Fermi Gamma-ray Space Telescope

A Study of Systematic Uncertainties in Diffuse Galactic Emission Models

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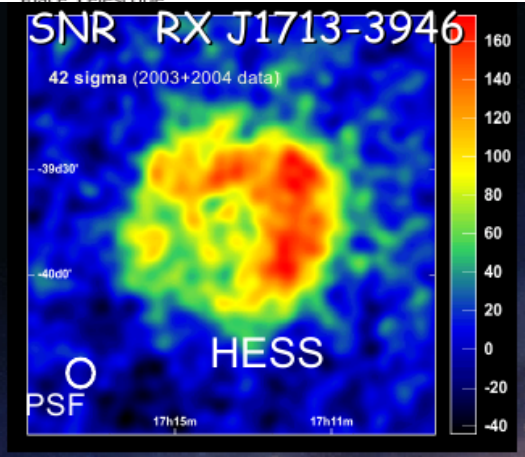
on behalf of the Fermi-LAT collaboration

The Big Picture



ISM

X,γ

$e^{\pm}$

$\vec{B}$

synchrotron

P
He
CNO

diffusion
energy losses
reacceleration
convection
etc.

ISRF

IC

gas

bremss

π^0

$e^{\pm}$

$\pi^{\pm}$

gas

$\bar{P}$

$\pi^{\pm}$

P

$e^{\pm}$

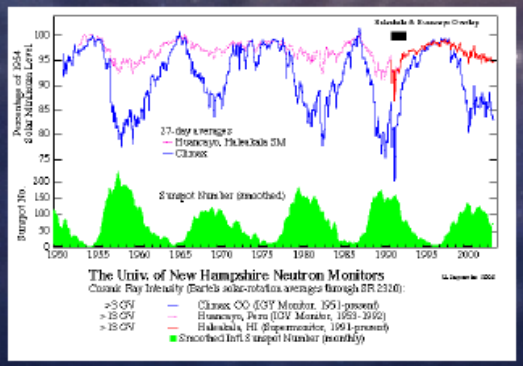
He
CNO

LiBeB

Chandra

HESS

FERMI



Credit: I.V. Moskalenko

BESS
PAMELA

ACE

helio-modulation

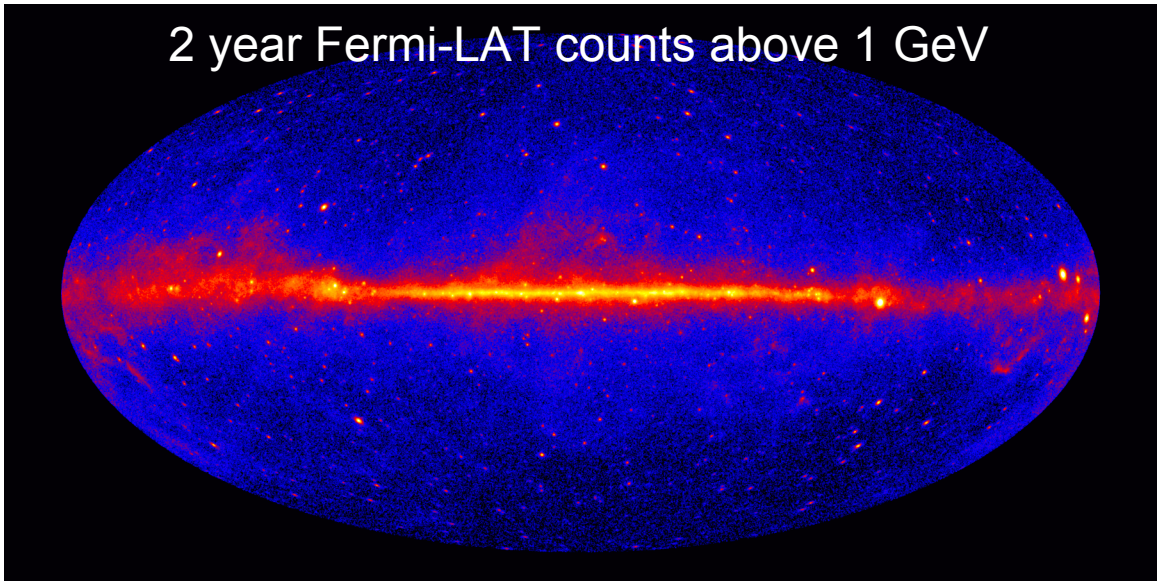
Flux

20 GeV/n

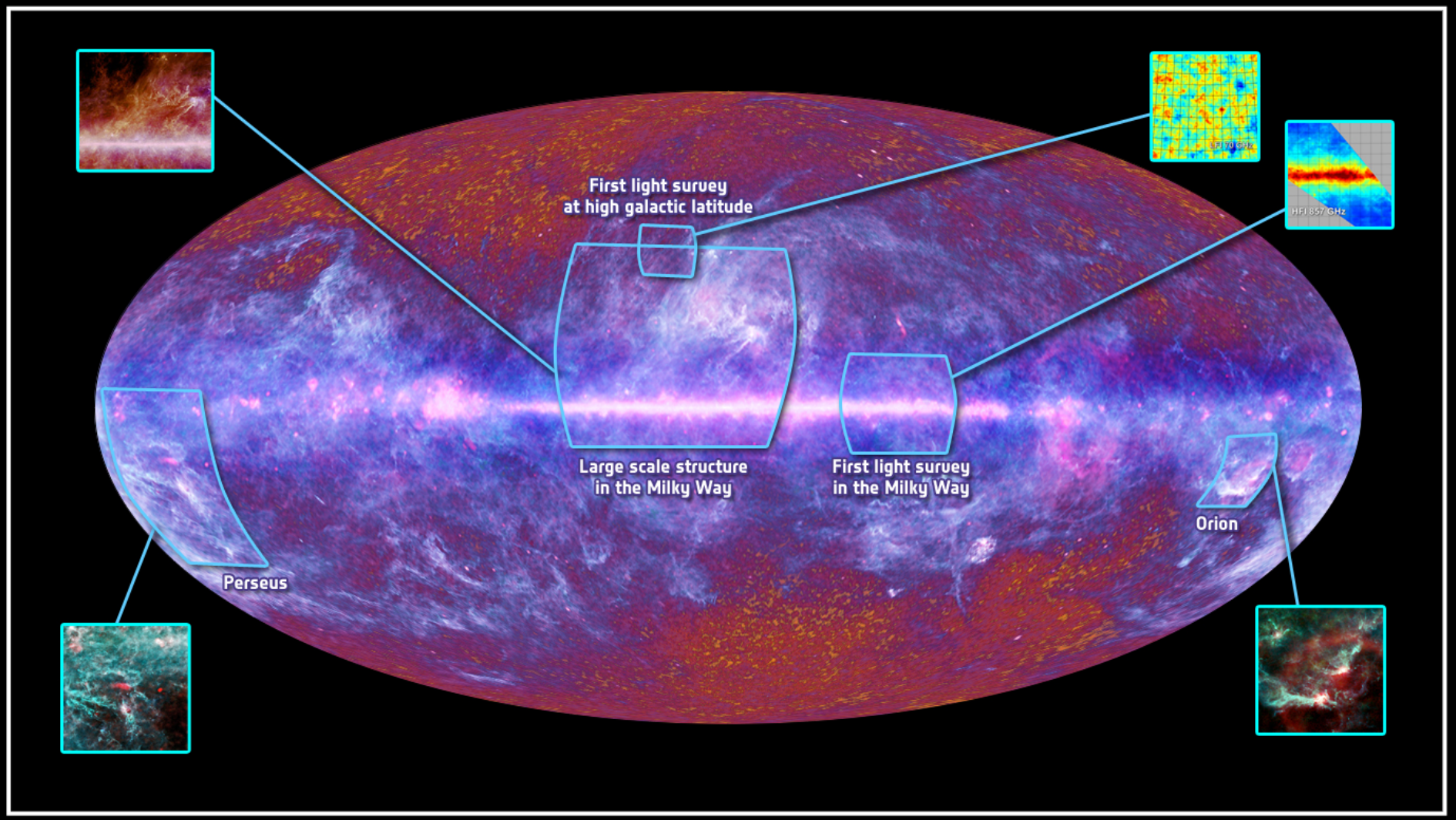
CR species:
- Only 1 location
