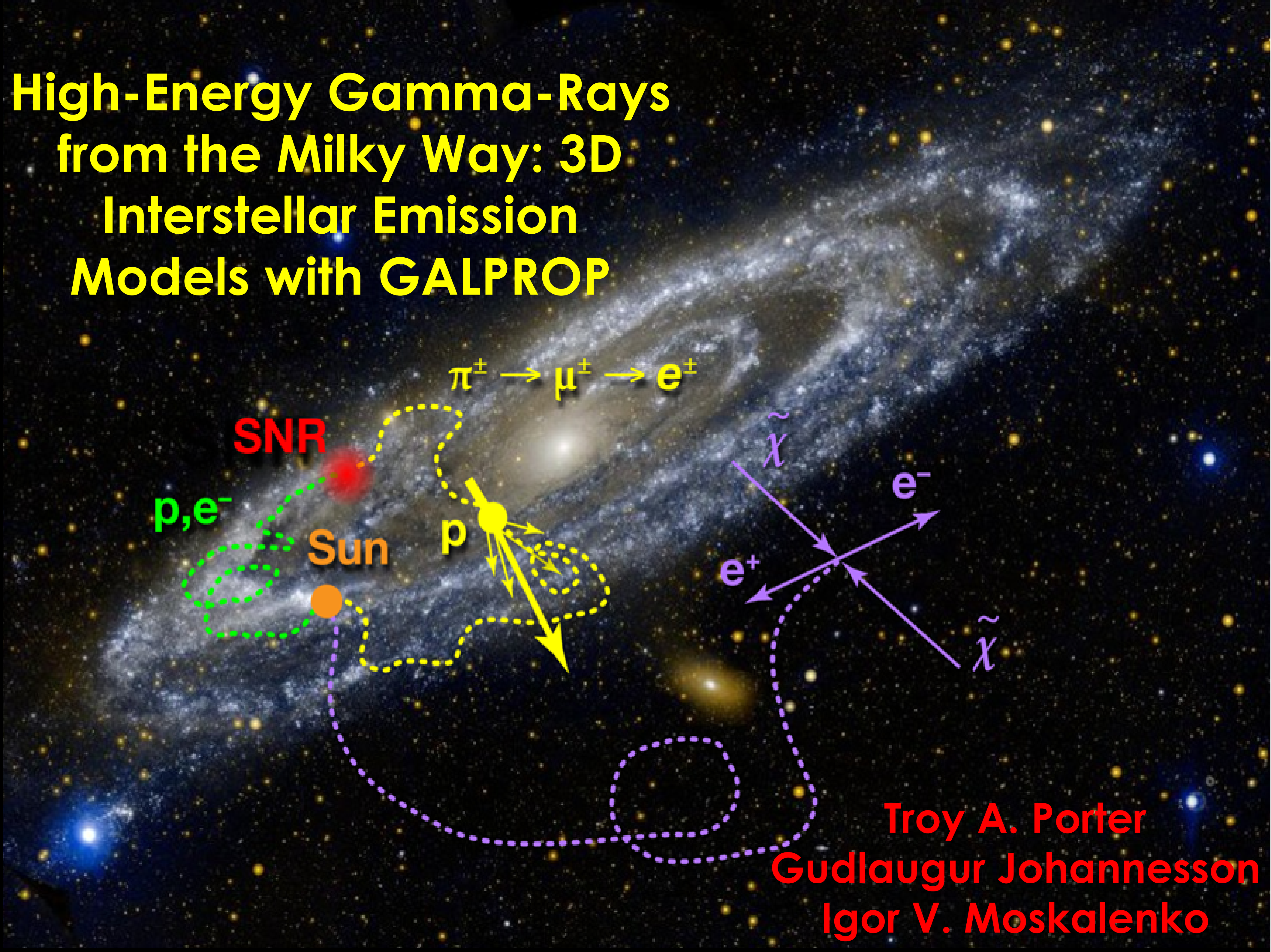
High-Energy Gamma-Rays from the Milky Way: 3D Interstellar Emission Models with GALPROP



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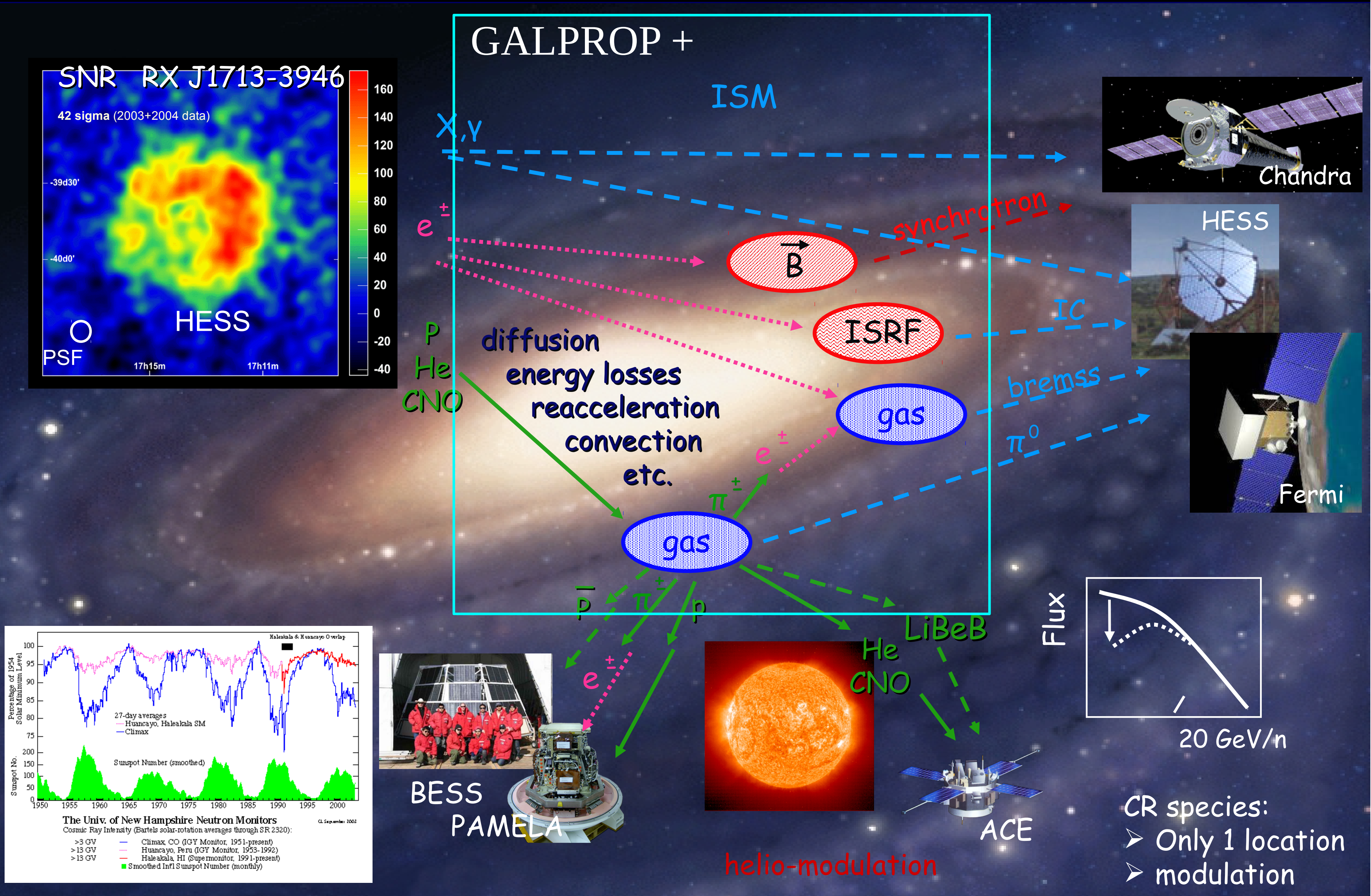
What is GALPROP?

- Tool for modelling and interpreting cosmic-ray (CR) and non-thermal emissions data for Milky Way and other galaxies
- 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 have propagated through the ISM losing energy, which result in other secondaries and broadband EM emissions
- 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

