Modelling Cosmic Rays and Interstellar Emission

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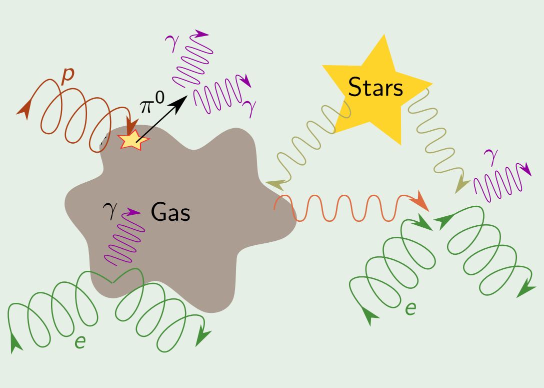
Outline

What is high-energy interstellar emission?

Emission processes

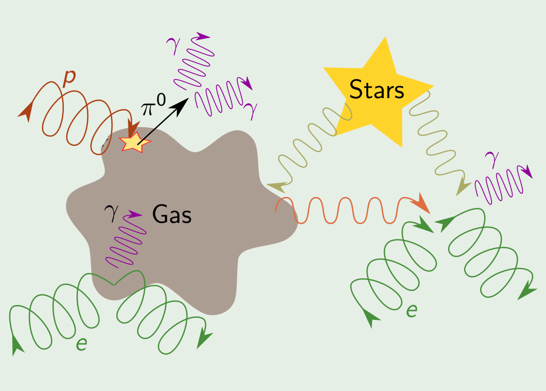


Typical definition

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

What is high-energy interstellar emission?

Emission processes



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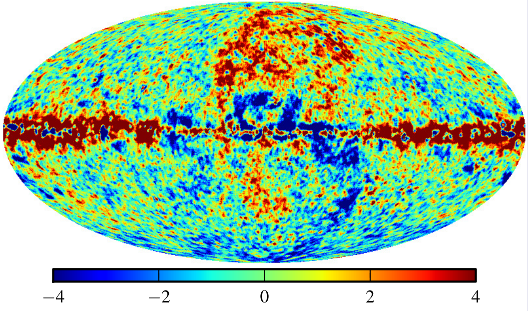
Very simple and useful

- "Only" need to know the distribution of CRs, the targets, and the interaction processes.

Example Interstellar Emission Models

Propagation models

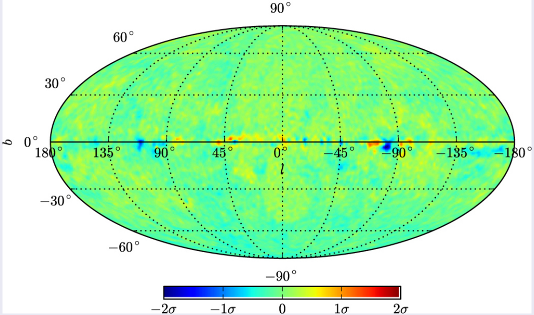
- CRs calculated assuming models for sources and propagation.
- Agrees reasonably well with data – residuals of the order of 10-30%



Ackermann et al. 2012, ApJ, 750, 3

Template models

- CRs calculated assuming each template is hit with constant CR flux.
- Additional EEE component with up to 10% of the emission in the plane.



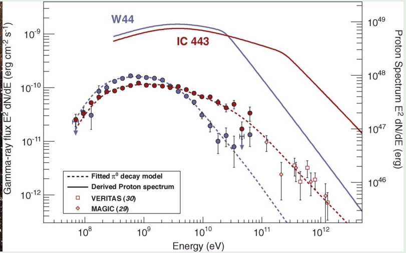
Acero et al. 2015, ApJS, 223, 26

Cosmic Rays – The Origin

Source classes

- Require significant power and ability to accelerate particles up to PeV energies.
- Most likely candidates are:
  - Supernova remnants

SNRs



Ackermann et al. 2013, Science, 339, 807

Cosmic Rays – The Origin

Source classes

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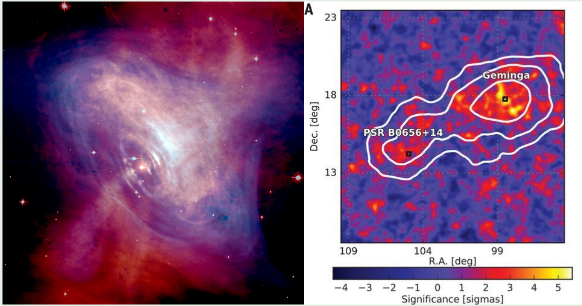
  - Pulsars

Pulsars



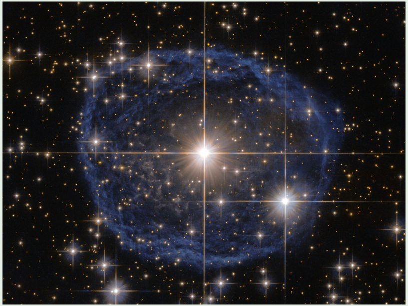
Abeysekara et al. 2017, Science, 358, 911

Cosmic Rays – The Origin

Source classes

- Require significant power and ability to accelerate particles up to PeV energies.
- Most likely candidates are:
  - Supernova remnants
  - Pulsars
  - Stellar wind ...
- Most associated with massive stars.

Stellar Wind



Judy Schmidt - https://www.spacetelescope.org/images/potw1608a/

Propagation of CRs

Effect of magnetic field

- CRs move at the speed of light, but are affected by magnetic fields in the Galaxy.
- Circular motion around field lines if they are regular.

B-field as noodles

Propagation of CRs

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- Turbulence causes the field lines to scramble leading to a diffusive process.
- Isotropic if field is random.

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- Turbulence causes the field lines to scramble leading to a diffusive process.
- Isotropic if field is random.
- Conditions in the ISM are likely somewhere in between.

Lots of uncertainties

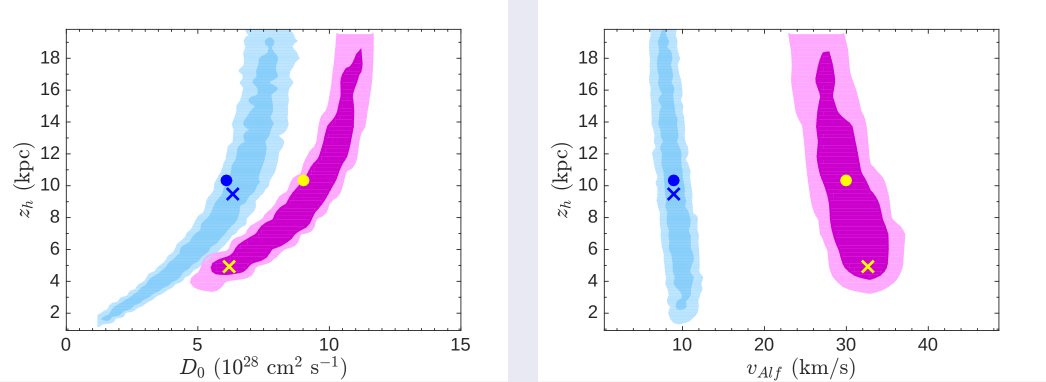
- Current theory far from complete and many details are missing.

