γ-ray observations of the Massive Stellar Cluster Westerlund 1 with H.E.S.S.

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

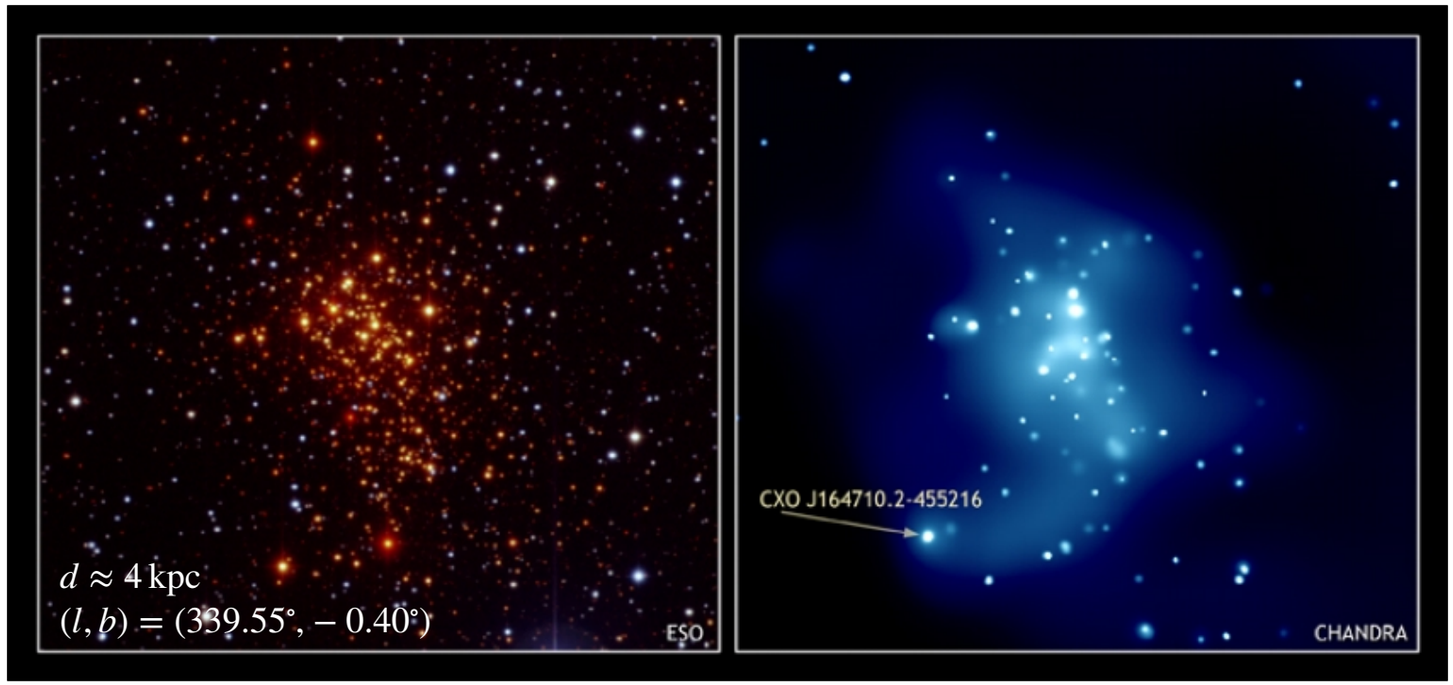
Friedrich-Alexander-Universität Erlangen-Nürnberg

Westerlund 1

- Most massive SC in our Galaxy
  - Total mass: $\sim 10^5 M_\odot$
  - Age: $3.5 - 5\,\mathrm{Myr}$
  - Distance: $\sim 3.9\,\mathrm{kpc}$

  } rather uncertain
  - Radius: $\sim 1\,\mathrm{pc}$
  - Cluster wind luminosity: $L_\mathrm{w} \sim 10^{39}\,\mathrm{erg\,s^{-1}}$ (Muno et al, 2006b)

- Content:
  - 1 Magnetar, but no more stellar remnants known
  - Many rare massive & evolved stars (e.g. >25 WRs, 6 YHGs, 4 RSGs, LBVs, OB super- & hypter giants, ...)
    → Potentially high mass loss



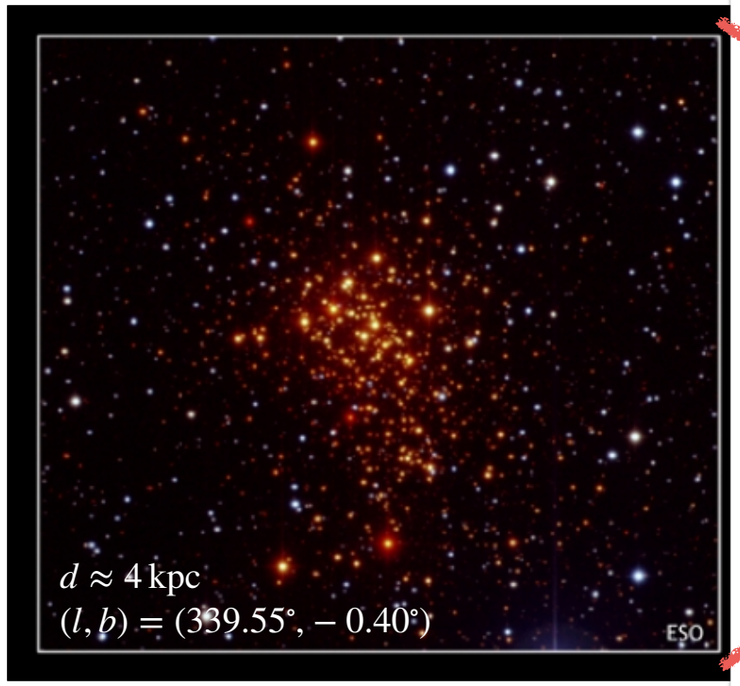
Central ~5'x5' region of Wd1 (Credit: NASA/CXC/UCLA/M.Muno et al., Clark et al. 2008)

