Time Dependent Interstellar Emission Models

– Recent GALPROP Developments –

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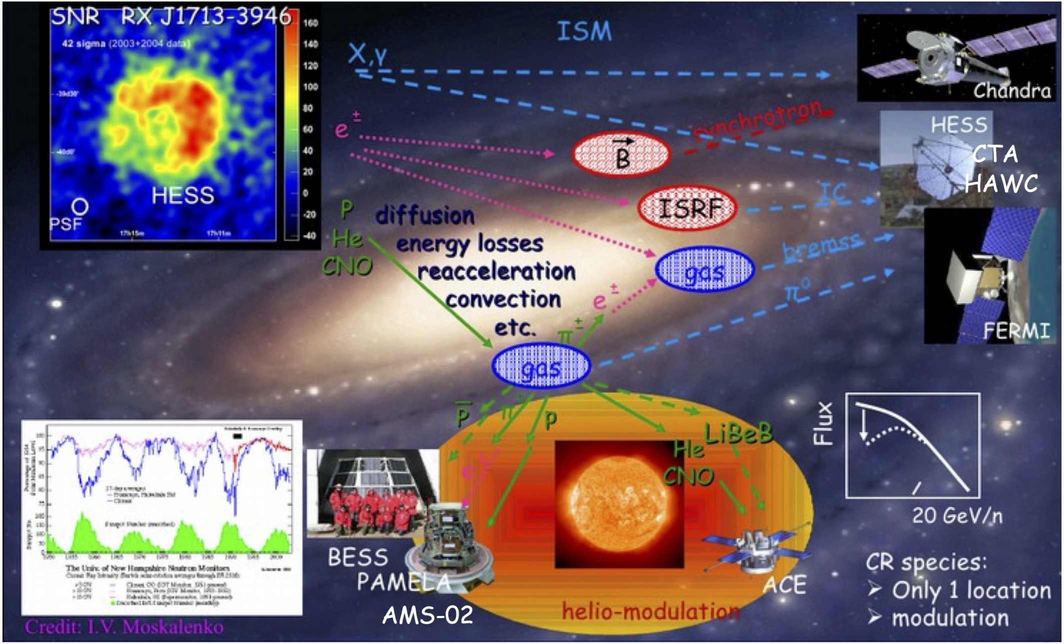
Collaborators: Troy Porter & Igor Moskalenko



SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
ISM
X,γ
Chandra
e±
B
synchrotron
HESS
CTA
HAWC
ISRF
IC
P
He
CNO
diffusion
energy losses
reacceleration
convection
etc.
gas
bremss
π0
FERMI
e±
π±
gas
P̄
p
LiBeB
He
CNO
Flux
20 GeV/n
BESS
PAMELA
AMS-02
ACE
helio-modulation
CR species:
➢ Only 1 location
➢ modulation
The Univ. of New Hampshire Neutron Monitors
Credit: I.V. Moskalenko

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 coefficient and Alfvén speed (re-acceleration).
  - Generalized source distributions (2D and 3D) and spectral models.
  - 3D gas and ISRF models.
  - Improved solvers for propagation – dramatic performance increase.
  - New integrators for non-thermal intensity map calculations.

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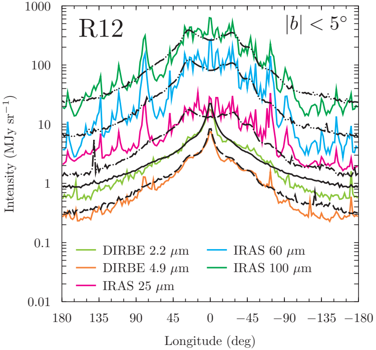
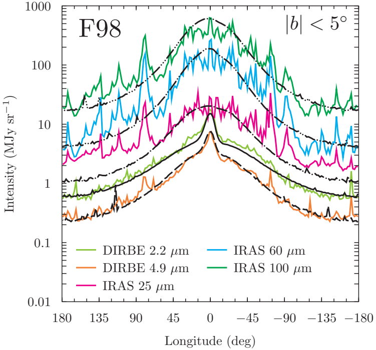
A little warning

