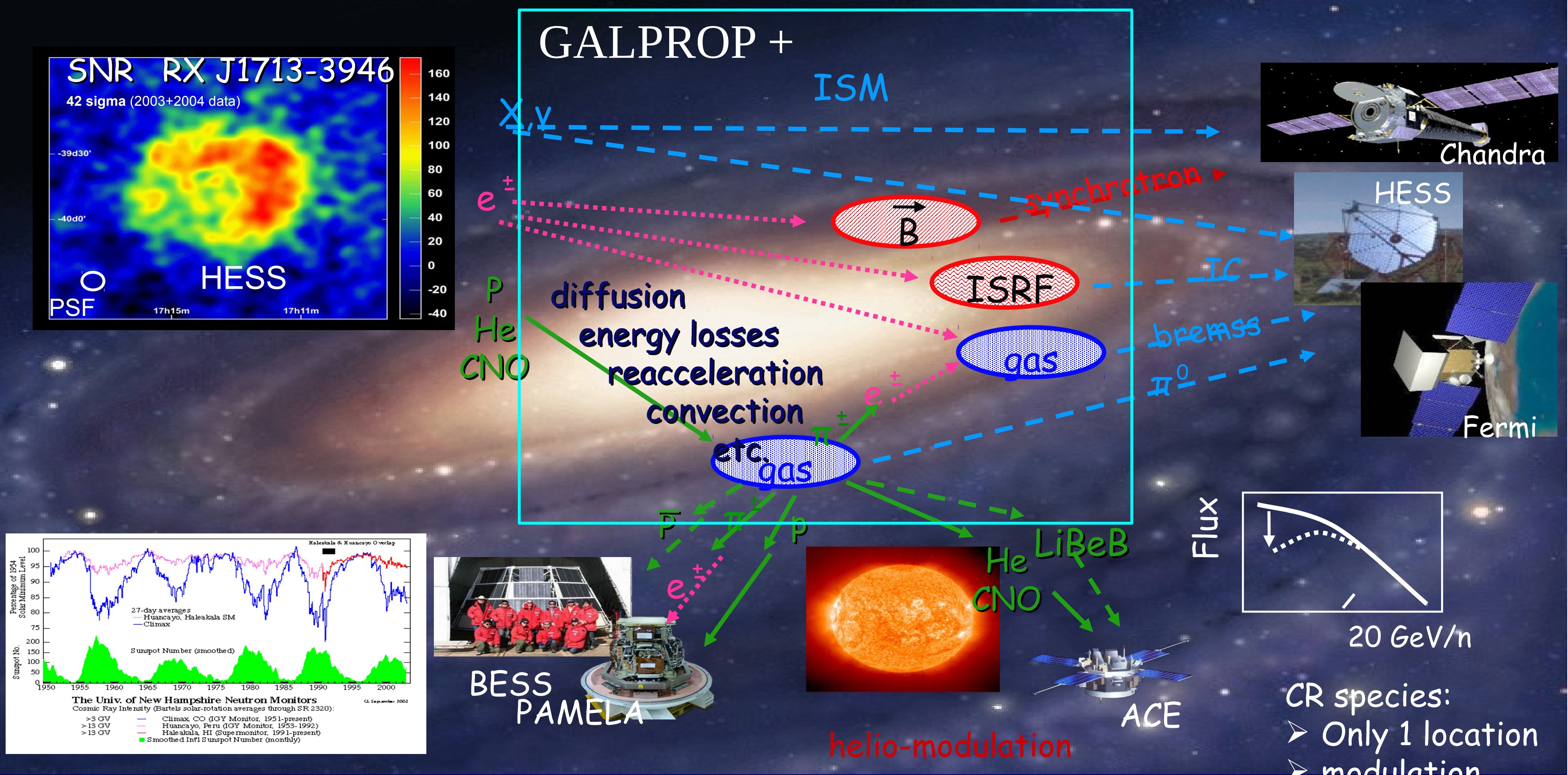
High-Energy Gamma-Rays from the Milky Way: 3D Spatial Models for the CR and Radiation Field Densities

Troy A. Porter
Stanford University

What is GALPROP?

- **Tool for modelling and interpreting cosmic-ray (CR) and non-thermal emissions data**
- **Key ideas: self-consistent modelling and realism**
- **Self-consistency: different kinds of data (CR data, radio, gamma rays) are inter-related because the measured CRs propagate in the ISM losing energy, which produce broadband EM emissions and other secondaries that are also measured**
- **Realism: objective to include as much realism into the underlying models for the ISM and CR sources, and propagation phenomenology – based on extensive collection of astronomical and nuclear/particle data with minimal simplifying assumptions**
- **GALPROP combines these into a framework that can be downloaded/installed locally, or run from a web-browser at the GALPROP website: galprop.stanford.edu**

Cosmic Rays and Interstellar Emission



Developments and New Release

- Numerous technical and physics improvements
- Spatial variations in propagation for diffusion via diffusion coefficient and Alfven speed (reacceleration)
- Generalised source distribution and spectral models: separately specified spatial densities and spectra for each CR species
- 2D/3D gas models
- 2D/3D interstellar radiation field models
- Arbitrary positioning of observer – useful for modelling also other galaxies
- Improved solvers for propagation equations, parallel and vectorised – dramatically decreases time for 3D calculations
- New integrator for non-thermal intensity map calculations – includes pair absorption on ISRF models (user-specified)
- Other improvements both large and small, including coupling to HelMod code – enabling tracing CRs from Heliopause (LIS) to Earth … no more ``force-field” approximation for solar modulation

