Interstellar Cosmic-Ray Spectrum from Gamma Rays and Synchrotron

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Goal: Determine the local interstellar cosmic-ray spectrum

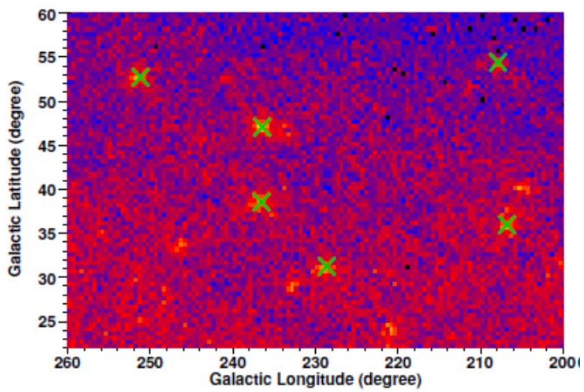
Direct detection $\gtrsim$10 GeV/nuc; γ-ray detection $\gtrsim$ 400 MeV/nuc

Outline

1. Fermi-LAT emissivity measurements
2. Uncertainties in nuclear production cross sections
3. Shock-acceleration spectrum: power-law in momentum
4. Fits to emissivity spectrum $\Rightarrow$ cosmic-ray spectrum
5. Deviations from momentum power-law
6. Implications for the theory of cosmic-ray origin

Fermi LAT Emissivity Measurements

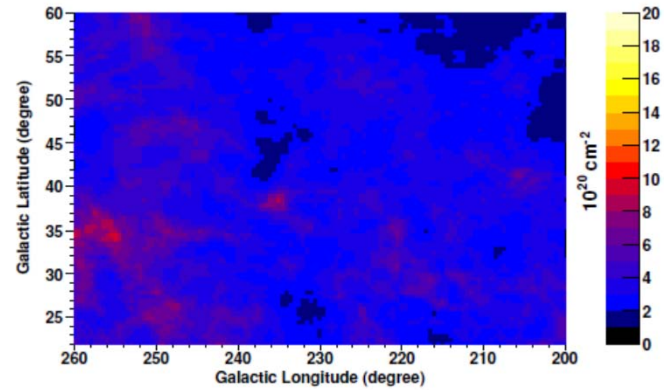
Abdo et al., Ap J, 703, 1249, 2009

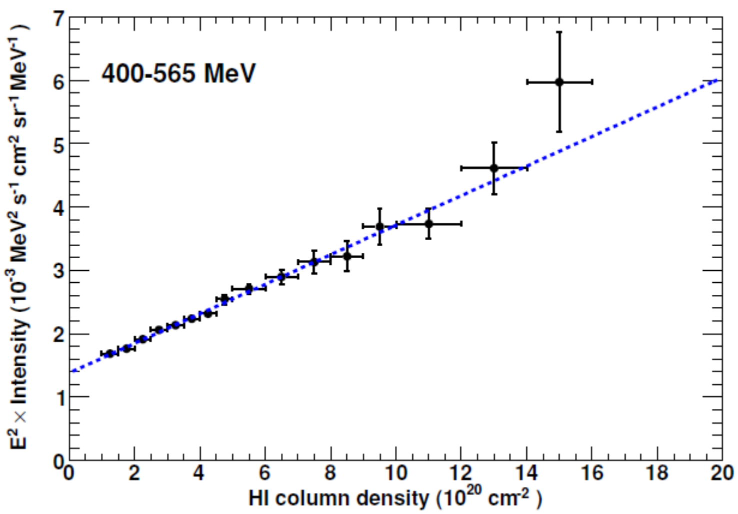


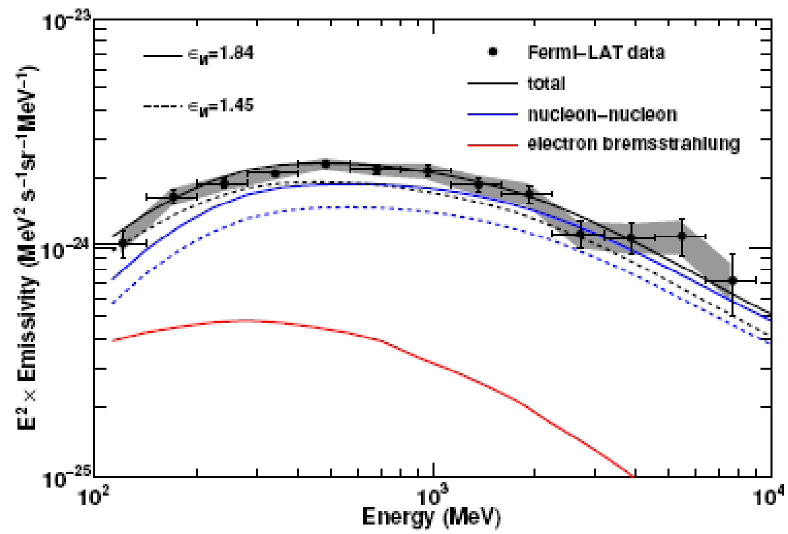
4 Aug 2008 – 31 Jan 2009 (6 mos)

LAT observations in third quadrant ($200^o < \ell < 260^o$, $22^o < |b| < 60^o$)

No known molecular clouds, point sources subtracted; low ionized H $N(HII) \sim 1\text{-}2\times10^{20} cm^{-2}$