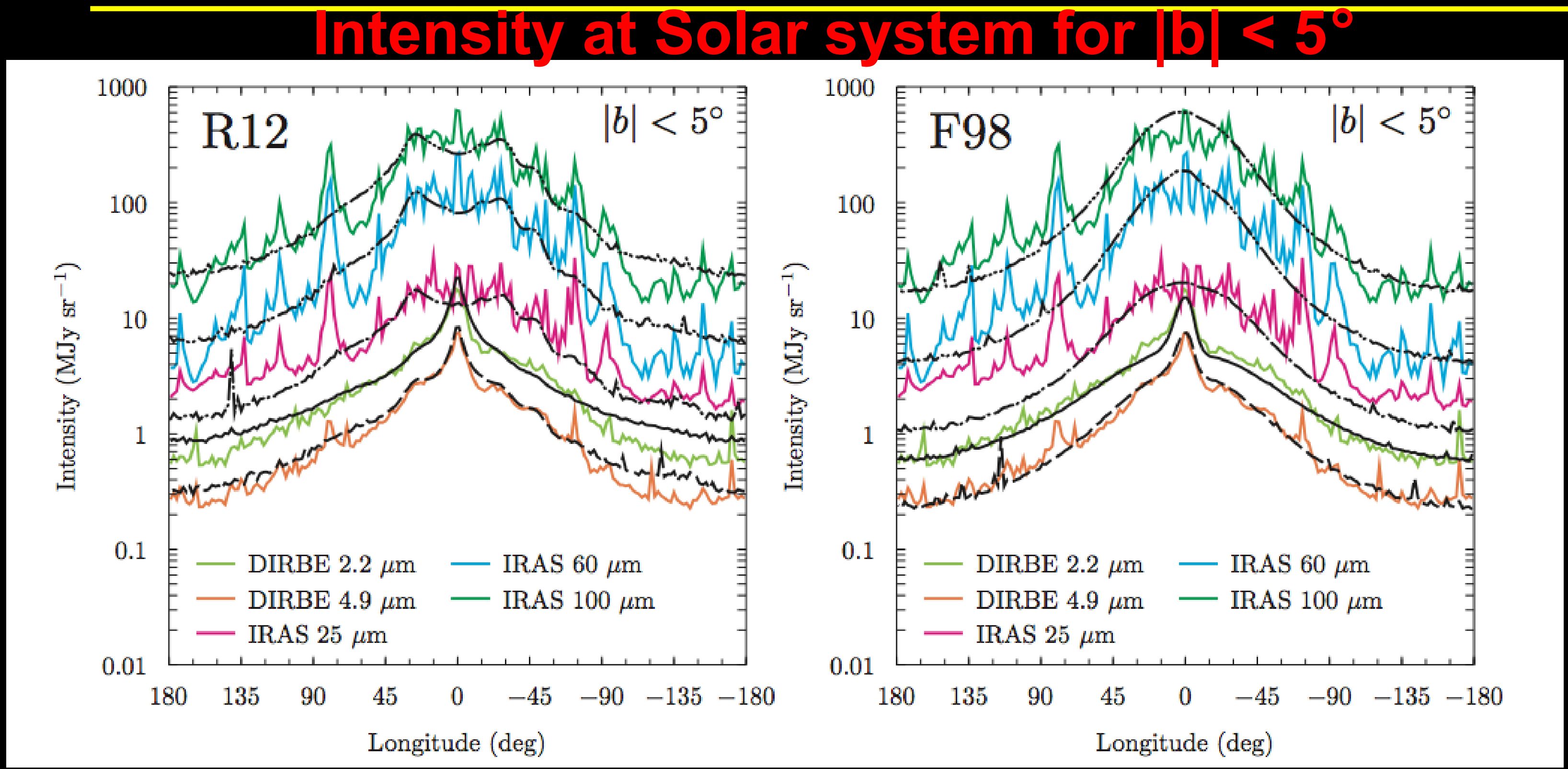
- Numerous technical and physics improvements
- Spatial variations in propagation for diffusion via diffusion coefficient and Alfven speed (reacceleration)
- Generalised source distribution and spectral models: separately specified spatial densities and spectra for each CR species
- 2D/3D gas models
- 2D/3D interstellar radiation field models
- Arbitrary positioning of observer for interstellar emission intensity calculations – useful for modelling also other galaxies (external viewer)
- 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 + 3D gas models
- Major effort to improve the underlying ISM density models (gas and ISRF) → interstellar emission depends on the densities of both gas/ISRF and CRs in ISM
- 2 ISRF models: one with spiral arms, star-forming ring, central bulge; one with smooth disc with inner hole, ellipsoidal bar
- ISRF model inputs for the stellar luminosity and dust spatial distributions taken from literature and 3D spectral intensity distribution calculated using FRaNKIE code: R12 (Robitaille et al. 2012) and F98 (Freudenreich 1998) – both reproduce near- to far-infrared data (shorter wavelengths not so useful because of strong dust extinction)
- New 3D gas model for HI and CO obtained using forward-folding likelihood method (GALGAS code) with emission line survey data for HI (LAB) and CO (Dame)
- 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
- Reference case: 2D CRs, 2D gas, 2D ISRF

Porter+ ApJ 846, 67 (2017) /arxiv:1708.00816
Johannesson+ in prep.

ISRF Models: R12 and F98

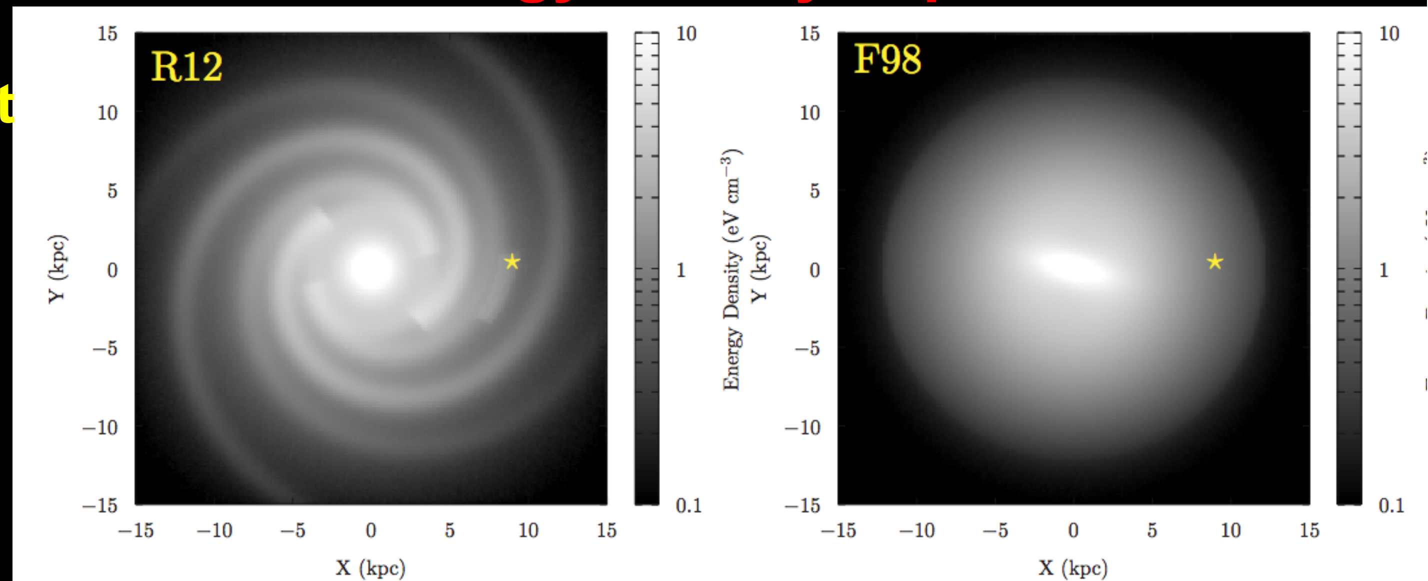


- Full radiation transport modelling using FRaNKIE code
- R12 includes stellar disc, ring, bulge, 4/2 major/minor arms + dust disc with inner hole toward GC
- F98 includes `old' and `young' stellar discs that are warped, spheroidal bar, and warped dust disc with inner hole toward GC
- R12 generally reproduces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

