Young massive stellar clusters as cosmic-ray sources: the case of Westerlund 1

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for the H.E.S.S. Collaboration

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H.E.S.S.

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

MAX PLANCK GESELLSCHAFT

Cosmic rays from young massive stellar clusters

- Proposed a long time ago (e.g., [1])

Space Science Reviews **36** (1983) 173–193.

GAMMA RAYS FROM ACTIVE REGIONS IN THE GALAXY: THE POSSIBLE CONTRIBUTION OF STELLAR WINDS*

CATHERINE J. CESARSKY and THIERRY MONTMERLE

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TABLE I

Contribution of stellar winds and supernovae to cosmic rays and gamma rays in the Galaxy

Scale	Medium (distance)	Stellar winds important for:	Supernovae important for:	Remarks
Very small ($\lesssim$1 pc)	Dark clouds ($\lesssim$200 pc)	T associations, if CR confinement strong enough: γ-ray sources?	if chance collision with field SNRs: γ-ray sources	ρOph cloud only known possible example
Small ($\sim$10–100 pc)	Molecular clouds ($\lesssim$3 kpc)	OB associations, if WR present (Carina, Cygnus): γ-ray sources $\bar{p}$ in CR very high-energy CR?	OB associations, if SN present (SNOBs): γ-ray sources $\bar{p}$ in CR	Average OB associations ('Orion-like') invisible as γ-ray sources
Medium ($\lesssim$1–2 kpc)	Solar neighborhood ($\lesssim$2.5 kpc) Gould Belt ($\lesssim$500 pc)	^{22}Ne excess in CR from isolated WC; diffuse γ-ray features	Local CR; diffuse γ-ray features	$\bar{P}_s/\bar{P}_w$ = 5 or 20 (depending on SN progenitors)
Large	Galaxy	dominant contribution to GCR from WR in the inner galaxy? part of diffuse γ-ray emission	probable major contribution to GCR; part of diffuse γ-ray emission	gives SN acceleration efficiency: η_s = 2.5 to 10%

Cosmic rays from young massive stellar clusters

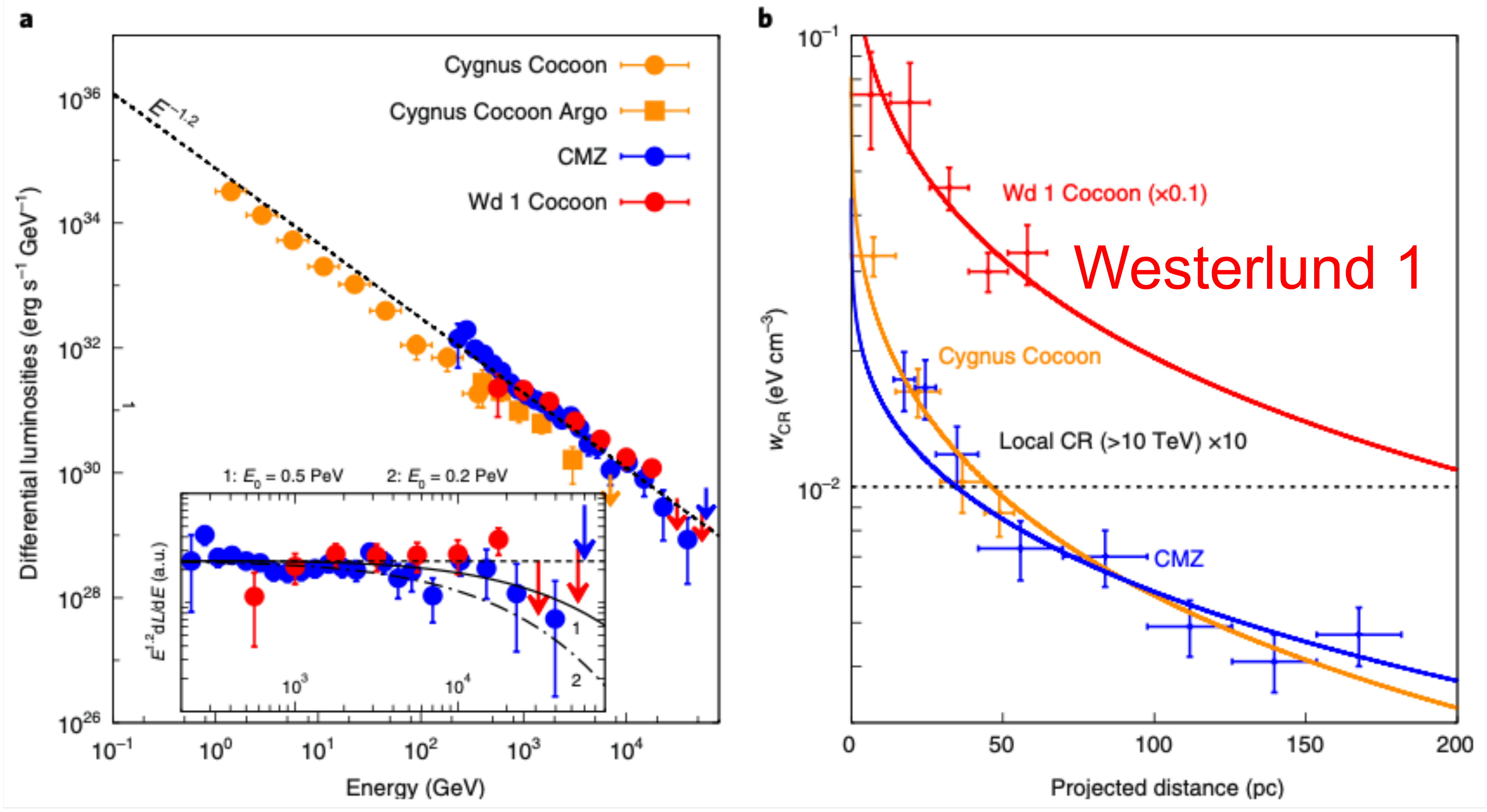
NATURE ASTRONOMY | VOL 3 | JUNE 2019 | 561–567

- Proposed a long time ago (e.g., [1])
- Renewed interest in recent years (e.g., [2])

nature astronomy ARTICLES
https://doi.org/10.1038/s41550-019-0724-0

Massive stars as major factories of Galactic cosmic rays

Felix Aharonian[1,2,3,7], Ruizhi Yang[2,7*] and Emma de Oña Wilhelmi[4,5,6,7]



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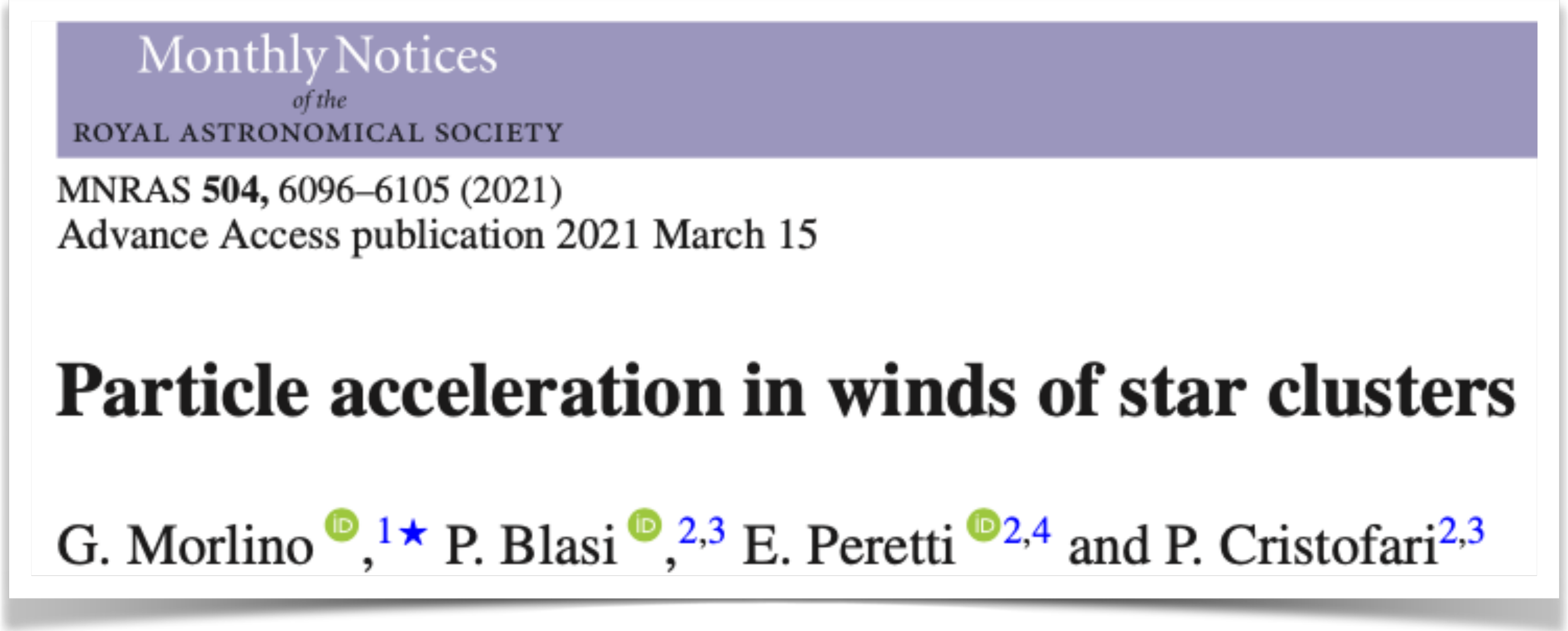
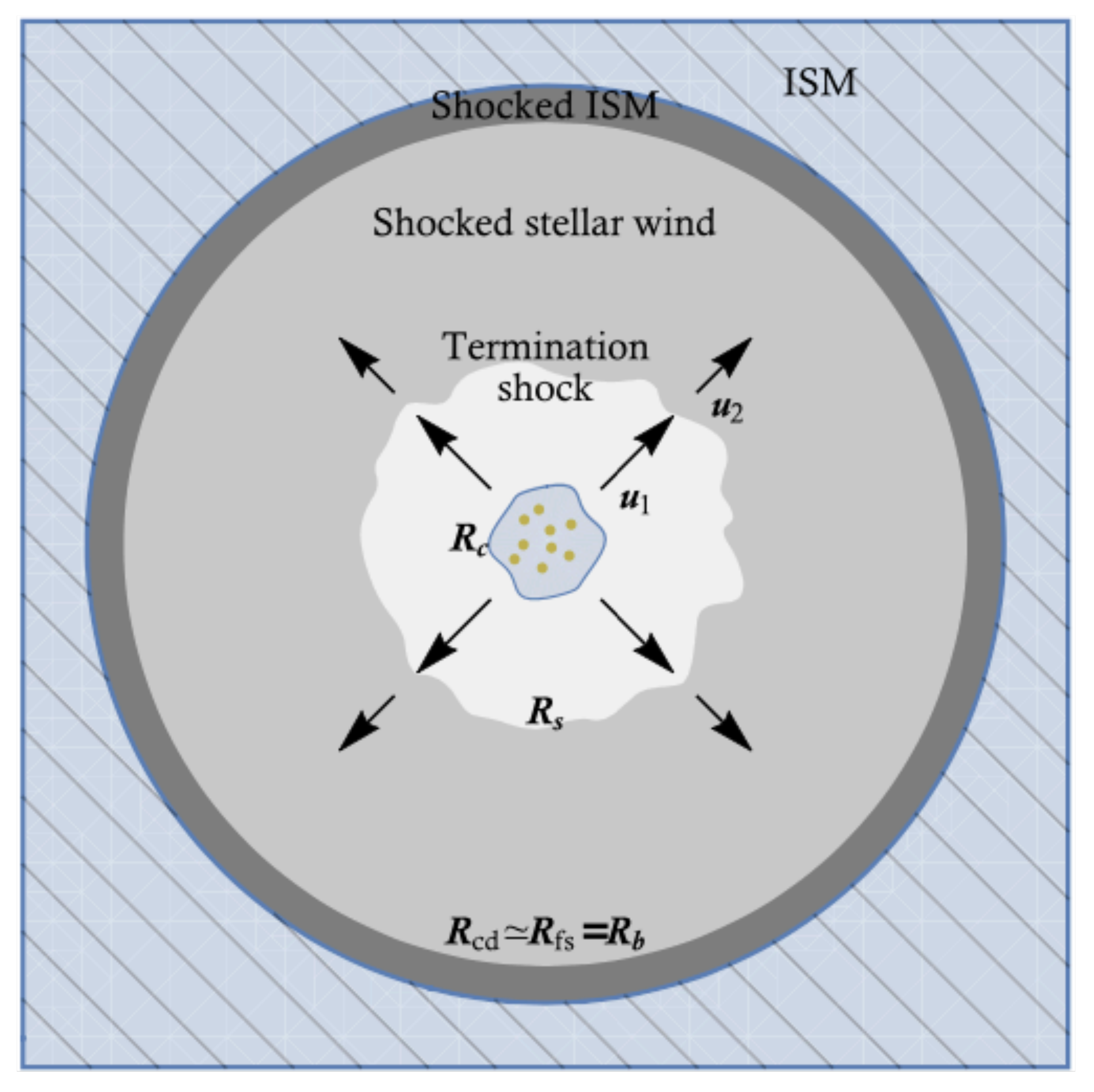


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **504,** 6096–6105 (2021)
Advance Access publication 2021 March 15

Particle acceleration in winds of star clusters

G. Morlino[1★], P. Blasi[2,3], E. Peretti[2,4] and P. Cristofari[2,3]



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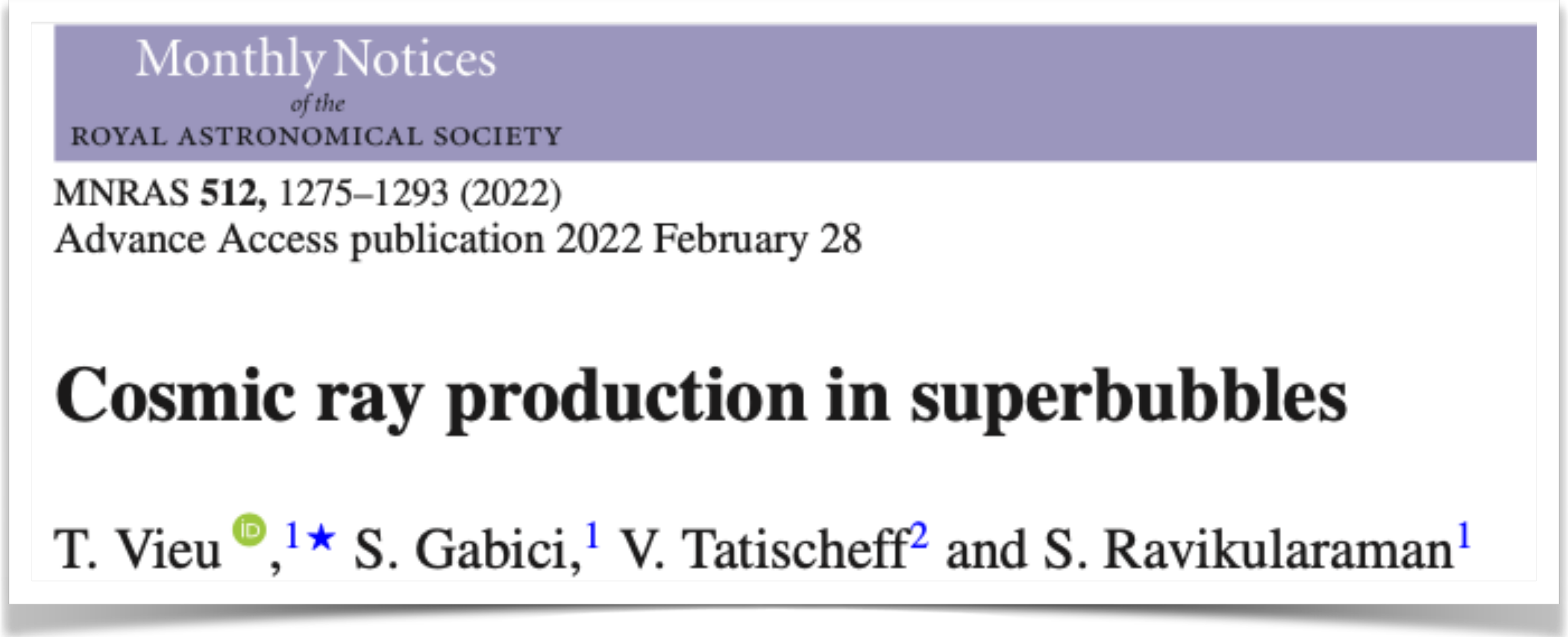
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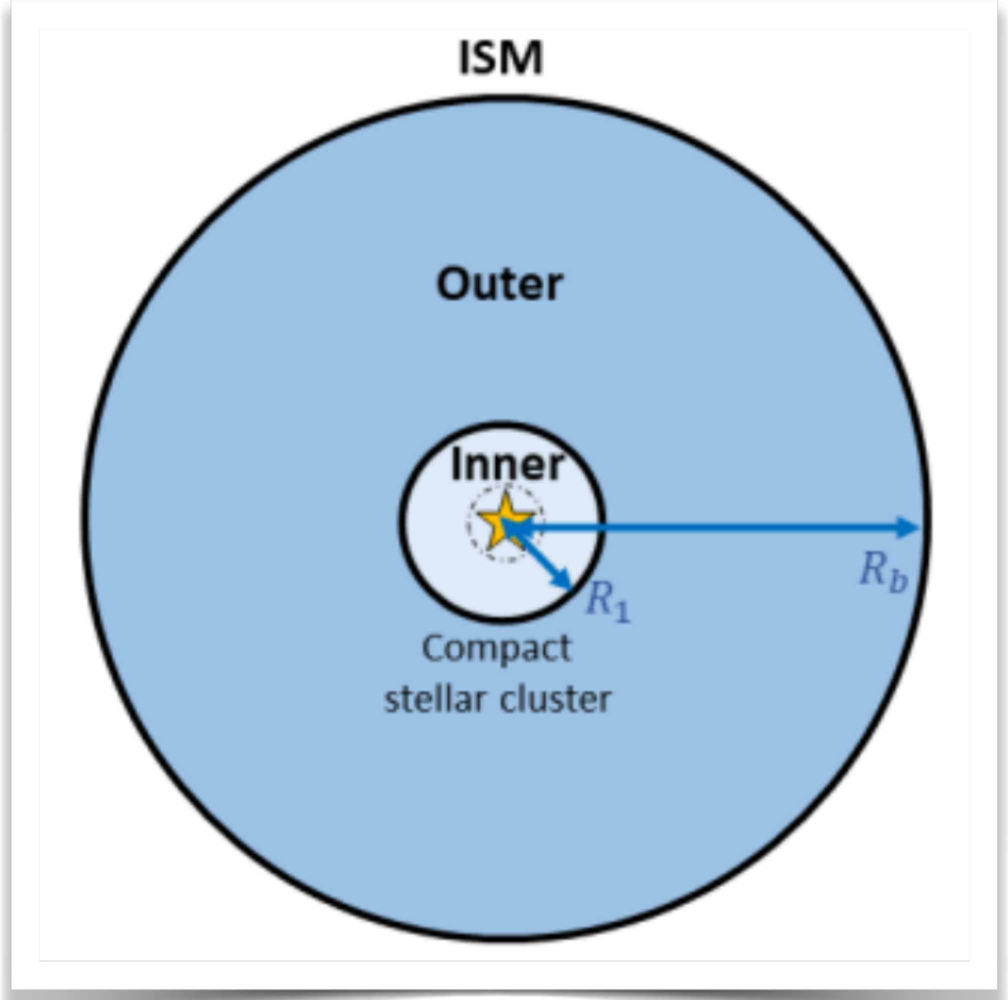
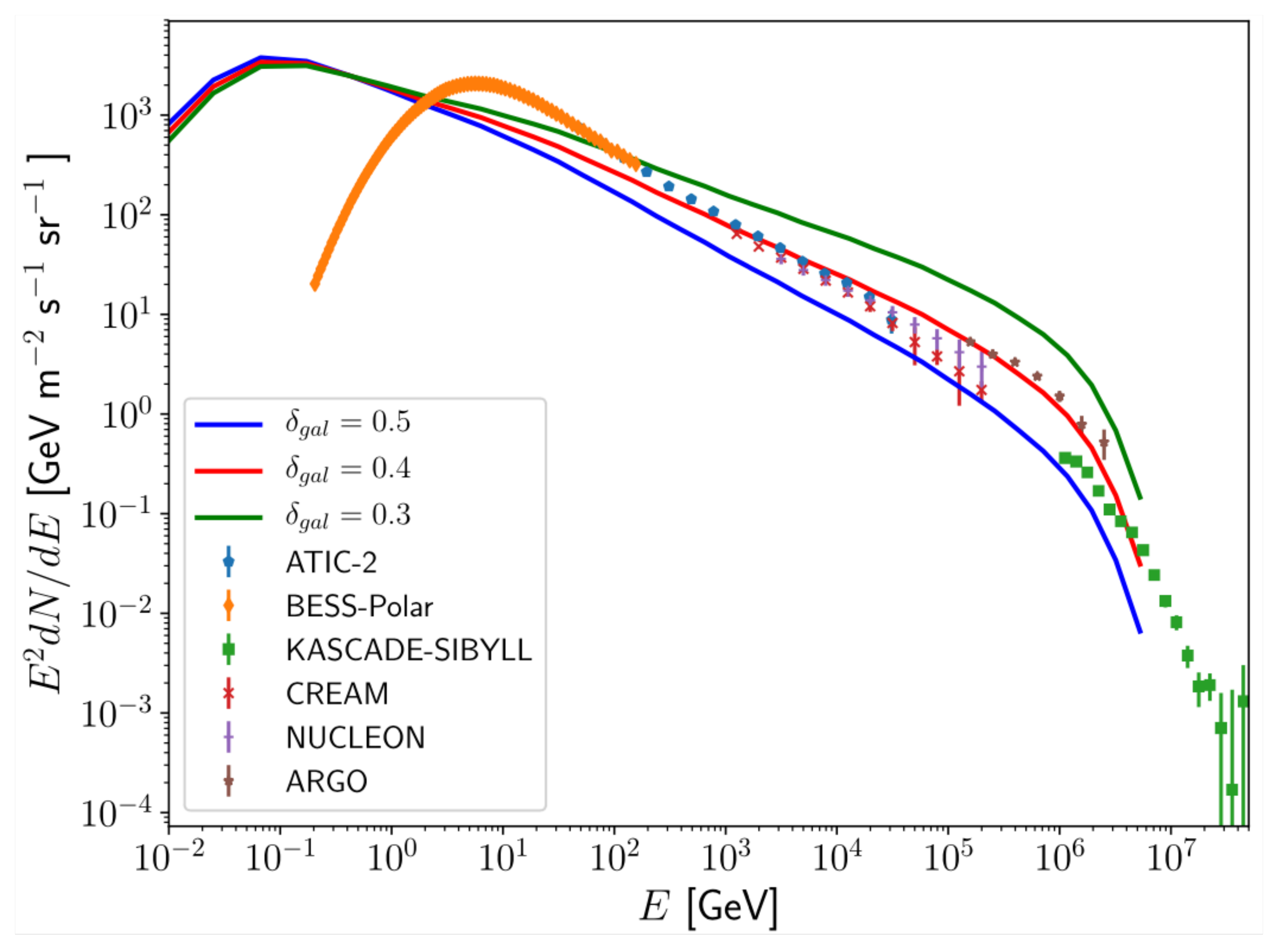
Cosmic ray production in superbubbles

