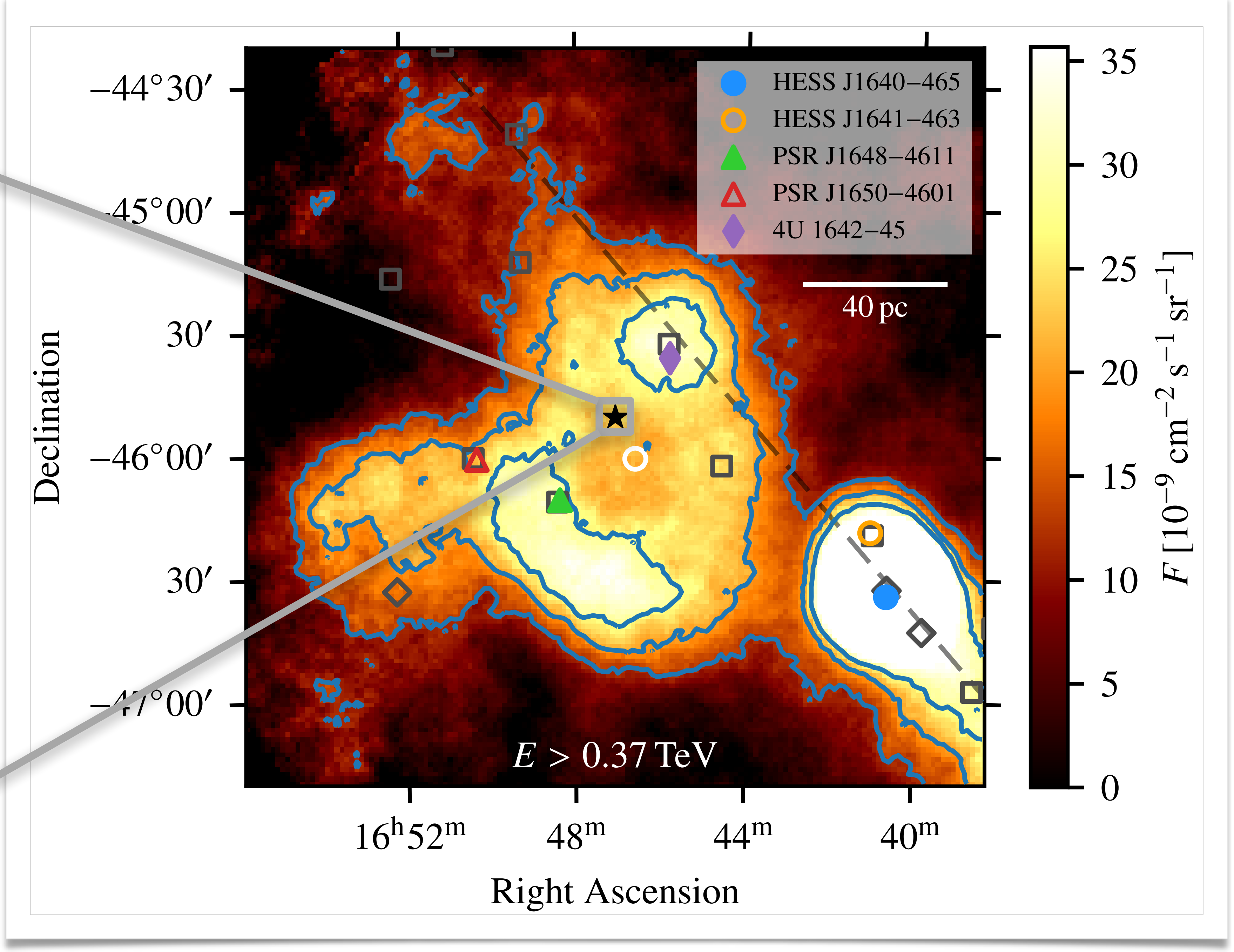
Morphological studies of star clusters using Imaging Atmospheric Cherenkov Telescopes

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

The massive star cluster Westerlund 1



Credit: H.E.S.S. Collaboration, A&A 666, A124 (2022)

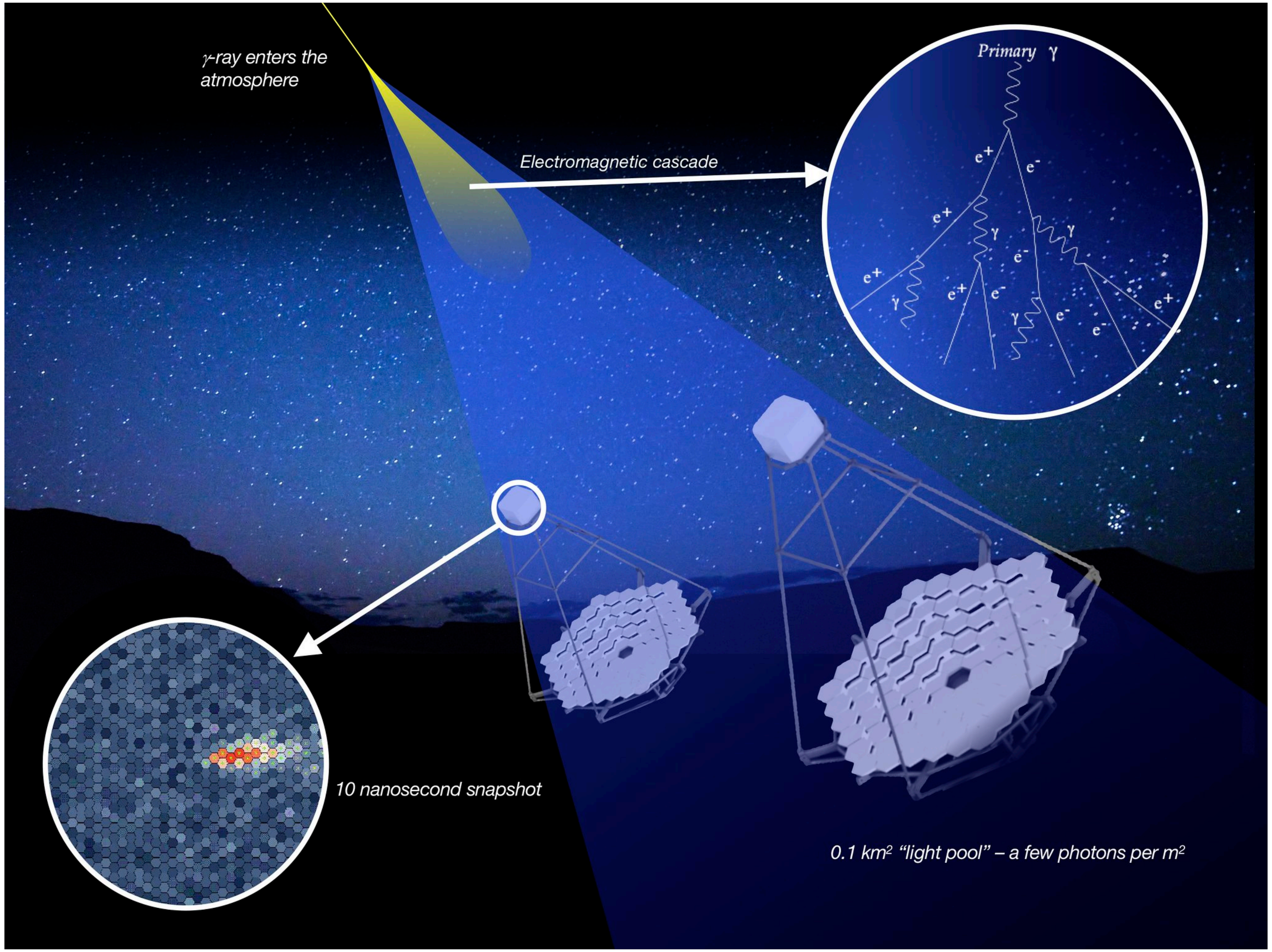
Lars Mohrmann

Max Planck Institute for Nuclear Physics, Heidelberg

lars.mohrmann@mpi-hd.mpg.de — https://lmohrmann.github.io

2nd HONEST workshop — PeVatrons and their environments — November 30, 2022

Imaging Atmospheric Cherenkov Telescopes (IACTs)



- Disadvantages
  - limited duty cycle (10-15%)
  - limited field of view (few degree)
  - ***cannot compete with wide-field instruments in terms of exposure at ultra-high energies***
- Advantages
  - low energy threshold ($\mathcal{O}(100\,\mathrm{GeV})$)
  - high angular resolution ($\lesssim 0.1^\circ$ at 1 TeV)
  - ***ideal for detailed morphological studies***

Star clusters as cosmic-ray sources

- Proposed a long time ago

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

Service d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette Cedex, France

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%

Star clusters as cosmic-ray sources

- Proposed a long time ago
- Renewed interest in recent years

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

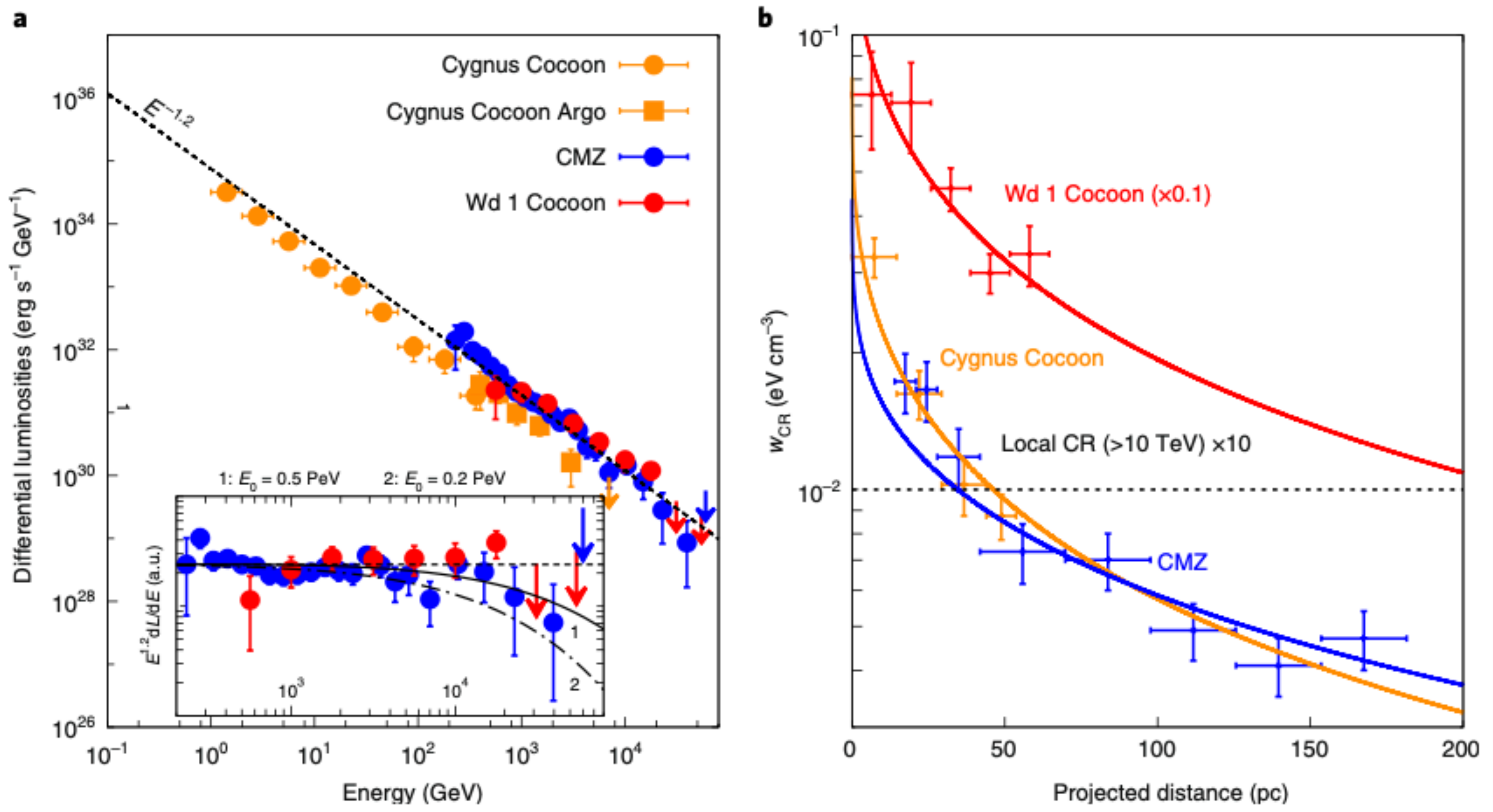
nature astronomy

ARTICLES

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

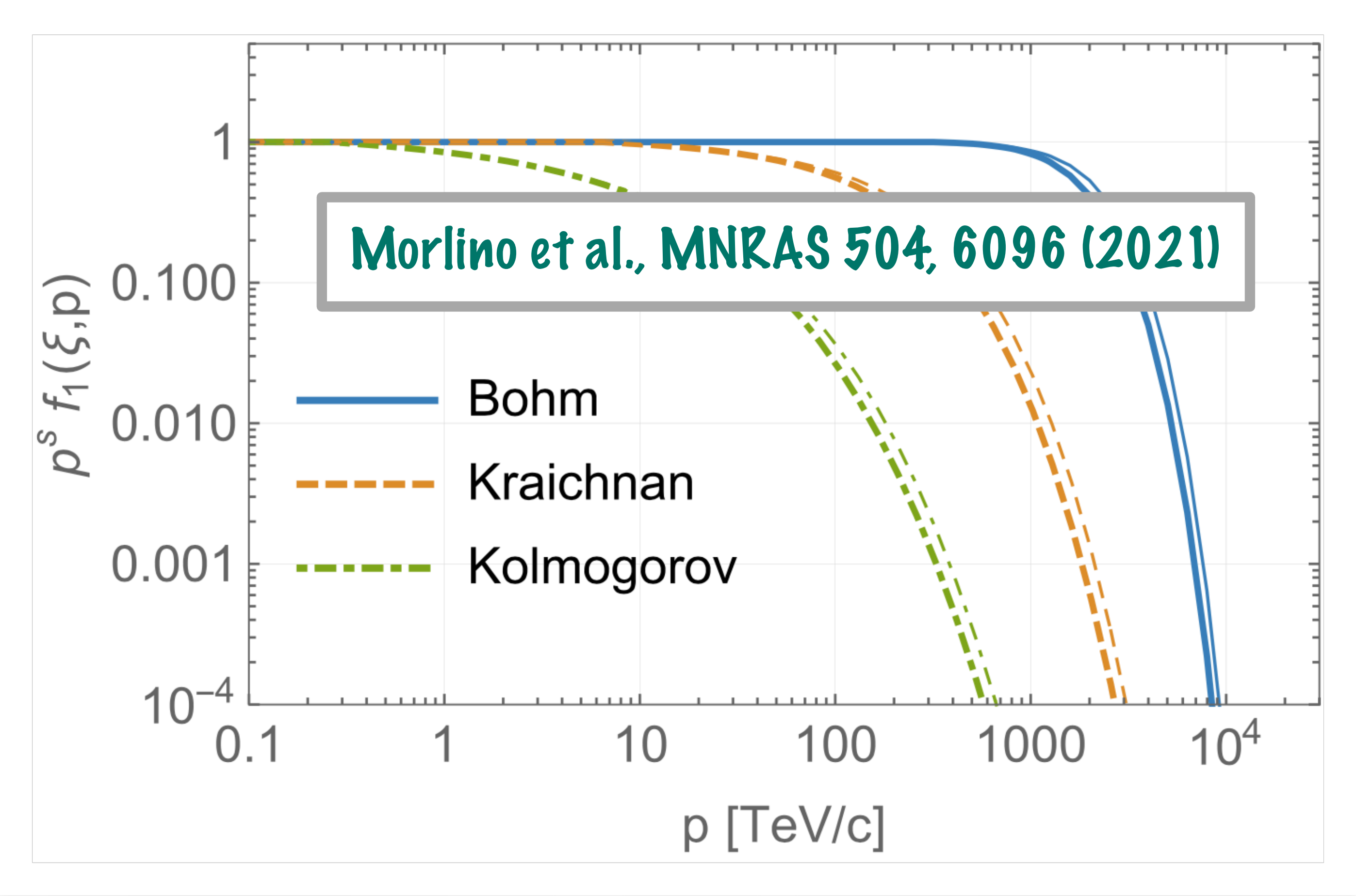
Massive stars as major factories of Galactic cosmic rays

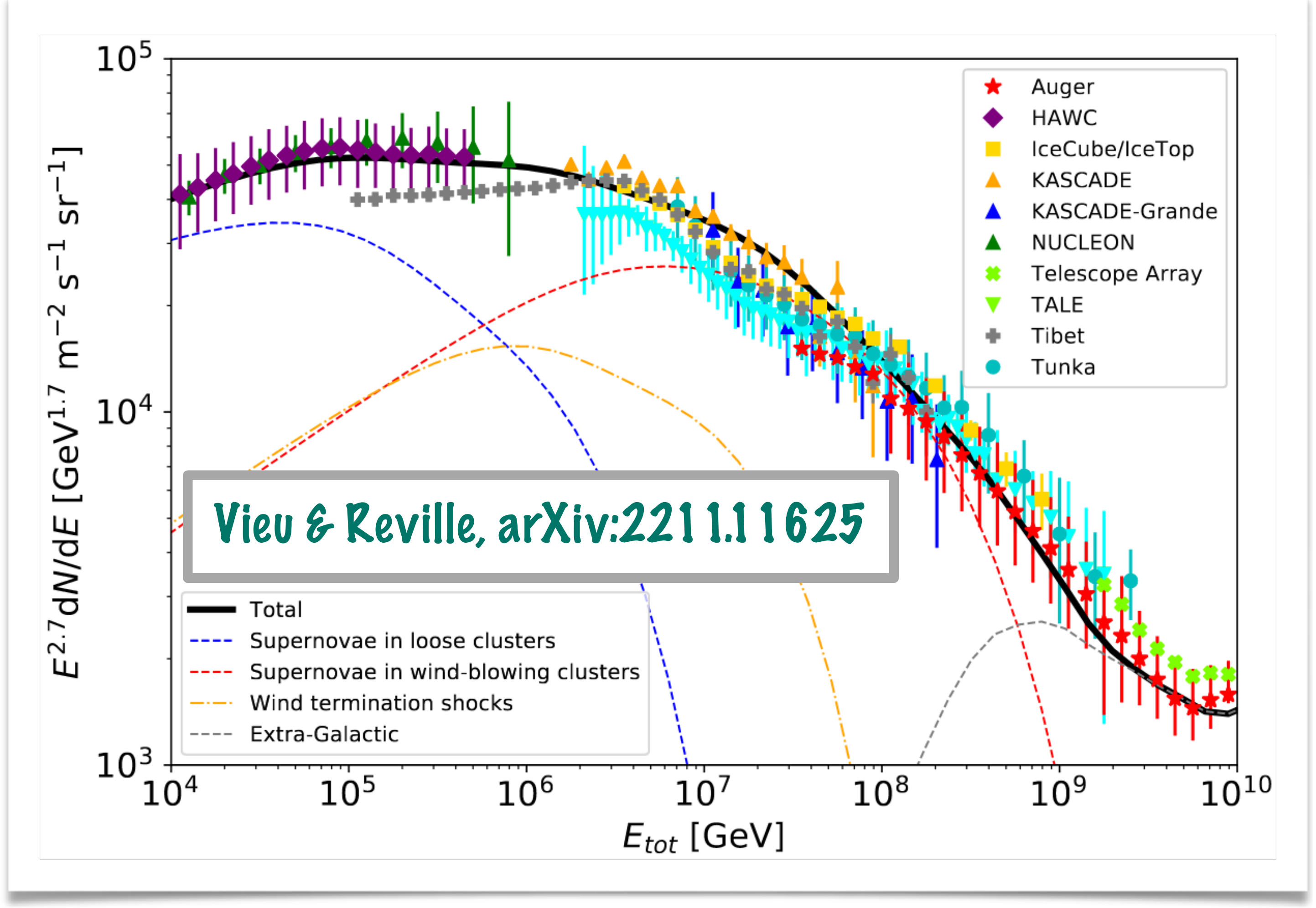
Felix Aharonian[1,2,3,7], Ruizhi Yang[2,7*] and Emma de Oña Wilhelmi[4,5,6,7]

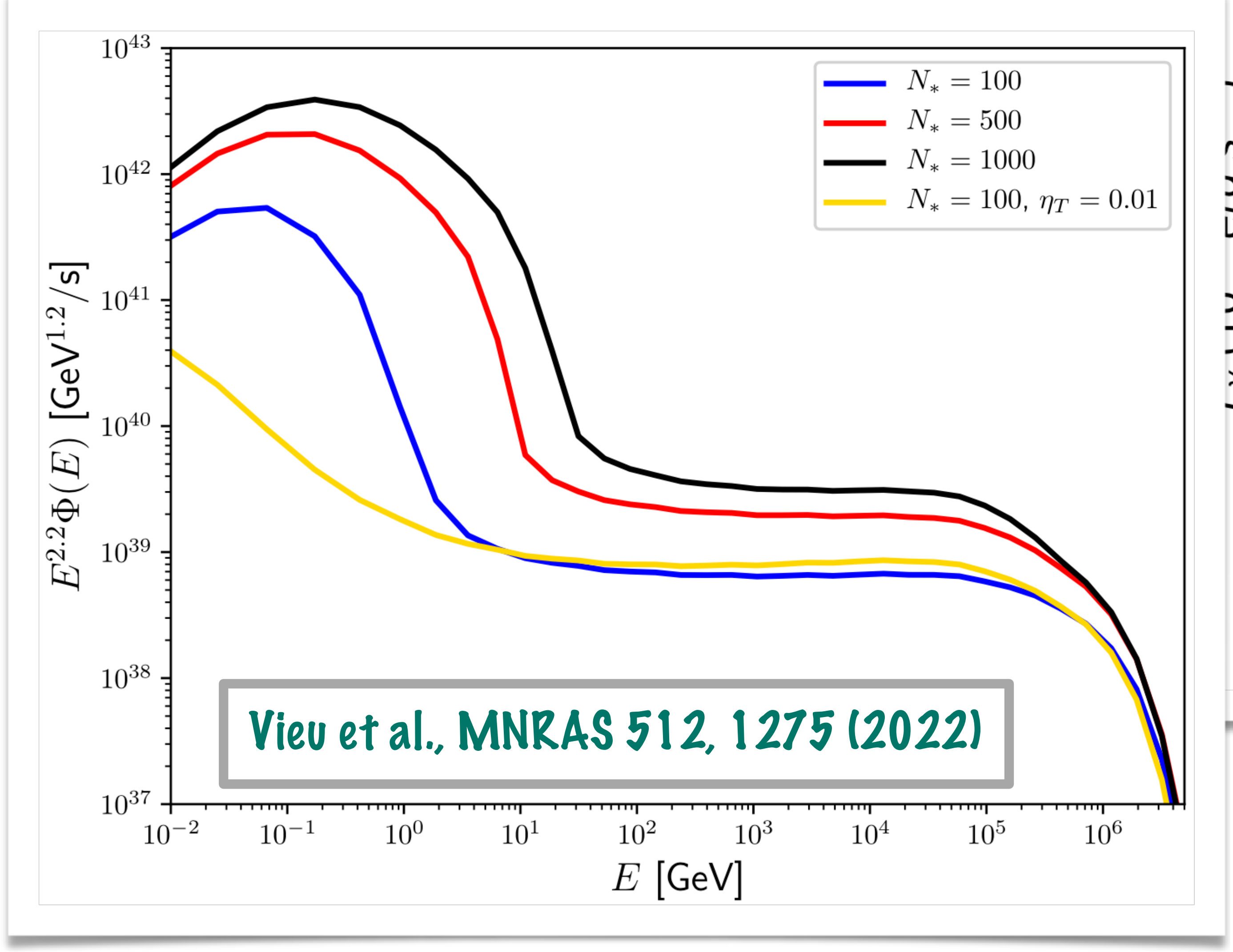


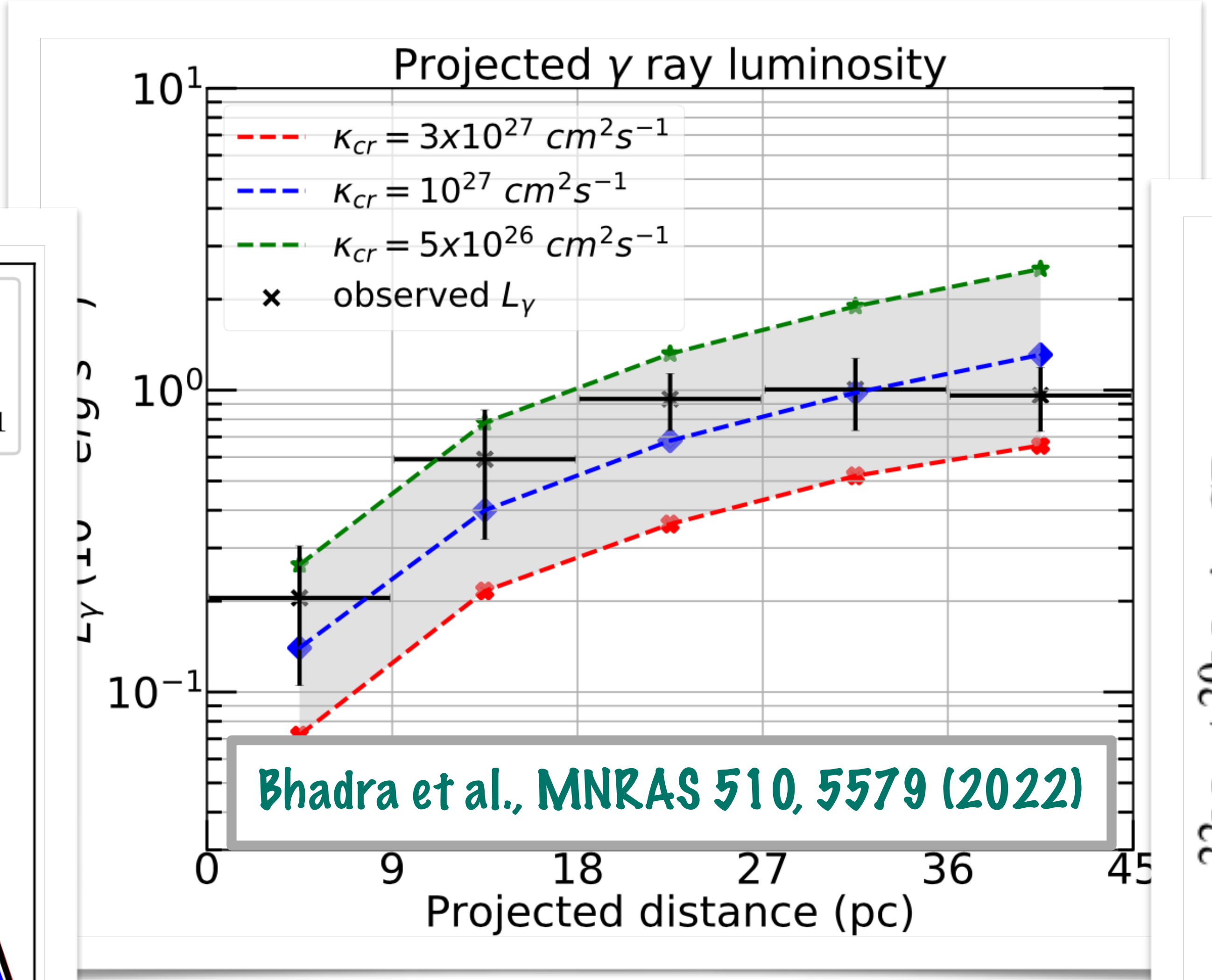
Star clusters as cosmic-ray sources

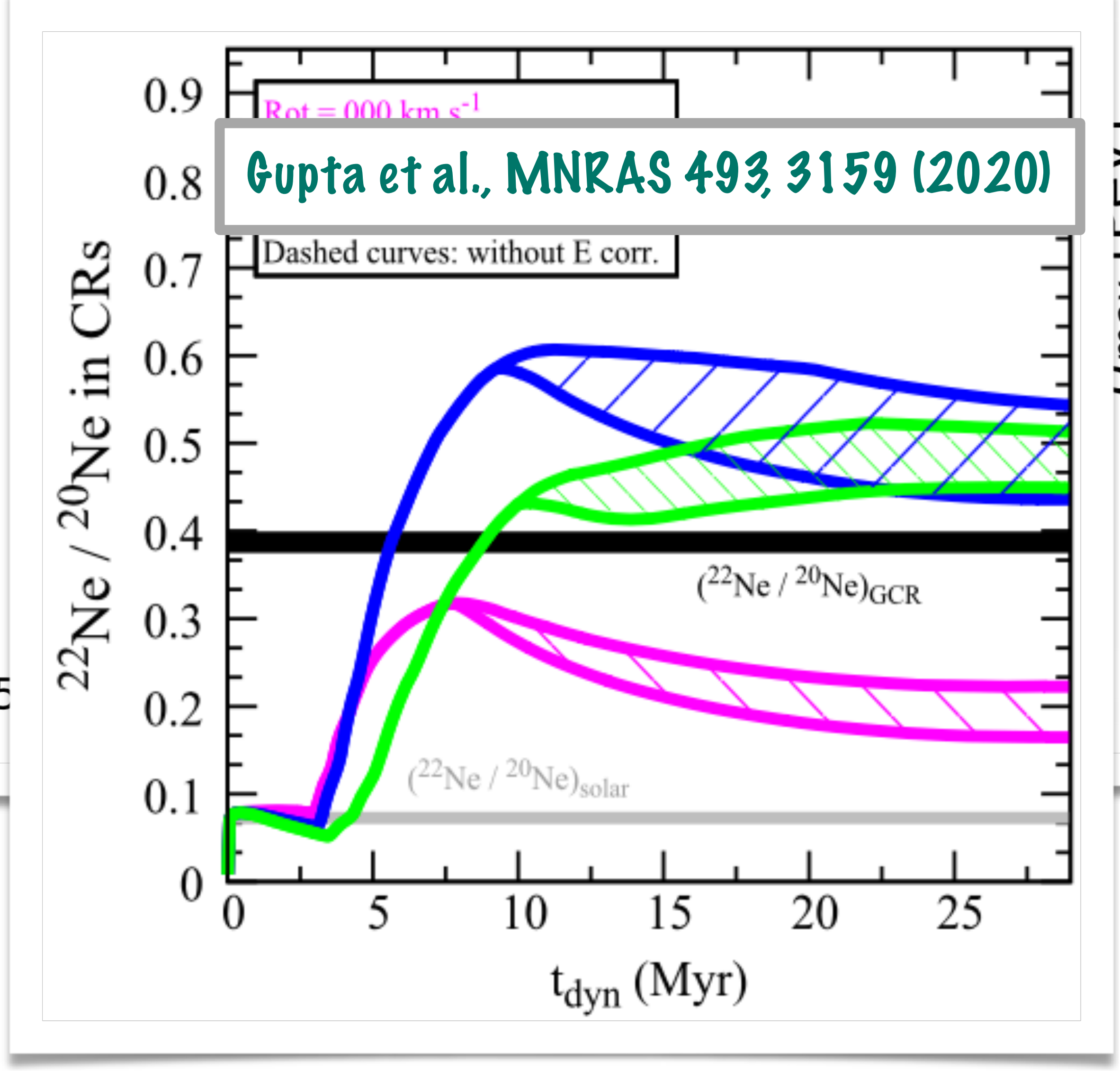
- Proposed a long time ago
- Renewed interest in recent years
- Many (recent) predictions

