Fermi LAT observations of diffuse γ-ray emission

modeling, uncertainties and implications for cosmic rays

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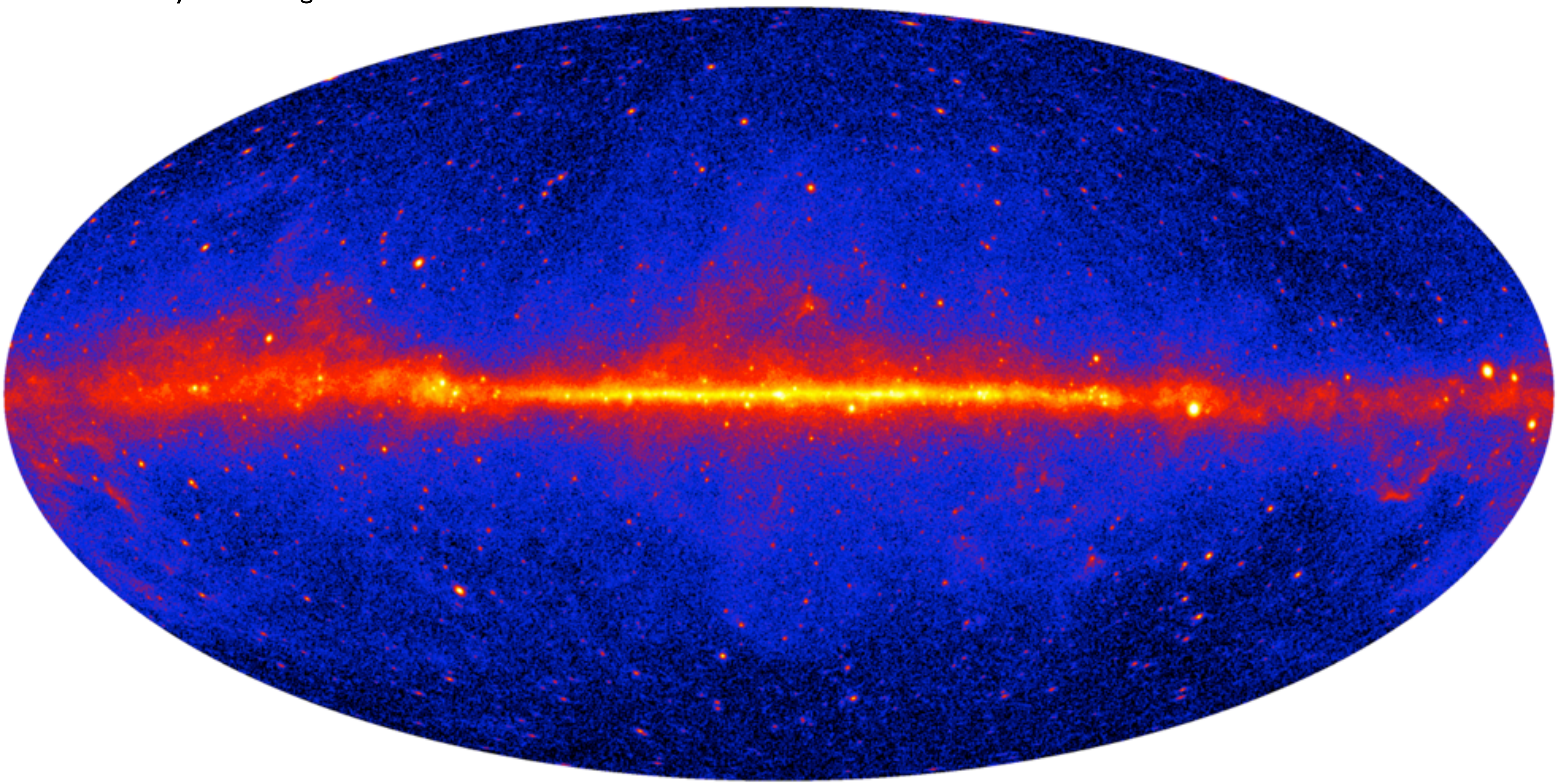
Outline

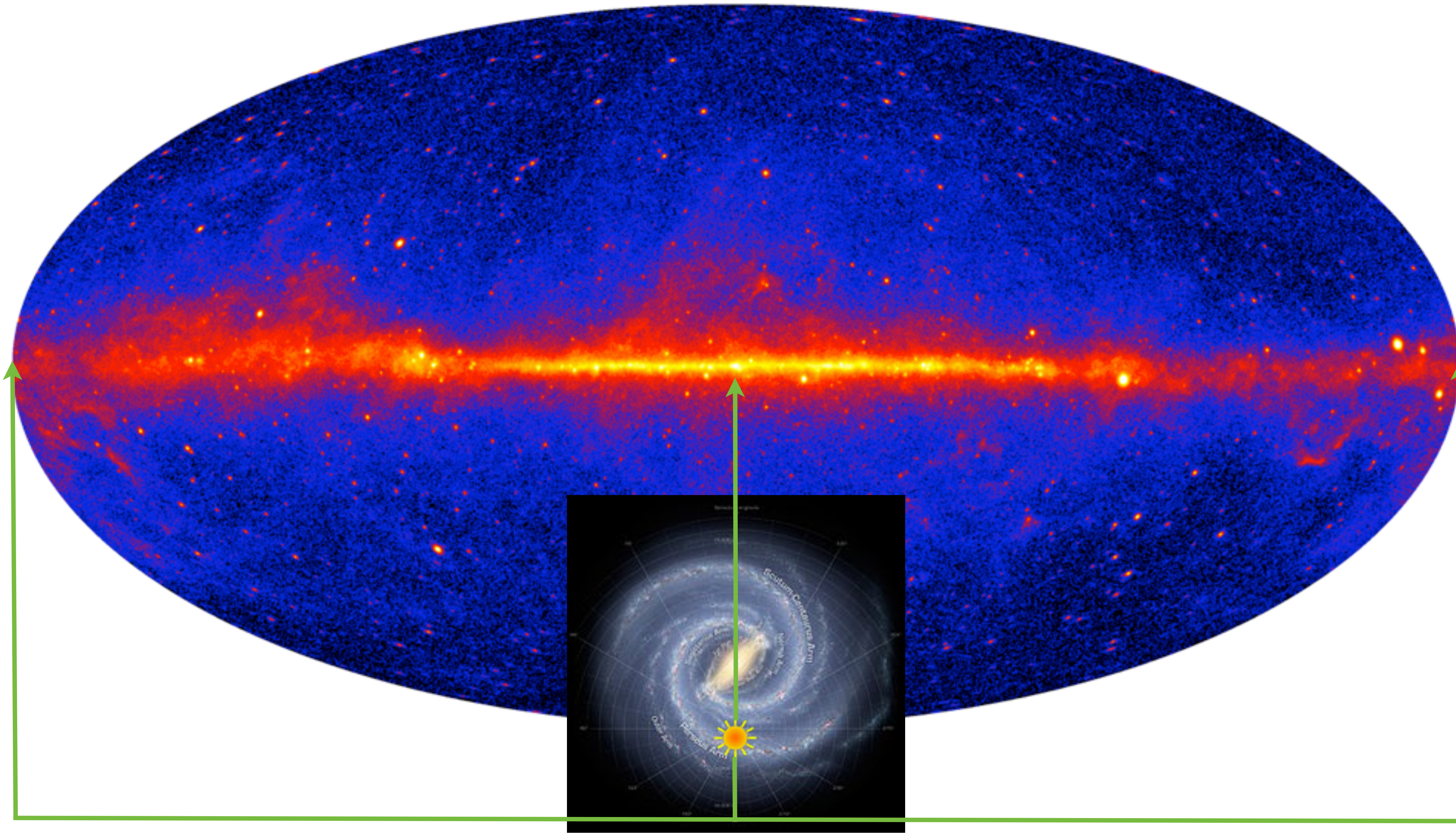
- The diffuse γ-ray sky
- Recipes to model Galactic interstellar emission
- Implications for cosmic rays
- Evaluating systematic uncertainties due to diffuse emission modeling