B-field as noodles

Indications of Non-Uniform Diffusion

Johannesson et al. 2016, ApJ, 824, 16

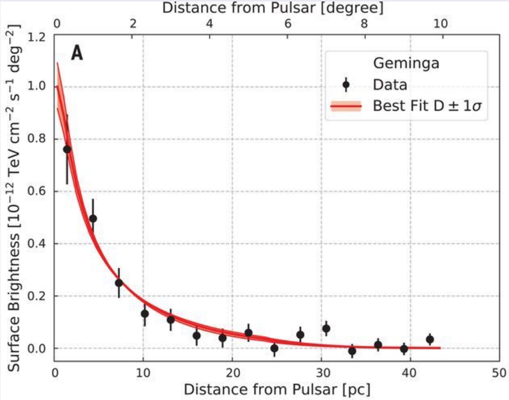
- Results from different secondary species indicate different propagation parameters.
- Hints at non-uniform propagation.



Indications of Non-Uniform Diffusion

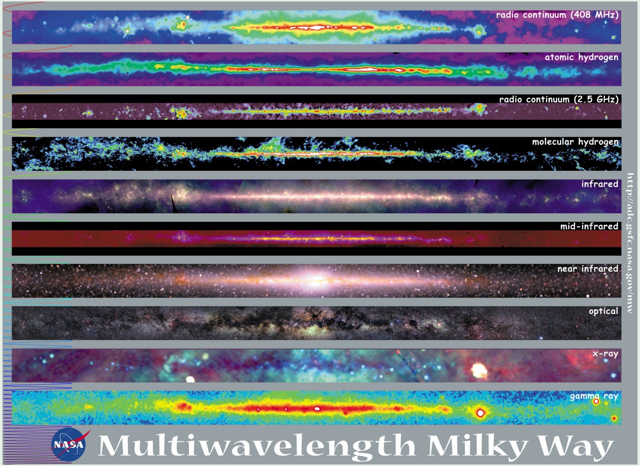
Abeysekara et al. 2017, Science, 358, 911

- HAWC observations of Geminga and PSR B0656+14 require diffusion coefficient that is two orders of magnitude smaller than estimated from CR secondaries.
- Observations of CR electrons at TeV energies not in agreement with such slow diffusion.



The Milky Way in several wavebands?

MW at different wavebands



Credit: NASA

The ISM

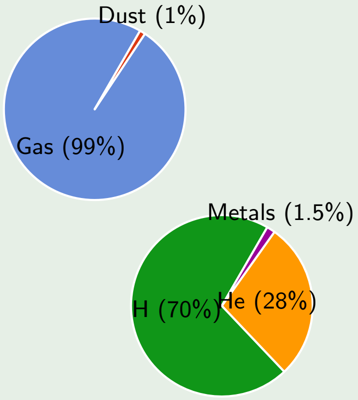
- Everything in a galaxy that is not a star is considered interstellar
  - Gas, dust, radiation, CRs, . . .
- It is very dynamic with structures on all scales.
- The energy density of the different components of the ISM are very similar
- No single component dominates the dynamics

Interstellar Matter

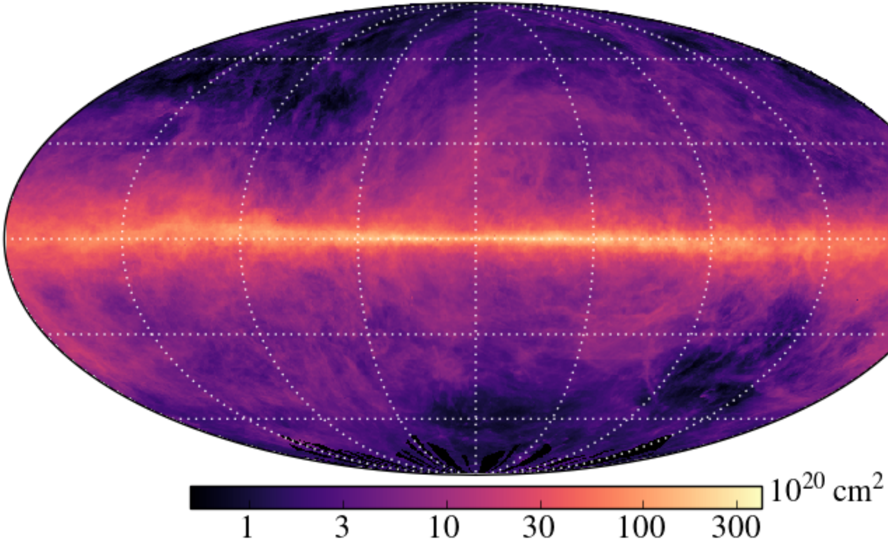
Gas and Dust

- Provides targets for production of secondary CR particles and energy losses.
- Split into dust and gas phase with a gas-to-dust ratio of ~ 100
  - Gas provides most of the mass.
- Interstellar gas is mostly hydrogen ($\sim 70\%$ of mass) and helium ($\sim 28\%$ of mass).
- Helium is really difficult to observe.
  - Assumed to follow the same distribution as hydrogen.
- Use 21-cm line emission of H I and 2.6-cm line of CO to constrain the distribution.