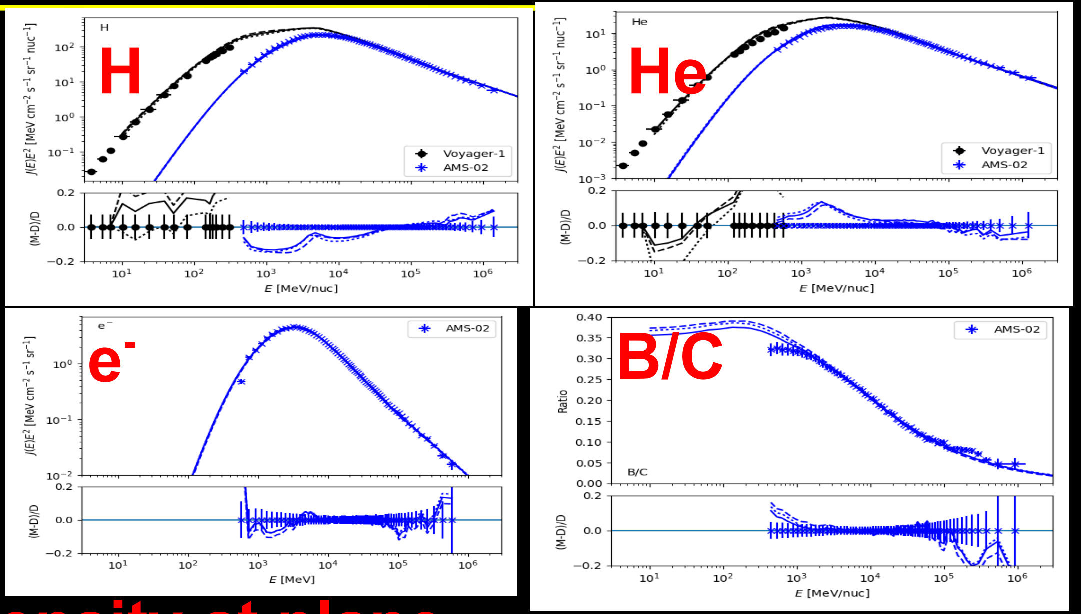
3D models for the Interstellar Emission

- New release of GALPROP (v56) + 3D CR source density models + 3D ISRF models
- 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 CR data: protons, secondaries, leptons from AMS-02, PAMELA, HEAO-3
- 2 ISRF models: one with spiral arms, star-forming ring, central bulge; one with smooth disc with inner hole, ellipsoidal bar … both calculated with FRaNKIE code and tested to reproduce near- to far-infrared data (shorter wavelengths not so useful because of strong dust extinction). Both model inputs for the stellar luminosity and dust spatial distributions taken from literature: R12 (Robitaille et al. 2012) and F98 (Freudenreich 1998)

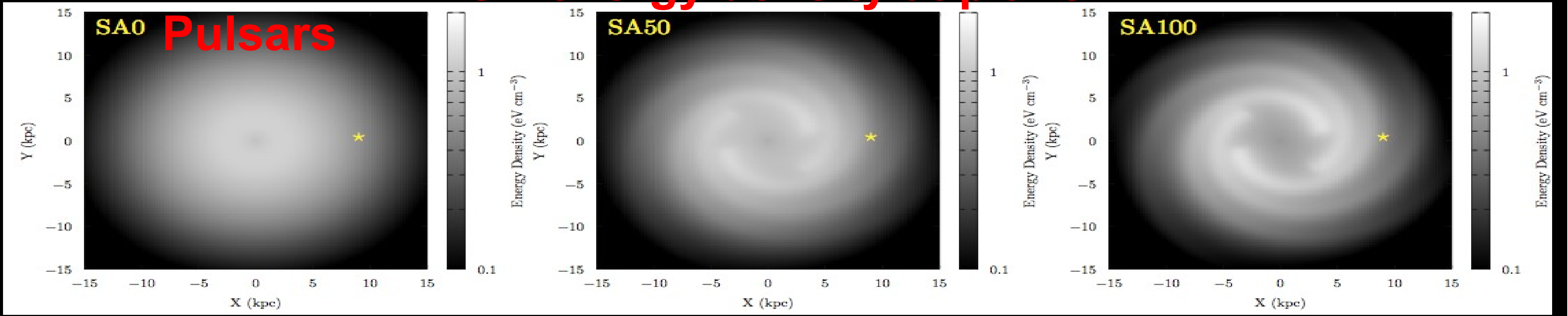
ApJ in press/arxiv:1708.00816

Cosmic Rays

- Source spectra modelled with broken power laws in rigidity
- Assume diffusive reacceleration model with 6 kpc halo and fit usual propagation parameters for each source distribution
- Normalisation for the propagated CR intensities is made to CR data (AMS-02, PAMELA, HEAO-3)