The (diffuse) γ-ray sky

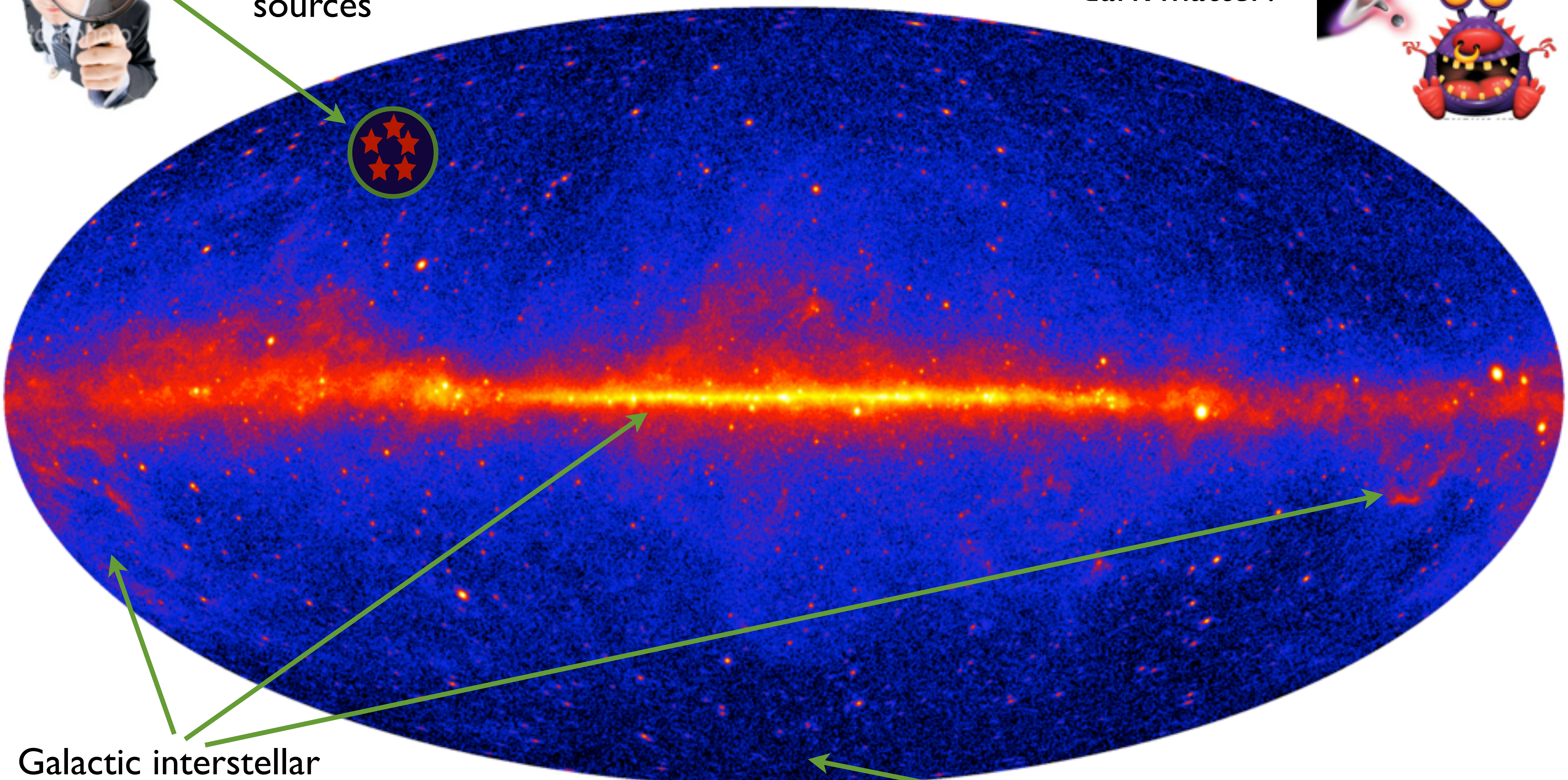
Fermi LAT, 4 years, energies > 1 GeV



The (diffuse) γ-ray sky



The (diffuse) γ-ray sky



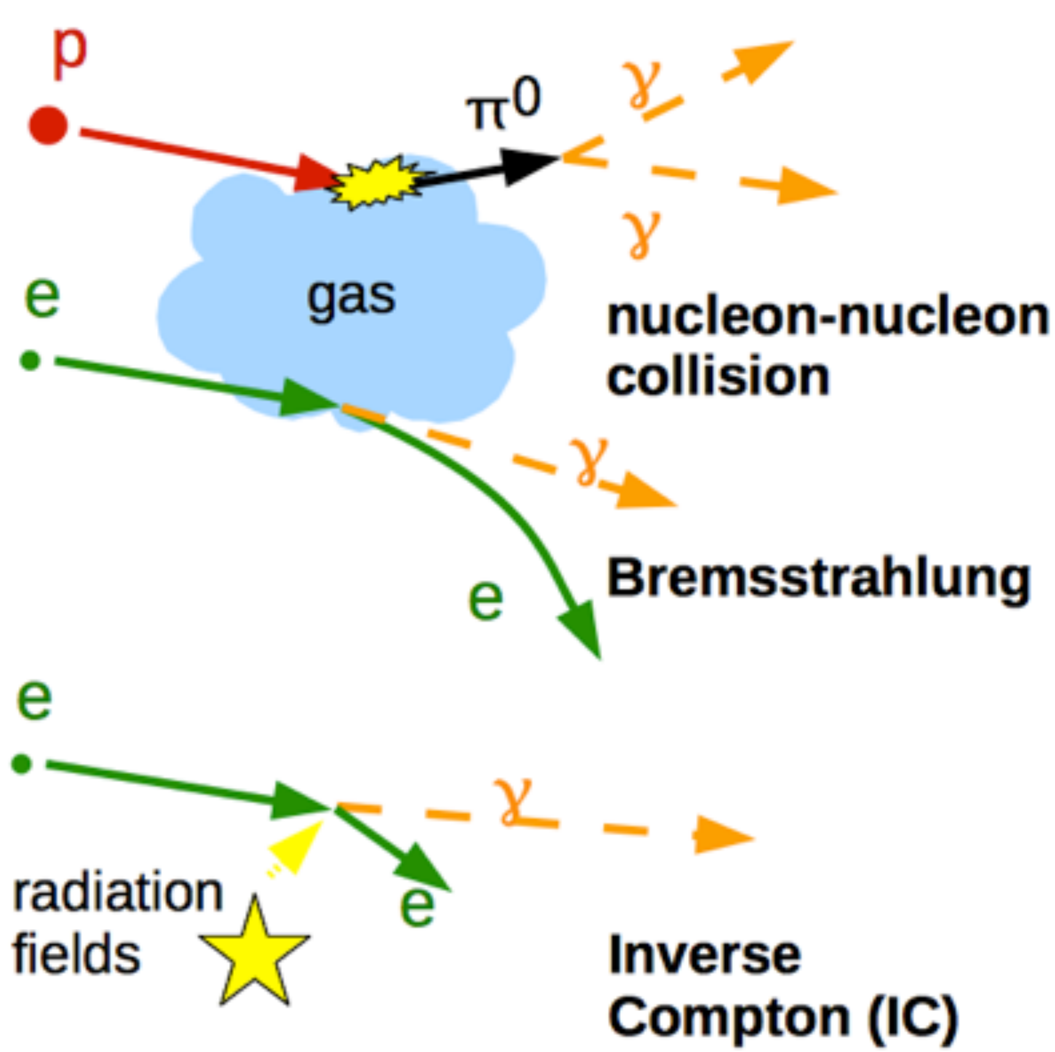
unresolved
sources

exotic Physics?
dark matter?

Galactic interstellar
emission:
cosmic rays +
interstellar gas/photons

isotropic (extragalactic?)
γ-ray background

Galactic interstellar γ-ray emission



- cosmic-ray interactions, distribution
- its understanding enables us to search for
  - sources
  - extragalactic emission
  - dark matter

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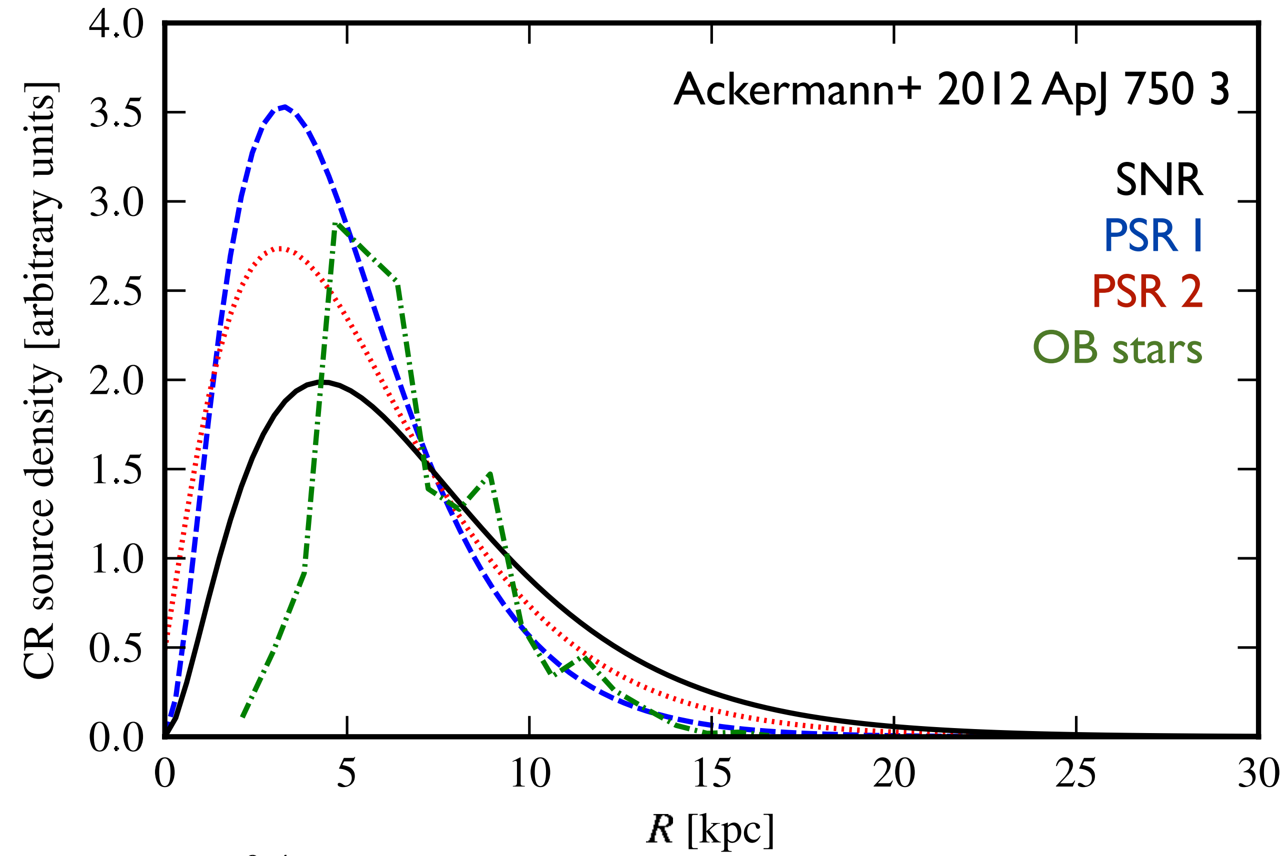
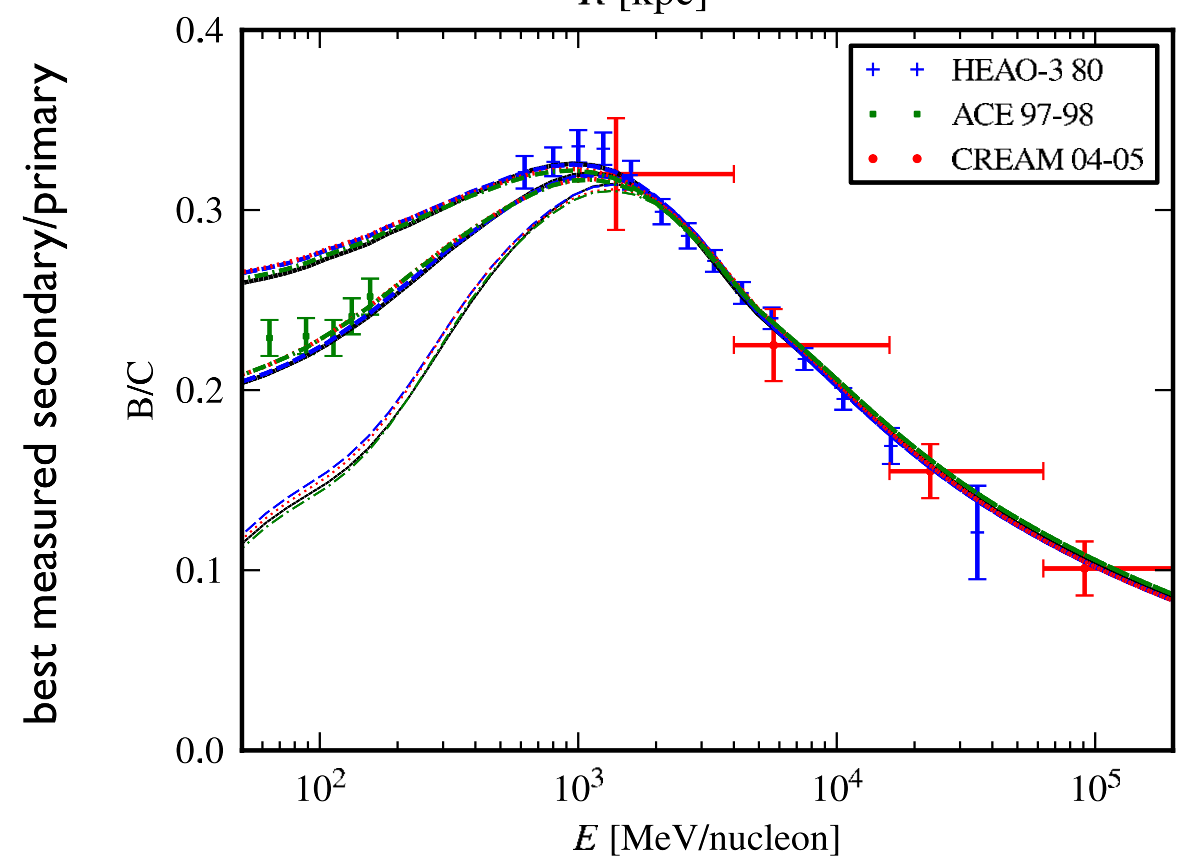
Ingredients: CR sources and transport

- CR source distribution
  - supernova remnants, pulsars, massive stars ...
  - spiral arm structure?
- CR injection spectrum at sources
- transport mechanism(s)
  - diffusion coefficient
  - role of convection, reacceleration?
- size of propagation volume



