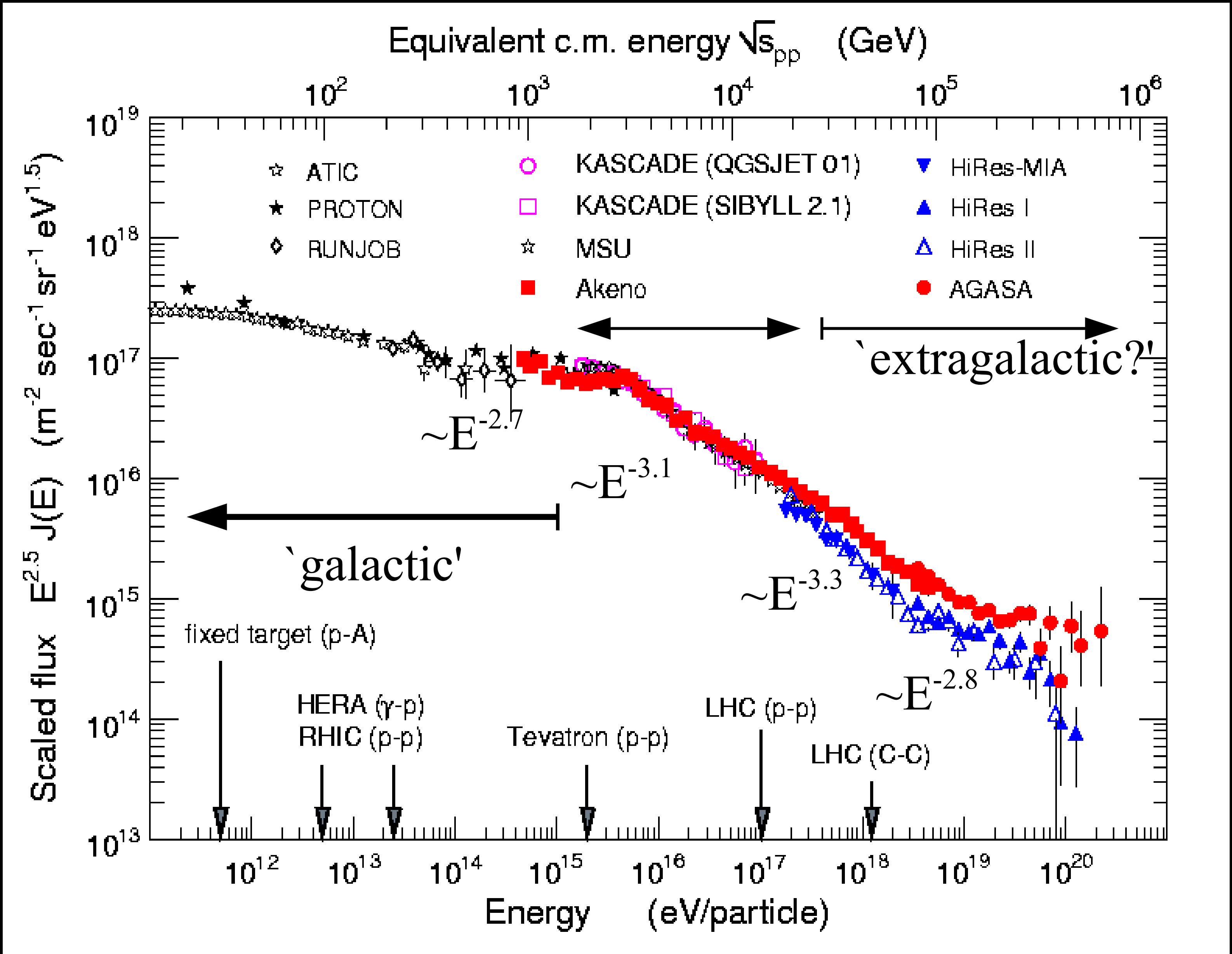
Cosmic Rays and Diffuse Emissions in the Milky Way

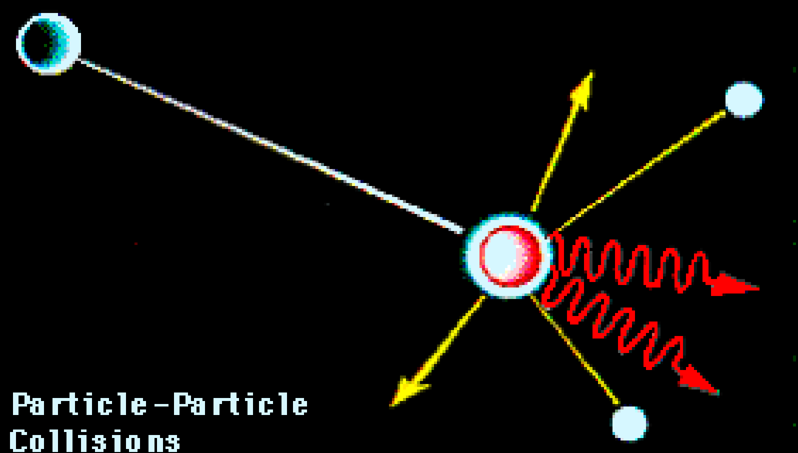
Troy A. Porter
Stanford University

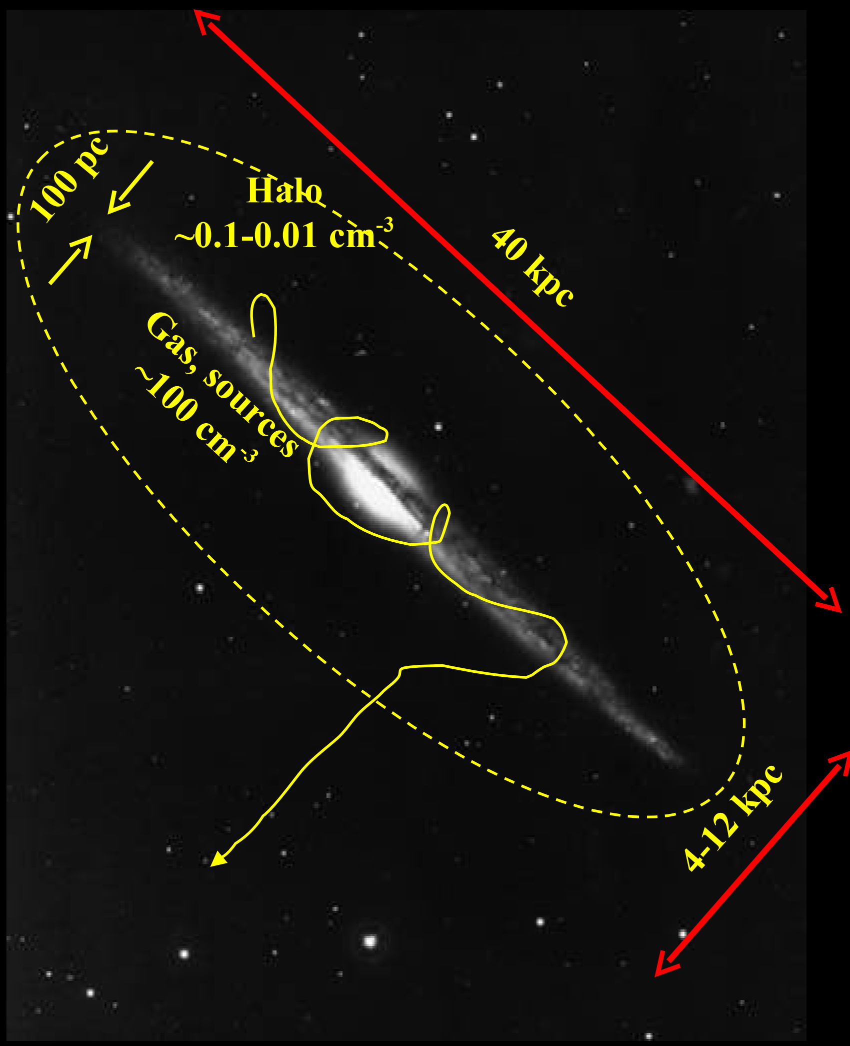
Cosmic Ray Spectrum



Connection Between Cosmic Rays and Diffuse Emission

- Cosmic rays injected into ISM propagate for millions of years before escape to intergalactic space
- Particle interactions with interstellar gas, radiation and magnetic fields produce EM radiation from radio to gamma rays, and other secondaries ($e^{\pm}$, ν, etc.)





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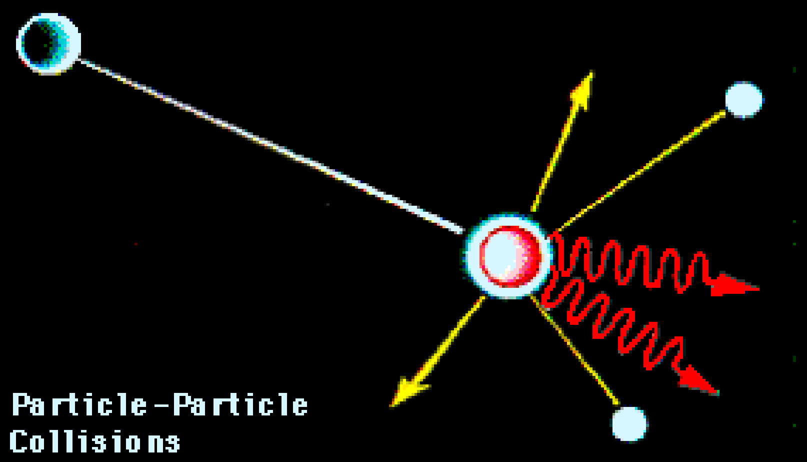
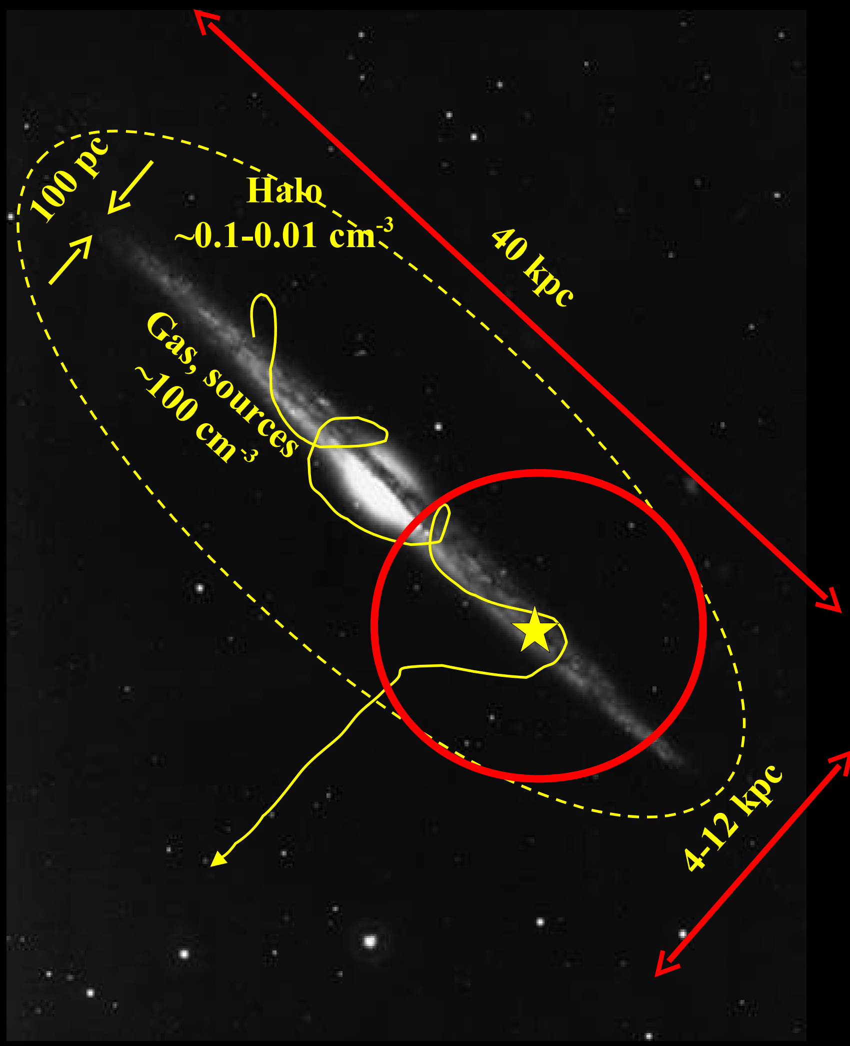
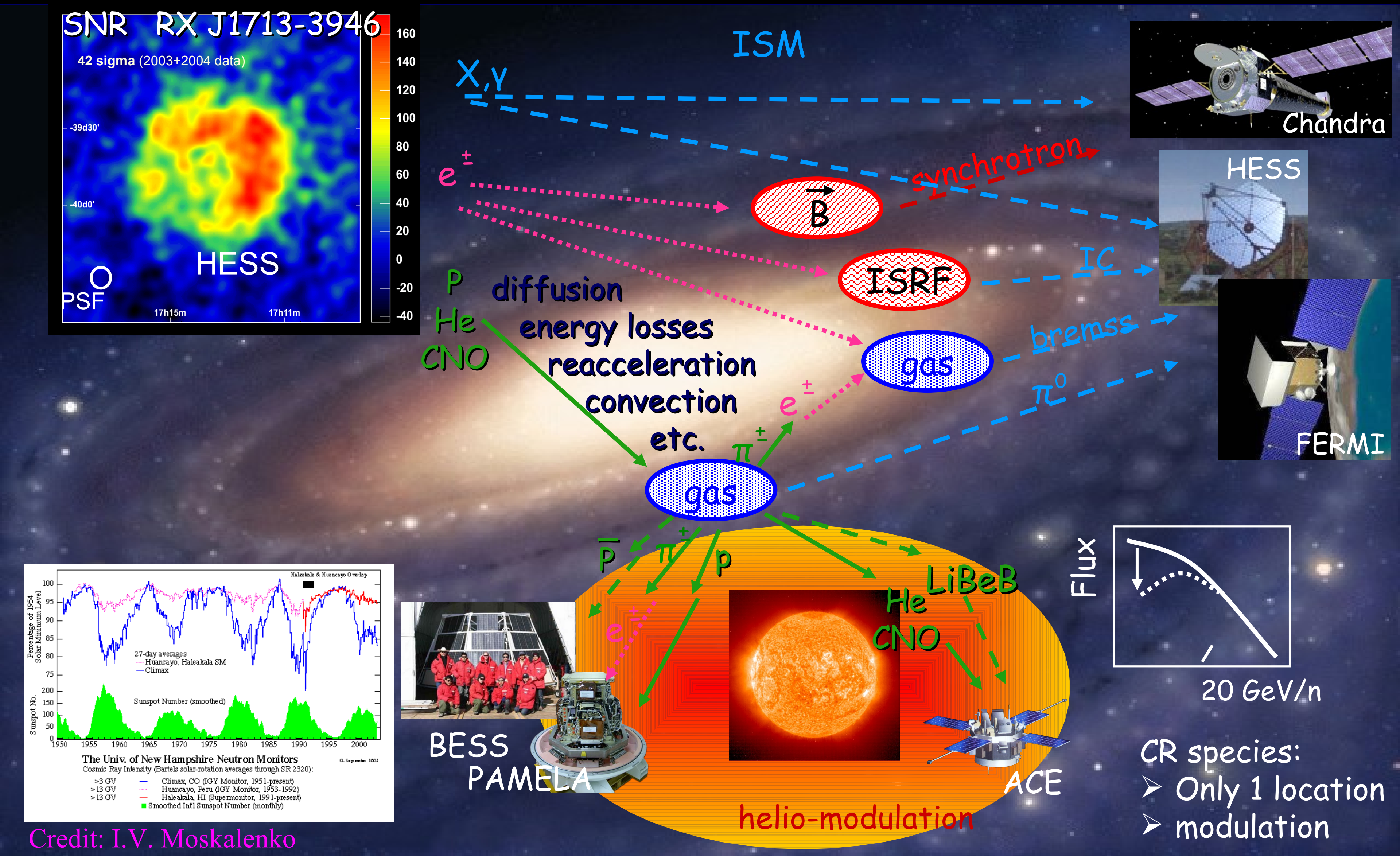




