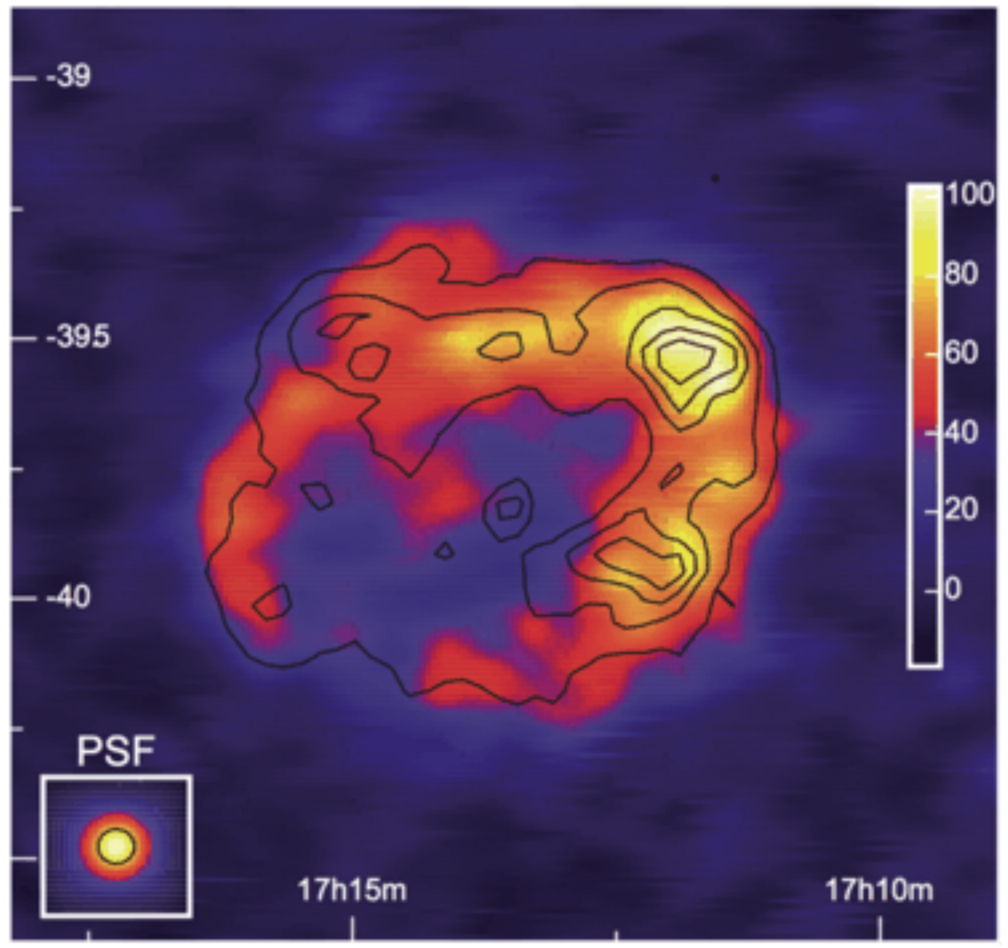
Background modeling for extended gamma-ray sources

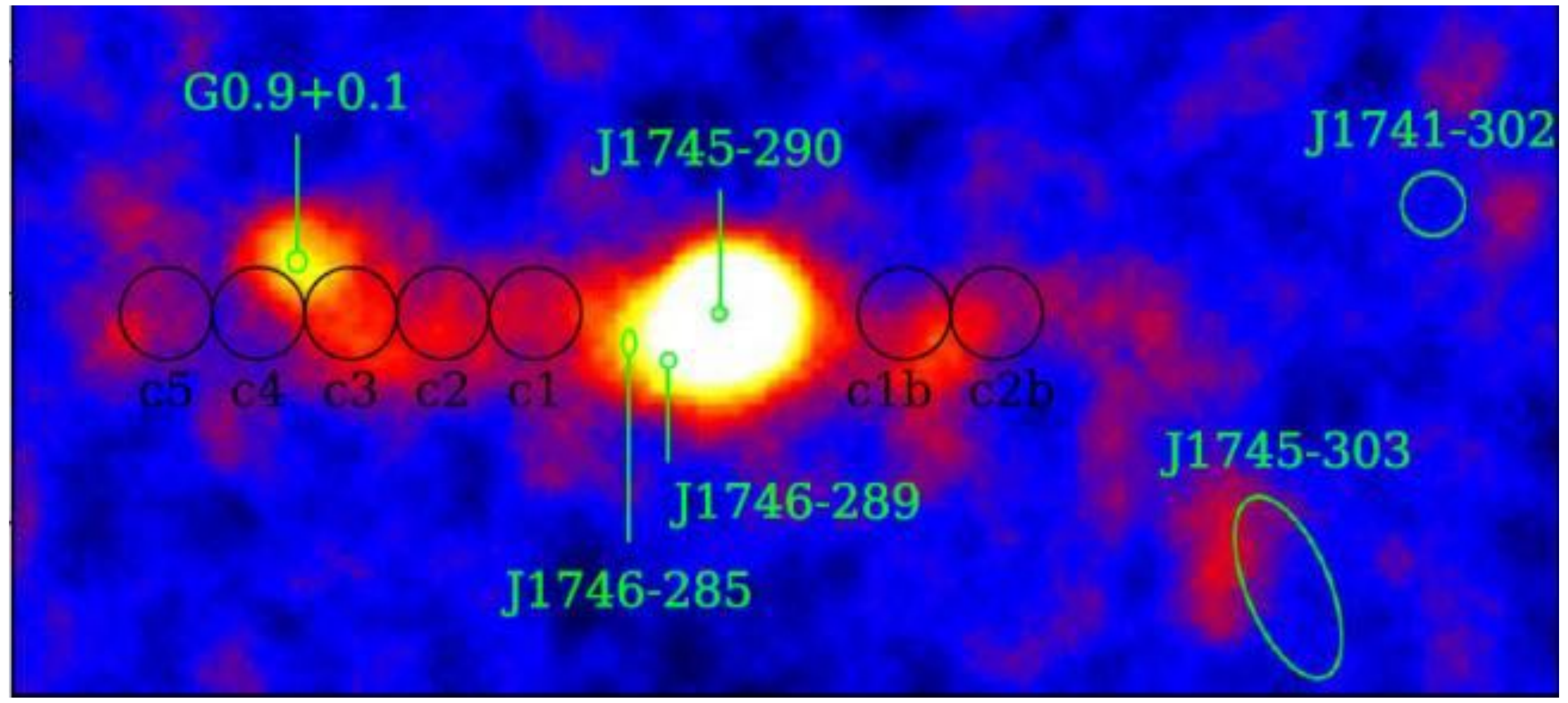
Workshop on Machine Learning for Analysis of High-Energy Cosmic Particles

Ruo-Yu Shang

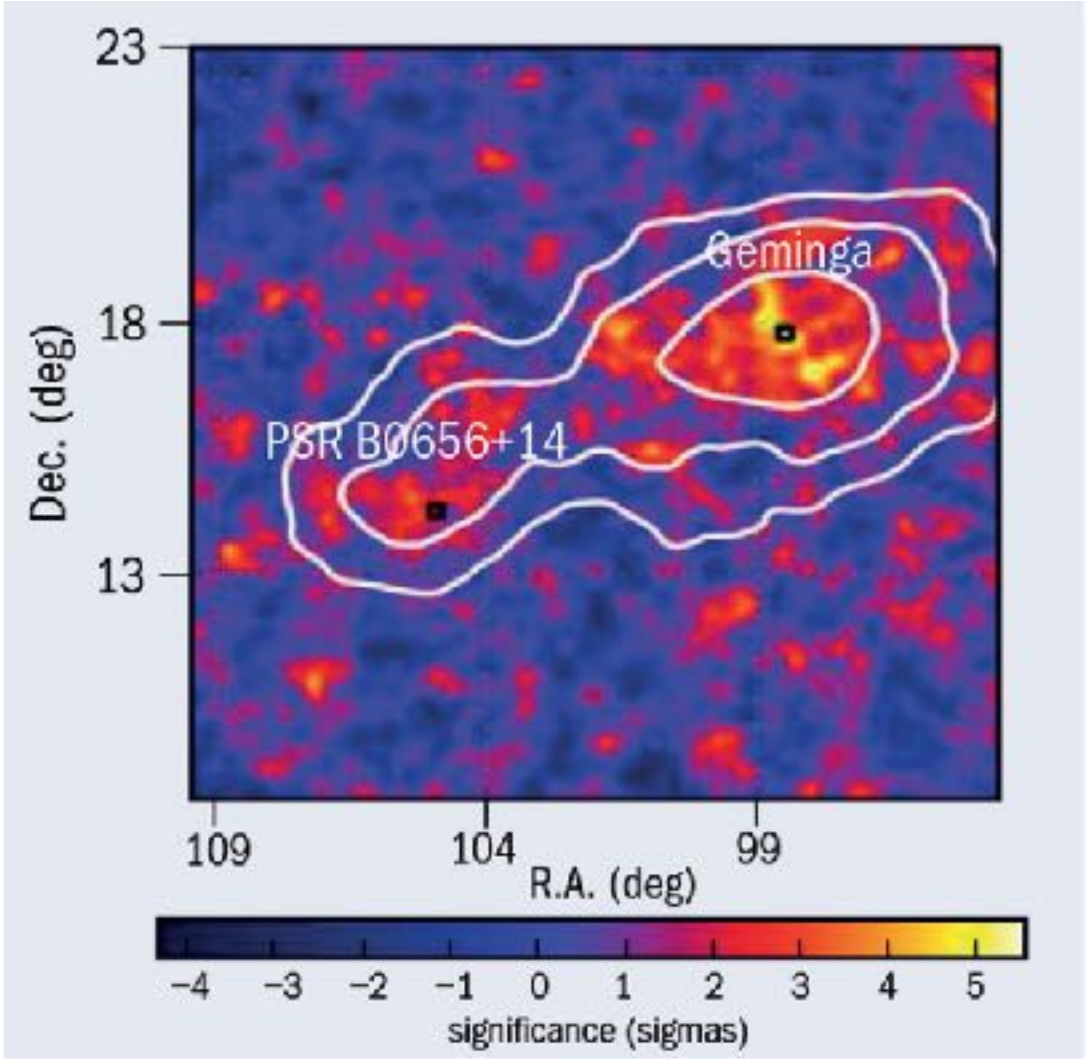
Science of extended γ-ray sources



RX J1713.7-3946
Space Sci Rev 173, 369–431 (2012)



