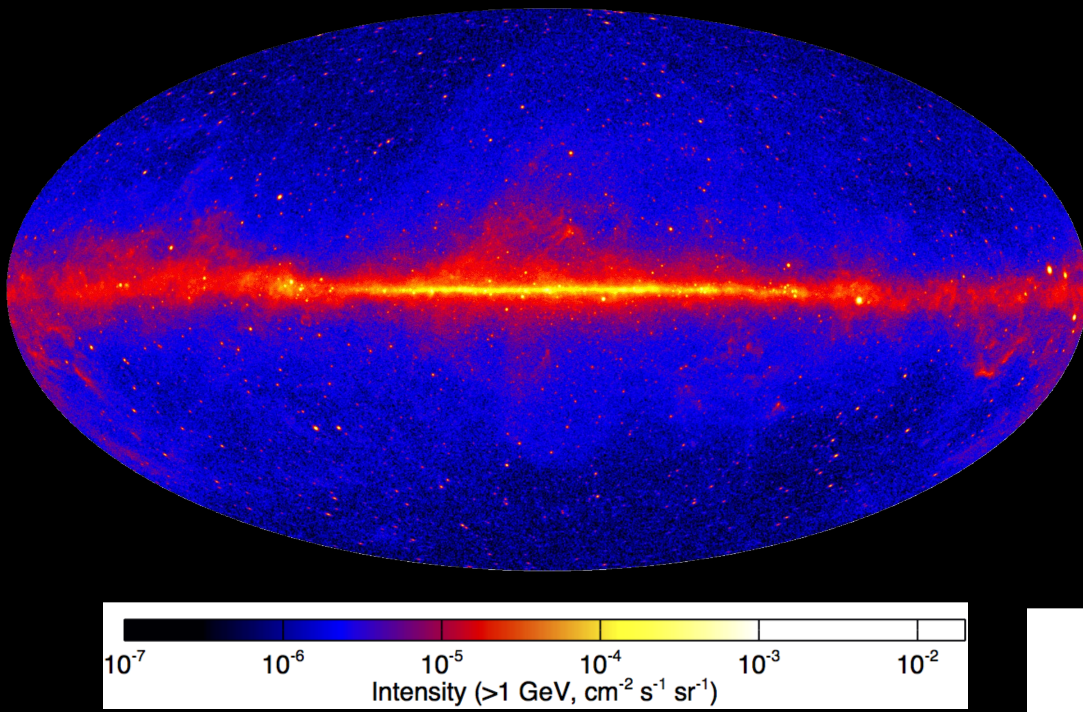
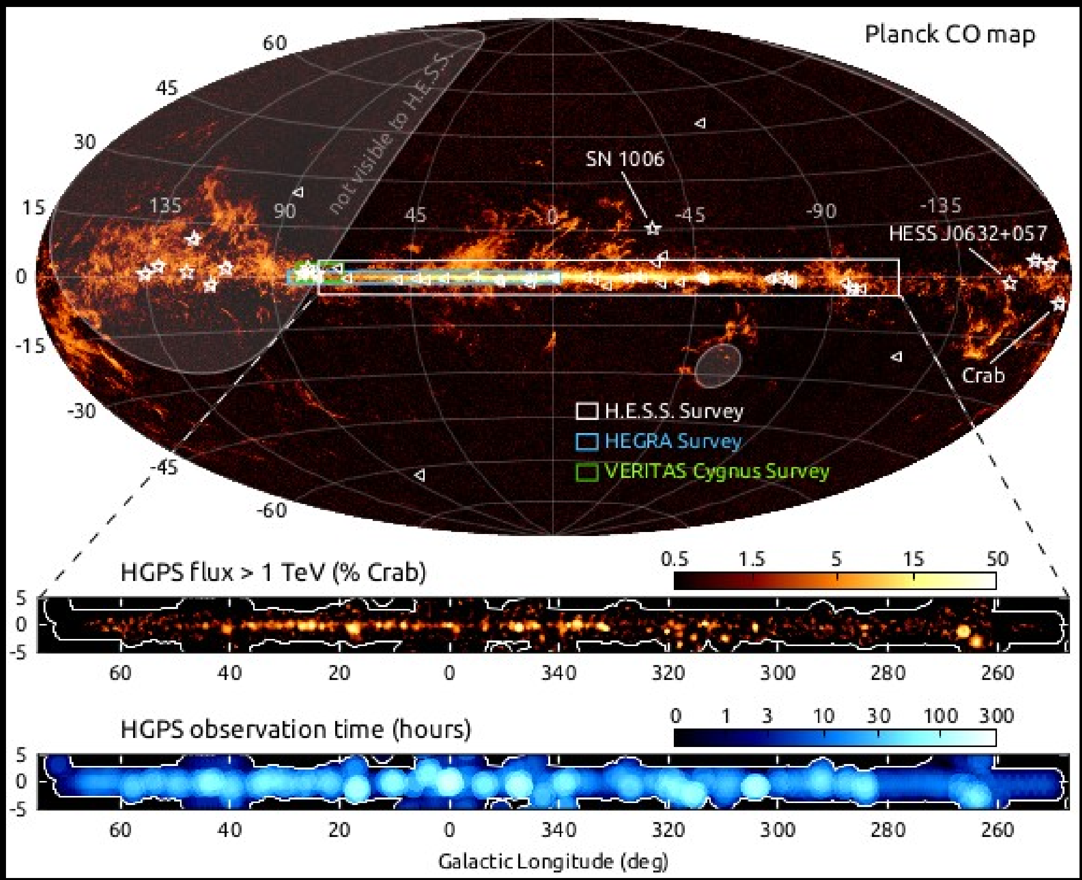
GeV-TeV Connection for Diffuse Galactic Emissions