Cosmic-Ray Propagation in the ISM



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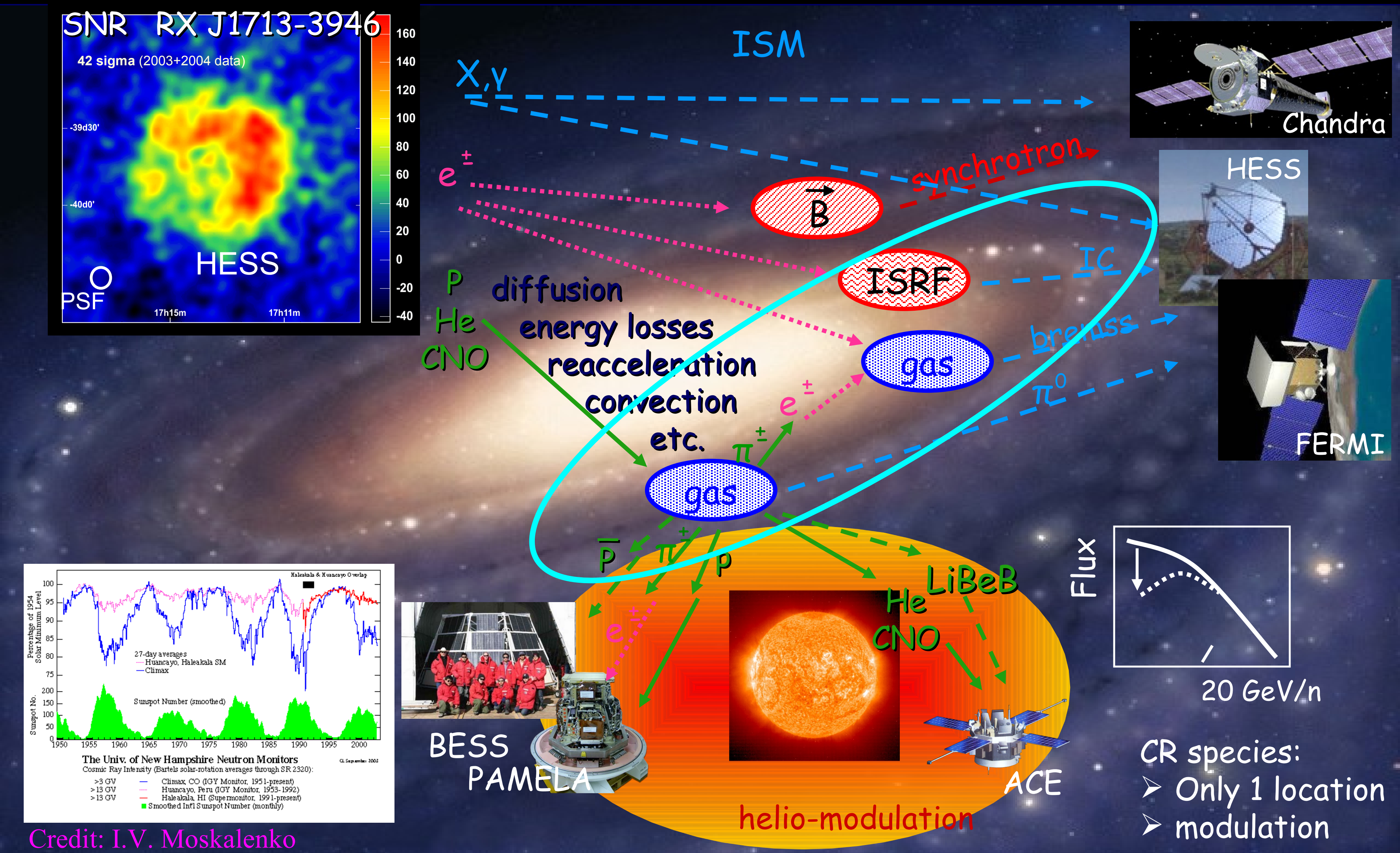
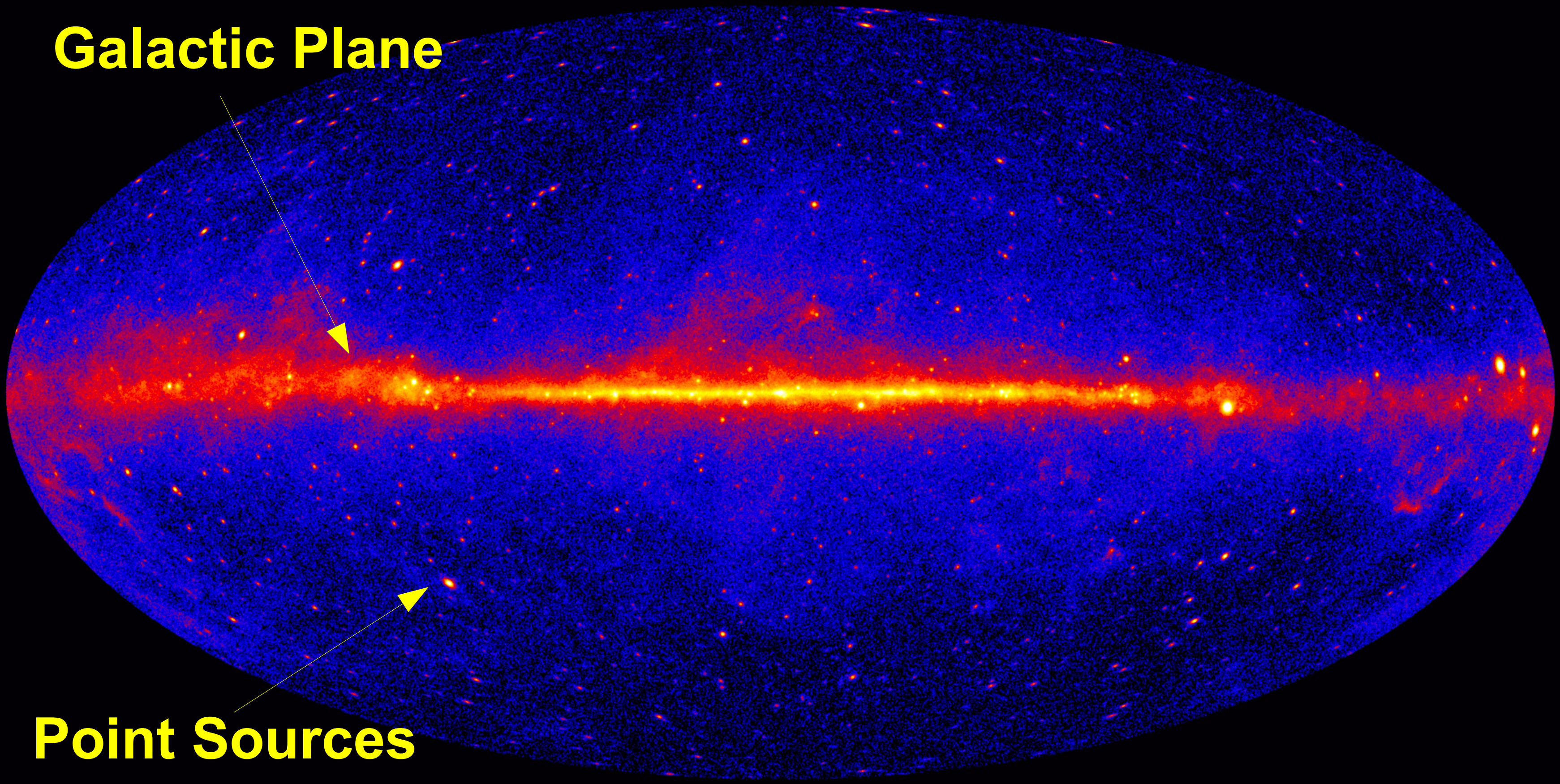


Fermi LAT 3-Year Sky Map



Diffuse γ-ray emission produced by cosmic rays interacting with interstellar gas and radiation fields. Comprises majority of the total γ-ray flux!

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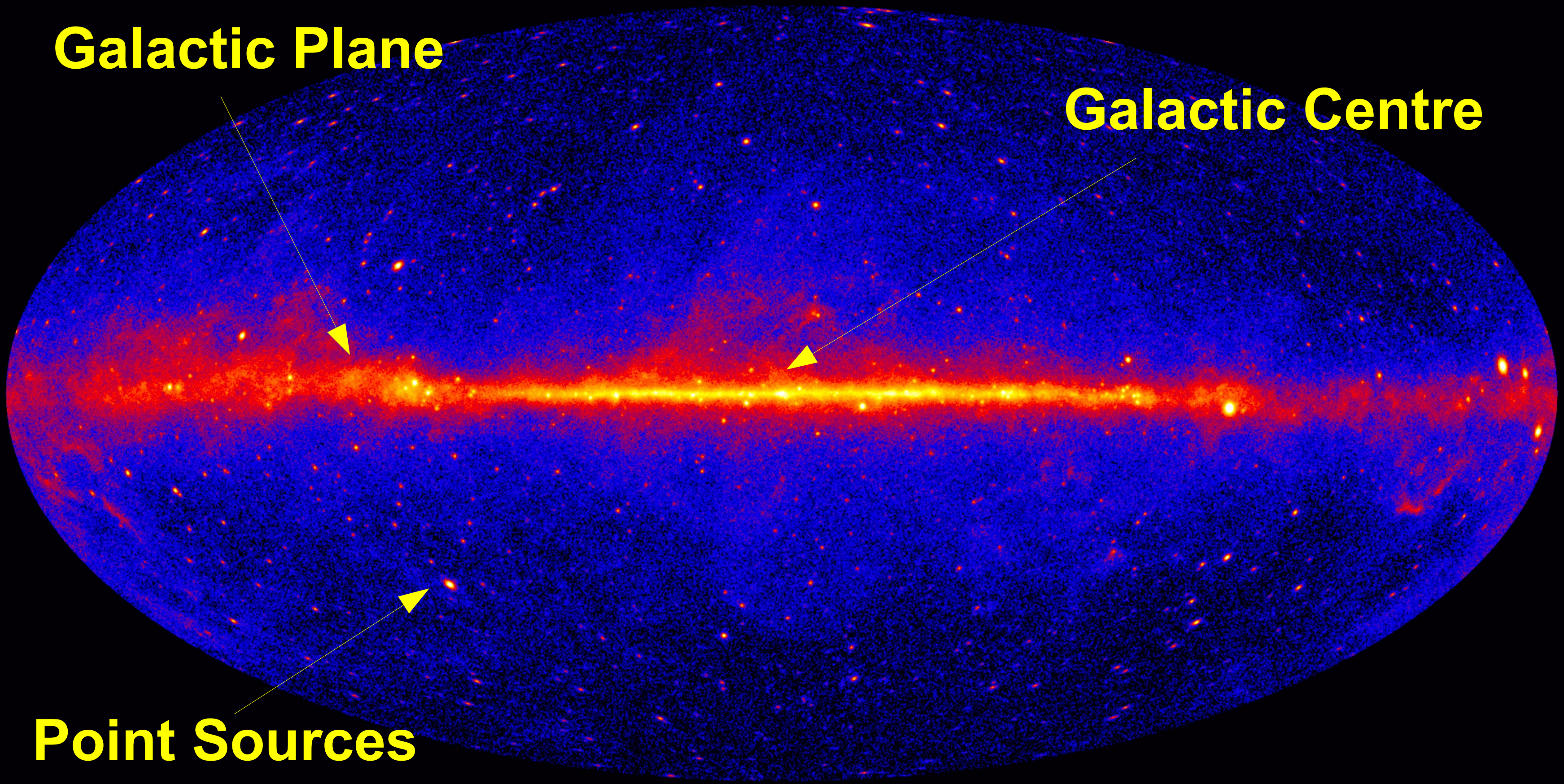

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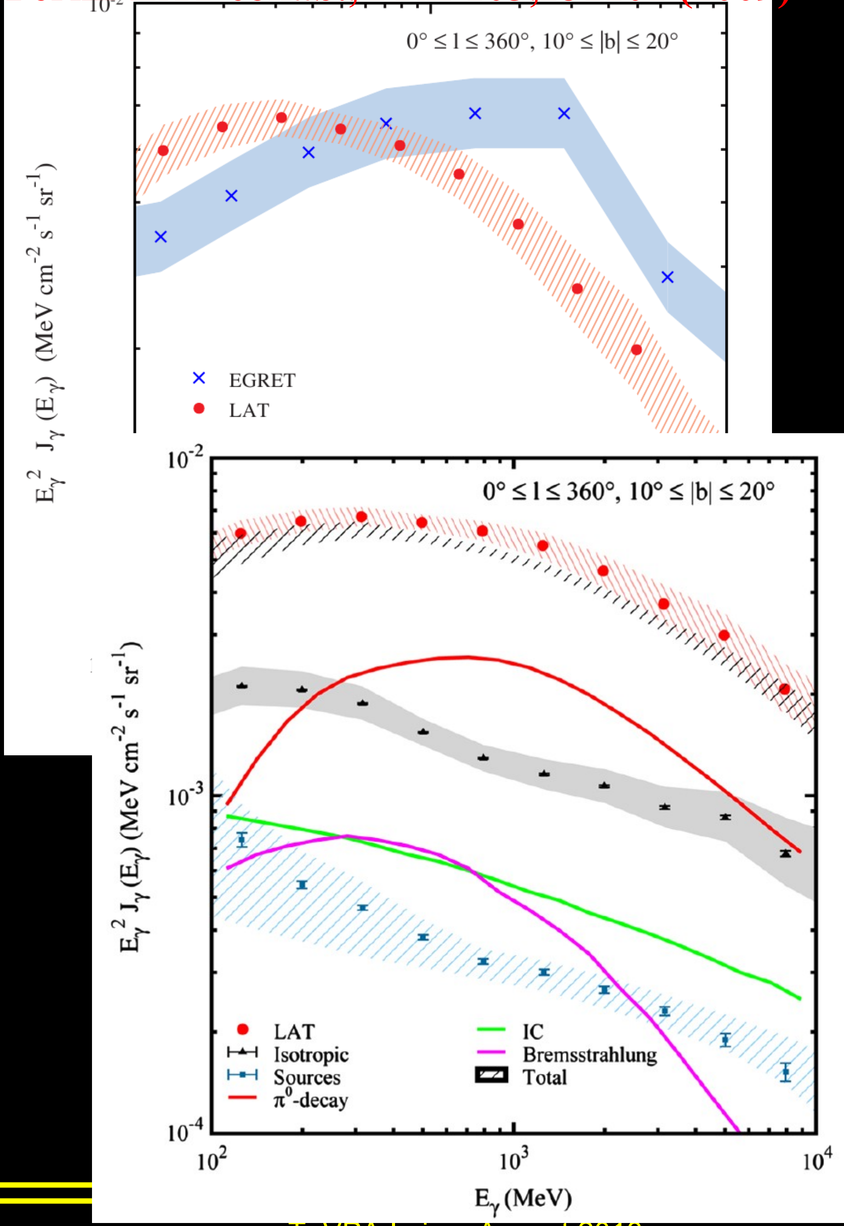
Testing the ``EGRET GeV Excess''

