# SPACE-BASED GAMMA-RAY ASTRONOMY: NEW RESULTS, NEW FRONTIERS, NEW HORIZONS


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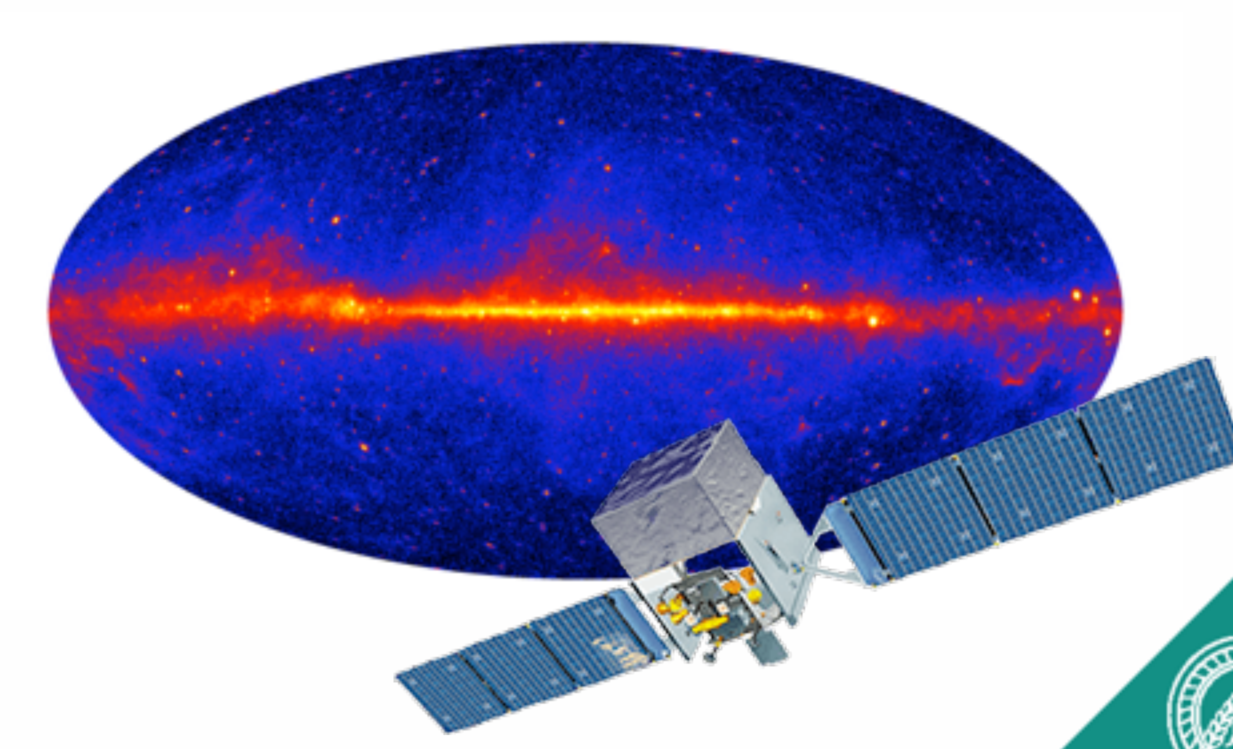


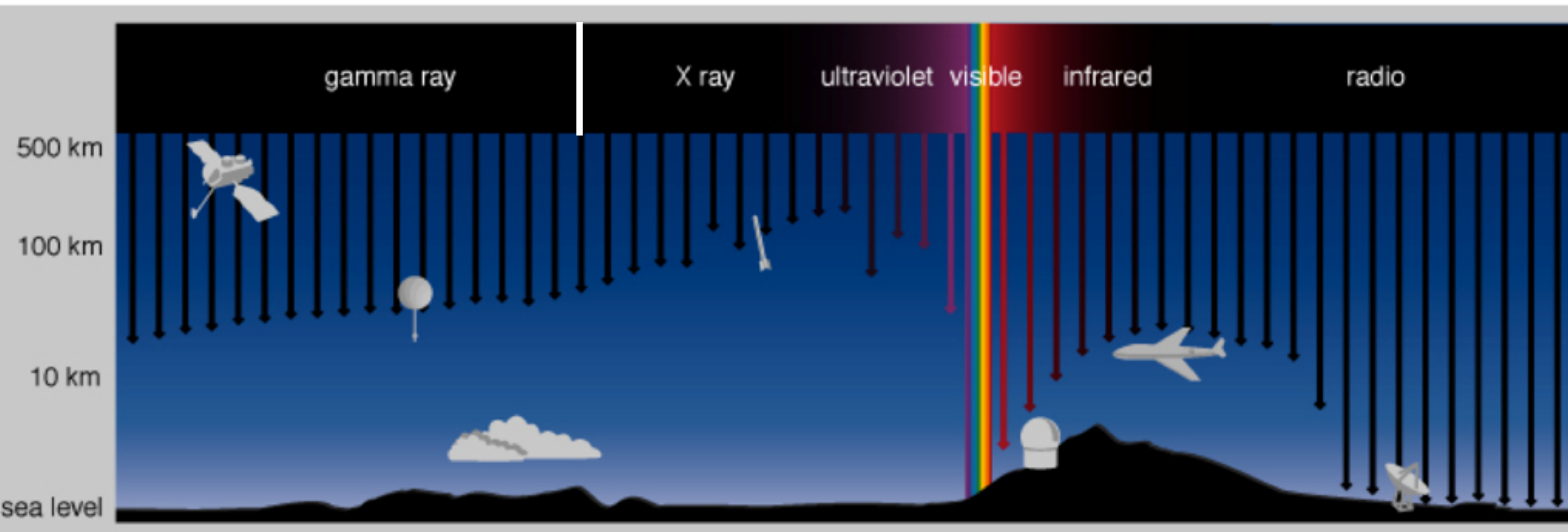
# Outline

- Introduction
- *Fermi*
  - diffuse γ-ray emission
  - source catalogs
- New results
  - origin of cosmic rays and particle acceleration
  - the nature of dark matter
- New frontiers
  - extension to TeV
  - new γ-ray emitters
  - long-term variability
- New horizons
  - upcoming and future missions

# Space-borne γ-ray telescopes

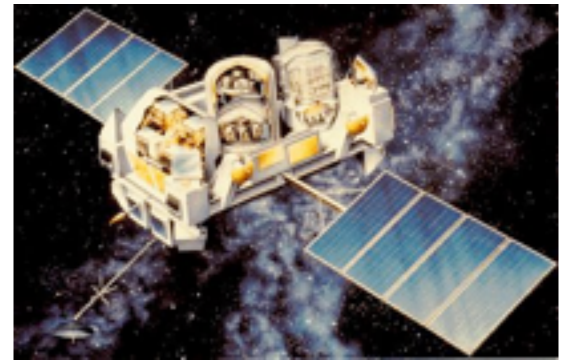
limited by γ-ray fluxes
and size constraints for satellites

(eV) $10^{12}$ $10^{10}$ $10^{8}$ $10^{6}$ $10^{4}$ $10^{2}$ $10^{0}$ $10^{-2}$ $10^{-4}$ $10^{-6}$

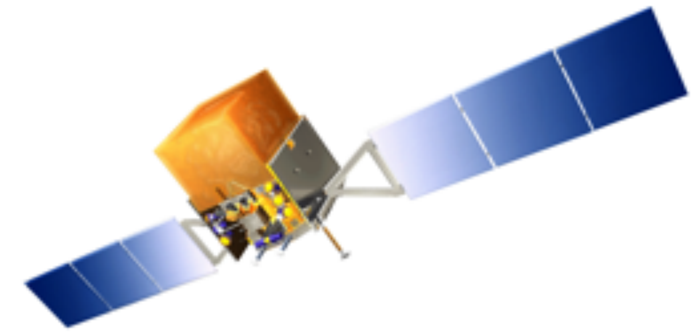


# Detecting γ rays in space

*INTEGRAL* IBIS&SPI
2002-present
15 keV-10 MeV
coded mask +
scintillating crystals/
semiconductor
detectors

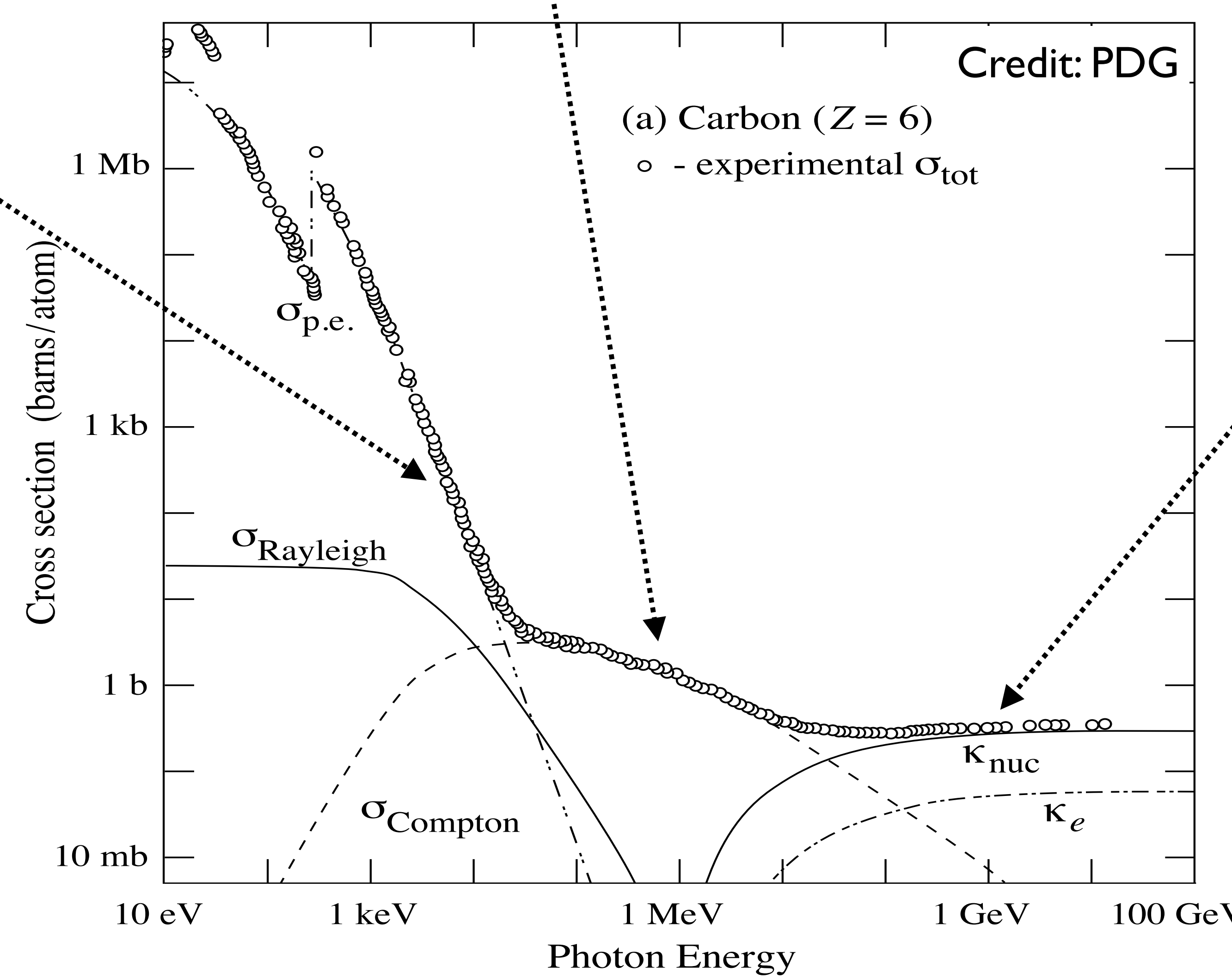


COMPTEL
1991-2000
800 keV-30 MeV
liquid+crystal scintillator



*Fermi* LAT
2008-present
30 MeV- > 300 GeV
Si-W tracker-
converter +
electromagnetic
calorimeter

and AGILE
2007-present



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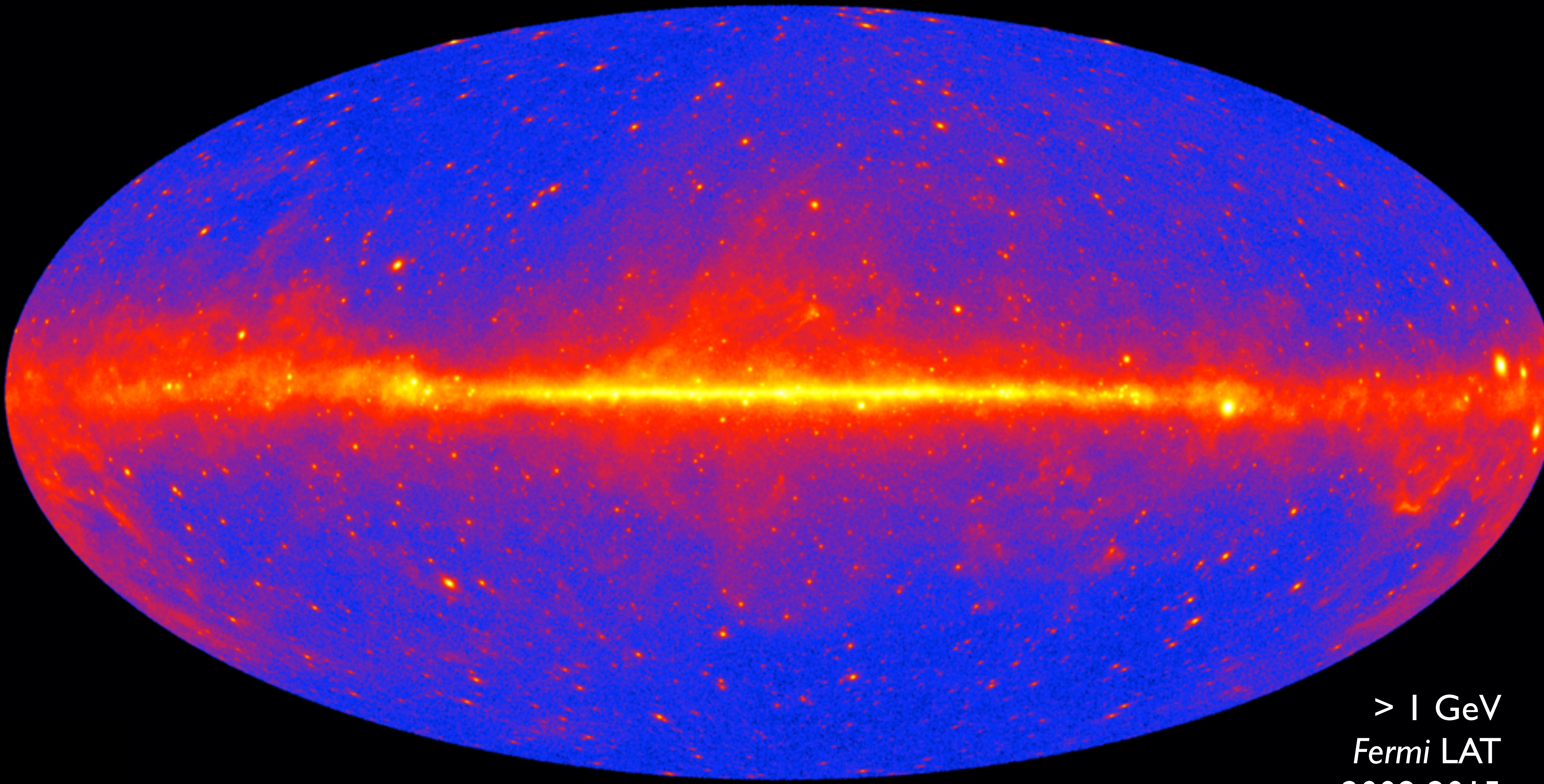
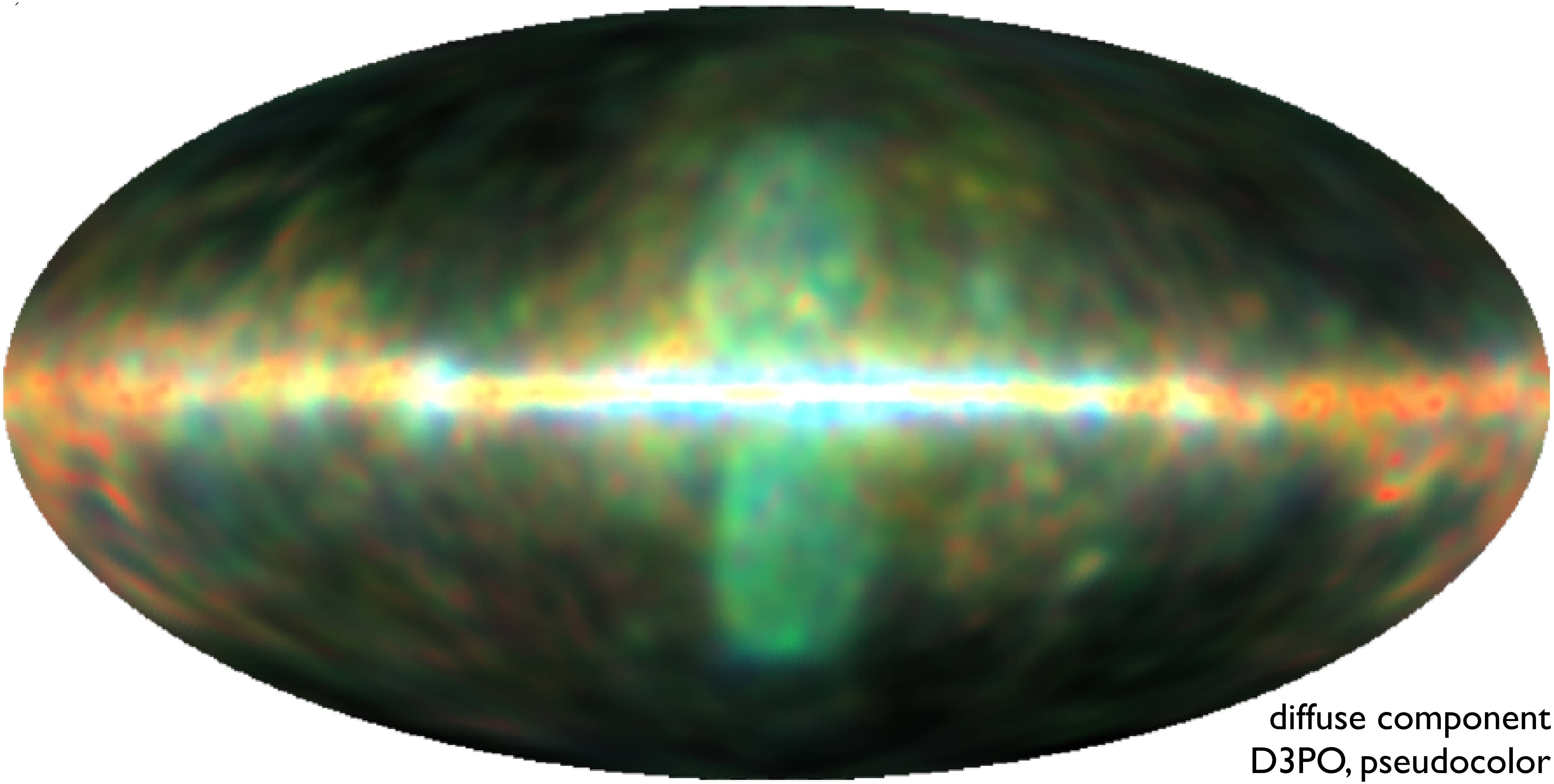
# The Fermi γ-ray sky



