The Energy-dependent Gamma-ray Morphology of the Crab Nebula Observed with the Fermi Large Area Telescope

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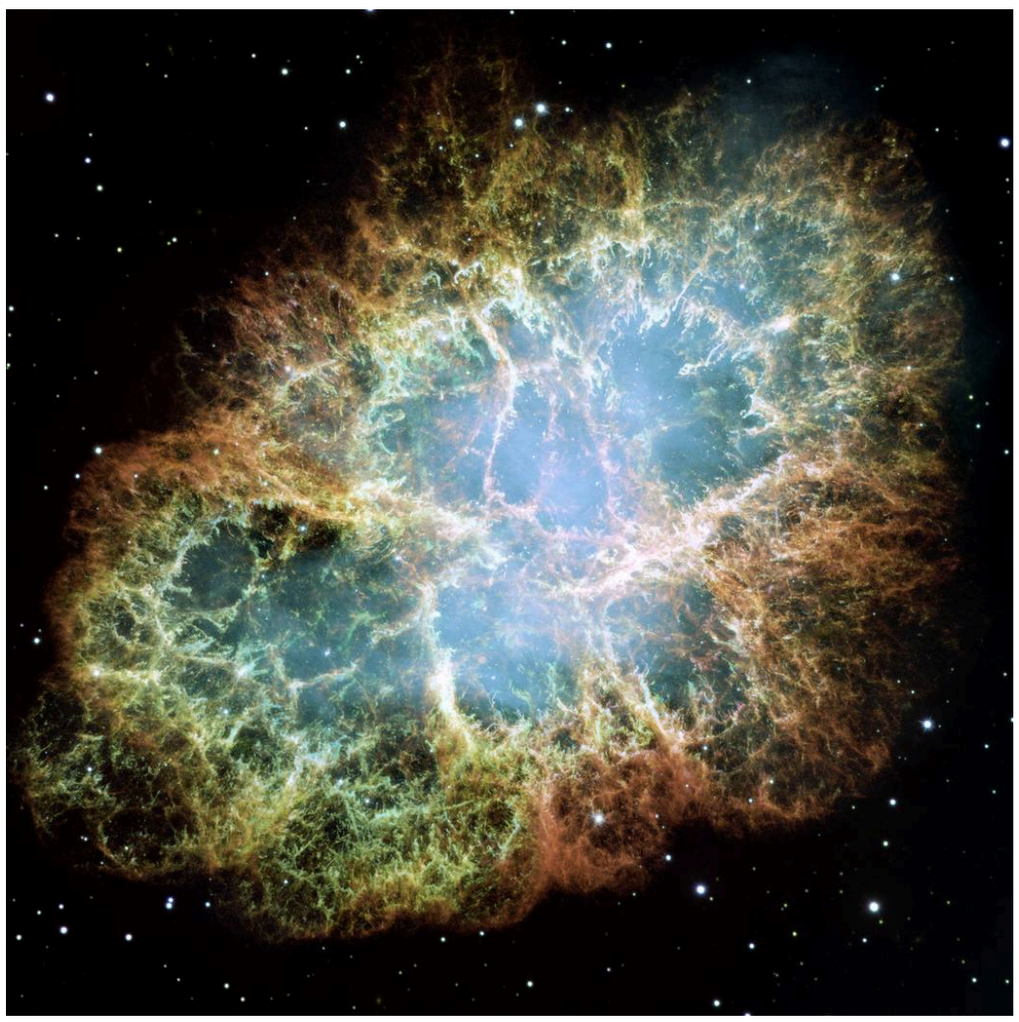
Introduction

- Crab Nebula: Type II SNR+PWN, ~1 kyr, ~1.7 pc
- Detected from ~10 MHz to ~100 TeV