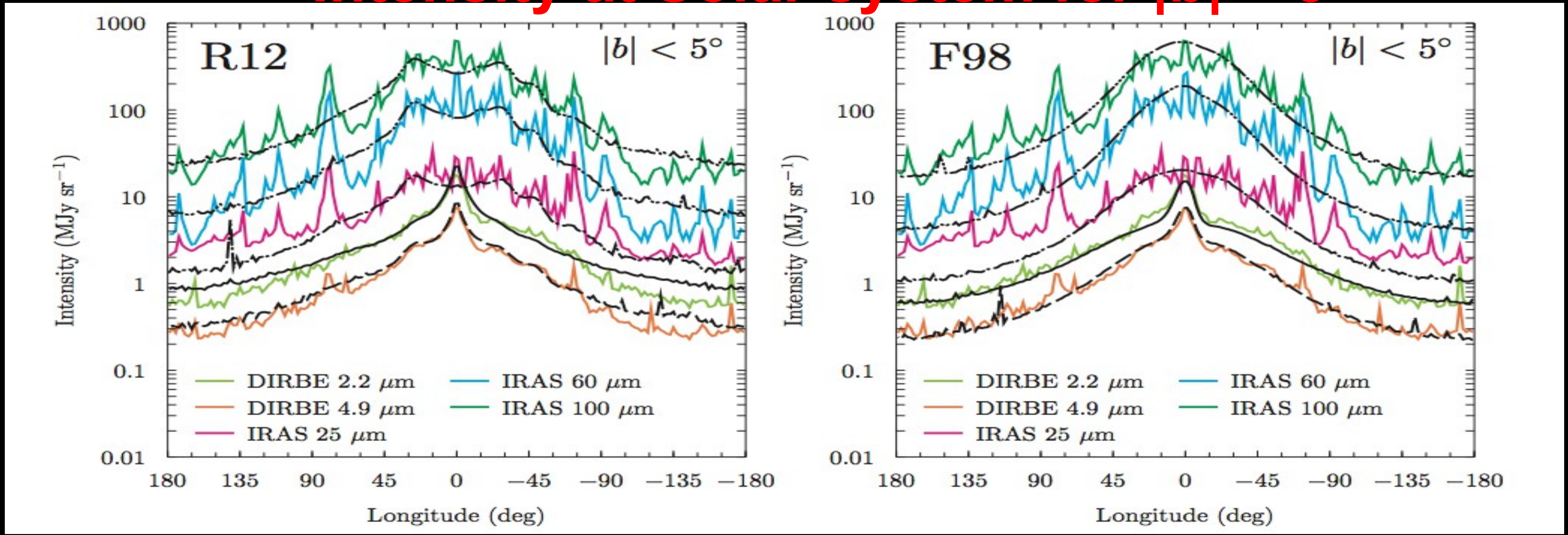


CR energy density at plane



ISRF Models: R12 and F98

Intensity at Solar system for |b| < 5°

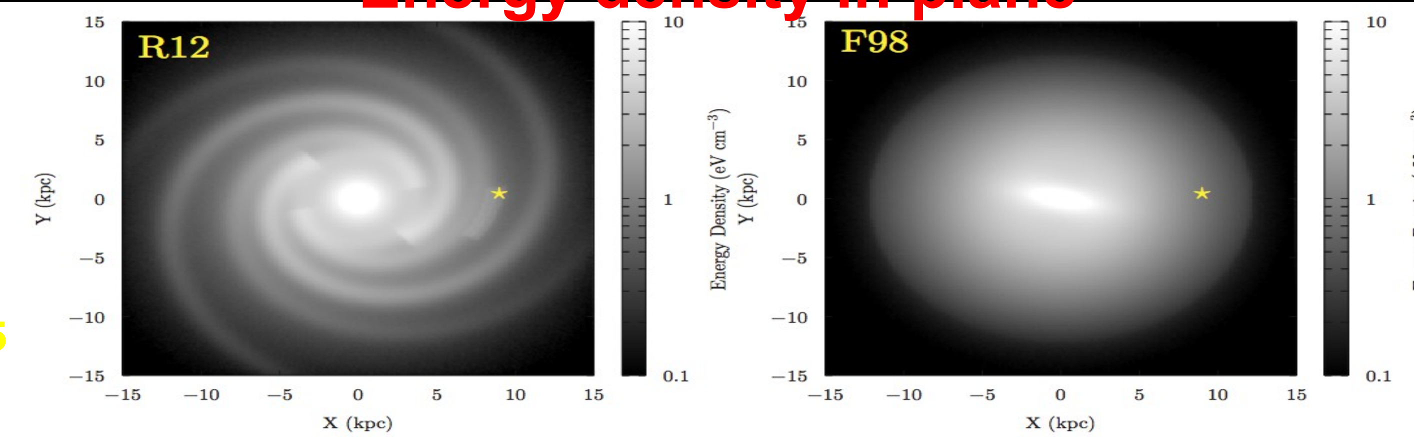


- Full radiation transport modelling using FRaNKIE code
- R12 includes stellar disc, ring, bulge, 4/2 major/minor arms + dust disc with inner hole toward GC
- F98 includes `old' and `young' stellar discs that are warped, spheroidal bar, and warped dust disc with inner hole toward GC
- R12 generally reproduces more structured features in the local intensity data, but both R12 and F98 ISRF models are consistent with data

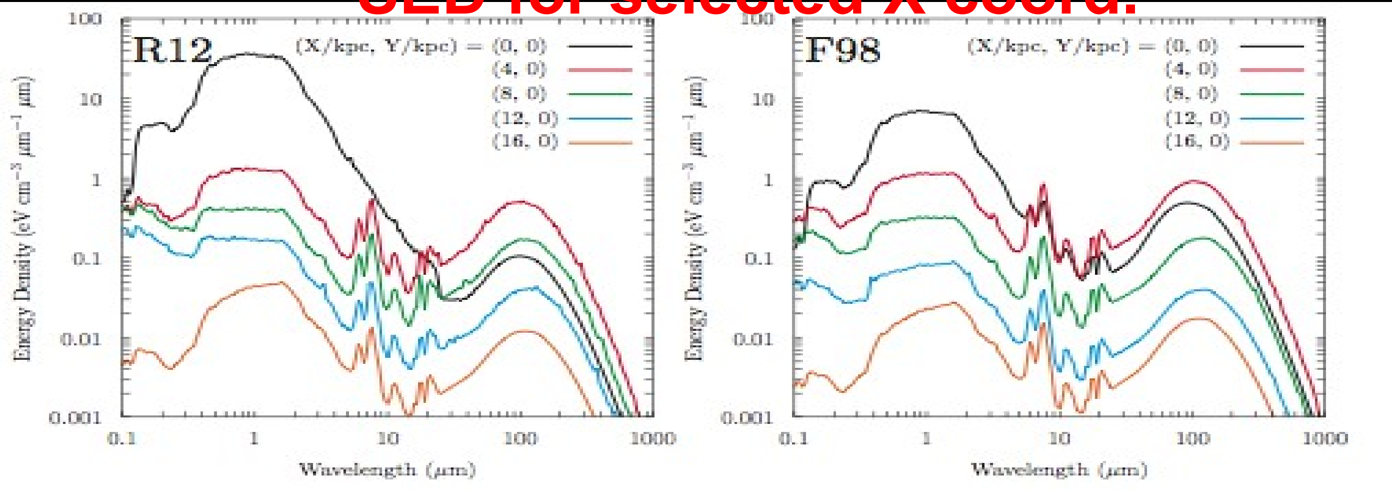
ISRF Models: R12 and F98

- R12 and F98 produced noticeably 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, even though locally they are both reasonably consistent with the data

Energy density in plane

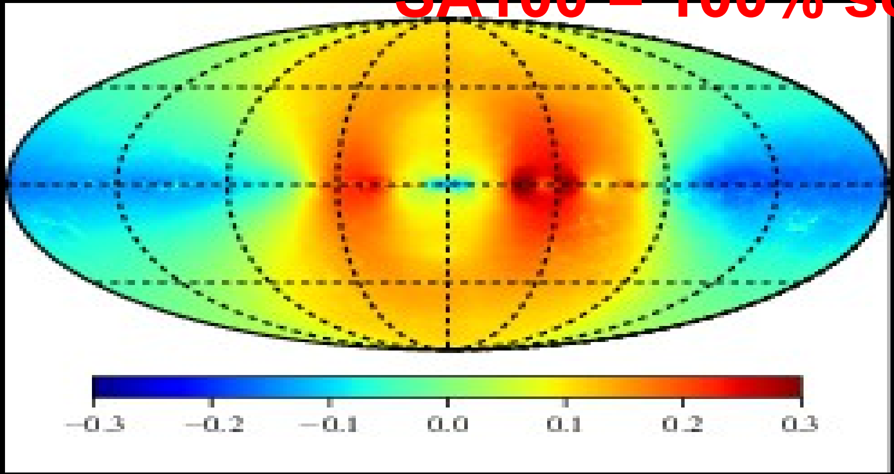


SED for selected X coord.

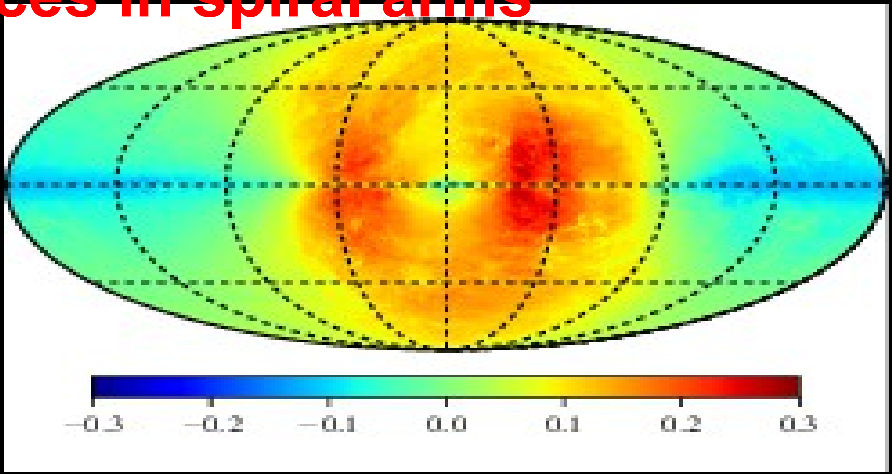


Fractional Residual: [(SA100-R12) – (SA0-Std)]/[SA0-Std]

