Friedrich-Alexander-Universität
Erlangen-Nürnberg

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H.E.S.S.

ecap Erlangen Centre for Astroparticle Physics

FAU

Background estimation for highly extended sources with IACTs

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Workshop High-energy astrophysics in the multi-messenger era
09.04.2024

Background estimation techniques for IACTs:

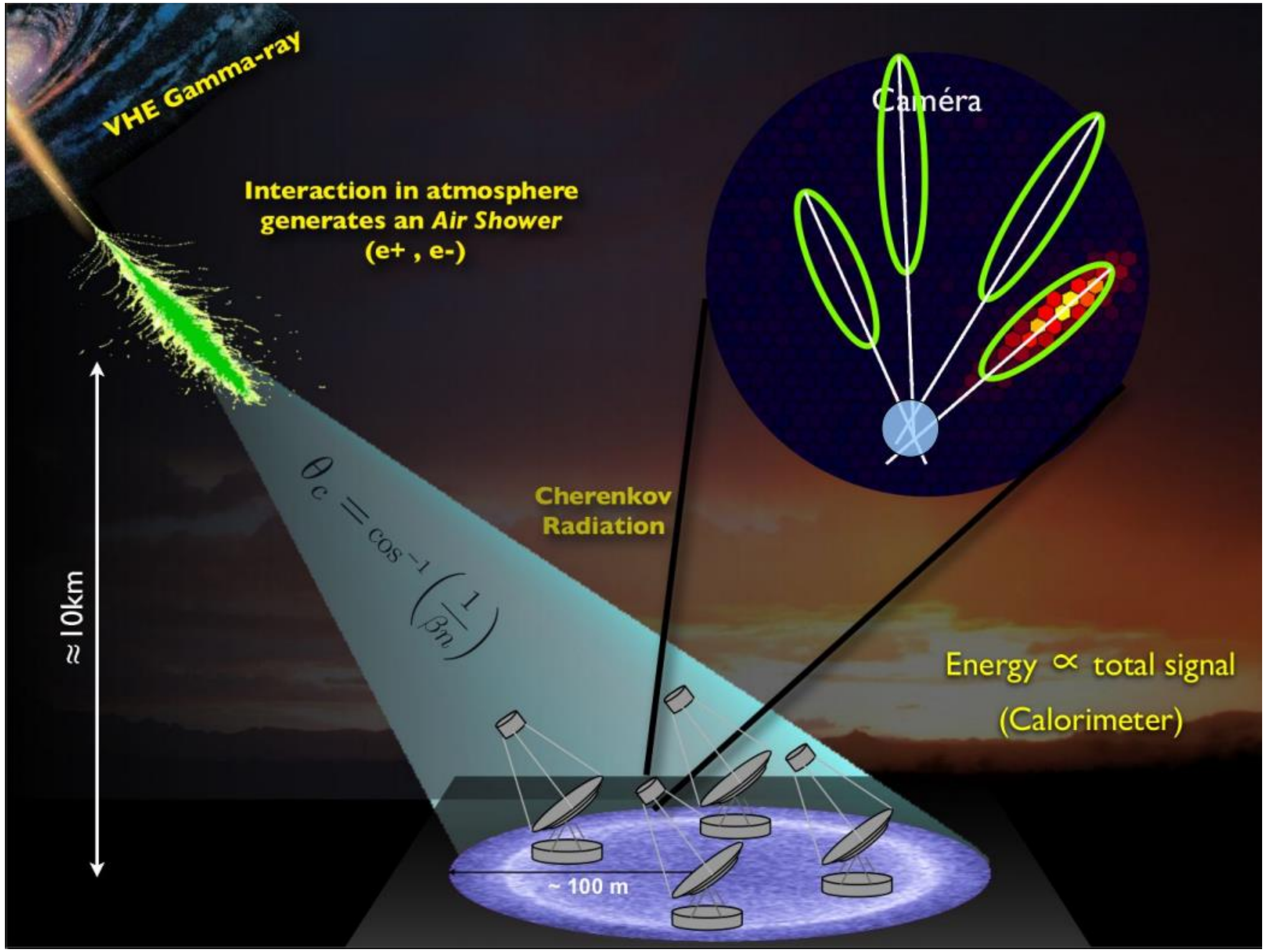
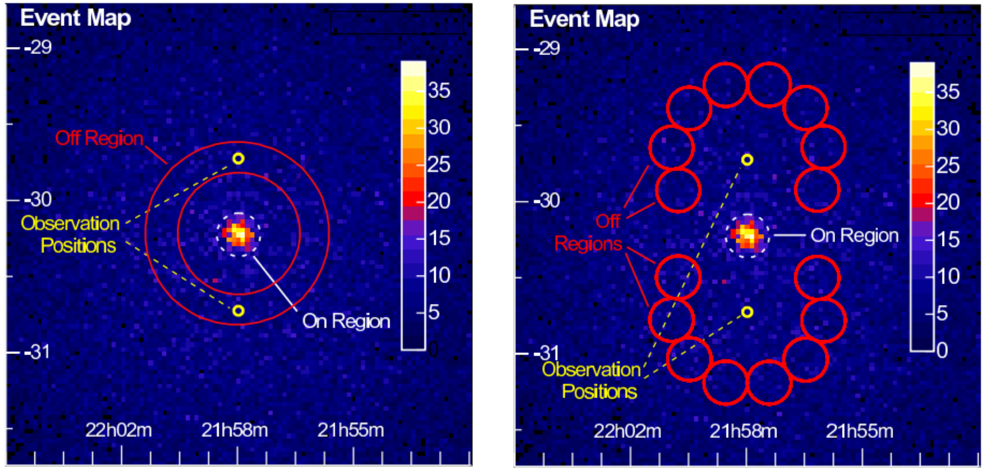