- modulation

Diffuse Galactic 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**
- **Production cross sections known to high accuracy**
  - **"Only" need to know CR flux and target density**



The Interstellar Medium (ISM)



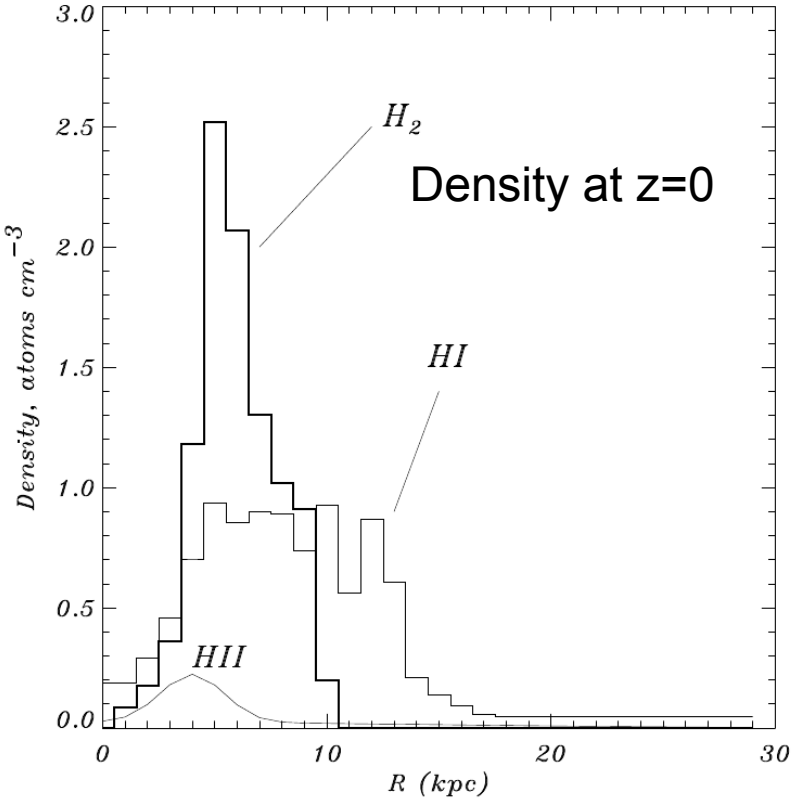
The Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, July 2010

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

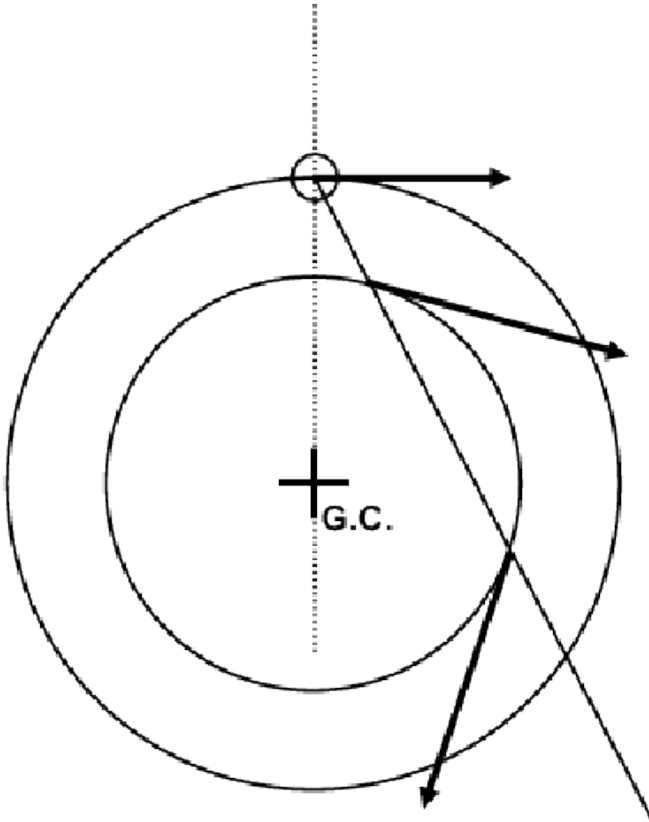
- **Emits radiation at 21 cm wavelengths**
  - **Hyperfine splitting of the ground state**
- **Not optically thin in all regions, need to correct for optical thickness**
  - **Often parametrized in terms of a spin temperature, T_s under the assumption of a homogeneous line of sight**

