A 3D likelihood based approach for extended VHE source extraction

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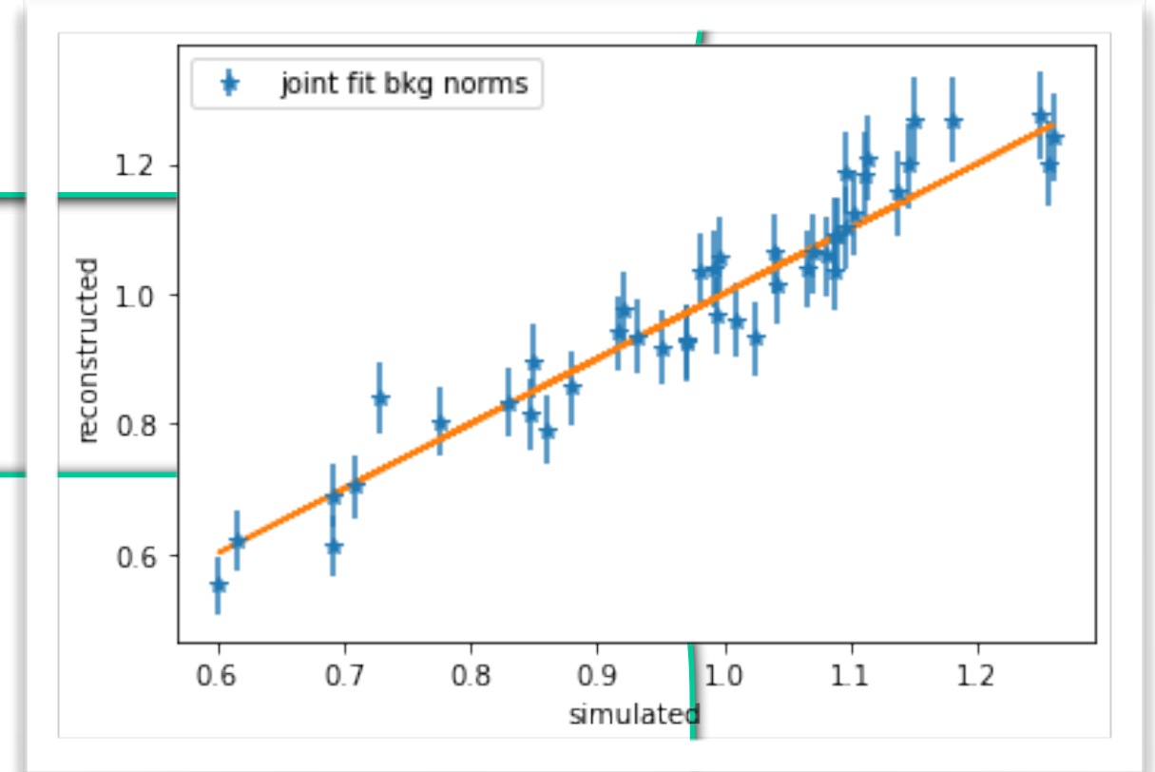
Efficiency of 3D FoV Background Models for IACTs

Context

Rejection of the residual hadronic background is a key challenge in data analysis for present generation Imaging Atmospheric Cherenkov Telescopes (IACTs). Since this is statistically removed using source free regions in the field of view (FoV), it becomes particularly relevant in the studies of large sources, where the extension is comparable to the FoV of the instrument. The use of FoV background models (eg: as used in [1] to detect extended sources in the galactic plane with H.E.S.S.) is expected to overcome this limitation and yield significant improvement in the sensitivity of IACT to large scale emission.

Aim

Using the IRFs from the First HESS DL3 Data Release [2] and the associated background models supplied in [3], we characterise here the efficiency of a 3D FoV likelihood minimisation as implemented in Gammapy [4] as compared with a traditional ring background estimation for a range of source sizes.

