Friedrich-Alexander-Universität
Erlangen-Nürnberg

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German Research Foundation

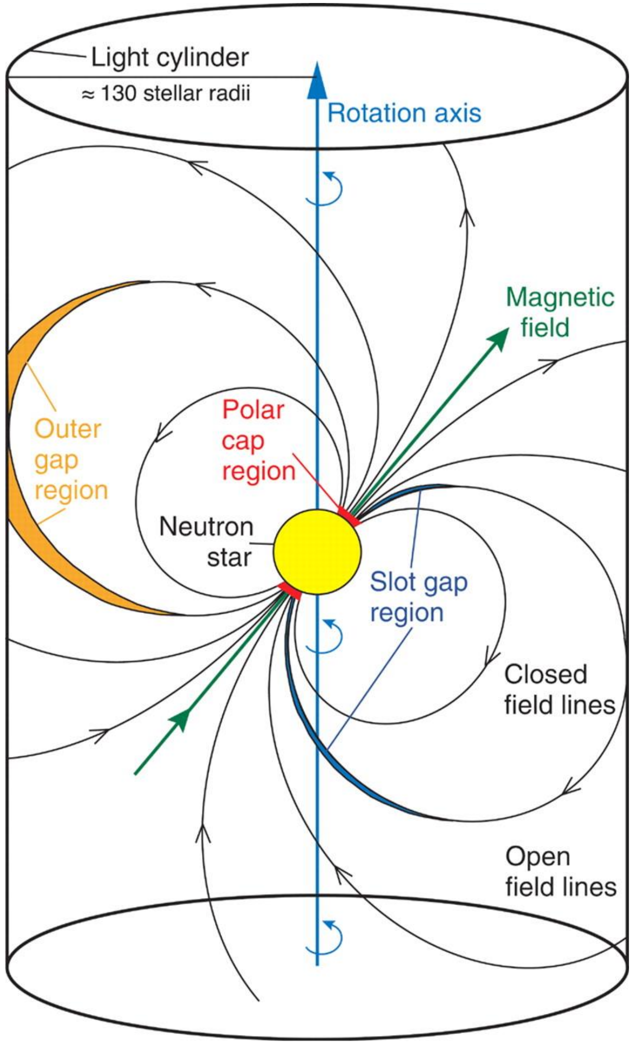
Detection of gamma-ray pulsar halos with H.E.S.S.

Tina Wach

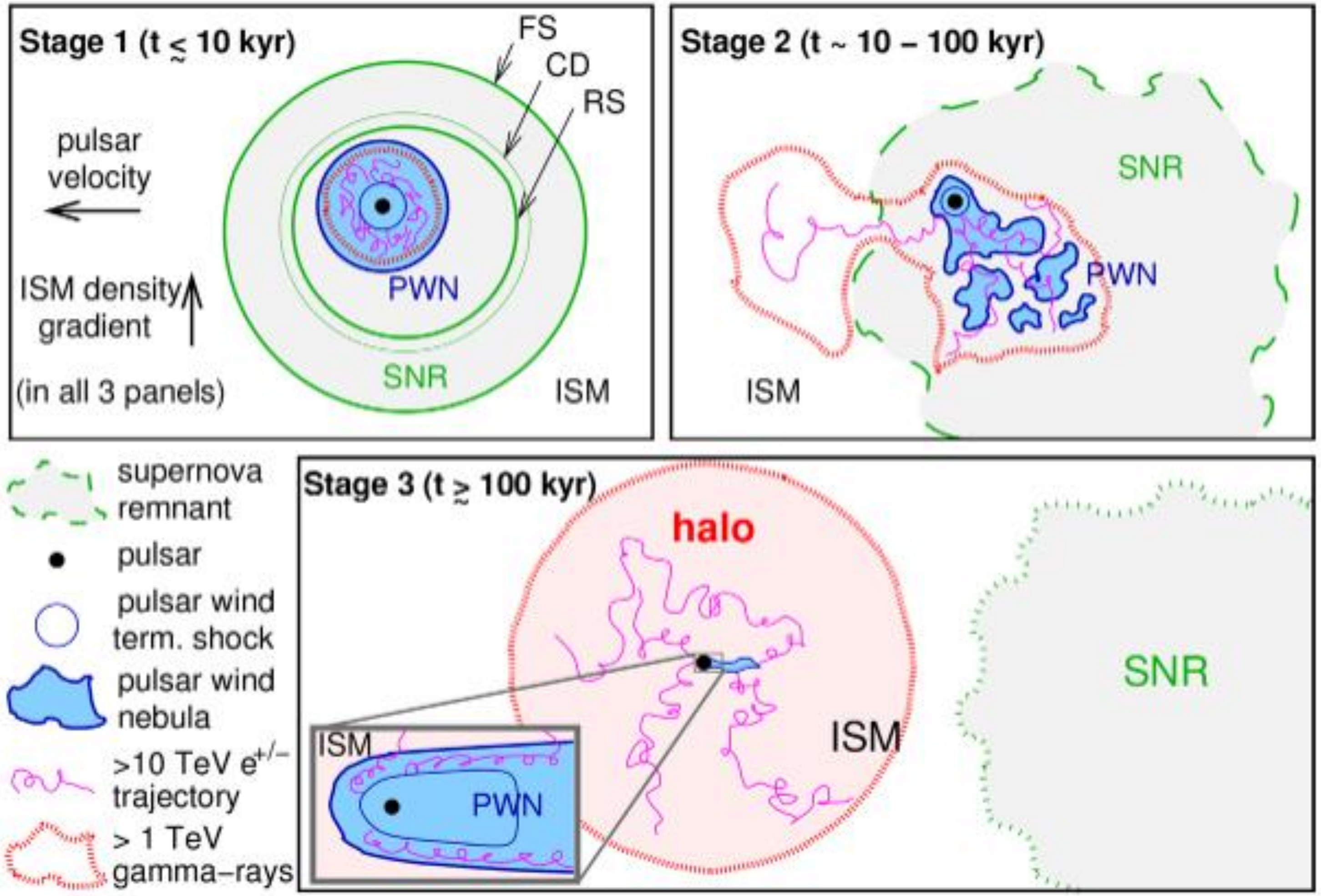
High-energy astrophysics in the multi-messenger era

Erlangen 2023

Evolution of a pulsar wind nebula



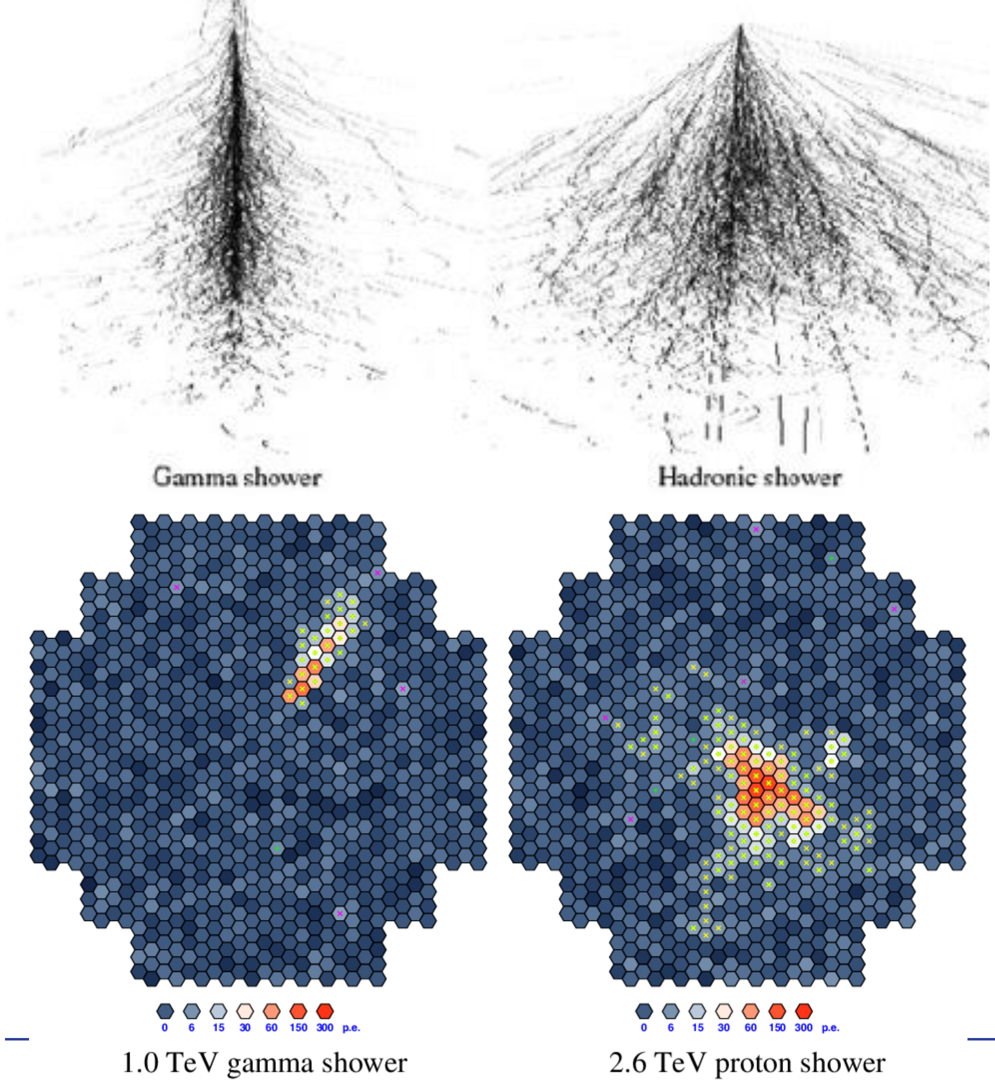
Magic Collab. 2008



G. Giancinti. 2020

Imaging Atmospheric Cherenkov Telescope

Image credit: O. Kirstein



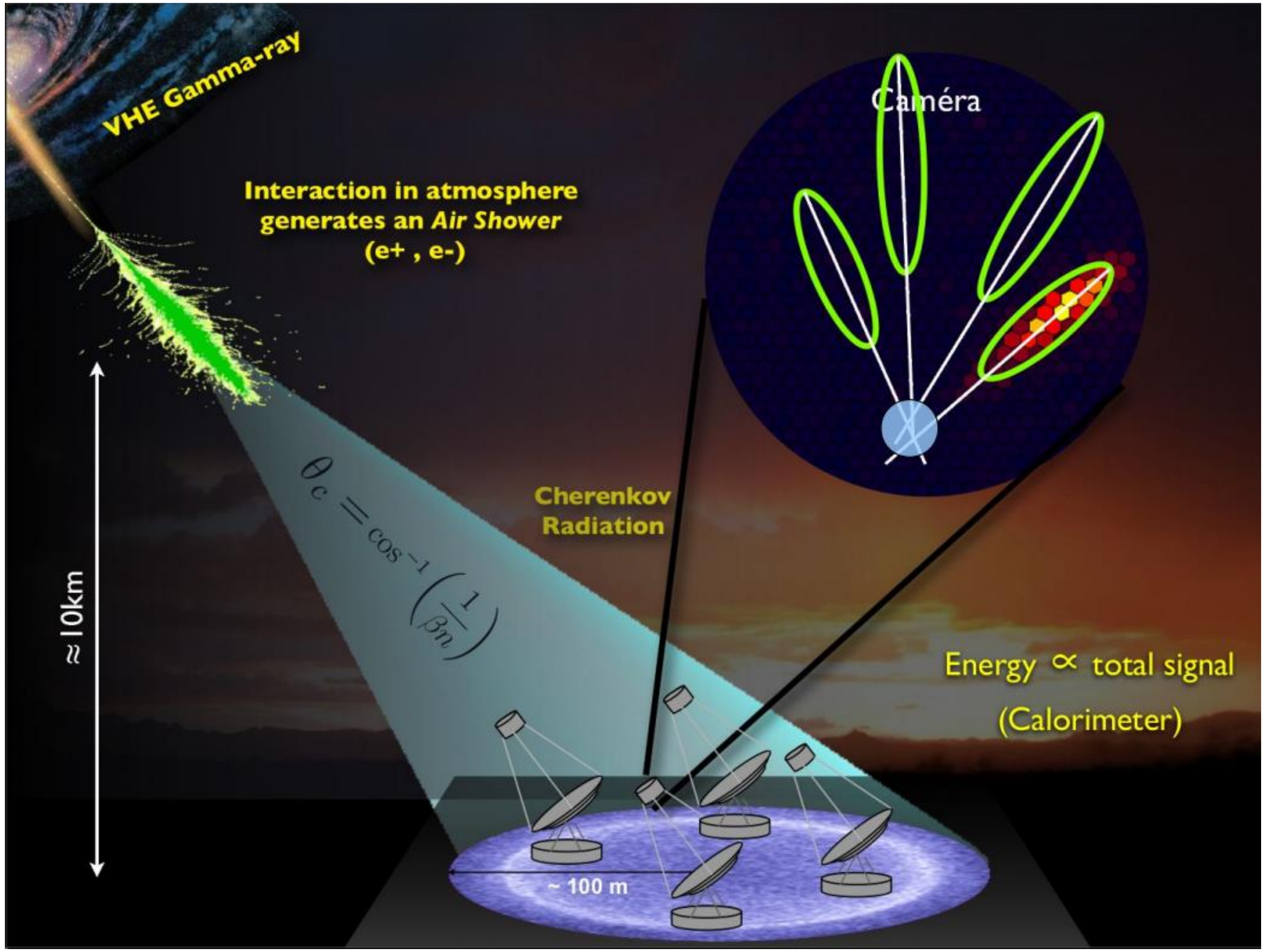


Image credit: K. Bernlöhr

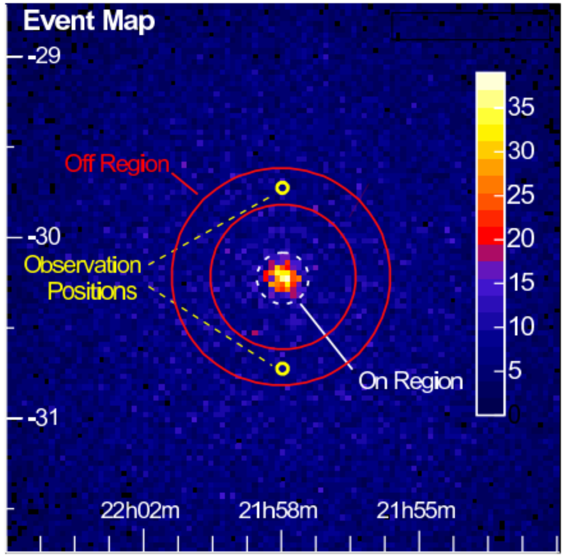
Analysis of largely extended sources:

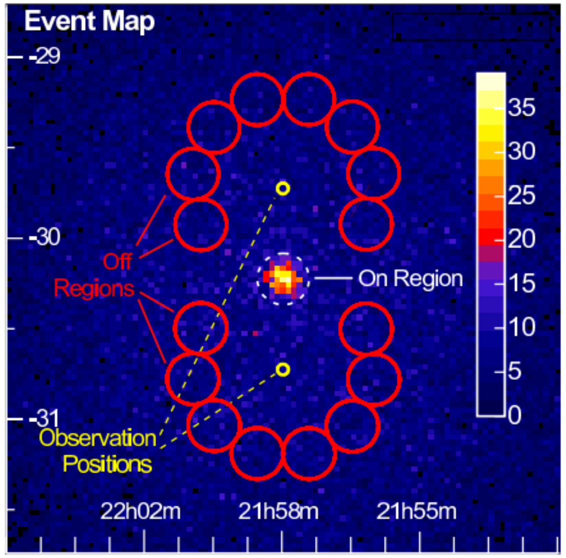
Ringbackground

On-Off background

Reflected Regions background

problematic for:
- extended sources
- sources without defined edge
- sources in highly populated area





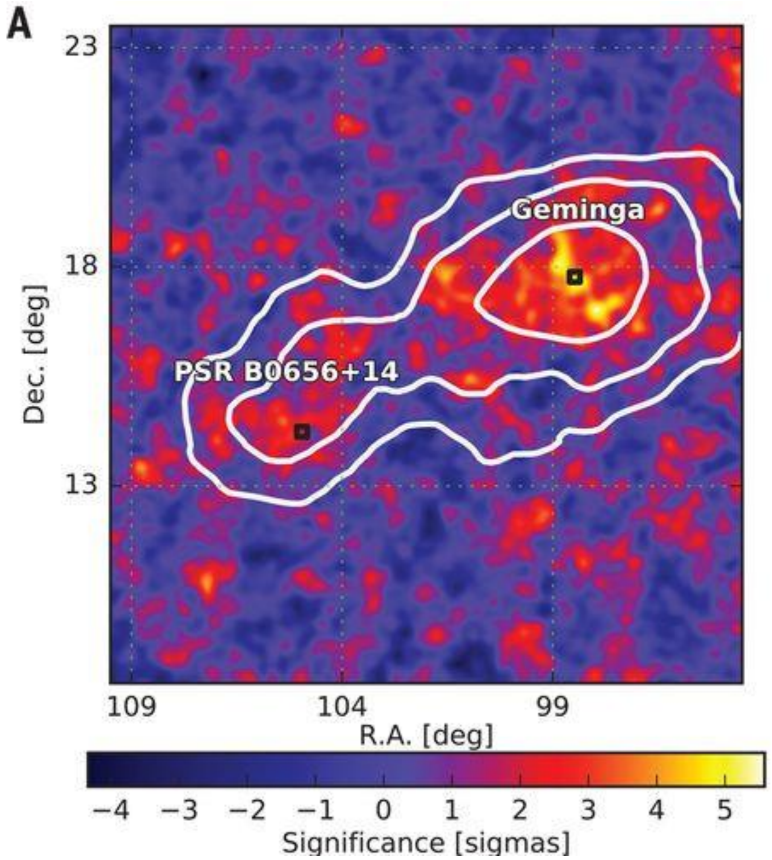
Berge, Funk, Hinton 2006

FOV background

- Only defined out to 2.5 ° from the pointing center
- Already at 2.3 ° edge artefacts start to appear
- Some off region is still necessary to adjust flux normalization and spectral index to the respective observation

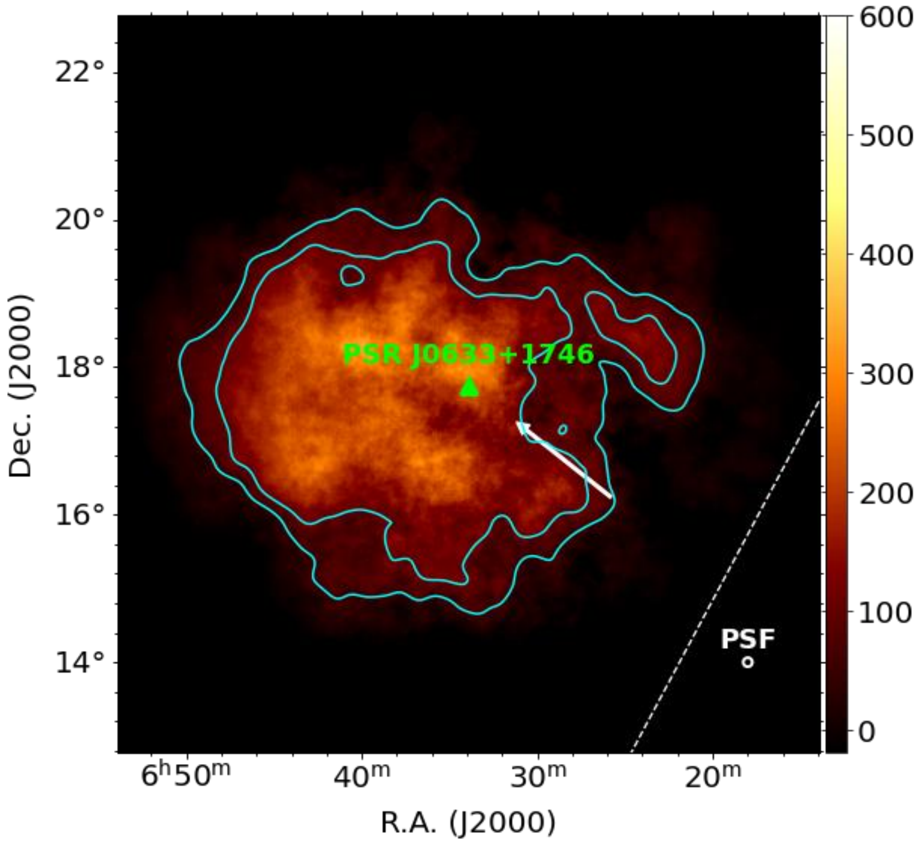
Motivation for the new method:

Geminga + Monogem region as seen with HAWC:



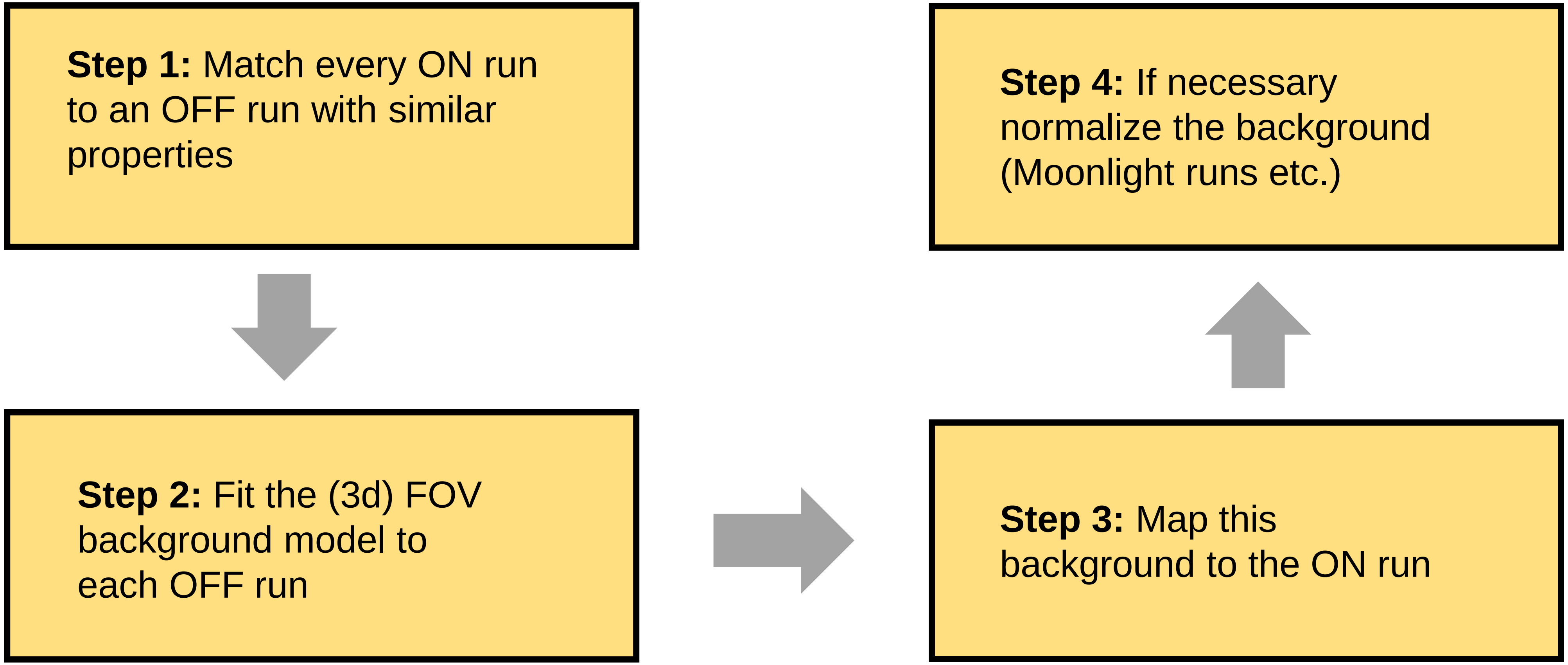
HAWC collaboration 2017

Geminga region as seen with H.E.S.S.:



HESS collaboration 2023

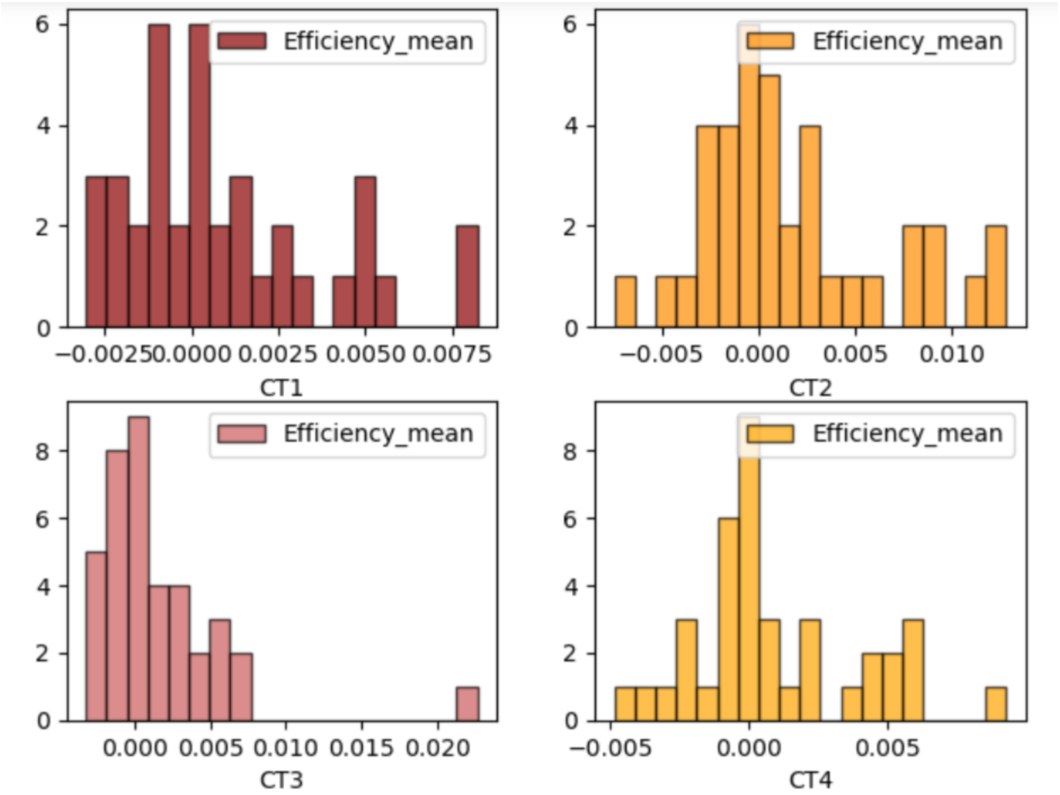
Outline of the idea:



Run matching:

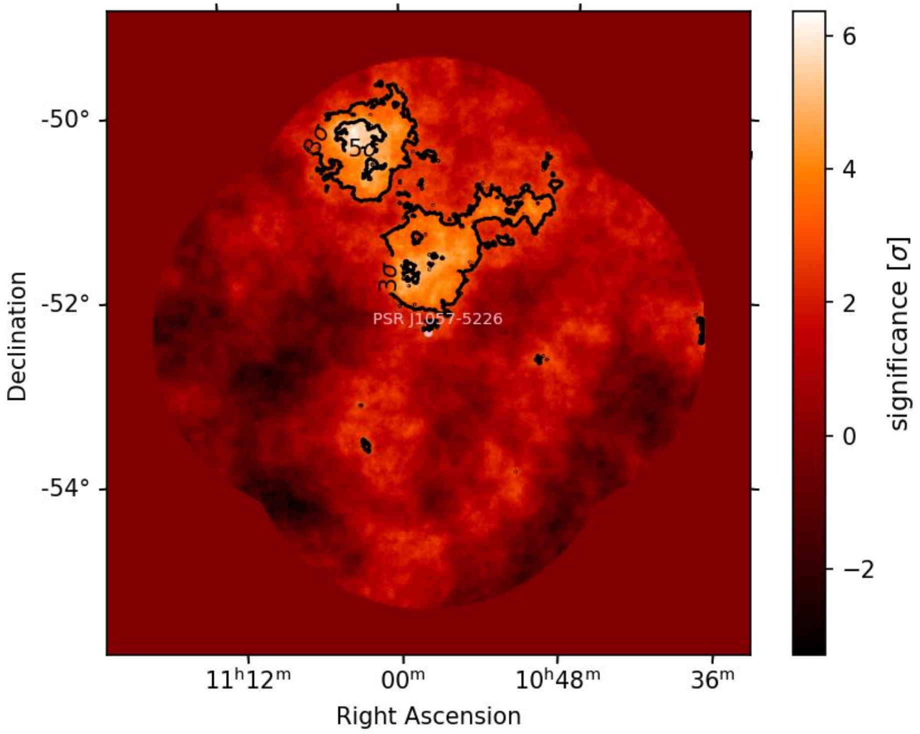
Matching criteria:

- Only consider runs with -10° > b > 10
- Only consider runs with similar optical efficiency
- Only consider runs with all telescopes participating
- OFF runs need to pass spectral quality criteria
- zenith and altitude deviation in the same bkg model bin
- run duration deviation: 2 minutes
- Atmospheric conditions:
  - NSB deviation: 50 Hz
  - muon efficiency deviation: 0.05
  - Transparancy coefficient deviation: 0.1

