Fermi
Gamma-ray
Space Telescope

Diffuse emission as seen by the LAT

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Outline

- Introduction
- Interaction processes
- * • Targets: Interstellar medium and the ISRF
- Modeling the diffuse emission – why and how
- Examples of results for local clouds
- Some results from large-scale modeling and GALPROP
- New components of the diffuse emission
- Isotropic diffuse analysis
- Practical advice
- Open issues

Living with diffuse emission

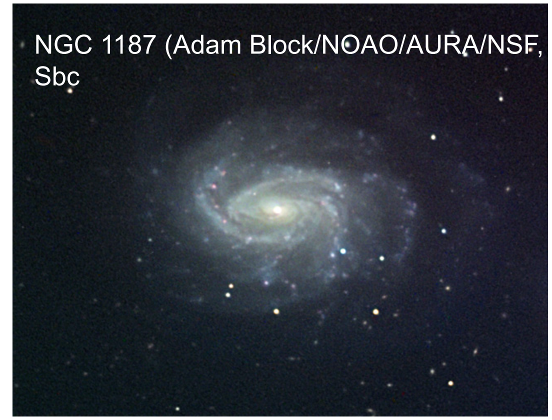
- **In the GeV range, if you don't care about the diffuse emission as a diagnostic tool, you might want to care about having it modeled accurately anyway**
  - **Discriminate between point sources and interstellar emission***
  - **Get coordinates correct for sources**
  - **Accurately measure the extragalactic component**

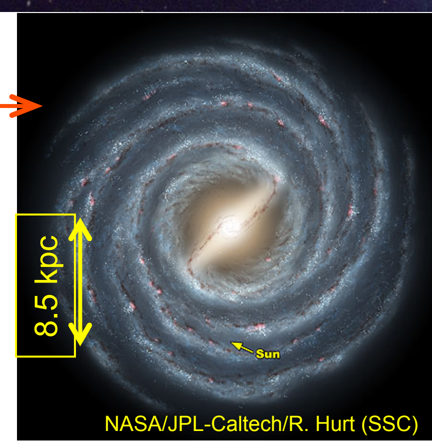
* Long history of misidentifying diffuse emission features as point sources, starting with the COS-B catalog; the LAT 2FGL catalog has a number of sources flagged

Milky Way as a γ-ray source

- The best galaxies (short of starbursts, merging galaxies) for diffuse γ-ray emission are massive spirals, probably barred
  - To have CRs in the first place in a galaxy you want to have interstellar gas to form massive stars out of
  - And you want the galaxy to keep its CRs

- Milky Way: A large SBbc spiral galaxy
- Semi-idealized diagram of Milky Way - don't take this too literally
- From an in-plane perspective tracing arms, gas distribution, CR sources in far side is hard

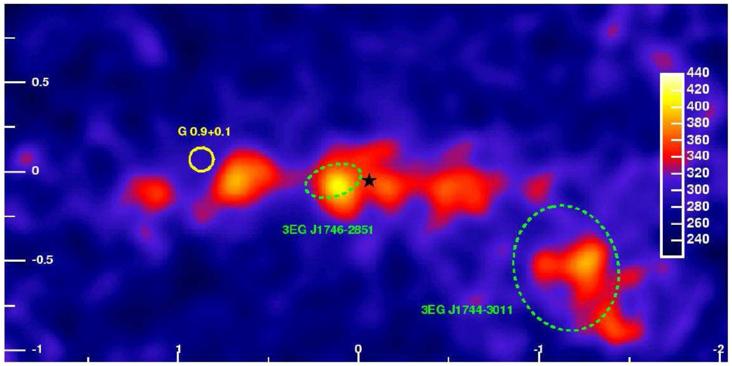


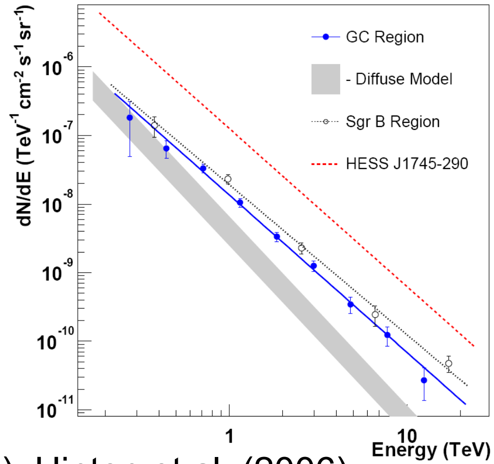


N.B. *GeV* diffuse emission

- **Although the central energy range for the LAT is blessed with bright diffuse emission – *other gamma-ray energy ranges have to do without***
- **At lower energies, INTEGRAL has resolved much of the emission into point sources (although a diffuse continuum probably remains below 1 MeV)**
- **At higher energies, point sources also dominate over diffuse emission, or nearly so**
  - **For H.E.S.S., diffuse emission is seen only in the Galactic Center (and after point-source removal)**

* H.E.S.S. would not have seen diffuse emission if the CR spectrum were not more intense and harder in the G.C. than locally
N.B. TeV electrons do not diffuse far, ~200 pc



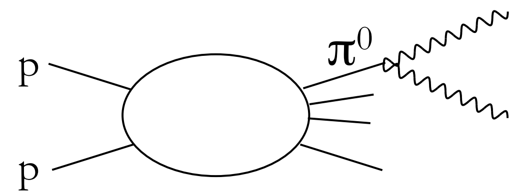


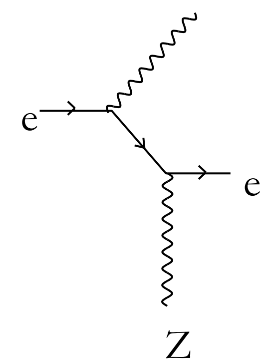
Aharonian et al. (2006); Hinton et al. (2006)

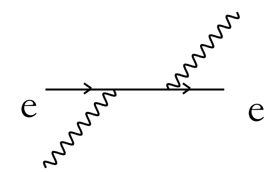
Production mechanisms for high-energy γ-rays

- **π^0 decay – secondaries from CR proton-nucleon collisions [peak at $M_{\pi^0}/2$, $\Gamma_\gamma \sim \Gamma_p$, $E_\gamma << E_p$]**
- **Bremsstrahlung – scattering of CR electrons by protons/nuclei [$\Gamma_\gamma = \Gamma_e$, $E_\gamma <\sim E_e$]**
- **Inverse Compton scattering of low-energy photons by CR electrons [$\Gamma_\gamma = (\Gamma_e + 1)/2$, $E_\gamma << E_e$]**

- **The nuclei that matter are in interstellar gas – stars do not have a large filling factor and also absorb the great majority of γ-rays produced by CR interactions**







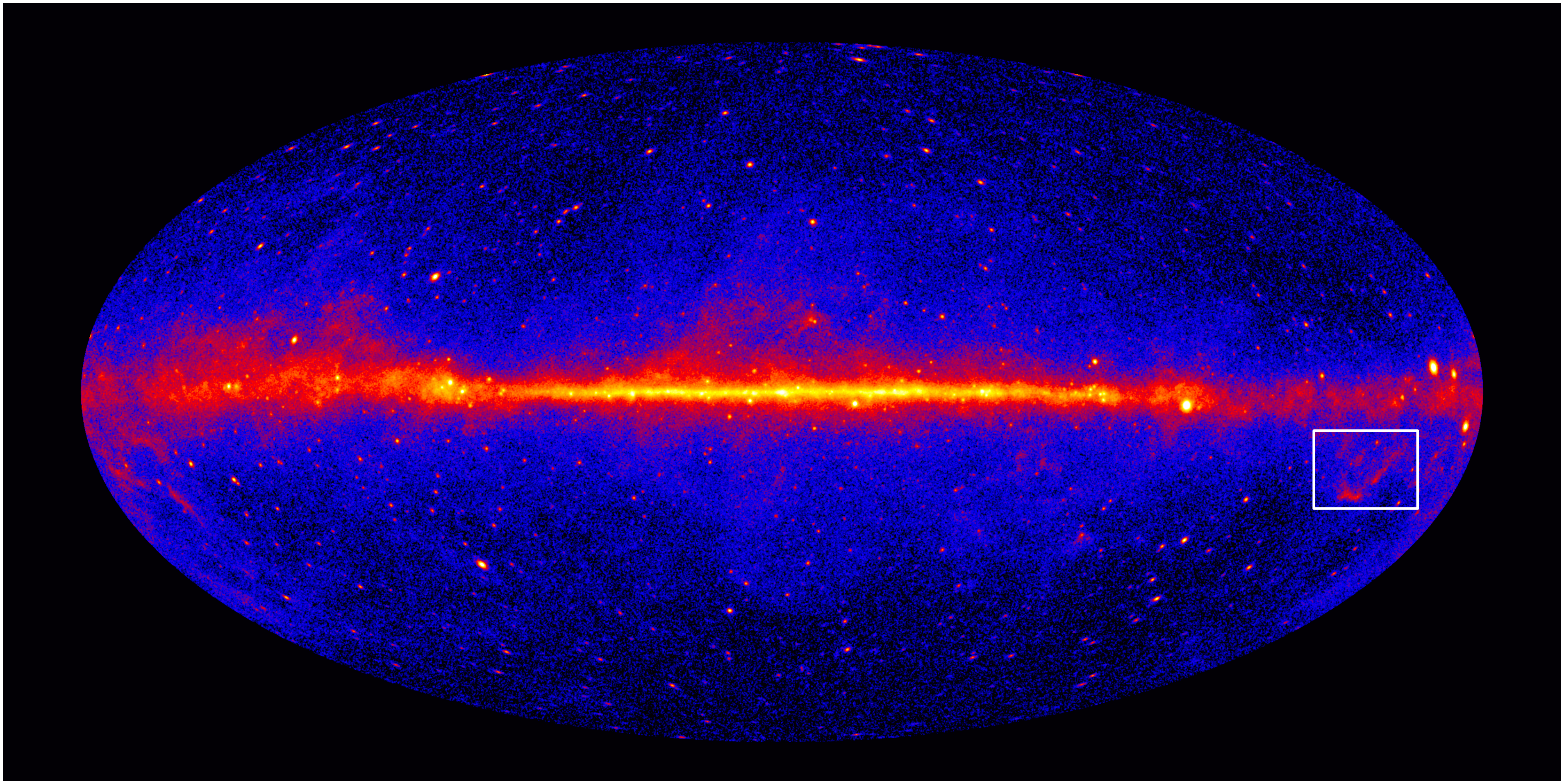
I will treat the physics as understood and gamma-ray production functions as known; for π^0 decay there are a lot of details like nuclear enhancement factors

