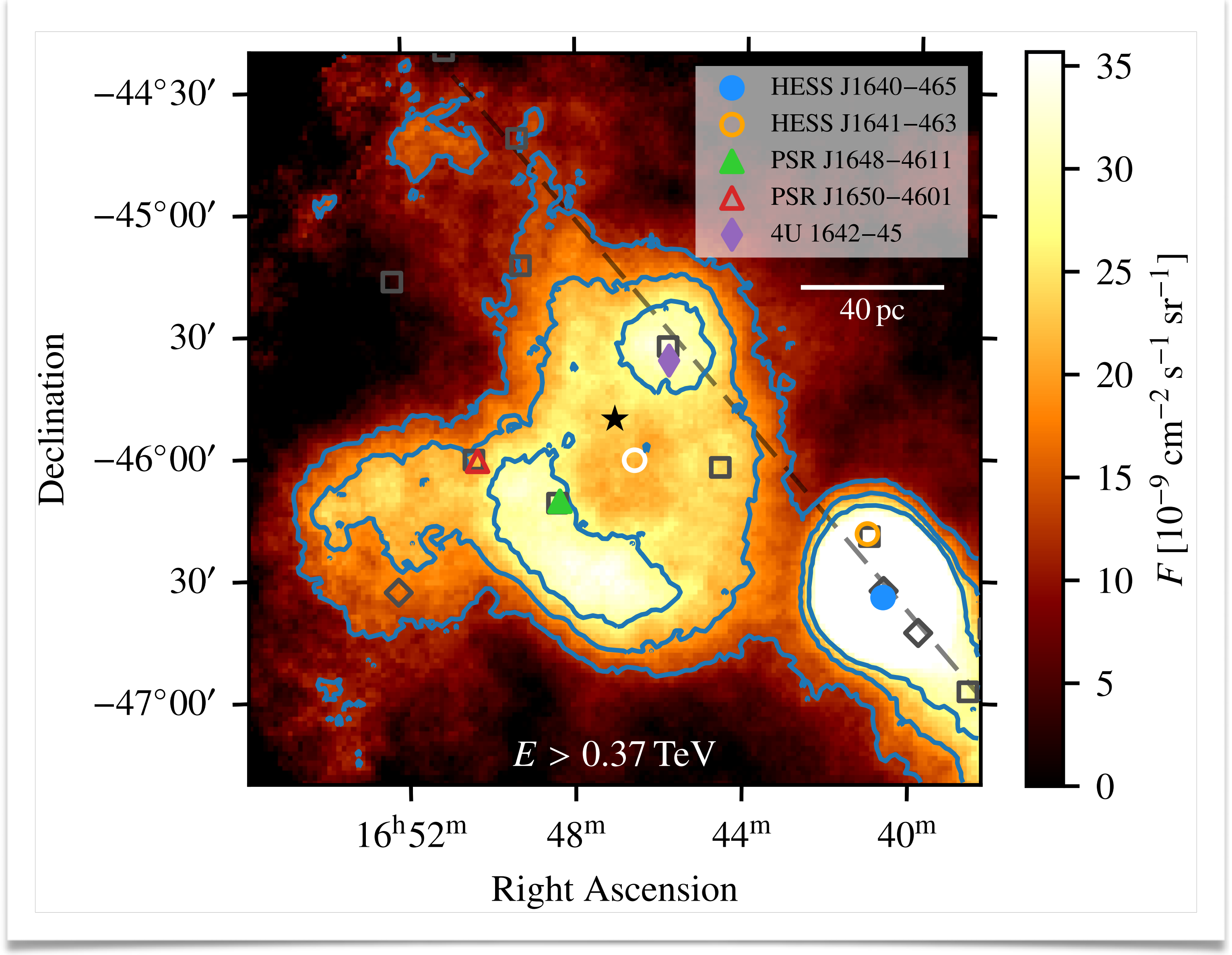
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

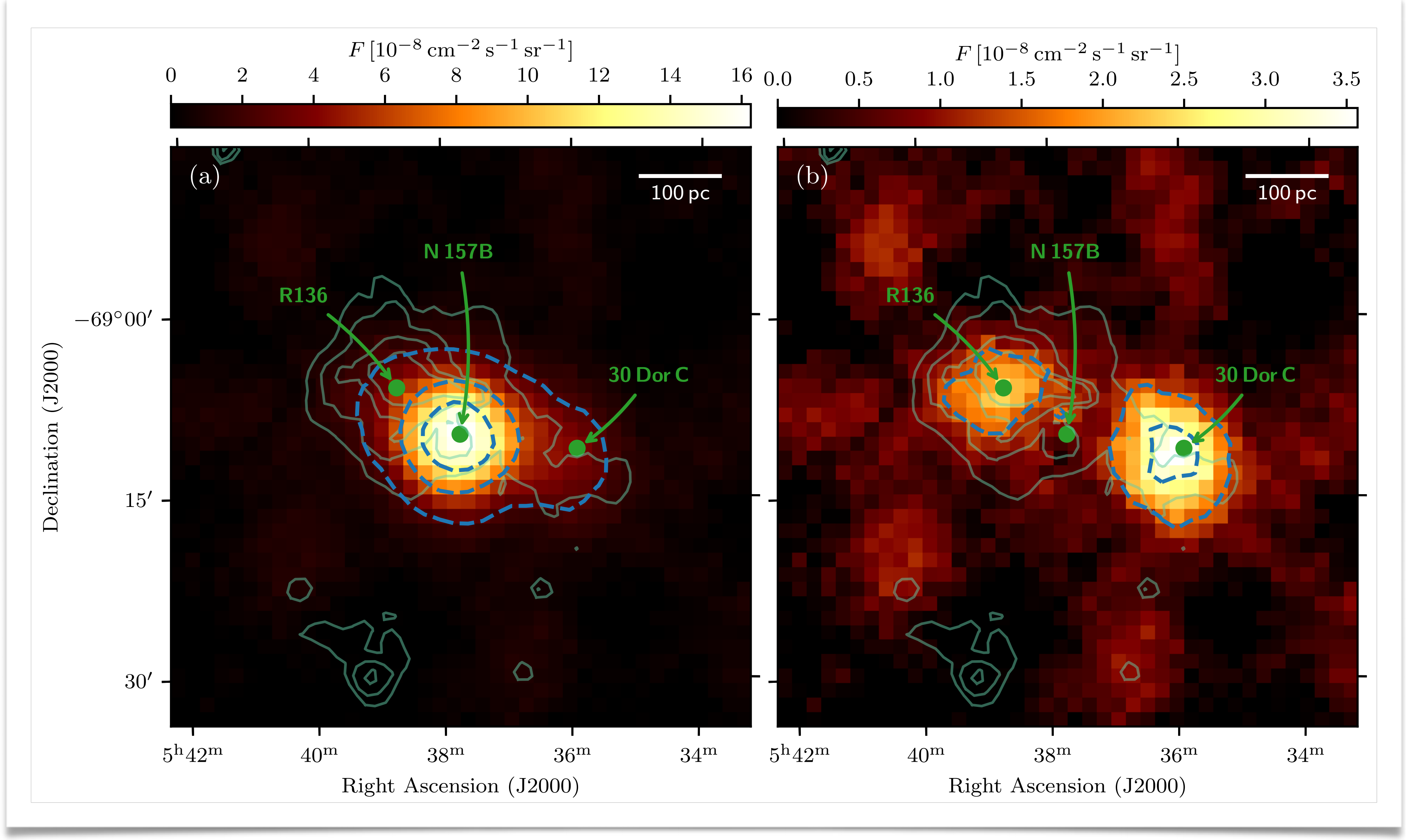
Recent results on gamma-ray emission from massive star clusters as detected with H.E.S.S.

The massive star cluster Westerlund 1



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

Massive star clusters in the Large Magellanic Cloud



Credit: H.E.S.S. Collaboration, ApJL 970, L21 (2024)

Lars Mohrmann

Max Planck Institute for Nuclear Physics, Heidelberg

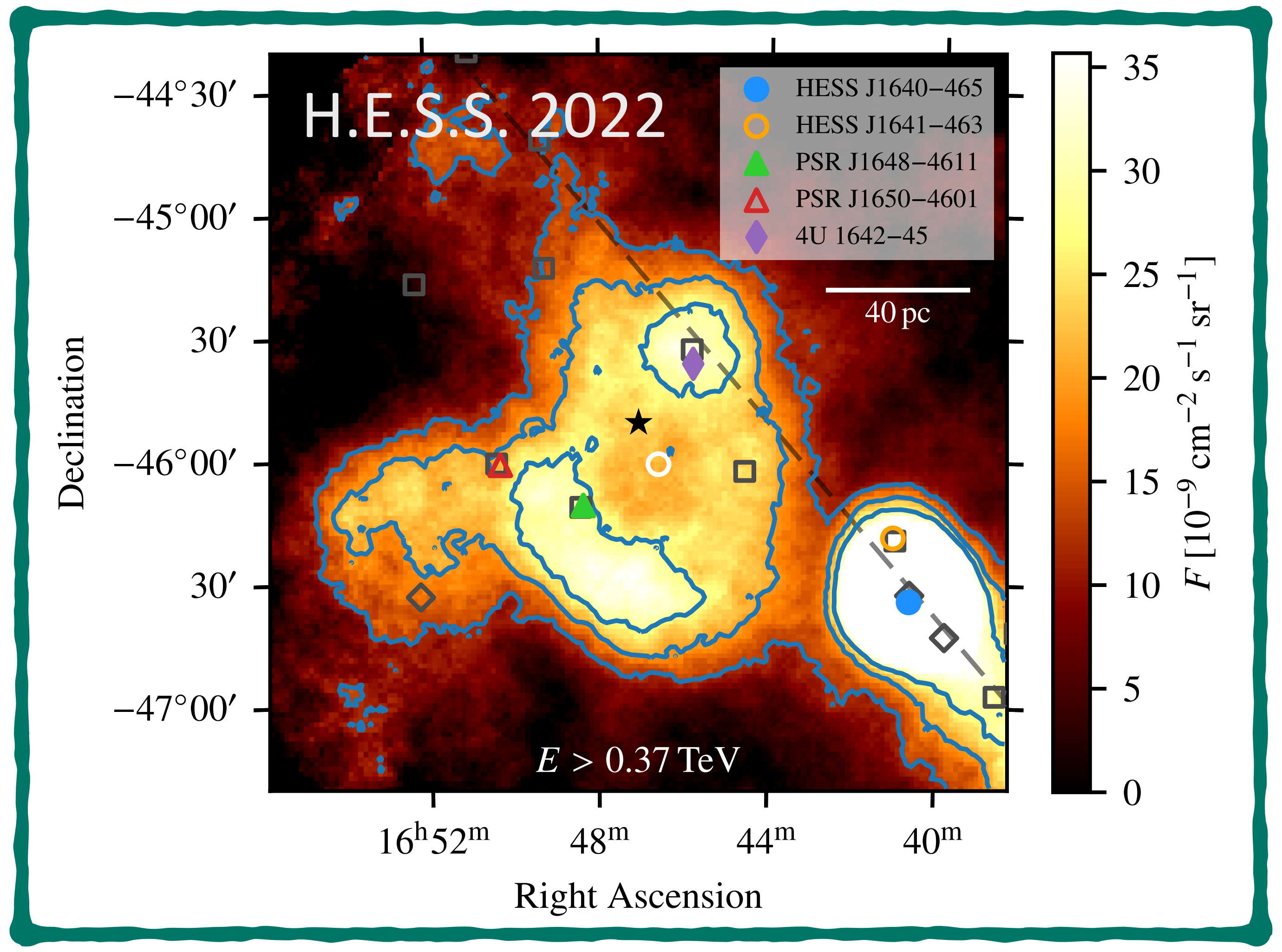
lars.mohrmann@mpi-hd.mpg.de | https://lmohrmann.github.io

TOSCA workshop — Siena, Italy — October 28, 2024

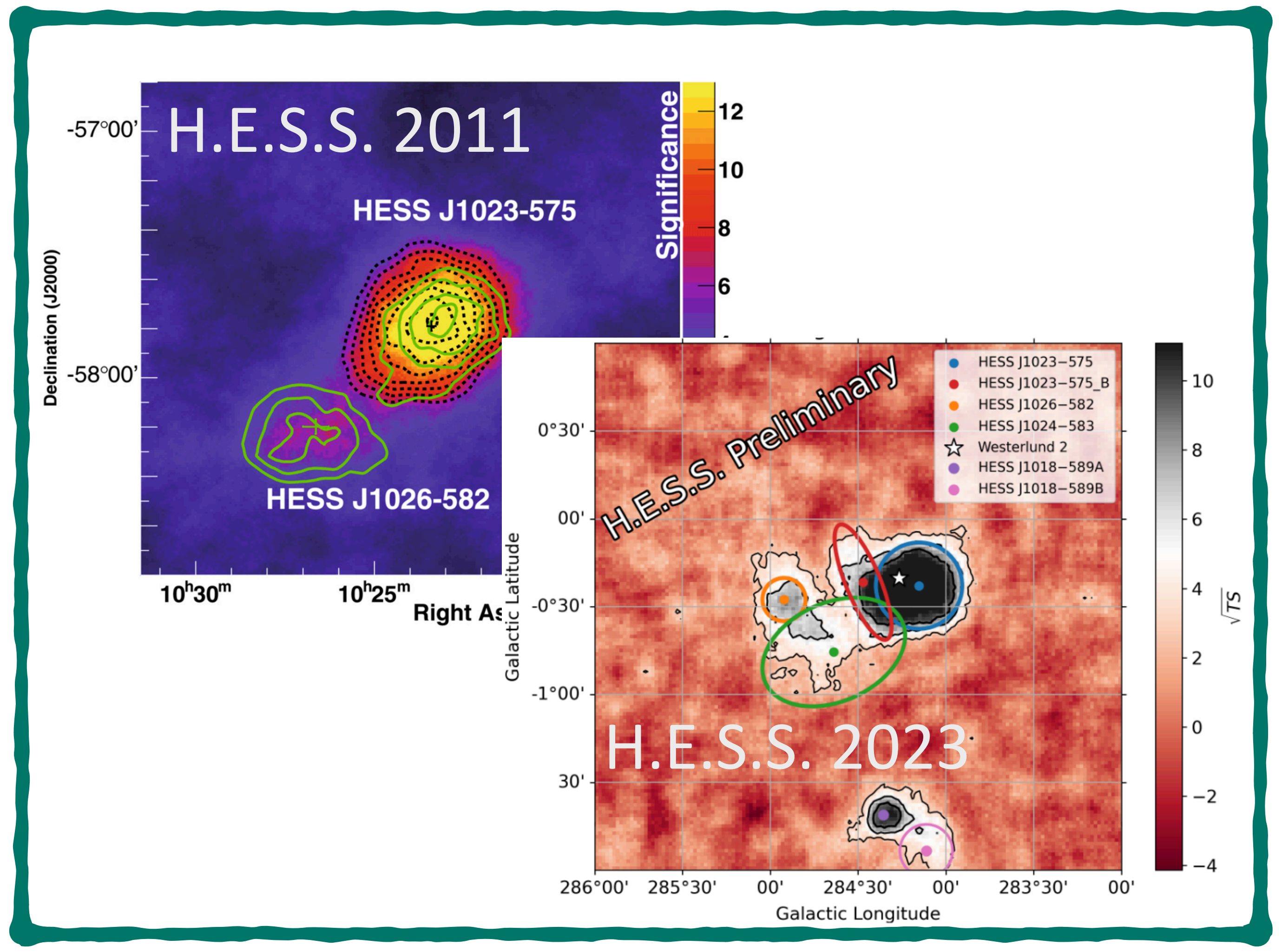
H.E.S.S.

VHE gamma-ray emission from (the vicinity of) star clusters

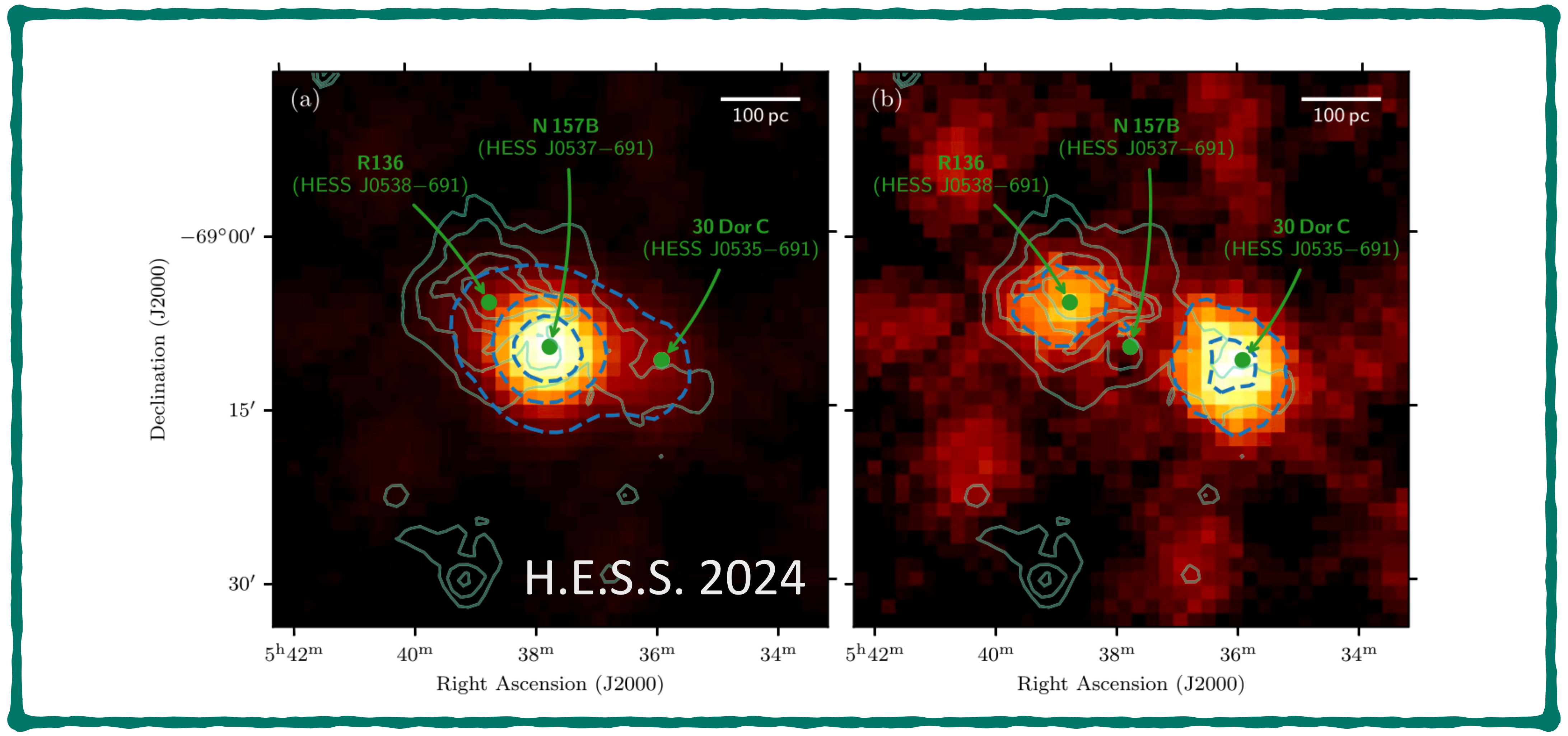
Westerlund 1



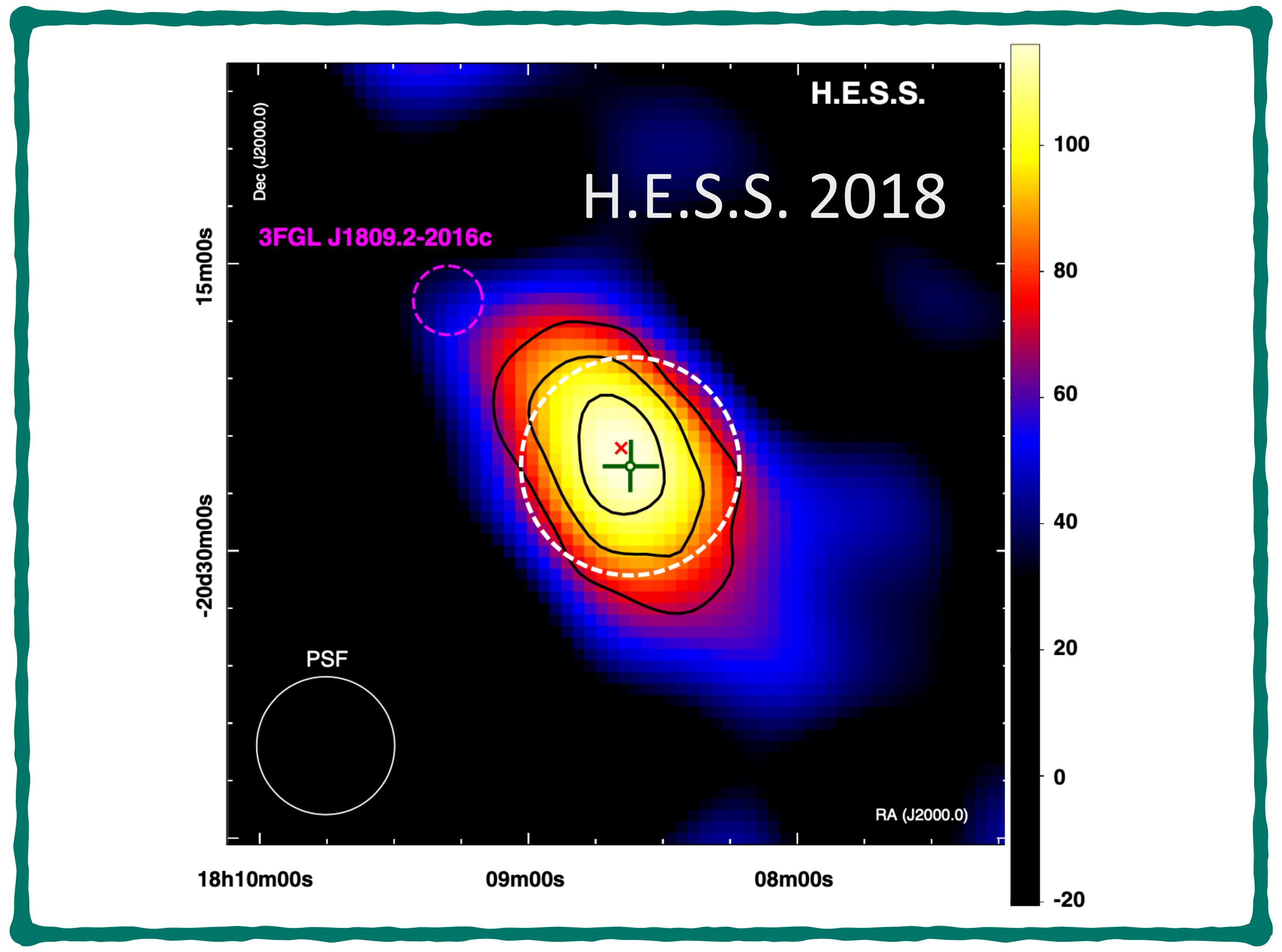
Westerlund 2



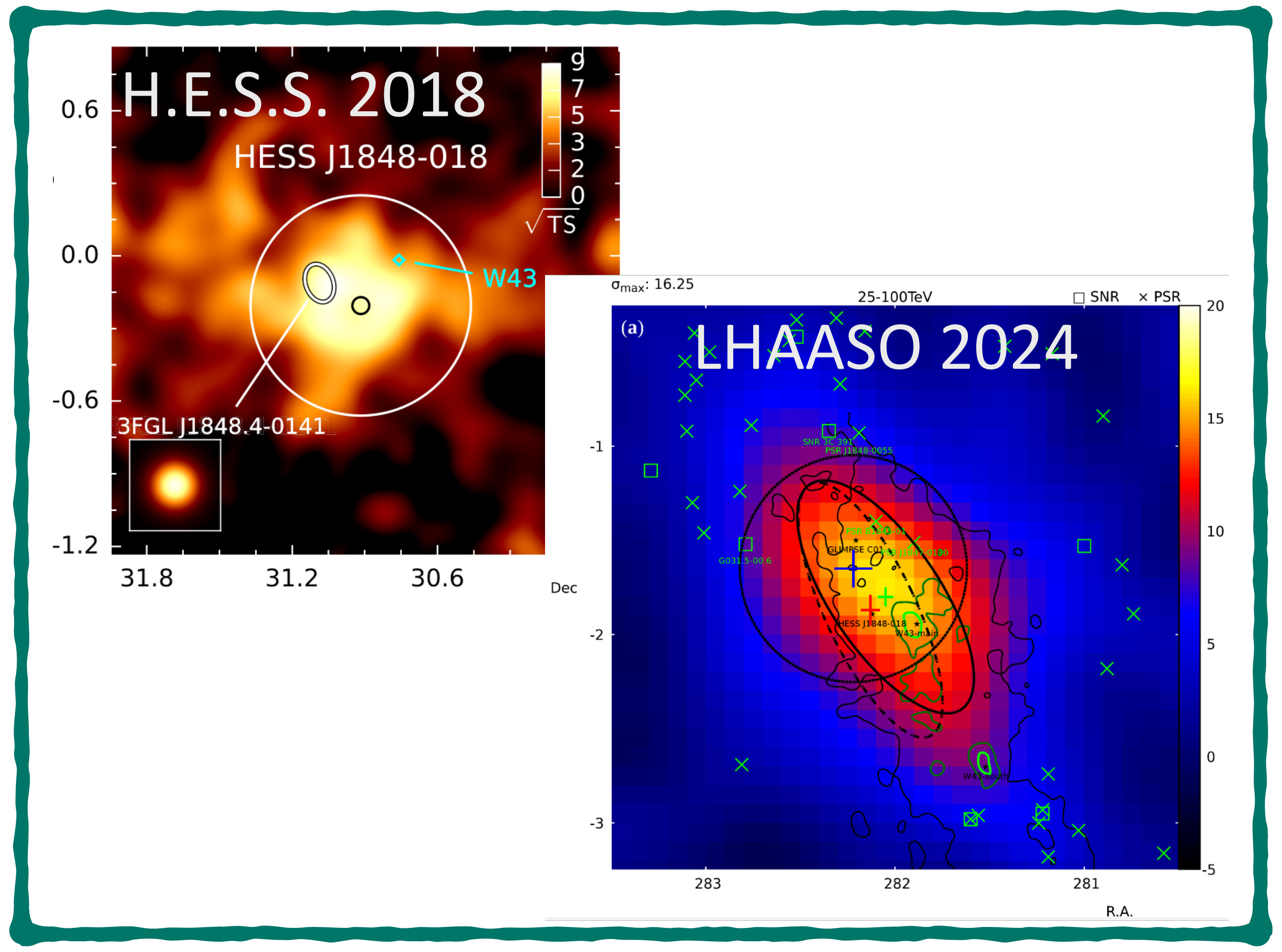
30 Dor C and R136



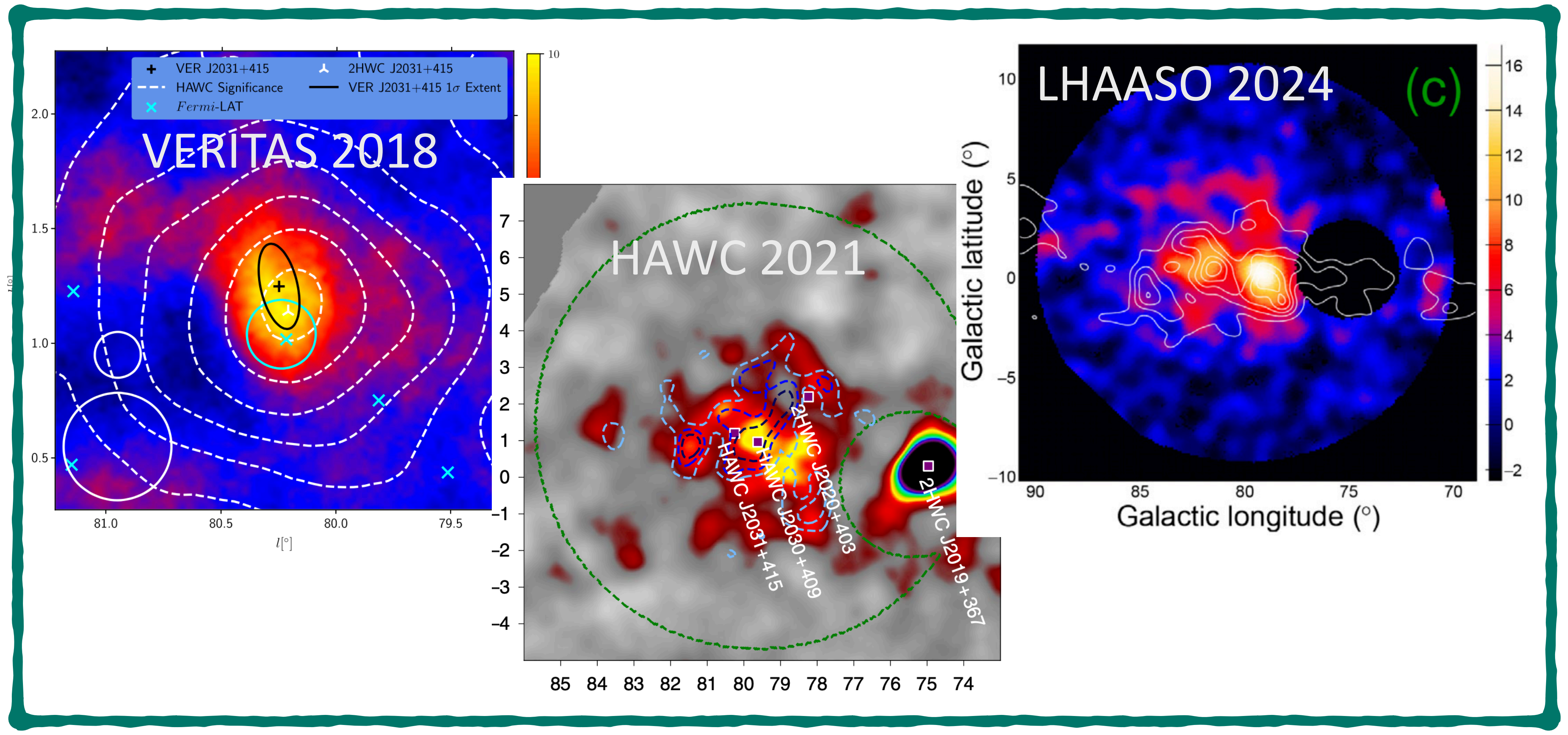
Cl* 1806-20



W43



Cygnus OB2



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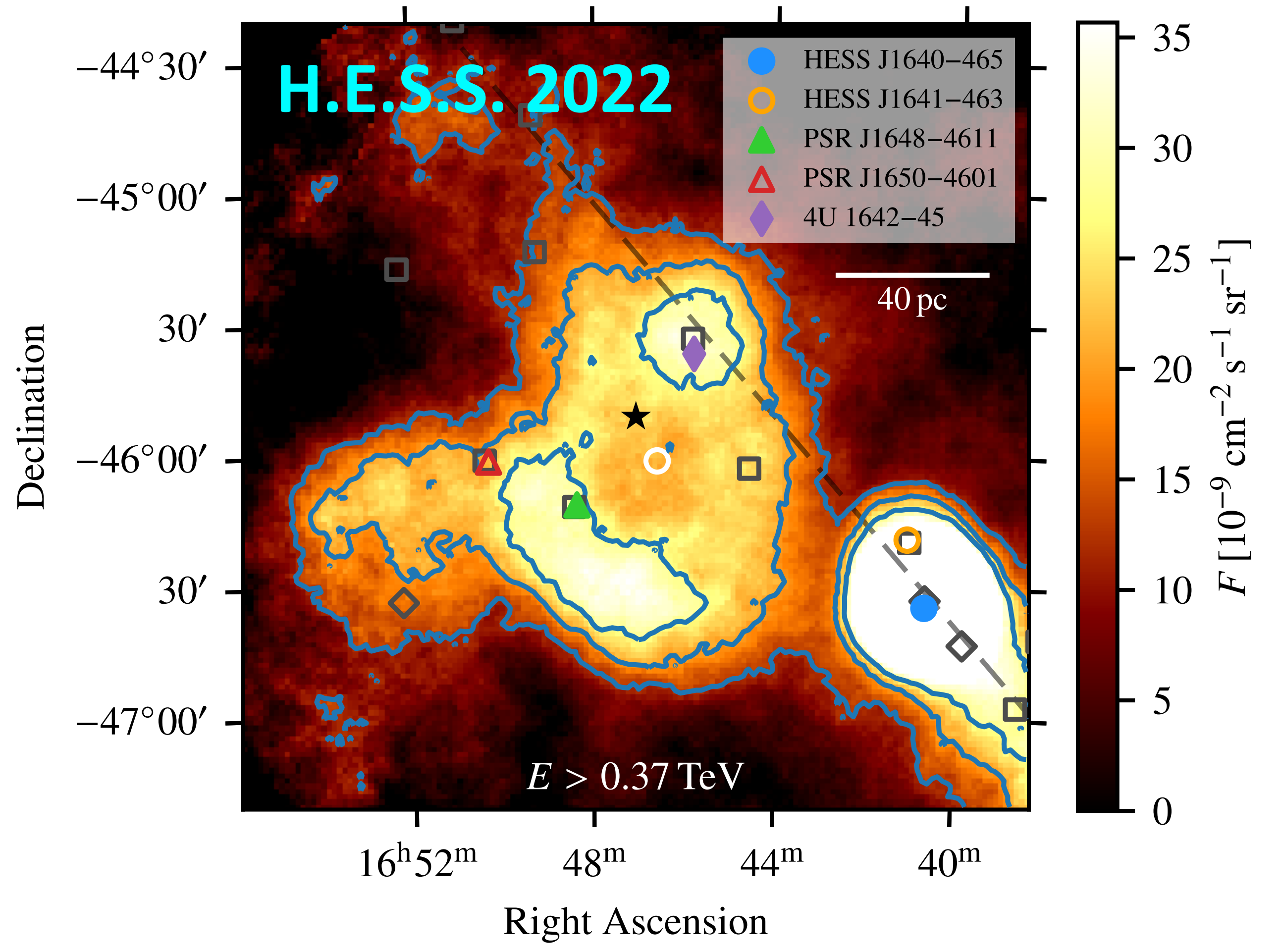

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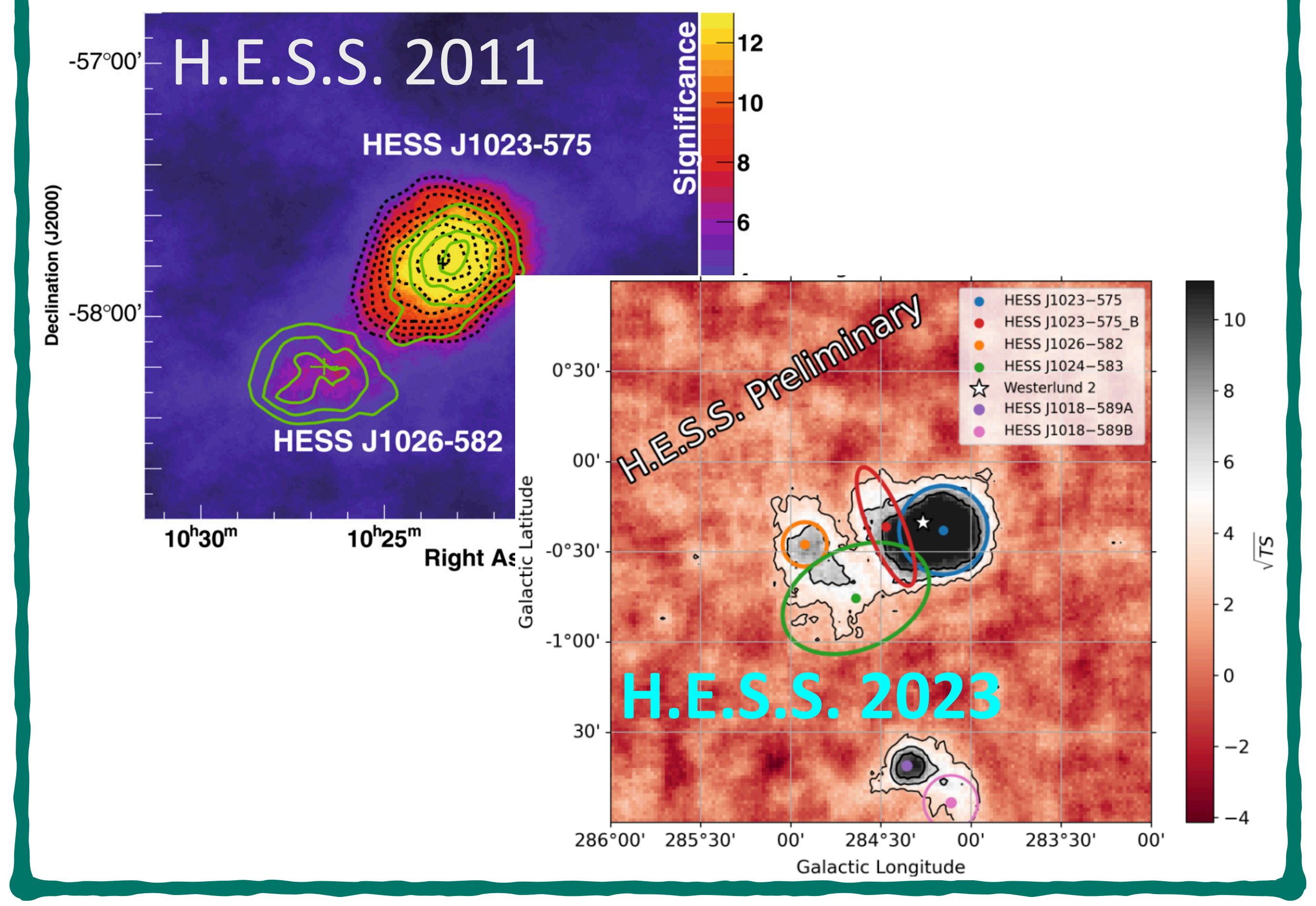

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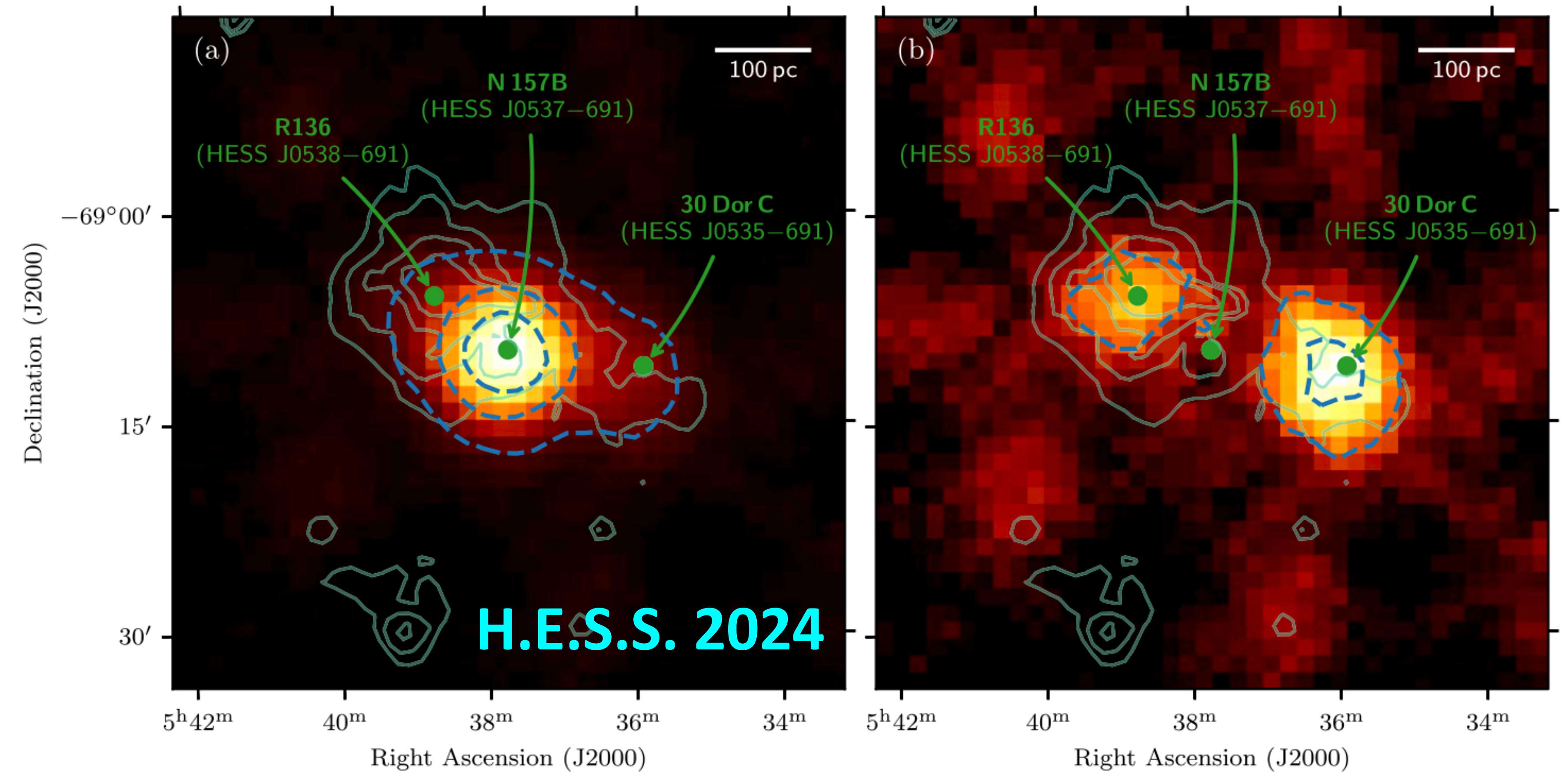

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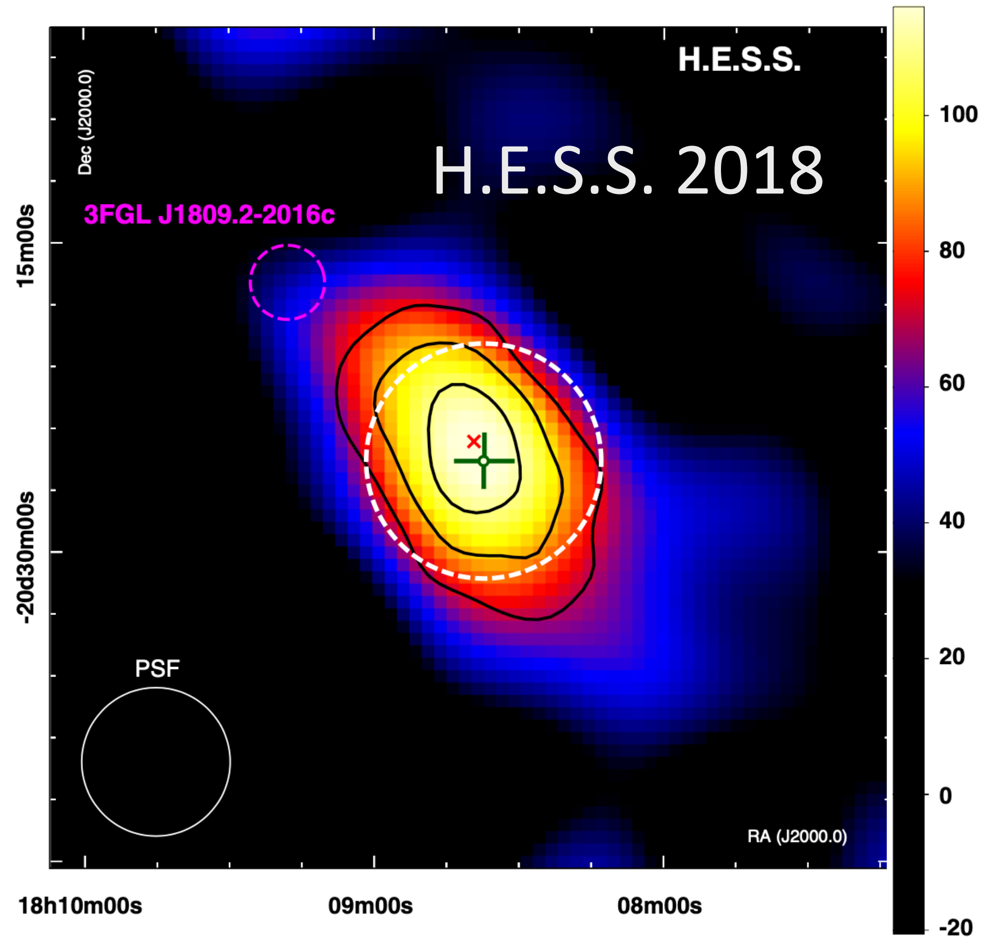

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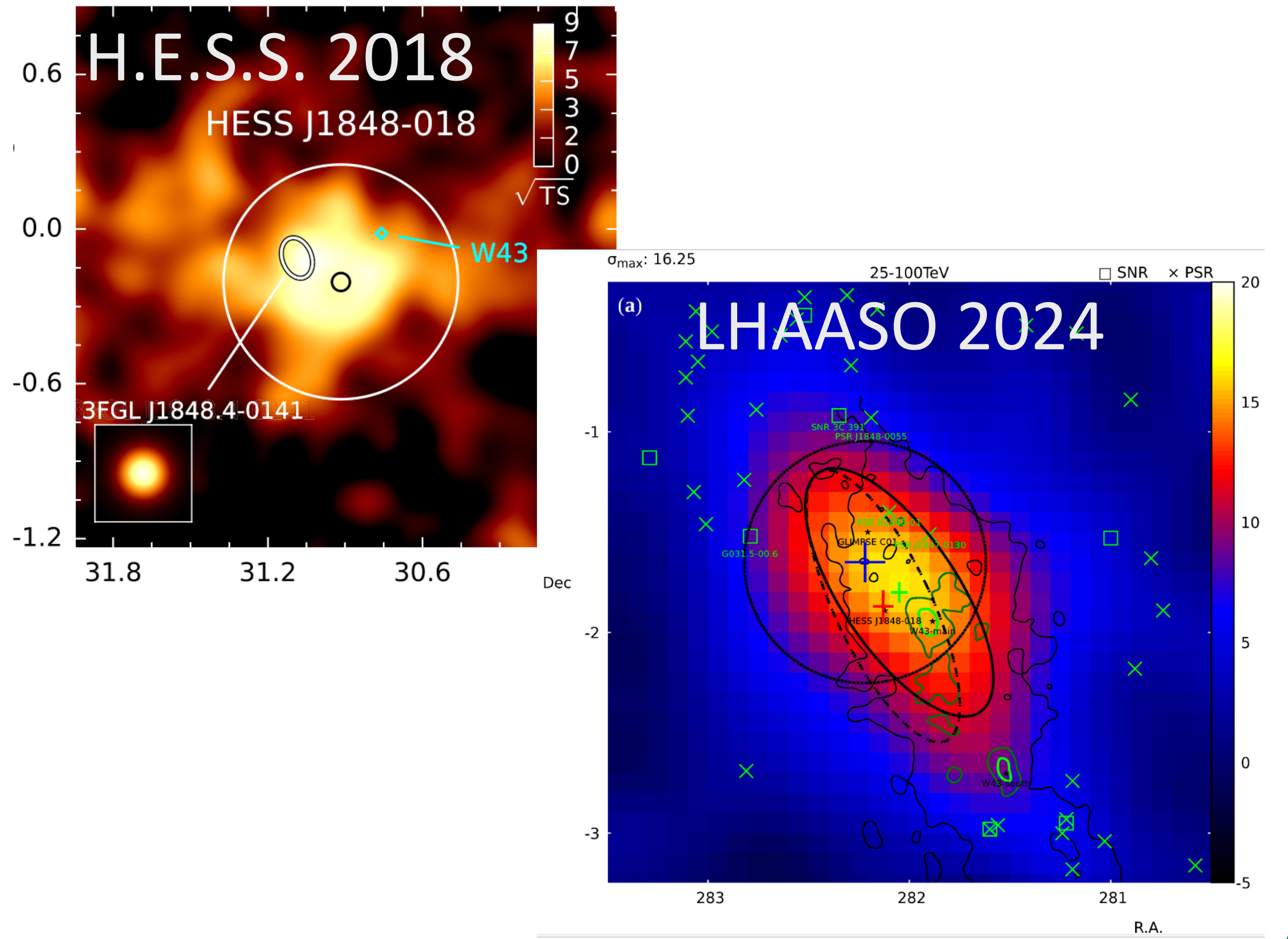