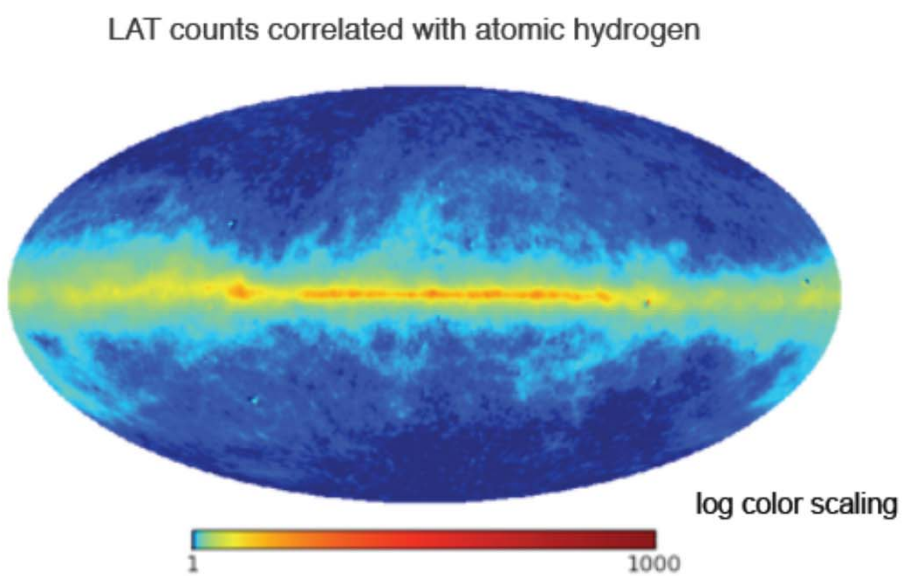


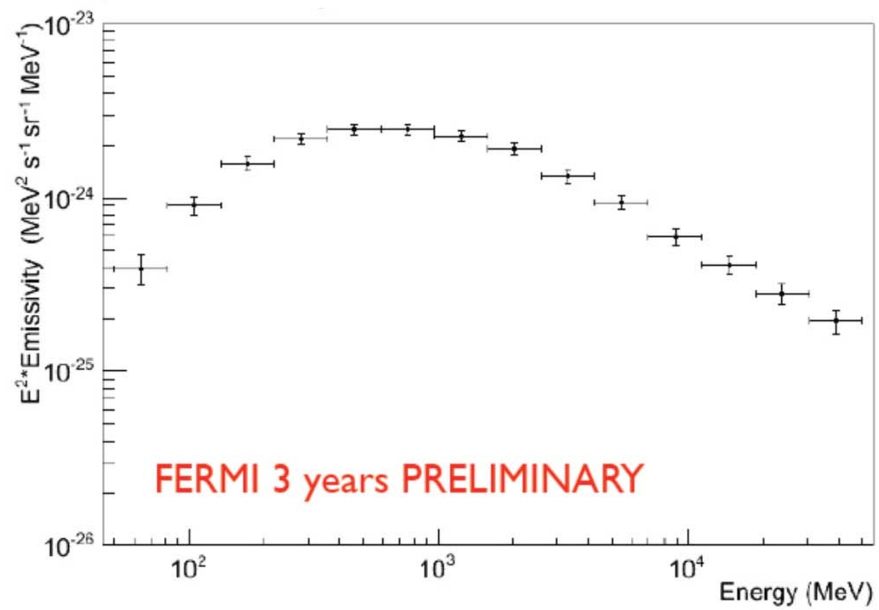


Residual 100 MeV - 10 GeV γ-ray intensity exhibits linear correlation with N(HI)
Measured integral γ-ray emissivity: **$(1.63\pm0.05)\times10^{-26}$ ph(>100 MeV) $s^{-1}sr^{-1}$ H−atom^{-1}**
with an additional systematic error of ~10%.

3 Year Fermi-LAT Emissivity Spectrum

Ref.: J.-M. Casandjian, Wednesday Parallel C, Gamma 2012, paper in preparation





Template mapping, after subtracting point and extended sources and isotropic emission
Dispersion correction at low energies

How to explain the spectrum? Cosmic rays colliding with gas in the Galaxy

- $p + p$, $p + \alpha$, etc. $\rightarrow \gamma + X$, dominated by $\pi^\circ \rightarrow 2\gamma$
- cosmic-ray electron bremsstrahlung

LAT Emissivity Spectrum of Molecular Clouds

- Molecular Clouds as GCR Detectors

  High Galactic latitude Gould Belt Clouds

  August 4, 2008 – July 15, 2011, P6_v11

  Subtract point sources from 2 yr catalog
- Flux ~ M/D^2 as inferred from CO maps
- Perform spectral analysis

- Molecular Cloud Spectra Consistent

  "Passive" Cosmic-ray Detectors
- Break in Photon Spectrum at ~2 GeV
- Invert for ISM CR spectrum