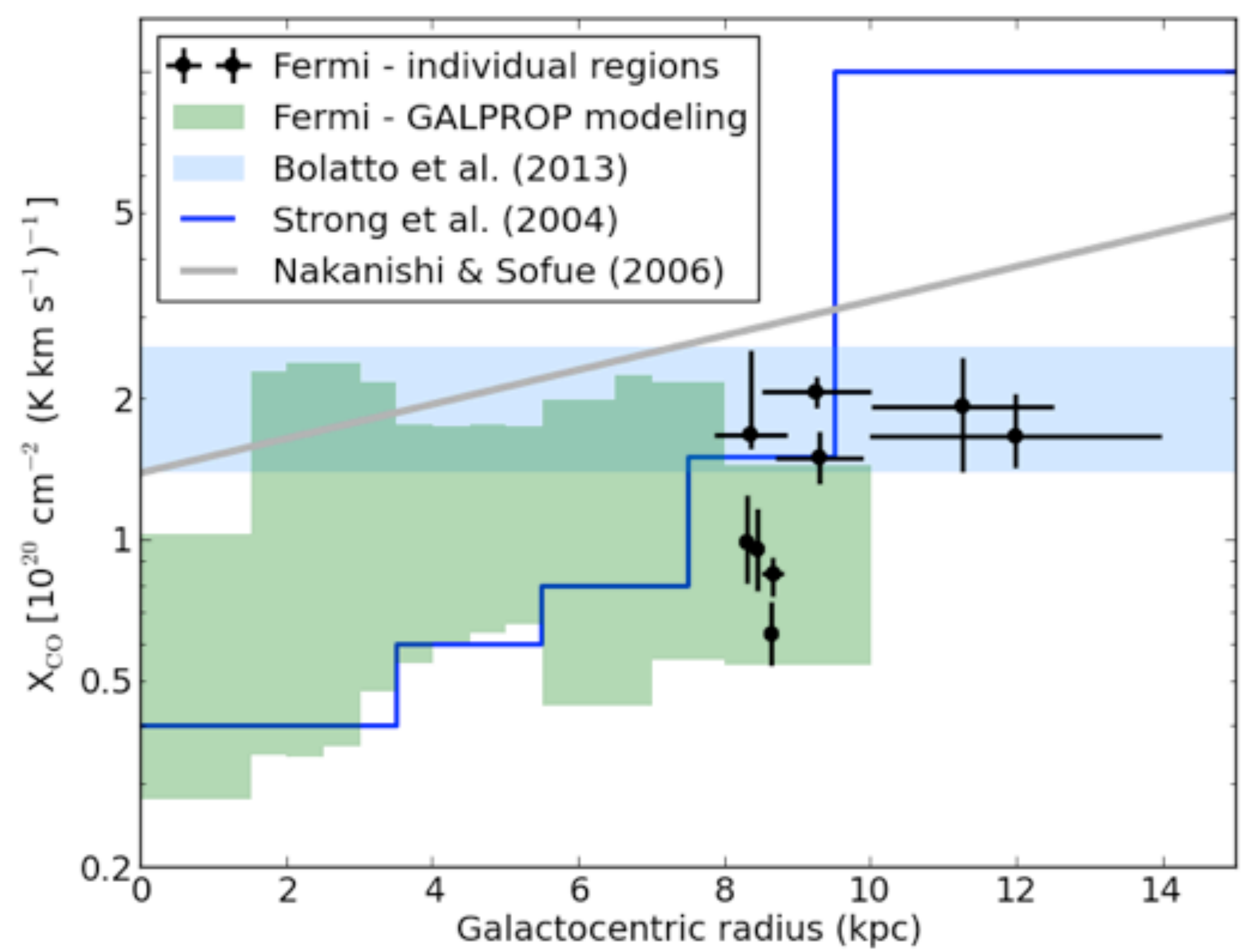


Ingredients: targets

- gas distribution from
  - radio lines (Doppler shift → distance), e.g., CfA CO survey
  - dust emission/extinction, e.g.., Planck
- photon fields from (observations+models)
  - starlight
  - dust irradiated by stars
  - CMB

CO traces molecular hydrogen

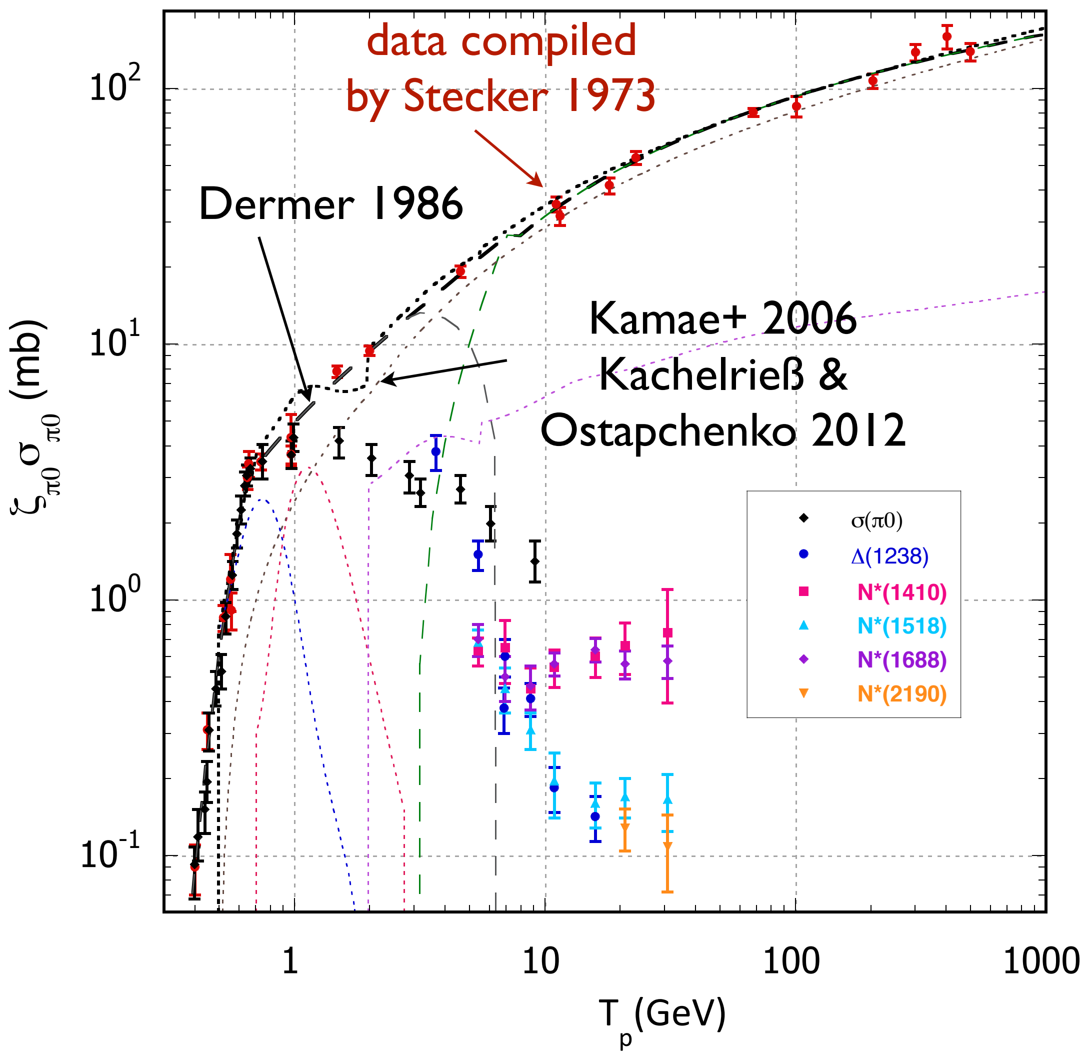
$$X_{\mathrm{CO}} = \frac{N(\mathrm{H}_2)}{W_{\mathrm{CO}}}$$