Components of an interstellar emission model

- Cosmic rays
- Interstellar gas (molecular, atomic, and ionized)
- Interstellar radiation field
- *Difficult or impossible to get unique answers for any of the above*

- At least radiative transfer is simple for gamma rays
- Different approaches for modeling depending on what you want to learn from the data

The LAT Sky

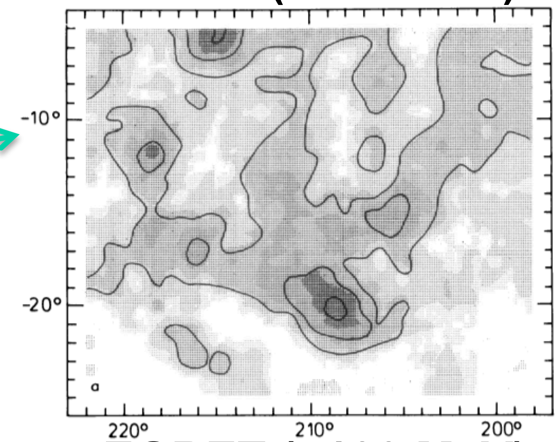


>1 GeV for three years

LAT diffuse emission in perspective

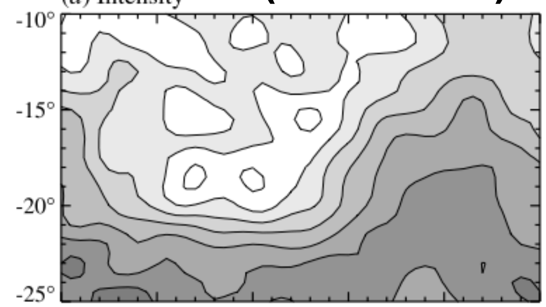
- **History of the observations**
  - Orion A&B as an example
  - Exposures are much more uniform with the LAT as well
  - Radio and mm surveys of the gas have improved markedly as well

COS-B (>100 MeV)



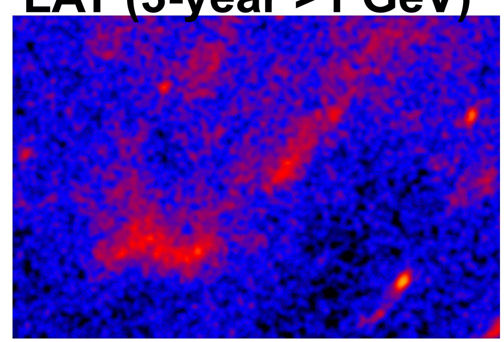
Bloemen et al. (1984)

EGRET (>100 MeV)



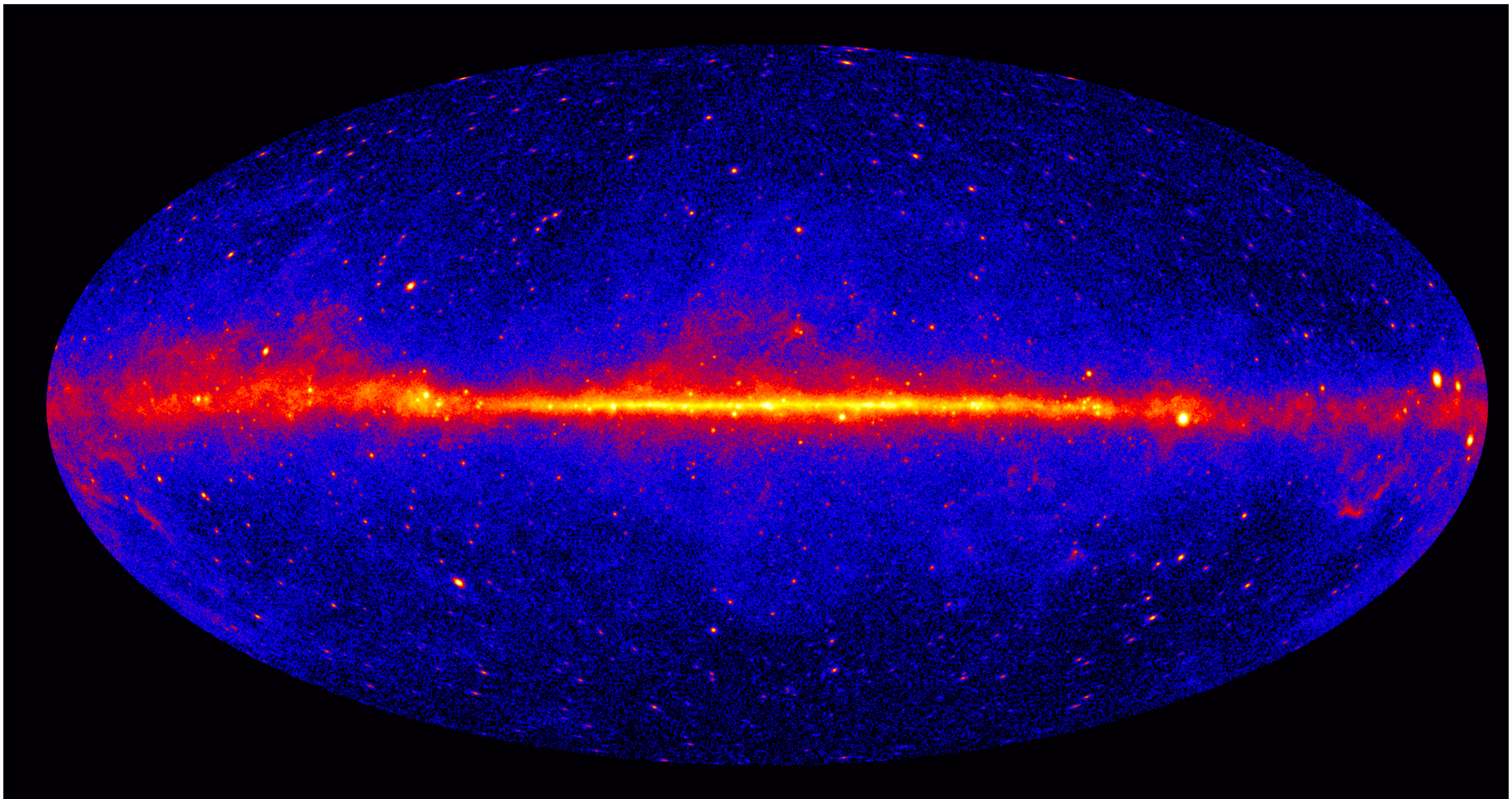
Digel et al. (1999)

LAT (3-year >1 GeV)



(Approx., cropped from the sky map)