> 1 GeV
*Fermi* LAT
2008-2015
NASA/DoE/*Fermi*-LAT collaboration

# Resolving the γ-ray sky: diffuse emission



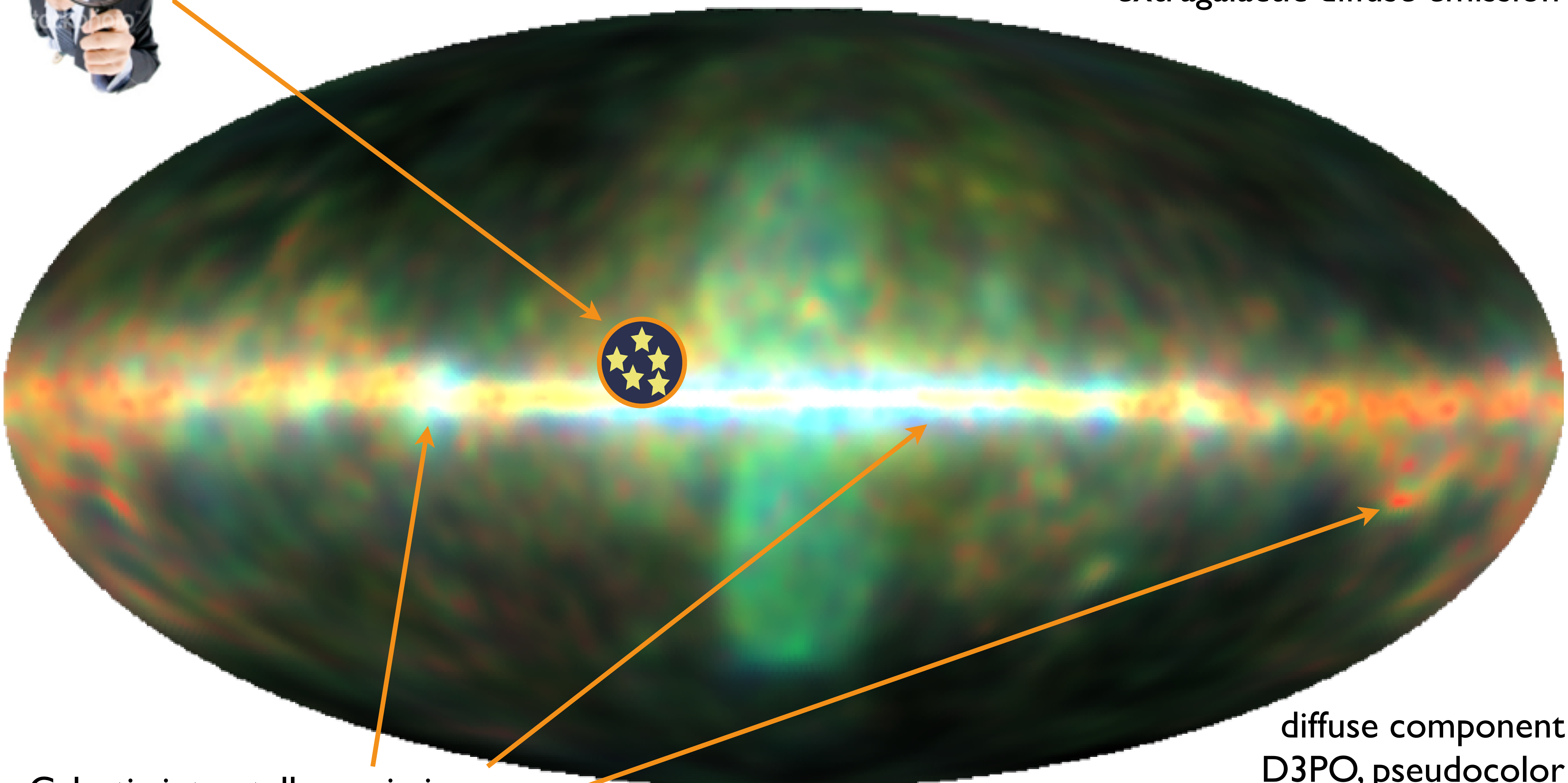
diffuse component
D3PO, pseudocolor
Selig+ A&A 581 2015 A126

diffuse emission = no individual sources

# Resolving the γ-ray sky: diffuse emission

unresolved sources

isotropic γ-ray background = residual CR contamination +extragalactic diffuse emission

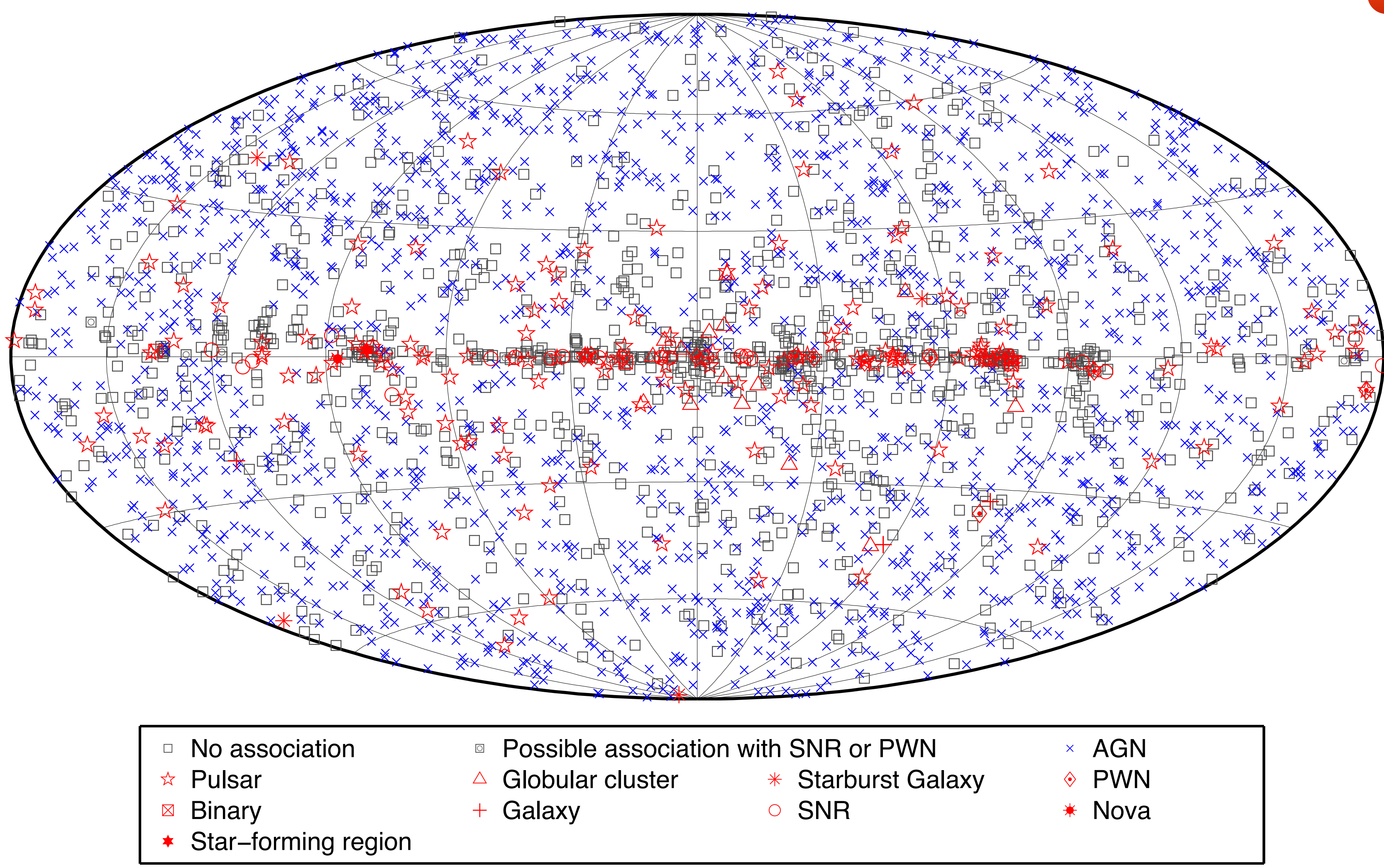


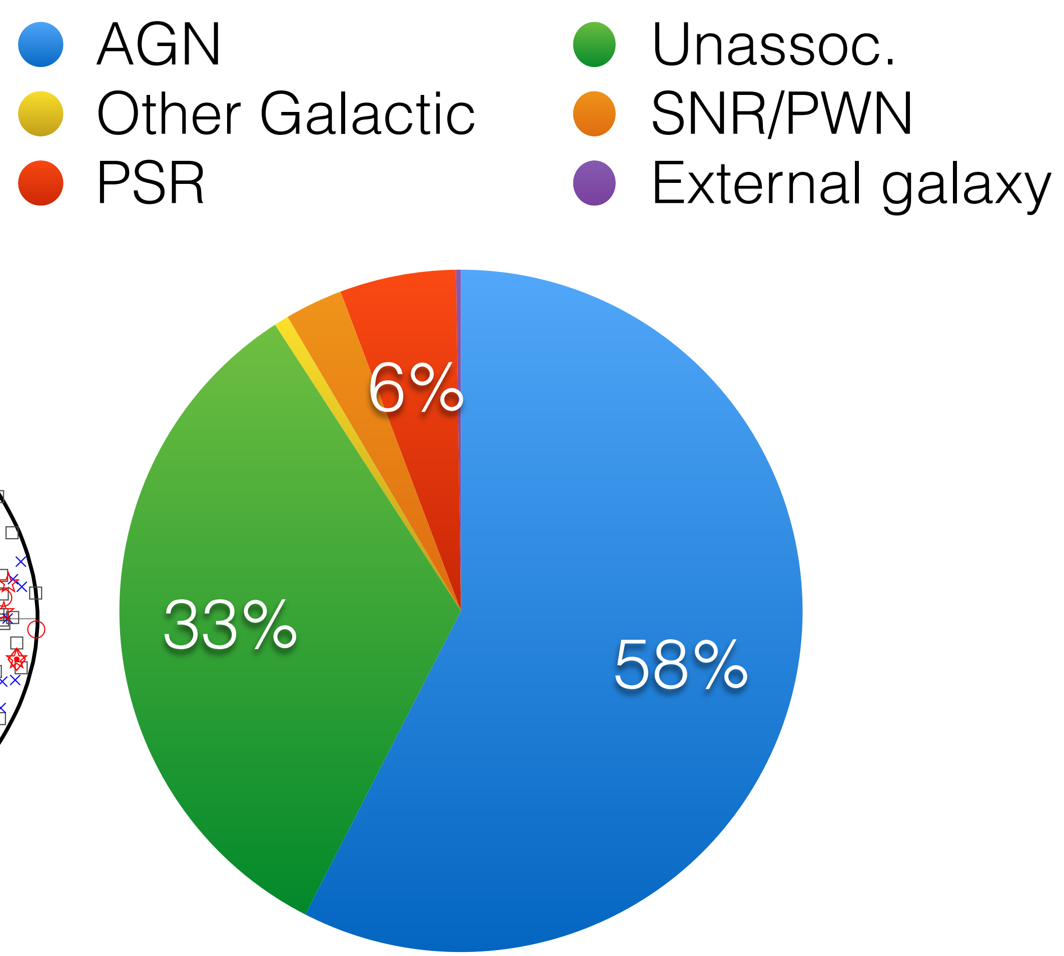
Galactic interstellar emission = nucleon-nucleon collisions Bremsstrahlung, inverse Compton

diffuse component D3PO, pseudocolor
Selig+ A&A 581 2015 A126

# Resolving the γ-ray sky: sources

- general catalogs, e.g., 3FGL
  - 4 years, 100 MeV-300 GeV
  - 3033 sources (> 4.1σ)
- specific source classes/energy ranges




Fermi LAT collab. ApJS 218 2015 23A

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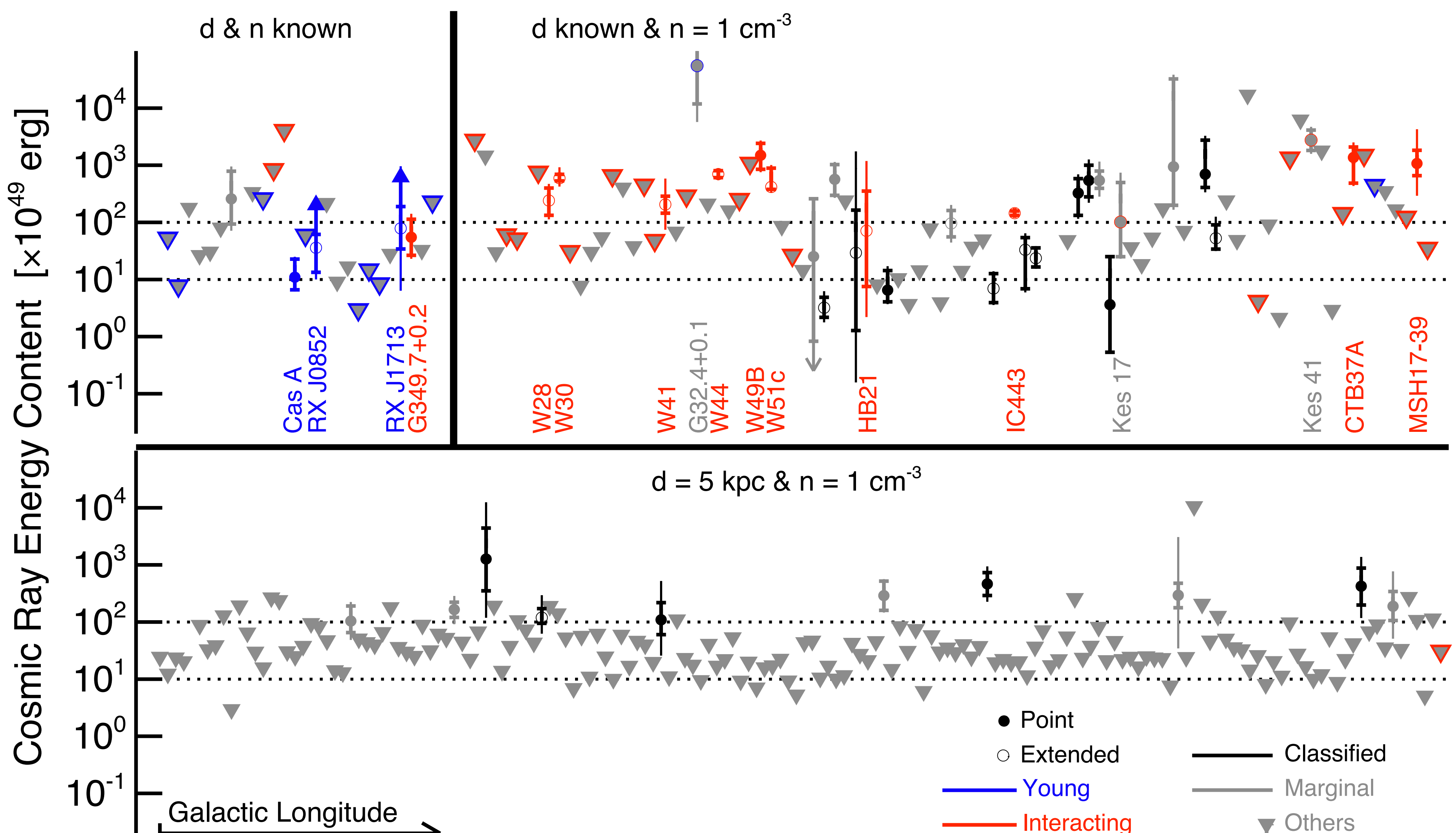
# CR origin: testing the SNR paradigm