Troy A. Porter
Stanford University



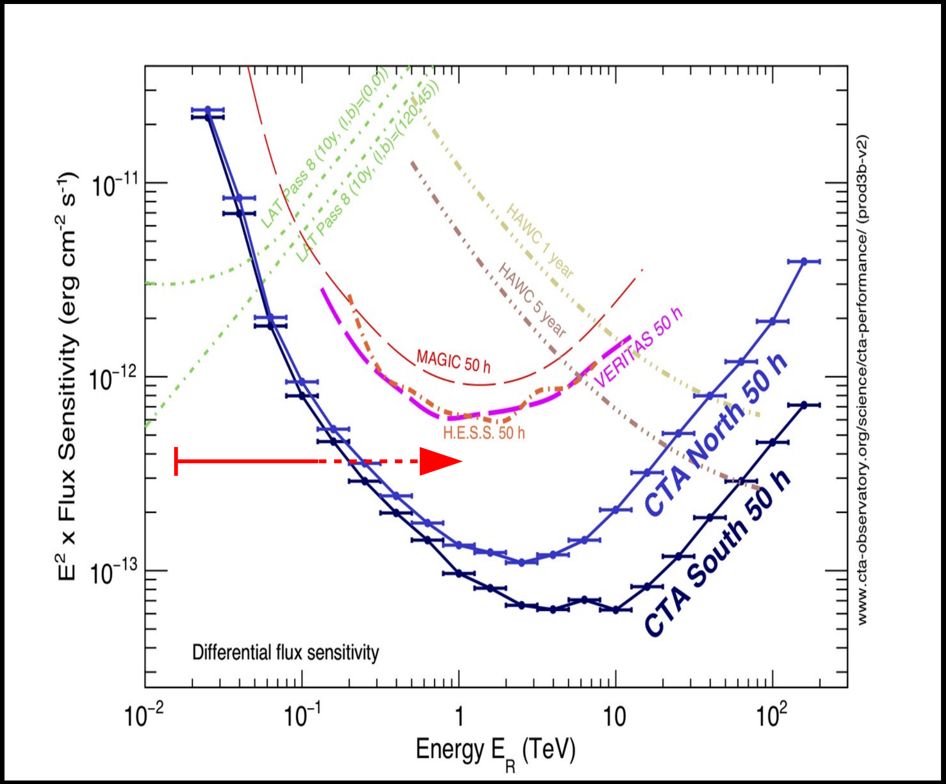
Fermi > 1 GeV, 8 years

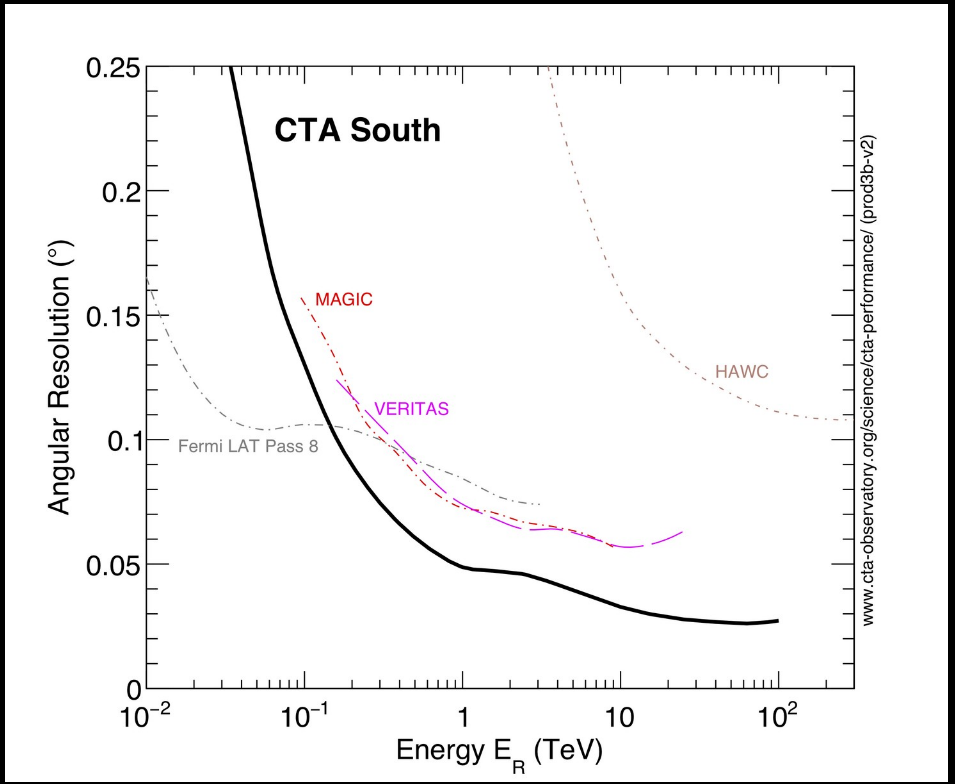
HESS Galactic Plane Survey



Dynamic range different but even if Fermi image has same as HESS the emissions from about the plane are similar but not the same → CR + ISM physics combined with instrumental effects