SA100 = 100% sources in spiral arms



SA100-R12 @ 10.6 MeV



SA100-R12 @ 1.2 GeV

- Reference case: 2D (SA0) + Std ISRF from GALPROP
- Fractional residual maps [(model-ref)/ref] for other combinations: SA50-R12, SA50-F98, SA100-R12, SA100-F98
- CR src and ISRF models with arms produce a density-squared effect because of enhanced CR and ISRF energy densities in these regions, produces `doughnut' in residual maps and the effect is energy-dependent

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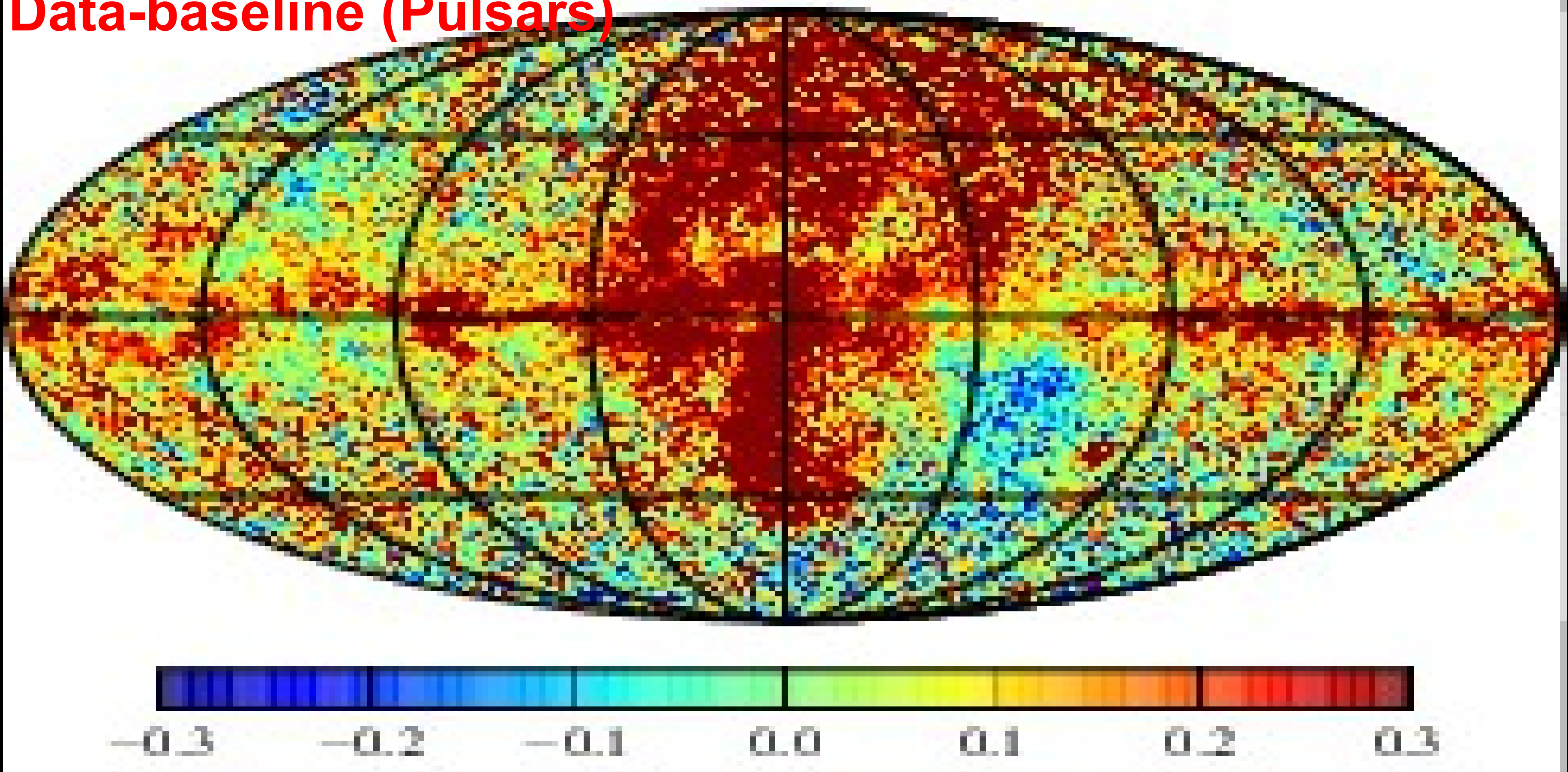
FERMI-LAT OBSERVATIONS OF HIGH-ENERGY γ-RAY EMISSION TOWARD THE GALACTIC CENTER

M. Ajello[1], A. Albert[2], W. B. Atwood[3], G. Barbiellini[4,5], D. Bastieri[6,7], K. Bechtol[8], R. Bellazzini[9], E. Bissaldi[10], R. D. Blandford[2], E. D. Bloom[2], R. Bonino[11,12], E. Bottacini[2], T. J. Brandt[13], J. Bregeon[14], P. Bruel[15], R. Buehler[16], S. Buson[6,7], G. A. Caliandro[2,17], R. A. Cameron[2], R. Caputo[3], M. Caragiulo[10], P. A. Caraveo[18], C. Cecchi[19,20], A. Chekhtman[21,64], J. Chiang[2], G. Chiaro[7], S. Ciprini[19,22,23], J. Cohen-Tanugi[14], L. R. Cominsky[24], J. Conrad[25,26,27], S. Cutini[19,22,23], F. D'Ammando[28,29], A. de Angelis[30], F. de Palma[10,31], R. Desiante[11,32], L. Di Venere[33], P. S. Drell[2], C. Favuzzi[10,33], E. C. Ferrara[13], P. Fusco[10,33], F. Gargano[10], D. Gasparrini[19,22,23], N. Giglietto[10,33], P. Giommi[22], F. Giordano[10,33], M. Giroletti[28], T. Glanzman[2], G. Godfrey[2], G. A. Gomez-Vargas[34,35], I. A. Grenier[36], S. Guiriec[13], M. Gustafsson[37], A. K. Harding[13], J. W. Hewitt[38], A. B. Hill[2,39], D. Horan[15], T. Jogler[2], G. Jóhannesson[40], A. S. Johnson[2], T. Kamae[41], C. Karwin[42], J. Knödlseder[43,44], M. Kuss[9], S. Larsson[26,45], L. Latronico[11], J. Li[46], L. Li[26,45], F. Longo[4,5], F. Loparco[10,33], M. N. Lovellette[47], P. Lubrano[19,20], J. Magill[48], S. Maldera[11], D. Malyshev[2], A. Manfreda[9], M. Mayer[16], M. N. Mazziotta[10], P. F. Michelson[2], W. Mitthumsiri[49], T. Mizuno[50], A. A. Moiseev[48,51], M. E. Monzani[2], A. Morselli[34], I. V. Moskalenko[2], S. Murgia[42], E. Nuss[14], M. Ohno[52], T. Ohsugi[50], N. Omodei[2], E. Orlando[2], J. F. Ormes[53], D. Paneque[2,69], M. Pesce-Rollins[2,9], F. Piron[14], G. Pivato[9], T. A. Porter[2], S. Rainò[10,33], R. Rando[6,7], M. Razzano[9], A. Reimer[2,63], O. Reimer[2,63], S. Ritz[3], M. Sánchez-Conde[25,26], P. M. Saz Parkinson[3,54], C. Sgrò[9], E. J. Siskind[55,56], D. A. Smith[57], F. Spada[9], G. Spandre[9], P. Spinelli[10,33], D. J. Suson[58], H. Tajima[2,59], H. Takahashi[52], J. B. Thayer[2], D. F. Torres[46,60], G. Tosti[19,20], E. Troja[13,48], Y. Uchiyama[61], G. Vianello[2], B. L. Winer[62], K. S. Wood[47], G. Zaharijas[4,5], and S. Zimmer[25,26]