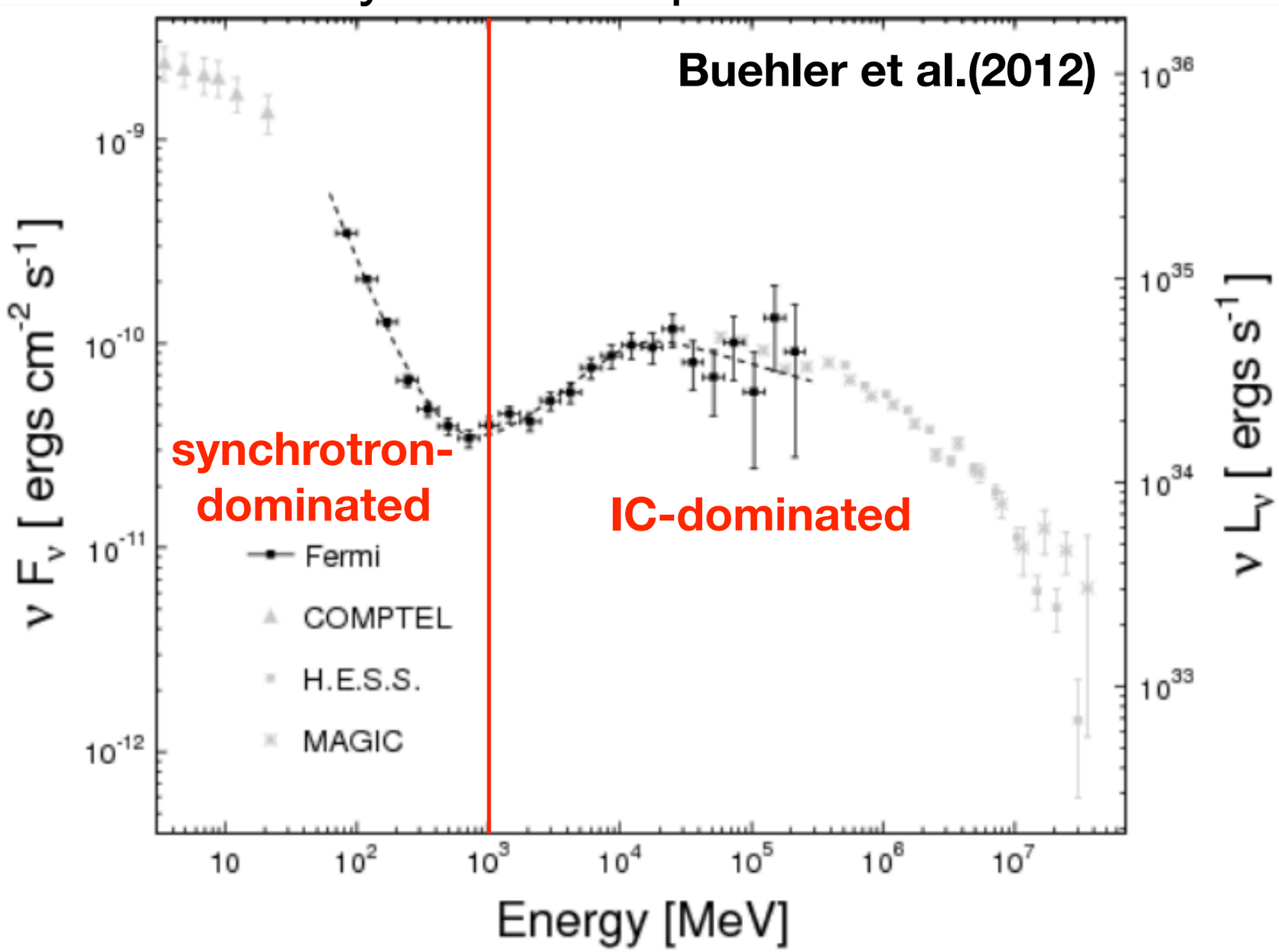


Optical observations of the Crab nebula with Hubble space telescope (Hester & Loll)

How about Gamma-ray view of Crab Nebula ???

Introduction

- >1 GeV: IC with synchrotron photons dominates



Introduction

- Synchrotron (spatial & spectral; radio to X-ray)

  —> seed photon field

- IC spectrum; the **gamma-ray morphology** and its **energy dependence**

  —> electron distribution, B-field structure

Previous studies

- Theoretical (MHD): Characteristic gamma-ray size: 60”—80”
  (Atoyan & Aharonian 1996, de Jager & Harding 1992)

- Observational:

  - >10 GeV: $\sigma=(108\pm10.8_{stat}\pm25.2_{sys})$” (Fermi LAT; Ackermann et al. 2018)

    - PSF systematics considered

  - TeV: $\sigma=(52.2\pm2.9_{stat}\pm7.8_{sys})$” (HESS; Holler et al. 2017)

