Interstellar Emission Modeling with Pass 8

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on behalf of the Fermi LAT collaboration

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Outline

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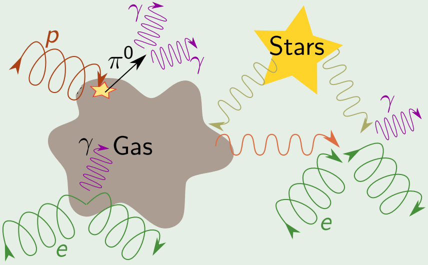
What this talk is not about

This is not a description of the next iteration of the *Fermi*–LAT interstellar emission model.

What is interstellar emission?

Emission processes



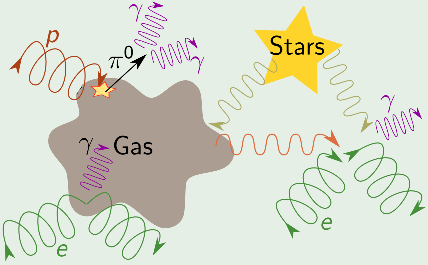
- CR nuclei
  - π^0–decay from interactions with gas
- CR electrons (e^+ and e^-)
  - Bremsstrahlung from interactions with gas
  - Inverse Compton (IC) from interactions with radiation.

Typical definition

- Interstellar emission arises from interactions between cosmic-rays (CRs) and the interstellar medium (gas and radiation).

What is interstellar emission?

Emission processes



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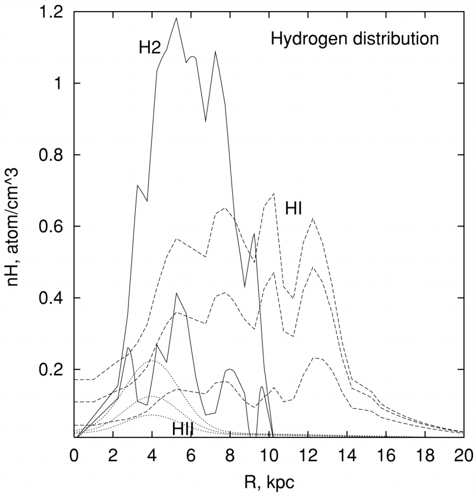
Some grey areas

- Supernova remnants (SNRs) interacting with molecular clouds
  - Are these freshly injected CRs and therefore interstellar emission?
- Superbubbles (e.g. Loop I)
  - Should these be considered supersized SNRs?
- The Fermi bubbles.
  - Depends on interpretation (Talks by Meng Su and Vladimir Dogiel)
- Emission from DM annihilation
  - Secondary charged particles are considered CRs.

Trivia

- Mass fraction of hydrogen is $\sim 75\%$ and helium is $\sim 25\%$.
- Hydrogen observed in three phases:
  - Atomic (H I): The most massive phase with a large filling factor. Scale height approximately 200 pc.
  - Molecular (H_2): The densest phase, very clumpy. Scale height approximately 100 pc.
  - Ionized (H II): The least significant component with a large scale height. Scale height approximately 1 kpc.
- Helium assumed to have the same distribution as hydrogen.
- Rest of the interstellar medium is not interesting as targets for CRs, but it can provide important information on the distribution of Hydrogen.

Radial distribution in and near the plane



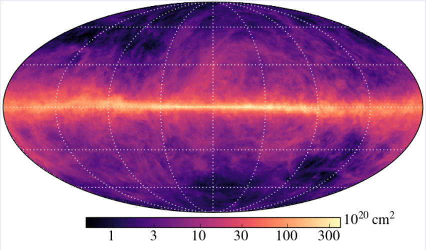
Moskalenko et al. 2002, ApJ 565

- Emits radiation at 21 cm wavelengths.
- Not optically thin along the plane, need to correct for optical depth
  - Usually done using the approximation of a homogeneous line of sight

$$N_{\mathrm{H\,I}}(v) = -\log\left(1 - \frac{T(v)}{T_S(v) - T_{bg}}\right) T_S(v) C$$

    where v is the observed Doppler velocity, $T_S(v)$ is the spin temperature, $T(v)$ is the brightness of the emission expressed as temperature, $T_{bg} \approx 2.7$ K, and C is a constant.
  - Need to know $T_S(v)$ for all lines of sight but usually assume a single value for the entire sky.

LAB survey (Kalberla et al. 2005, A&A 440)



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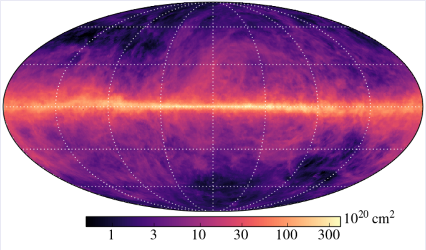


This is the "easy" component!

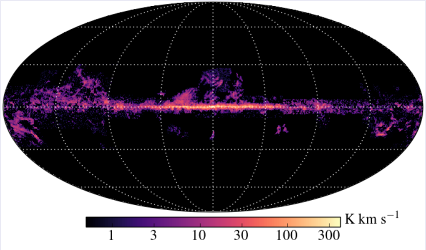
- Works very well at high latitudes where optical depth is small.
- Significant issues in the plane where optical depth is larger, especially the inner Galaxy.

- No line emission from cold H_2 – Need to use a surrogate tracer.
  - The most common tracer is the CO molecule that forms under similar conditions as H_2.
  - The CO line emission is collisionally excited by H_2.
  - The column density of H_2 is found observationally to be roughly linearly dependent on the integrated line intensity of the CO line emission (W_{CO})

$$N_{H_2}(v) = X_{CO} W_{CO}(v).$$

  - X_{CO} has been shown to vary throughout the Galaxy and even in the local ($\lesssim$ 1 kpc) medium.

