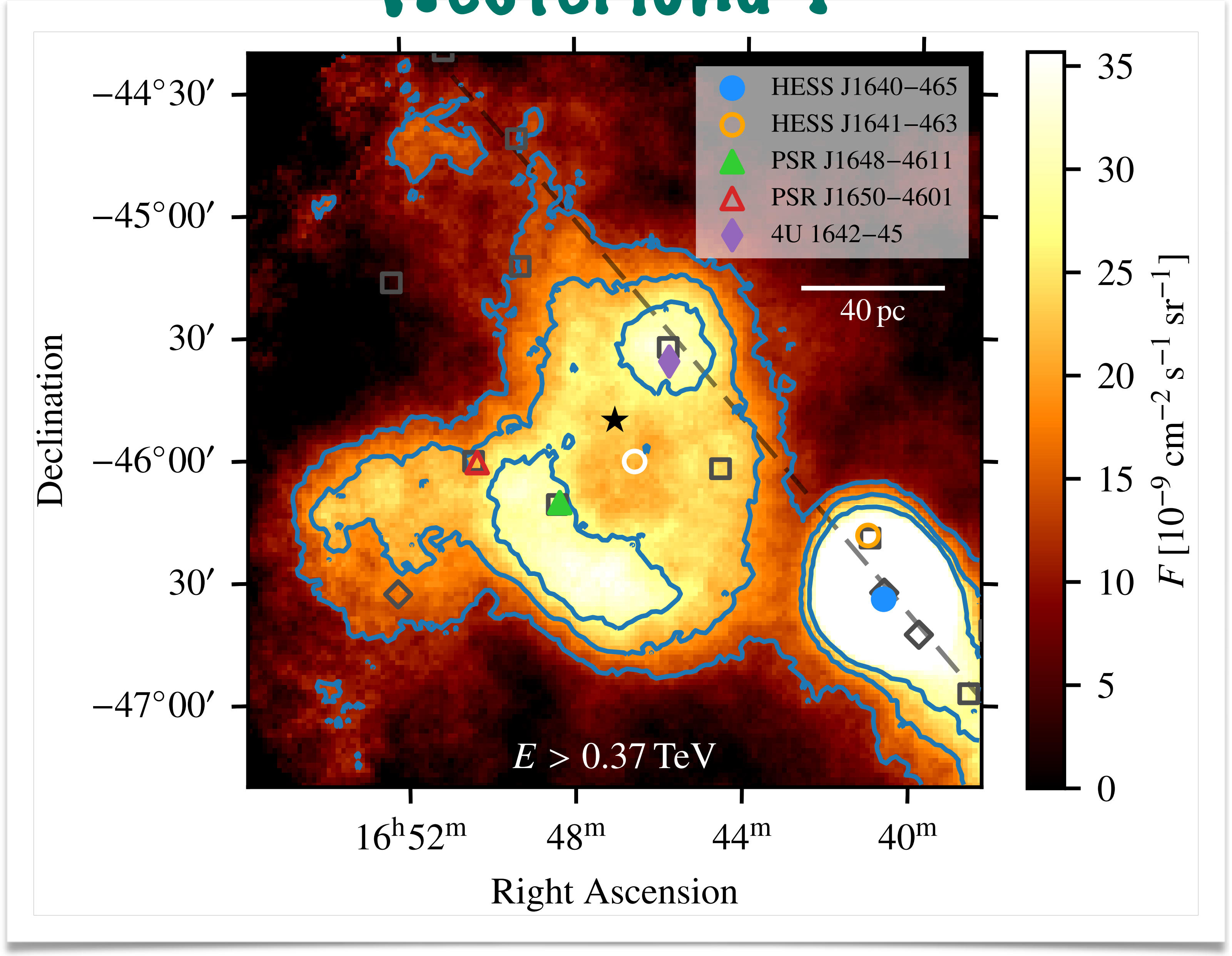
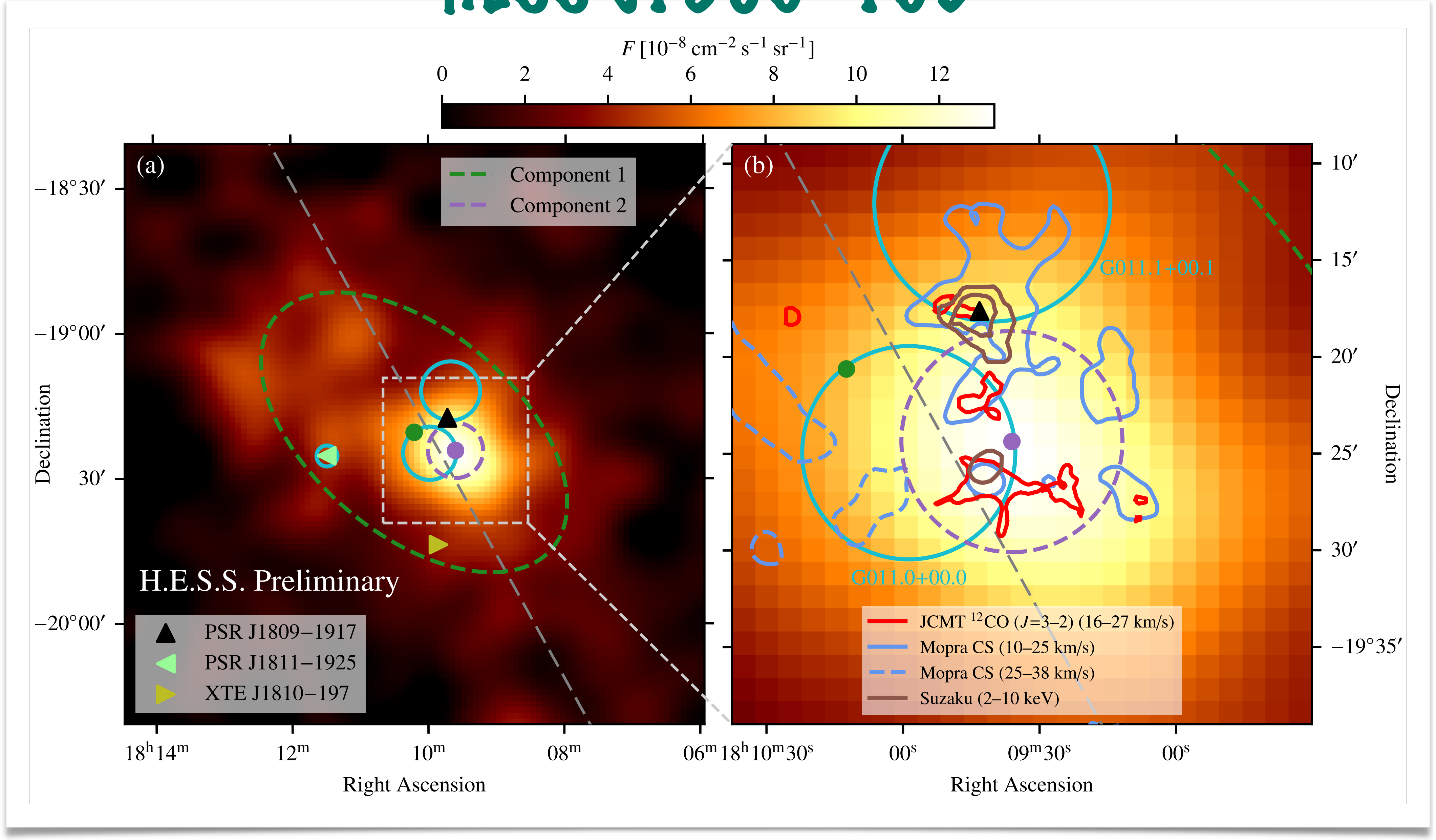
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Westerlund 1



HESS J1809-193



Measurements of Galactic γ-ray Sources with Imaging Atmospheric Cherenkov Telescopes

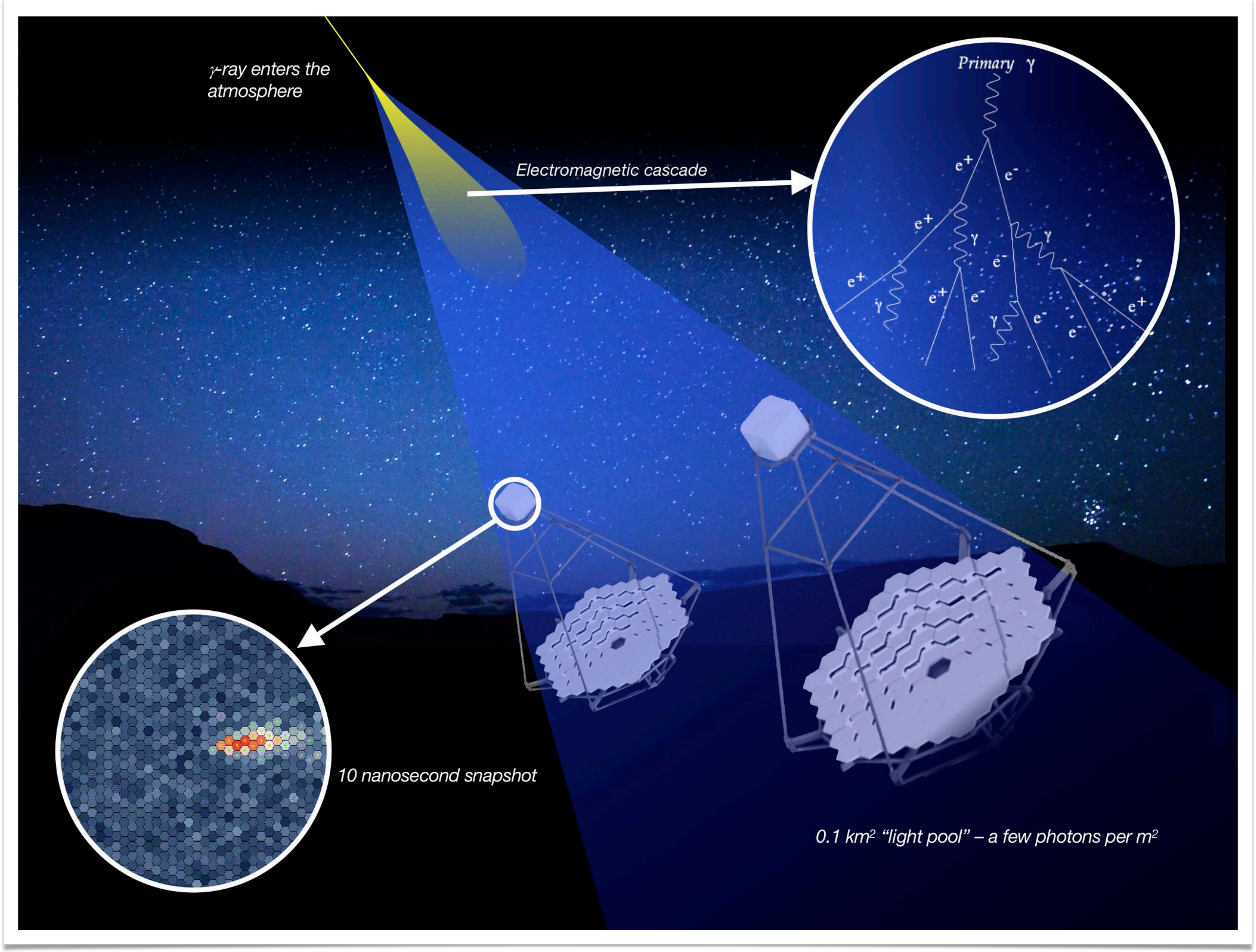
Lars Mohrmann

Max Planck Institute for Nuclear Physics, Heidelberg

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

TeVPA 2022 — Kingston, Ontario, Canada — August 11, 2022

Imaging Atmospheric Cherenkov Telescopes (IACTs)



- Disadvantages
  - limited duty cycle (10-15%)
  - limited field of view (few degree)
- Advantages
  - low energy threshold ($\mathcal{O}(100\,\mathrm{GeV})$)
  - ***high angular resolution***
    ($\lesssim 0.1^\circ$ at 1 TeV)

Current IACT instruments

- H.E.S.S.
  - Khomas highland, Namibia
  - since 2004
  - 1x 28-m + 4x 12-m IACTs

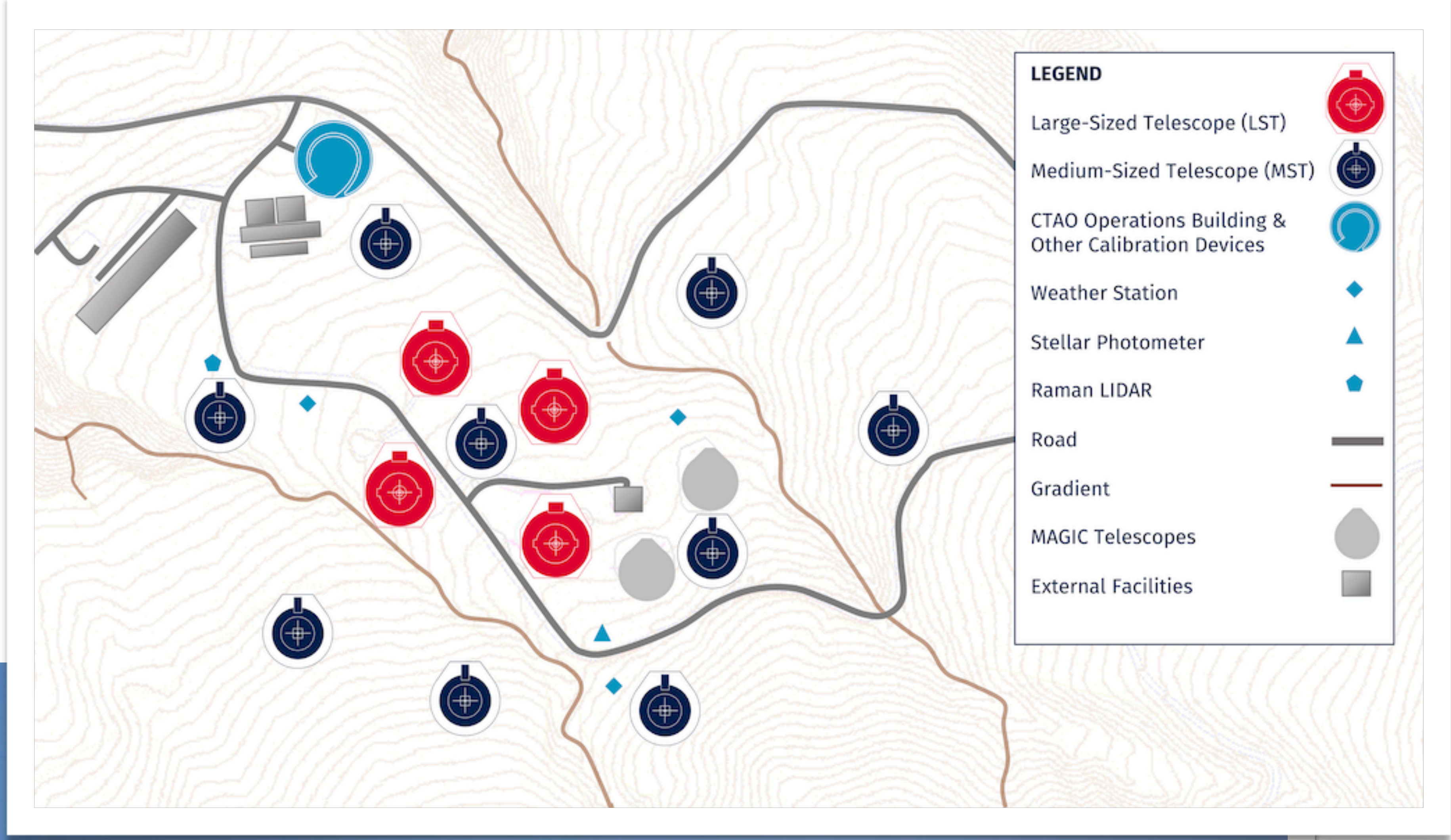
- MAGIC
  - La Palma, Spain
  - since 2004
  - 2x 17-m IACTs

- VERITAS
  - Arizona, USA
  - since 2007
  - 4x 12-m IACTs

…also: FACT, MACE, … (not covered here)

Cherenkov Telescope Array (CTA)

- CTA-North
  - La Palma, Spain
  - initial configuration: 4 LST + 9 MST



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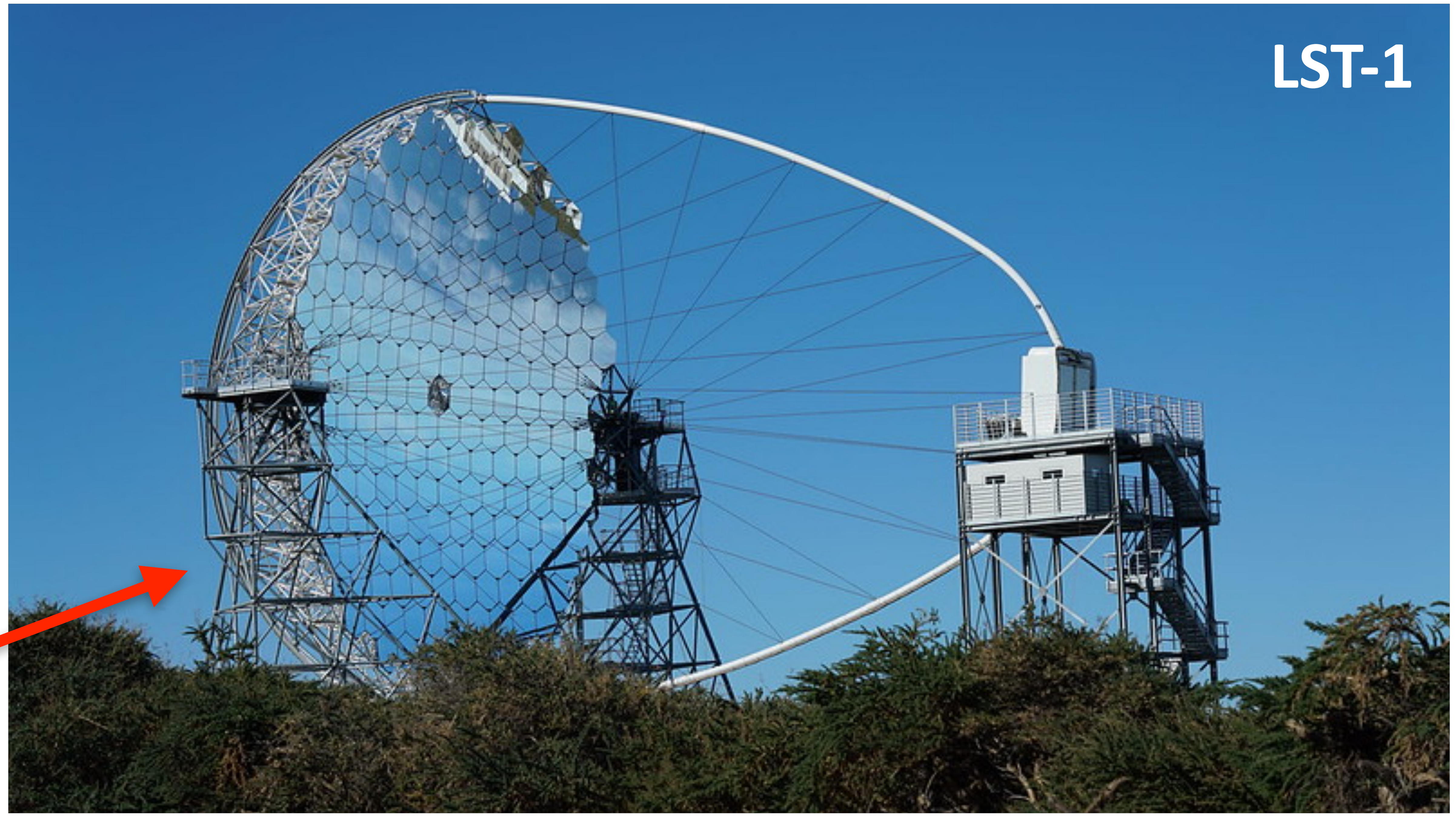
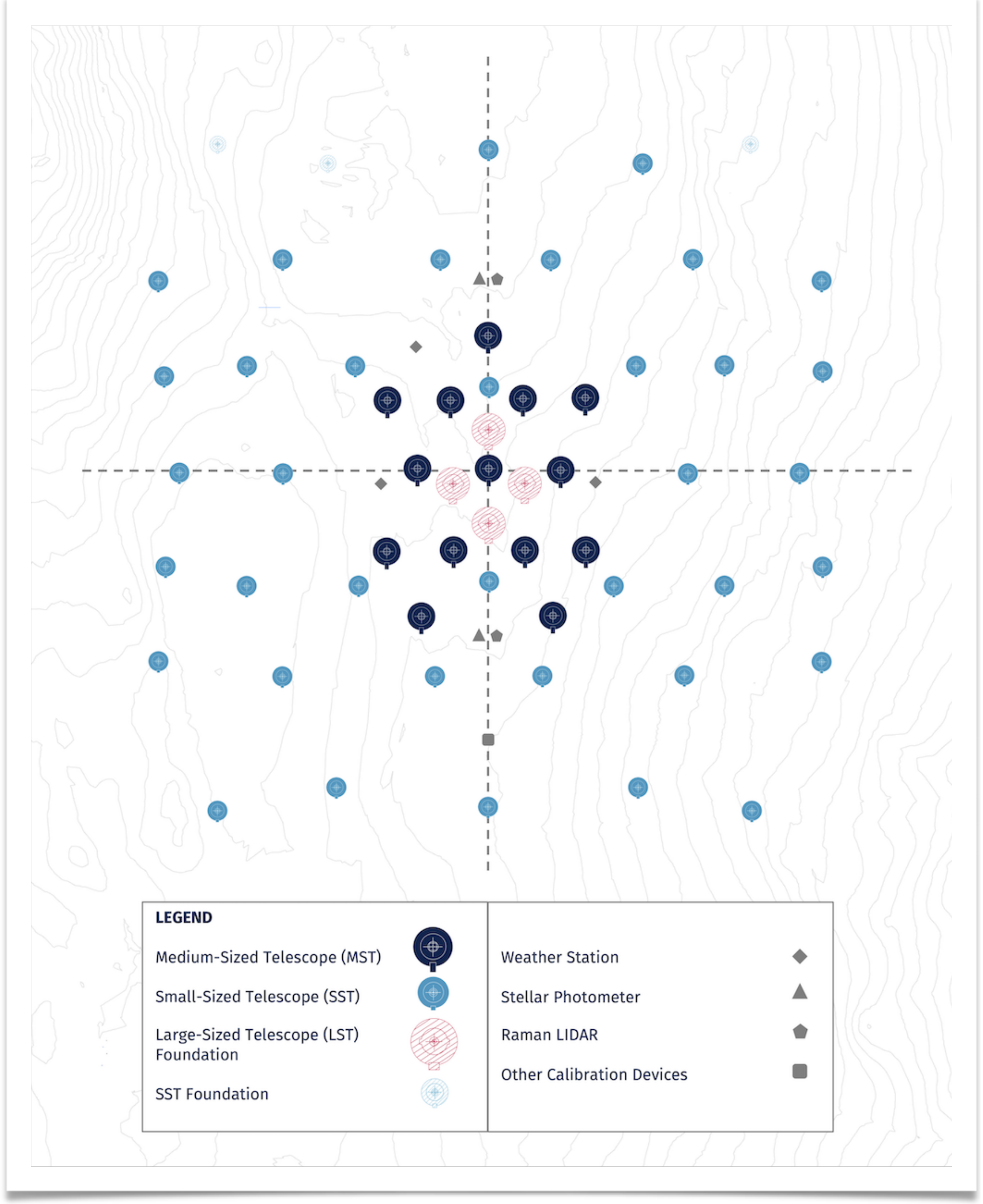
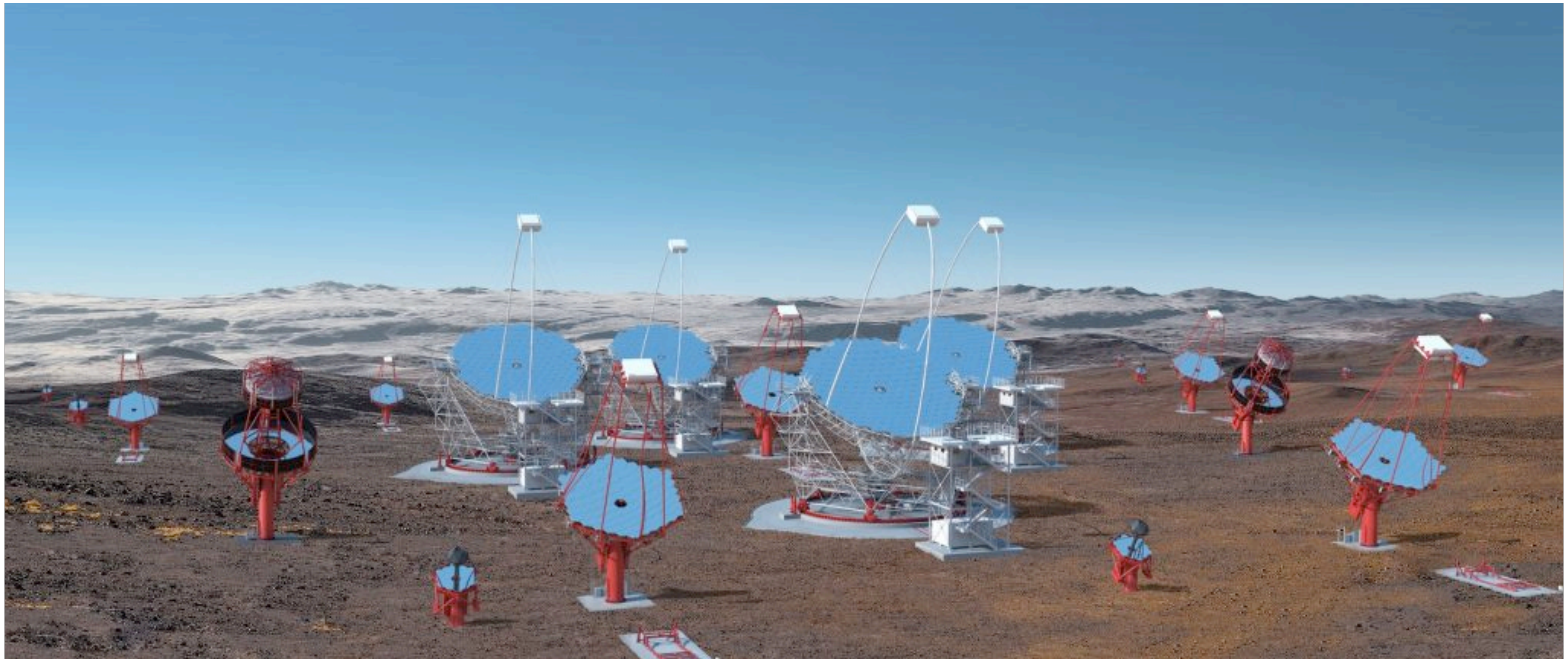


Cherenkov Telescope Array (CTA)

- CTA-South
  - Paranal, Chile
  - initial configuration: 14 MST + 37 SST





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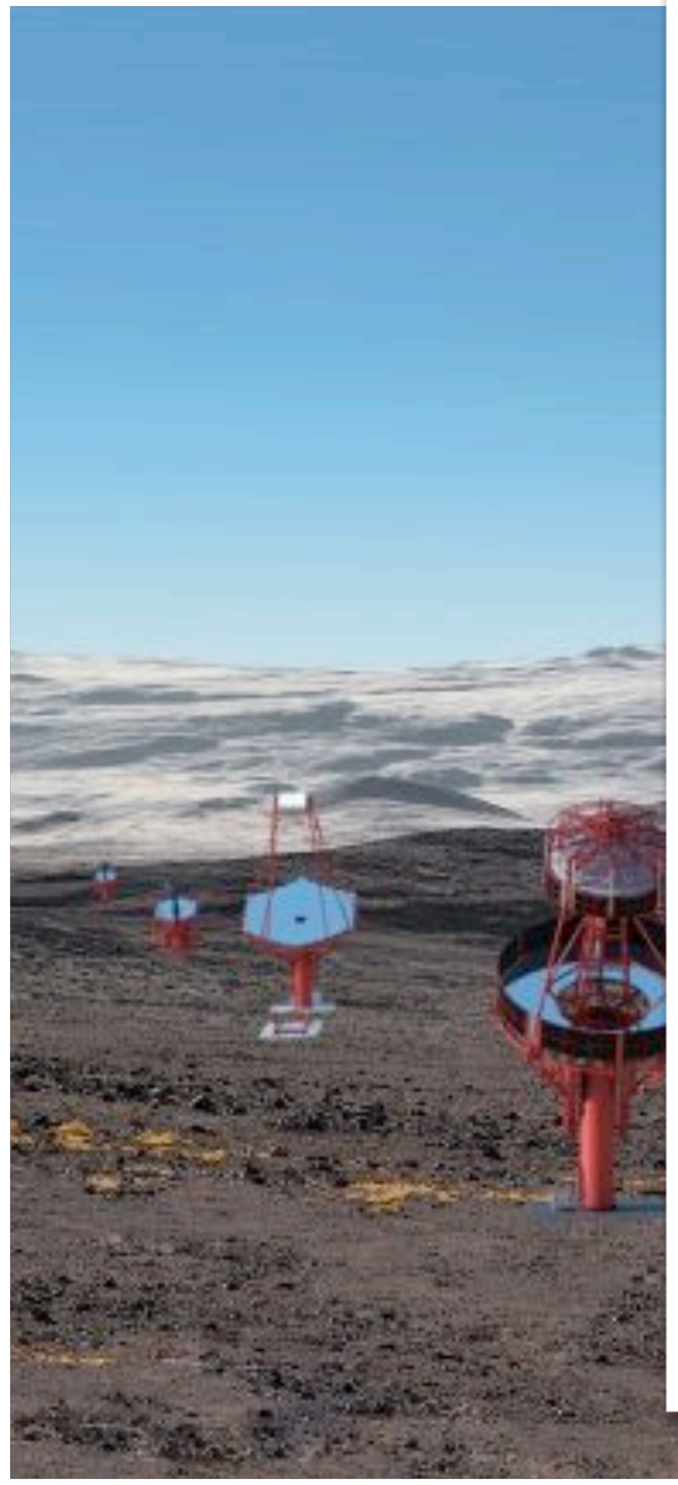
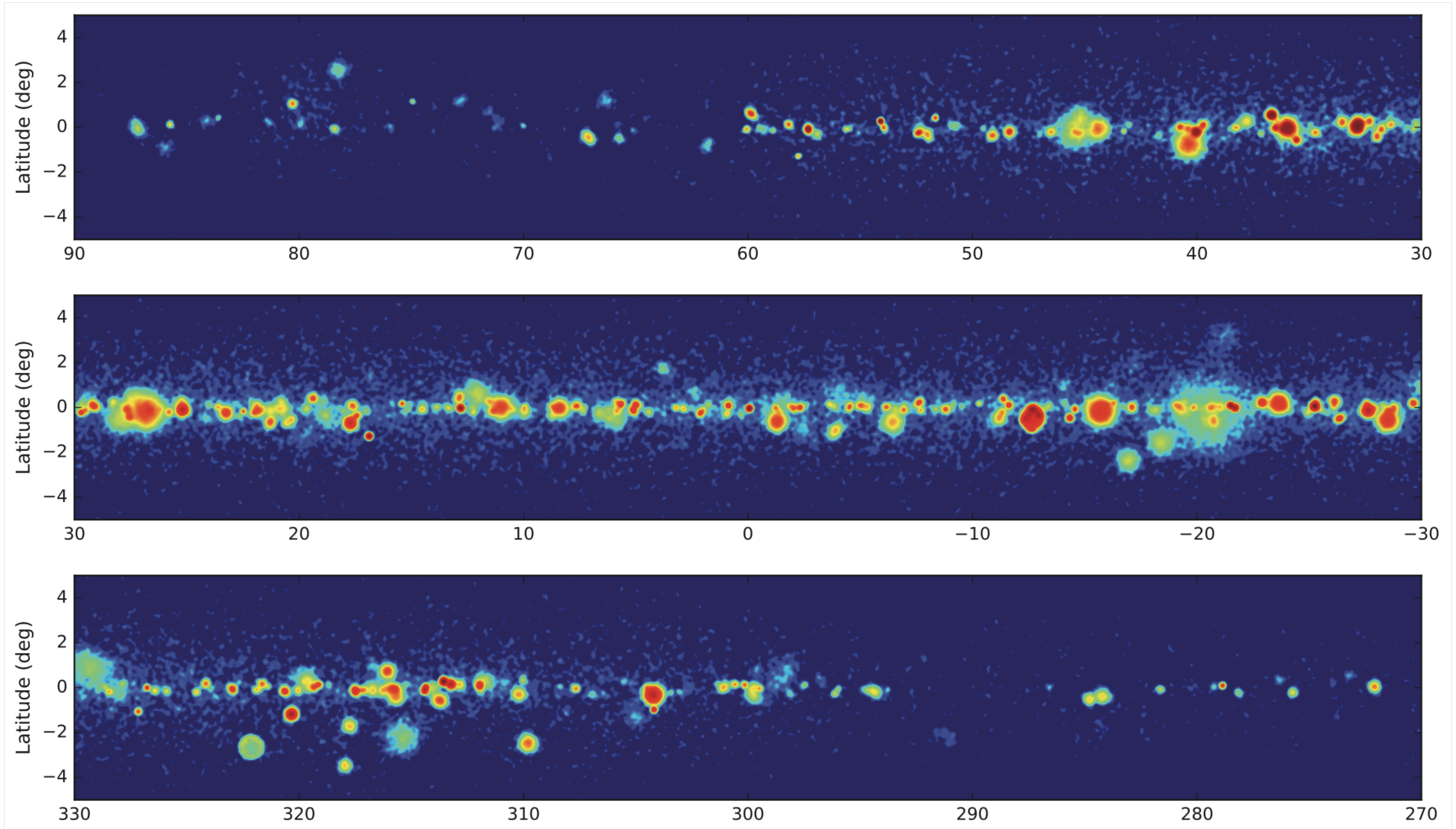
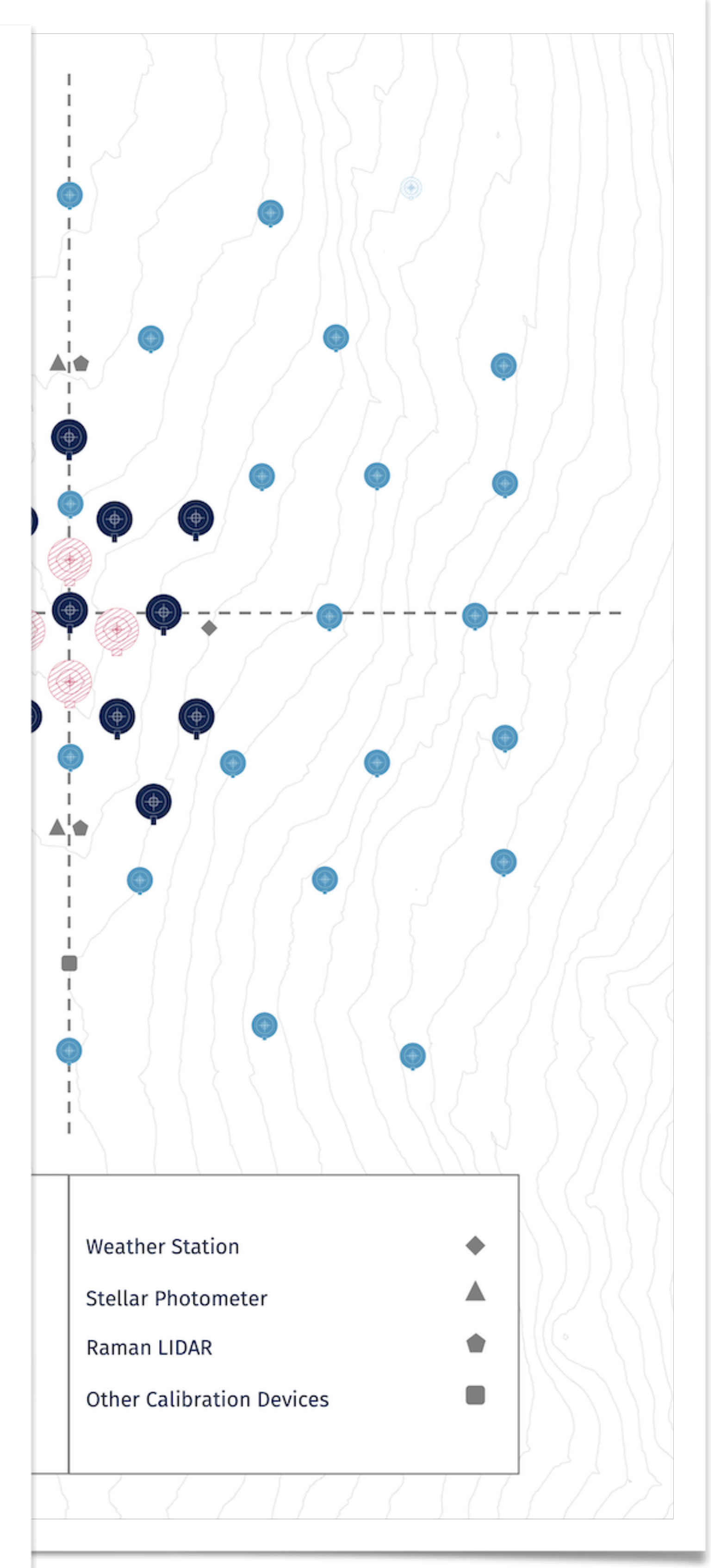