Image credit:K. Korsak

Background signal in IACTs:

- Misclassified cosmic-rays
- Diffuse γ-ray emission
- Often estimated from source-free regions in FOV
- Problematic for:
  - Extended sources
  - sources without a clear boundary
  - Emission located in highly populated areas



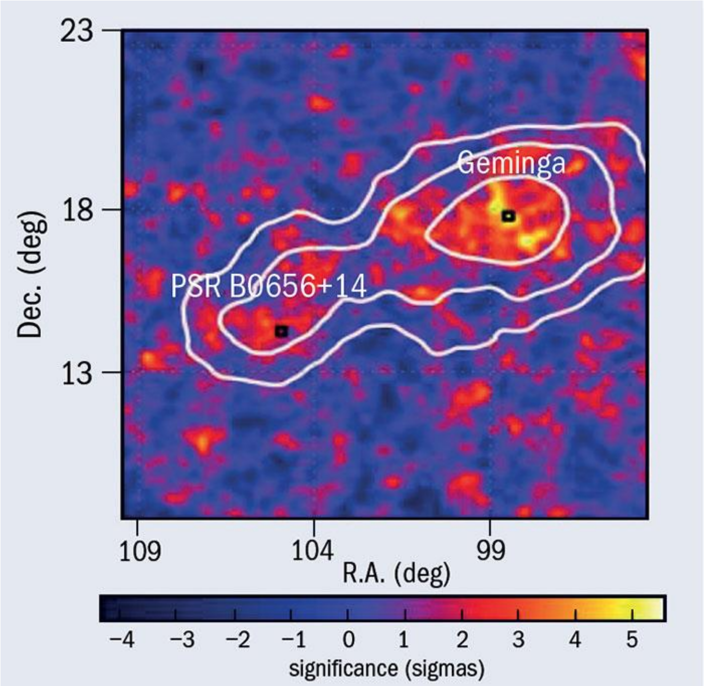
Berge, Funk, Hinton 2006

Background estimation and large, extended γ-ray sources: The Geminga Pulsar

The Halo around Geminga as seen by WCDs:

- first detection by Milagro (2009)
- Large, extended emission

HAWC Collab., 2017



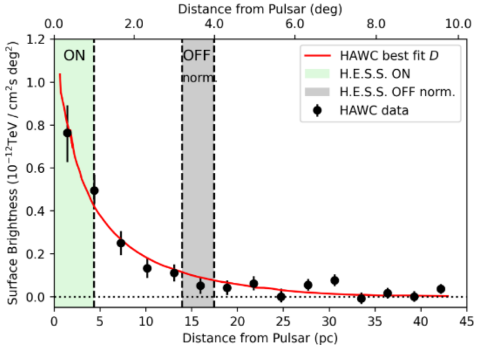
Background estimation and large, extended γ-ray sources: The Geminga Pulsar

The Halo around Geminga as seen by WCDs:

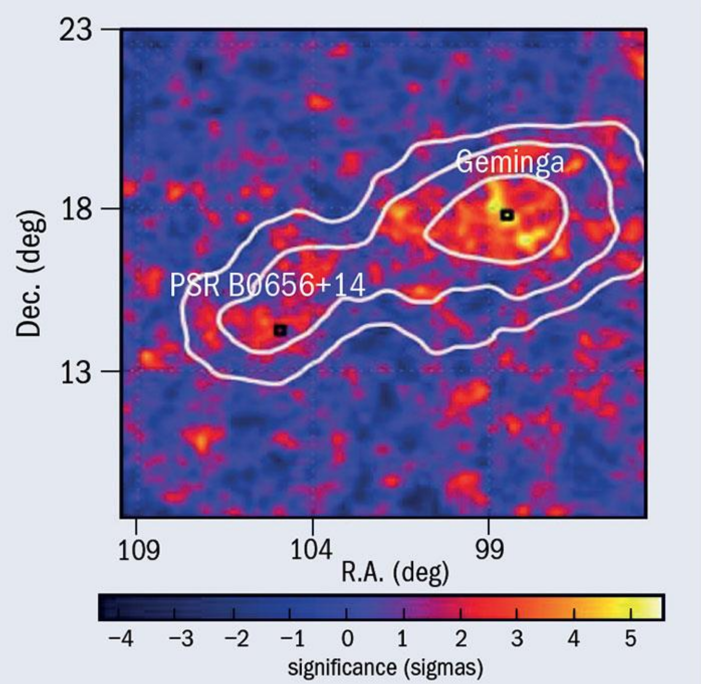
- first detection by Milagro (2009)
- Large, extended emission

The Halo around Geminga as seen by H.E.S.S.:

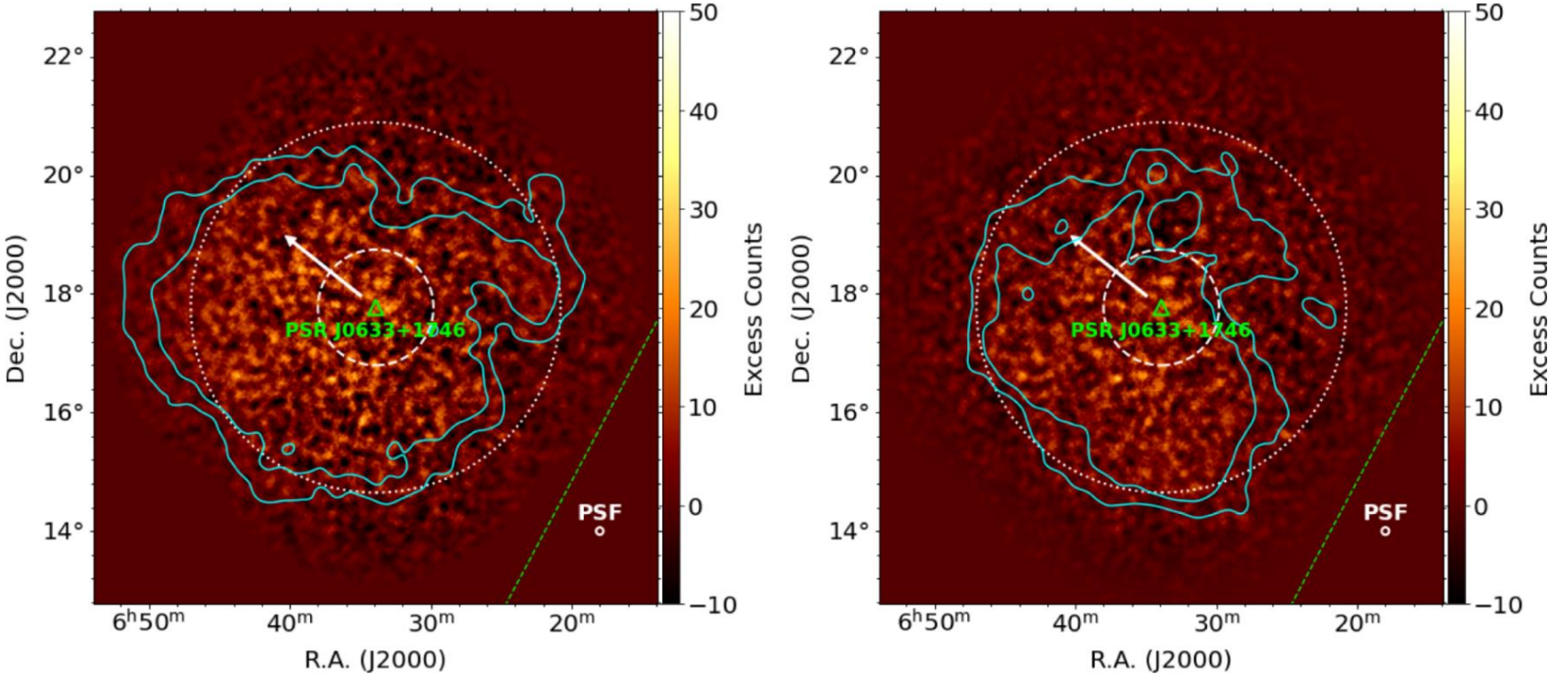
- Edge of the emission can‘t be detected
- No absolute flux measurement
- Strongly dependent on background estimation (left:On-Off background, right: FoV background)



HAWC Collab., 2017



HESS Collab., 2023



Background estimation techniques for IACTs:

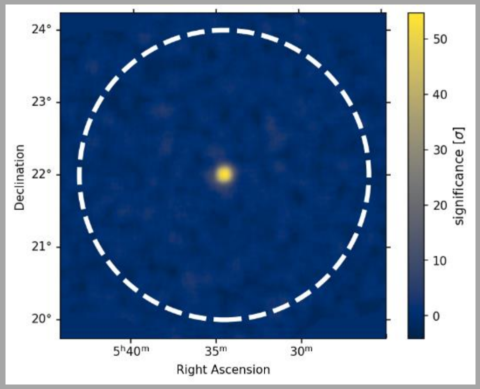
ON-OFF method:

Advantages:

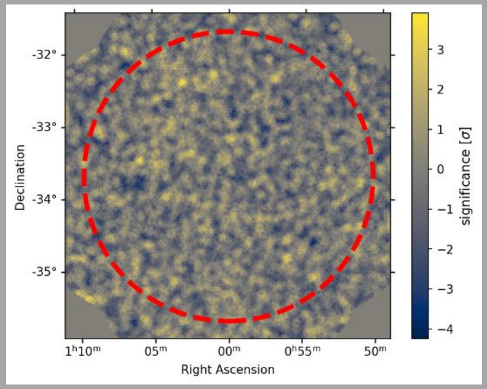
- no assumptions for source morphology necessary

Disadvantages:

- Short timespans between ON and OFF run necessary
- Only half of the observation time is spent on the Target



ON-Region



OFF-Region

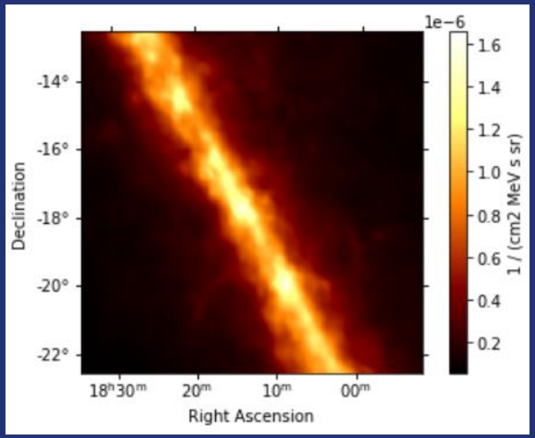
3d background model template:

Advantages:

- Very robust
- Valid for observations between major hardware changes

Disadvantages:

- Requires emission-free region in the FOV



Example of an background model template for galactic diffuse emission from the Fermi-LAT Collaboration

Background estimation techniques for IACTs:

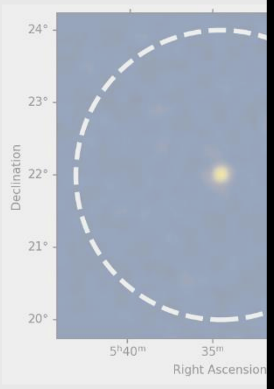
ON-OFF method:

Advantages:

- no assumpt

Disadvantage

- Short times necessary
- Only half of Target



ON-Re

3d background model template:

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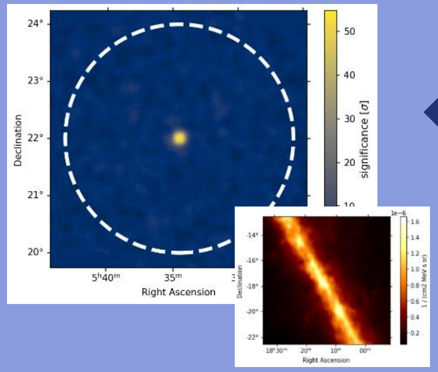
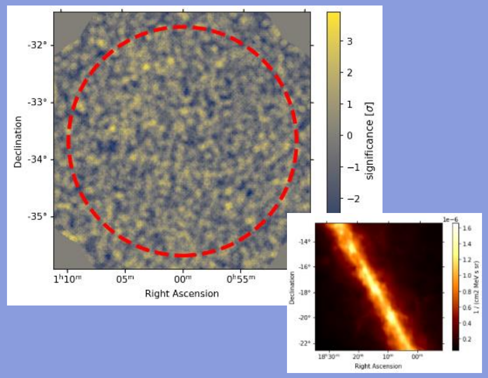
Collaboration

Run-matching approach:

- Obtain normalisation factor from an OFF run
- Apply the normalisation to the target ON run
- **Advantages:**
  - No source-free region necessary
  - Small statistical uncertainty





Background estimation using the run-matching approach:

Step 1: Run matching

- Find OFF runs acquired under similar observation conditions
  - latitude b > |10 °|
  - timespan with stable optical efficiency
  - Same telescope combination
- The best match:
  - Evaluate influence of all matching parameters (r_j^2)
  - Minimise fractional run deviation **f**

$$f = \sum_j r_j^2 \cdot \frac{x^j_{\text{on}} - x^j_{\text{off}}}{x^j_{\text{on}}}$$

Matching Parameter	Validity range
Zenith angle	Background model bins
Trigger Rate	Δr < 100 Hz
Observation duration	Δt < 120s
Transparancy coefficient	Δτ < 0.05
Muon Efficiency	Δε < 0.01
Night Sky Background	ΔNSB < 100 Hz

Background estimation using the run-matching approach:

Step 1: Run matching

- Find OFF runs acquired under similar observation conditions
  - latitude -10° < b > 10 °
  - Only consider runs in a timespan with stable optical efficiency
  - Same telescope pattern
- The best match:
  - Identify influence of all matching parameters (r_j^2)
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$$f = \sum_j r_j^2 \cdot \frac{x_{\text{on}}^j - x_{\text{off}}^j}{x_{\text{on}}^j}$$

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Night Sky Background	$\Delta NSB < 100$ Hz

Step 2: Fit of the background model template

Fit background model template to the OFF run using the spectral index δ and the flux normalization Φ, such that:

$$R_{BG}^{*} = \Phi \cdot R_{BG} \cdot (E/E_0)^{-\delta}$$

Background estimation using the run-matching approach:

Step 3: Map the background template to the ON run

- Use spectral index δ and flux normalization Φ from Step 2 for the ON run

Step 1: Run matching

- Find OFF runs acquired under similar observation conditions
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Background estimation using the run-matching approach:

Step 4: Correct for differences between ON and OFF run

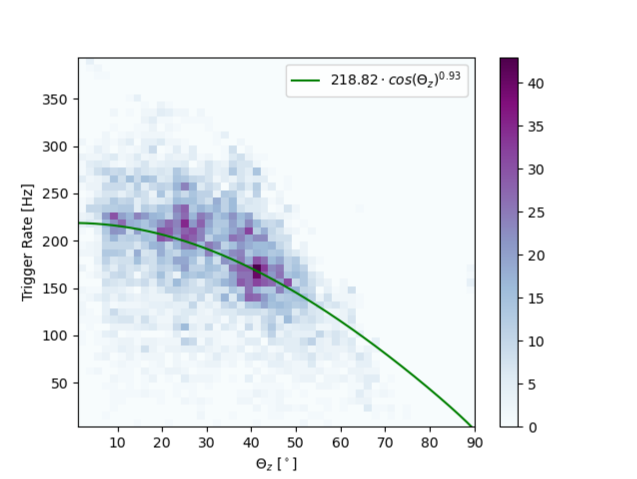
- Correct for differences in observation time via:

$$b_{i,ON} = \frac{b_{i,OFF} \cdot t_{ON}}{t_{OFF}}$$

- Correct for differences in Zenith angle via:

$$b_{ON} = b_{OFF} \cdot p_1 \cos\left(\Theta_z\right)^{p_2}$$

with p_1 and p_2 derived from a fit to the system trigger rates (time-/epoch-dependent)



Step 1: Run matching

- Find OFF runs acquired under similar observation conditions
  - latitude -10° < b > 10 °
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$$f = \sum_j r_j^2 \cdot \frac{x_{\rm on}^j - x_{\rm off}^j}{x_{\rm on}^j}$$

Matching Parameter	Validity range
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Step 3: Map the background template to the ON run

- Use spectral index δ and flux normalization Φ from Step 2 for the ON run

Step 2: Fit of the background model template

Fit BT to the OFF run using the spectral index δ and the flux normalization Φ, such that:

$$R^*_{BG} = \Phi \cdot R_{BG} \cdot (E/E_0)^{-\delta}$$

Background estimation using the run-matching approach:

Step 4: Co

- Correct

$b_{i,ON}$

- Correct

$b_{ON} =$

with p_1 a

Successfully tested for the H.E.S.S. array:

- Empty field regions (Reticulum II, Tucana II, NGC 253)
- Crab Nebula
- Galactic, extended sources (MSH 15-52, RX J1713.7-3946)
- Soft spectrum sources (PKS 2155-304)