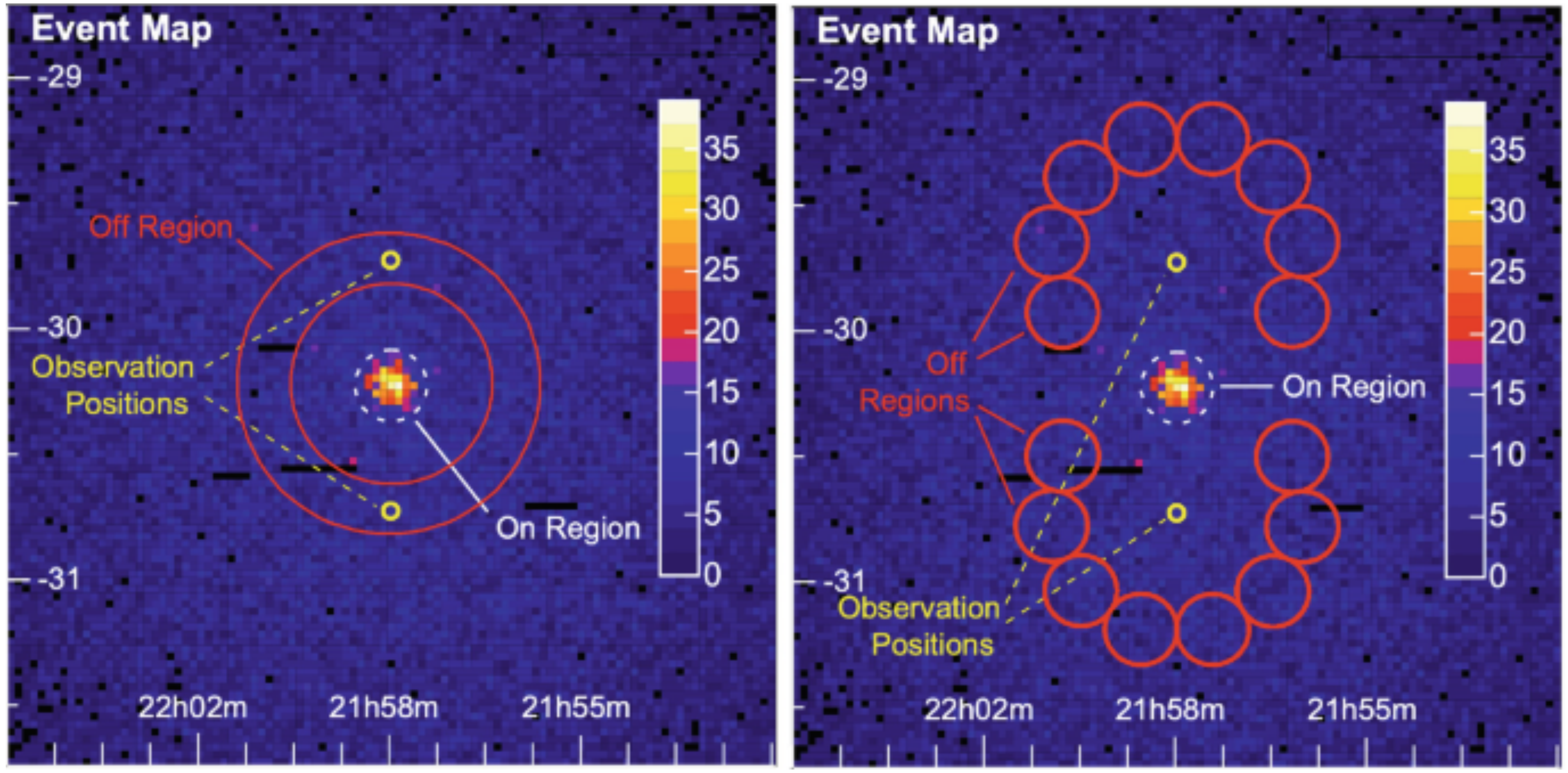
Galactic Center
VERITAS, and Adams et al. 2021

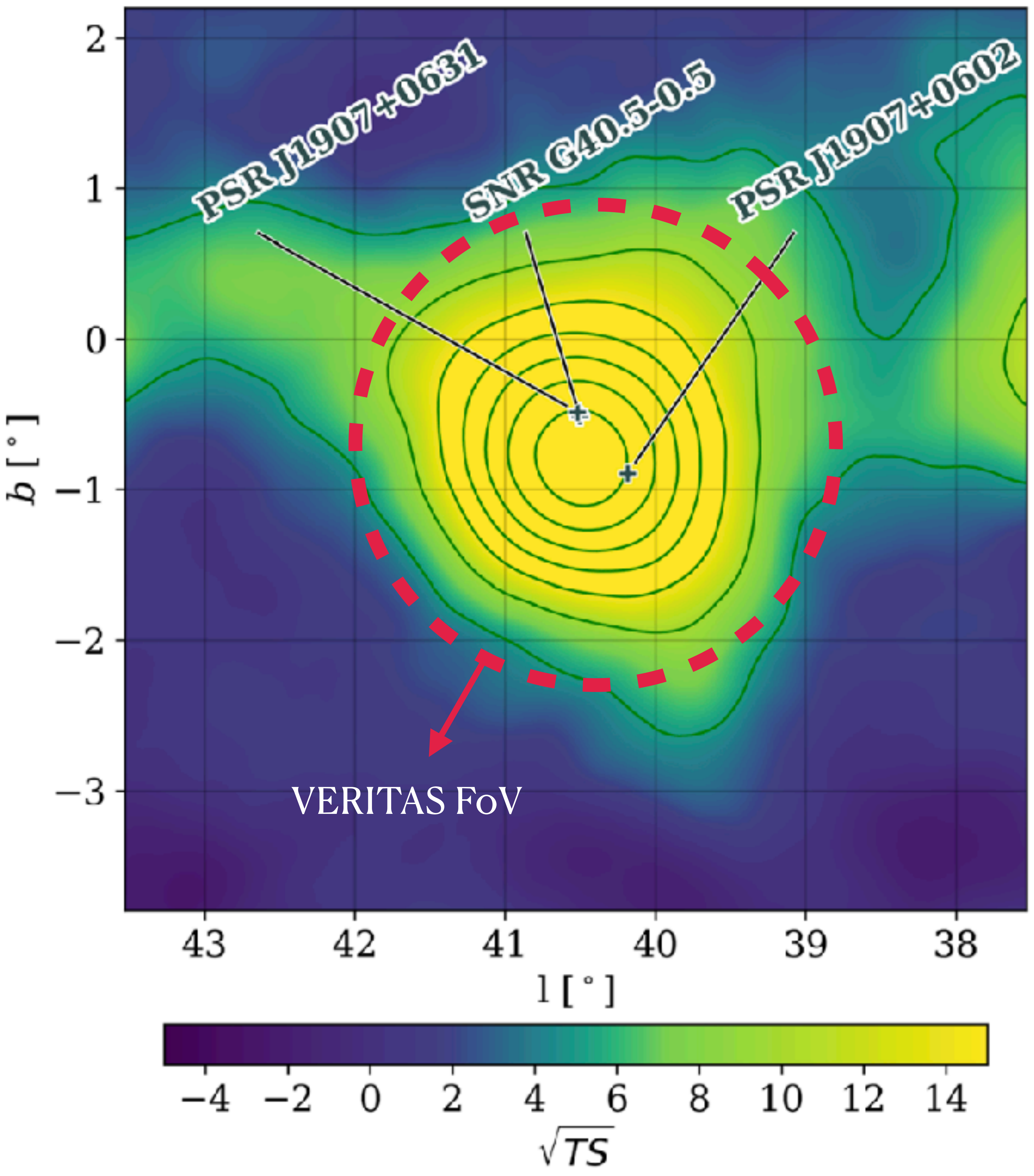


Geminga halo
Science 358 (2017) 6365, 911-914

- Many TeV sources (PWNe/SNRs/halos etc.) exhibit interesting morphology that allow us to study physics of particle acceleration and propagation
- IACTs offer excellent angular resolution ($\sim 0.1^{\circ}$ at TeV), however, they also have small FoV ($\sim 4^{\circ}$ diameter), making the analyses of extended sources challenging

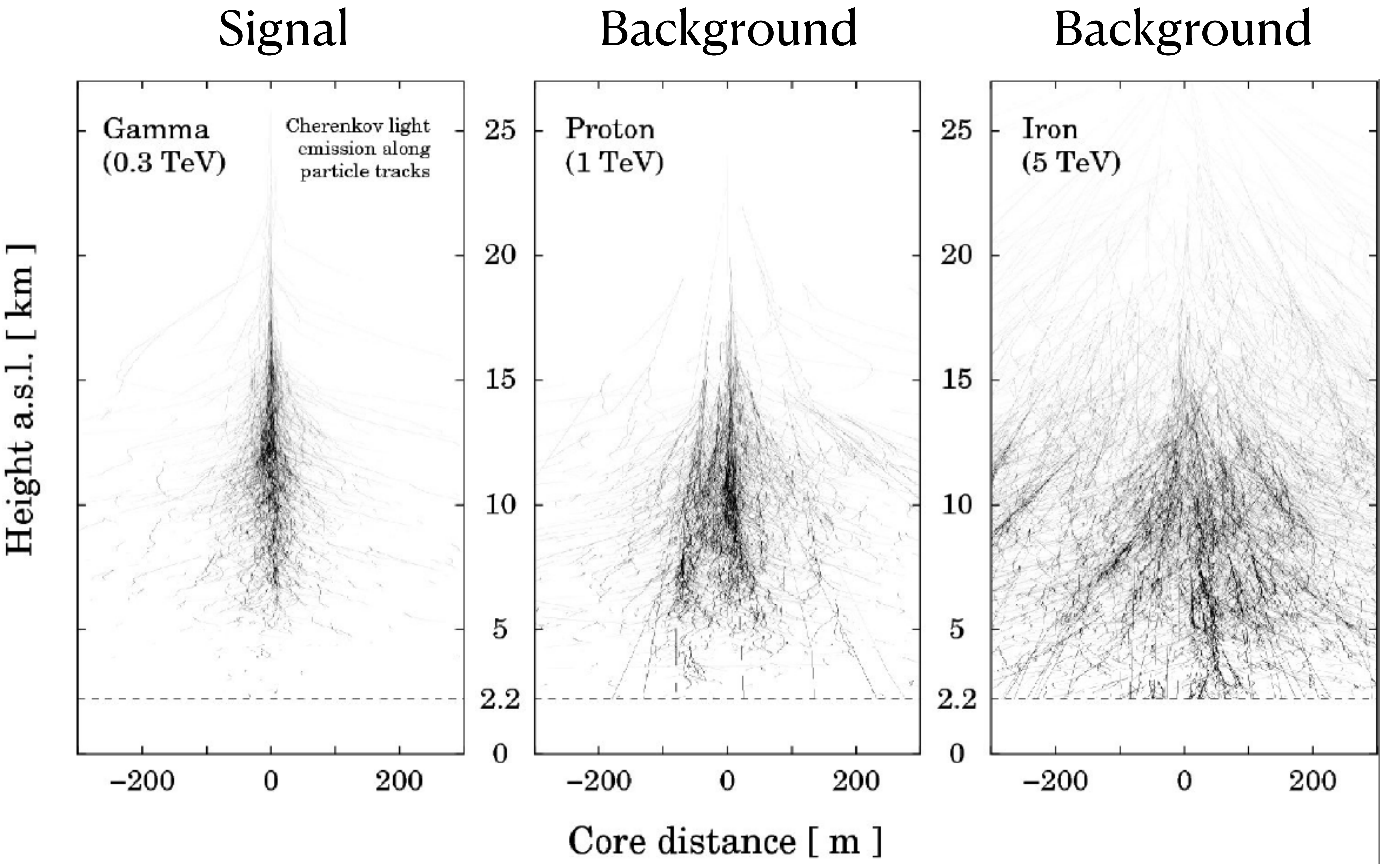
Conventional background estimation method





