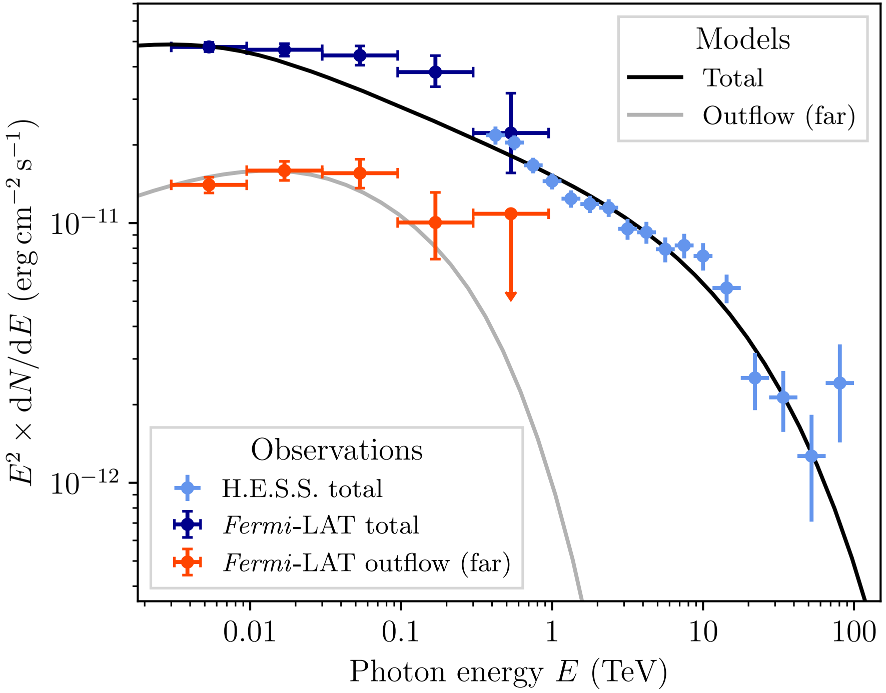
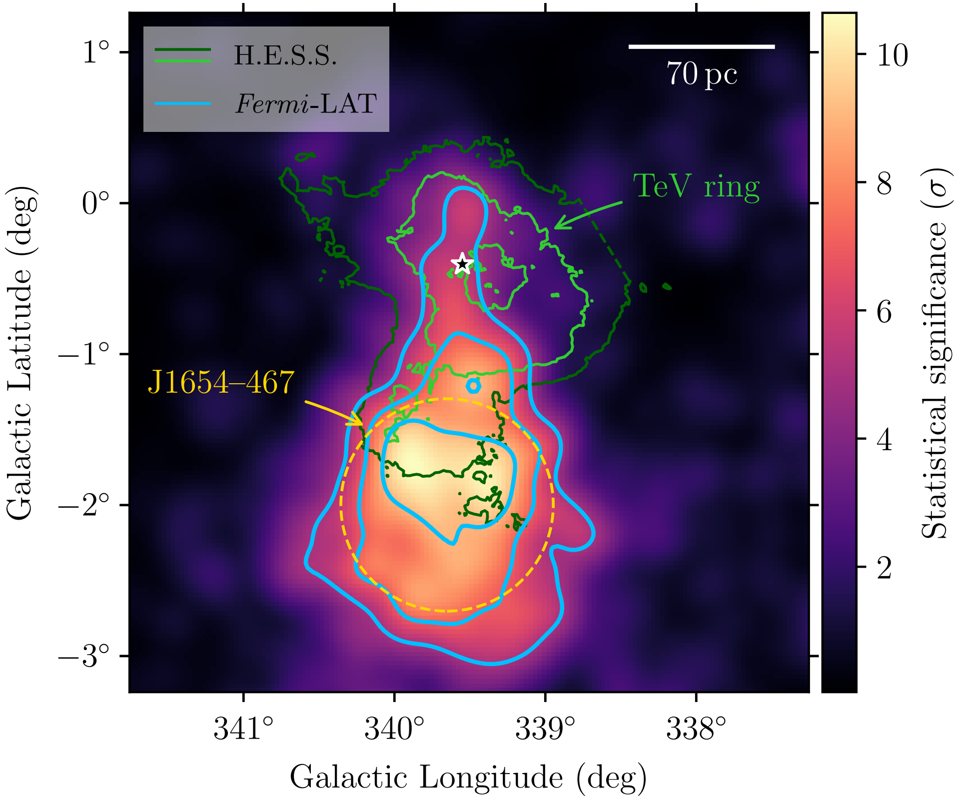
  - cosmic rays are accelerated at **cluster wind termination shock**
  - **high-energy electrons** loose energy quickly → produce TeV emission close to star cluster
  - **low-energy electrons** are transported along outflow → produce GeV emission far from star cluster
- **Basic theoretical modelling:**
  - can reproduce spectra of GeV+TeV emission
  - electron energy density in outflow: $U_e \sim (1\text{–}10)$ eV cm^{-3}
  - expect $U_p > U_e \gtrsim U_{CR,avg} \approx 1$ eV cm^{-3}



→ ***the outflow is loaded with cosmic rays!***

Outflow from Westerlund 1

- New GeV γ-ray source **traces emergence of outflow** from star cluster
- Plausibly a **channel for cosmic-ray transport** into the Galactic halo
- Study contributes to our **understanding of the matter cycle** in the Milky Way



Star clusters in the Large Magellanic Cloud

- **Tarantula Nebula** (30 Doradus) in the **Large Magellanic Cloud**
  - distance ~50 kpc
  - most active starburst region in Local Group
  - one of the largest known HII regions