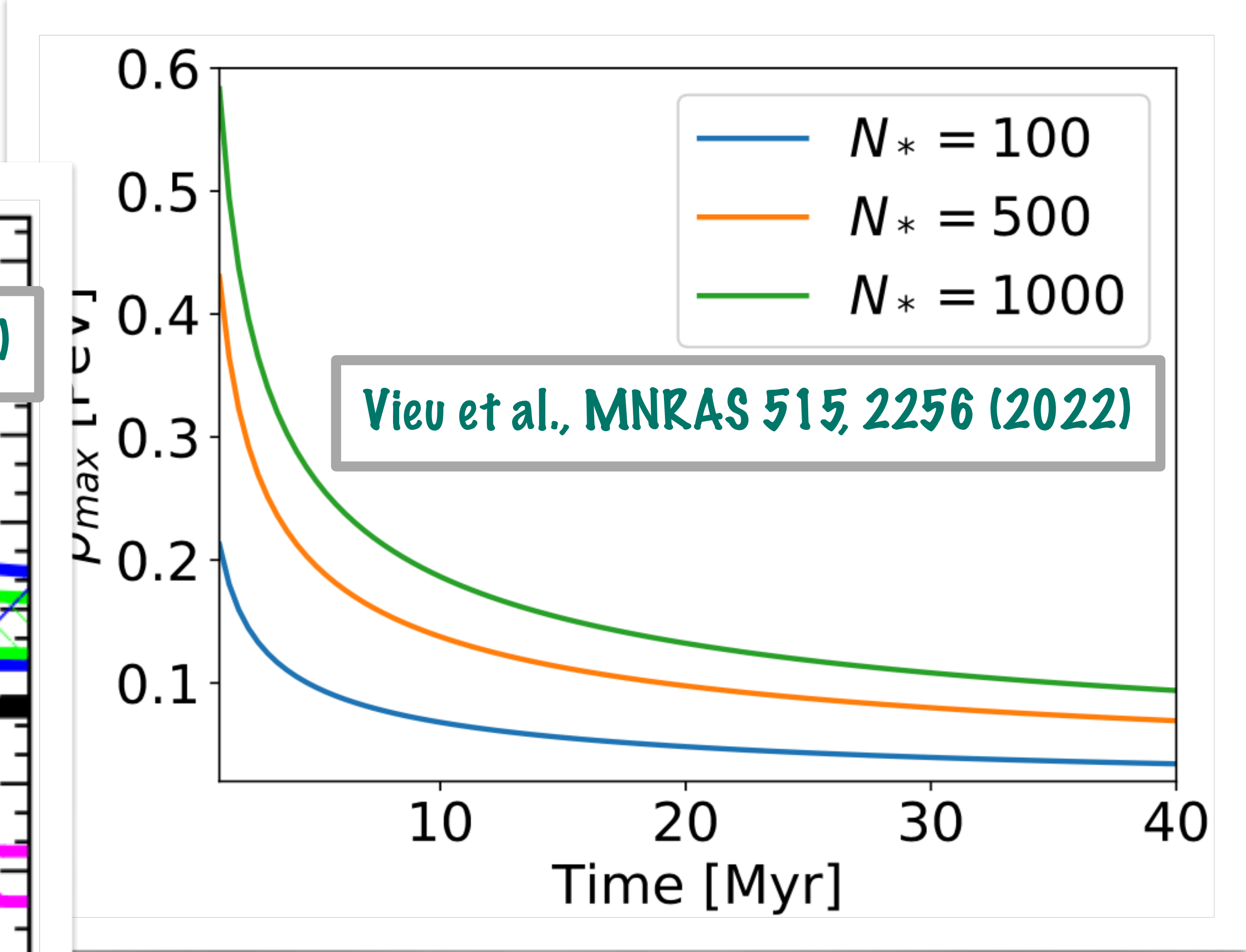








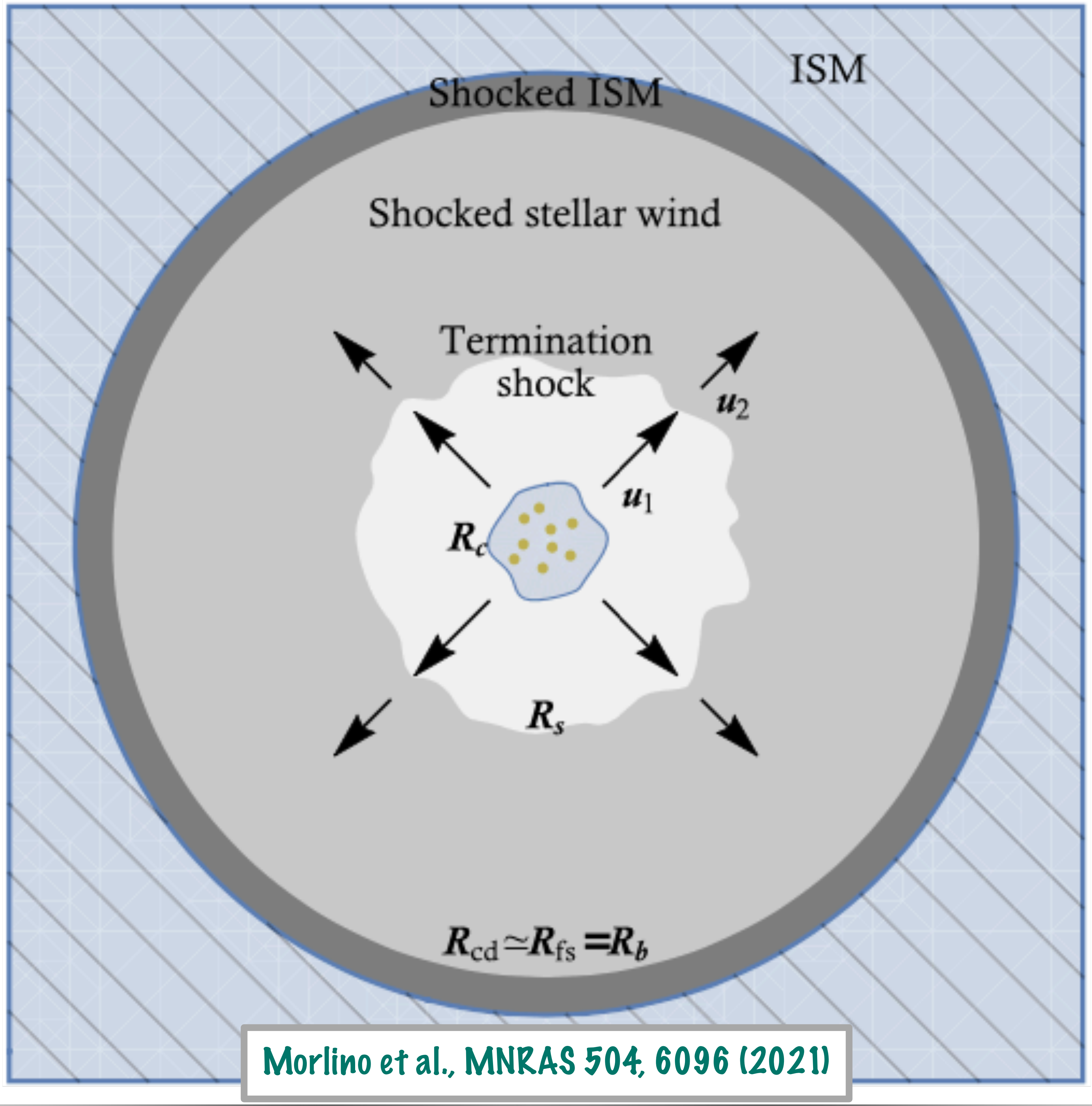




see following talk by G. Morlino for more details!

Star clusters as cosmic-ray sources

- Proposed a long time ago
- Renewed interest in recent years
- Many (recent) predictions
  - ***young, massive*** clusters most promising
  - compact clusters:
    formation of ***superbubble*** & ***wind termination shock***
  - several possible ***acceleration sites***:
    central cluster, termination shock, turbulence in bubble, …
  - for massive clusters: termination shock at tens of pc,
    entire bubble can be > 100 pc
    → expect ***extended gamma-ray emission***
  - contributions from ***stellar winds*** & ***supernovae***
    to be understood

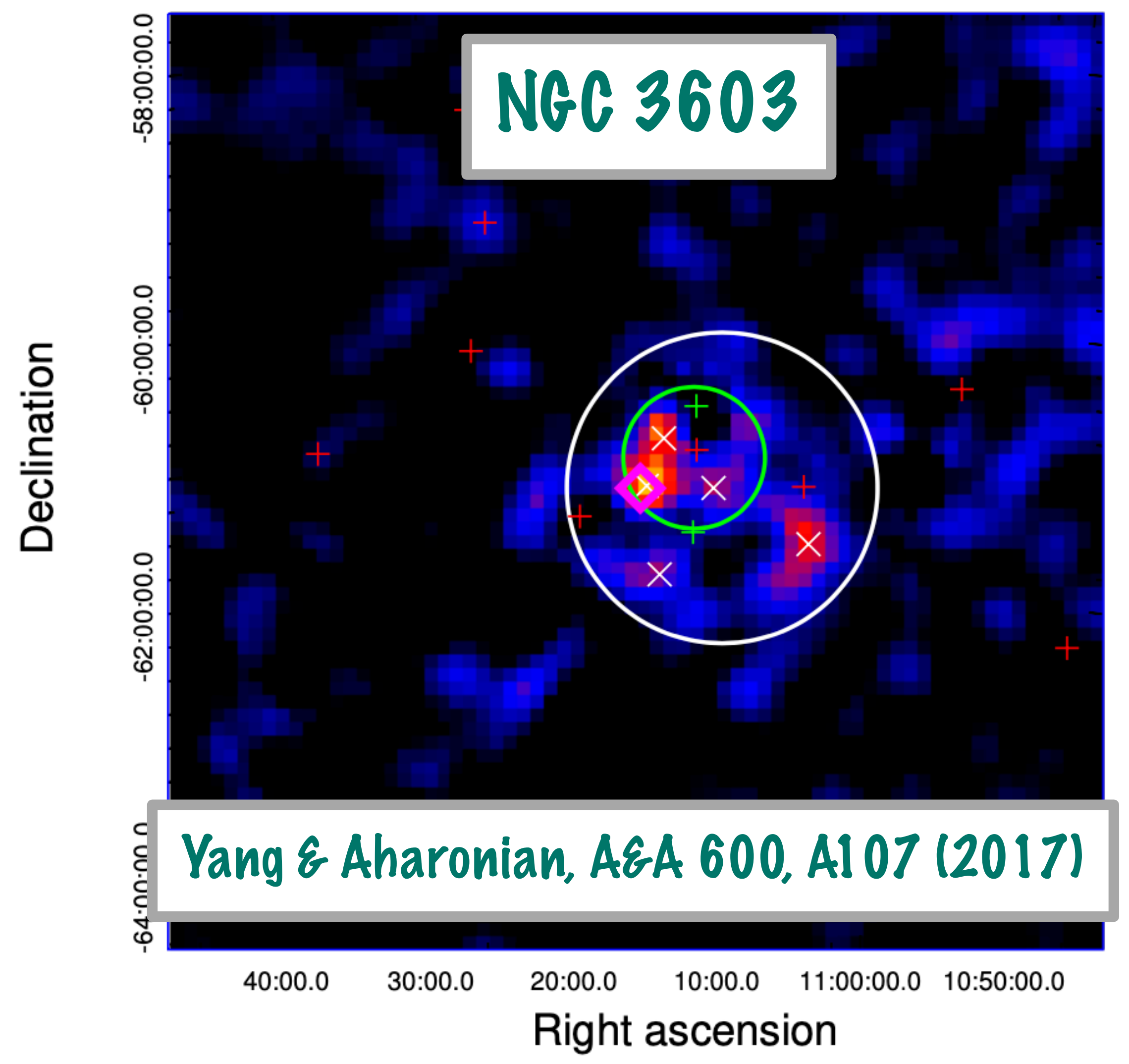


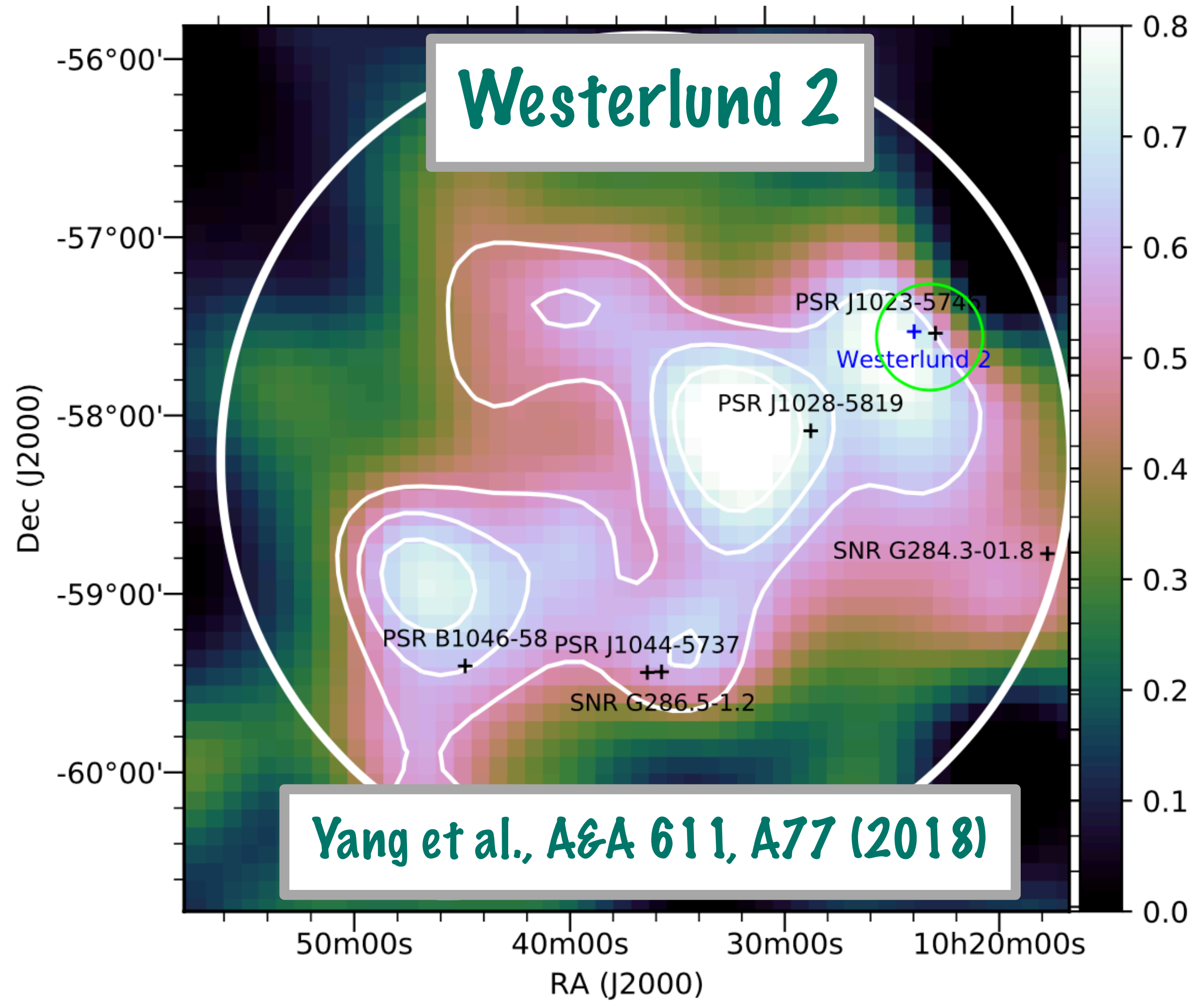
Morlino et al., MNRAS 504, 6096 (2021)

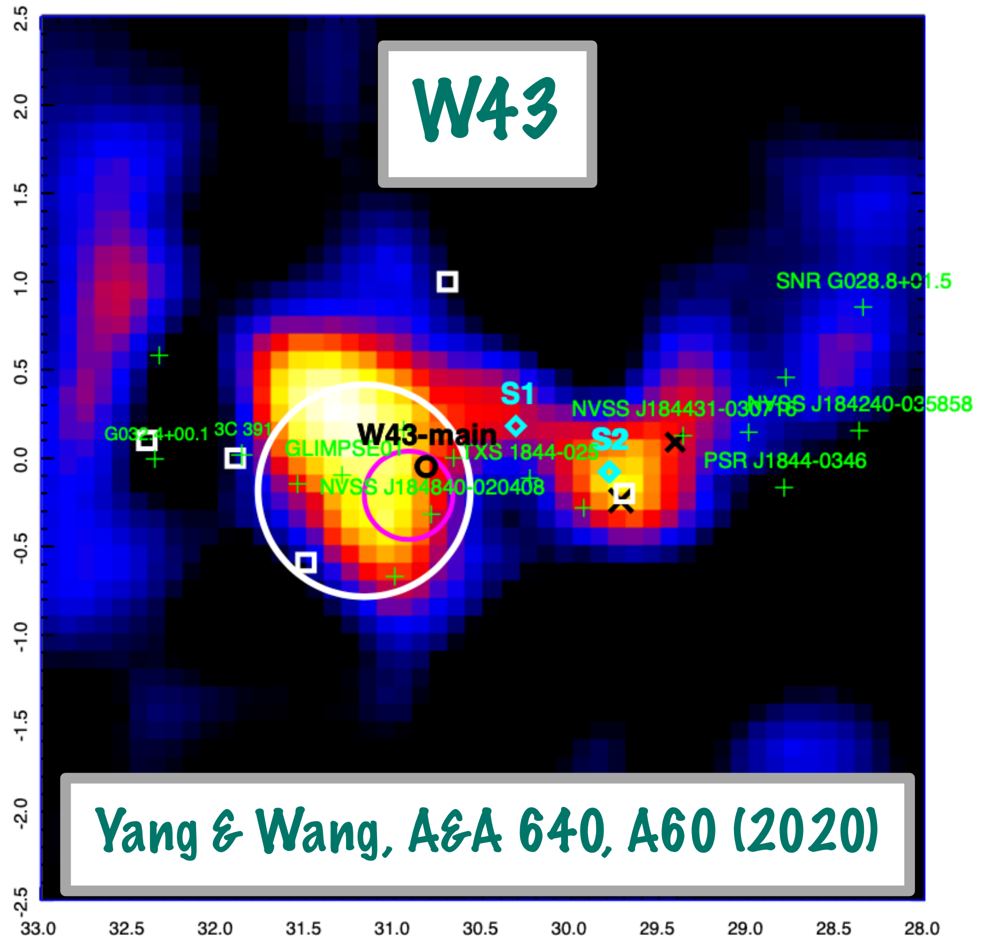
Young massive star clusters challenge (isolated) supernova remnants as major sources of the highest-energy Galactic cosmic rays!

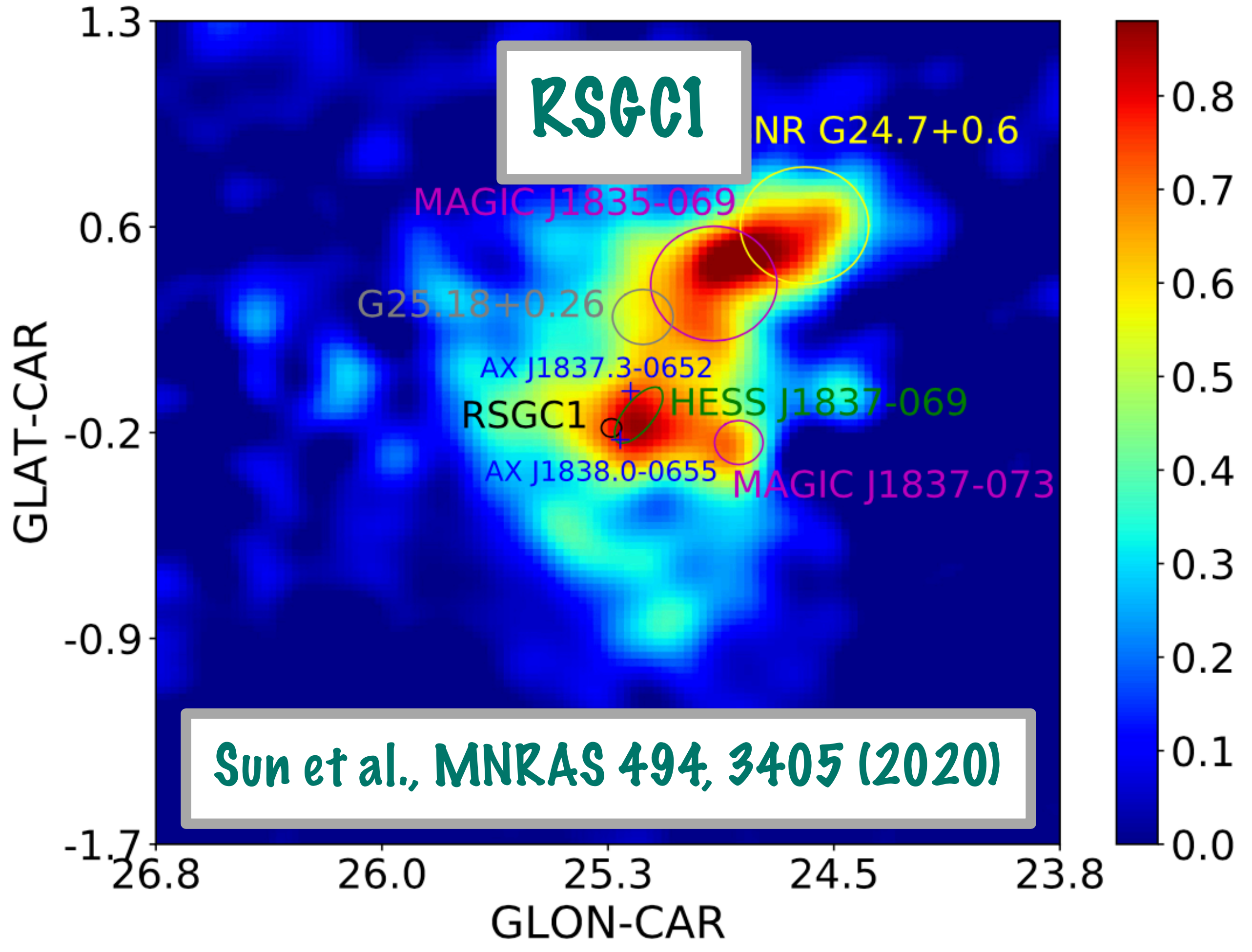
Star clusters as cosmic-ray sources

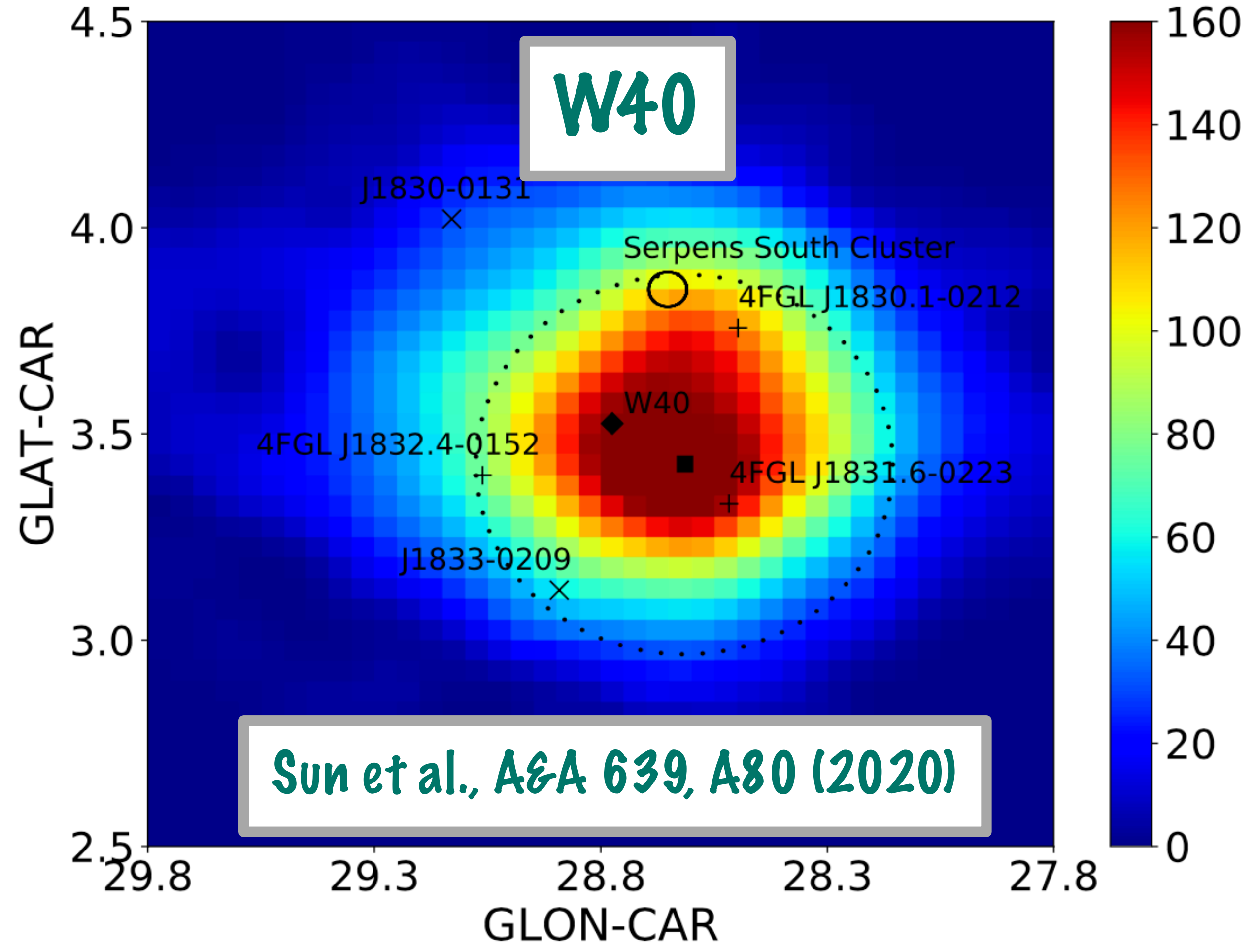
- Proposed a long time ago
- Renewed interest in recent years
- Many (recent) predictions
- Few (often putative!) detections
  - with *Fermi*-LAT in the GeV range