Gamma-ray background: atmospherical cosmic rays

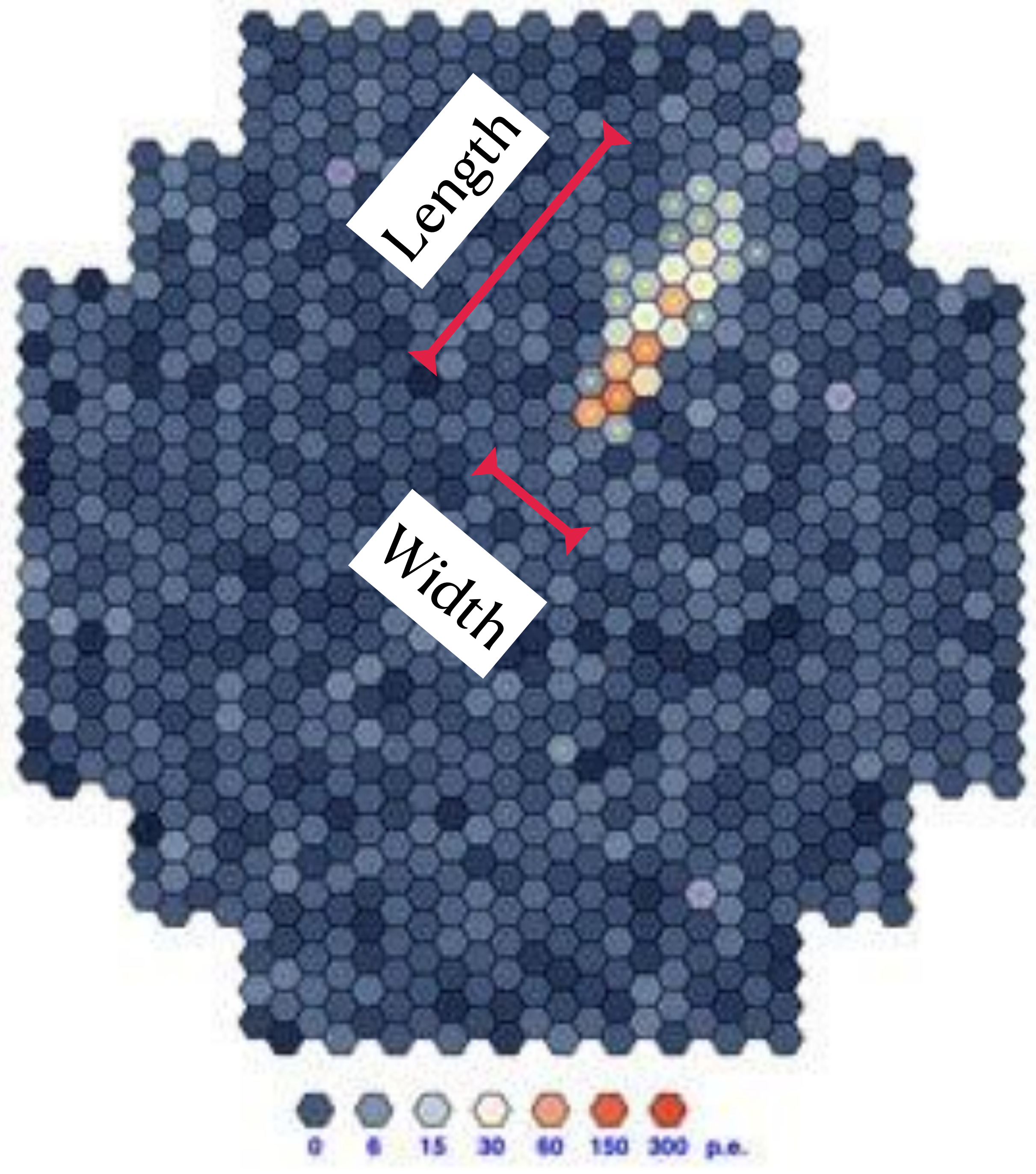
- IACTs operate in a background dominated regime
- Gamma-ray showers: clean and narrow
- Hadronic showers: fat and messy



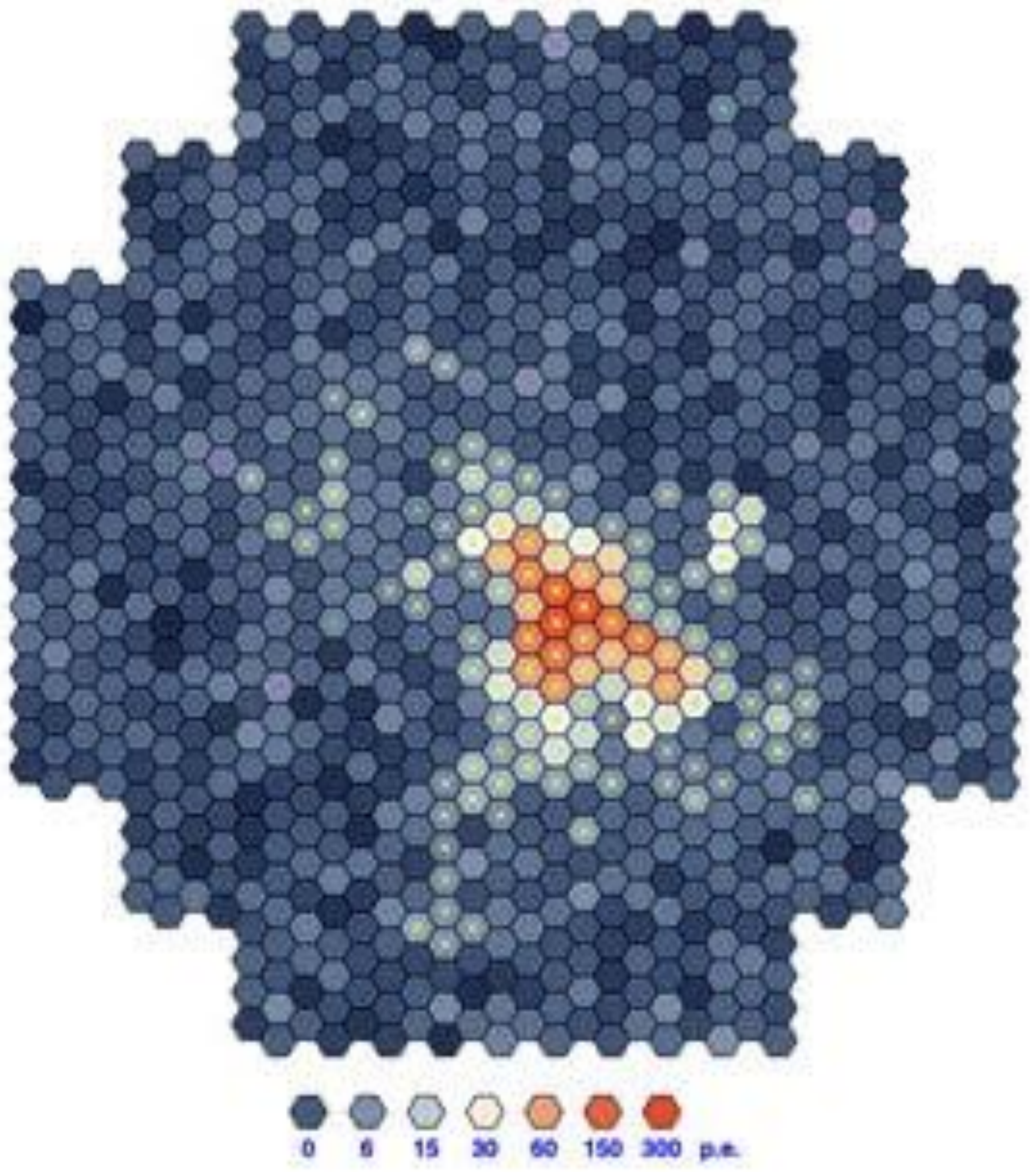
Credit: https://ar5iv.labs.arxiv.org/html/0808.2253

Shower width/length distribution

- We use width and length of a shower image to separate γ rays and cosmic rays
- γ-ray-like events have small width and small length
- Cosmic-ray-like events have large width and large length
- Background events are cosmic rays mis-identified as γ rays

