A tale of cosmic rays narrated in γ rays by *Fermi*

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KIPAC   SLAC

on behalf of
the *Fermi*-LAT collaboration

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Outline

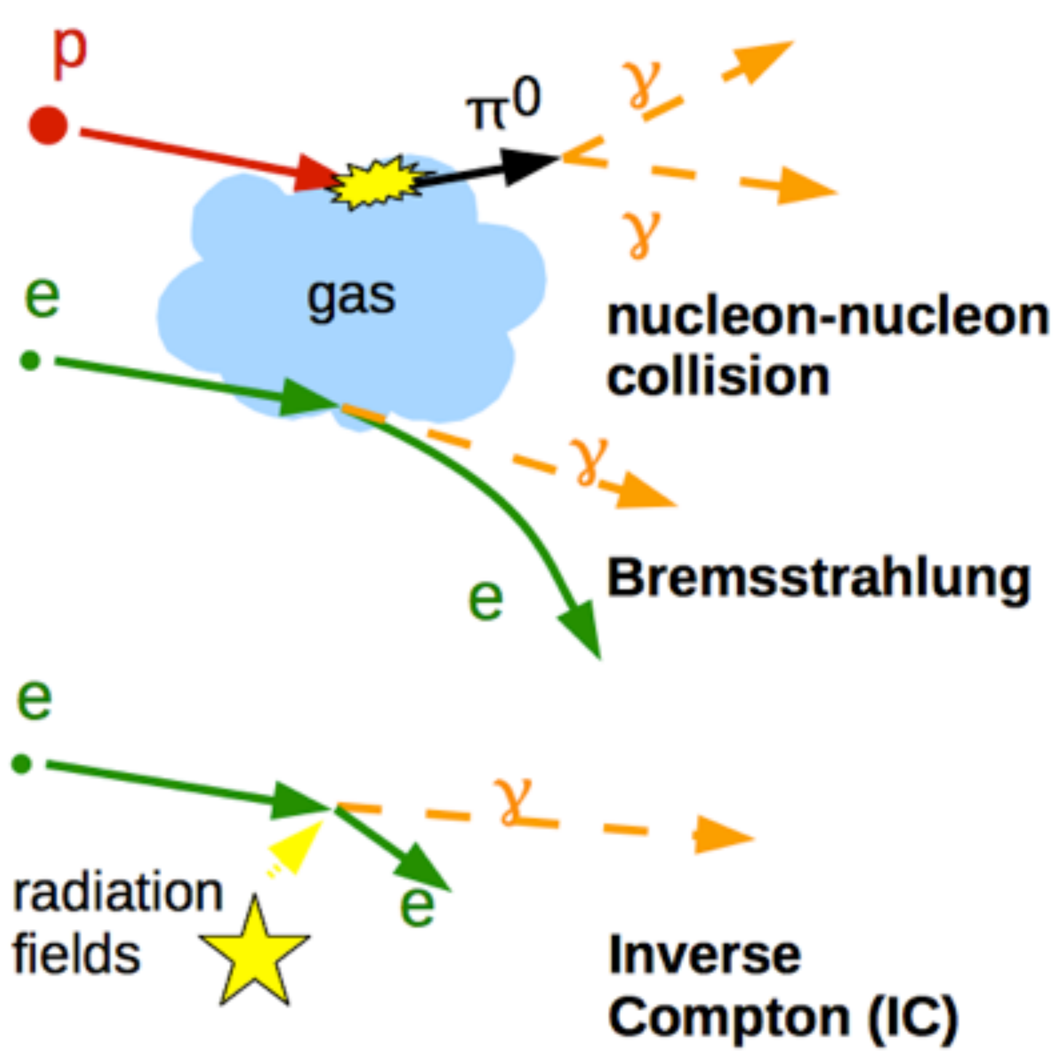
- γ rays as a cosmic-ray tracer
- Cosmic-ray acceleration in supernova remnants
- Cosmic rays in massive star-forming regions
- Large-scale propagation of cosmic rays in the Milky Way
- Cosmic rays in external galaxies
- Challenges and summary

Chasing cosmic rays

CR are charged + B fields → do not track back to sources (< 10^{18} eV)

- acceleration
- propagation
- interactions with galactic ecosystems
- dark-matter signatures?

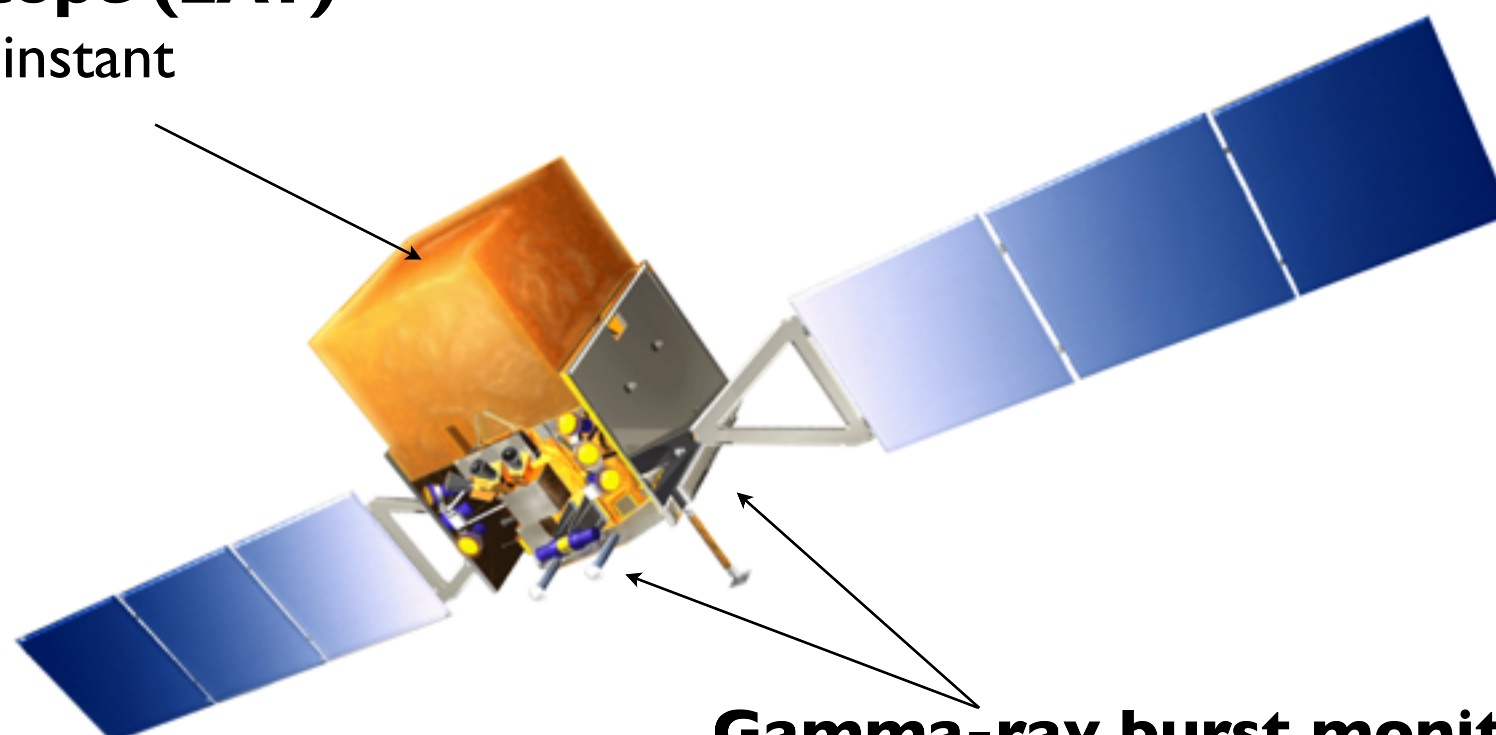
γ rays as a charged particle tracer



- neutral secondaries → complement direct observations
- γ rays → neutral and easy to detect (≠ ν)

The *Fermi Gamma-ray Space Telescope*

Large Area Telescope (LAT)
20% of the sky at any instant
20 MeV to >300 GeV



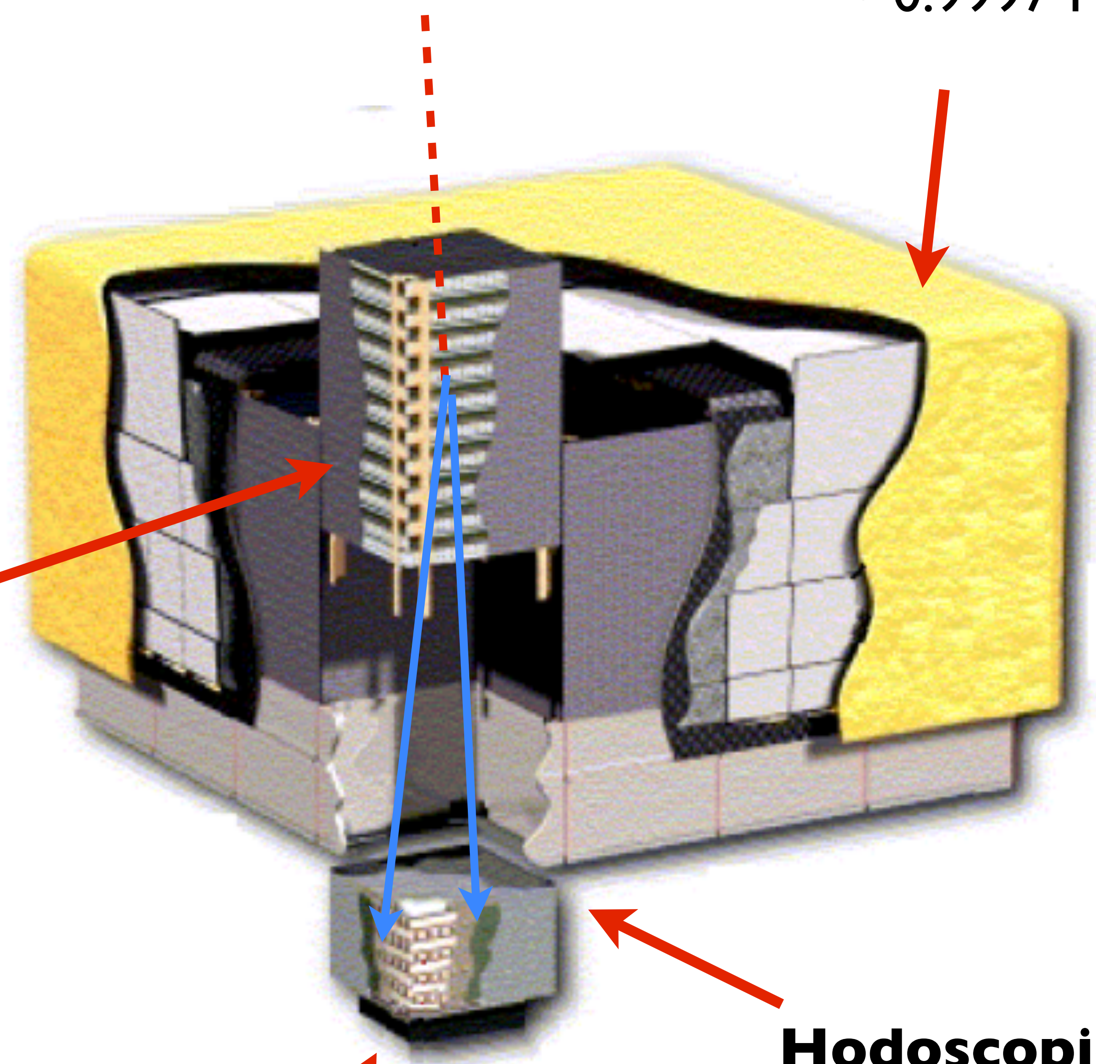
Gamma-ray burst monitor (GBM)
entire unocculted sky
transients from 8 keV to 40 MeV

launched in 2008
nearly circular orbit 565 km, 25.6°
sky survey: 2008-2013
Galactic center biased survey: 2014 ...
(+ target of opportunities, autonomous repointings)

The Large Area Telescope

Pair-tracking telescope
- 1.8 m x 1.8 m x 0.72 m
- 4x4 towers

Anticoincidence Detector
- segmented
- 0.9997 MIP efficiency

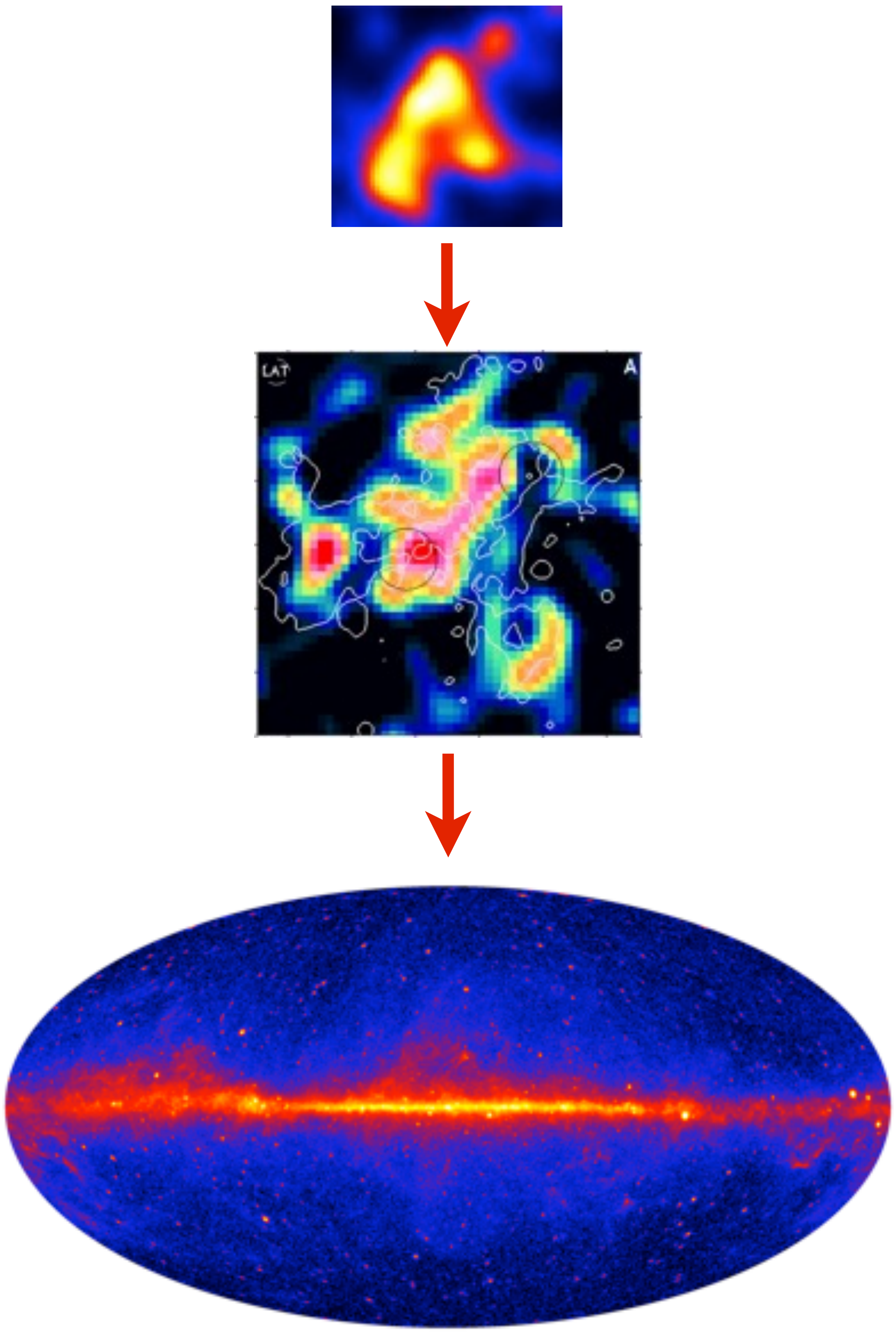


Precision Si-strip tracker + W converters
- 12 planes 3% r.l. (FRONT)
- 4 planes 12% r.l. (BACK)
- 2 planes with no converter
- 0.9 M channels
- 70 m^2 active Si

Hodoscopic CsI calorimeter
- 1536 logs
- 8.5 r.l. on axis

DAQ

Fermi tells us the story of cosmic rays



focus on CRs below the knee, $<10^{15}$ eV

- acceleration in supernova remnants
- link with massive-star forming regions/early propagation
- large-scale propagation
- external galaxies

