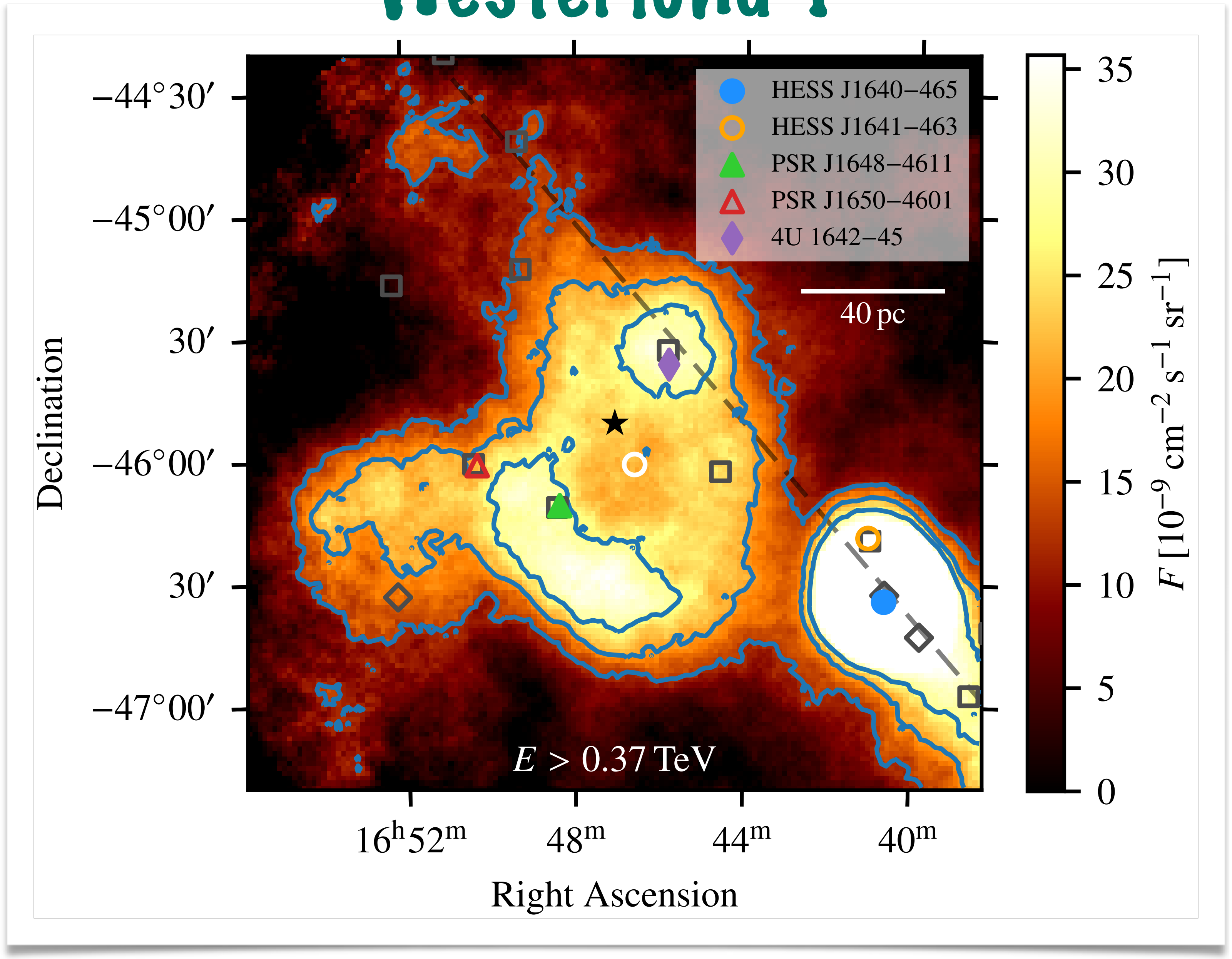
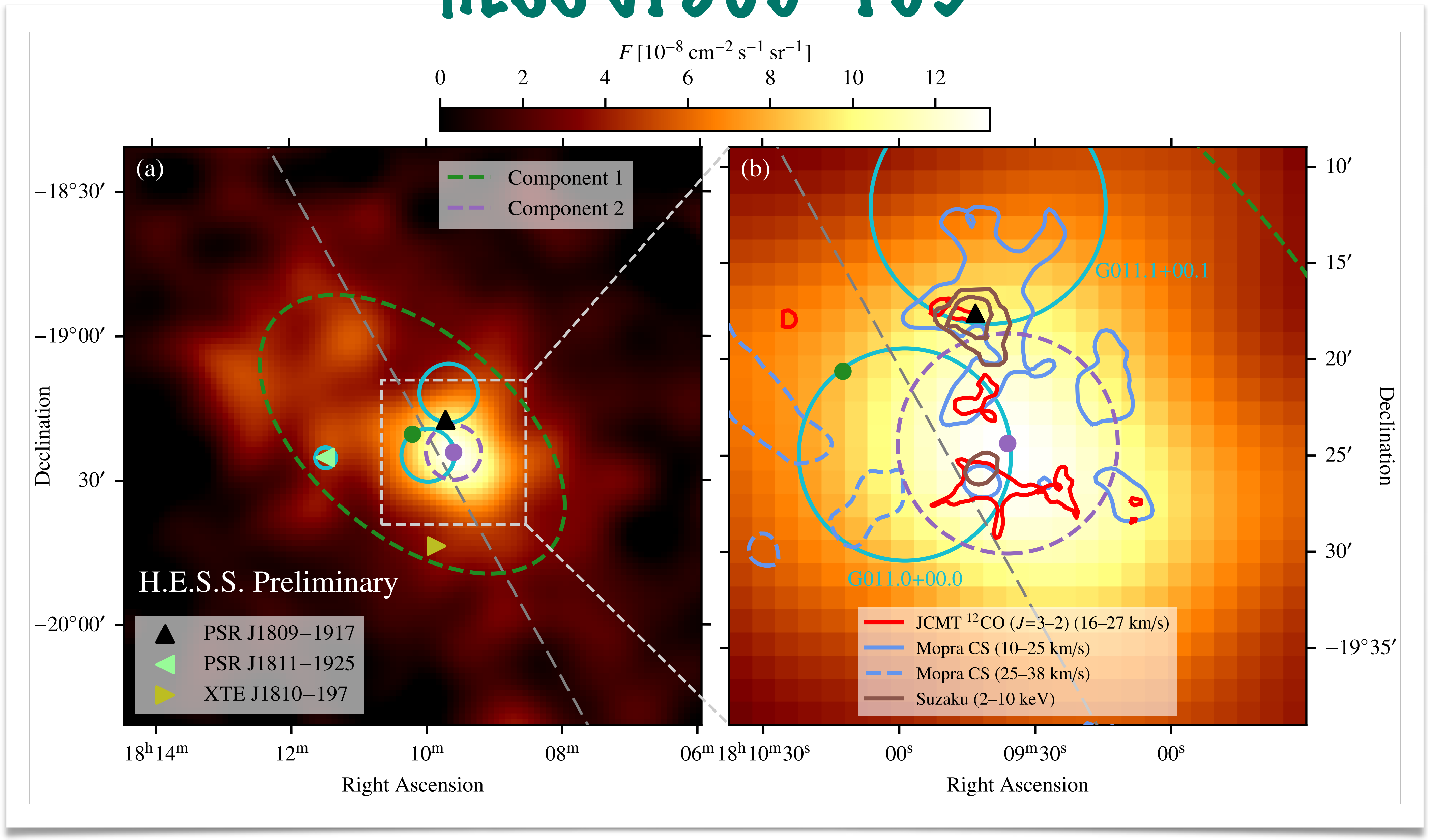
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Westerlund 1



HESS J1809−193



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

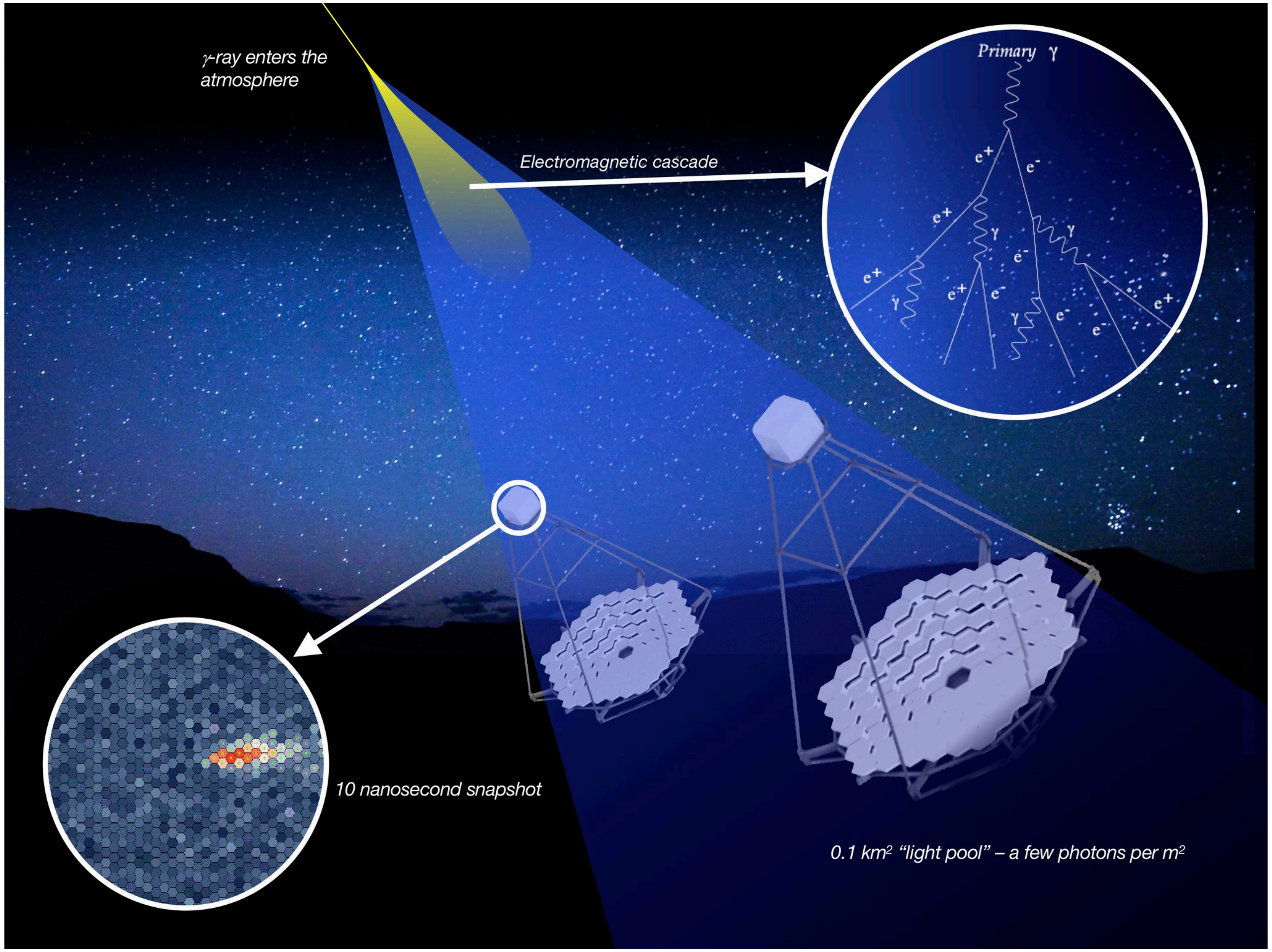
Lars Mohrmann

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

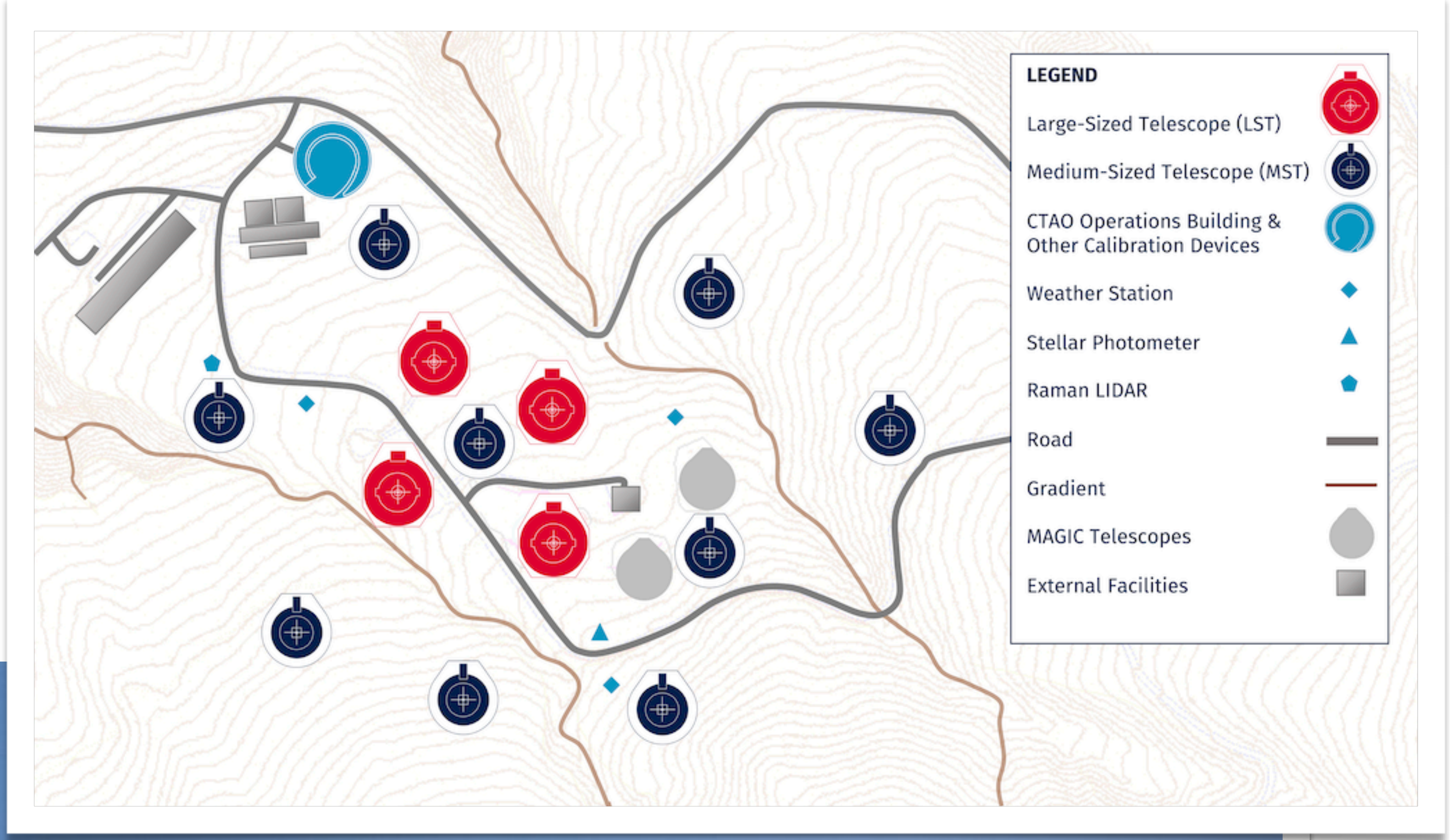
- MAGIC
  - La Palma, Spain
  - since 2004
  - 2x 17-m IACTs

- 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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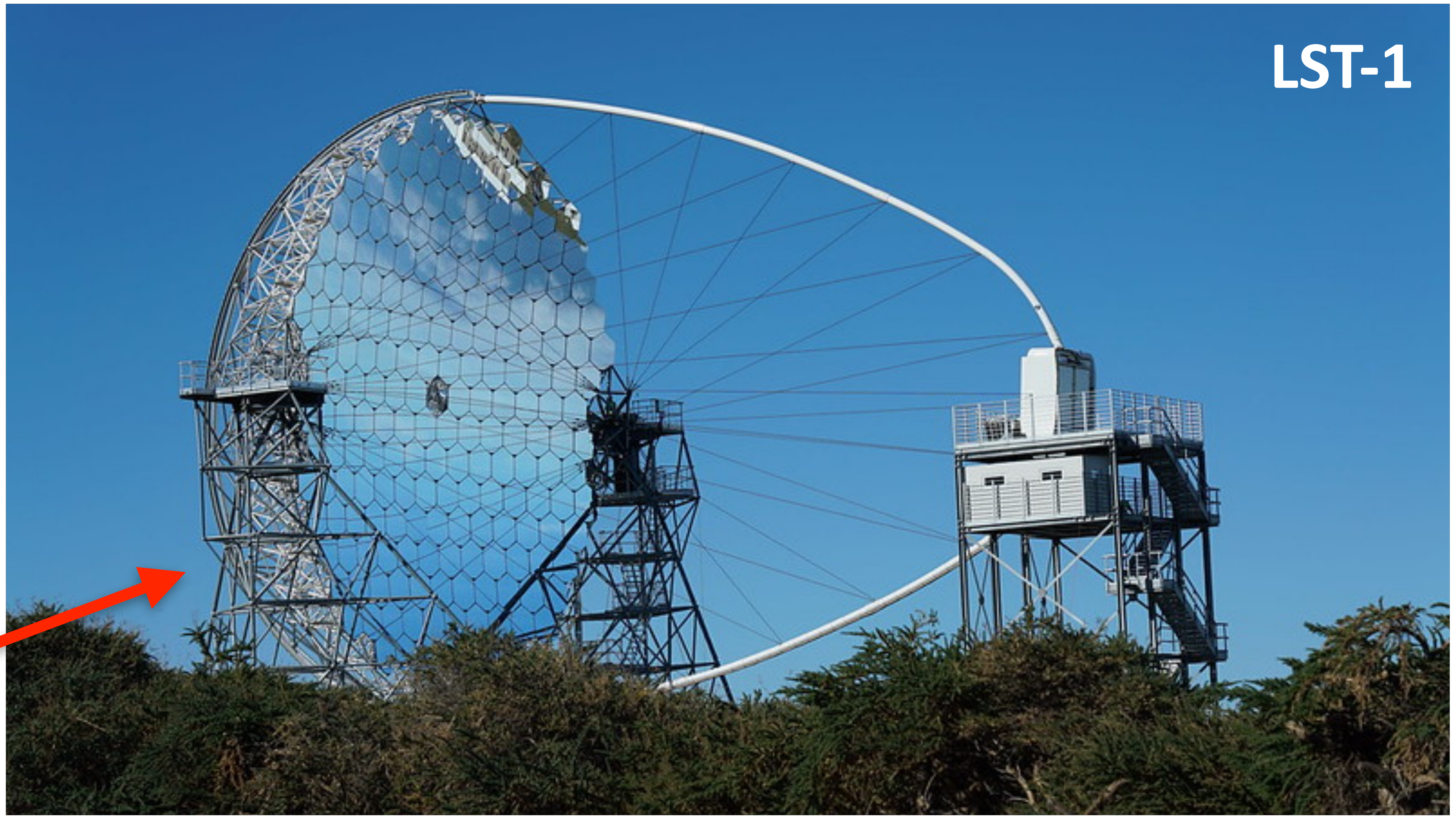
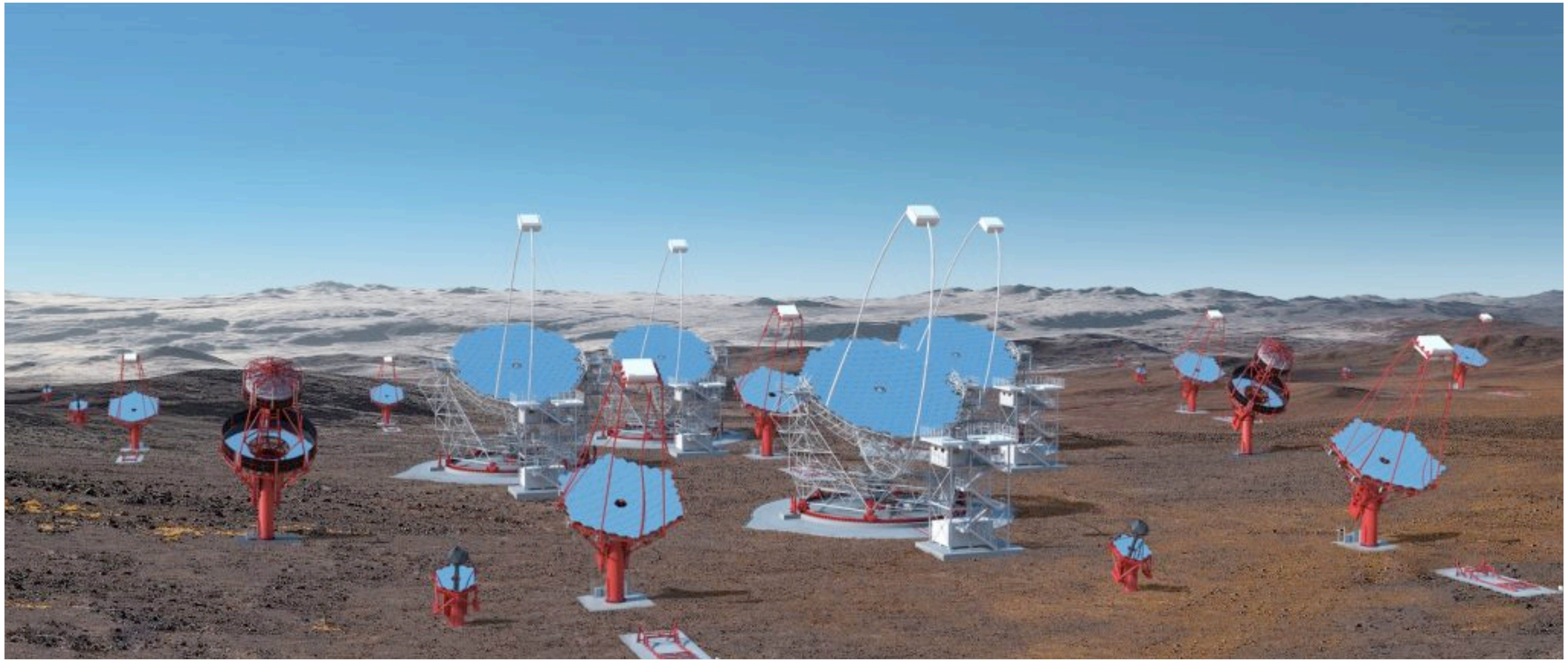
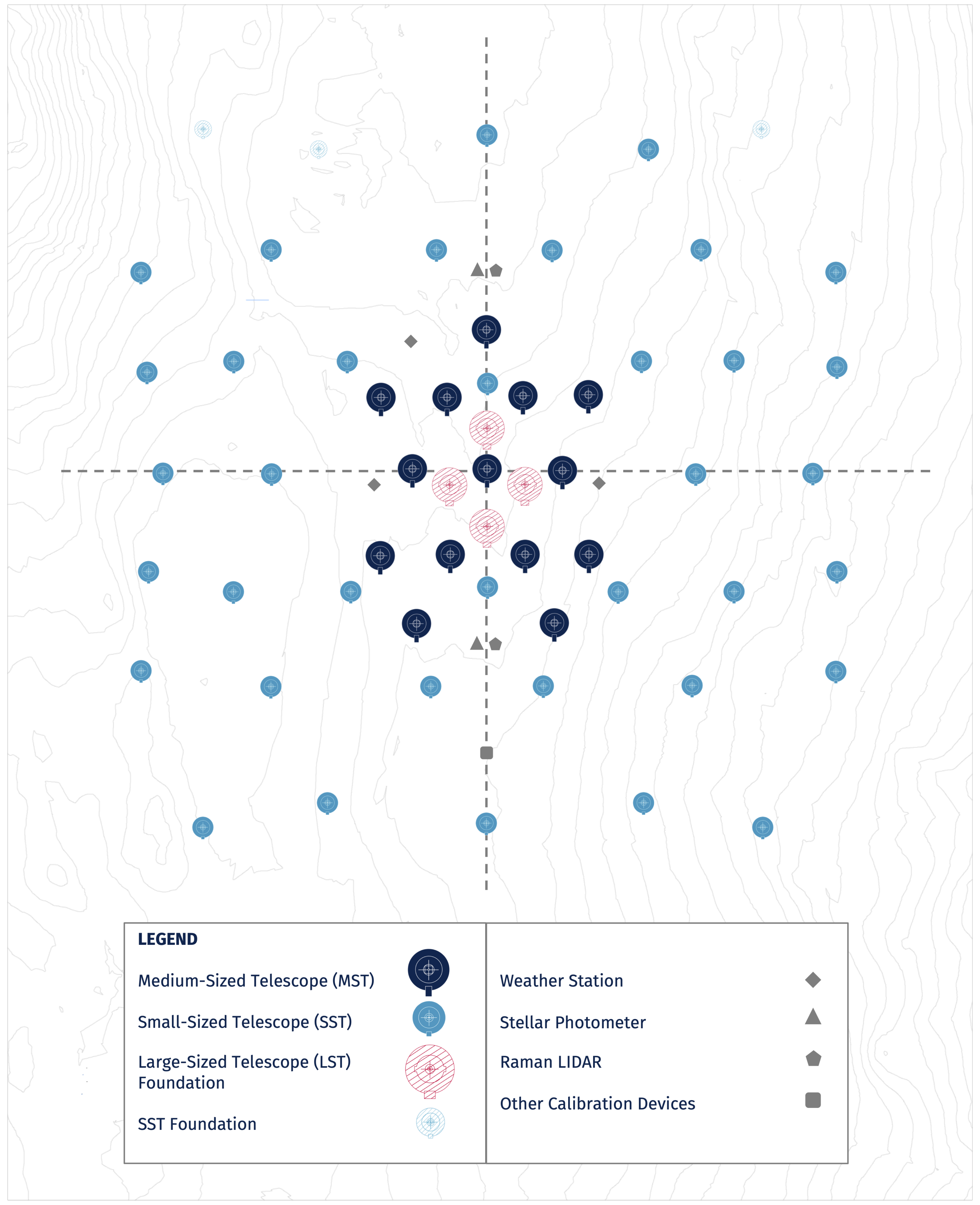


Cherenkov Telescope Array (CTA)

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





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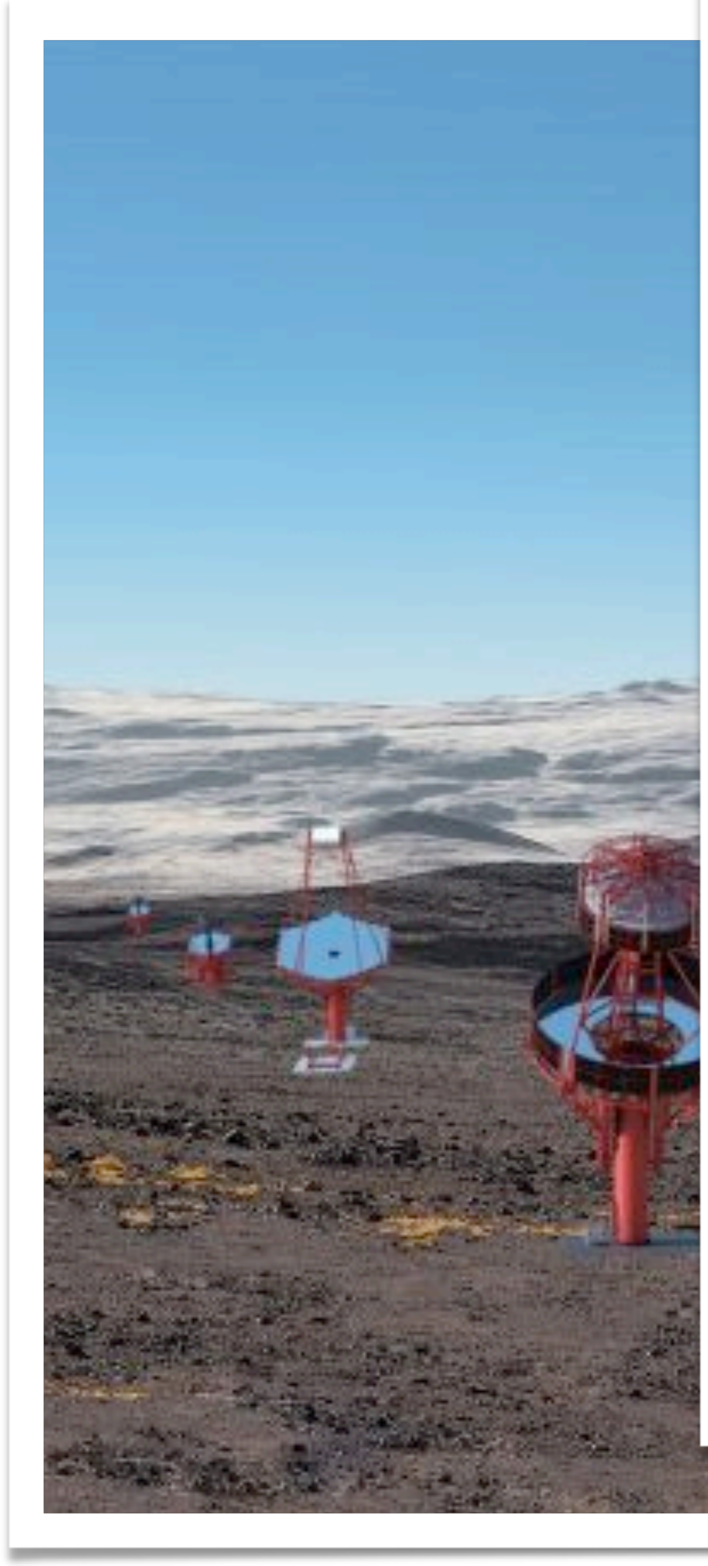
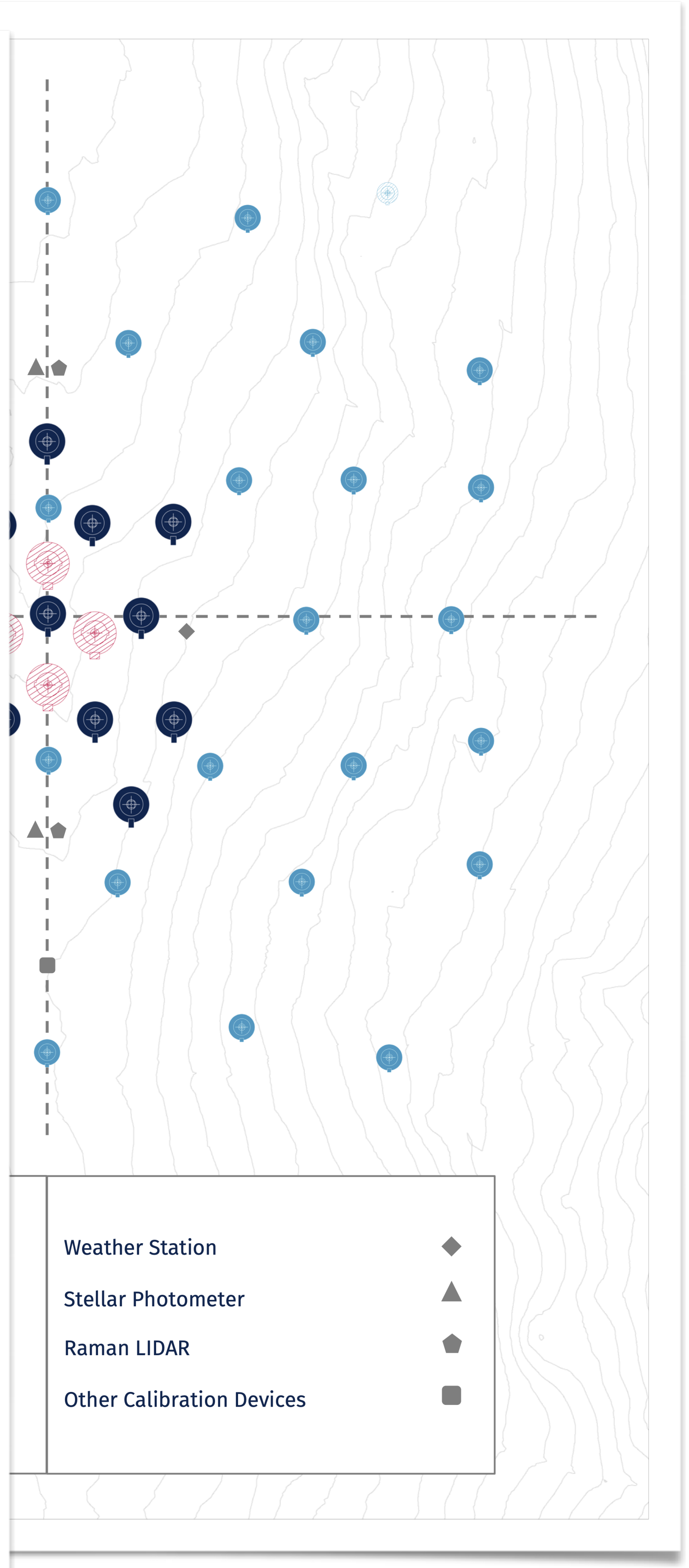
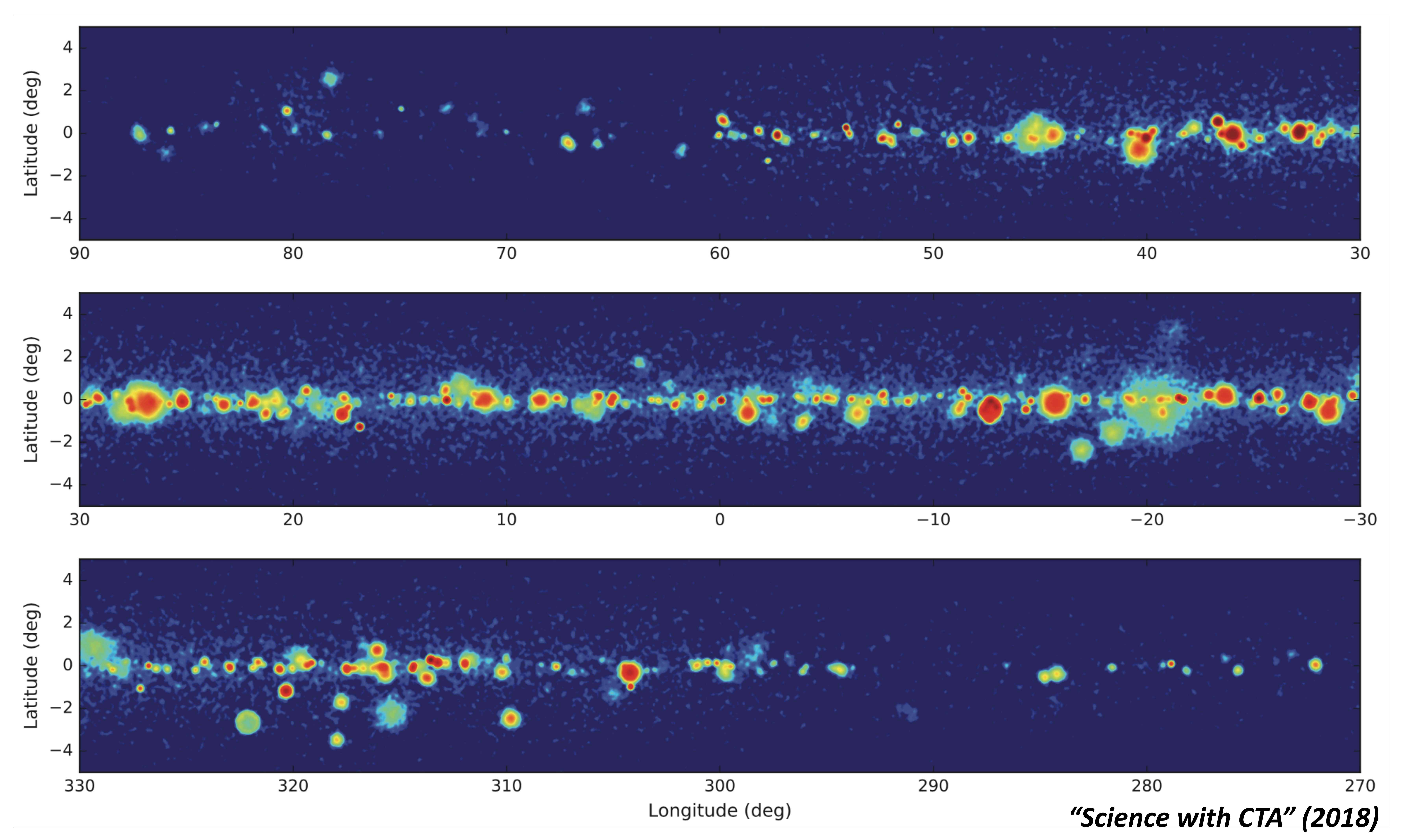


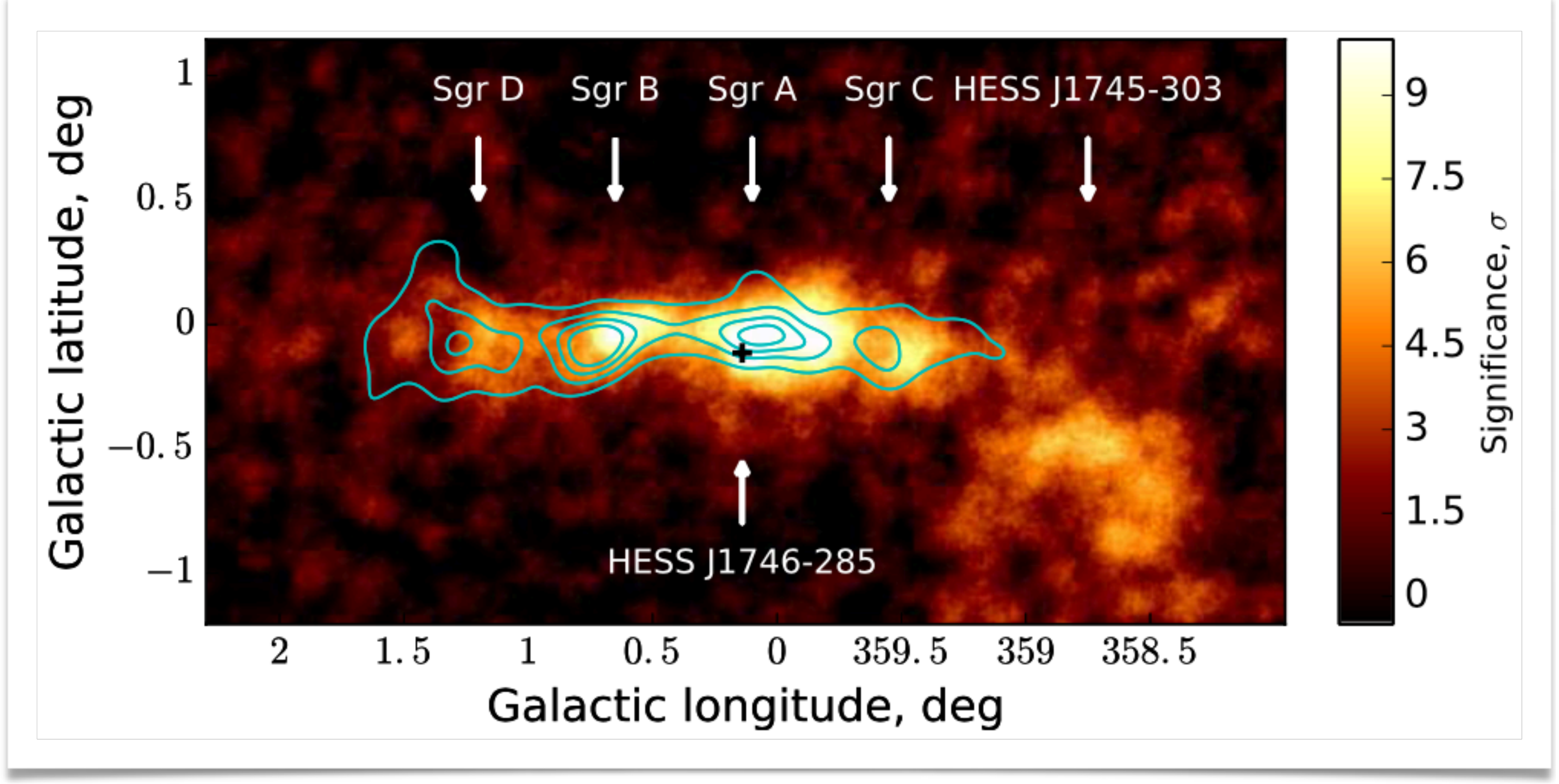




"Science with CTA" (2018)

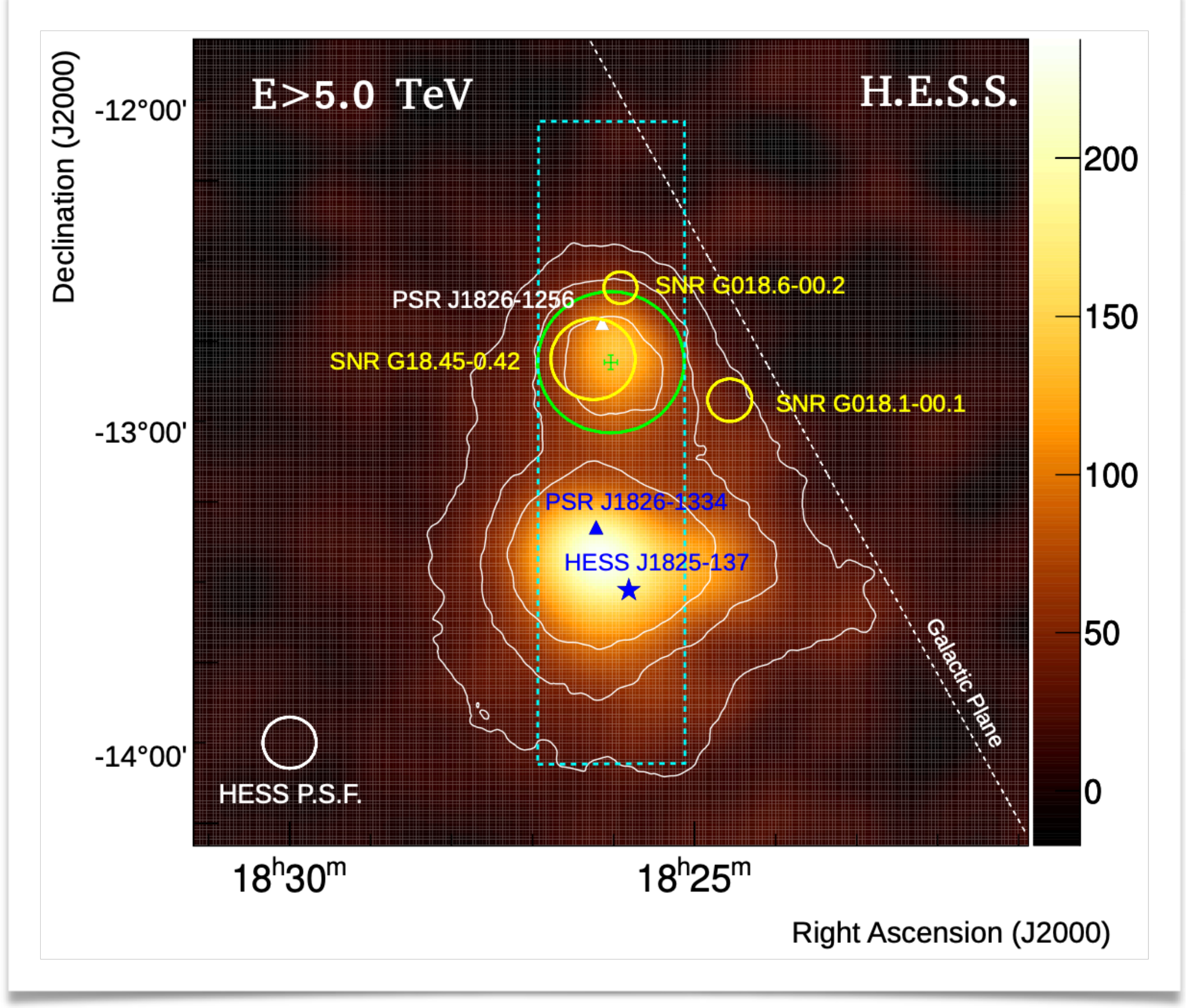
Measuring galactic γ-ray sources with IACTs: challenges

- 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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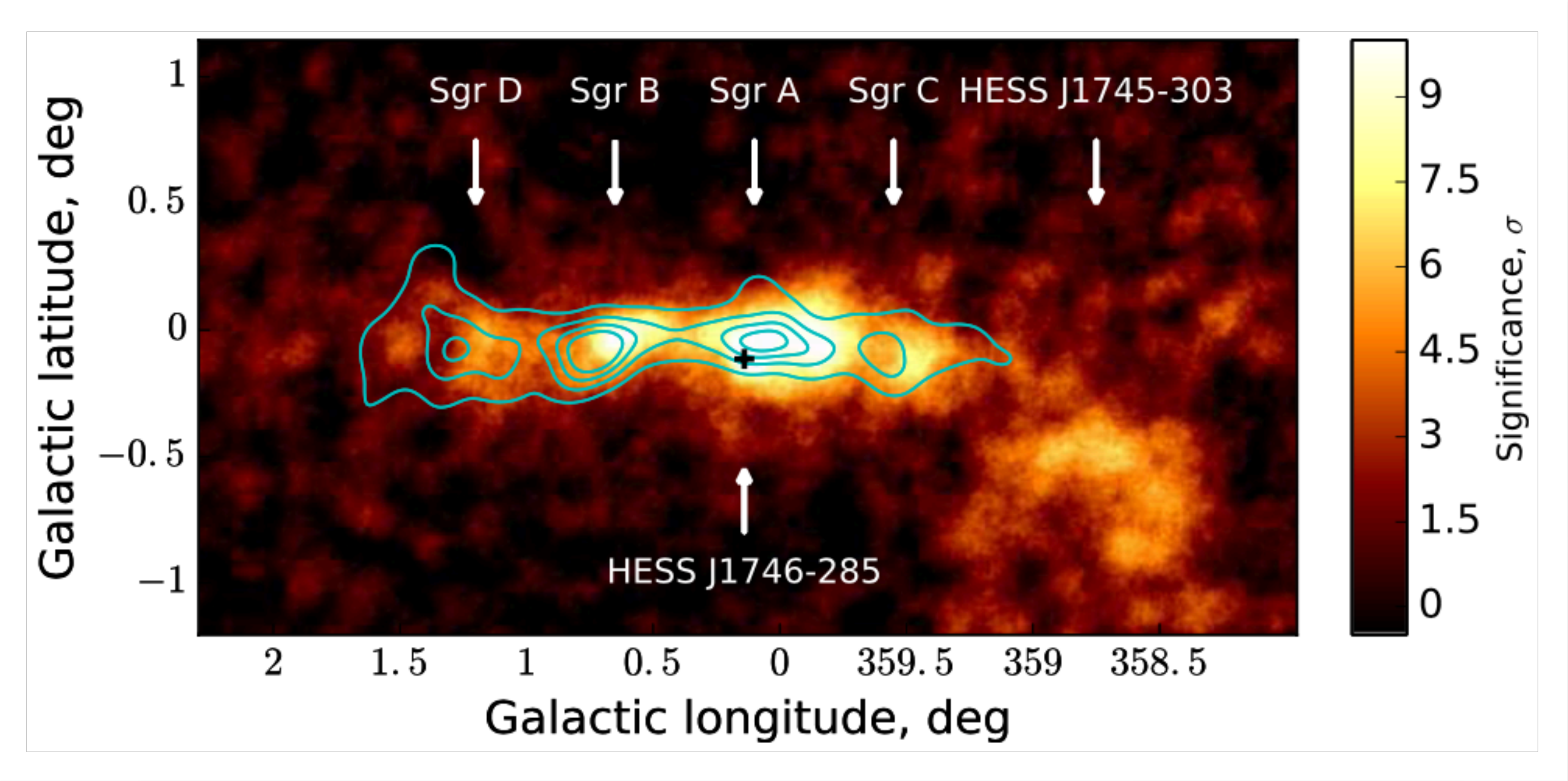

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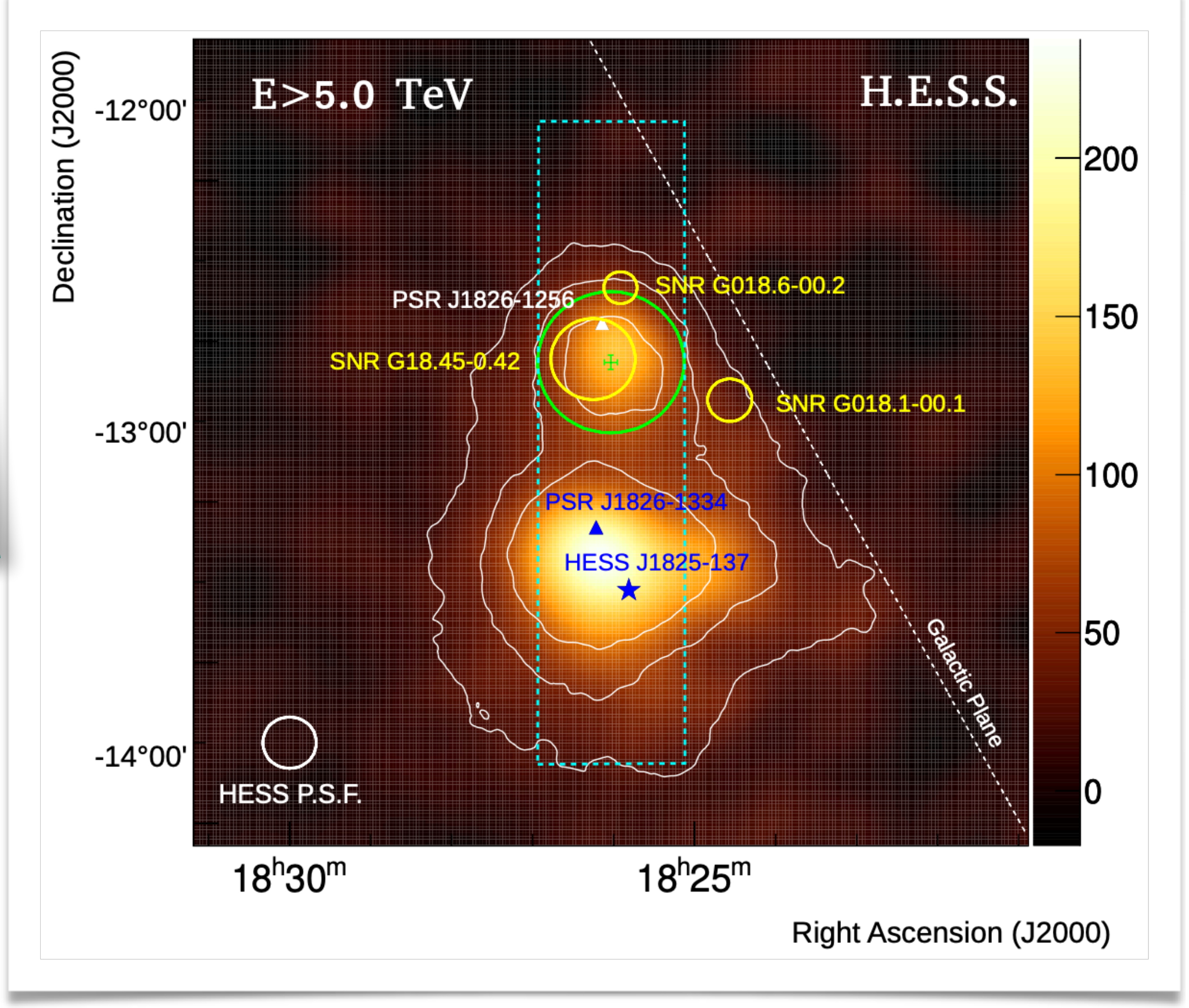
But: of all instruments, IACTs are best equipped to tackle this!