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

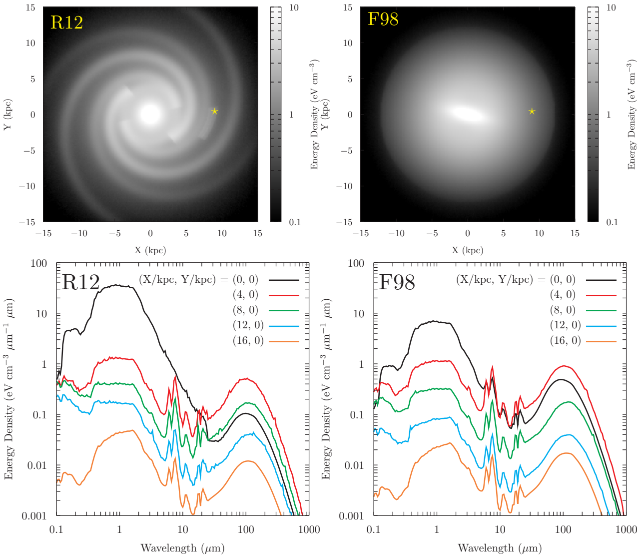
3D Interstellar radiation field (ISRF)





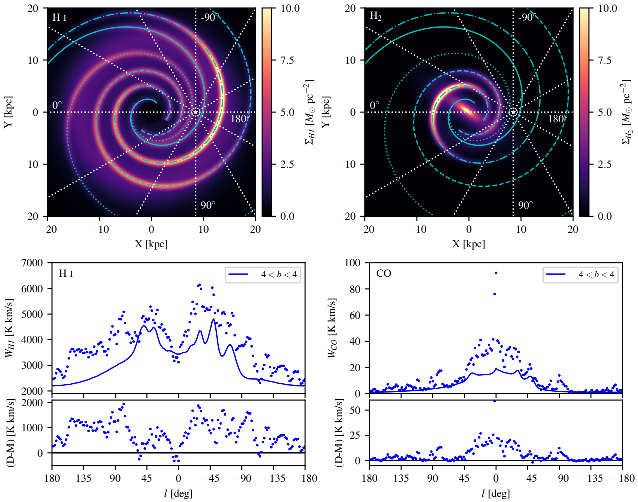
- R12 includes stellar disc, ring, bulge, 4/2 major/minor arms + dust disc with inner hole toward GC.
- F98 includes 'old' and 'young' stellar discs that are warped, spheroidal bar, and warped dust disc with inner hole toward GC.
- Full radiation transfer modelling using FRaNKIE code. Both models consistent 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.

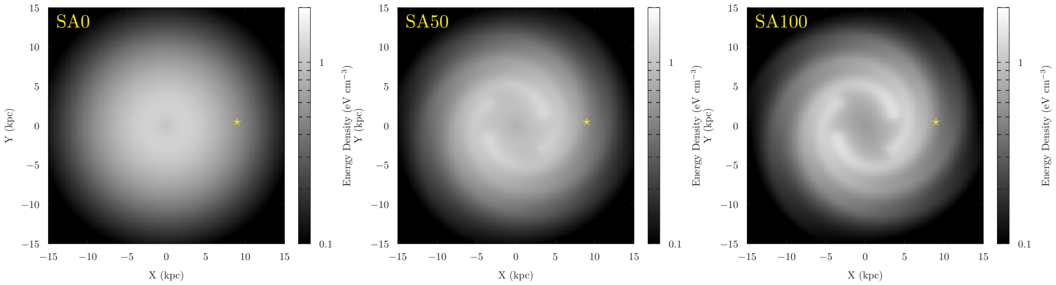
New 3D distributions for interstellar gas



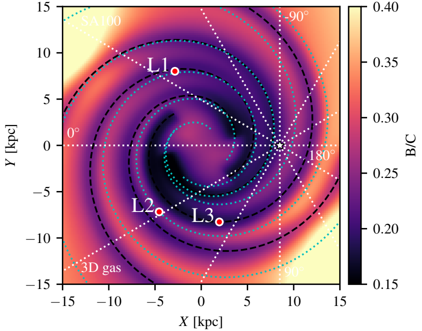
- Forward-folding fitting method.
- H I on left (LAB) and CO on right (CfA).
- Disk and arms have same scale-height and radial distribution.
- Spiral arm shape same for H I and CO but each arm has free normalization.
- Johannesson et al. 2018, ApJ, 856, 45 / arXiv:1802.08646