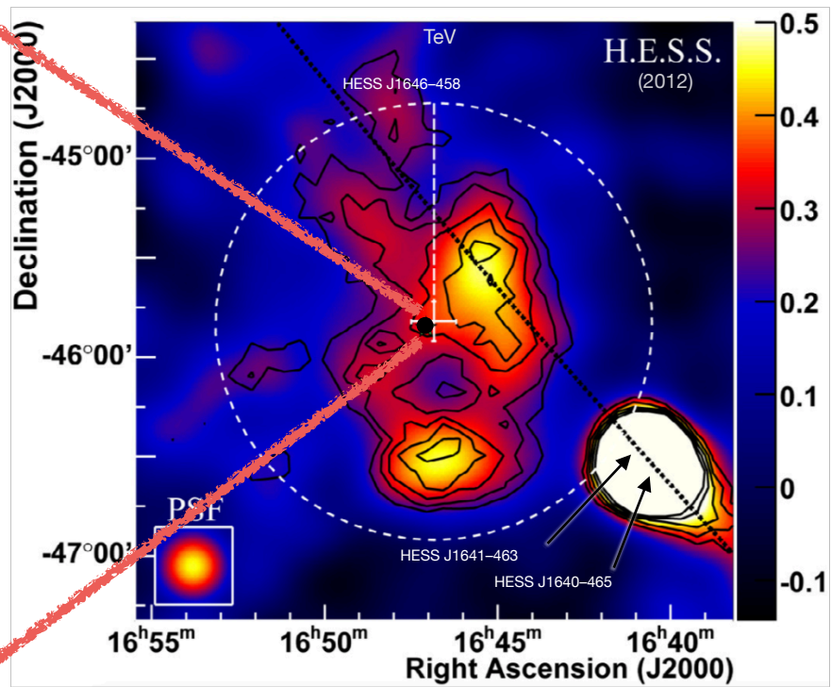
HESS J1646−458

- Detection of VHE γ-ray emission *HESS J1646−458* (H.E.S.S., 2012)
  - Large extension (~2°)
  - Centroid coincident with Wd 1
  - Hard Spectrum (Γ~2.2)
  - no cut-off / break up to ~20 TeV
    → PeVatron candidate

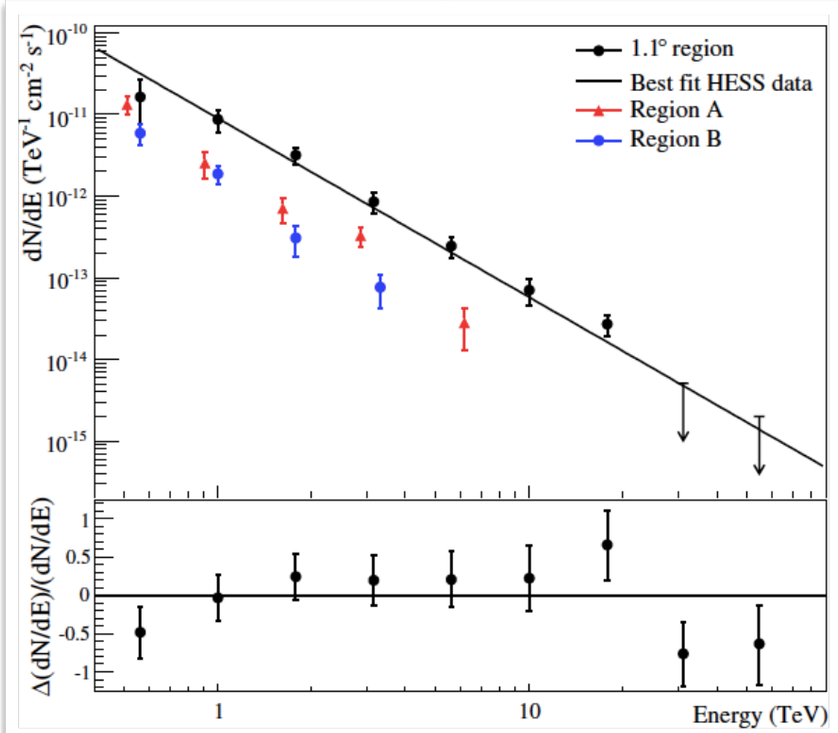
High Energy Stereoscopic System, H.E.S.S.

- However, connection to Wd 1 not firmly established





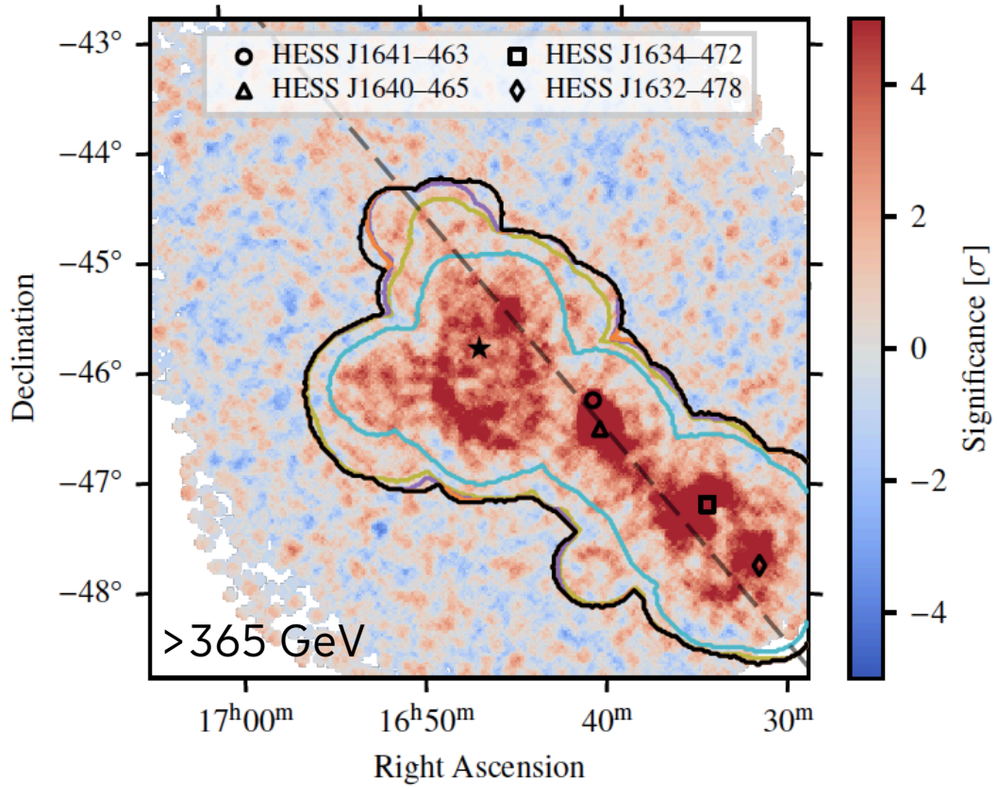
Central ~5'x5' region of Wd1 (Credit: NASA/