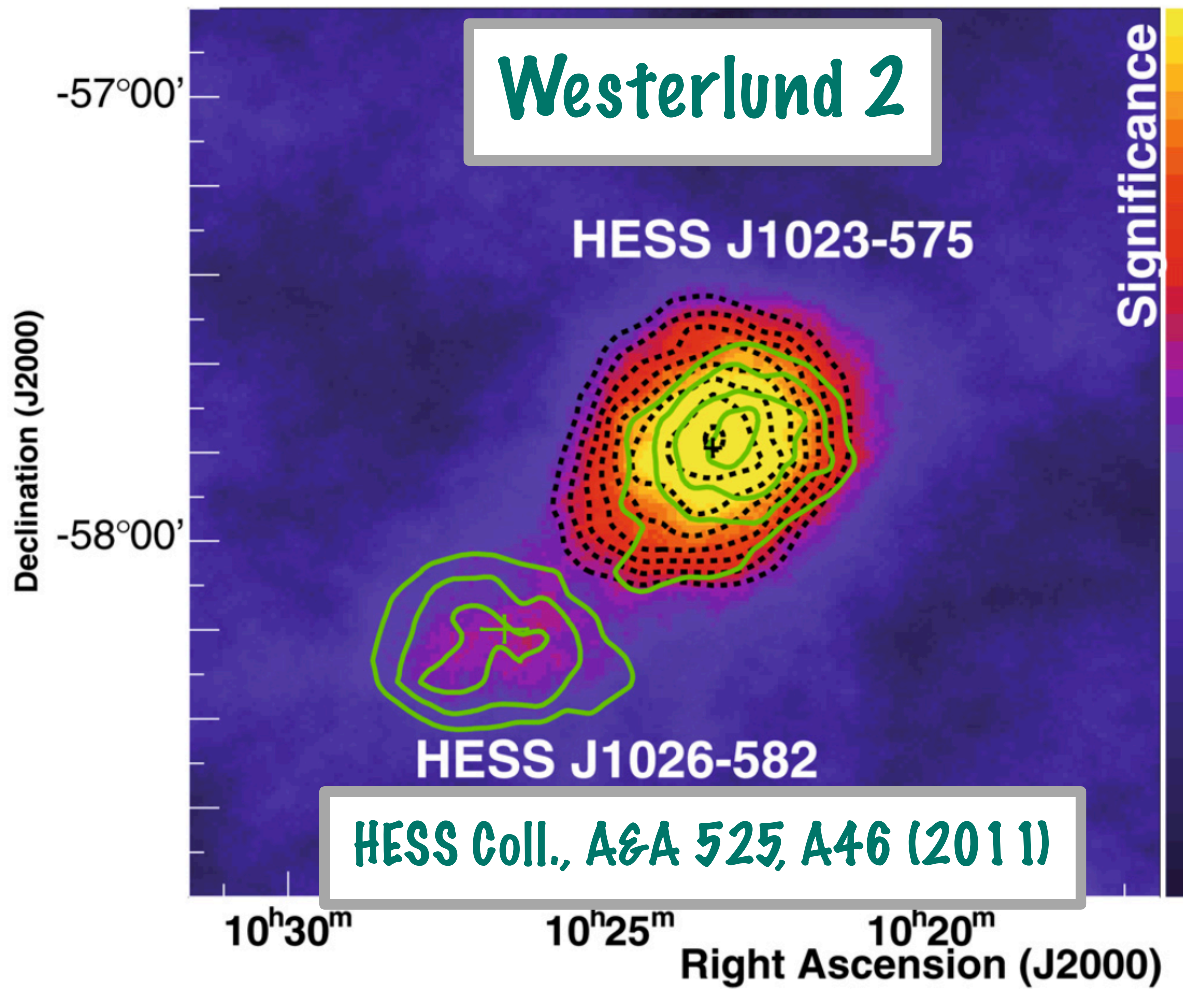


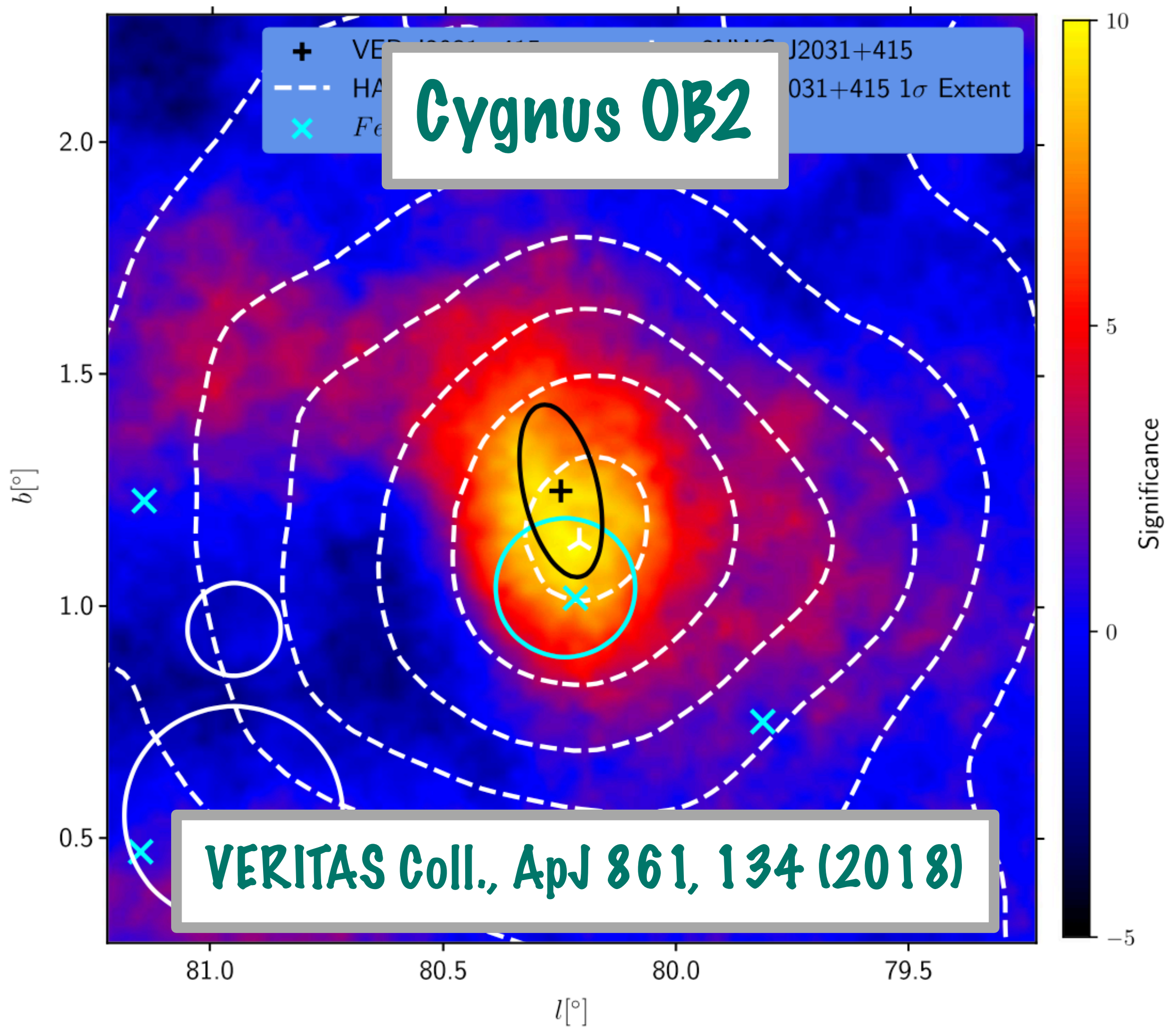


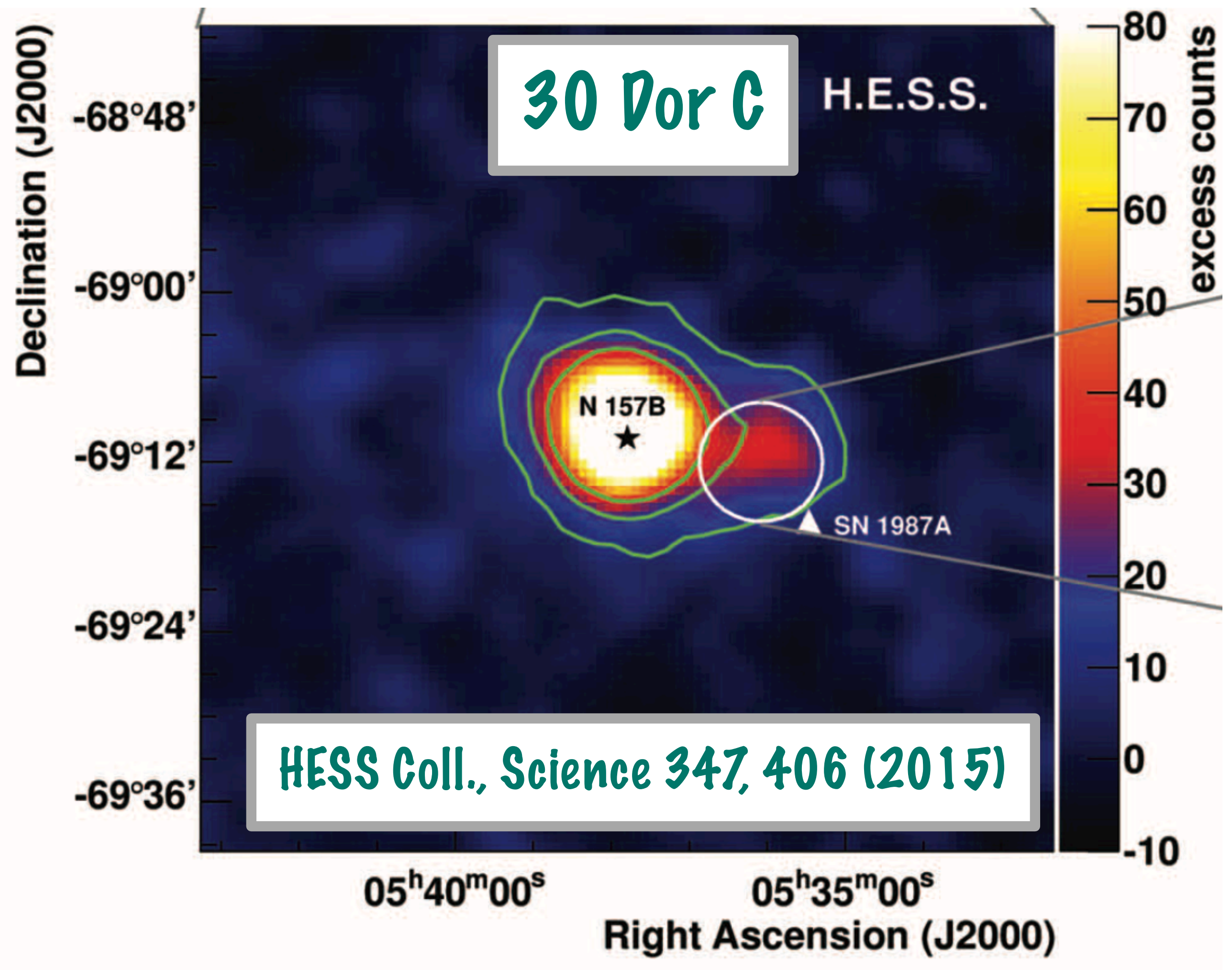


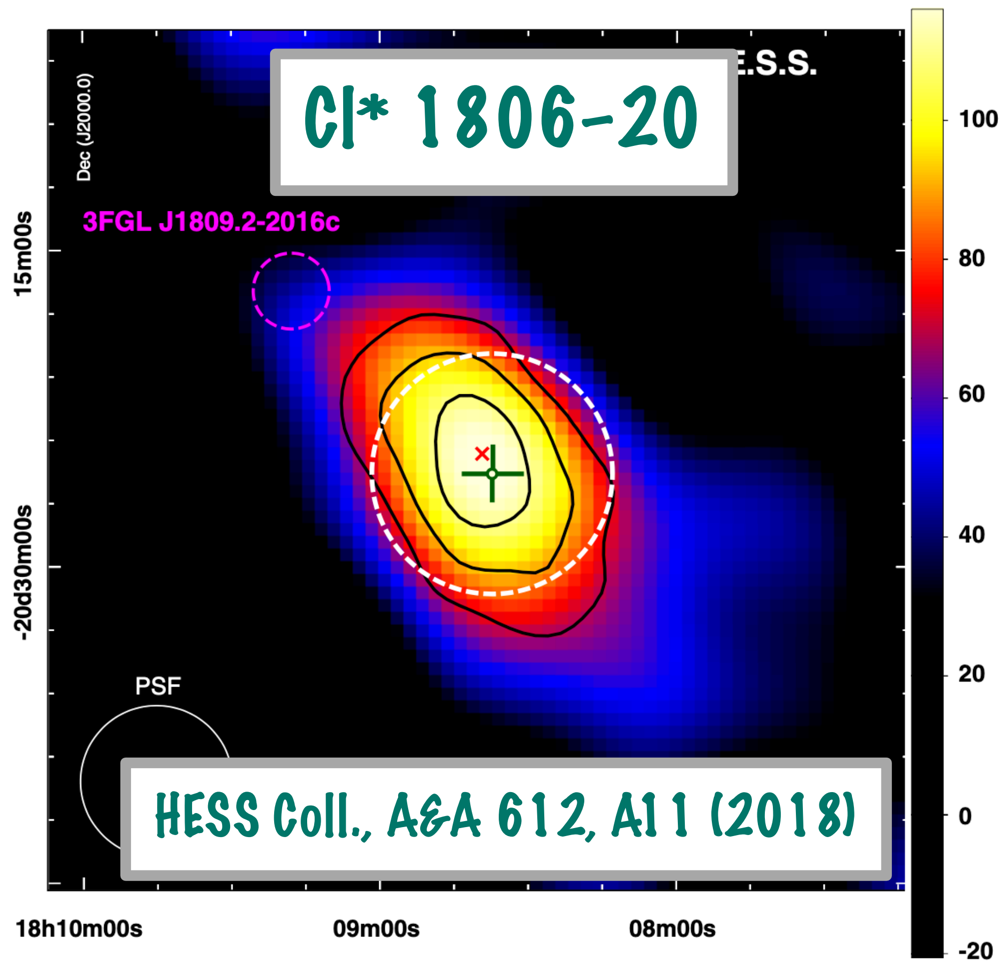
Star clusters as cosmic-ray sources

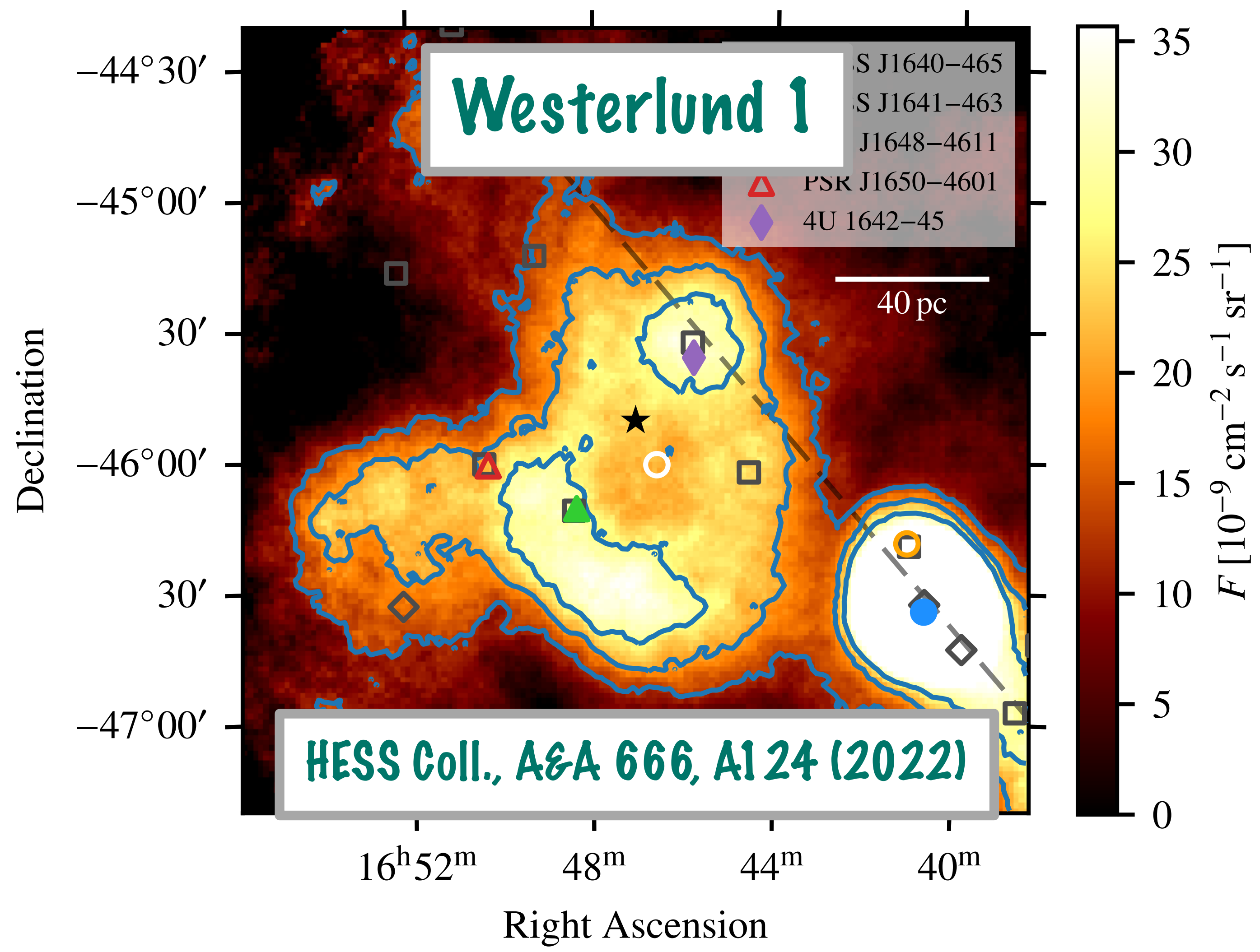
- Proposed a long time ago
- Renewed interest in recent years
- Many (recent) predictions
- Few (often putative!) detections
  - with *Fermi*-LAT in the GeV range
  - (mostly) with IACTs in the TeV range





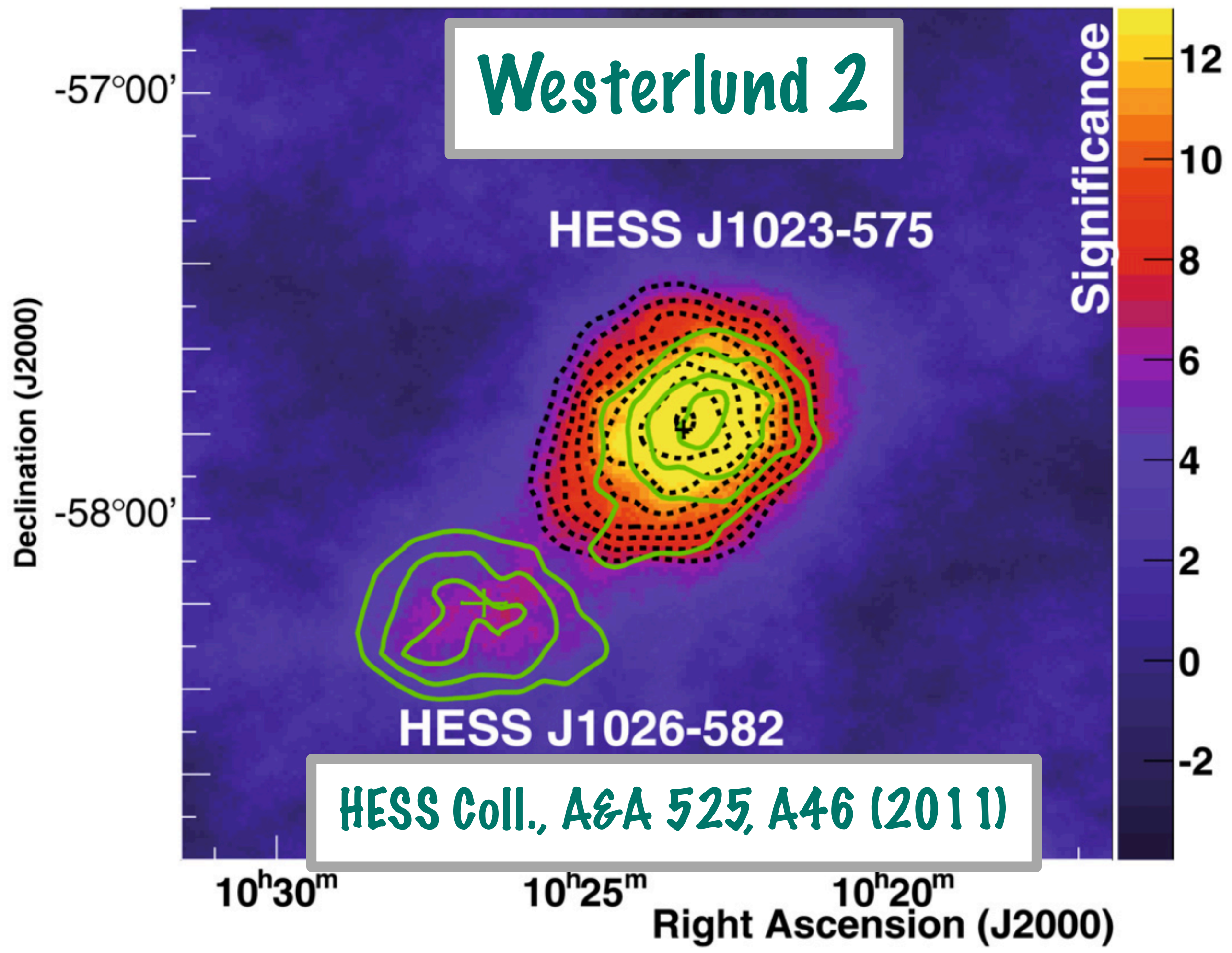


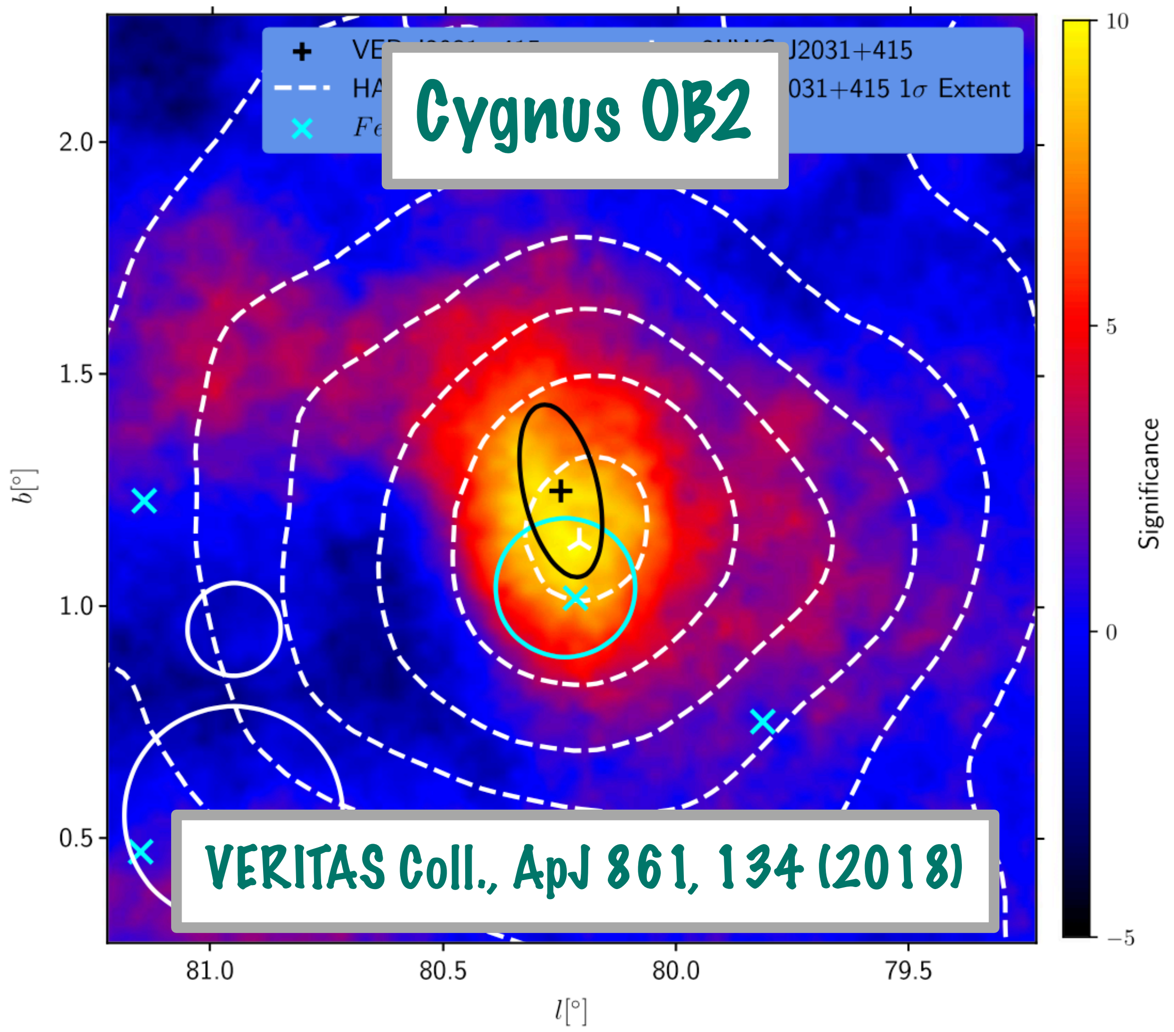


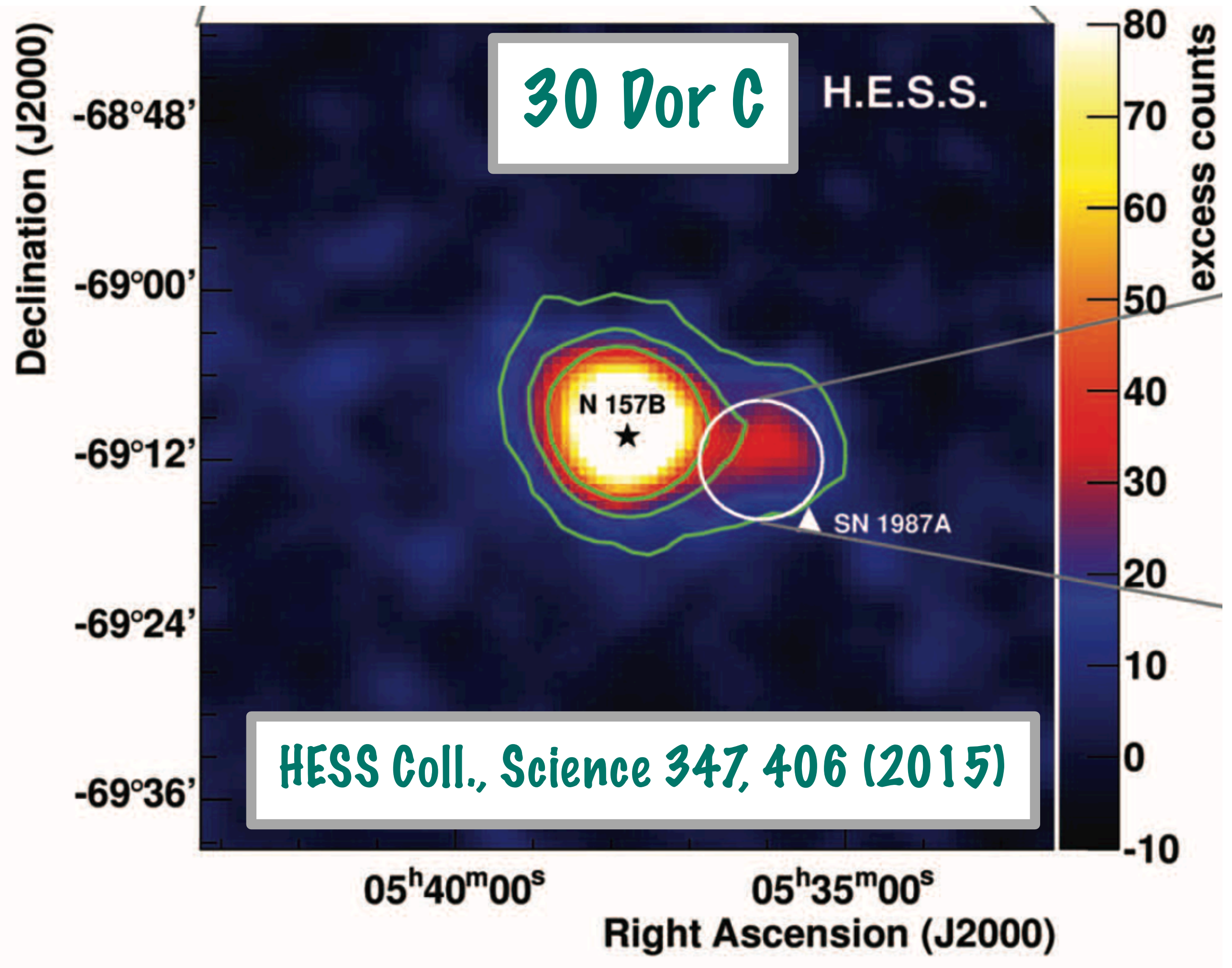


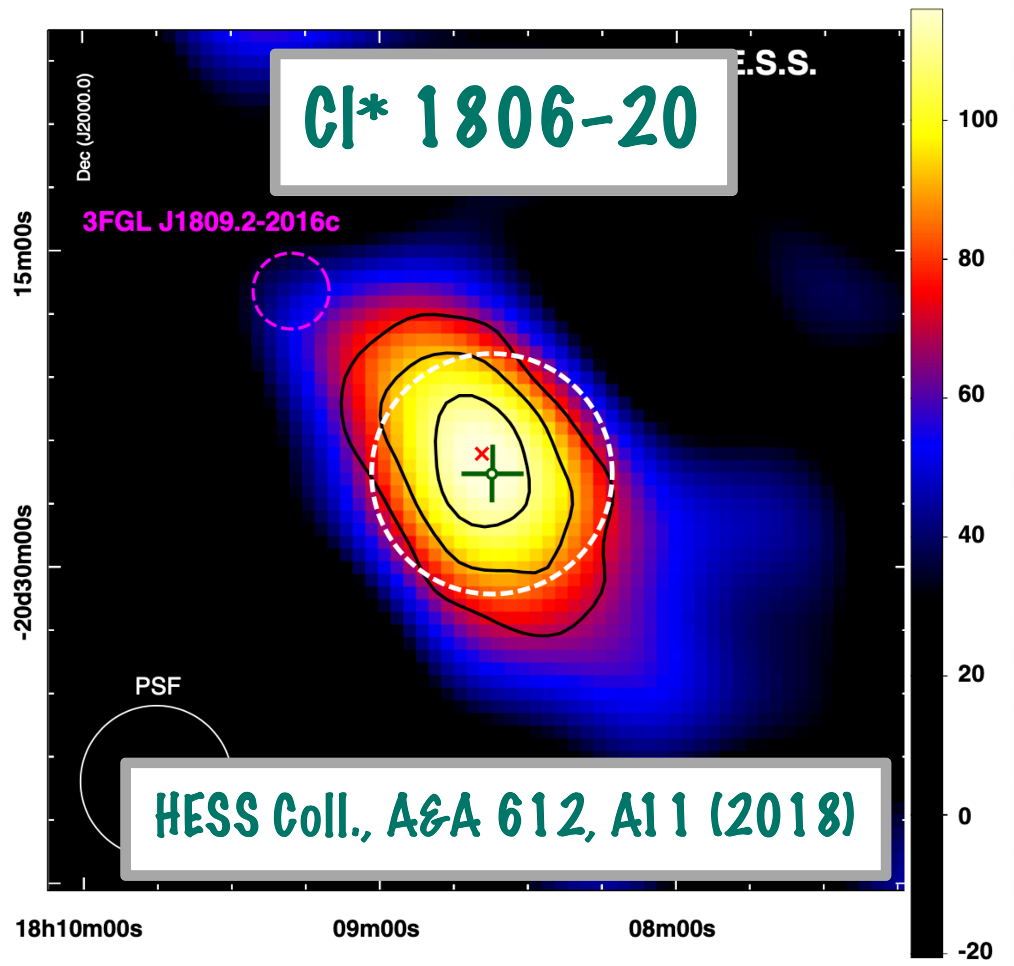
Star clusters as cosmic-ray sources

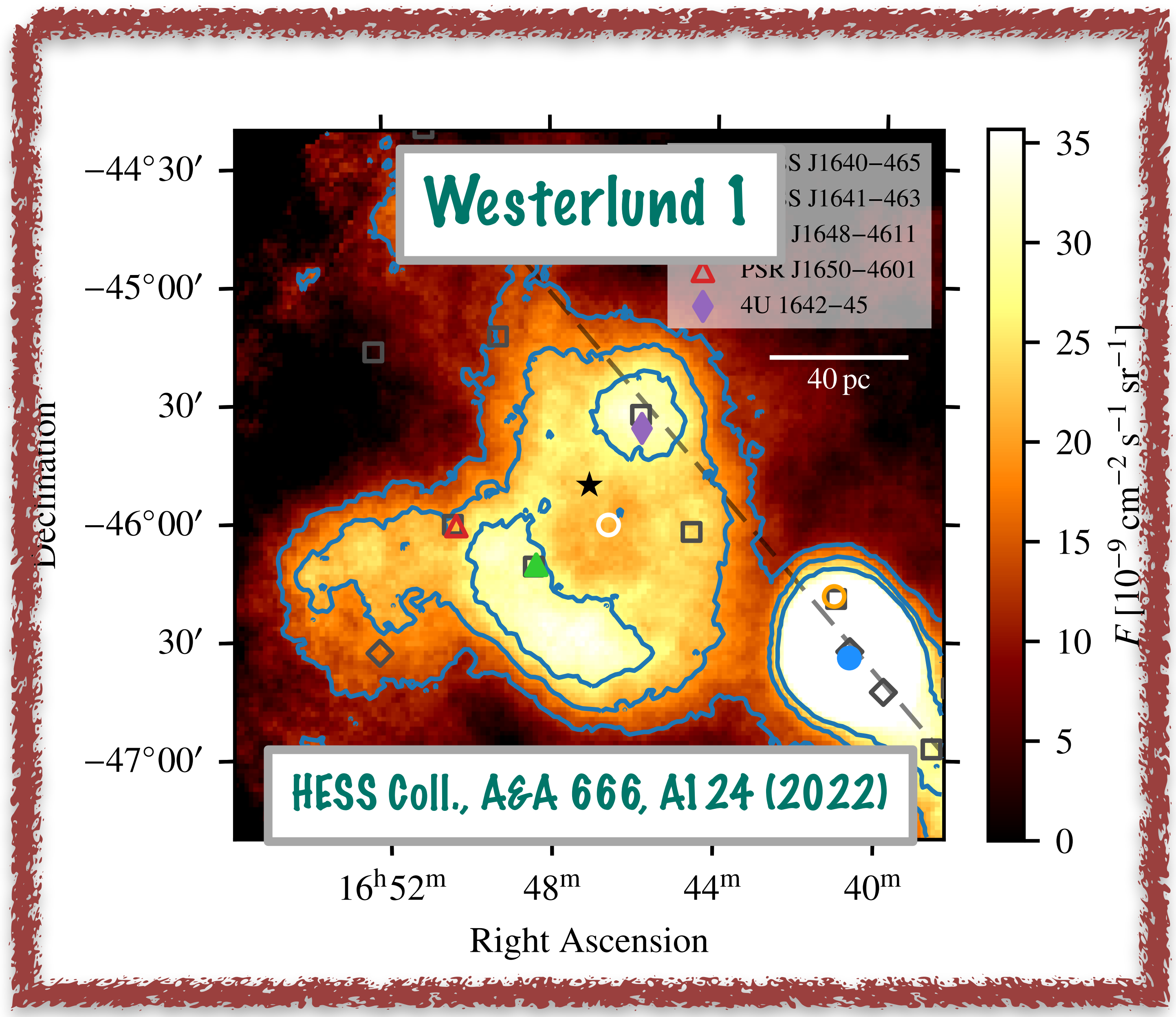
- Proposed a long time ago
- Renewed interest in recent years
- Many (recent) predictions
- Few (often putative!) detections
  - with *Fermi*-LAT in the GeV range
  - (mostly) with IACTs in the TeV range









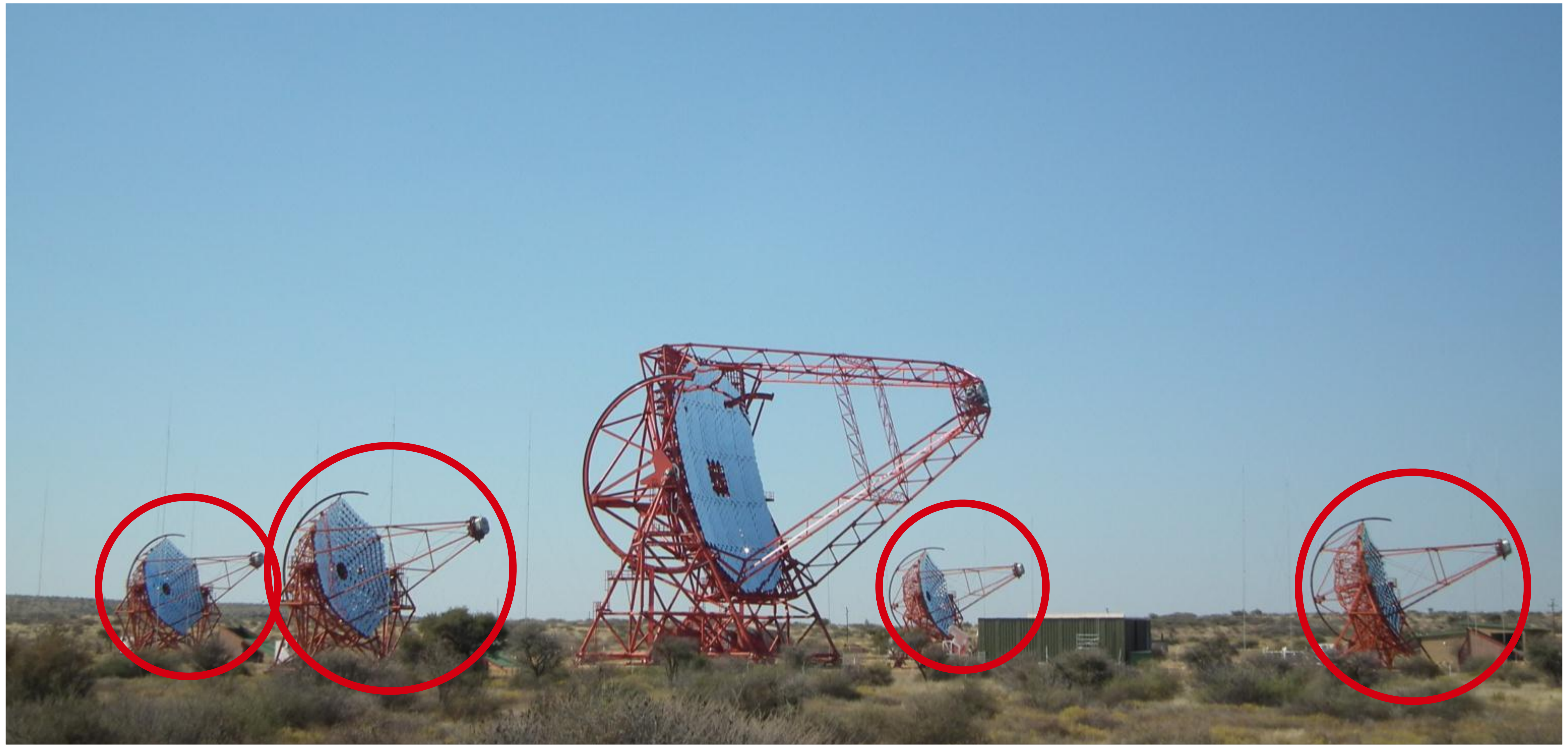


High Energy Stereoscopic System (H.E.S.S.)