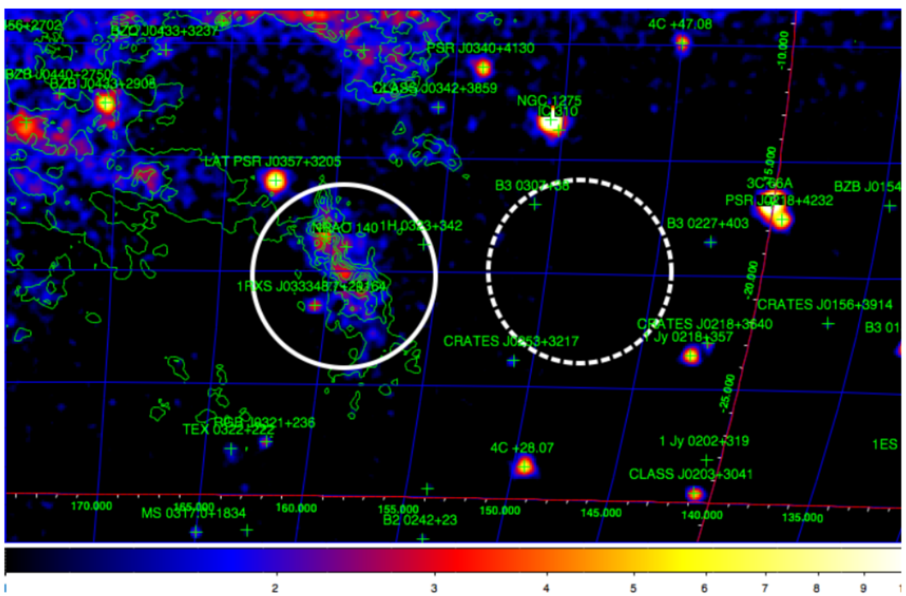
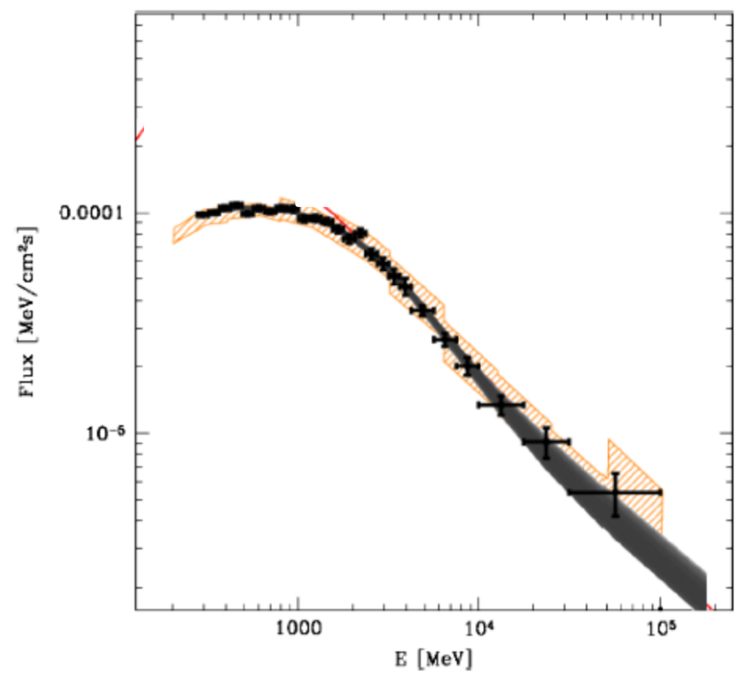
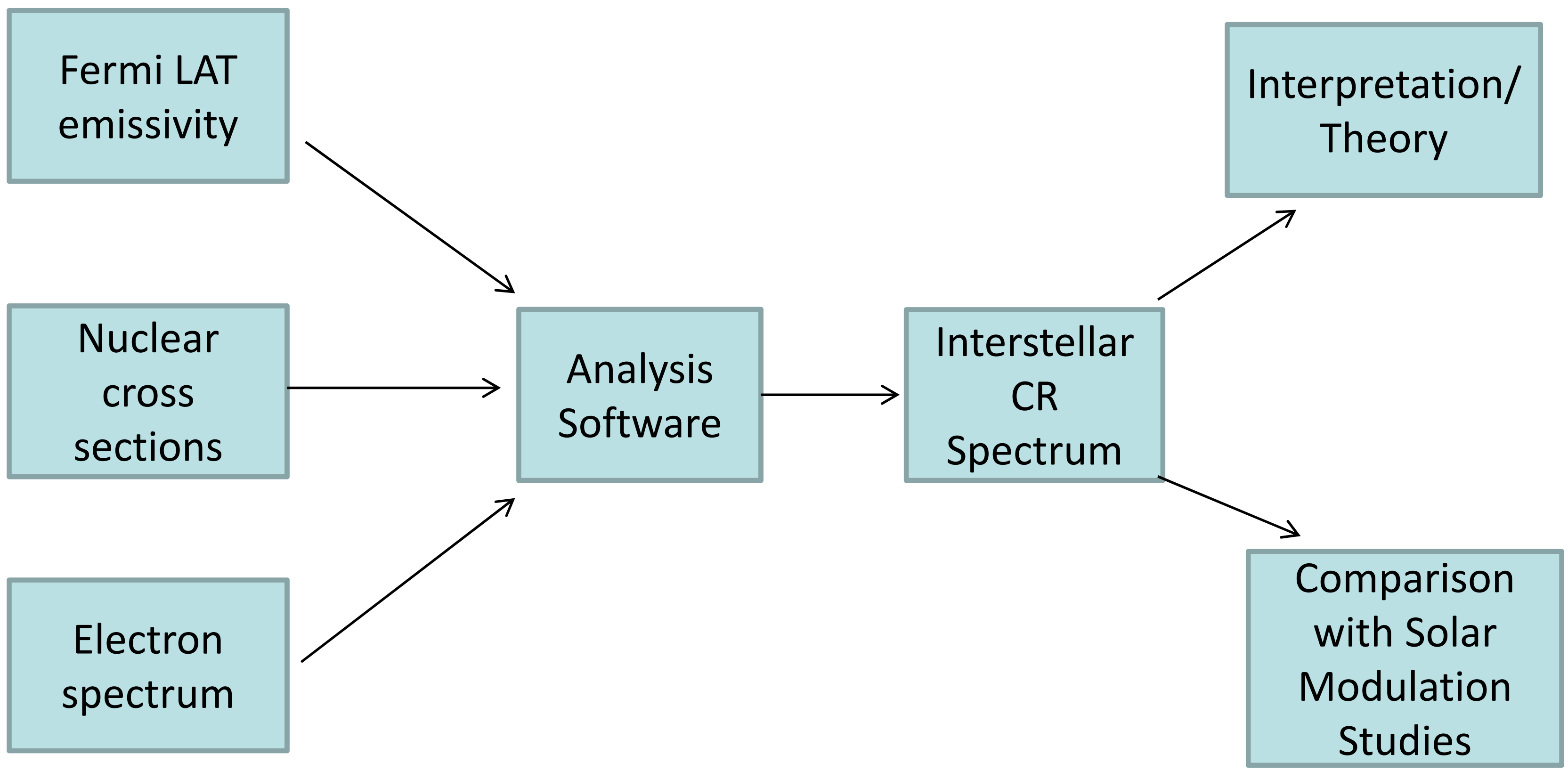


Figure S1. Count map of Perseus OB2 cloud region in the energy range E>1 GeV smoothed with a Gaussian of the width 0.3°. Green contours show CO emission intensity with the levels 5,15,25,35 and



Neronov, Semikoz, & Taylor (2012)

Deriving Local Interstellar Cosmic Ray Spectrum



Uncertainties in Nuclear Production Physics

$p+p \rightarrow \gamma + X$ (most through $p+p \rightarrow \pi^0 \rightarrow 2\gamma$)

- **Isobar + Scaling Model**

  Fireball /Fermi (1950) Statistical Theory

  Resonance Baryon Excitation (Stecker 1968)

  Feynman Scaling (Stephens & Badhwar 1981; Blattnig et al. 2000)

  Hybrid Model (Dermer 1986)

- **Diffractive Effects + Scaling Violations**

1. Δ(1236) 2. N(1600) 3. Diffractive
4. Non-diffractive/scaling (Kamae et al. 2005, 2006)

- **Monte Carlo Event Generators** Kamae et al. (PYTHIA); Huang et al. (2007: DPMJET-III); Kelner et al. (2006; SIBYLL); Kachelriess & Ostapchenko (2012: QGSJET-II); FLUKA