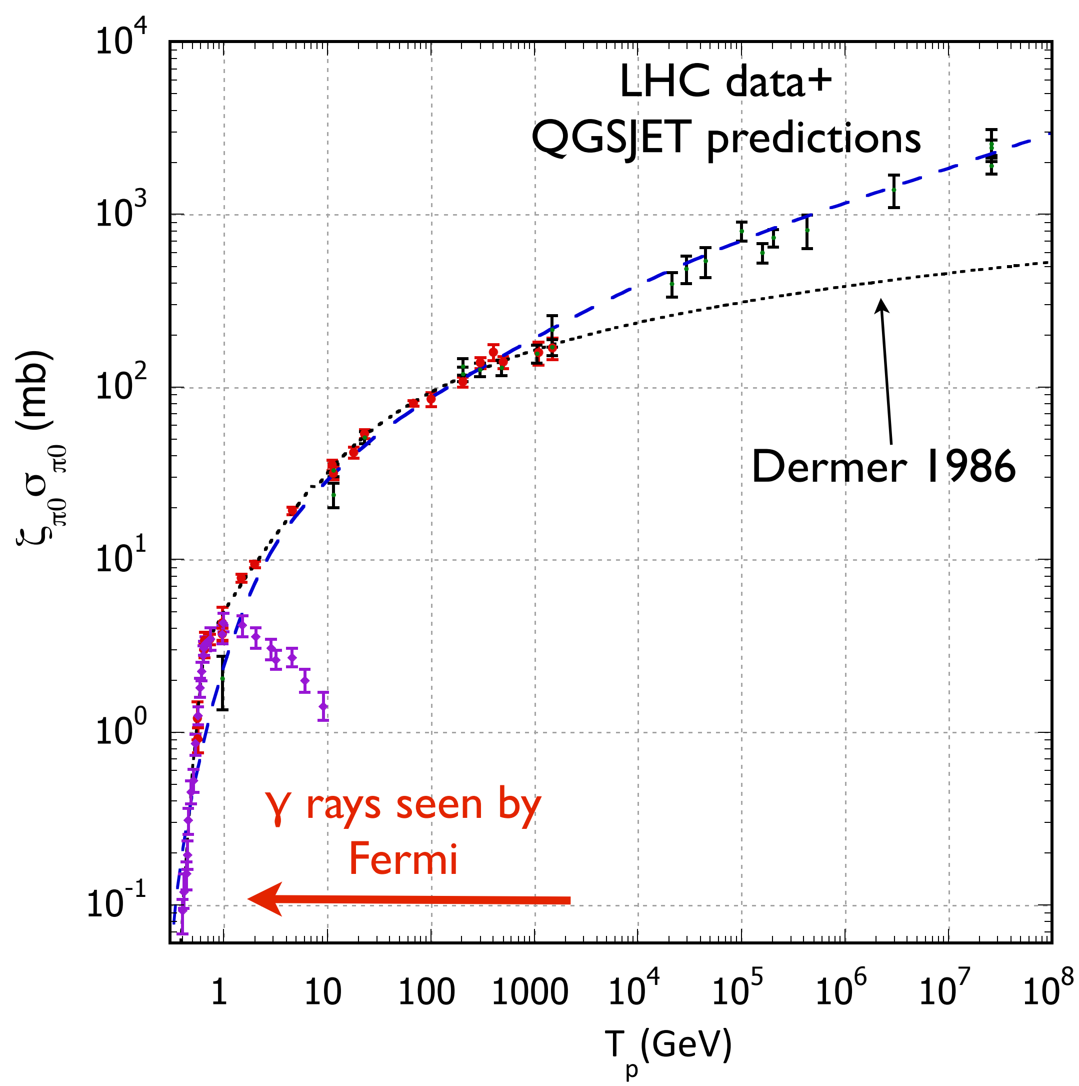


Ingredients: interaction models

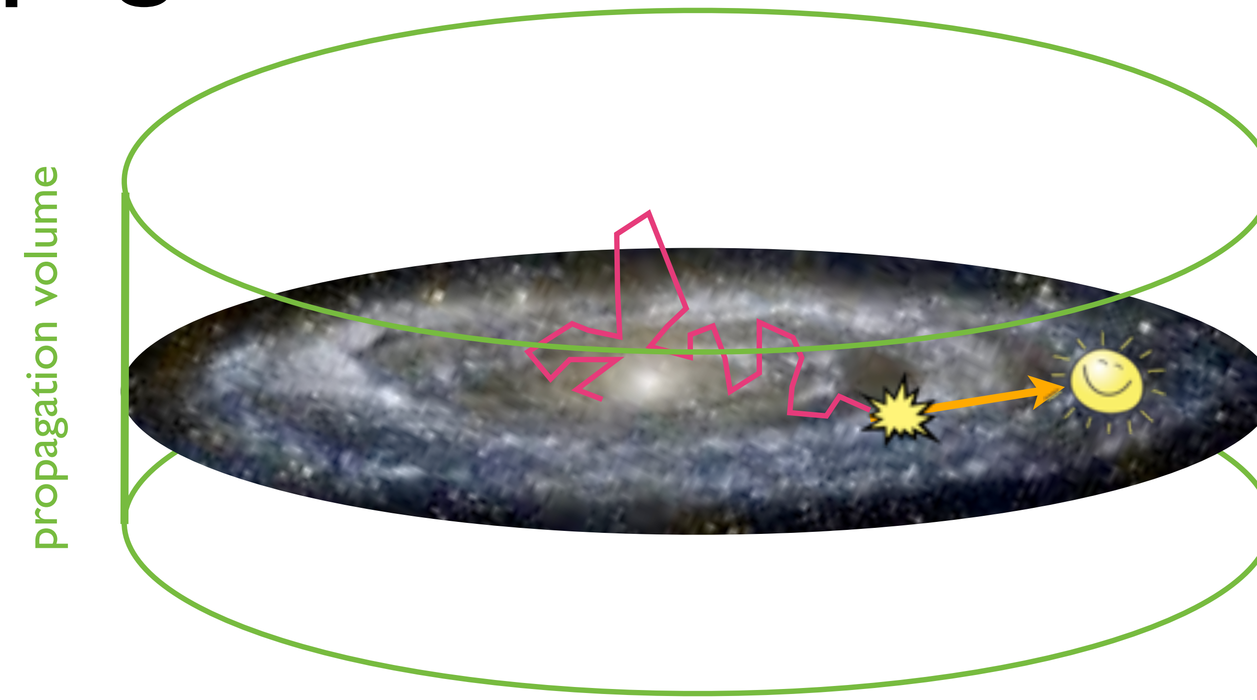
- data and theory from particle physics
- for nuclear interactions
  - limited measurements (bullet energies, bullet/target species, angular distribution)
  - bridged by theoretical framework(s)
  - 5-15% uncertainties at T_p < 10 GeV

Dermer+ 2013, ICRC, arXiv:1307.0497



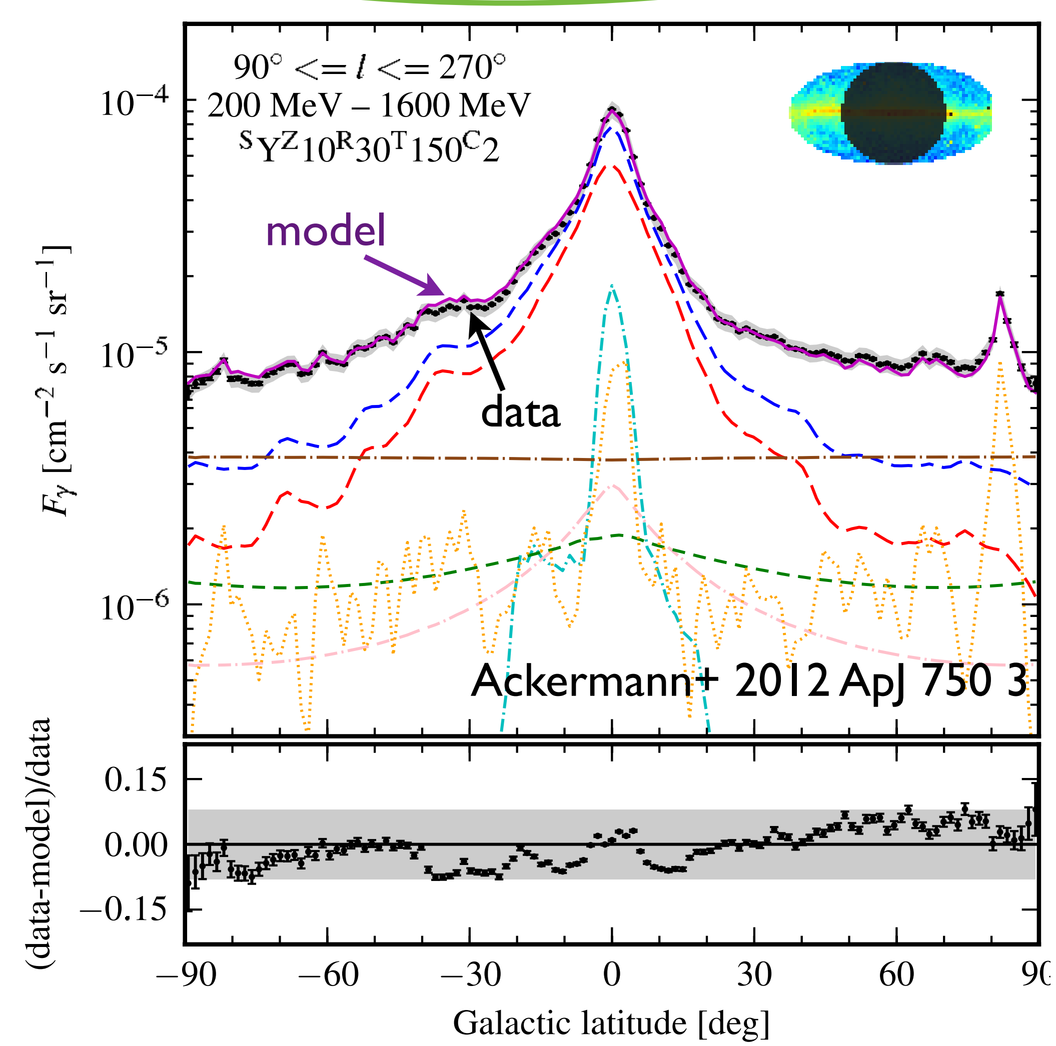


Recipe 1: CR propagation codes

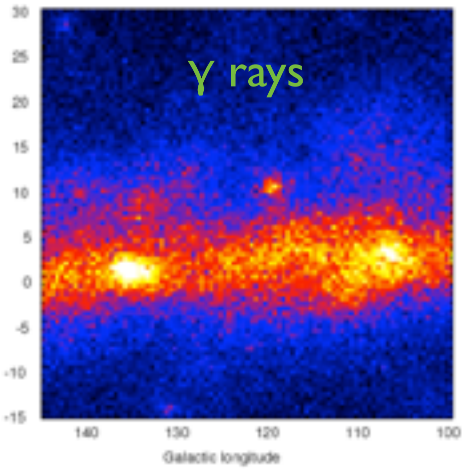


- calculate CR propagation in the Galaxy
- simplified but realistic model of the Galaxy from observations
  - cosmic-ray sources
  - targets for gamma production
- *Fermi* LAT collaboration extensively uses GALPROP (Strong, Moskalenko et al.)

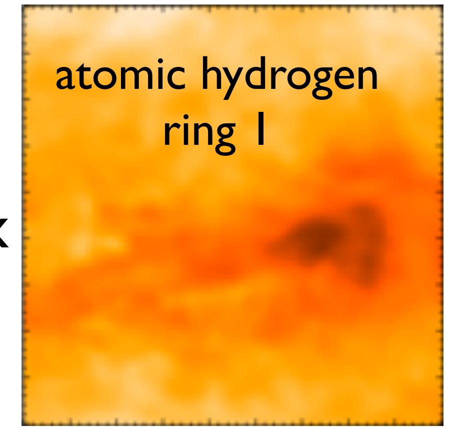
  http://galprop.stanford.edu/
- agreeement with LAT data within 20% over whole sky