- Located in Khomas highland, Namibia
- System of 5 IACTs
  - 4 telescopes with 12m mirrors
  - 1 telescope with 28m mirror
- Sensitive to gamma rays in energy range $\sim 100\,\mathrm{GeV} - 100\,\mathrm{TeV}$

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

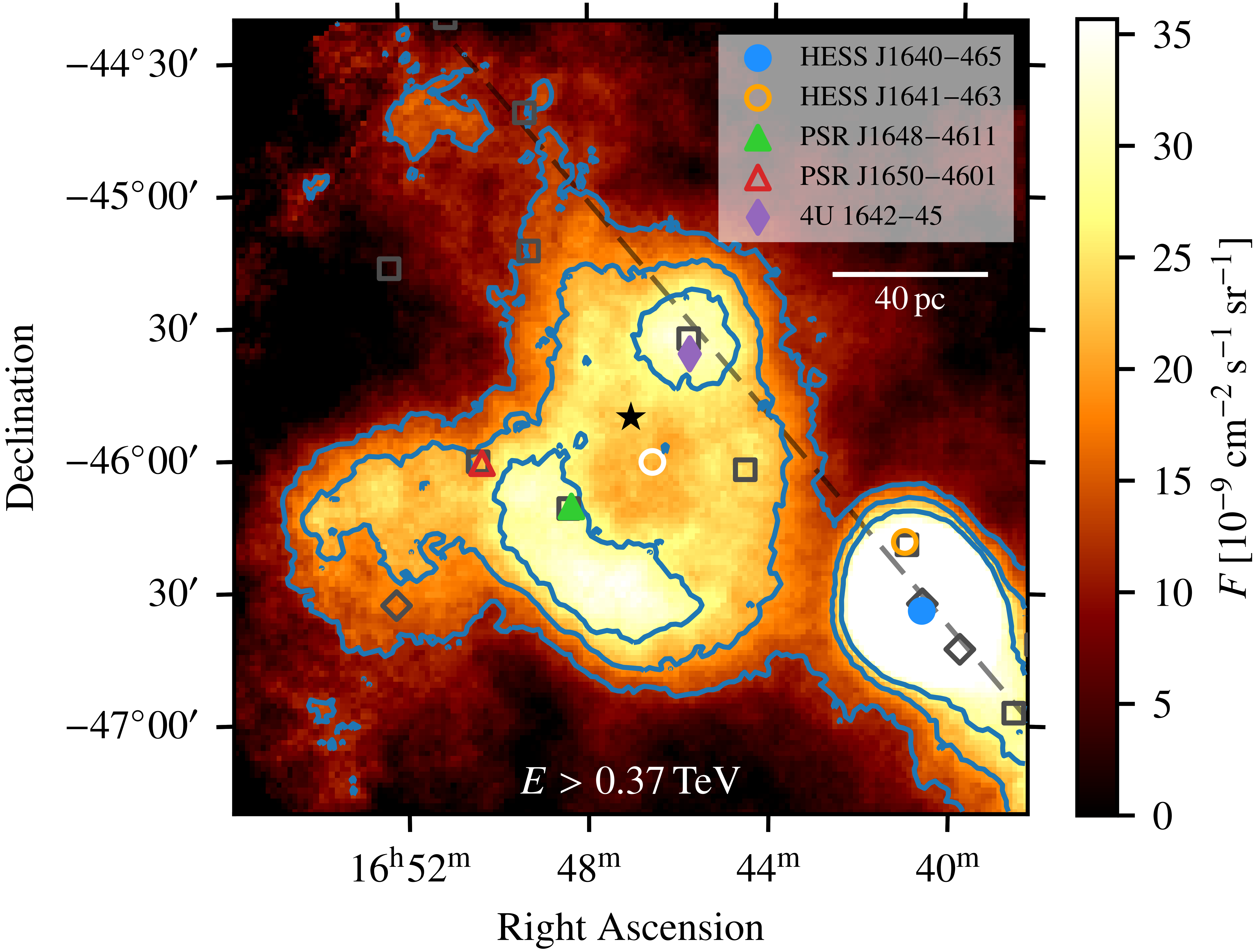
- Located in Khomas highland, Namibia
- System of 5 IACTs
  - 4 telescopes with 12m mirrors
  - 1 telescope with 28m mirror
- Sensitive to gamma rays in energy range $\sim 100\,\mathrm{GeV} - 100\,\mathrm{TeV}$



- Westerlund 1 data analysis
  - 164h live time, taken 2004–2017
  - 12m telescopes only
  - very large source extent & other nearby sources
    → ***cannot estimate background from source-free regions***
  - Employ ***background model*** from archival observations Mohrmann et al., A&A 632, A72 (2019)
  - Perform high-level analysis with open-source package ***Gammapy***

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

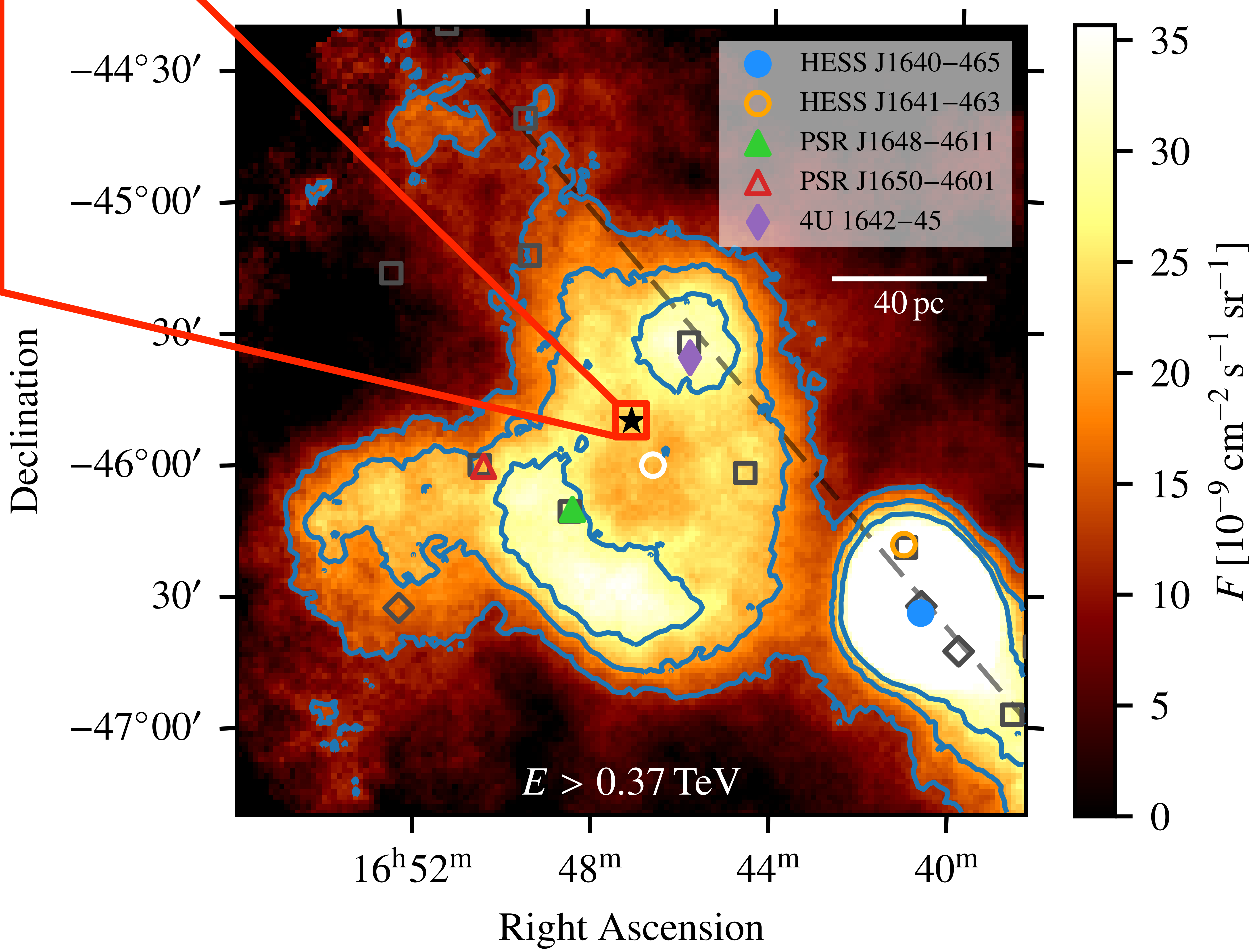
Westerlund 1



Reference: HESS Coll., A&A 666, A124 (2022) arXiv:2207.10921

Westerlund 1

Credit: ESO

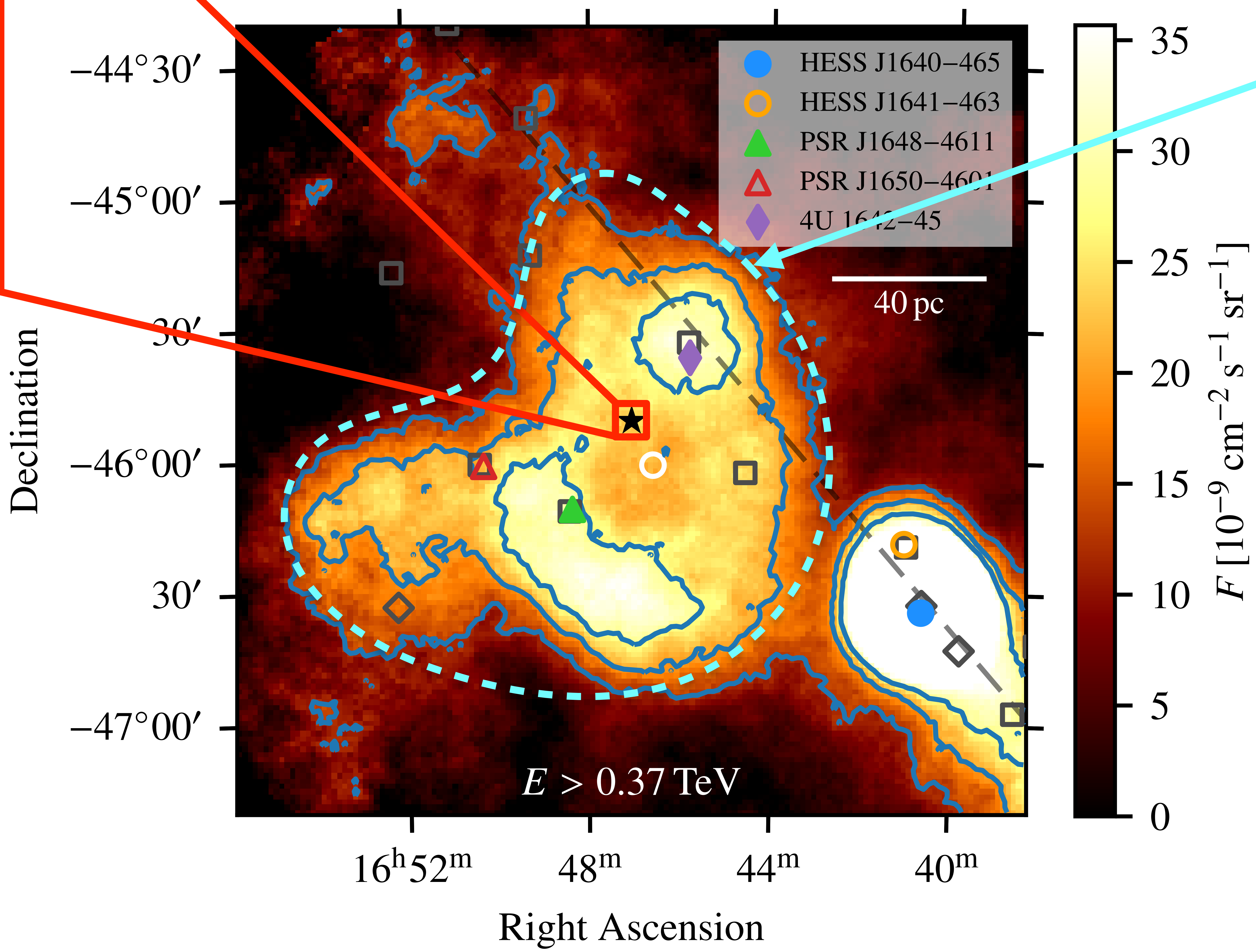


- Westerlund 1
  - most massive young star cluster in our Galaxy
  - $M \sim 10^5\, M_\odot$
  - half-mass radius: 1 pc
  - Age $\sim 3 - 5$ Myr
  - Distance ~ 4 kpc

Reference: HESS Coll., A&A 666, A124 (2022) arXiv:2207.10921

Westerlund 1

Credit: ESO



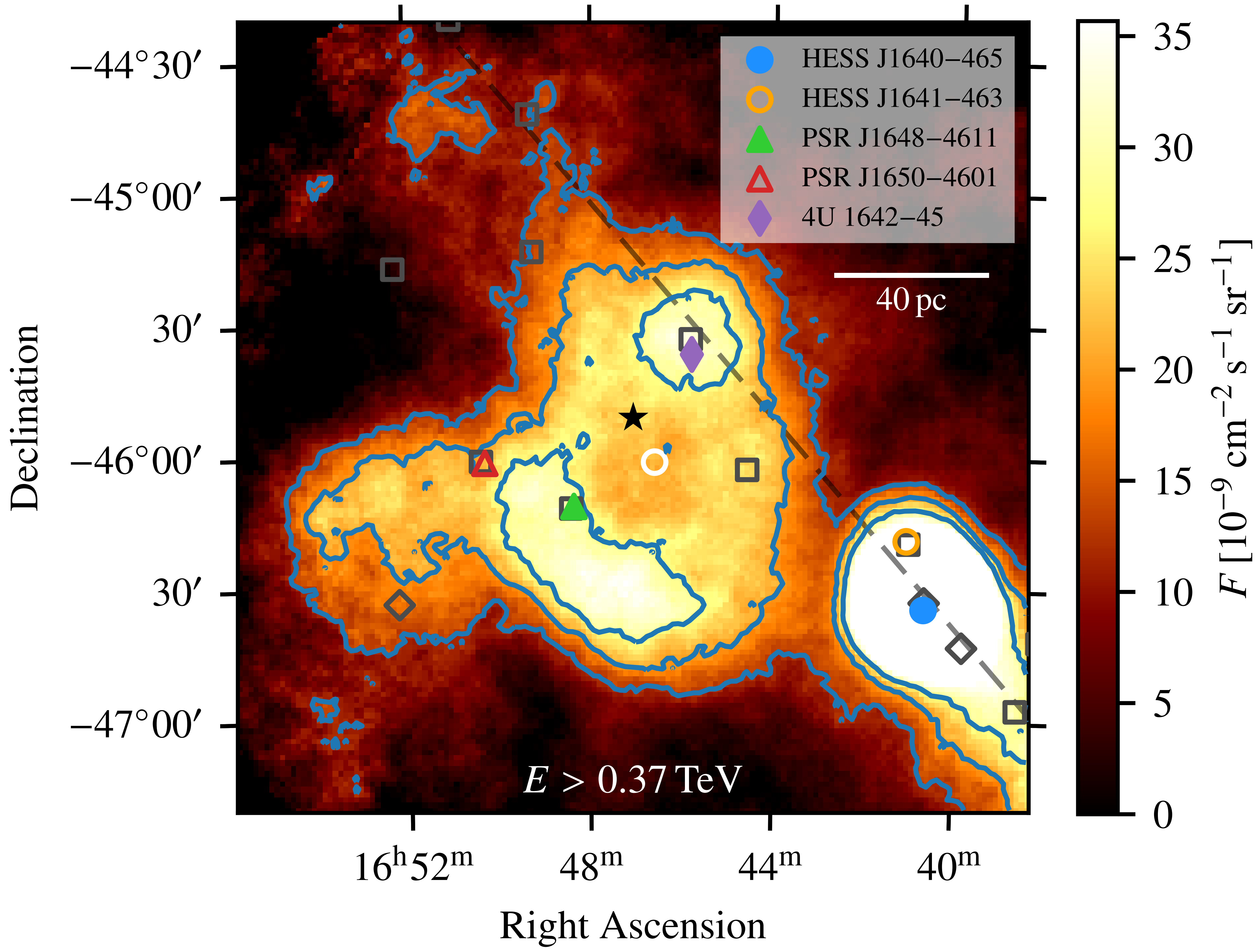
- Westerlund 1
  - most massive young star cluster in our Galaxy
  - $M \sim 10^5\,M_\odot$
  - half-mass radius: 1 pc
  - Age $\sim 3-5$ Myr
  - Distance ~ 4 kpc

- HESS J1646–458
  - largely extended γ-ray source
  - diameter $\sim 2°$ (140 pc)
  - very likely associated with Westerlund 1

Reference: HESS Coll., A&A 666, A124 (2022) arXiv:2207.10921

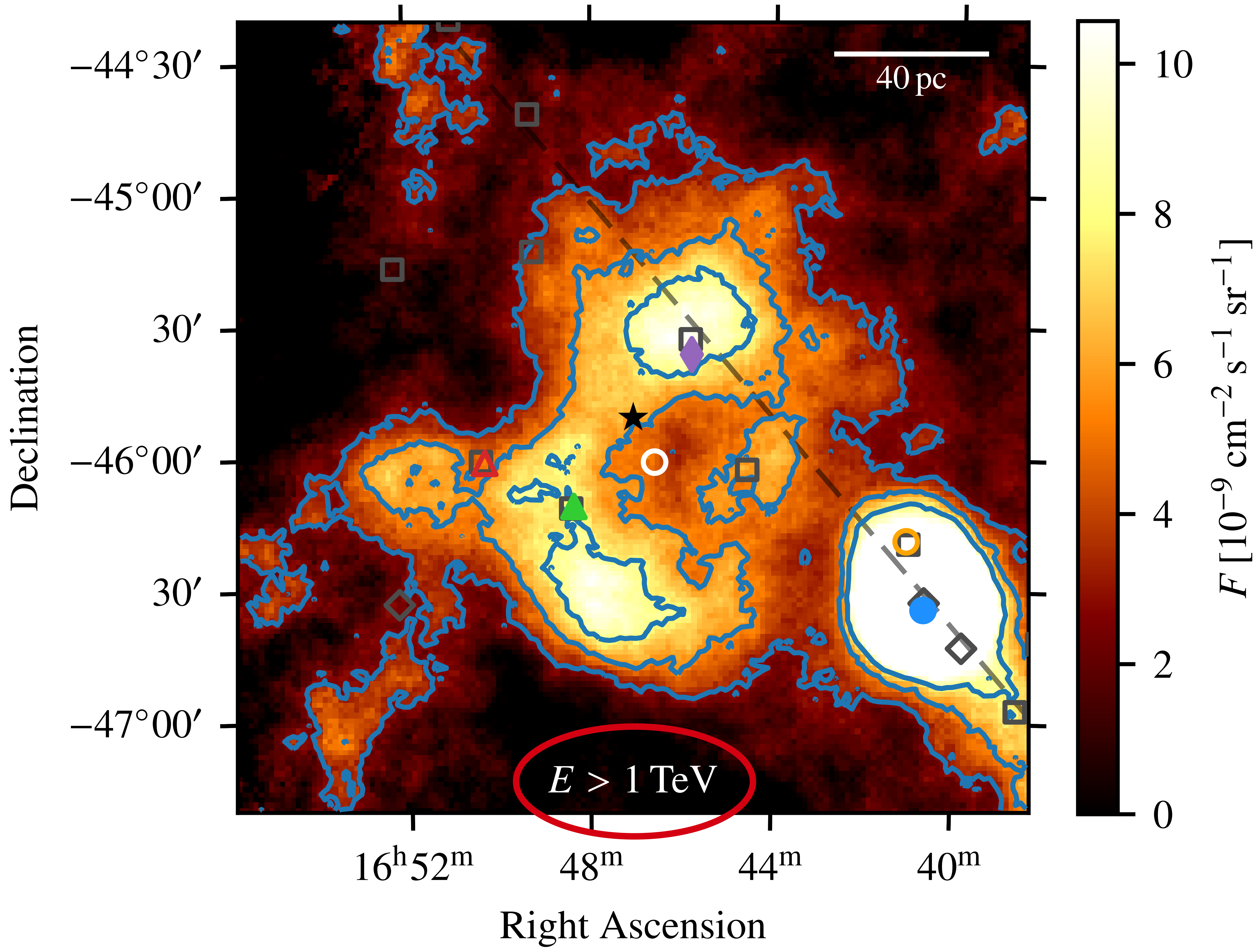
Source morphology

- Source morphology
  - very large extent: $\sim 2^\circ / 140\,\mathrm{pc}$
  - very complex
  - not peaked at position of Westerlund 1
  - ***shell-like structure!***
  - centroid slightly shifted from cluster position
  - bright spots along shell



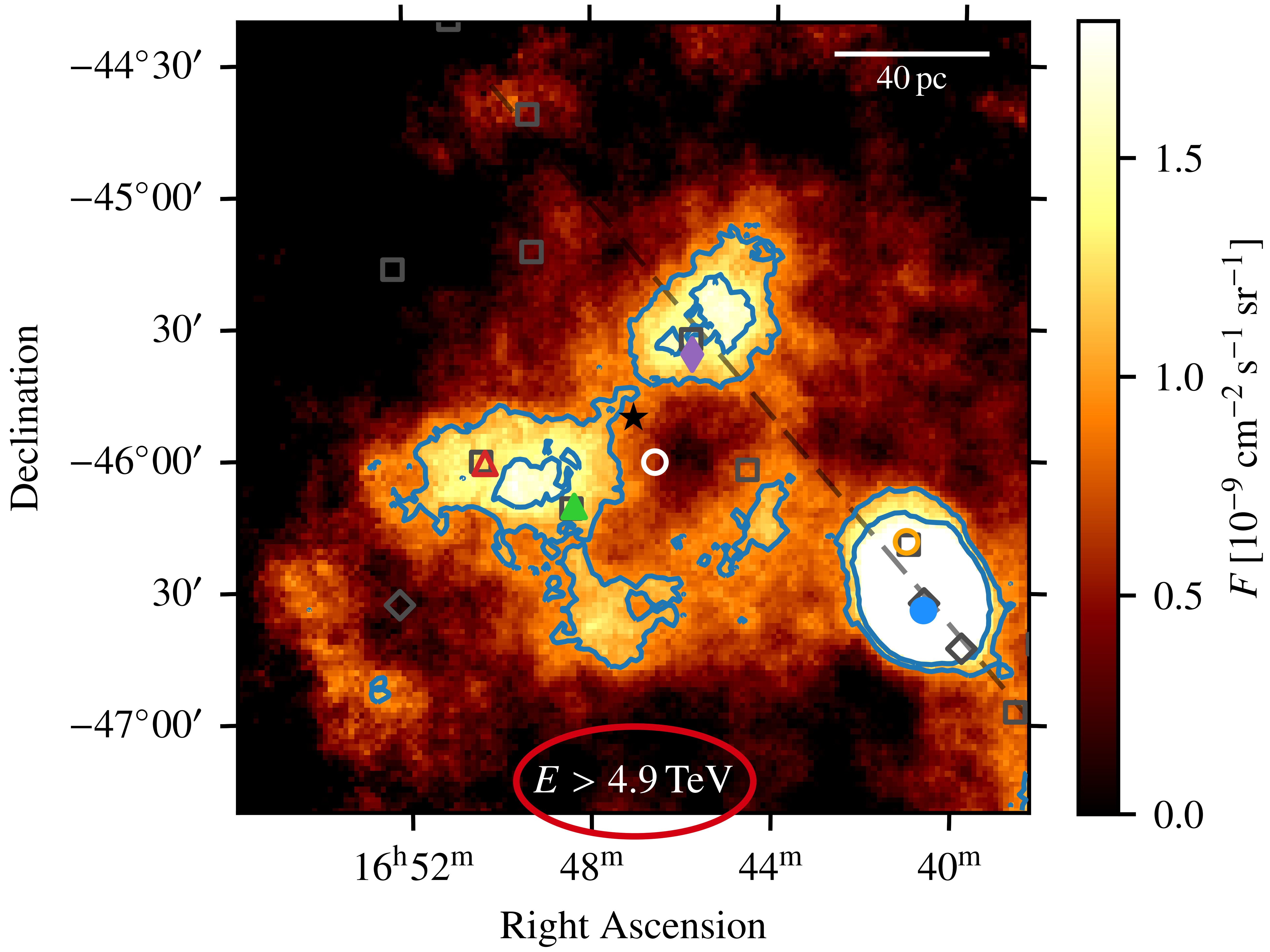
Source morphology

- Source morphology
  - very large extent: $\sim 2^\circ$ / 140 pc
  - very complex
  - not peaked at position of Westerlund 1
  - ***shell-like structure!***
  - centroid slightly shifted from cluster position
  - bright spots along shell
- Energy-dependence?
  - bright spots remain
  - ***shell-like structure persists!***