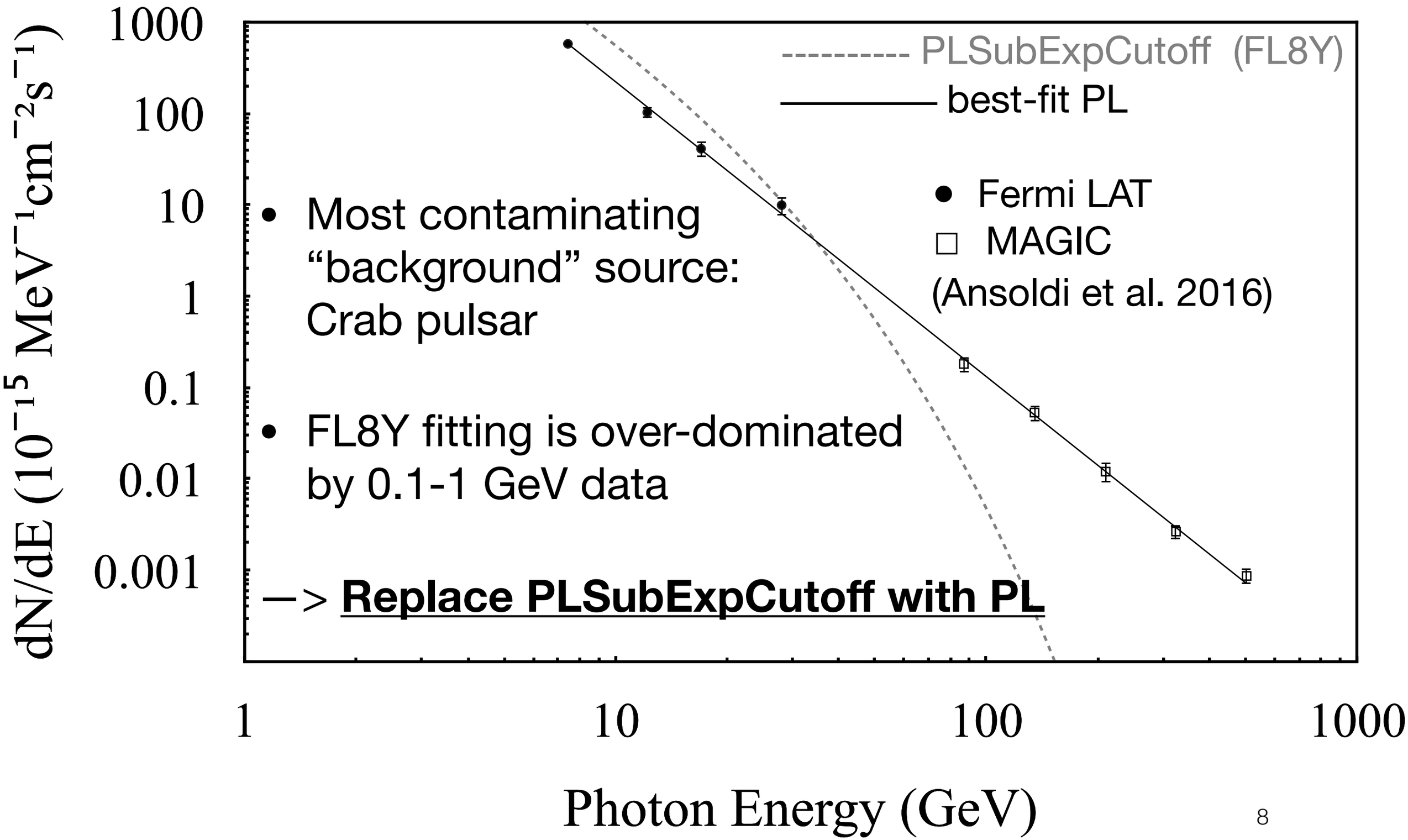
Data reduction criteria

- Energy: >5 GeV (synchrotron negligible)
- Time: 2008 August 4 — 2017 Sep 25
- Event class: Pass8 “Clean”
- Maximum zenith angle: 90 deg
- Region of interest: 15° radius, centred at Crab’s center

