The structure of the ISM:
Lessons from the EGRET analysis and what we can learn with GLAST

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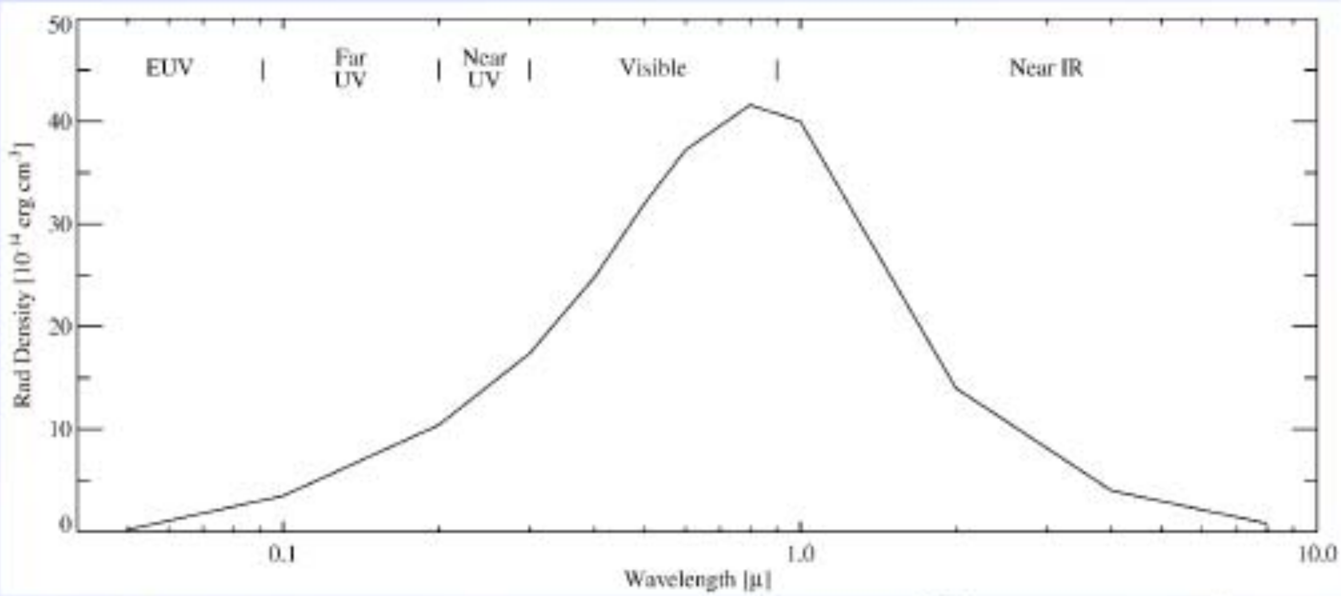
Composition of the ISM - Matter

- Interstellar Clouds
  $0.011 M_\odot/pc^3$, ~90% of ISM
  - Bright Nebulae, e.g. Orion (M42)
  - Dark Nebulae, e.g. Ophiuchus
  - H I 8 H-atoms/cm^3, 0.01 elec/cm^3
  - H_2 1 H-mol/cm^3
  - All other elements
  - H II ~8 elec/cm^3
- Interstellar Gas
  - Mean density between clouds
    0.1 H-atoms/cm^3, 0.035 elec/cm^3
- Interstellar Grains
  $0.0015 M_\odot/pc^3$, ~10% of ISM
  - Number density 0.5×10^{-12} cm^{-3}
  - Mass density ~1g/cm^3

- *Should this list also include dark matter?*

Composition of the ISM - Radiation

- Stellar radiation 7×10^{-13} erg/cm^3



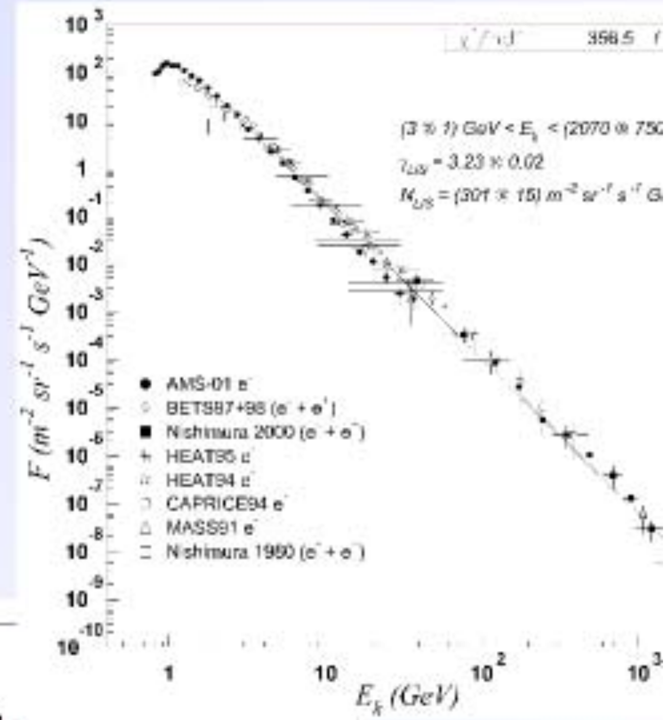
- CMB (2.7 °K) 4×10^{-13} erg/cm^3

- Turbulent gas motion 5×10^{-13} erg/cm^3
- Cosmic rays 16×10^{-13} erg/cm^3
- Magnetic field 15×10^{-13} erg/cm^3

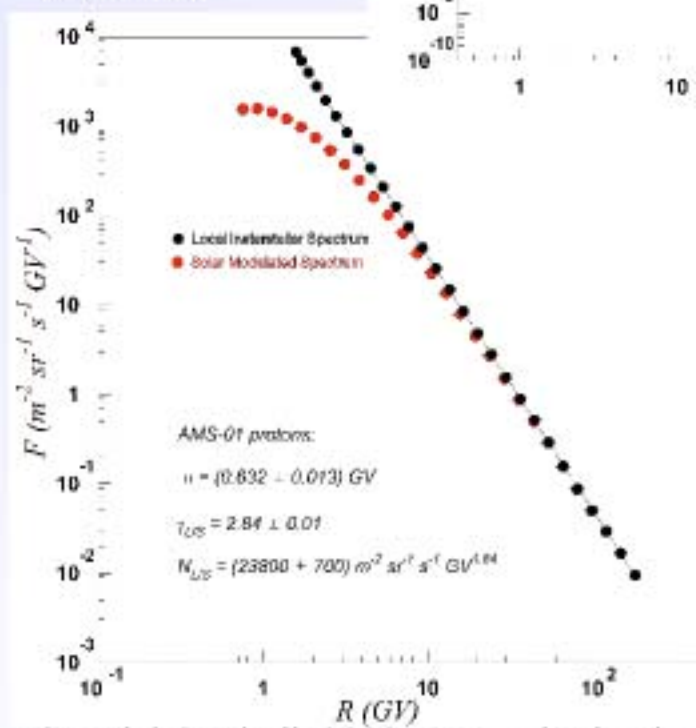
Composition of the ISM - Cosmic Rays

- Cosmic Rays
  - Electrons (positrons ~10%)
  - Protons (He and heavier)
  - Probably accelerated by supernovae
- Spectrum measured only in the Solar neighborhood
  - Indicative of Galactic average spectrum?
- Subject to Solar modulation
  - Requires a model to estimate the solar modulation parameter ϕ
  - Spherical diffusion model by Parker 1965, Gleeson & Axford 1967, 1968

Electrons



Protons



Casadei & Bindi, 2003, ApJ, submitted, astro-ph/0302307

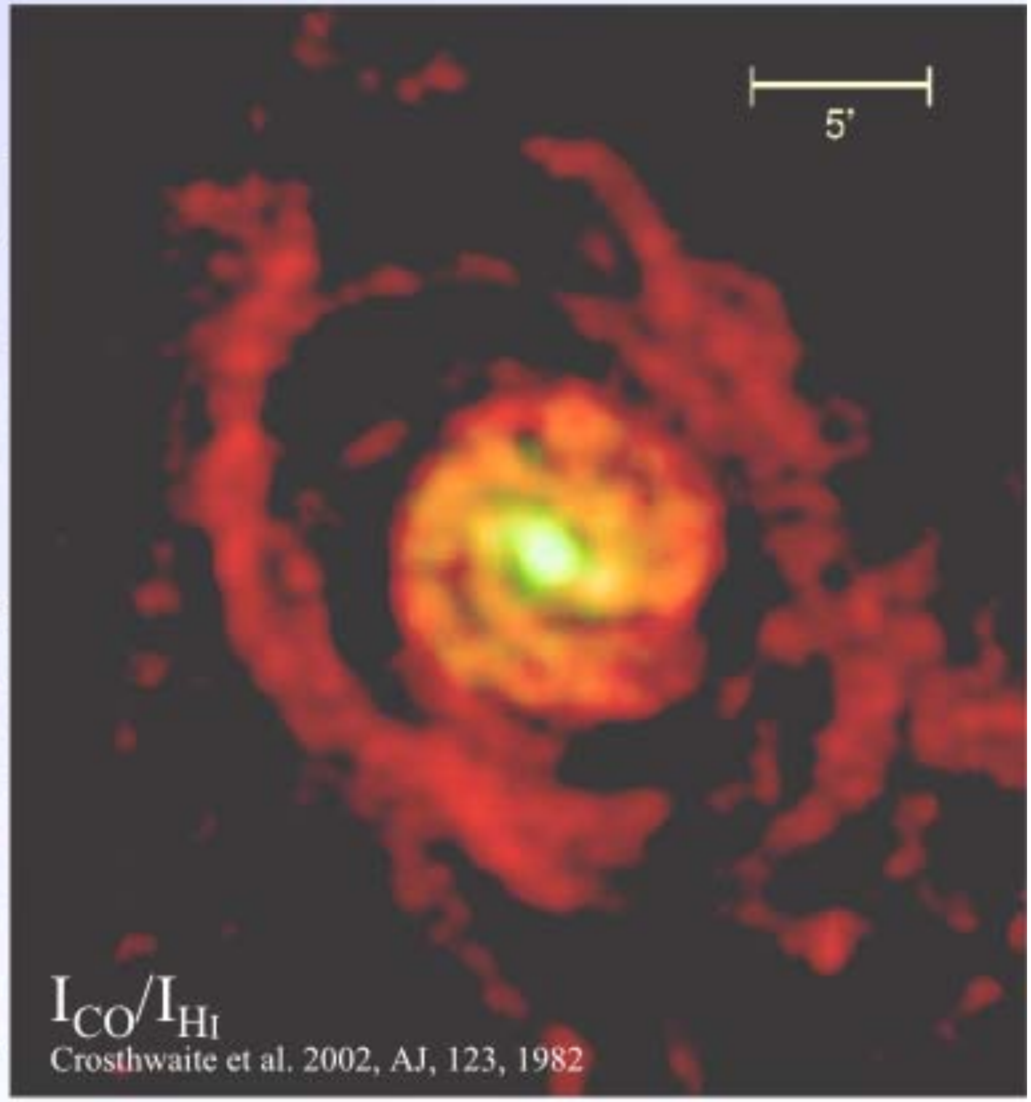
Galactic Distribution of the ISM - 1

- We can directly observe the radial distribution of the ISM in face-on galaxies ...