Source morphology

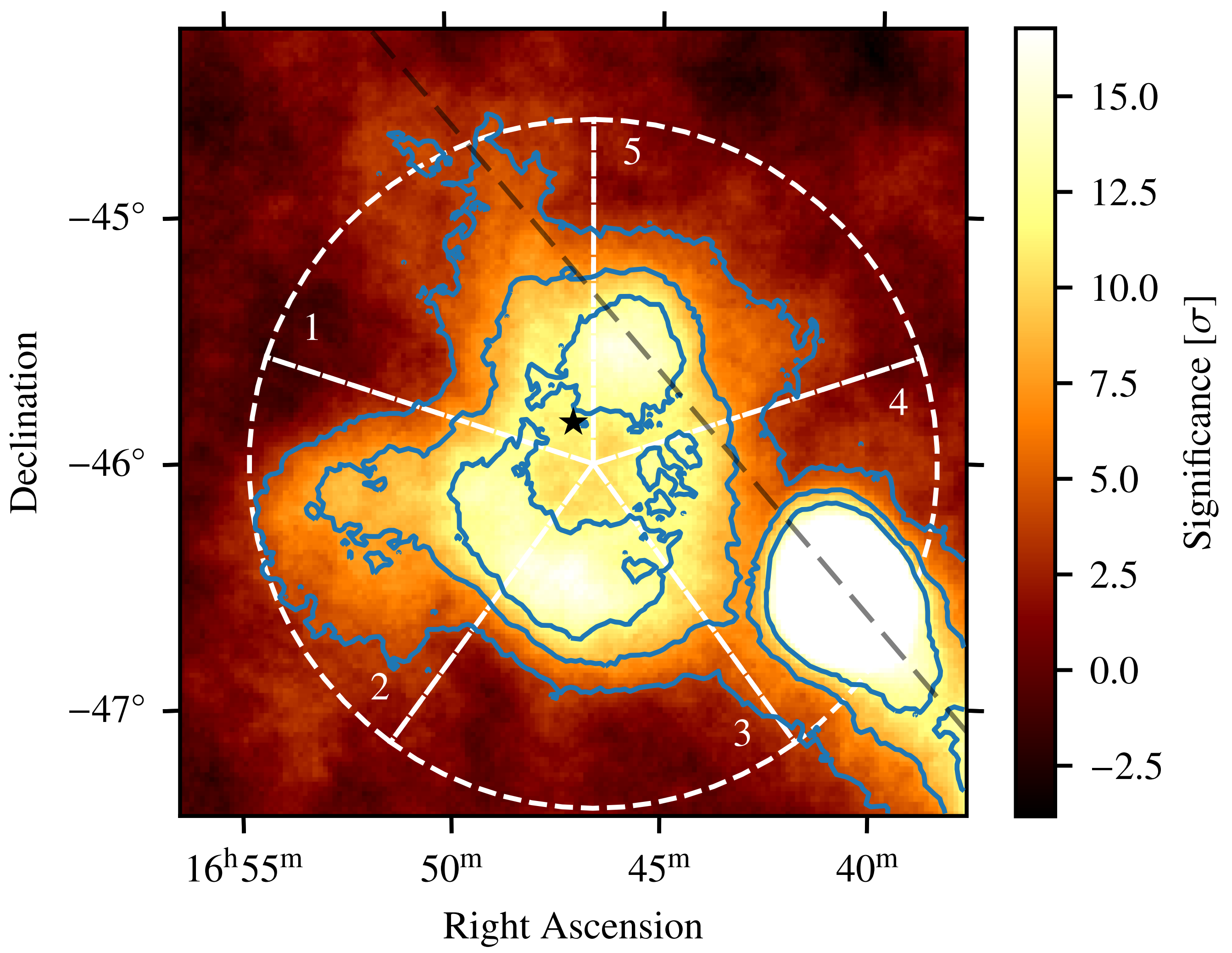
- Source morphology
  - very large extent: $\sim 2^\circ$ / 140 pc
  - very complex
  - not peaked at position of Westerlund 1
  - ***shell-like structure!***
  - centroid slightly shifted from cluster position
  - bright spots along shell

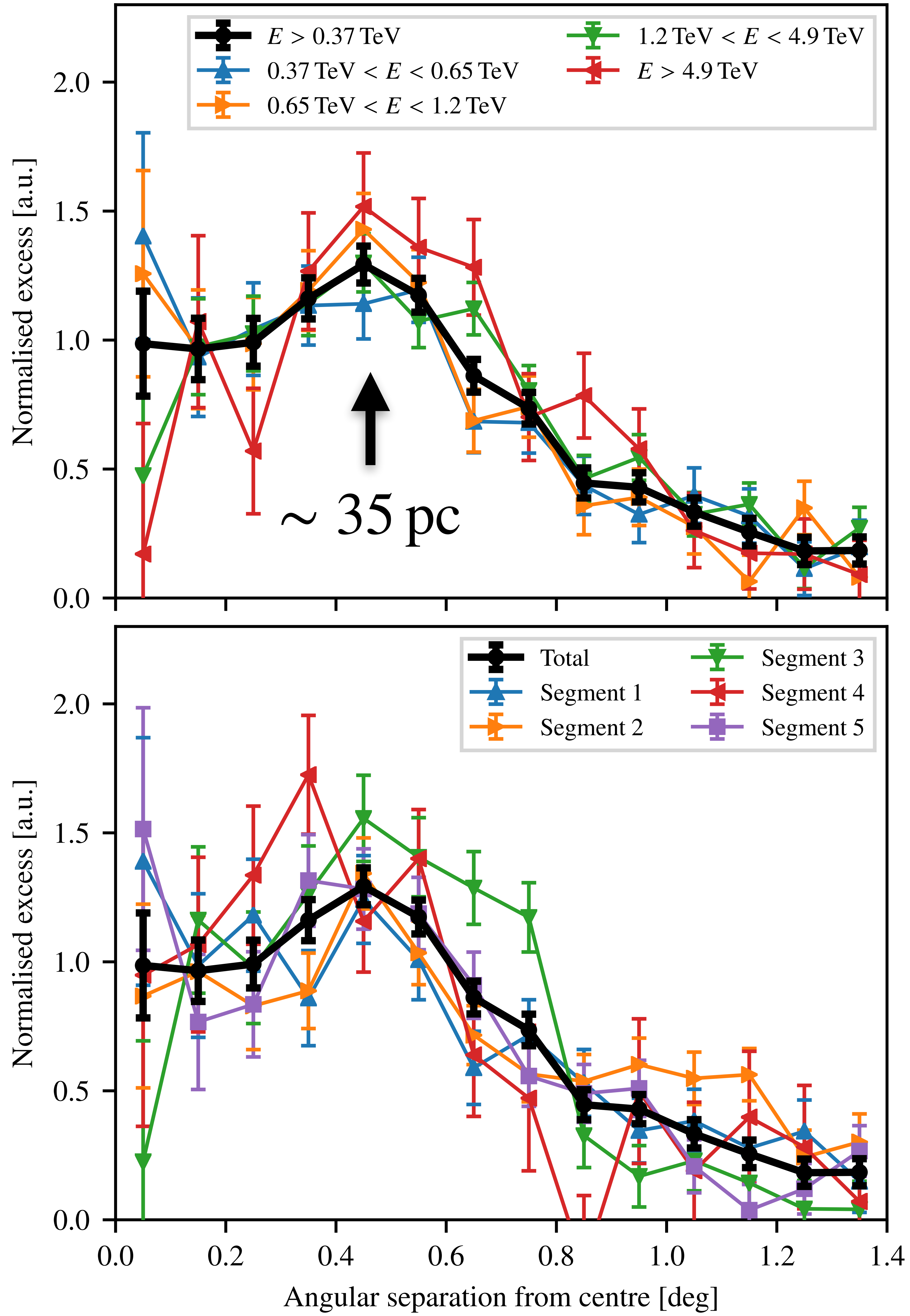


- Energy-dependence?
  - bright spots remain
  - ***shell-like structure persists!***

Source morphology

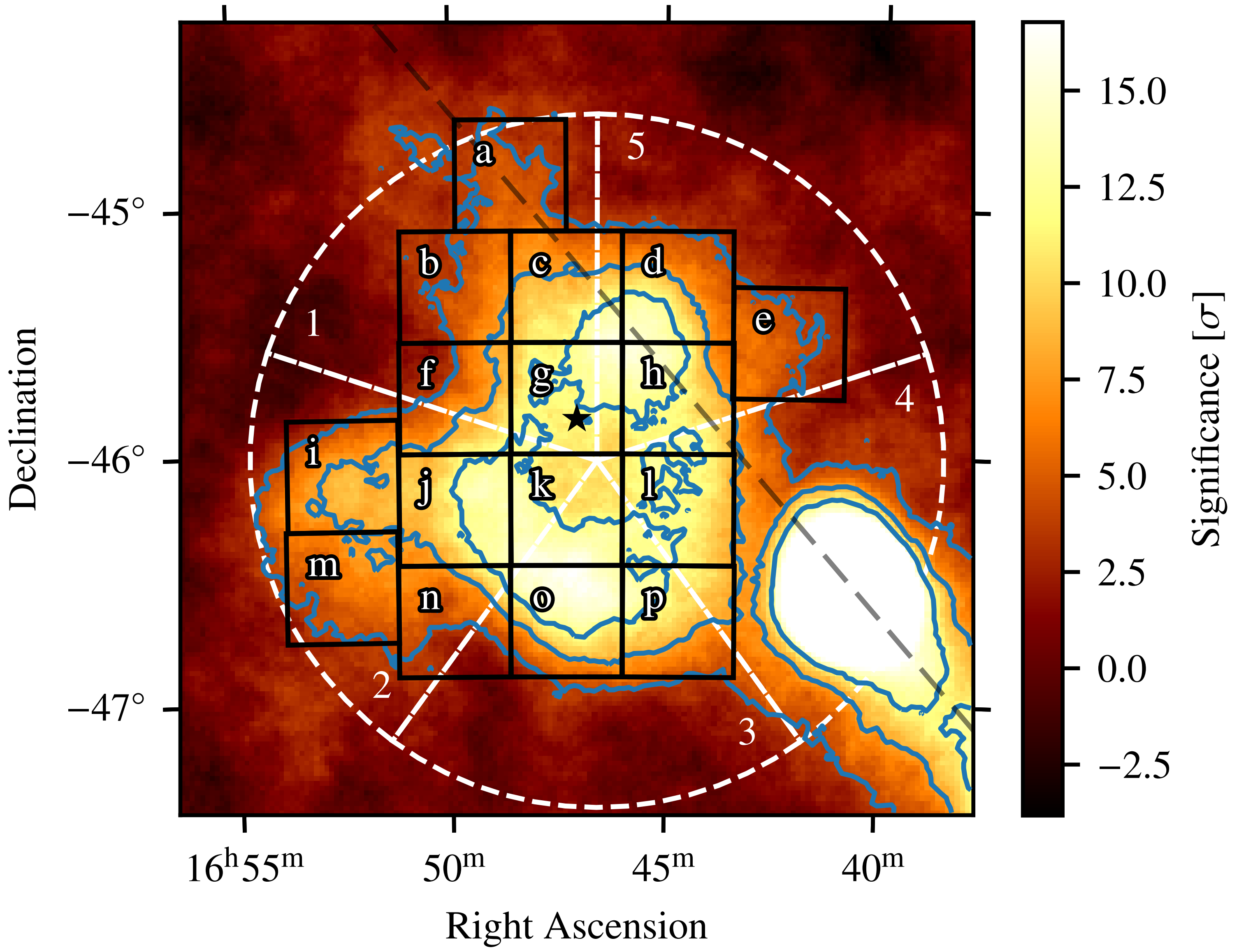
- Source morphology
  - very large extent: $\sim 2° / 140\,\mathrm{pc}$
  - very complex
  - not peaked at position of Westerlund 1
  - ***shell-like structure!***
  - centroid slightly shifted from cluster position
  - bright spots along shell
- Energy-dependence?
  - bright spots remain
  - ***shell-like structure persists!***
- Confirmed by radial excess profiles
  - profiles in energy bands compatible
  - peak visible in all segments

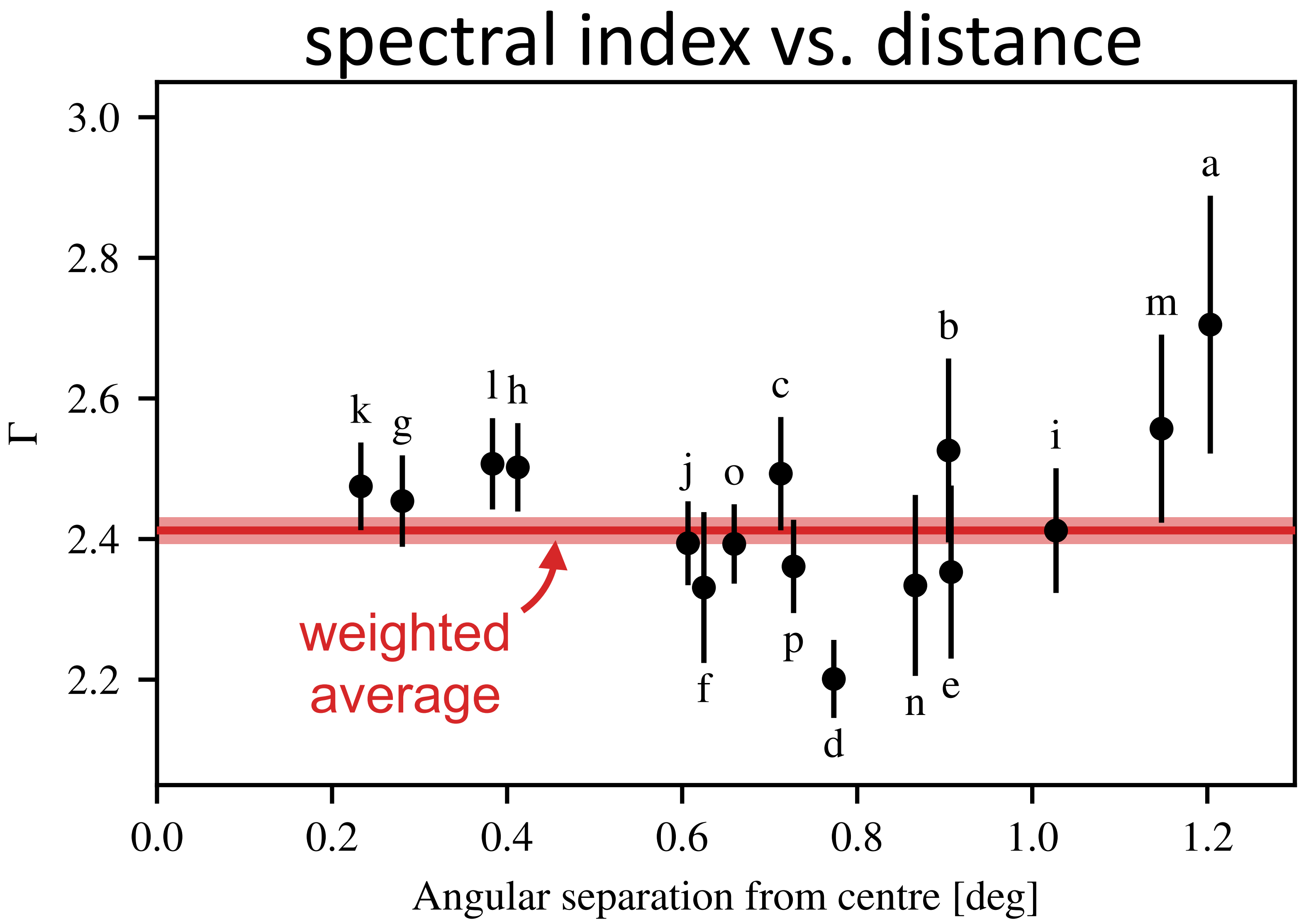


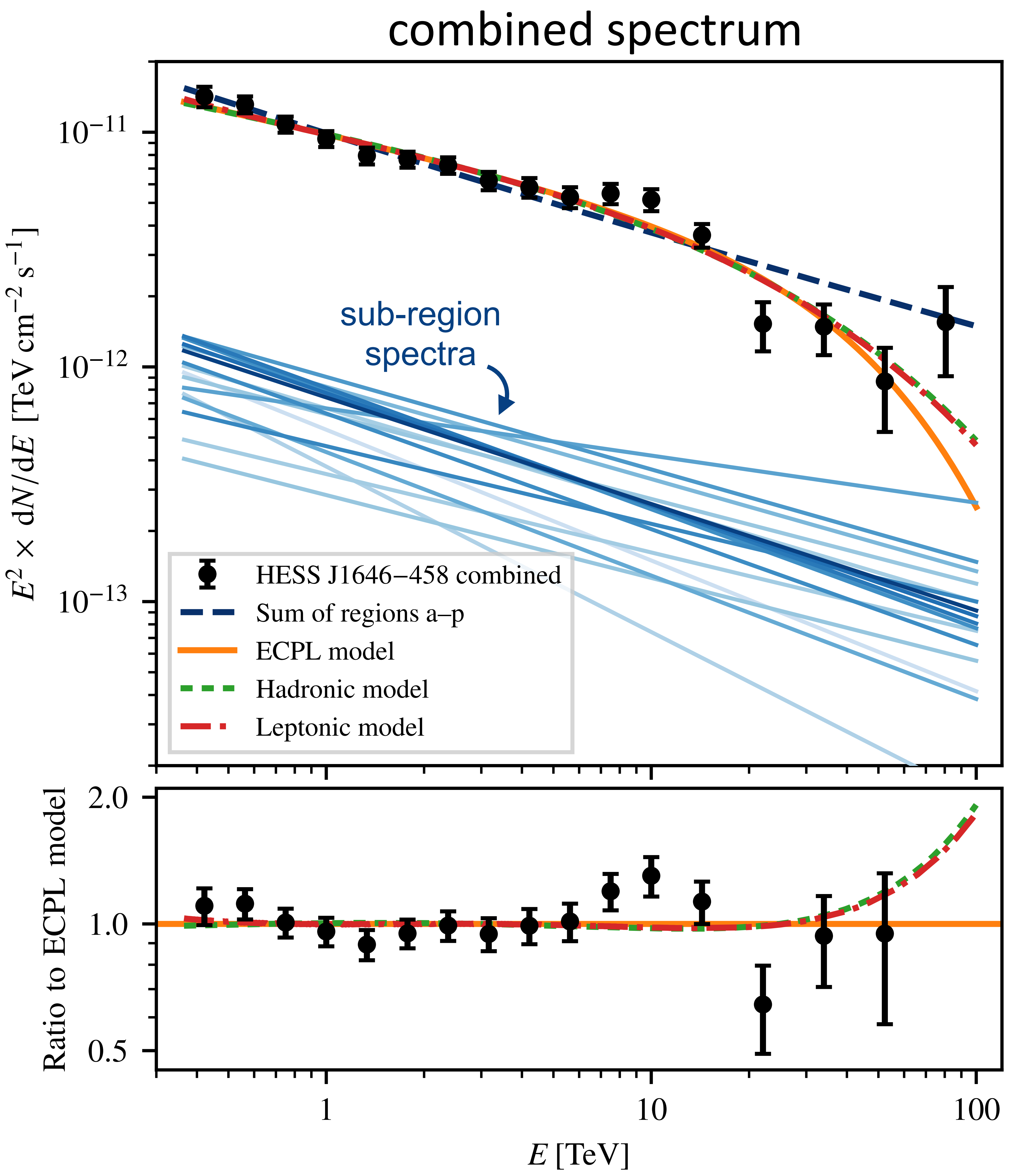


Energy spectrum

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



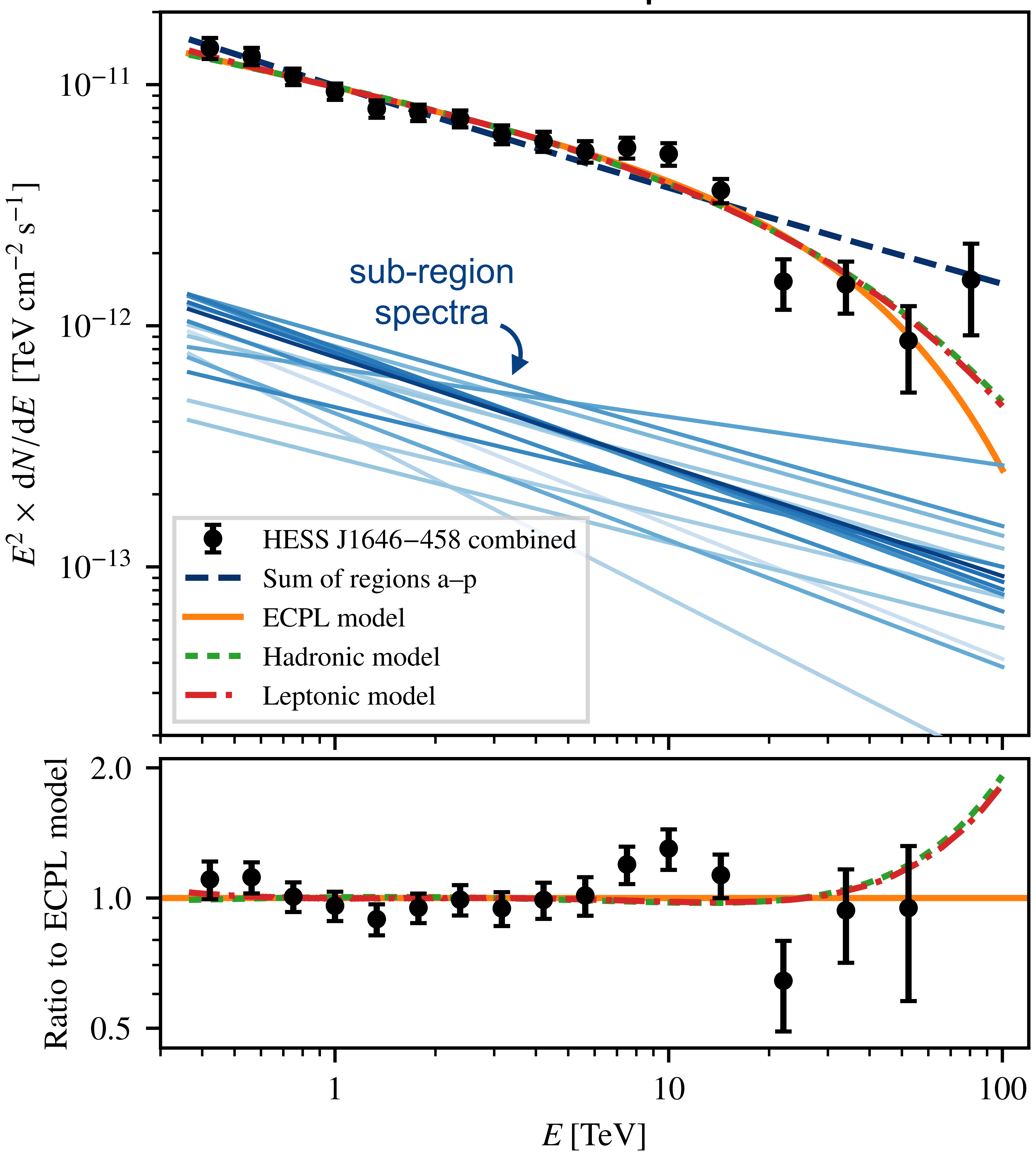




Energy spectrum

- Energy spectrum
  - extracted in 16 signal regions
  - individual spectra remarkably similar
  - add up region spectra → combined spectrum
  - ***extends to several ten TeV!***
  - $\Gamma = 2.30 \pm 0.04,\ E_c = \left(44^{+17}_{-11}\right)$ TeV
- Hadronic model (*proton-proton*)
  - $\Gamma_p = 2.33 \pm 0.06,\ E_c^p = \left(400^{+250}_{-130}\right)$ TeV (almost a PeVatron…)
  - $W_p(>1\,\mathrm{GeV}) = 6 \times 10^{51} \left(\frac{n}{1\,\mathrm{cm}^3}\right)^{-1}$ erg
- Leptonic model (*inverse Compton*)
  - $\Gamma_e = 2.97 \pm 0.07,\ E_c^e = \left(180^{+200}_{-70}\right)$ TeV
  - $L_e(>0.1\,\mathrm{TeV}) > 4.1 \times 10^{35}\,\mathrm{erg\,s^{-1}}$

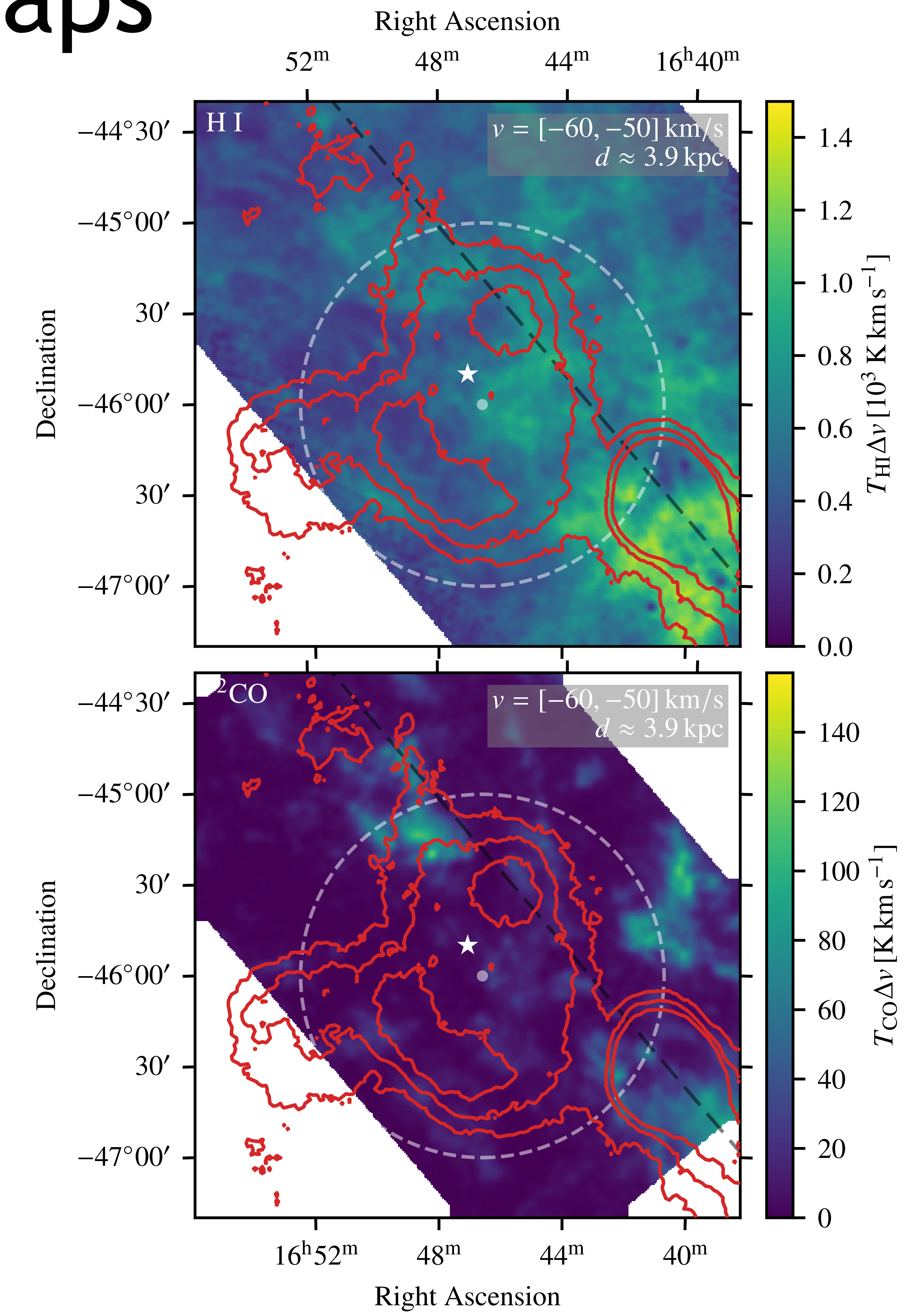
combined spectrum



Correlation with gas maps

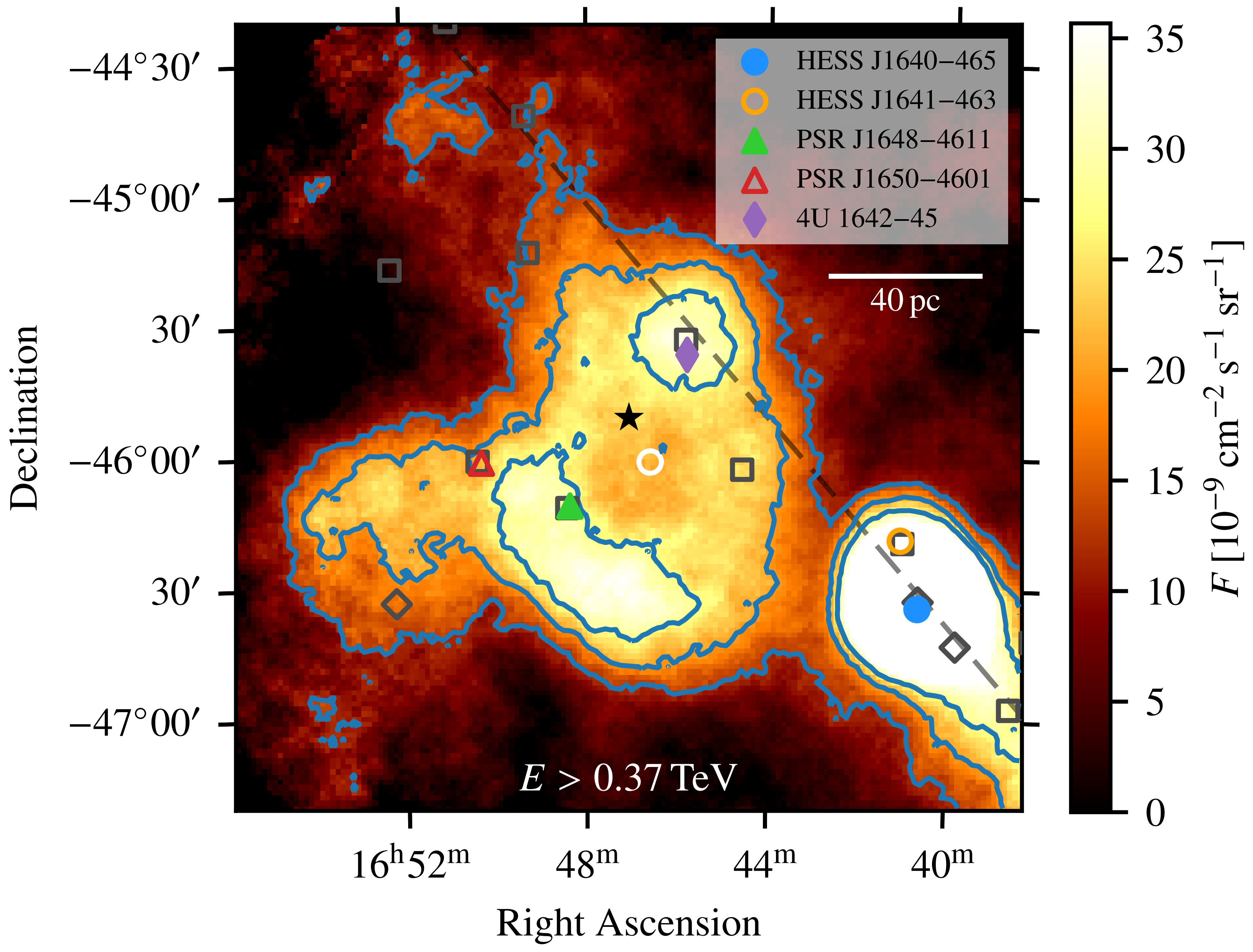
- Hadronic scenario requires target material for interactions
- Comparison with HI (→ atomic hydrogen) and
  ^{12}CO (→ molecular hydrogen) line emission

- ***Low density*** in regions with bright gamma-ray emission!
- A challenge for the hadronic scenario …
  … but there could still be ways out:
  - strong UV radiation from cluster can *ionise* gas or *photo-dissociate* CO molecules
  - distribution of cosmic rays need not be uniform