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

  - **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

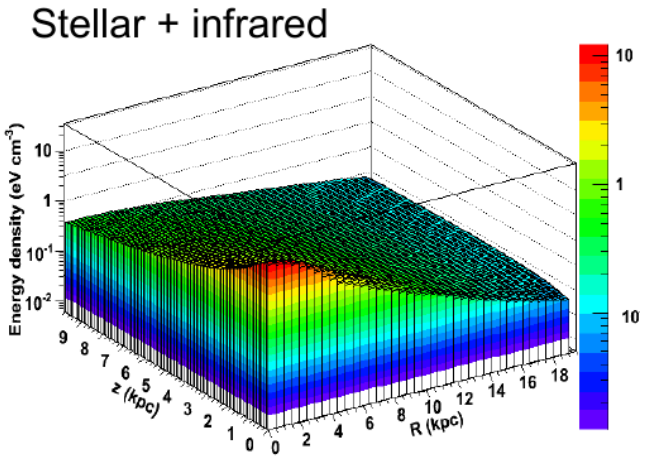


Dust and Gamma-Rays

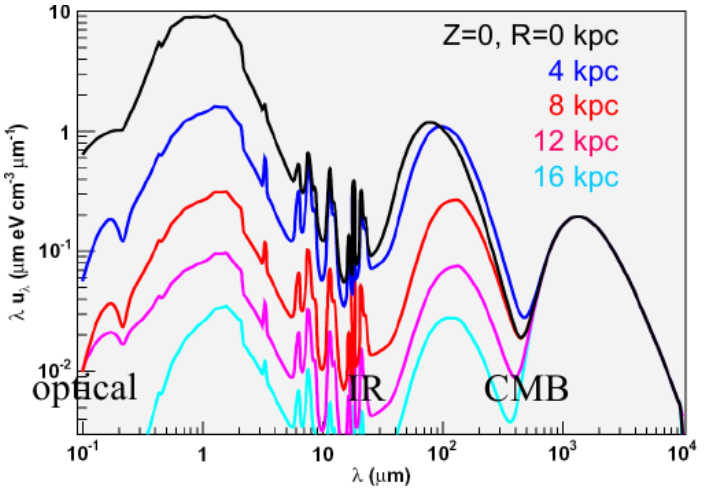
- **Shown by Grenier et al. 2005 to be essential in analyzing EGRET data to account for dark gas (H_2 not traced by CO)**
  - **This has been confirmed by the Fermi-LAT data**
- **Observations of dust are in IR continuum (turned into reddening E(B-V)), so we must use CO and H I for distance information:**
  - **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**
    - **A good first approximation is to use the distribution of H I for dust**

The Interstellar Radiation Field (ISRF)

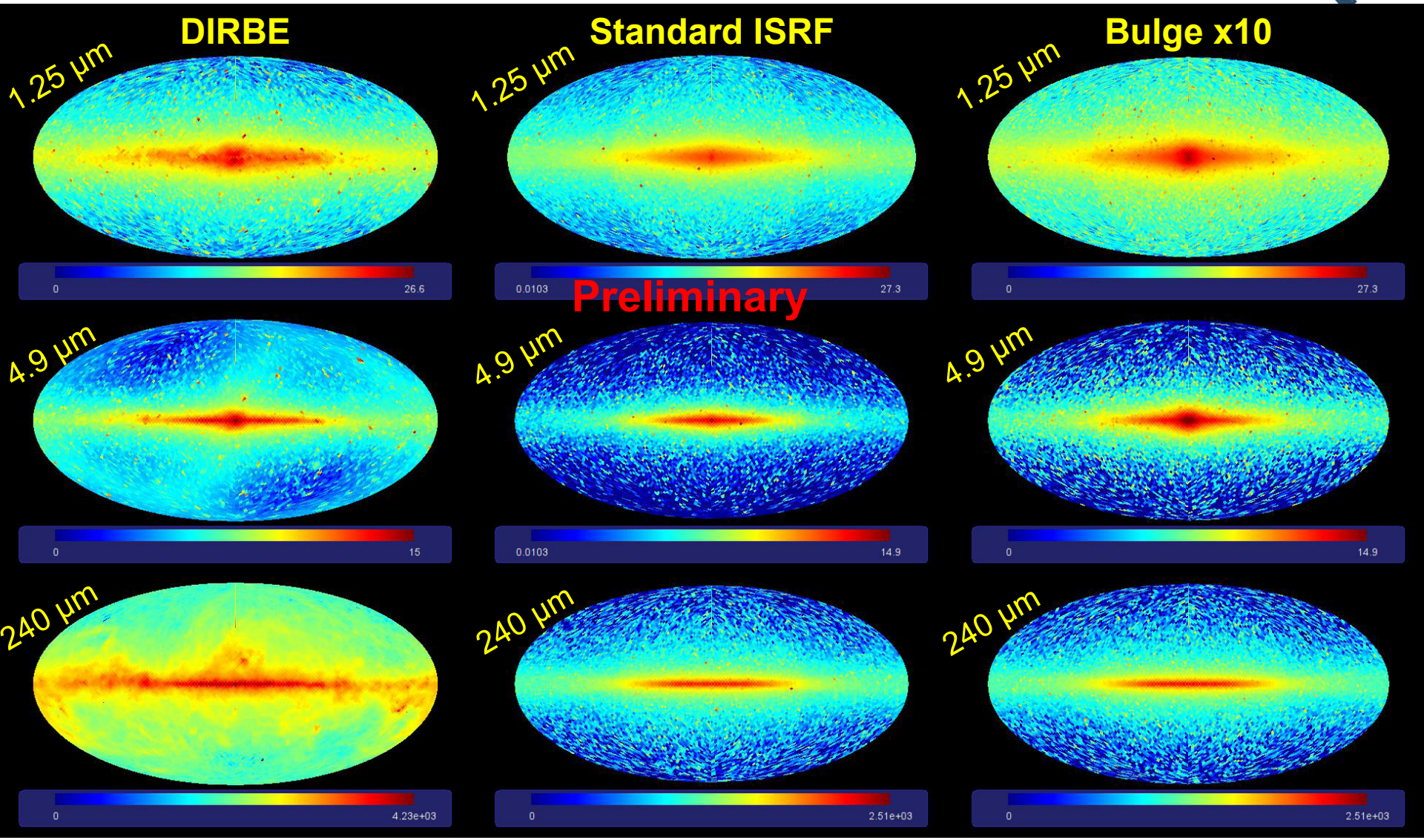
- **Three main components**
  - **Stellar light**
  - **Dust re-emission of stellar light**
  - **The Cosmic microwave background**
- **Only directly observable in one location**
  - **Need sophisticated modeling**
    - **Stellar distribution and properties**
    - **Dust distribution and properties**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