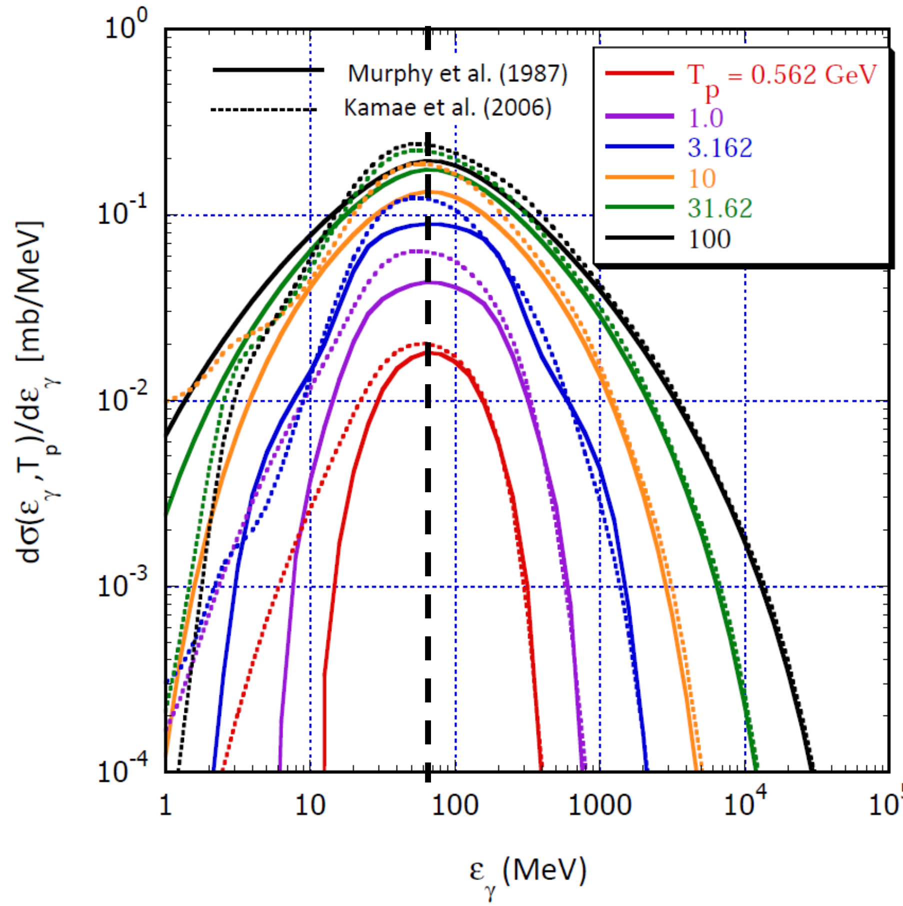
  Comparison of Different Models:
  30% uncertainty at E_γ < 100 MeV and
  <10-15% uncertainty at E_γ > 1 GeV

- **Cross Section Enhancement**

  p+α, α+p α+α, p+C, …; nuclear enhancement factor

  k = 1.45 – 1.84 ($\approx$ 1.8-2.0 Mori 1997, 2009)

  But…spectral differences



Measured Cosmic-Ray Spectrum

Naïve Theoretical Expectations:

1st order Fermi shock spectrum

- Test particle limit
- Strong shock

$$\frac{d\dot{N}}{dp} \propto p^{-s_{inj}}, \; s_{inj} = 2.2 - 2.3$$

Steepening due to escape

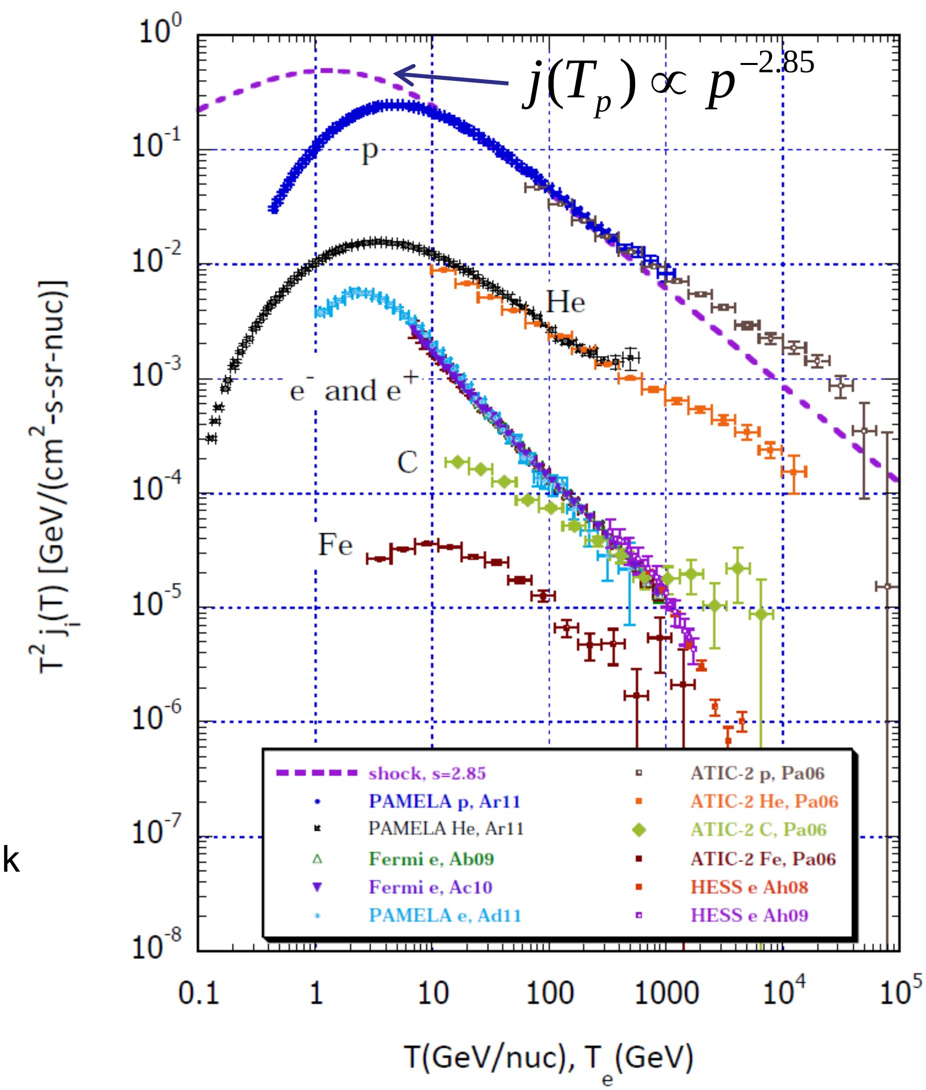
$$t_{esc} \propto p^{\delta}, \delta \approx 0.5$$

$$\frac{dN}{dp} \propto \frac{d\dot{N}}{dp} t_{esc} \propto p^{-s}, \;\; s = s_{inj} + \delta$$

$$\therefore \; j(T_p) \propto \beta \frac{dN}{dT_p} \propto \frac{dN}{dp} \propto p(T_p)^{-s}$$