Era of Precision VHE Gamma-Ray Astronomy

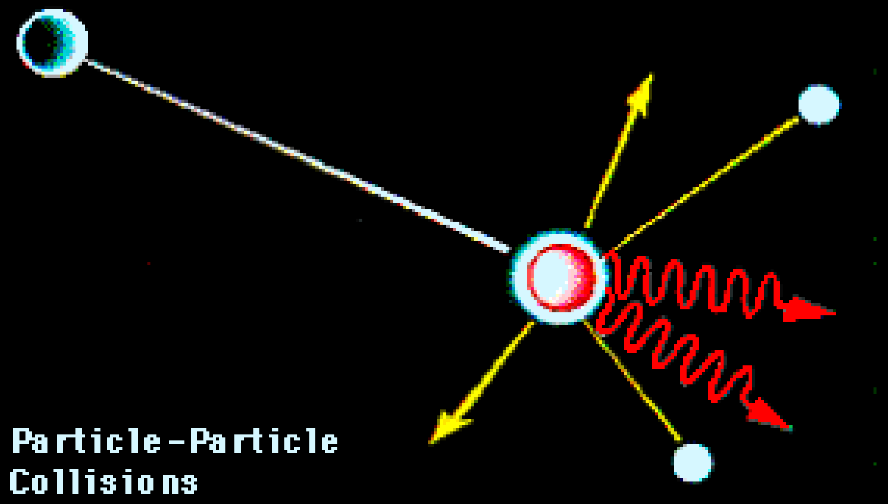


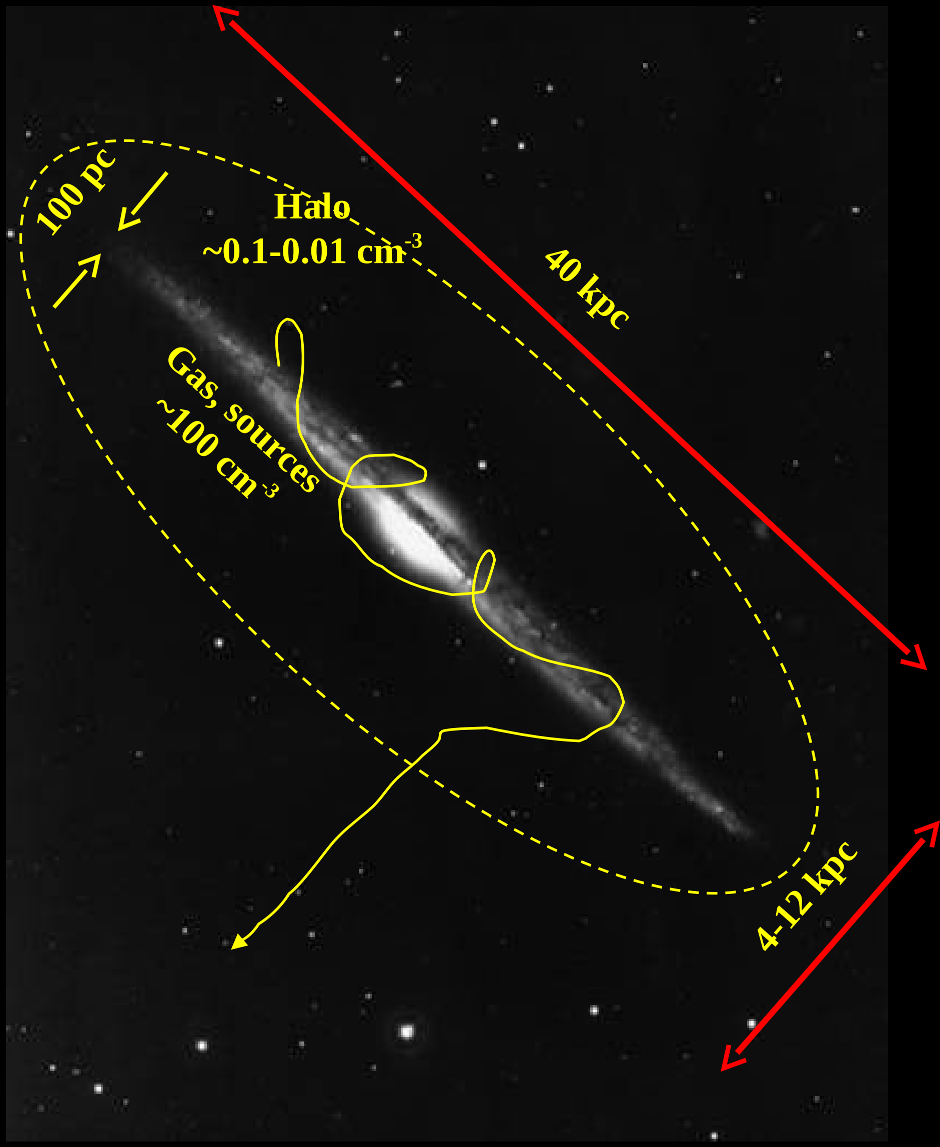


- Sensitivity improvement comparable to that experienced by space-based gamma-ray astronomy EGRET → Fermi-LAT
- Angular resolution improvement → tracing ISM and CR distributions into densest/highest flux regions about acceleration regions
- CTA now sensitive to fine details of the interstellar emission and so understanding/modelling is key for extracting maximum science