CO survey (Dame et al. 2001, ApJ 547)



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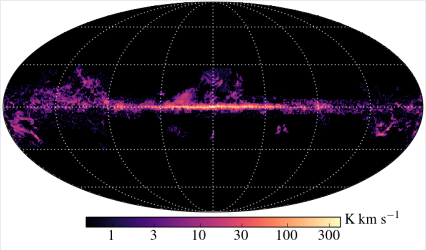
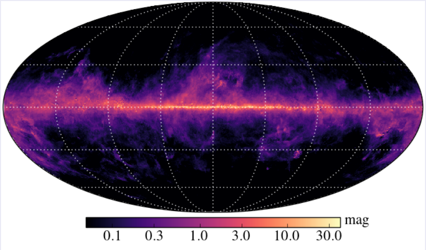


CO is not a perfect tracer of H_2

- Need other tracers as well to account for CO dim H_2:
  - Dust (Talk by Isabelle Greinier)
  - Other line emitter, e.g. OH (Talk by Ronald Allen) or C II

- Defined as gas not traced by H I and CO emission line surveys
  - Was revealed for the first time using γ-rays and dust in analysis of EGRET data (Grenier et al. 2005, Science 307).
- This gas is likely low density H_2 on the outskirts of molecular clouds that is not dense enough to shield CO from UV-light.
- Interstellar dust is mixed with interstellar gas.
  - Can be used as an alternative tracer of interstellar gas to probe the dark neutral medium.
  - Can also correct for incorrect T_S values in H I.

E(B-V) (Schlegel et al. 1998, ApJ 500)



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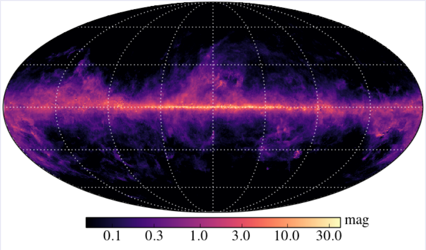


Dust comes with its own set of issues

- No distance information in dust emission, need absorption measures for distance estimates.
- Dust emission is strongly temperature dependent that can be difficult to correct for near star-forming regions.
- The dust to gas ratio is not constant throughout the Galaxy.

Gas Placement

- Doppler shift of emission lines used to place gas given a model for its rotation around the Galactic center.
- Circular rotation assumed.
  - Near–far ambiguity in the inner Galaxy.
  - Does not work for directions near dotted line.

Clemens 1985, ApJ 295

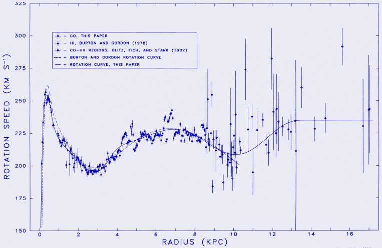
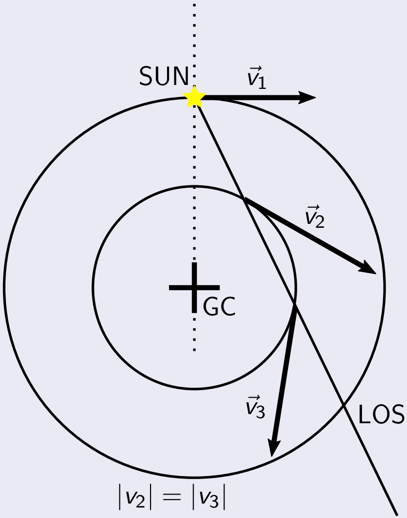


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*)(R_0, θ_0) = (10 kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).

Illustration



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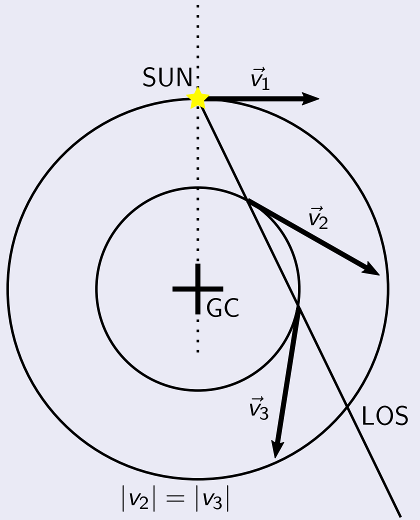
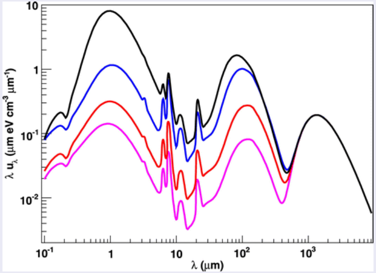
Some known issues

- Non-circular rotation:
  - Turbulence
  - Streaming
- Large scatter in measurements, especially in the outer Galaxy.
- Kinematic resolution limited to ~ 1 kpc.

Illustration



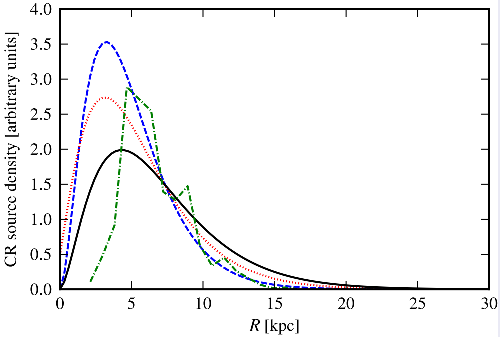
Porter et al. 2008, ApJ 682



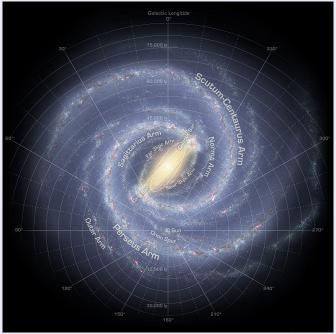
- Three main components:
  - Stellar light.
  - Dust re-emission of stellar light.
  - The cosmic microwave background.
- Only directly observable from our position $\Rightarrow$ Need modeling codes to predict its distribution.
  - Stellar distribution and properties.
  - Dust distribution and properties.
  - Radiative transport.
- Inverse Compton (IC) cross section is angle dependent so we need angular dependent SEDs throughout the Galaxy.
  - A skymap of SEDs at each grid point.
- Current models are axisymmetric but three dimensional models are in the pipeline.
- Significant freedom in model properties, especially in the inner Galaxy.