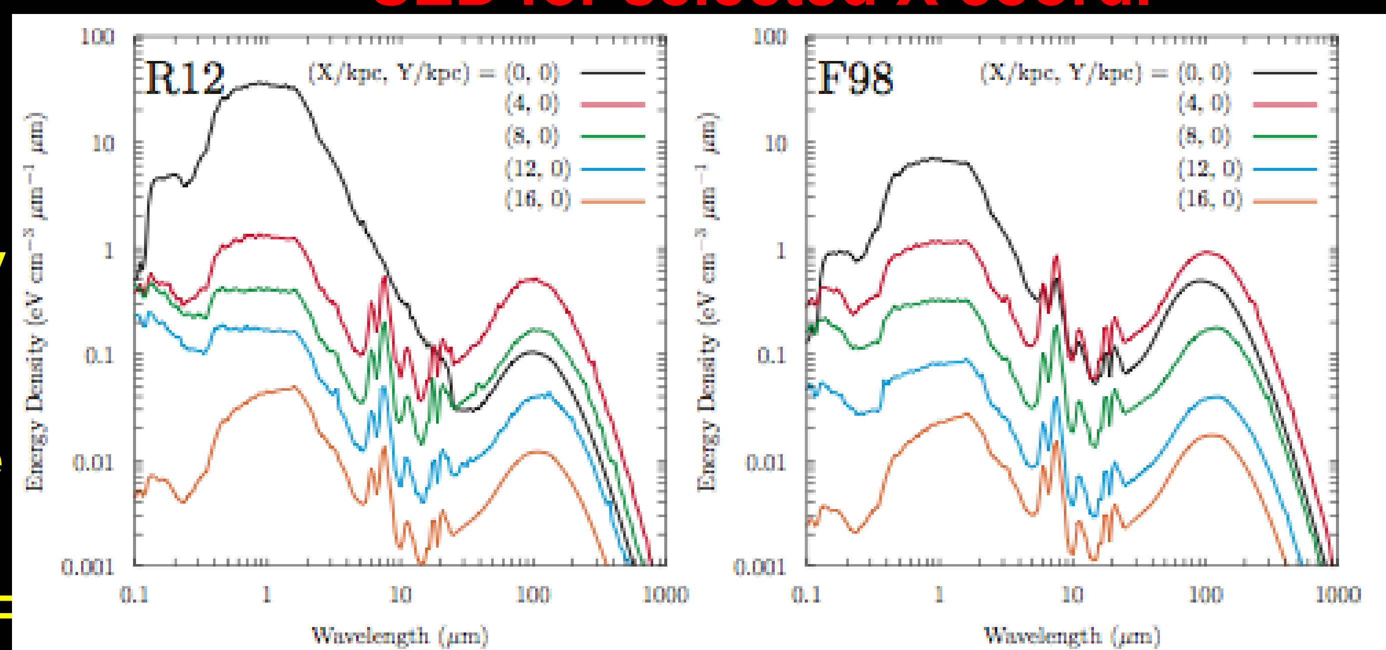
ISRF Models: R12 and F98

- 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

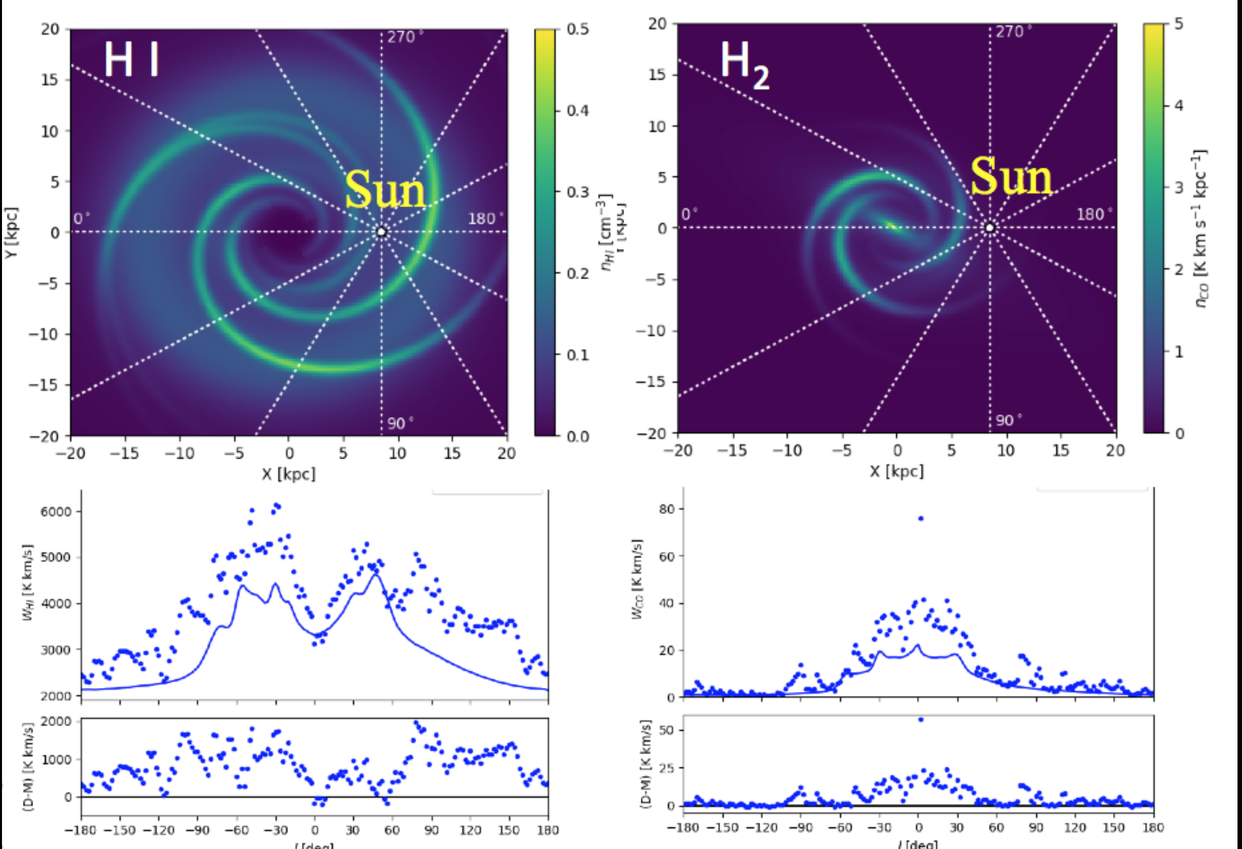


SED for selected X coord.



3D atomic and molecular gas models

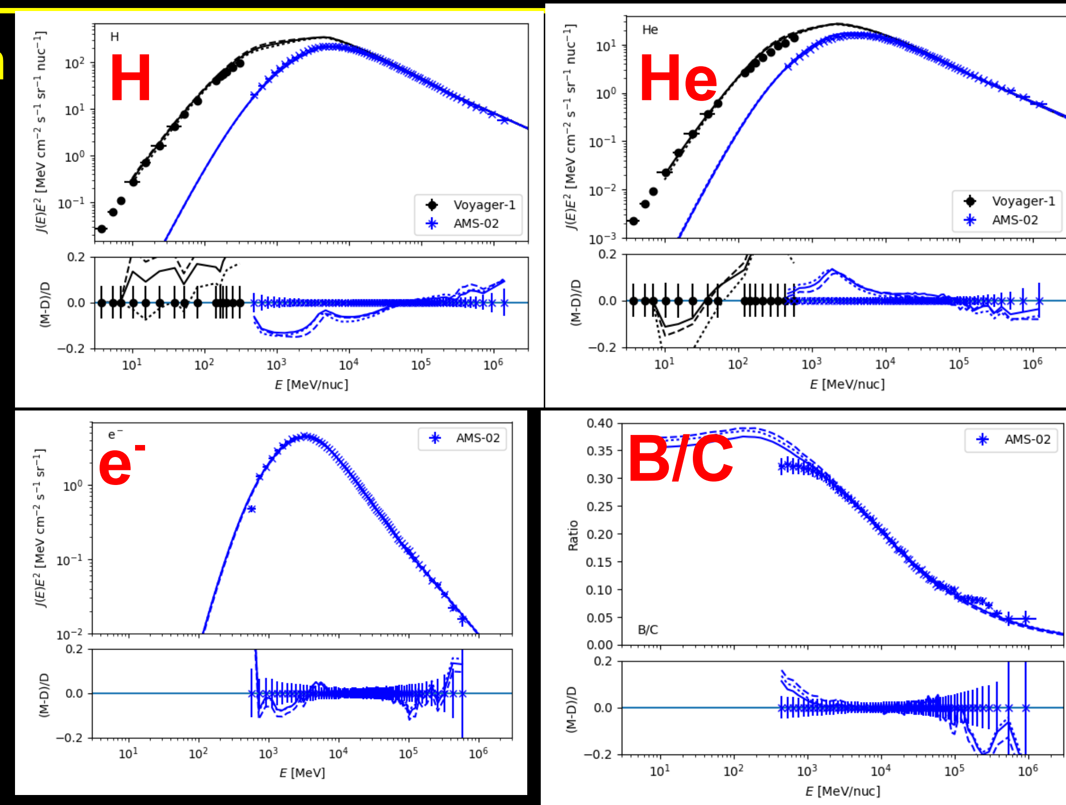
- Forward-folding model fitting method
- ML fit to HI LAB and DHT CO surveys
- Build model iteratively: 2D disc, add warp, bulge/bar, flaring (outer Galaxy), spiral arms
- Spiral location and shape same for HI and CO but scale-heights and normalisations differ
- Each arm has free normalisation in model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



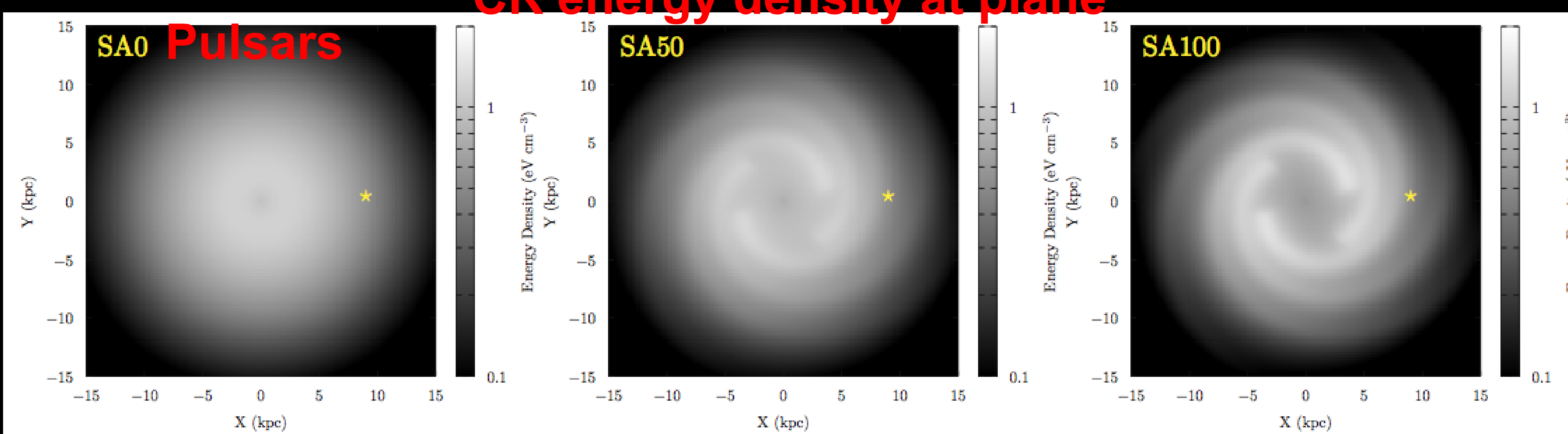
Longitude profiles of gas models |b|≤4°

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 and gas model
- Normalisation for the propagated CR intensities is made to CR data (AMS-02, PAMELA, HEAO-3)