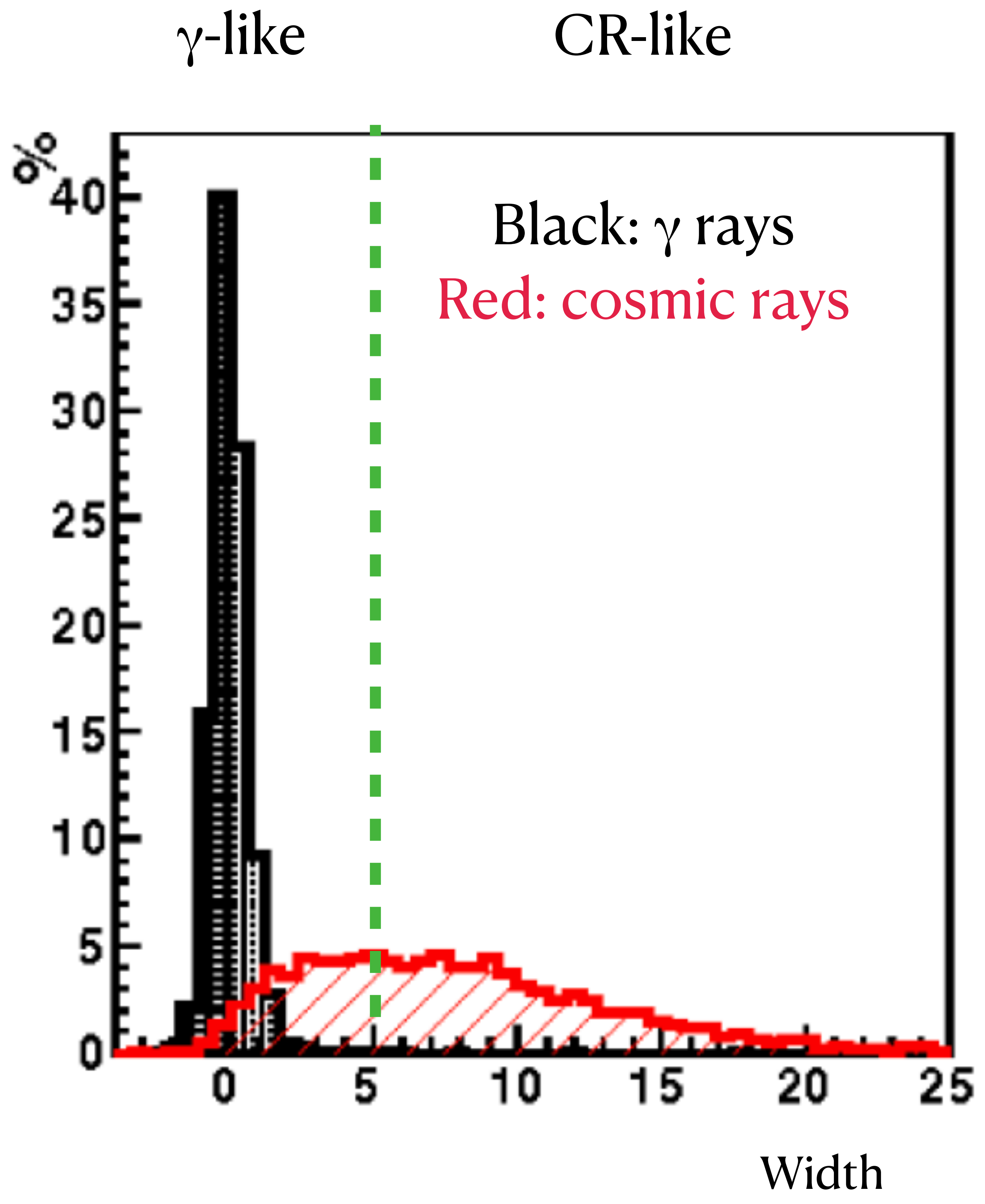


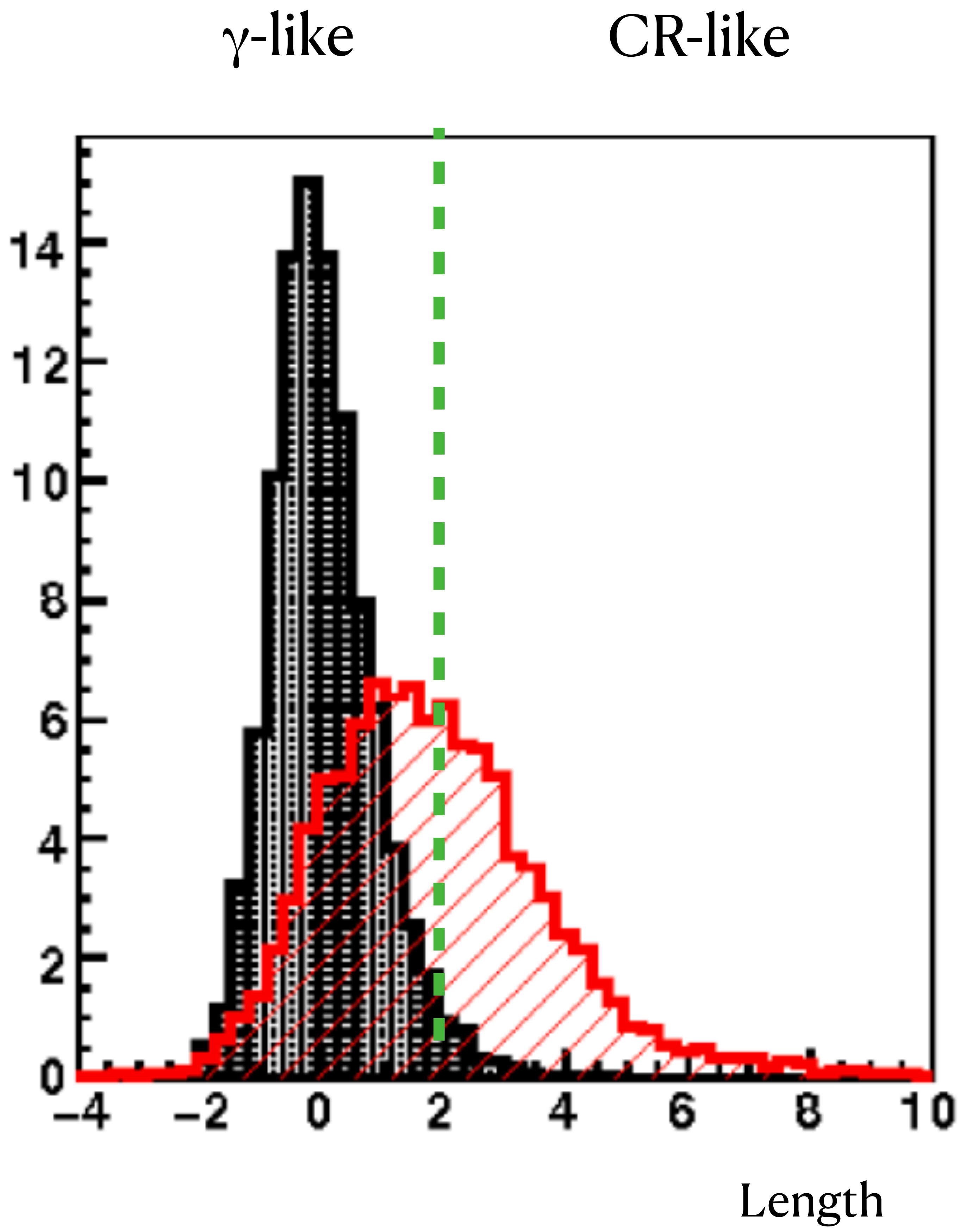
Gamma-ray shower

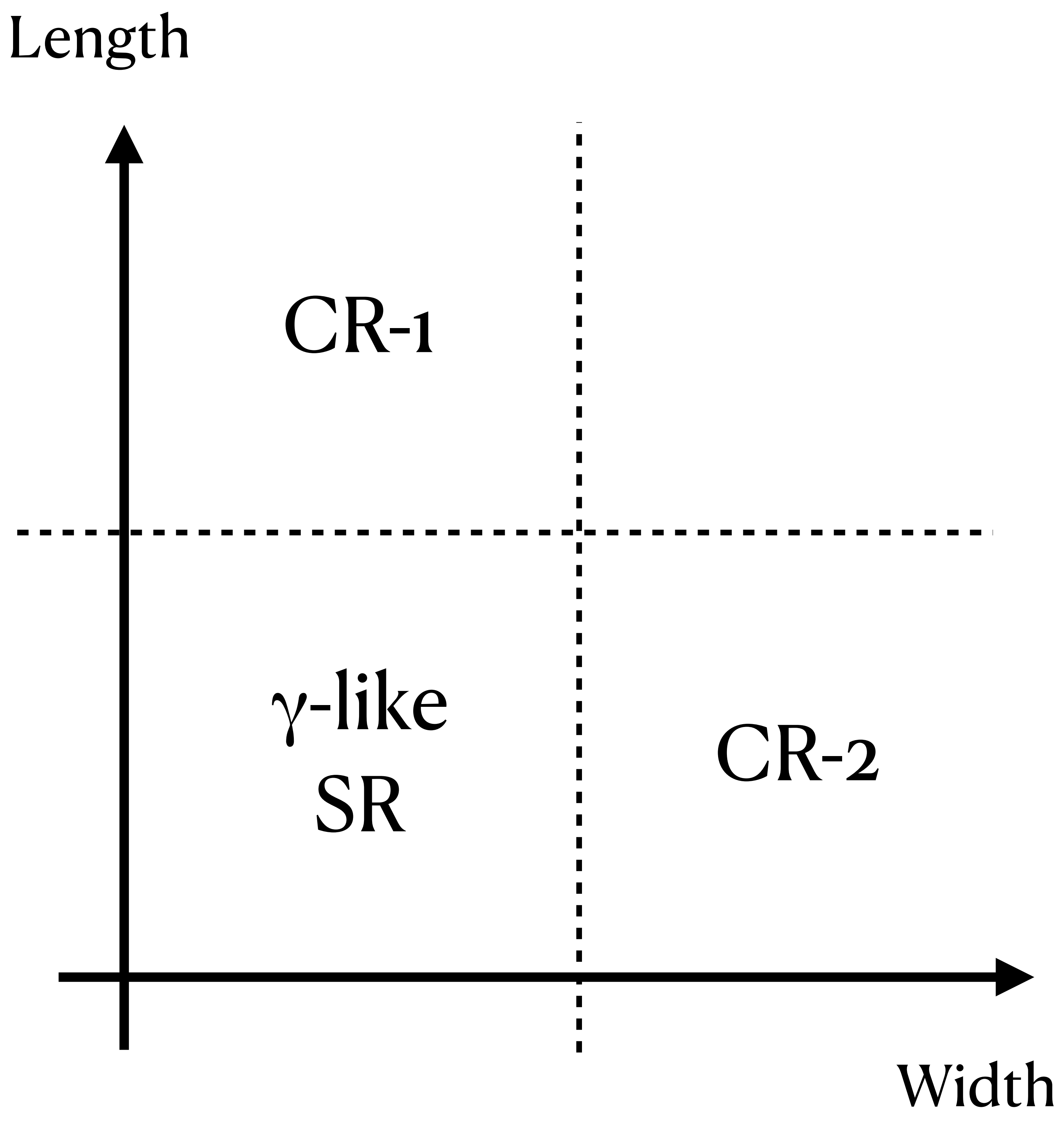


Cosmic-ray shower

Define background region in image-parameter space

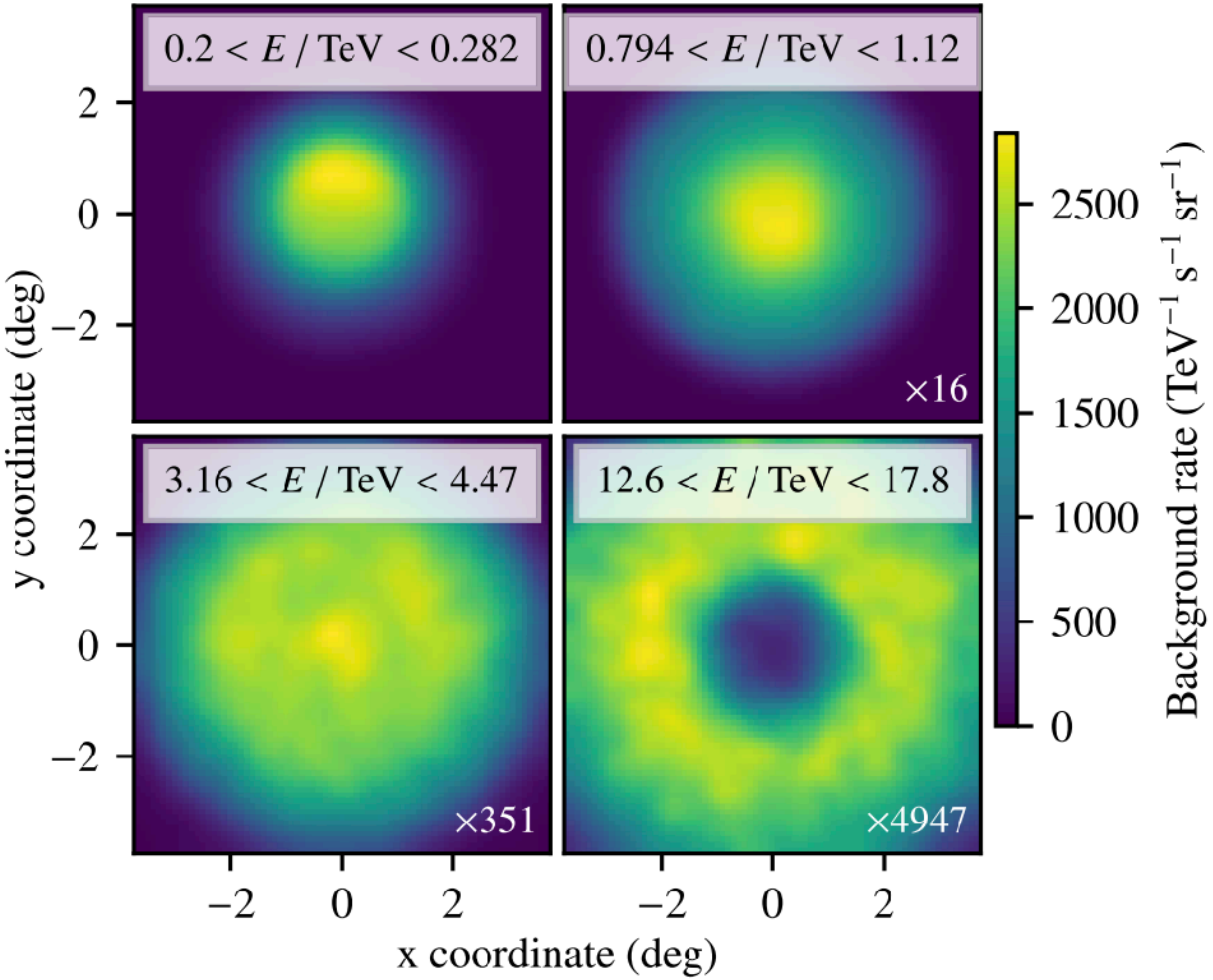




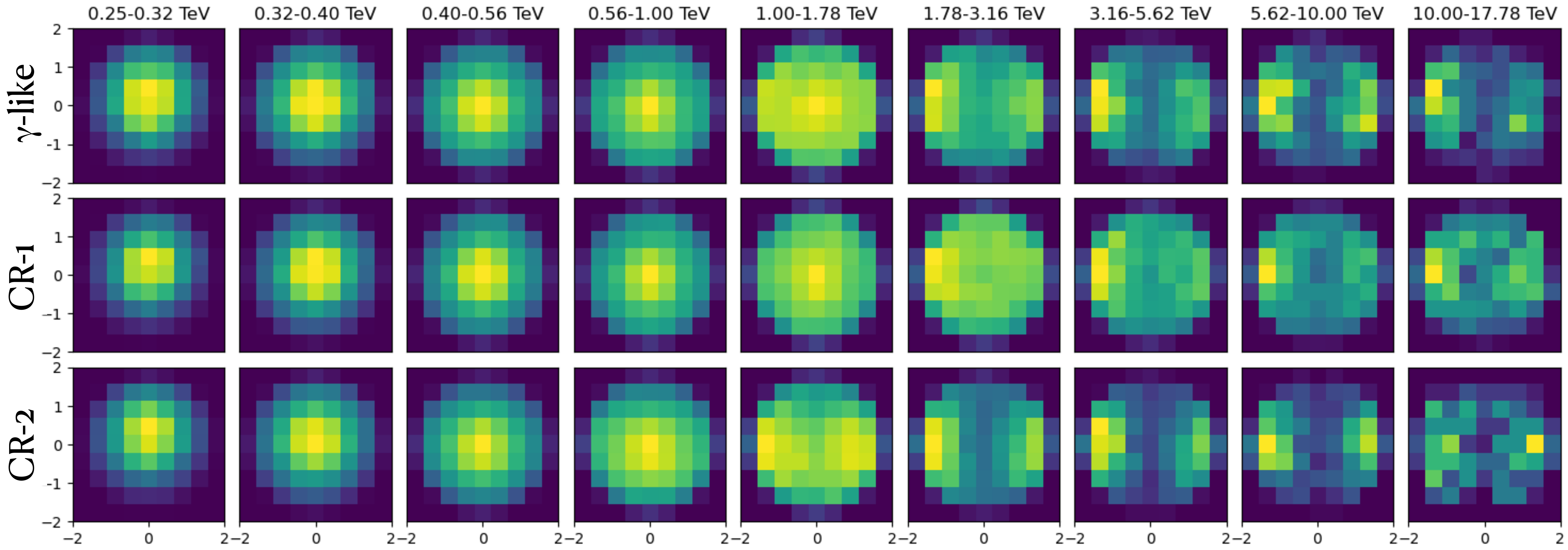


Background rate in camera frame

- At low energy,
  - Higher background rate at the center of the camera
  - Rate is asymmetric along vertical axis (elevation effect)
- At high energy,
  - Increase of background rate at large offset angles
  - Likely due to truncated high-energy showers