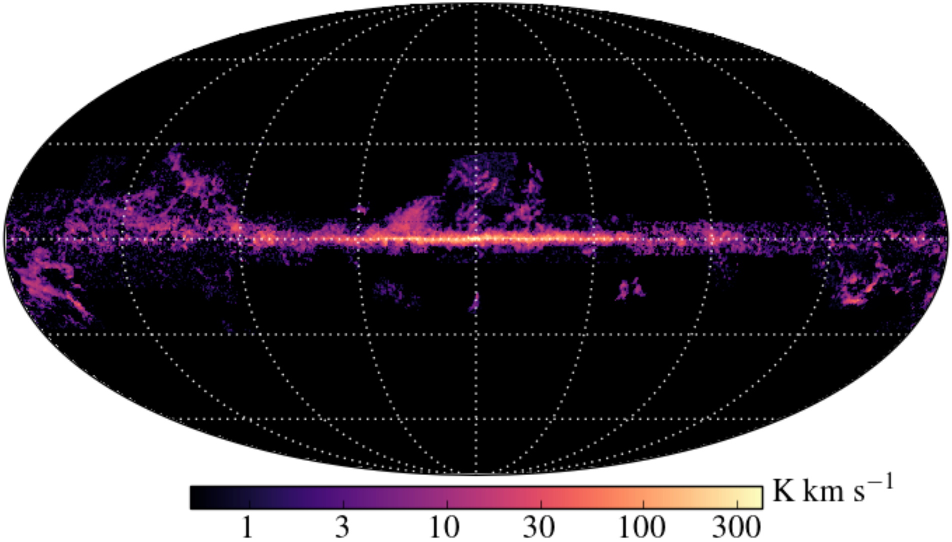
Components by mass



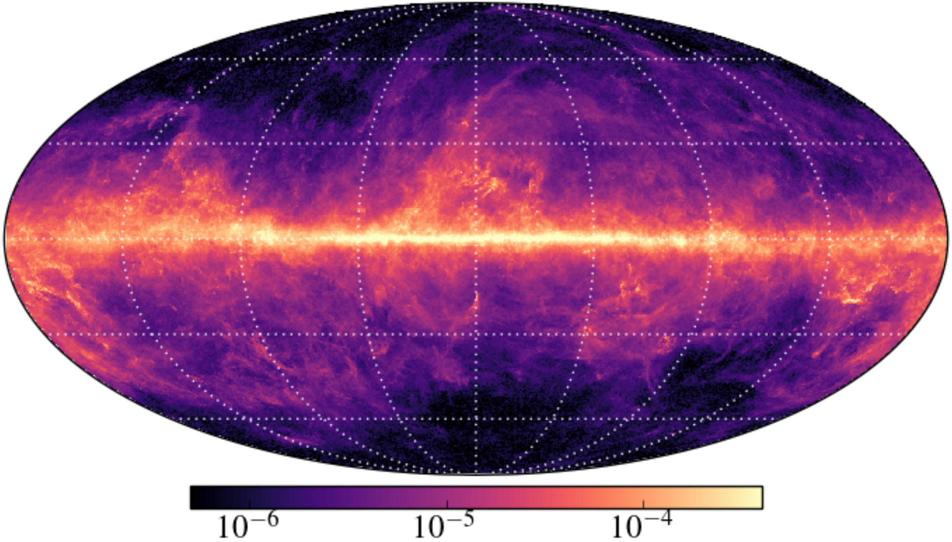
HI4PI survey (Ben Bekhti, N. et al. 2016, A&A 594)



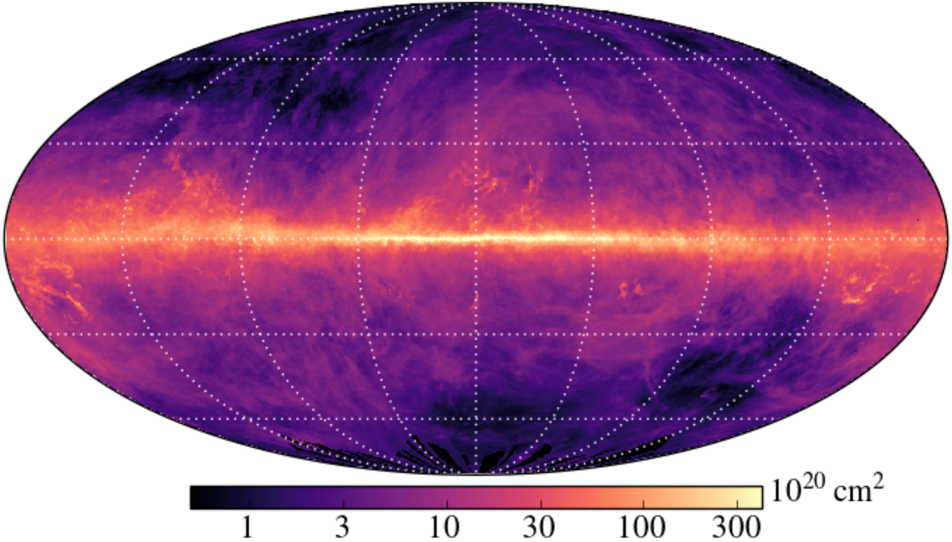
CO survey (Dame et al. 2001, ApJ 547)



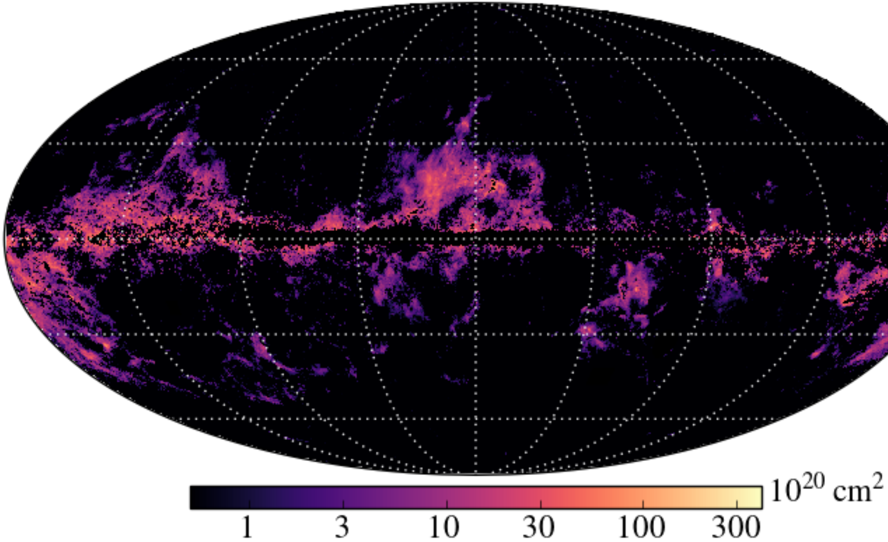
Planck τ_{353} (Planck Collaboration XI 2014, A&A, 571)



HI4PI + Dame CO using $X_{CO} = 2 \cdot 10^{20}$ cm^{-2} (K km/s)$^{-1}$



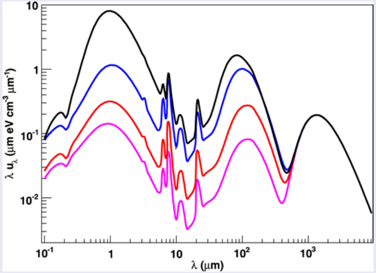
The DNM Sky



The Interstellar Radiation Field (ISRF)

Stars and dust

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.
- Significant freedom in model properties, especially in the inner Galaxy.

GALPROP code for CR transport and diffuse emission

GALPROP

- Tool for modelling and interpreting CR and non-thermal emissions data for Milky Way and other galaxies in a self consistent and realistic way.
- GALPROP can be downloaded/installed locally, or run from a web-browser at the GALPROP website: `http://galprop.stanford.edu`
- Newly released v56 includes among other things
  - Spatial variation in diffusion and re-acceleration.
  - Generalized source distributions and spectral models.
  - 3D gas and ISRF models.
  - Improved solvers for propagation – dramatic performance increase.

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A little warning

- Note that there is no such thing as "the" GALPROP model.