3D models for interstellar emission

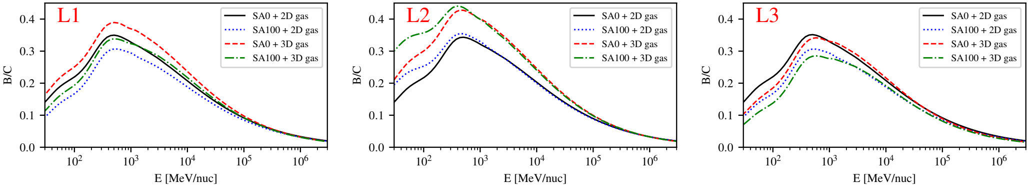
- GALPROP v56 + 3D ISRF + 3D gas + 3D CR source density.
- 3 CR source density models: CR power injected according to 'Pulsars' (2D), 50% Pulsars + 50% spiral arms, 100% spiral arms.
- Propagation parameters adjusted for each to reproduce measurements of CRs near Earth.
- The models are not tuned to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



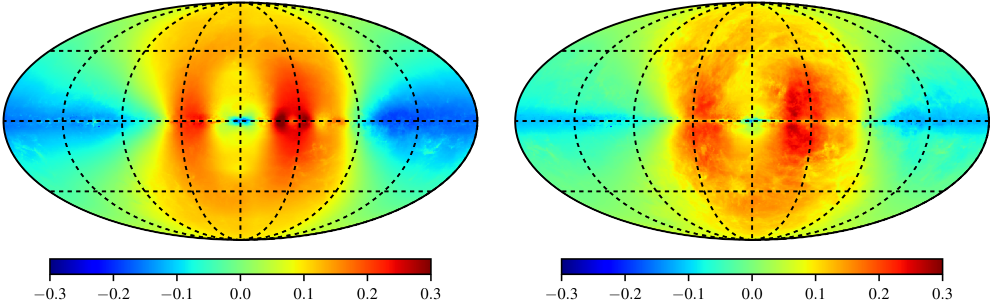
CRs in the plane, SA100 + 2D ISRF + 3D gas



- 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.

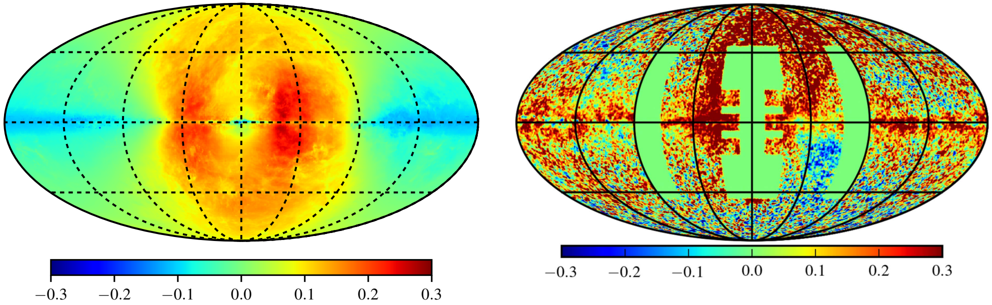


Interstellar Emission for SA100 + R12 + 2D gas



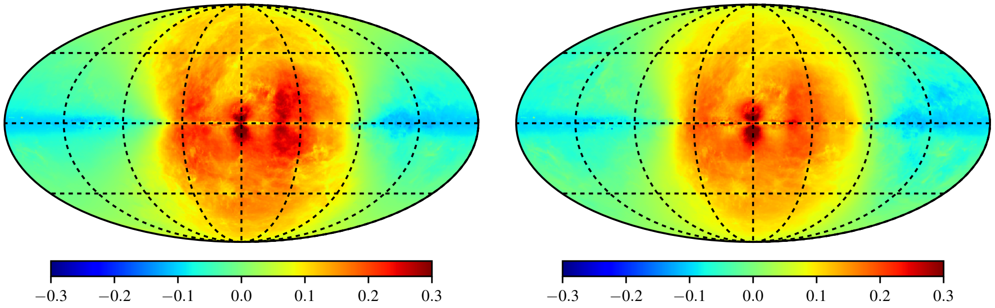
- Fractional residual maps (model/reference - 1) at 10 MeV (left) and 1 GeV (right).
- Most of the enhancement in the IC component. Squared effect because spiral arms of CR sources and ISRF align.
- The 'hole' at the GC is because the spiral arm cut off for $R \lesssim 4$ kpc.