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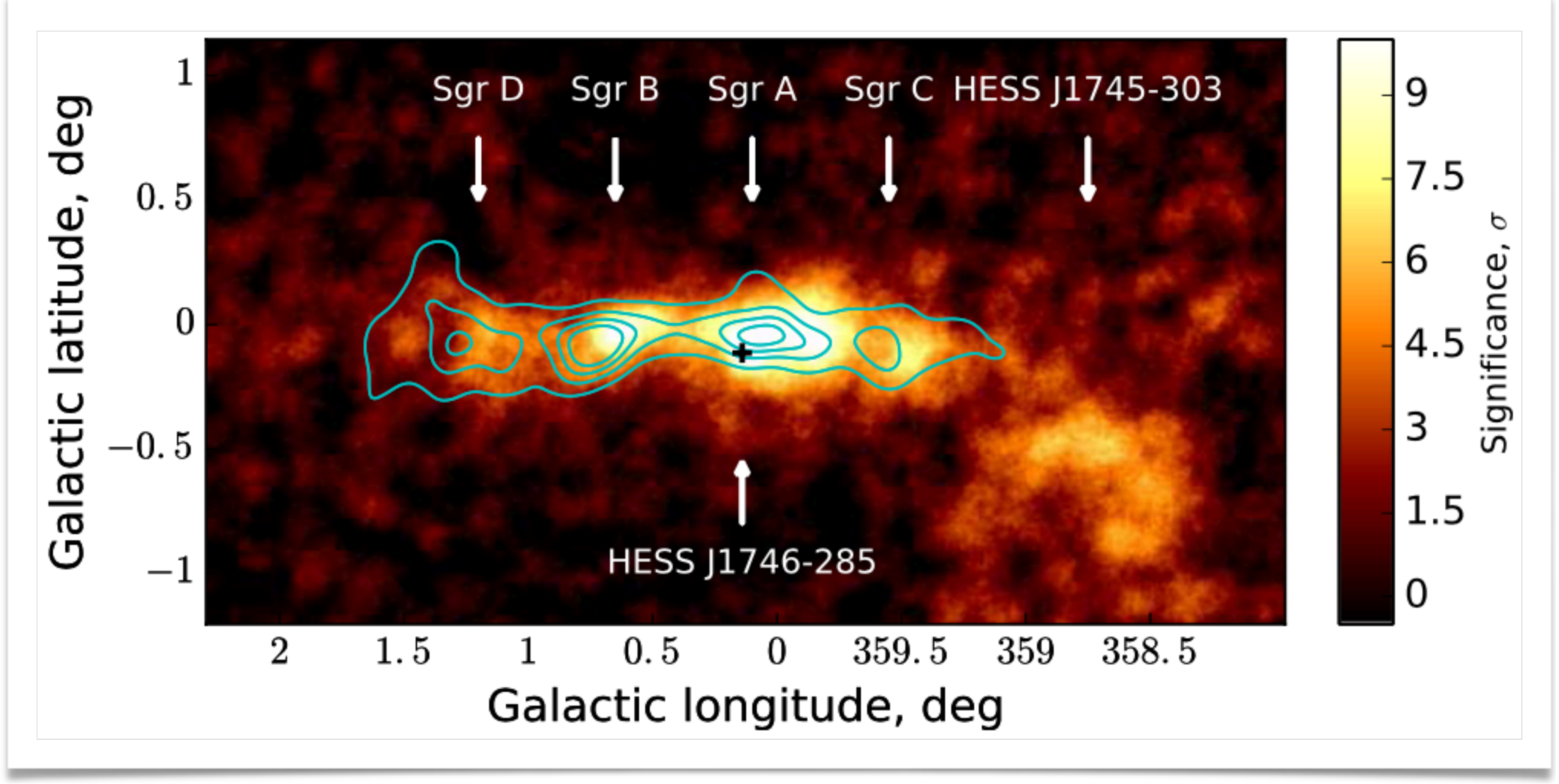
CTA telescopes will have significantly larger fields of view



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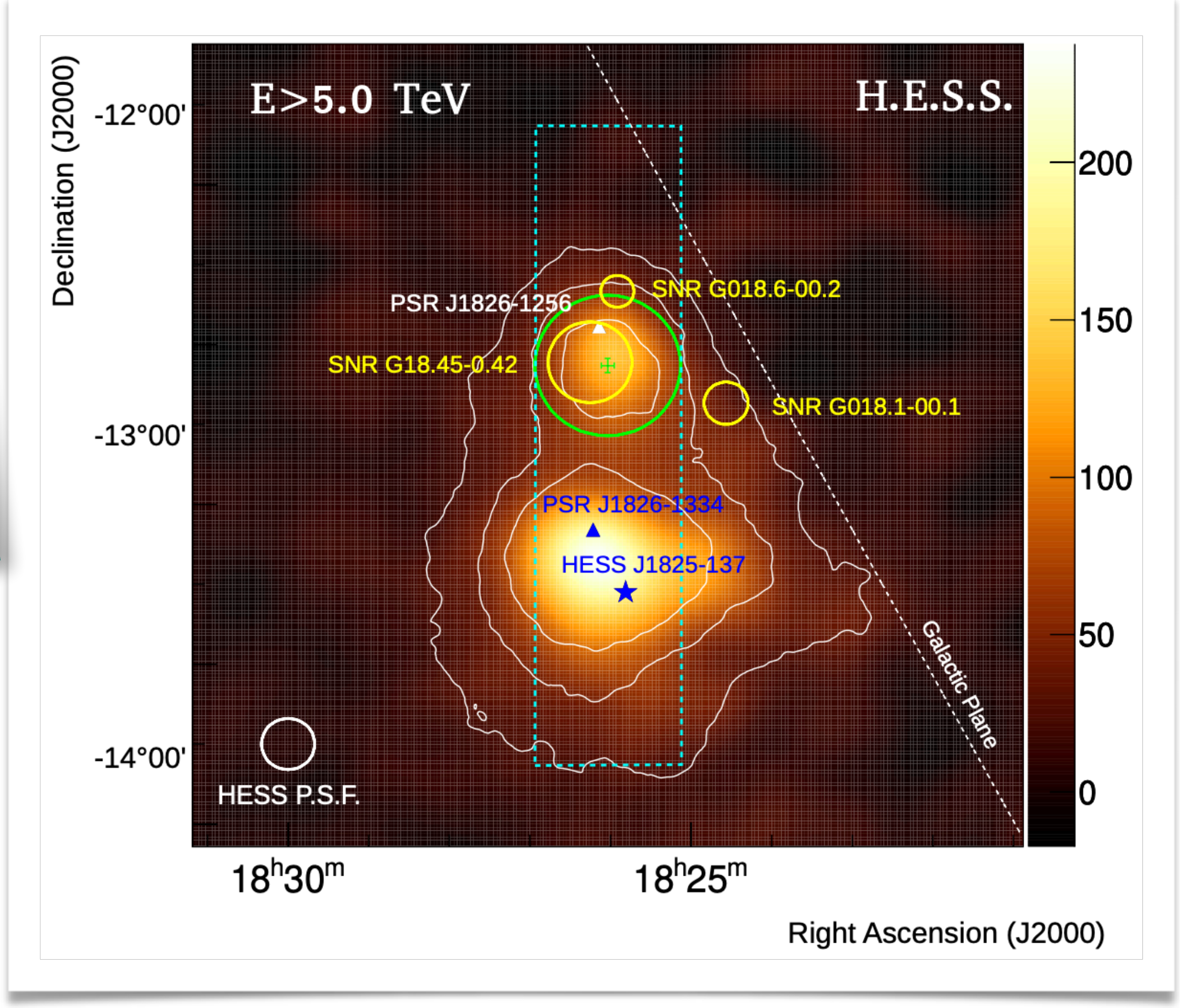
But: of all instruments, IACTs are best equipped to tackle this!

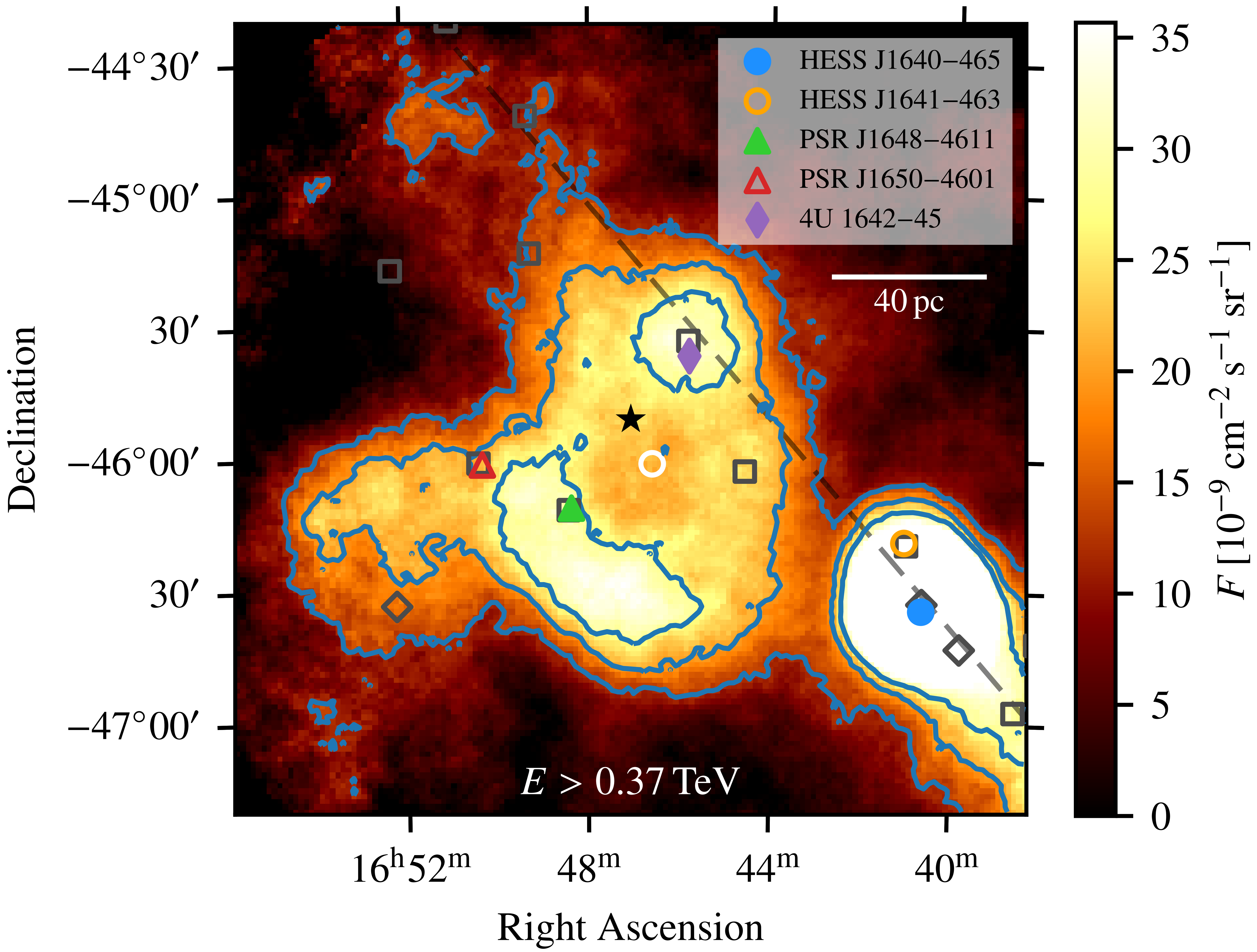
CTA will provide even better angular resolution



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

Westerlund 1

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

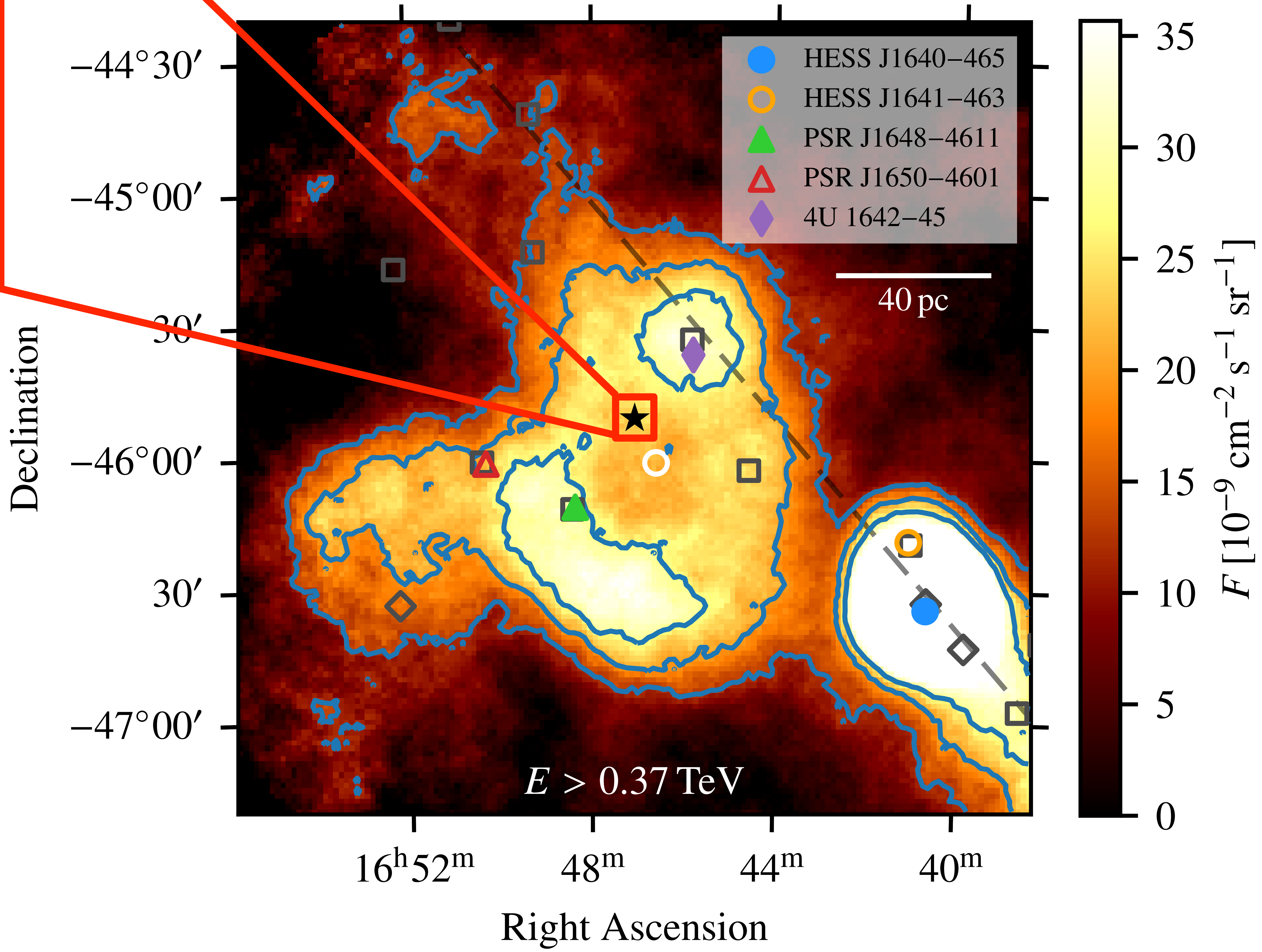


Westerlund 1

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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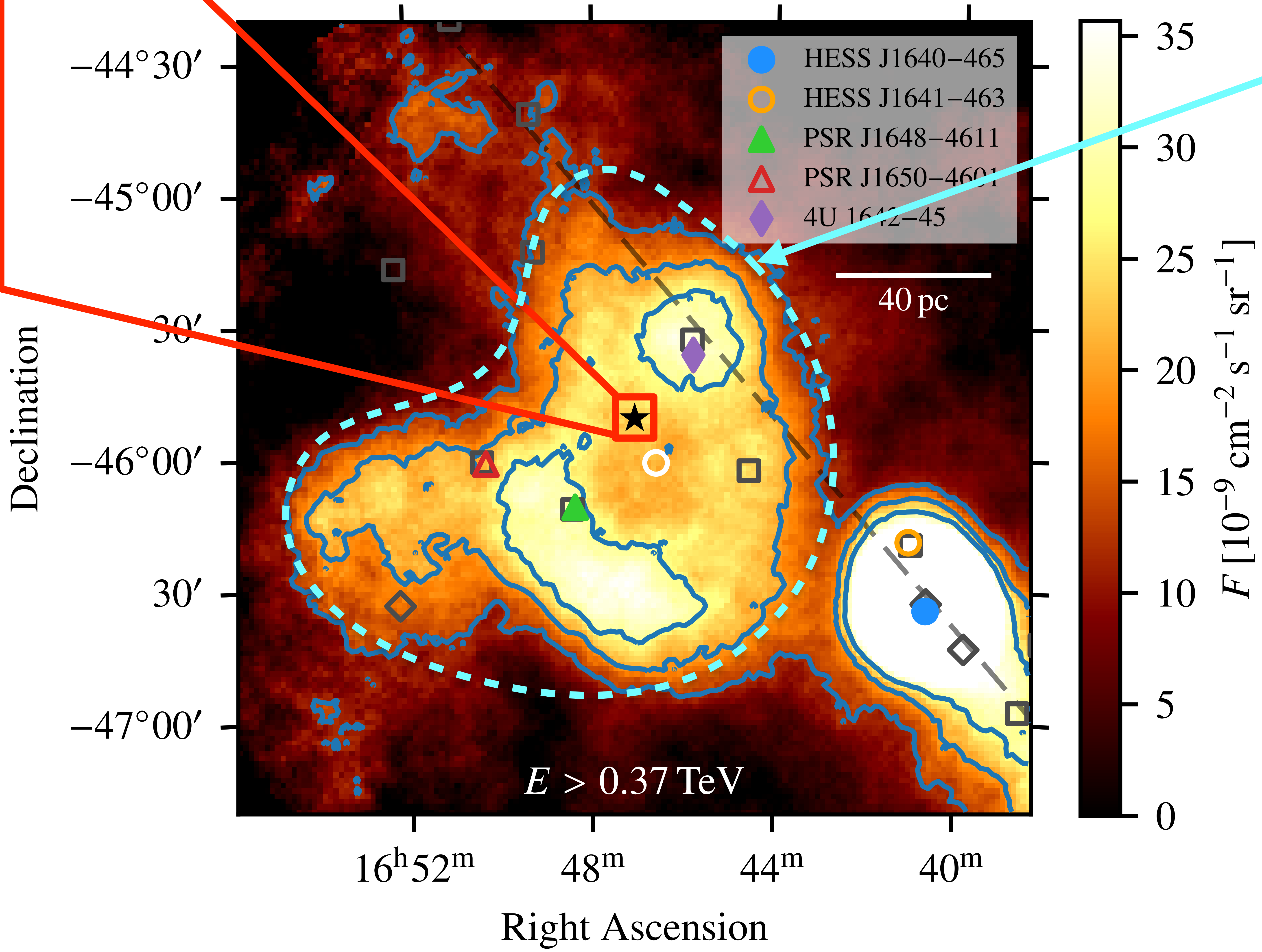

- HESS J1646–458
  - largely extended γ-ray source
  - diameter $\sim 2^\circ$ (140 pc)
  - very likely associated with Westerlund 1

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

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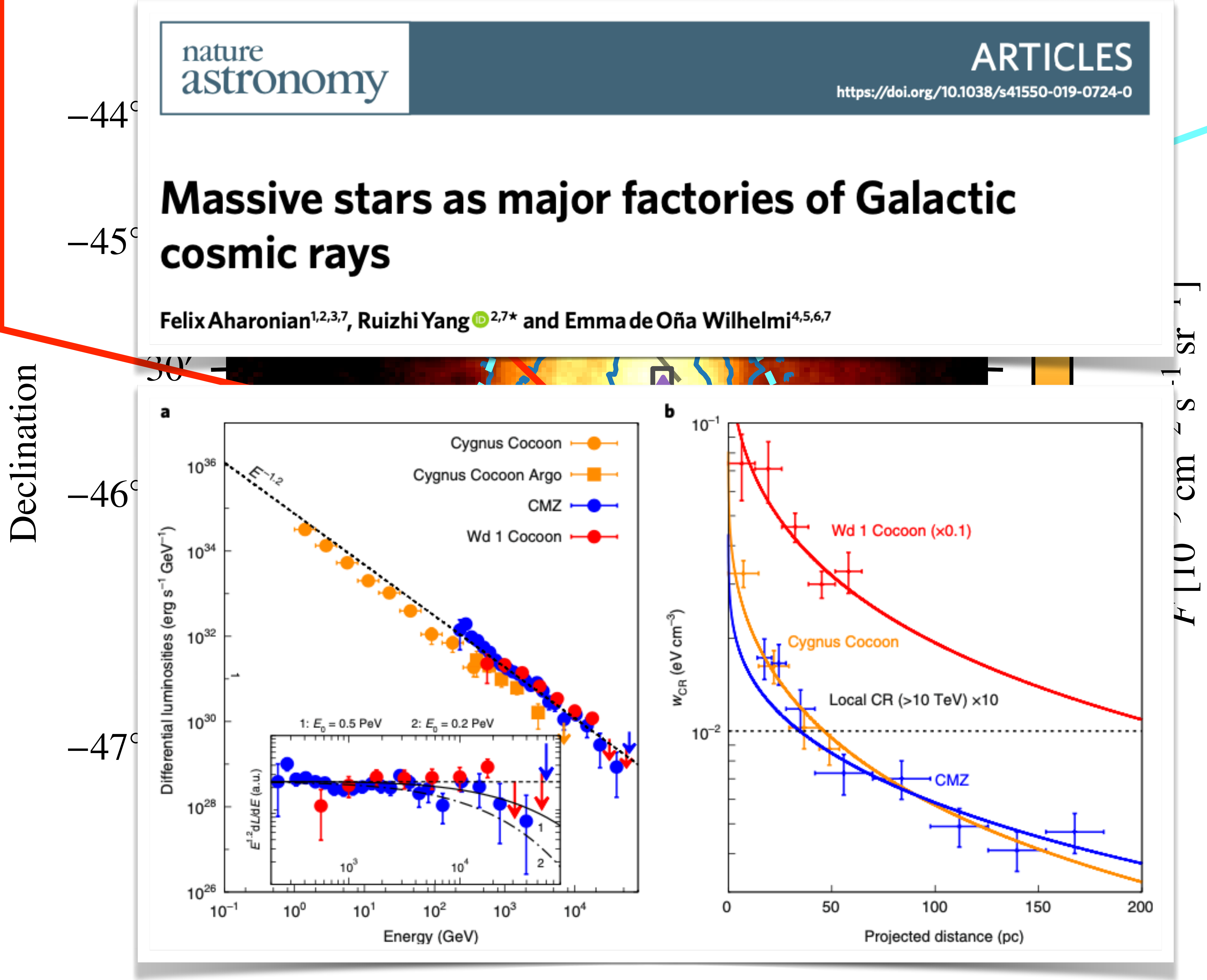

nature astronomy
ARTICLES
https://doi.org/10.1038/s41550-019-0724-0

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: $1\,\mathrm{pc}$

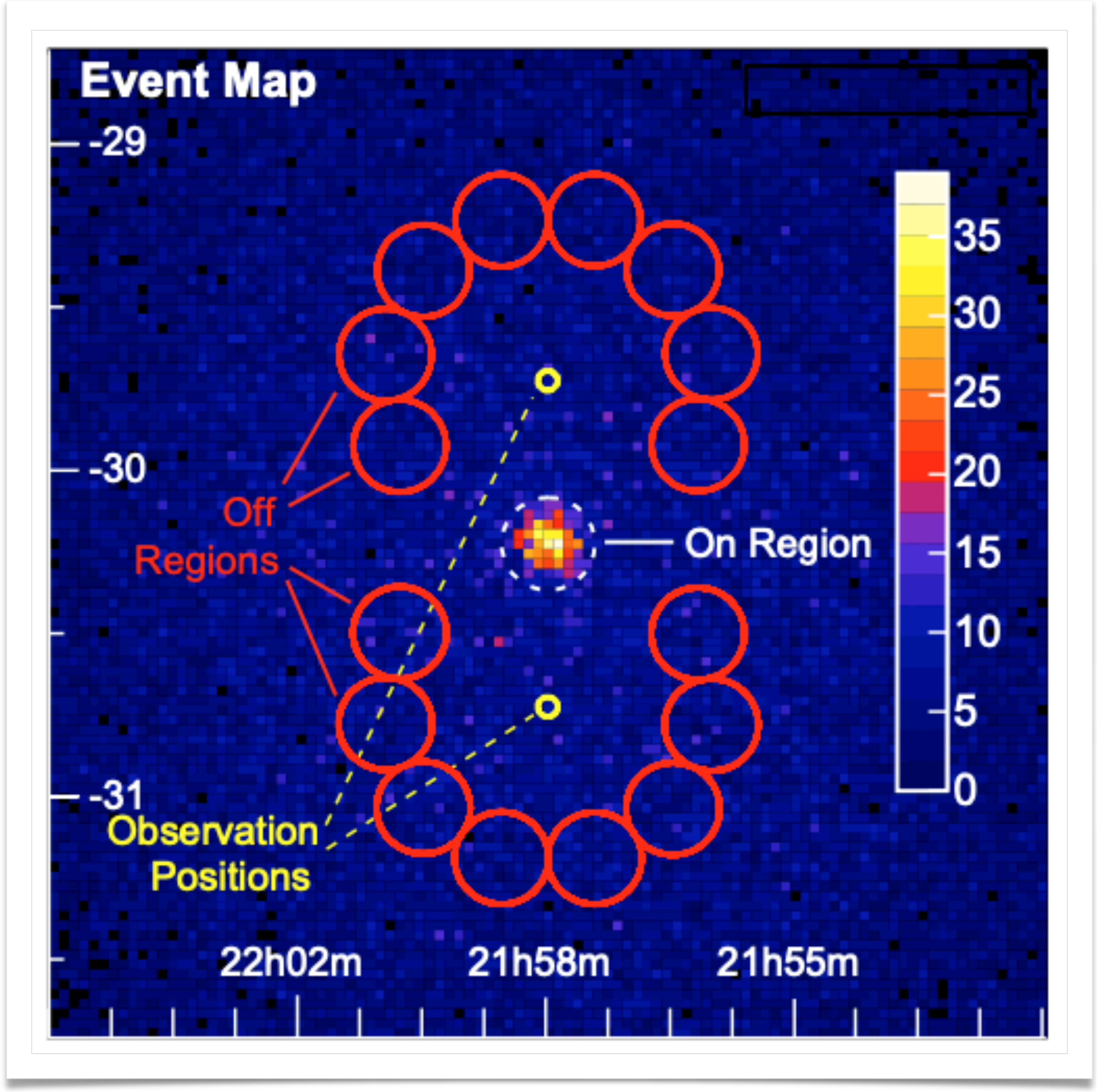
- ◉ HESS J1646–458
  - ▸ largely extended γ-ray source
  - ▸ diameter $\sim 2^\circ$ ($140\,\mathrm{pc}$)
  - ▸ very likely associated with Westerlund 1

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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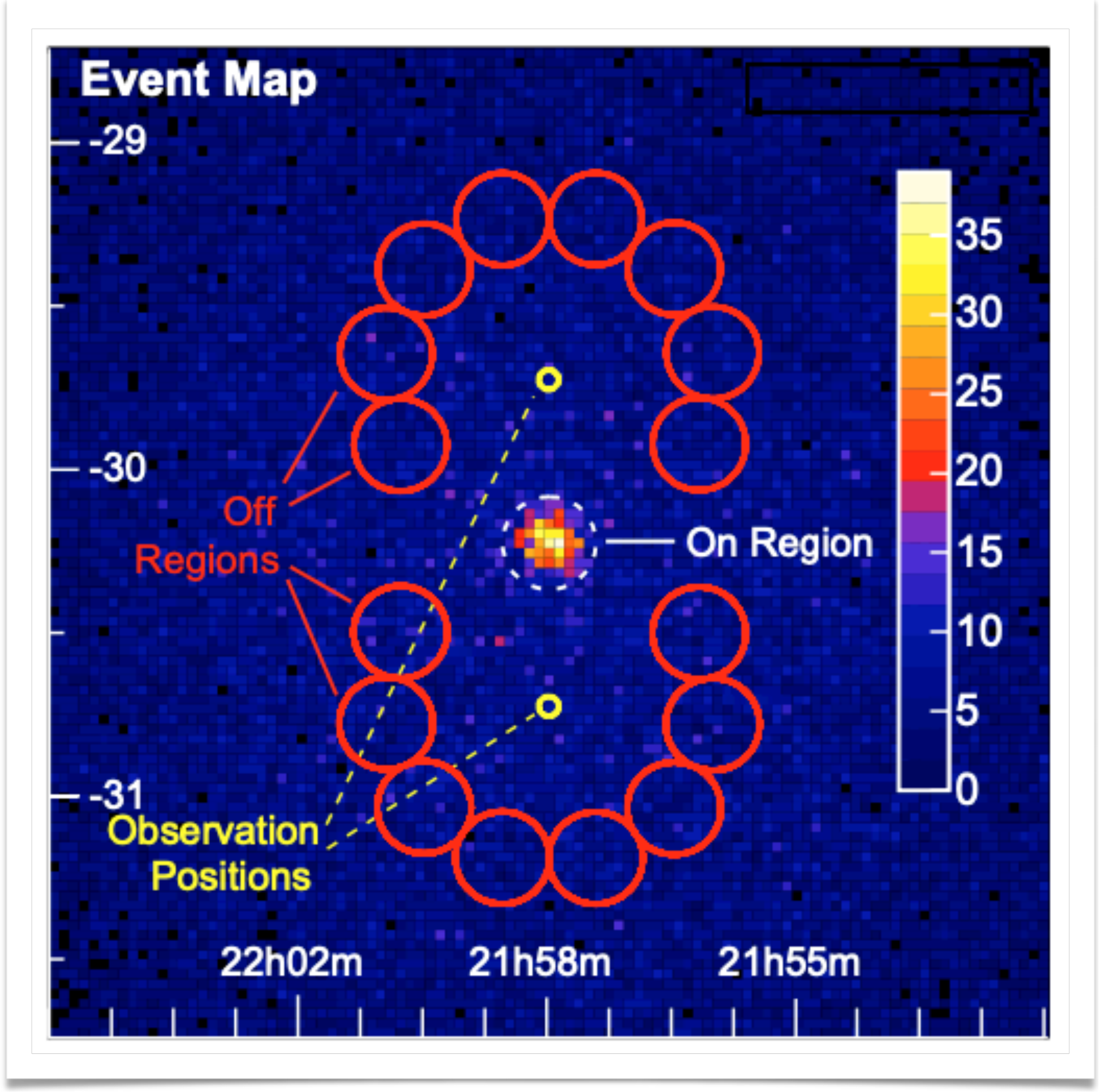

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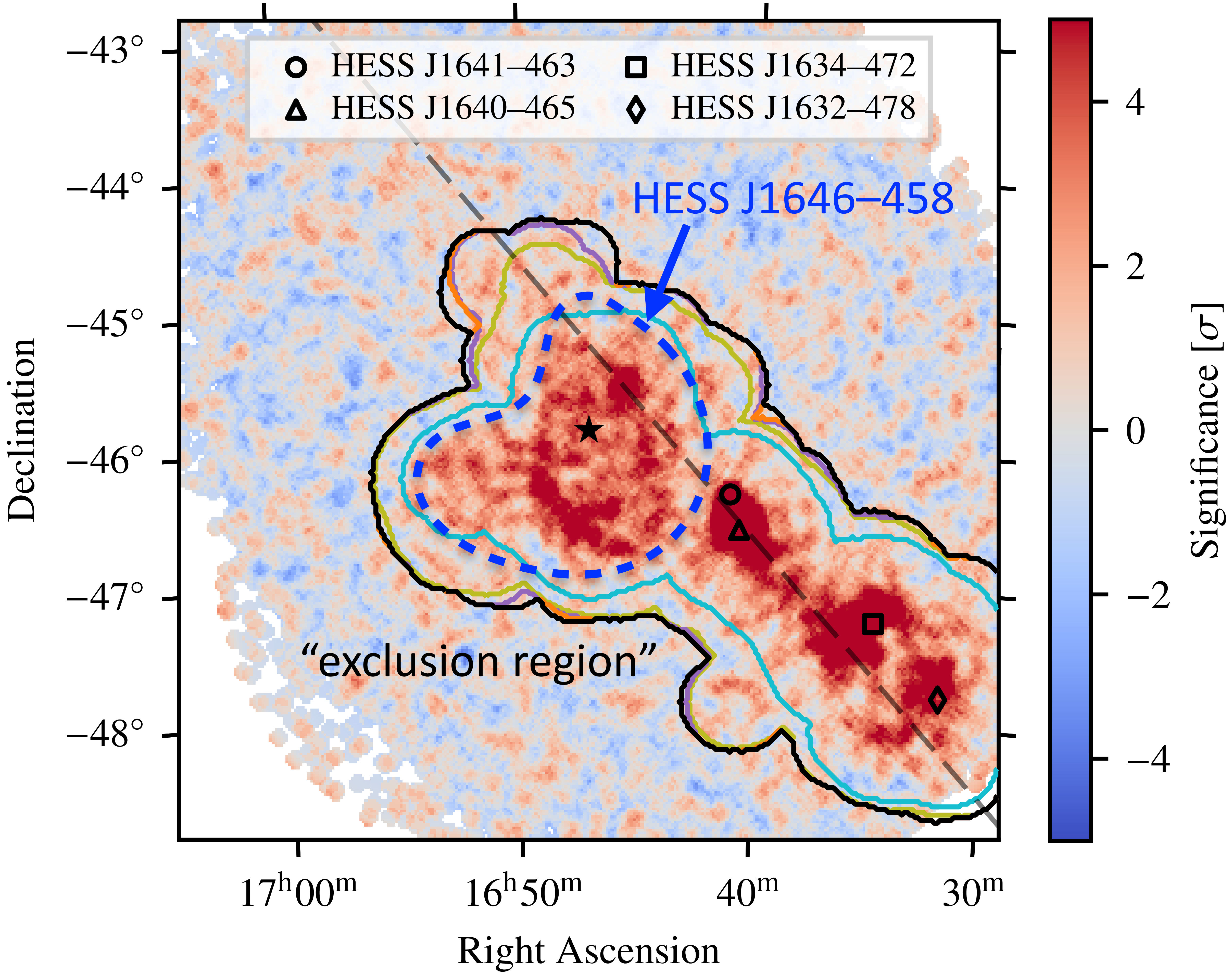
Significance map



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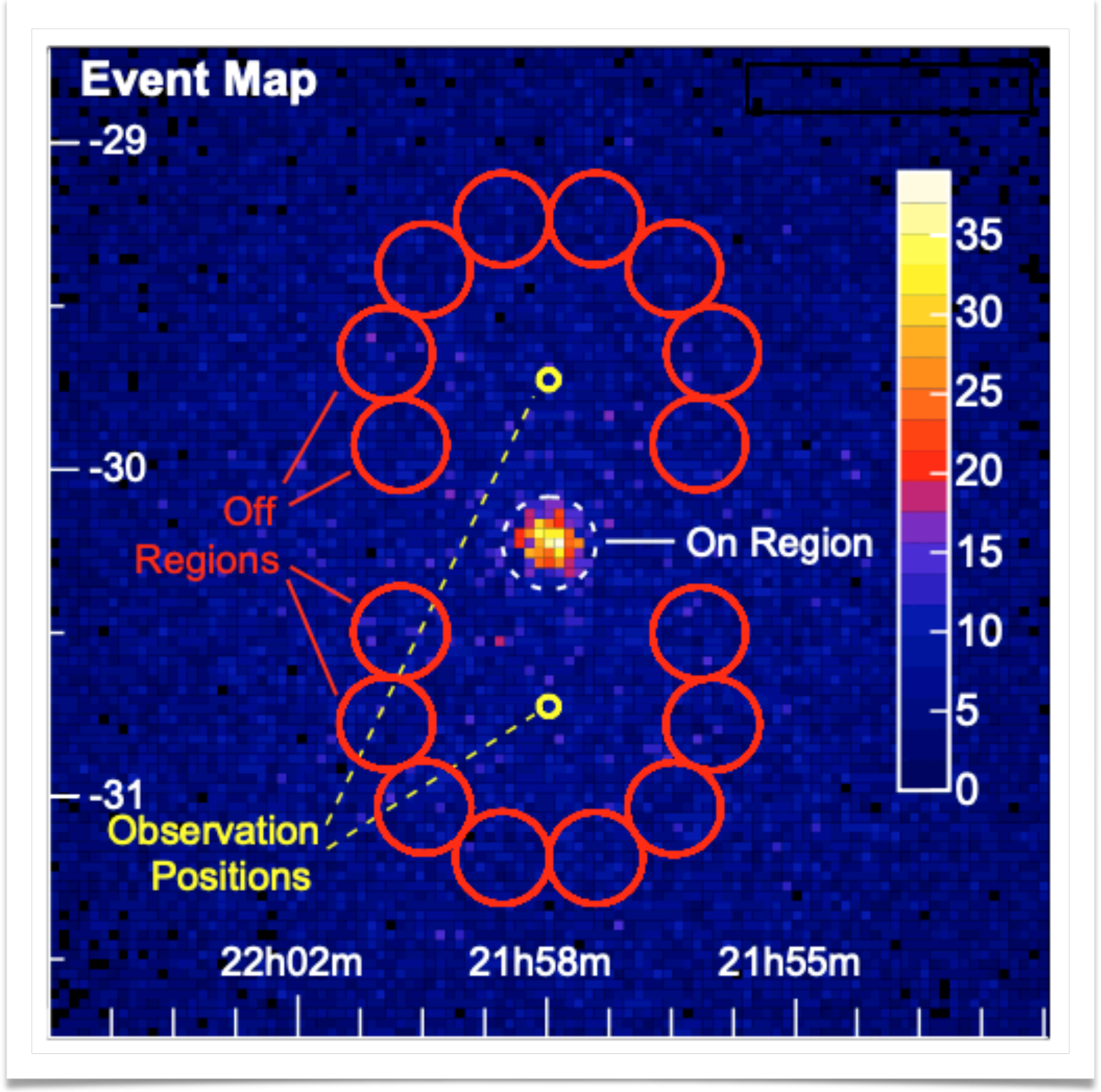

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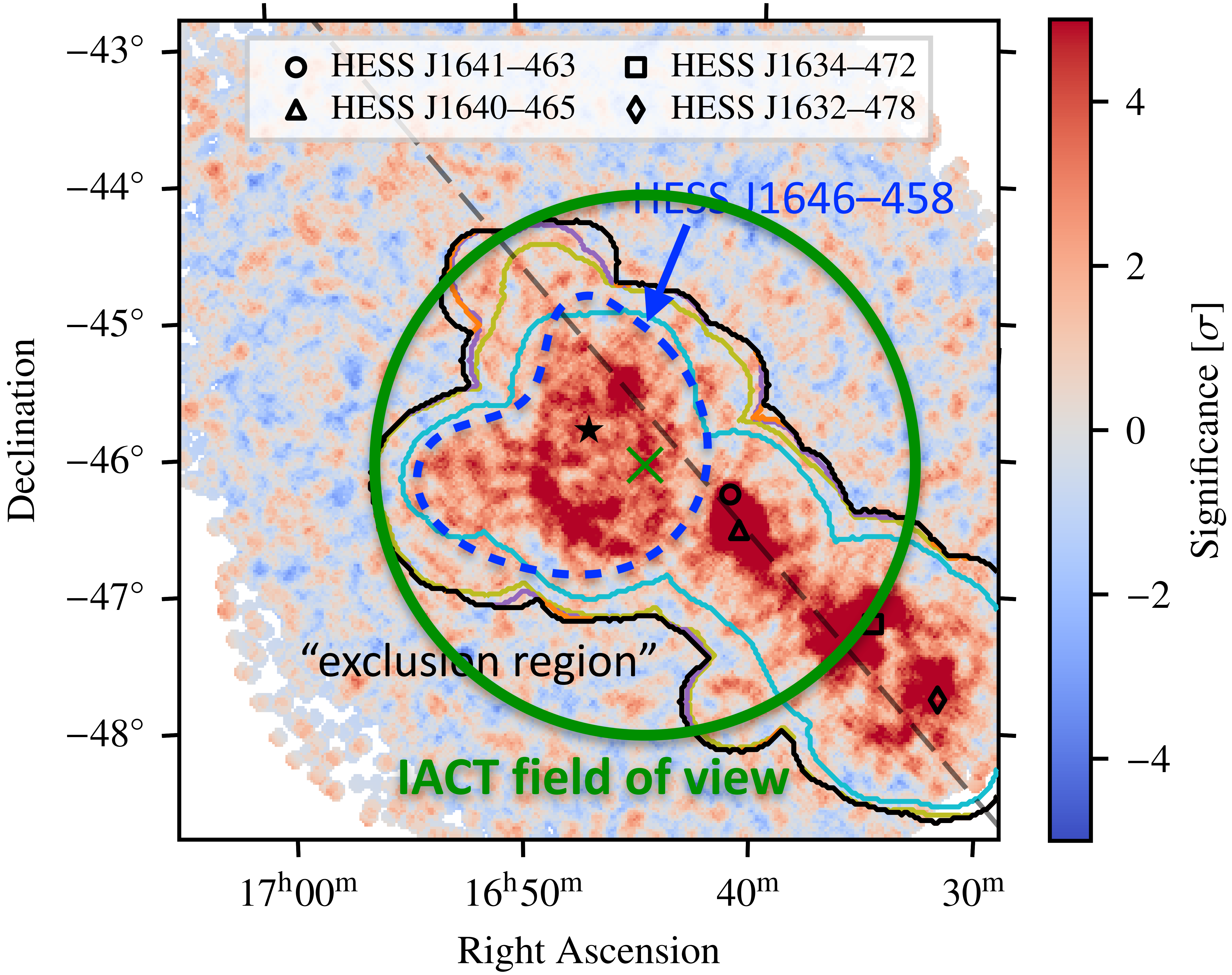

Excursion: treating the residual cosmic-ray background

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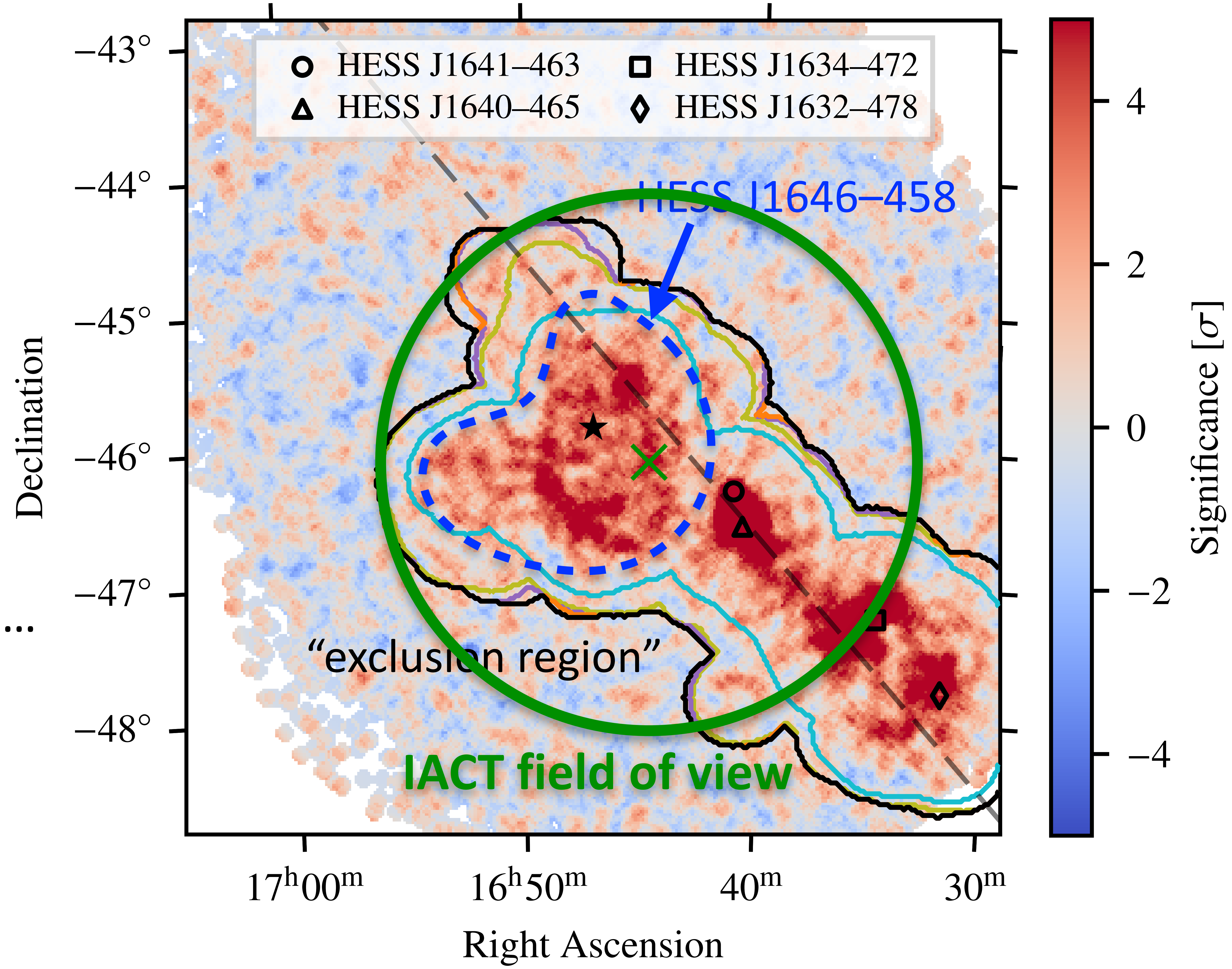
- Background model
  - derived from archival observations
  - ***challenge:*** need to match (or correct for) observation conditions
    - zenith angle, optical throughput, atmospheric conditions…
  - very relevant for CTA!