- Only directly observable from our position.
- No directional information in observations.
- Source properties badly constrained.

Example CR source distributions



Ackermann et al. 2012, ApJ 750



http://www.wolaver.org/Space/milky_way_illustration.htm

CR Distribution

- Only directly observable from our position.
- No directional information in observations.
- Source properties badly constrained.

Template method

- Uses templates for the target properties and determines the CR distribution from a fit to γ-ray data
- Does not depend on source properties and propagation.
- Fast method, no need to solve complex propagation equations.
- Generally gives a better representation of data.

Propagation method

- Assumes CR source properties and propagation parameters to determine the CR distribution solving the propagation equation.
- Not biased by unmodeled components.
- Smoothly varying CR distribution.
- Self-consistent IC emission.

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Potential merger solution

Create templates using propagation codes and fit them to data. Feed fit results to propagation code and iterate.

Fermi–LAT is crucial for CR physics

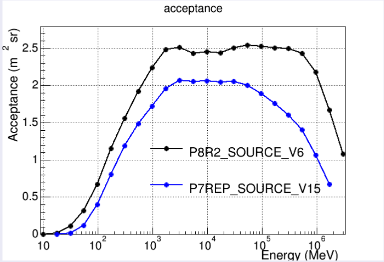
- γ-rays are the best way we have to probe the distribution of CRs in the Galaxy and learn about their origin and propagation.
- *Fermi*–LAT data have been invaluable in learning about CR properties in:
  - Local region:
    - Abdo, A. A. et al. 2009, ApJ, 703
    - Abdo, A. A. et al. 2009, Phys. Rev. Lett., 103
    - Ackermann, M. et al. 2011, Science, 334
    - Ackermann, M et al. 2012, ApJ, 756
    - Ade P. A. R et al. 2015, A&A, 582
    - Casandjian, J-M. 2015, ApJ, 806
  - Outer Galaxy:
    - Abdo, A. A. et al. 2010, ApJ, 710
    - Ackermann, M. et al. 2011, ApJ, 726
    - Ackermann, M. et al. 2012, A&A, 538
  - Galactic halo:
    - Tibaldo, L. et al. 2015, ApJ, 807 and poster at this symposium.
  - External galaxies:
    - Abdo, A. A. et al. 2010, ApJL, 709
    - Abdo, A. A. et al. 2010, A&A, 523
    - E. Murphy et al. 2012, ApJ, 750
    - Ackermann, M. et al. 2015, A&A, accepted

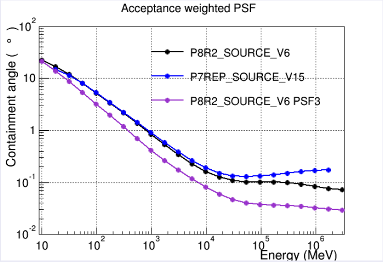
Pass 8 Performance

Short overview

- Pass 8 was a complete overhaul of the entire data processing pipeline providing improvements in all areas.
  - Many thanks to the people putting in the hard work to make this a reality.
- Most notable improvements for interstellar emission modeling:
  - Increased acceptance at lowest and highest energies.
  - Better PSF over all energy ranges.
  - Split into PSF subclasses allows for optimal resolution.
- Together this allows for better separation of components at all energies and therefore a better model.
  - Interstellar emission modeling is systematically limited over nearly the entire energy range of the *Fermi*–LAT.