Possible interpretations



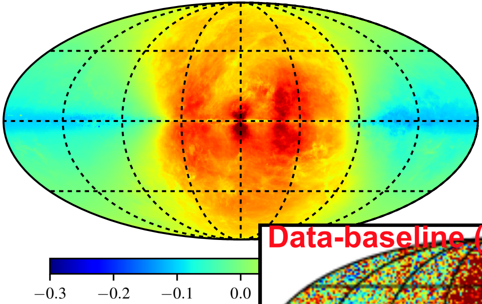
- Fractional residuals for (SA100 + R12 + 2D gas) (left) compared to fractional residual map from Ajello et al. (2016) ApJ 819, 44 using 62 months of *Fermi*-LAT data 1 - 3.16 GeV.
- Clear similarities between some of the features at about the correct magnitude.

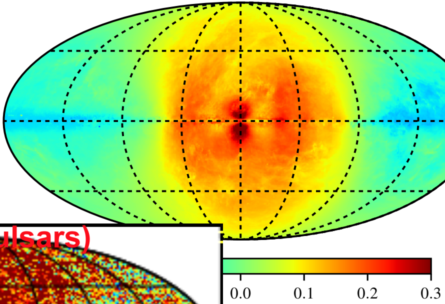
Adding CR sources in the bulge

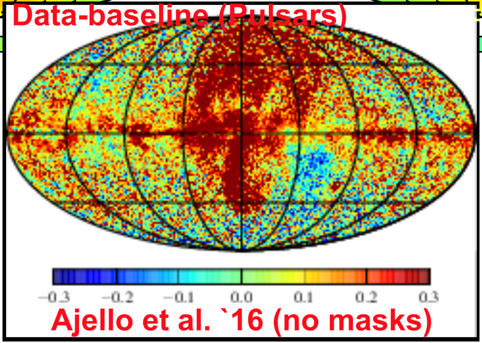


- Fractional residuals using SA100 + 3D ISRF + 2D gas for R12 bulge (left) and F98 bar (right) at 1 GeV.
- CR power injected in bulge $\sim$ 25 times smaller than in arms.
- Hint of a asymmetric bulge component that could explain the increased IC needed in Ajello et al. (2016) ApJ 819, 44.

Adding CR sources in the bulge







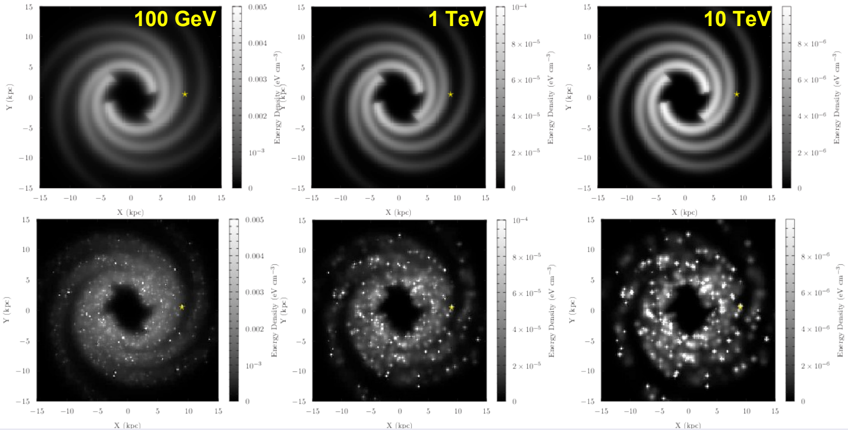
Recent developments – Time dependent calculations

- CRs are most likely generated in individual sources over short periods of time and not continuously from a smooth distribution.
- Transition from a smooth "sea" of old propagated CRs to distribution of freshly accelerated sources caused by energy losses.
- Most notable in IC emission at $\gtrsim$ 100 GeV energies.
  - Lots of photons collected by *Fermi*-LAT; HESS Galactic plane survey; HAWC; CTA in the near future.
  - Very important to have a tool that can explore these features.
- GALPROP now efficiently calculates full 3D interstellar emissions using time dependent CR injection and/or propagation.
- Implemented a discrete sampler that can use arbitray underlying source density. Number of sources, their duration, and their size are user defined parameters.
- Also allows for non-linear grid spacing to improve resolution where needed.