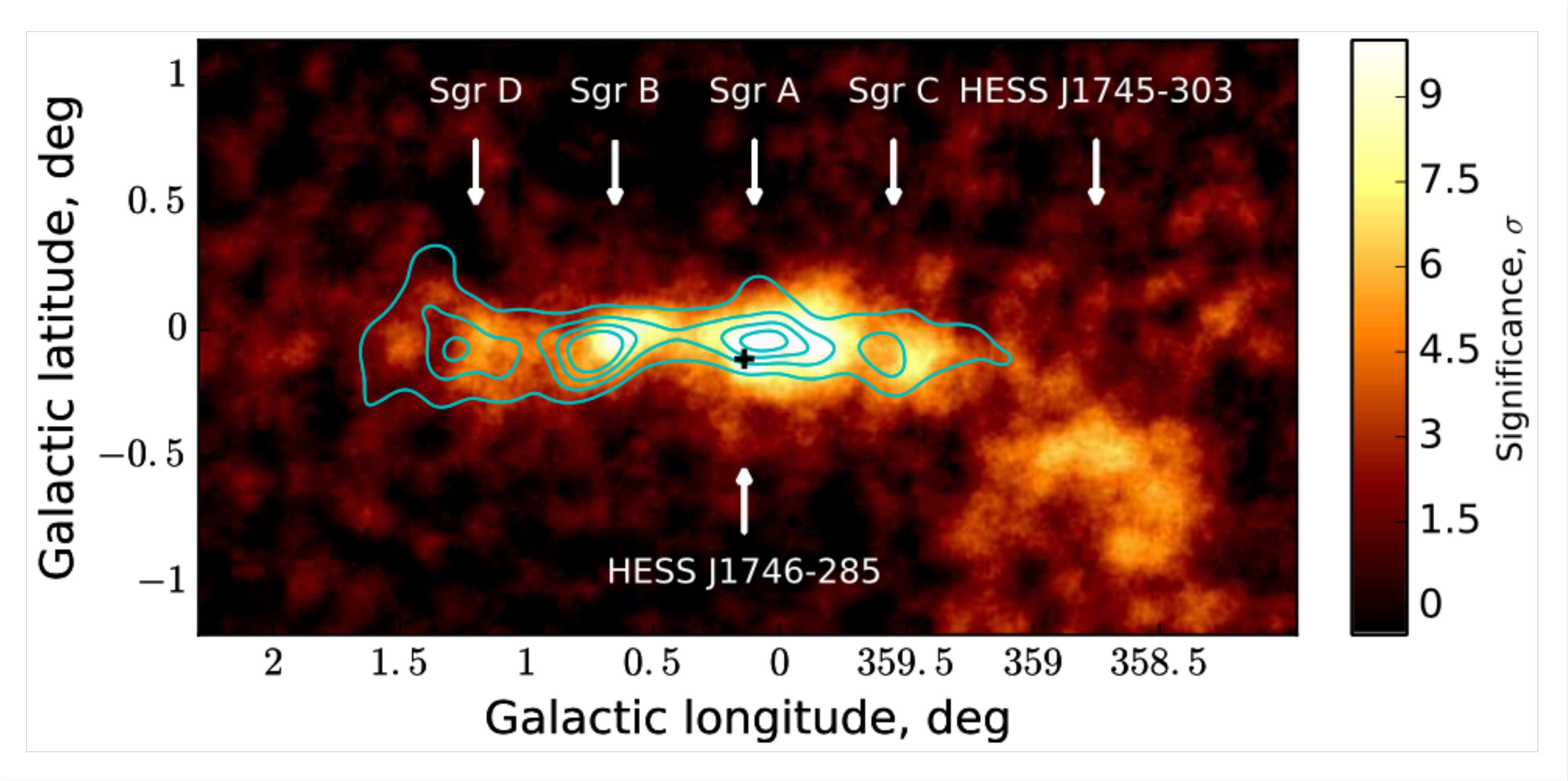


"Science with CTA" (2018)



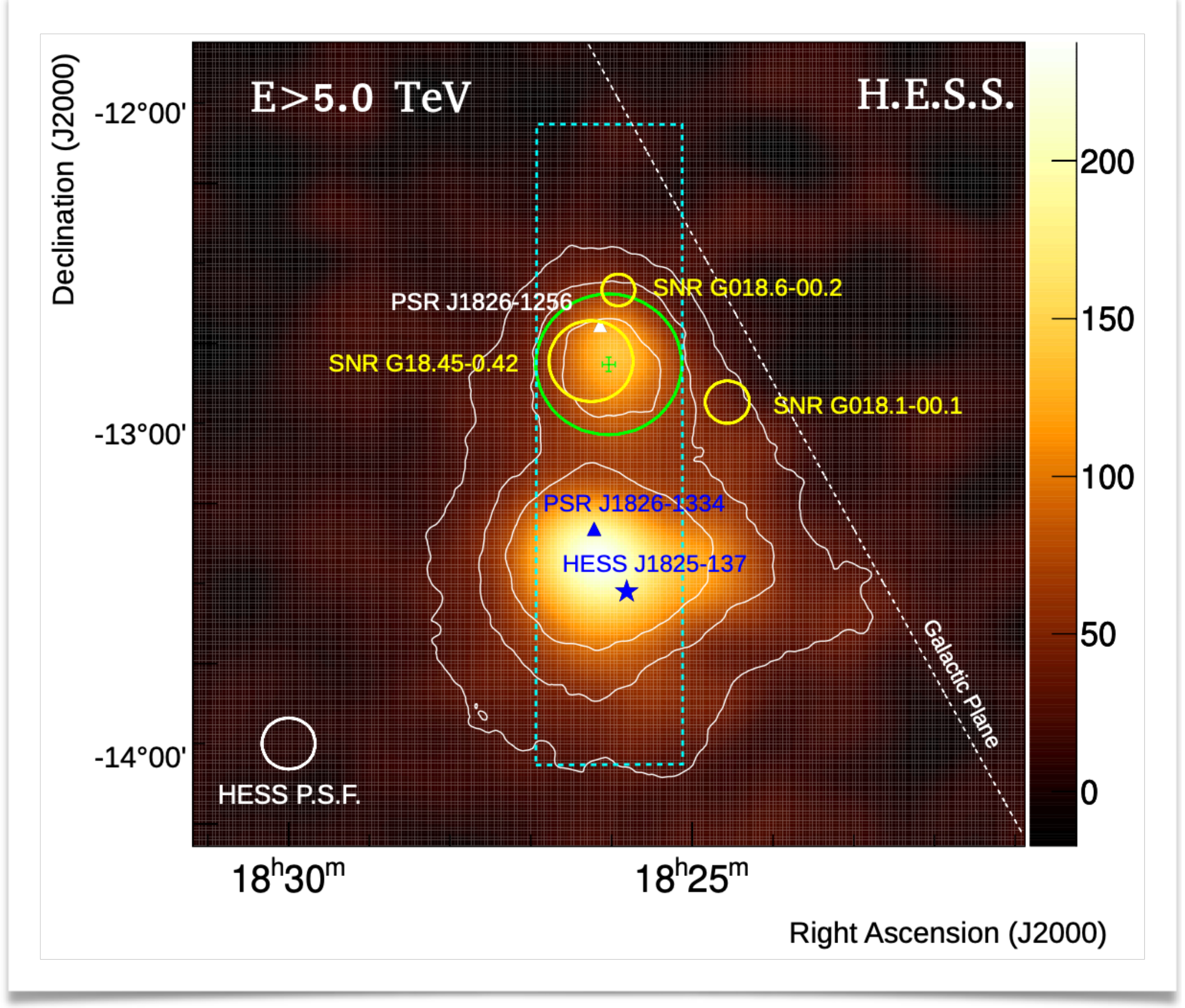
Measuring galactic γ-ray sources with IACTs: challenges

- Limited IACT field of view (typically $\sim 2^\circ$ radius)
  - galactic sources often appear extended — some very much
    → a problem for background estimation (see later)
  - diffuse γ-ray emission — an irreducible background



H.E.S.S. Collaboration, A&A 612, A9 (2018)

- Complex source structure / source confusion
  - source morphology can be complex
    - disk / Gaussian model not sufficient
    - multiple source components
  - different sources can overlap
    - need to model all relevant sources



H.E.S.S. Collaboration, A&A 644, A112 (2020)

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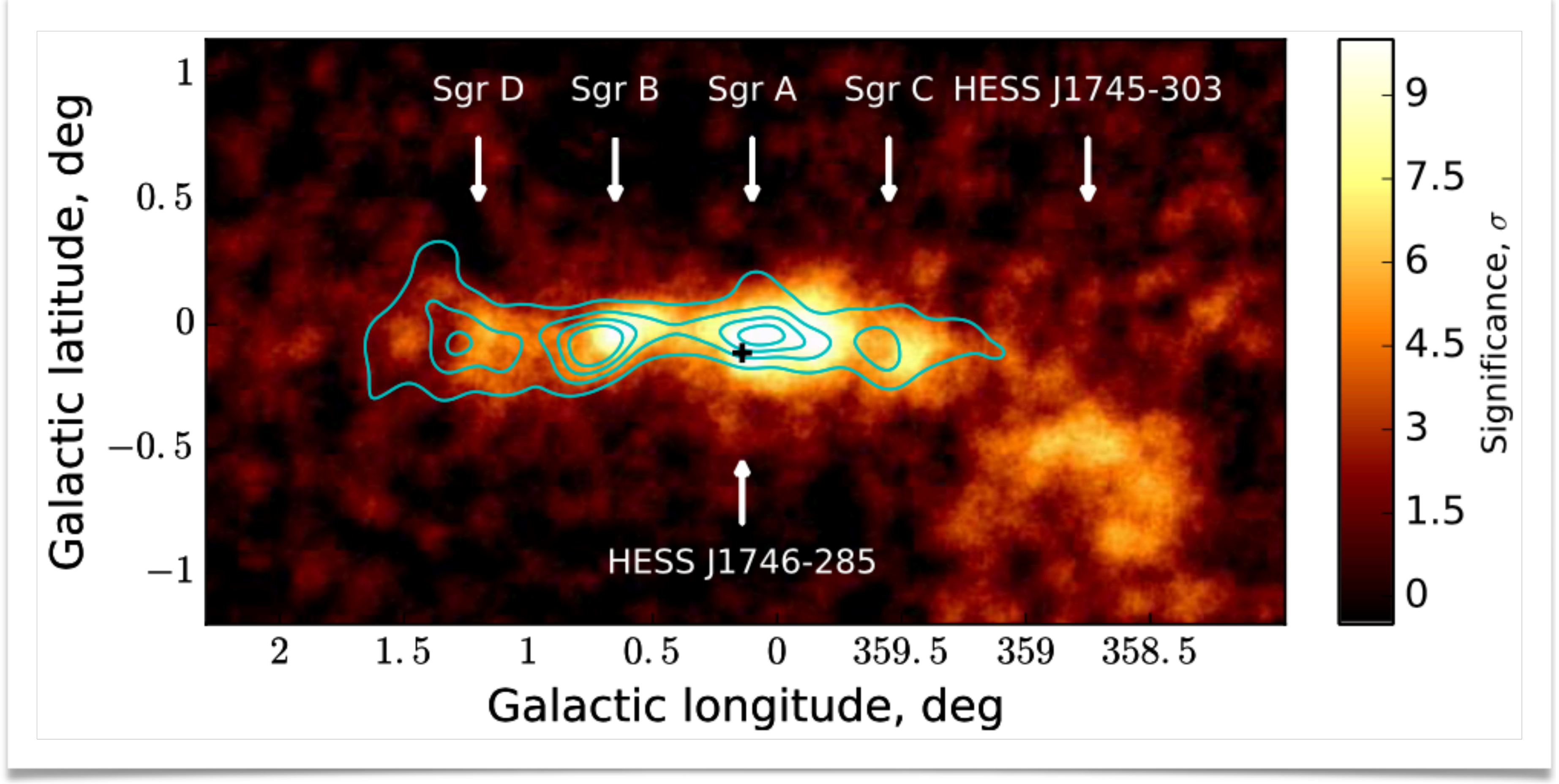

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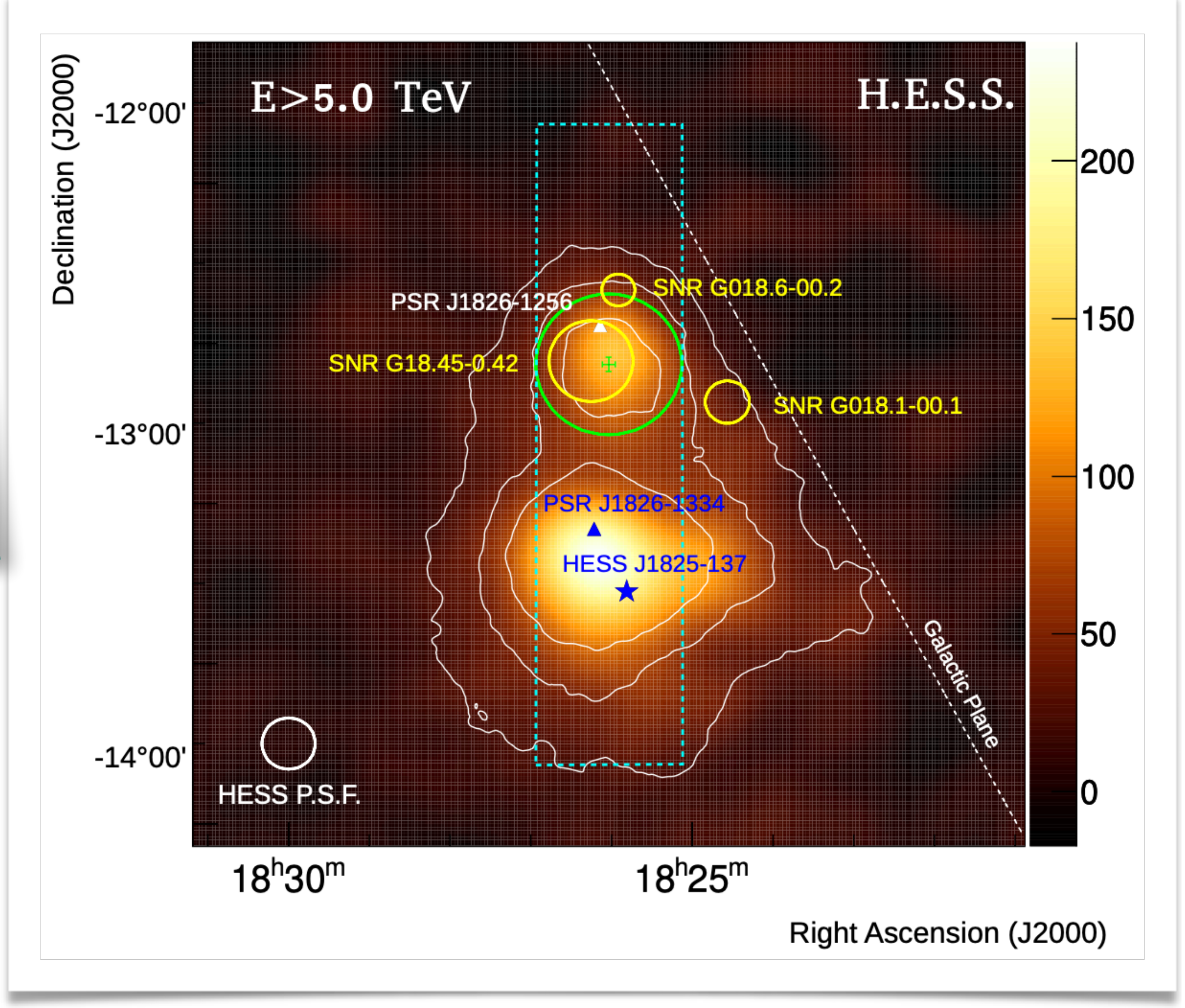
But: of all instruments,
IACTs are best equipped to tackle this!



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Measuring galactic γ-ray sources with IACTs: challenges

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    → a problem for background ...
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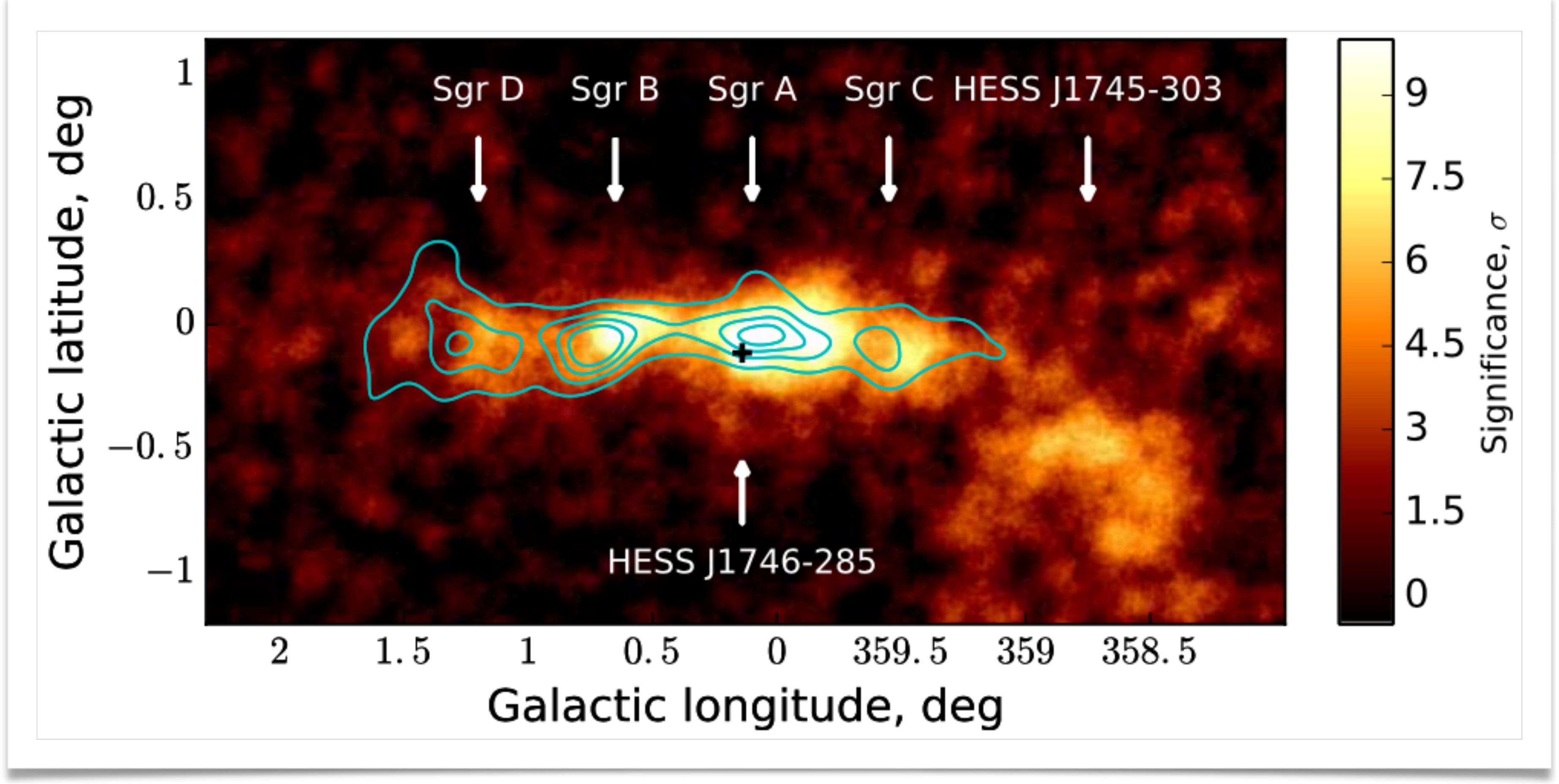
CTA telescopes will have significantly larger fields of view



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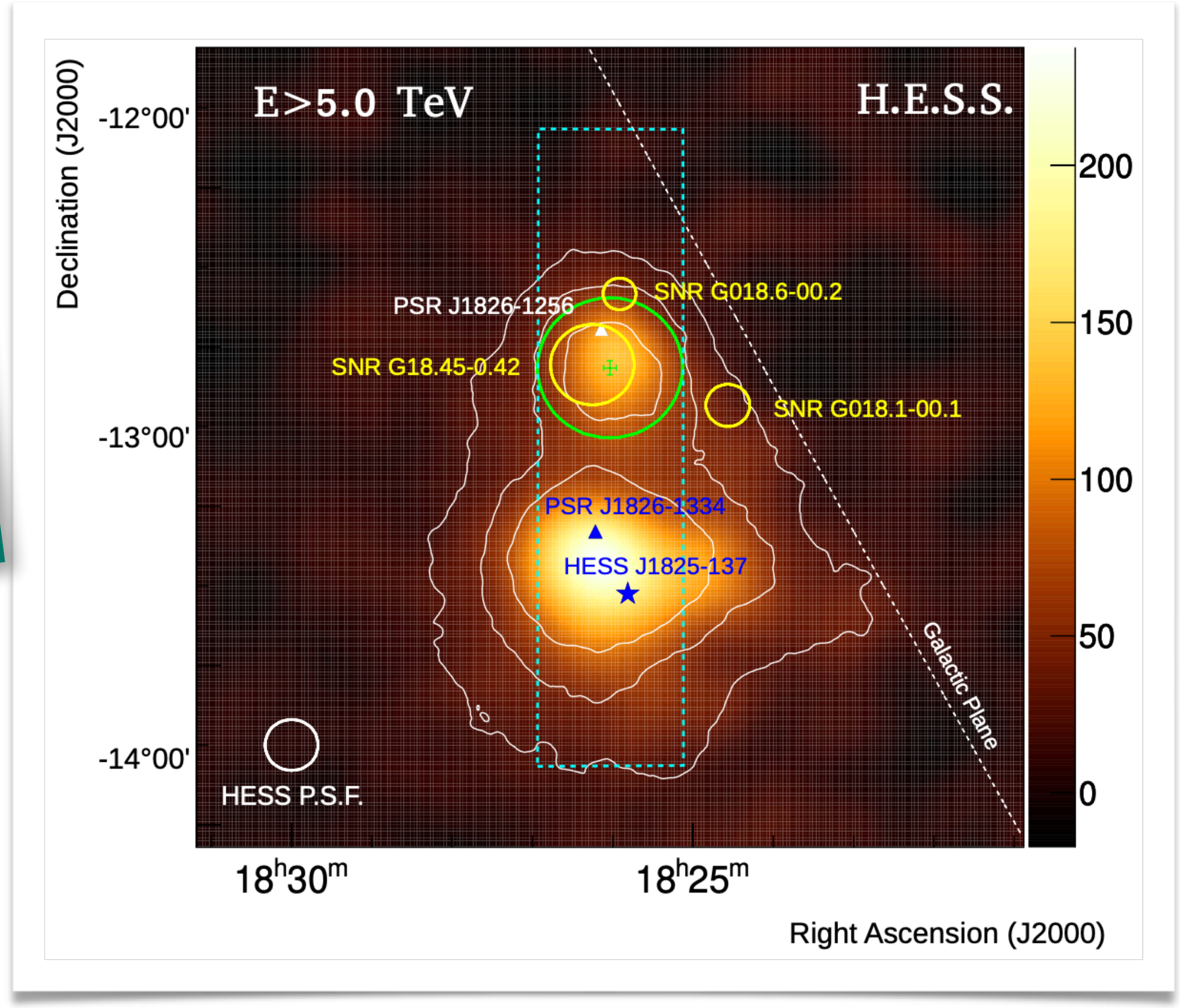
But: of all instruments, IACTs are best equipped to tackle this!

CTA will provide even better angular resolution



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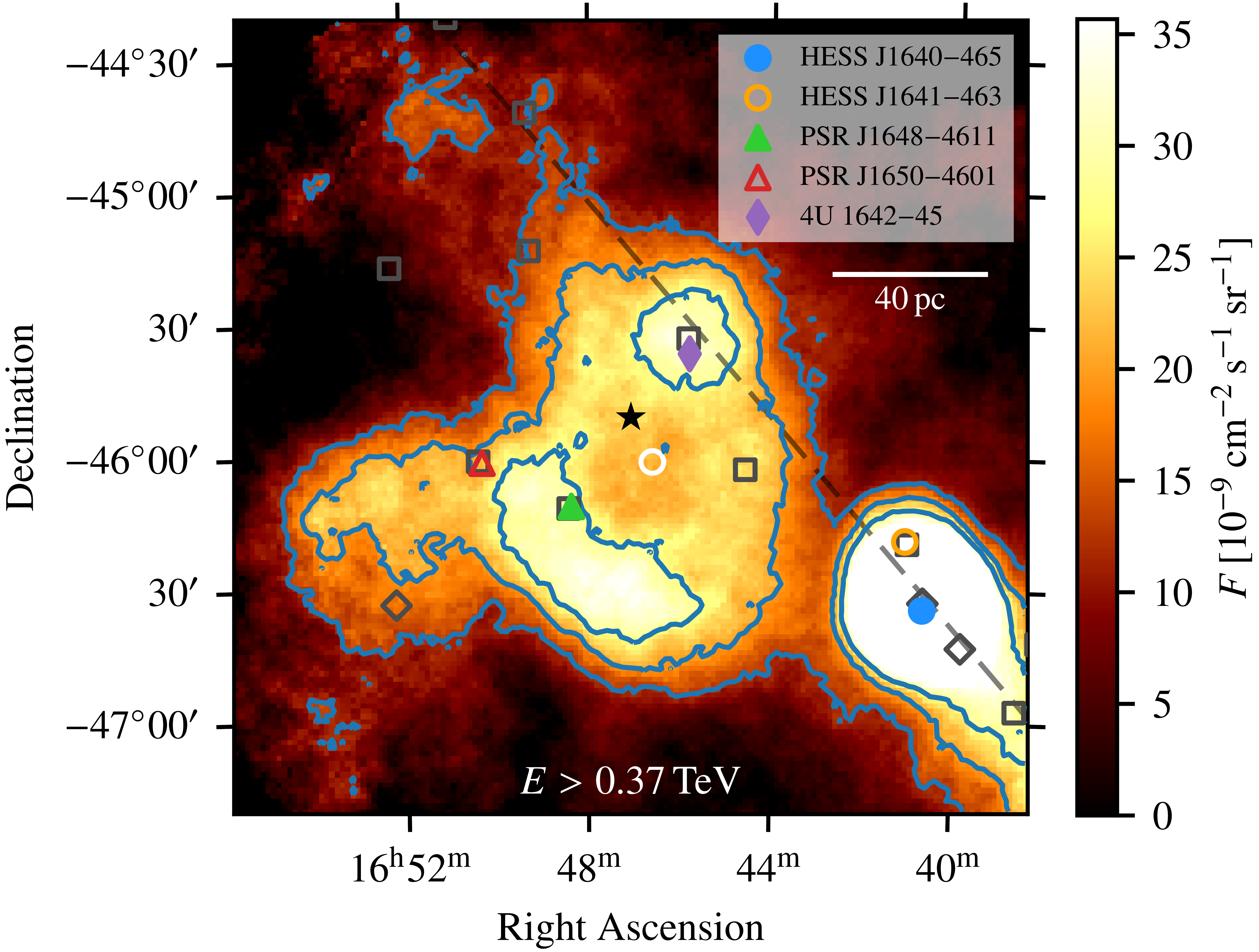
Westerlund 1

H.E.S.S. Collaboration, A&A accepted (2022)
arXiv:2207.10921

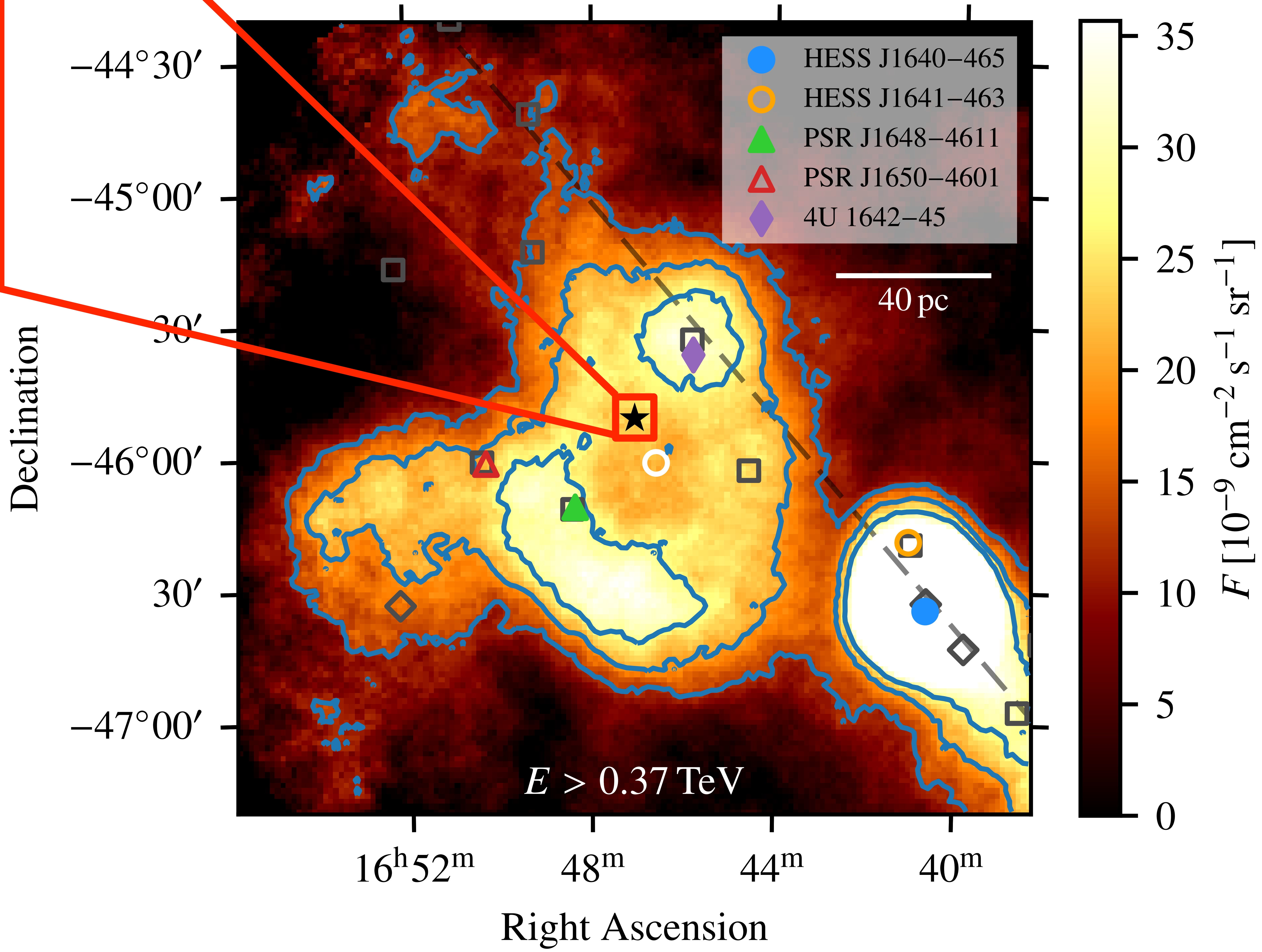


Westerlund 1

H.E.S.S. Collaboration, A&A accepted (2022) arXiv:2207.10921

Credit: ESO

- Westerlund 1
  - massive young stellar cluster
  - $M \sim 10^5\,M_\odot$
  - half-mass radius: 1 pc