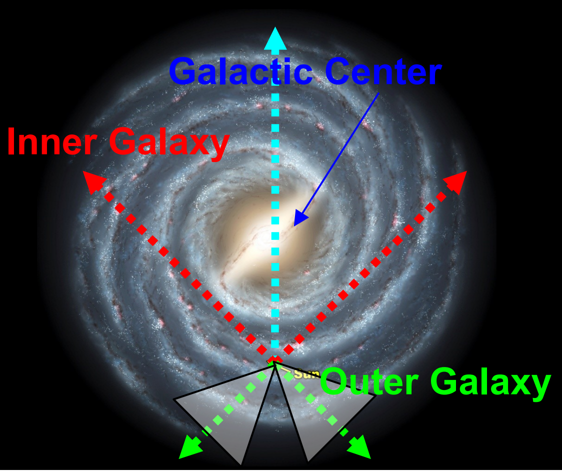
- Observations with the EGRET instrument showed excess emission above a few GeV when compared to conventional diffuse emission models
    - `Conventional' means based on local CR measurements
- Possible hint for
    - Dark matter
    - Local CR bubble
    - Unresolved sources
    - ...
- Not seen in Fermi LAT data
- Instrumental origin: similar discrepancy seen between EGRET and LAT Vela pulsar spectra

Fermi-LAT collab., PRL 103,251101 (2009)

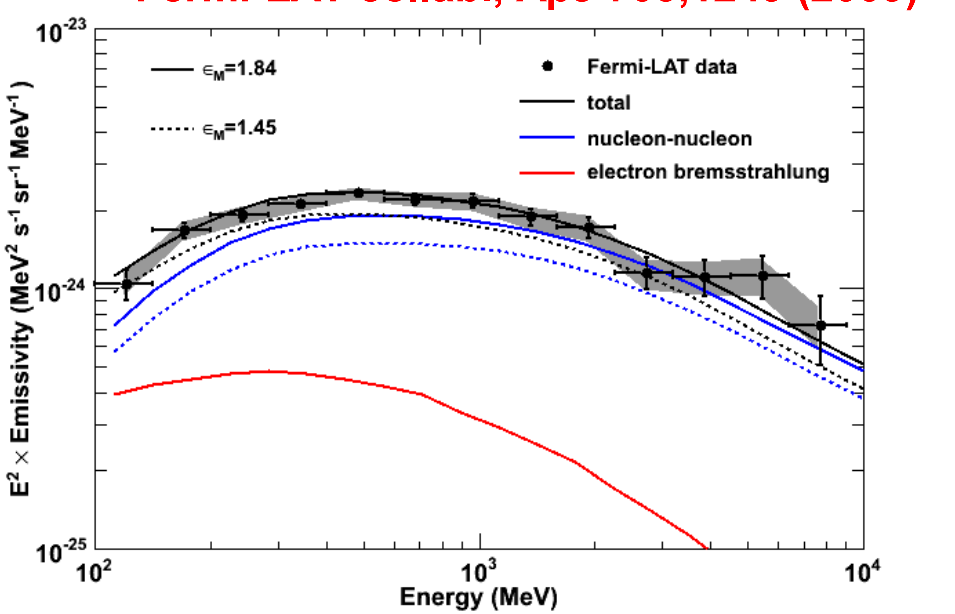


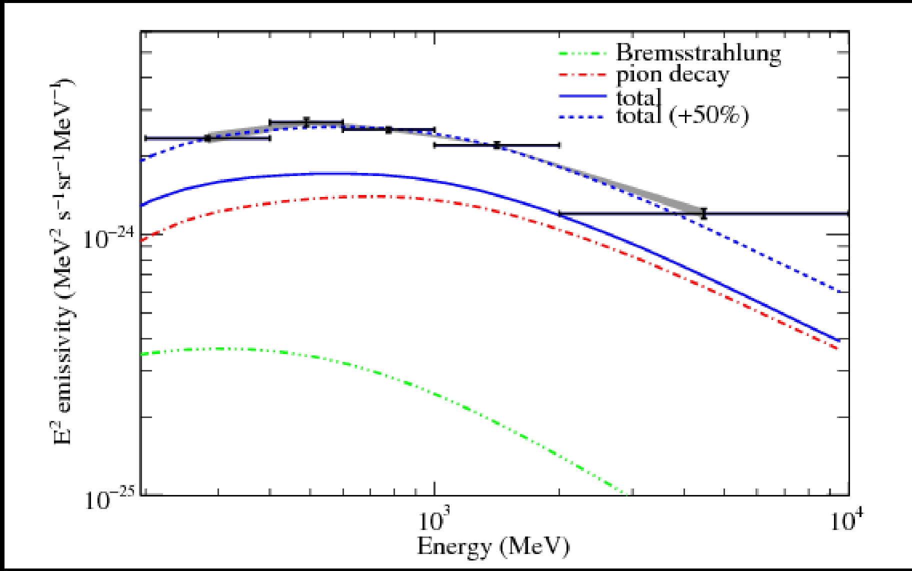
Nearby Diffuse Emission – Local Gas

- Selected region with good radial resolution
- Two independent analysis show agreement with local observations of CRs
- Hints for an increased nuclear enhancement factor (effects of high Z nuclei)



Fermi-LAT collab., ApJ 703,1249 (2009)

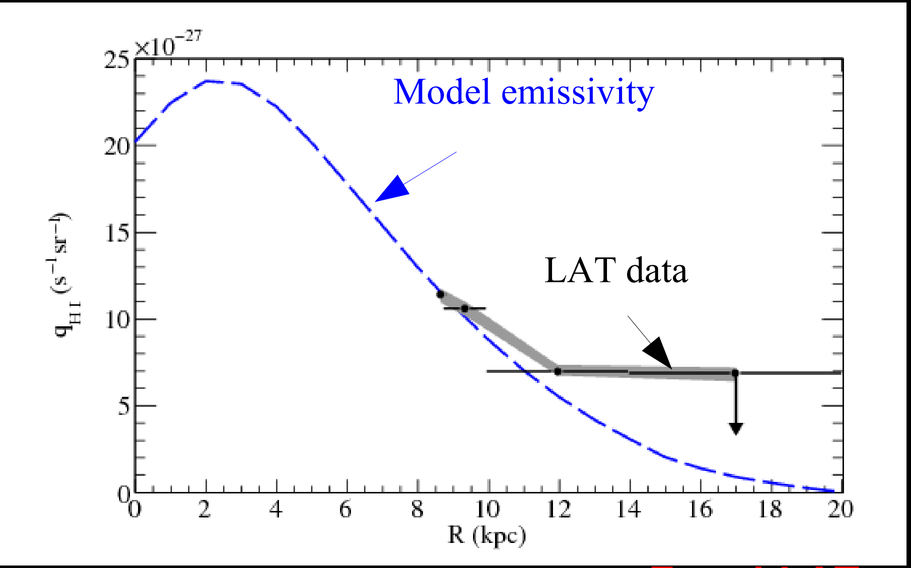


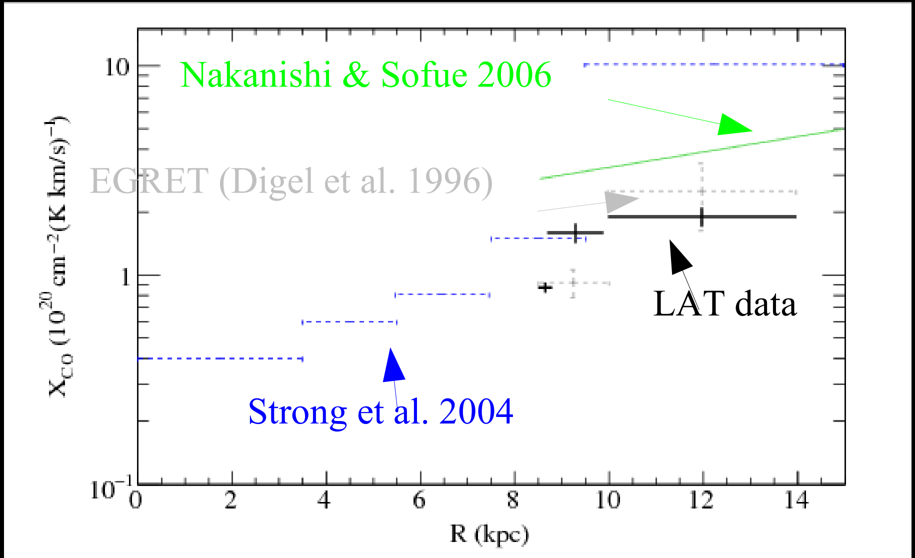


Fermi-LAT collab. ApJ 710,133 (2010)

Cosmic Ray Flux and X_{CO} factor in outer Galaxy

- CR emissivity higher than predicted by some conventional propagation models
  - Conventional models are consistent with local observations of CRs but still have some freedom.
  - A hint for a different halo size or CR source distribution
- X_{CO} factor does not rise as steeply as older predictions

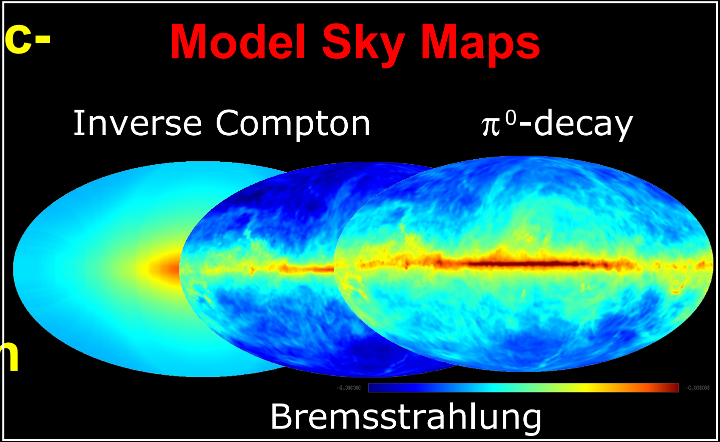




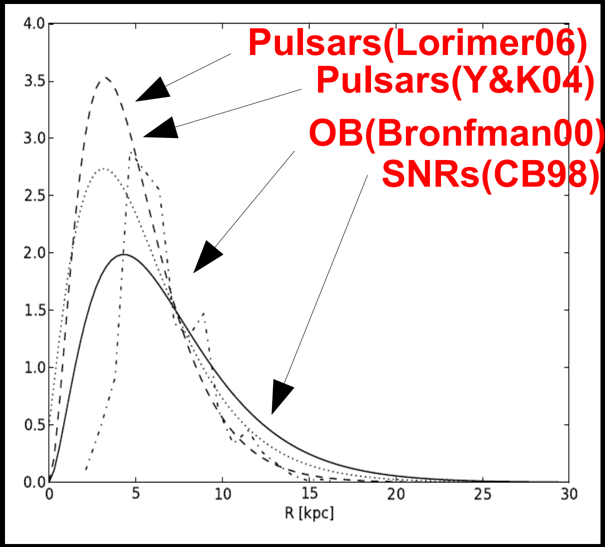
Fermi-LAT collab., ApJ 710, 133 (2010)

Large-Scale Study of Diffuse Emission

- Starting point for our studies: the cosmic-ray spectra consistent with local observations (cosmic-ray nuclei, Fermi LAT electrons) → `conventional model'
- Use GALPROP code with diffusion-reacceleration model for CR propagation - propagation parameters found using CR data
- Grid of 128 models covering plausible confinement volume, CR source distributions, etc.
- Corresponding model sky maps compared with data using maximum likelihood
- Iterative process because the model parameters depend on outcome of fits



CR sources



Determining propagation parameters

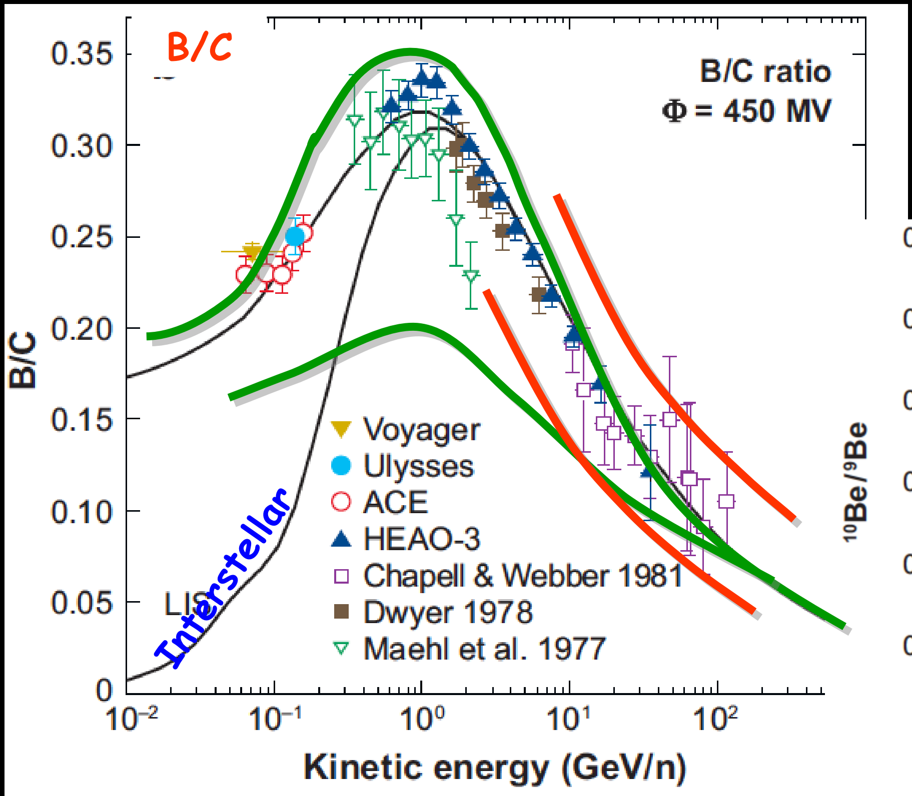
Typical Parameters (model dependent):

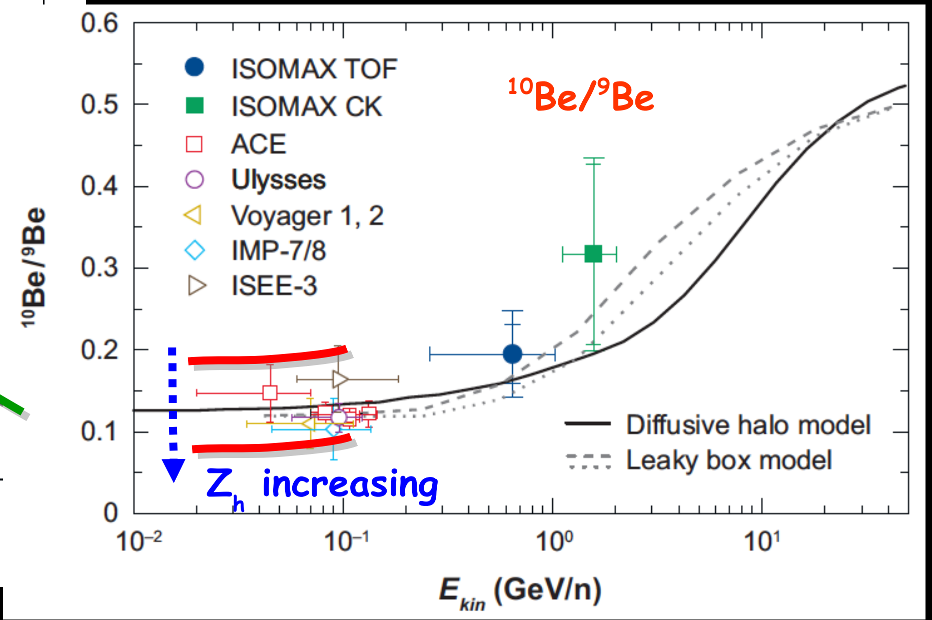
$D \sim 10^{28} (\rho/1\ GV)^{\delta}\ cm^2/s$