T. Vieu [1]★ S. Gabici,[1] V. Tatischeff[2] and S. Ravikularaman[1]





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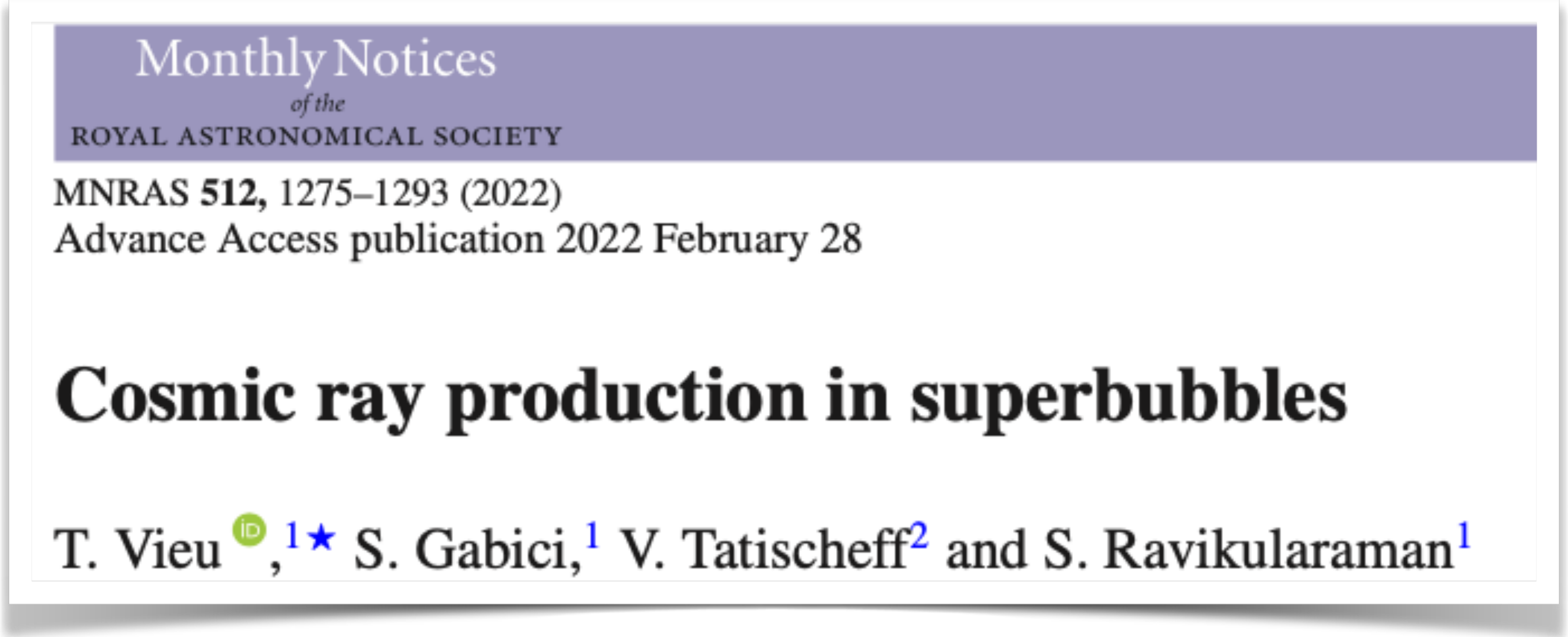
- **Young** & **massive** stellar clusters could contribute substantially to flux of Galactic cosmic rays
  → challenging the "SNR paradigm"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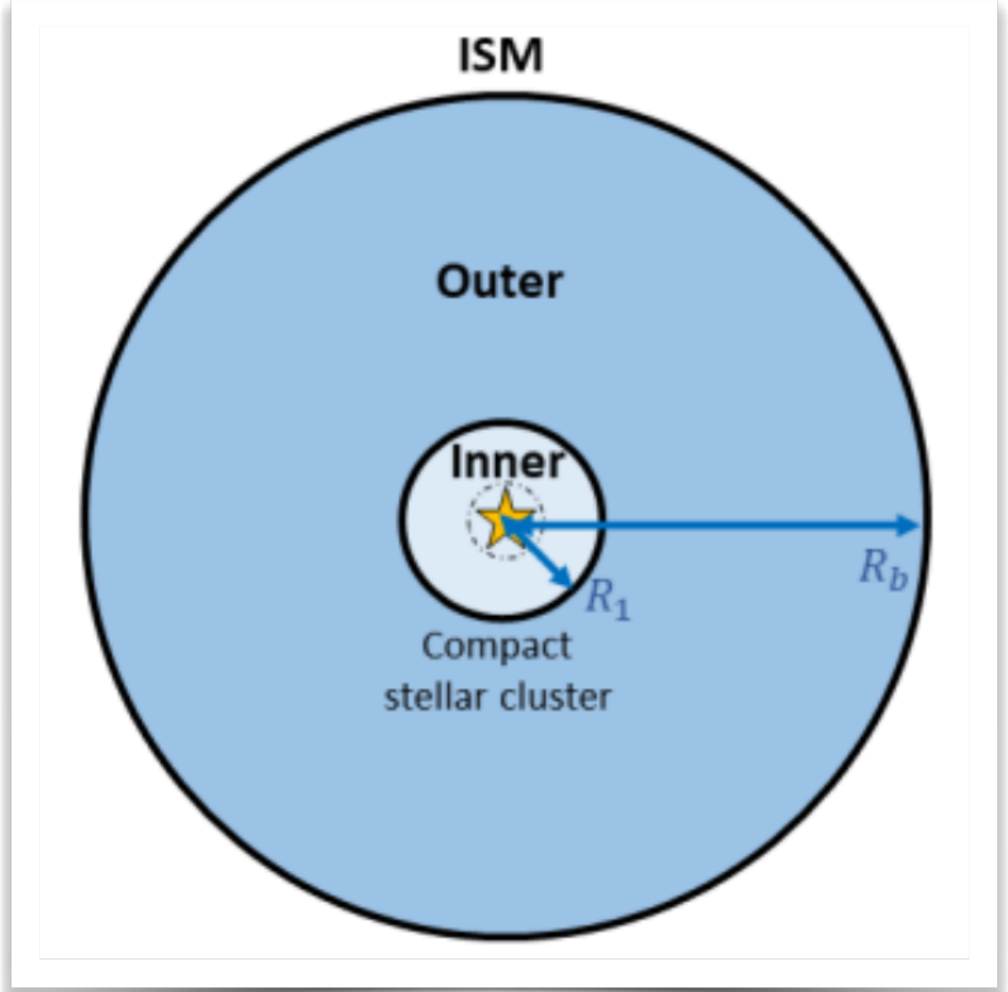
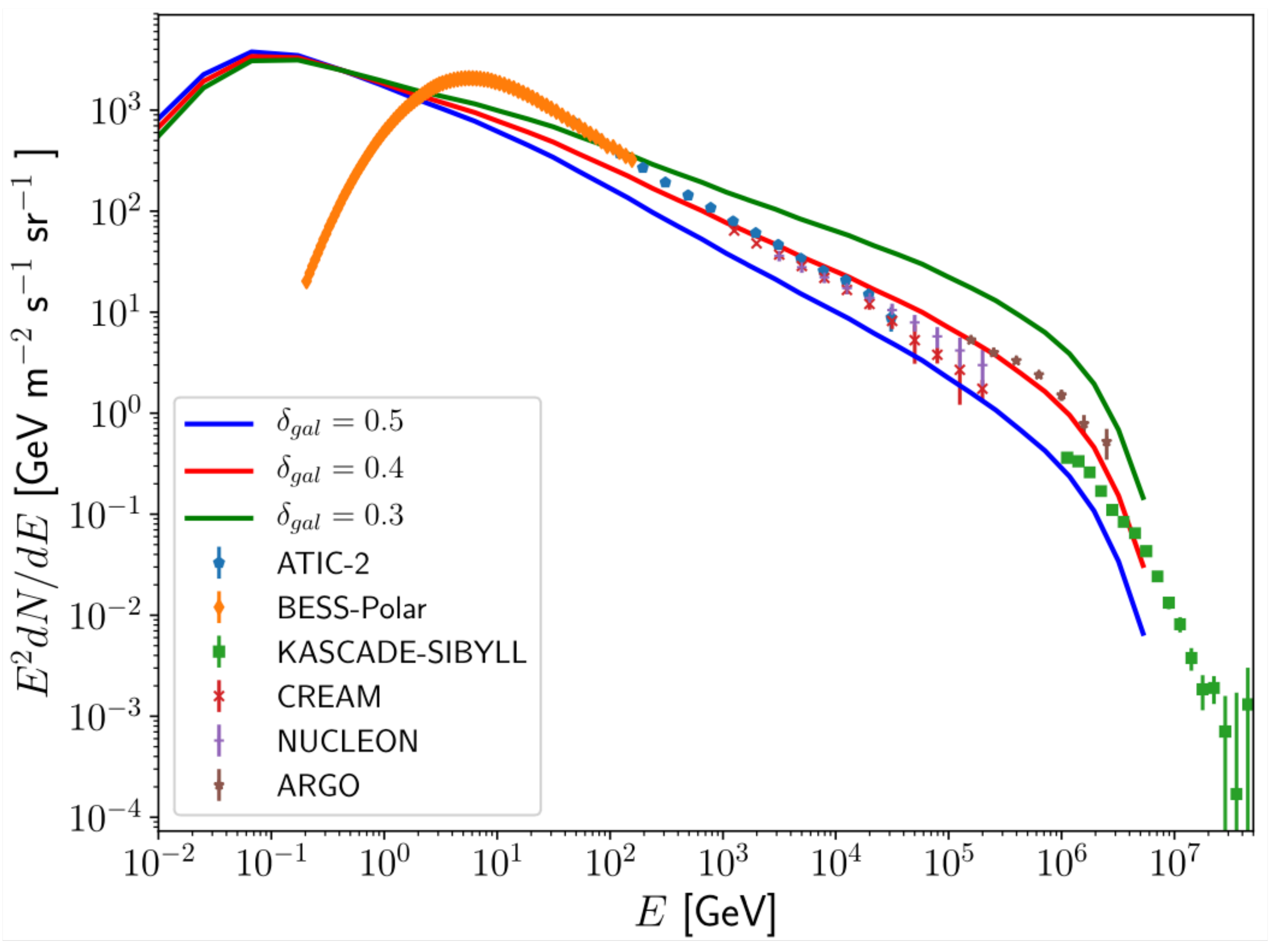
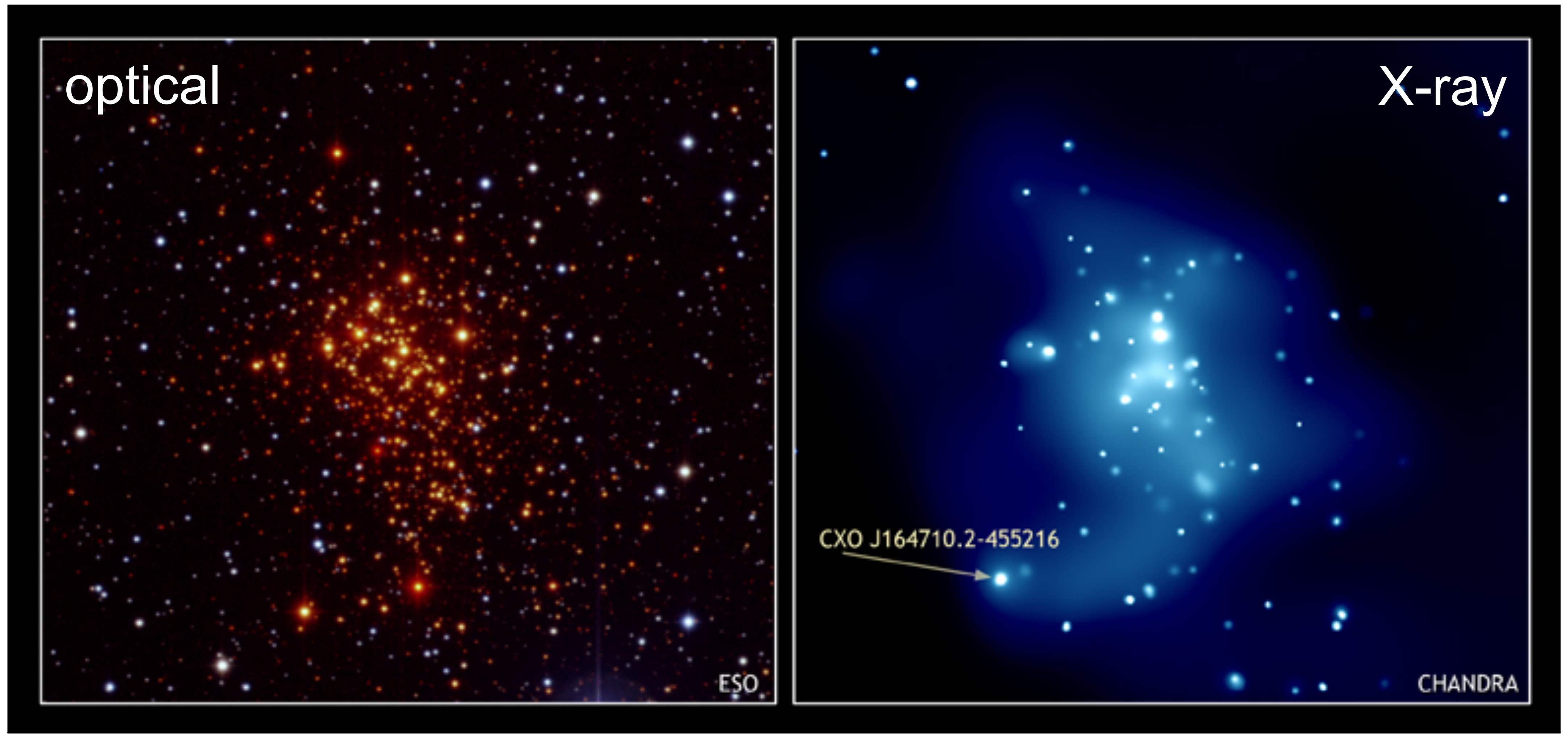




Westerlund 1

- Most massive known young stellar cluster in Milky Way
  - Half-mass radius: $\sim 1\,\mathrm{pc}$
  - Total mass: $\sim 10^5\,M_\odot$
  - Age: $3.5 - 5\,\mathrm{Myr}$
  - Distance: $\sim 4\,\mathrm{kpc}$

  } all uncertain / debated!
- Harbours X-ray magnetar, but no other known stellar remnants



Credit: NASA/CXC/UCLA/M.Muno et al.

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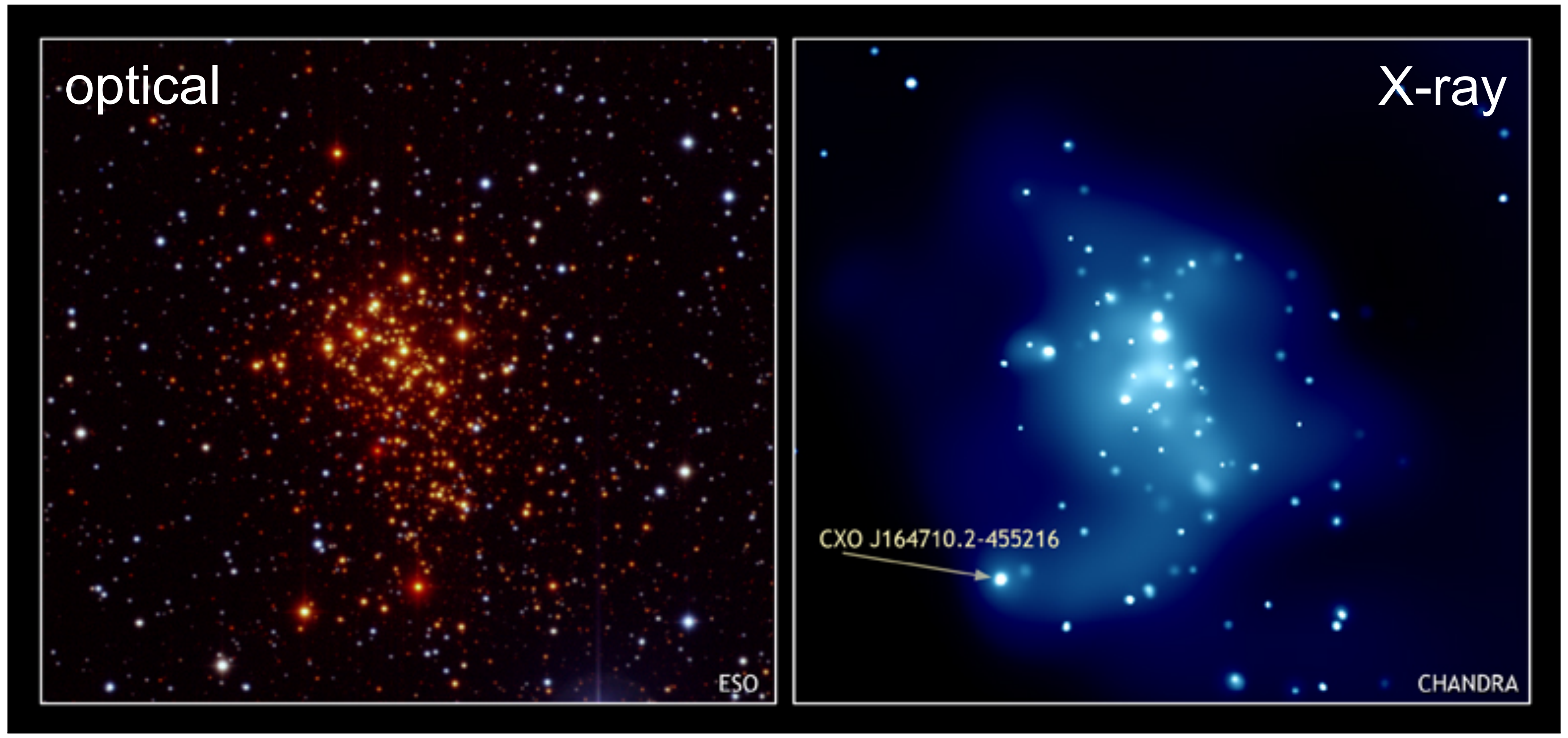
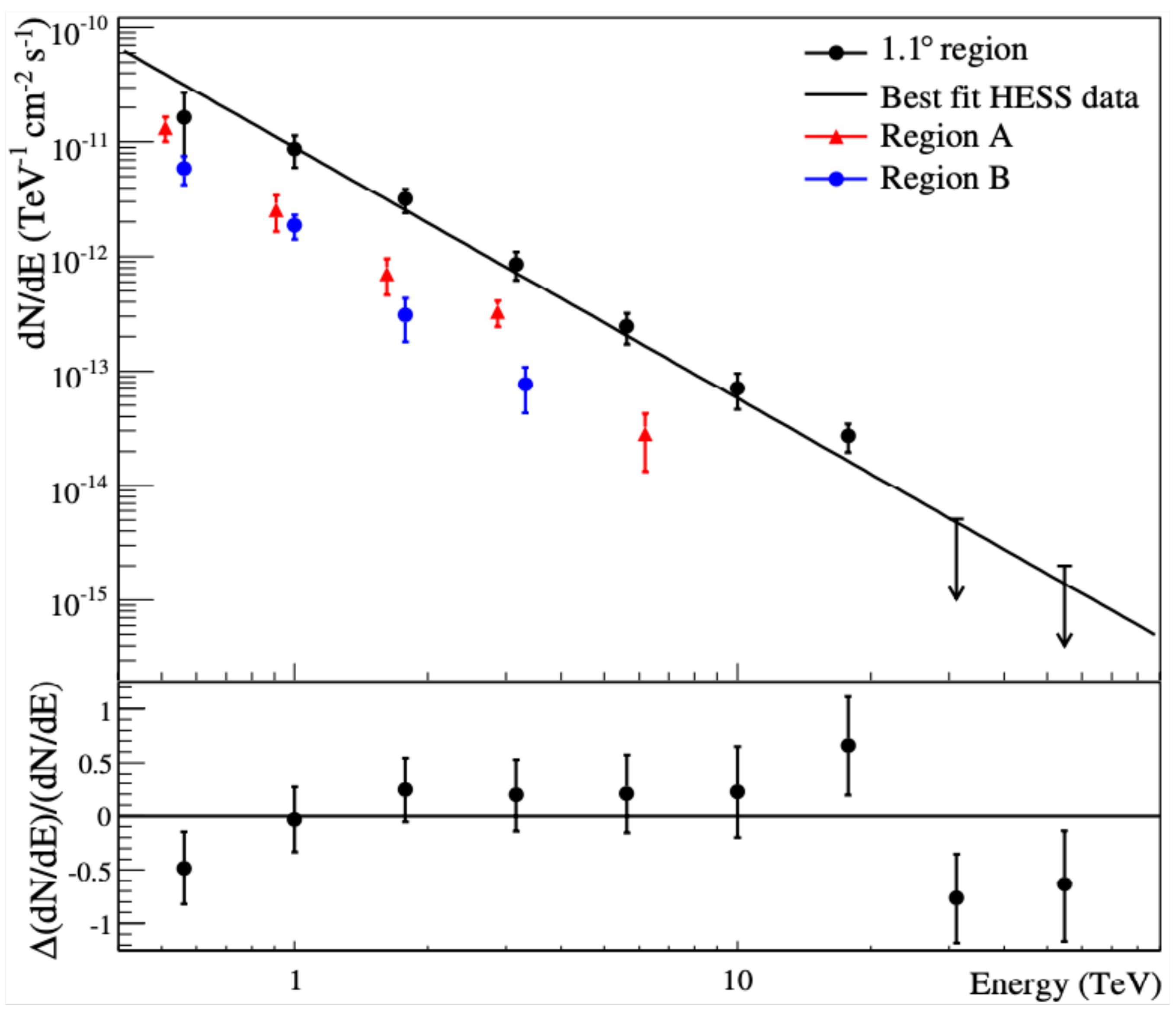
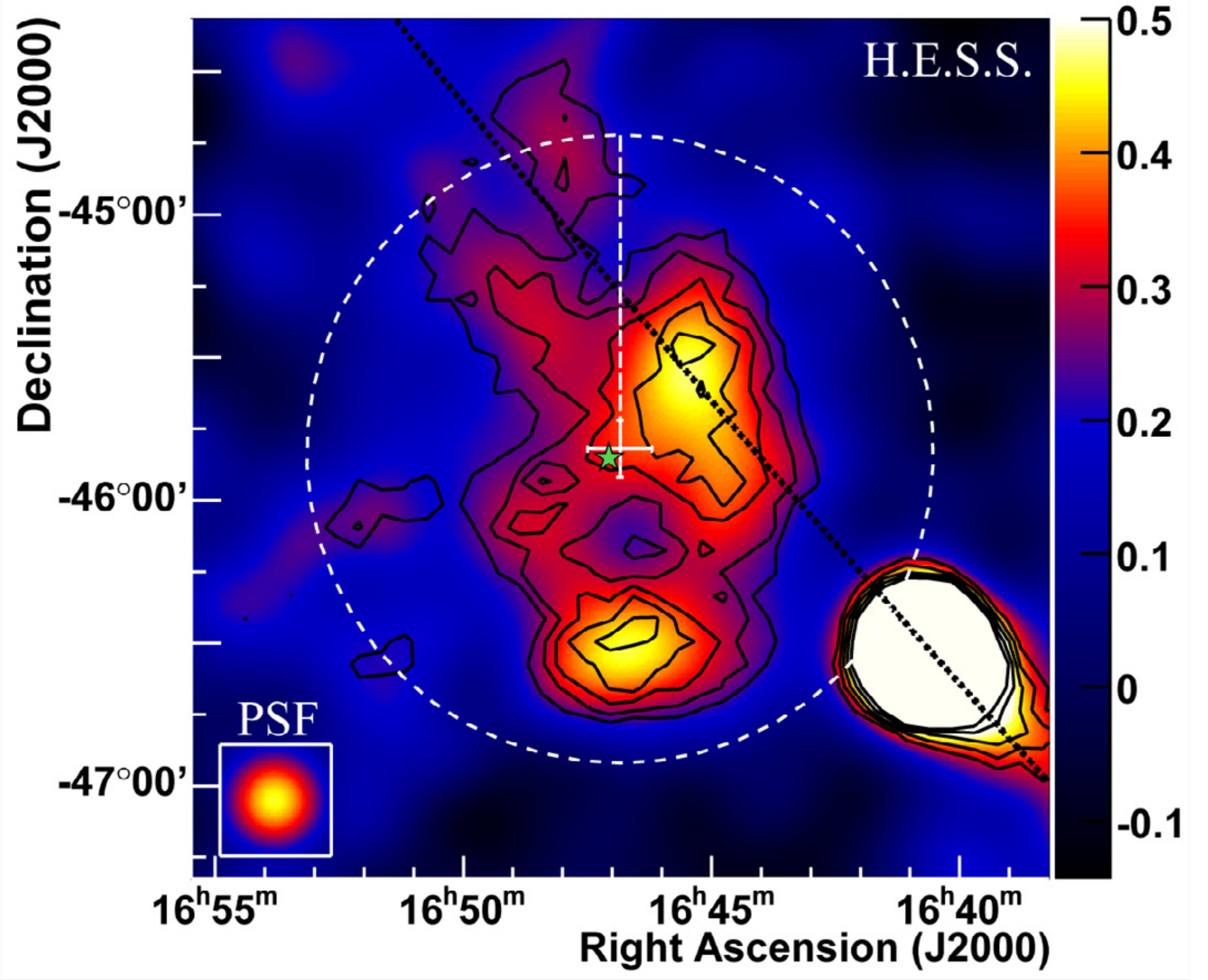


