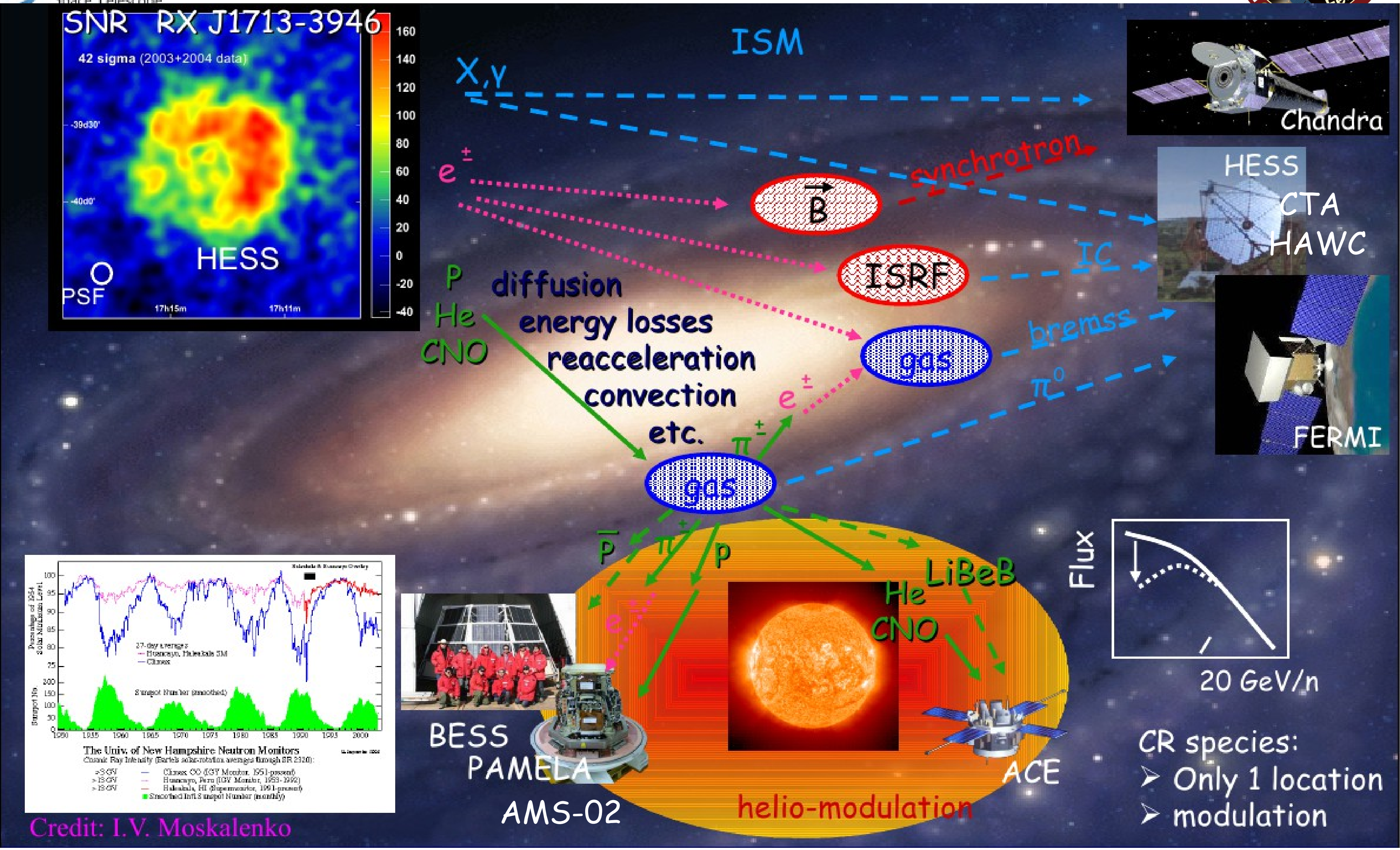
Cosmic-Ray Induced Gamma-Ray Emission Observed by Fermi-LAT

Guðlaugur Jóhannesson
Science Institute, University of Iceland

on behalf of the Fermi-LAT collaboration

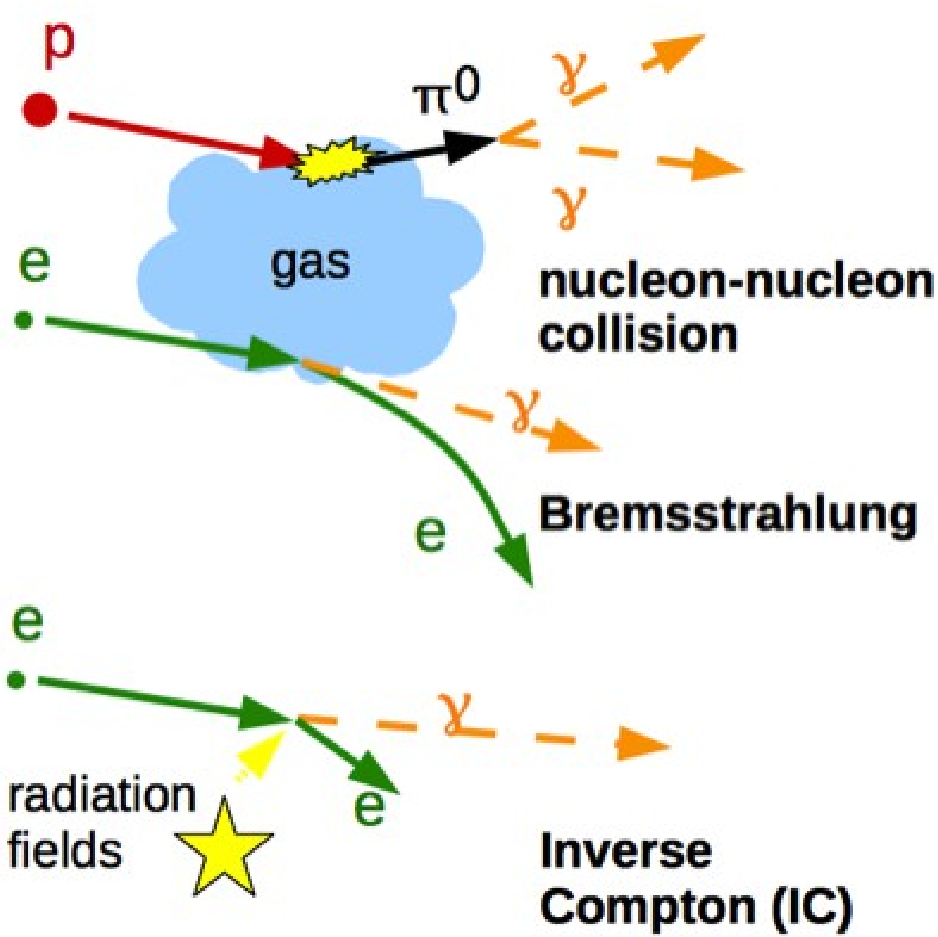
The Big Picture



SNRs as CR sources

- **Energetics fit**
  - $E_{SN} \times R_{SN} \times \varepsilon_{SN} = P_{CR}$
  - $10^{51} \times 10^{-9} \times 0.1 = 10^{41}$
- **Theory predicts that particles in the ISM are accelerated to high energies in the SNR shock**
  - **Both electrons and protons should be accelerated**
- **Observations show evidence of shock accelerated particles to high energies**
  - **Until recently, no clear evidence of proton acceleration in SNRs, observations could always be interpreted using only electrons**

Emission processes



- Interactions between accelerated particles and the surrounding medium create gamma-ray emission in three ways
  - Signature of π^0-decay is the smoking gun for accelerations of protons

π^0-decay bump

Dermer 1986, A&A, 157

- In the rest frame of the pion, the two gamma-rays created each have an energy of 67.5 MeV
- Conversion to lab frame with a proton power-law spectrum smears out the line but keeps symmetry in dN/dE in a logarithmic plot
- Multiplying with E^2 breaks the symmetry and creates a bump

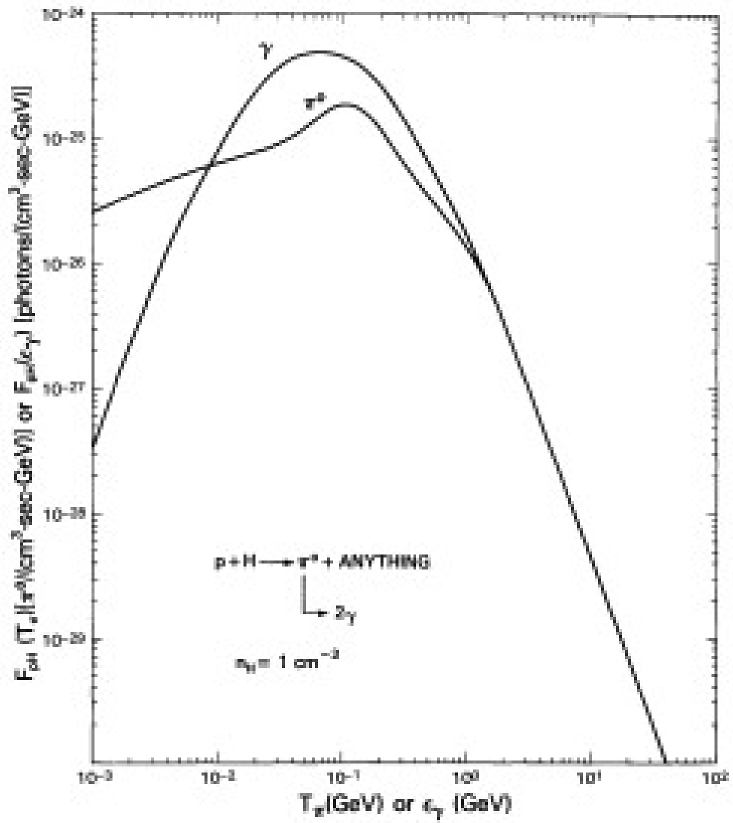
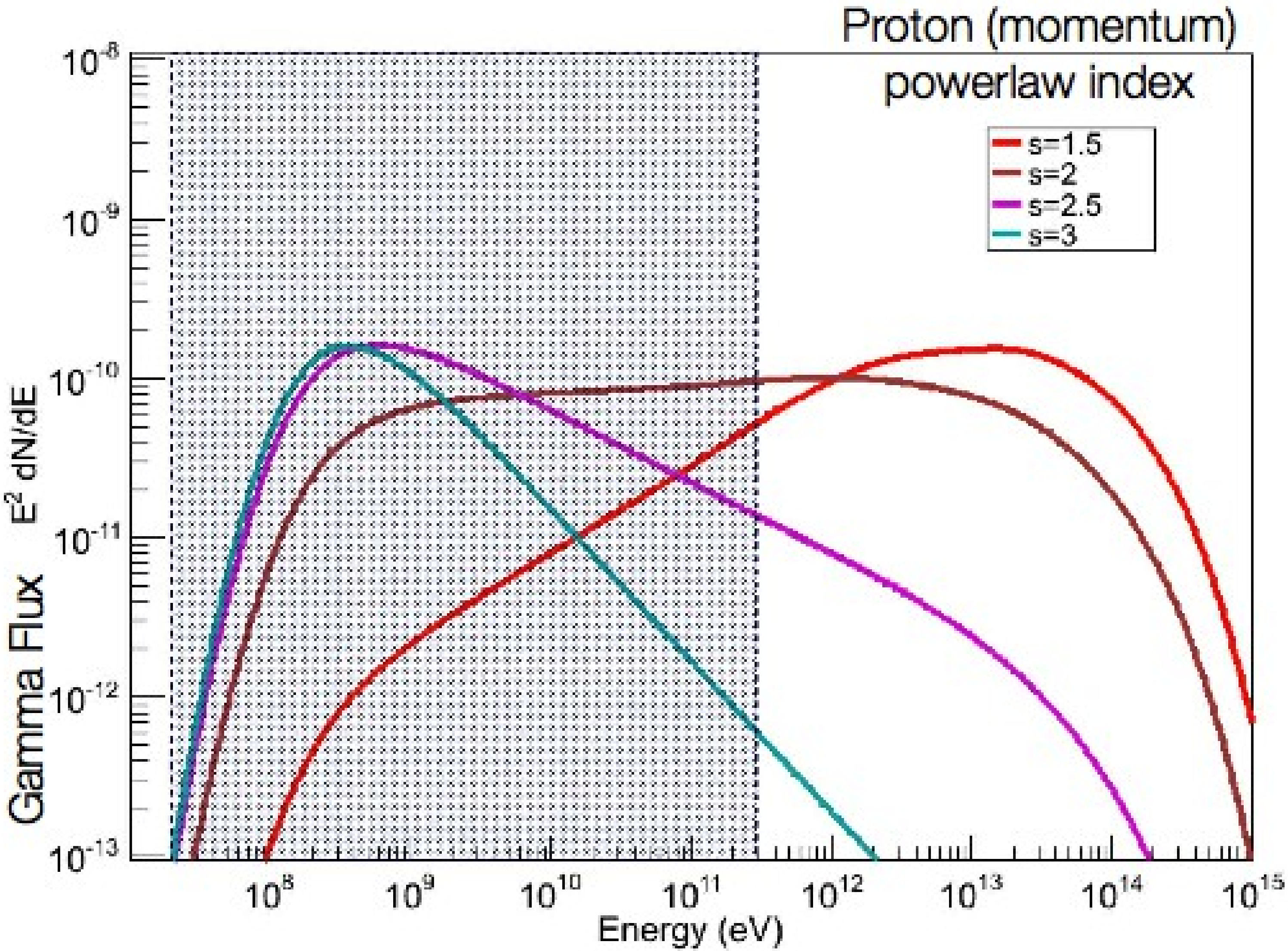