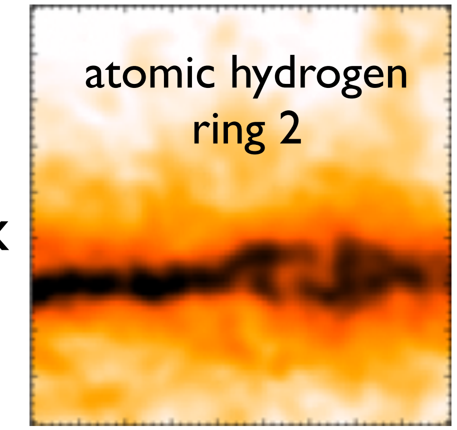
Recipe 2: templates



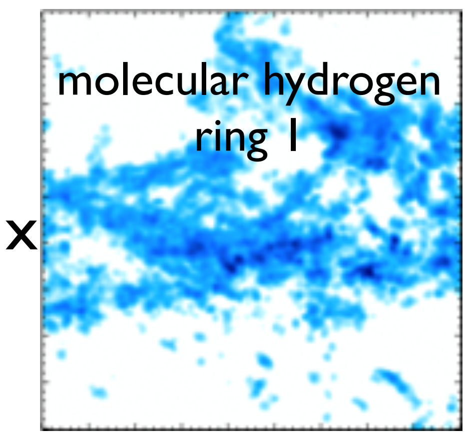
= PSF ⊕ exposure x [$q(\text{H I})_1$ x



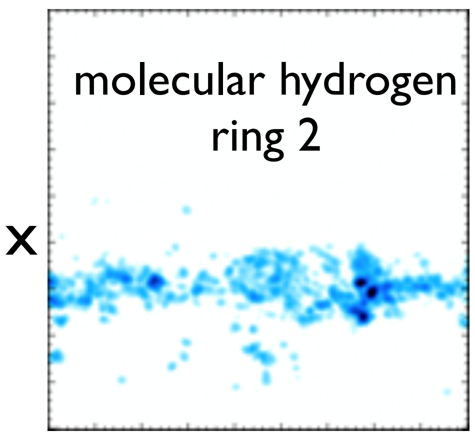
+ $q(\text{H I})_2$ x



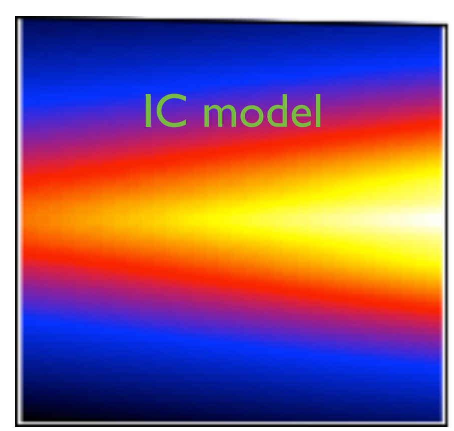
+ $q(\text{CO})_1$ x



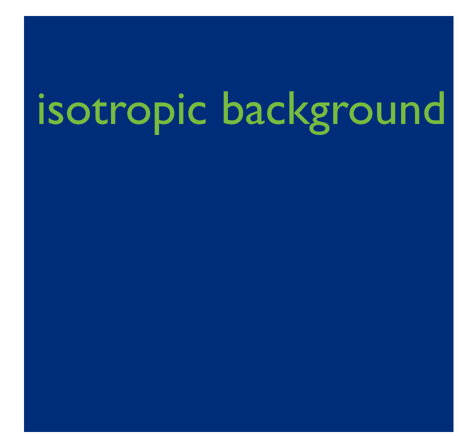
+ $q(\text{CO})_2$ x



+ α_{IC} x



+ I_{iso} x

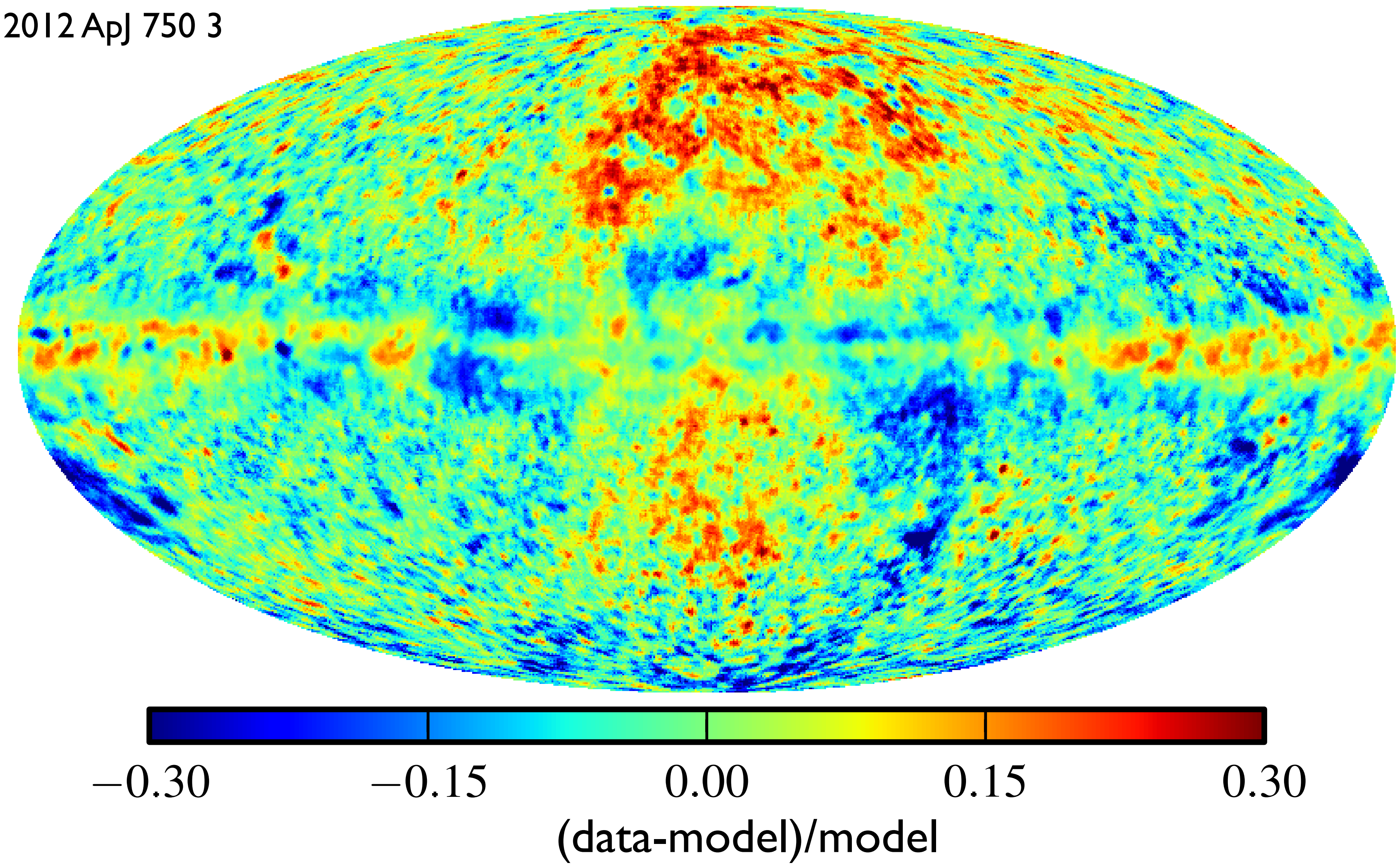


+ sources]

gas tracer maps
lines → kinematic separation
of different structures along the line of sight

Not everything is in our templates ...

Ackermann+ 2012 ApJ 750 3



Large scale features:

- Fermi bubbles

  (Su, Slatyer & Finkbeiner 2010)

- Loop I (Casandjian & Grenier 2009)

- Many features on the Galactic plane

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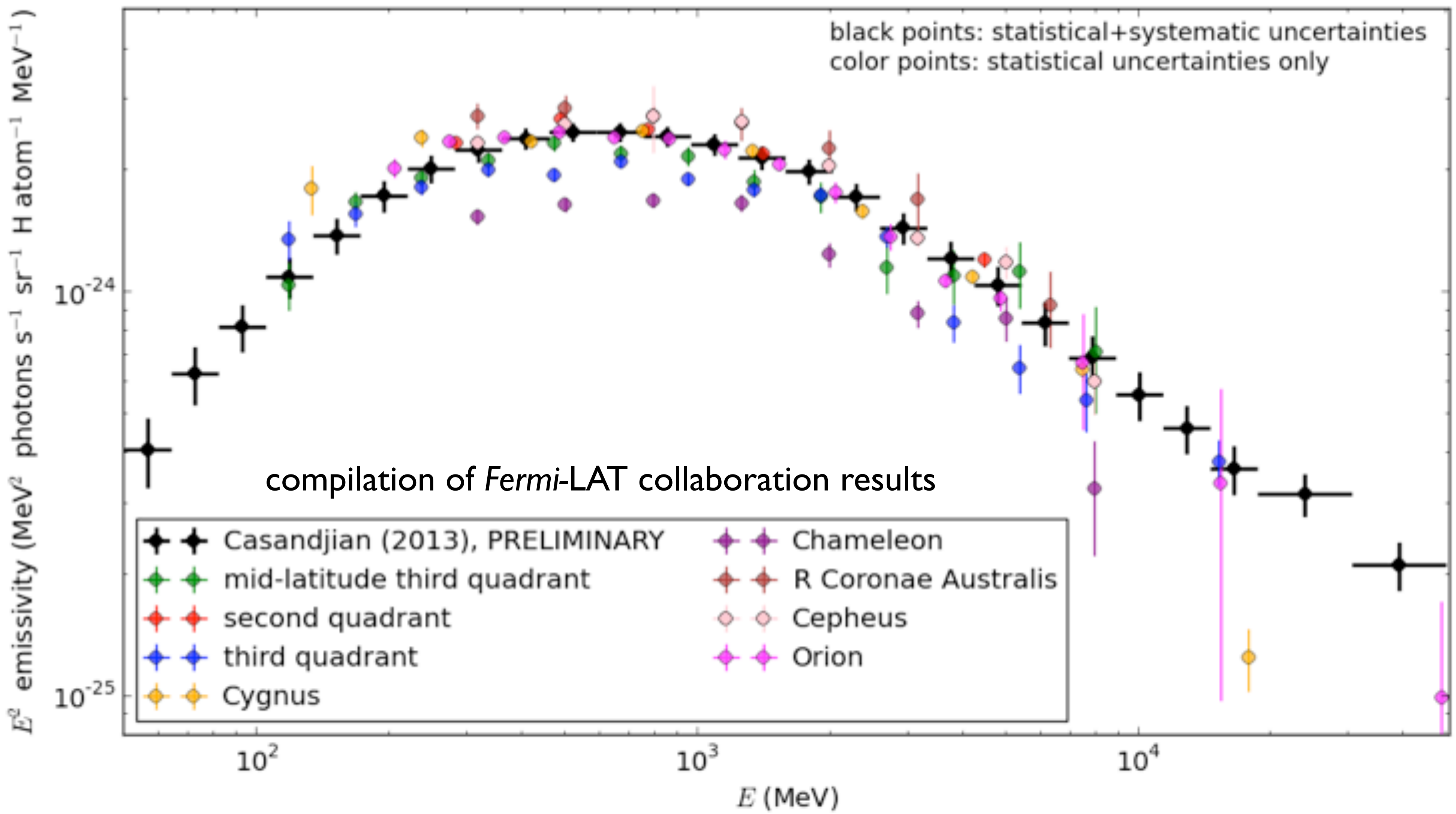
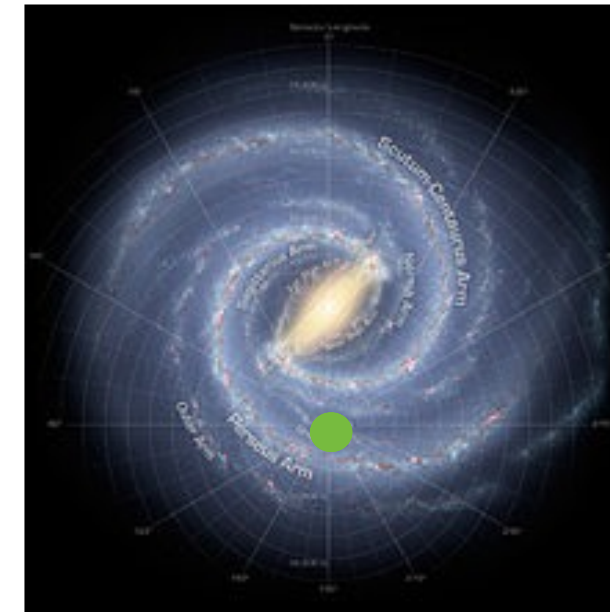
The local γ-ray emissivity

