# Revisiting HESS J1809–193

## A very-high-energy gamma-ray source in a fascinating environment

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H.E.S.S.

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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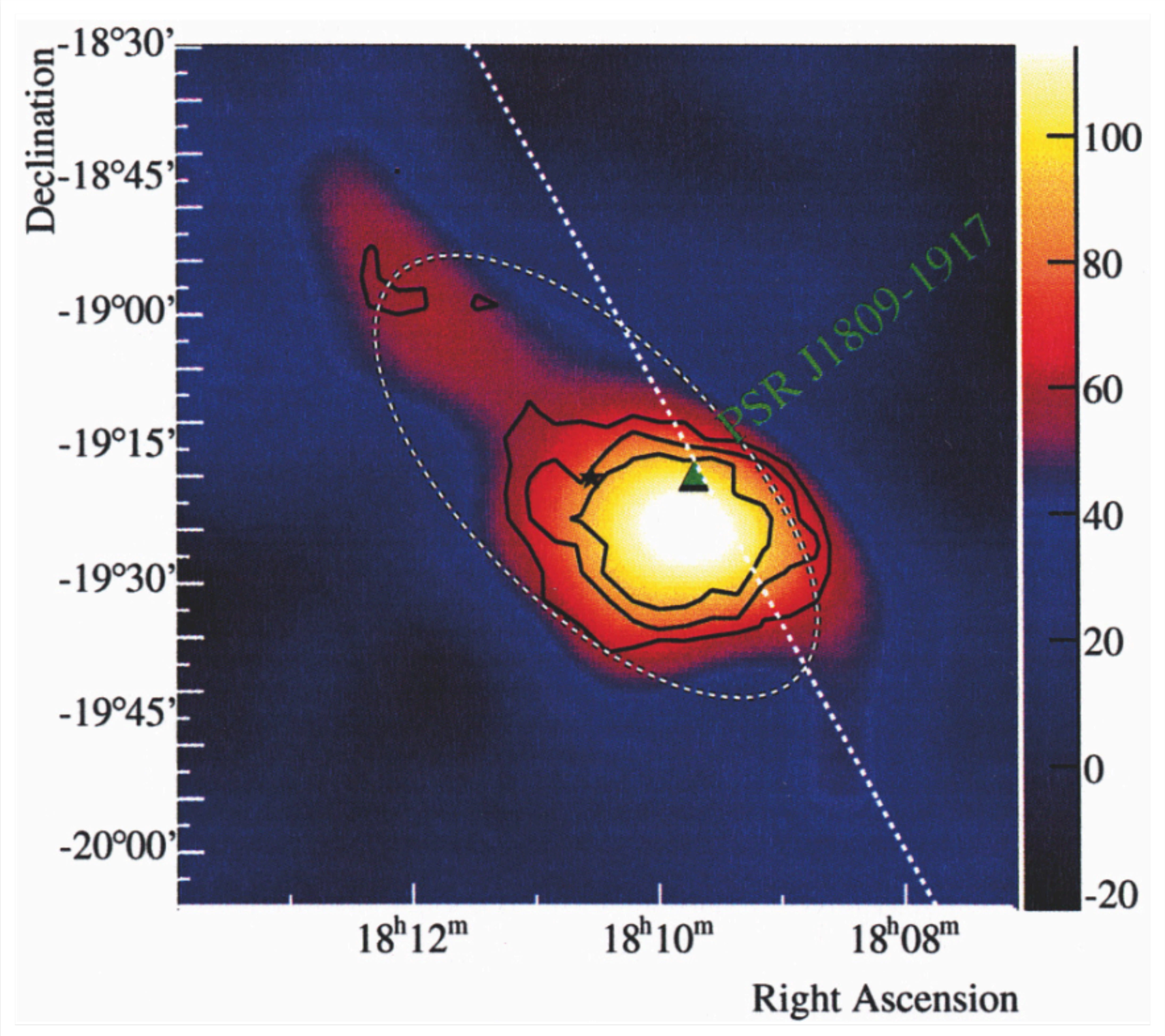
  - Based on 25h of observations (9h for spectrum)
  - Associated with PSR J1809–1917
    ($\dot{E} = 1.8 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, $\tau_c = 51\,\mathrm{kyr}$)



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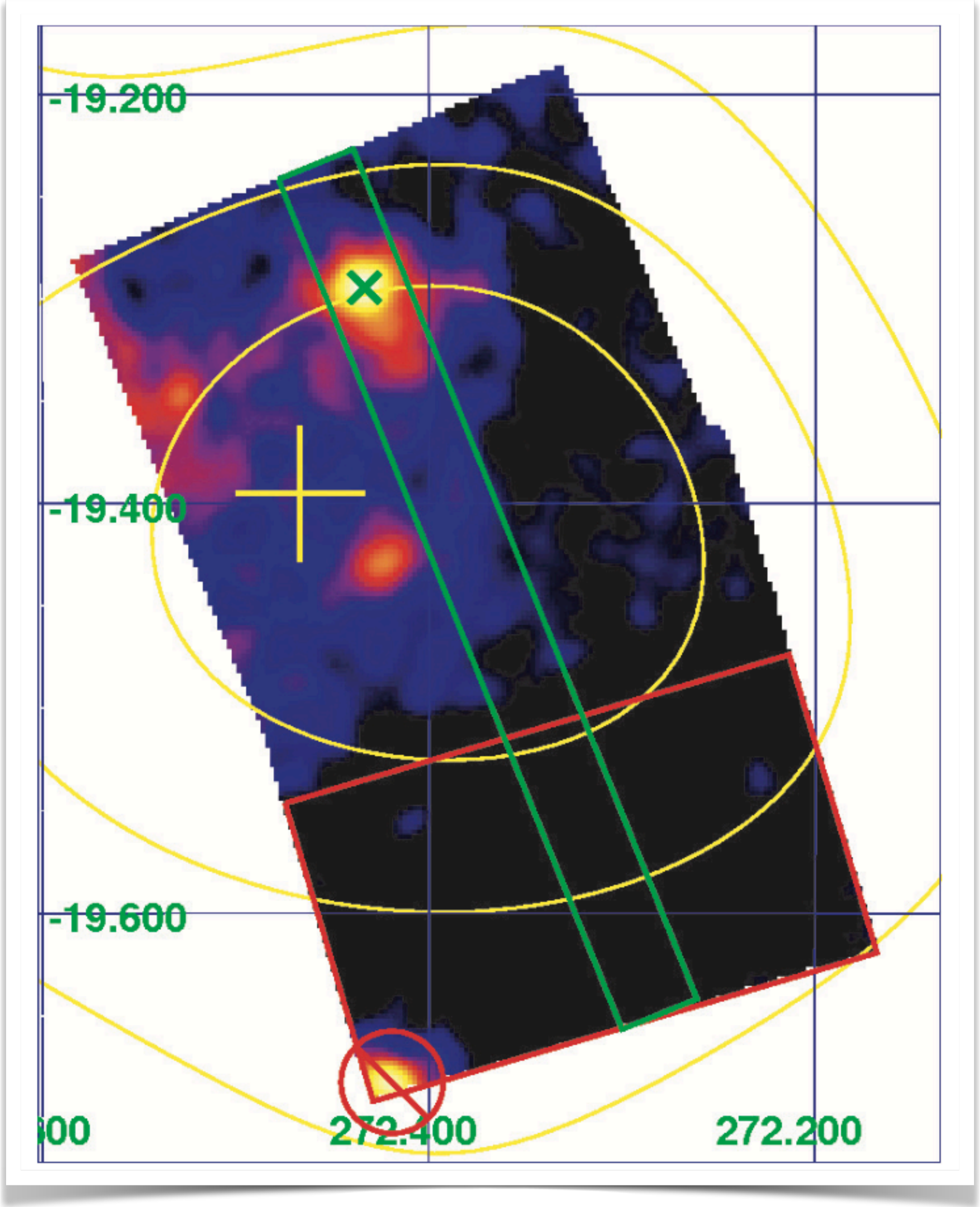
  - Supporting the leptonic/PWN scenario



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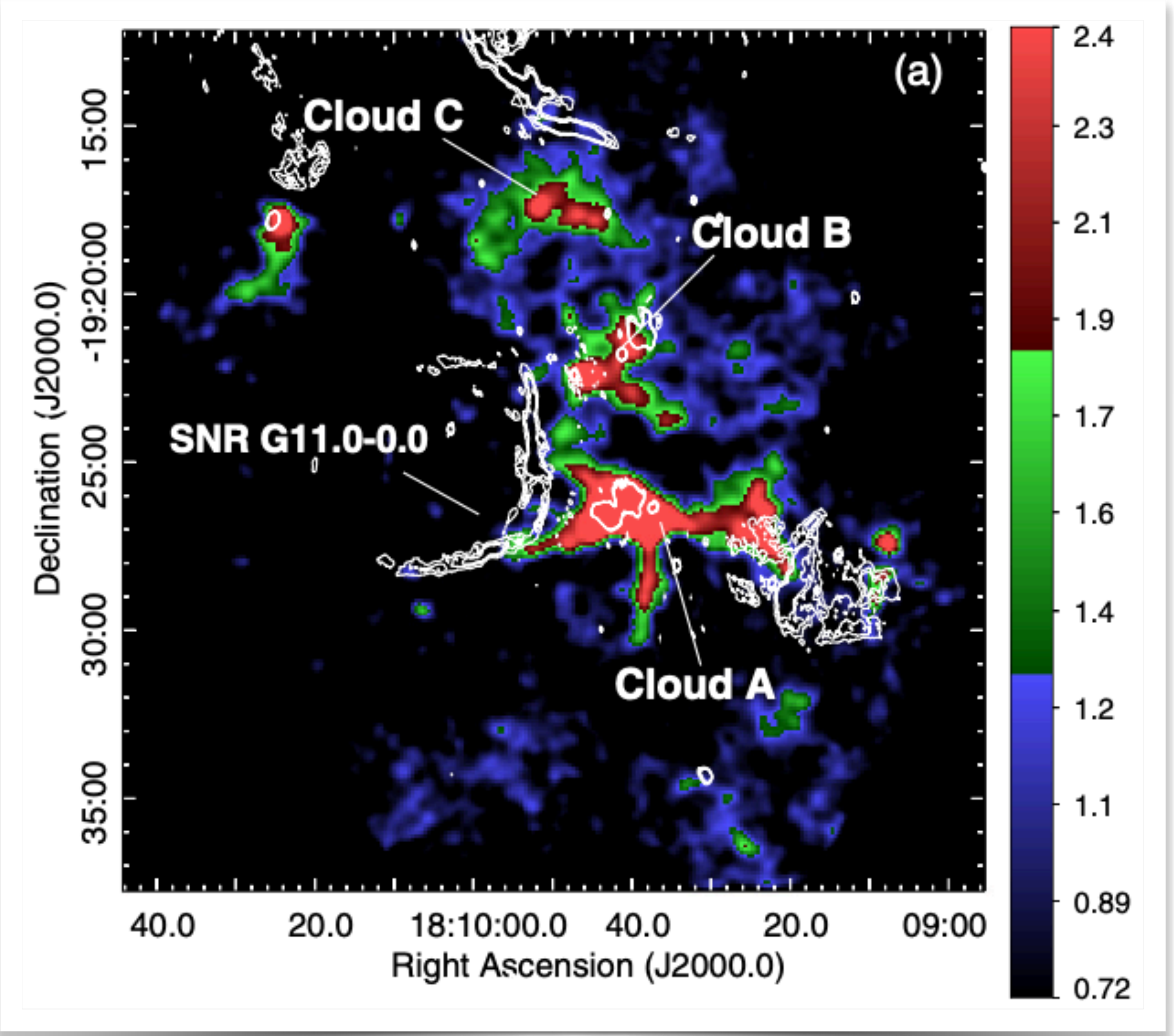
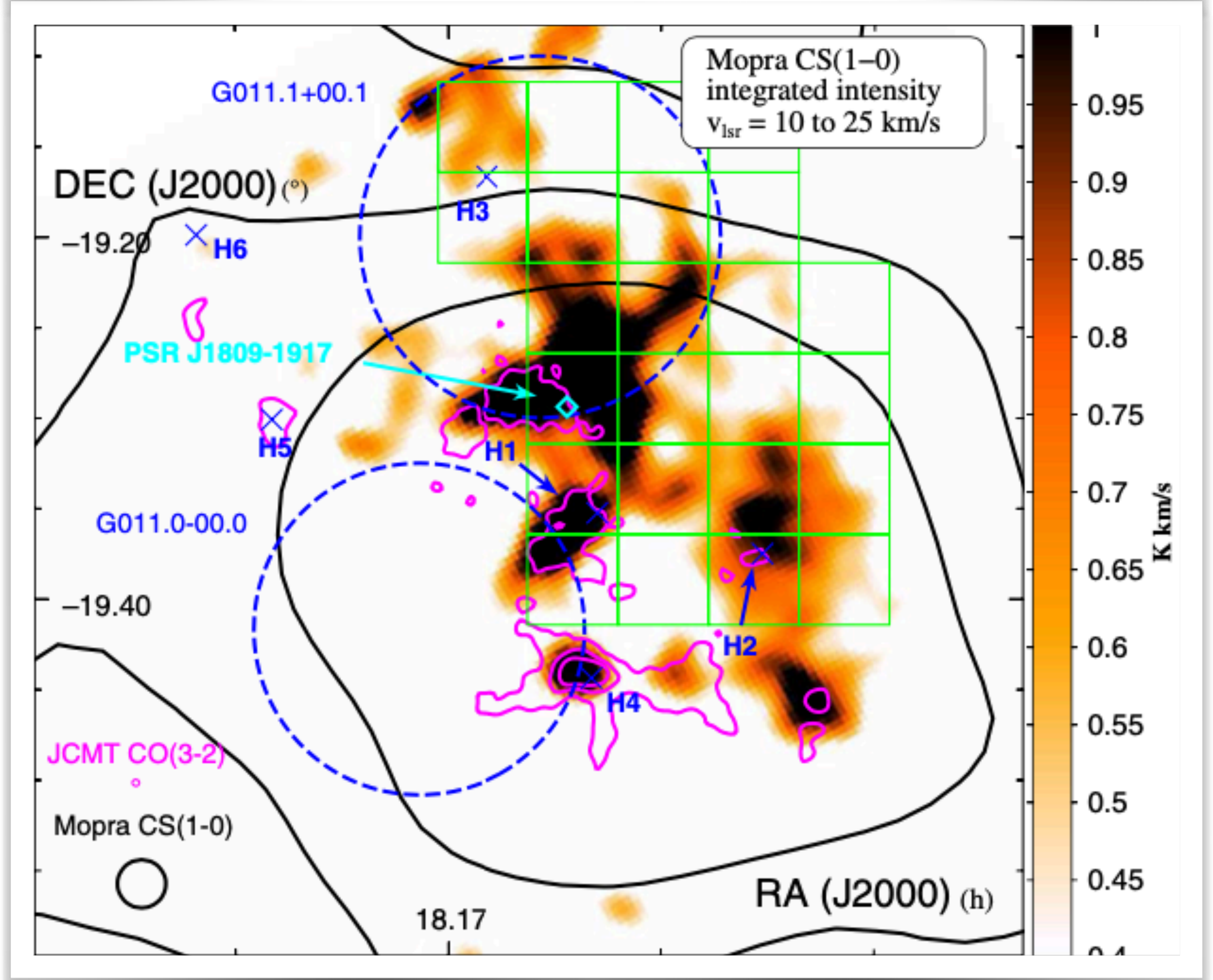
  - Distance compatible with SNR G011.0–00.0
  - Cloud densities → hadronic/SNR scenario viable!




JCMT CO(3–2)




Mopra CS(1–0)

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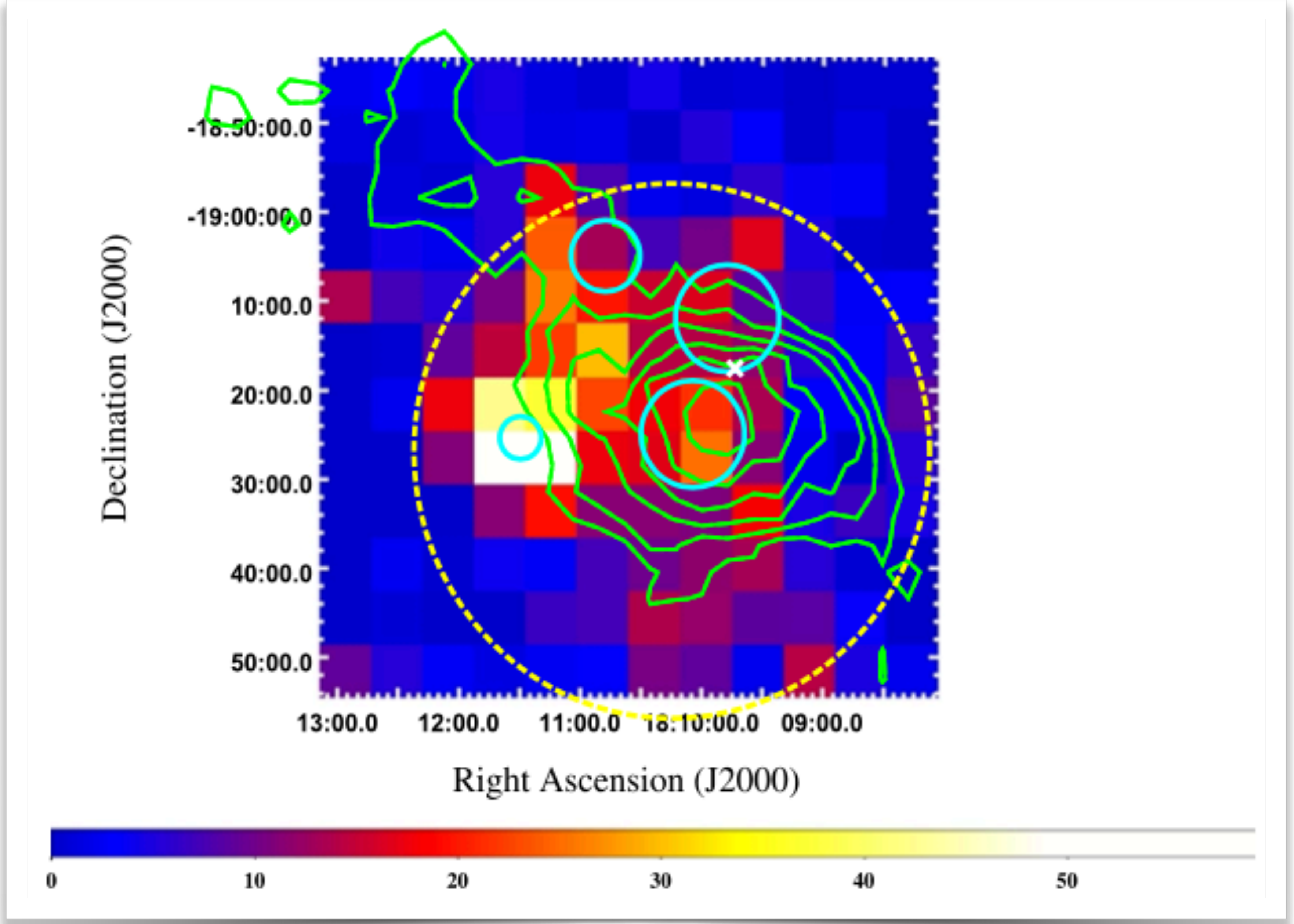