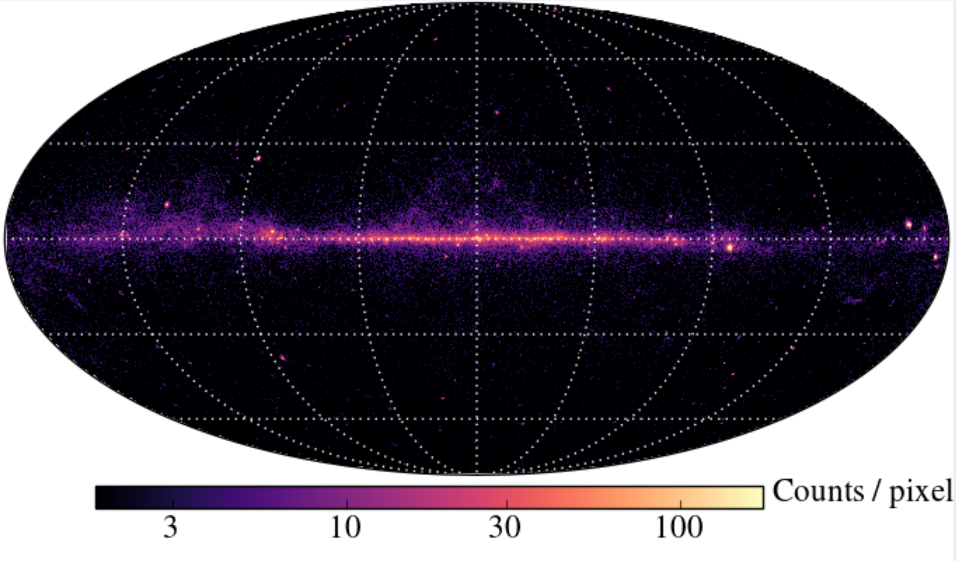
Performance Comparison





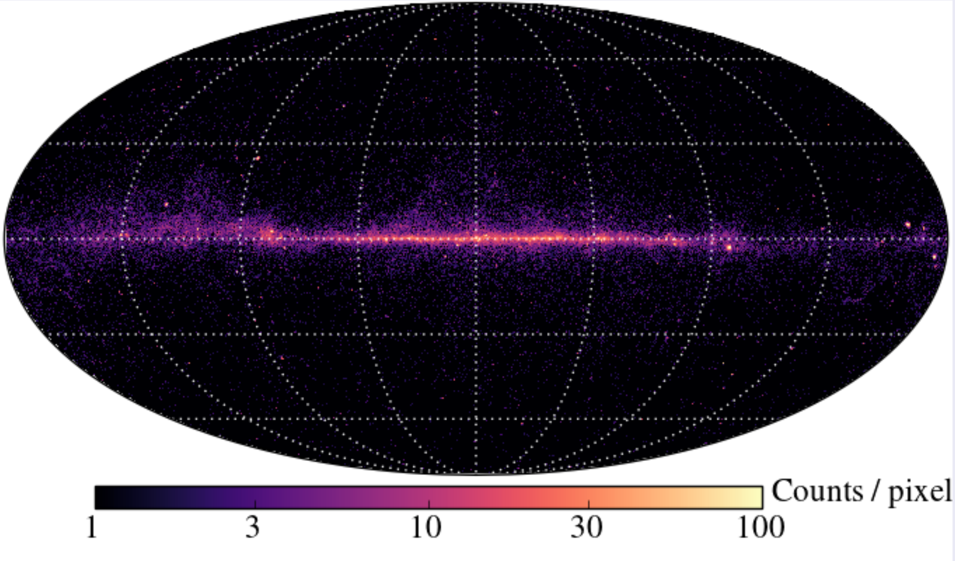
Pass 8 vs. Pass 7 Reprocessed

Pass 7 reprocessed, source front, $> 1\,\mathrm{GeV}$, 4 year counts



Pass 8 vs. Pass 7 Reprocessed

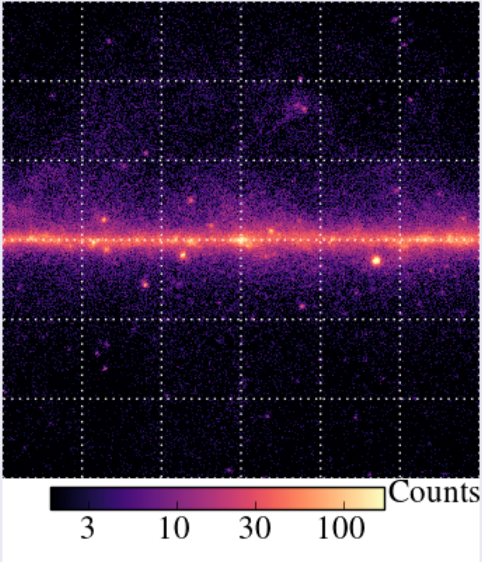
Pass 8, source PSF3, > 1 GeV, 4 year counts



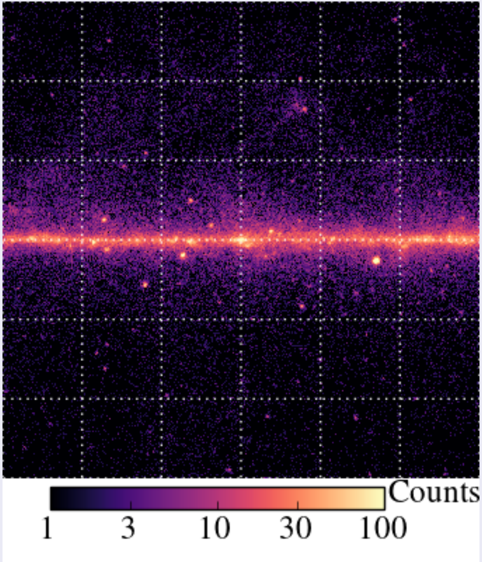
Pass 8 vs. Pass 7 Reprocessed

Zoom in on the GC, $60^\circ \times 60^\circ$

Pass 7

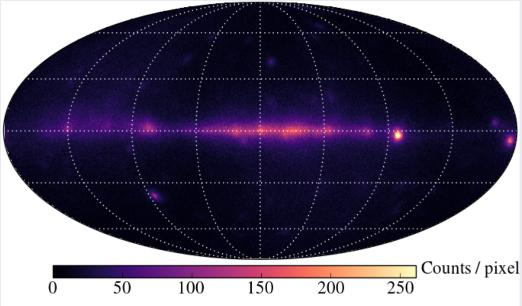


Pass 8

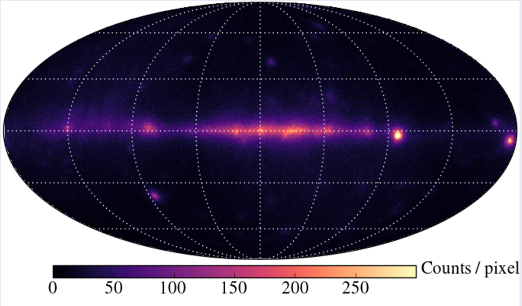


50 MeV – 100 MeV, 4 year counts

Pass 7 front



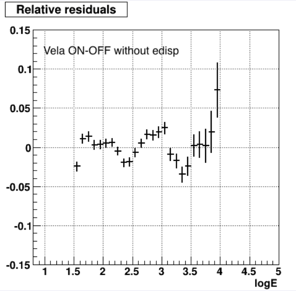
Pass 8 PSF3

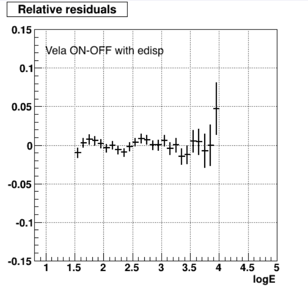


- More statistics with Pass 8 at low energies degrades the average PSF over the total energy range.
  - The Pass 8 PSF3 class still provides a better angular resolution with higher statistics compared to Pass 7 reprocessed front.
  - Will provide significant improvement in discriminating components at these energies.