Image Credit: HESS Collab

Step 1: Run matching

- Find OFF runs a
  - latitude -
  - Only co
  - Same te
- The best match:
  - Identify i
  - Minimise

$$f = \sum_j r_j^2 \cdot \frac{x_{\text{on}}^j - x_{\text{off}}^j}{x_{\text{on}}^j}$$

Transparency coefficient	Δτ < 0.05
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Fit BT to the OFF run using the spectral index δ and the flux normalization Φ, such that:

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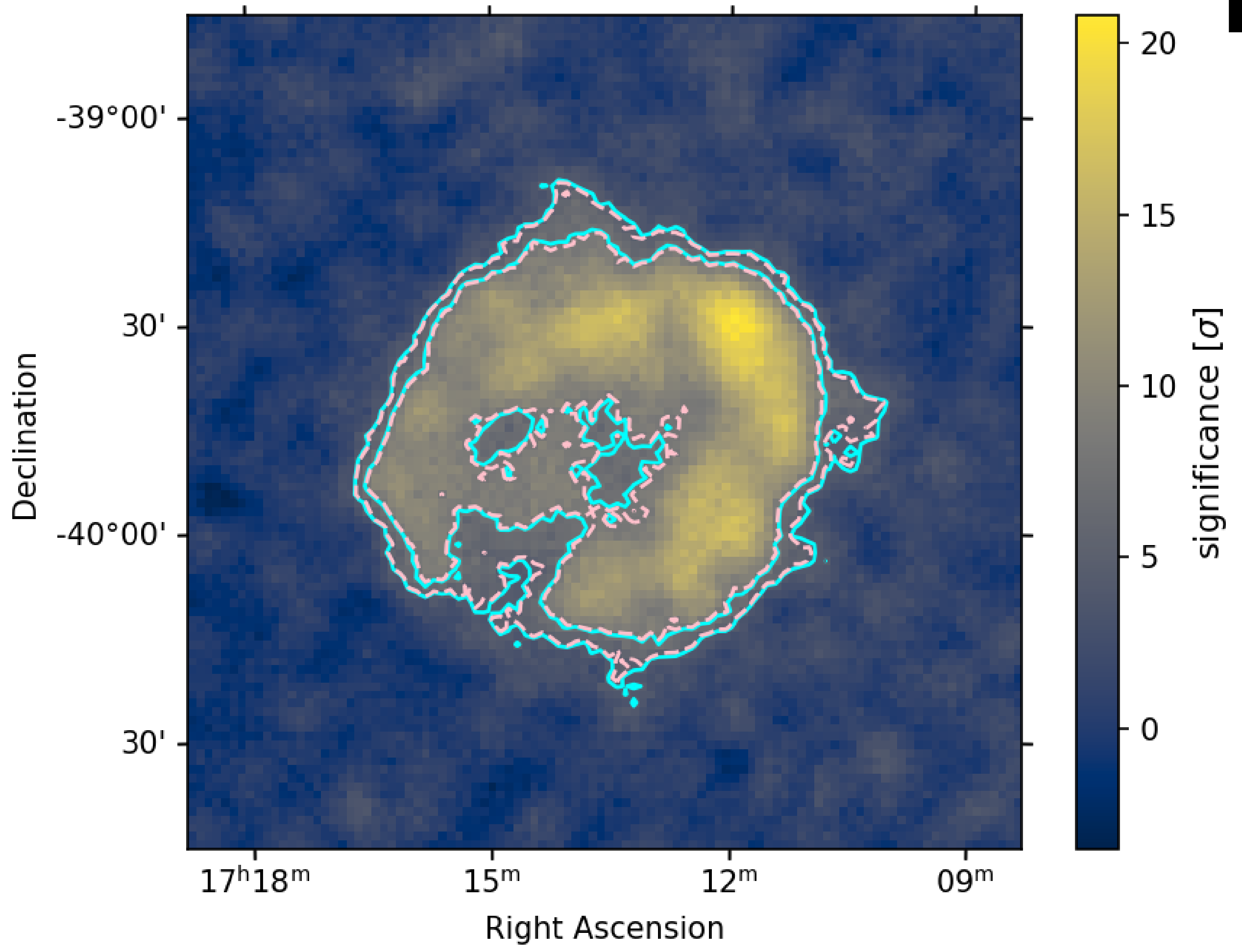
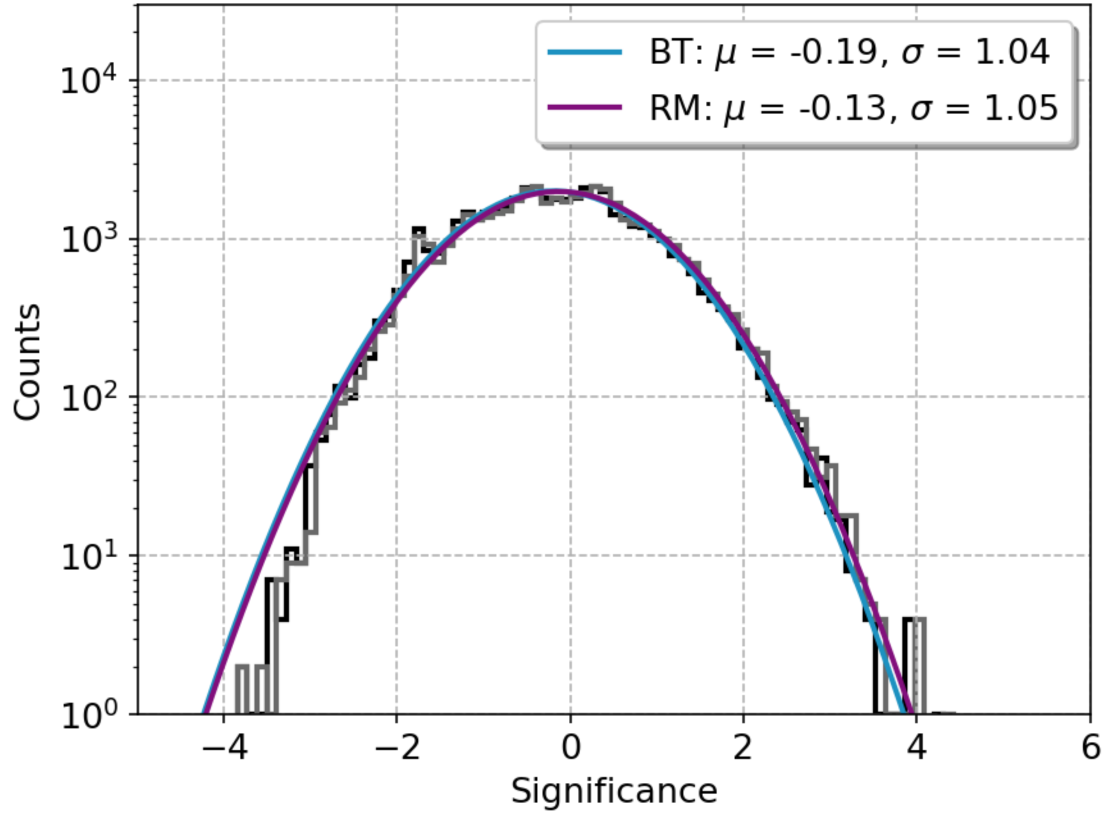
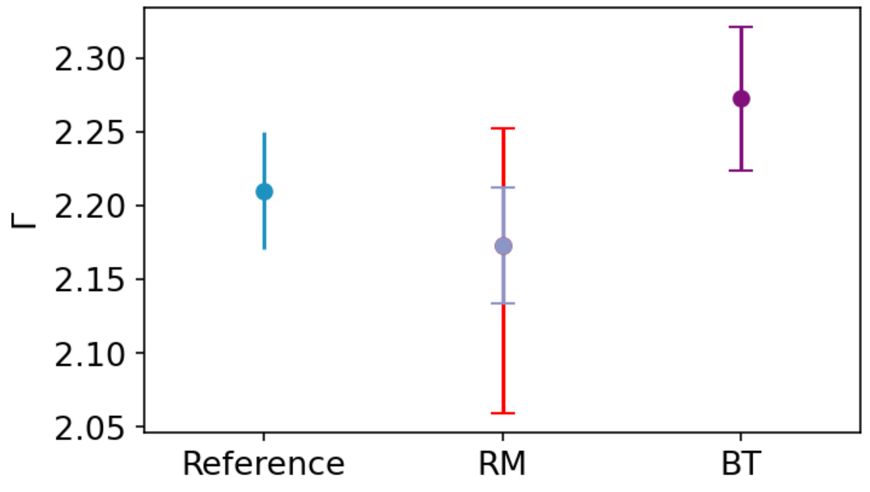
Validation: RX J1713.7-3946