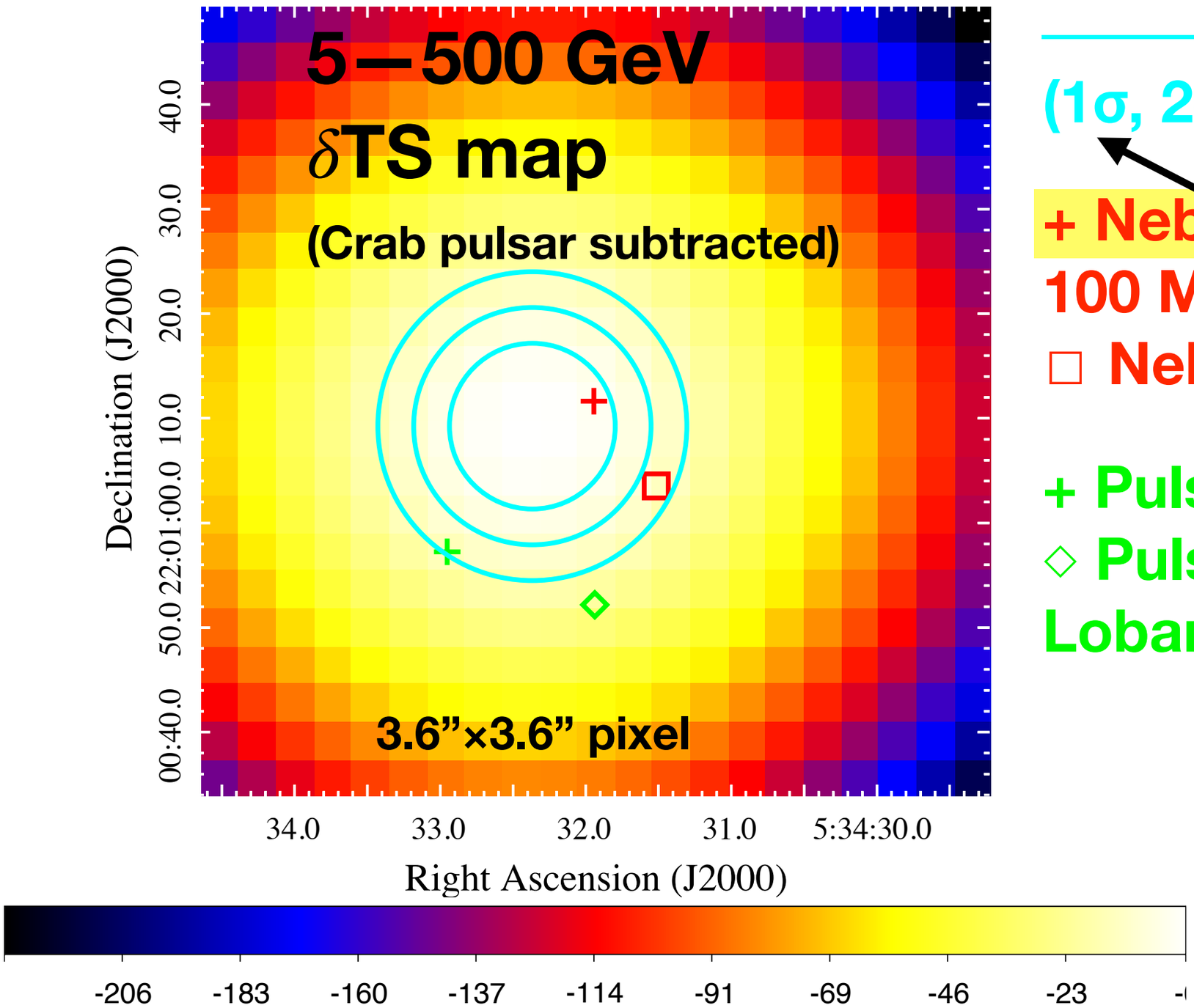
Analysis scheme

- **Unbinned** likelihood analyses
- IRF: Default (P8R2_CLEAN_V6)
- Source model: 8-year source list (FL8Y), Default Galactic Diffuse Model, Default Isotropic Extragalactic Model
- Set free parameters of: Galactic Diffuse, Isotropic