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

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on behalf of
the *Fermi*-LAT collaboration

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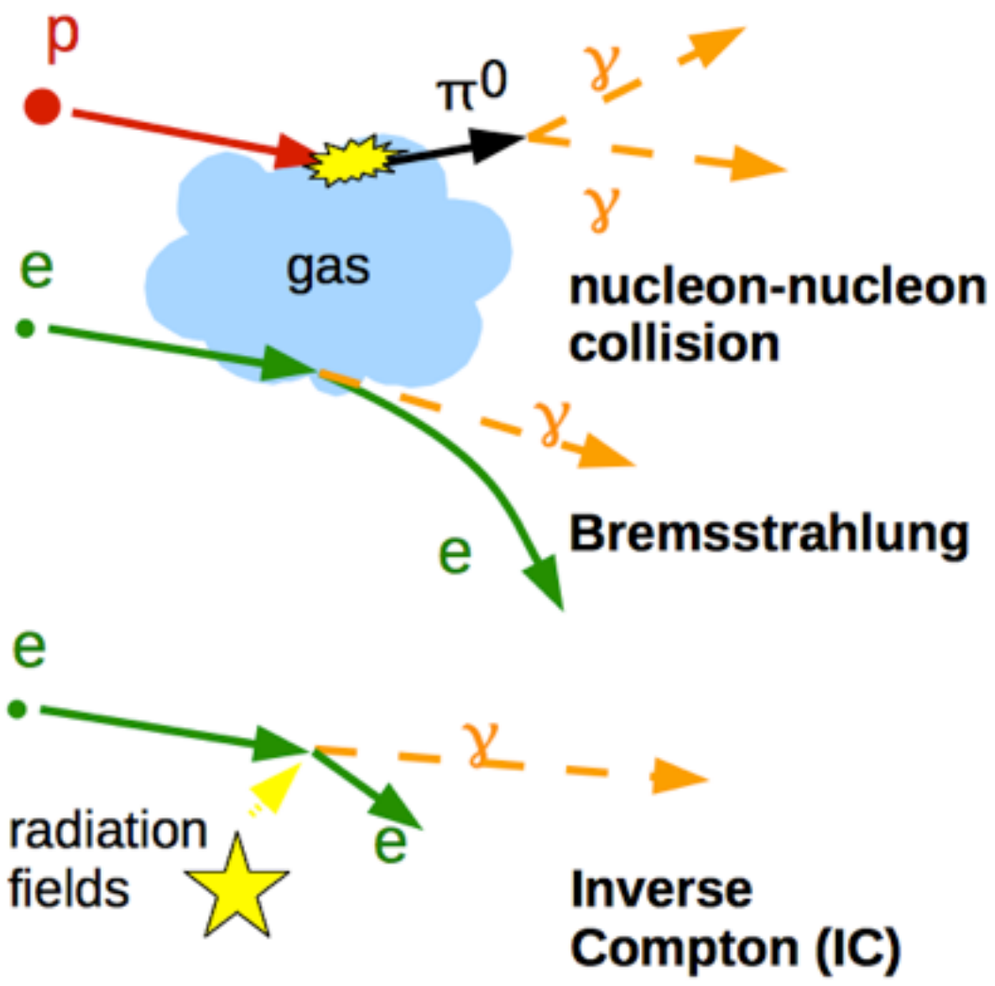
Outline

- 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

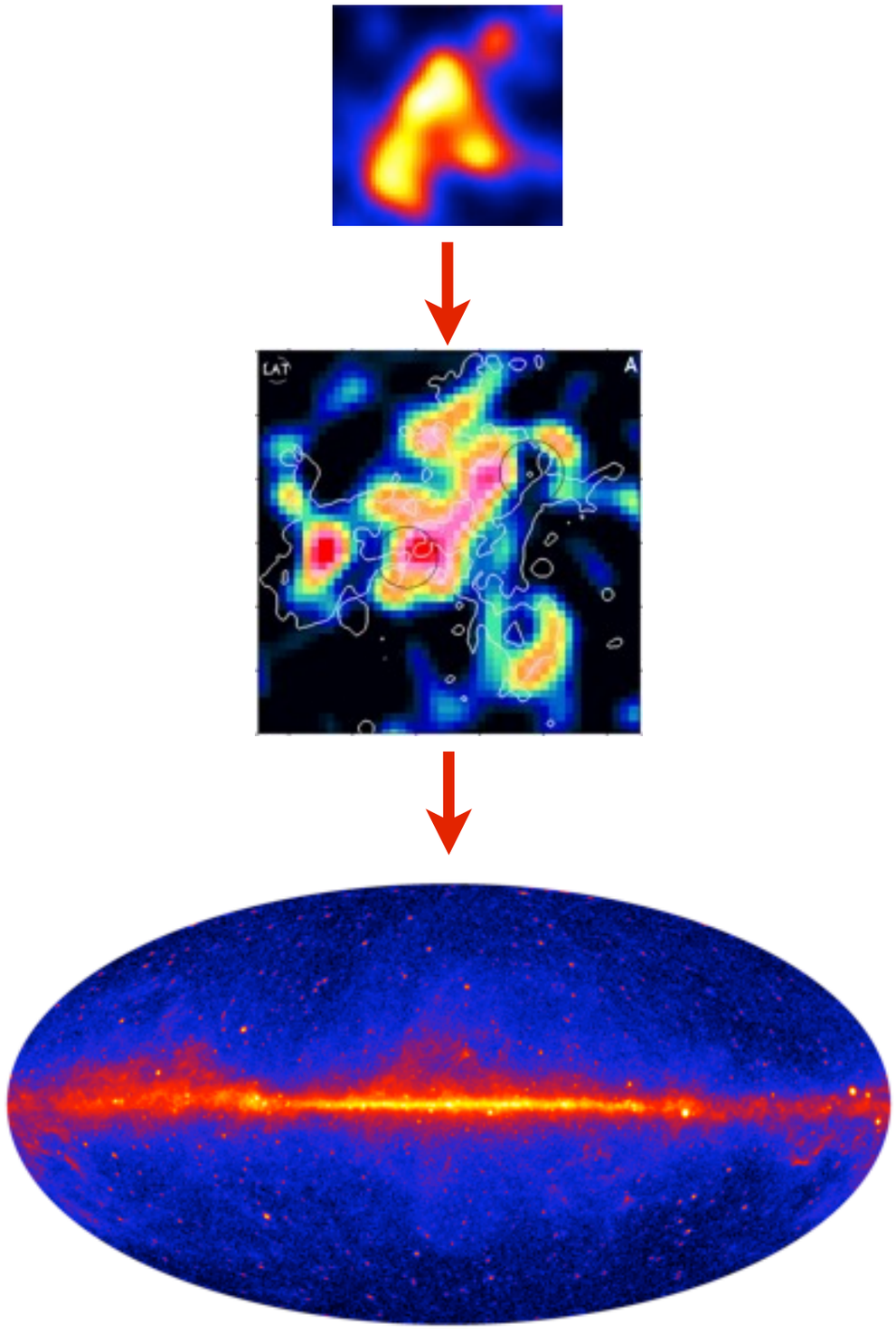
CR are charged + B fields
→ do not track back to sources (< 10^{18} eV)

γ rays as a charged particle tracer



- neutral secondaries → complement direct observations
- γ rays → neutral and easy to detect

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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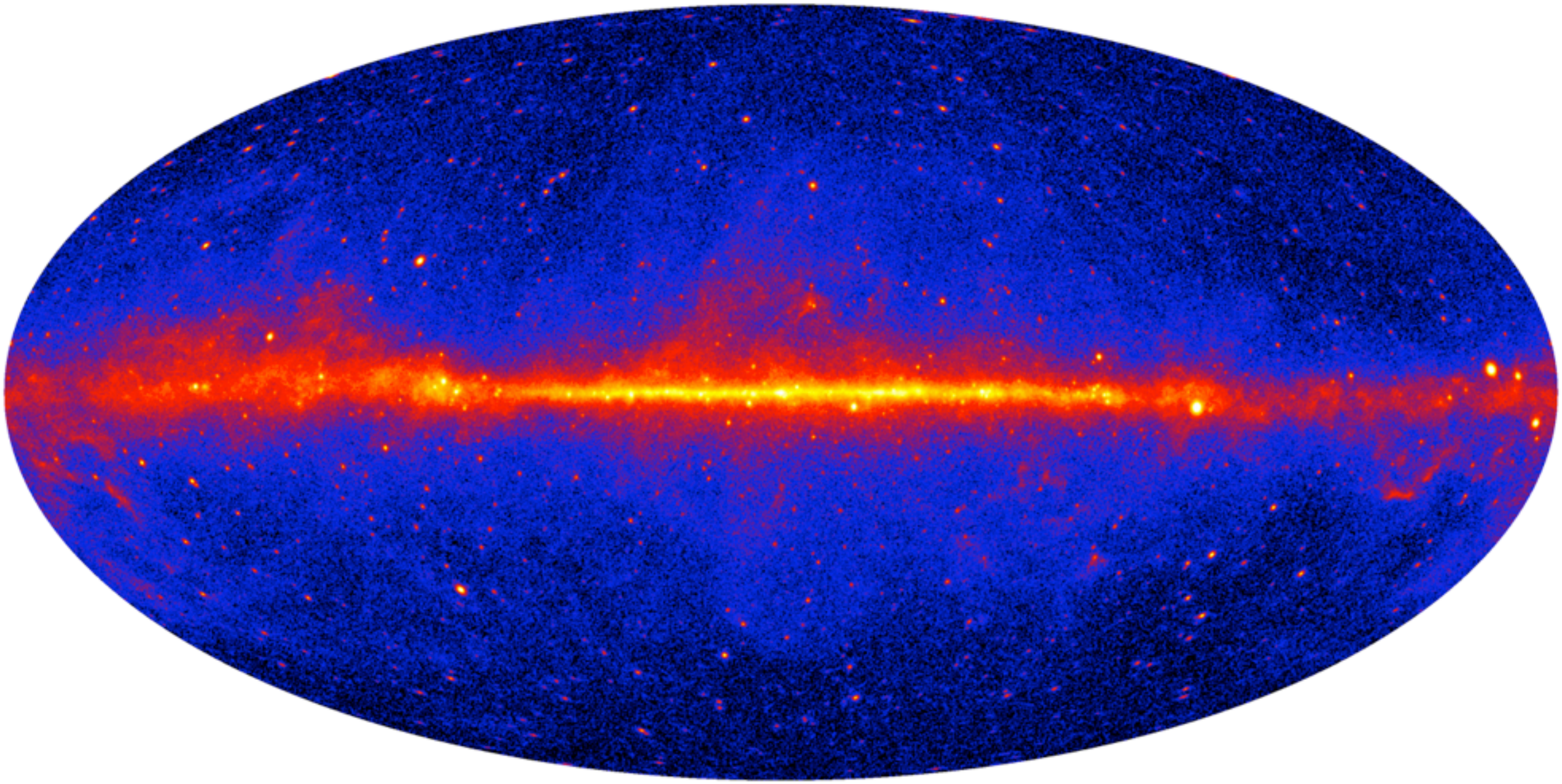
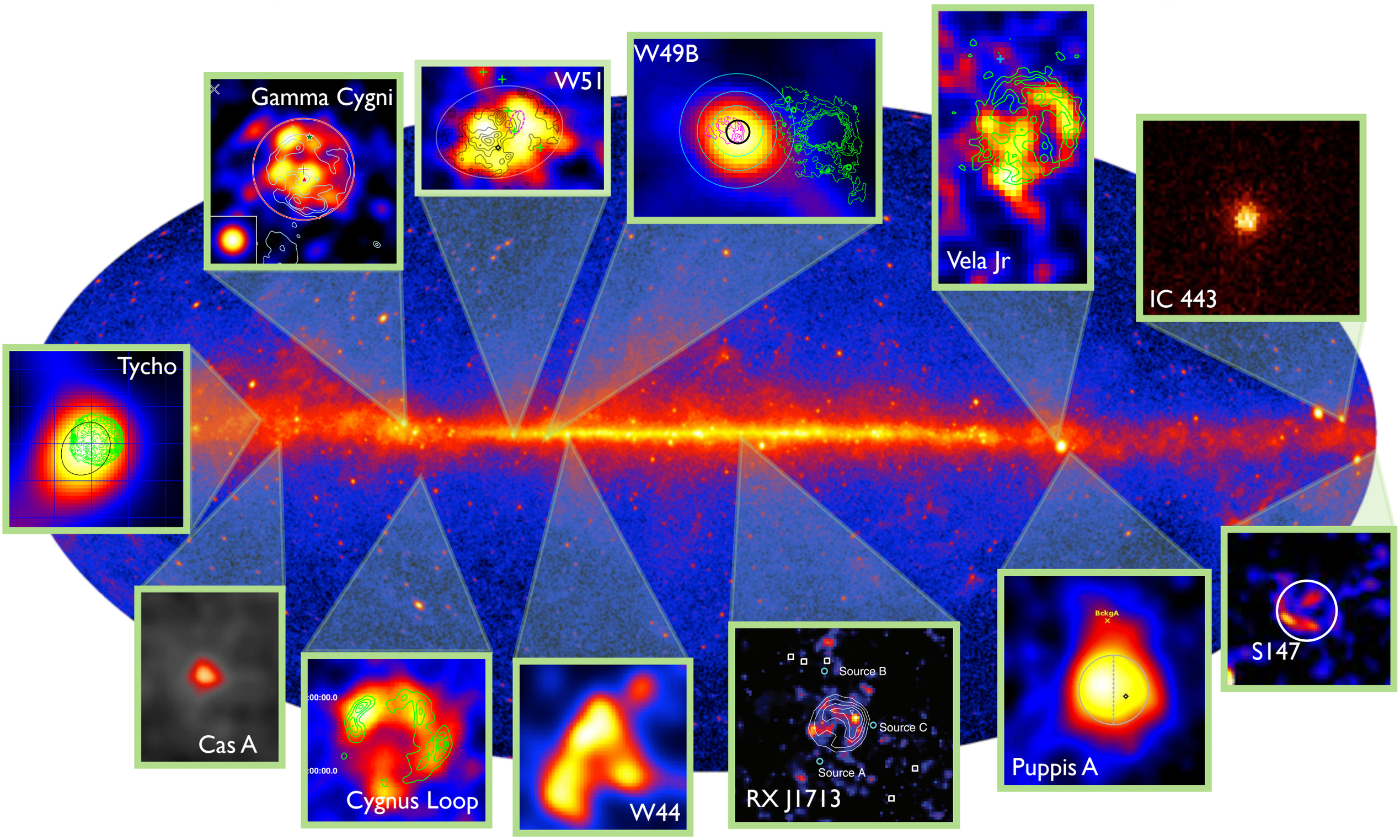
Supernova remnants as CR sources