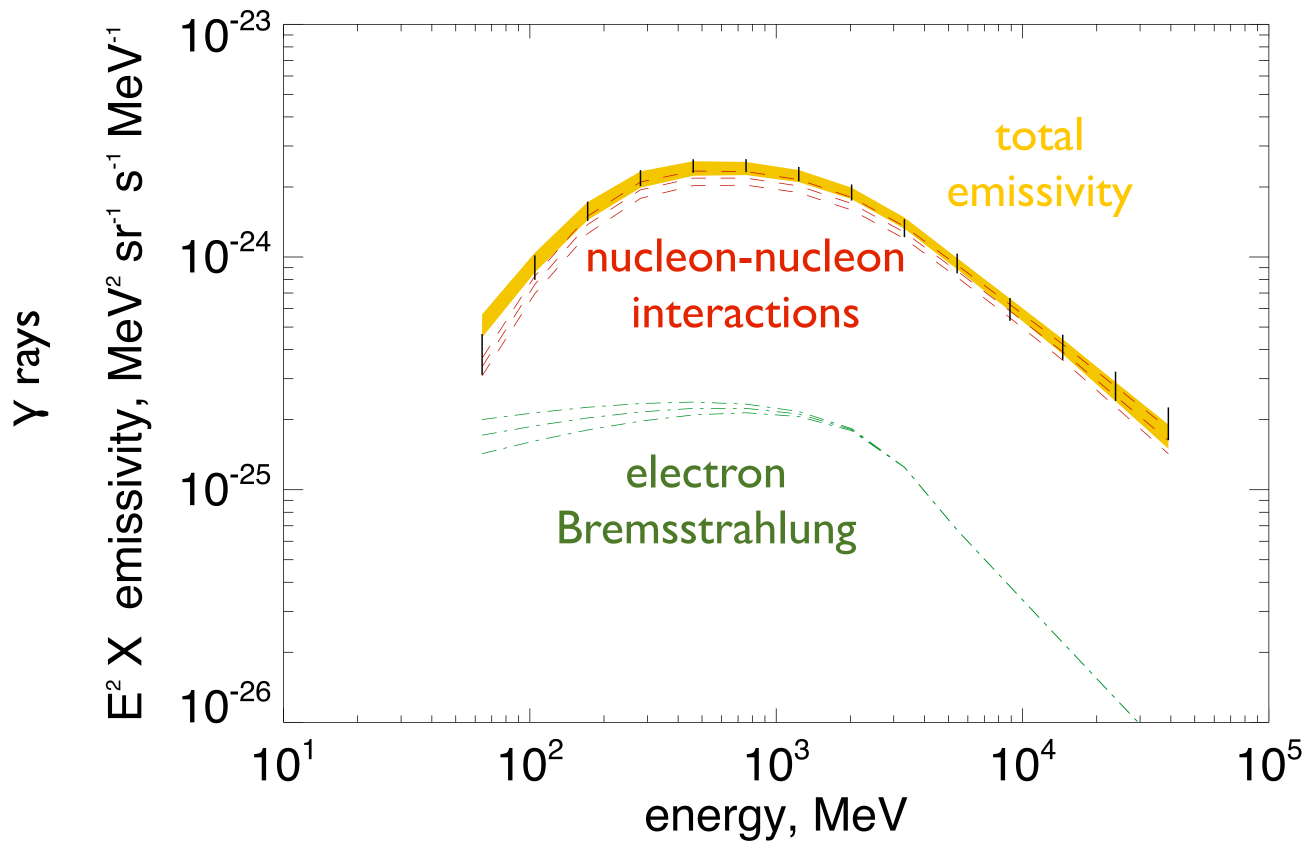


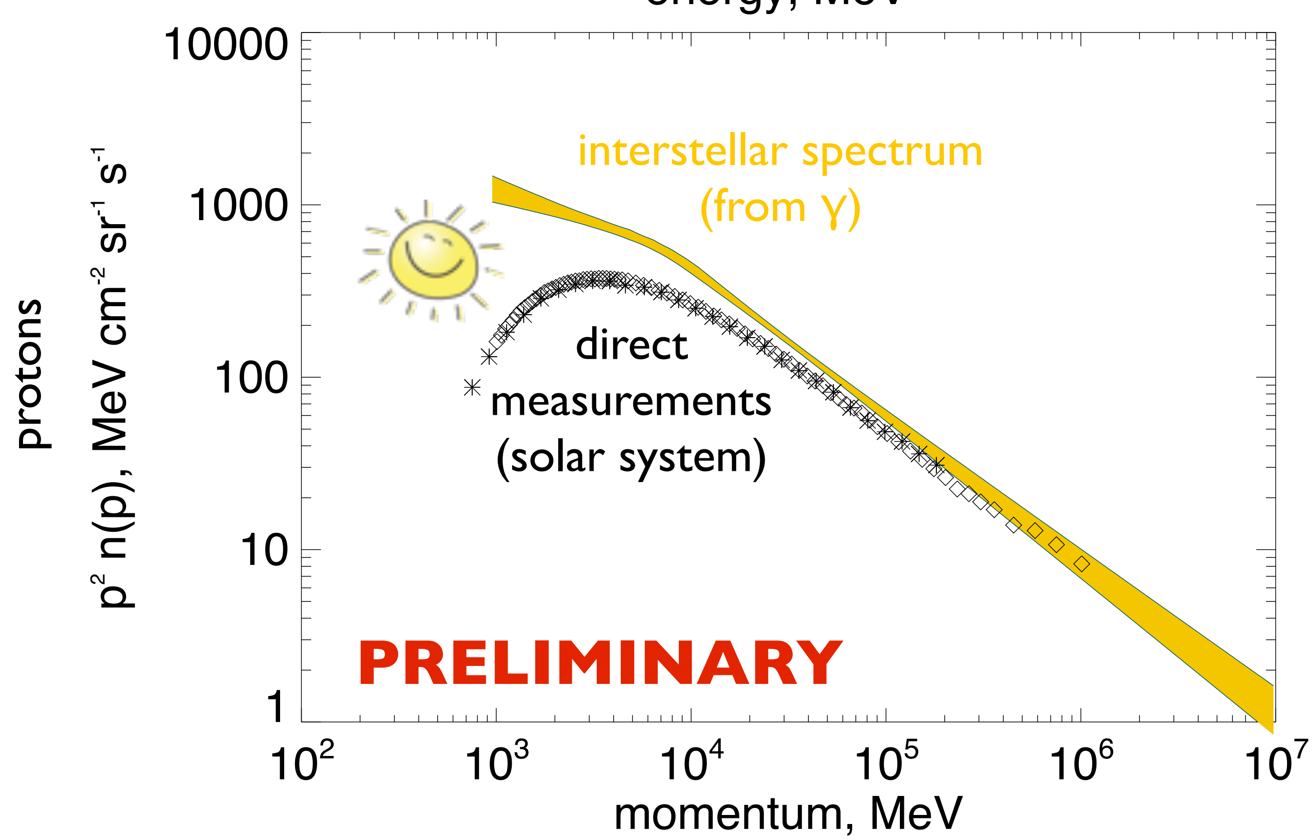


within
~1 kpc
from the Sun

- γ-ray emission rate per H atom in the local interstellar medium
  - 10-20% uncertainties in the measurement
  - can be compared to direct cosmic-ray measurements

Local interstellar cosmic-ray spectra



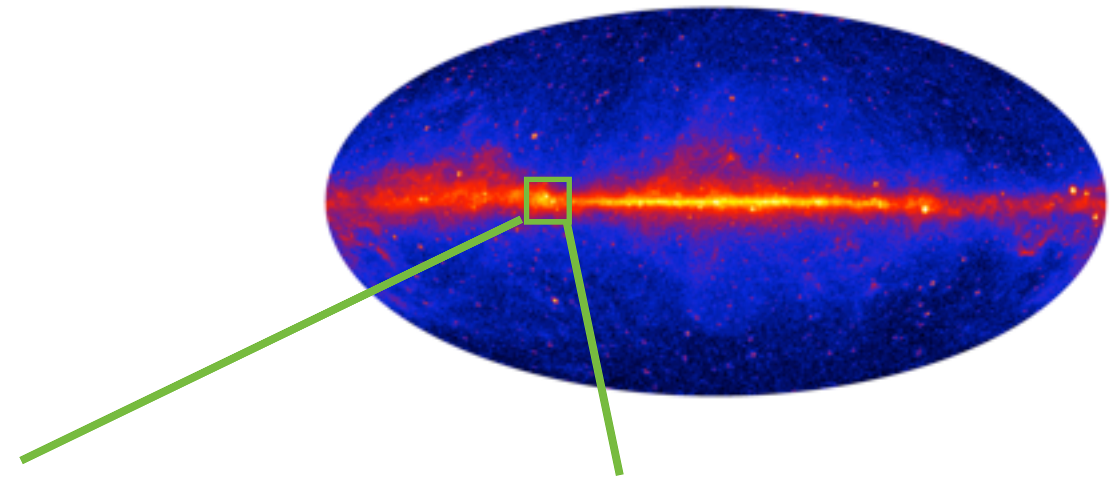


- can measure interstellar p spectrum from γ alone
- need to take into account uncertainties in nuclear production models

Dermer+ 2013, ICRC, arXiv:1307.0497

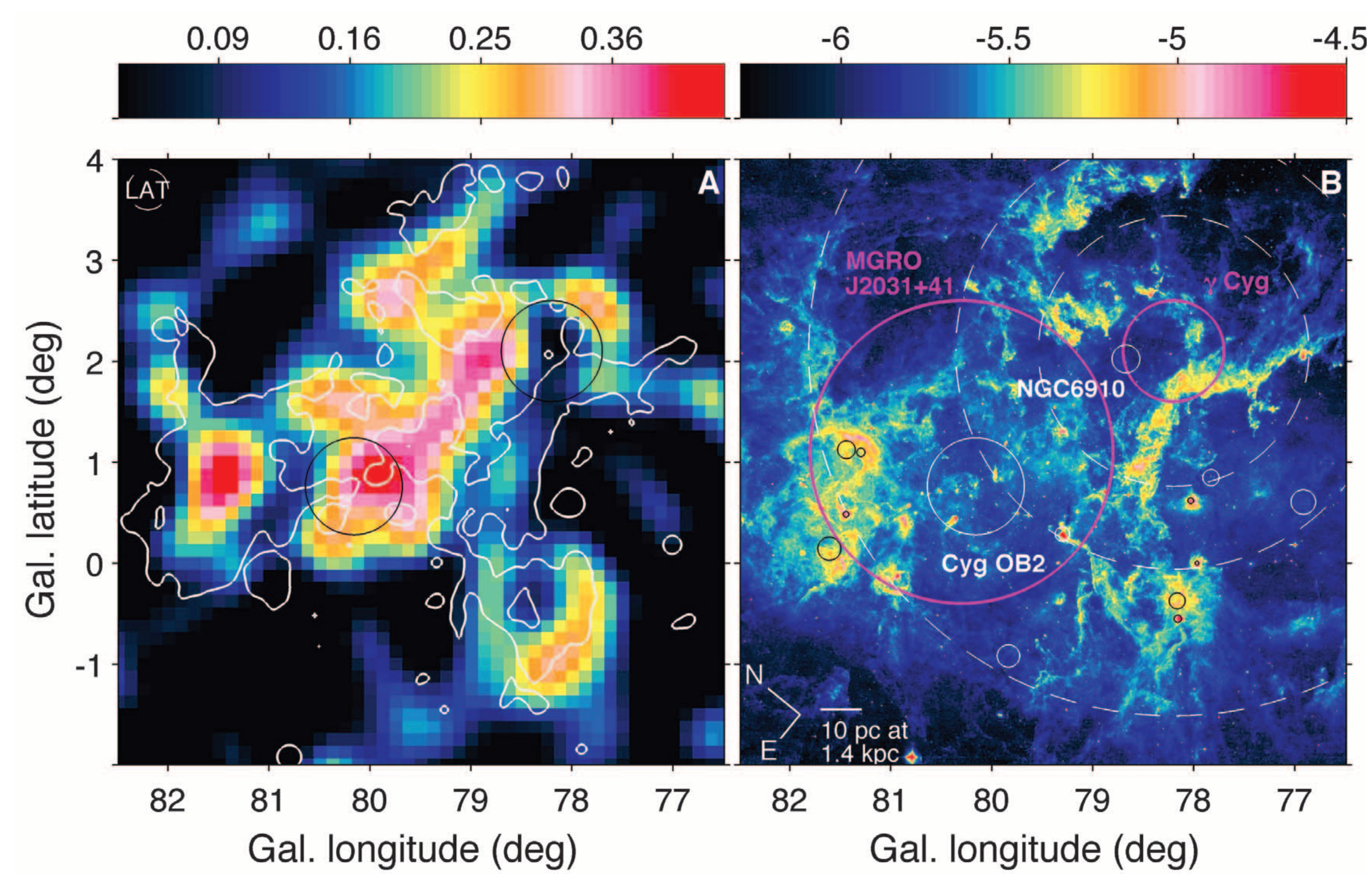
The *Fermi* LAT view of Cygnus X

- massive star-forming region:
  - 1.5 kpc from the Sun
  - > 100 O stars
  - 10M solar masses of gas
- extended excess of γ rays with hard spectrum w.r.t. model with local emissivity