Example distribution of H I in external galaxies (THINGS)

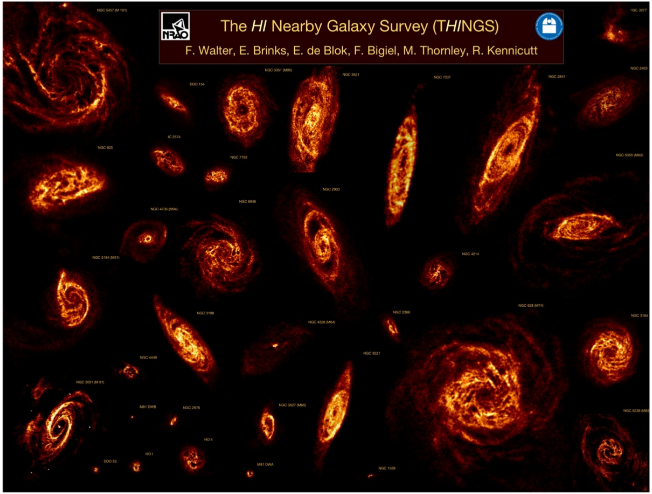
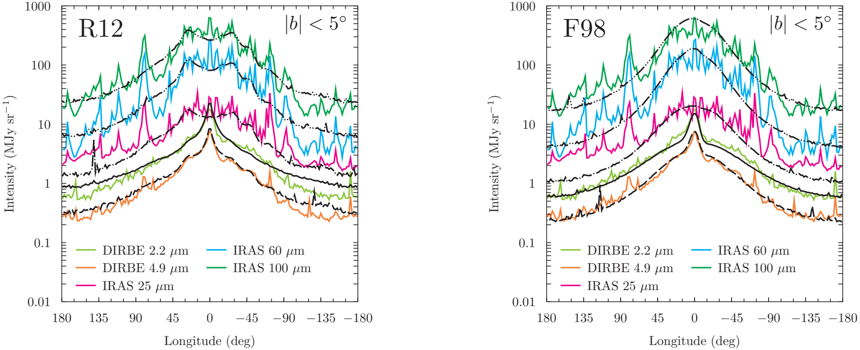


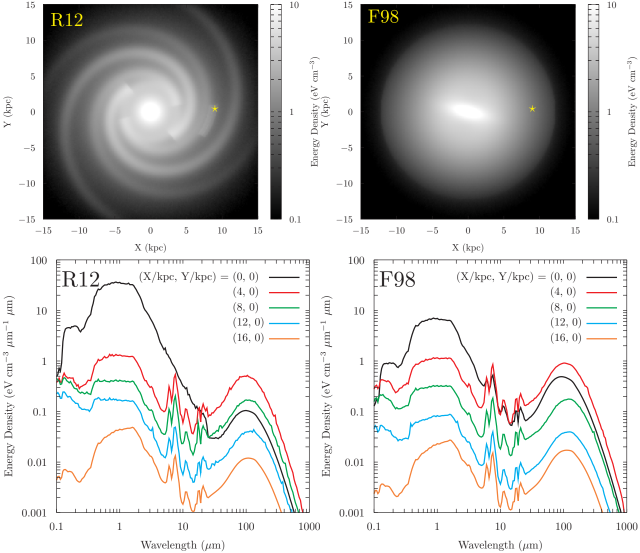
Image courtesy of NRAO/AUI and Fabian Walter, Max Planck Institute for Astronomy

3D Interstellar radiation field (ISRF)



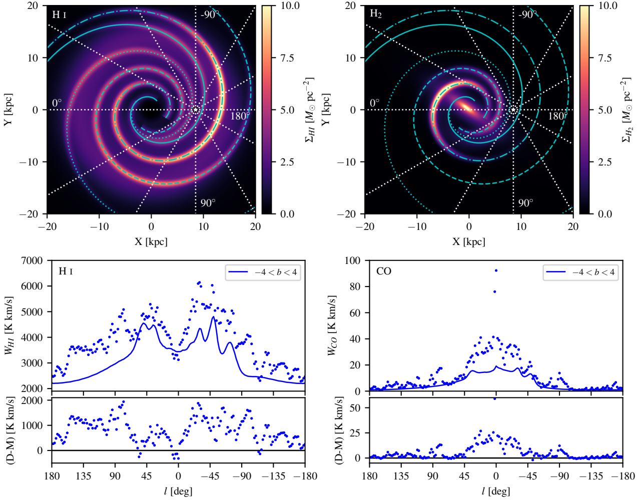
- R12 includes stellar disc, ring, bulge, 4/2 major/minor arms + dust disc with inner hole toward GC.
- F98 includes 'old' and 'young' stellar discs that are warped, spheroidal bar, and warped dust disc with inner hole toward GC.
- Full radiation transfer modelling using FRaNKIE code. Both models consistent with data.
- Porter et al. ApJ 846, 67 (2017) /arxiv:1708.00816

3D ISRF in the plane



- Different integrated energy density distributions that reflect the stellar and dust distributions.
- In and about the inner Galaxy there is a factor ~ 5 difference between the models.

New 3D distributions for interstellar gas

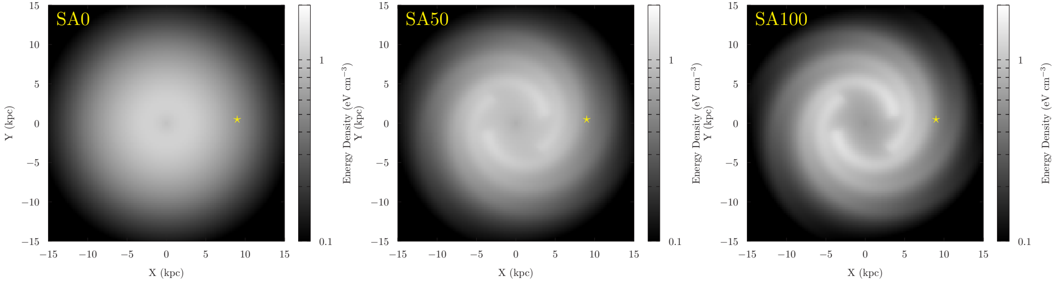


- Forward-folding fitting method.
- H I on left (LAB) and CO on right (CfA).
- Disk and arms have same scale-height and radial distribution.
- Spiral arm shape same for H I and CO but each arm has free normalization.

