

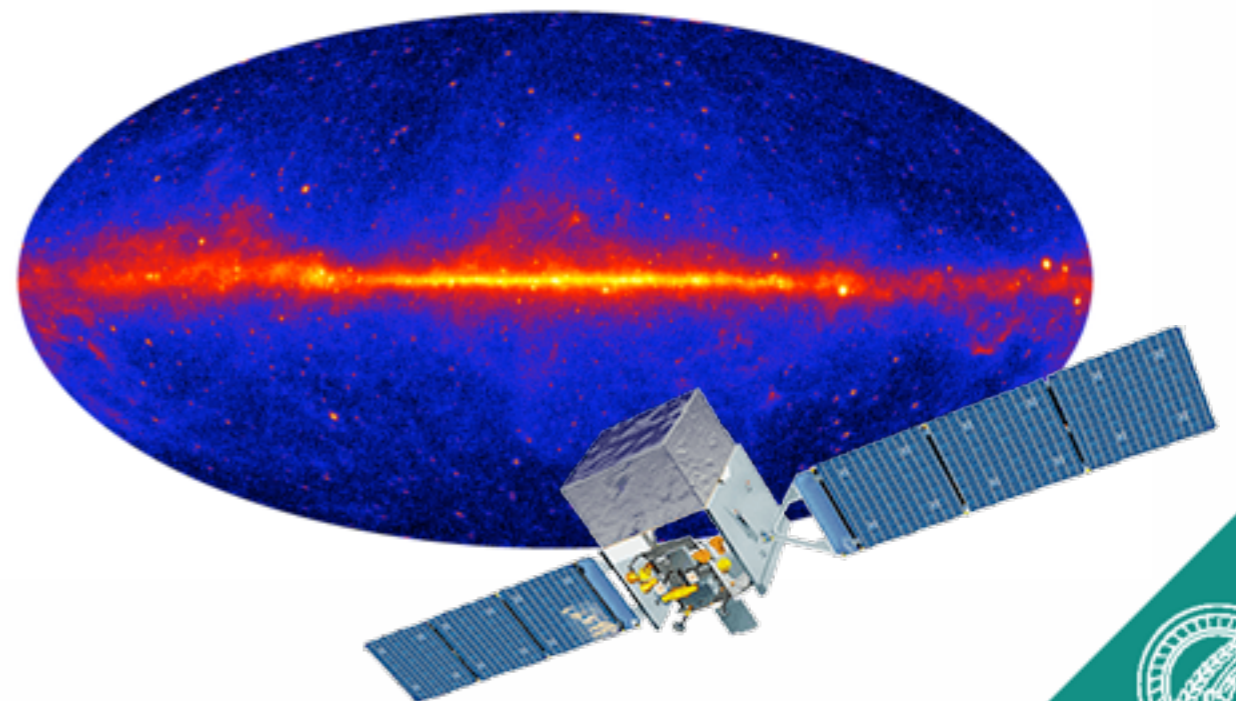
SPACE-BASED GAMMA-RAY ASTRONOMY: NEW RESULTS, NEW FRONTIERS, NEW HORIZONS

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Outline

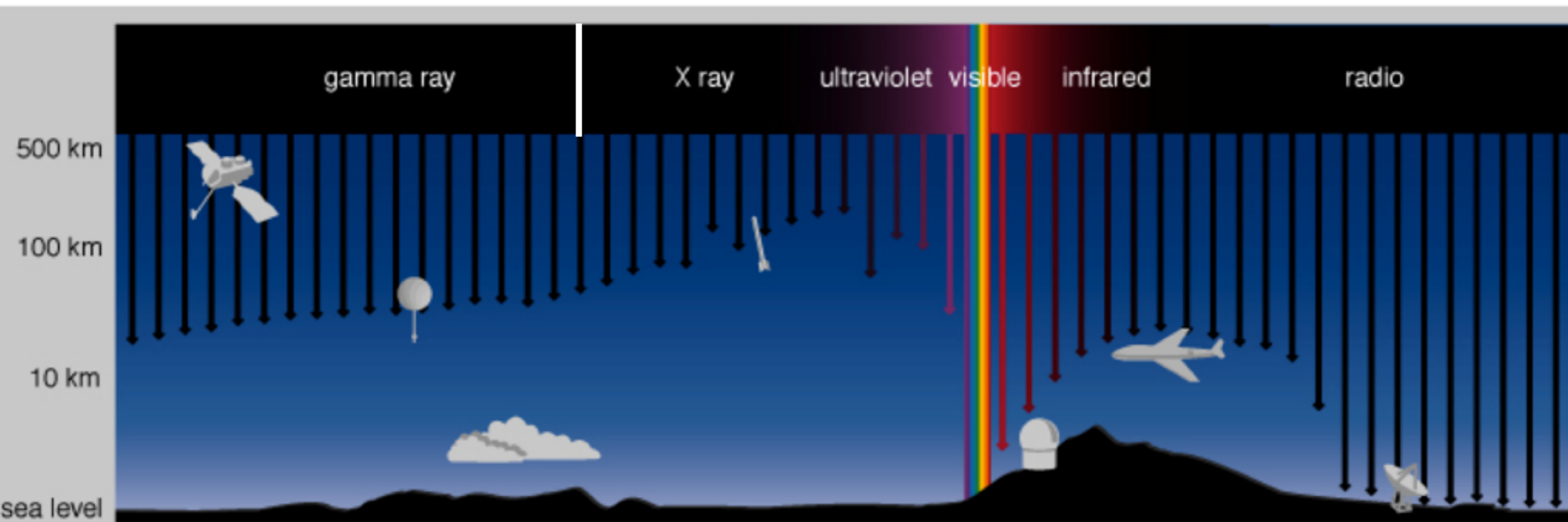
- **Introduction**
- *Fermi*
 - diffuse γ -ray emission
 - source catalogs
- **New results**
 - origin of cosmic rays and particle acceleration
 - the nature of dark matter
- **New frontiers**
 - extension to TeV
 - new γ -ray emitters
 - long-term variability
- **New horizons**
 - upcoming and future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



© Addison-Wesley Longman

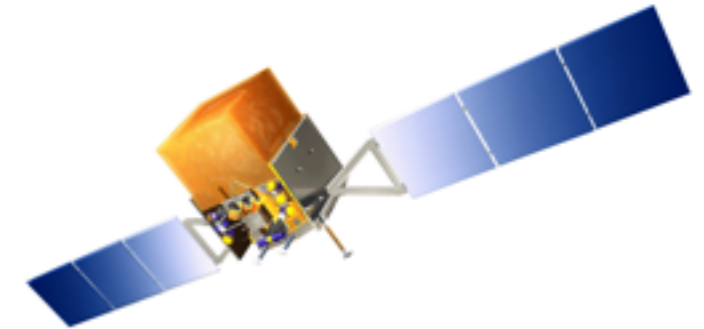
Detecting γ rays in space



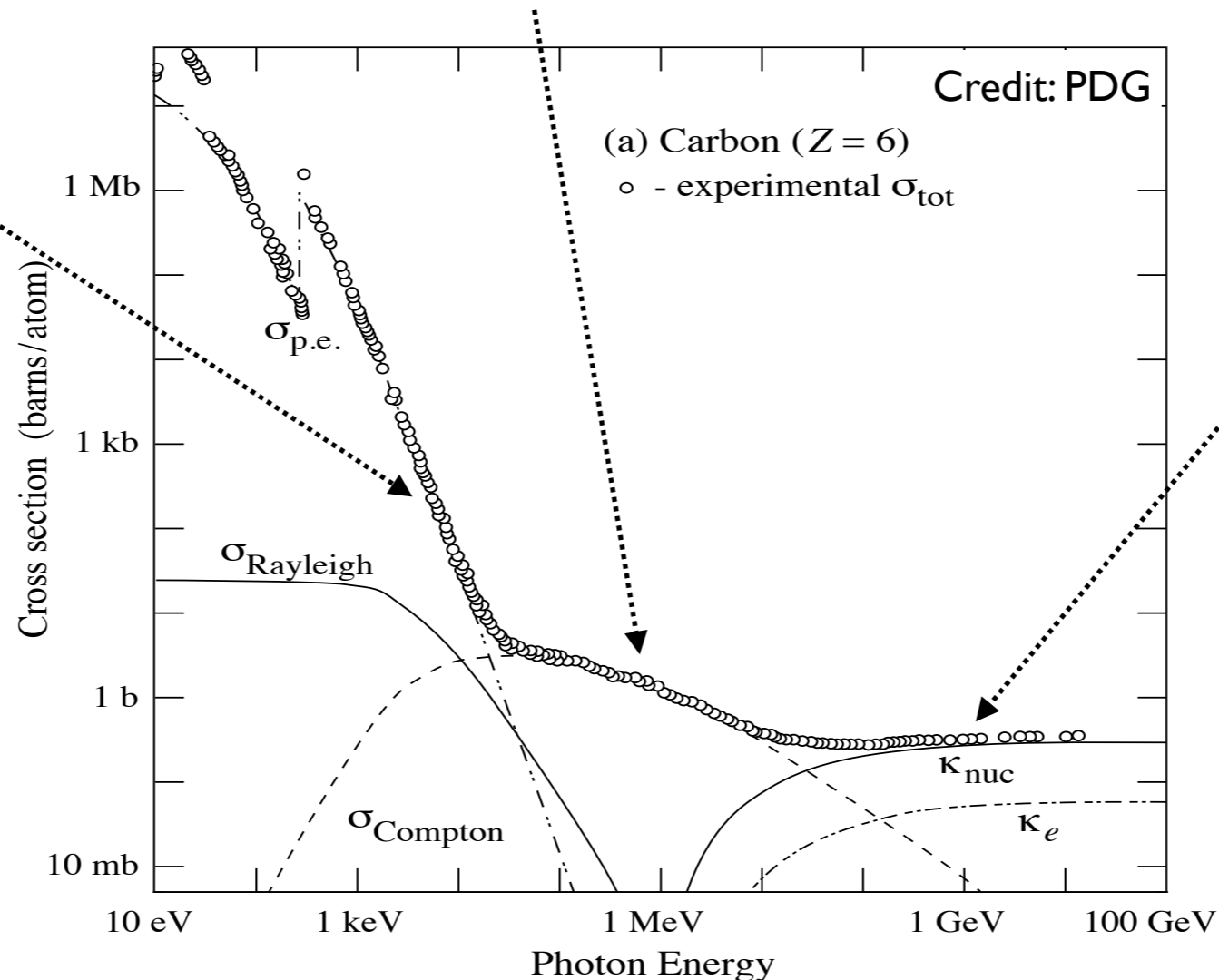
COMPTEL
 1991-2000
 800 keV-30 MeV
 liquid+crystal scintillator



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



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

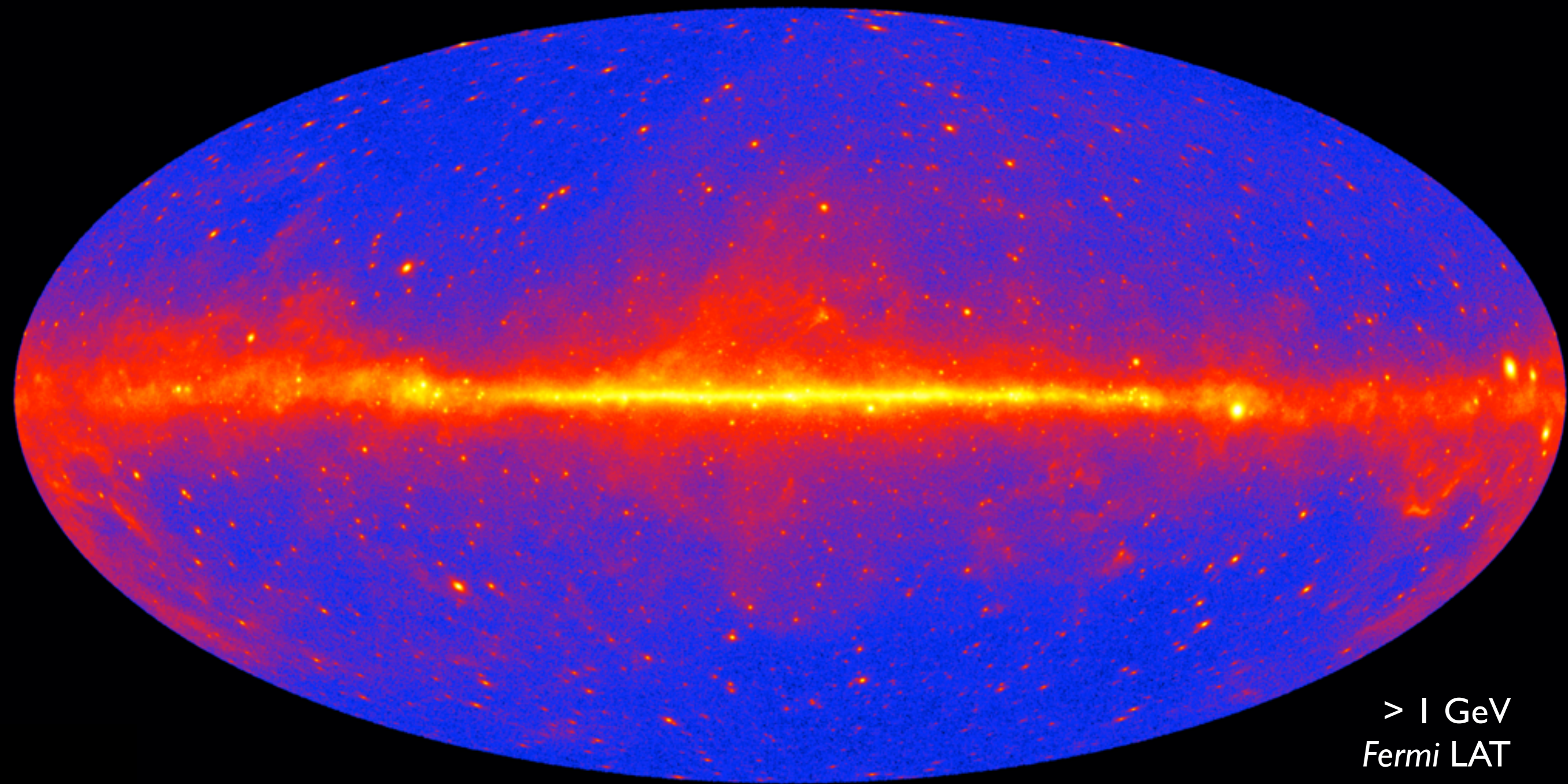


and **AGILE**
 2007-present

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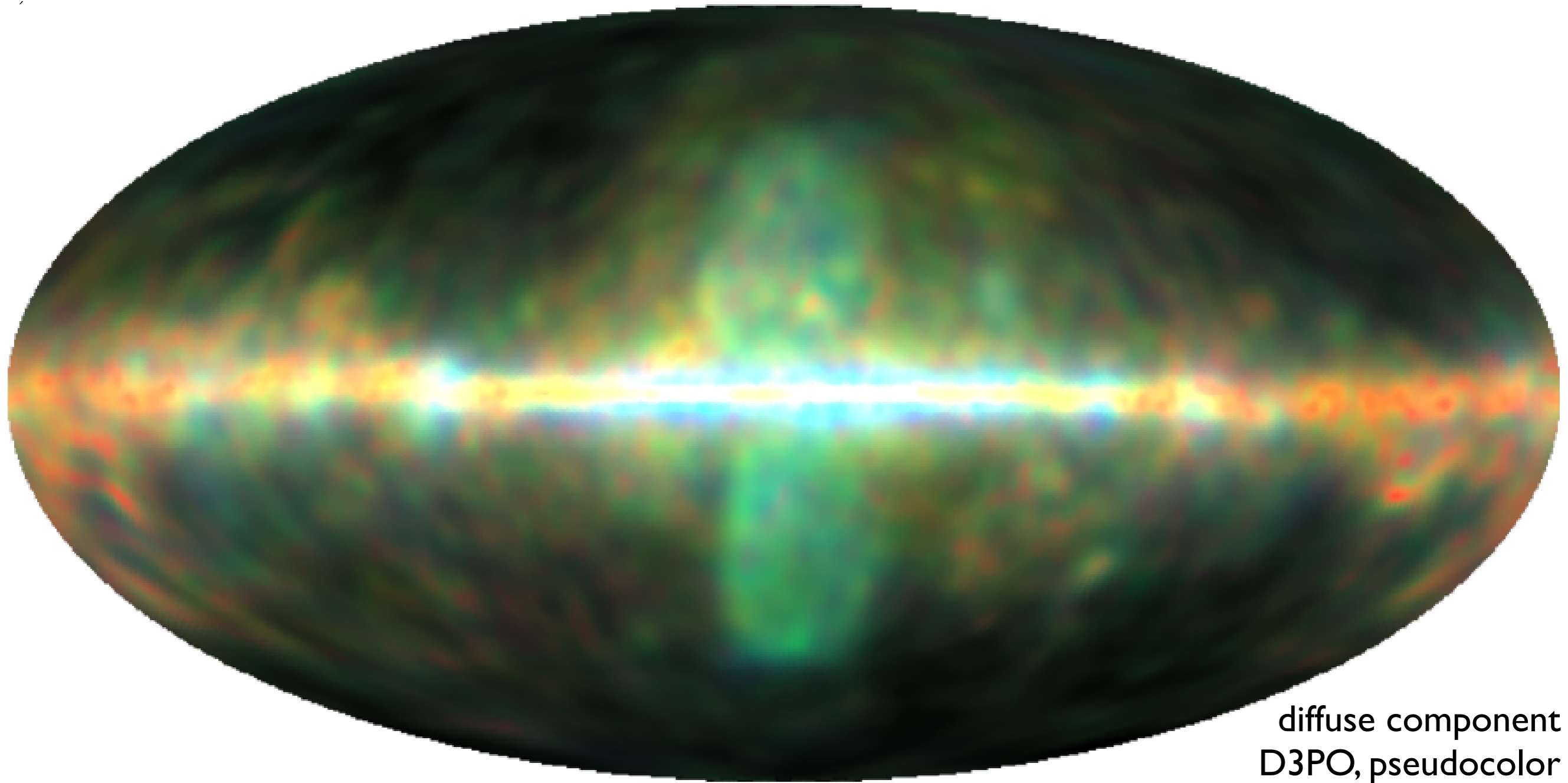
The Fermi γ -ray sky