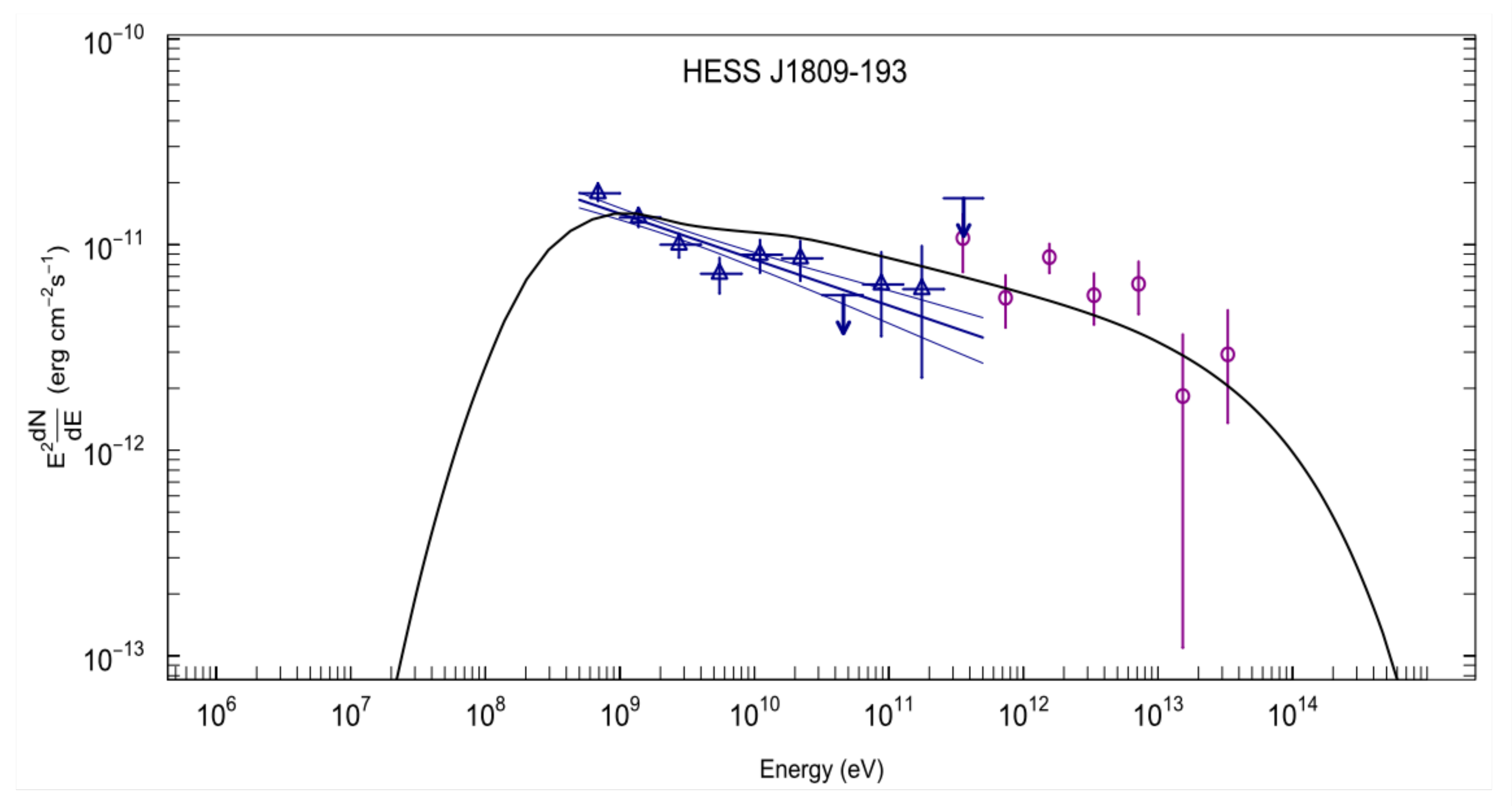

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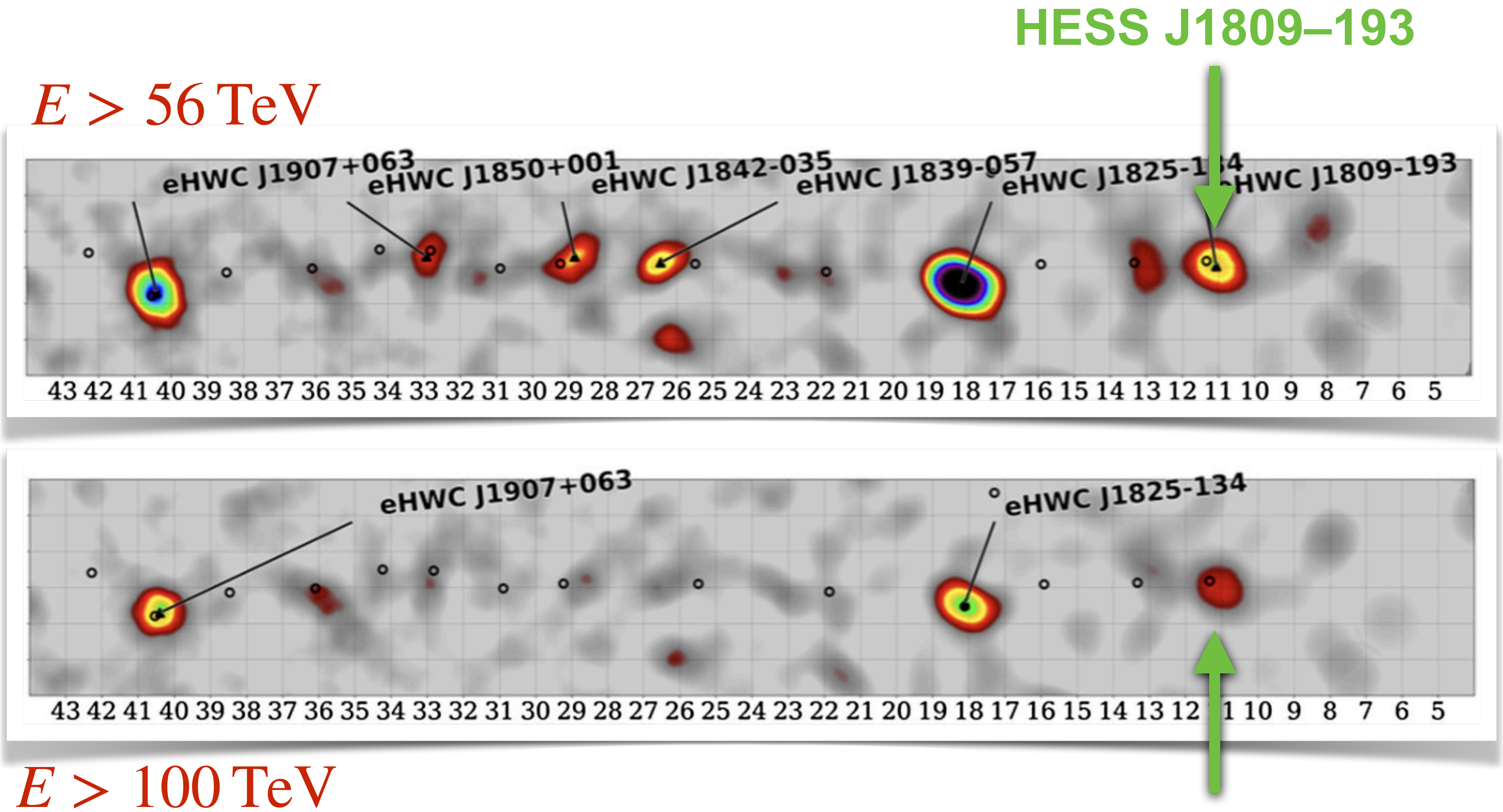
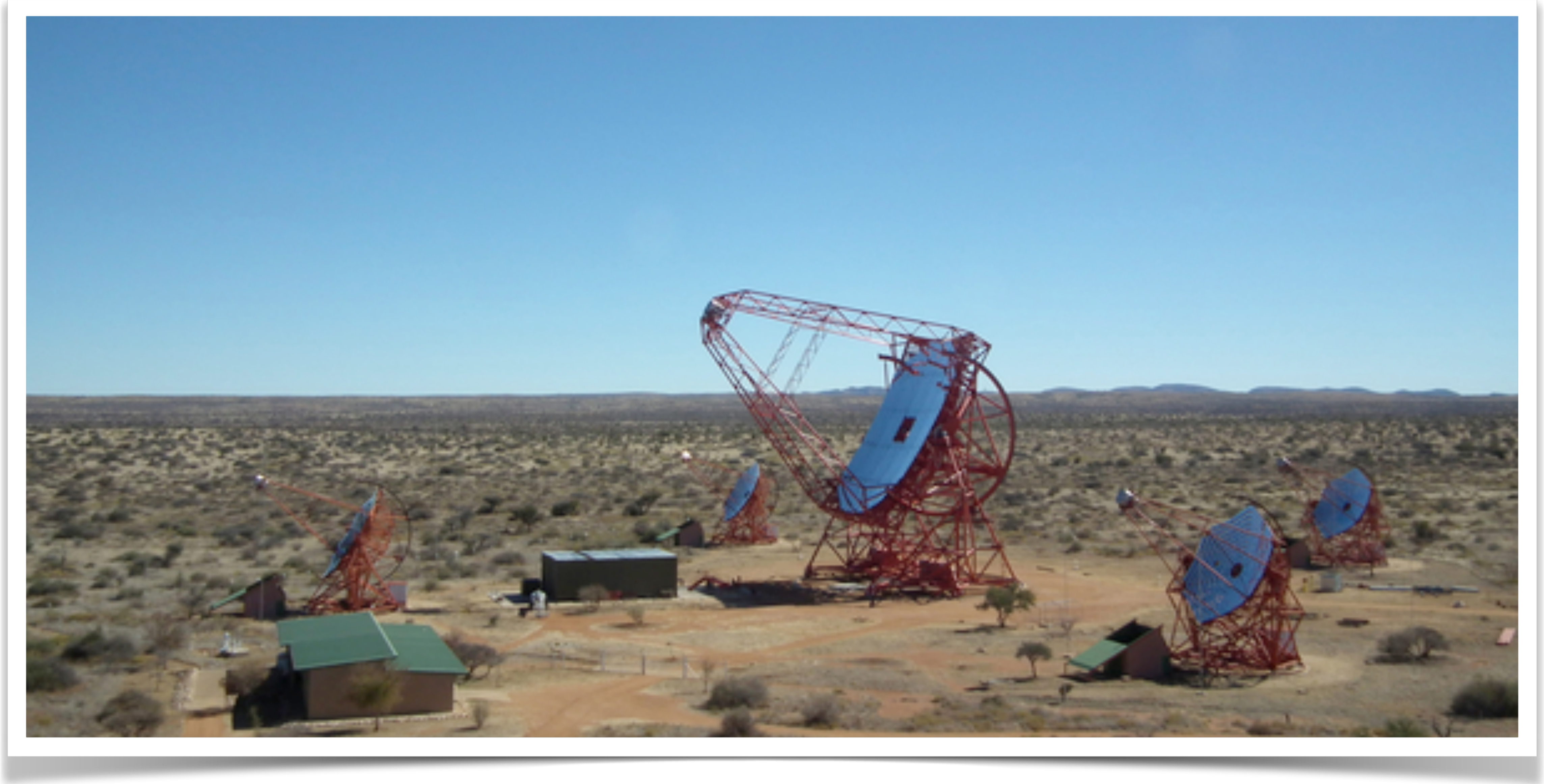
- Detailed *Fermi*-LAT study [5]
  - Is HESS J1809–193 a PeVatron?
- HAWC detection >56 TeV [6]
  - Spectrum possibly extending to beyond 100 TeV
  - Supports PeVatron hypothesis



# Revisiting HESS J1809–193 with H.E.S.S. (and *Fermi*-LAT)

- New H.E.S.S. analysis
  - 93.2h exposure (with four 12m telescopes only)
    → more than doubled since Gamma 2008 [7]
  - **Sophisticated background model**
    constructed from archival observations [8]
  - Employ **Gammapy** (v0.17) [9]
  - → **spectro-morphological (3D) likelihood analysis**
    (“*Fermi*-LAT style”)
  - Energy threshold of combined data set: 0.27 TeV

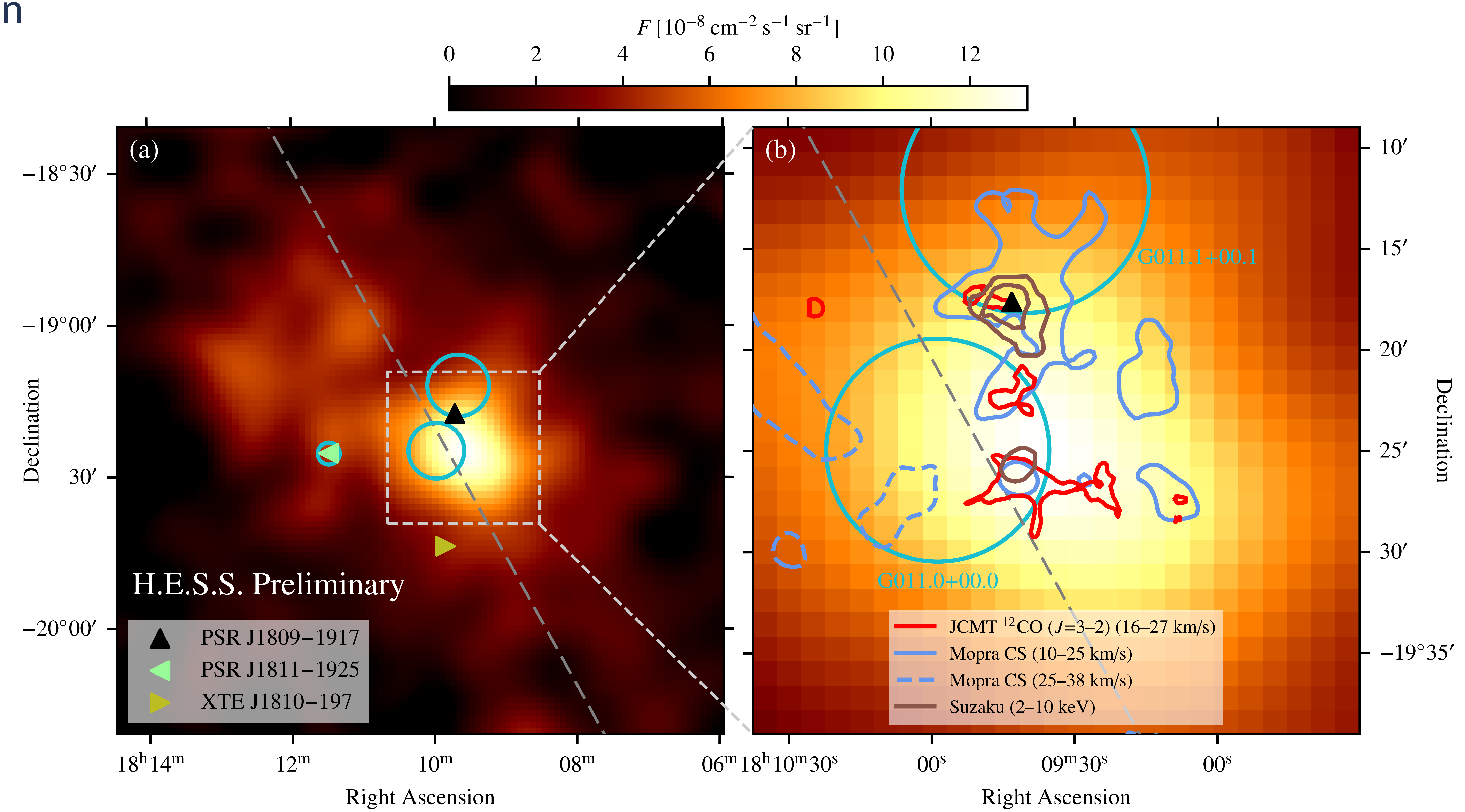


- New *Fermi*-LAT analysis
  - 12.4 years of data (until Dec. 2020)
  - ScienceTools v2.1.0 / Fermipy v1.0.1 [10]
  - Modelling consistent with H.E.S.S. analysis

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

# H.E.S.S. Flux map

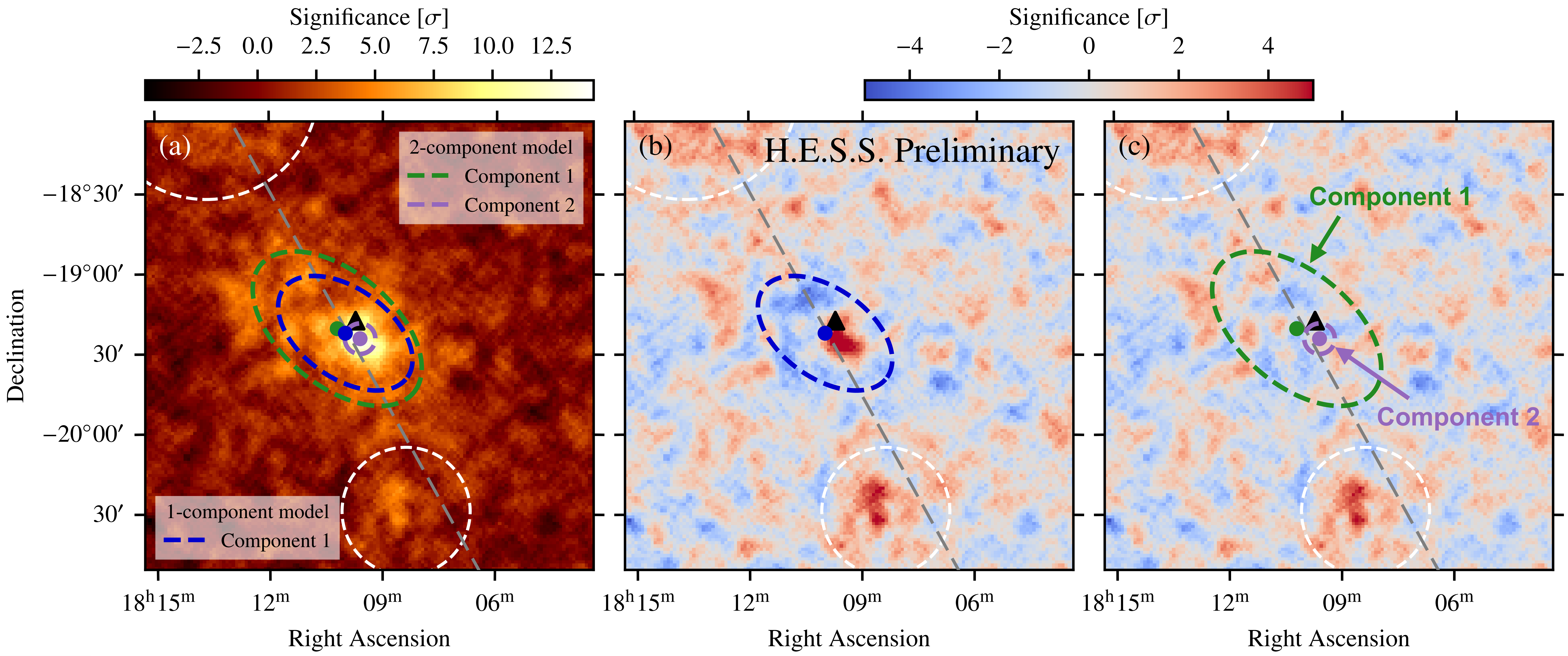
- Source morphology
  - Extended (1°-scale) emission
  - Bright peak at the centre
- Peak of emission…
  - … is slightly offset from X-ray PWN
  - … coincides with molecular clouds / shell of SNR