Credit: NASA/CXC/UCLA/M.Muno et al.

- Harbours X-ray magnetar, but no other known stellar remnants

- γ-ray source: HESS J1646–458 [5]
  - largely extended ($\sim 2^\circ$ diameter)
  - centroid coincident with Westerlund 1
  - unbroken spectrum to $\sim 20\,\mathrm{TeV}$
  - limited data set (34 h)
    → no definitive conclusion on association of γ-ray emission



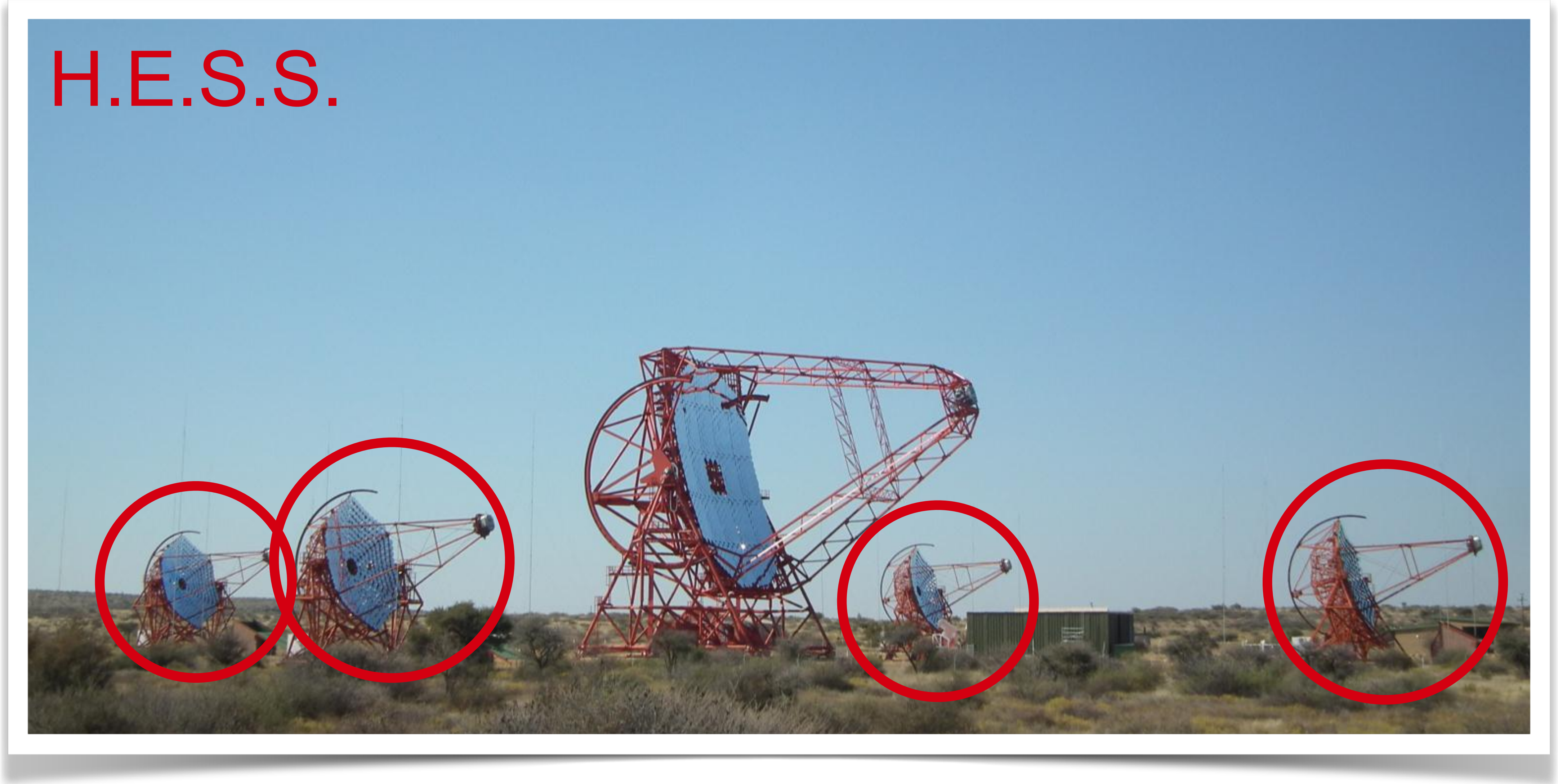


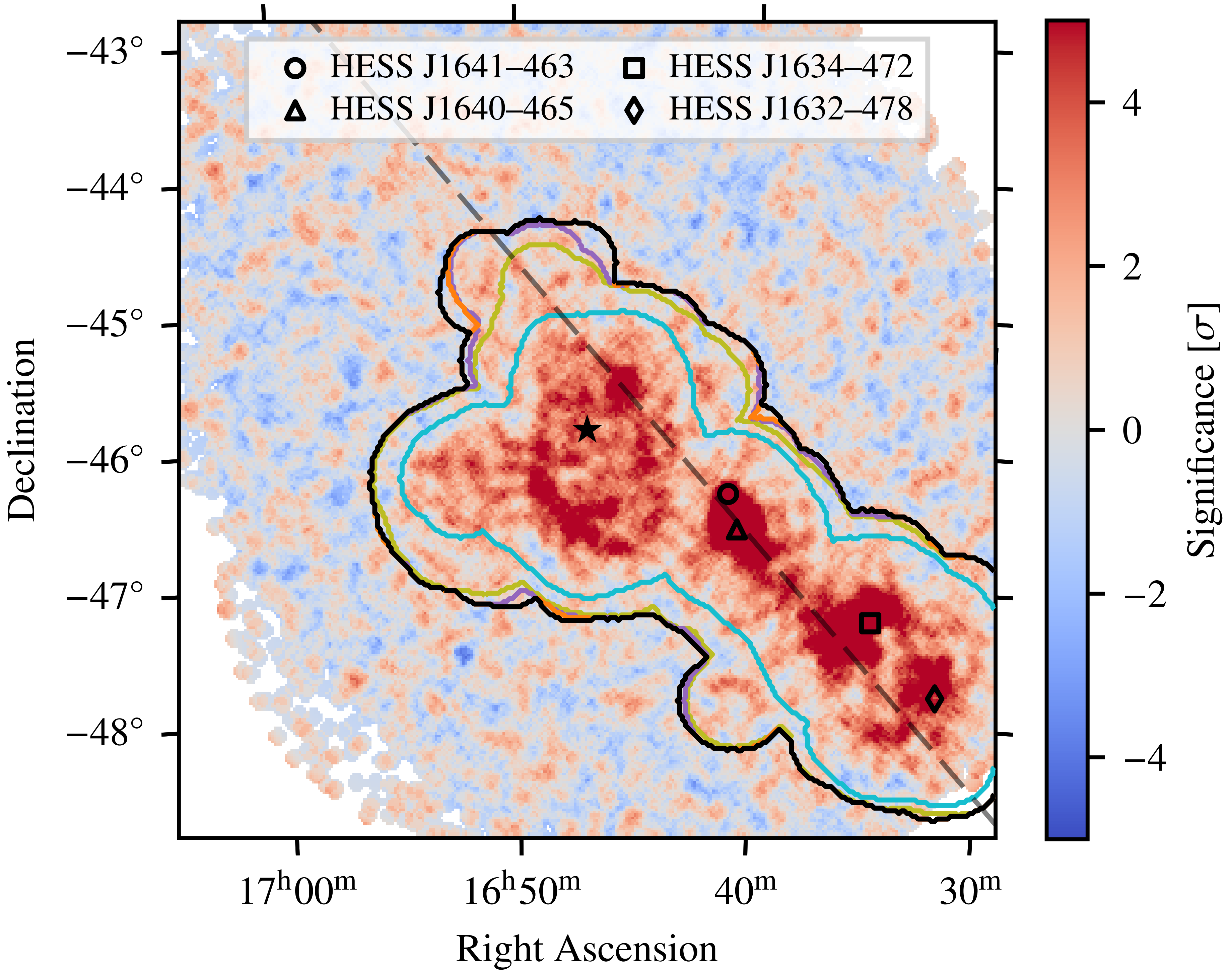
New H.E.S.S. analysis

- Data set
  - 164 h live time, taken 2004–2017
  - 12-m telescopes only
- Data analysis
  - Very large source extent & other nearby sources
    → ***cannot estimate background from source-free regions***
  - Employ ***background model*** from archival observations (see [6])
  - Perform high-level analysis with Gammapy (https://gammapy.org)
  - Energy threshold: 0.37 TeV

A **Python** package for **gamma-ray** astronomy

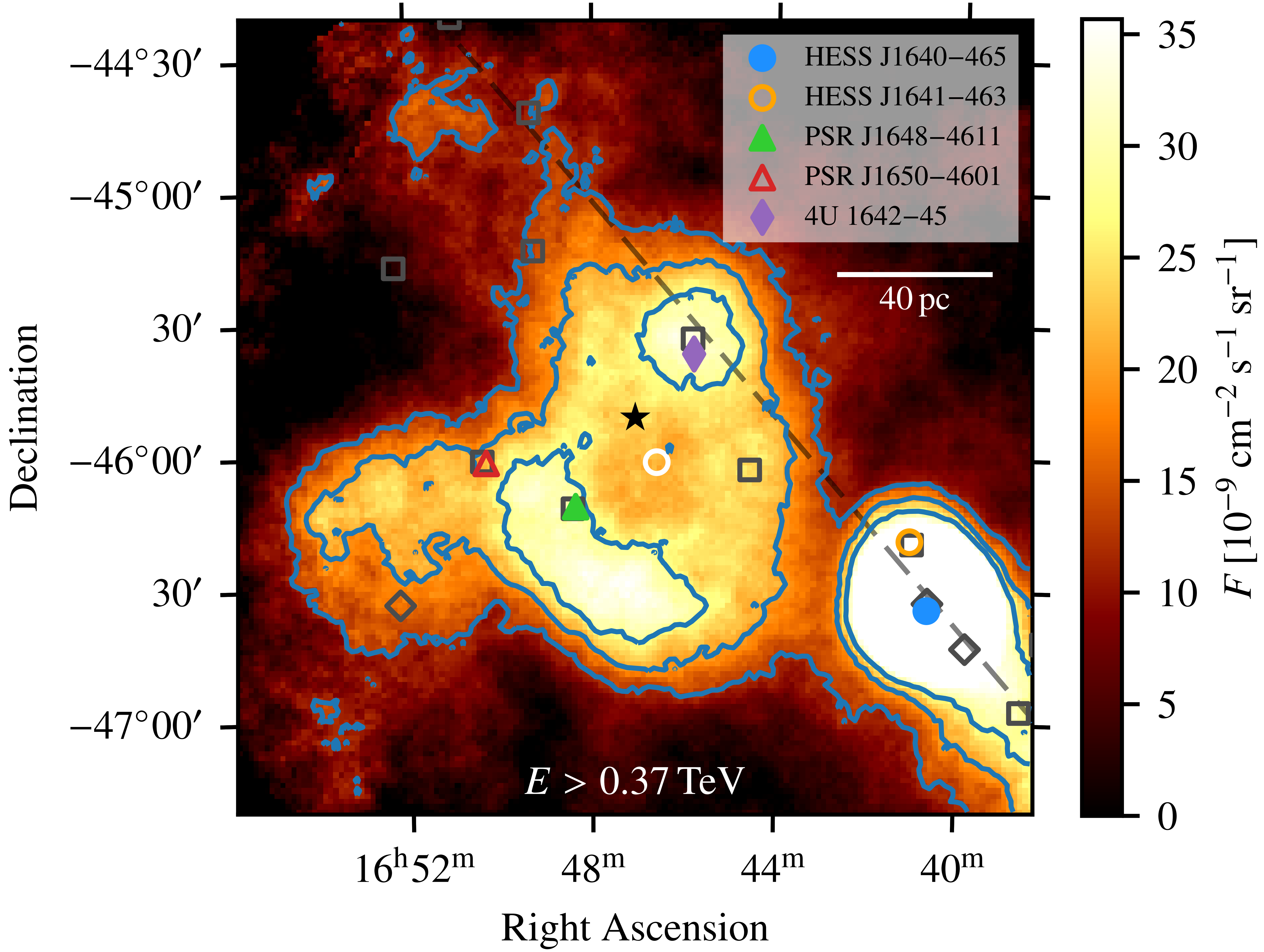
- Publication
  - *"A deep spectromorphological study of the γ-ray emission surrounding the young massive stellar cluster Westerlund 1"*
  - Accepted in A&A on July 21
  - Pre-print: arXiv:2207.10921





Results: Flux map

- Source morphology
  - very large extent: $\sim 2^\circ$ / 140 pc
  - very complex
  - not peaked at cluster position
  - ***shell-like structure***
  - some bright spots on top
  - centroid slightly shifted from Westerlund 1



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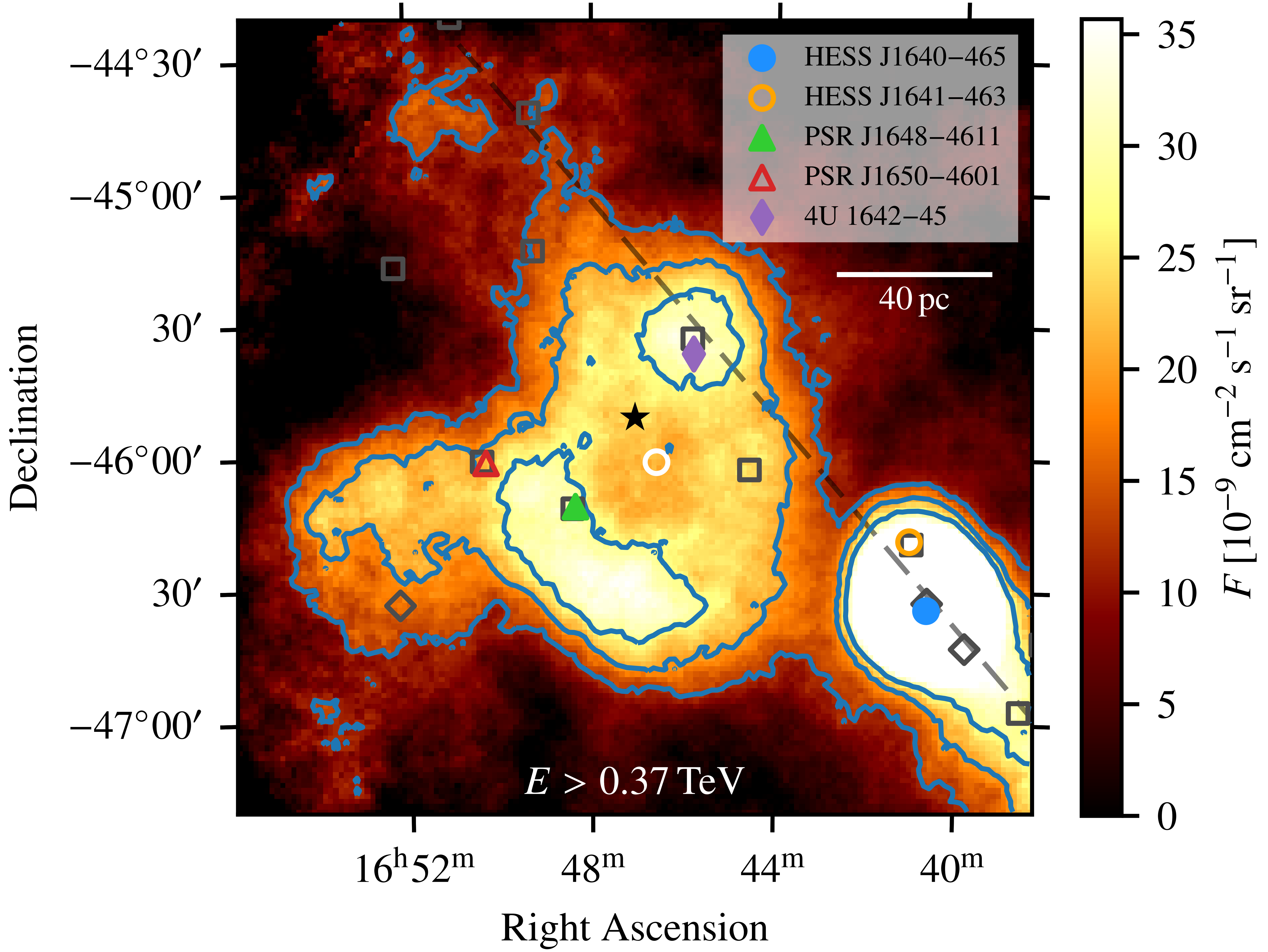
- Potential counterparts
  - Westerlund 1 (★)
  - Magnetar within Westerlund 1
    (CXOU J164710.2–455216)
  - LMXB 4U 1642–45 (♦)
  - PSR J1648–4611 (▲) / PSR J1650–4601 (△)