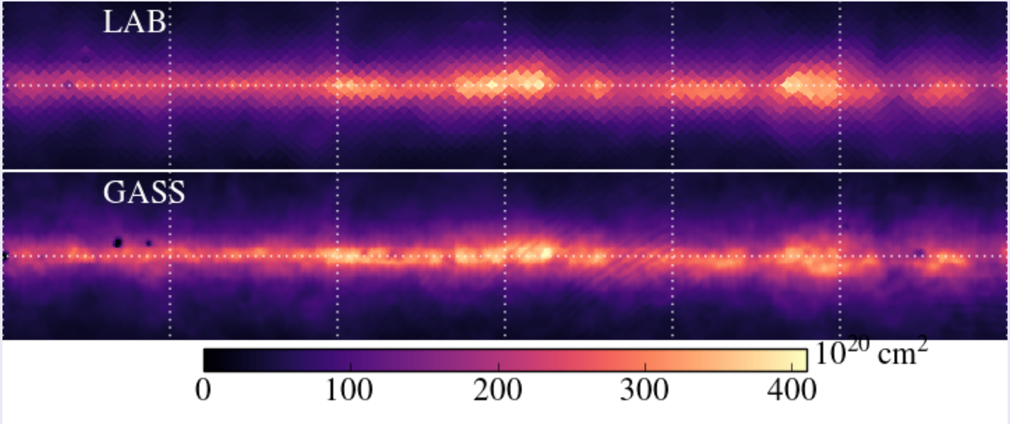
A note on energy dispersion

- Energy dispersion has not been previously taken into account in model fitting so far because it only affects the spectrum at low energies ($\lesssim 500\,\mathrm{MeV}$) and the fit gives the spectrum in observed energies.
- Combination of energy dependence of effective area and energy dispersion cause a few percent effect at a few GeV with Pass 8.
  - Causes discrepancies if we use physical models for the spectrum.
- Energy dispersion also affects effective PSF.
  - Causes a few percent effect around the Galactic plane below few hundred MeV. Important to account for this effect.



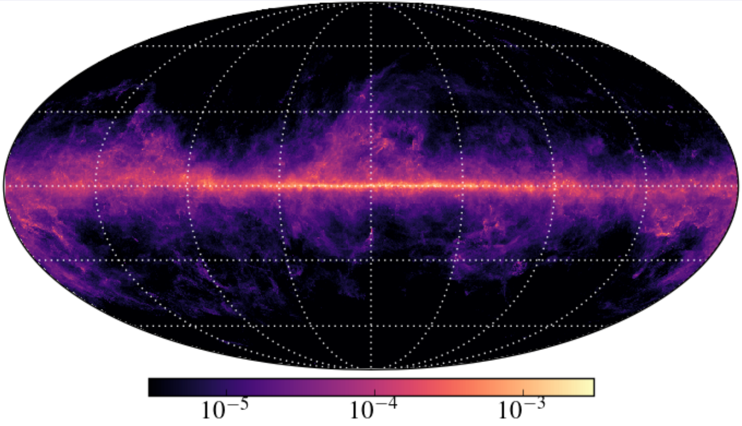


- To fully utilize the improved PSF of the Pass 8 data we need higher resolution H I surveys; The LAB survey is limited to $\sim 0^\circ.5$ resolution.
  - GASS (McClure-Griffiths et al. 2009, ApJS 181) and EBHIS (Kerp et al. 2011, AN, 6) will provide full sky coverage with $\sim 0^\circ.1$ resolution and same sensitivity as LAB.
  - Higher resolution surveys can also help with identifying regions with large optical depths.



- Planck dust extinction maps (Planck Collaboration XI 2014, A&A, 571) are providing better temperature correction and higher resolution compared to the previously used SFD maps.
  - Revealing with help from γ-rays a better (and more complex) correlation between dust opacity and gas column density (Talk by Isabelle Grenier).

HFI Planck τ_{353} extinction map R1.20



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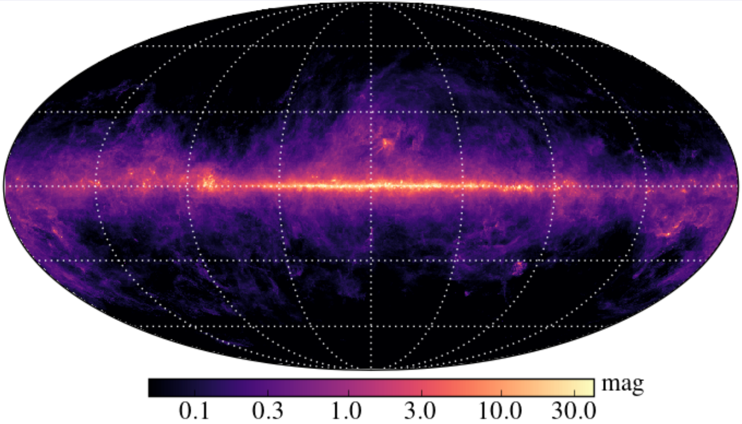