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

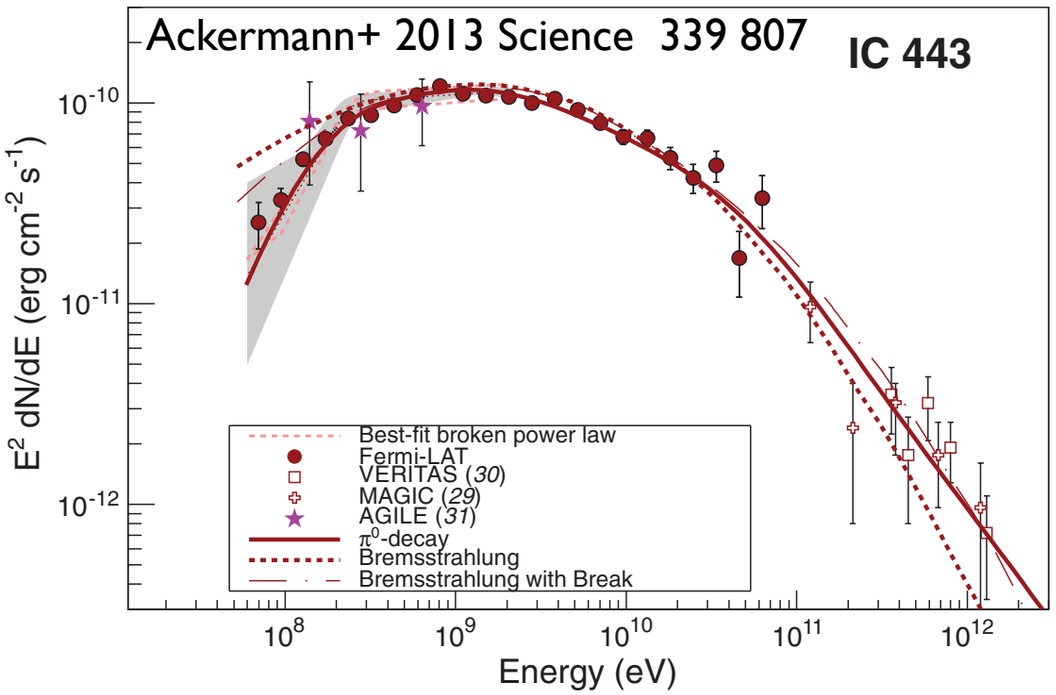
Supernova remnants in the γ-ray sky

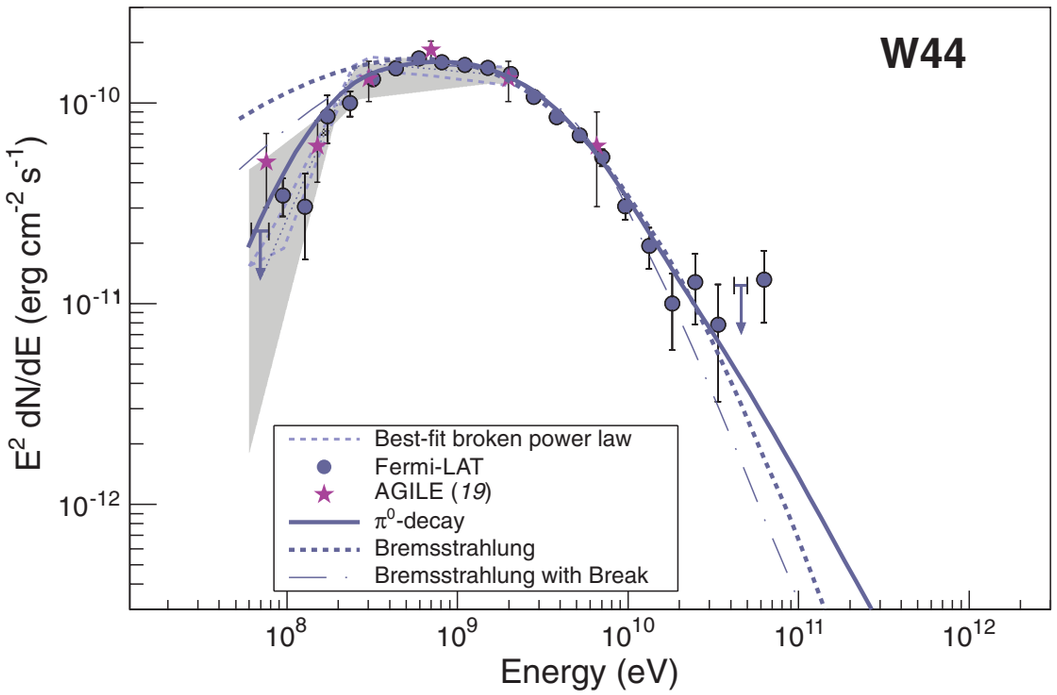


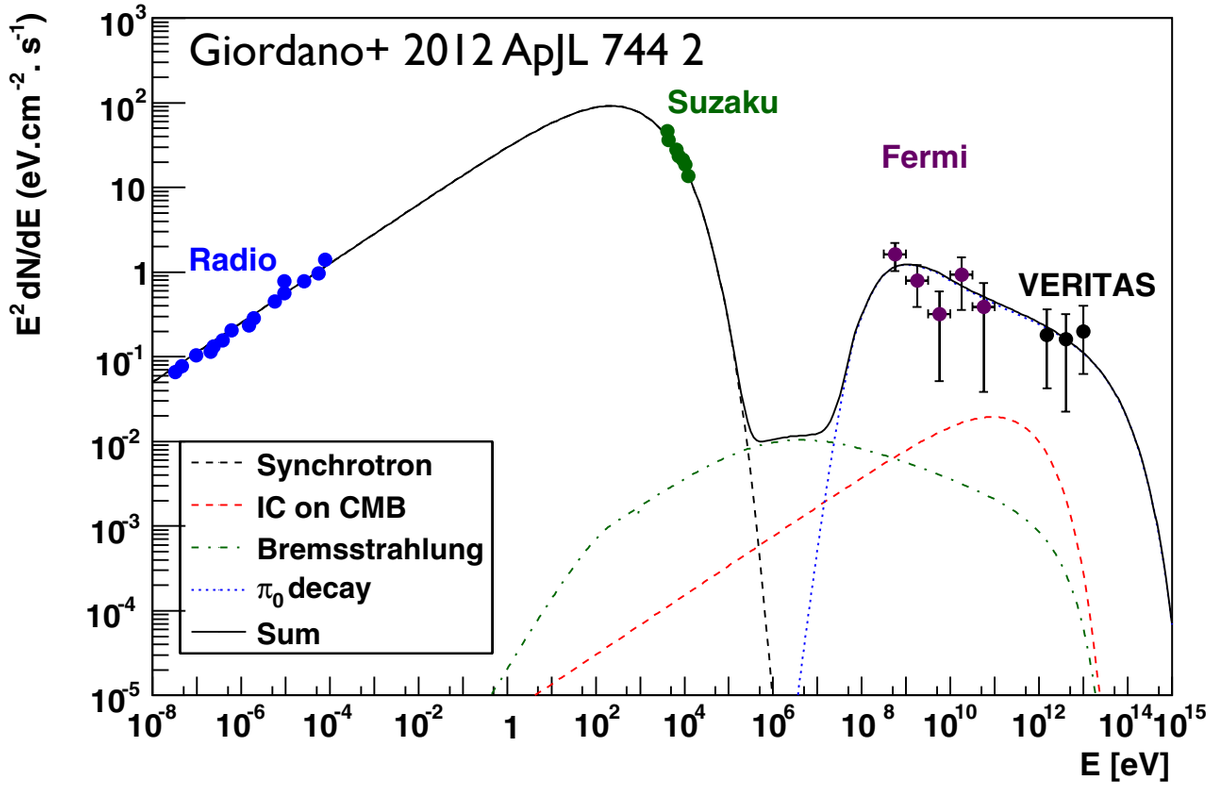
Supernova remnants in the γ-ray sky



Accelerated nuclei!