> 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

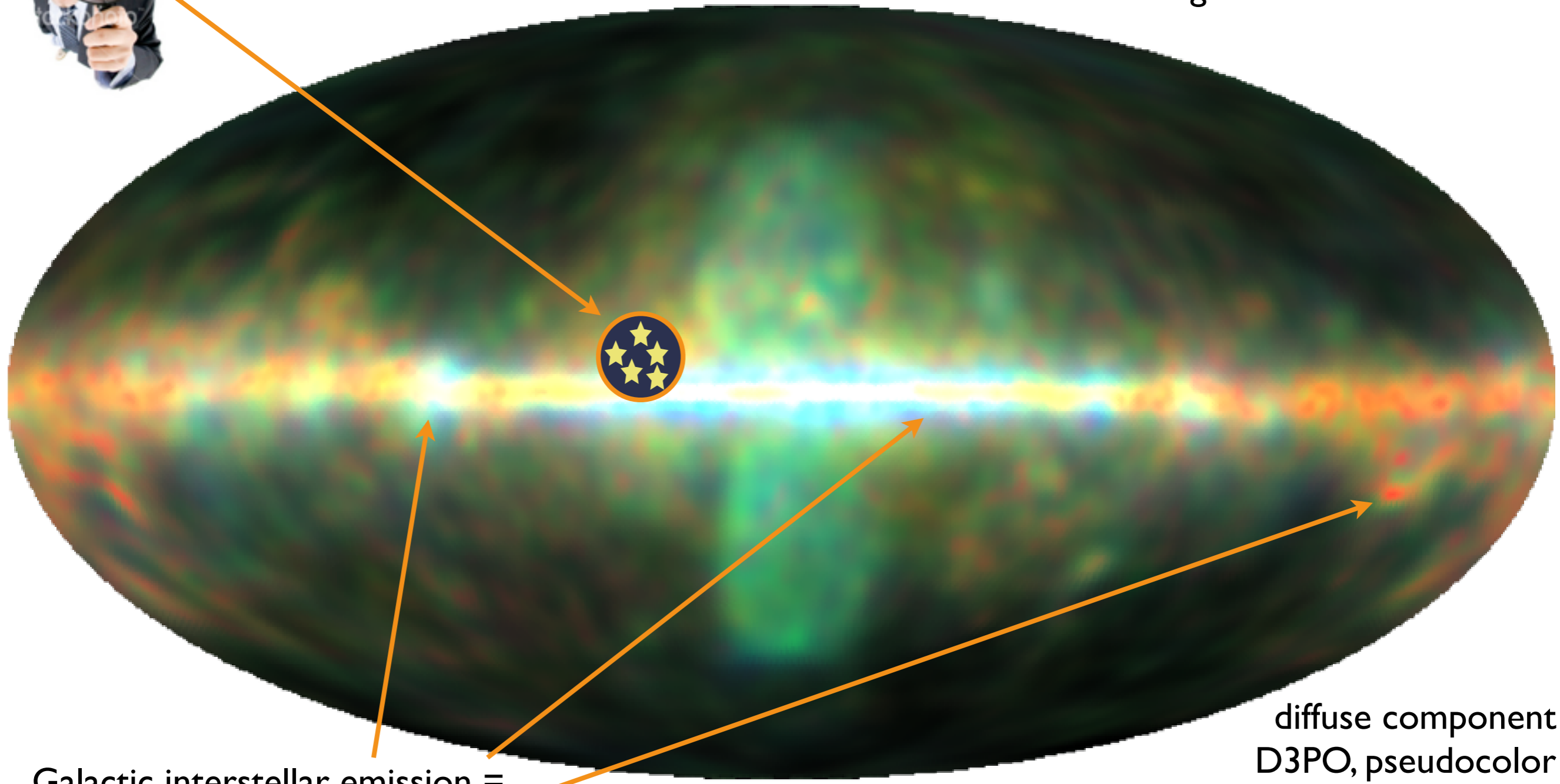
diffuse emission = no individual sources

Resolving the γ -ray sky: diffuse emission



unresolved
sources

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



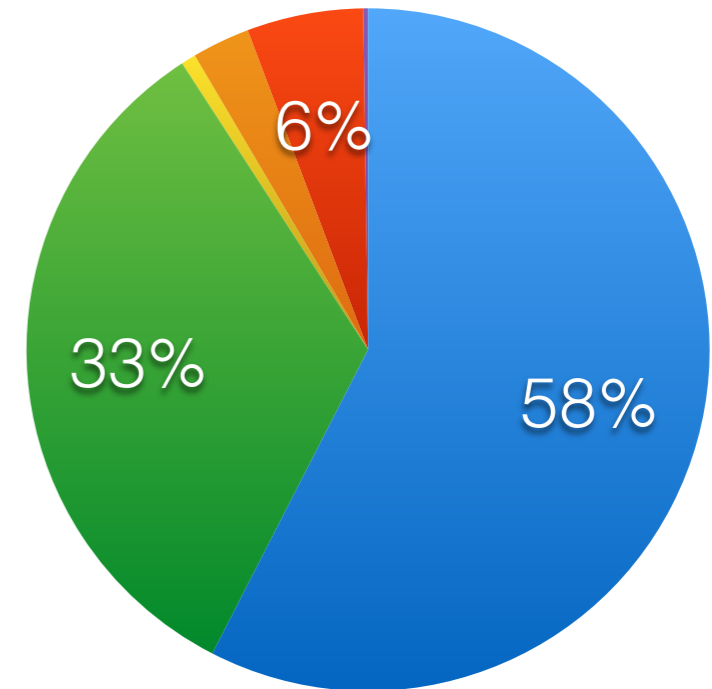
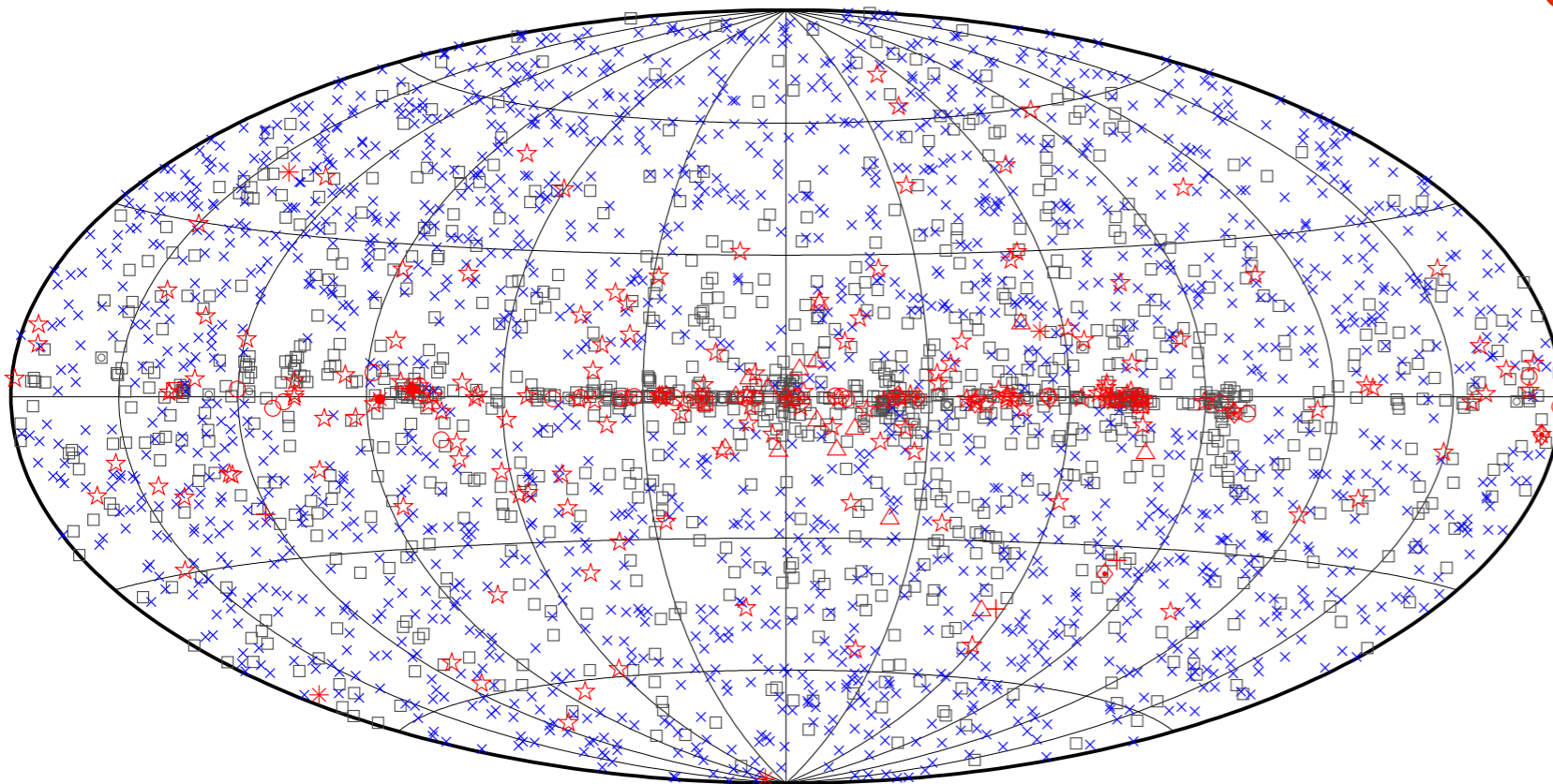
Galactic interstellar emission =
nucleon-nucleon collisions
Bremsstrahlung, inverse Compton

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 ($> 4.1\sigma$)
- specific source classes/energy ranges

- AGN
- Other Galactic
- PSR
- Unassoc.
- SNR/PWN
- External galaxy



□ No association	▣ Possible association with SNR or PWN	× AGN
☆ Pulsar	△ Globular cluster	◇ PWN
⊠ Binary	+ Galaxy	○ SNR
★ Star-forming region	* Starburst Galaxy	● Nova

Fermi LAT collab. ApJS 218 2015 23A

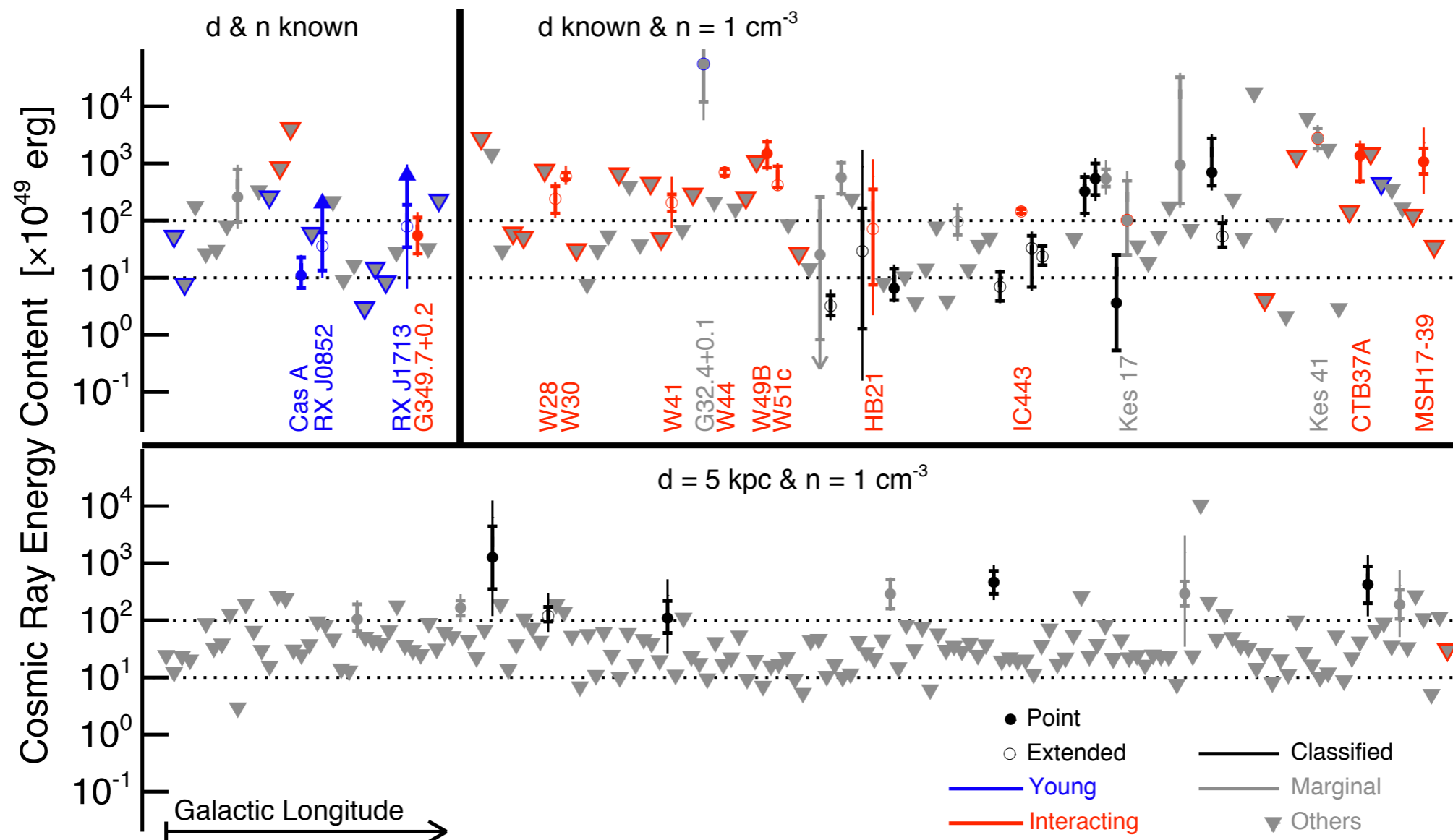
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CR origin: testing the SNR paradigm