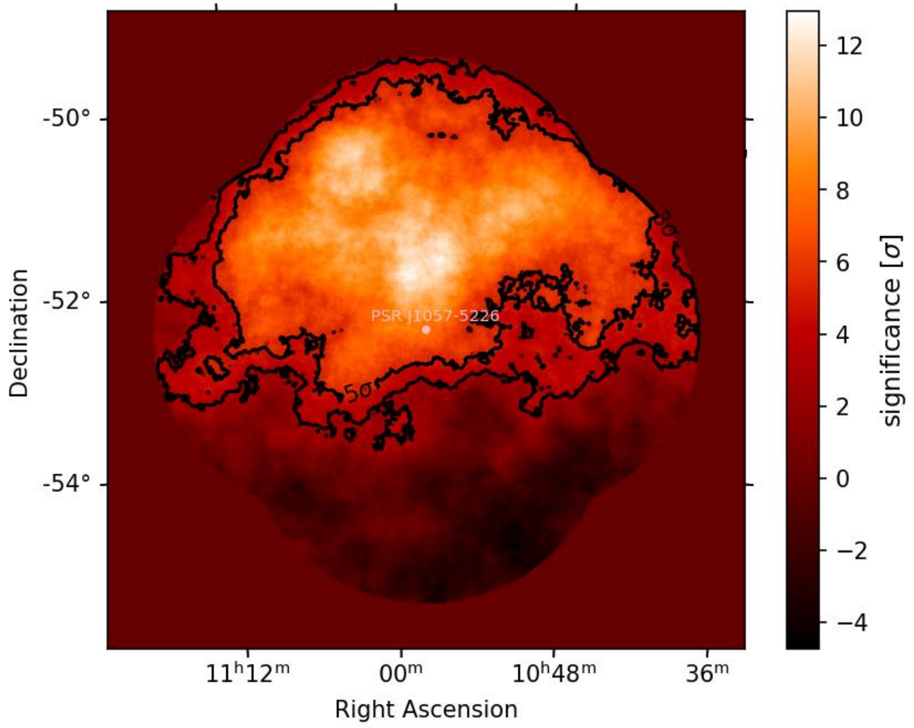


3d background model vs. OFF-run matching

Standard HESS bkg method:



OFF run matching:



Summary

- Analysis of the high energy gamma ray emission around pulsar halos using Fermi-LAT and H.E.S.S.
- New method for background estimation suited for large diffuse emission
- First detection of extended emission around PSR J1057-5226 from an IACT

Backup Slides

Summary & Outlook

- Analysis of the high energy gamma ray emission around pulsar halos using Fermi-LAT and H.E.S.S.
- New method for background estimation suited for large diffuse emission
- First detection of extended emission around PSR J1057-5226 from an IACT

Outlook:

- Improvment of the run matching by introducing weights for every matching parameter corresponding on the influence on the trigger rate
- Estimation of the systematic error of the method
- Establishment of a firm detection and model for the emission around PSR J1057-5226

PSR B1055-52

Properties:

- From EGRET observations: highest conversion efficiency known
- Location: l = 285.98°, b = 6.65°
- Located in the southern hemisphere
- distance estimation: 400 kpc

Multi-wavelength data:

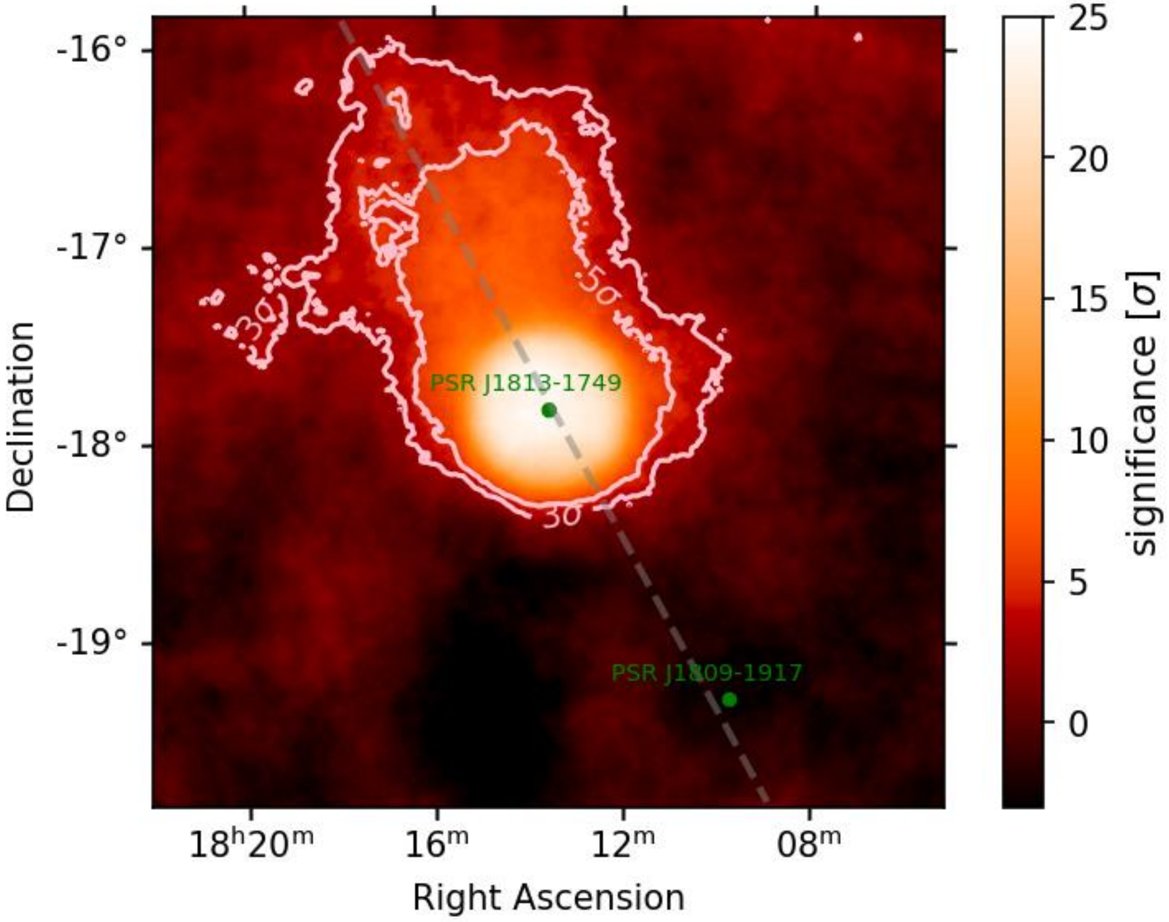
- No PWN detected in ATCA and XMM-Newton data
- Faint detection of PWN in Chandra
- No detection of diffuse emission in Fermi data
- No detection from IACTs, LHASOO and HAWC

“Three Musketeers”:

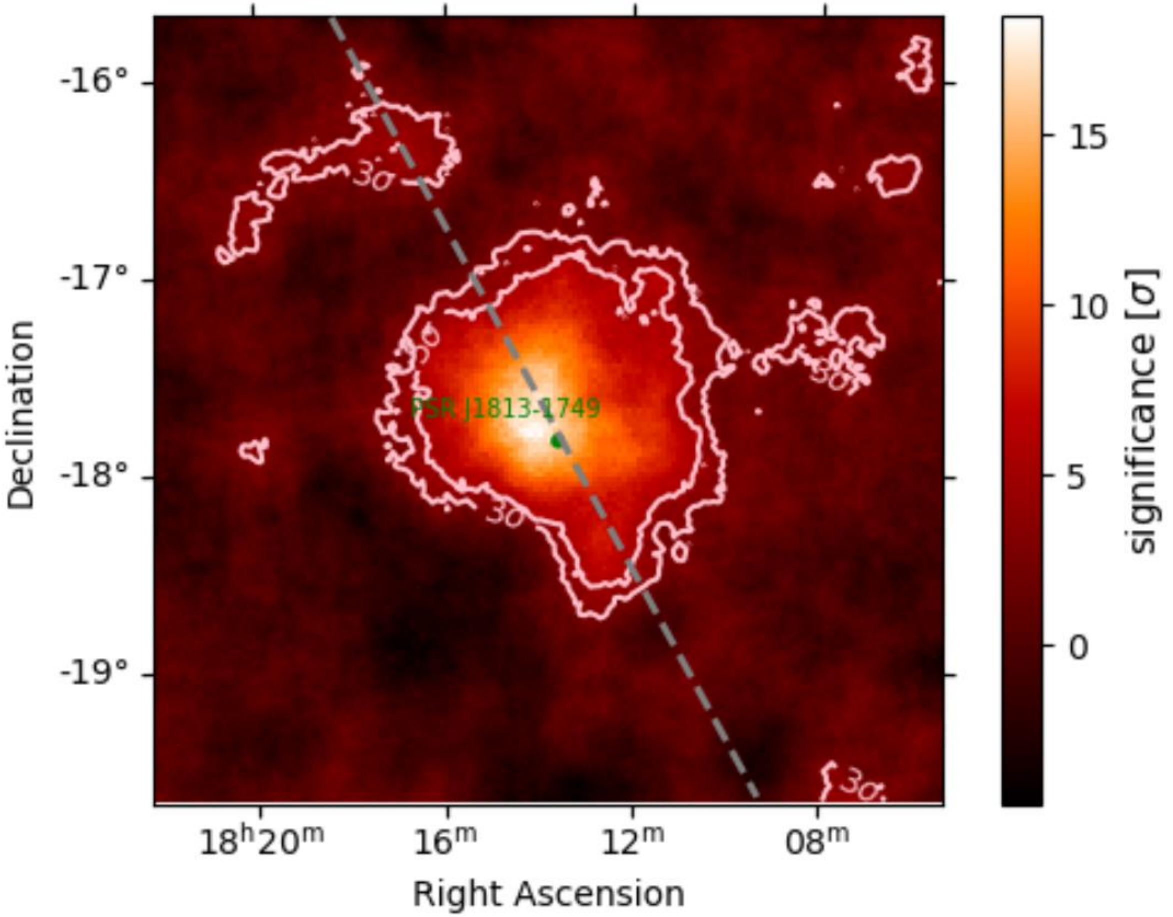
- Geminga, PSR B1055-52, PSR B0656+14
- EGRET 6
- Middle aged pulsar (approx. 500 kyrs)
- Spin-down luminosity $\dot{E}$ = 3.0e+34 erg/s
- Similar magnetic fields (~ 10^{12} G)
- All detected in γ-rays (one of the brightest pulsars)

Example: PSR J1813-1749

H.E.S.S. Data:
- 400 GeV to 70 TeV

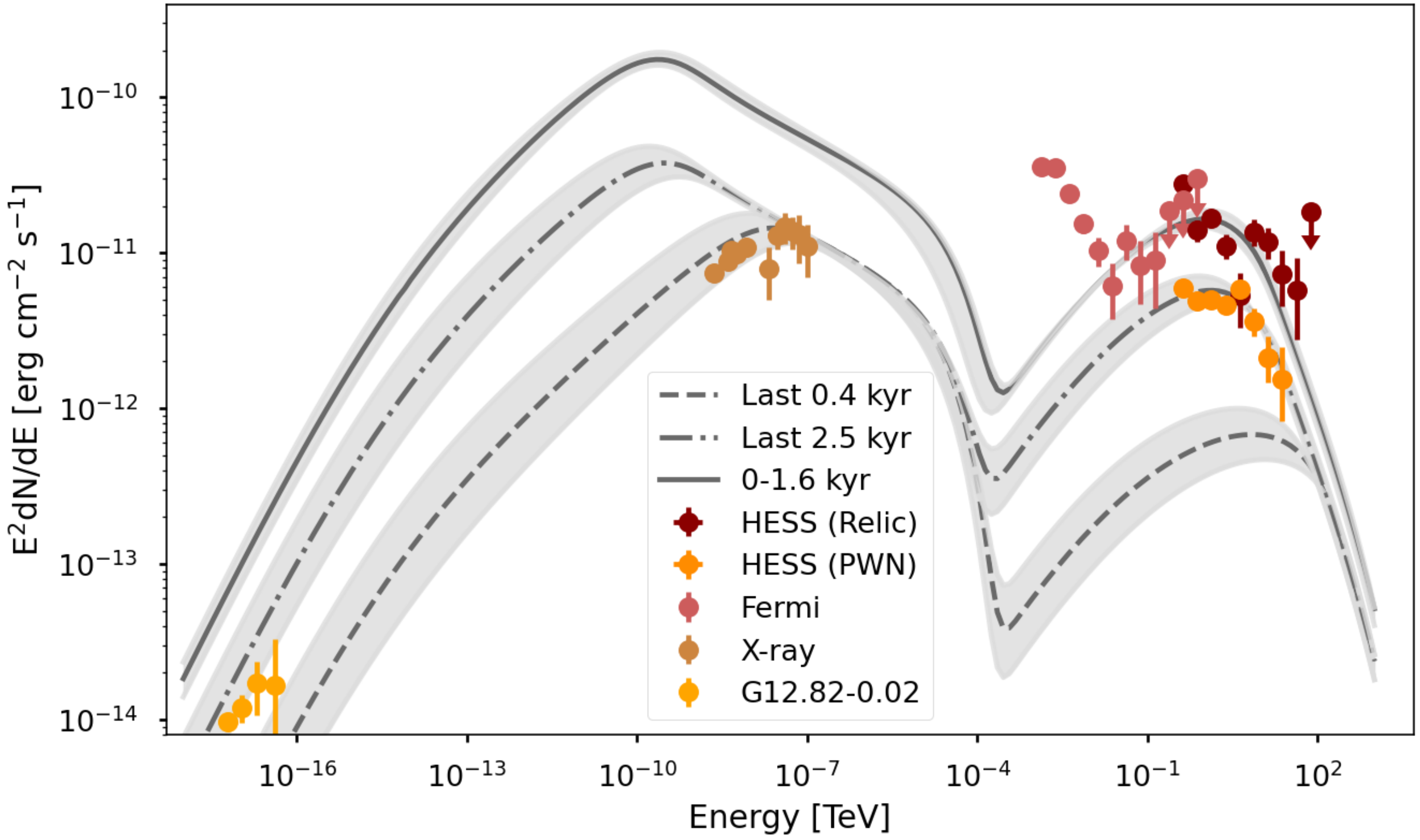


Fermi-LAT Data:
- 1 GeV to 1 TeV



Example: PSR J1813-1749

- One zone model
- Time dependent model of pulsar energy output, ambient magnetic field and injected electrons
- Time evolution of pulsar period, spin-down power and magnetic field following Gaensler & Slane 2006



Assumptions:

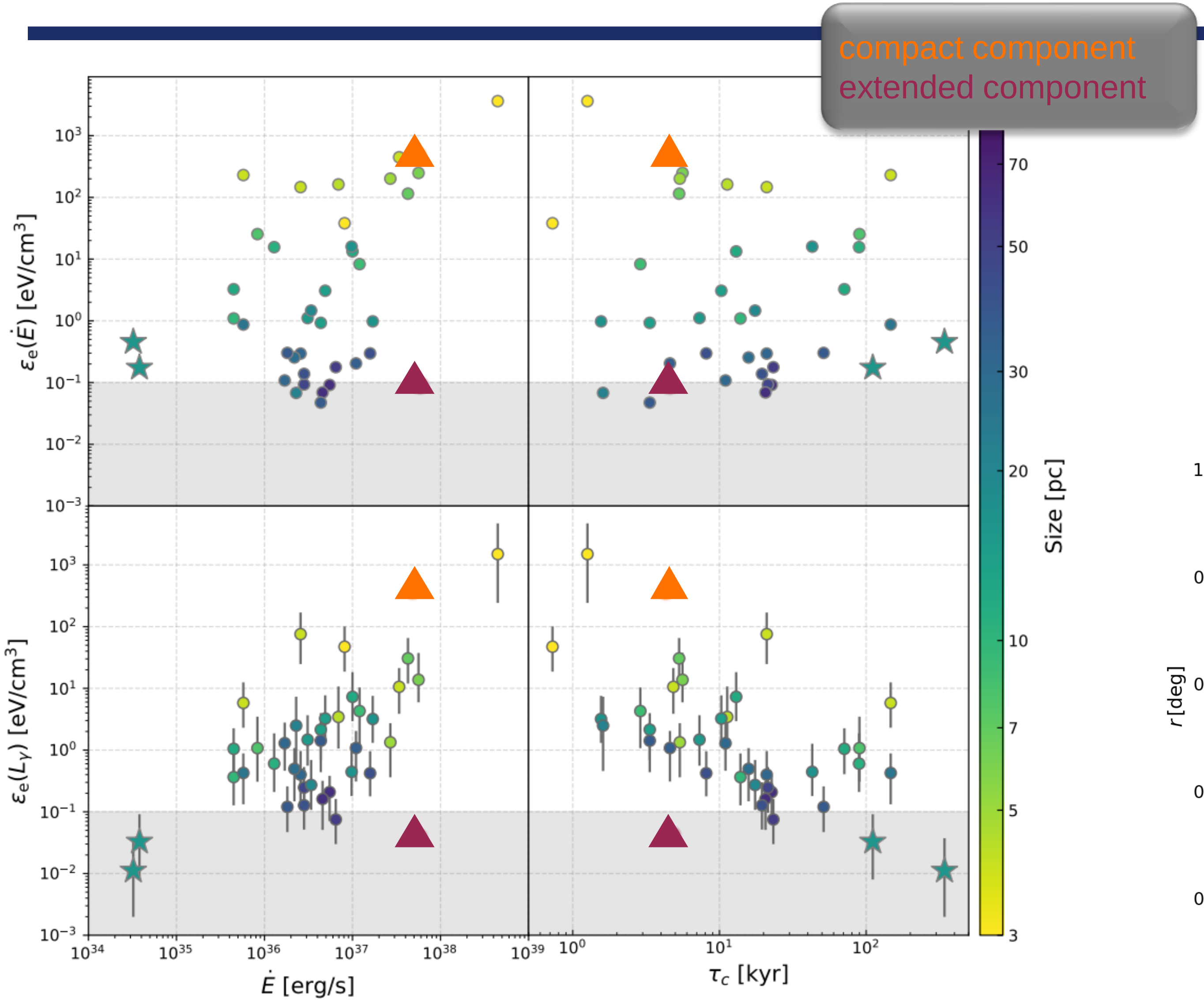
- Distance: 6.2 kpc
- E_dot = 5.6e37 erg/s
- P = 44.7e-3 s
- P_dot = 1.26999e-13 s/s
- Braking index = 3.0
- Breaking energy = 100 GeV
- Spectral index = 1.5

Fit parameters:

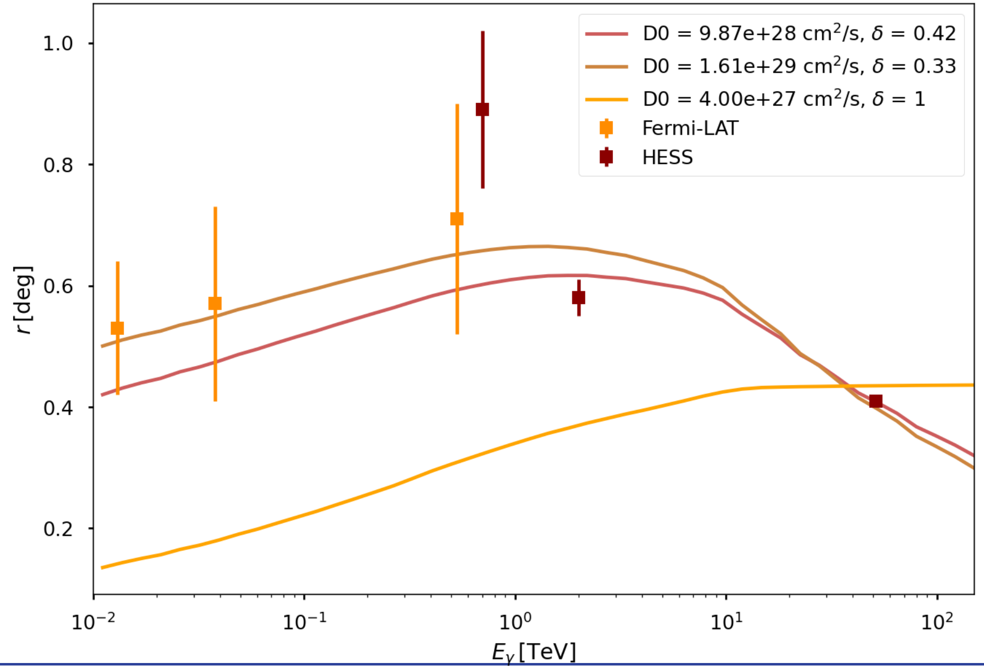
- B(now) = [10.4 – 12.6] μG
- P0 = [18.4 – 21.8] ms
- Conversion frac = [0.12 – 0.26]
- Spectral index = [2.3 – 2.4]
- Time frac(X-ray) = [0.08 – 0.13]
- Time frac(pwn) = [0.57 – 0.69]

True age estimated in this study: (5.7 - 6.5) kyrs

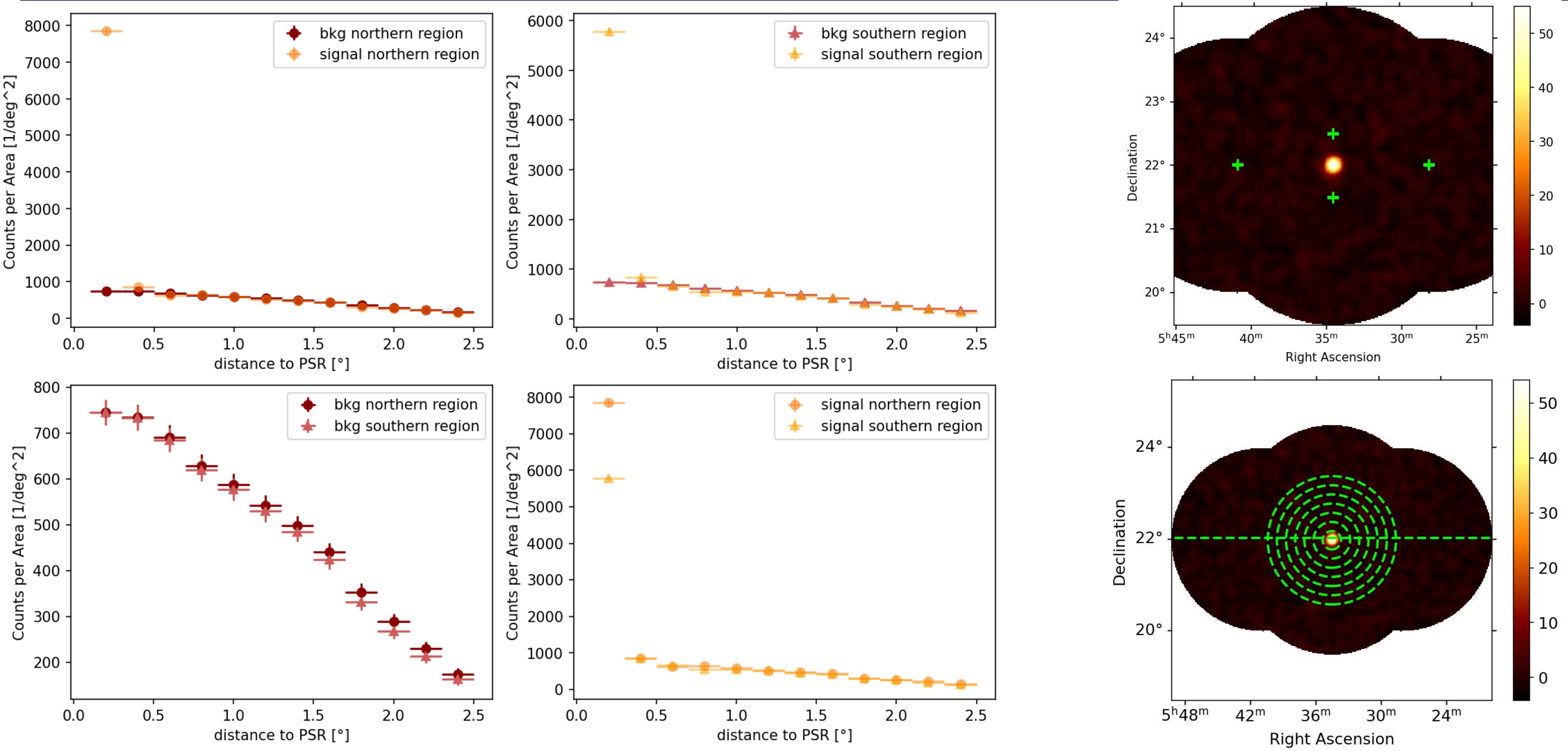
Example: PSR J1813-1749



	Compact component	Extended component
ϵ_e(Edot) in eV/cm^3	707	0.09
ϵ_e(L_γ) in eV/cm^3	351	0.04