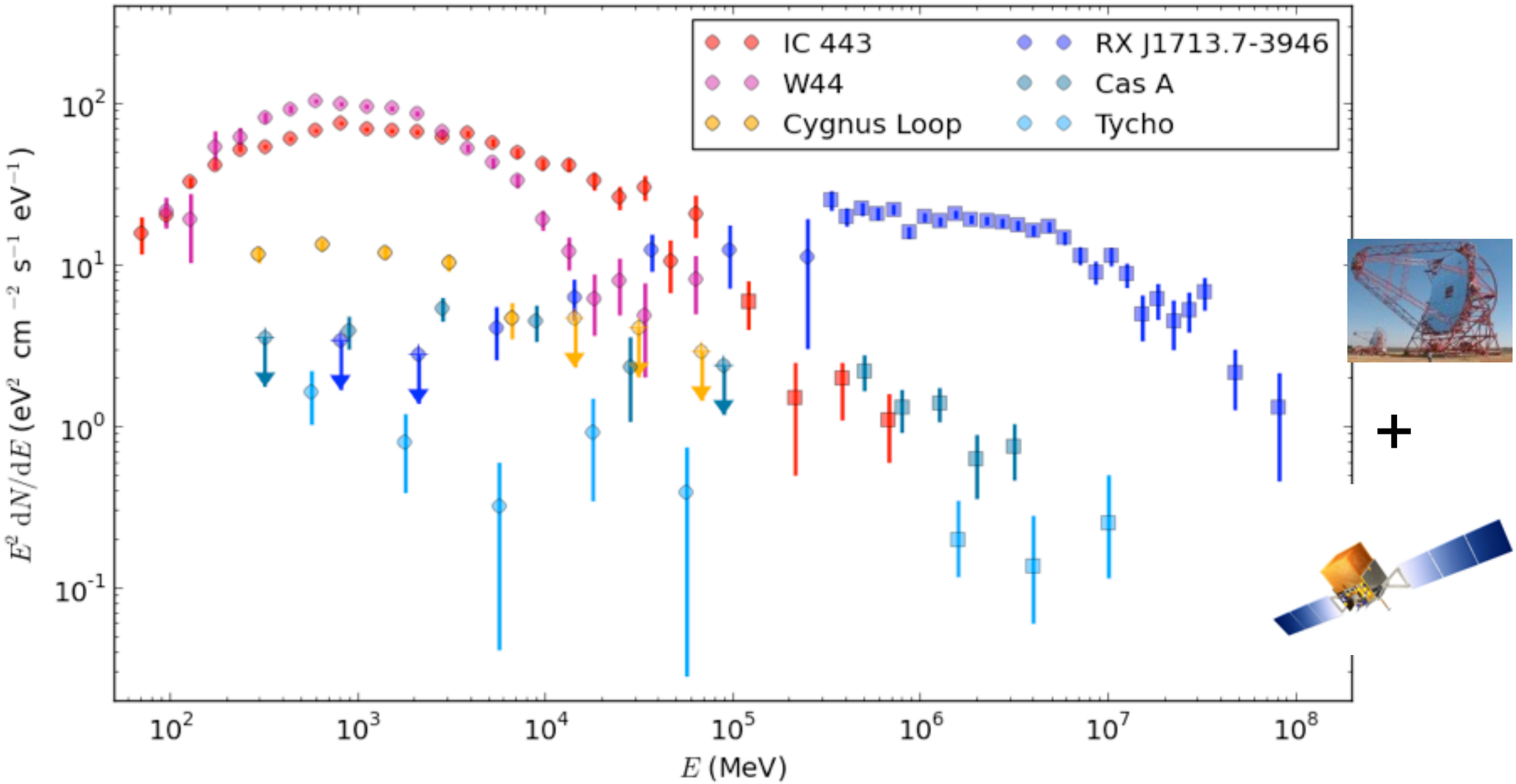




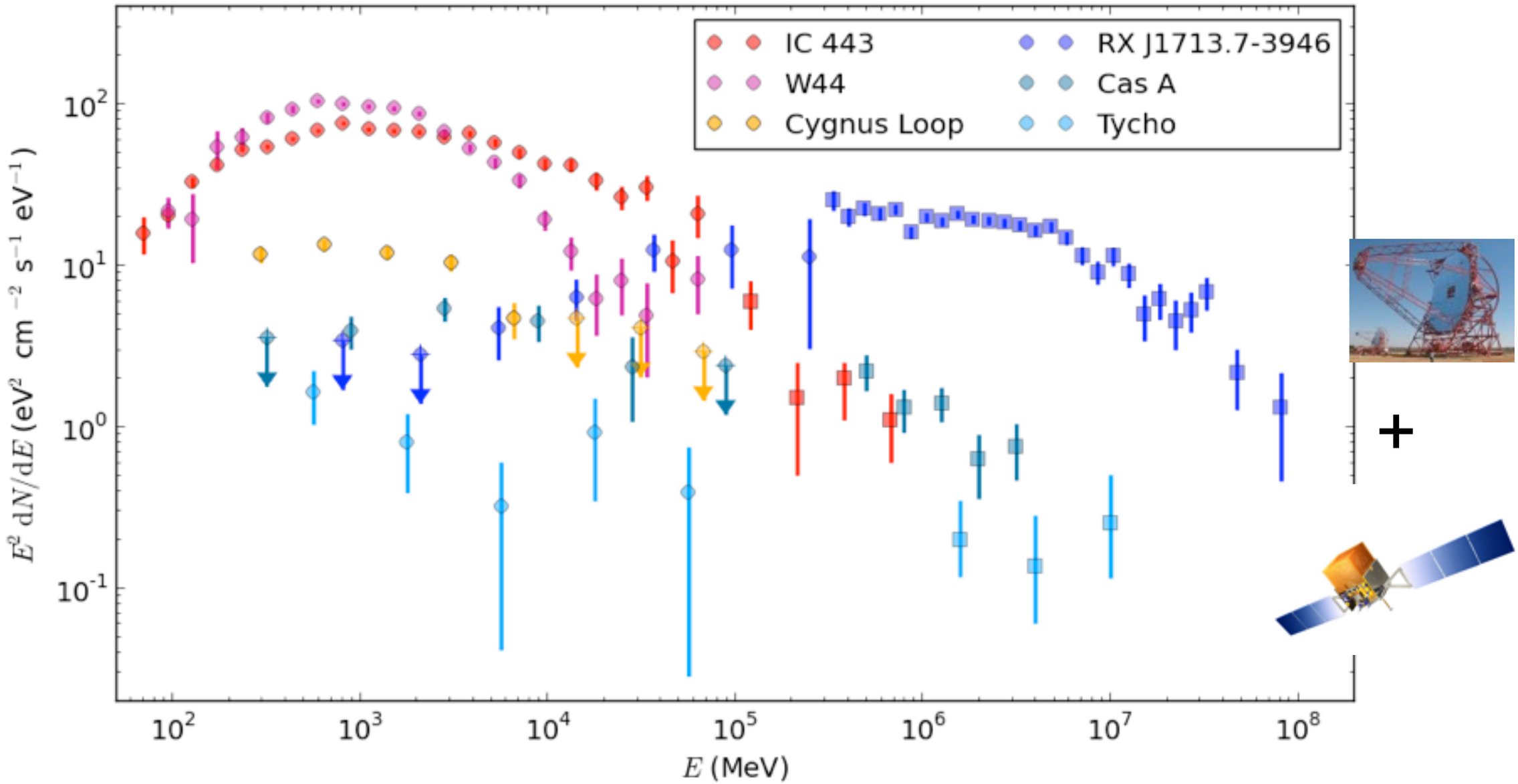
- IC 443 & W44: pion bump (+AGILE)
- Tycho: accelerated nuclei up to ~500 TeV
  (Morlino&Caprioli 2012)

???

The ages of supernova remnants



The ages of supernova remnants



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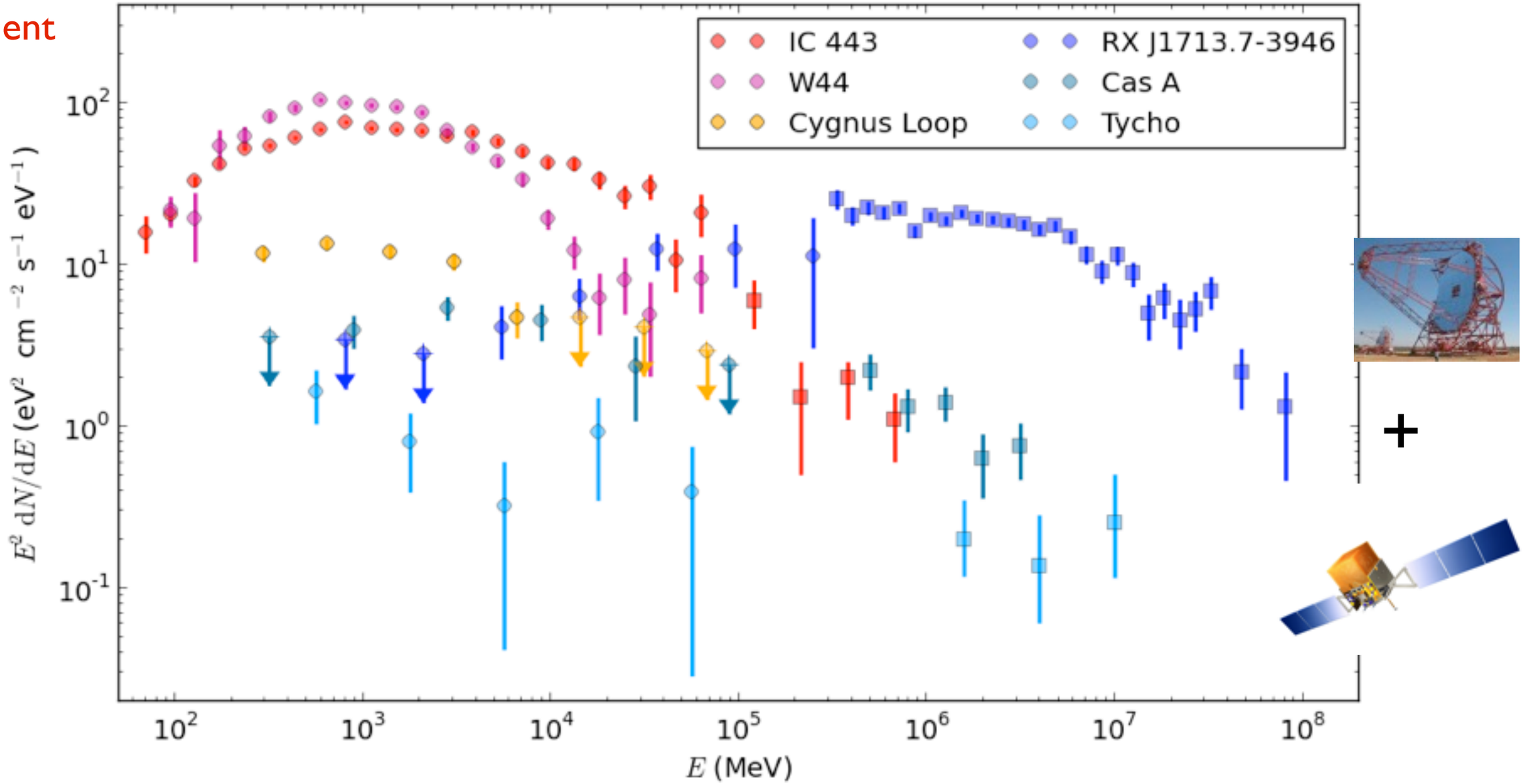
old — young