LAT - γ-ray background subtracted > 10 GeV (counts/bin)

interstellar cavities MSX - 8 μm (W m^{-2} sr^{-1})



Ackermann+ 2011 Science 334 1103

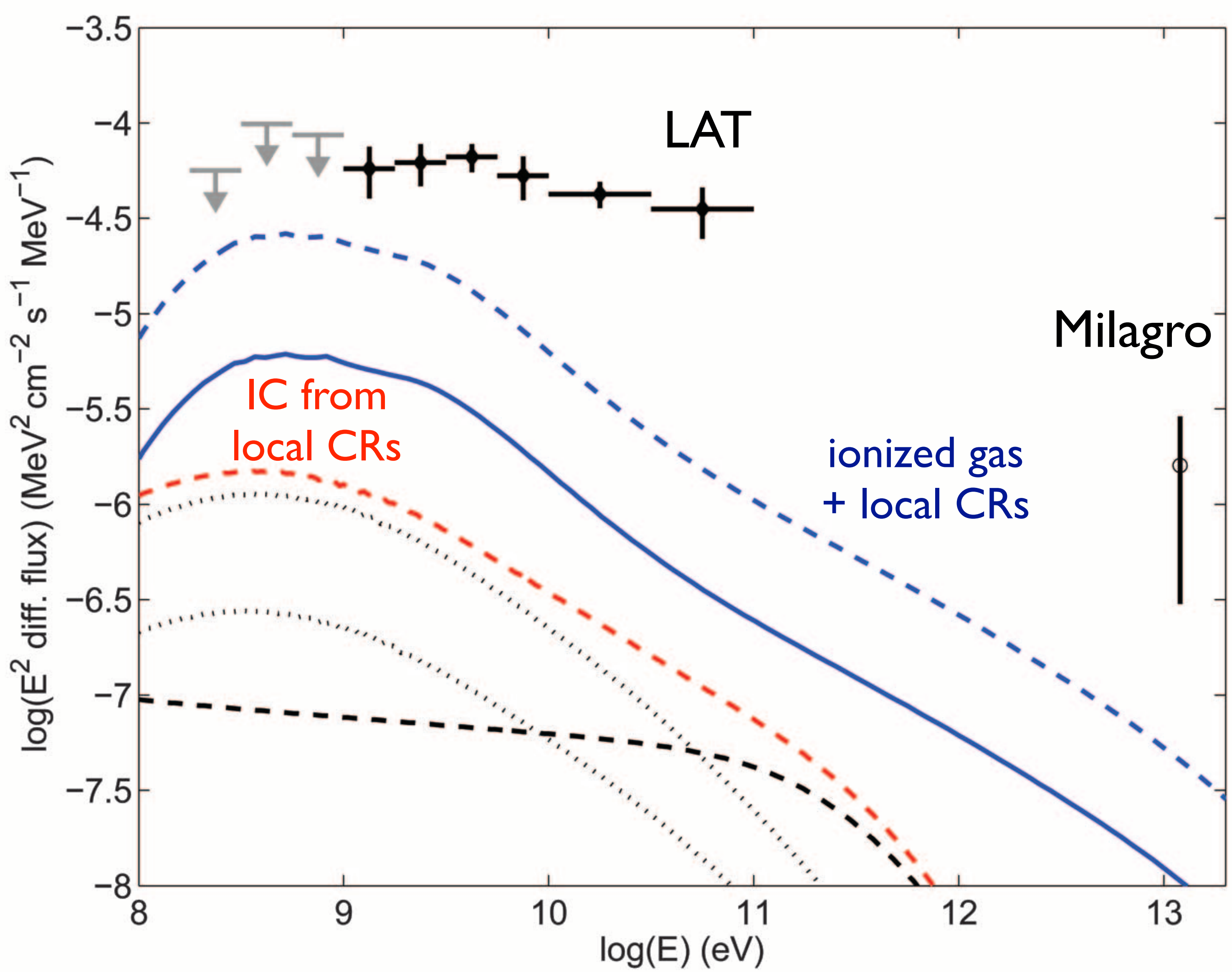
A cocoon of young cosmic rays

- requires **freshly-accelerated CRs**, for local CRs
  - hadronic → too soft amplification factor

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

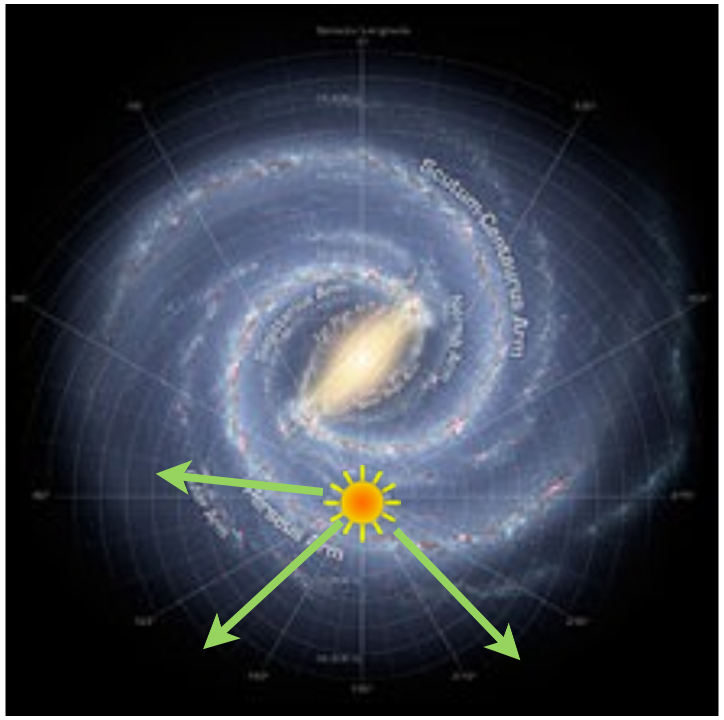
  - leptonic → too soft and faint amplification factor