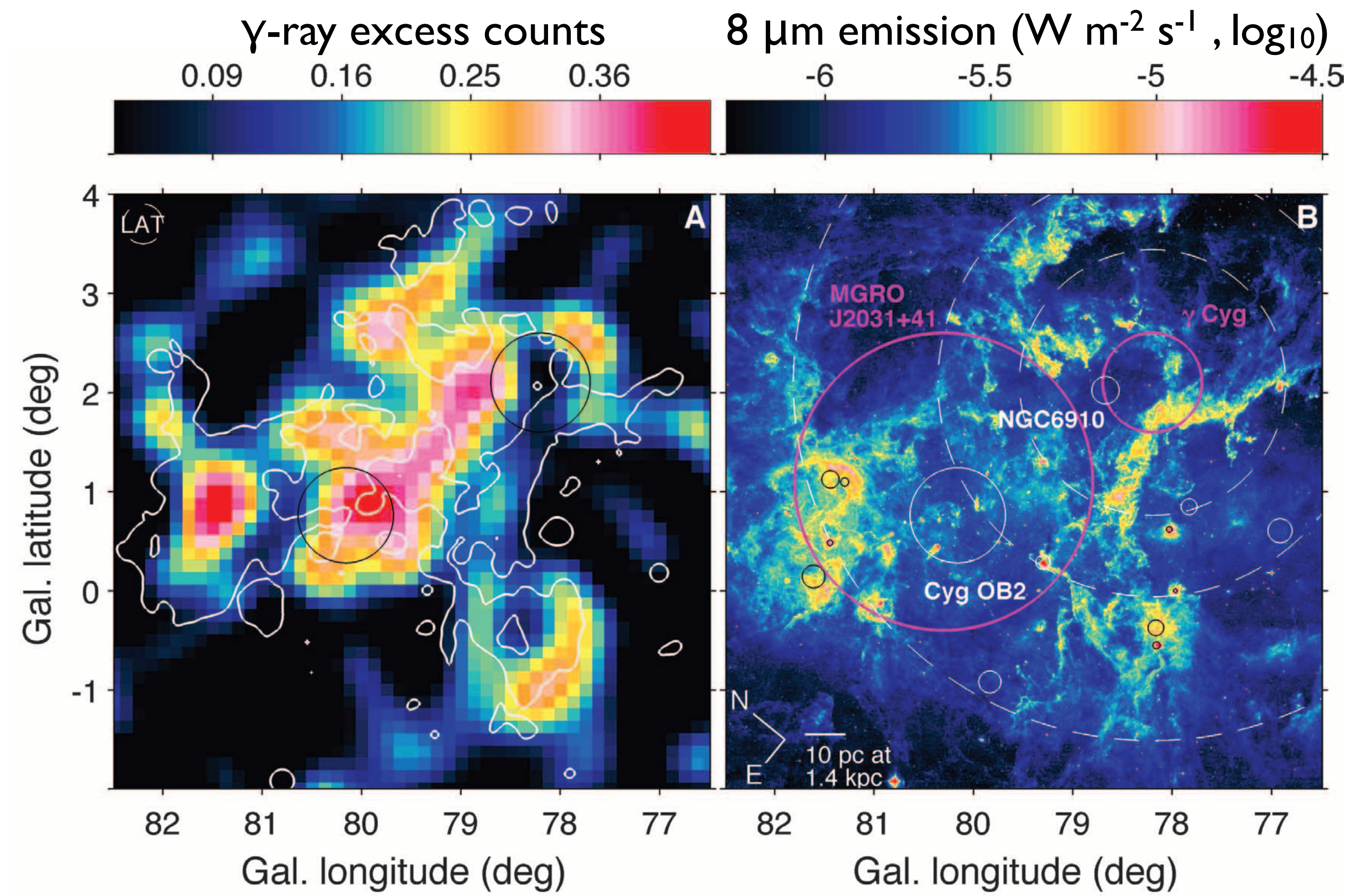
- SNR paradigm: 10% of SN energy into cosmic rays
- LAT SNR Catalog, 1-100 GeV
  - 30 sources classified as SNRs
  - 14 marginal candidates
  - 245 upper limits on radio SNRs

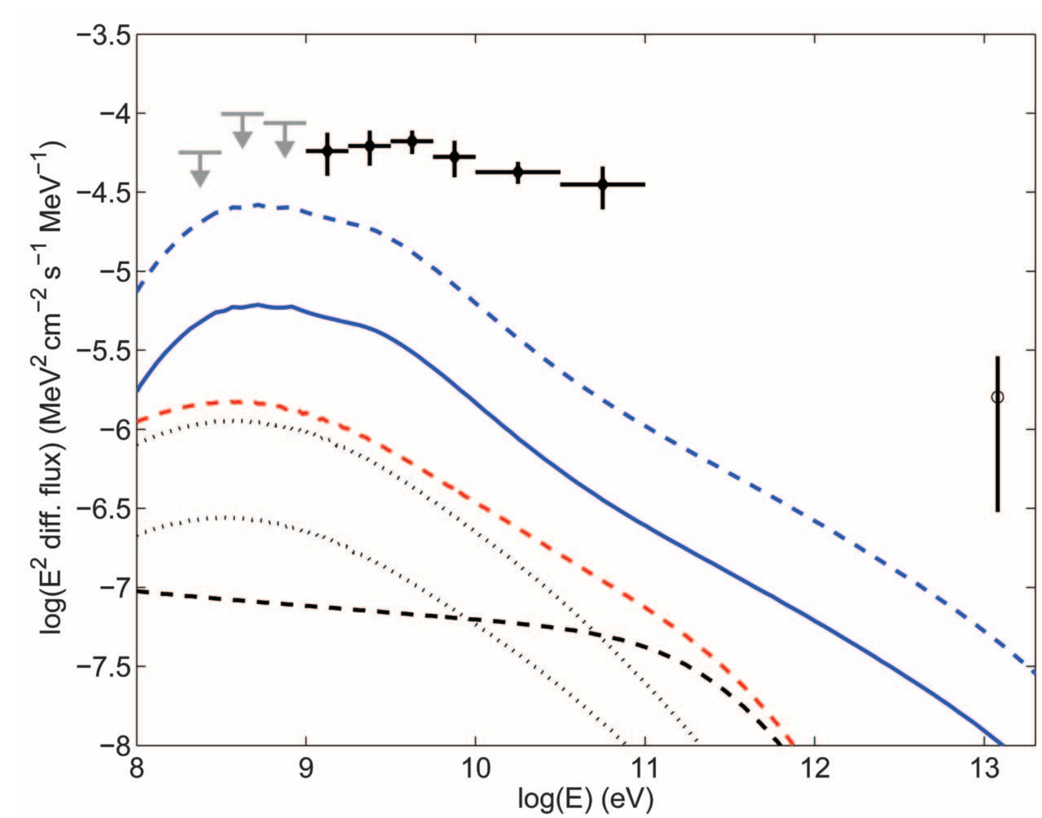
Fermi LAT collab. ApJS 224 2016 8A



# A cocoon of freshly accelerated CRs in Cygnus

- massive star-forming regions
  - CR isotopic abundances ($^{22}$Ne, trans-iron)
  - 80% SN = gravitational collapse of massive star
  - superbubbles
- CR cocoon in Cygnus
  - single source or superbubble?
  - advection? confinement?




Fermi LAT collab. Science 334 2011 1103

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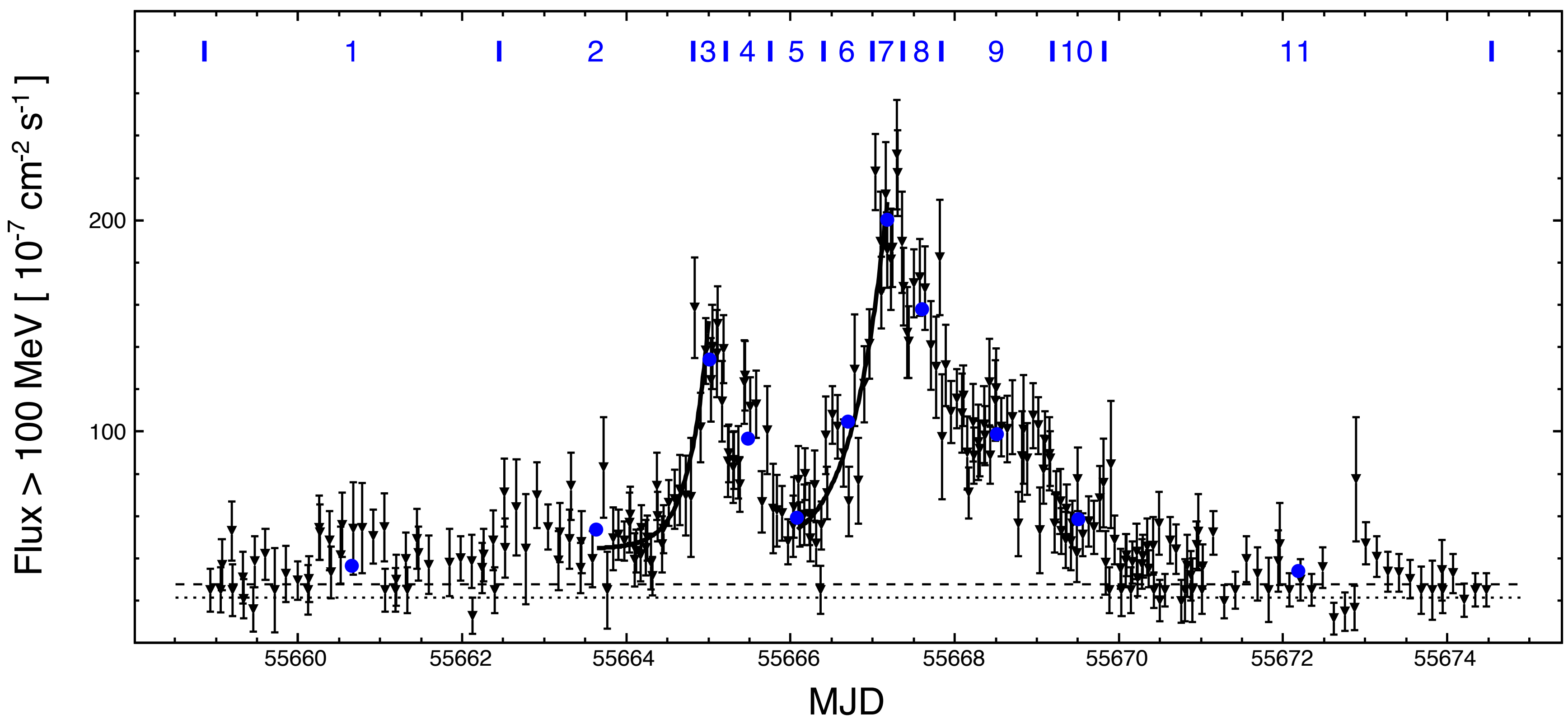
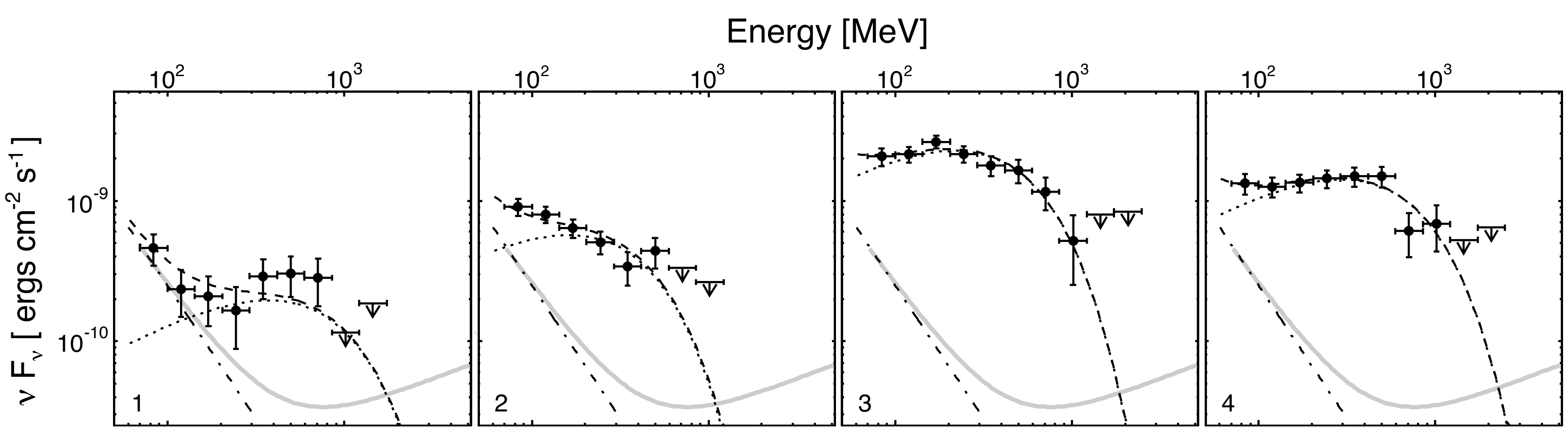
# The Crab nebula flares

- variability < 8 h, 1% pulsar spindown power
  - emitting region < 3 $10^4$ pc
- PeV electrons emitting γs up to 1 GeV
- magnetic reconnection?

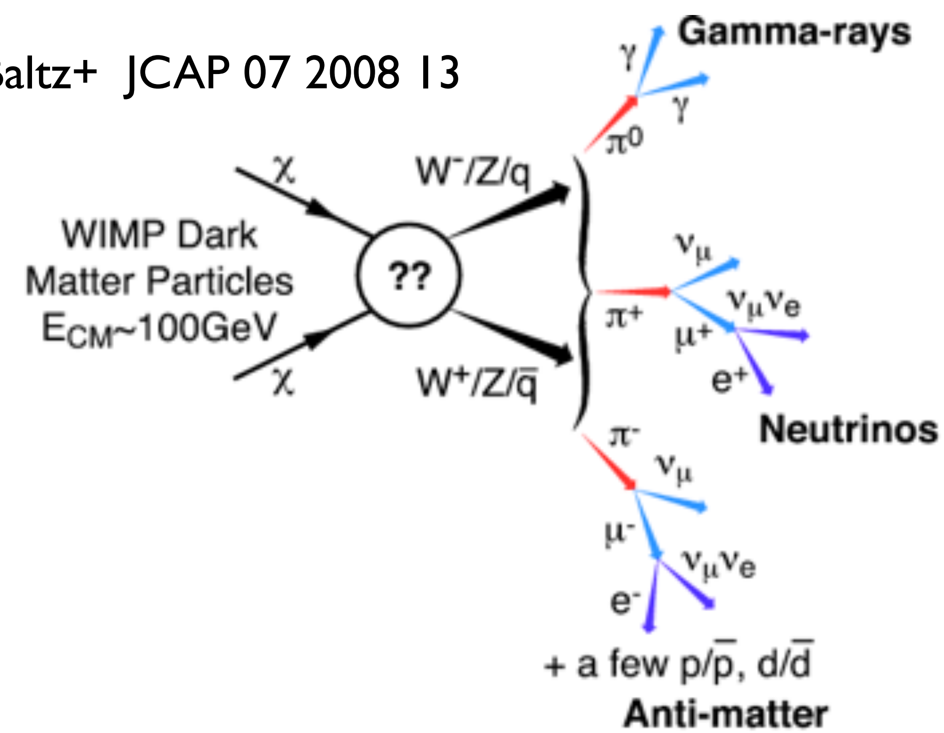



Buehler+ ApJ 749 2012 26B

# Searches for DM

Baltz+ JCAP 07 2008 13

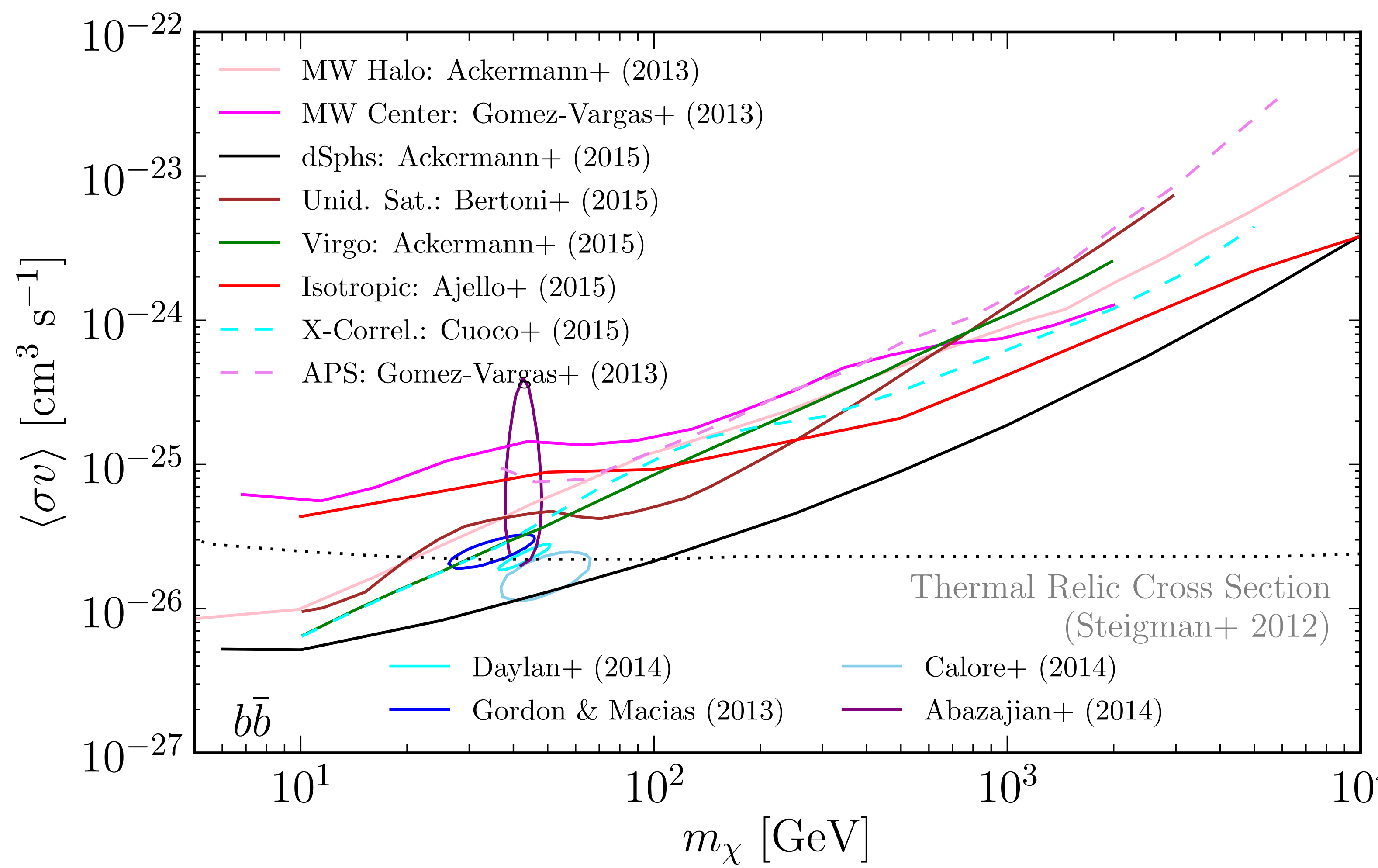



$$\Phi(E_\gamma) = \int_\Omega d\Omega \int_{\mathrm{l.o.s}} dl\, \rho^2(\theta)\; \frac{1}{2}\frac{<\sigma v>}{4\pi m_\chi^2}\sum_f \frac{dN_f}{dE_\gamma}B_f$$

DM content of target

properties of DM particle

Charles+ PhR 636 2016 1C




- start constraining thermal relic cross section
- strongest limits from dwarf spheroidal galaxies
  - DM density best constrained
- detection at Galactic center?