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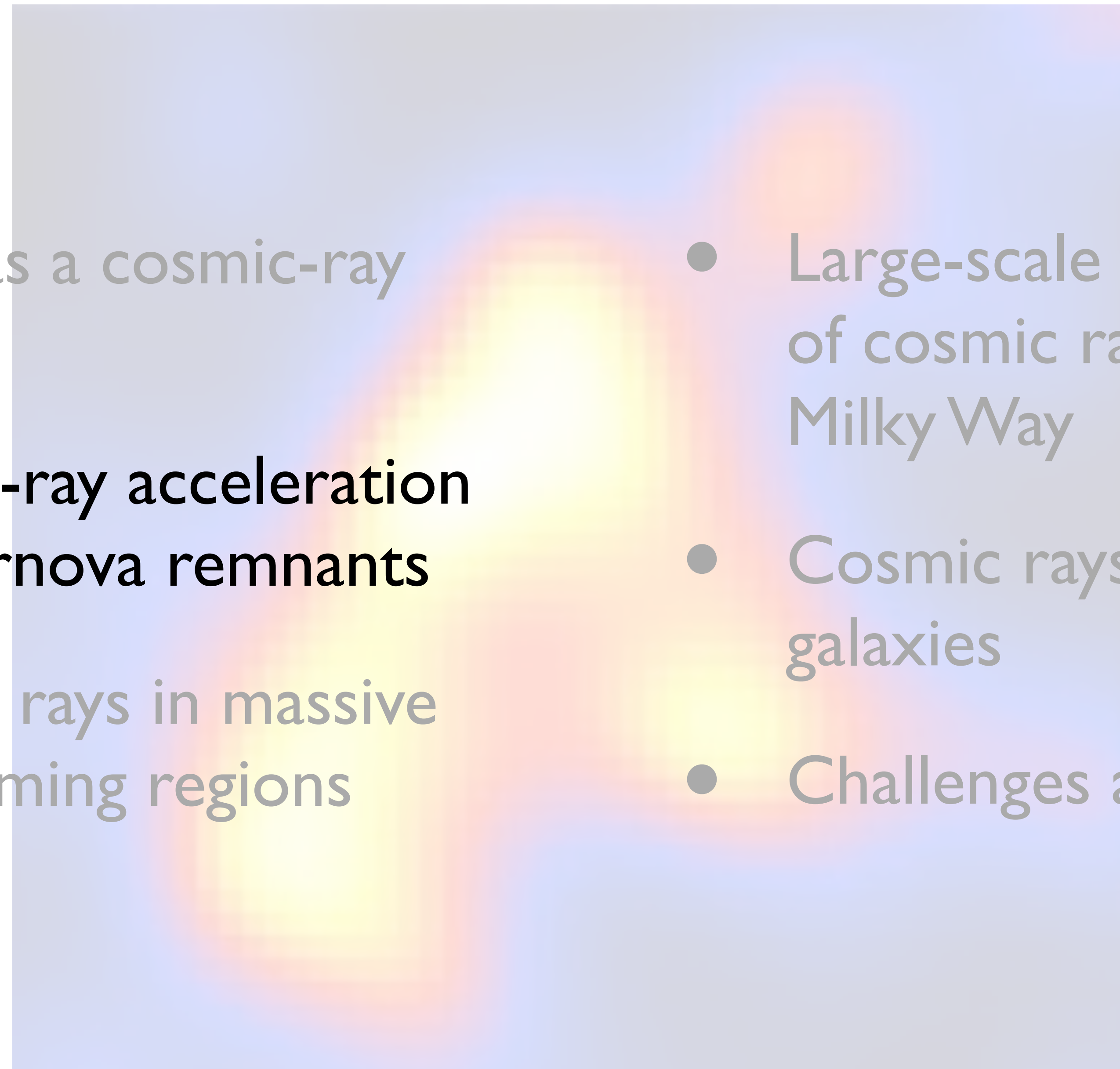

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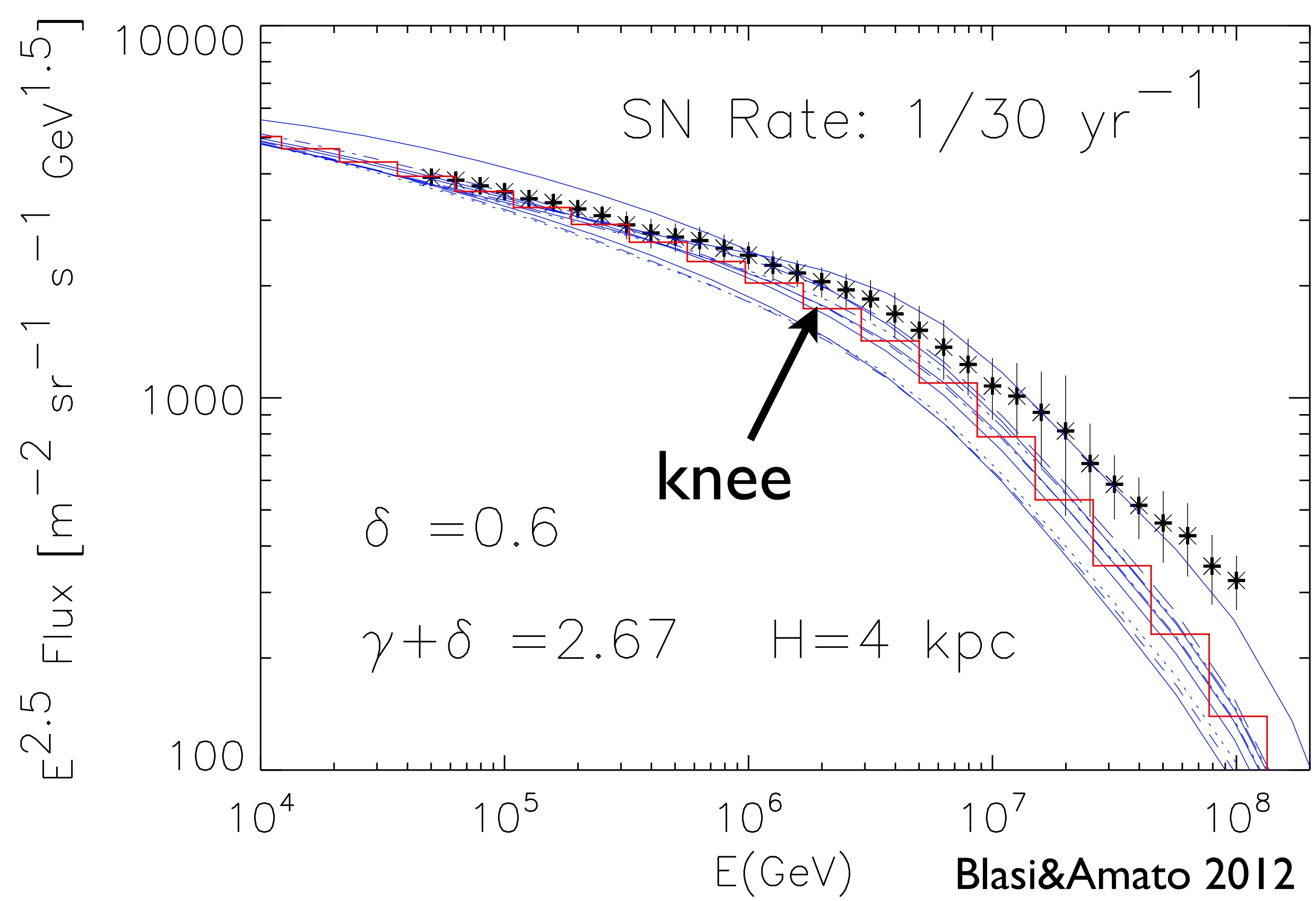
Supernova remnants as CR sources

- energetic and numerous enough
- non-linear diffusive shock acceleration
- SNRs accelerate
  - electrons
  - nuclei? up to the knee?

SNR paradigm

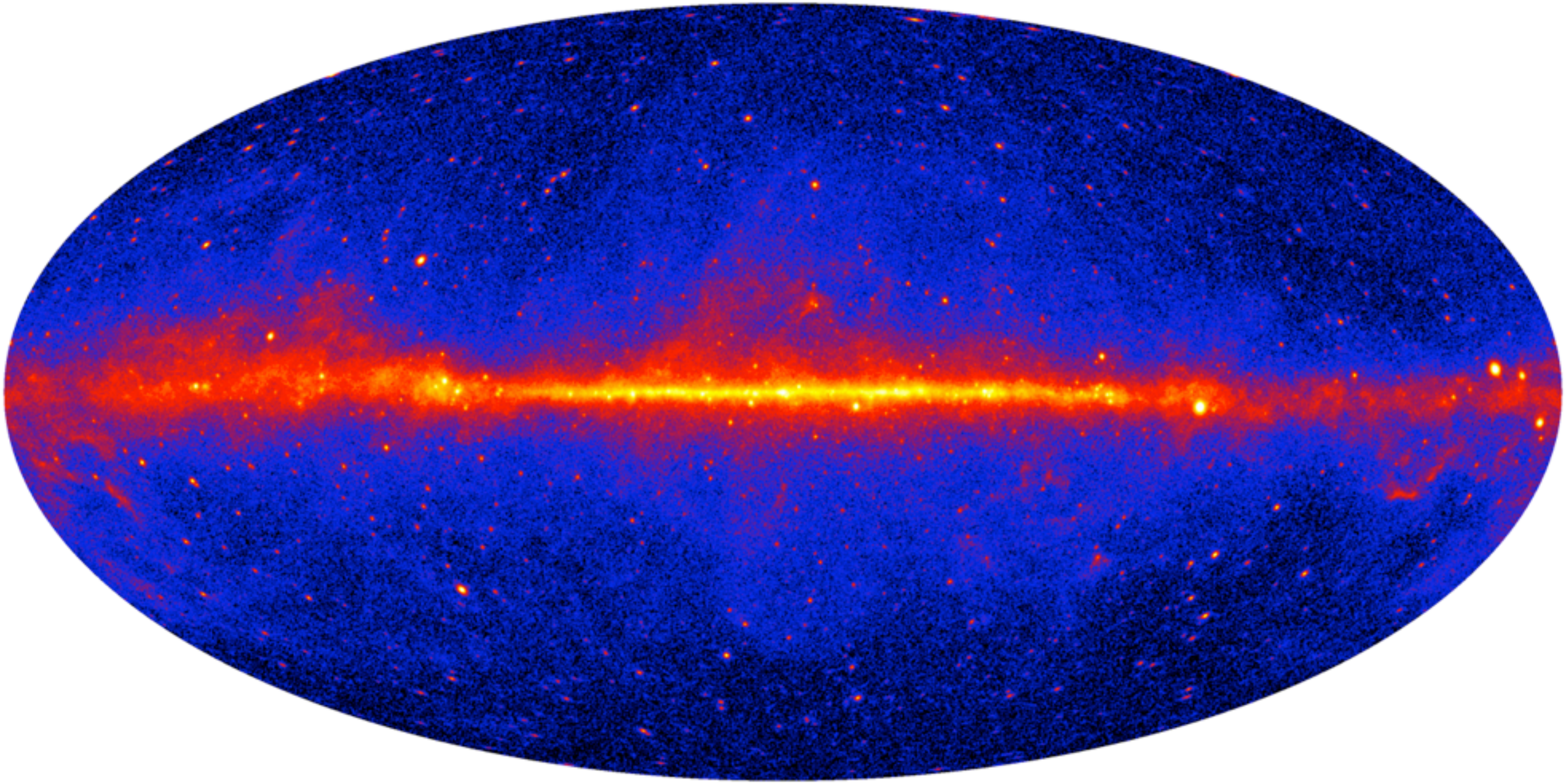
$$10^{-13}\,\mathrm{J\,m^{-3}} \times 10^{62}\,\mathrm{m^3} \times \frac{1}{10^8\,\mathrm{yr}} \simeq 3 \times 10^{33}\,\mathrm{W}$$

$$\frac{1}{50}\,\frac{\mathrm{SNR}}{\mathrm{yr}} \times 0.1 \times 10^{44}\,\mathrm{J} \simeq 5 \times 10^{33}\,\mathrm{W}$$