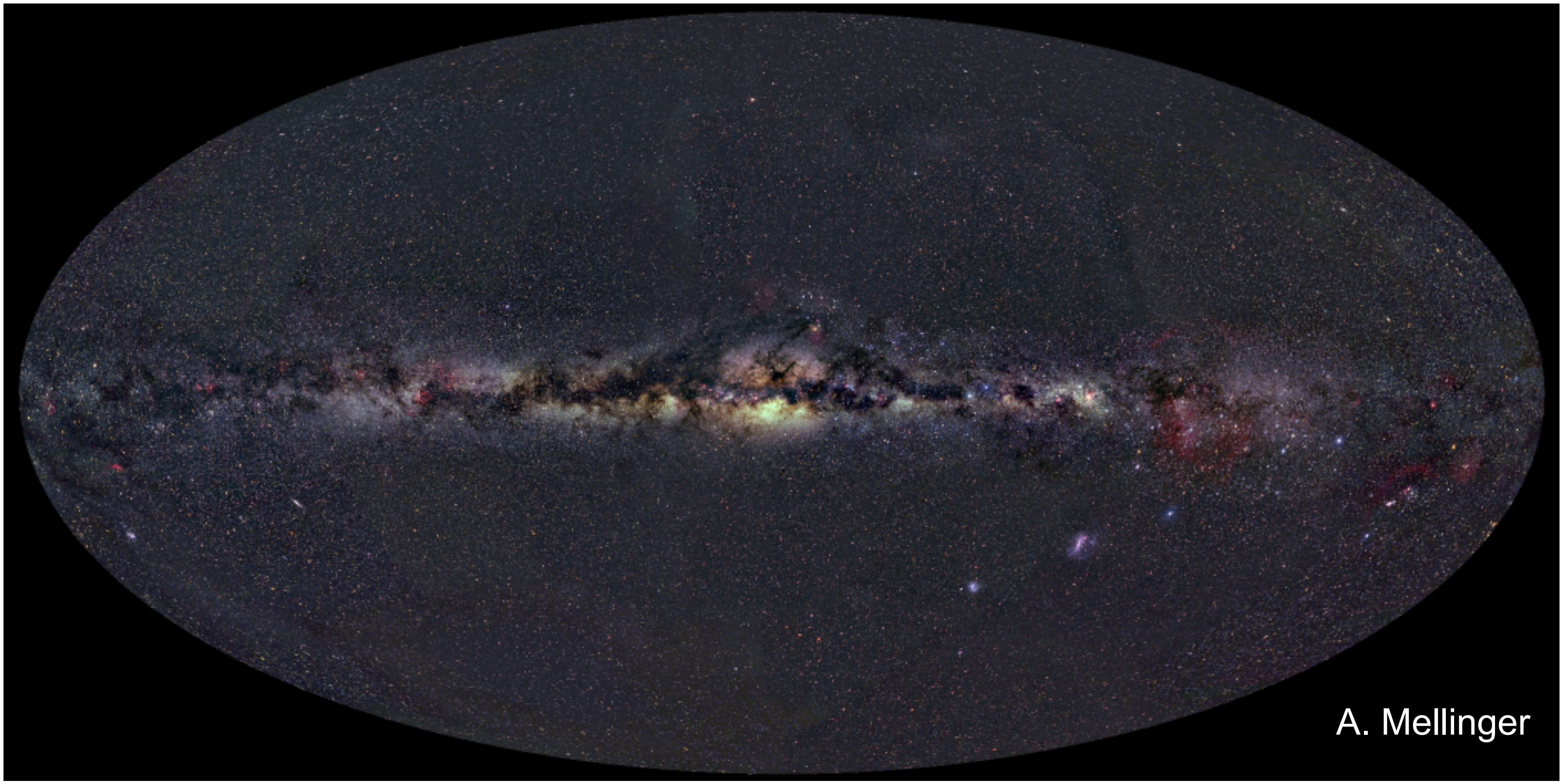
The LAT Sky Again



>1 GeV for three years

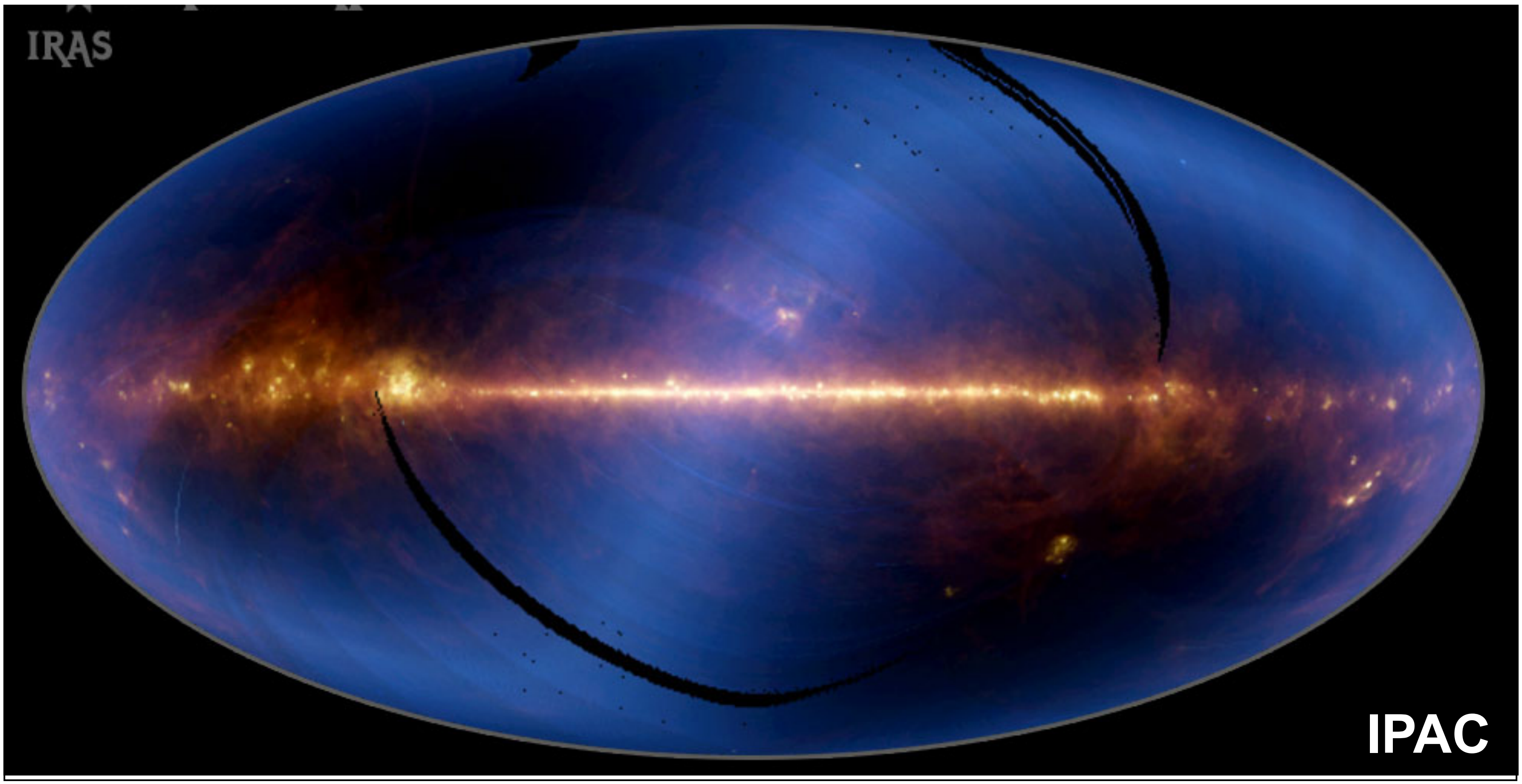
Interstellar clouds?

- **Interstellar clouds are not literally clouds but appear as dark nebulae or 'clouds' against the Milky Way**



Why are the clouds dark?

- **What we see (in absorption) is the interstellar *dust***



25-60-100 µm

Neutral interstellar medium

- The neutral interstellar medium is gas mixed with dust; associations of gas, especially dense ones, are referred to as clouds – which doesn't meaningfully help for understanding them
- Overall, most of the mass of the interstellar medium is atomic hydrogen*
  - The densest component of the neutral medium is primarily H_2
  - This is where stars (OB assoc., SNR, pulsars, XRB, …) form

- The gas is very, very cold (few K to 10s of Kelvin) and very, very tenuous (10^3 cm^{-3} is a *high* density)
  - 10^3 H_2 molecules cm^{-3} at 5 K corresponds to a pressure of 10^{-13} torr, much lower than can be achieved in the laboratory
- They are quite unlike atmospheric clouds in other ways
  - To the extent that they are stable, they are (sort of) self gravitating, with important magnetic support
  - They are huge and massive – largest ~100 pc and ~10^6 M_{sun}.

* He makes up 21% by mass of the ISM and is assumed to be in proportion to the H

Atomic hydrogen

- Directly detected via the 21-cm hyperfine (spin flip) transition
- H I is pervasive in the Milky Way – you cannot find a direction in the sky with less than 6×10^{19} cm^{-2} column density (Lockman Hole)
- It is also generally optically thick (and self absorbing)
- The optical depth correction is important and cannot be done precisely – historically in studies of diffuse gamma-ray emission this was not always appreciated (by, e.g., me)
  - The standard approach had been to assume a spin temperature of T_S = 125 K

Brightness temperature (intensity) of the line at velocity *v*

$$N_{\mathrm{HI}}(v, T_S) = -\log\left(1 - \frac{T_B}{T_S - T_{bg}}\right) T_S C \Delta v$$

Brightness of the CMB at 1.4 GHz

1.83×10^{18} cm^{-2} km^{-1} s

Molecular hydrogen in the ISM

- It is hard to see
  - H_2 has no dipole moment, and so no rotational spectrum.
  - The lowest vibrational bands are a few 1000 K above ground and is not directly detectable under ordinary interstellar conditions
- For various reasons, CO ought to be at least an ok tracer of H_2
  - CO is the 2nd most abundant molecule (~10^{-5} H_2), but it does have a permanent dipole moment (0.1 Debye or so) and the lowest excited rotational level (J = 1) is only ~5 K above ground
  - Conditions for their formation and destruction are similar, and collisional excitation is well matched to conditions of molecular clouds

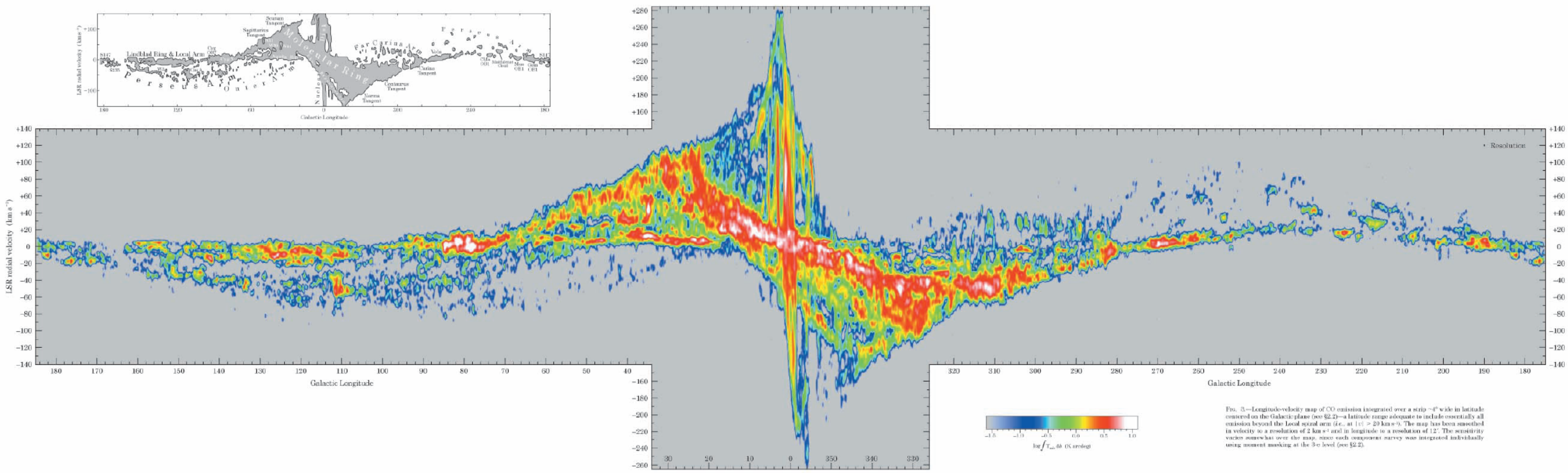
CO as a tracer of molecular clouds

Dame/Mellinger

- However, CO is certainly optically thick (*=bad news for a mass tracer*; in principle you measure its temperature rather than its column density)
- The relationship between *W*(CO) and N(H_2) obviously needs to be calibrated indirectly
  - Various ways, including γ-rays, suggested a proportionality
  - The 'standard' value of N(H_2)/*W*(CO) is ~2 x 10^{20} cm^{-2} s^{-1} (K km s^{-1})$^{-1}$, and of course it is not a physical constant of Nature

Distribution of CO in velocity

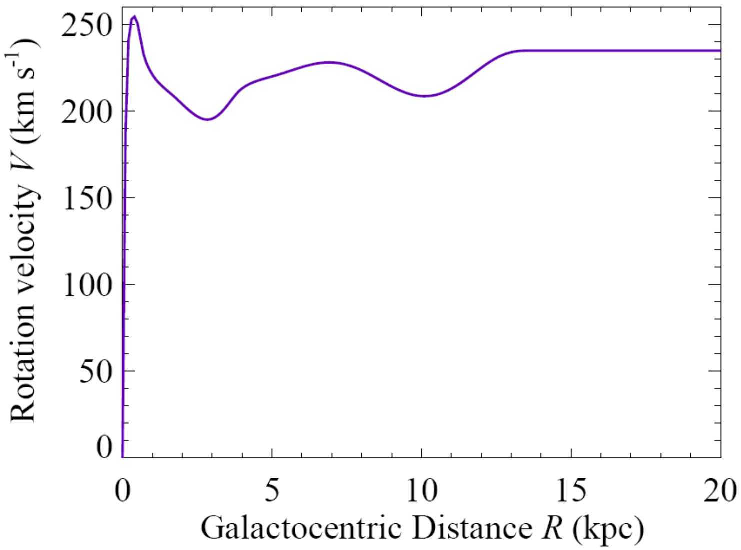
- **Dame, Hartmann, & Thaddeus (2001) composite survey**



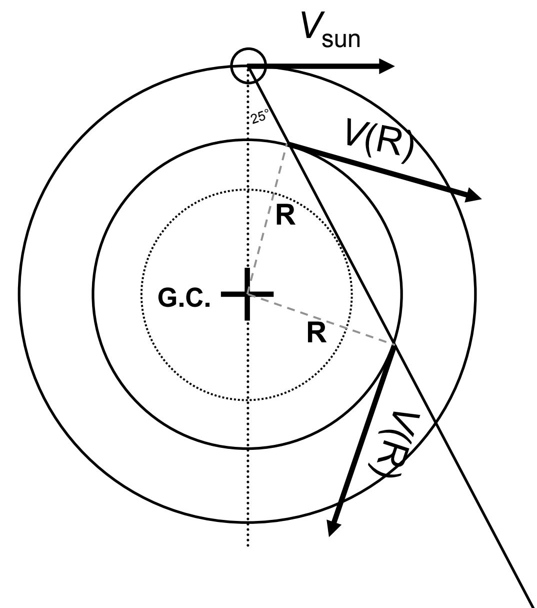
- **Notice that you can infer the sense of Galactic rotation, you can see (some spiral arms), as well as the molecular ring (and the molecular hole), and clear evidence of non-circular motions**

Distribution of interstellar gas

- **Rotation curve *V*(*R*), Near-far distance ambiguity, …**



Rotation curve of Clemens (1985) based on CO tangent point observations continued beyond the solar circle with Blitz, Fich, & Starck (1982) observations of H II regions; the curve has been scaled to Rsun = 8.5 kpc.