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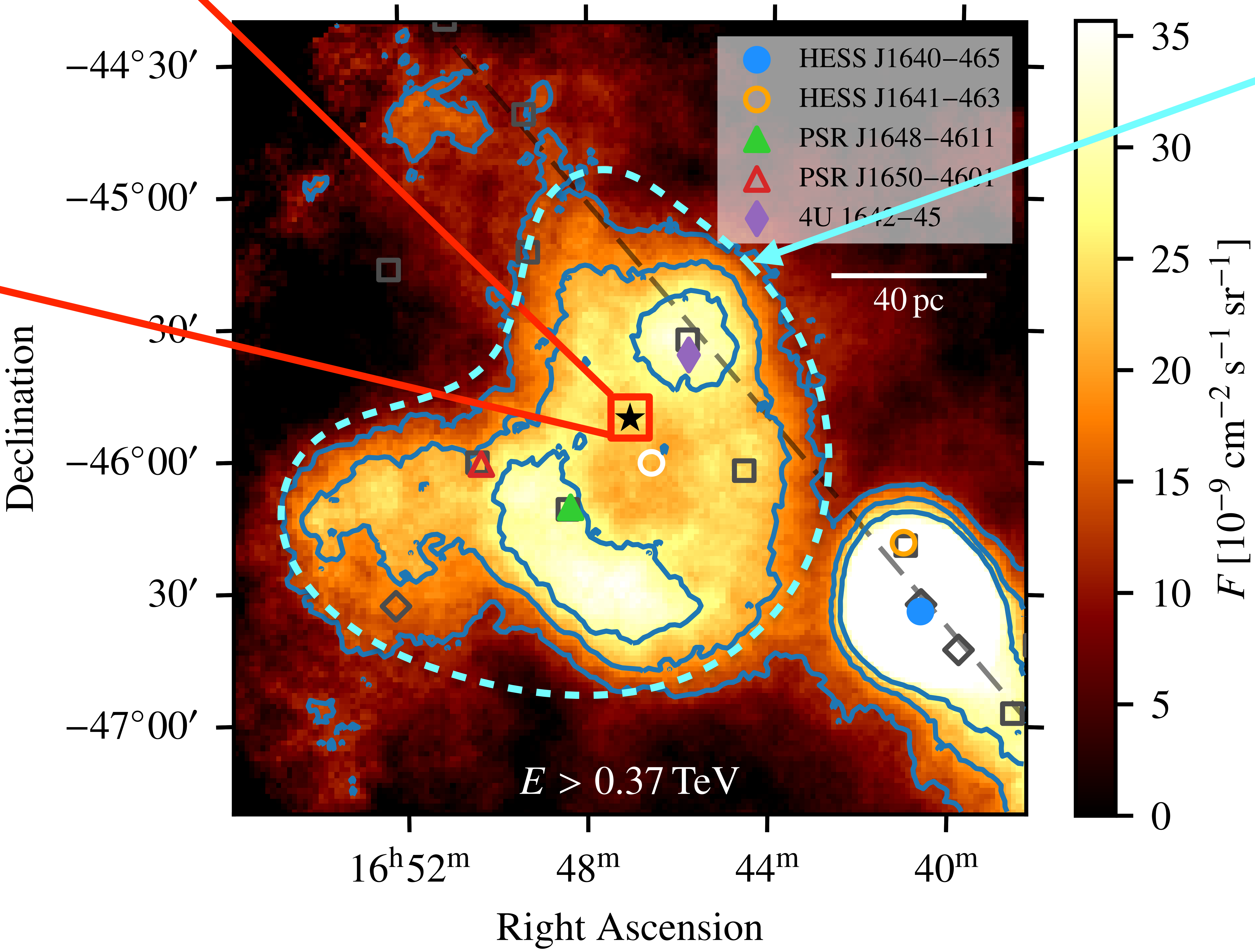

- HESS J1646–458
  - largely extended γ-ray source
  - diameter $\sim 2^\circ$ (140 pc)
  - very likely associated with Westerlund 1

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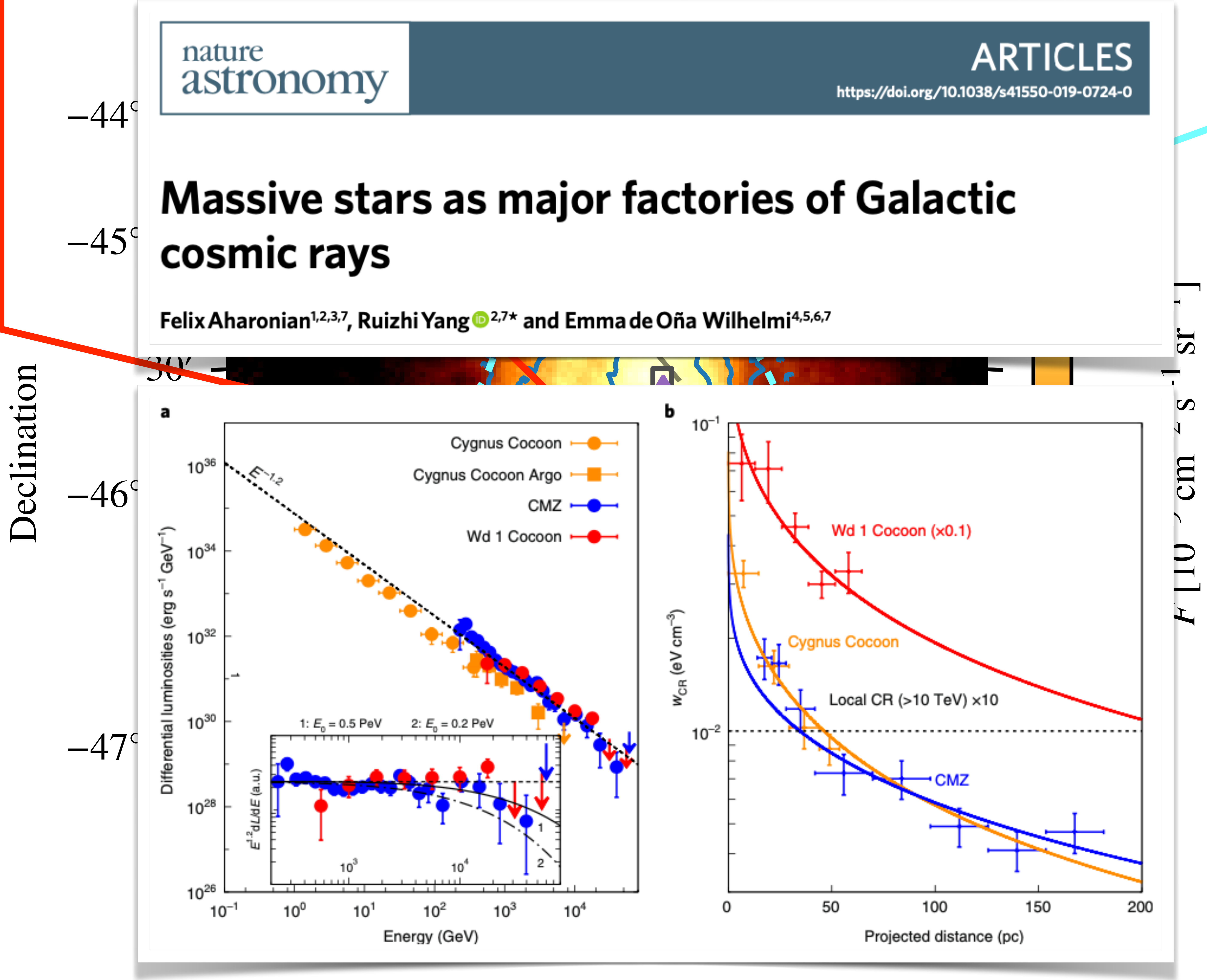


nature astronomy
ARTICLES
https://doi.org/10.1038/s41550-019-0724-0

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]

- Westerlund 1
  - massive young stellar cluster
  - $M \sim 10^5\,M_\odot$
  - half-mass radius: $1\,\mathrm{pc}$

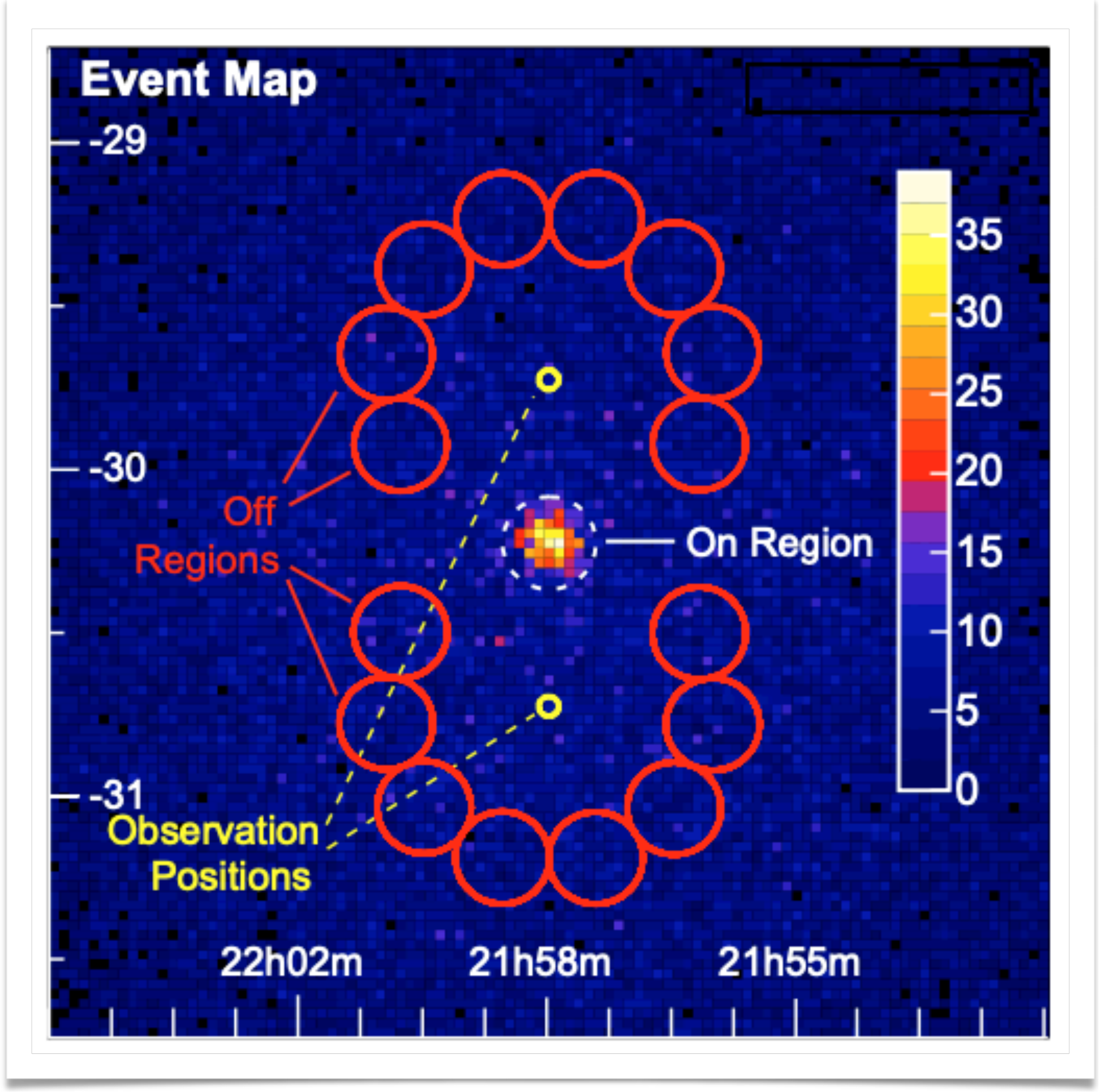
- HESS J1646–458
  - largely extended γ-ray source
  - diameter $\sim 2^\circ$ ($140\,\mathrm{pc}$)
  - very likely associated with Westerlund 1

also see talk by G. Morlino on Tuesday!

Aharonian et al., Nature Astronomy 3, 561 (2019)

Excursion: 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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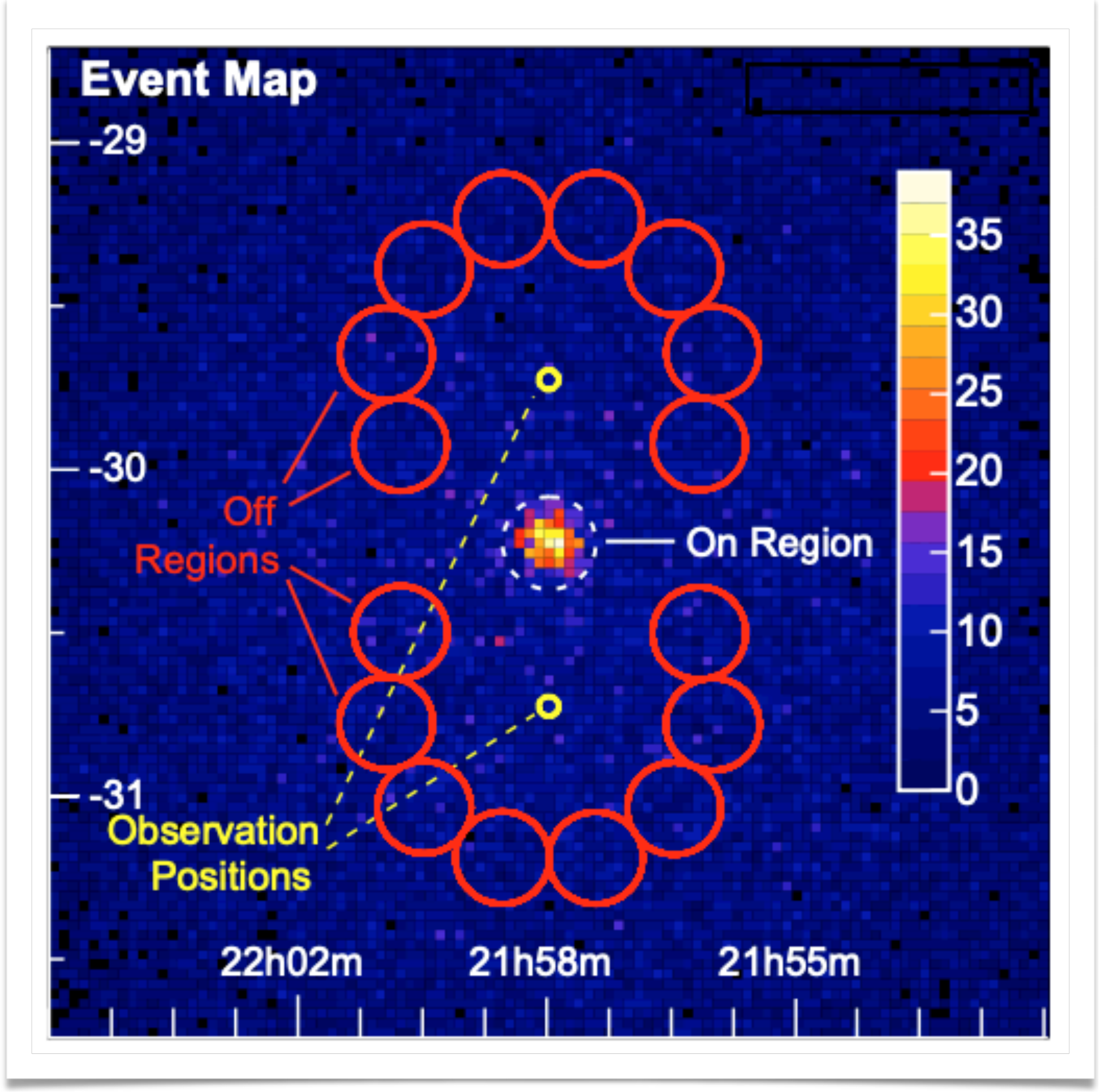

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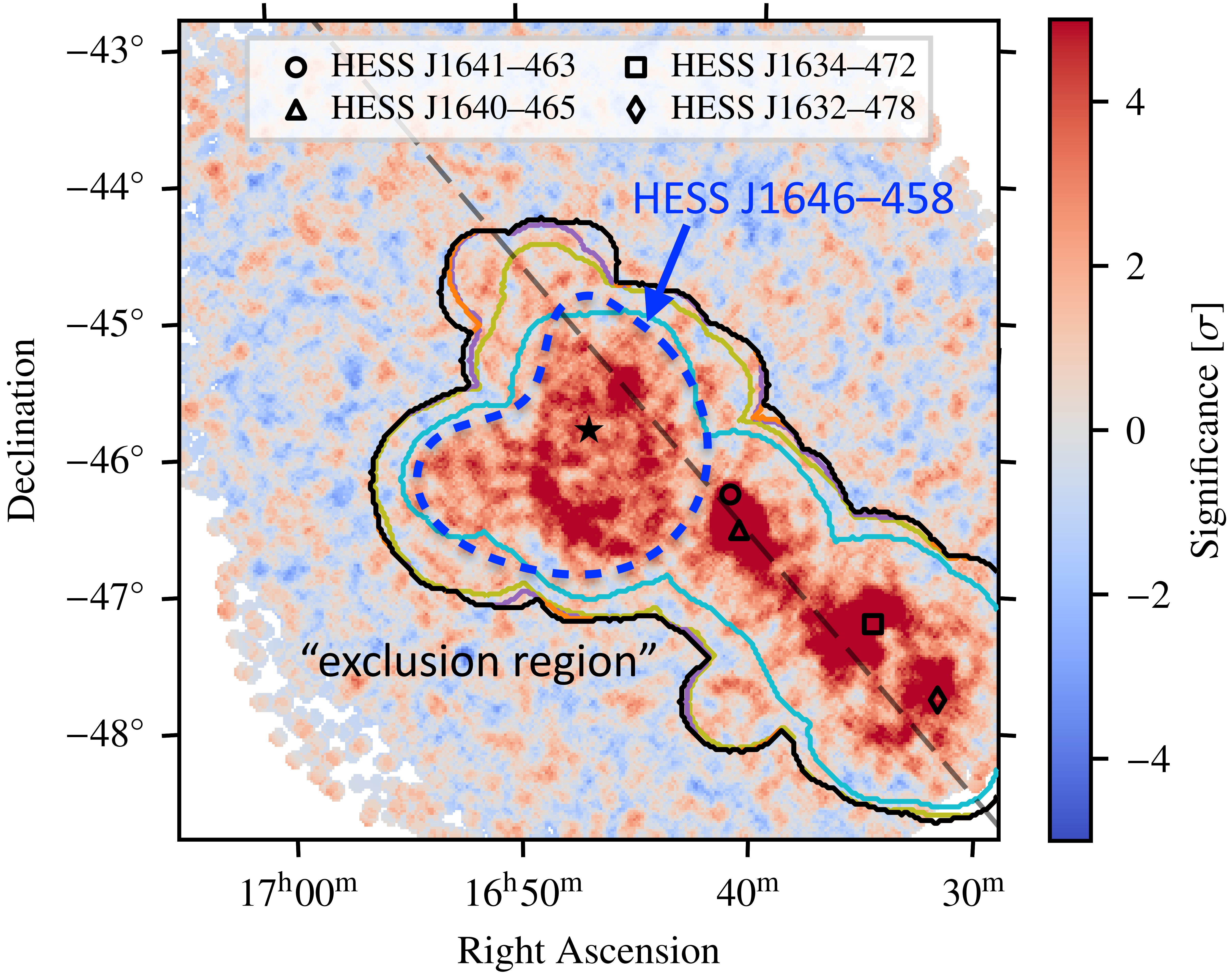
Significance map



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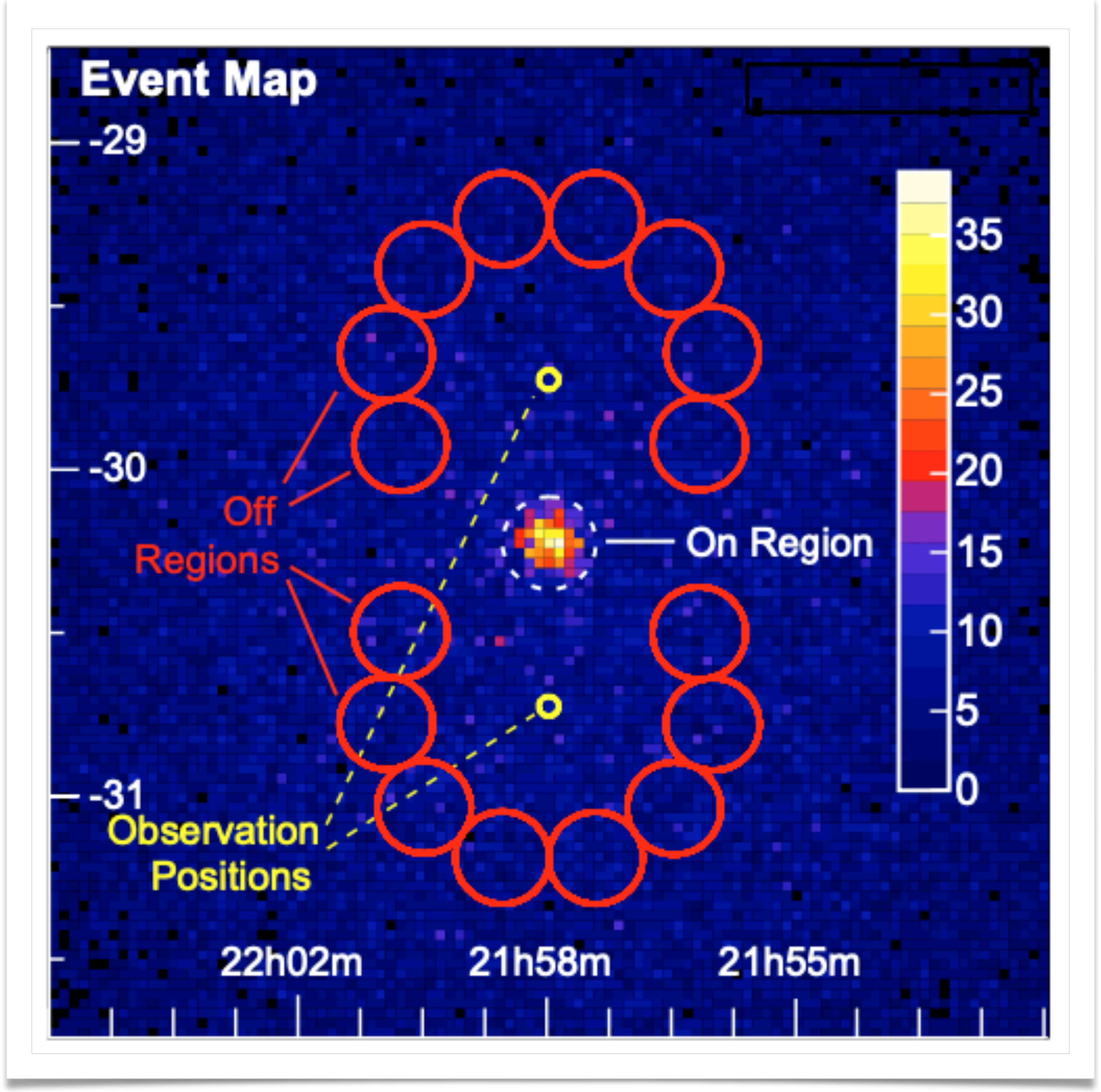

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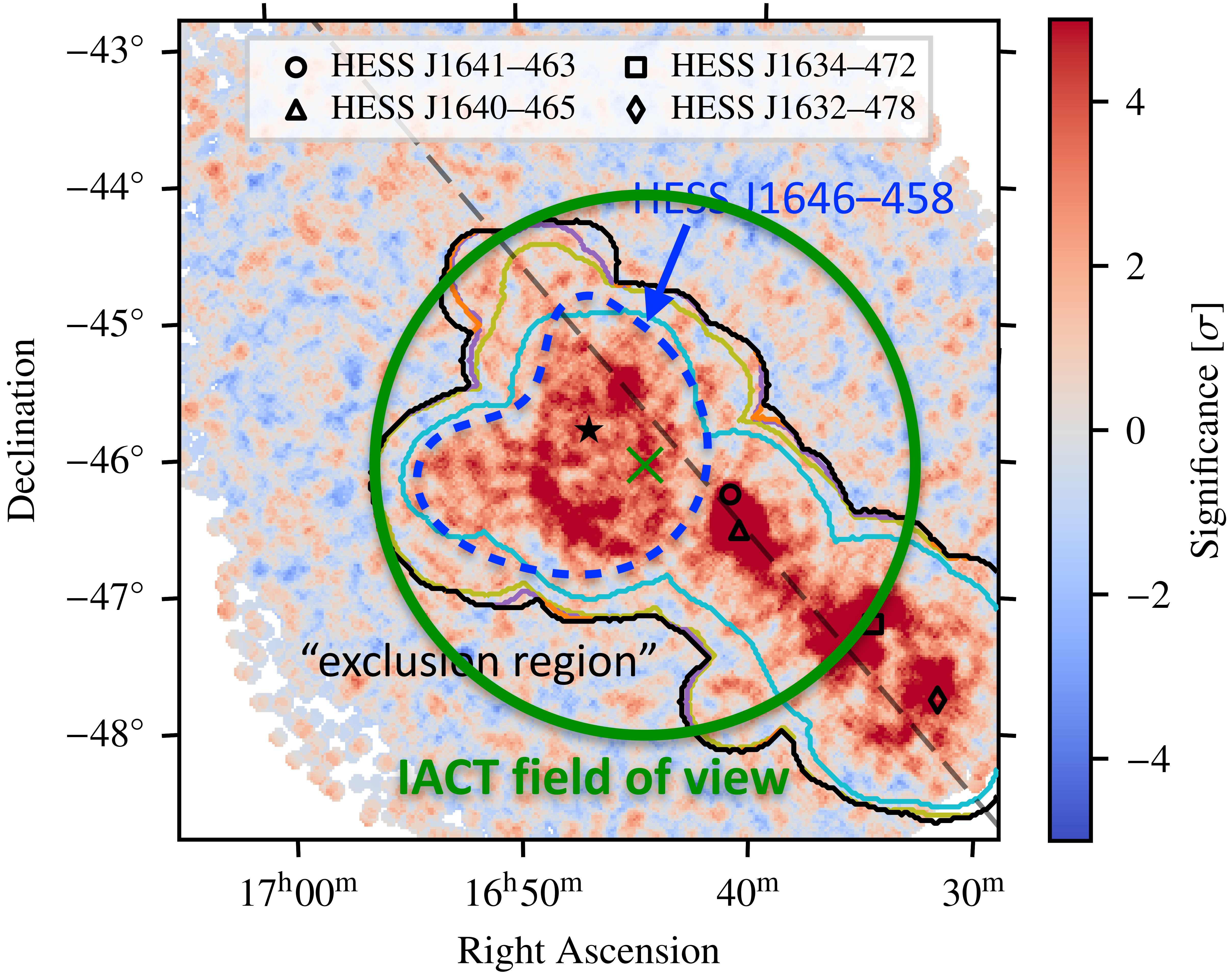

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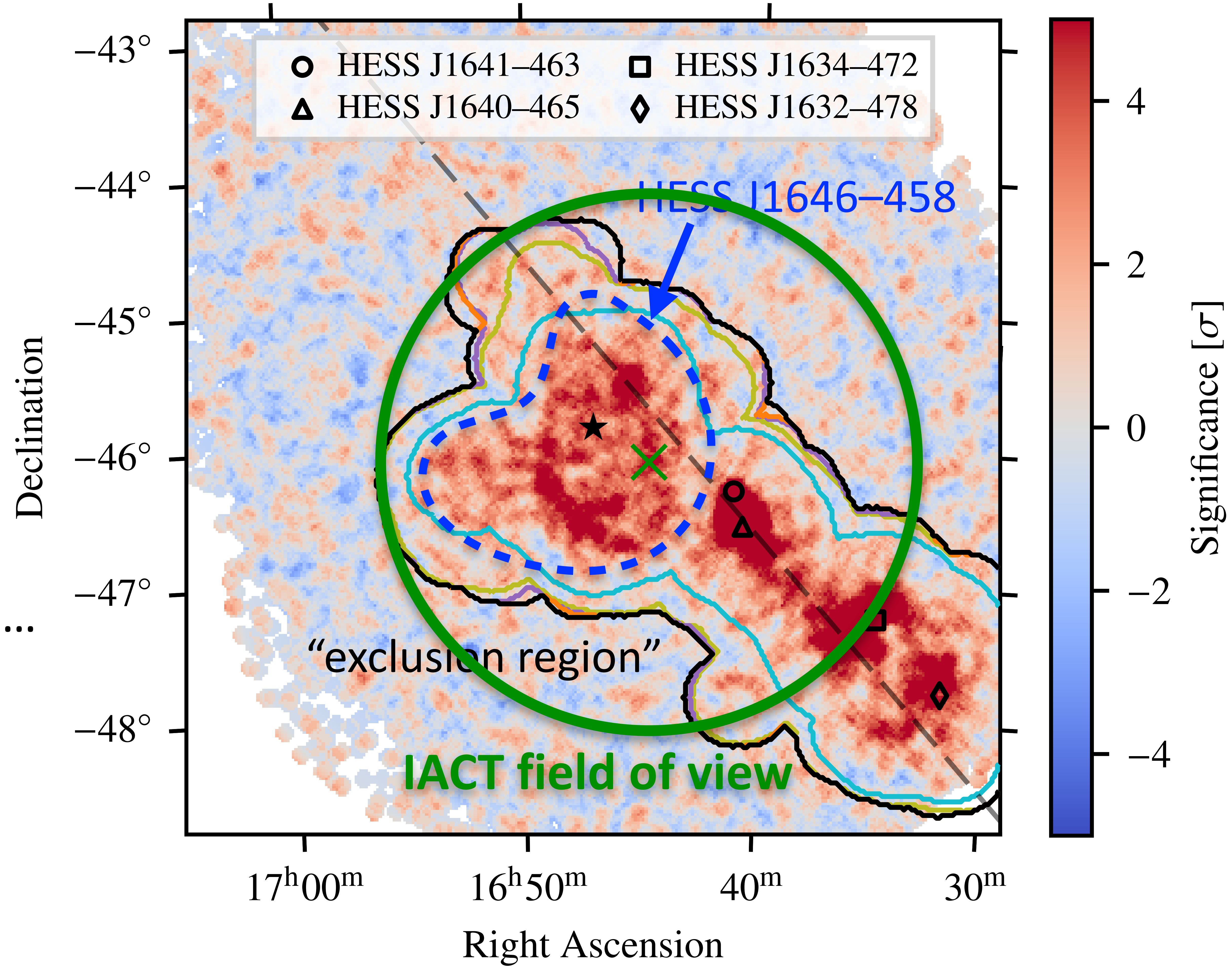
- Background model
  - derived from archival observations
  - ***challenge:*** need to match (or correct for) observation conditions
    - zenith angle, optical throughput, atmospheric conditions…
  - very relevant for CTA!

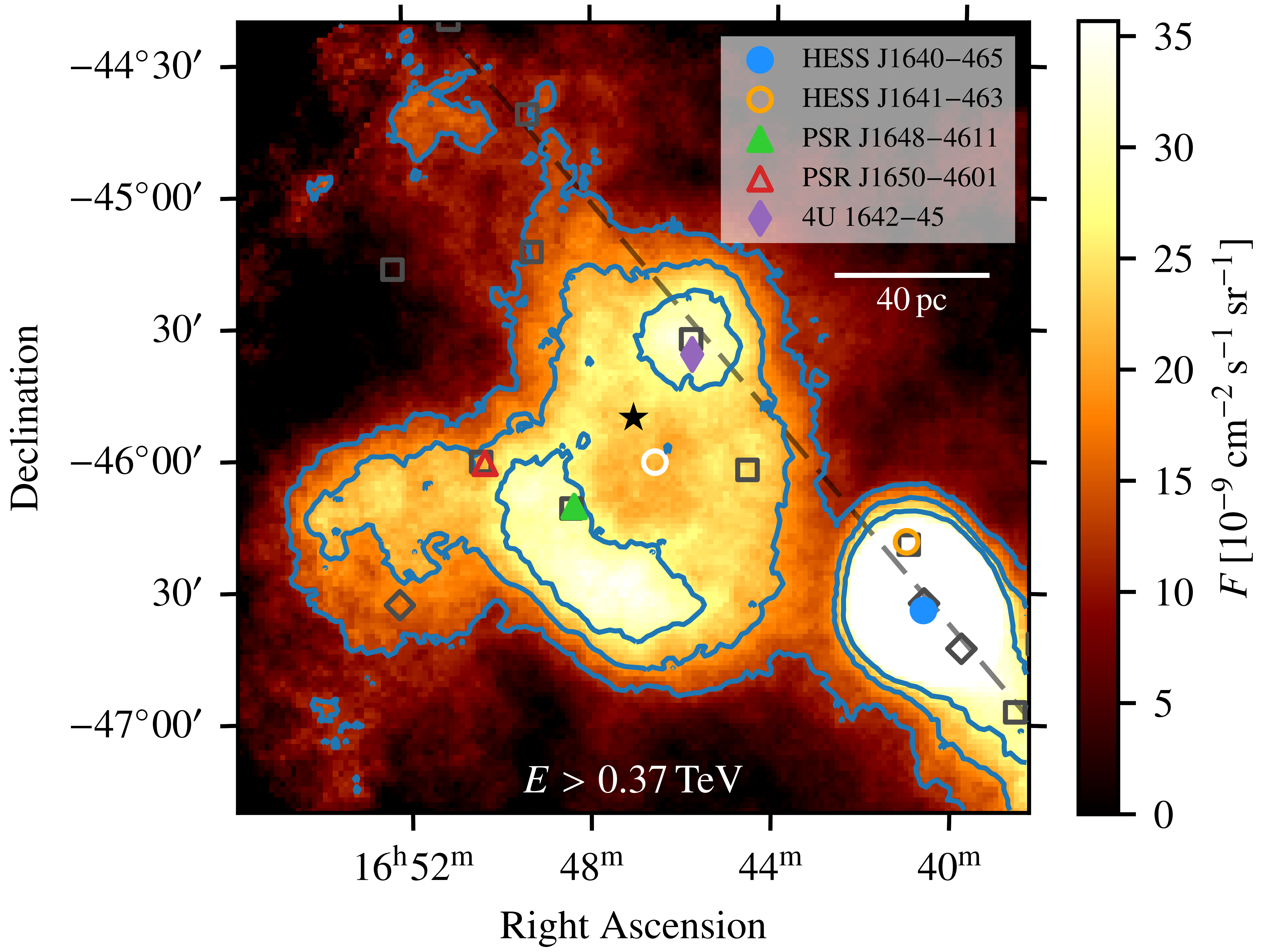
  - Details: ***Mohrmann et al., A&A 632, A72 (2019)***