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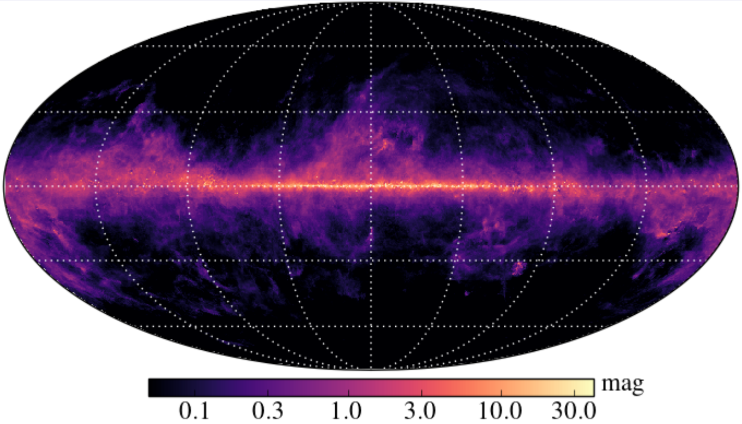
SFD E(B-V) extinction map



H I Optical Depth Correction

- Using a single value for T_S throughout the sky is barely a zeroth order correction for optical depth.
  - The value has been shown to vary significantly throughout the sky creating error in $N_{\mathrm{H\,I}}$ of the order of 40% close to the Galactic plane.

Strasser & Taylor 2004, ApJ 603

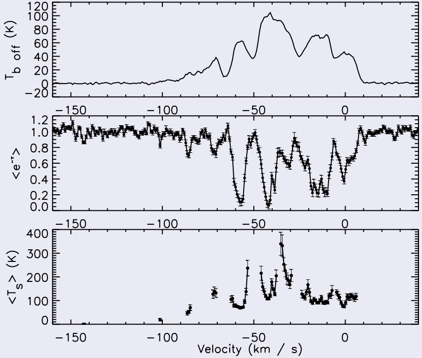


FIG. 3.—Spectra for 87GB 032246.6+572847 (T_{bg} = 77 K)

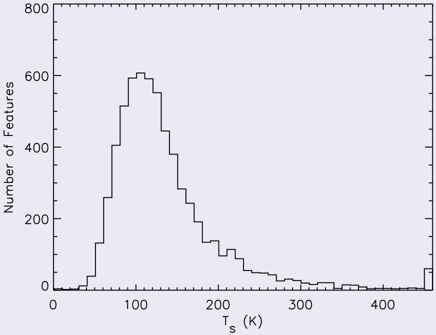
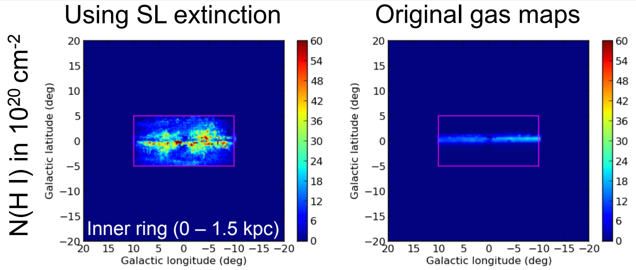


FIG. 4.—Distribution of spin temperatures for all channels where T_{on-off} S/N > 5. The last bin contains all channels with T_s higher than 450 K.

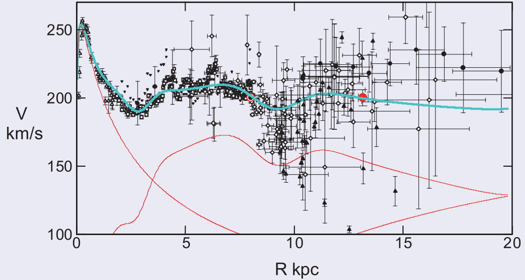
- Using distance estimates to stars along with their absorption we can derive a three dimensional dust absorption map
  - Not affected by the near-far ambiguity.
  - Works in the GC and anti-GC.
  - Still affected by gas-to-dust ratio and we must assume some H I – H_2 ratio.
  - Requires significant amount of work to get a complete map of the Galaxy; is still limited to small regions
- First attempt using alternative gas maps in the inner Galaxy from starlight extinction data by Schultheis et al, arxiv:1405.0503 (Talk by Dmitry Malyshev)



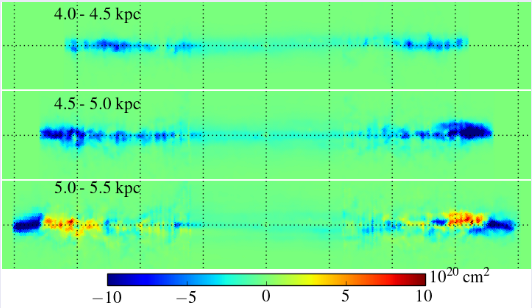
Rotation Curves

- The used rotation curve has a non-trivial effect on how we assign the gas column densities to galacto-centric annuli.
  - Figure shows difference in a few H I annuli using rotation curve of Clemens 1985 and that of Sofue et al. 2009.
  - The changes correspond to roughly 30% difference in column density between rings.