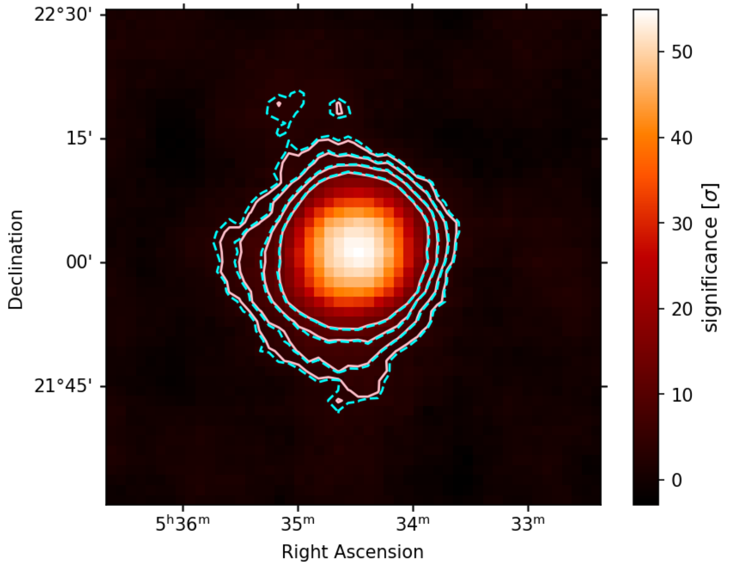


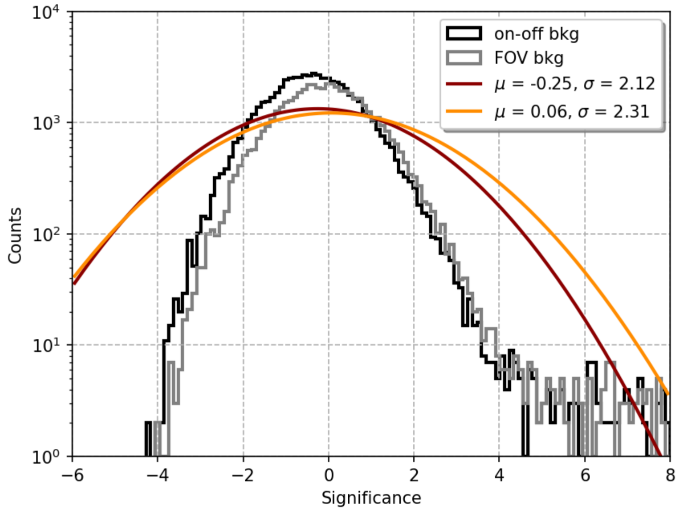
Crab Nebula – Radial profile

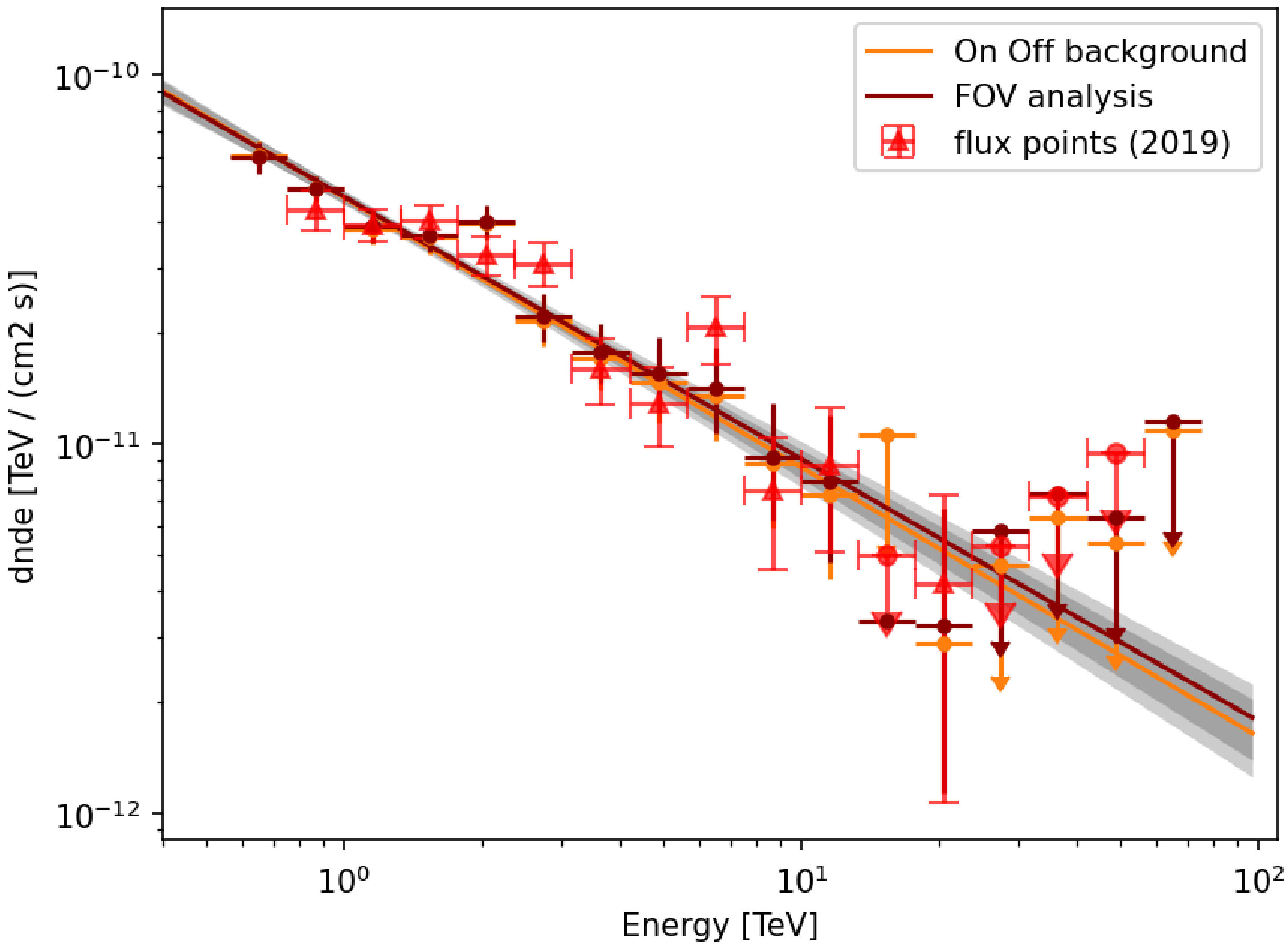


Proof of concept: Crab Nebula

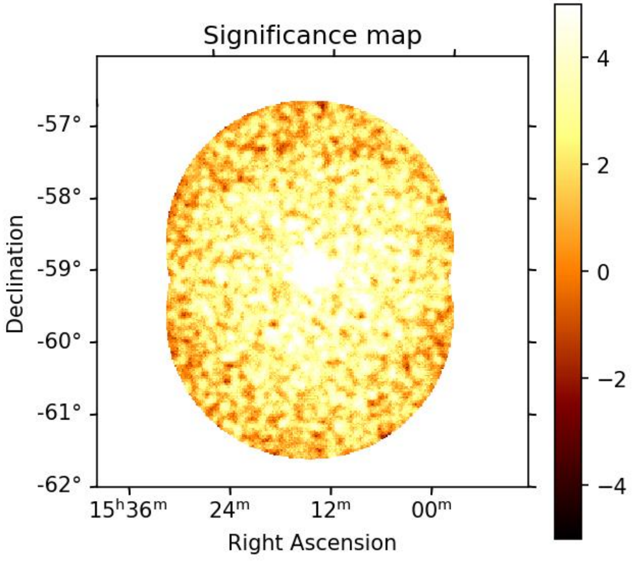
solid pink: on-off bkg
dashed blue: FOV bkg

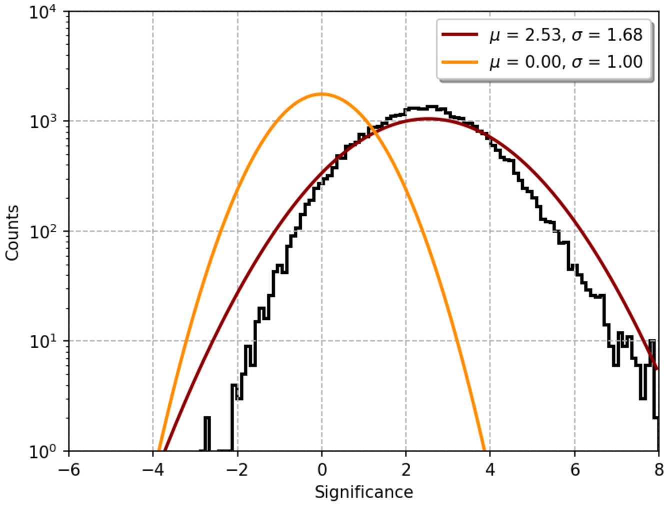






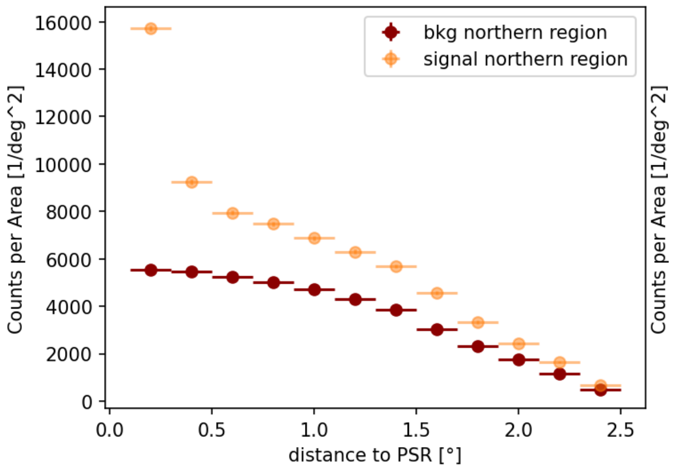
Proof of concept: galactic sources – MSH 15-52

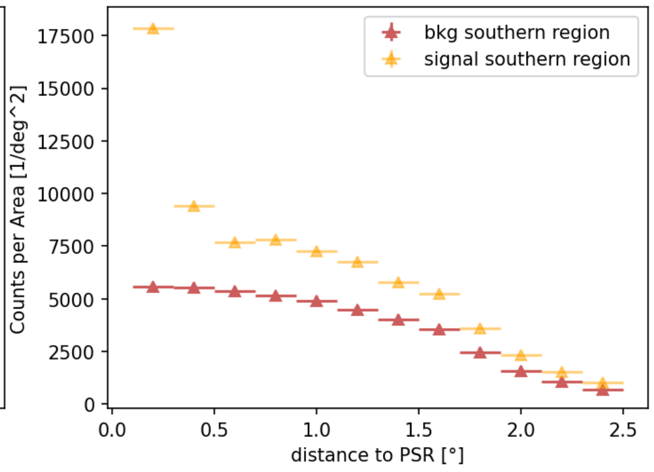




Type	Latitude	Runs	Dates
PWN	-1.19°	20	2004-03-26 - 2004-04-19

Obs time	Zenith anlge
9.1 hrs	36.1° - 40.2°

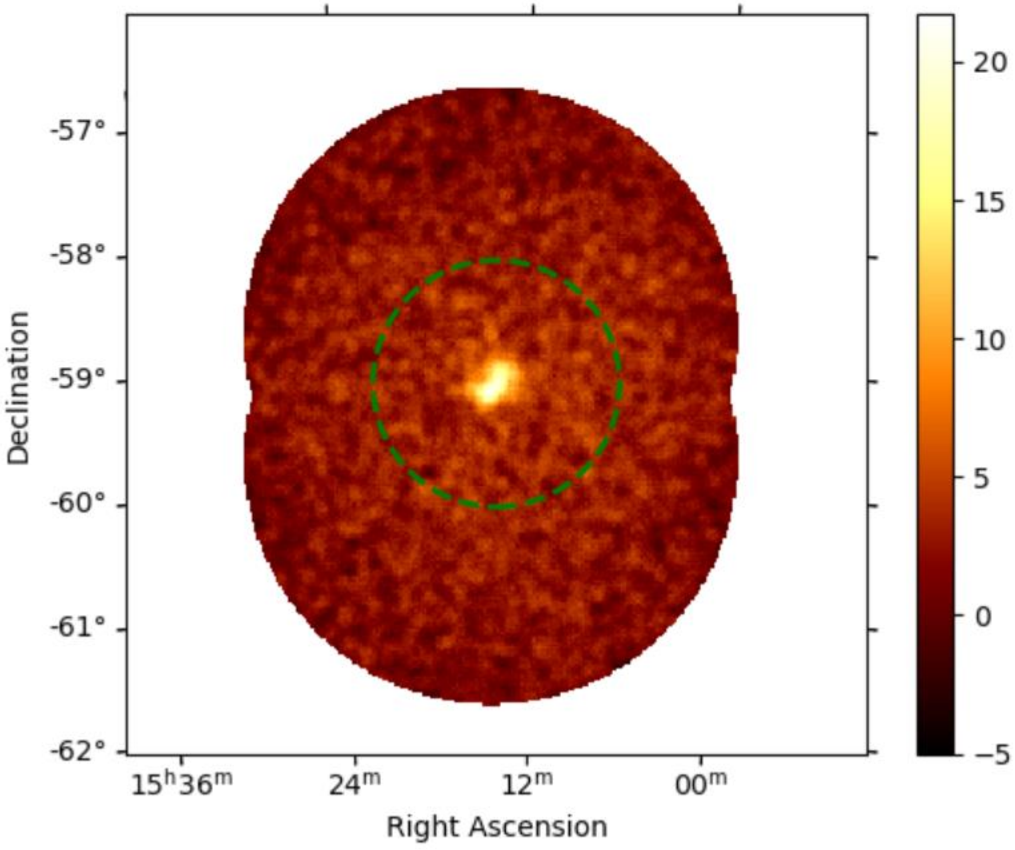




- Source is more extended than in the literature
- Significance distribution is shifted
- Observed counts never reaches the background level

→ Background is underestimated

MSH 15-52 – Normalization



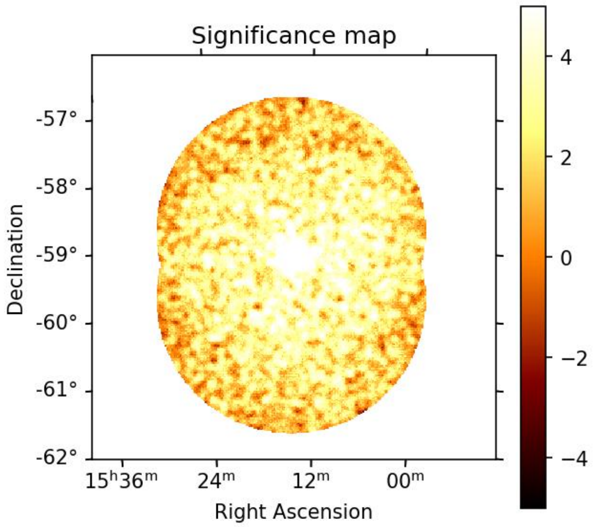
Normalize the background beyond certain Radius:

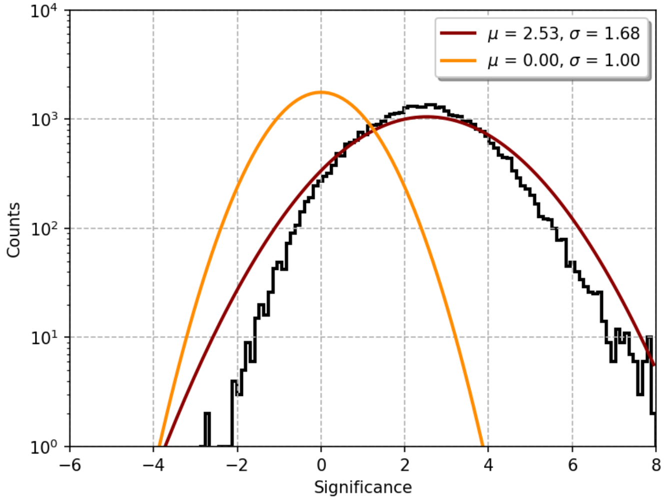
- Source extension: 0.15 °
- Radius > 1.0 °

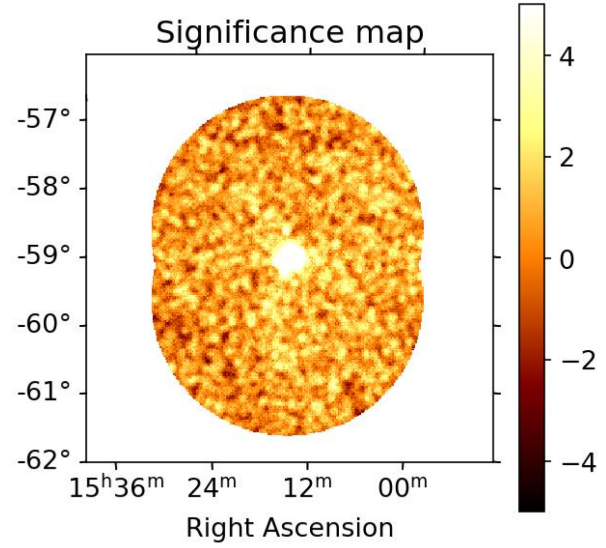
$$x = \sum_{\text{pixel}} \frac{\text{off}_{\text{counts}} - \text{bkg}_{\text{counts}}}{\text{bkg}_{\text{counts}}}$$

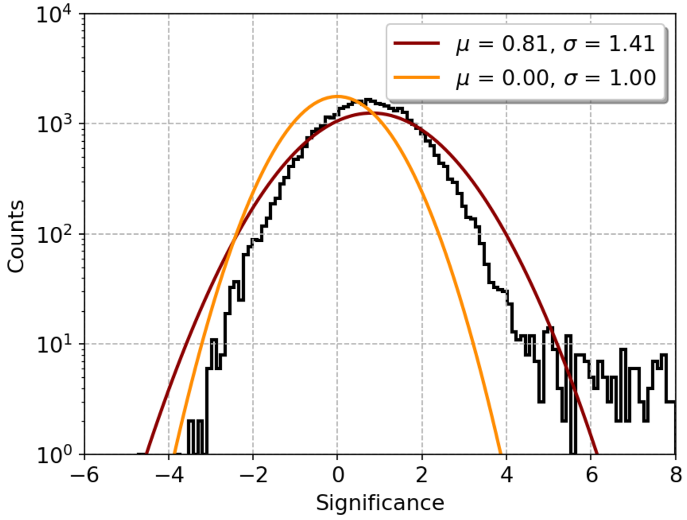
$$\text{bkg}_{\text{counts, new}} = x \cdot \text{bkg}_{\text{counts}}$$

Improvement of the run matching: include muon phase cut – MSH 15-52









- Public data release data: taken within one muon phase
- Previous OFF run matching: across the entire history of one telescope area