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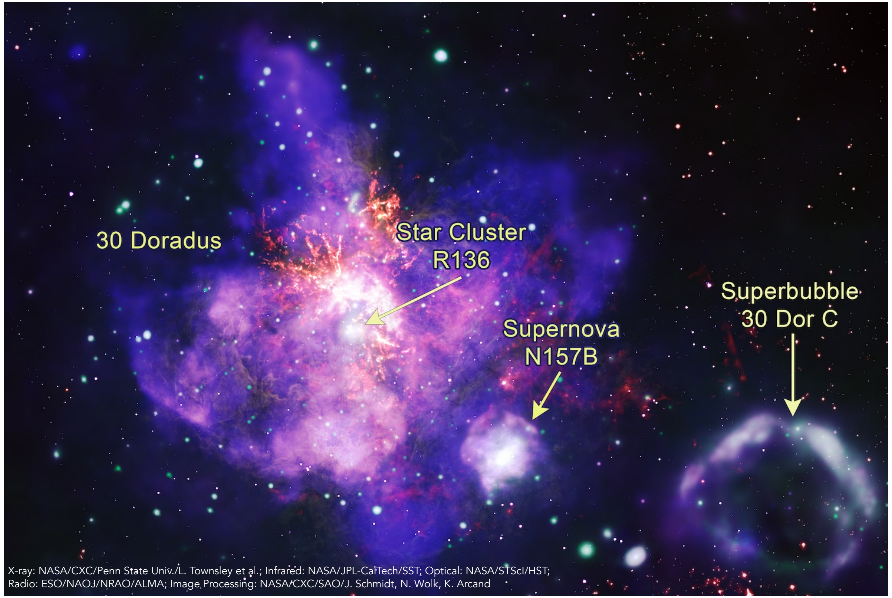
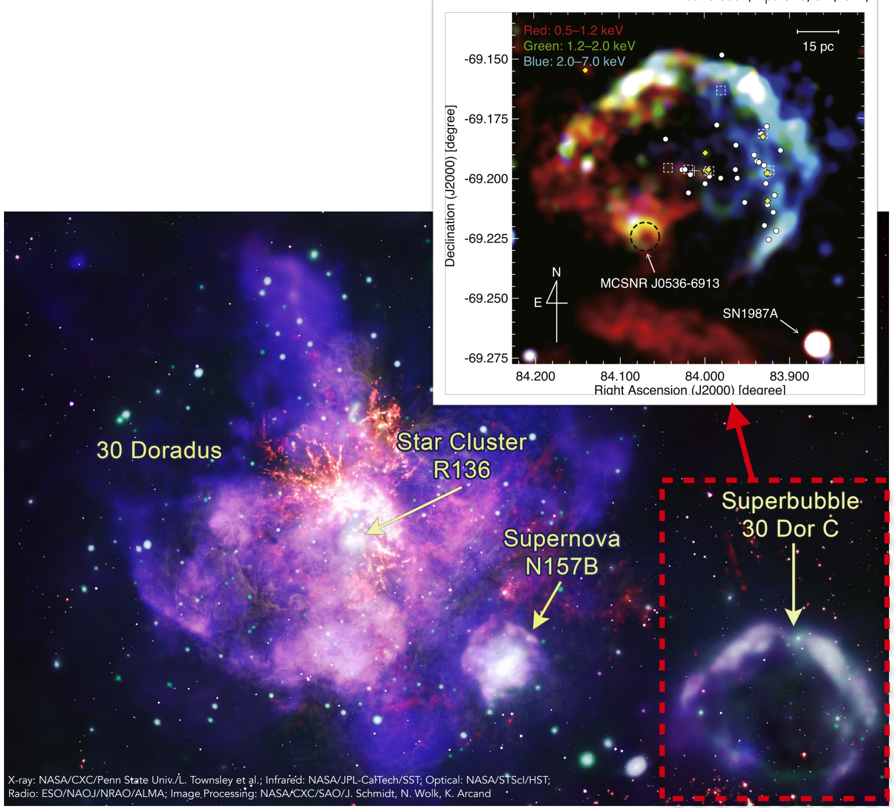


Star clusters in the Large Magellanic Cloud

- **30 Dor C**
  - X-ray resolved superbubble
  - surrounding OB association LH90
  - non-thermal X-rays trace relativistic electrons
  - age ~4 Myr

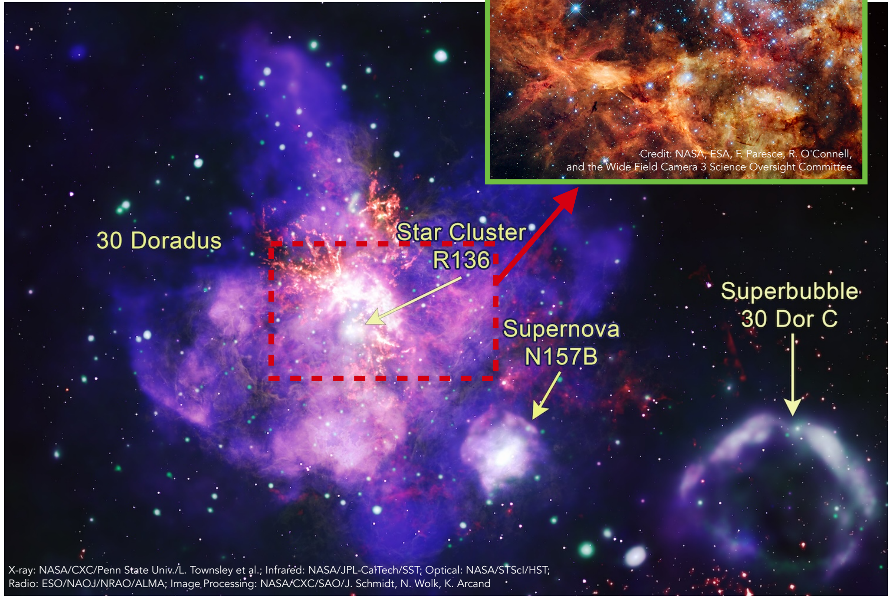
Sano et al., ApJ **843**, 61 (2017)



Star clusters in the Large Magellanic Cloud

- **R136**
  - "super star cluster"
  - age ~1–2 Myr

  - **extremely rich** in massive stars
    → ~50 (~10) stars with $M > 10\ M_\odot$ ($M > 100\ M_\odot$) within radius of 0.5 pc