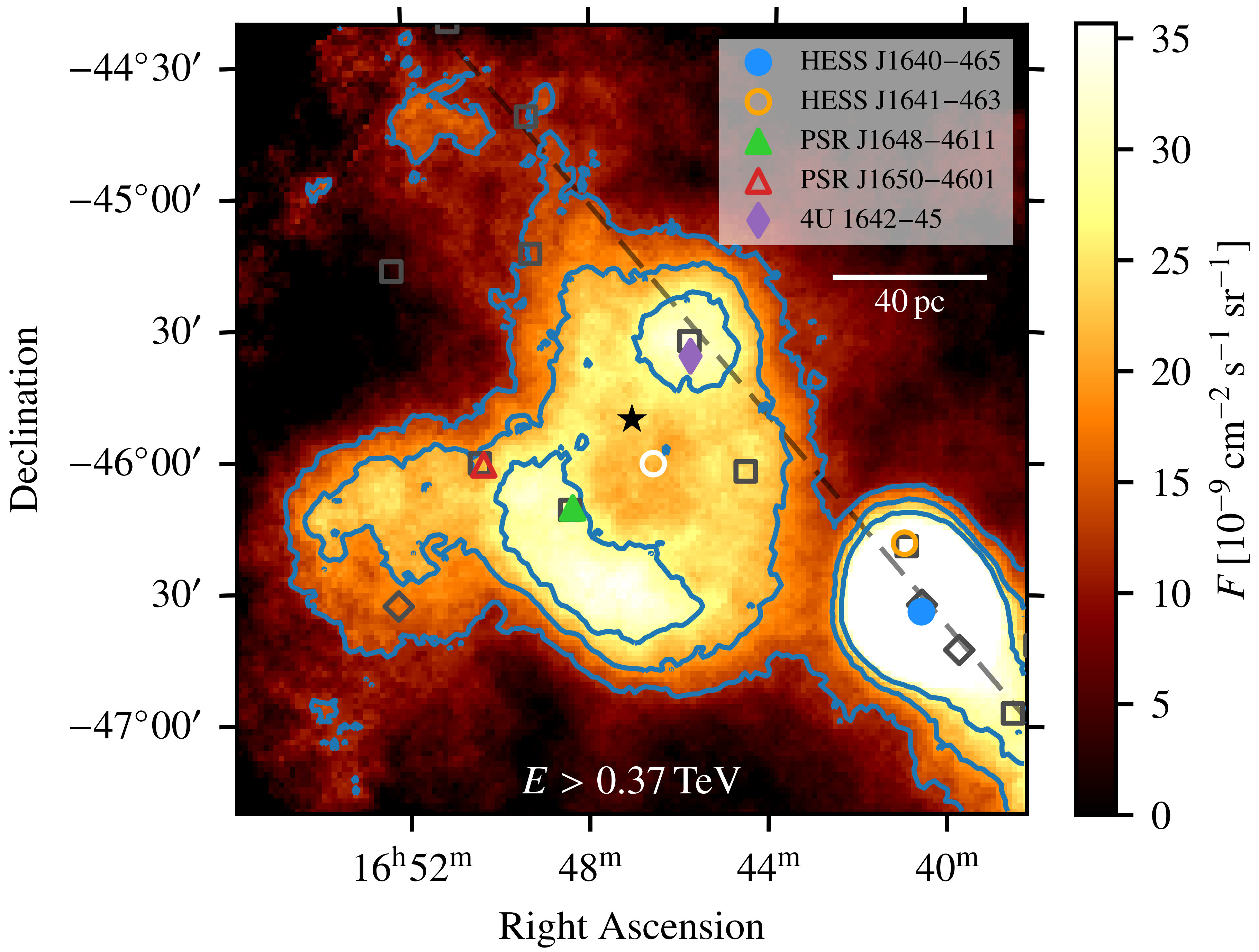
Interpretation

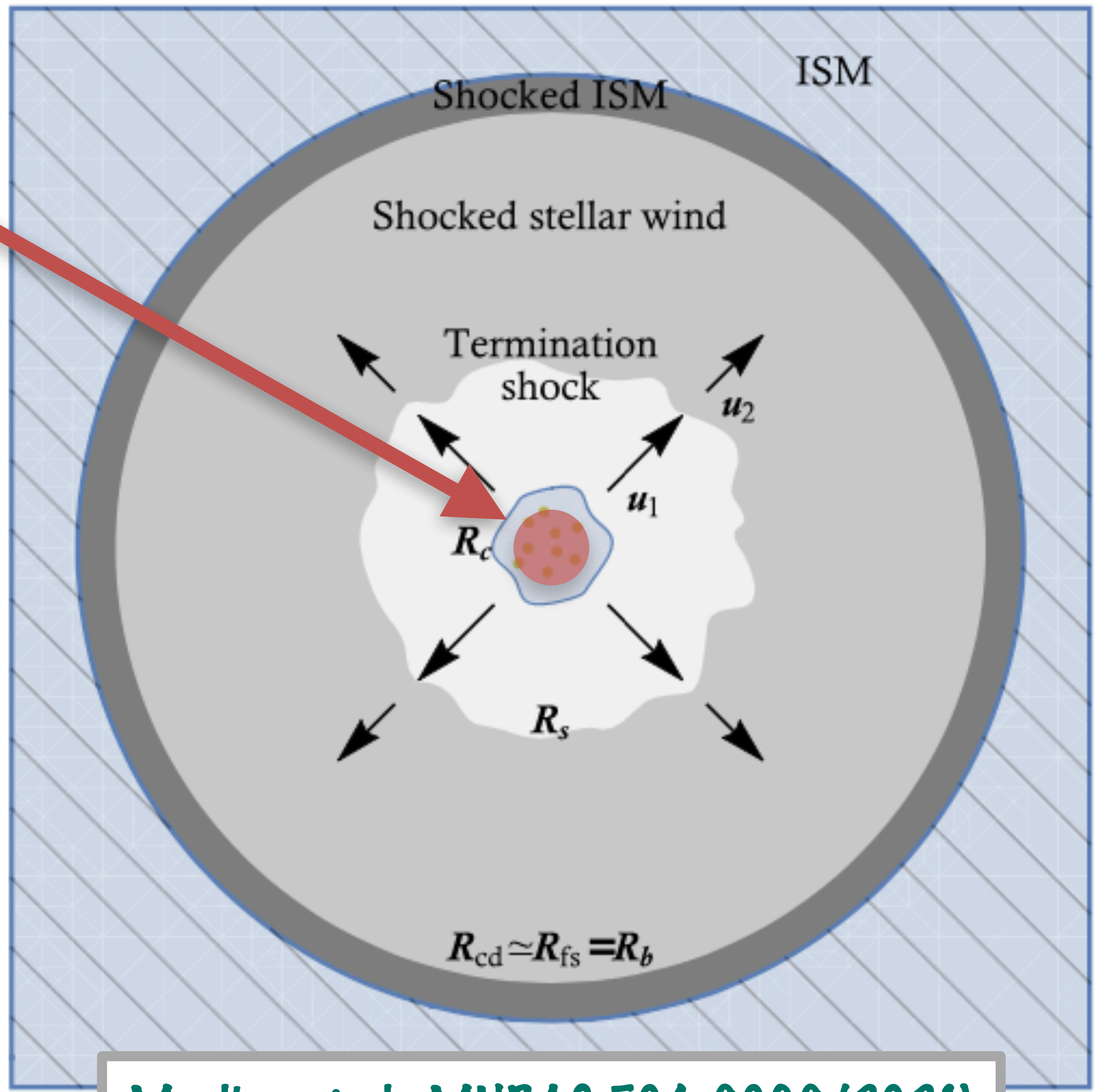
- Source association
  - only Westerlund 1 can explain majority of emission
  - pulsars / PWN may contribute locally



Interpretation

- Source association
  - only Westerlund 1 can explain majority of emission
  - pulsars / PWN may contribute locally
- Acceleration within cluster
  - at wind-wind or wind-supernova interactions
  - no energy-dependent morphology rules out leptonic scenario
  - hadronic scenario viable energetically, but need > PeV cosmic rays to overcome adiabatic energy losses during propagation





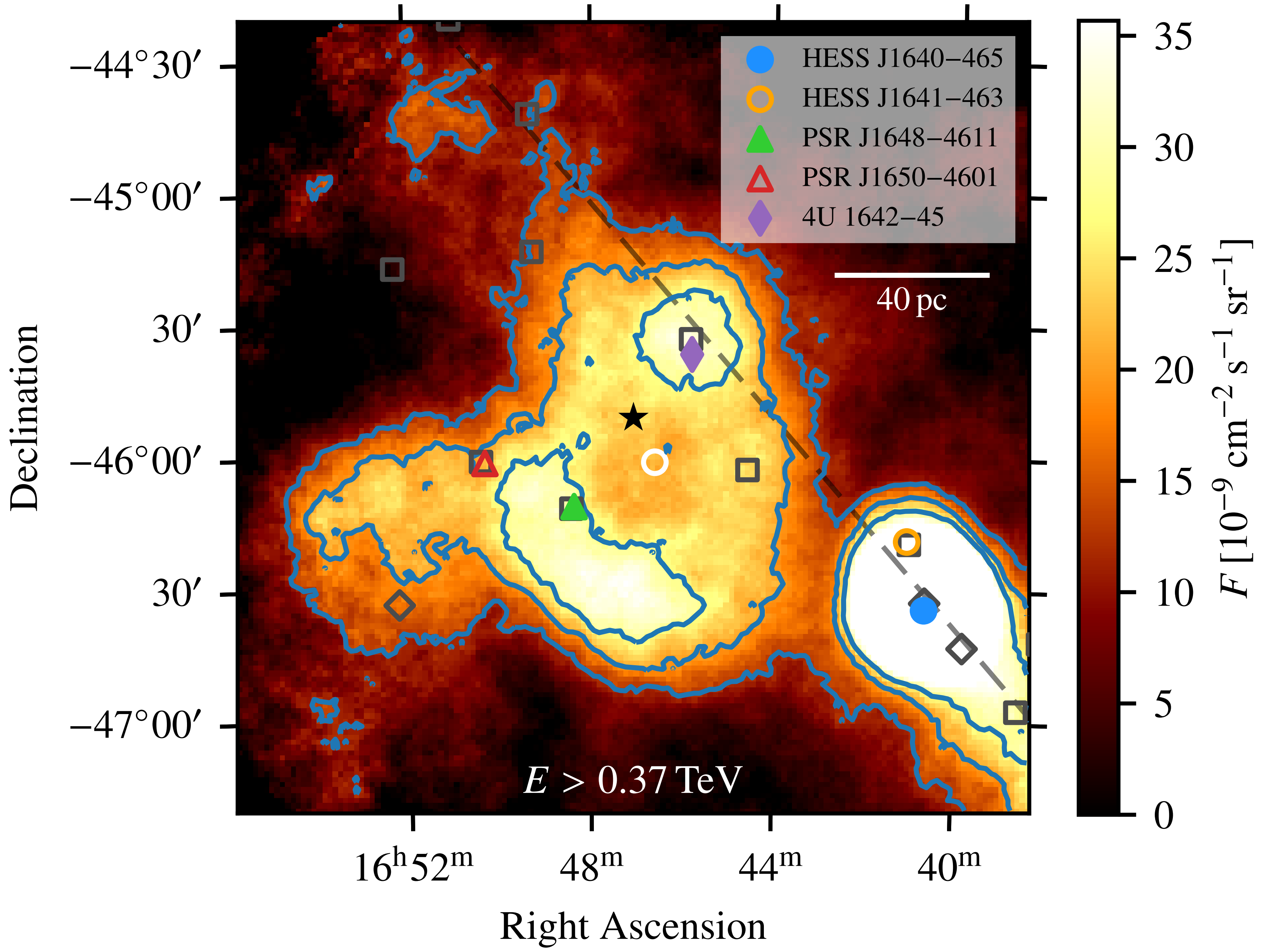
Morlino et al., MNRAS 504, 6096 (2021)

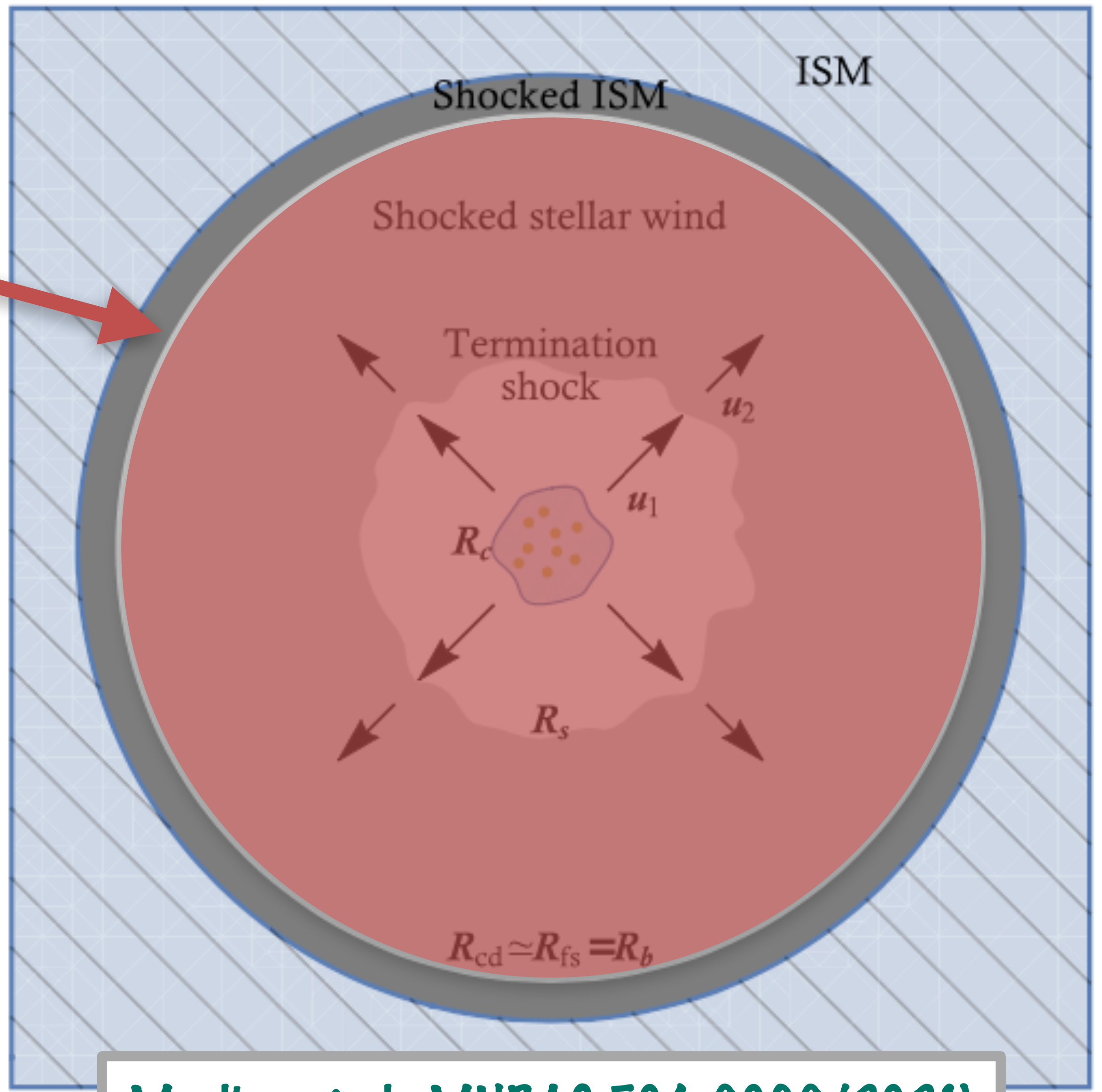
Interpretation

- Source association
  - only Westerlund 1 can explain majority of emission
  - pulsars / PWN may contribute locally

- Acceleration within cluster

- Acceleration in turbulent superbubble
  - Fermi type 2 acceleration via scattering off magnetic turbulences
  - basic superbubble models suggest $R_{\mathrm{SB}} \sim \mathcal{O}(180\,\mathrm{pc})$
  - exceeds gamma-ray emission, outer shock not observed
    → not favoured (but reality is more complex than basic models!)

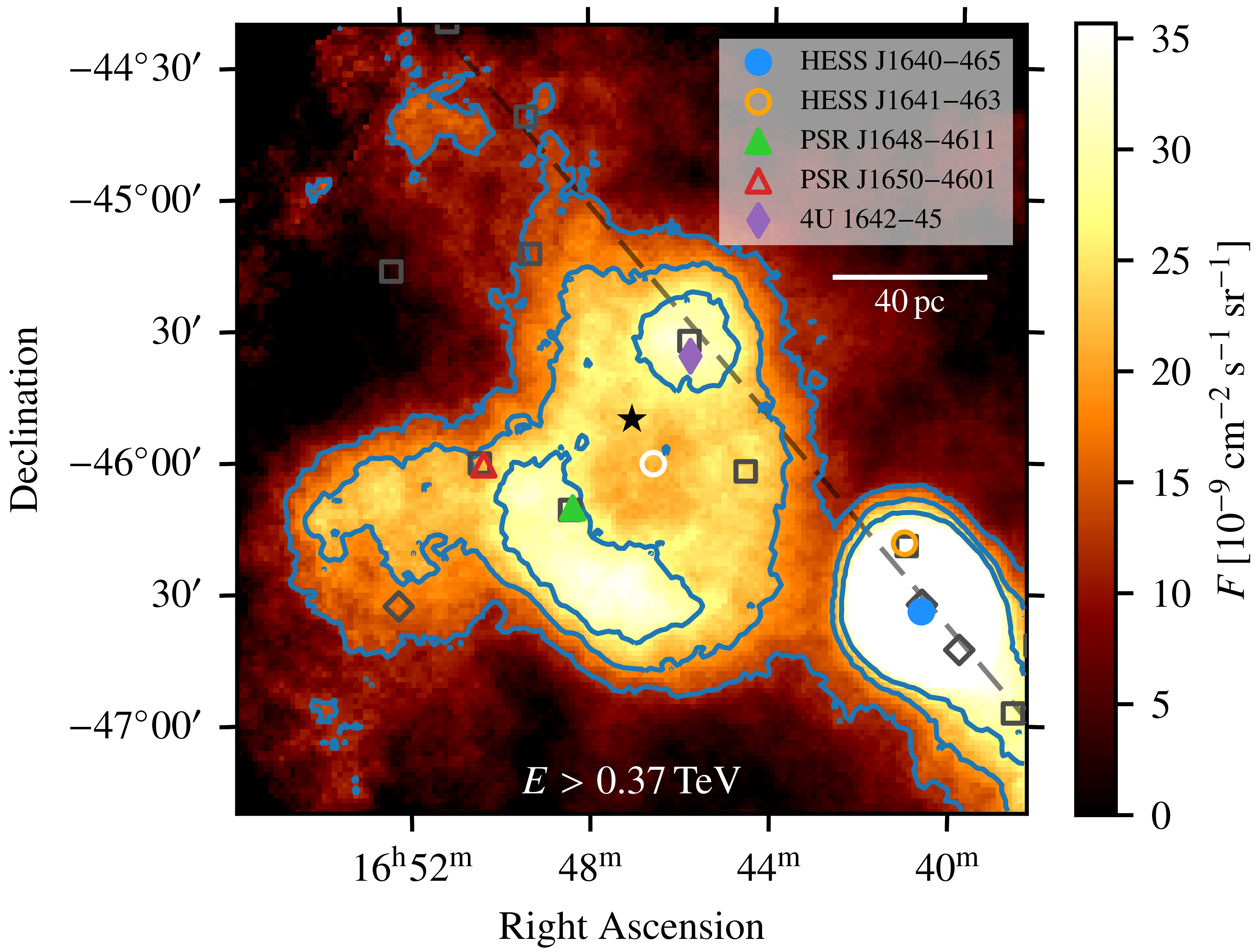


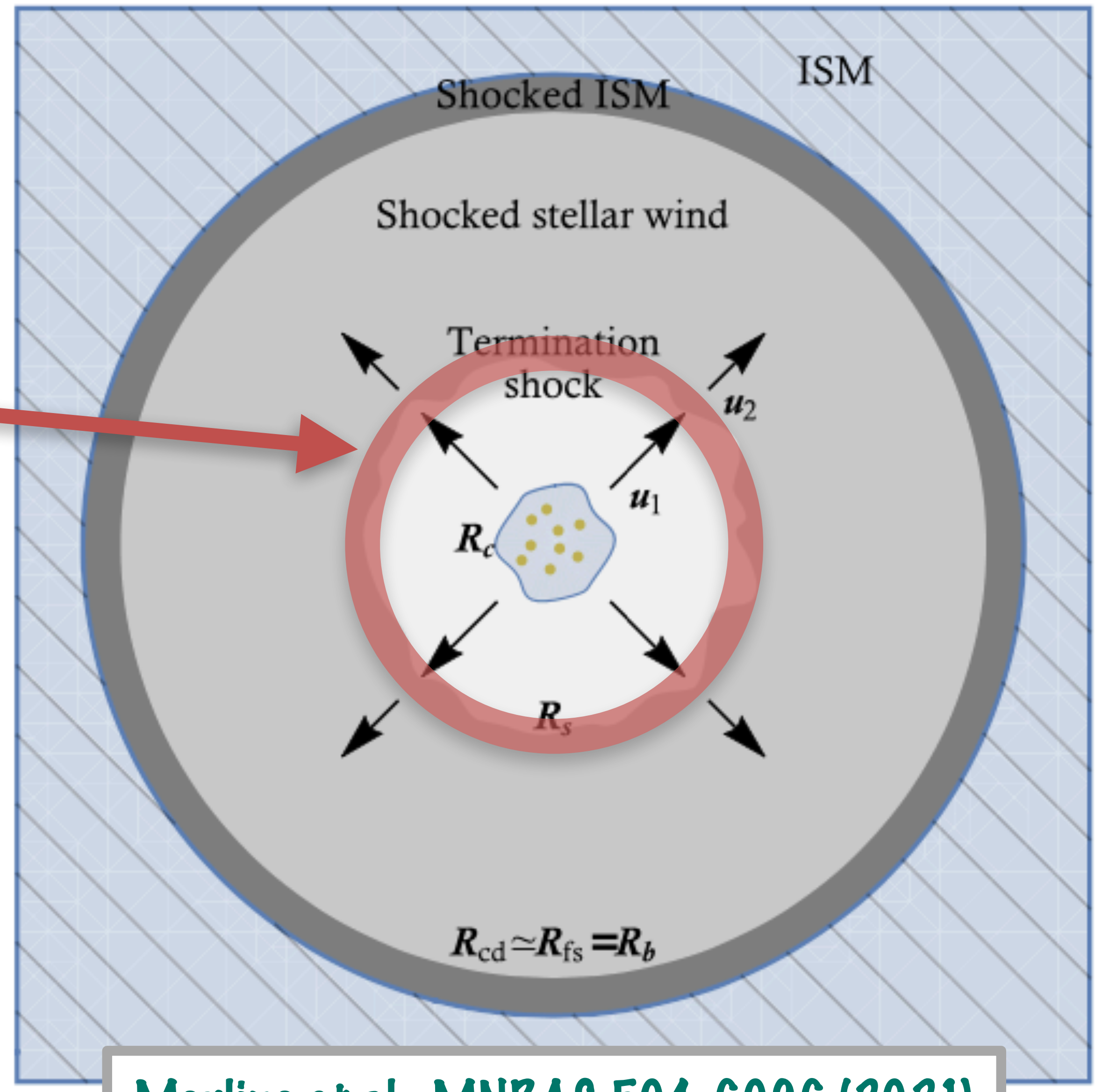


Morlino et al., MNRAS 504, 6096 (2021)

Interpretation

- Source association
  - only Westerlund 1 can explain majority of emission
  - pulsars / PWN may contribute locally
- Acceleration within cluster
- Acceleration in turbulent superbubble
- Acceleration at cluster wind termination shock
  - shock forms where wind pressure equals that of ISM
  - favourable acceleration site
  - basic superbubble models suggest $R_{\mathrm{TS}} \sim \mathcal{O}(30\,\mathrm{pc})$
  - ***matches radius of shell-like structure seen in gamma rays!***
  - 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)



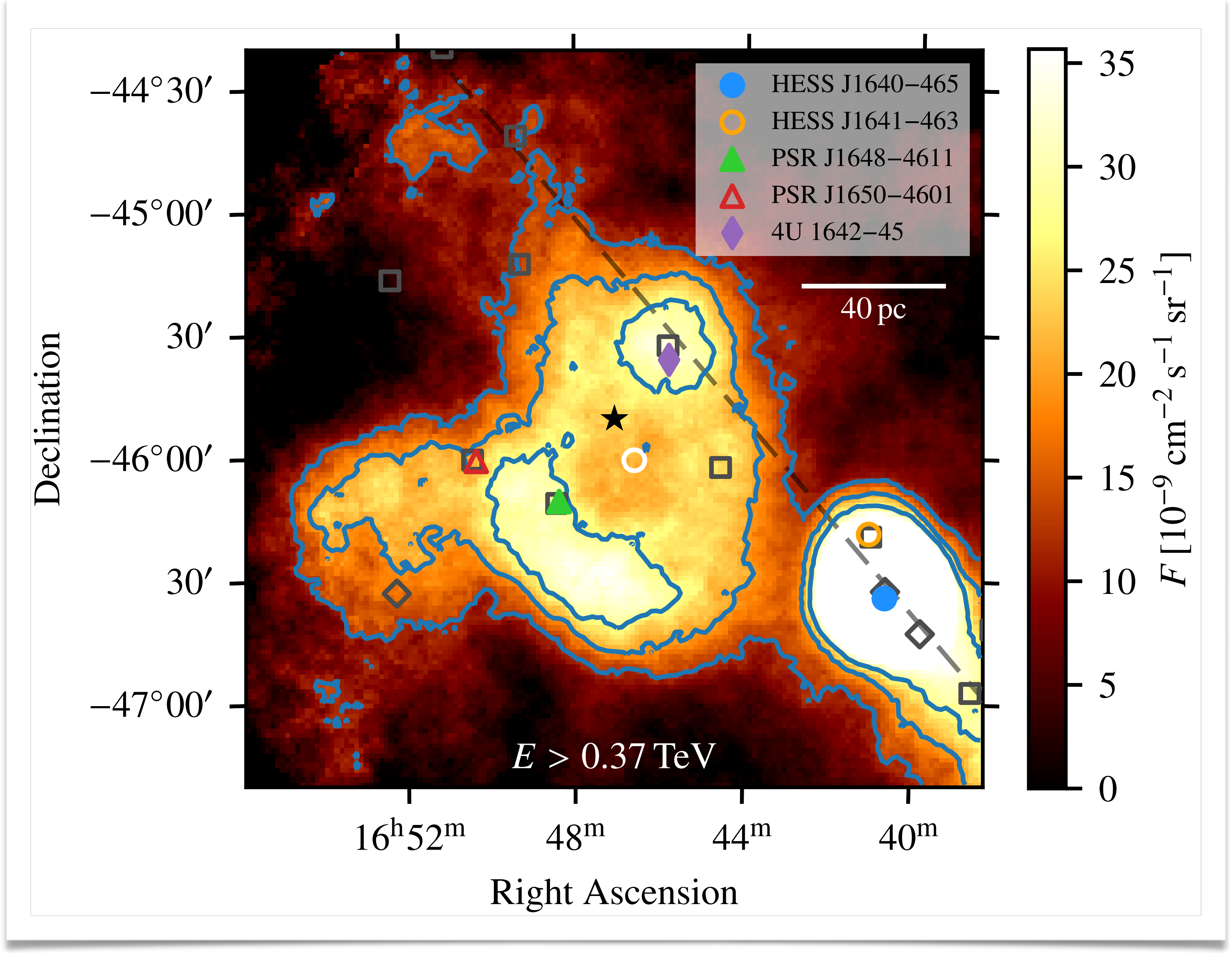


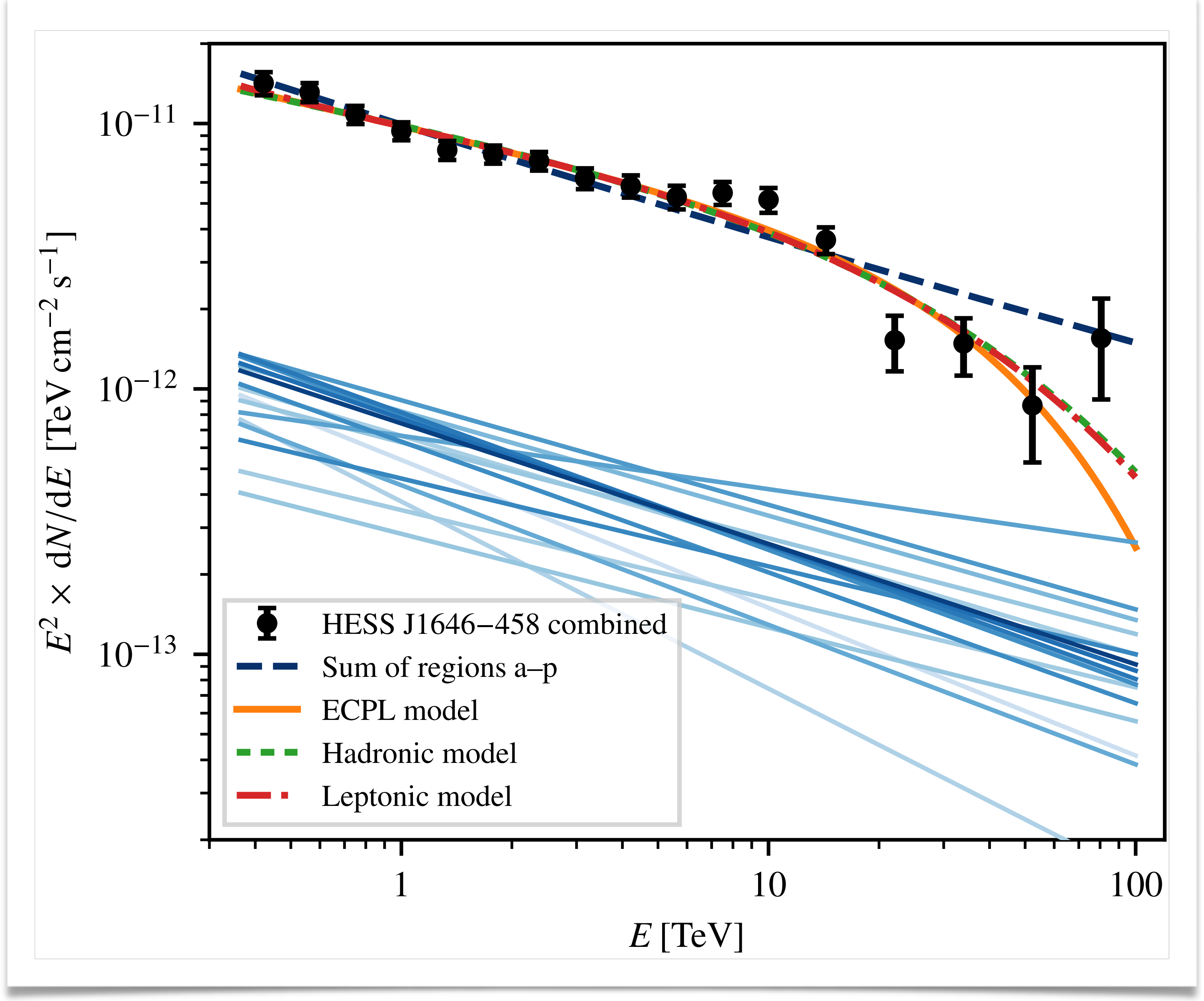
Morlino et al., MNRAS 504, 6096 (2021)

Conclusion

- Westerlund 1 is a powerful cosmic-ray accelerator!
- Gamma-ray emission exhibits intriguing shell-like structure
  - high angular resolution of IACTs crucial for observing this
  - connected to cluster wind termination shock?
- Spectrum extends to several tens of TeV
  - if hadronic origin → cosmic rays with hundreds of TeV

- Some open questions:
  - can we pinpoint the exact acceleration site/mechanism?
  - is Westerlund 1 a special case, or can we identify more clusters?
  - what is the contribution of star clusters to the flux of Galactic cosmic rays?