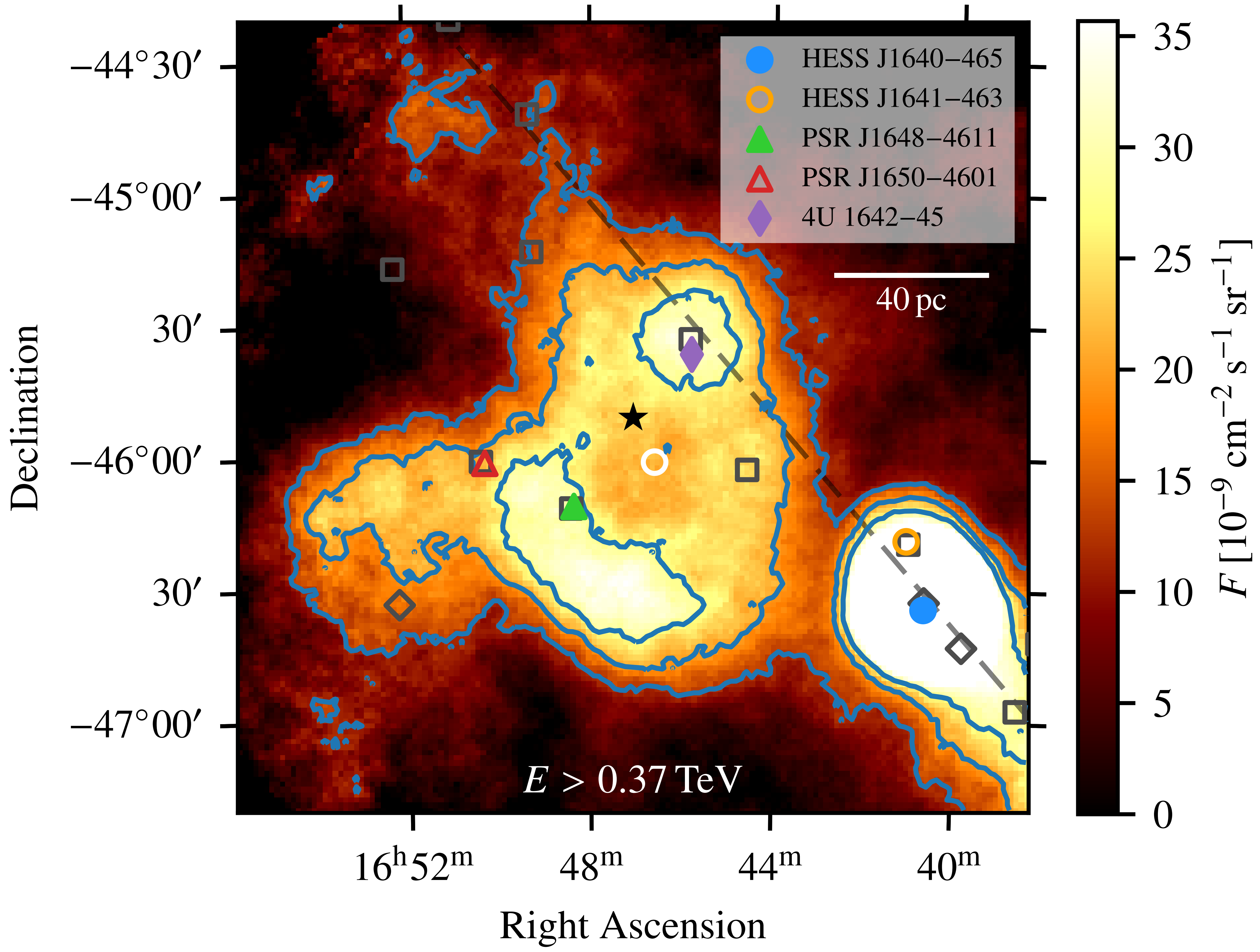
  - Details: ***Mohrmann et al., A&A 632, A72 (2019)***

Significance map



Source morphology

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



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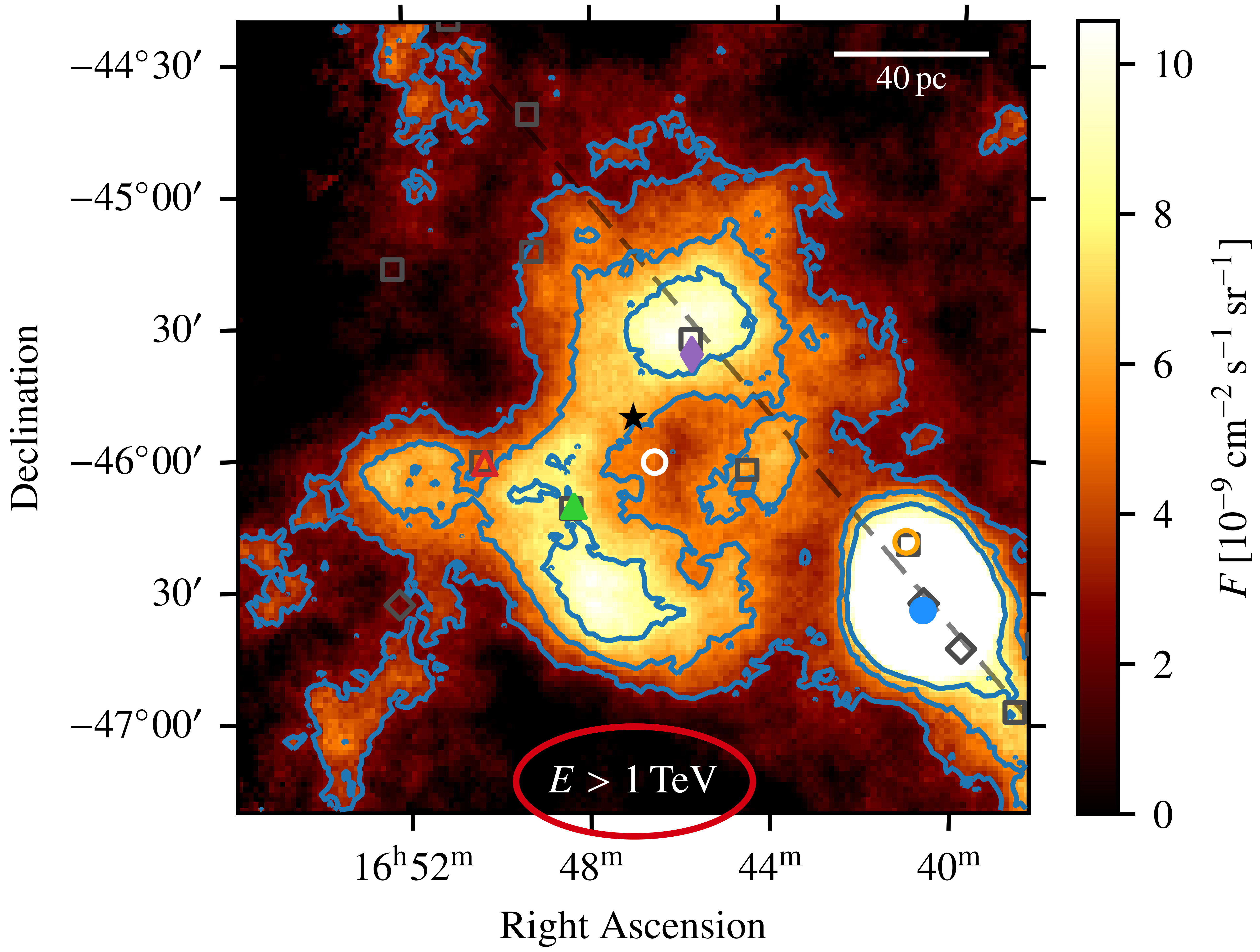

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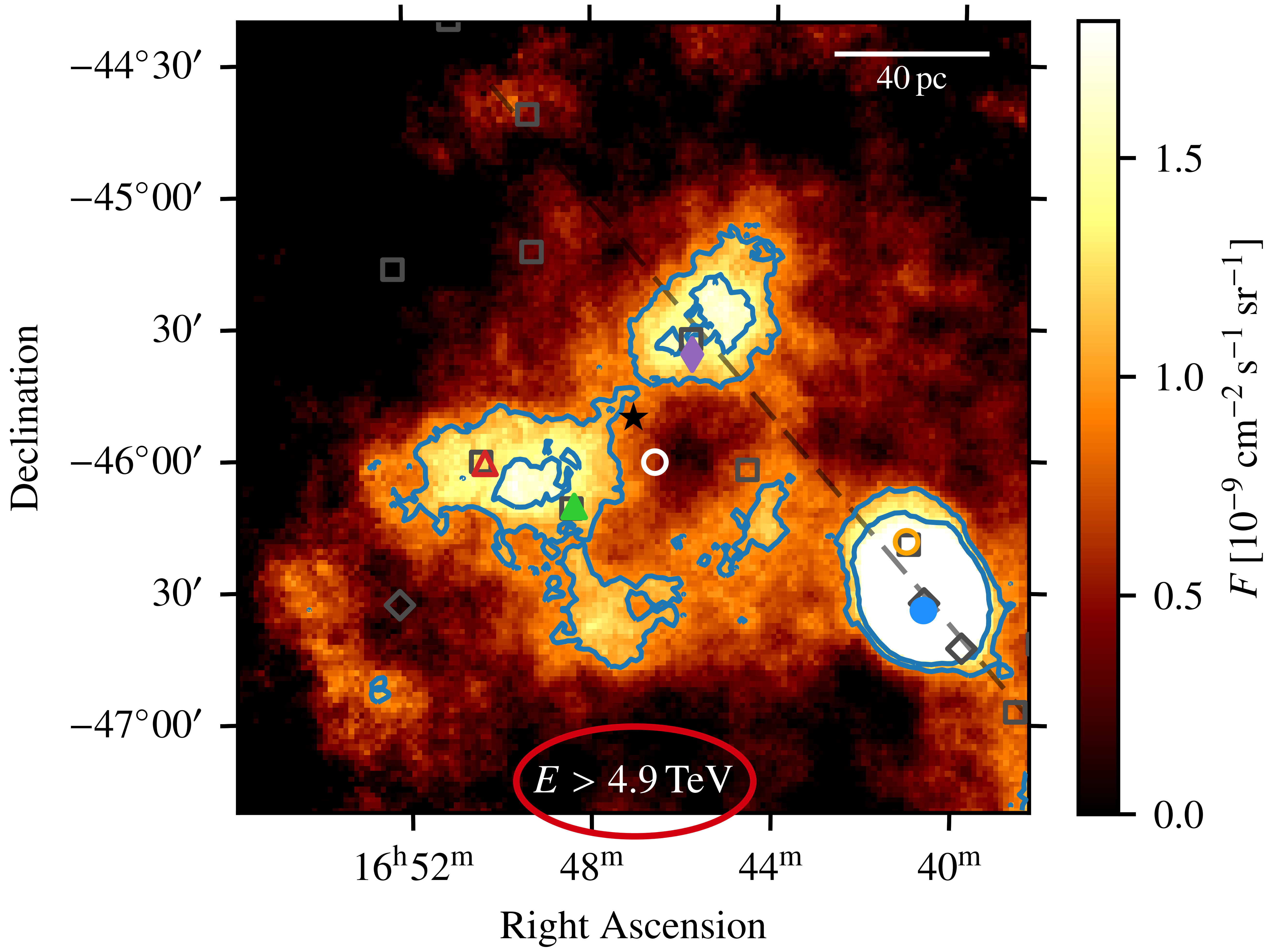

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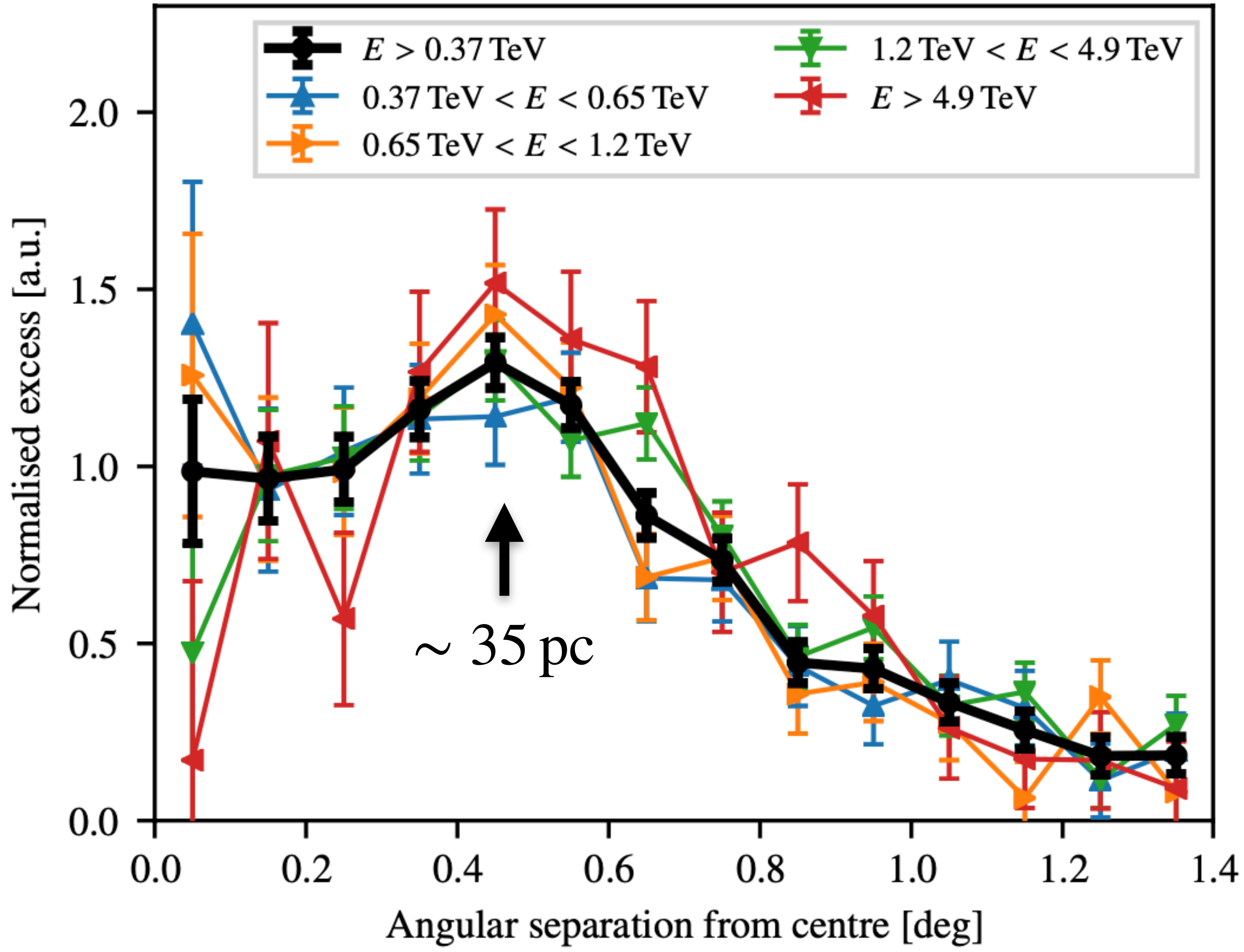
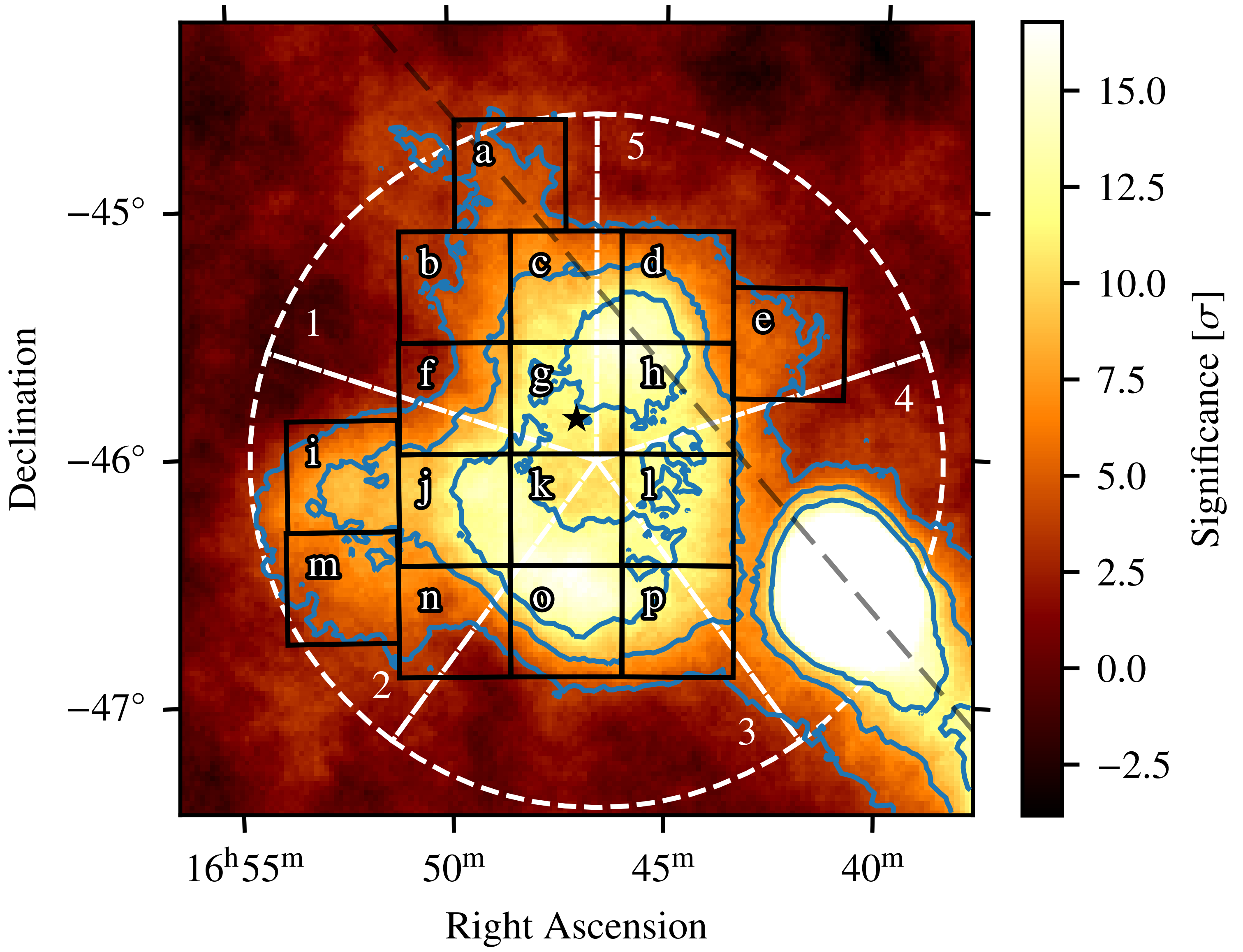
  - ***shell-like structure persists!***
- Confirmed by radial excess profiles
  - profiles for different energy bands well compatible

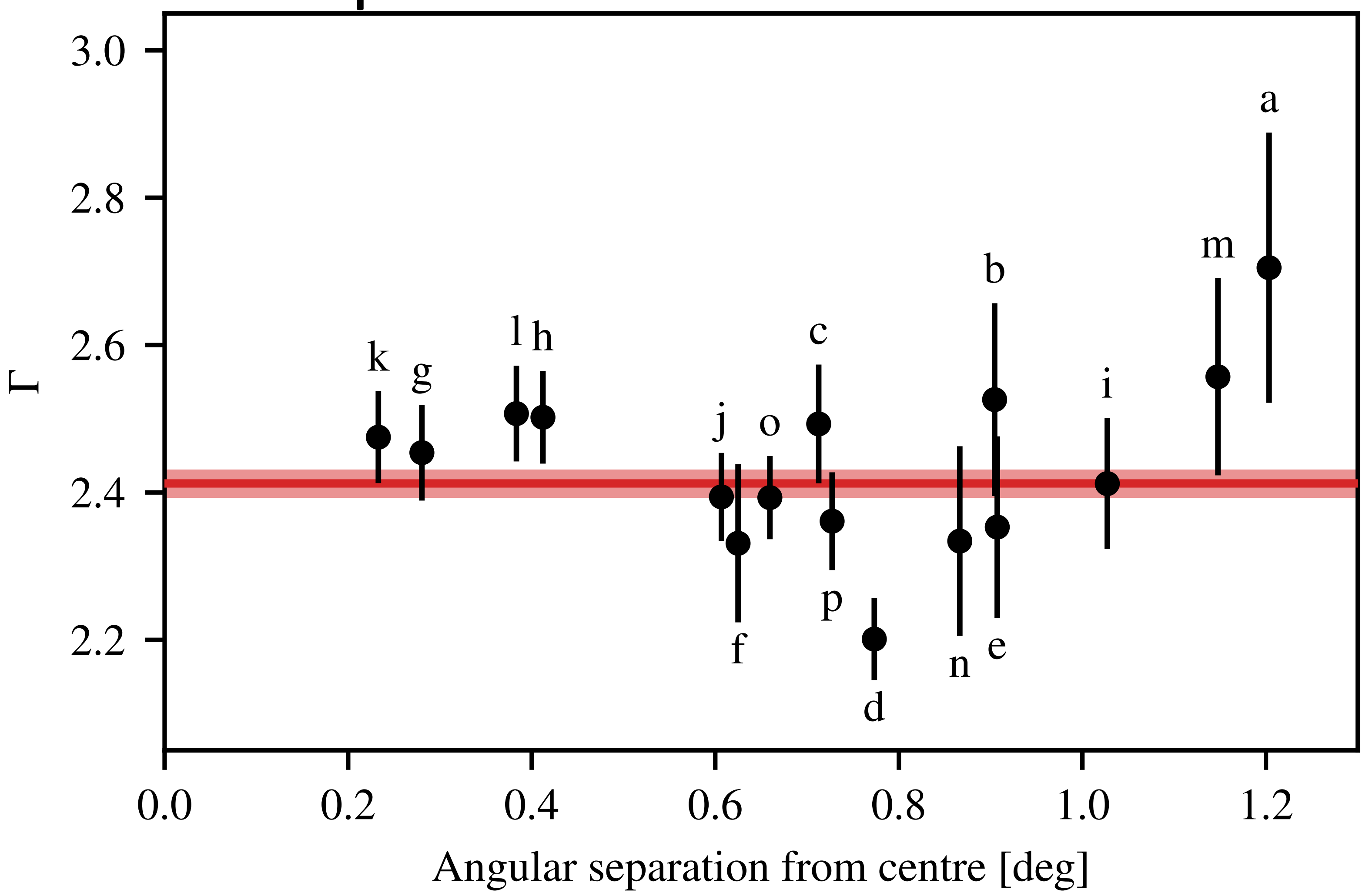


Energy spectrum

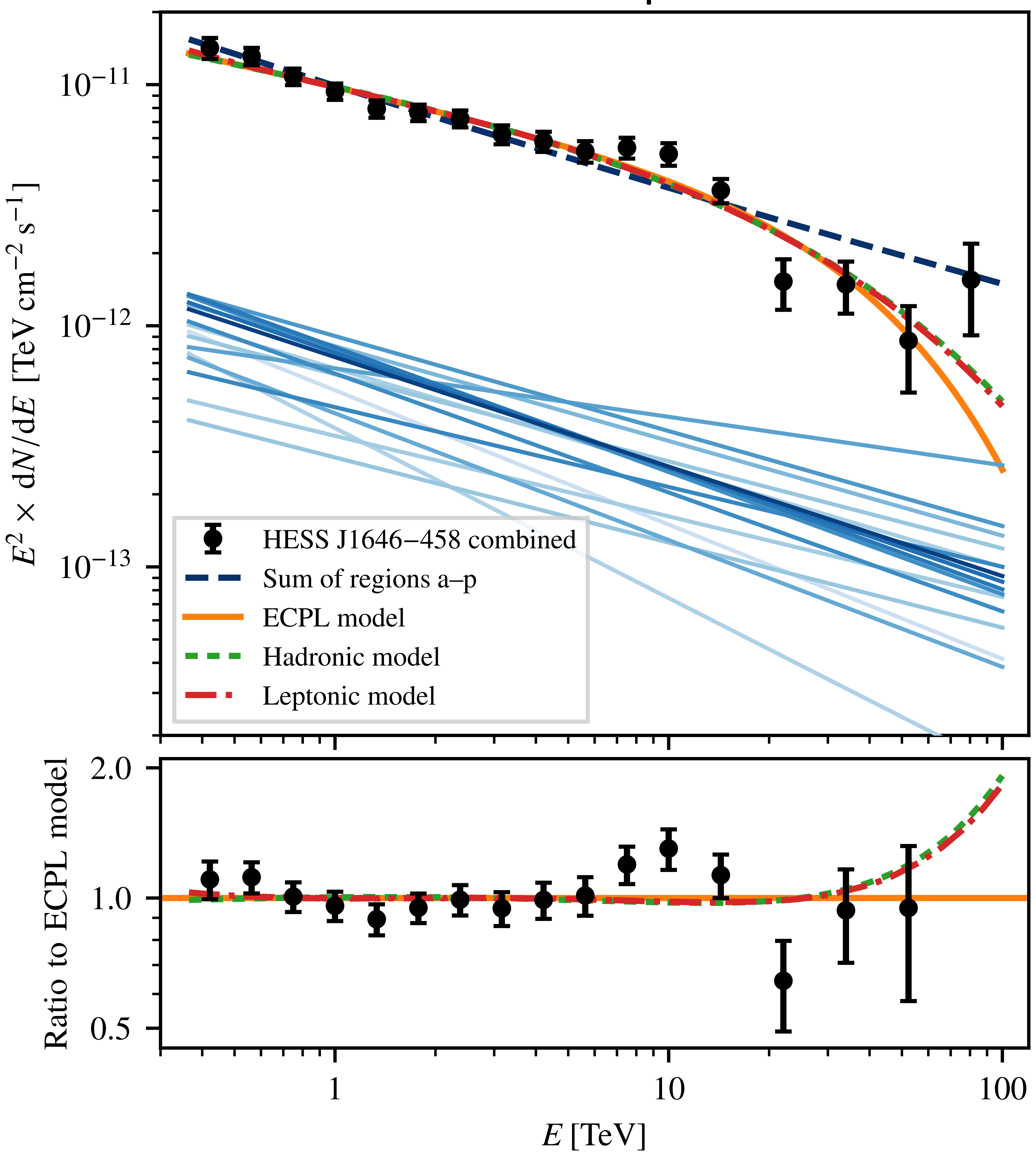
- Energy spectrum
  - extracted in 16 signal regions
  - individual spectra remarkably similar
  - add up region spectra → combined spectrum
  - ***extends to several ten TeV!***
  - $\Gamma = 2.30 \pm 0.04,\ E_c = \left(44^{+17}_{-11}\right)$ TeV



spectral index vs. distance

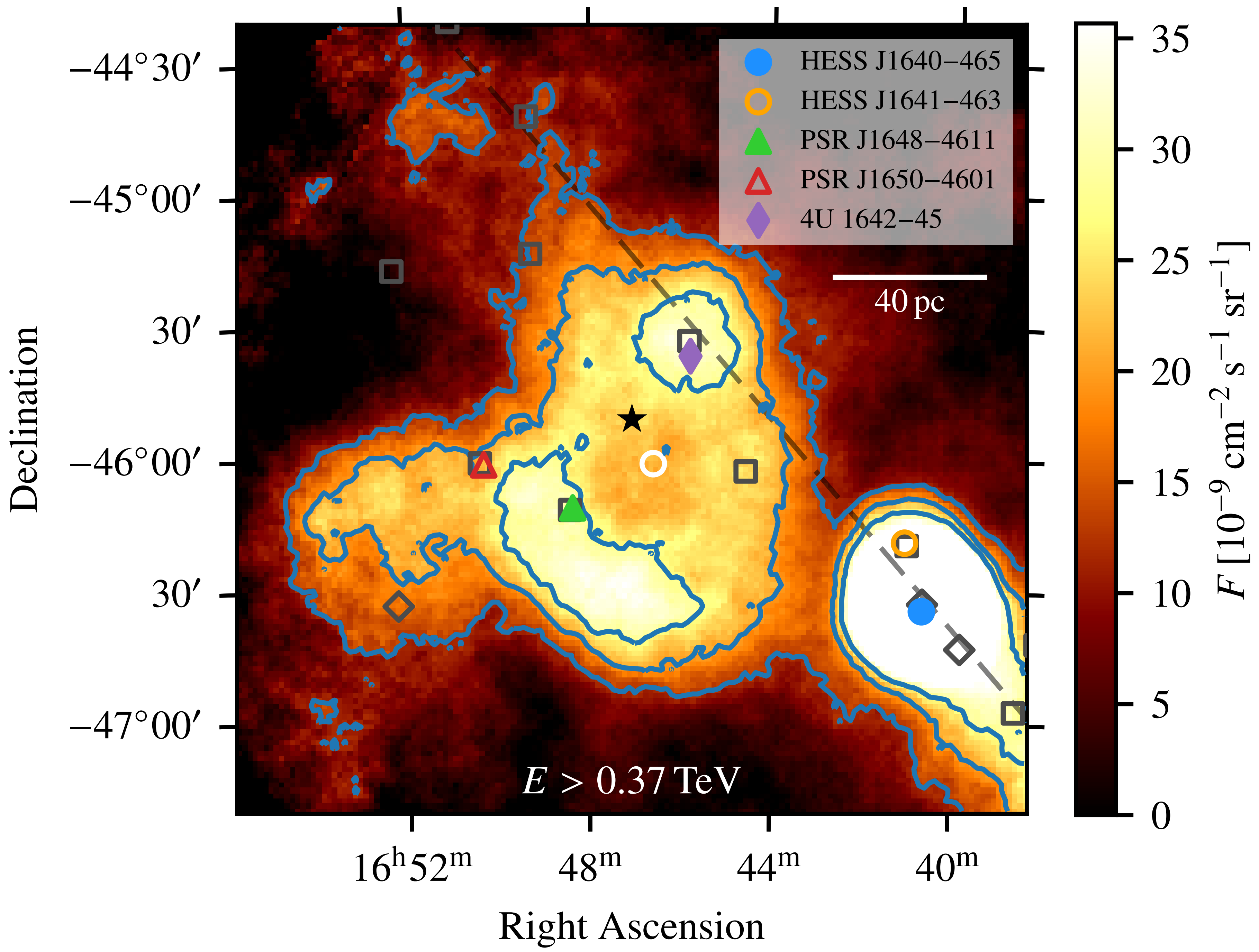


combined spectrum



Interpretation

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



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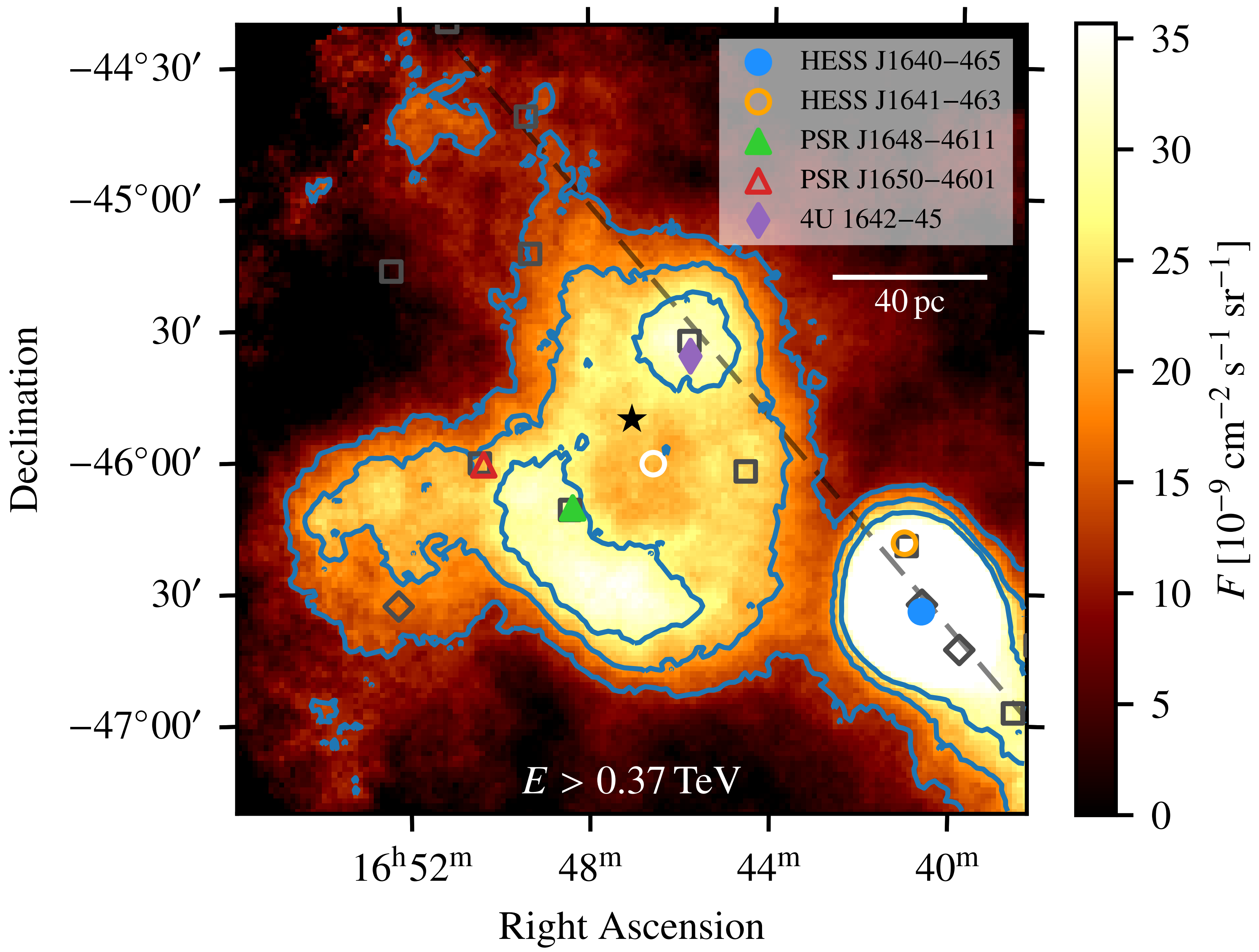
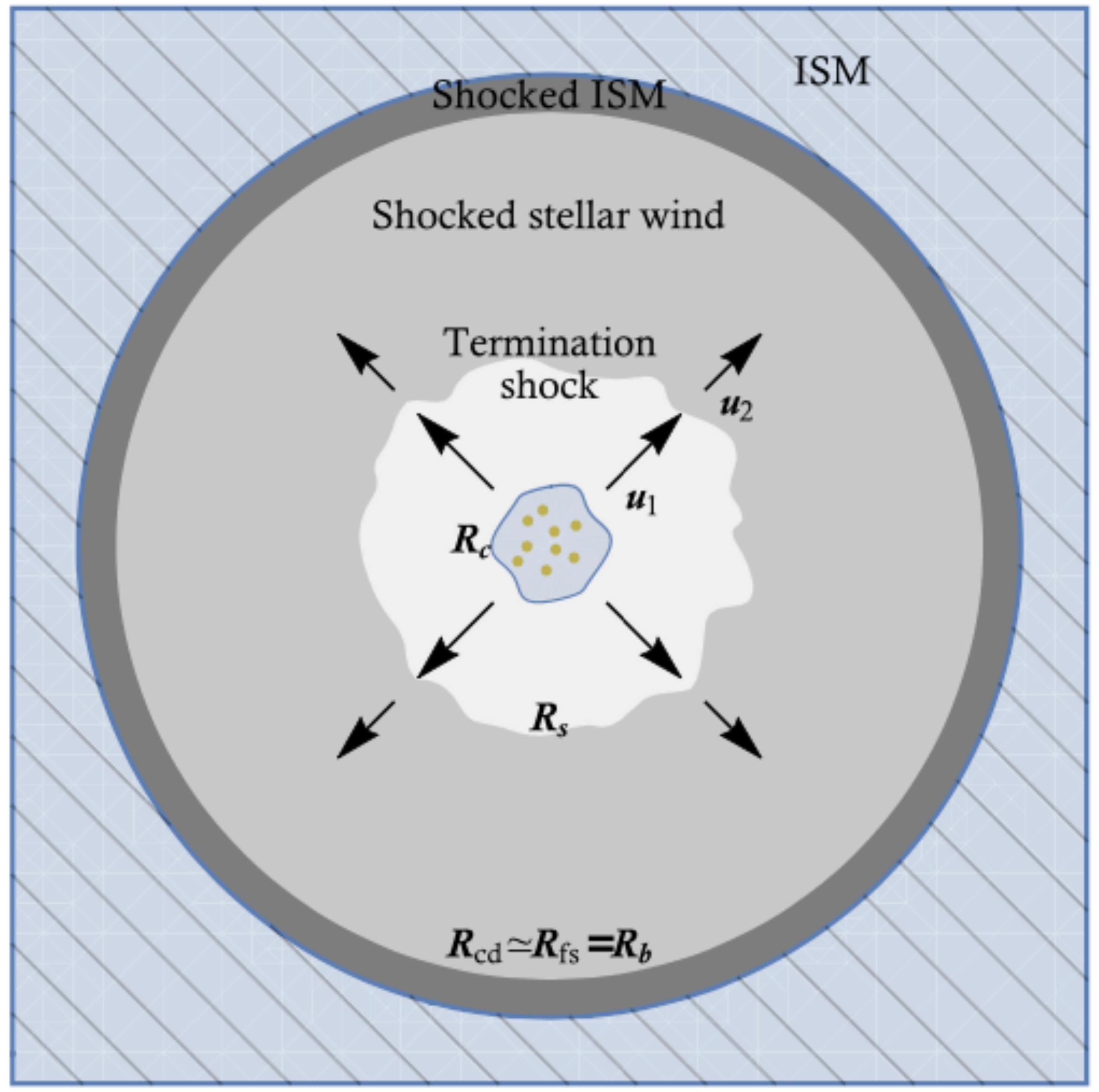
  - within the cluster (wind-wind or wind-SN interactions)
  - collective cluster wind / superbubble
    - MHD turbulences in superbubble
    - cluster wind termination shock





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

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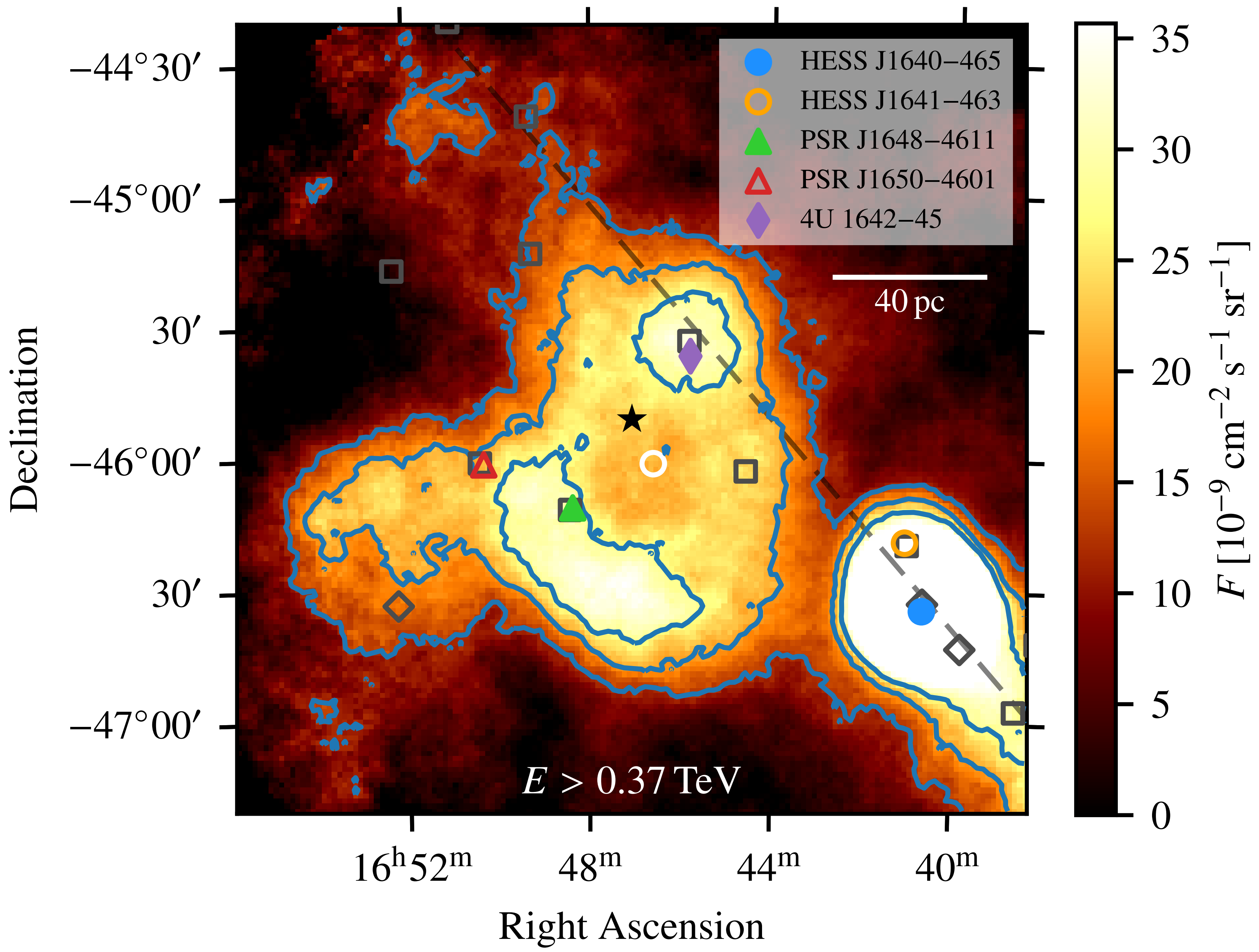
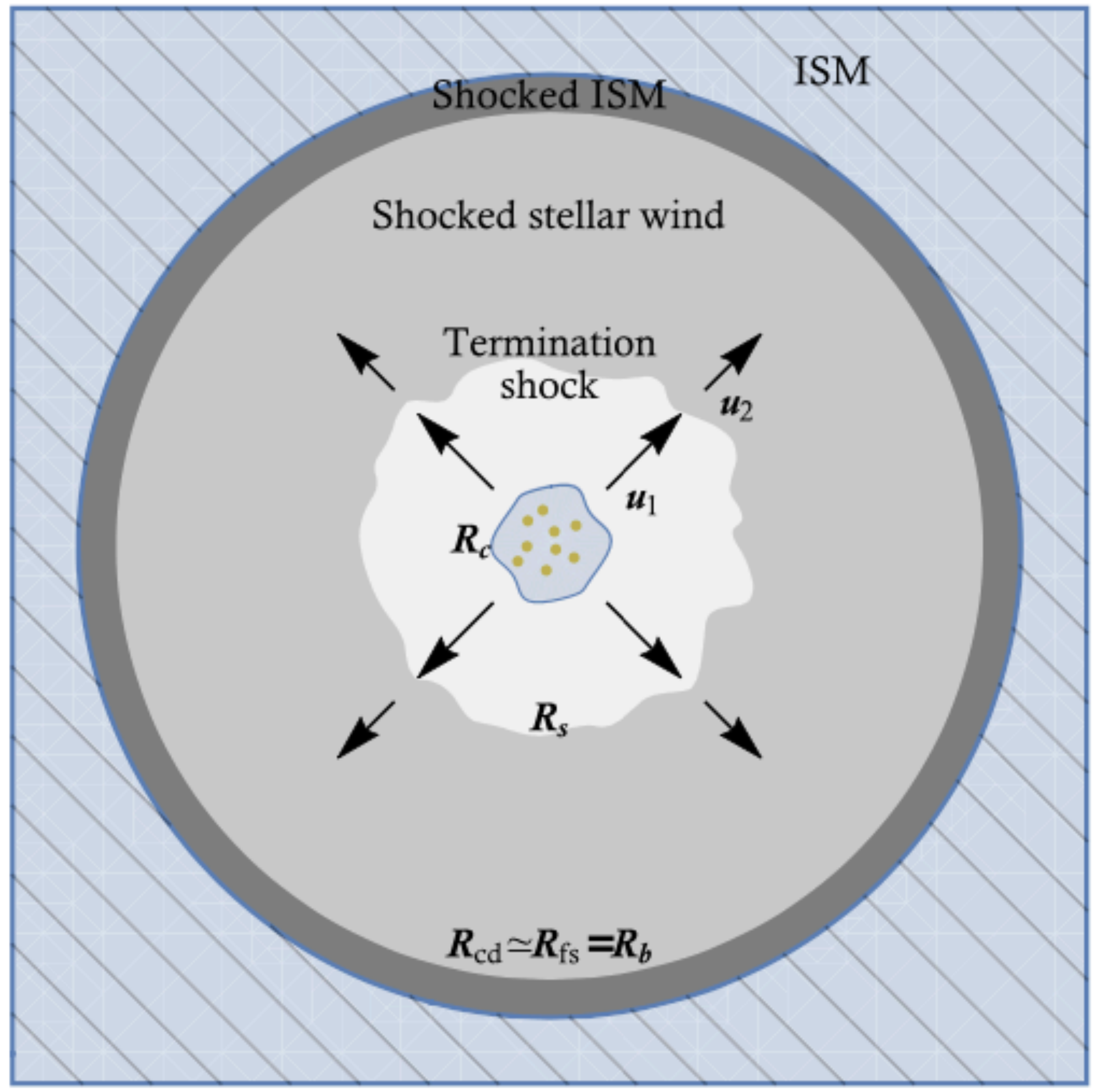
- **Cluster wind termination shock**
  - basic models suggest $R_{TS} \sim \mathcal{O}(30\,\mathrm{pc})$
  - matches radius of shell-like structure in γ-ray emission!
  - however, ***cannot firmly claim this association***
  - hadronic & leptonic scenario could work



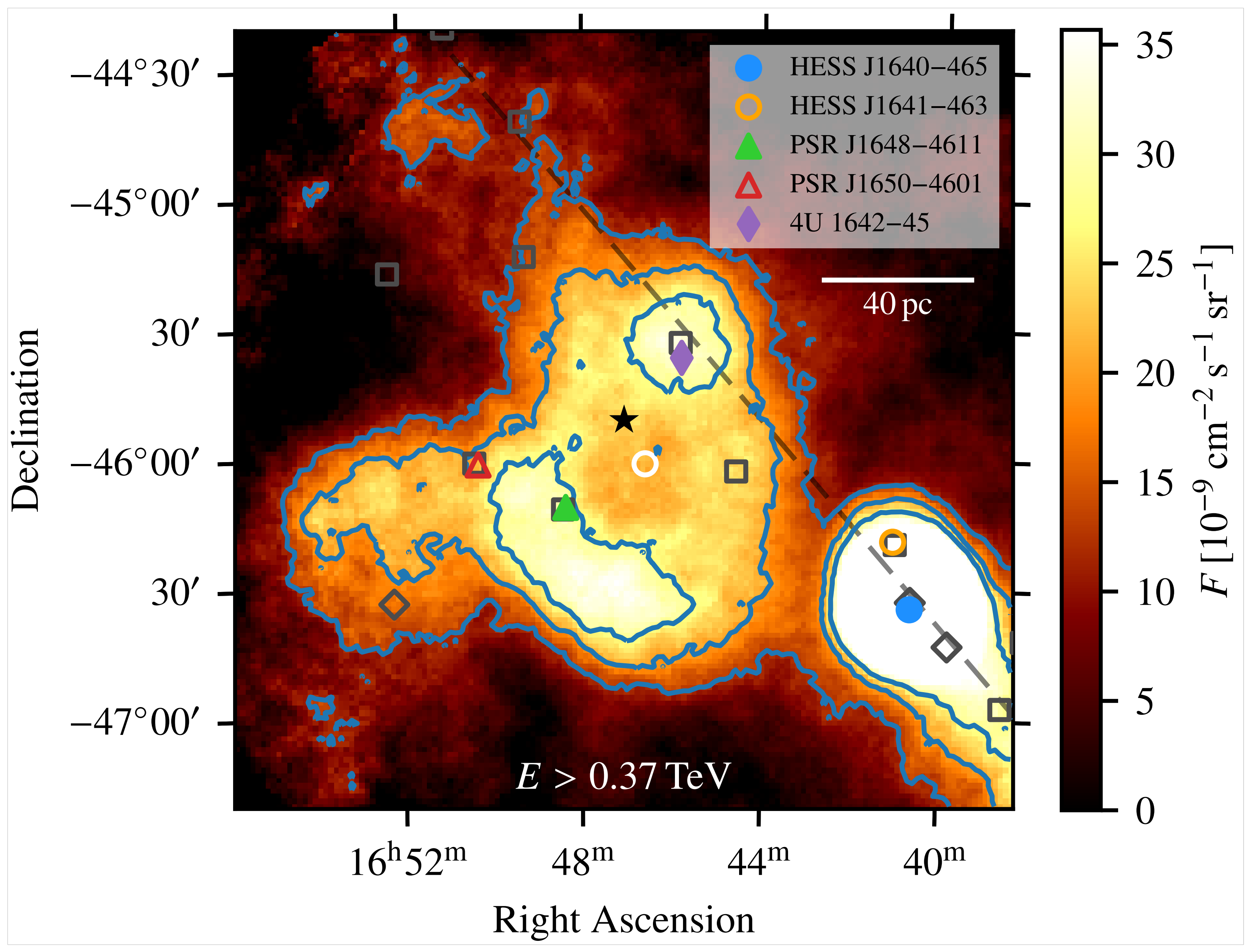


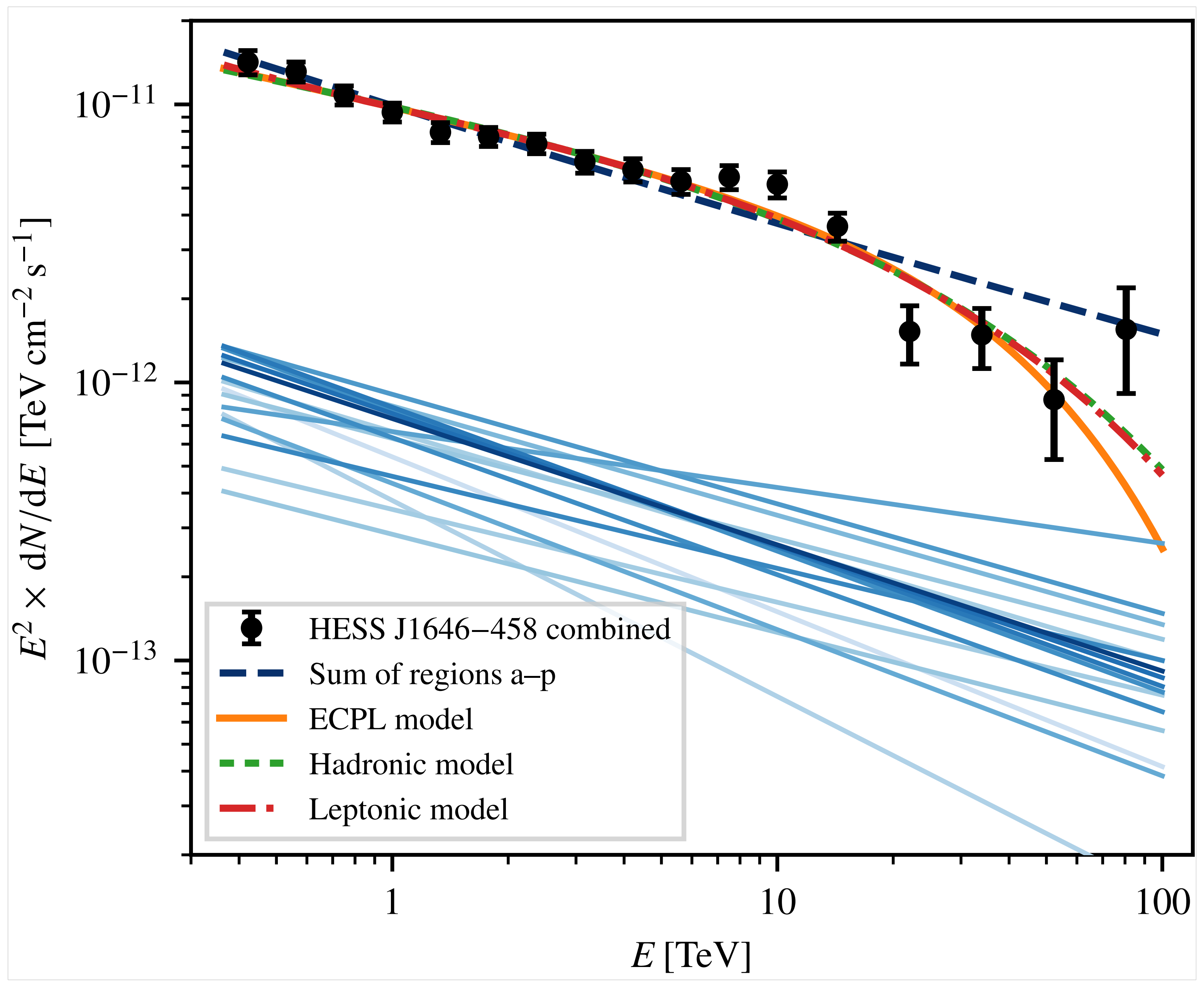
Morlino et al., MNRAS 504, 6096 (2021)

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

Westerlund 1: summary

- 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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L. Mohrmann et al.
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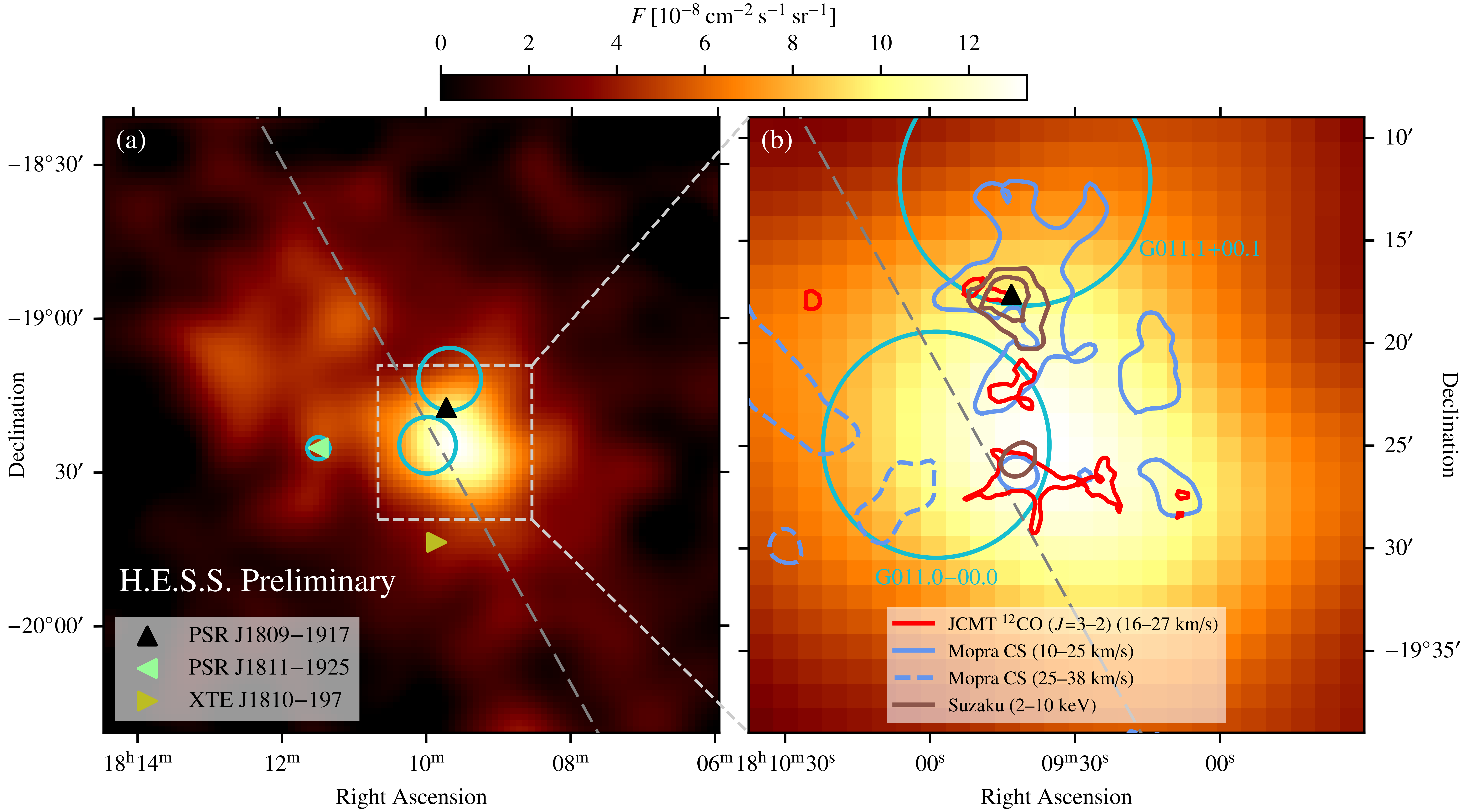
Gamma 2022, Barcelona



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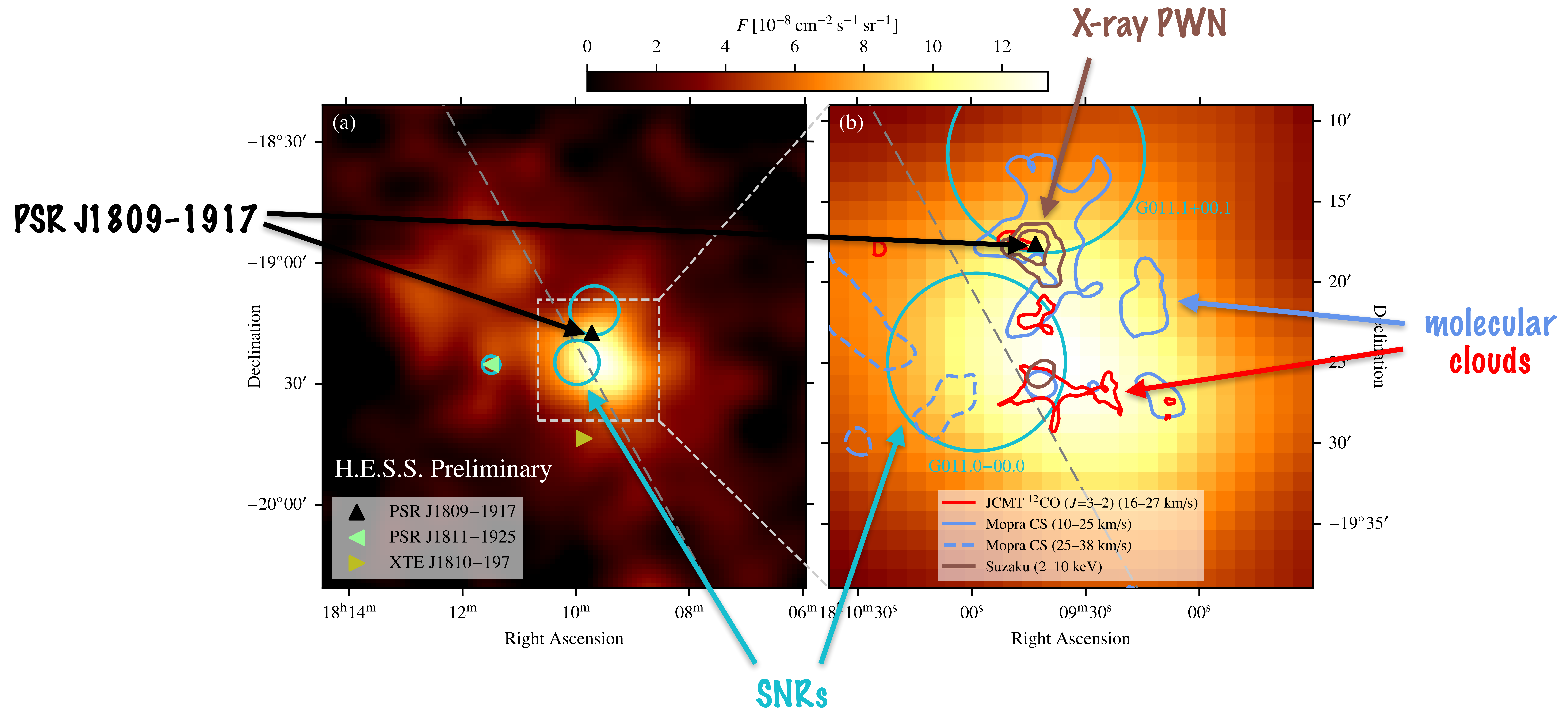