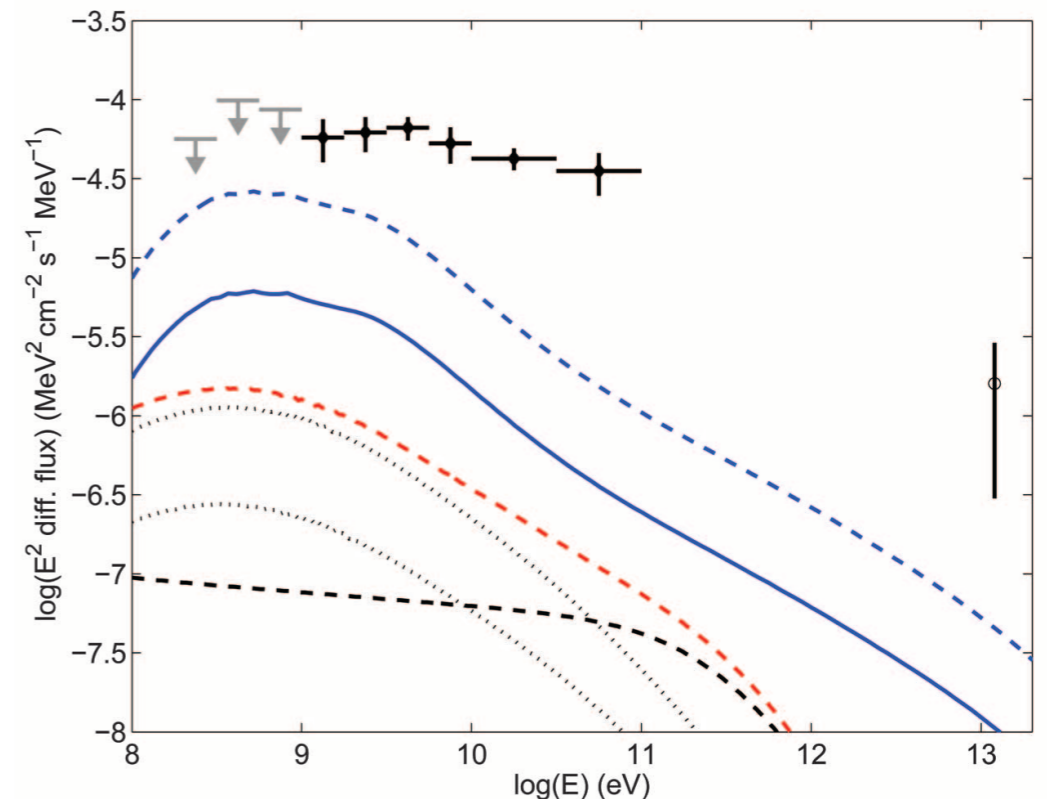
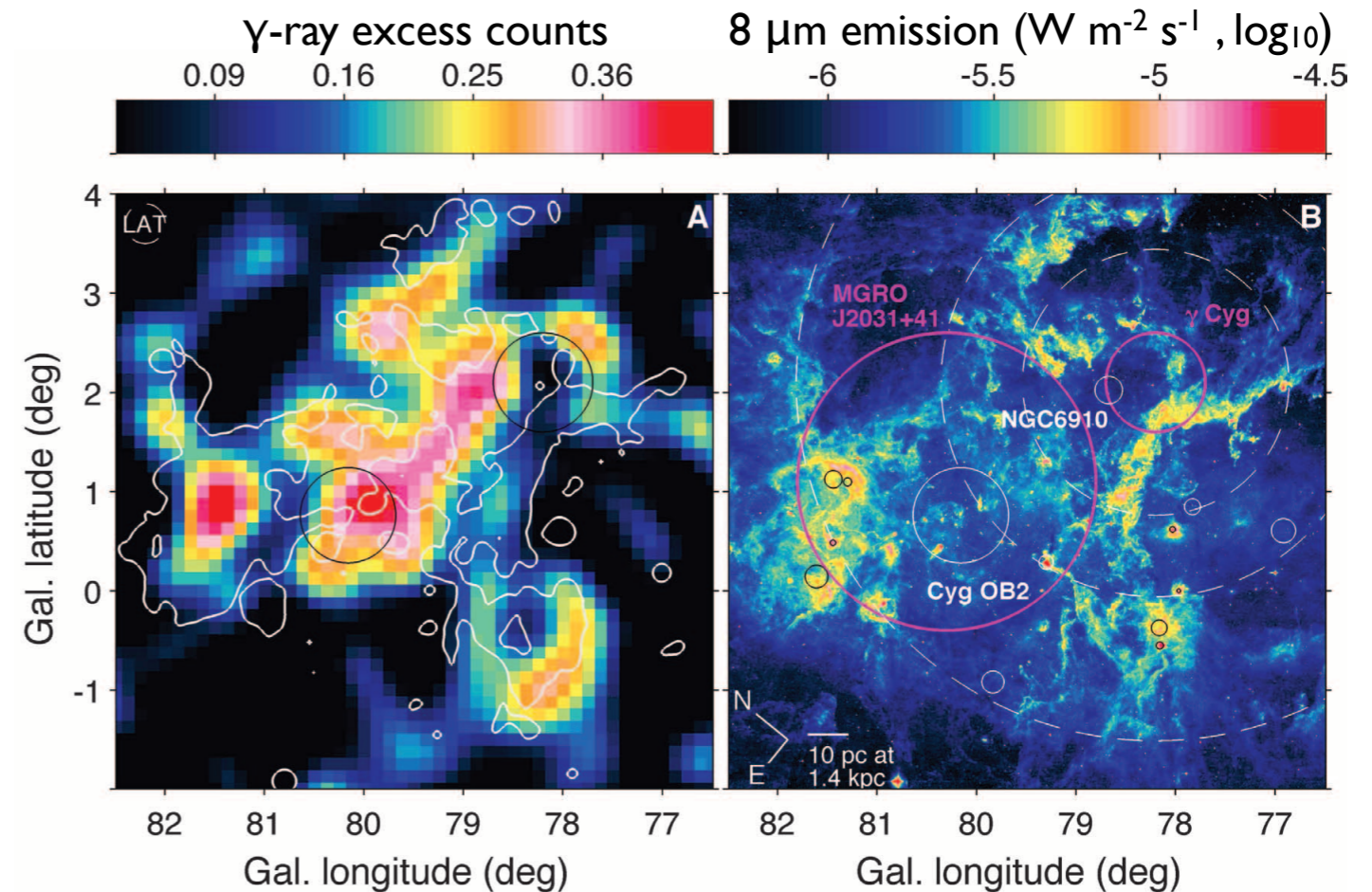
- SNR paradigm: 10% of SN energy into cosmic rays
- LAT SNR Catalog, 1-100 GeV
 - 30 sources classified as SNRs
 - 14 marginal candidates
 - 245 upper limits on radio SNRs

Fermi LAT collab. ApJS 224 2016 8A



A cocoon of freshly accelerated CRs in Cygnus

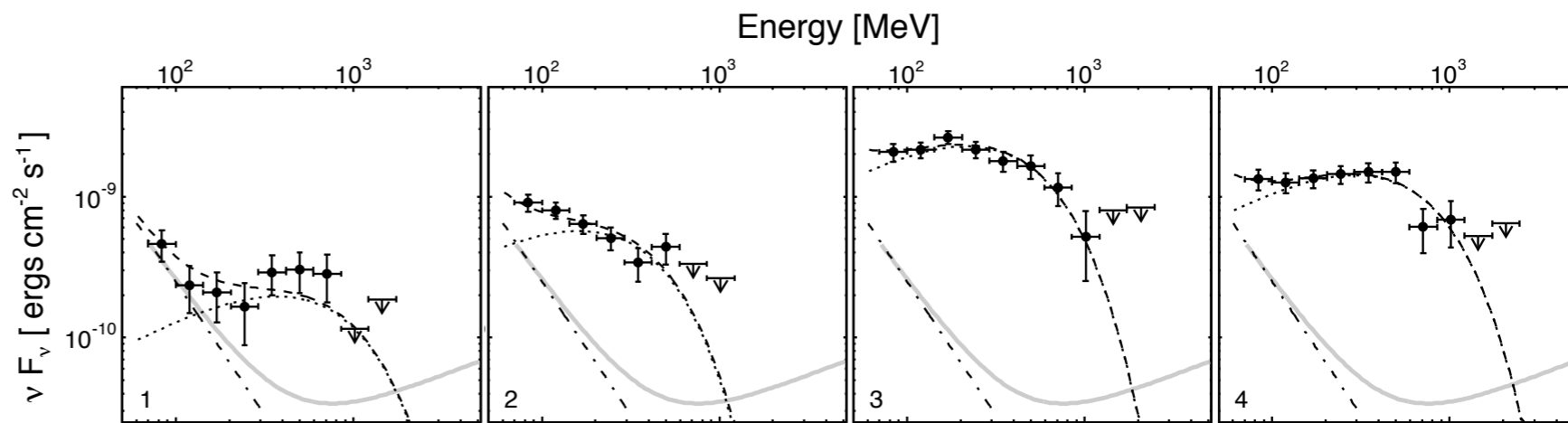
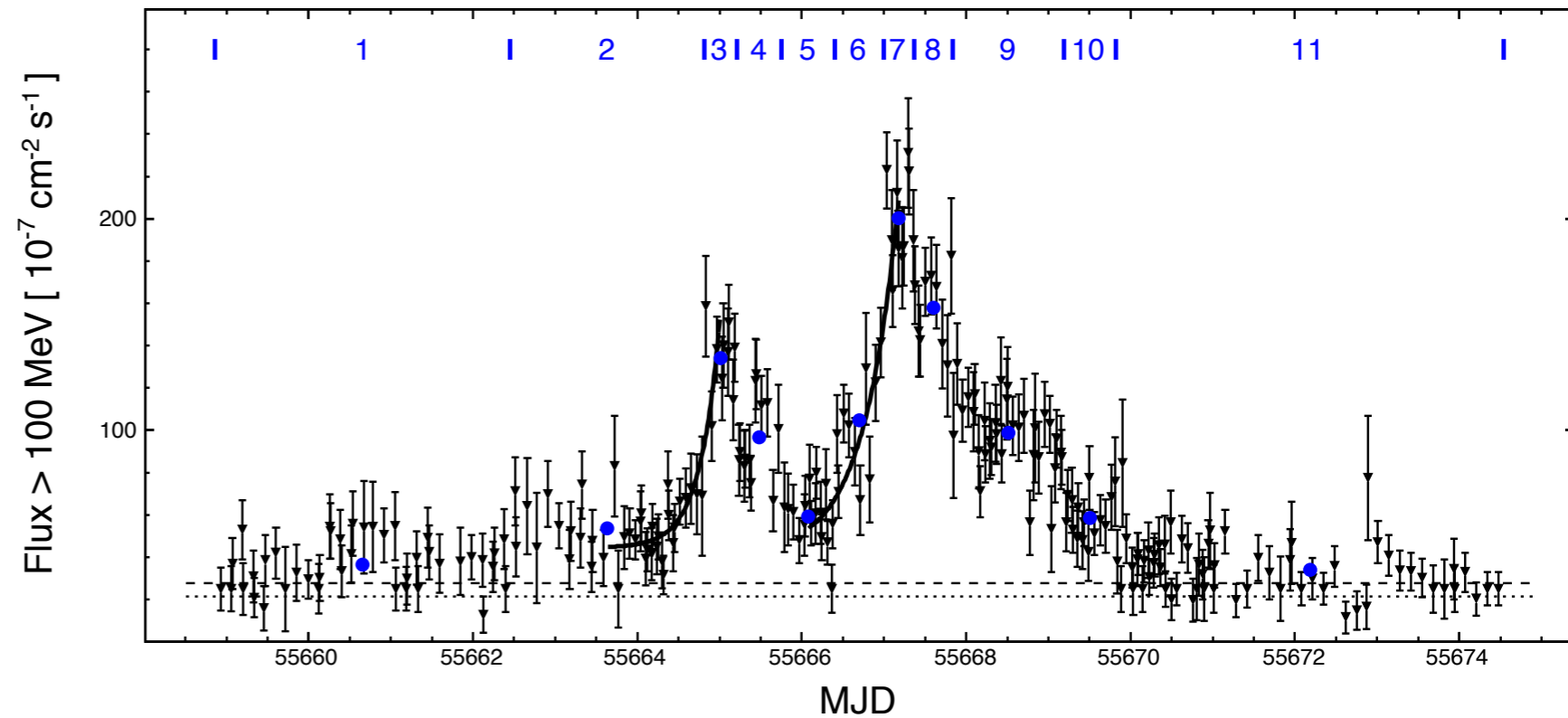
- massive star-forming regions
- CR isotopic abundances (^{22}Ne , trans-iron)
- 80% SN = gravitational collapse of massive star
- superbubbles
- CR cocoon in Cygnus
 - single source or superbubble?
 - advection? confinement?



Fermi LAT collab. Science 334 2011 1103

The Crab nebula flares

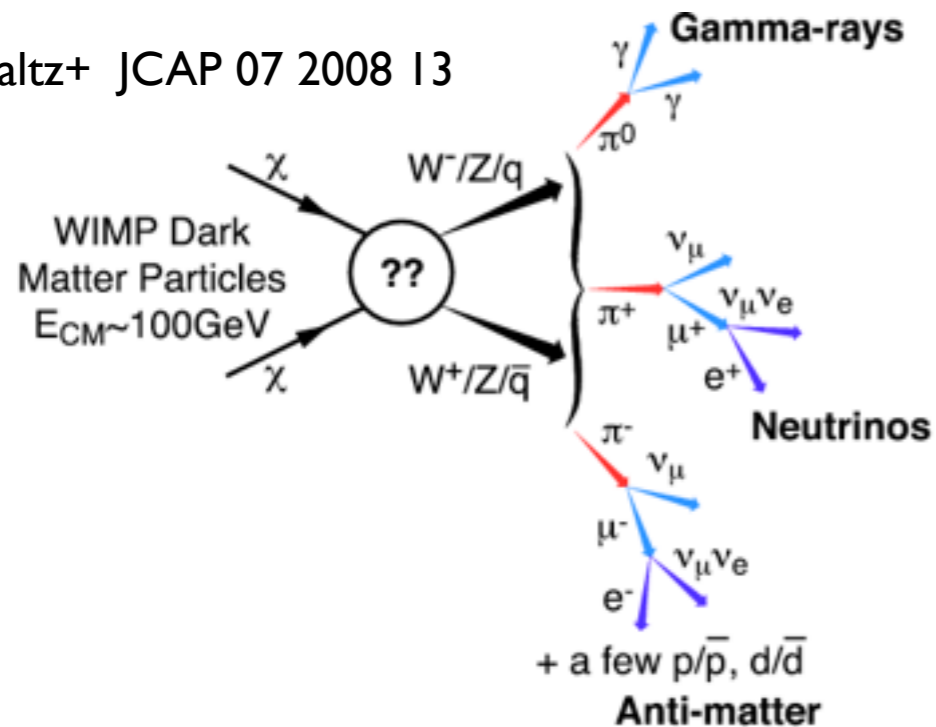
- variability < 8 h, 1% pulsar spindown power
- emitting region $< 3 \cdot 10^{-4}$ pc
- PeV electrons emitting γ s up to 1 GeV
- magnetic reconnection?



Buehler+ ApJ 749 2012 26B

Searches for DM

Baltz+ JCAP 07 2008 13



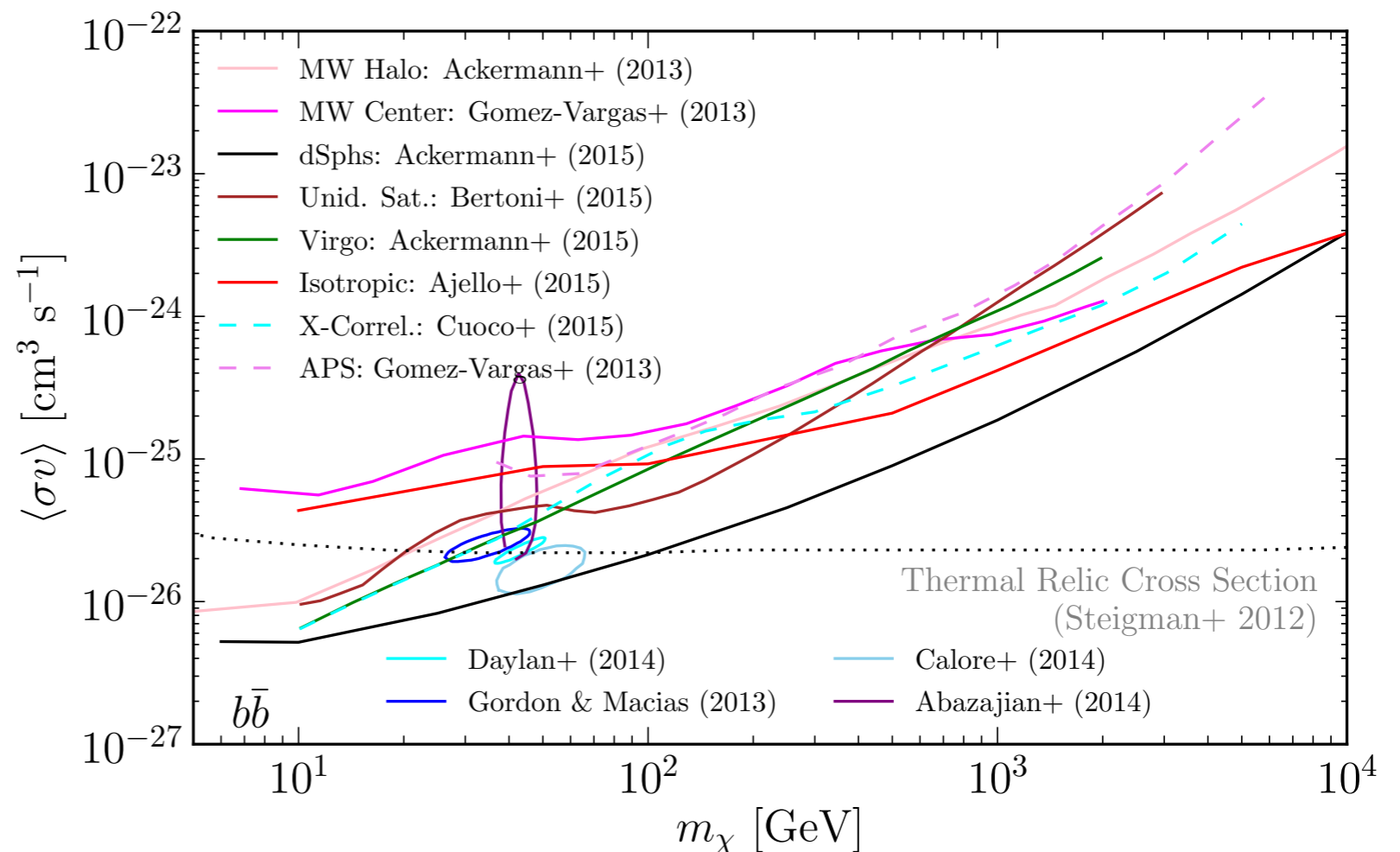
$$\Phi(E_\gamma) = \int_{\Omega} d\Omega \int_{\text{l.o.s}} dl \rho^2(\theta) \frac{1}{2} \frac{\langle \sigma v \rangle}{4\pi m_\chi^2} \sum_f \frac{dN_f}{dE_\gamma} B_f$$