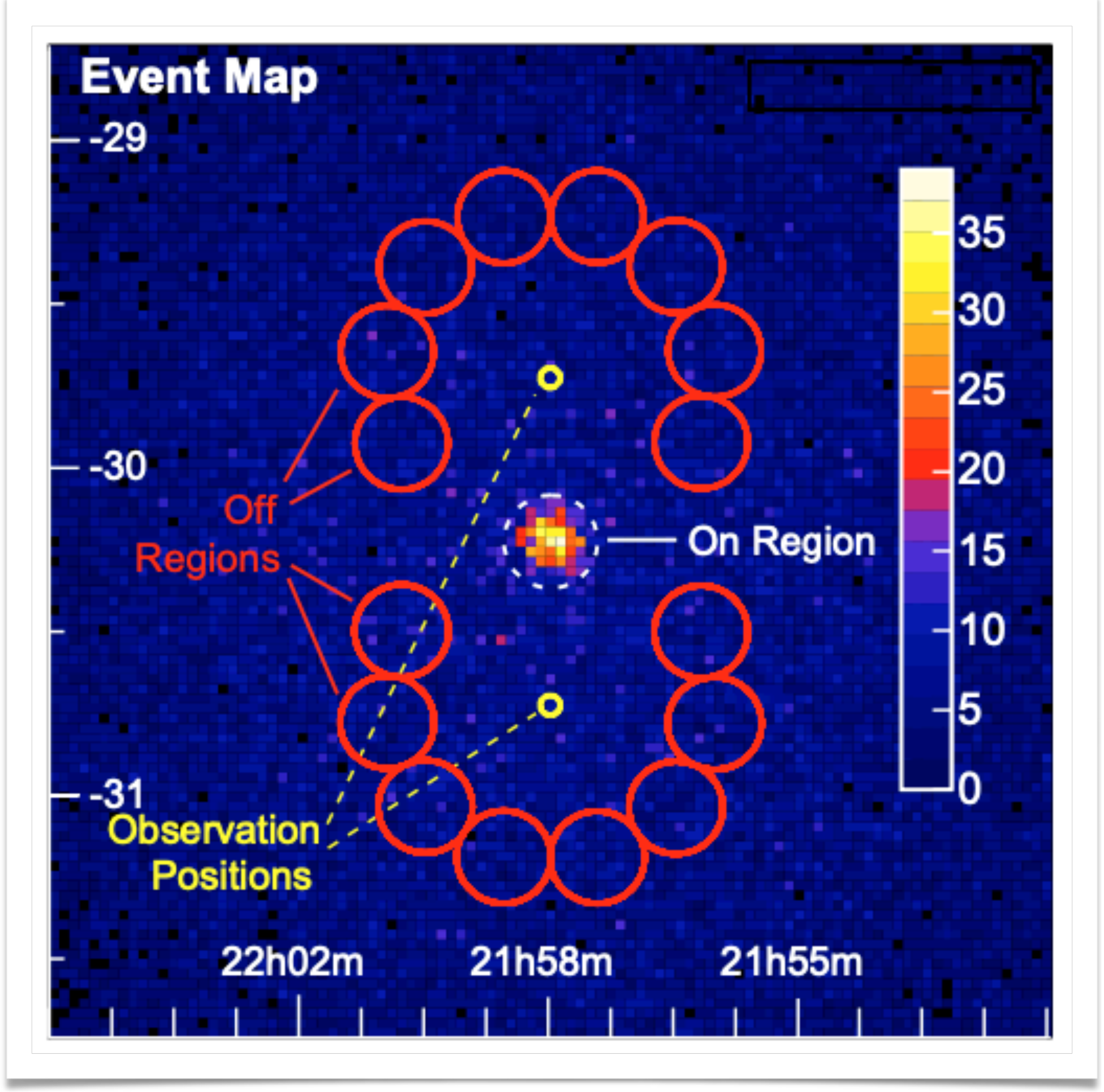




Backup slides

Treating the residual cosmic-ray background

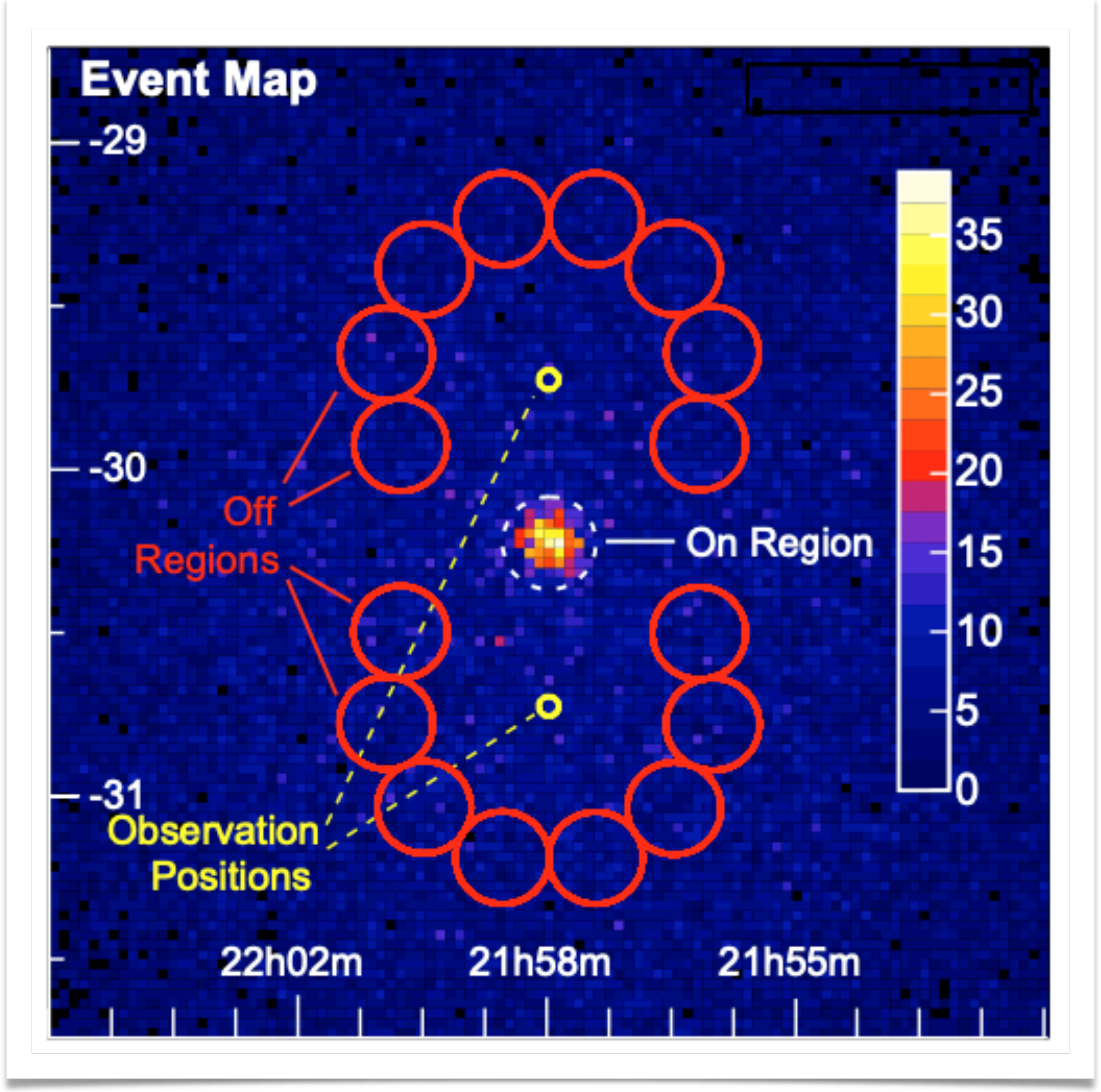
- “Residual background”
  - cosmic-ray events that remain after selection cuts
  - traditionally estimated from source-free regions in the field of view



Berge et al., A&A 466, 1219 (2007)

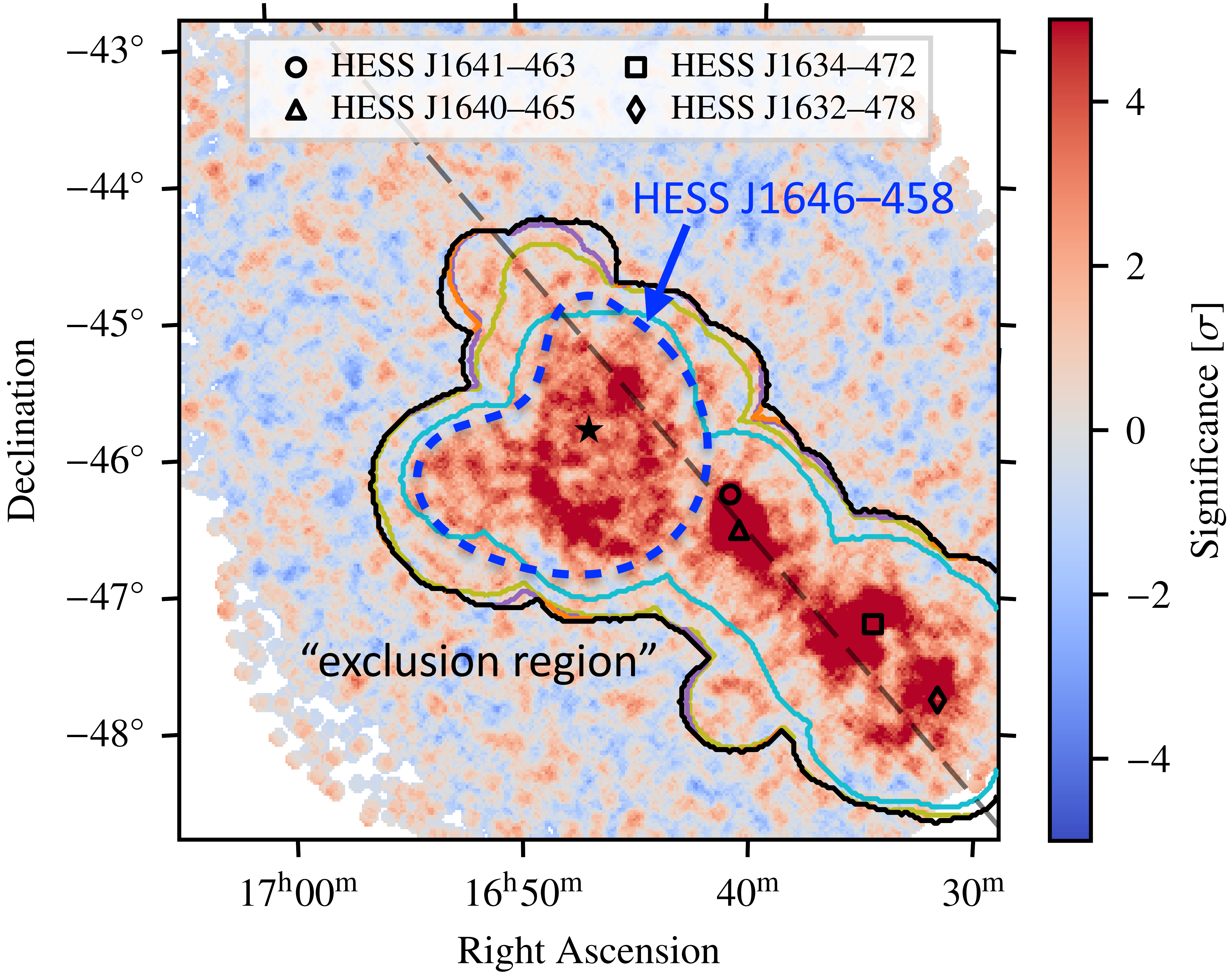
Treating the residual cosmic-ray background

- “Residual background”
  - cosmic-ray events that remain after selection cuts
  - traditionally estimated from source-free regions in the field of view



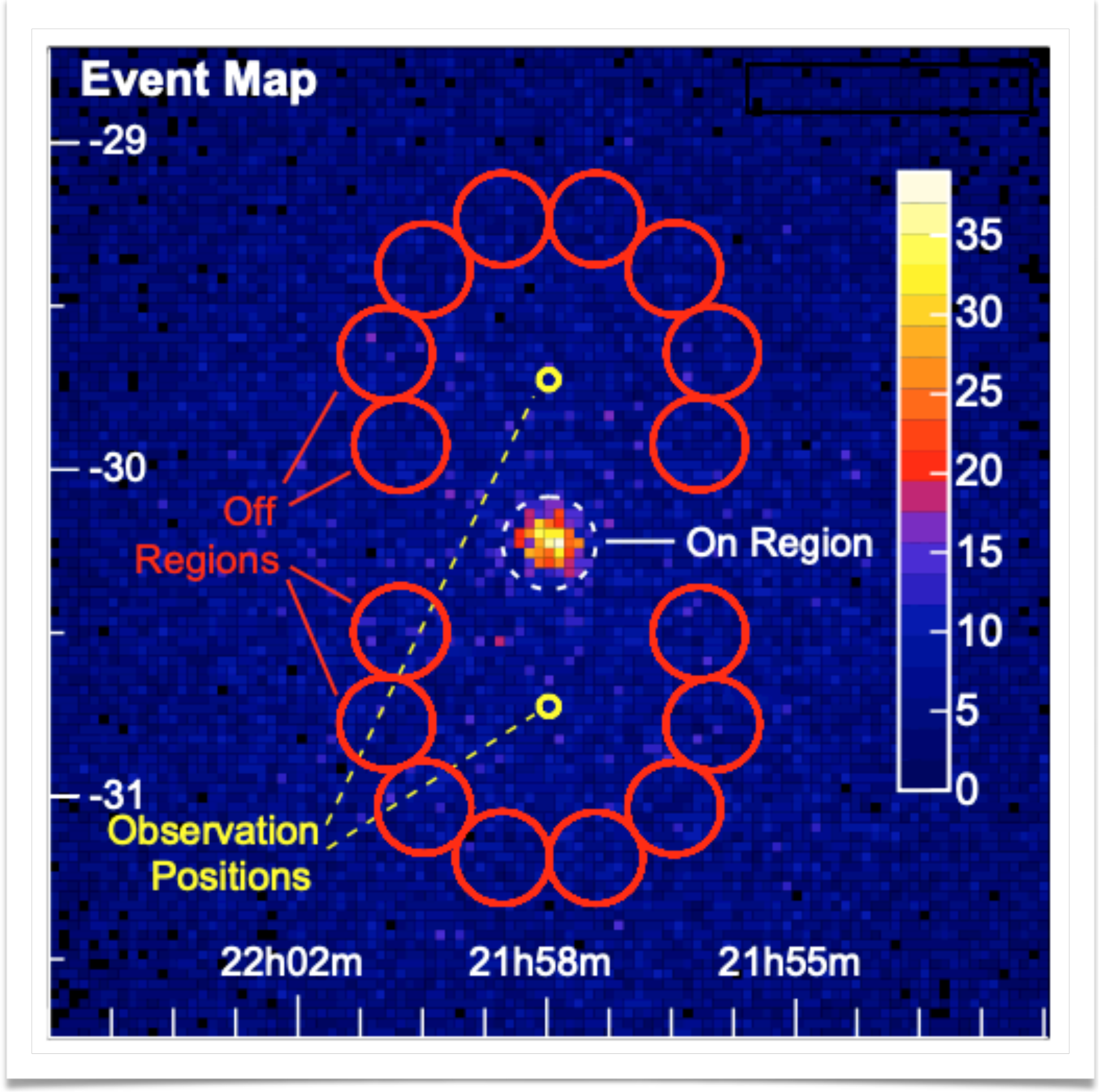
Berge et al., A&A 466, 1219 (2007)

Significance map



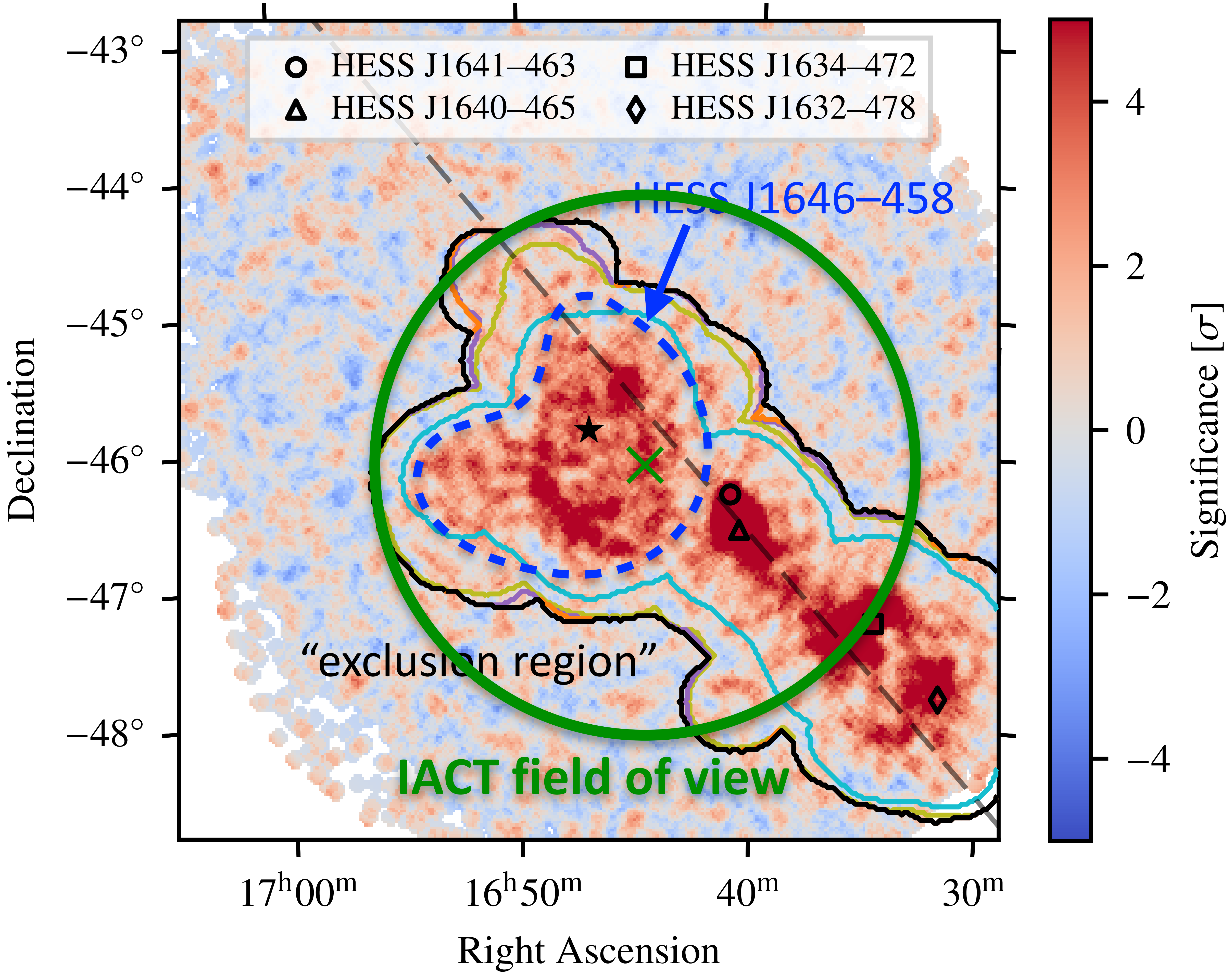
Treating the residual cosmic-ray background

- "Residual background"
  - cosmic-ray events that remain after selection cuts
  - traditionally estimated from source-free regions in the field of view



Berge et al., A&A 466, 1219 (2007)

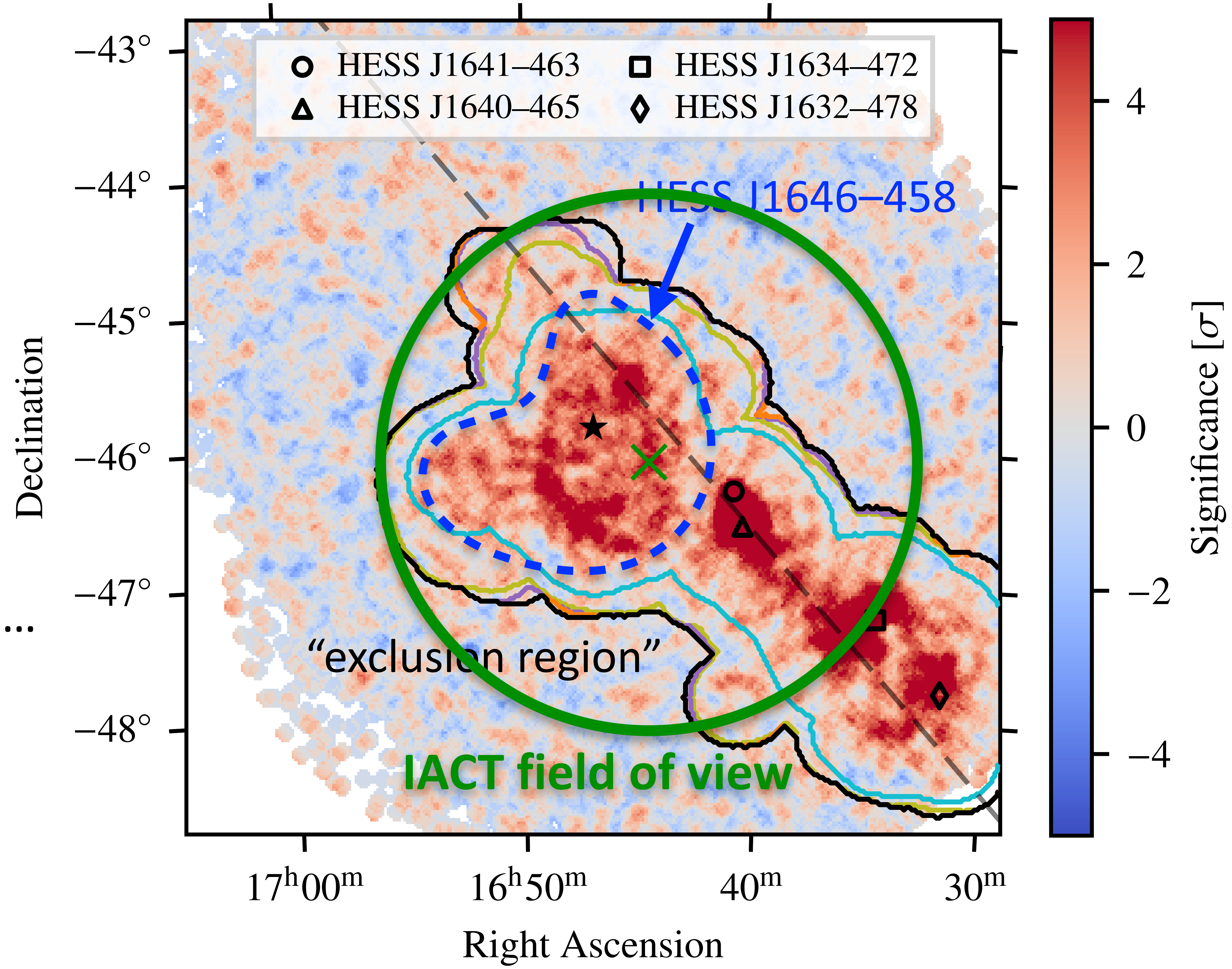
Significance map



Treating the residual cosmic-ray background

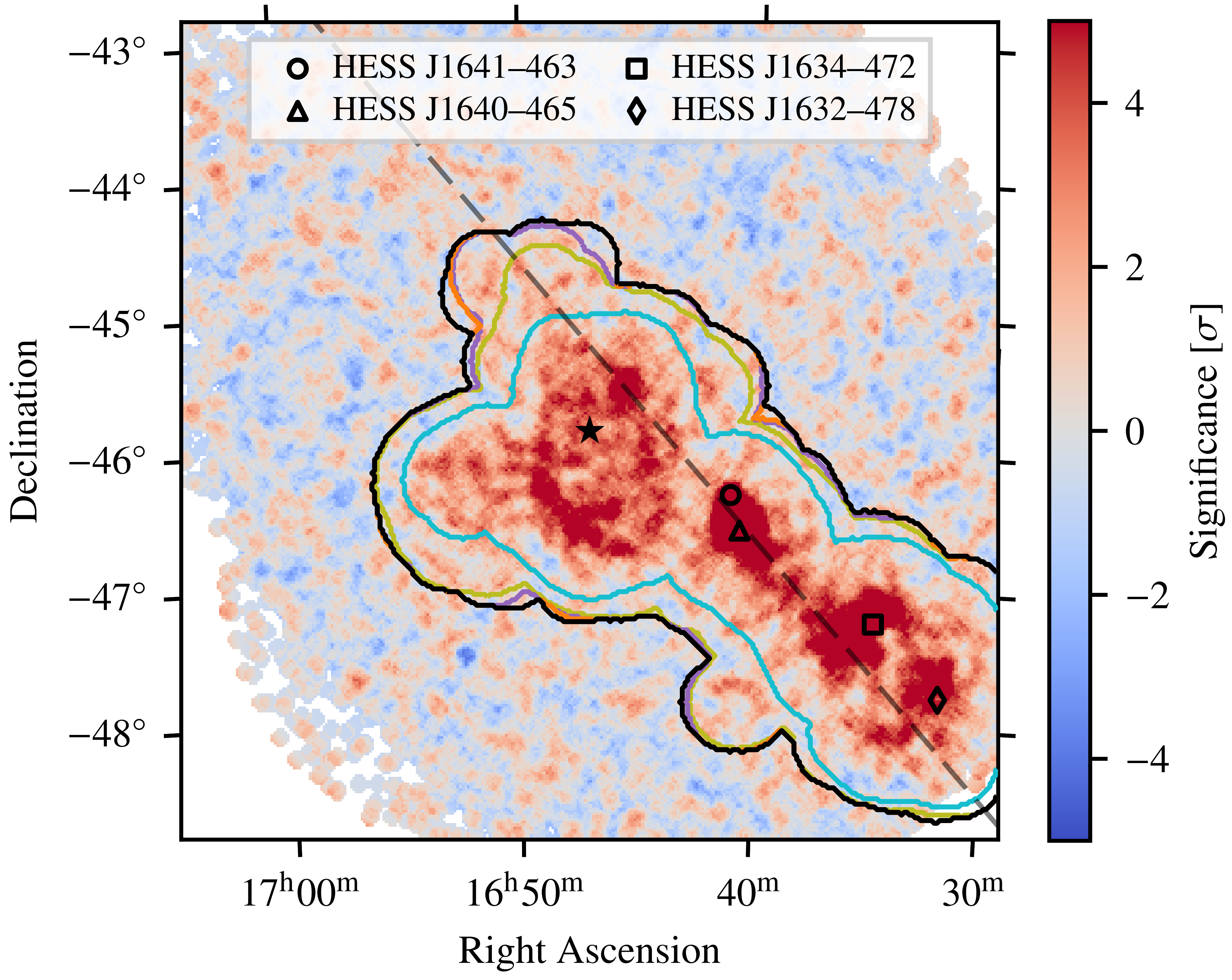
- “Residual background”
  - cosmic-ray events that remain after selection cuts
  - traditionally estimated from source-free regions in the field of view
- Background model
  - derived from archival observations
  - ***challenge:*** need to match (or correct for) observation conditions
    - zenith angle, optical throughput, atmospheric conditions…
  - very relevant for CTA!
  - Details: ***Mohrmann et al., A&A 632, A72 (2019)***

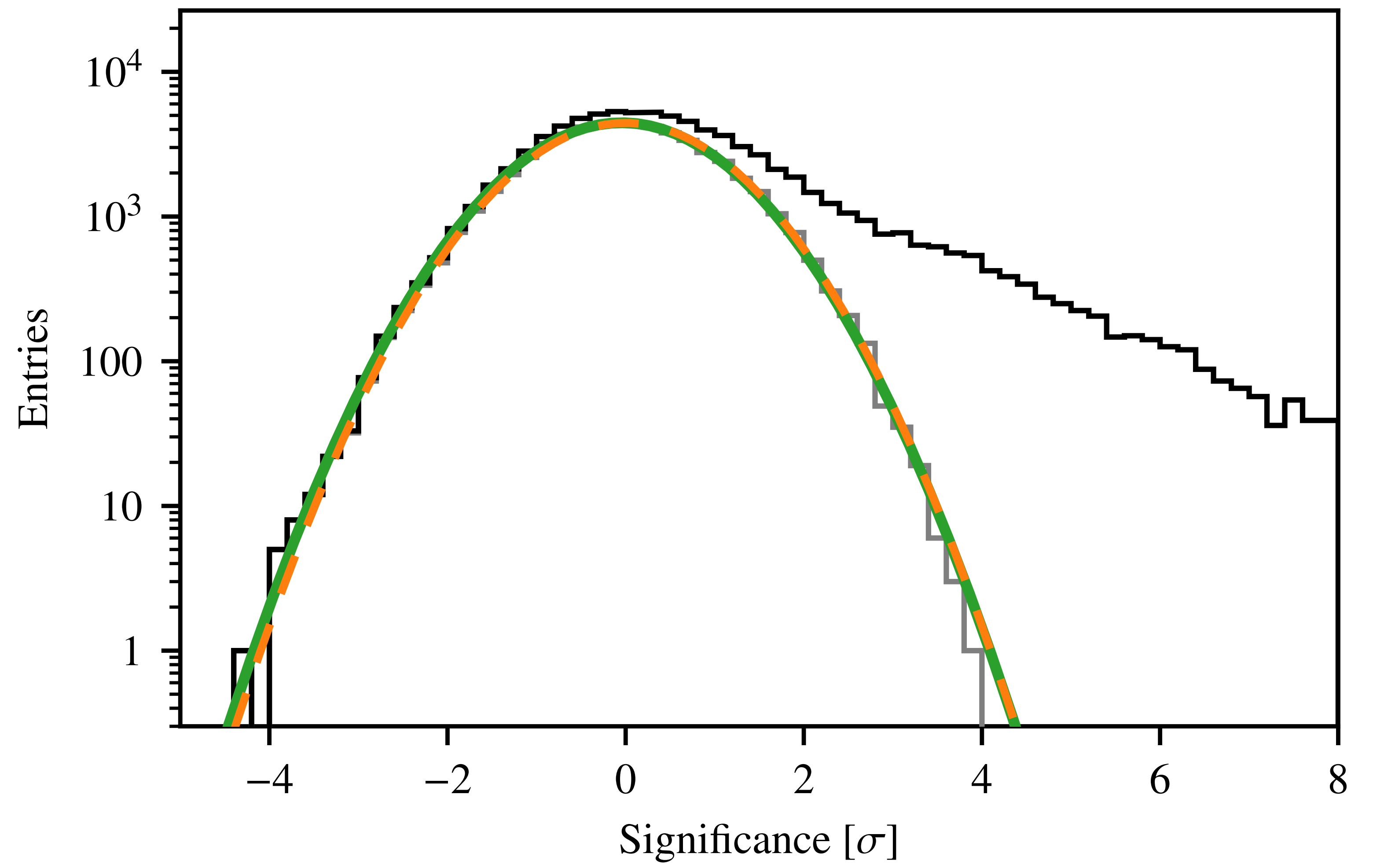
Significance map

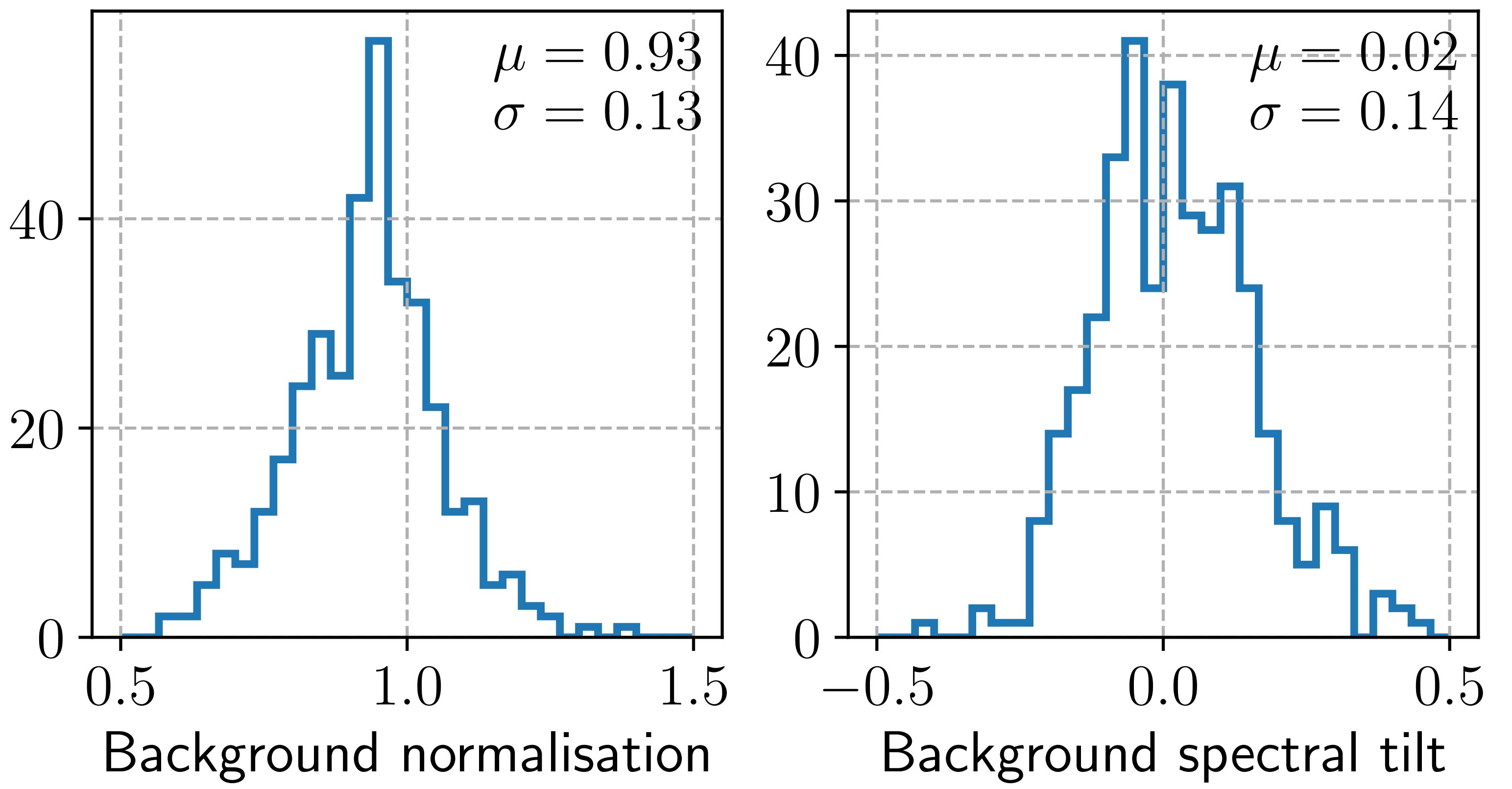


Fit of hadronic background model

- Adjust model for each run via two parameters
  - normalisation (global scaling)
  - spectral tilt (factor $(E/E_0)^{-\delta}$)
- Adjustment done outside exclusion region
  - derived in iterative procedure
- Resulting significance distribution indicates good agreement