M83

Optical
Anglo-American Observatory David Malin

Infrared
Two Micron All Sky Survey IPAC & Univ. of Massachusetts



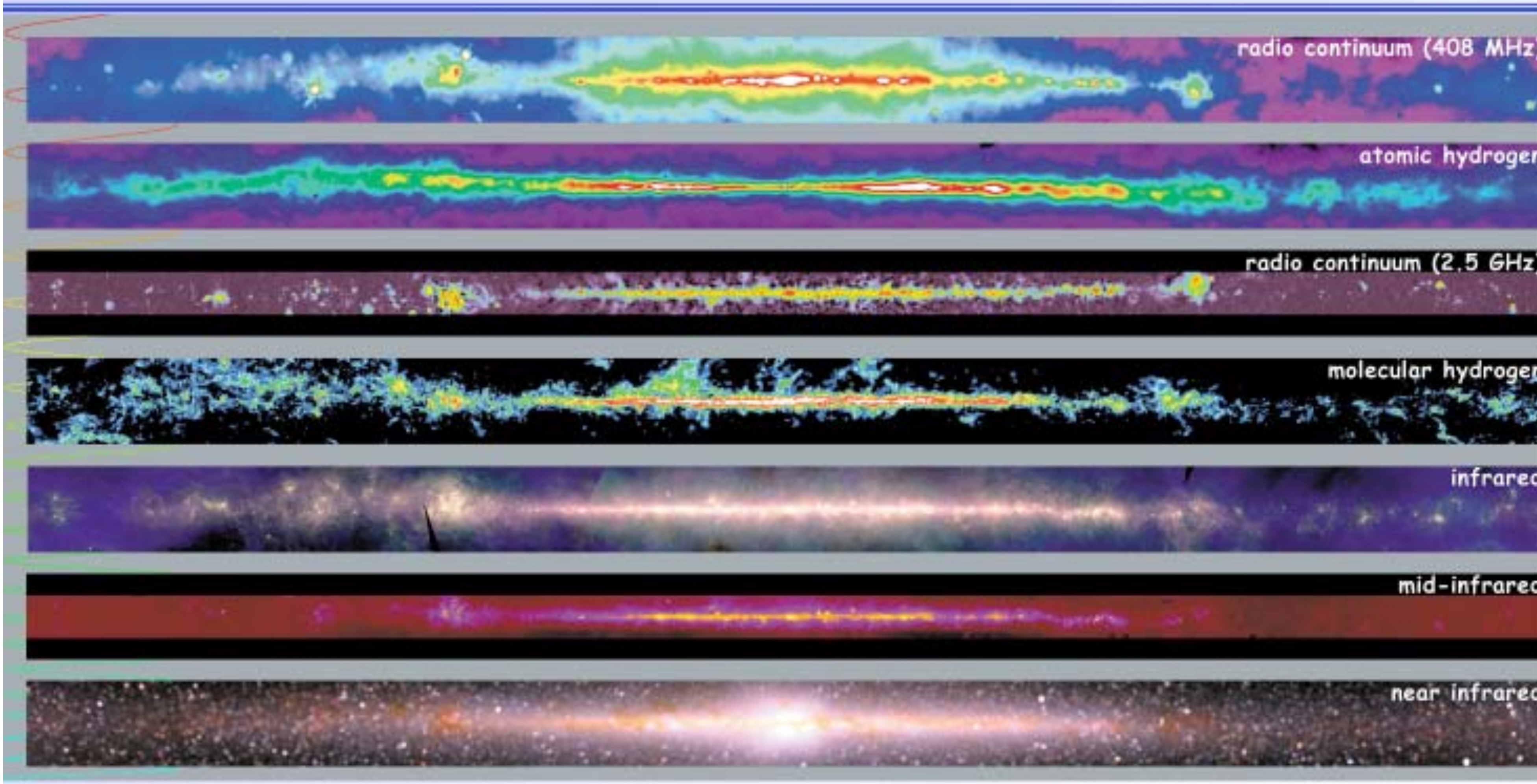
Crosthwaite et al. 2002, AJ, 123, 1982

Galactic Distribution of the ISM - 2

… and the vertical distribution in edge-on galaxies

The Milky Way is another matter - because of our position *within* the Galaxy, our observations of ISM tracers give the integrated column density through the Galaxy.

Galactic Tracers of the ISM



Question: *What is the 3-D distribution of the ISM in the Milky Way?*

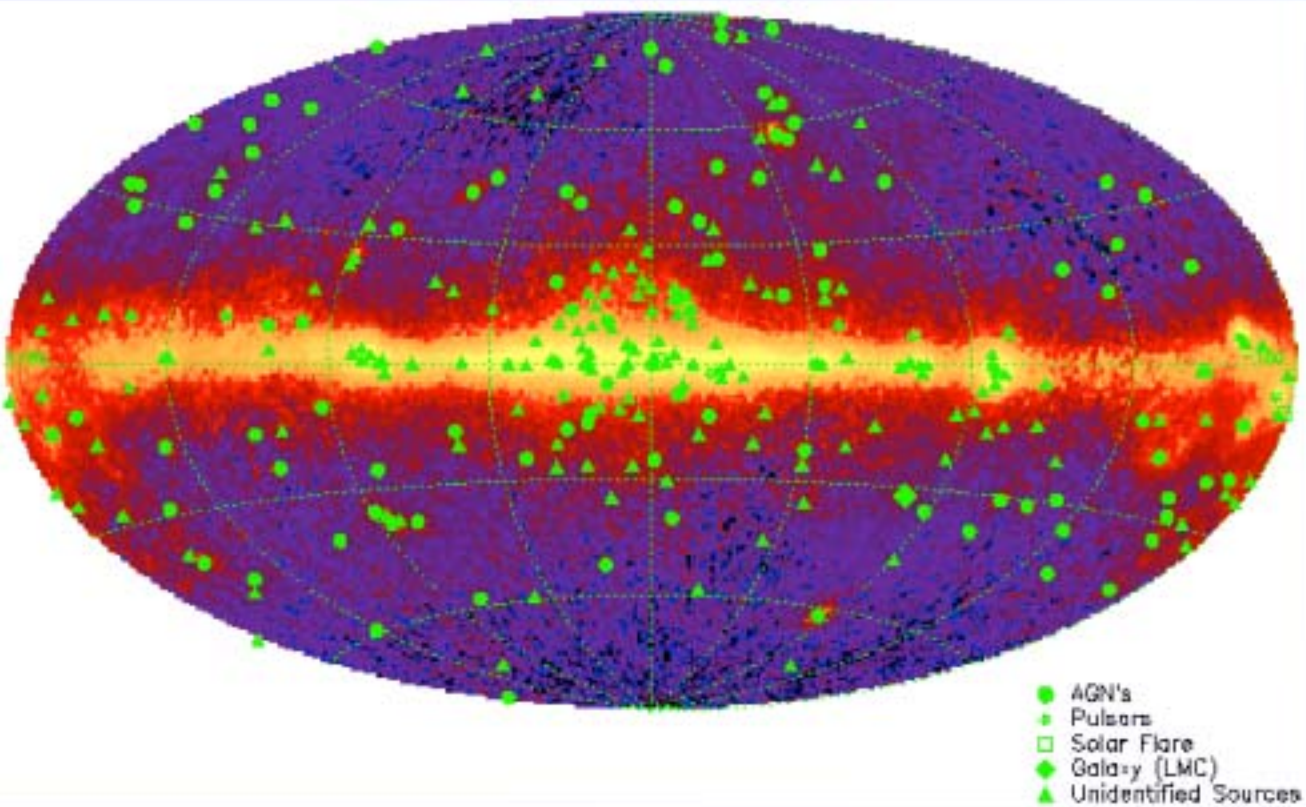
- Tracers give line-of-sight column density through disk of Galaxy
- Total column density (often?) reduced by absorption

Distribution and Structure of the ISM

- Matter - HI, H_2, HII
  - Non-radially symmetric distribution, arm structure
  - Poorly known scale height
  - 300 pc at the R_{sun}, >1 kpc at R = 20 kpc
    (Burton, 1992, SAAS-FEE Proc. Springer-Varlag)
- Radiation - Low energy photons
  - Poorly known scale height
- Cosmic Rays - p, e^2
  - Unknown distribution, production sites, diffusion rate
  - Poorly known scale height
  - Single spectral measurement
- Galactic Halo? High latitude matter?

- *The diffuse gamma-ray emission provides another probe of the ISM and the CR distribution ...*

The Galactic Diffuse Gamma-ray Emission



The all-sky intensity distribution of Eγ > 100 MeV gamma-rays, overlaid with the Third EGRET catalog (Hartman et al. 1999).

The Galactic diffuse gamma-ray emission is probe of the *Galactic ISM* and *CR distributio*

A *model* of the diffuse emission is a *study* of the ISM and CRs.

Relation to the AGILE Science:

What is the physical structure of the interstellar medium (ISM) in the Milky Way and the distribution of the cosmic rays that pervade it?

The Galactic Diffuse Emission

Diffuse emission is readily calculated … with only a few assumptions

Galactic cosmic-ray distribution of electrons and nucleons (+ He, heavies)

Galactic matter distribution of atomic, molecular, and ionized hydrogen

$$j(E_{\gamma}, l, b) = \frac{1}{4\pi}\int (c_e \cdot q_{eb} + c_n \cdot q_{nn}) \times (n_{\mathrm{H\,I}} + n_{H2} + n_{\mathrm{H\,II}})\, \mathrm{d}\rho \, +$$

$$\frac{1}{4\pi}\sum_i \int c_e \cdot q_{ic,i} \cdot u_{ic,i}\, \mathrm{d}\rho \quad [\mathrm{ph\ cm^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}}]$$

Gamma-ray production functions electron bremsstrahlung, nucleon-nucleon (π^o), and inverse Compton
Synchrotron emission is not significant

Low-energy photon energy density cosmic microwave background, infra-red, visible, and ultraviolet

EGRET Diffuse Model

- Dual role of diffuse model
  - Study the Galactic diffuse emission
  - 'Background' for point source analyses
- Low-latitude model, $|b| < 10°$
  - Galactic Emission