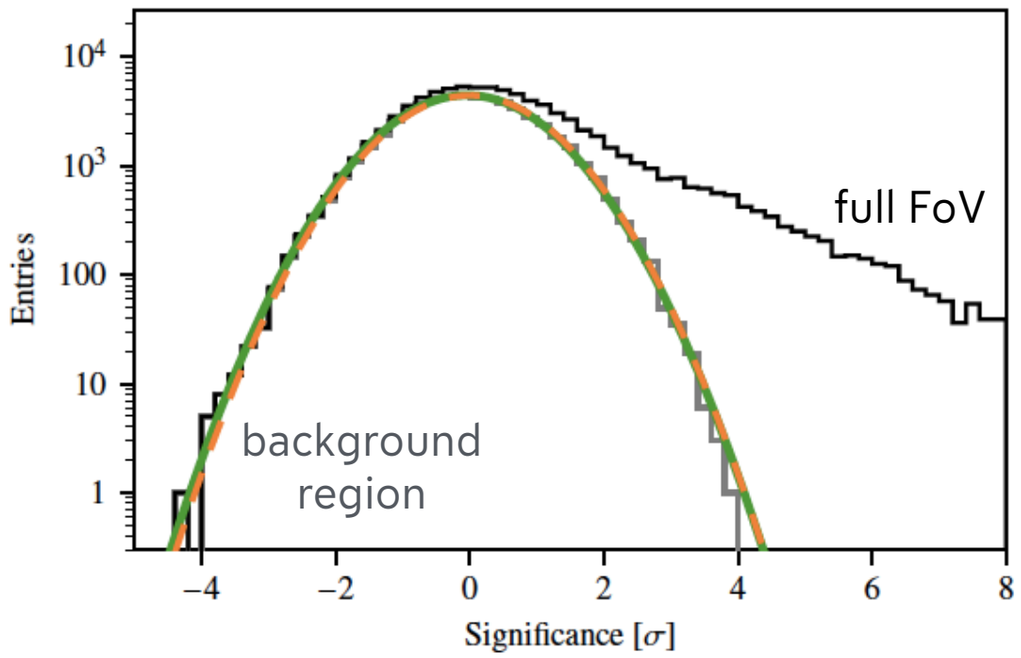


New H.E.S.S. analysis

- Dataset:
  - ~164 hours live time, taken within 2004 — 2017
    → 5x more data (34h in 2012 analysis)
  - Energy threshold 365 GeV

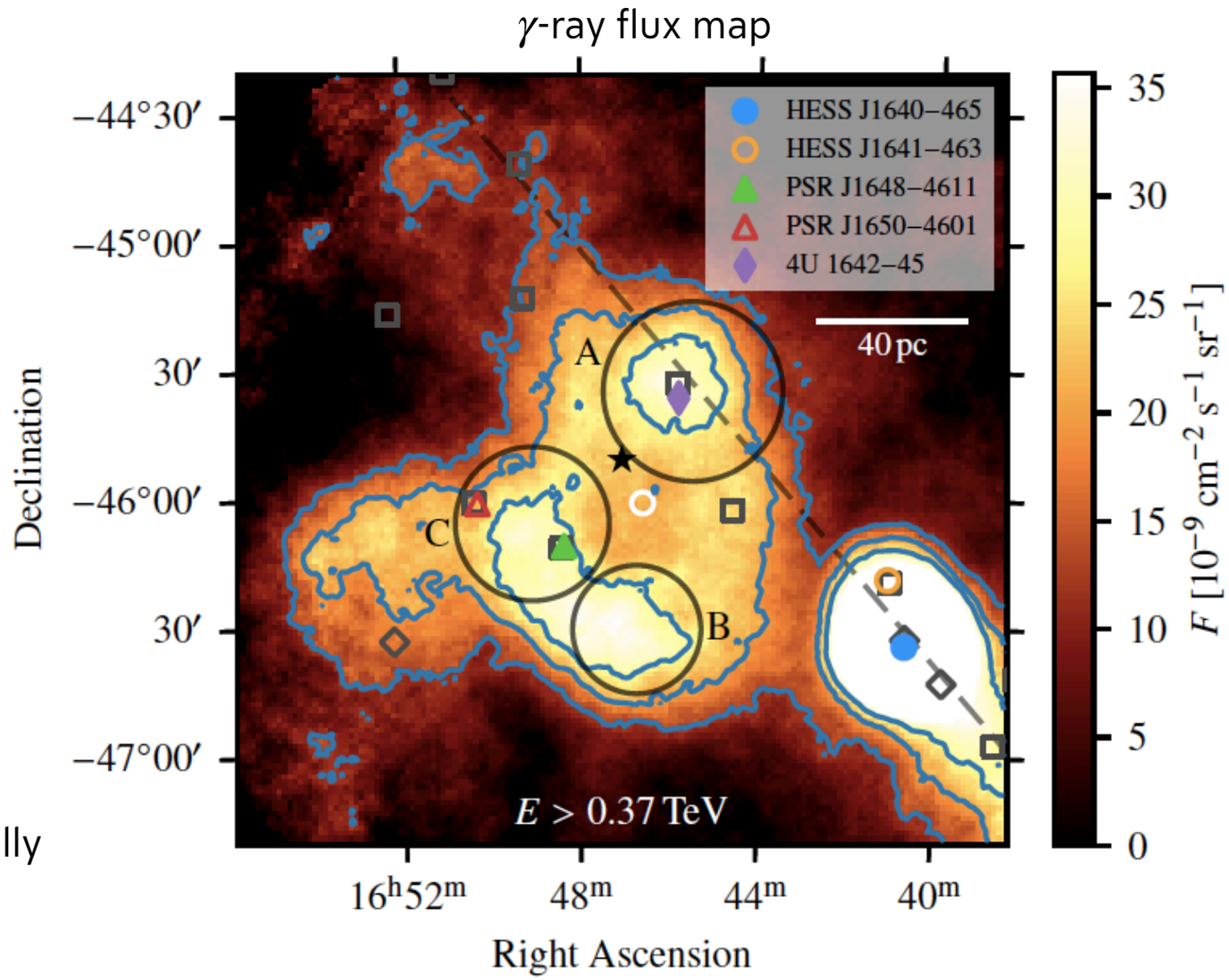
- Analysis:
  - Complex FoV,
    i.e. large extent, bright close-by sources, Gal. Plane
    → Std. techniques to estimate background fail
    → Background model from archival observations
  - High-level analysis with the Gammapy (& ctools)





Signal Morphology

- Clumpy, shell-like structure
- Extent: ~2° (~140 pc at ~4 kpc)
- Signal not peaked at the cluster
- Centroid slightly shifted from Wd 1



- Potential counterparts:
  - ~~LMXB 4U 1642-45~~
  - ▲ PSR J1648−4611
  - △ PSR J1650−4601