➡ mismatch because of changes in the optical system

➡ match only across one muon phase

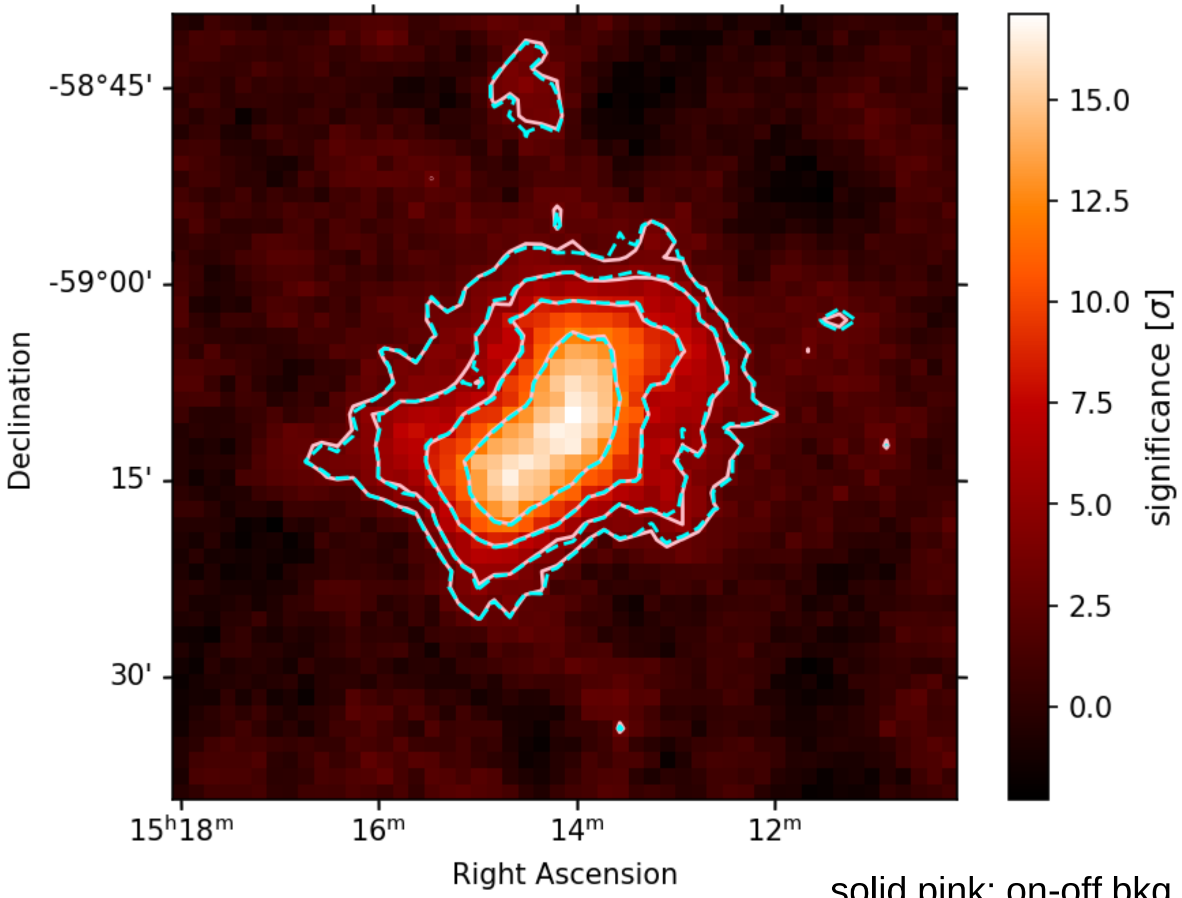
BUT:

- For the public data release this is not possible (not enough OFF runs in the first muon phase)