DM content
of target

properties of DM
particle

Charles+ PhR 636 2016 IC

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



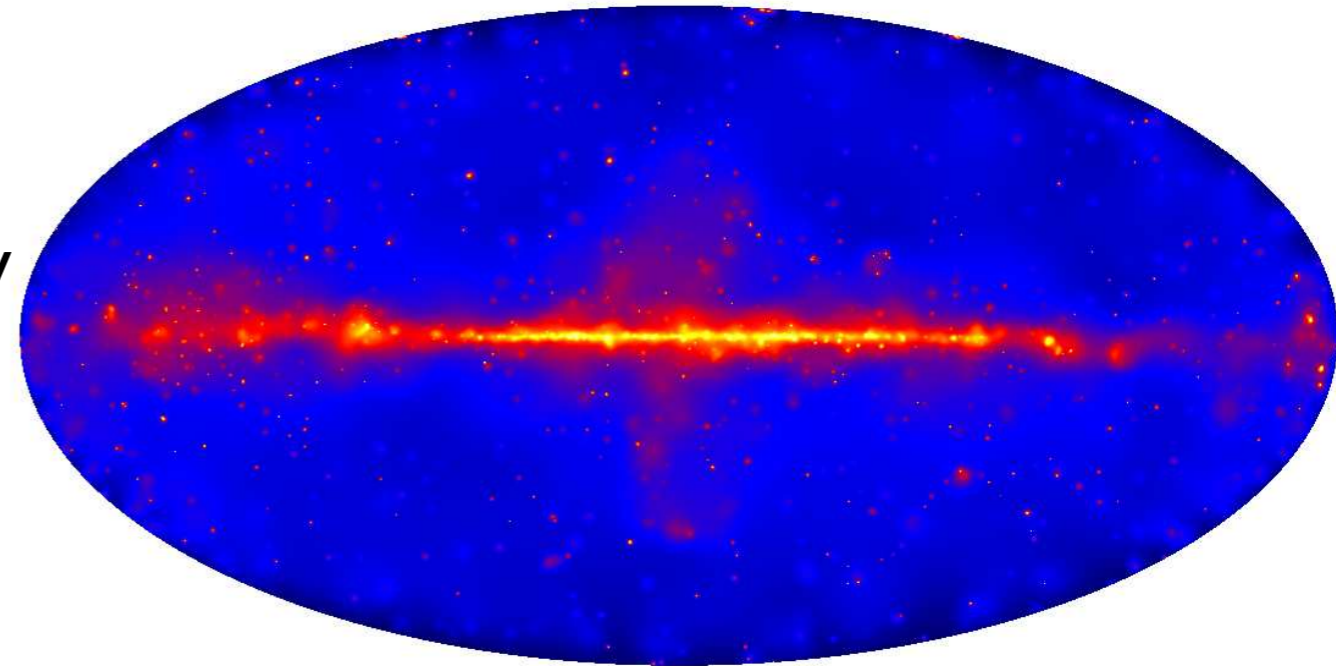
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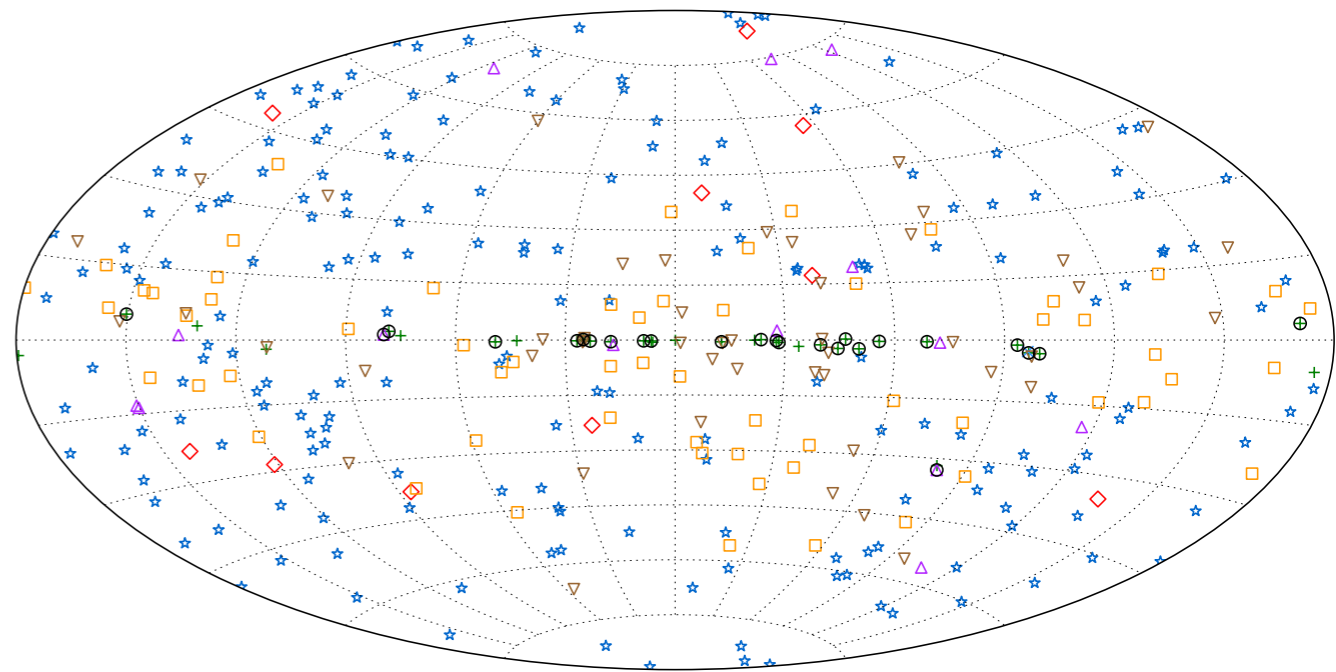
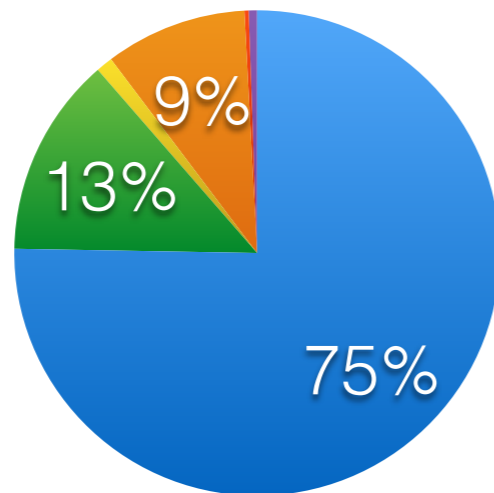
Extension to TeV energies

Fermi LAT collab. ApJS 222 2016 5A

- 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 \rightarrow 75% previously unknown
- upcoming: 3FHL (1720 sources, 10 GeV-2 TeV)



- AGN
- Unassoc.
- Other Galactic
- SNR/PWN
- PSR
- External galaxy

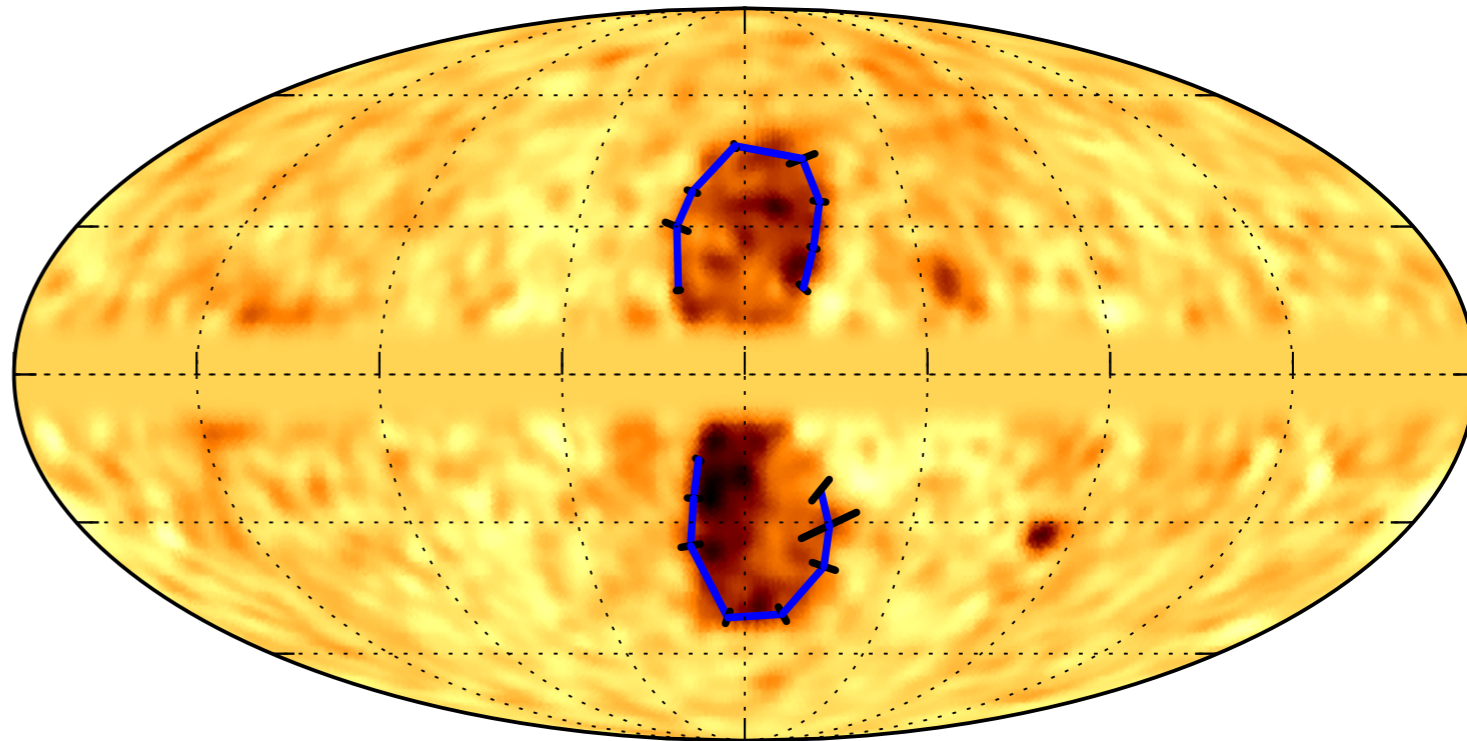


+	SNRs and PWNe	*	BL Lacs	□	Unc. Blazars	▽	Unassociated
×	Pulsars	◇	FSRQs	△	Others	○	Extended

The *Fermi* bubbles

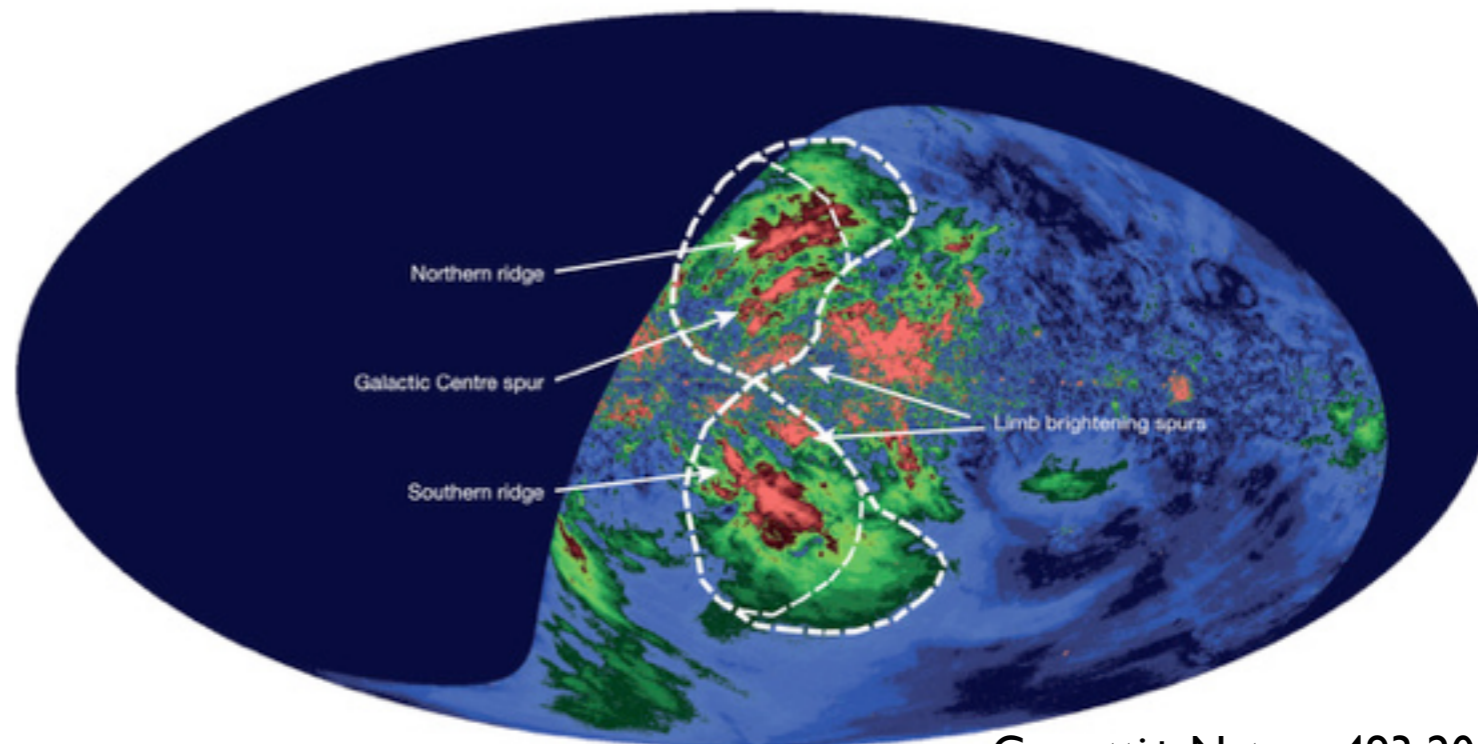
- lobe-like structures from the Galactic center
- giant nuclear magnetized outflow