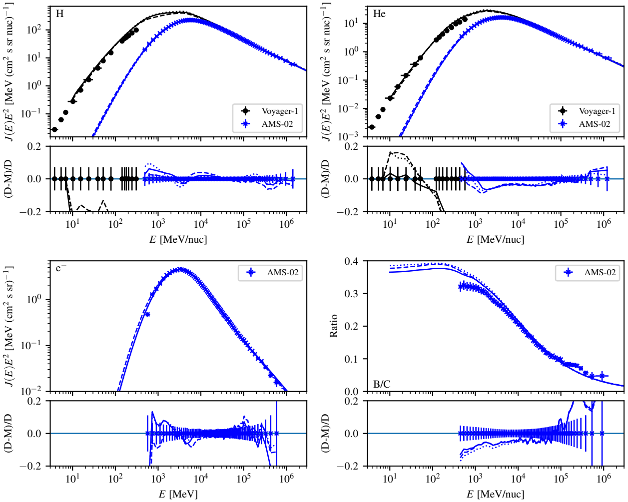
- Johannesson et al. 2018, ApJ, 856, 45

3D models for interstellar emission

- GALPROP v56 + 3D ISRF + 3D gas + 3D CR source density.
- 3 CR source density models: CR power injected according to 'Pulsars' (2D), 50% Pulsars + 50% spiral arms, 100% spiral arms.
- Propagation parameters adjusted for each to reproduce measurements of CRs near Earth.
- The models are not tuned to γ-ray data.
- Reference case: 2D CR, 2D gas, 2D ISRF

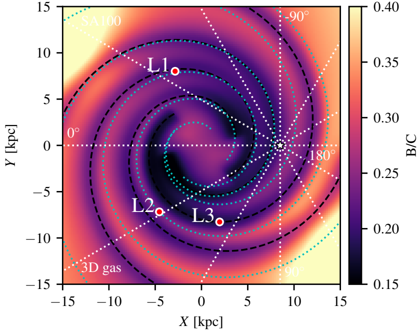


CR propagation tuning

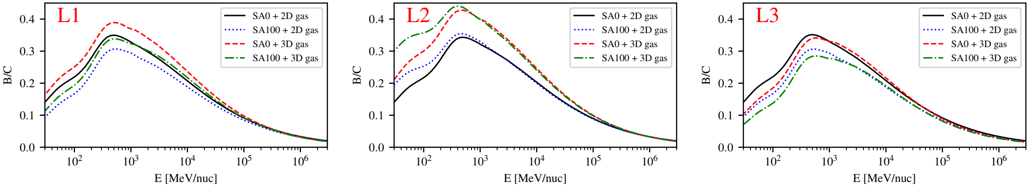


- Tune propagation and CR source injection spectra to match local CR data: AMS-02, PAMELA, HEAO-3.
  - Propagation depends on the details of the gas and CR source distributions.
  - Diffusion slower with new 3D gas models compared to previous 2D models.
- All the models agree reasonable with data and well with each other at the solar location.

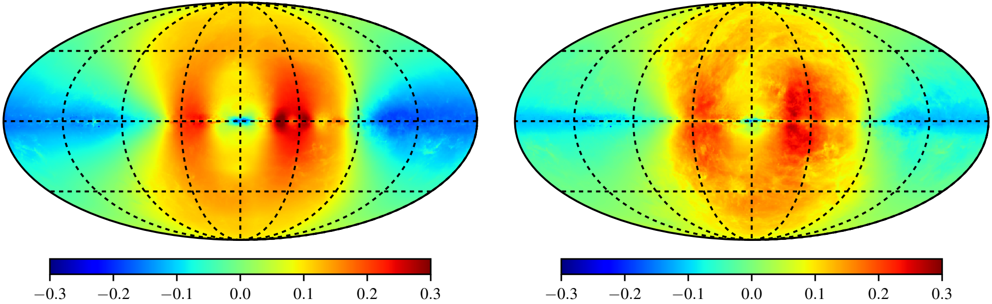
CRs in the plane



- The interpretation of local data now strongly depends on our position relative to the 3D structure.
- More secondaries in dense gas regions while more primaries near the CR sources.
- Extent of these regions depends on the estimated propagation.

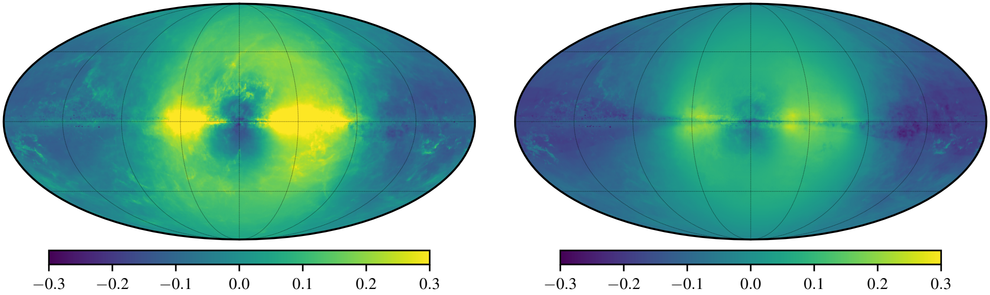


Interstellar Emission for SA100 + R12 + 2D gas



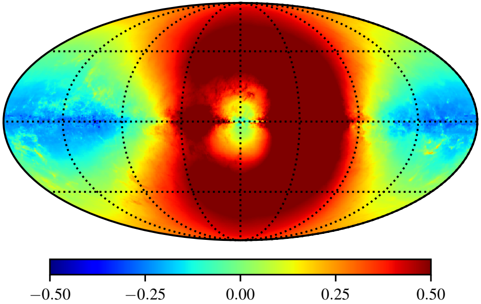
- Fractional residual maps (model/reference - 1) at 10 MeV (left) and 1 GeV (right).
- Most of the enhancement in the IC component. Squared effect because spiral arms of CR sources and ISRF align.
- The 'hole' at the GC is because the spiral arm cut off for $R \lesssim 4$ kpc.

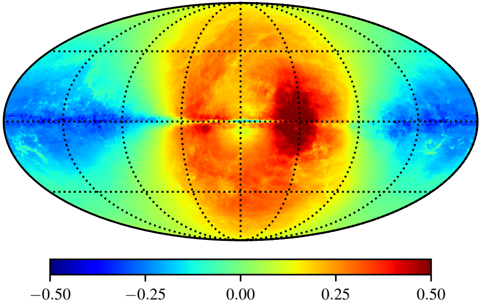
Interstellar Emission for SA100 + 2D ISRF + 3D gas



- Fractional residual maps (model/reference - 1) at 30 MeV (left) and 1 GeV (right).
- Similar features as before but more confined to the plane because diffusion coefficient is smaller and ISRF is 2D.
- The CR e^- injection spectrum is softer at low energies which produces more low energy γ-rays.