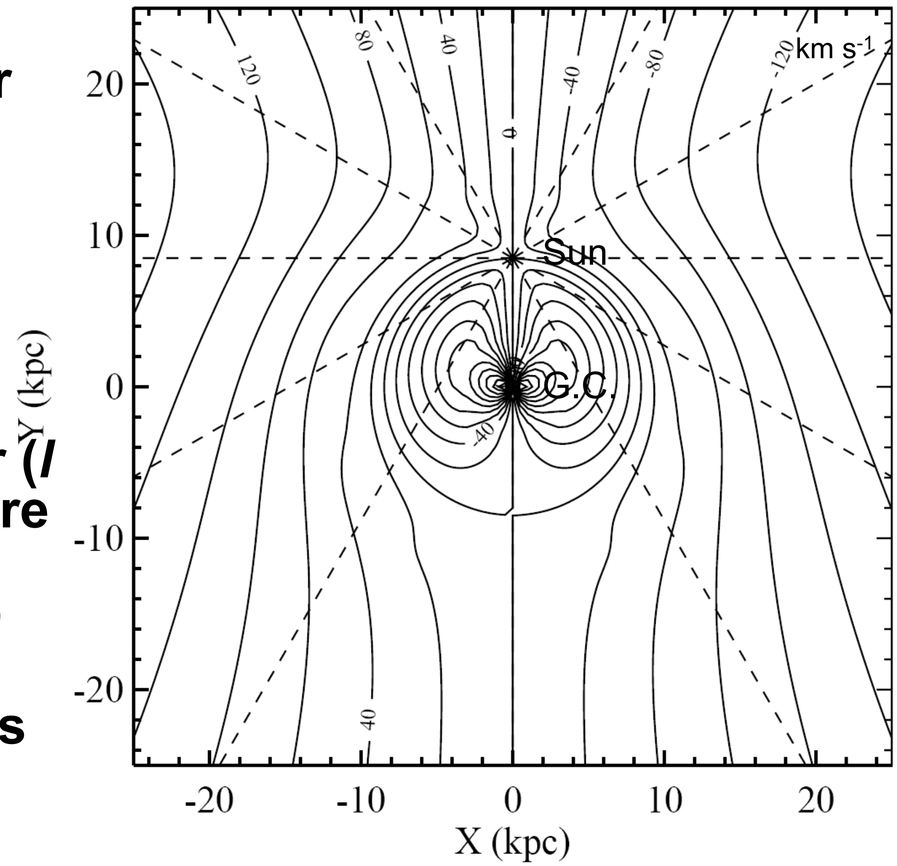


$$V_{LSR} = (V(R)/R_o - V_{sun}/R_o)\, R_o \sin l$$

Line-of-sight velocity vs. position

- Kinematic distances are double-valued within the solar circle (the orbit of the sun)
  – Except at the terminal velocity (which traces out the 'locus of subcentral points')
- Within about 10-15° of the Galactic center and anticenter (l = 180°), kinematic distances are useless (lines of sight are parallel to the 0 km/s contour)
- At large Galactocentric distances, kinematic distances also become useless (lines of sight are parallel to some contour of velocity)*

Mapping V_{lsr} to position



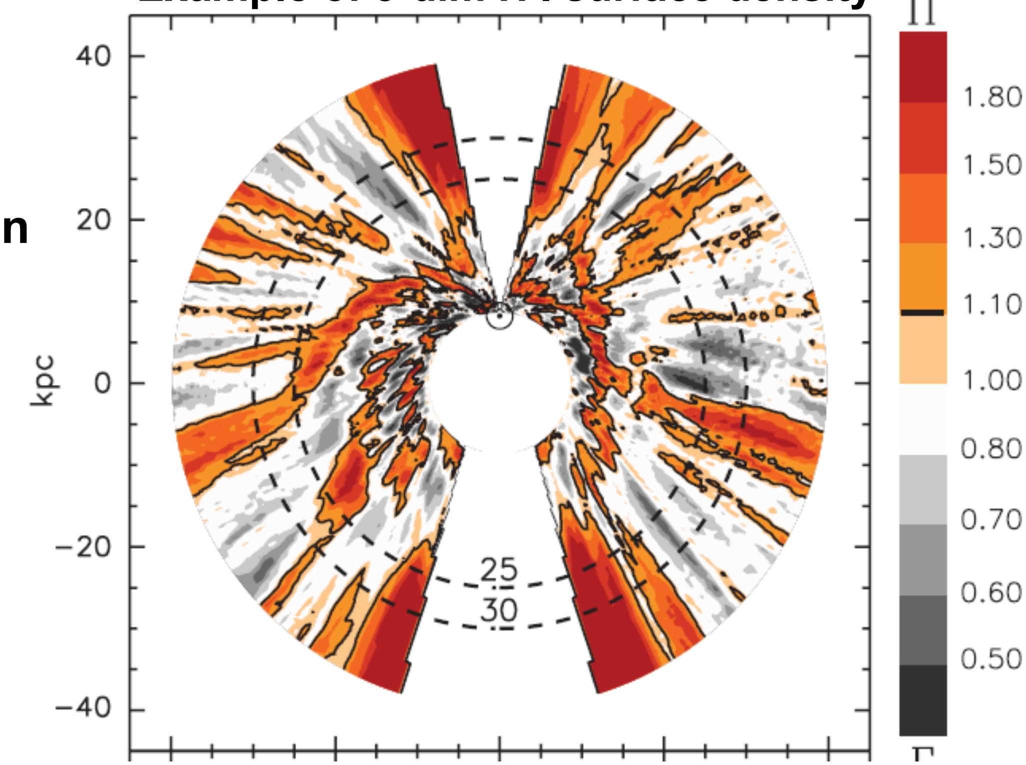
The specific details of the contours of course depend (somewhat) on the rotation curve used

* Loss of kinematic distance resolution can be thought of as amplifying small deviations from circular motion
Exercise for you: Make a map of dv/ds, line-of-sight velocity gradient

Why we don't have 3-dim gas distributions

- A velocity-to-distance algorithm together with a large-area H I or CO survey leads to the temptation to derive thee 3-dim distribution of gas across the Milky Way
- Automatic procedures to resolve the ambiguity ***don't work very well***
- For example, systematic noncircular motions, especially in regions with poor kinematic distance resolution were early (late 1950s) recognized to produce 'fingers of God' pointing at us (Bok)
  - ***They still do***

Example of 3-dim H I surface density

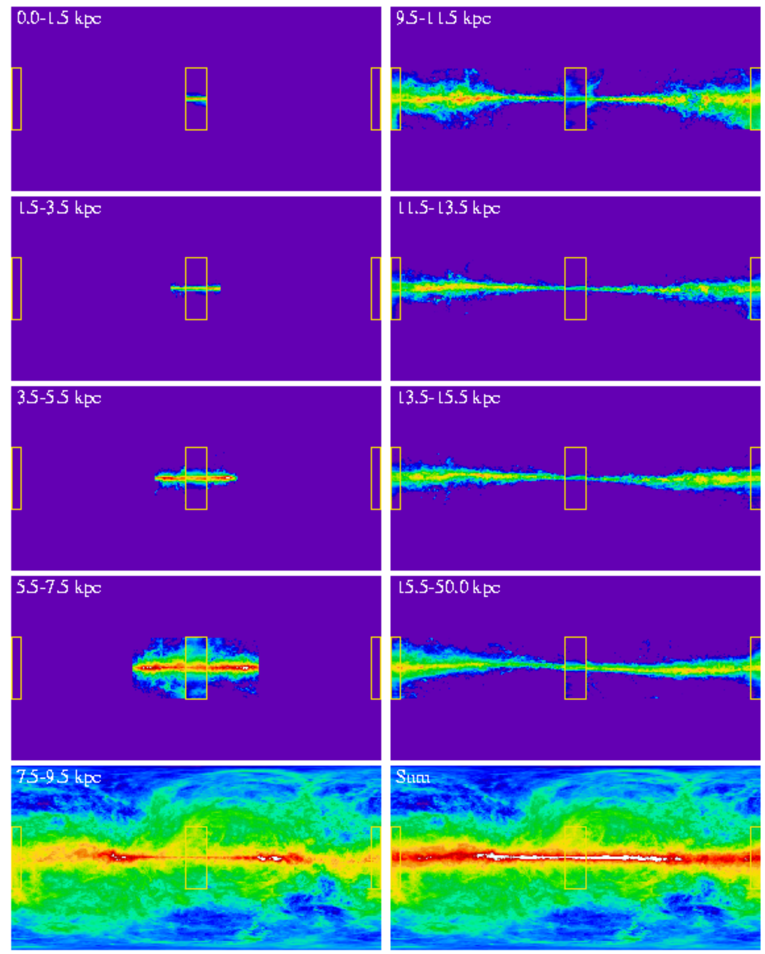


Levine, Blitz, & Heiles (2006)

Gas rings γ-ray astronomy

- Since the COS-B era, ‘rings’ of H I and CO gas (column density) have been used to study and model the Galactic diffuse emission. This eliminates the kinematic distance ambiguity in the inner Galaxy
- The down sides:
  – It builds in axisymmetry to underlying models for distributions of cosmic rays
  – And *does not* map directly to the 3-dimensional distribution of gas density.
  – And the Galactic center and anticenter longitude ranges need to be filled in