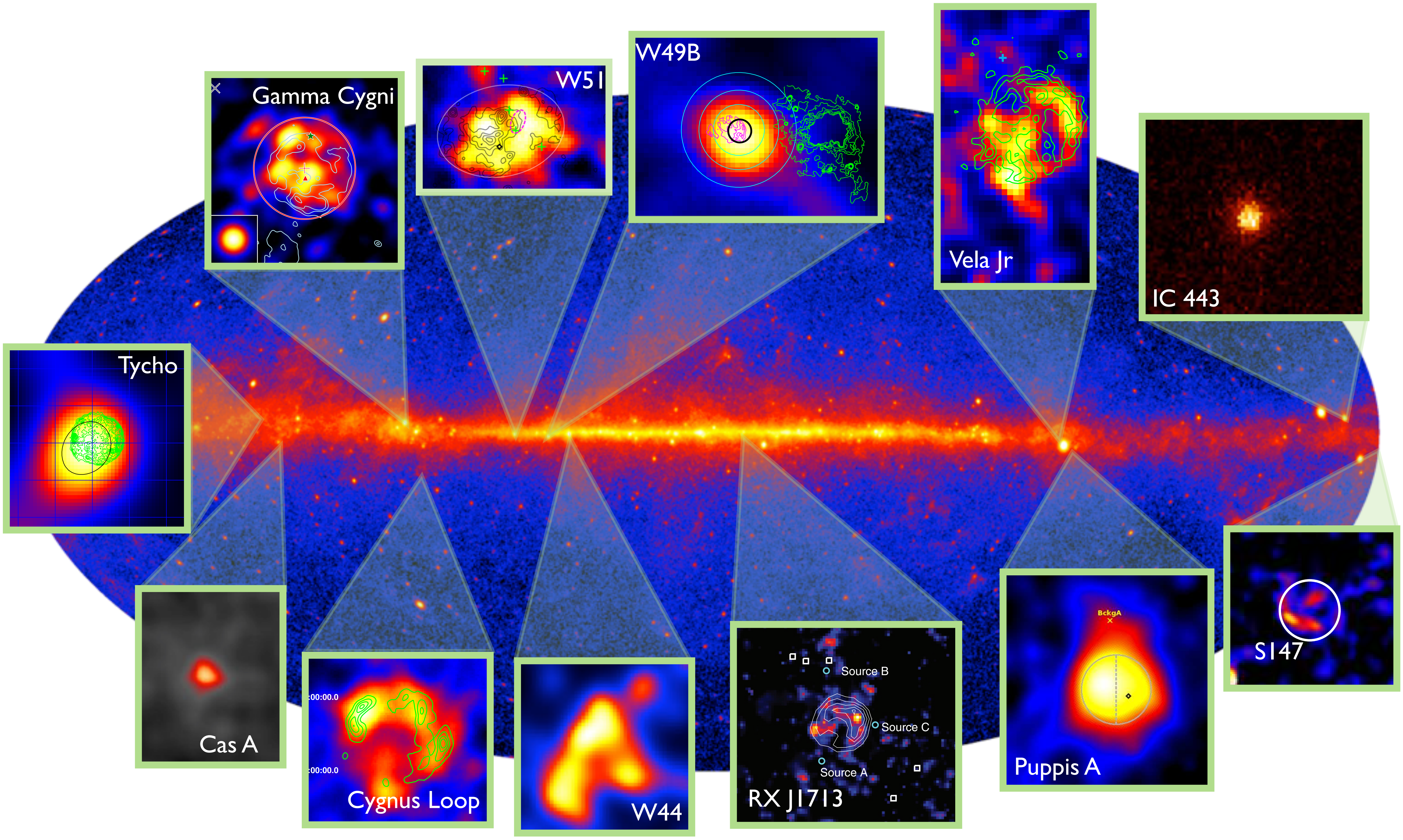


Blasi&Amato 2012

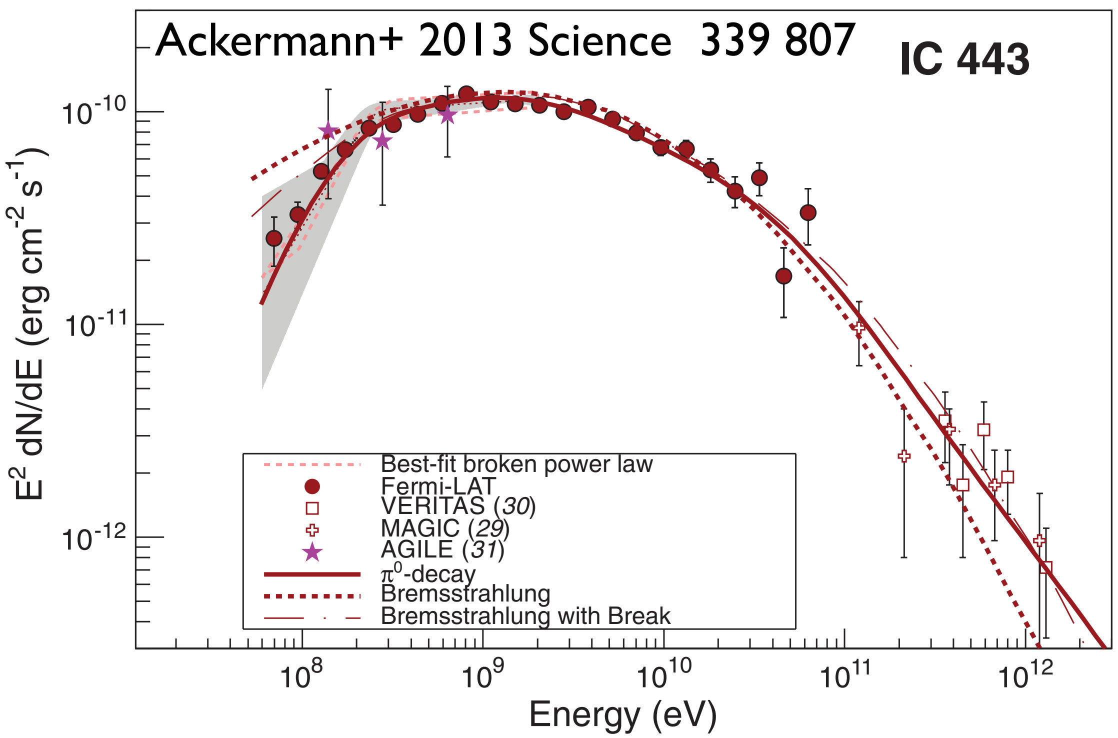
Supernova remnants in the γ-ray sky

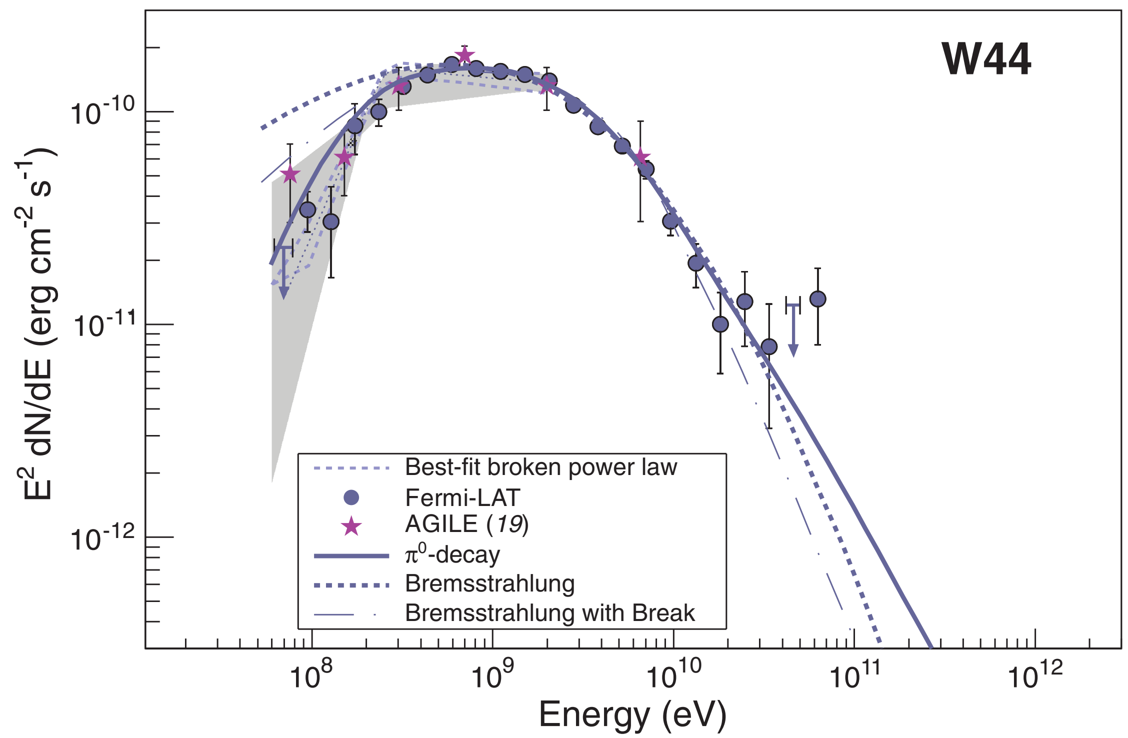


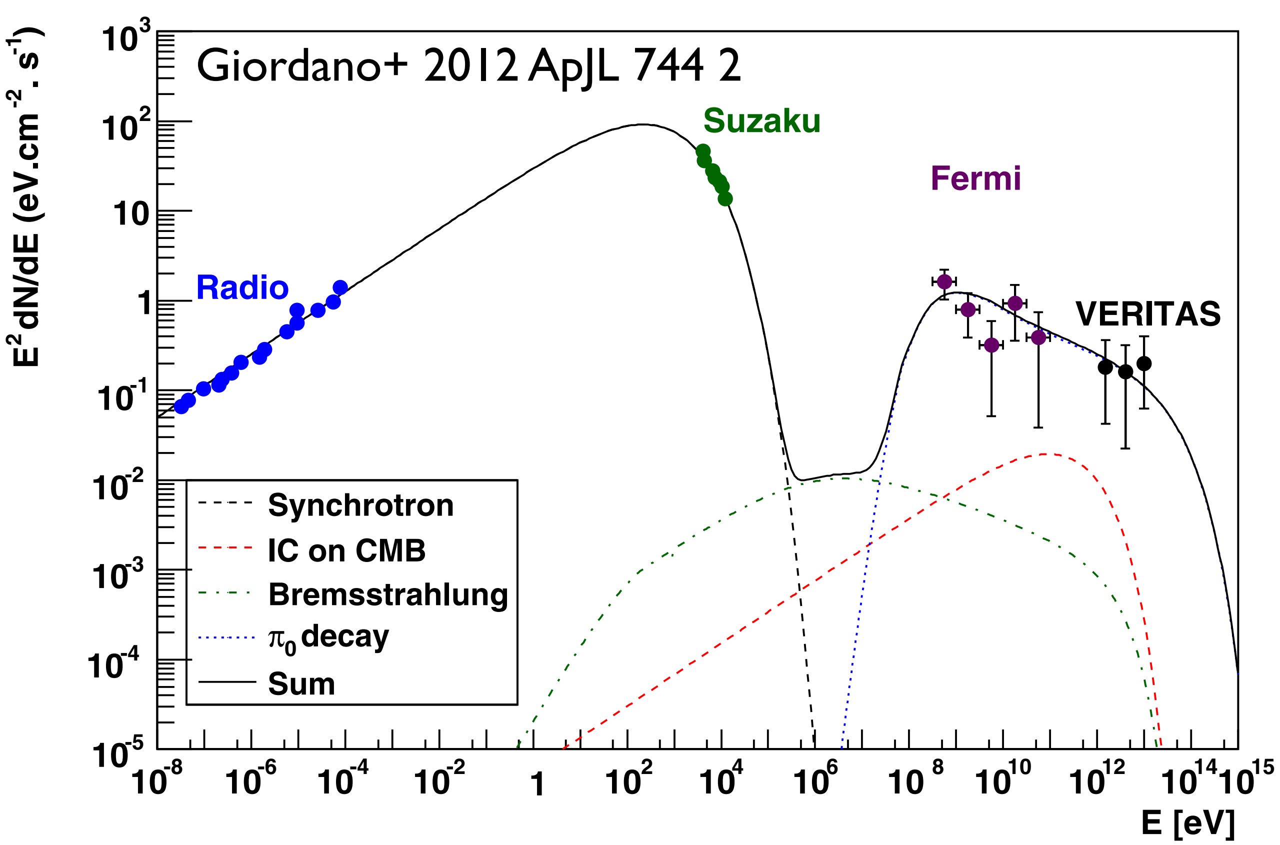
Supernova remnants in the γ-ray sky



Accelerated nuclei!



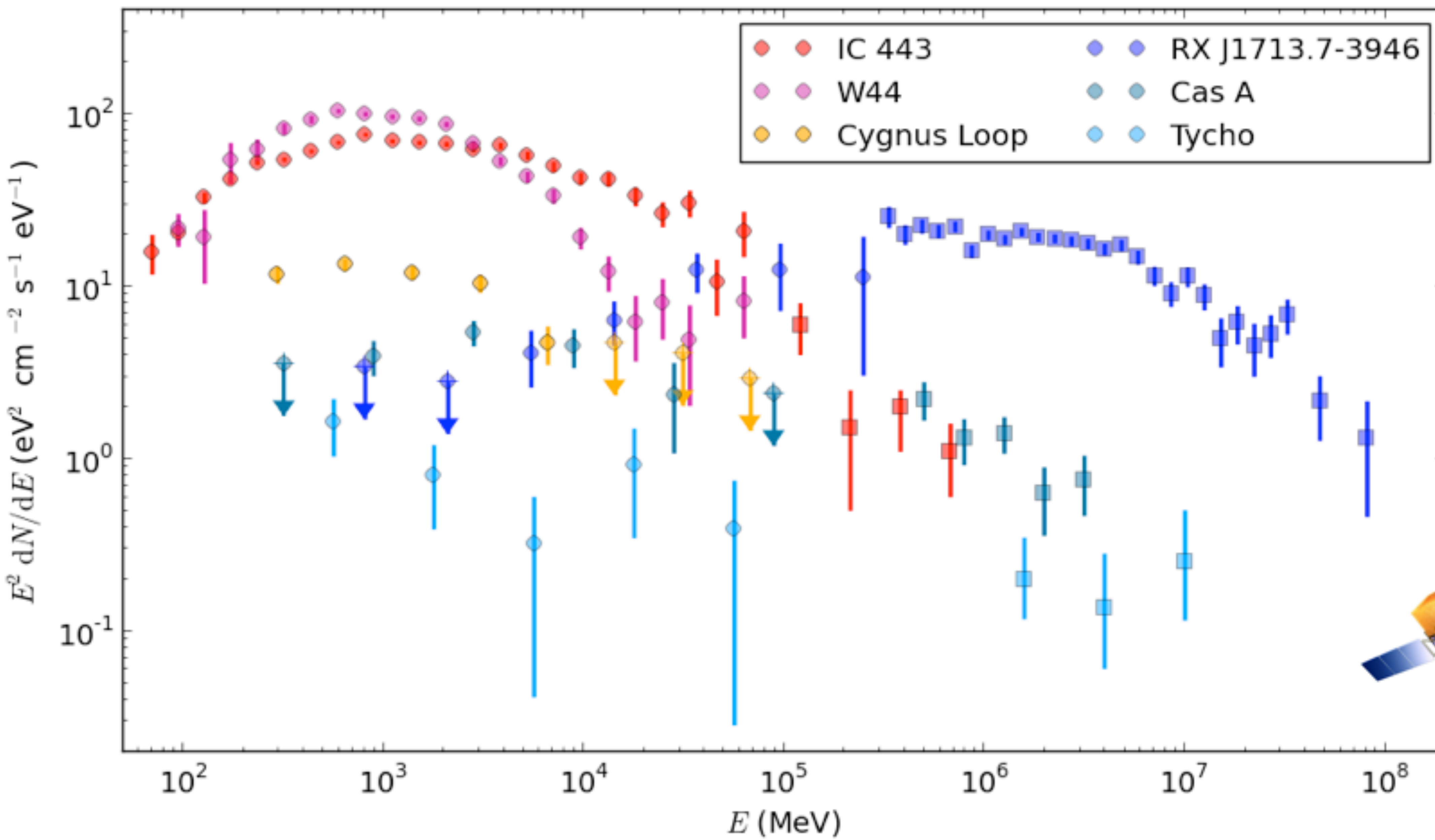




- IC 443 & W44: pion bump (+AGILE)
- Tycho: accelerated nuclei up to ~500 TeV
  (Morlino&Caprioli 2012)

???

The ages of supernova remnants



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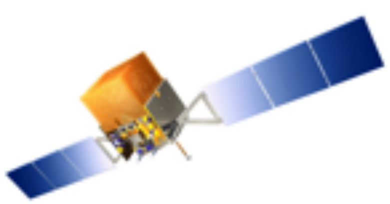
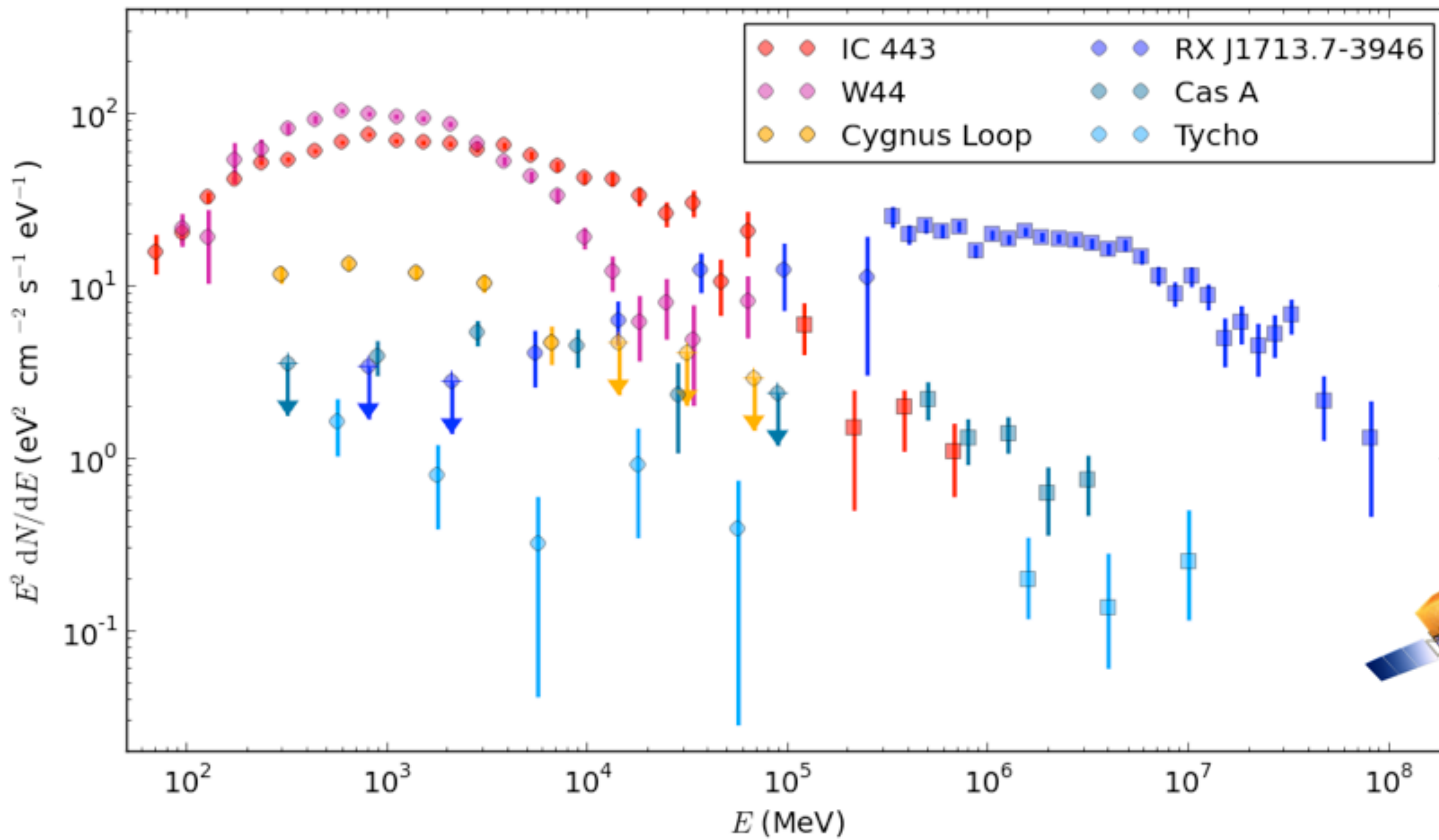


The ages of supernova remnants



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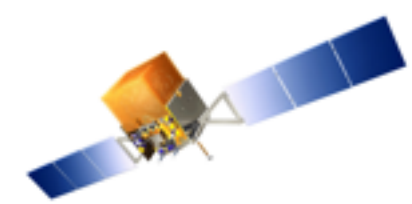
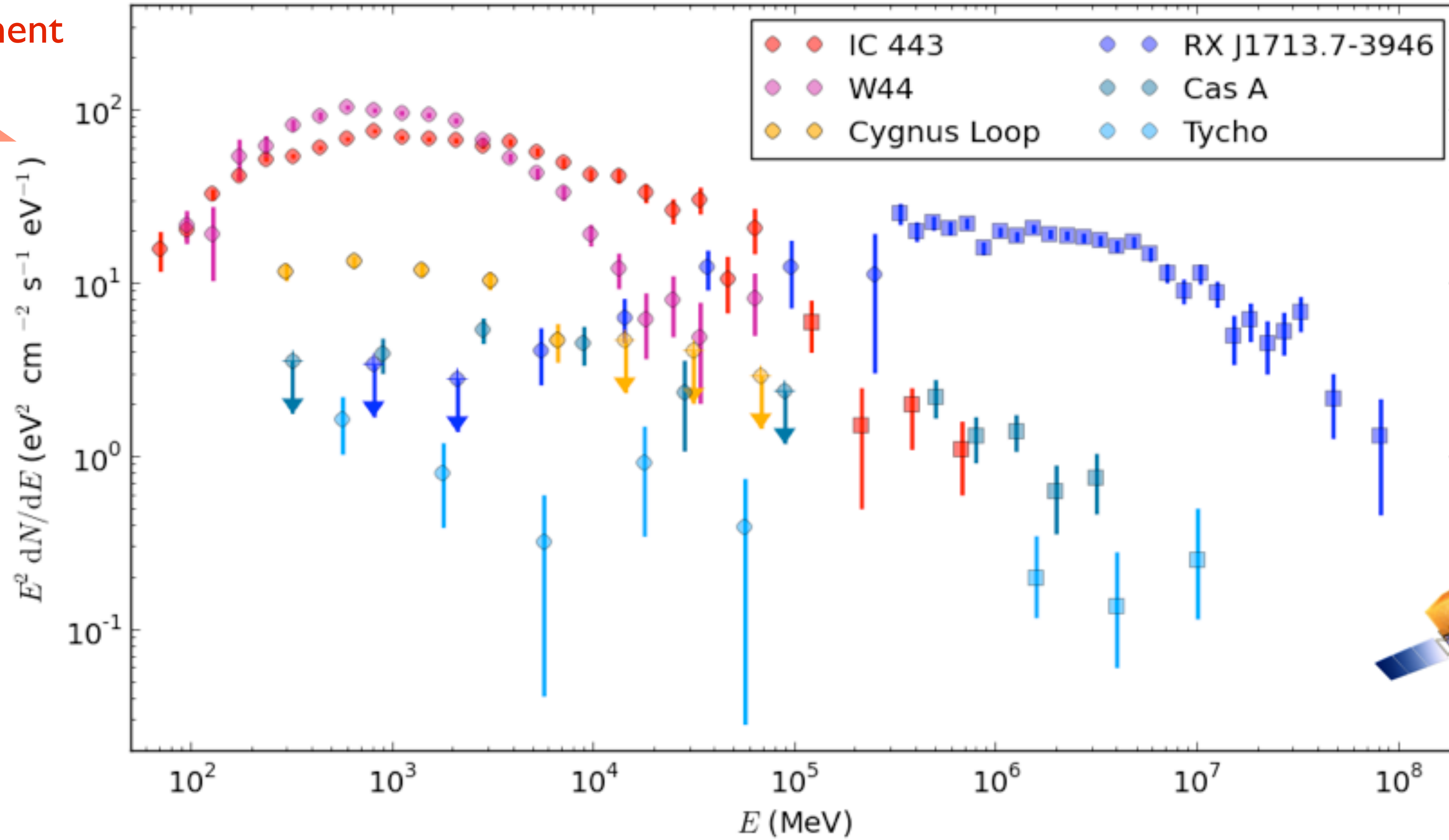