The ages of supernova remnants

denser environment



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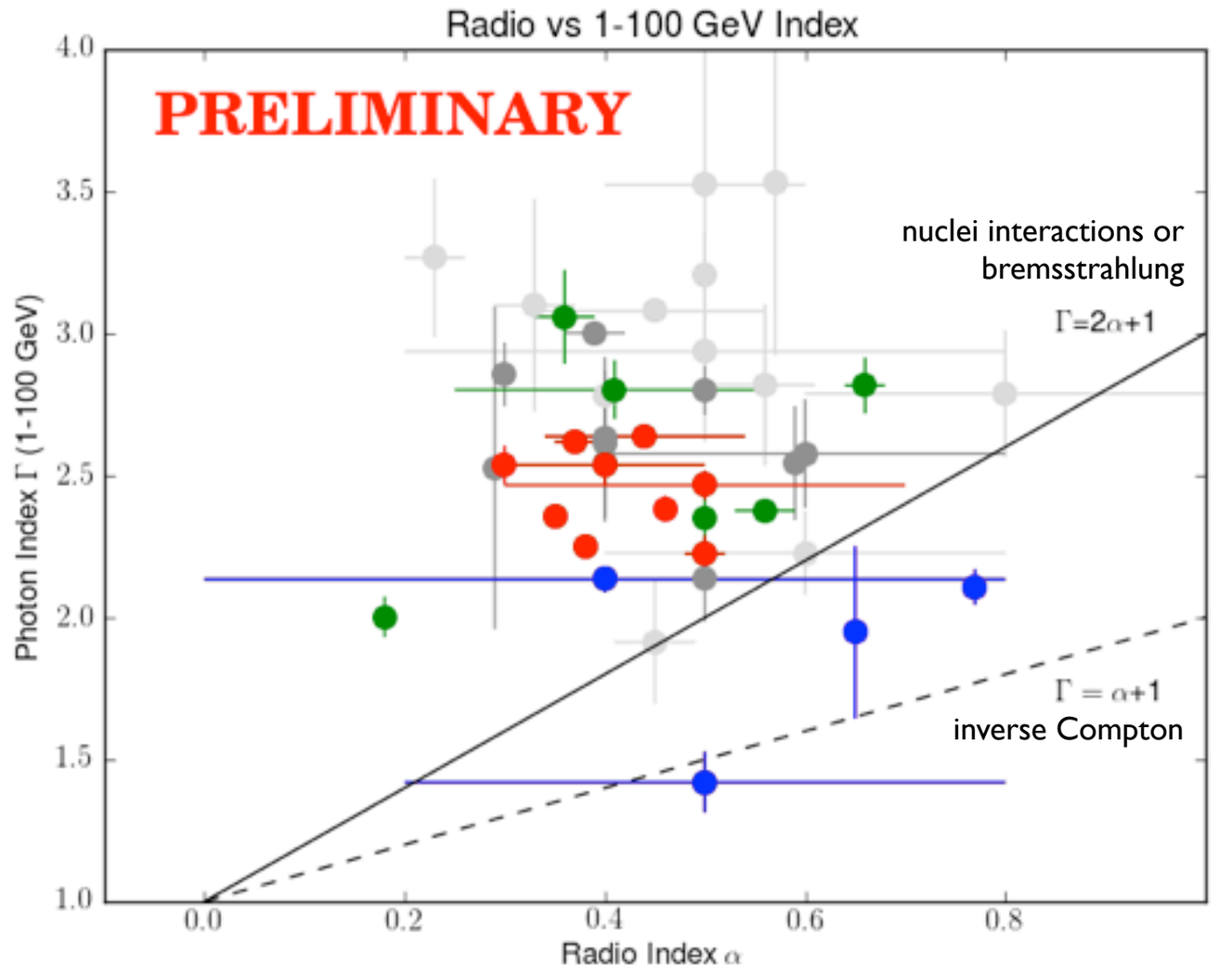
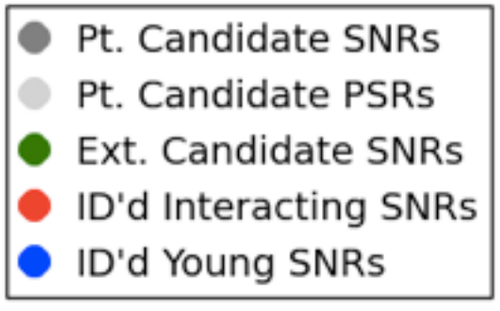
The first LAT SNR Catalog

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



talks by Brandt, Hewitt



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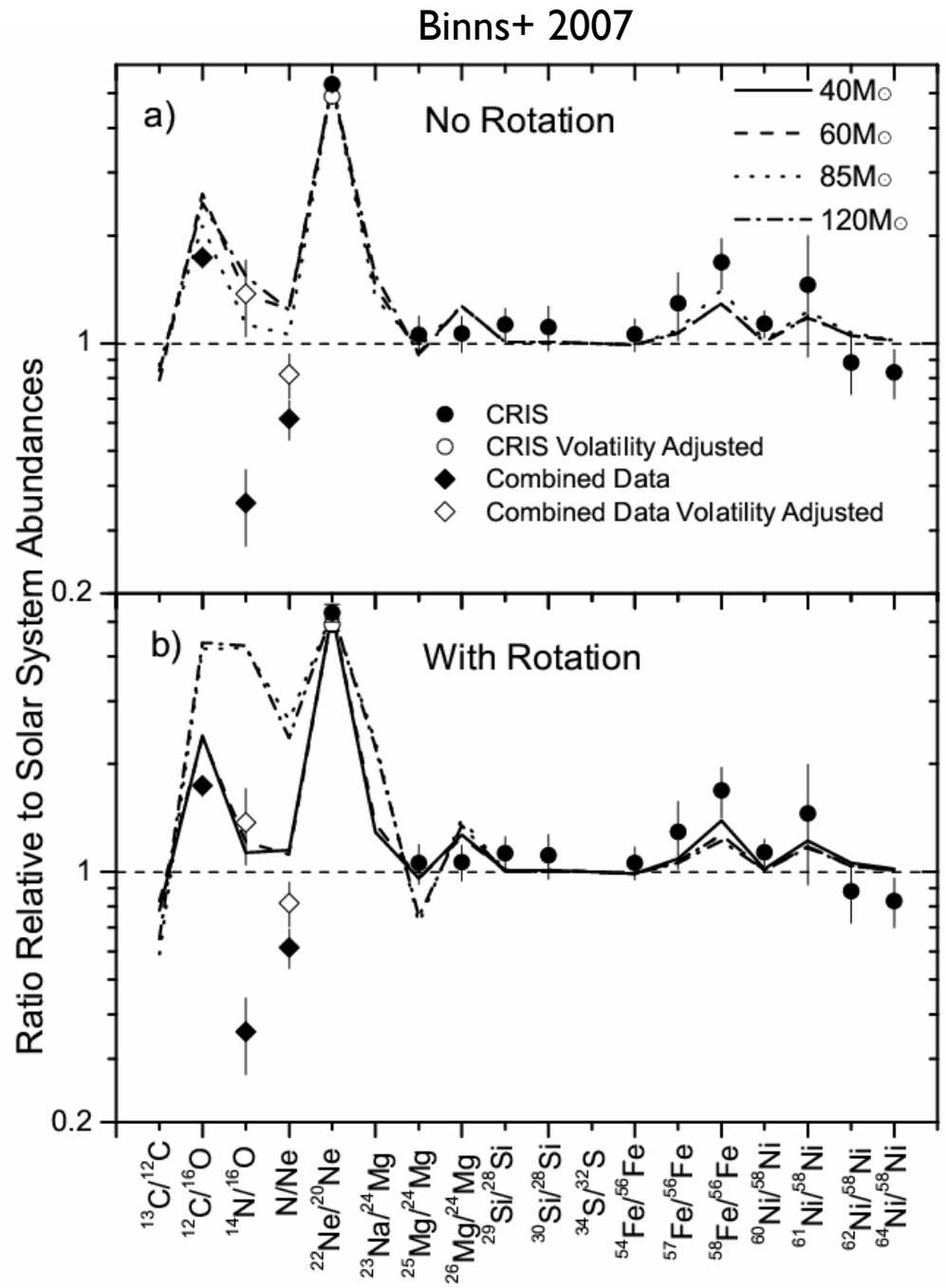
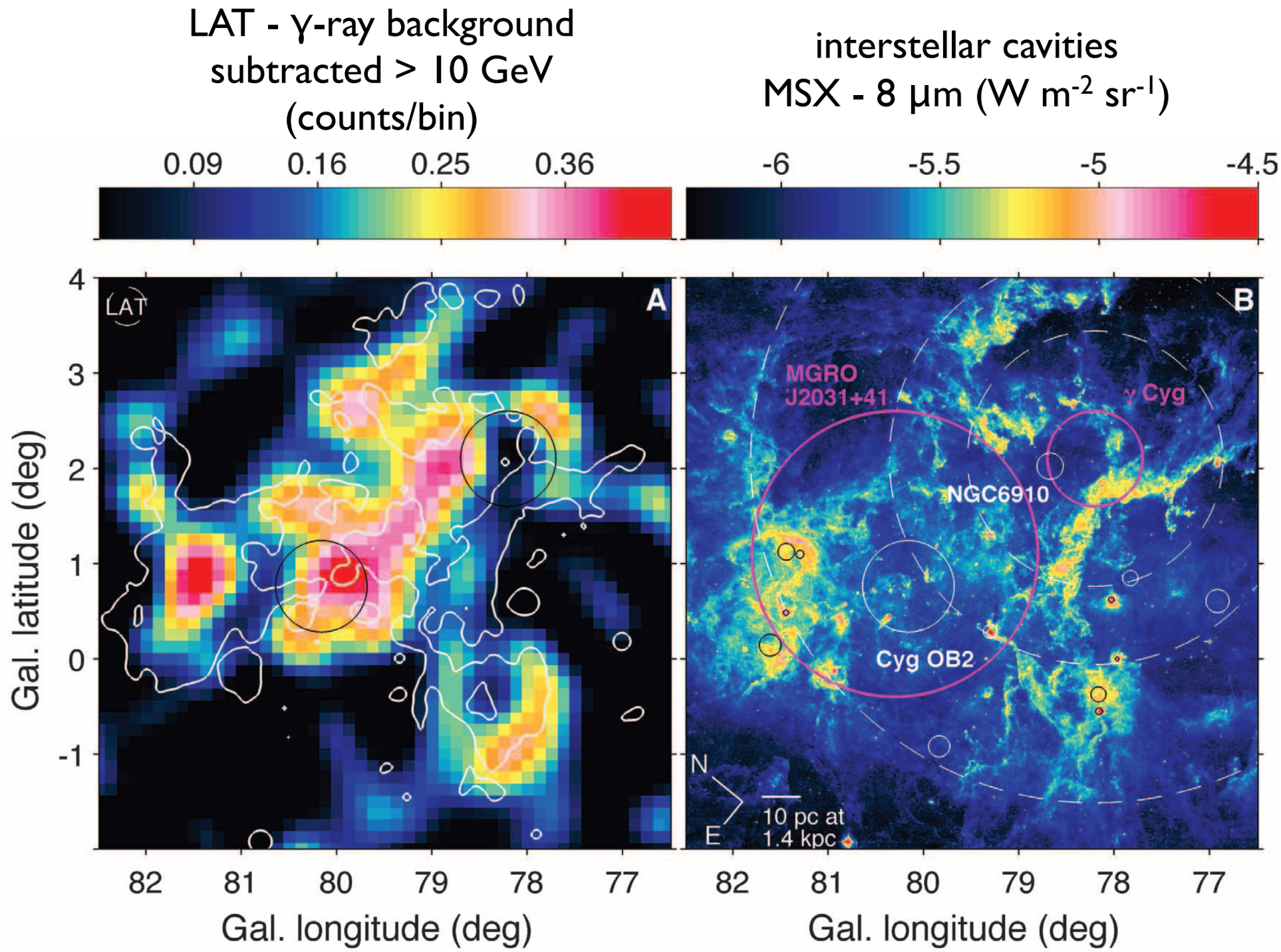
A link with massive-star forming regions?