$$\frac{dN}{dE} \times 60\left(\frac{E}{10\ \mathrm{GeV}}\right)^{0.5}$$



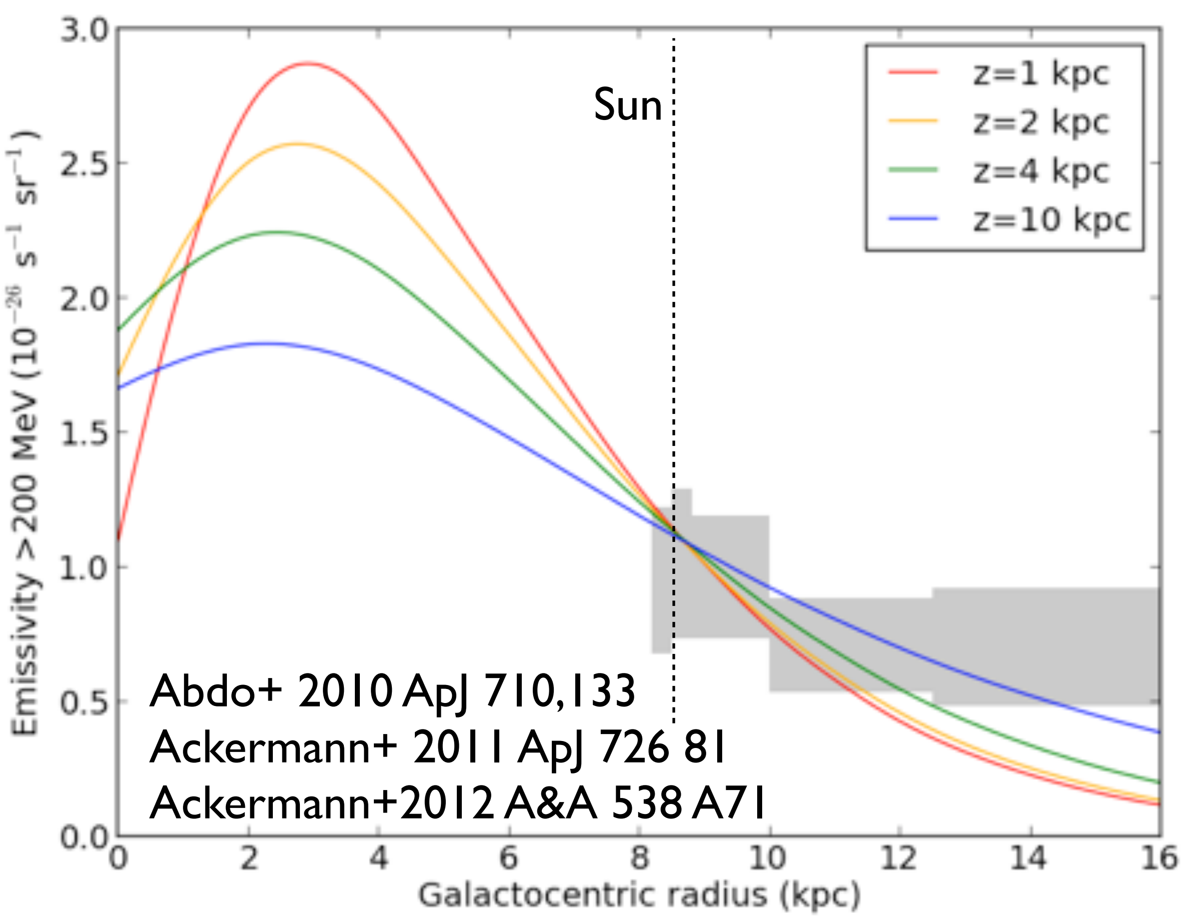
Ackermann+ 2011 Science 334 1103

Outer Galaxy: the gradient problem

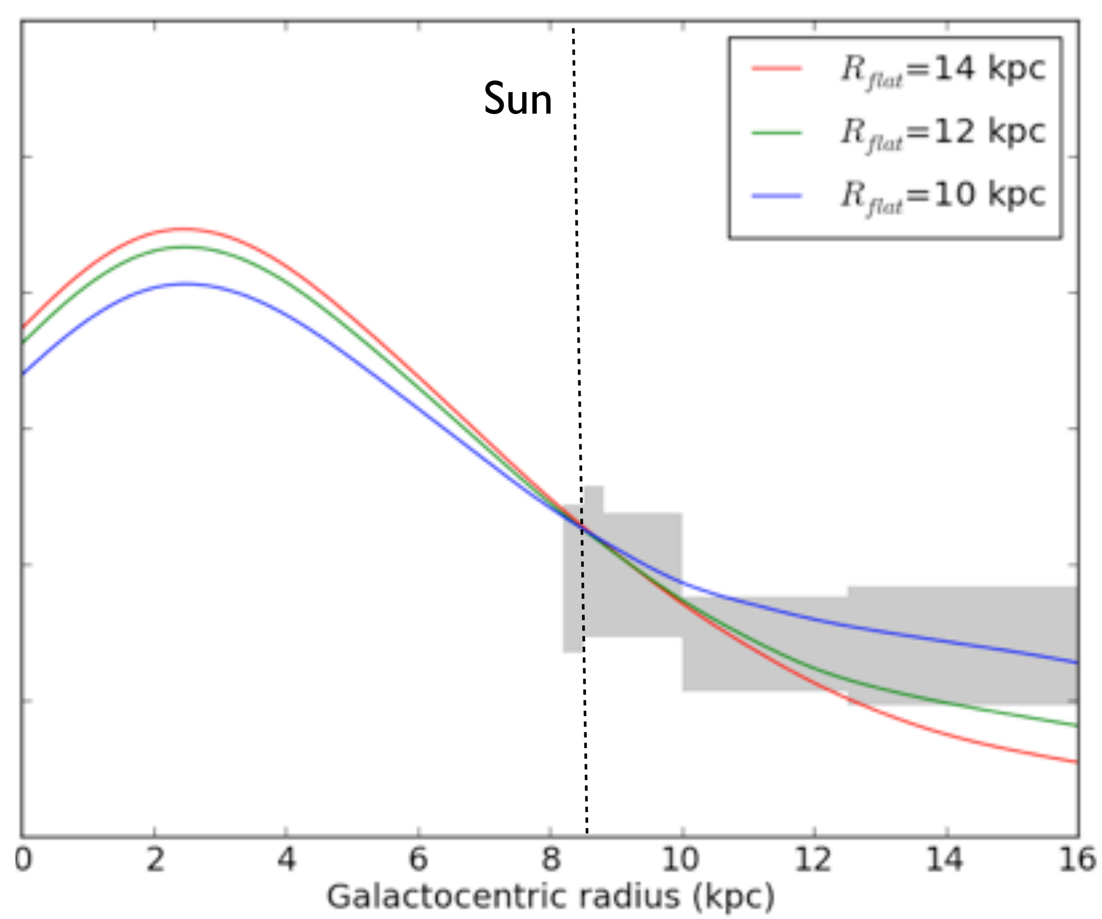


CR densities larger than expected in outer Galaxy

- large propagation halo (z)
- more sources
- missing gas
- varying diffusion coefficient (e.g. Evoli+ 2012), Galactic wind convection (e.g. Breitschwerdt+ 2002)



Abdo+ 2010 ApJ 710,133
Ackermann+ 2011 ApJ 726 81
Ackermann+2012 A&A 538 A71



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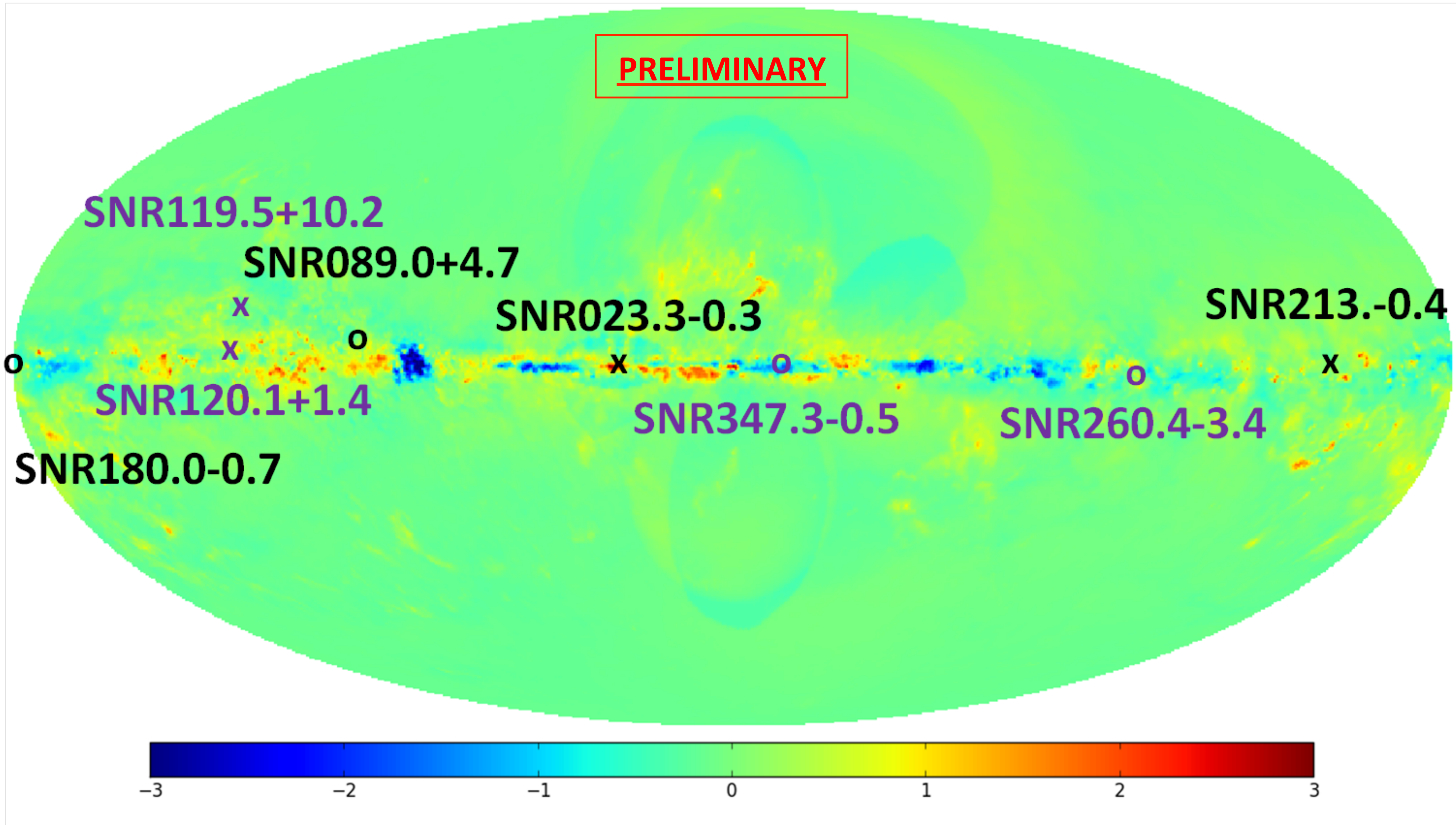
Systematics effects on source studies

- Galactic interstellar emission bright and structured → use alternative models
- for alternative models change
  - building strategy (gas column densities/emissivities)
  - input parameters on a grid (H I spin temperature, CR source distribution, CR propagation halo height)
  - additional components to account for large-scale residuals
- and allow for more freedom in the fit to the γ-ray data (gas in ‘rings’)
- do not bracket standard model or cover the complete range of uncertainties

De Palma+ 2012, Fermi Symposium arXiv:1304.1395

Test case: the supernova remnant Catalog

De Palma+ 2012, Fermi Symposium arXiv:1304.1395

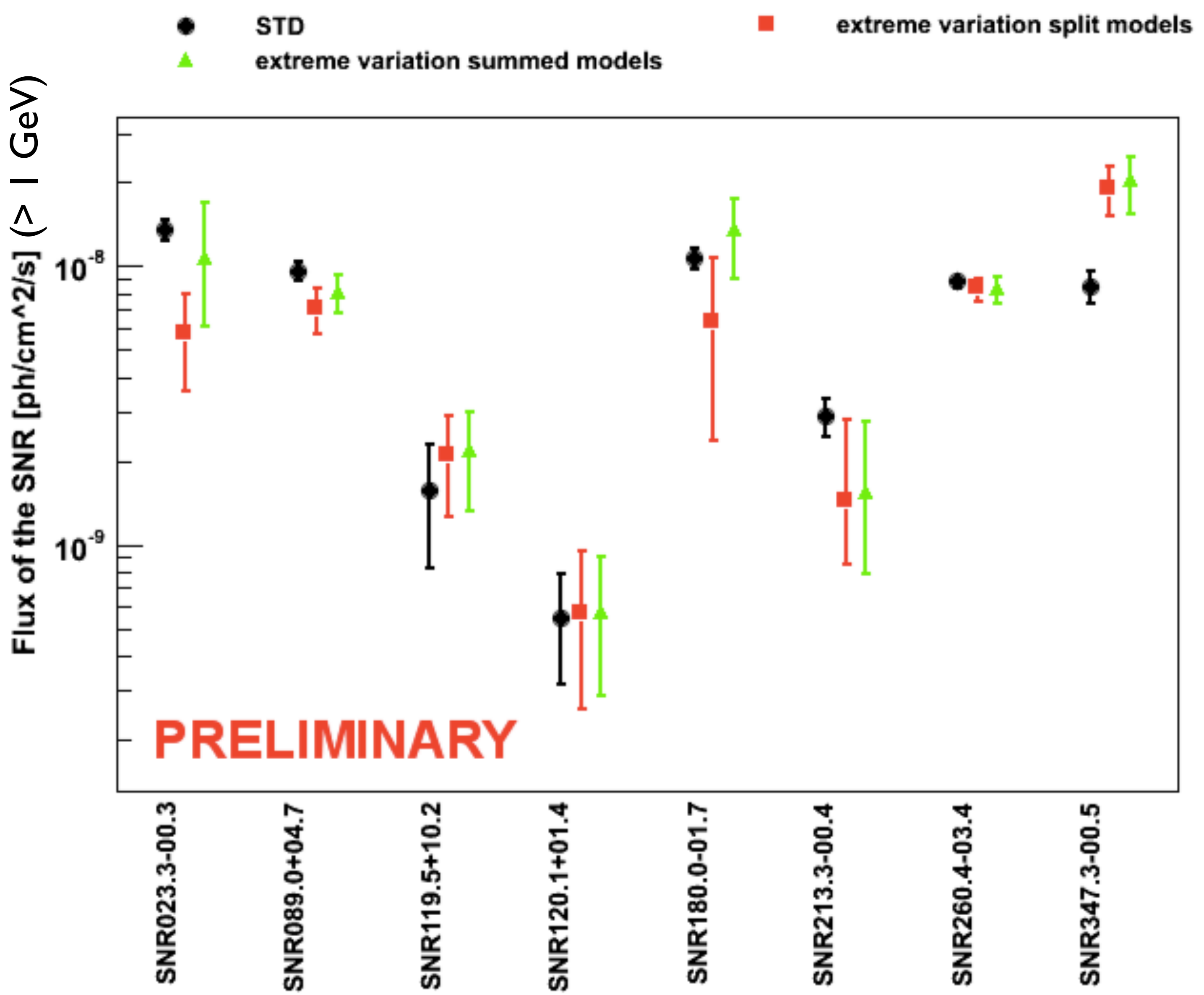


$$\frac{counts_{ALT} - counts_{STD}}{\sqrt{counts_{ALT} + counts_{STD}}}$$

1-100 GeV, 2 years
standard model vs. alternative model

Impact on sources

De Palma+ 2012, Fermi Symposium arXiv:1304.1395



- can have large impact on source parameters
- strongly depends on source properties/location
- can be generalized to other classes of sources (next talk by Alex Drlica-Wagner)

Standard IEM:
value,
statistical error

Alternative IEMs:
Avg of 8 values with
split rings
summed rings

maximal range
of values' 1σ
statistical errors

Final remarks

- Galactic interstellar γ-ray emission is a tracer of cosmic rays
  - cosmic-ray acceleration and propagation,
  - complementary to direct cosmic-ray measurements
- Galactic interstellar emission models enable us to study sources, isotropic emission, dark matter
  - uncertainties are not trivial to address and critical for the interpretation of the data