The ages of supernova remnants

denser environment

10^5 cm^{-3}

1 cm^{-3}



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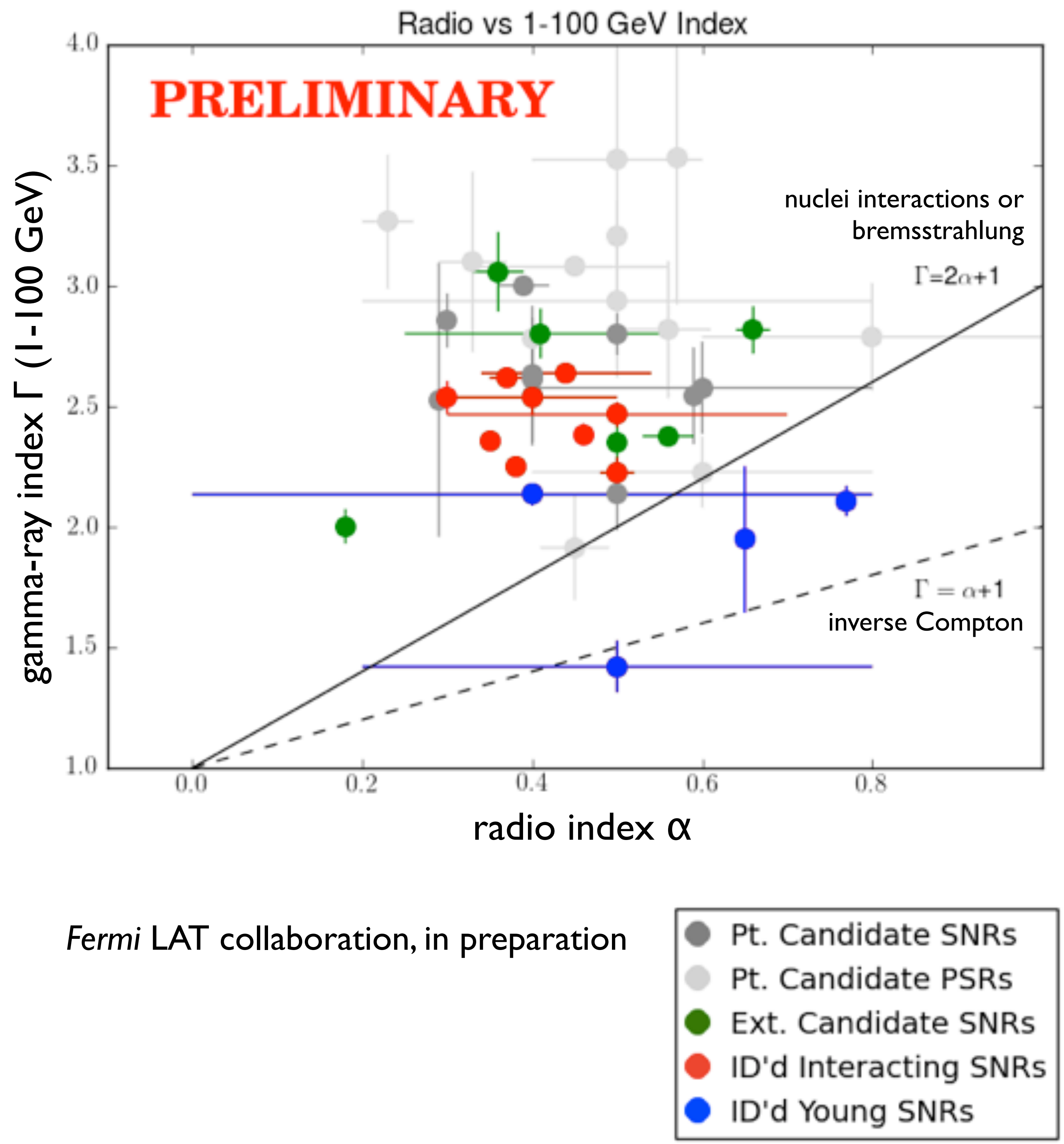
The first LAT SNR Catalog

- systematic/uniform characterization of radio SNRs
- SNRs as a population of CR sources



Fermi LAT collaboration, in preparation

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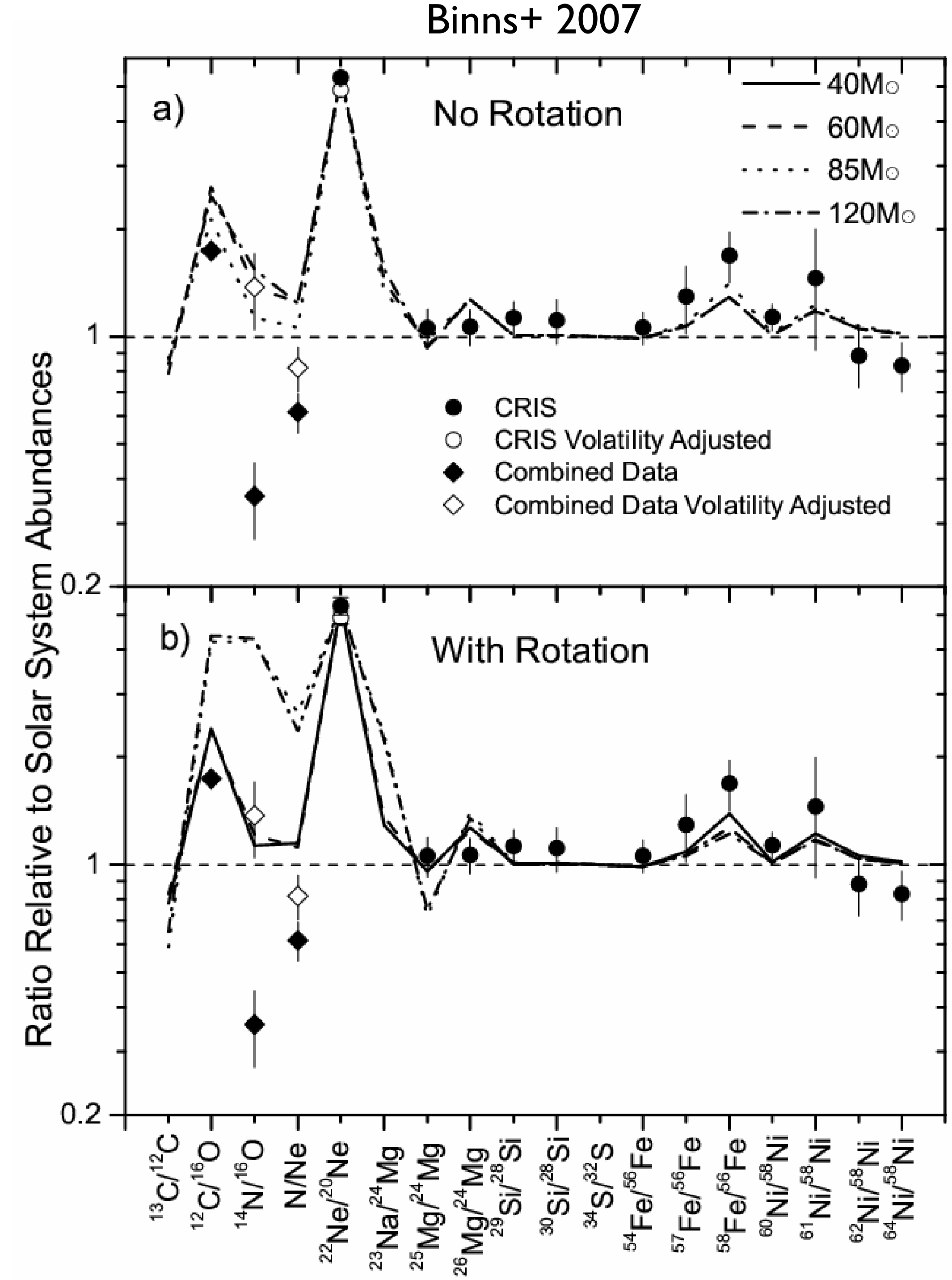
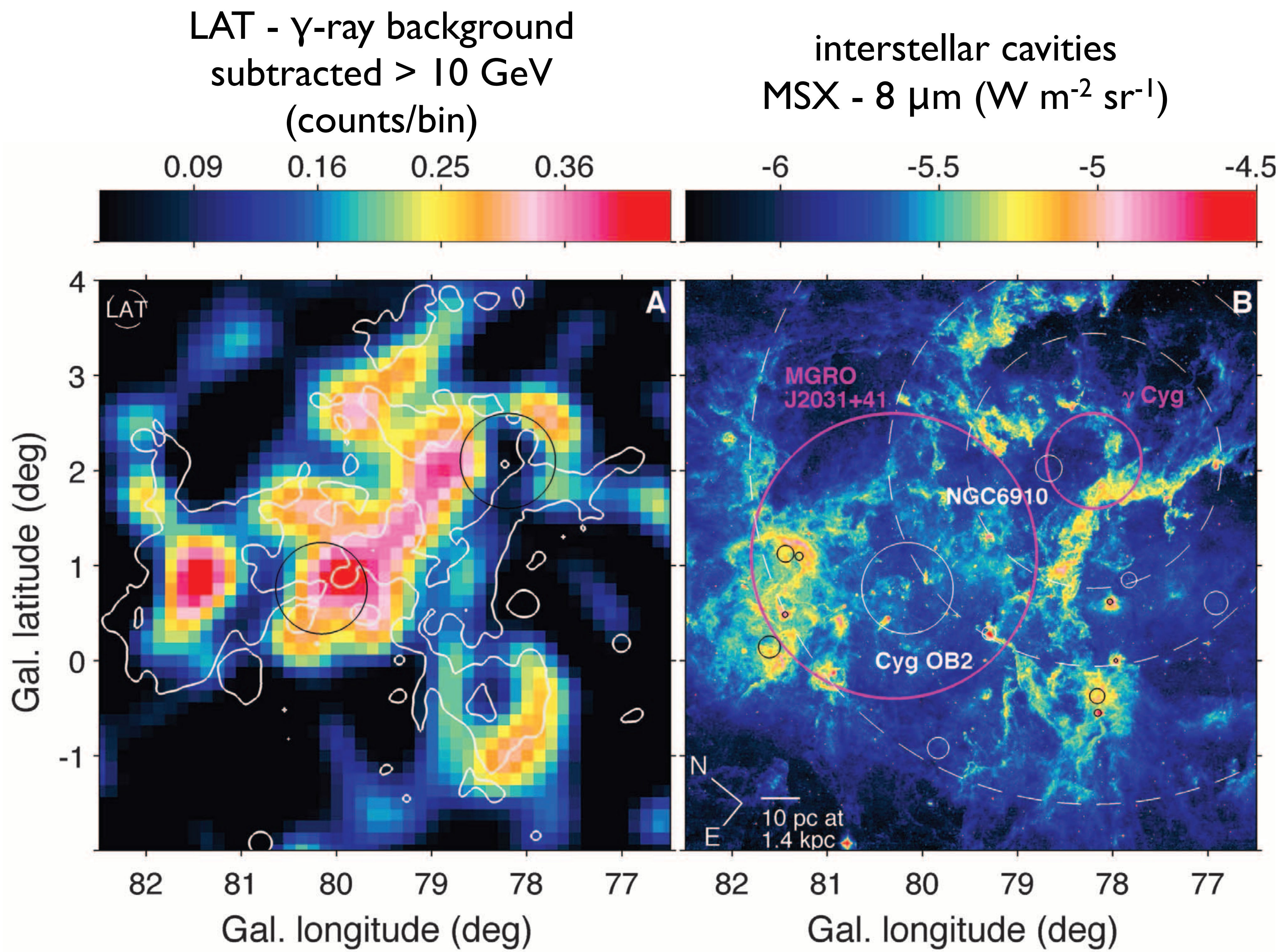
A link with massive-star forming regions?

- isotopic abundances of WR stars (^{22}Ne, > Fe)
- ~80% of supernovae in massive-star clusters
- superbubbles?
- impact of massive-star environment on young CRs?

Binns+ 2007



The *Fermi* LAT view of Cygnus X



Ackermann+ 2011 Science 334 1103

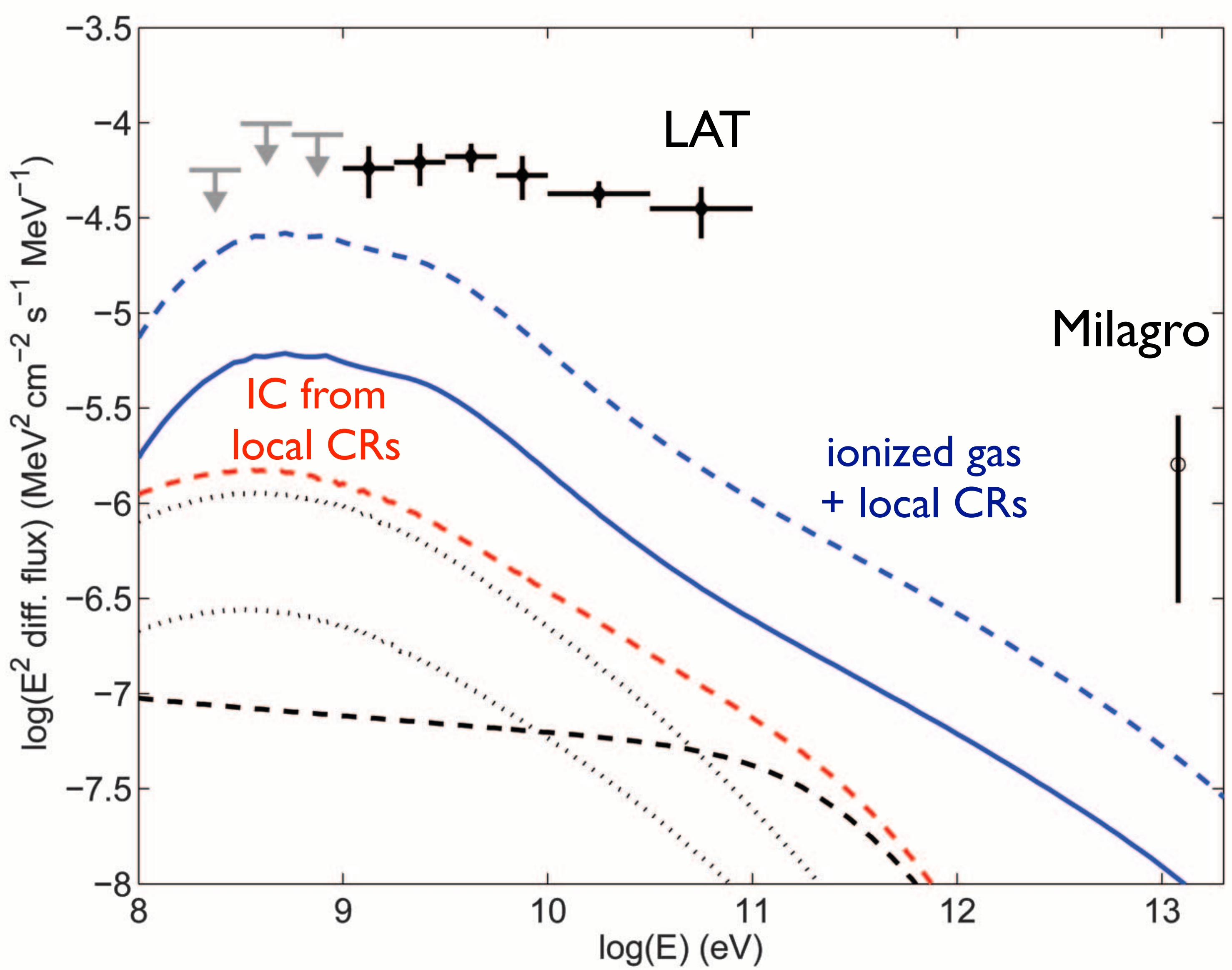
A cocoon of young cosmic rays

- requires **freshly-accelerated CRs**
  - hadronic → too soft

$$\frac{\mathrm{d}N}{\mathrm{d}E} \times (1.5-2)\left(\frac{E}{10\ \mathrm{GeV}}\right)^{0.3}$$

  - leptonic → too soft and faint

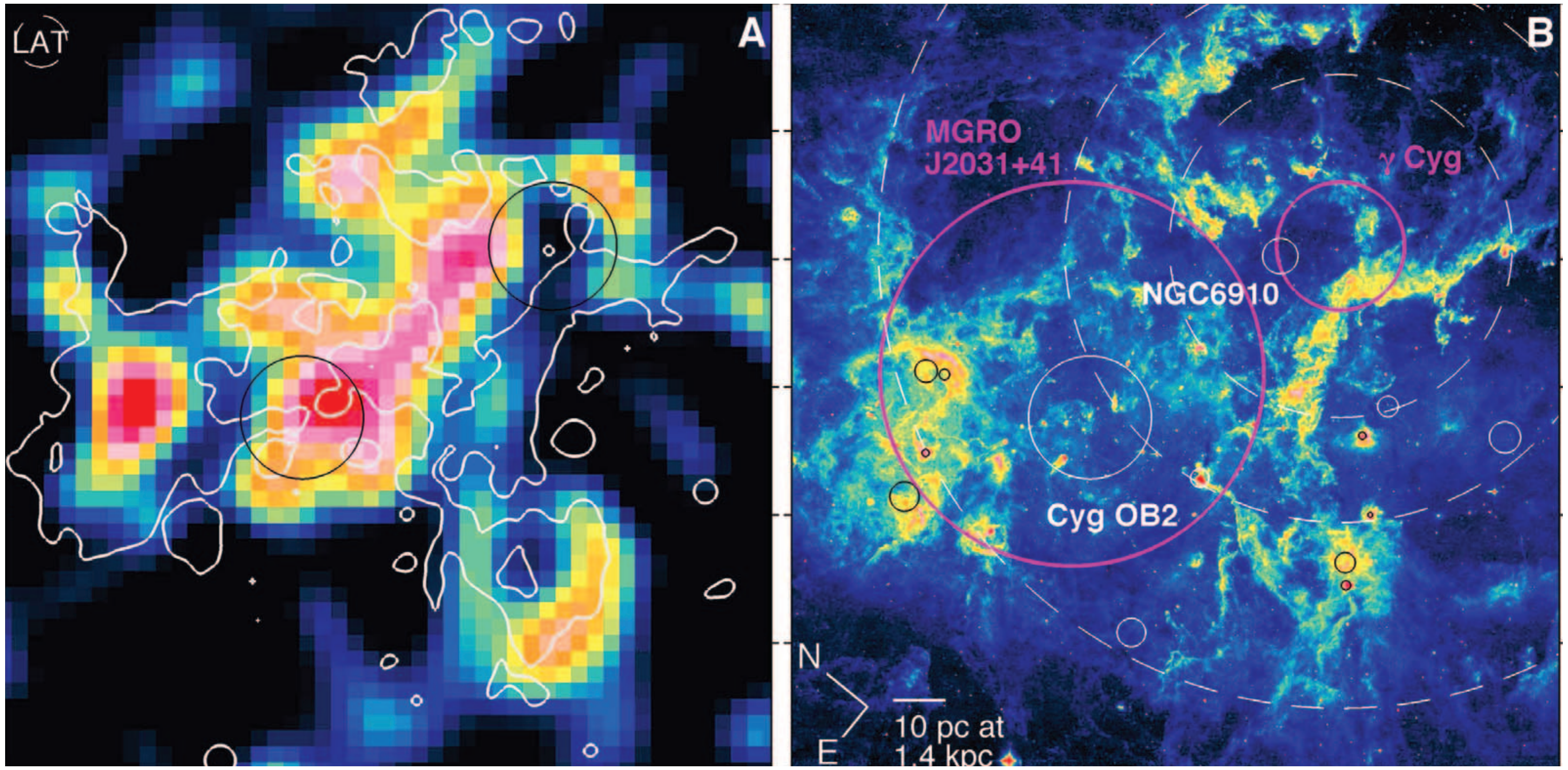
$$\frac{\mathrm{d}N}{\mathrm{d}E} \times 60\left(\frac{E}{10\,\mathrm{GeV}}\right)^{0.5}$$