Significance map



Source morphology

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



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  - bright spots remain
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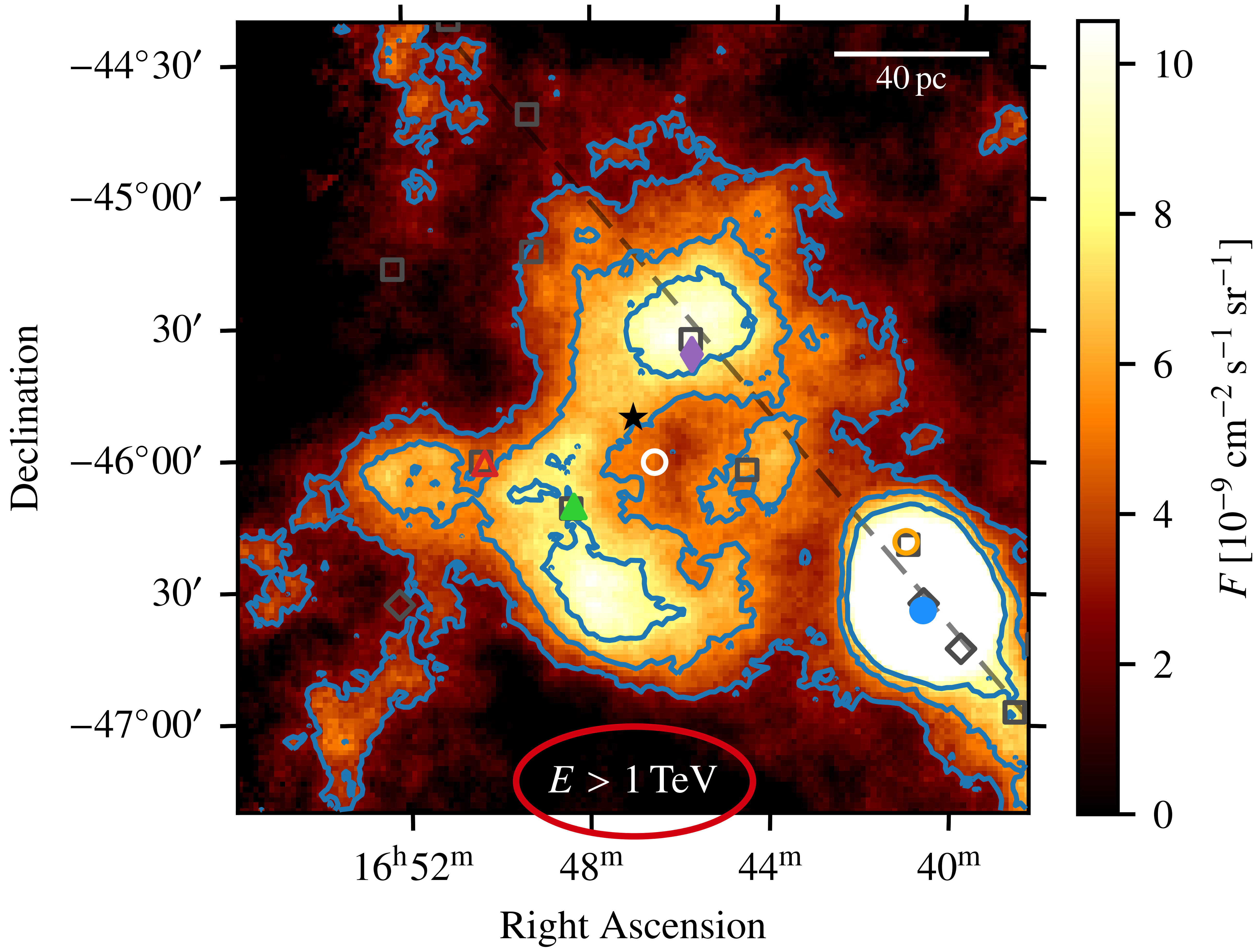

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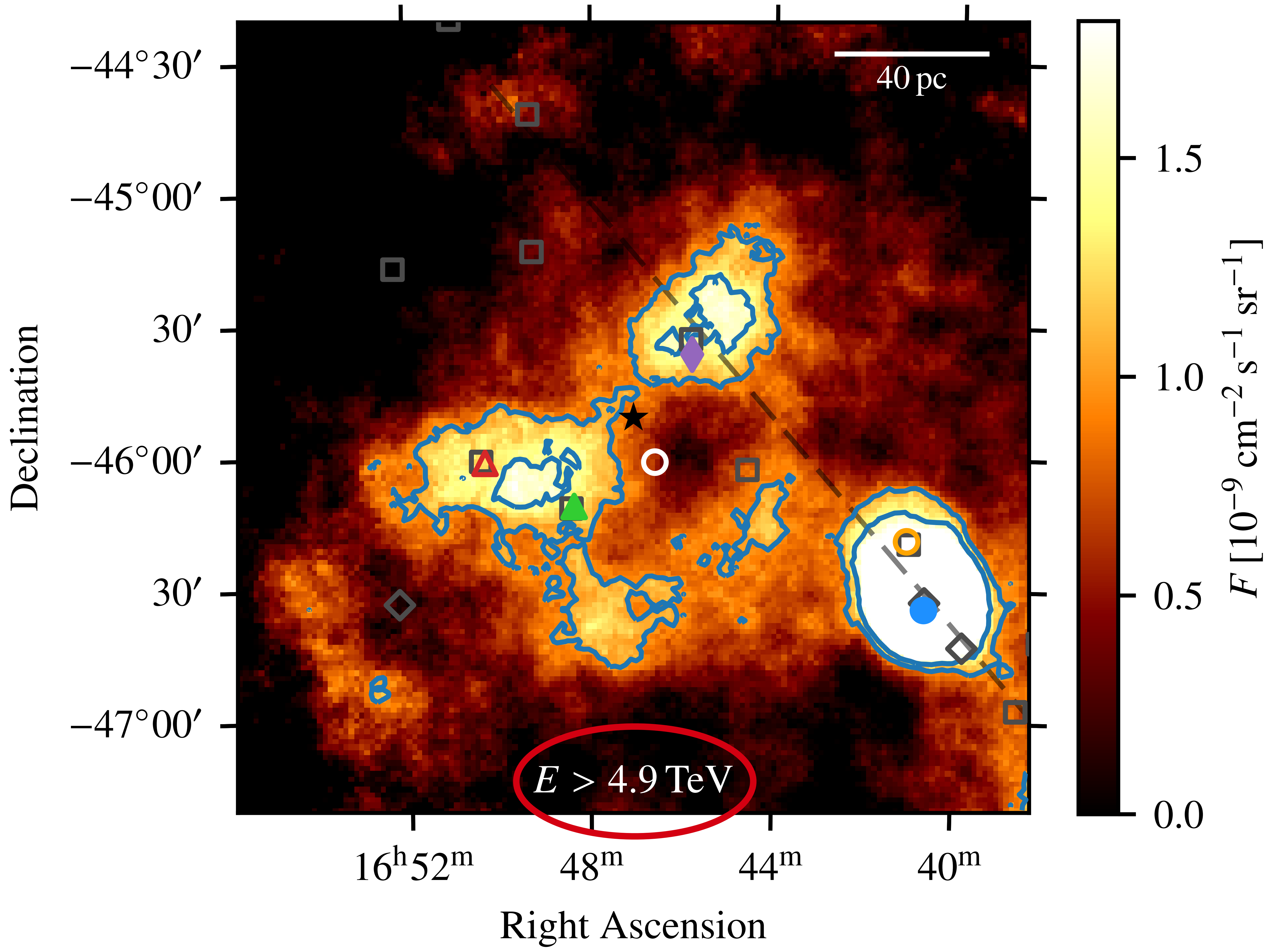

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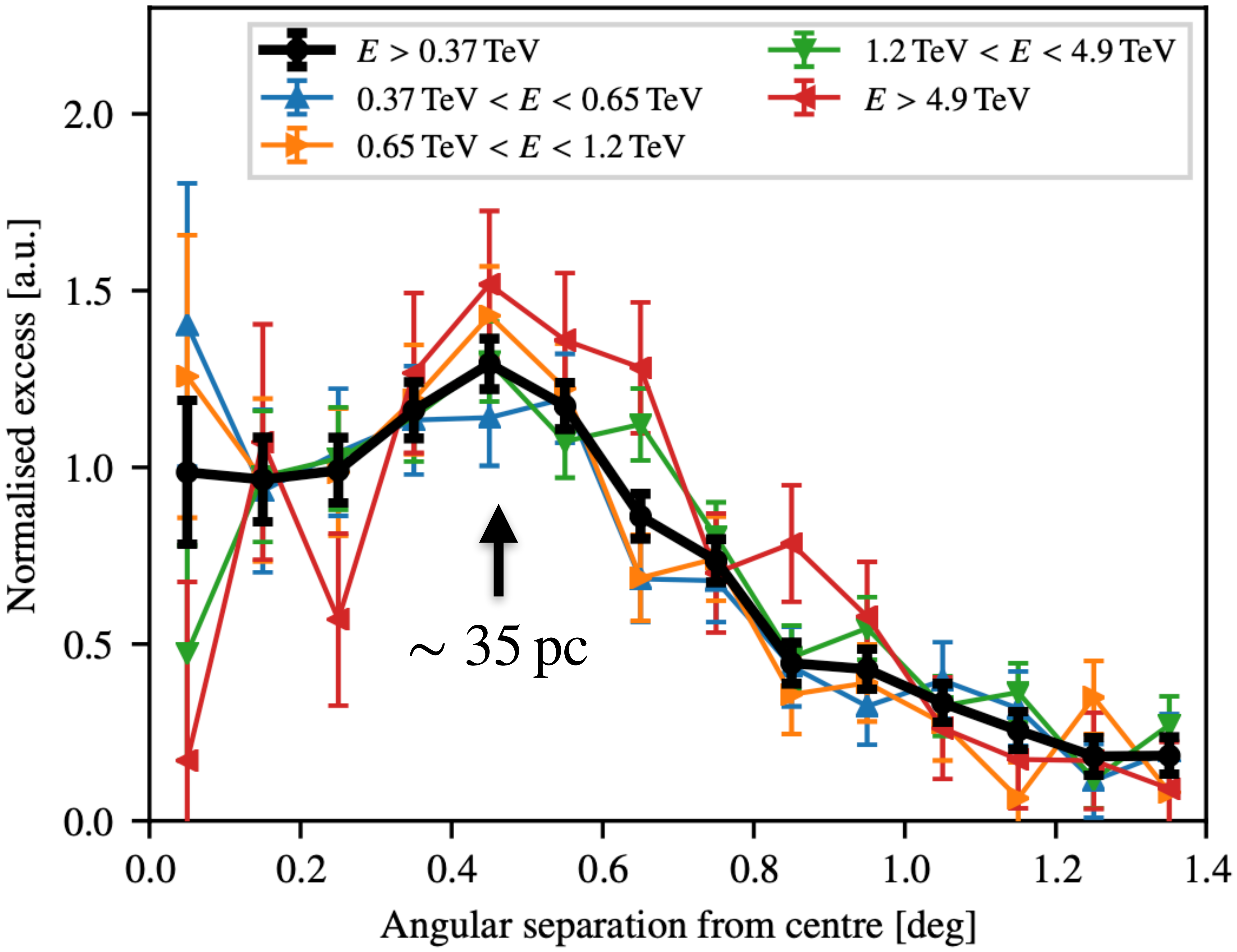
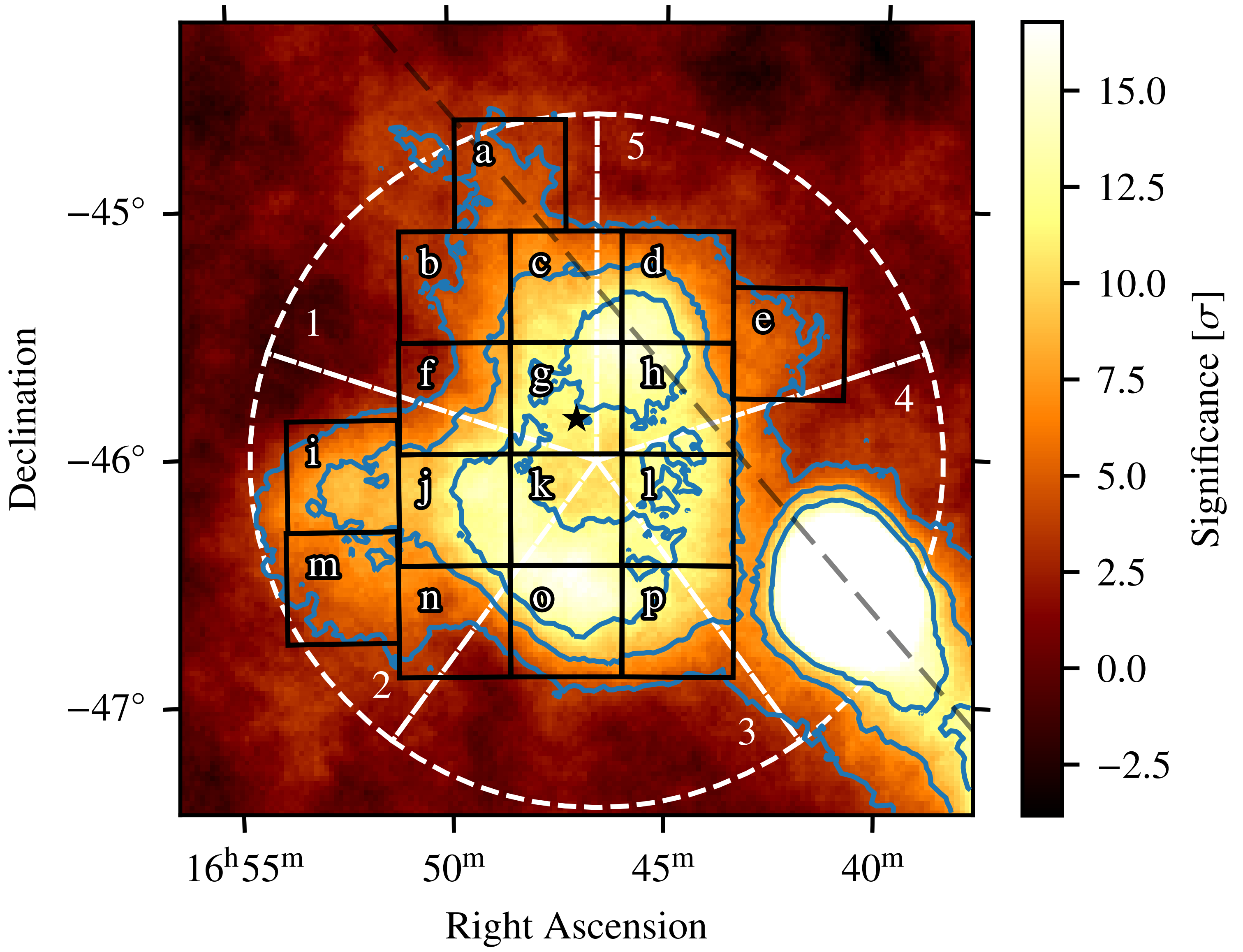
  - ***shell-like structure persists!***
- Confirmed by radial excess profiles
  - profiles for different energy bands well compatible

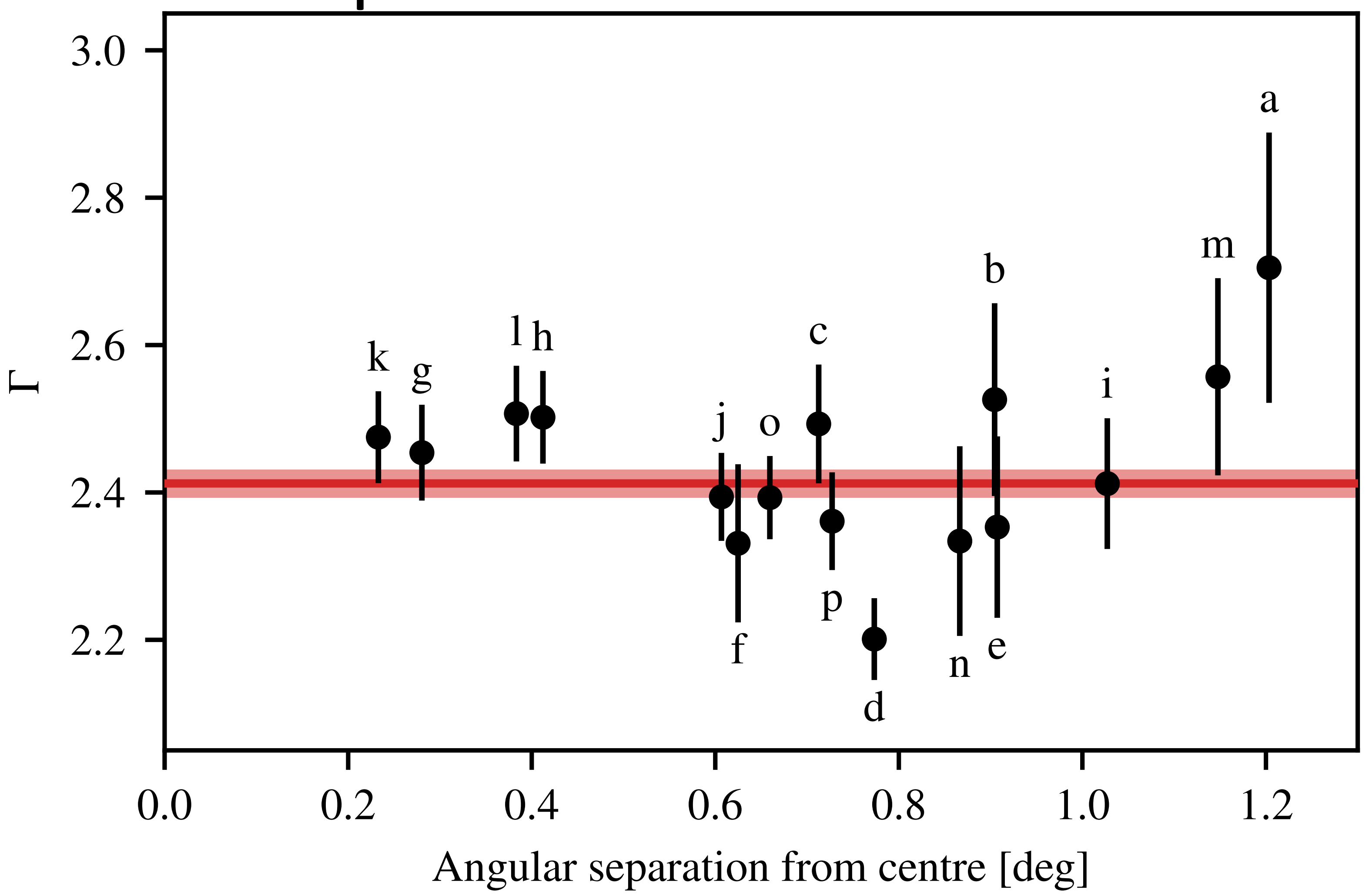


Energy spectrum

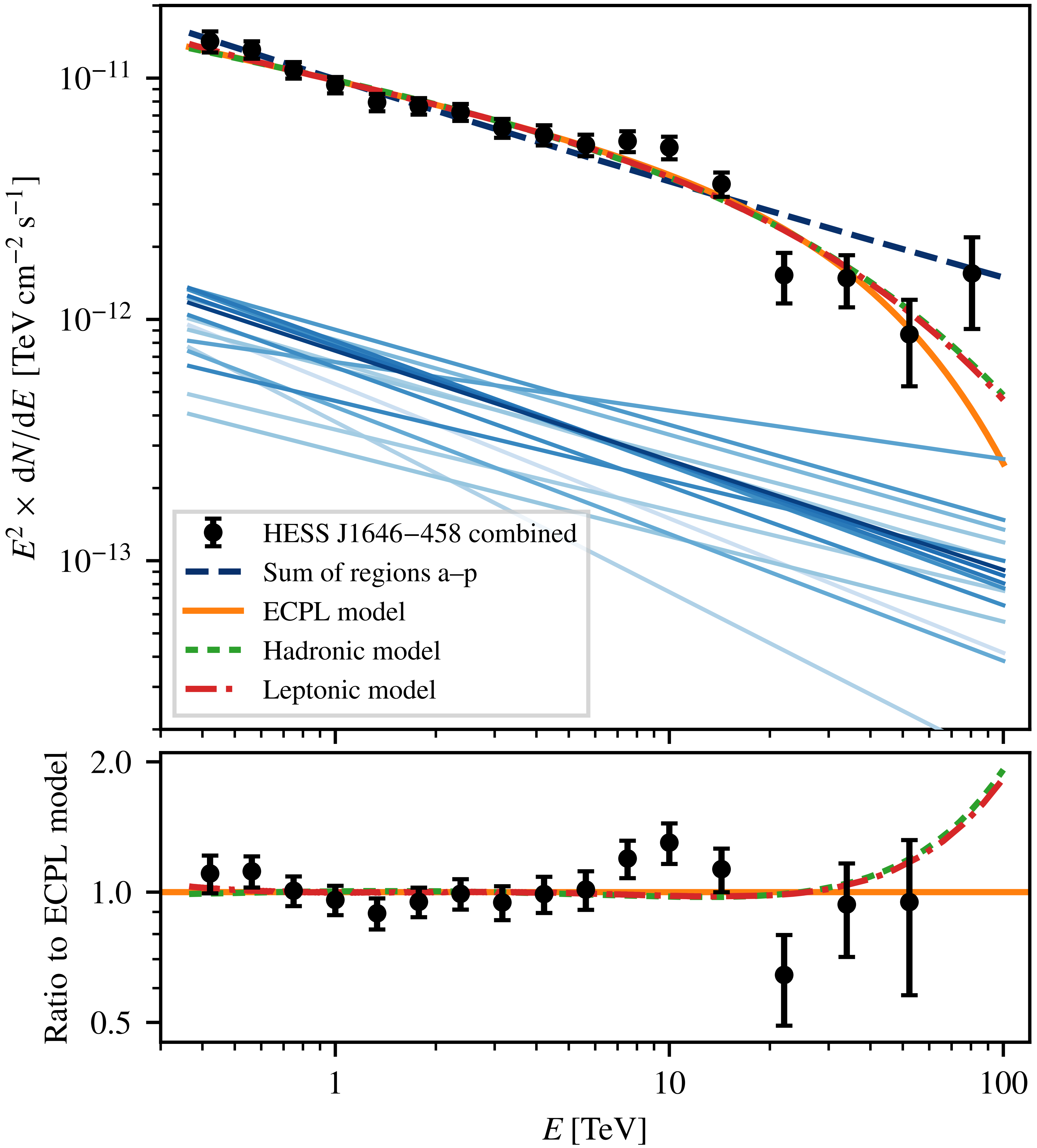
- Energy spectrum
  - extracted in 16 signal regions
  - individual spectra remarkably similar
  - add up region spectra → combined spectrum
  - ***extends to several ten TeV!***
  - $\Gamma = 2.30 \pm 0.04$, $E_c = \left(44^{+17}_{-11}\right)$ TeV



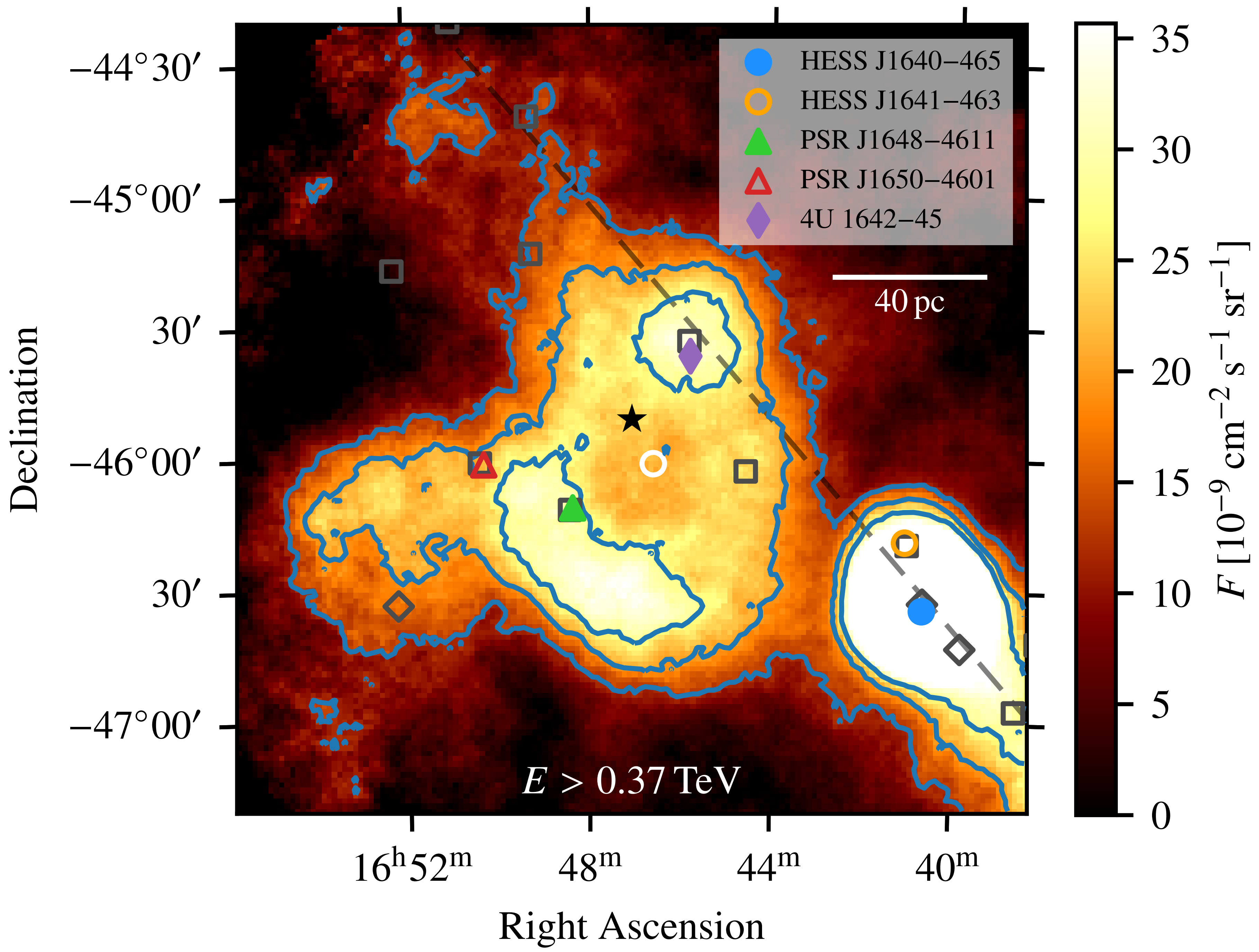
spectral index vs. distance



combined spectrum



Interpretation



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  - only Westerlund 1 can explain majority of emission
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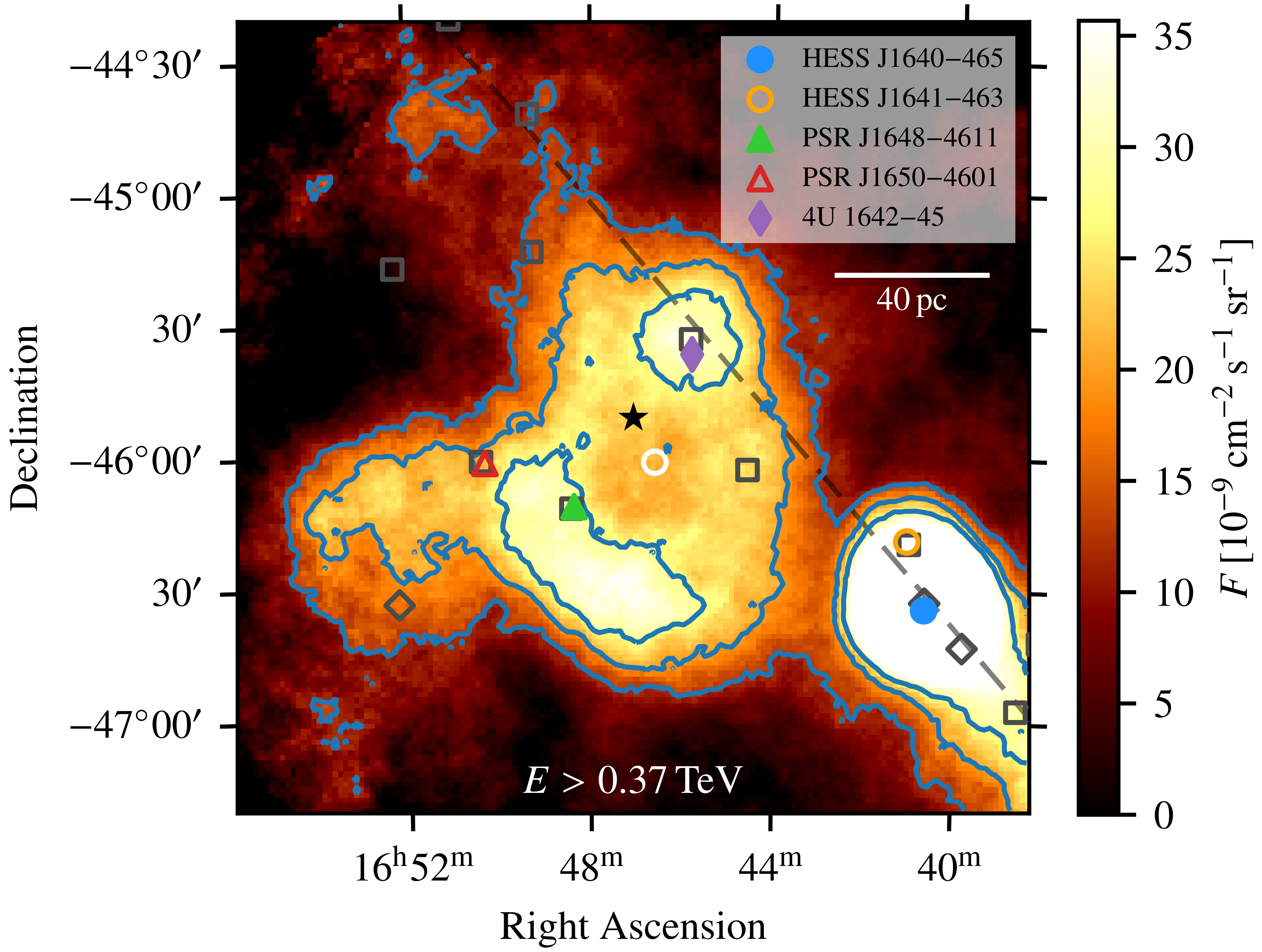
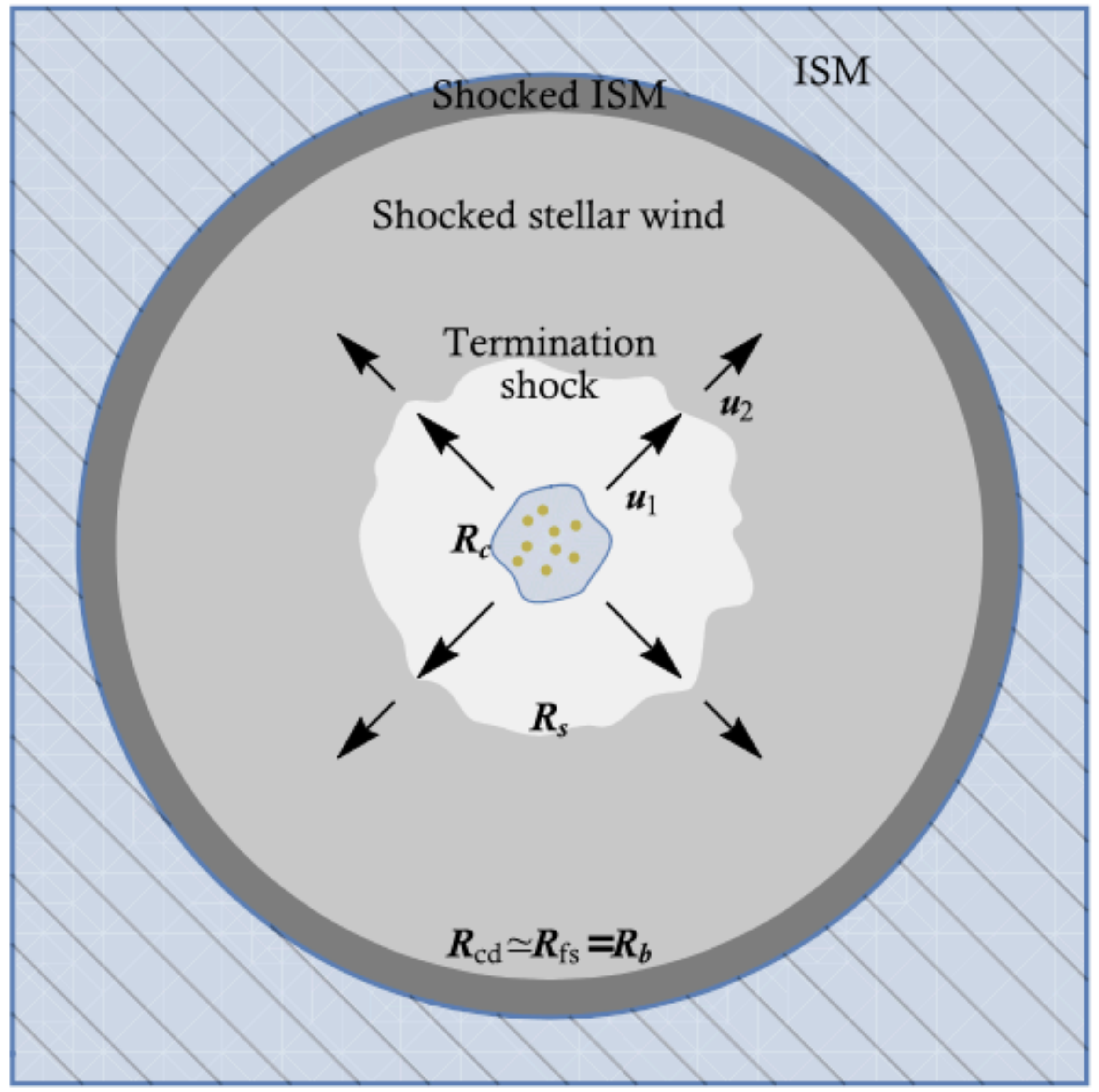
- Acceleration site?
  - within the cluster (wind-wind or wind-SN interactions)
  - collective cluster wind / superbubble
    - MHD turbulences in superbubble
    - cluster wind termination shock