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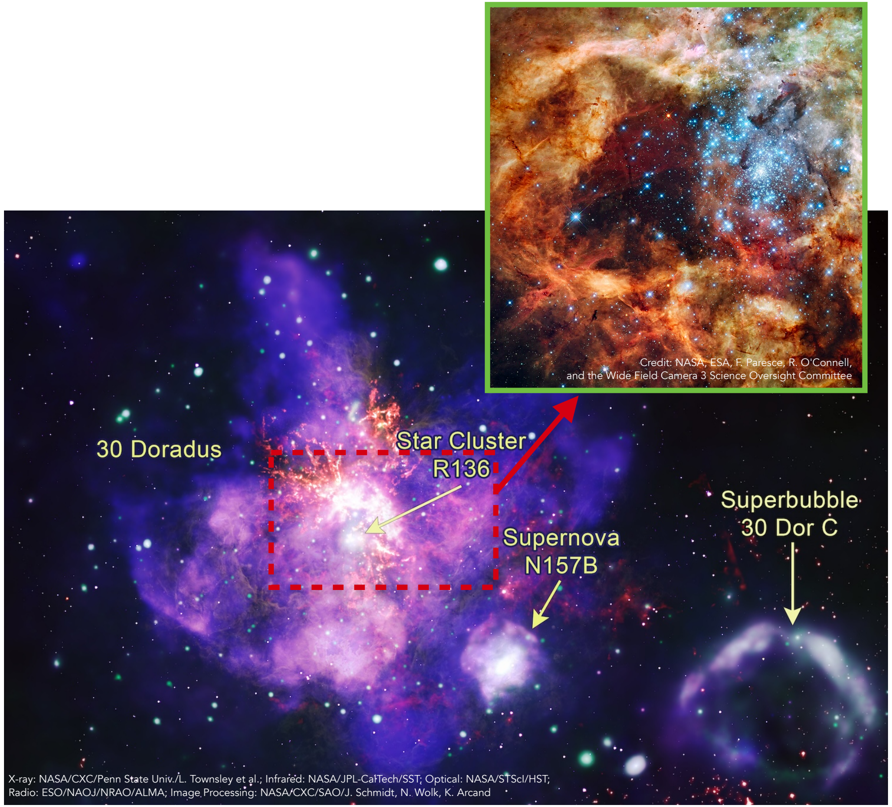
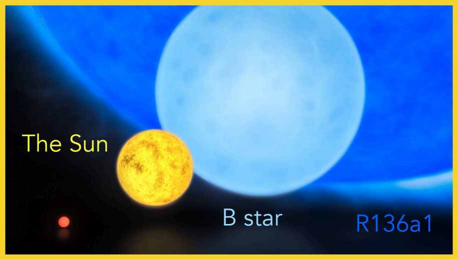
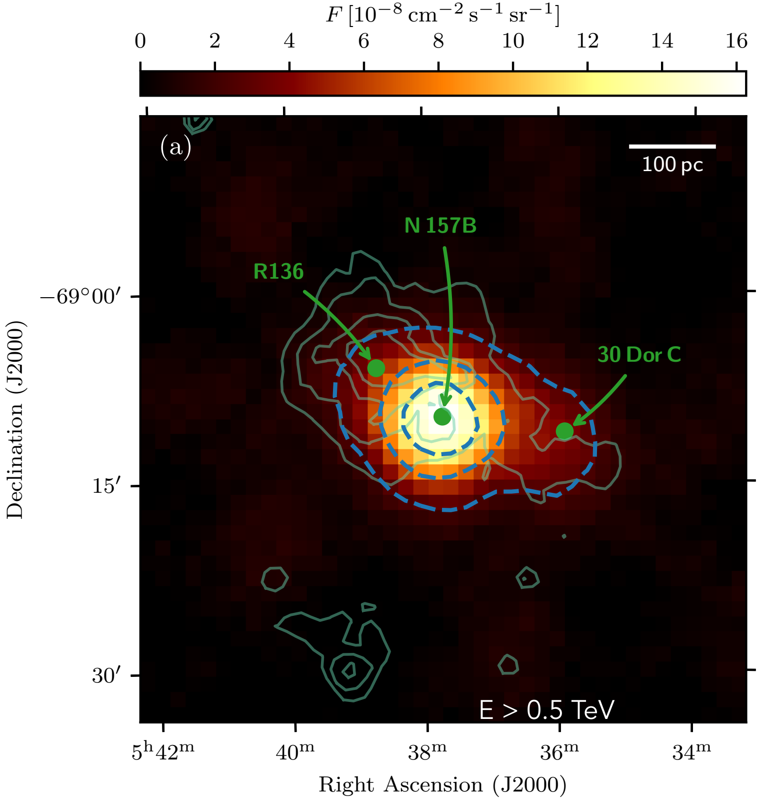
  - **most massive star known:** R136a1
    – initial mass: $\approx 250\ M_\odot$
    – luminosity: $4.7 \times 10^6\ L_\odot$





Star clusters in the Large Magellanic Cloud

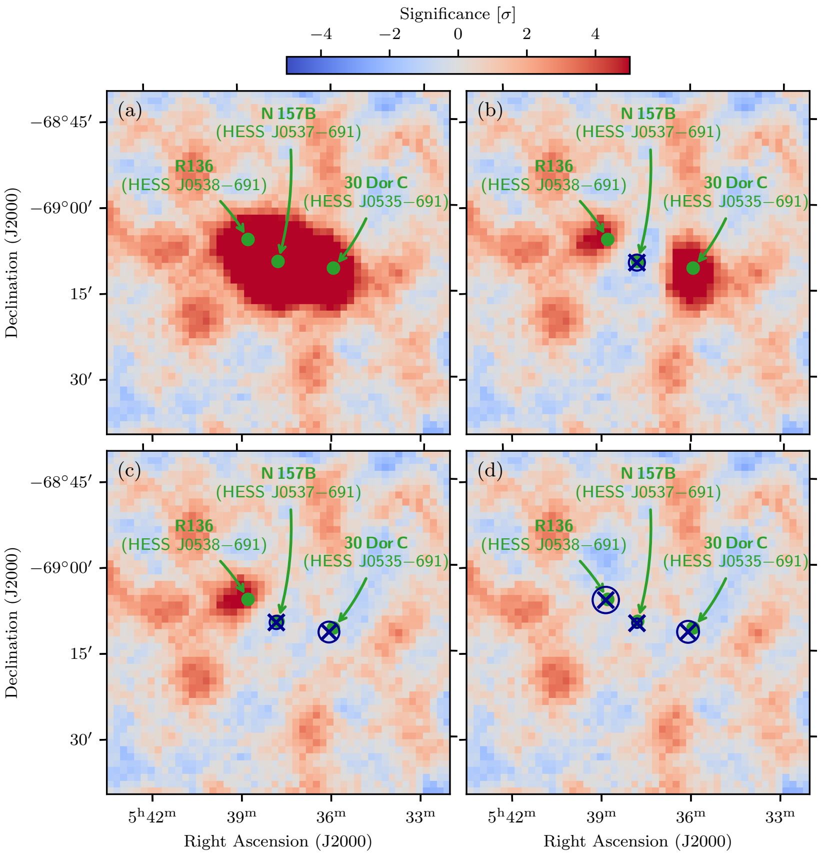
- **H.E.S.S. flux map**
  - pulsar wind nebula N 157B outshines entire nebula
  - difficult to claim a signal from 30 Dor C or R136 from this map



H.E.S.S. Collaboration, *Astrophysical Journal Letters* **970**, L21 (2024)

Star clusters in the Large Magellanic Cloud

- **Spectro-morphological modelling**
  - three-dimensional likelihood fit (2 spatial + 1 energy)
  - 2D Gaussians as spatial models
  - power law / log parabola as spectral models
  - iteratively add source models until no significant emission remains



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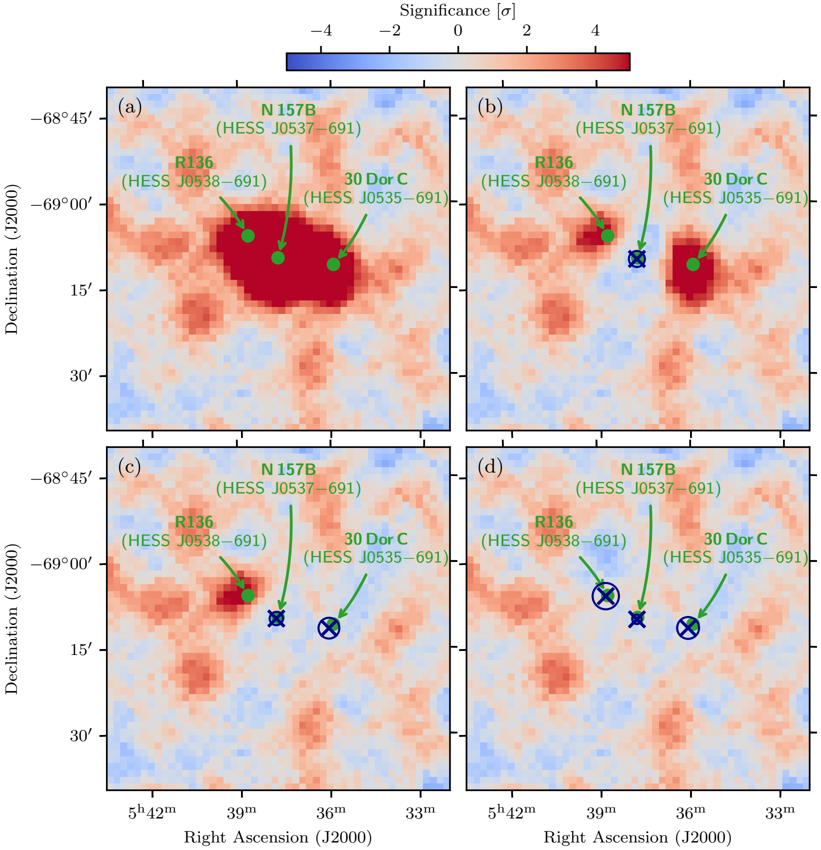
  - R136 (6.3σ) ← new: significant detection!