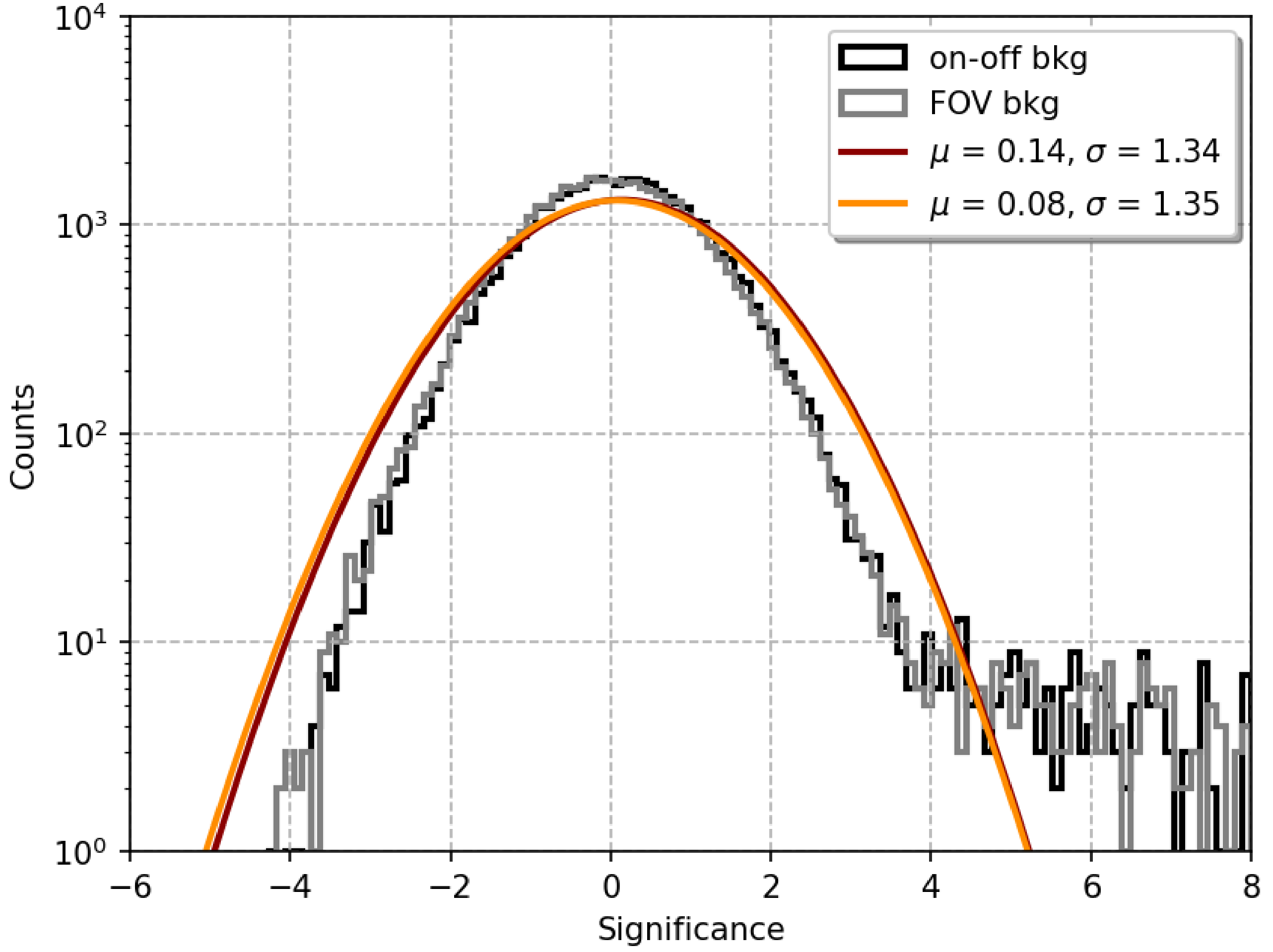
➡ match over the first two muon phases

➡ Improvement but still slight mismatch

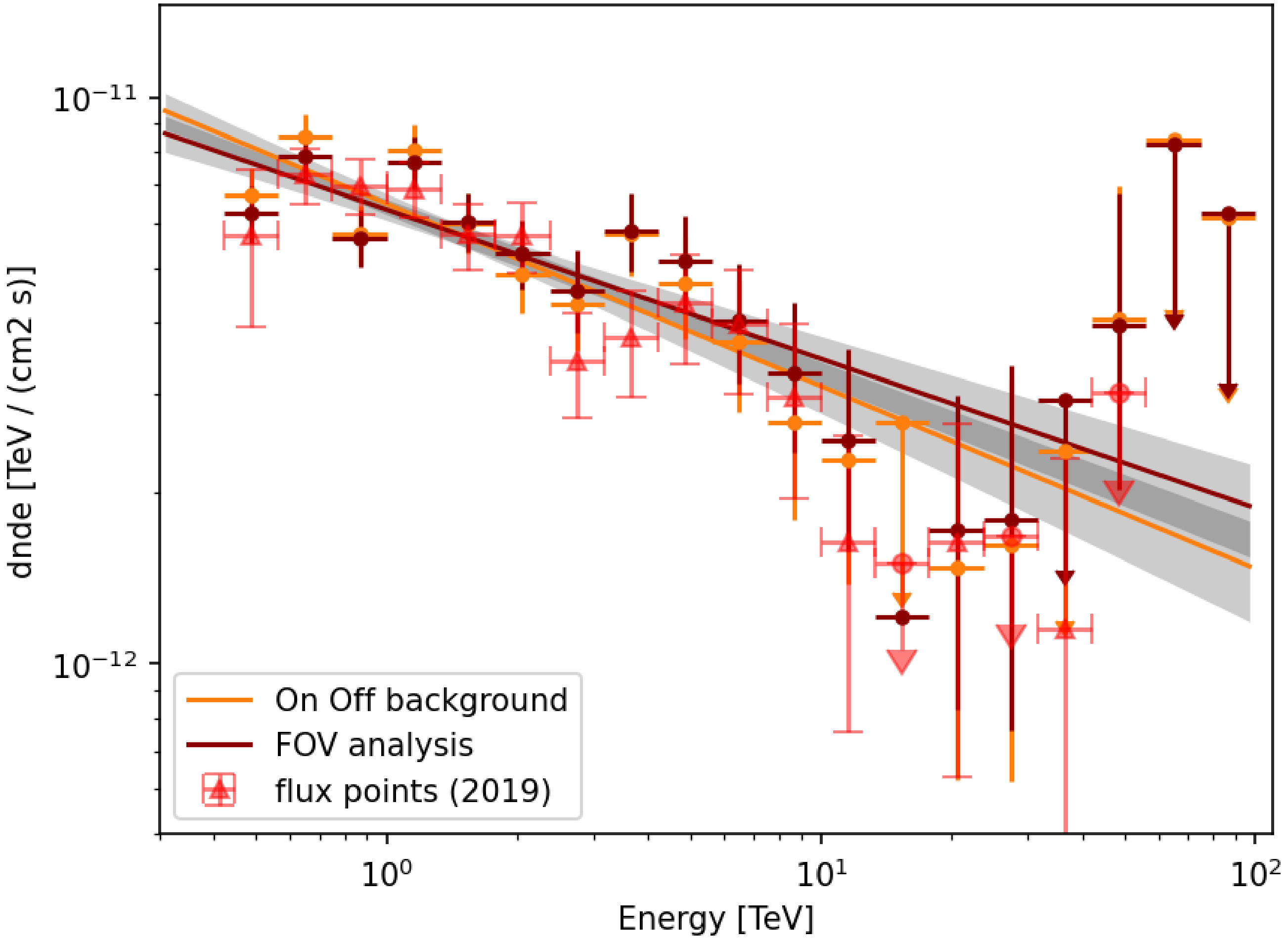
MSH 15-52 – comparison to FOV analysis

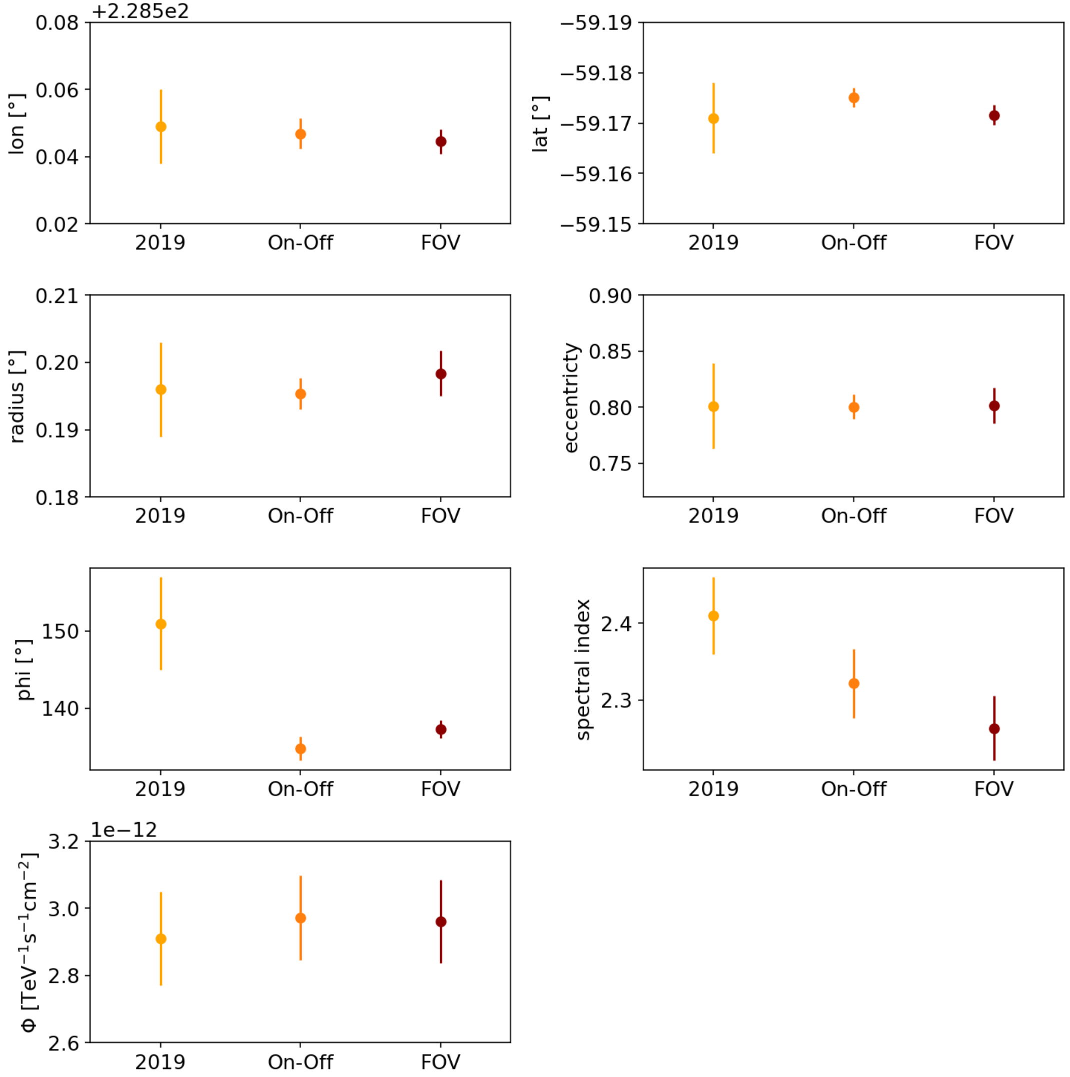


solid pink: on-off bkg
dashed blue: FOV bkg

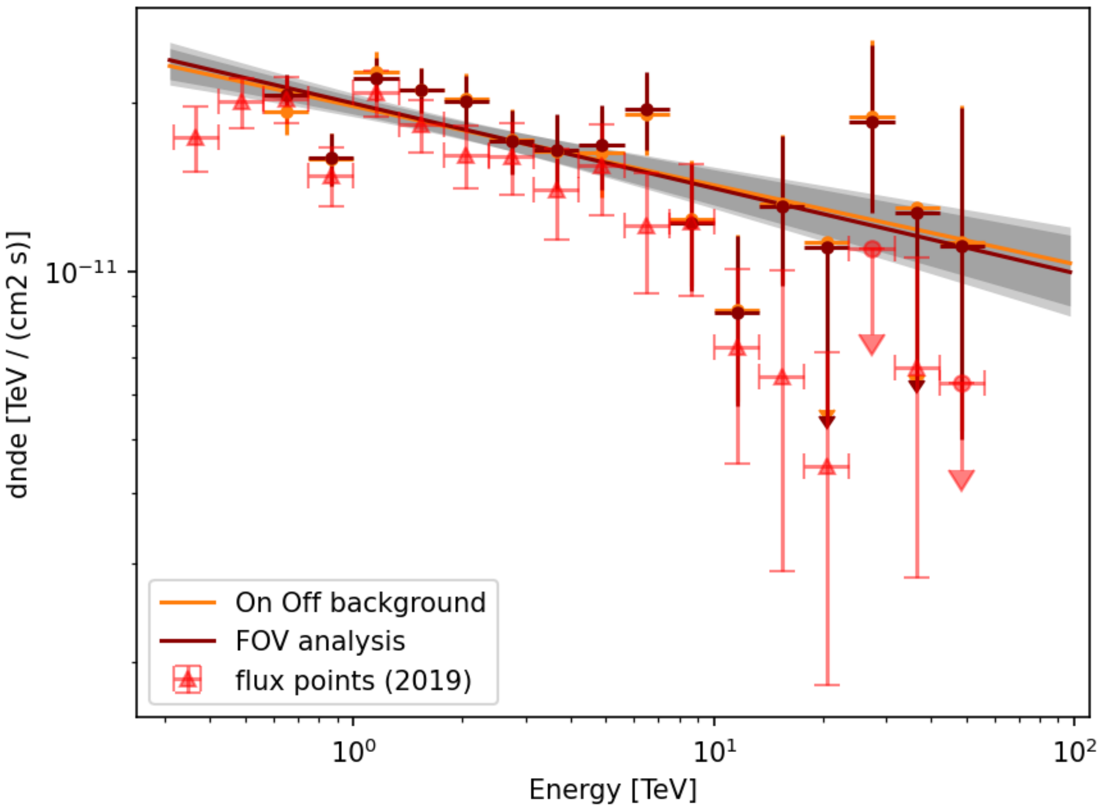


MSH 15-52 – comparison to previous publications



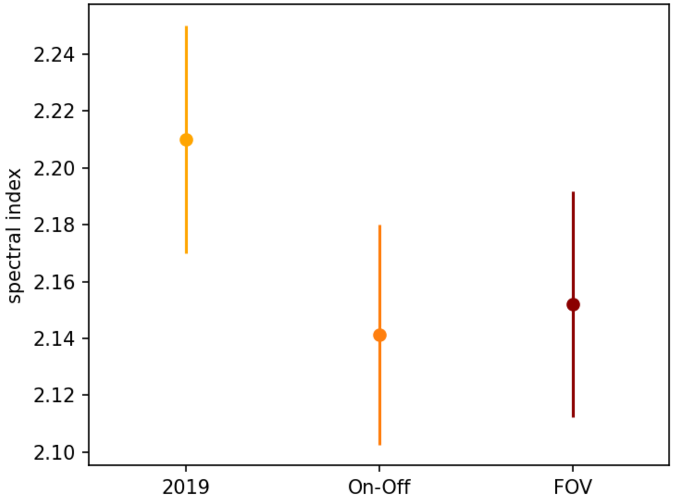


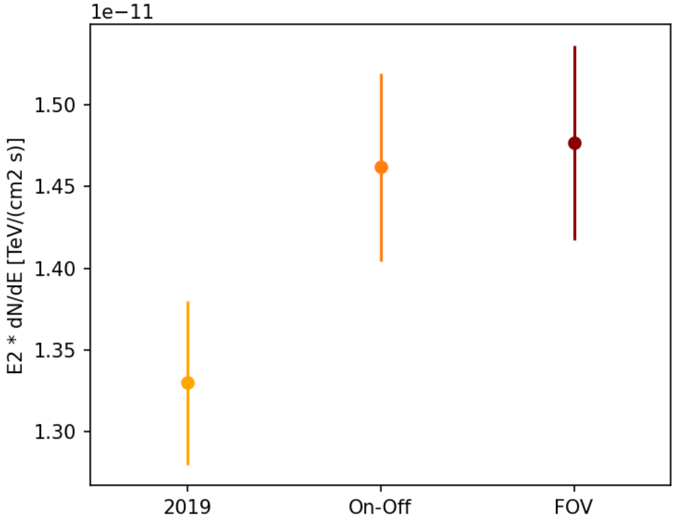
RX J1713.7-139 – comparison to FOV analysis



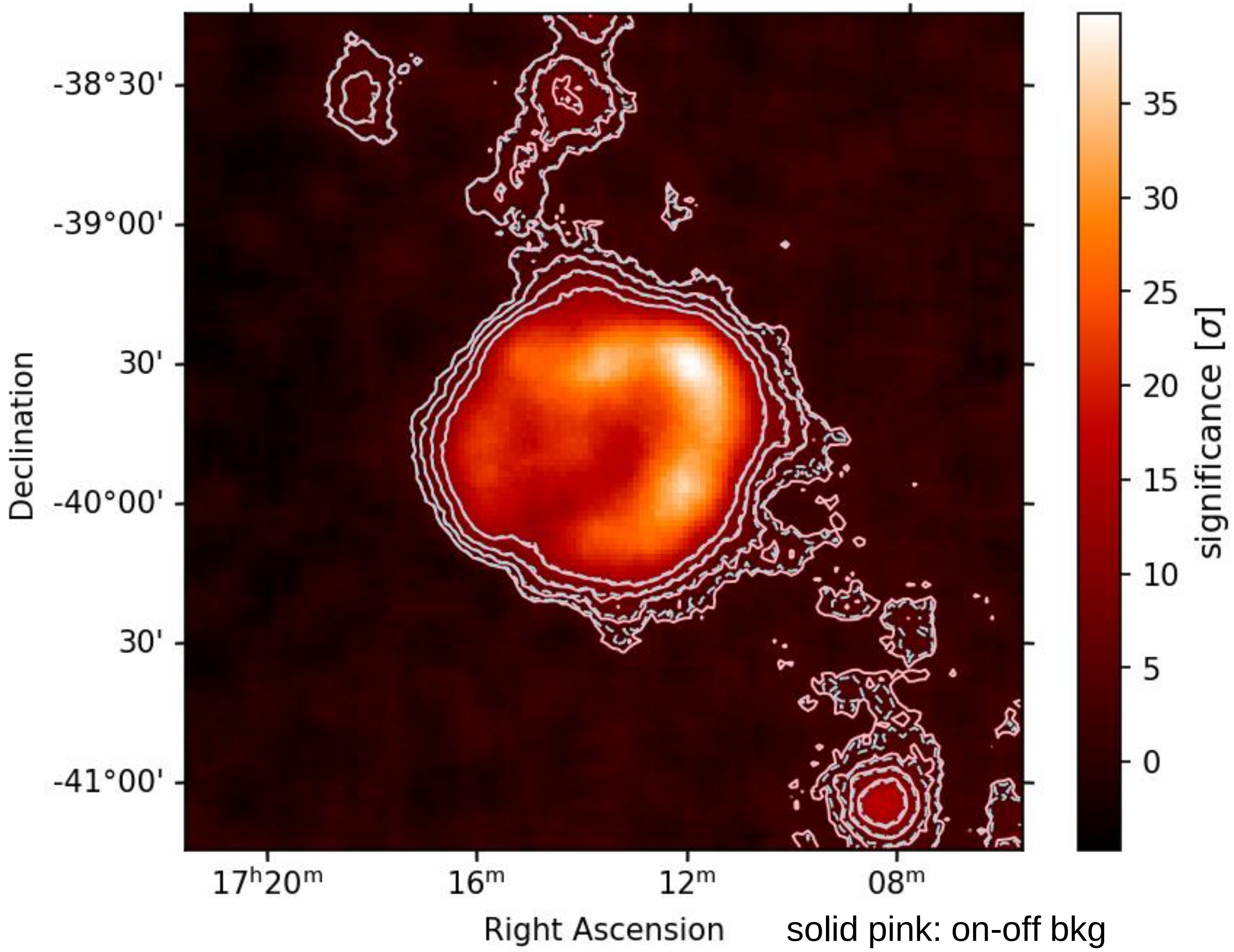
Morphological model: (see Mohrmann et. al. 2019)

- Estimate bkg level
- Extract excess counts
- Smooth excess map using two-dimensional cubic spline function
- Clip map at zero





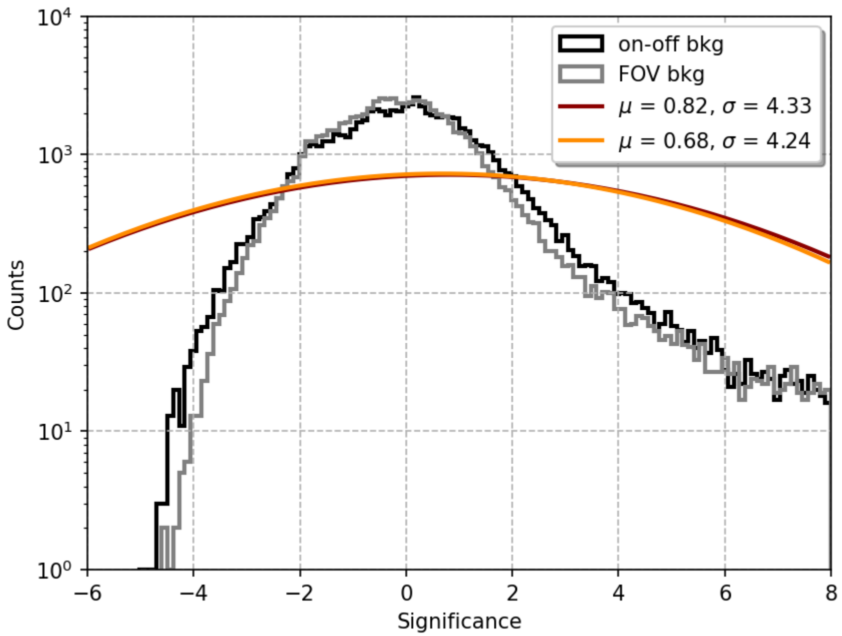
Proof of concept: large datasets – RX J1713.7-139



solid pink: on-off bkg
dashed blue: FOV bkg

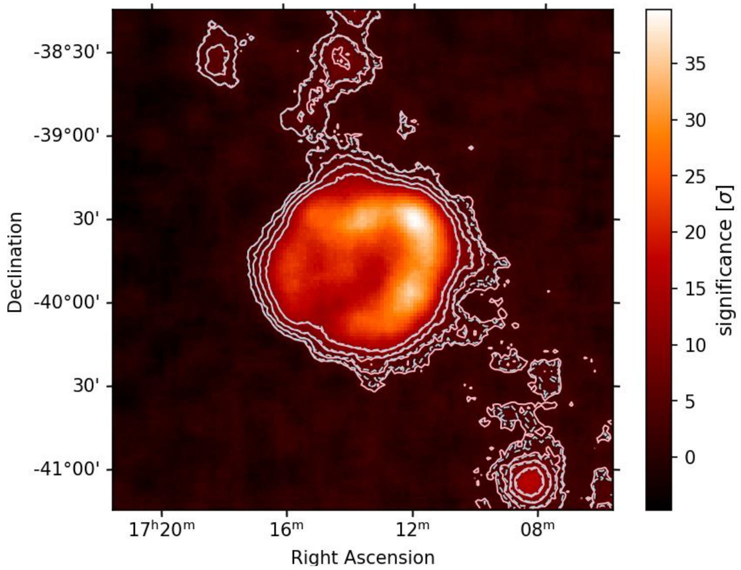
Type	Latitude	Runs	Dates
SNR	-0.47°	249	2004-04-16 - 2012-08-121

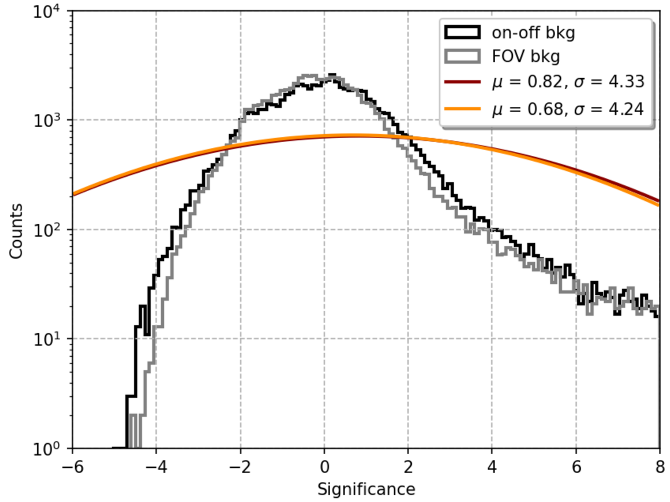
Obs time	Zenith anlge
115 hrs	15.4° - 56.5°