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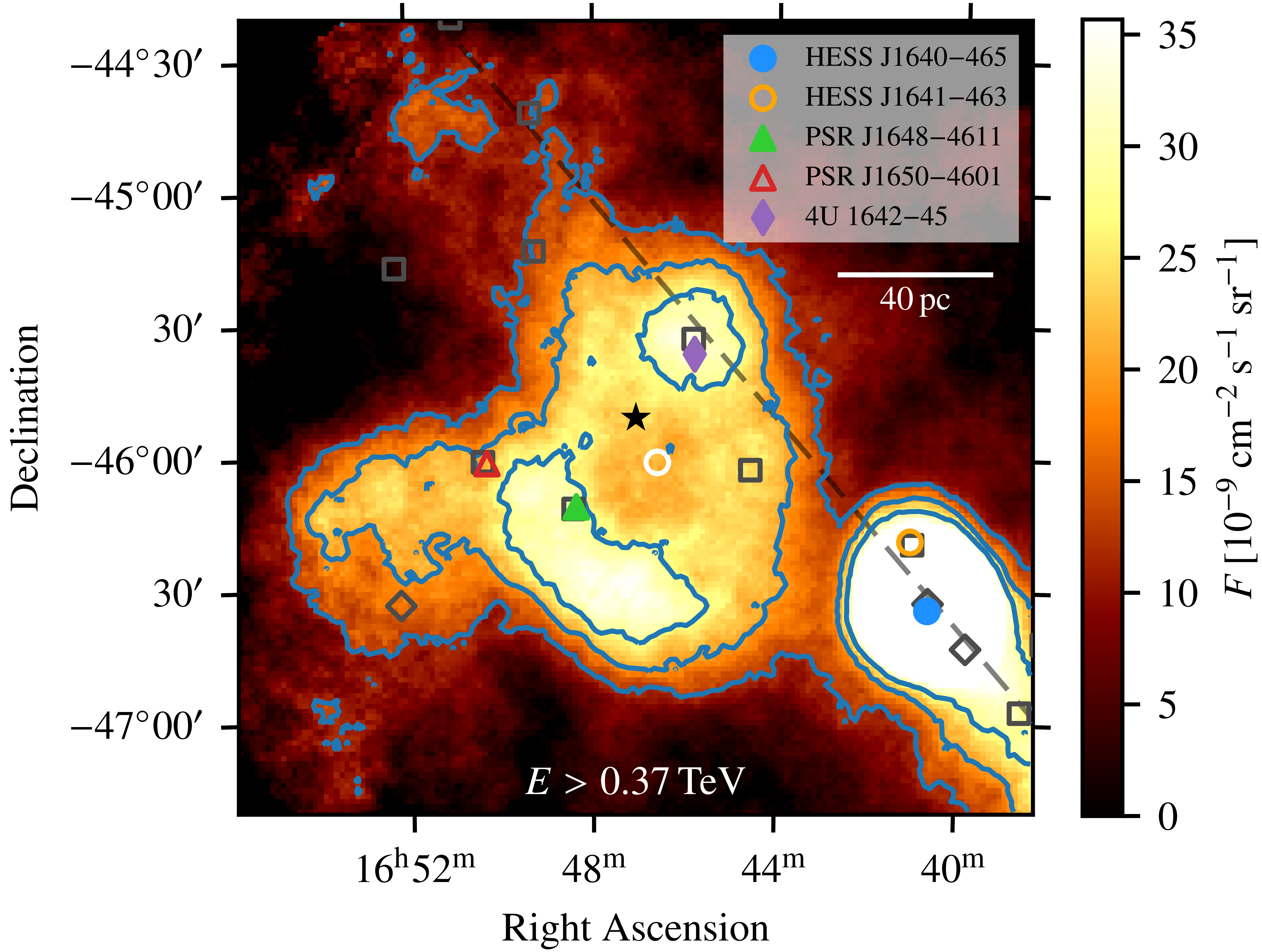
- Potential counterparts
  - ***Westerlund 1*** (★) → bulk of emission
  - ~~Magnetar within Westerlund 1 (CXOU J164710.2–455216)~~
  - ~~LMXB 4U 1642–45 (♦)~~
  - PSR J1648–4611 (▲) / PSR J1650–4601 (△) → may contribute locally



Results: Flux map ($E > 1\,\mathrm{TeV}$)

- Source morphology
  - very large extent: $\sim 2^\circ$ / $140\,\mathrm{pc}$
  - very complex
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  - ***shell-like structure***
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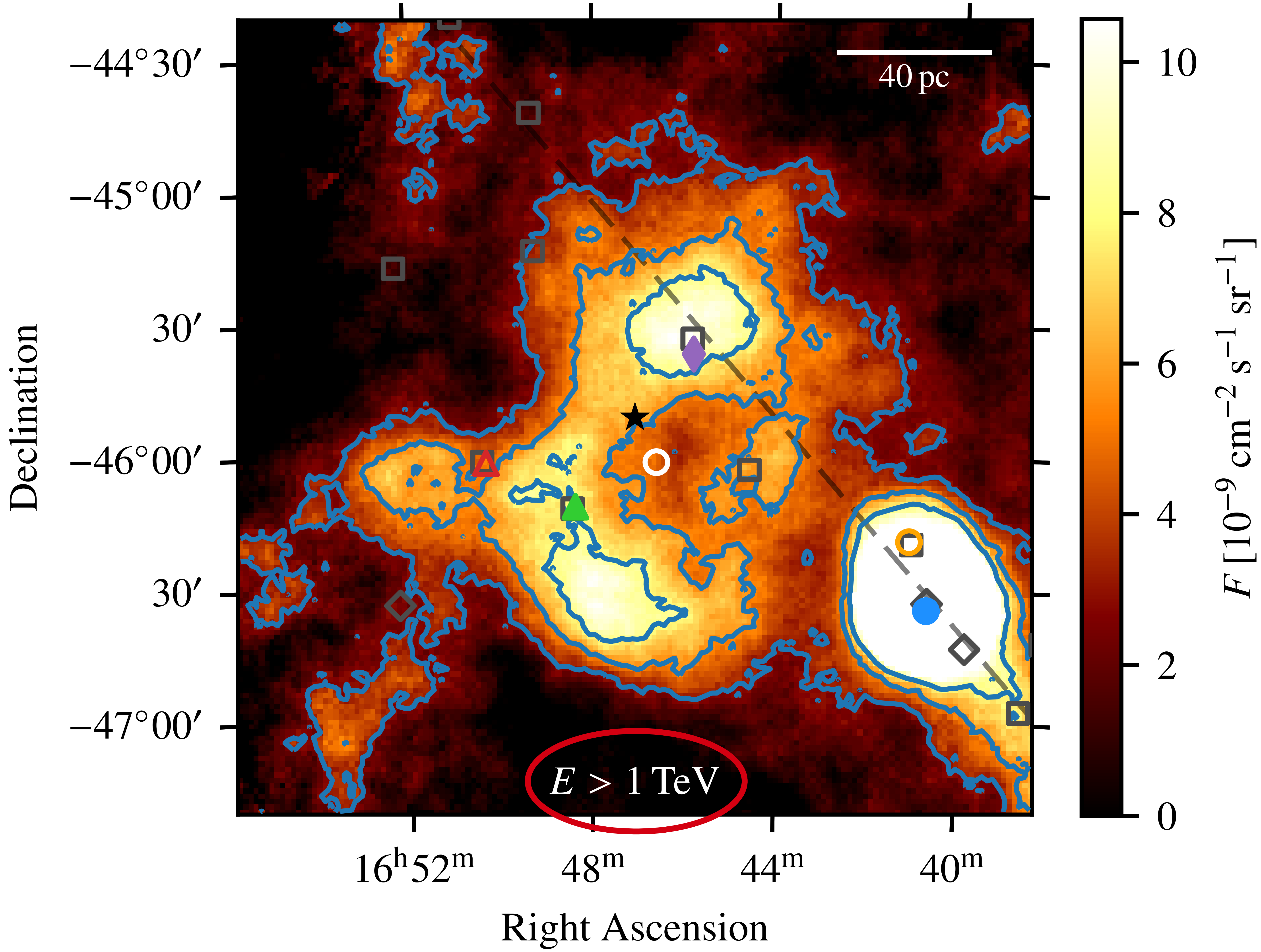
- Energy-dependent morphology?
  - bright spots remain
  - ***shell-like structure persists***



Results: Flux map ($E > 4.9\,\mathrm{TeV}$)

- Source morphology
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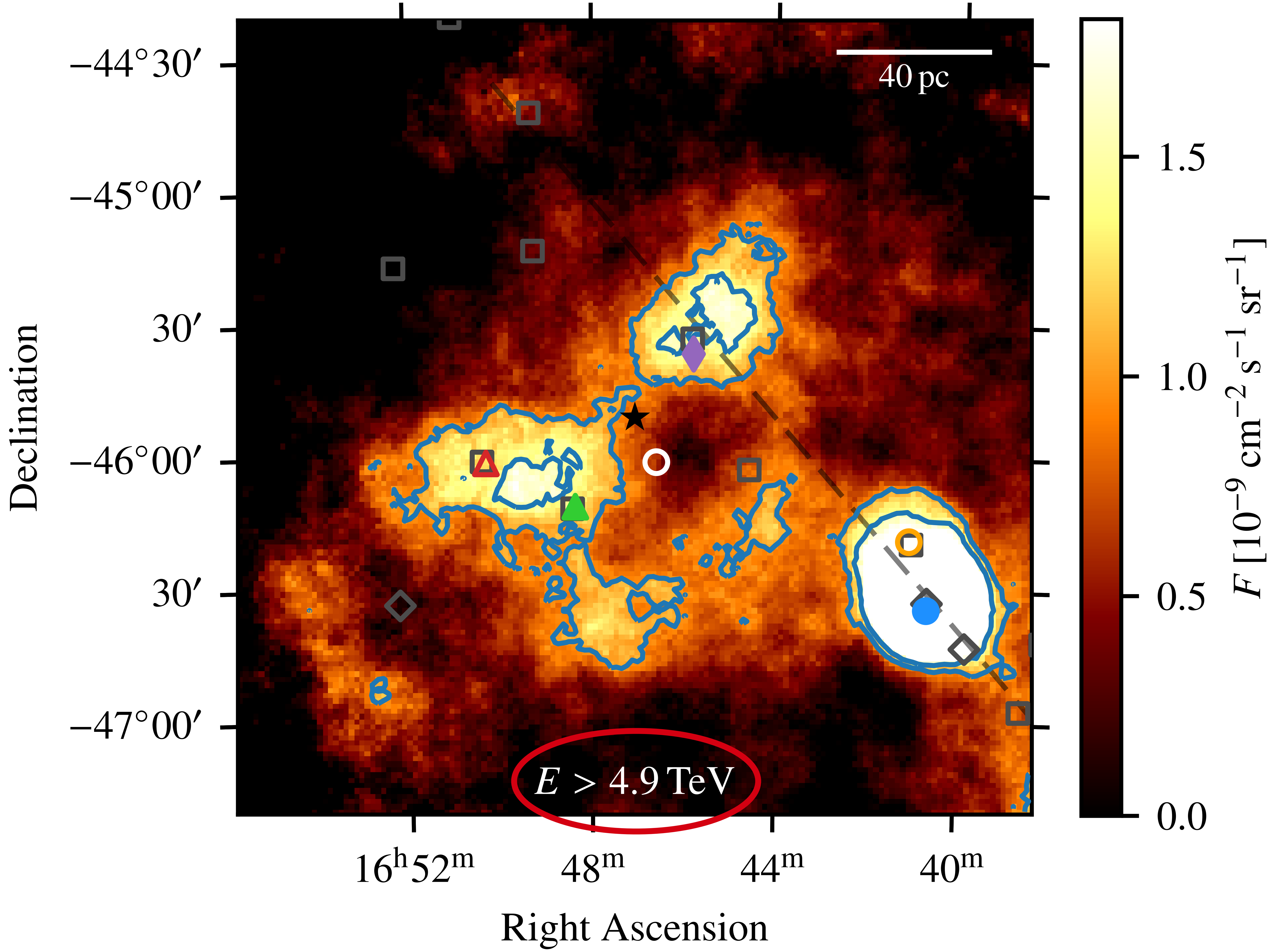
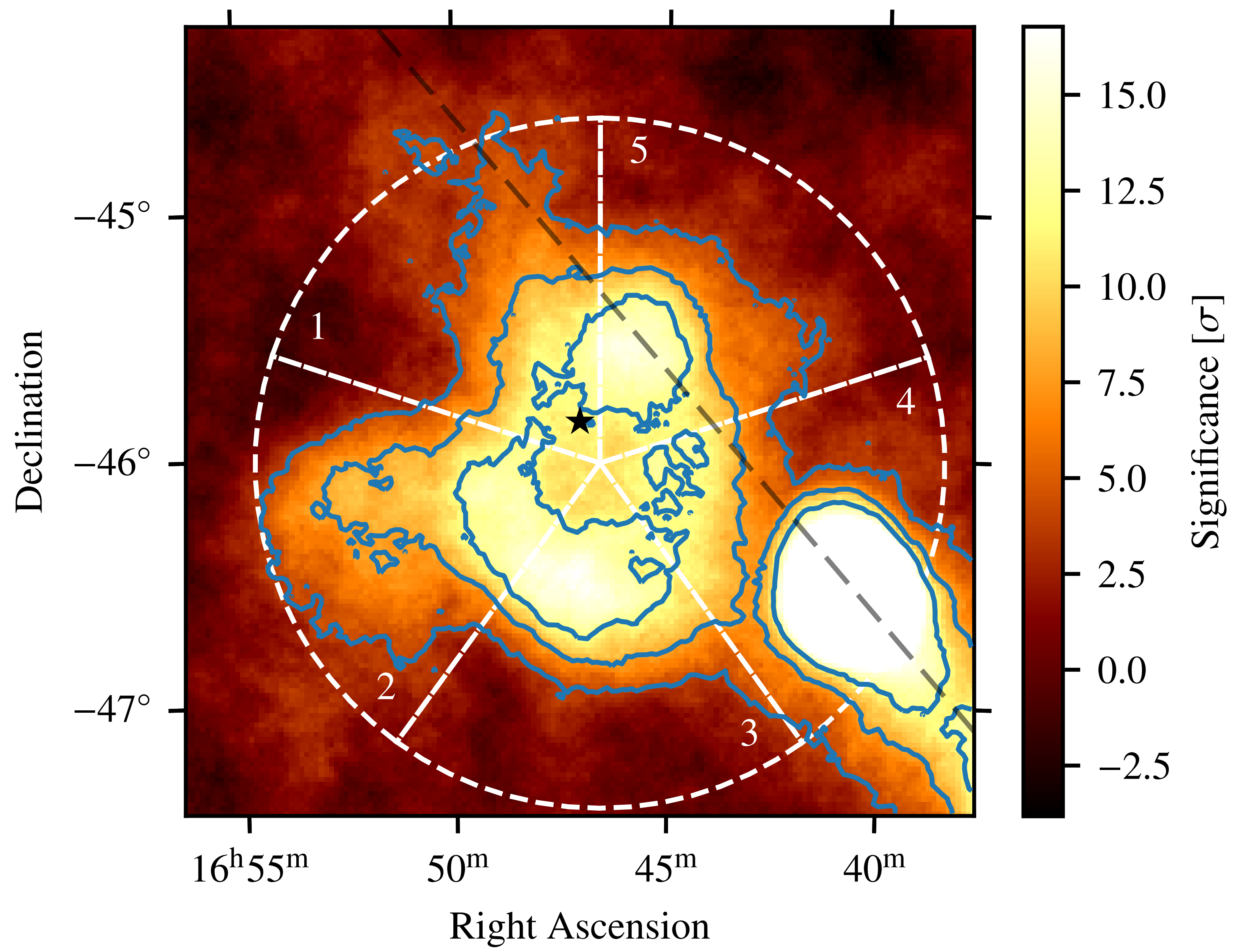
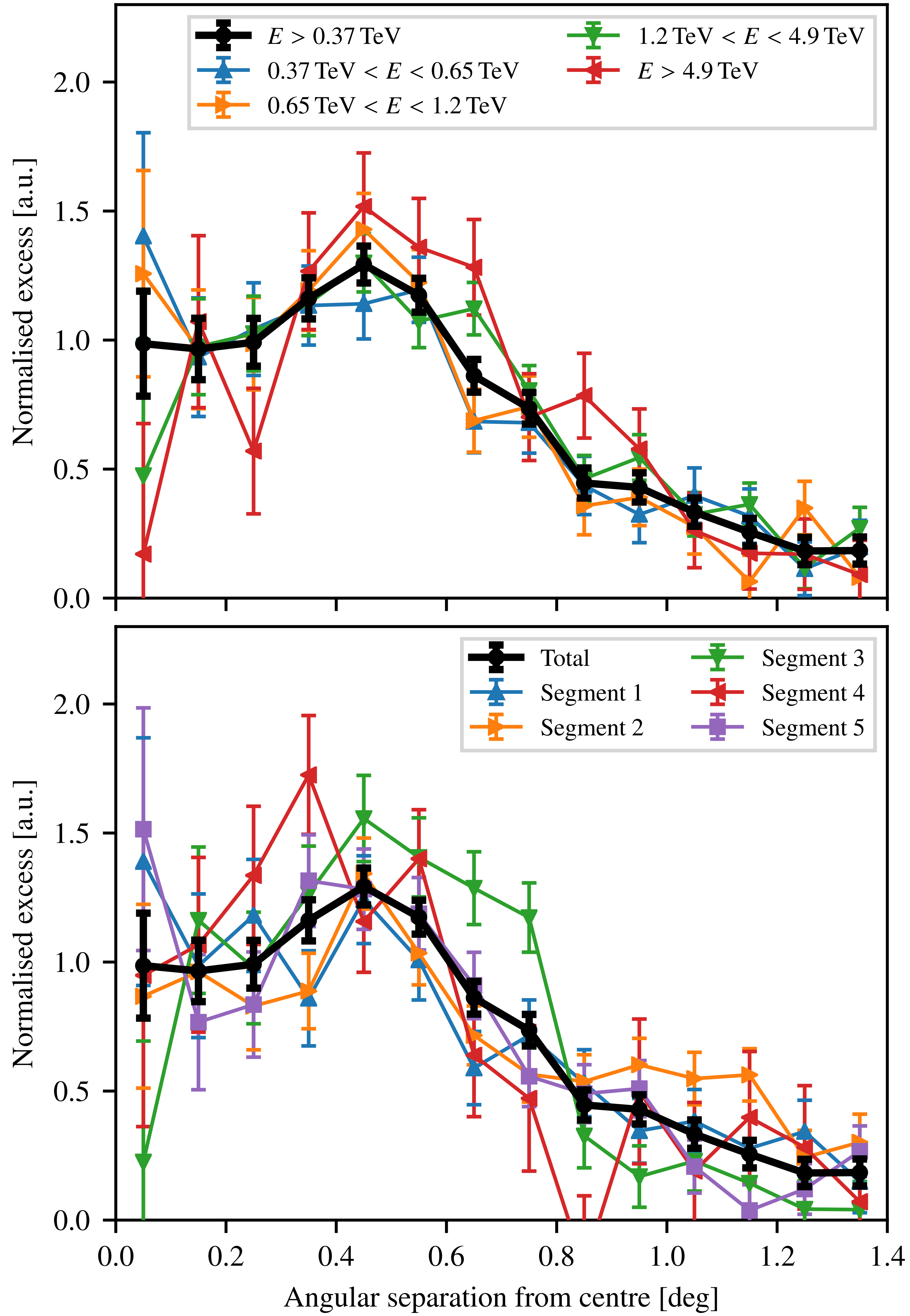


Results: Radial excess profiles

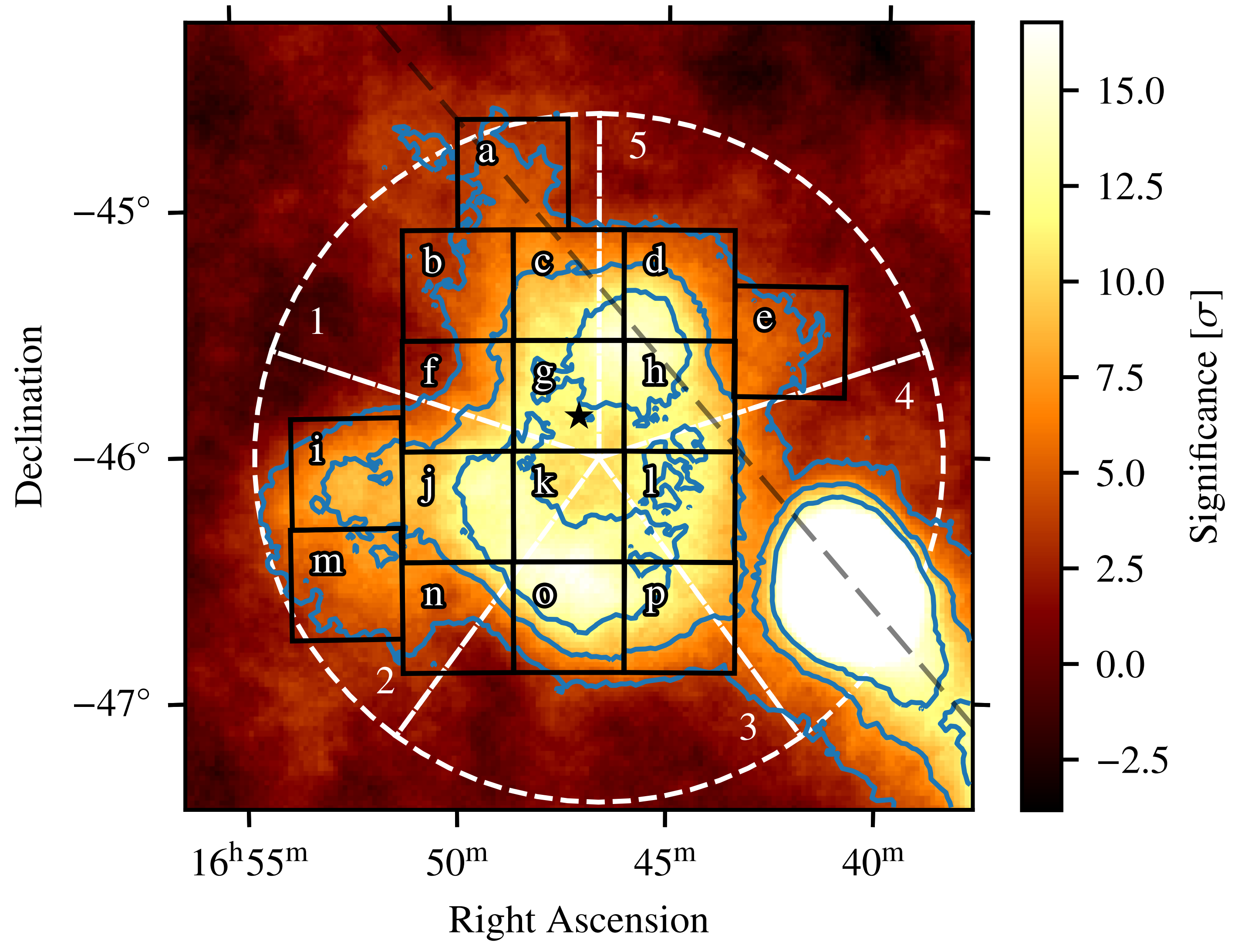
- Profiles are with respect to centroid of emission
- Confirm shell-like structure
- Peak at $\sim 0.5^\circ \;\rightarrow\; \sim 34\,\mathrm{pc}$
- Remarkably similar in all energy bands
  → ***no energy-dependent morphology***
- Also no significant variations
  in azimuthal segments