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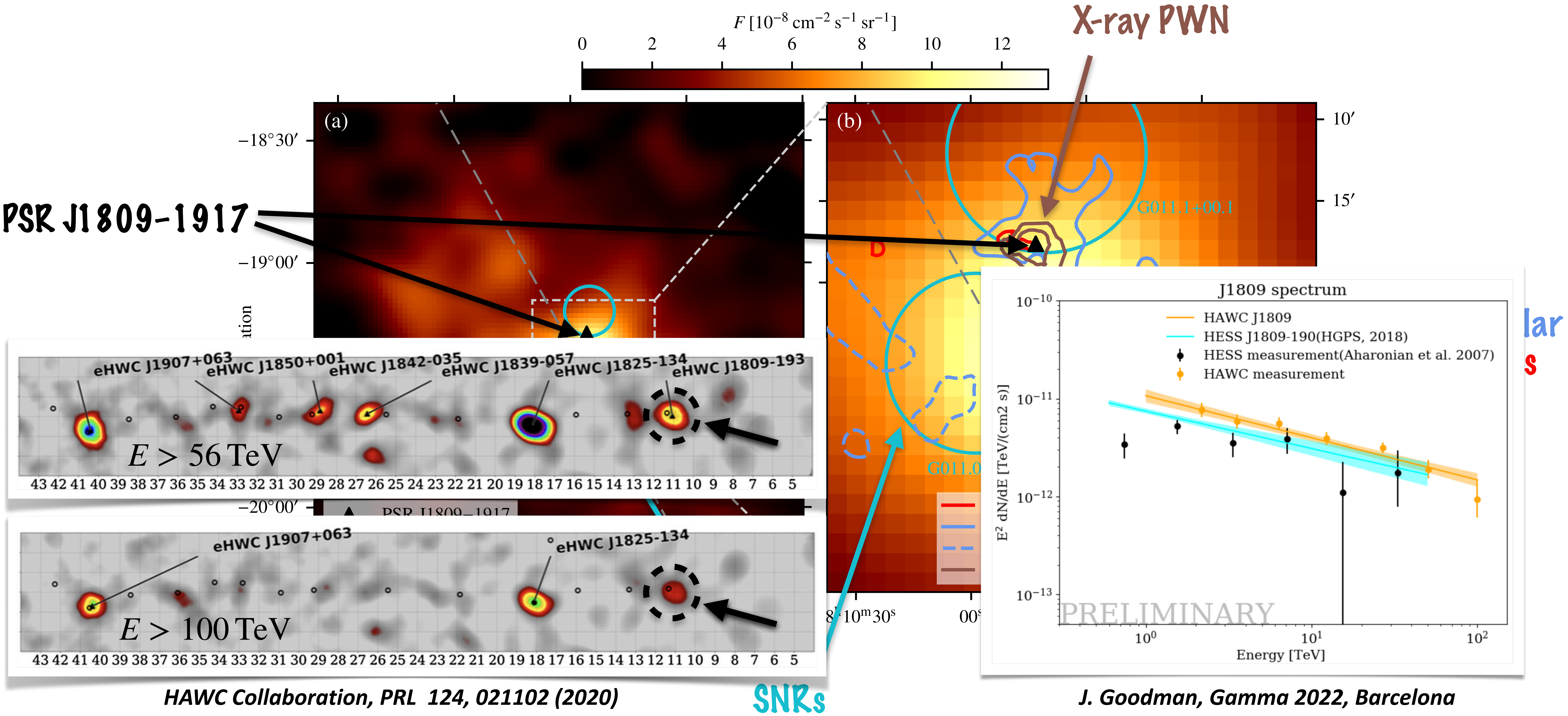

HAWC Collaboration, PRL 124, 021102 (2020)

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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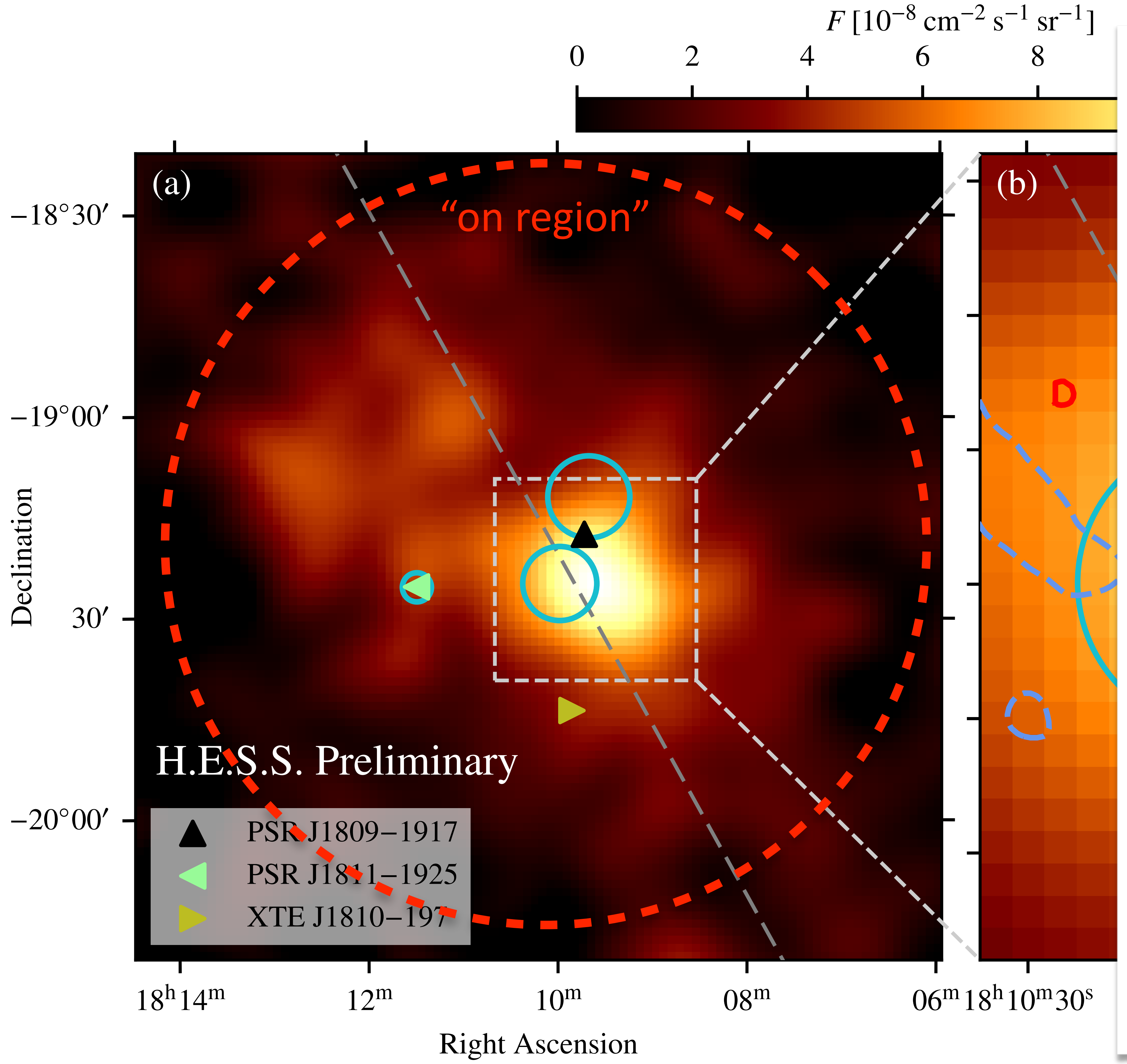
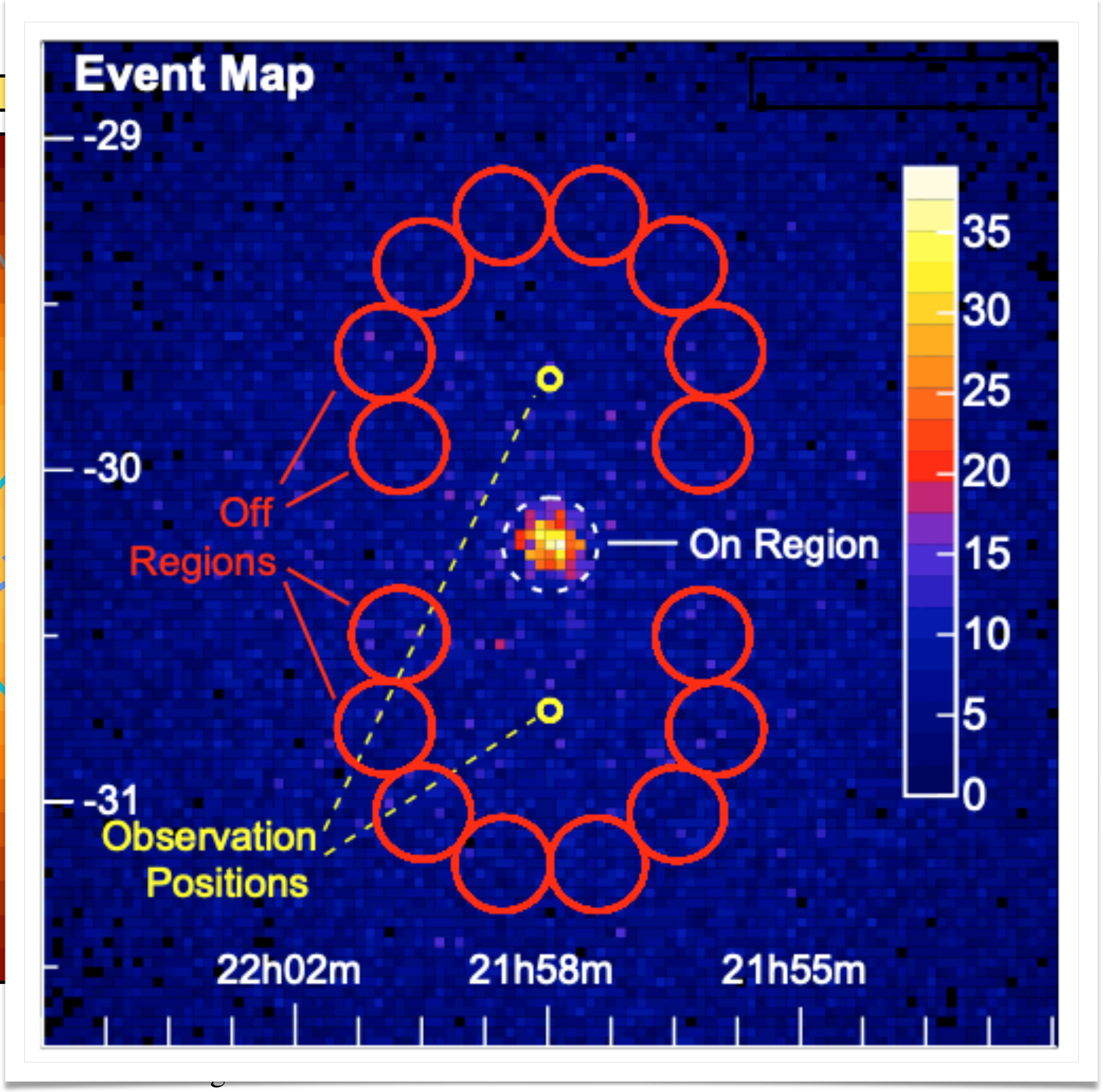


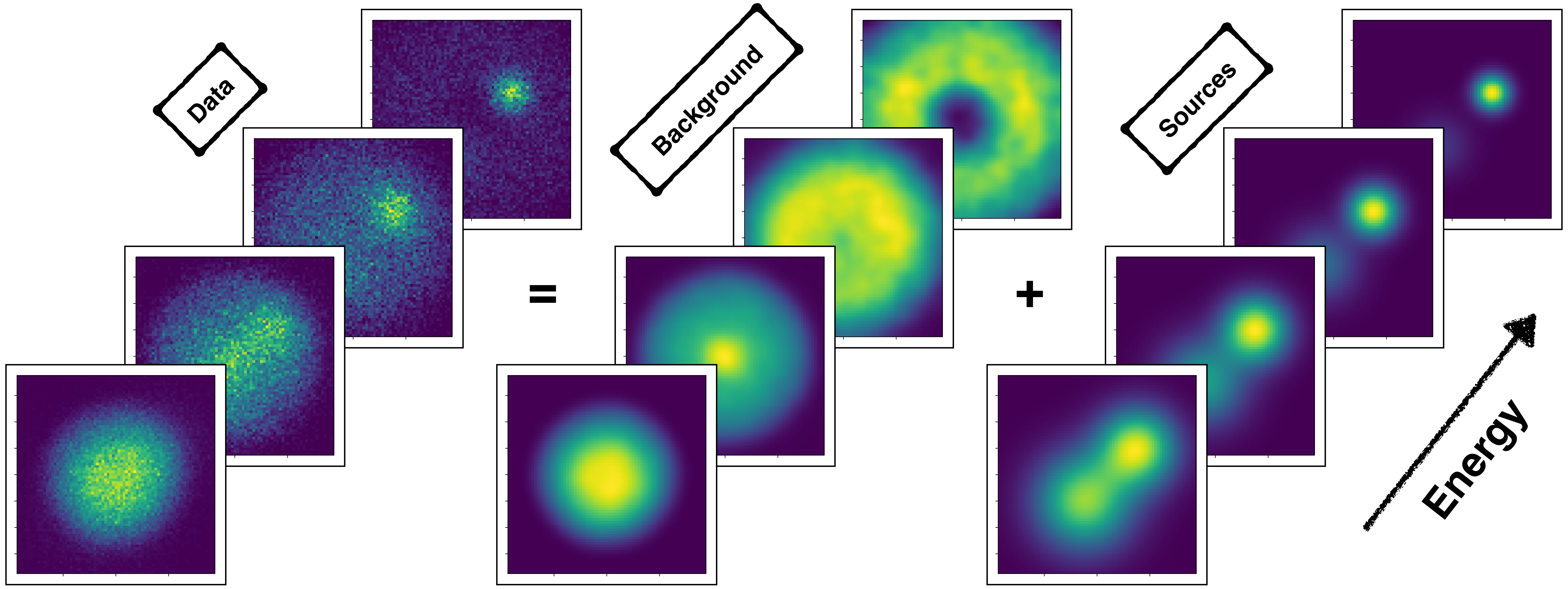


Berge et al., A&A 466, 1219 (2007)

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"



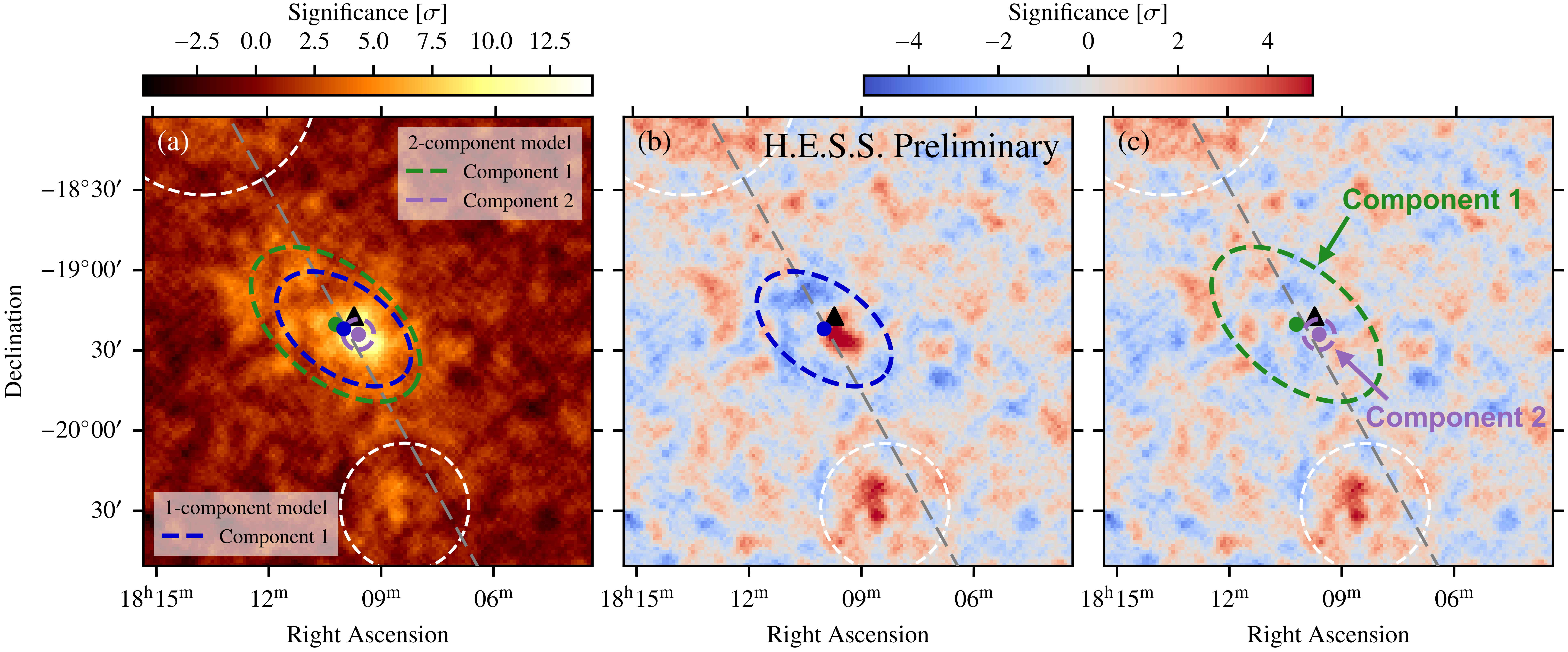
- Requires ***model*** for residual cosmic-ray ***background***

- Can include ***arbitrary number*** of ***model components***
  - e.g. also for diffuse emission

3D likelihood analysis: spatial models

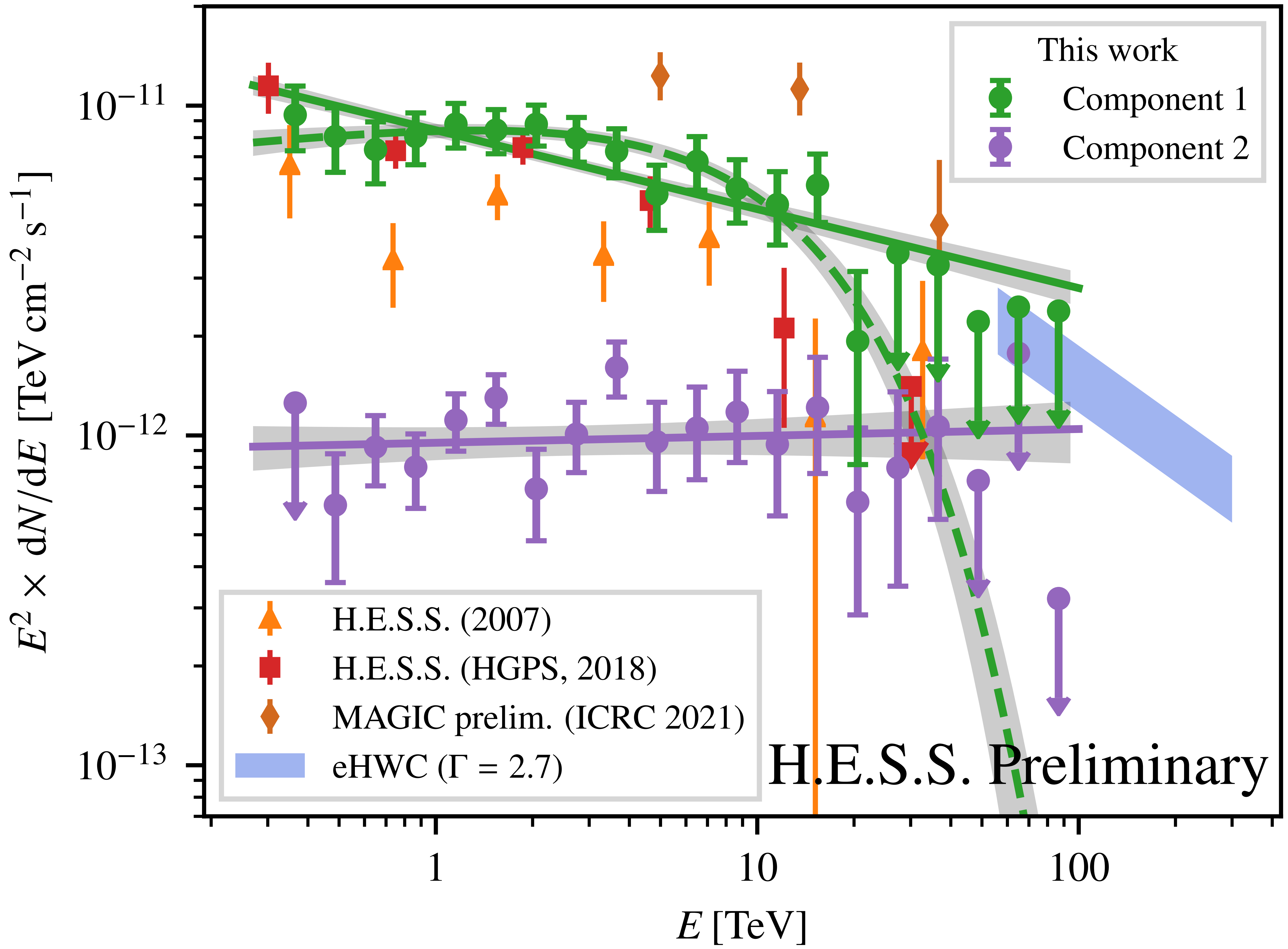
- 1-component model
  - spatial model: elongated Gaussian
  - spectral model: power law
  - not a good fit!

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

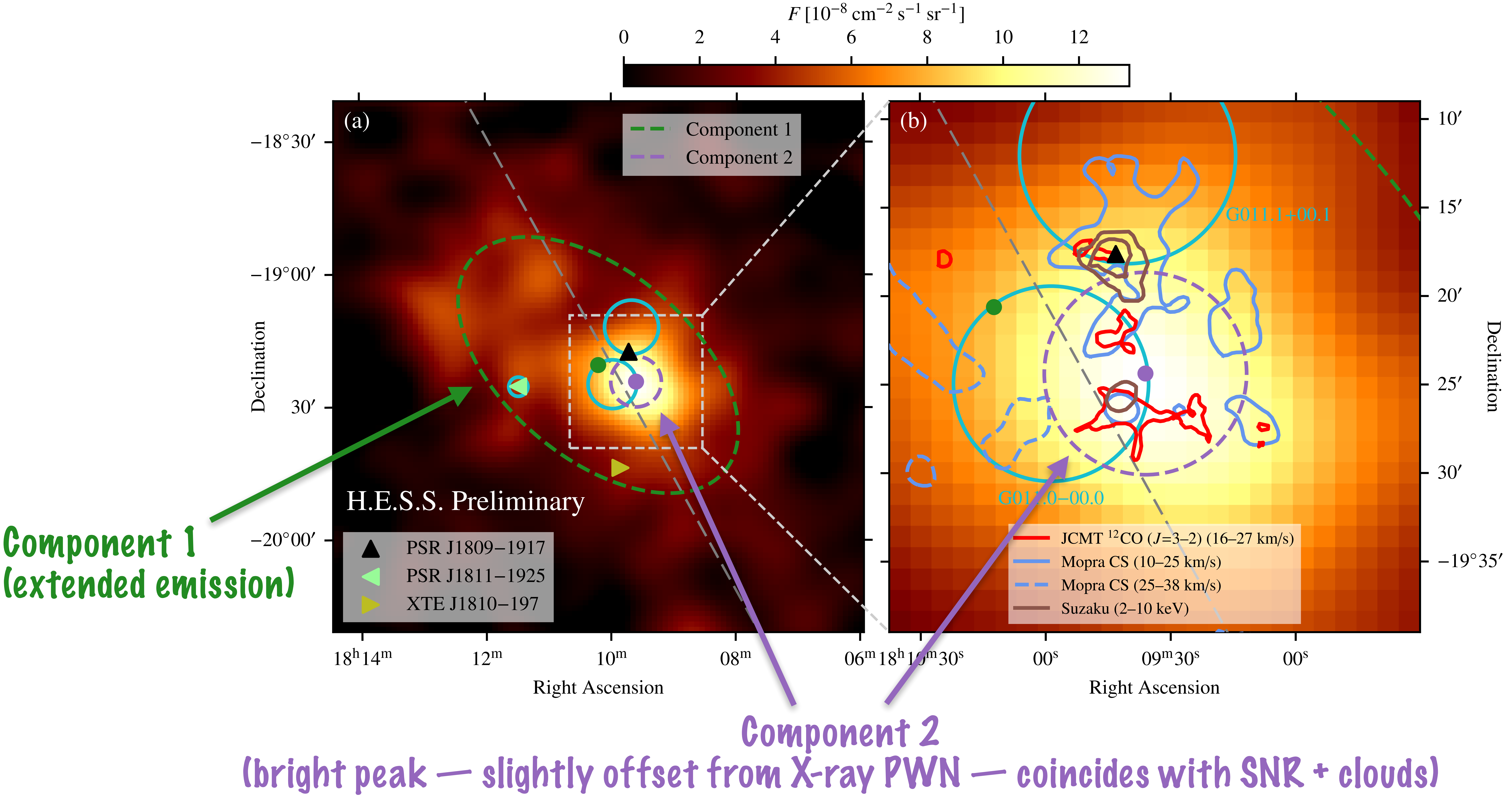


3D likelihood analysis: spectral models

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

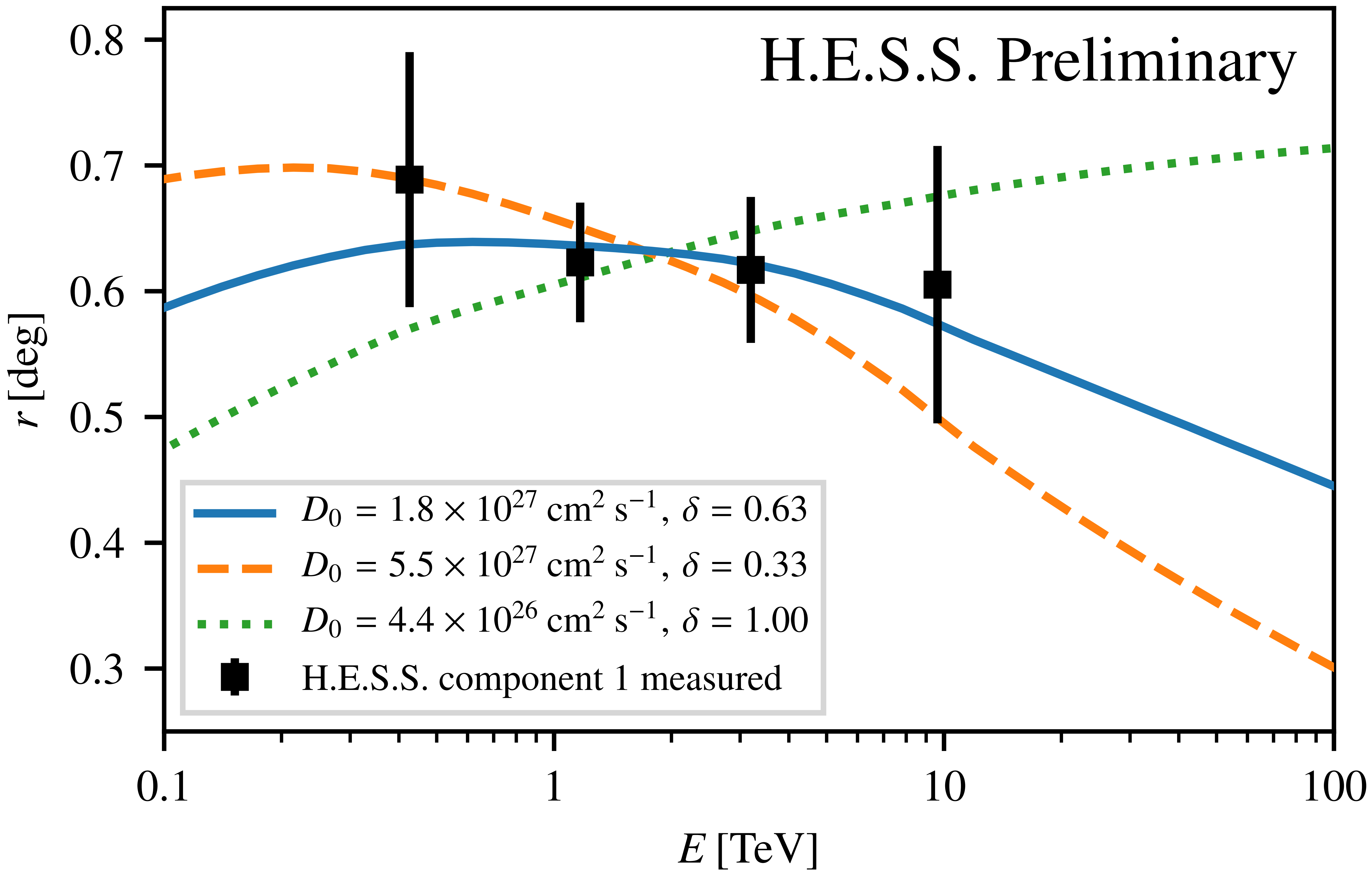


Flux map with H.E.S.S. models



Extended component: a “halo” of old electrons?

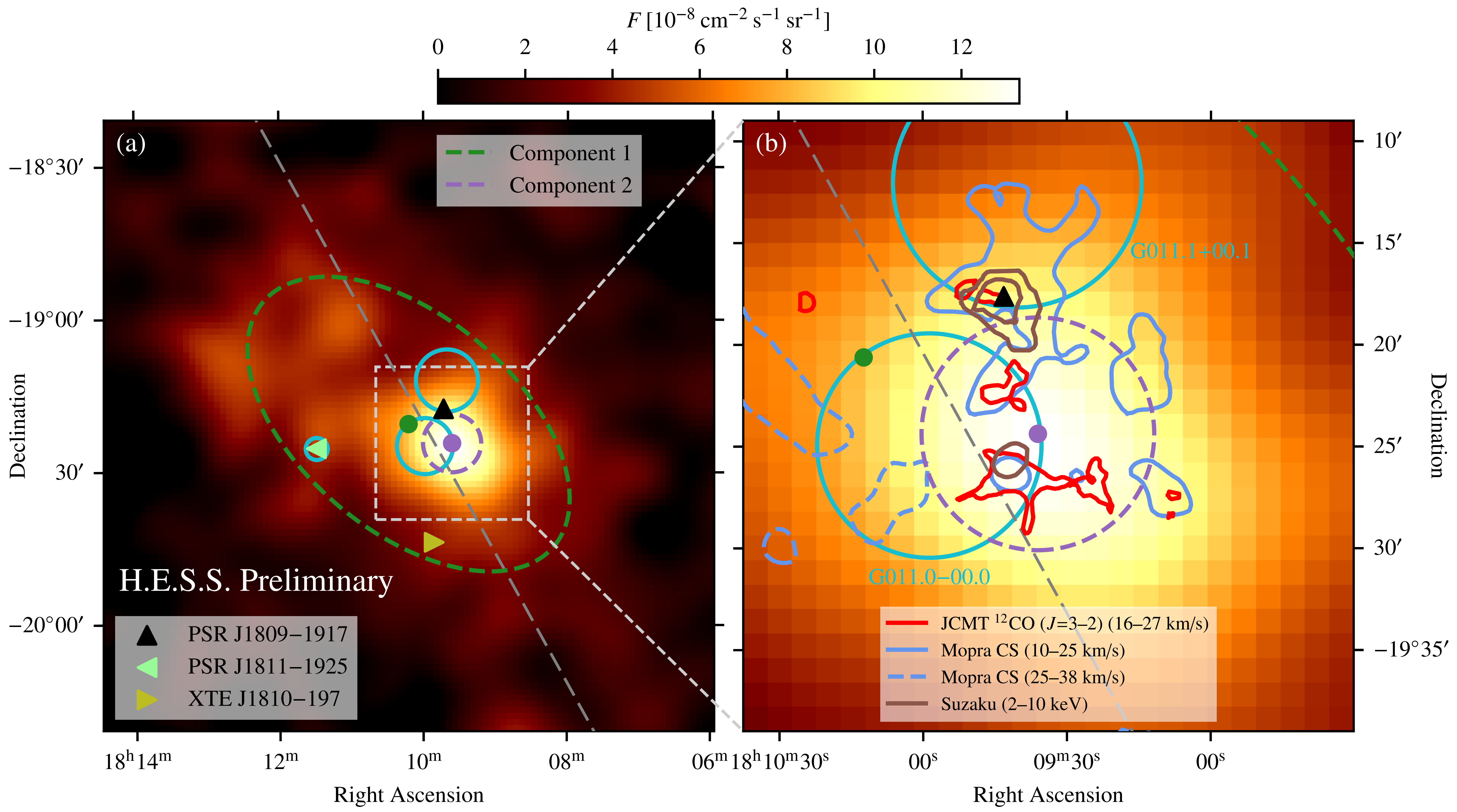
- Extent of emission
  - assume electrons started diffusing 20 kyr ago (age of system)
  - compute expected size of halo and compare with measurement
  - good agreement for $D_0 \sim 2 \times 10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ → a reasonable value!

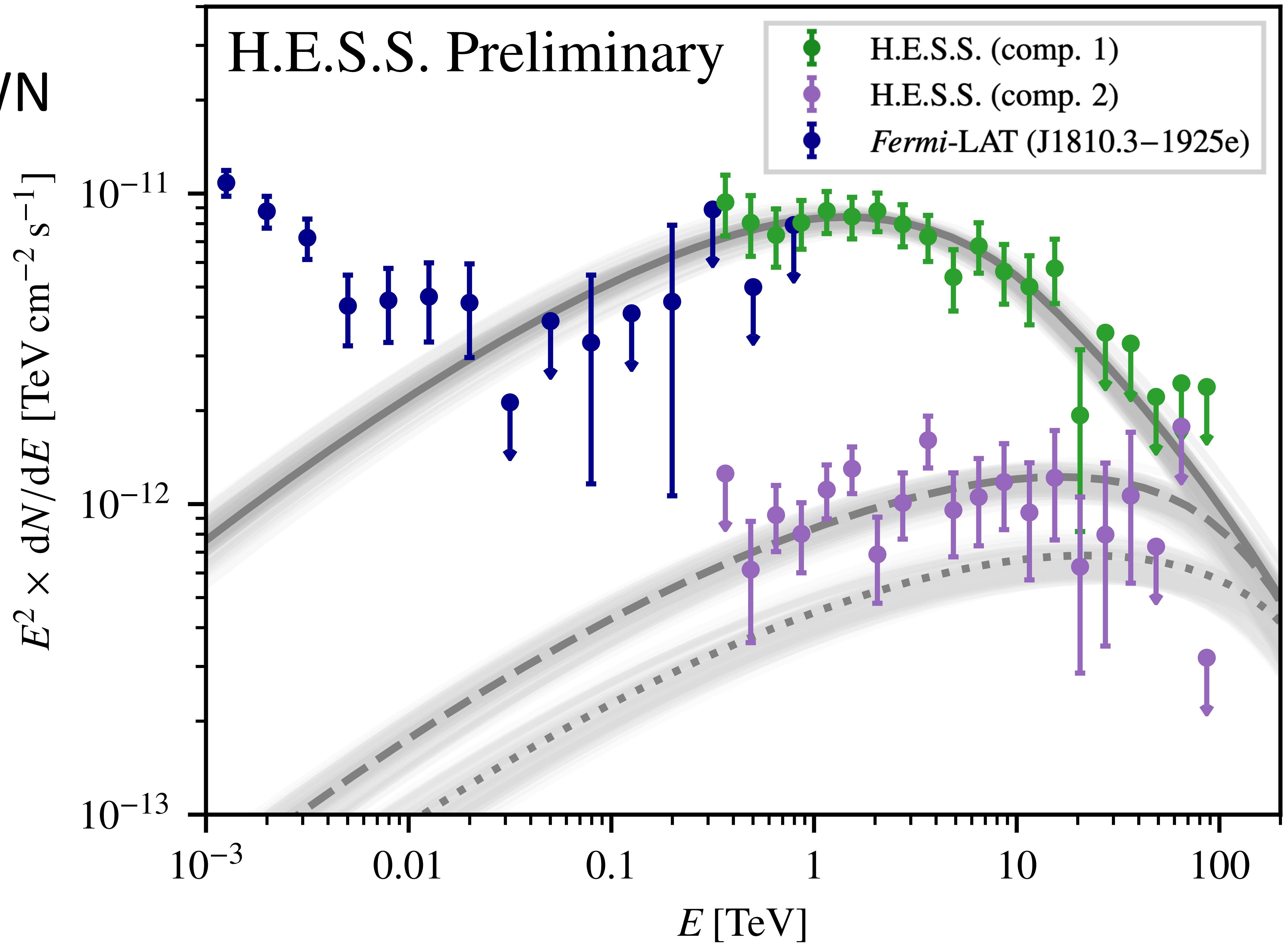


- Energy spectrum
  - expect cut-off in γ-ray spectrum because highest-energy electrons have cooled
  - as observed!

Compact component: leptonic or hadronic?

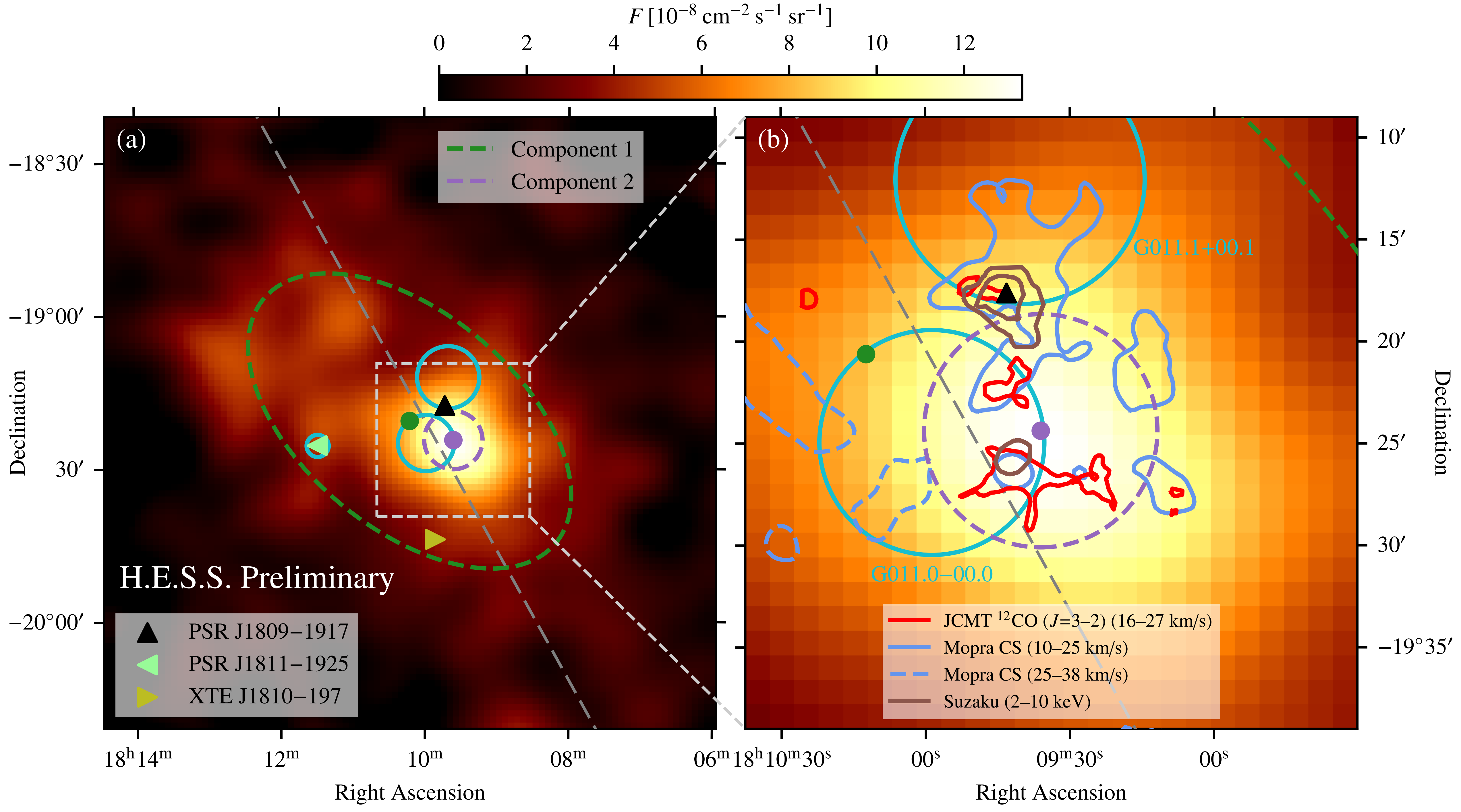
- Leptonic
  - inverse Compton emission from PWN electrons
  - peak of emission slightly offset from pulsar / X-ray PWN
  - "medium-aged" electrons escaping into broader region?

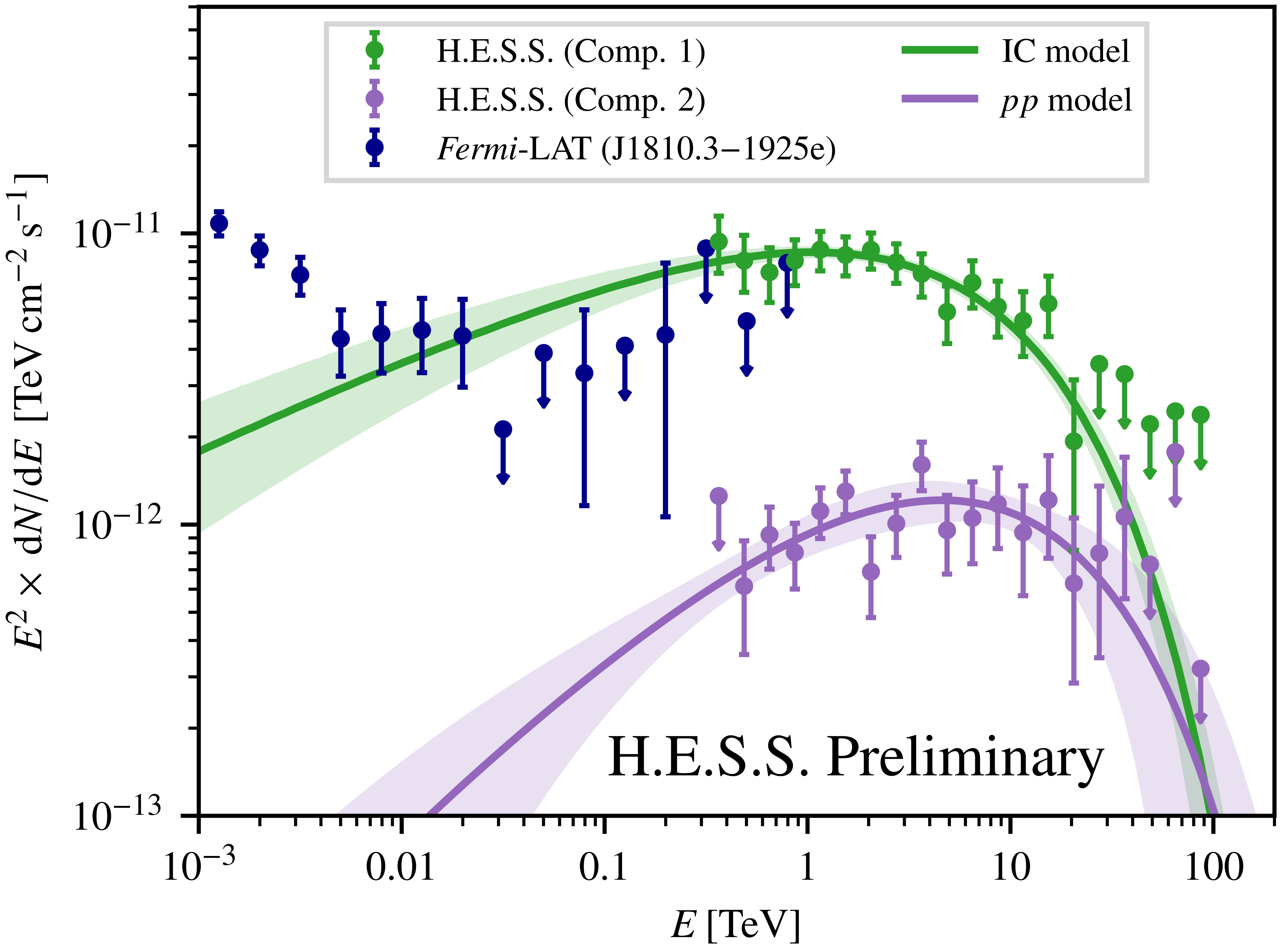




Compact component: leptonic or hadronic?

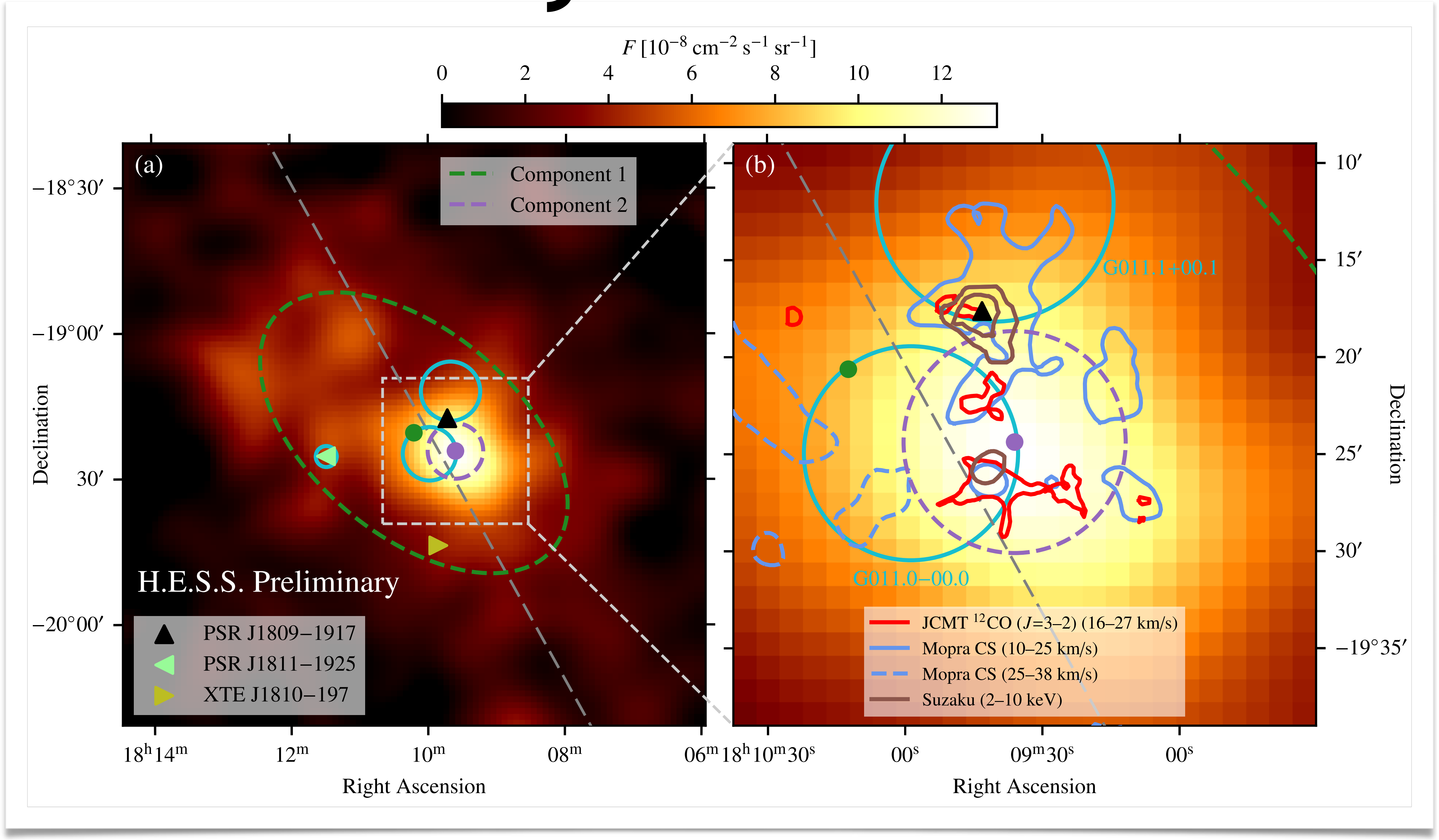
- Hadronic
  - cosmic-ray nuclei accelerated in SNR and interacting in molecular clouds
  - peak of emission coincident with SNR shell & clouds
  - viable energetically ($W_p \sim 3 \times 10^{49}\ \left(n / 1\,\mathrm{cm}^{-3}\right)^{-1}$ erg)

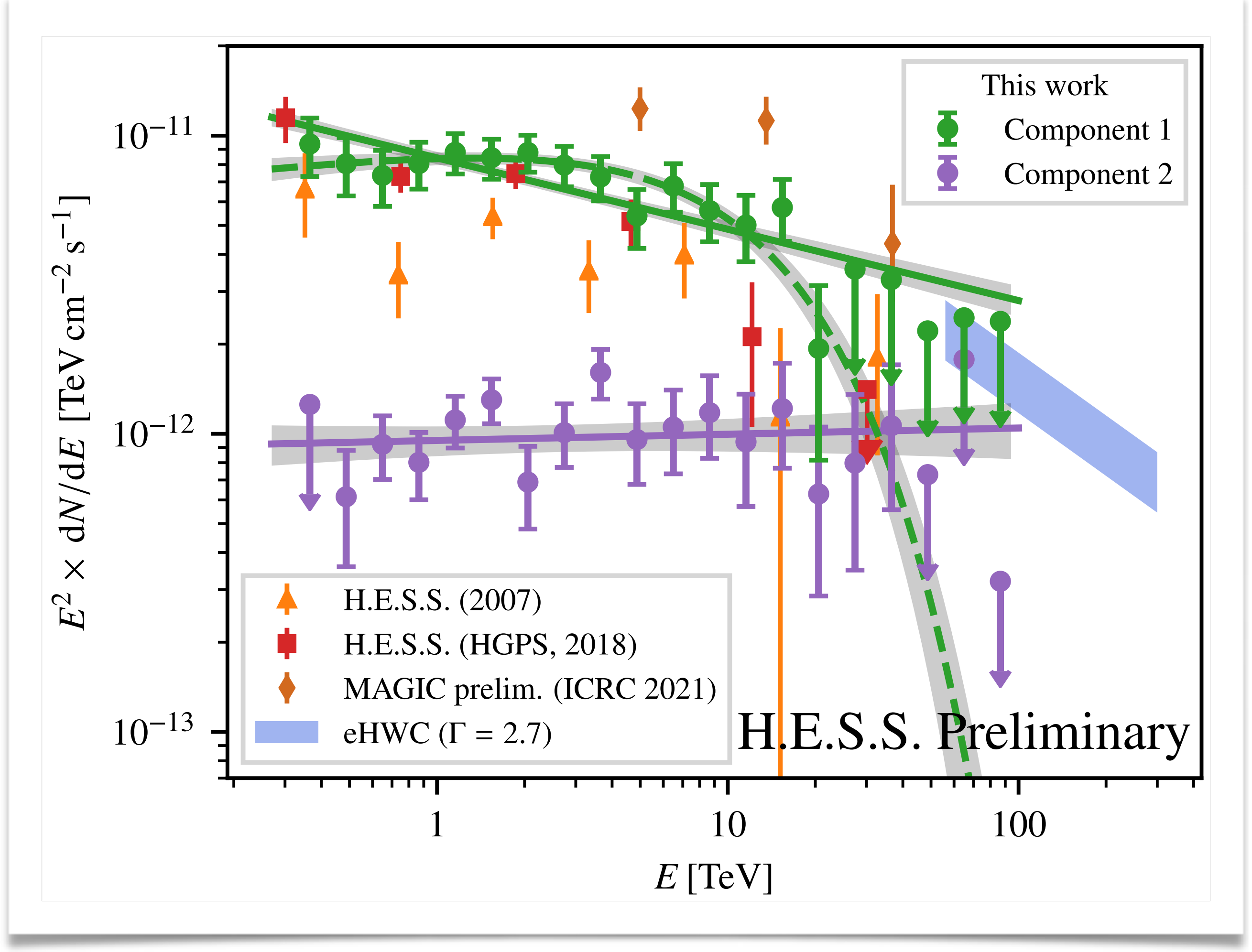




HESS J1809–193: summary

- 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!