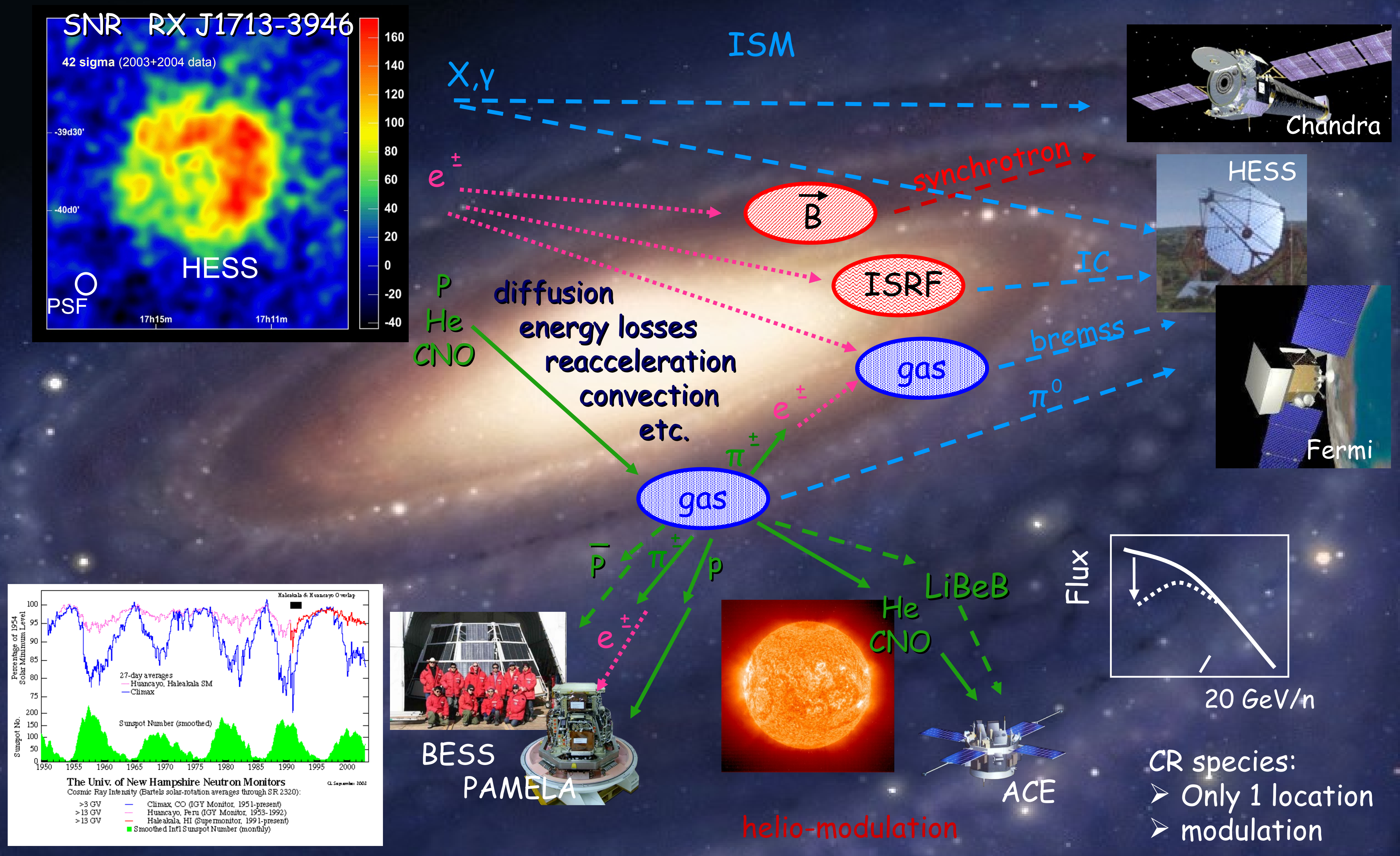
Connection Between Cosmic Rays and Diffuse Emission

- Cosmic rays injected into ISM propagate for millions of years before escape to intergalactic space
- Particle interactions with interstellar gas, radiation and magnetic fields produce EM radiation from radio to gamma rays, and other secondaries ($e^{\pm}$, ν, etc.)