All-sky H I ‘Ring’ maps*



*These are not the currently-used rings but similar

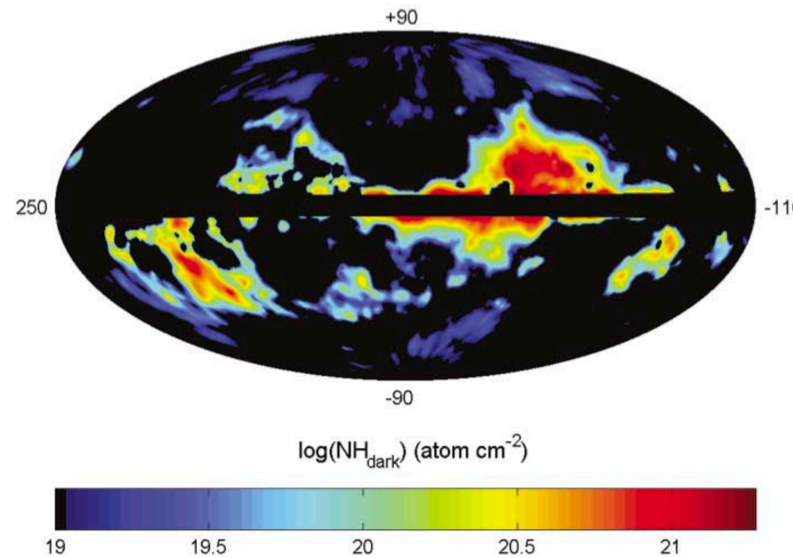
Dark gas

- CO is not a perfect tracer of H_2 and we do not really know N(H I) perfectly
  - The challenge is in what to do about it
- Schlegel, Finkbeiner, & Davis (1998) used IRAS and COBE/DIRBE data to infer dust column densities
  - ‘Color correcting’ to a uniform dust temperature scale
  - Results were expressed in terms of E(B-V) [excess reddening] equivalent
  - If you can believe in constant gas-to-dust ratio and uniform grain size distributions then E(B-V) is a tracer of total column density
- Grenier et al. (2005) pointed out in an analysis of EGRET data that E(B-V) is not a linear combination of W(CO) and N(H I)
  - So… ‘dark gas’

Dark gas (2)

- The (long-standing) provisional solution has been deriving the ‘dark gas’ component as a residual from correlations with dust column density map
- Positives:
  - The $E(B\text{-}V)_{res}$ component can compensate for errors in N(HI) from spin temperature or self absorption corrections
- Challenges:
  - What to do in the Galactic plane (where the gas-to-dust ratio and $N(H_2)/W(CO)$ ratio could vary along the line of sight
  - Failure of E(B-V) derivation near bright star-forming regions (next slide)

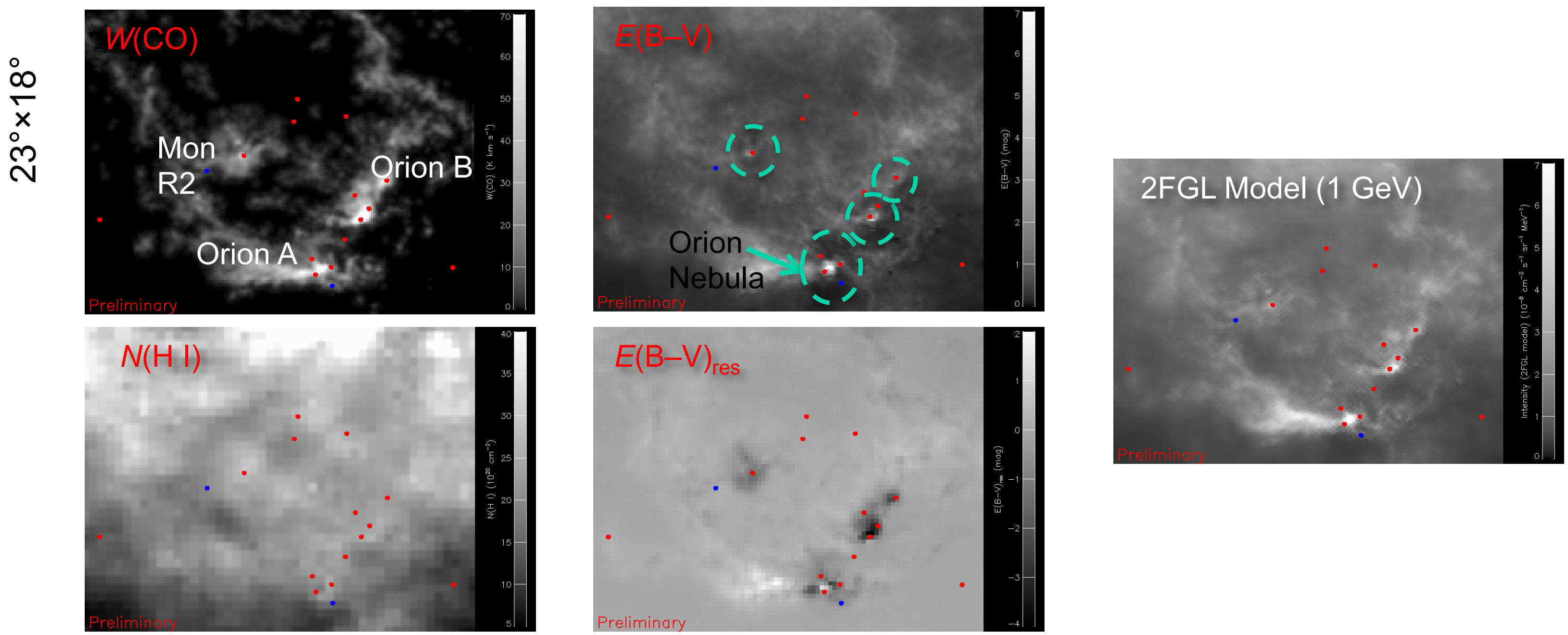
Early Dark Gas residual map



Grenier, Casandjian, & Terrier (2005)
N.B. centered on (70°,0°)

Illustration for Orion: Dark gas complications

- **Schlegel et al. flag 4 regions in Orion as difficult to process (bright IR sources and 42' beam of DIRBE)**
- **Independently we smooth across bright IR sources**
- **Result is deep holes in 'dark gas' map where suspicious 2FGL* sources collect – these are flagged in the 2FGL catalog**

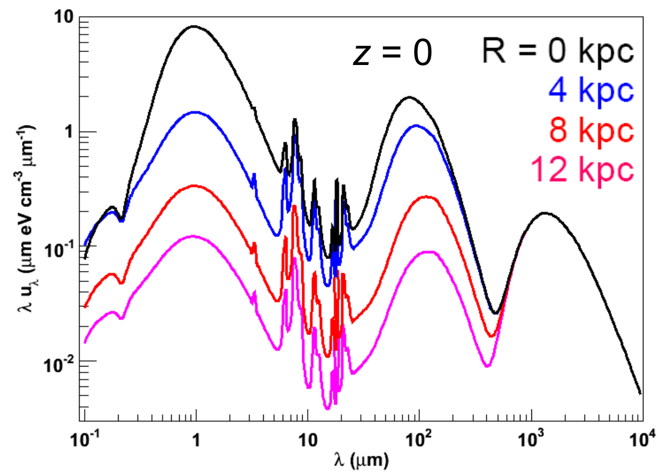


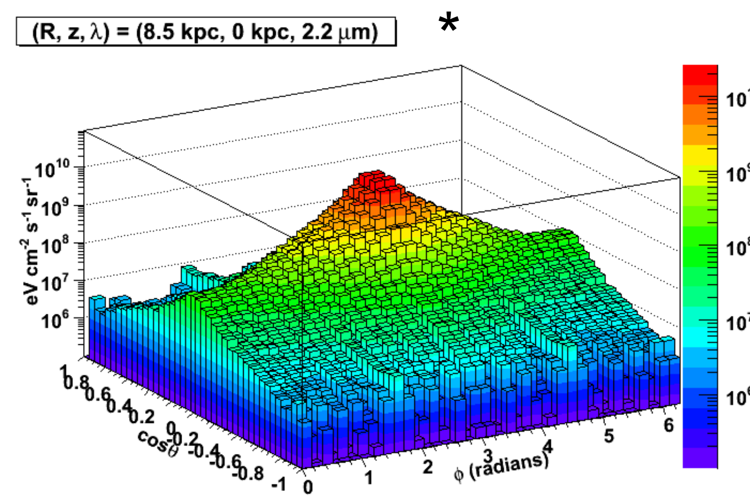
Red points are unassociated 2FGL sources (**blue** point is a 2FGL source associated with a blazar)

*2FGL = Second Fermi gamma-ray source catalog

Interstellar radiation field

- **Built from detailed stellar population and distribution models, detailed model for dust absorption and scattering, and variation of dust properties across the Milky Way (Porter)**
- **The recent calculation retains the intrinsic anisotropy – count the dimensions**





Porter, Strong, & Moskalenko (2007)

* This pretty picture example at *z* = 0 does not show the important anisotropy in θ that exists for *z* ≠ 0

Modeling the Diffuse Emission

- **The diffuse gamma-ray emission is modeled as a linear combination of templates of gas tracers and other diffuse components**

Model for diffuse gamma-ray intensity (q_{HI} is the emissivity, related to cosmic-ray intensities)

$$N_{pred}(l,b) = \iint d\Omega_k \Bigg(\sum_{i=rings} [q_{HI,i} N_{HI}(r_i, l_k, b_k) + q_{CO,i} W_{CO}(r_i, l_k, b_k)]$$

$$+ q_{EBV} E(B-V)_{res}(l_k, b_k) + q_{IC} I_{IC}(l_k, b_k) + I_{iso}(l_k, b_k) \Bigg) \epsilon(l_k, b_k)\, PSF(l, b, l_k, b_k)$$

$$+ \sum_{j=sources} F_j\, \epsilon(l_j, b_j)\, PSF(l_j, b_j, l, b)$$

Exposure

Effective point-spread function

Point sources

Ionized ISM is not included as a 'template' and Helium and heavier elements are included by assuming that they are proportional to H