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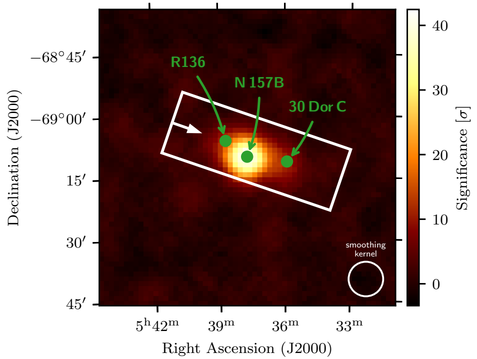

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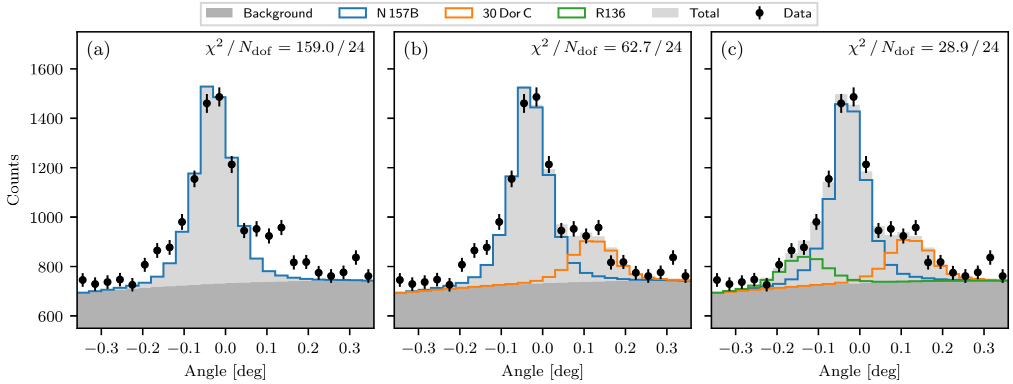

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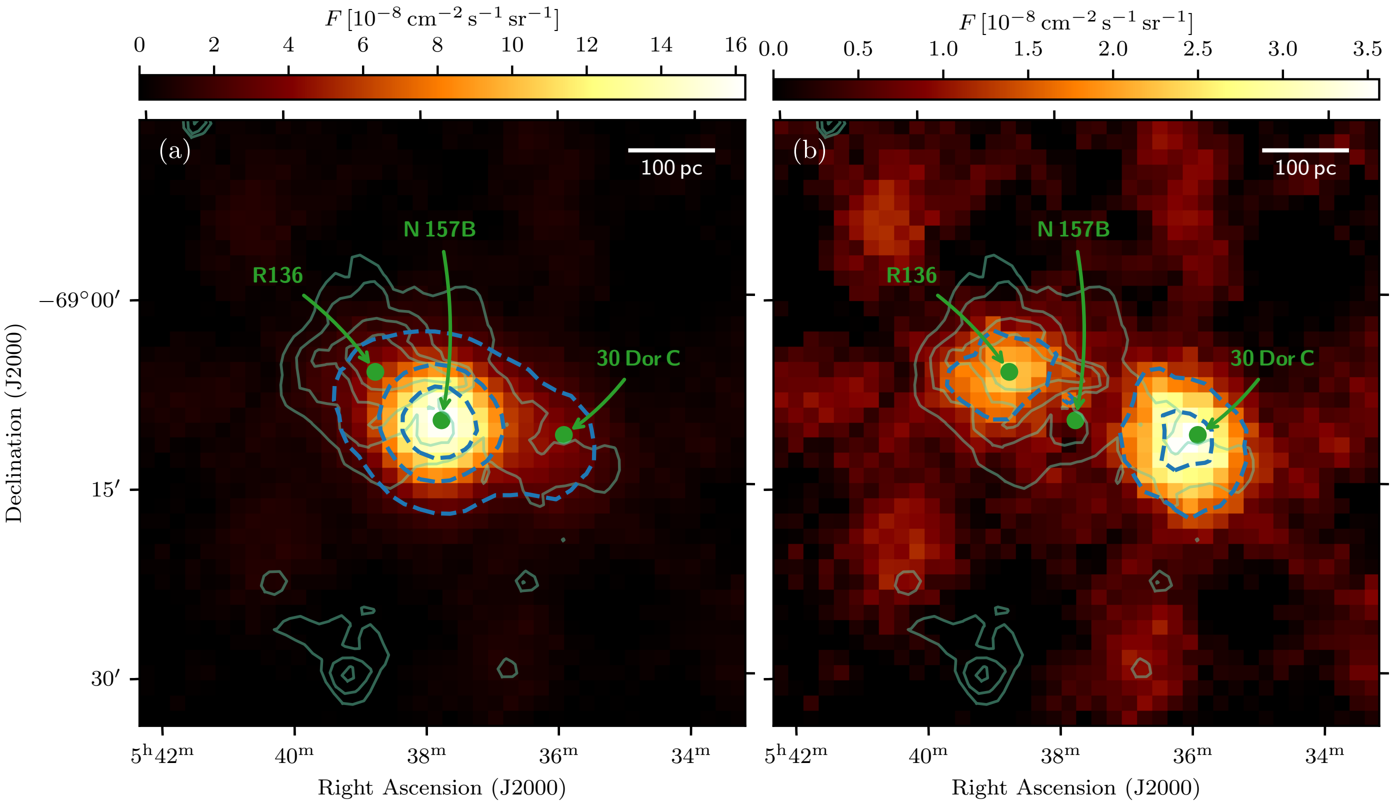
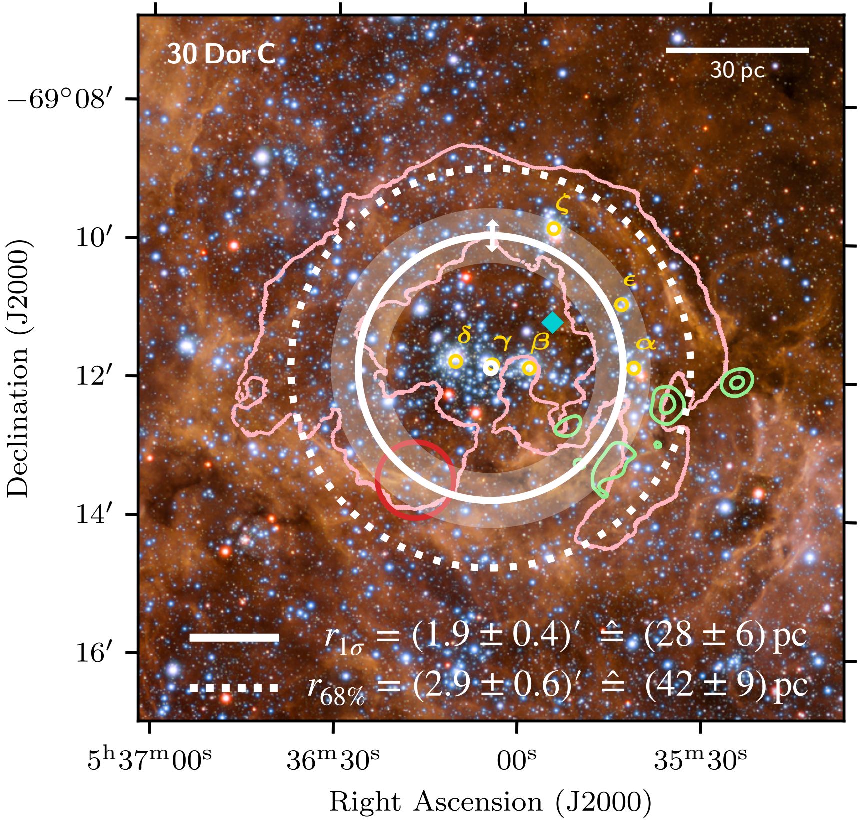