[1] Department of Physics and Astronomy, Clemson University, Kinard Lab of Physics, Clemson, SC 29634-0978, USA
[2] W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA; tporter@stanford.edu
[3] Santa Cruz Institute for Particle Physics, Department of Physics and Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
[4] Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34127 Trieste, Italy
[5] Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[6] Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
[7] Dipartimento di Fisica e Astronomia "G. Galilei," Università di Padova, I-35131 Padova, Italy
[8] Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706, USA
[9] Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy
[10] Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy
[11] Istituto Nazionale di Fisica Nucleare, Sezione di Torino, I-10125 Torino, Italy
[12] Dipartimento di Fisica Generale "Amadeo Avogadro," Università degli Studi di Torino, I-10125 Torino, Italy

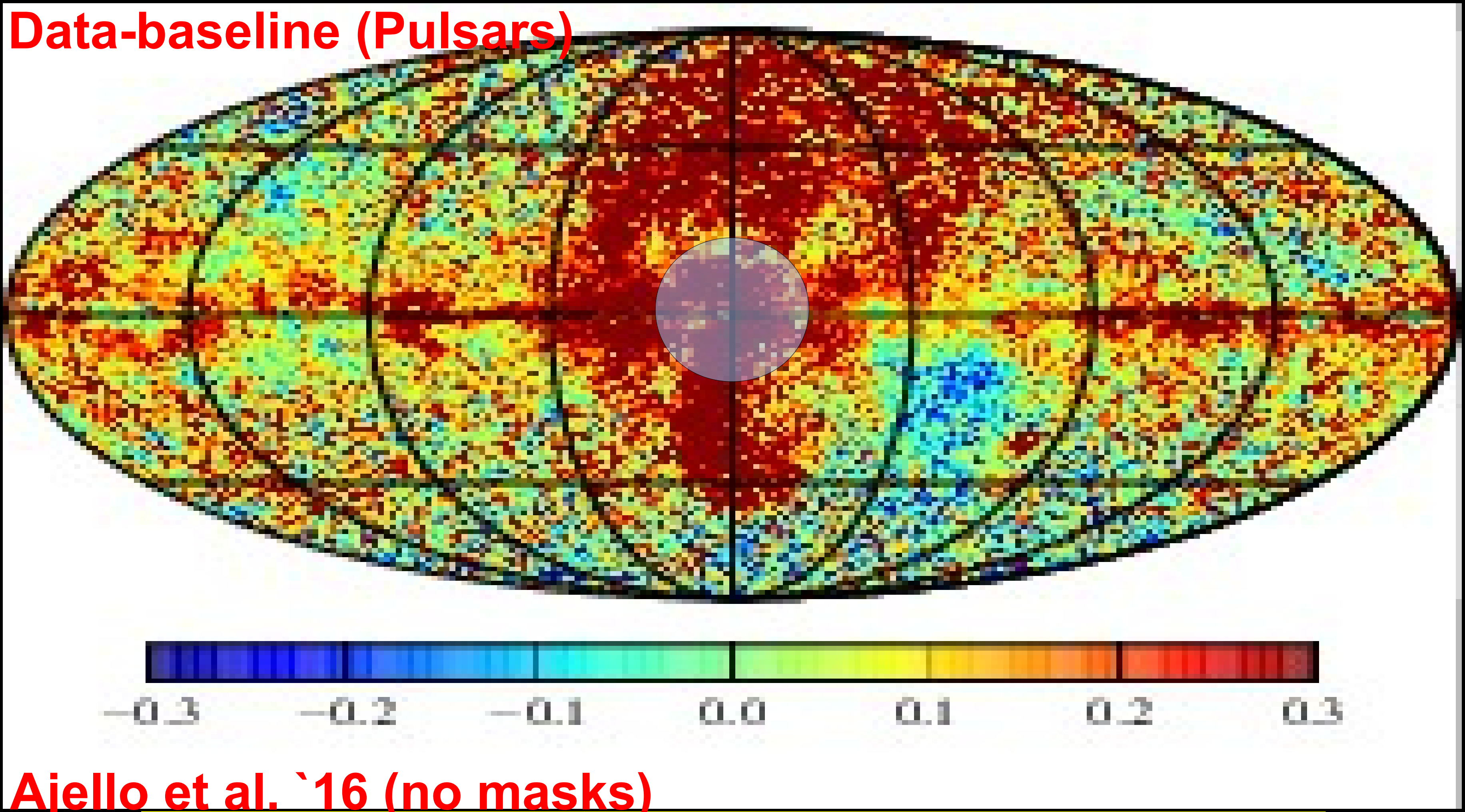
All-Sky Residuals 1-3.16 GeV

Data-baseline (Pulsars)