# Modelling the emission: spatial models

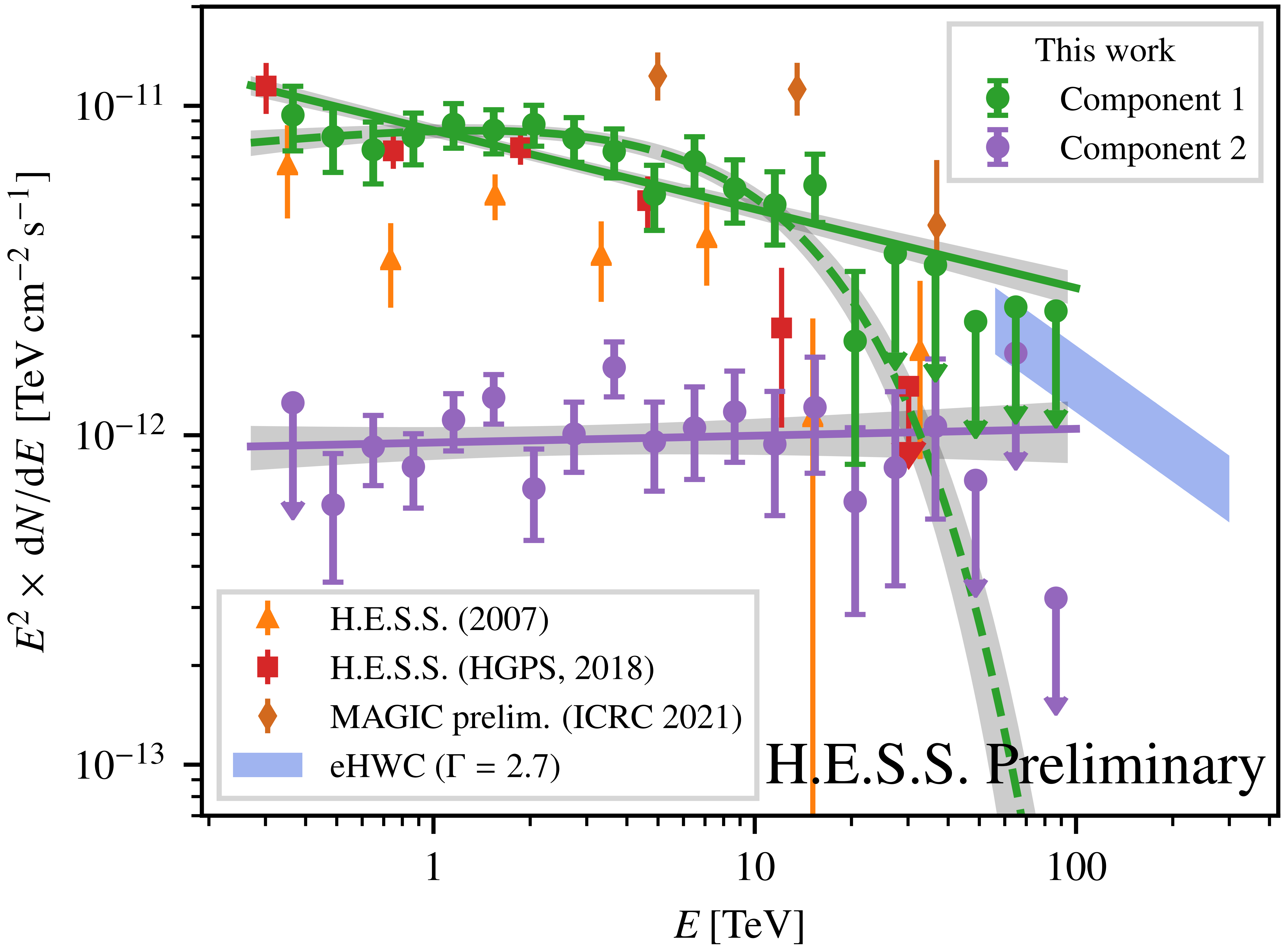
$\sigma_1 = (0.62 \pm 0.03_{stat} \pm 0.02_{sys})$ deg
$\sigma_2 = (0.095 \pm 0.007_{stat} \pm 0.003_{sys})$ deg

- 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 of data! (preferred by 13.3σ)



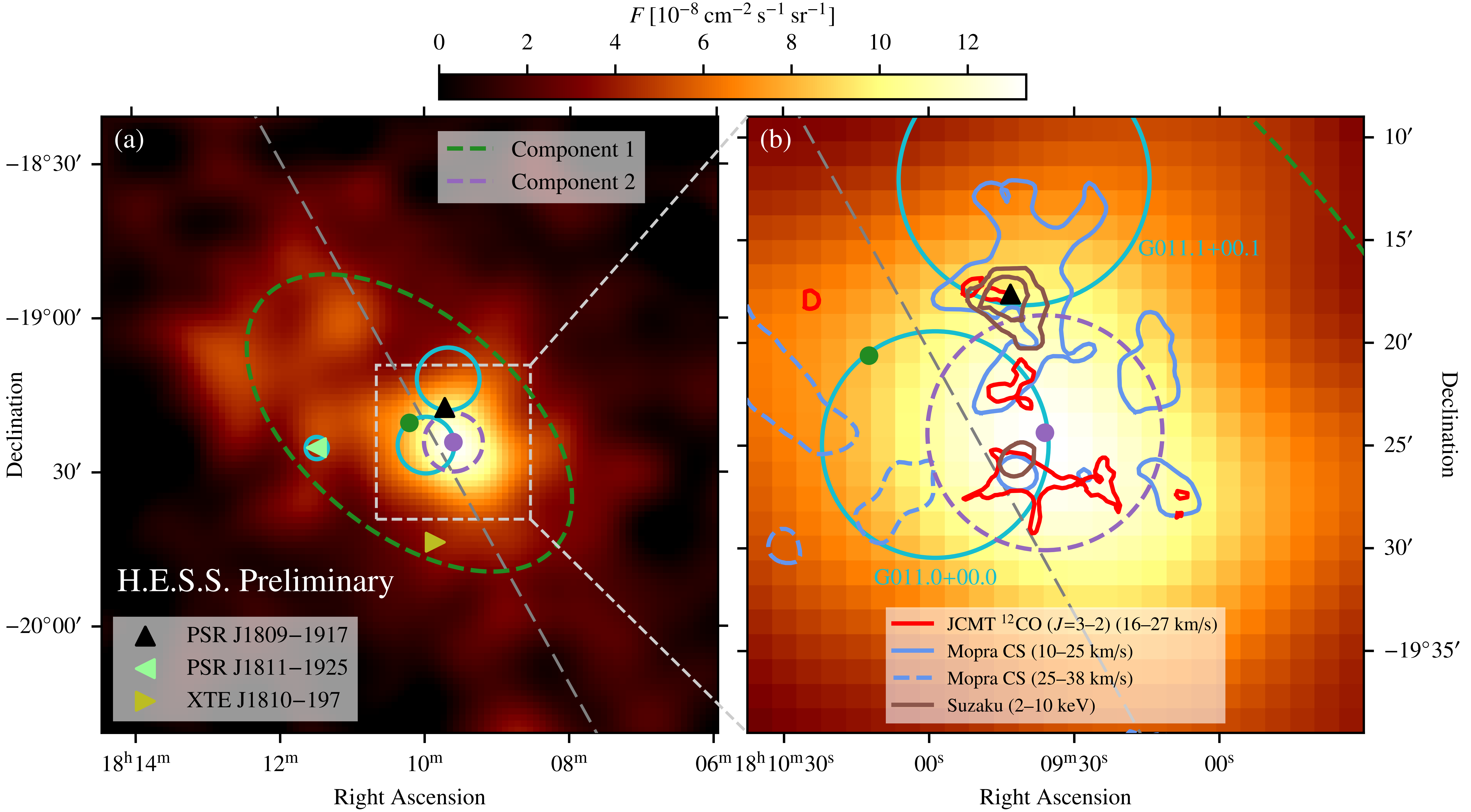
# Modelling the emission: spectral models

- Component 1
  - Power law (PL) or
    Power law with exponential cut-off (ECPL)
  - PL model
    - $\Gamma = 2.24 \pm 0.03_{\mathrm{stat}} \pm 0.02_{\mathrm{sys}}$
  - ECPL model (preferred by 8σ)
    - $\Gamma = 1.90 \pm 0.05_{\mathrm{stat}} \pm 0.05_{\mathrm{sys}}$
    - $E_c = \left(12.7\,^{+2.7}_{-2.1}\Big|_{\mathrm{stat}}\,^{+2.6}_{-1.9}\Big|_{\mathrm{sys}}\right)$ TeV
- Component 2
  - PL model
    - $\Gamma = 1.98 \pm 0.05_{\mathrm{stat}} \pm 0.03_{\mathrm{sys}}$
  - ECPL model not significantly preferred
    (+ would require even harder index)



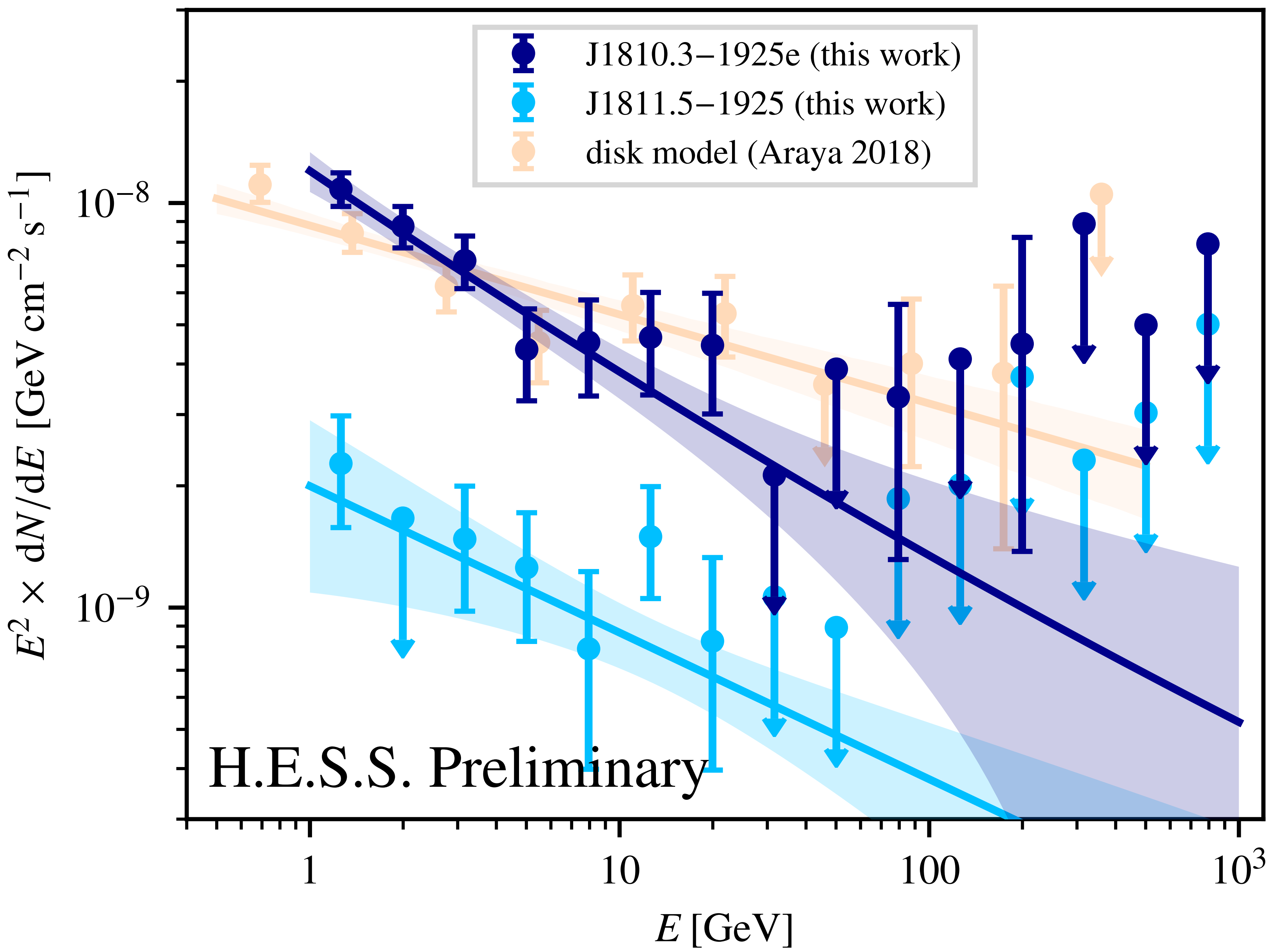
# Flux map with H.E.S.S. models

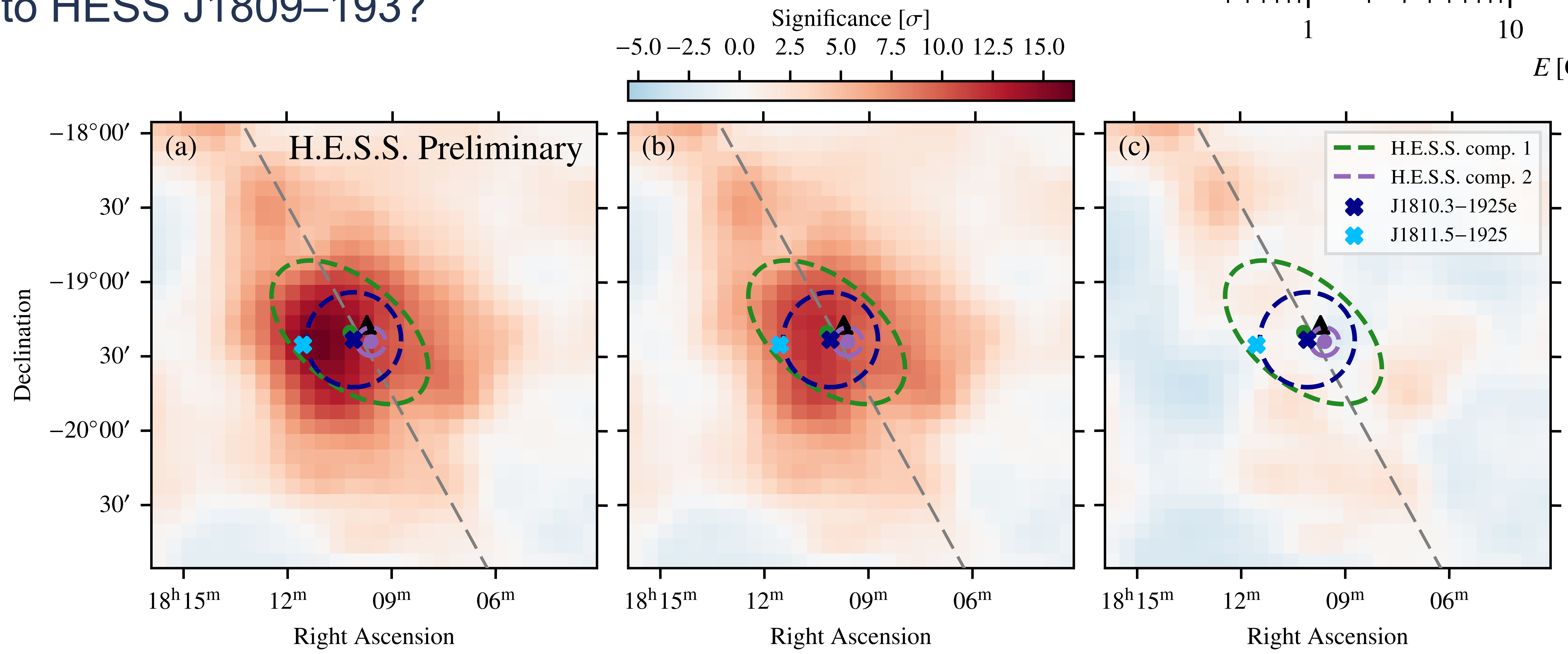
- Component 1 describes extended emission
  - centre point offset from peak of emission
- Component 2 describes bright peak
  - coincides with molecular clouds / shell of SNR
  - Also overlaps with X-ray PWN



# *Fermi*-LAT analysis results

- 4FGL J1811.5–1925
  - Point source
  - Connected to PSR J1811–1925
- 4FGL J1810.3–1925e
  - Extended emission, morphology similar to H.E.S.S. comp. 1
  - Counterpart to HESS J1809–193?