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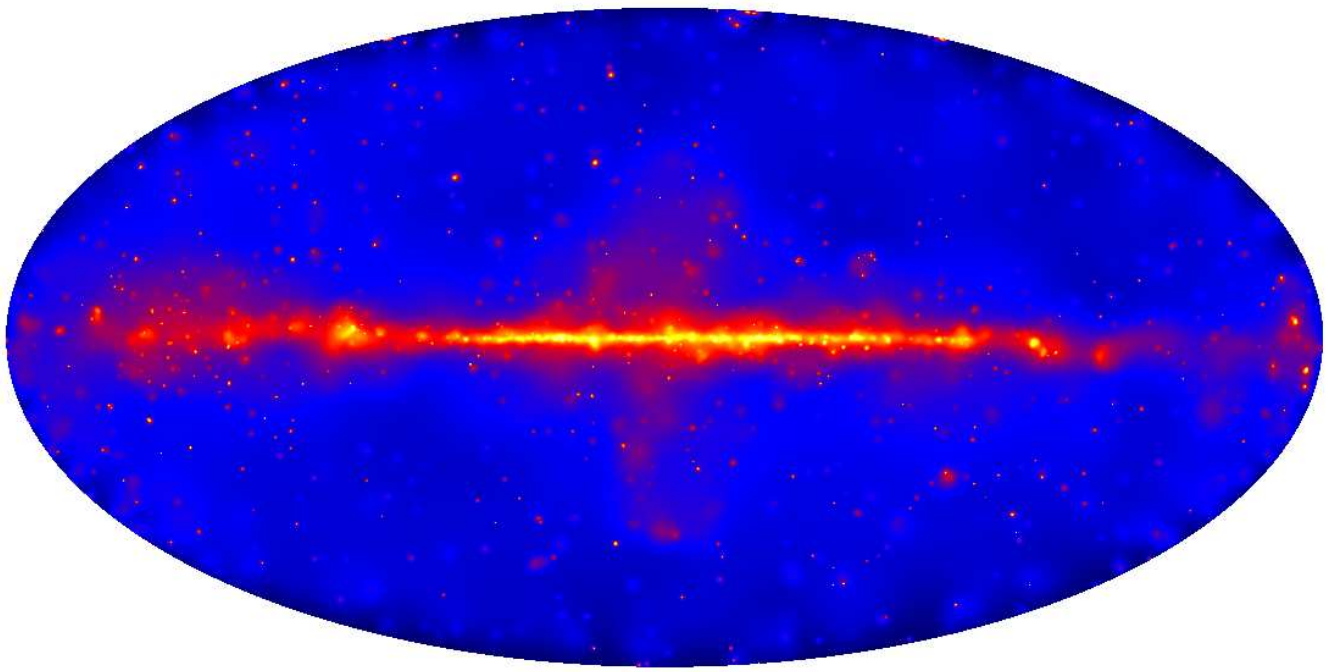
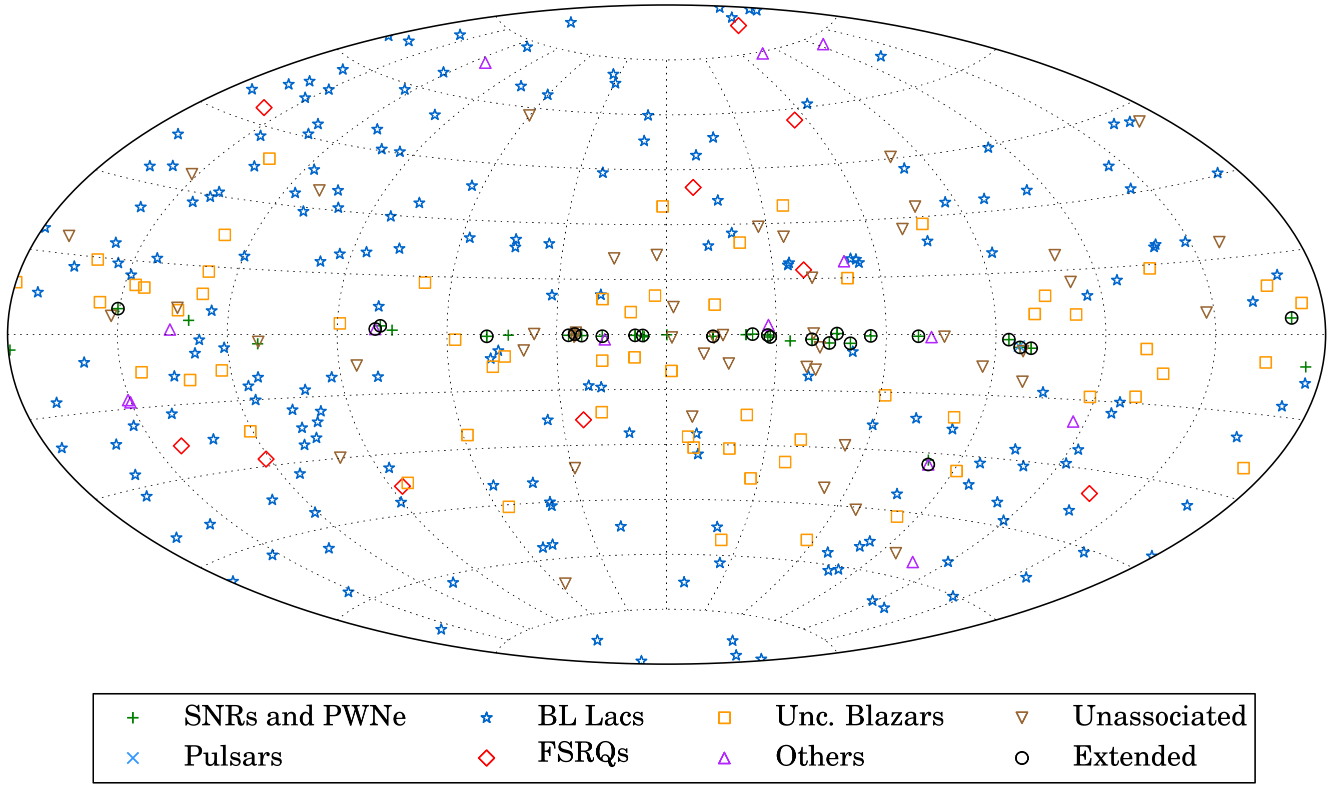
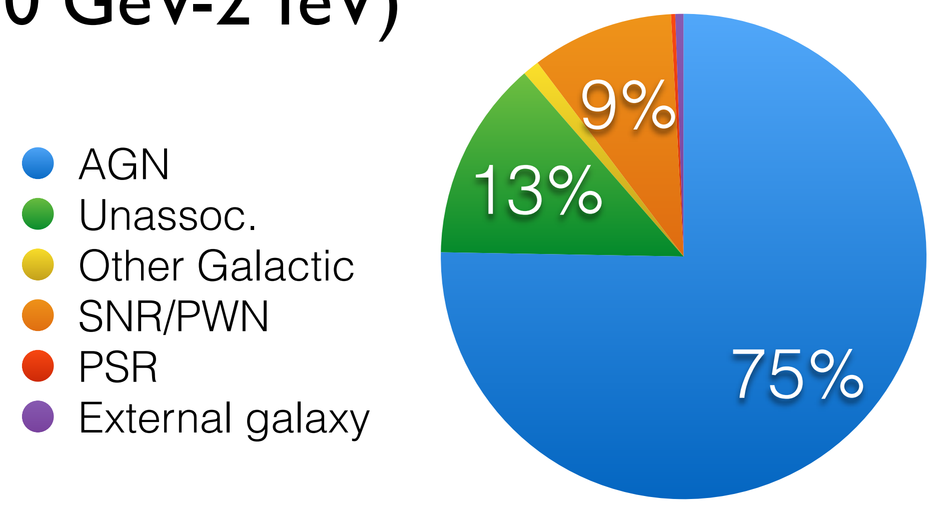
# Extension to TeV energies

- segmented ACD/calorimeter: reduce back-splash self-veto
- Pass8 analysis
  - reliable energy estimate up to 2 TeV
  - 25% larger effective area > 10 GeV
- 2FHL Catalog
  - 80 months, 50 GeV-2 TeV
  - 360 sources → 75% previously unknown
- upcoming: 3FHL (1720 sources, 10 GeV-2 TeV)

Fermi LAT collab. ApJS 222 2016 5A



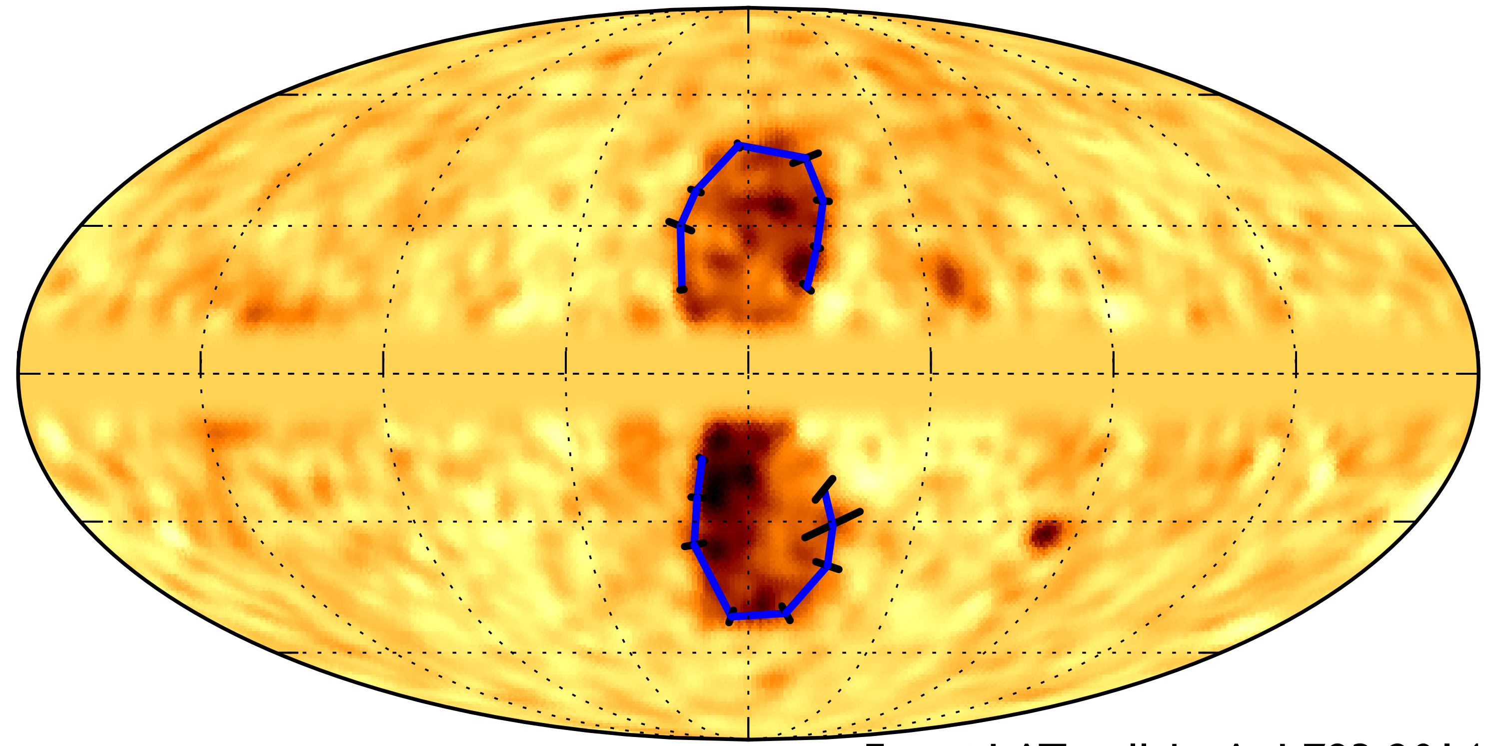


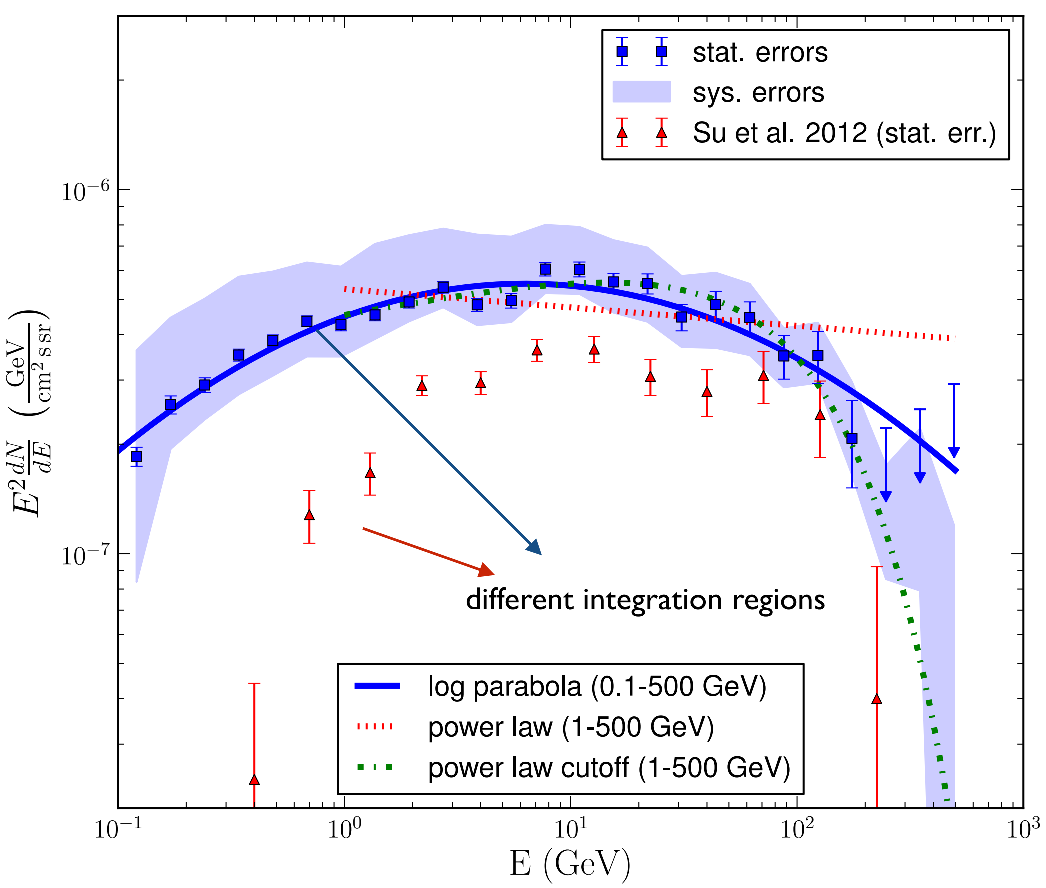
# The *Fermi* bubbles

- lobe-like structures from the Galactic center
- giant nuclear magnetized outflow