Porter et al. 2008 ApJ 682

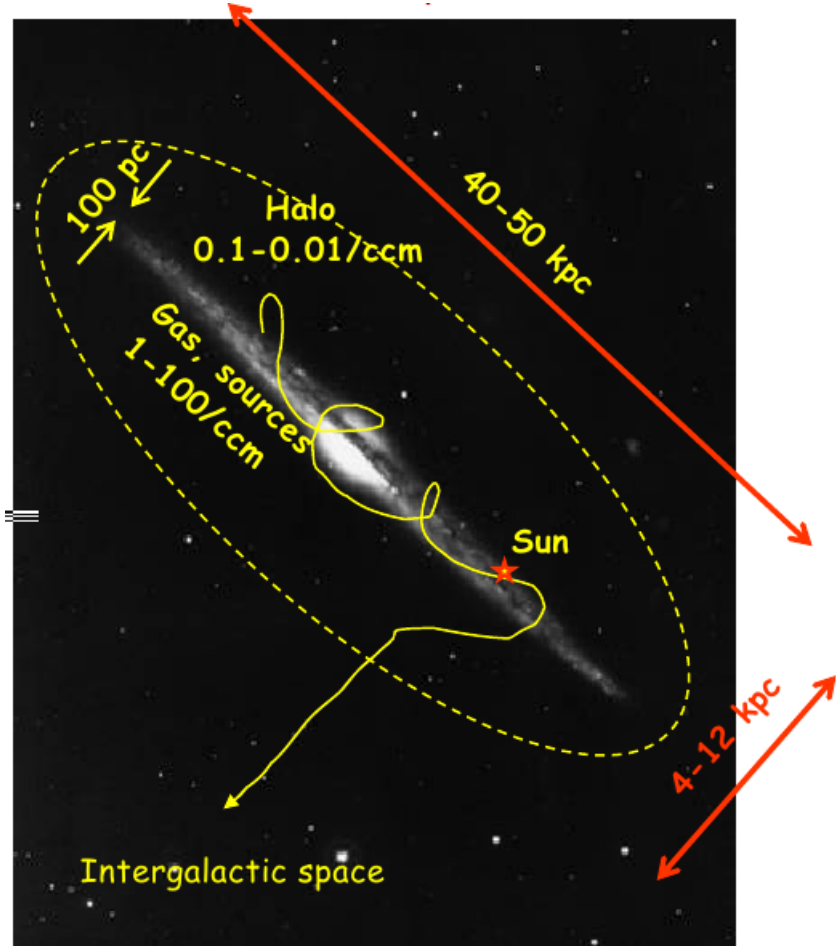


Increasing the ISRF in the Galactic Bulge



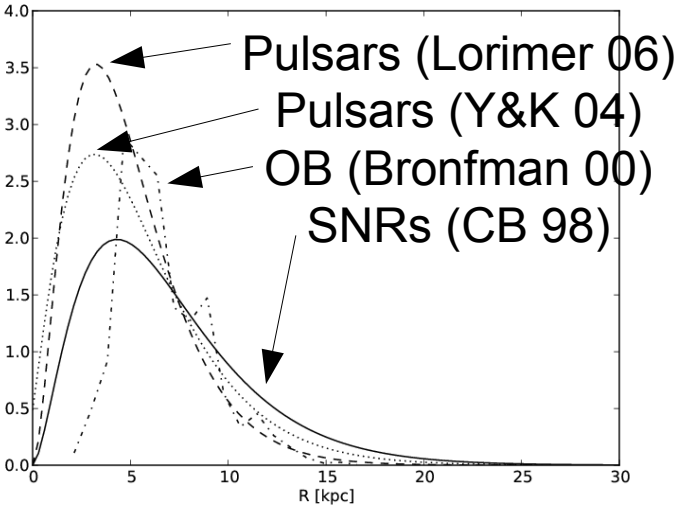
CR propagation

- CRs are generated at the source
  - SNRs, pulsars, stellar wind, ISM shocks, DM, ...
  - Distribution of CR sources mostly unknown
  - Injection spectra determined from CR observations
- And propagate through the Galaxy
  - Energy losses, spallation, convection, reacceleration, halo size, diffusion coefficient
  - Uncertainty in all processes



Studying Systematics Using GALPROP

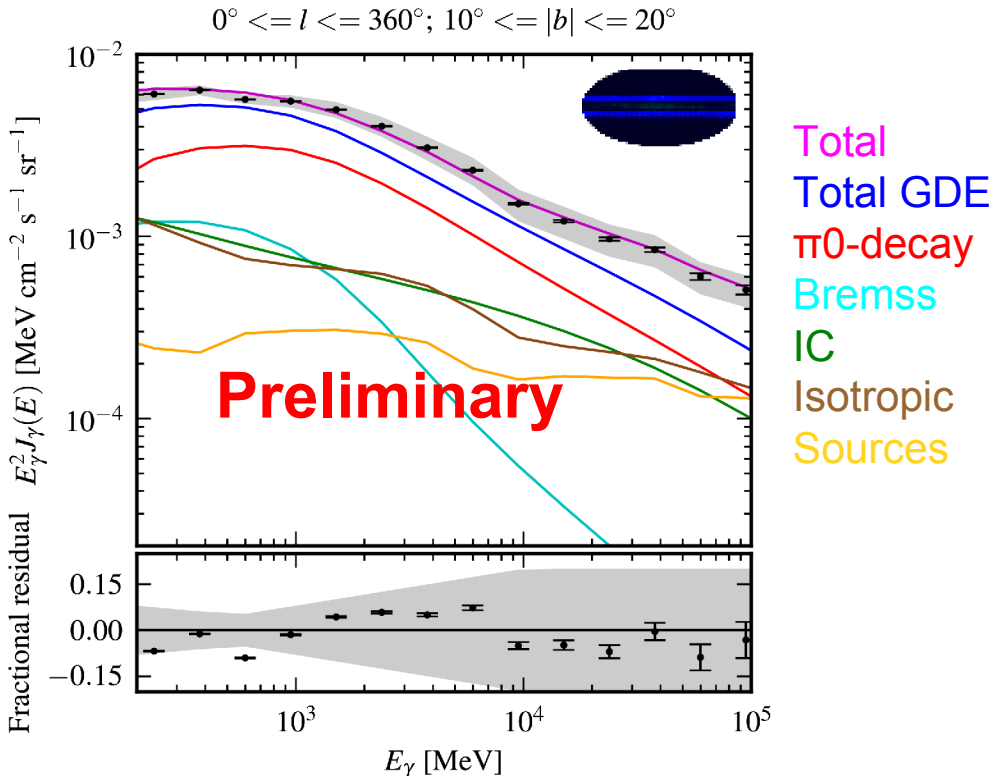
- **CR source distribution from literature**
  - **Pulsars (2 versions), SNRs, OB stars**
  - **Assumes massive star origin**
- **CR confinement volume (halo)**
  - **Vertical: 4, 6, 8, 10 kpc**
  - **Radial: 20, 30 kpc**
- **Spin temperature**
  - **T_s: 150 K, Optically thin (100,000 K)**
- **E(B-V)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