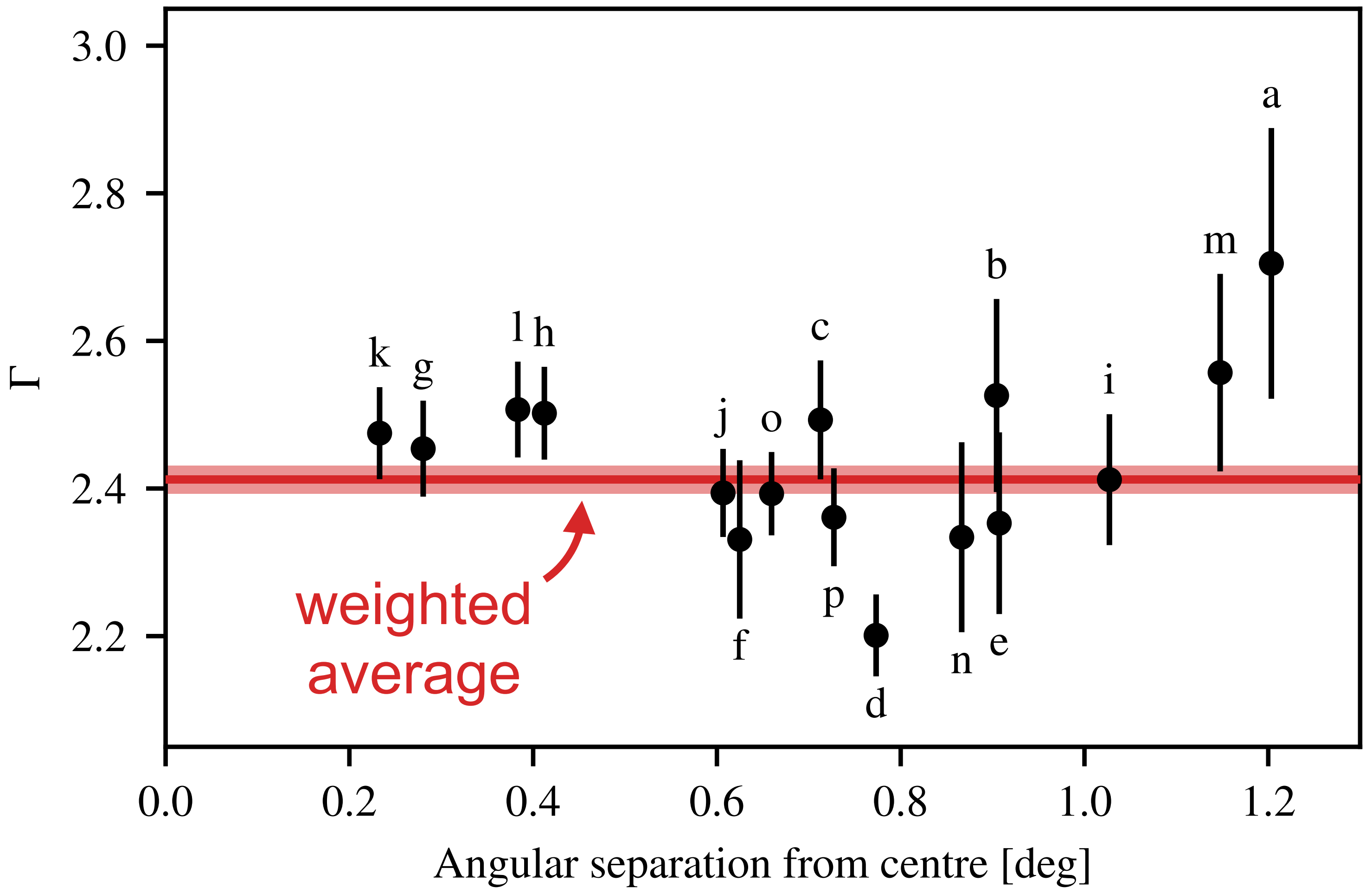


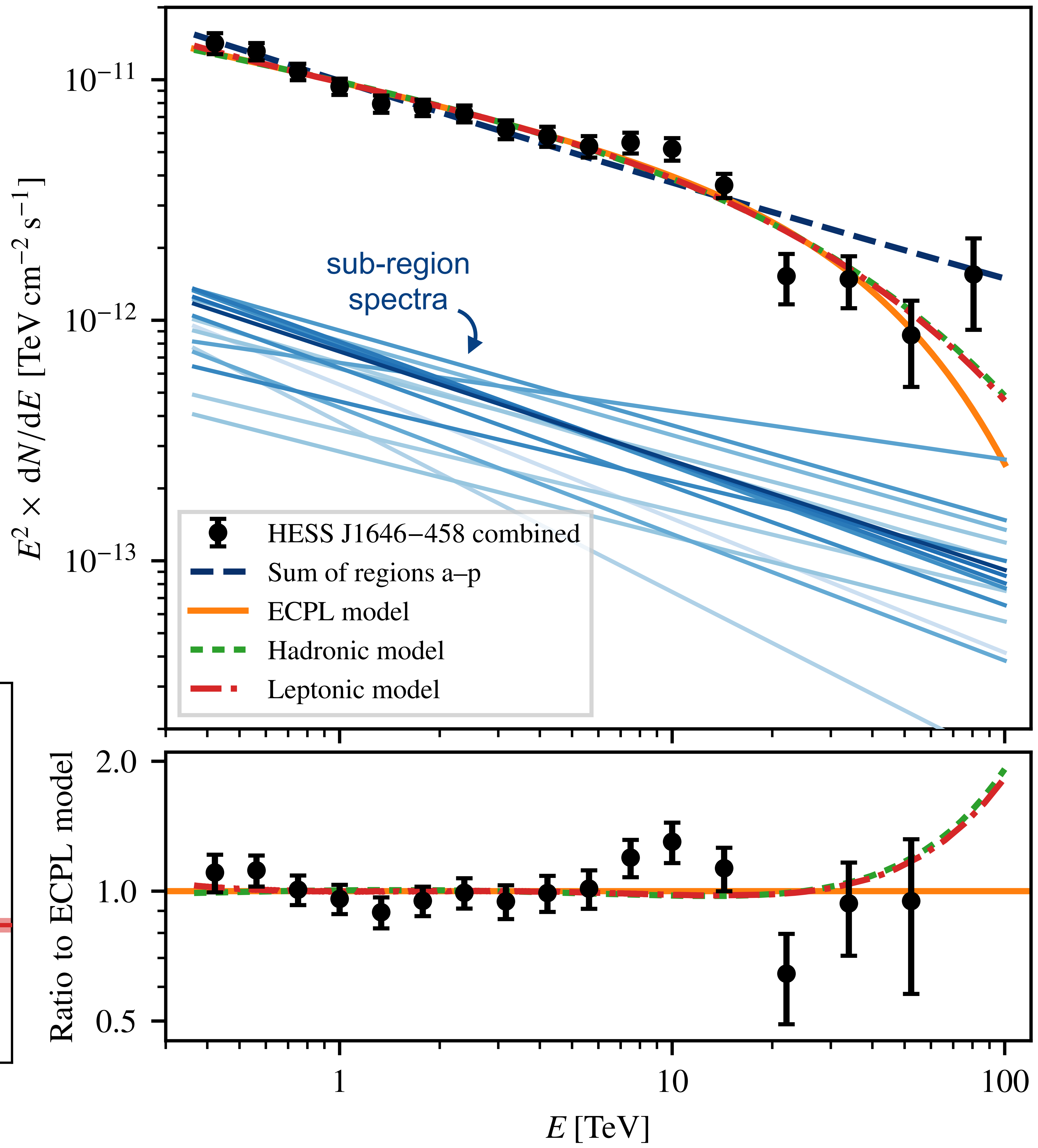


Results: Energy spectrum

- Extract spectrum in 16 signal regions
- Individual spectra remarkably similar
- Combined spectrum extends to several tens of TeV
- $\Gamma = 2.30 \pm 0.04,\ E_c = \left(44^{+17}_{-11}\right)$ TeV







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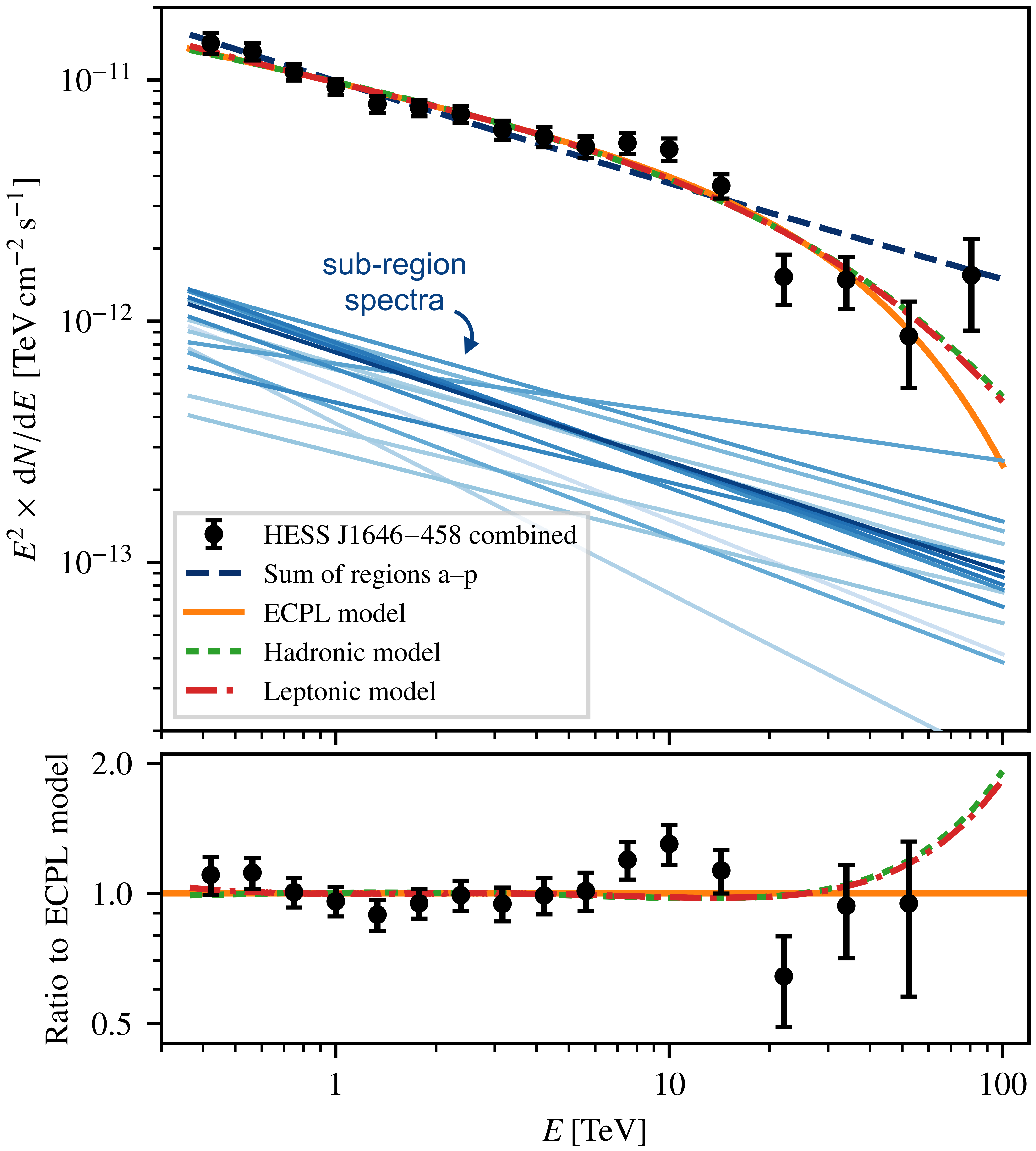
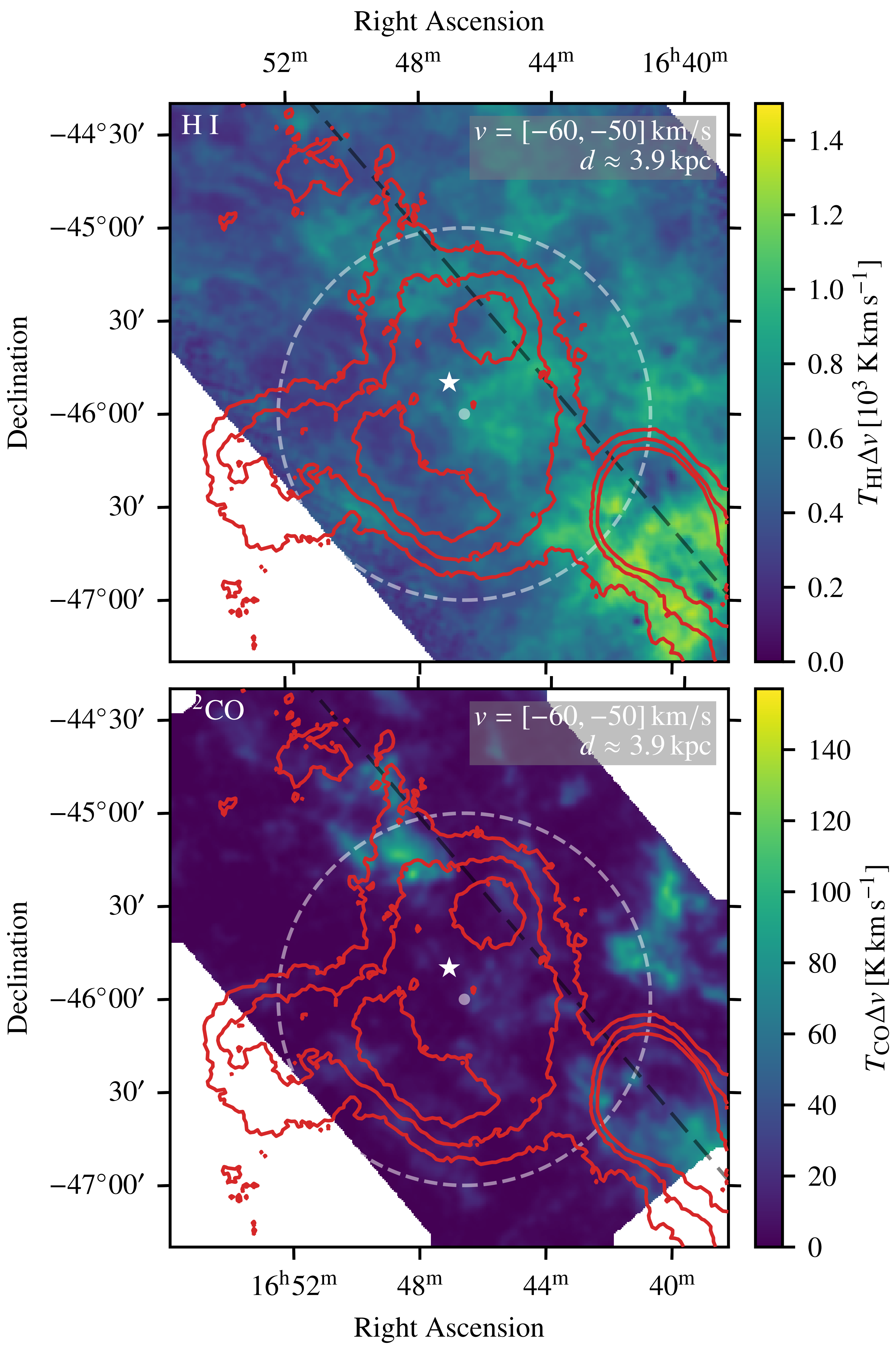
- Hadronic model (*proton-proton*)
  - $\Gamma_p = 2.33 \pm 0.06,\ E_c^p = \left(400^{+250}_{-130}\right)$ TeV
  - $W_p(>1\,\mathrm{GeV}) = 6 \times 10^{51} \left(\frac{n}{1\,\mathrm{cm}^3}\right)^{-1}$ erg
- Leptonic model (*Inverse Compton*)
  - $\Gamma_e = 2.97 \pm 0.07,\ E_c^e = \left(180^{+200}_{-70}\right)$ TeV
  - $L_e(>0.1\,\mathrm{TeV}) > 4.1 \times 10^{35}$ erg s^{-1}



Results: Correlation with gas maps

- Hadronic scenario requires target material for interactions
- Comparison with H I (→ atomic hydrogen) and CO (→ molecular hydrogen) line emission [7,8]
- Indicates low density in regions of bright γ-ray emission
- A challenge for the hadronic scenario… …but there could be ways out:
  - gas distribution uncertain (uncertain distance, photodissociation of molecules due to cluster radiation, …)
  - distribution of cosmic rays need not be uniform