Rotation curve from Sofue et al. 2009, PASJ 61



Difference in a few annuli

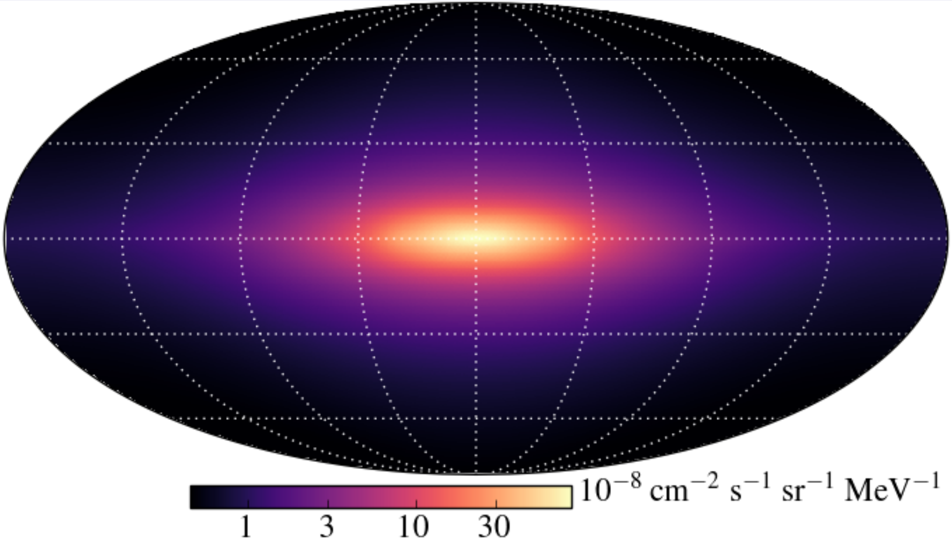


Three Dimensional ISRF

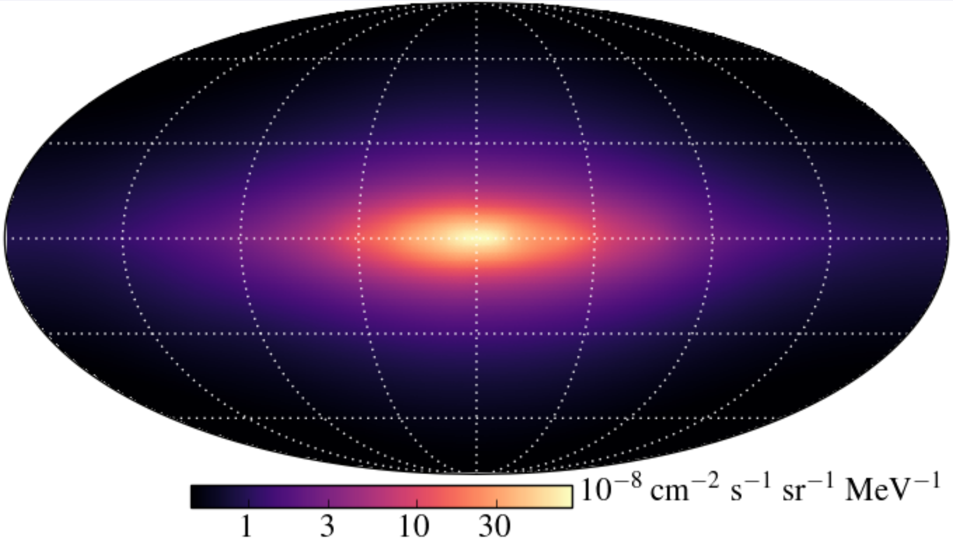
- Adding spiral arm structure and a bar to the ISRF model can significantly improve the agreement with observations.
  - Should not come as a surprise because we know our Galaxy is a spiral arm galaxy and more degrees of freedom usually improve the fit quality.
- This does not come for free, the increase size in the parameter space makes it more difficult to find the best model.
- The resulting ISRF model also takes an order of magnitude more space than the equivalent axisymmetric model
- The 3D ISRF model is preliminary, we are still scanning the parameter space for a better model.
  - The 2D model showed here is not the "Standard" model distributed with GALPROP but rather the axisymmetric version of the 3D model.

Three Dimensional ISRF and IC emission

IC with 2D ISRF at 200 MeV

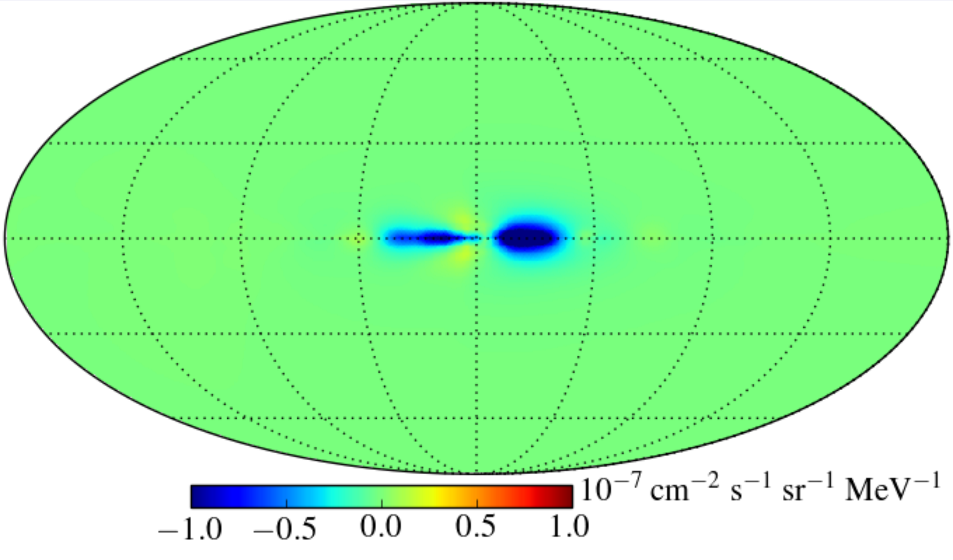


IC with 3D ISRF at 200 MeV



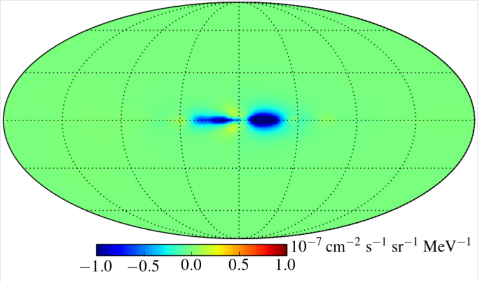
Three Dimensional ISRF and IC emission

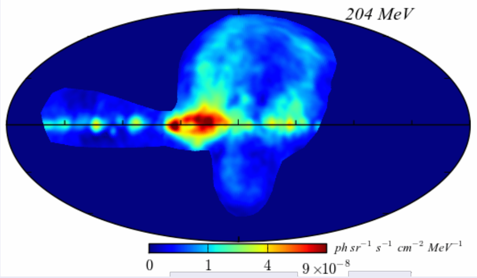
Difference between 3D ISRF and 2D ISRF at 200 MeV (3D - 2D)