  } may contribute locally
  - ★ Westerlund 1 → bulk of emission?
  - ★ ~~Magnetar within Wd 1~~ ~~(CXOU J164710.2−455216)~~

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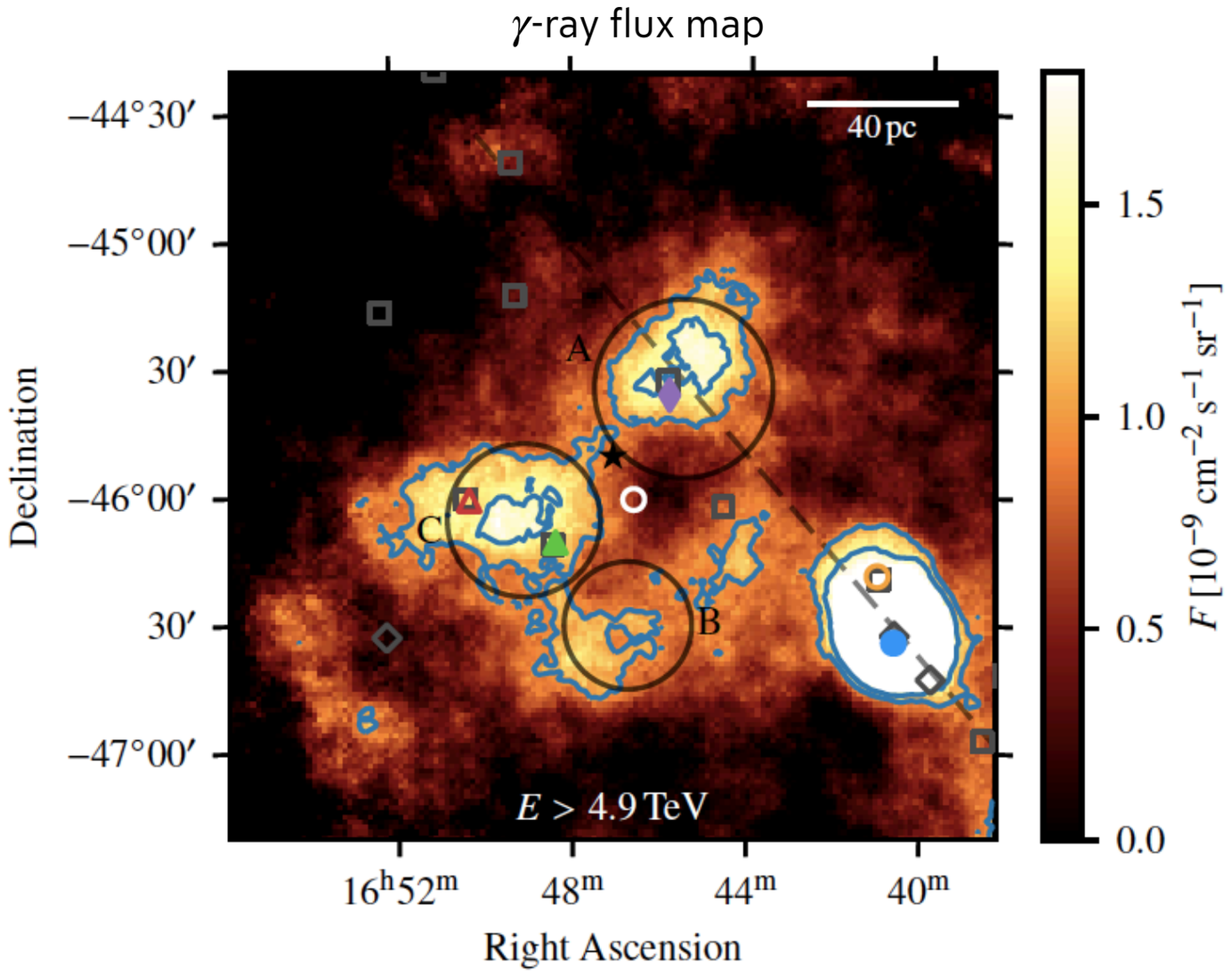
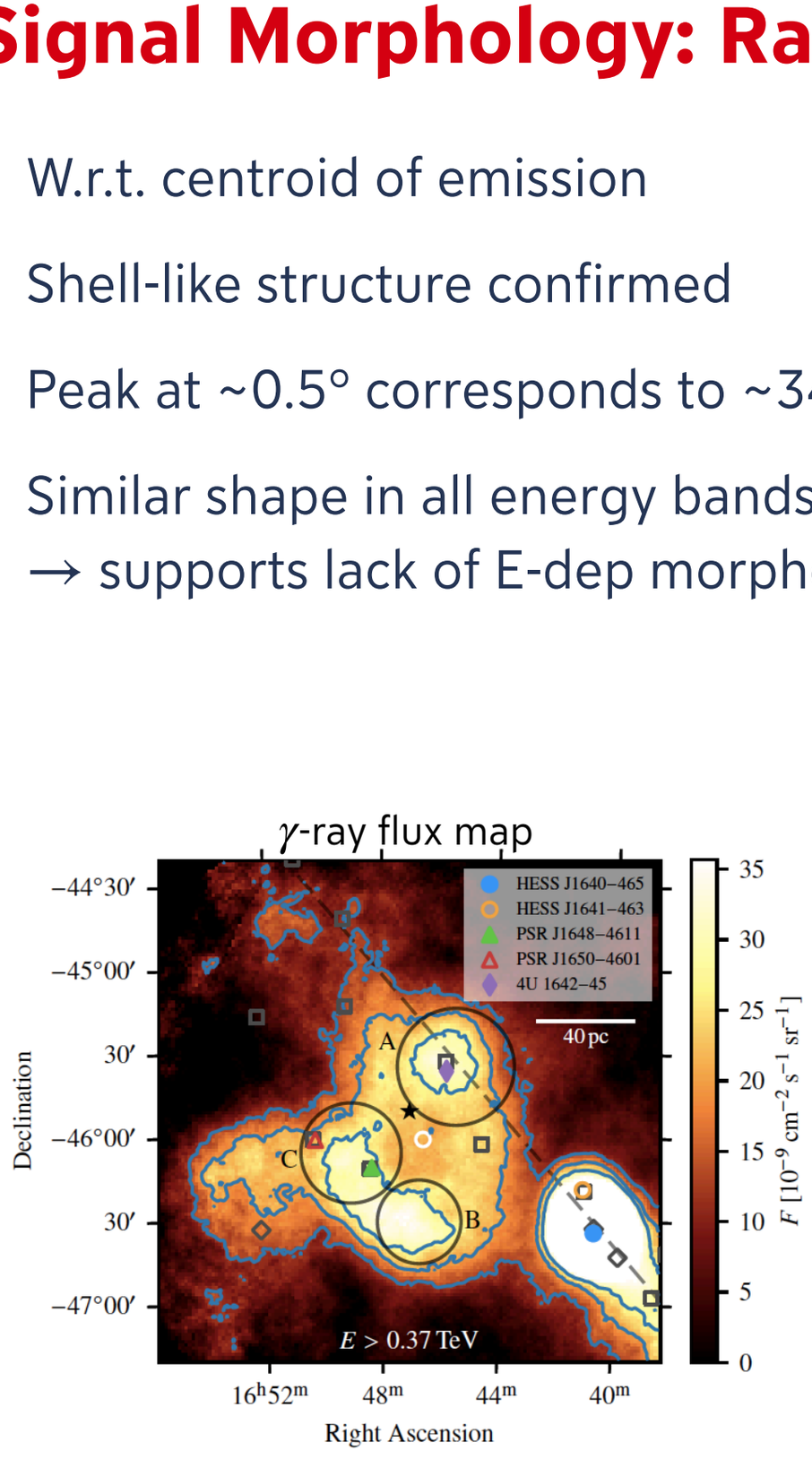
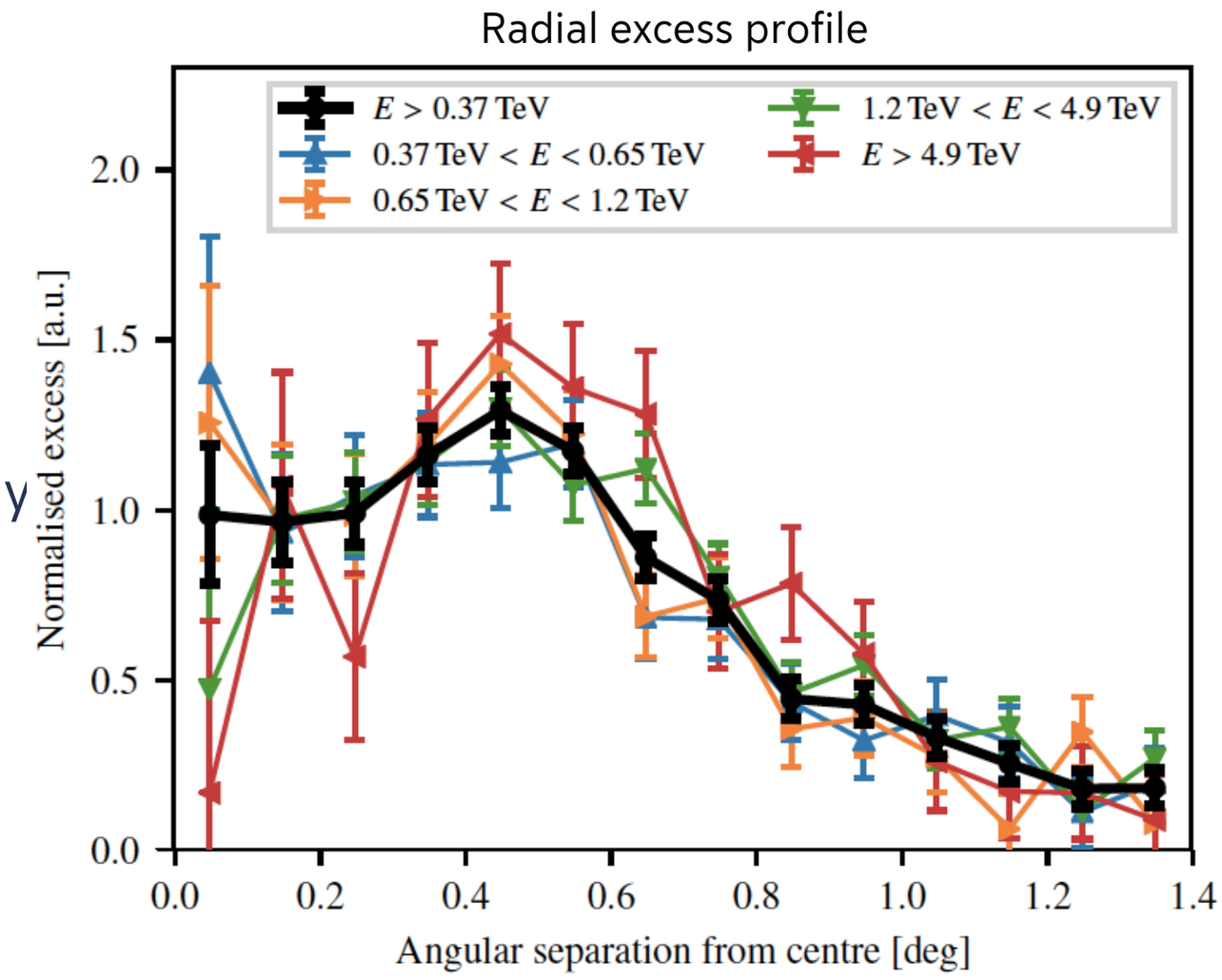