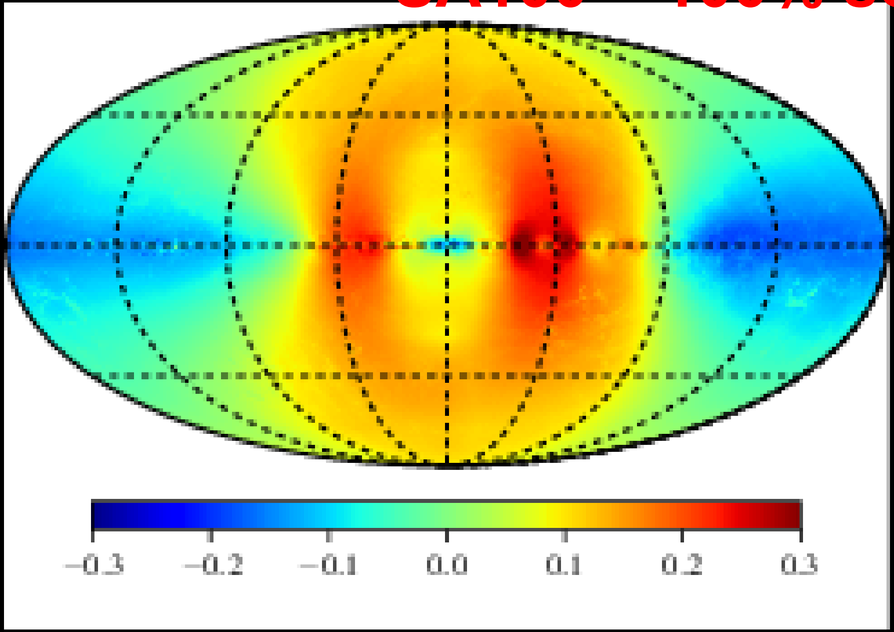


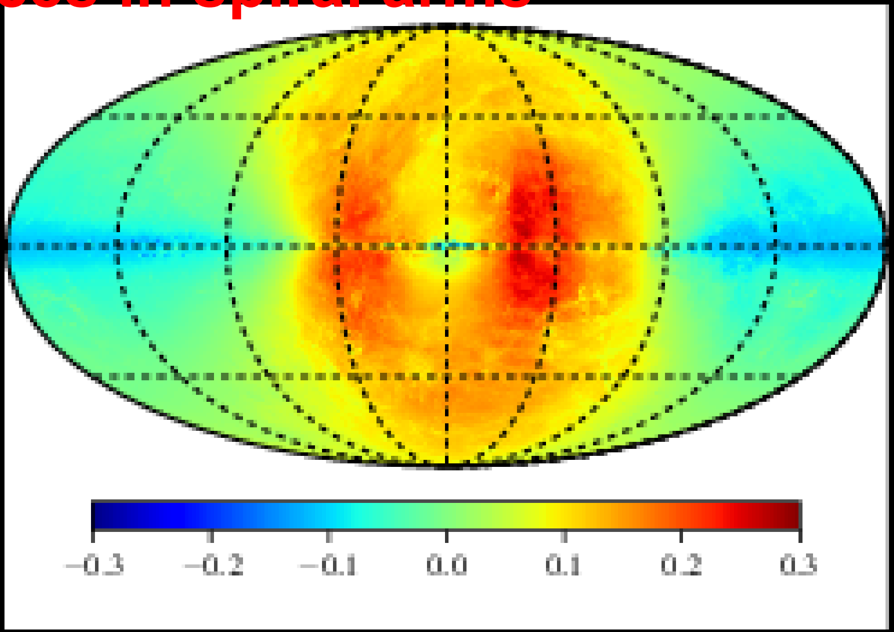
CR energy density at plane



Interstellar Emissions for 3D CRs + R12 ISRF + 2D Gas

Fractional Residual: [(SA100-R12) – (SA0-Std)]/[SA0-Std]
SA100 = 100% sources in spiral arms



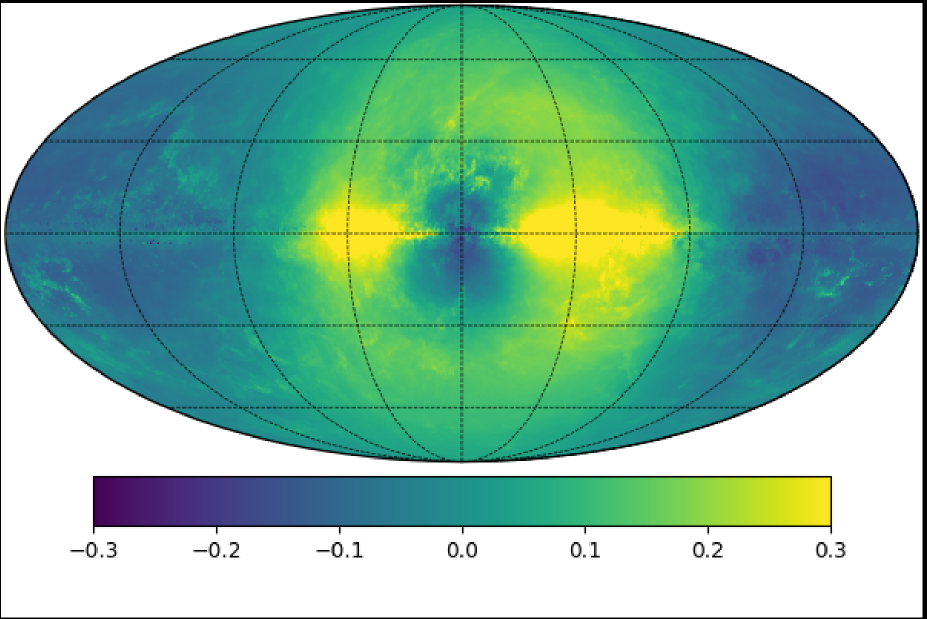


SA100-R12 @ 10.6 MeV **SA100-R12 @ 1.2 GeV**

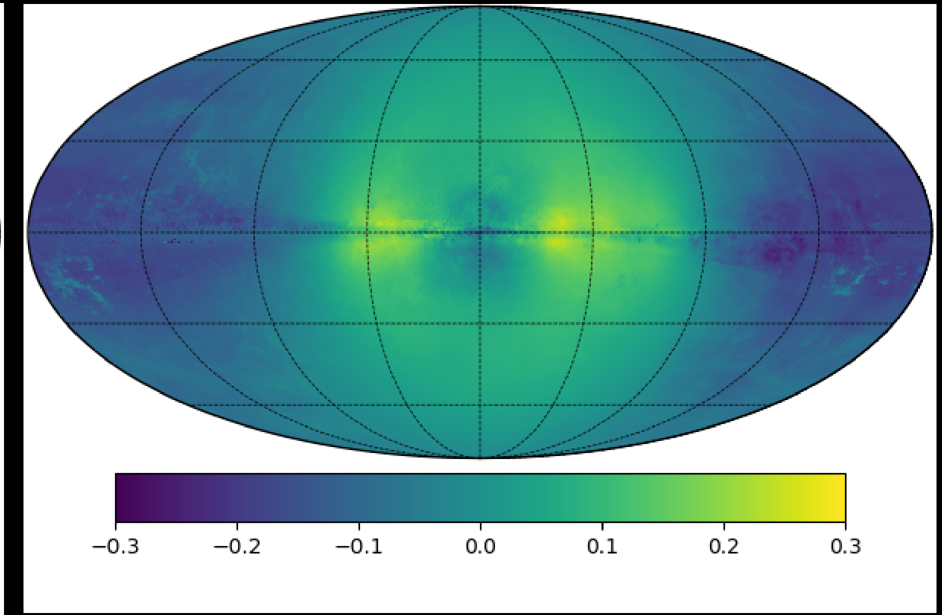
- Reference case: 2D (SA0) + 2D Std ISRF + 2D gas
- Fractional residual maps [(model-ref)/ref] for other combinations: SA50-R12, SA50-F98, SA100-R12, SA100-F98
- CR src and ISRF models with arms produce a density-squared effect because of enhanced CR and ISRF energy densities in these regions, produces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

Interstellar Emissions for 3D CRs + 3D gas + 2D ISRF

Fractional Residual: [(SA100-3Dgas) – (SA0-Std)]/[SA0-Std]
SA100 = 100% sources in spiral arms