Diffuse, sources within 5° from ROI center, **except Crab pulsar**

Refine Crab pulsar's spectrum



Locating the centroid



error circle (this map (1σ, 2σ, 3σ)

within

+ Nebula centroid (FL8Y; 100 MeV—1 TeV)

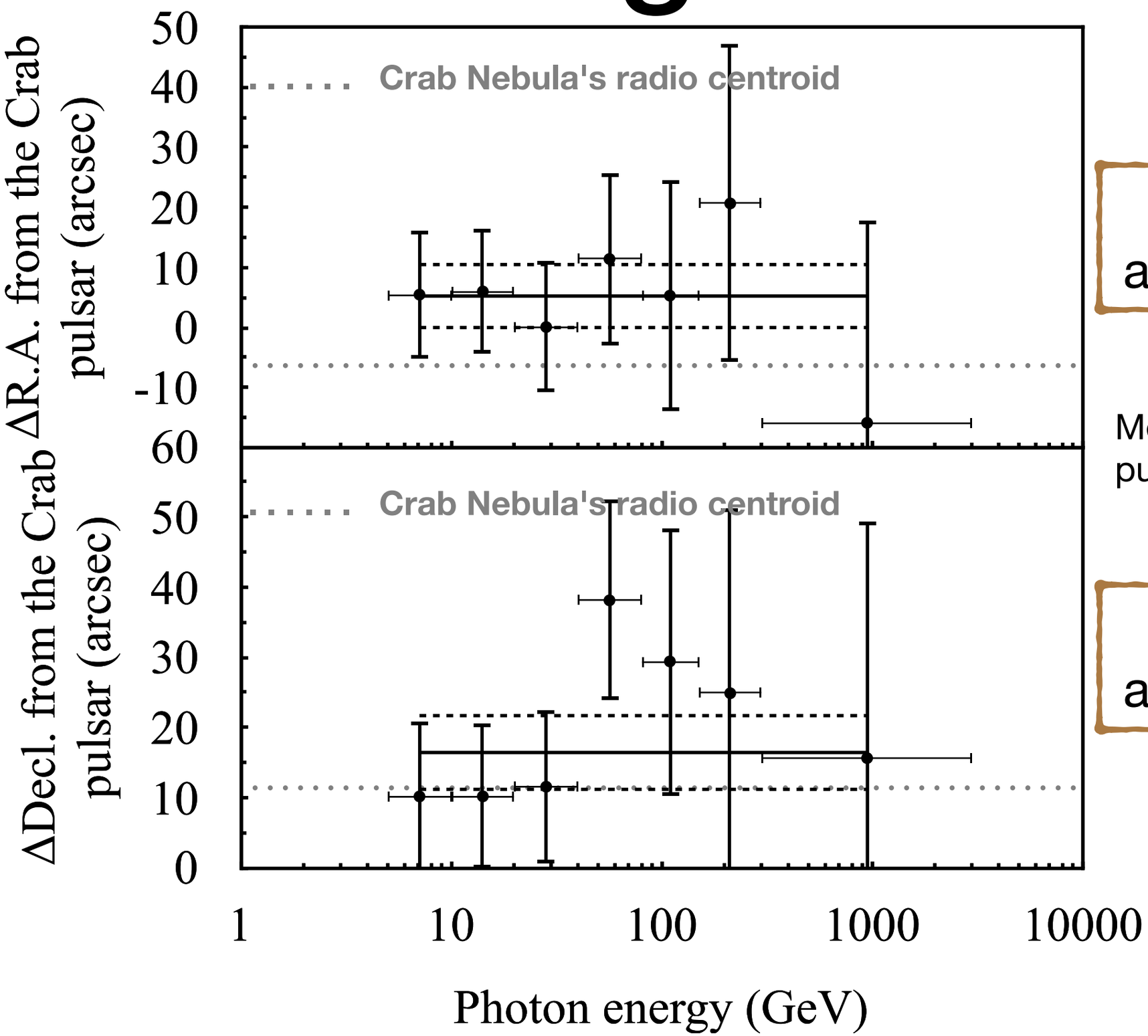
□ Nebula centroid (radio)