Distance to Westerlund 1

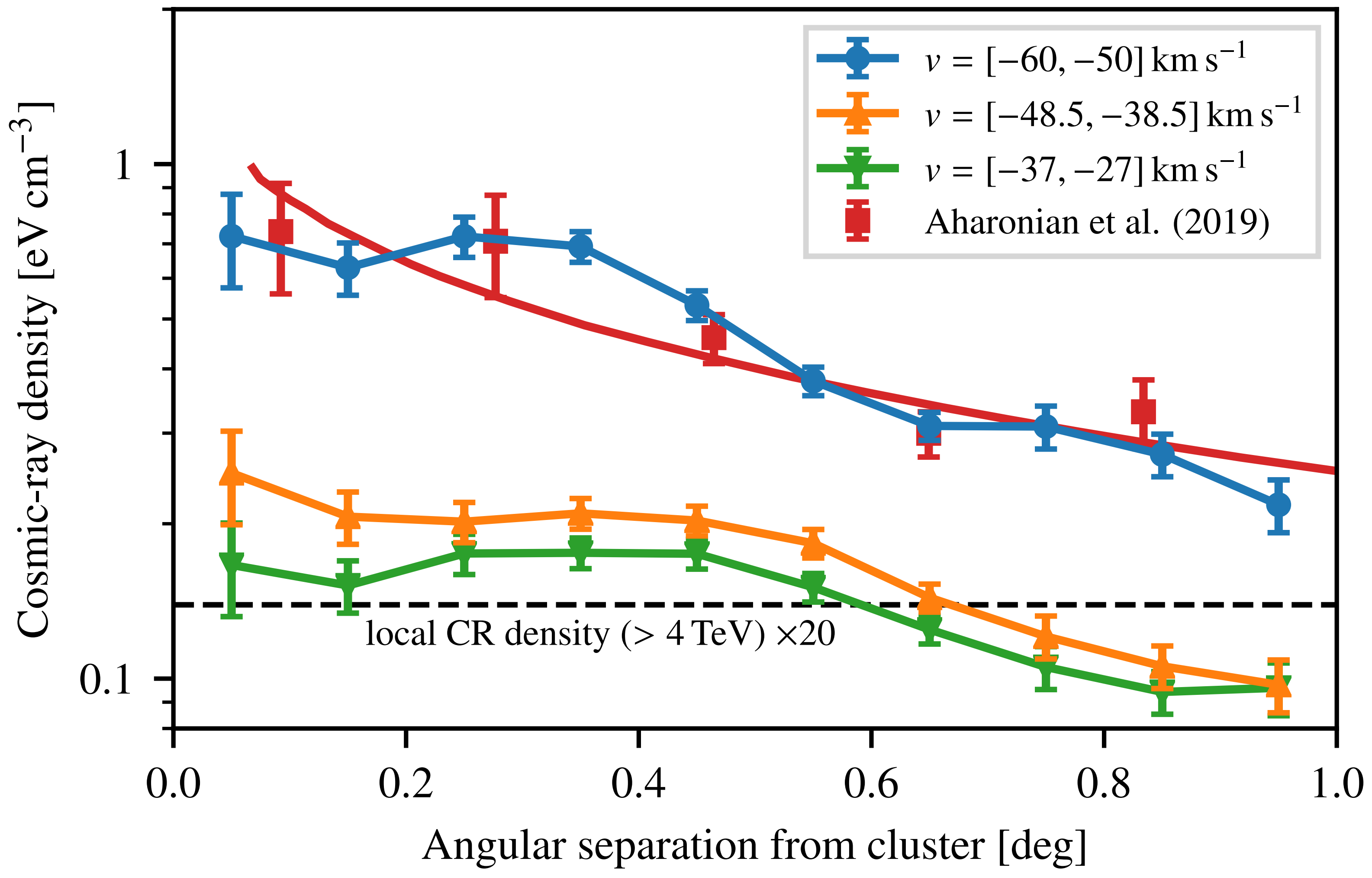
Reference	Distance (kpc)	Method
Clark et al. 2005	< 5.5	Yellow Hypergiants
Crowther et al. 2006	$5.0^{+0.5}_{-1.0}$	Wolf-Rayet stars
Kothes & Dougherty 2007	3.9 ± 0.7	H I observations
Brandner et al. 2008	3.55 ± 0.17	Near-infrared observations, colour-magnitude diagram
Aghakhanloo et al. 2020	$2.6^{+0.6}_{-0.4}$	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
Navarete et al. 2022	4.05 ± 0.20	Gaia (EDR3) parallaxes, eclipsing binary W36

- Uncertain for a long time
- Recent studies based on Gaia data converge on 4 kpc — seems relatively secure

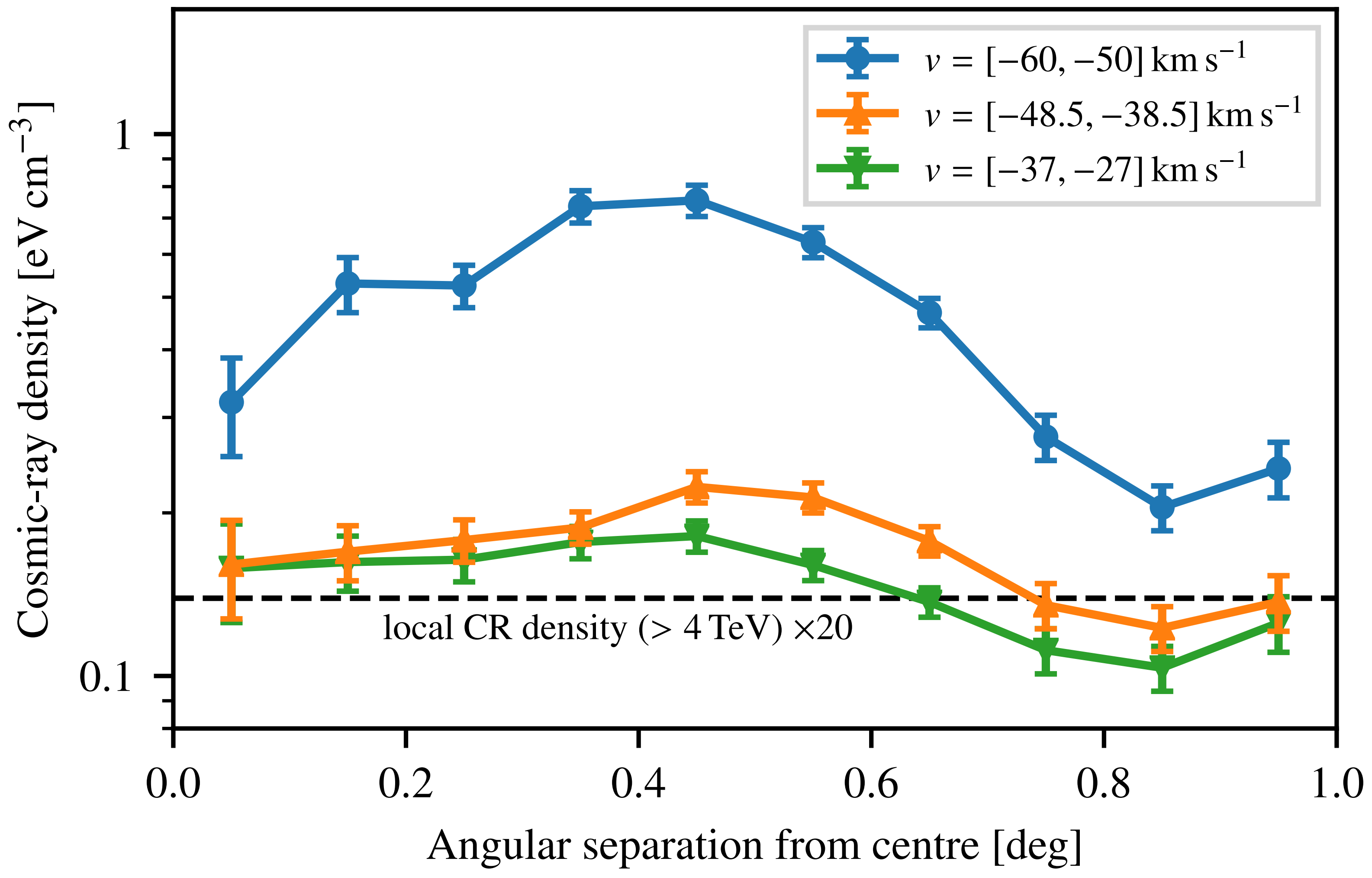
Cosmic-ray density profiles

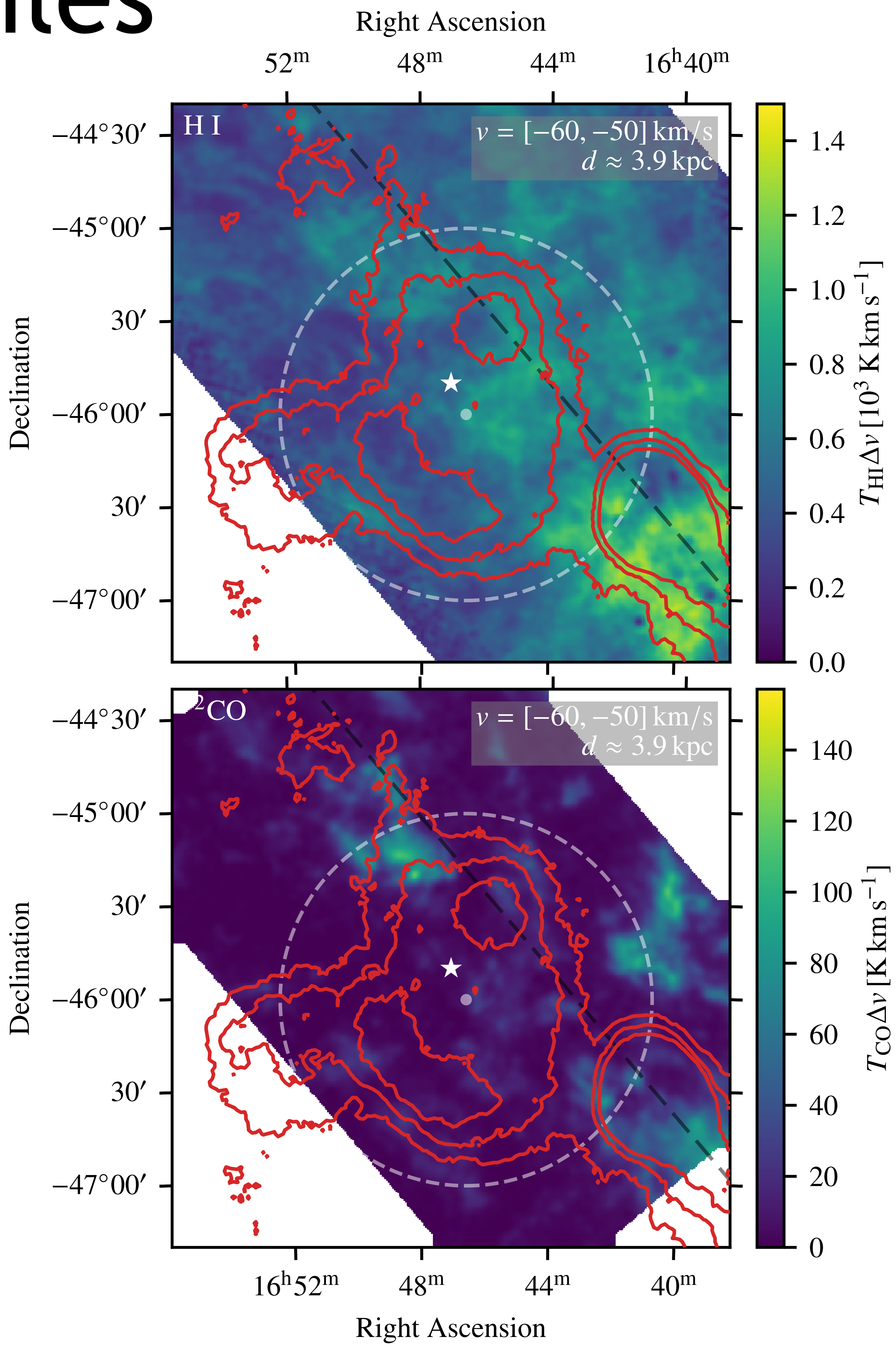
- Assume gamma-ray emission is fully hadronic and we know the gas distribution → can infer cosmic-ray distribution
- Profile w.r.t. cluster position compatible with Aharonian et al. (who claimed to observe 1/r profile)
- However, profile w.r.t. centroid of emission not peaked towards centre!

w.r.t. cluster position



w.r.t. centroid



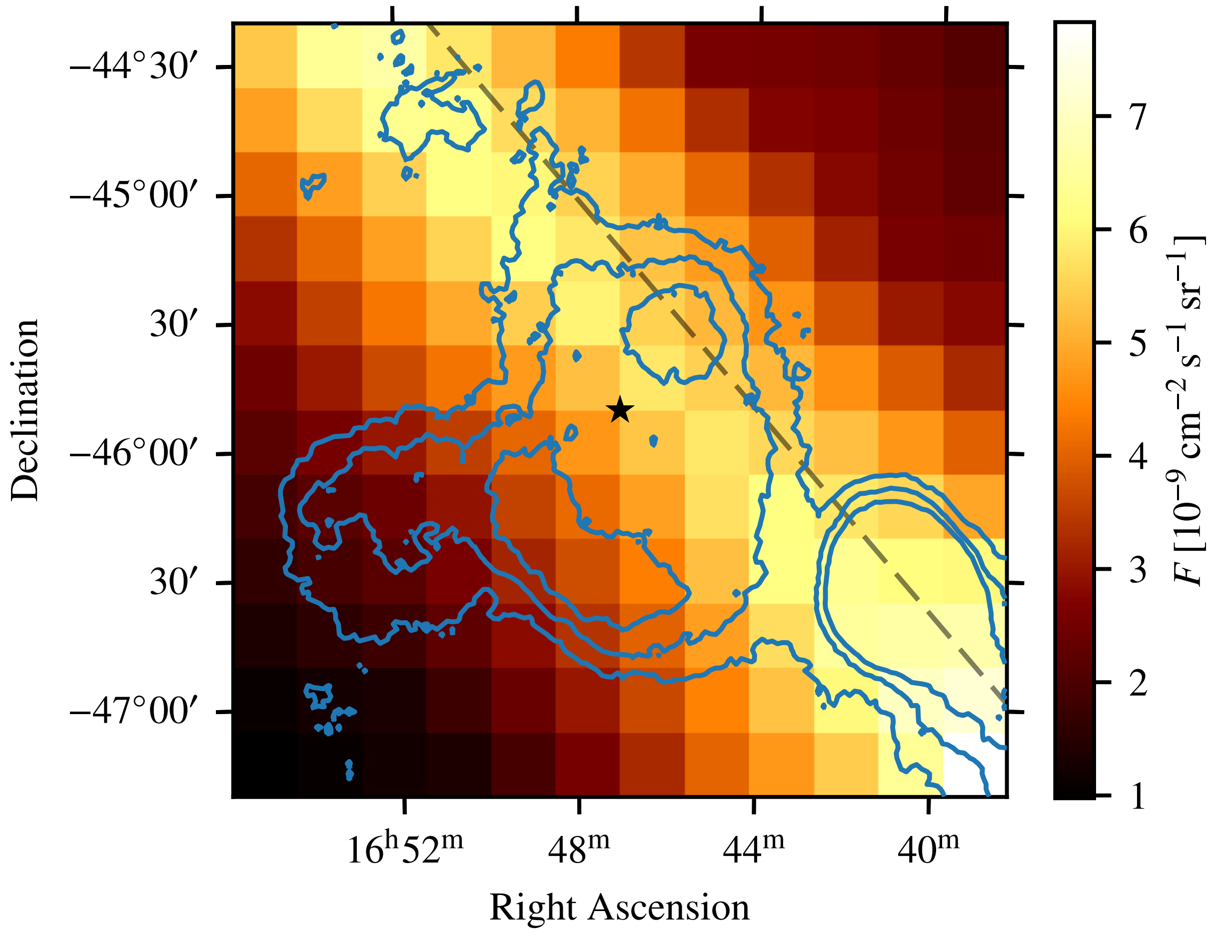


Galactic diffuse emission

- Likely contributes to emission, but is difficult to estimate

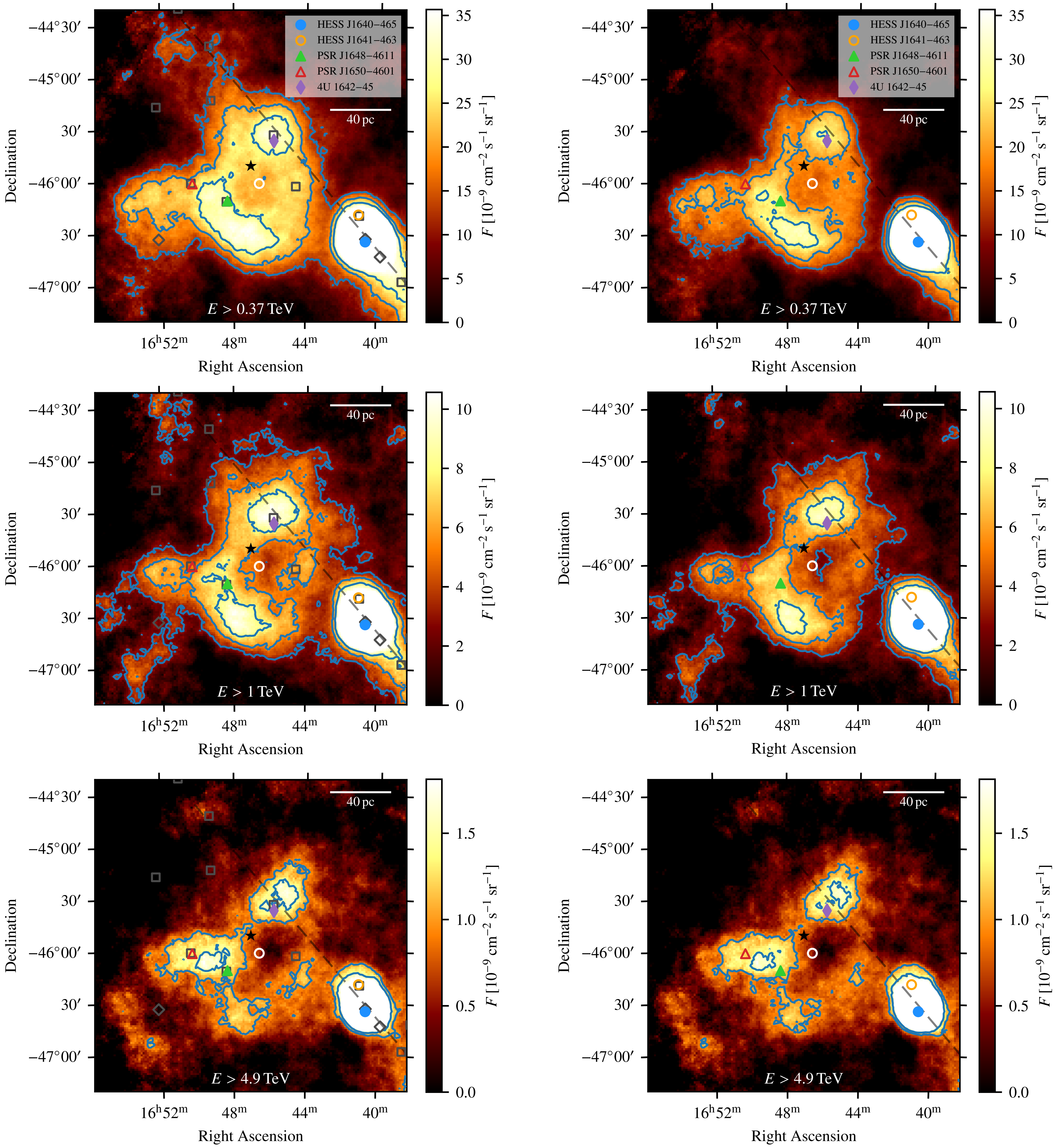
Kissmann, Astropart. Phys. 55, 37 (2014)

- Use prediction from PICARD propagation code
- Absolute flux level is very uncertain!
- Shell-like structure not affected



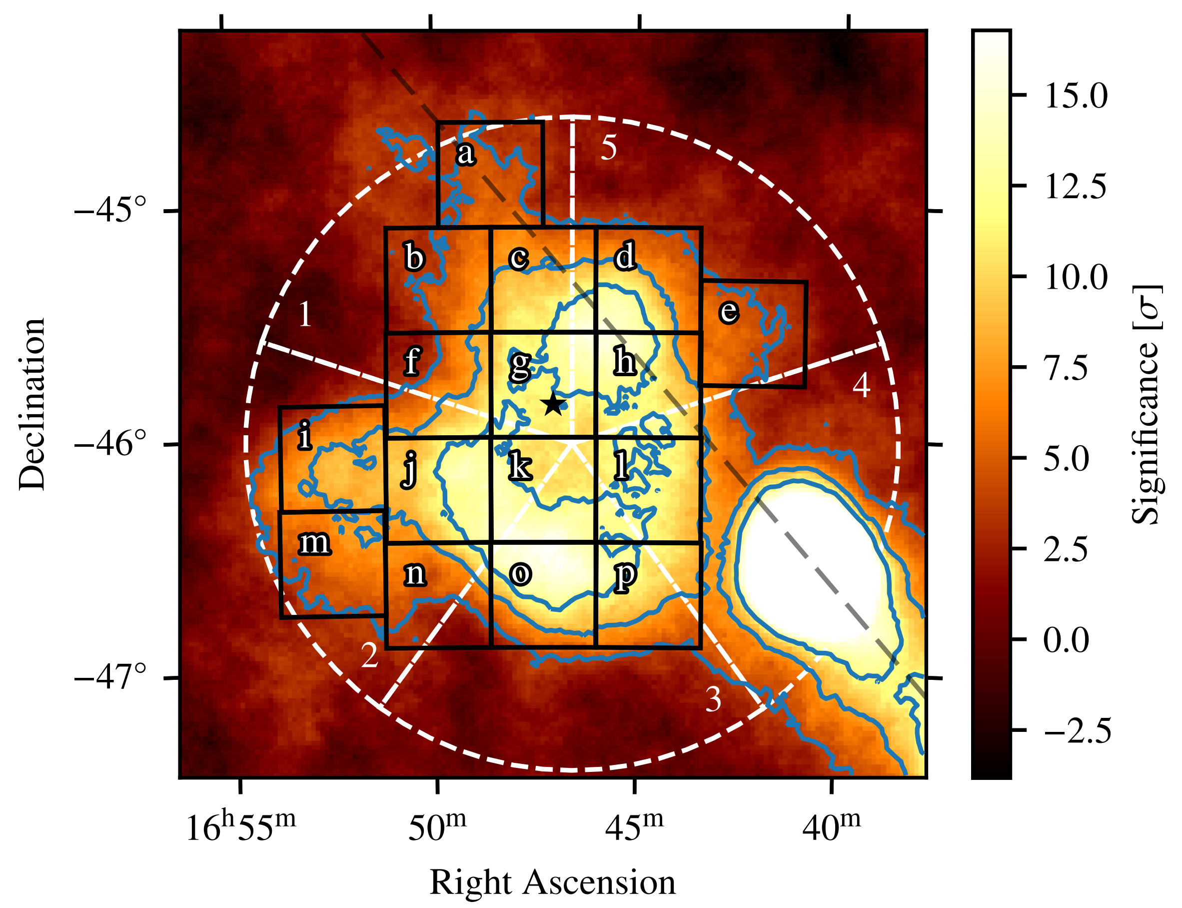
original

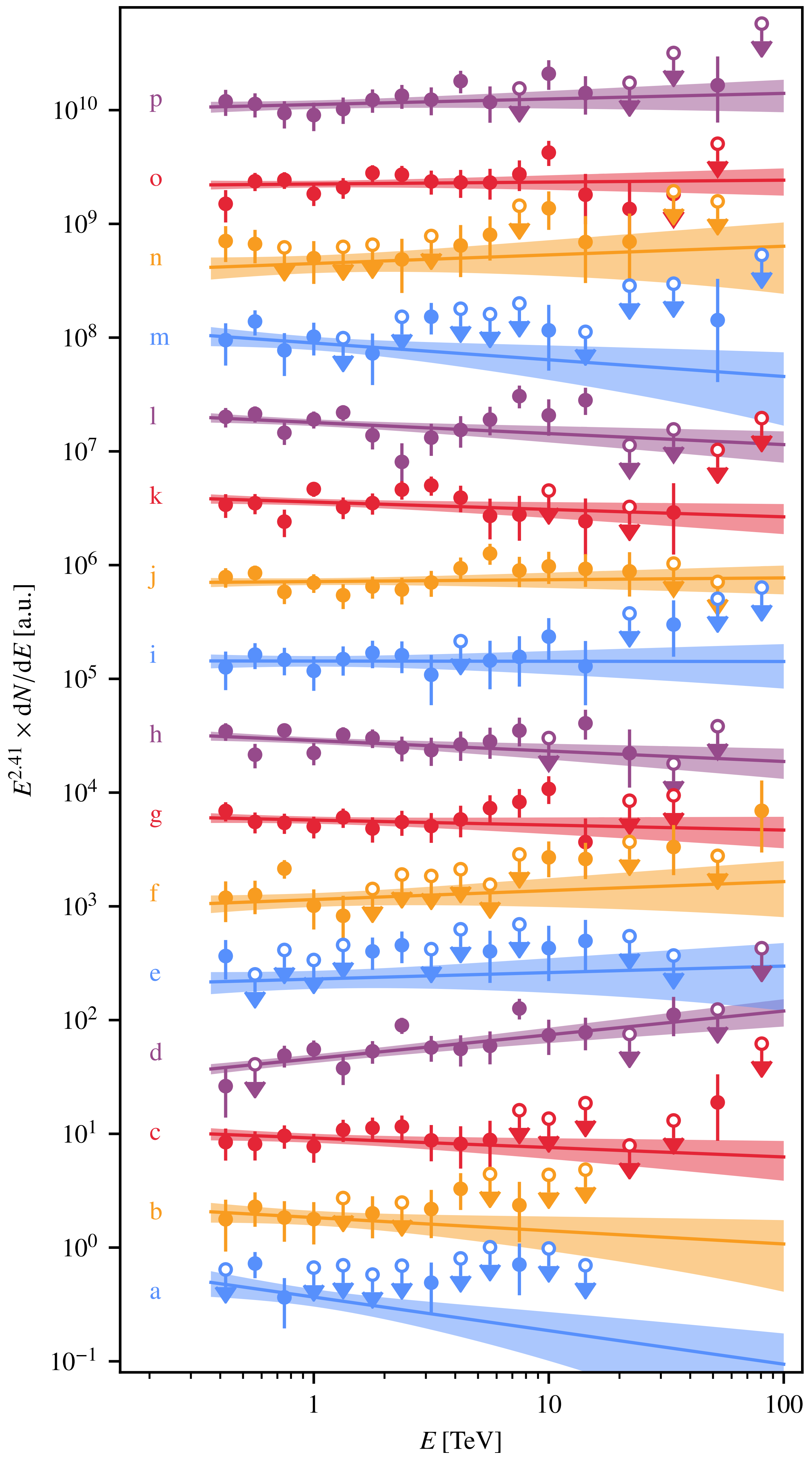
diffuse subtracted



Signal region energy spectra

- Very similar 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