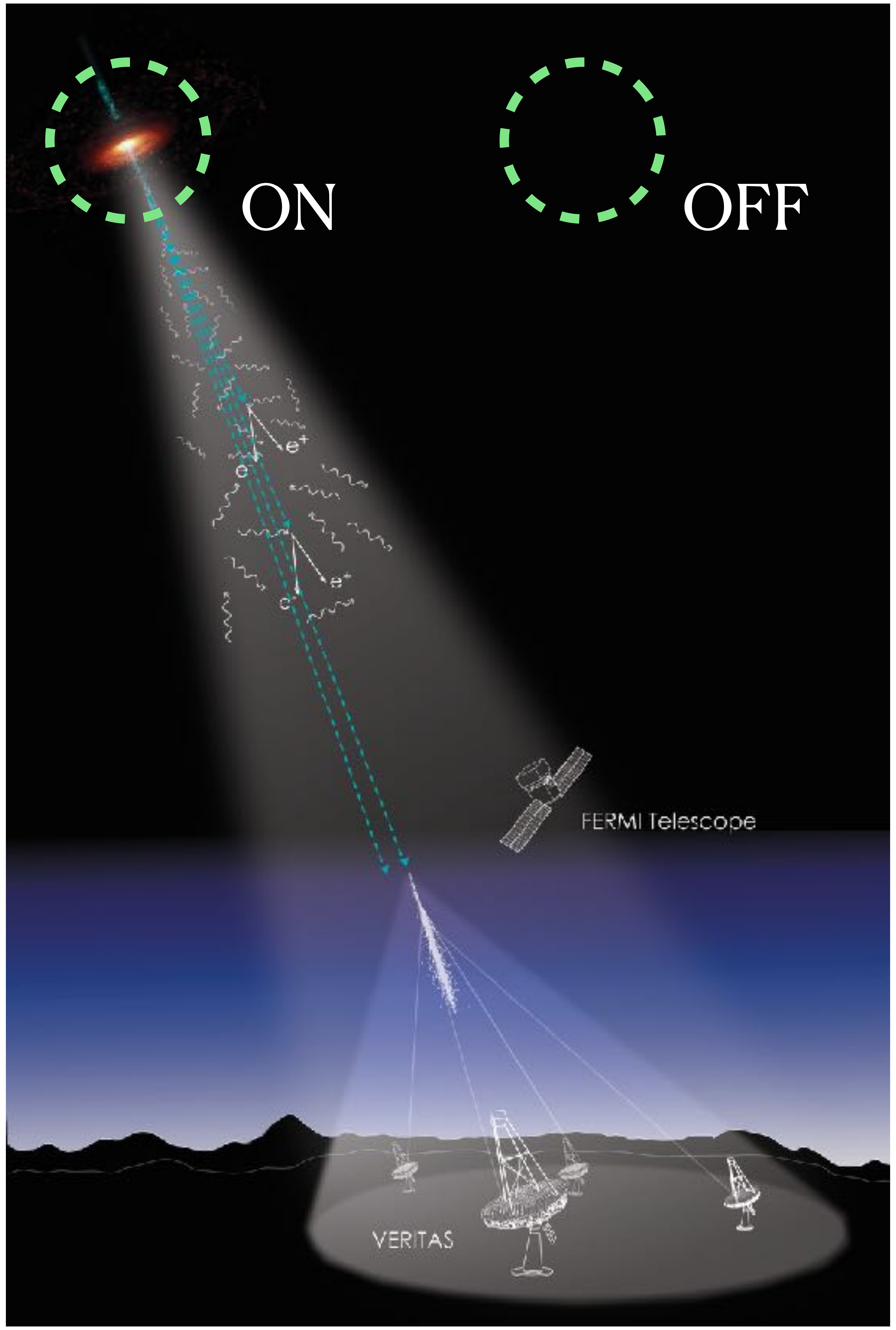


Background rate in camera frame

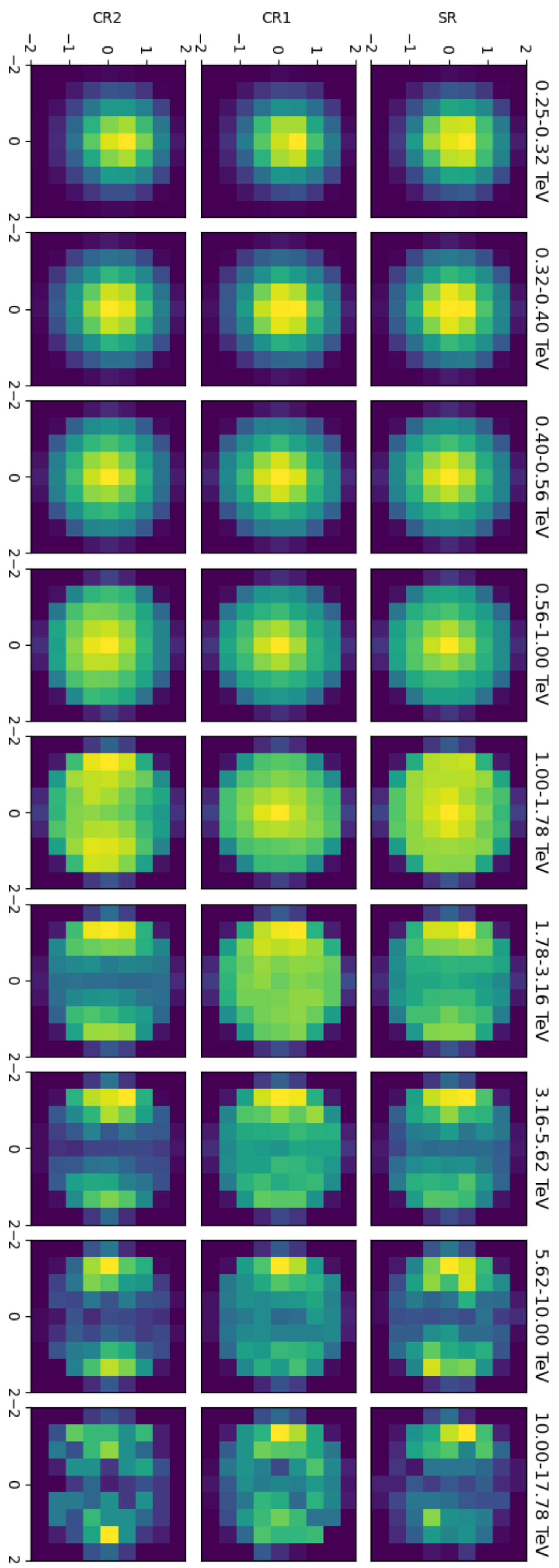


The matched-run method

- We select OFF runs to build the background model
- The OFF runs need to match the ON runs in:
  - Observation elevation
  - Observation azimuth
  - Observation night-sky brightness
  - Pointings of OFF observations have to be $> 10°$ away from the source of interest
  - Galactic $|b| > 10°$ (only extragalactic fields)



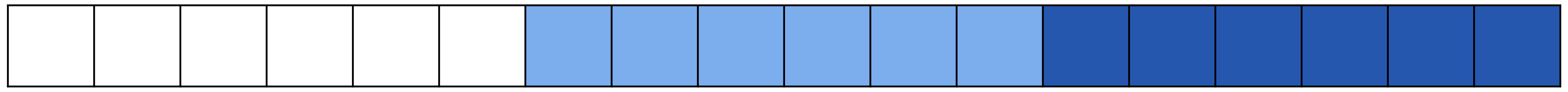
Background principle components



Background templates from a matched OFF run

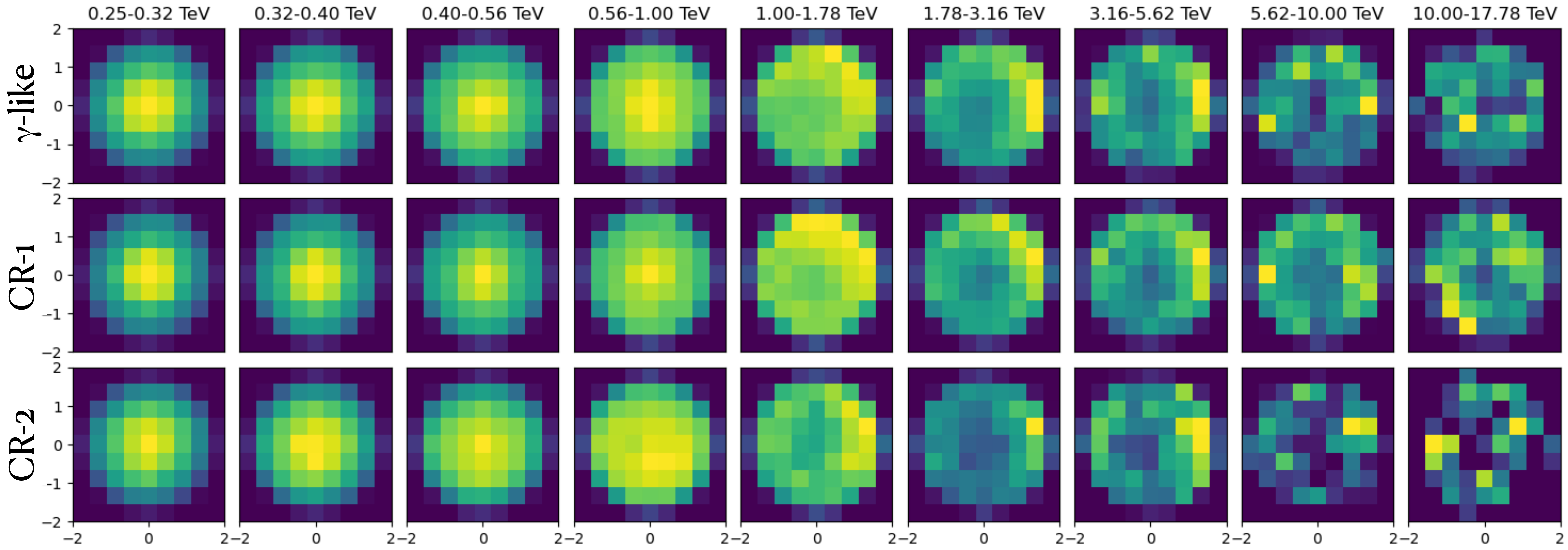
Vectorize

$\vec{x}_i$ from i-th OFF run

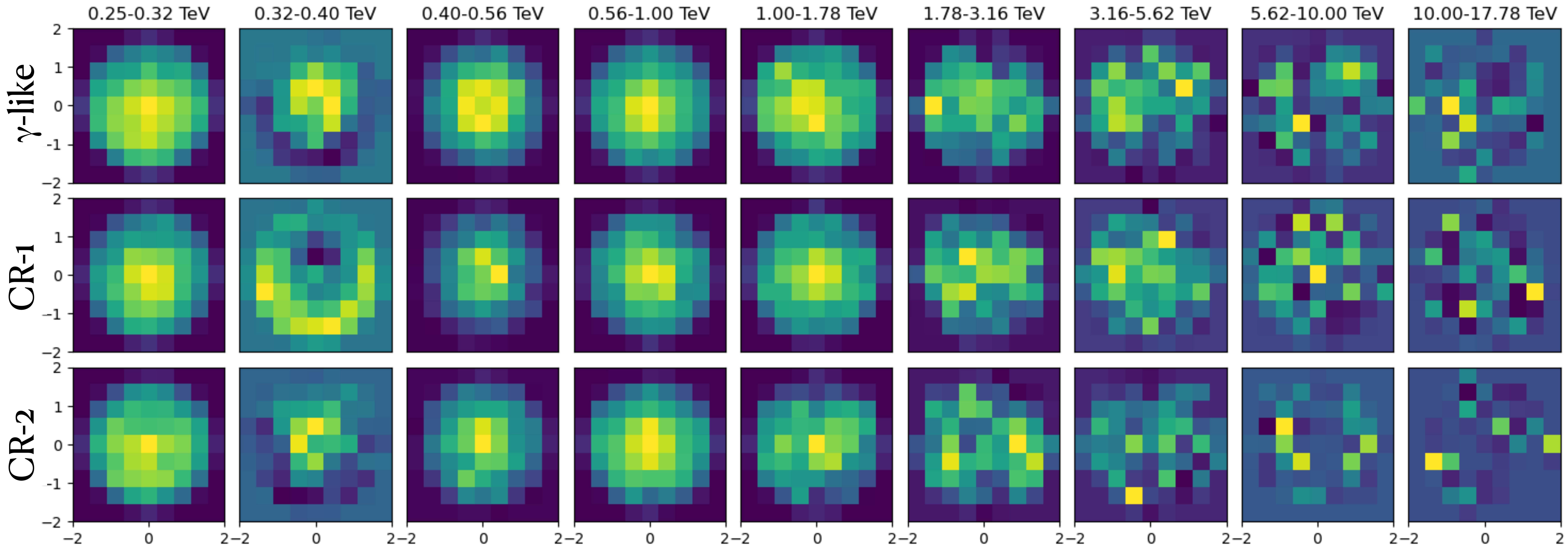


$$M = \begin{bmatrix} - - \vec{x}_0 - - \\ - - \vec{x}_1 - - \\ - - \vec{x}_2 - - \\ \vdots \\ \vdots \end{bmatrix} = \sum_k \sigma_k \vec{u}_k \vec{v}_k$$