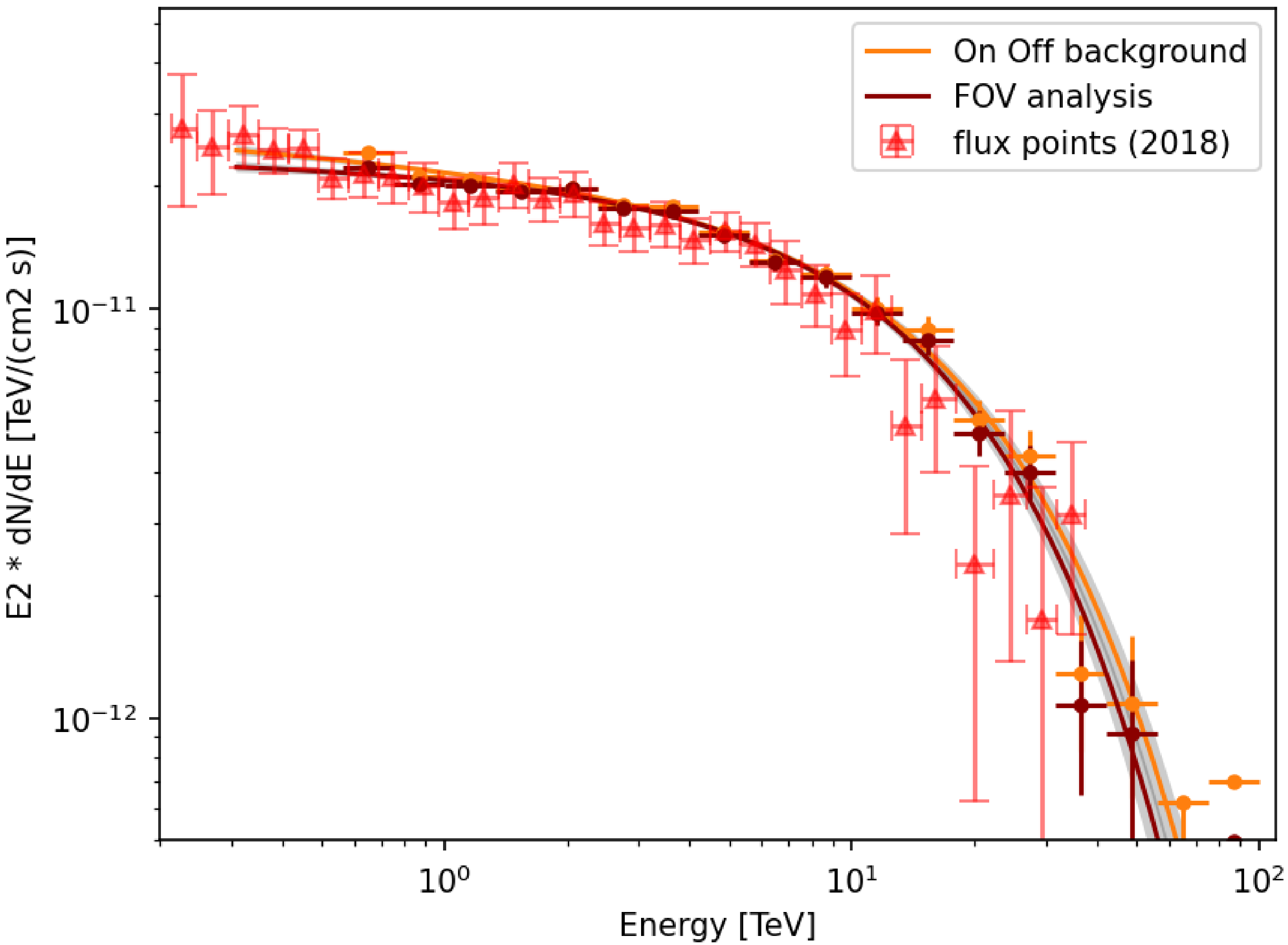


Proof of concept: large datasets – RX J1713.7-139

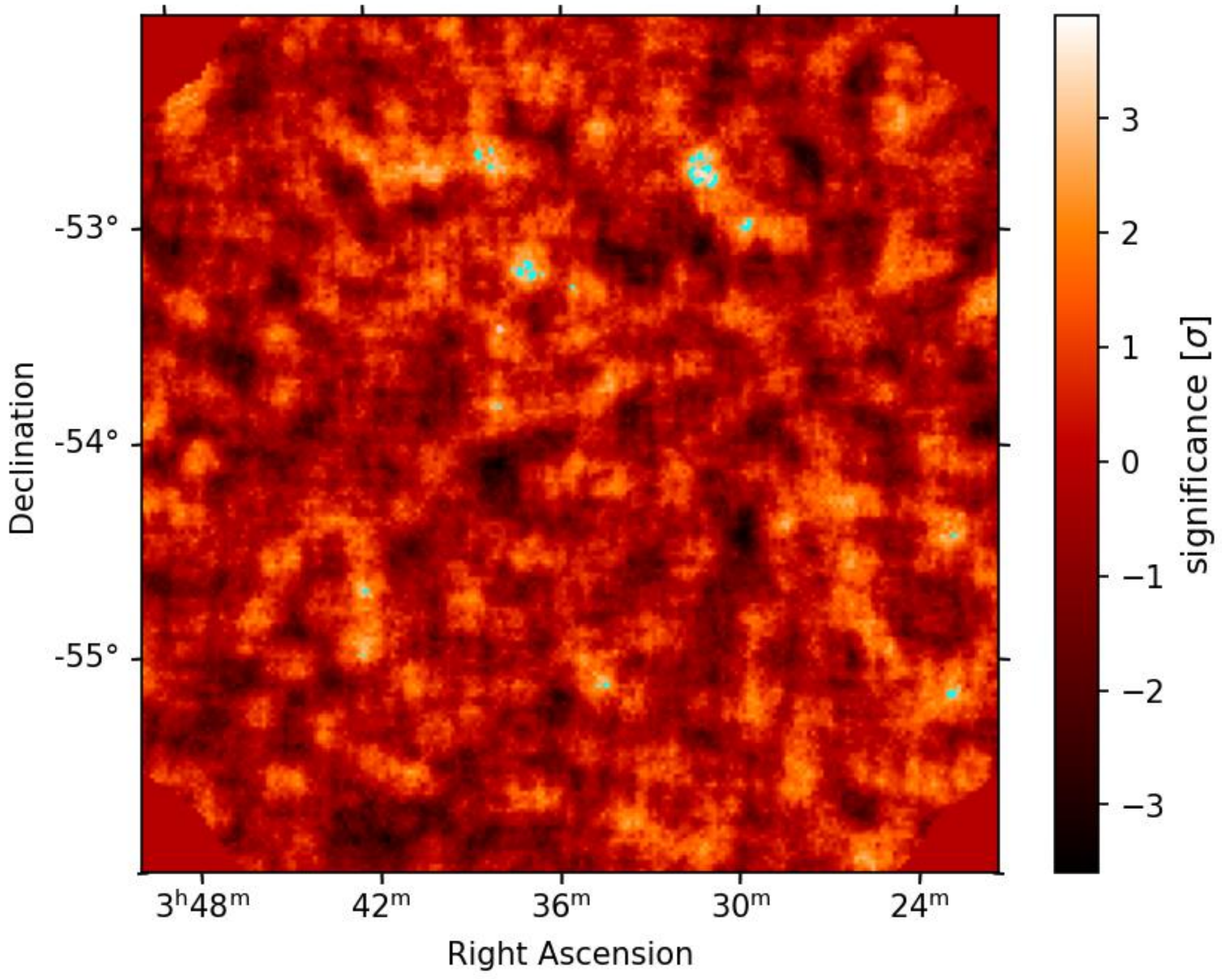
solid pink: on-off bkg
dashed blue: FOV bkg

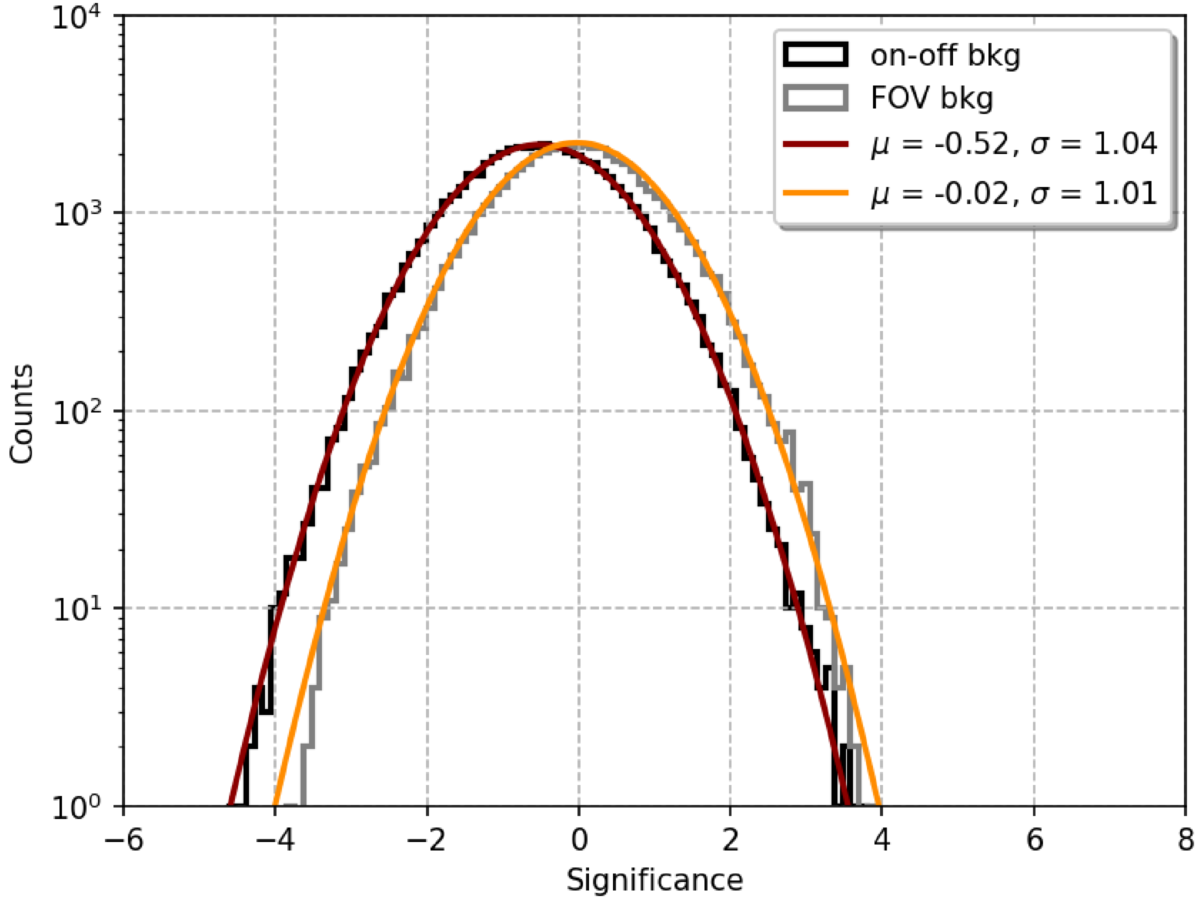






Reticulum 2 – comparison to FOV analysis

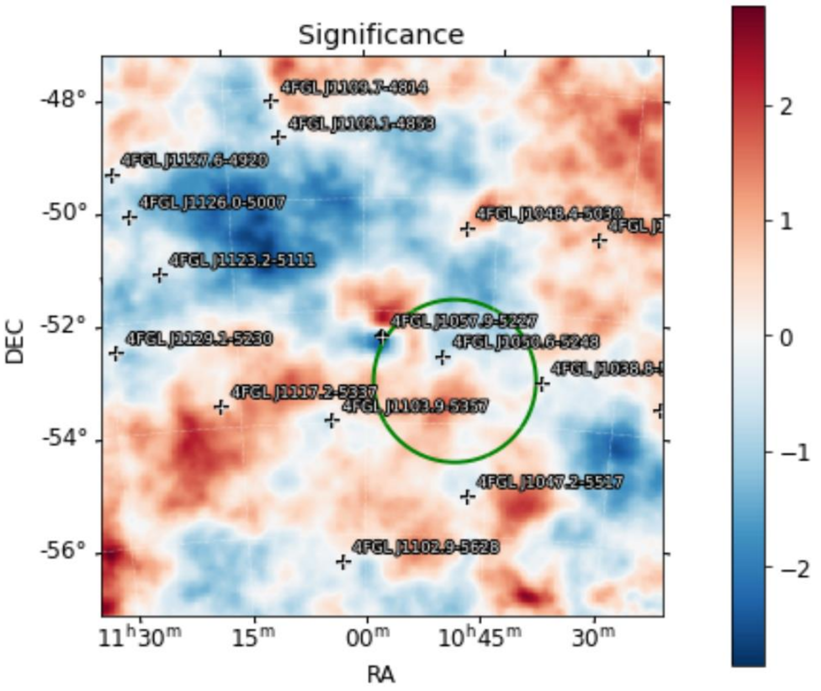




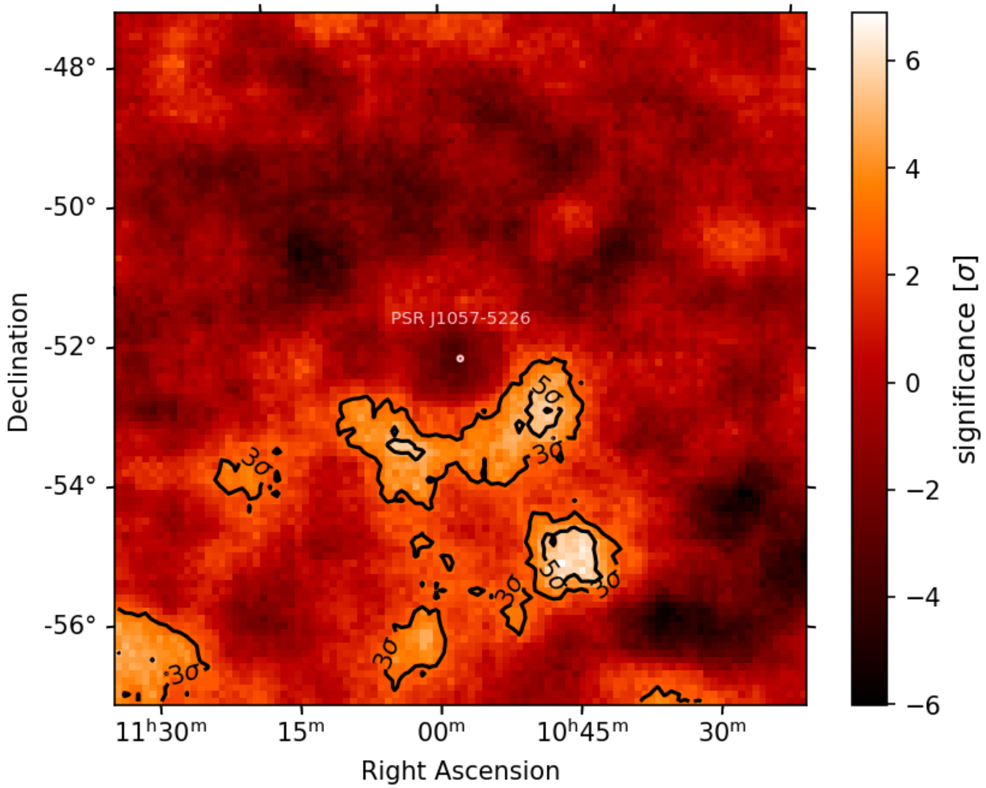
Fermi-LAT data

Analysis of Fermi-LaT data since mission start

- Using pass 8 release 3 IRFs
- 4FGL-DR3 source catalog
- Energy range: 100 MeV < E < 1 TeV
- Remodeling the pulsar with a point source model with exponential cutoff power law



Removing UNID sources in the region:



A first glance at the region does not show extended emission

Summary & Outlook

- **Advantages:**
  - estimate bkg in regions where the source extends beyond the FOV
  - Because a 3d background model is used, the statistical error is small

- **Disadvantages:**
  - Good matching required
  - Good understanding of changes in the intrument required
  - Only good quality runs can be included in the analysis
  - Galactic diffuse emission can only be estimated over a normalization factor or an energy threshold of a few hundred GeV needs to be set

Outlook:

- Estimation of the statistical error introduced through the fit of the 3d background model
- Estimation of the systematic error using Nuisance parameters (see talk from Katrin Streil)
- A short extension of the background method validation paper from Mohrmann et. al. 2019