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**

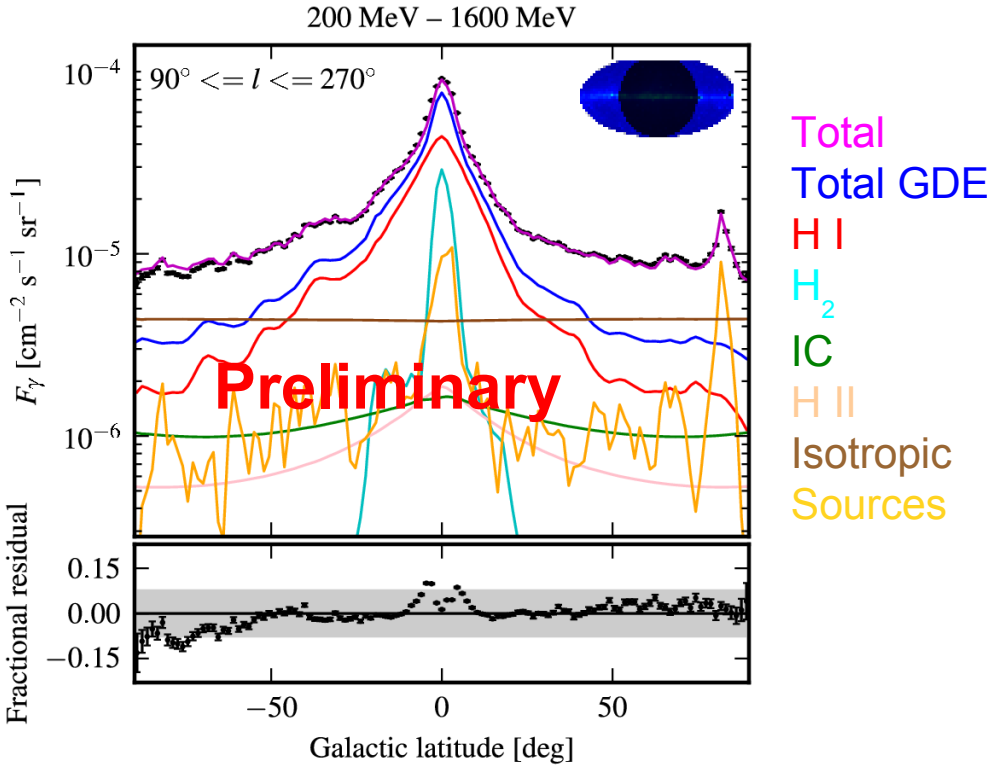
Model 2: SNR, 4 kpc, 20 kpc, 150 K, 5 mag



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**

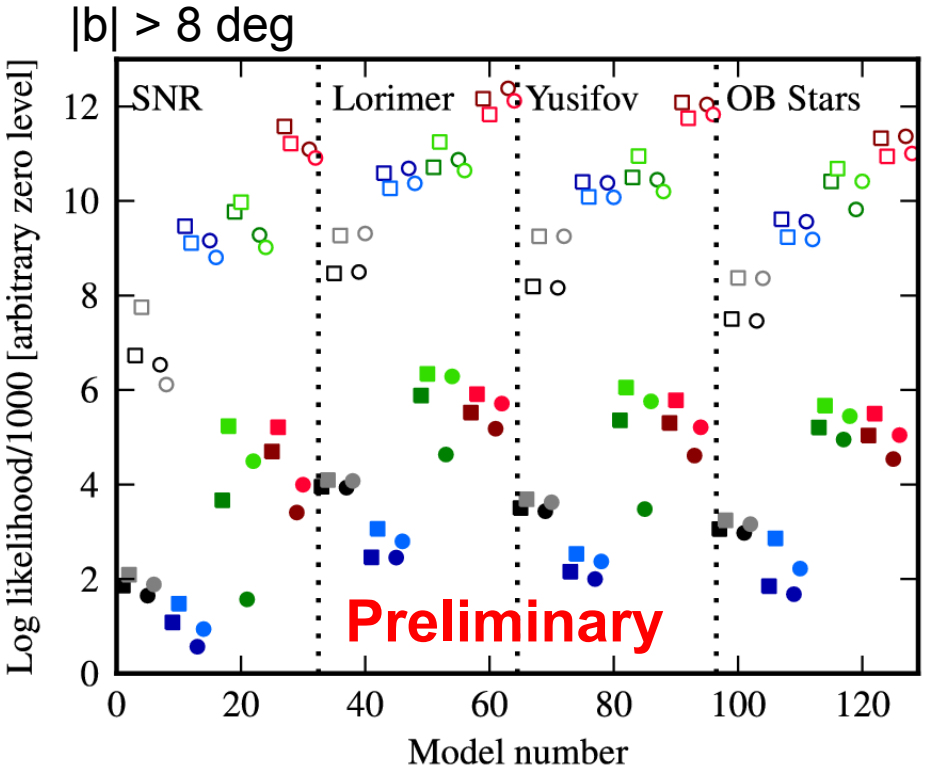
Model 44: Lorimer, 6 kpc, 20 kpc, OT, 5 mag