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

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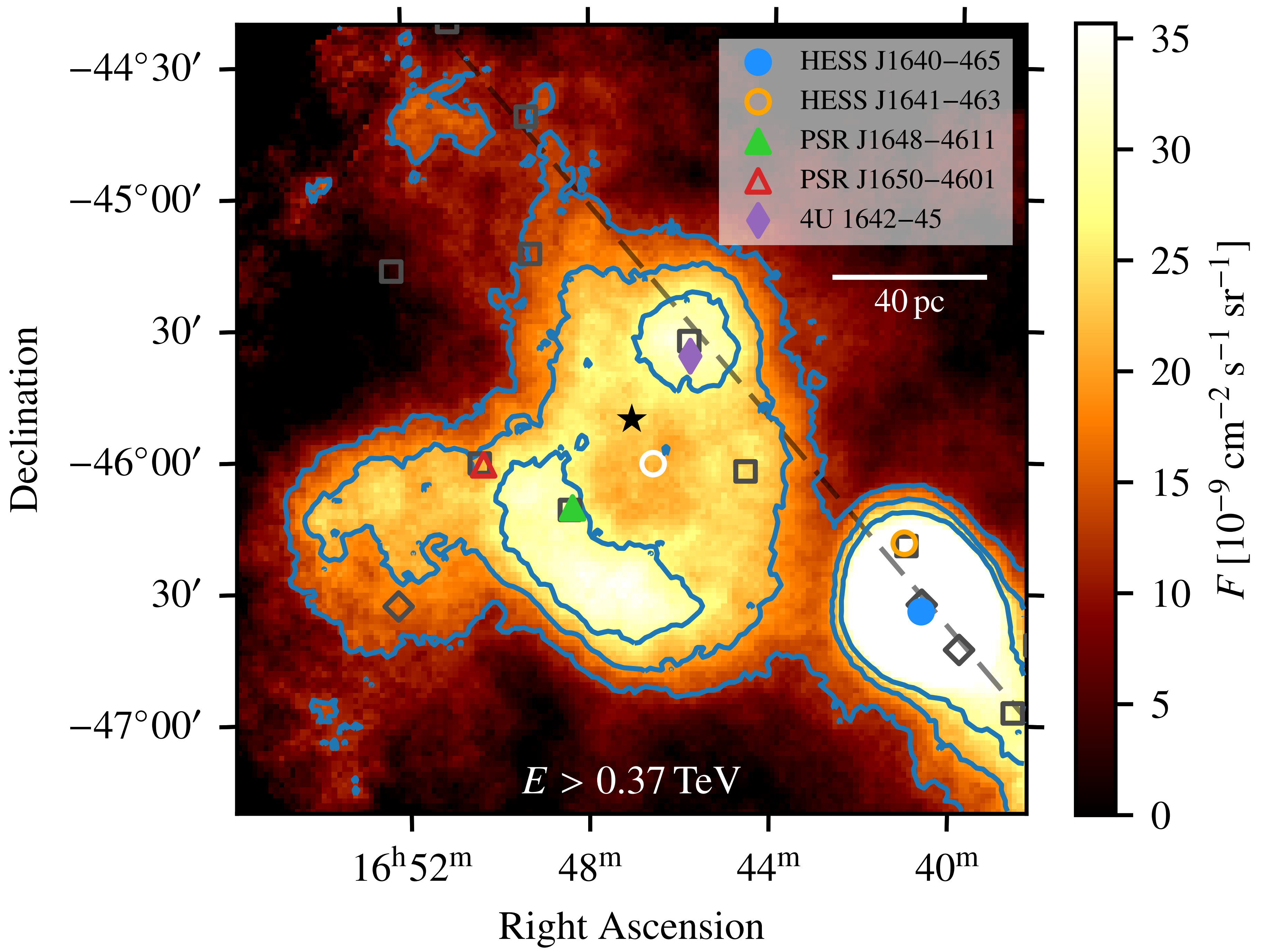
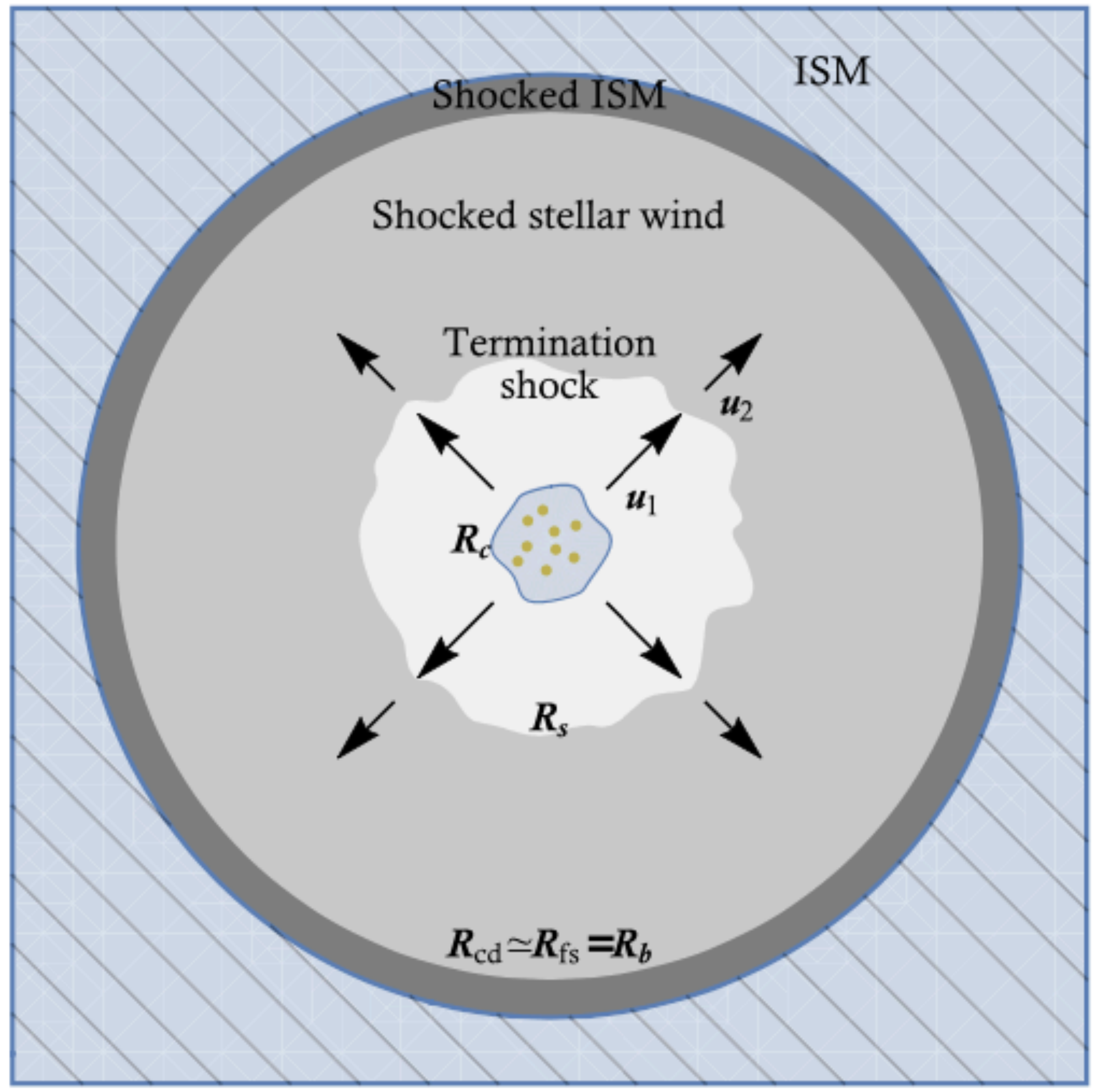
    - ***cluster wind termination shock***
- Cluster wind termination shock
  - basic models suggest $R_{\mathrm{TS}} \sim \mathcal{O}(30\,\mathrm{pc})$
  - matches radius of shell-like structure in γ-ray emission!
  - however, ***cannot firmly claim this association***
  - hadronic & leptonic scenario could work



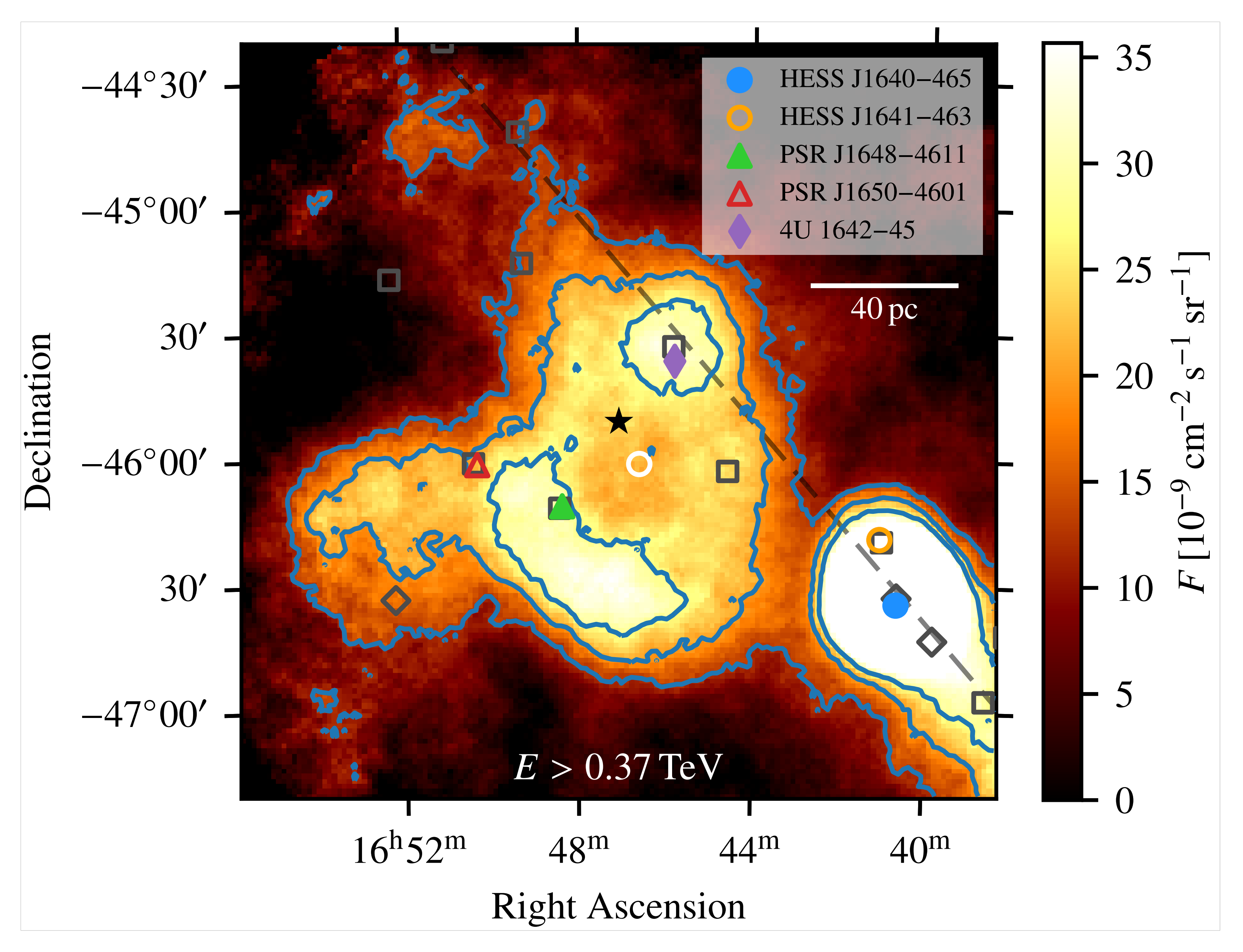


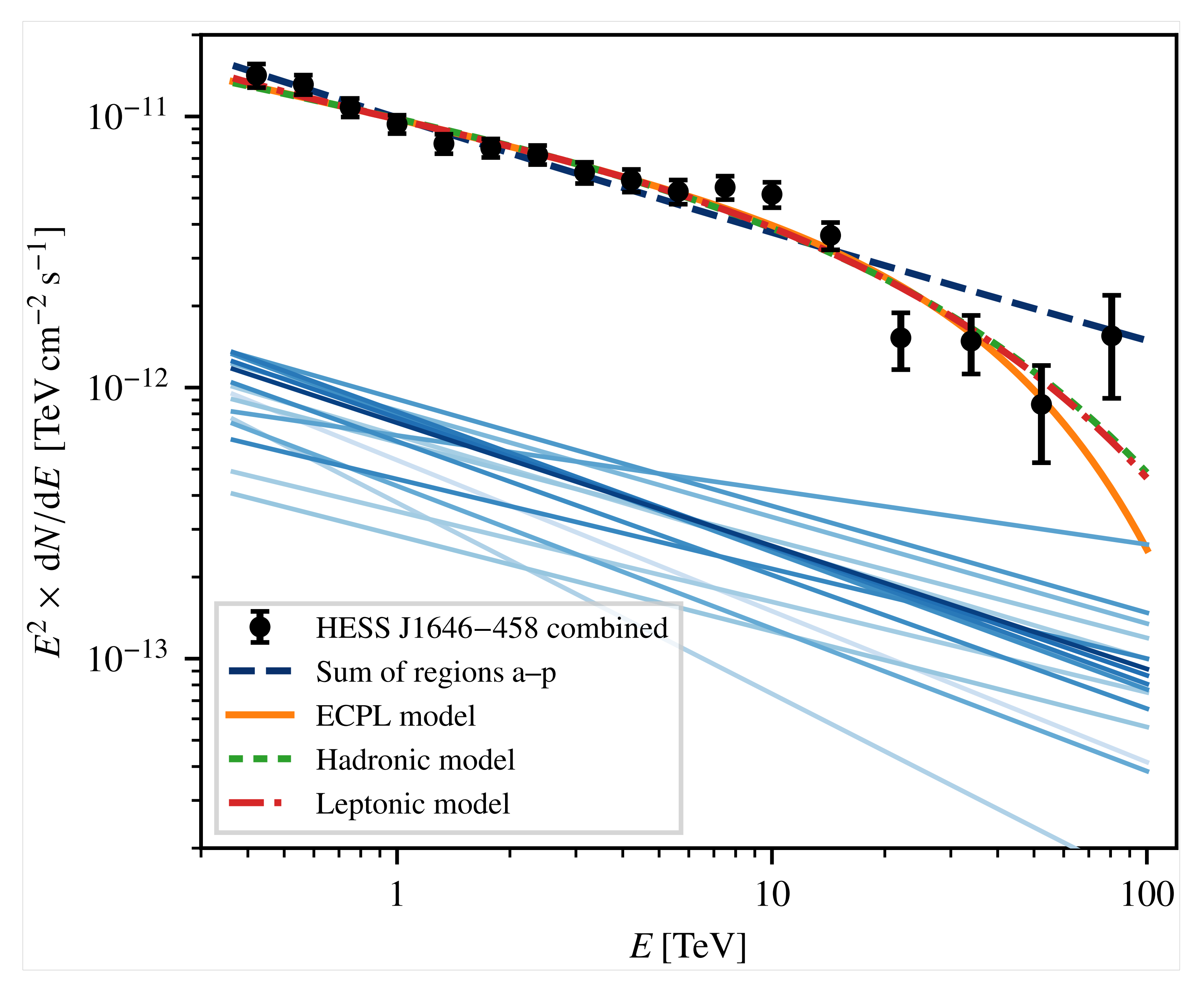
Morlino et al., MNRAS 504, 6096 (2021)

Westerlund 1: summary

H.E.S.S. Collaboration, A&A accepted (2022) arXiv:2207.10921

- HESS J1646–458
  - shell-like morphology
  - no variation with energy
  - energy spectrum to several ten TeV
- Westerlund 1
  - a powerful cosmic-ray accelerator!
  - acceleration site/mechanism not firmly identified
  - intriguing connection to cluster wind termination shock?





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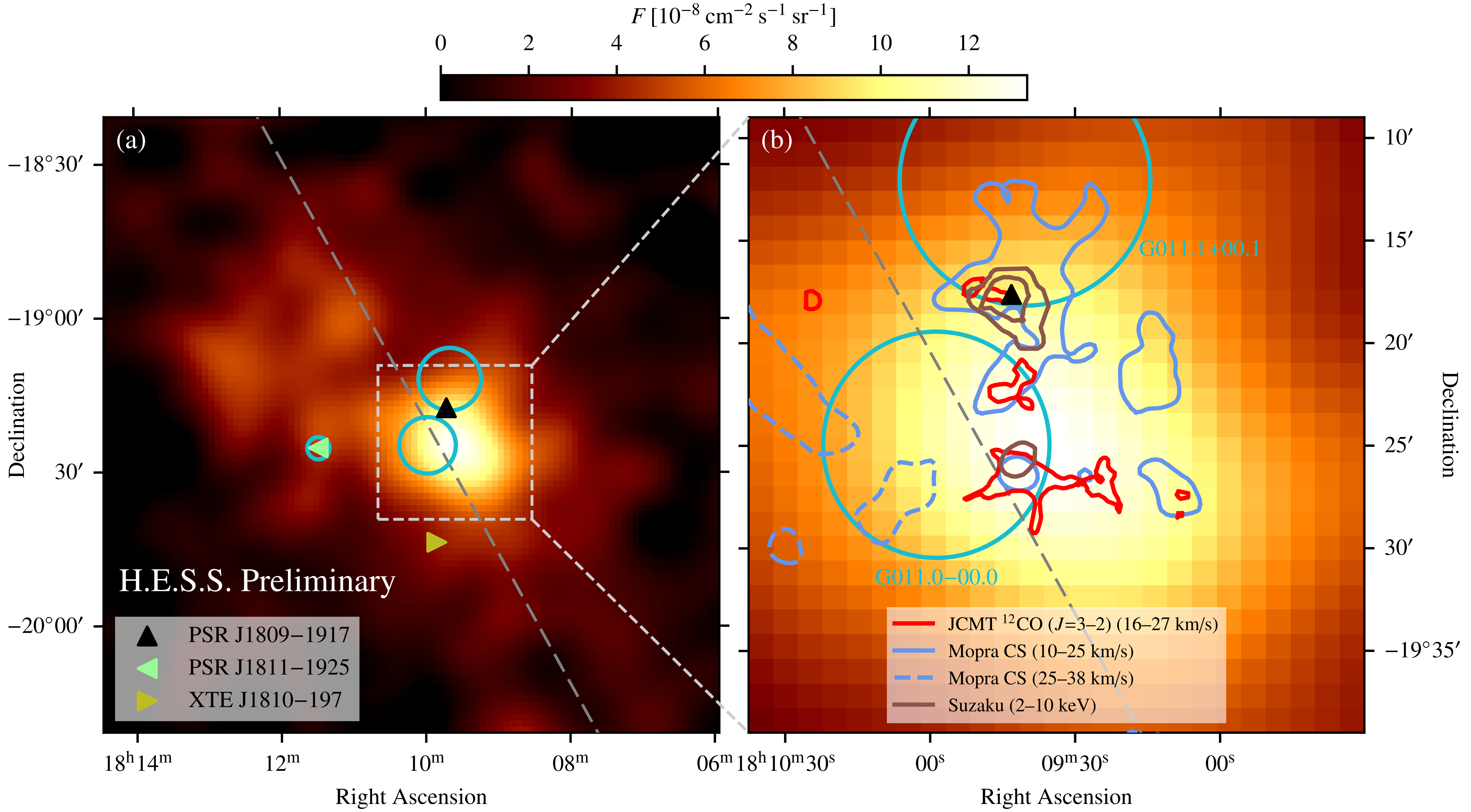
Gamma 2022, Barcelona



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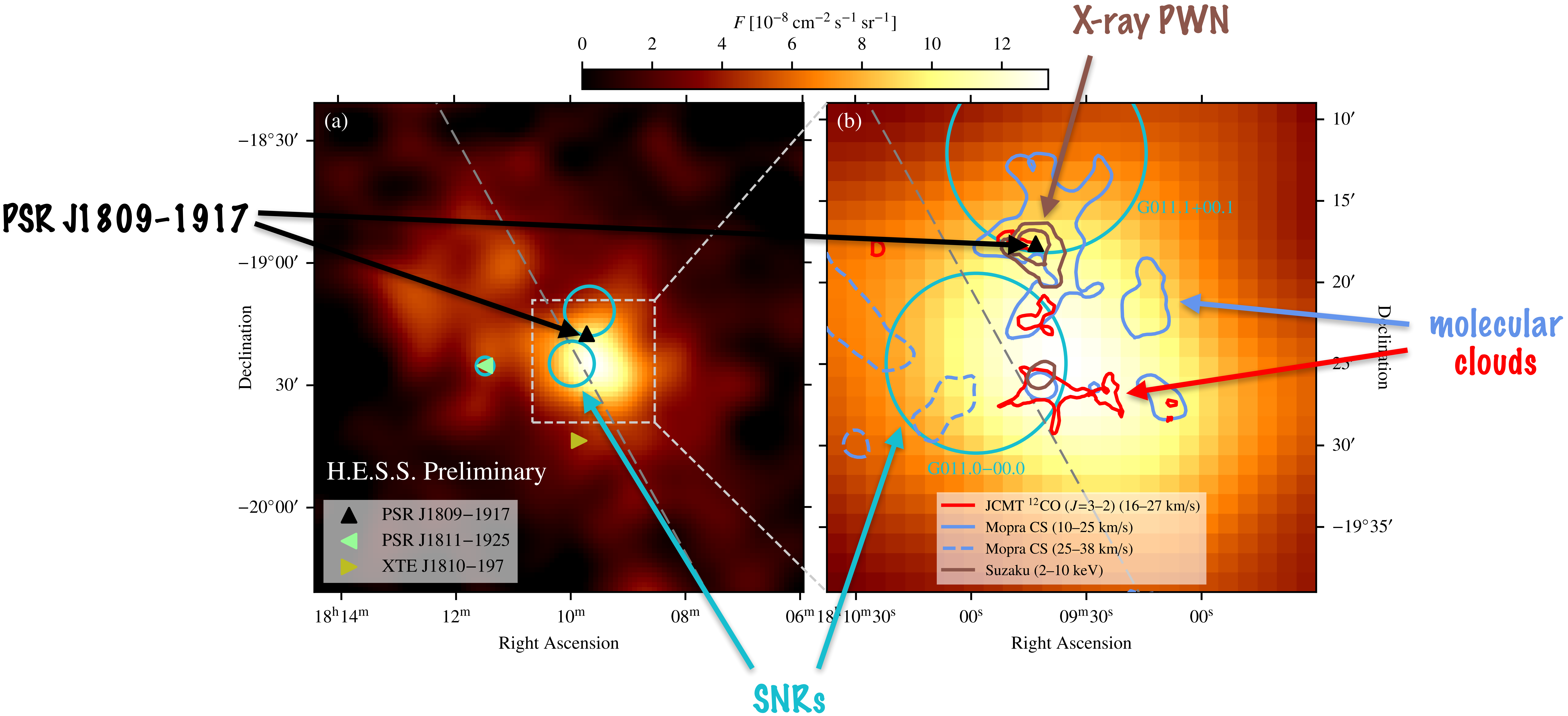

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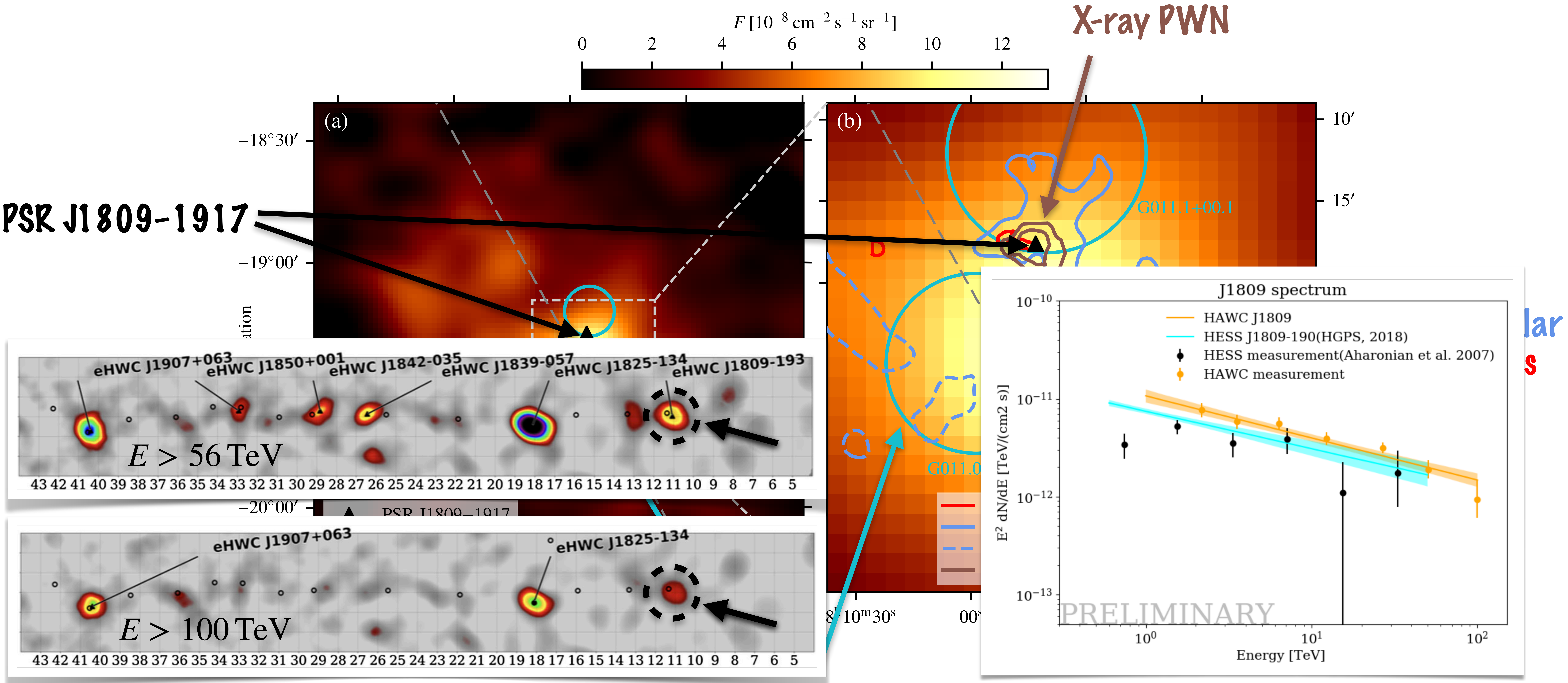

HAWC Collaboration, PRL 124, 021102 (2020)

J. Goodman, Gamma 2022, Barcelona

"Classical" approach: aperture photometry

- count events in (circular) "on region"
- estimate background from "off regions"

HESS J1809−193

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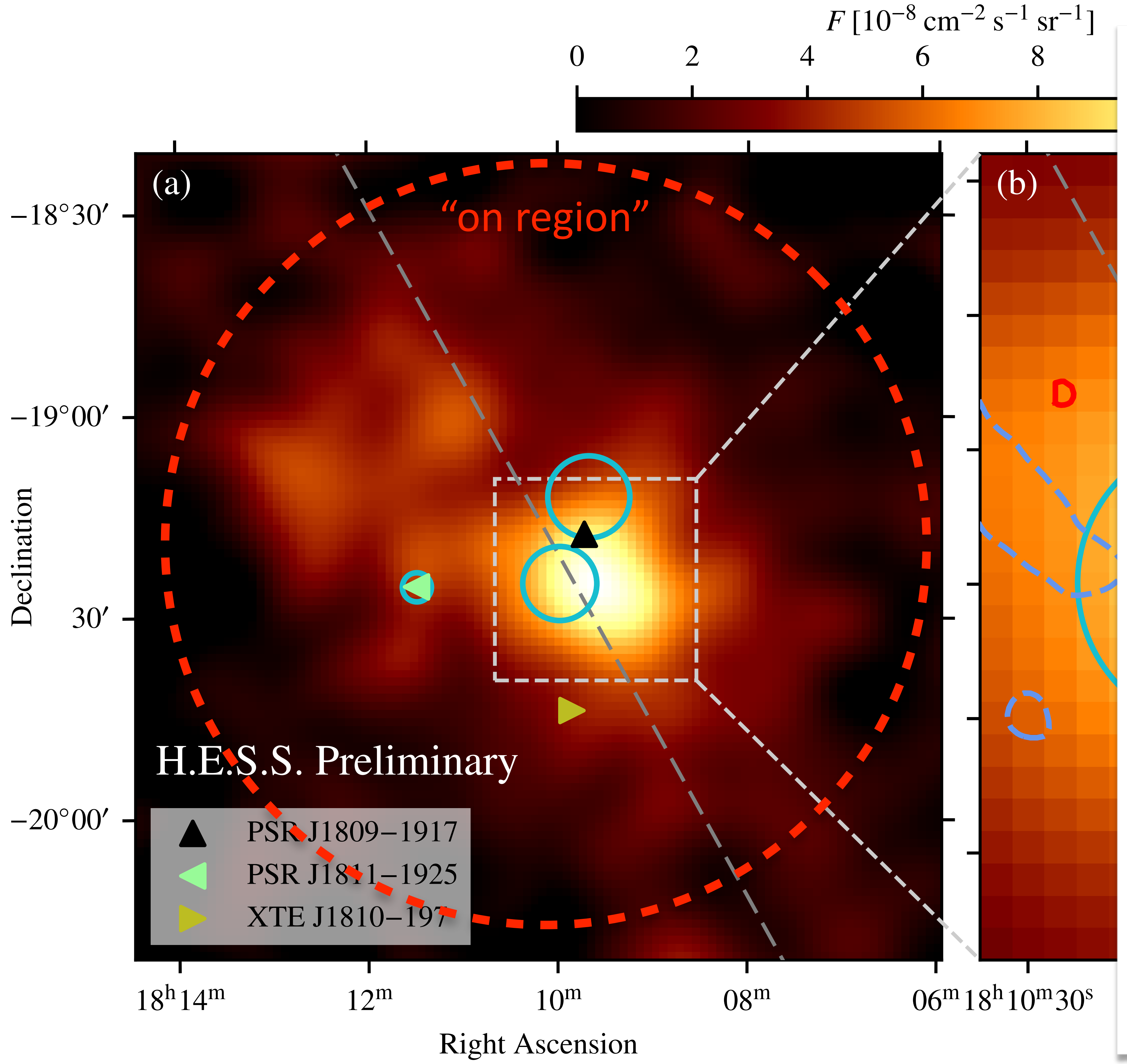
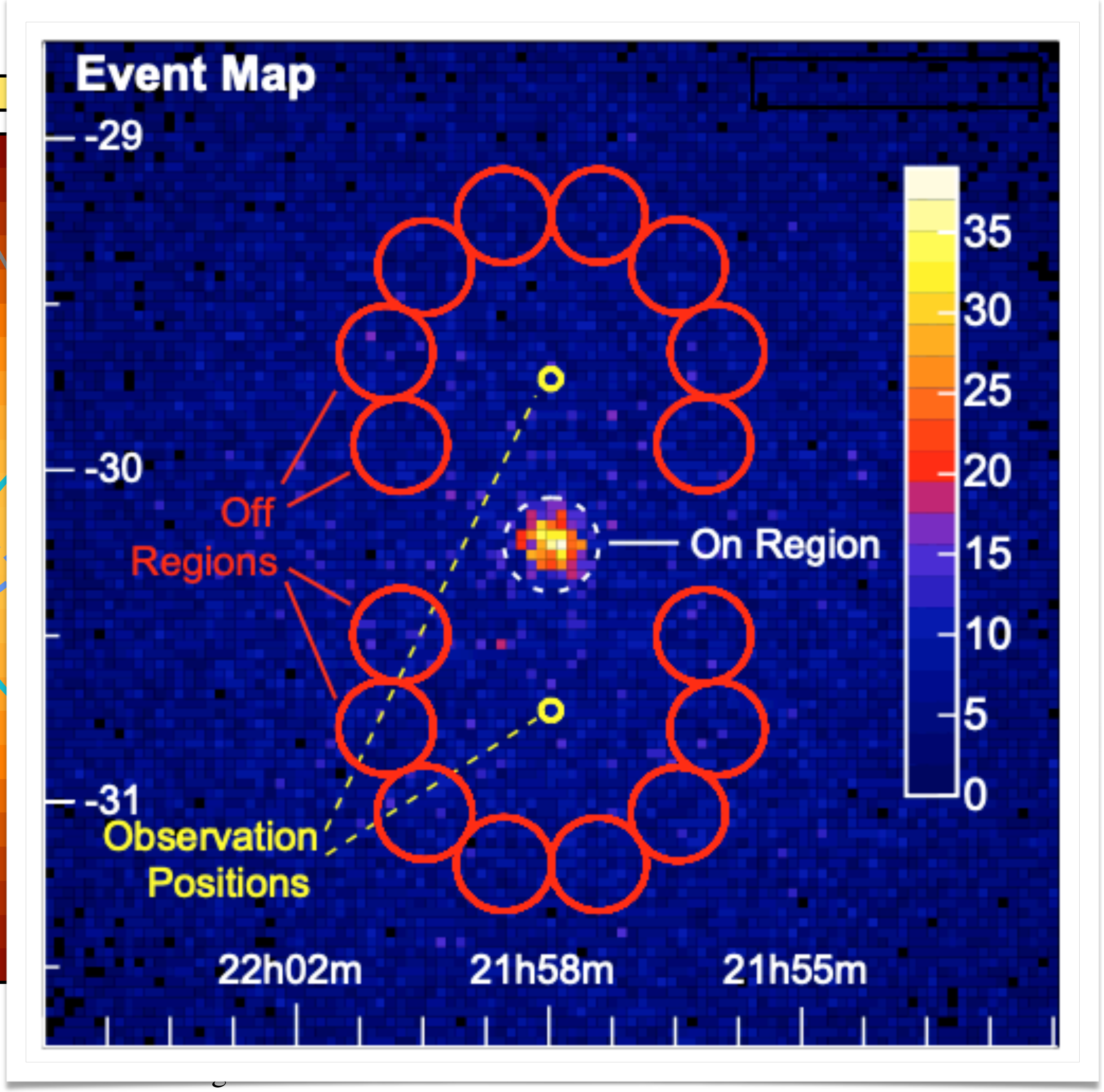




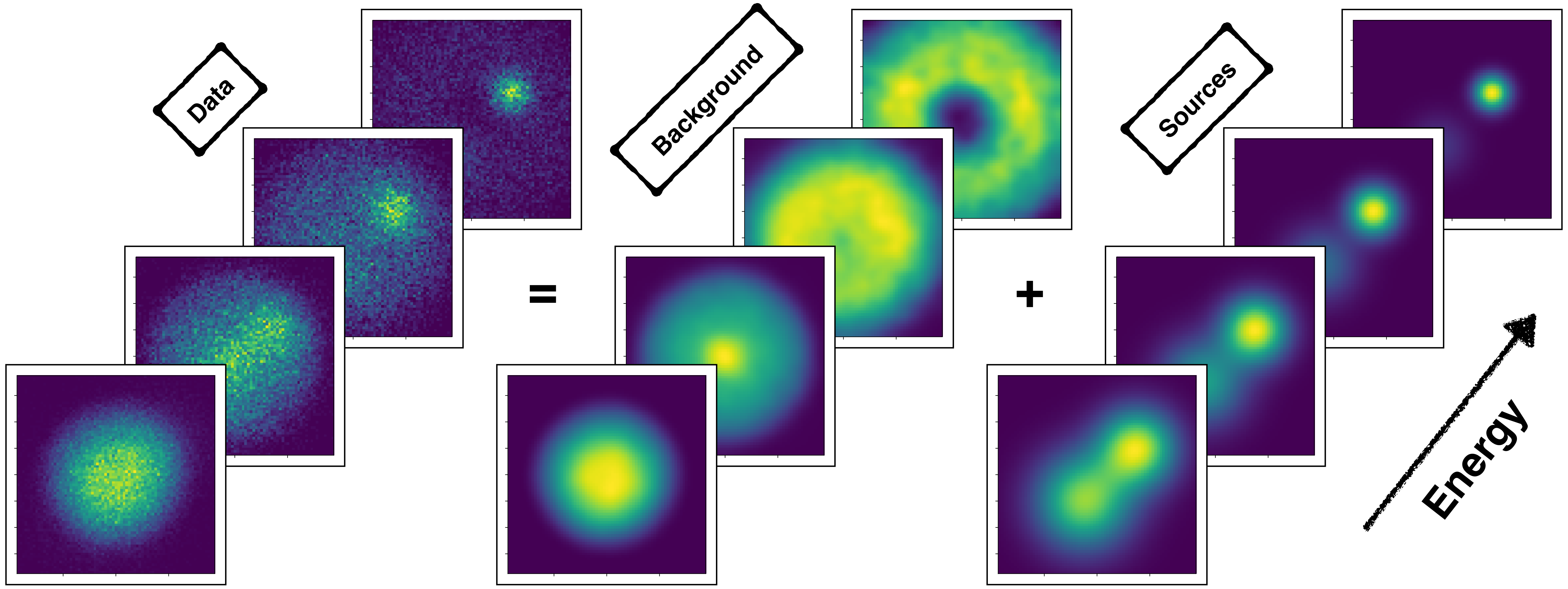
Berge et al., A&A 466, 1219 (2007)