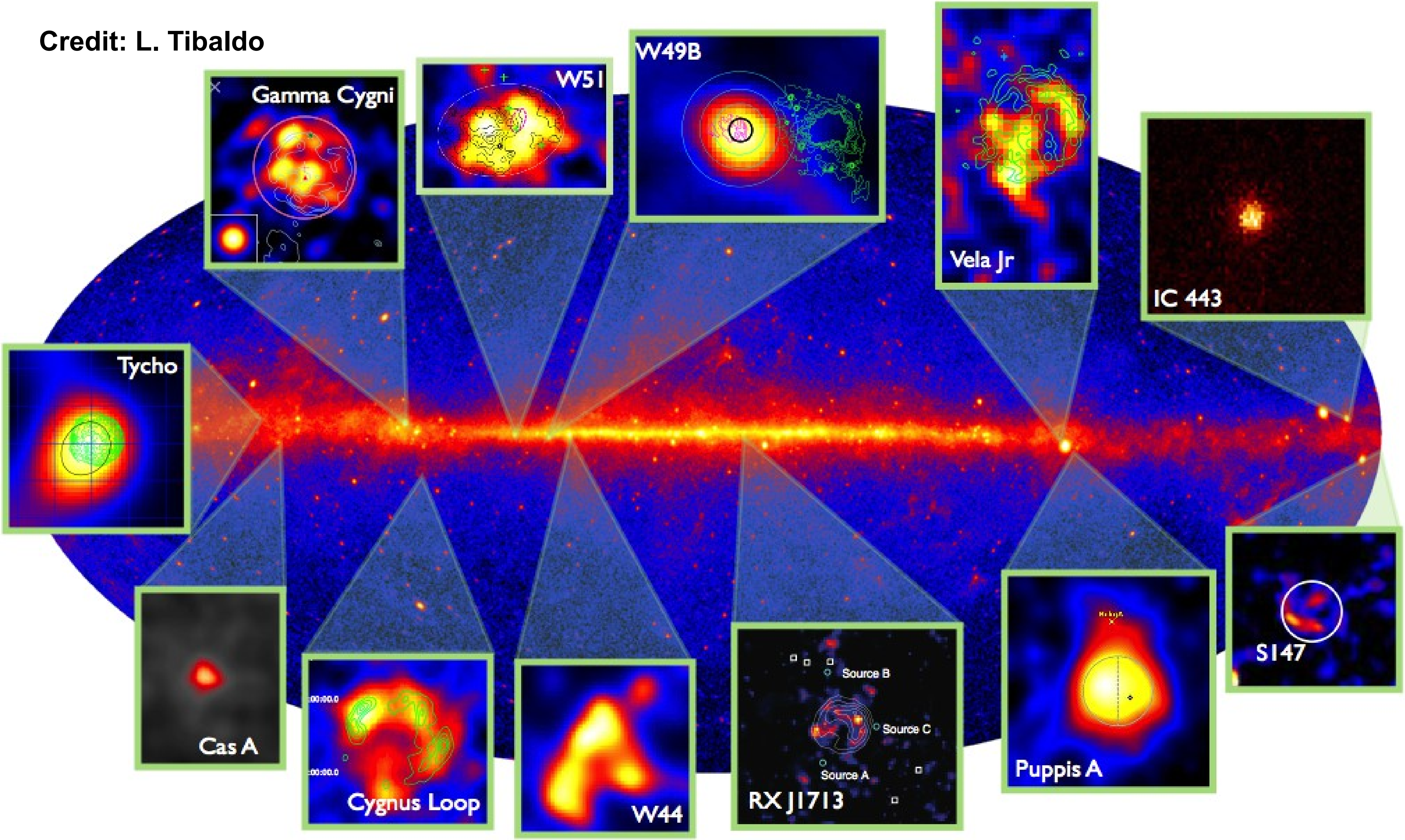
Fig. 7. The secondary π^0 and γ-ray emissivities from the interaction of the local demodulated cosmic ray proton spectrum with unit density of atomic hydrogen

π^0-decay bump



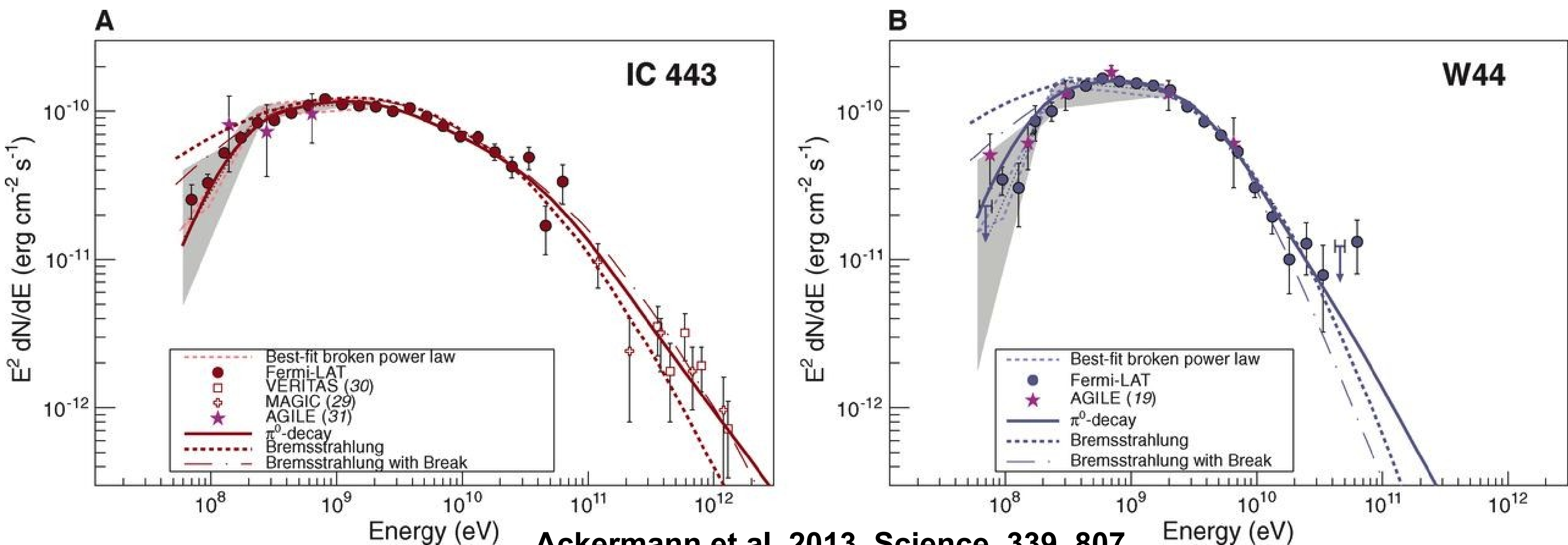
SNRs in the gamma-ray sky

Credit: L. Tibaldo



Pion bump in IC 443 and W44

- **Turnover at low energies clearly favors a hadronic model over a leptonic one**
  - **Even an abrupt cut of the electron spectrum at 300 MeV is not enough to explain the data with bremsstrahlung**
  - **Electron to proton ratio about 0.01**

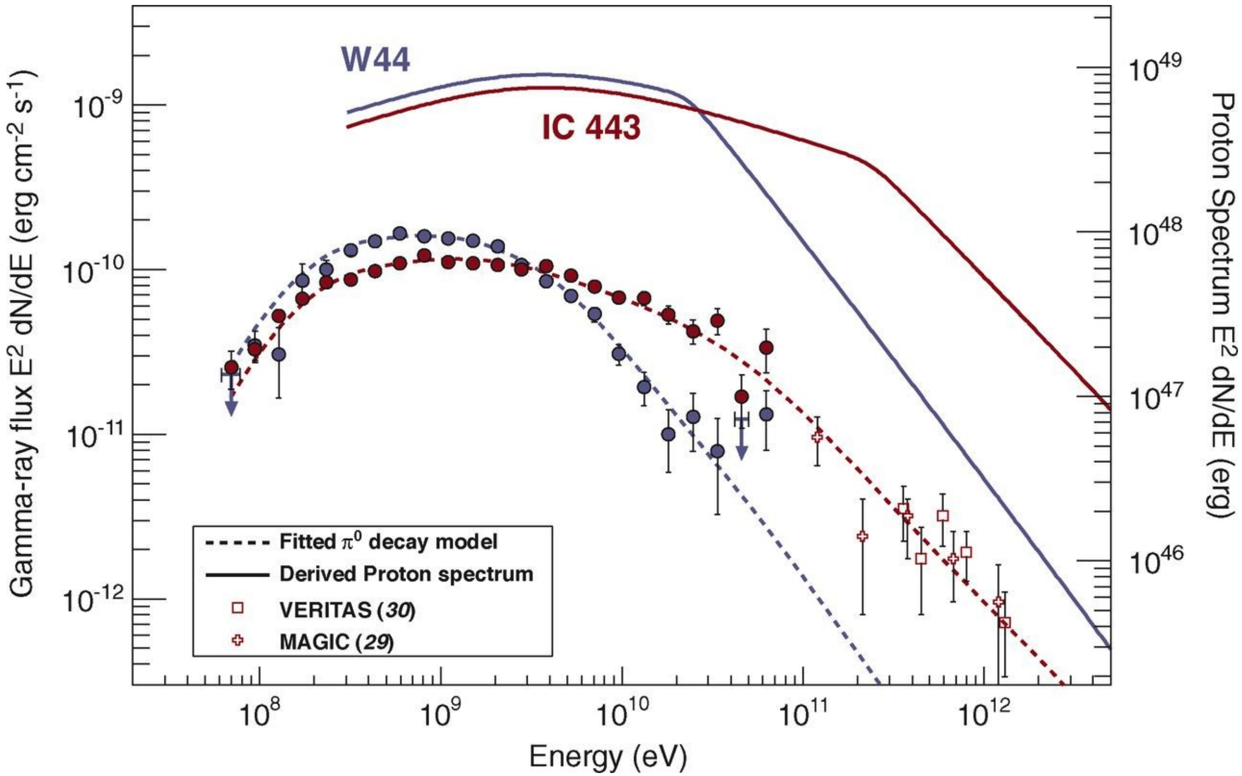


Ackermann et al. 2013, Science, 339, 807

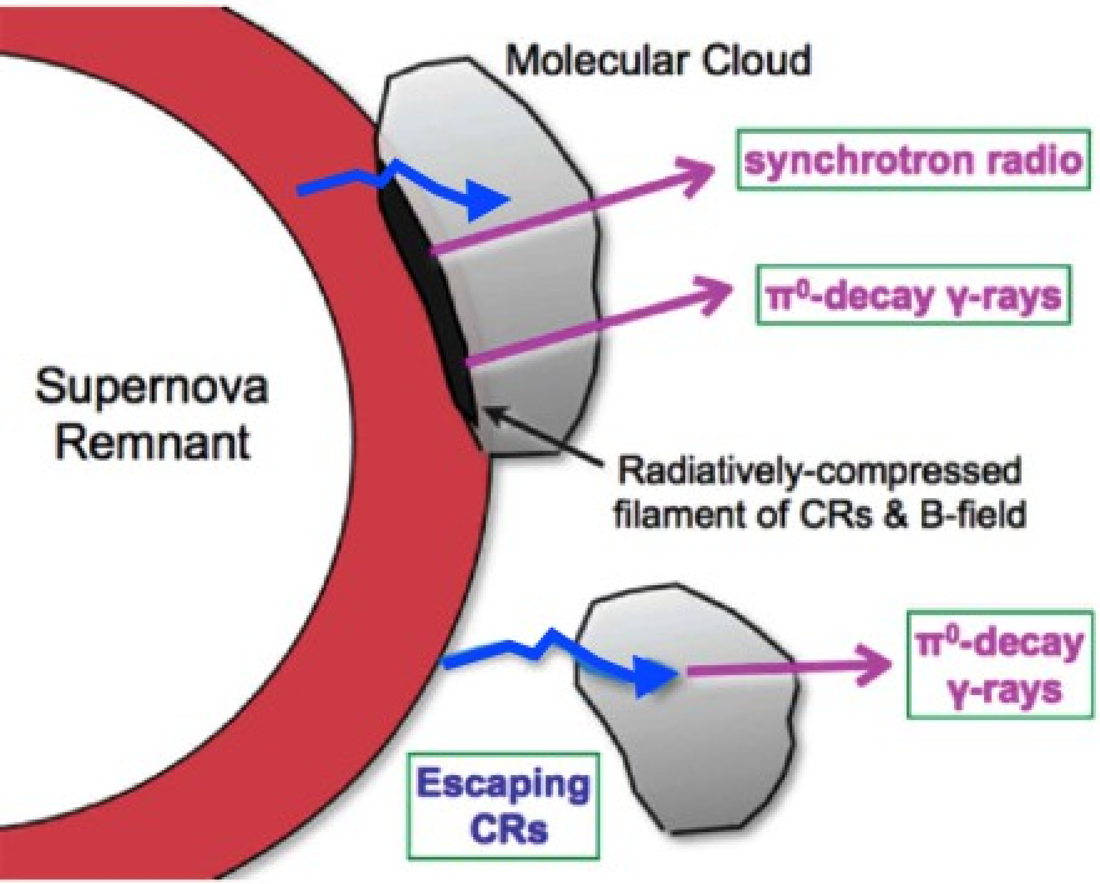
Spectrum of freshly accelerated CRs

- **Smoothly broken power-law in momentum**
- **Low energy index compatible with shock acceleration**
  - **2.36 for both SNRs**
- **High energy break likely due to inefficiency in confining high energy CRs**

$$\frac{dN_p}{dp} \propto p^{-s_1}\left[1+\left(\frac{p}{p_{\rm br}}\right)^{\frac{s_2-s_1}{\beta}}\right]^{-\beta}$$