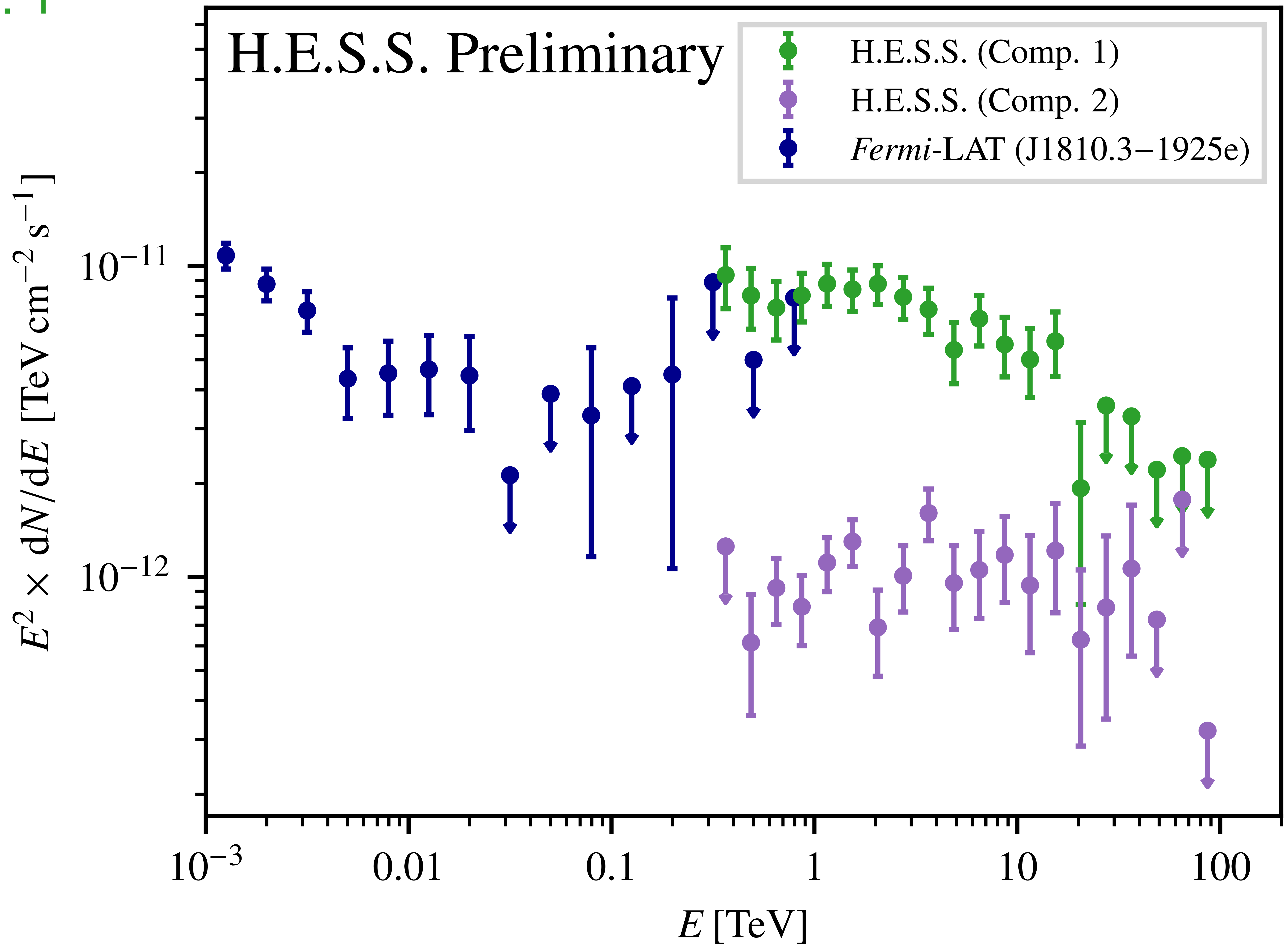


# Combined *Fermi*-LAT & H.E.S.S. spectrum

- Spatial models suggest that H.E.S.S. comp. 1 and J1810.3–1925e are connected
  - Requires a spectral break around 0.1 TeV!

- Spectra of H.E.S.S. comp. 2 and J1810.3–1925e connect more smoothly
  - But a spectral break is still required
  - Also: *Fermi*-LAT source much more extended than H.E.S.S. component!



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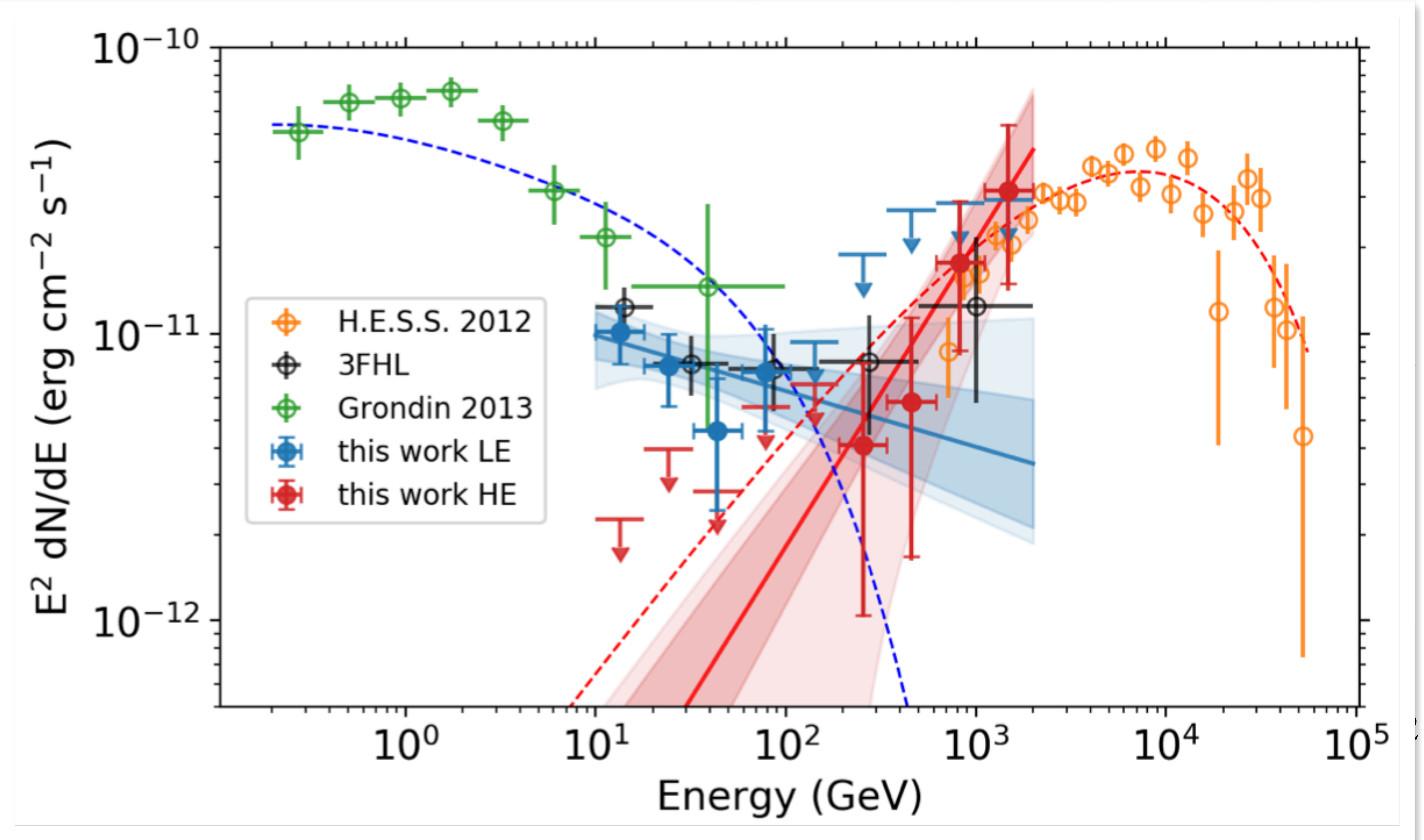
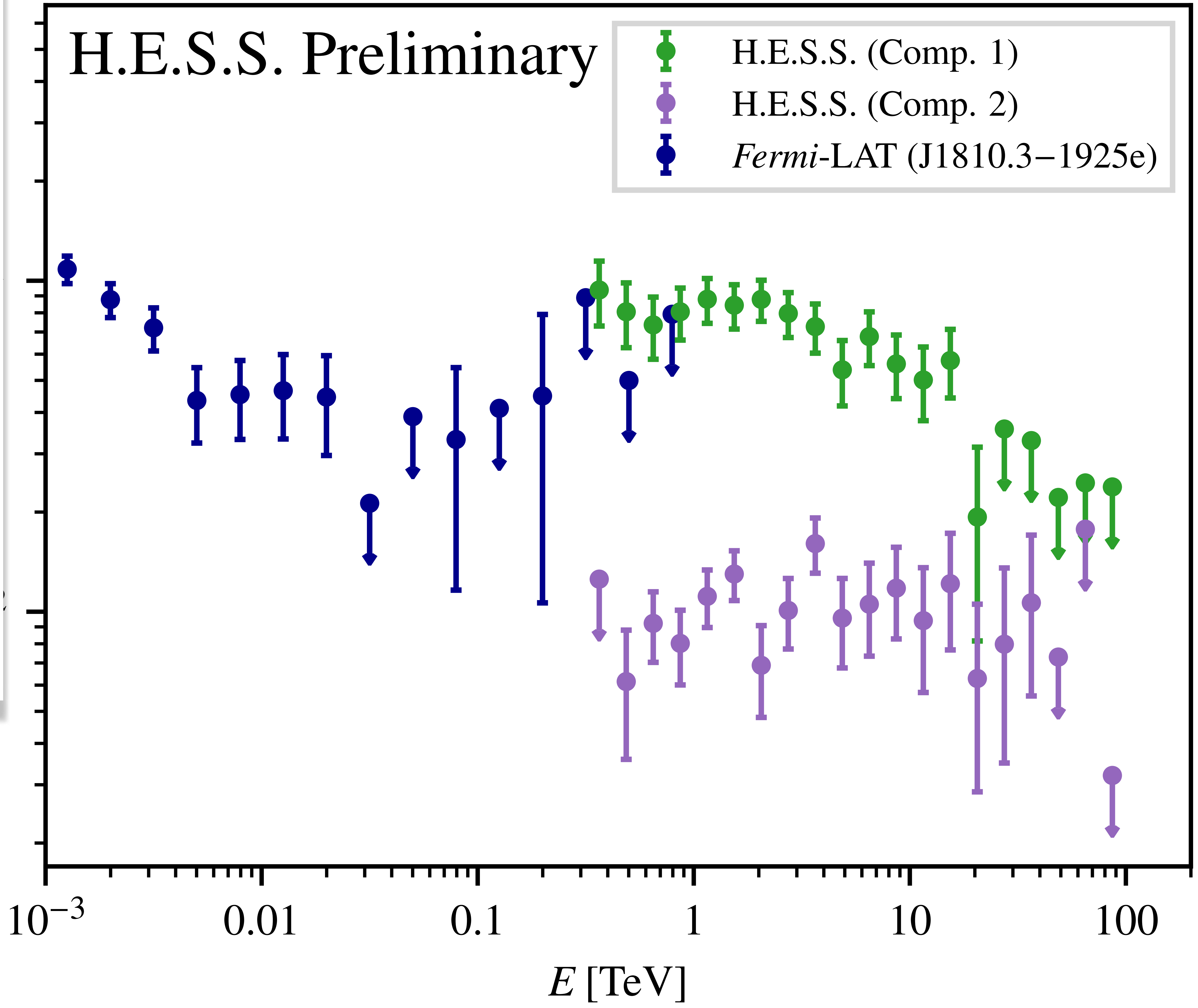


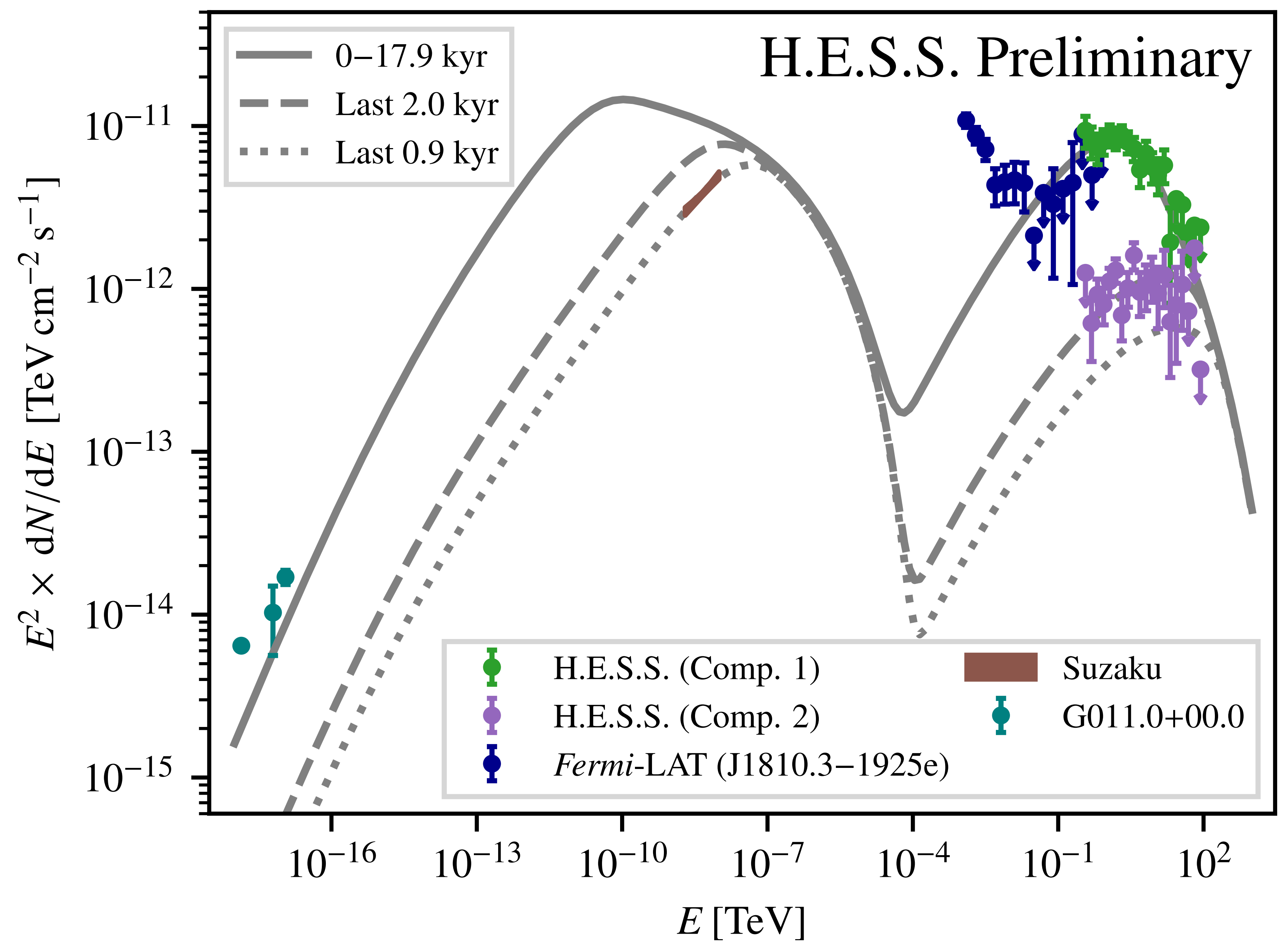

- Reminiscent of Vela X…?! [11]

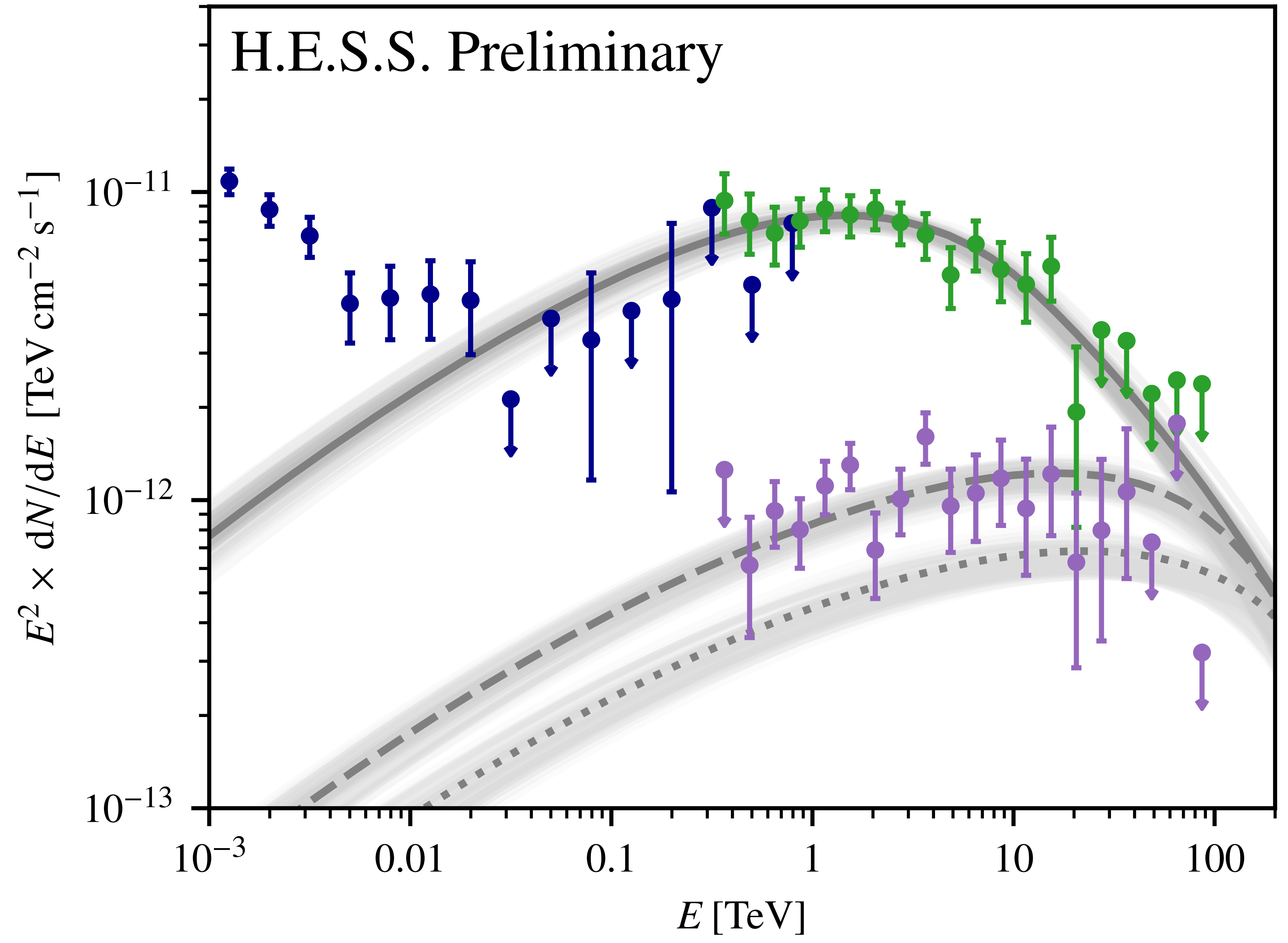
# Interpretation: PWN model

- Modelling performed with GAMERA library [12]
  - Time-evolved spectral modelling of non-thermal radiation

- 3 generations of electrons
  - Halo of “relic” electrons (20 kyr) → H.E.S.S. component 1
  - Recently (< 2 kyr) injected electrons → H.E.S.S. component 2
  - Youngest (< 1 kyr) electrons → X-ray nebula