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



The *Fermi* LAT view of Cygnus X



Ackermann+ 2011 Science 334 1103

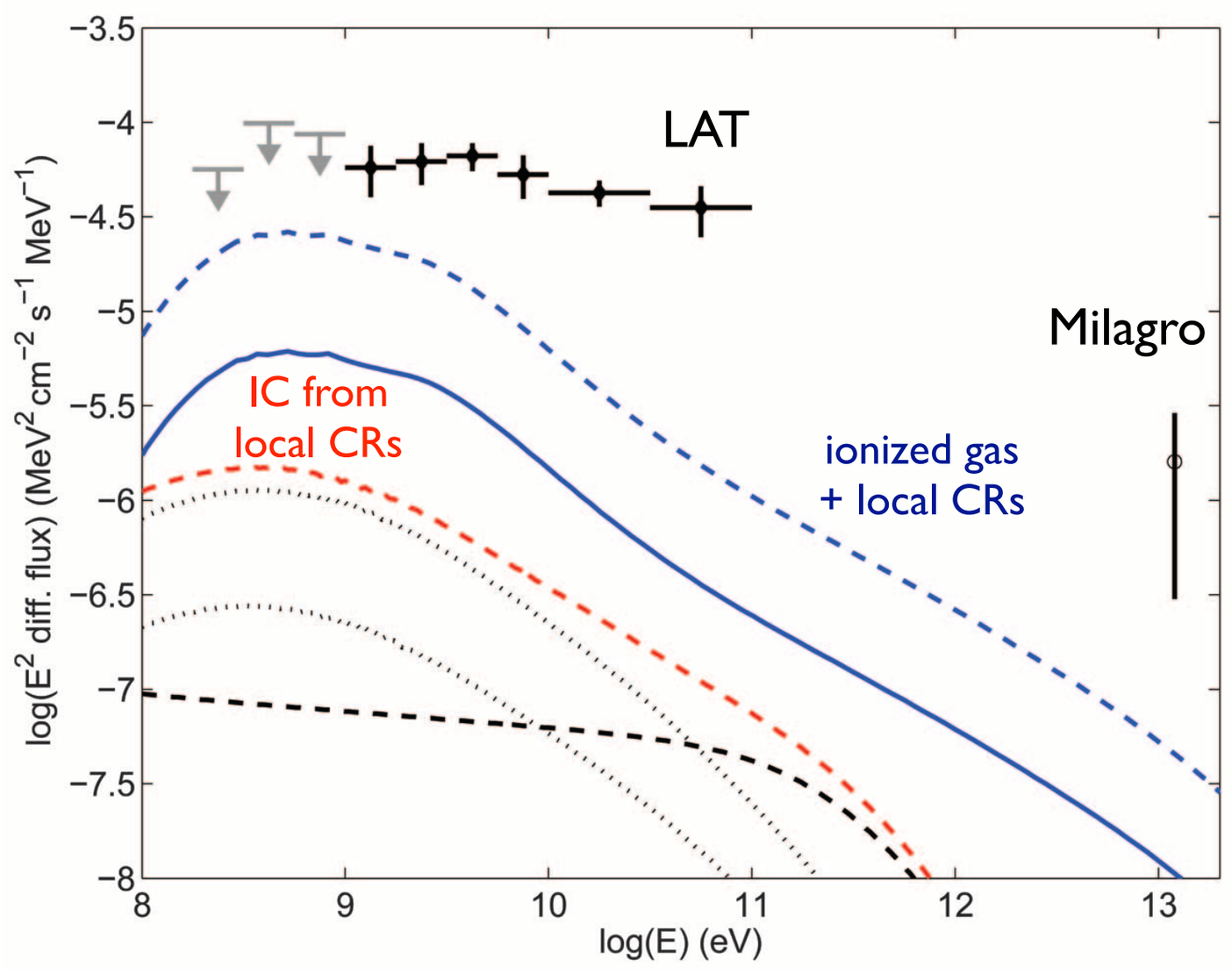
A cocoon of young cosmic rays

- 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

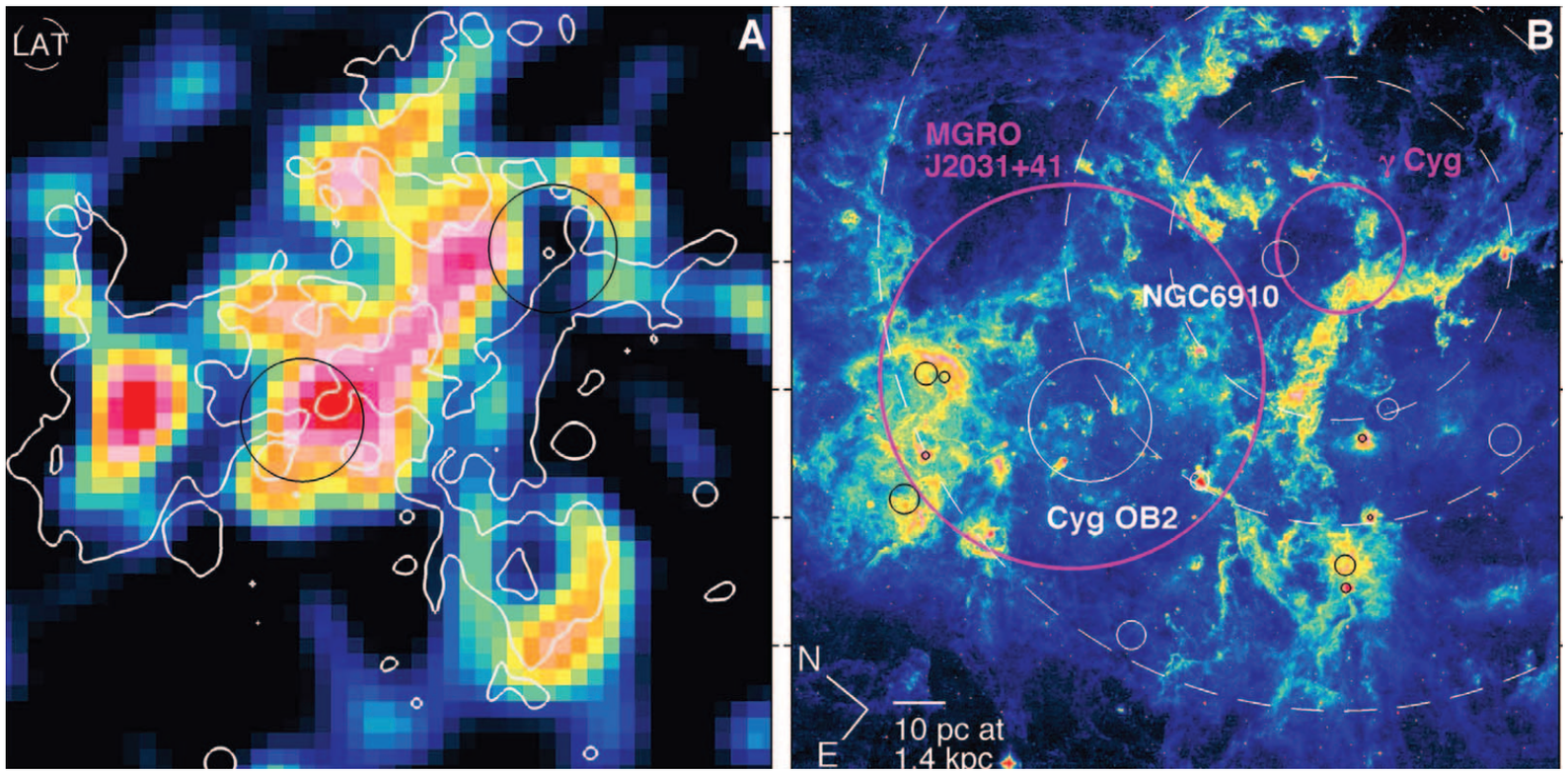
$$\frac{\mathrm{d}N}{\mathrm{d}E} \times 60 \left(\frac{E}{10\,\mathrm{GeV}} \right)^{0.5}$$



Ackermann+ 2011 Science 334 1103

Origin and propagation

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



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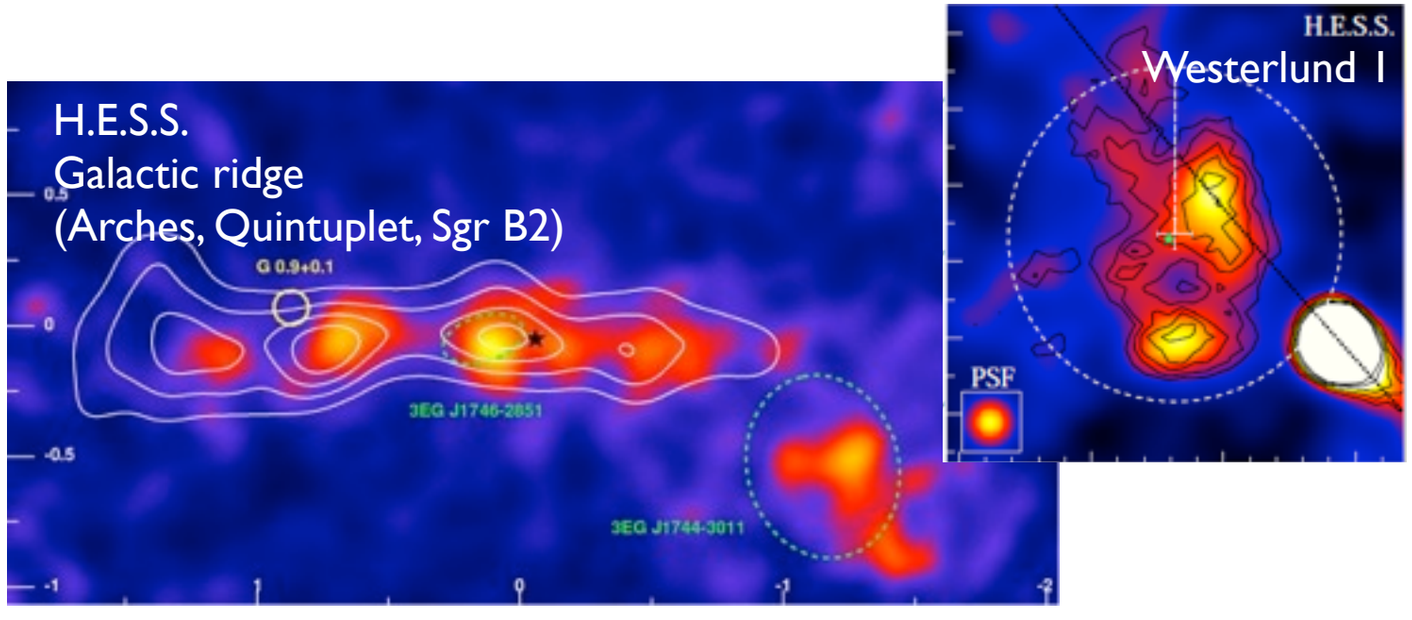