Power-law momentum spectrum makes break in kinetic energy representation

Search for deviations from cosmic ray flux given by power-law in momentum



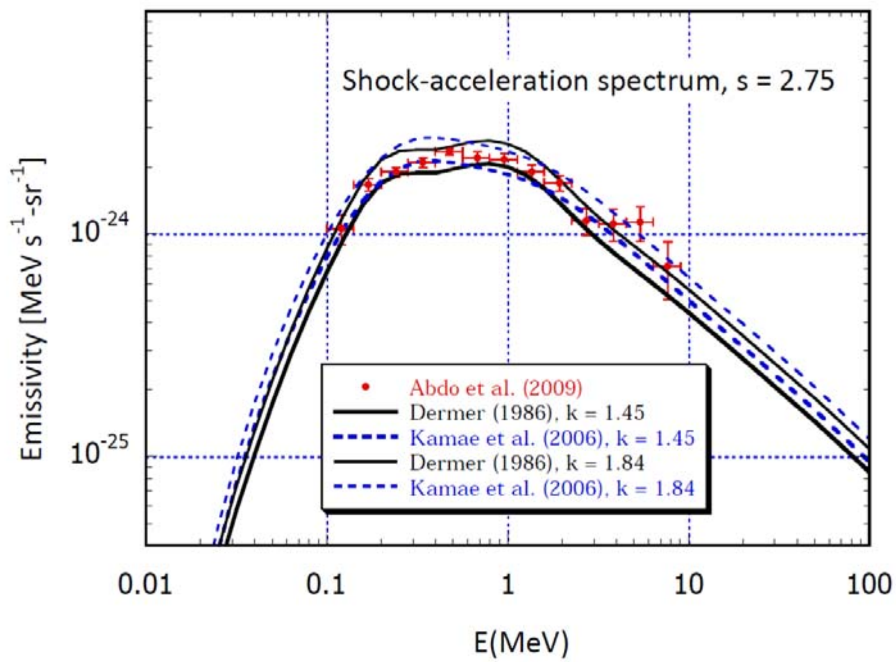
Fits to γ-ray Emissivity

Protons only; ions treated through nuclear enhancement factor k

$$j(T_p) = 2.2\, p^{-2.75} (\mathrm{cm^2\text{-}s\text{-}sr\text{-}GeV})^{-1}$$

Gives adequate fit to data within uncertainties of nuclear physics

Photon Spectrum



Dermer (2012)

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But exceeds CR flux between 10 GeV and 4 TeV (black solid curve)

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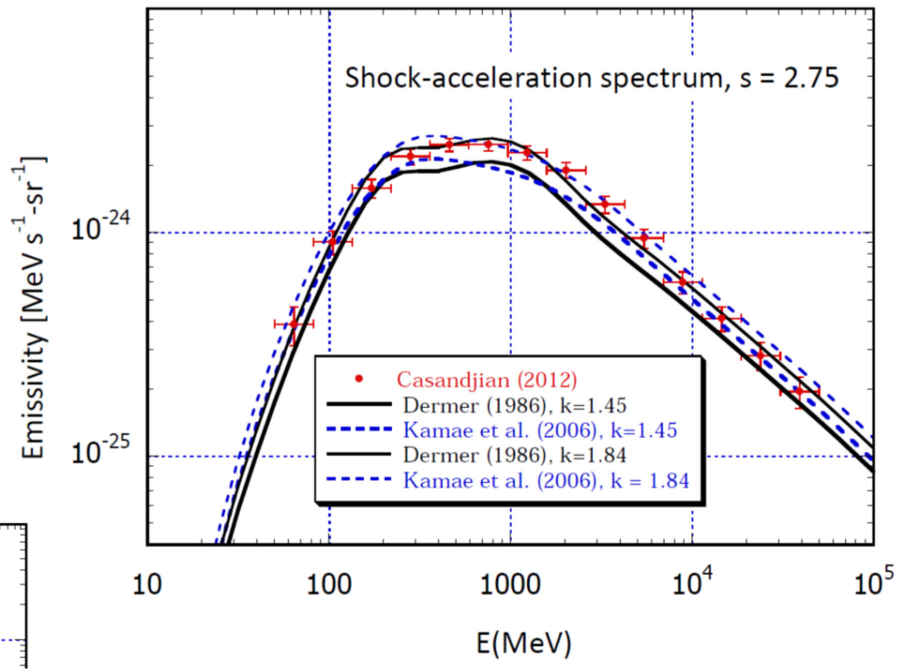
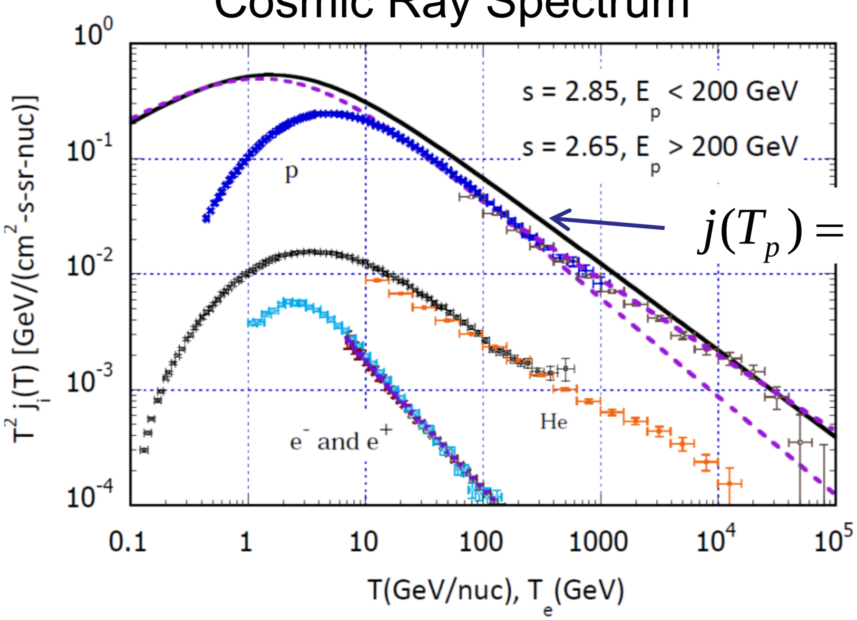


Cosmic Ray Spectrum



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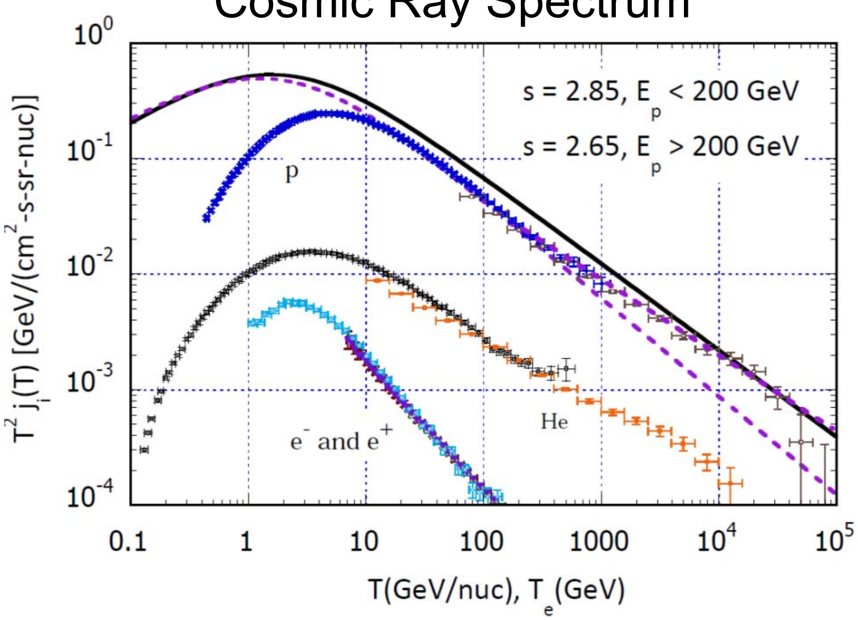