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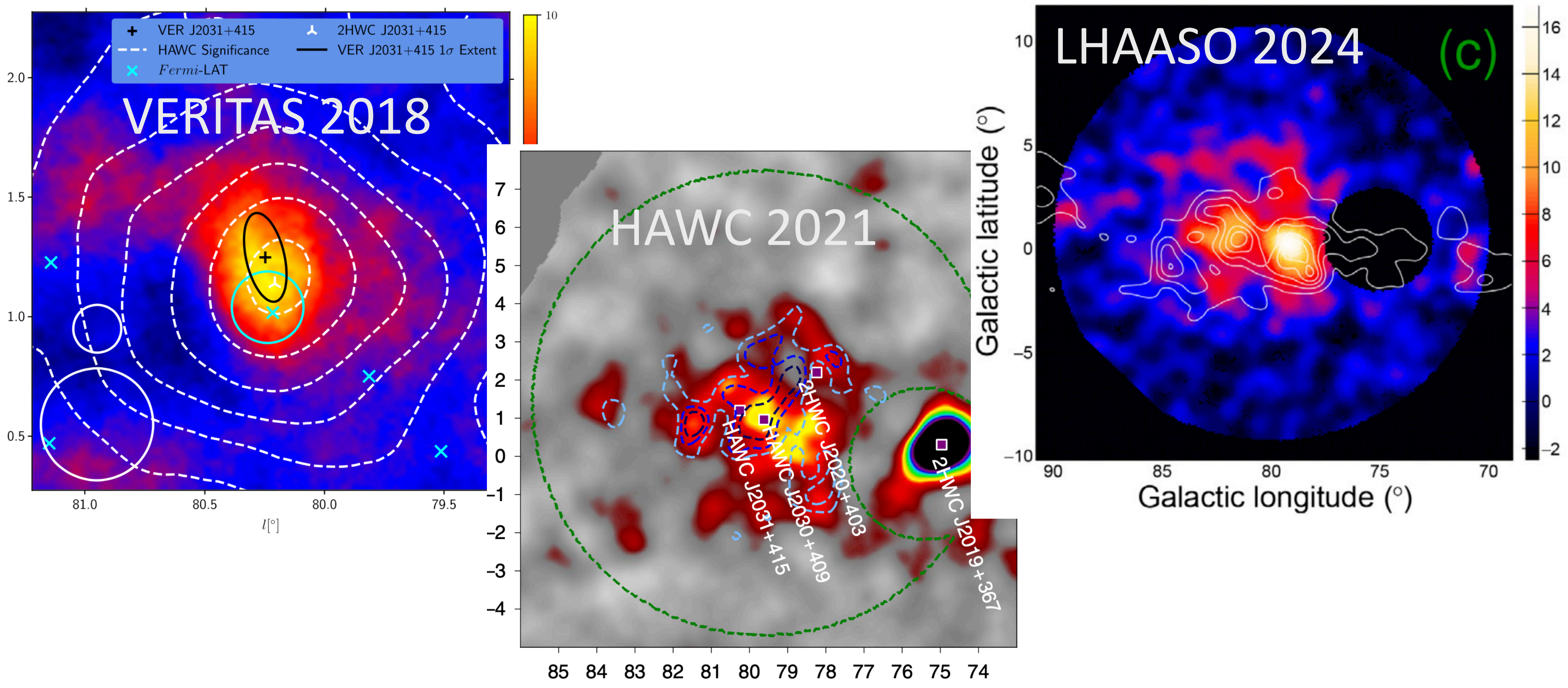
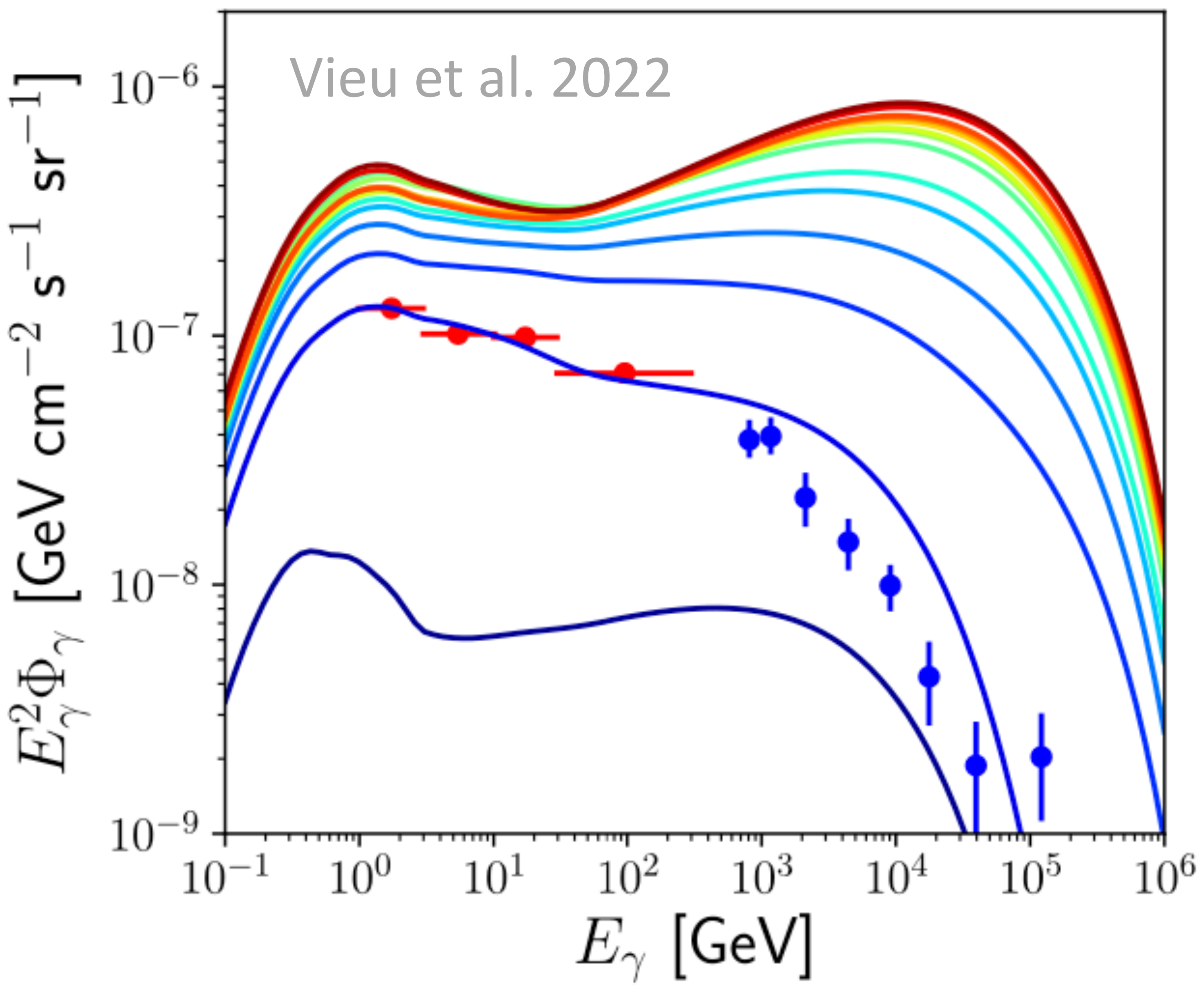


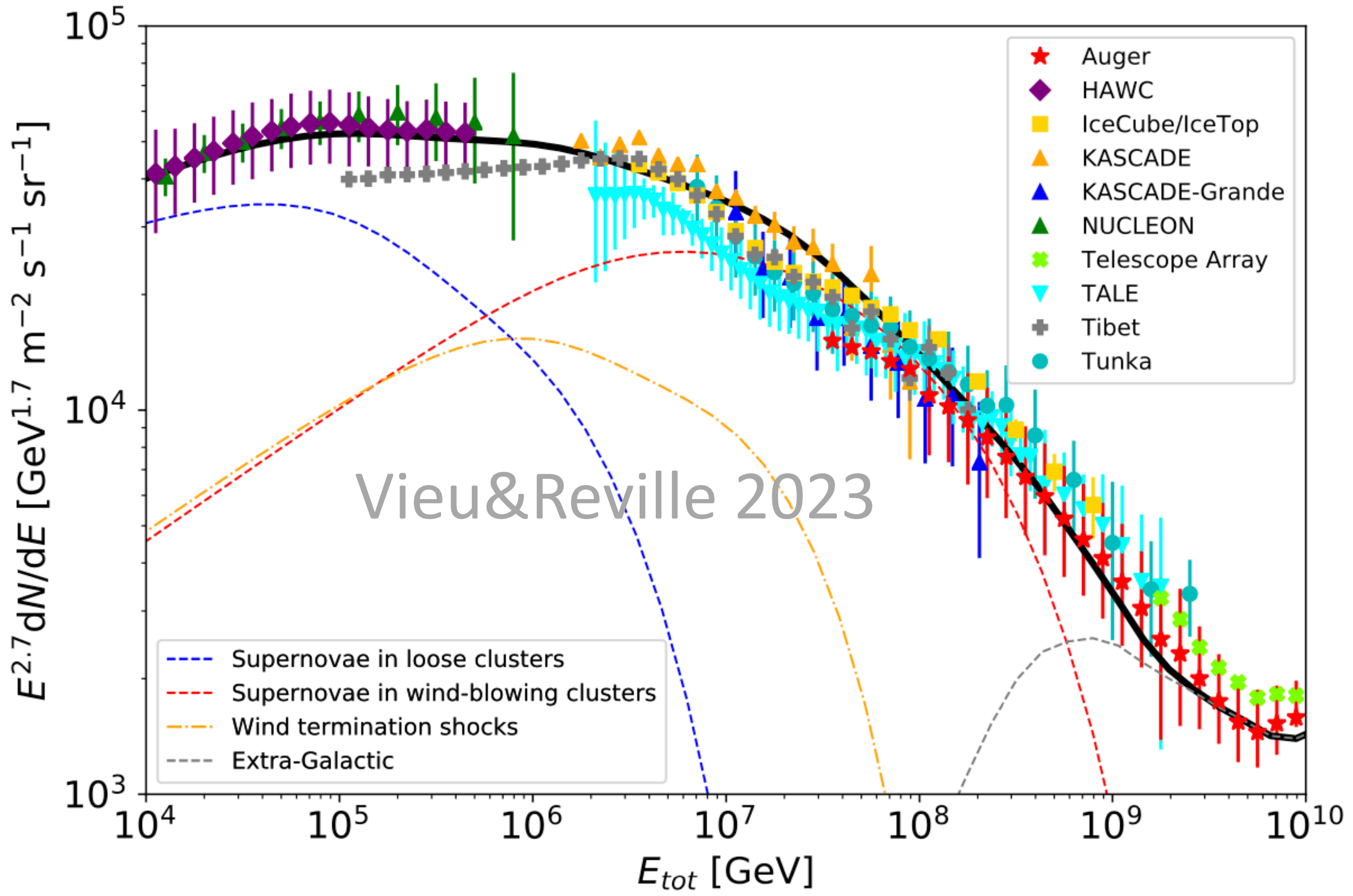
Star clusters as cosmic-ray sources

- Loads of ideas how / where cosmic rays are accelerated!

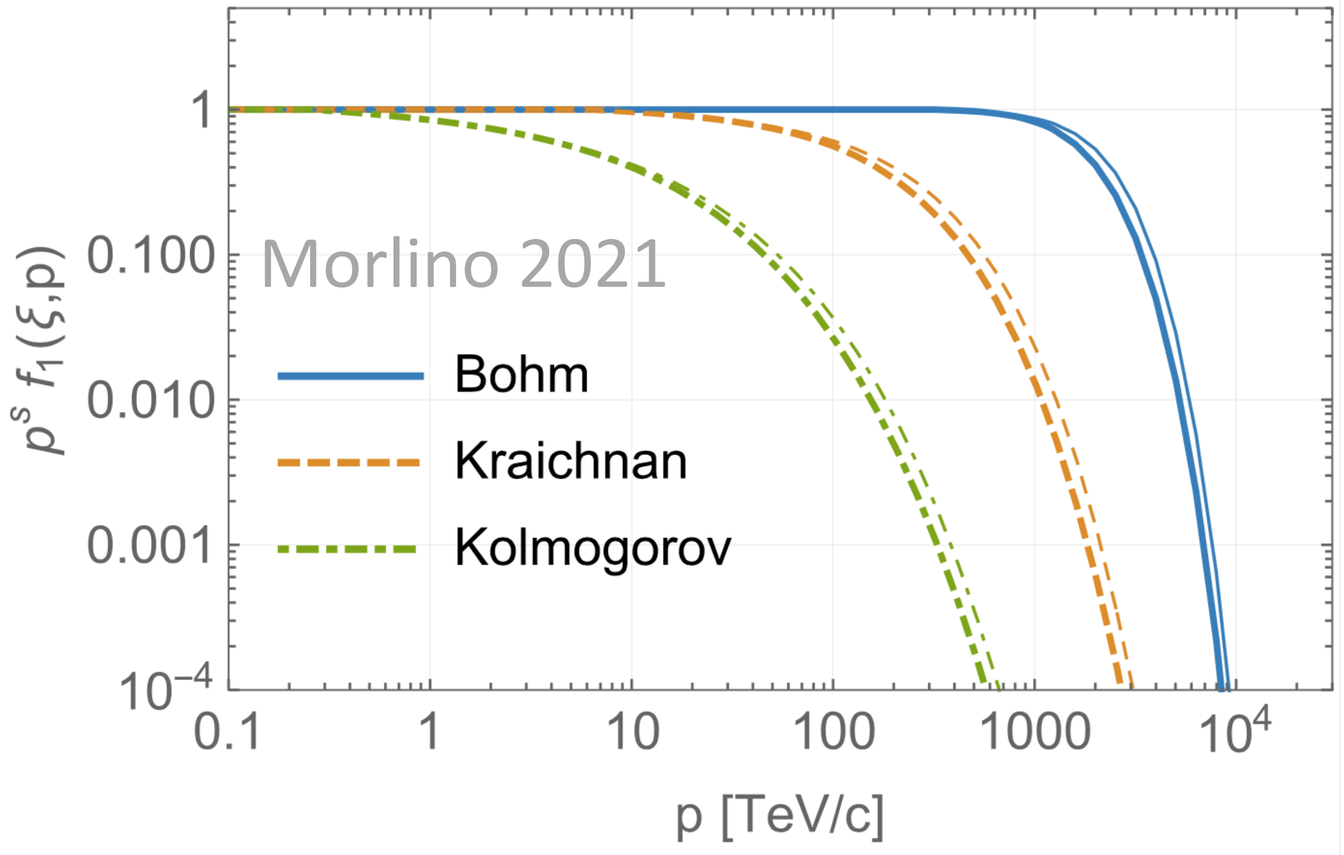
in superbubble



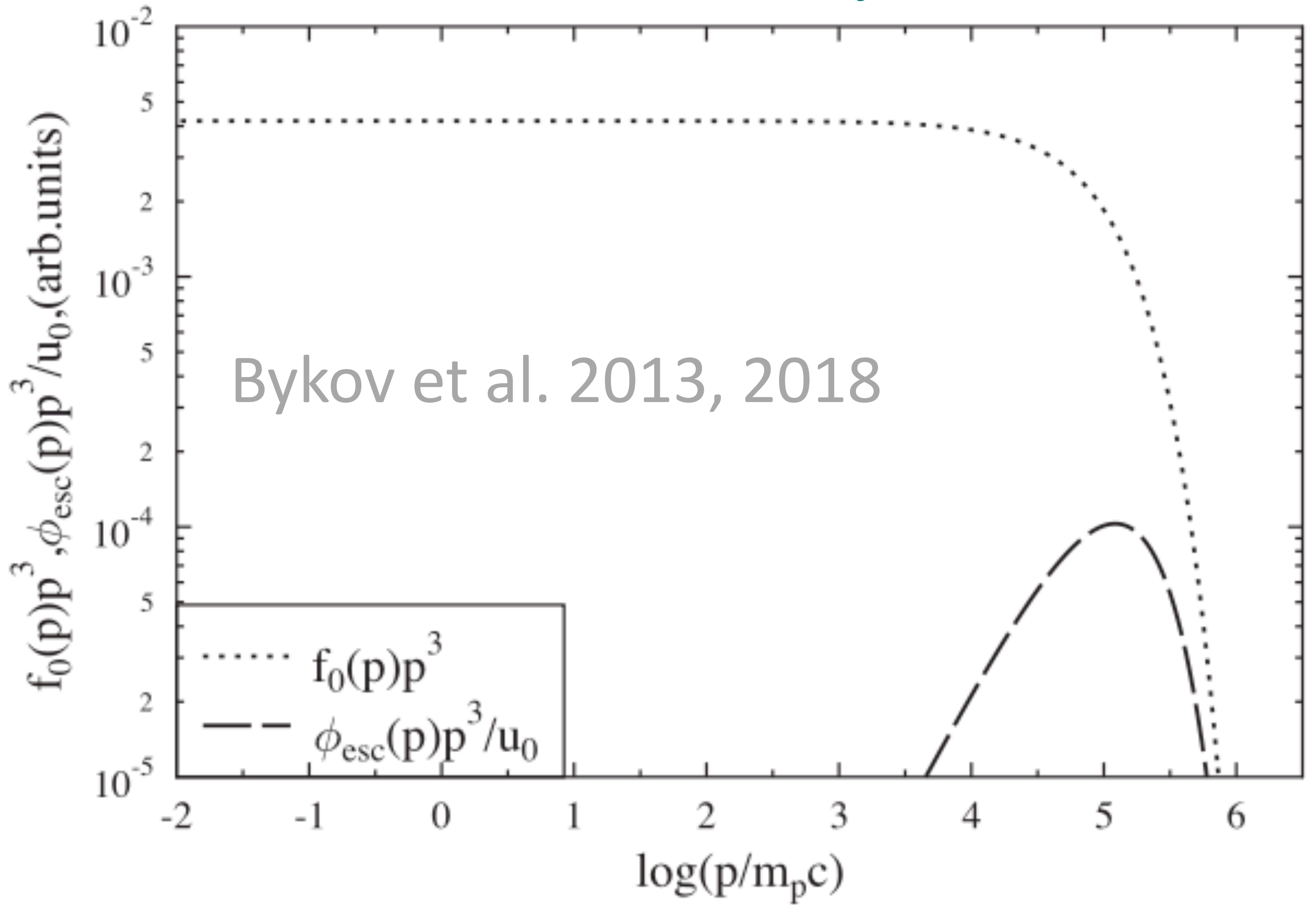
supernovae in compact cluster environments

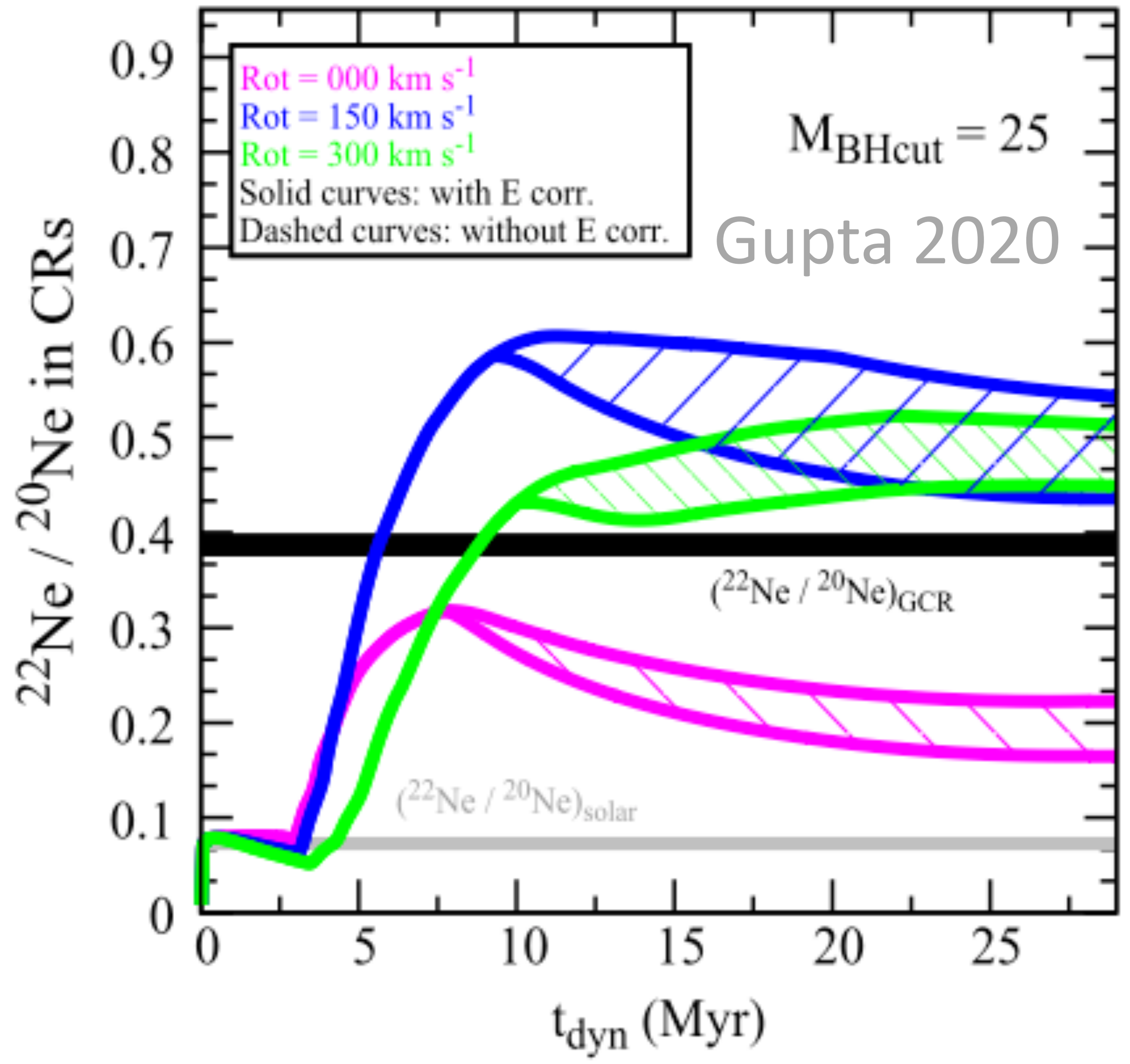


cluster wind termination shock



colliding shocks in compact clusters





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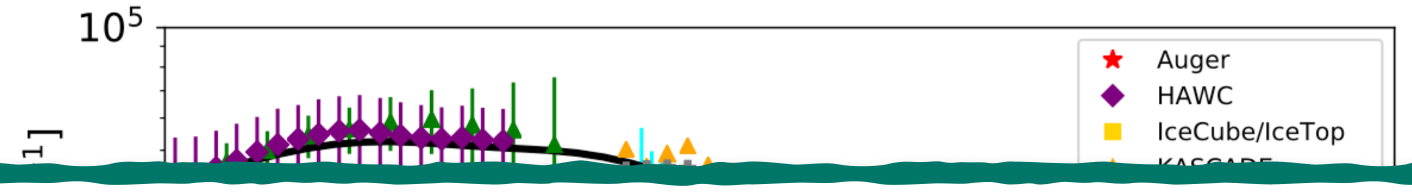

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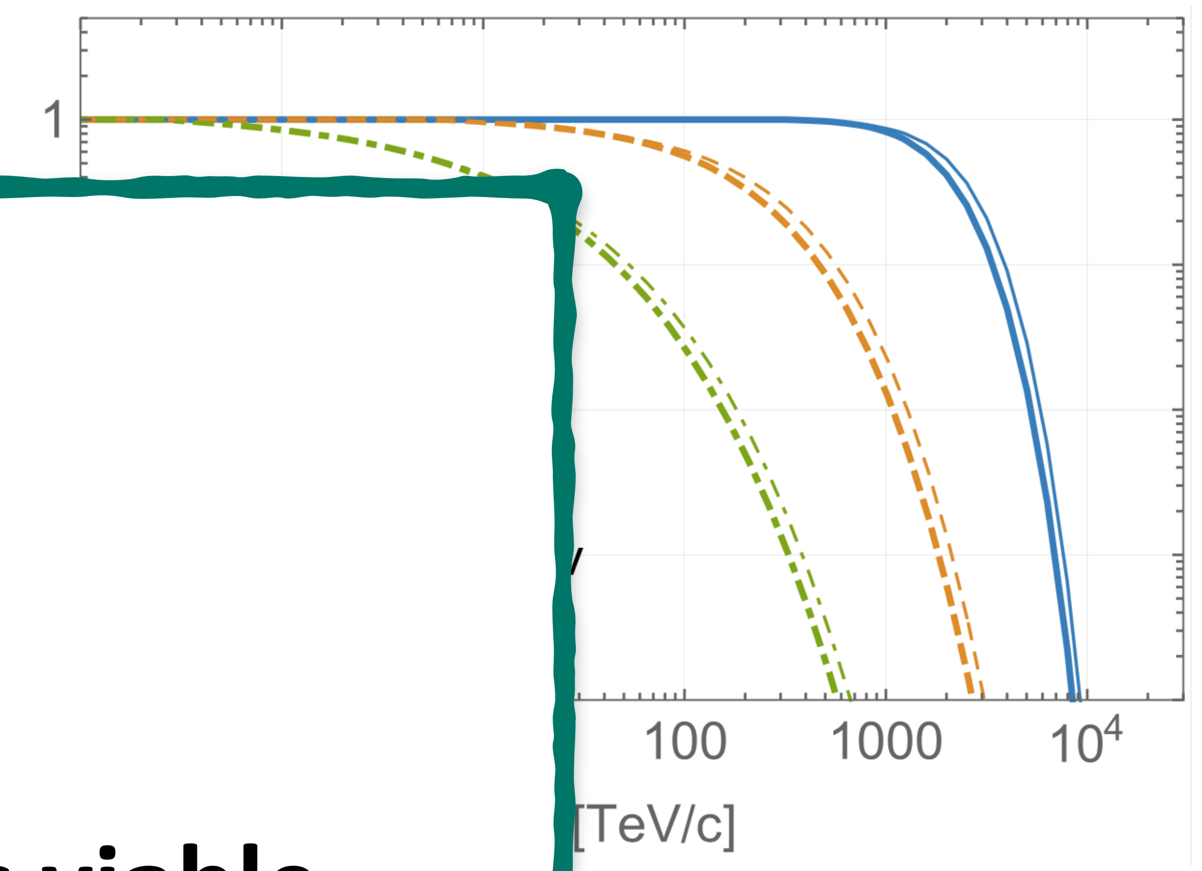
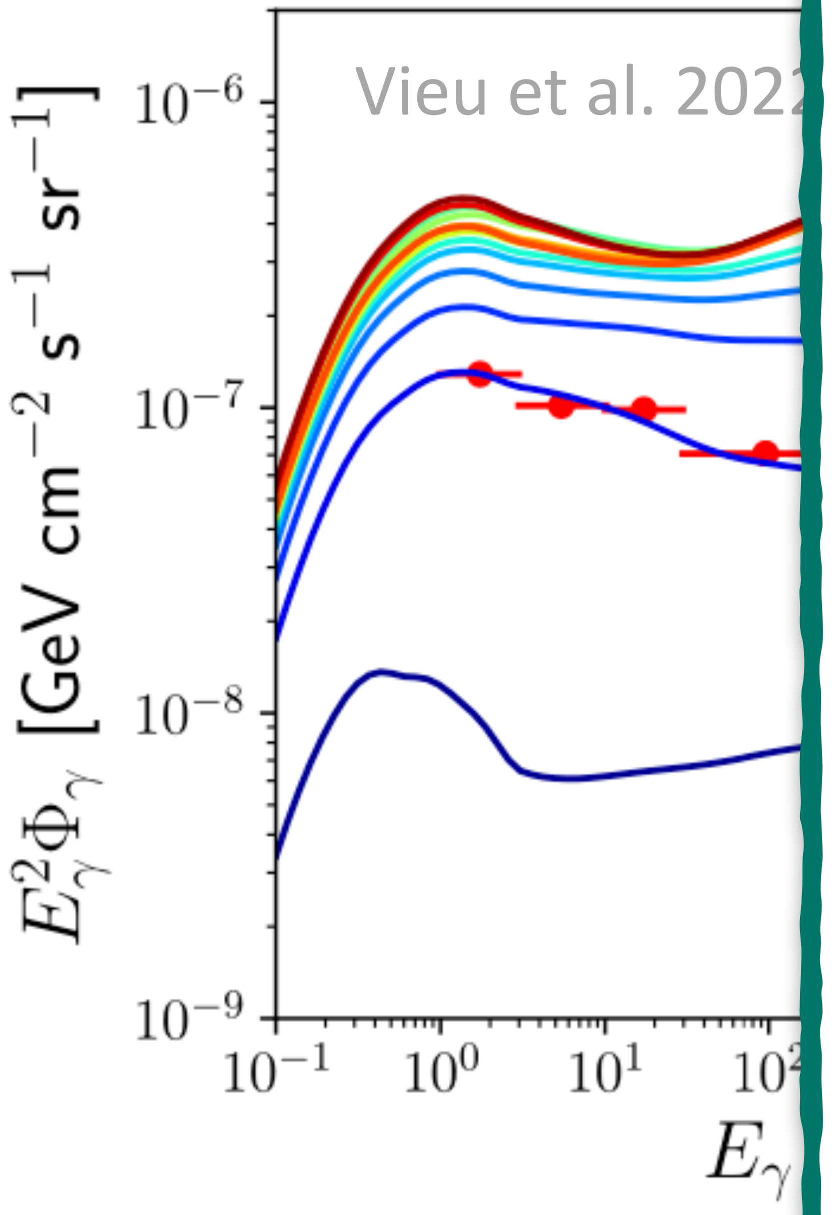


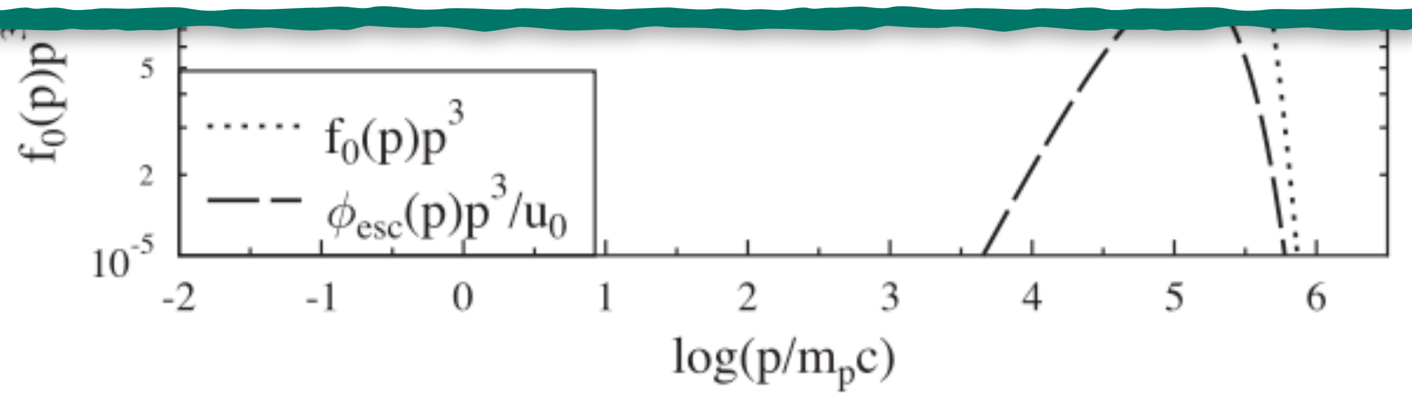
in supe

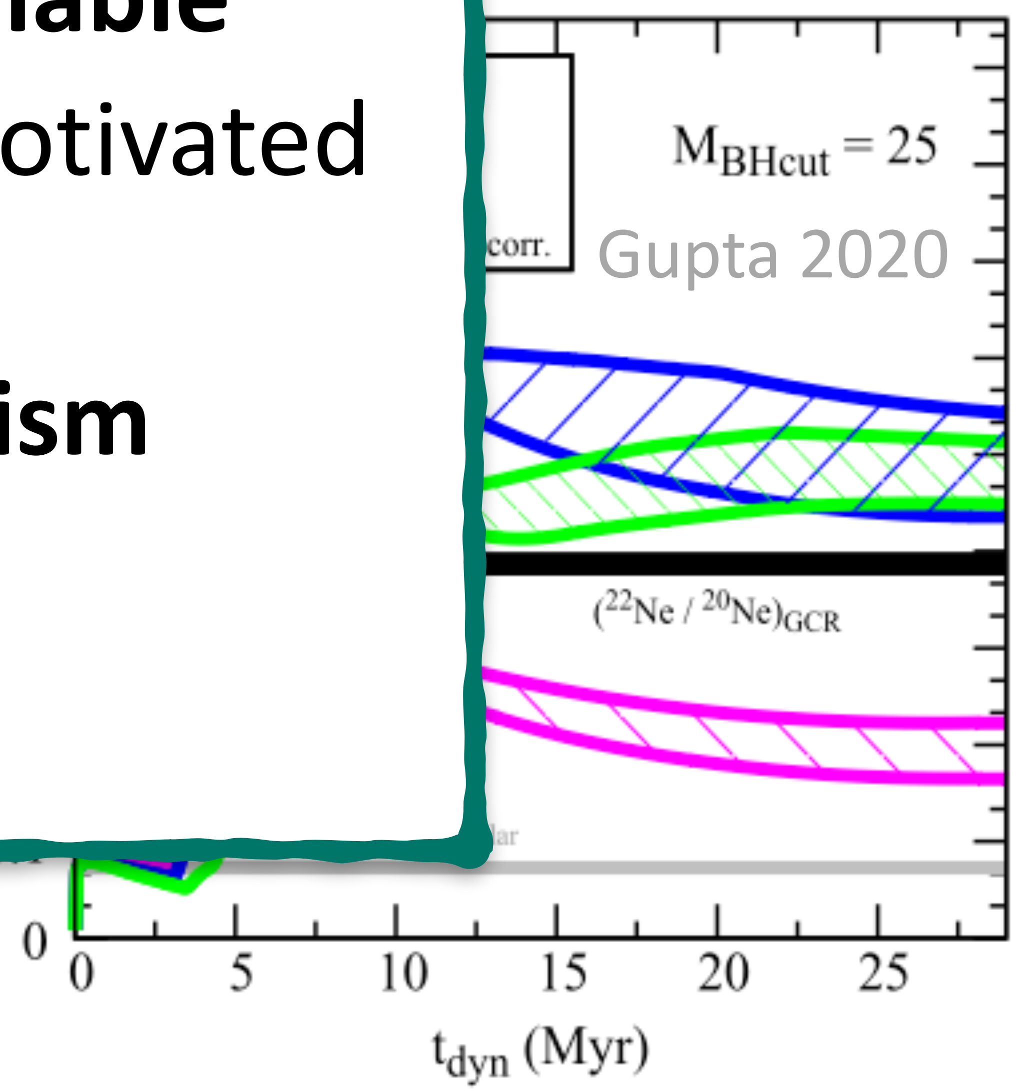


1) population of massive star clusters is diverse
→ need as many detections as possible

2) acceleration to PeV energies in compact clusters seems viable
→ searches with UHE instruments (e.g. HAWC, LHAASO) well motivated

3) multiple options for precise acceleration site / mechanism
→ resolving sources spatially is critical





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

- Located in Khomas highland, Namibia
- System of 5 imaging atmospheric Cherenkov telescopes
  - 4 telescopes with 12m mirrors
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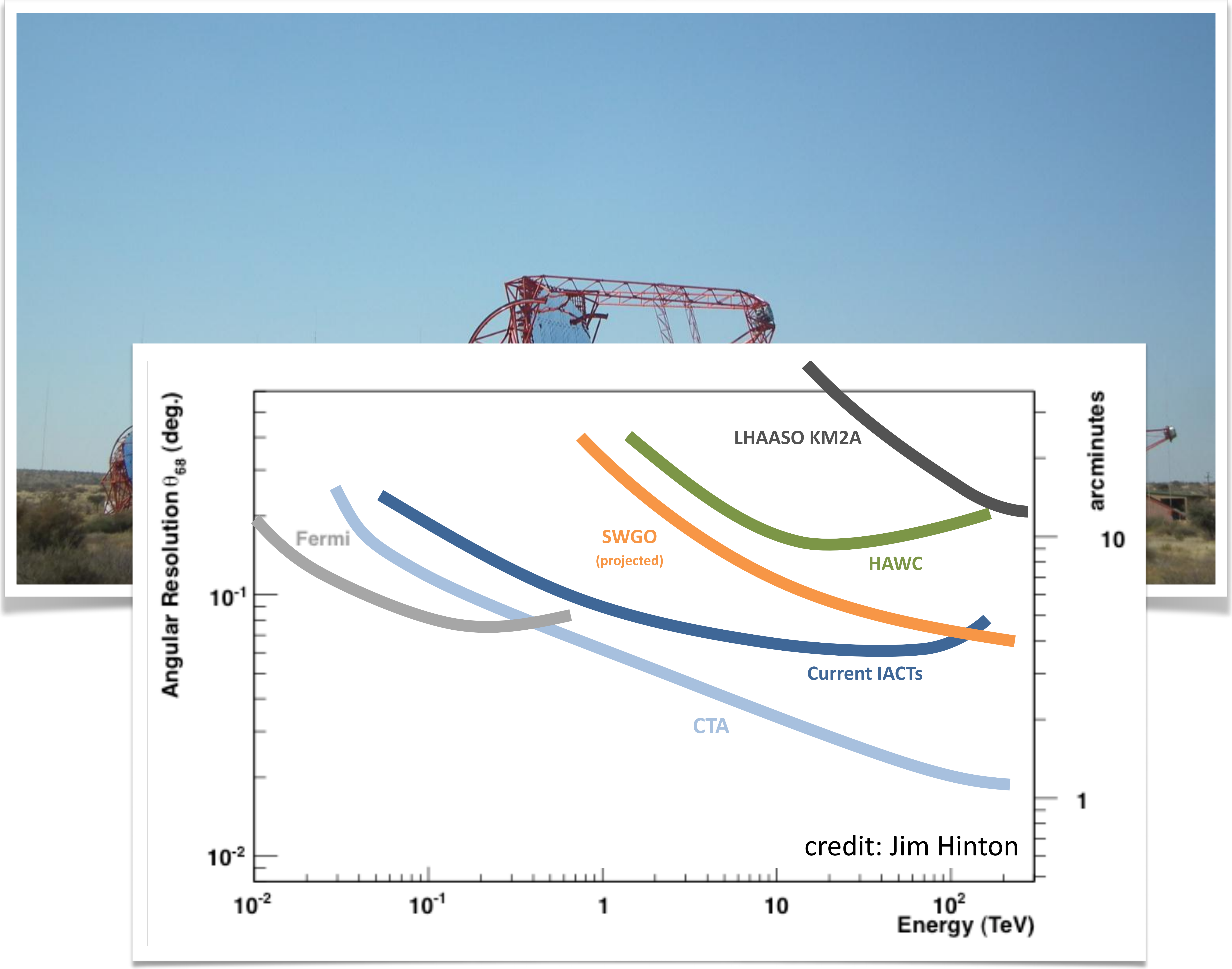
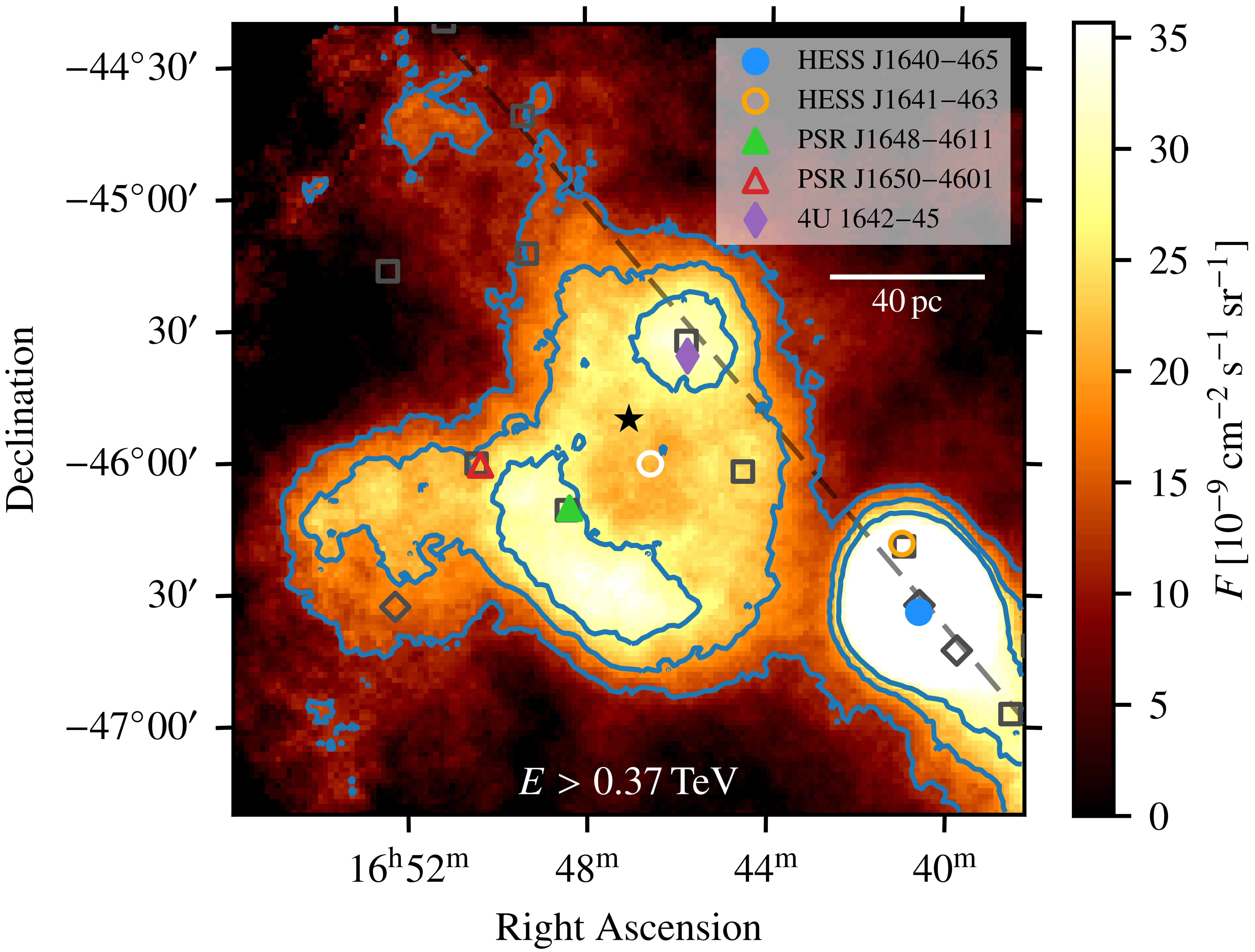
- High angular resolution ($< 0.1^\circ\,\mathrm{deg}$ at $E > 1\,\mathrm{TeV}$)
  → ideally suited for morphological studies



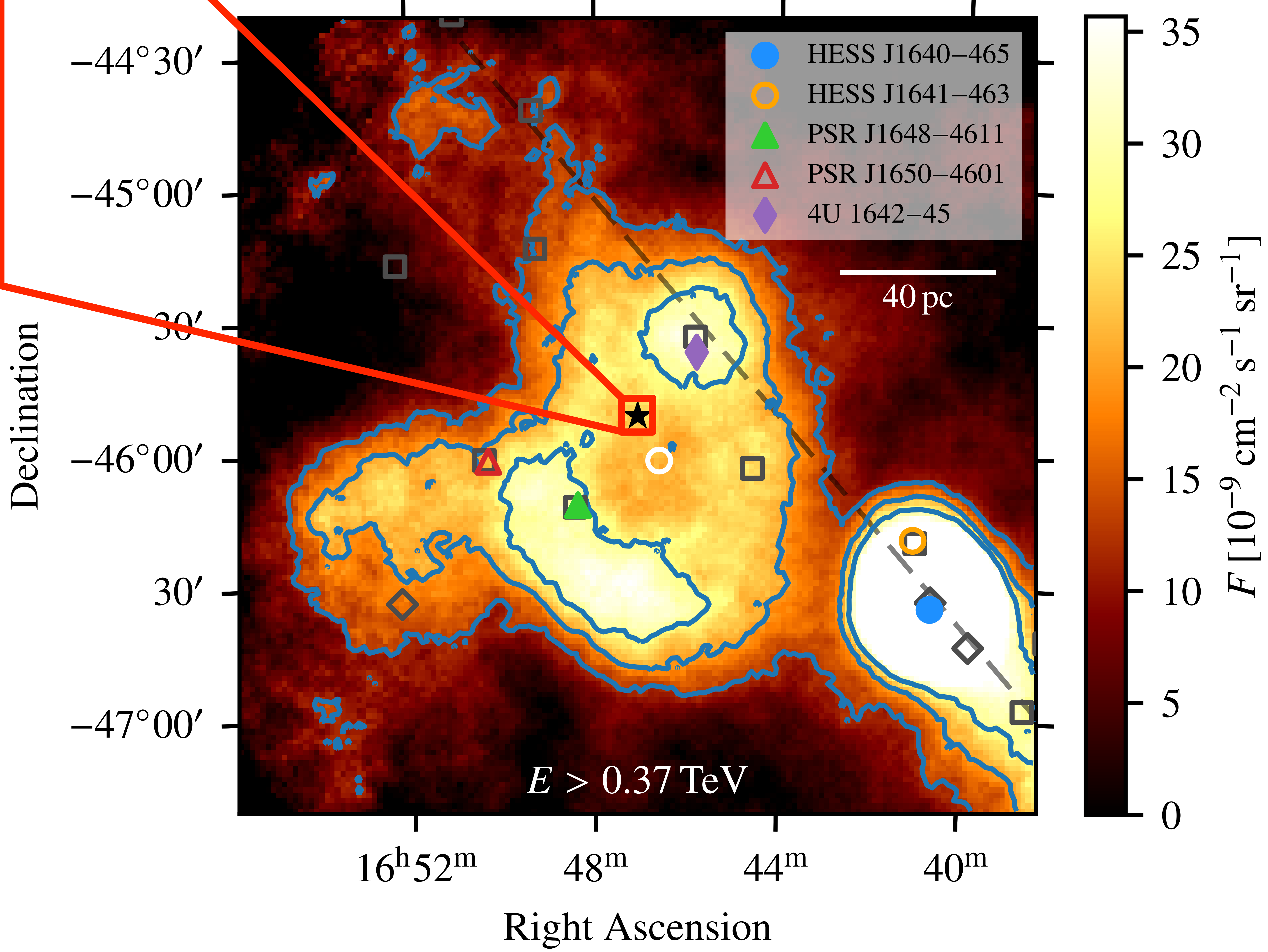
Westerlund 1



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: $1\,\mathrm{pc}$
  - Age $\sim 3 - 5\,\mathrm{Myr}$
  - Distance $\sim 4\,\mathrm{kpc}$