γ rays (foreground subtracted) 10-500 GeV

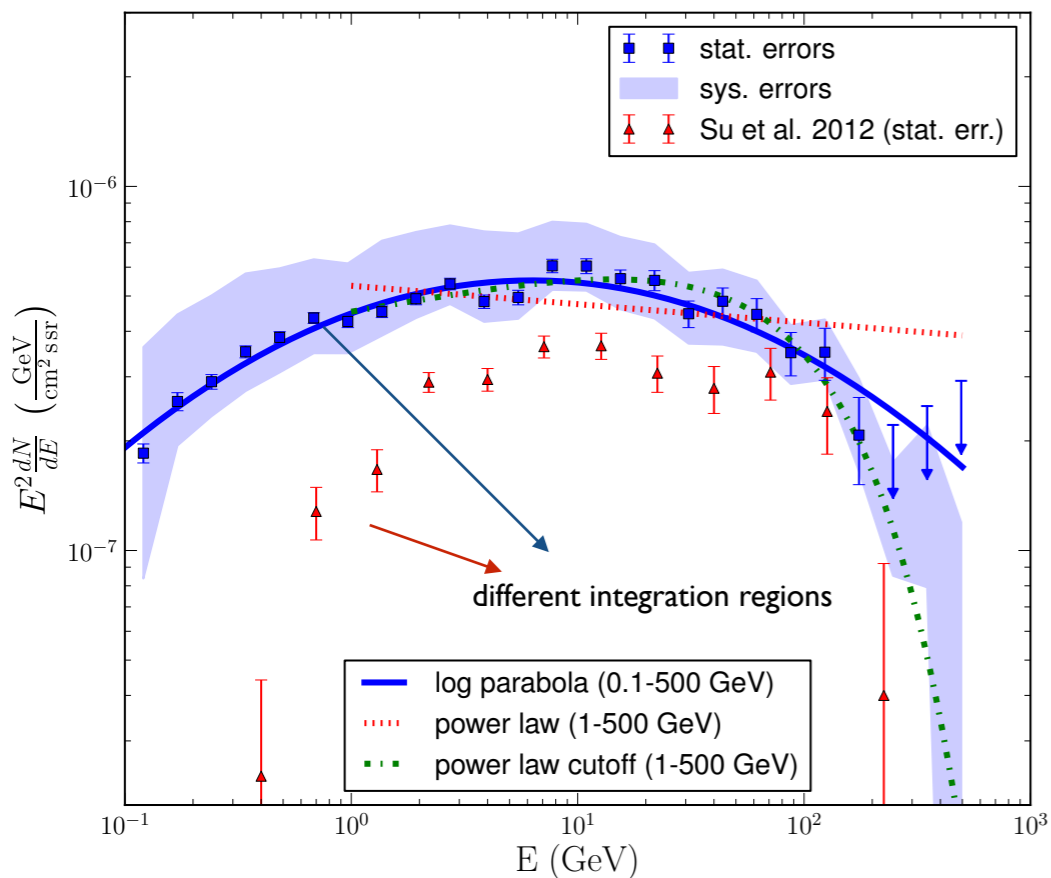


Fermi LAT collab. ApJ 793 2014 64A

linearly-polarized intensity 2.3 GHz



Carretti+ Nature 493 2013 66

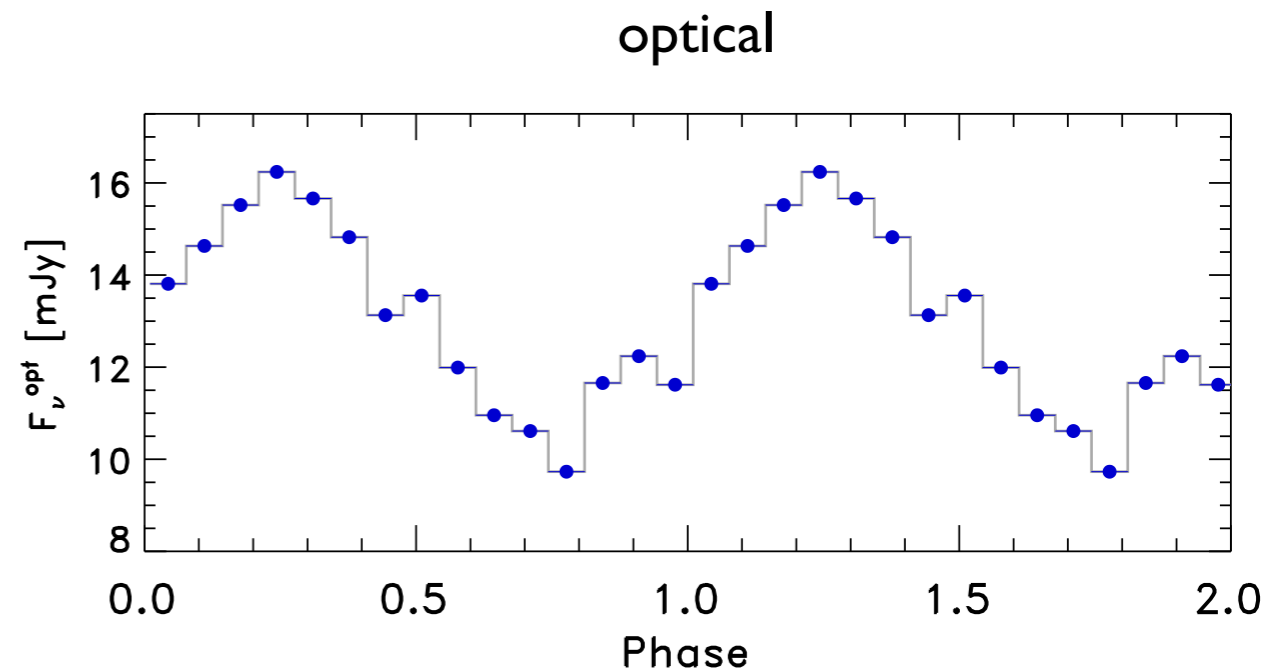
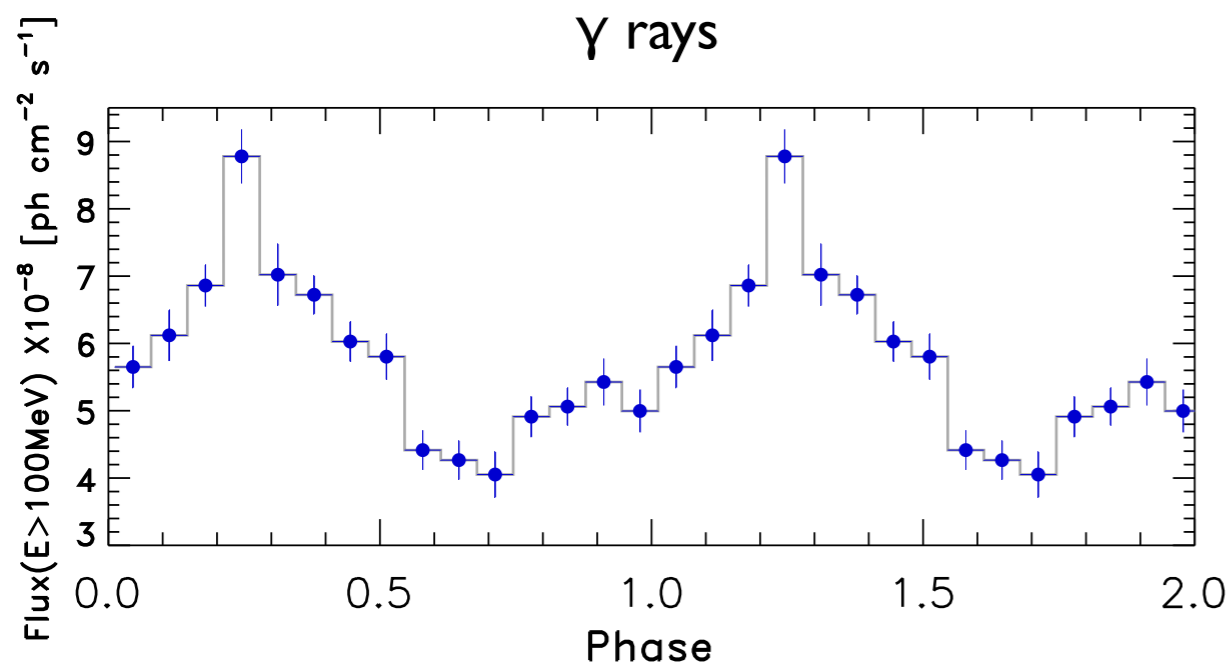


Fermi LAT collab. ApJ 793 2014 64A

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

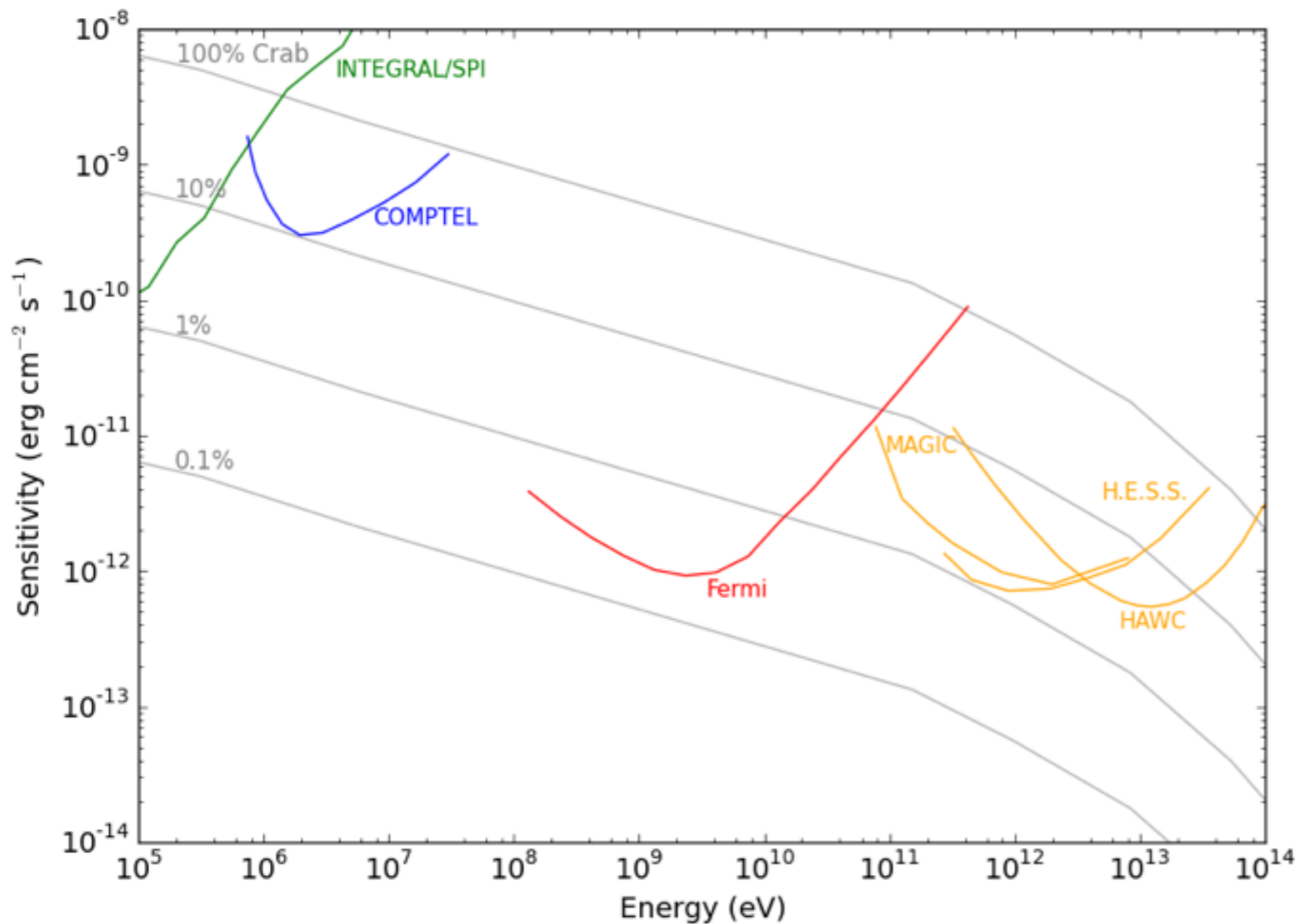


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- **New horizons**
 - **upcoming and future missions**

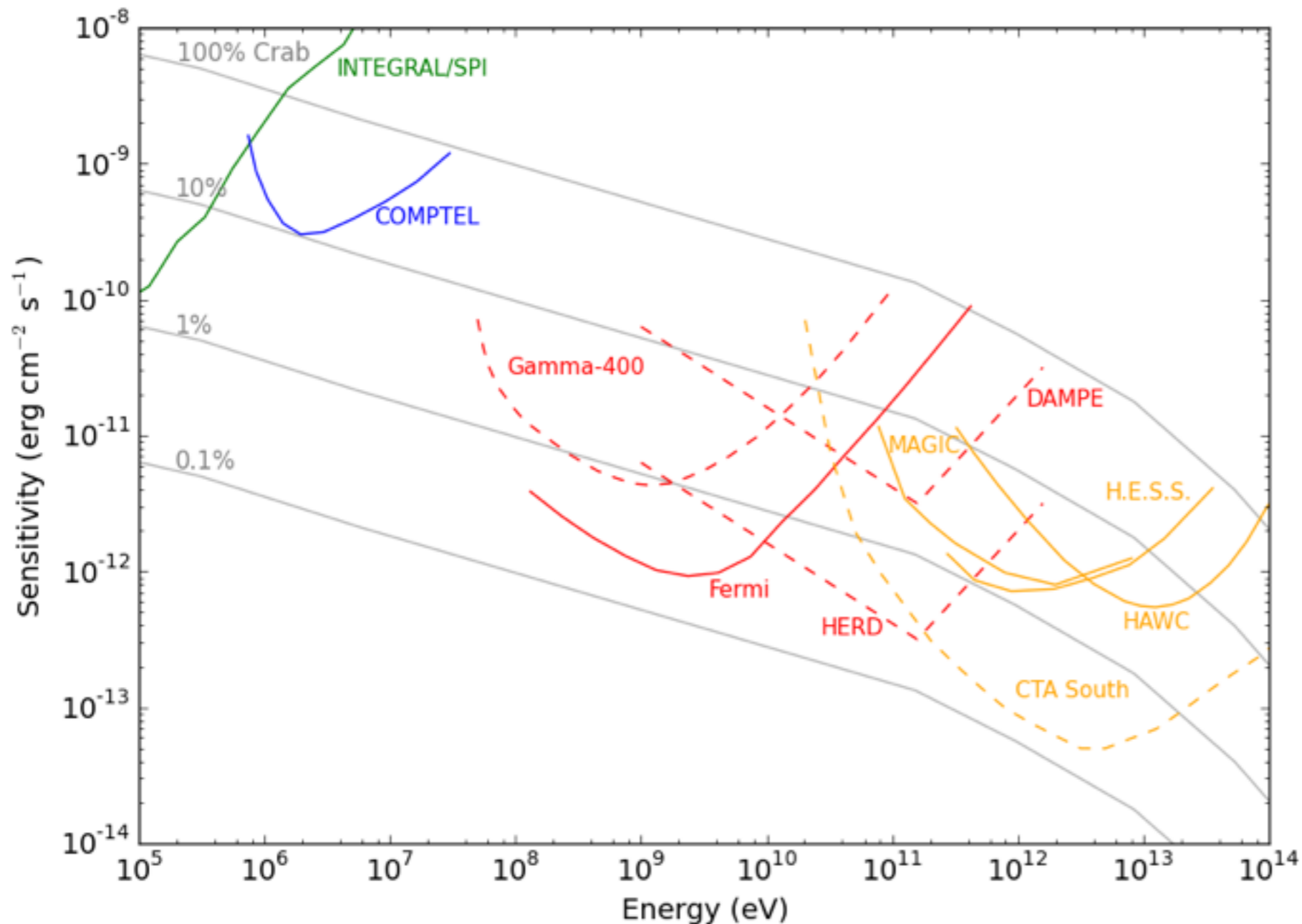
The past, the present, and the future

adapted from Knödseder CRPhy 17 2016 663



The past, the present, and the future

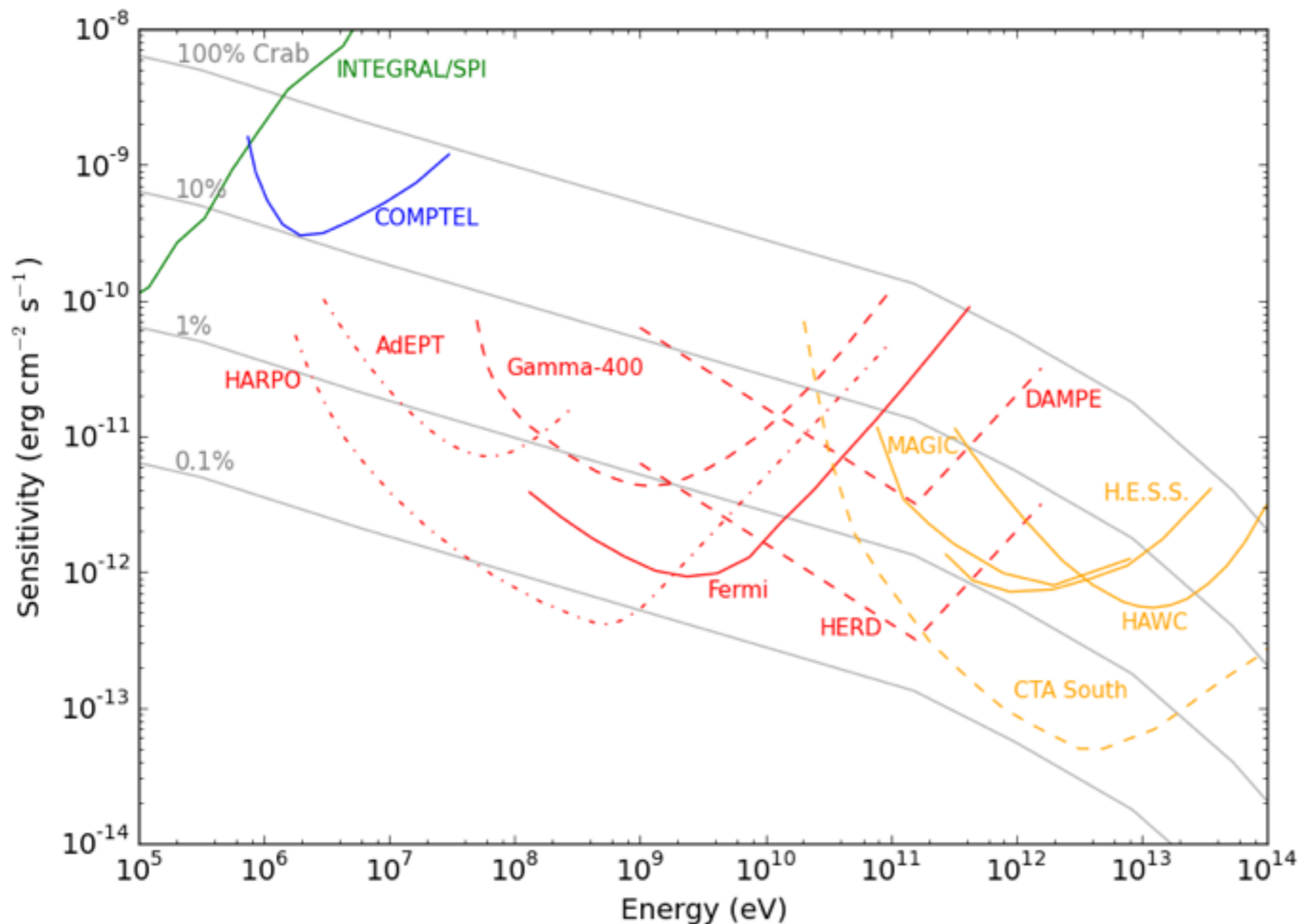
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- deep calorimeter (multi TeV, % energy resolution)
 - DAMPE (2015)
 - HERD (>2020)
- + TKR/imaging CAL separation (0.02° PSF)
 - Gamma-400 (2021?)