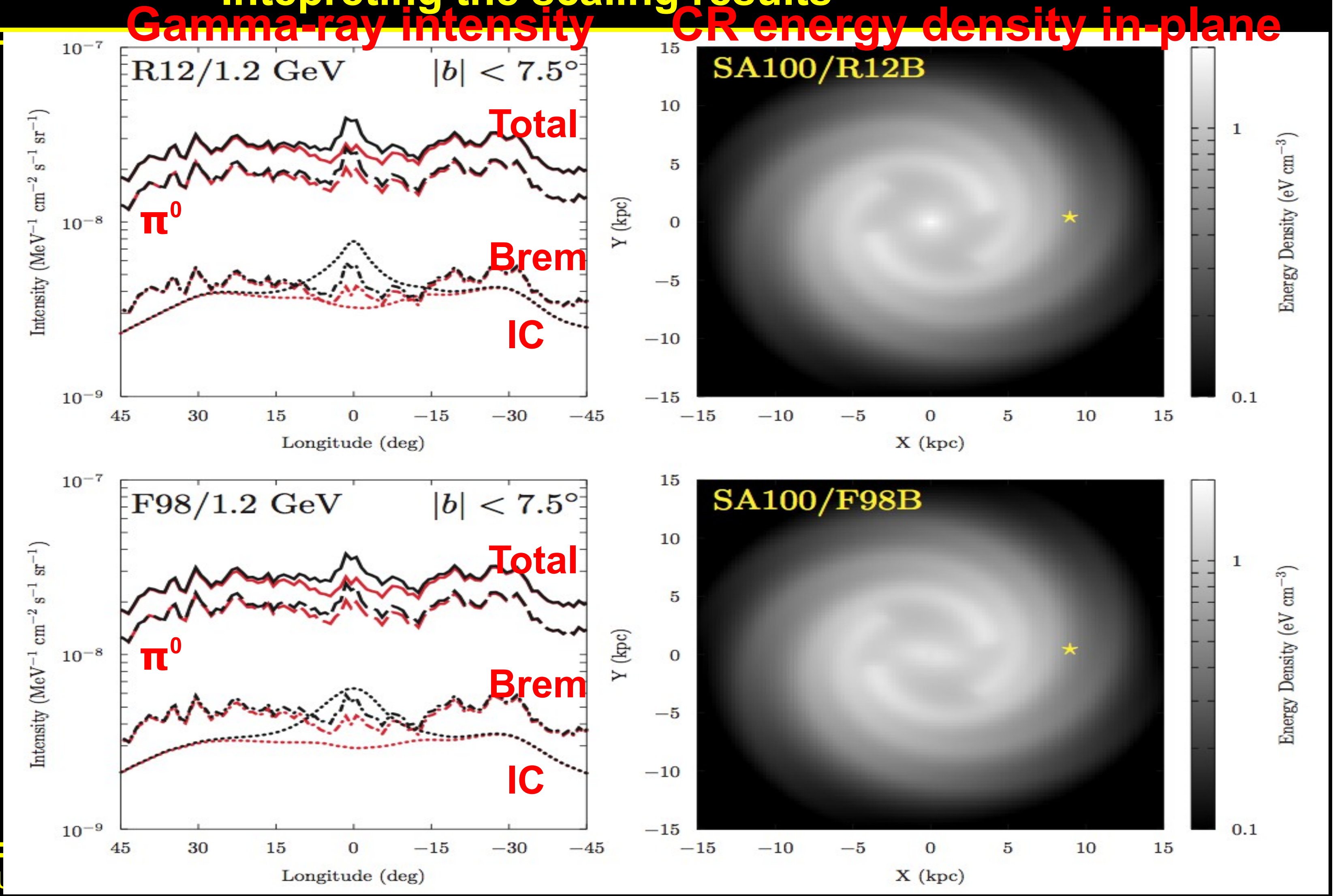
Ajello et al. `16 (no masks)

All-Sky Residuals 1-3.16 GeV

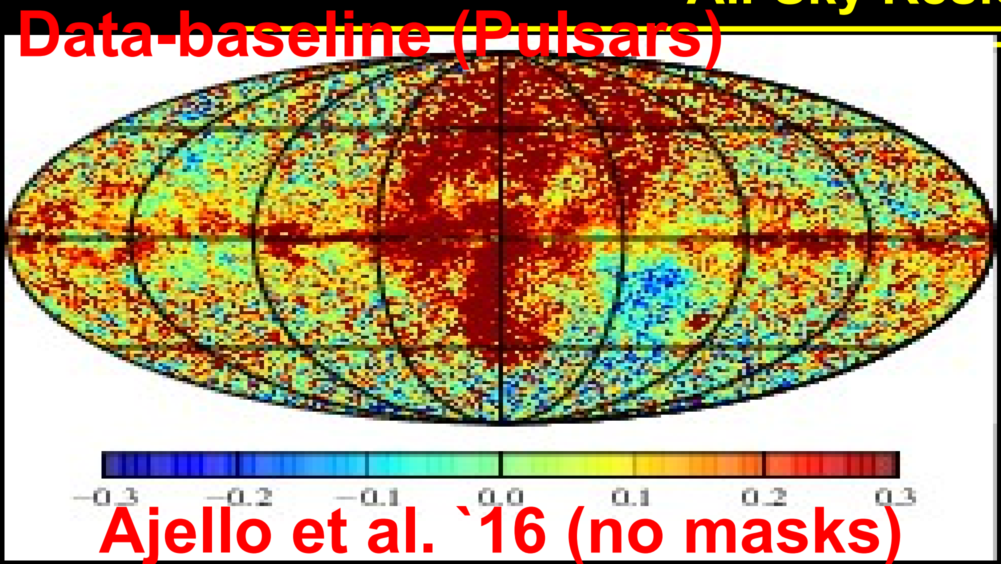


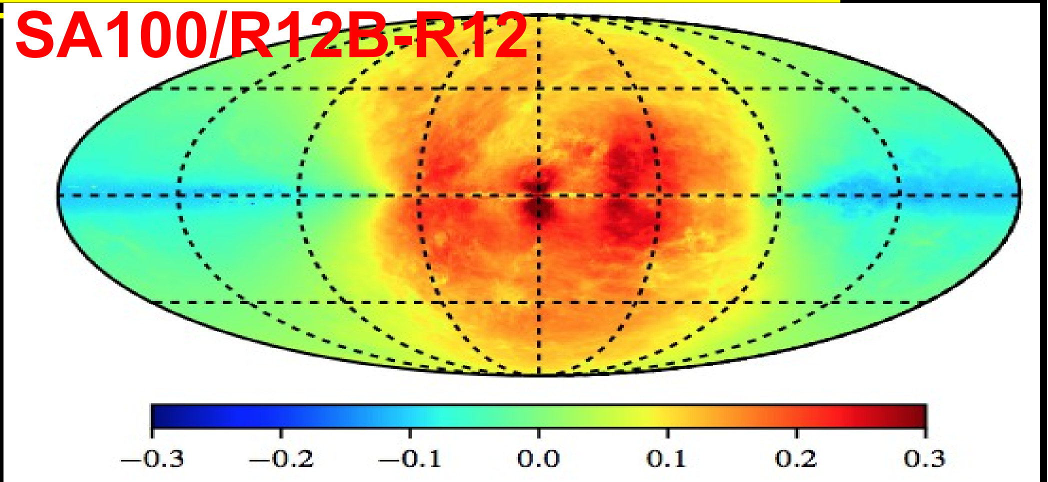
Intepreting the scaling results

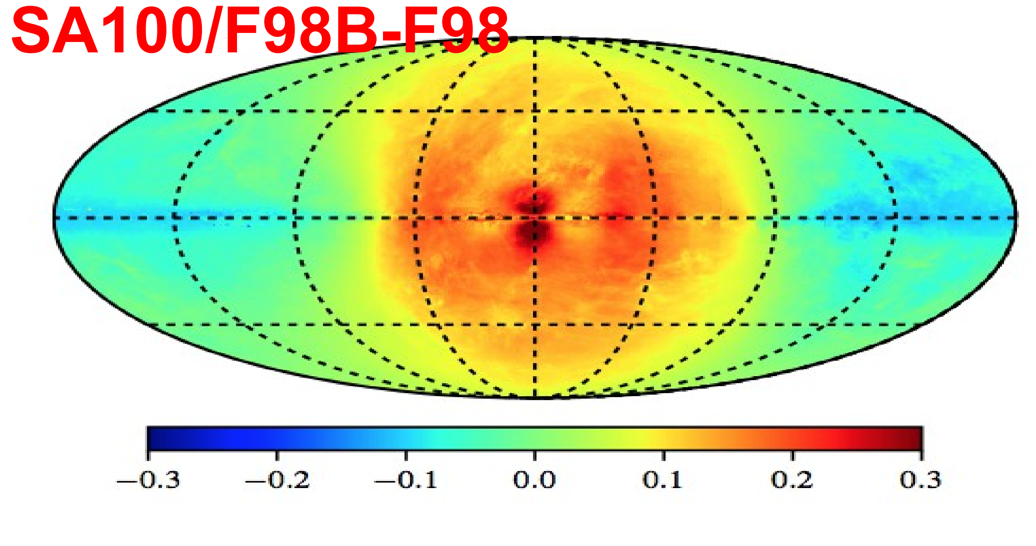
Red curves: No CR bulge
Black curves: With CR bulge
Dot: IC
Dash: π^0
Dash-dot: Brem
Solid: total