Issues:

- "on region" very large
- ***source structure not taken into account***

Excursion: spectro-morphological likelihood analysis

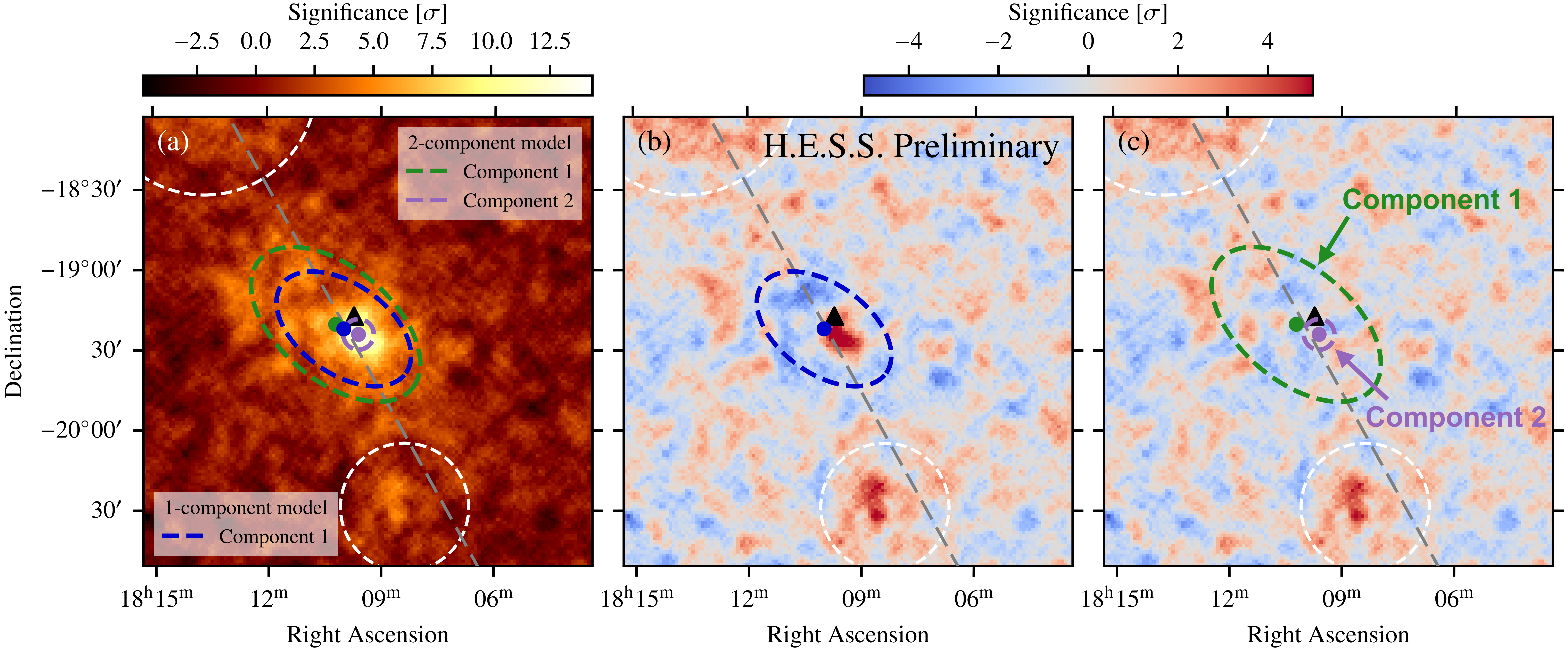
- Model ***spectrum*** & ***morphology*** of source(s) simultaneously
  - likelihood fit in 3 dimensions
  - "Fermi-LAT style"
- Requires ***model*** for residual cosmic-ray ***background***
- Can include ***arbitrary number*** of ***model components***
  - e.g. also for diffuse emission



3D likelihood analysis: spatial models

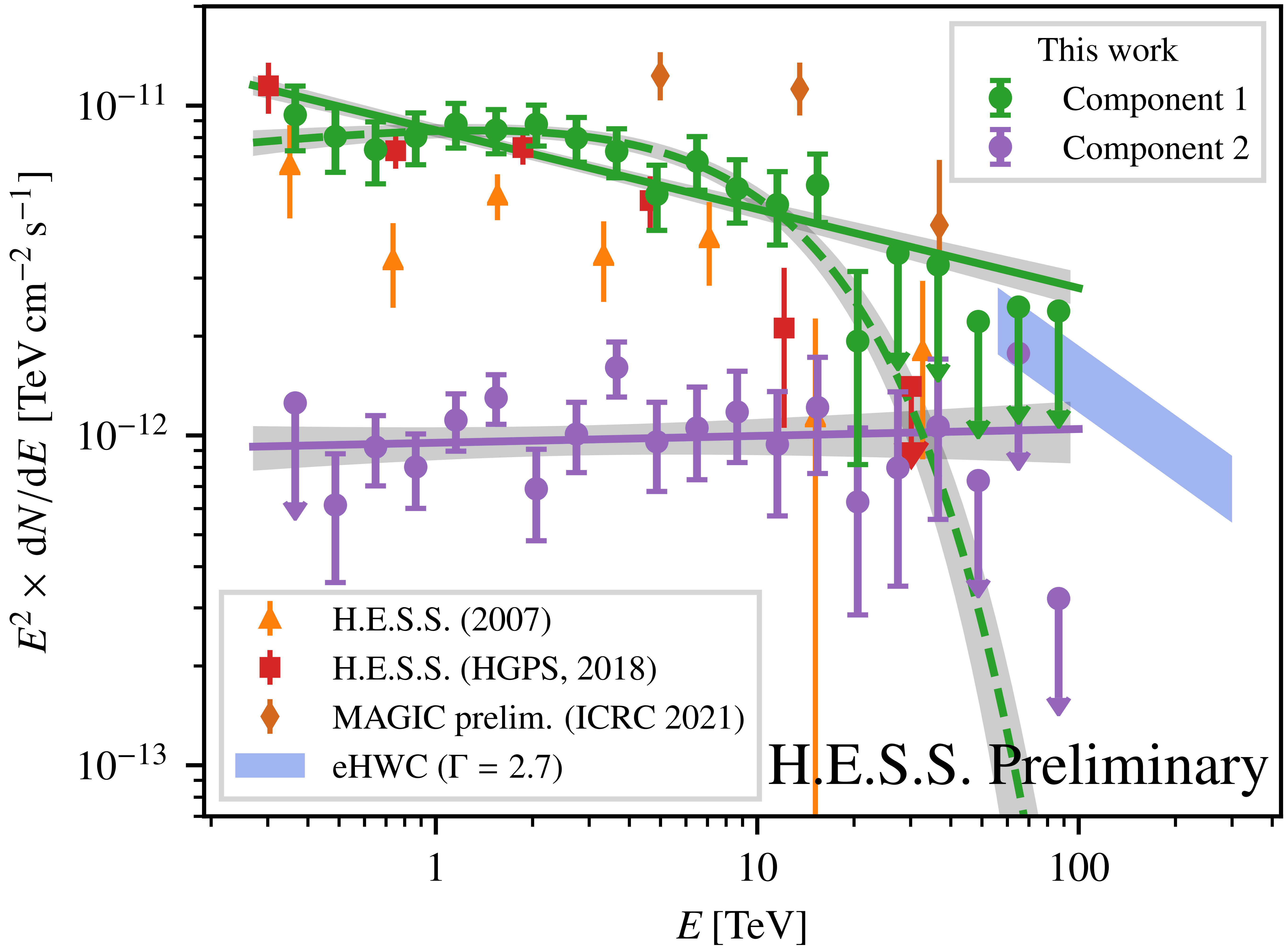
- 1-component model
  - spatial model: elongated Gaussian
  - spectral model: power law
  - not a good fit!

- ***2-component model***
  - add 2nd component (radial Gaussian / power law)
  - much better description! (preferred by 13.3σ)

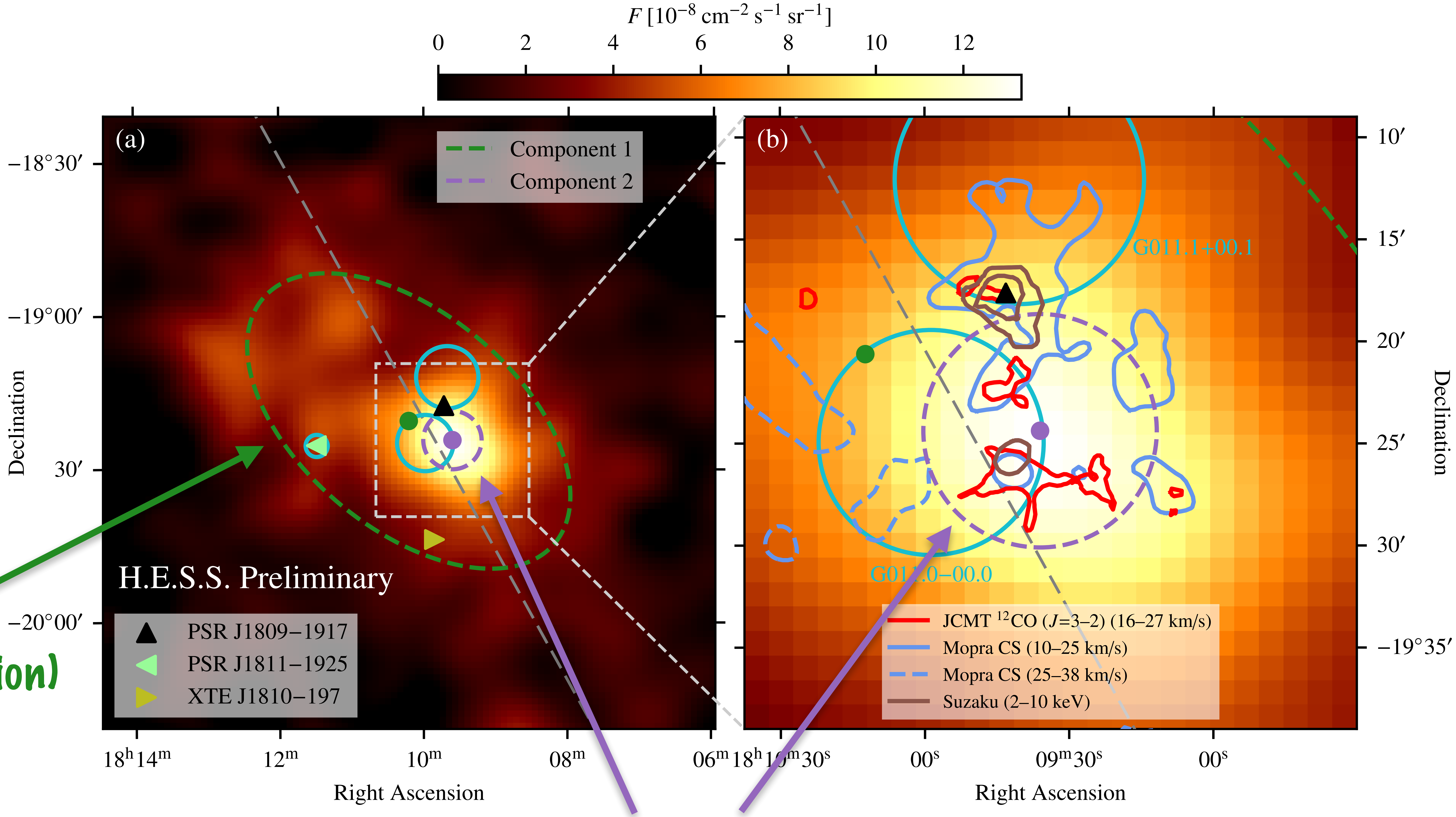


3D likelihood analysis: spectral models

- Component 1
  - power law ***with exp. cut-off***
    - $\Gamma = 1.90 \pm 0.05_{\mathrm{stat}} \pm 0.05_{\mathrm{sys}}$
    - $E_c = \left(12.7\,^{+2.7}_{-2.1}\Big|_{\mathrm{stat}}\,^{+2.6}_{-1.9}\Big|_{\mathrm{sys}}\right)$ TeV
    - preferred over power law by 8σ
- Component 2
  - power law
    - $\Gamma = 1.98 \pm 0.05_{\mathrm{stat}} \pm 0.03_{\mathrm{sys}}$
    - cut-off ***not significantly preferred***



Flux map with H.E.S.S. models

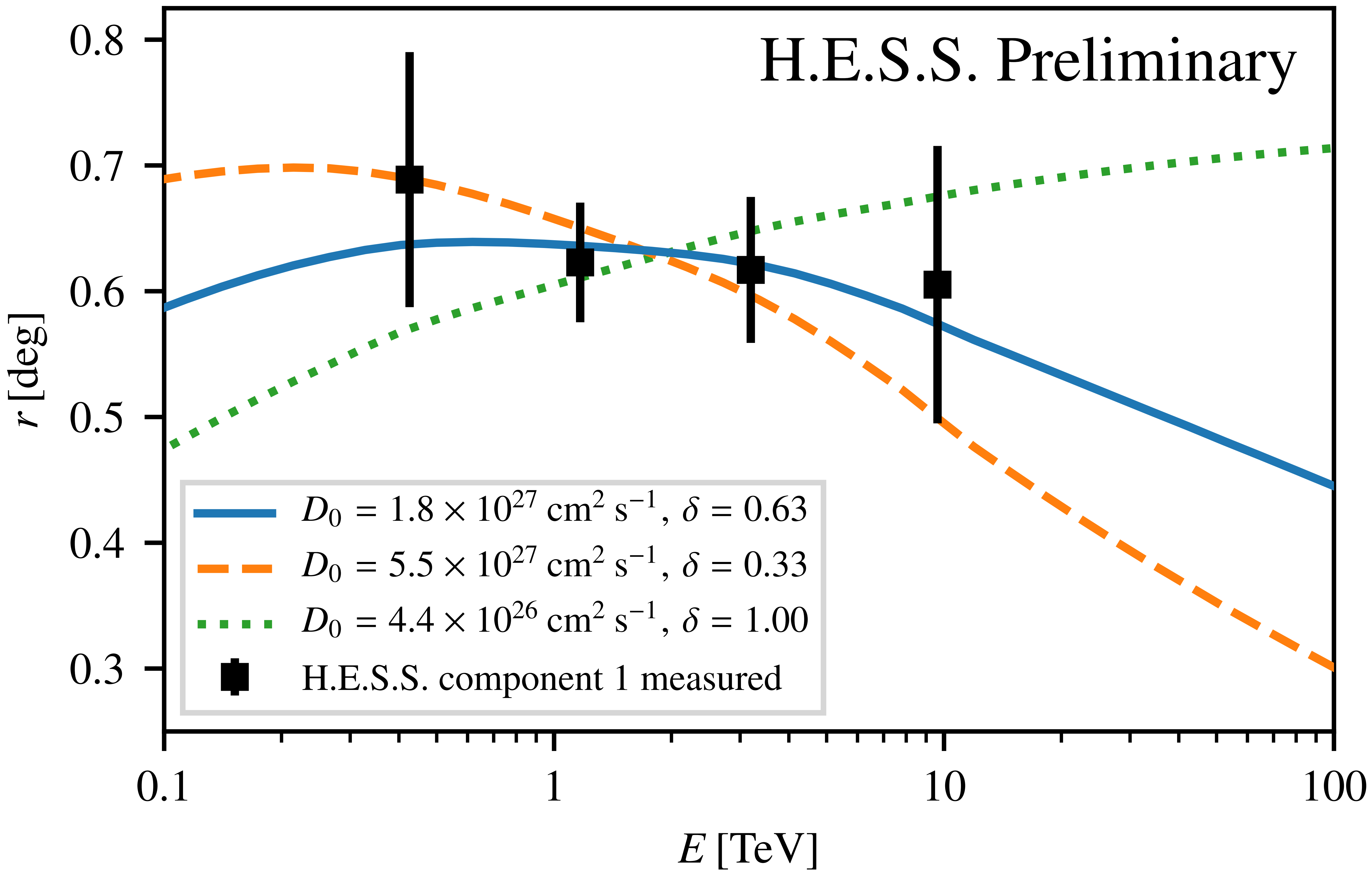


Component 1 (extended emission)

Component 2 (bright peak — slightly offset from X-ray PWN — coincides with SNR + clouds)

Extended component: a “halo” of old electrons?

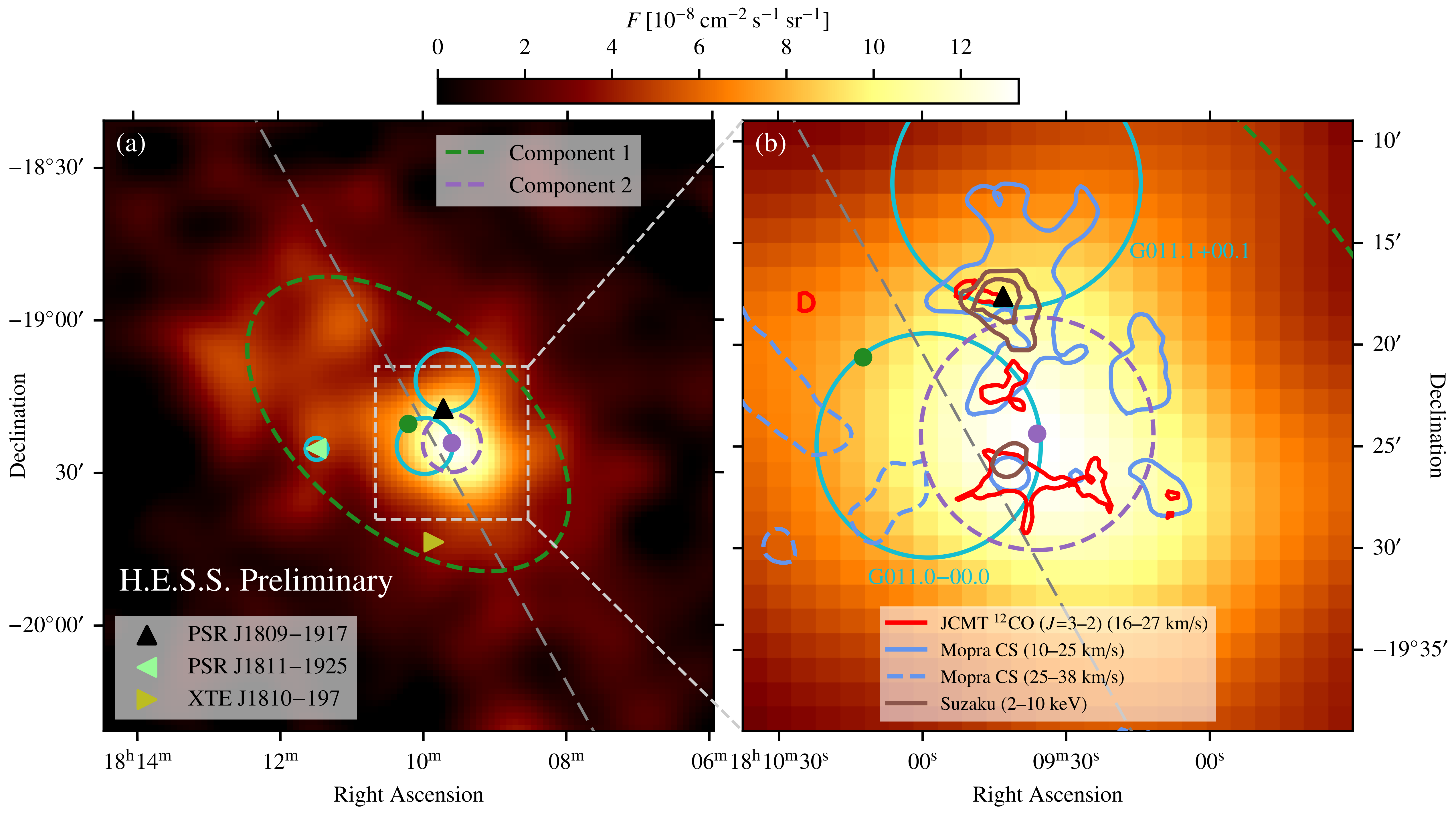
- Extent of emission
  - assume electrons started diffusing 20 kyr ago (age of system)
  - compute expected size of halo and compare with measurement
  - good agreement for $D_0 \sim 2 \times 10^{27}\,\mathrm{cm^2\,s^{-1}}$ → a reasonable value!

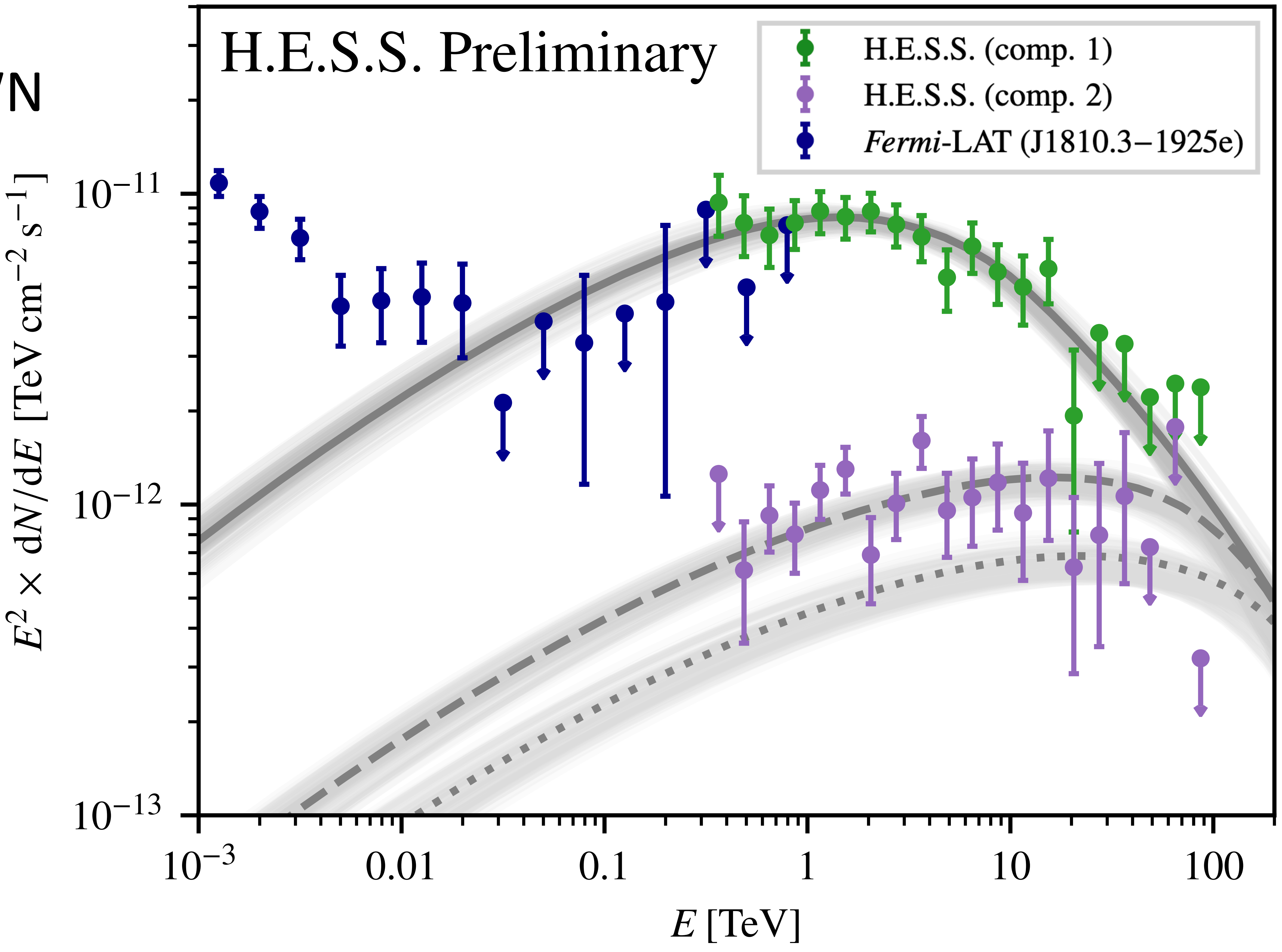


- Energy spectrum
  - expect cut-off in γ-ray spectrum because highest-energy electrons have cooled
  - as observed!

Compact component: leptonic or hadronic?

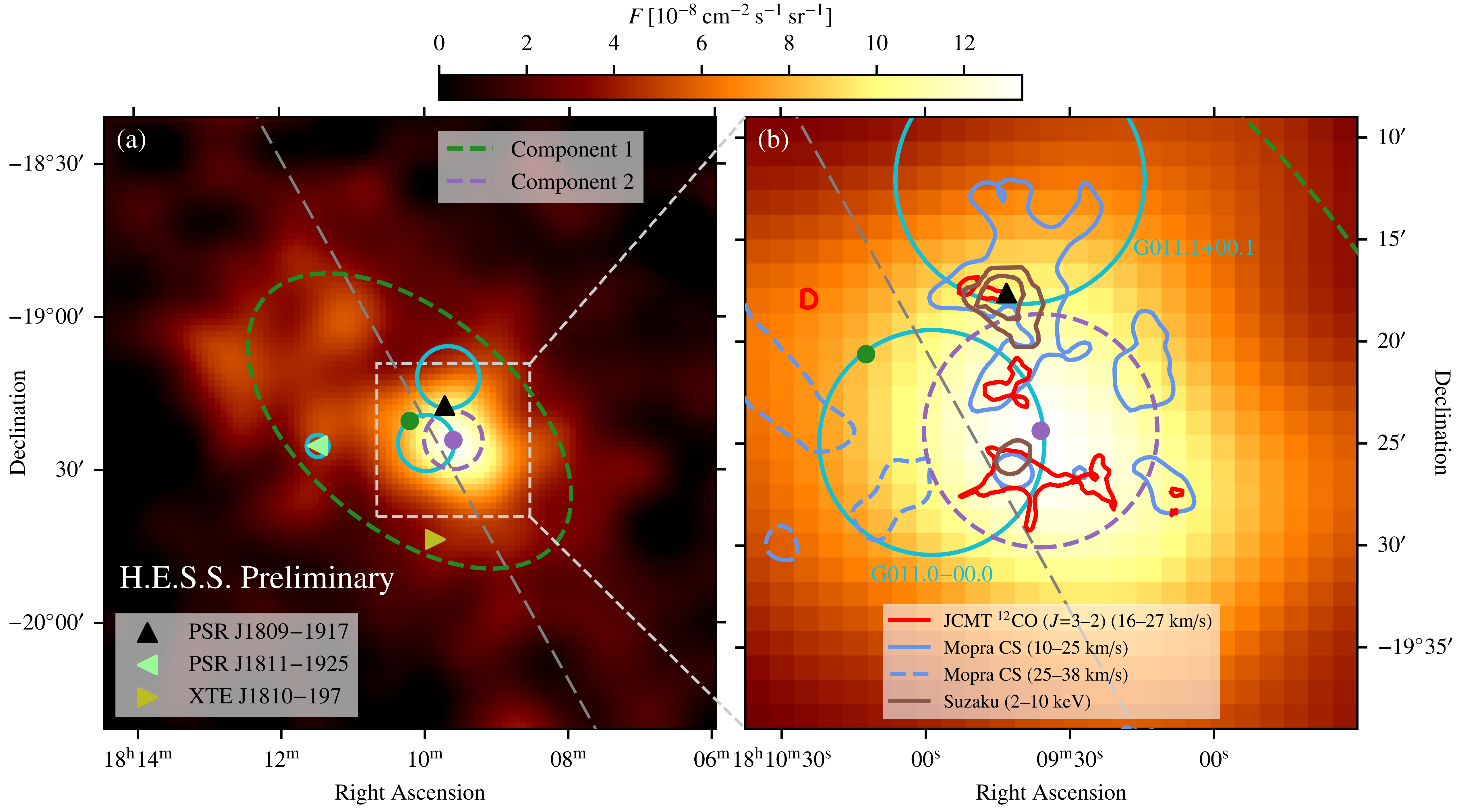
- Leptonic
  - inverse Compton emission from PWN electrons
  - peak of emission slightly offset from pulsar / X-ray PWN
  - "medium-aged" electrons escaping into broader region?

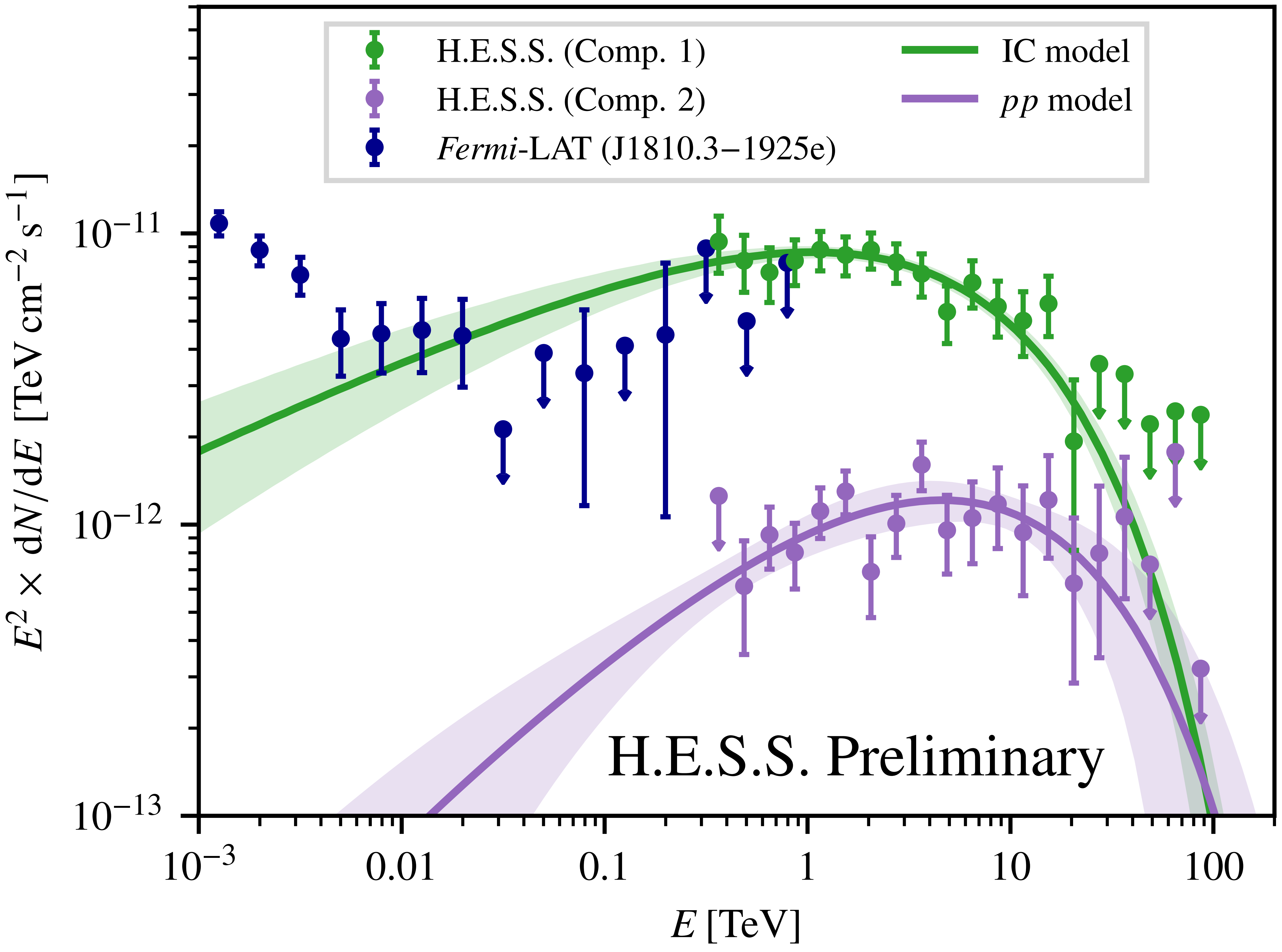




Compact component: leptonic or hadronic?