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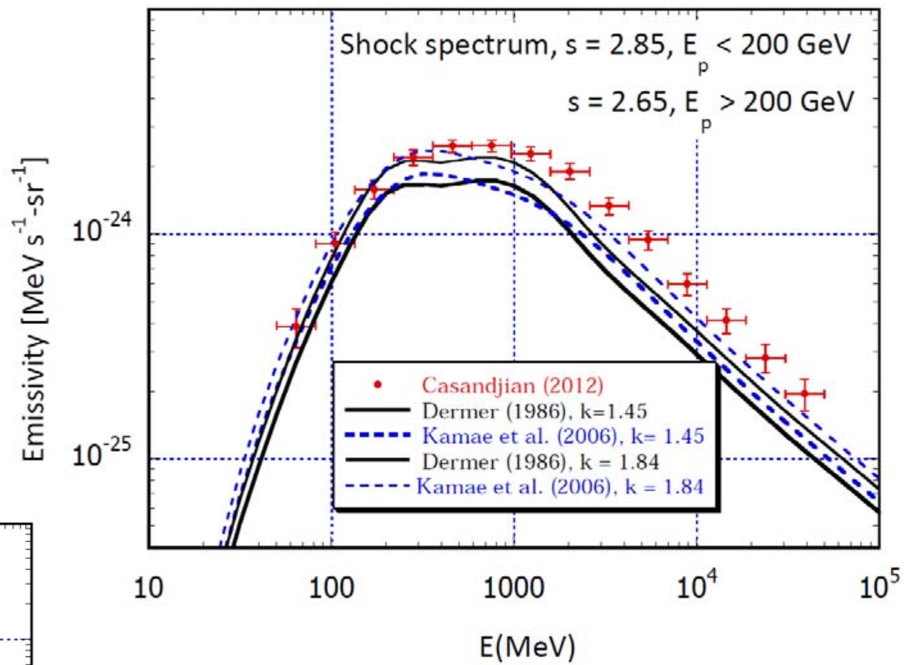


Fit to CR proton flux above 10 GeV (purple dashed curve), shock spectrum below

Underproduces γ-ray emissivity

But,….no electron emissions

Cosmic Ray Electrons from Radio Observations

- Derive *ambient* spectrum using Fermi-LAT electron spectrum above 7 GeV, and synchrotron spectrum at lower energies

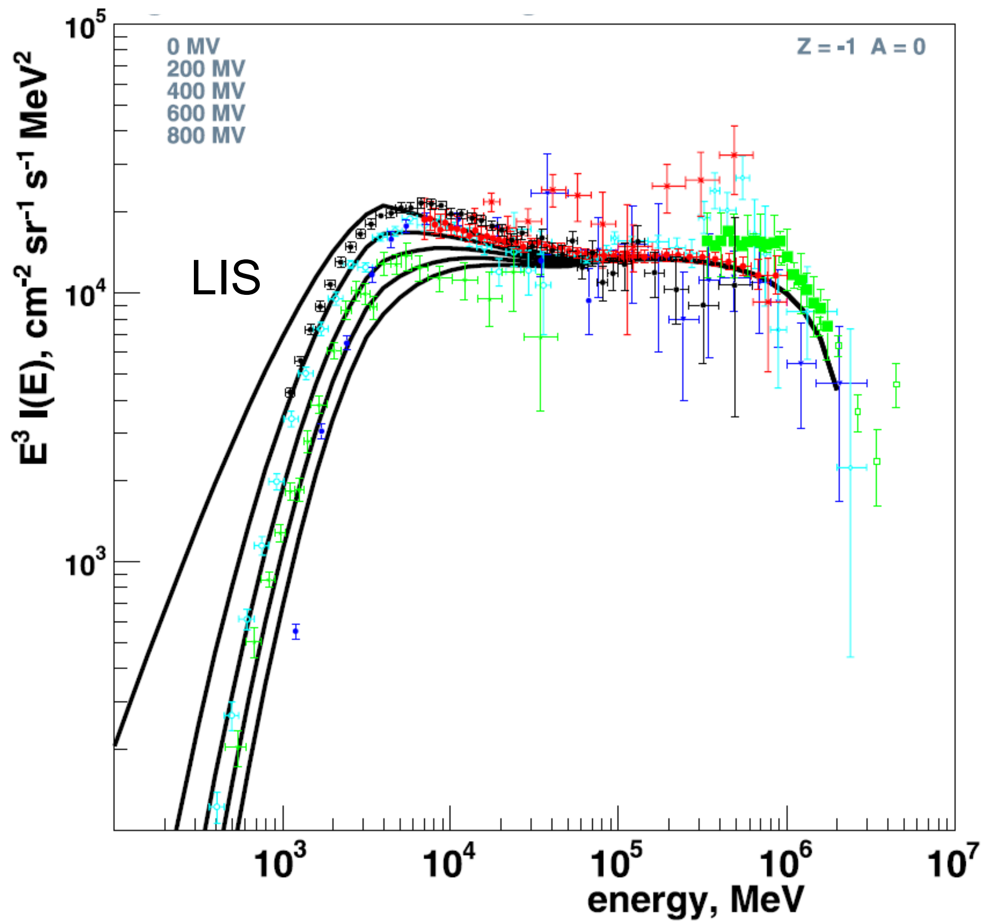
- Synchrotron energy index = 0.4 – 0.6 below a few GHz $\Rightarrow$ electron index = 1.8 – 2.2 below a few GeV

- Compare with GALPROP propagation model at lower energies using parameters from GALPROP modeling of CR secondary to primary nuclei

- Injection cannot be too hard (1.3 – 1.6), or underproduce directly measured electrons

For more details, see poster: ***Diffuse radio emission from the Galaxy, Implication for cosmic rays and magnetic fields***, Orlando & Strong

Injection index = 1.6 below 4 GeV



Strong, Orlando, & Jaffe (2011)