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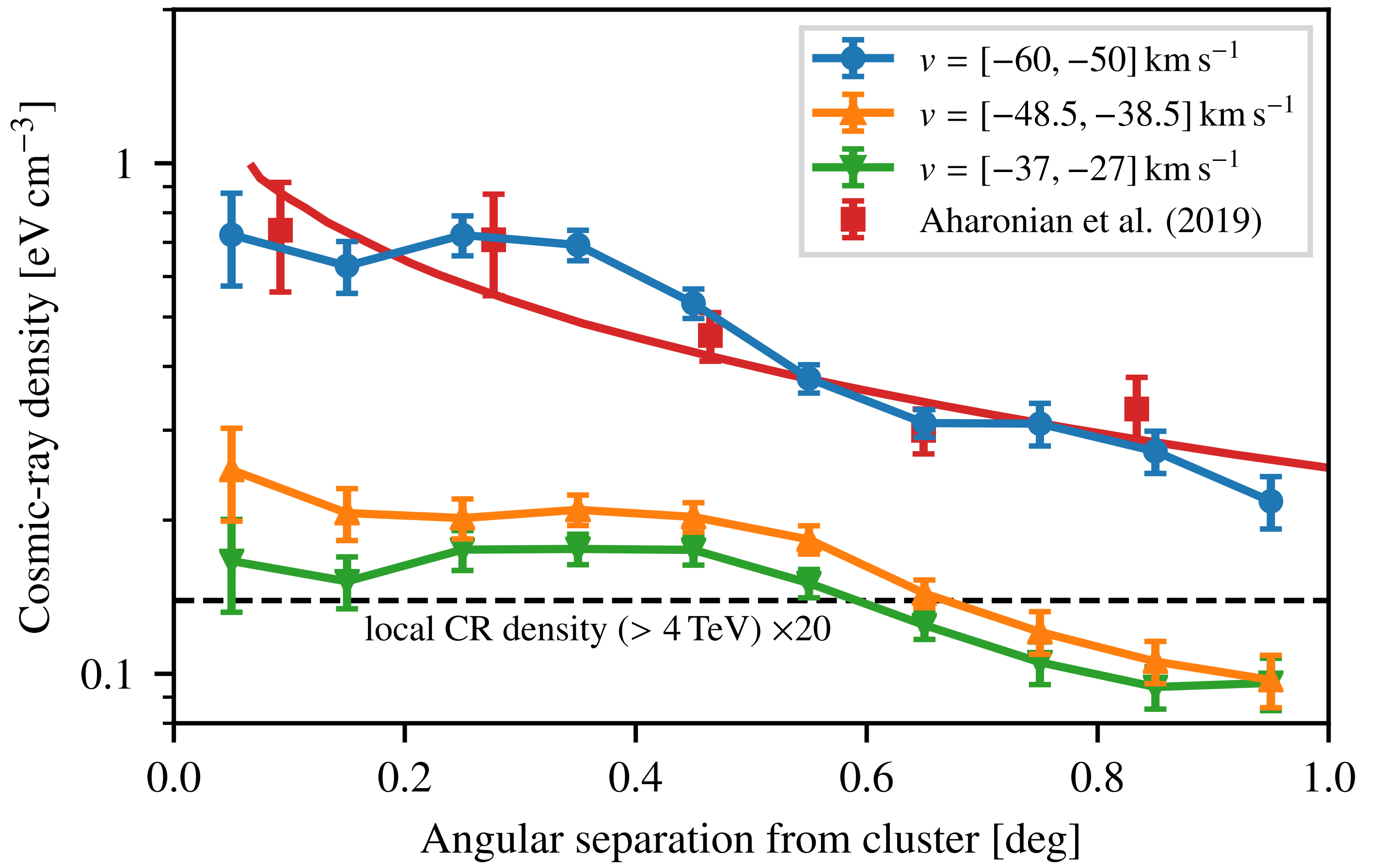
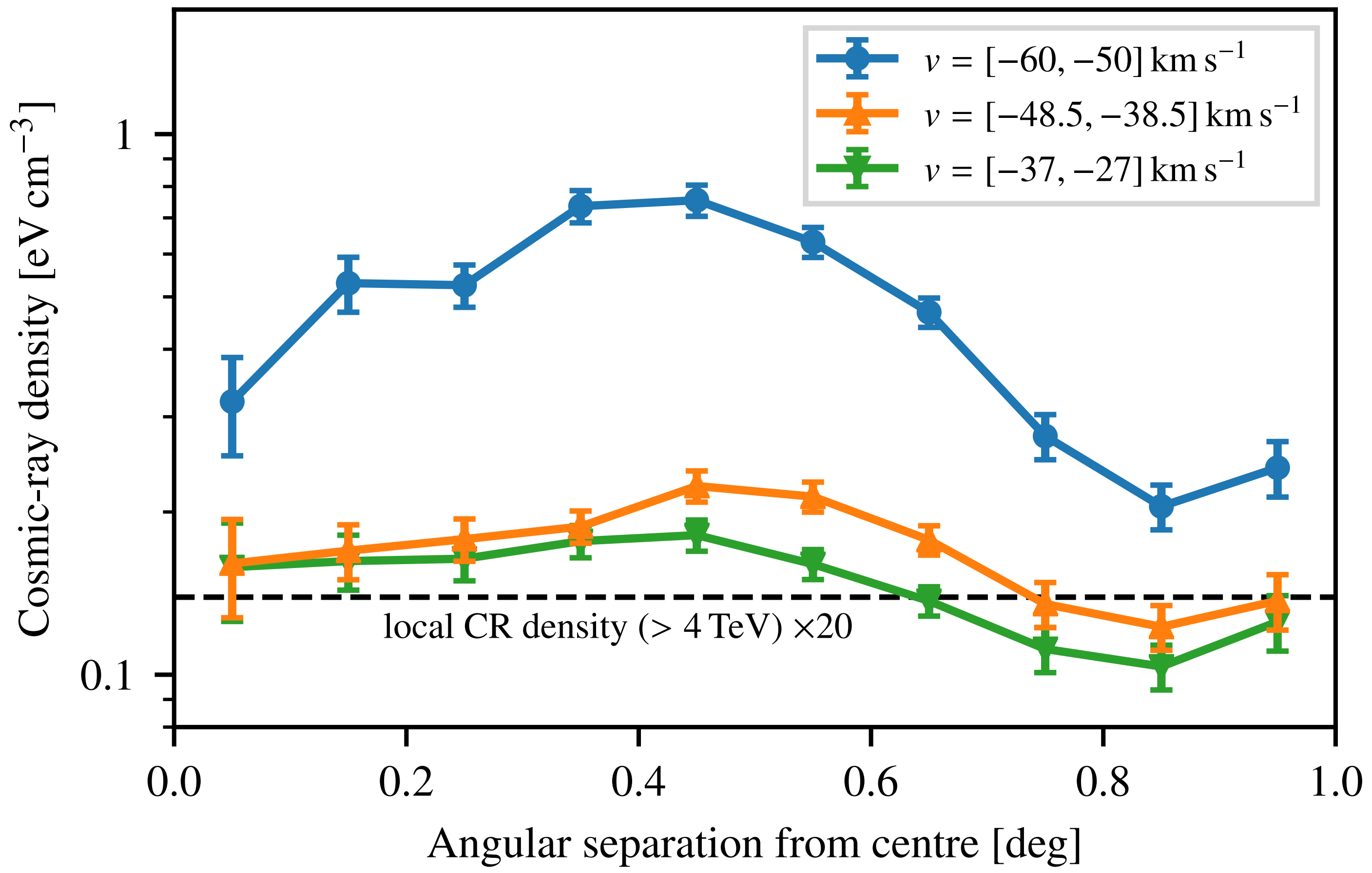
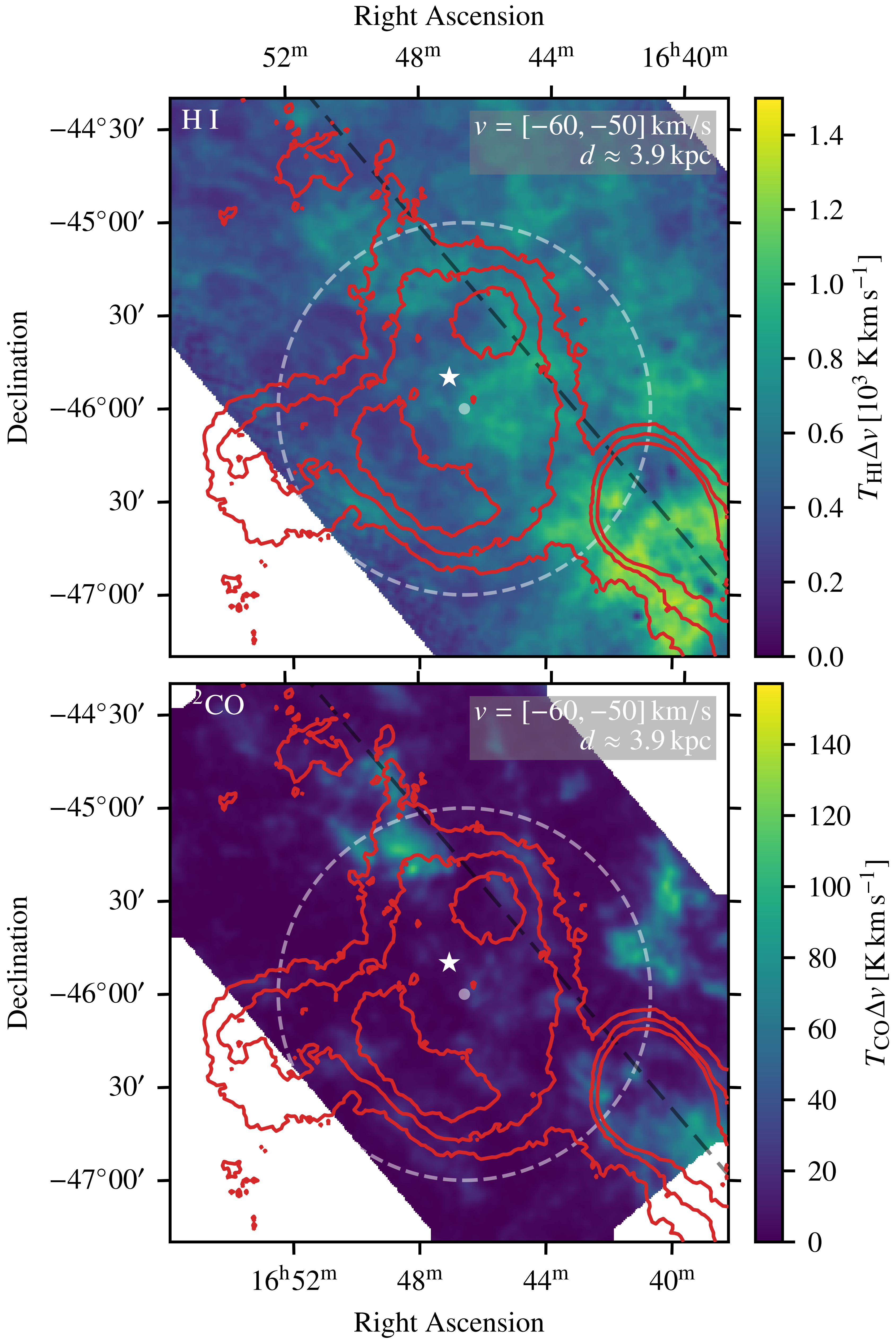
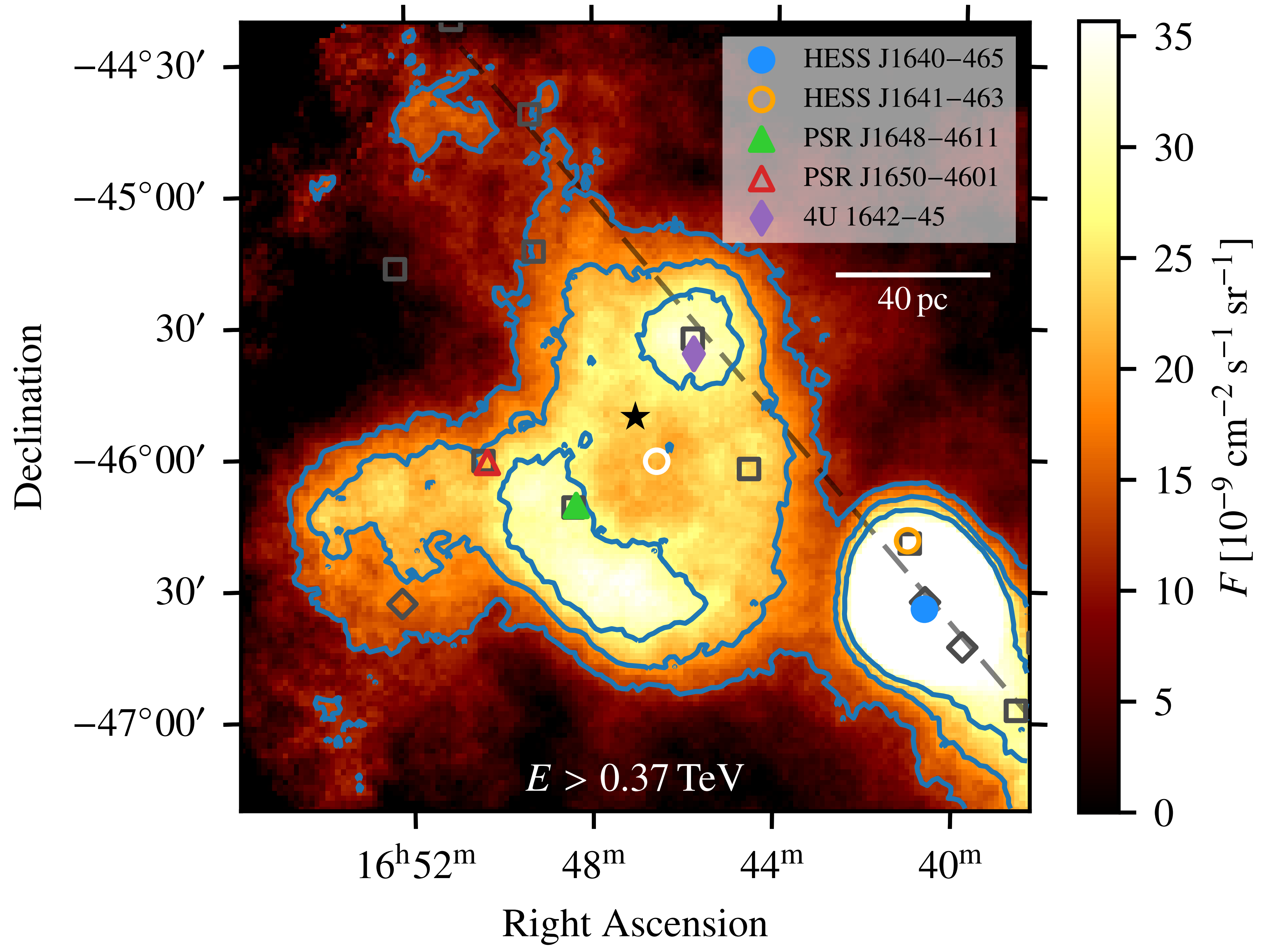






Discussion

- No energy-dependent morphology + energetics:
  - Only Westerlund 1 can explain bulk of emission
  - Pulsars may contribute locally



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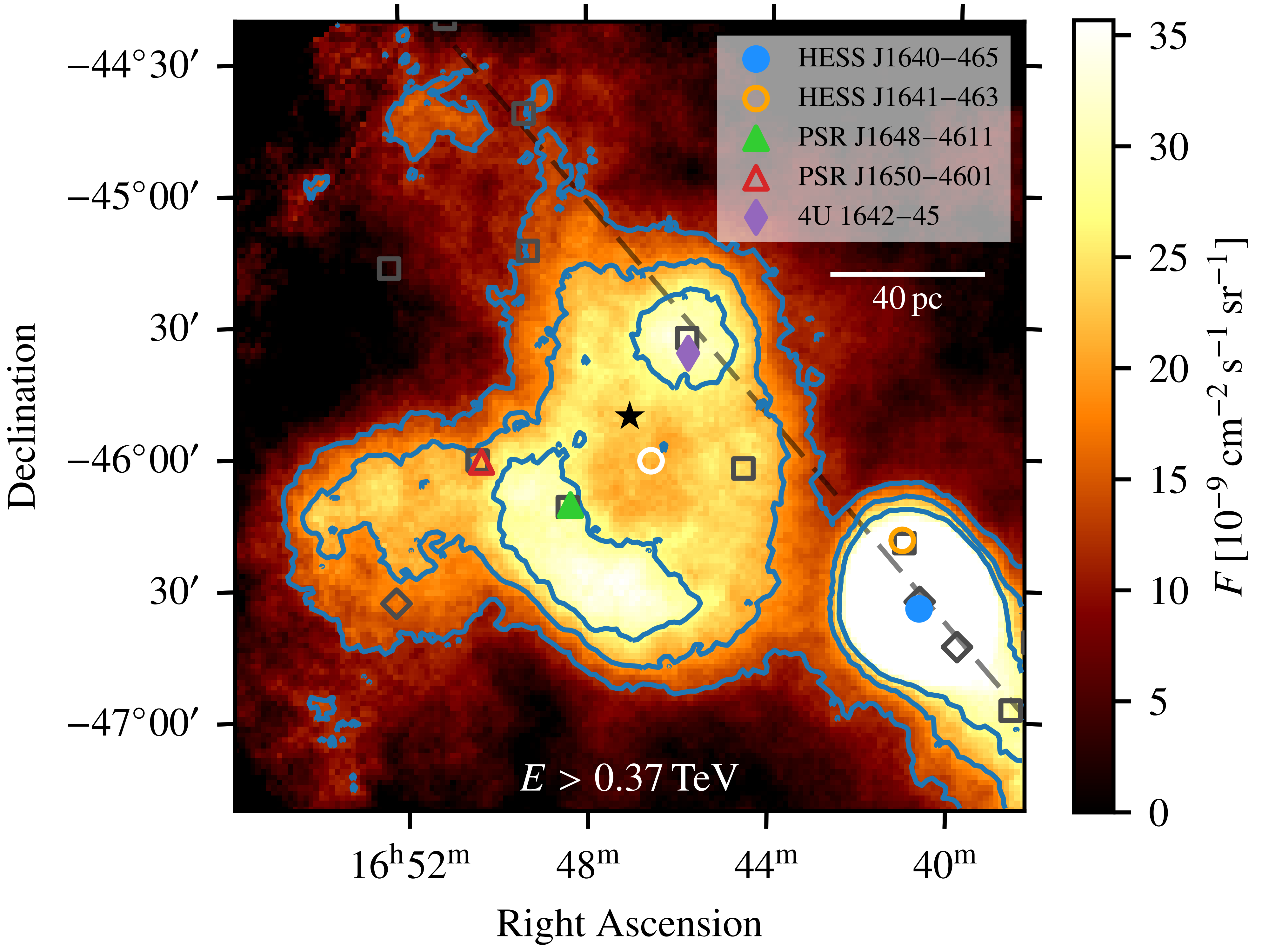

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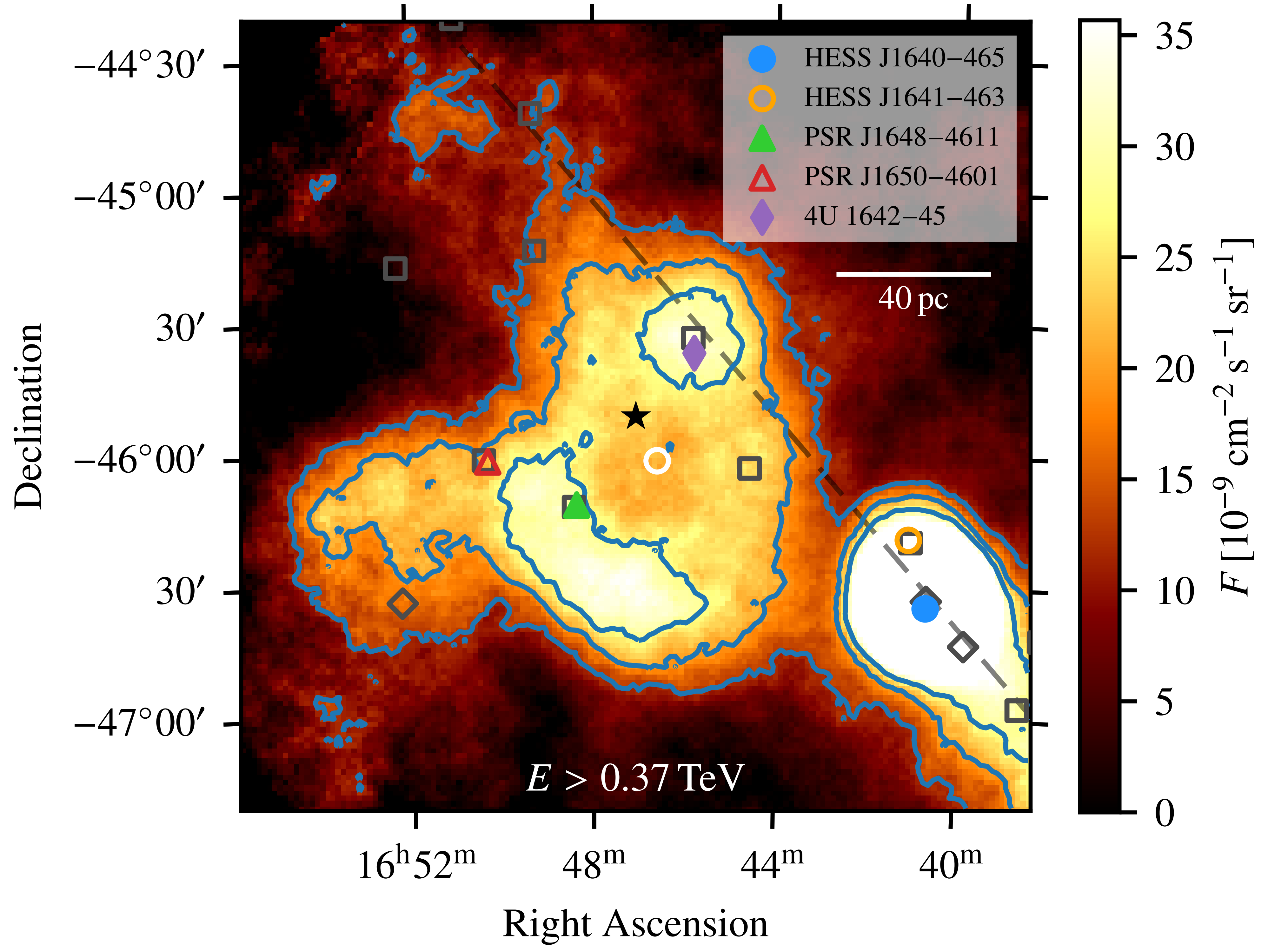
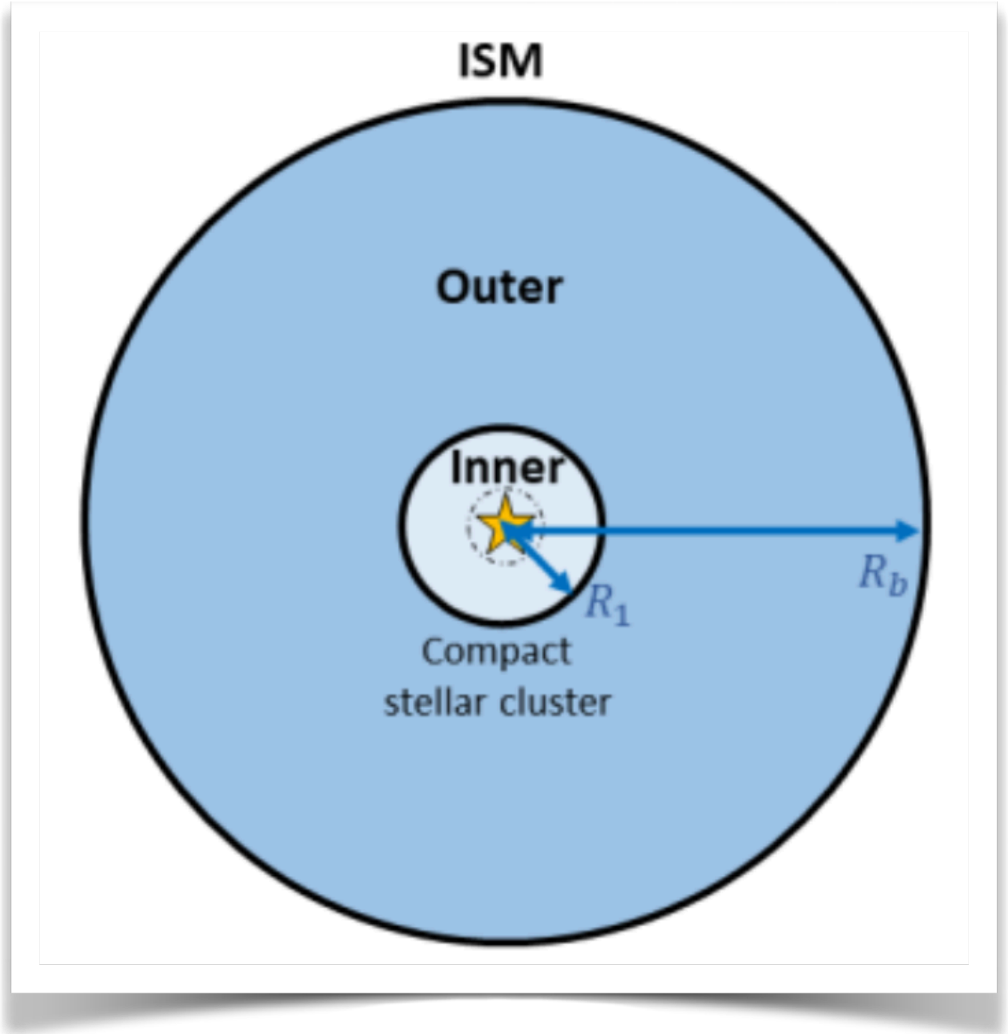
  - Exceeding γ-ray emission region, outer shock not observed at other wavelengths → not favoured (but reality is certainly more complex!)