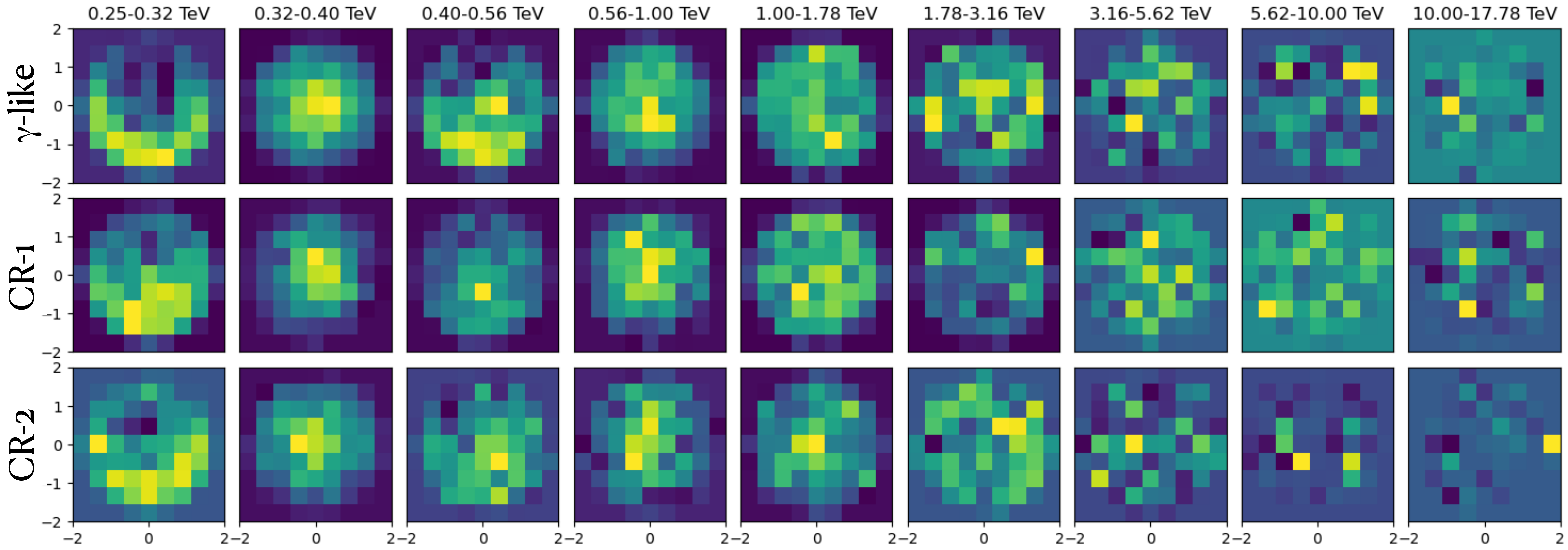
$k = 1$ eigenvector of background rate



$k = 2$ eigenvector of background rate



$k = 3$ eigenvector of background rate

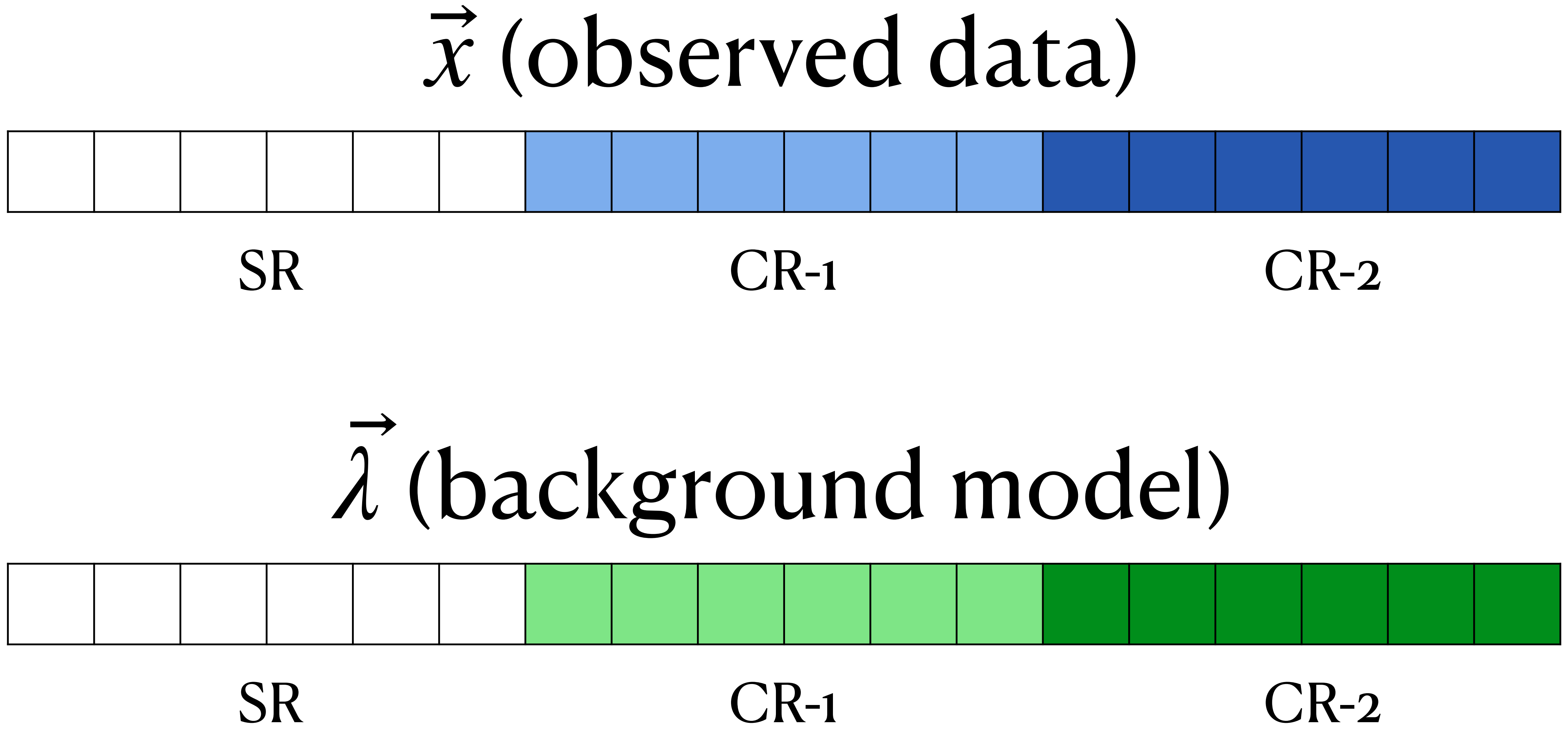


Building background model

$$\underbrace{\vec{\lambda}}_{\text{background model}} = \sum_{k=1}^{k_c} a_k \vec{v}_k$$

$$L_j(x_j \mid \lambda_j) = \frac{\lambda_j^{x_j} e^{-\lambda_j}}{x_j!}$$

$$\frac{\partial}{\partial \vec{a}} \left(\sum_{j \in \mathrm{CR}} \log L_j(\vec{a}) \right) = 0$$