+ Pulsar (FL8Y)

◇ Pulsar (radio; Lobanov et al. 2011)

>5 GeV centroid is consistent with >100 MeV centroid

Locating the centroid

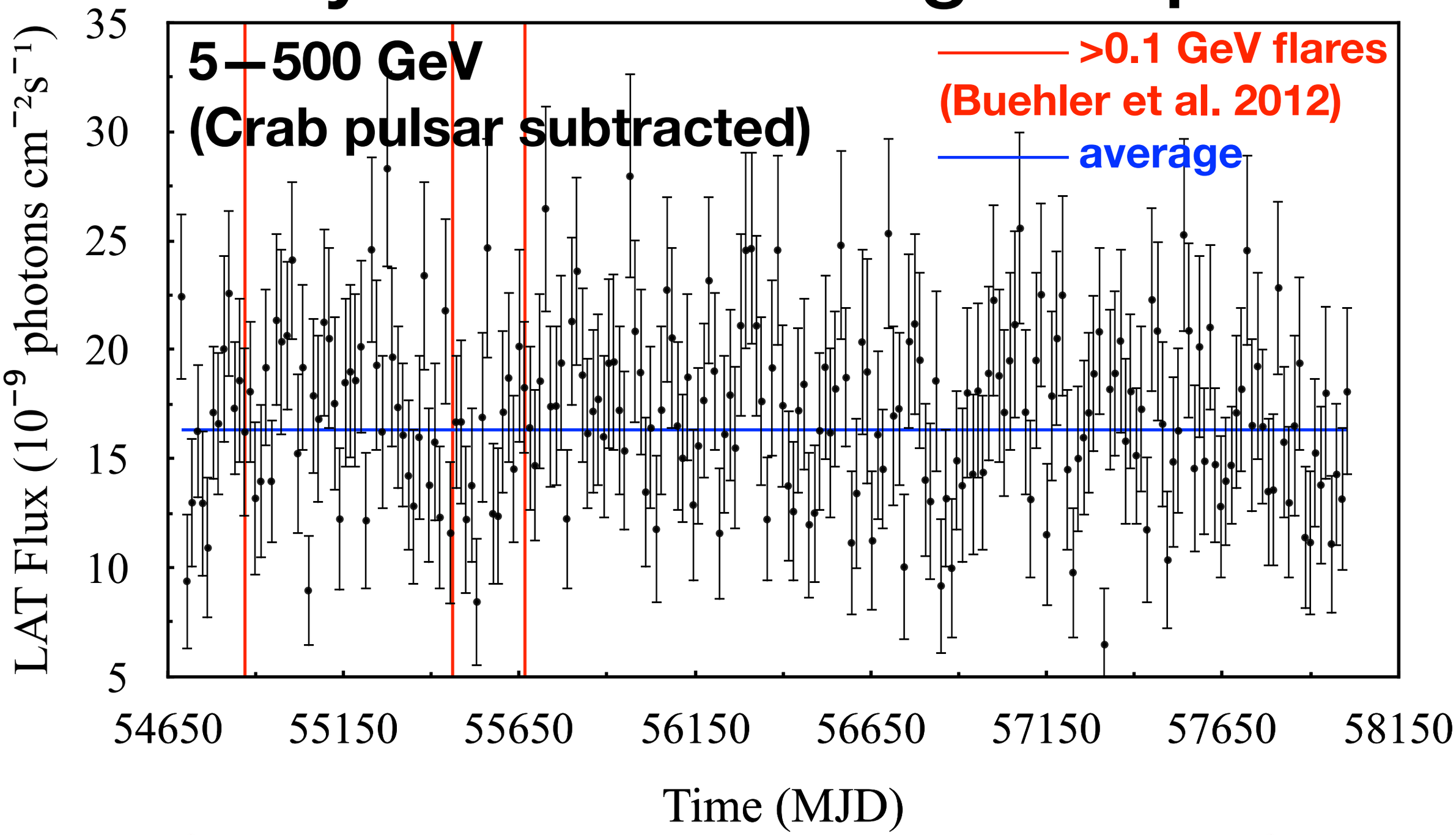


No discrepancy among energy bands

Measured from pulsar's radio position

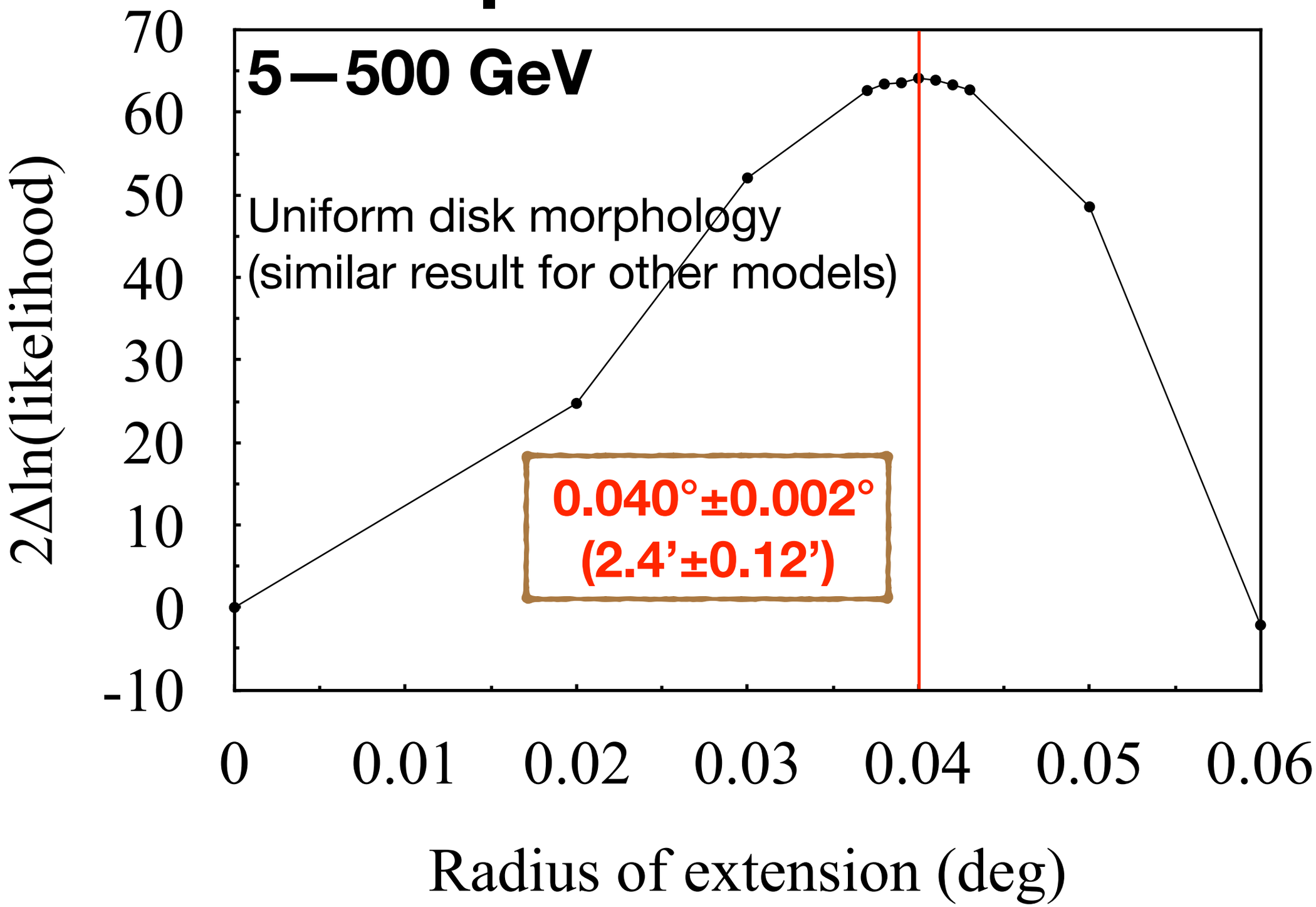
No discrepancy among energy bands

Variability of flux? Flaring component?



No variability (<2σ; $\chi 2$ test, Wald-Wolfowitz run test)
No correlation with >0.1 GeV flares