γ rays (foreground subtracted) 10-500 GeV

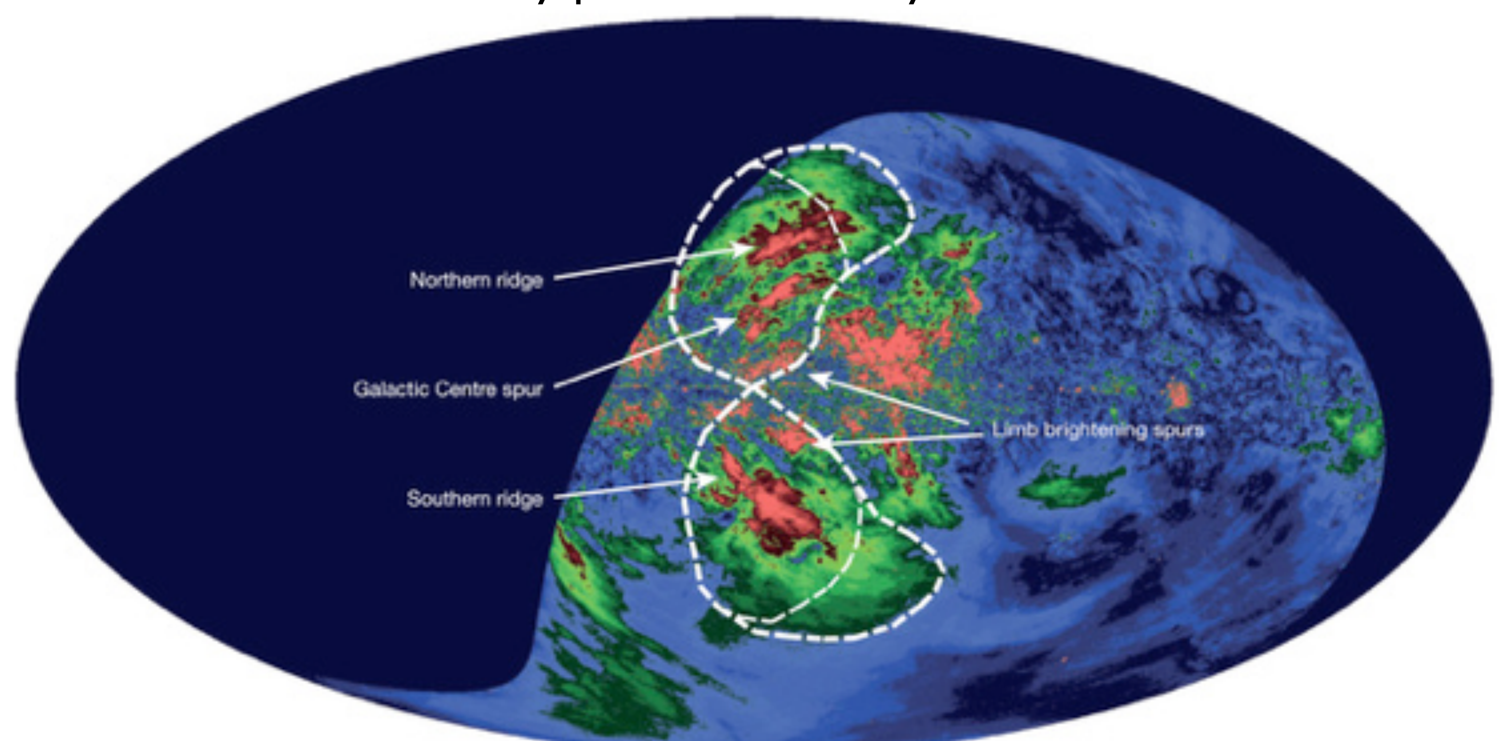


Fermi LAT collab. ApJ 793 2014 64A




Fermi LAT collab. ApJ 793 2014 64A

linearly-polarized intensity 2.3 GHz

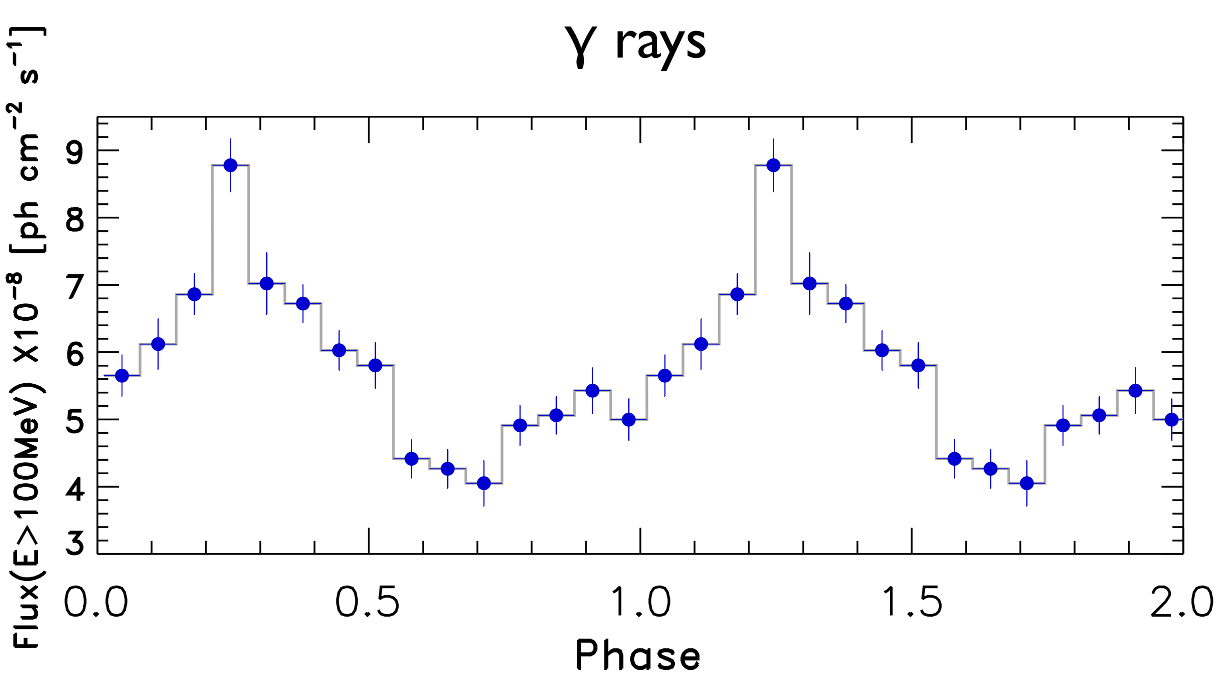


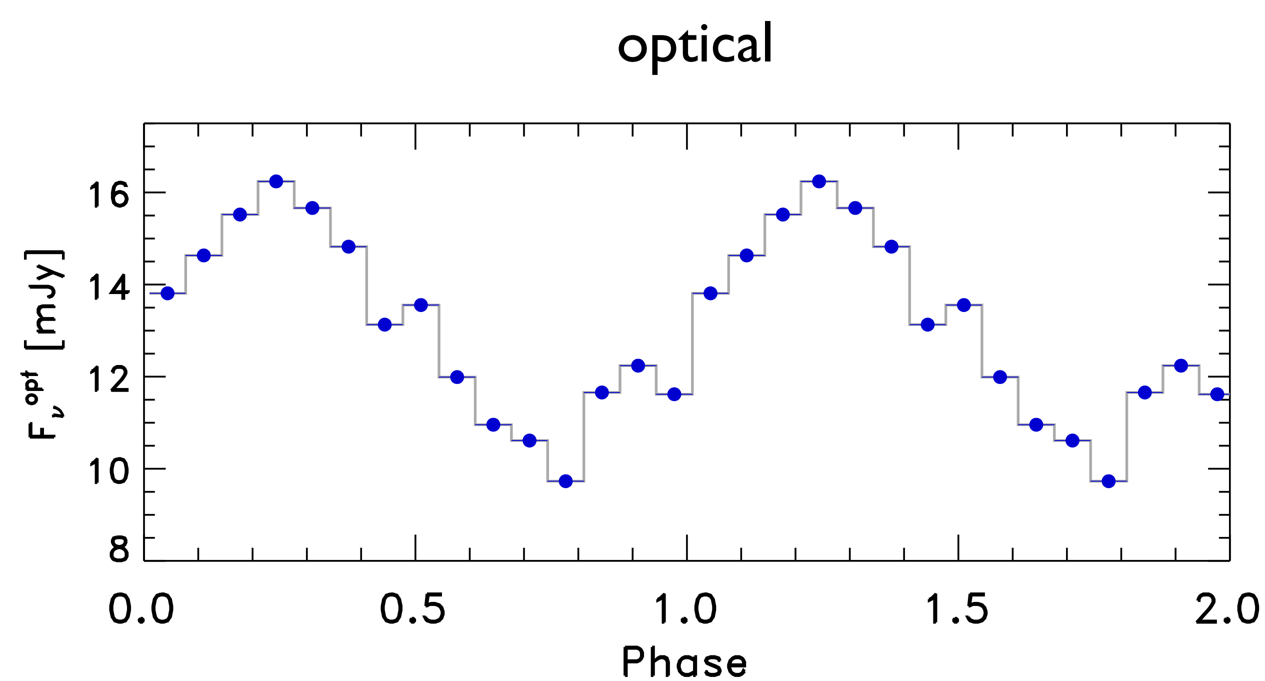

Carretti+ Nature 493 2013 66

# Quasi-periodic flux modulation in a γ-ray AGN

- blazar PG 1553+113
  - nearly-periodic oscillation 2.18 y period
  - LAT: c.l. 99% over 6.9 years
  - correlated with optical (> 9 y), radio, X rays
- pulsational accretion flow instabilities? jet precession? accretion-outflow coupling? SMBH binary system?

Fermi LAT collab. ApJL 813 2015 41A



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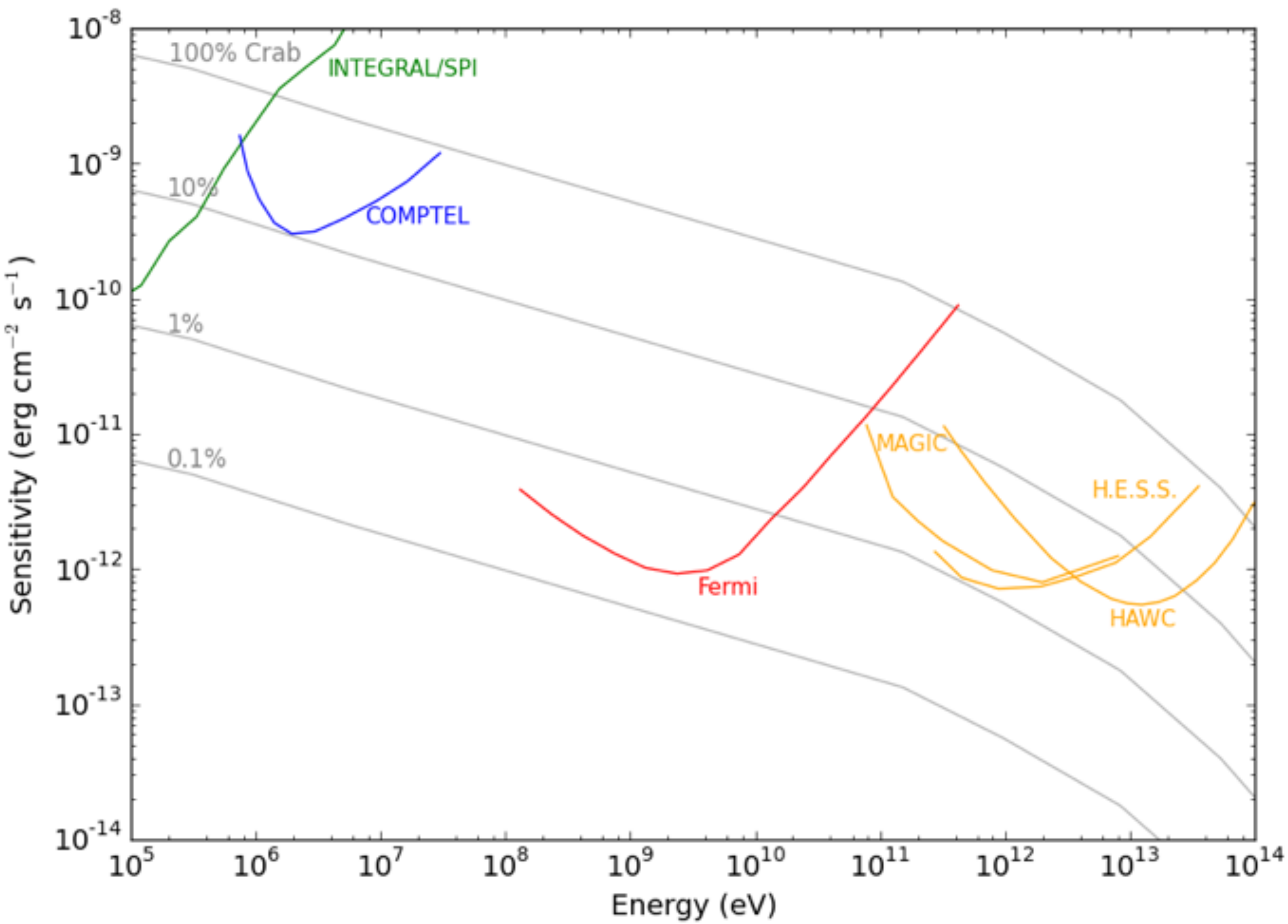
# The past, the present, and the future

adapted from Knödlseder CRPhy 17 2016 663



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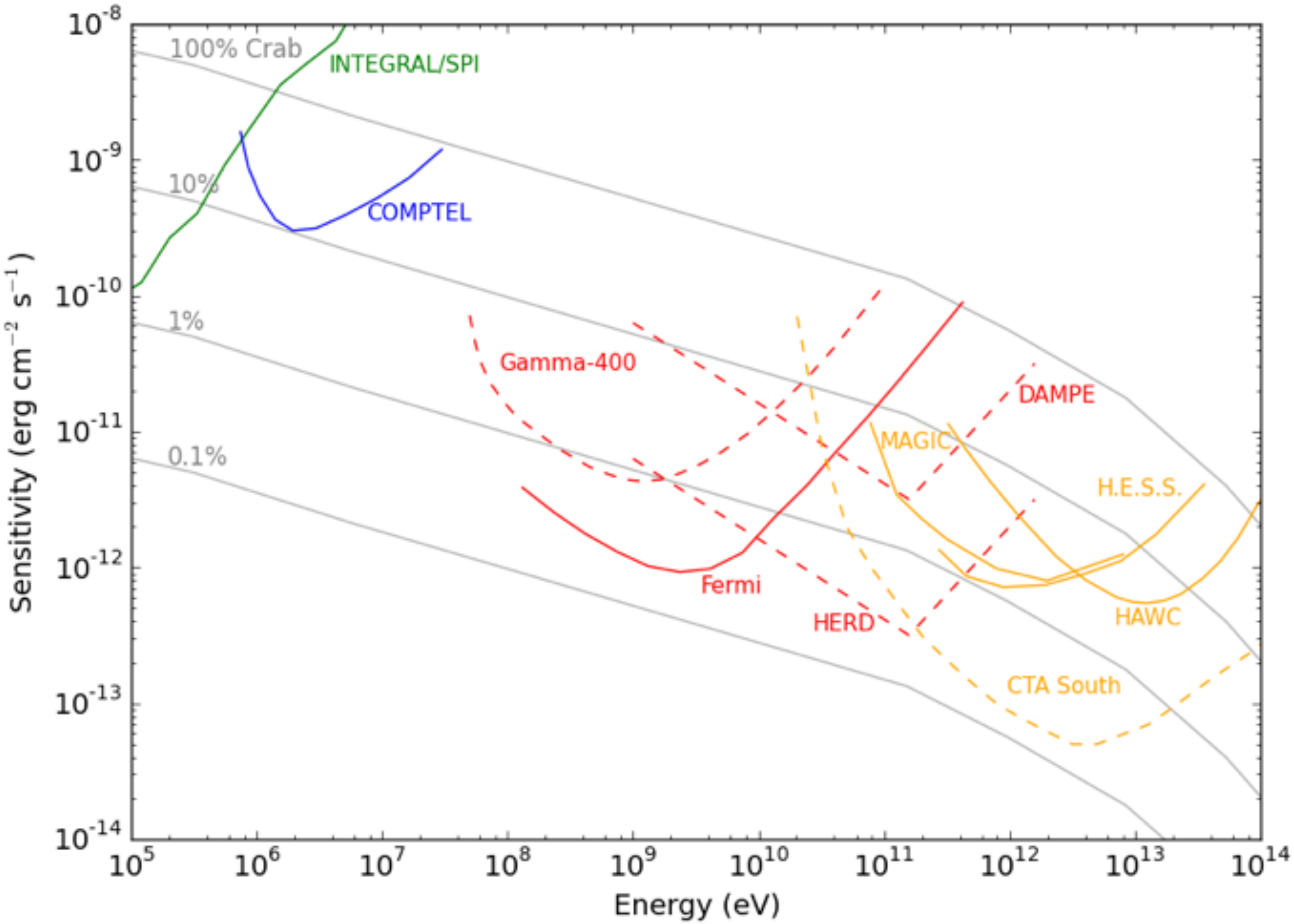


- deep calorimeter (multi TeV, % energy resolution)
  - DAMPE (2015)
  - HERD (>2020)
- + TKR/imaging CAL separation (0.02° PSF)
  - Gamma-400 (2021?)

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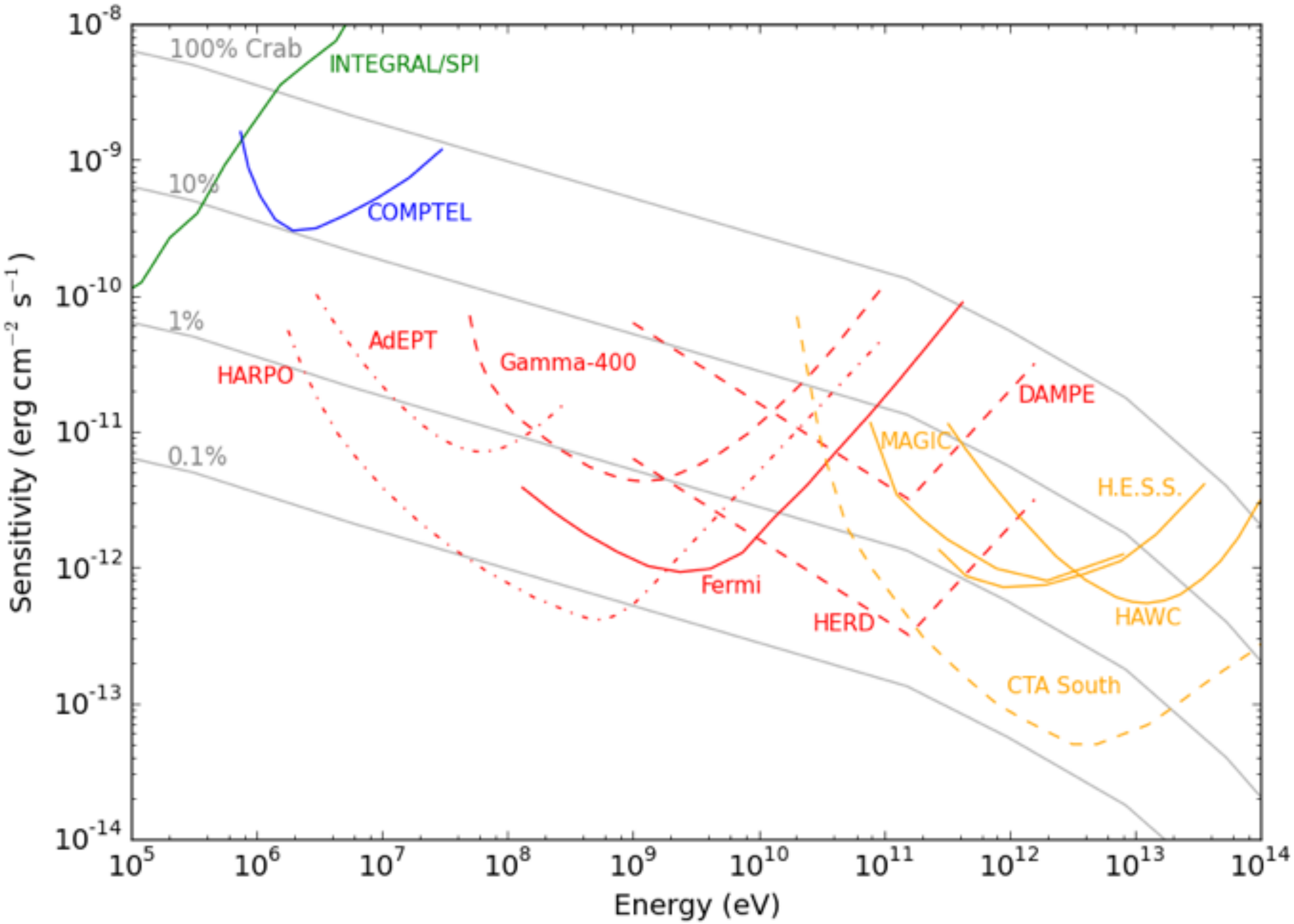
adapted from Knödlseder CRPhy 17 2016 663




- gas time projection chambers
  - 3 to > 100 MeV energy range
  - PSF < 1°
  - polarization
- R&D: AdEPT, HARPO