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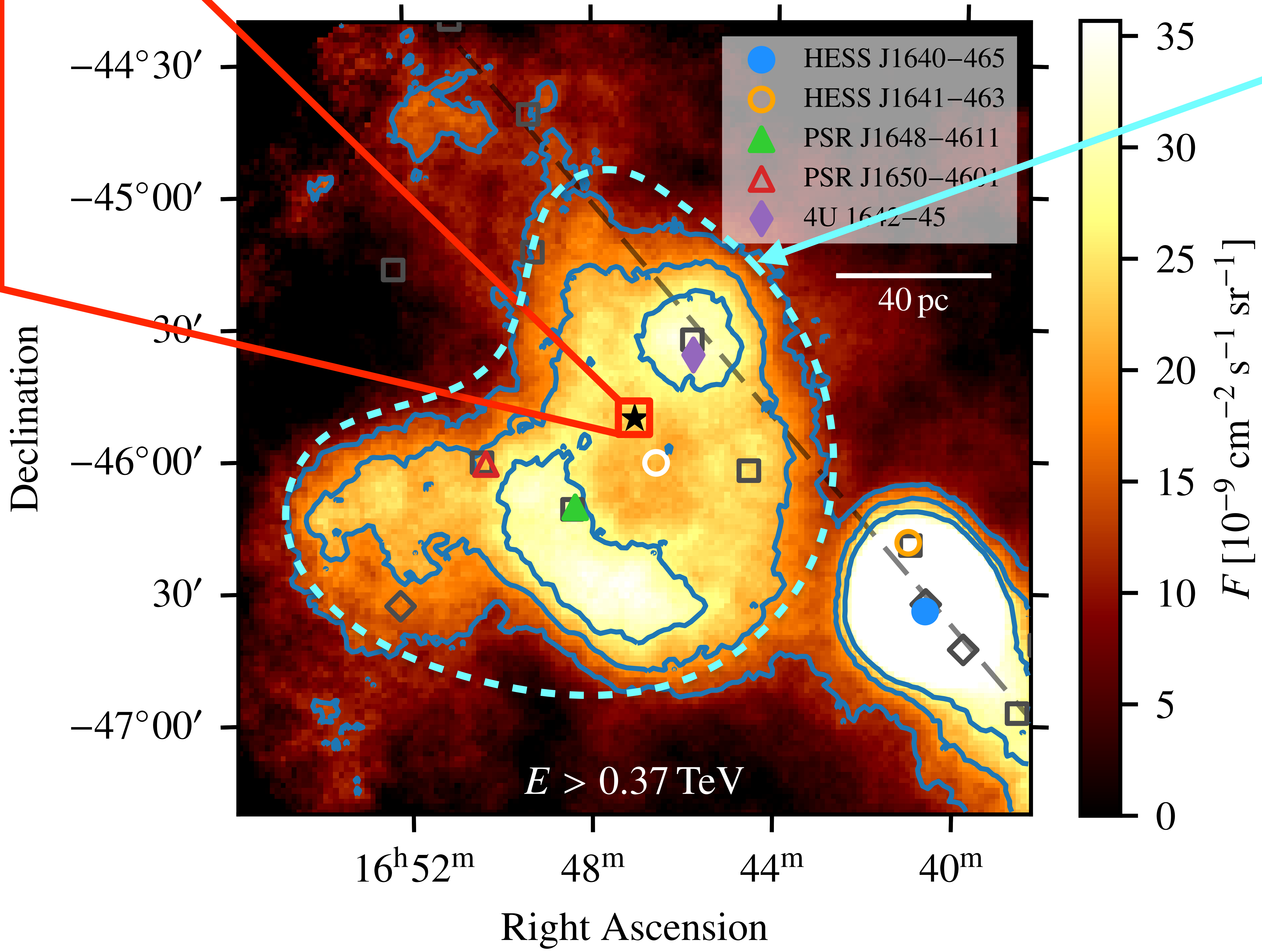

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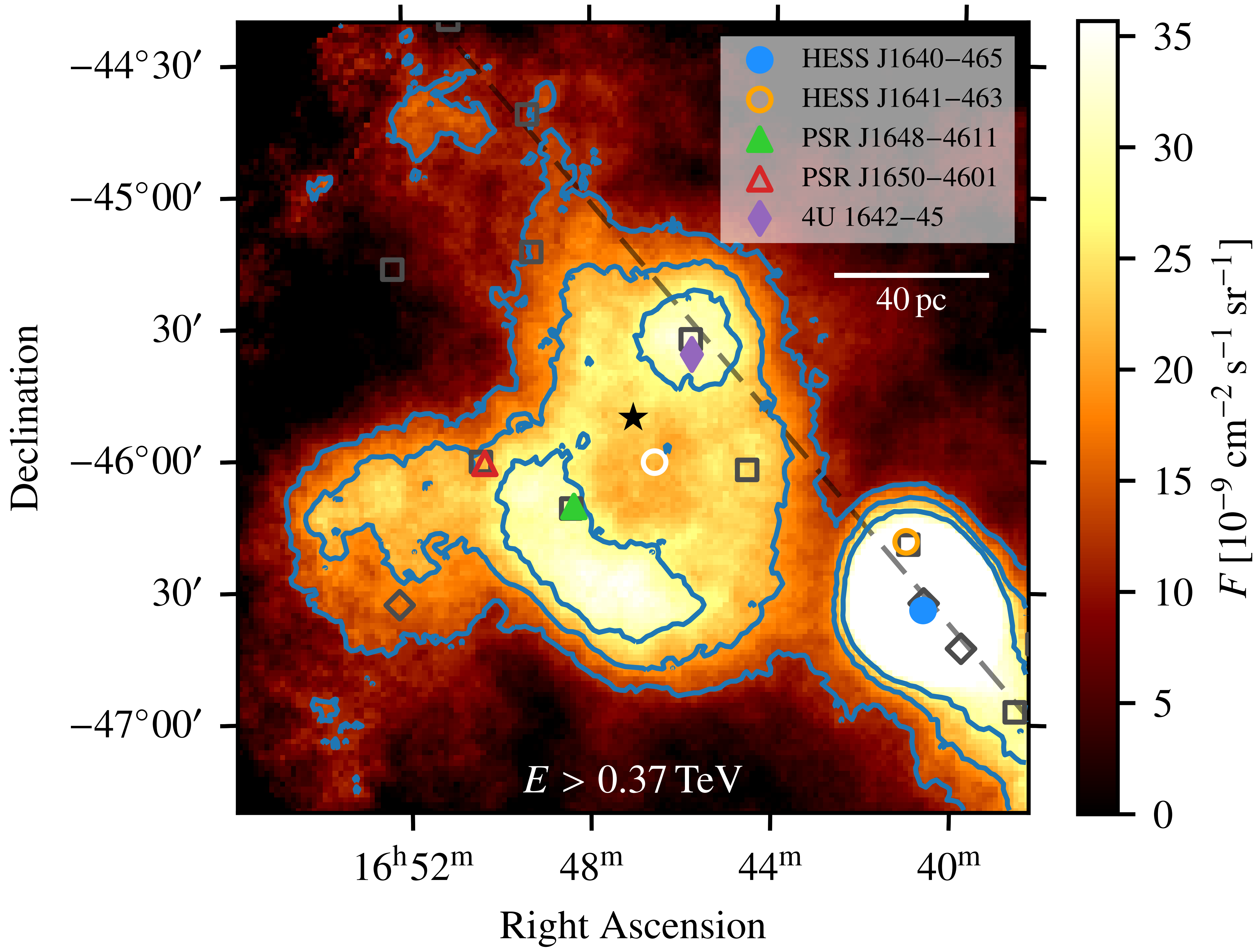
  - most massive young star cluster in our Galaxy
  - $M \sim 10^5\,M_\odot$
  - half-mass radius: 1 pc
  - Age ∼ 3 – 5 Myr
  - Distance ∼ 4 kpc

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

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

Westerlund 1 — 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



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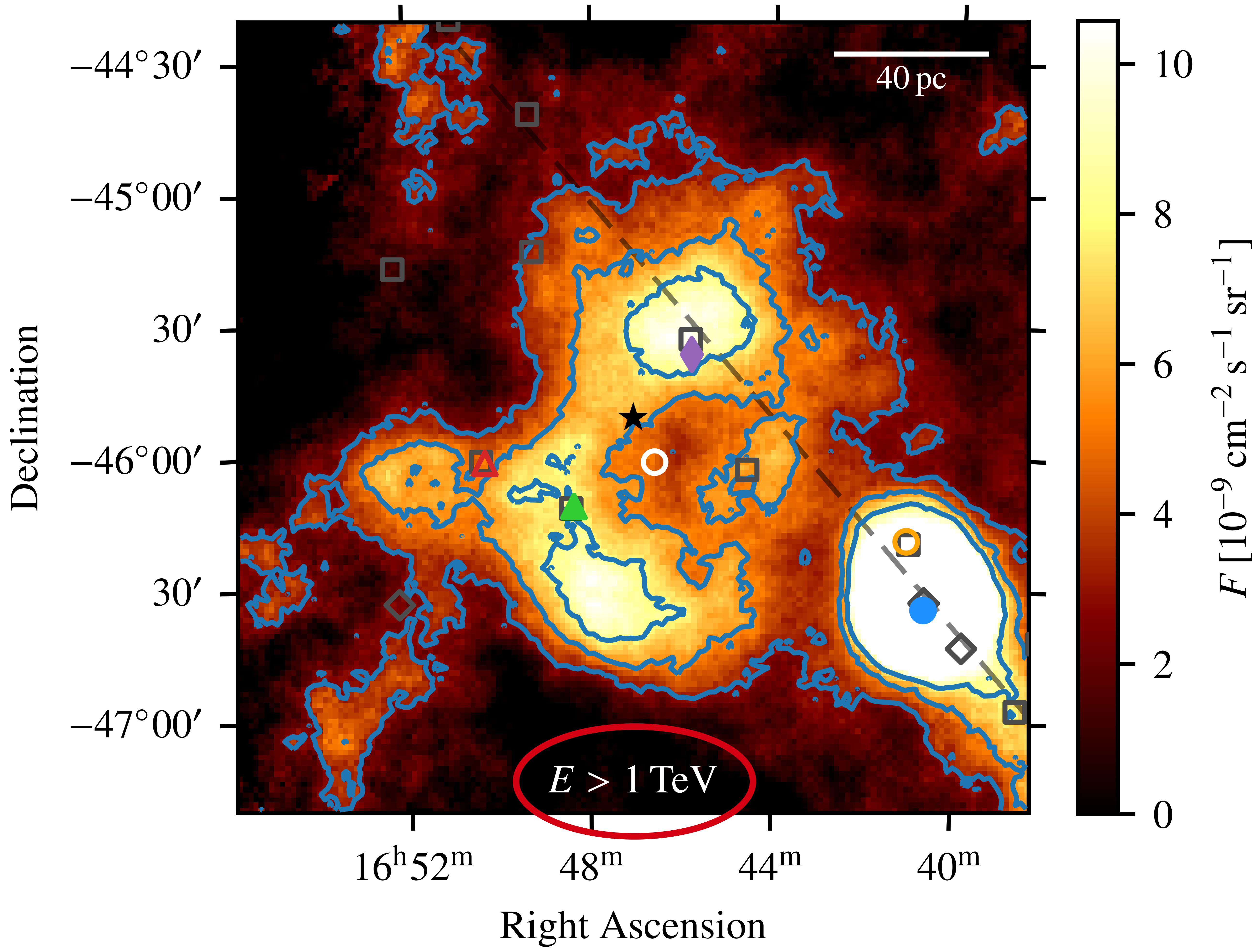
- Energy-dependence?
  - bright spots remain
  - ***shell-like structure persists!***



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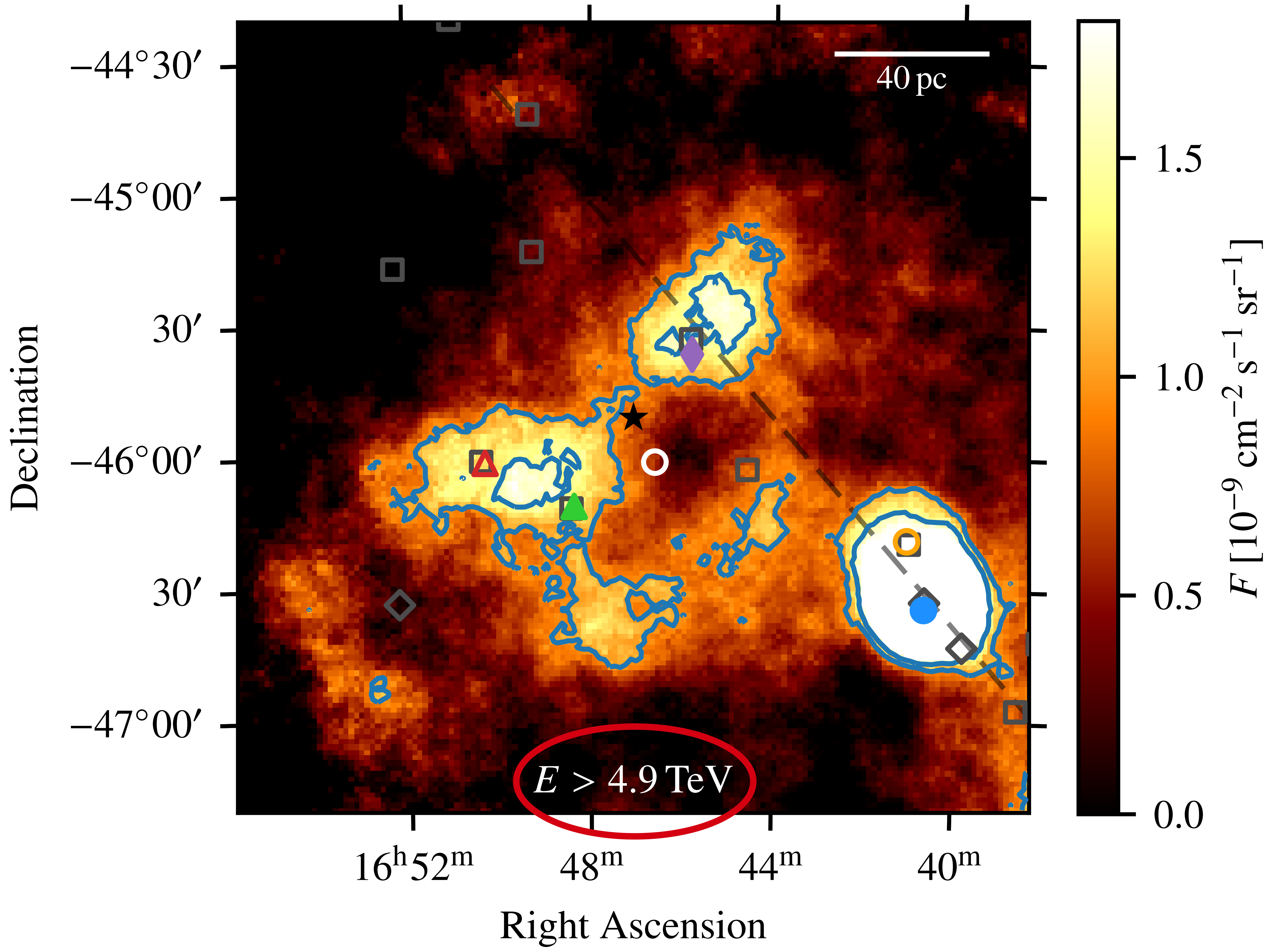

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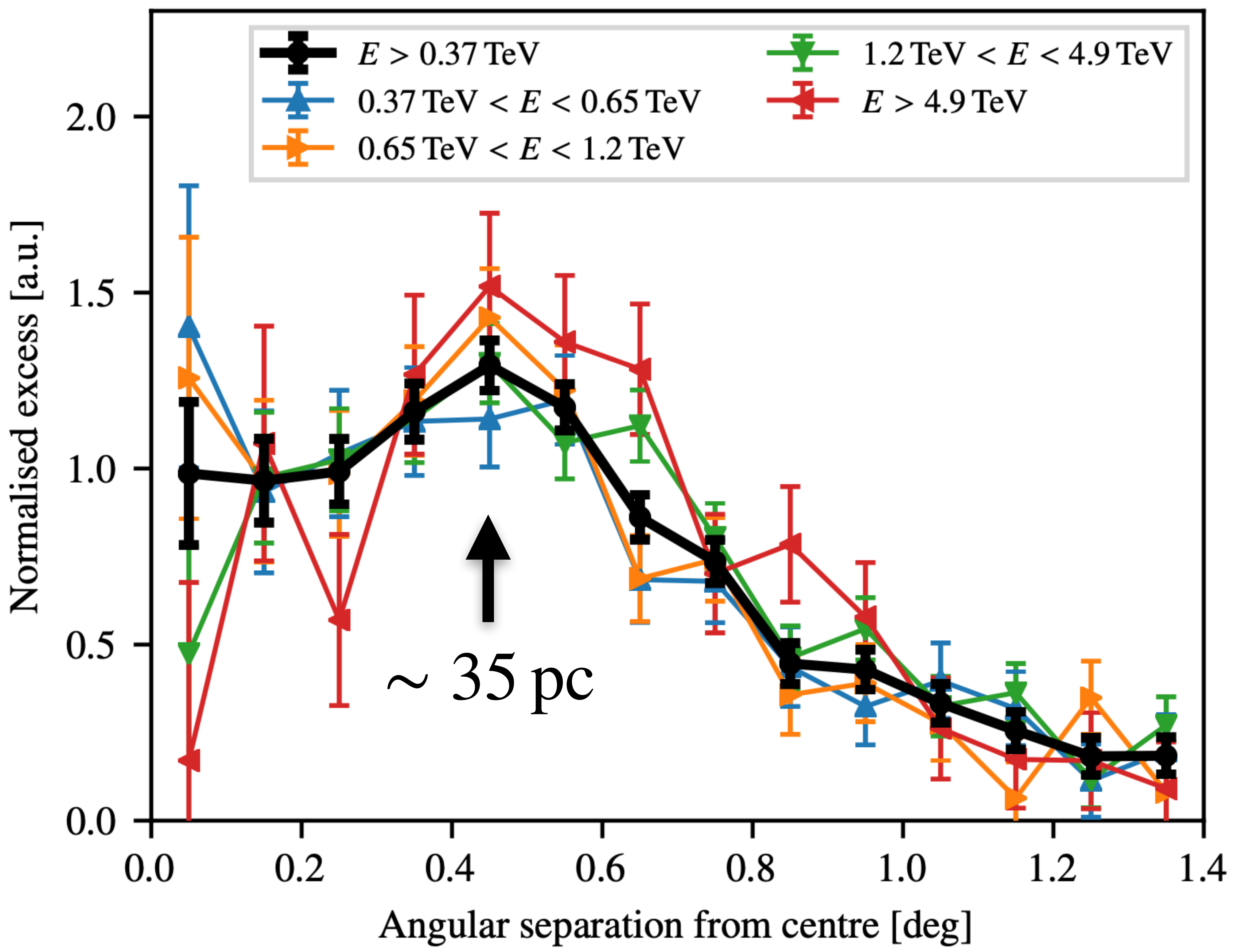
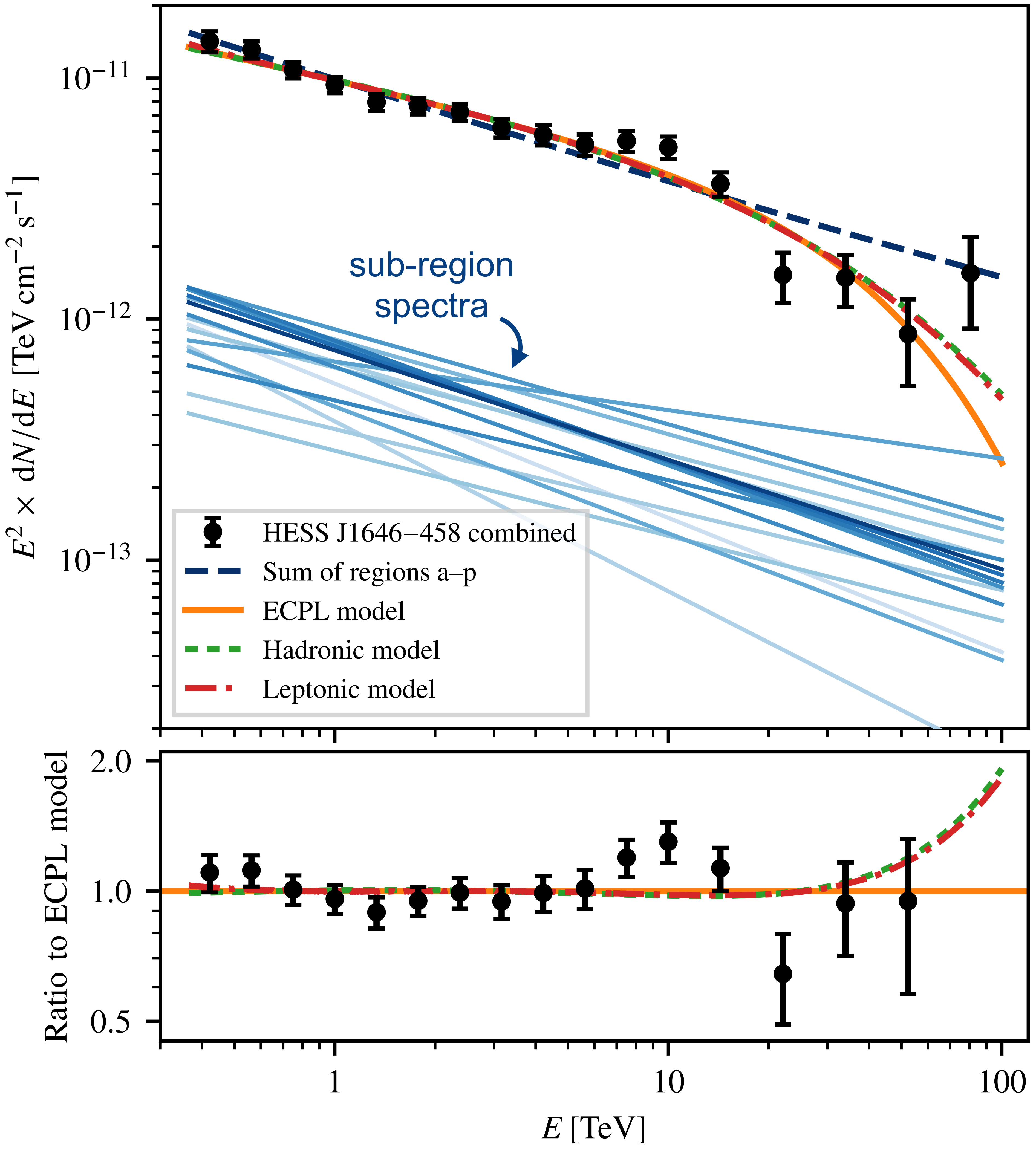
  - ***shell-like structure persists!***
- Confirmed by radial excess profiles

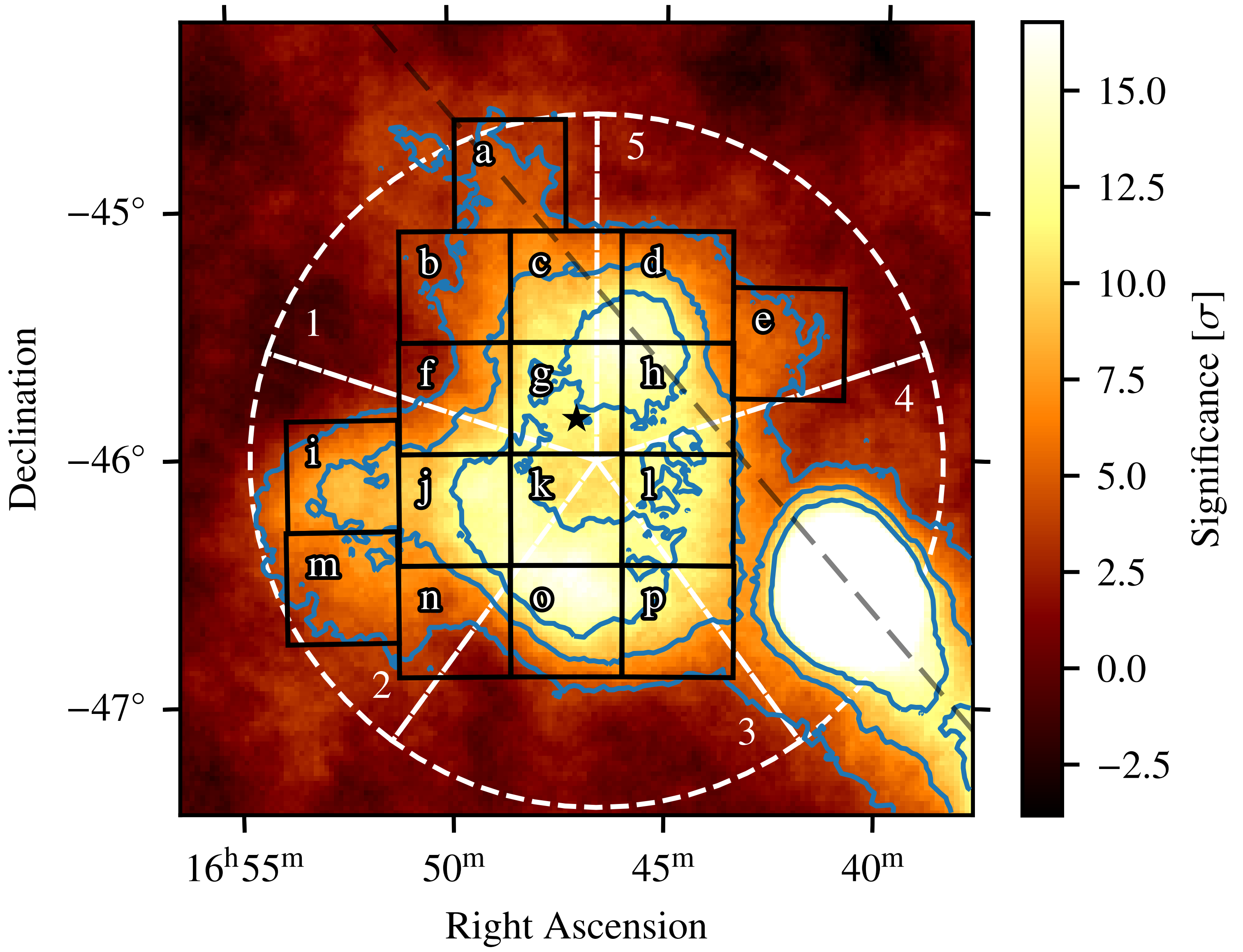


Westerlund 1 — energy spectrum

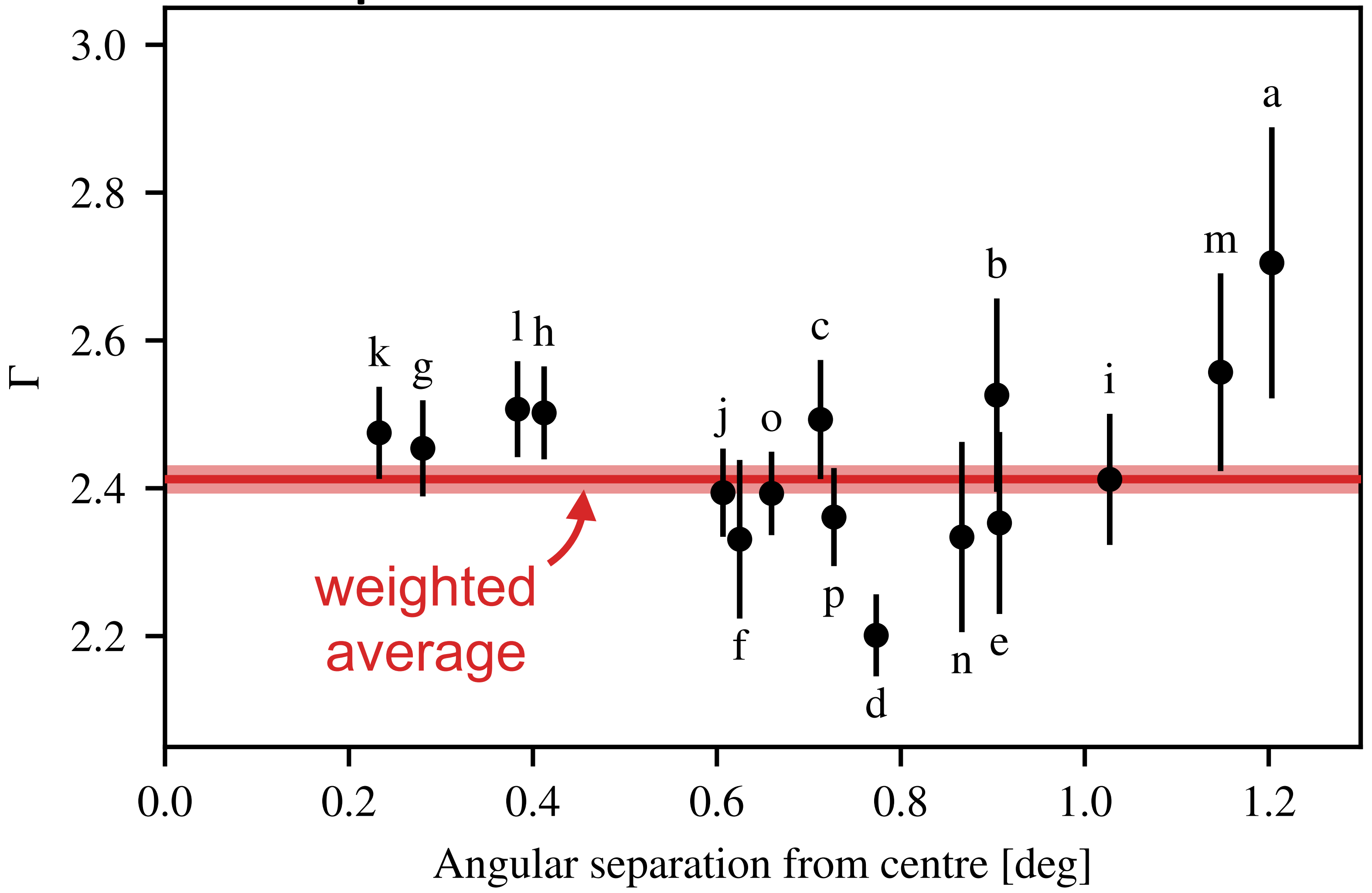
- Energy spectrum
  - extracted in 16 signal regions
  - individual spectra remarkably similar
  - add up region spectra → combined spectrum
  - ***extends to several ten TeV!***
  - $\Gamma = 2.30 \pm 0.04,\ E_c = \left(44^{+17}_{-11}\right)$ TeV

combined spectrum





spectral index vs. distance

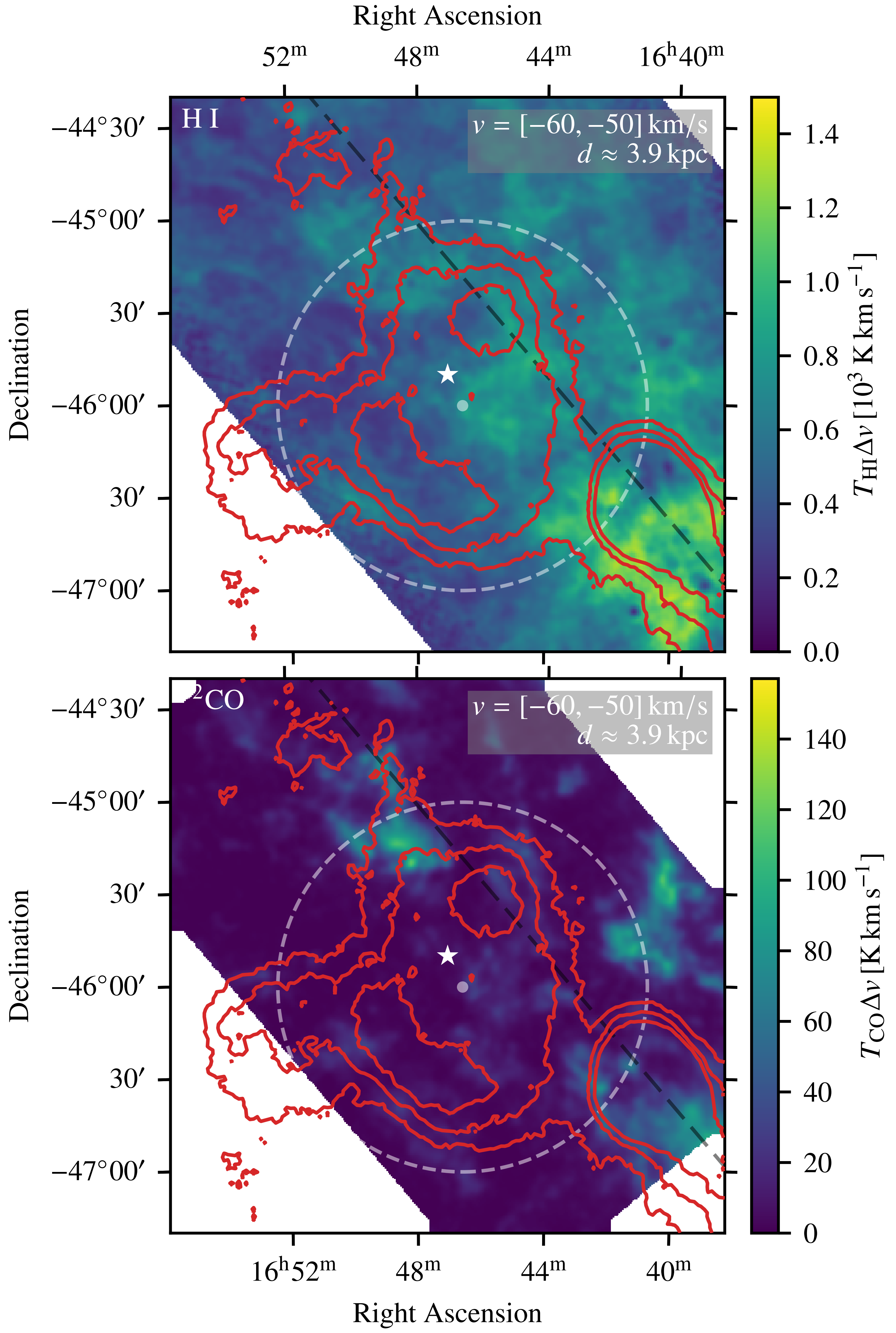


Westerlund 1 — correlation with gas maps

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

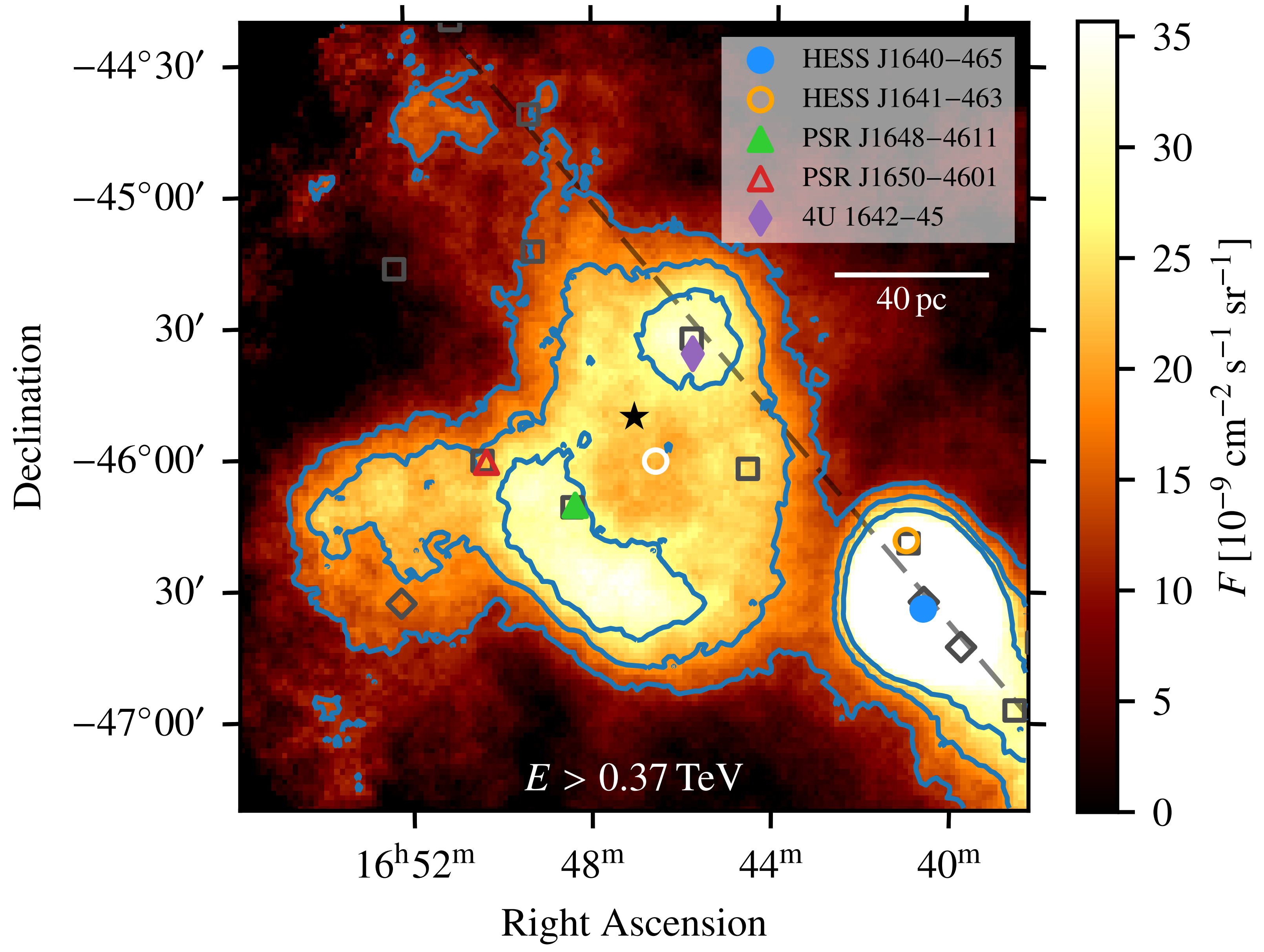
- ***Low density*** in regions with bright gamma-ray emission!
- A challenge for the hadronic scenario …
  … but there could still be ways out:
  - strong UV radiation from cluster can *ionise* gas or *photo-dissociate* CO molecules
  - distribution of cosmic rays need not be uniform

- But see Härer et al., A&A 671, A4 (2023) !
  - leptonic model preferred



Westerlund 1 — wrap-up

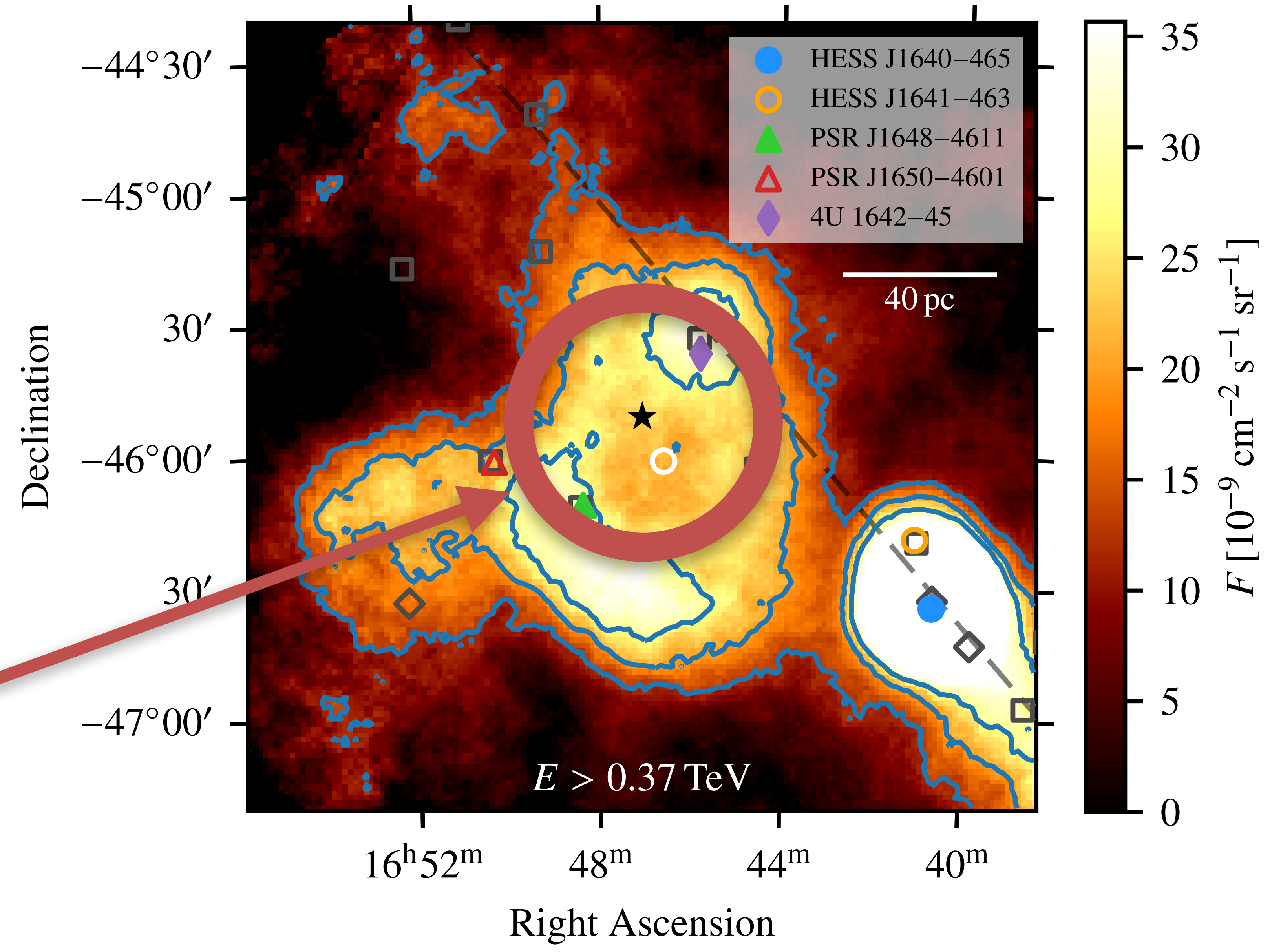
- Source association
  - ***only Westerlund 1 can explain majority of emission***
  - other objects (e.g. pulsars) may contribute locally

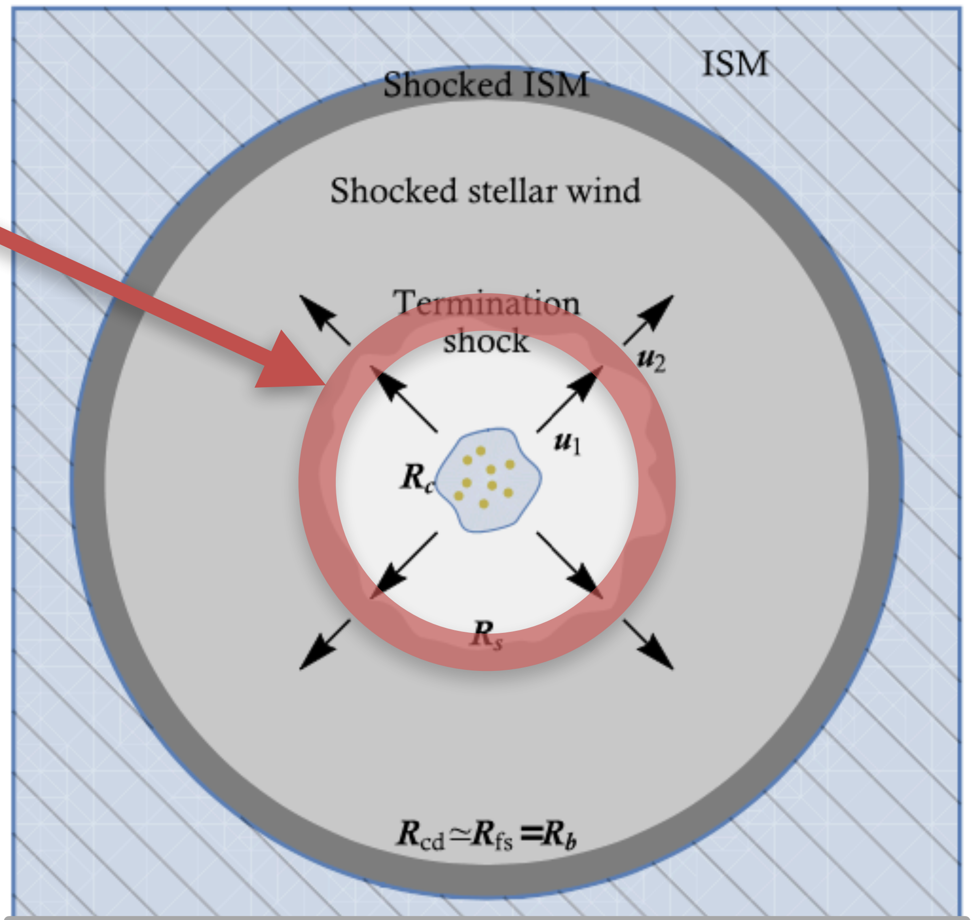


Westerlund 1 — wrap-up

- Source association
  - ***only Westerlund 1 can explain majority of emission***
  - other objects (e.g. pulsars) may contribute locally

- Shell-like morphology
  → connection to cluster wind termination shock?!
  - basic superbubble models suggest $R_{\mathrm{TS}} \sim \mathcal{O}(30\,\mathrm{pc})$
  - ***matches radius of shell-like structure seen in gamma rays!***





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

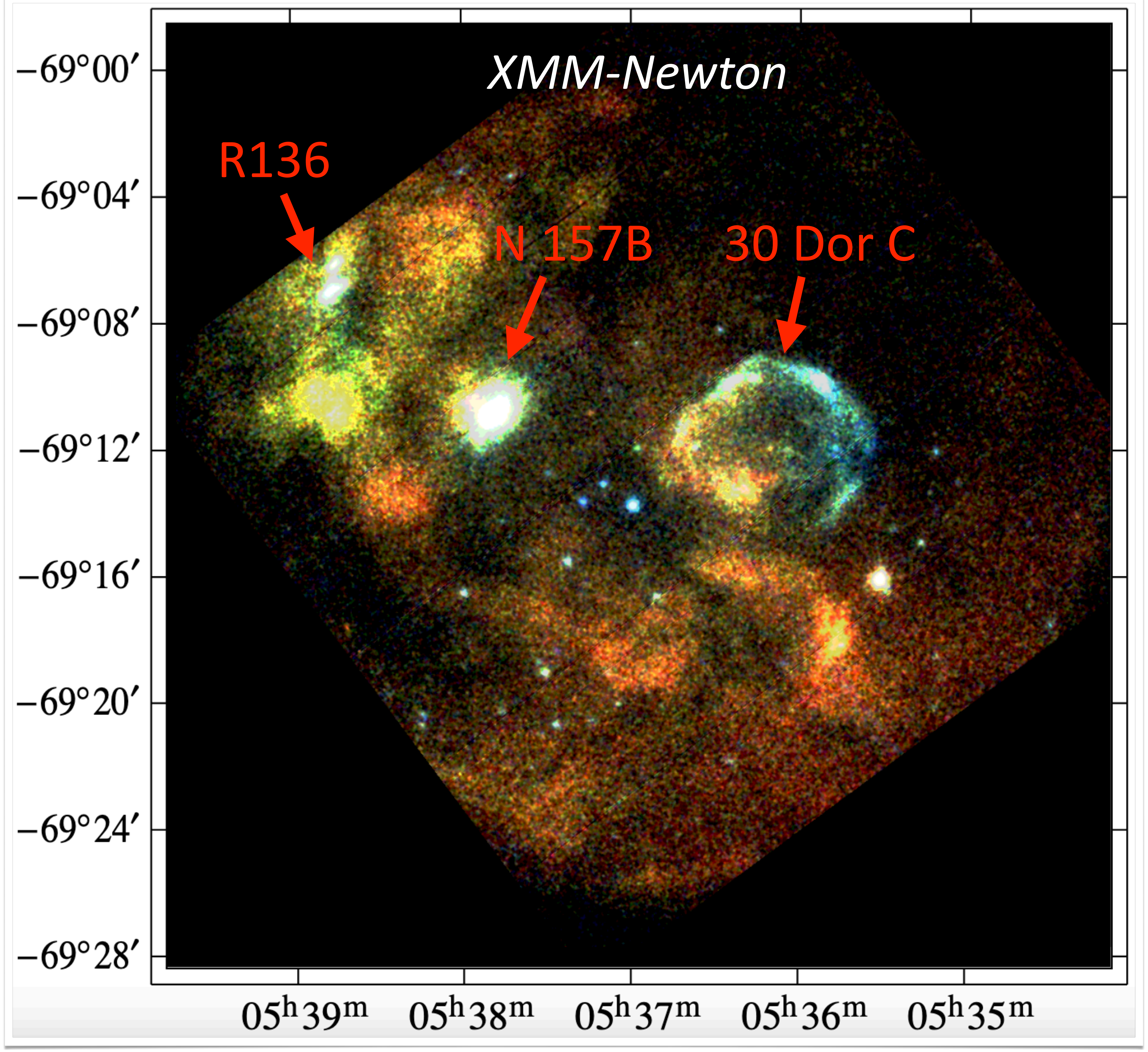
Massive star clusters in the Large Magellanic Cloud

Credit: ESO

- Tarantula Nebula
  - most active starburst region in Local Group
  - one of the largest known H-II regions
  - host to numerous massive star clusters