SA100-3Dgas @ 30 MeV

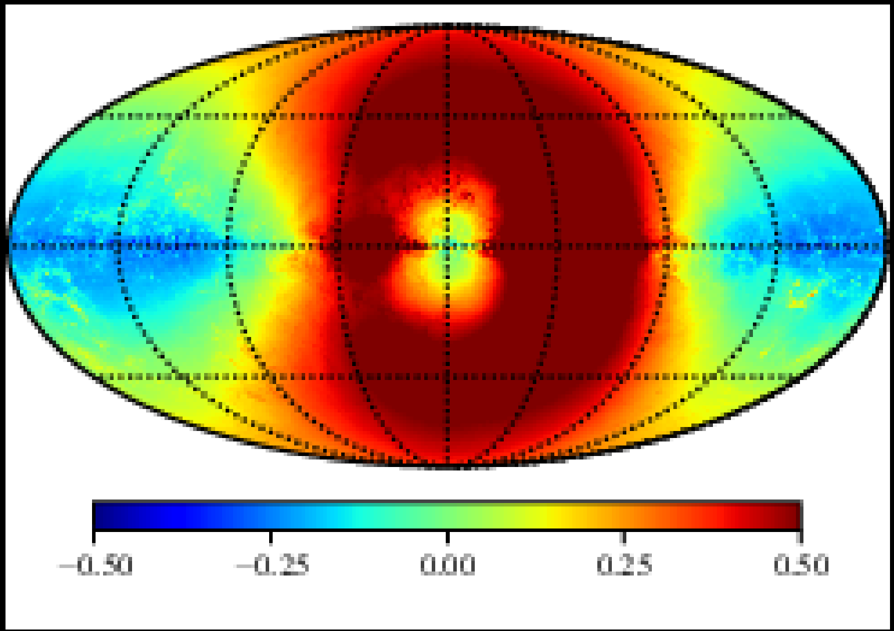


SA100-3Dgas @ 1.2 GeV

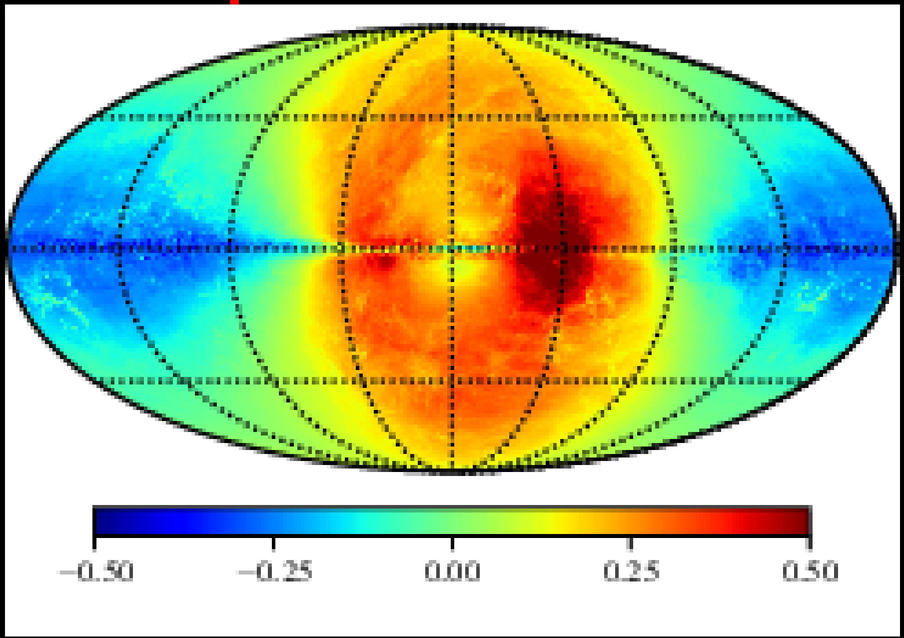
- Reference case: 2D (SA0) + 2D Std ISRF + 2D gas
- Because 3D gas changes propagation parameters → predict softer electron spectrum below ~1 GeV in ISM, produces more low-E gamma-rays
- This affects both IC and bremsstrahlung at low energies → even though using 2D ISRF here the IC is brighter because of higher electron intensity, bremsstrahlung due to higher electron intensity + gas density about arms

Interstellar Emissions for 3D CRs + R12 ISRF + 3D Gas

Fractional Residual: [(SA100-R12/3Dgas) – (SA0-Std)]/[SA0-Std]
SA100 = 100% sources in spiral arms



SA100-R12/3Dgas @ 10.6 MeV

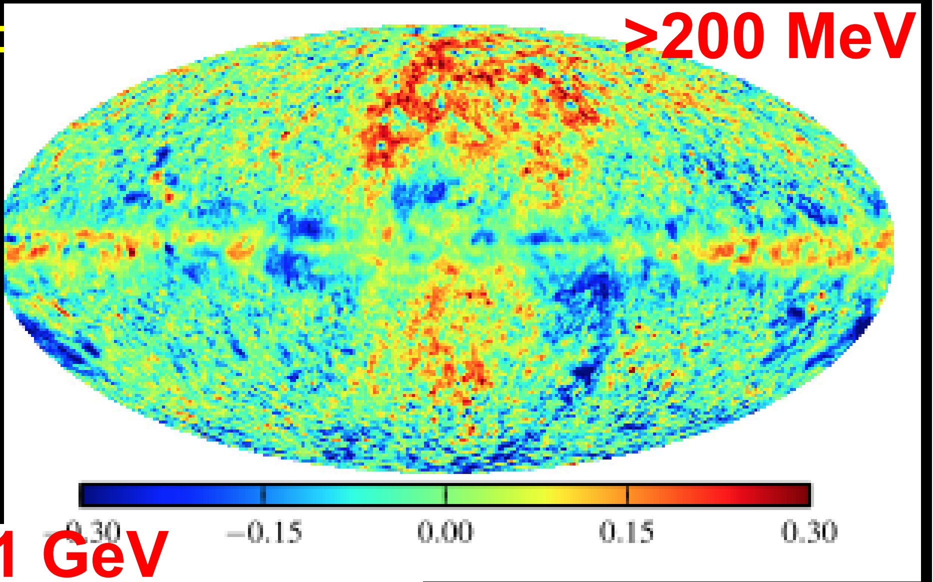


SA100-R12/3Dgas @ 1.2 GeV

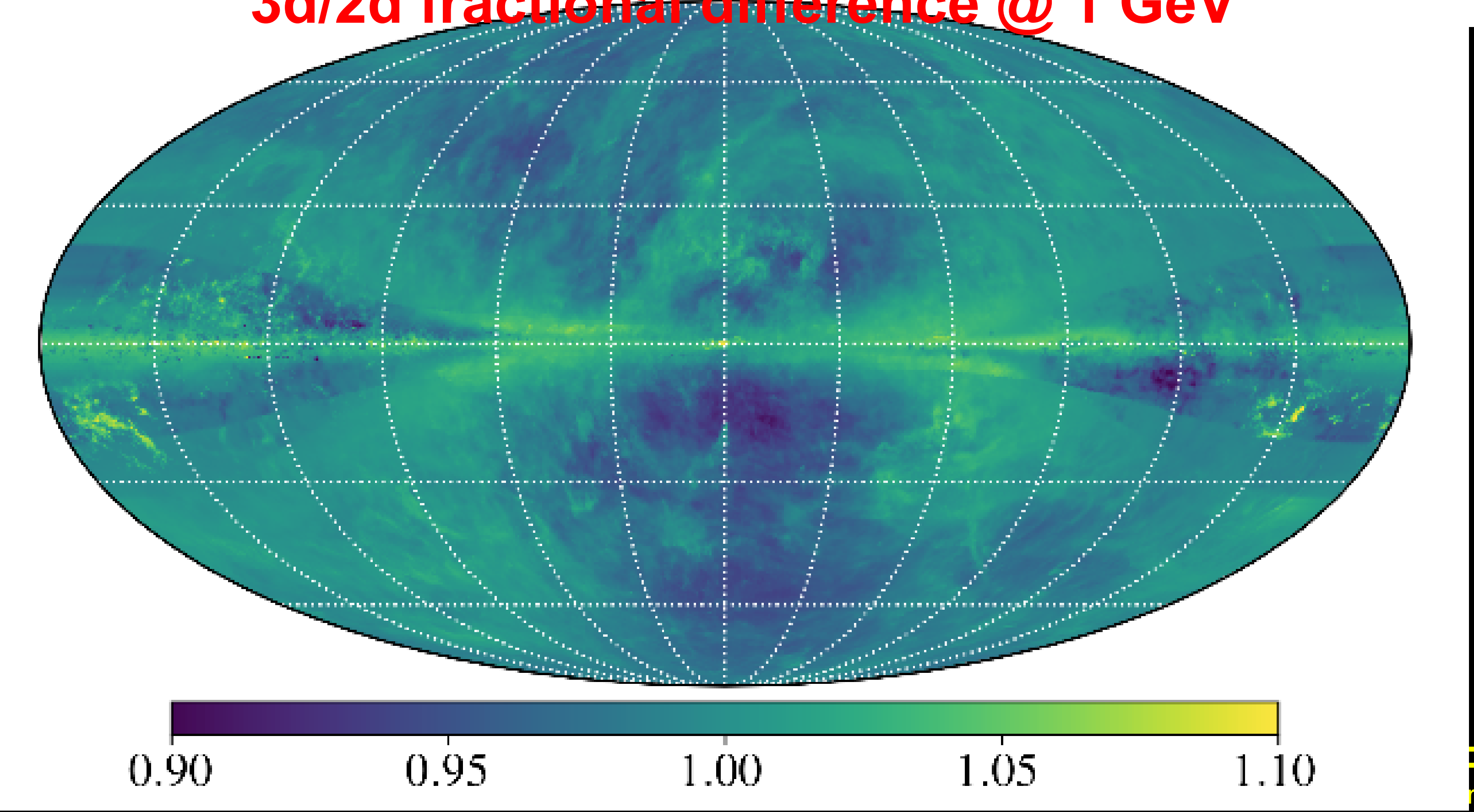
- Reference case: 2D (SA0) + 2D Std ISRF + 2D gas
- 3D gas and R12 model produce density-squared (CRxISM densities) for π^0-decay, bremsstrahlung, and IC → all enhanced compared to reference model
- Note scale change compared with previous 2 slides

Interpretation of HE Gamma-Ray Residuals 1

- Ratio of 3d/2d gas model, same CR source distribution (SA0/Pulsars) → residuals solely due to the different gas density distributions
- Clear correlation of structures from Ackermann et al. ApJ 750, 3 (2012)