The past, the present, and the future

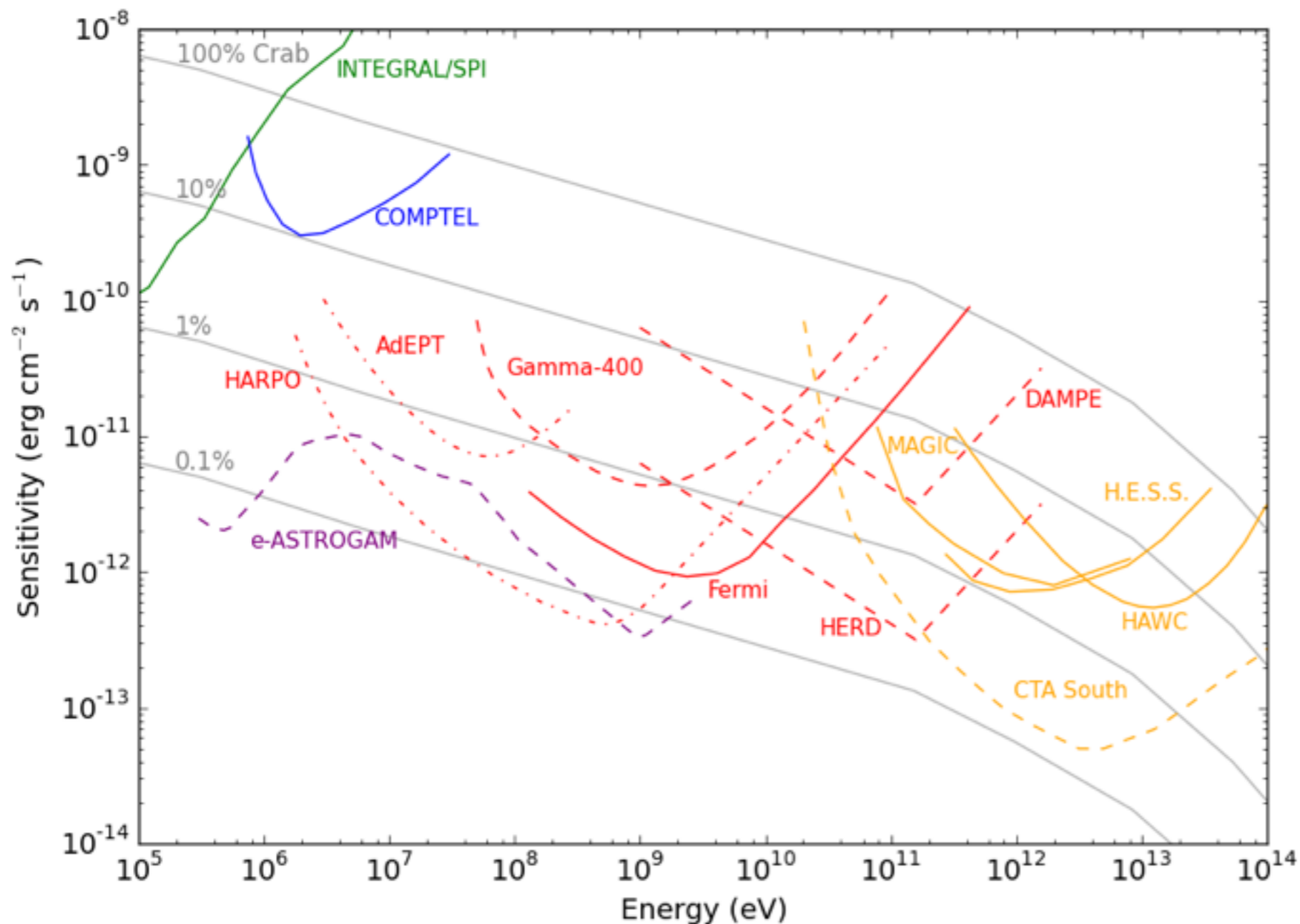
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- gas time projection chambers
 - 3 to > 100 MeV energy range
 - PSF < 1°
 - polarization
- R&D: AdePT, HARPO

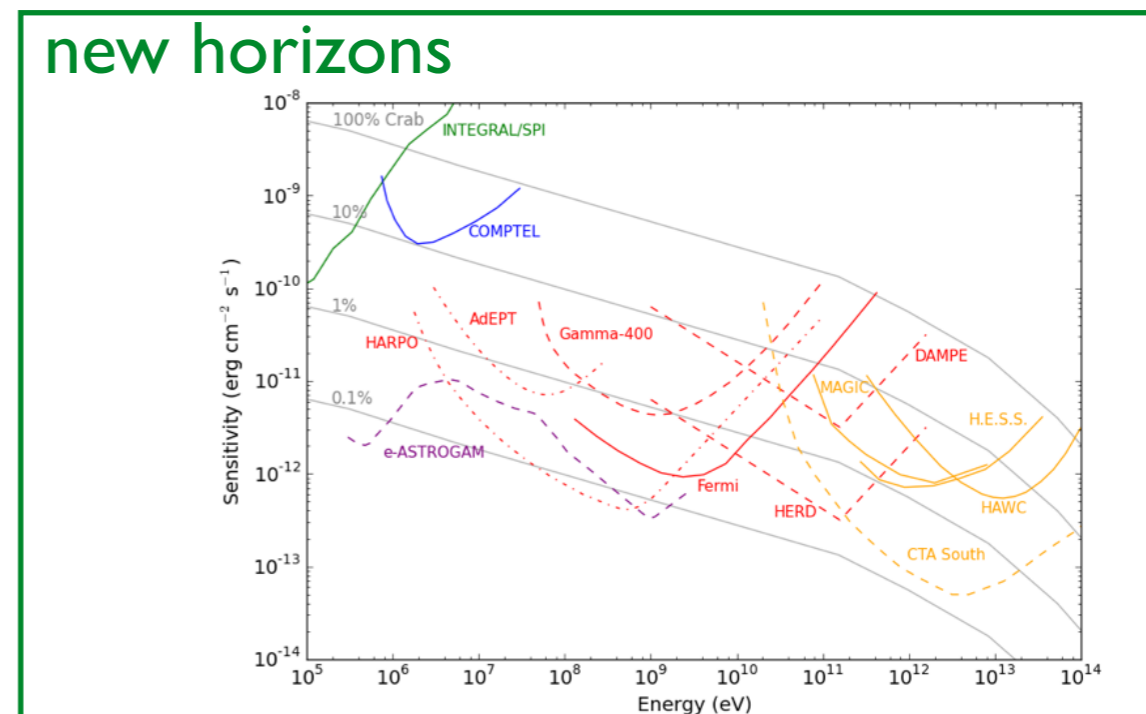
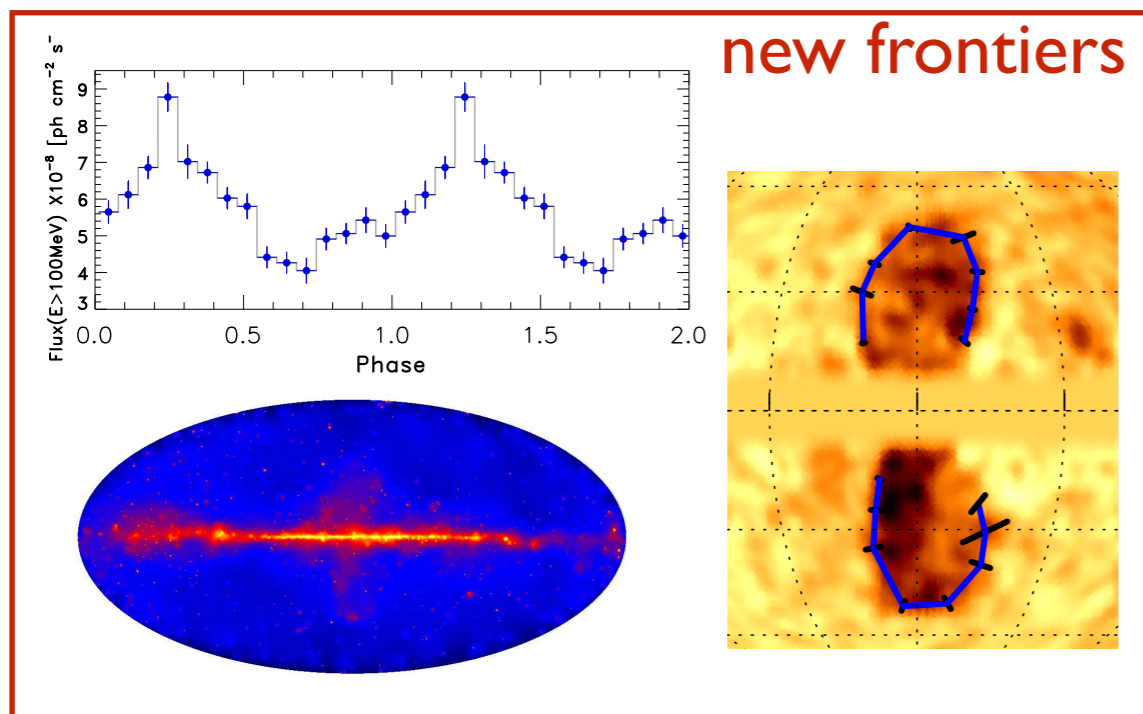
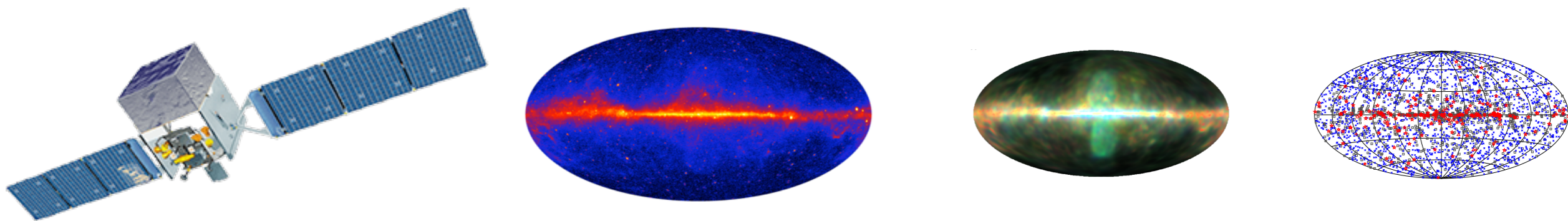
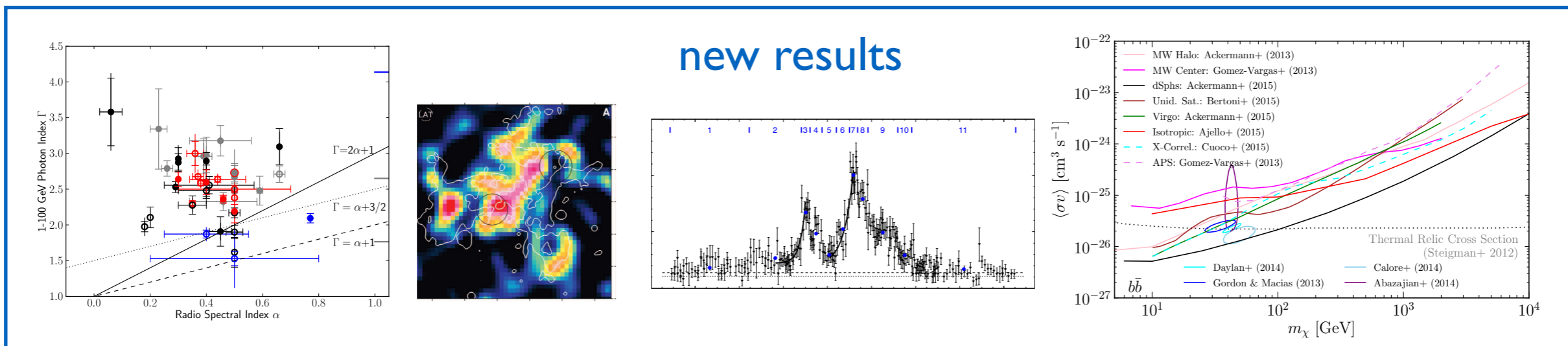
The past, the present, and the future

adapted from Knödseder 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

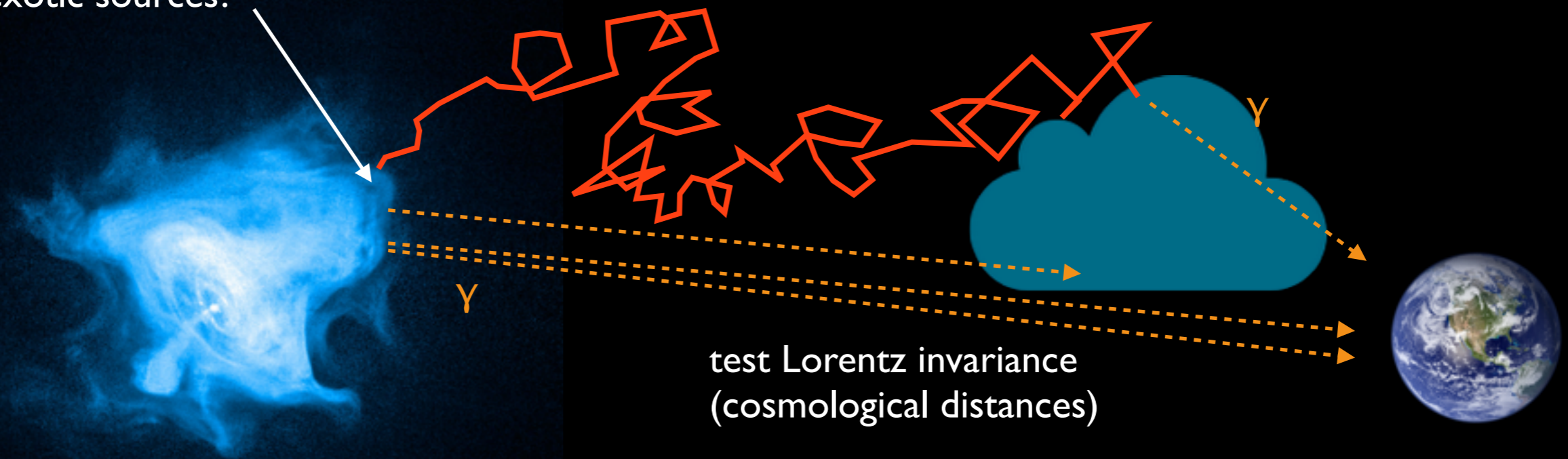


Backup

Science with gamma rays

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

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



- relatively easy to detect
- not deflected by magnetic fields

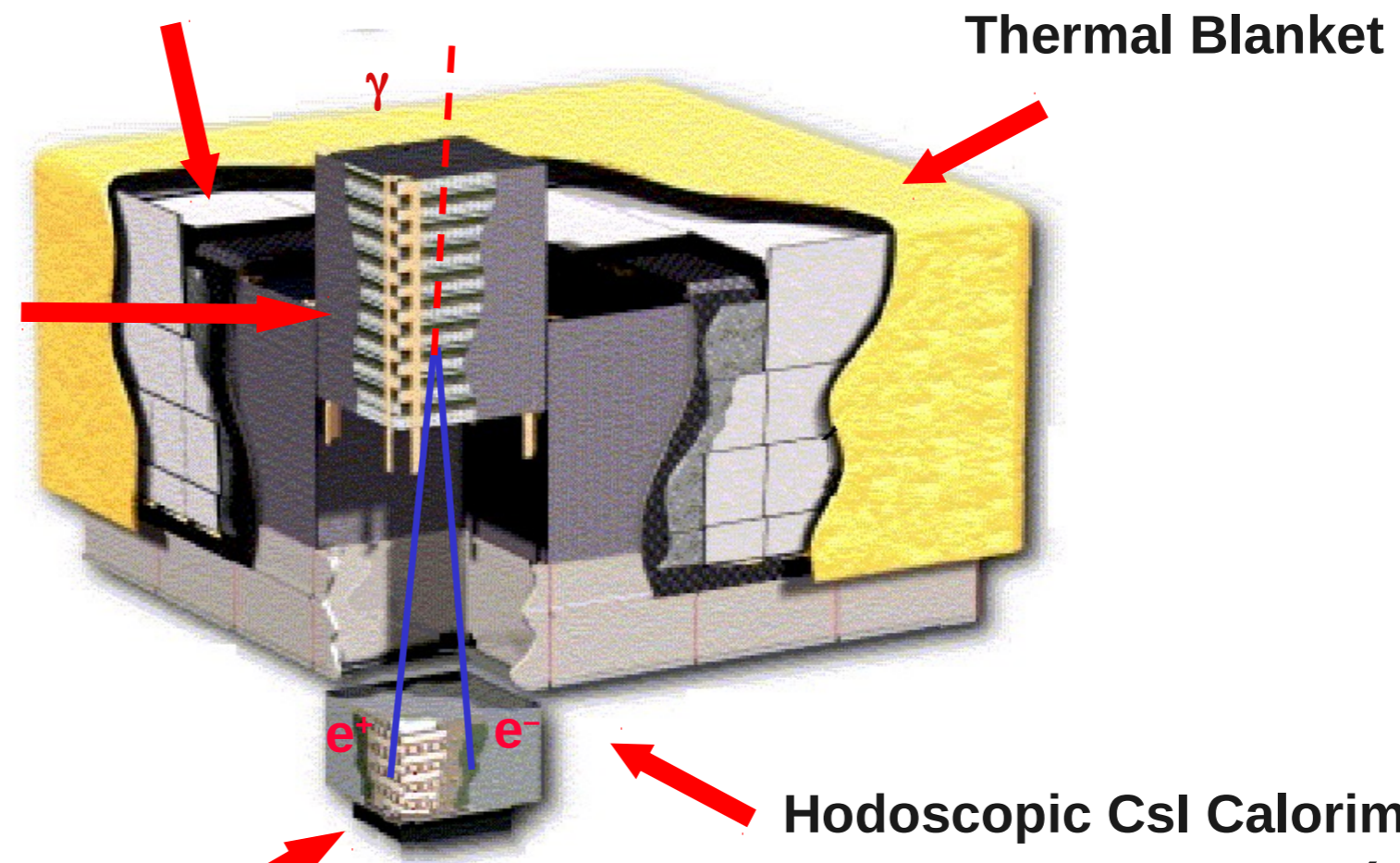
The *Fermi* Large Area Telescope

Pair-tracking Telescope

1.8 m x 1.8 m x 0.72 m

Anticoincidence Detector (ACD)