Bertsch, et al. 1993, ApJ, 416, 587
Hunter et al. 1997, ApJ, 481, 205

- High-latitude model, $|b| > 10°$
  - Galactic + extra-galactic emission

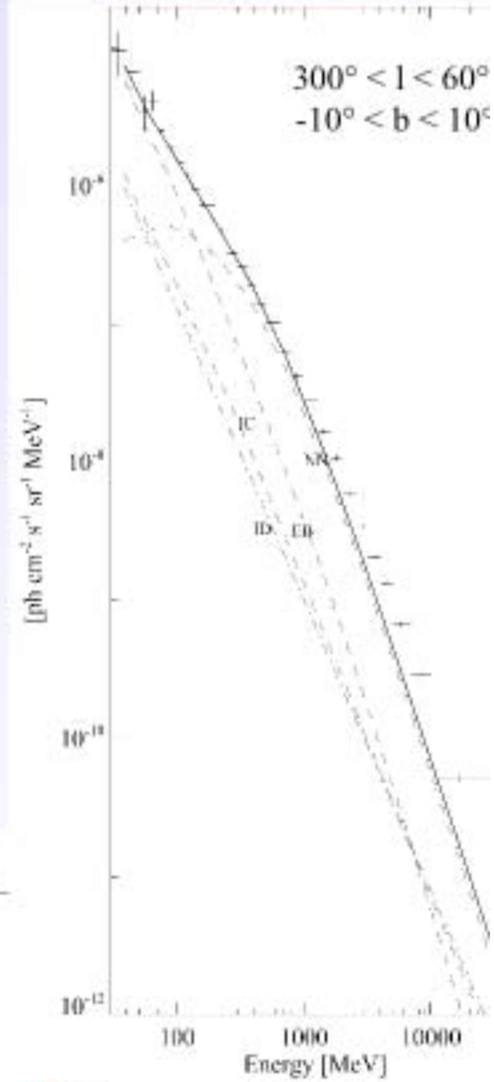
Sreekumar et al. 1998, ApJ, 494, 52

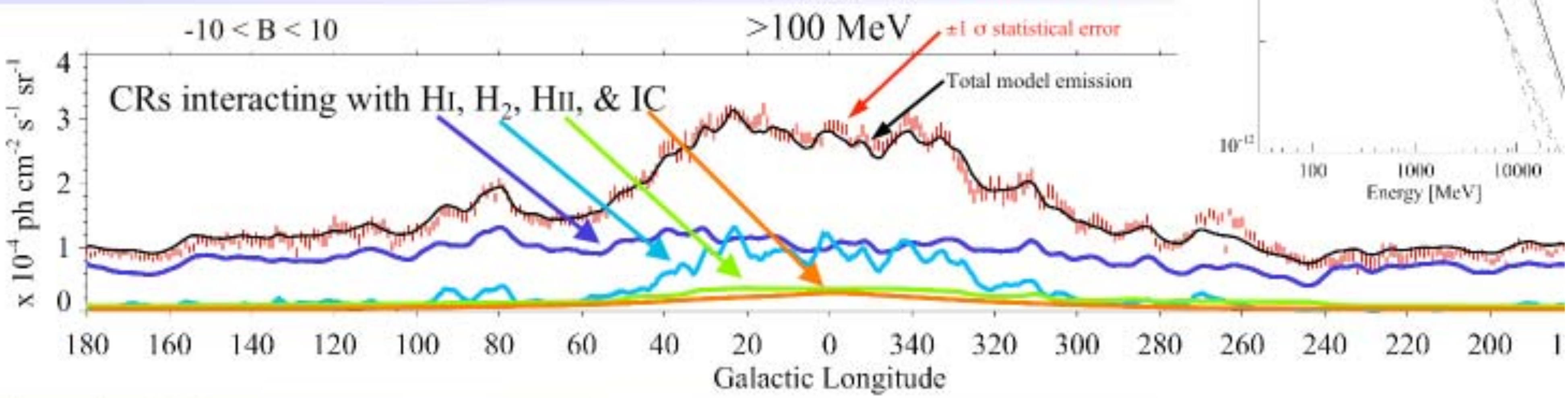
- Inputs to model:
  - Gamma-ray production processes in the ISM
  - Tracers of the ISM, matter and radiation
  - Galactic rotation curve (3-D Galactic matter distribution)
  - Physical parameters and model dependent parameters

⇒ *Cosmic ray distribution derived on assumption of dynamic balance*

Conclusions - 1

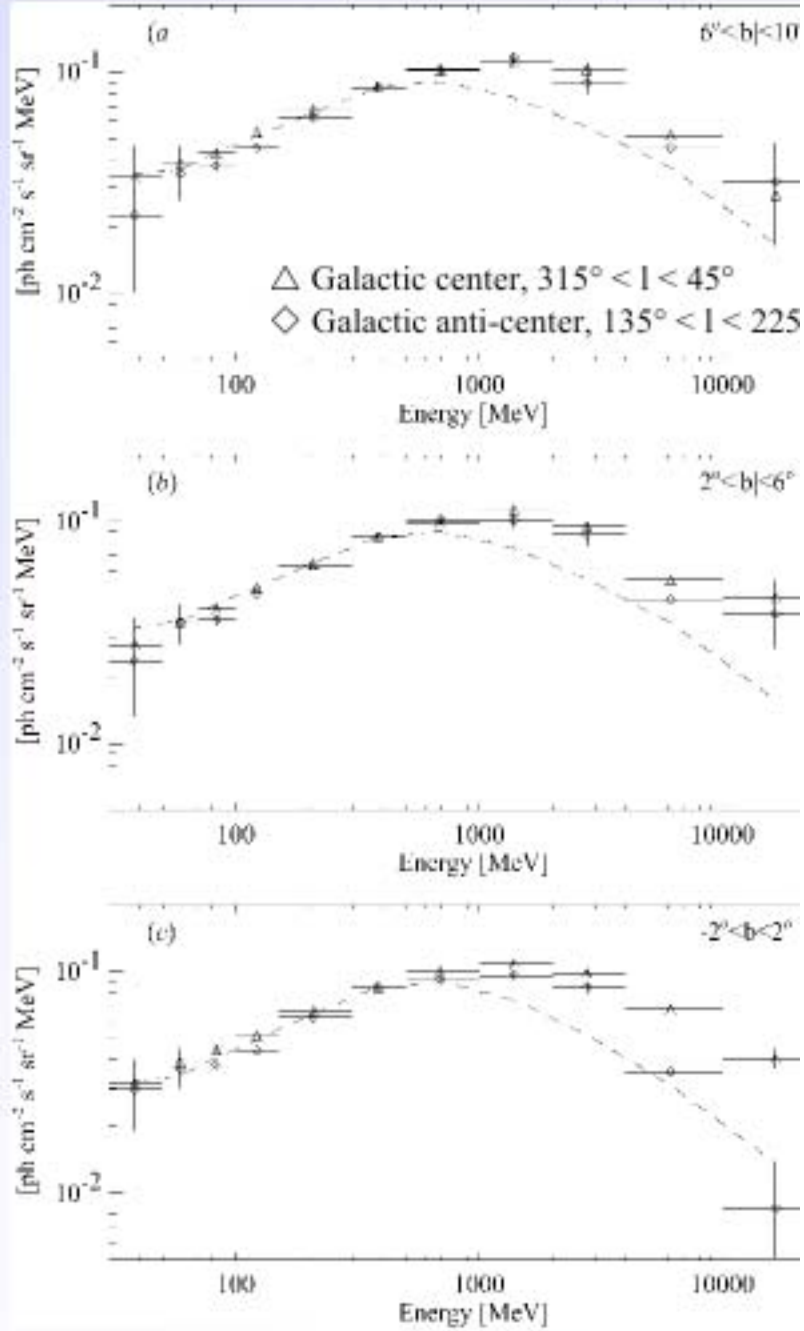
- Large scale spectral agreement
  - The Inverse Compton, electron bremsstrahlung, and nucleon-nucleon (π^0) components confirmed; "Pion bump" seen
  - The strong correlation of gamma-ray emission with Galactic structural features is also confirmed.
- Large scale spatial agreement
  - Assumption of **dynamic balance** is reasonably correct
  - The fraction of **unresolved sources** is small (unless distributed like the interstellar gas and uniform on a scale smaller than the EGRET PSF)





Conclusions - 2

- The spectrum of the Galactic diffuse gamma-ray emission does not vary, within relatively small uncertainties, with Galactic longitude or position in the Galaxy.
  - The CR electron-to-proton ratio is essentially constant throughout the Galaxy
- Unresolved point source contribution is < ~10%

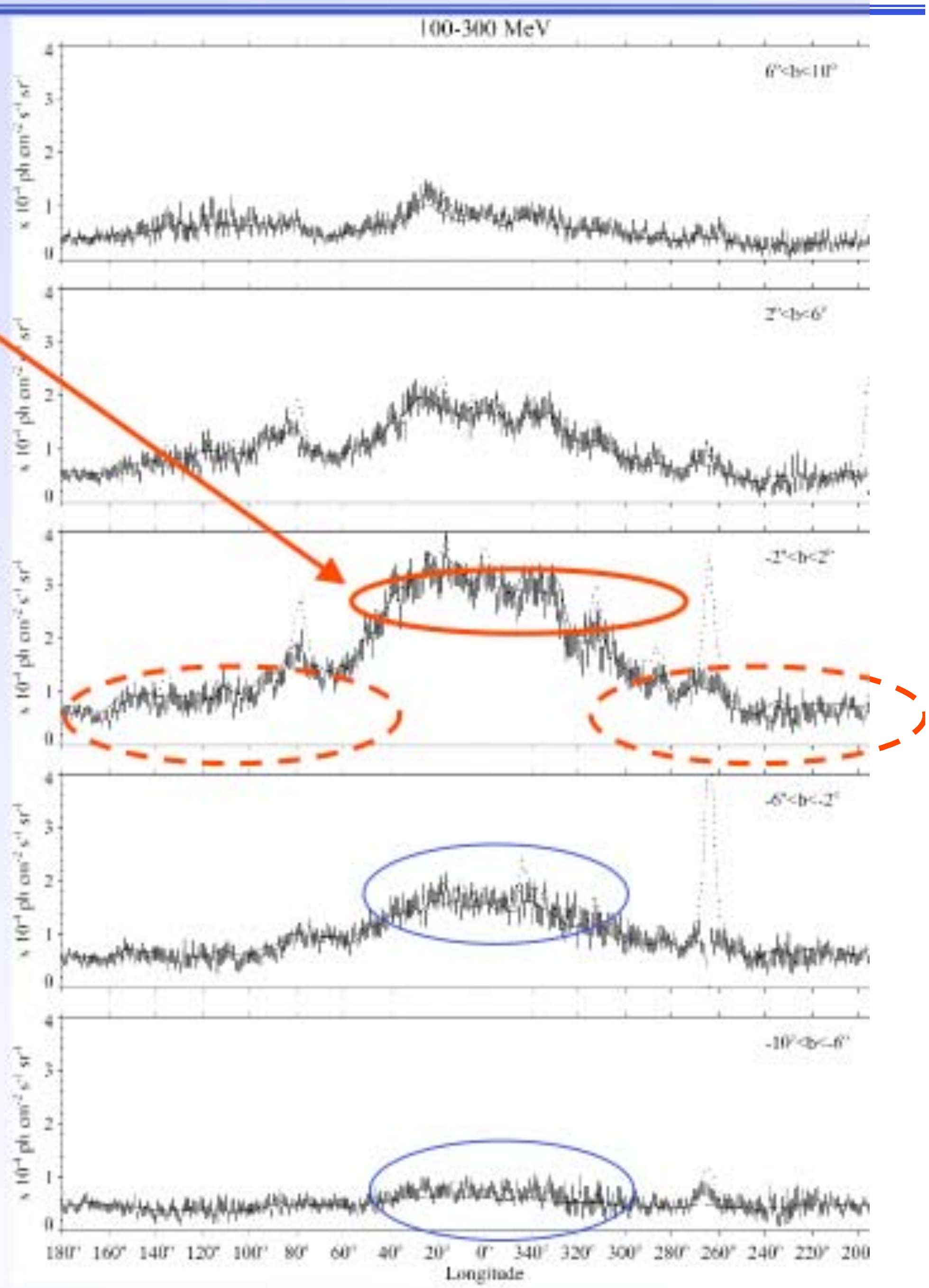


Spatial Discrepancies - 1

Over-prediction of the low-latitude, $|b| < 2^o$, emission in the inner- and outer-galaxy

» **Considered together**: the over-prediction at low-latitudes and not at medium-latitudes, $|b| > 2^o$, suggests an over estimate of the cosmic-ray density in the plane and an under estimate of the comic-ray scale height.