Extension & its energy-dependence

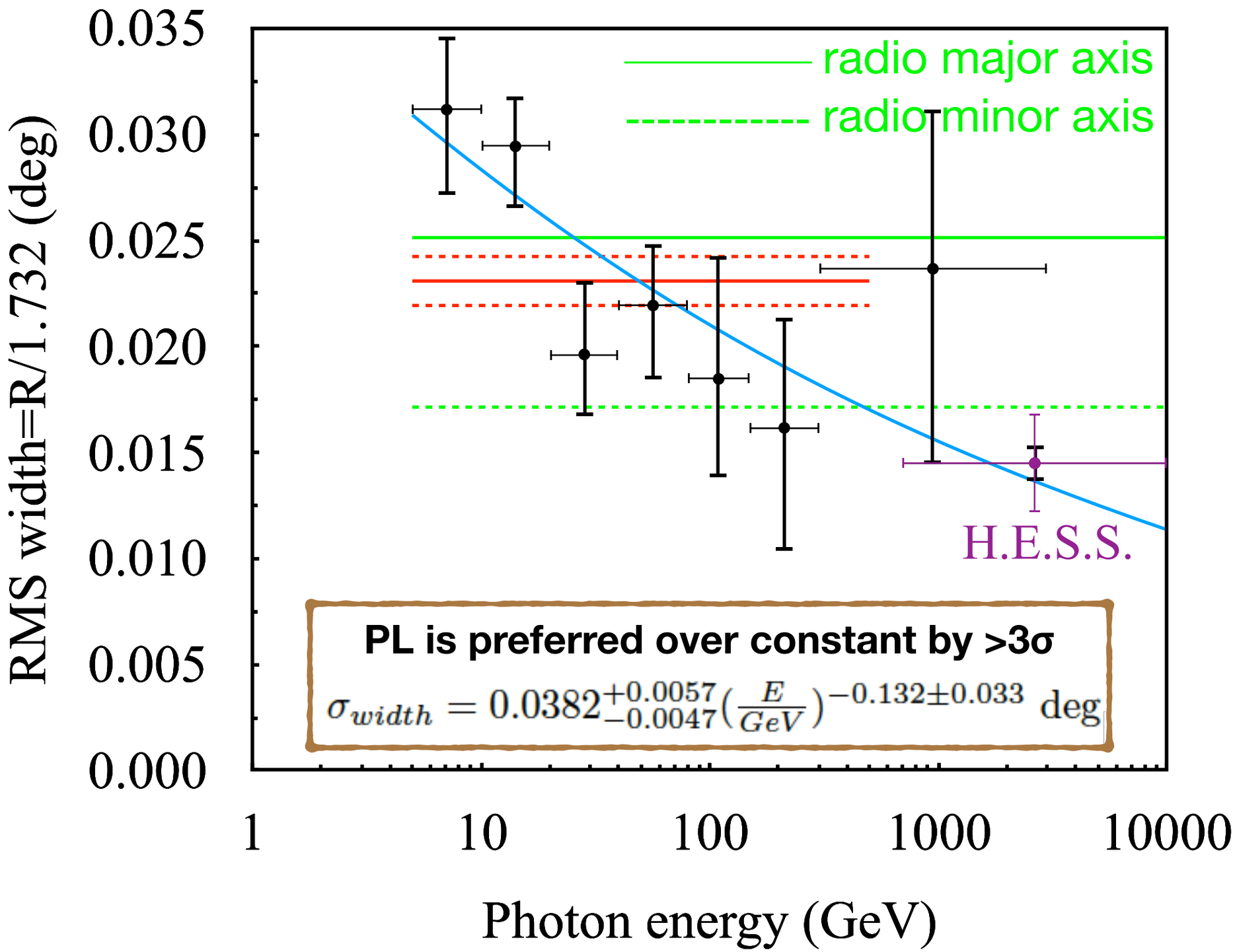


Extension & its energy-dependence

Energy range (GeV)	Radius of extension (deg)
5–10	$0.054^{+0.006}_{-0.007}$
10–20	$0.051^{+0.004}_{-0.005}$
20–40	$0.034^{+0.006}_{-0.005}$
40–80	$0.038^{+0.005}_{-0.006}$
80–150	$0.032^{+0.010}_{-0.008}$
150–300	$0.028^{+0.009}_{-0.010}$
300–3000	$0.041^{+0.013}_{-0.016}$

No energy-dependence based on Fermi data only (<2σ)

Extension & its energy-dependence



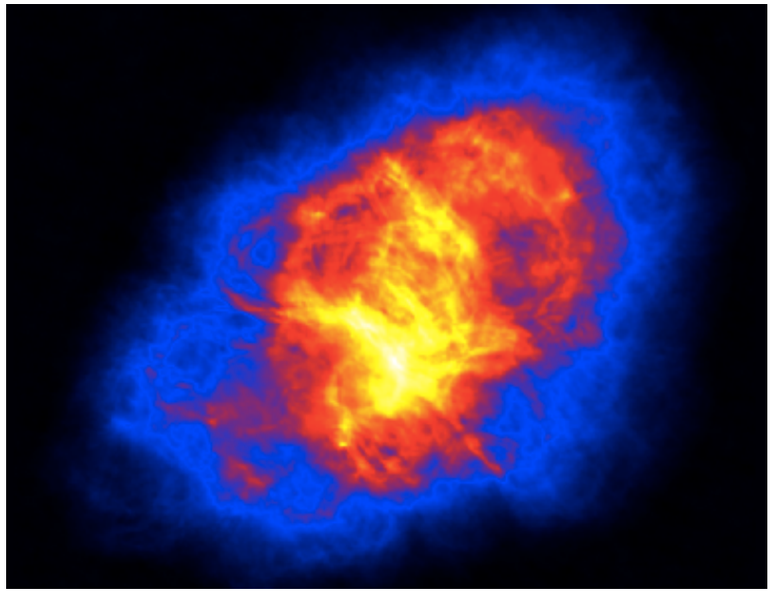
PL is preferred over constant by >3σ

$$\sigma_{width} = 0.0382^{+0.0057}_{-0.0047}\left(\frac{E}{GeV}\right)^{-0.132\pm0.033}\ \mathrm{deg}$$

Discussion: Comparison with radio nebula

Expectation: Gamma-rays and radio are emitted by the same electrons

- Radio centroid is beyond 2σ error circle of >5 GeV centroid but is within the 3σ one
- Both centroids are northward offset from Crab pulsar
- 5–20 GeV extensions are marginally consistent with radio extension along major axis (2σ)
- >20 GeV extensions are smaller than radio extension along major axis



VLA radio (5.5 GHz) image (Bietenholz et al. 2004)