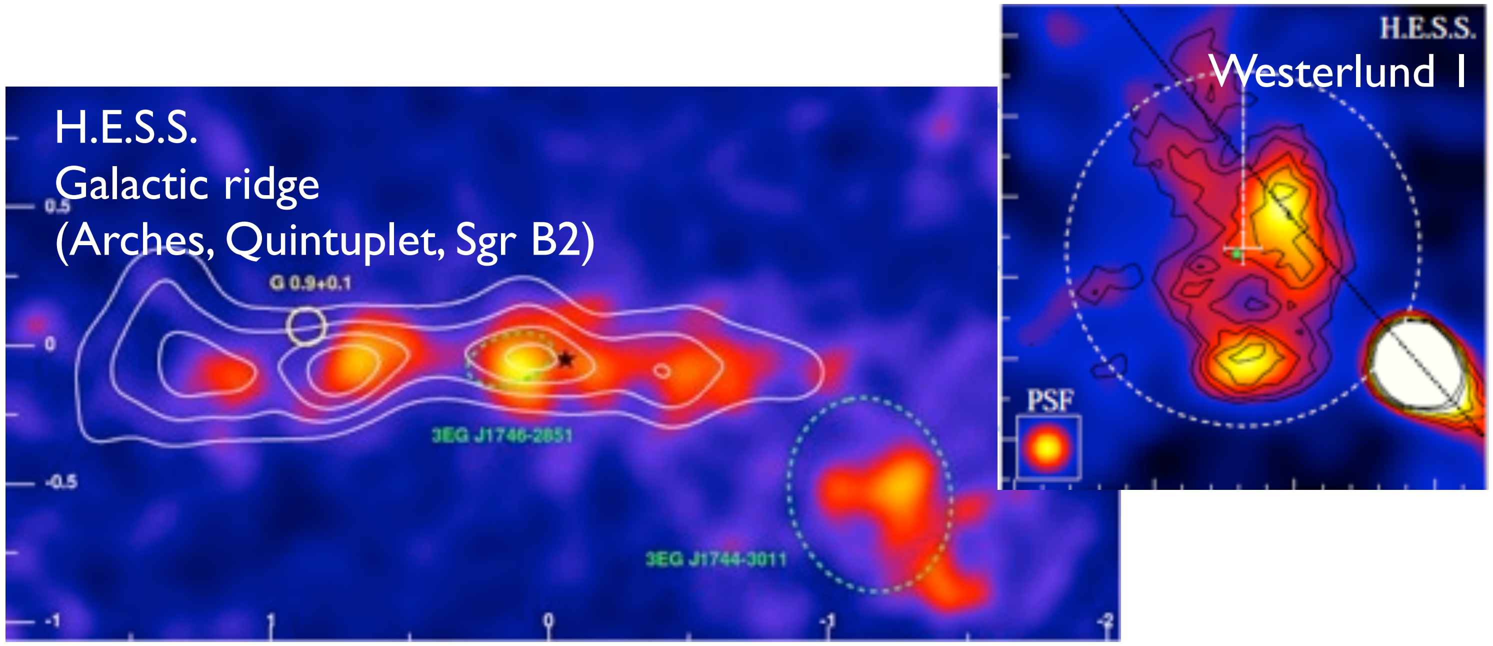
Ackermann+ 2011 Science 334 1103

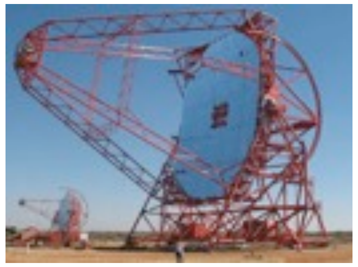
Origin and propagation

- Gamma Cygni supernova remnant?
- stellar-wind superbubble?
- active airlock?



Ackermann+ 2011 Science 334 1103





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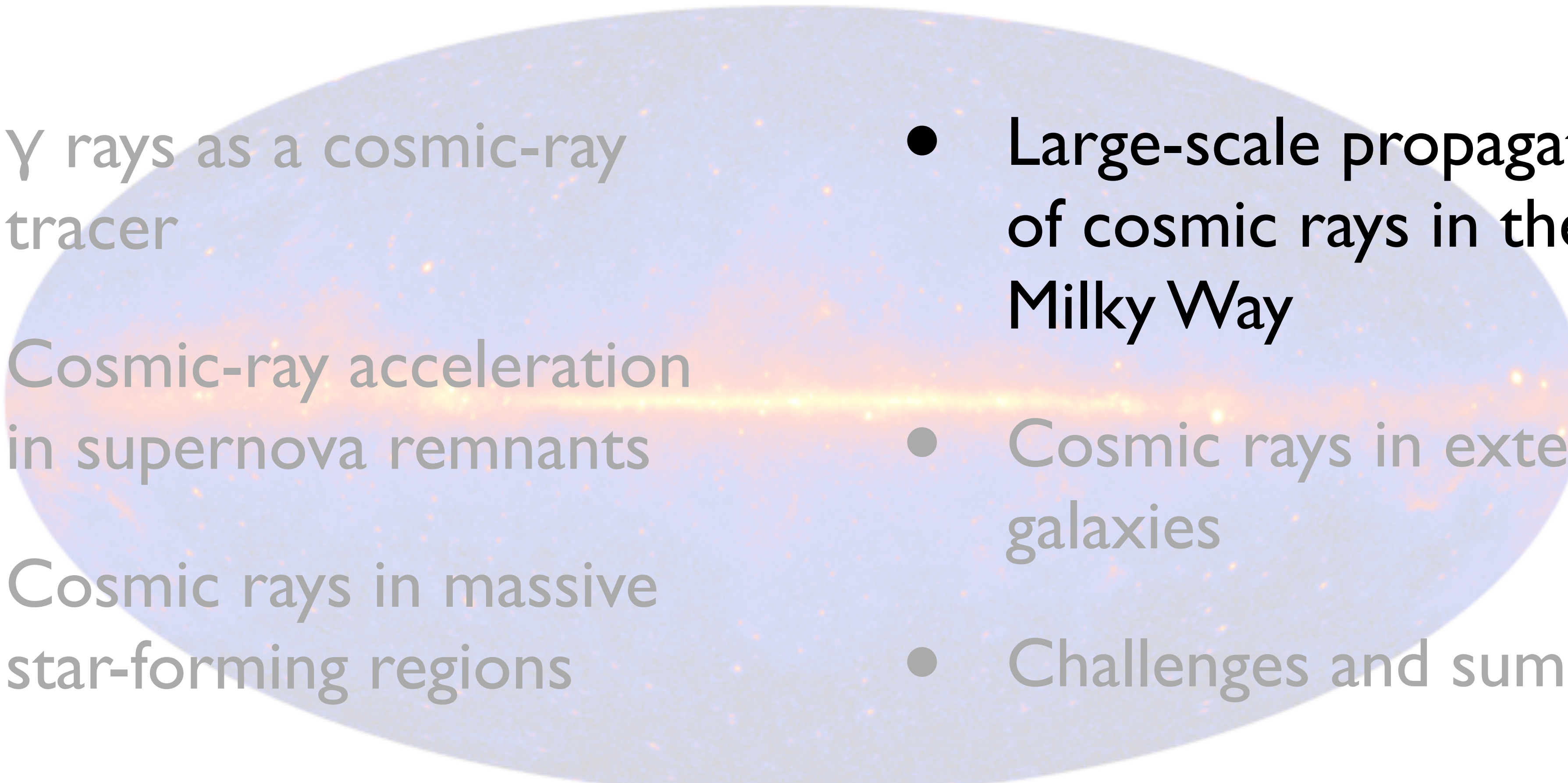

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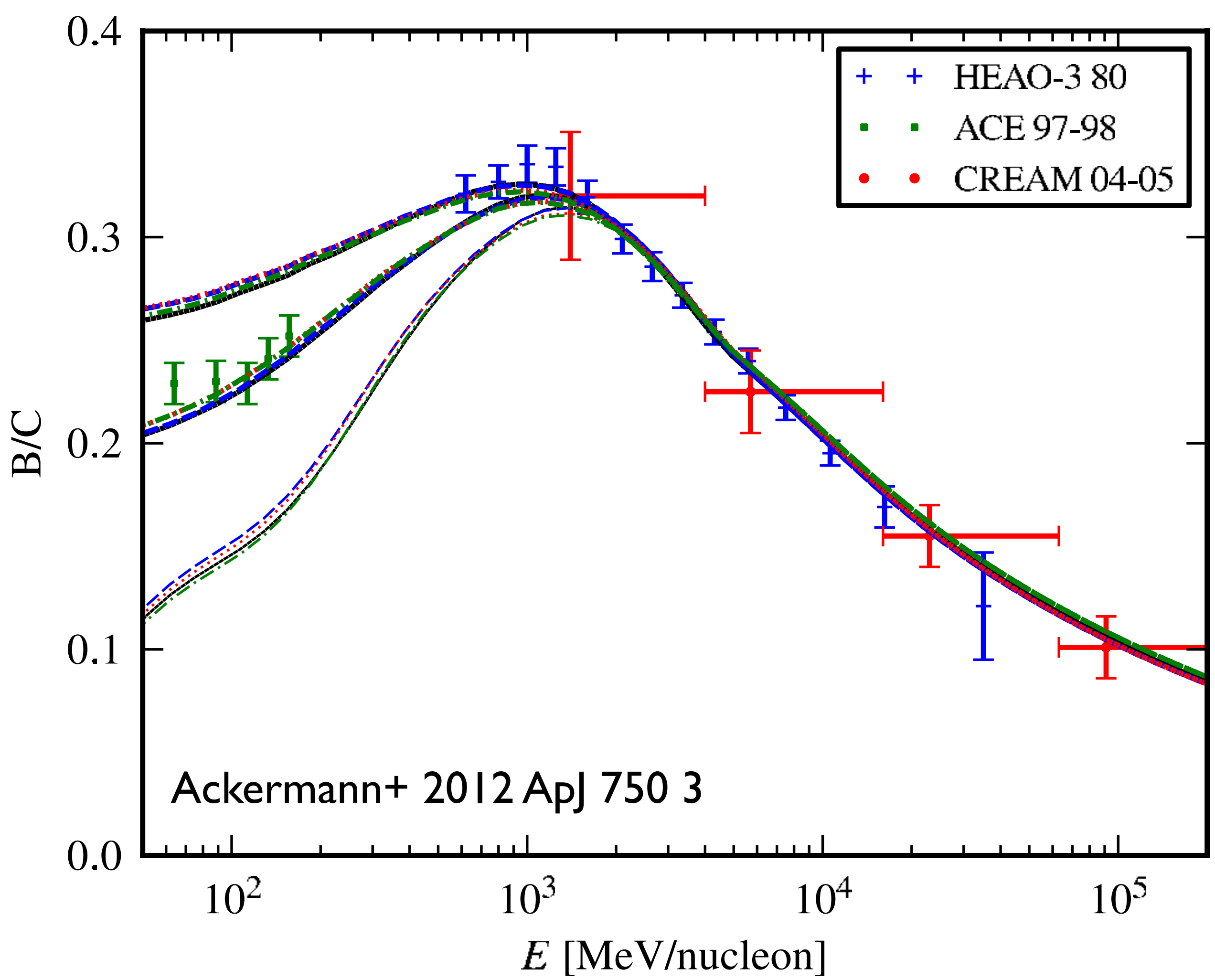
A trip through the Galaxy

- diffusion on magnetic fields

$$D = D_0 \left(\frac{R}{R_0} \right)^{\delta}$$

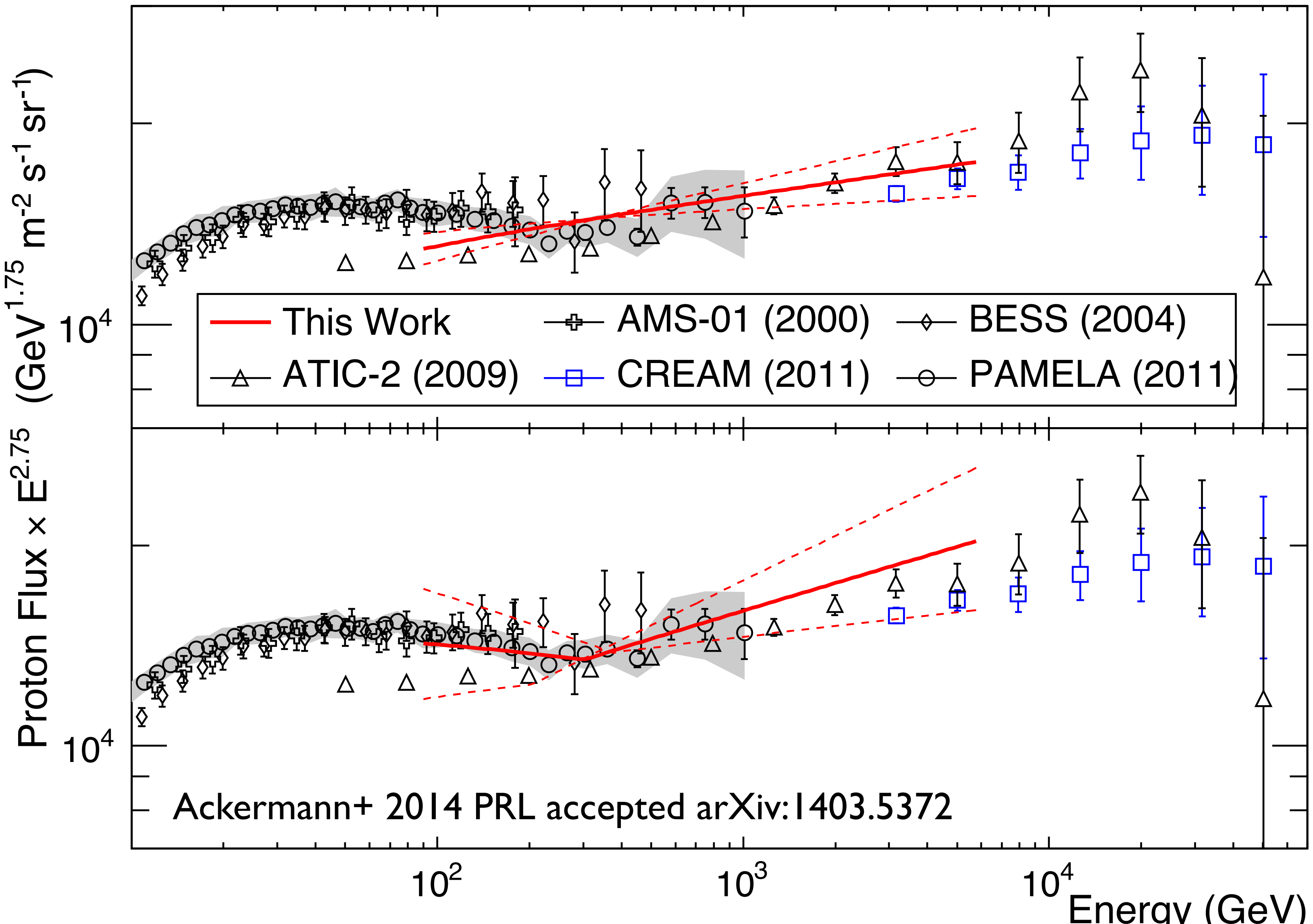
particle rigidity

  - δ = 1/3, 1/2, 0.7?
  - breaks in D and/or CR spectra?
  - size of the propagation halo?
- convection? reacceleration?