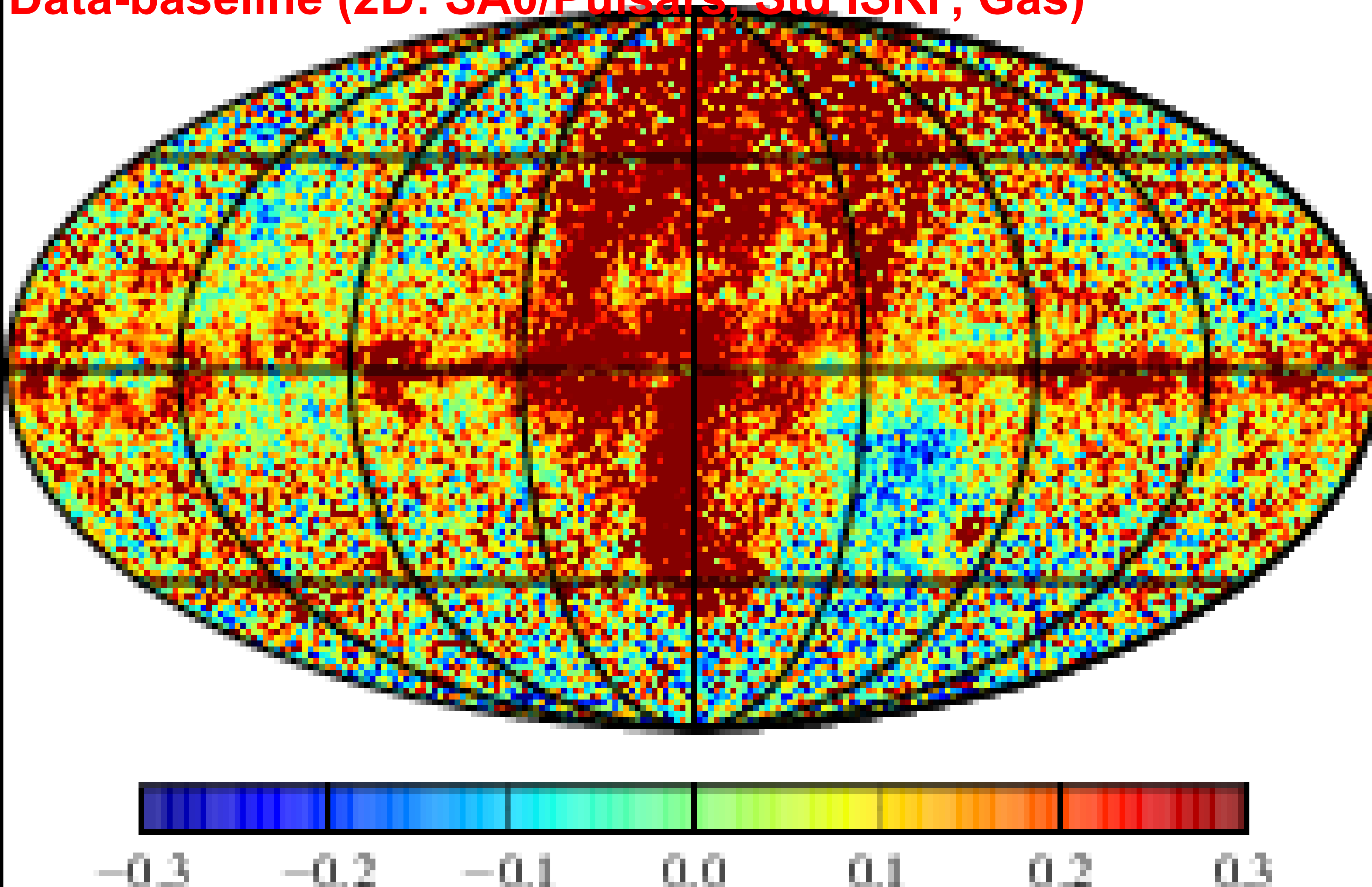


3d/2d fractional difference @ 1 GeV



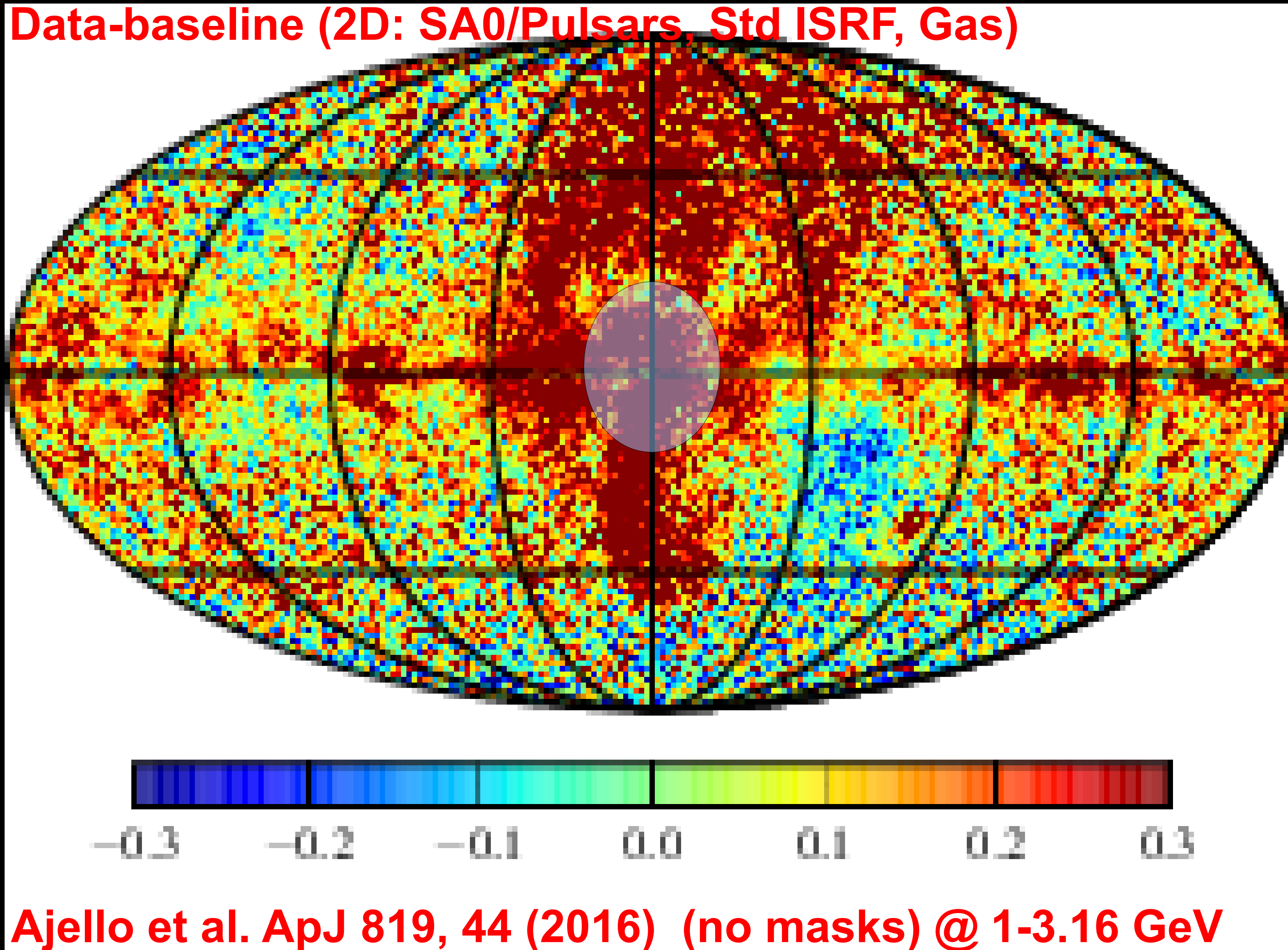
Interpretation of HE Gamma-Ray Residuals 2

Data-baseline (2D: SA0/Pulsars, Std ISRF, Gas)



Ajello et al. ApJ 819, 44 (2016) (no masks) @ 1-3.16 GeV

Interpretation of HE Gamma-Ray Residuals 3



Intepretation of HE Gamma-Residuals 4

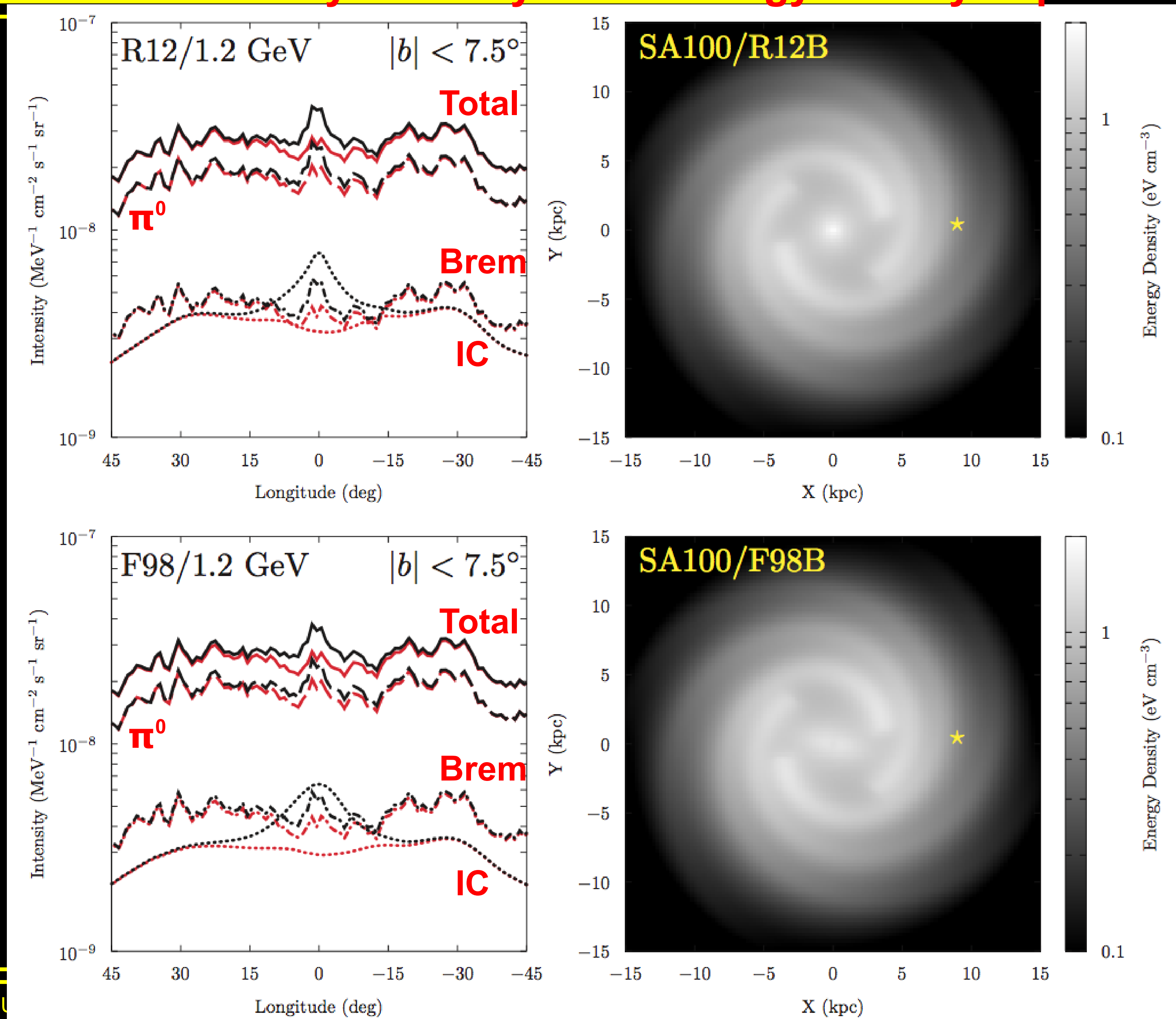
Gamma-ray intensity **CR energy density in-plane**