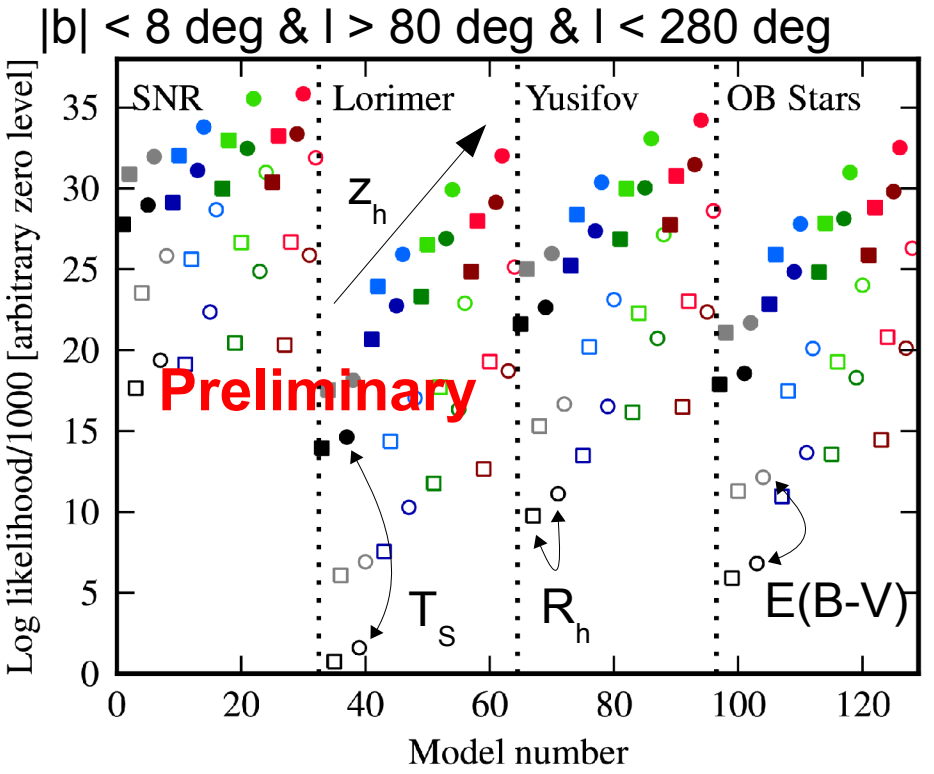


Statistical Comparison

- **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)