Massive star clusters in the Large Magellanic Cloud

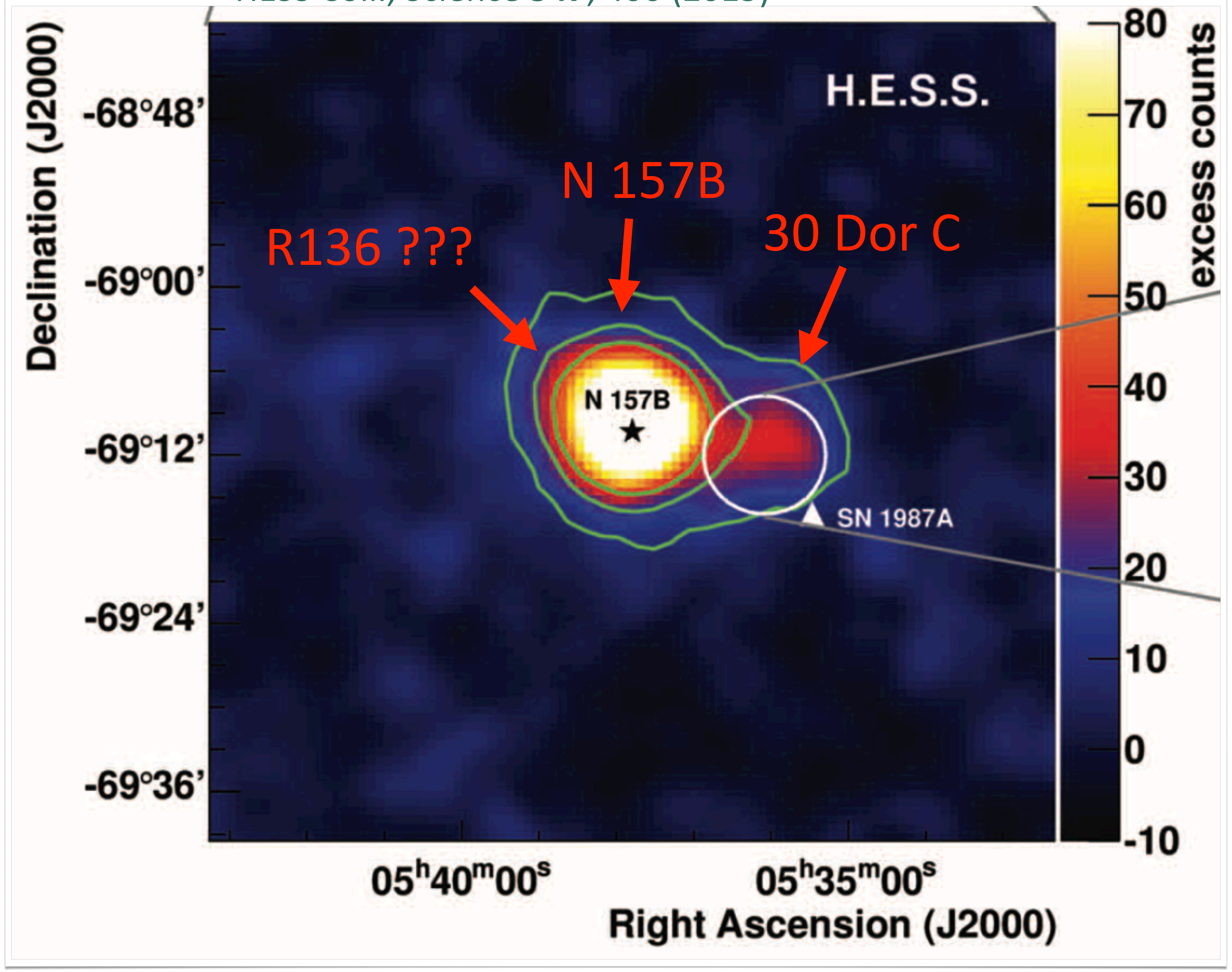
Dennerl et al., A&A **365**, L202 (2001)



- Tarantula Nebula
  - most active starburst region in Local Group
  - one of the largest known H-II regions
  - host to numerous massive star clusters
- Objects of interest (for this talk)
  - **N 157B** — pulsar wind nebula
  - **30 Dor C** — superbubble
  - **R136** — super star cluster

Massive star clusters in the Large Magellanic Cloud

HESS Coll., Science **347**, 406 (2015)



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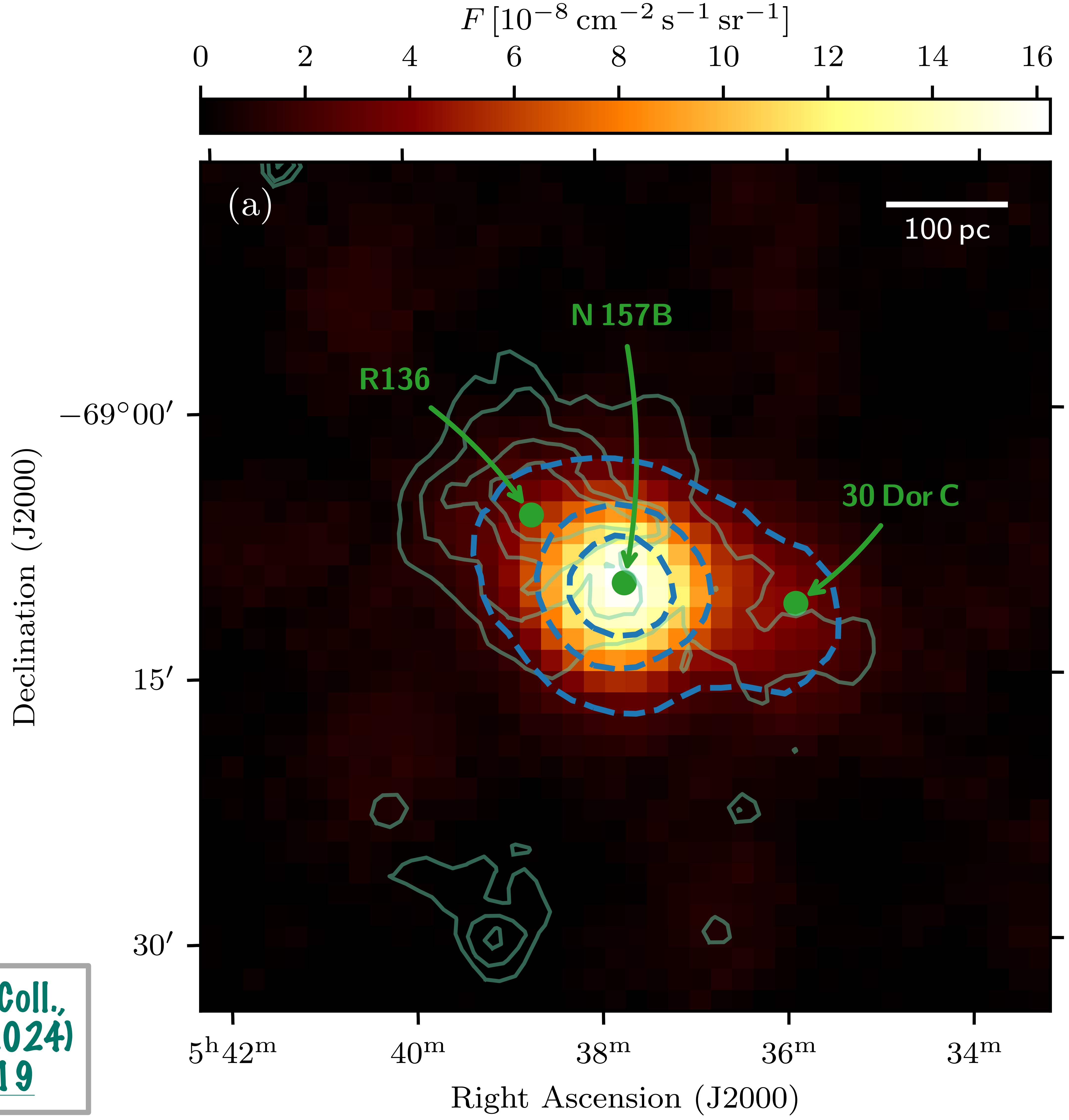
- Objects of interest (for this talk)
  - **N 157B** — pulsar wind nebula
    → <u>*very bright*</u> in gamma rays
  - **30 Dor C** — superbubble
    → only confirmed one in gamma rays
  - **R136** — super star cluster
    → no gamma rays so far…

Massive star clusters in the Large Magellanic Cloud



Reference: HESS Coll., ApJL 970, L21 (2024) arXiv:2407.16219

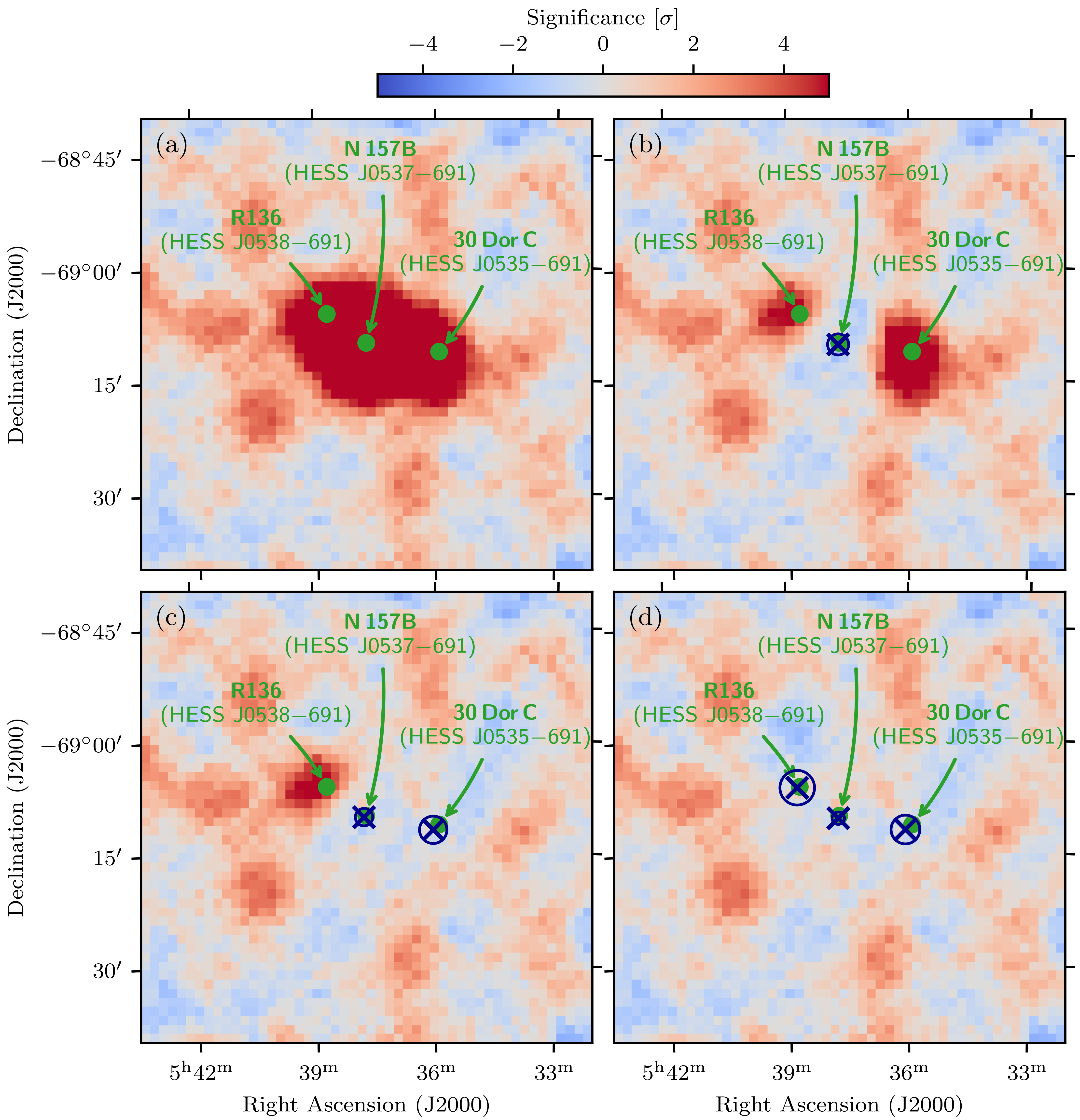
Massive star clusters in the Large Magellanic Cloud

- Advanced analysis techniques (γπ — A **Python** package for **gamma-ray** astronomy)
  → modelling of emission in 3D (RA, Dec, energy)

- Iteratively add sources to model until no significant emission remains
  - 2D Gaussians as spatial models

- Need three separate sources for a good description of the data

Source	Significance
N 157B	51σ
30 Dor C	11σ
R136	6.3σ



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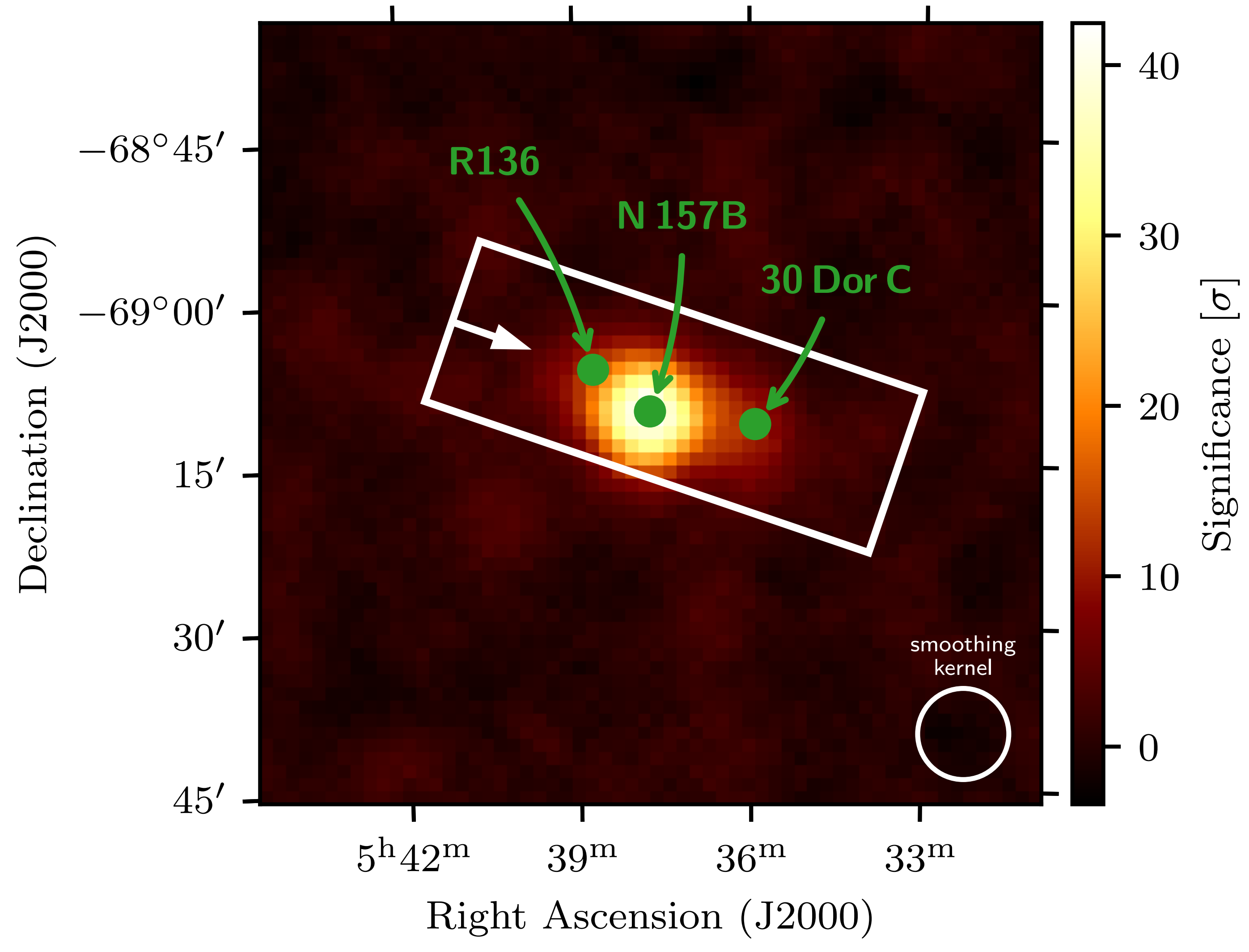

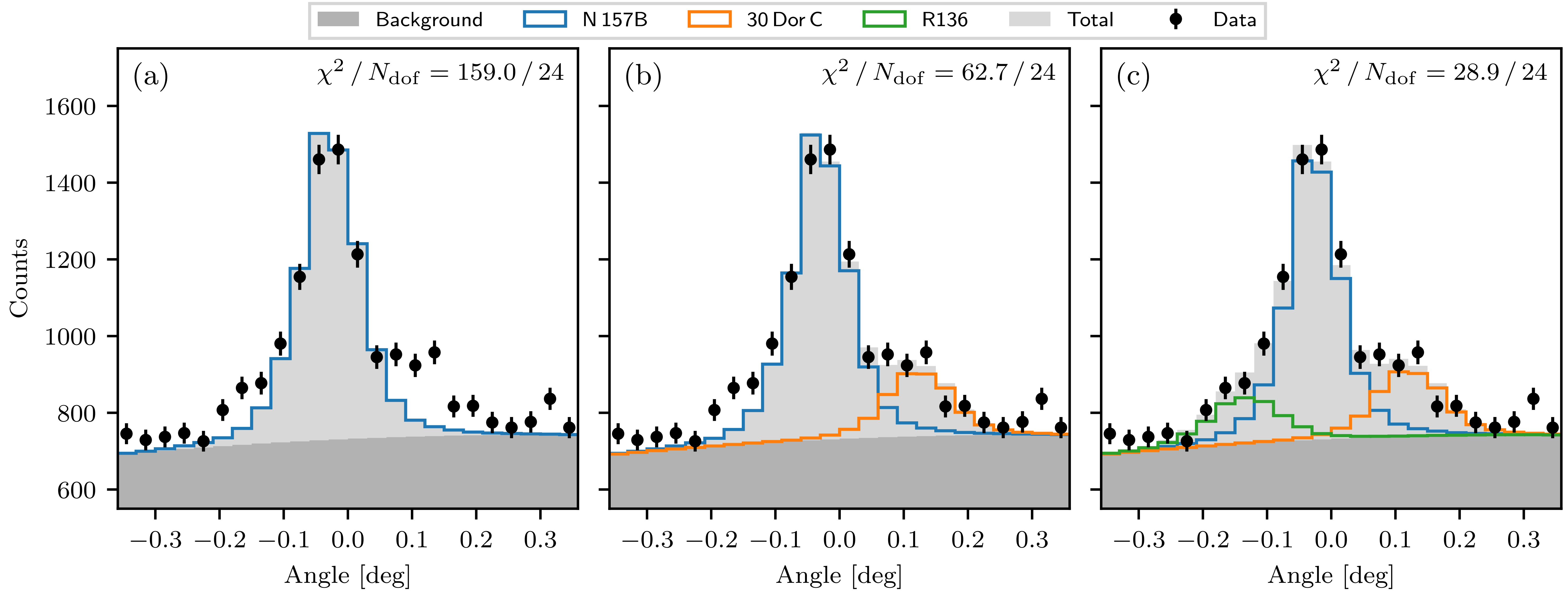

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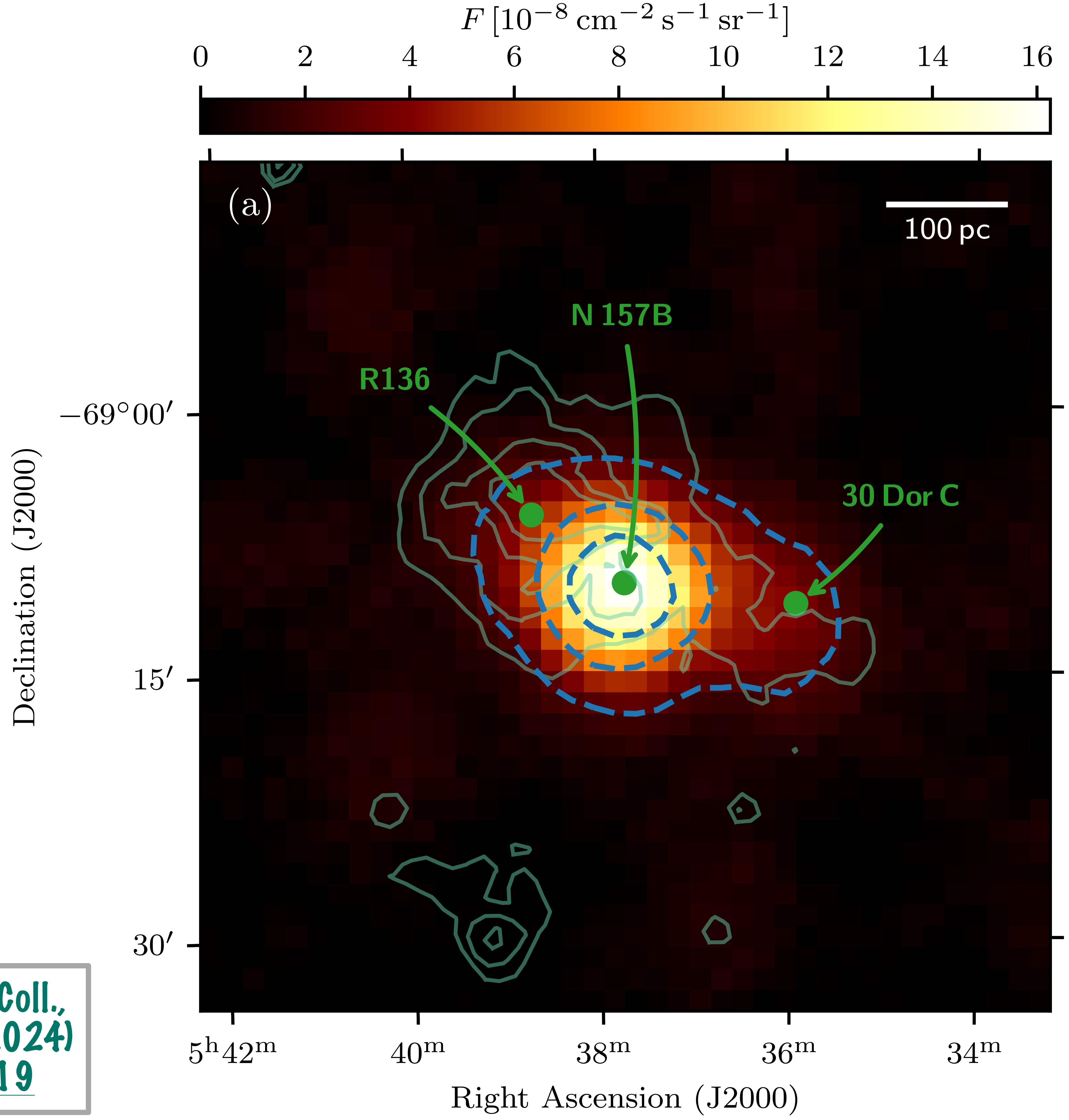

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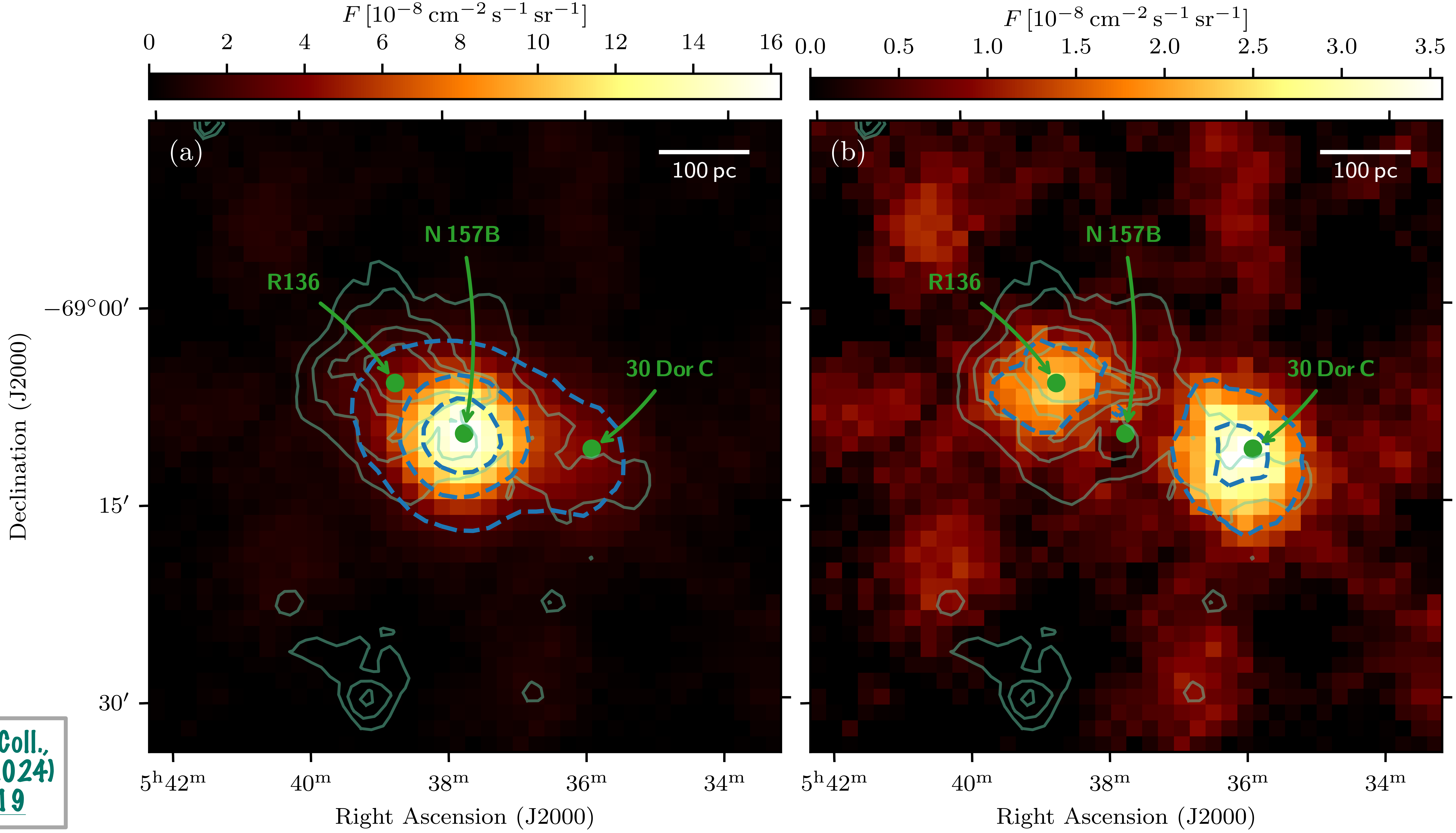

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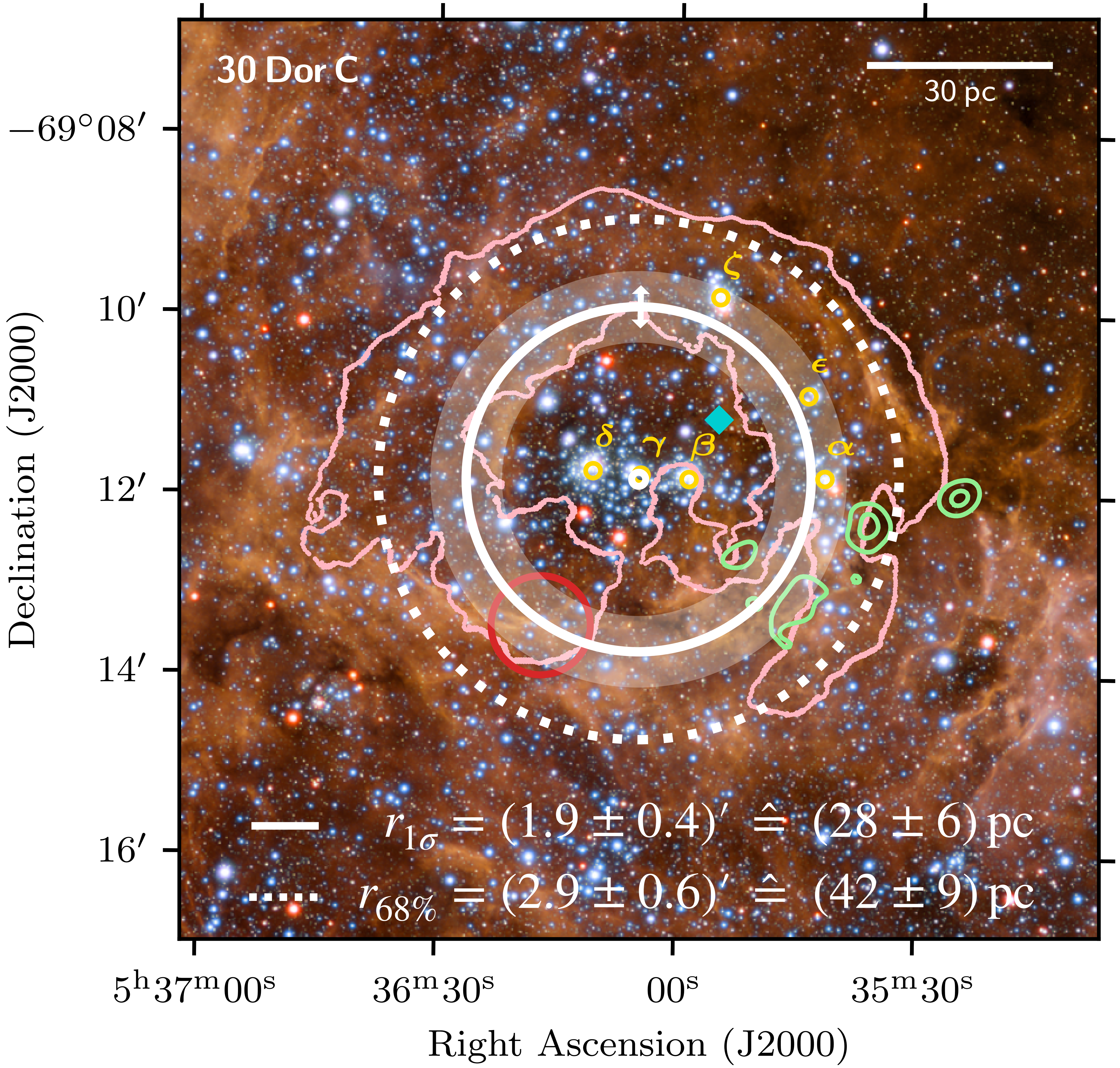
30 Dor C

- Extension in gamma rays established (3.3σ) for the first time!
  - size roughly compatible with X-ray shell
  - suggestive of a connection?
- Peak of emission ***not*** coincident with locations of densest gas clouds



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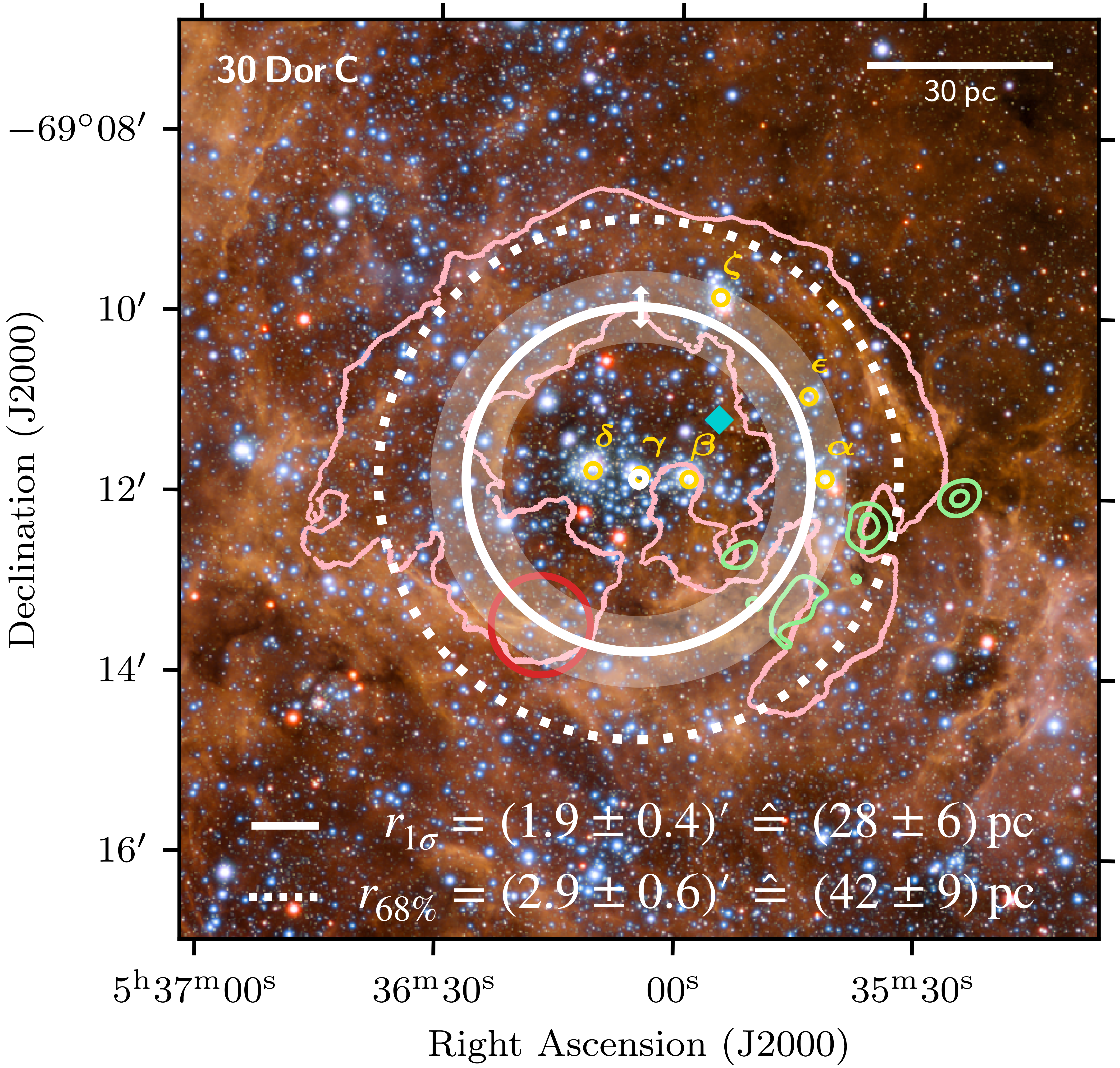
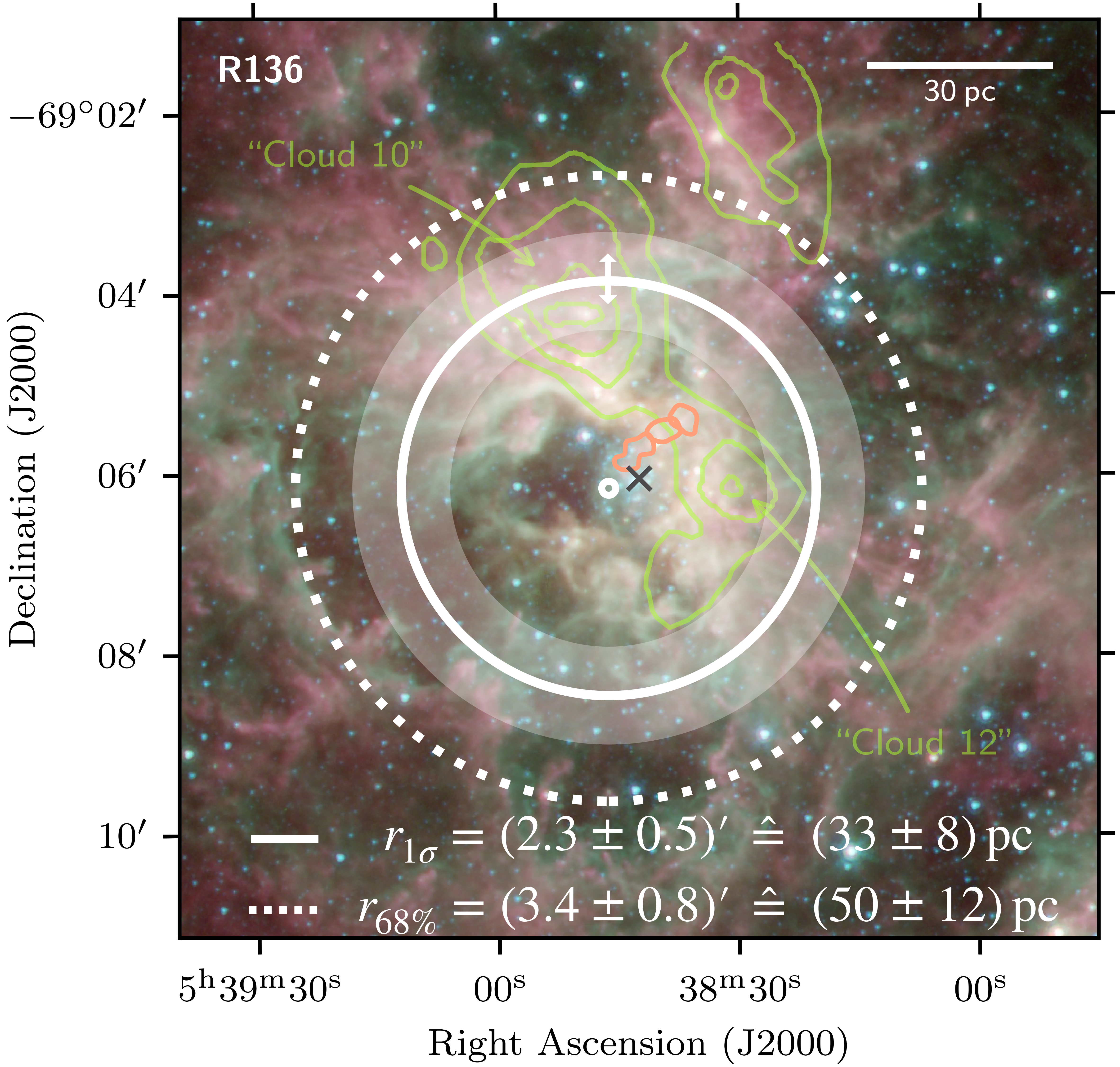
- Peak of emission ***not*** coincident with locations of densest gas clouds
- Expanding superbubble model (Weaver 1977)
  - $L_w = 1.5 \times 10^{38}\,\mathrm{erg\,s^{-1}}$, $v_w = 3\,000\,\mathrm{km\,s^{-1}}$, $T = 4\,\mathrm{Myr}$, $n = 100\,\mathrm{cm^{-3}}$
  - ***superbubble*** radius $\approx 74\,\mathrm{pc}$
  - ***termination shock*** radius $\approx 7.9\,\mathrm{pc}$



R136

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



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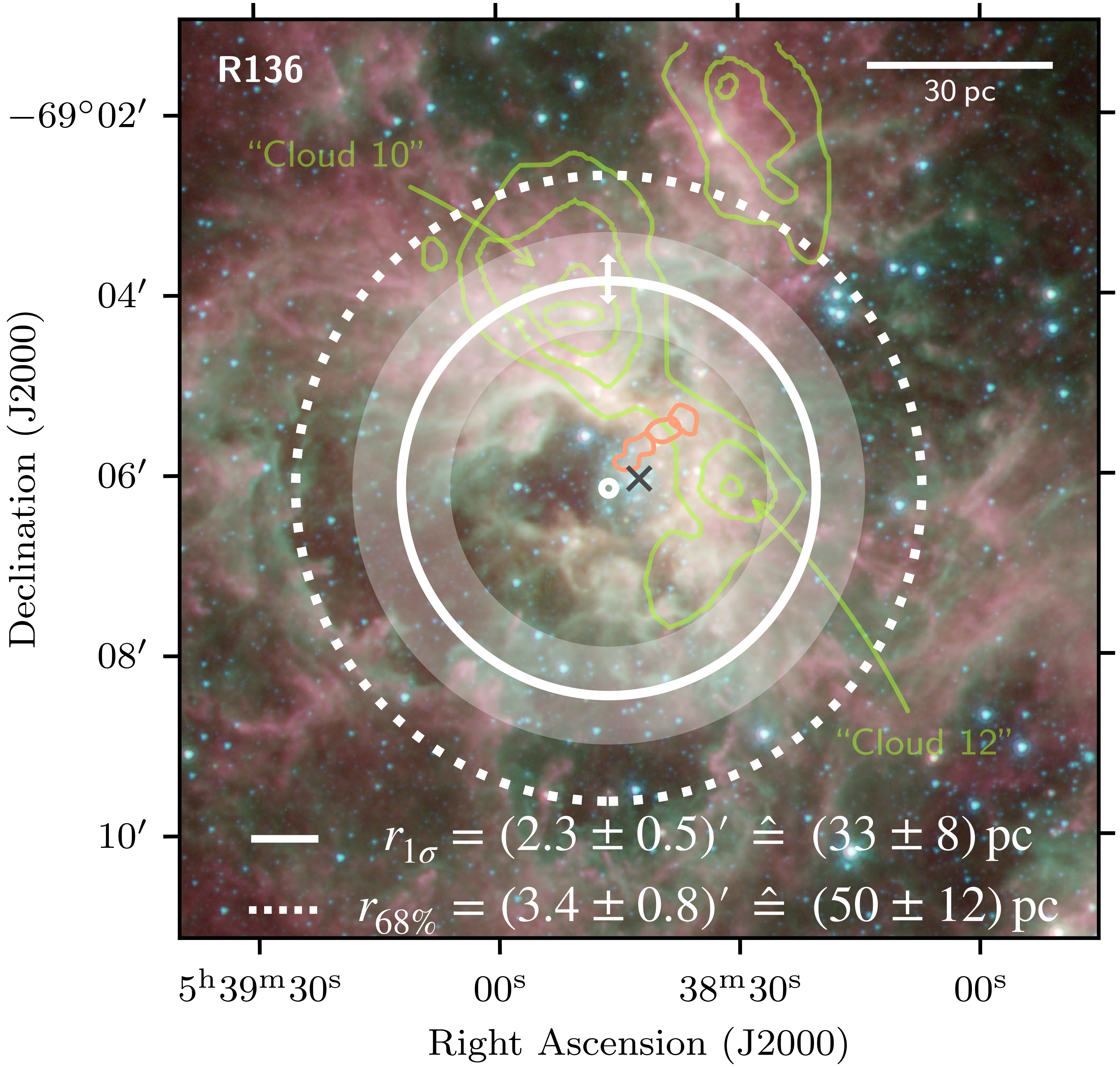
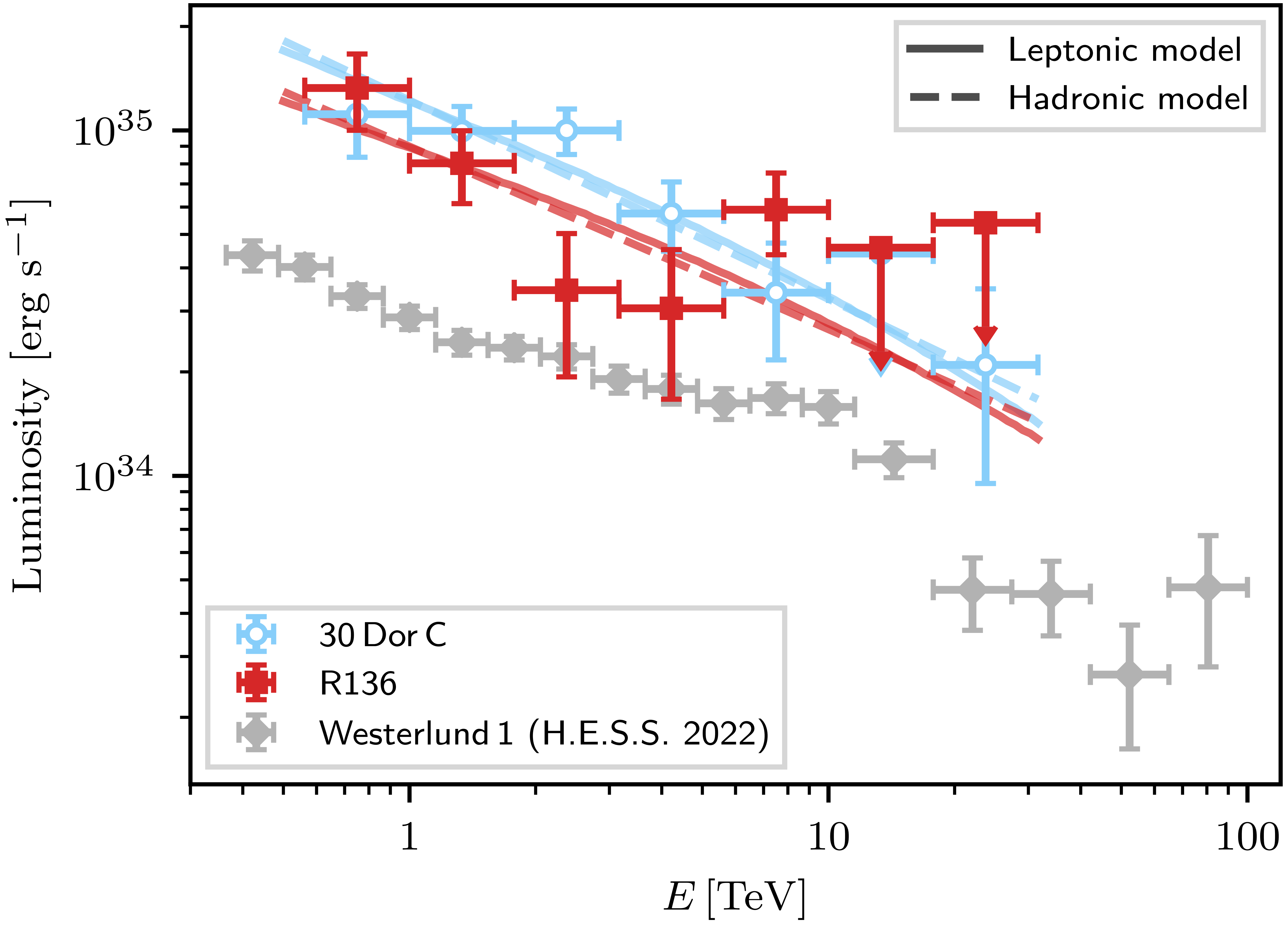
- Also observed as an extended source (3.1σ)!

- Expanding superbubble model (Weaver 1977)
  - $L_w = 10^{39}\,\mathrm{erg\,s^{-1}}$, $v_w = 3\,000\,\mathrm{km\,s^{-1}}$, $T = 1.5\,\mathrm{Myr}$, $n = 100\,\mathrm{cm^{-3}}$
  - ***superbubble*** radius $\approx 56\,\mathrm{pc}$
  - ***termination shock*** radius $\approx 8.7\,\mathrm{pc}$



30 Dor C and R136 — energetics

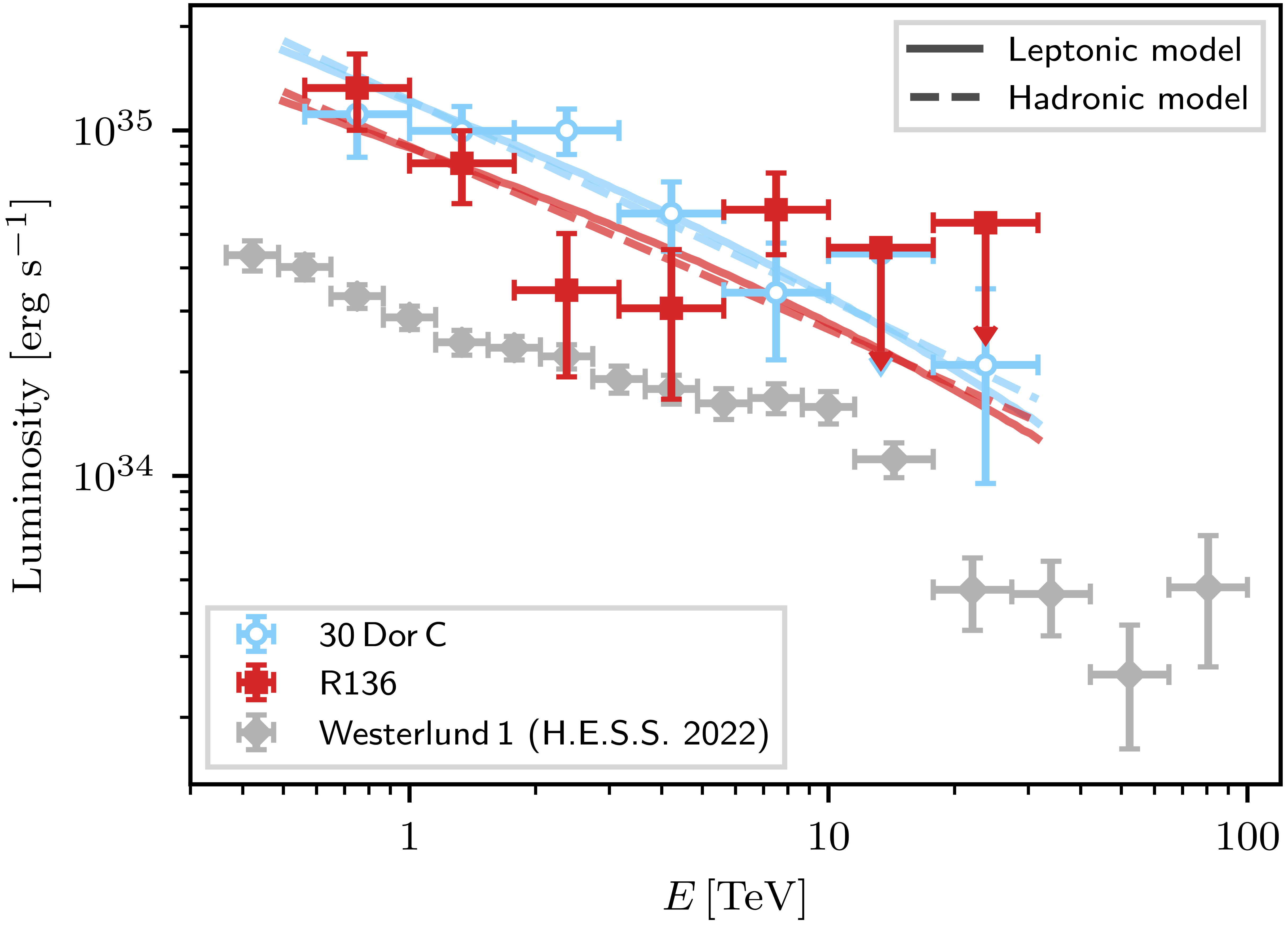
- 30 Dor C and R136 are ***twice as luminous*** as Westerlund 1 — the most massive young star cluster in the Milky Way!