» **Considered separately**: the over-prediction toward the Galactic center, roughly correlated with the emission from H2, suggests that the value of X = N(H2)/WCO is high by about 5% and that the assumption of dynamic balance breaks down in the outer Galaxy.

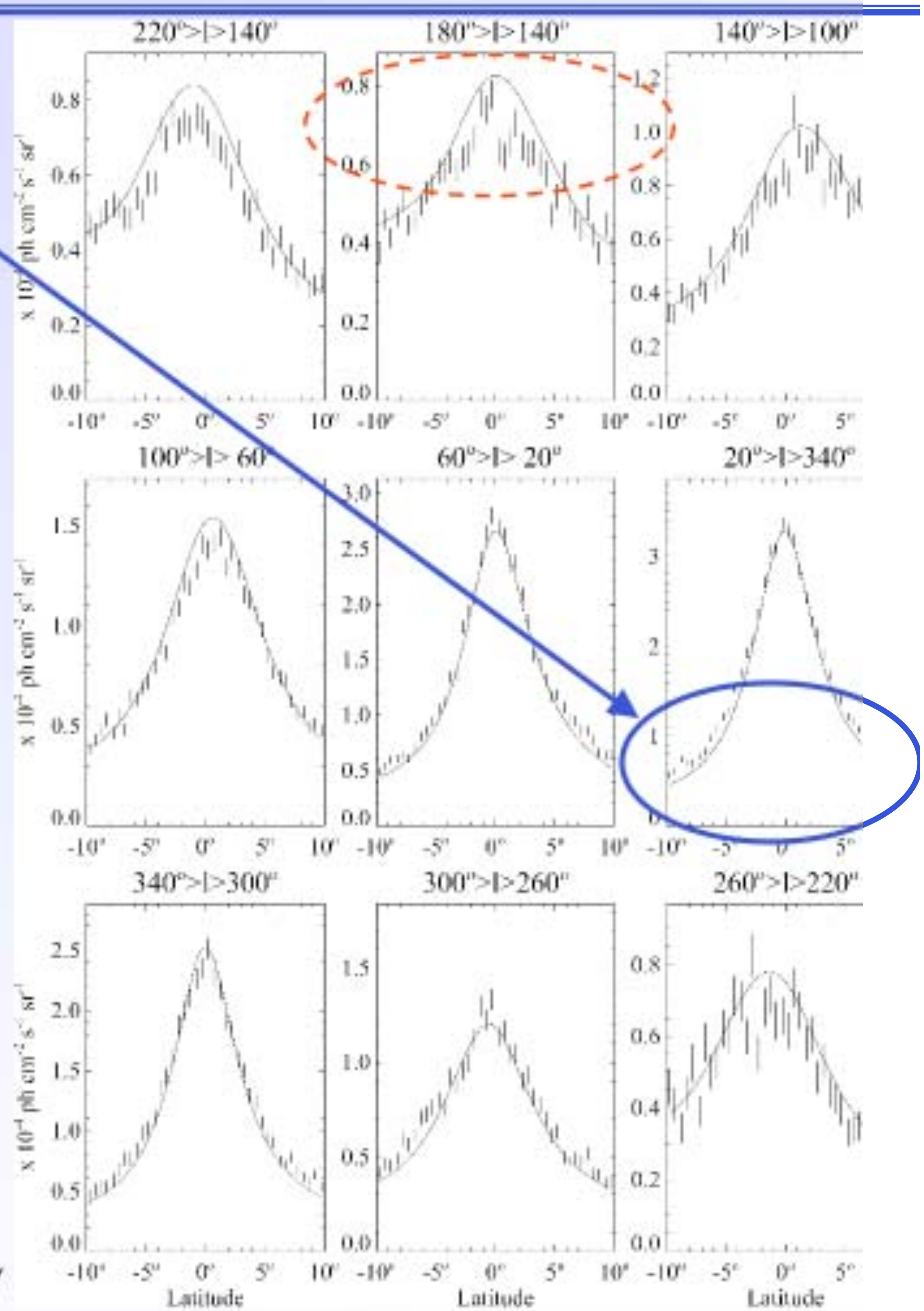


Spatial Discrepancies - 2

Under-prediction of the medium-latitude, ~3° < |b| < 35°, emission in the inner-galaxy

» The calculated emission in the inner-Galaxy is 10-20% lower than the observed emission. The agreement at these latitudes in the outer-Galaxy, however, is rather good suggesting an unmodeled spheroidal contribution to the Galactic center emission. Under-prediction of the inverse Compton emission is a possible source of this emission.

» Under-estimation of the cosmic-ray electron scale height (1 kpc) and/or the fall-off of the low-energy photon density perpendicular to the Galactic plane.



$E_\gamma > 100$ MeV

Spectral Discrepancy

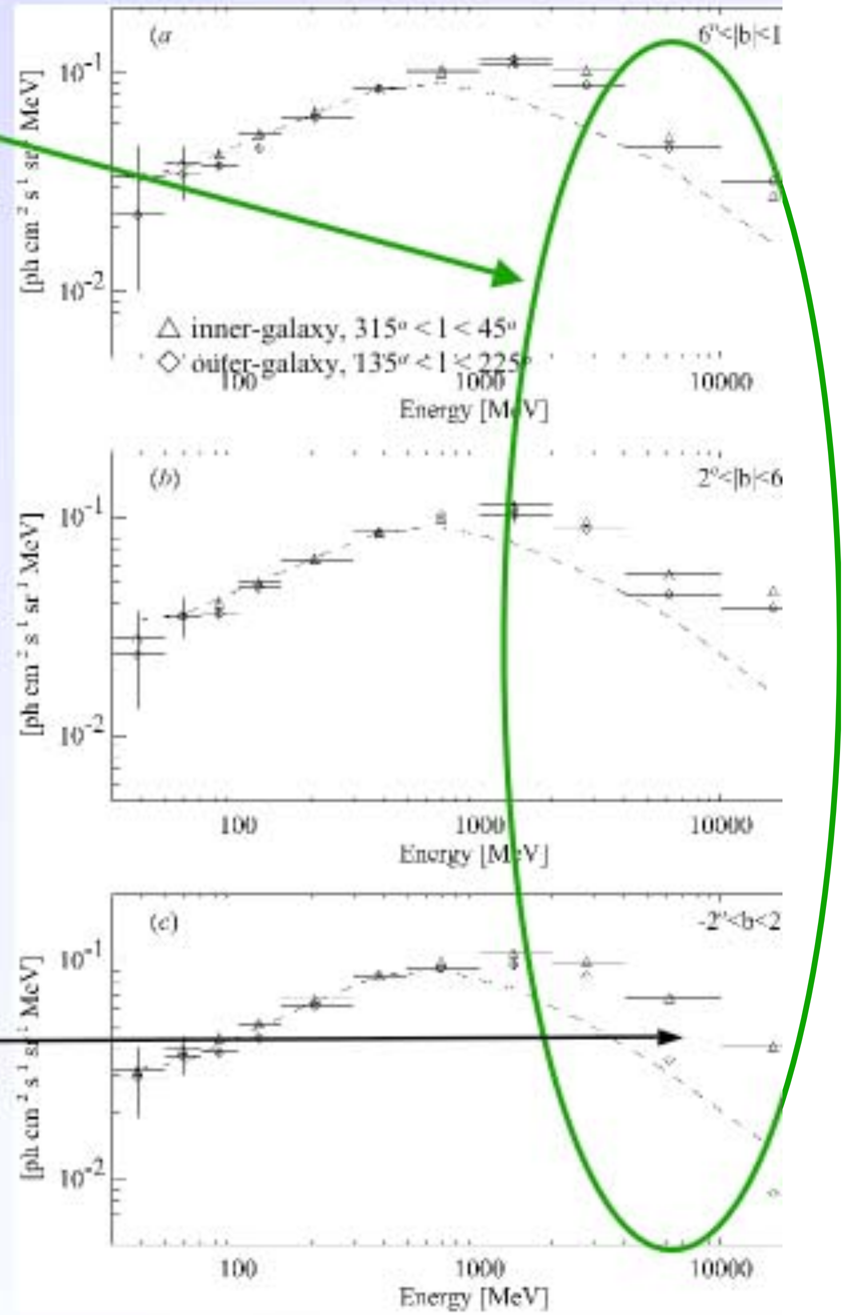
- High energy excess above ~1 GeV

  Possible explanations of excess

  Unlikely:
  - EGRET calibration error
  - π^0 production spectrum and/or and multiplicity in high-energy interactions may be wrong

  Possible:
  - Unresolved point source distribution
    - ♦ Similar to HI + H_2 distribution
    - ♦ Spectrum must have low-energy cut-off
  - Galactic average cosmic ray spectrum may be flatter than local spectrum

- However, there are hints of spectral variation with longitude and latitude



Conclusions - ISM & Galactic Structure

- Model based on dynamic balance is fairly accurate
  - Deviations from model are indicate that linear coupling assumption may break down in outer Galaxy
- Galactic halo emission
  - Scale height of CR electrons and/or low energy photon density has been underestimated
- Point source contribution appears to be small
- GeV excess is a mystery

What to do next?