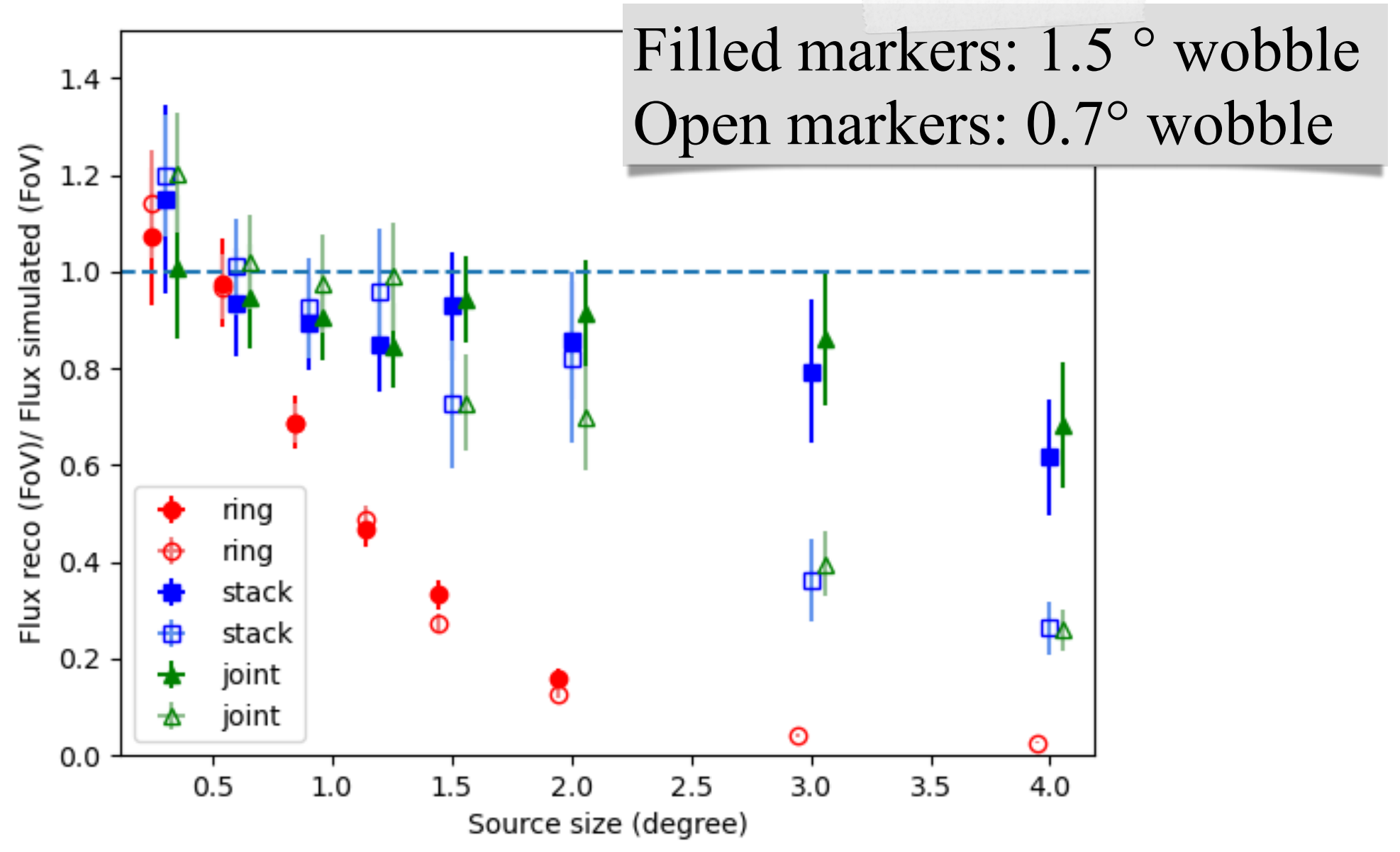


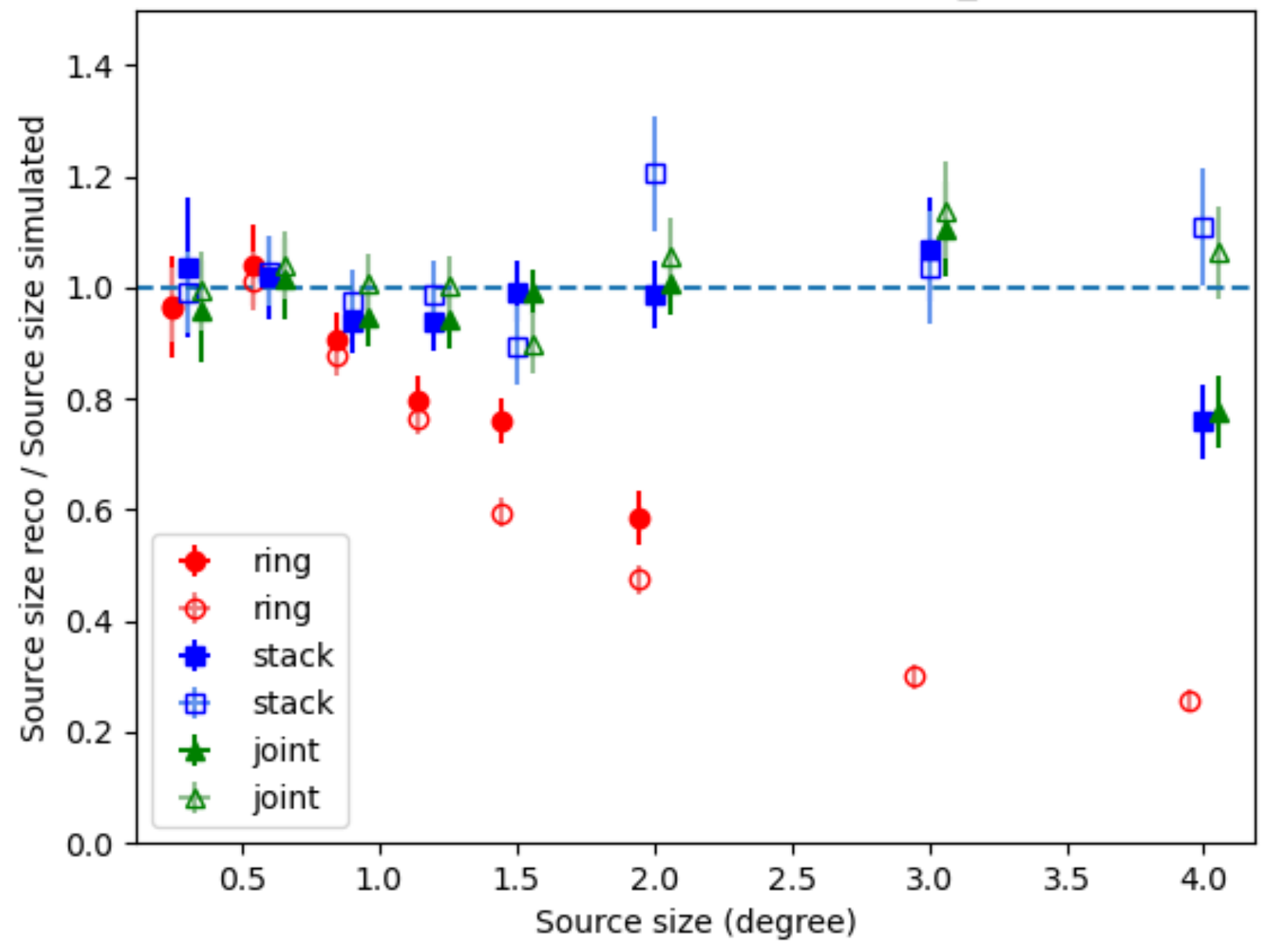
Results

- Consistent results for up to 0.6° source size for all analyses
- Ring estimator fails with increasing source size
- Good stability of reconstructed flux, size for both stacked and joint fits
- Joint fitting convergence time increases non-linearly with the number of observations
- Better stability of reconstructed flux for larger wobble offsets
- Reconstructed background norms correlate well with injected ones

Set-up

- Simulate 20 hrs of observation - 44 runs * 28 mins each
- 4 different wobble positions around the source, different wobble offsets
- Add 15% Gaussian fluctuations on the background normalisation to account for typical background uncertainties.
- Poisson fluctuate source + background
- Simulate sources of different sizes - Gaussian morphology with varying sigma
- Analyse simulated observations using
  - a) Ring Background estimation (radius=1.5°, width=0.3°)
  - b) Stacked analysis - all datasets stacked, 1 free background parameter in total
  - c) Joint analysis - all datasets fitted simultaneously - 1 free background parameter per run - computationally heavy