- segmented
- 0.9997 MIP efficiency



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 m² active Si

Thermal Blanket

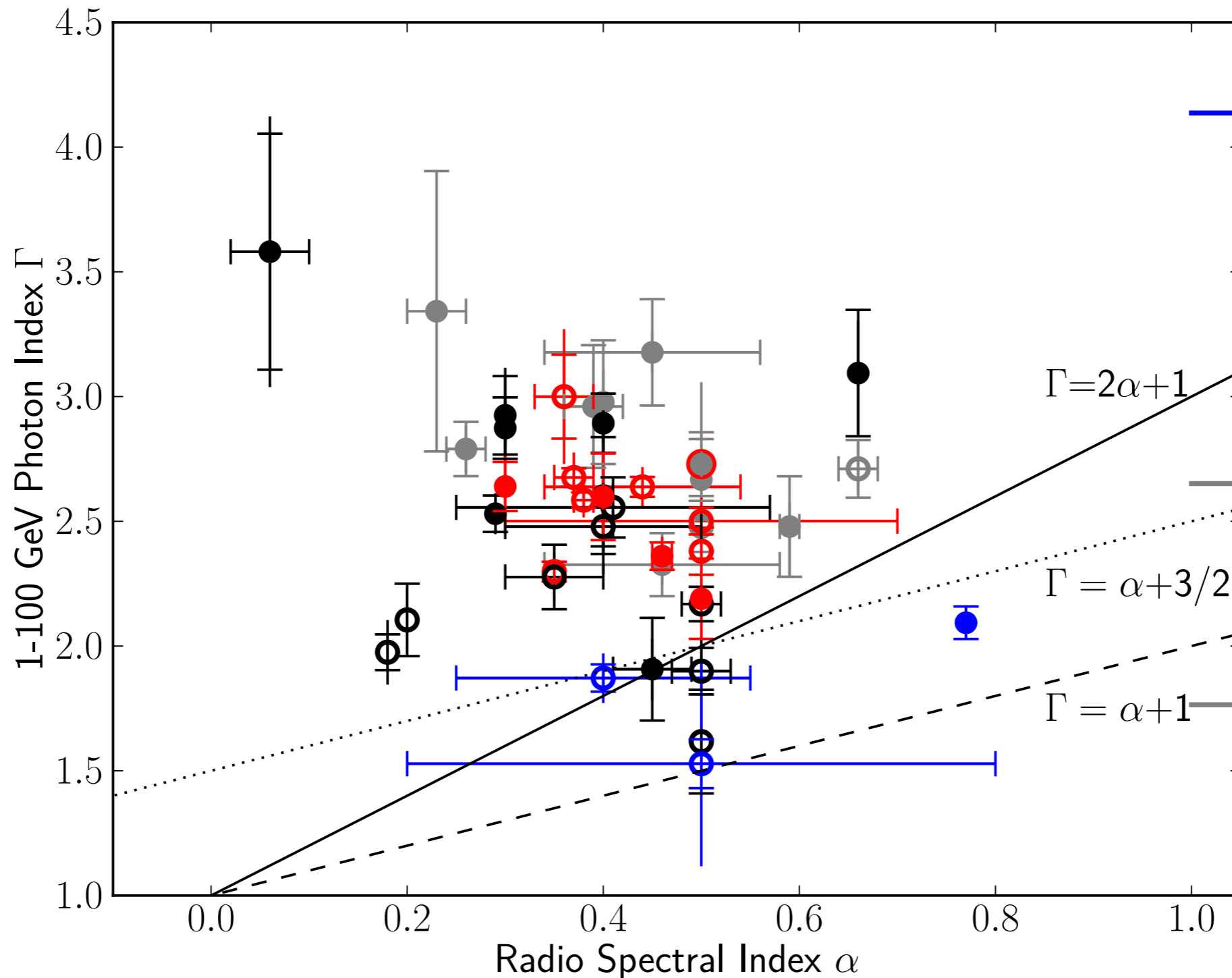
Hodoscopic CsI Calorimeter (CAL)

- 1536 logs
- 8.5 r.l. on axis

DAQ

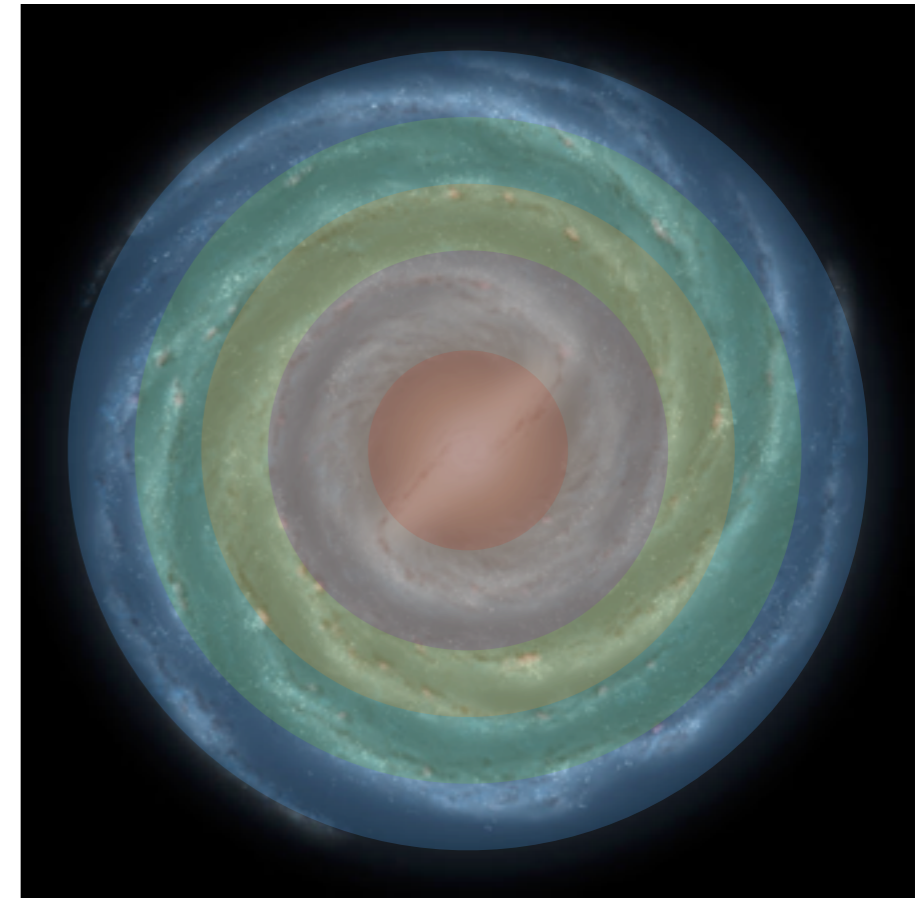
Data challenge simple SNR models

Fermi LAT collab. ApJS 224 2016 8A

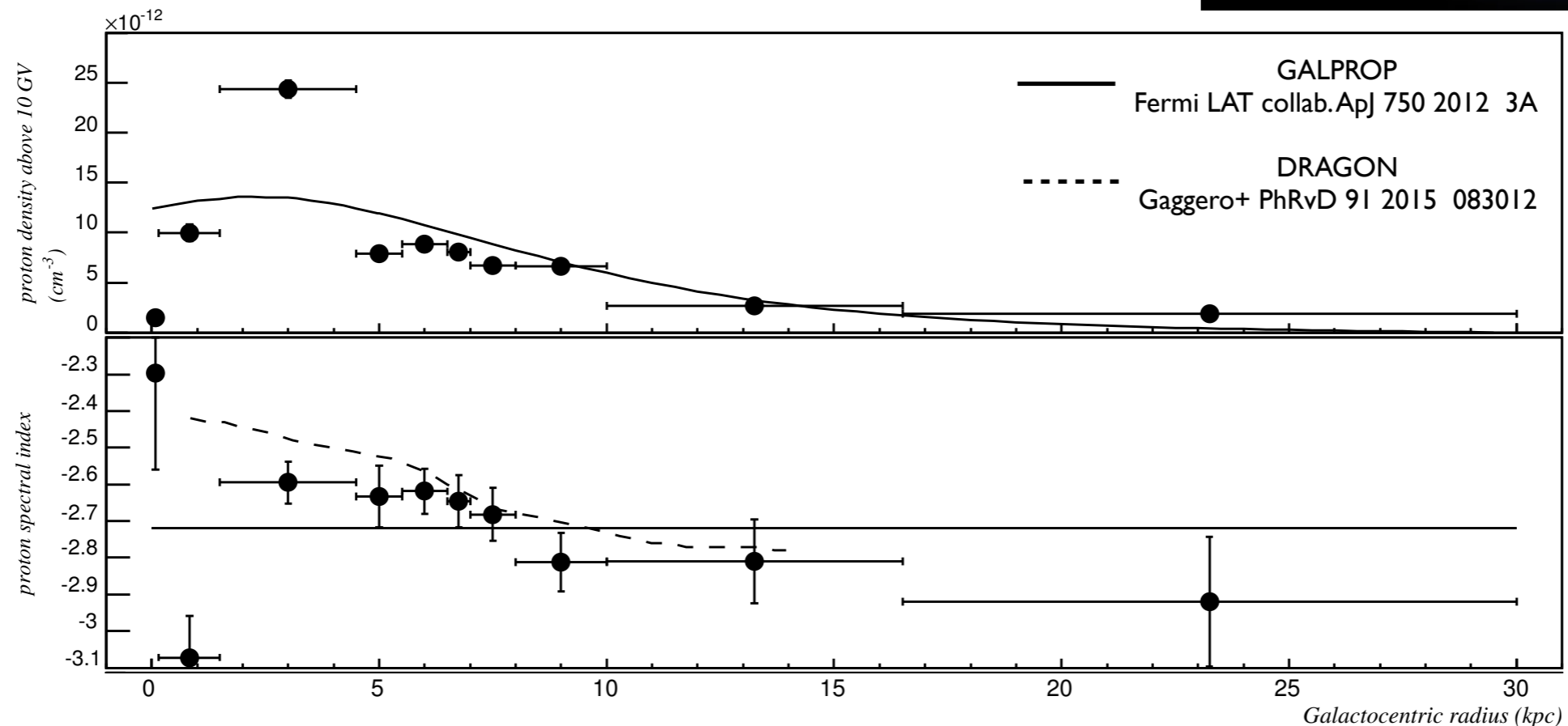


The cosmic-ray gradient across the Milky Way

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



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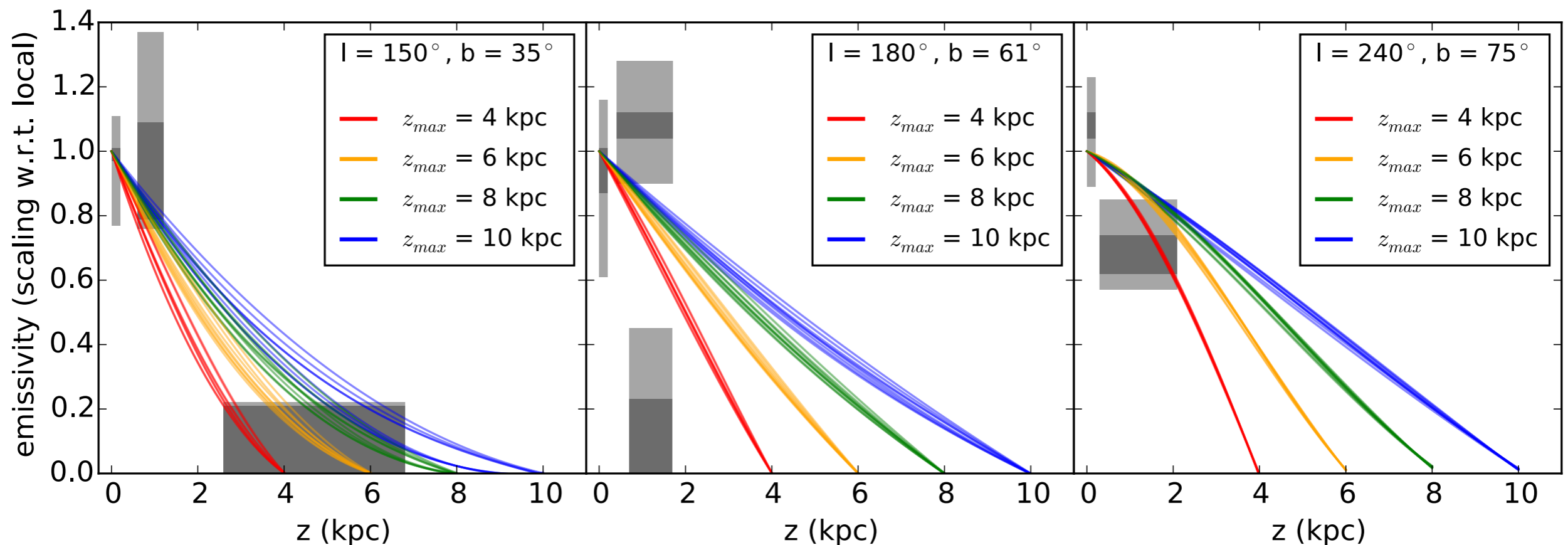


CRs in the halo of the Milky Way

- 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 $^{10}\text{Be}/^9\text{Be}$
(confinement region: 4-6 kpc)