30 Dor C and R136 — energetics

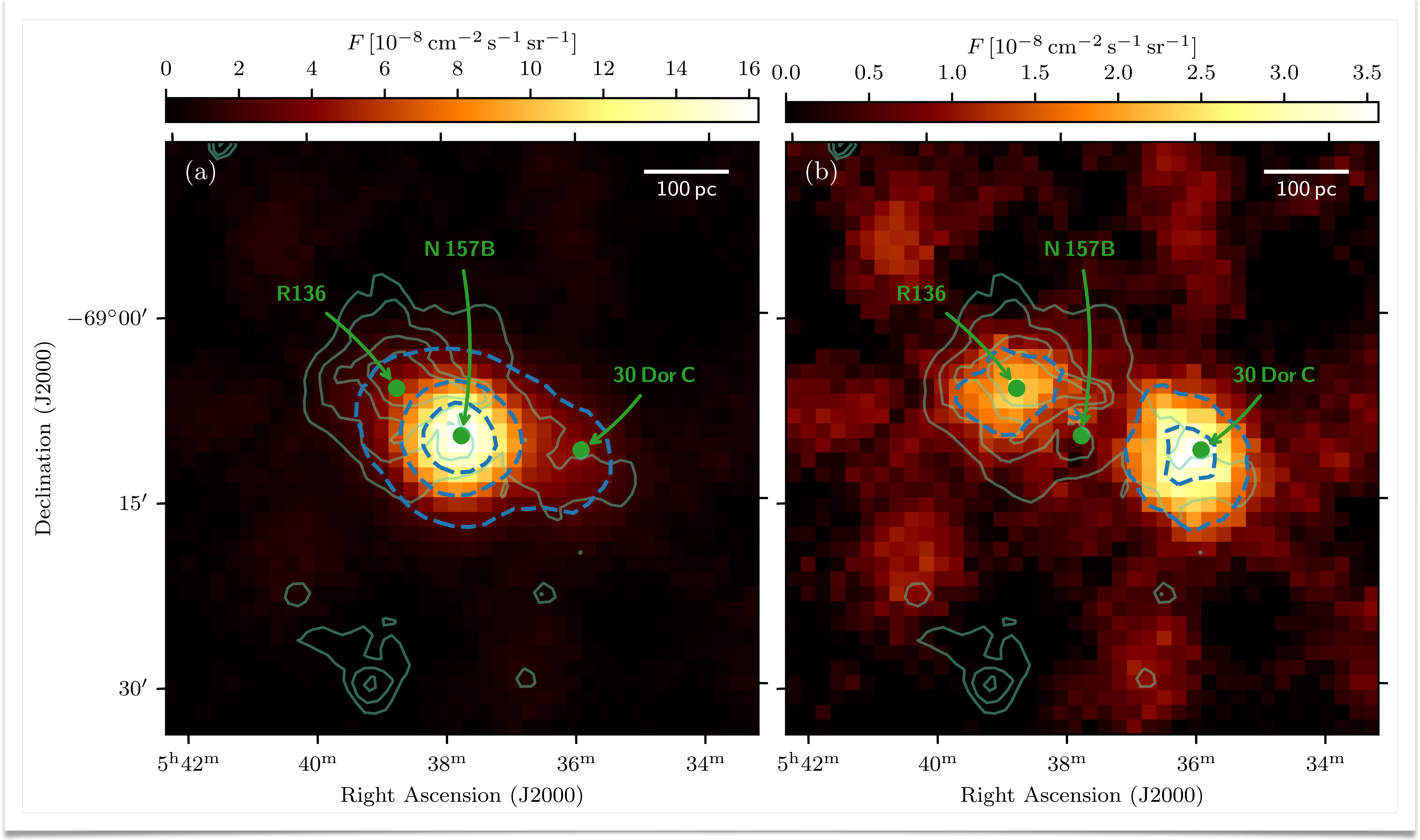
- 30 Dor C and R136 are ***twice as luminous*** as Westerlund 1 — the most massive young star cluster in the Milky Way!

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



Massive star clusters in the LMC — wrap-up

- Detected bright gamma-ray emission from two young massive star clusters
  - 30 Dor C (→ OB association LH90)
  - R136 (*new!*)



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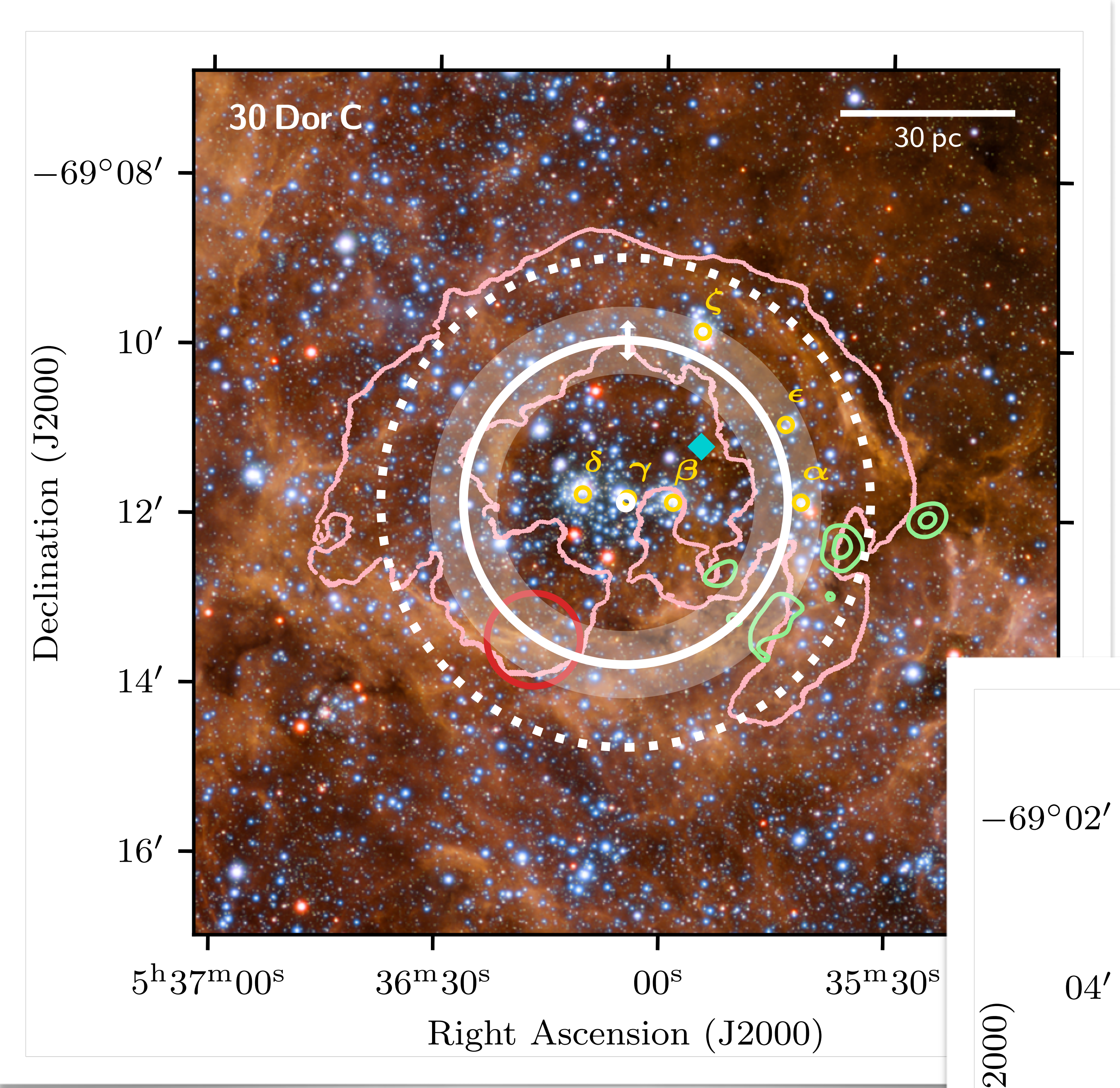
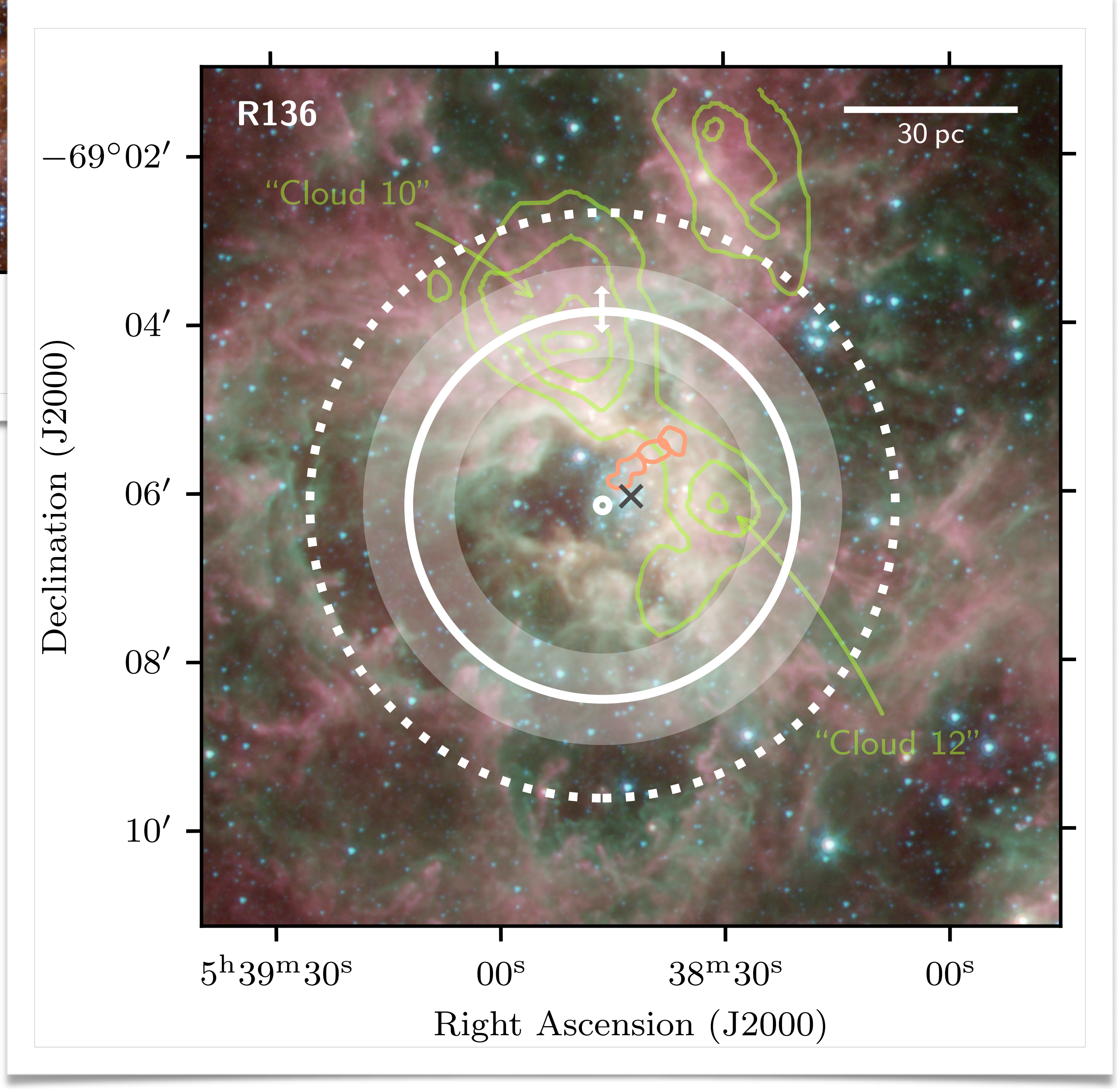
- Both sources appear spatially extended
  - extension comparable to expected size of superbubble in both cases





Massive star clusters in the LMC — wrap-up

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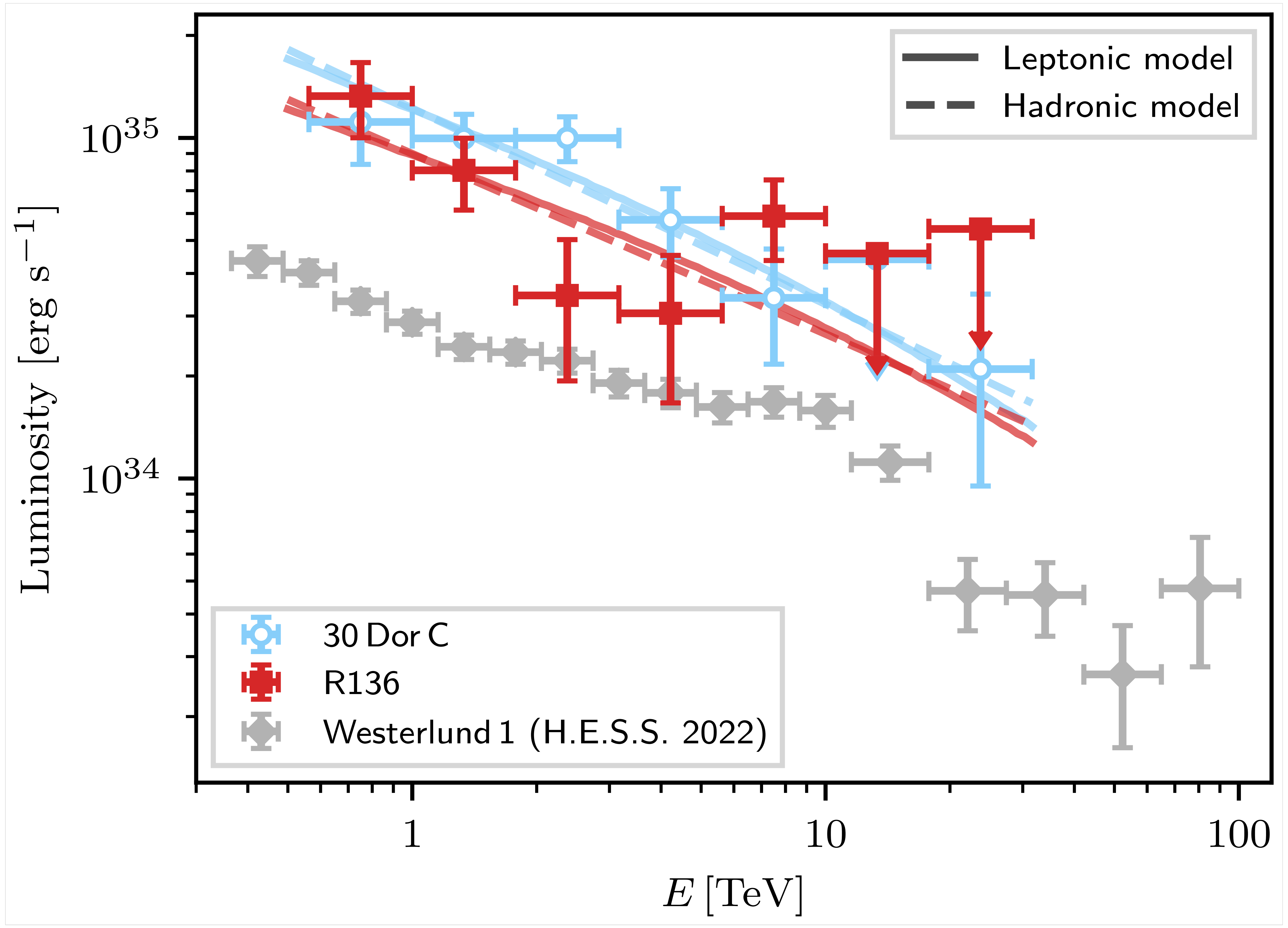
  - both hadronic or leptonic scenario can work



Massive star clusters in the LMC — wrap-up

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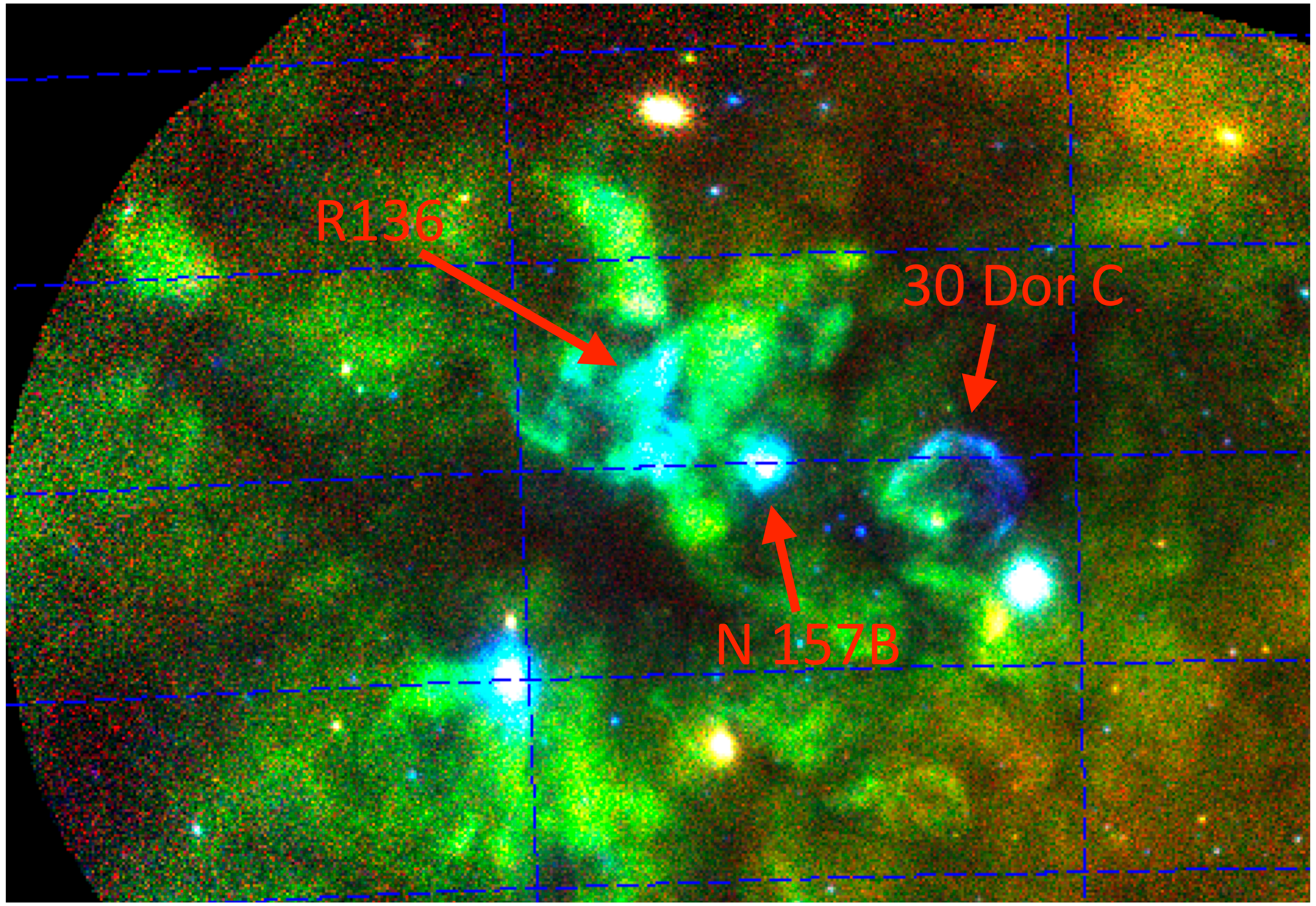
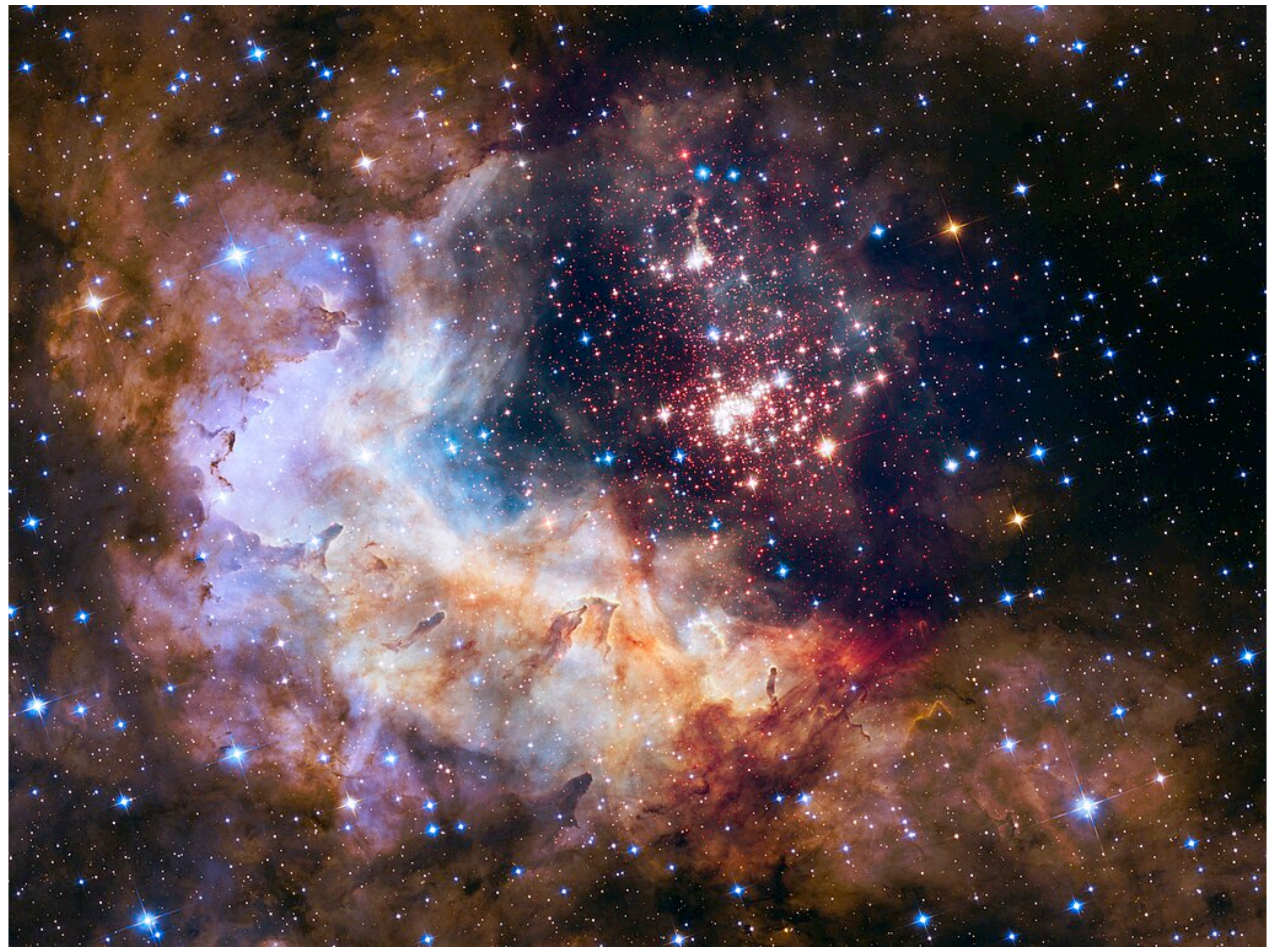
- Both sources appear spatially extended
  - extension comparable to expected size of superbubble in both cases
- Basic energetics consideration indicates clusters are powerful enough
  - both hadronic or leptonic scenario can work
- MWL picture quite different
  - Resolved X-ray bubble for 30 Dor C, but not R136…

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

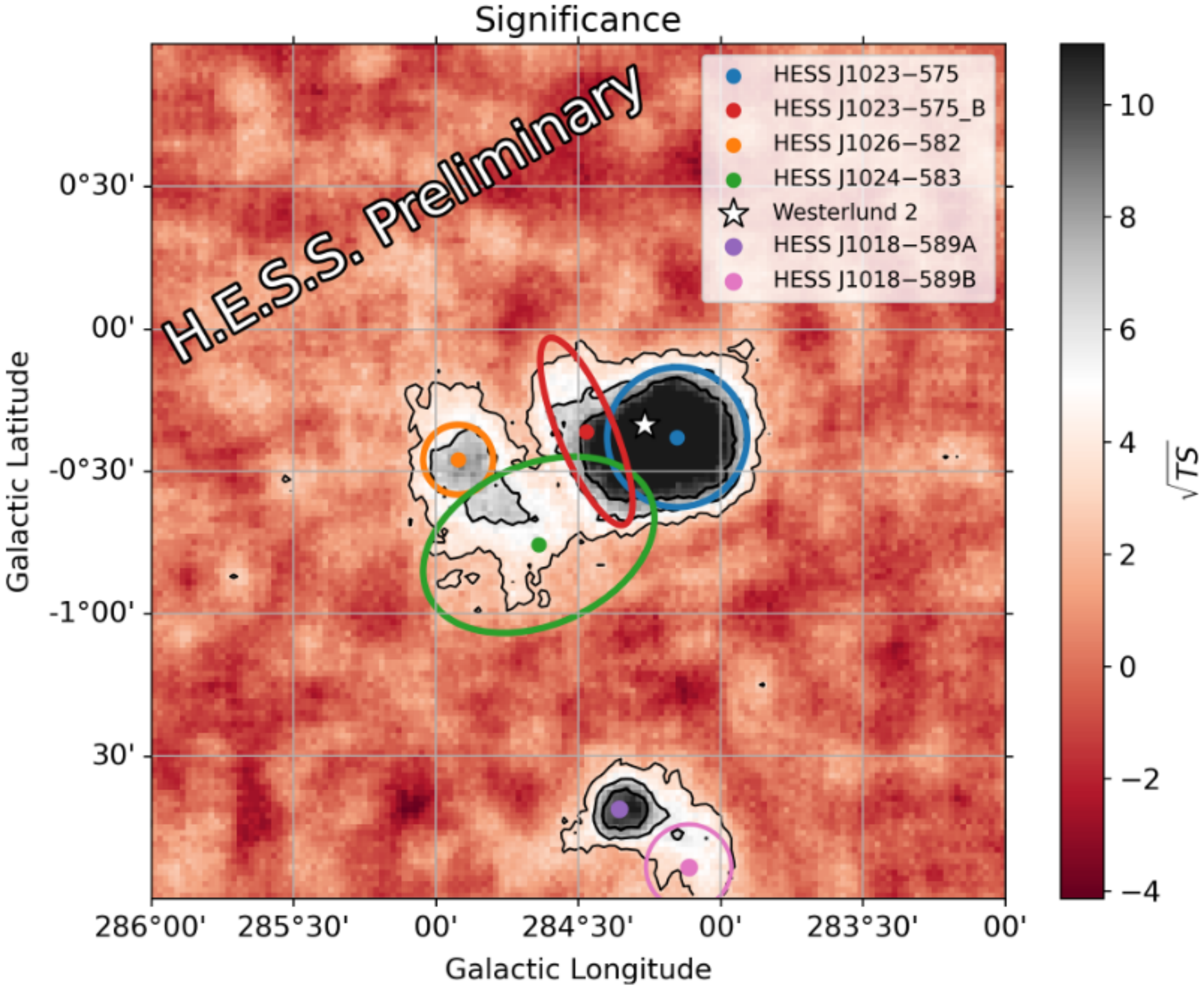


Westerlund 2

- Young massive star cluster
  - age $\lesssim 2\,\mathrm{Myr}$
  - distance very uncertain $(2 - 8\,\mathrm{kpc})$
- Updated H.E.S.S. analysis with 3x increased exposure
  - confirms HESS J1023–575 & HESS J1026–582
  - new: HESS J1023–575B & HESS J1024–583



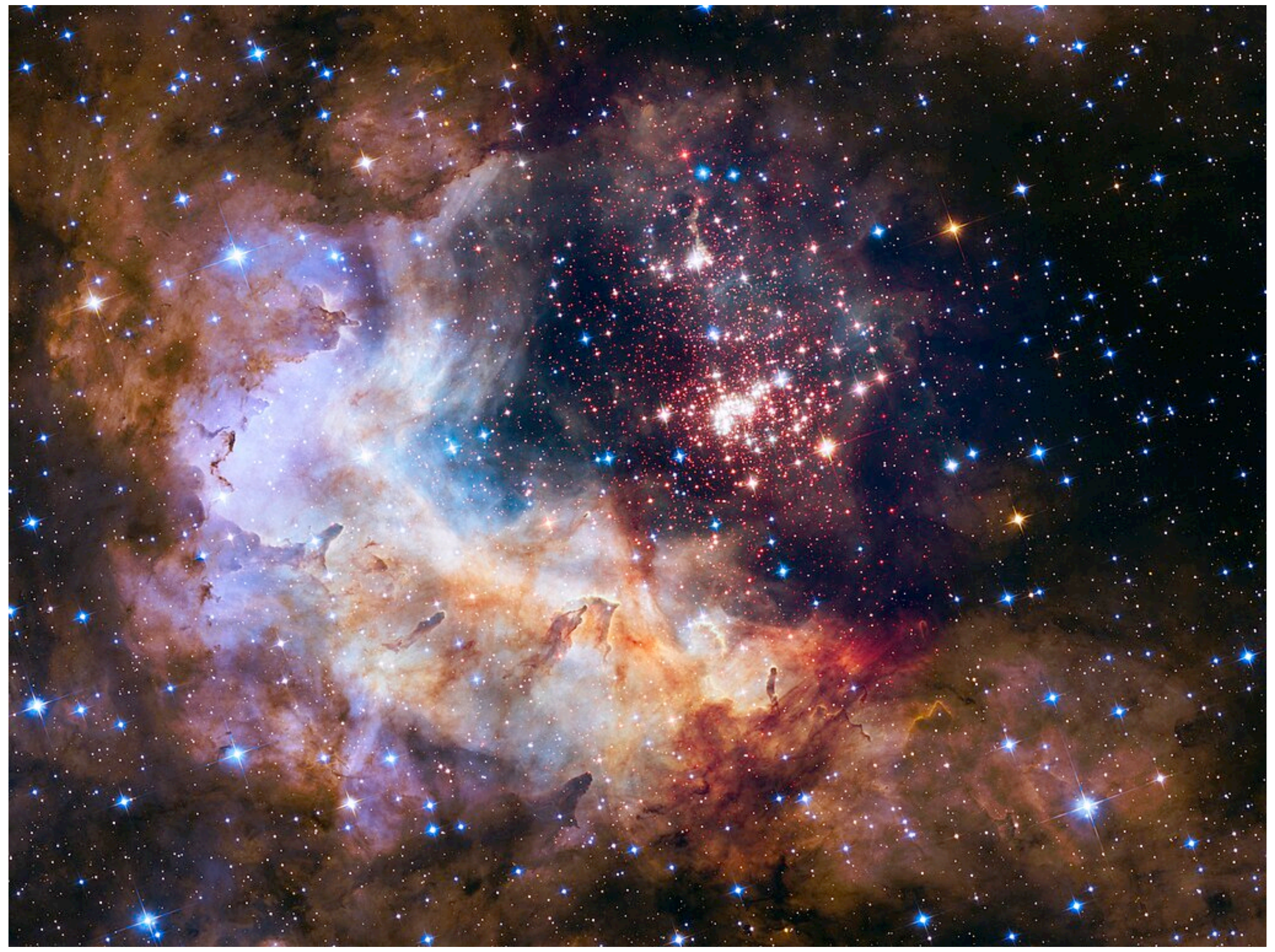
Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), A. Nota (ESA/STScI), and the Westerlund 2 Science Team



Reference: Holch et al., PoS (ICRC2023) 778

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



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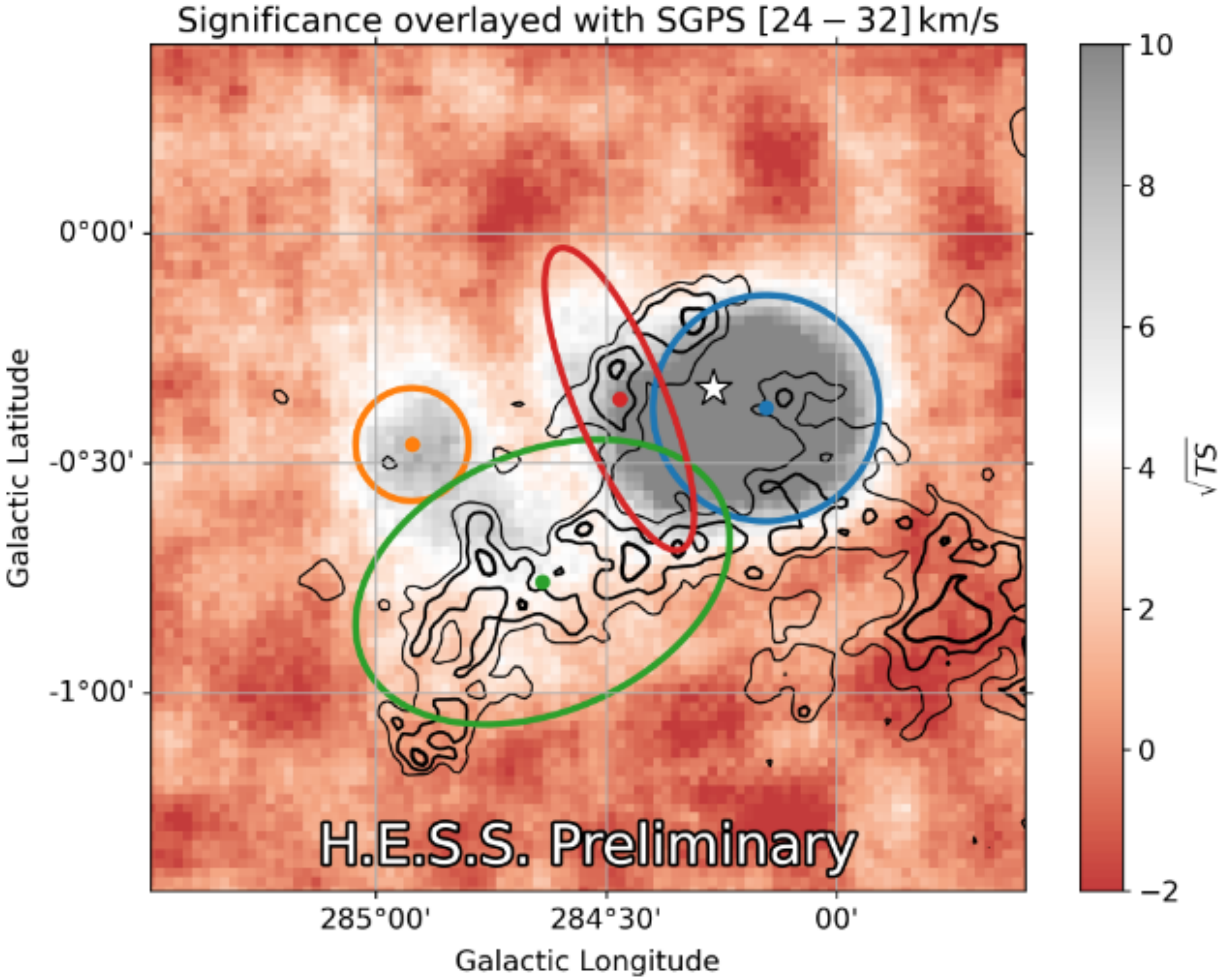

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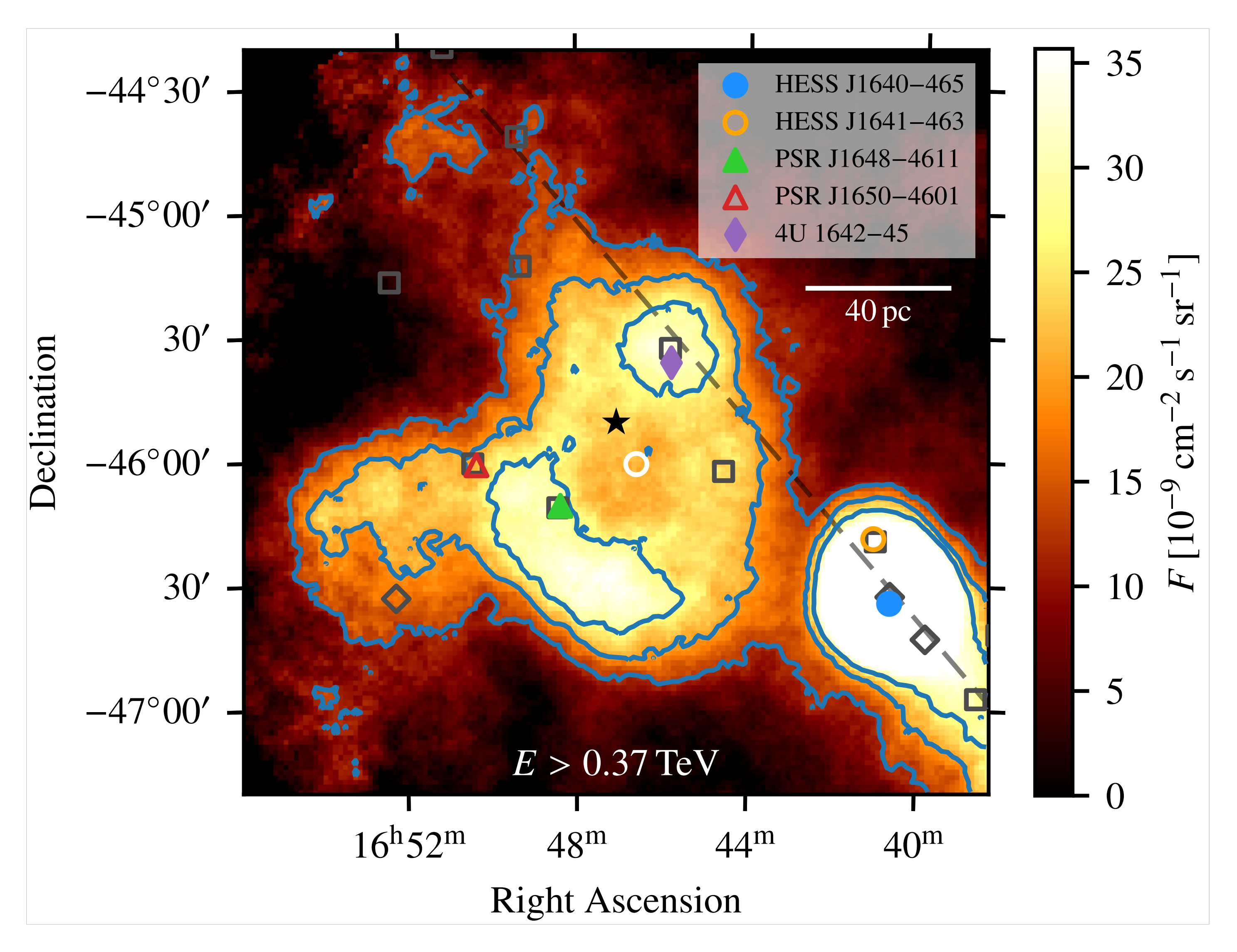
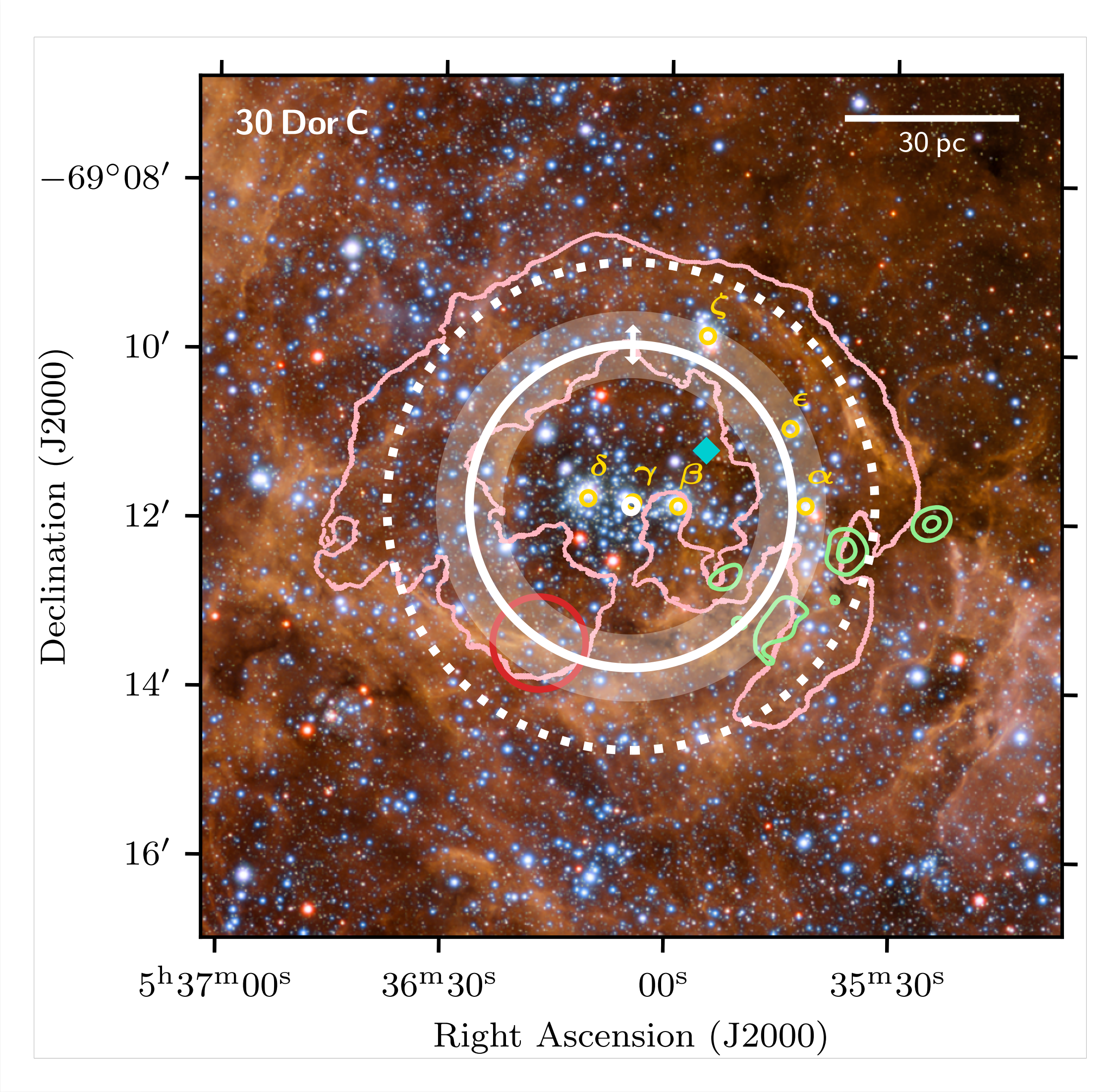
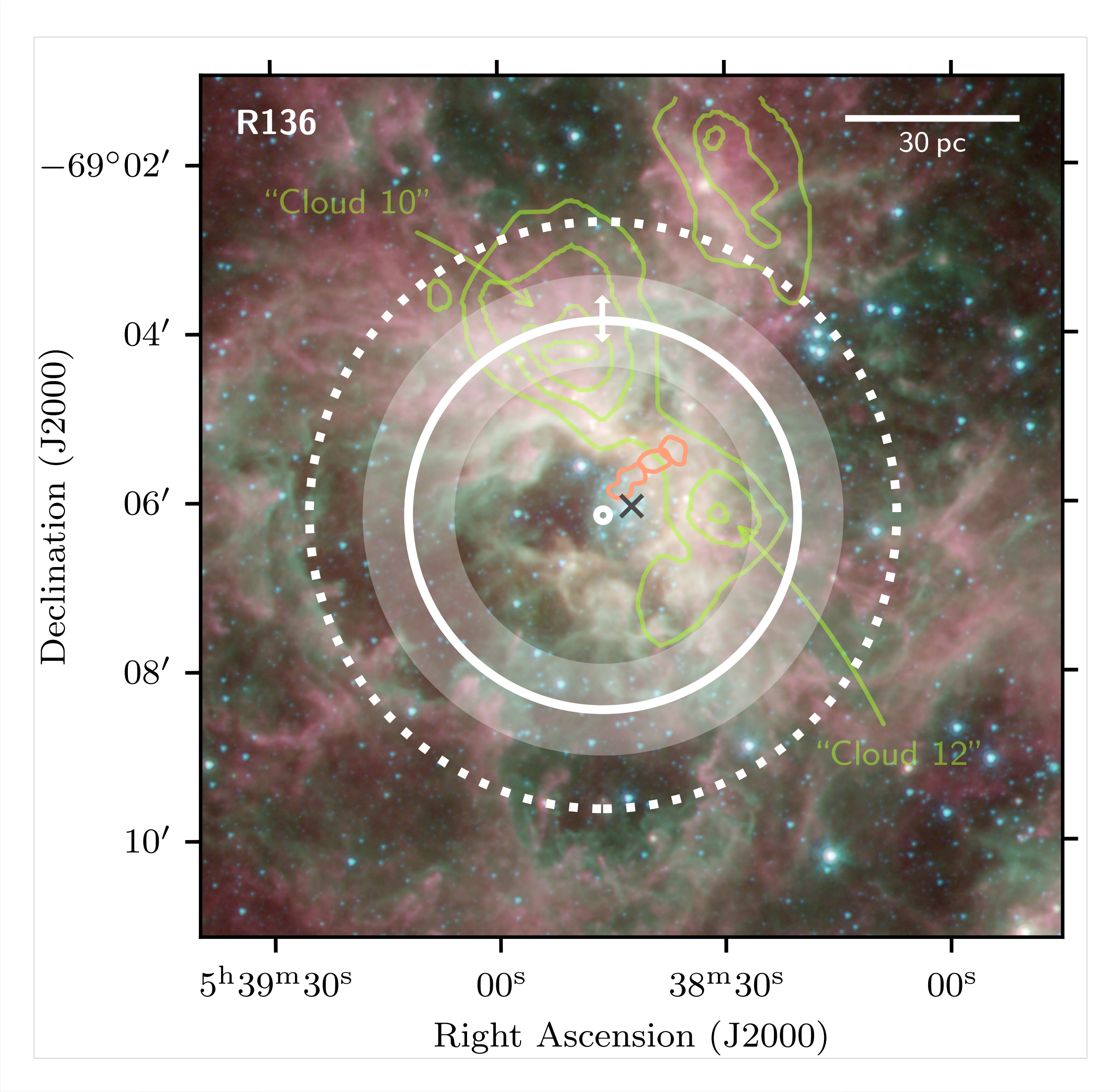
Conclusion

- Westerlund 1
  - very extended gamma-ray emission
  - shell-like structure
  - spectrum to $\sim 100\,\mathrm{TeV}$
- Massive star clusters in the LMC
  - two bright sources associated with 30 Dor C & R136
  - both measured as extended for the first time
- Westerlund 2
  - promising results in the pipeline