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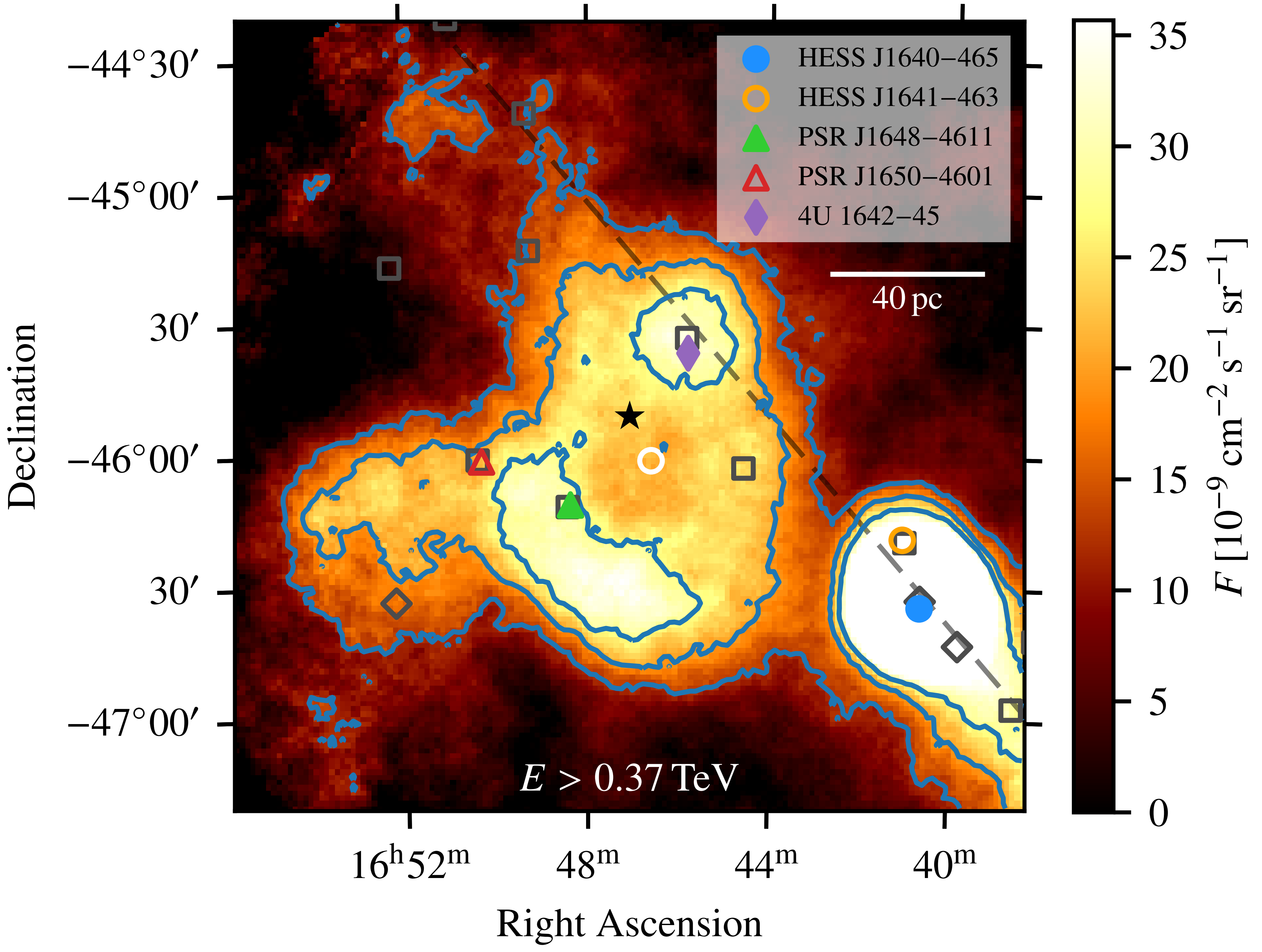
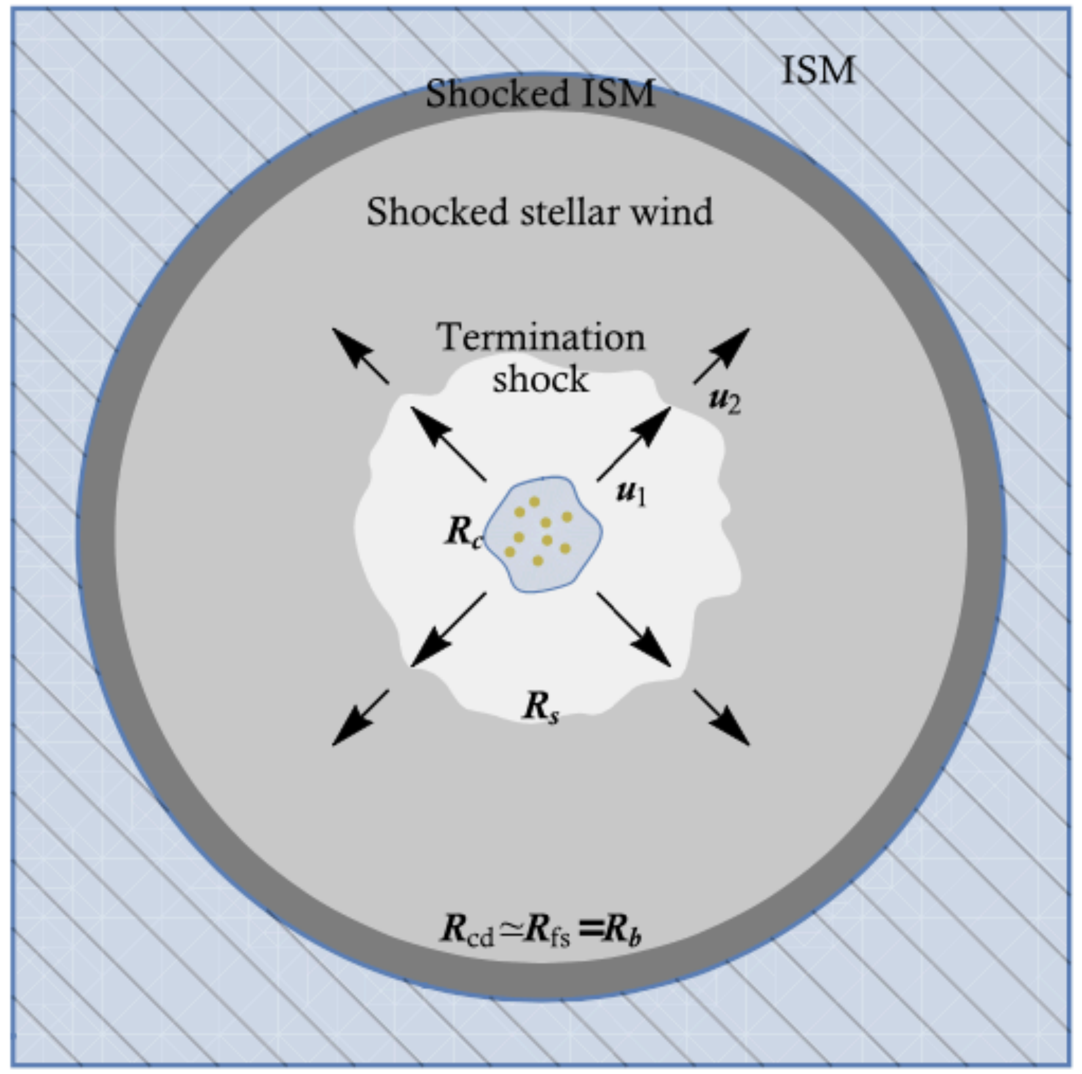
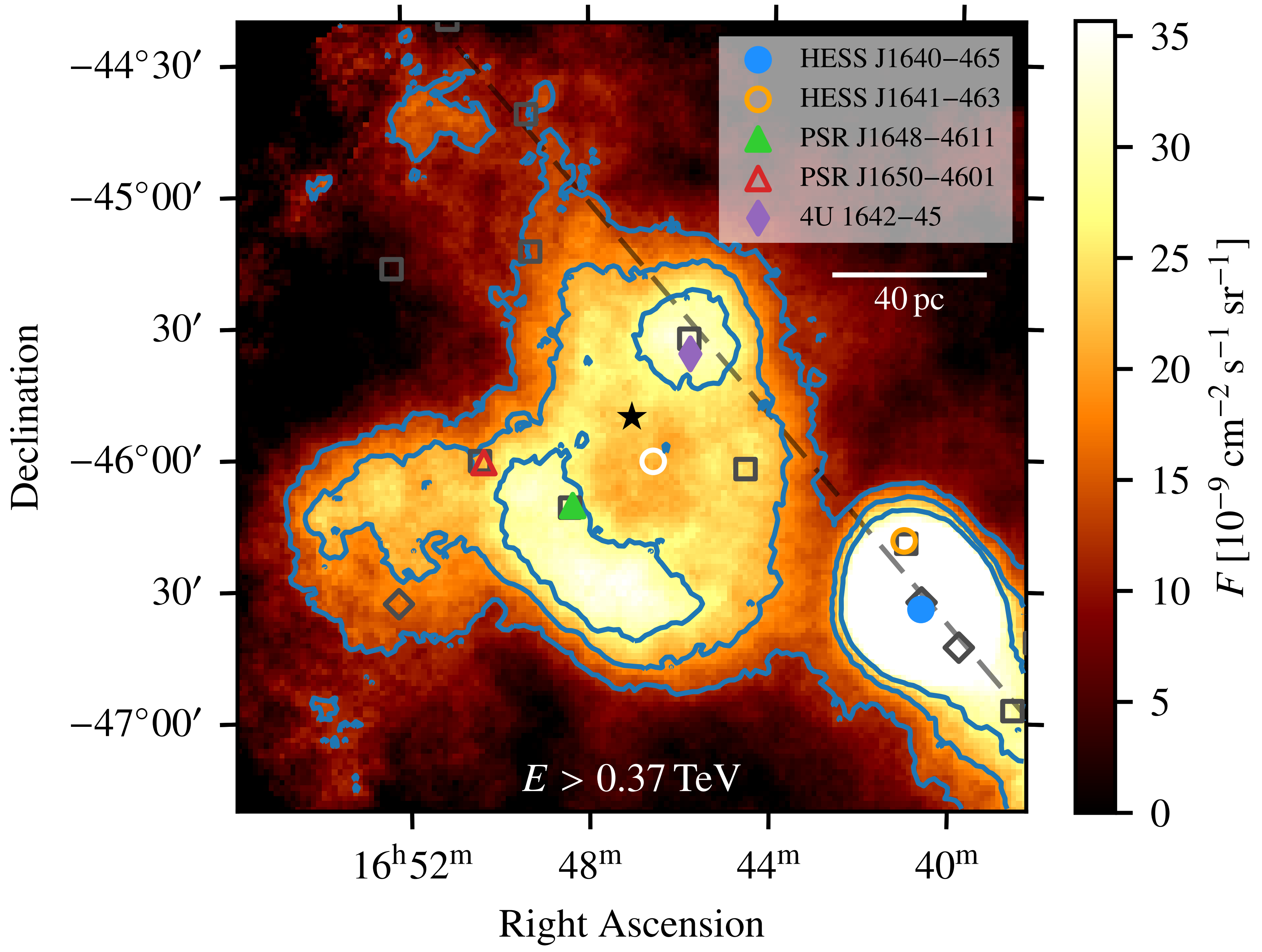
- Acceleration in turbulent superbubble
  - Basic superbubble models suggest $R_{SB} \sim \mathcal{O}(180\,\mathrm{pc})$
  - Exceeding γ-ray emission region, outer shock not observed at other wavelengths → not favoured (but reality is certainly more complex!)
- Acceleration at cluster wind termination shock
  - Basic superbubble models suggest $R_{TS} \sim \mathcal{O}(30\,\mathrm{pc})$
  - Matches radius of shell-like structure in γ-ray emission!
  - Hadronic scenario works energetically, but need $B \sim \mathcal{O}(50\mu\mathrm{G})$ to confine cosmic rays
  - Leptonic scenario also feasible! (need $B \lesssim 10\mu\mathrm{G}$ to "hide" synchrotron emission)

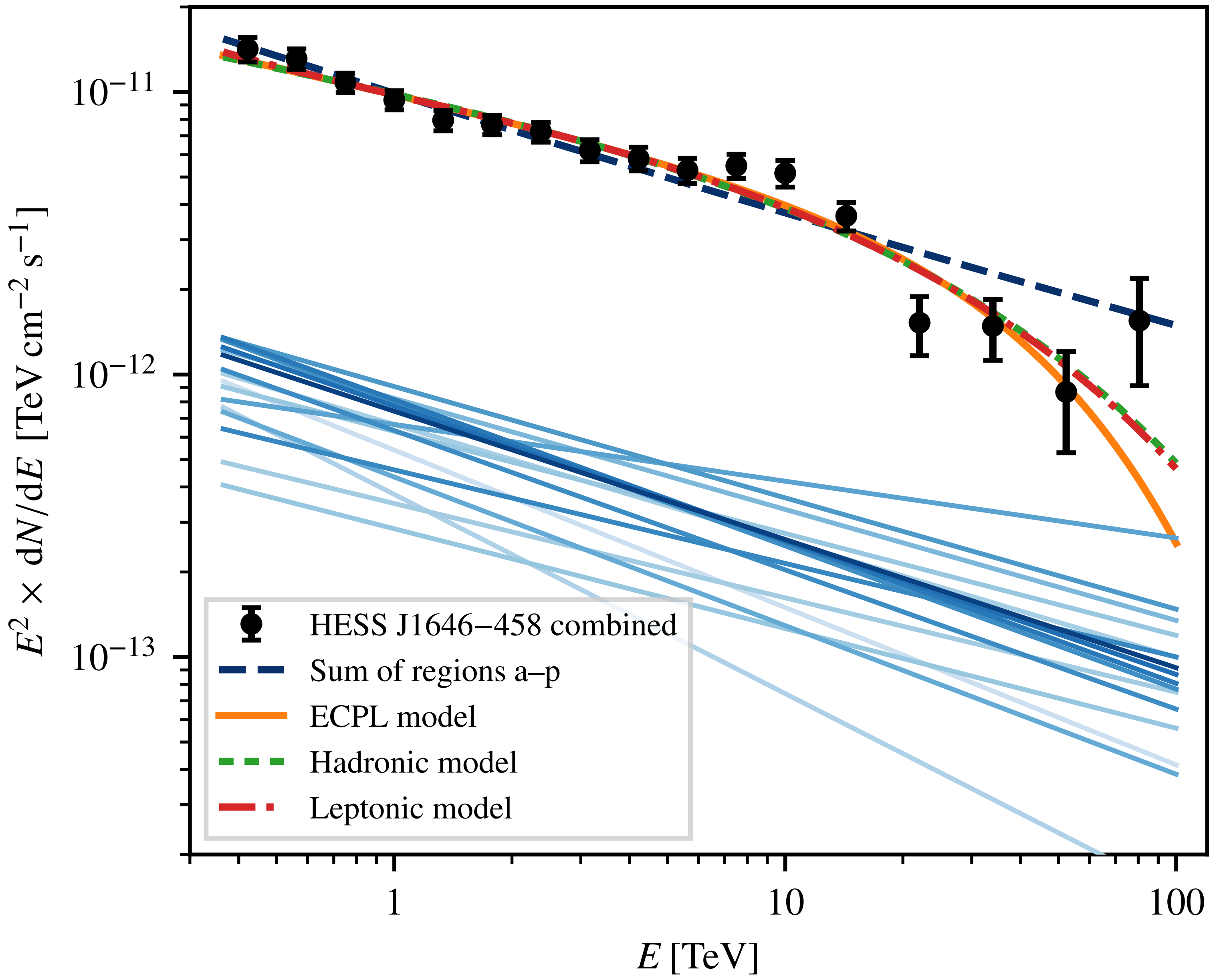




Conclusion

- HESS J1646–458
  - Complex, very extended morphology
  - Shell-like structure, no variation with energy
  - Combined spectrum extending to several ten TeV
- Westerlund 1
  - A powerful cosmic-ray accelerator!
  - Cannot determine acceleration site / mechanism unambiguously, but H.E.S.S. results provide important constraints
  - Intriguing connection between shell-like structure and wind termination shock?
- Young massive stellar clusters
  - Likely contribute to flux of Galactic cosmic rays…
  - …but we need a better understanding of the acceleration mechanism to assess how much → follow-up studies necessary!
- See paper (arXiv:2207.10921) for details!





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- [9] Kissmann, Astropart. Phys. **55**, 37 (2014) [arXiv:1401.4035]

Backup slides

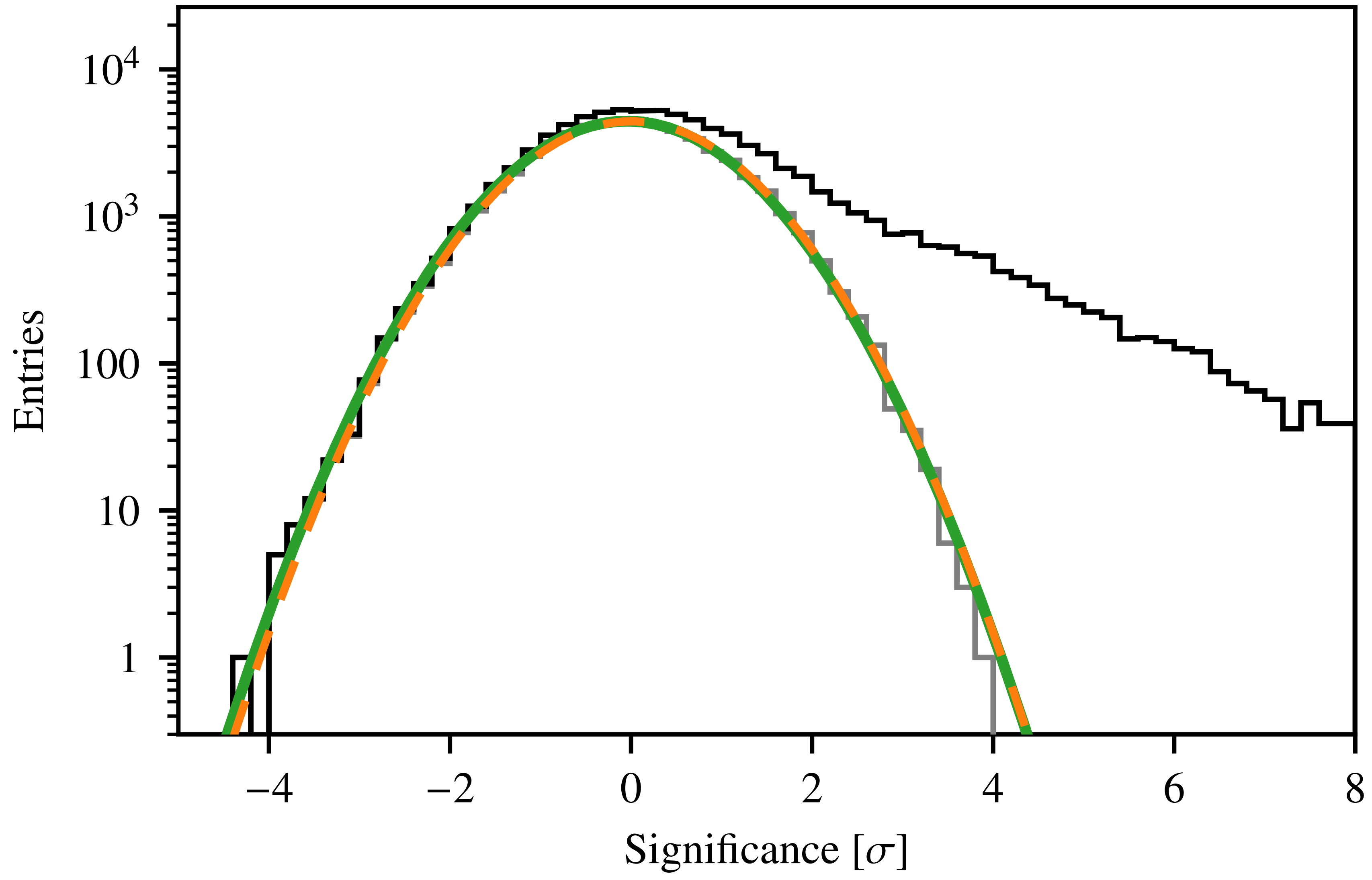
Distance to Westerlund 1

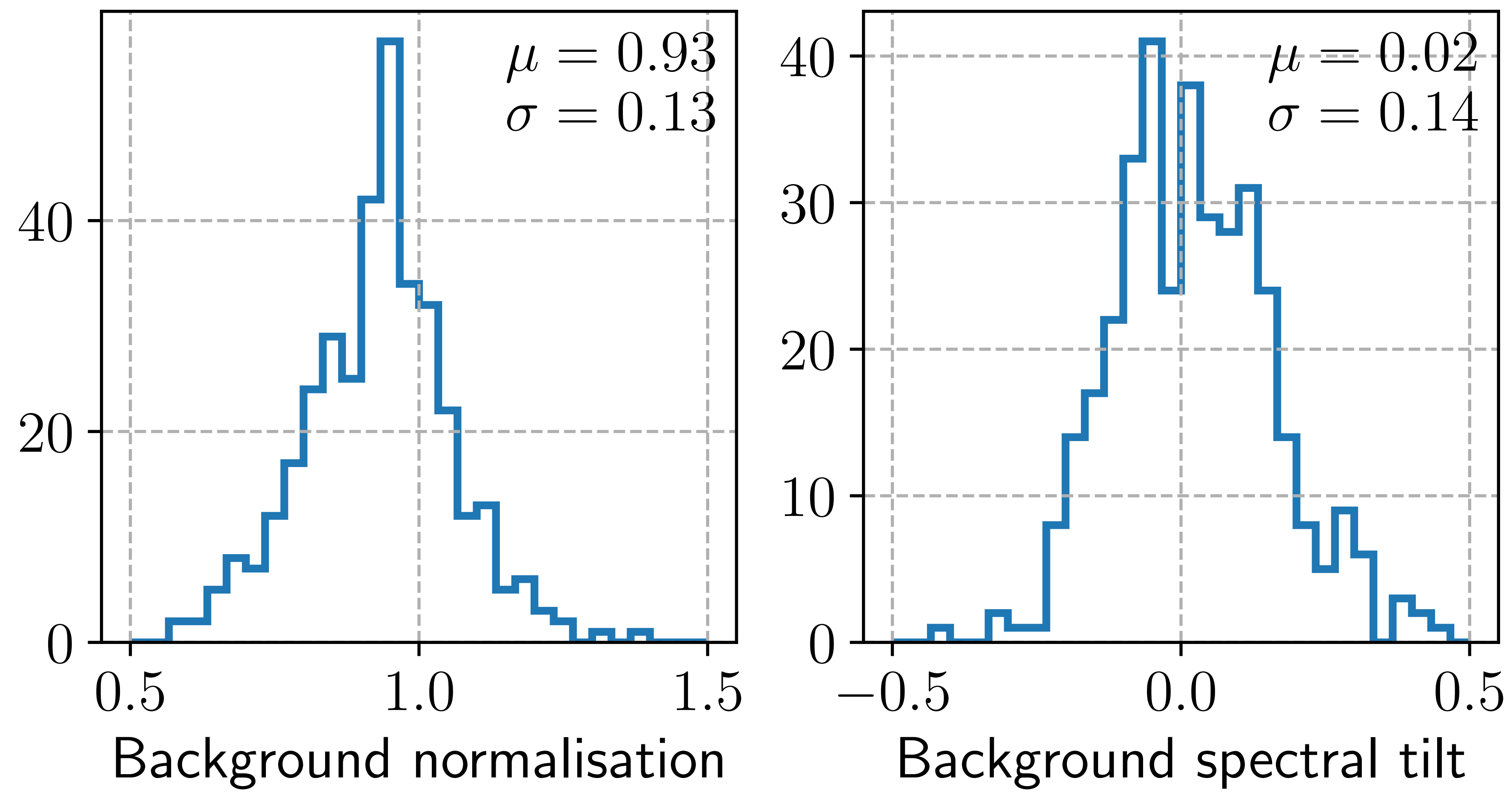
Reference	Distance (kpc)	Method
Clark et al. 2005	< 5.5	Yellow Hypergiants
Crowther et al. 2006	$5.0^{+0.5}_{-1.0}$	Wolf-Rayet stars
Kothes & Dougherty 2007	3.9 ± 0.7	H I observations
Brandner et al. 2008	3.55 ± 0.17	Near-infrared observations, colour-magnitude diagram
Aghakhanloo et al. 2020	$2.6^{+0.6}_{-0.4}$	Gaia (DR2) parallaxes
Aghakhanloo et al. 2021	$2.8^{+0.7}_{-0.6}$	Gaia (EDR3) parallaxes
Davies & Beasor 2019	$3.87^{+0.95}_{-0.64}$	Gaia (DR2) parallaxes, smaller (cleaner?) sample
Rate et al. 2020	$3.78^{+0.56}_{-0.46}$	Gaia (DR2) parallaxes of WR stars
Beasor et al. 2021	$4.12^{+0.66}_{-0.33}$	Gaia (EDR3) parallaxes
Negueruela et al. 2022	$4.23^{+0.23}_{-0.21}$	Gaia (EDR3) parallaxes