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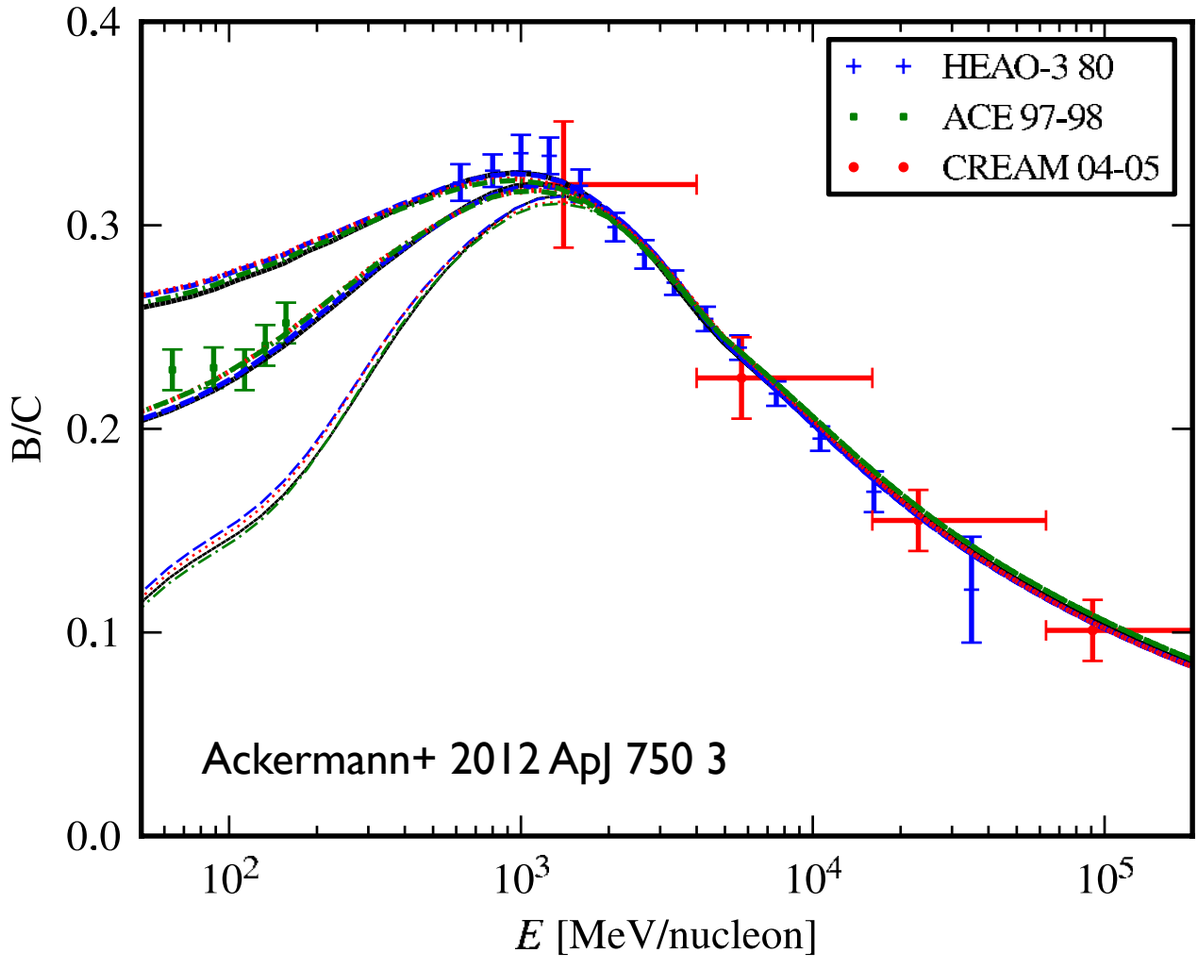
A travel through the Galaxy

- diffusion on magnetic fields

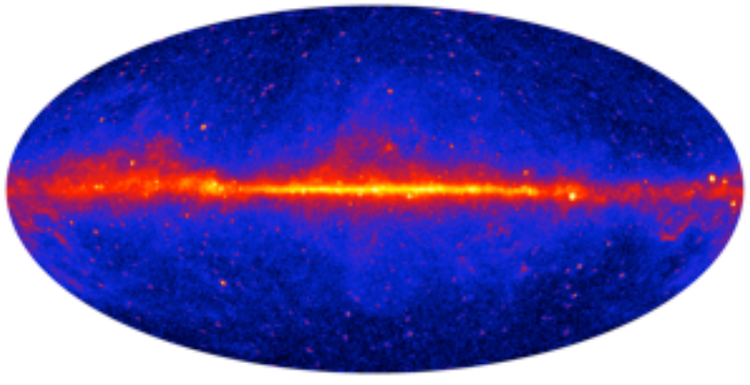
$$D = D_0 \left(\frac{R}{R_0} \right)^{\delta}$$

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

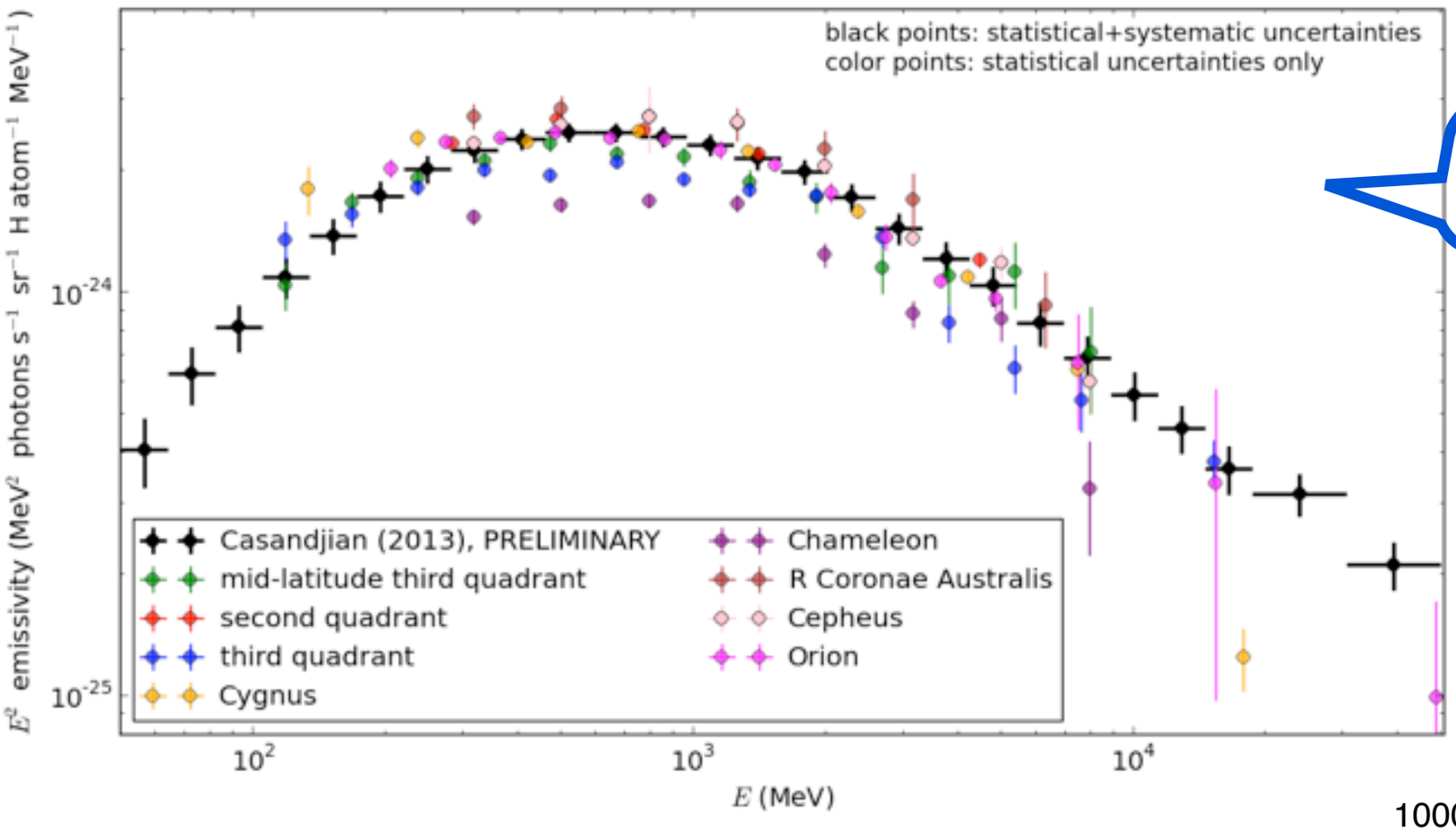


- convection? reacceleration?

cosmic-ray interactions produce
~60% of these γ rays!