Energy dependent morphology

Context

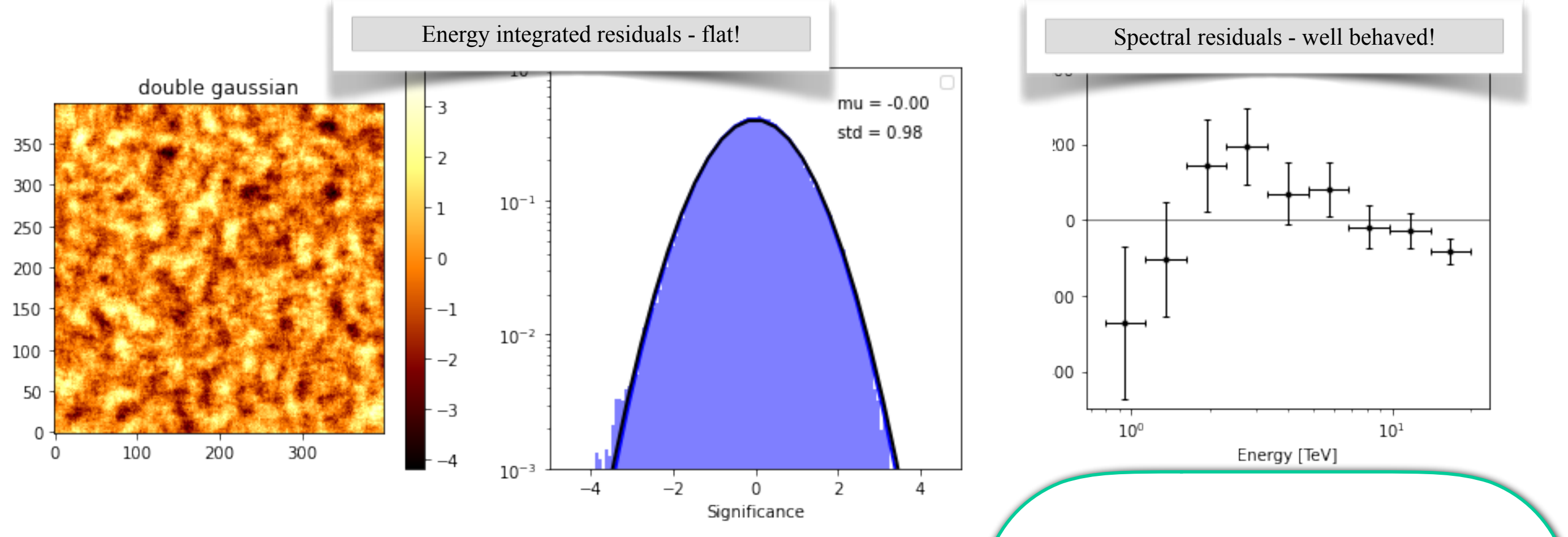
Pulsar wind nebulae and halos are expected to have an energy dependent morphology. However, such signatures can be complicated to detect even using 3D FoV likelihood minimisation