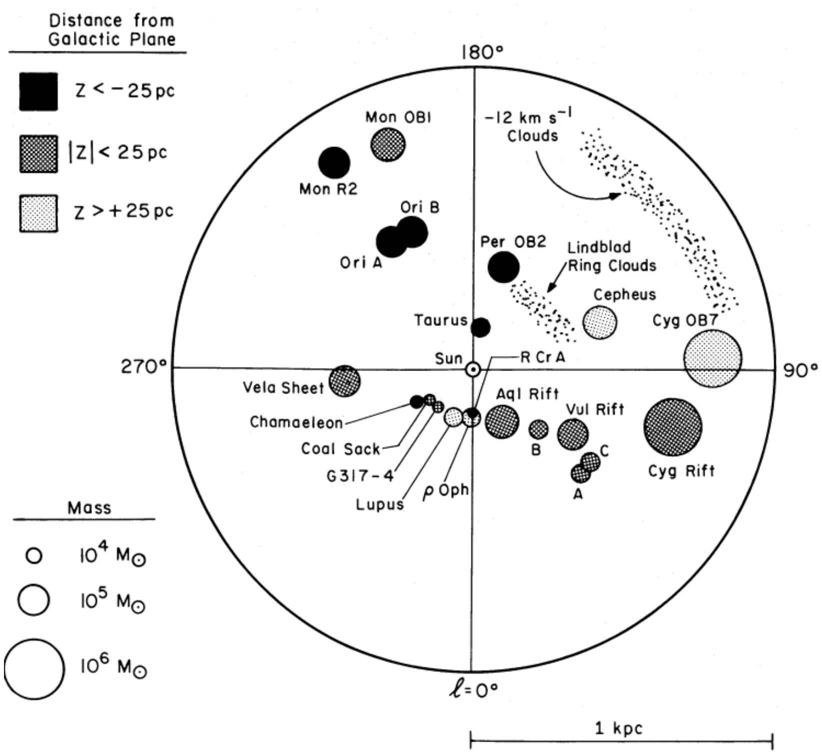
As long as the maps are not linearly dependent, a likelihood analysis can tell you the contribution from each one

Note important assumption: CR densities & spectra are uniform across the region being studied

Interpretations are emissivity (effective rate of gamma-ray emission per H atom), $N(H_2)/W(CO)$

Local interstellar clouds and γ-rays

Schematic top-down view



Dame et al. (1987)

- **Some LAT team investigations:**

"Fermi LAT Observation of Diffuse Gamma-Rays Produced Through Interactions between Local Interstellar Matter and High Energy Cosmic Rays" (0908.1171)

"Fermi Large Area Telescope measurements of the diffuse gamma-ray emission at intermediate Galactic latitudes" (0912.0973)

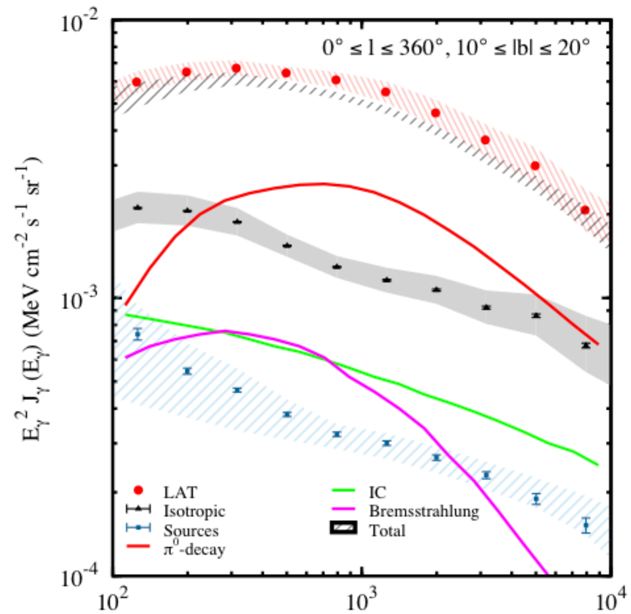
"Fermi observations of Cassiopeia and Cepheus: diffuse gamma-ray emission in the outer Galaxy"

+ Preliminary results on Chamaeleon, R CrA, Cepheus-Polaris, Orion A&B

Local emissivities

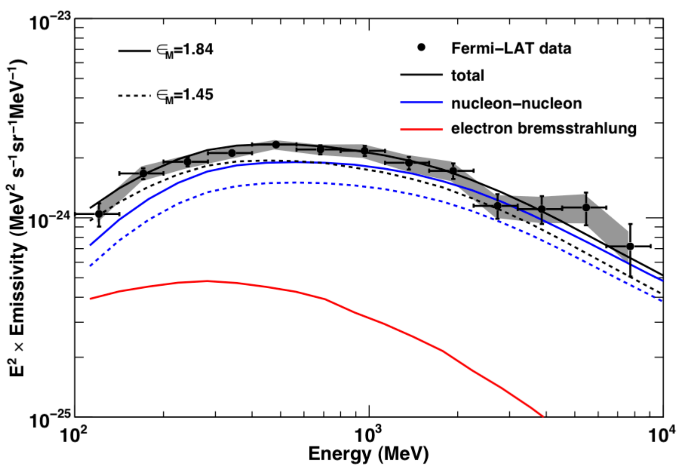
- Emissivity spectra are essentially consistent with what would be expected from local interstellar spectrum, i.e., what GALPROP would predict
- Deviations are within systematic uncertainties

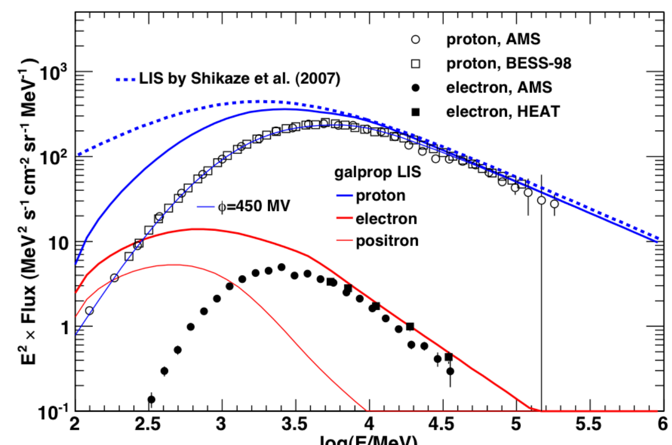
Avg. spectrum at inter-mediate latitudes



0912.0973

Emissivity spectrum in the 3rd quadrant

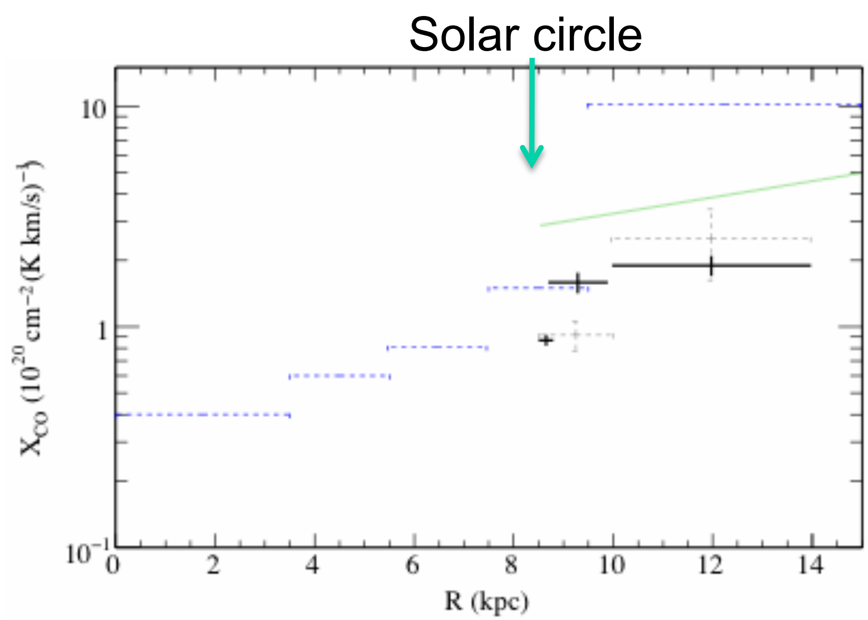




0908.1171

Local X-ratios

- **X-ratios are not much changed since the pre-dark gas era, although the interpretation is not the same**
- **In a sense X-ratio is not as central as it had been in terms of describing the ISM**



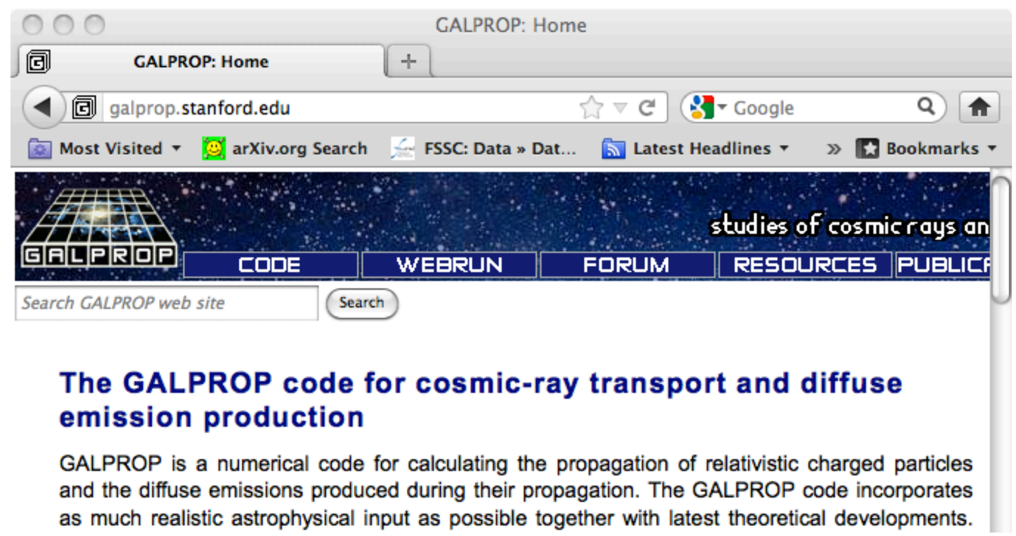
Local clouds here are Cepheus flare and ‘Lindblad ring’

0912.3618

Dashed grey = EGRET results for Cepheus
Dashed blue = EGRET Galactic gradient (Strong et al. 2004)
Green line = Nakanishi & Sofue (2006) virial masses

Parameter optimization with GALPROP*

- GALPROP uses the same ring/E(B-V)_res inputs as the template fitting
  - It enforces consistency, e.g., between IC and Bremss. and can evaluate consistency with local CR data
- In Ackermann et al. (2012) some of the adjustable parameters are investigated systematically, optimized against the LAT data
- CR source distribution with R, CR halo scale height z_h, and radial scale R_h, H I spin temperature, E(B-V) magnitude cut
- $X_{CO} = N(H_2)/W(CO)$ is fit in each ring and D_0 and v_A are adjusted for CR secondary-primary ratios to match observations