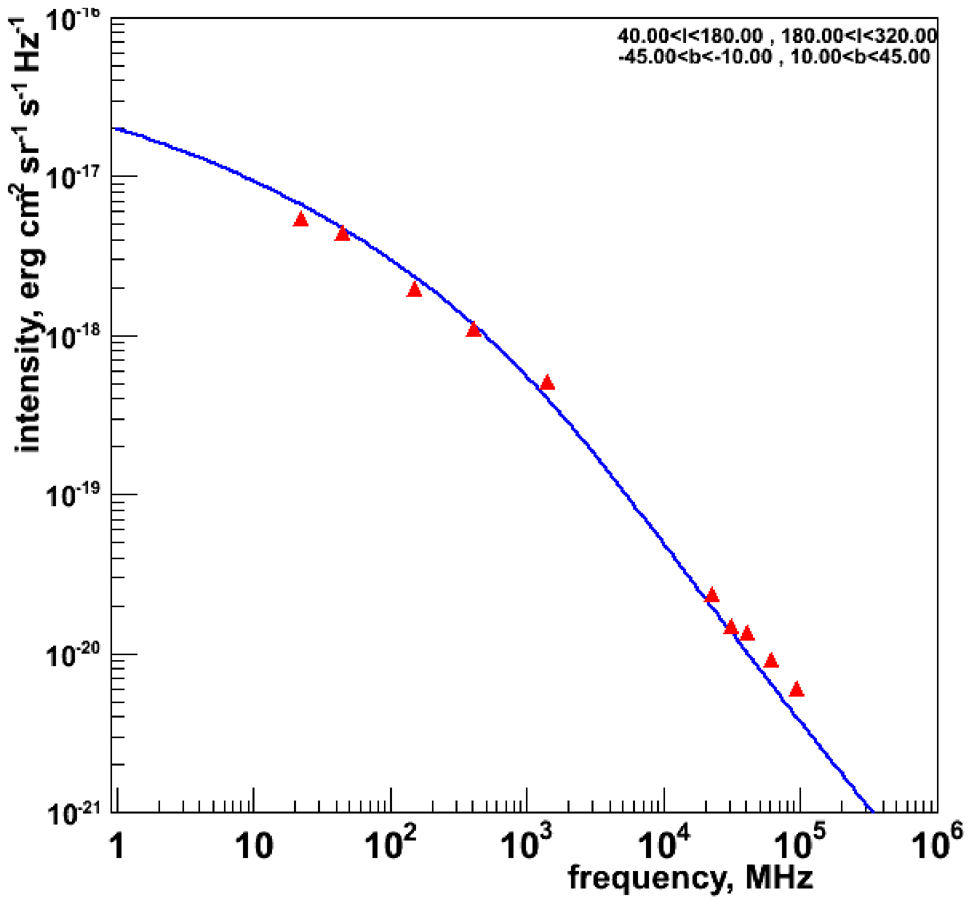
Synchrotron from Cosmic Ray Electrons

Injection index = 1.6 below 4 GeV

• Require break in electron injection spectrum from ~1.6 to 2.5 at ~4 GeV to fit synchrotron, so hard injection spectra

• Implies less Solar modulation than usually assumed

Alternate approach of Casandjian: derive proton and helium spectra from emissivity, heliospheric fluxes using Solar modulation model, and synchrotron



Strong, Orlando, & Jaffe (2011)

Bayesian Model Analysis

1. Explicit scan of model parameters

2. Spectra using posterior averaging

3. No use made of modulation approximations

4. Base models on momentum spectra n(p)

5. Express problem in matrix form

$$q(E) = M_H(E,p)\, n_H(p) + M_L(E,p)\, n_L(p)$$

q(E) = emissivity
E = gamma-ray energy
p = momentum
$n_H(p)$ = proton, Helium spectrum
$n_L(p)$ = electron + positron spectrum
M_H = Hadronic production matrix
M_L = Leptonic production matrix

Free parameters in the most general case:

protons:
1. proton break momentum
2. proton index g_{p1} below break
3. proton index g_{p2} above break
4. proton normalization

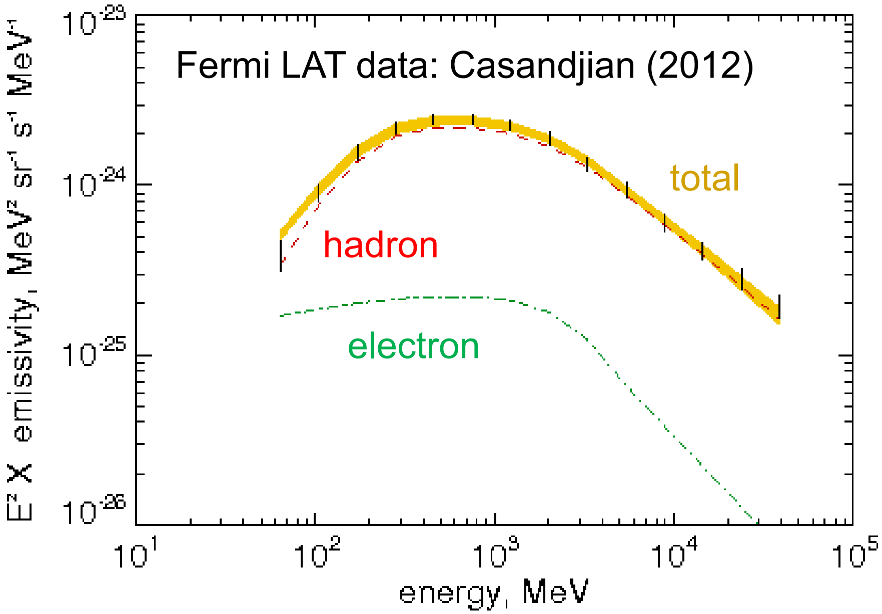
electrons:

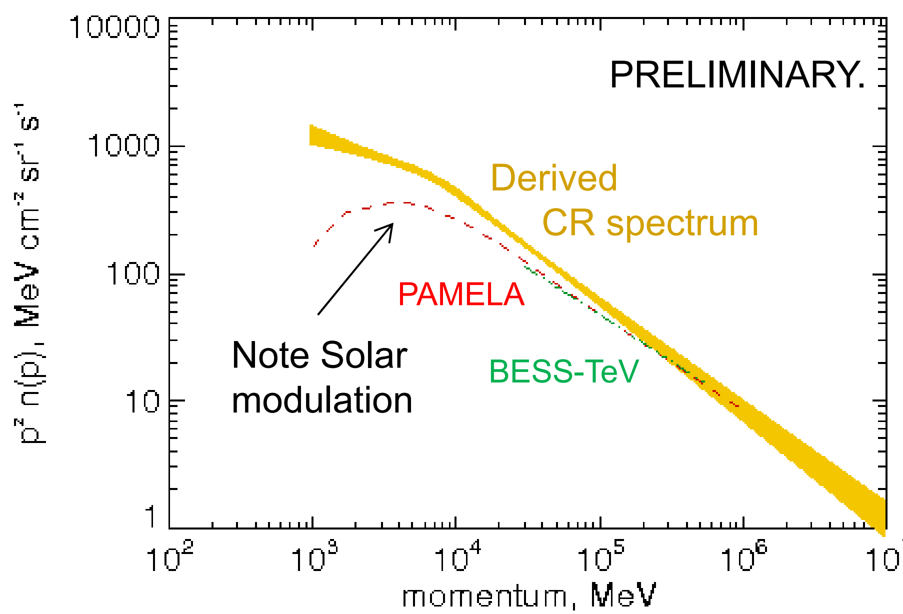
5. electron break momentum
6. electron index g_{e1} below break (constrained by synchrotron)

Fix electron index above break and normalization to Fermi > 20 GeV electron spectrum.