Emission region

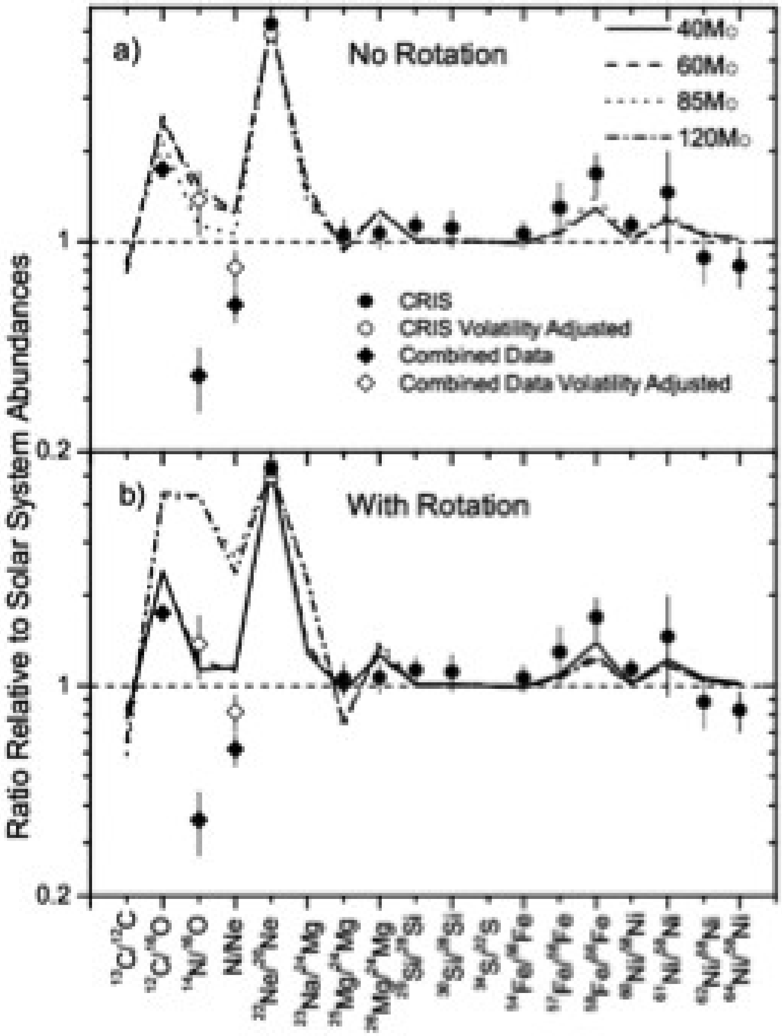


- **Bulk of the emission likely from regions where the SNR shell interacts with an external cloud.**
  - **Escaping CRs are expected to have a harder spectrum**

Massive star-forming regions

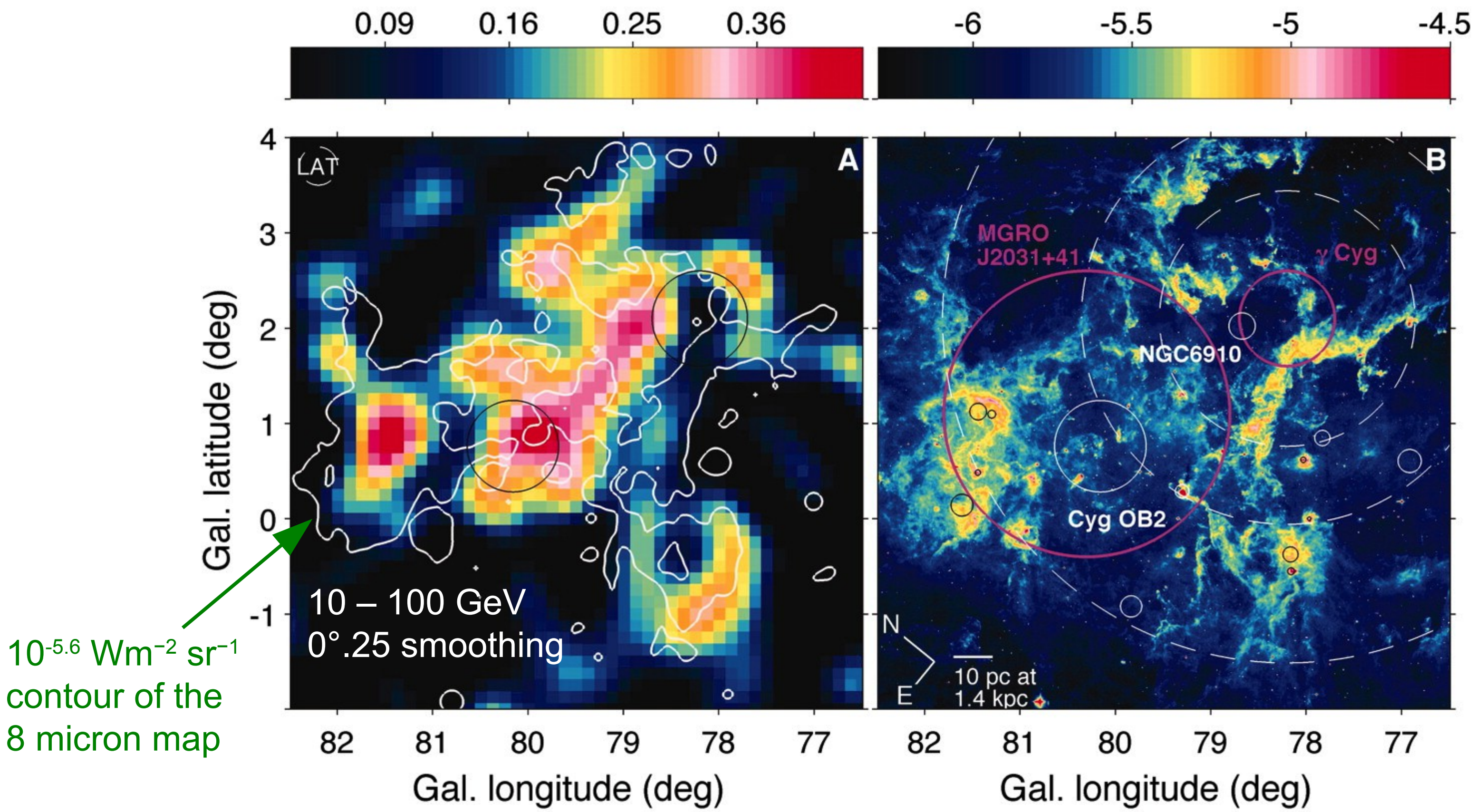
- Most supernova expected to occur in star-forming regions
- Isotopic abundance of CRs indicate WR star origin
- Shocks in stellar winds are possible sources of CRs

Binns et al. 2007, SSR, 130, 449



Gamma-ray excess in the Cygnus region

- **Gamma-ray excess (left) associated with photo dissociation regions from 8 micron map from MSX (right)**



Ackermann et al 2011, Science, 334, 1103

Hard spectrum => freshly accelerated CRs

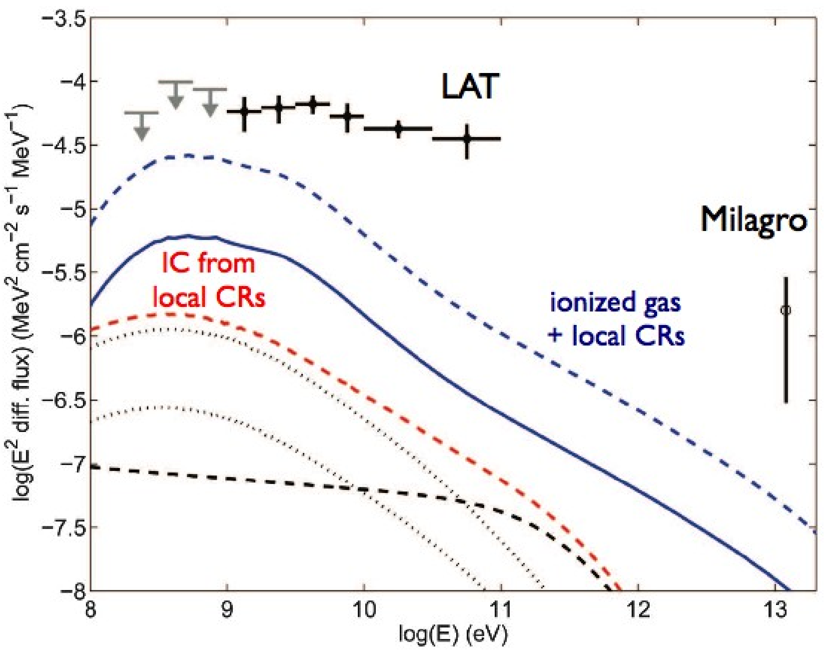
- **Spectrum of excess harder than expected from large scale CRs after propagation**
  - **Hadronic**

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

  - **Leptonic**

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

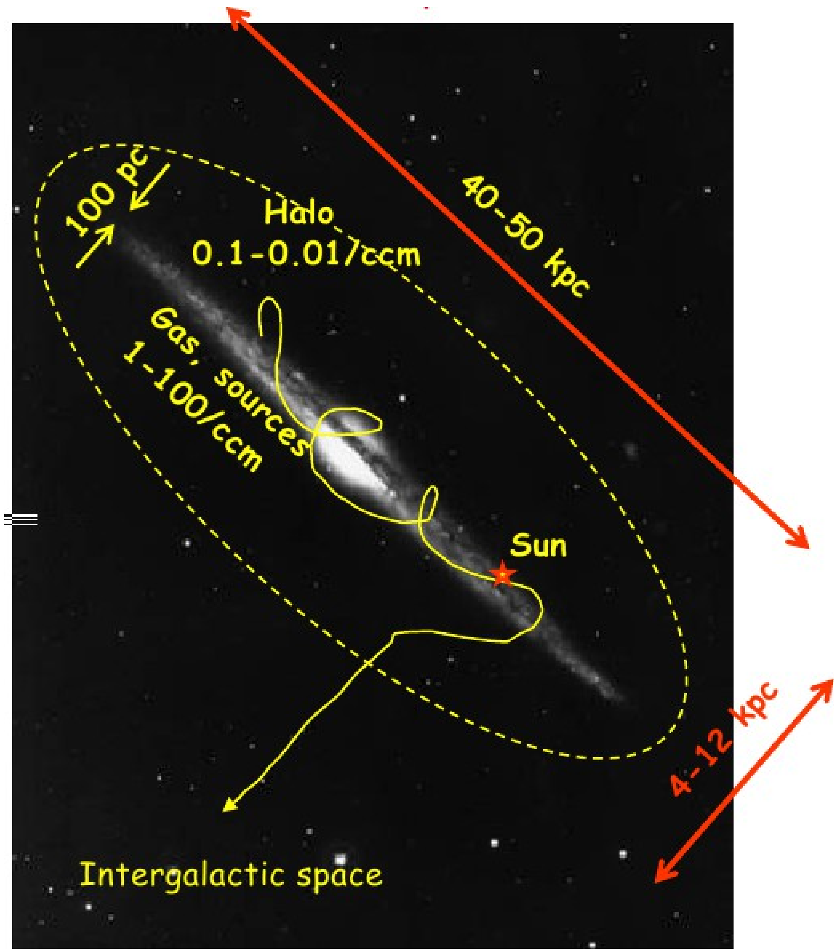
- **Evidence for freshly accelerated CRs**



Ackermann et al 2011, Science, 334, 1103

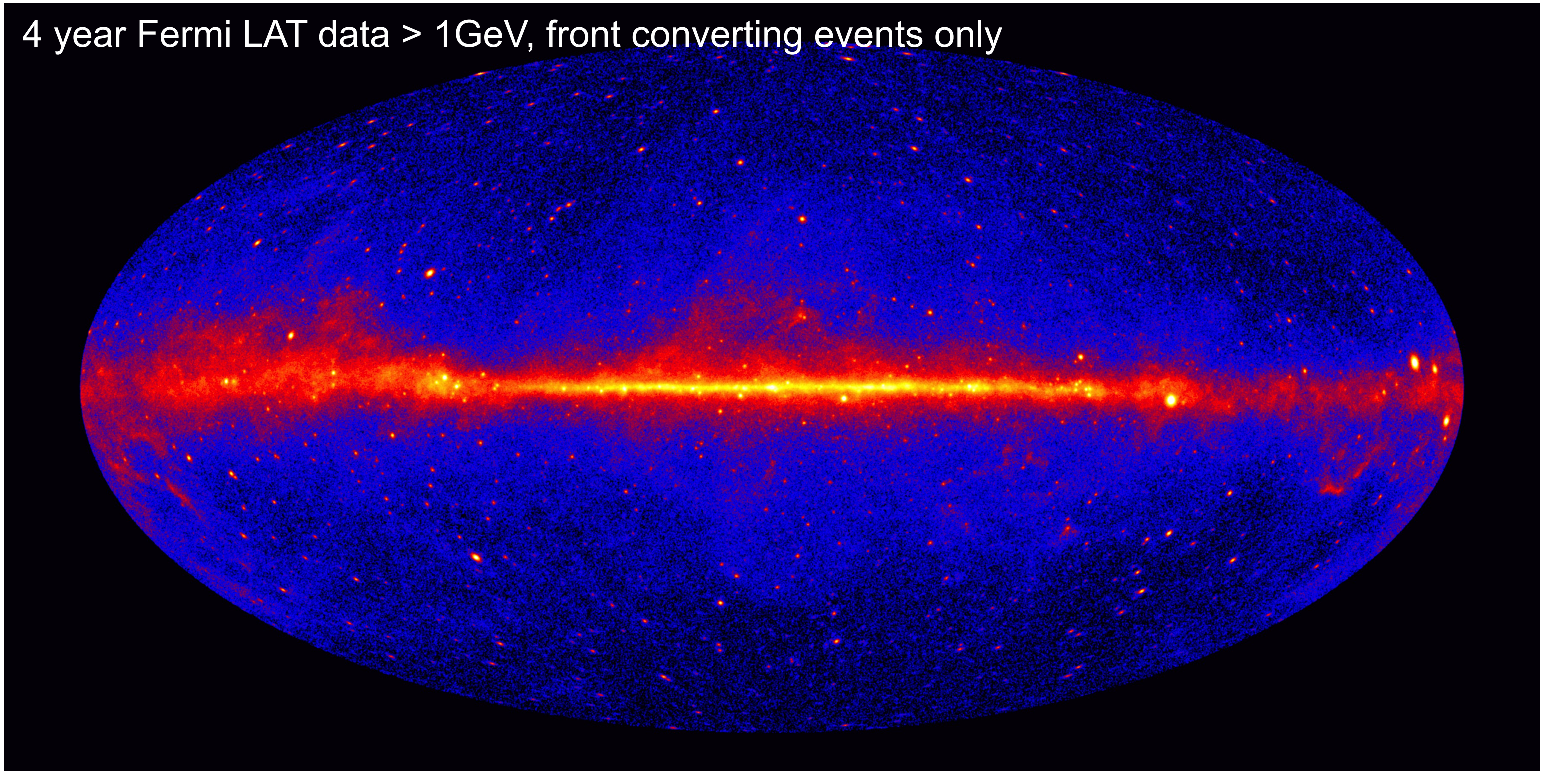
CR propagation

- CRs are generated at the source
  - SNRs
  - pulsars, stellar wind, ISM shocks, DM, ...
- CRs propagate through the Galaxy
  - Energy losses, spallation, convection, reacceleration, …
  - Scattering by magnetic fields makes CR astronomy impossible for all but the very highest energies
    - Gamma rays important for understanding CRs