30 Dor C

- **Extension in gamma rays** established (3.3σ) for the first time
  - size compatible with X-ray shell
  - suggestive of a connection?

- **Peak of emission** does **not** coincide with location of **densest gas clouds**



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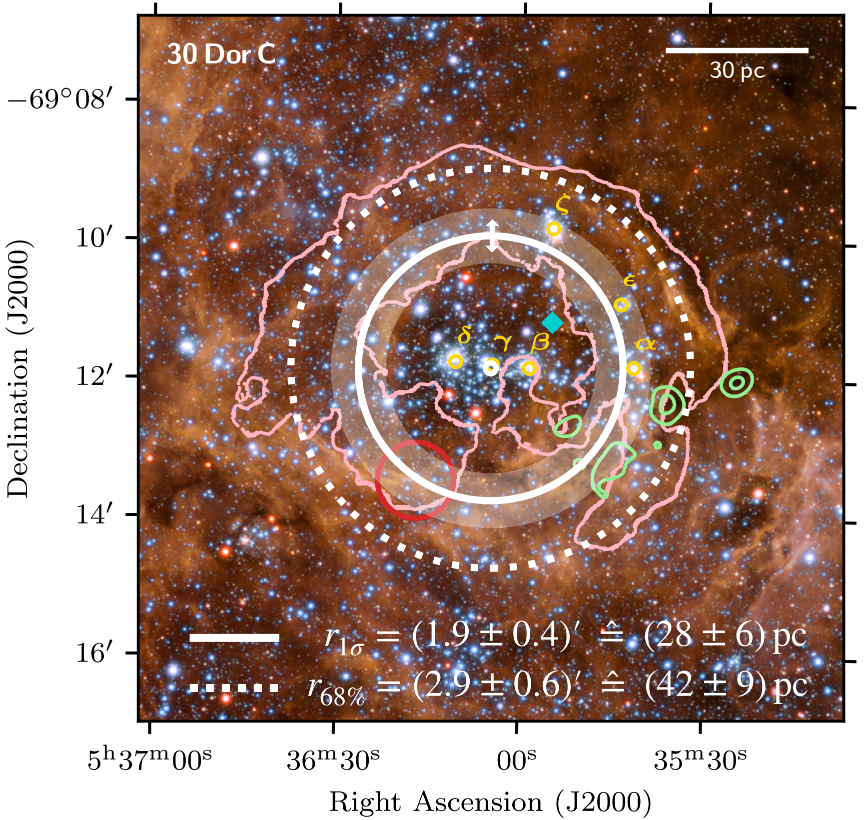
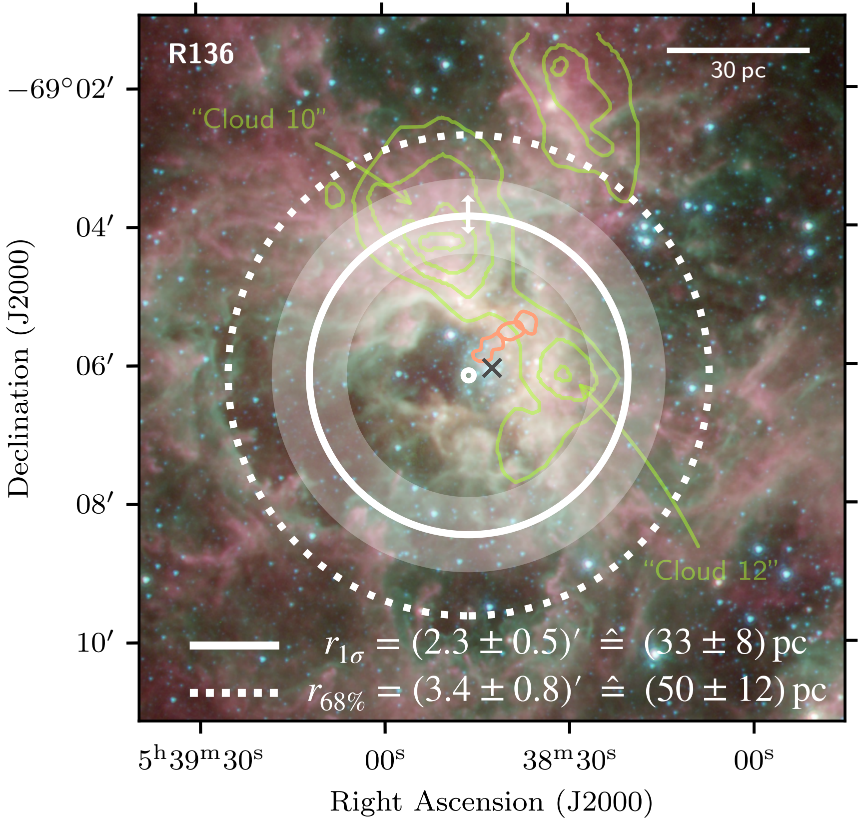
- **Expanding superbubble model**
  - $L_w = 1.5 \times 10^{38}$ erg s^{-1}, $v_w = 3{,}000$ km s^{-1}, $T = 4$ Myr, $n = 100$ cm^{-3}
  - superbubble radius ≈ 74 pc
  - termination shock radius ≈ 7.9 pc



R136

- **Best-fit position** compatible with location of star cluster (separation ≈ 20″)
- **Weak correspondence** between gamma-ray emission and molecular gas
- Also observed as an **extended source** (3.1σ)!