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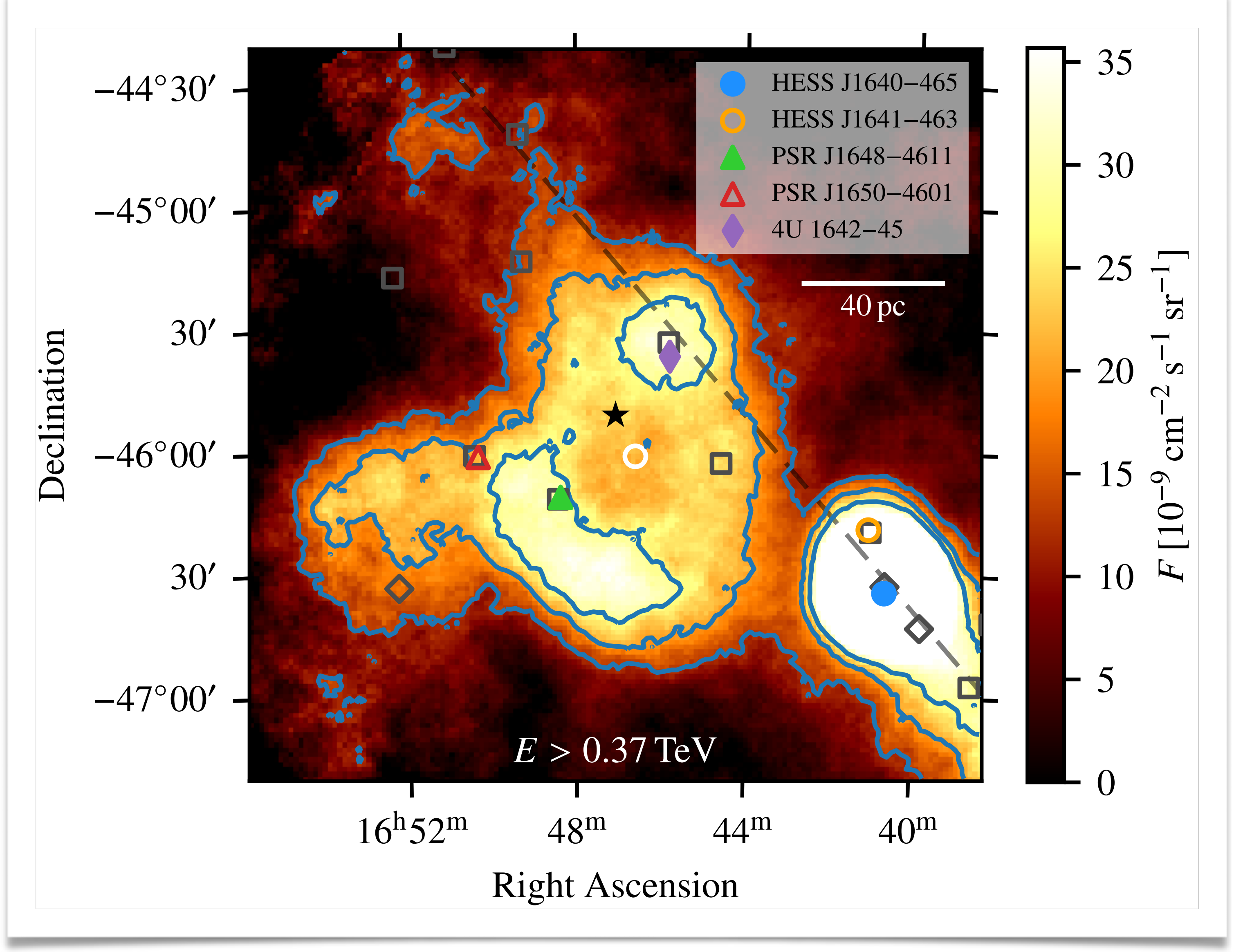
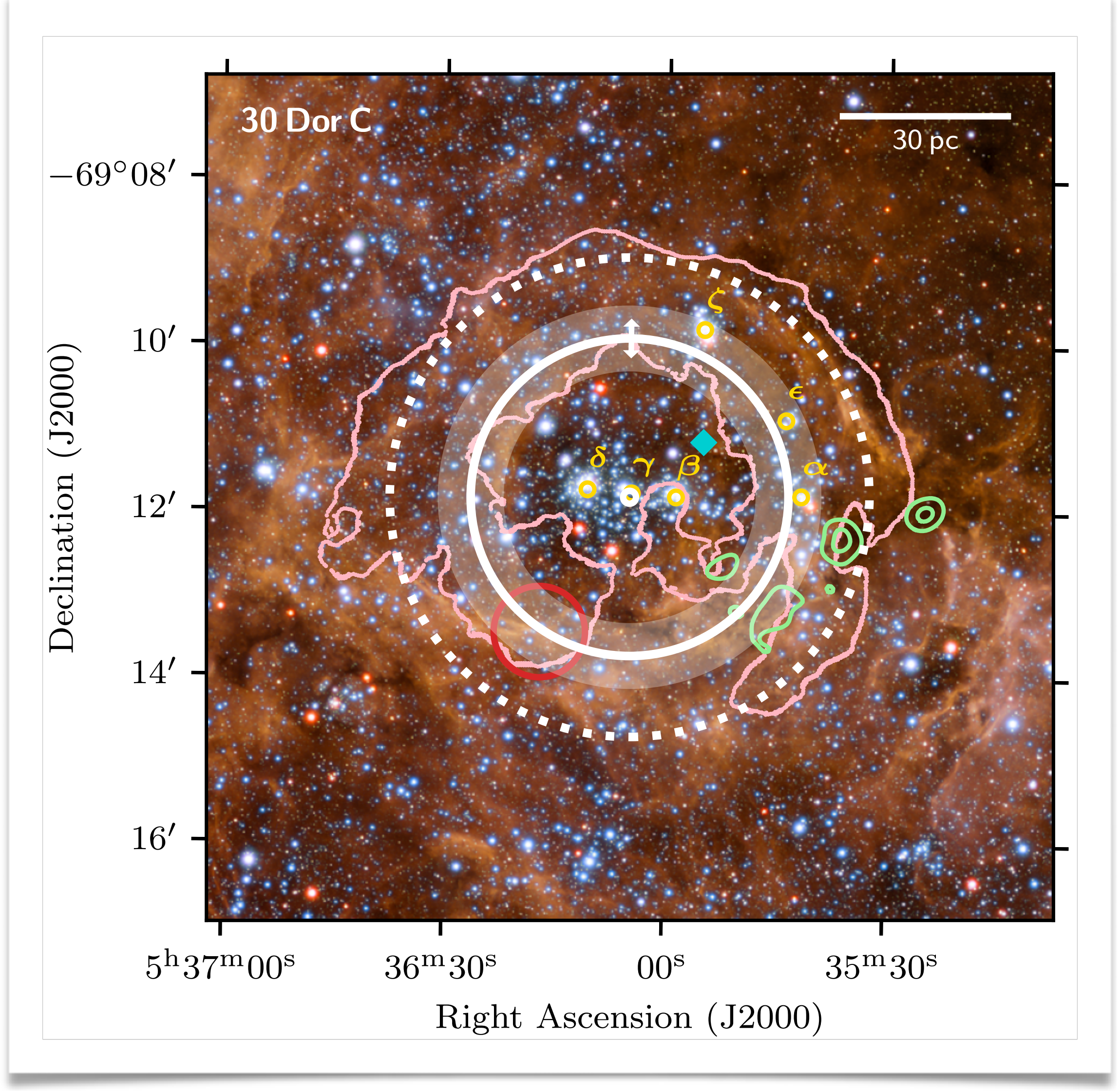
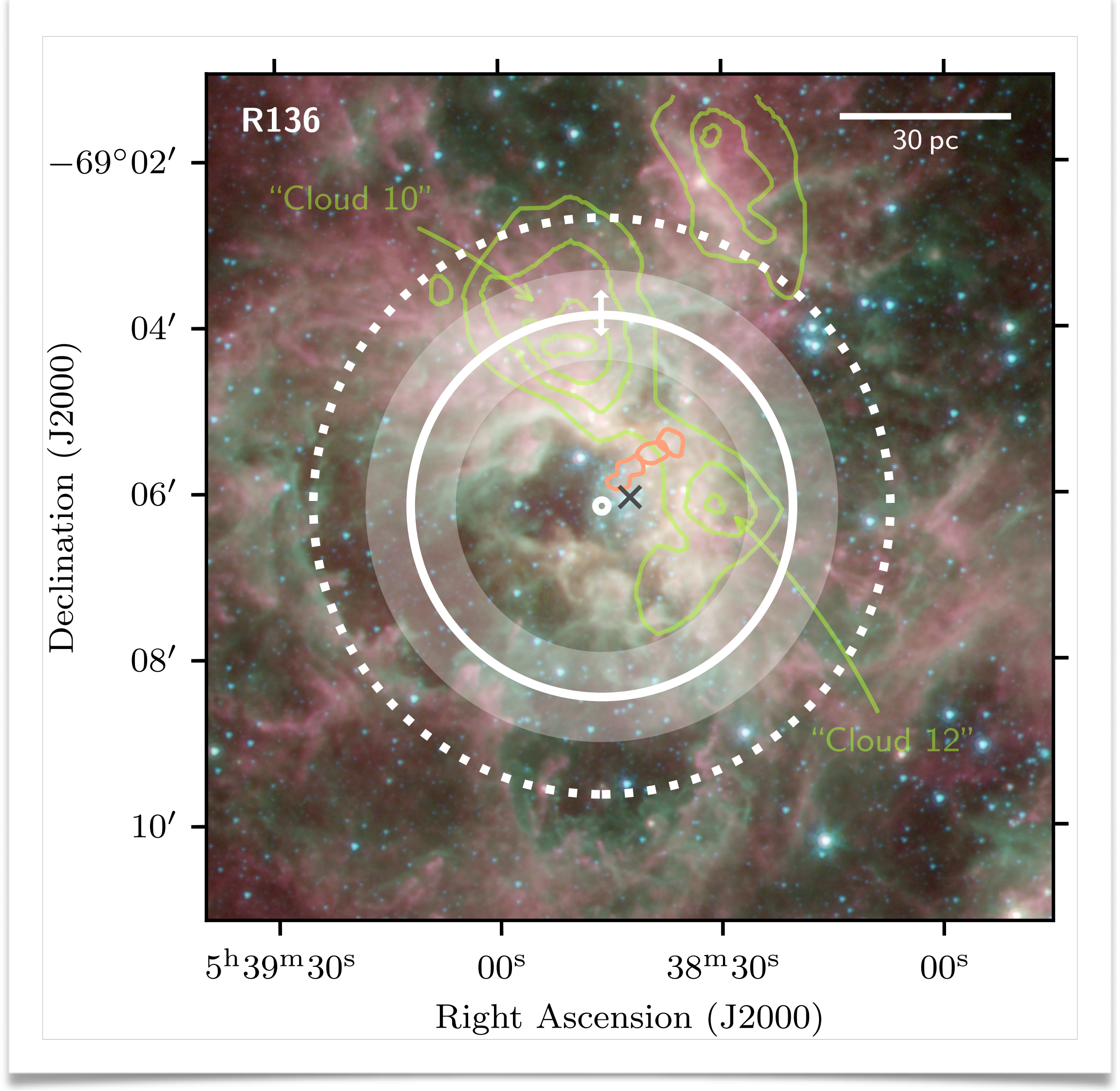
  - both measured as extended for the first time
- Westerlund 2
  - promising results in the pipeline
- *Excellent angular resolution of H.E.S.S. has been crucial in these measurements*
- *Massive star clusters continue to be an important science topic for H.E.S.S.*



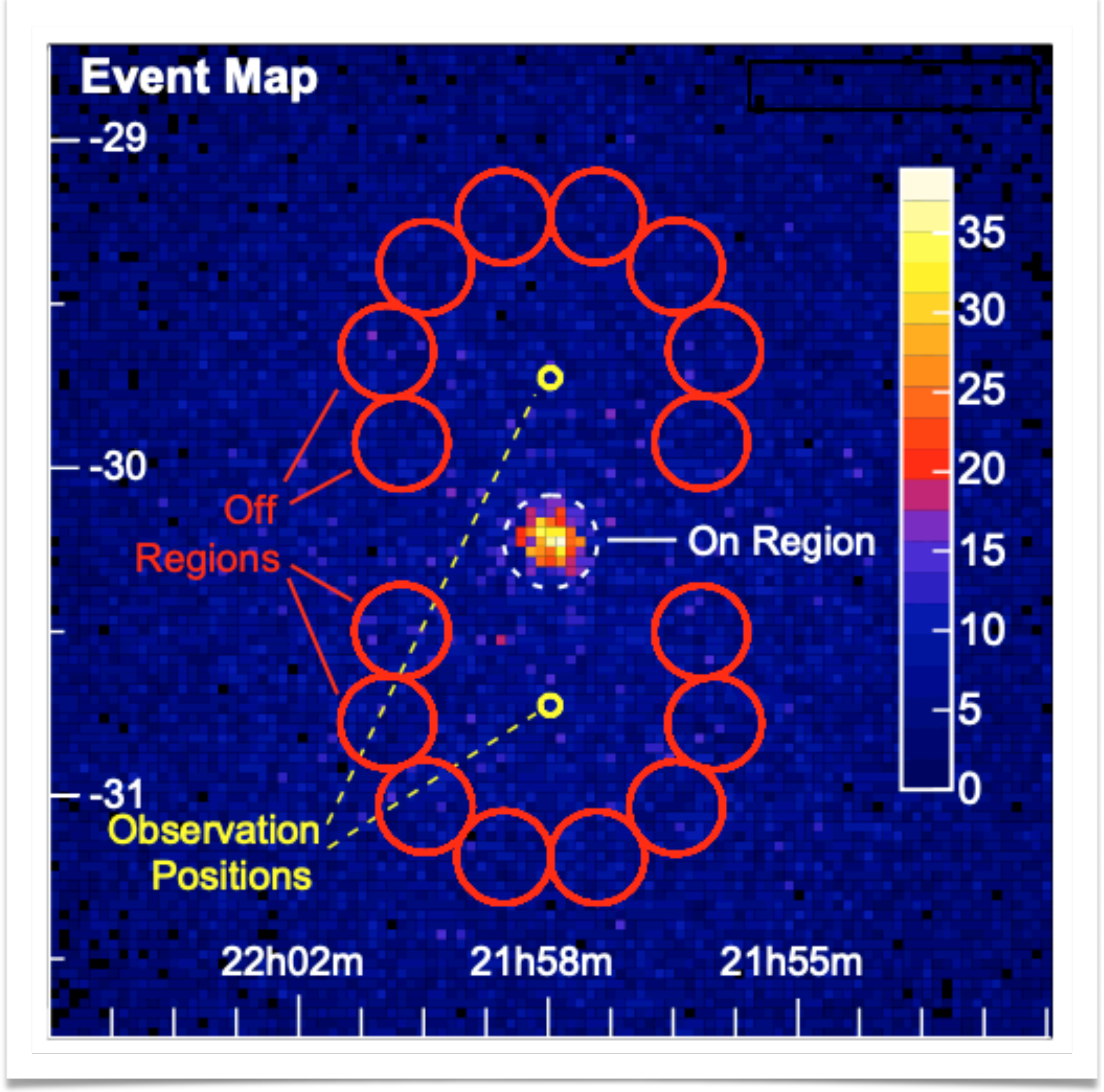




Backup slides

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)

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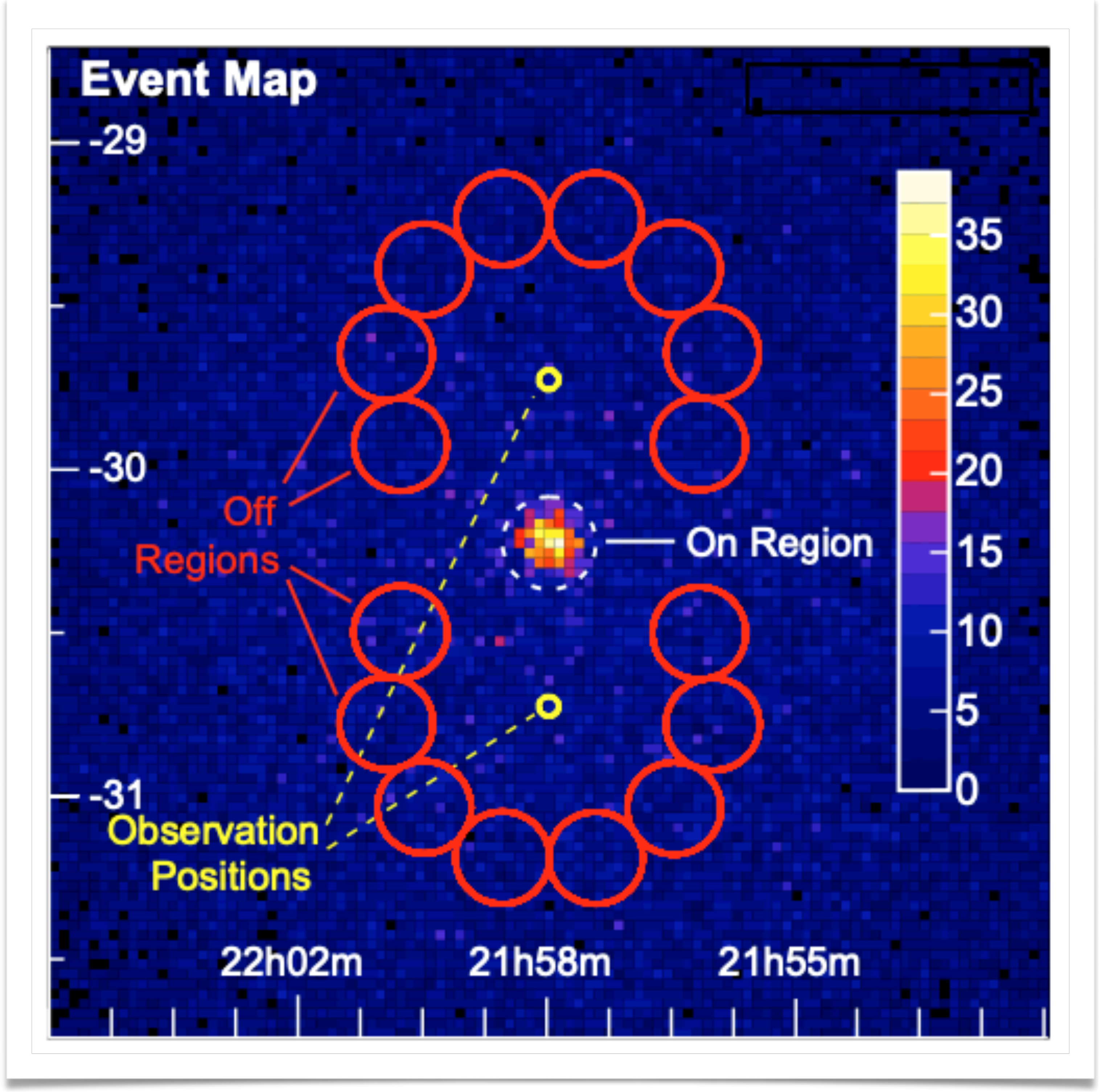
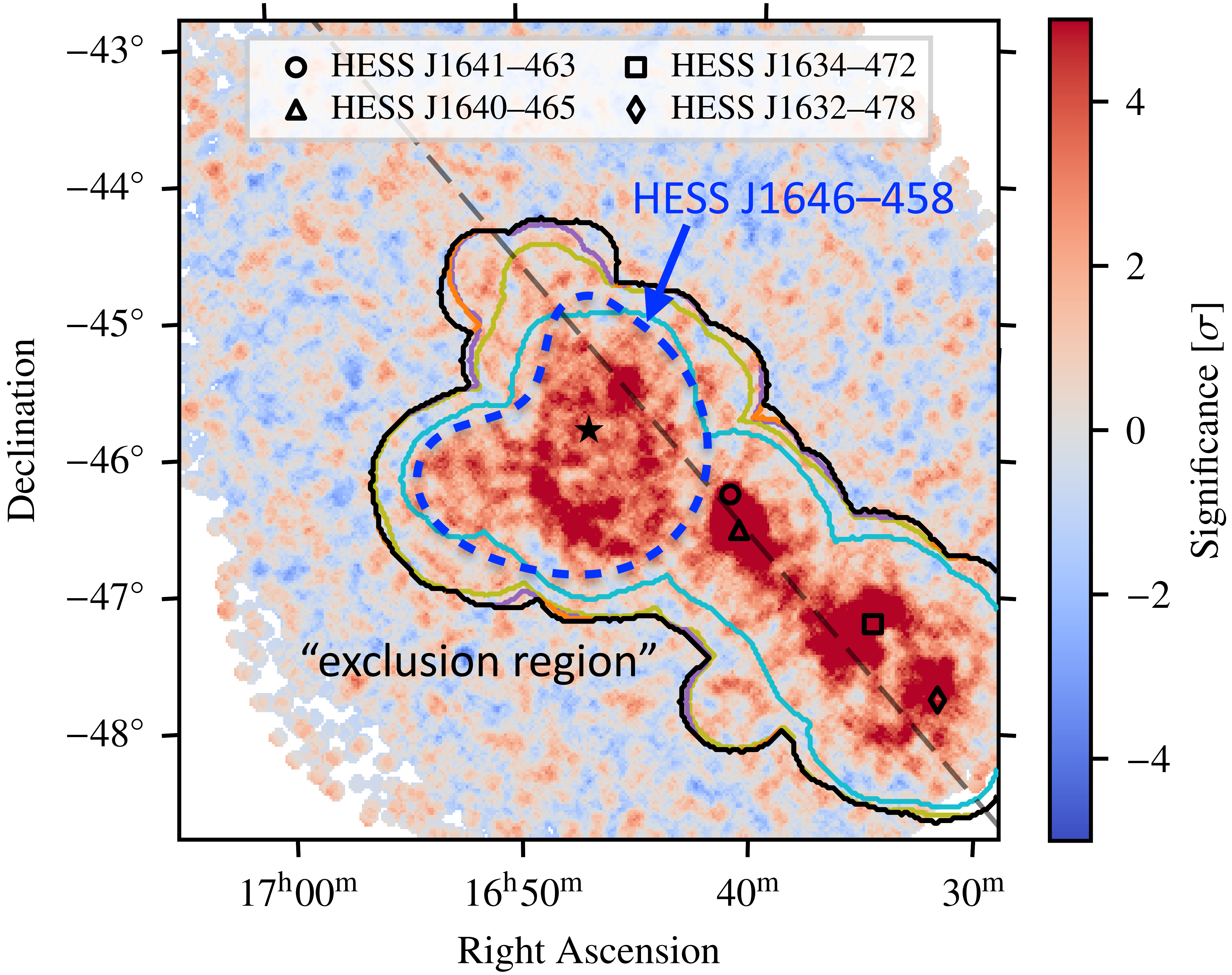


Berge et al., A&A 466, 1219 (2007)

Significance map



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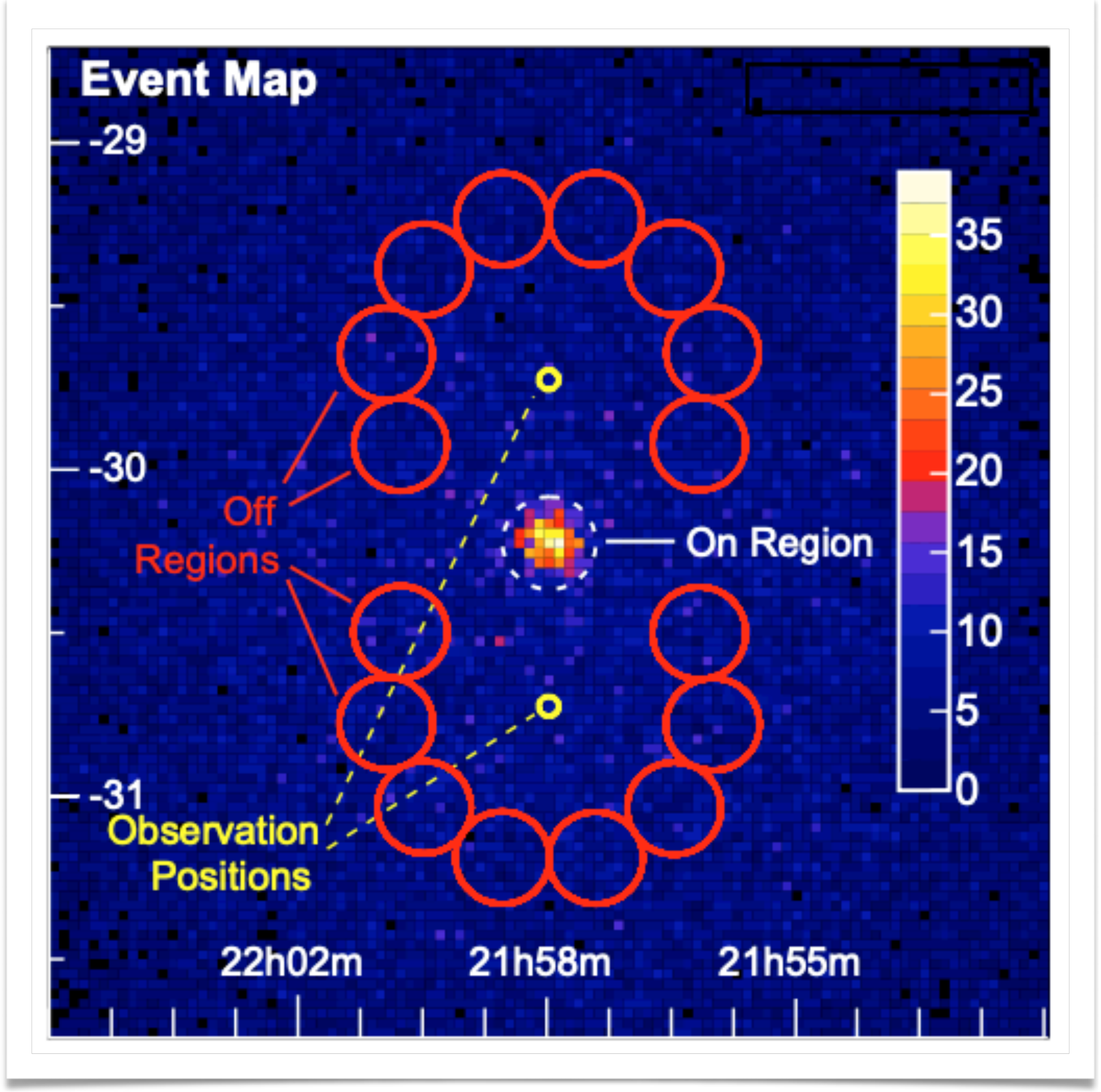

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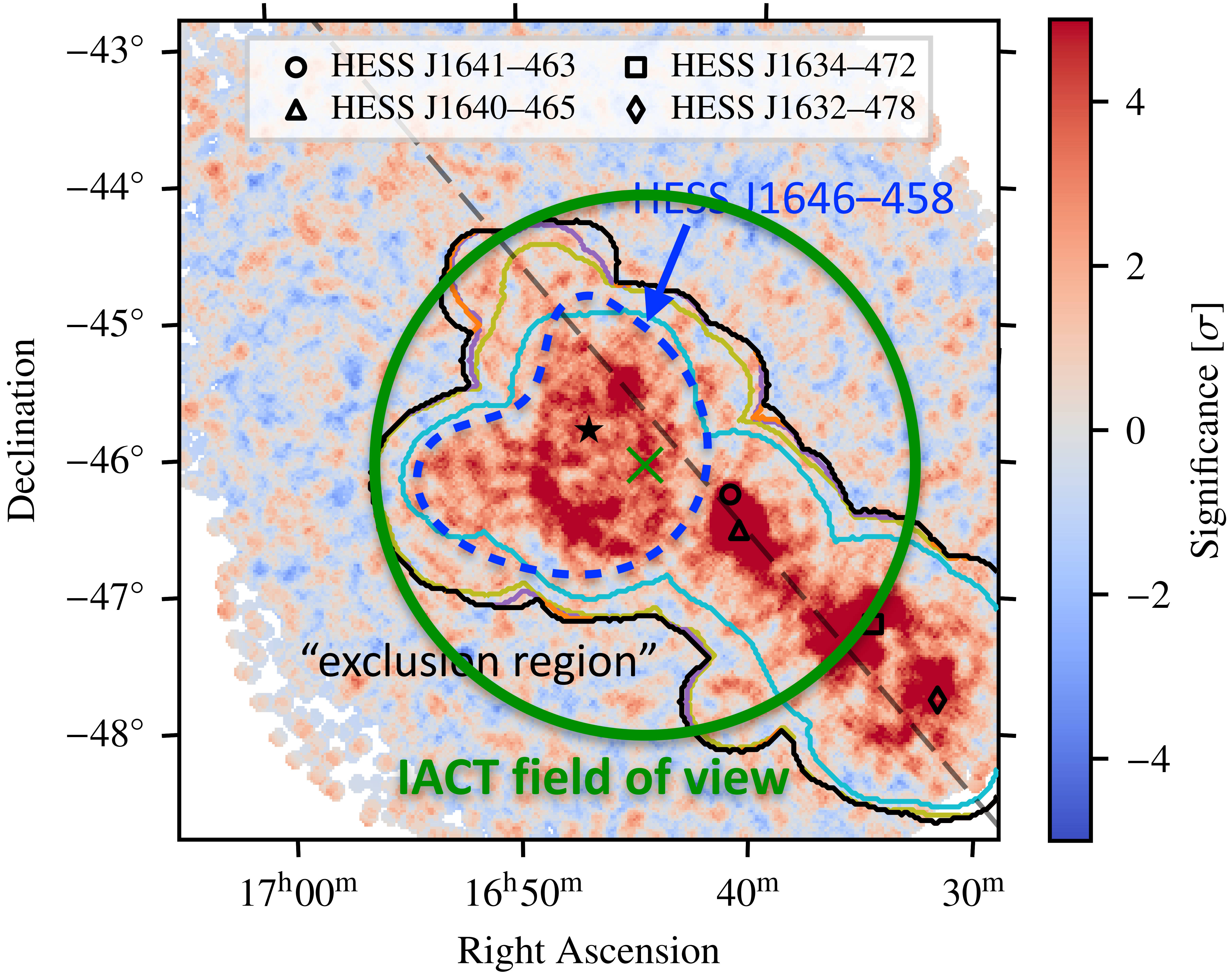


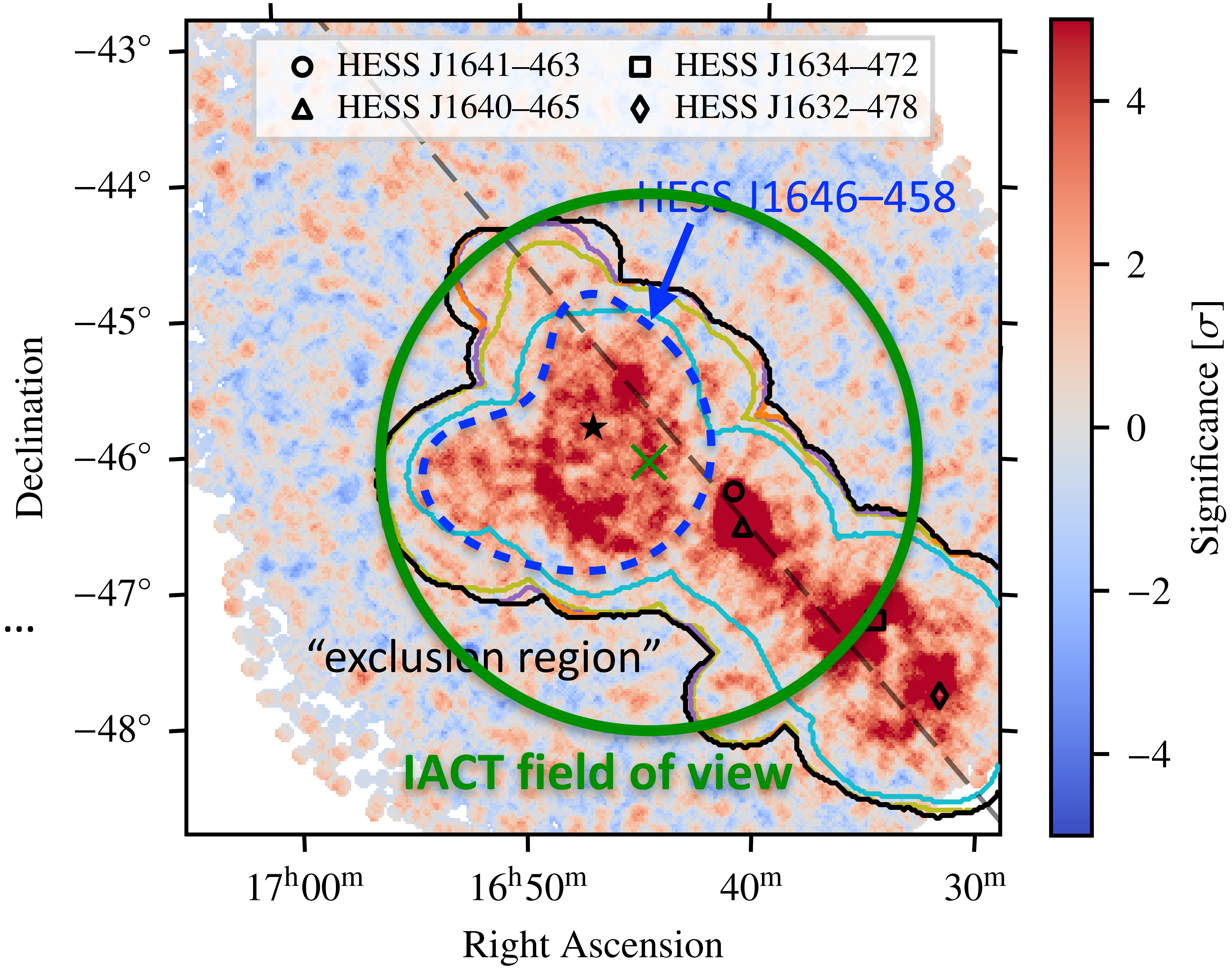
Treating the residual cosmic-ray background

- "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!

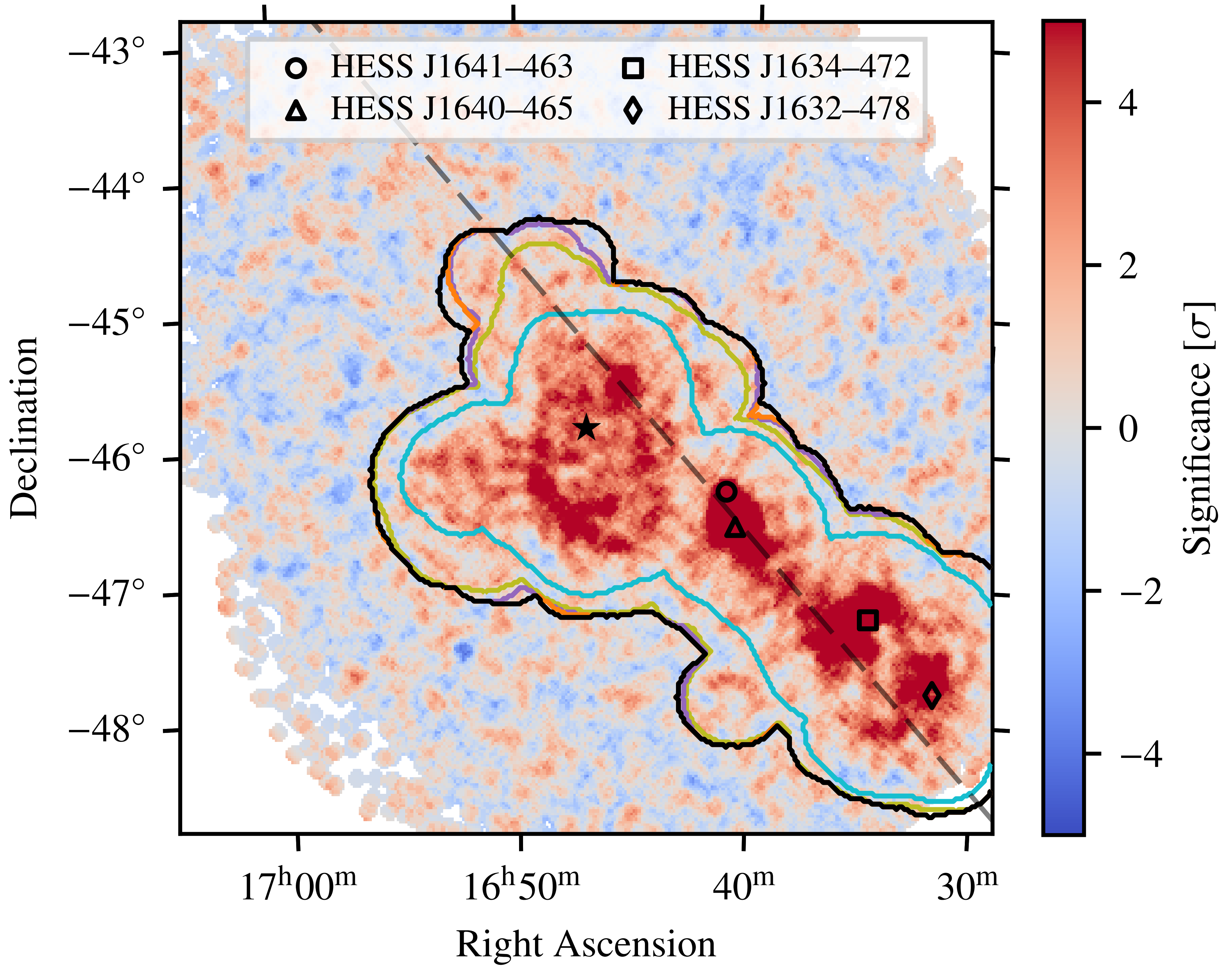
  - Details: ***Mohrmann et al., A&A 632, A72 (2019)***

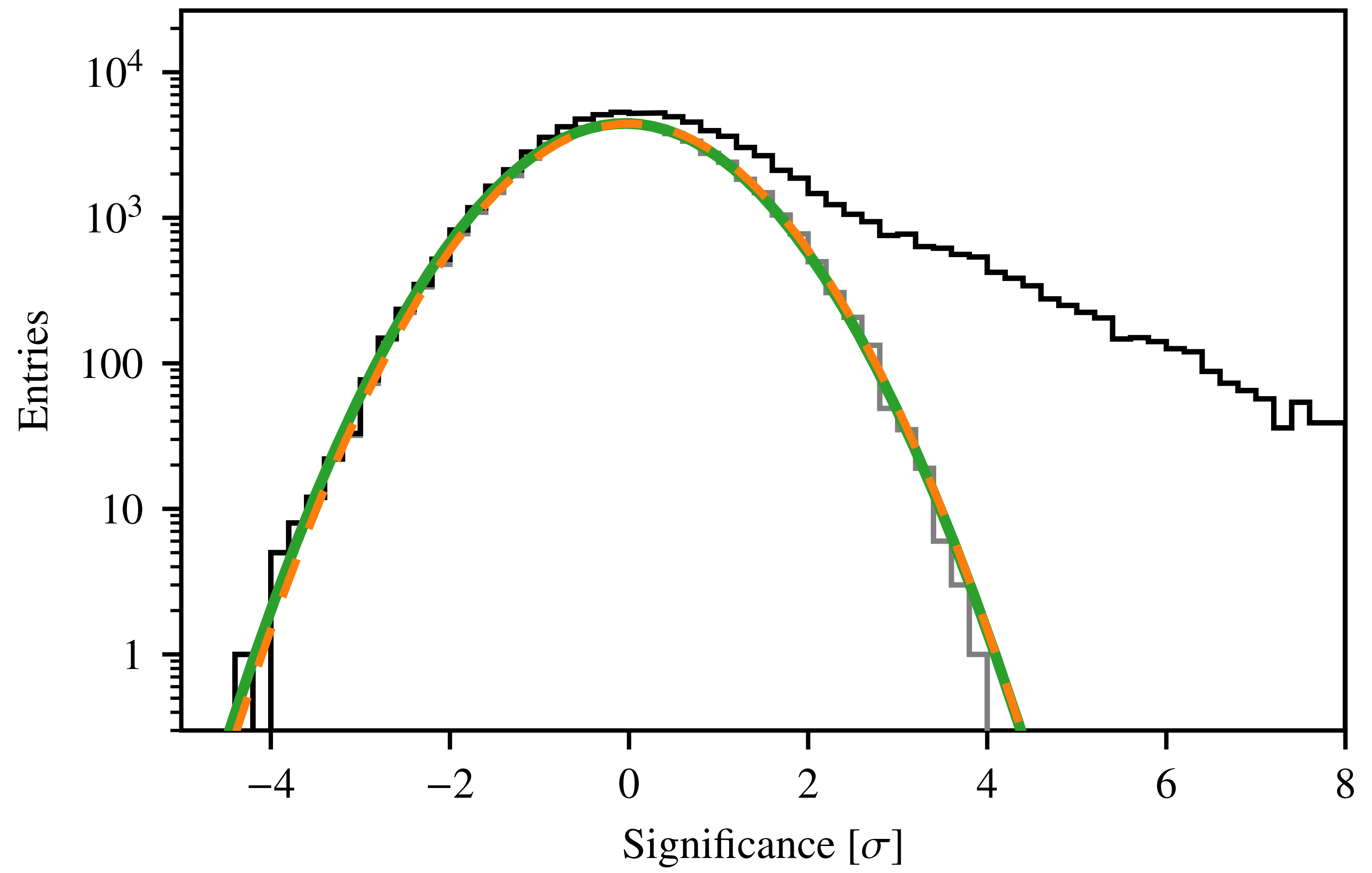
Significance map

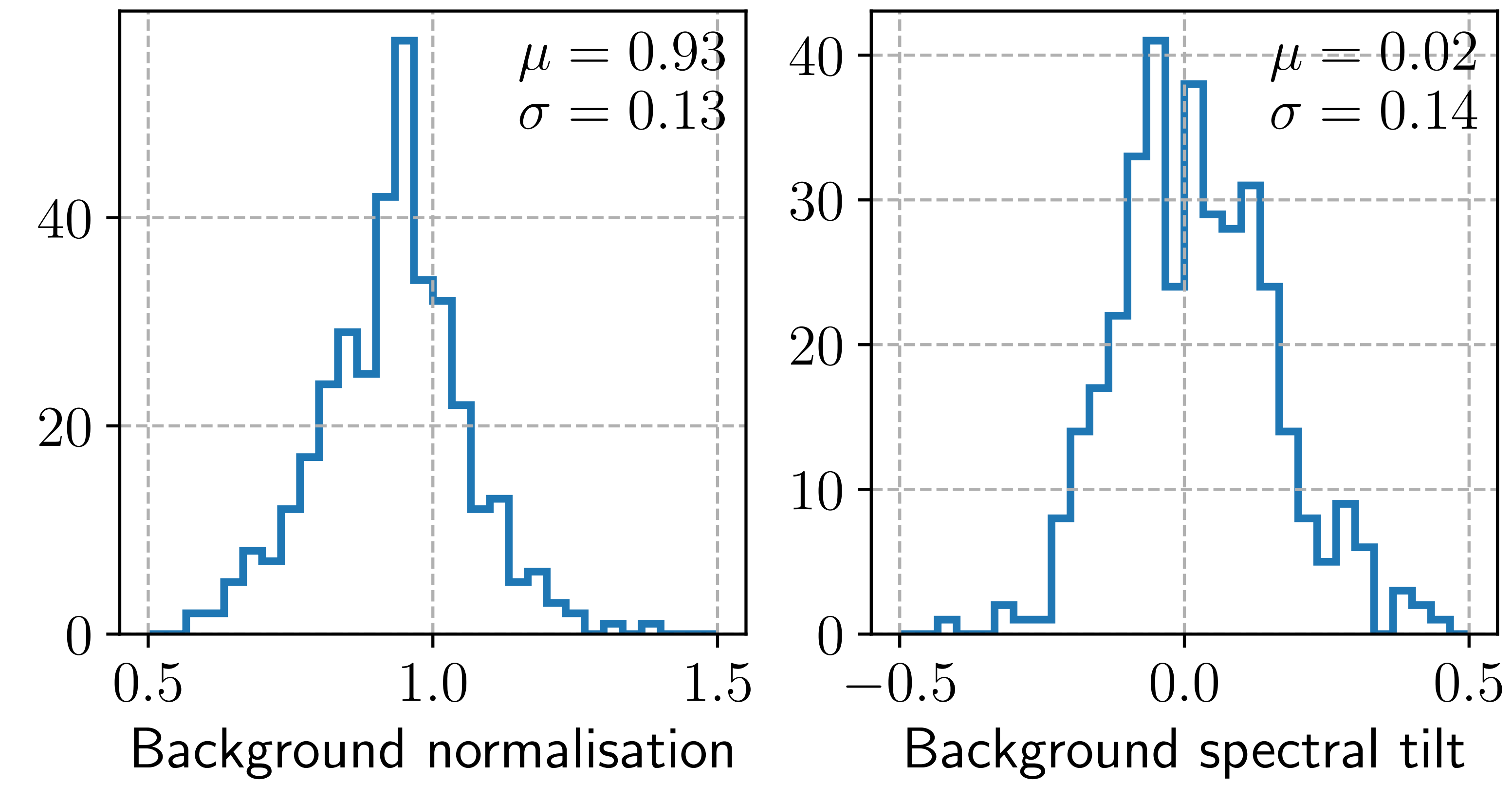


Westerlund 1 — fit of hadronic background model

- 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







Westerlund 1 — distance

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

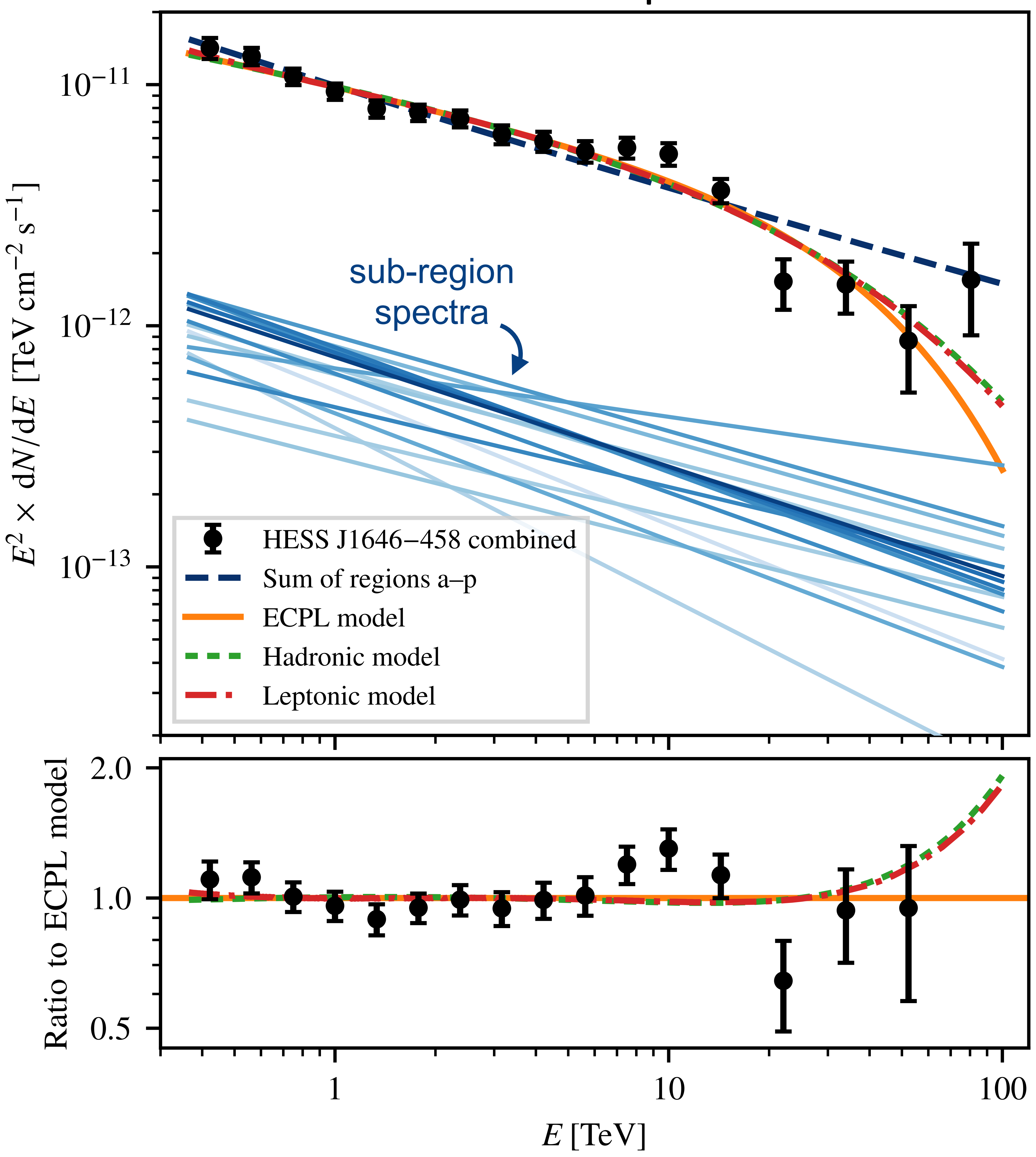
Westerlund 1 — energy spectrum

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

- Hadronic model (*proton-proton*)
  - $\Gamma_p = 2.33 \pm 0.06,\ E_c^p = \left(400^{+250}_{-130}\right)\ \mathrm{TeV}$ (almost a PeVatron…)
  - $W_p(>1\,\mathrm{GeV}) = 6 \times 10^{51} \left(\frac{n}{1\,\mathrm{cm}^3}\right)^{-1}\ \mathrm{erg}$