$\delta \approx 0.3\text{-}0.6$

$Z_h \sim 4\text{-}6$ kpc

($V_A \sim 30$ km/s)





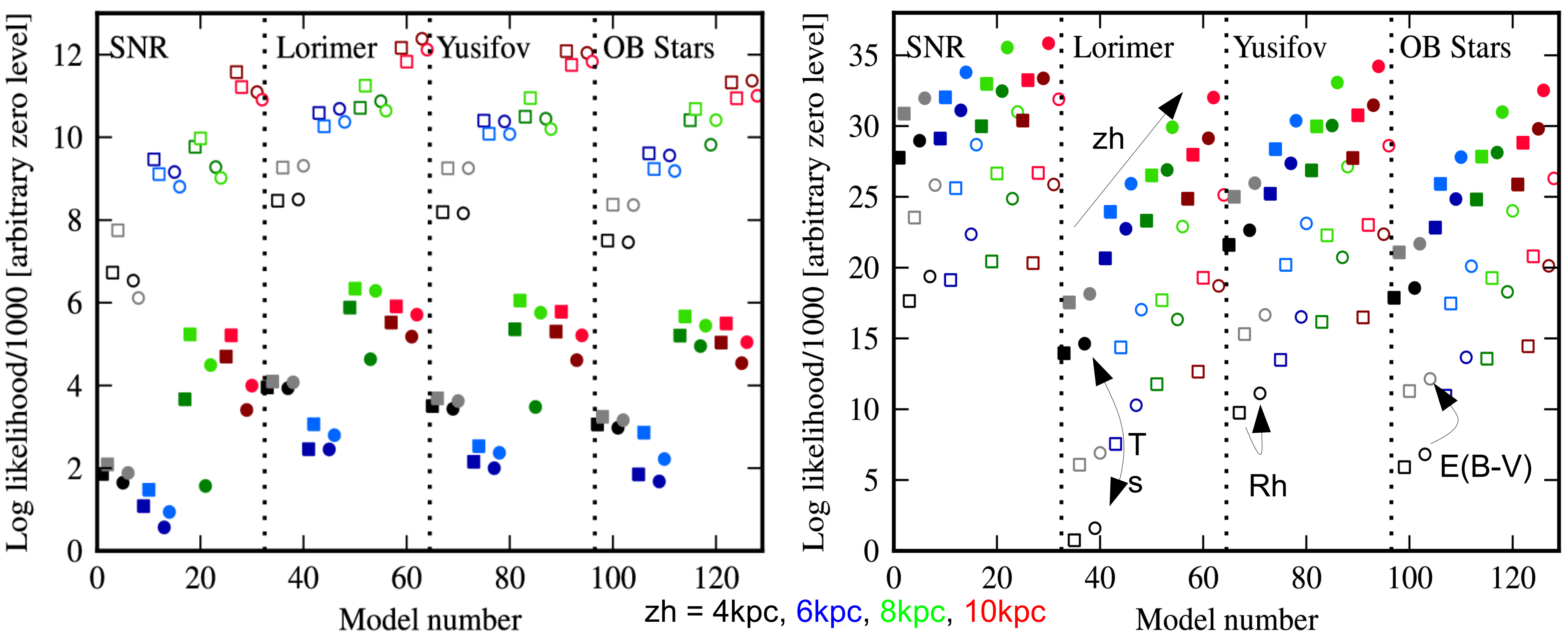
- Using secondary/primary and flux:
  - Diffusion coefficient and index
  - Propagation mode and parameters (e.g., convective velocity, etc.)
  - Parameters are <u>model dependent</u>

Statistical Comparison

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

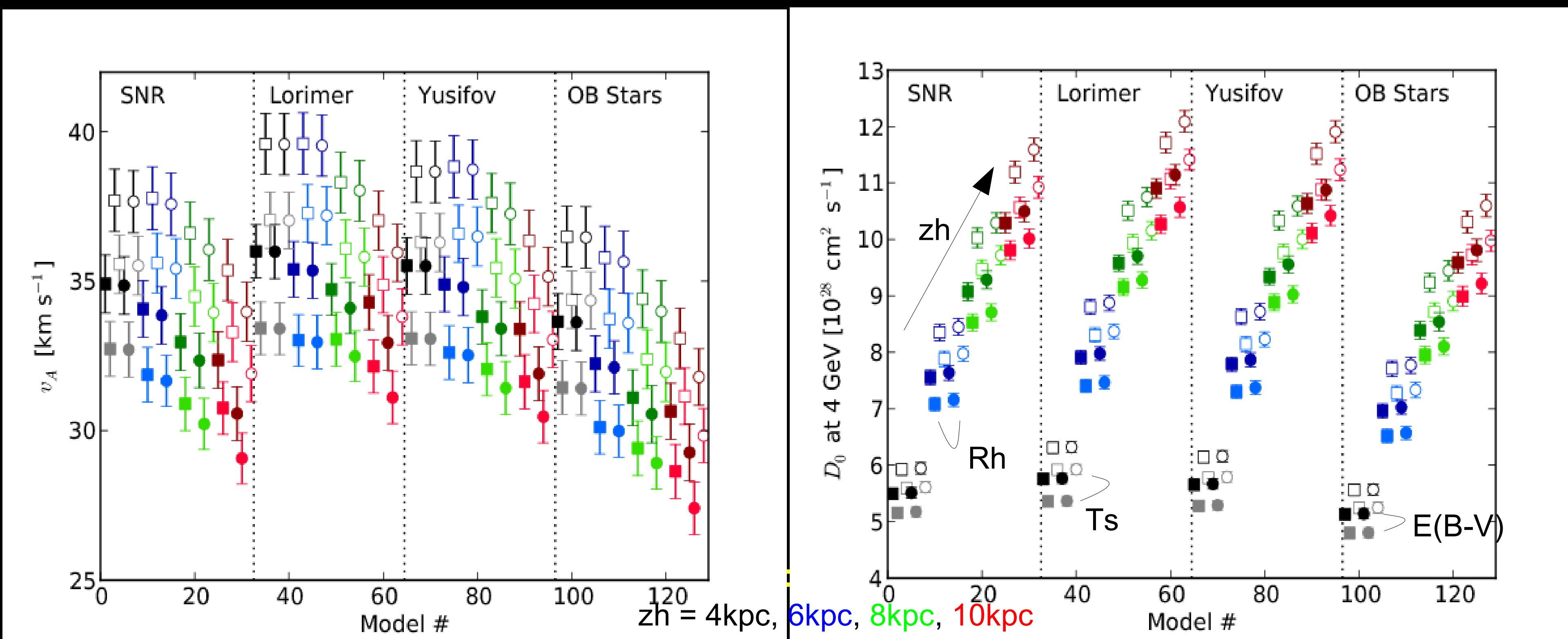
|b| > 8 deg

|b| < 8 deg && l > 80 deg && l < 280 deg



Cosmic Ray Propagation Parameters

- **Determined from fit to H, He, C, O, and B/C (errors statistical only)**
  - **Xco feedback from gamma-ray fit important**
  - **Propagation parameters depend on ISM and CR source distribution**
  - **Only Xco determined from gamma rays**



Systematic Large-Scale Study: Cosmic Ray Propagation

- **Main result: propagation parameters depend on**
  - **Assumed source distribution**

(Z_{max} = 6 kpc, R_{max} = 20 kpc, T_S = 150 K, mag = 5)

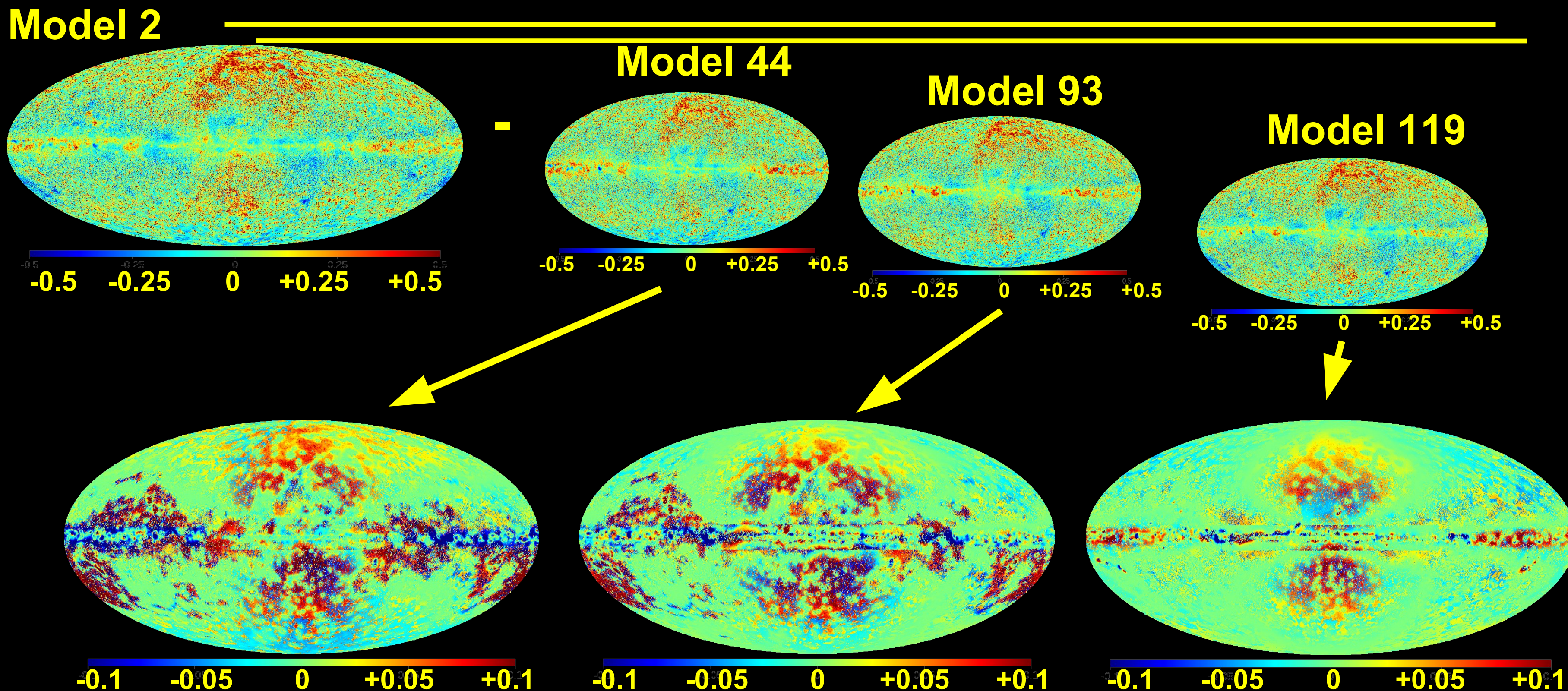
Parameter	SNR	Lorimer	Yusifov	OBstars
$D_{0,xx}$ *	7.08 +/- 0.12	7.40 +/- 0.11	7.30 +/- 0.12	6.51 +/- 0.12
p norm_{100GeV} **	4.06 +/- 0.05	3.98 +/- 0.05	4.02 +/- 0.05	4.22 +/- 0.05

(SNR, Z_{max} = 6 kpc, R_{max} = 20 kpc, mag = 5)

Parameter	HI, T_S = 150 K	HI, optically thin
v_{Alfven} ***	31.9 +/- 0.9	35.6 +/- 1.0
$D_{0,xx}$ *	7.08 +/- 0.12	7.88 +/- 0.14

* 10^{28} cm^2 s^{-1}
** 10^{-9} cm^{-2} s^{-1} sr^{-1} MeV^{-1}
*** km s^{-1}

Systematic Large-Scale Study: Residuals



- **Agreement for models is overall good but features are visible in residuals at ~ % level. Lower maps: structure due to variations of model parameters, details:**

2: SNR, Z_h=4kpc, R_{max}=20kpc, T_S=150K, mag=5

44: Lorimer, Z_h=6kpc, R_{max}=20kpc, mag=5, optically thin HI

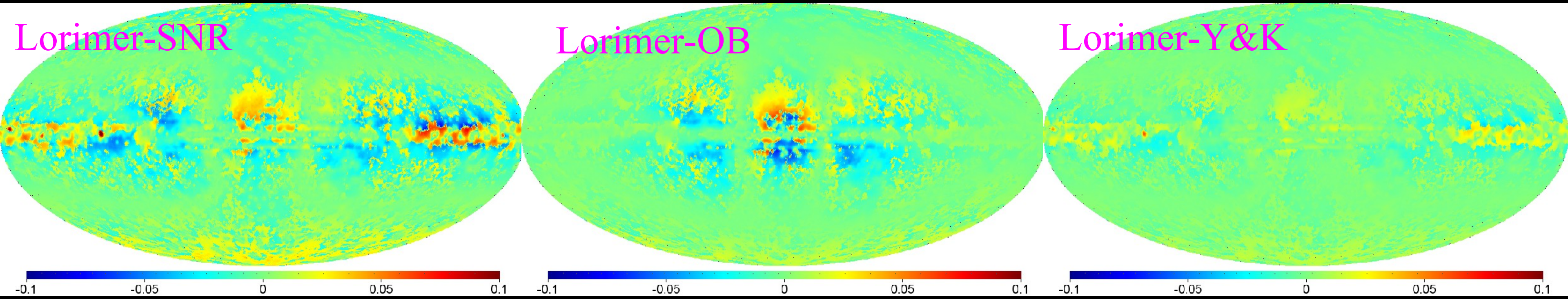
93: Yusifov, Z_h=10kpc, R_{max}=30kpc, T_S=150K, mag=2

119: OB, Z_h=8kpc, R_{max}=30kpc, mag=2, optically thin HI

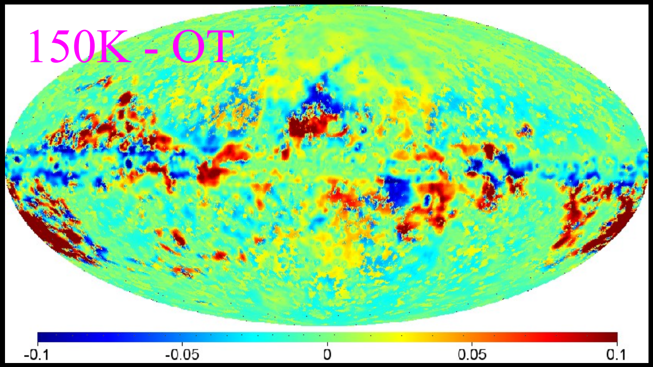
Fermi-LAT collab. ApJ 750, 3 (2012), arXiv:1202.4039