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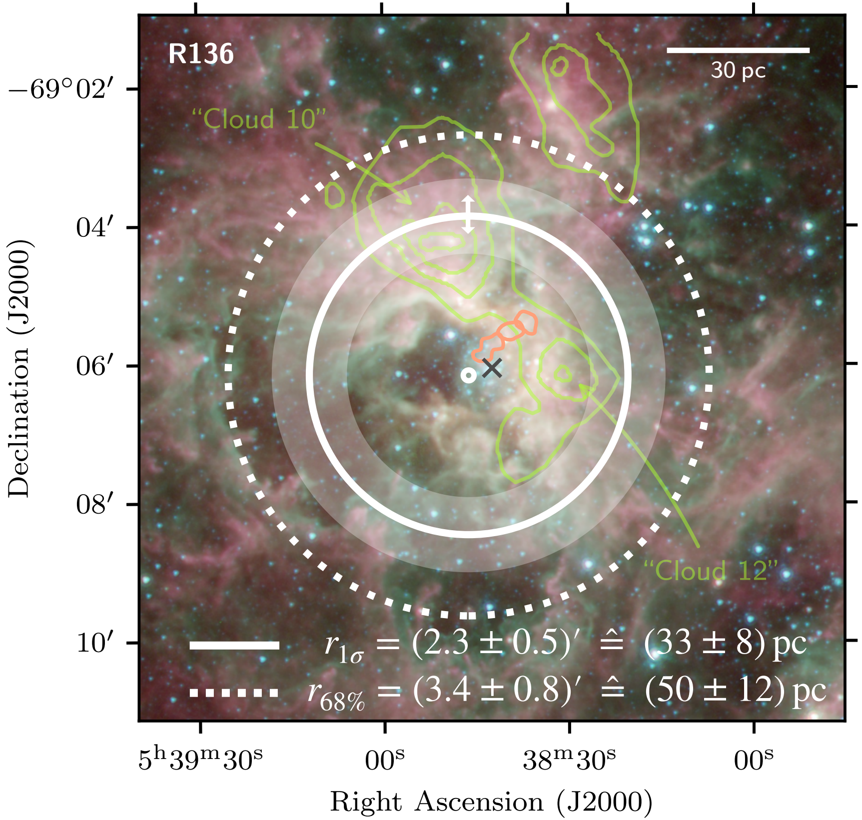
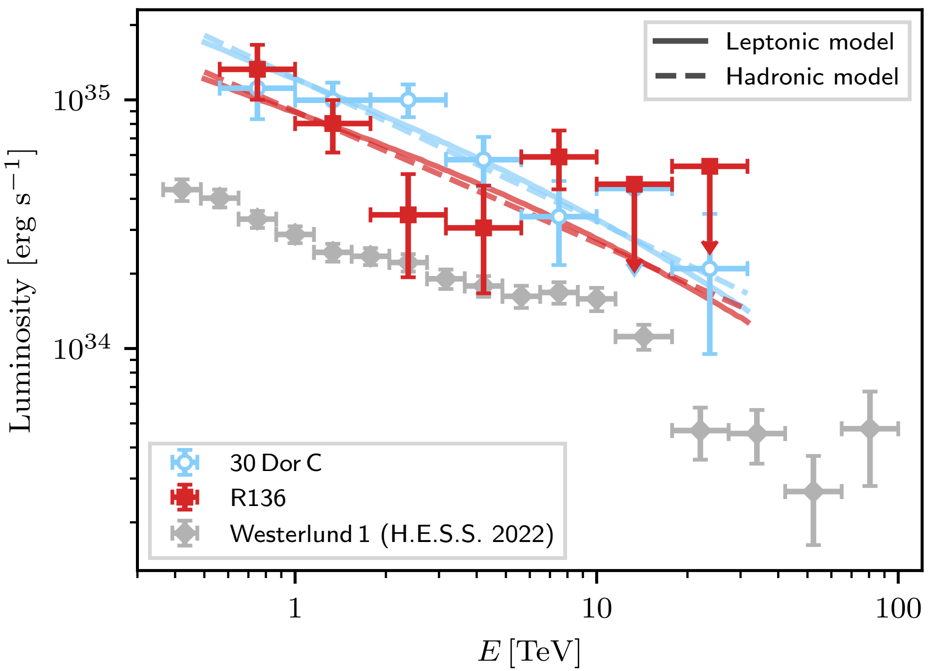


Energetics

- **30 Dor C** and **R136** are **twice as luminous** as Westerlund 1!



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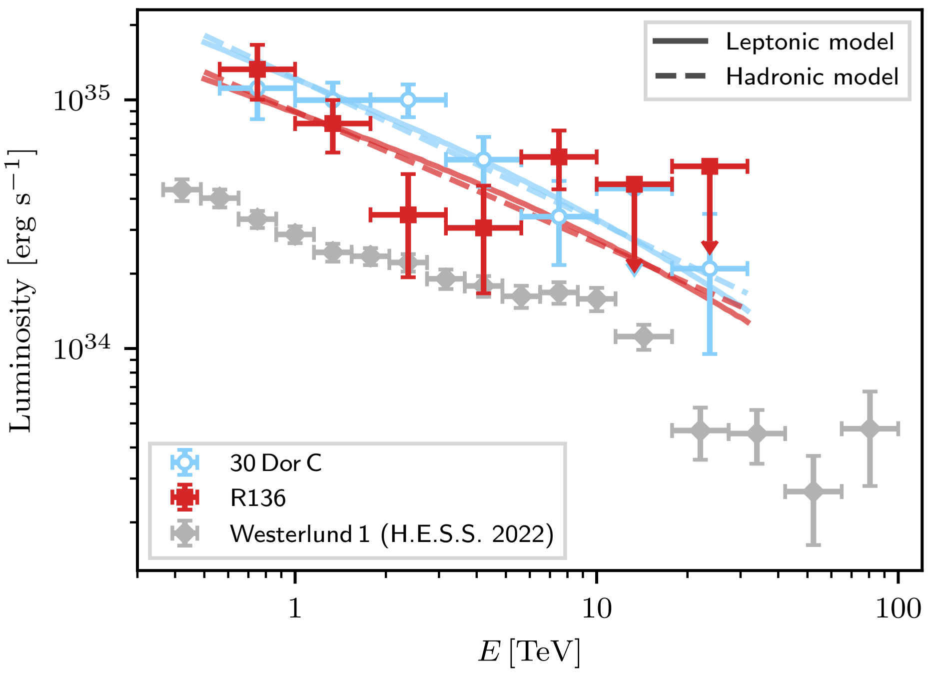
- **Physical spectral models**
  (here: R136)
  - **hadronic** (pp)
    – W_p (E_p > 1 GeV) ~ 1.1 × 10^{51} (n/100 cm^{-3})$^{-1}$ erg
      → need high gas densities
  - **leptonic** (inverse Compton)
    – L_e (E_e > 0.1 TeV) ~ 5.3 × 10^{36} erg s^{-1} (B=5μG)
      → affordable, given cluster wind power of ~10^{39} erg s^{-1}