- Energy-dependent morphology?
  - Bright spots persist up to the highest energies
  - Shell-like structure persists up to the highest energies

Signal Morphology: Radial Profiles

- W.r.t. centroid of emission
- Shell-like structure confirmed
- Peak at ~0.5° corresponds to ~34 pc
- Similar shape in all energy bands
  → supports lack of E-dep morphology

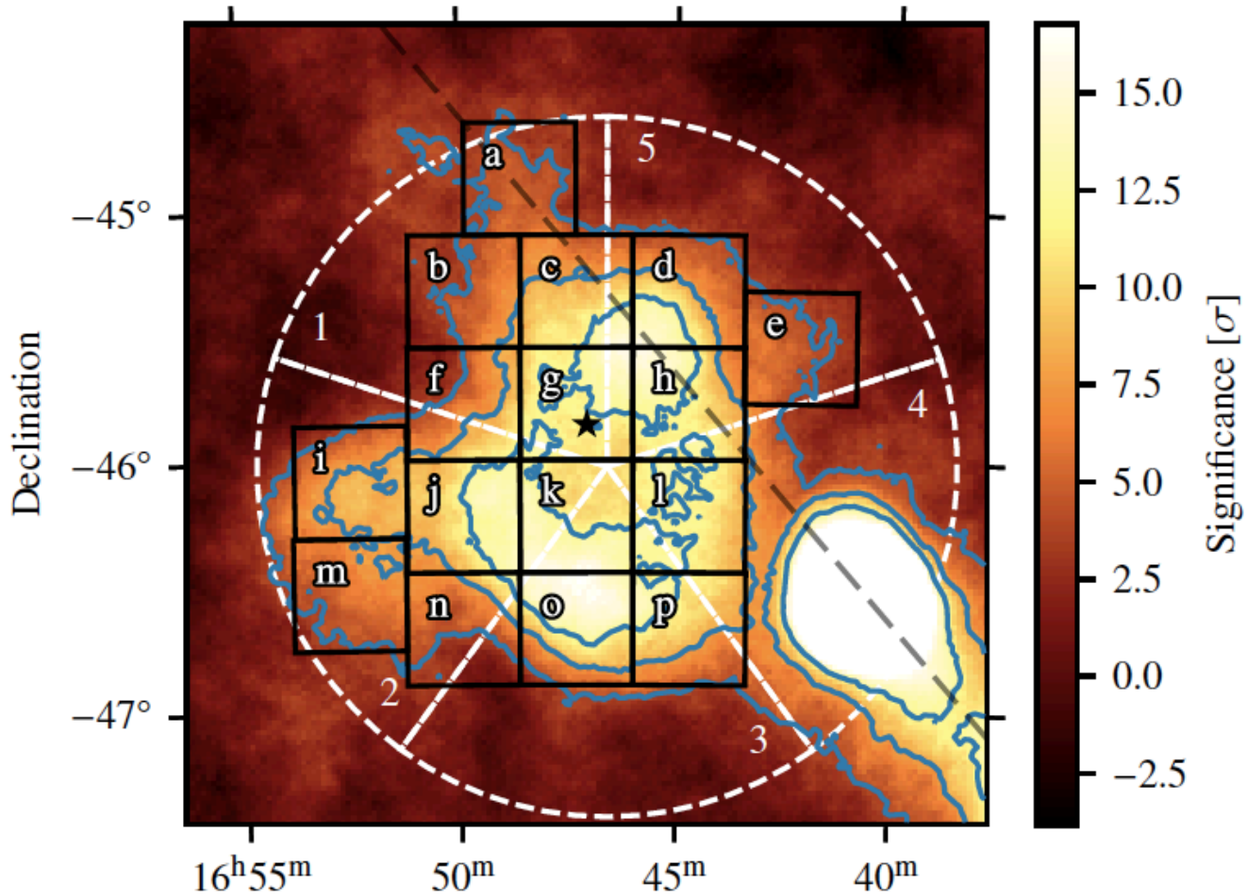


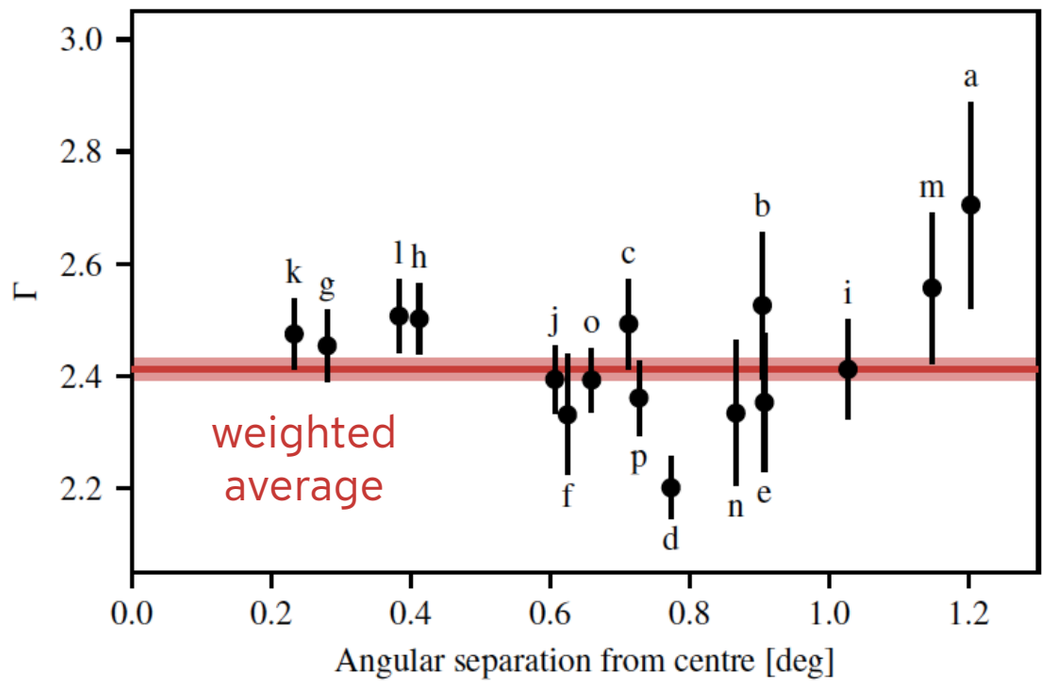


Energy range (TeV)	Excess	χ^2/N_{dof}	p_{χ^2}
> 0.37	15 310 ± 440	–	–
0.37 – 0.65	5080 ± 300	12.2 / 14	59.0%
0.65 – 1.2	3910 ± 230	16.2 / 14	30.3%
1.2 – 4.9	5190 ± 220	20.9 / 14	10.3%
> 4.9	1130 ± 80	19.5 / 14	14.6%

Signal Spectrum

- Analysis in 16 sub-regions
  - Follow signal morphology
  - PL spectral model fit
- Spectra remarkably similar
- Region d harder (~4σ)
- Combined spectrum: $\Gamma = 2.41 \pm 0.2$
- Support for lack of E-dep. morphology