Comparison with extra emission component from P7REP IEM

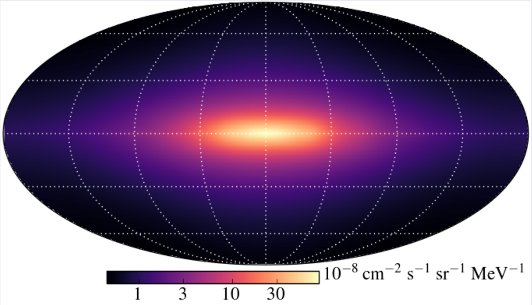
- When creating the P7REP IEM we included a filtered residual component in the model to account for structures in the model that did not have a proper template (Casandjian et al. arXiv:1502.07210).
- The differences between the 2D and 3D model are of the same order of magnitude as the extra emission template
  - Some of the structures might be related to 3D structures in the ISRF
  - The sign is incorrect, but fitting other components in a template method may create the positive structure in the residual component. This has not yet been tested.



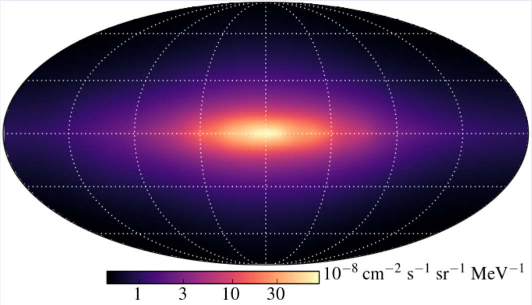


- We can also try to put some of the CR sources into a spiral arm structure.
- Following figures from a toy model containing spiral arms with density three times higher than that of the disk.
  - These have not been tuned to γ-ray data; They are for illustration only
  - The models shown below have either a 2D or 3D ISRF as indicated.

3D CRs with 2D ISRF IC at 200 MeV



3D CRs with 3D ISRF IC at 200 MeV



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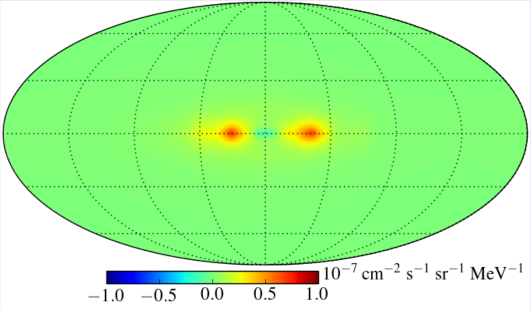
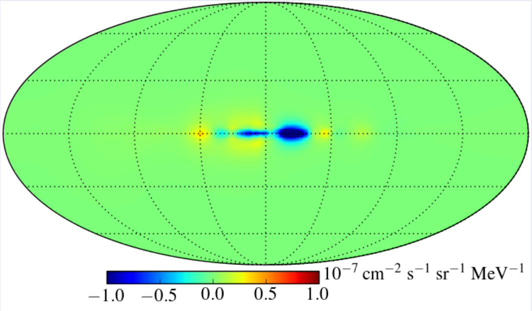
(3D CRs, 2D ISRF) - (2D CRs, 2D ISRF)

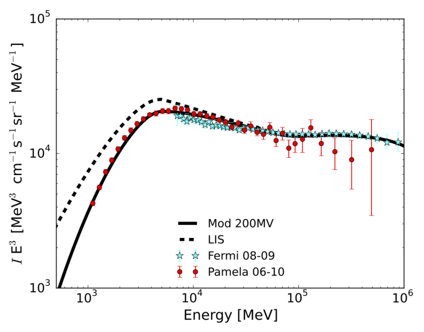


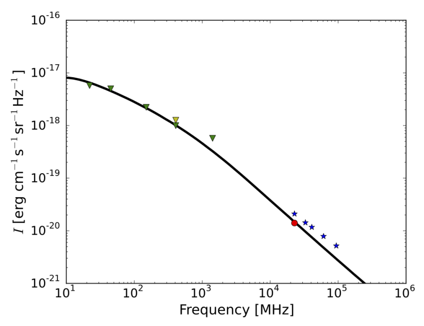
(3D CRs, 3D ISRF) - (2D CRs, 2D ISRF)



- Electron induced emission more prominent, both IC and bremsstrahlung.
- Getting constraints on the electron distribution from other data important.
  - CR electrons are strongly affected by heliospheric propagation.
  - Synchrotron emission can give important information on the CR electron spectra at low energies.

Synchrotron results from Orlando et al. ICRC 2015





Conclusions and Outlook

- Modeling the interstellar emission is a non-trivial task.
  - Many components, all of which have uncertainties to various degrees.
  - Important to simultaneously determine point source properties when modeling the interstellar emission.
- Pass 8 data provides improved resolution and acceptance that will help with source confusion.
  - Interstellar emission modeling is generally not statistically limited, but improved statistics allows us to make more severe quality cuts for better modeling.
- Synergies with multi-wavelength data like Planck and radio line emission surveys can allow us to study the physics of the interstellar medium with *Fermi*–LAT data.
- New and interesting modeling capabilities required to explain the high quality data the *Fermi*–LAT has been accumulating over the years.