Red curves: No CR bulge

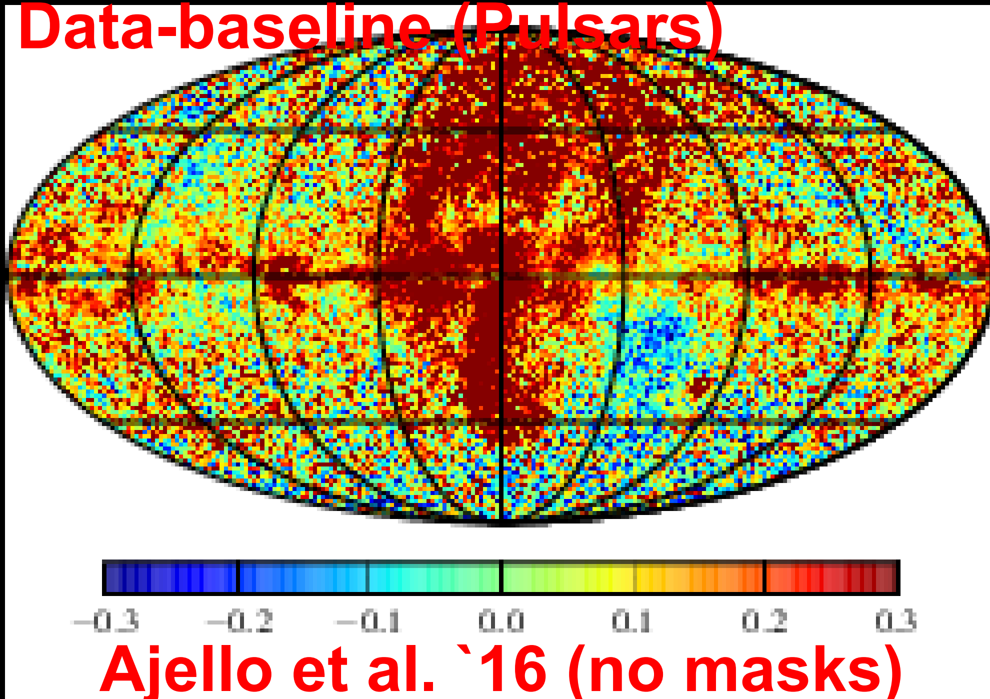
Black curves: With CR bulge

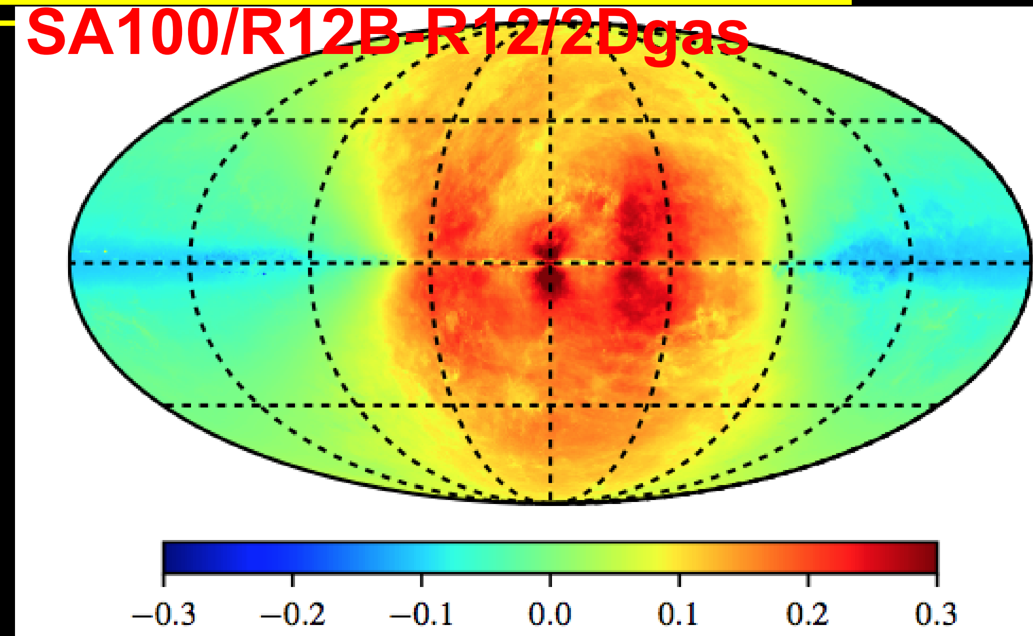
Dot: IC
Dash: π^0
Dash-dot: Brem
Solid: total

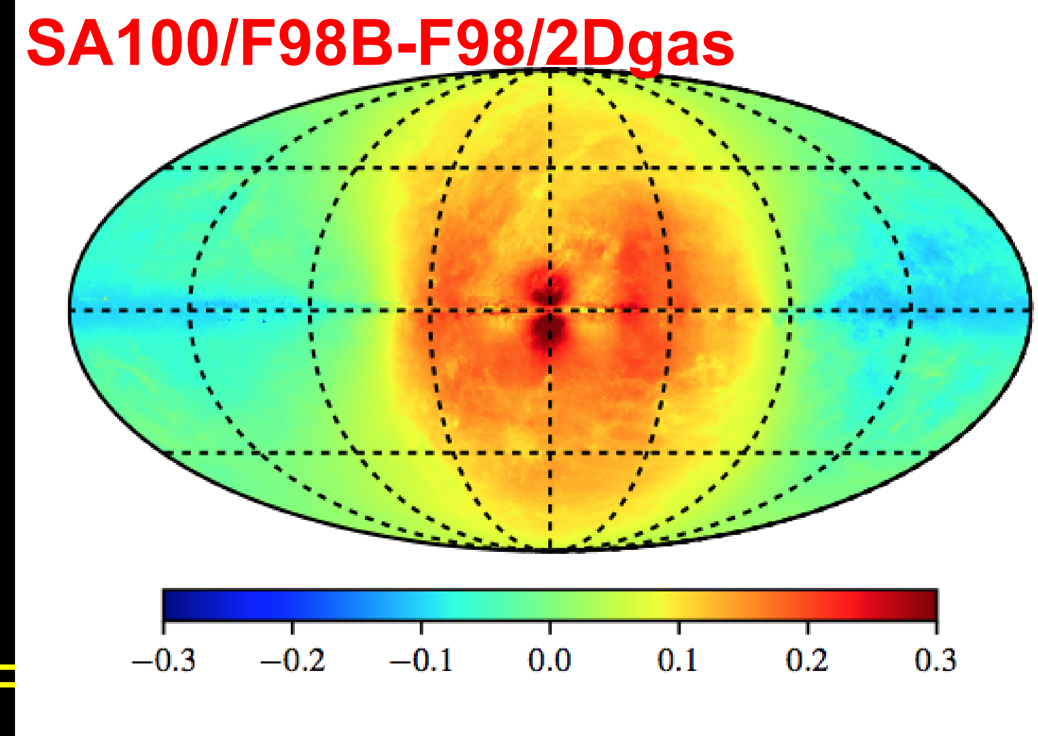
This is a `what-if' – no fits to gamma rays