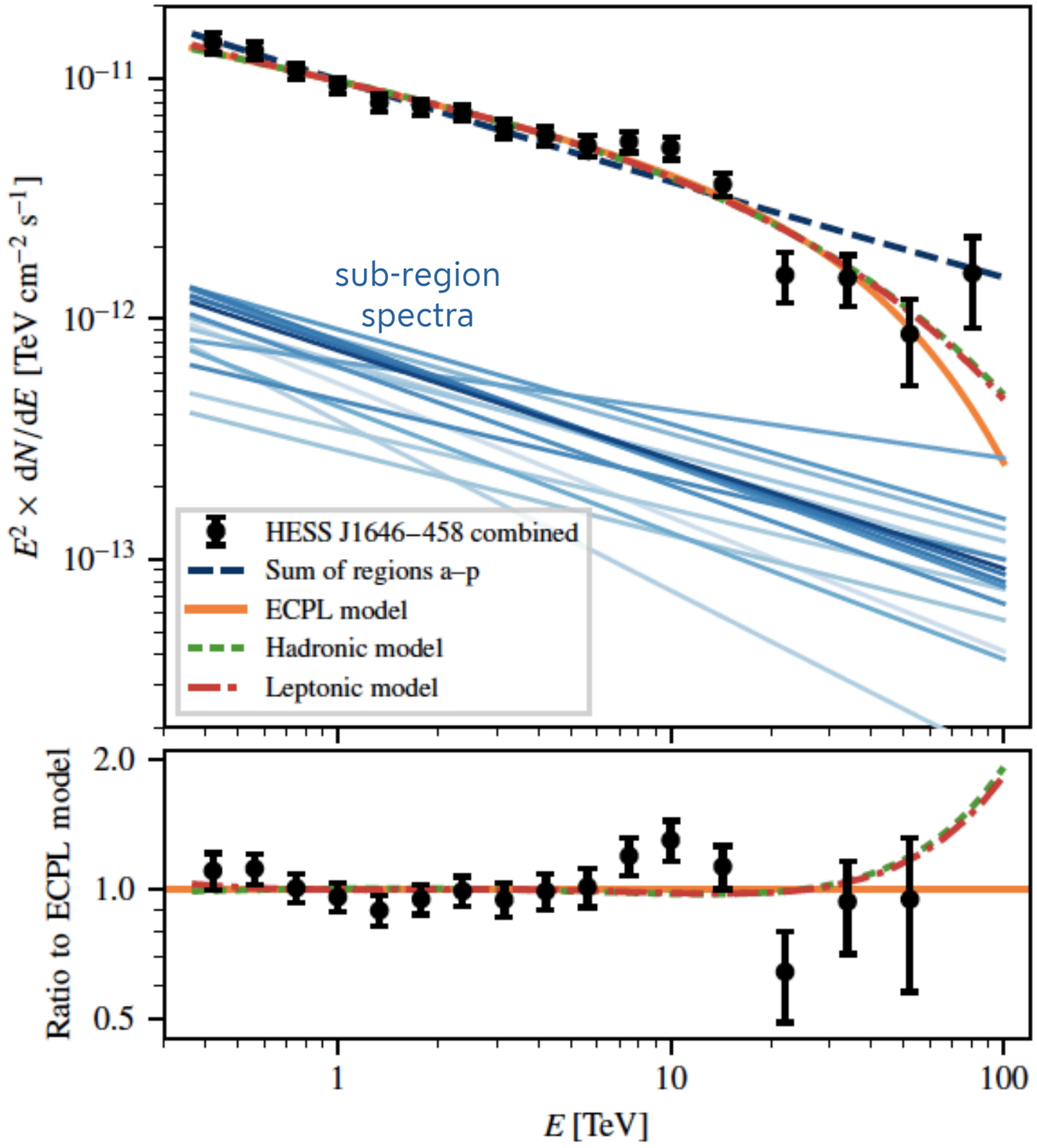
Signal Spectrum

- Spectrum extends to several tens of TeV

- Simple PL no satisfying model
  - p-value: ~0.06%

- ECPL:
  - p-value more satisfying (~6.3%), but flux points do not provide a clear indication for cut-off in the spectrum
  - $L_\gamma \sim 10^{35}\,(d/3.9\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$
  - $\Gamma = 2.30 \pm 0.04$ & $E_\mathrm{c} = 44^{+17}_{-11}\,\mathrm{TeV}$