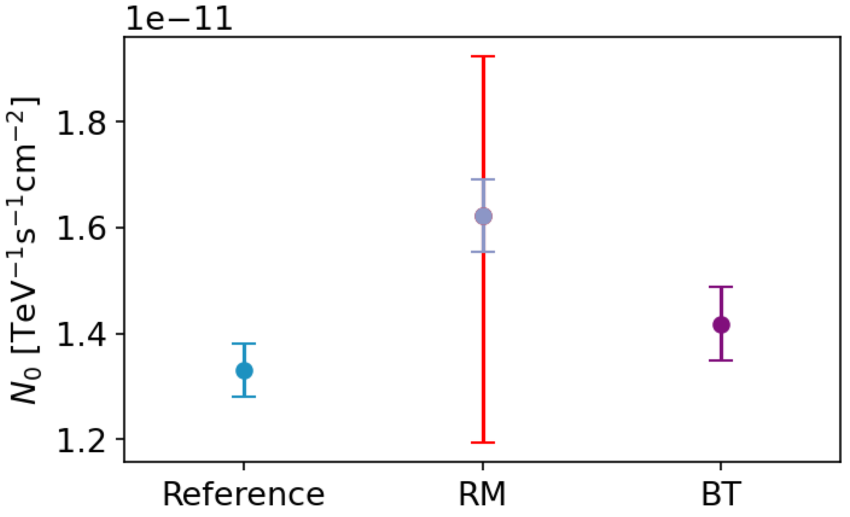
Background template
Run matching approach