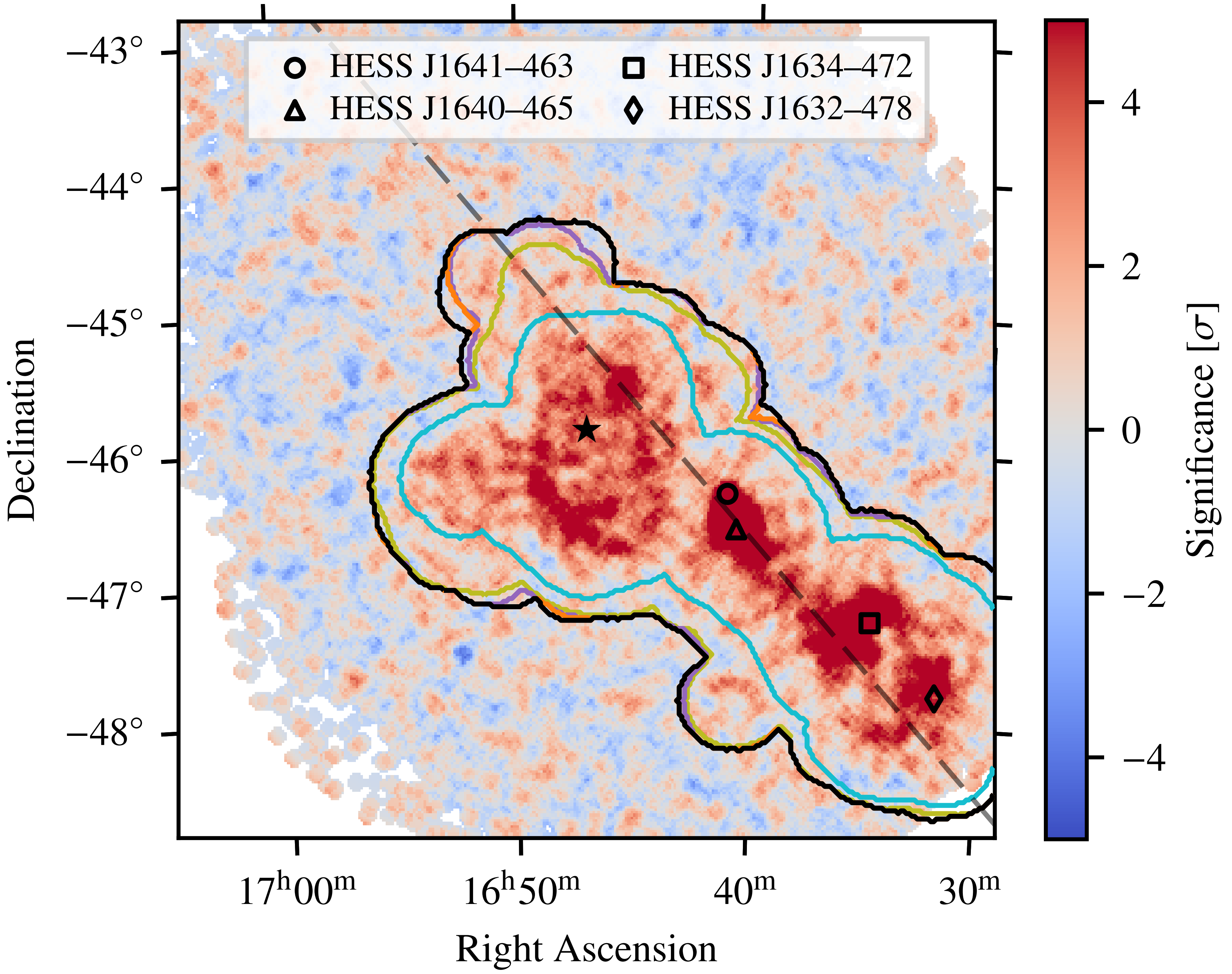
- A matter of ongoing debate
- Most estimates agree with ~4 kpc

Fit of hadronic background model

- Construction of model described in [6]
- Adjust model for each run via two parameters:
  - Background normalisation (global scaling)
  - Background spectral tilt (factor $(E/E_0)^{-\delta}$)
- Fit background model outside exclusion region
- Derive exclusion region with iterative procedure
- Resulting significance distribution indicates good agreement

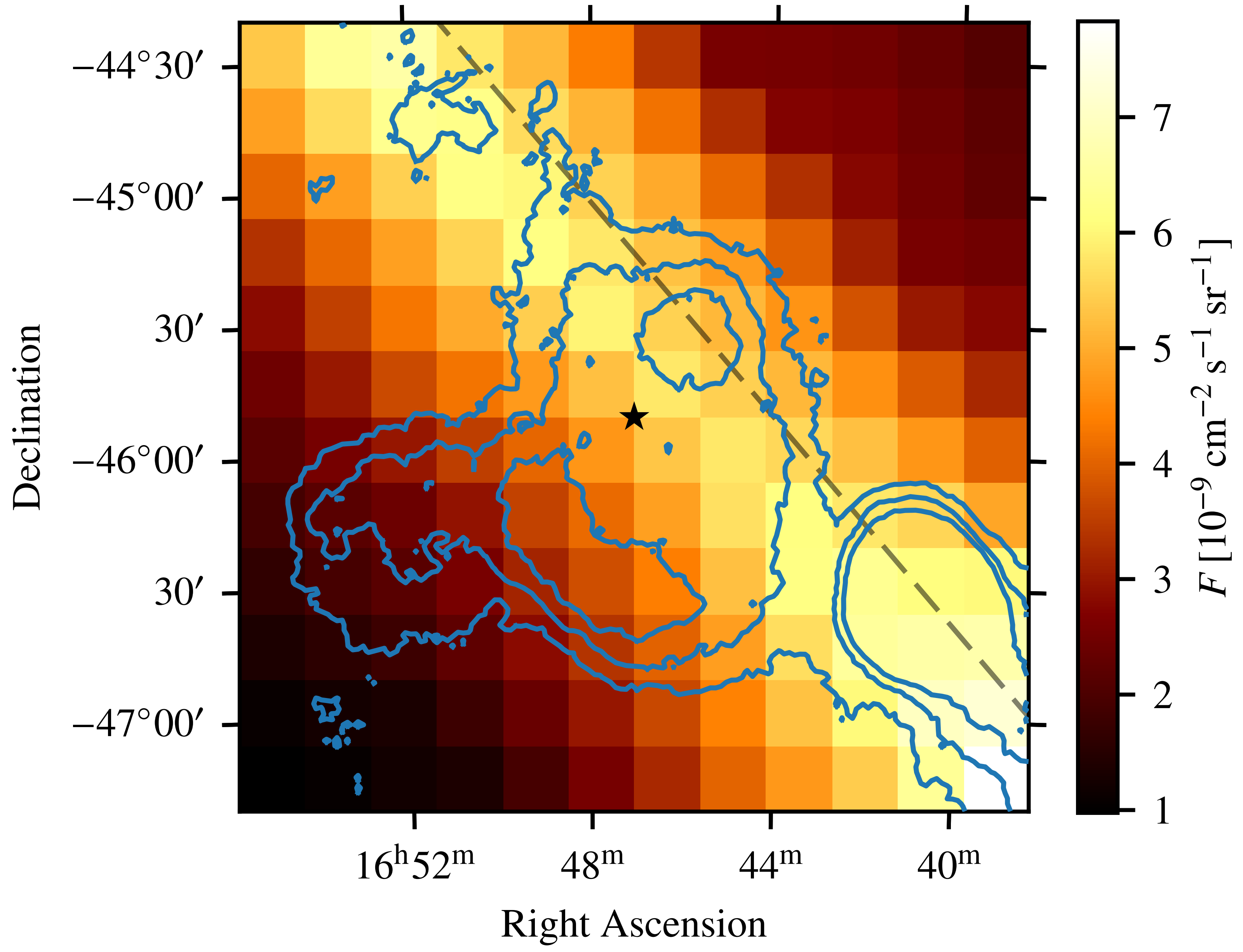


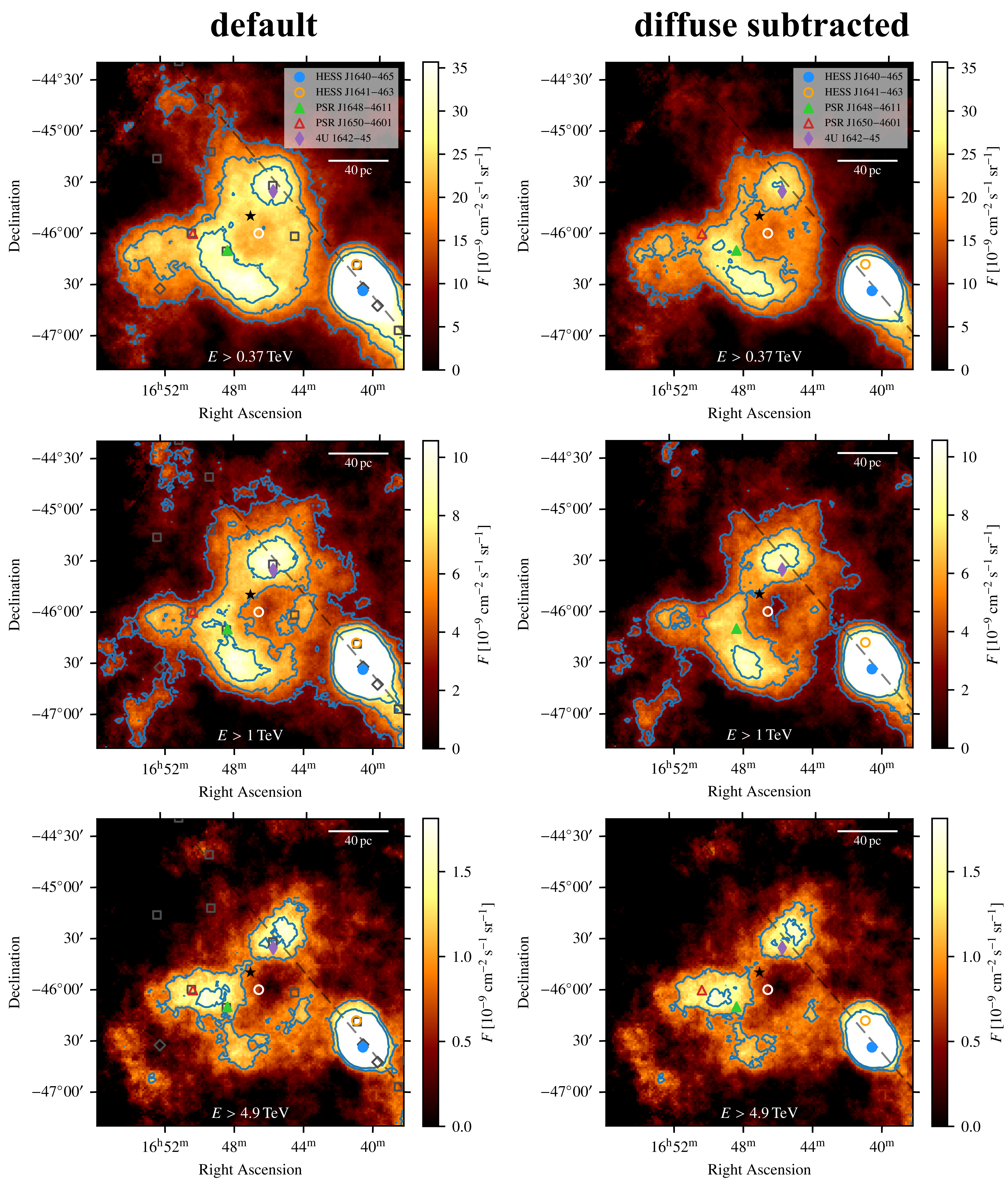




Galactic diffuse emission

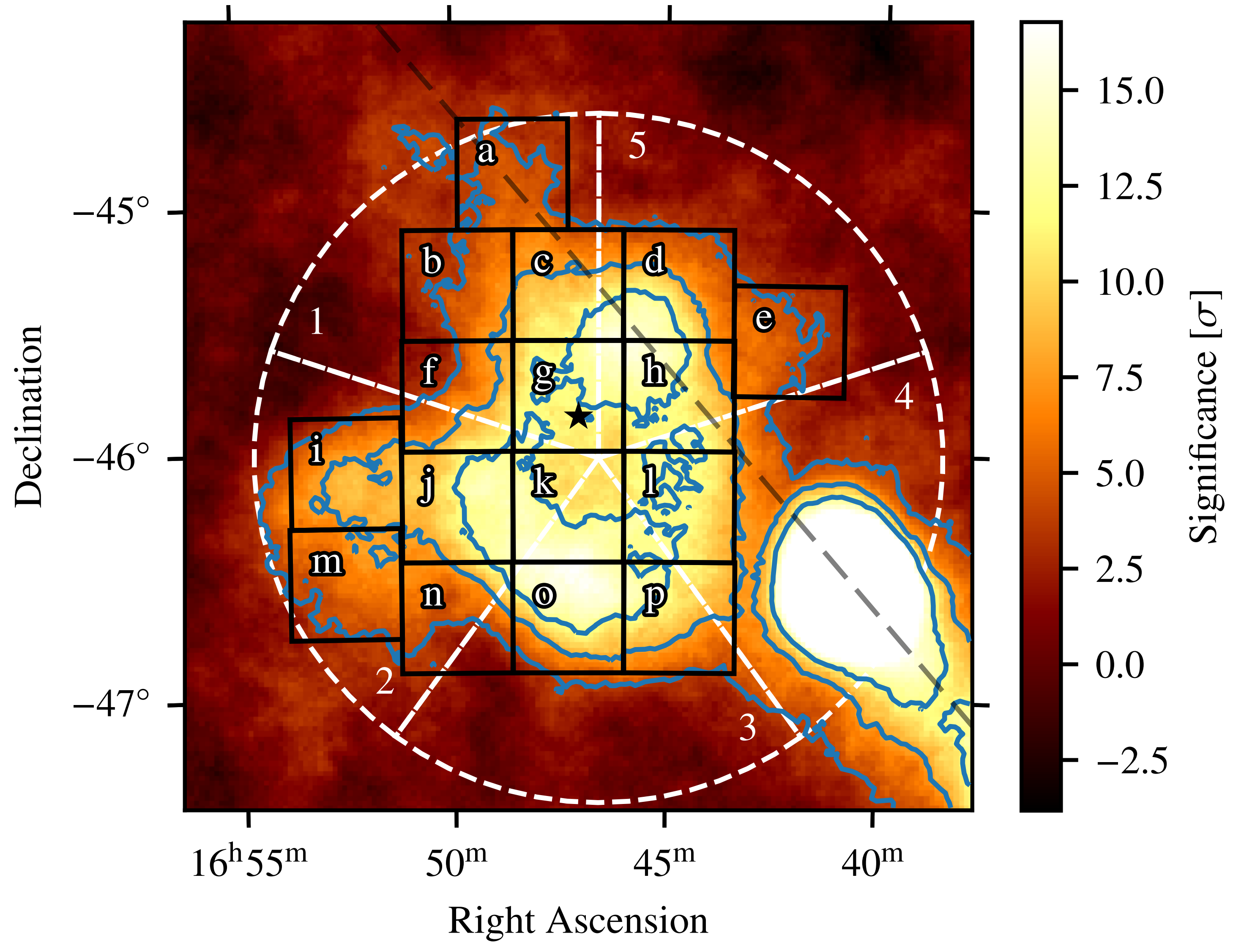
- Likely contributes to emission, but is difficult to estimate
- Use prediction from PICARD propagation code [9]
- **Absolute flux level is very uncertain!**
- **Shell-like structure not affected**

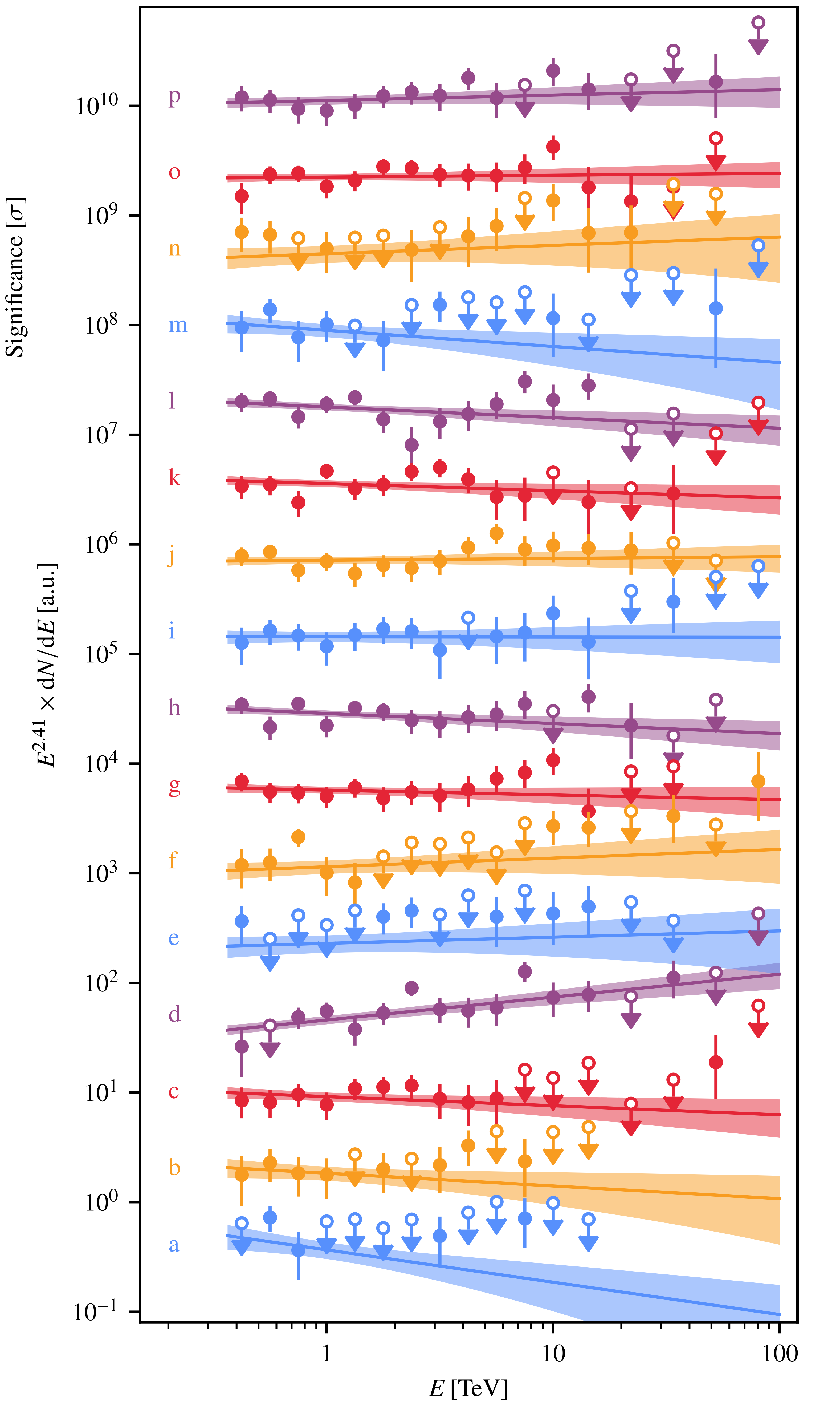




Signal region energy spectra

- Very similar spectra in all regions
- Only significant deviation: region "d"





Signal region	Excess events	Significance	Significance ($E > 4.9$ TeV)	ϕ_0 (10^{-13} TeV^{-1}cm^{-2}s^{-1})	Γ	$\sqrt{\Delta TS}$
a	396.1	5.3σ	0.9σ	3.76 ± 0.66	2.71 ± 0.18	5.9
b	454.9	5.6σ	1.7σ	4.34 ± 0.64	2.53 ± 0.13	7.5
c	901.8	10.3σ	2.8σ	6.33 ± 0.58	2.49 ± 0.08	12.3
d	1014.0	10.8σ	7.7σ	6.66 ± 0.58	2.20 ± 0.06	16.1
e	430.7	4.7σ	2.9σ	2.84 ± 0.51	2.35 ± 0.12	6.7
f	648.9	7.7σ	4.0σ	4.60 ± 0.64	2.33 ± 0.11	10.0
g	1238.5	13.5σ	6.0σ	7.41 ± 0.54	2.45 ± 0.07	16.1
h	1409.2	14.5σ	4.6σ	8.14 ± 0.54	2.50 ± 0.06	17.3
i	653.4	9.0σ	4.0σ	6.65 ± 0.71	2.41 ± 0.09	11.4
j	1229.0	14.0σ	6.8σ	9.07 ± 0.63	2.39 ± 0.06	17.7
k	1246.4	13.2σ	3.6σ	7.73 ± 0.54	2.48 ± 0.06	16.5
l	1405.7	14.1σ	6.3σ	7.95 ± 0.54	2.51 ± 0.06	16.9
m	469.5	6.8σ	1.7σ	5.40 ± 0.73	2.56 ± 0.13	8.2
n	415.4	5.1σ	3.5σ	3.49 ± 0.62	2.33 ± 0.13	7.4
o	1259.2	14.1σ	5.9σ	8.23 ± 0.57	2.39 ± 0.06	17.7
p	996.7	10.5σ	4.0σ	6.29 ± 0.55	2.36 ± 0.07	14.7

Gas maps for alternative distances

$d \approx 3.9$ kpc | $d \approx 3.3$ kpc | $d \approx 2.7$ kpc