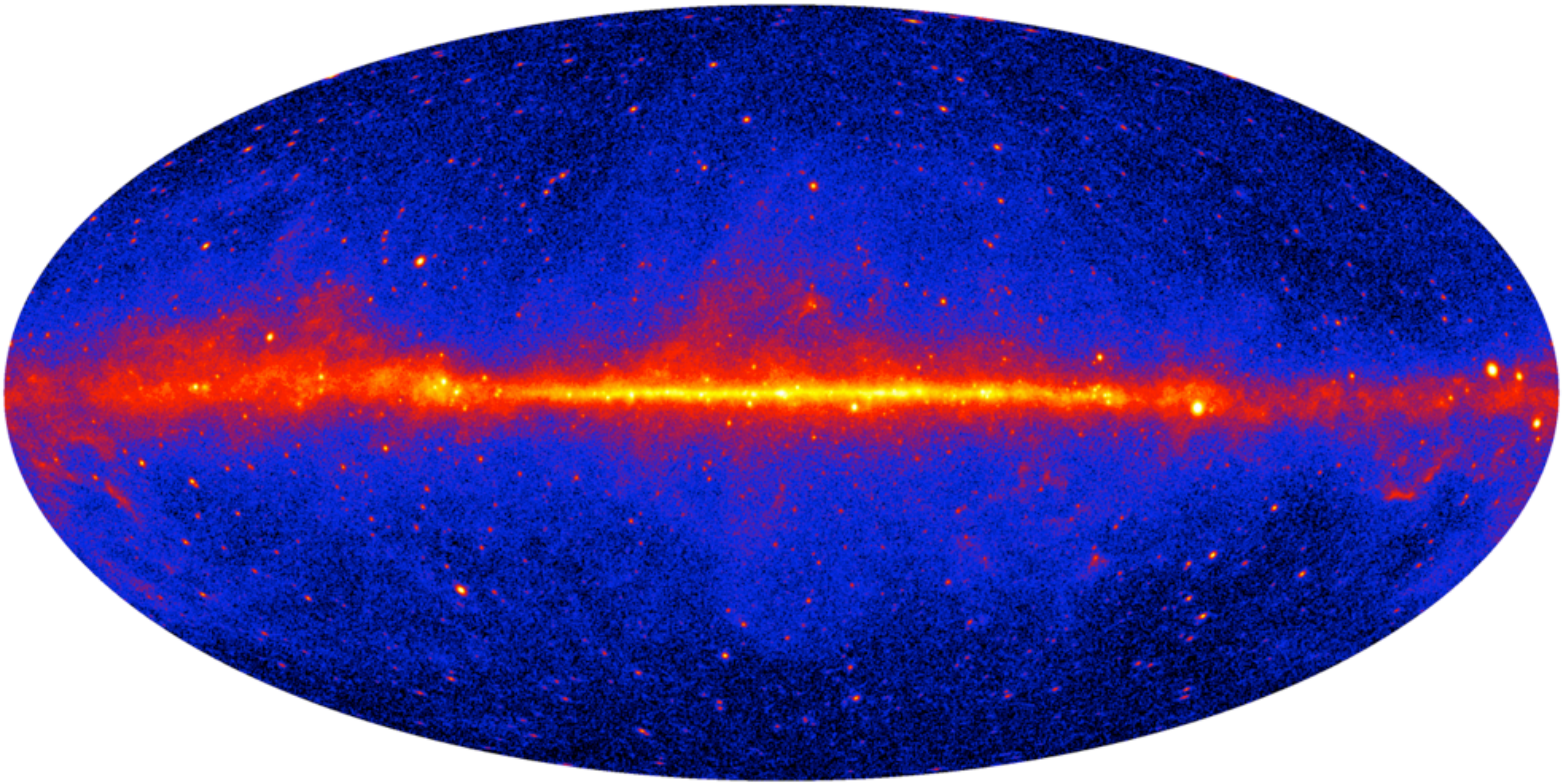


Local CRs from Earth limb emission

- γ rays 15 GeV - 1 TeV → protons ~90 GeV - 6 TeV
- simple power law or broken power law à la PAMELA fit the γ-ray data equally well
- simple power law 3σ harder than Pamela below break

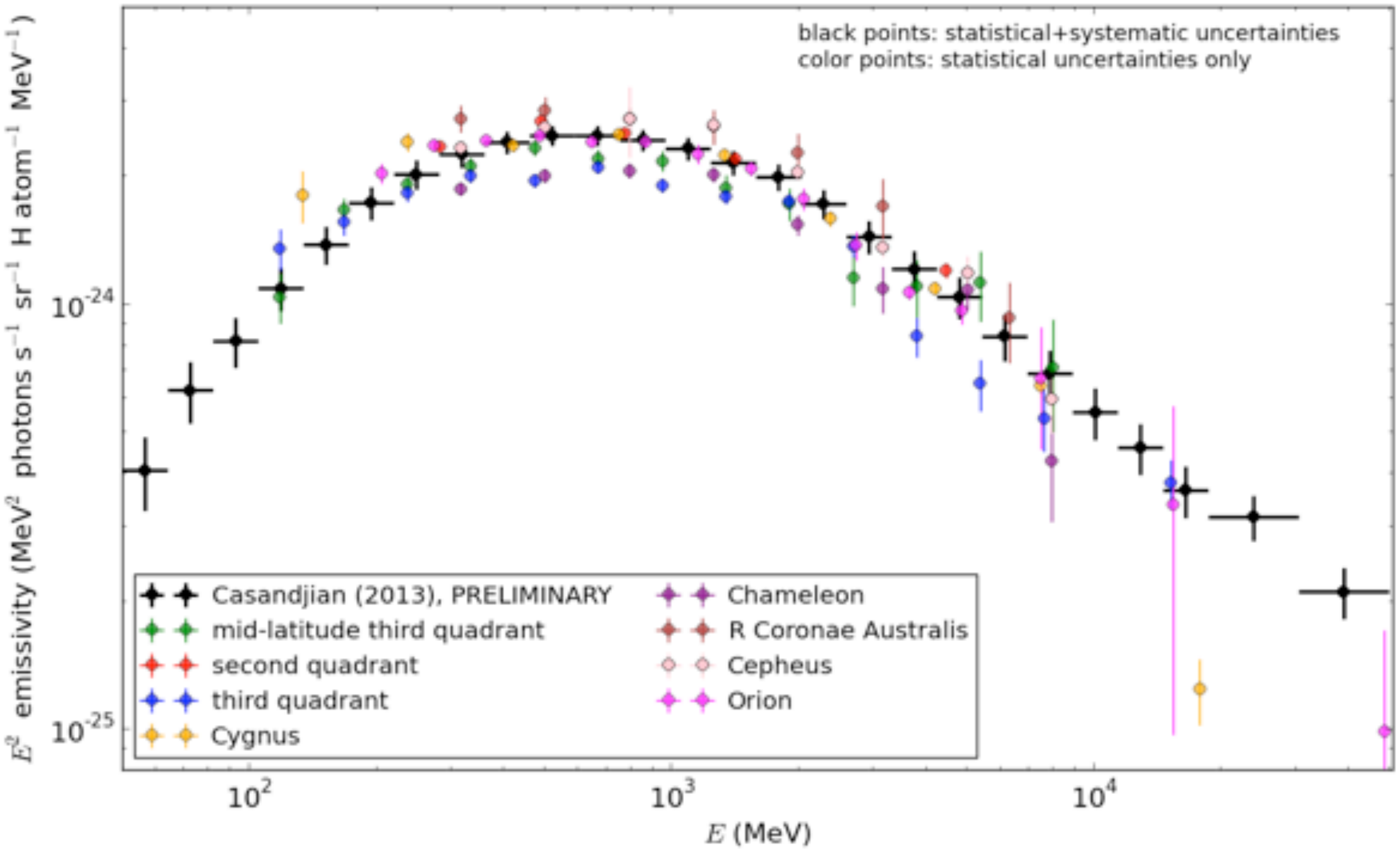


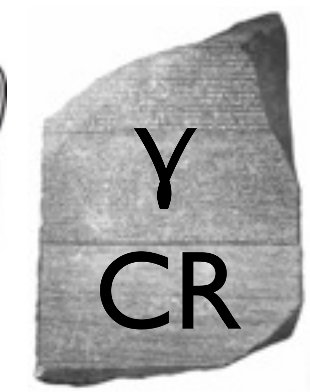
Galactic interstellar emission



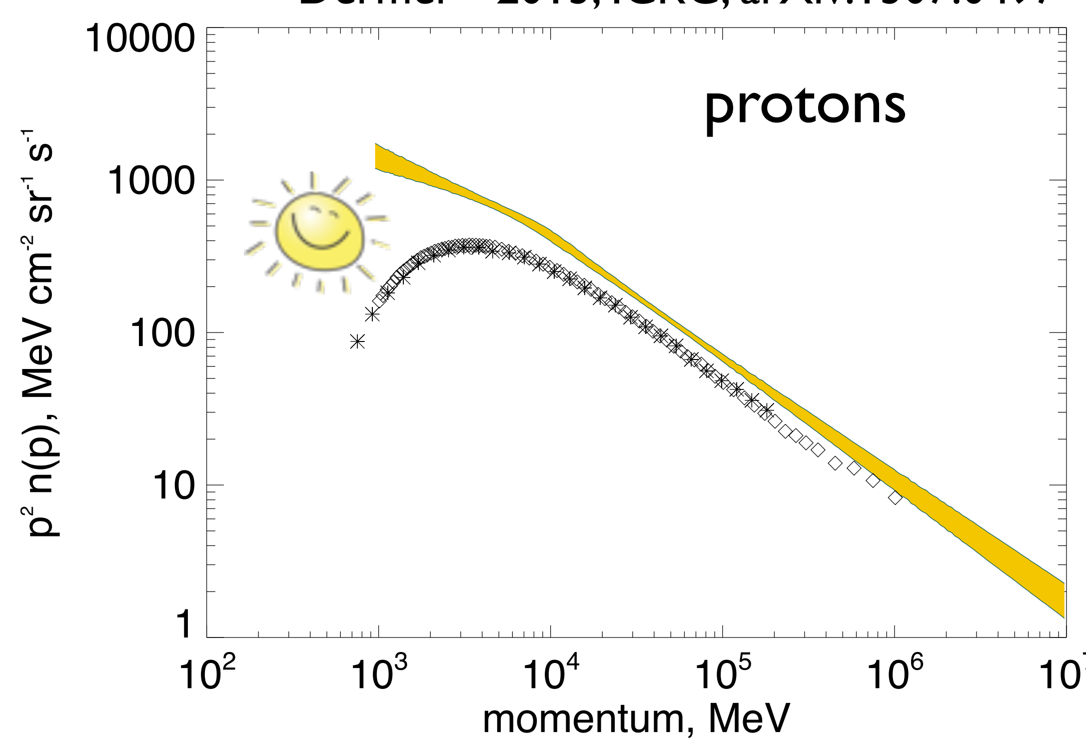
60% of these γ rays are produced by CR interactions in the Milky Way!

The Rosetta stone of interstellar γ rays



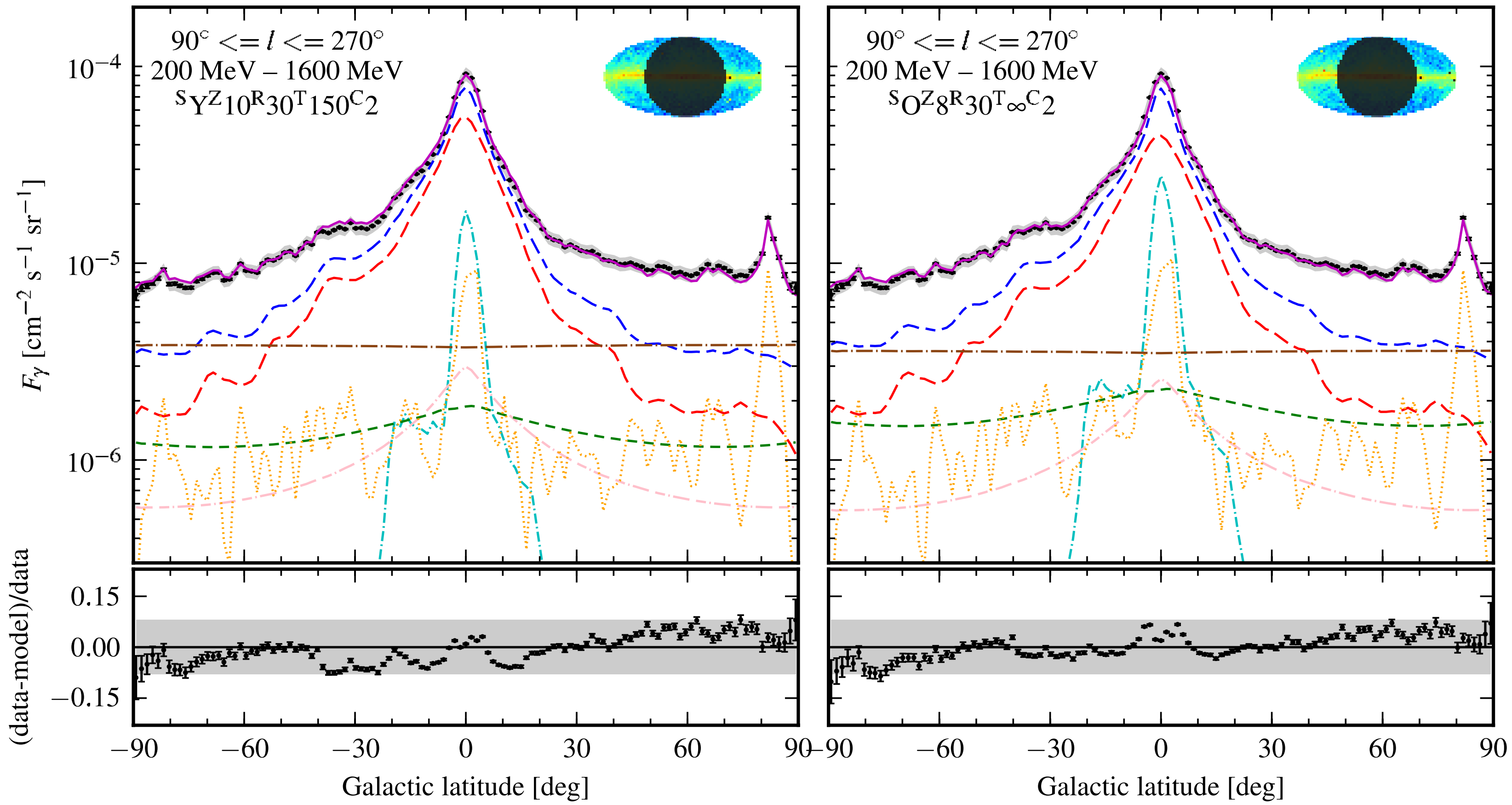


Dermer+ 2013, ICRC, arXiv:1307.0497



- γ-ray emission rate per H atom in the local interstellar medium
  - propagation
  - solar modulation