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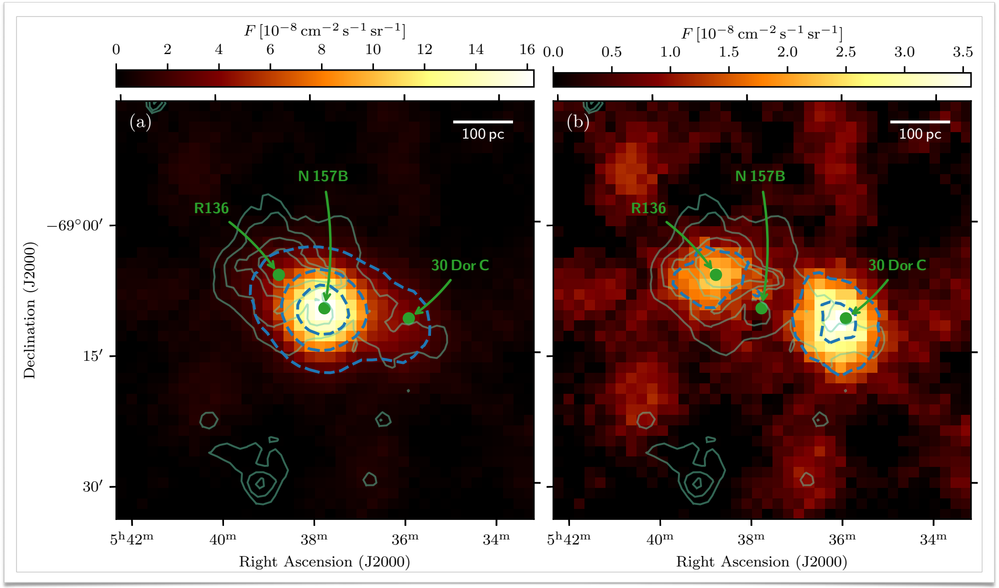

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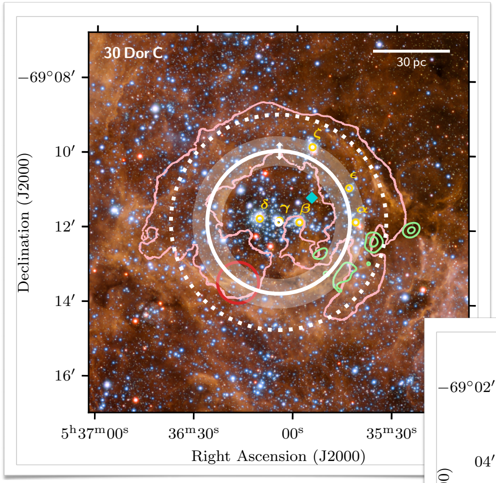

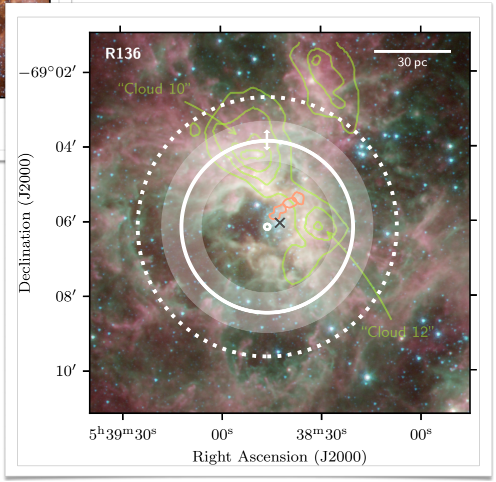

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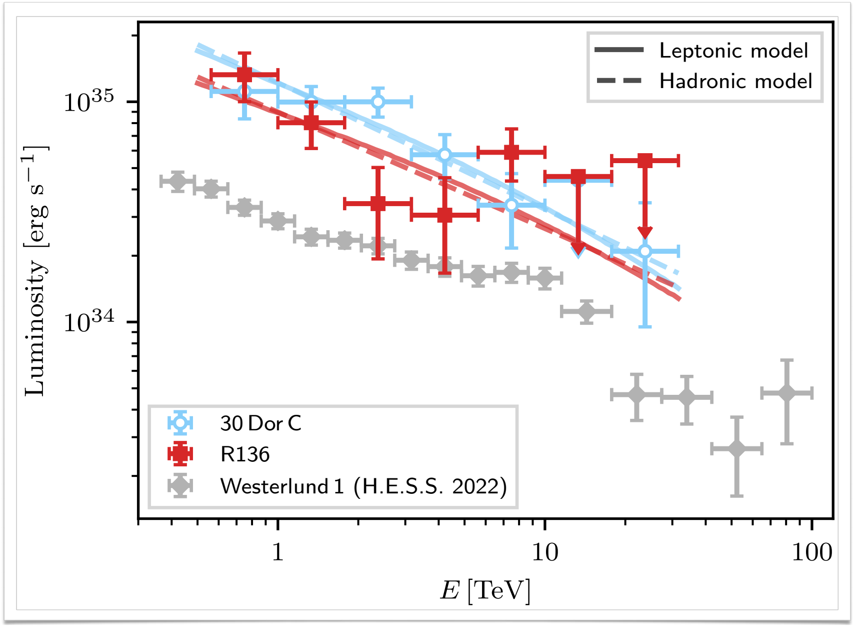

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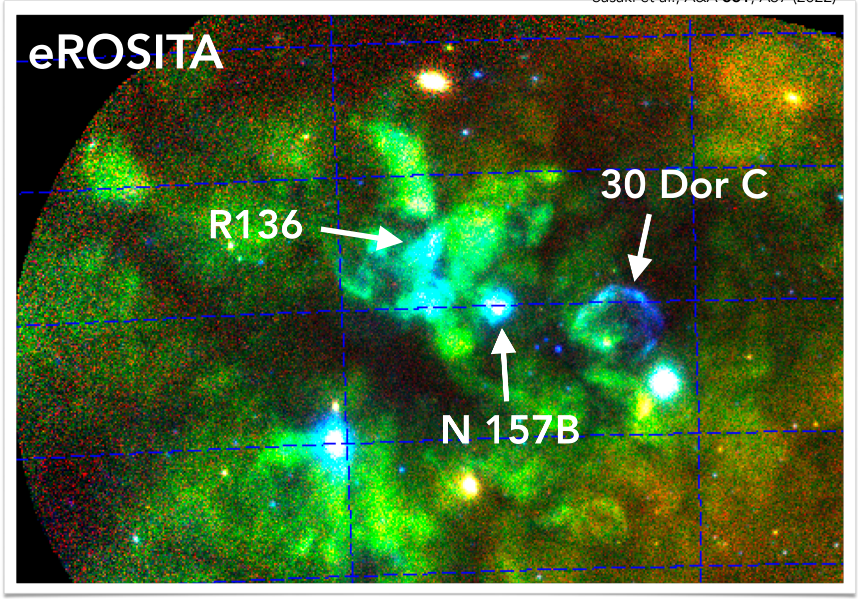
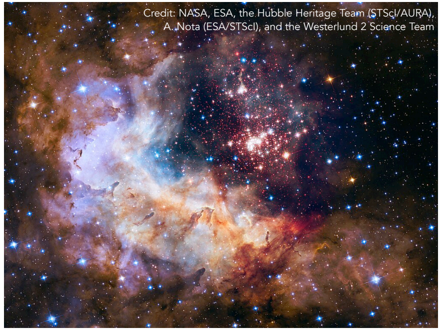
Sasaki et al., A&A **661**, A37 (2022)