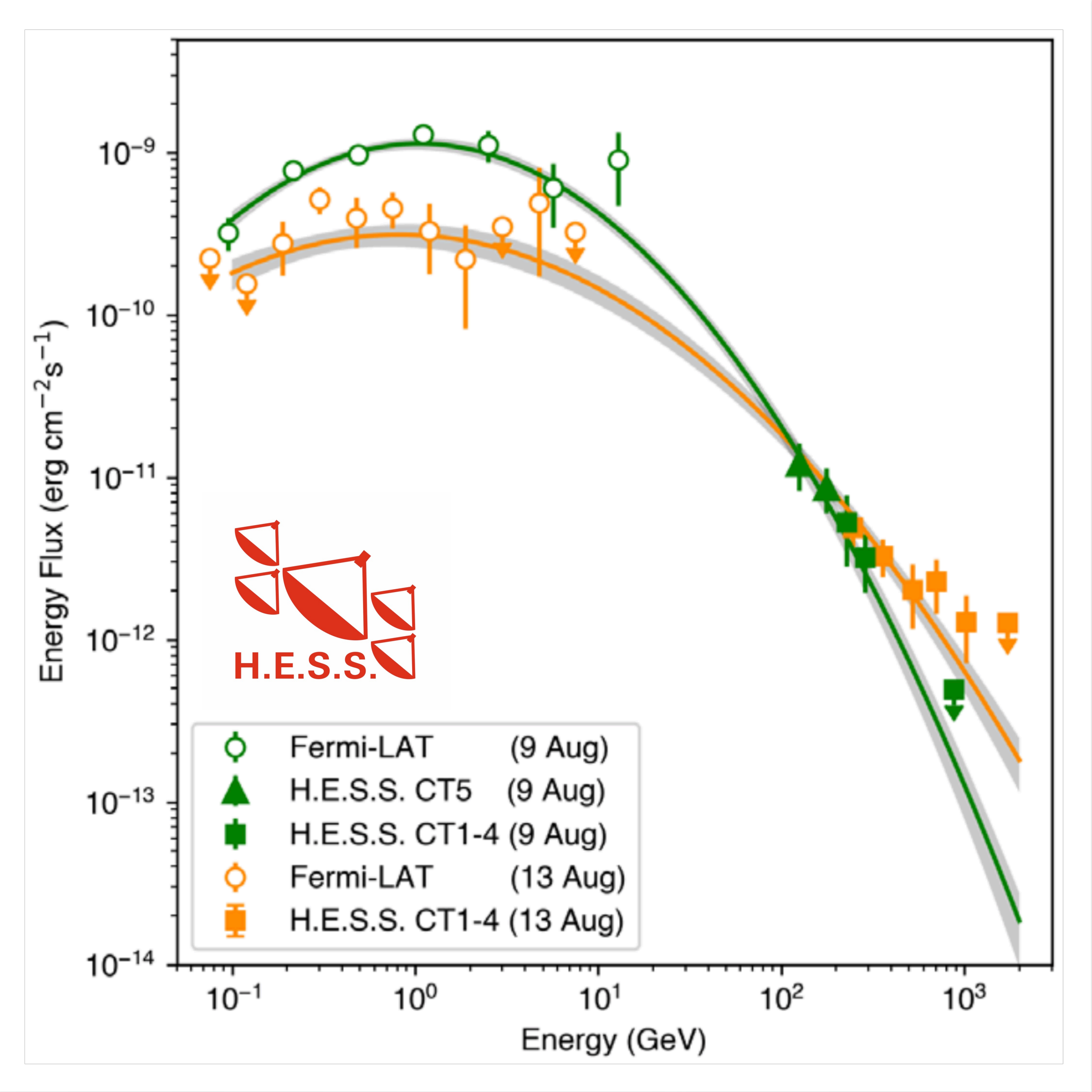


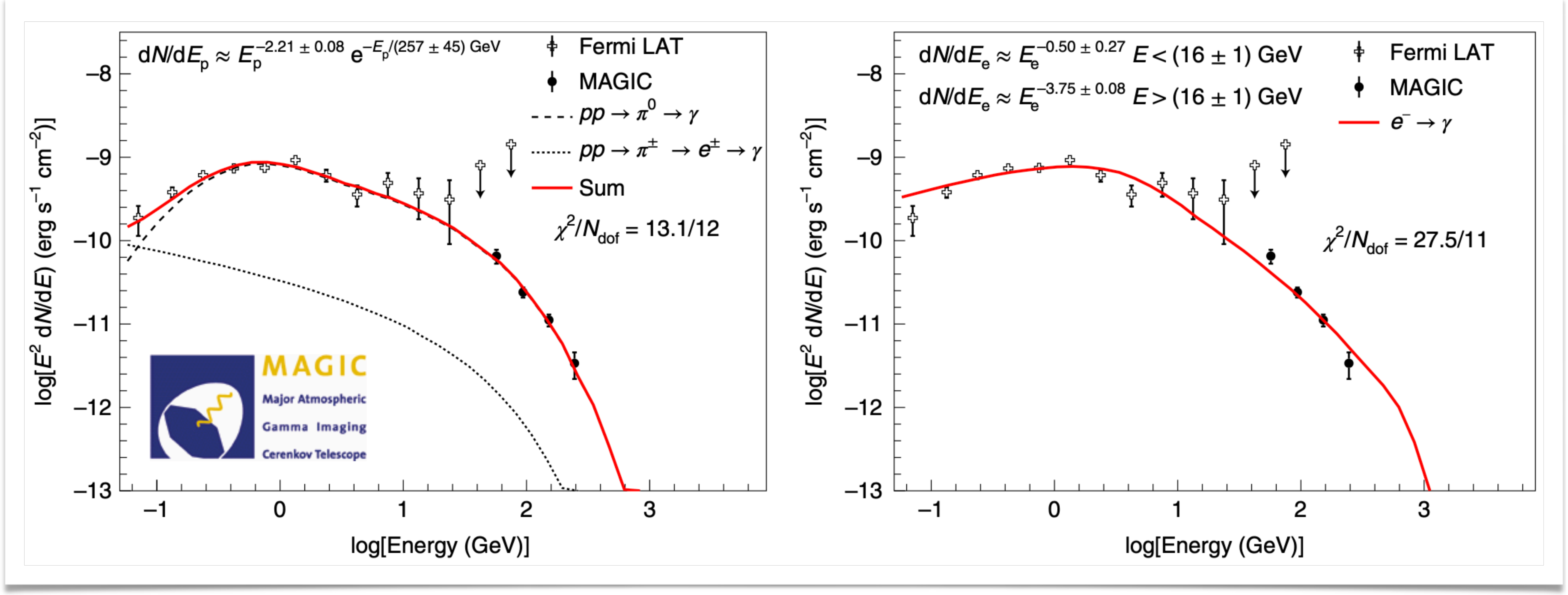
Other recent highlights

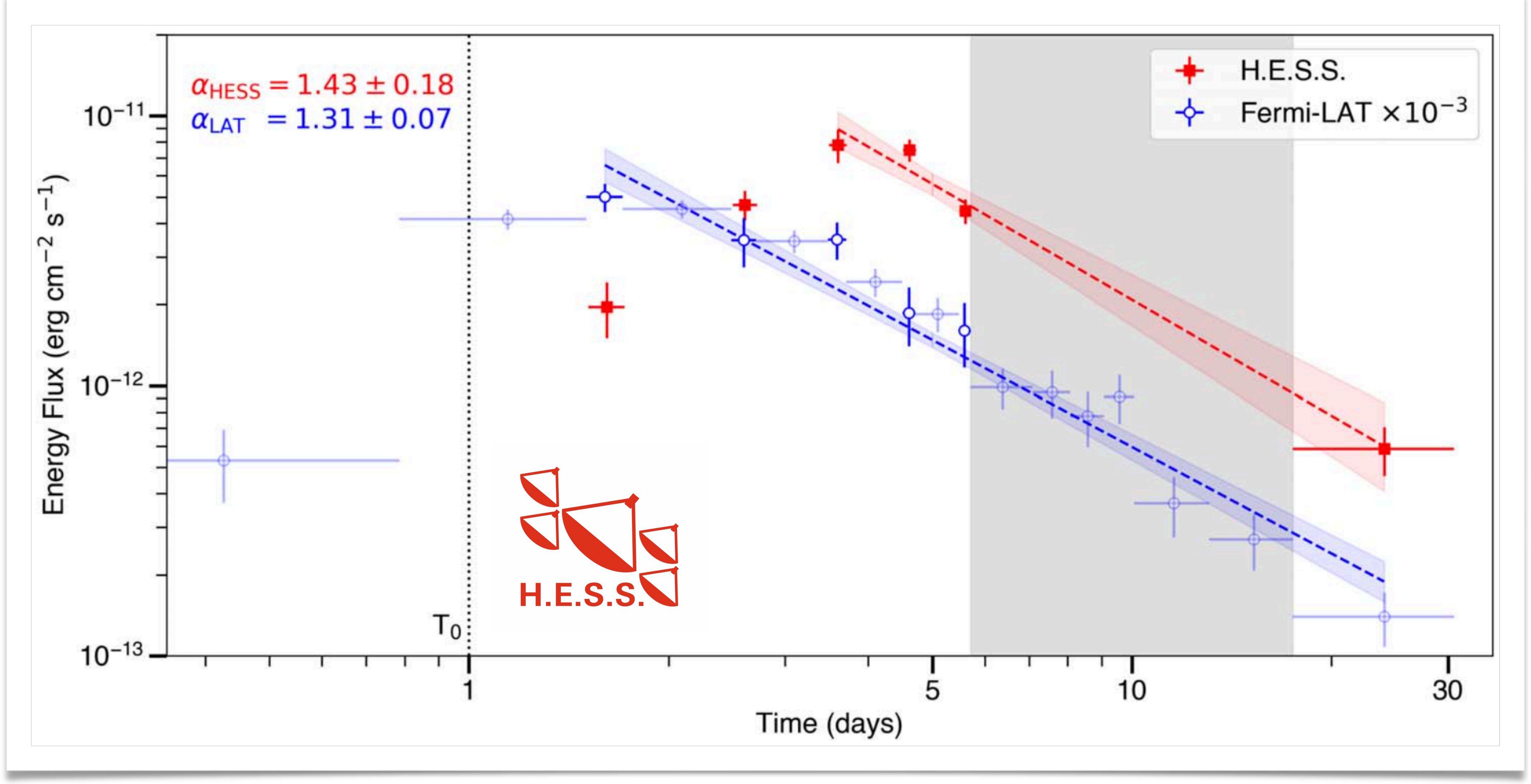
(a personal selection — not exhaustive!)

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





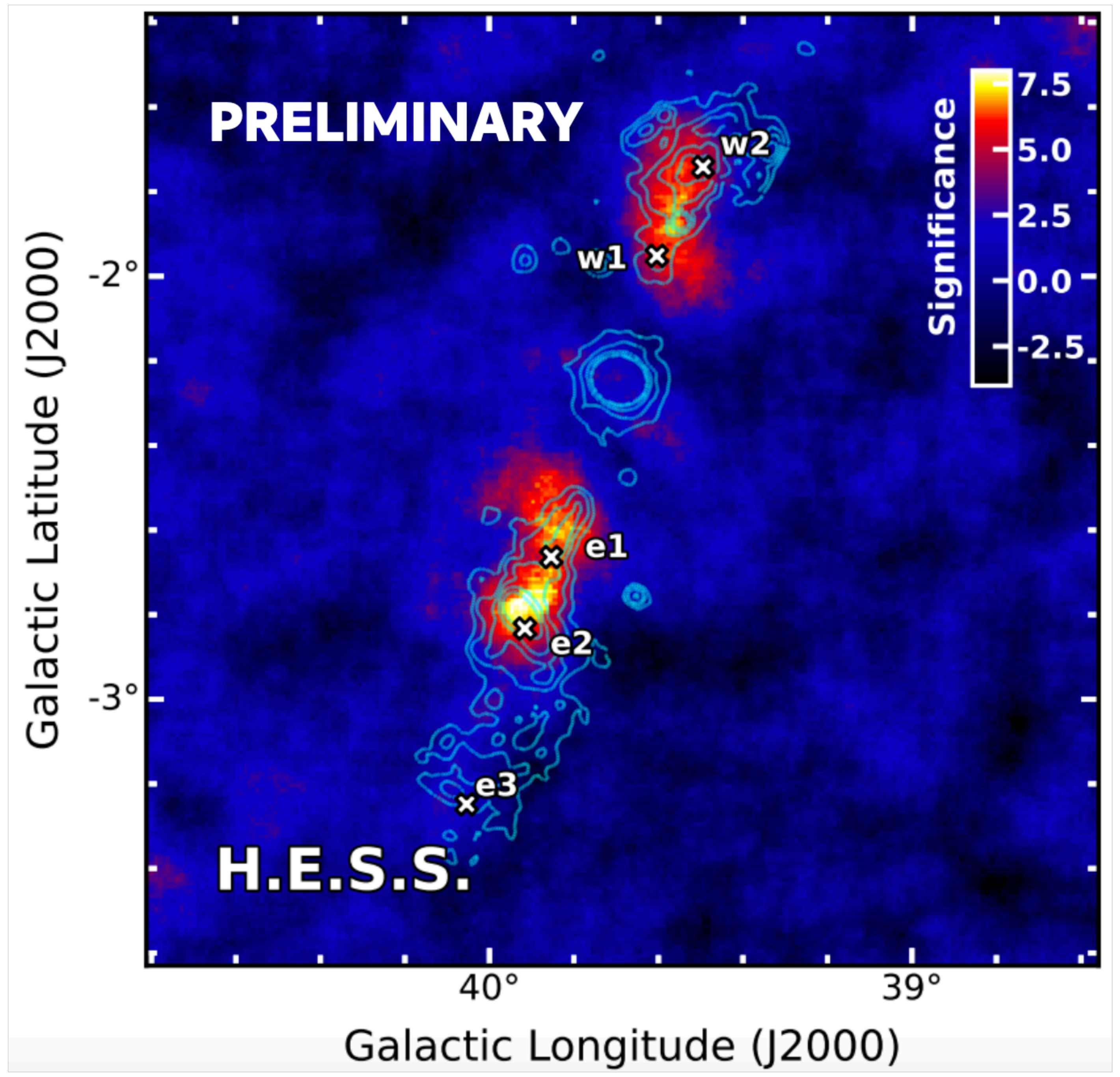


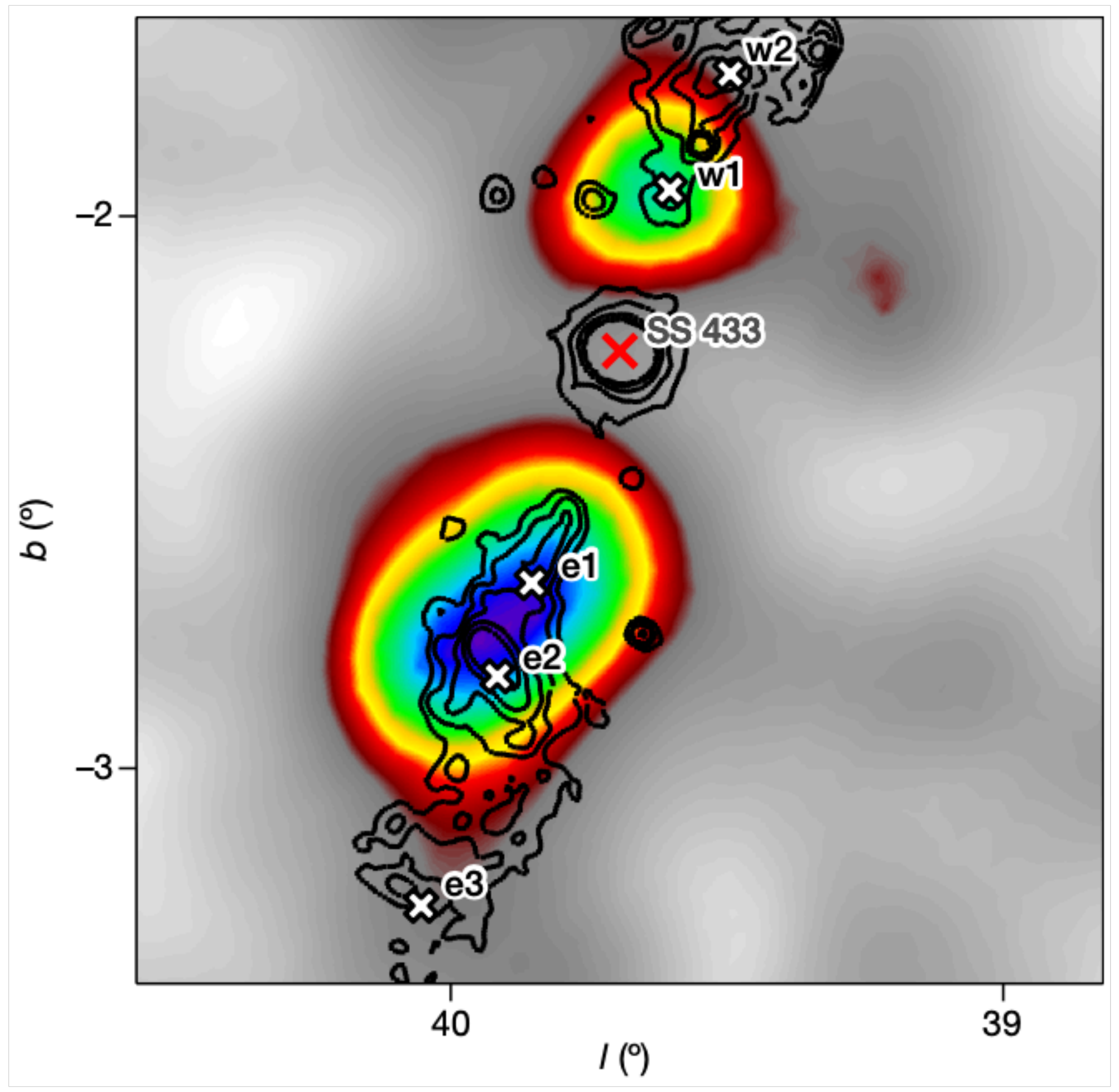
MAGIC Collaboration, Nature Astronomy 6, 689 (2022)

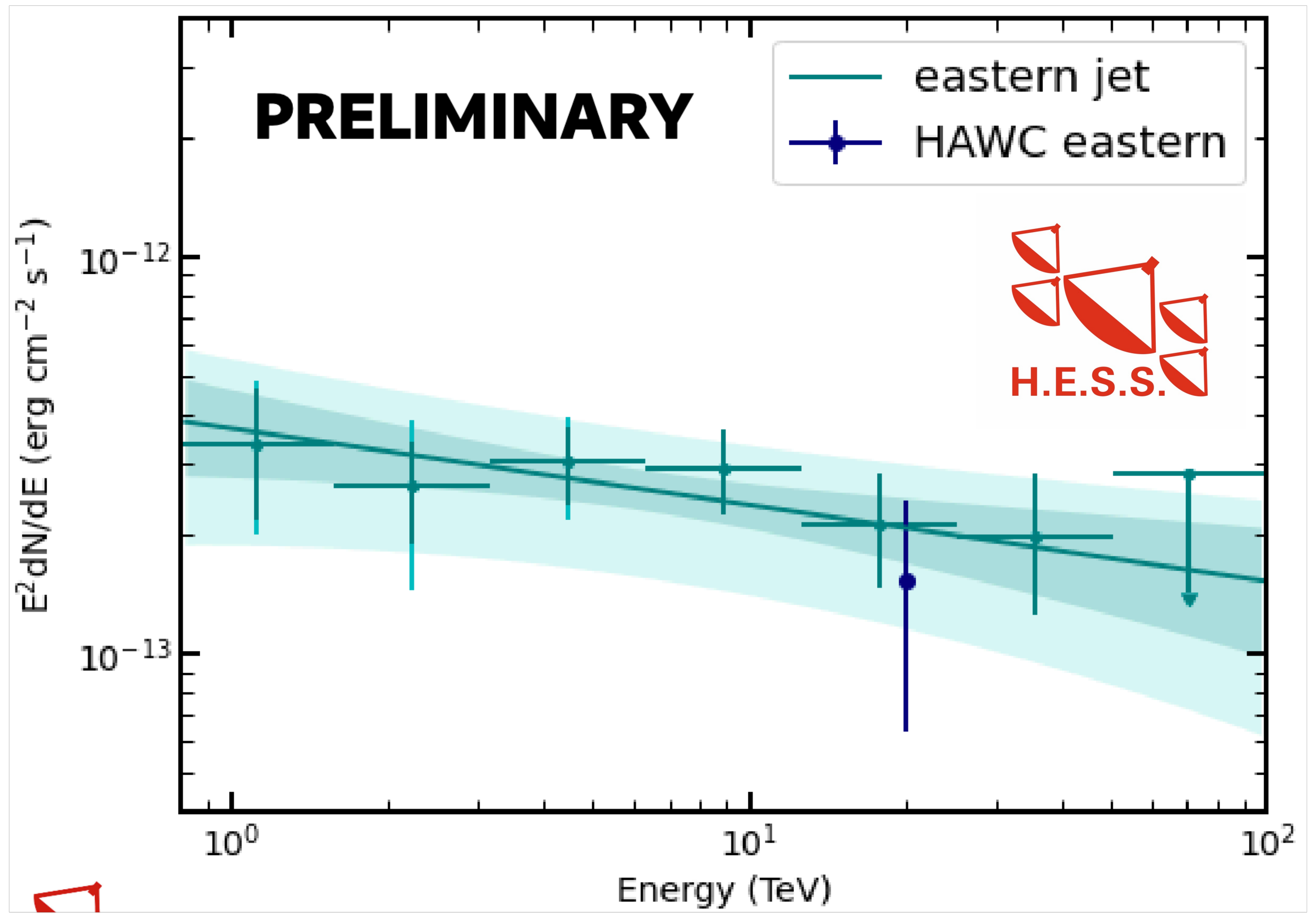
H.E.S.S. Collaboration, Science 376, 77 (2022)

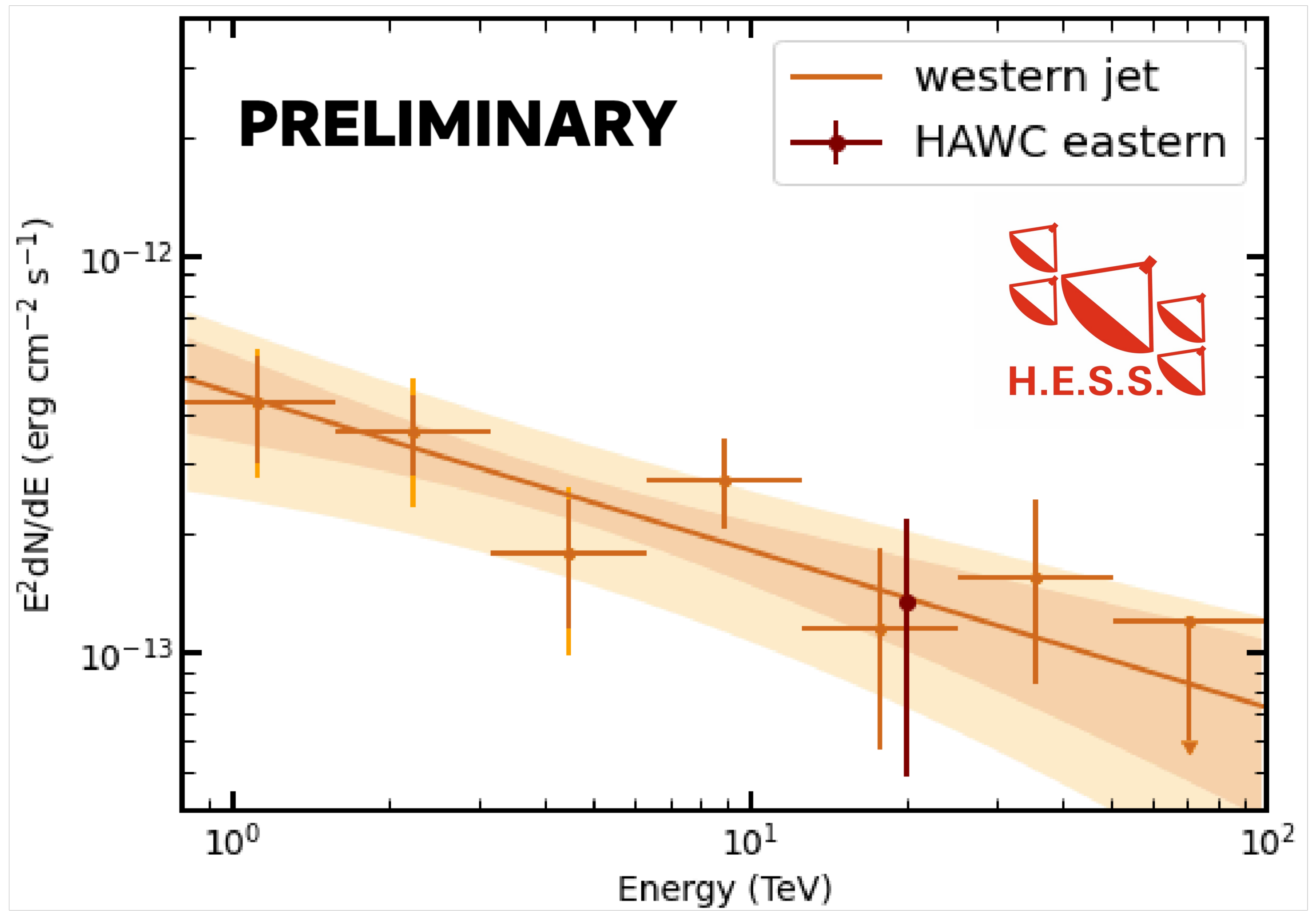
SS 433

- 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)

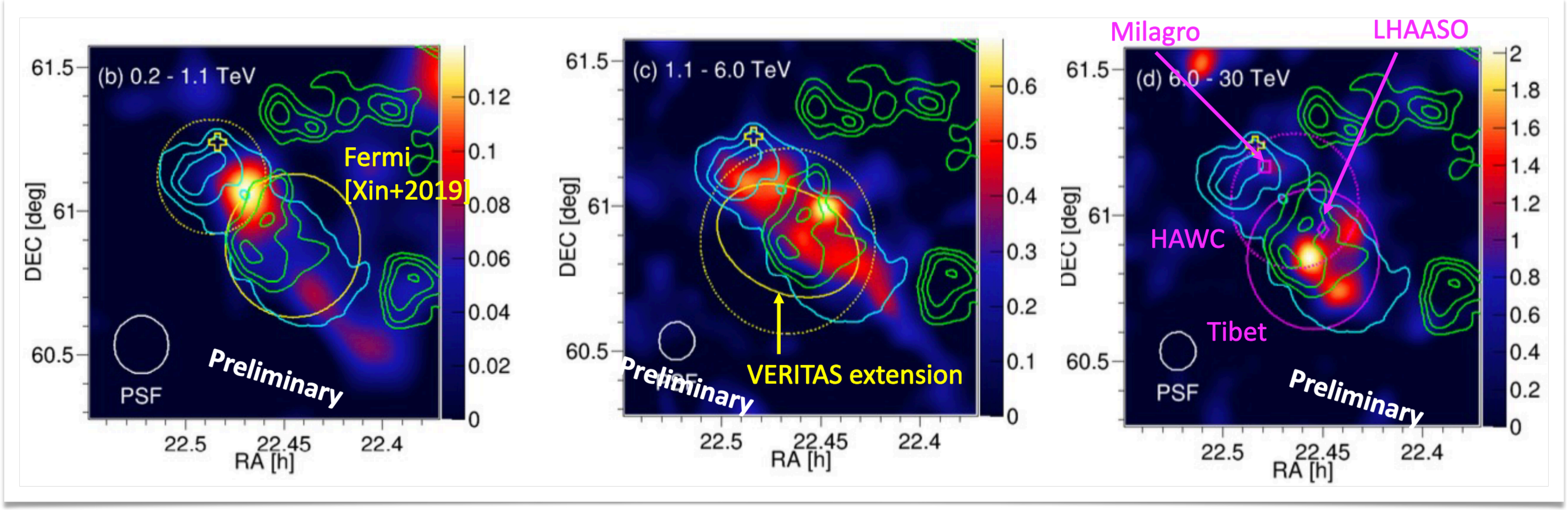
L. Olivera-Nieto et al. (for the H.E.S.S. Collaboration), Gamma 2022, Barcelona

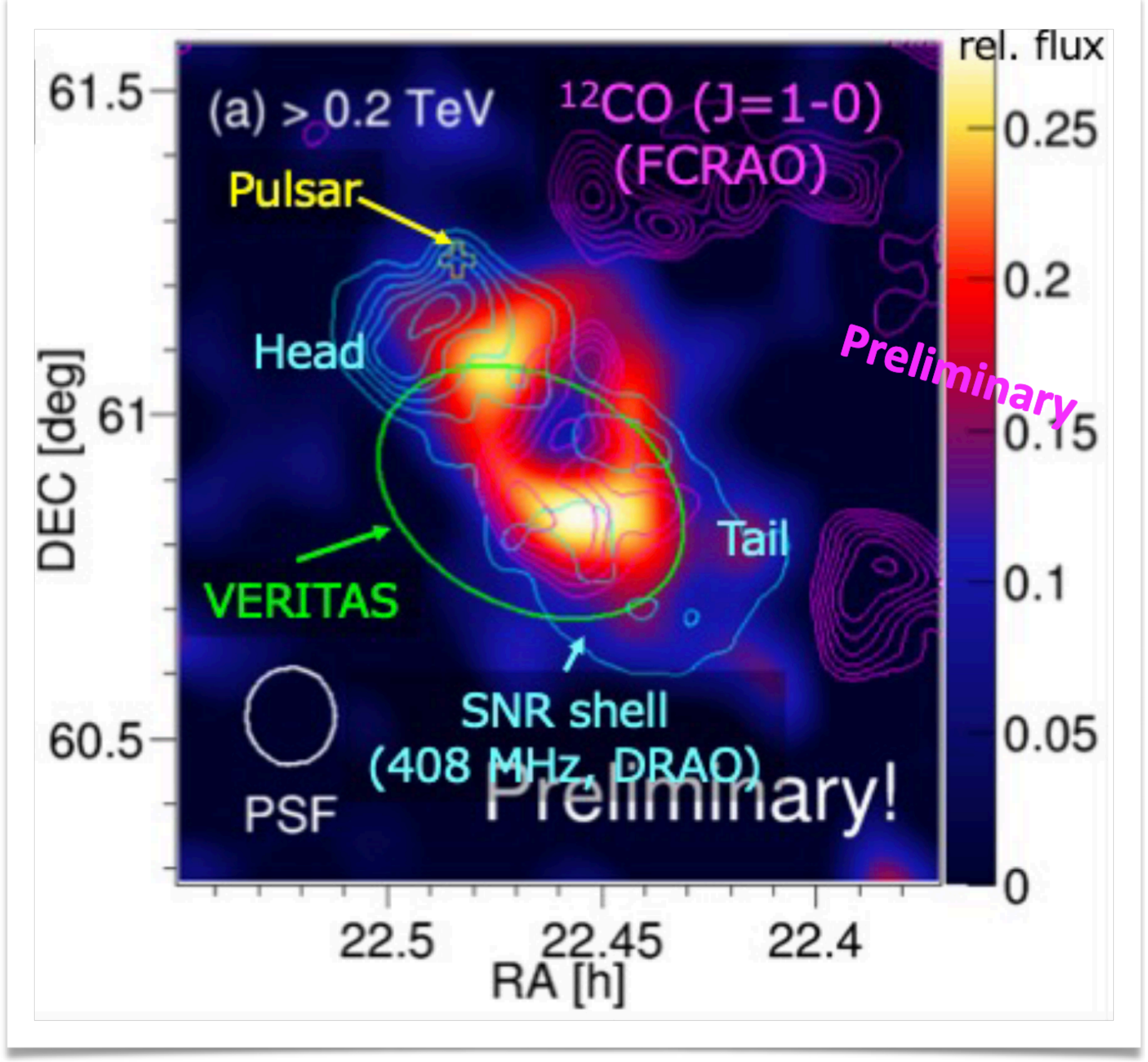
SNR G106.3+2.7 / Boomerang PWN

- 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

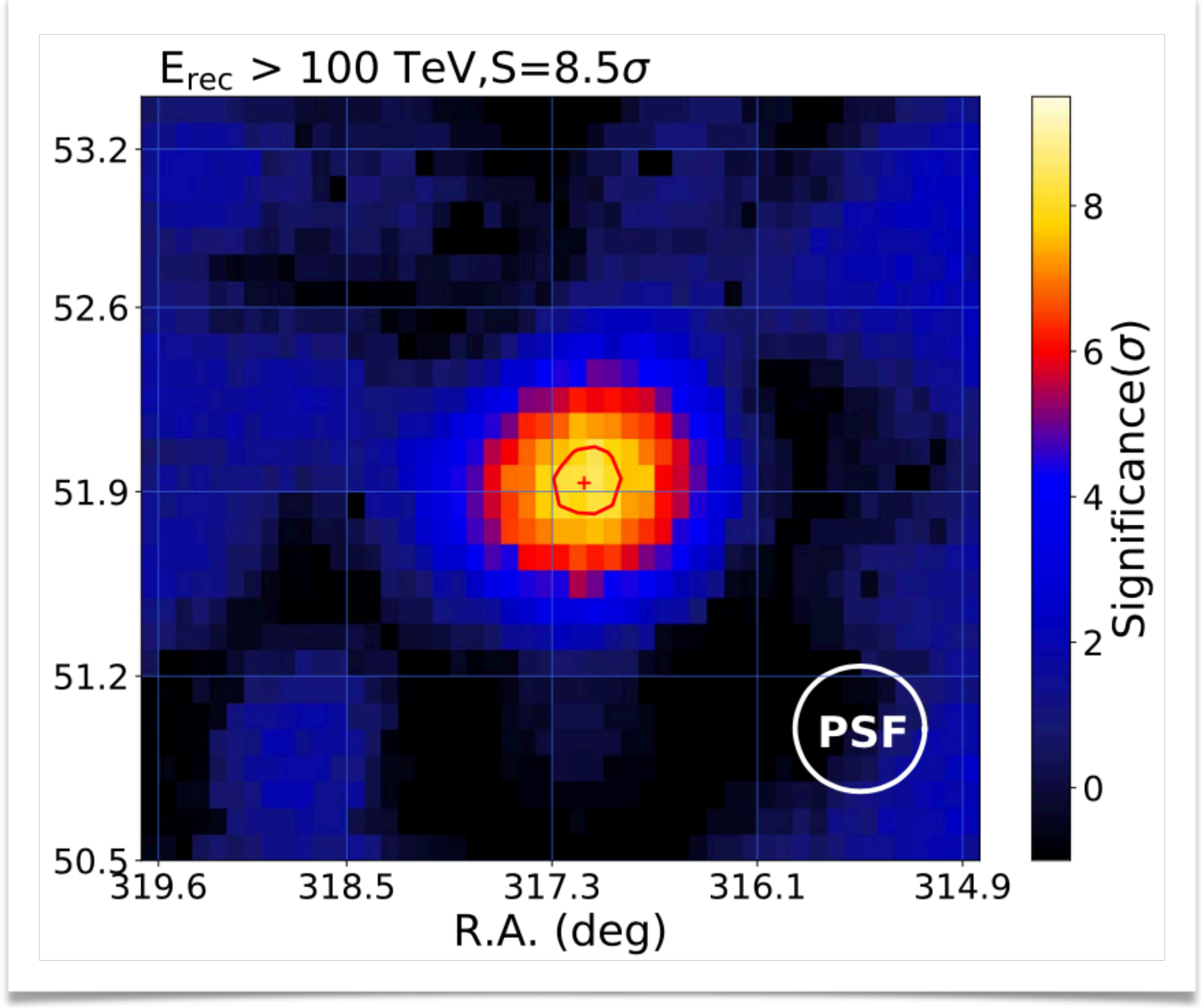




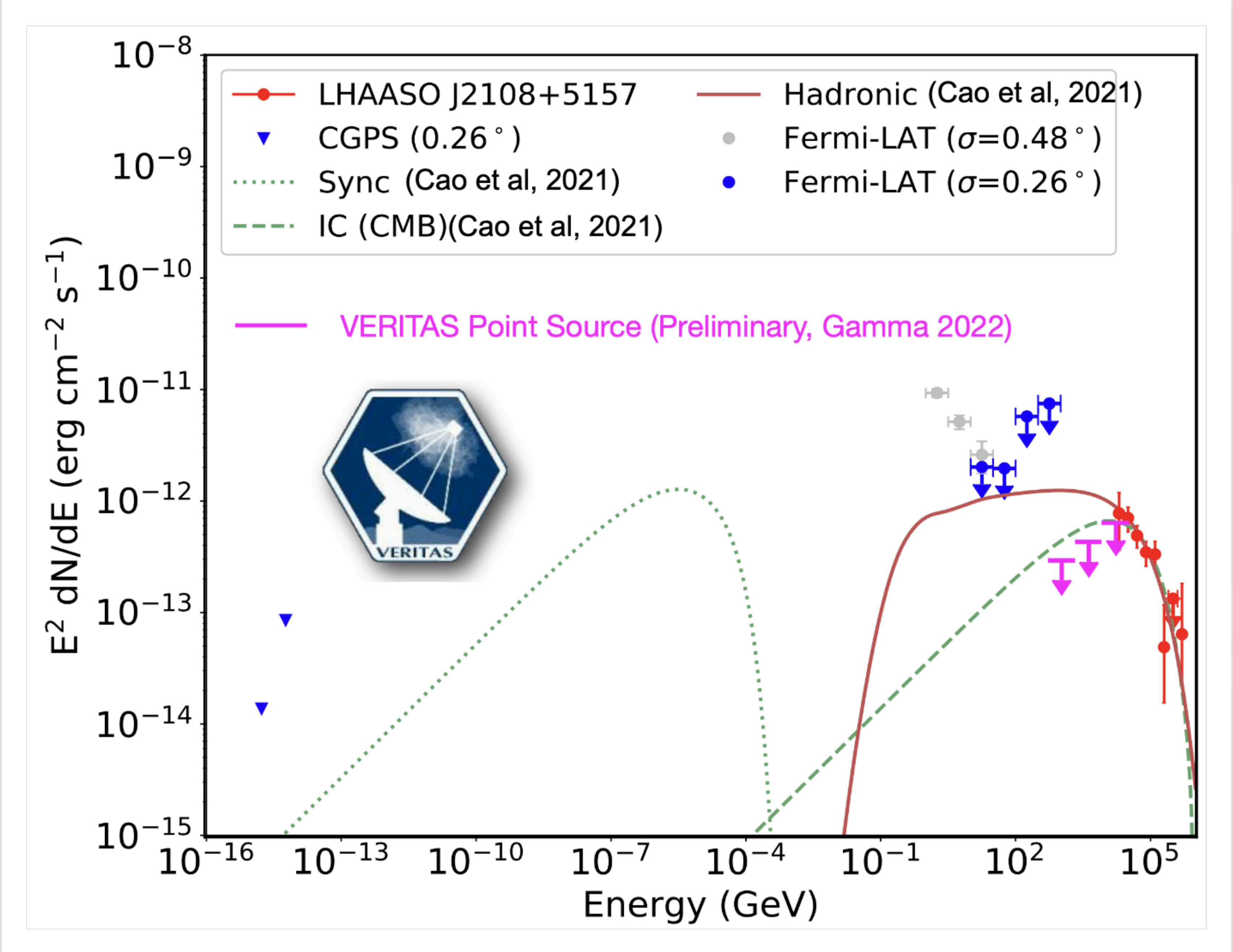
LHAASO J2108+5157

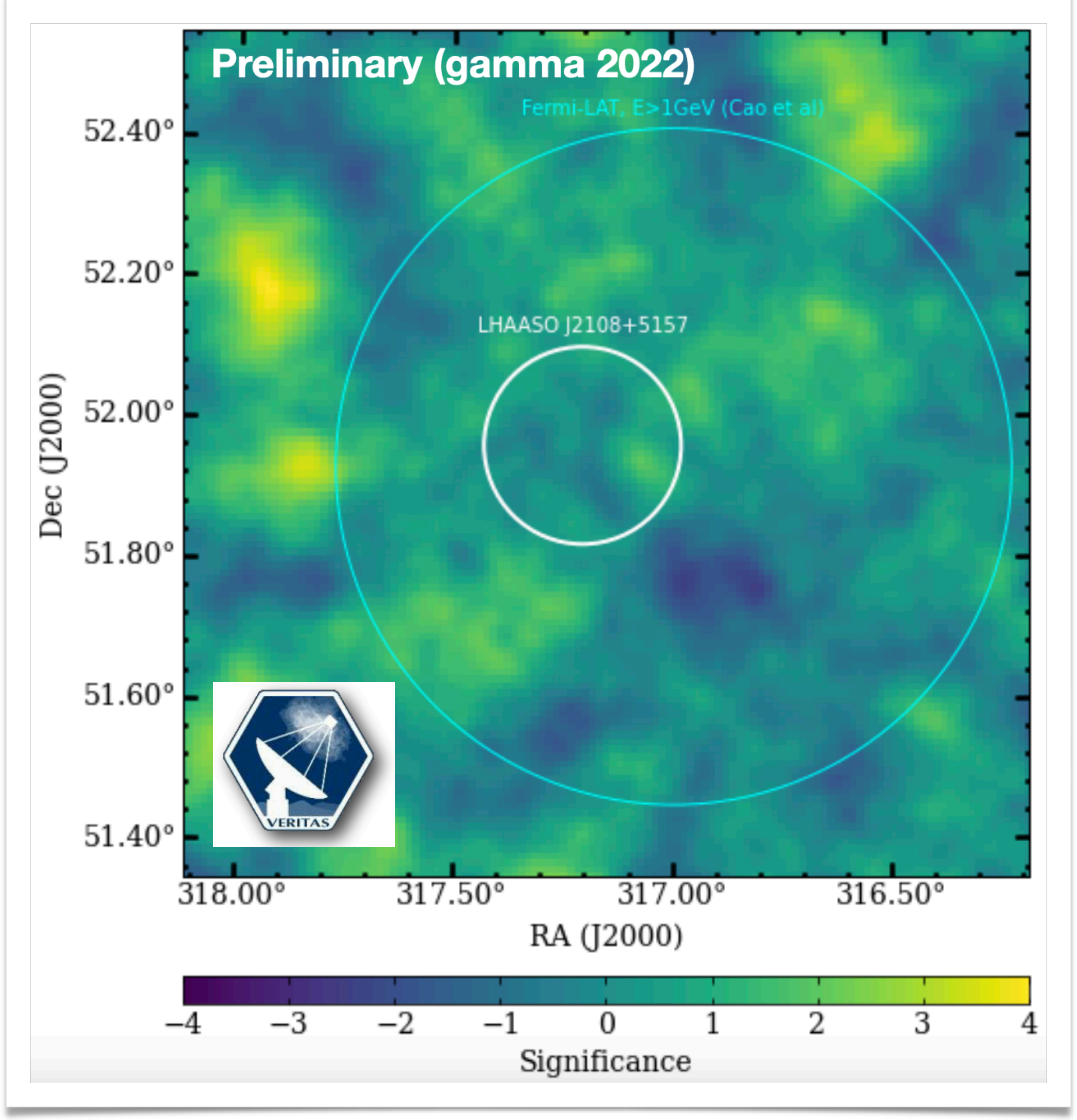
- Discovered by LHAASO above 100 TeV — no detection with IACTs yet!
- No obvious counterpart — coincident with molecular cloud
- VERITAS: no detection in 35 hours
- Point-source upper limits challenge hadronic scenario

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



LHAASO Collaboration, ApJL 919, L22 (2021)

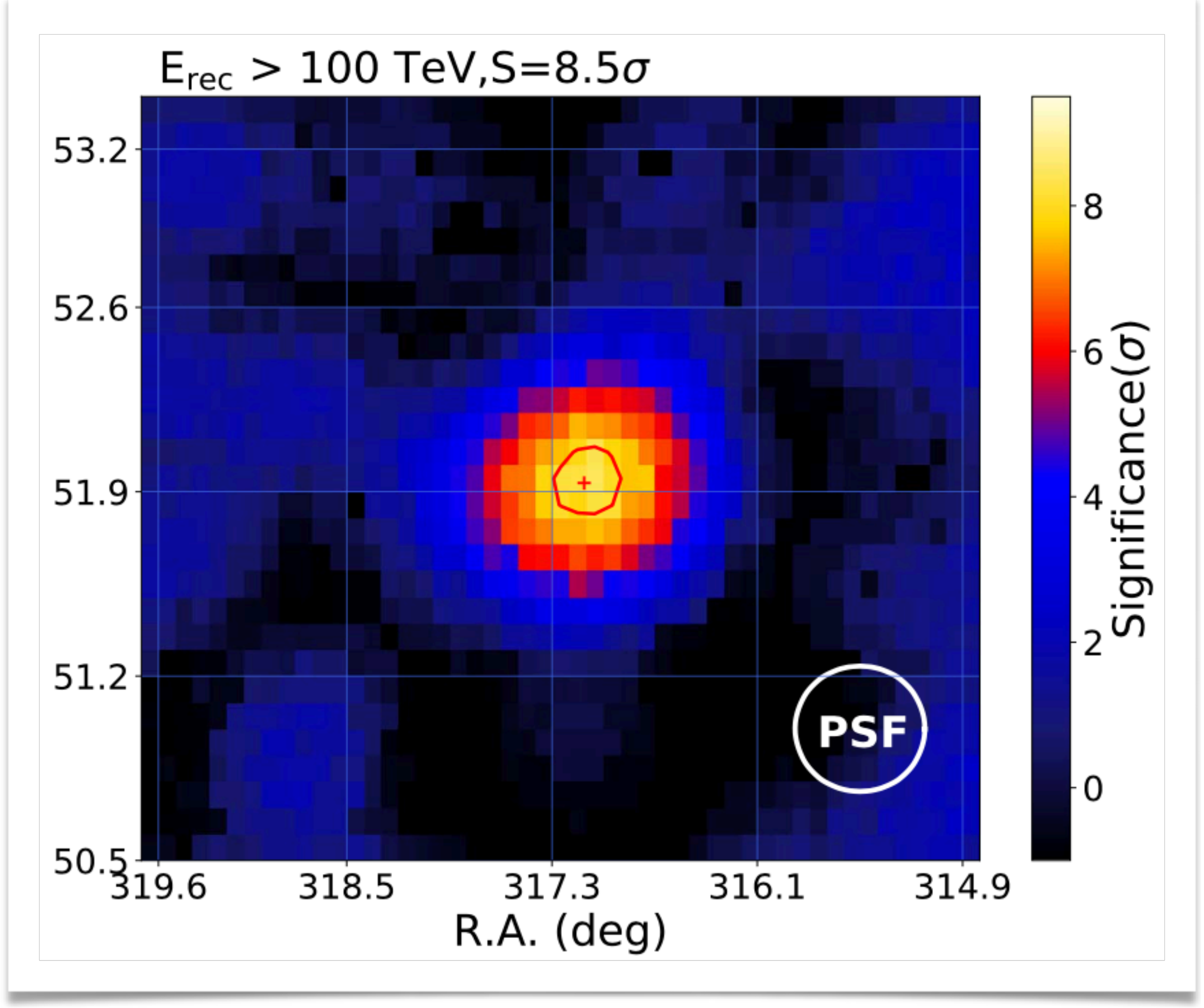




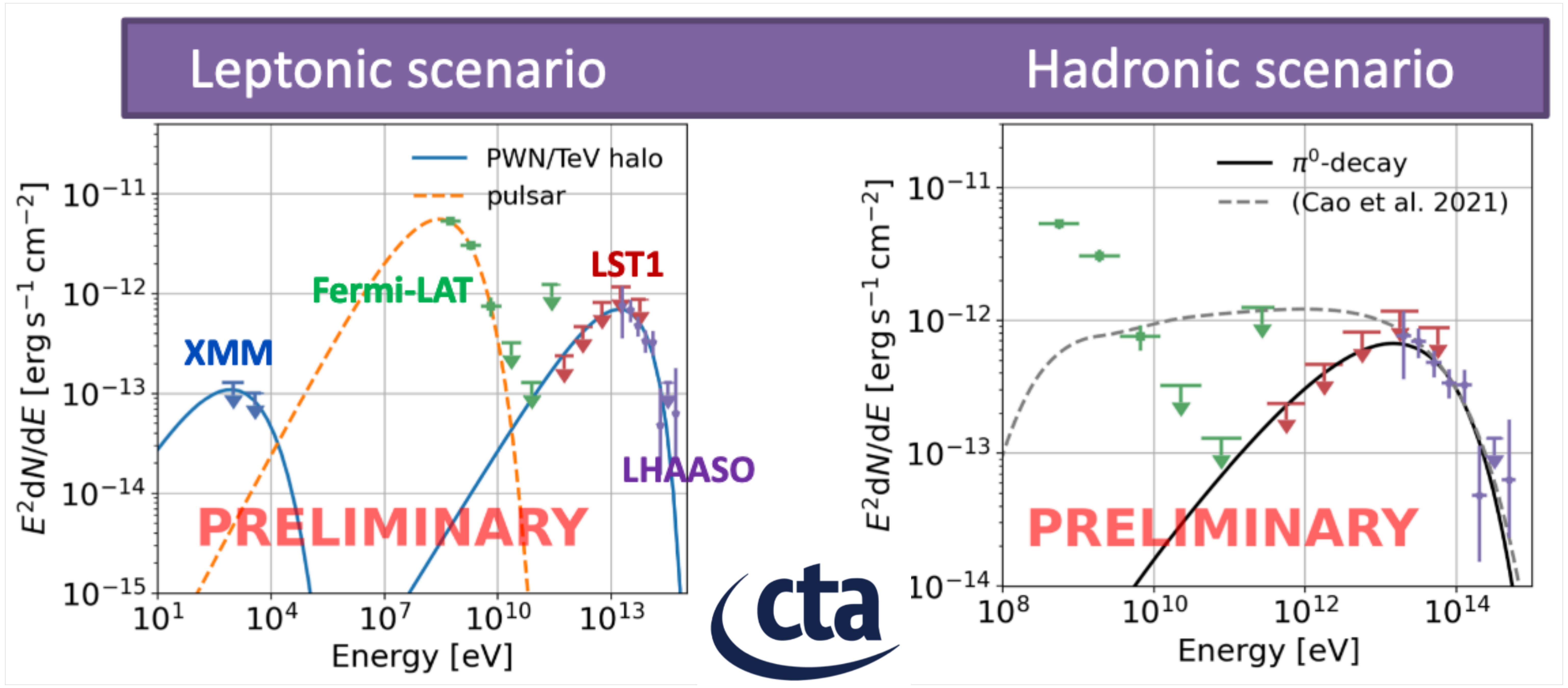
LHAASO J2108+5157

- 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

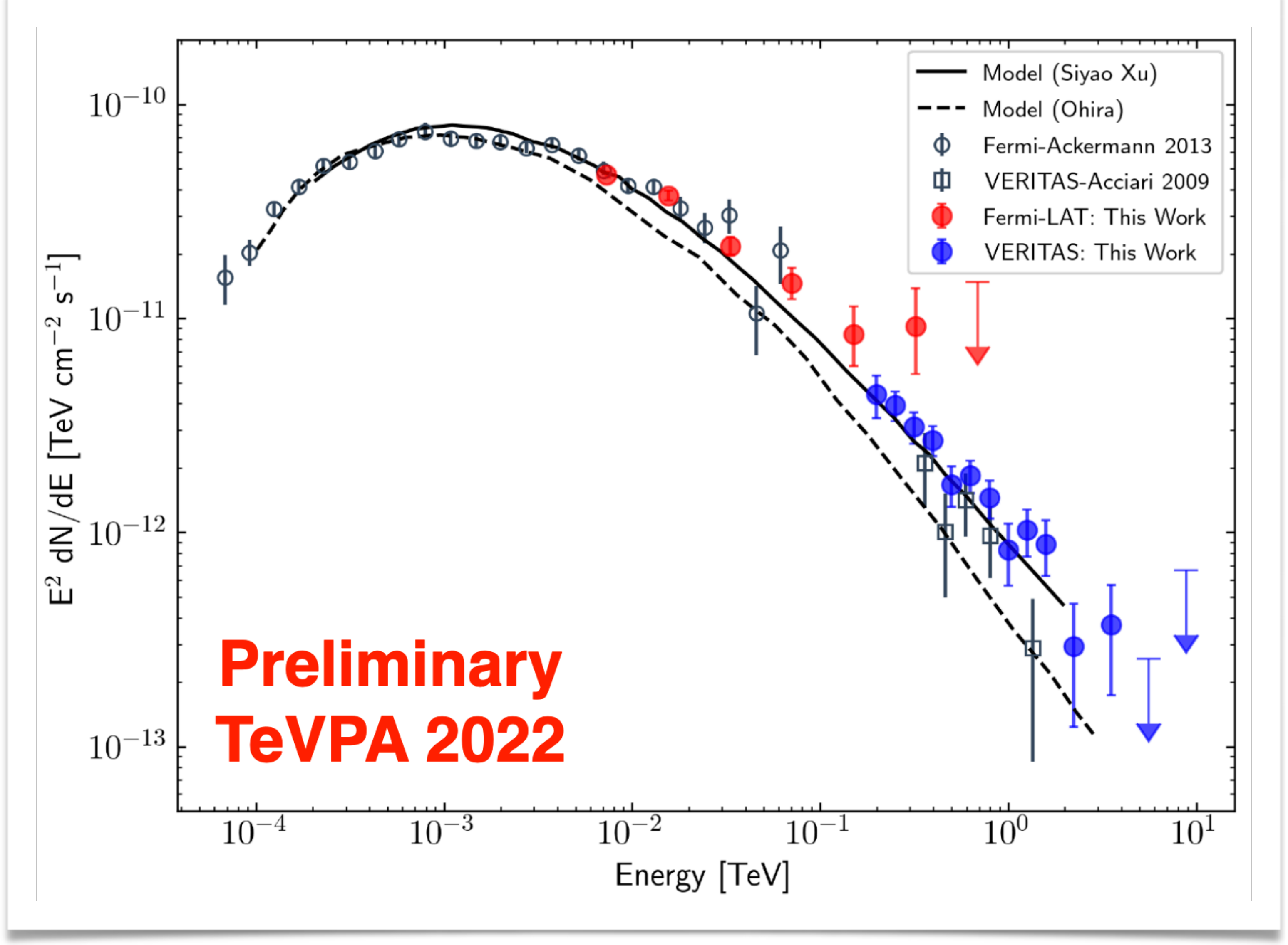


LHAASO Collaboration, ApJL 919, L22 (2021)