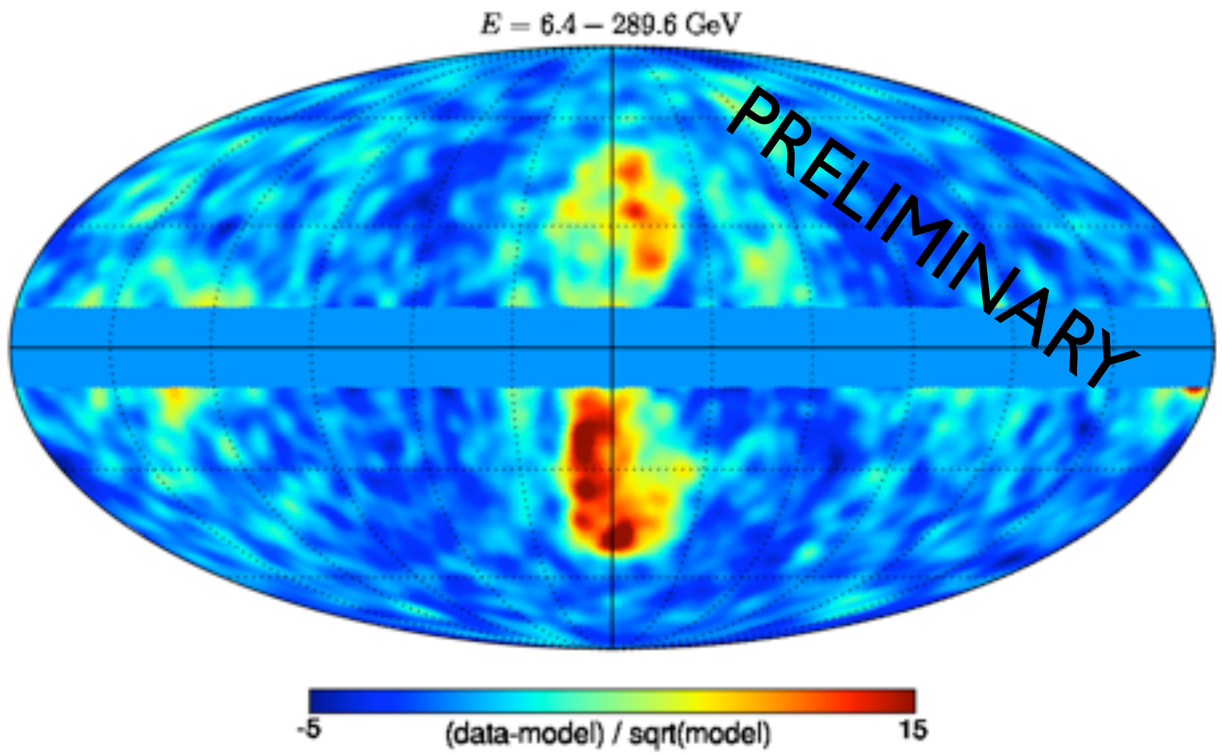
The modeling of large-scale propagation

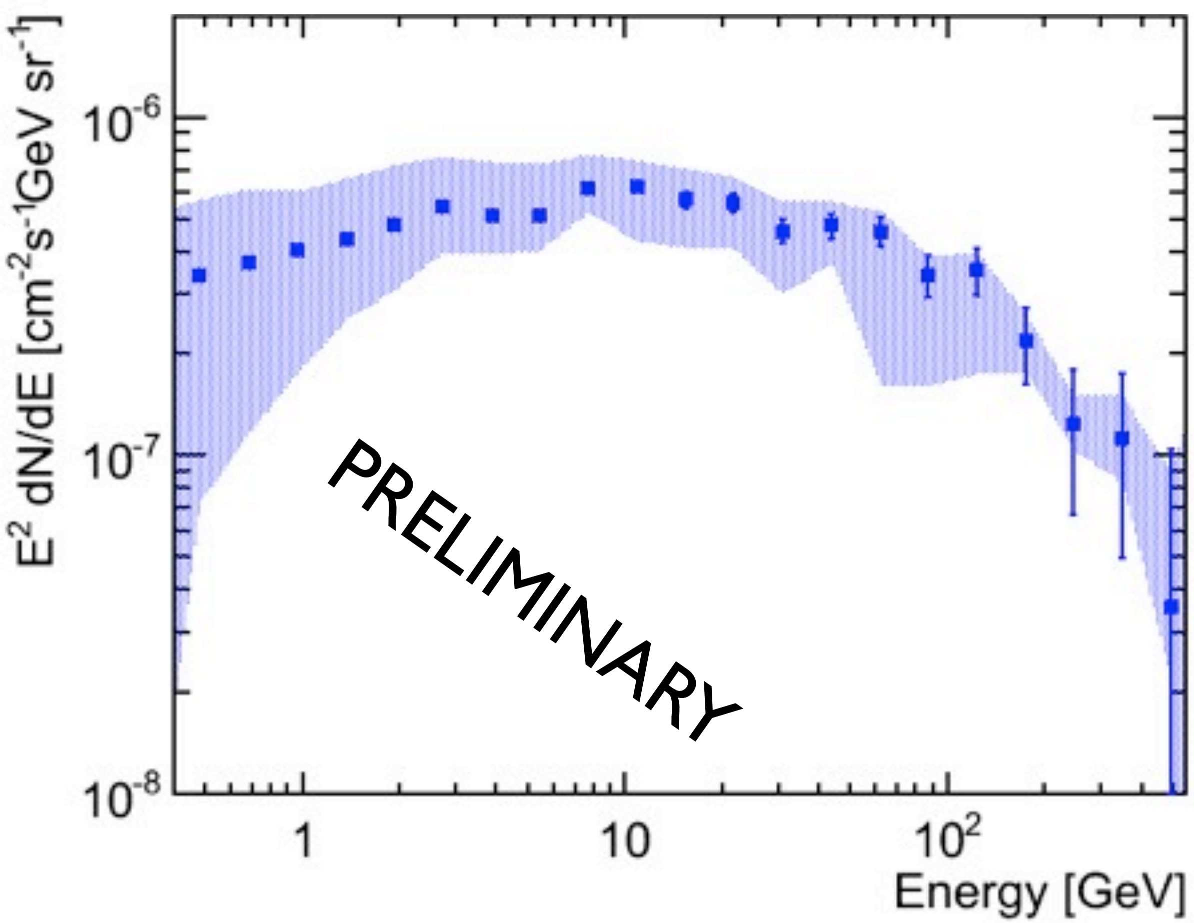


Ackermann+ 2012 ApJ 750 3

- large-scale structures reproduced at ~15%
- degeneracies between sources and propagation
- unmodeled features

The *Fermi* bubbles

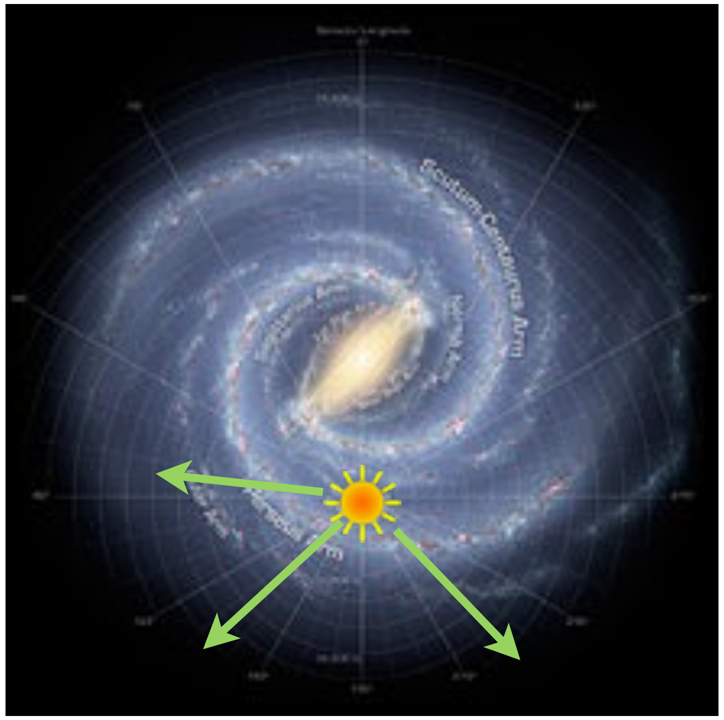




- past activity in/around the Galactic center?
- hard spectrum, softening > 100 GeV
- substructures? jet?
- nuclei or leptons? relationship with WMAP/ Planck haze?

Su+ 2010 ApJ 724 1044
Su+ 2012 ApJ 753 61
Ackermann+ 2014 in preparation

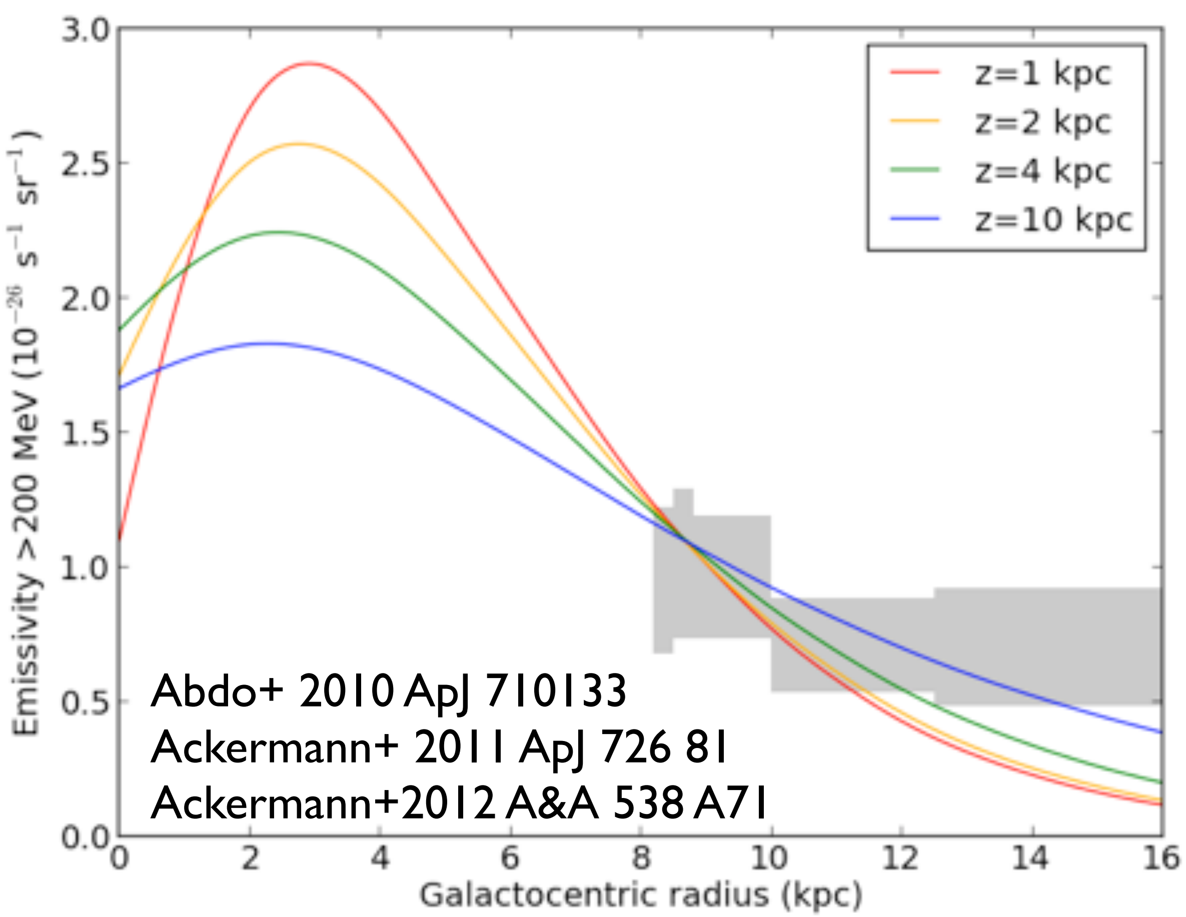
The gradient problem



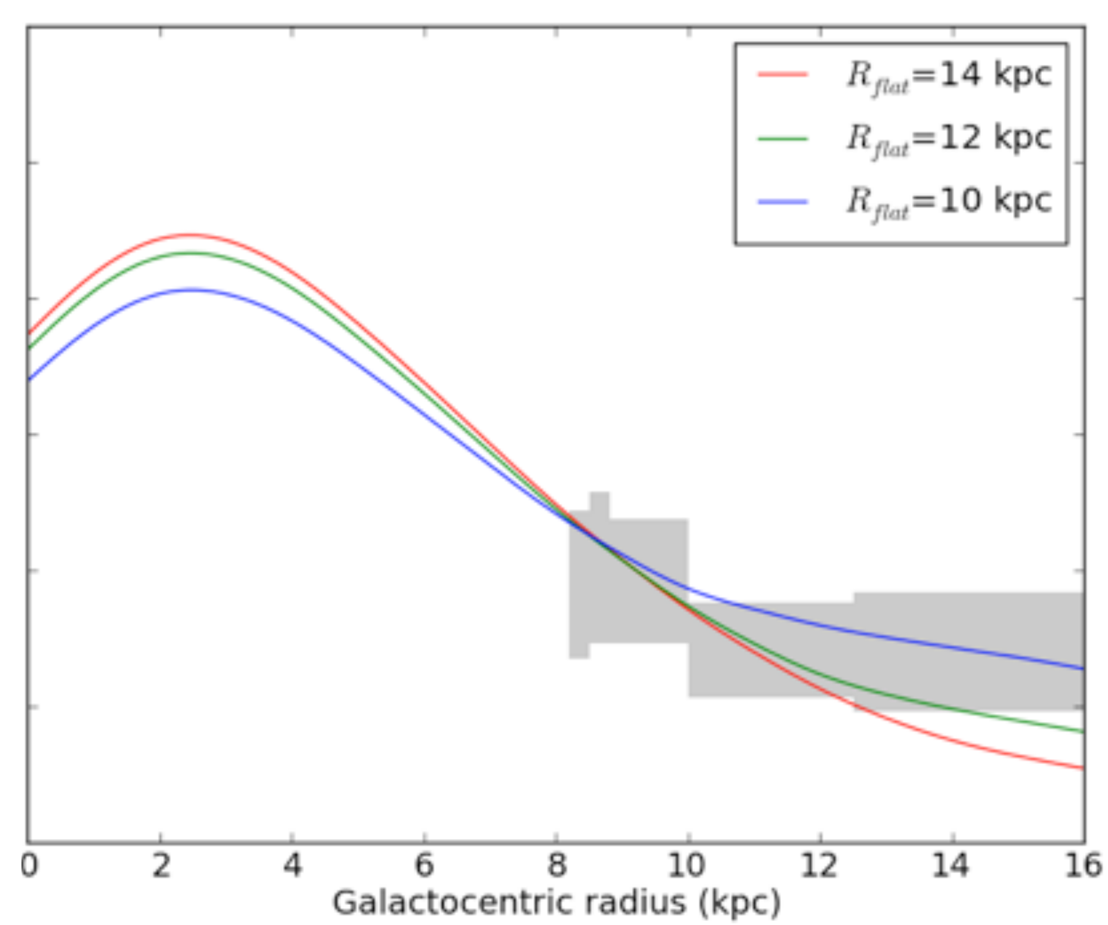
CR densities larger than expected in outer Galaxy

- large propagation halo
- more sources
- missing gas
- varying diffusion coefficient

(e.g. Evoli+ 2012)



Abdo+ 2010 ApJ 710133
Ackermann+ 2011 ApJ 726 81
Ackermann+2012 A&A 538 A71



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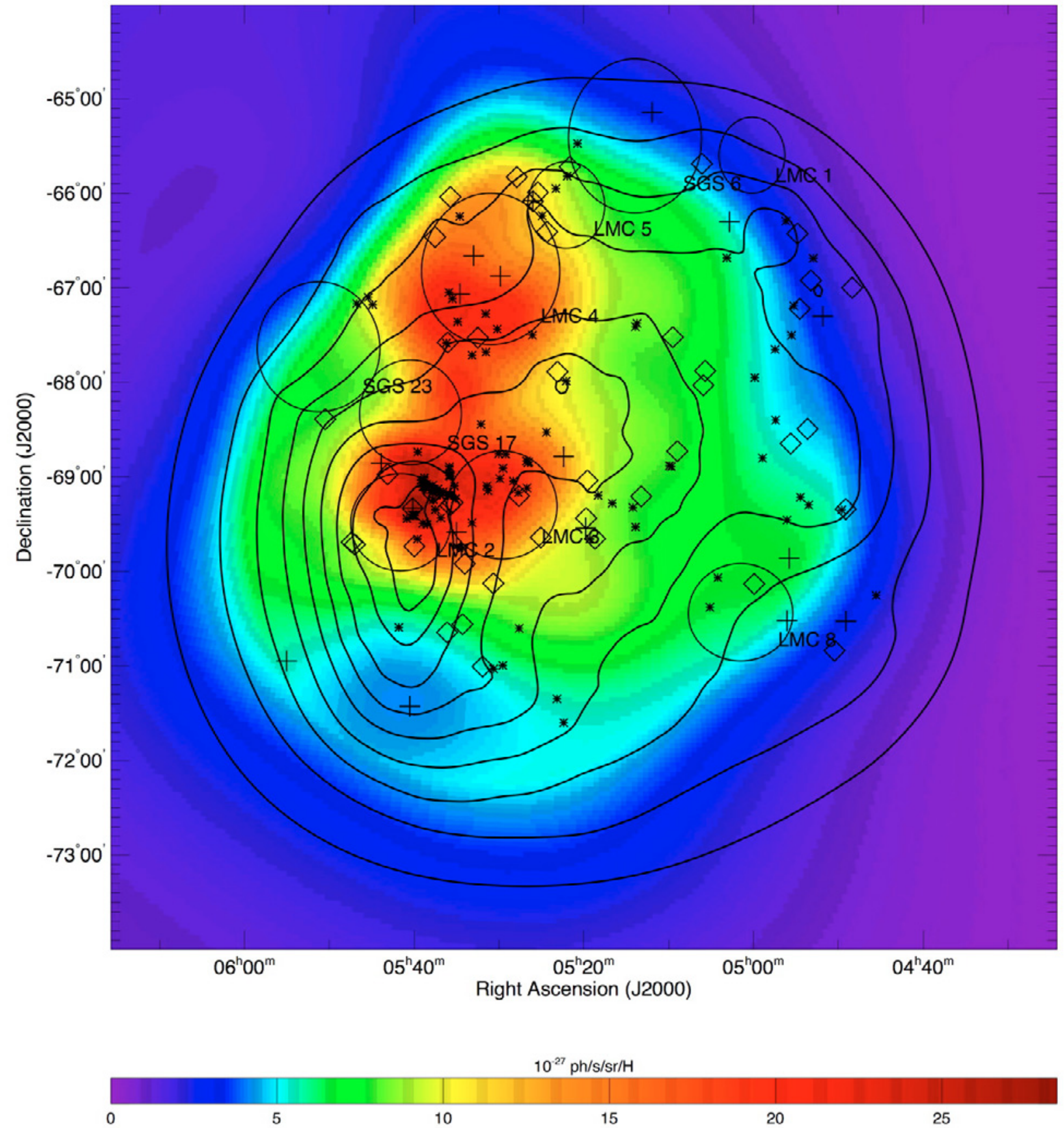
Probing cosmic rays in external galaxies

- EGRET: CRs < 10^{15} eV are Galactic in origin
- *Fermi* images CR propagation in nearby galaxies

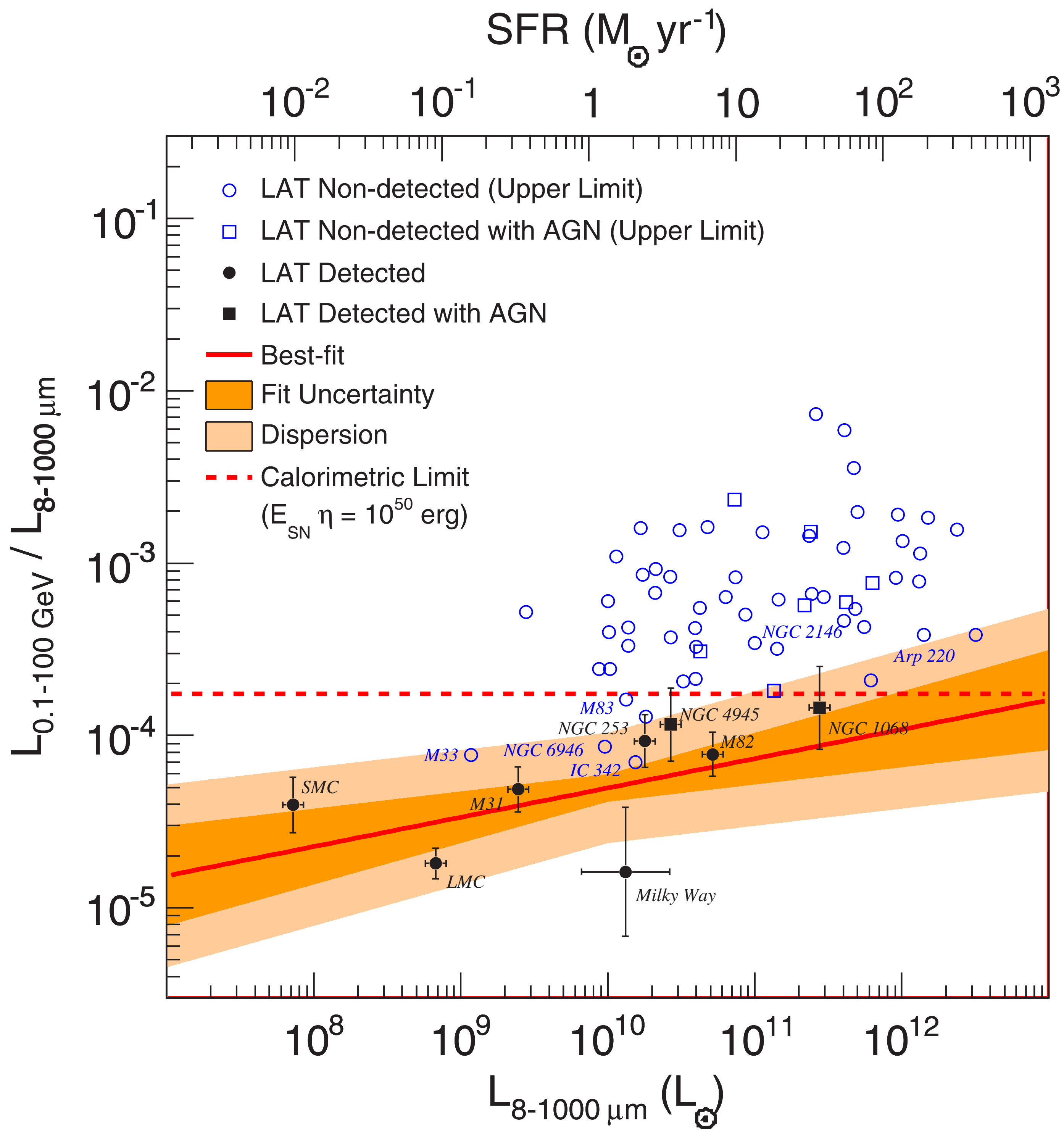


Large Magellanic Cloud:
γ-ray emissivity map
(Abdo+ 2010 A&A 512 A7
Murphy+ 2012 ApJ 750 126)

The star formation rate-γ correlation

Ackermann+ 2012 ApJ 755 164

- quasi-linear scaling γ luminosity with radio/IR
- large fraction of energy in CRs escapes
- starbust galaxies: E-independent CR cooling? interactions overcoming diffusion?