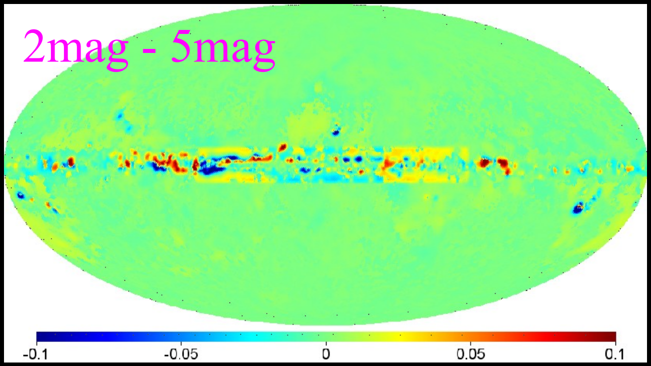
Differences Between Residuals

Varying only cosmic-ray source distribution



Varying only gas properties





Gas properties have a larger influence

Cosmic-ray Propagation Model Constraints from Global Parameter Scans

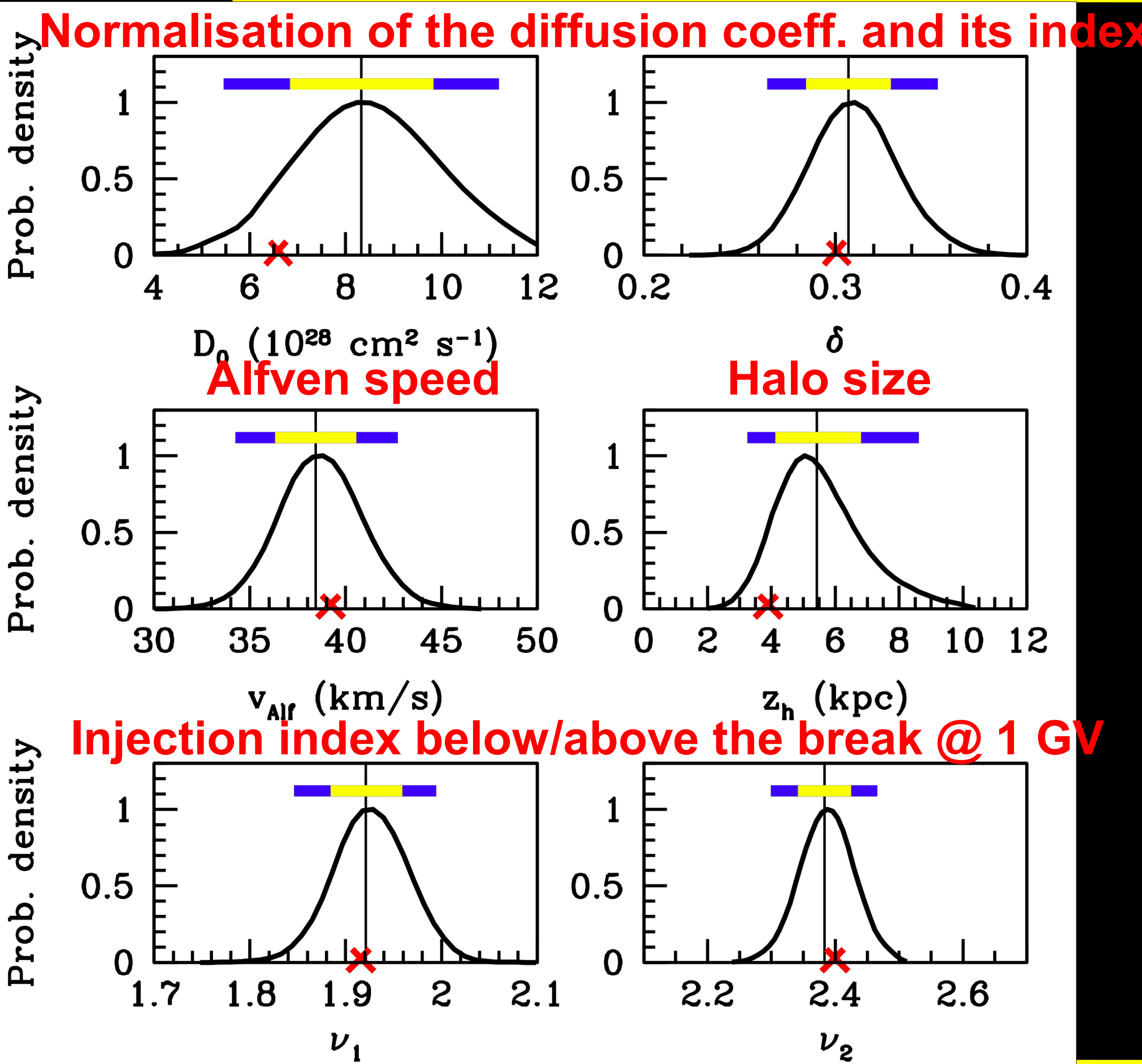
- Bayesian method (Q – parameter vector, D – observations):

$$P(\mathrm{Q}\,|\,D) = \frac{P(D\,|\,\mathrm{Q})P(\mathrm{Q})}{P(D)}$$

  P(Q|D)
  P(D|Q) – likelihood function (for fixed D)
  P(Q) – prior distribution
  P(D) – Bayesian evidence
- Allows for more sophisticated treatment of systematics
- Nested sampling (Skilling '04,'06) and MultiNest (Feroz&Hobson '08) in SuperBayeS ↔ GALPROP
- > 10^5 samples, ~ 13 CPU years
- Tested posterior distribution agrees very well with MCMC-derived distribution
- Used representative data from ACE, ISOMAX, HEAO-3, ATIC-2, CREAM
- Total of 17 parameters fitted, best-fit χ^2/dof ~ 1

Trotta et al., ApJ 729, 106 (2011), arXiv:1011.0037

Posterior Probability Distributions



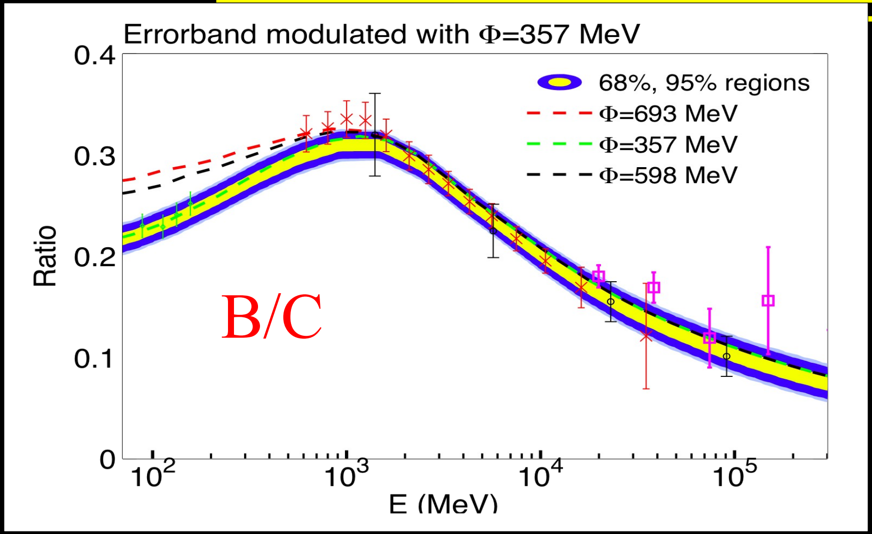
X – best fit

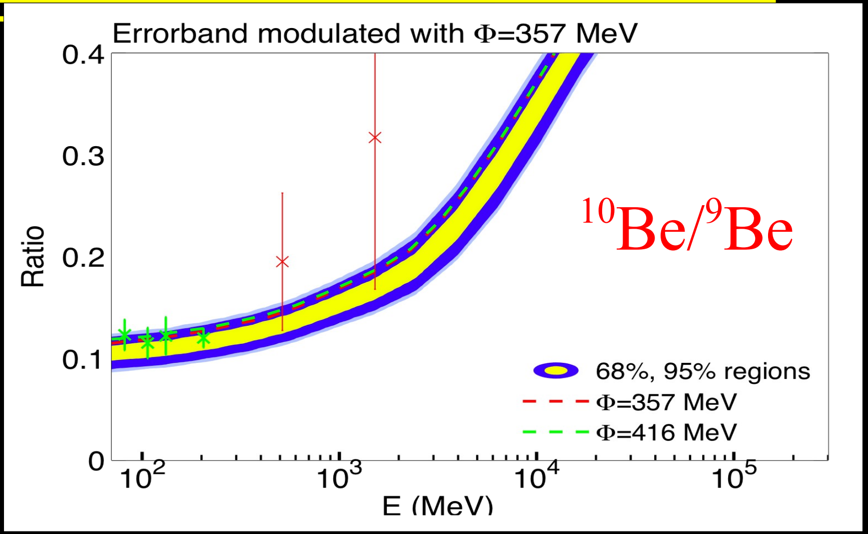
Vertical line – posterior mean

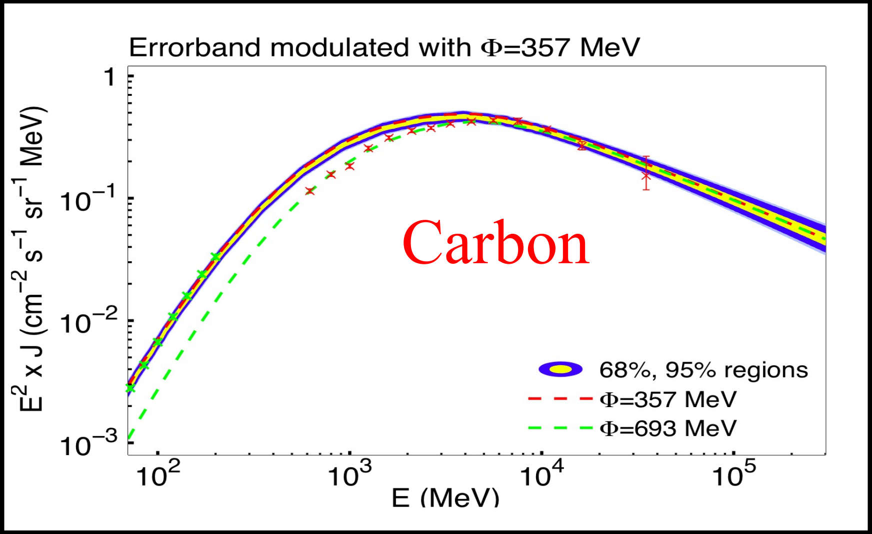
Colour bar – 68/95% range

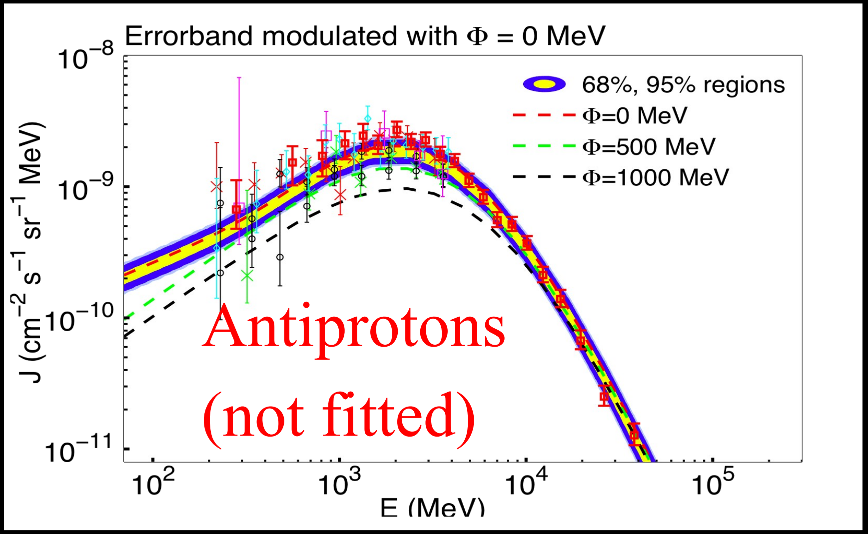
- **Reacceleration model**
- **Parameters very close to those derived by `chi-by-eye'**

Examples: B/C and Be ratios, Carbon and antiprotons





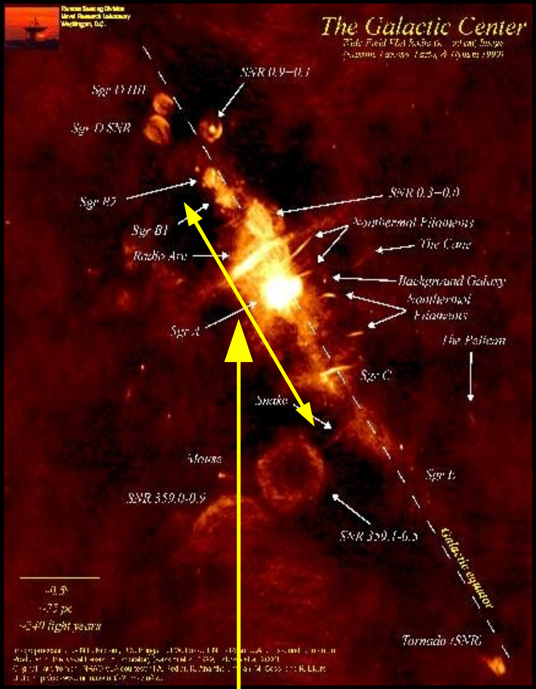




Gamma-Rays Toward the Galactic Centre

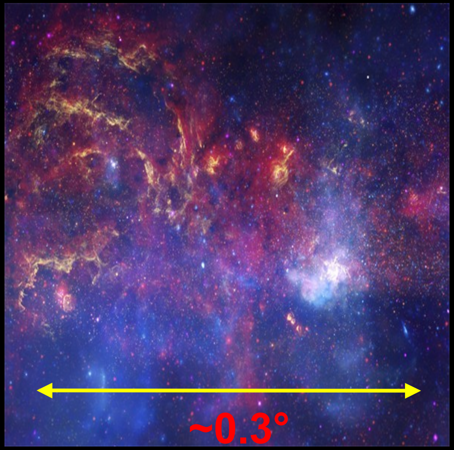
- The region surrounding the GC is complicated containing
  - Potential signal of particle dark matter
  - Intense emission by cosmic rays interacting with the ISM
  - Many astrophysical sources
- Continuous on-orbit presence of the Fermi-LAT significantly adds to the available data allowing these topics to be addressed

Radio (90 cm)

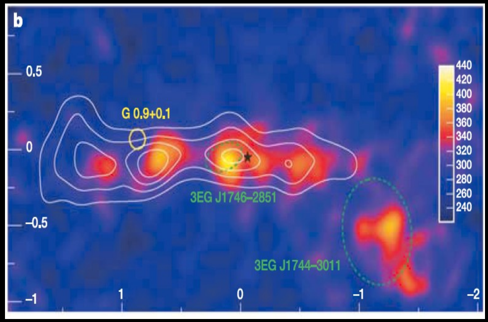


~0.4° effective 68% radius > 1 GeV (front)

Optical/Infrared/X-ray



HESS TeV γ-rays

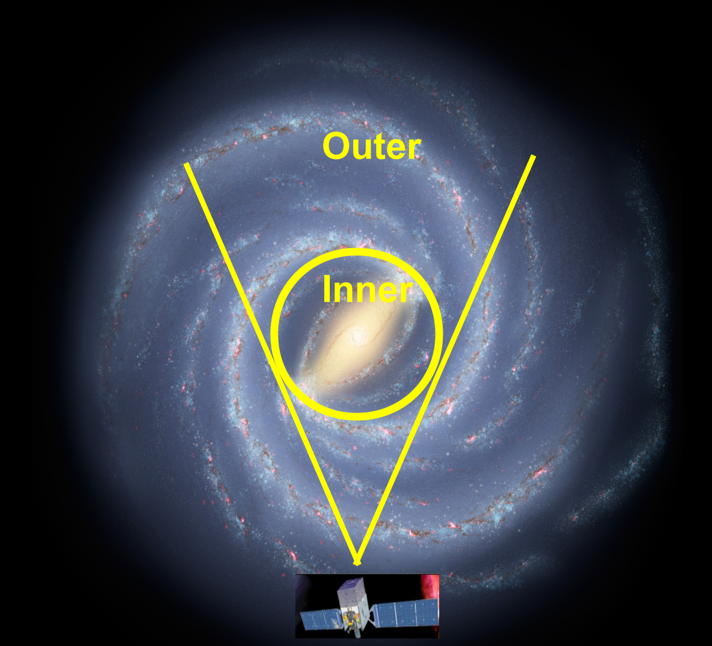


l = ±2°

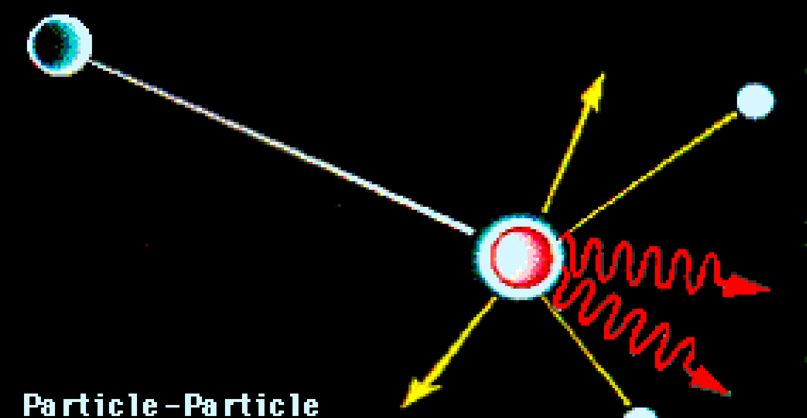
Disentangling the Many Sources of Gamma-Ray Emission is Challenging ...