- Incorporate new survey data
  - CfA CO survey - $|b| < 30°$, 8.7 arcmin resolution
  - Leiden-Dwingaloo HI (21 cm) survey, $\delta > -30^{o}$
  - IAR southern sky survey, $\delta < -25^{o}$
  - COBE ISRF data, improved low-energy photon model

- Investigate validity of EGRET model assumptions
  - Dynamic balance & *linear coupling* of cosmic-ray density to ISM
  - Constant HI spin temperature
  - Independence of *X*-factor on Galactic radius
  - Constant e/p ratio
  - Cosmic ray scale height
  - Point source contribution

LAT Observations

	GLAST	EGRET	Improvement
• $A_{eff}\Omega$	2.5×10^4 cm^2 sr	750 cm^2 sr	33×
• Exposure	8×10^{11} cm^2 s sr	3×10^8 cm^2 s sr	2700×
(Digel & Grenier, 2003)	1-yr scanning	average	

Improved spatial and spectral resolution

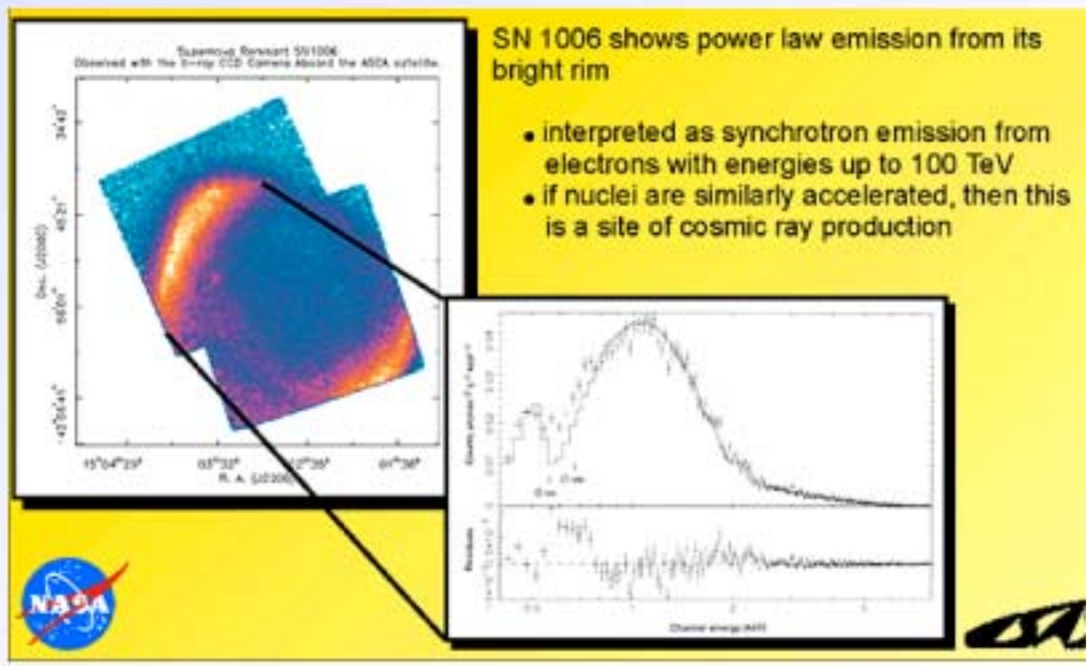
• Spatial bin	2 deg^2	40 deg^2	20×
• Spectral bin ($\Delta E/\langle E\rangle$)	~ 0.1-0.7	~ 0.4-2	3×
• Statistics	45	1	45×

ISM Science Goals

- Study diffuse emission on smaller spatial and spectral scales
  - Arm/inter-arm contrast/variations
  - Evidence of proton acceleration in SNRs
  - Different CR e- and p diffusion
- Confirm GeV excess
  - Latitude variations of GeV excess
- Point source contribution
  - Resolve the diffuse emission?
  - **SNRs as the source of cosmic rays?** →
- Study the medium- and high- latitude emission
  - Constrain the CR scale height
  - **Dark Matter Halo?** →
  - Extra-gal diffuse emission?

SNRs as the Source of CRs

- Diffuse emission can be used to deduce the distribution of the CRs after they diffuse
- The gamma-ray spectrum of SNRs interacting with nearby molecular clouds may indicate CR acceleration
- Electron acceleration
  - Evidence from X-ray measurements
- Protons acceleration -
  - Harder π^0 spectrum corresponding to accelerated proton spectrum
  - Visible only if there is a nearby molecular cloud ‘target’ and ‘favorable’ geometry

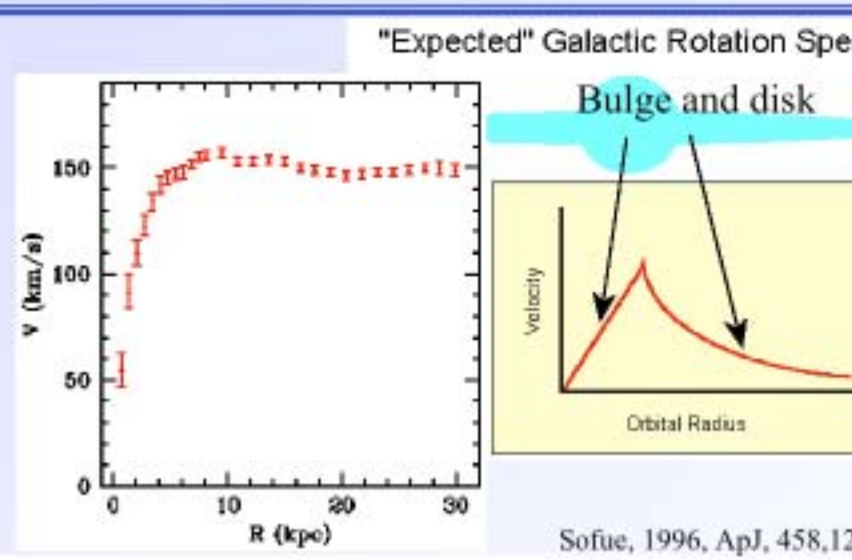


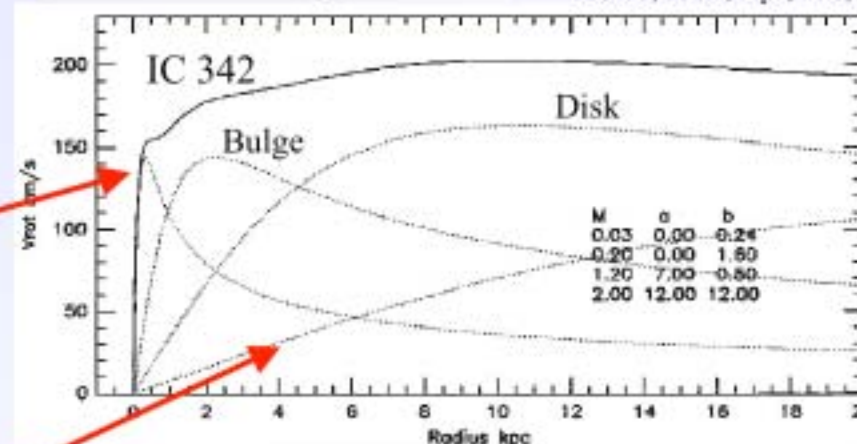
Dark Matter Halo

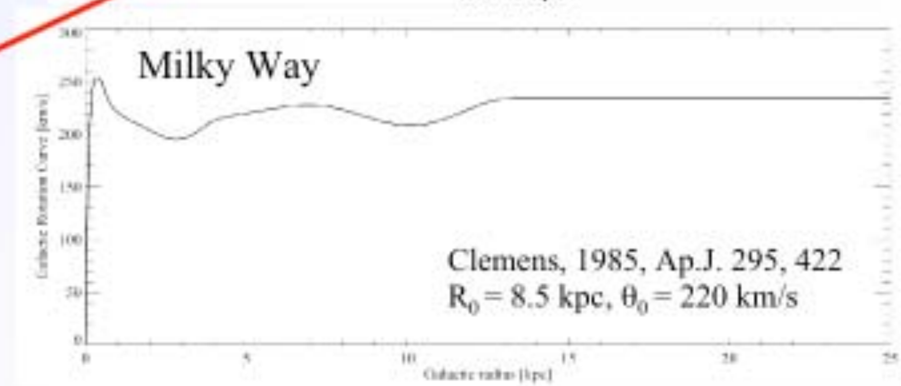
- Presence *inferred* from flat rotation curve
- $M(R) \propto R$, $\rho(R) \propto R^{-2}$ (for large R), spheroidal
- Composition is unknown
  - Red or brown dwarf stars unlikely
  - "Jupiters" or rocks possible, not dust
  - Black holes (remnants of Population III stars that made first metals)
  - Some elementary particle, WIMPS etc.
- Size? Filling factor? Feature of local group?
  - Galaxy clusters may have common halo
  - Evidence from high latitude HI cloud streaming motion (López-Corredoira, Beckman, & Casuso, 1999, A&A, 351, 920)
- Gamma-ray signature?
  - Depends on composition and cosmic ray density

Galactic Rotation Curve

- Observed rotation curve from visible matter (stars)
  - As "expected," gravitational and centrifugal forces are in balance, assume Keplerian rotation
- Derived rotation curve from ISM (gas) tracers
  - Tangent point analysis
  - Curve remains flat at large radii Can not assume Kepleriam rotation
- Gas and stars do *not* co-rotate ⇒ the mass of a galaxy is distributed differently than the visual matter
- Rapid rise at small radii
  - Add dense central core (confirmed by X-ray observations)
- 'Flat' rotation curve at large radii
  - Large dark matter halo, *unseen*, but may account for 90% of the total galactic mass
  - *Alternative hypothesis: magnetic-support*





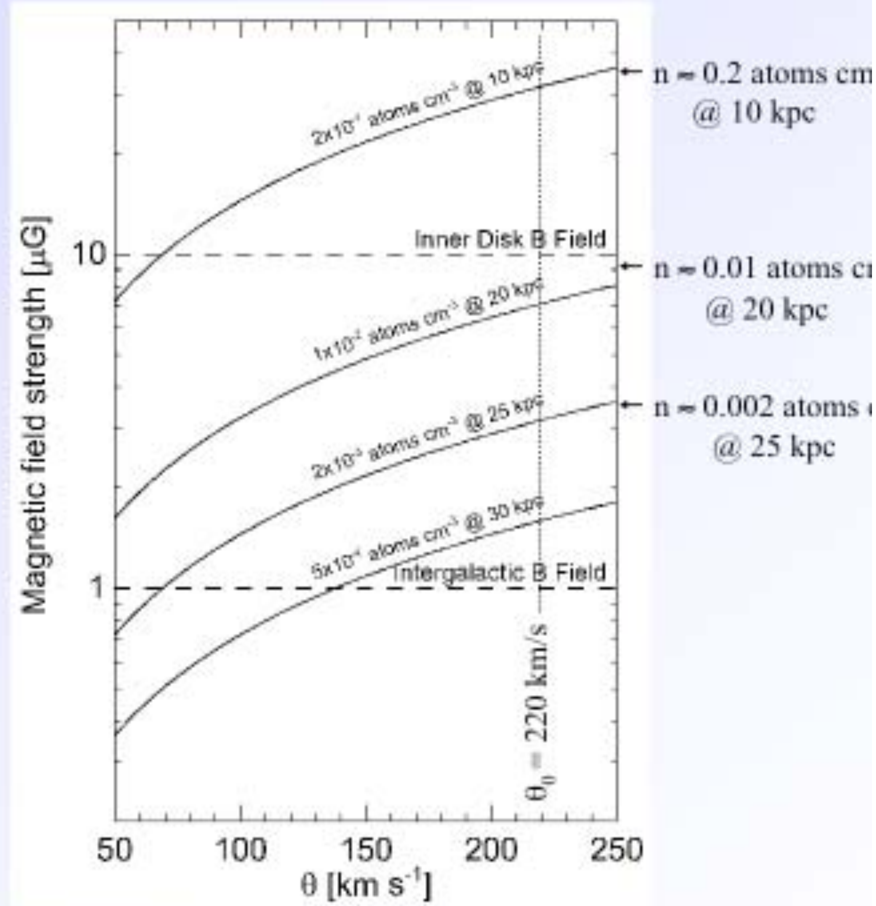


Is the Magnetic Field Ignorable?