The Interstellar Galactic Gamma-ray Emission

- **Comprises more than half of the observed photons by Fermi-LAT**
  - **Strong signal to constrain CR physics**
  - **Needs to be modeled accurately for data analysis**

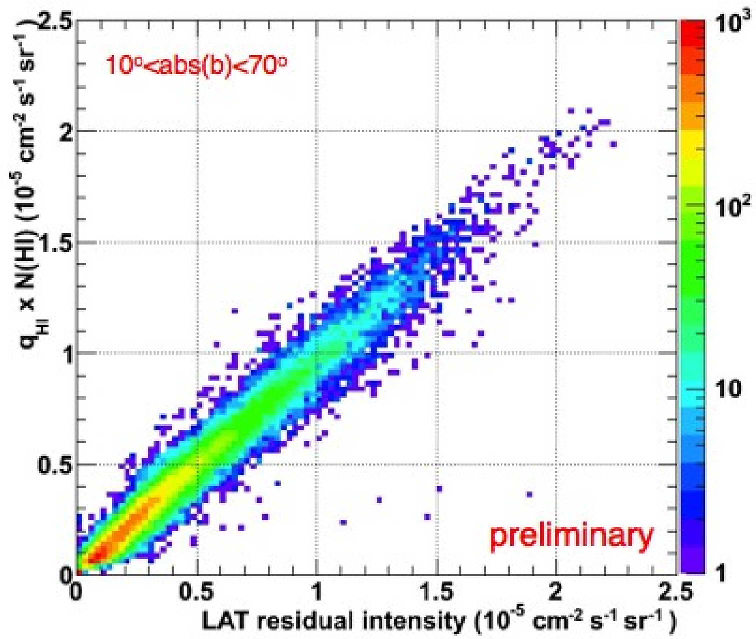


Two main analysis methods

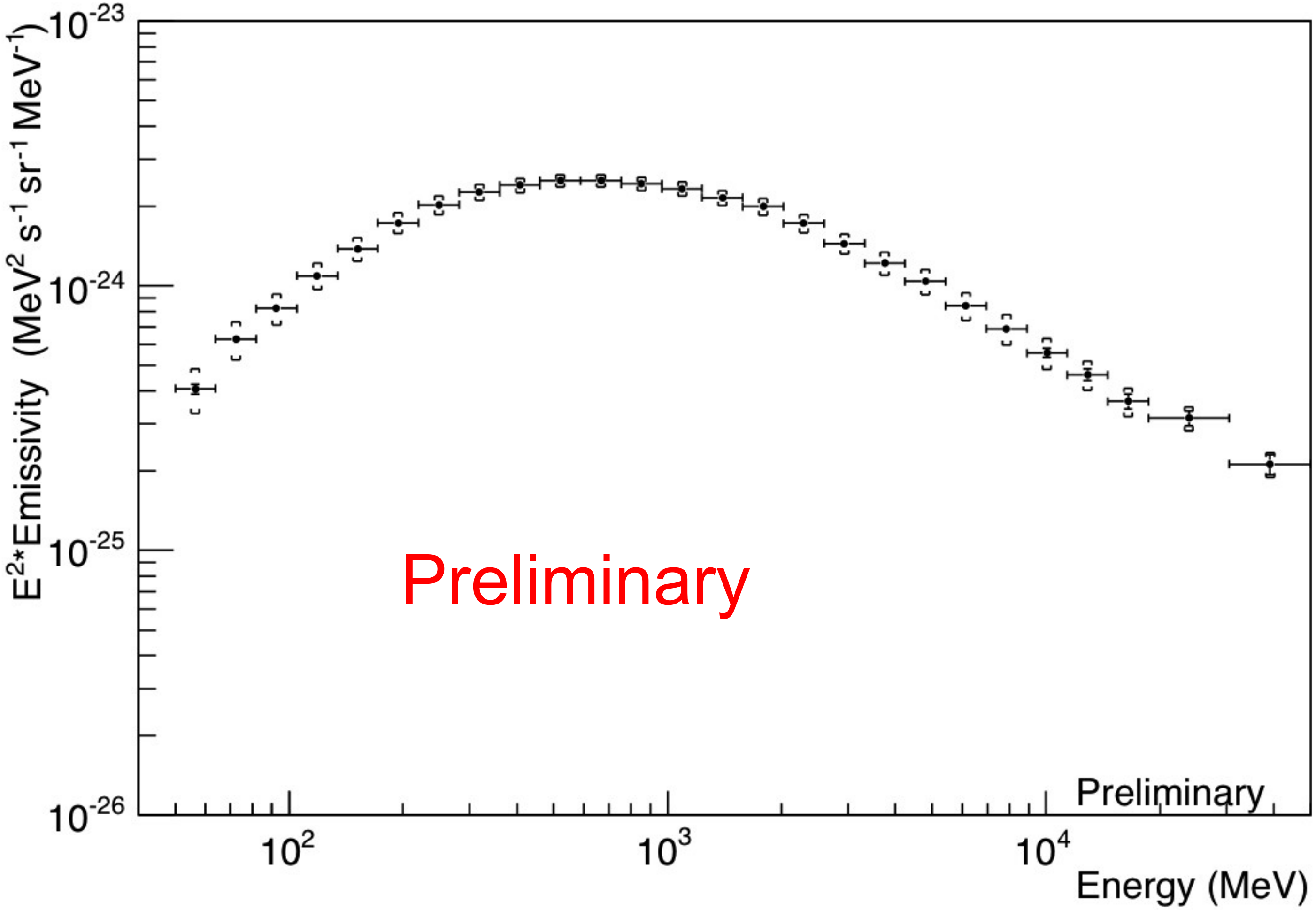
- Template analysis
  - Use templates for gas column density and IC emission
  - CR flux determined from a fit to gamma-ray data
    - Requires no knowledge of CR propagation
    - Limited to uniform CR flux distribution for each template
    - Does not separate bremsstrahlung and hadronic interactions with gas.
- Physical modeling
  - Use template for gas column density
  - CR flux and IC calculated with a propagation code (e.g. GALPROP).
    - Requires complex CR propagation calculations
    - Can account for variation in CR flux within templates
    - Constrained by other observations (e.g. CR and synchrotron).

Local emissivity

- In latitude range |b| > 10 degrees gas is located within ~ 1 kpc from the sun.
  - Useful to probe the local interstellar CR spectrum
- Using the template method we can determine the emissivity of local HI gas
  - Clear correlation between HI column density and gamma-rays after subtracting those associated with other templates

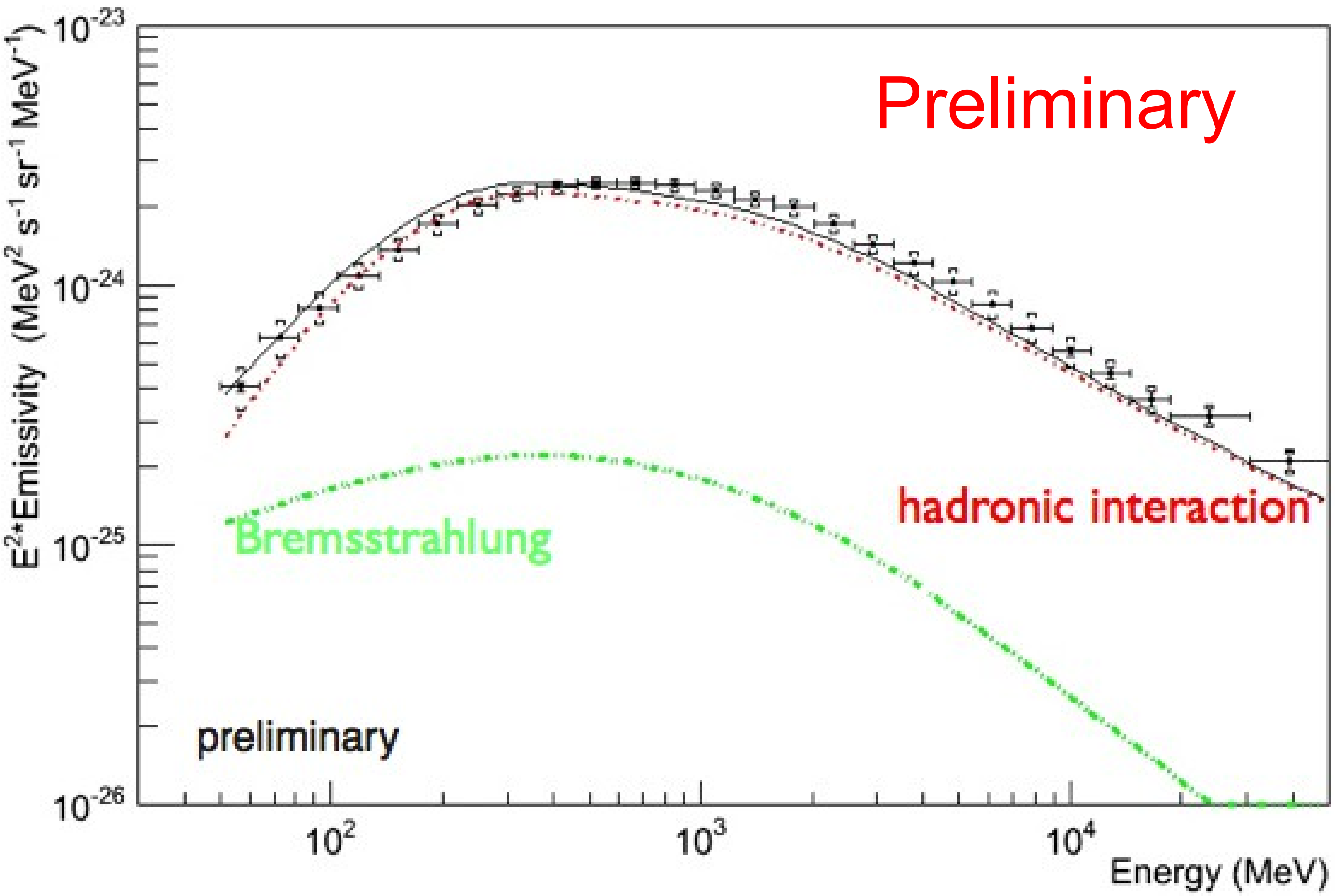


Local emissivity



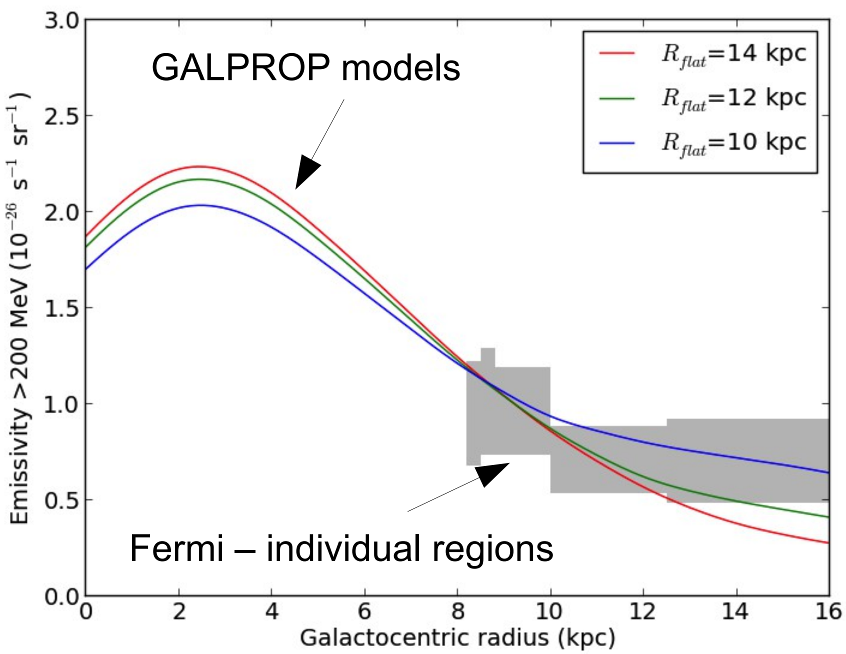
Local emissivity

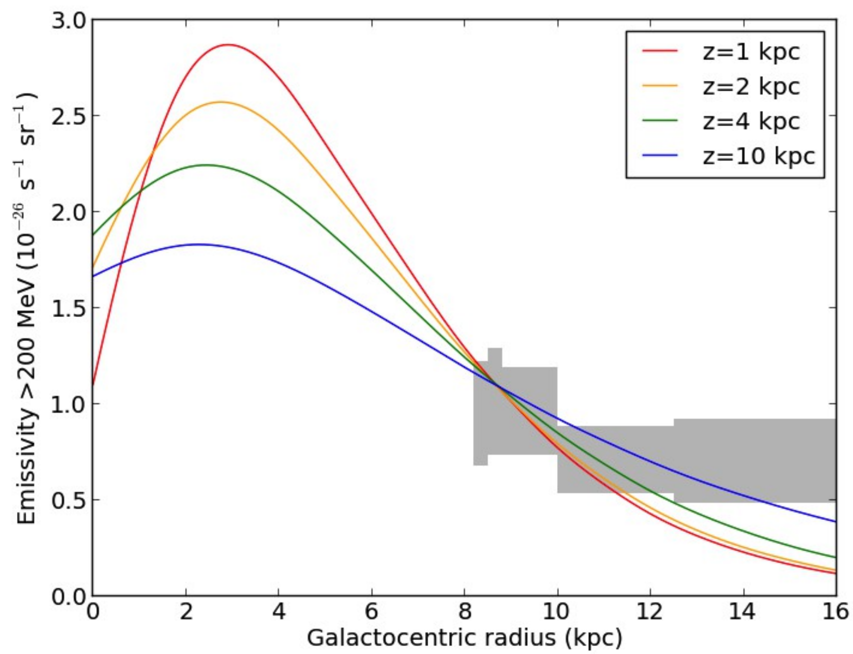
- **Compatible with observed CR proton, helium, and electron spectra once solar modulation has been taken into account!!**