Time dependent CR source distribution

- SA100 source density, propagation parameters determined from calculations using smooth distribution. Same average CR injected power.
- Smooth on top, discrete after 10 Myr on bottom.

CR electron density in the plane



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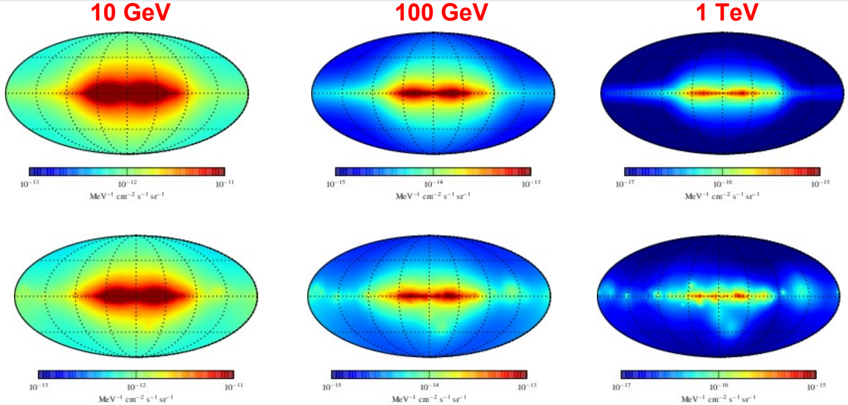
IC intensity maps

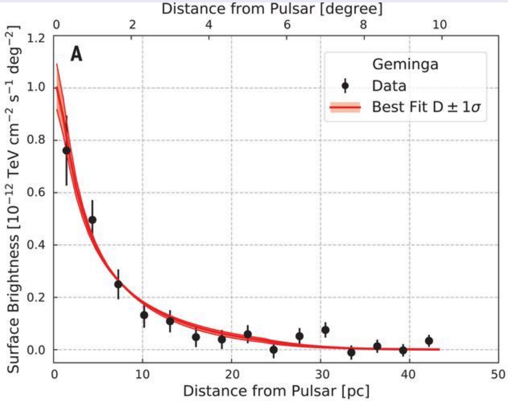


Indications of Non-Uniform Diffusion

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.

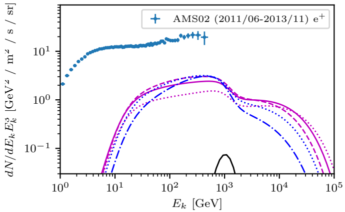
- Observations of CR electrons at TeV energies not in agreement with such slow diffusion.
- Can be mitigated by having a small zone of slow diffusion around the PWN.
- See also talk by Andy Smith on Tuesday.



Two zone diffusion model for Geminga

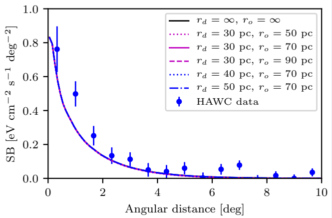
- Small diffusion coefficient within r_d increasing to ISM diffusion at r_o. Fixed fraction of spin-down energy converted to electrons and positrons.
- Significantly affects the predictions for CRs reaching earth and the predicted emission in the *Fermi*-LAT energy range
- See also poster by Mattia Di Mauro et al.

Positrons at Earth

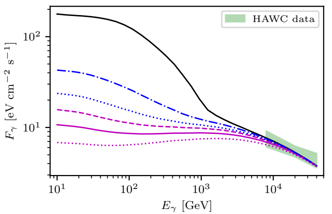


GALPROP calculations

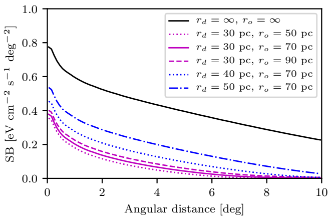
Profile at 8–40 TeV



Spectrum within 15°



Profile at 3–10 GeV



Summary

- 3D models for ISM density distributions have been developed: ISRF (Porter et al.) and Gas (Johannesson et al.).
- 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 TeV interstellar emission very sensitive to the point like stochastic nature of CR sources. Inverse Compton intensity has more structure than previously estimated at those energies.
- Strong indication that diffusion may be smaller near CR sources. This will further enhance the effect of source stochasticity.