- At large radii, gravity decreases as R^{-2}
- Magnetic fields evolve locally due to gas motions
- Evidence indicates ~10 μG fields in inner disk
- Evidence that ~1 μG fields exist in the intergalactic medium

  (See review of synchrotron radiation and its Faraday rotation by Kronberg, 1995, Nature 374, 404)
- At some radius, the kinetic and magnetic energy densities should be similar

$$\frac{1}{2}\rho\theta^2 \approx \frac{B^2}{8\pi}$$



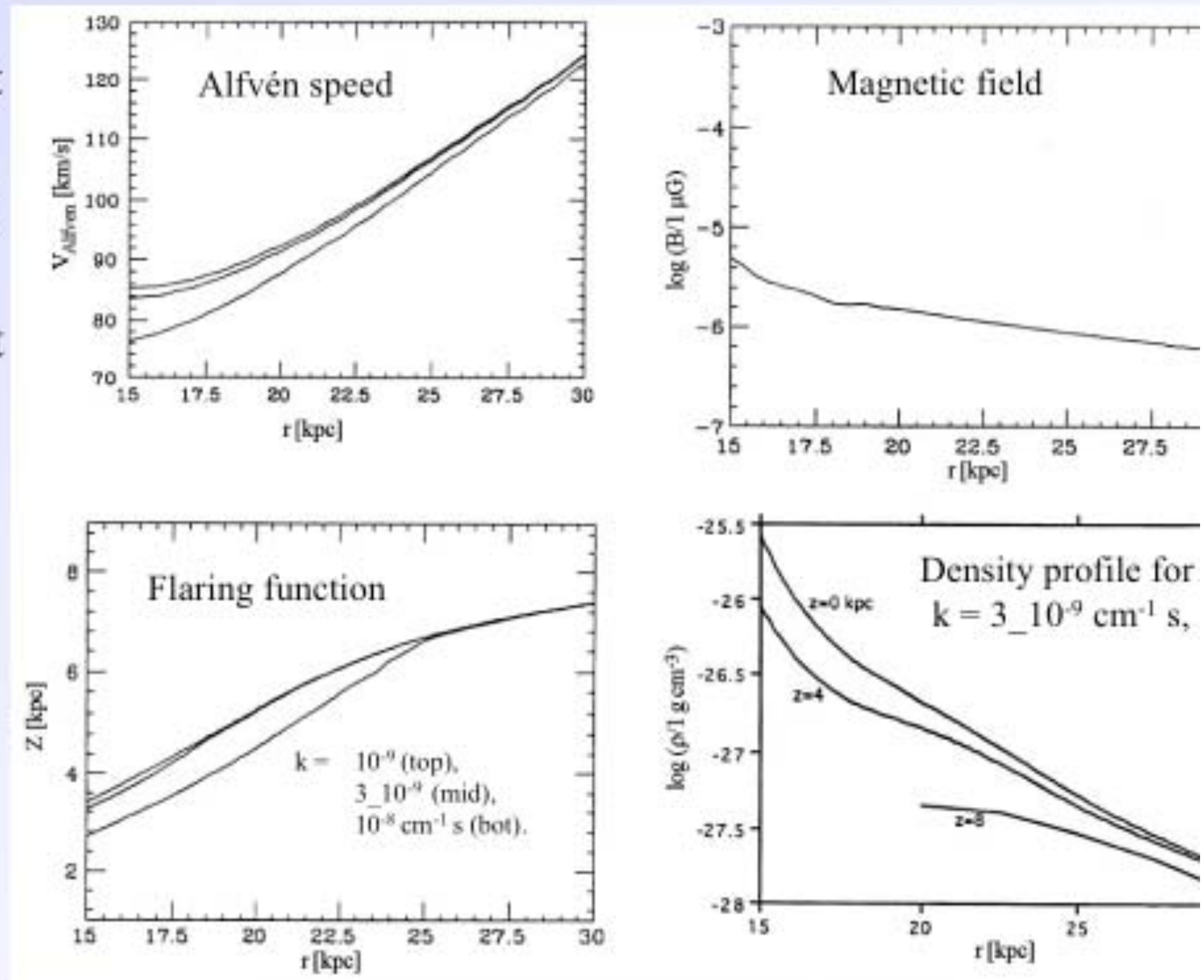
Adapted from:
http://nedwww.ipac.caltech.edu/level5/March01/Battaner/revision.html

- In the Milky Way, the magnetic field would be negligible at the Solar radius, important at 20 kpc, and dominant at the rim.

Magnetic-Support Hypothesis

First suggested by Nelson (1988, MNRAS, 261, L21) to explain the flat rotation curve

- Evidence that ~1 μG fields exist in the intergalactic medium (Kronberg, 1995, Nature, 374, 404)
- Battaner & Florido (1995, MNRAS, 277, 1129; Battaner et al. 1992, Nature, 360, 652)
  - Two-dimensional model (r, ϕ) with spiral magnetic field lines
  - Reasonable agreement with observed ~30° pitch angle and magnetically driven radial wind
  - Leads to larger flaring of HI at large R

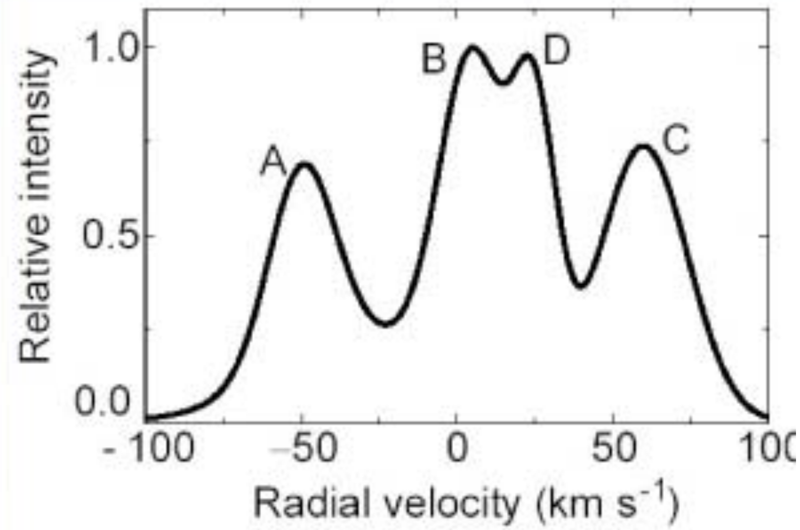


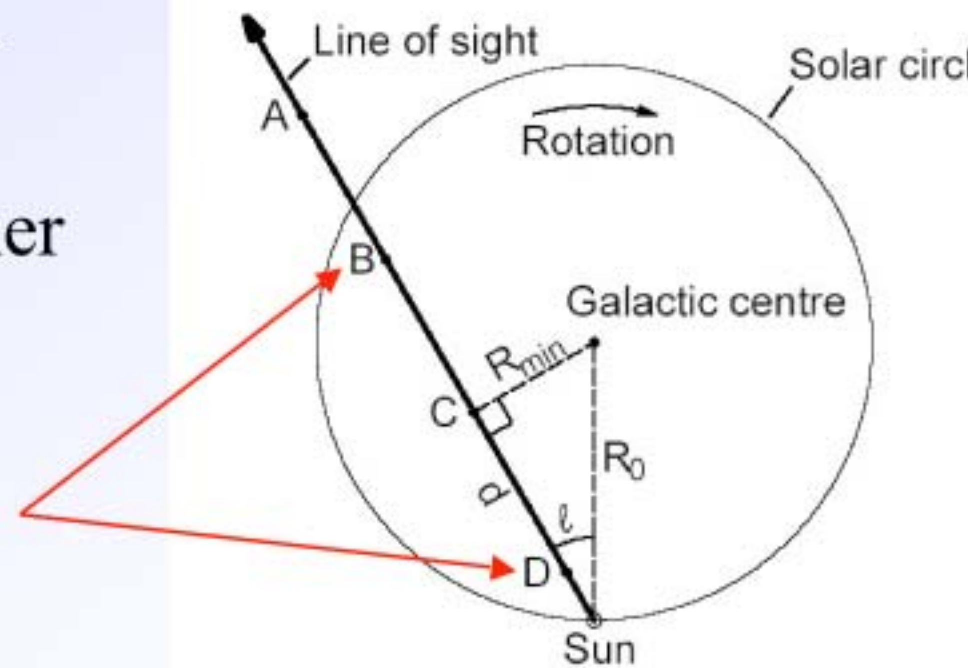
Conclusions

- GLAST will make several major steps towards our understanding c the structure of the ISM
- Study the diffuse emission on smaller spatial and spectral scales
  - Arm/inter-arm contrast/variations
  - Evidence of proton acceleration in SNRs
  - Different CR e- and p diffusion
- Confirm GeV excess
  - Latitude variations of GeV excess
- Point source contribution
  - Resolve the diffuse emission?
  - SNRs as the source of cosmic rays?
- Study the medium- and high- latitude emission
  - Constrain the CR scale height
  - Dark Matter Halo?
  - Extra-gal diffuse emission?

Kinematic Transformation

- Fundamental equation of galactic structure analysis
  $v_{lsr} = R_{\odot}[\Omega(R) - \Omega_{\odot}] \sin l$
  - If this function is known then distances along the line-of-sight can, in principle, be assigned to each measured velocity
- Near/far ambiguity in the inner Galaxy
  - Points B and D have the same apparent velocity





radio.astro.gla.ac.uk/a2ta/

Cosmic Rays and Matter Distribution

- Cosmic rays are Galactic, not universal (Sreekumar et al. 1992; 1993)
- The cosmic ray and magnetic fields are in a quasi-stationary state, *dynamic balance* (Parker 1969)
  - The CR pressure may not exceed the magnetic field pressure (Parker 1968) and appears to be close to the maximum
- The Galactic magnetic field is confined to the disk by the weight of the interstellar gas
- CRs (at least $< 10^{16\text{-}17}$ eV per nucleon) are bound to the lines of force and the lines of force are normally closed
- CR age, based on isotopic abundance, is slightly more than 10^7 years
  - Consistent with secondary abundance and Galactic matter density
  - Slow diffusion rate in magnetic field and small anisotropy
- ⇒ Energy density of the cosmic rays is larger where the matter density is larger on some coarse scale - ***Dynamic Balance***
- Unanswered questions:
  - *What is the CR/matter coupling scale? What is the vertical scale height?*

Model Assumptions - Cosmic Rays

- The cosmic-ray electron and proton spectra throughout Galaxy are the same as the local spectra, corrected for Solar modulation.
- The CR scale height is constant.
- The electron to proton ratio is constant and independent of b, and R_G i.e. $c_e = c_n \equiv c(l, \rho)$.
- The cosmic-ray density is derived on the assumption of ***dynamic balance***. Modeled by convolving the total matter surface density with a Gaussian whose width is r_0.