The emission from the inner Galaxy consists of a number of components:

- Outer Galaxy
- True inner Galaxy
- Point or small extended sources
- Unresolved sources
- Extragalactic emission
- Cosmic-ray instrumental background



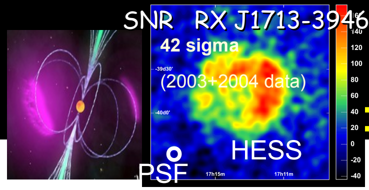
Diffuse gamma rays produced by cosmic rays interacting with the interstellar gas and radiation fields

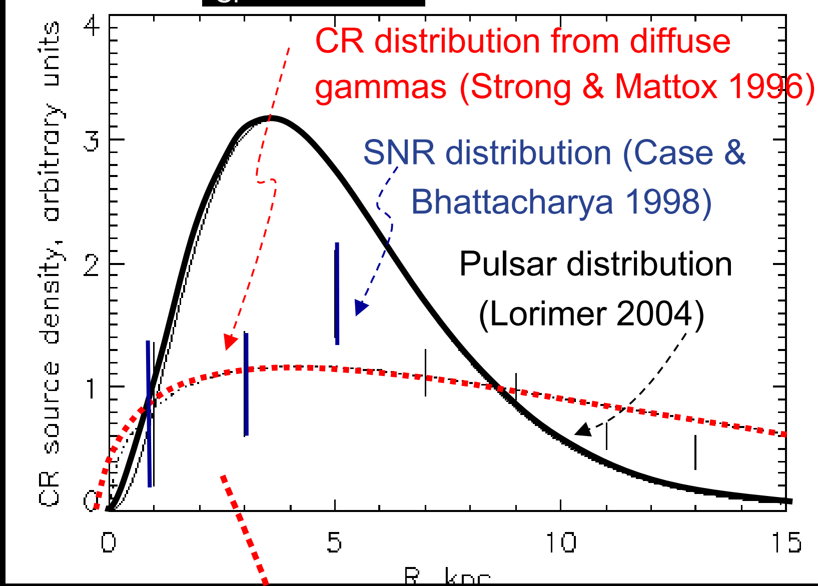


Use GALPROP cosmic ray propagation/diffuse emission code

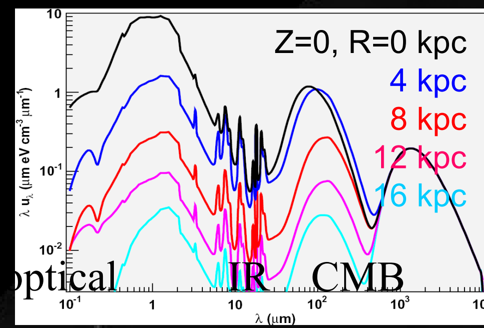
http://galprop.stanford.edu

Modelling the Diffuse Emission

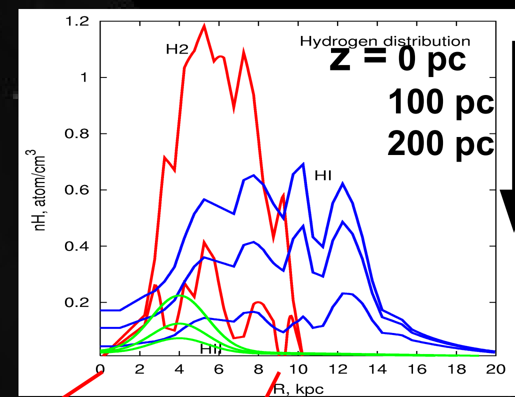




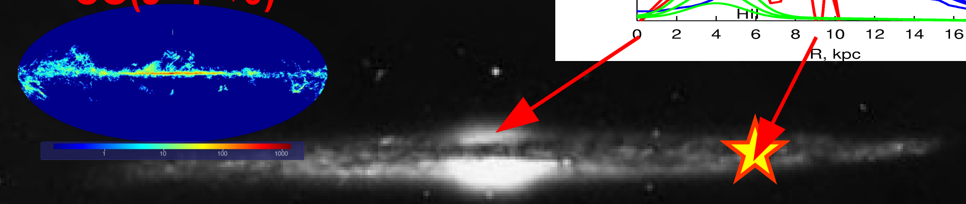
Interstellar radiation field

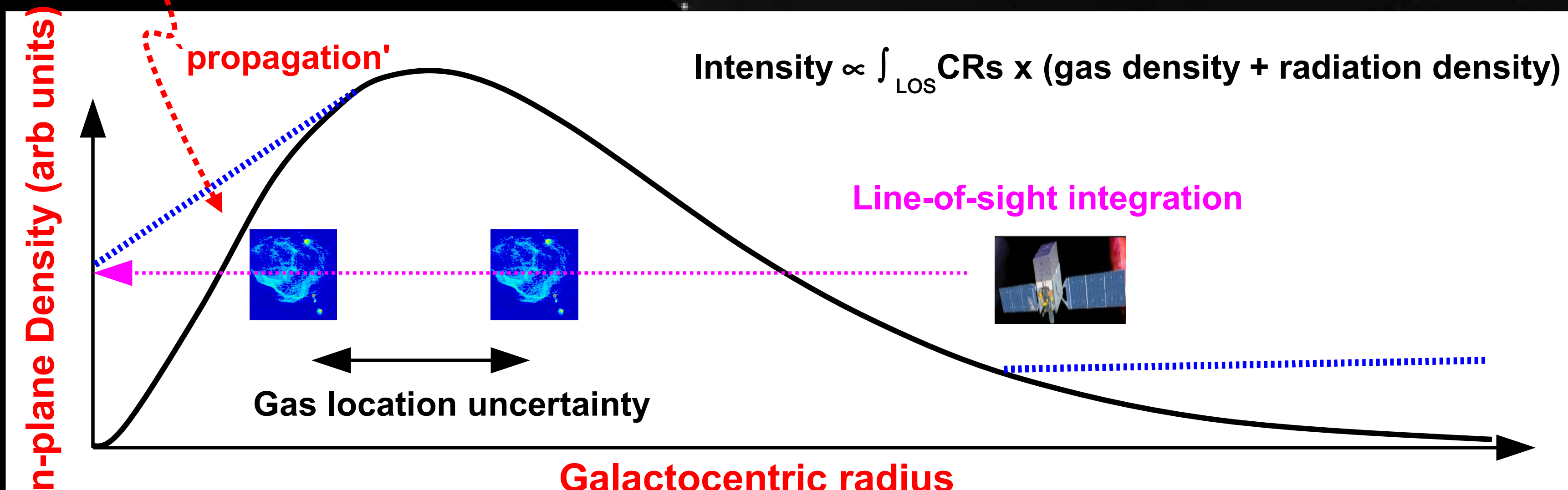


Average gas density

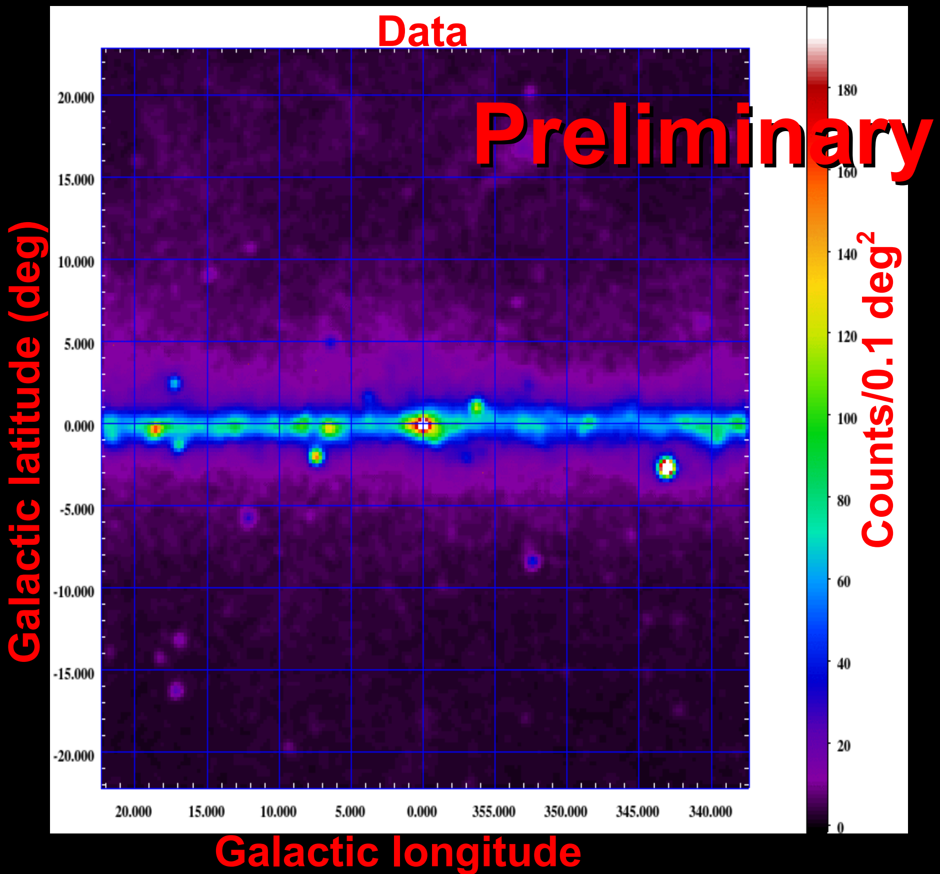


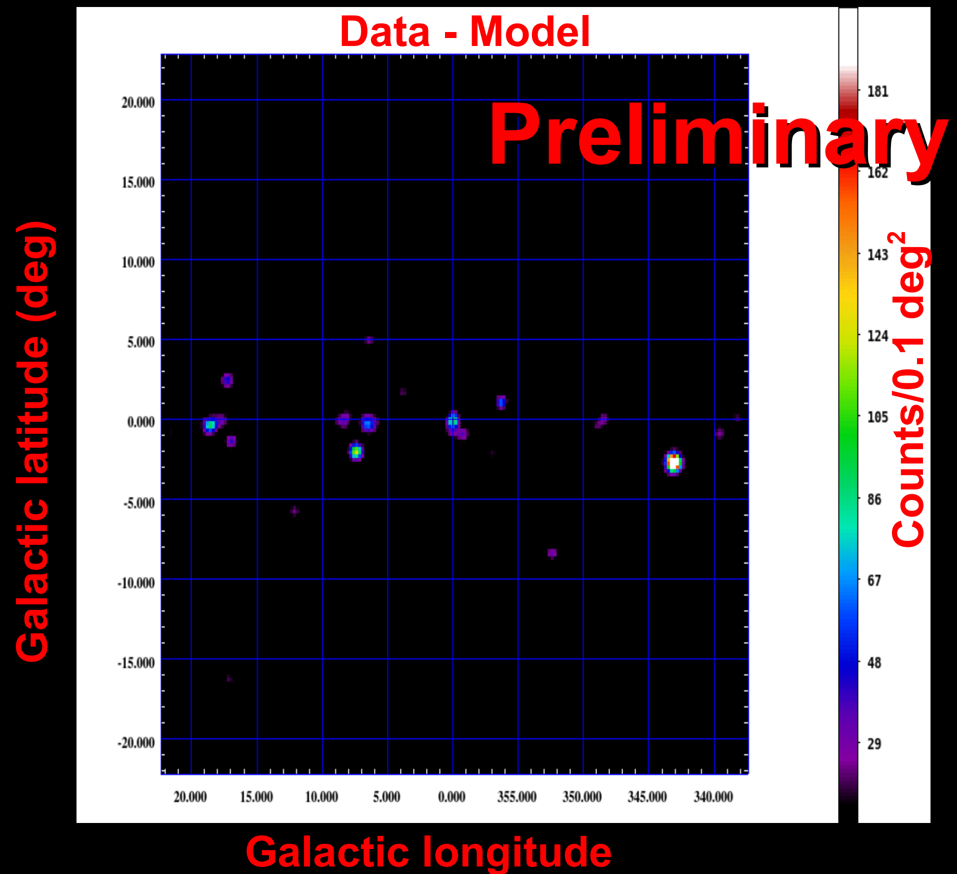
CO(J=1→0)