Interpretation of HE Gamma-Ray Residuals 5

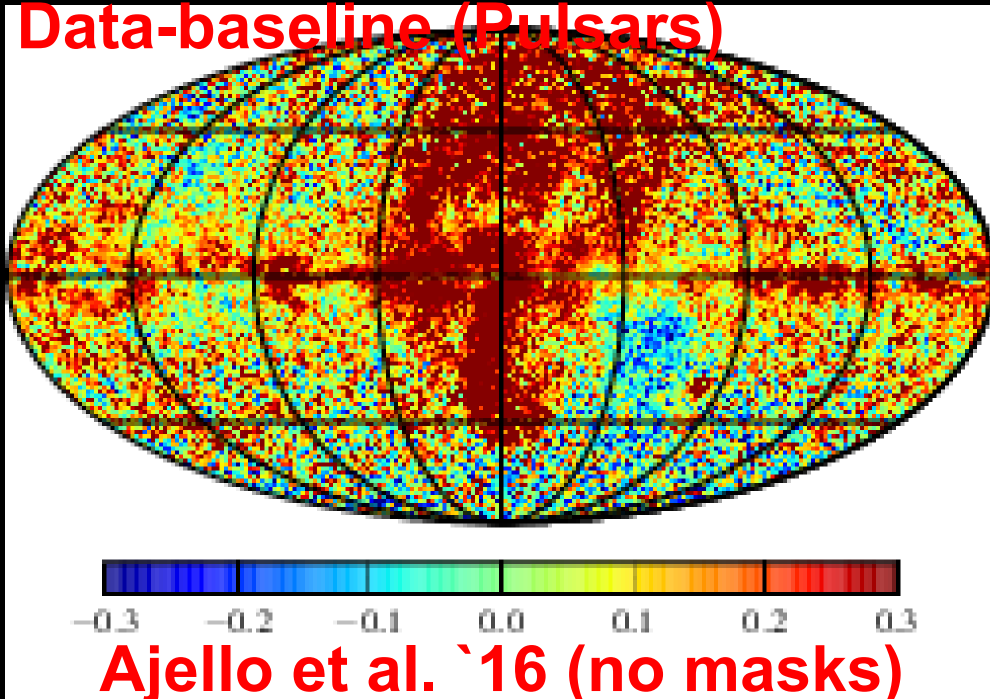


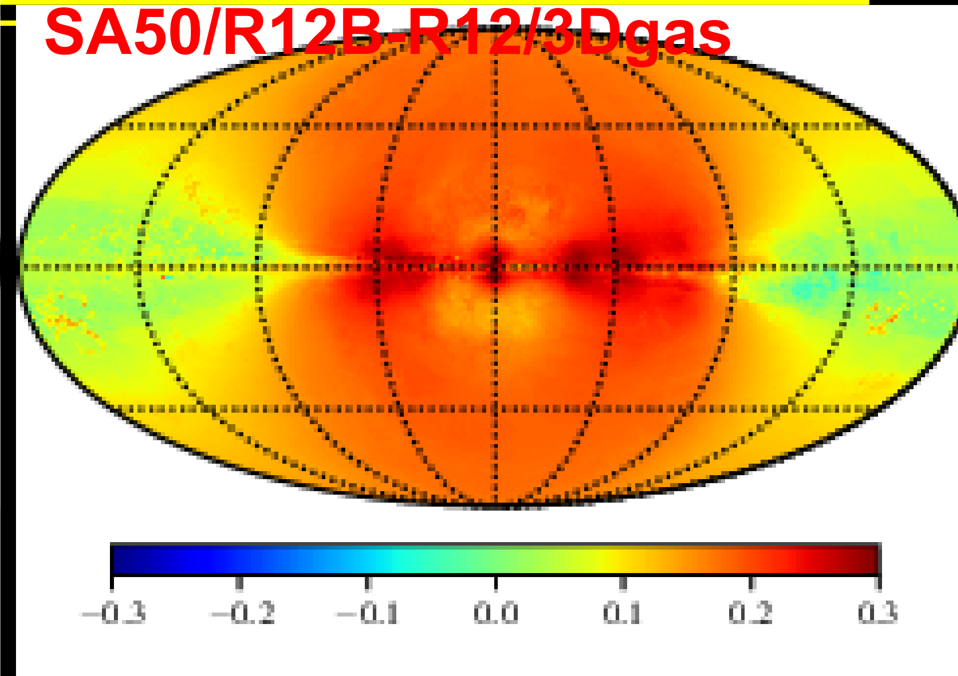




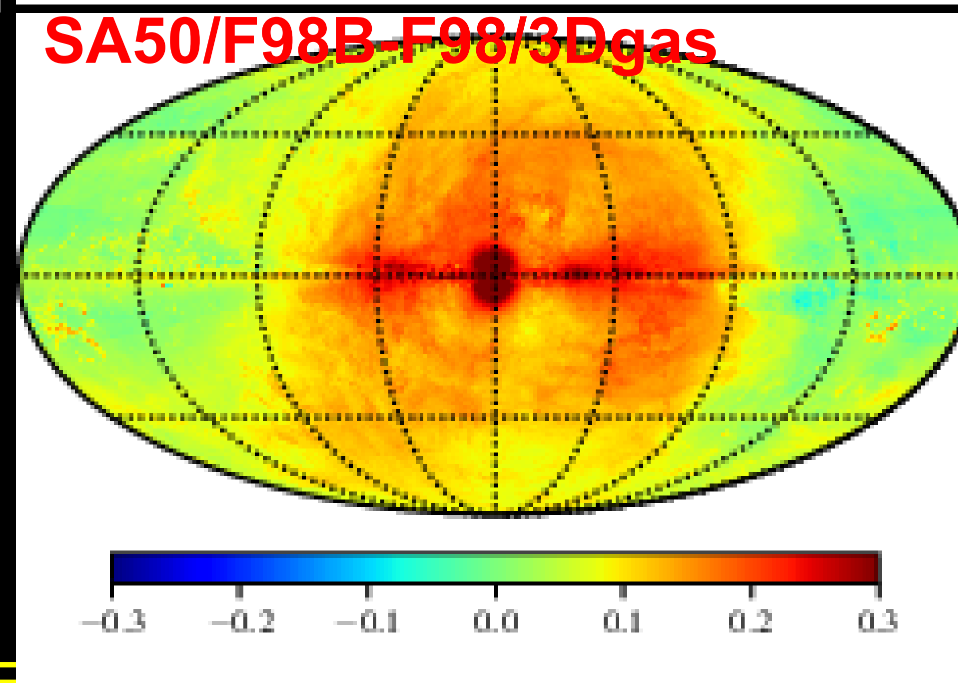
Injected CR power for the `bulge/bar' is ~25x smaller than the arms for the residuals shown. Increase CR power by ~50% for the bulge/bar makes the modelled residuals look more like those from the data (above). Can be done with CR nuclei/leptons or leptons only

Interpretation of HE Gamma-Ray Residuals 6





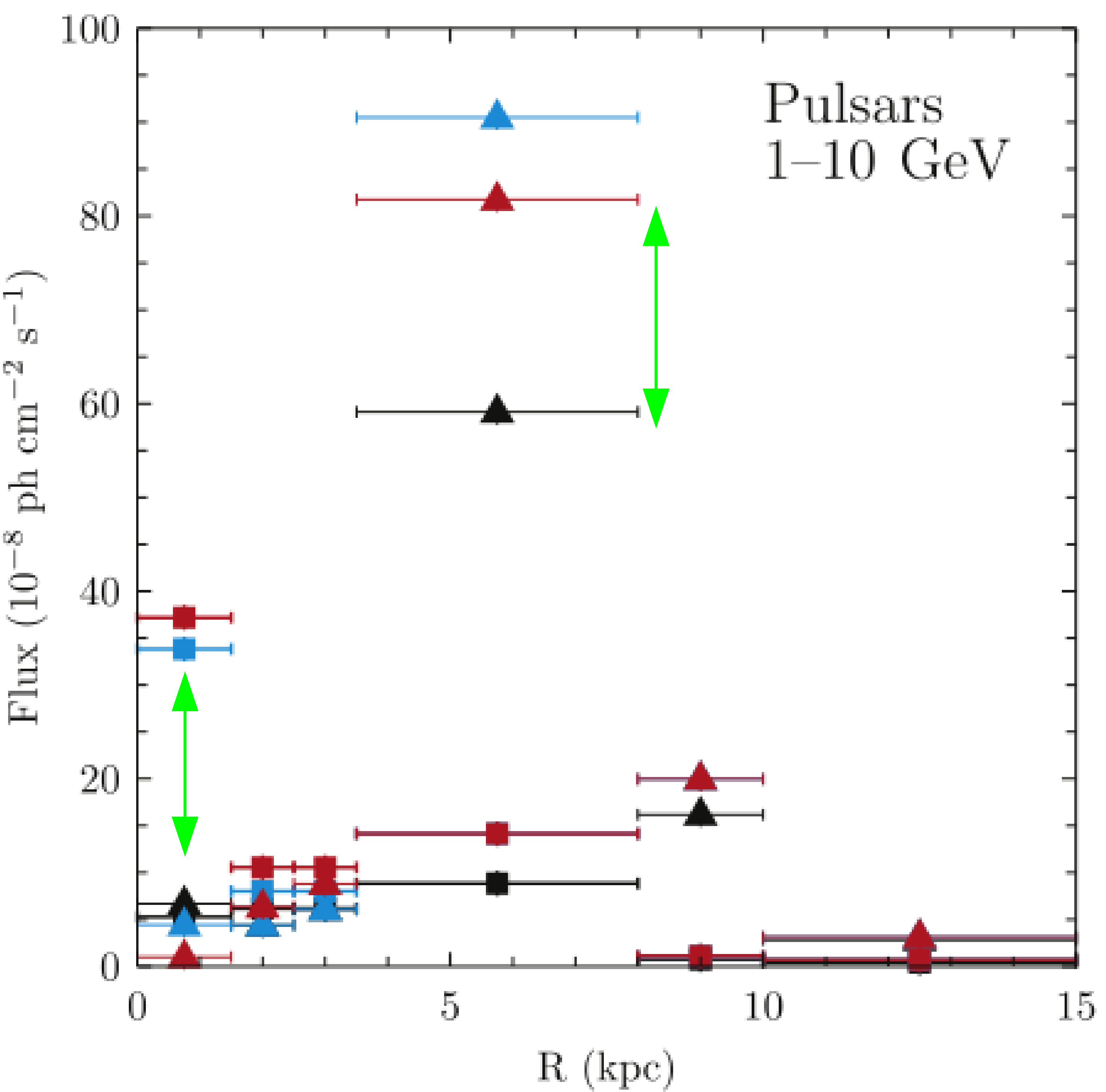
These are for full 3D CR + ISRF + Gas models → the inner `bulge/bar' injected power same as previous slide
Clear that residuals sensitive, particularly about plane and IG, to 3D CR and gas/ISRF density models



Summary

- 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 GALPROP v56 release using 3D CR source and ISM density models show new features in residual maps compared to 2D-based reference calculations → interstellar emission sensitive to 3D spatial structure of CRs, gas, 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
- Check out galprop.stanford.edu and galprop.stanford.edu/webrun for configuration files and data products, and the facility to run code via browser

Summary of Fits for 15°x15° RoI



Fit to data requires increase over baseline. Interpretation with 2D models unclear – ad hoc source dist, …

3D bulge/arm models provide more physical basis for understanding these results