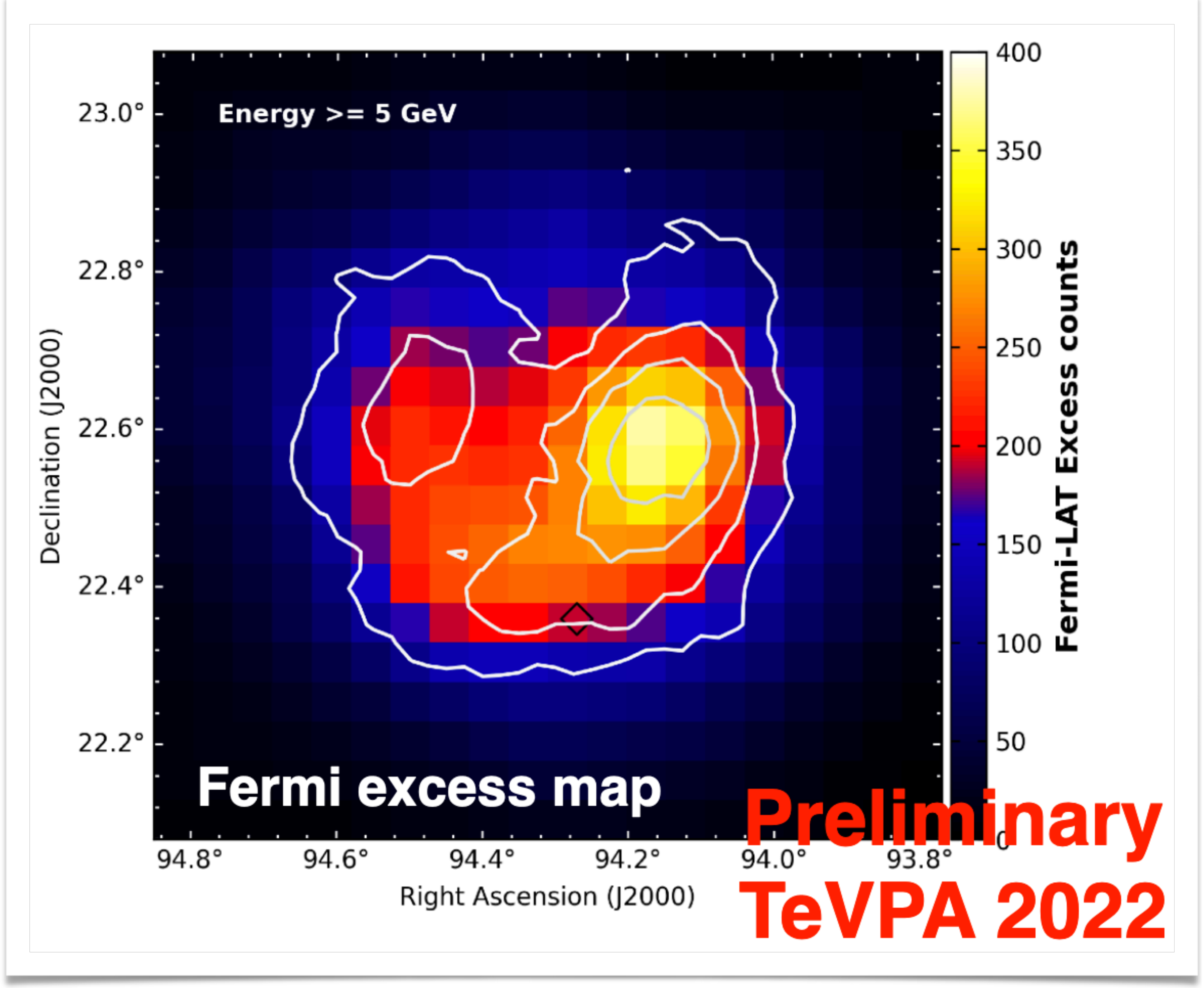


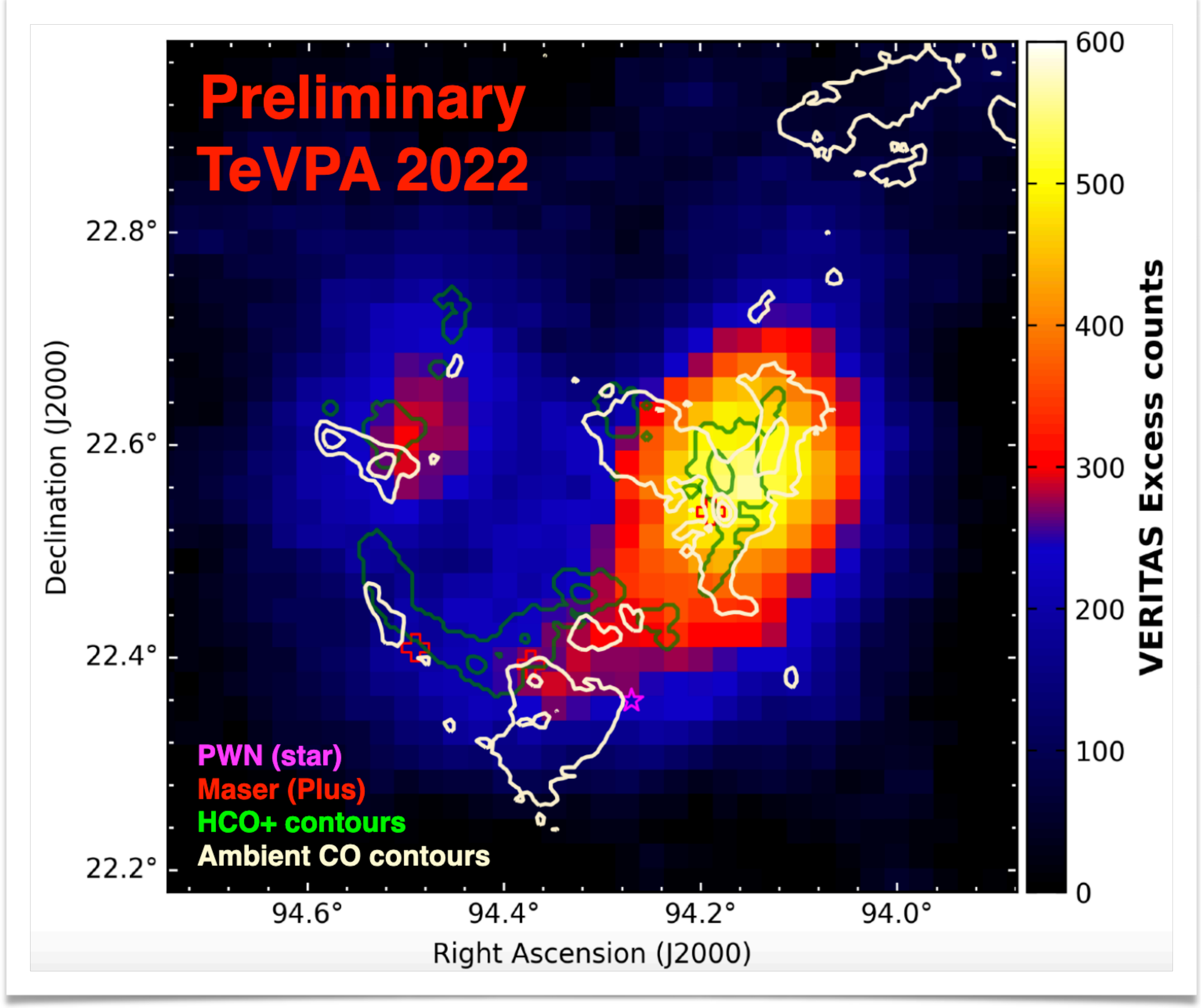
SNR IC 443

- 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…



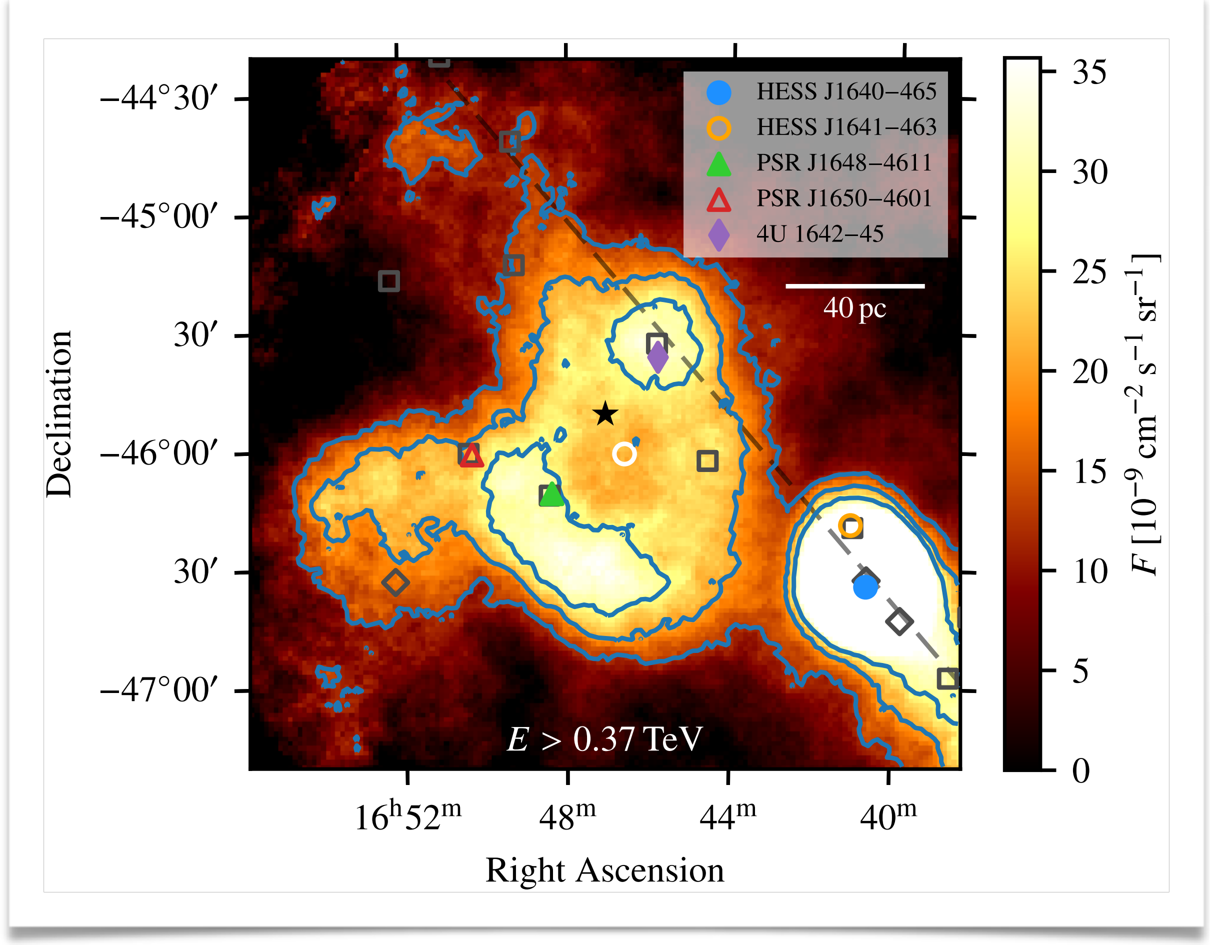
Sajan Kumar (for the VERITAS Collaboration), TeVPA 2022, Kingston (Mon 08/08, Galactic Sources I)

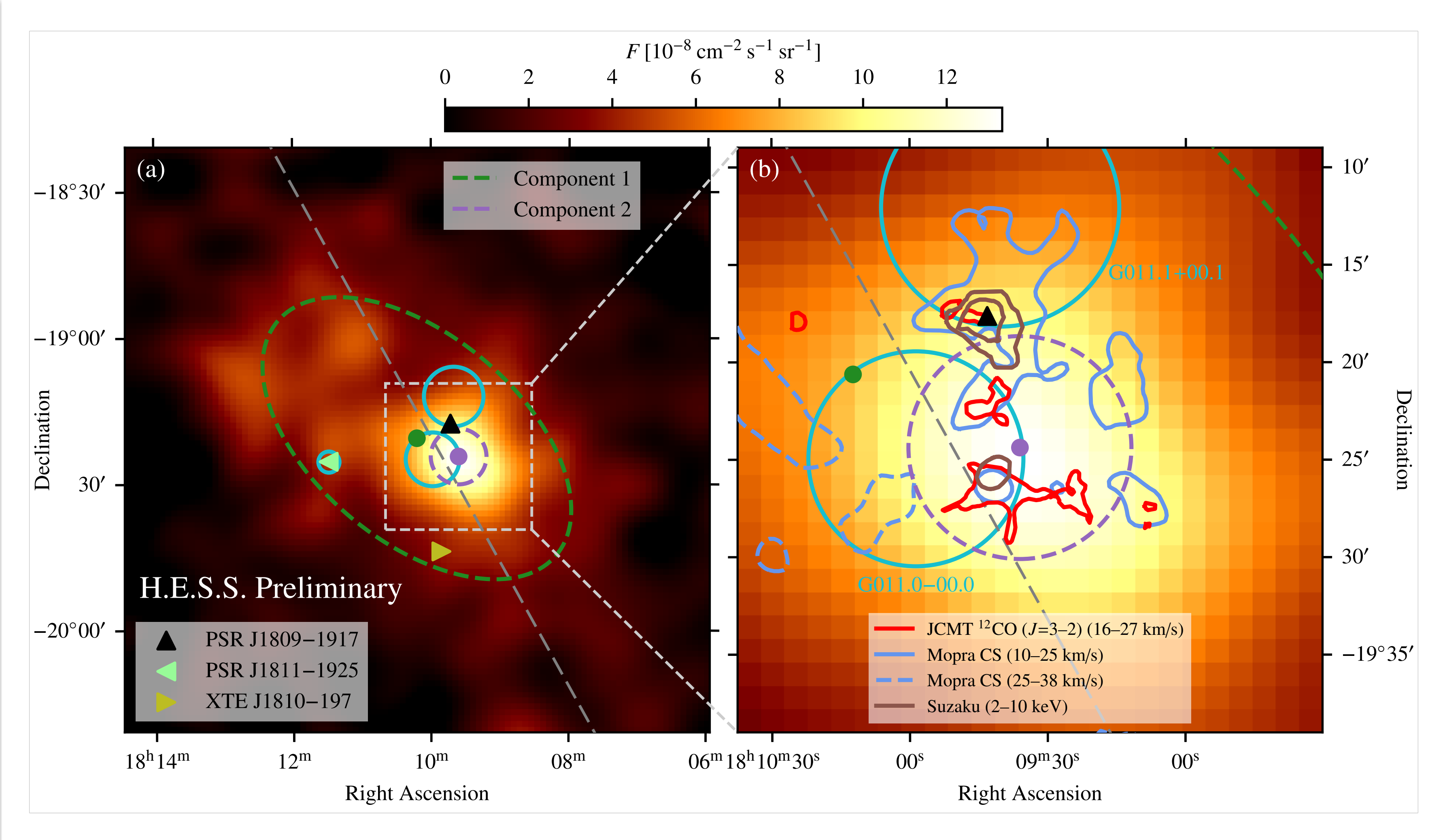




Conclusion

- 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!

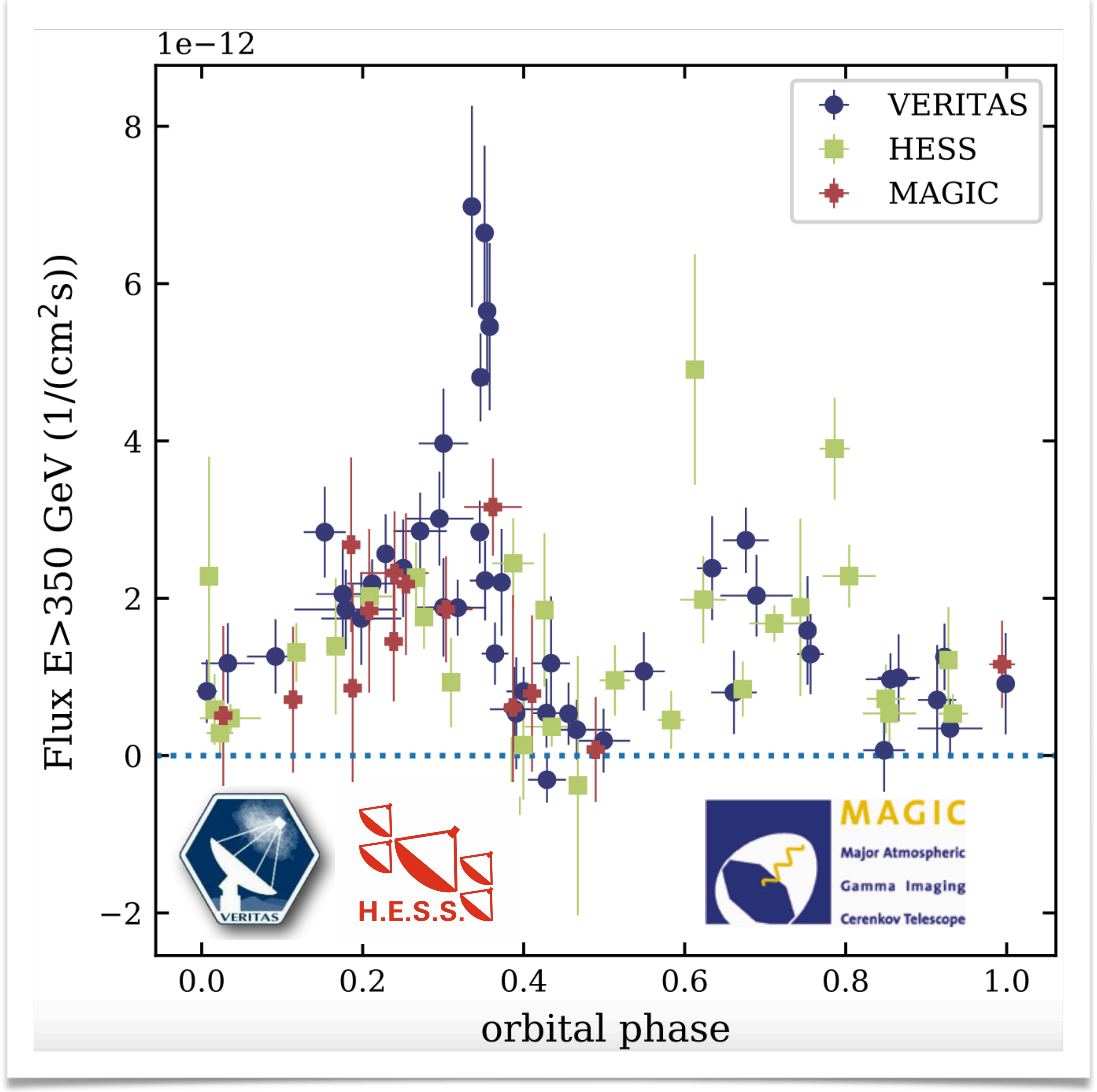




Bonus: even more recent interesting measurements of Galactic sources!

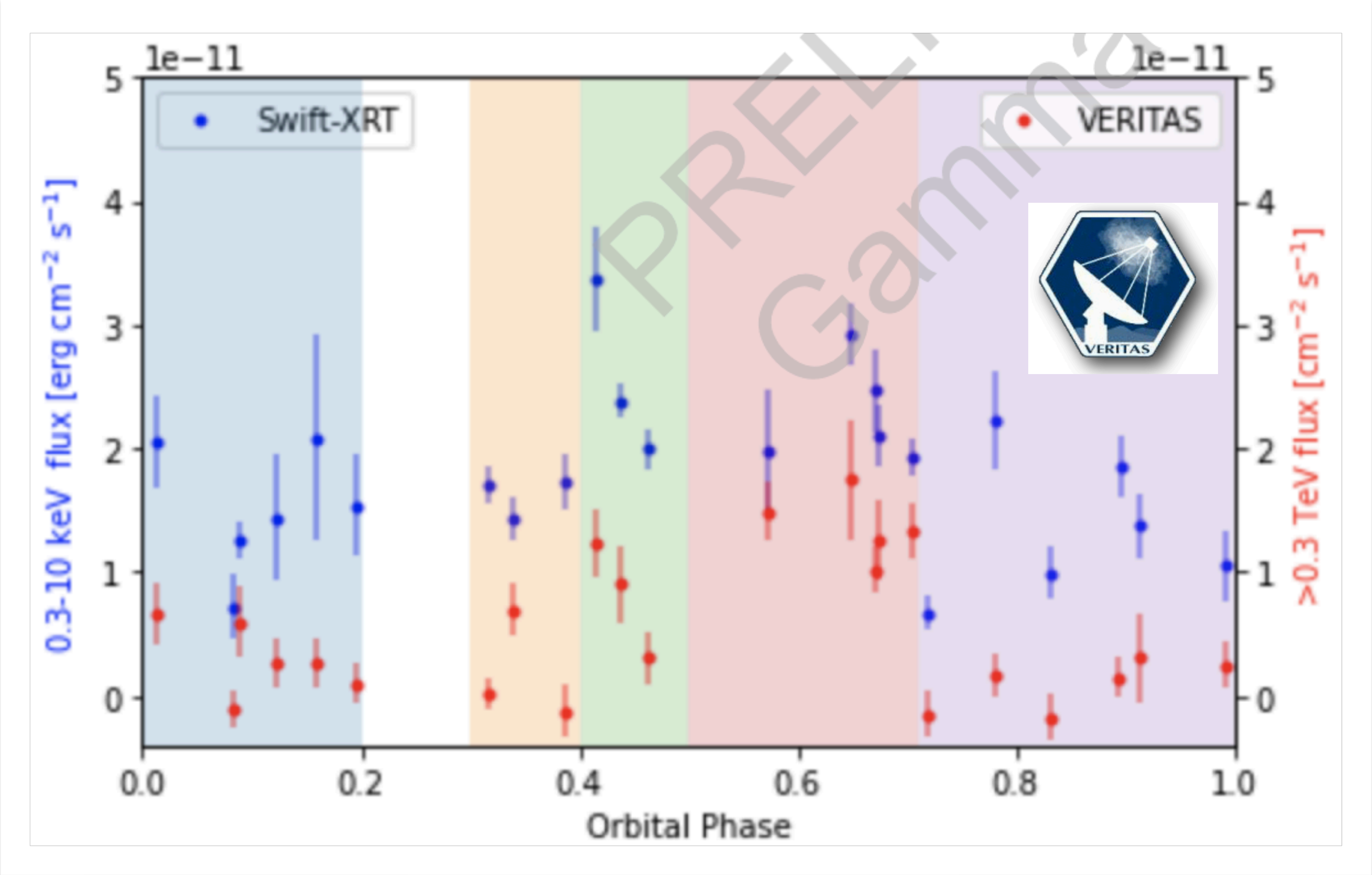
Gamma-ray binaries

- **HESS J0632+057**
- Period: 317 days
- H.E.S.S. + MAGIC + VERITAS
- Orbit-to-orbit variability



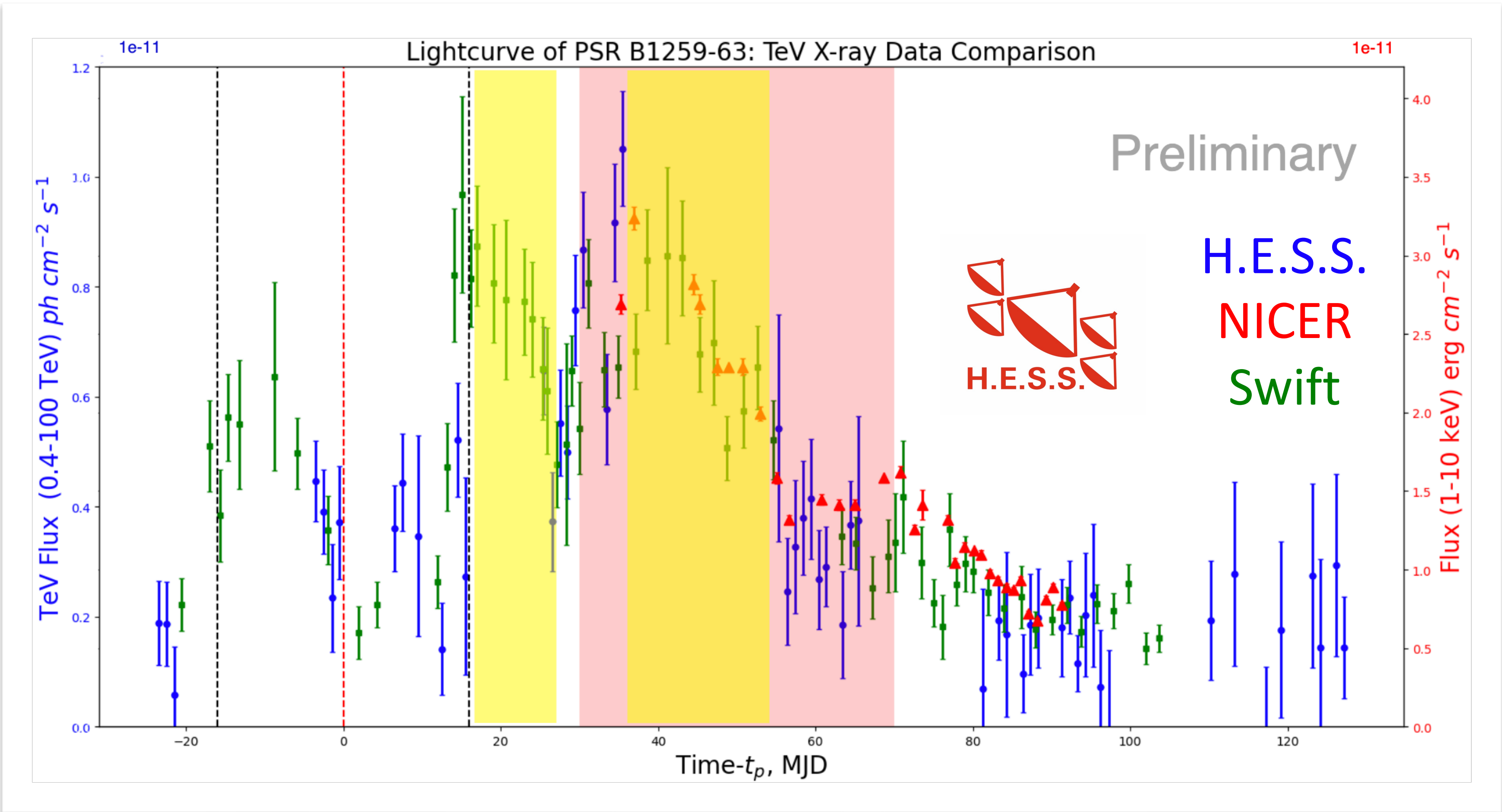
VERITAS+MAGIC+H.E.S.S. Collaboration, ApJ 923, 241 (2021)

- **LS I +61° 303**
- Period: 26.5 days
- VERITAS
- Correlation with Swift-XRT (simultaneous within 0.5h)



S.R. Patel (for the VERITAS Collaboration), Gamma 2022, Barcelona

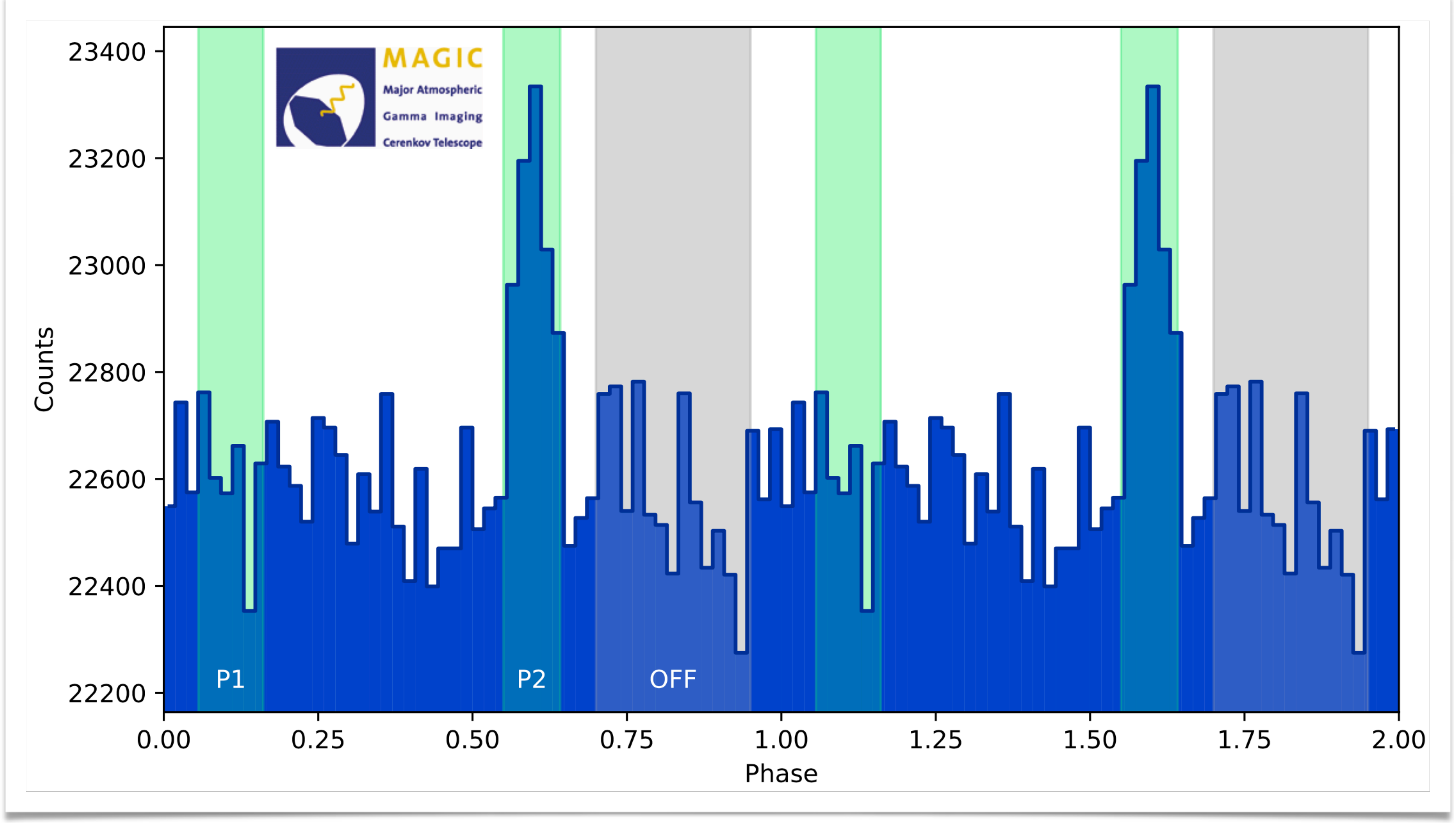
- **PSR B1259-63**
- Period: 3.4 years
- H.E.S.S.
- Correlation with X-ray curve
- Detection out to ~120 days after periastron!



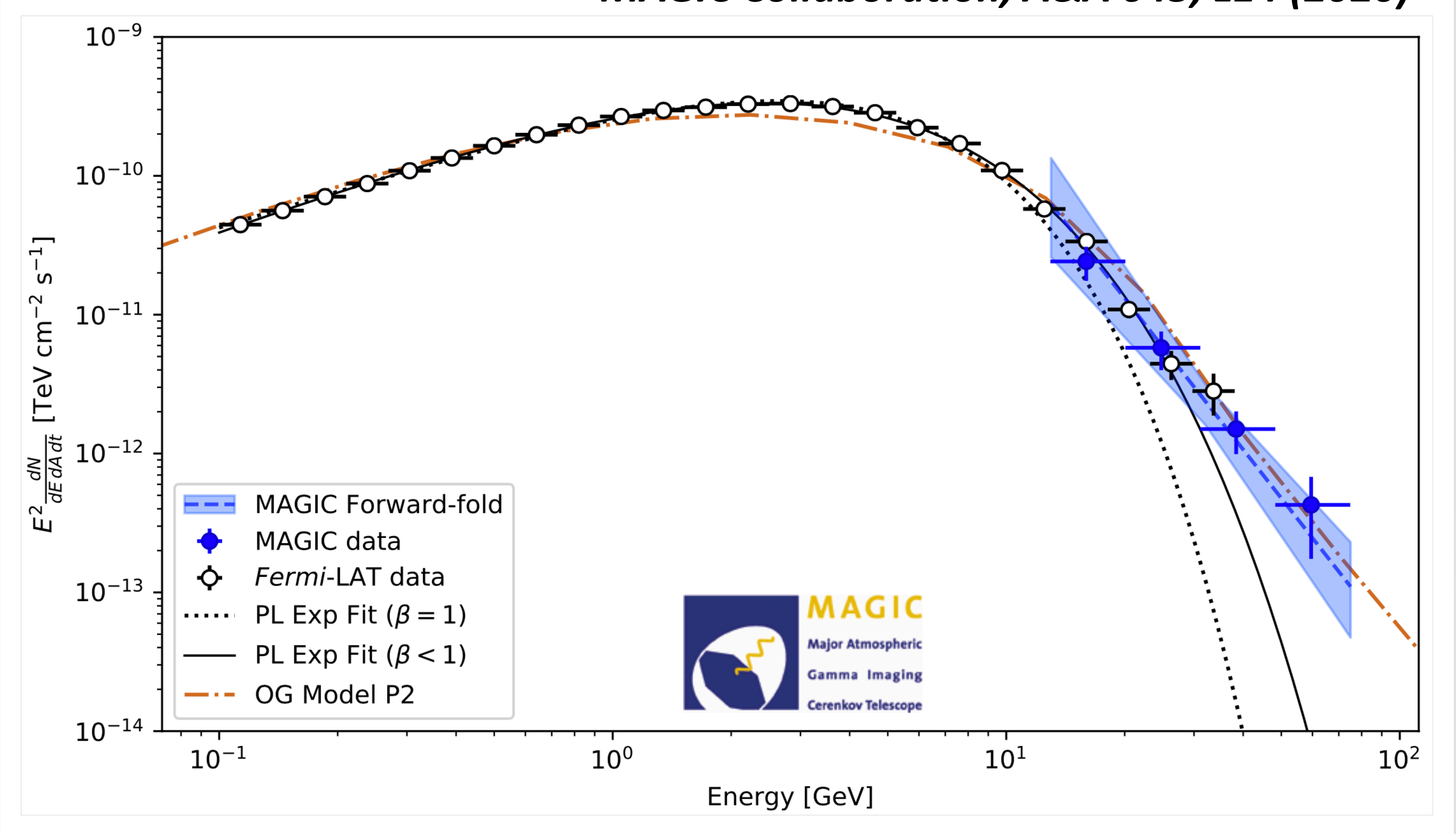
C. Thorpe-Morgan (for the H.E.S.S. Collaboration), Gamma 2022, Barcelona

Geminga pulsar

- 3rd pulsar detected from ground (after Crab & Vela)
- Detected up to 75 GeV with MAGIC
- Evidence for power-law tail beyond 15 GeV
- Spectral index 5.6 ± 0.5 (!)



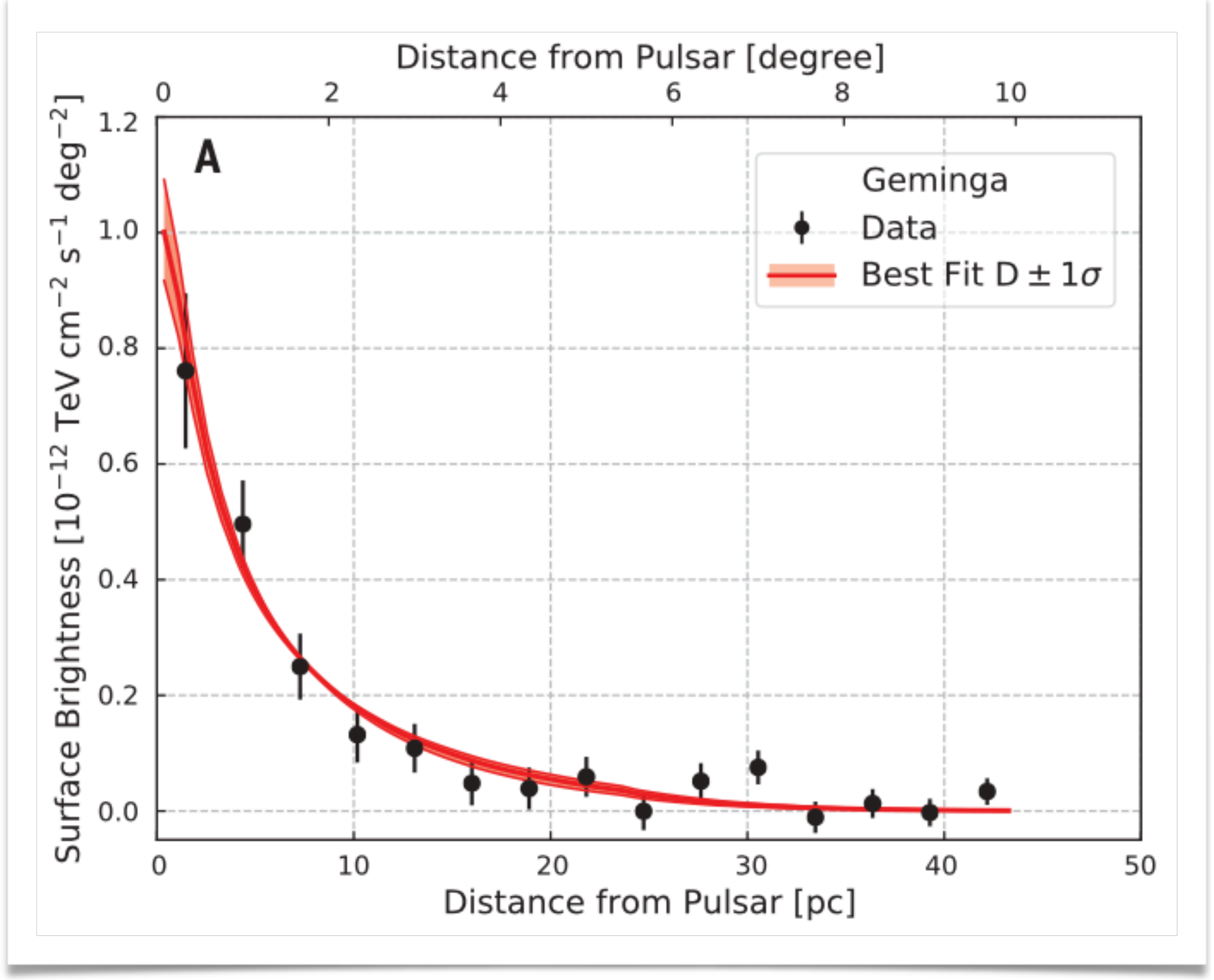
MAGIC Collaboration, A&A 643, L14 (2020)



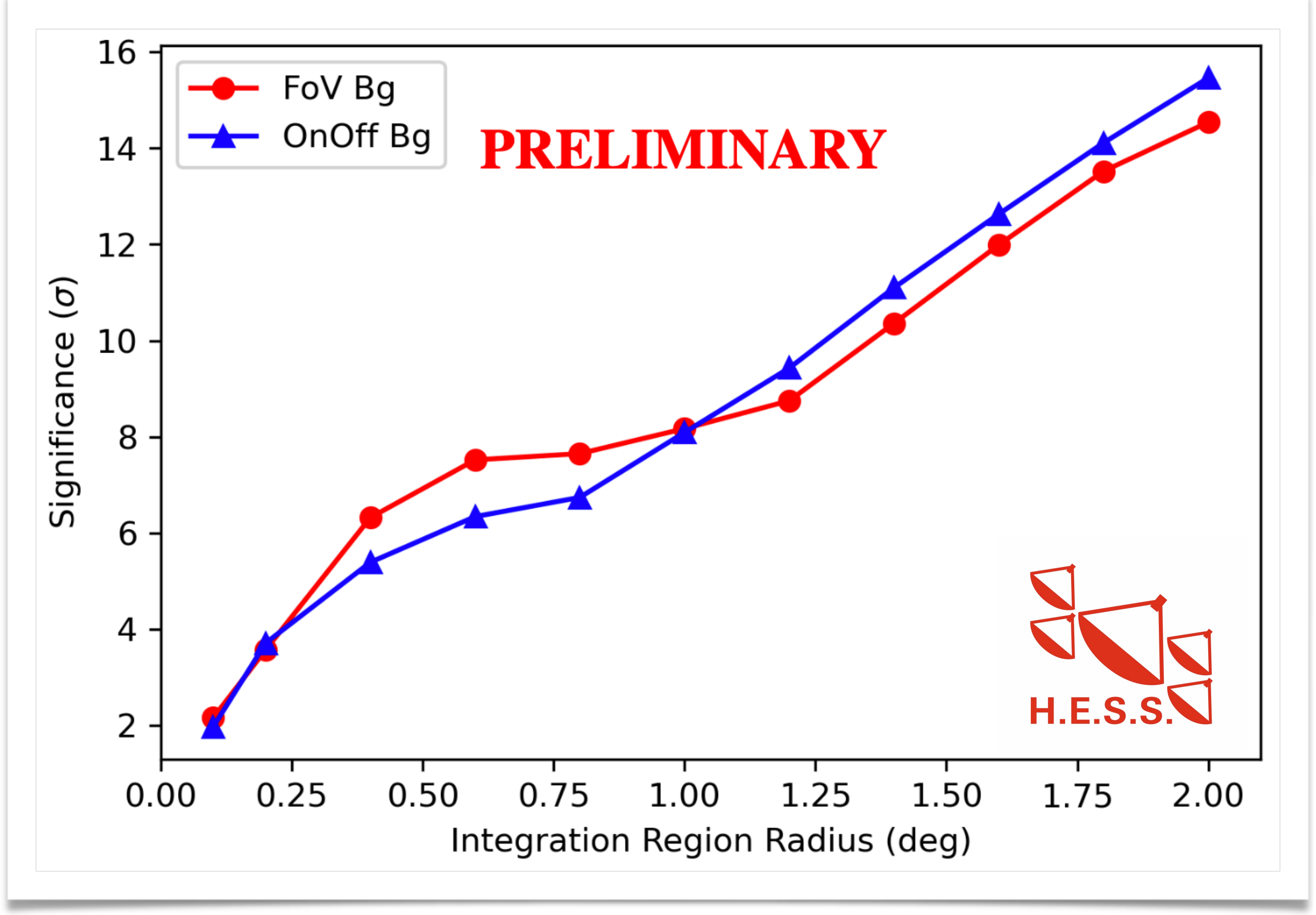
Geminga PWN

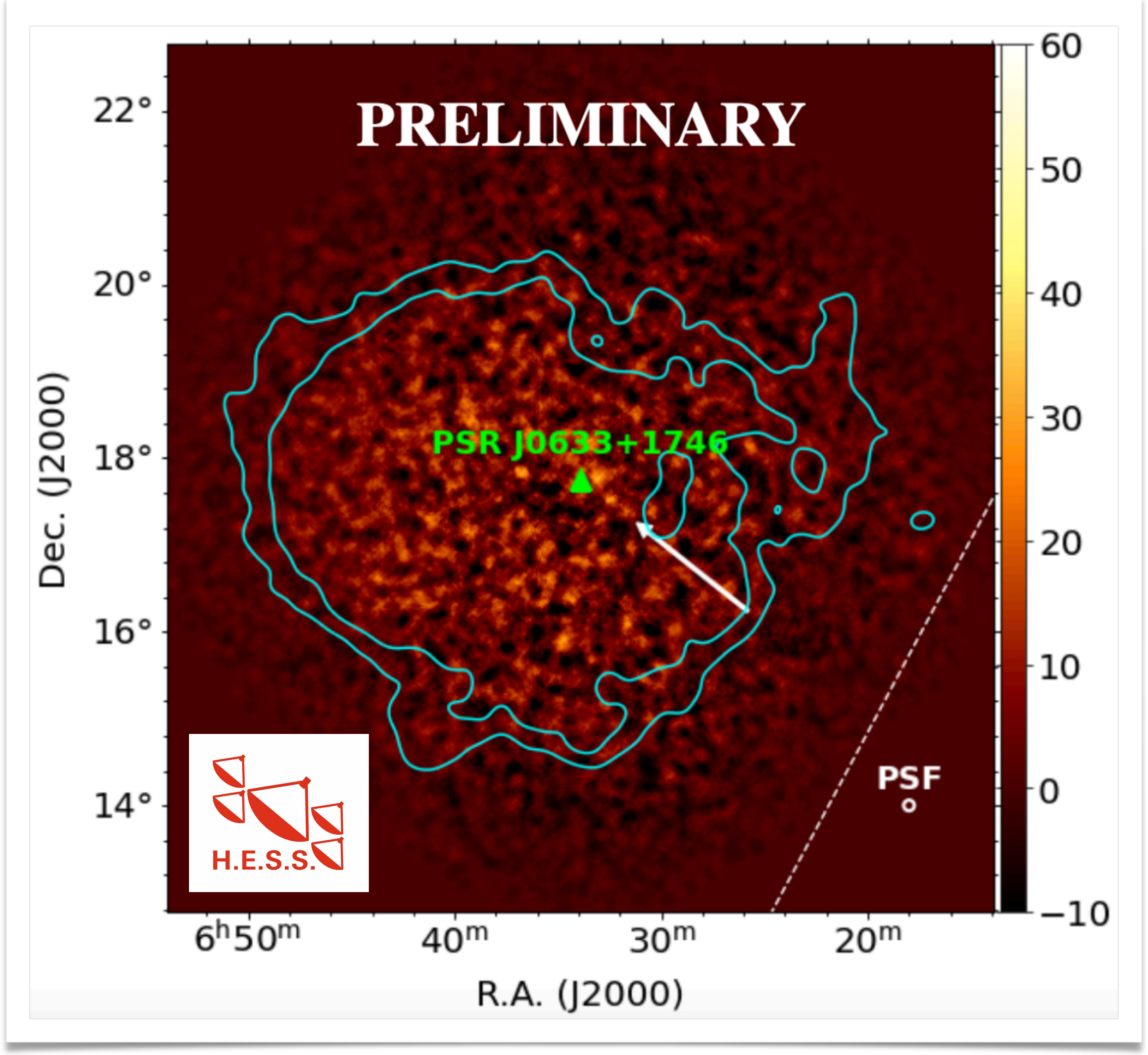
- ***Extremely*** extended emission — reported in 2017 by HAWC
- Emission larger than typical IACT field of view → a real challenge!
- H.E.S.S. has reported detection at ICRC 2021

A. Mitchell et al. (for the H.E.S.S. Collaboration), ICRC 2021, Berlin, id. 780



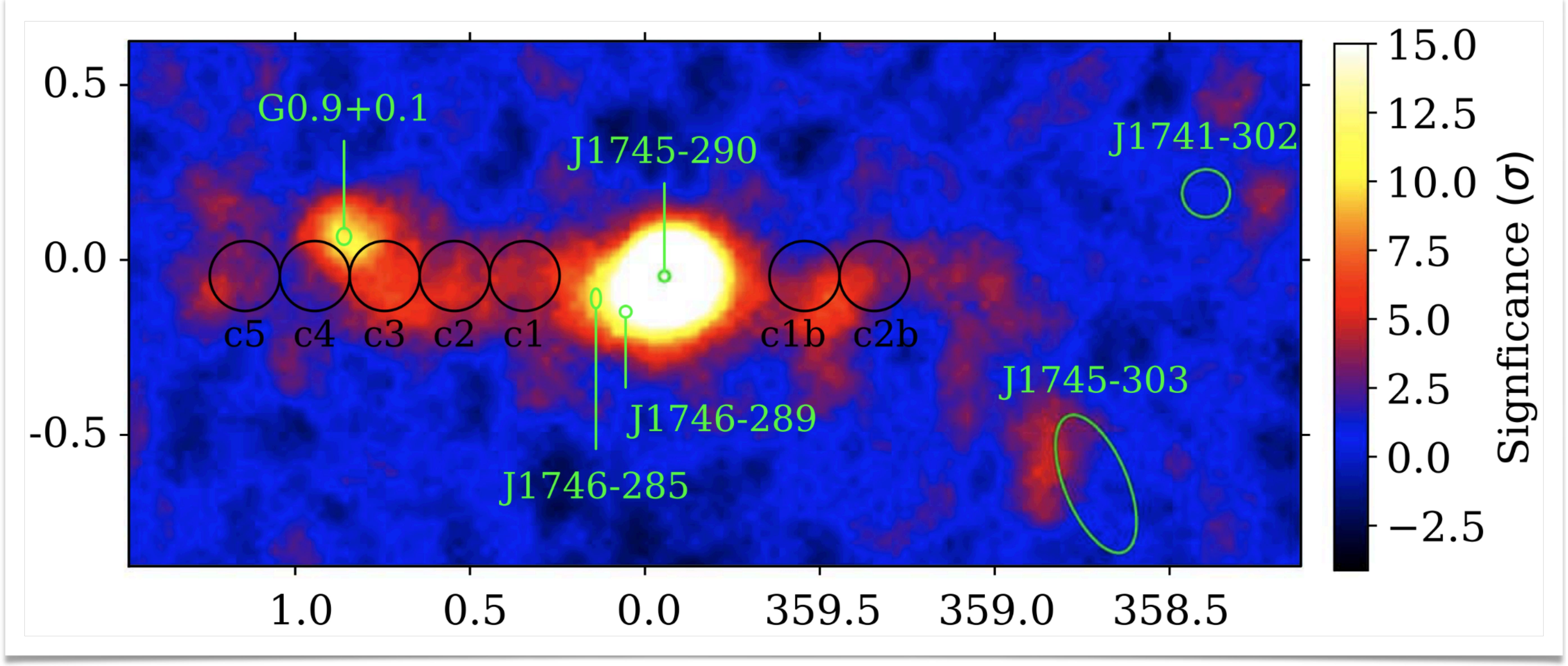
HAWC Collaboration, Science 358, 911 (2017)