Outer Galaxy

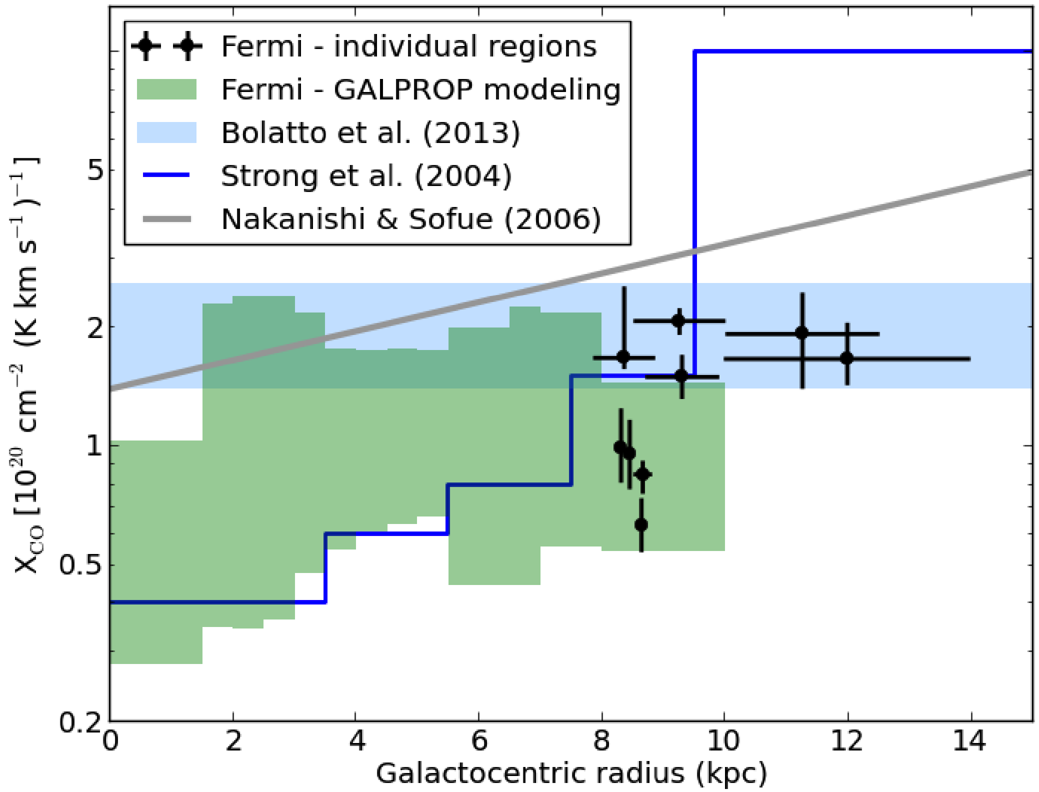
- **More emissivity in the outer Galaxy than expected by propagation models**
  - **Requires more CR sources in the outer Galaxy or modified propagation.**





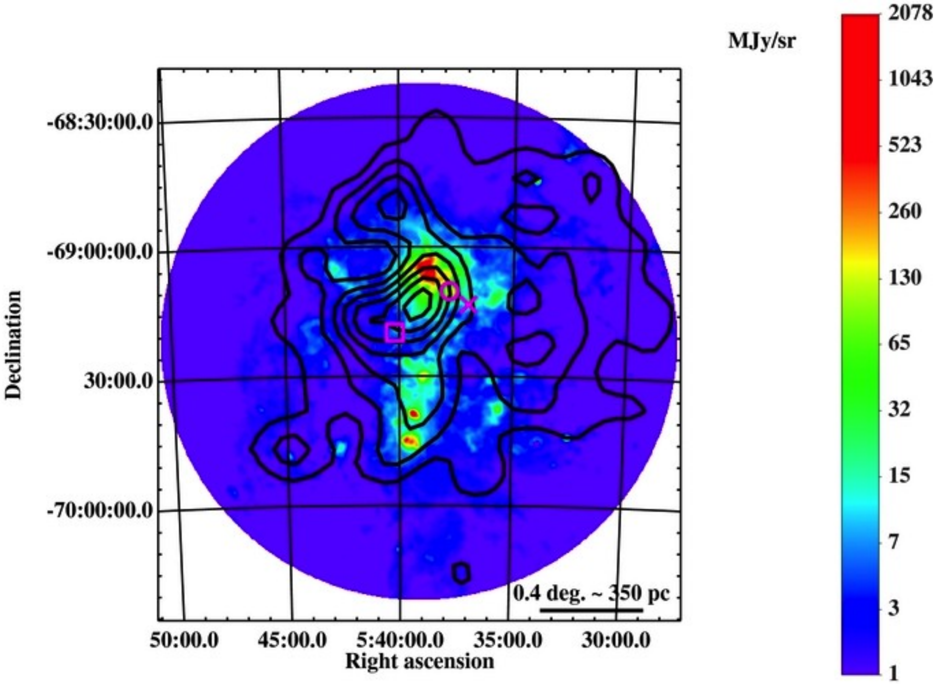
X_{CO}: conversion from CO to H_2

- **Gamma rays are a useful probe to study X_{CO}**
  - **CRs penetrate the clouds => uniform emissivity**
  - **Emissivity can be determined from nearby HI regions**
  - **Not dependent on assumptions about the dynamical state of the clouds**
- **Note that green shaded region was determined using an a priori assumption on CR flux**

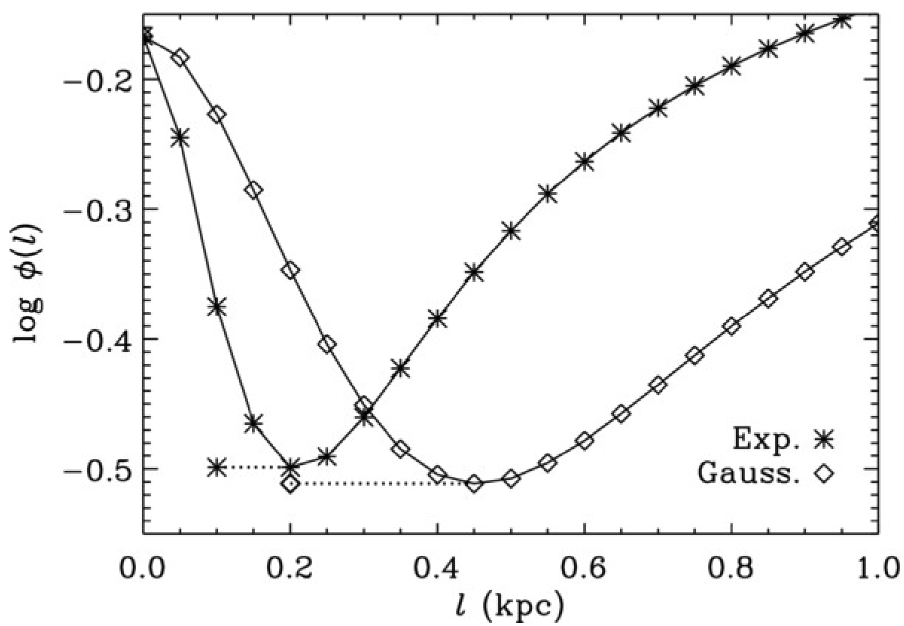


External galaxies

- **Observations of external galaxies allow us to probe CR physics outside of the Milky Way**
  - **LMC is the best target for such exploration**
  - **Correlation between gamma-ray skymaps and IR skymaps allows an estimate for CR propagation length**

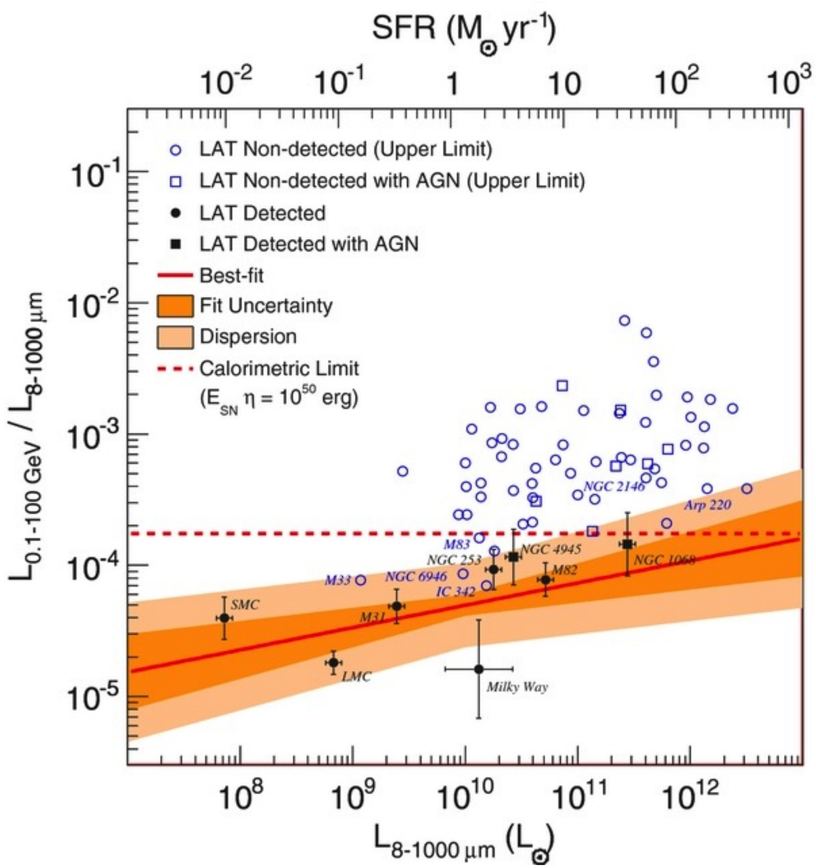


Murphy et al. 2012 ApJ, 750, 126



External galaxies

- **Quasi linear correlation found between IR and gamma-ray luminosities**
  - **IR luminosity expected to trace star formation => link between CRs and massive stars**



Ackermann et al. 2012, ApJ, 755, 164

Summary

- SNRs now observed to accelerate CR nuclei to high energies
  - Connection between massive star-forming regions and CR acceleration
- Gamma rays in the local environment agree well with direct observations of CRs
  - Emission mechanism understood
- Gamma rays provide a wealth of information to constrain CR propagation models
  - More gamma rays than expected in outer Galaxy
    - More CR sources? More gas? Different propagation?
  - Larger halo size is preferred
- There is currently no single best fit interstellar emission model
  - A range of models can be put forward that explain the data reasonably well

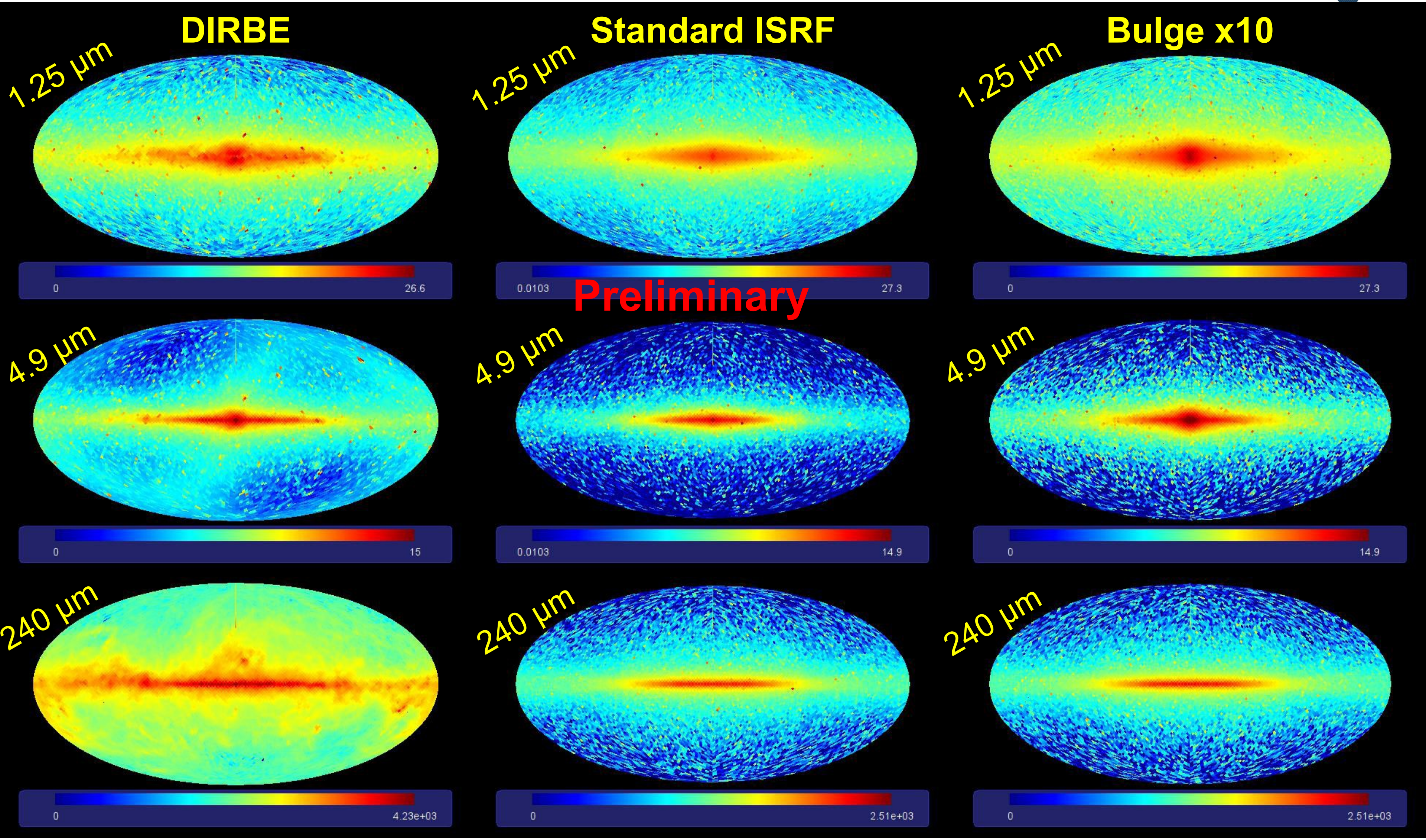
Backup slides ...