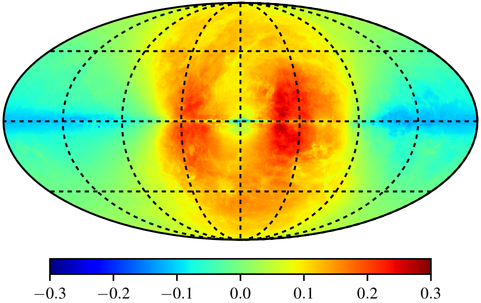
Interstellar Emission for SA100 + R12 + 3D gas

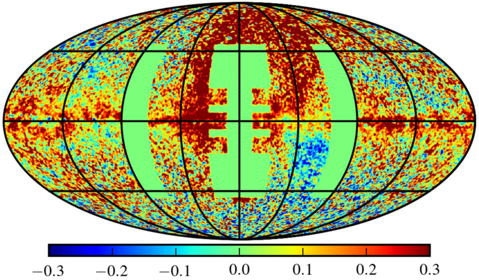




- Fractional residual maps (model/reference - 1) at 10 MeV (left) and 1 GeV (right).
- A combination of the effects of all 3 show significantly stronger features for all emission processes.
- Note the different scale compared to previous 2 slides.

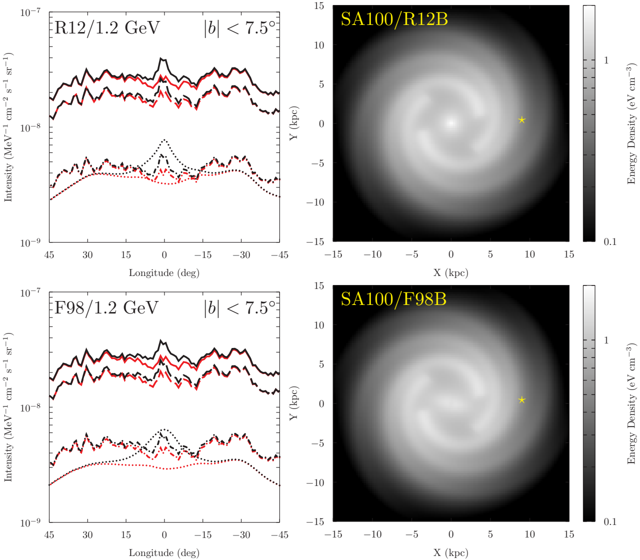
Possible interpretations





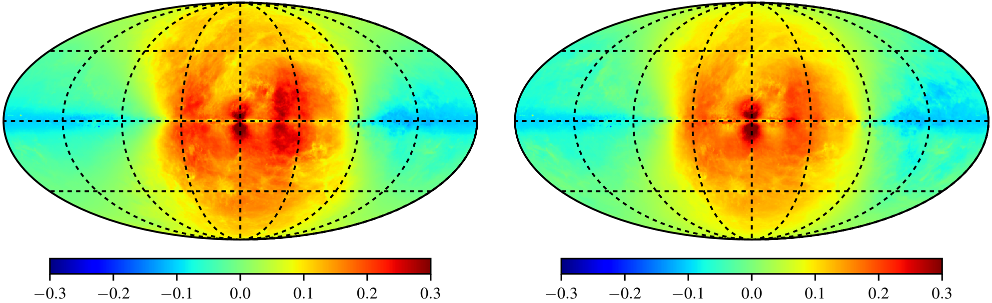
- Fractional residuals for (SA100 + R12 + 2D gas) (left) compared to fractional residual map from Ajello et al. (2016) ApJ 819, 44 using 62 months of *Fermi*-LAT data 1 - 3.16 GeV.
- Clear similarities between some of the features at about the correct magnitude.

Filling in the GC hole



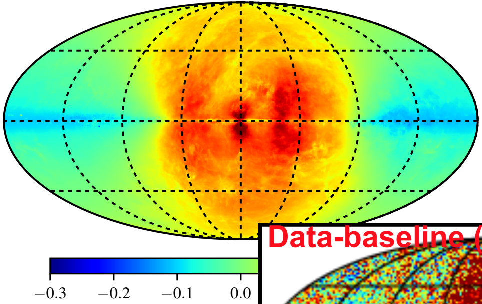
- Add CR sources in the bulge/bar (black curves) and compare to same model without bulge/bar (red curves).
- This is a “what if” scenario, no fitting involved.
- Power of source adjusted so local CR predictions are not affected.

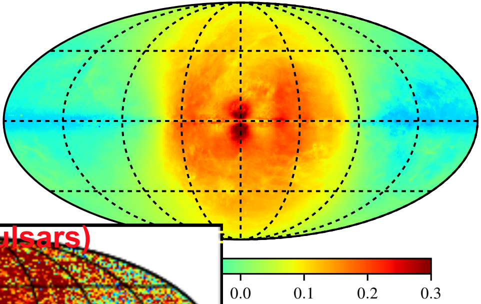
Hole has been filled

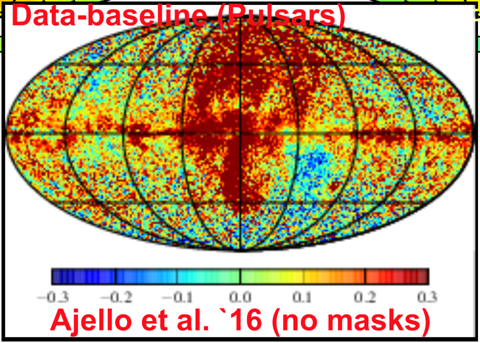


- Fractional residuals using SA100 + 3D ISRF + 2D gas for R12 bulge (left) and F98 bar (right) at 1 GeV.
- CR power injected in bulge $\sim$ 25 times smaller than in arms.
- Hint of a asymmetric bulge component that could explain the increased IC needed in Ajello et al. (2016) ApJ 819, 44.

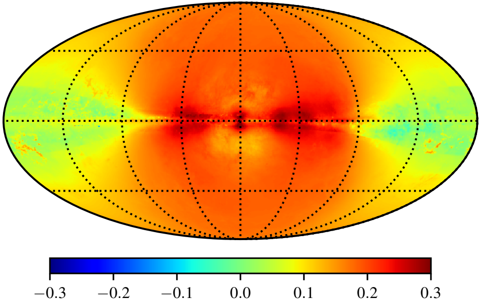
Hole has been filled

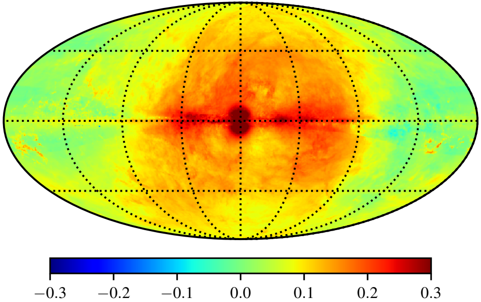






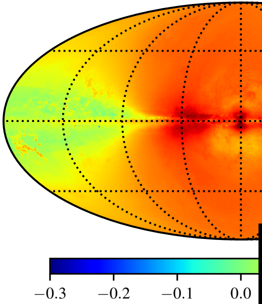
Hole has been filled again

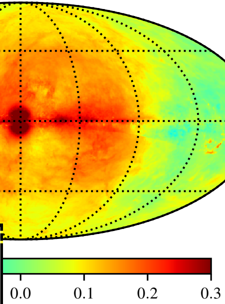


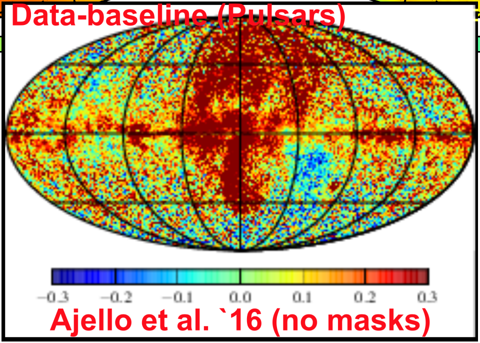


- Fractional residuals for using SA50 + 3D ISRF + 3D gas for R12 bulge (left) and F98 bar (right) at 1 GeV.
- CR power injected in bulge/bar same as before but the extra component in the GC is even brighter.