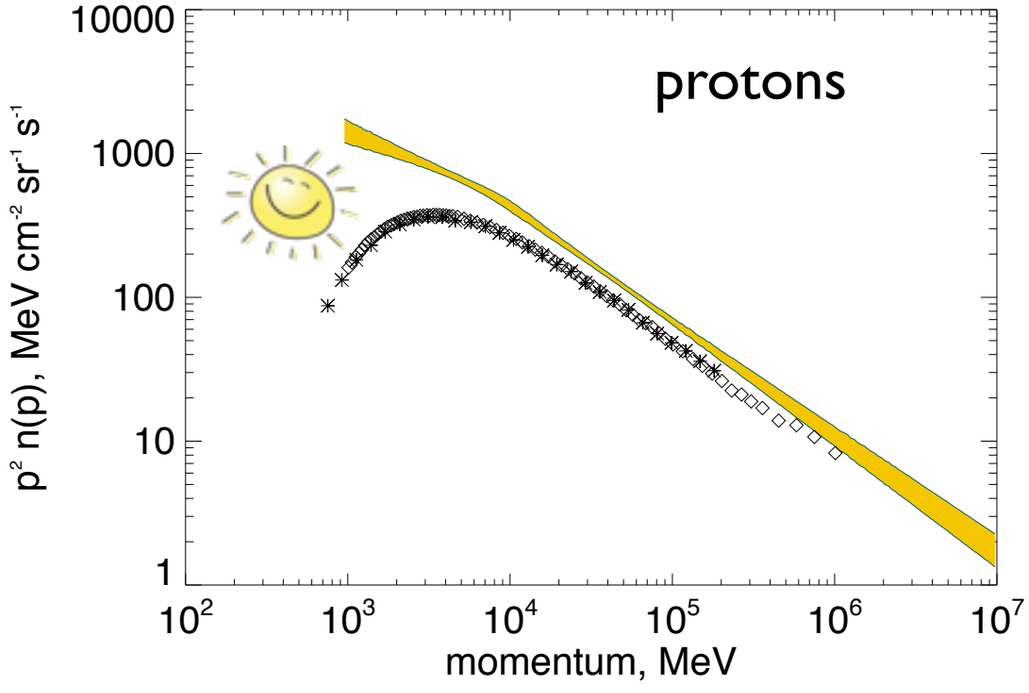
The Rosetta stone of diffuse γ rays



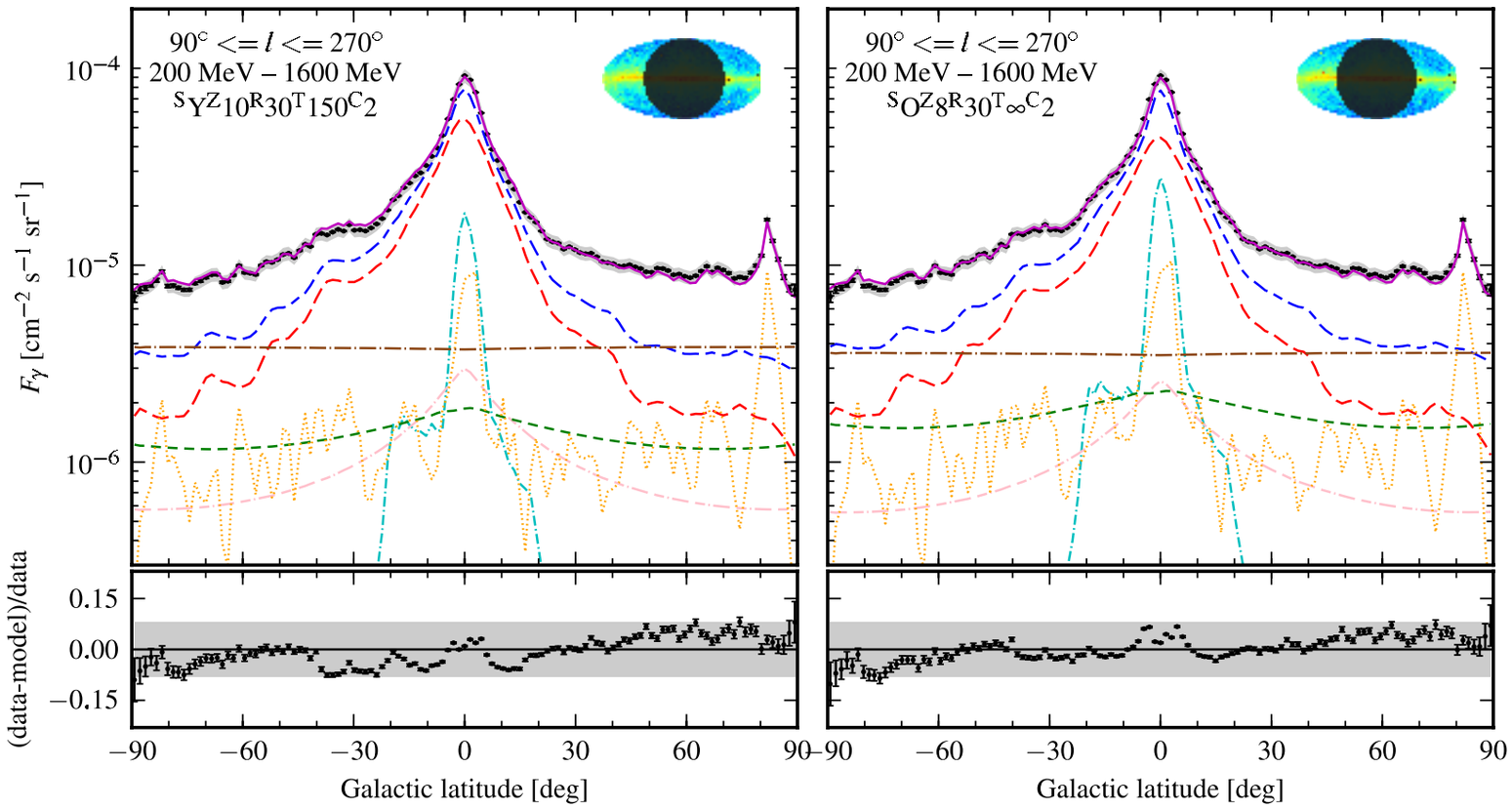
talk by Casandjian

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

talk by Casandjian, poster by Dermer



The modeling of large-scale propagation



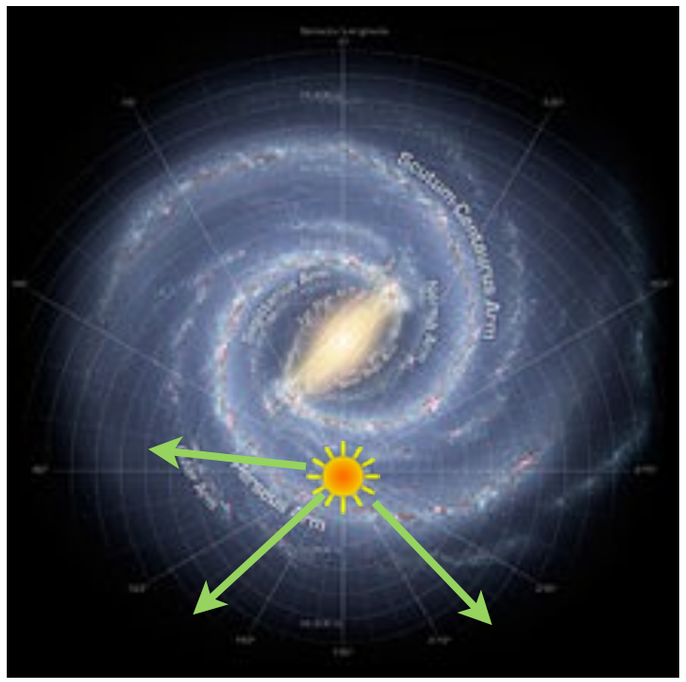
talk by Moskalenko

Ackermann+ 2012 ApJ 750 3

- large-scale structures reproduced at ~15%
- degeneracies between sources and propagation
- unmodeled features (e.g. bubbles)

talk by Franckowiak

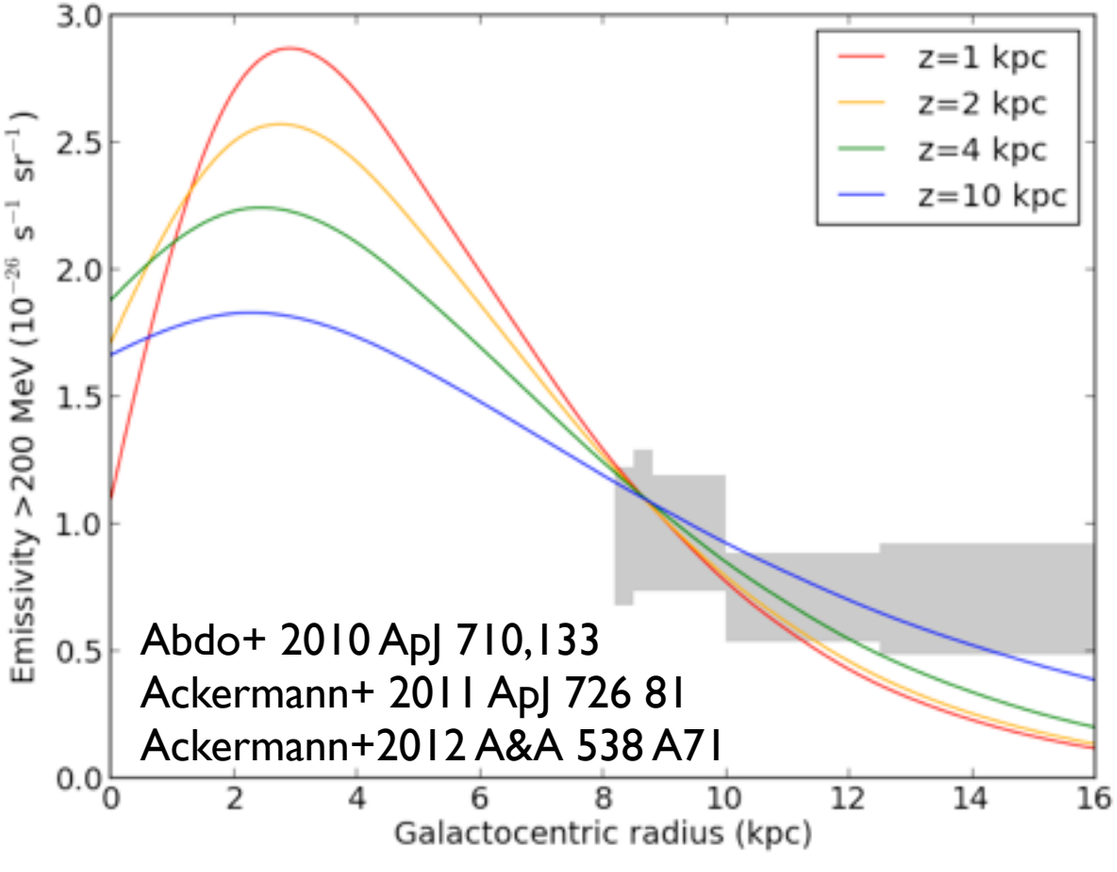
The gradient problem

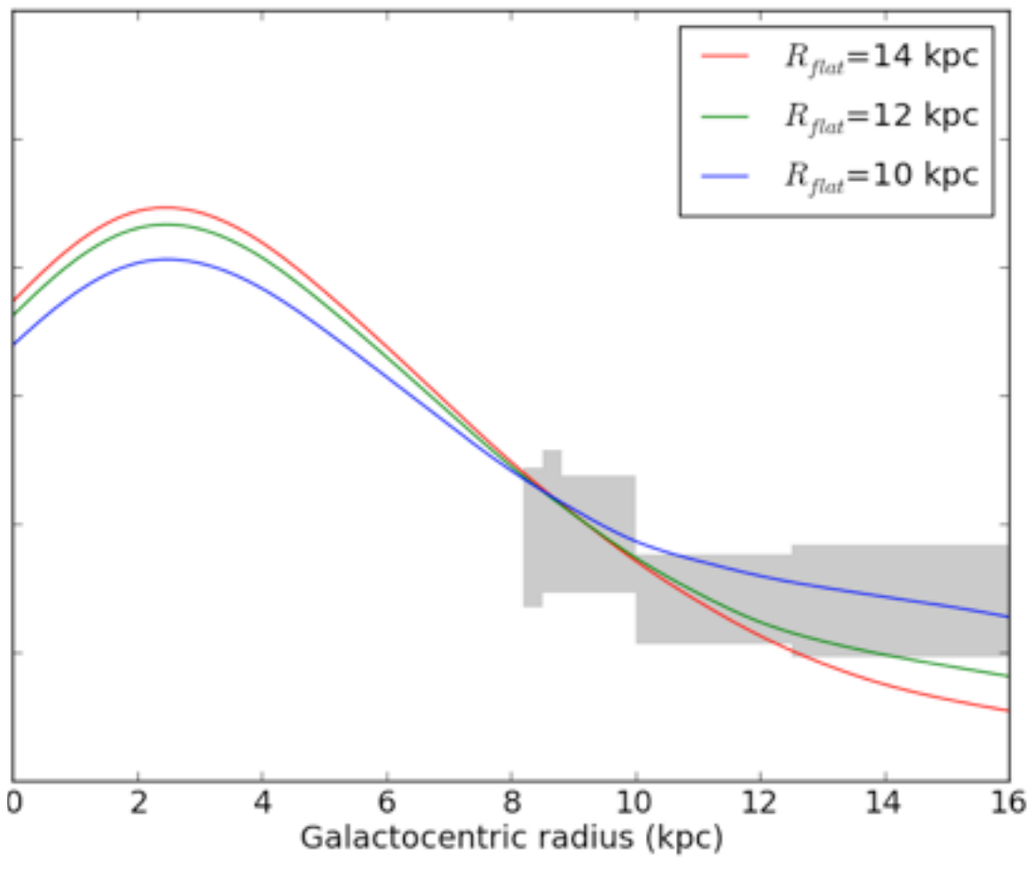


CR densities larger than expected in outer Galaxy

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

(e.g. Evoli+ 2012)