The Interstellar Radiation Field (ISRF)

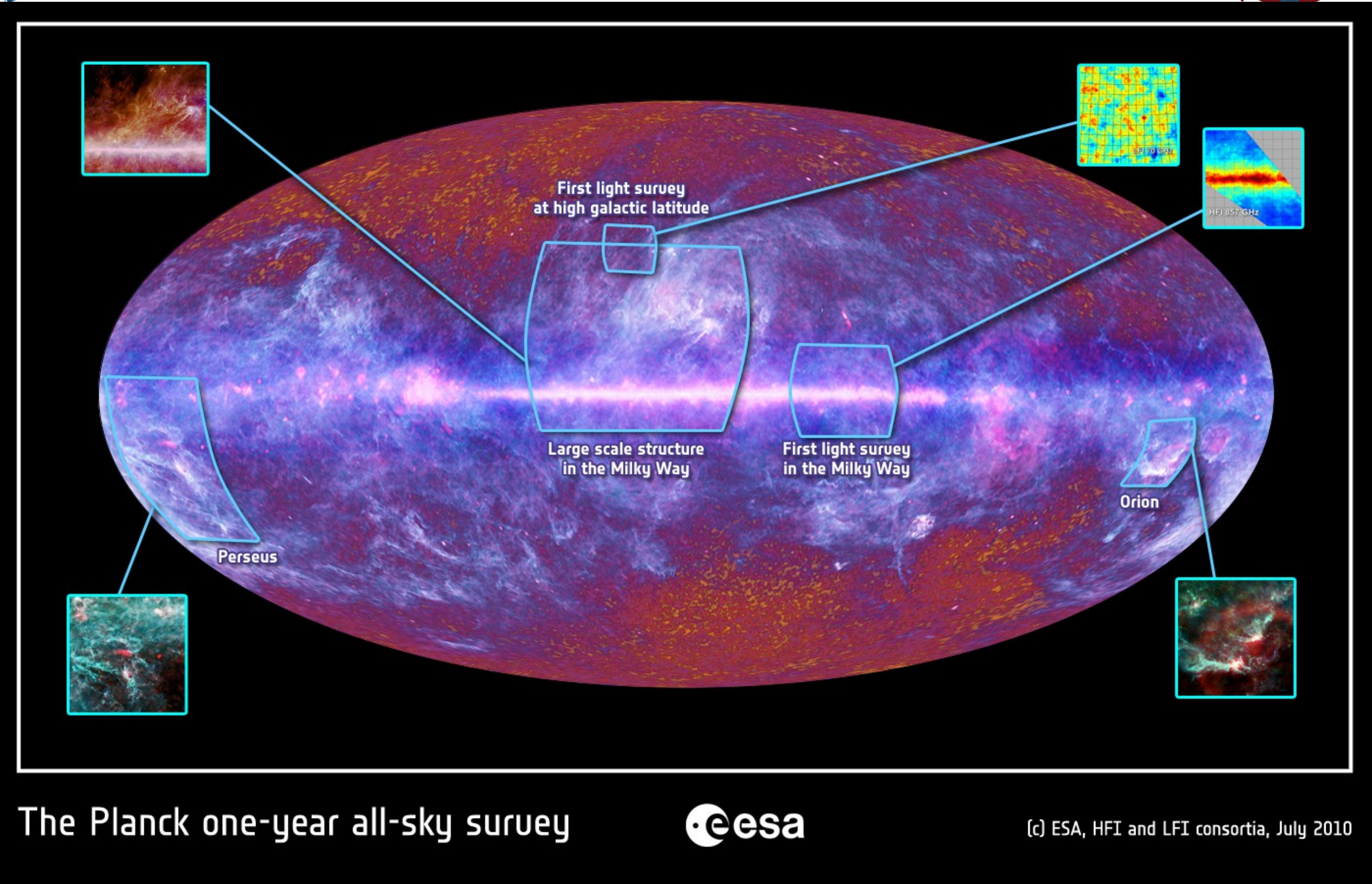
- Three main components
  - Stellar light
  - Dust re-emission of stellar light
  - The Cosmic microwave background
- Only directly observable in one location
  - Need sophisticated modeling
    - Stellar distribution and properties
    - Dust distribution and properties
    - Radiation transport
  - Some freedom in the model
    - Especially in the inner Galaxy (both dust and stars)

Porter et al. 2008 ApJ 682

Couple of ISRF models

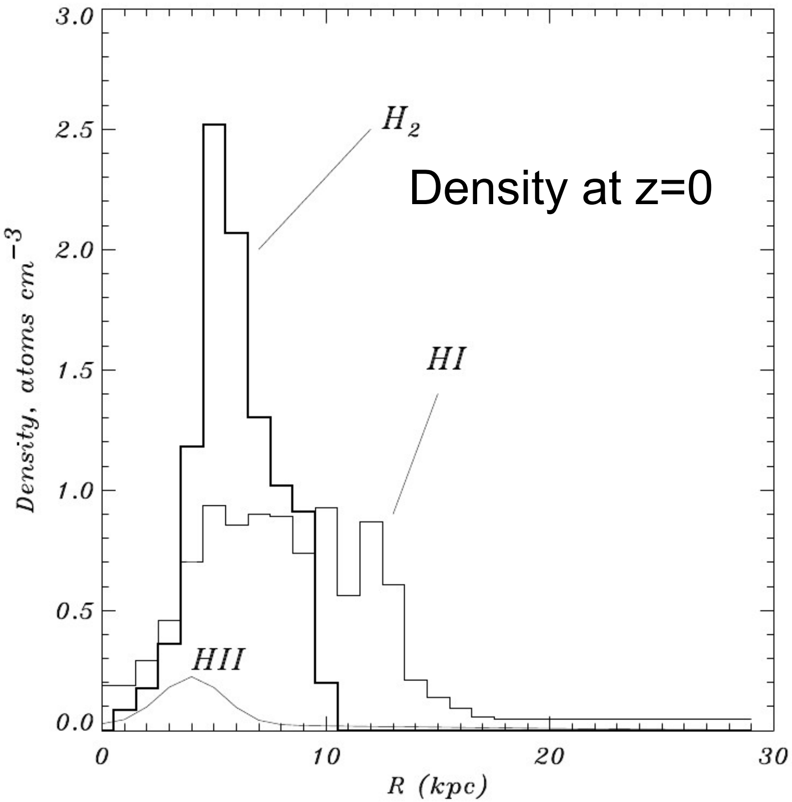


The Interstellar Medium (ISM)



The Three Components of the ISM

- **Most of the ISM is hydrogen gas in three different forms:**
  - **Atomic (H I)**
    - **The most massive component with a large filling factor, $z_{1/2}$ ~ 200 pc.**
  - **Molecular (H_2)**
    - **The most dense component, very clumpy, $z_{1/2}$ ~ 100 pc.**
  - **Ionized (H II)**
    - **The least significant component, very widespread, $z_{1/2}$ ~ 1 kpc.**



Strong A.W., Moskalenko I.V. 1998, ApJ 509, 212-228

Atomic Hydrogen

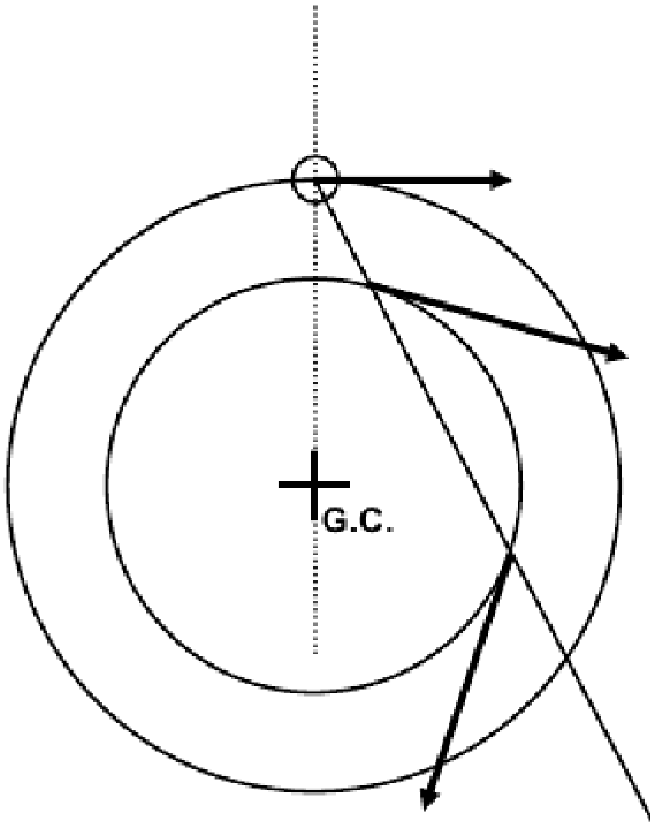
- Emits radiation at 21 cm wavelengths
  - Hyperfine splitting of the ground state
- Not optically thin in all regions, need to correct for optical thickness
  - Often parametrized in terms of a spin temperature, T_s under the assumption of a homogeneous line of sight

$$N_{HI}(T_S(v)) = -\log\left(1 - \frac{T(v)}{T_S(v) - T_{bg}}\right) * T_S(v) * C$$

  - Need to know $T_s(v)$ for all lines of sight
    - Observations in radio show T_s to be in the range 50 K – 8000 K
    - Usually pick a single value for TS and apply it to the entire sky

Molecular Hydrogen

- No line emission observed from cold H_2
  - CO used as a surrogate as both molecules form under similar conditions (H_2 shields from UV light)
- CO J 1->0 line used for tracing CO
  - The integrated line intensity, W_{CO}, is found to be roughly linearly related to H_2 column density
    - $N_{H2} = X_{CO} * W_{CO}$
- Velocity information and rotation curve used to create a radial profile from emission lines



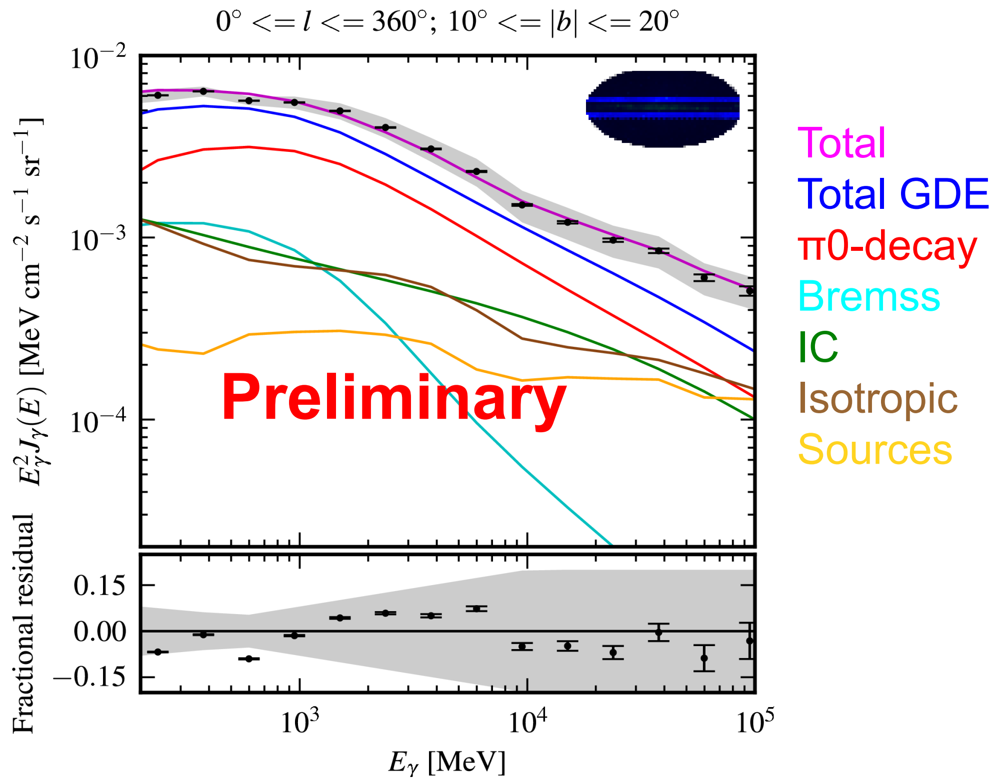
Dust and Gamma-Rays

- **Shown by Grenier et al. 2005 to be essential in analyzing EGRET data to account for dark gas (H_2 not traced by CO)**
  - **This has been confirmed by the Fermi-LAT data**
- **Observations of dust are in IR continuum (turned into reddening E(B-V)), so we must use CO and H I for distance information:**
  - **Gas to dust ratio determined from H I and CO**
  - **Contribution of H I and CO subtracted from dust**
    - **Corrects for dark gas and also uncertain T_s and X_{CO} under the assumption of constant gas to dust ratio**
    - **Use optically thin H I as a lower limit**
  - **Radial distribution of the residual dust unknown**