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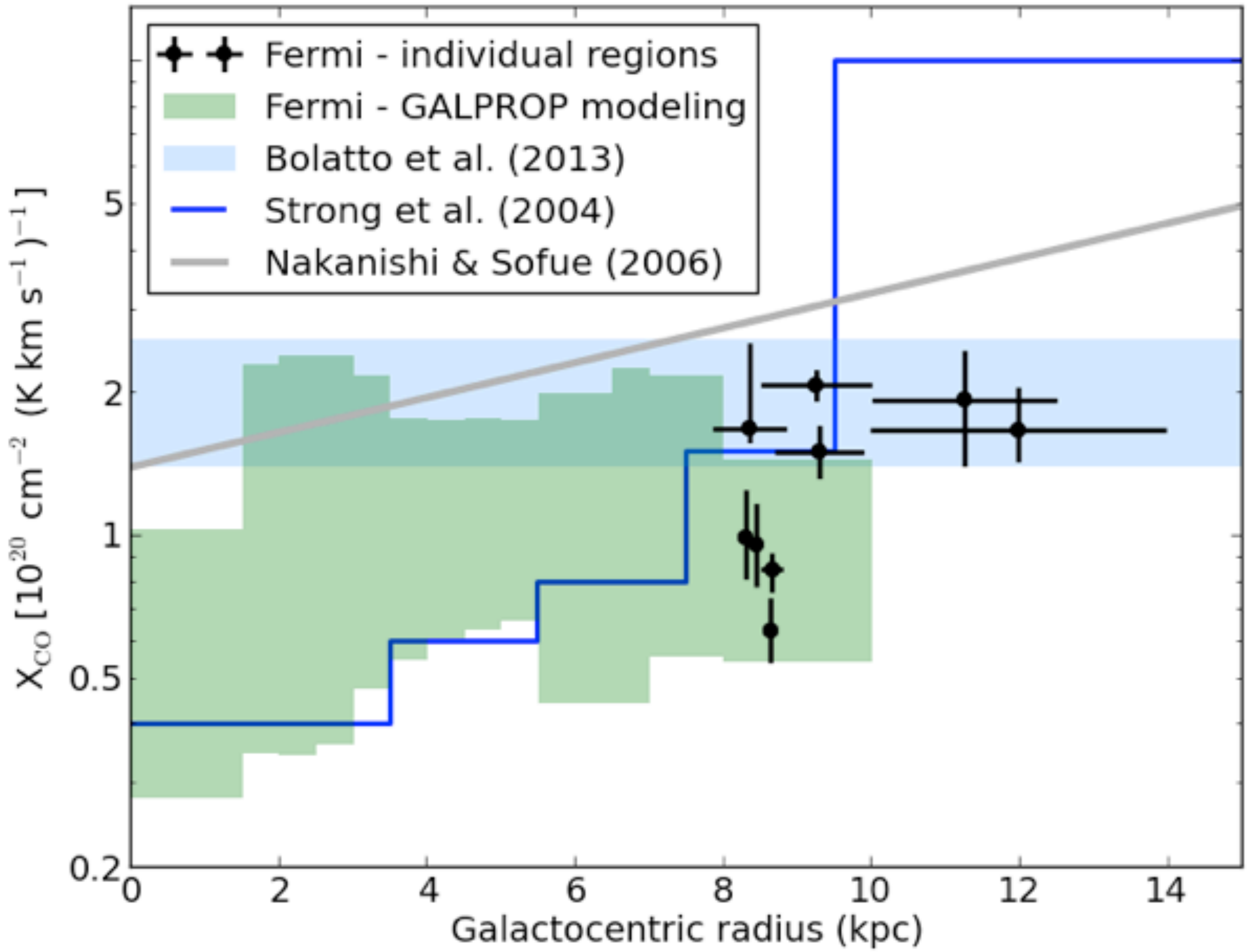
Uncertainties in target distributions

- gas
  - neutral
  - ionized
- interstellar radiation field

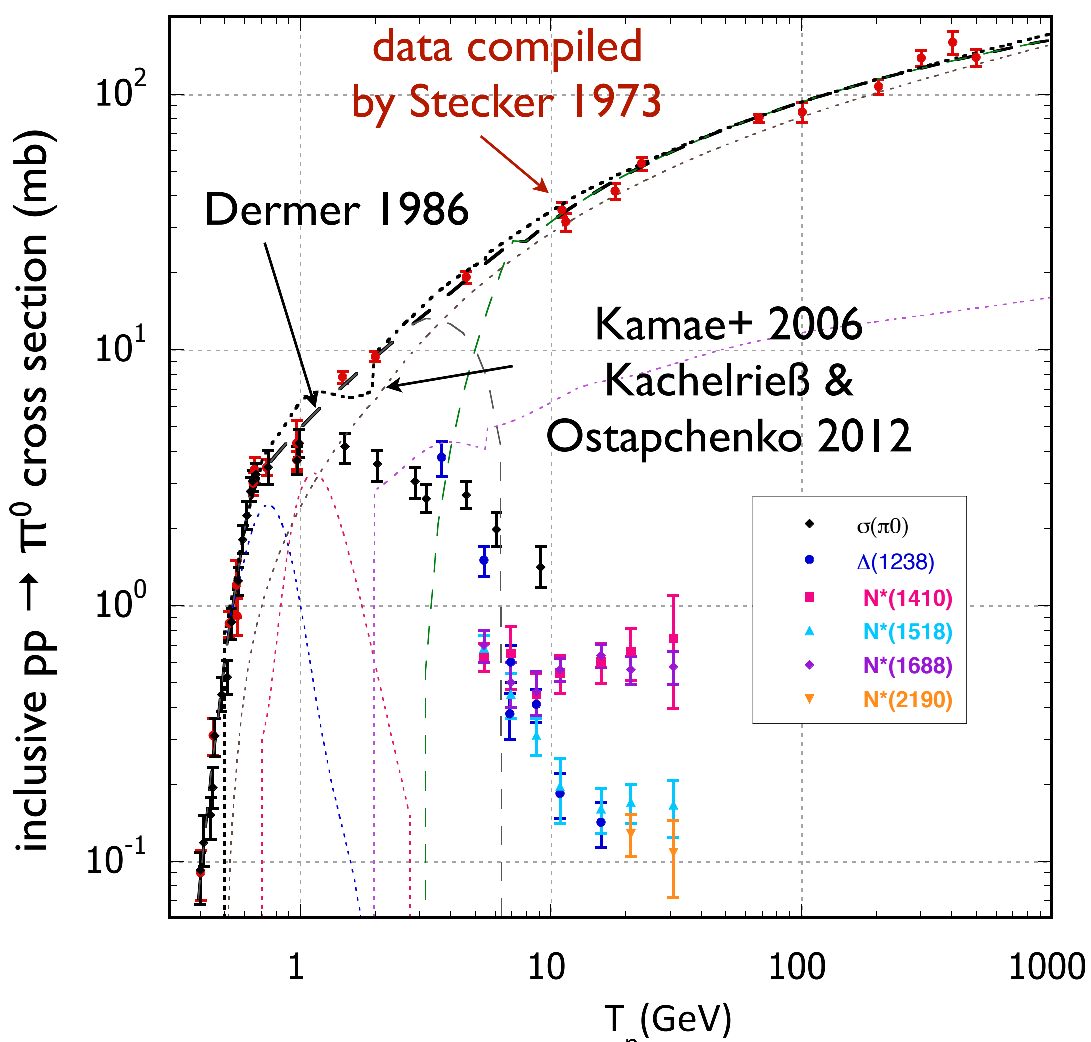
example: CO → H_2

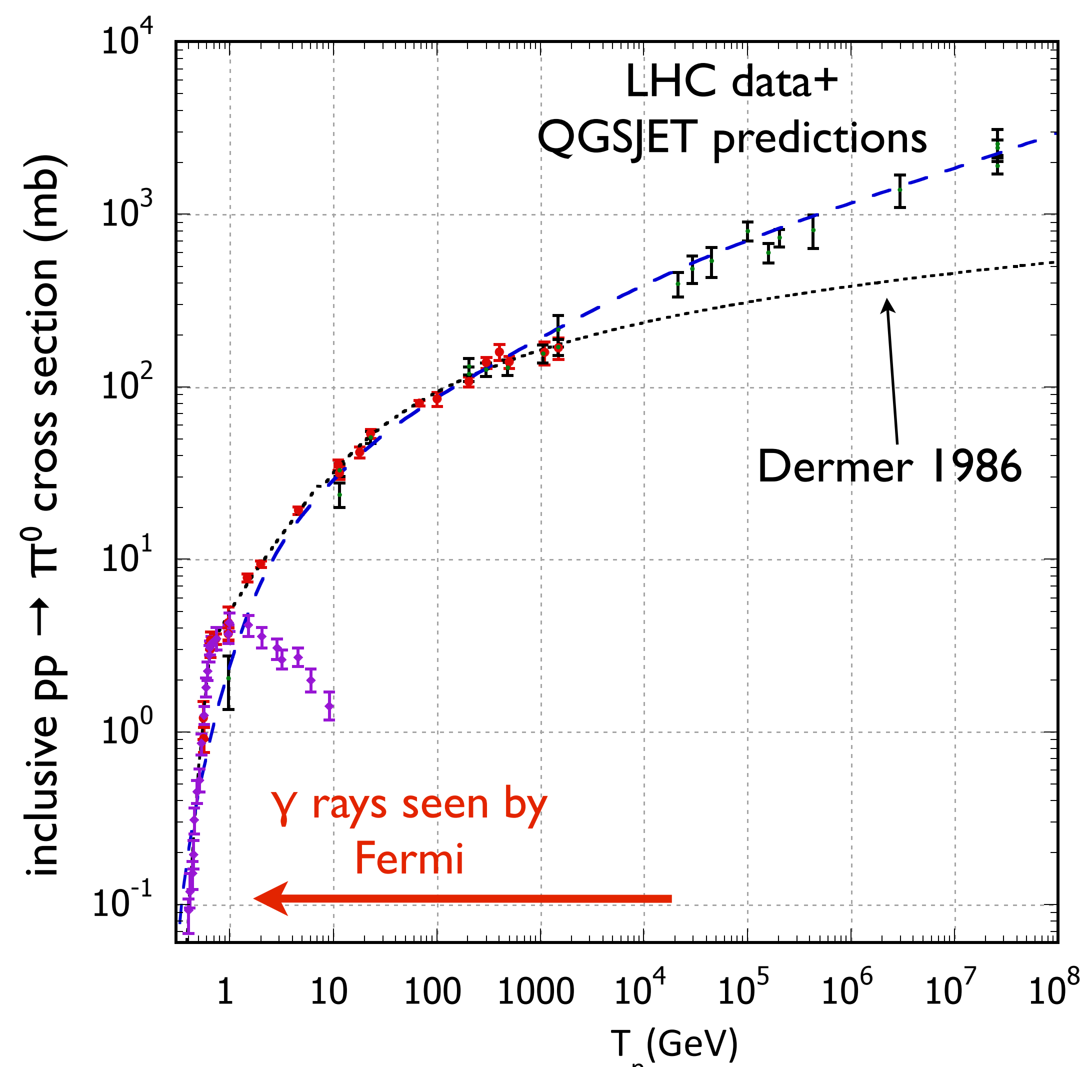


Nuclear production models

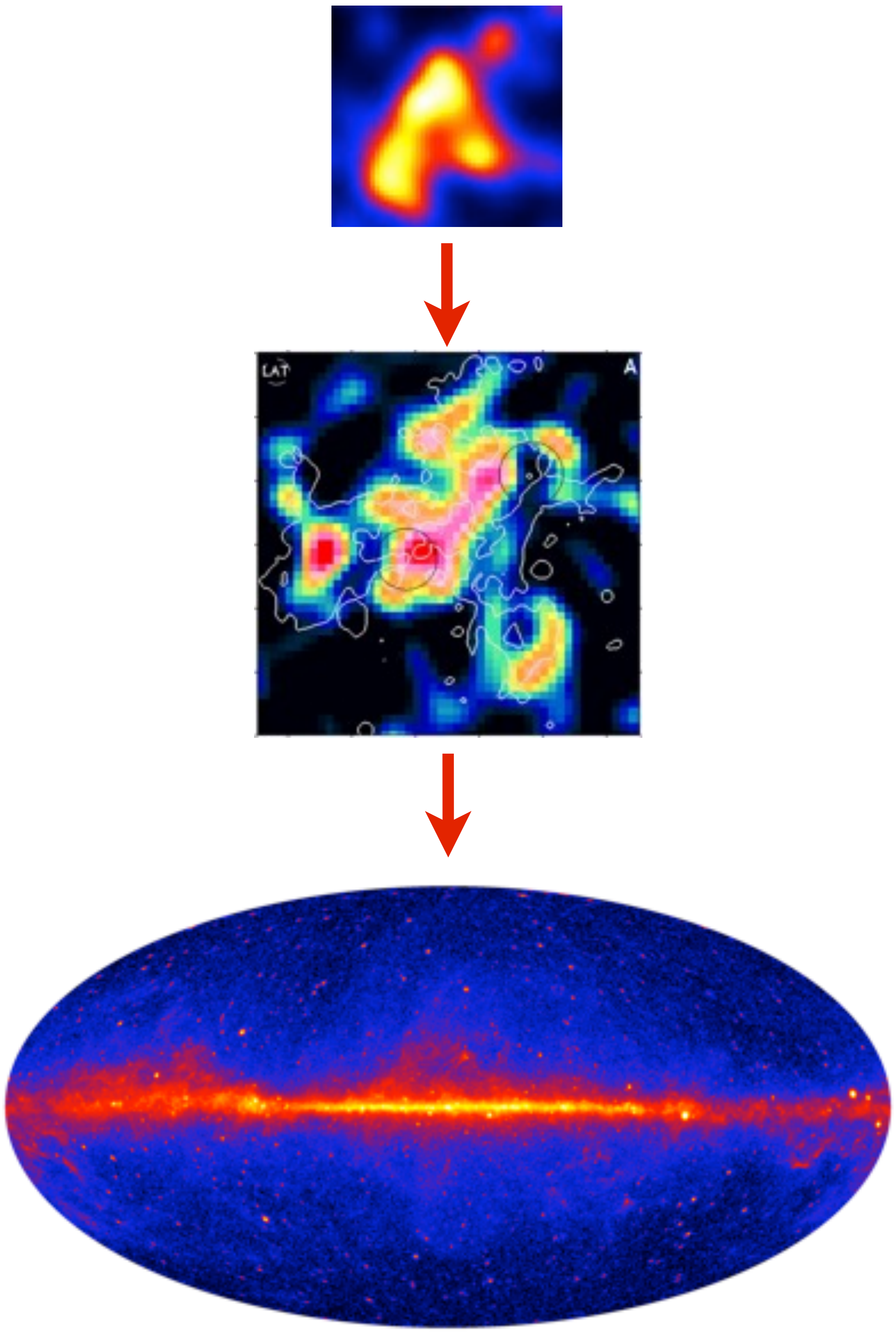
- data and theory from particle physics
- for nuclear interactions
  - limited measurements (bullet energies, bullet/target species, angular distribution)
  - bridged by theoretical framework(s)
  - 5-30% uncertainties at T_p < 10 GeV

Dermer+ 2013, ICRC, arXiv:1307.0497





Summary



- supernova remnants
- massive-star forming regions
- galaxies

LT+ 2013 ICRC, arXiv:1311.2896