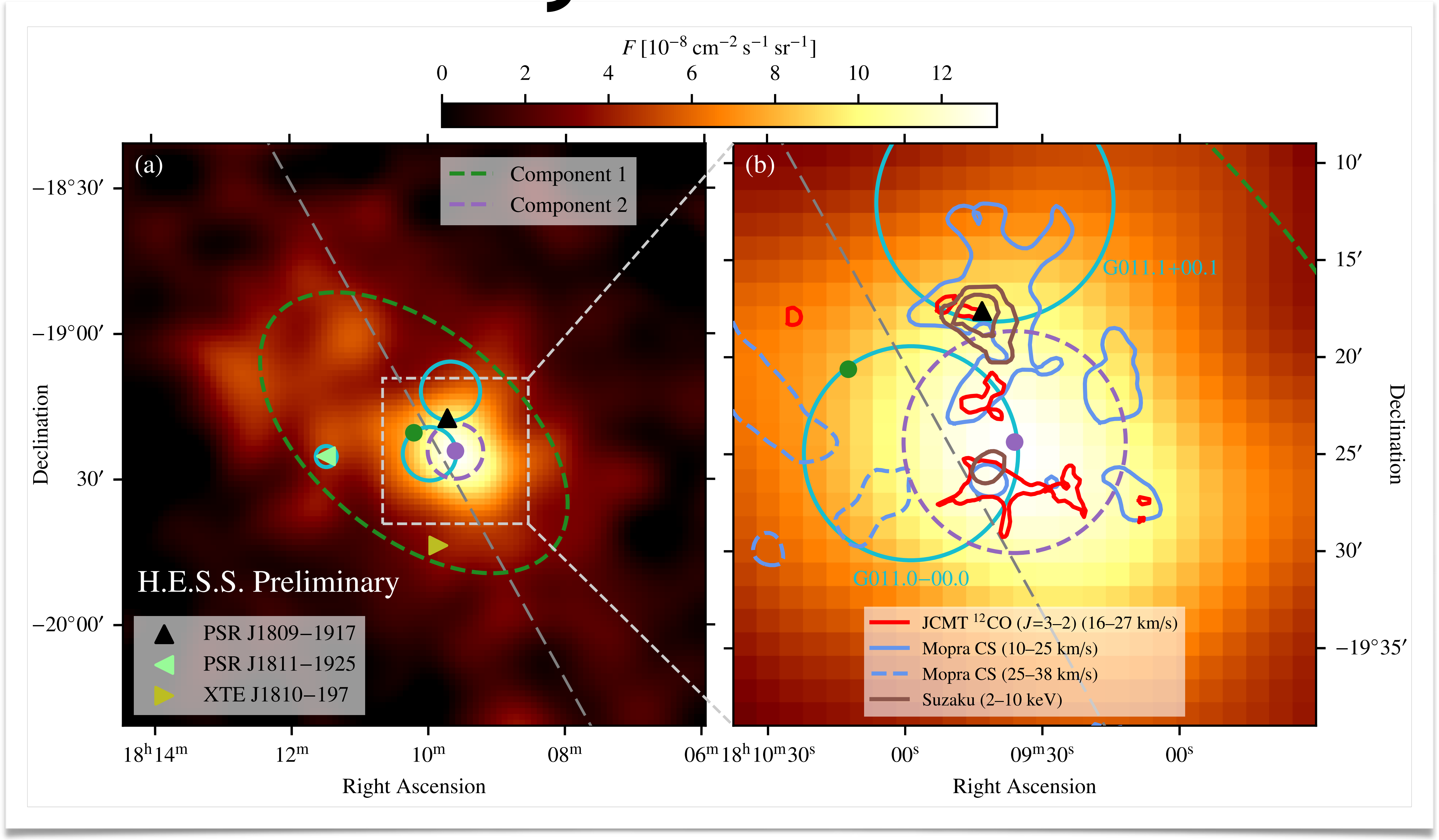
- Hadronic
  - cosmic-ray nuclei accelerated in SNR and interacting in molecular clouds
  - peak of emission coincident with SNR shell & clouds
  - viable energetically ($W_p \sim 3 \times 10^{49} \left(n / 1\,\mathrm{cm}^{-3}\right)^{-1}$ erg)

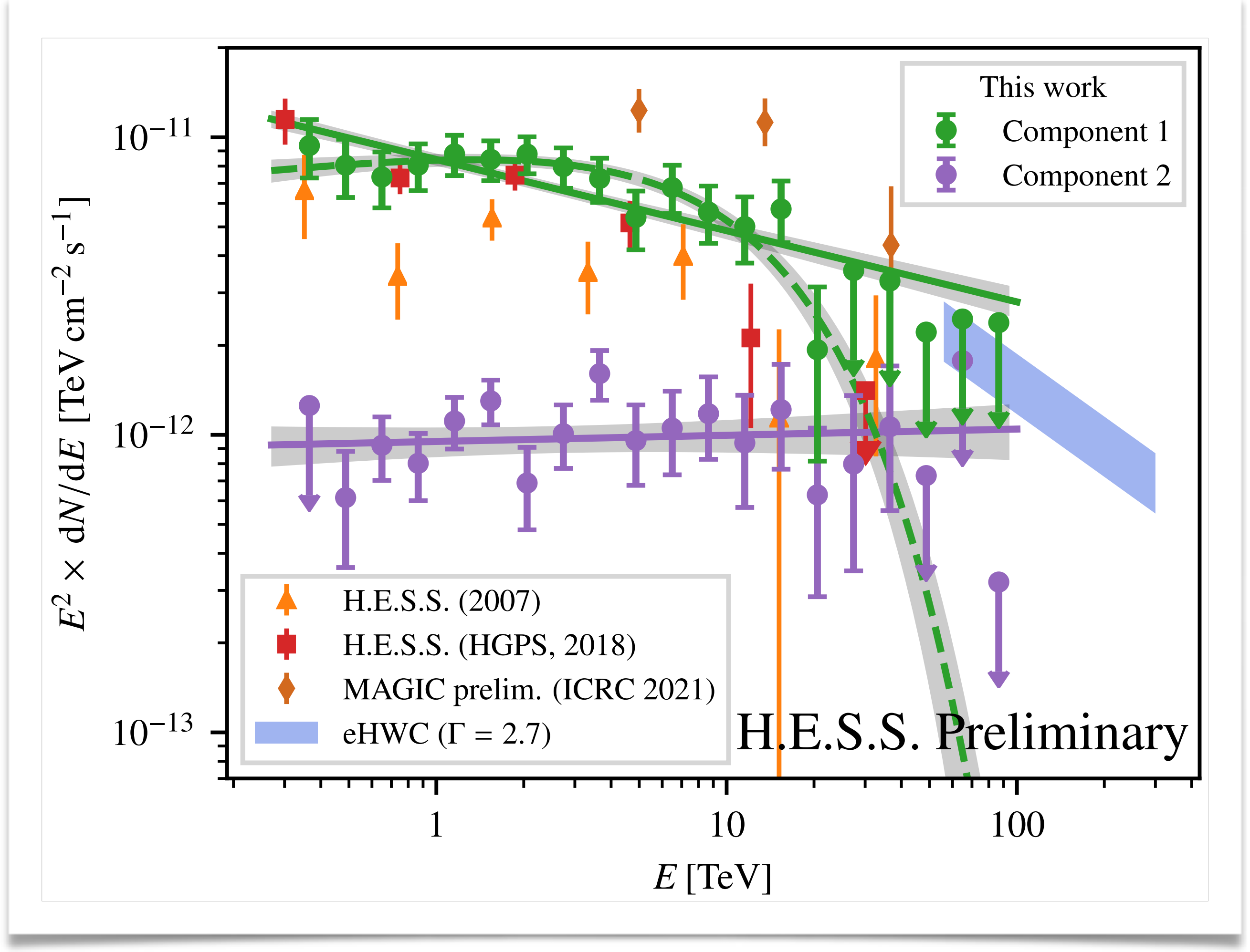




HESS J1809–193: summary

- HESS J1809–193
  - unidentified PeVatron candidate
  - fascinating environment — several plausible associations
- New H.E.S.S. analysis
  - resolved emission into two distinct components
  - 3D likelihood analysis has been crucial for this!
- Publication almost ready — watch out!



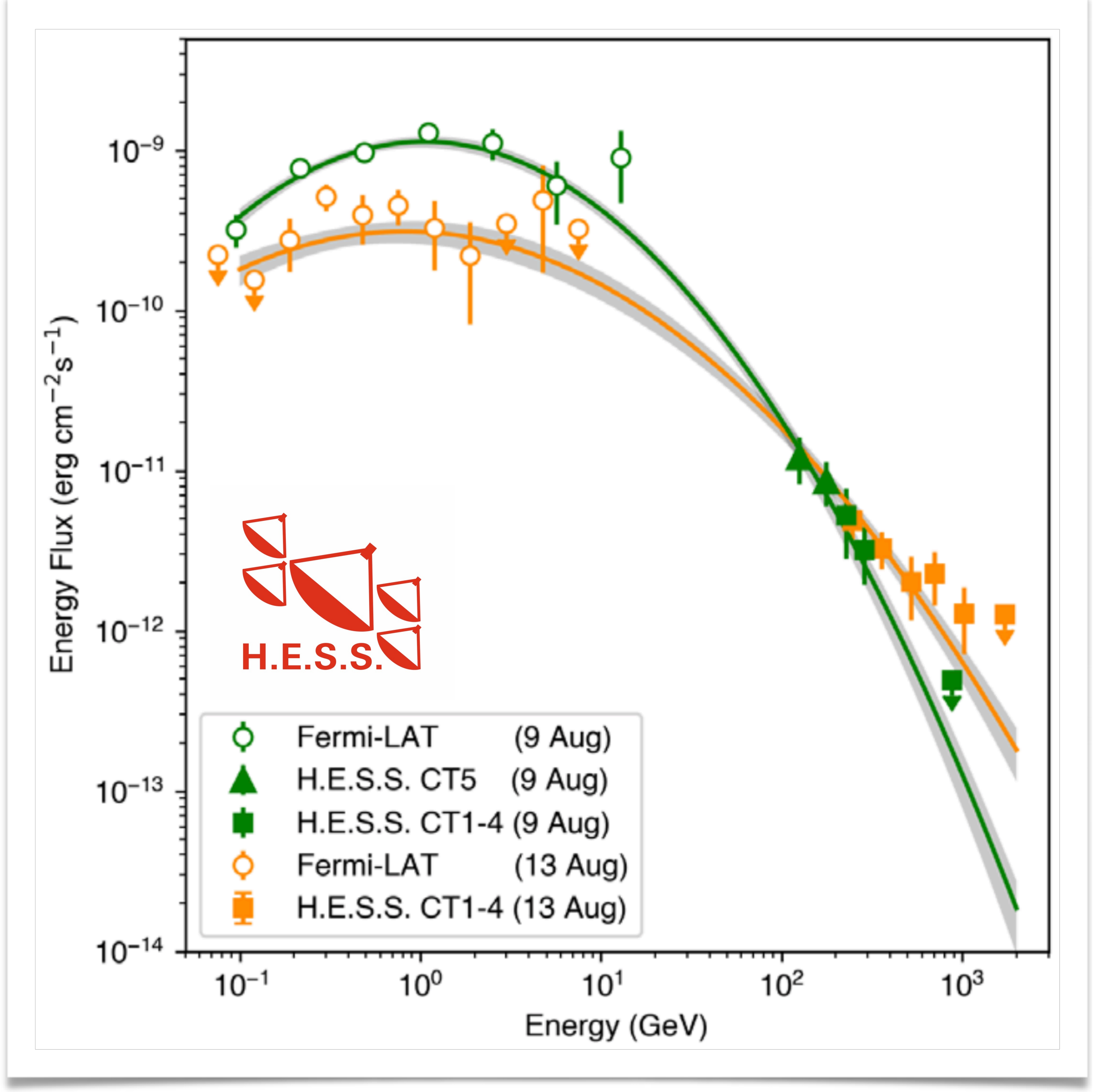


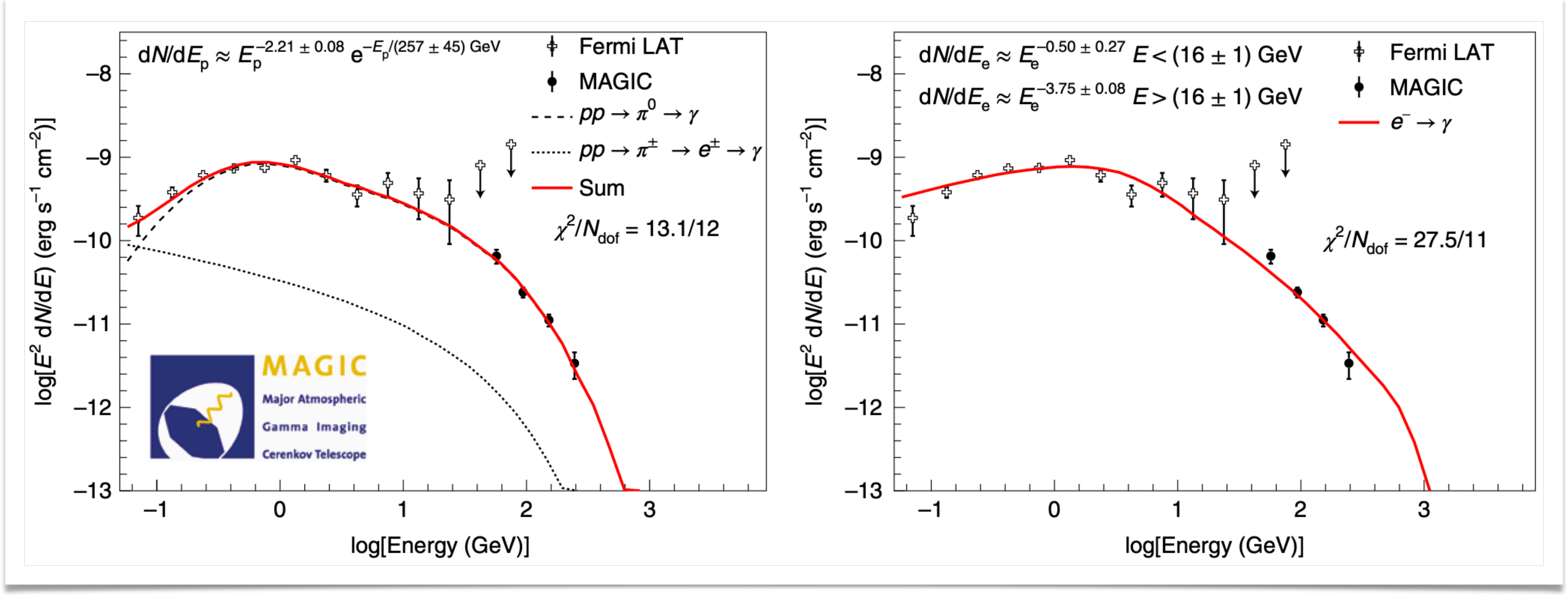
Other recent highlights

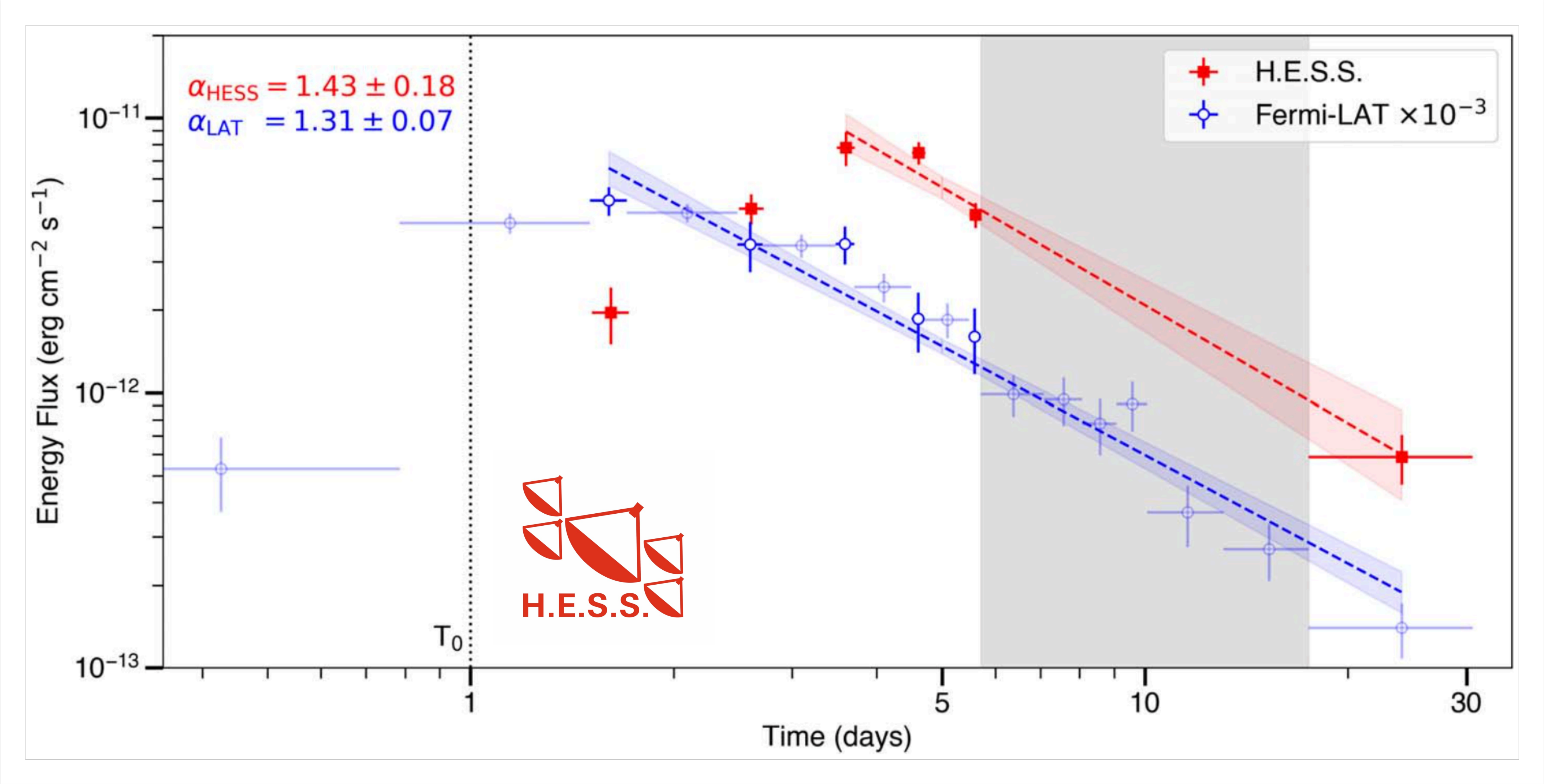
(a personal selection — not exhaustive!)

Nova RS Ophiuchi

- New VHE source class & the first Galactic transient!
- Detected with H.E.S.S. and MAGIC (and LST-1!)
- Hadronic scenario favoured in both cases
- Implications for cosmic-ray acceleration in supernovae





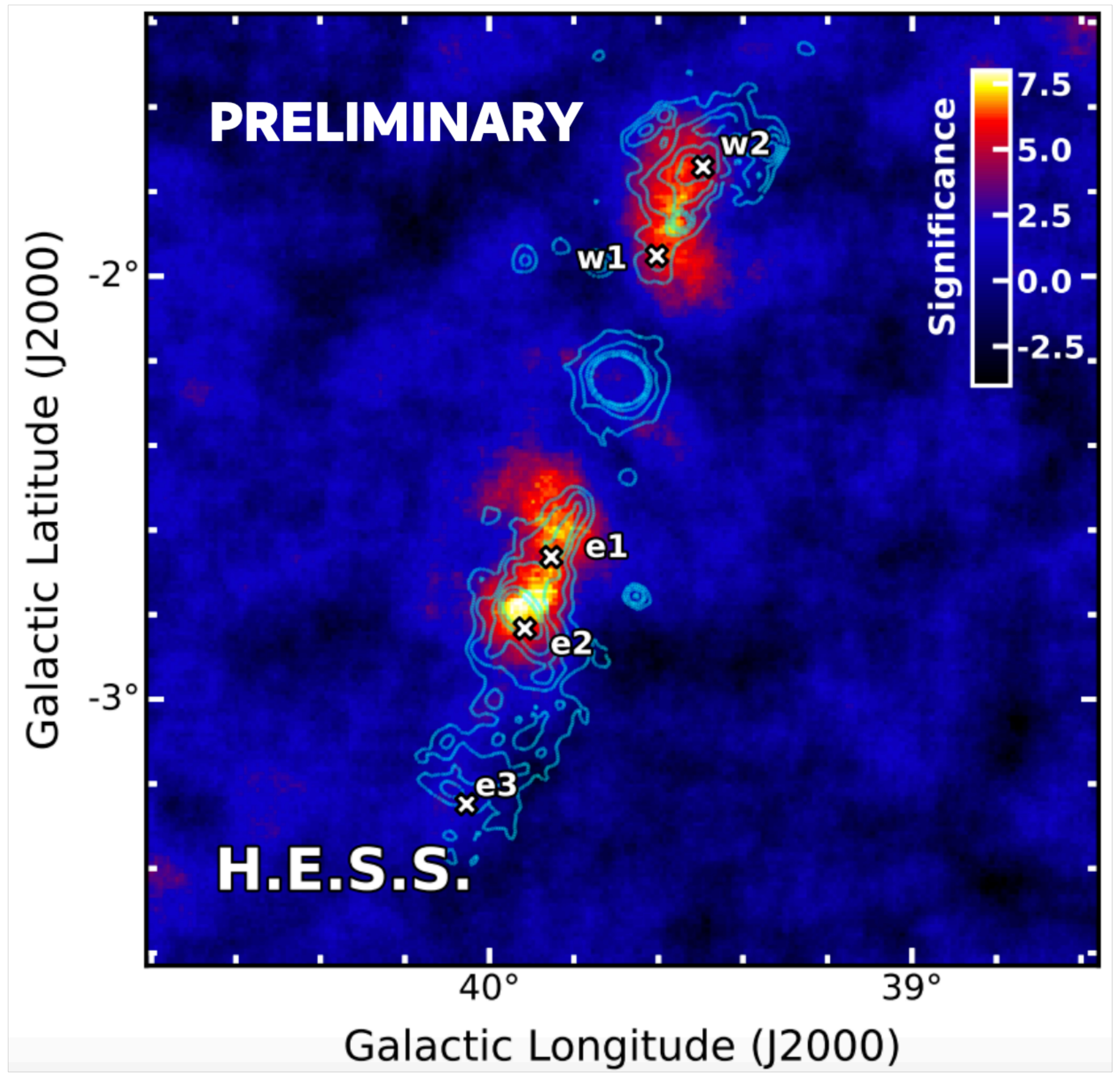


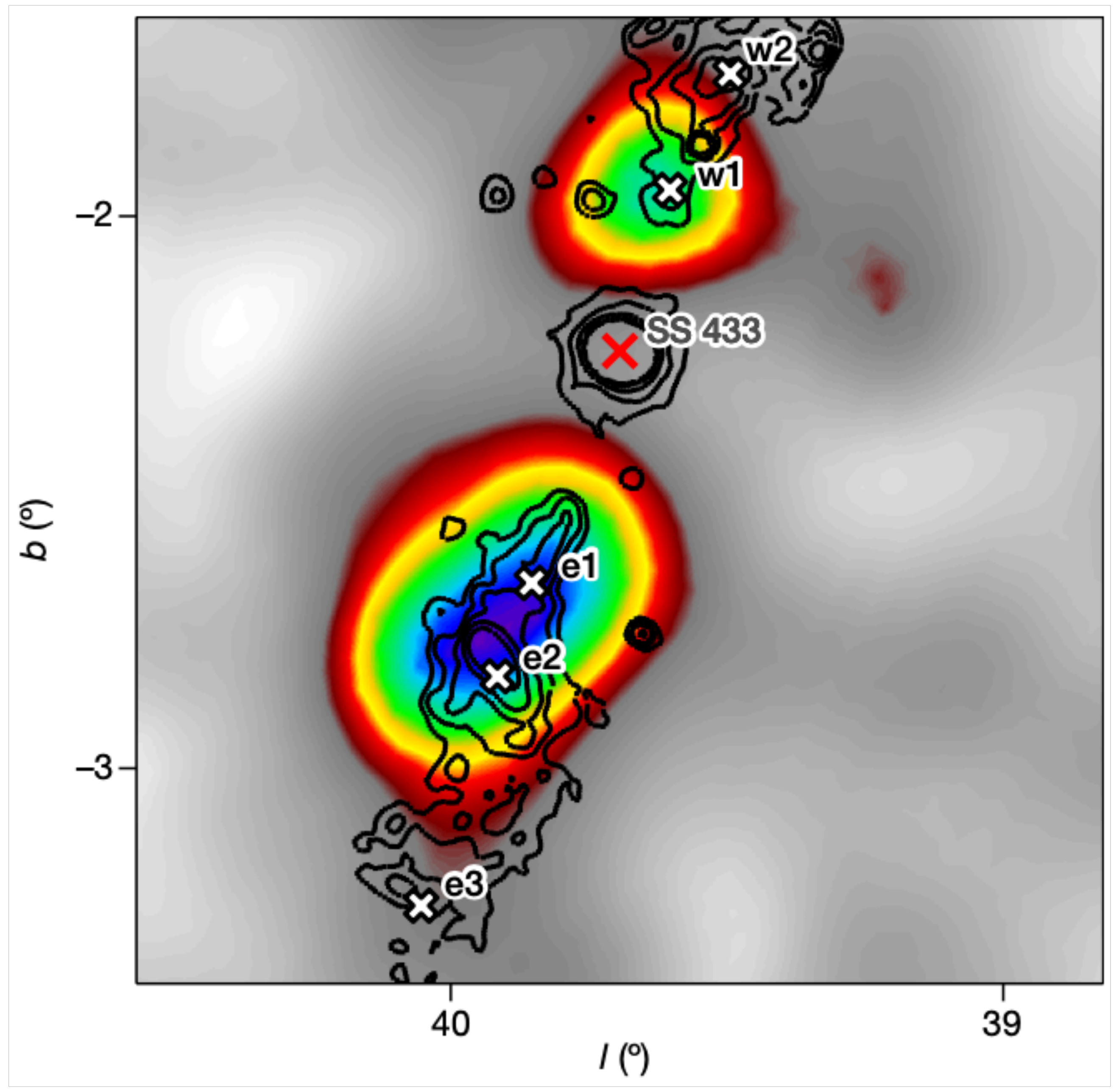
MAGIC Collaboration, Nature Astronomy 6, 689 (2022)

H.E.S.S. Collaboration, Science 376, 77 (2022)

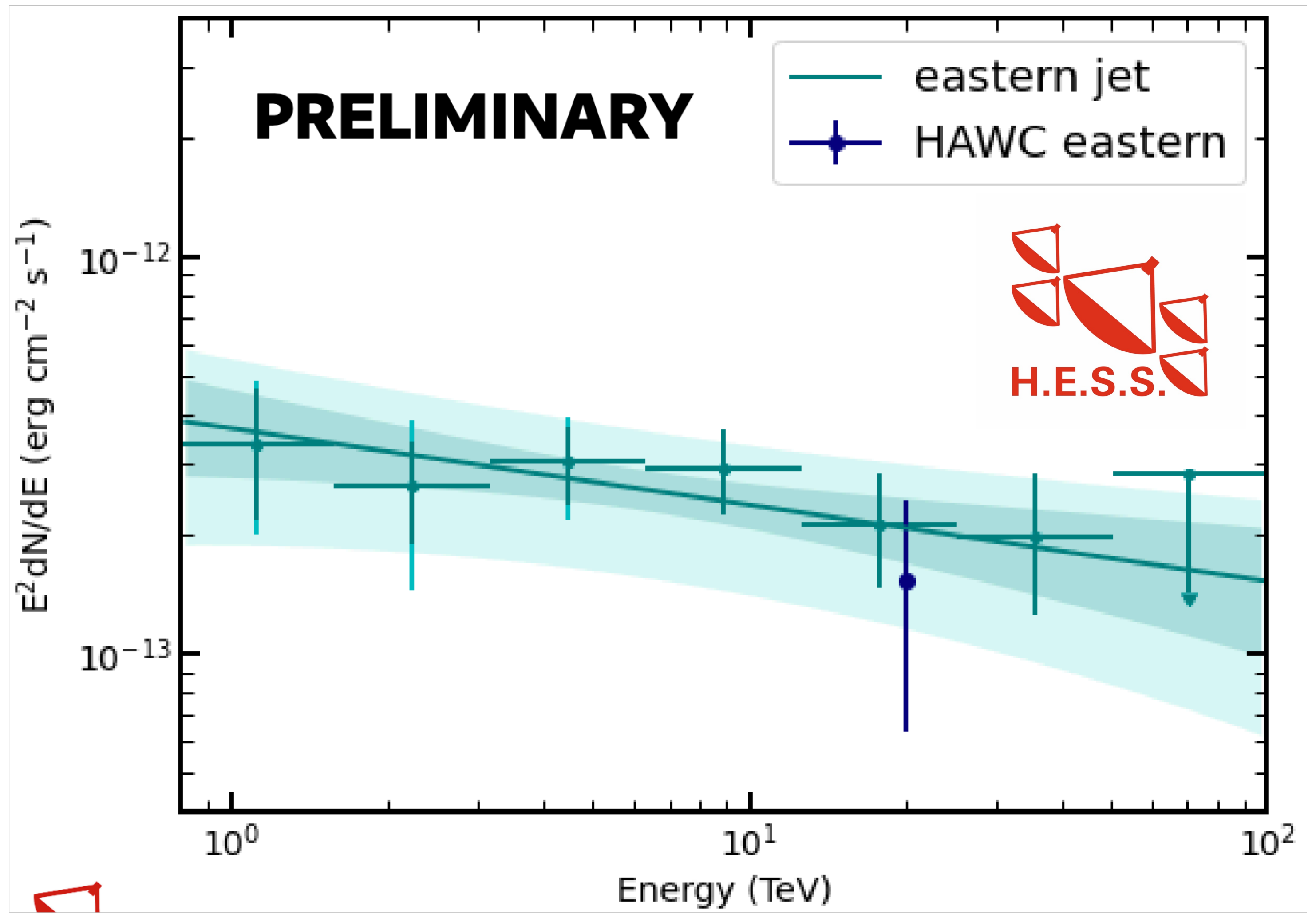
SS 433

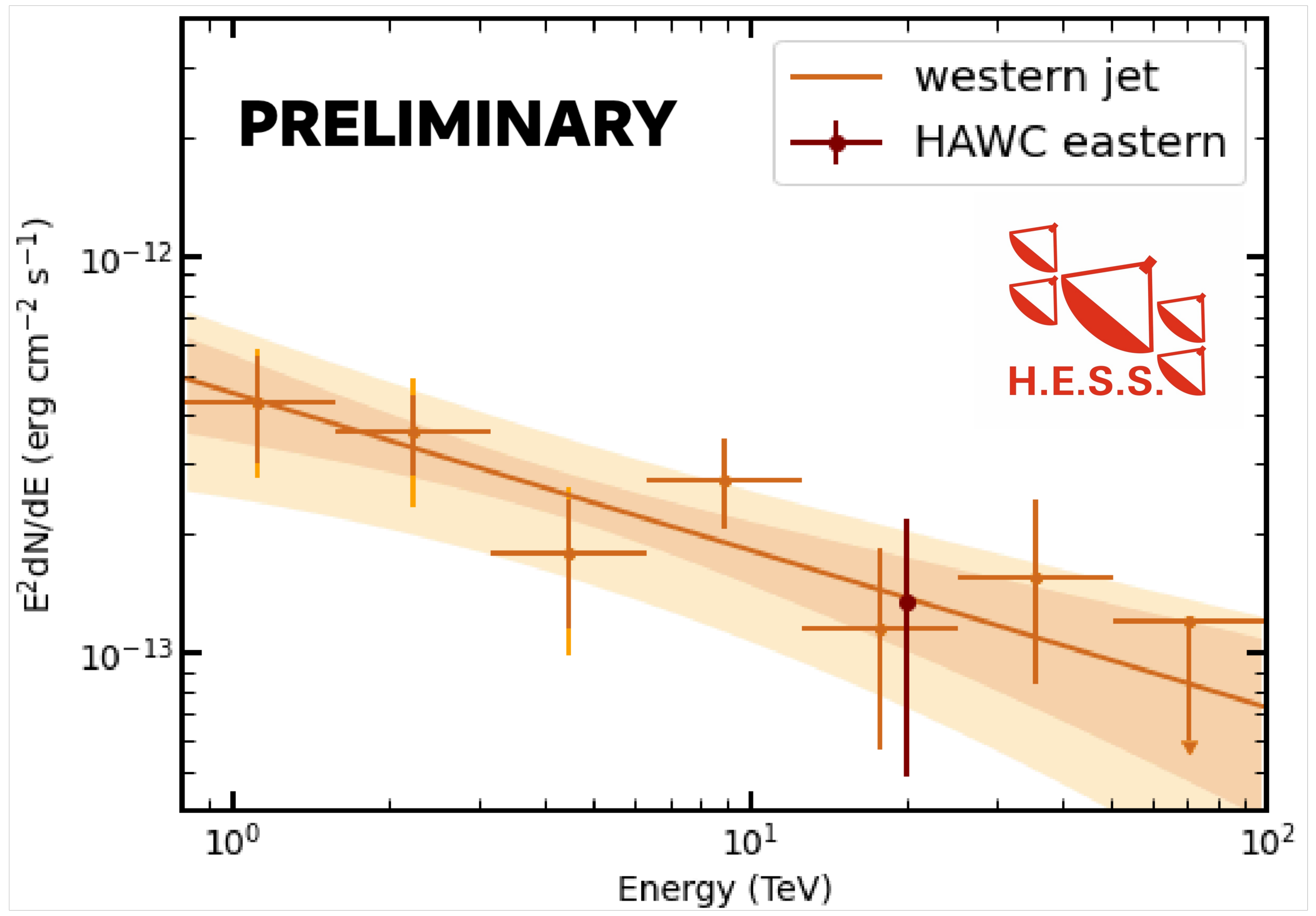
- Microquasar, jets perpendicular to line of sight
- 2018: detection of jets reported by HAWC
- Gamma ’22: now confirmed with H.E.S.S.
  → will be able to resolve emission better!





HAWC Collaboration, Nature 562, 82 (2018)





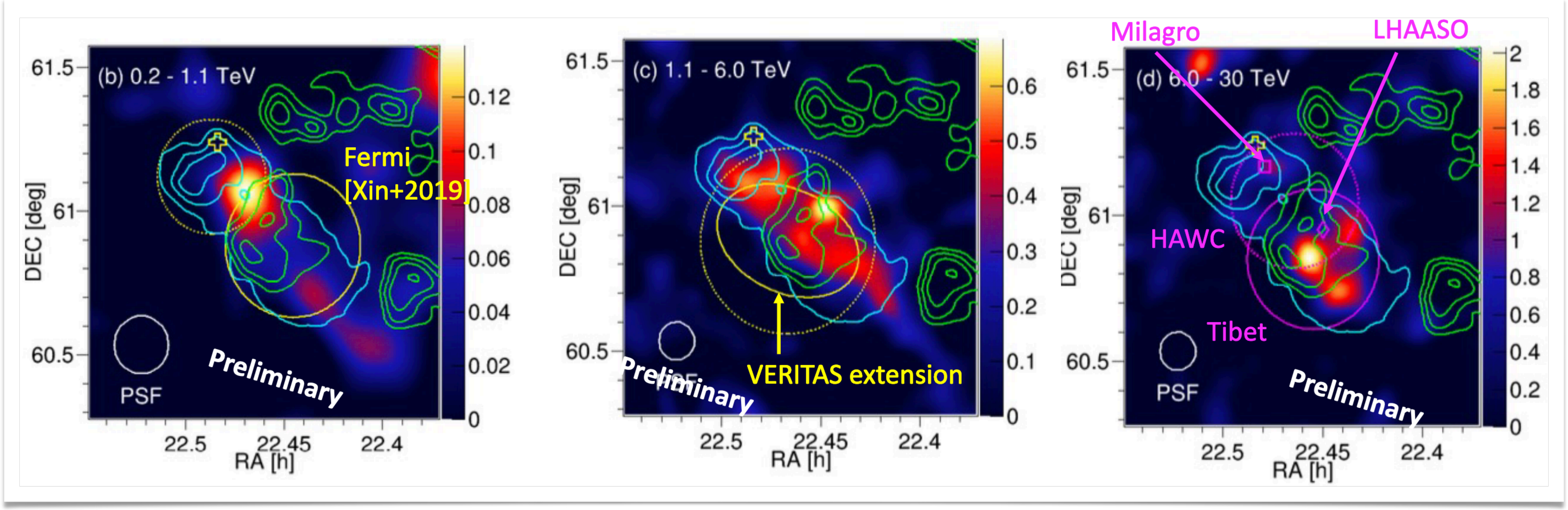
L. Olivera-Nieto et al. (for the H.E.S.S. Collaboration), Gamma 2022, Barcelona

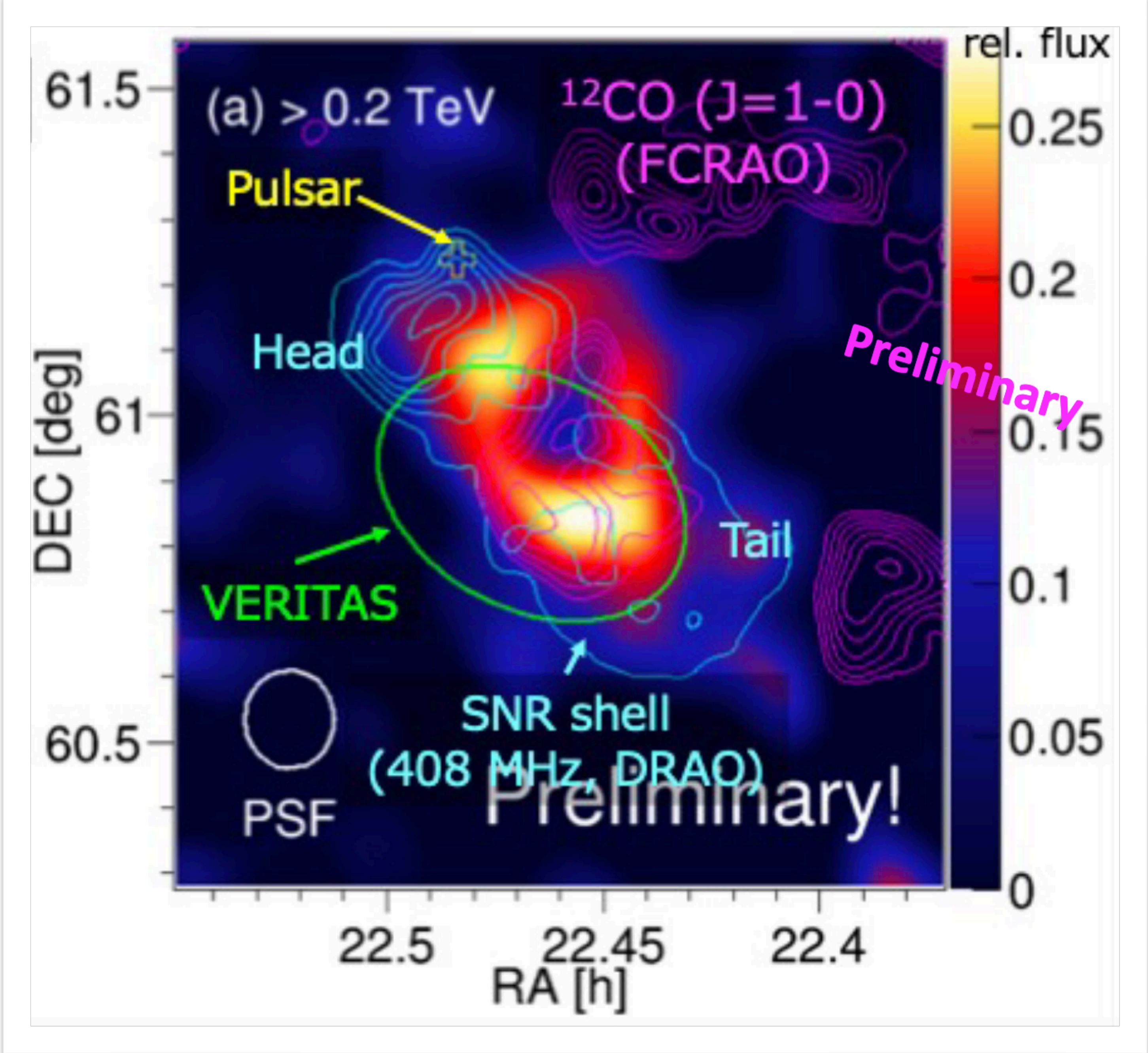
SNR G106.3+2.7 / Boomerang PWN

- Well-known extended gamma-ray source (e.g. VERITAS 2009, Milagro 2009)
- Recently detected up to 100 TeV (Tibet) / 500 TeV (LHAASO)
- Gamma '22: MAGIC provides high-resolution view!
- Two emission regions:
  - ***head***: seen only at low energies → escaped electrons from PWN?
  - ***tail***: seen only at high energies → escaped protons from SNR, colliding with cloud now?