Intermediate Latitude Spectra

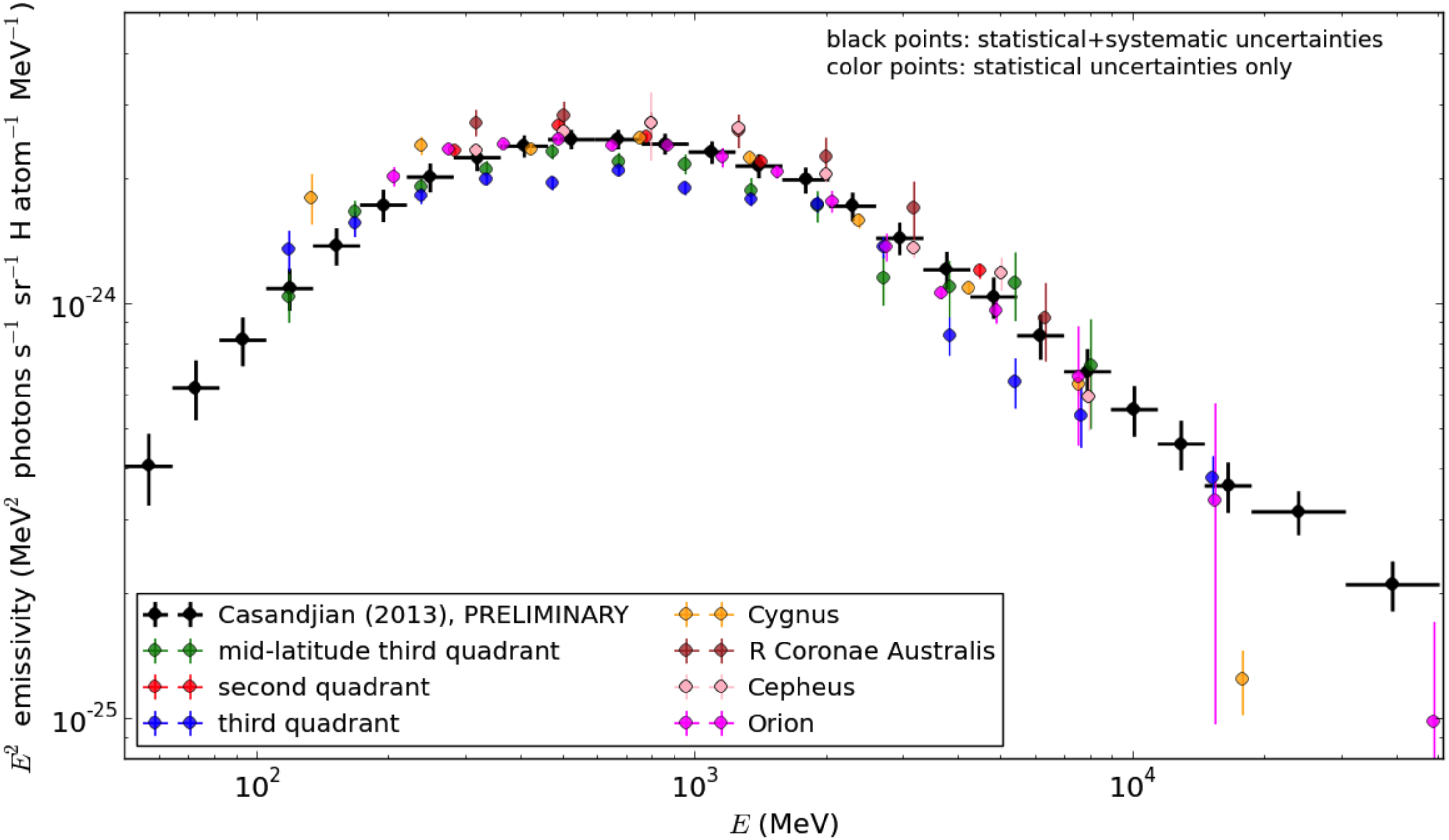
- **Gas has small scale height => probes local CRs**
  - **Good agreement between data and model**
  - **Modeling works when ingredients are reasonably well known**

Model 2: SNR, 4 kpc, 20 kpc, 150 K, 5 mag



Local emissivity

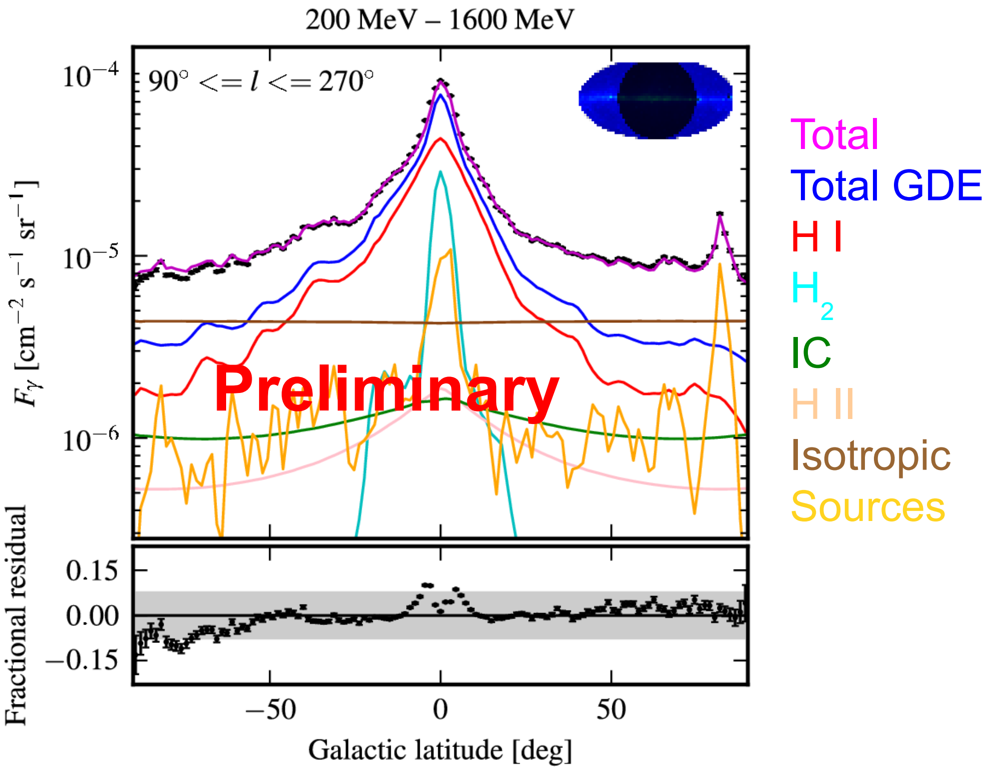
- **Analyses of other region suggest a slight variation of CR density within 1 kpc of the solar system**
  - **Within systematic uncertainties in most cases**



Latitude profile

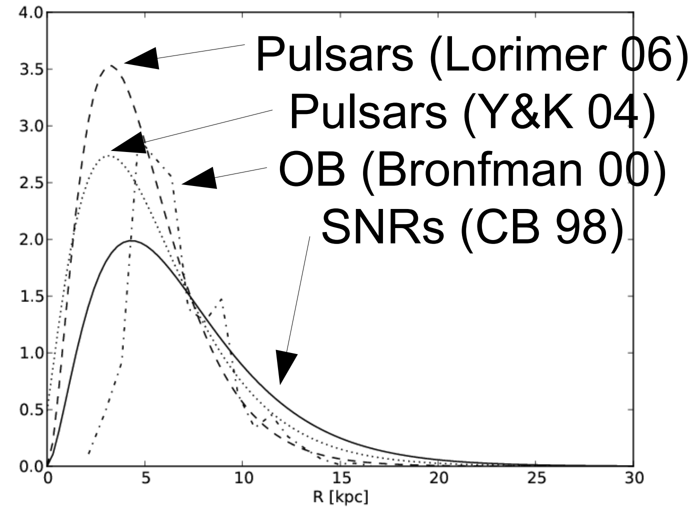
- **Models agree with data spanning more than an order of magnitude in flux**
  - **Models underpredict the data in the outer Galaxy plane**
    - **CR sources? Gas densities? Propagation?**
  - **North-south asymmetry visible**
    - **Origin not known**

Model 44: Lorimer, 6 kpc, 20 kpc, OT, 5 mag



Studying Systematics Using GALPROP

- CR source distribution from literature
  - Pulsars (2 versions), SNRs, OB stars
  - Assumes massive star origin
- CR confinement volume (halo)
  - Vertical: 4, 6, 8, 10 kpc
  - Radial: 20, 30 kpc
- Spin temperature
  - T_s: 150 K, Optically thin (100,000 K)

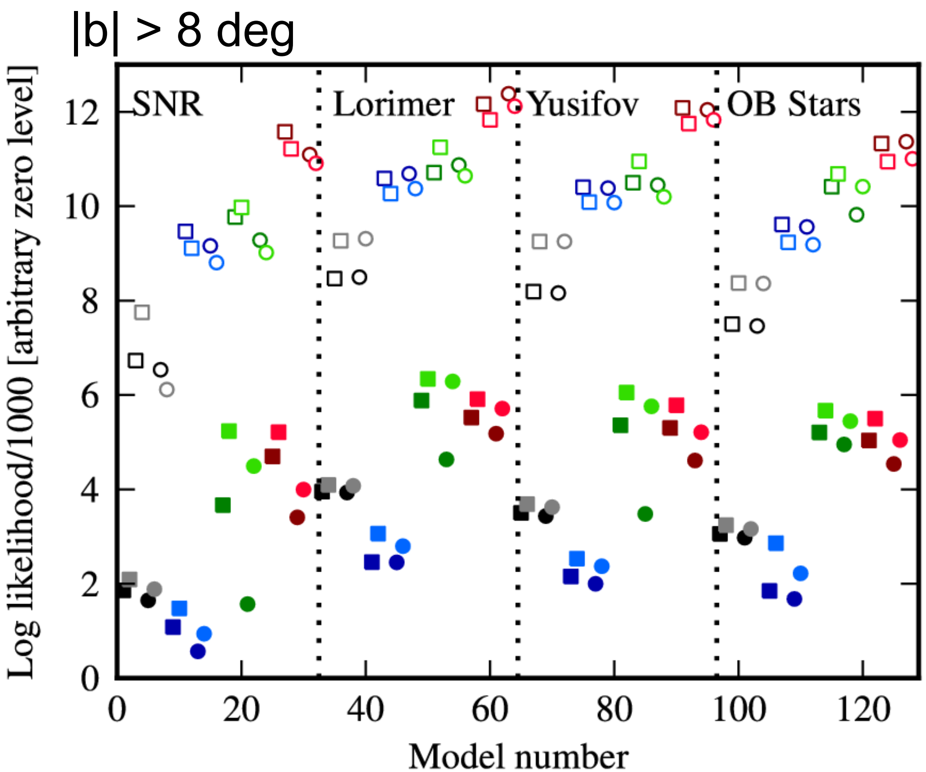


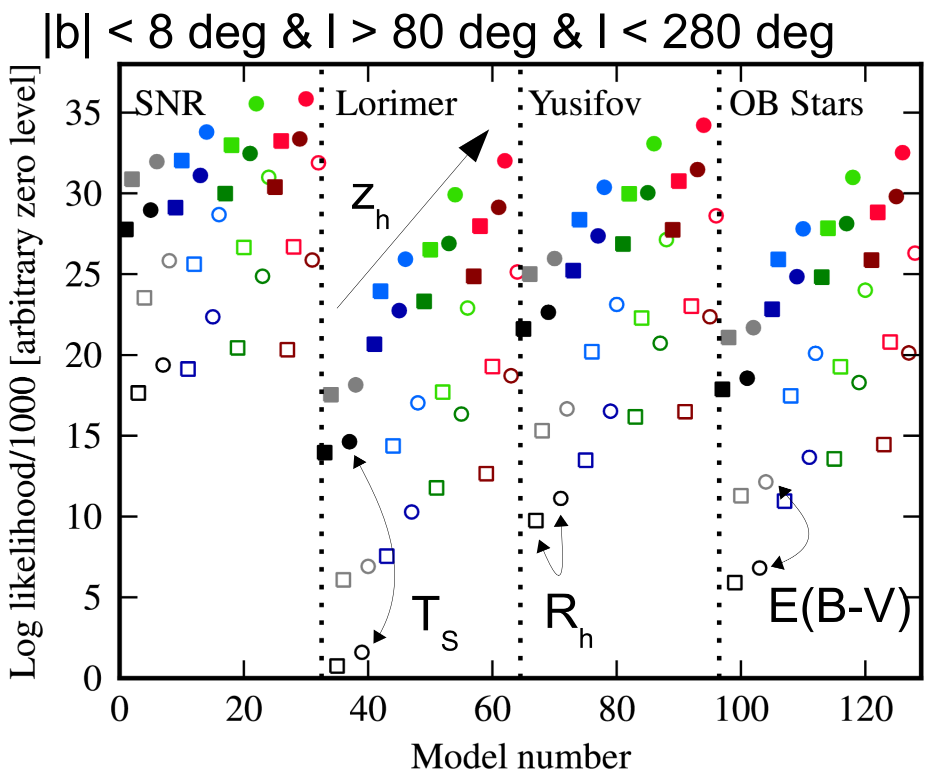
- E(B-V) magnitude cut
  - 2 and 5 magnitudes
- ISRF scaling and X_{co} determined from gamma-ray fit to 21 months of Fermi-LAT data
- Propagation determined from CR data (B/C, element spectra) with Iterative X_{co} feedback from gamma-ray fit
- Grid comprises 4x4x2x2x2=128 models

Statistical Comparison

- **Large difference in likelihood between models**
  - **No single model gives best fit over all sky regions**
- **Large halo, flat CR source distribution and more gas favored in outer Galaxy**
- **5 mag E(B-V) cut favored**
  - **Dust better than CO + HI only**

z_h = 4kpc, 6kpc, 8kpc, 10kpc
R_h = 20kpc (sq), 30kpc (circ)
T_S = 150K (filled), OT (open)
E(B-V) cut = 2mag (dark), 5mag (light)