All-Sky Residuals 1-3.16 GeV

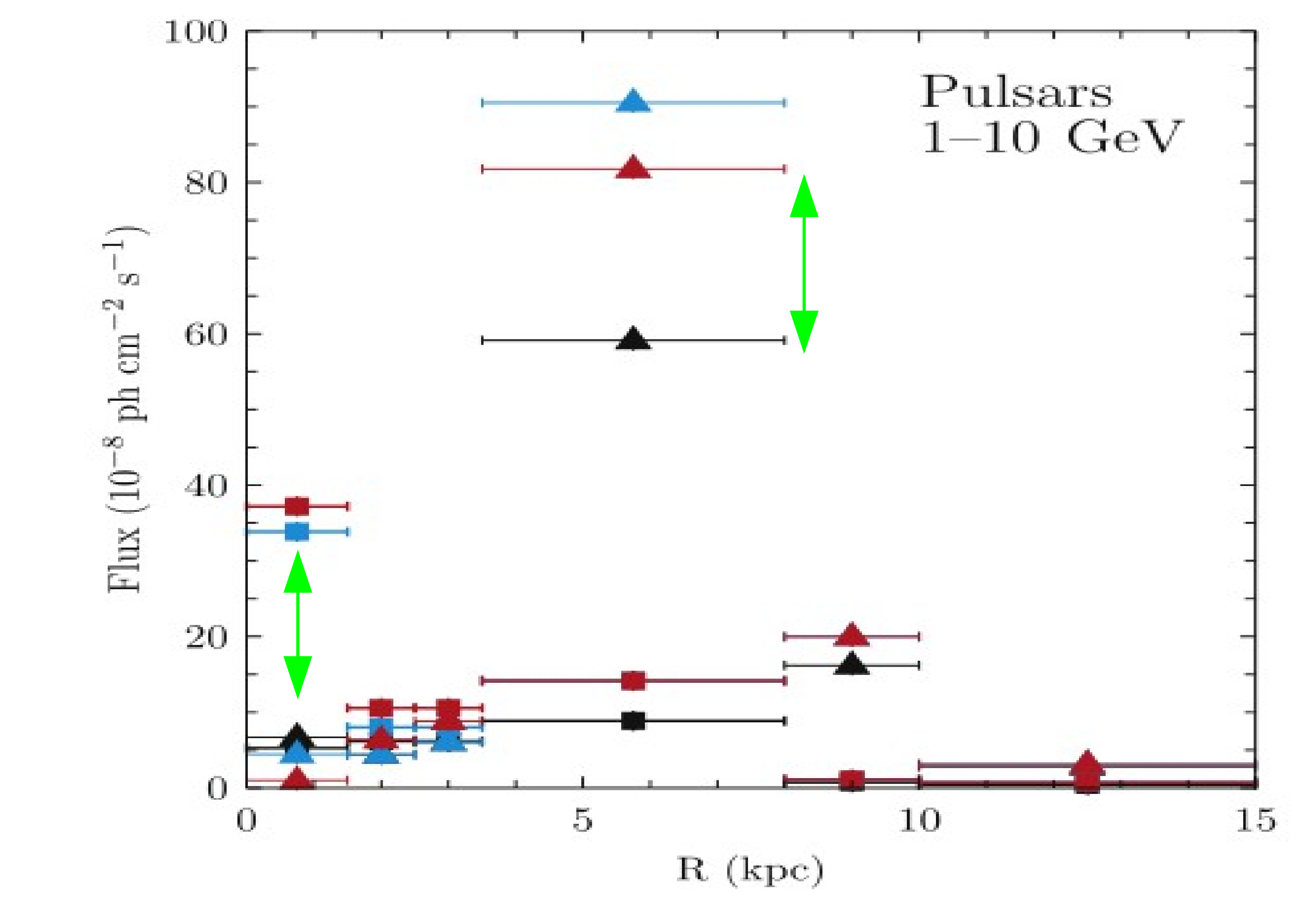






Injected CR power for the `bulge/bar' is ~25x smaller than the arms for the residuals shown. Can be done with CR nuclei/leptons or leptons only

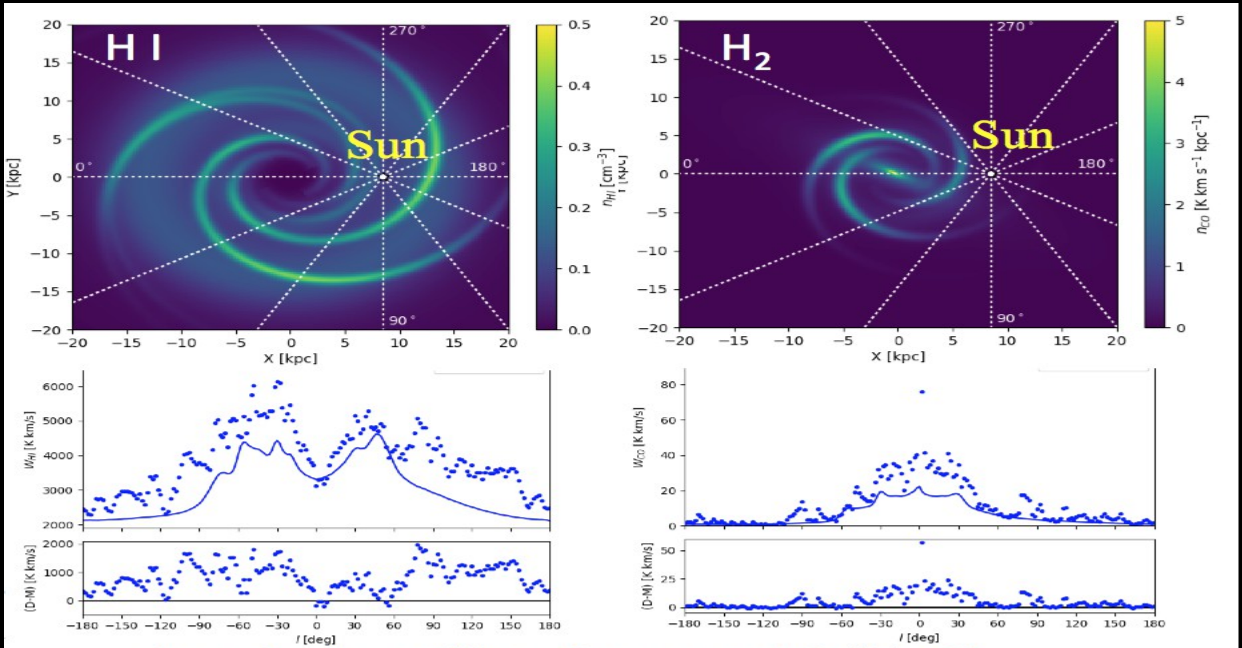
Summary of Fits for 15°x15° RoI



Fit to data requires increase over baseline. Interpretation with 2D models unclear – 3D bulge/arm models provide more physical basis for understanding these results