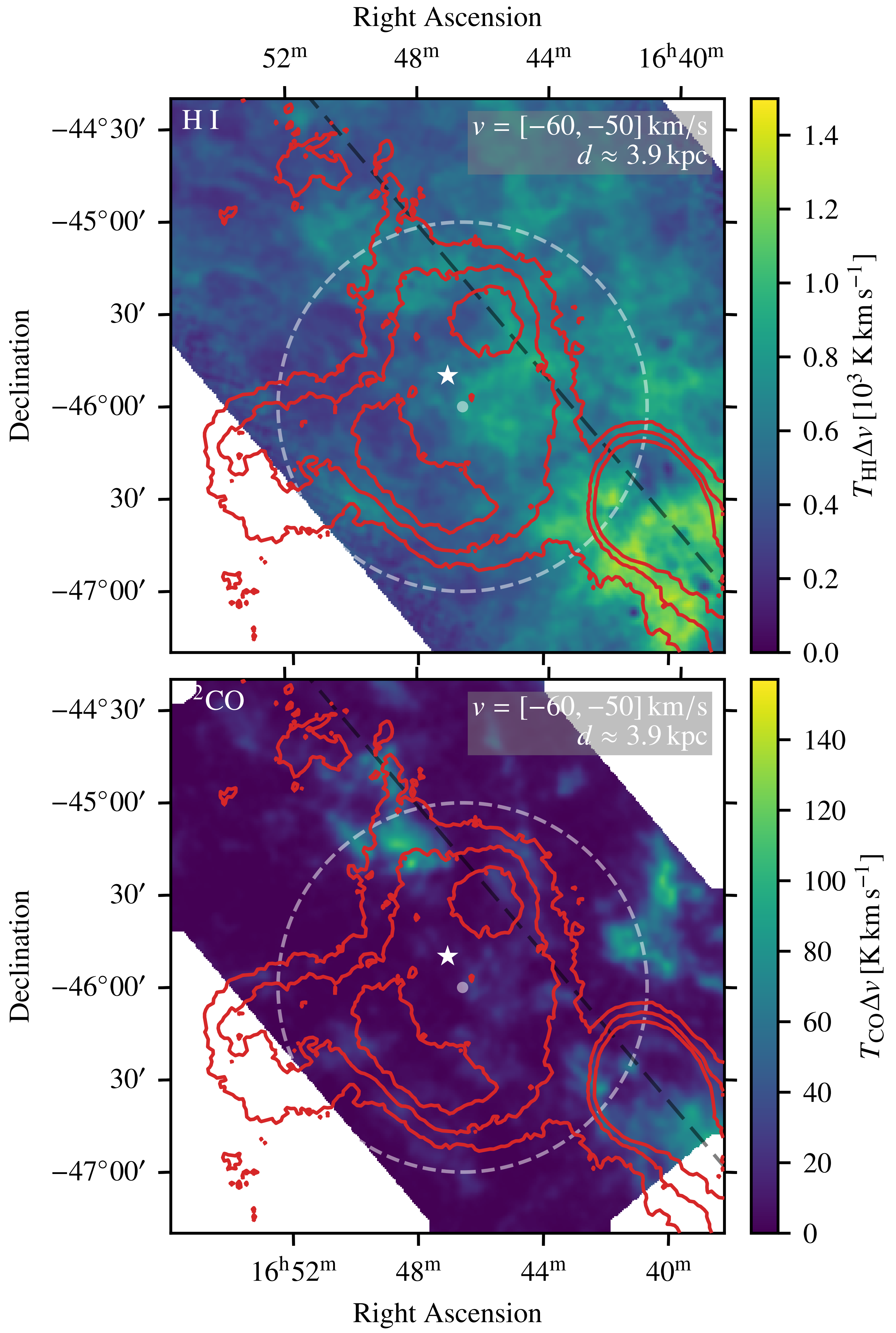
- Leptonic model (*inverse Compton*)
  - $\Gamma_e = 2.97 \pm 0.07,\ E_c^e = \left(180^{+200}_{-70}\right)\ \mathrm{TeV}$
  - $L_e(>0.1\,\mathrm{TeV}) > 4.1 \times 10^{35}\ \mathrm{erg\ s^{-1}}$

combined spectrum

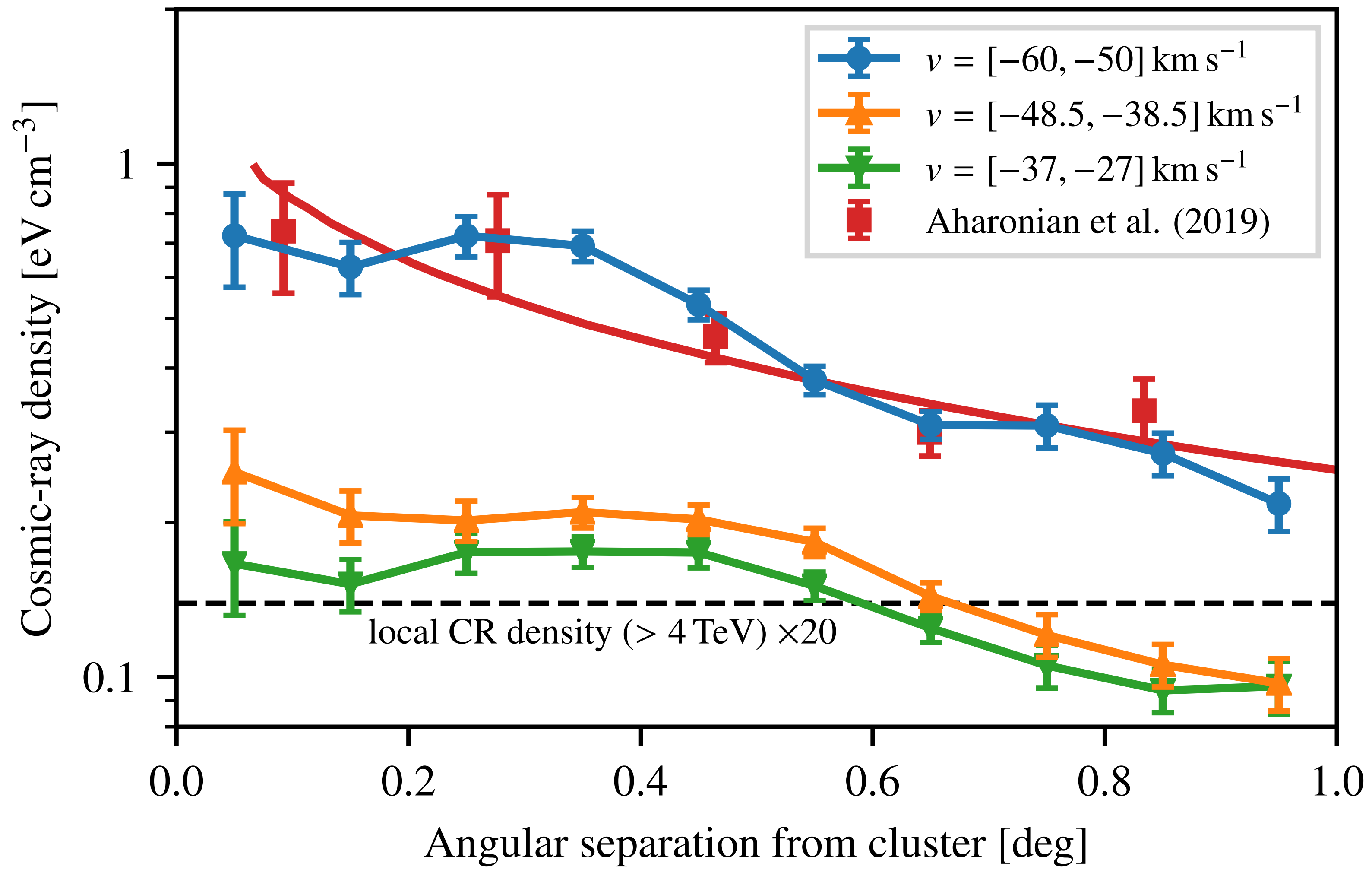


Westerlund 1 — cosmic-ray density profiles

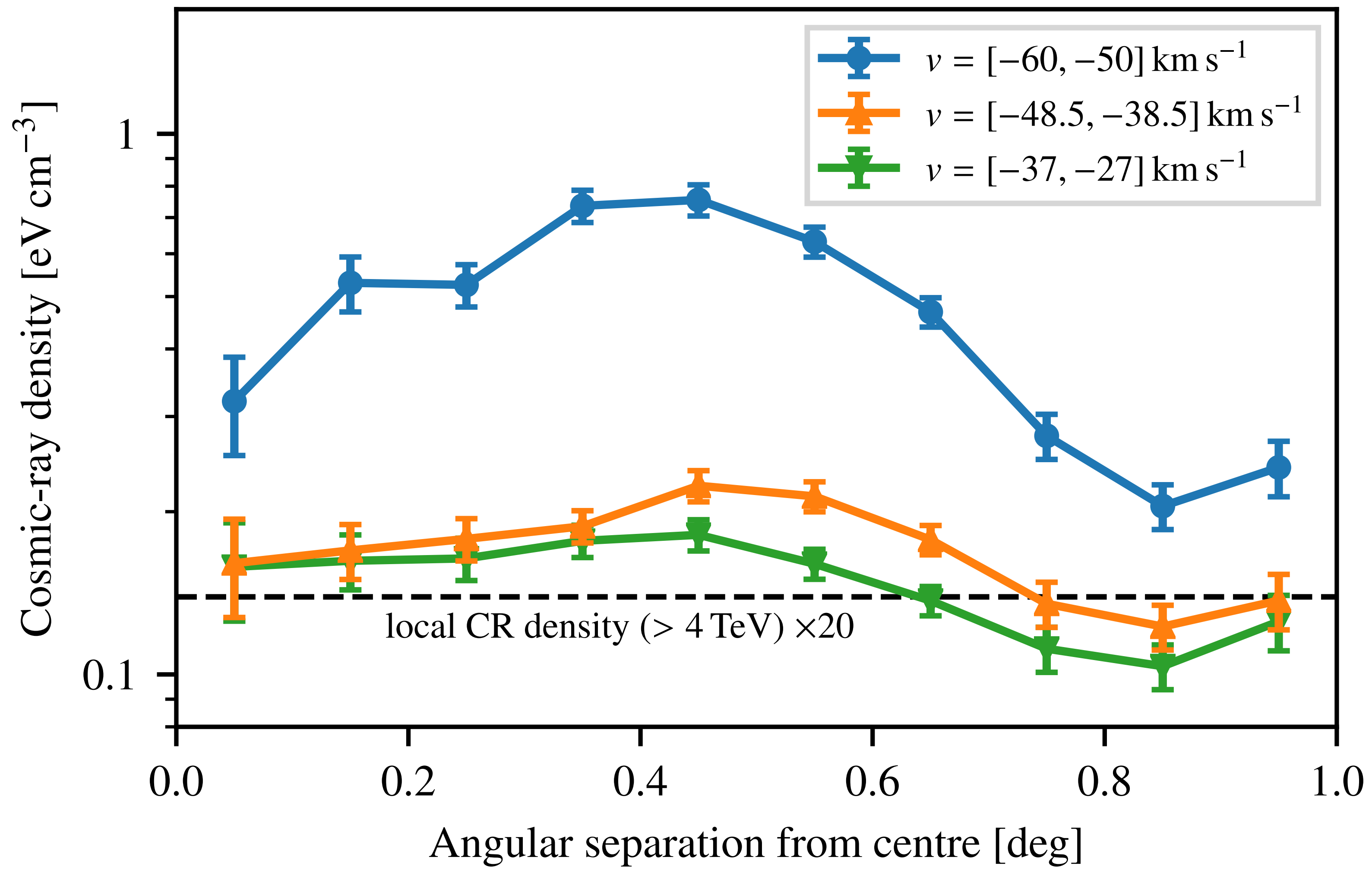
- Assume gamma-ray emission is fully hadronic and we know the gas distribution → can infer cosmic-ray distribution
- Profile w.r.t. cluster position compatible with Aharonian et al. (who claimed to observe 1/r profile)
- However, profile w.r.t. centroid of emission not peaked towards centre!



w.r.t. cluster position

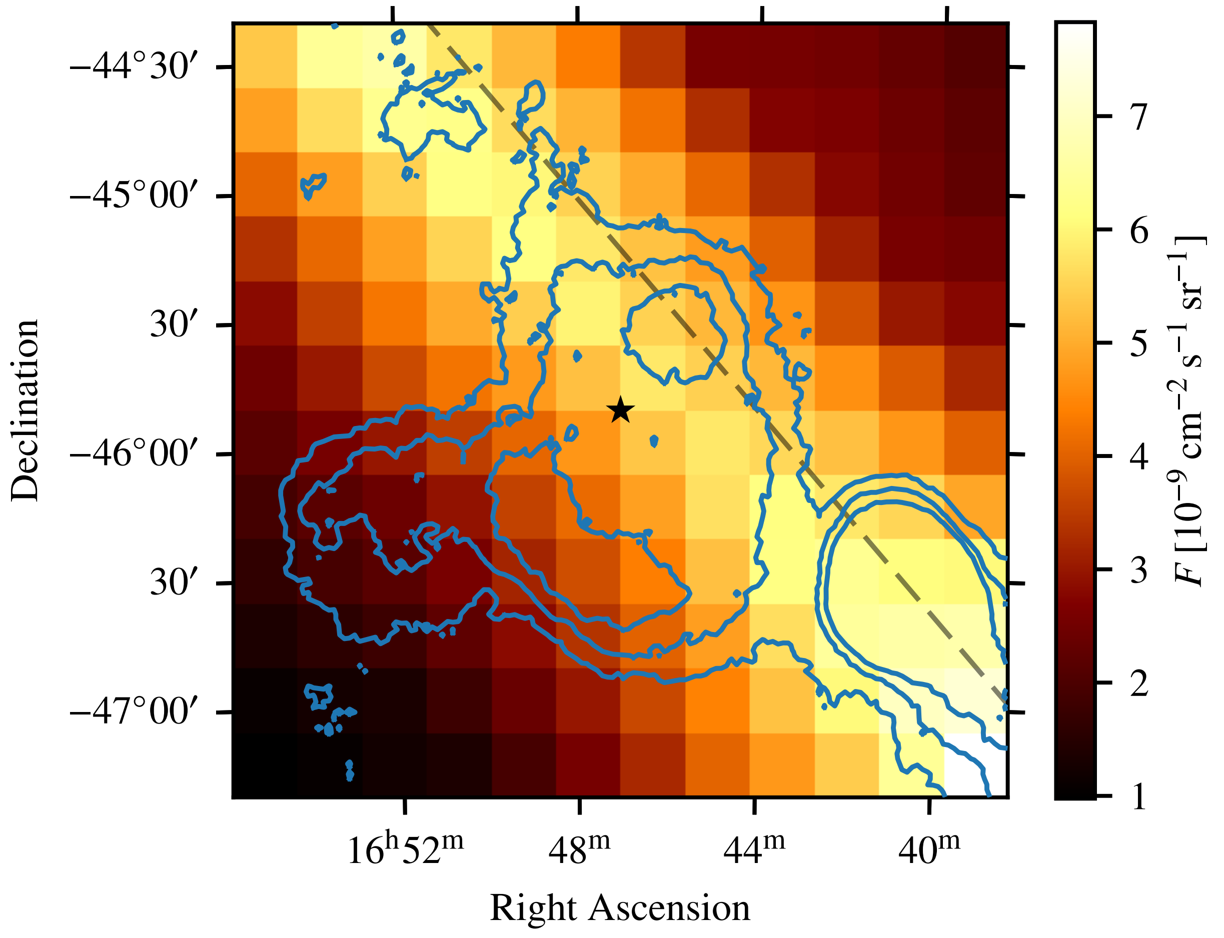


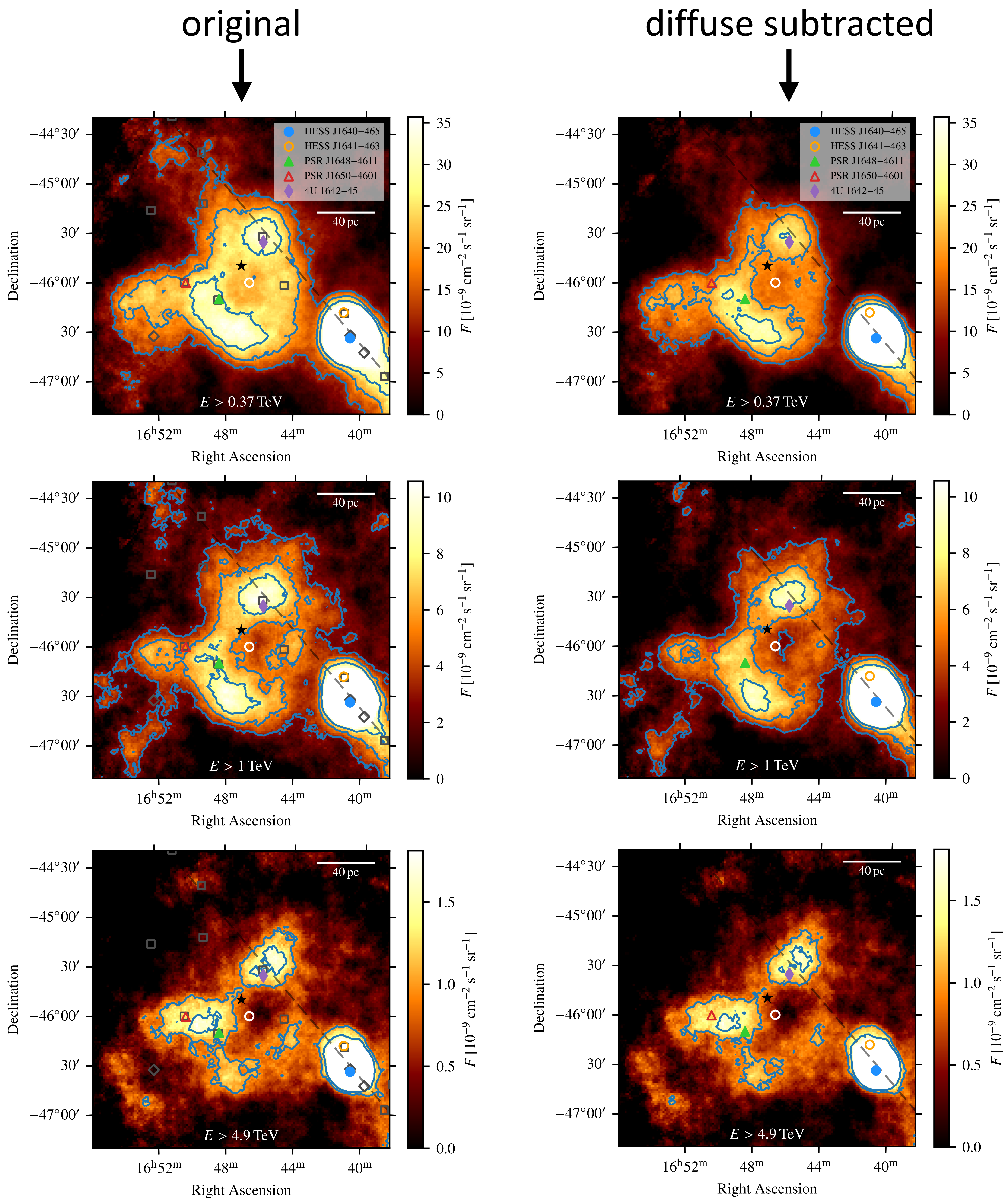
w.r.t. centroid



Westerlund 1 — Galactic diffuse emission

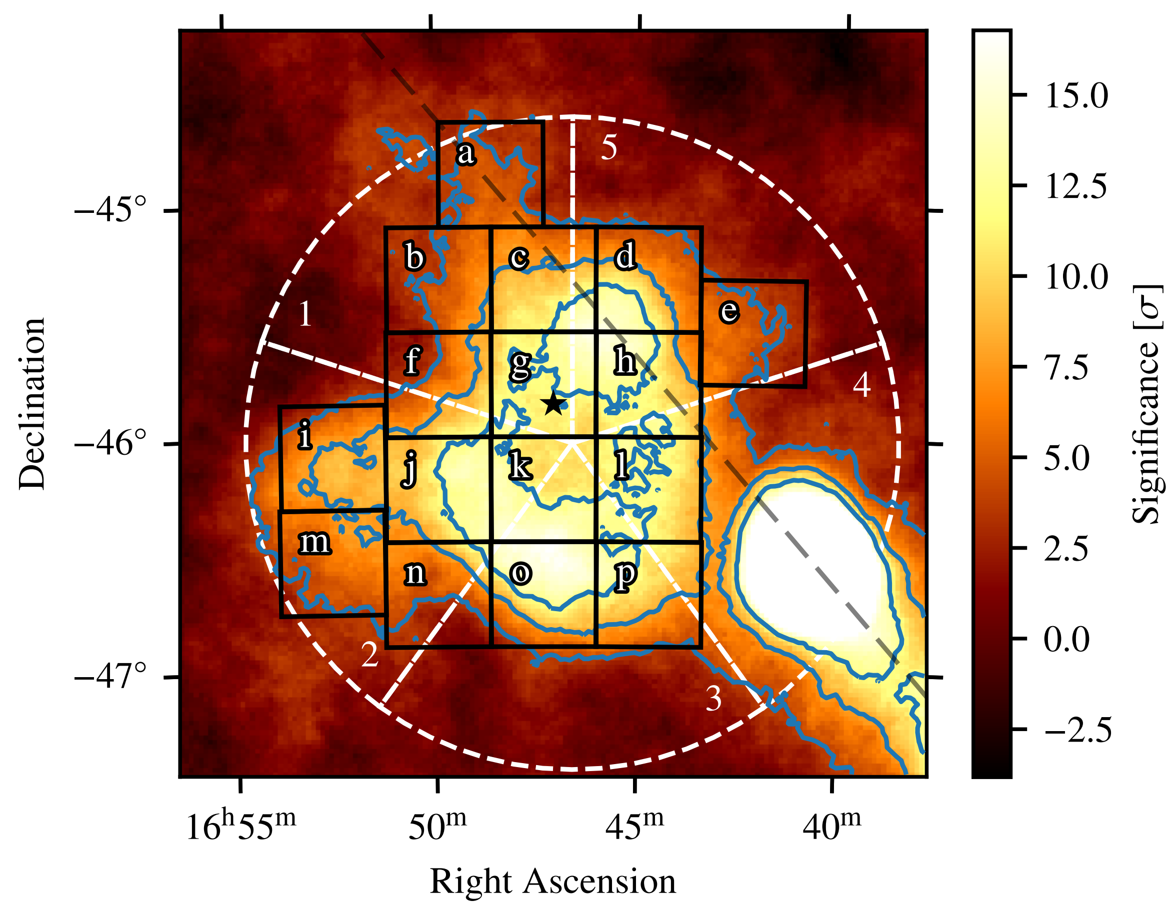
- Likely contributes to emission, but is difficult to estimate
  Kissmann, Astropart. Phys. 55, 37 (2014)
- Use prediction from PICARD propagation code
- Absolute flux level is very uncertain!
- Shell-like structure not affected

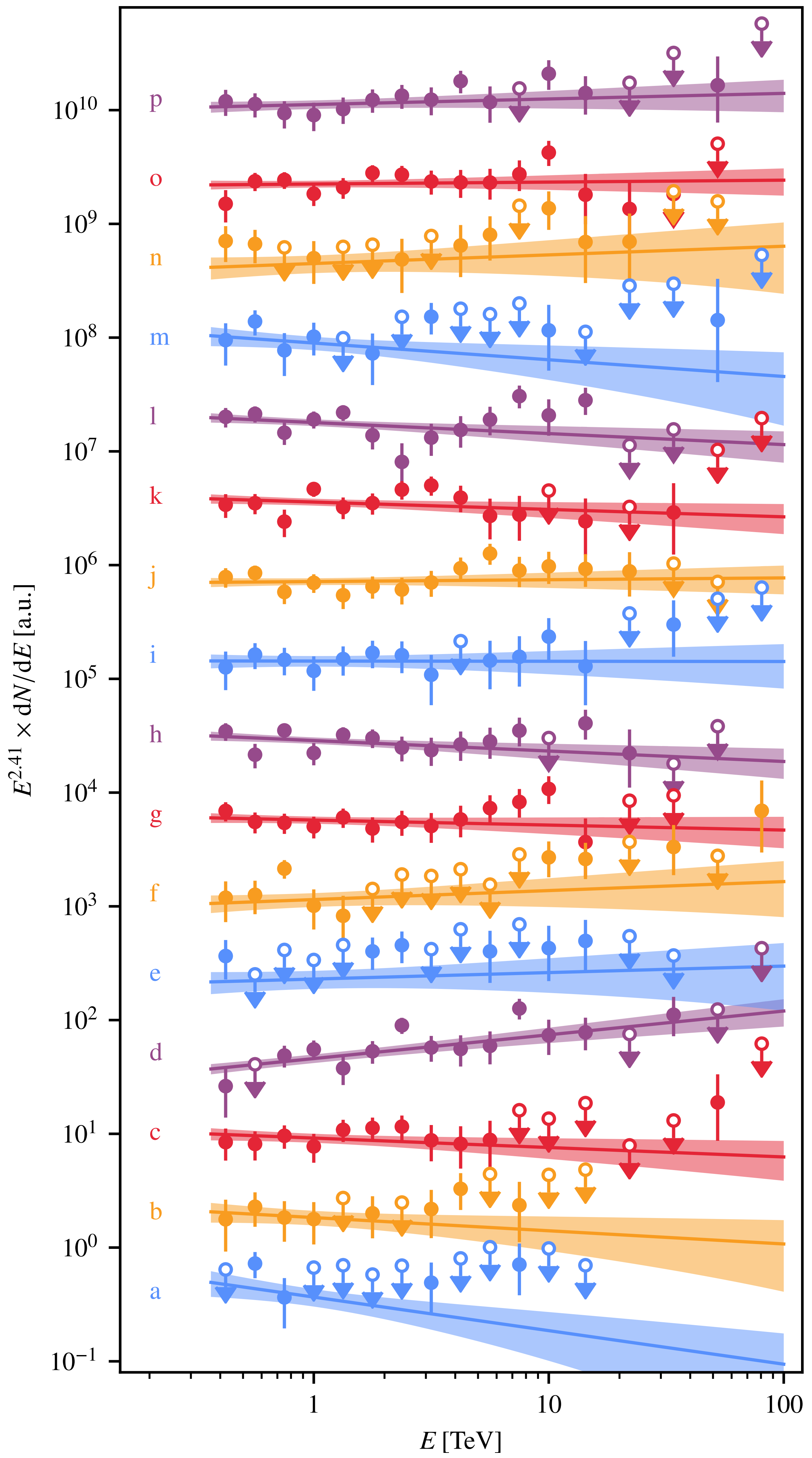




Westerlund 1 — signal region energy spectra

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



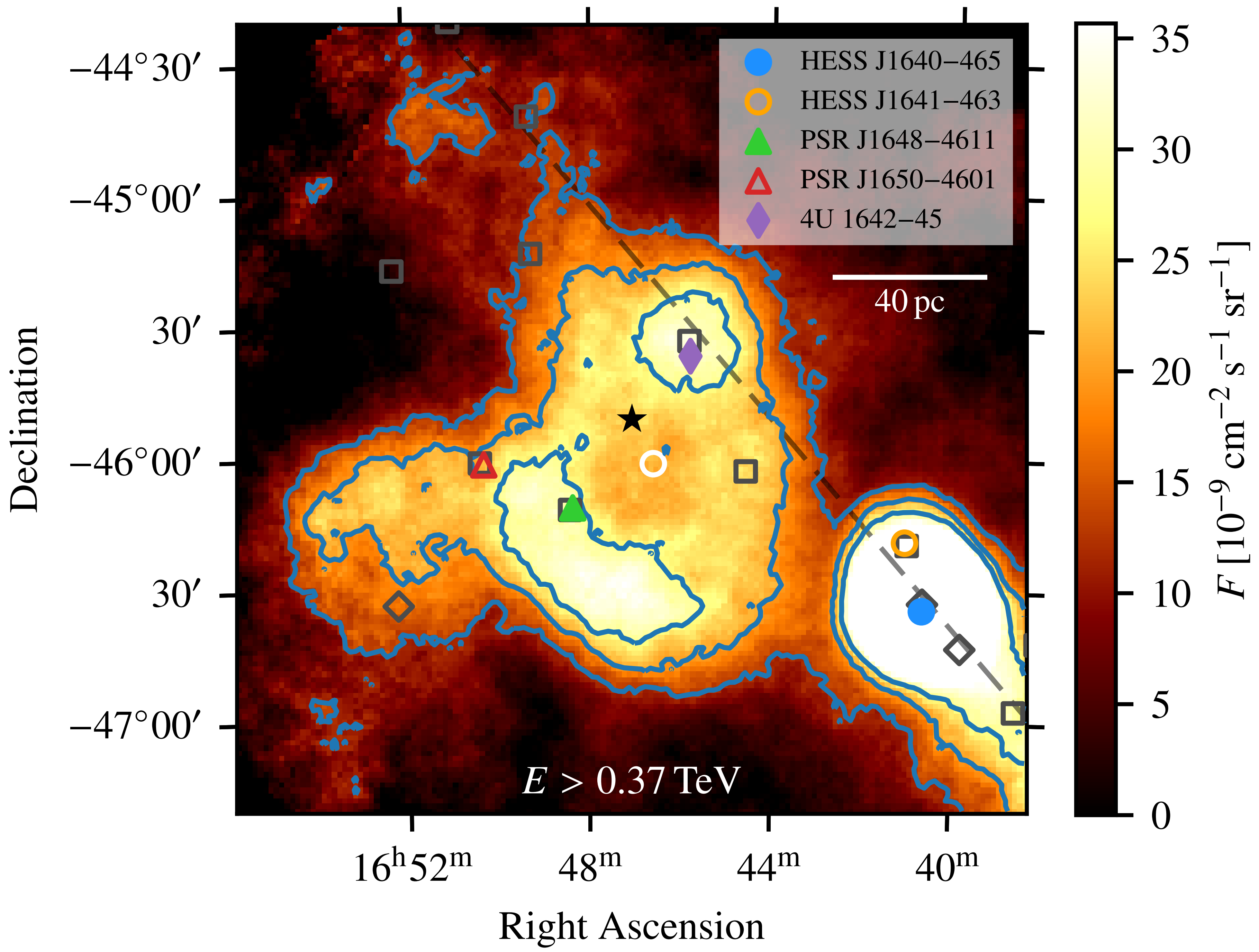


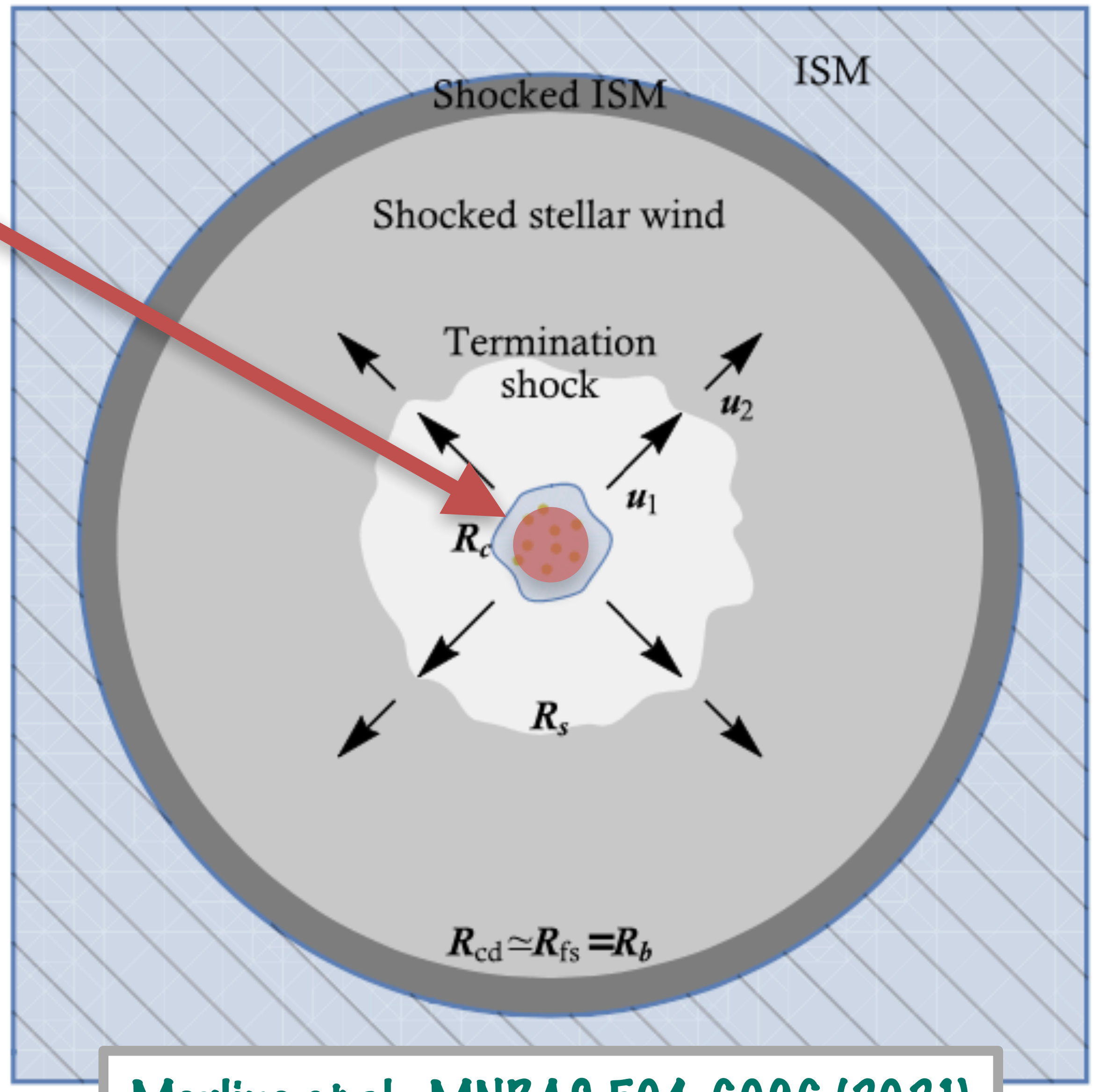
Signal region	Excess events	Significance	Significance ($E > 4.9$ TeV)	ϕ_0 (10^{-13} TeV^{-1}cm^{-2}s^{-1})	Γ	$\sqrt{\Delta TS}$
a	396.1	5.3σ	0.9σ	3.76 ± 0.66	2.71 ± 0.18	5.9
b	454.9	5.6σ	1.7σ	4.34 ± 0.64	2.53 ± 0.13	7.5
c	901.8	10.3σ	2.8σ	6.33 ± 0.58	2.49 ± 0.08	12.3
d	1014.0	10.8σ	7.7σ	6.66 ± 0.58	2.20 ± 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

Westerlund 1 — 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

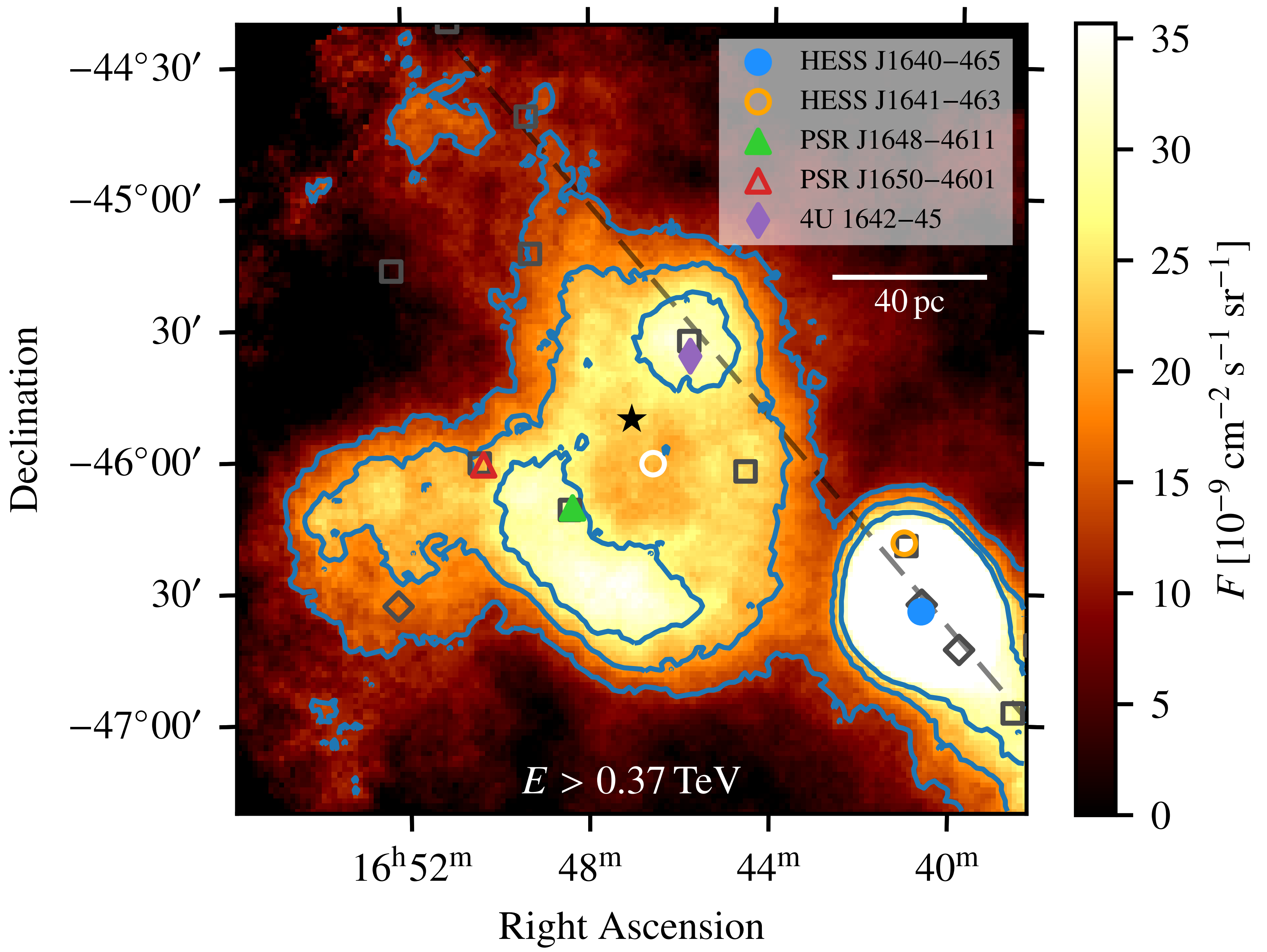


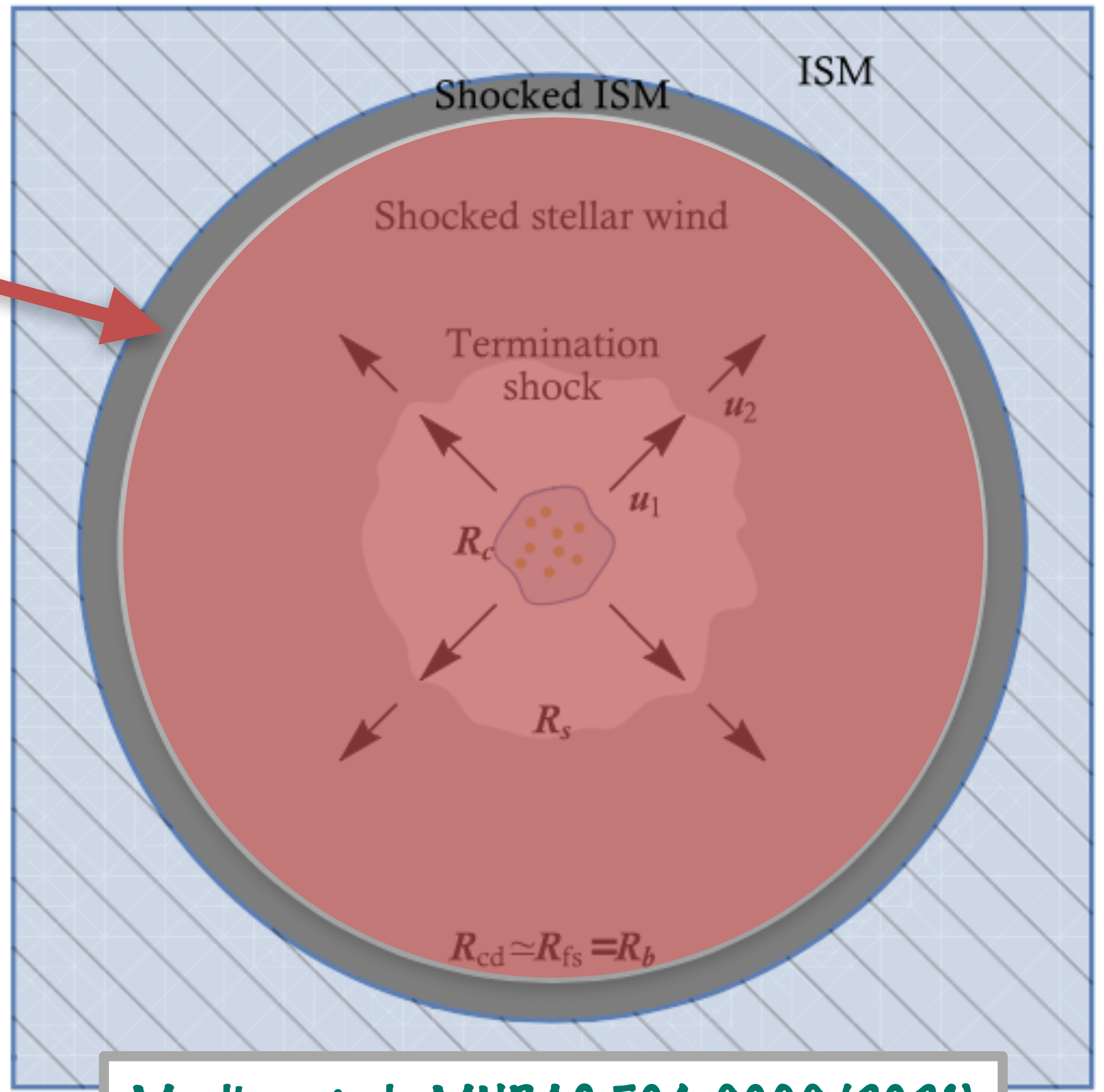


Morlino et al., MNRAS 504, 6096 (2021)

Westerlund 1 — 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 $R_{SB} \sim \mathcal{O}(180\,\mathrm{pc})$
  - exceeds gamma-ray emission, outer shock not observed
    → not favoured (but reality is more complex than basic models!)