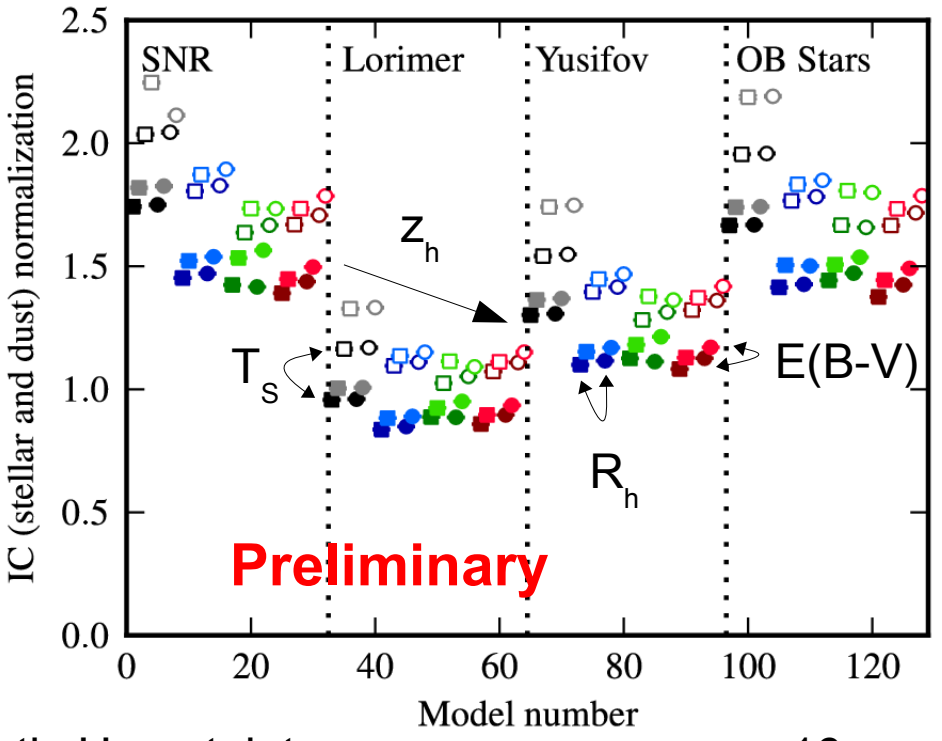


Inverse Compton normalization

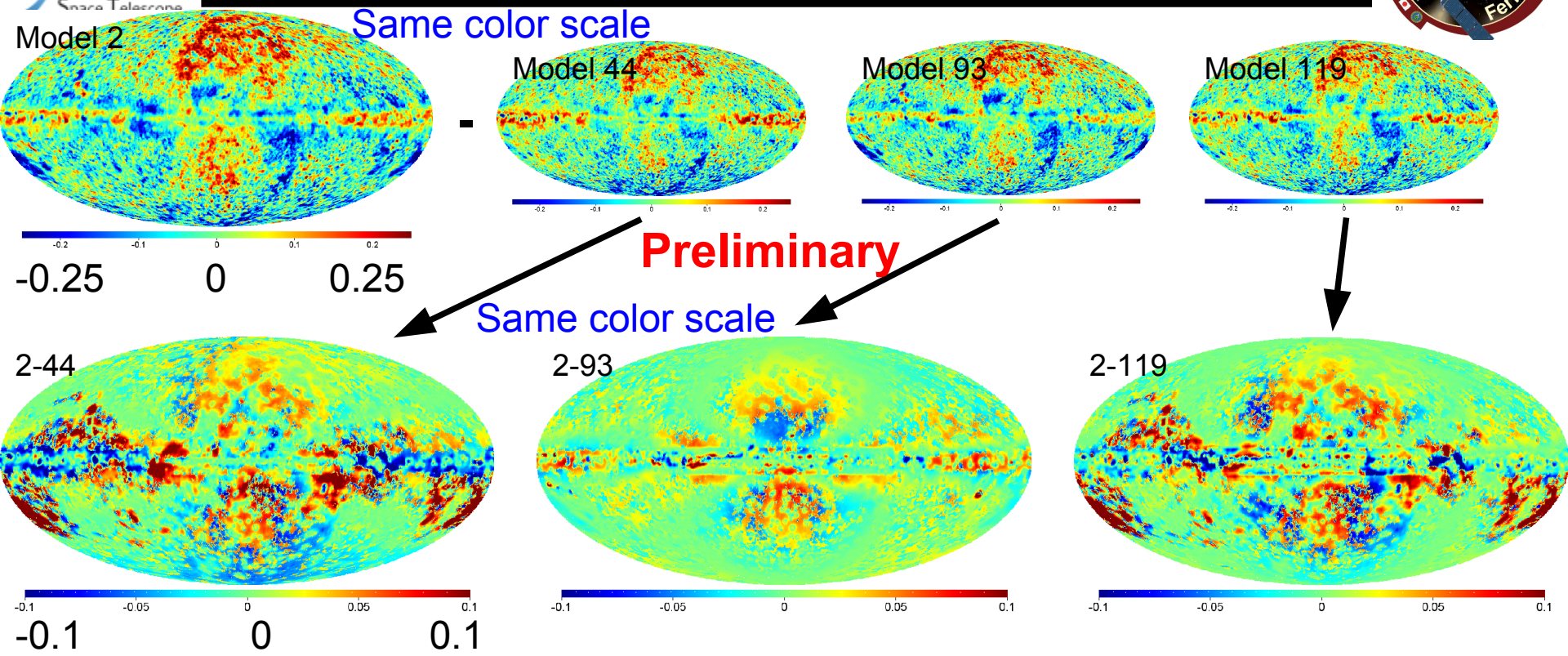
- **Evidence for a large halo from IC**
  - **Depends on the assumed CR source distribution, smaller effect for distribution peaking close to GC.**
- **IC fit compensates for changes in gas densities**
  - **Despite spatial and spectral difference between the two components**
- **Normalization factor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

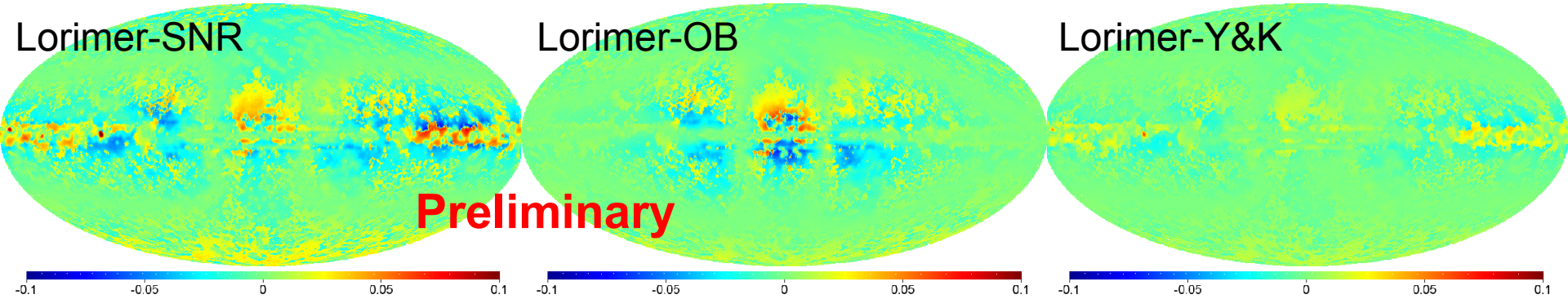


- **Structure overall good to within ~10%**
  - **Exceptions are Fermi lobes (Su et al. 2010 ApJ 724), Loop I, outer Galaxy**
- **Structure in lower maps due to variations of model parameters**

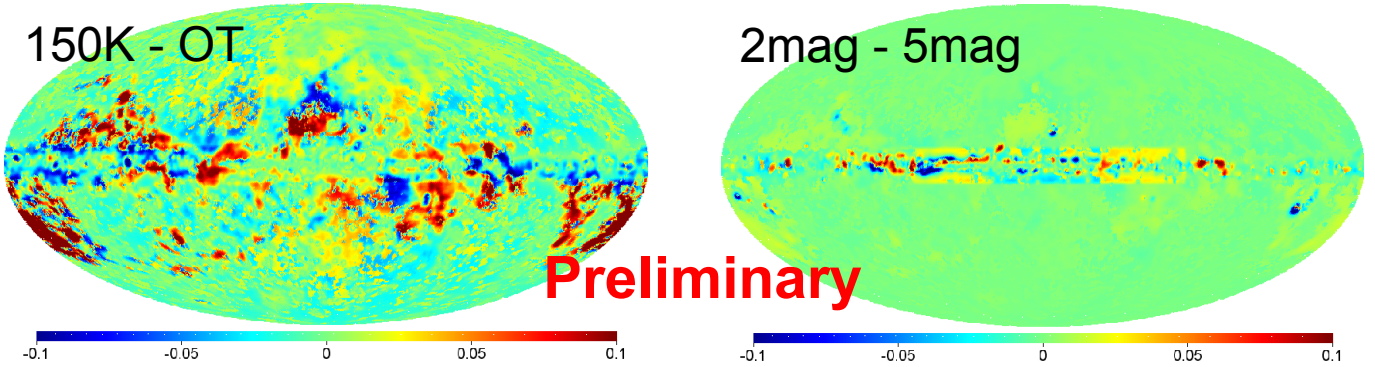
Model details:
2: SNR, 4kpc, 20kpc, 150K, 5m
44: Lorimer, 6kpc, 20kpc, OT, 5m
93: Y&K, 10kpc, 30kpc, 150K, 2m
119: OB, 8kpc, 30kpc, OT, 2m