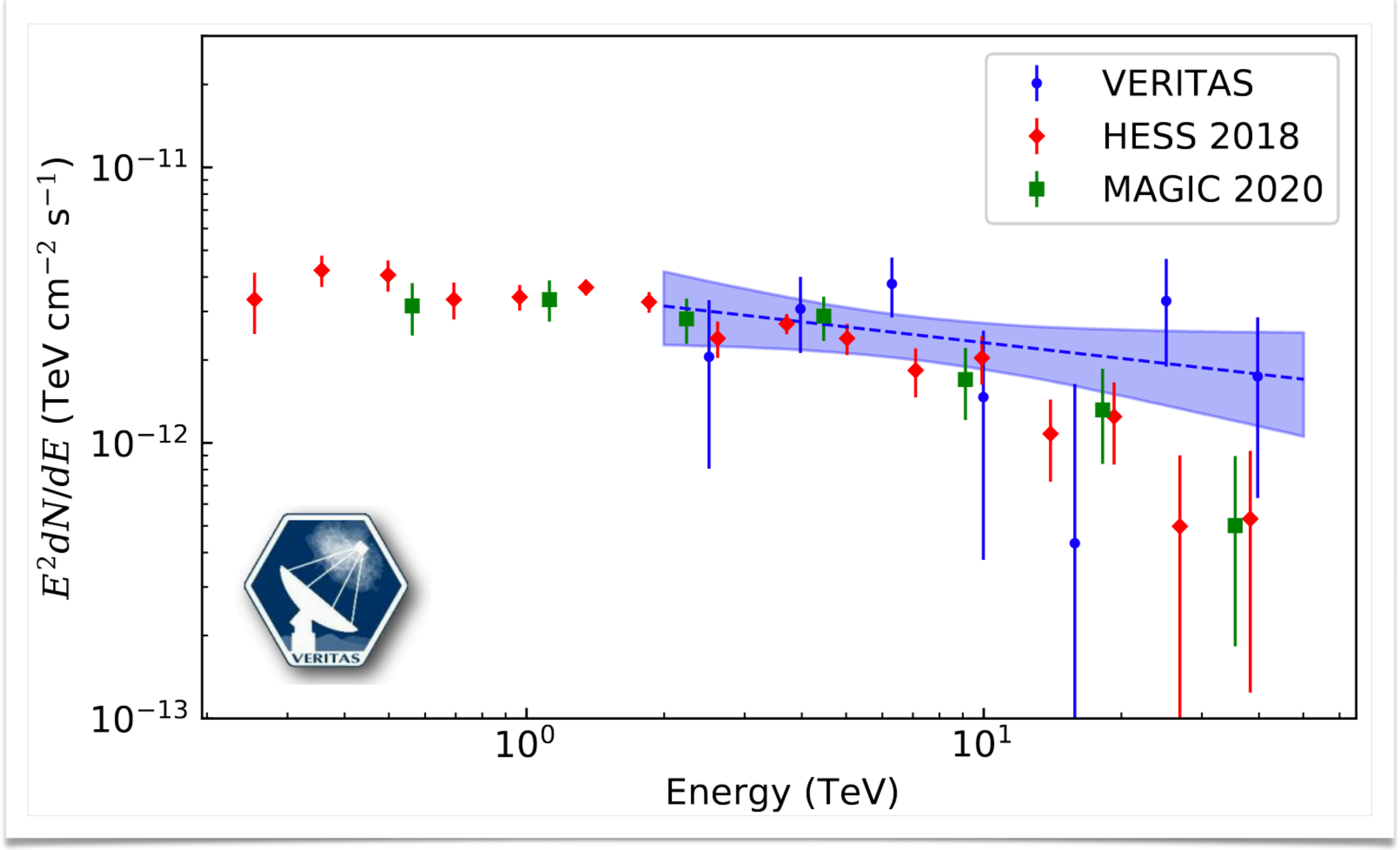


Galactic Centre

- Very detailed study by VERITAS
- Deep exposure: 125 hours
- ***Observed at >60° from zenith!***
- Spectrum of diffuse emission measured up to 40 TeV, with no sign for a cut-off

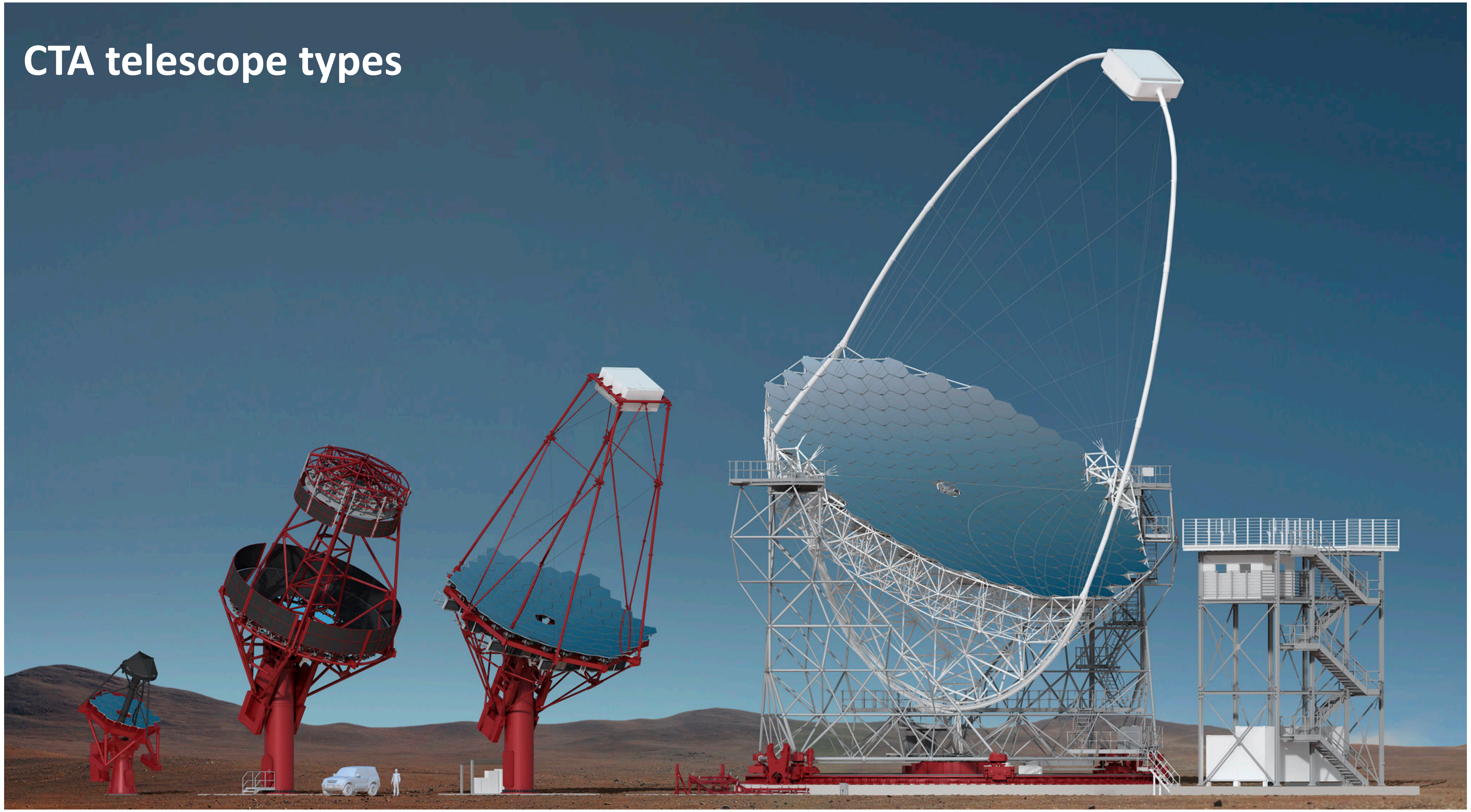


VERITAS Collaboration, ApJ 913, 115 (2021)



Backup slides

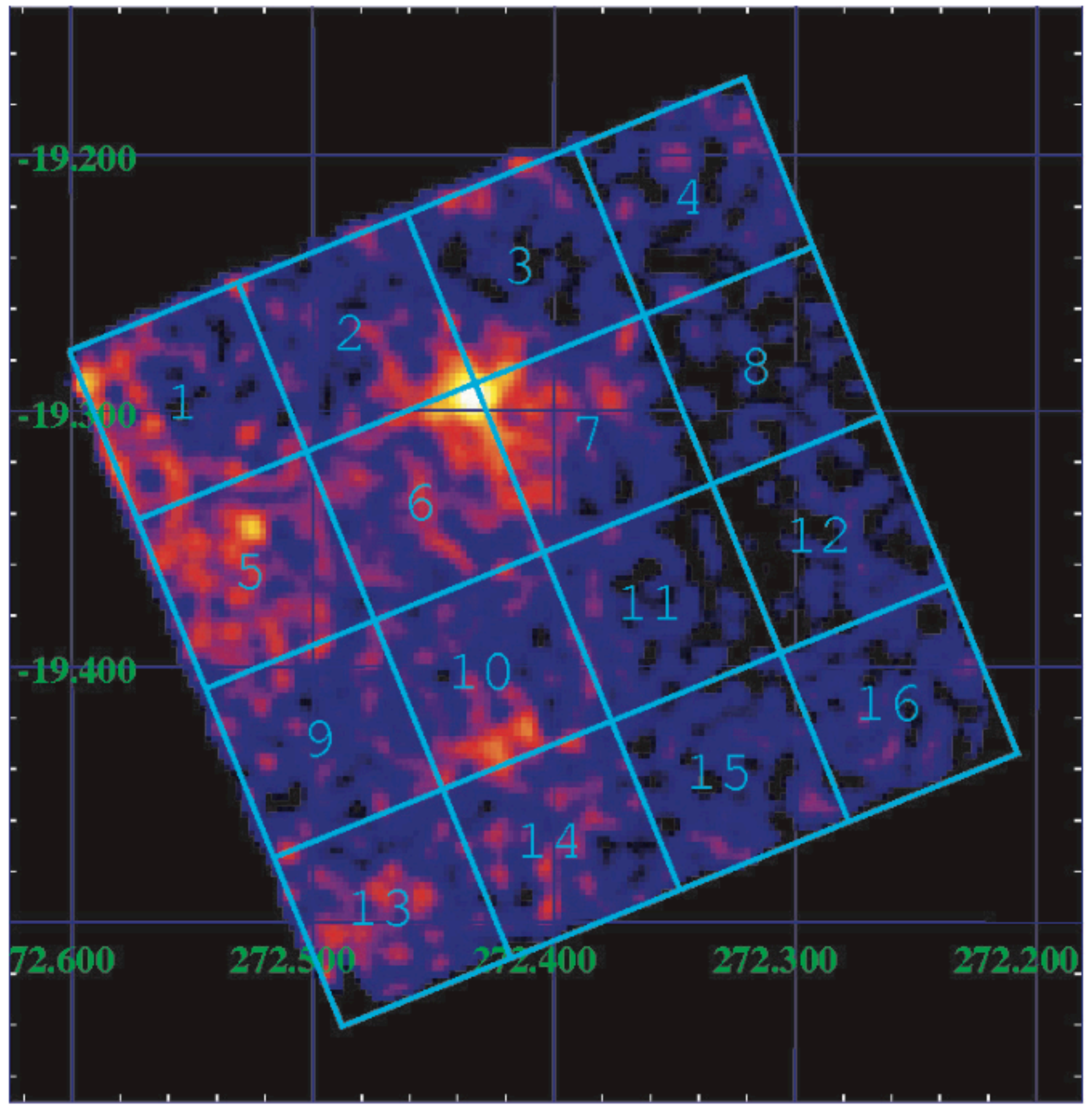
Cherenkov Telescope Array (CTA)

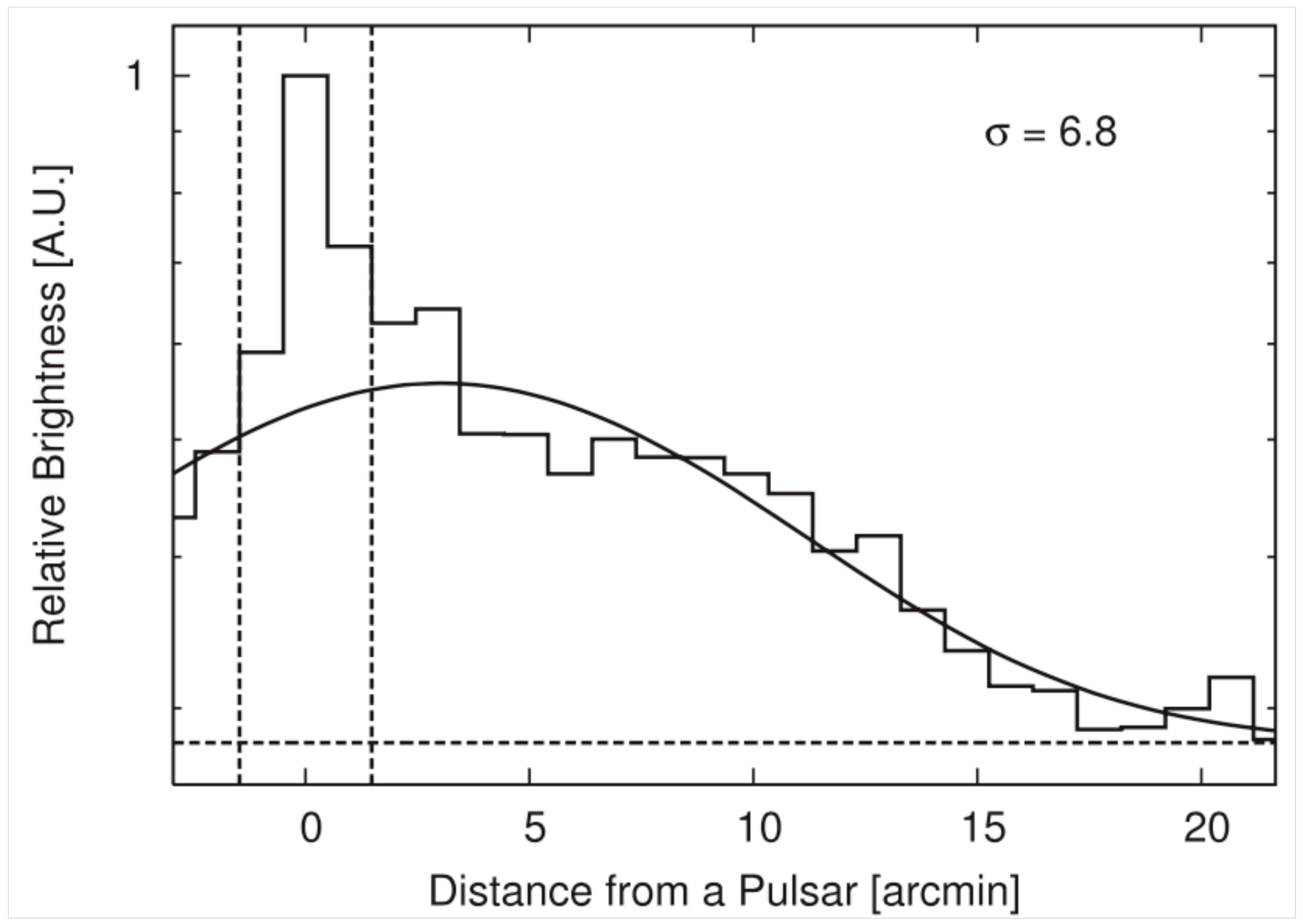


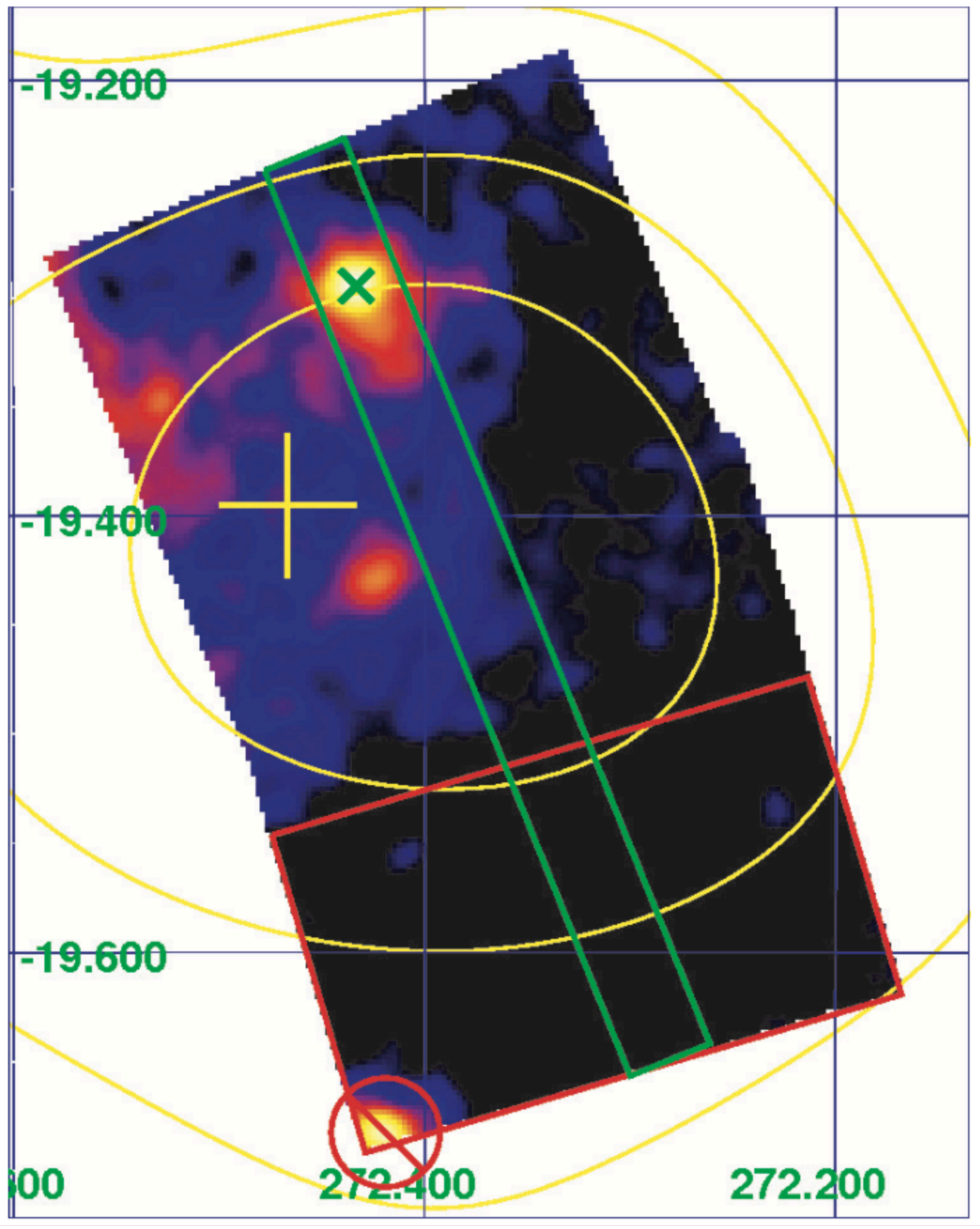
SST ($8m^2$) | SCT ($41m^2$) | MST ($88m^2$) | LST ($370m^2$)

HESS J1809-193: Suzaku X-ray data

- Hard X-ray emission (2-10 keV)
- In immediate vicinity of PSR J1809–1917
- + diffuse emission around it





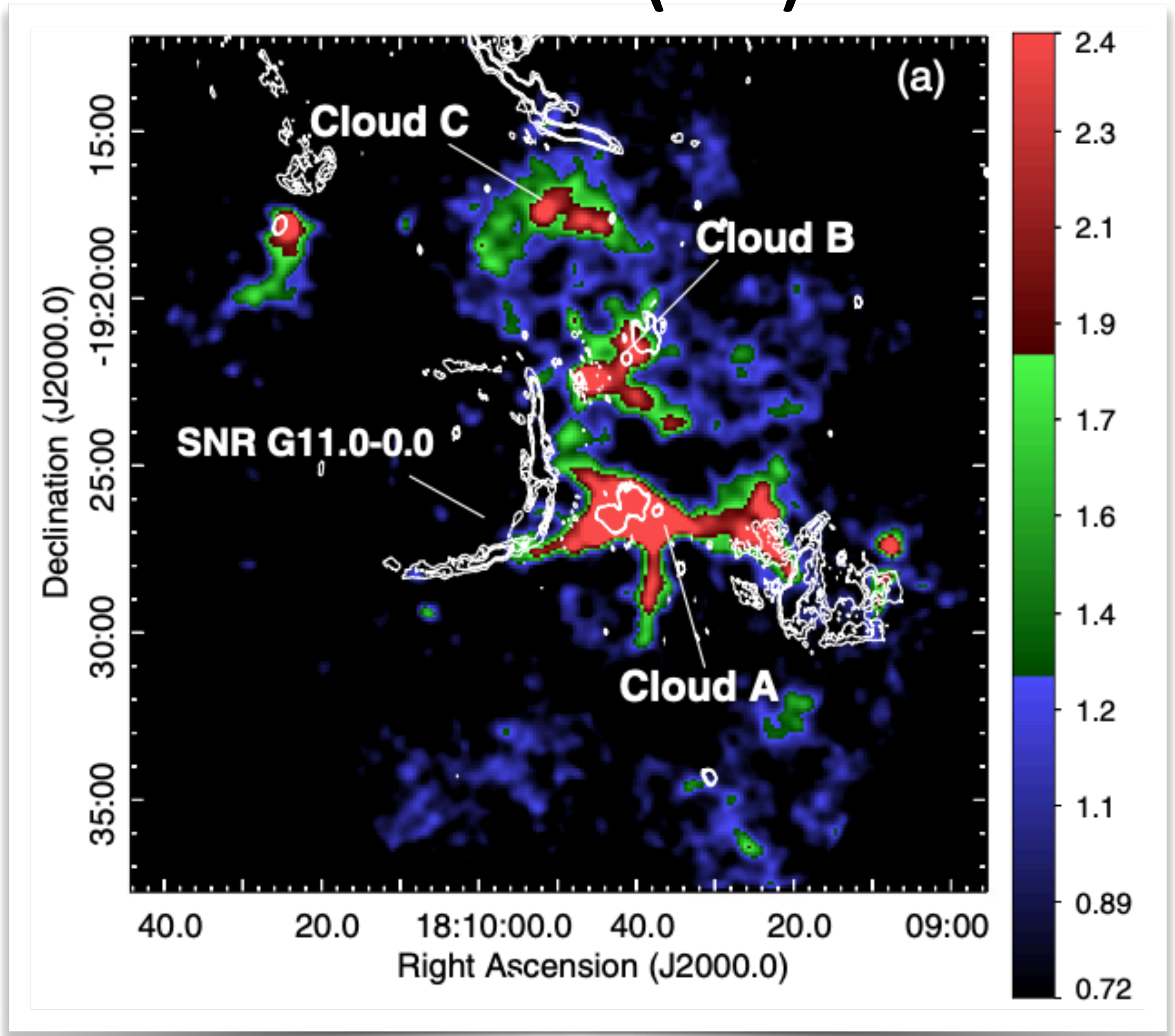


Anada et al., PASJ 62, 179 (2010)

HESS J1809–193: molecular clouds

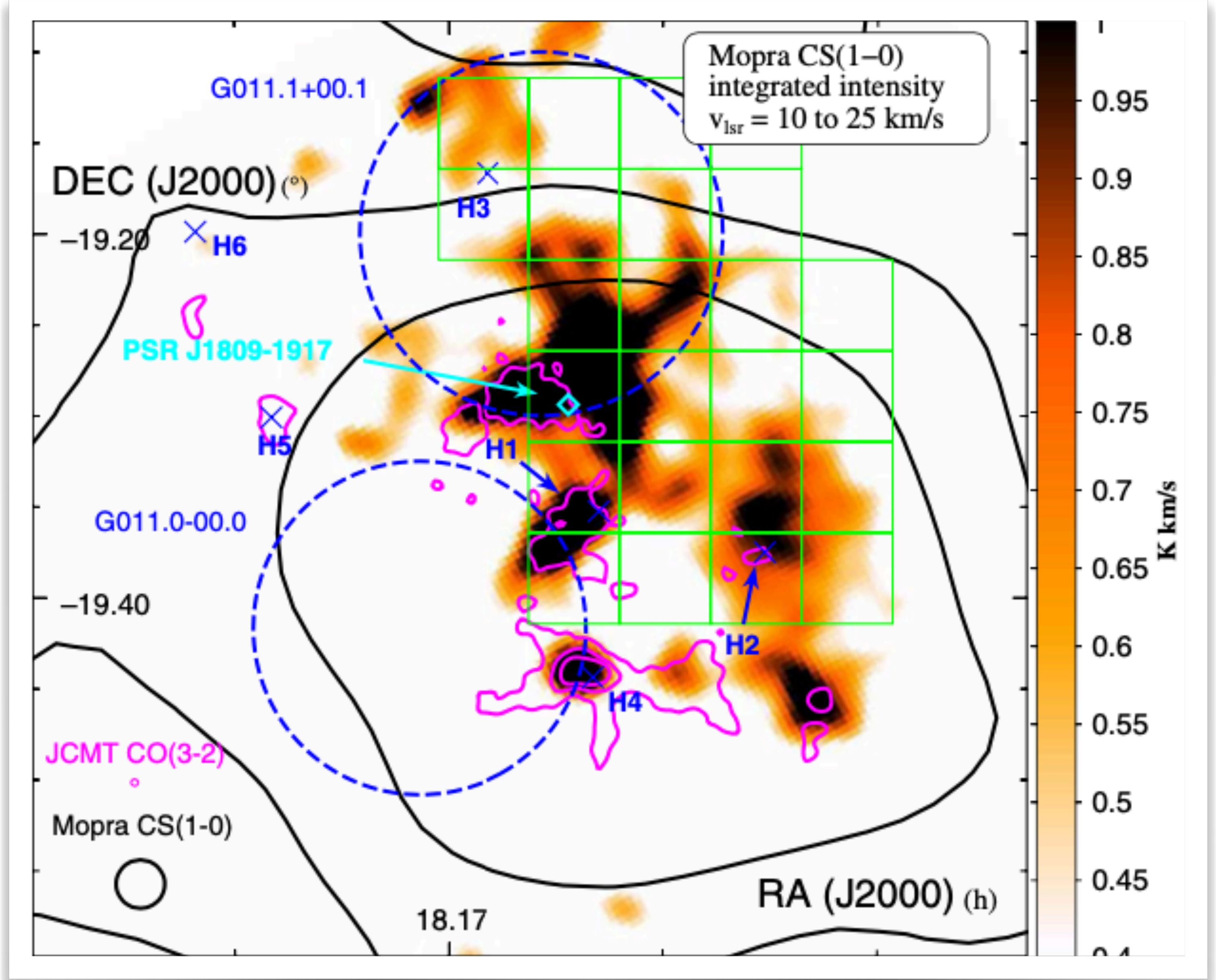
- Distance: about 3 kpc
- Compatible with SNR G011.0–00.0

JCMT CO(3–2)



Castelletti et al., A&A 587, A71 (2016)

Mopra CS(1–0)

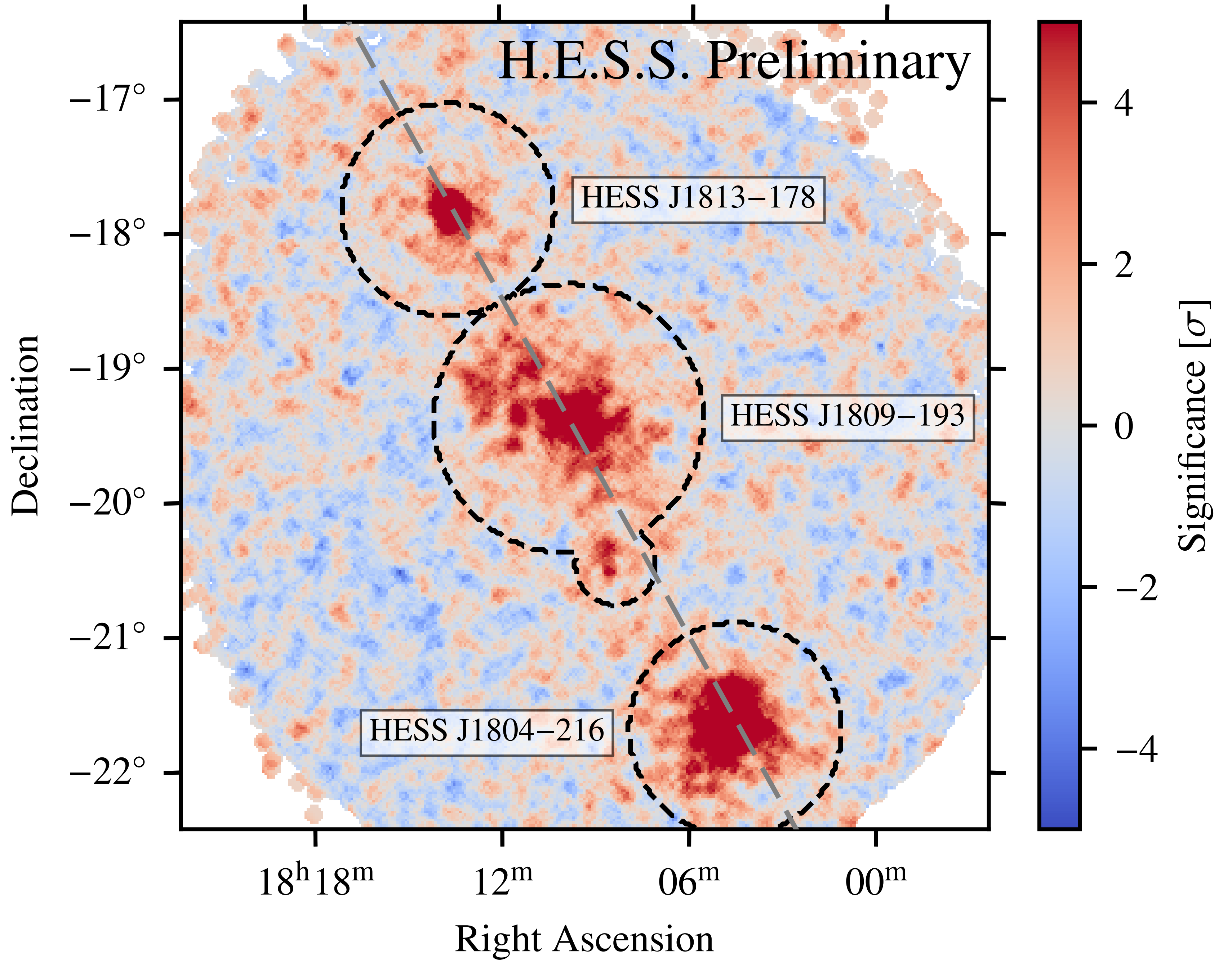


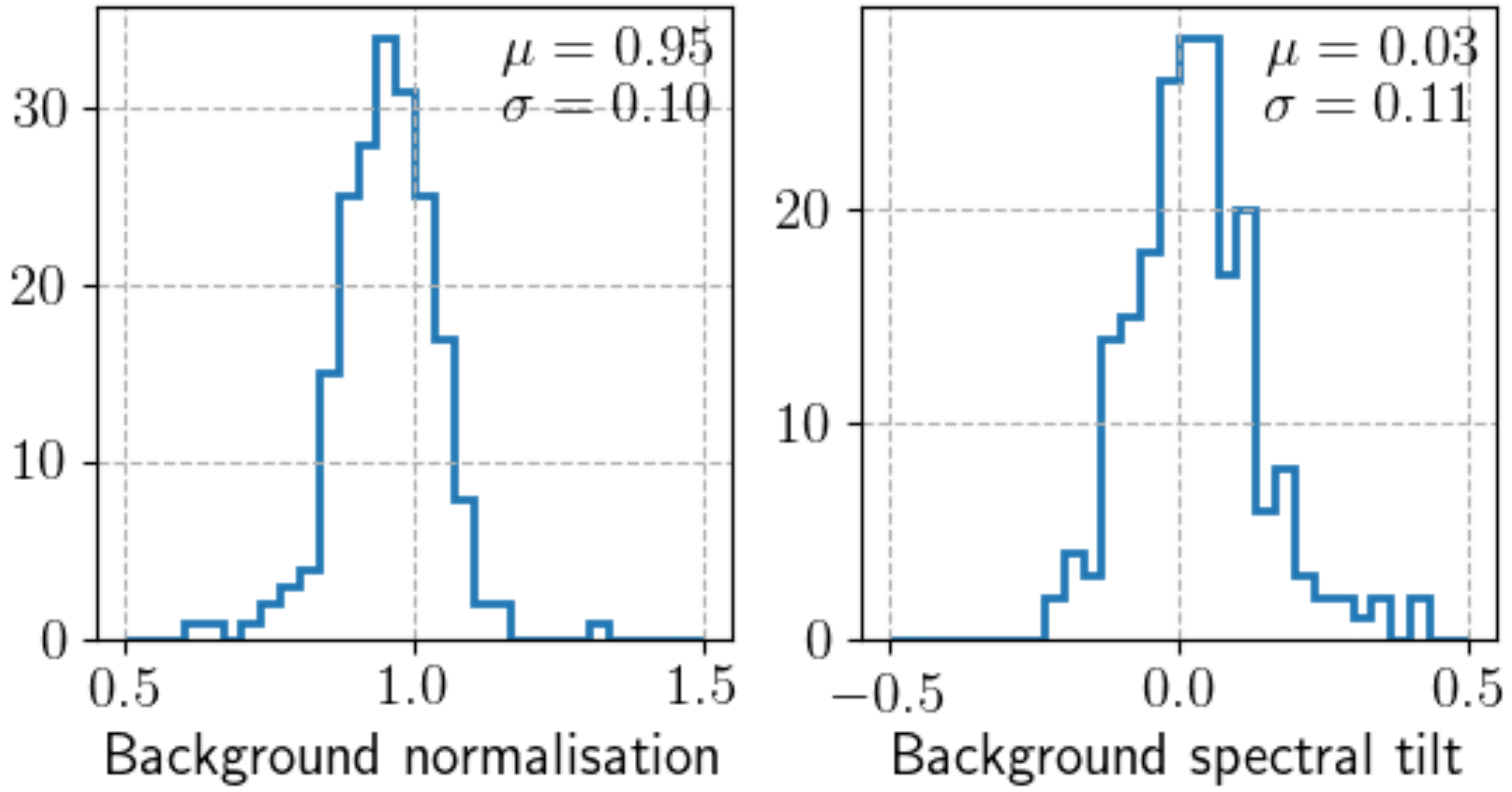
Voisin et al., PASA 36, e014 (2019)

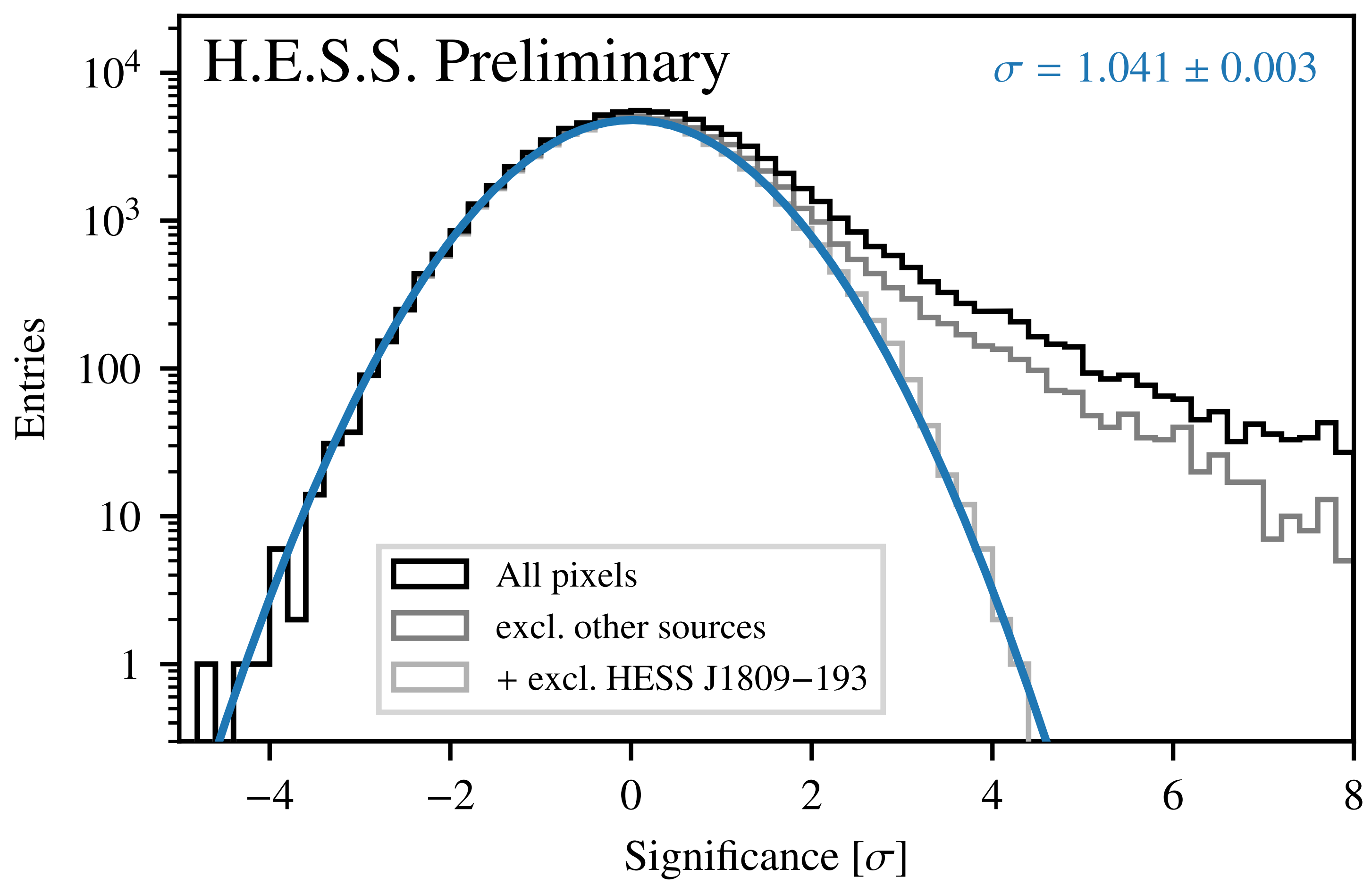
HESS J1809–193: background model fit

- Background model adjusted to each observation run
  - Background normalisation (global scaling)
  - Background spectral tilt (factor $(E/E_0)^{-\delta}$)

- Distribution of significance map entries outside exclusion regions indicates good description of background

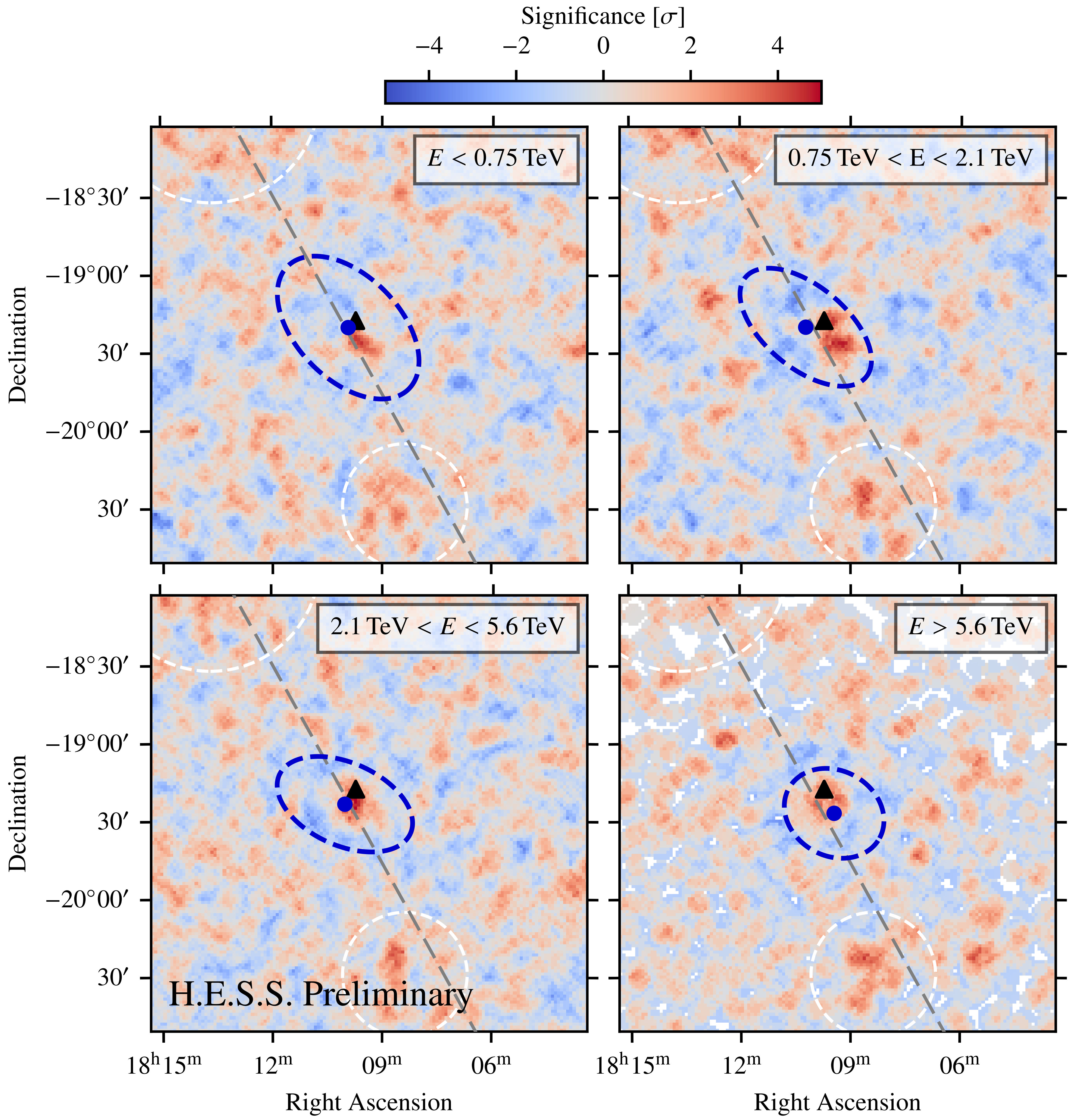






HESS J1809–193: 1-component model in energy bands

- Would the 1-component model work if its spatial extent would be allowed to vary with energy?
- Re-performed fit in four (mutually exclusive) energy bands
  - spectral index fixed
- Still not a good description!



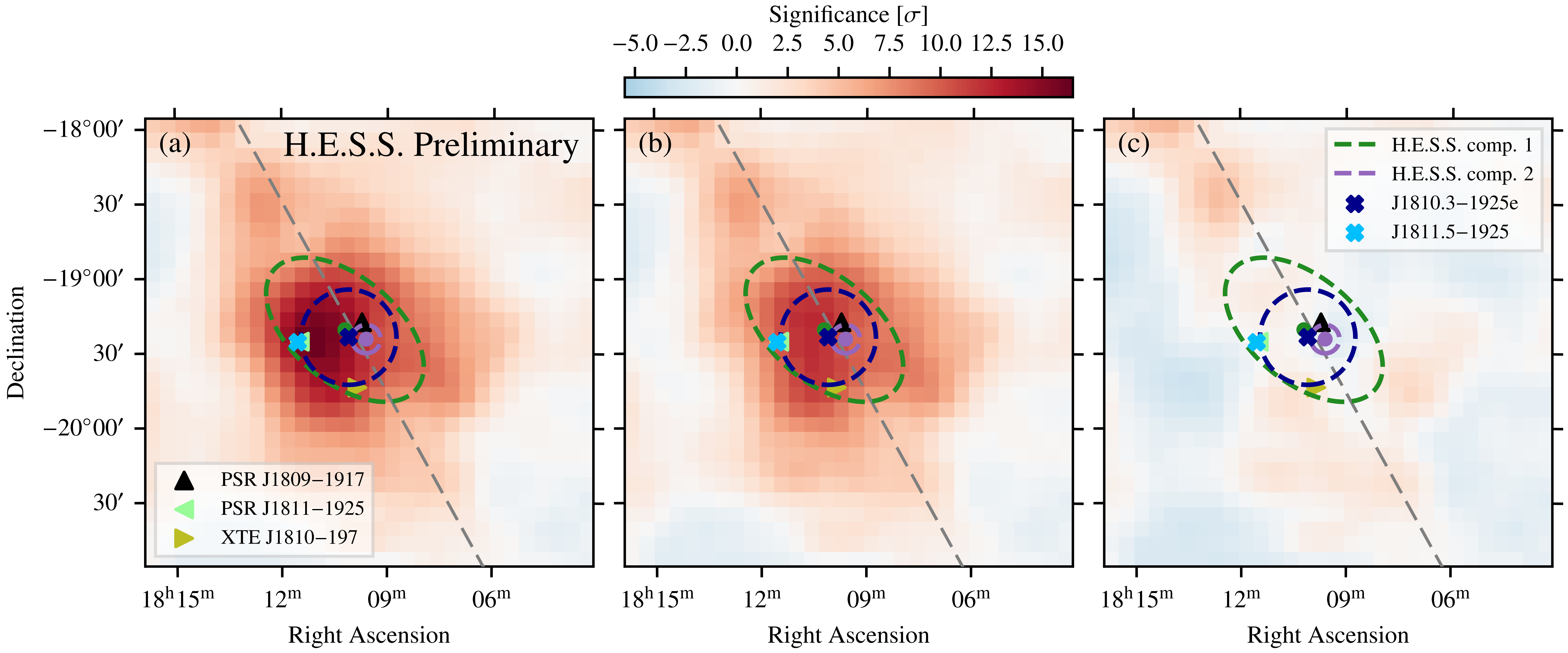
HESS J1809–193: parameters of 2-component model

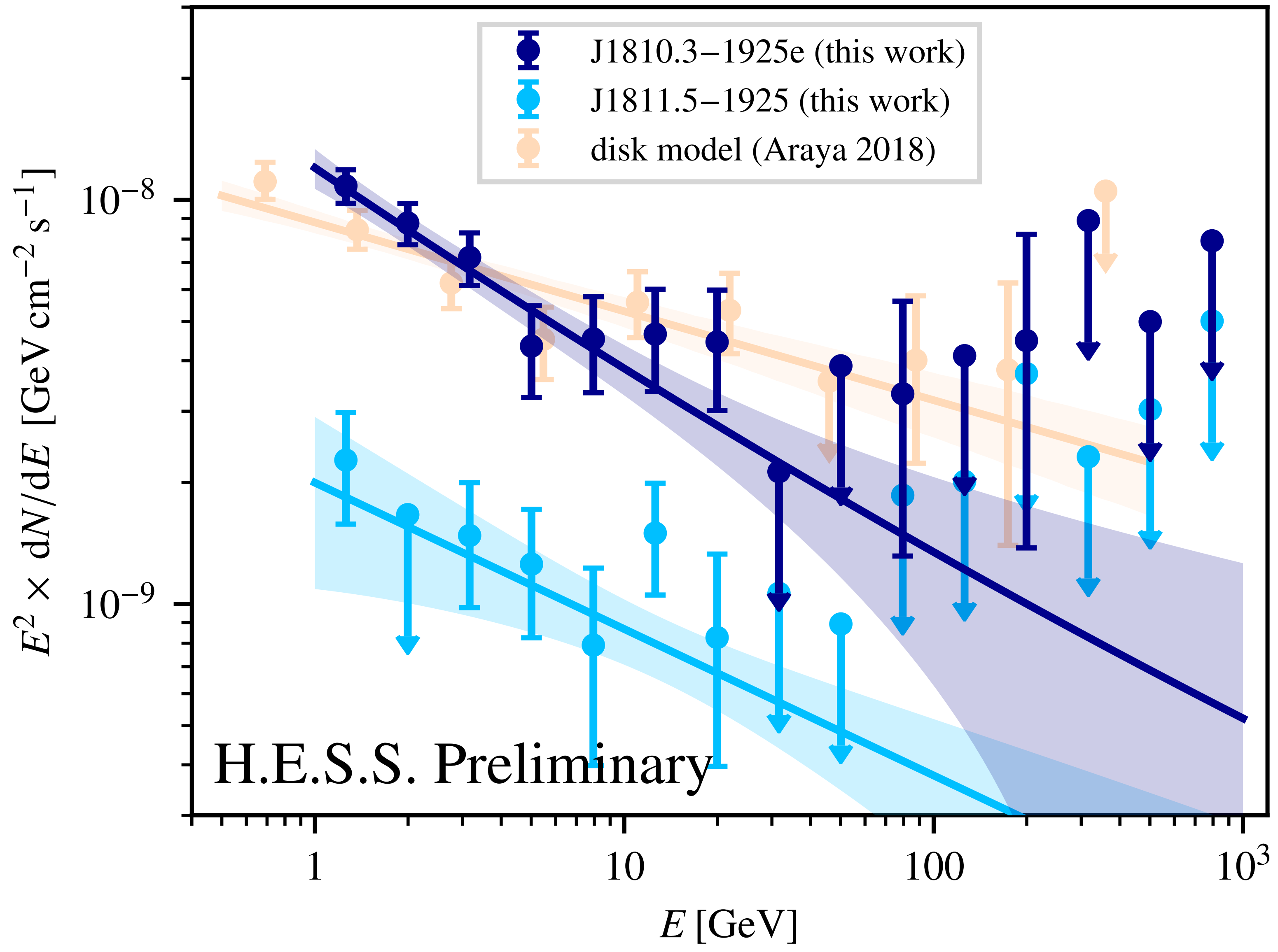
- Two different spectral models for component 1
  - PL = power law
  - ECPL = power law with exp. cut-off
  - ECPL model is preferred
  - Parameters of component 2 do not depend on this