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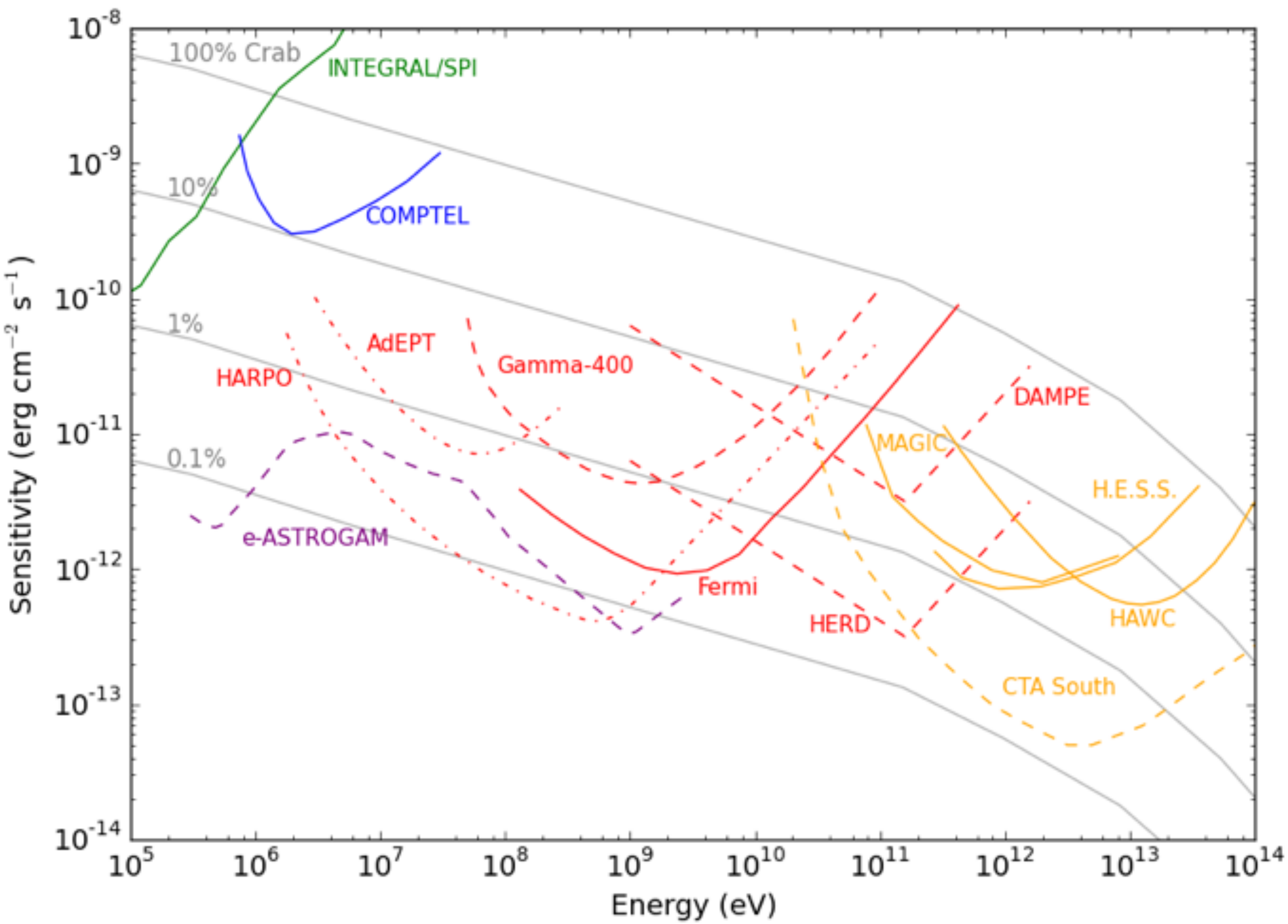
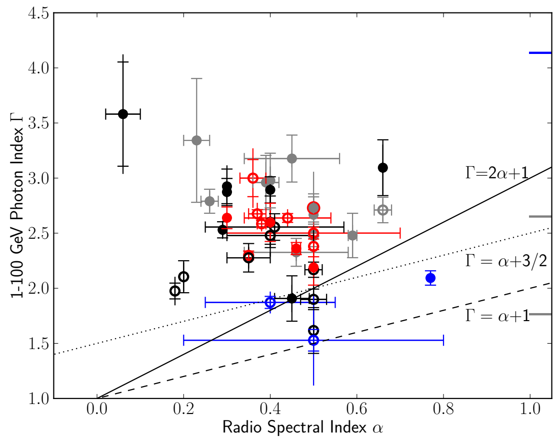
adapted from Knödlseder CRPhy 17 2016 663

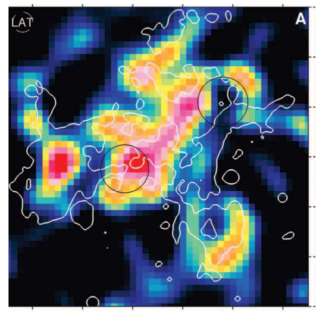


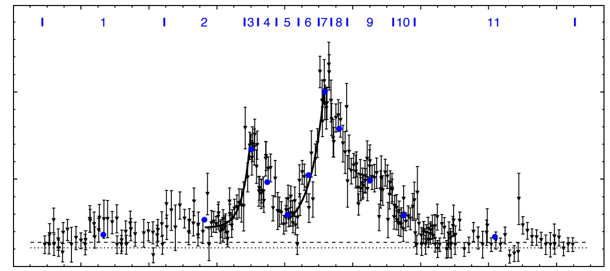

- Si tracker with no passive converter: Compton+pairs
    - 500 keV to > 100 MeV
    - 1° PSF
    - polarization
- e-ASTROGAM (M5?), ComPair (MIDEX?)

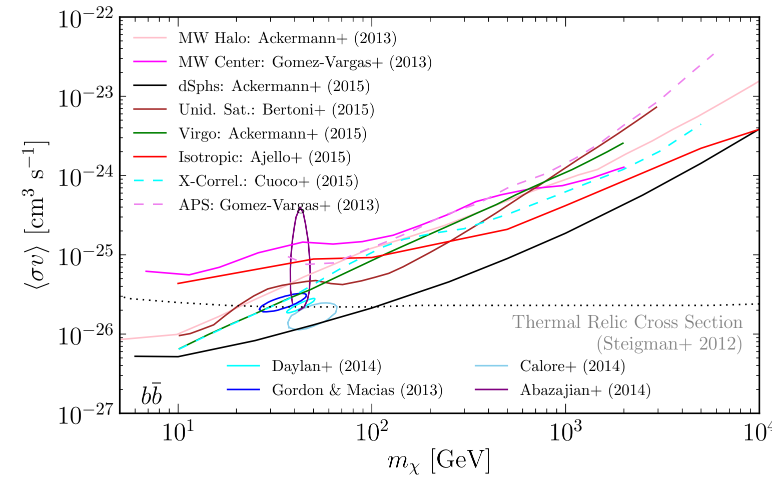
# Summary

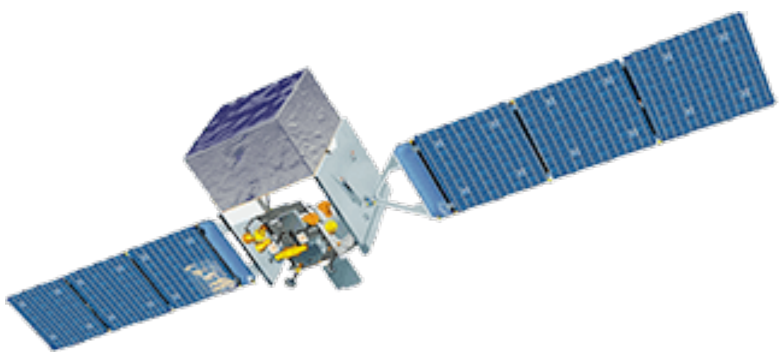
## new results

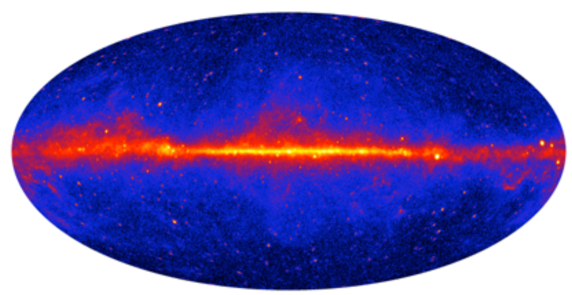


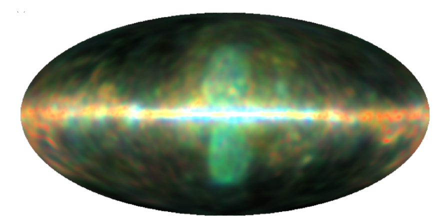



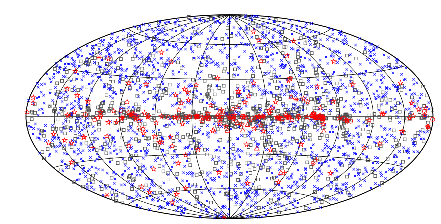





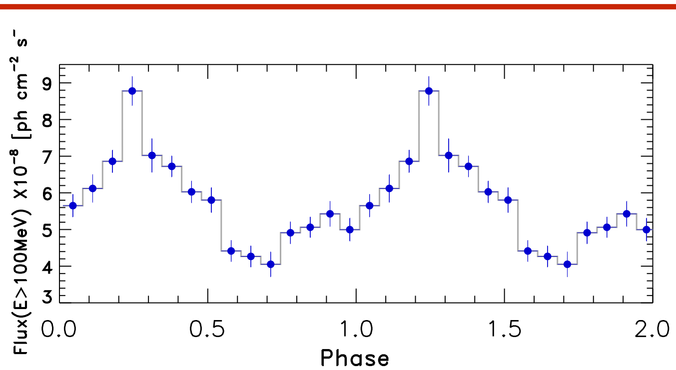



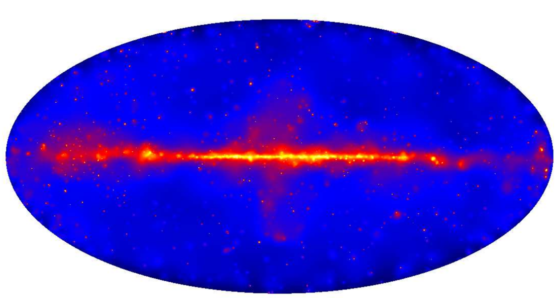


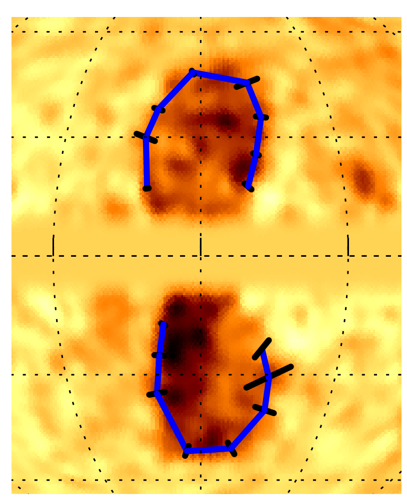




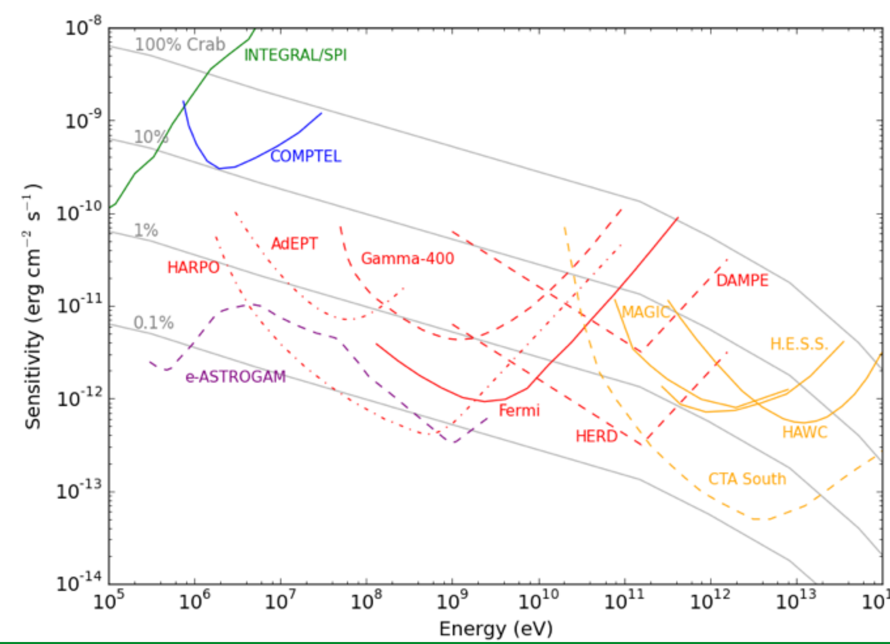
## new frontiers





## new horizons

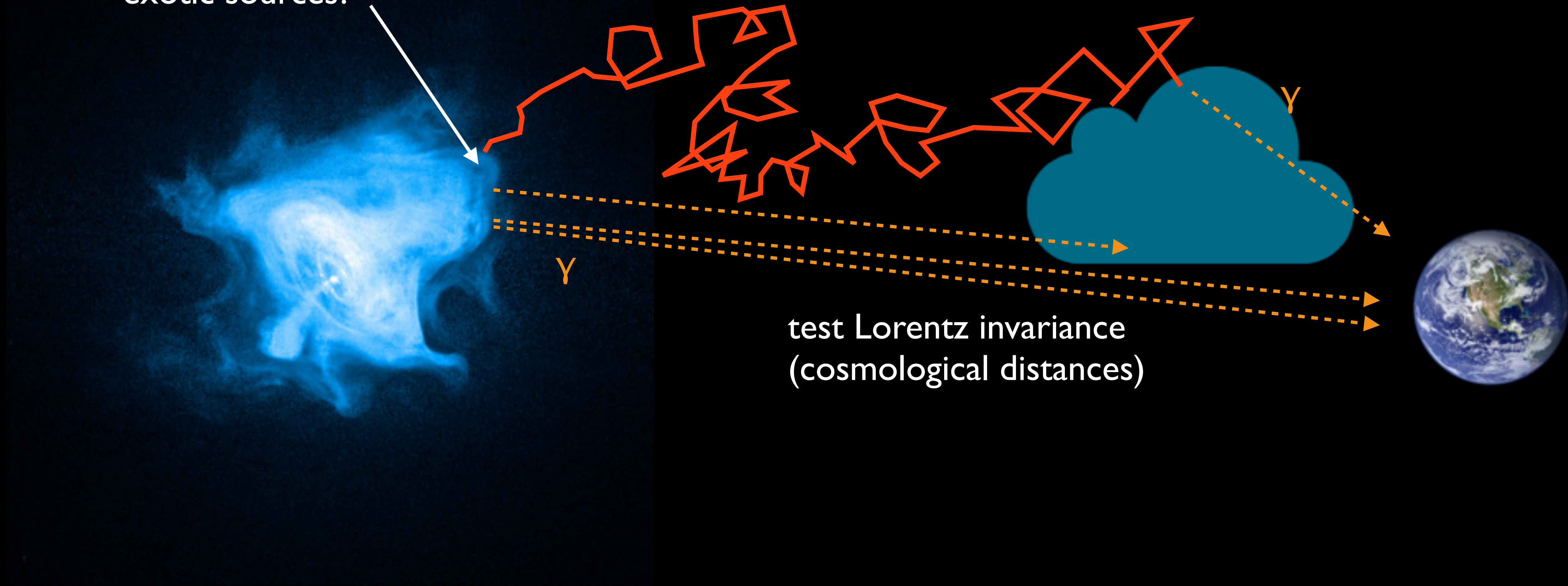


# Backup

# Science with gamma rays

- high-energy particle propagation
- interstellar/intergalactic medium and fields

- extreme astrophysical objects
  - nuclear phenomena
  - particle acceleration and interactions
- exotic sources?