- *Fermi*-LAT data below 10 GeV unexplained
  - 4th electron generation, even older???
  - Hadronic emission related to molecular clouds / SNR?
    - Extent of *Fermi*-LAT emission unexpectedly large



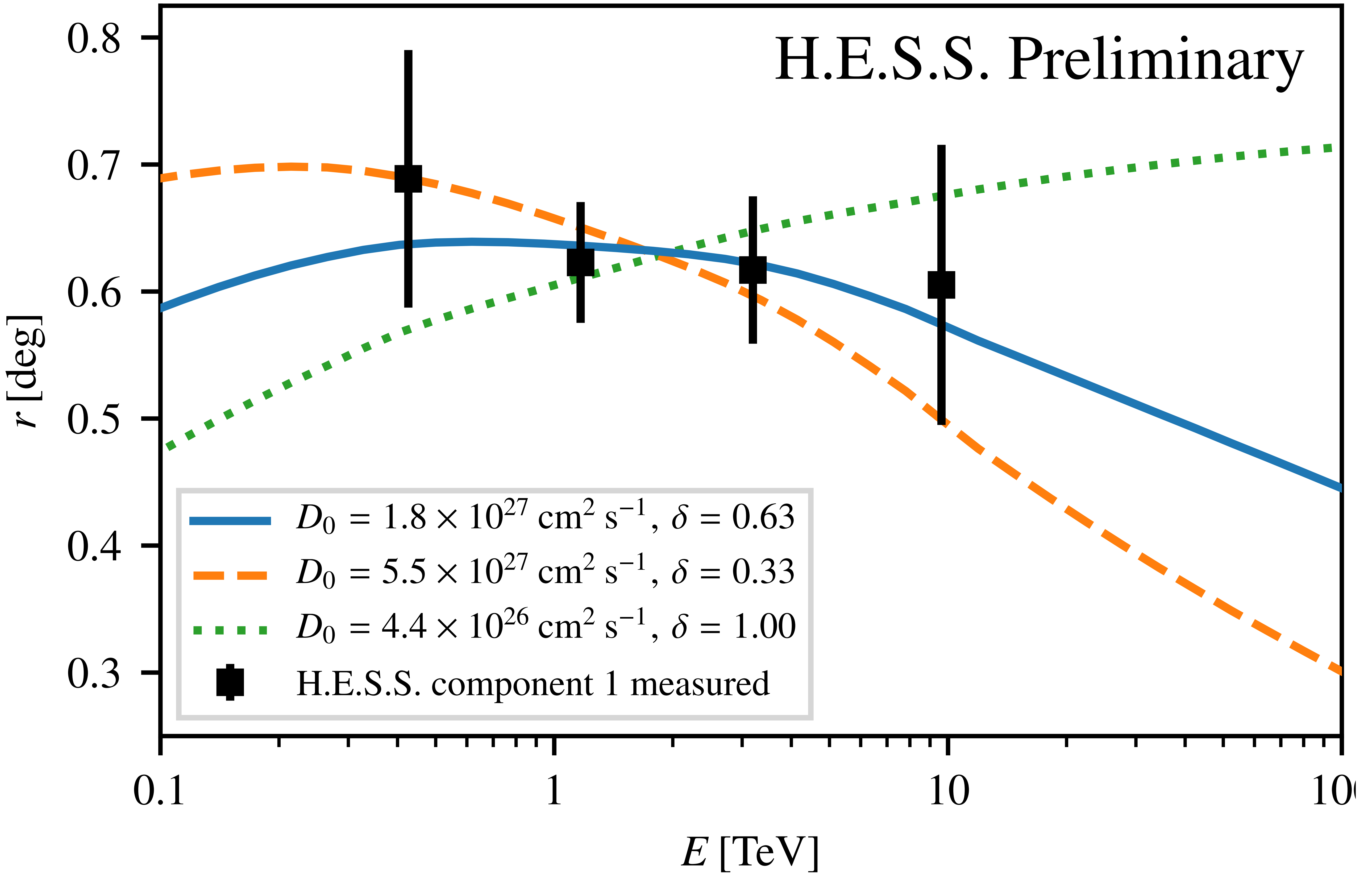



# Interpretation: PWN model — spatial extent

- Assume "relic" electrons started propagating 20 kyr ago (age of system)

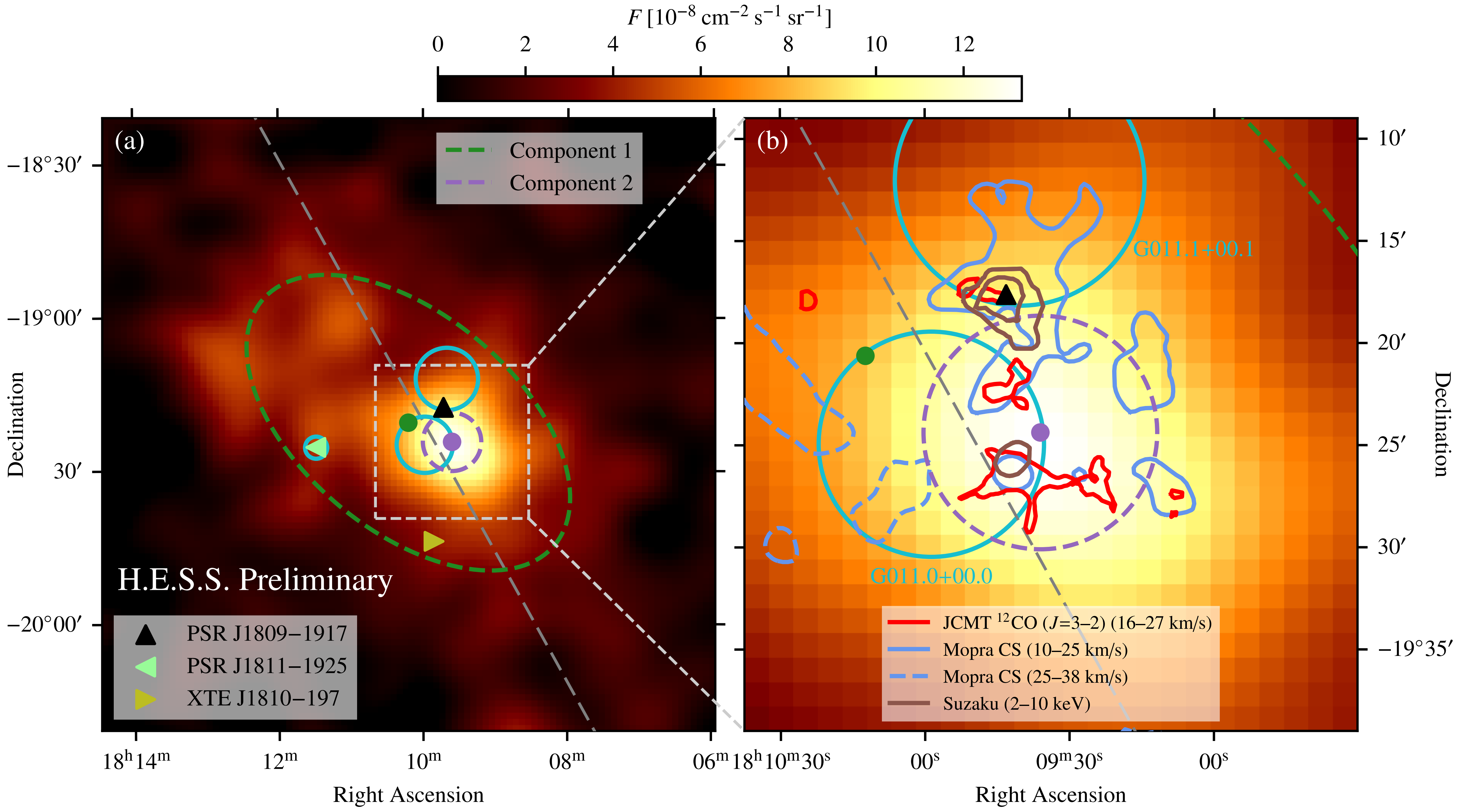
- Compute expected size of halo as a function of $\gamma$-ray energy
  - Compare with extent of emission as measured for H.E.S.S. component 1
  - Good match for $D_0 = 1.8 \times 10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$, $\delta = 0.63$ → well compatible e.g. with Geminga case

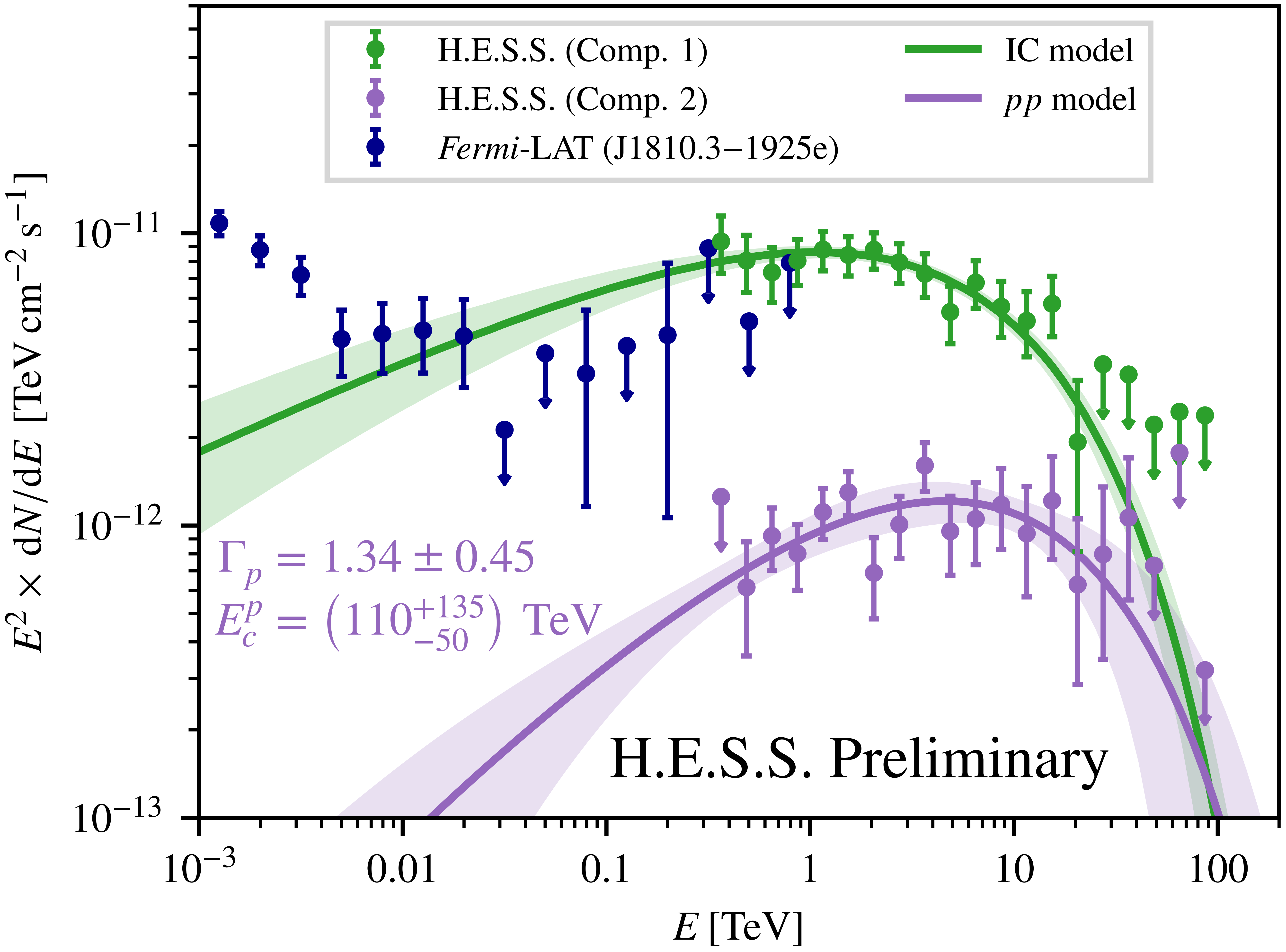
- Highest-energy electrons have cooled away
  - Expect cut-off in $\gamma$-ray spectrum
  - …as observed for H.E.S.S. component 1!



# Alternative: PWN + SNR model?

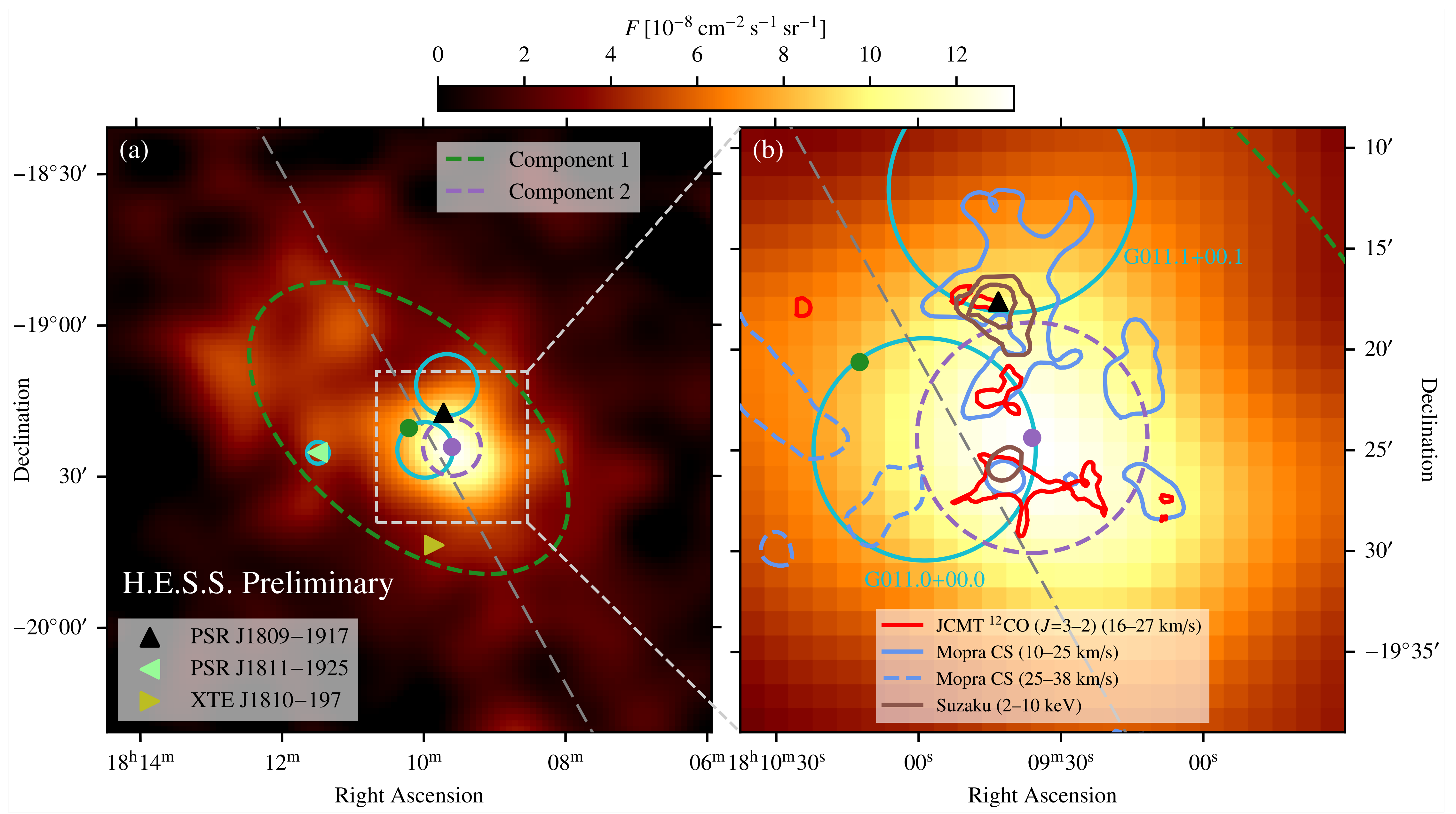
- H.E.S.S. component 2
  - Overlaps with molecular clouds / shell of SNR → hadronic origin?
  - Fit hadronic *pp* model with naima [13]
  - Required energy in protons: $W_p \sim 4 \times 10^{49}\,(n/1\,\mathrm{cm}^{-3})^{-1}\,\mathrm{erg}$

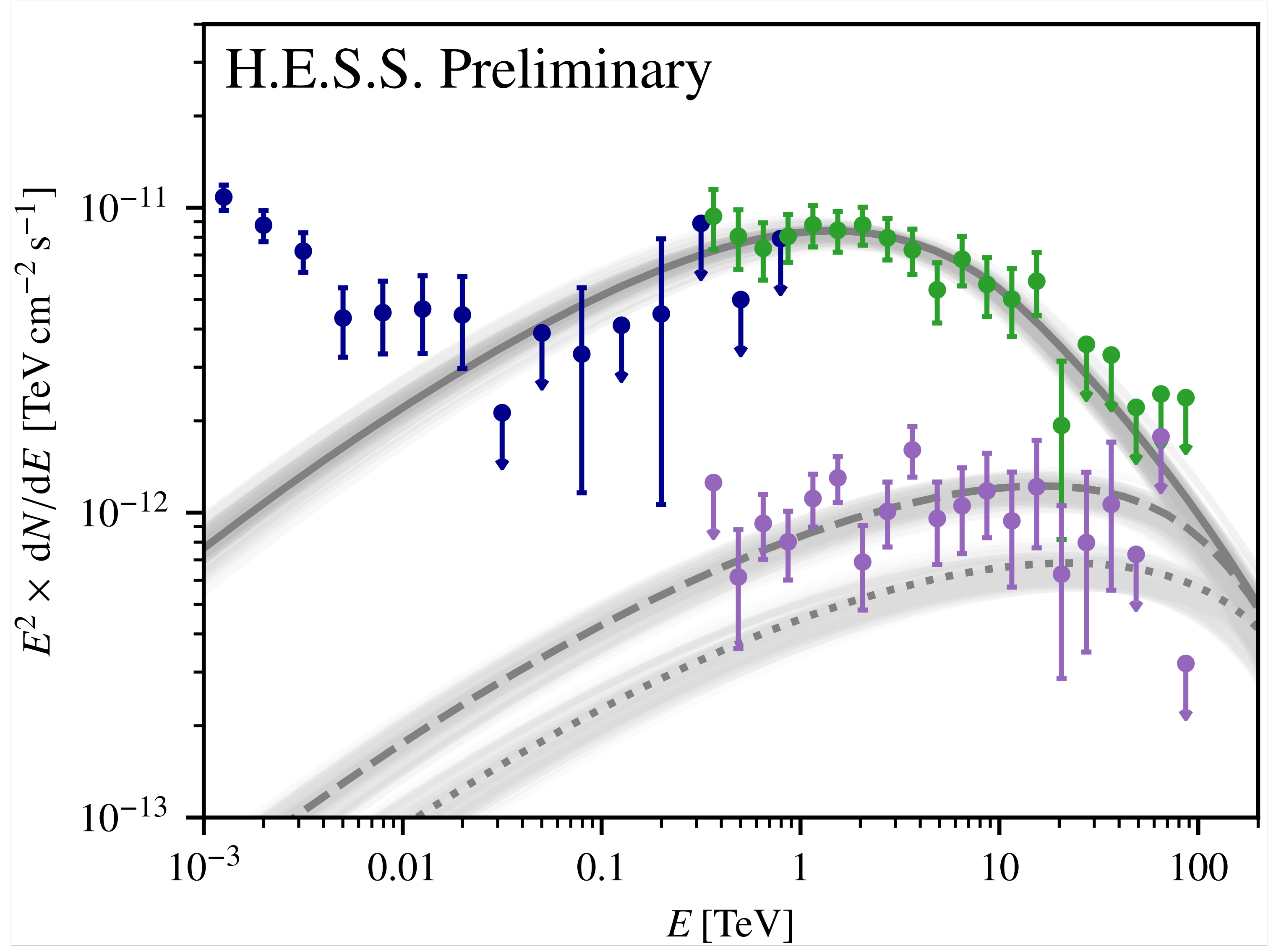


# Conclusion

- New H.E.S.S. analysis of HESS J1809–193
  - Resolved two components with distinct morphologies and energy spectra
- New *Fermi*-LAT analysis
  - Confirming extended emission, arguably connected with HESS J1809–193
- Complex environment → interpretation challenging!
  - Extended H.E.S.S. component compatible with a halo of “relic” electrons (cf. Vela X)
  - Origin of compact H.E.S.S. component & relation to *Fermi*-LAT emission unclear
- Watch out for the paper soon!