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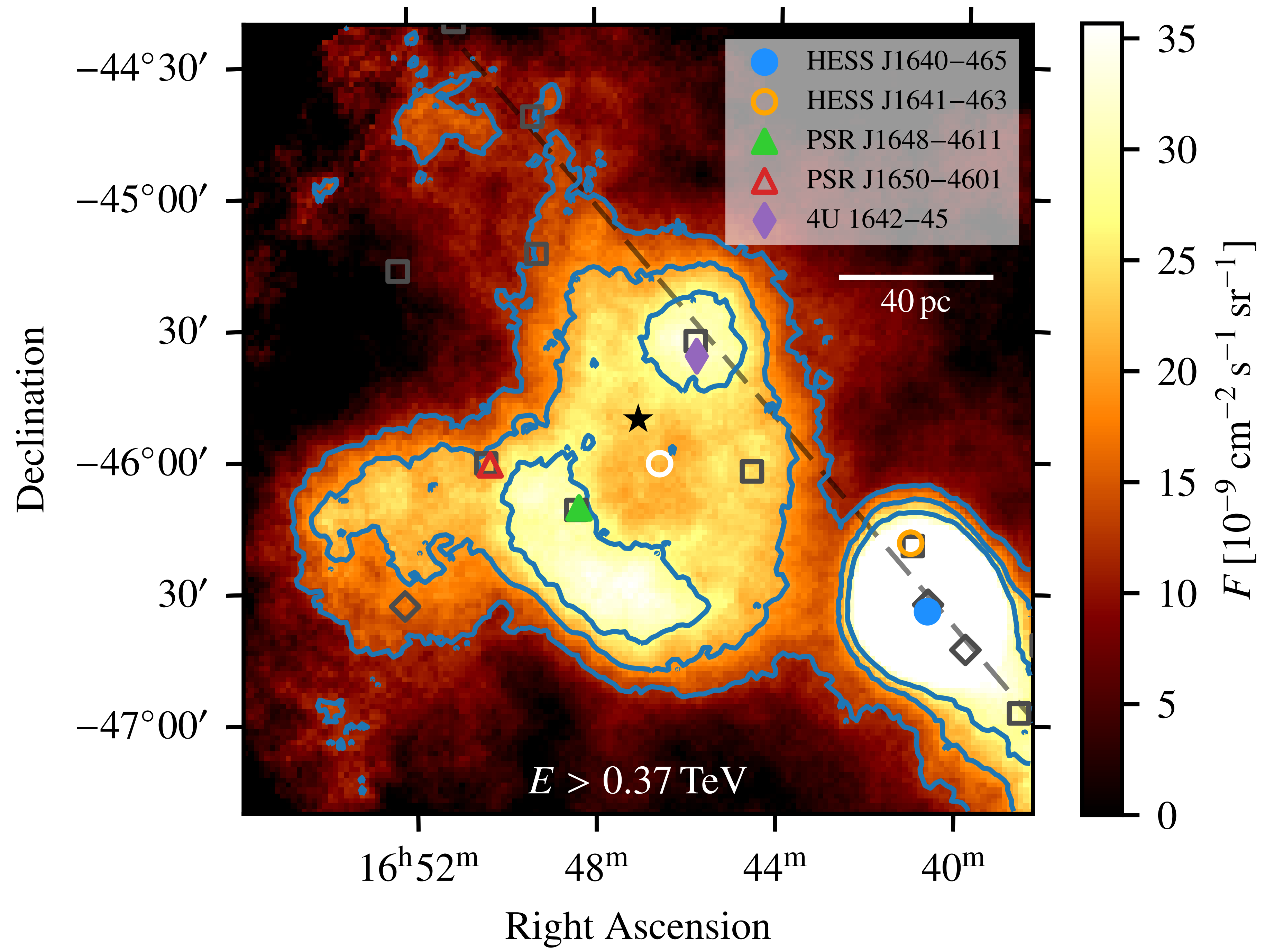
Westerlund 1 — interpretation

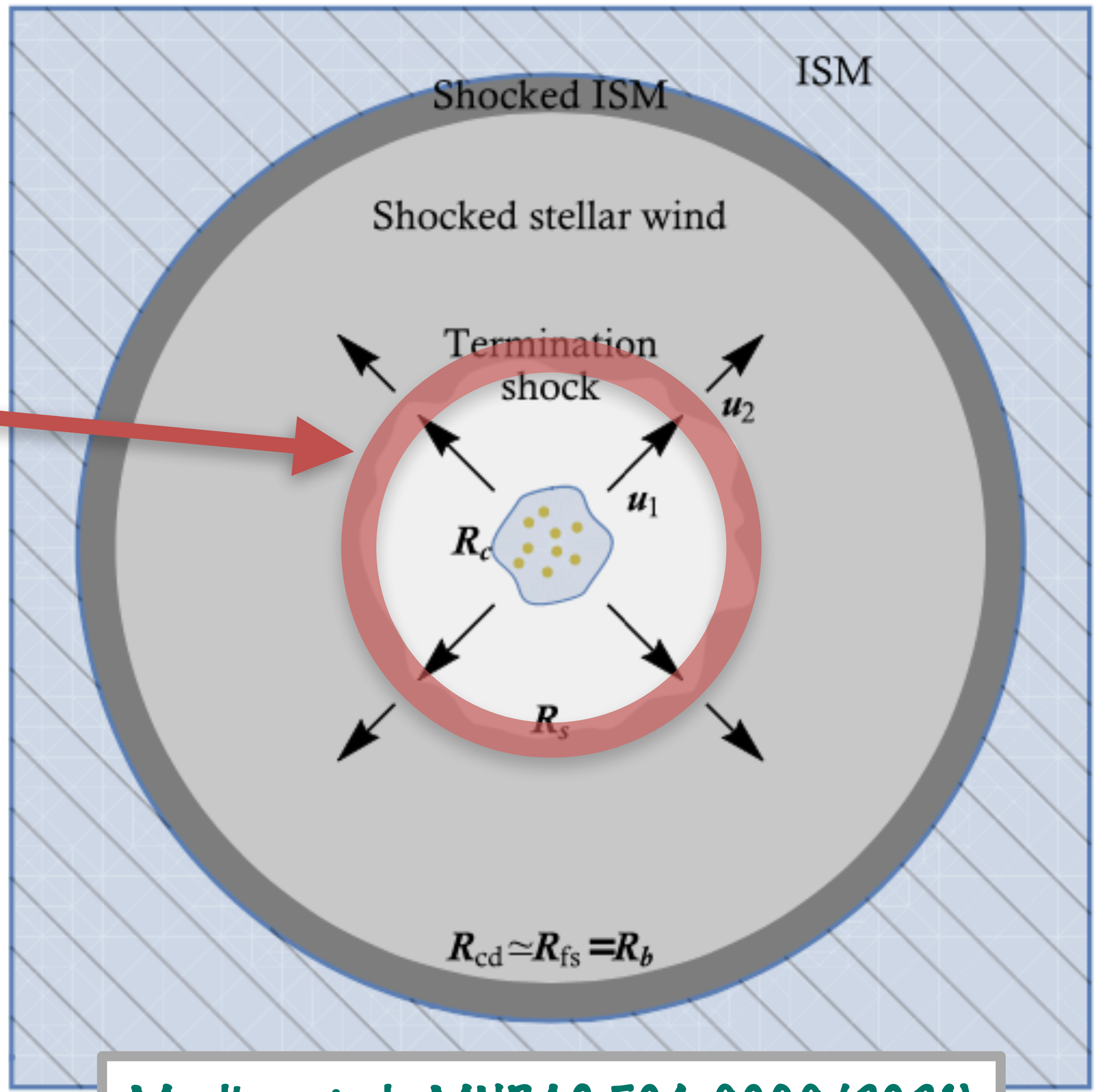
- Source association
  - only Westerlund 1 can explain majority of emission
  - pulsars / PWN may contribute locally

- 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)



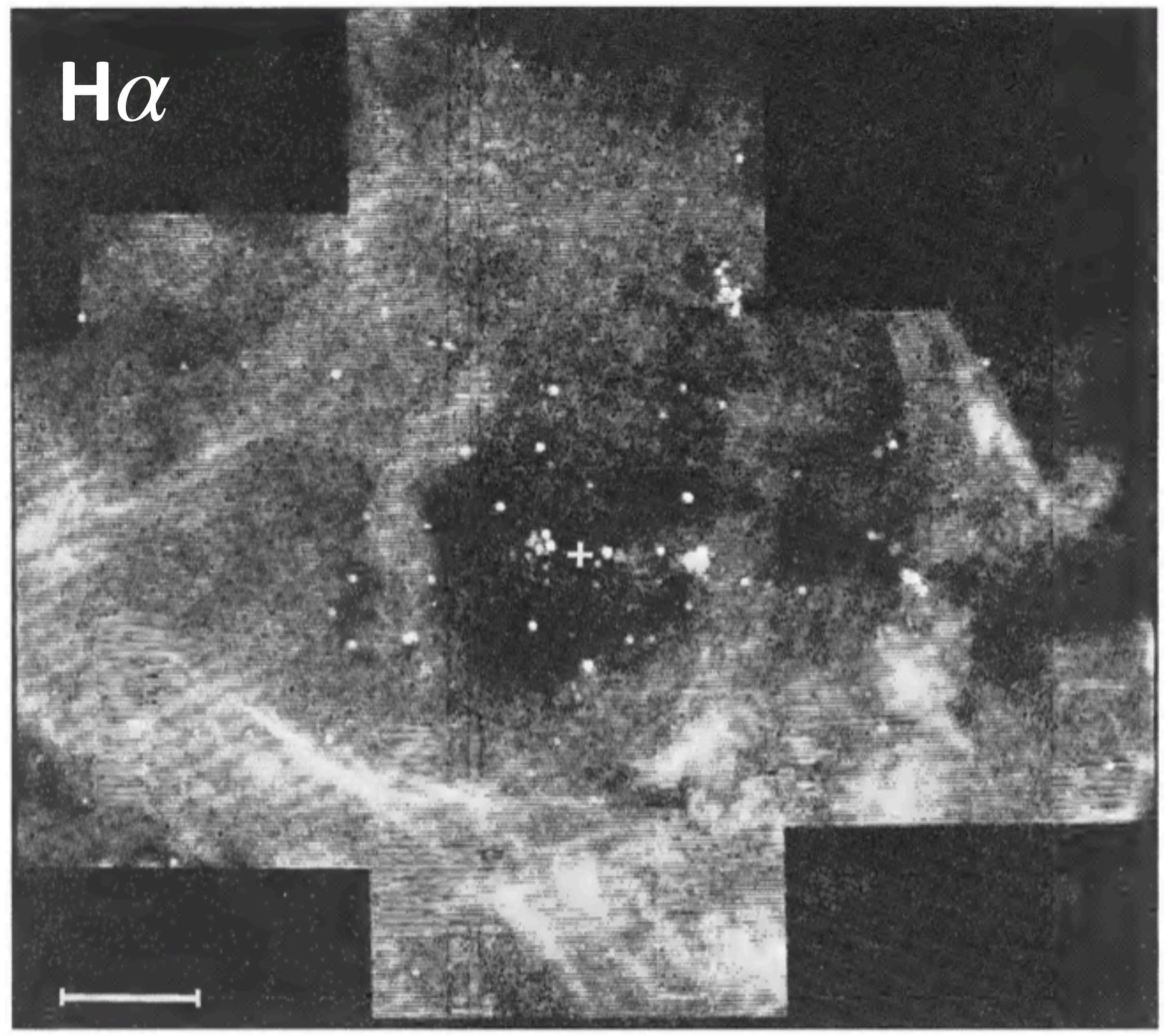


Morlino et al., MNRAS 504, 6096 (2021)

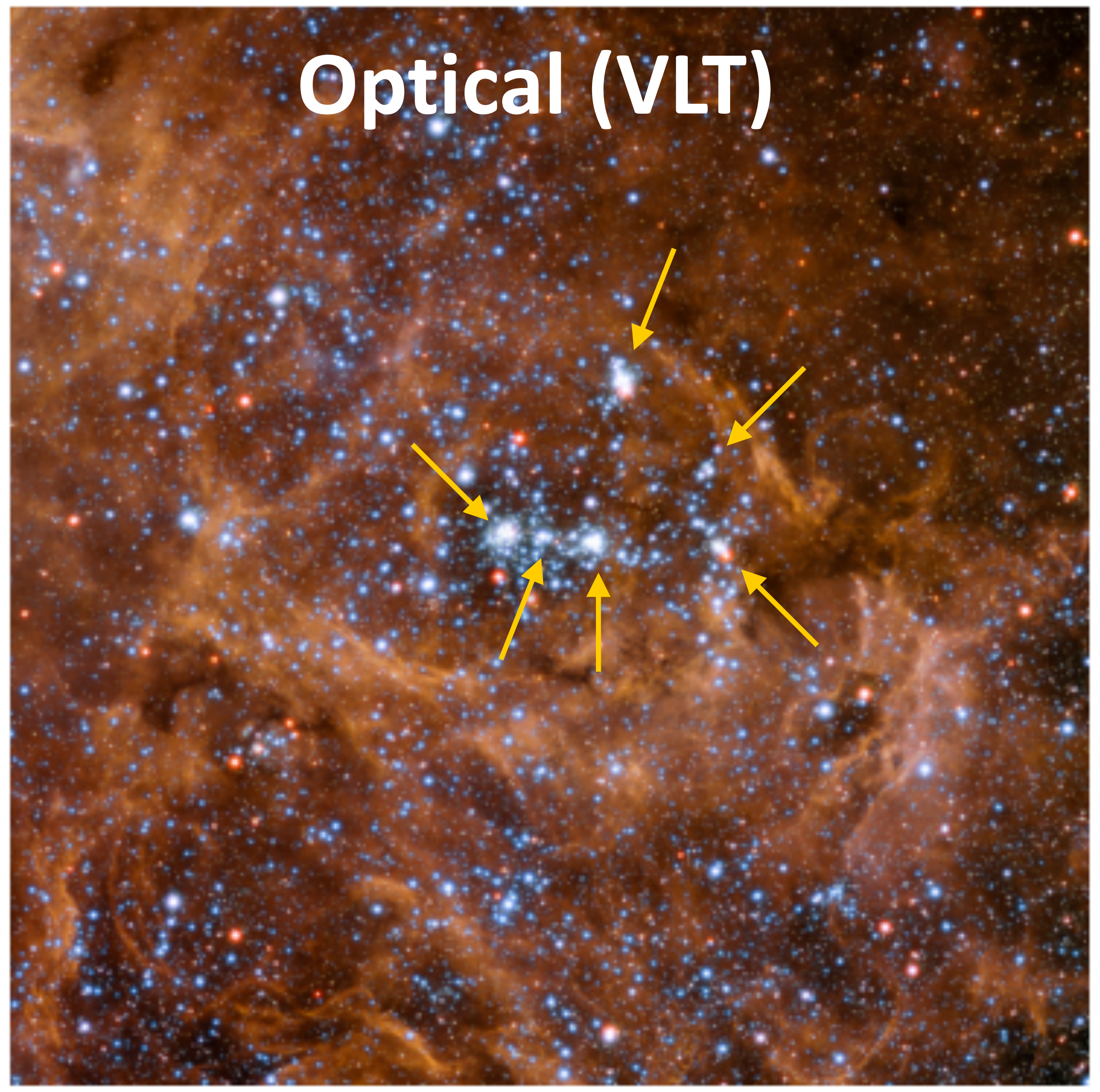
The superbubble 30 Dor C

- Superbubble (seen e.g. in Hα)
- Surrounds “LH 90” association of star clusters
  - age $\sim 4\,\mathrm{Myr}$ (but older sub-populations exist)
  - several WR stars
  - wind power $\sim 2 \times 10^{38}\,\mathrm{erg\,s^{-1}}$ (uncertain!)
- X-ray synchrotron emission
  - not from Hα shell (too slow, $\sim 100\,\mathrm{km\,s^{-1}}$)
  - rather: SNR expanding fast ($\gtrsim 3{,}000\,\mathrm{km\,s^{-1}}$) in low-density superbubble
  - low B-field ($\lesssim 20\,\mu\mathrm{G}$) suggests leptonic origin of TeV emission
- MCSNR J0536–6913: another putative SNR

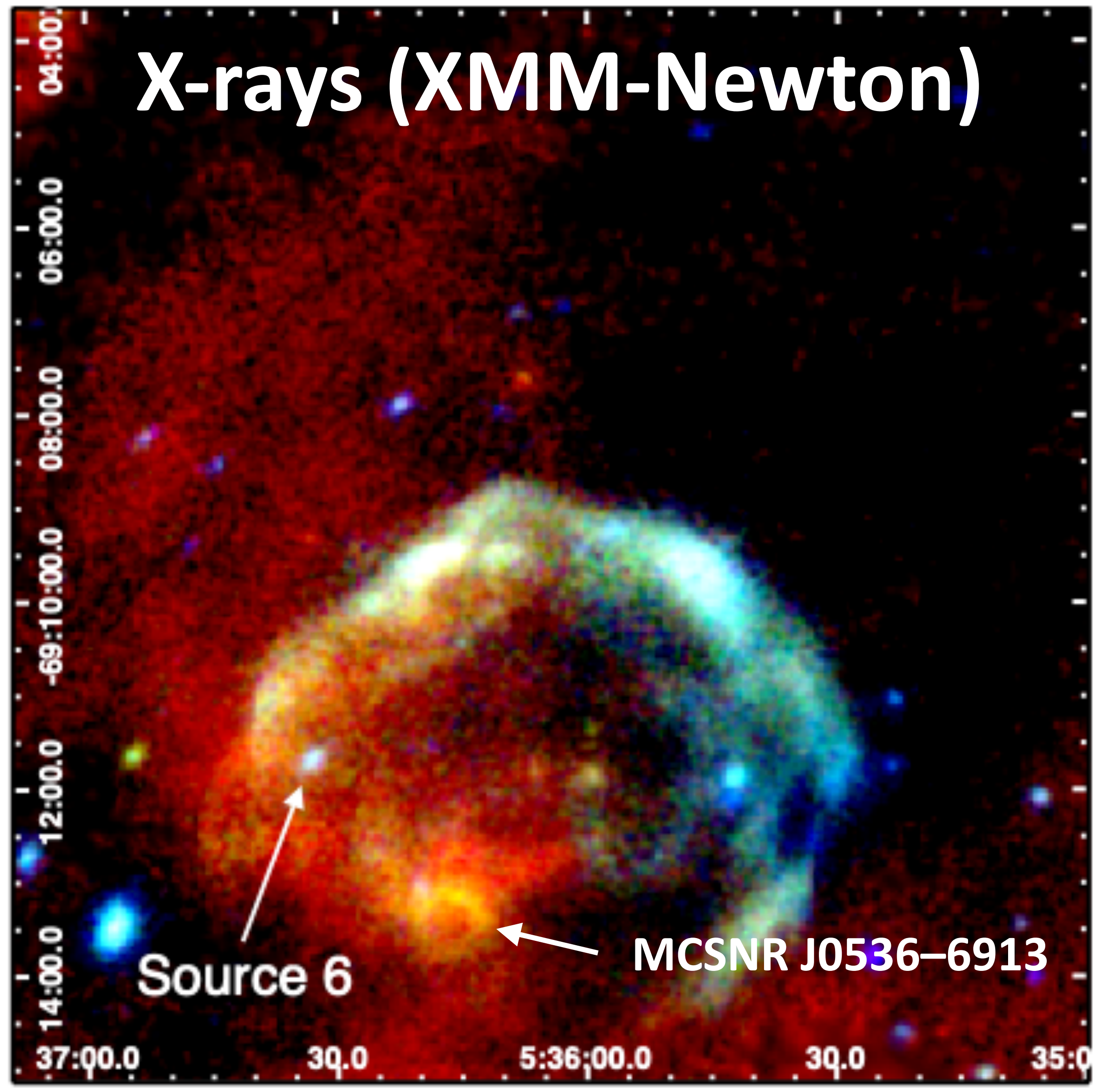
Mathewson et al., ApJS **58**, 197 (1985)



Credit: ESO



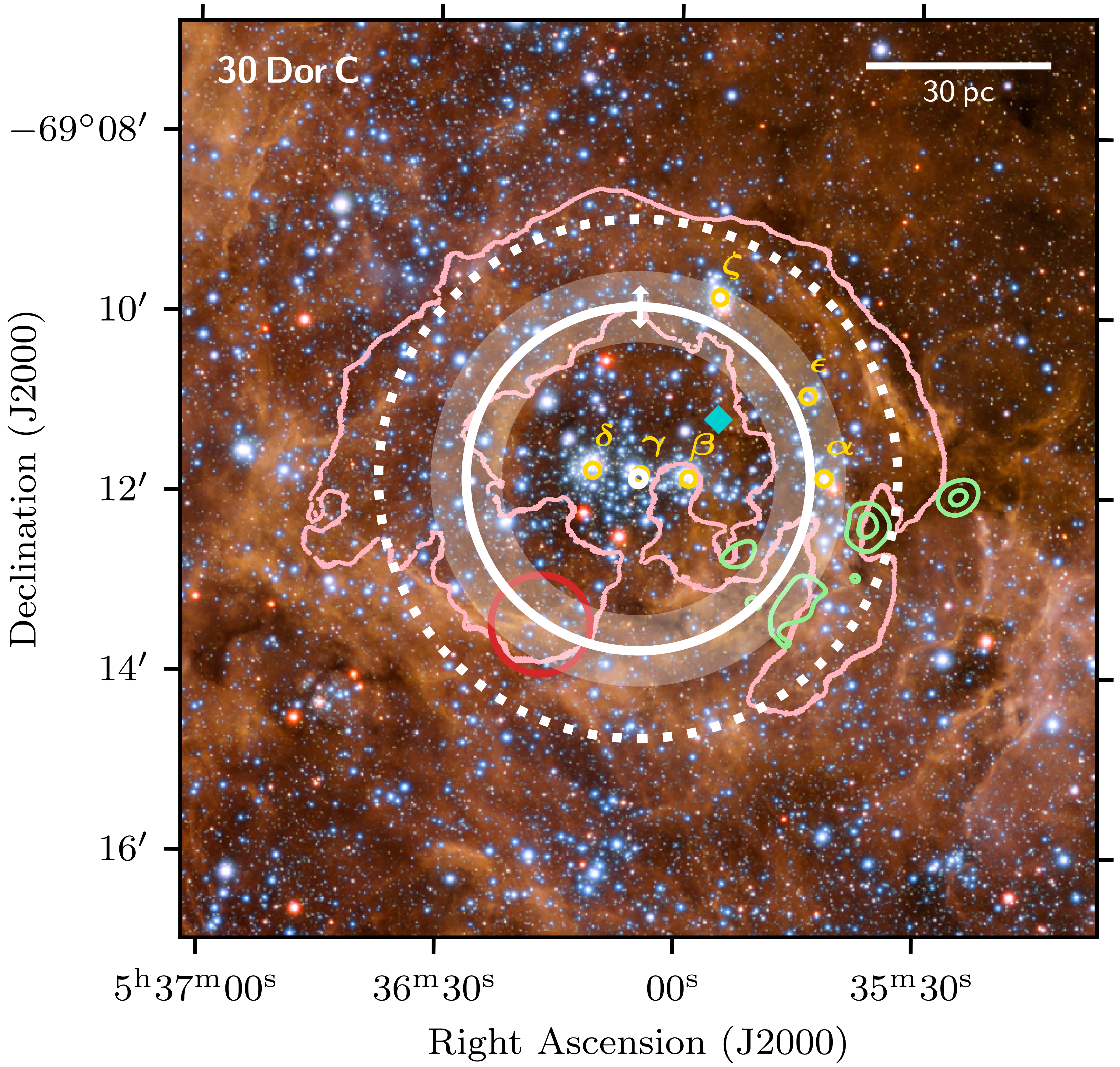
Kavanagh et al., A&A **573**, A73 (2015)



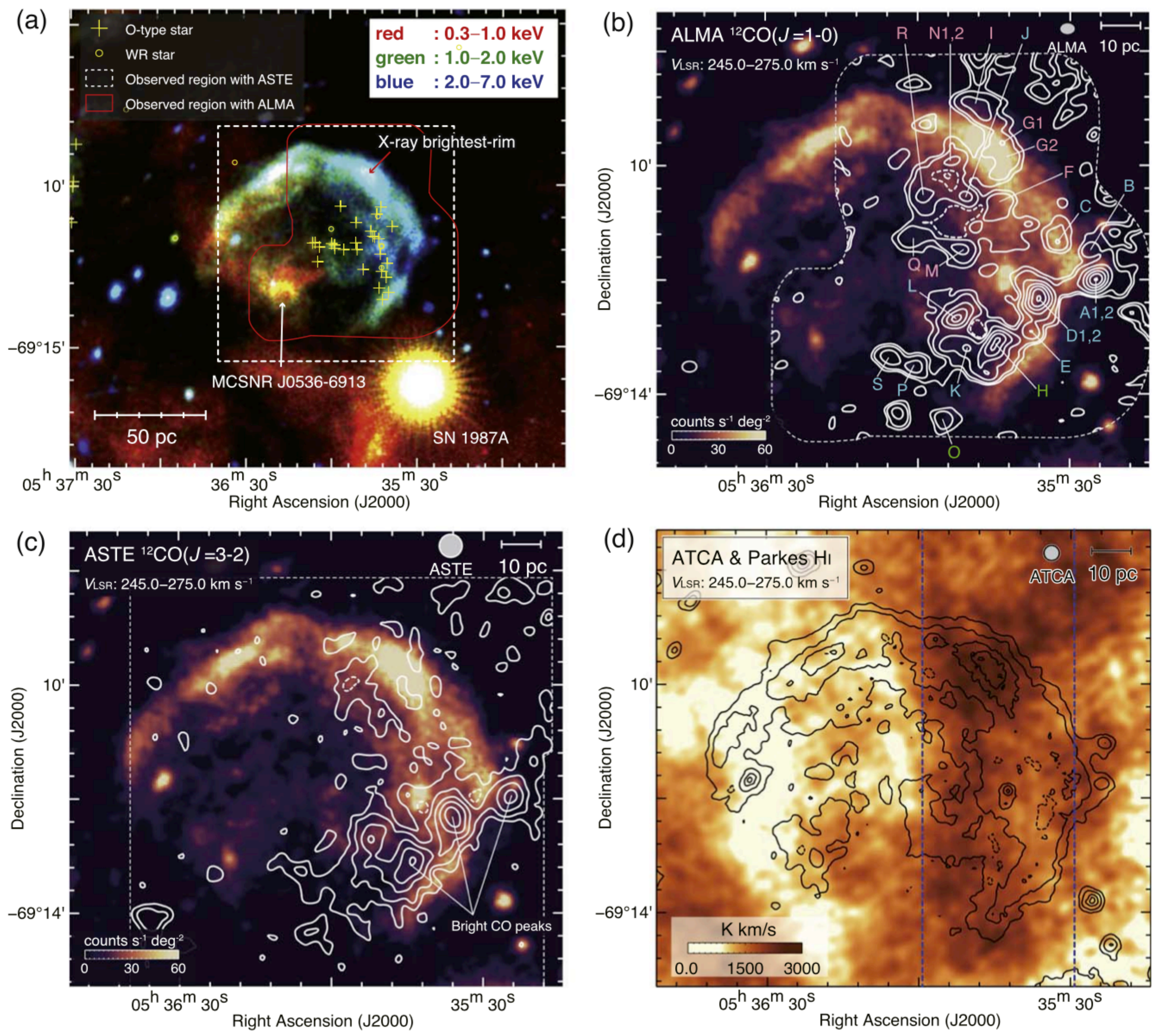
30 Dor C — MWL view

- Dense ($\gtrsim 100\,\mathrm{cm}^{-3}$) molecular clouds, in particular in western part of shell

Background image credit: ESO



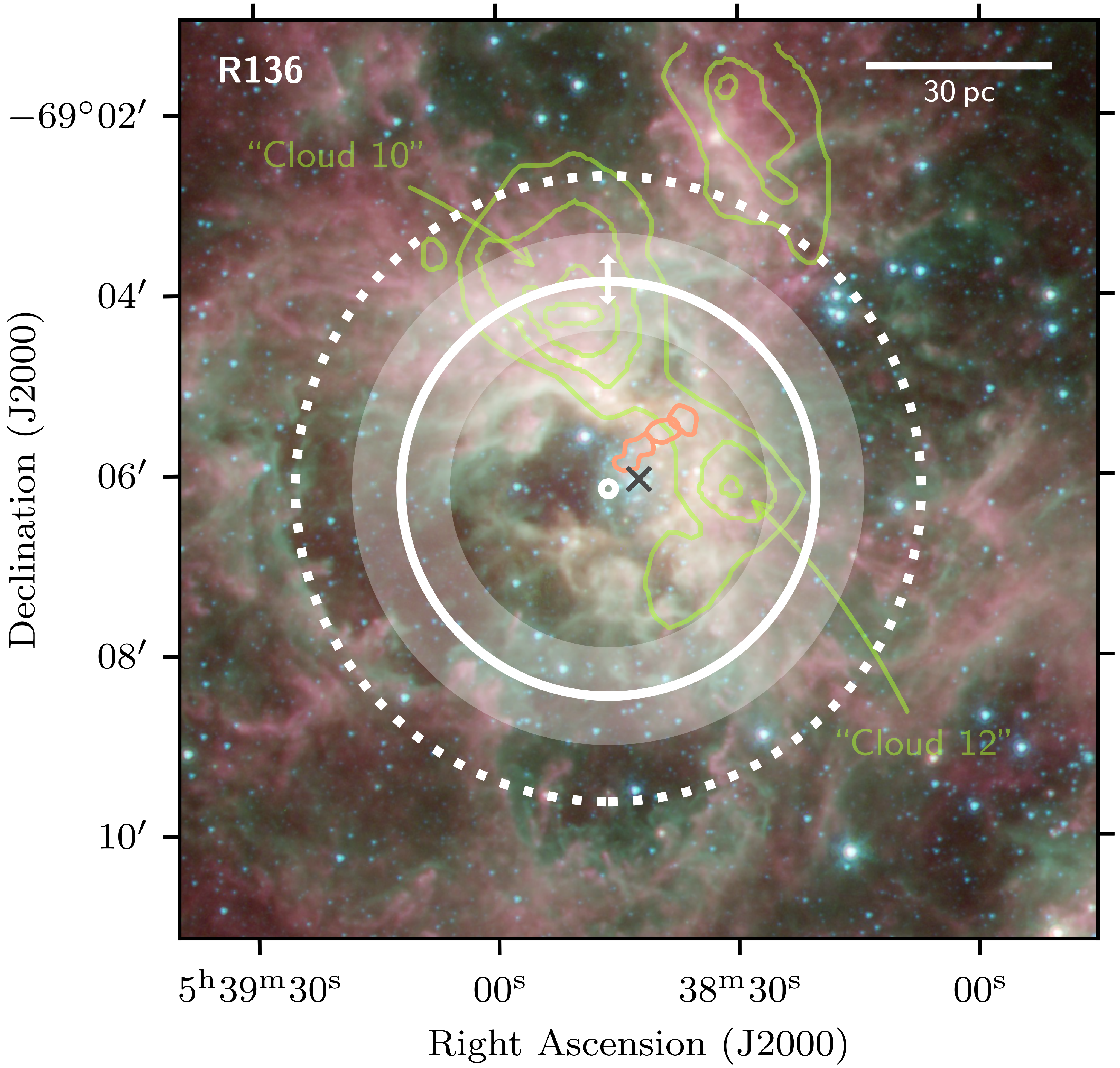
Yamane et al., ApJ **918**, 36 (2021)



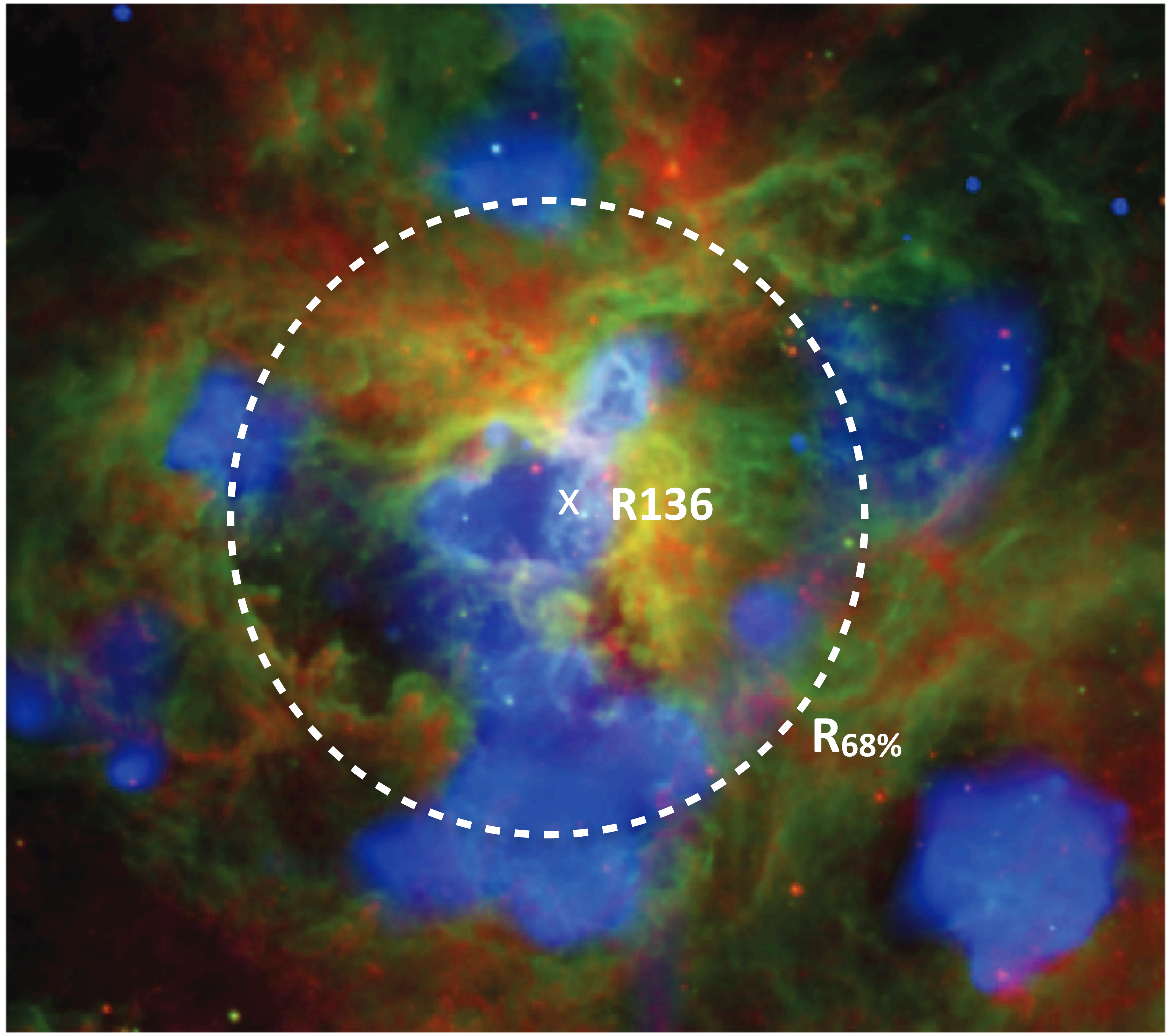
R136 — MWL view

- Size of TeV emission ≈ size of superbubble?

Background image credit: NASA/JPL-Caltech



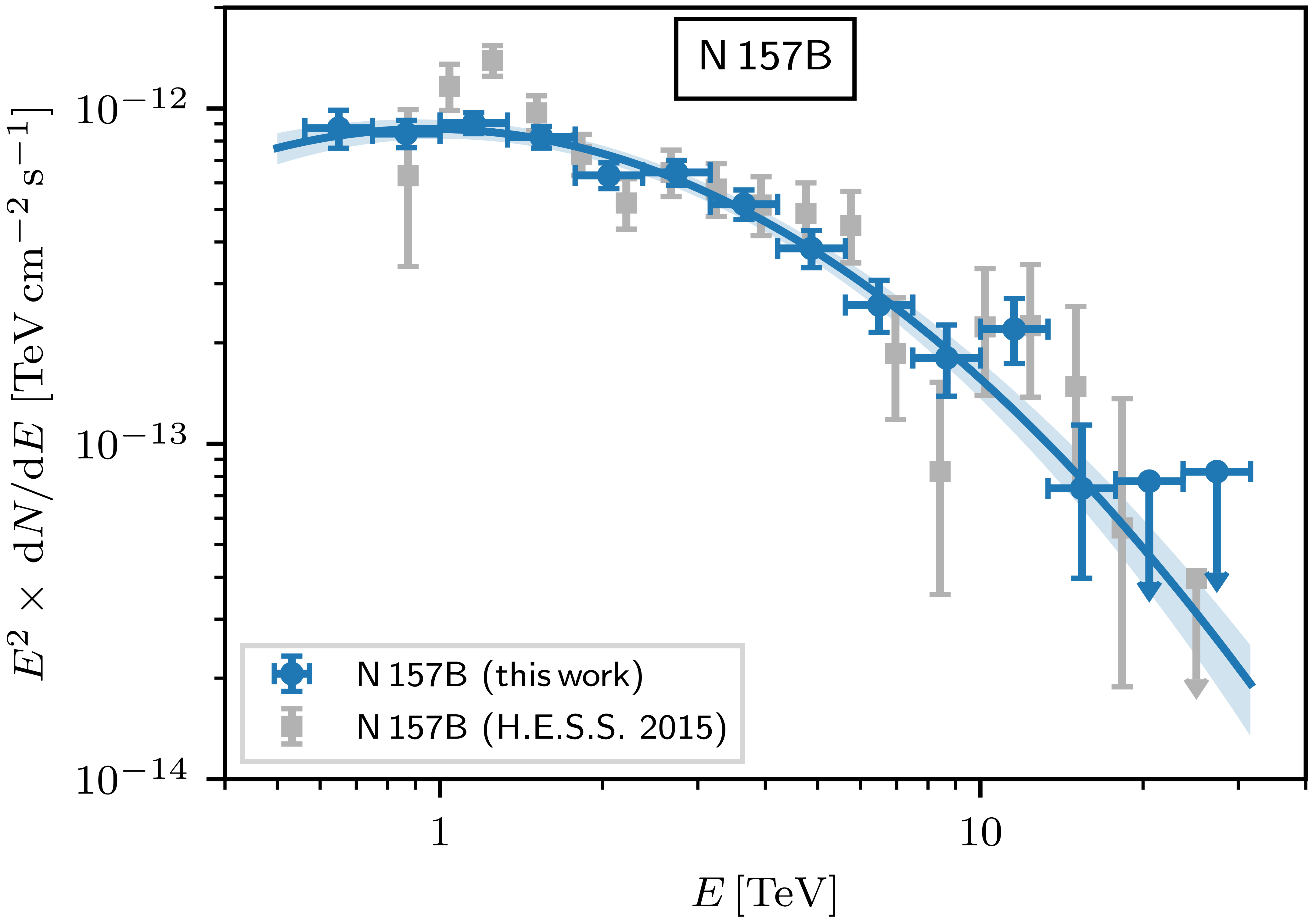
Townsley et al., AJ **131**, 2140 (2006)

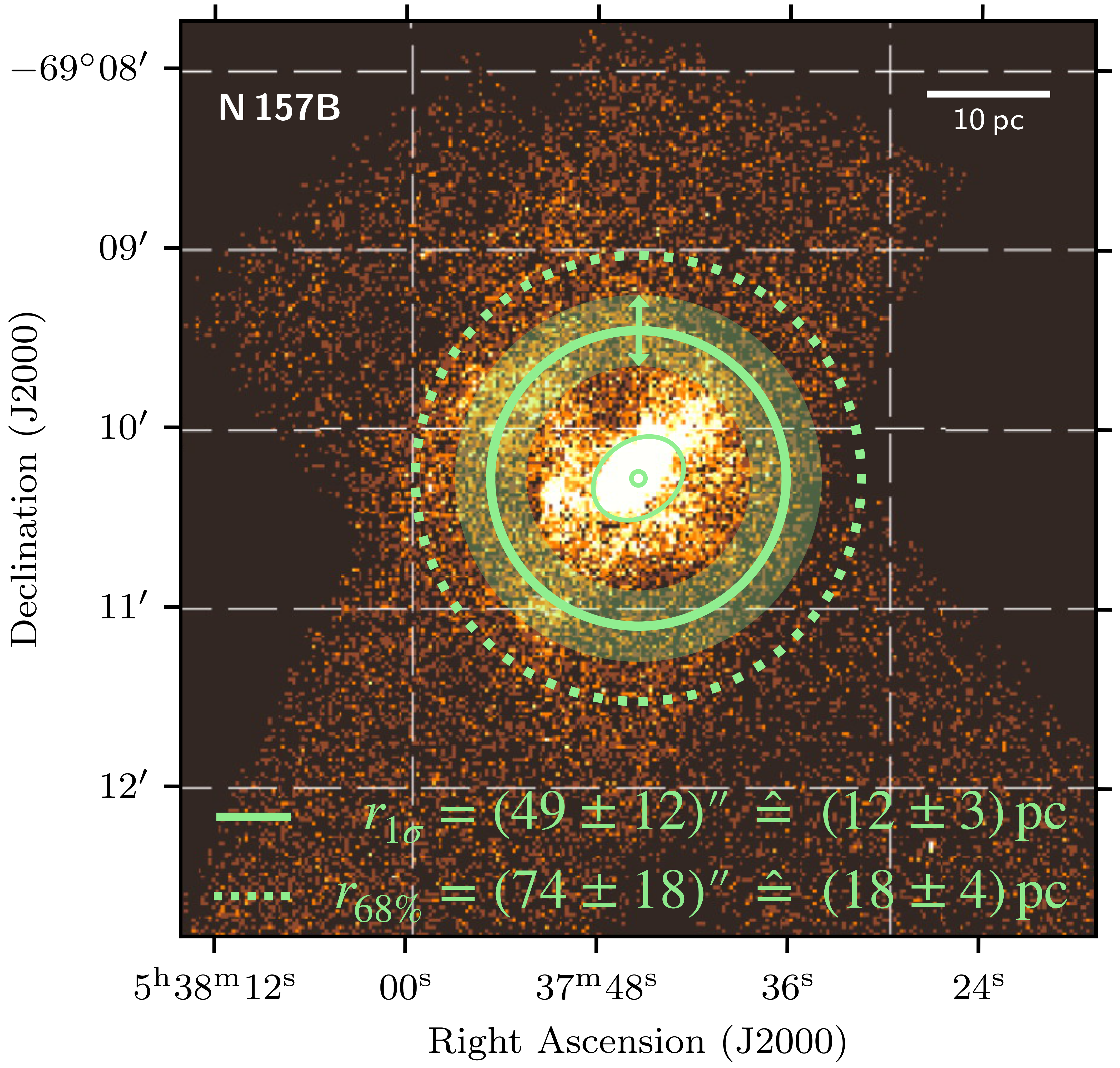


infrared 6.5–9.4 µm   Hα   X-ray 0.9–2.3 keV

N 157B

- Spectrum consistent with published result
- Position and extent match with *Chandra* X-ray image





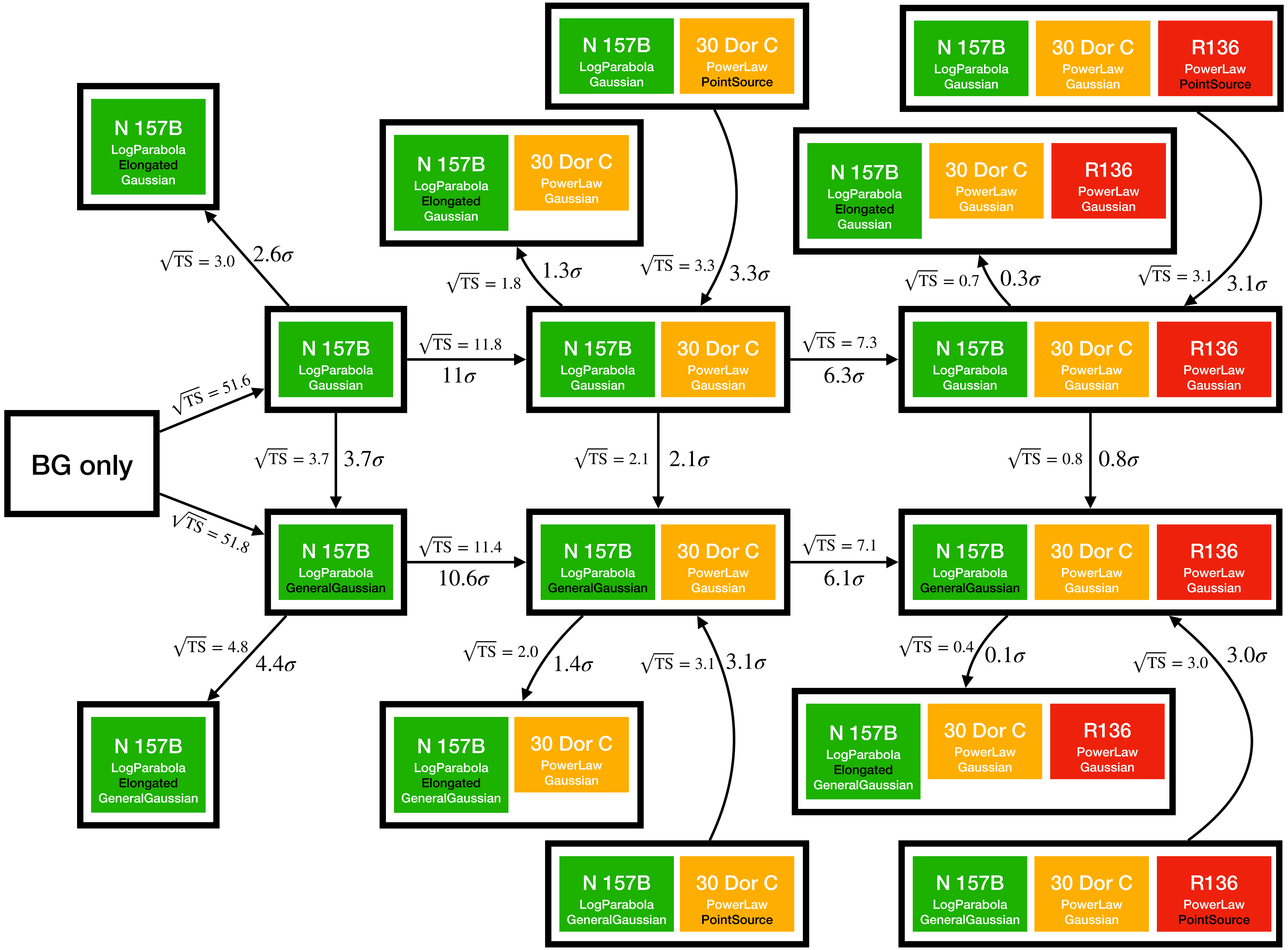
Massive star clusters in the LMC — model parameters

Best-fit Parameters of the γ-Ray Source Models

Parameter	Unit	Value
N157B/HESS J0537−691		
R.A.	deg	$84.4394 \pm 0.0048_{stat}$ ($5^h37^m45.^s5 \pm 1.1^s_{stat}$)
decl.	deg	$-69.1713 \pm 0.0016_{stat}$ ($-69°10'17'' \pm 6_{stat}''$)
σ_{Gauss}	deg	$0.0137 \pm 0.0033_{stat} \pm 0.0030_{sys}$
ϕ_0	10^{-13} TeV^{-1} cm^{-2} s^{-1}	$8.69 \pm 0.56_{stat} \pm 0.85_{sys}$
α	...	$2.03 \pm 0.07_{stat} \pm 0.08_{sys}$
β	...	$0.311 \pm 0.037_{stat}$
30 Dor C/HESS J0535−691		
R.A.	deg	$84.021 \pm 0.018_{stat}$ ($5^h36^m5.^s0 \pm 4.3^s_{stat}$)
decl.	deg	$-69.197 \pm 0.006_{stat}$ ($-69°11'49'' \pm 22_{stat}''$)
σ_{Gauss}	deg	$0.0319 \pm 0.0066_{stat} \pm 0.0034_{sys}$
ϕ_0	10^{-13} TeV^{-1} cm^{-2} s^{-1}	$2.54 \pm 0.37_{stat} {}^{+0.44}_{-0.40}\vert_{sys}$
Γ	...	$2.57 \pm 0.09_{stat}$
R136/HESS J0538−691		
R.A.	deg	$84.692 \pm 0.038_{stat}$ ($5^h38^m46^s \pm 9^s_{stat}$)
decl.	deg	$-69.103 \pm 0.013_{stat}$ ($-69°06'11'' \pm 47_{stat}''$)
σ_{Gauss}	deg	$0.0384 \pm 0.0090_{stat} {}^{+0.0045}_{-0.0037}\vert_{sys}$
ϕ_0	10^{-13} TeV^{-1} cm^{-2} s^{-1}	$1.90 \pm 0.58_{stat} {}^{+0.45}_{-0.38}\vert_{sys}$
Γ	...	$2.54 \pm 0.15_{stat}$

Alternative models

- Many alternatives tested
- In particular, allowed more flexible spatial model for N 157B
  - elongation
  - "generalised Gaussian"
  - → model with 3 sources is always strongly preferred

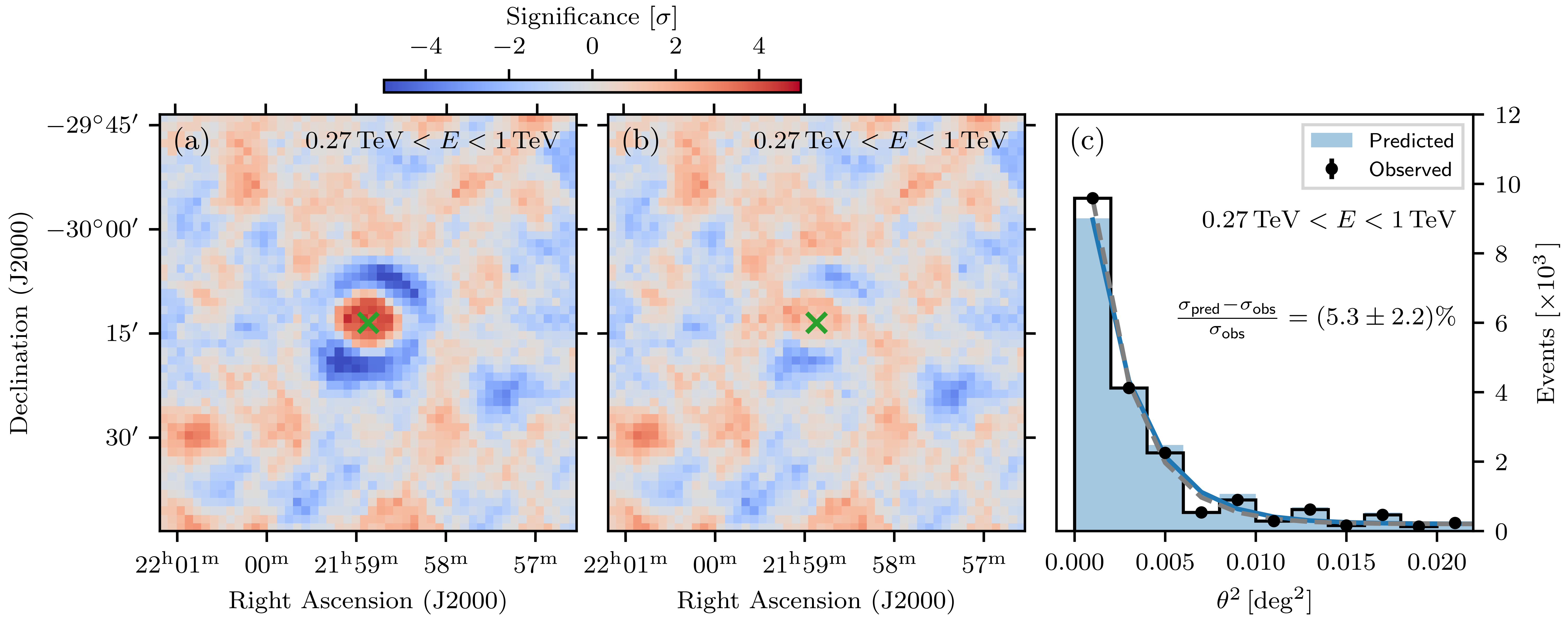


Estimation of systematic uncertainties

- Systematic uncertainties derived with "bracketing" approach
  - vary instrument response functions
  - repeat modelling analysis
  - systematic error = difference to default best-fit parameter value
  - total systematic error is quadratic sum of different contributions
  - do not quote error if negligible compared to statistical one

- Systematic effects considered:
  - background normalisation* ($\pm 0.5\,\%$)
  - energy scale ($\pm 10\,\%$)
  - PSF width ($\pm 5\,\%$)

  (derived from study on PKS 2155–304, see below)



* of the stacked data sets (i.e. not per run!)

Westerlund 2 — analysis details