Combined energy spectrum

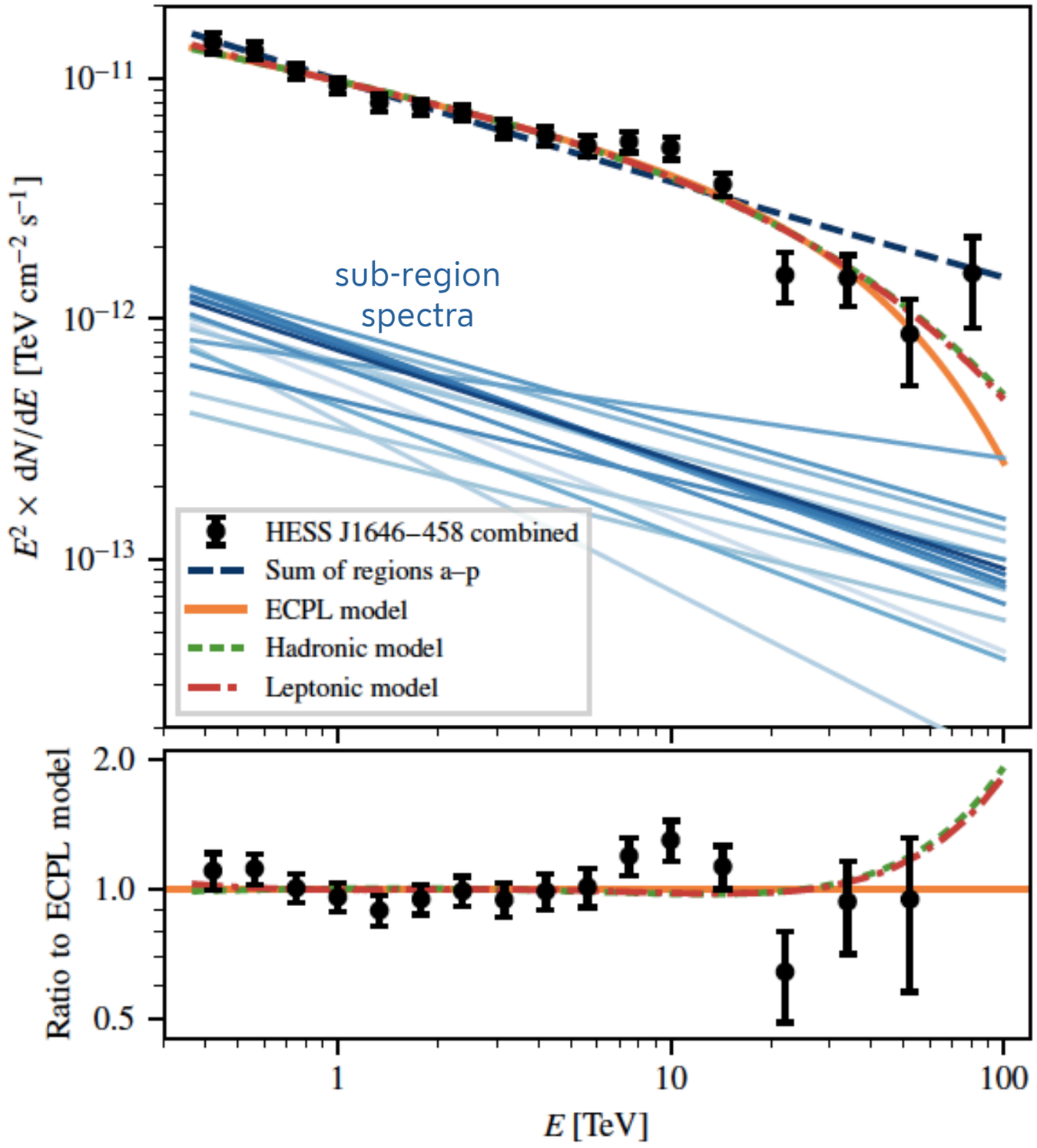


Simple Modelling with Naima

- Simple **hadronic** model
  - $\Gamma_{\mathrm{p}} = 2.33 \pm 0.06$
  - $E_{\mathrm{c}}^{\mathrm{p}} > 214\,\mathrm{TeV}$ (95% c.l.)
    (i.e. $E_{\mathrm{c}}^{\mathrm{p}} = 400^{+250}_{-130}\,\mathrm{TeV}$)
  - $W_{\mathrm{p}}^{>1\,\mathrm{GeV}} \sim 6 \times 10^{51}\,(\frac{1\,\mathrm{cm}^{-3}}{n})\,\mathrm{erg}$
    vs $L_{\mathrm{w}} \times t \sim 10^{53}\,\mathrm{erg}$

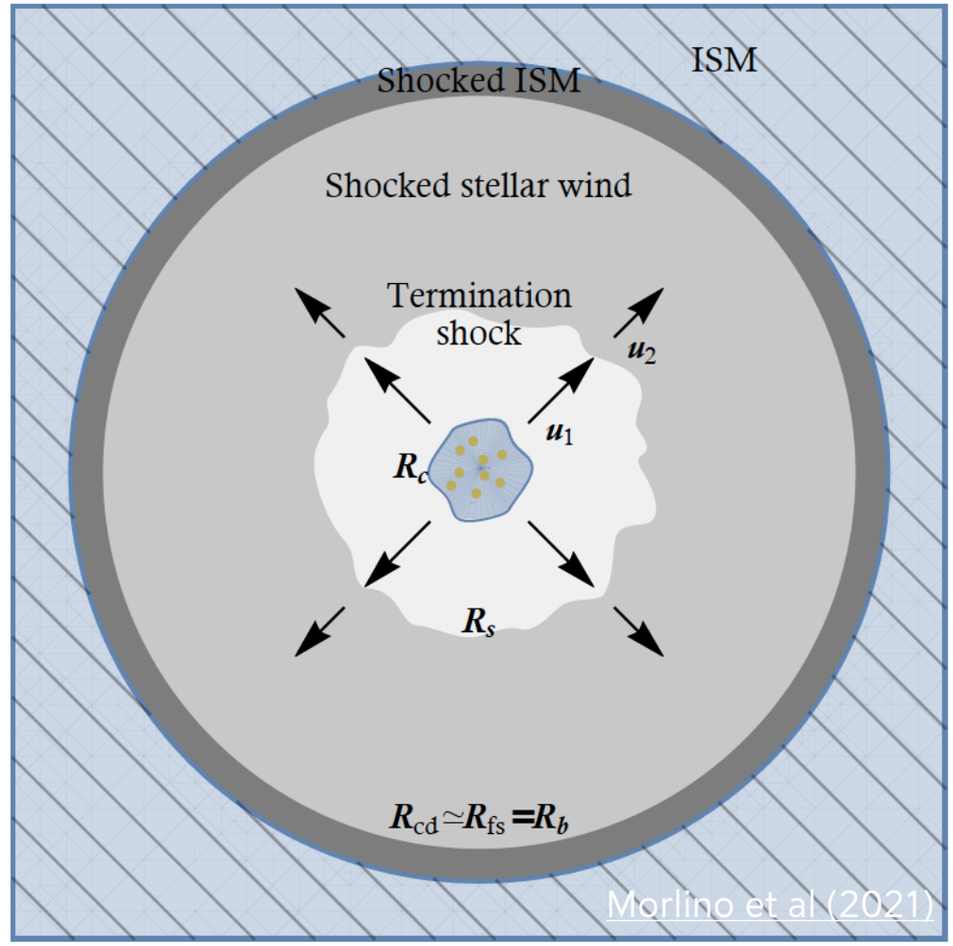
- Simple **leptonic** model
  - $\Gamma_{\mathrm{e}} = 2.97 \pm 0.07$
  - $E_{\mathrm{c}}^{\mathrm{e}} > 87\,\mathrm{TeV}$ (95% c.l.)
    (i.e. $E_{\mathrm{c}}^{\mathrm{p}} = 180^{+200}_{-70}\,\mathrm{TeV}$)
  - Required energy in primary e:
    $W_{\mathrm{e}}^{>100\,\mathrm{GeV}} \sim 7 \times 10^{48}\,\mathrm{erg}$
    → Min. required power:
    $L_{\mathrm{e}} > 4 \times 10^{35}\,\mathrm{erg\,s^{-1}}$

Combined energy spectrum



Discussion

- No energy-dependent morphology
  - Westerlund 1 may explain bulk of emission
  - Pulsars may contribute locally
- Acceleration within cluster
  - Leptonic scenario ruled out by lack of E-dep. morphology
  - Hadronic scenario viable energetically but would need >PeV CRs
- Acceleration in turbulent SpB
  - $R_{\mathrm{SB}} \sim 180\,\mathrm{pc}$ (basic models) exceeding γ-ray emission region
  - Outer shock not observed at other wavelengths
- Acceleration at cluster wind termination shock
  - $R_{\mathrm{TS}} \sim 30\,\mathrm{pc}$ (basic models), matching radius of shell-like structure
  - Hadronic scenario works energetically but need $B \sim \mathcal{O}(50\,\mu\mathrm{G})$ to confine CRs
  - Leptonic scenario also feasible but would need $B \lesssim 10\,\mu\mathrm{G}$ to "hide" synchrotron emission



Morlino et al (2021)

Conclusion

- HESS J1646−458
  - Complex, very extended morphology
  - Shell-like structure, no variation with energy
  - Spectrum extending to several ten TeV

- Westerlund 1
  - A powerful CR accelerator
  - Acceleration site not unambiguously identified, but H.E.S.S. results provide important constraints
  - Intriguing connection between shell-like structure and wind termination shock ?

- Paper accepted for publication by A&A, arXiv:2207.10921