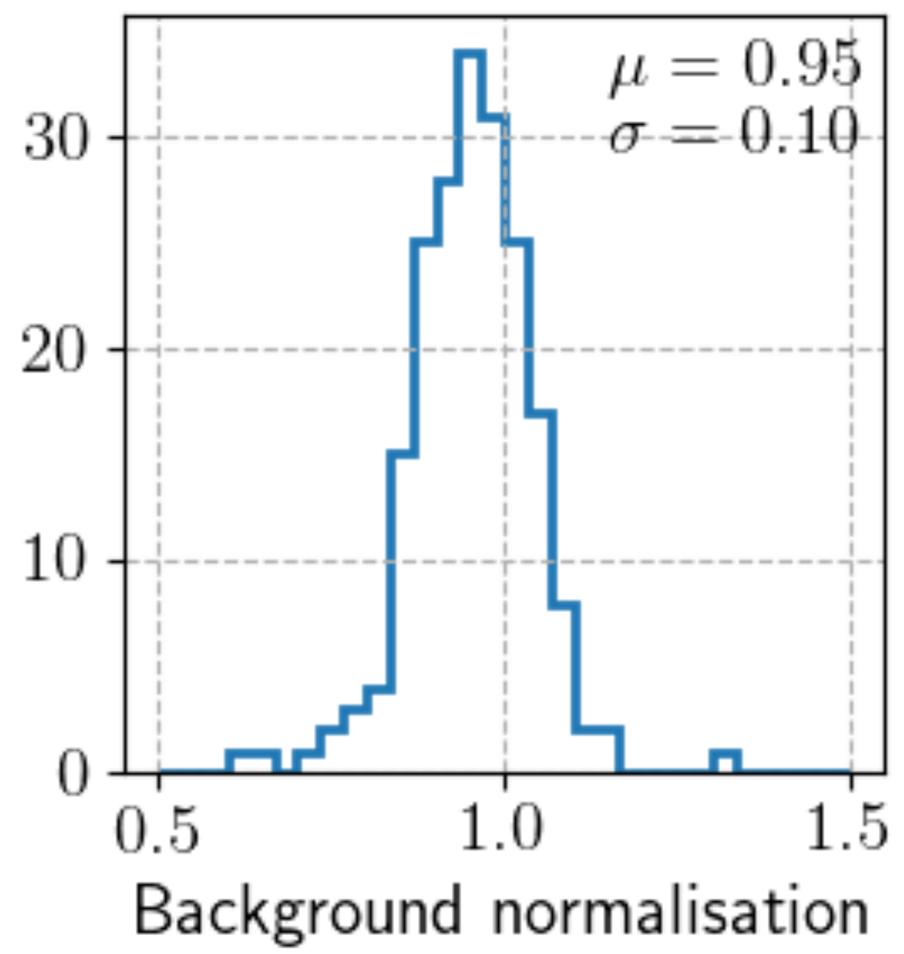
# References

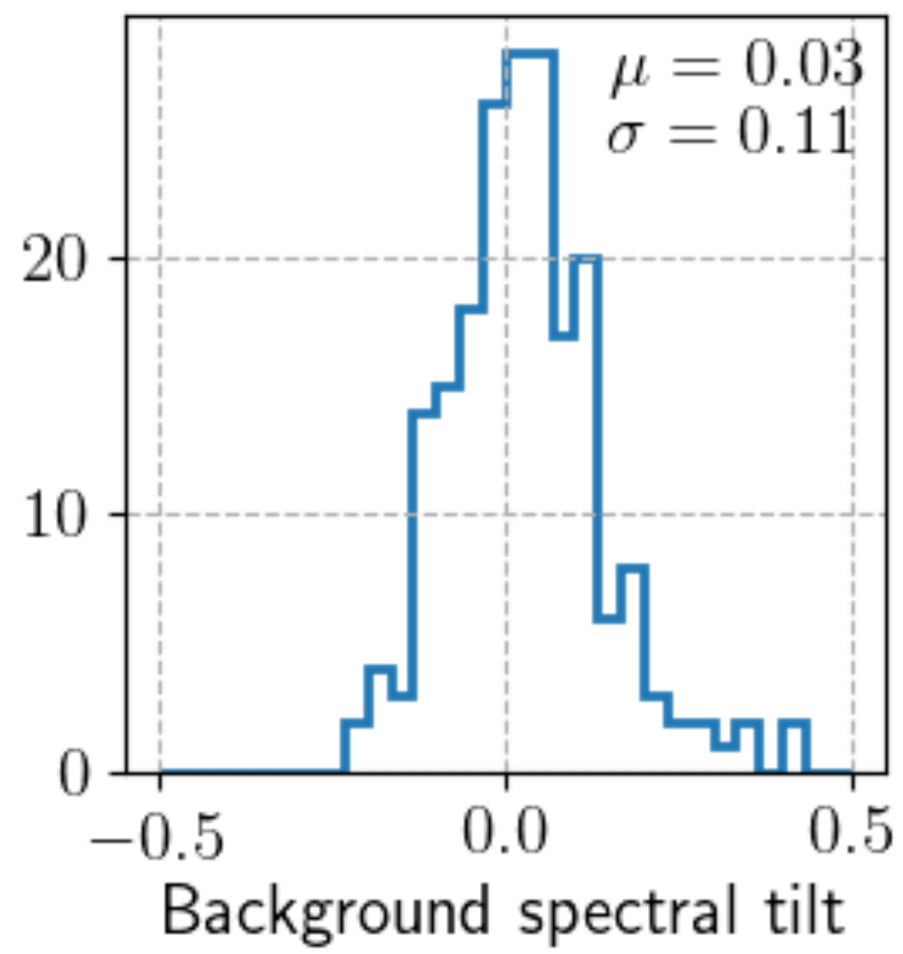

- [1] Aharonian et al., A&A **472**, 489 (2007) [arXiv:0705.1605]
- [2] Anada et al., PASJ **62**, 179 (2010) [arXiv:0912.1931]
- [3] Castelletti et al., A&A **587**, A71 (2016) [arXiv:1601.04962]
- [4] Voisin et al., PASA **36**, e014 (2019) [arXiv:1905.04517]
- [5] Araya, ApJ **859**, 69 (2018) [arXiv:1804.03325]
- [6] Abeysekara et al., PRL **124**, 021102 (2020) [arXiv:1909.08609]
- [7] Renaud et al., AIP Conf. Proc. **1085**, 285 (2008) [arXiv:0811.1559]
- [8] Mohrmann et al., A&A **632**, A72 (2019) [arXiv:1910.08088]
- [9] Deil et al., Proc. 35th Int. Cosmic Ray Conf. (**ICRC2017**), ID 766 [arXiv:1709.01751], https://gammapy.org
- [10] Wood et al., Proc. 35th Int. Cosmic Ray Conf. (**ICRC2017**), ID 824 [arXiv:1707.09551]
- [11] Tibaldo et el., A&A **617**, A78 (2018) [arXiv:1806.11499]
- [12] Hahn, Proc. 34th Int. Cosmic Ray Conf. (**ICRC2015**), ID 917, http://libgamera.github.io/GAMERA
- [13] Zabalza, Proc. 34th Int. Cosmic Ray Conf. (**ICRC2015**), ID 922, https://naima.readthedocs.io

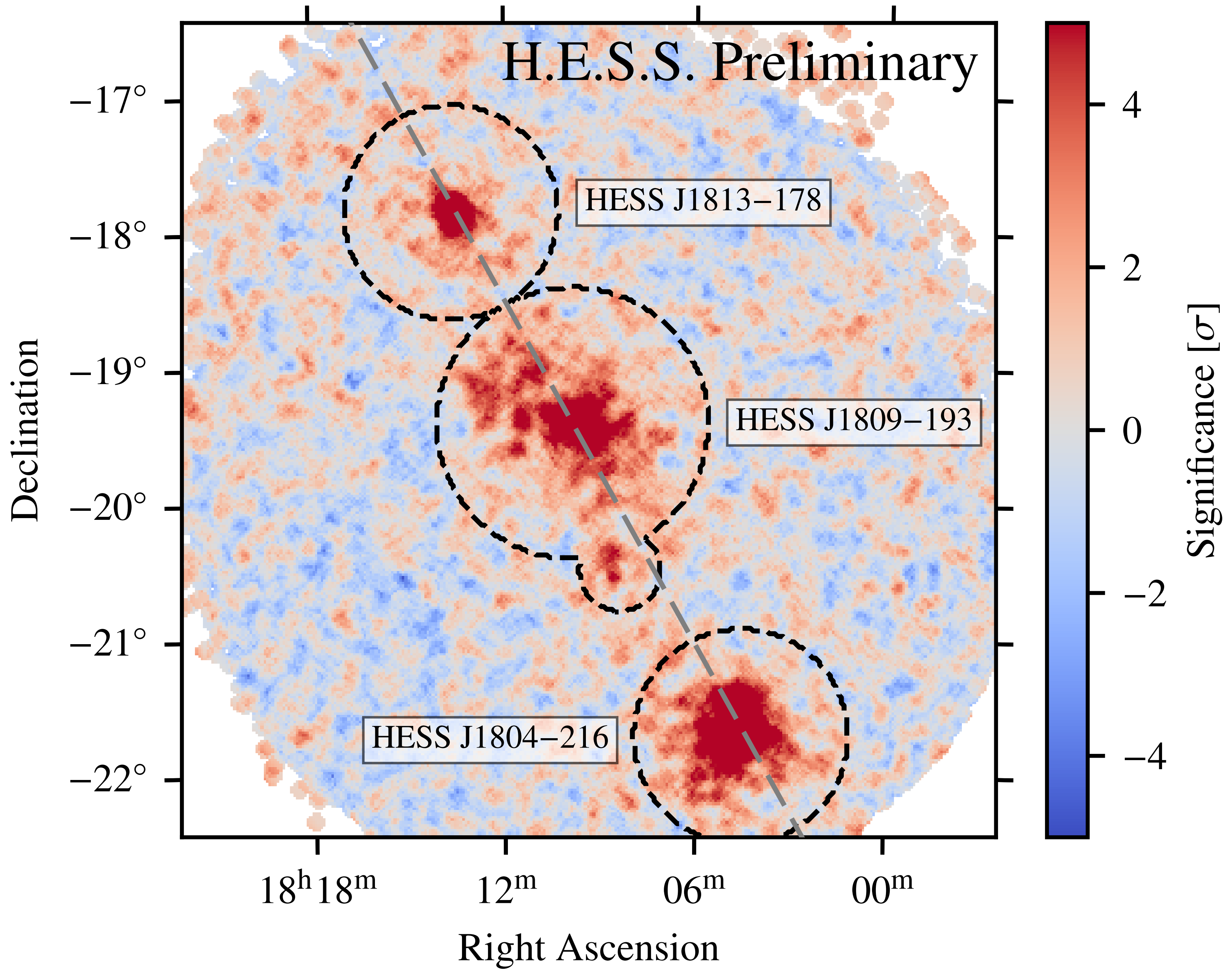
# Backup slides

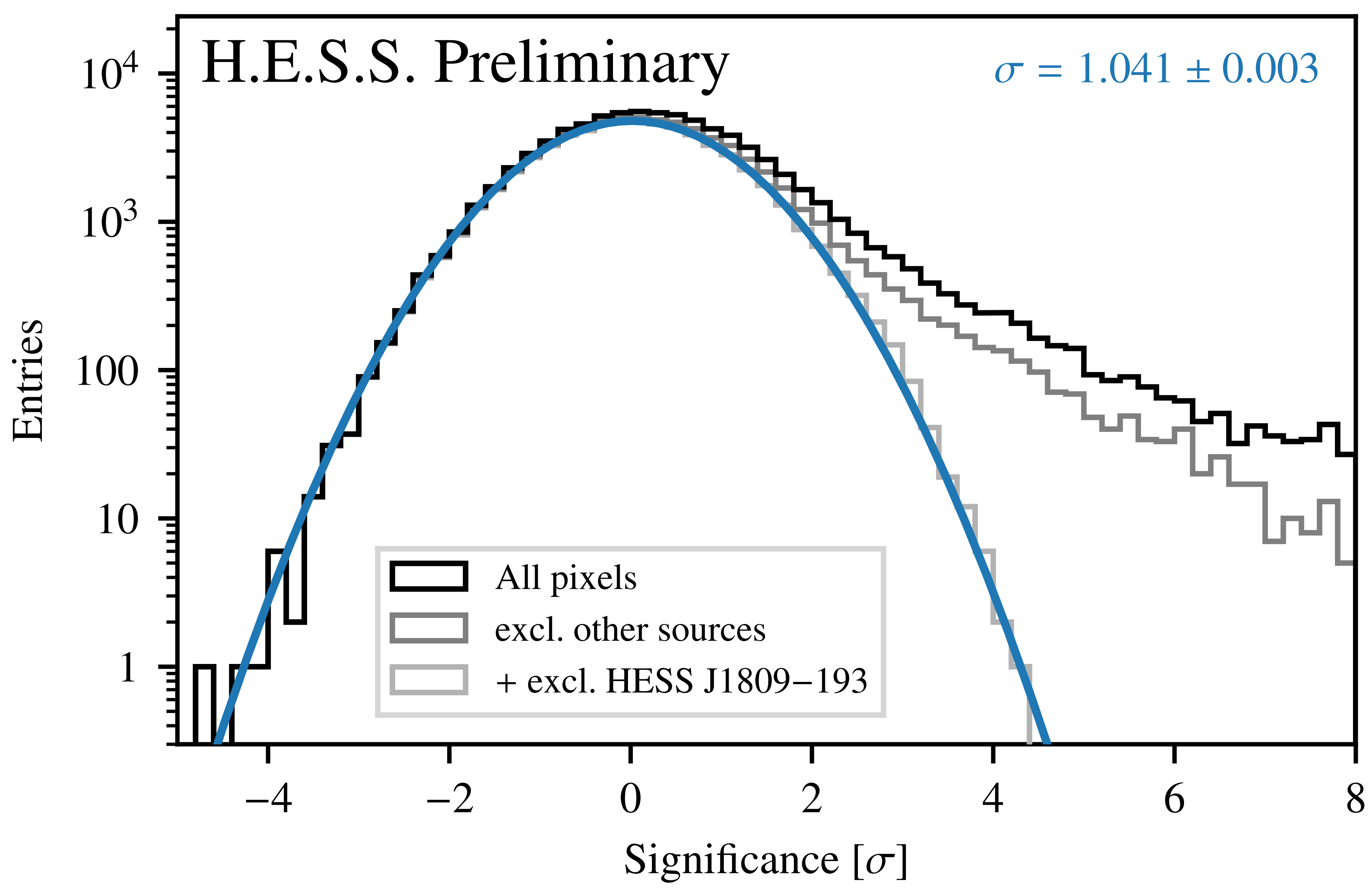
# Fit of hadronic background model

- Exclude regions with significant gamma-ray emission
- Fit normalisation + spectral tilt of background model for each observation run
- “Stack” observed counts / background model prediction for all observation runs → study residuals
- Very good description outside the exclusion regions!



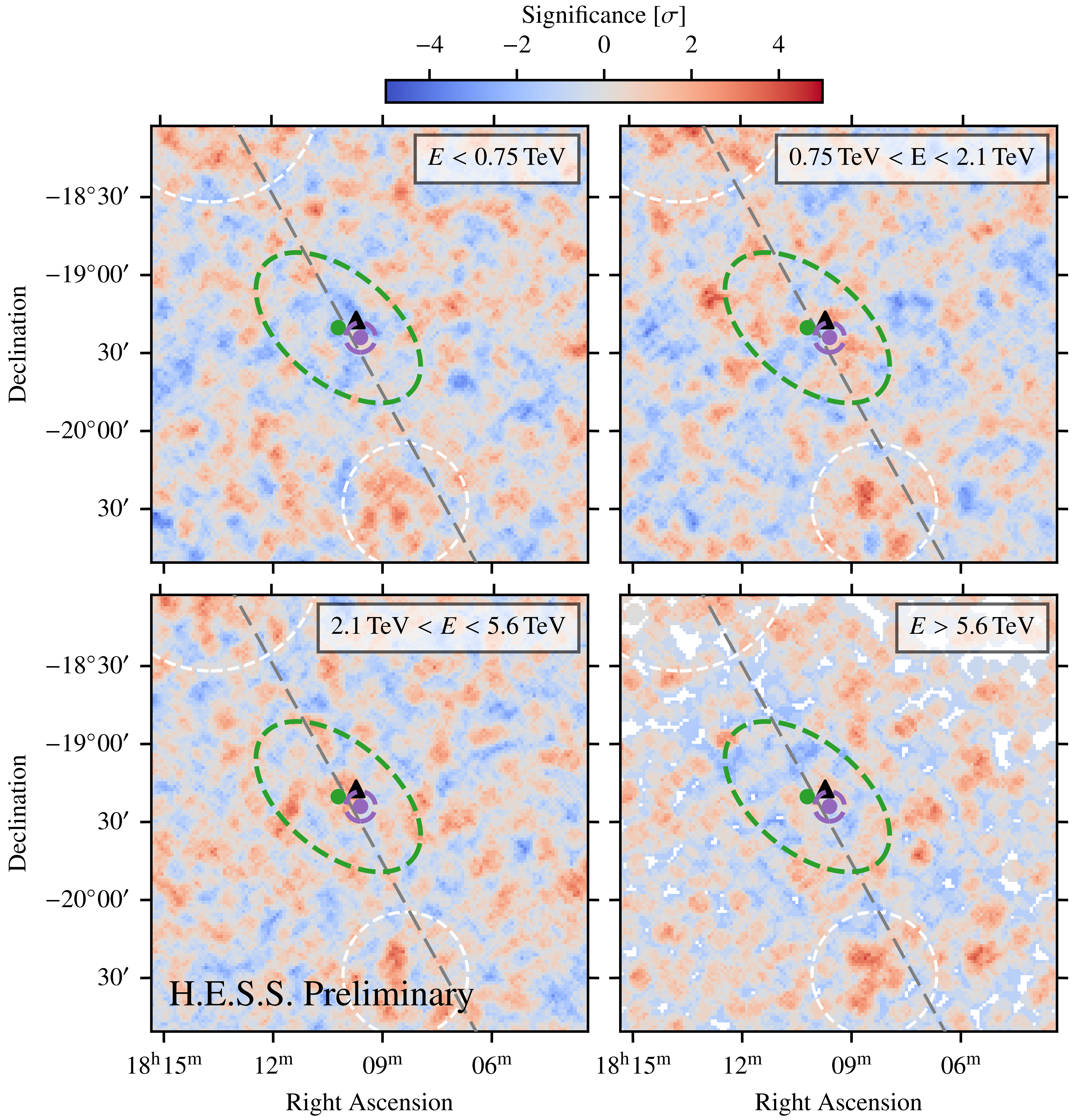



# 2-component model — significance maps for energy bands

- No strong residuals in any of the maps
- 2-component model is a good fit across all energies!