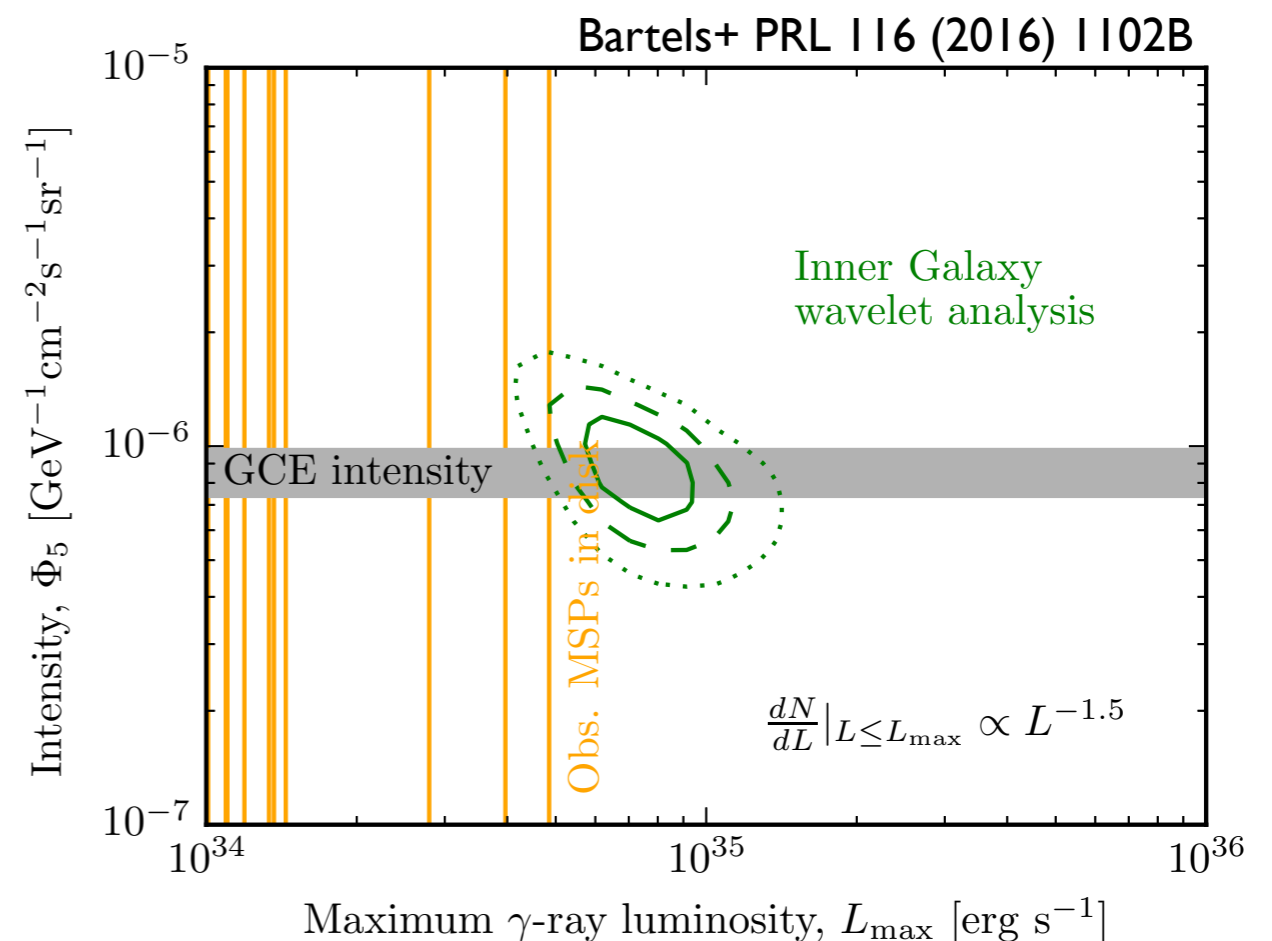
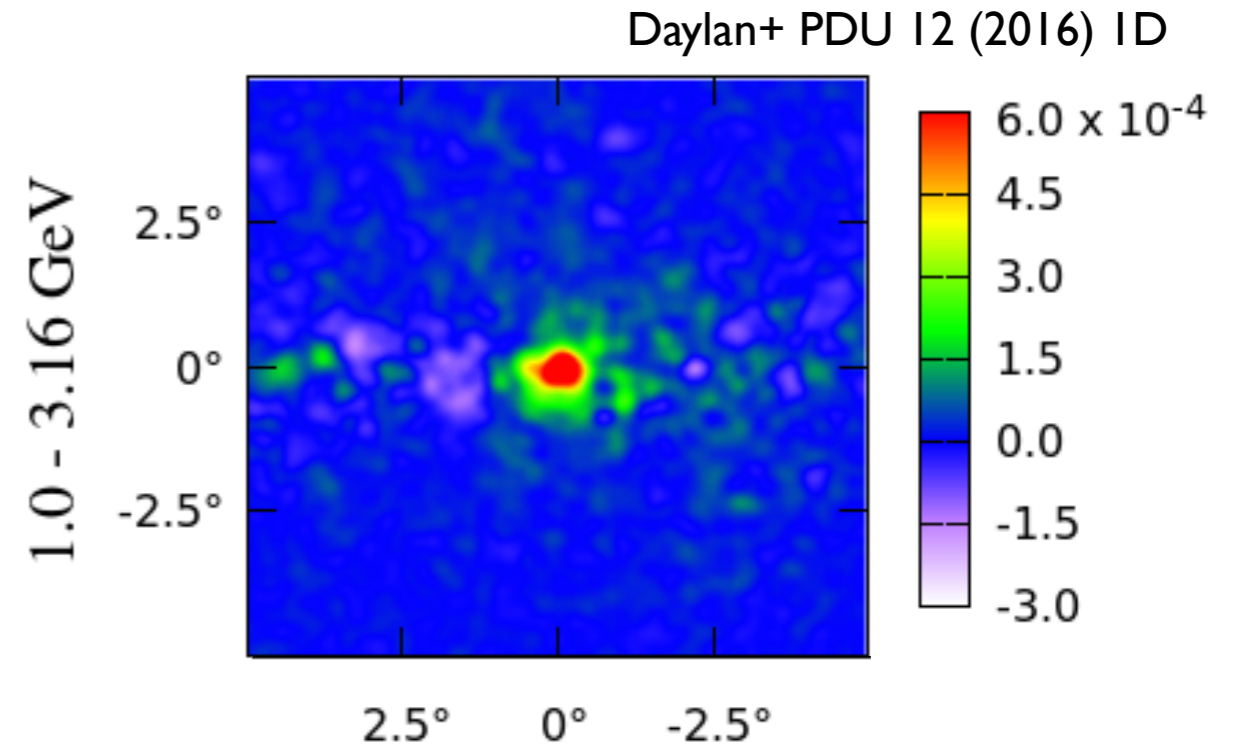


Tibaldo+ Apj 807 2015 161



The GeV Galactic center excess

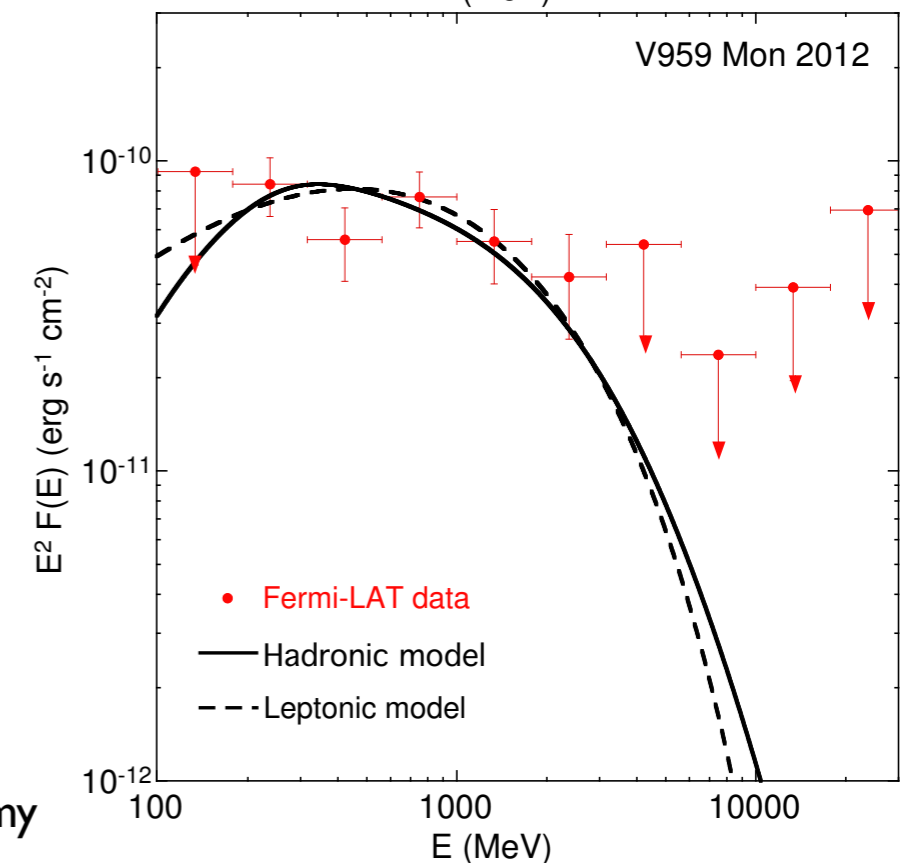
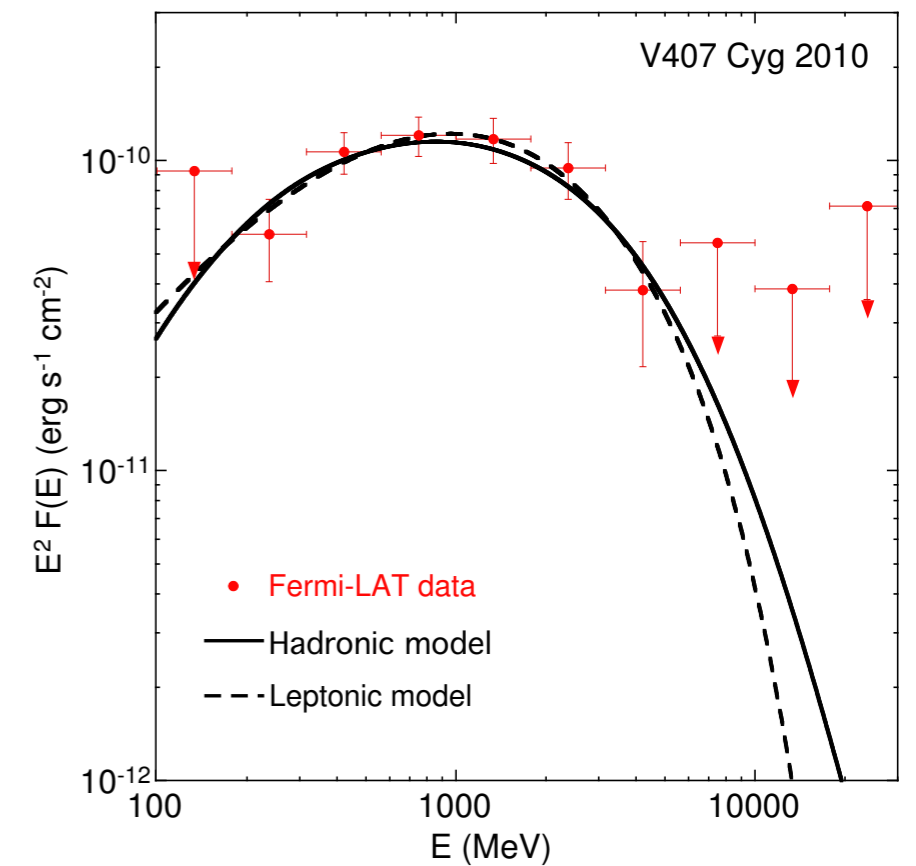
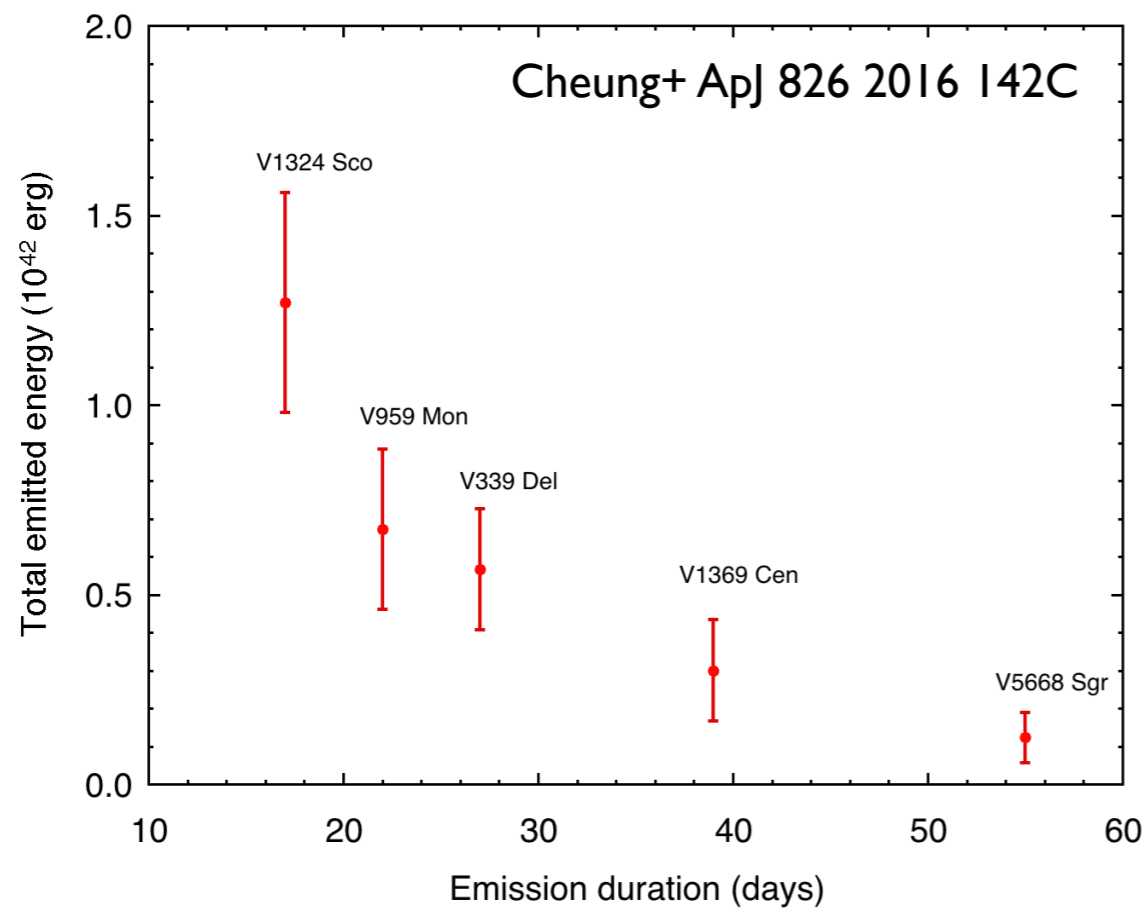
- residual emission near the Galactic center peaking at few GeV
 - spherical or bipolar?
 - low/high-energy shape of spectrum uncertain
- origin
 - DM annihilation?
 - poorly modeled interstellar emission?
 - *Fermi* bubbles?
 - unresolved sources (ms pulsars)?



Novae as γ -ray sources

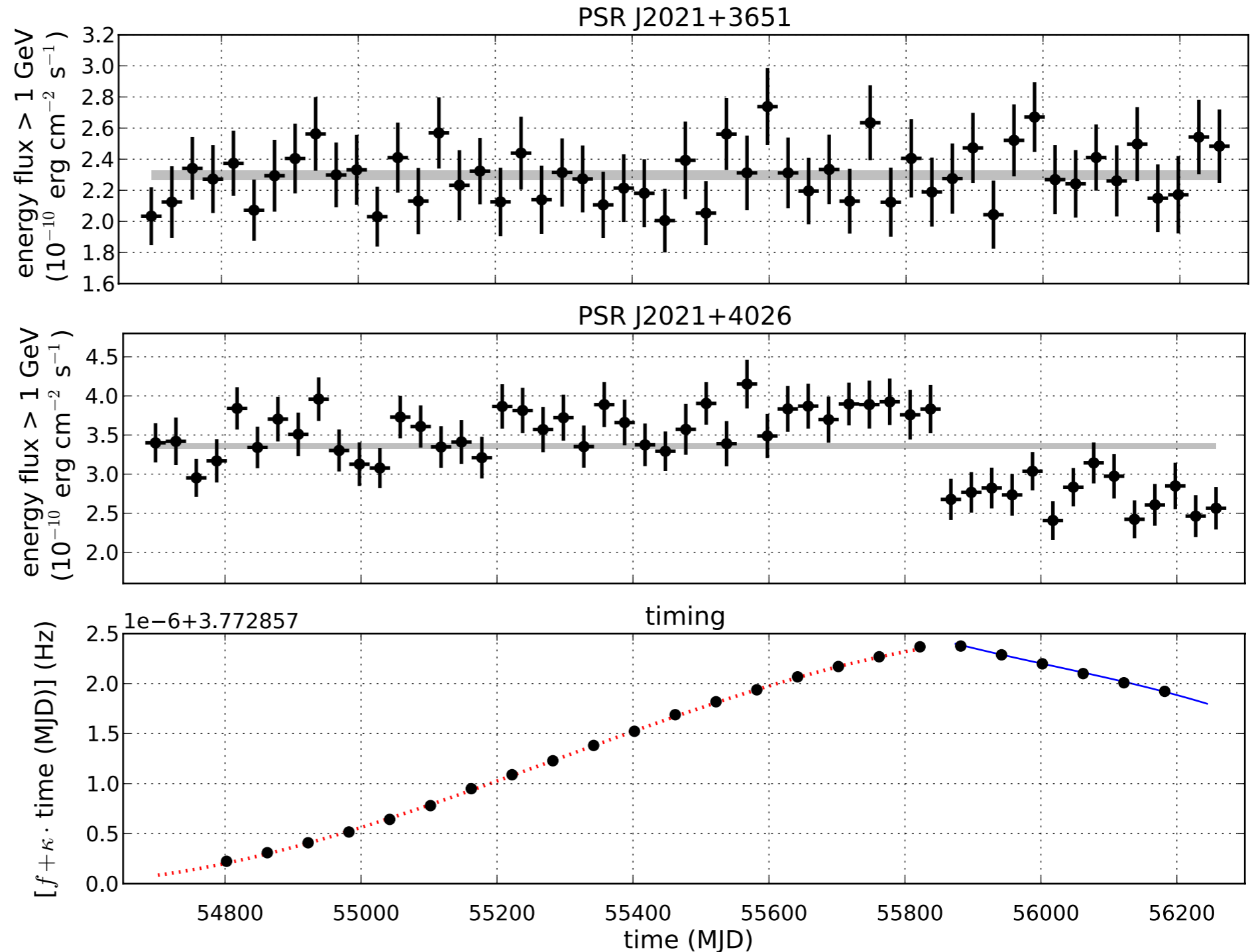
Fermi LAT collab. Science 345 2014 554A

- > 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