The **CR scaling length**, r_0, is the second free parameter in this model.
Best fit value is (1.76 ± 0.2) kpc

$$c(\rho, l, b) = \frac{\mu_{\mathrm{cr}}(r, l, b)}{\mu_{\mathrm{cr,\,local}}}$$

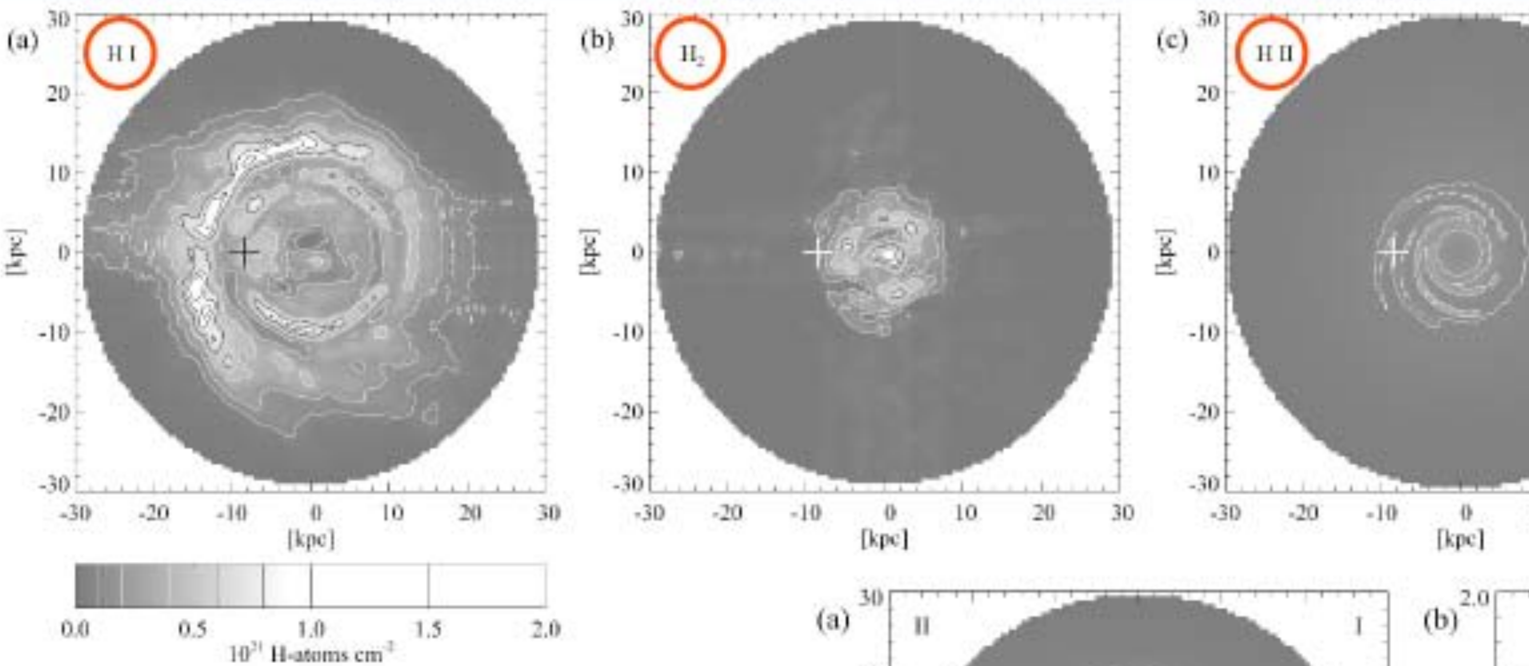
$$= \left[2\pi\, r_0^2 \int \mu_{\mathrm{m}}\, dz\right]_{\mathrm{local}} \iiint \mu_{\mathrm{m}}(r', l', z)\, dz \times \exp(-\zeta^2 / 2r_0^2)\, \zeta\, d\zeta\, d\psi$$