Read appendix for detail

Discussion: Comparison with electron distribution

- Gamma-ray extension width (observed): $r(E_{\rm IC}) \propto E_{\rm IC}^{-0.132\pm0.033}$

comparable

- Electron distribution: $r_e \propto \gamma^{-0.17}$

(Meyer et al. 2010)

consistent (2σ)

- Thomson scattering ($E_{\rm IC} \approx \gamma^2 \epsilon$)

  - Gamma-ray extension width (predicted): $r(E_{\rm IC}) \propto E_{\rm IC}^{-0.085}$

What if further considering dust emission?
Predicted index ↓
Please read poster #GR07

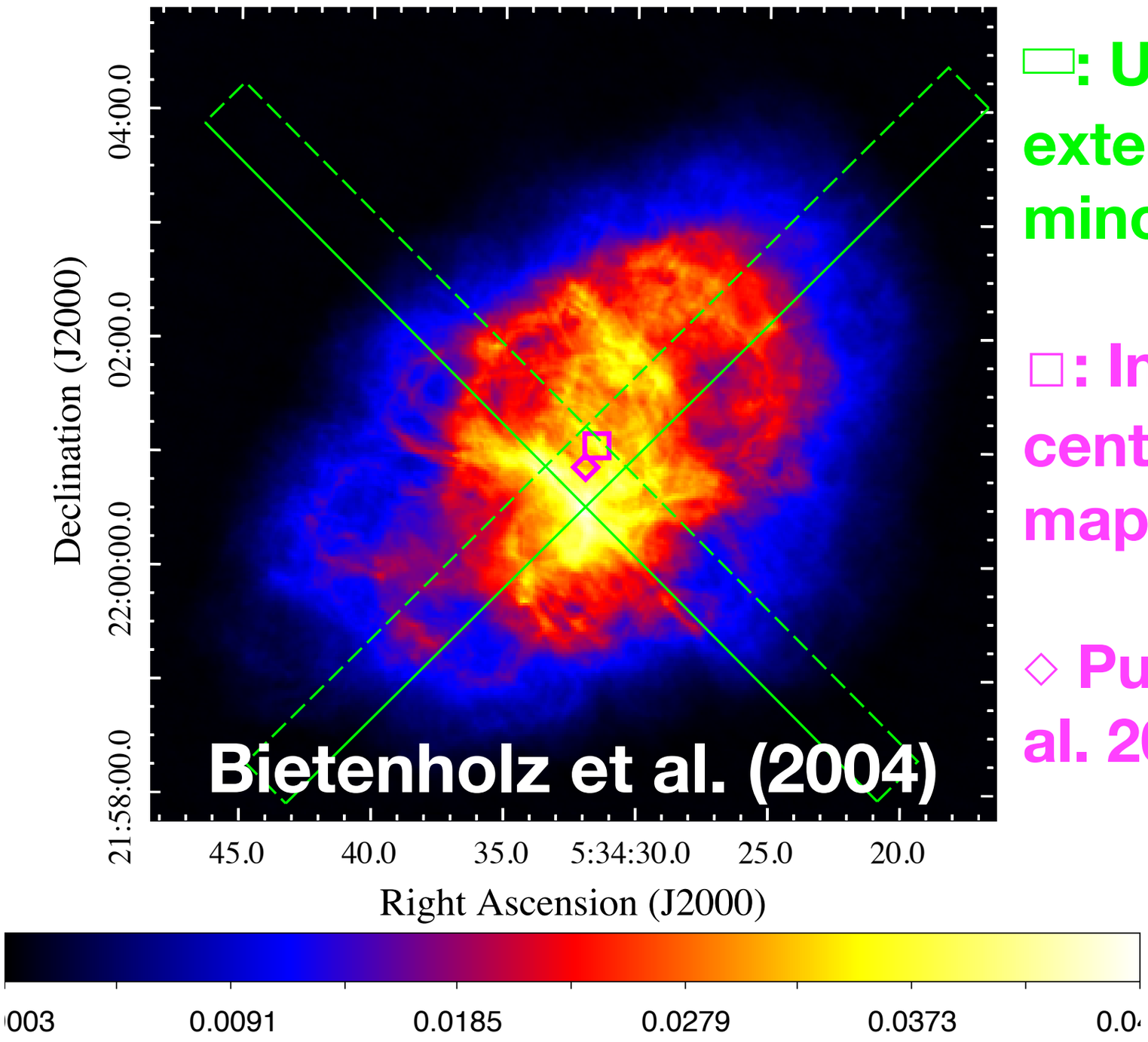
Summary

Keep Calm
&
Study Astrophysics

- ~9.1 years of Fermi LAT data
- Refined Crab pulsar's spectrum (PLSubExpCutoff —> PL)
- 0.040°±0.002° radius (uniform disk) in 5—500 GeV
  - PSF systematics are evaluated (read appendix for detail)
- Surprisingly strong **energy-dependent shrinking of extension** from 5 GeV to 10 TeV (index=0.132±0.033)
  - Shrink faster than predicted index (<0.085)

Appendices

VLA radio (5.5 GHz) image



▭: Used to measure radio extensions along major and minor axes

□: Intensity-weighted centroid determined on this map

◇ Pulsar (radio; Lobanov et al. 2011)

Comparison with “apparent” extension of AGN Mkn 421: to test IRF