Fits to Emissivity Spectrum with Break

Cross sections (1) Kamae et al. (2006) at low energies; Kachelriess & Ostapchenko (2012) > 20 GeV





(Left) **Data:** Local gamma-ray emissivity measured by Fermi-LAT

Model: Hadronic (red), bremsstrahlung (green).

Total (yellow, with one standard deviation range).

(Right) **Cosmic-ray proton momentum spectrum derived from emissivity**.

Displayed as a power-law in momentum, with low-energy break.

Analysis includes bremsstrahlung contribution and synchrotron constraints on electrons.

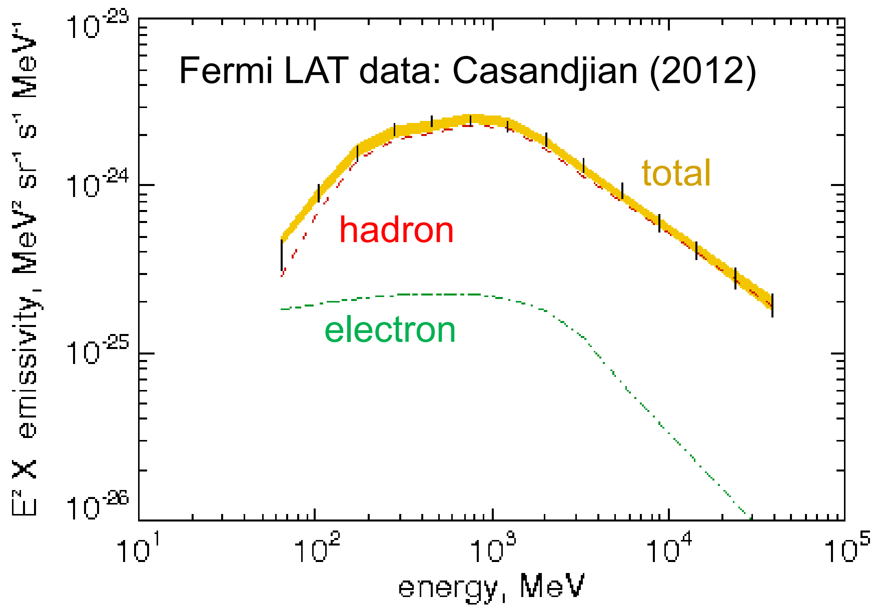
One standard deviation range.

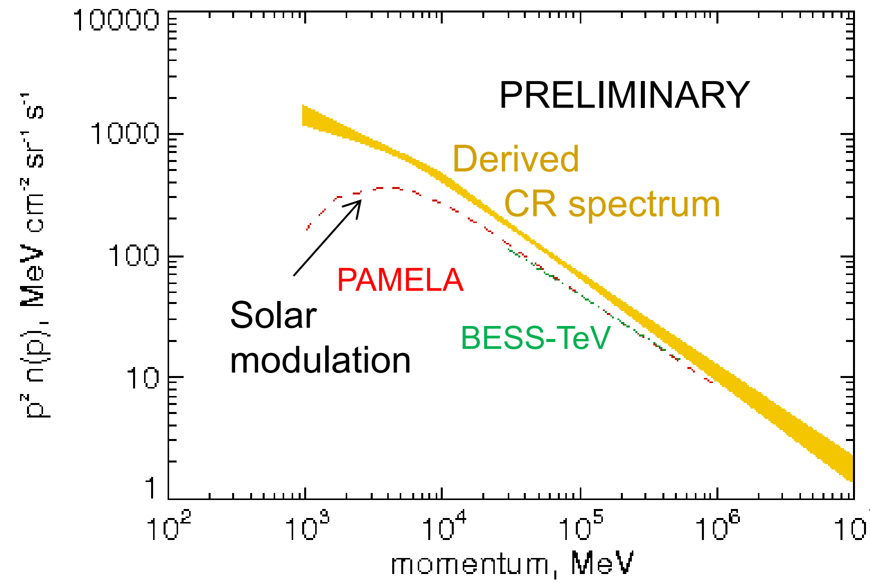
Dashed red (green) curve is PAMELA (BESS-TeV) cosmic-ray proton data

Note agreement (within ~26%) at high energies and modulation at low energies.

Effects of Cross Section on Fits to Emissivity

Cross sections (2) Dermer (1986): Stecker isobar model at low energies; Stephens & Badhwar at high energies





Cross sections:	(1)	(2)
1. proton break momentum	6.5 (±2.1) GeV	6.7 (±2.5) GeV
2. proton index g_{p1} below break	2.4 (0.1)	2.5 (0.1)
3. proton index g_{p2} above break	2.9 (0.1)	2.8 (0.1)
4. proton normalization	1.3 (0.1)	1.4 (0.1)
5. electron break momentum (fixed)	3.0 GeV	3.0 GeV
6. electron index g_{e1} below break	1.8 (0.1)	1.9 (0.1)

PRELIMINARY

Summary

- **Derive local interstellar cosmic-ray proton spectrum solely from γ-ray emissivity measured by Fermi-LAT, synchrotron, and Fermi electron spectrum**
- **Requires knowledge of cosmic-ray electron spectrum and nuclear cross sections**
- **Simplest spectral model is power-law in momentum; good fit to emissivity with s=2.75, but implies CR spectrum larger than observed at >10 GeV, also neglects electron bremsstrahlung**
- **Low-energy break in proton spectrum at ~6 GeV, also found in approach by Casandjian, consistent with injection momentum power-law modified by propagation, as expected from path length distribution inferred from B/C ratio**
- **Cosmic ray spectrum implied by γ-ray emissivity in accord with origin of cosmic rays by acceleration at supernova remnant shocks**
- **Gamma-ray observations demonstrate absolute level of Solar modulation on interstellar cosmic-ray spectrum**

Range of uncertainties in production cross sections are examined in Fermi-LAT paper in preparation (Strong et al., 2013) to assess reality of features in cosmic-ray proton spectrum