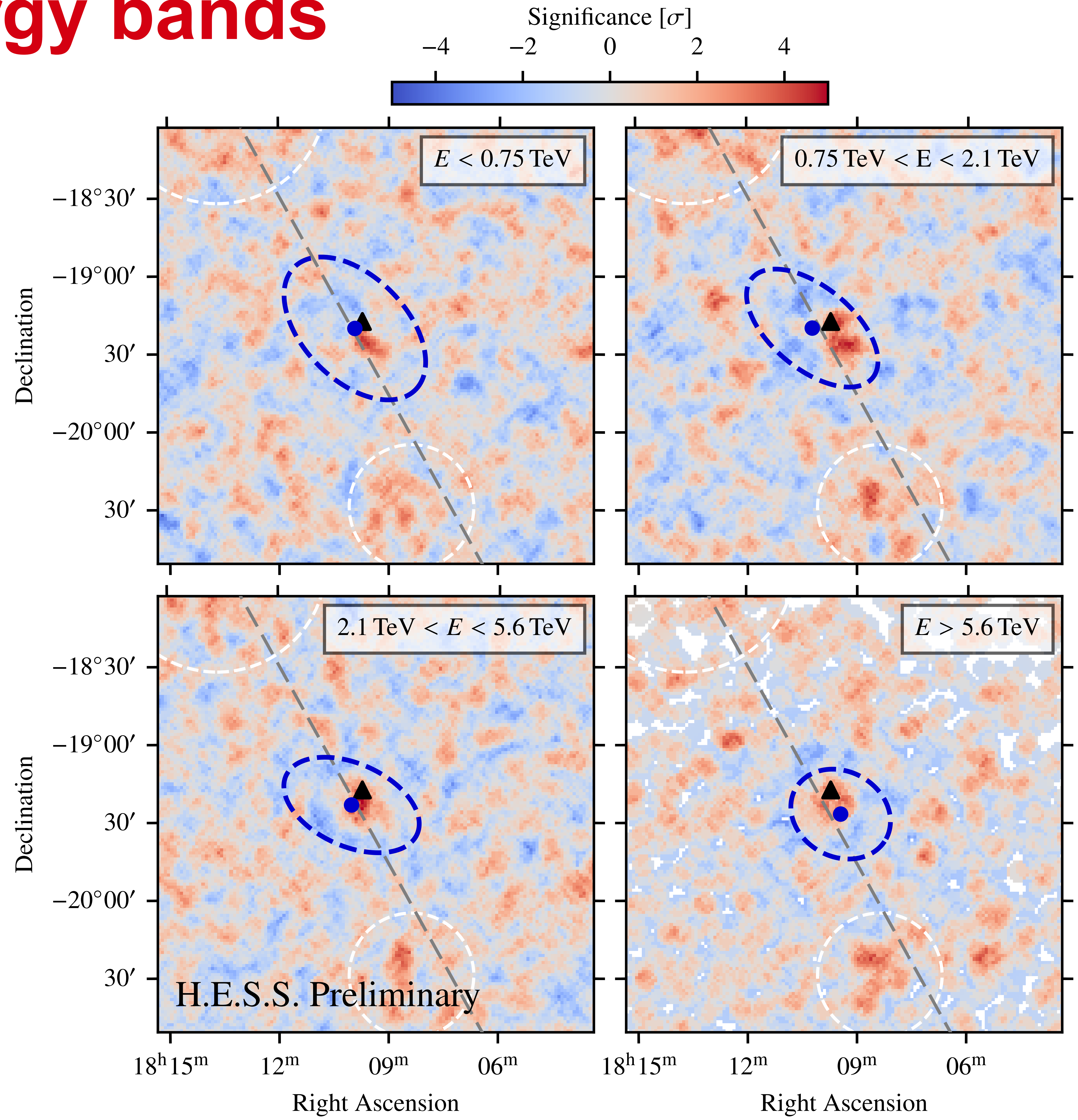


# 1-component model fitted in energy bands

- Possibility of energy-dependent morphology
→ does the 1-component model work
if its spatial extent is allowed to
vary with energy?

- Re-performed fit in four distinct energy bands
  - Spectral index fixed to best-fit value from regular fit
  - All other parameters left free

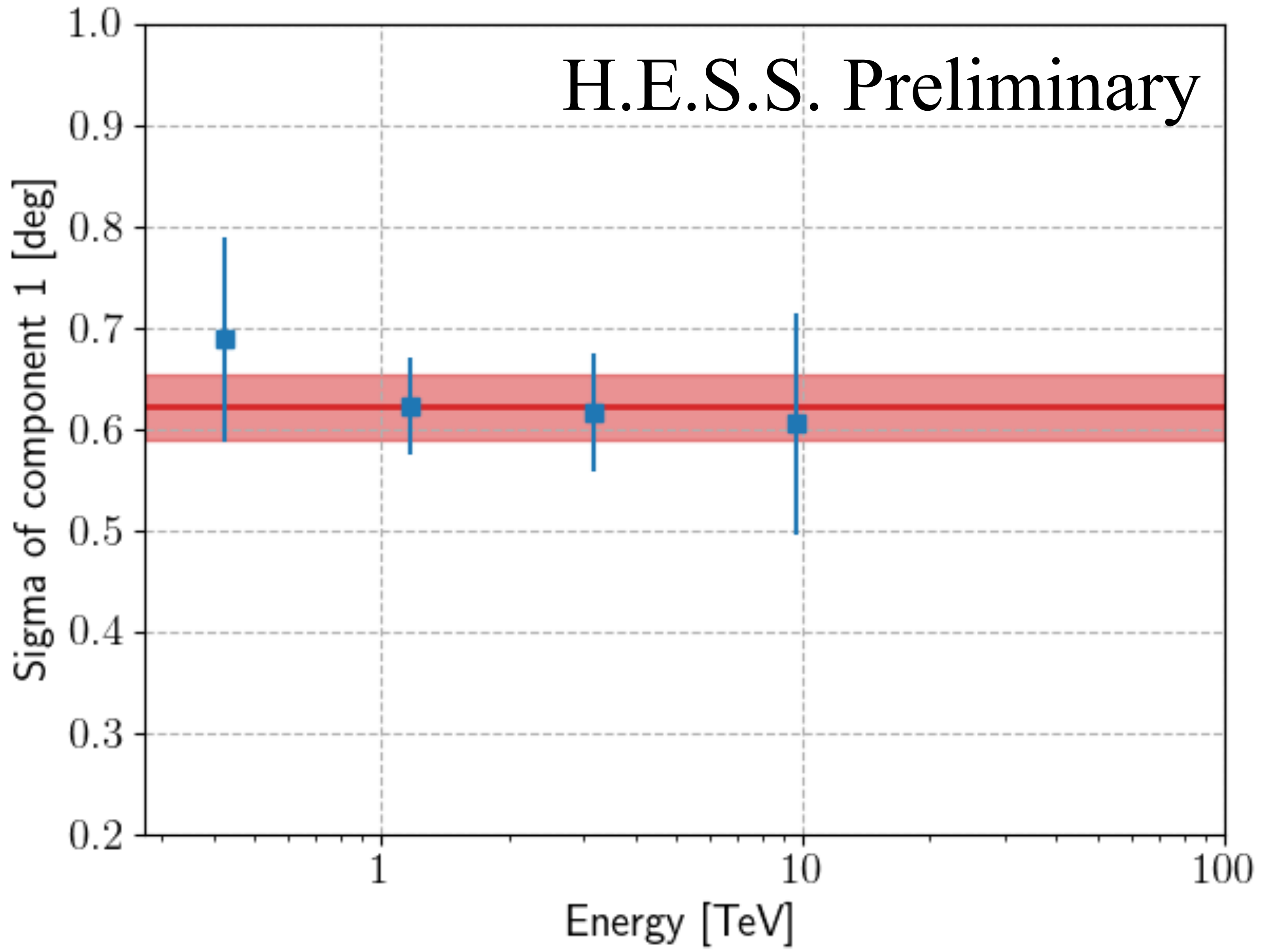
- Still not a good description of the data!

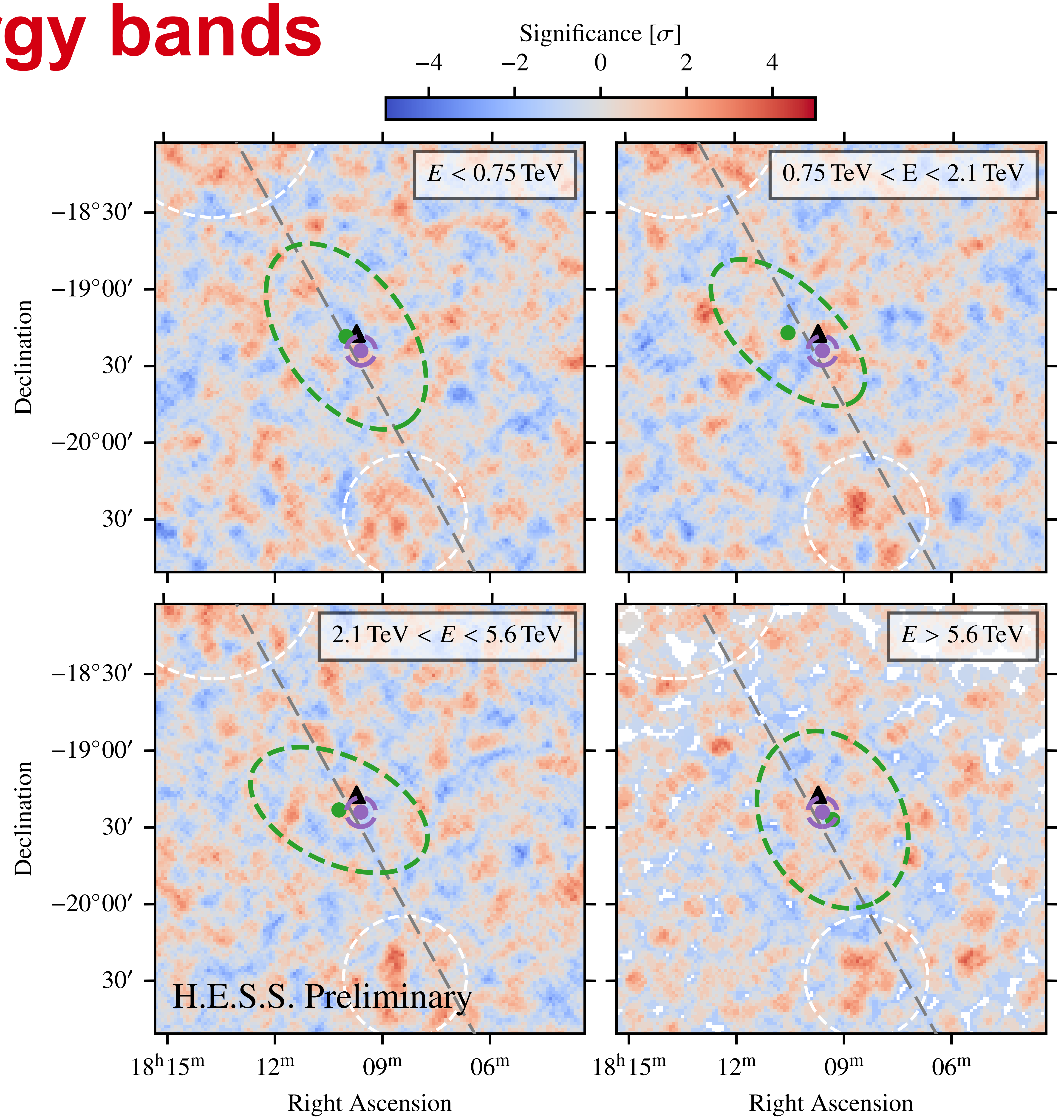


# 2-component model fitted in energy bands

- Re-performed fit in four distinct energy bands
  - Parameters of component 2 & spectral index of component 1 fixed
  - All other parameters of component 1 left free

- Fitted spatial models compatible between energy bands!



# Best-fit parameter values of 2-component model

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

- Systematic errors computed as described on following slide

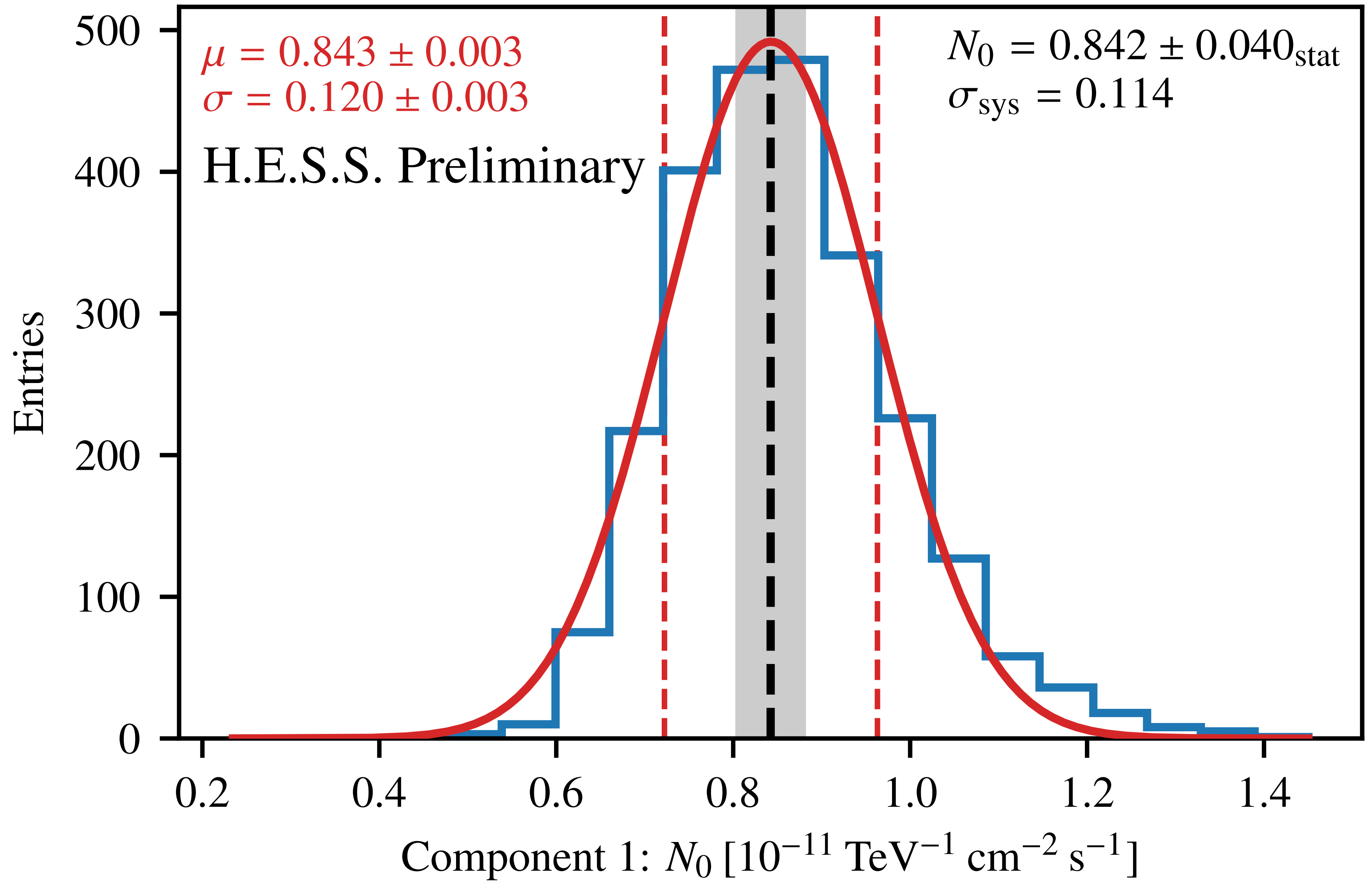
| Par. [unit] | Value |
|---|---|
| **Component 1 (PL spectral model)** | |
| R.A. [deg] | $272.551 \pm 0.025_{stat} \pm 0.018_{sys}$ |
| Dec. [deg] | $-19.344 \pm 0.023_{stat} \pm 0.013_{sys}$ |
| $\sigma$ [deg] | $0.622 \pm 0.032_{stat} \pm 0.020_{sys}$ |
| $e$ | $0.824 \pm 0.025_{stat}$ |
| $\phi$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