ISM & CR Density Distributions

Weaver & Williams, 1973; Maryland-Parks, 1986; Leiden-Green Bank, 1985

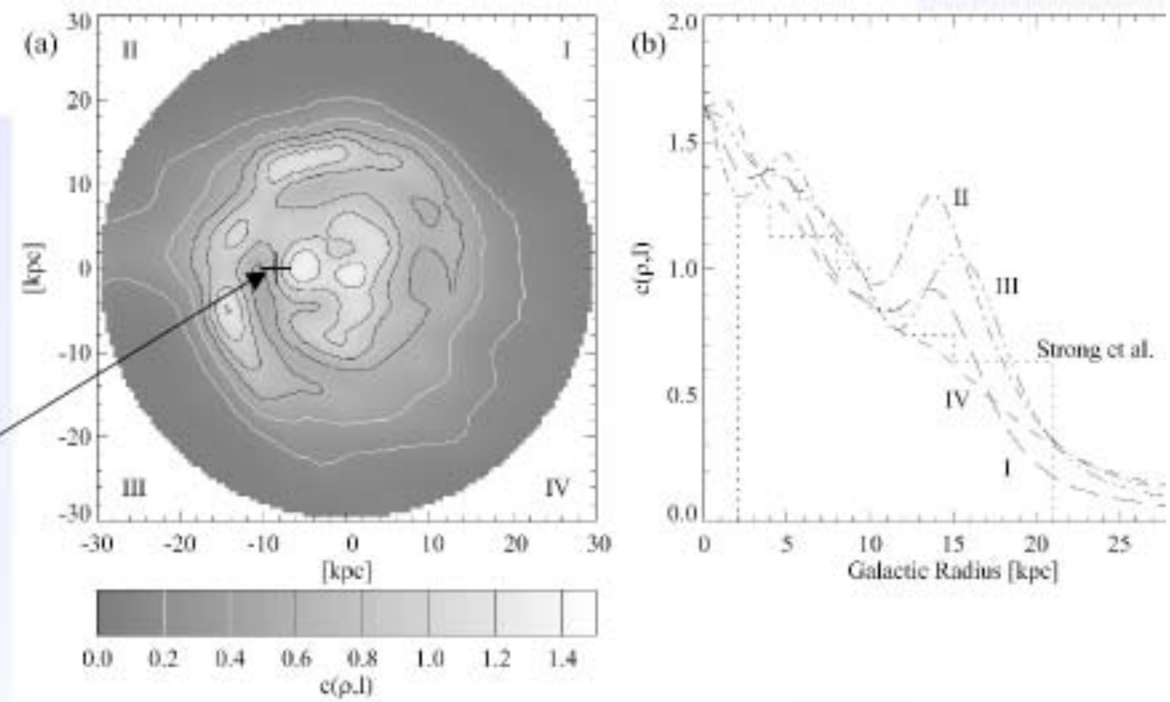
Dame et al. 1987

Taylor & Cordes, 1993

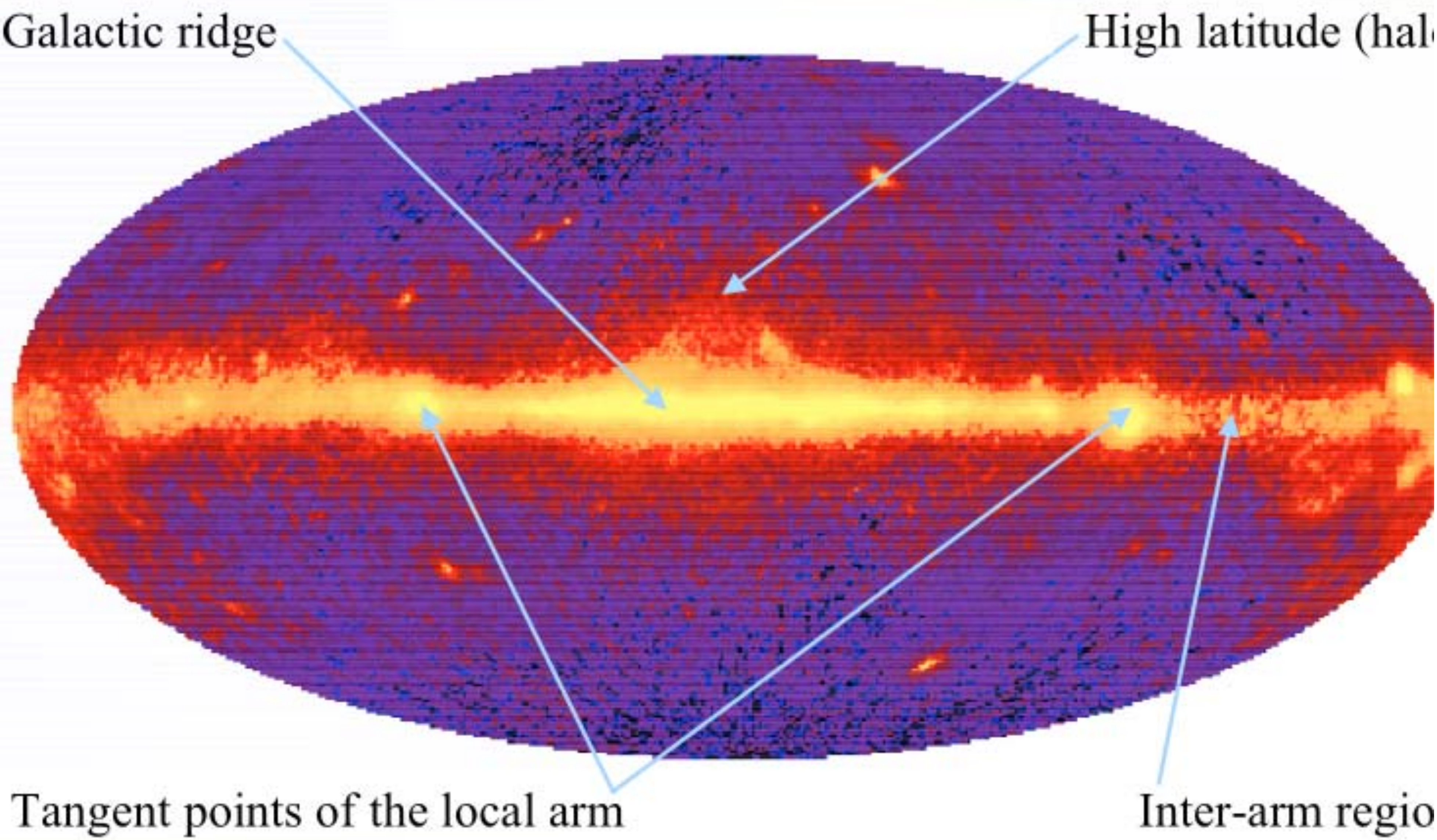


Cosmic-ray density relative to local density

Position of Sun indicated by cross

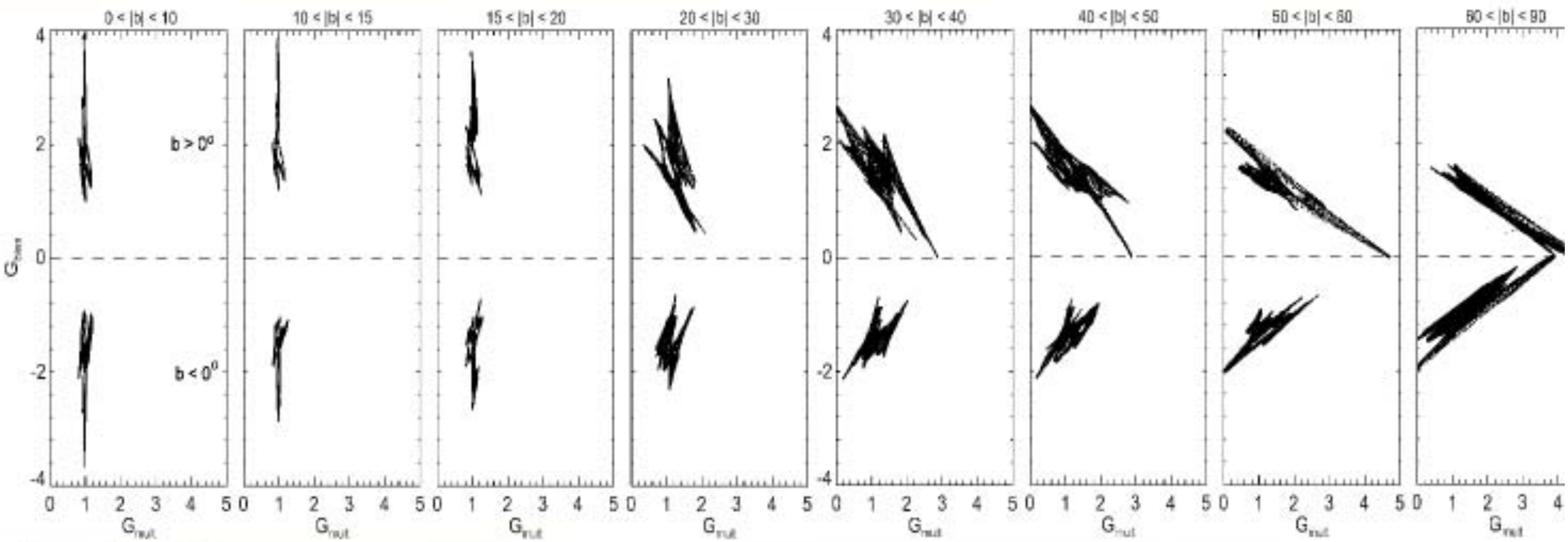


Large Scale Structure - $E_\gamma > 100$ MeV



Gmult and Gbias

- Maximum likelihood fitting parameters
  $I_{obs} = G_{mult} \cdot I_{model} + G_{bias}$
- Gbias ≡ Extra-galactic diffuse
- Gmult to 'correct' the diffuse model on scale of PSF
- Strong correlation at med- and high-latitudes



- Bosma (1978, 1981b) and Carignan et al. (1990)
  - General trend as well individual features for the gas distribution to have the same shape as DM distribution.
    This correlation between gas and DM has no easy explanation in the light of present CDM models.
- Inspired theory identifying dark matter with an as yet undetected dark gas.
- The magnetic hypothesis would provide another explanation, as the rotation curve is due in part to magnetic fields, which are generated by gas.

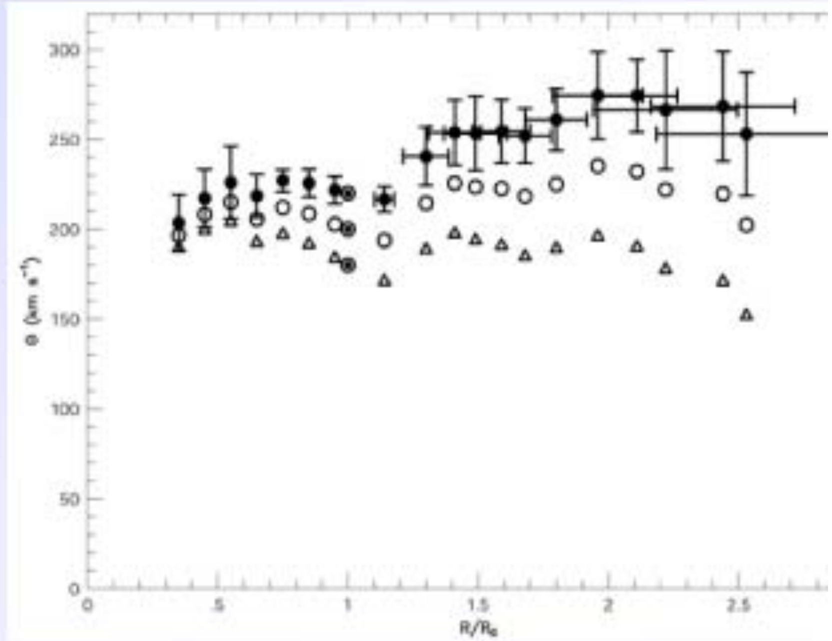
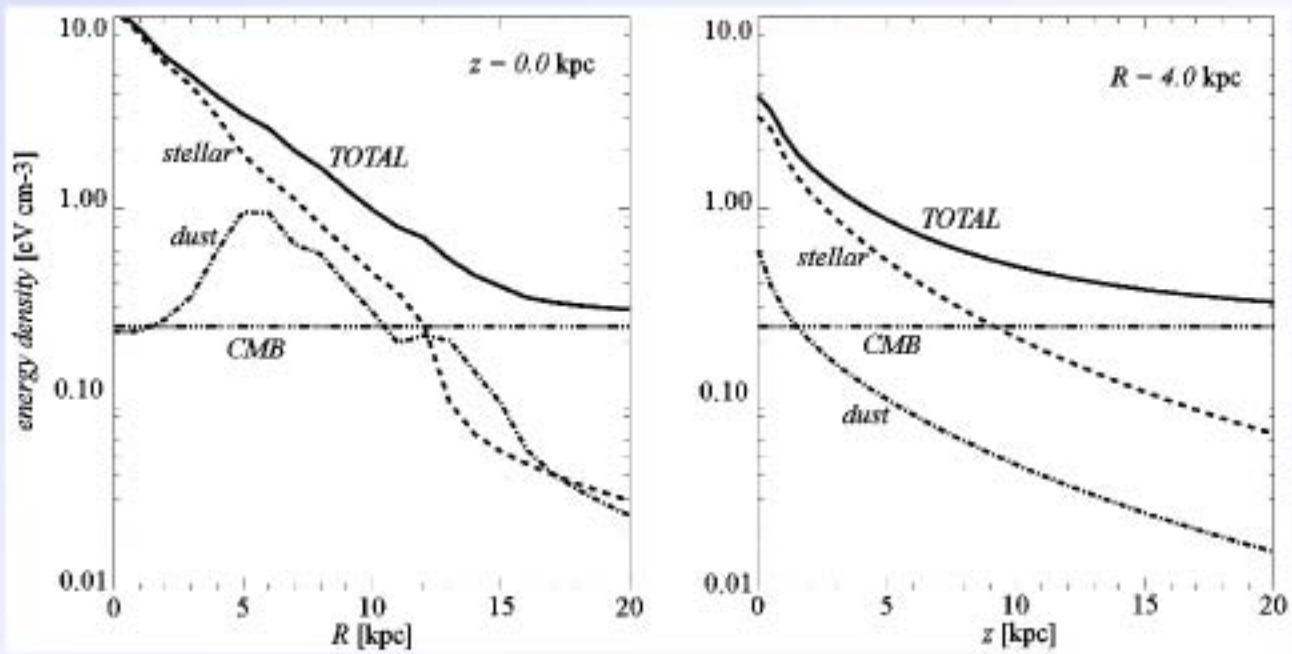


Figure 11. Overall rotation curves of the Galaxy for = 220kms-1 (filled circles), = 200kms-1 (open circles), and = 180kms-1 (open triangles). The data for the inr rotation curve were taken from Fich et al. (1989). The outer rotation curve are those obtained by Merrifield's method. The error bars are indicated only for = 220kms-1, and are almost the same for the three cases From Honma and Sofue (1997).

Model Inputs 1 - Radiation

- EGRET
  - Cosmic background radiation - 2.7 K, 0.25 eV cm^{-3}
  - Far-infrared radial distribution (Cox, Krügel, & Metzger, 1986)
    Assume exponential vertical distribution, scale height ~ 0.1 kpc
    Total luminosity normalized to 1.5 x 10^{10} L_{sun}
  - Near-infrared, optical, and ultraviolet (Chi & Wolfendale, 1991)
- More recent work by Strong, Moskalenko, & Reimer (2000)



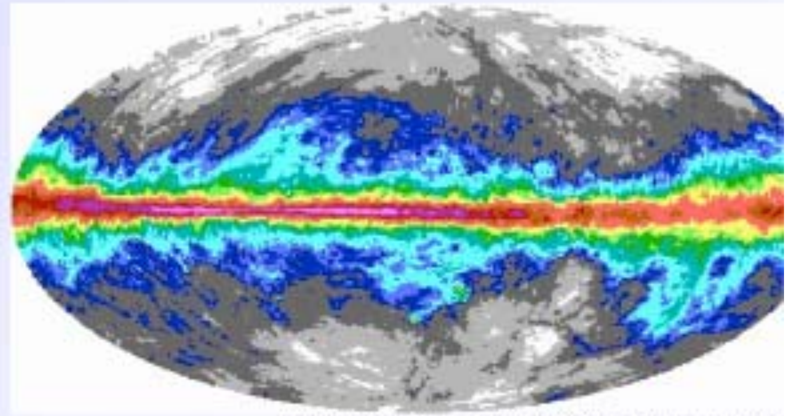
Model Inputs 2 - HI, H_2, and HII

- **Atomic hydrogen** column density is derived from the optical depth using uniform spin temperature, $T_s = 125$ K.

$$N_{HI}[v(i+1),v(i)] = (1.83\times10^{18}) \int_{v(i)}^{v(i+1)} T_S\,\tau(v)\,dv$$

where $\tau(v) = -\ln[1 - T_B(v)/T_S]$

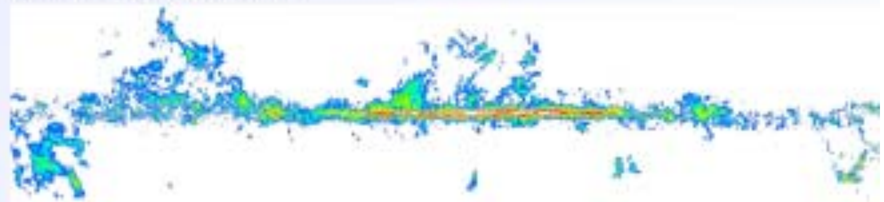
and T_B is truncated at 119 K



www.iar.unlp.edu.ar/ES/imagenes-astron.

- **Molecular hydrogen** column density derived from

$$N_{H_2}[v(i+1),v(i)] = X \int_{v(i)}^{v(i+1)} T_B(v)\,dv$$



cfa-www.harvard.edu/cfa/m

The **molecular mass calibrating ratio**, $X = N(H_2)/W_{CO}$, is the first of the two free parameters in this model. Best-fit value is $(1.56 \pm 0.05)\times10^{20}$ mol cm^{-2} (K km s^{-1})$^{-1}$.

- **Ionized hydrogen** is modeled using fitted distribution of Taylor & Cordes (1993). HII contribution is small compared to HI and H_2