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 =
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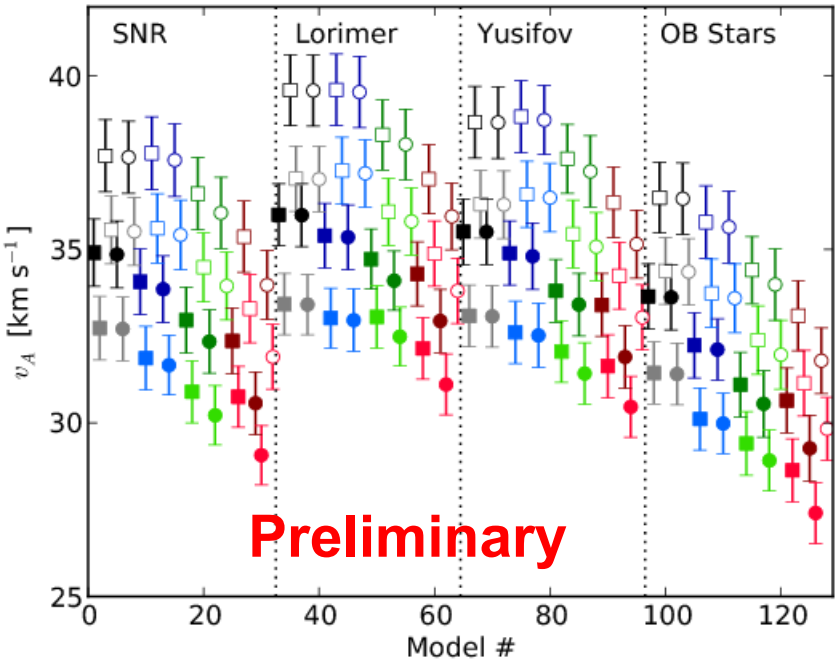
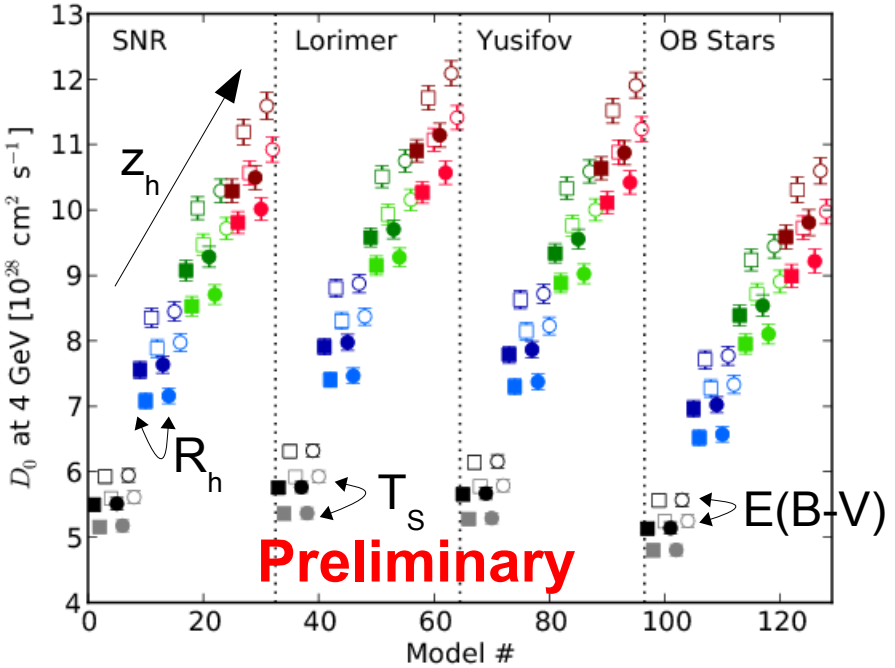


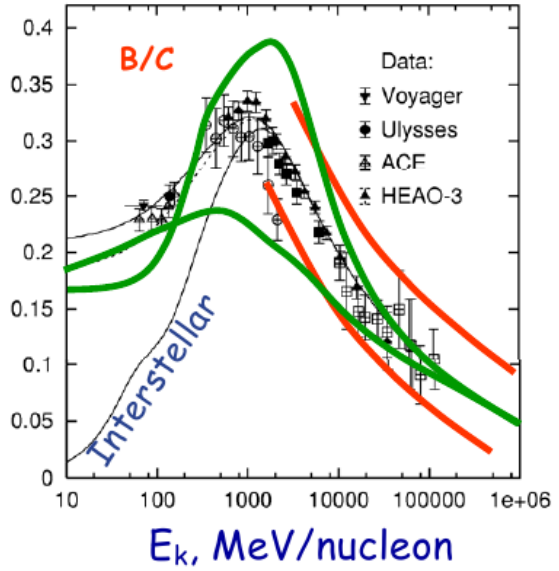
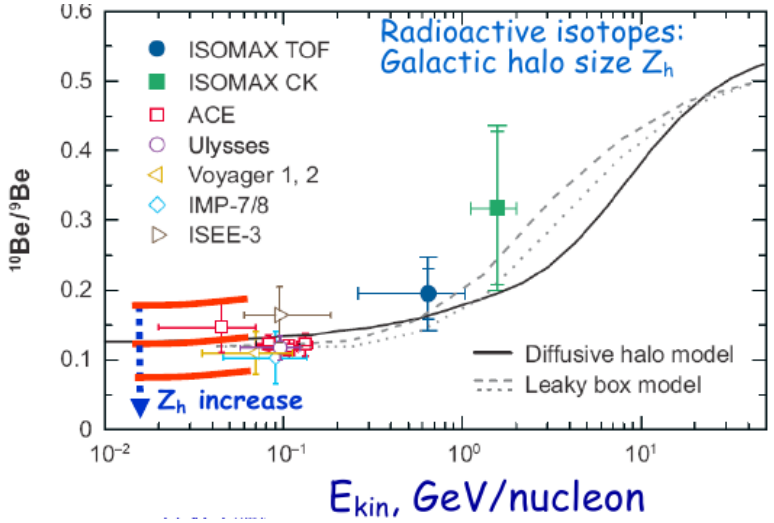


Summary

- 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
- Important to account for systematic uncertainty in input
  - Gas distribution, ISRF, cross sections, ...
- CR propagation parameters are dependent on distribution of gas and CR sources in Galaxy
- There is no single best fit diffuse Galactic emission model
  - A range of models can be put forward that explain the data reasonably well

Backup slides ...

The "Conventional" Model

- **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**

Credit: Moskalenko, I. V.