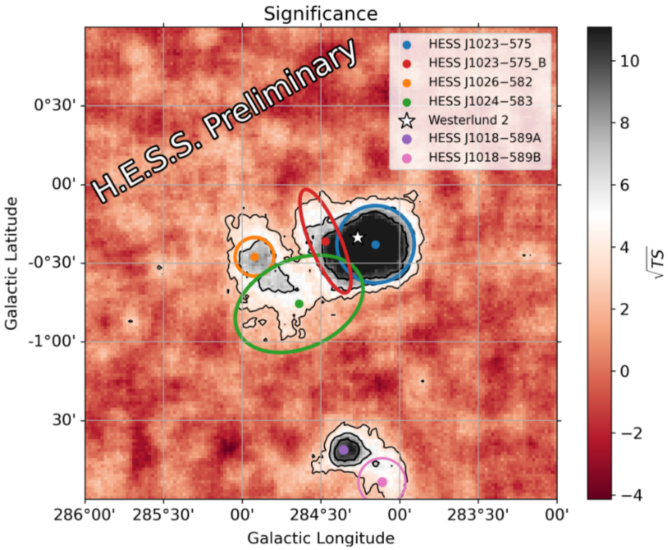


Brief update on Westerlund 2

- **Westerlund 2**
  - young massive star cluster
  - age ≲ 2 Myr
  - distance very uncertain (2–8 kpc)

- **Updated H.E.S.S. analysis**
  with 3× increased exposure
  - confirms HESS J1023–575, HESS J1026–582
  - new: HESS J1023–575B, HESS J1024–583



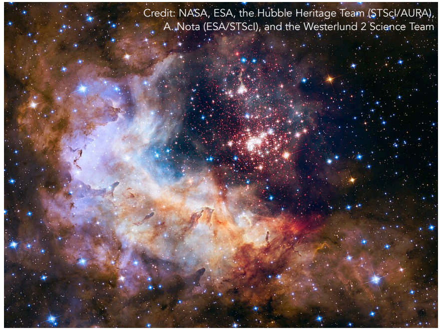


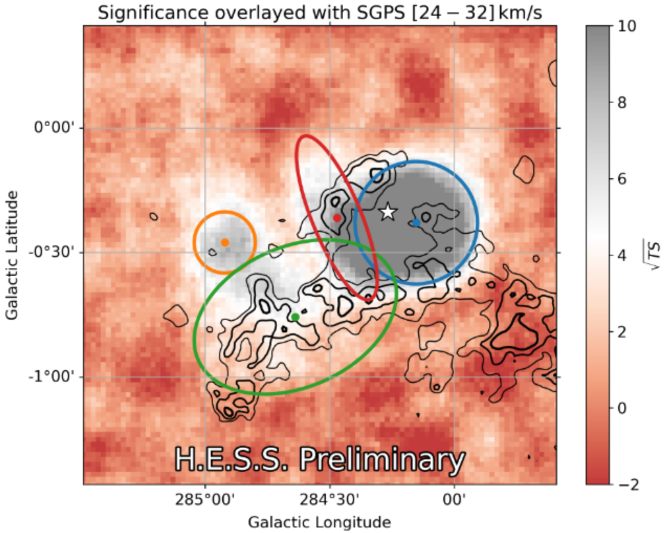
T. Holch et al. for the H.E.S.S. Collaboration, PoS (ICRC2023) 778

Brief update on Westerlund 2

- **HESS J1024–583**
  - coincident with molecular cloud filament
  - protons escaping from HESS J1023–575 region?

- **HESS J1023–575**
  - coincident with Westerlund 2, but association still unclear
  - e.g. connection to energetic pulsar PSR J1023–5746 also a viable explanation



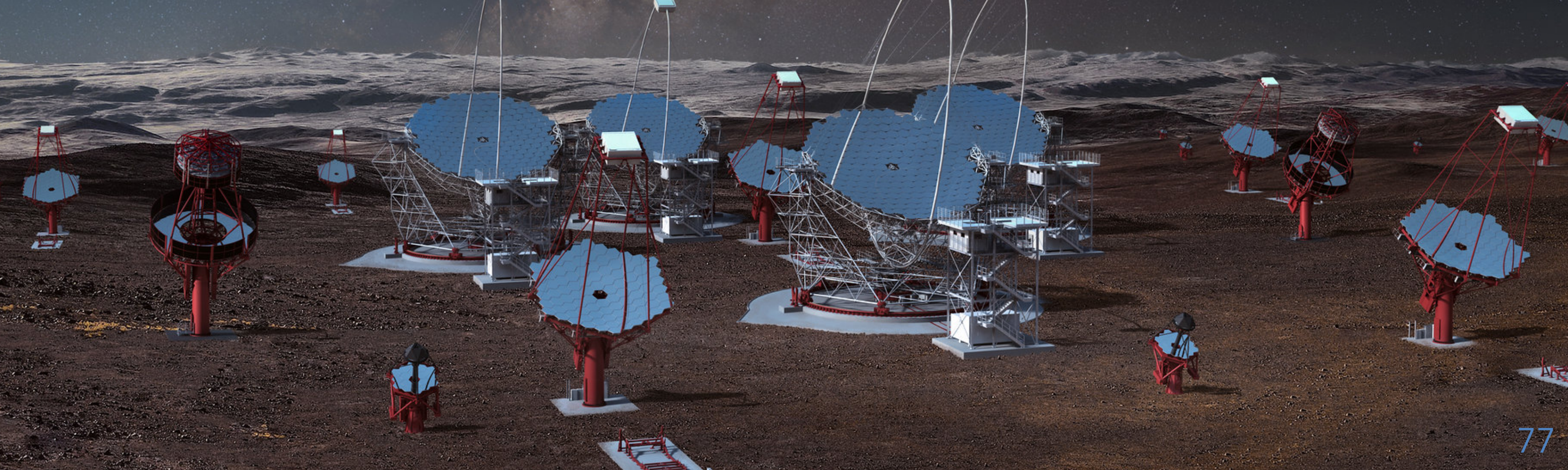


H.E.S.S. — Outlook

- Operations secured until **Sep. 2028**
- **Exciting science program** for remaining years
  - "legacy" program on young massive star clusters
- Vast opportunities with **20+ years of archival data!**

Cherenkov Telescope Array Observatory

- **CTAO-South**
  - Atacama desert, Chile
  - ~50 telescopes
  - first telescopes on site end of 2026
- **30 GeV – 300 TeV**
- **>1,000 sources**



Thank you for the attention!