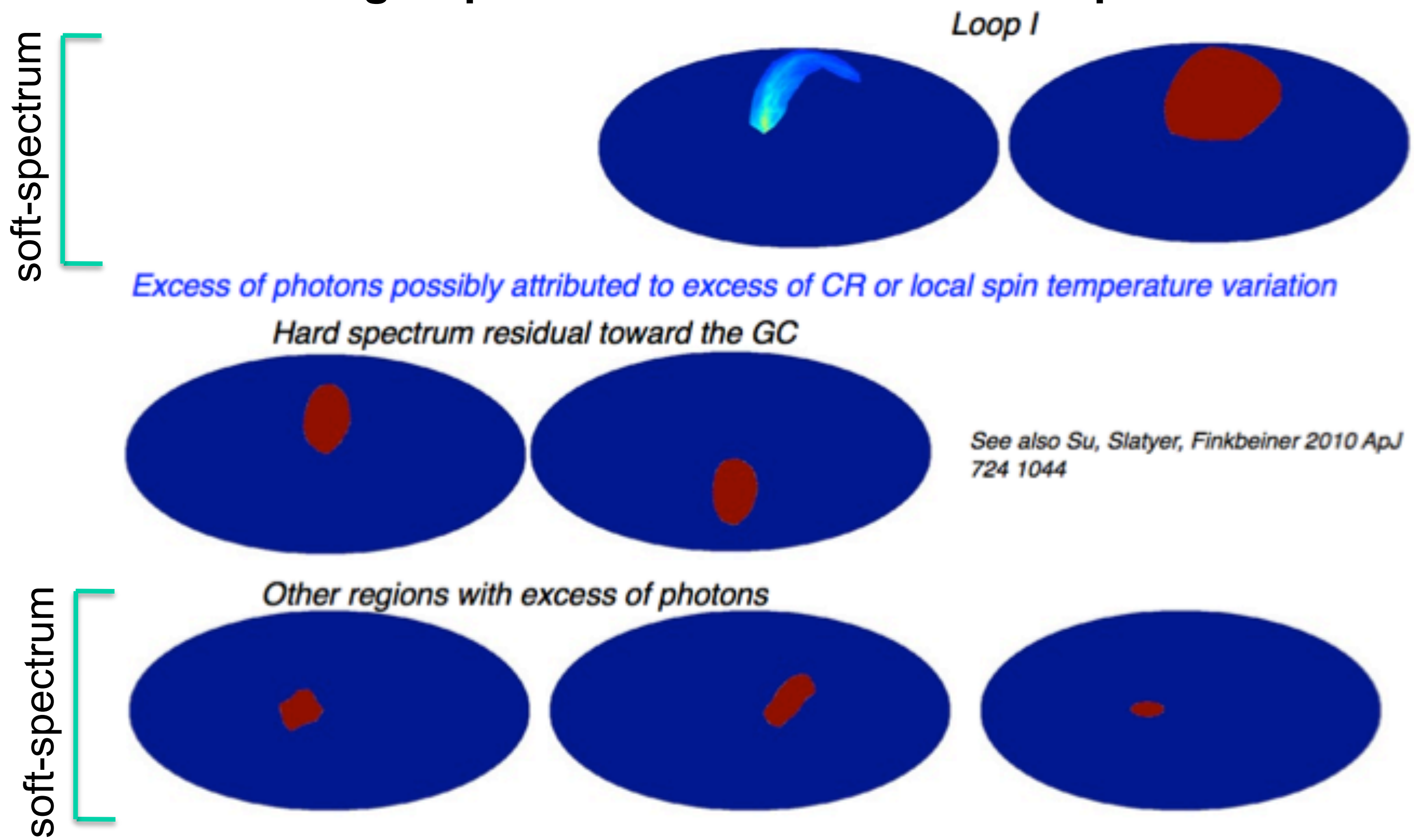


Findings from GALPROP parameter optimization

- Galactic diffuse emission was generally under-predicted in the inner Galaxy above a few GeV and over-predicted in the 200-400 MeV range
  - Possibly due to errors in removing solar modulation from the local CR spectrum and/or unresolved Galactic sources
- Large γ-ray emissivity in the outer Galaxy suggests large values of $z_h > 4$ kpc, which would allow more CR diffusion there, but then the $^{10}Be/^{9}Be$ ratio is not matched

What the models did not predict

- **As shown on Monday, the model used for the analysis for the 2FGL catalog required additional diffuse components**

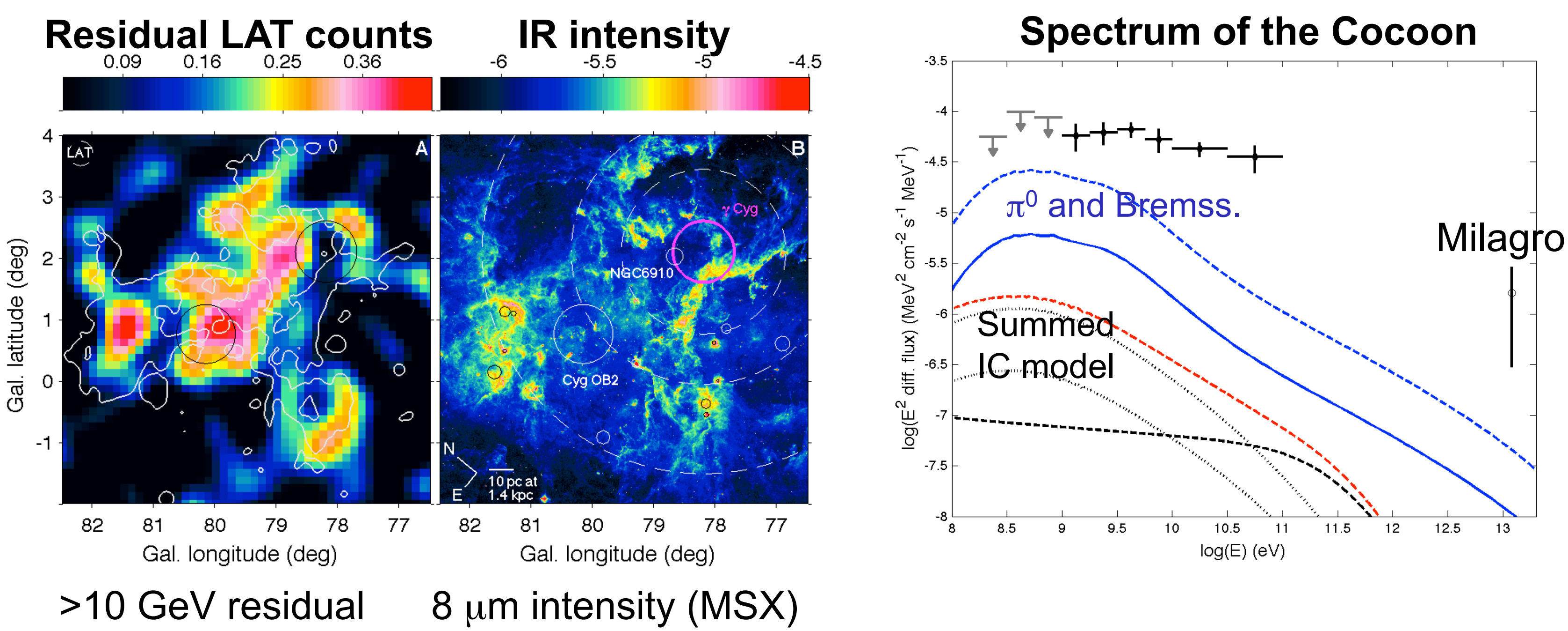


Casandjian on behalf of the LAT Collaboration (Fermi Symposium 2011)

See also http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/Pass7_galactic.html

What the models did not predict (2)

- On a much smaller scale, a study of the diffuse emission in Cygnus indicated a residual interpreted as a localized region of enhanced CR density with a hard spectrum

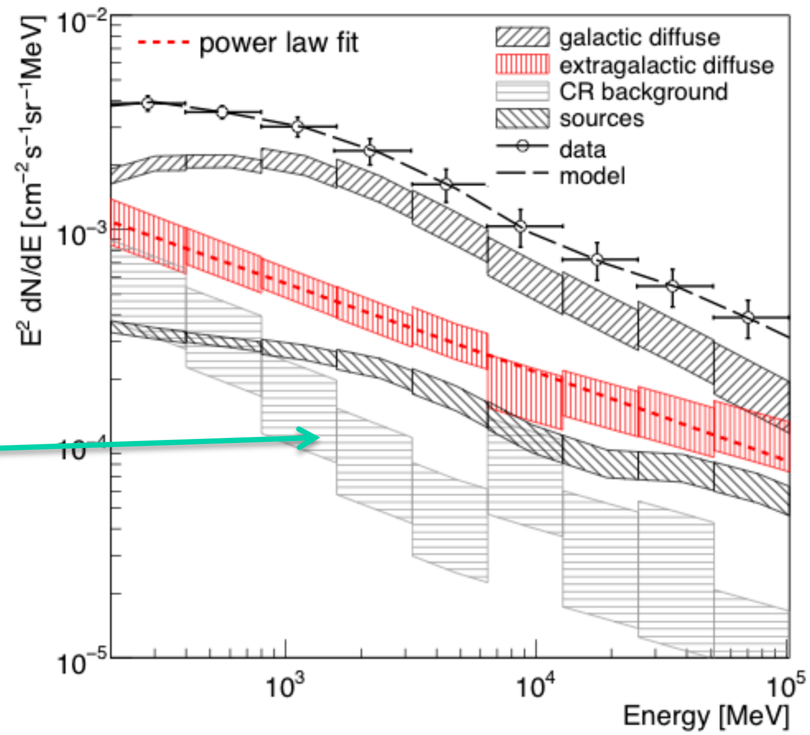


Ackermann et al. (2011)

Isotropic diffuse emission

- Described on Monday
- The fitting is more or less like standard template fitting, for the high-latitude sky
- A great deal of effort went into reducing and evaluating the residual level of CR contamination in the data
- Statistics are a limitation only at the highest energies (both in the data and for Monte Carlo background studies)

Derivation of the EGB



|*b*| > 10°

Fermi Bubbles

- A variety of processes have been proposed to explain them
  - Dark matter annihilation
  - 2nd order Fermi acceleration of electrons into the halo of the Milky Way on plasma shocks in the bubbles
  - Winds from massive star formation in the GC region advecting cosmic rays into the halo
  - Recent AGN activity in at the GC
- The lobes are increasingly well characterized in the LAT data
  - Tracing them through the GC region remains a great challenge – for example it would be worth knowing whether they cross the plane at the GC – and their profile at low latitudes is correspondingly model dependent
  - Su & Finkbeiner (2012) have recently proposed that the bubbles have a jet/cocoon structure