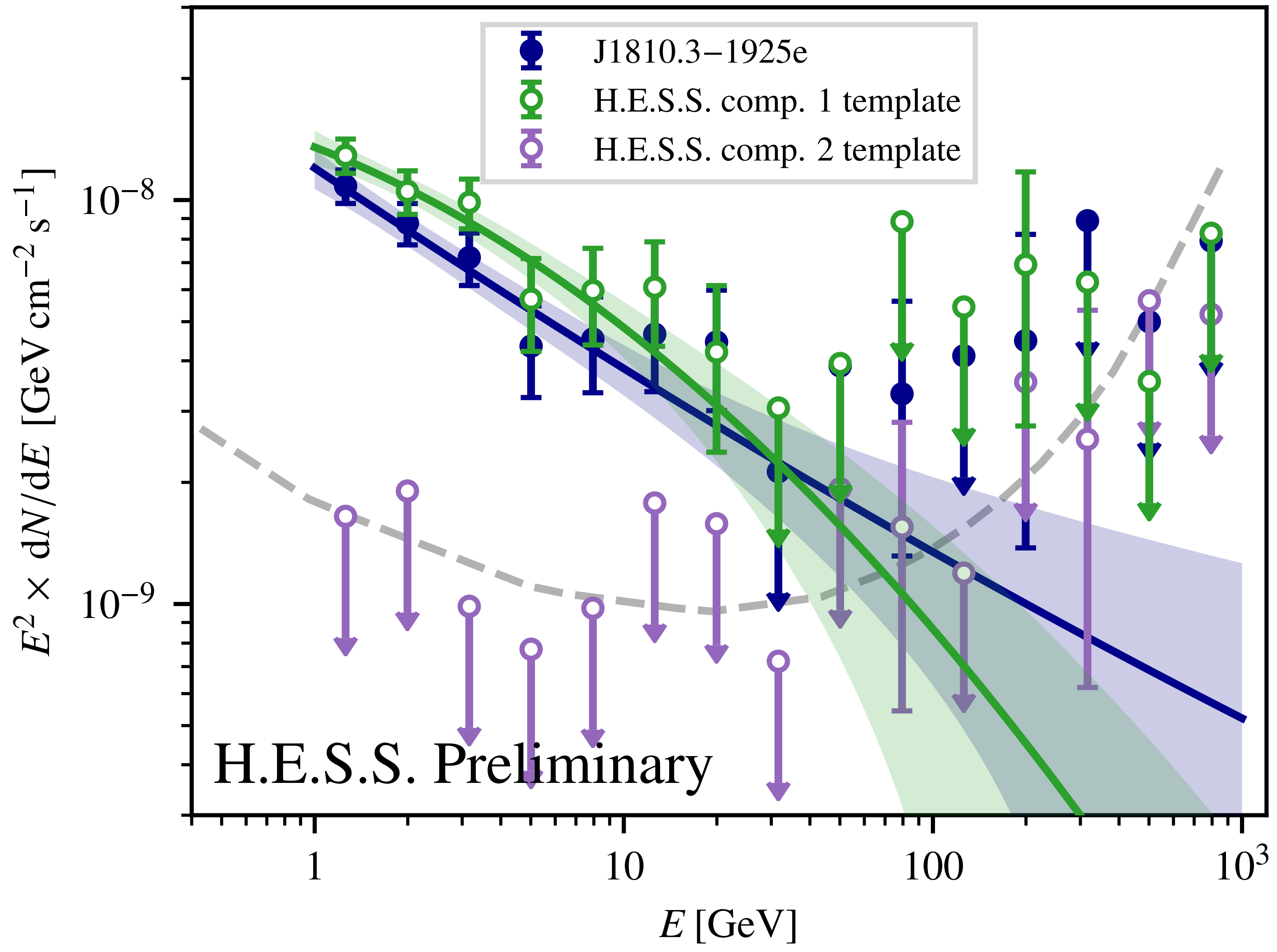
Par. [unit]	Value
Component 1 (PL spectral model)	
R.A. [deg]	$272.551 \pm 0.025_{stat} \pm 0.018_{sys}$
Dec. [deg]	$-19.344 \pm 0.023_{stat} \pm 0.013_{sys}$
σ [deg]	$0.622 \pm 0.032_{stat} \pm 0.020_{sys}$
e	$0.824 \pm 0.025_{stat}$
ϕ [deg]	$50.0 \pm 3.1_{stat}$
N_0 [10^{-12} TeV^{-1} cm^{-2} s^{-1}]	$8.42 \pm 0.40_{stat} \pm 1.14_{sys}$
Γ	$2.239 \pm 0.027_{stat} \pm 0.020_{sys}$
E_0 [TeV]	1 (fixed)
Component 1 (ECPL spectral model)	
R.A. [deg]	$272.554 \pm 0.025_{stat} \pm 0.019_{sys}$
Dec. [deg]	$-19.344 \pm 0.021_{stat} \pm 0.012_{sys}$
σ [deg]	$0.613 \pm 0.031_{stat} \pm 0.015_{sys}$
e	$0.820 \pm 0.025_{stat}$
ϕ [deg]	$51.3 \pm 3.1_{stat}$
N_0 [10^{-12} TeV^{-1} cm^{-2} s^{-1}]	$9.05 \pm 0.47_{stat} \pm 0.91_{sys}$
Γ	$1.90 \pm 0.05_{stat} \pm 0.05_{sys}$
E_c [TeV]	$12.7^{+2.7}_{-2.1}\big\|_{stat}\ {}^{+2.6}_{-1.9}\big\|_{sys}$
E_0 [TeV]	1 (fixed)
Component 2	
R.A. [deg]	$272.400 \pm 0.010_{stat}$
Dec. [deg]	$-19.406 \pm 0.009_{stat}$
σ [deg]	$0.0953 \pm 0.0072_{stat} \pm 0.0034_{sys}$
N_0 [10^{-12} TeV^{-1} cm^{-2} s^{-1}]	$0.95 \pm 0.11_{stat} \pm 0.011_{sys}$
Γ	$1.98 \pm 0.05_{stat} \pm 0.03_{sys}$
E_0 [TeV]	1 (fixed)

HESS J1809–193: *Fermi*-LAT analysis

- Found same best-fit models as in 4FGL catalog
- J1811.5–1925
  - Point source, associated with PSR J1811–1925
- J1810.3–1925e
  - Extended source, shape similar to component 1 of HESS J1809–193







Interpretation: PWN model

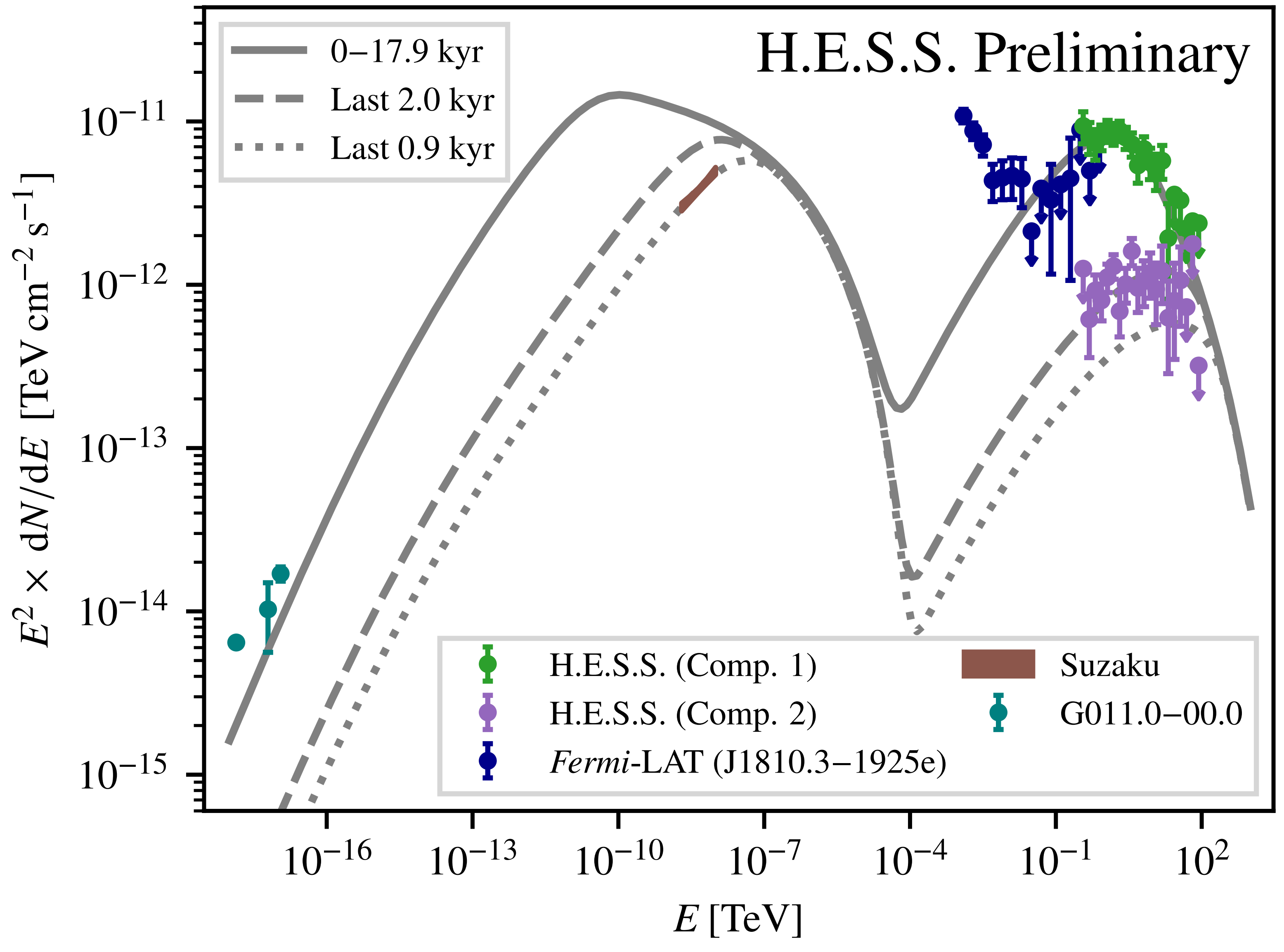
- Time-dependent modelling with GAMERA

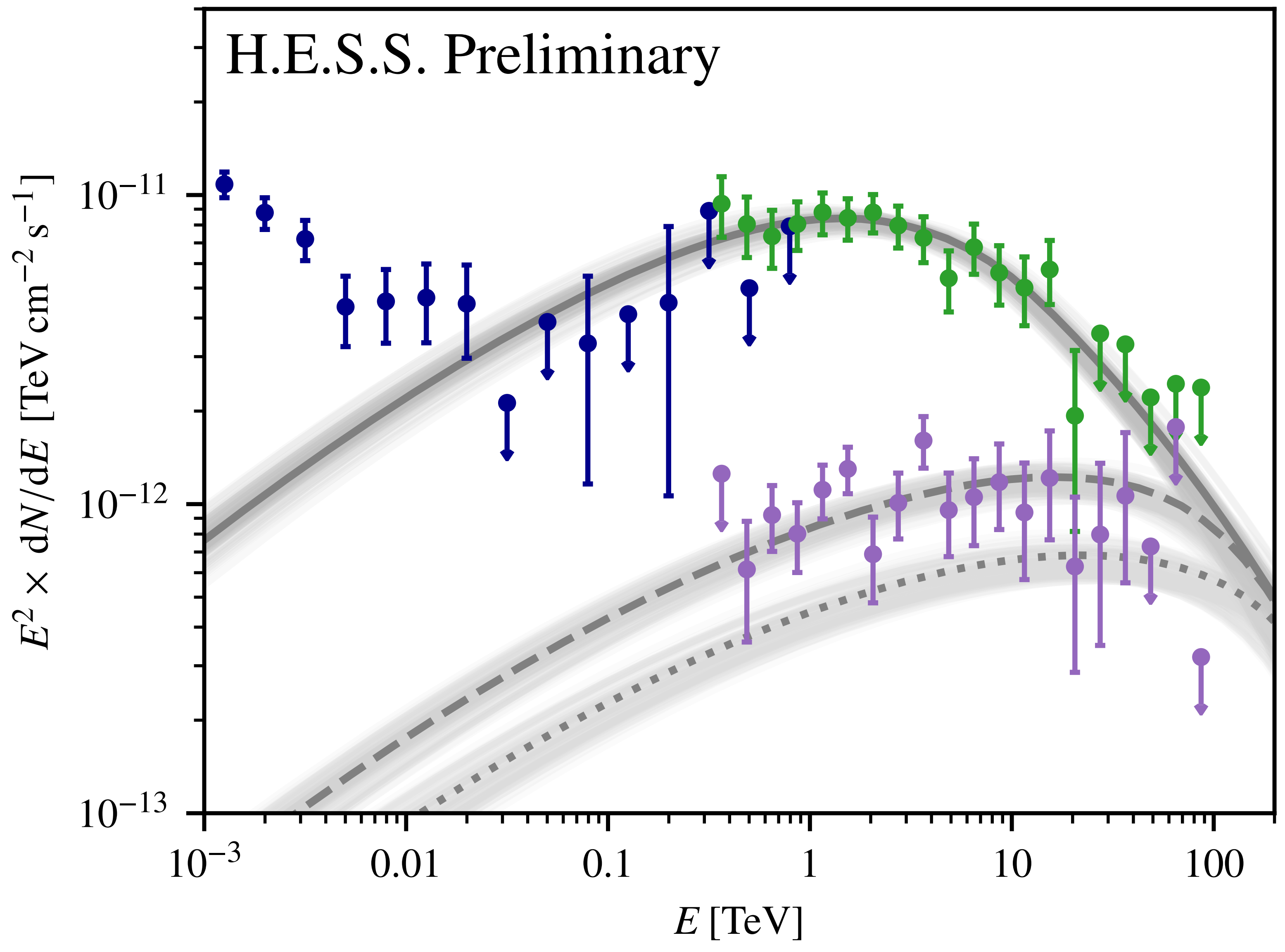
  Hahn, ICRC2015, id. 917

- 3 “generations” of electrons
  - halo of “relic” electrons (20 kyr) → Component 1
  - medium-aged electrons (< 2 kyr) → Component 2
  - youngest electrons (< 0.9 kyr) → X-ray PWN

- Model works well for X-ray and H.E.S.S. data

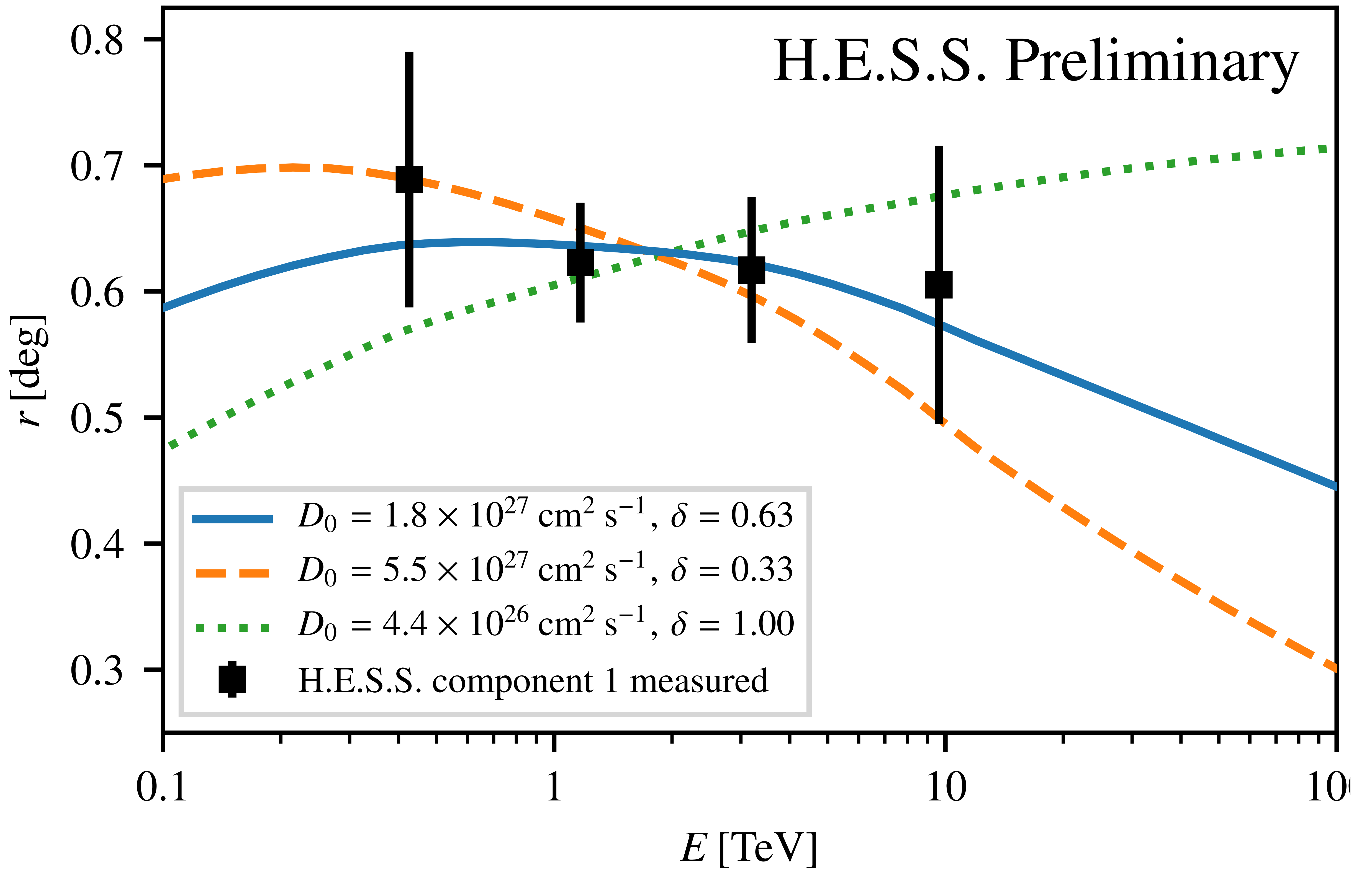
- Fermi-LAT data below 10 GeV unexplained
  - connection to H.E.S.S. components not straightforward





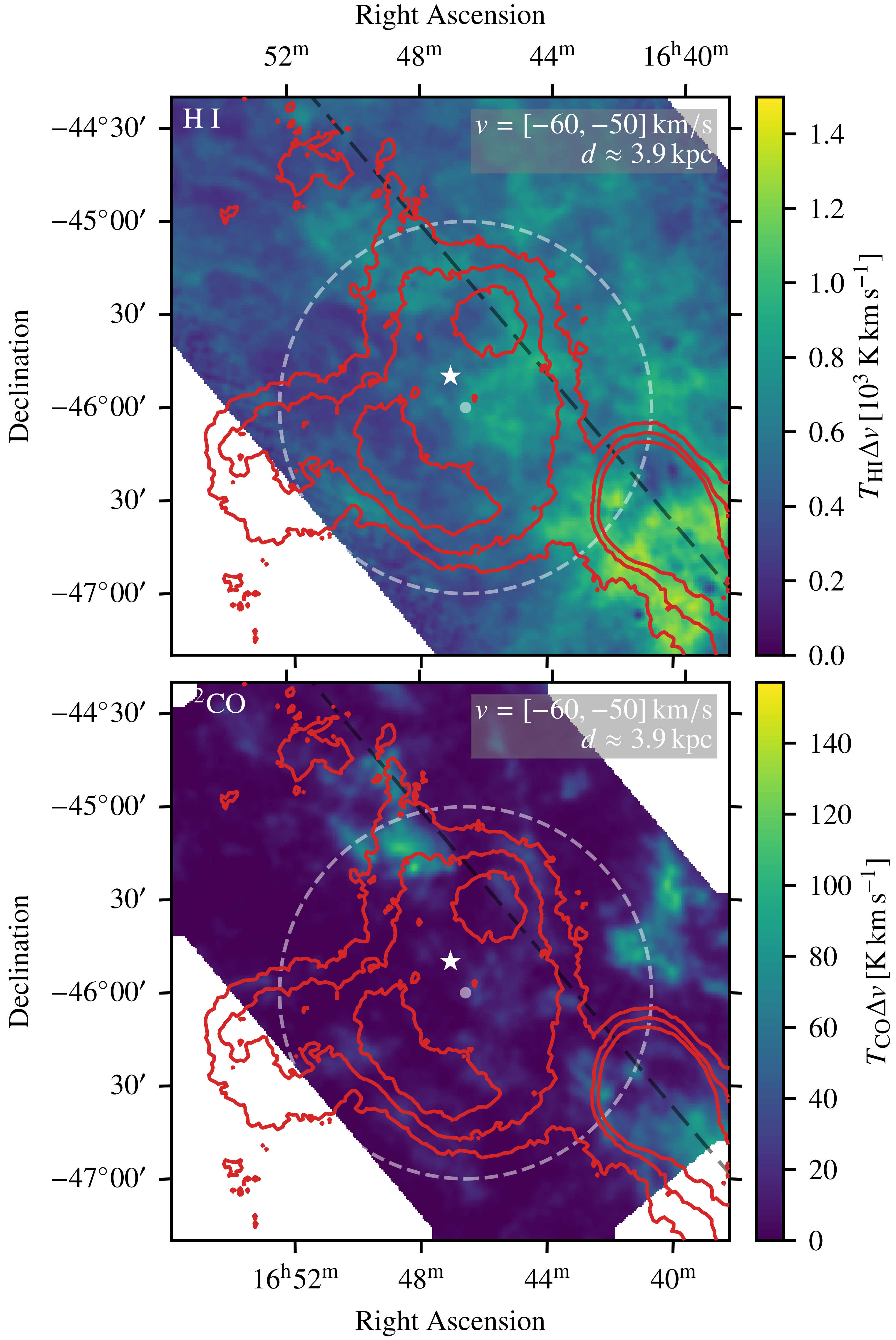
HESS J1809-193: PWN model — spatial extent

- Size of extended H.E.S.S. component
  - assume "relic" electrons started diffusing 20 kyr ago (age of system)
  - compute expected size of halo as a function of gamma-ray energy
  - compare with measured size
  - good agreement for $D_0 \sim 2 \times 10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$
    $\rightarrow$ a reasonable value!



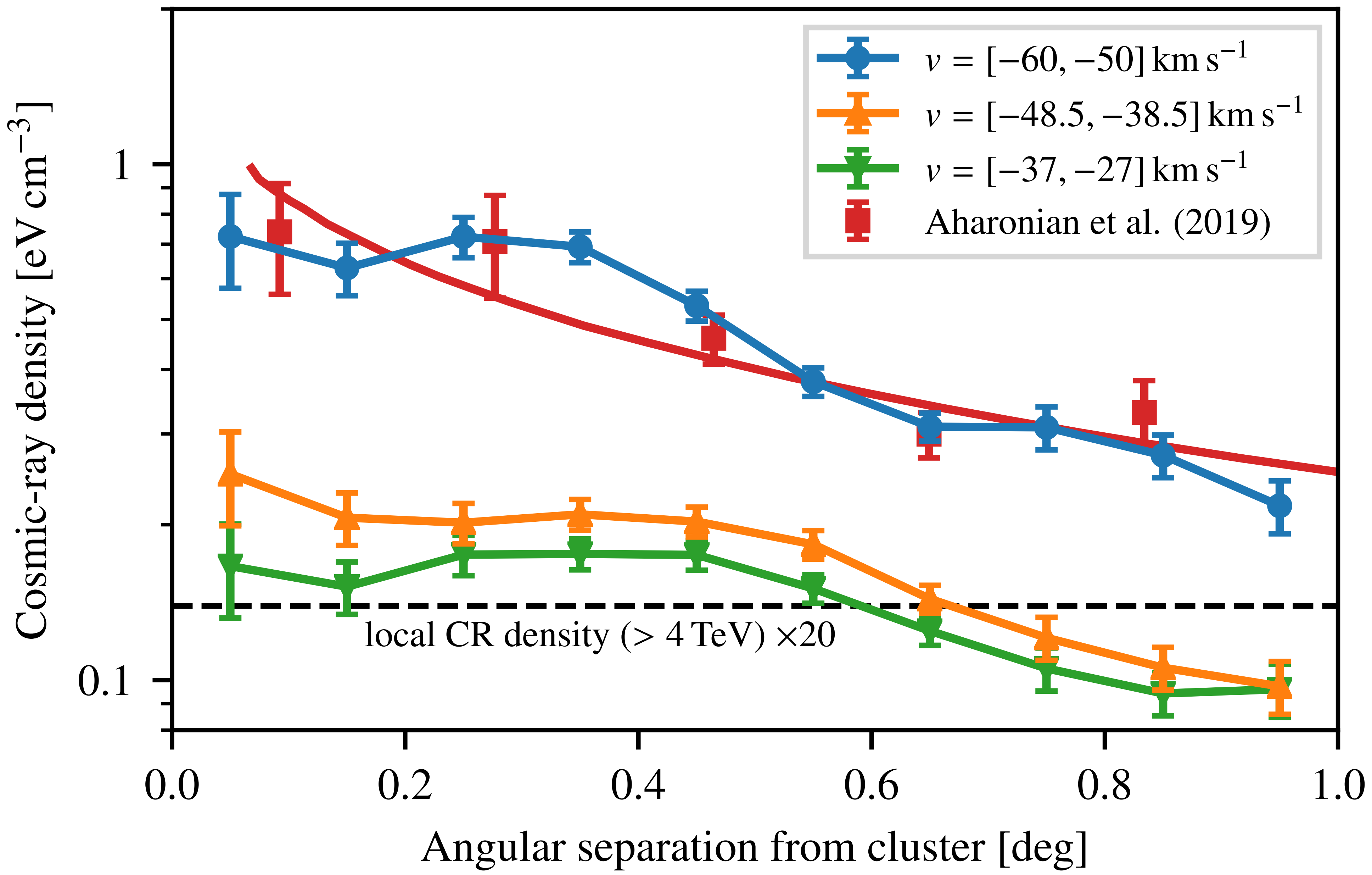
Westerlund 1: gas maps

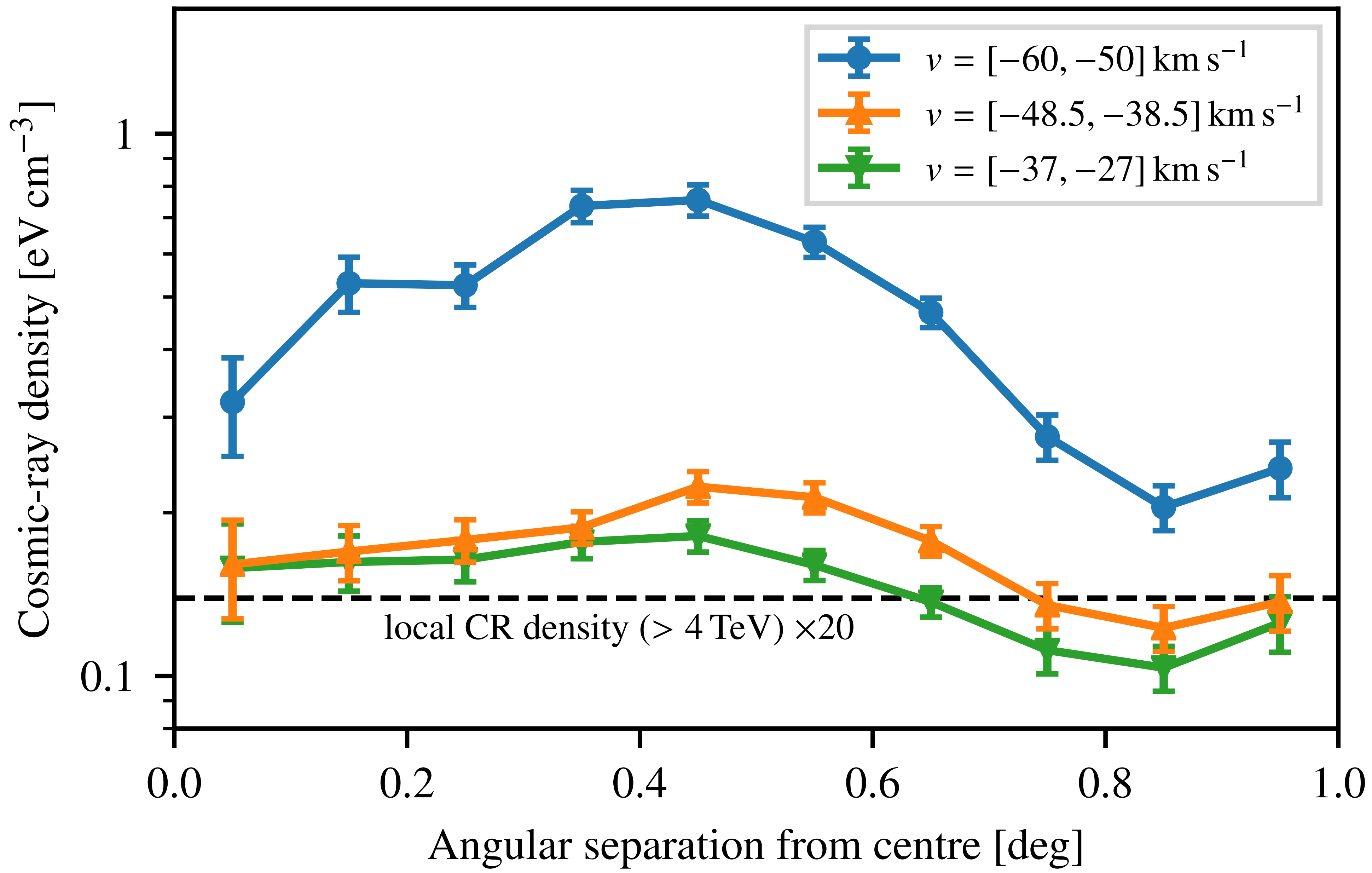
- Hadronic scenario: need target material for interactions
- H I line emission from SGPS survey *McClure-Griffiths et al., ApJS 158, 178 (2005)*
  - indicates atomic hydrogen
- CO line emission from Mopra telescope *Braiding et al., PASA 35, e029 (2018)*
  - traces molecular hydrogen
- ***Low*** gas density in regions of bright gamma-ray emission
- Challenge for hadronic scenario
  - but there could be “CO-dark”, e.g. due to photodissociation



Westerlund 1: cosmic-ray density profiles

- Assume gamma-ray emission is fully hadronic
  → infer cosmic-ray density using gas maps
- Profile w.r.t. cluster position compatible with Aharonian et al. (2019)
- Profile w.r.t. centroid of gamma-ray emission not peaked towards centre



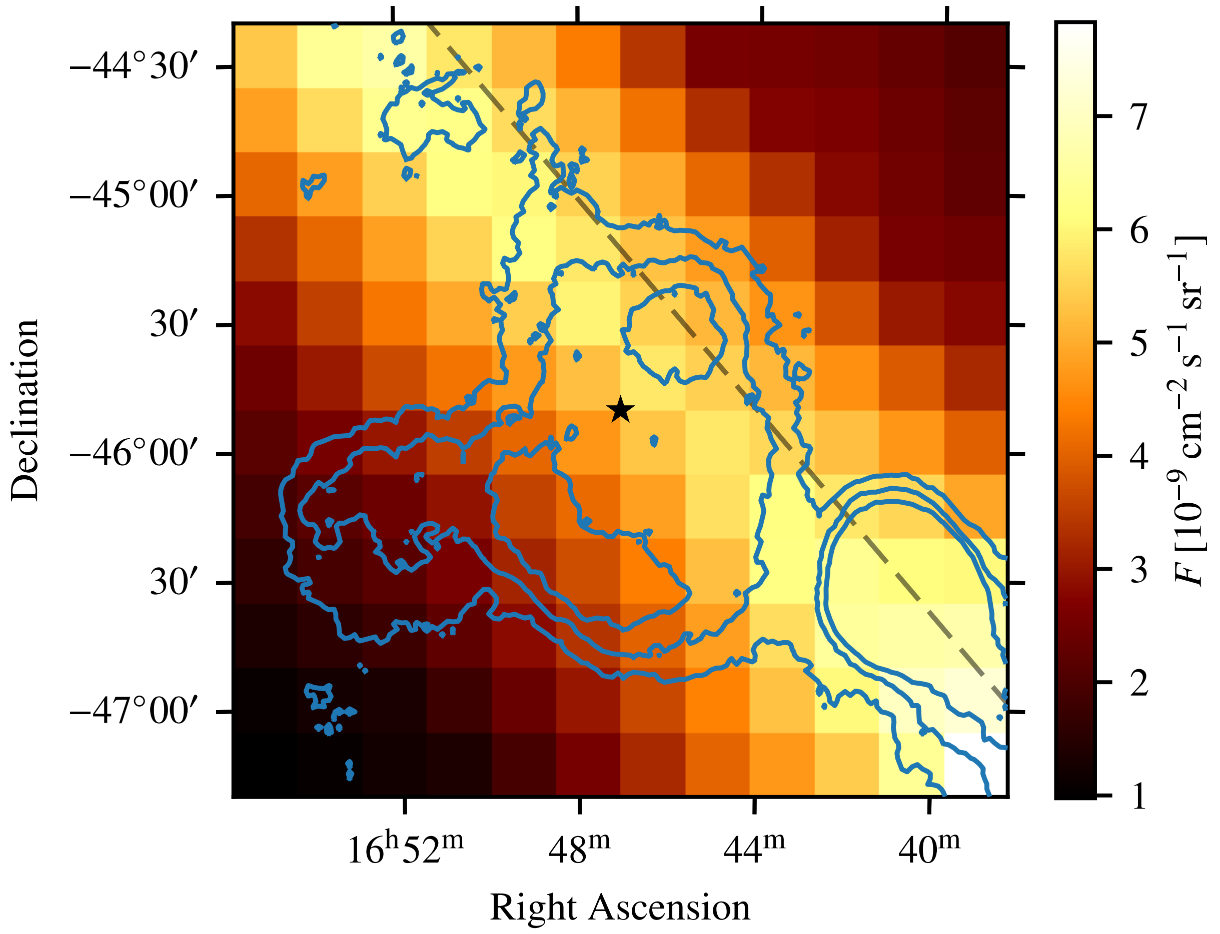


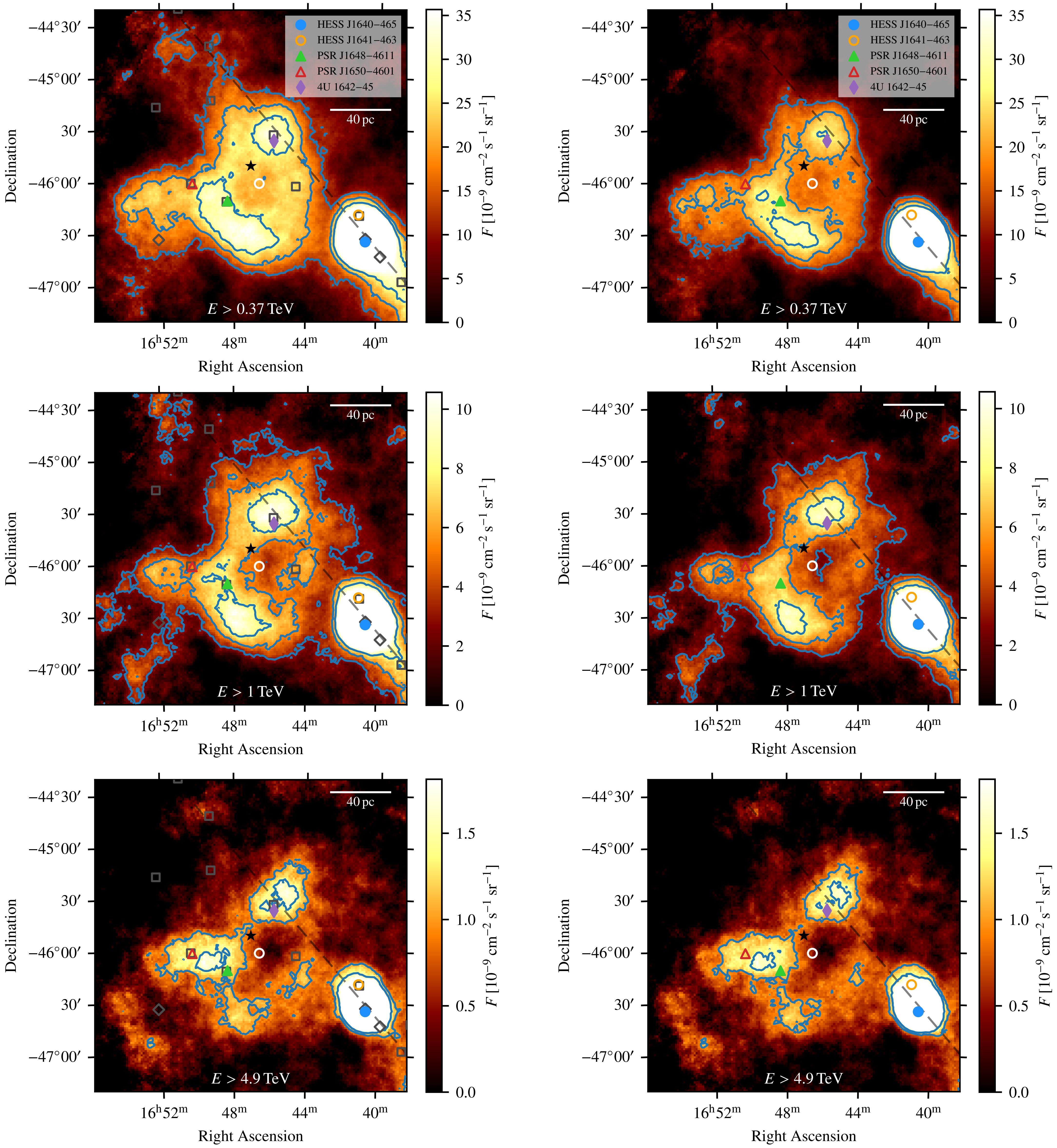
Westerlund 1: galactic diffuse emission

- Likely contributes to emission, but is difficult to estimate

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

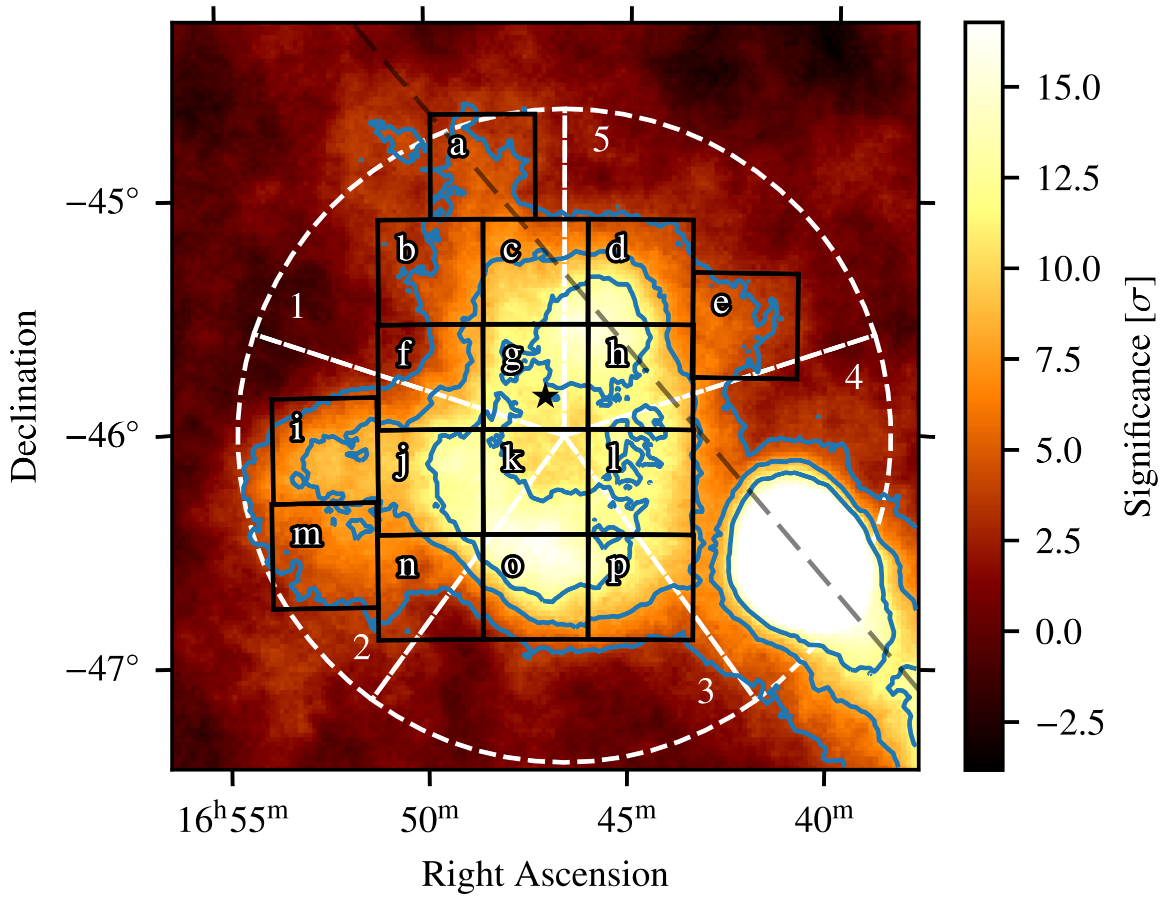
- Use prediction from PICARD propagation code
- Absolute flux level is very uncertain!
- Shell-like structure not affected

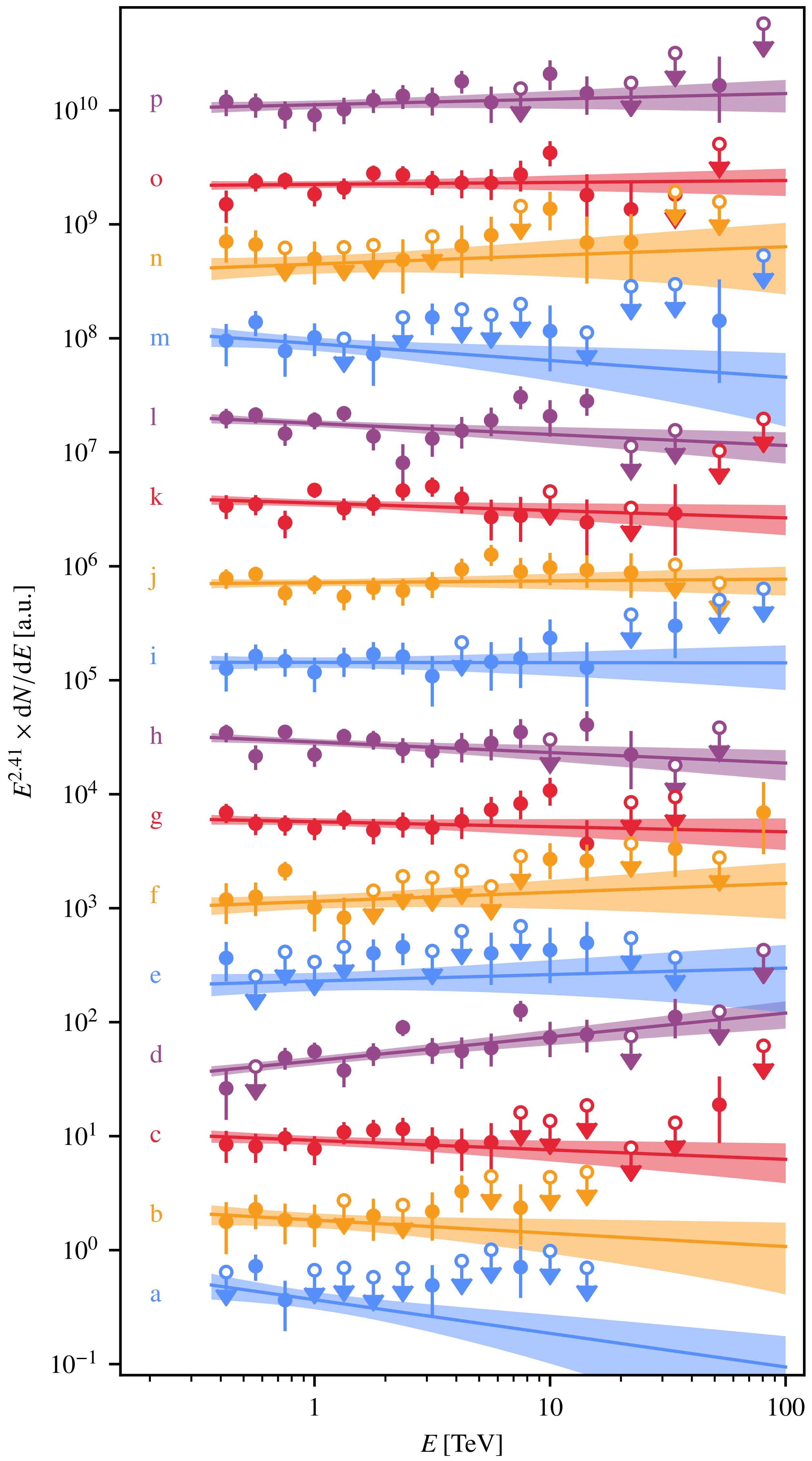




Westerlund 1: signal region energy spectra

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



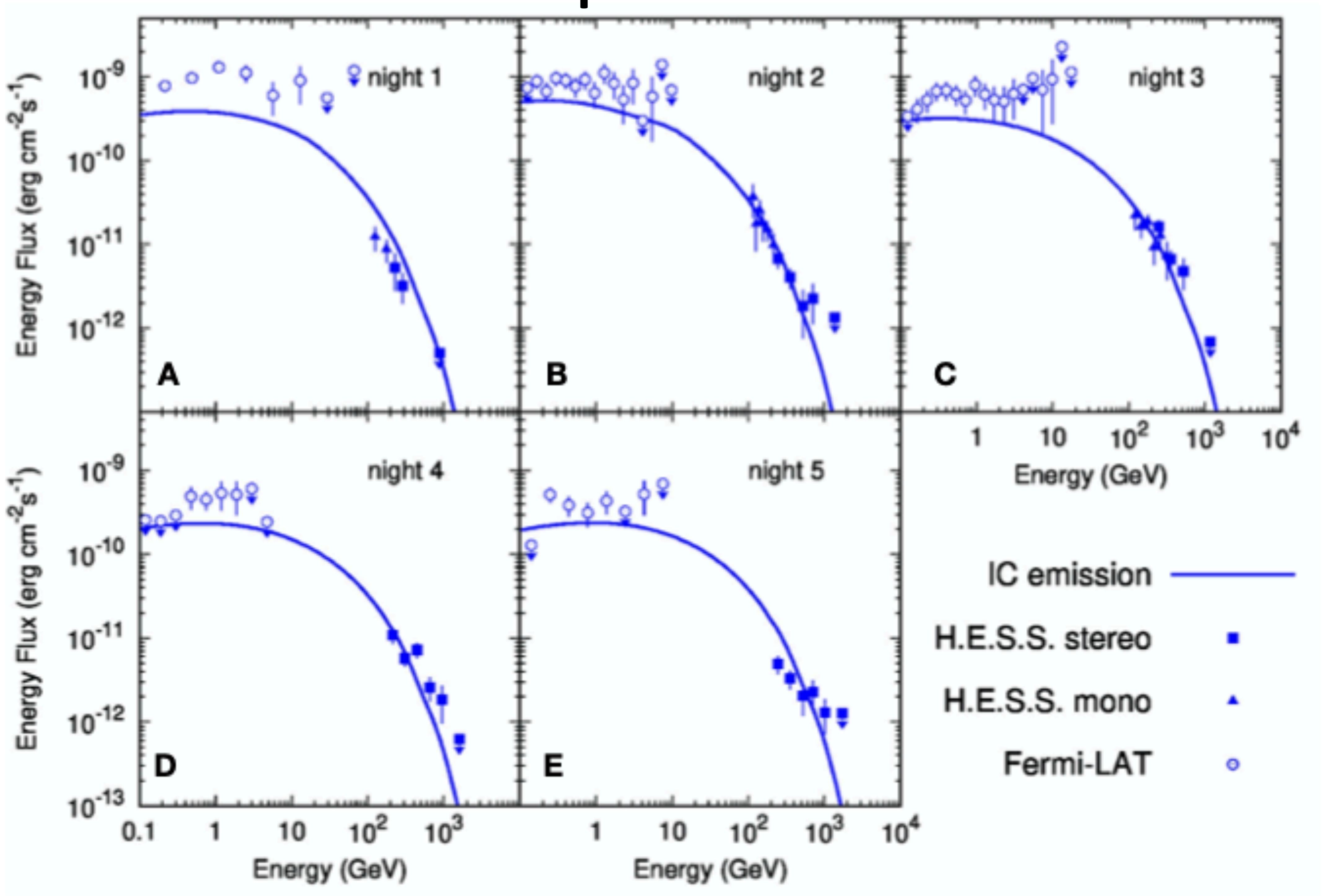


Signal region	Excess events	Significance	Significance ($E > 4.9$ TeV)	ϕ_0 (10^{-13} TeV^{-1}cm^{-2}s^{-1})	Γ	$\sqrt{\Delta TS}$
a	396.1	5.3σ	0.9σ	3.76 ± 0.66	2.71 ± 0.18	5.9
b	454.9	5.6σ	1.7σ	4.34 ± 0.64	2.53 ± 0.13	7.5
c	901.8	10.3σ	2.8σ	6.33 ± 0.58	2.49 ± 0.08	12.3
d	1014.0	10.8σ	7.7σ	6.66 ± 0.58	2.20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

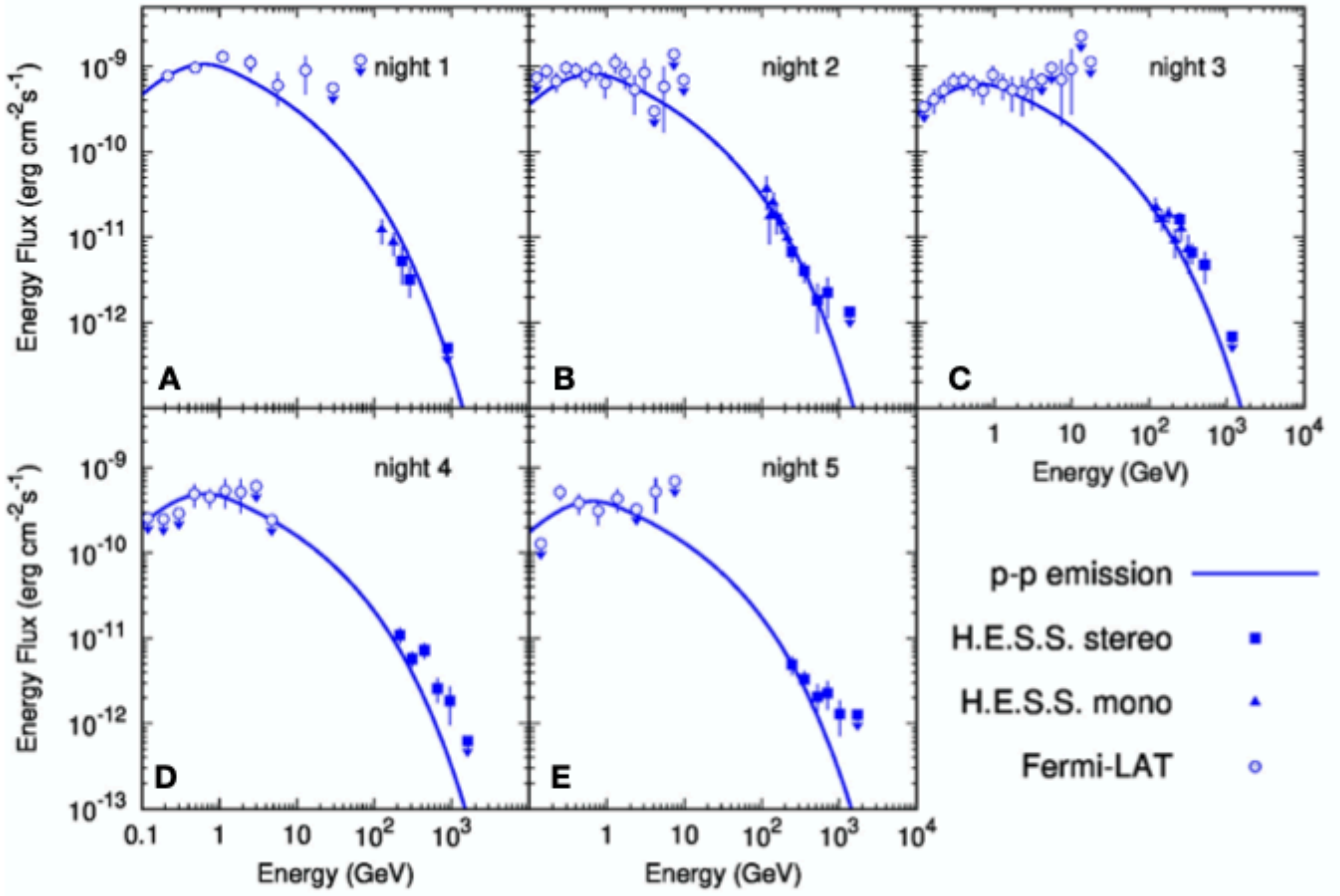
Nova RS Ophiuchi

- H.E.S.S. leptonic and hadronic model fits
- Clear preference for hadronic model

leptonic model



hadronic model



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