- relatively easy to detect
- not deflected by magnetic fields

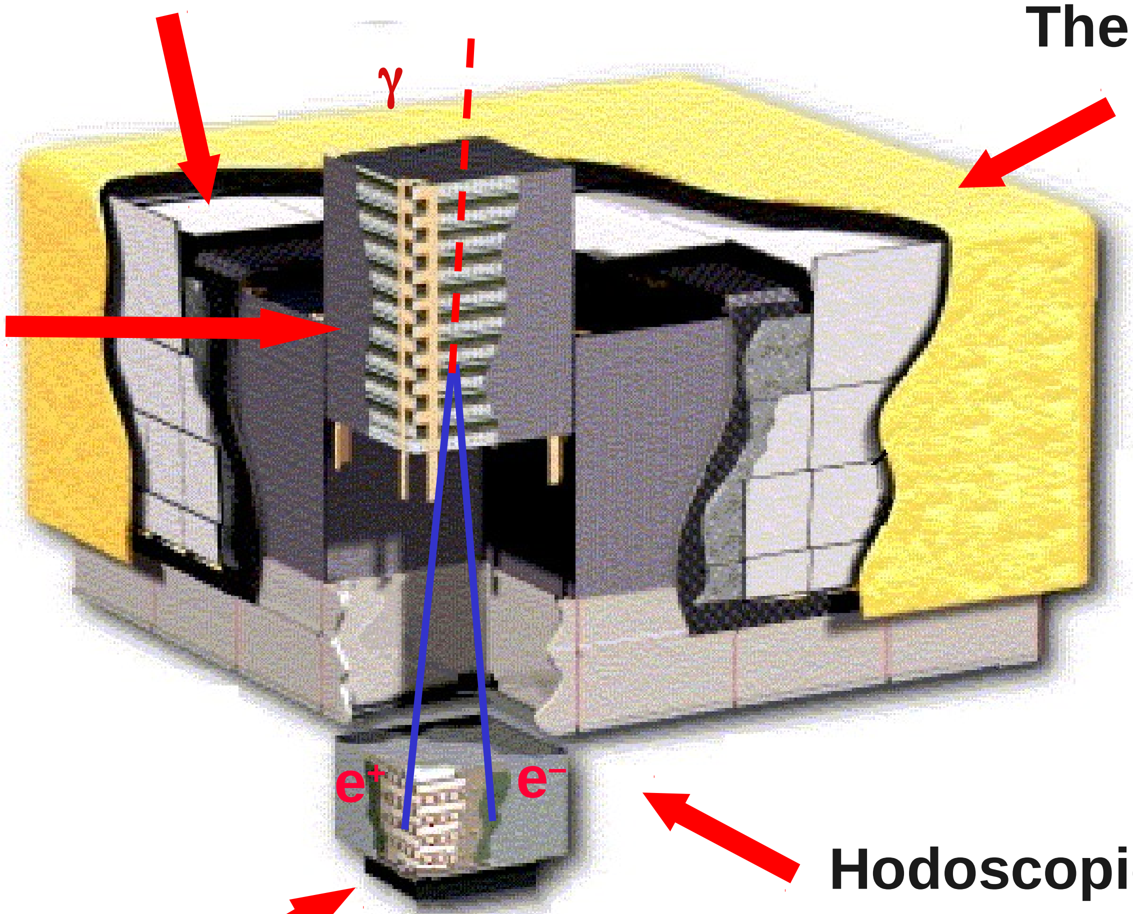
# The *Fermi* Large Area Telescope

**Anticoincidence Detector (ACD)**
- segmented
- 0.9997 MIP efficiency

**<u>Pair-tracking Telescope</u>**
1.8 m x 1.8 m x 0.72 m

**Thermal Blanket**

**Precision Si-strip Tracker + W Converters (TKR) :**
- 12 planes 3% r.l. (FRONT)
- 4 planes 12% r.l. (BACK)
- 2 planes with no converter
- 0.9 M channels
- > 0.7 $m^2$ active Si

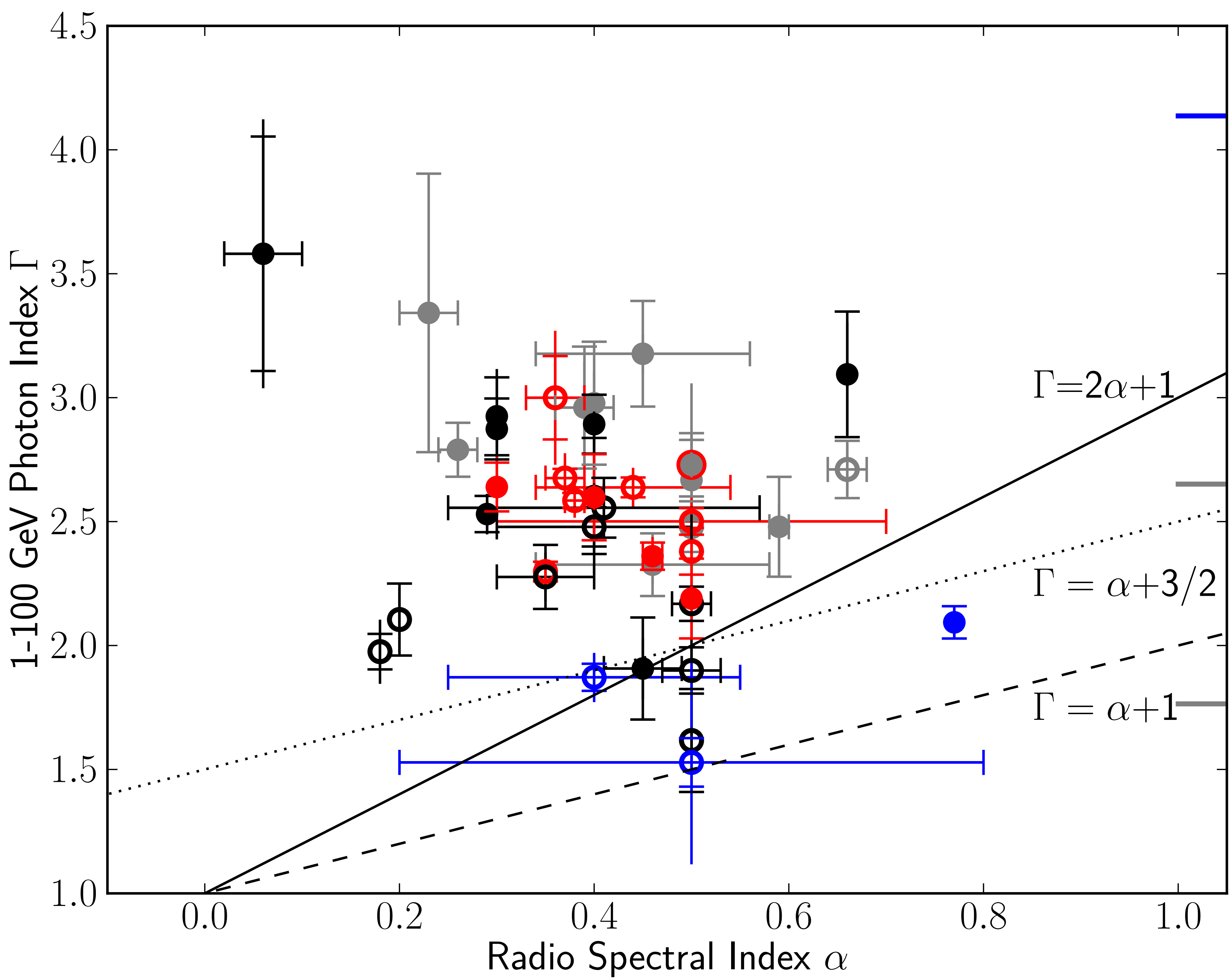



**Hodoscopic CsI Calorimeter (CAL)**
- 1536 logs
- 8.5 r.l. on axis

**DAQ**

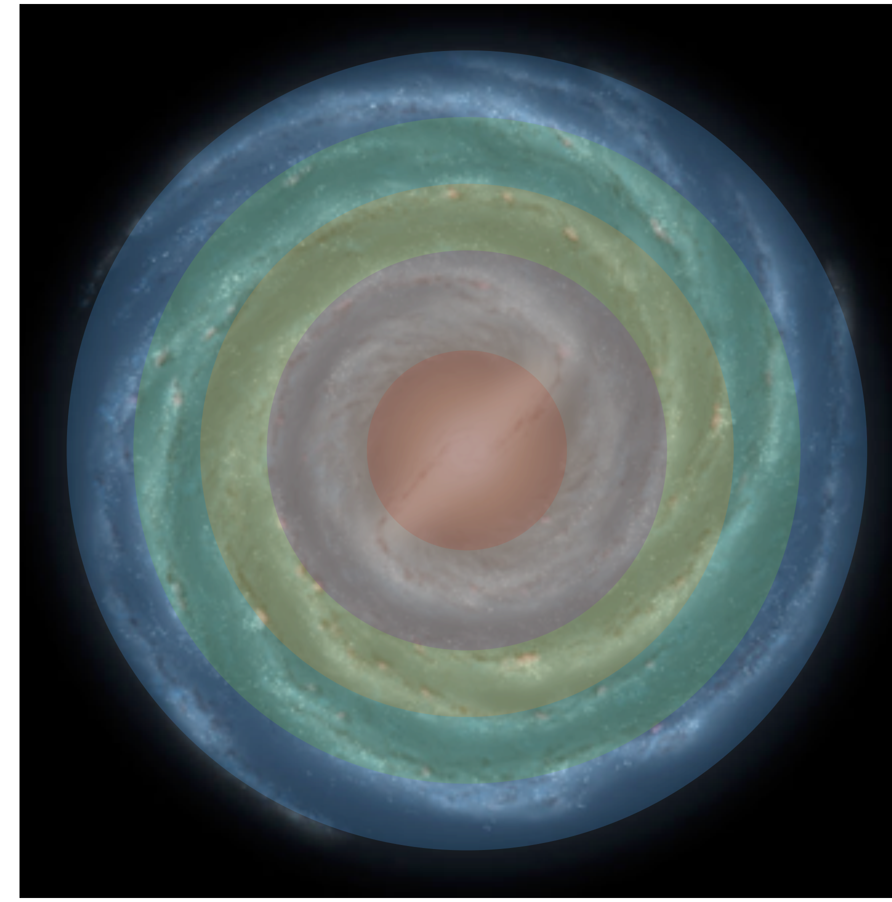
# Data challenge simple SNR models

Fermi LAT collab. ApJS 224 2016 8A

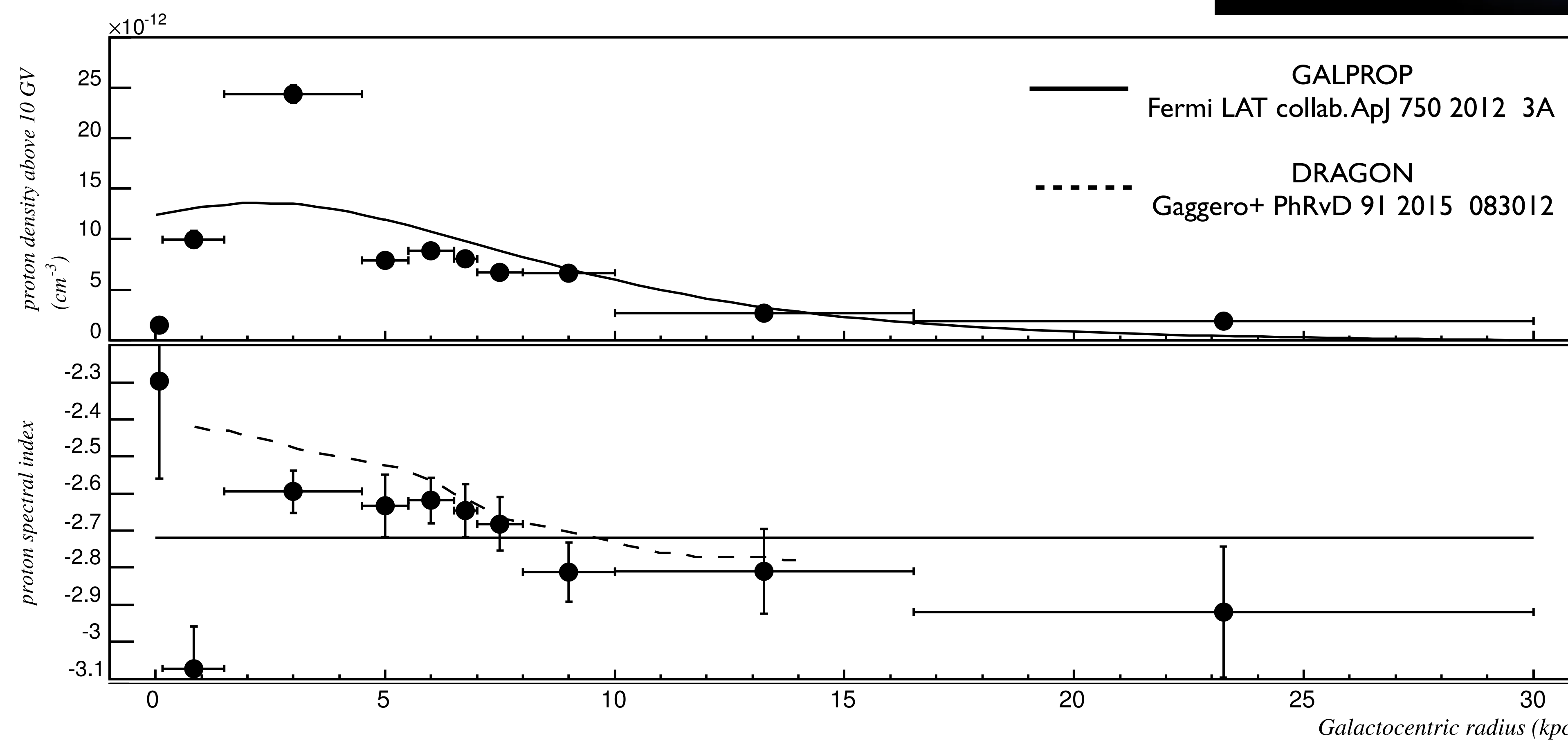


# The cosmic-ray gradient across the Milky Way

- emissivity spectrum in rings (H I line Doppler shift)
- intensity/spectral variations
- challenge simple propagation models

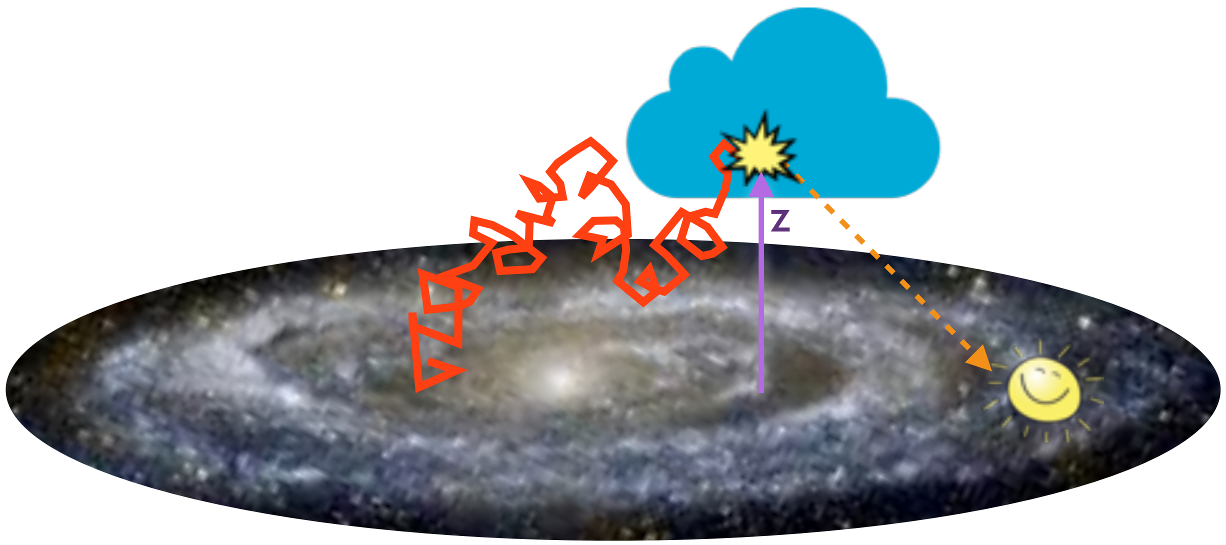


*Fermi* LAT collab. ApJS 223 2016 26

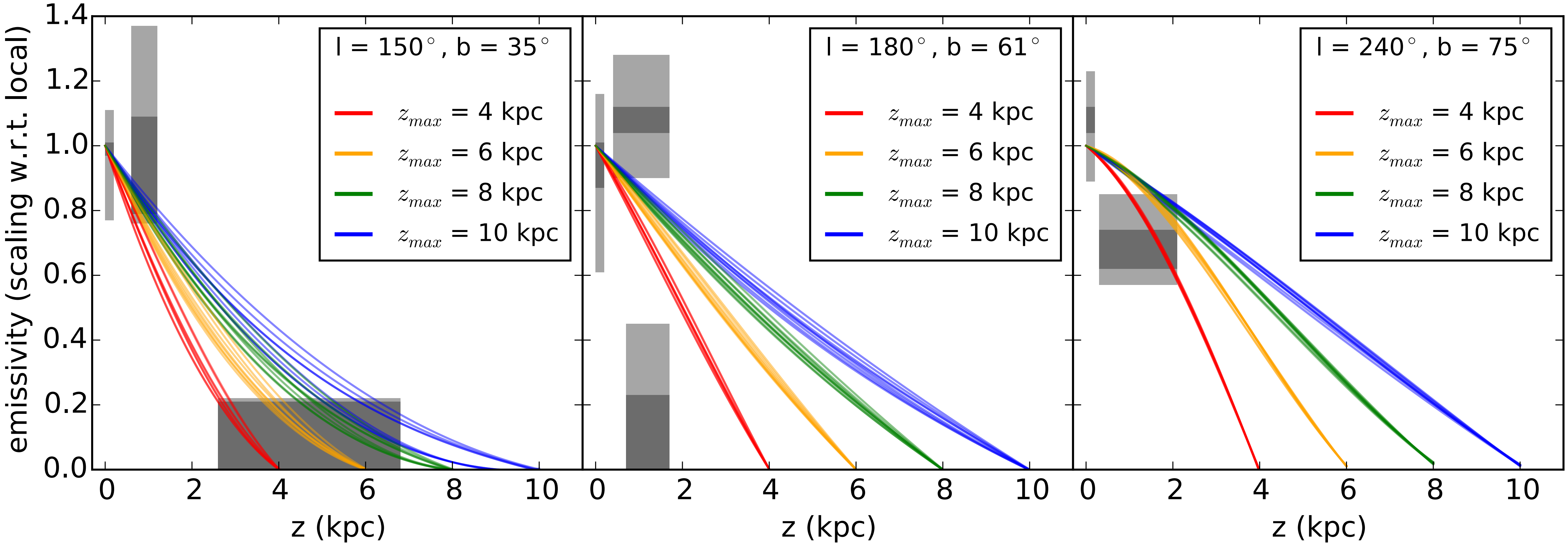


# CRs in the halo of the Milky Way

- high- and intermediate velocity clouds
  → CR densities in the Galactic halo
- decrease with distance from disk at 97.5% c.l.
- agreement with propagation models
  - OK with B/C $^{10}$Be/$^{9}$Be
    (confinement region: 4-6 kpc)