Hole has been filled again







Summary

- New 3D models for ISM density distributions have been developed: ISRF (Porter et al.) and Gas (Johannesson et al.).
- New GALPROP release v56 with many additions and optimisations: specific focus improving performance for full 3D CR and interstellar emission calculations.
- Modelling with GALPROP v56 release using 3D CR source and ISM density models show new features in residual maps compared to 2D-based reference calculations $\rightarrow$ interstellar emission sensitive to 3D spatial structure of CRs, gas, and ISRF in ISM.
- The 3D models provide plausible explanation for the puzzling results from the analysis based on 2D axisymmetric models: CR sources in spiral arms and central bulge/bar *in combination* with 3D ISM models are the key.

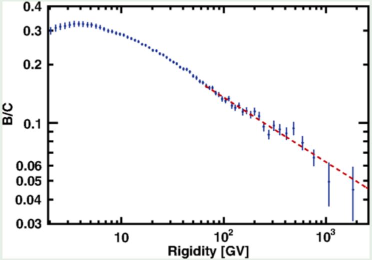
The End

Secondary CR particles

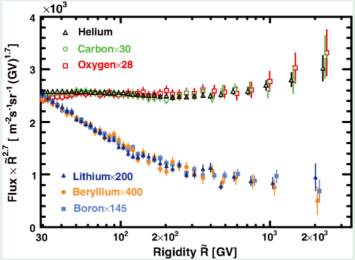
Basic idea

- Interactions between CRs and interstellar matter results in “secondary” CR particles.
- The ratio of “secondary” to “primary” CR particle indicates effect of propagation.
- Need to know the production cross sections accurately to properly use them.

AMS results



Phys. Rev. Lett. 117, 231102 (2016)



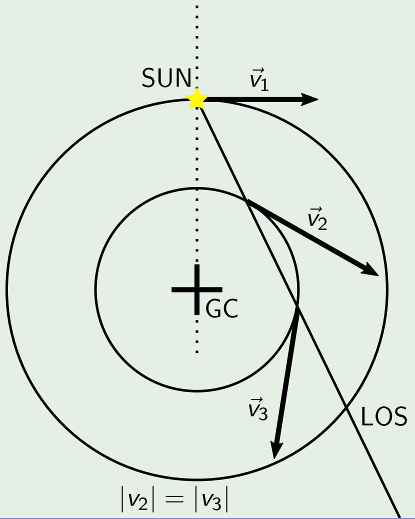
Phys. Rev. Lett. 120, 021101 (2018)

Kinematic Distances and Rotation Curves

Velocity model

- Doppler shift of emission lines used to place gas given a model for its velcotiy field in the Galaxy.
- Cylindrical rotation is a good approximation for the gas motion.

Illustration



Kinematic Distances and Rotation Curves

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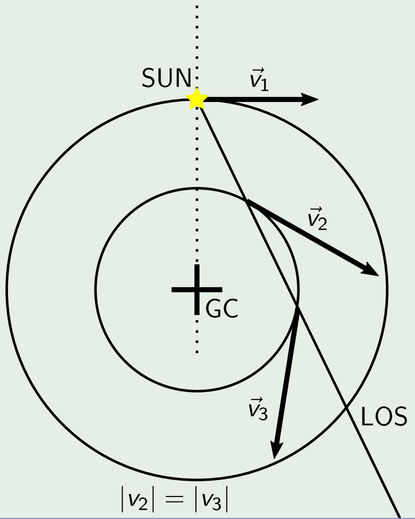
- Cylindrical rotation is a good approximation for the gas motion.

Some known issues

- Near–far ambiguity in the inner Galaxy.
- Does not work for directions near dotted line.
- Limited distance resolution because of thermal and turbulent motion.
- Non–circular motion.
- Difficult to measure rotation curve, especially in the outer Galaxy.

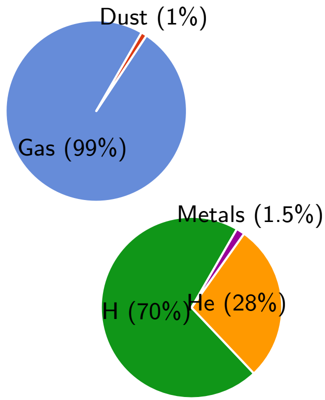
Illustration



Interstellar Matter

- Provides targets for production of secondary CR particles and energy losses.
- Split into dust and gas phase with a gas-to-dust ratio of ~ 100
  - Gas provides most of the mass.
- Interstellar gas is mostly hydrogen ($\sim 70\%$ of mass) and helium ($\sim 28\%$ of mass).
- Helium is really difficult to observe.
  - Assumed to follow the same distribution as hydrogen.
- Use 21-cm line emission of H I and 2.6-cm line of CO to constrain the distribution.