Subtraction of the Diffuse Emission



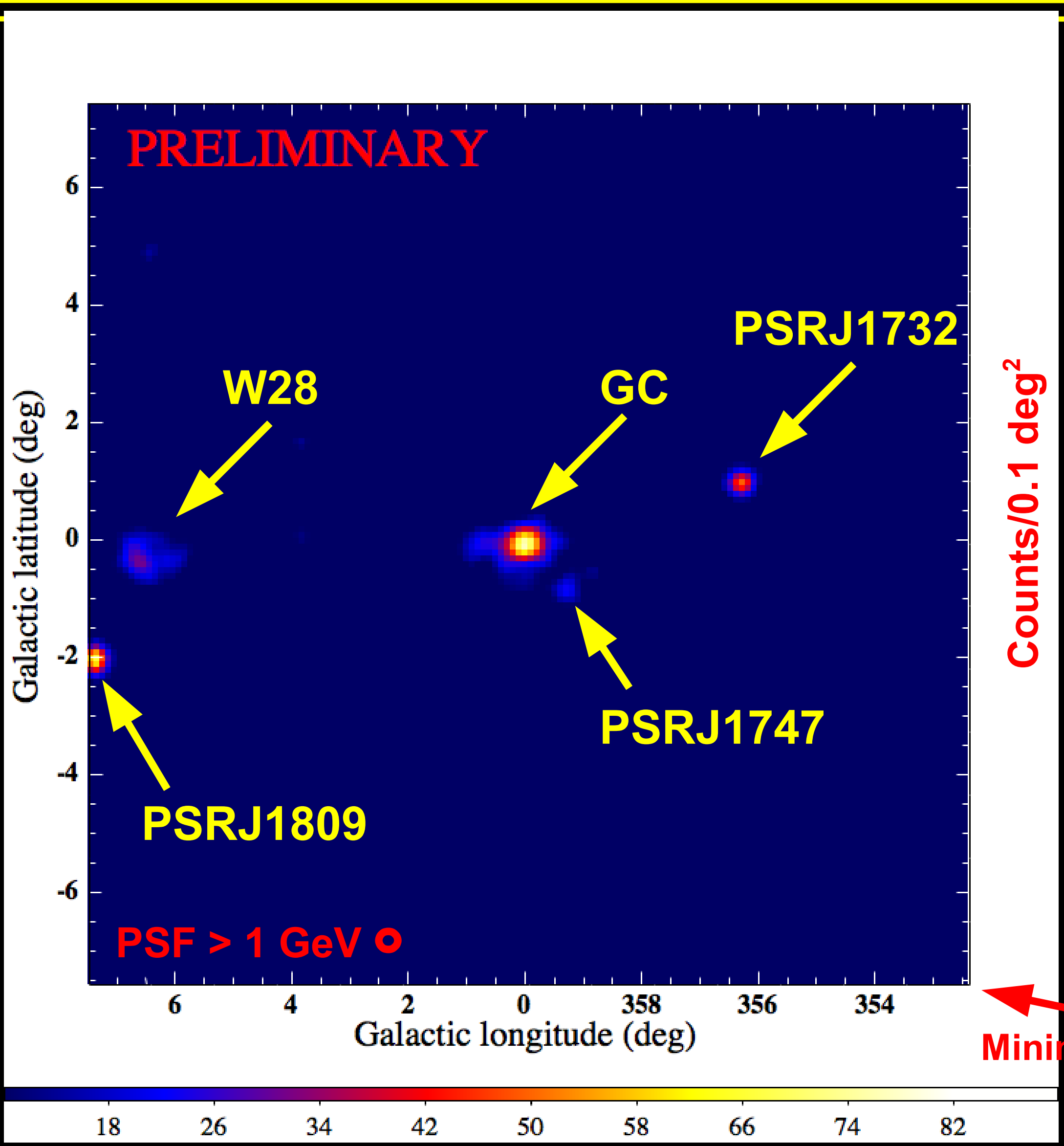


Data > 1 GeV for 45°x45° region about GC

Data – Diffuse Model > 1 GeV for 45°x45° region about GC

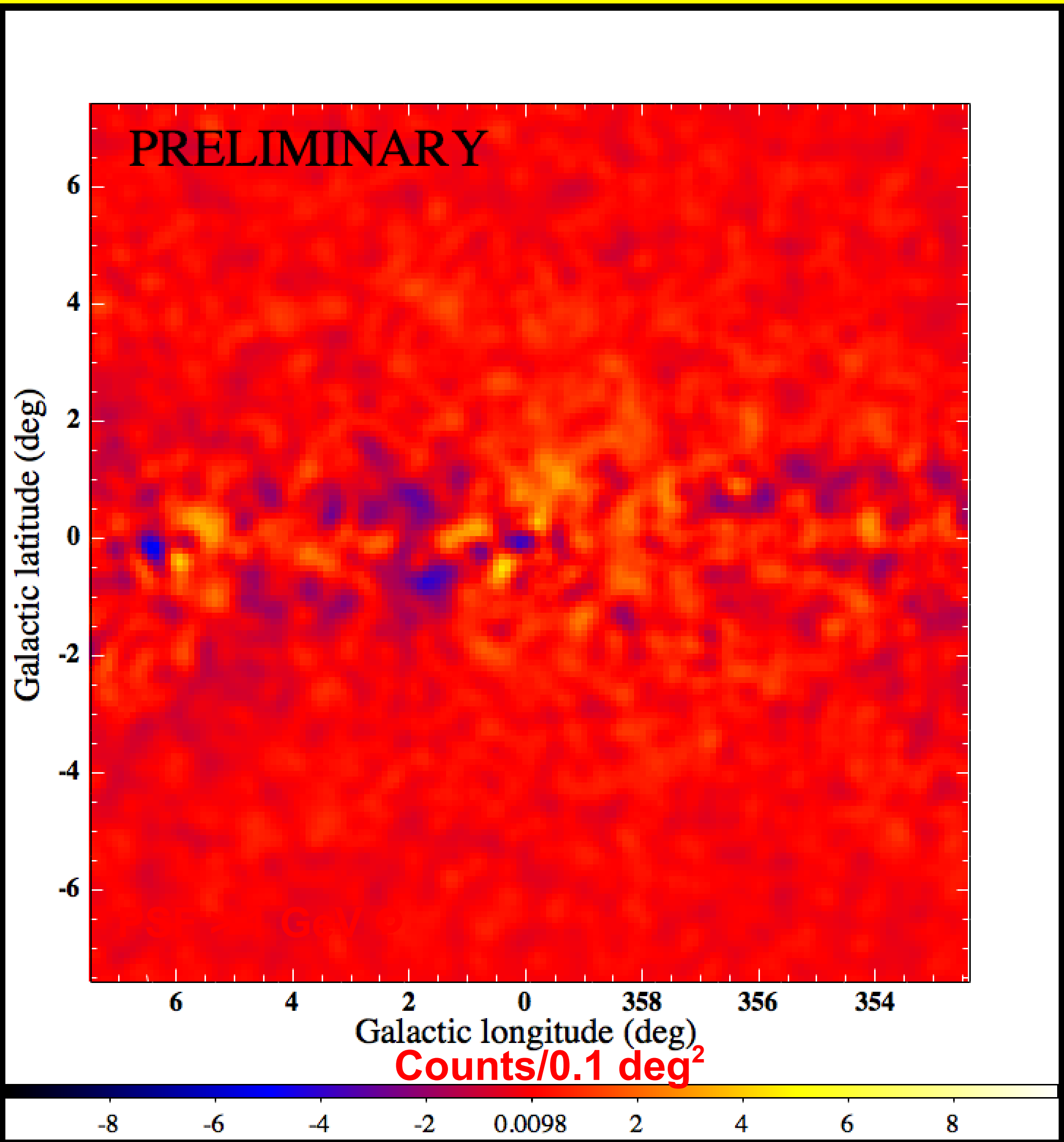
32 Months Data (Front)

Residual Emission for 15°x15° about GC



Bright excesses remain after diffuse model subtraction

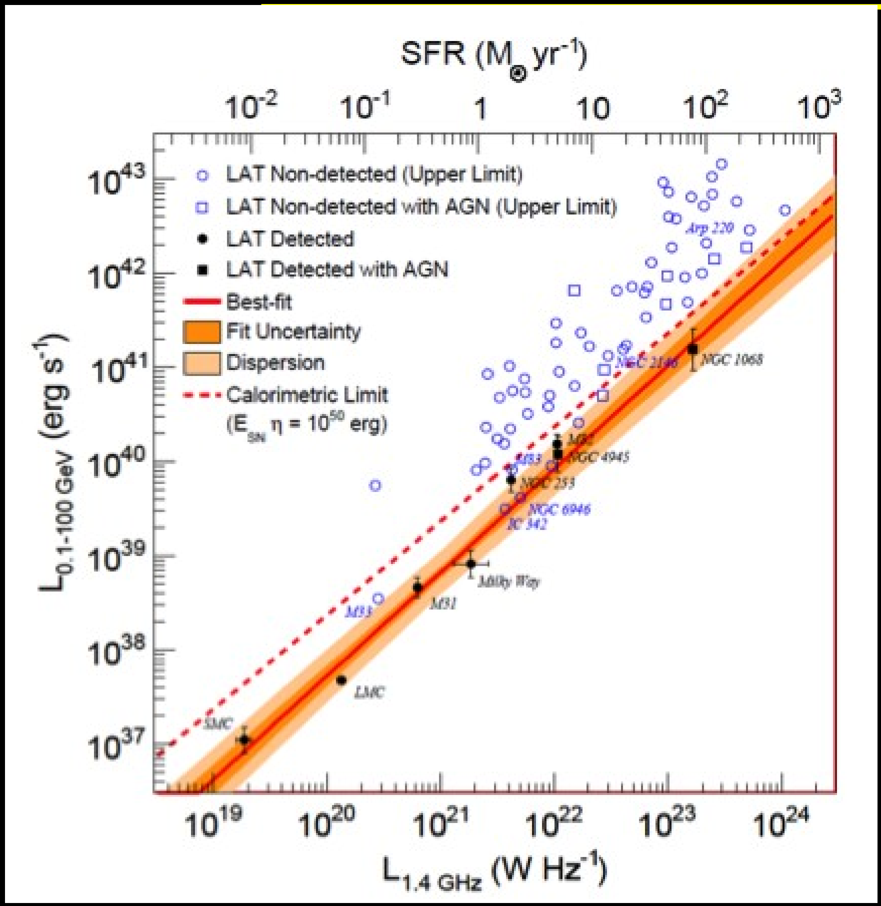
Residual > 1 GeV After Diffuse and Point Source Fitting

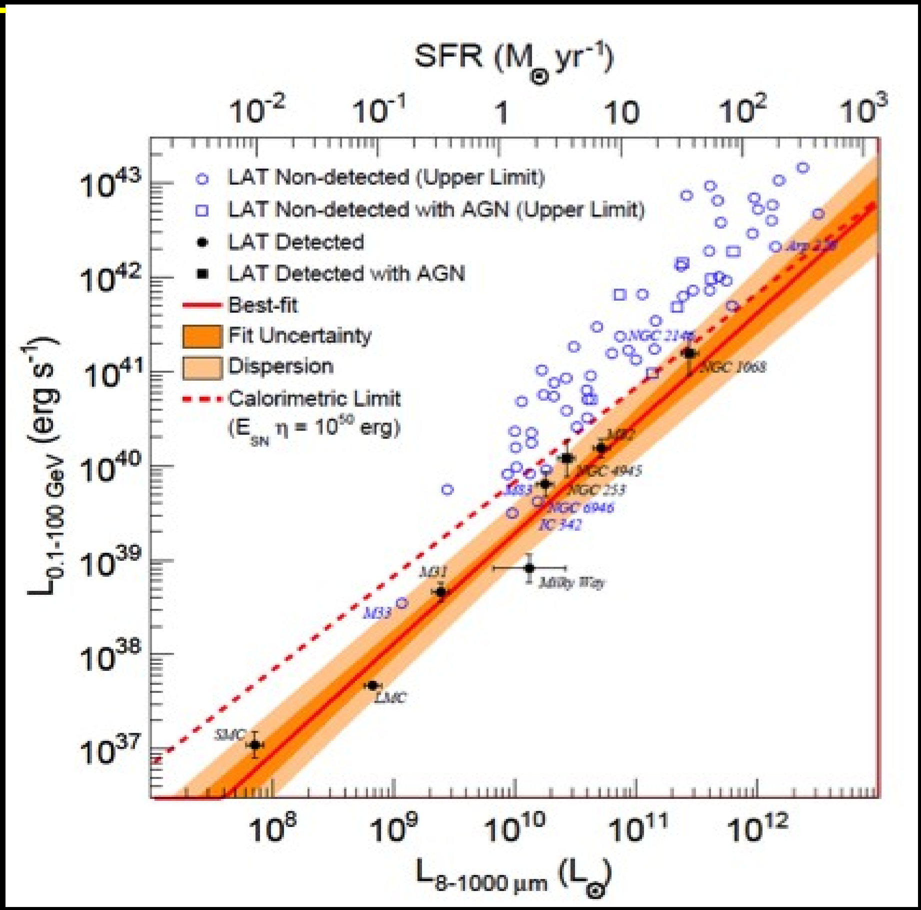


Summary

- 5+ years of Fermi data have dramatically improved our knowledge of cosmic rays and the interstellar medium in the Milky Way
- The systematics associated with inputs to the models now need to be addressed because of the data quality
- We find that
  - Cosmic ray intensities and spectra directly measured and inferred from gamma rays within ~1 kpc are consistent
  - Appears that relatively large halo sizes (~8-10kpc) are favoured by the data
  - Cosmic ray sources are not particularly well constrained (reliant on a-priori distribution selection) and need to be flatter in the outer Galaxy
  - Cosmic ray intensities in the inner Galaxy seem to be higher than resulting from `standard' propagation models

Scaling Relations: Gamma Ray vs. Radio and IR





- Fermi-LAT team analysis of detected SF galaxies and ULs
- Scaling relation with PL slope
  - Gamma ray vs. radio : 1.10 ± 0.05
  - Gamma ray vs. IR: 1.17 ± 0.07

Fermi-LAT collab. ApJ 755, 164 (2012)

Why study the Diffuse Emissions?

The Milky Way and its Structure

→ Origin and propagation of cosmic rays
- Nature and distribution of sources
- The propagation mode itself ↔ relationship to magnetic turbulence in the ISM
- Relative proportions of primary species
- Production of secondary species
- etc.

→ Interstellar Medium
- Distribution of HI, H_2, HII gas
- Nature of X_{CO} relation in Galaxy
- Distribution and intensity of interstellar radiation field ↔ formation of H_2
- etc.