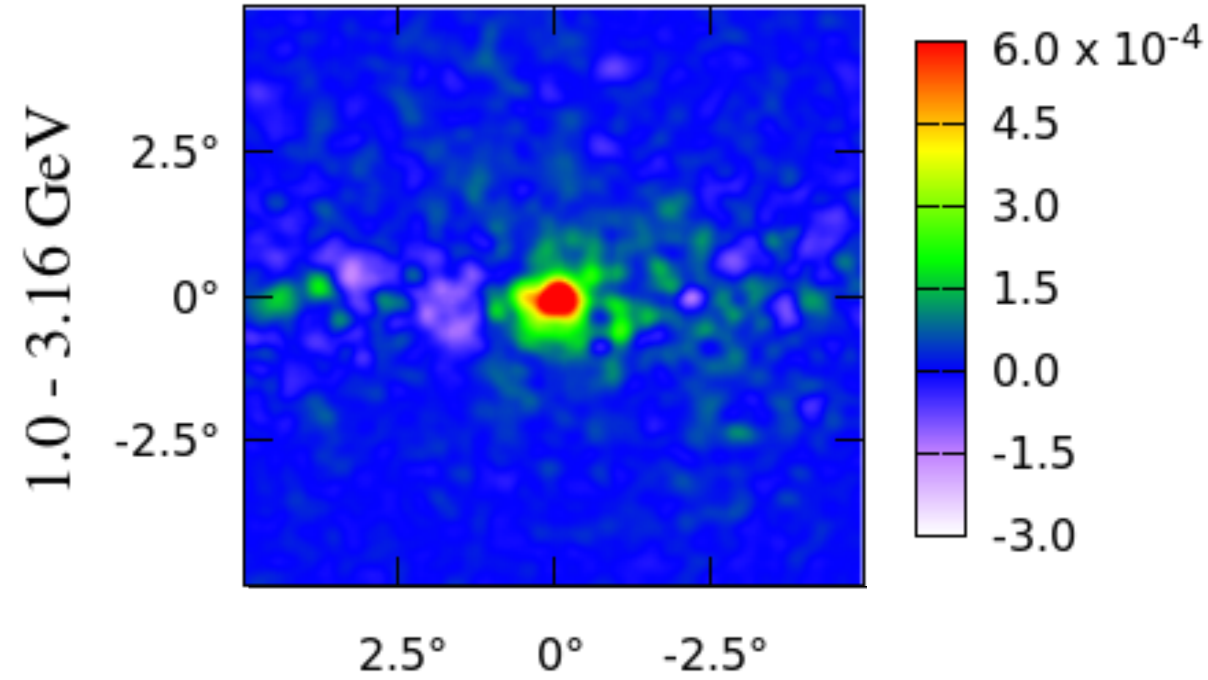

Tibaldo+ ApJ 807 2015 161



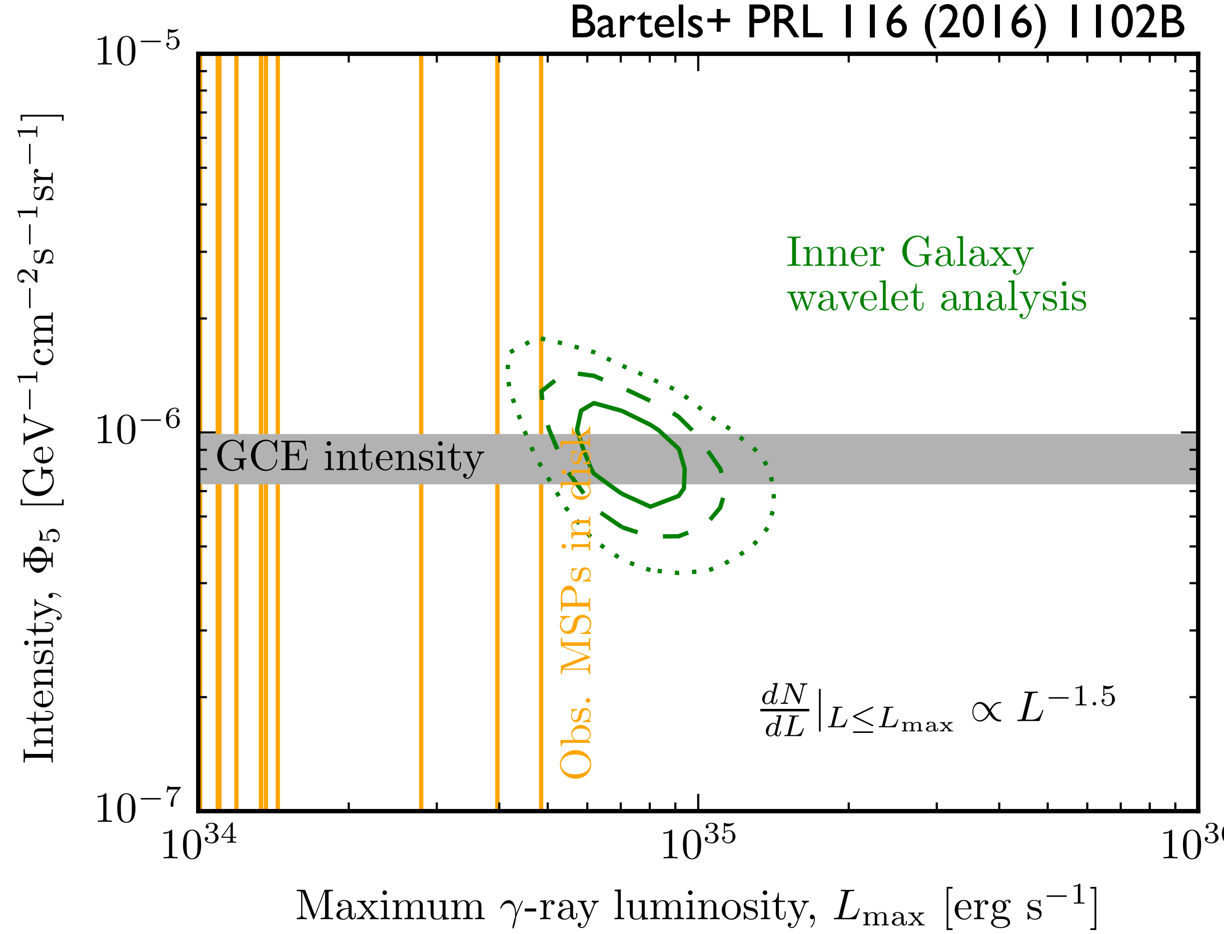
# The GeV Galactic center excess

- residual emission near the Galactic center peaking at few GeV
  - spherical or bipolar?
  - low/high-energy shape of spectrum uncertain
- origin
  - DM annihilation?
  - poorly modeled interstellar emission?
  - *Fermi* bubbles?
  - unresolved sources (ms pulsars)?

Daylan+ PDU 12 (2016) 1D



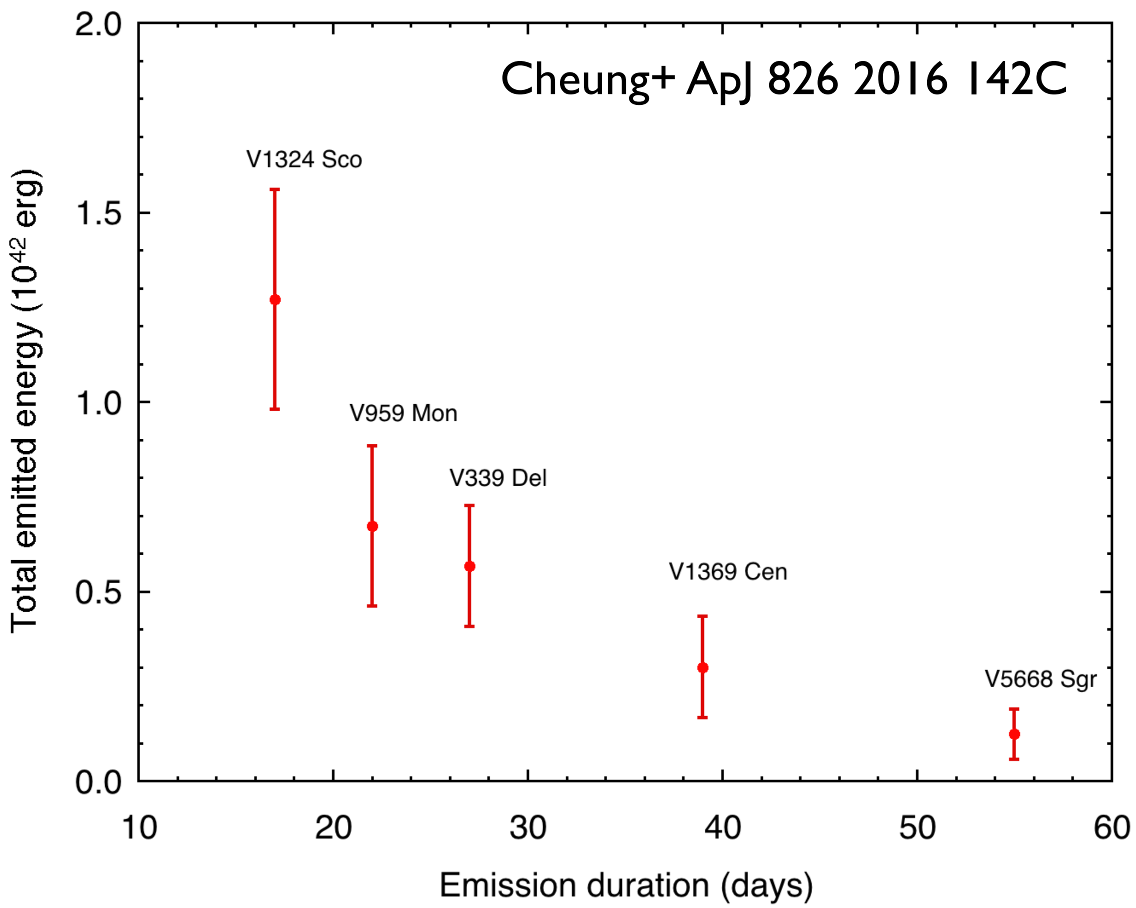

Bartels+ PRL 116 (2016) 1102B

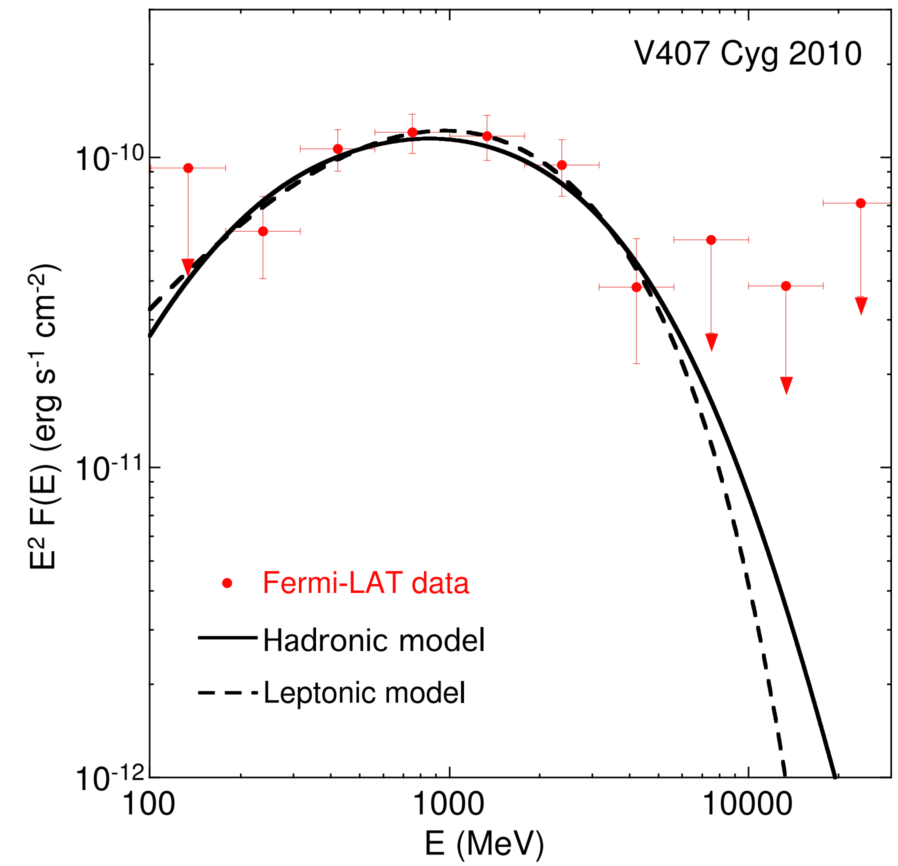


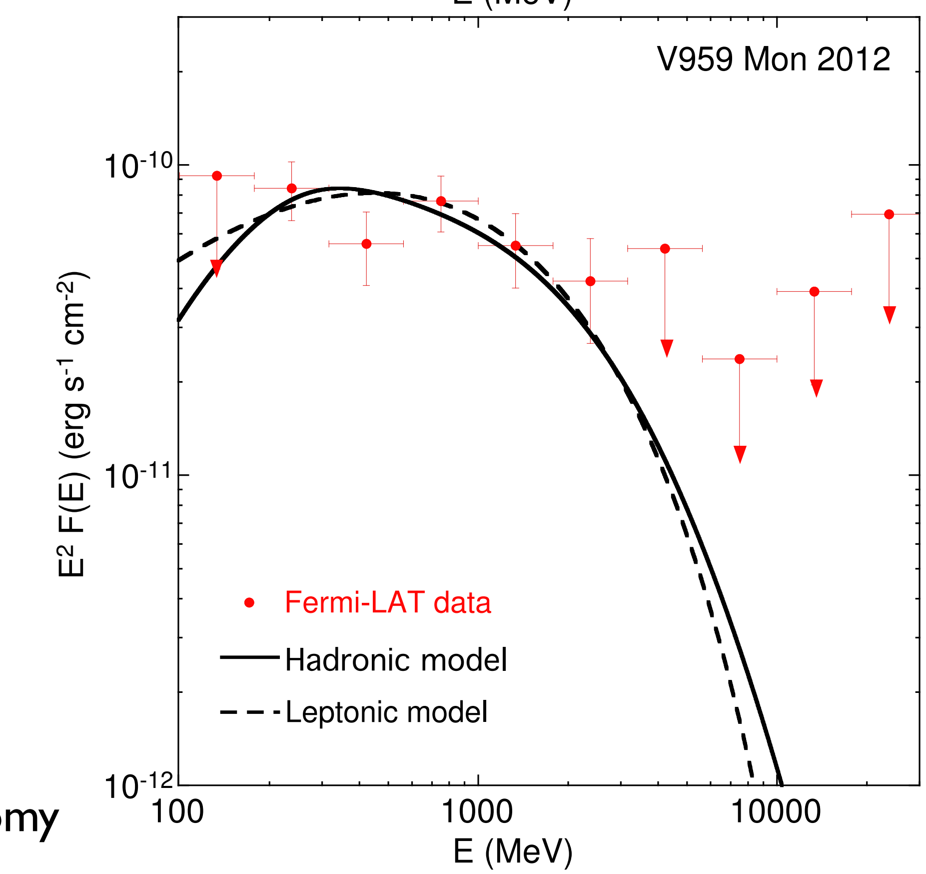
# Novae as γ-ray sources

Fermi LAT collab. Science 345 2014 554A

- > 100 MeV detections for 1 symbiotic + 5 classical novae
- particle acceleration mechanism unclear

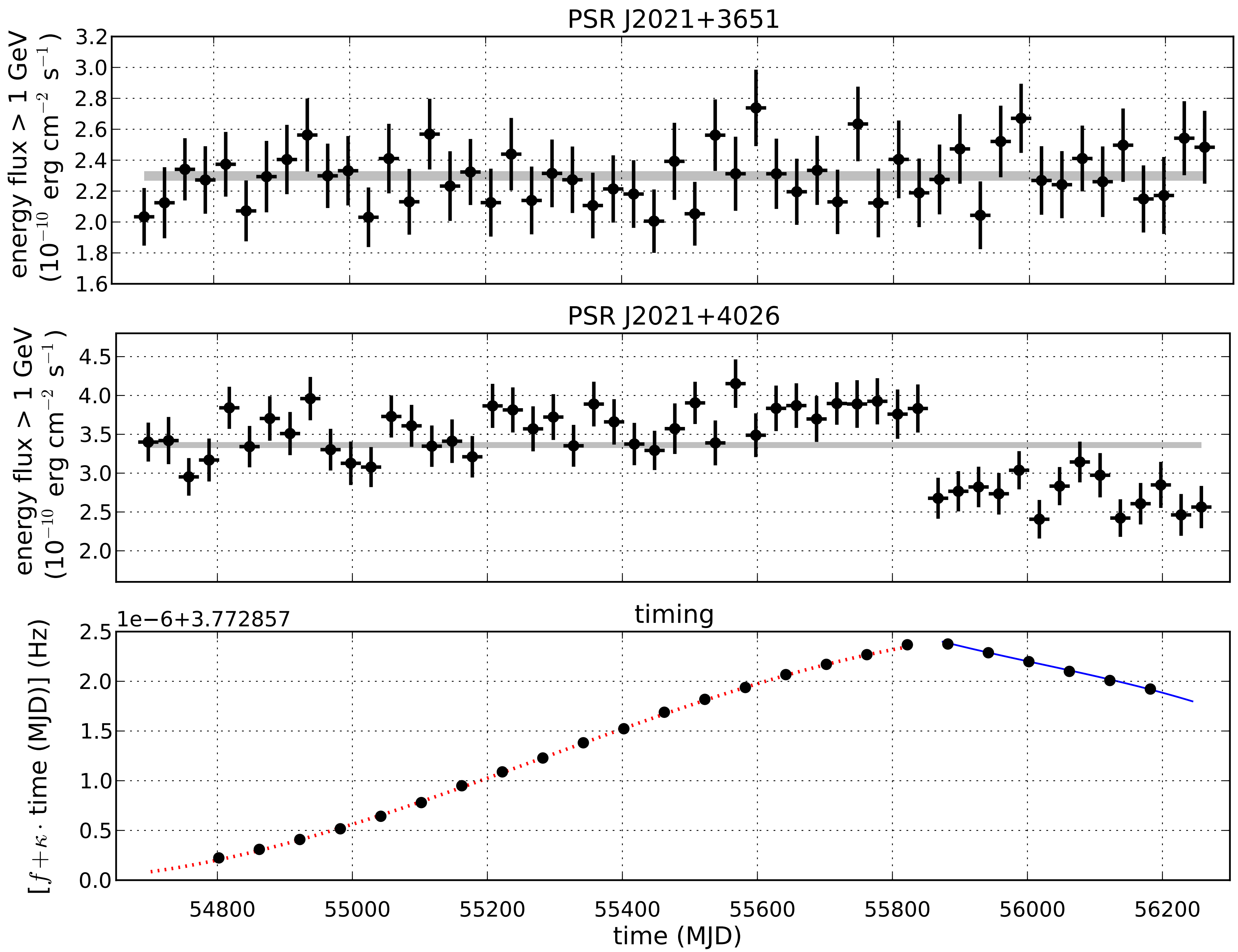


# A state-change in a γ-ray pulsar

- PSR J2021+4026: simultaneous flux/ spindown change
- reconfiguration of magnetosphere?
- new state change in 2015




Fermi LAT collab. ApJL 777 2013 2