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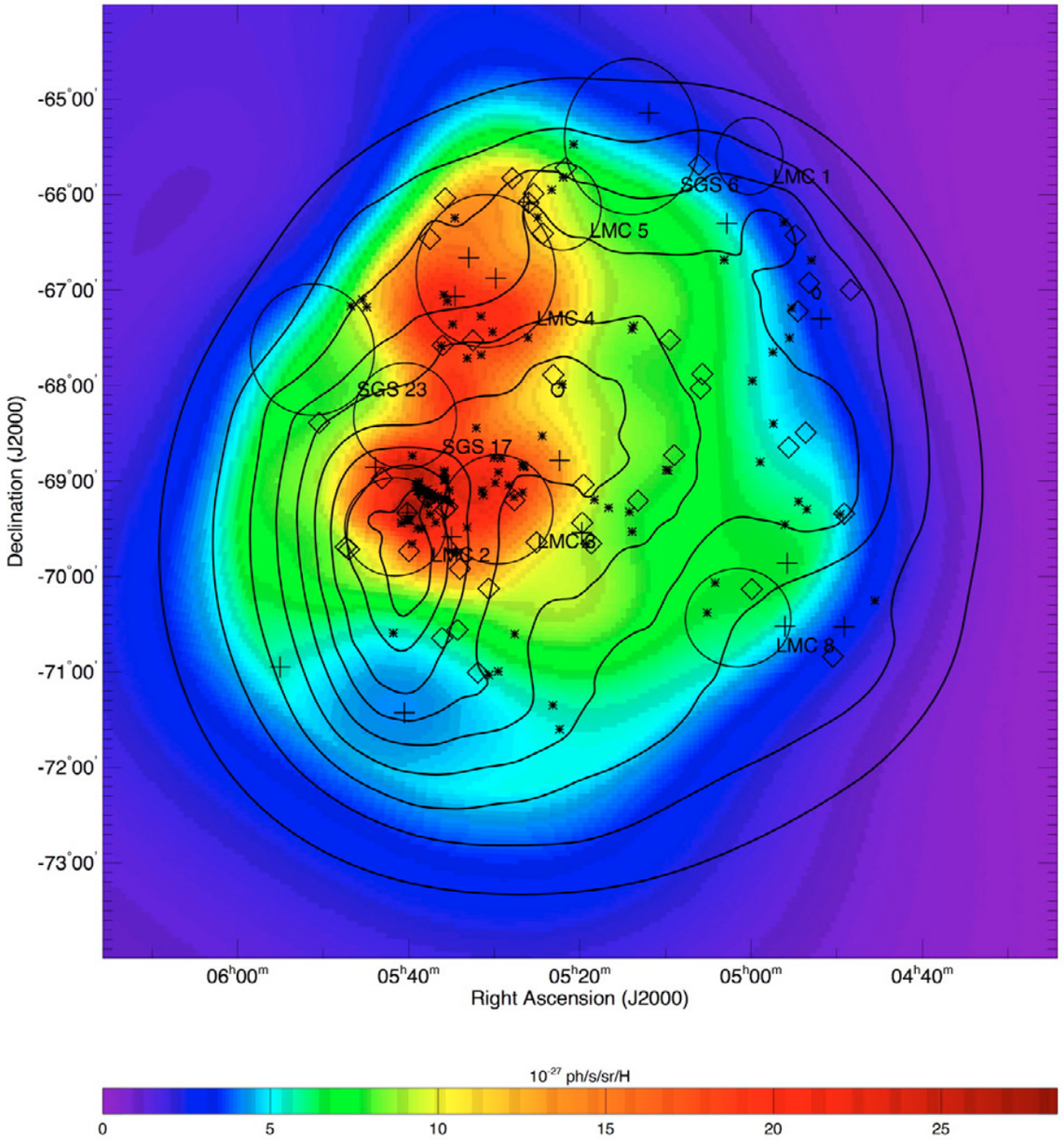
Probing cosmic rays in external galaxies

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

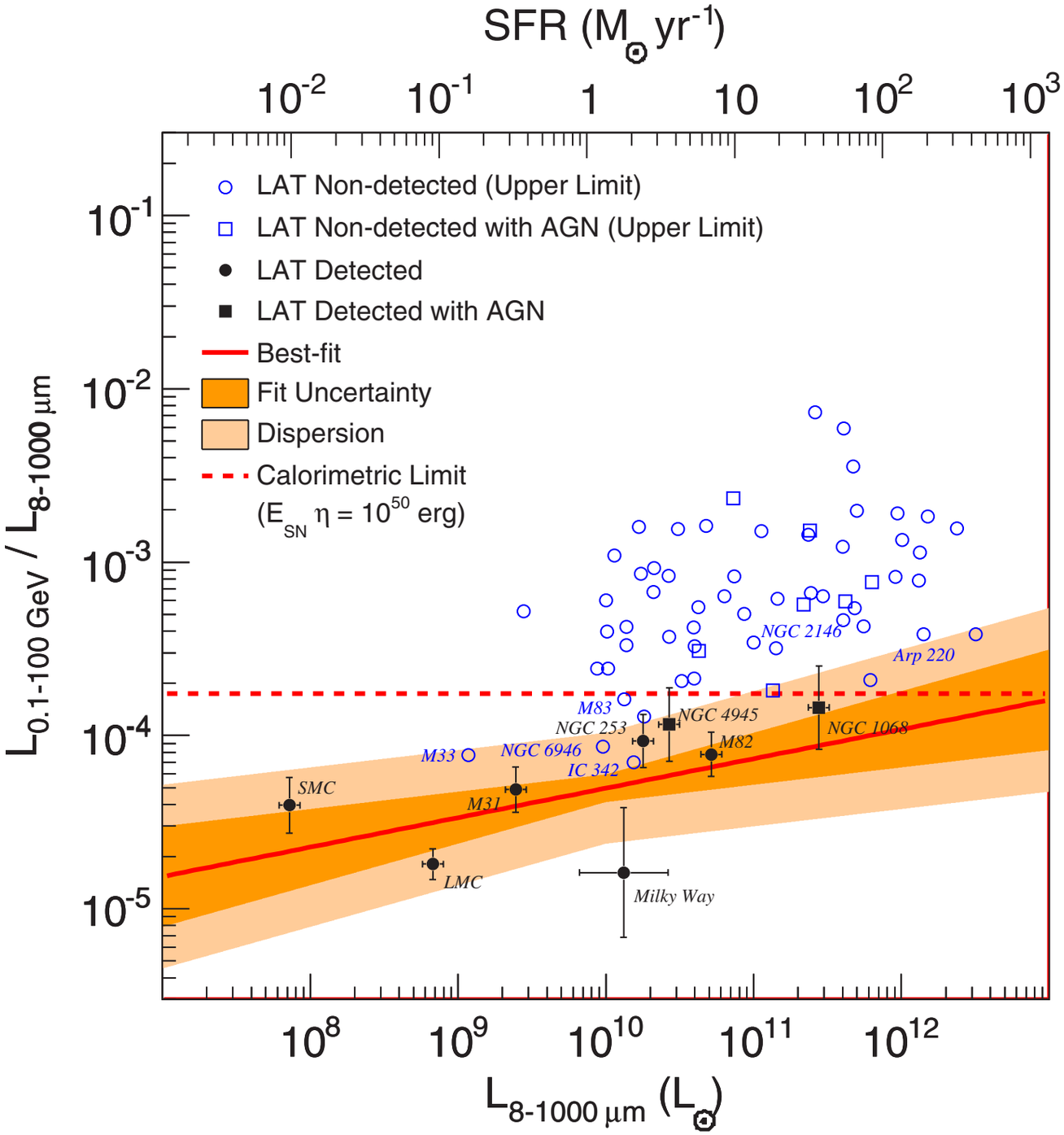


Large Magellanic Cloud:
γ-ray emissivity map
(Abdo+ 2010 A&A 512 A7
Murphy+ 2012 ApJ 750 126)

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?



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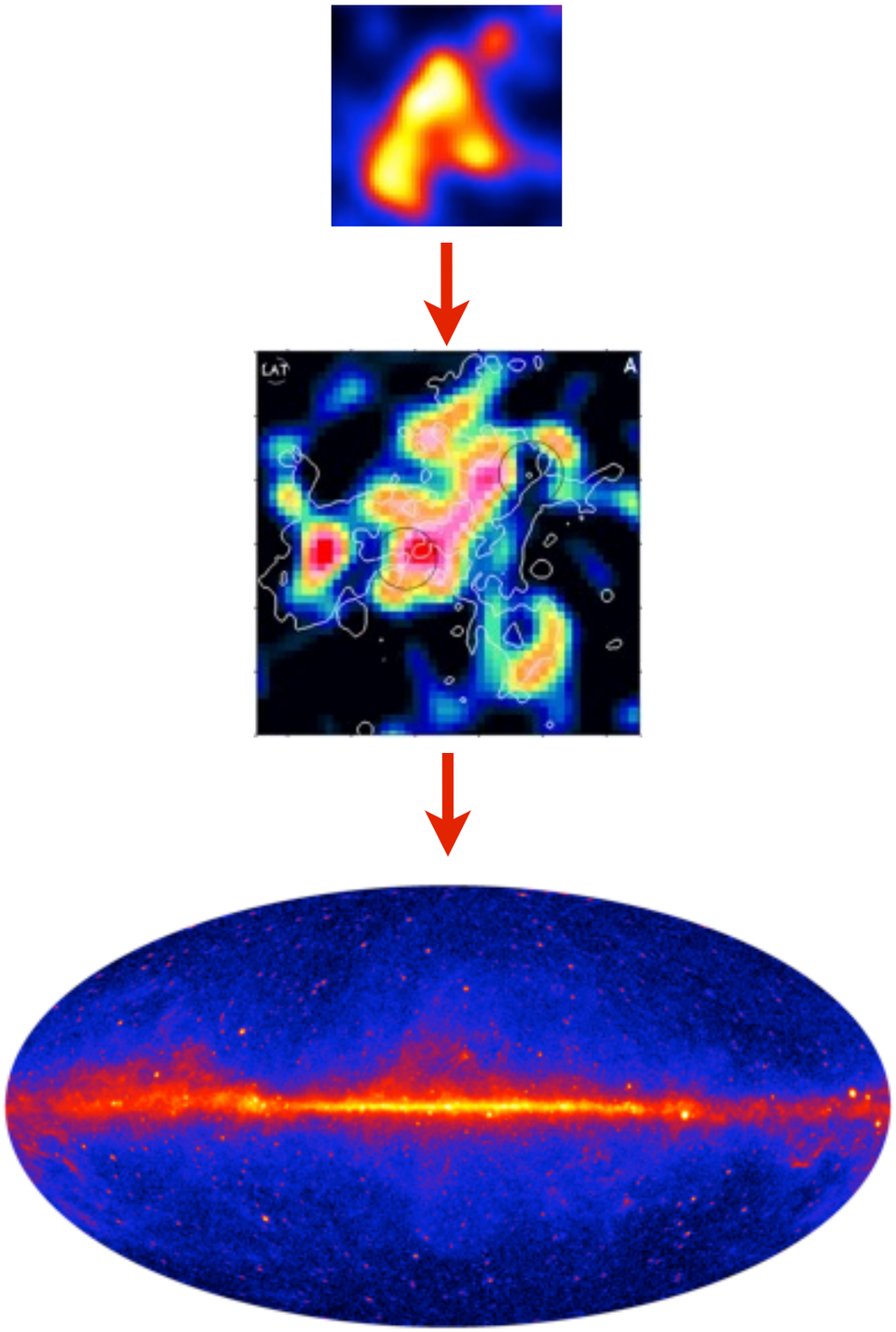
Summary



- supernova remnants
- massive-star forming regions
- galaxies