Coming soon: 3D atomic and molecular gas models

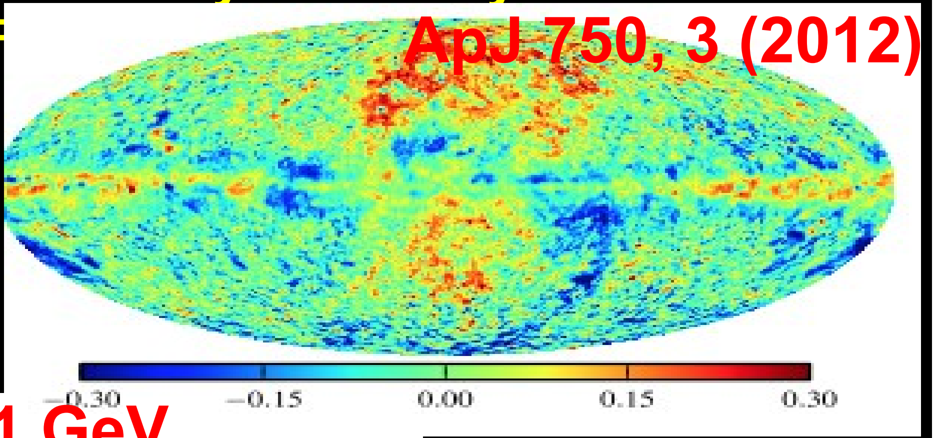
- Forward-folding model fitting method
- ML fit to HI LAB and DHT CO surveys
- Build model iteratively: 2D disc, add warp, bulge/bar, flaring (outer Galaxy), spiral arms
- Spiral location and shape same for HI and CO but scale-heights and normalisations differ
- Each arm has free normalisation in model fitting method

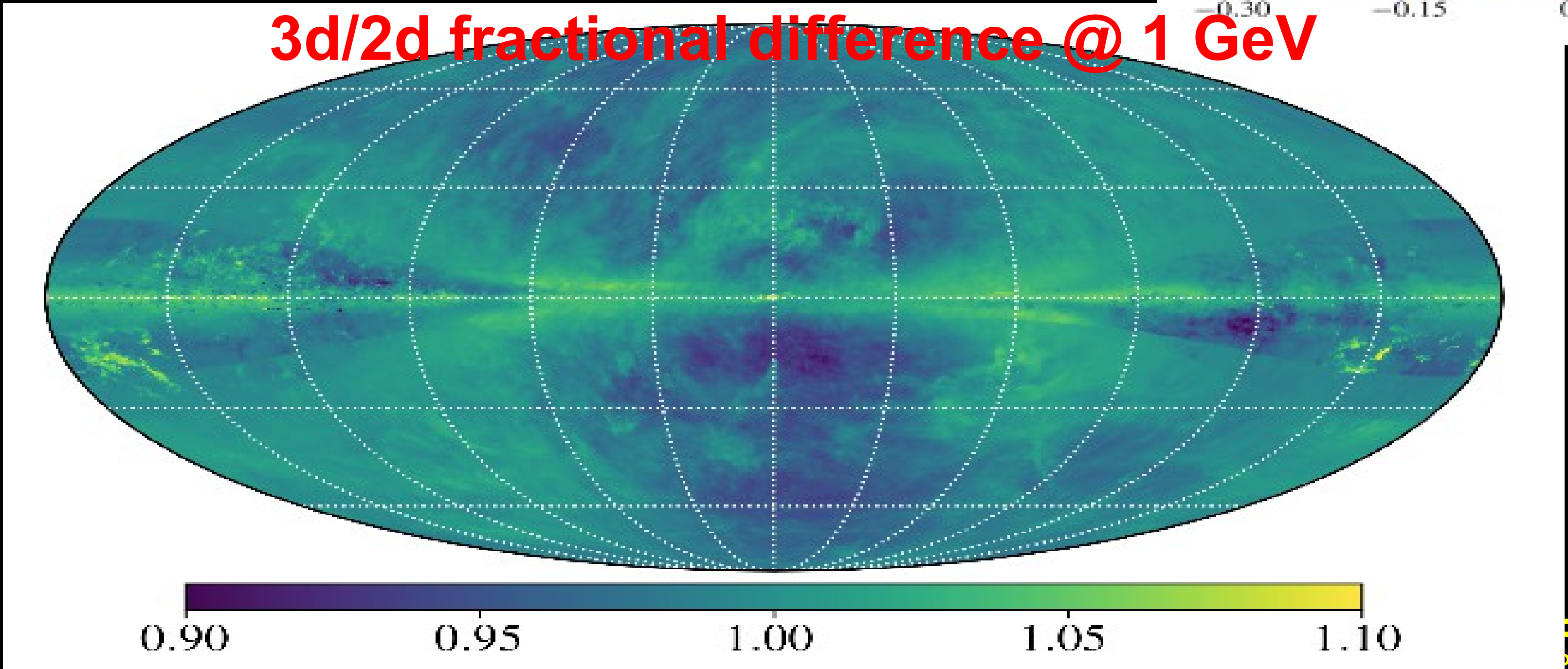


Longitude profiles of gas models |b|≤4°

Effect of 3D gas models for gamma-ray data analysis

- Ratio of 3d/2d gas model, same CR source distribution (SA0/Pulsars)
- Clear correlation of structures from Ackermann et al. ApJ 750, 3 (2012)





Summary

- GALPROP is officially of drinking age in the US (21+ years development)!
- New release v56 with many additions and optimisations: specific focus improving performance for full 3D CR and interstellar emission calculations.
- New 3D models for ISM density distributions have been developed: ISRF (Porter et al.) and Gas (Johannesson et al.).
- Modelling with upcoming GALPROP release using 3D CR source and ISRF densities show new features in residual maps compared to 2D-based reference calculations.
- The 3D models provide a plausible explanation for the puzzling results from the analysis based on 2D axisymmetric models.
- CR sources in spiral arms and central bulge/bar <u>in combination</u> with 3D ISRF models are required.
- Coming soon: results with 3D gas and CR sources
- Check out galprop.stanford.edu and galprop.stanford.edu/webrun for configuration files and data products and facility to run code via browser