Practical advice for your work

- **In likelihood analysis, the Galactic diffuse emission model can be scaled by a power-law in energy rather than just a normalization factor**
- **This was done for the 1FGL and 2FGL catalog analyses**
- **The spectrum of the model generally is a good match for the data but because the Galactic diffuse emission is so bright, especially at low latitudes a small error can result in biasing fit parameters for point sources**


```
<source_library title="source library">
<source name="Isotropic" type="DiffuseSource">
  <spectrum file="xxx" type="FileFunction"><parameter free="1" max="1000" min="0.001"
name="Normalization" scale="1" value="1"/>
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 <spatialModel type="ConstantValue">
   <parameter free="0" max="10" min="0" name="Value" scale="1" value="1"/>
  </spatialModel>
 </source>
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  <spectrum type="PowerLaw">
   <parameter free="1" max="100" min="1e-05" name="Prefactor" scale="1" value="1."/>
   <parameter free="1" max="1" min="-1" name="Index" scale="1" value="0."/>
   <parameter free="0" max="2000" min="50" name="Scale" scale="1" value="500"/>
  </spectrum>
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   <parameter free="0" max="1000" min="0.001" name="Normalization" scale="1"
value="1"/>
   </spatialModel>
  </source>
 </source_library>
```
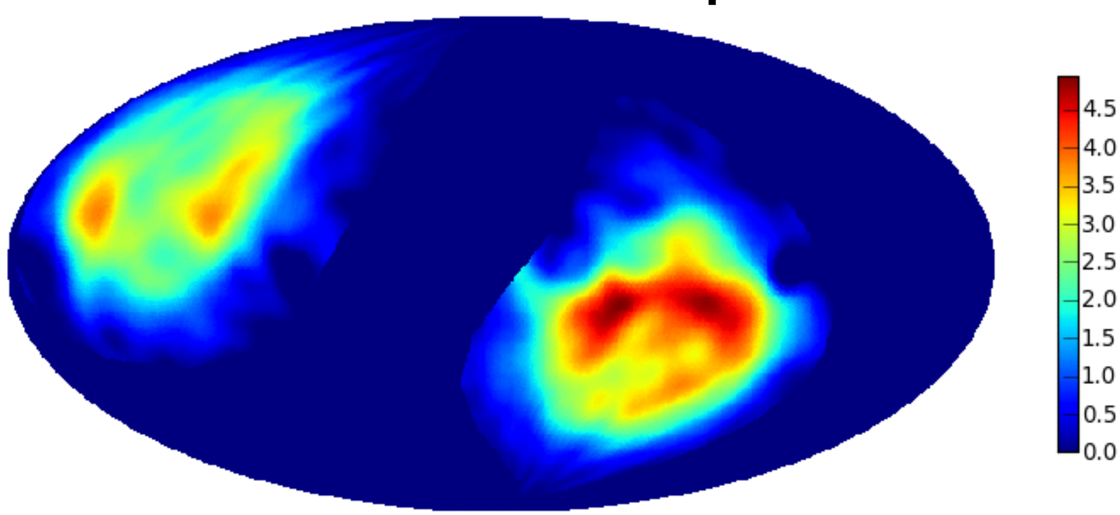

Practical advice (2)

- For 2FGL analysis, large regions (~50° radius) around the celestial poles required an additional diffuse emission component with a soft spectrum
- Essentially zero above 300 MeV
- The specific template used is available from the FSSC*
- We attribute this component to Earth limb gamma rays in the tails of the PSF and misreconstructed back-entering gamma rays
- The template is valid only for long time intervals; it depends on the rocking profile and the precession of the orbital pole



* See http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

Some current issues

- Galactic center diffuse emission
- Large emissivity in the outer Galaxy relative to CR source abundance there
- Unresolved Galactic point source populations

Conclusions

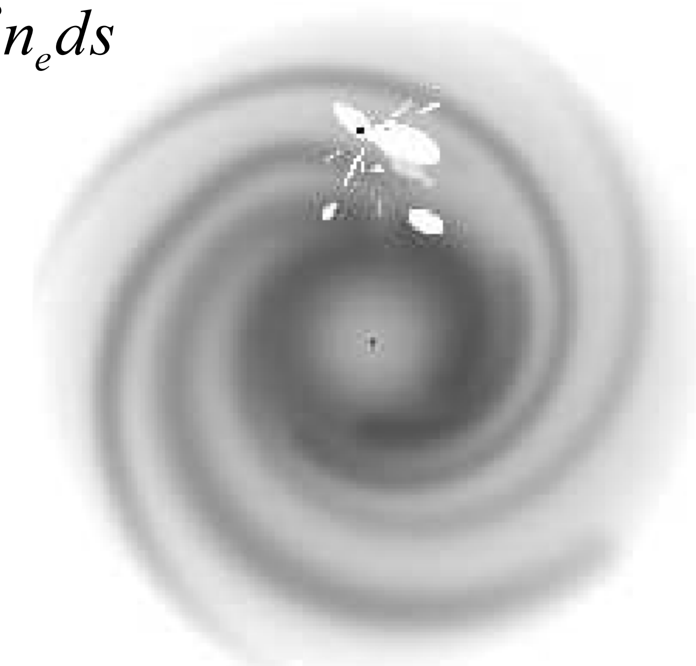
- We understand the Galactic diffuse emission processes and components, but the details matter
- The statistics and angular resolution of the LAT data are constraining models and revealing new challenges

Backup slides

Ionized hydrogen for completeness

- The very-low density Warm Ionized Medium traced by pulsar dispersion measures
- The Cordes & Lazio model is sometimes formally included but it has little impact, small contribution to column densities
- The model necessarily has an assumed shape (spiral structure) built in

$$D = \int n_e ds$$

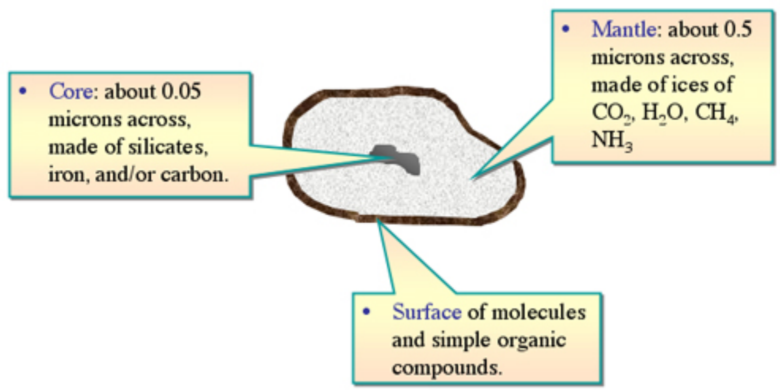


1143 pulsars

Cordes & Lazio (2002)

Dust

- Grains of ‘metals’ – carbon-ish and silicon-ish – with a size spectrum ranging from very small to small and
  - About 1% by mass of the interstellar medium



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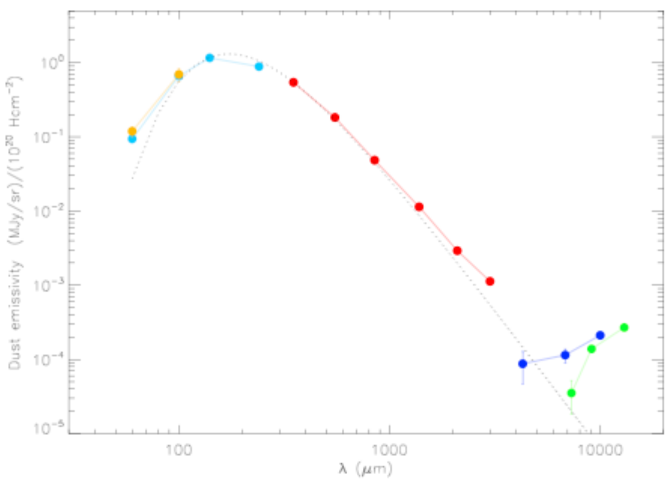
- Dust is fantastically important to the interstellar medium – reprocesses star light (incidentally absorbs UV to shield clouds), and catalyzes the formation of molecular hydrogen
  - Otherwise, even if they wanted to, two H atoms would have no phase space for combining to form H_2
- Realization of the catalytic aspect of dust (Hollenbach & Salpeter 1971) was a great advance and (I imagine) spurred the search for tracers of molecular hydrogen

Looking one step ahead

- Planck Collaboration has made a dark gas analysis this year, deriving ‘dark gas column densities’ using HFI 857 GHz and IRAS long-wavelength bands

Planck column densities of Dark Gas

Dust Emissivity



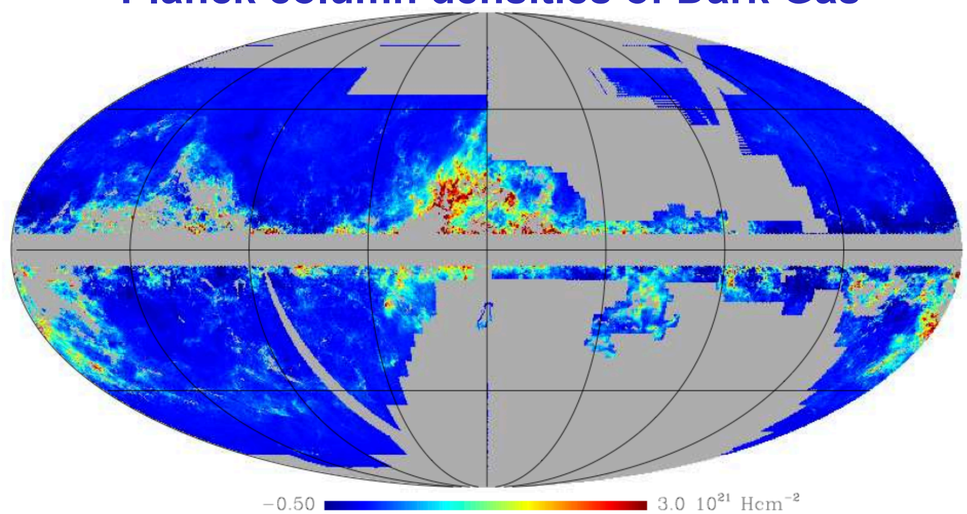


Fig. 8. Map of the excess column density derived from the 857 GHz data. The map is shown in Galactic coordinates with the Galactic centre at the centre of the image. The grey regions correspond to those where no *IRAS* data are available, regions with intense CO emission (W_{CO} > 1 Kkms^{-1}) and the Galactic plane ($|b_{II}| < 5°$).

Planck Collaboration (2011)

- HFI beam is 5’ vs. 42’ for DIRBE (Good)
- N.B.: Their analysis avoided the tough regions, and Planck data are not going to be released soon