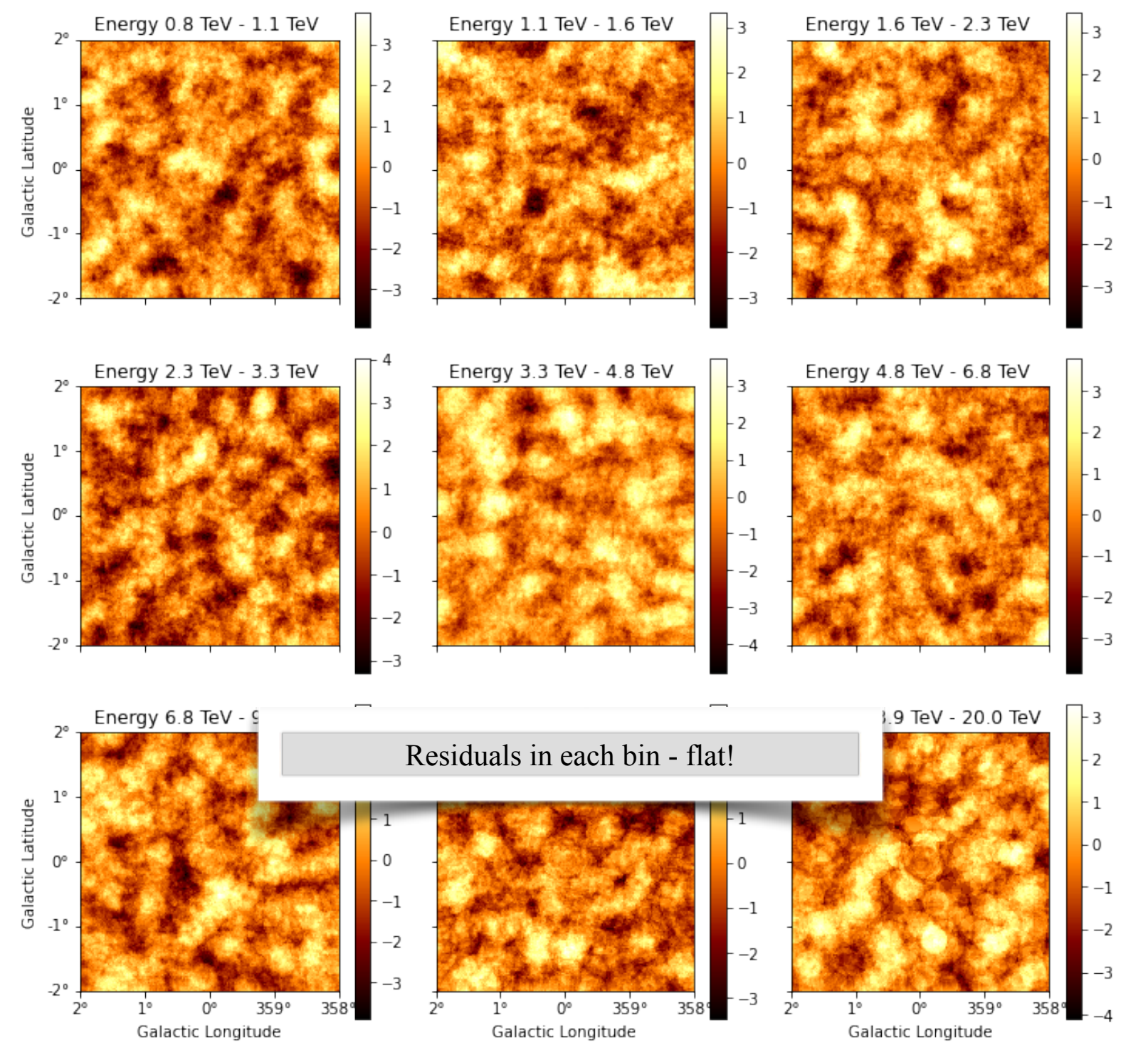
Set-up

- Implement a 3D Energy Dependent Gaussian model (`PWNGaussian`), with a power law dependence of the size on the energy $\sigma \sim \sigma_0 E^{-\alpha}$
- Simulate HESS observations using the above model and a PowerLaw Spectral dependance for the total spectrum
- Present case, $\alpha = 1$ as expected for a constant velocity advection driven energy loss scenario
- Fit the simulated observation using
  - (A)`PWNGaussian` Model - reconstructed parameters match injected ones
  - (B)A double Gaussian
    - i) A normal gaussian with a power law spectrum
    - ii) Residuals not flat - add a second gaussian
    - iii) End up with flat residuals!!!