Error maps of background modelings

$k_c = 1$

Error maps of background modelings

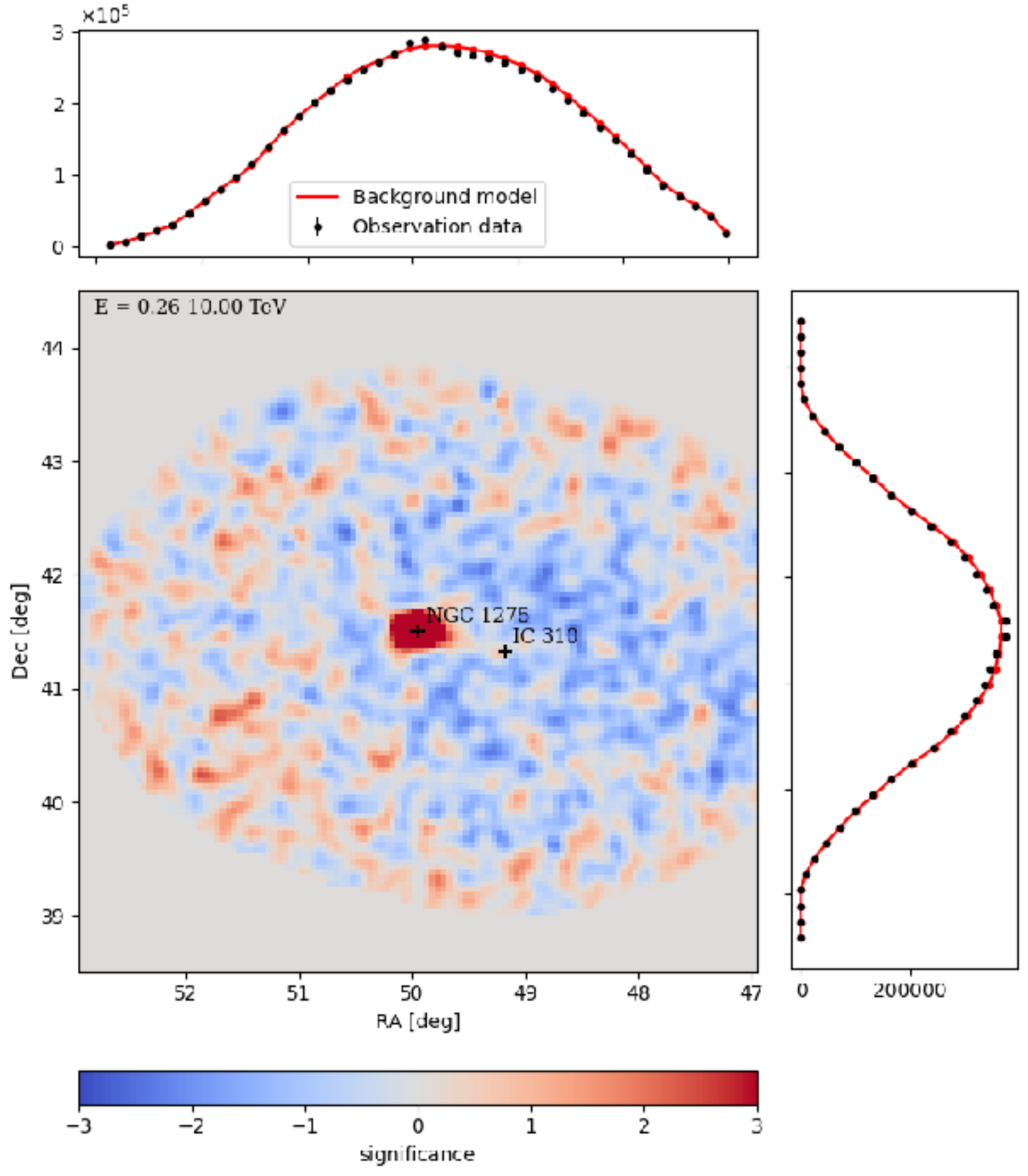
$k_c = 2$

Error maps of background modelings

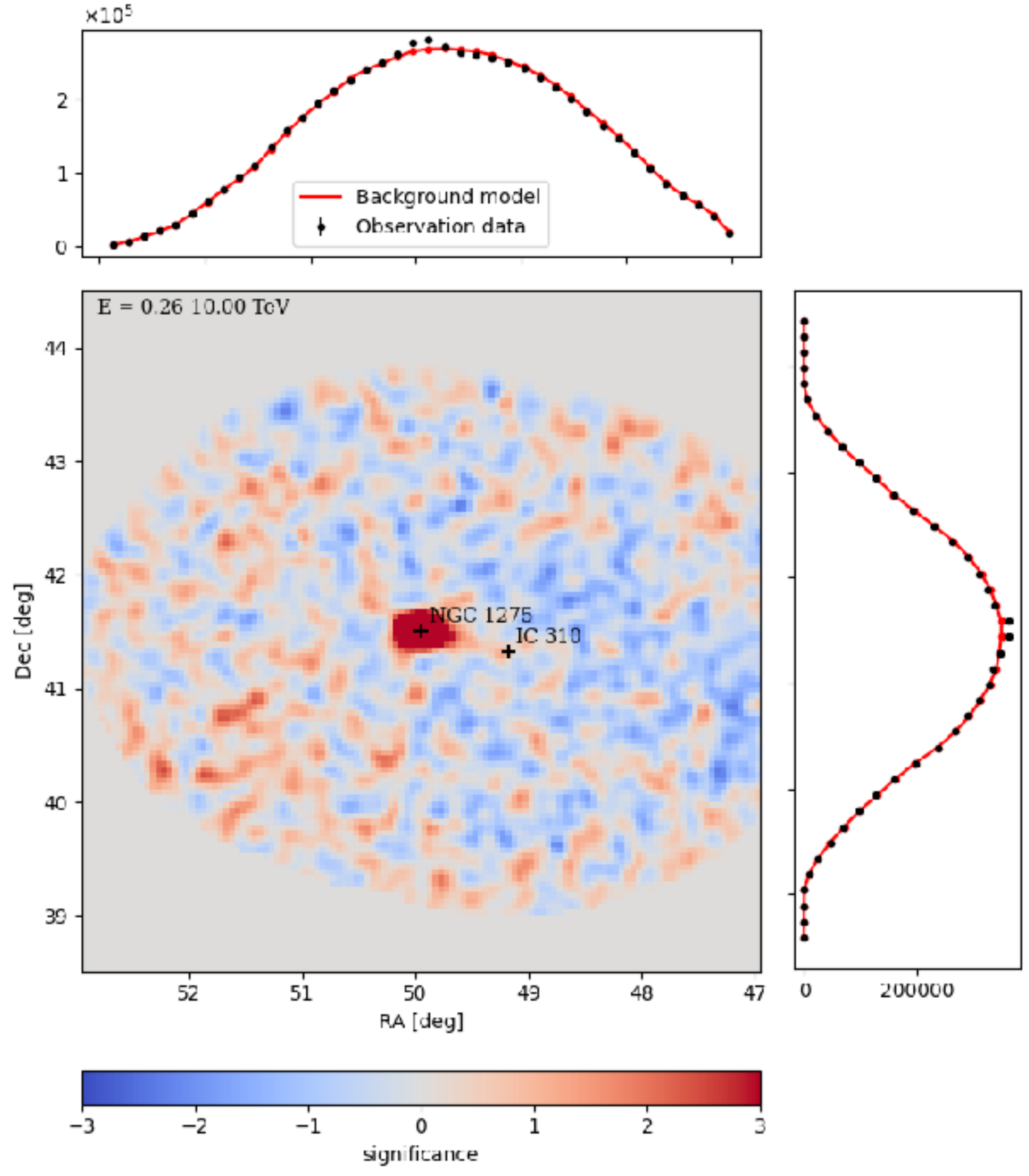
$k_c = 16$

Test with extragalactic point-like source

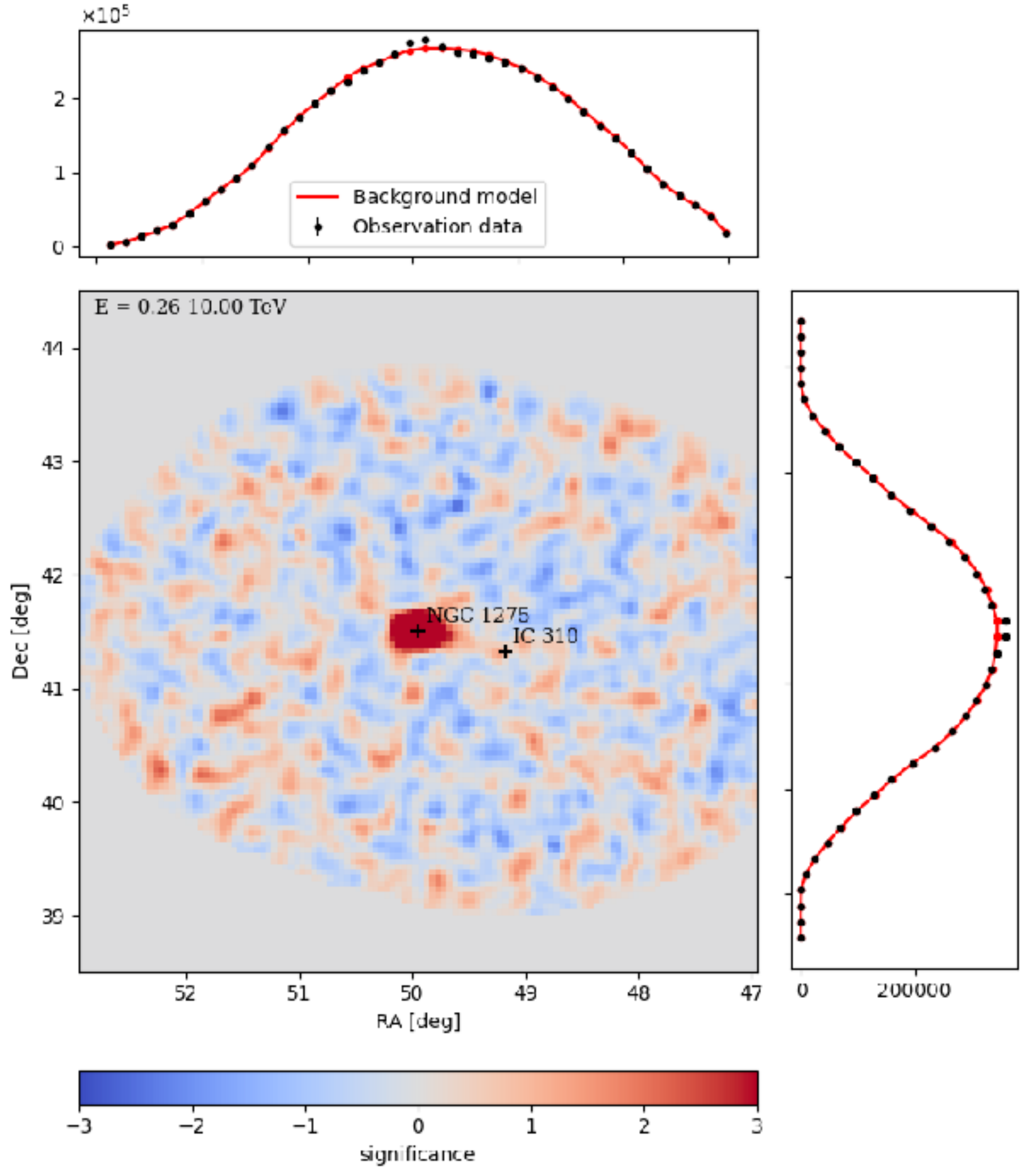
$k_c = 1$



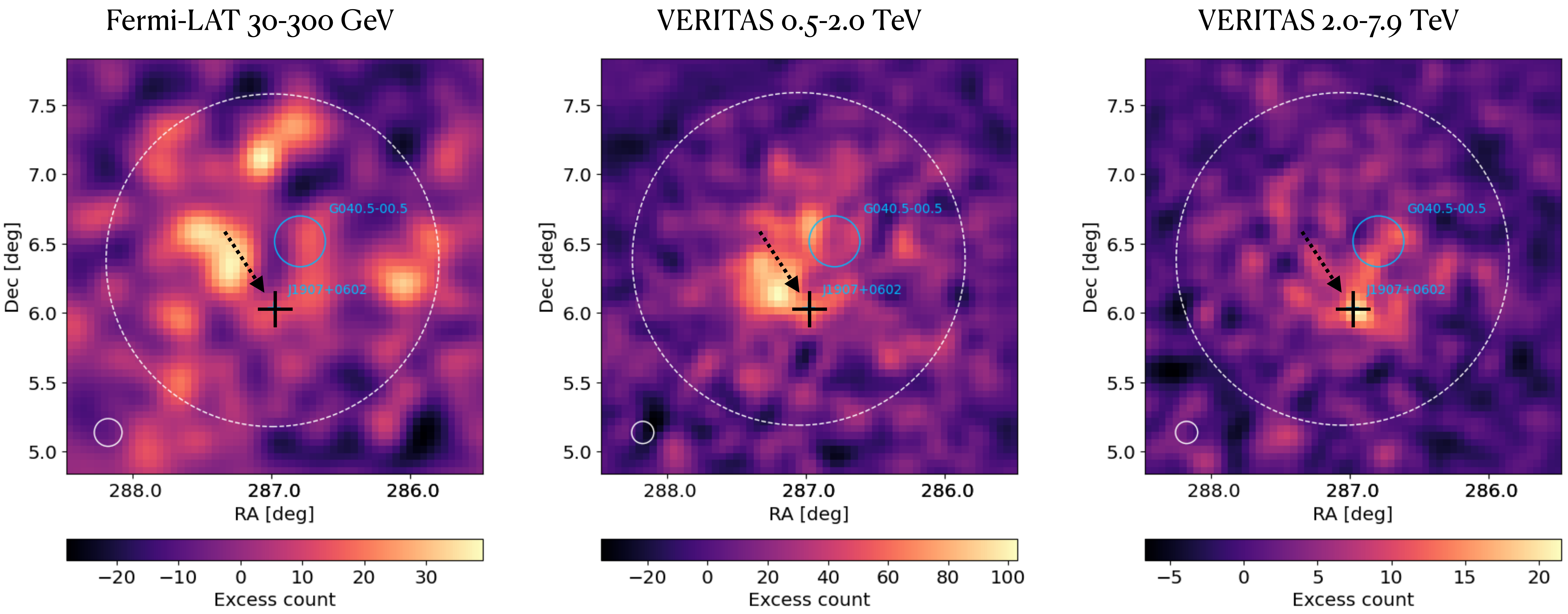
$k_c = 2$



$k_c = 16$



Gamma-ray morphology of an evolved PWN



Images of extended γ-ray emissions at different energies show the evolution of a middle-aged PWN

Future Plans

- The eigen-template background method enables analyses of sources with large angular extension (> instrument FoV)
- We are analyzing VERITAS data of Geminga observation
- We also plan to develop this technique as an official background model for the CTAO data