As a Foreground

→ The diffuse emission is the foreground against which sources are detected
- Point sources : limitation on sensitivity
- Extended sources : disentanglement

→ Indirect dark matter detection
- Predicted gamma-ray/cosmic-ray signals rely on accurate subtraction of standard astrophysical sources

→ Foreground for isotropic diffuse background
- Whatever its nature

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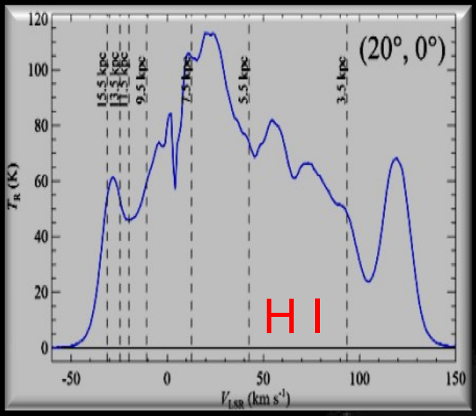
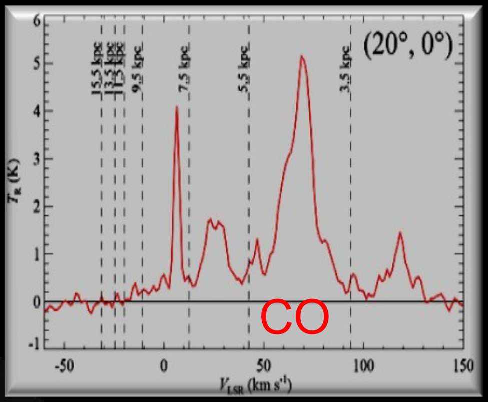
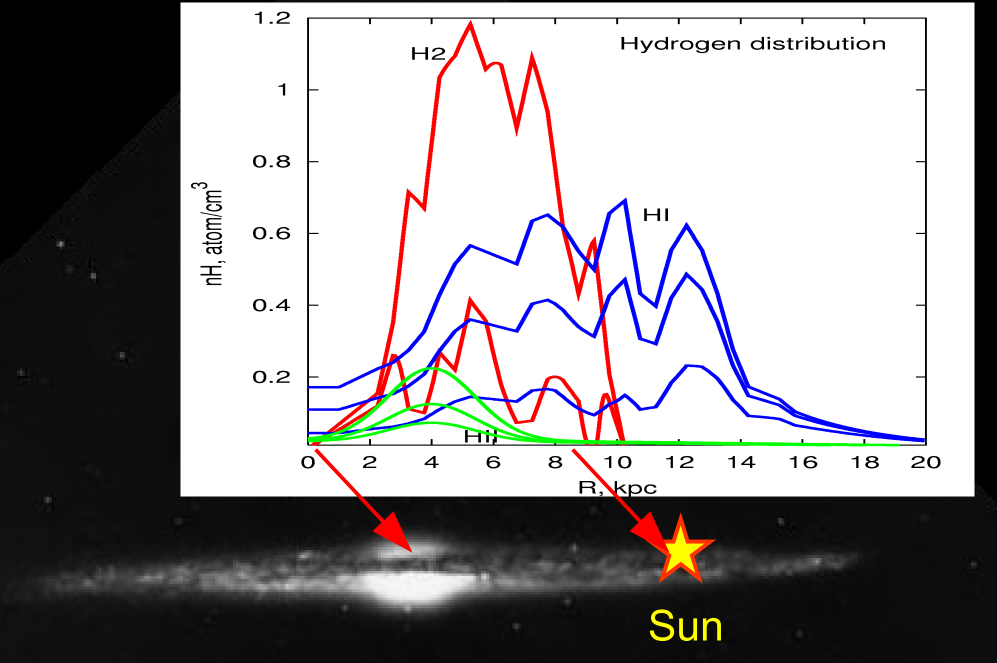
Whatever its nature

The ISM #1: Interstellar gas

- Neutral interstellar medium – most of the interstellar gas mass
- Obtain information via 21-cm H I & 2.6-mm CO (second most abundant molecule in ISM - surrogate for H_2)
- Transitions excited even for interstellar conditions
- Allow determinations of column densities → Doppler shifts of lines interpreted as distance measure
- HII low density → obtained from modelling pulsar dispersion measurements
- Helium ~10% by number
- `Metals' (i.e., Z > 2) contribute very small fraction compared with H and He

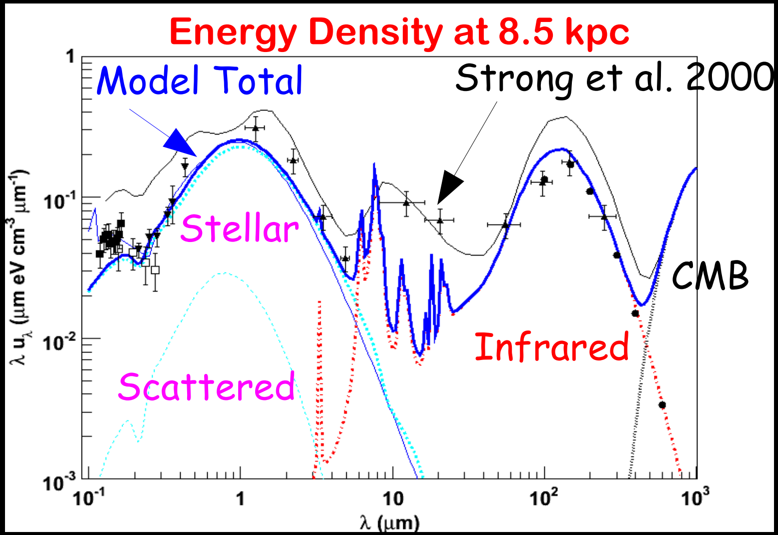


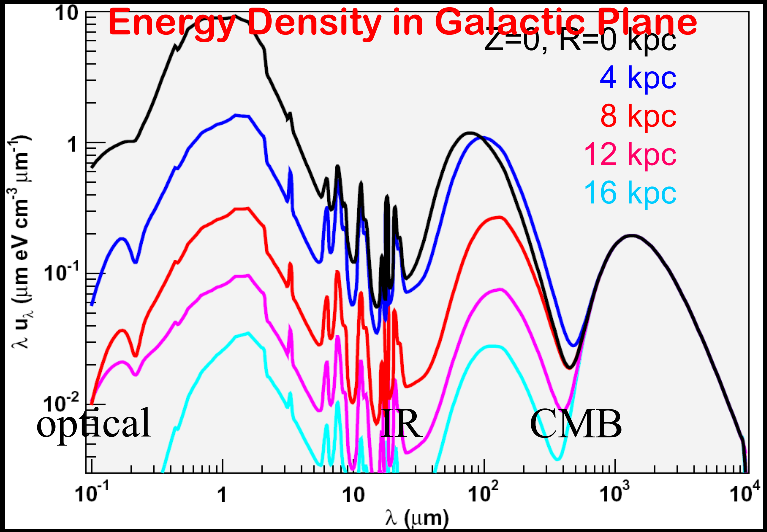




The ISM #2: Interstellar Radiation Field

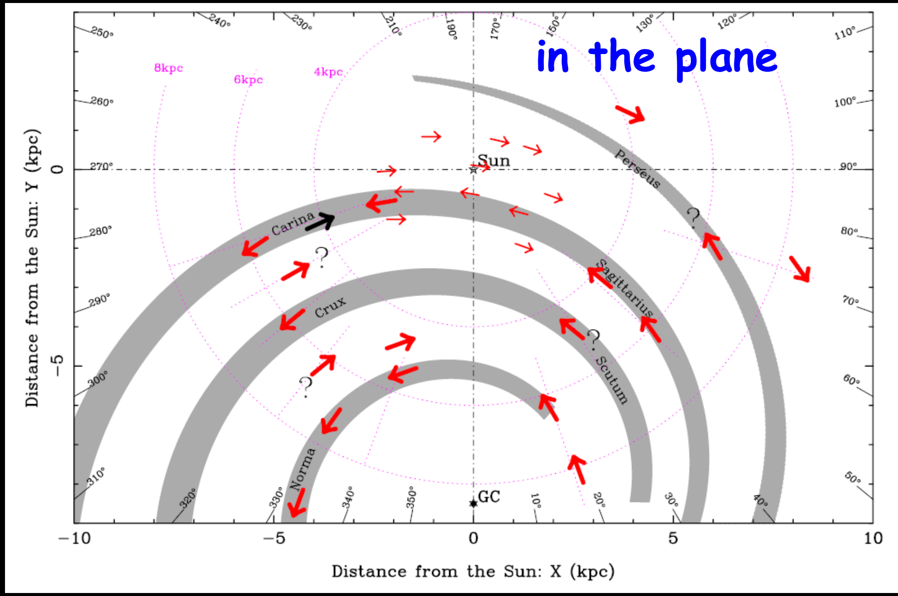
- Interstellar radiation field = low energy photon populations in Galaxy from stellar emission and dust reprocessing of starlight
- Only observed locally so use modelling for spectral energy and angular distributions throughout Galaxy
- Inner Galaxy ISRF energy density > x100 local
- The scale height above the Galactic plane is large (~10 kpc) → pervasive contribution by IC over the sky



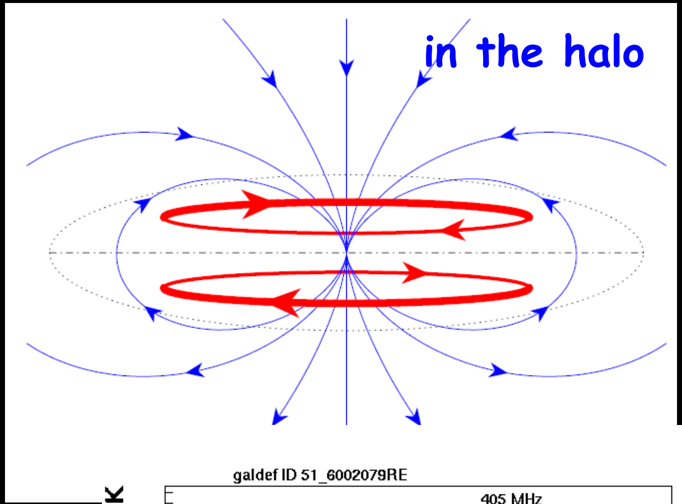


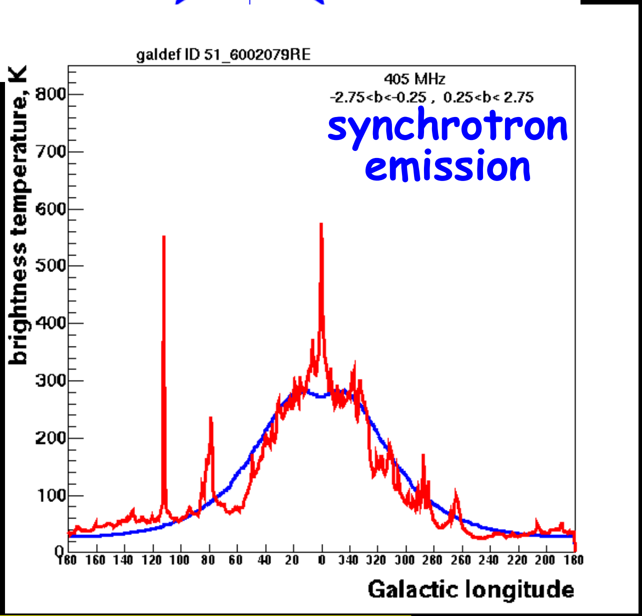
The ISM #3: Galactic Magnetic Field

Regular B-field: large-scale structure (from pulsar RM and DM)



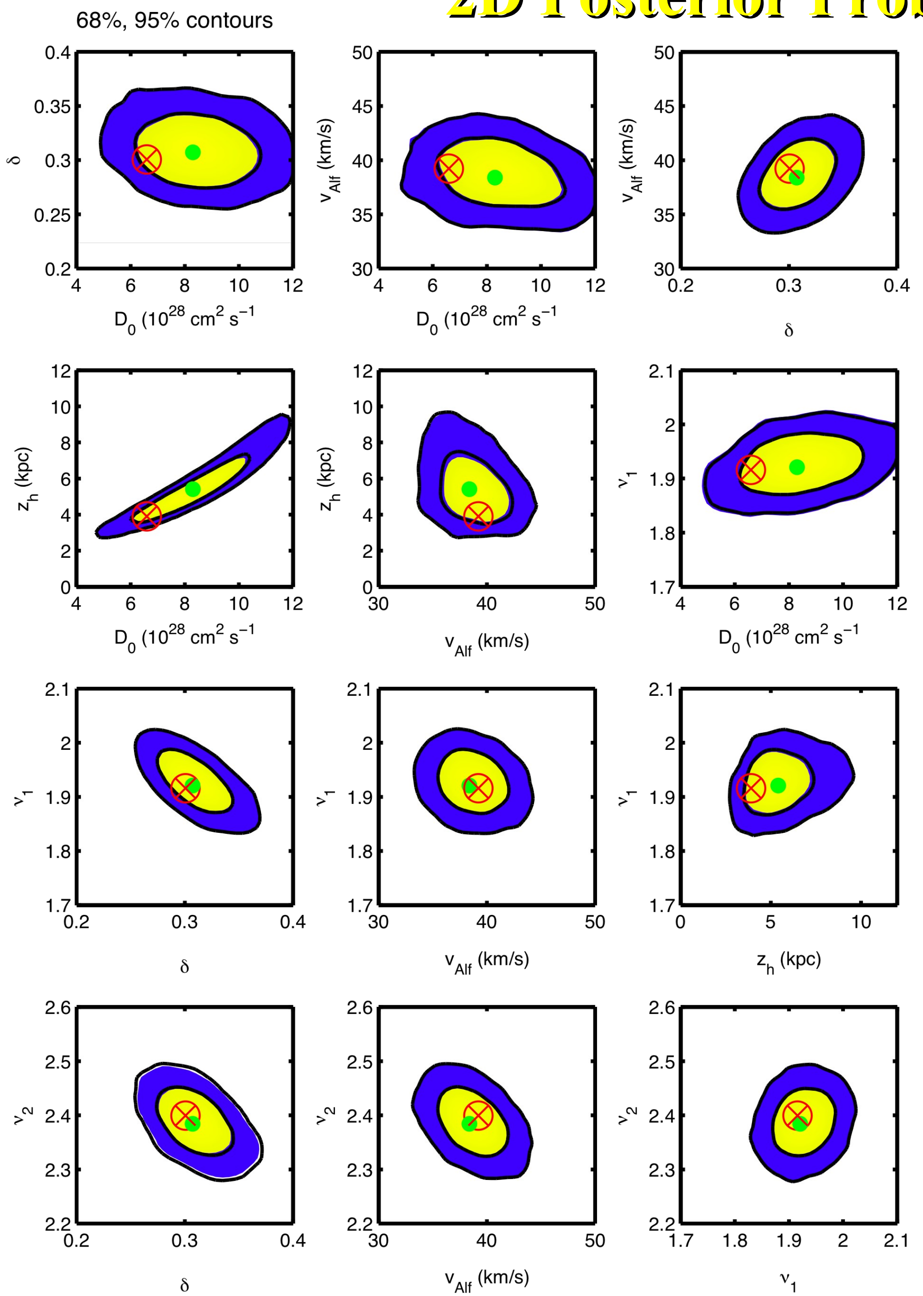
Han'08





- Plane: bisymmetrical field with reversals on arm-interarm boundaries
- Halo: azimuth B-fields with reversed directions below and above the plane
- Random field ≈ Regular field
- Consistent with observations of the synchrotron emission

2D Posterior Probability Distributions



- **Contours enclose 68% and 95% probability regions**

- best fit

- posterior mean

Input Parameters and Priors

Quantity	Symbol	Prior Range	Prior Type
Diffusion model parameters Θ			
Diffusion coefficient[a] (10^{28} cm^2 s^{-1})	D_0	[1, 12]	Uniform
Rigidity power-law index	δ	[0.1, 1.0]	Uniform
Alfvén speed (km s^{-1})	$v_{\rm Alf}$	[0, 50]	Uniform
Diffusion zone height (kpc)	z_h	[1.0, 10.0]	Uniform
Nucleus injection index below 10^4 MV	ν_1	[1.50, 2.20]	Uniform
Nucleus injection index above 10^4 MV	ν_2	[2.05, 2.50]	Uniform
Proton normalization (10^{-9} cm^2 sr^{-1} s^{-1} MeV^{-1})	N_p	[2, 8]	Uniform
Experimental nuisance parameters			
Modulation parameters ϕ (MV)			Gaussian prior[b]
HEAO-3	$m_{HEAO\text{-}3}$	[420, 780]	$\mathcal{N}(600, 60)$
ACE	m_{ACE}	[175, 475]	$\mathcal{N}(325, 50)$
CREAM	m_{CREAM}	[420, 780]	$\mathcal{N}(600, 50)$
ISOMAX	m_{ISOMAX}	[370, 490]	$\mathcal{N}(430, 20)$
ATIC-2	$m_{ATIC\text{-}2}$	0	Fixed (no modulation)
Variance rescaling parameters ($j = 1, \ldots, 5$)	$\log \tau_j$	[−1.5, 0.0]	Uniform on $\log \tau_j$

Notes.

[a] At $\rho = 4 \times 10^3$ MV.

[b] We use the notation $\mathcal{N}(\mu, \sigma)$ to indicate a Gaussian distribution of mean μ and standard deviation σ.

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