•Compare (A) and (B)

Investigating a fit with a double Gaussian

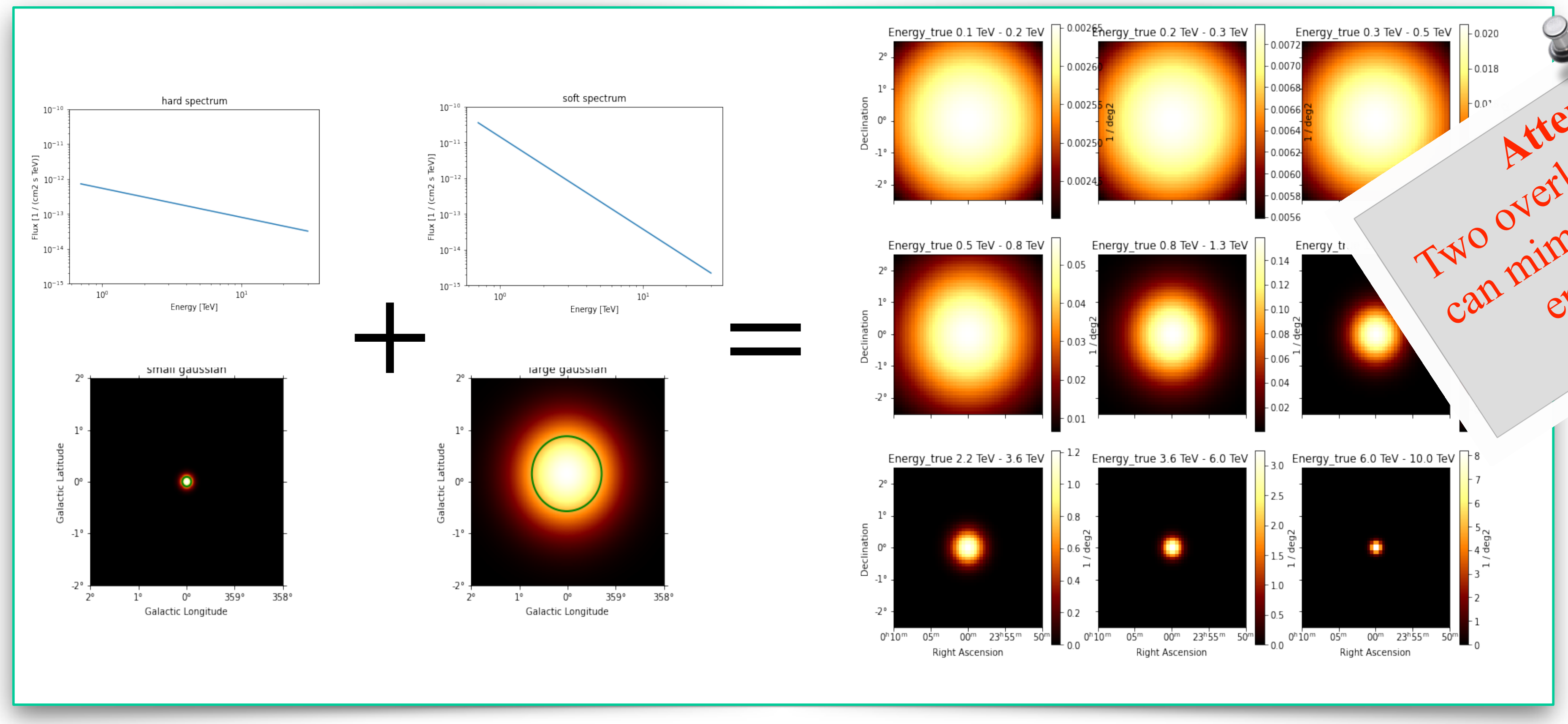




Results

- Significant detection of two components
  - (a) Small gaussian with hard spectrum
  - (b) Large gaussian with soft spectrum
- No smoking gun signature that this is not a good description of the underlying morphology
- Use the AIC to statistically study energy dependent morphology

To verify if the observations point to (A) A true energy dependent morphology or (B) two overlapping sources in the same region, a likelihood ratio test cannot be performed since these are non-nested models wit different number of free parameters. In this case, we suggest to use the Akaike Information Criterion (AIC)(eg: see, [5], eq 3) to probe the improvement of the fit. In our present case, the AIC yields a significant change in the test statistic (del AIC = 98.5, p-value=3e-22), correctly pointing to the simulated case of (A).



Attention!!!
Two overlapping gaussians can mimic to an underlying energy dependent morphology

References

1. Jardin-Blicq et al, *PoS* ICRC2019 (2020) 706
2. H.E.S.S. Collaboration [arXiv:1810.04516]
3. L. Mohrmann et al Astron. Astrophys. 632 (2019) A72
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