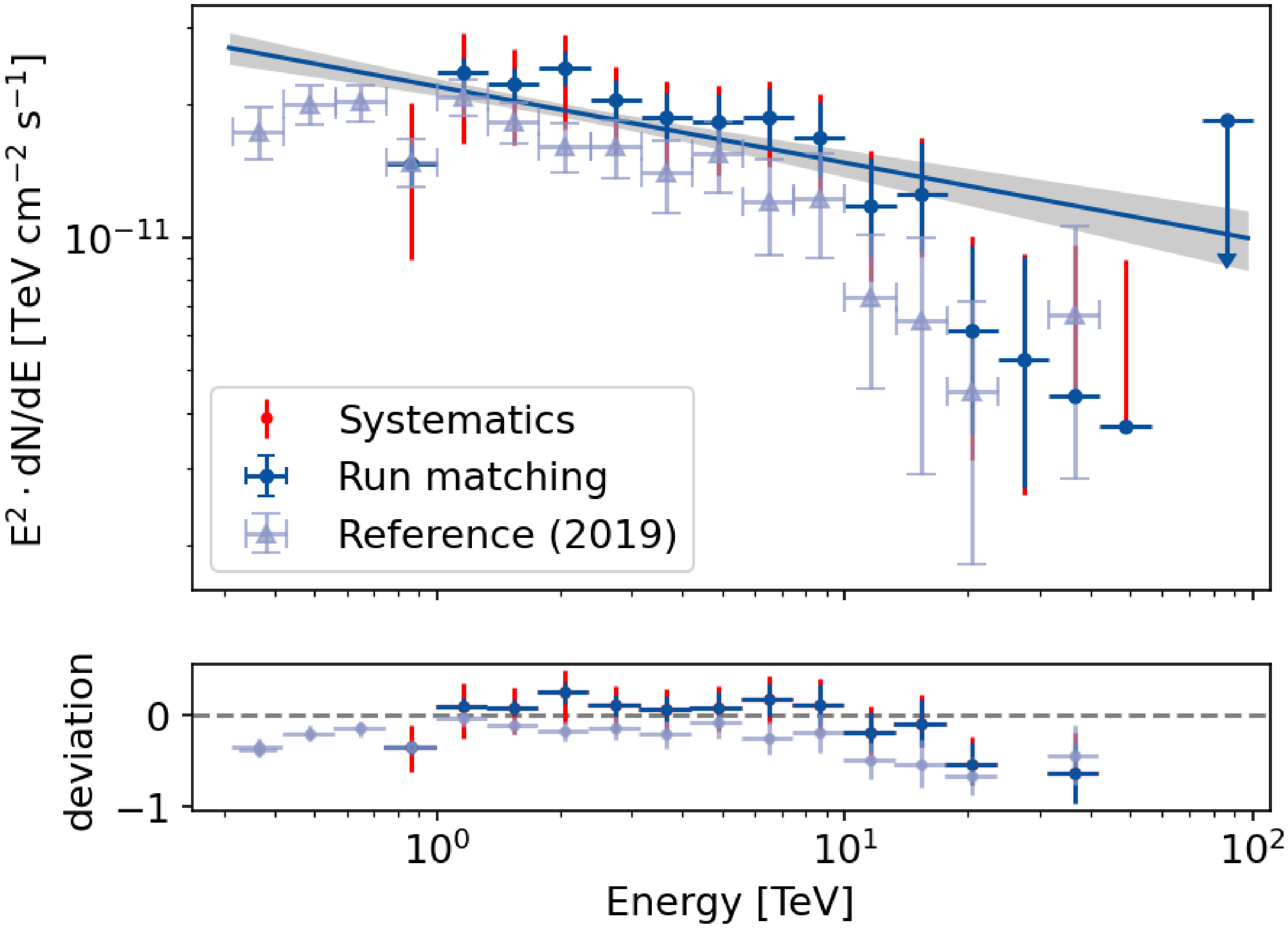




Validation: RX J1713.7-3946 with systematic uncertainties





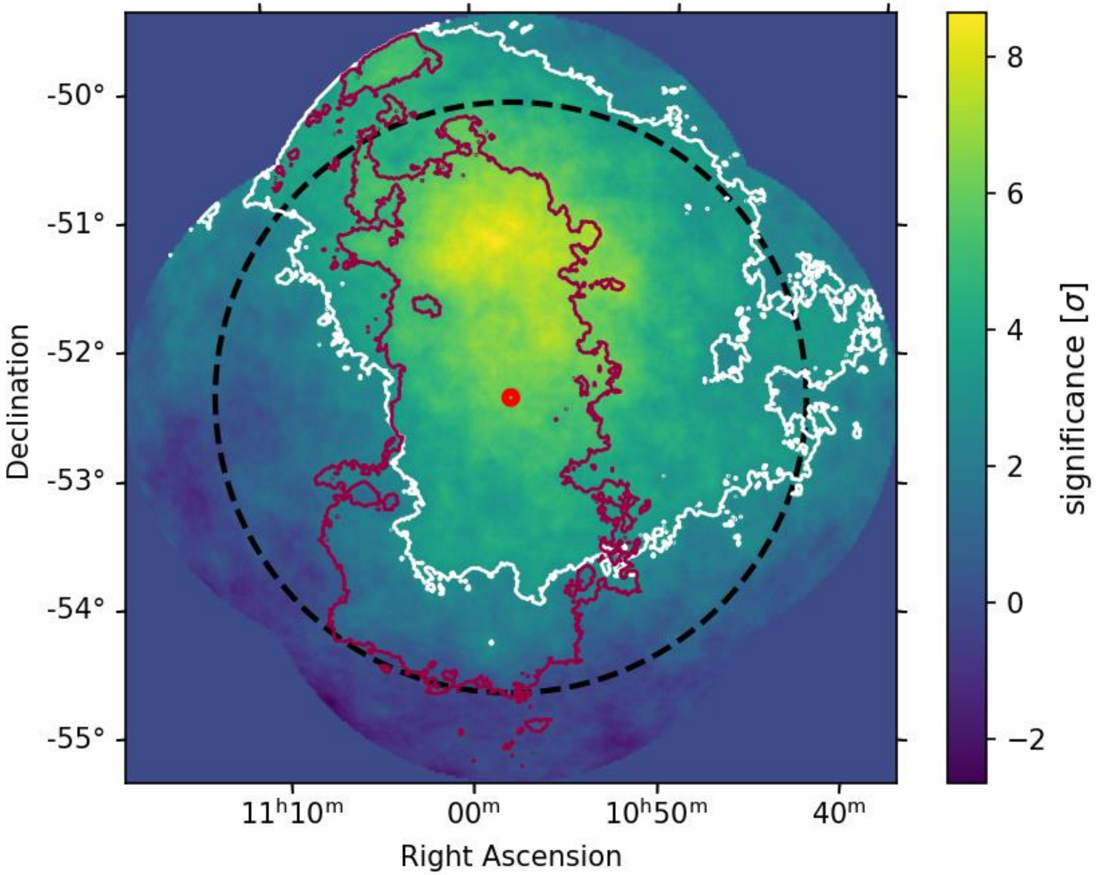


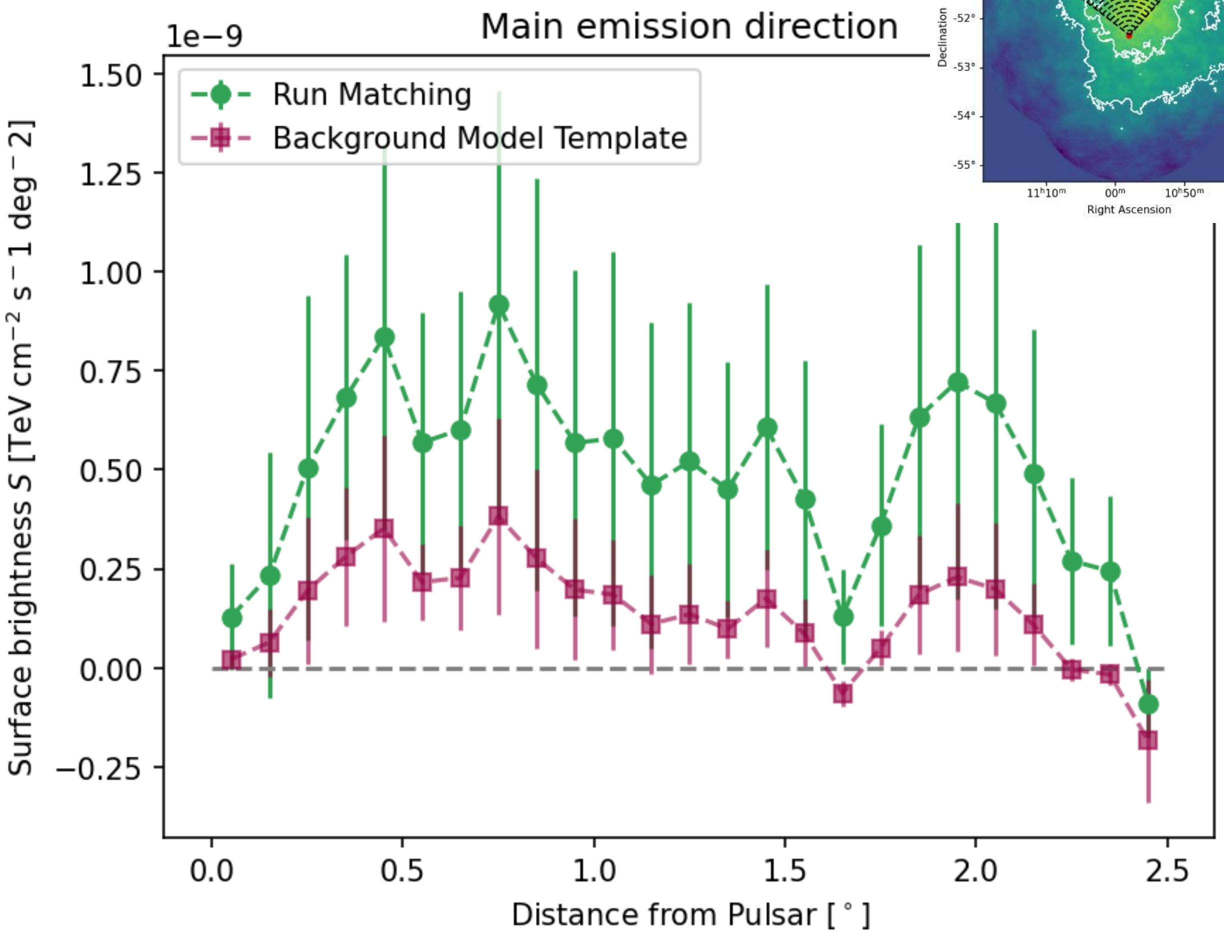
The Application: PSR B1055-52

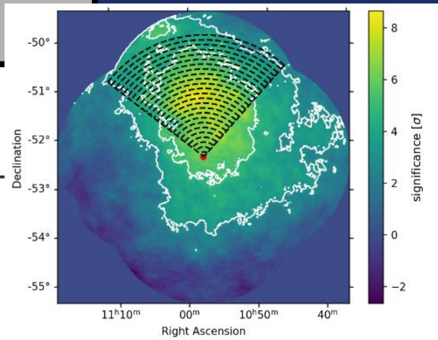
3 σ contours for the RM dataset

3 σ contours for the BT dataset

excl region for BT in black, 1° correlation radius







Summary

Advantages:
- Small statistical error
- Large timespans between ON and OFF run possible
- Background estimation becomes possible in challenging sky regions
- Absolute flux measurement of sources filling the FOV of the telescope
- Can be done completely with open source tools

Disadvantages:
- Substantial amount of archival data on empty-sky regions required
- Relies on a good understanding of insturment response
- For galactic sources an energy threshold is needed to exclude the galactic diffuse emission

Backup Slides

Systematic errors:

Estimation of systematics:

1. Identify observations on a with small γ-ray contamination shortly before and after the target runs
2. Find all possible OFF runs
3. Analyze these observation pairs using the BT directly and with the Run matching (RM) approach
4. Compute the deviation:

$$\Delta R_{BG} = \frac{|R_{BG,BT} - R_{BG,RM}|}{R_{BG,BT}}$$

5. Group by fractional run deviation
6. Calculate standard deviation for each frac run deviation