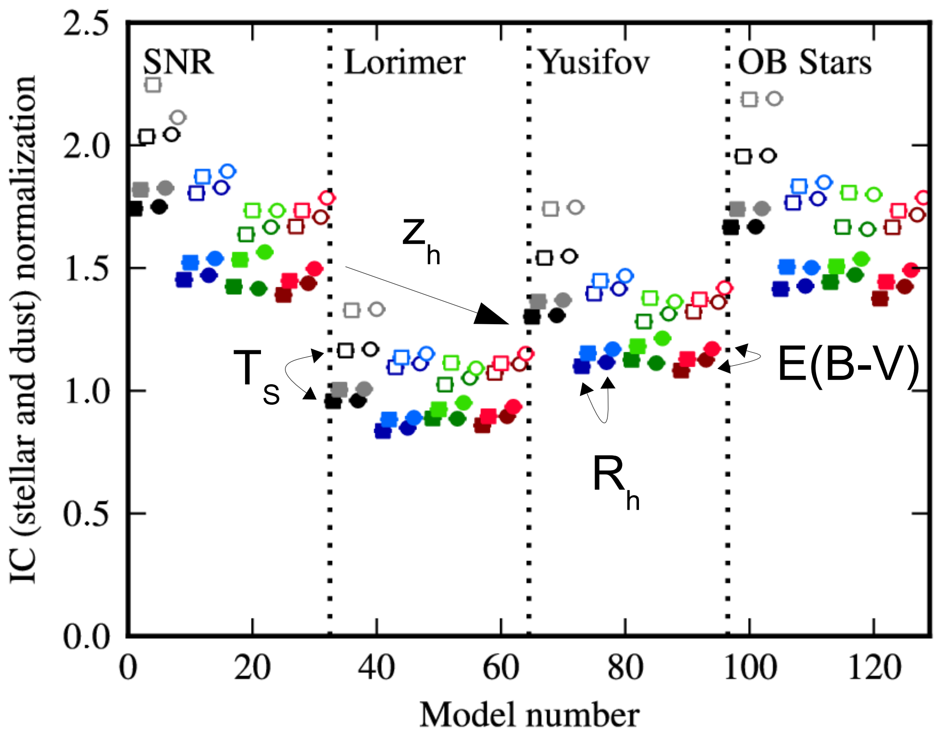


Inverse Compton normalization

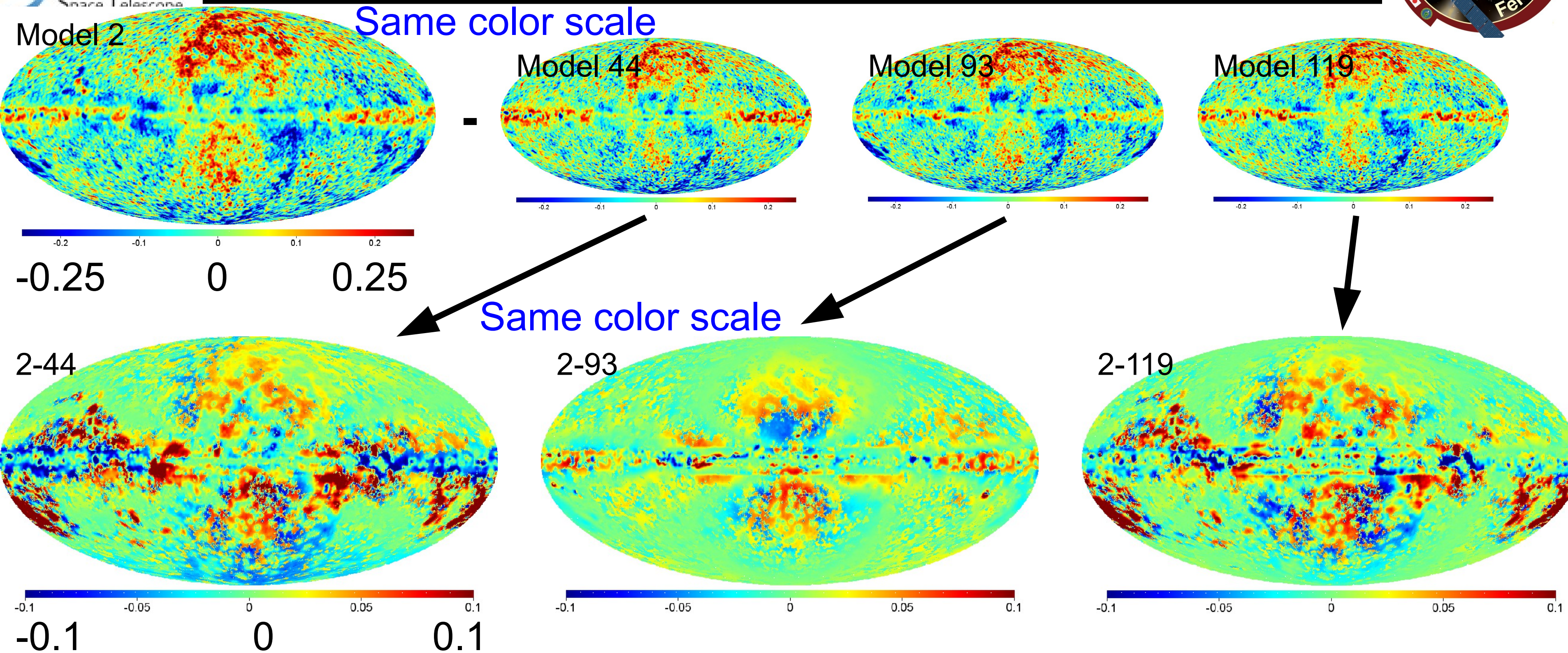
- **Evidence for a large halo from IC**
  - **Depends on the assumed CR source distribution, smaller effect for distribution peaking close to GC.**
- **IC fit compensates for changes in gas densities**
  - **Despite spatial and spectral difference between the two components**
- **Normalization factor of IC affected by uncertainties in both CR electrons and ISRF**

z_h = 4kpc, 6kpc, 8kpc, 10kpc
R_h = 20kpc (sq), 30kpc (circ)
T_S = 150K (filled), OT (open)
E(B-V) cut =
2mag (dark), 5mag (light)

|b| > 8 deg



Residual Maps and their Differences

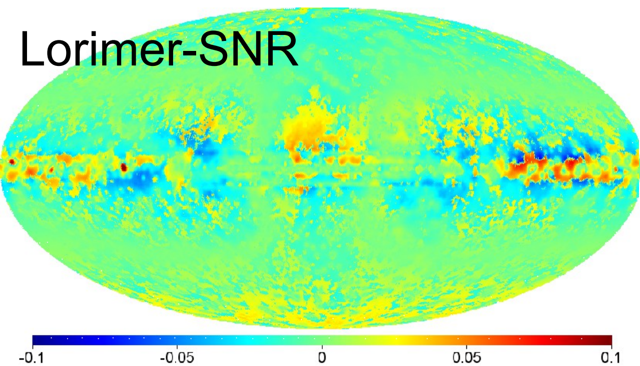


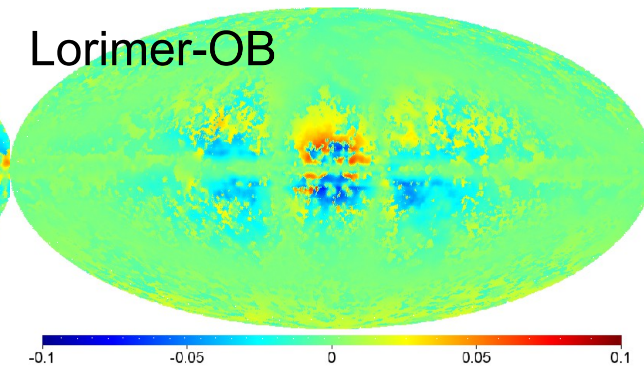
- **Structure overall good to within ~10%**
  - **Exceptions are Fermi lobes (Su et al. 2010 ApJ 724), Loop I, outer Galaxy**
- **Structure in lower maps due to variations of model parameters**

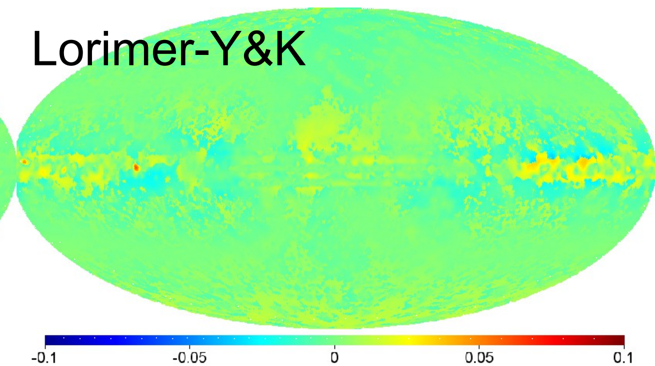
Model details:
2: SNR, 4kpc, 20kpc, 150K, 5m
44: Lorimer, 6kpc, 20kpc, OT, 5m
93: Y&K, 10kpc, 30kpc, 150K, 2m
119: OB, 8kpc, 30kpc, OT, 2m

Residual Differences

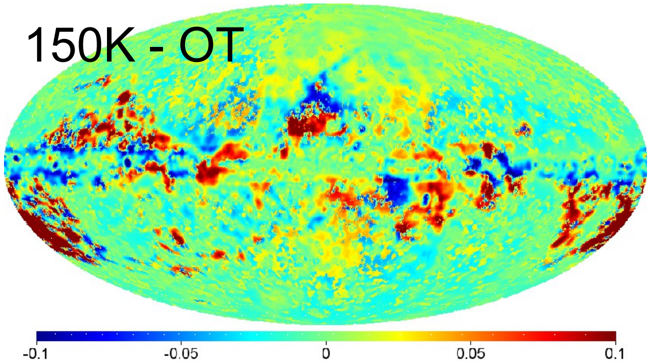
- **Only varying CR source distribution**

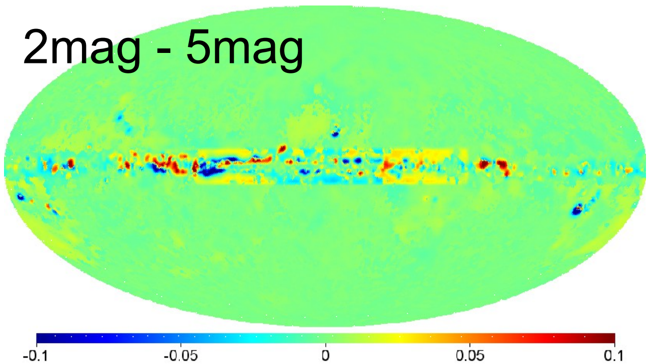






- **Only varying gas properties**



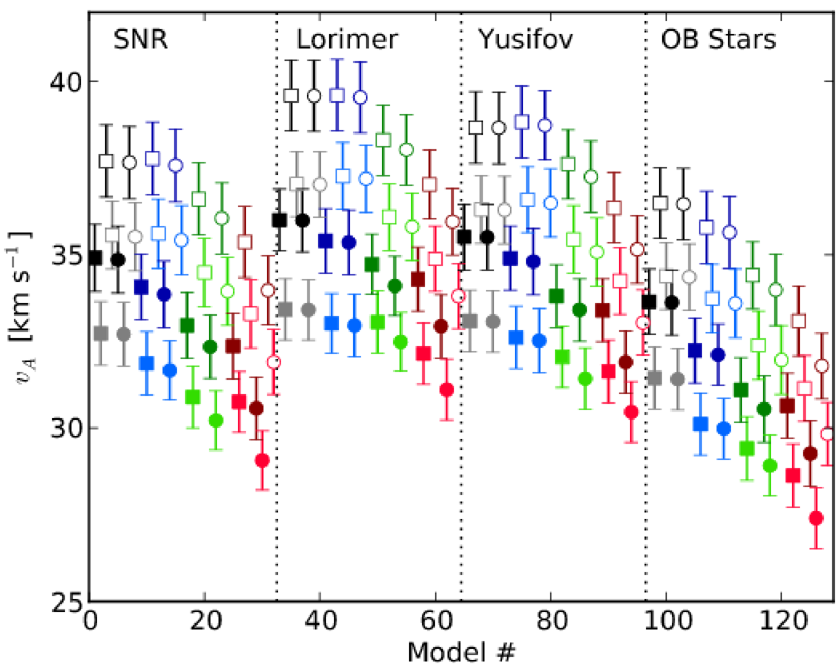


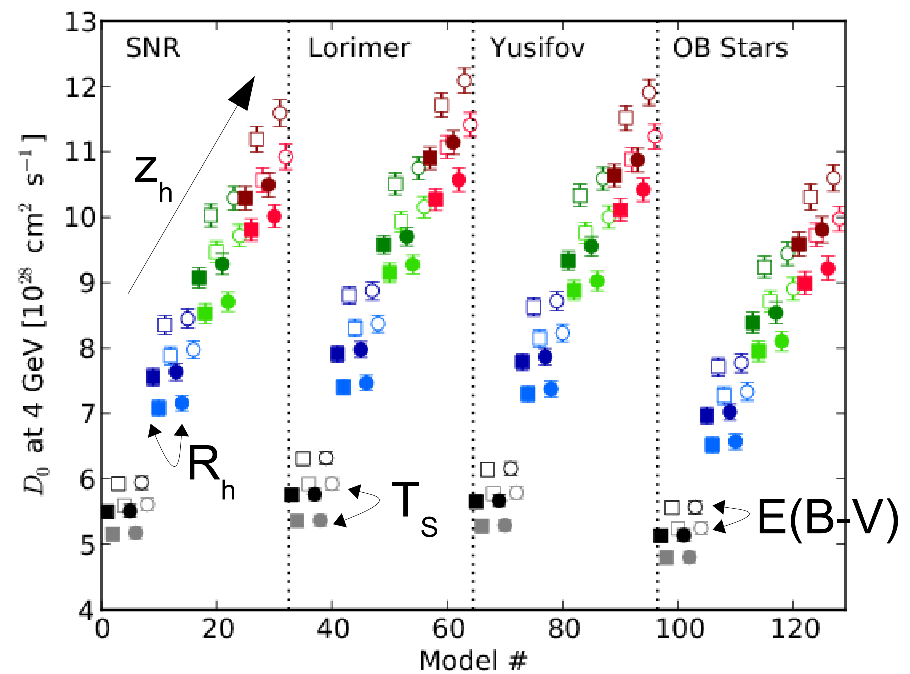
- **Gas properties clearly have a larger influence**

CR Propagation Parameters

- **Determined from a fit to H, He, C, O, and B/C (error bars statistical only)**
  - **X_{co} feedback from gamma-ray fit important**
  - **Propagation parameters depend on ISM and CR source distribution**
  - **Only X_{co} determined from gamma-rays**

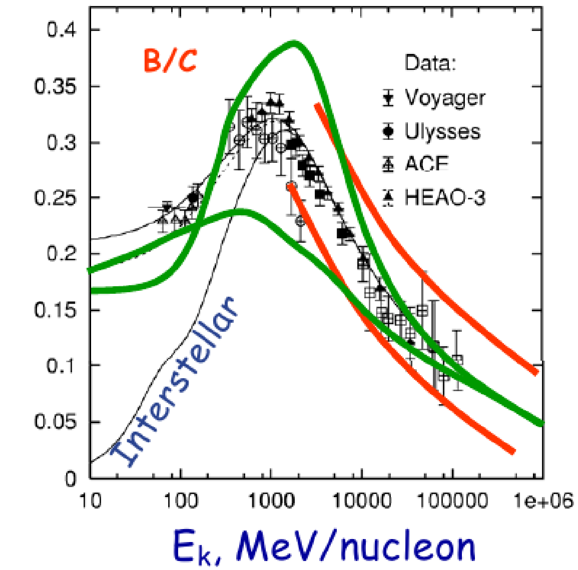
z_h = 4kpc, 6kpc, 8kpc, 10kpc
R_h = 20kpc (sq), 30kpc (circ)
T_s = 150K (filled), OT (open)
E(B-V) cut =
2mag (dark), 5mag (light)





The “Conventional” Model

Credit: Moskalenko, I. V.



- **CR injection spectra and propagation parameters adjusted so model matches CR observations**
  - **Secondary/primary ratio determines D_0/z_h ratio**
  - **Radioactive/stable ratio determines z_h**
  - **Injection spectra adjusted to fit observed spectra**
- **CR source distribution cannot be determined**
- **Halo size not well constrained**
- **Limited by solar modulation at low energies**