Components by mass



Example distribution of H I in external galaxies

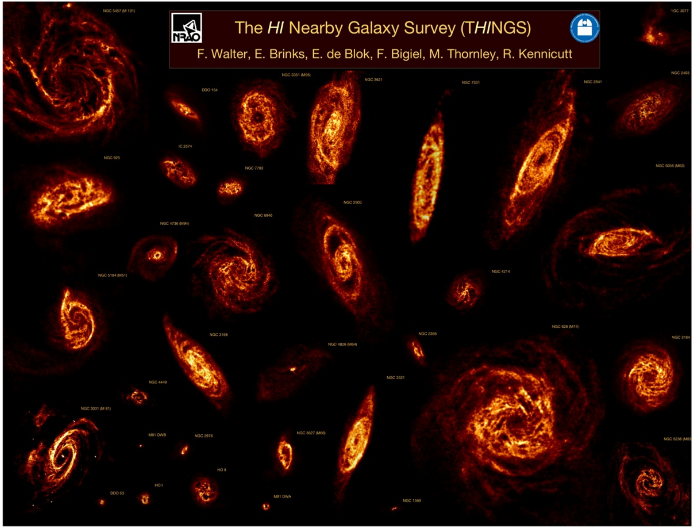
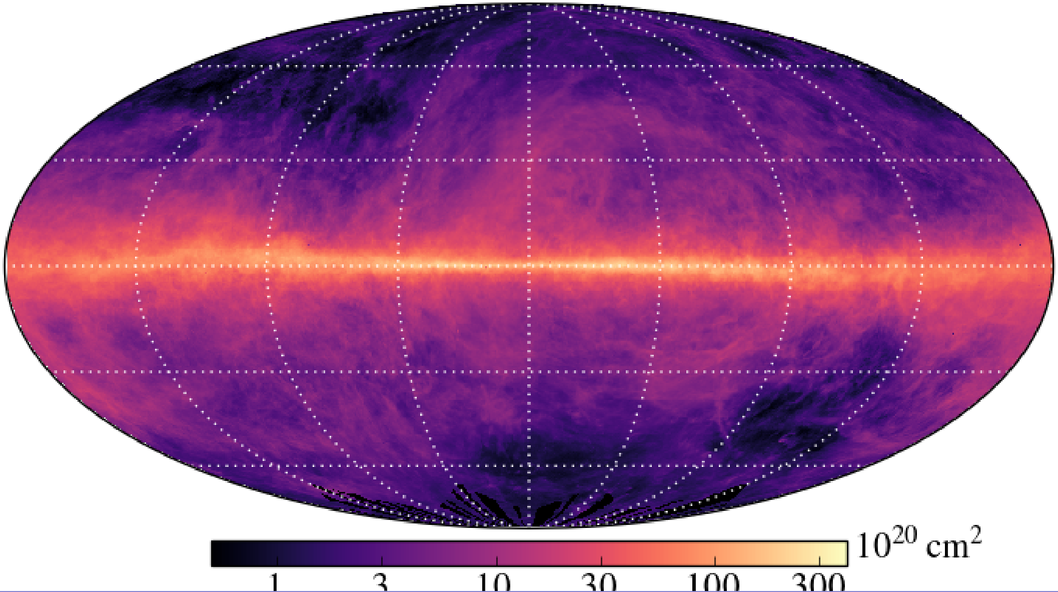


Image courtesy of NRAO/AUI and Fabian Walter, Max Planck Institute for Astronomy

Observed distribution of H I in the Milky-Way



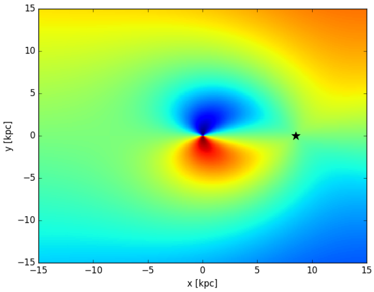
Obtaining 3D information

- Under the assumption that the gas is in spherical rotation around the Galactic center we can easily turn velocity into distance

$$V_{LSR} = \sin l \cos b \left[\frac{R_\odot}{R} \Theta(R) - \Theta(R_\odot) \right]$$

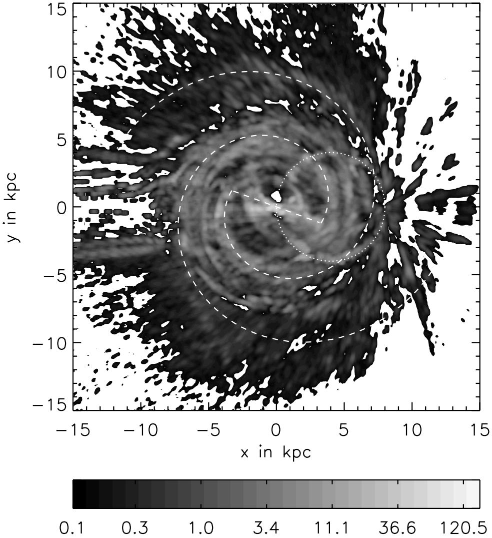
  where $\Theta(R)$ is the Galactic rotation curve, $R_\odot$ is the radius of the sun and l and b are Galactic longitude and latitude, respectively.
- V_{LSR} is the velocity measured with respect to the local standard of rest that is moving in a circular orbit around the Galactic center.

Figure showing V_{LSR} in the Galactic plane for a fixed rotation curve.

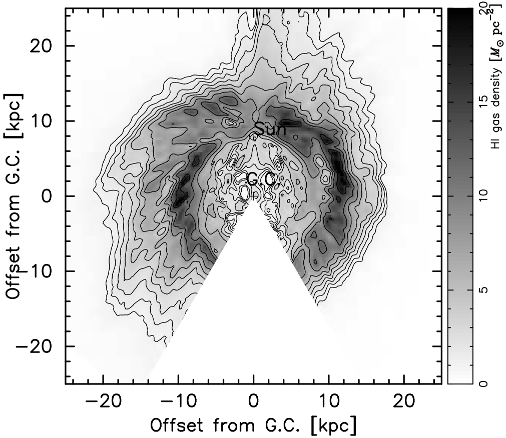


Lines of sight with $\sin l \approx 0$ provide no distance information.

3D distributions using kinematic distances



CO from Pohl et al. 2008.

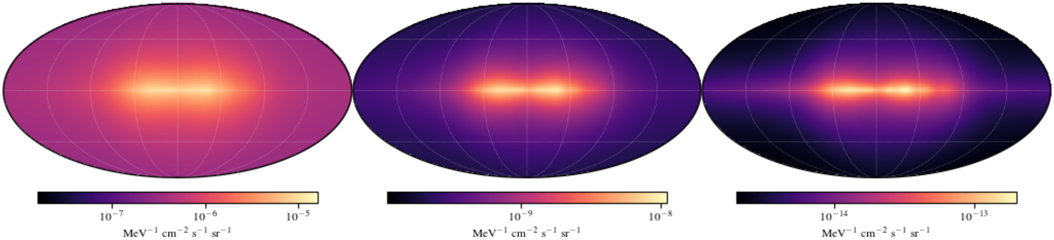


H I from Nakanashi & Sofue 2015.

Our Approach - Forward Folding Model

- Parameterized model that is integrated along lines-of-sight to create emission profiles that can be directly compared to data.
    - GALGAS code handles the integration and comparison.
    - Model built from simple geometrical components.
- Has several advantages:
    - Automatic interpolation over longitude ranges around $l = 0^\circ$ and $l = 180^\circ$.
    - Smoothness of model enforced, no fingers of god.
    - Complexity of model controlled, effects of individual components on CR propagation can be studied.
    - Easier to explore complex models for gas rotation.
- And some disadvantages:
    - Need a lot of components to capture the complex structure of the interstellar gas.
    - The number of model parameters quickly grows and model tuning becomes very time consuming.

γ-ray maps for SA100 + 2D ISRF + 3D gas



- IC maps at 30 MeV (left), 1 GeV (center), and 100 GeV (right).
- Effect of spiral arms visible but a bit fuzzy because of diffusion.