T. Saiko et al. (for the MAGIC Collaboration), Gamma 2022, Barcelona

M. Strzys (for the MAGIC Collaboration), TeVPA 2022, Kingston

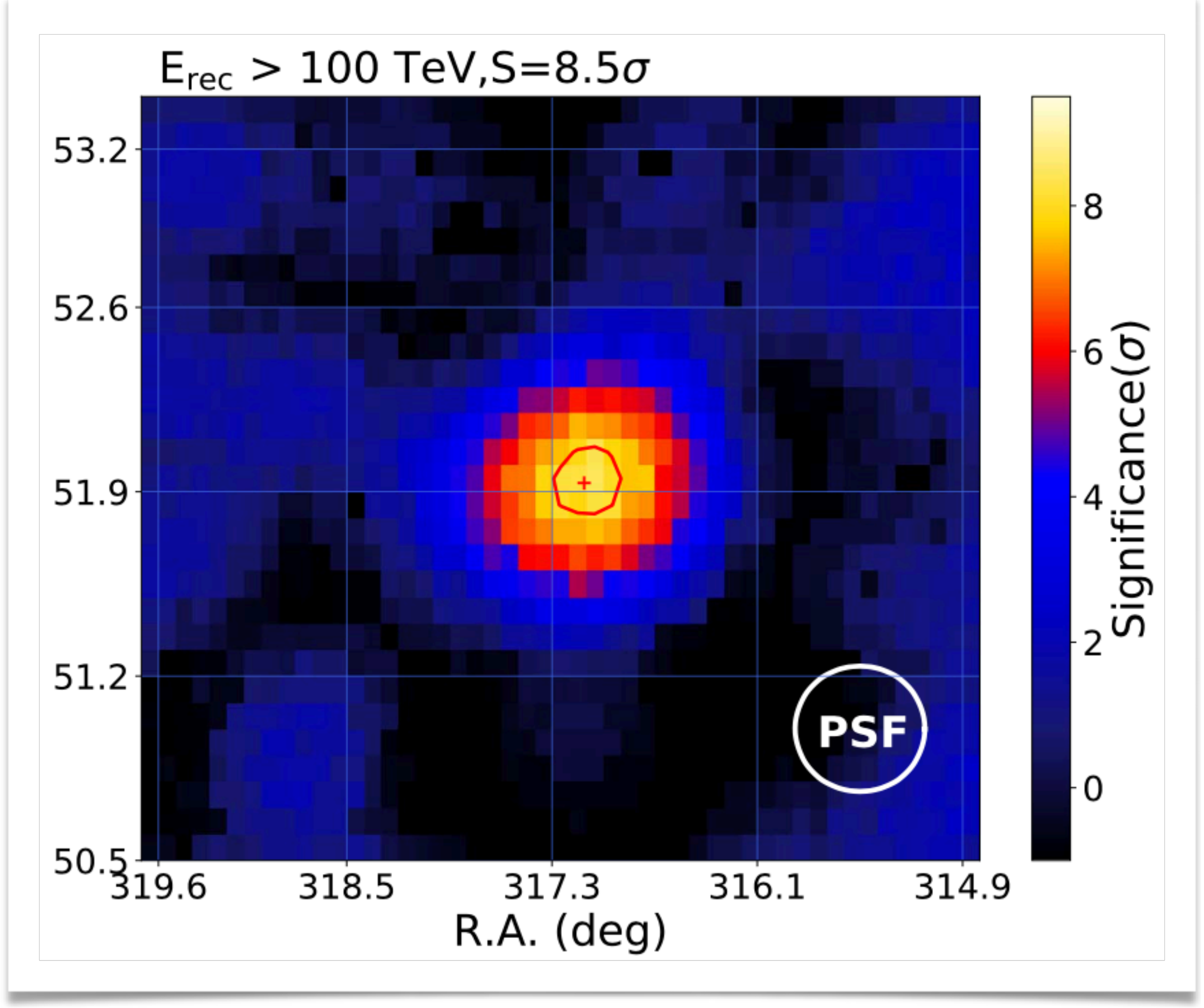




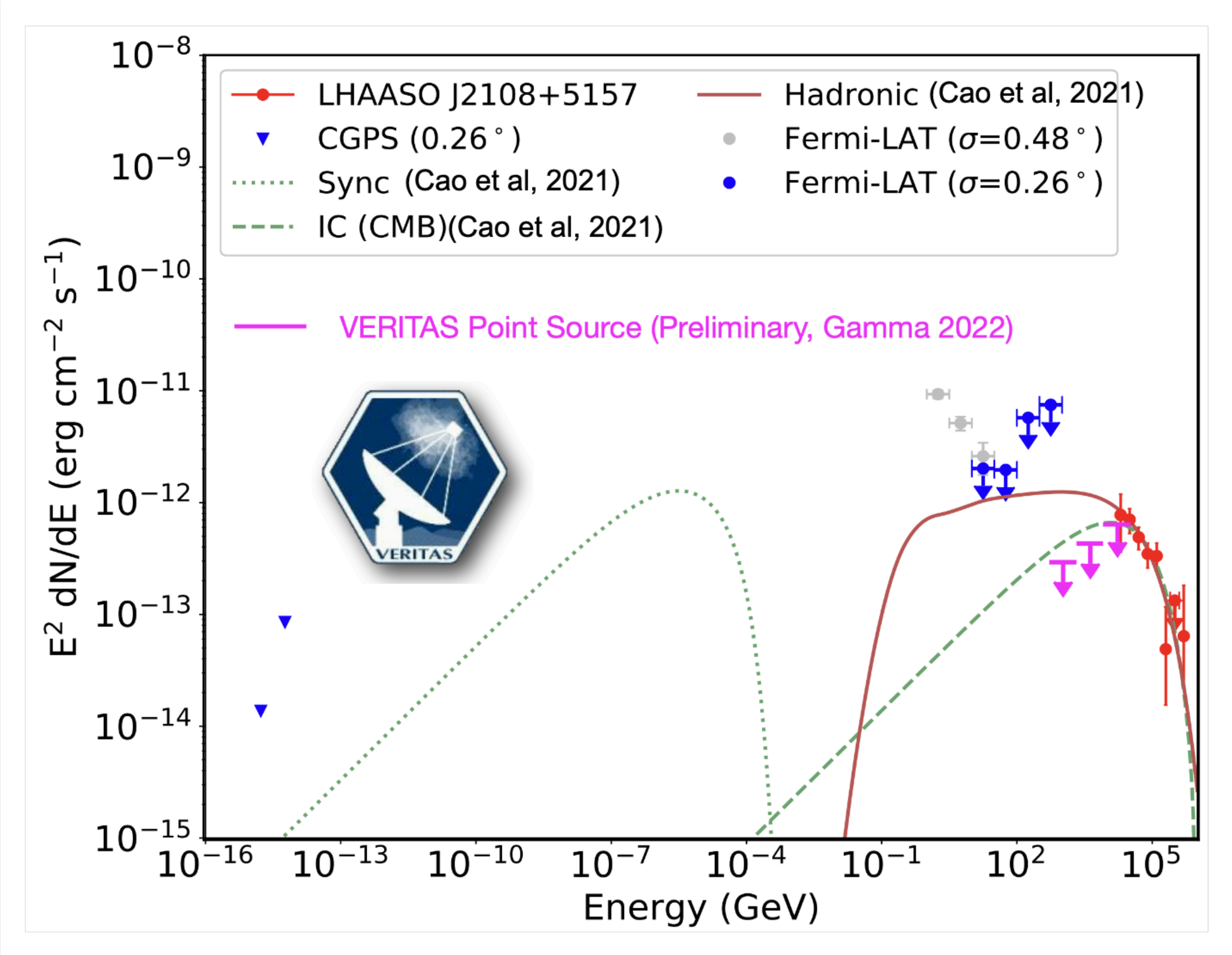
LHAASO J2108+5157

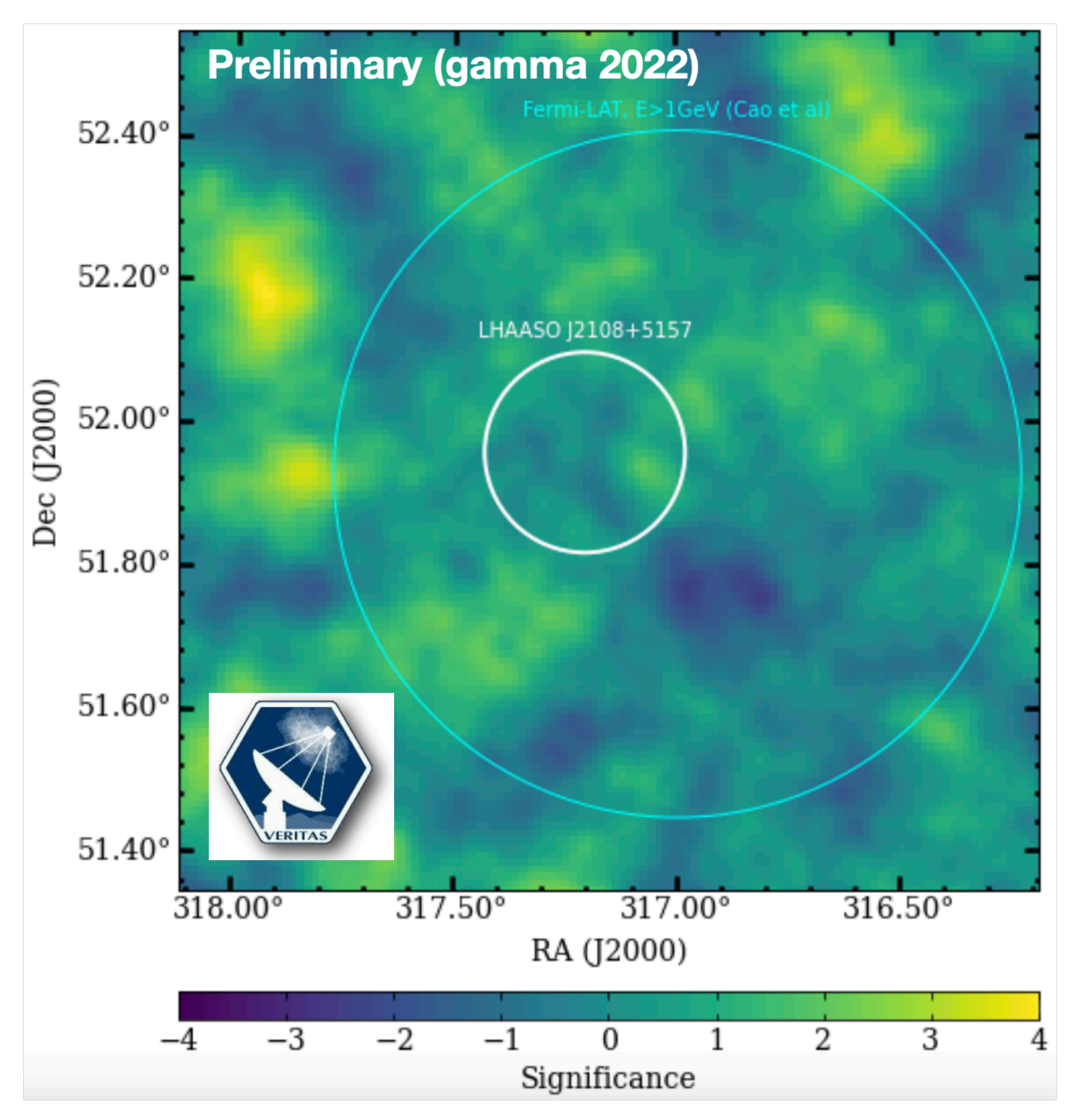
- Discovered by LHAASO above 100 TeV — no detection with IACTs yet!
- No obvious counterpart — coincident with molecular cloud
- VERITAS: no detection in 35 hours
- Point-source upper limits challenge hadronic scenario

N. Park et al.
(for the VERITAS Collaboration),
Gamma 2022, Barcelona



LHAASO Collaboration, ApJL 919, L22 (2021)

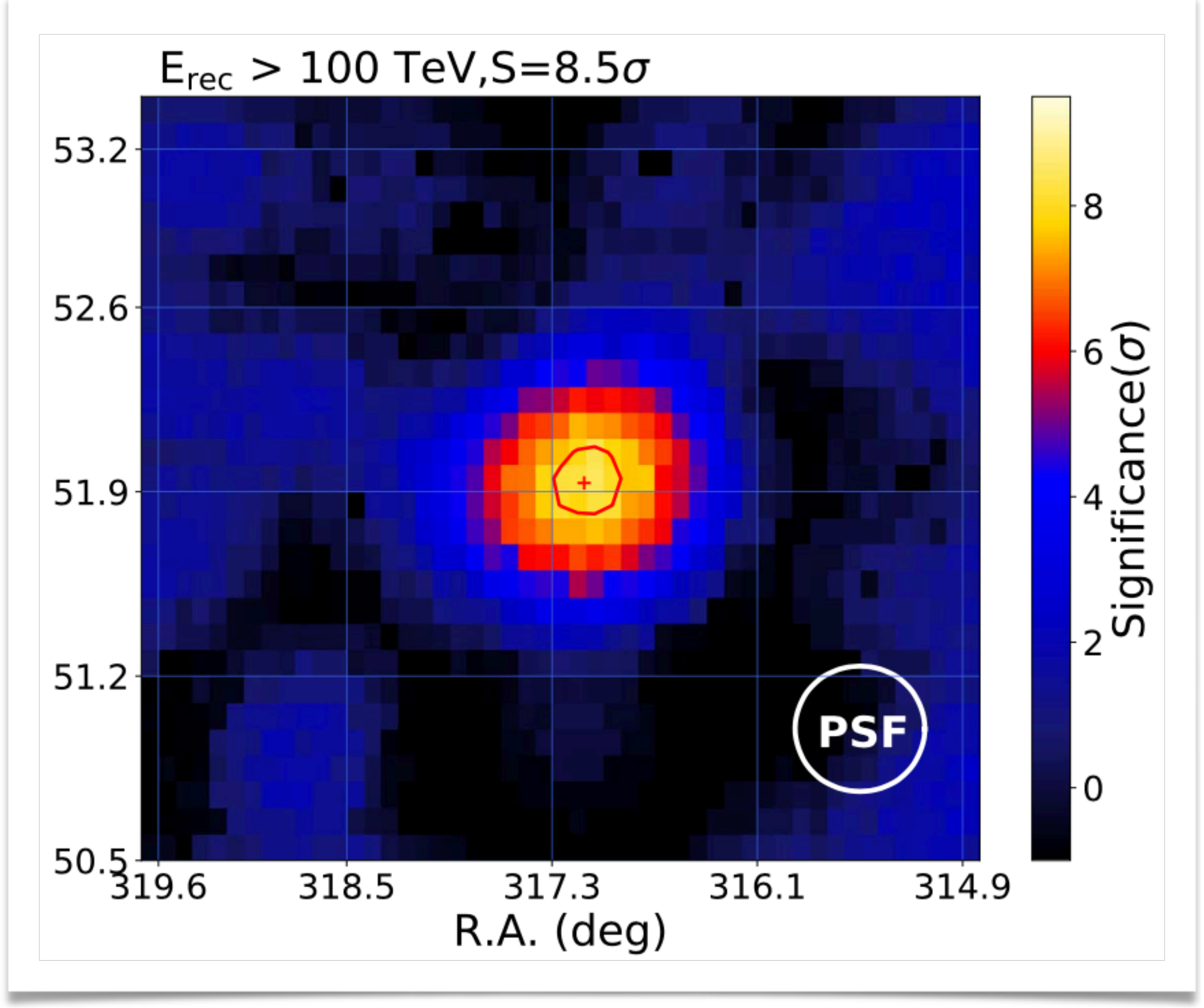




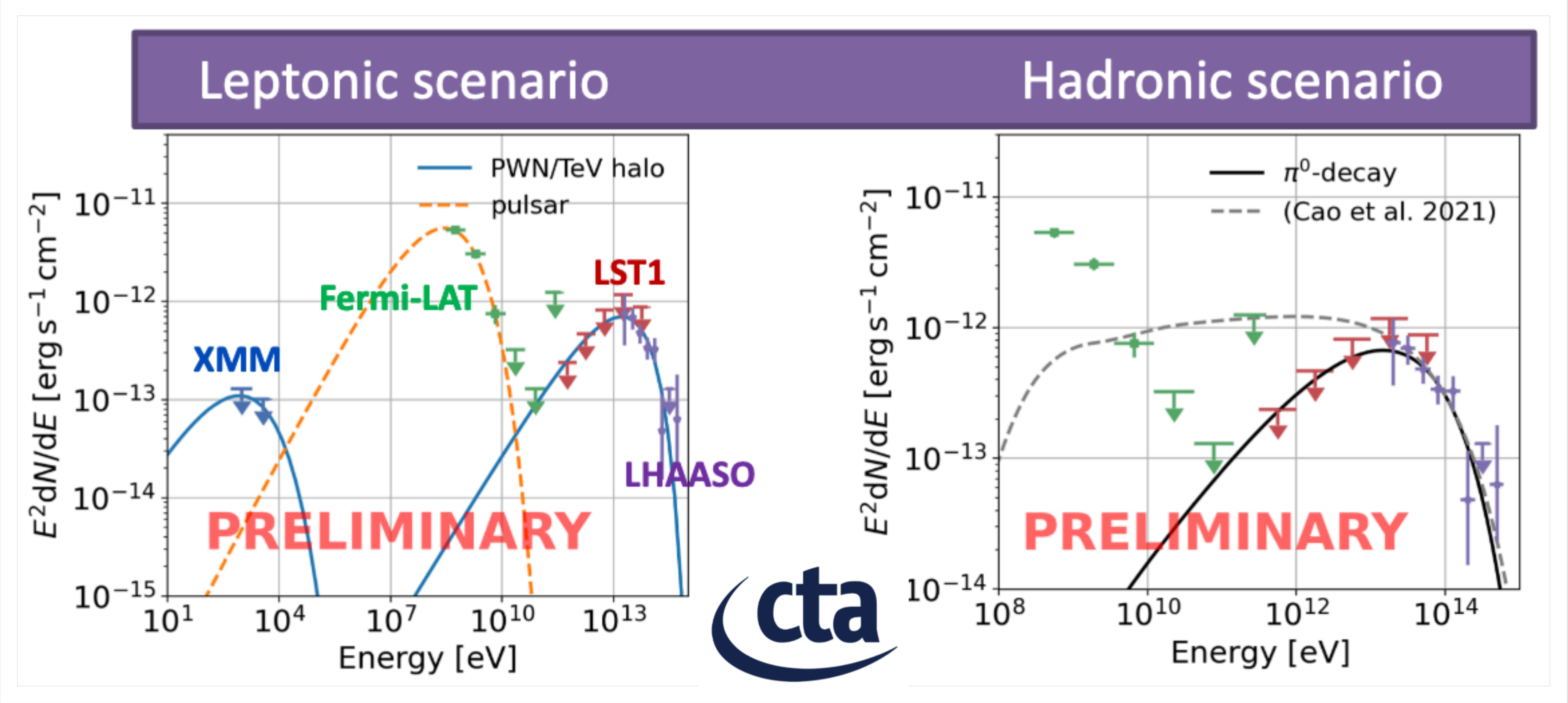
LHAASO J2108+5157

- Discovered by LHAASO above 100 TeV — no detection with IACTs yet!
- No obvious counterpart — coincident with molecular cloud
- VERITAS: no detection in 35 hours
- Point-source upper limits challenge hadronic scenario
- ***Similarly with CTA LST-1: no detection in 91 hours***

J. Cortina / J. Jurišek (for the LST-1 Collaboration), Gamma 2022, Barcelona

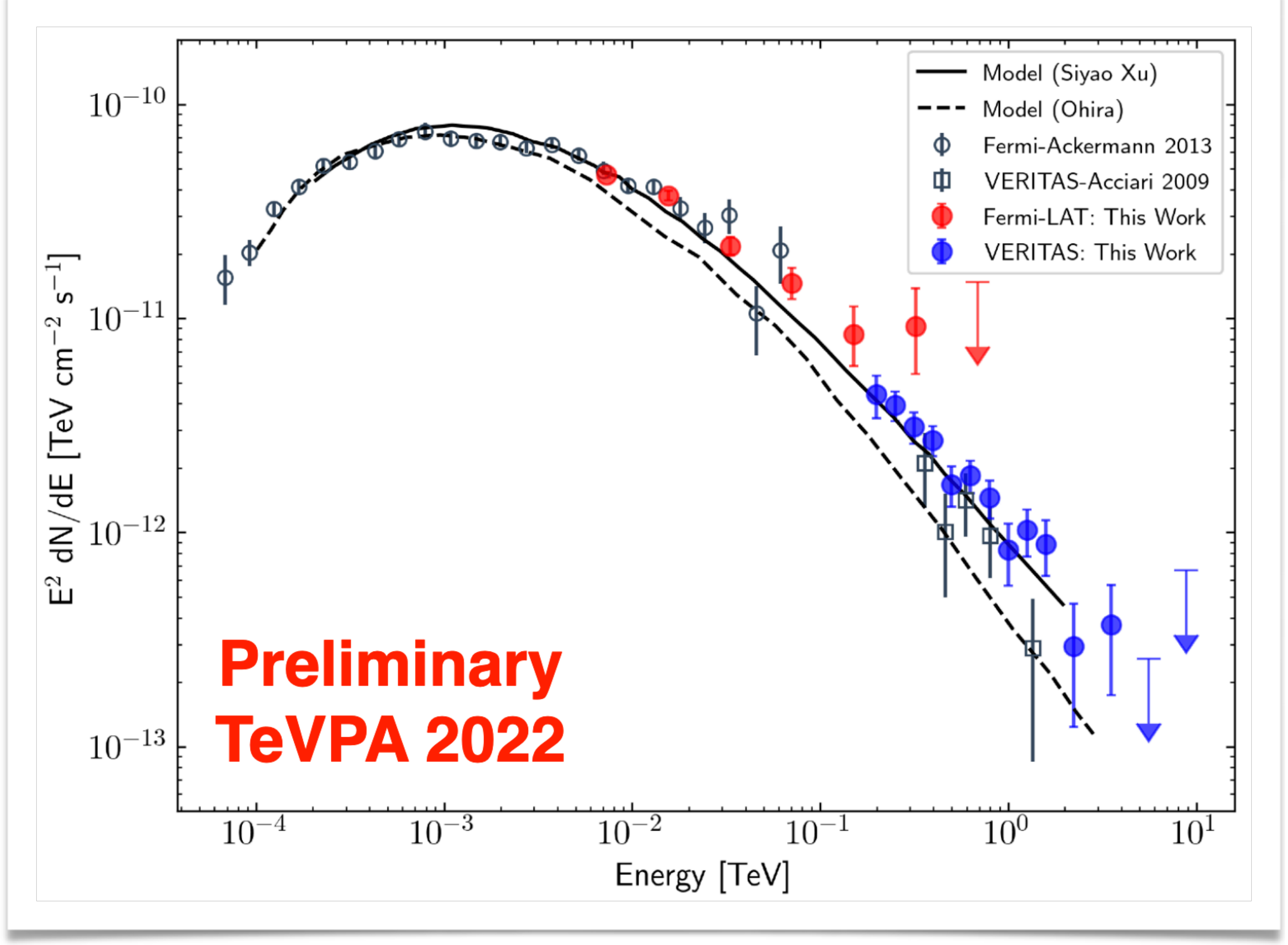


LHAASO Collaboration, ApJL 919, L22 (2021)

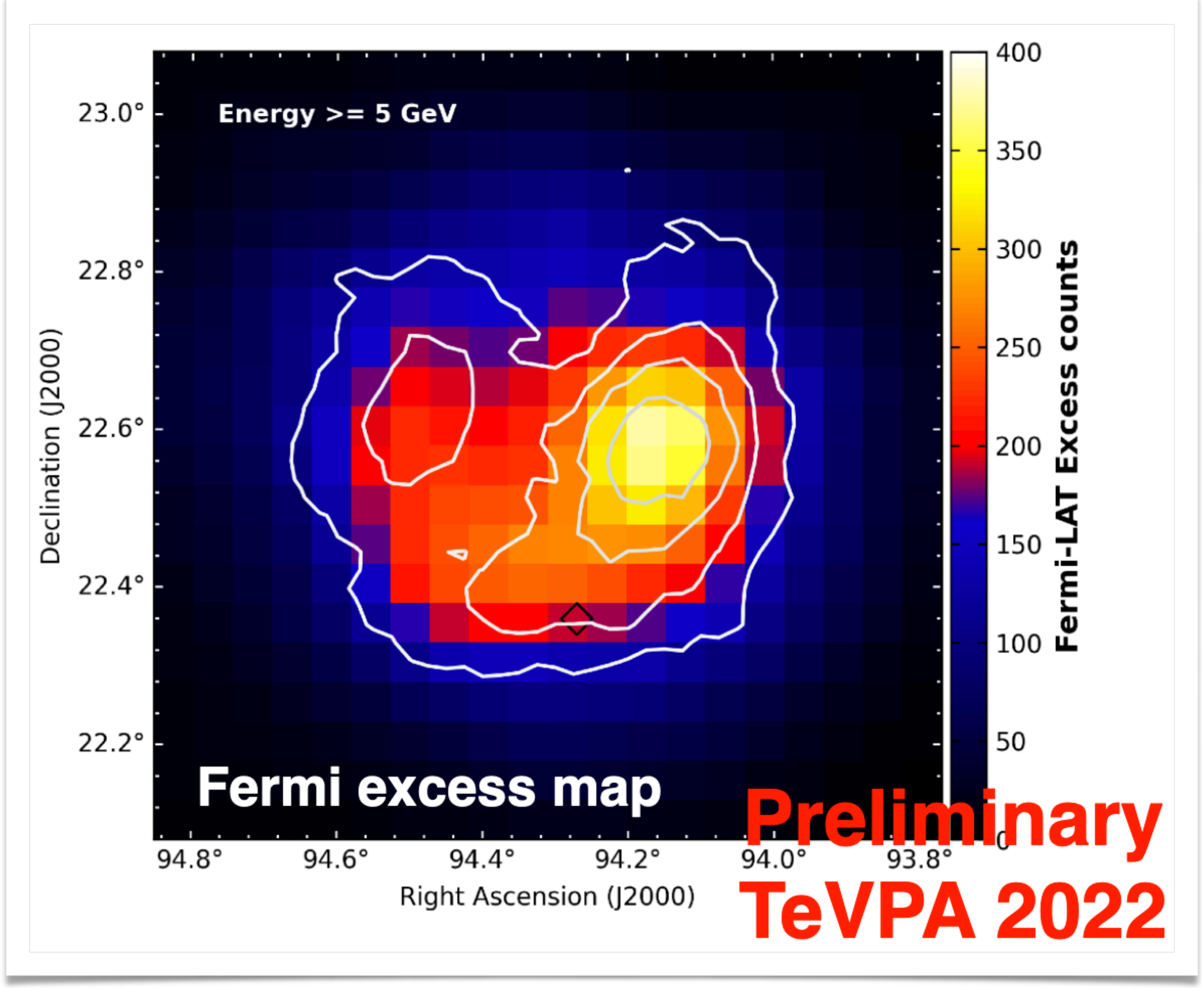


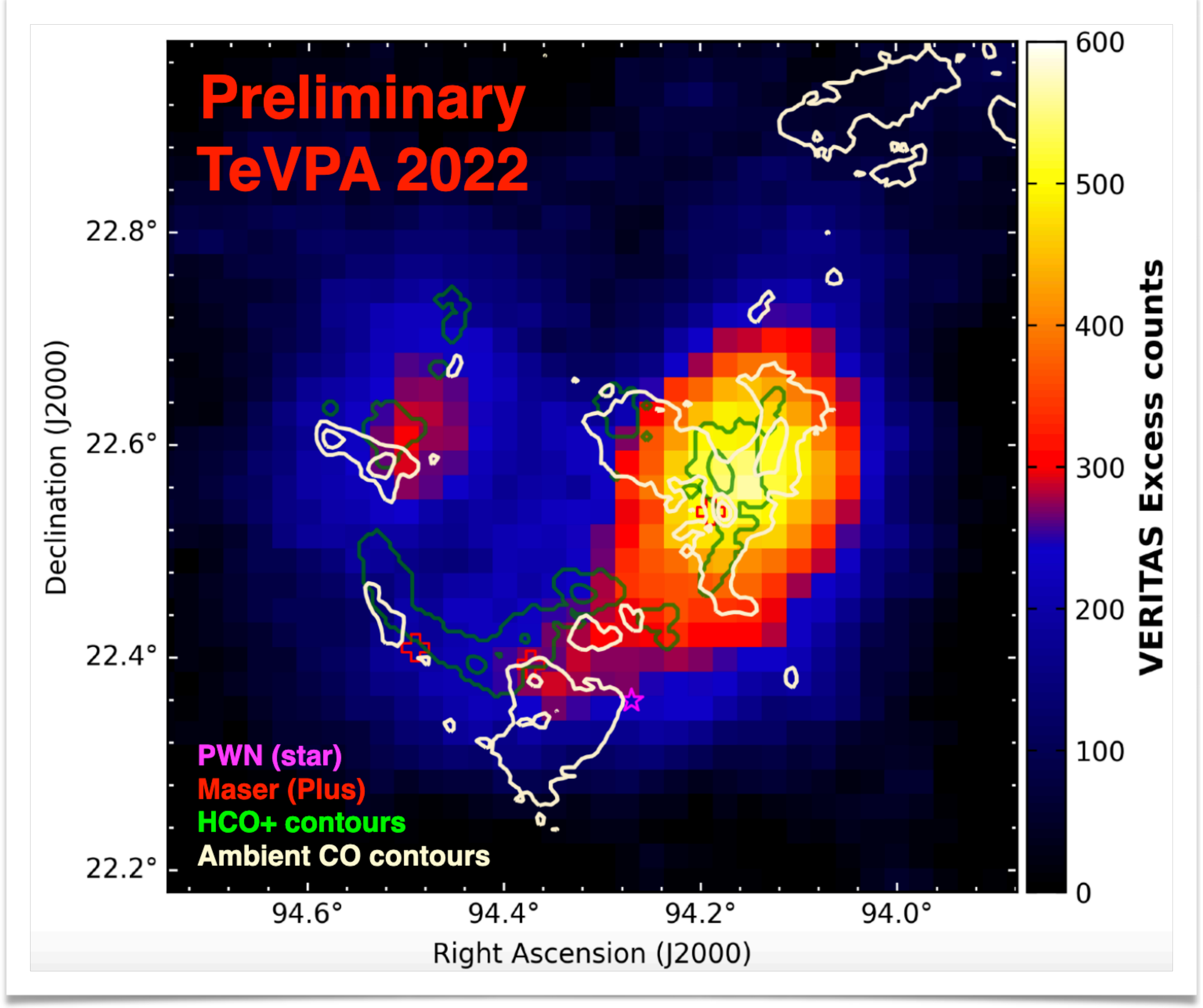
SNR IC 443

- Detailed study by VERITAS
- Nice correlation with GeV emission measured with Fermi-LAT
  - suggests common origin of emission
- Emission also correlated with gas tracers
- A hadronic accelerator — but not a PeVatron...



Sajan Kumar (for the VERITAS Collaboration), TeVPA 2022, Kingston (Mon 08/08, Galactic Sources I)





Conclusion

- Galactic gamma-ray sources are often extended / complex in morphology
  - high angular resolution of IACTs is crucial
  - 3D likelihood analysis can be a powerful tool
- Westerlund 1
  - complex gamma-ray emission with shell-like structure
  - are stellar clusters the main accelerators of Galactic cosmic rays?
- HESS J1809–193
  - resolved into two distinct components
  - dynamic PWN system or mixed PWN / SNR scenario?
- After more than a decade, H.E.S.S., MAGIC & VERITAS are still providing exciting results
  - recently, very fruitful interplay with wide-field instruments (HAWC, LHAASO, Tibet)
  - exciting prospects with CTA!