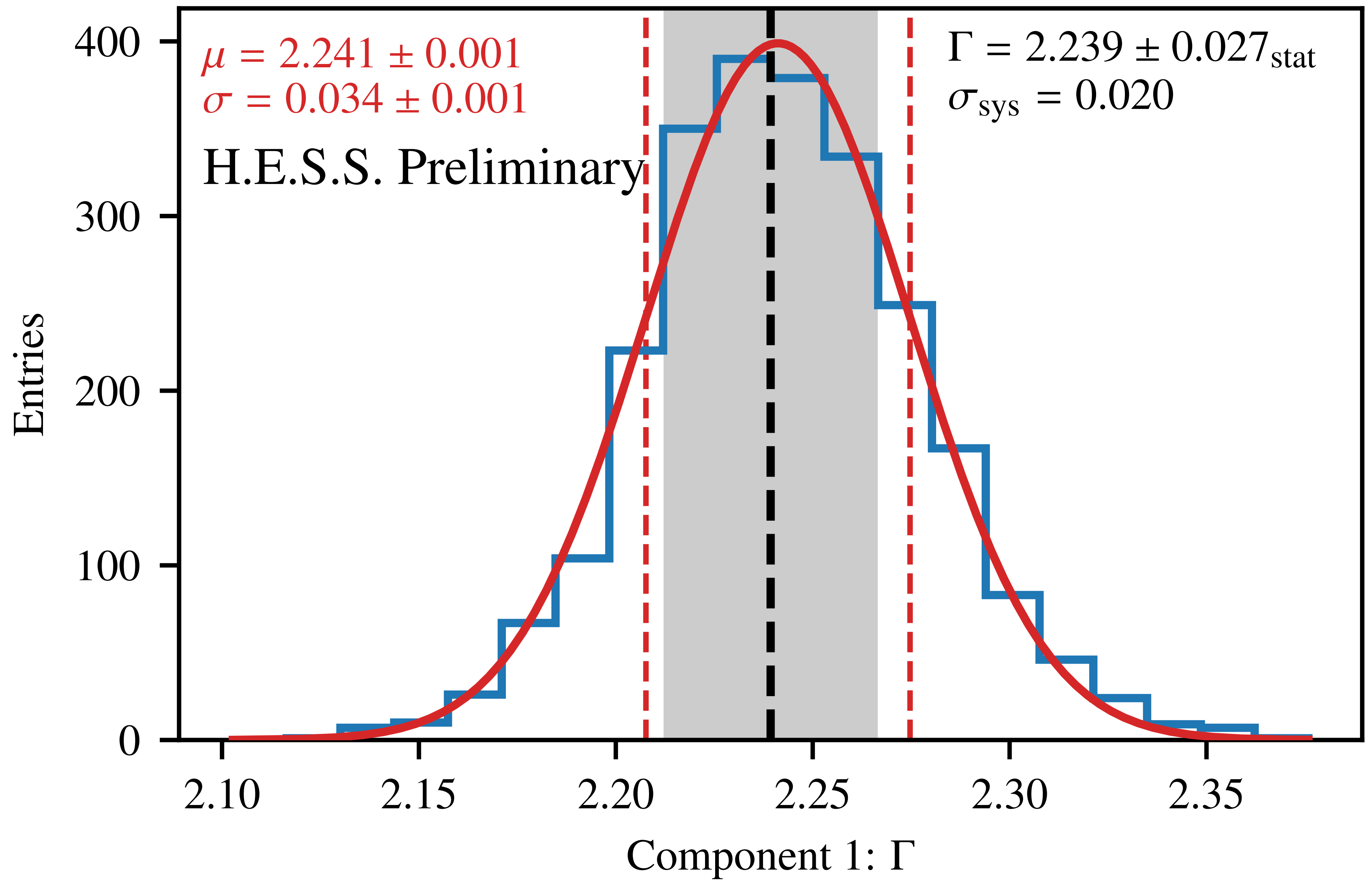
# Estimation of systematic uncertainties

- Consider four systematic effects:
  - Global energy scale shift
  - Background model normalisation
  - Background model spectral tilt
  - Background model linear gradient
- Procedure:
  - Randomly vary instrument response functions (IRFs)
  - Generate pseudo data set based on varied IRFs + best-fit source models
  - Fit pseudo data set with original (unmodified) IRFs
  - Repeat 2,500 times
- Systematic error can be estimated from resulting distributions of fitted source parameters
- Systematic error on flux points deduced from those on flux normalisation / spectral index

**Table B.1.** Parameter variations for systematic uncertainty estimation.

| Par. | Variation | Description |
|---|---|---|
| | Global energy scale | |
| $\phi_E$ | Gaussian ($\mu = 1$, $\sigma = 0.1$) | Shift of energy scale |
| | Background model variations | |
| $\phi_{BG}$ | Gaussian ($\mu = 1$, $\sigma = 0.01$) | Background model normalisation |
| $\delta_{BG}$ | Gaussian ($\mu = 0$, $\sigma = 0.02$) | Background model spectral tilt |
| $A_{BG}^{grad}$ | Gaussian ($\mu = 1$, $\sigma = 0.01$) | Amplitude of background gradient (in $deg^{-1}$) |
| $\alpha_{BG}^{grad}$ | Uniform ($0° - 360°$) | Direction of background gradient |



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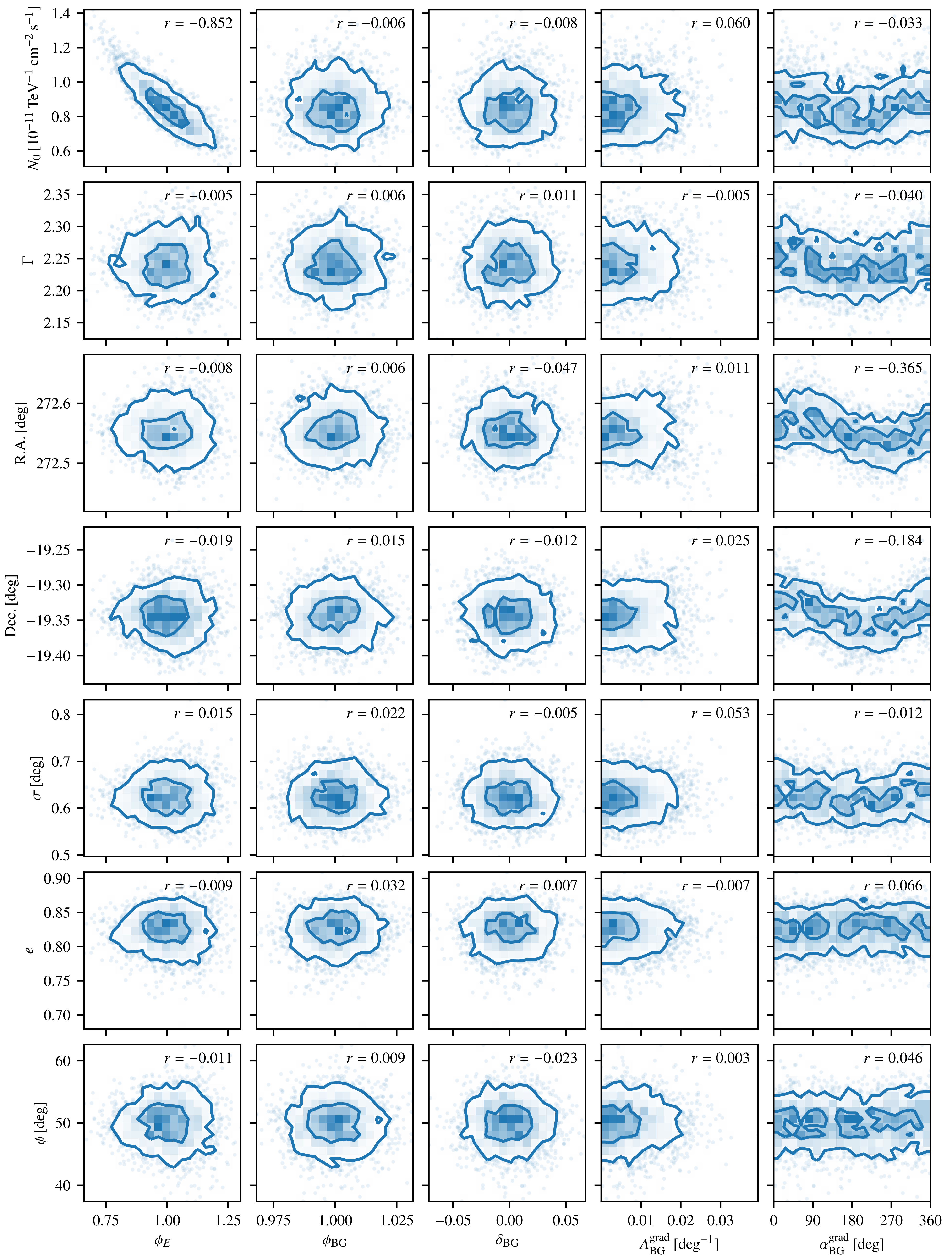
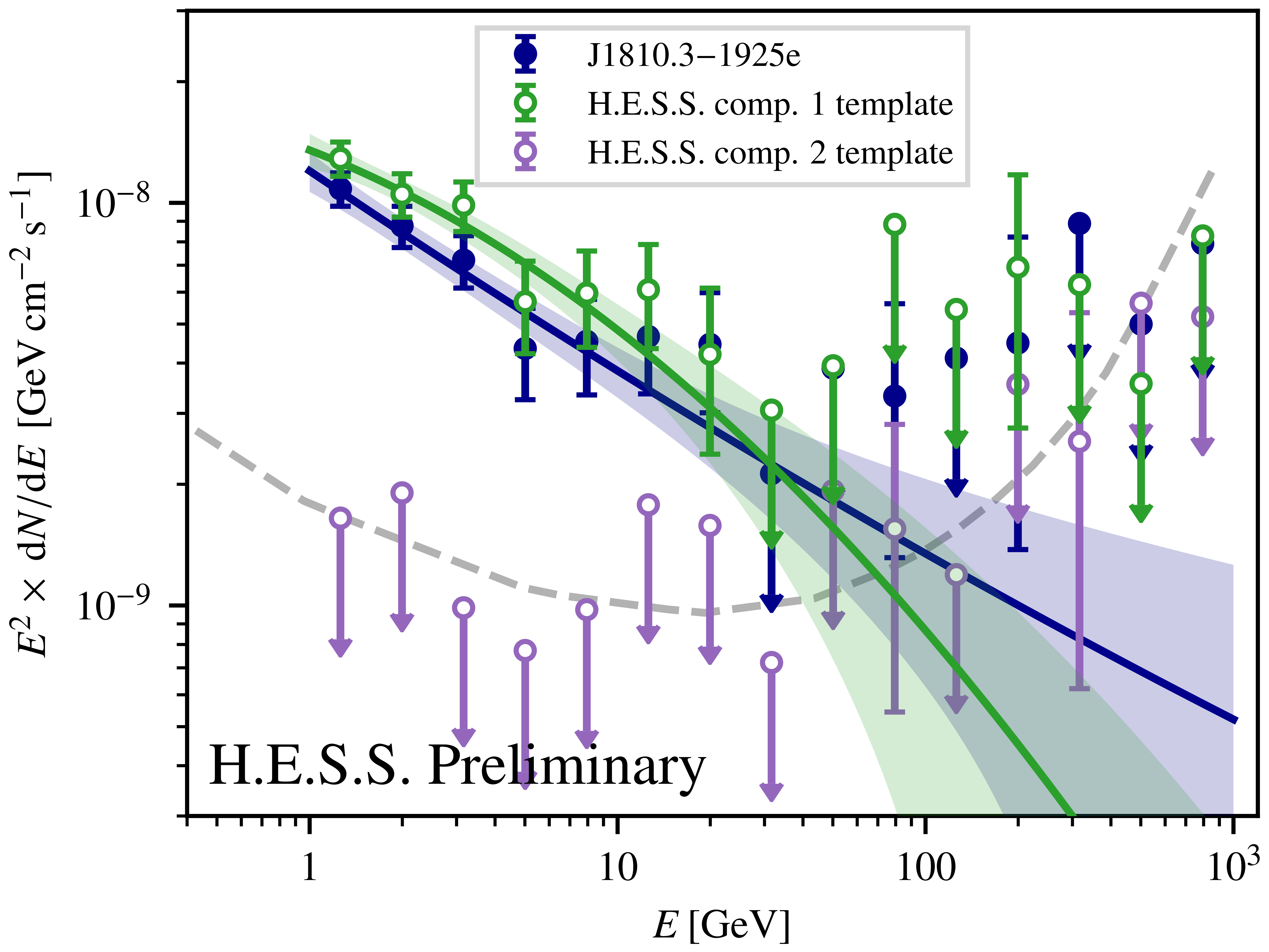
| | Background model variations | |
| $\phi_{\mathrm{BG}}$ | Gaussian ($\mu = 1$, $\sigma = 0.01$) | Background model normalisation |
| $\delta_{\mathrm{BG}}$ | Gaussian ($\mu = 0$, $\sigma = 0.02$) | Background model spectral tilt |
| $A_{\mathrm{BG}}^{\mathrm{grad}}$ | Gaussian ($\mu = 1$, $\sigma = 0.01$) | Amplitude of background gradient (in deg$^{-1}$) |
| $\alpha_{\mathrm{BG}}^{\mathrm{grad}}$ | Uniform ($0° - 360°$) | Direction of background gradient |

- Procedure:
  - Randomly vary instrument response functions (IRFs)
  - Generate pseudo data set based on varied IRFs + best-fit source models
  - Fit pseudo data set with original (unmodified) IRFs
  - Repeat 2,500 times
- Systematic error can be estimated from resulting distributions of fitted source parameters
- Systematic error on flux points deduced from those on flux normalisation / spectral index



# *Fermi*-LAT spectra for H.E.S.S. model components

- Extracted spectra for H.E.S.S. model components
- Component 1
  - Flux slightly larger than with nominal *Fermi*-LAT model
  - Not surprising, given slightly larger extent
- Component 2
  - No significant detection with *Fermi*-LAT
  - Expected given broad-band sensitivity (grey dashed line in plot)

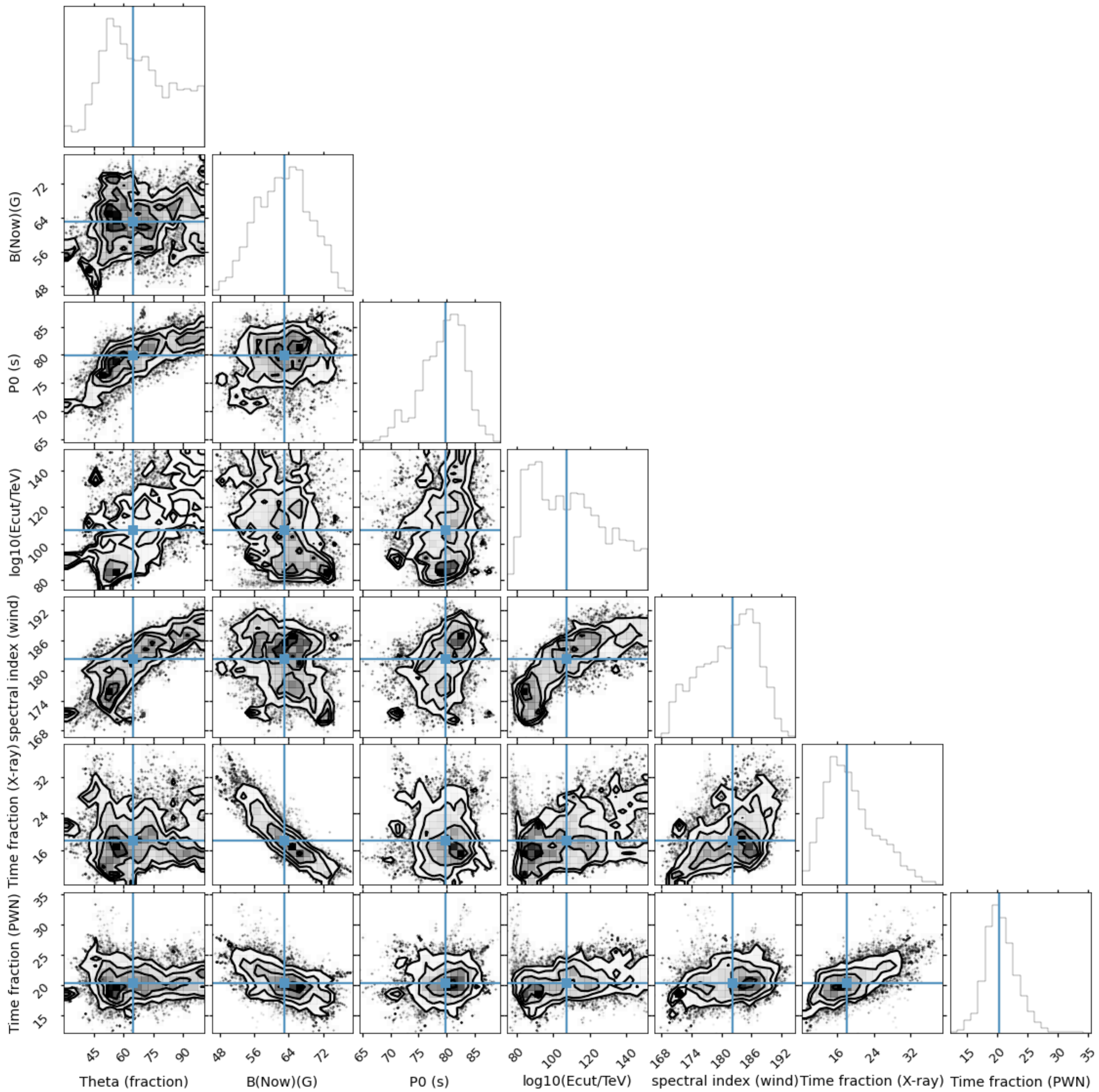


# GAMERA PWN model: parameters

- Input
  - Pulsar distance: $d = 3.27\,\mathrm{kpc}$
  - Pulsar spin-down power: $\dot{E} = 1.8 \times 10^{36}\,\mathrm{erg\,s^{-1}}$
  - Pulsar characteristic age: $\tau_c = 51.4\,\mathrm{kyr}$
  - Pulsar period: $P = 82.76\,\mathrm{ms}$
  - Pulsar period derivative: $\dot{P} = 2.55 \times 10^{-14}\,\mathrm{s\,s^{-1}}$
  - Pulsar braking index: $n = 3$
  - Cooling break energy: $E_b = 0.1\,\mathrm{TeV}$
  - Initial spectral index of wind electrons: $\alpha_0 = 1.5$
- Fitted
  - Fraction of spin-down power in electrons: $\theta = 0.64^{+0.23}_{-0.14}$
  - Present-day B-field: $B_{\mathrm{today}} = (5.7 \pm 0.6)\,\mu\mathrm{G}$
  - Initial pulsar period: $P_0 = (65 \pm 3)\,\mathrm{ms}$
  - Injection spectrum cut-off energy: $\log_{10}(E_c/\mathrm{TeV}) = 3.5^{+0.8}_{-0.6}$
  - Spectral index of wind electrons: $\alpha = 2.2^{+0.06}_{-0.09}$
  - Time fraction (X-ray electrons): $f_{\mathrm{X-ray}} = 0.045^{+0.018}_{-0.011}$
  - Time fraction (PWN electrons): $f_{\mathrm{PWN}} = 0.10 \pm 0.01$

# GAMERA PWN model: diagnostic plots

- Resulting distributions from MCMC fit



# GAMERA PWN model: diagnostic plots