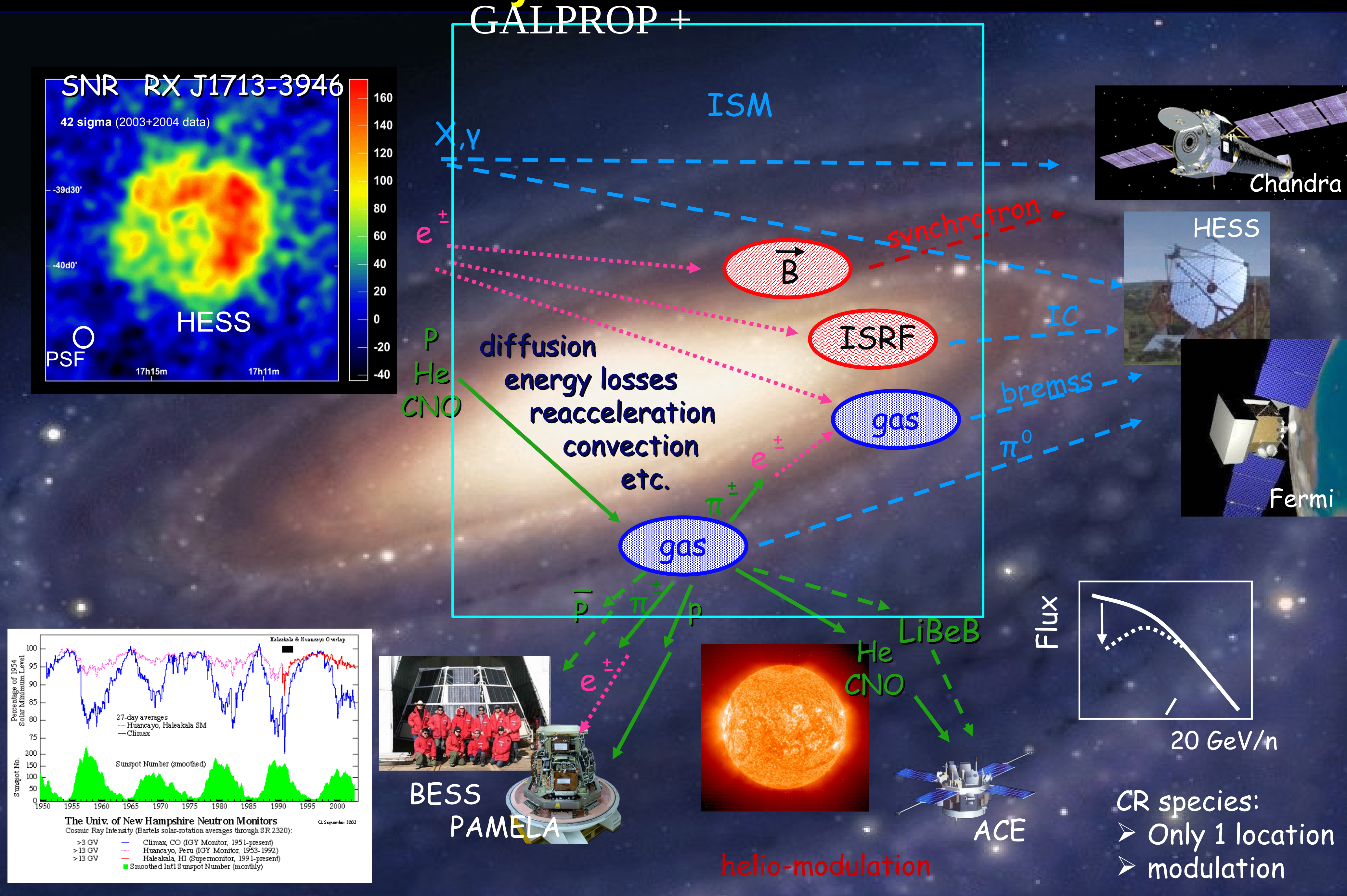




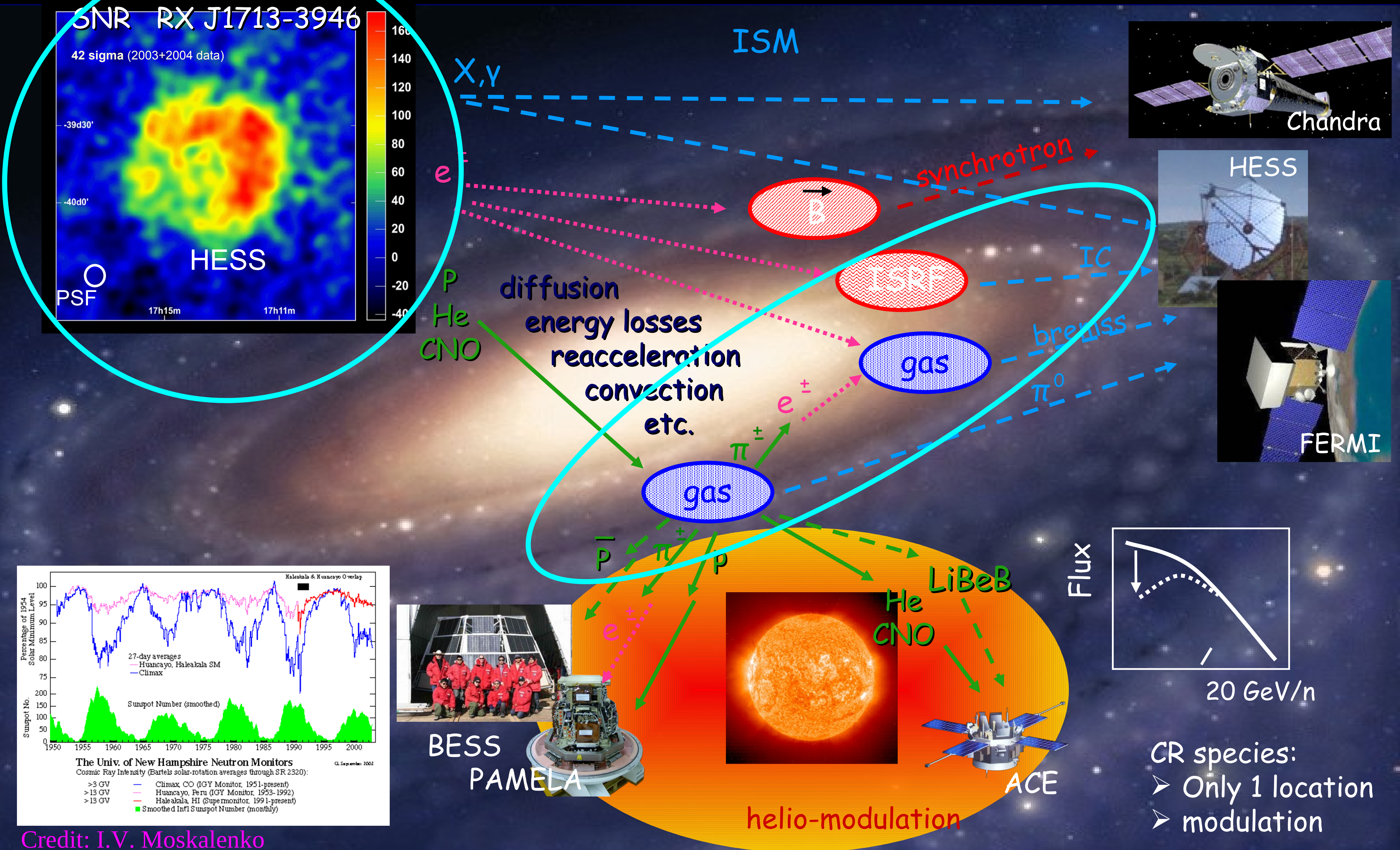
Cosmic Rays and Interstellar Emission



Cosmic Rays and Interstellar Emission



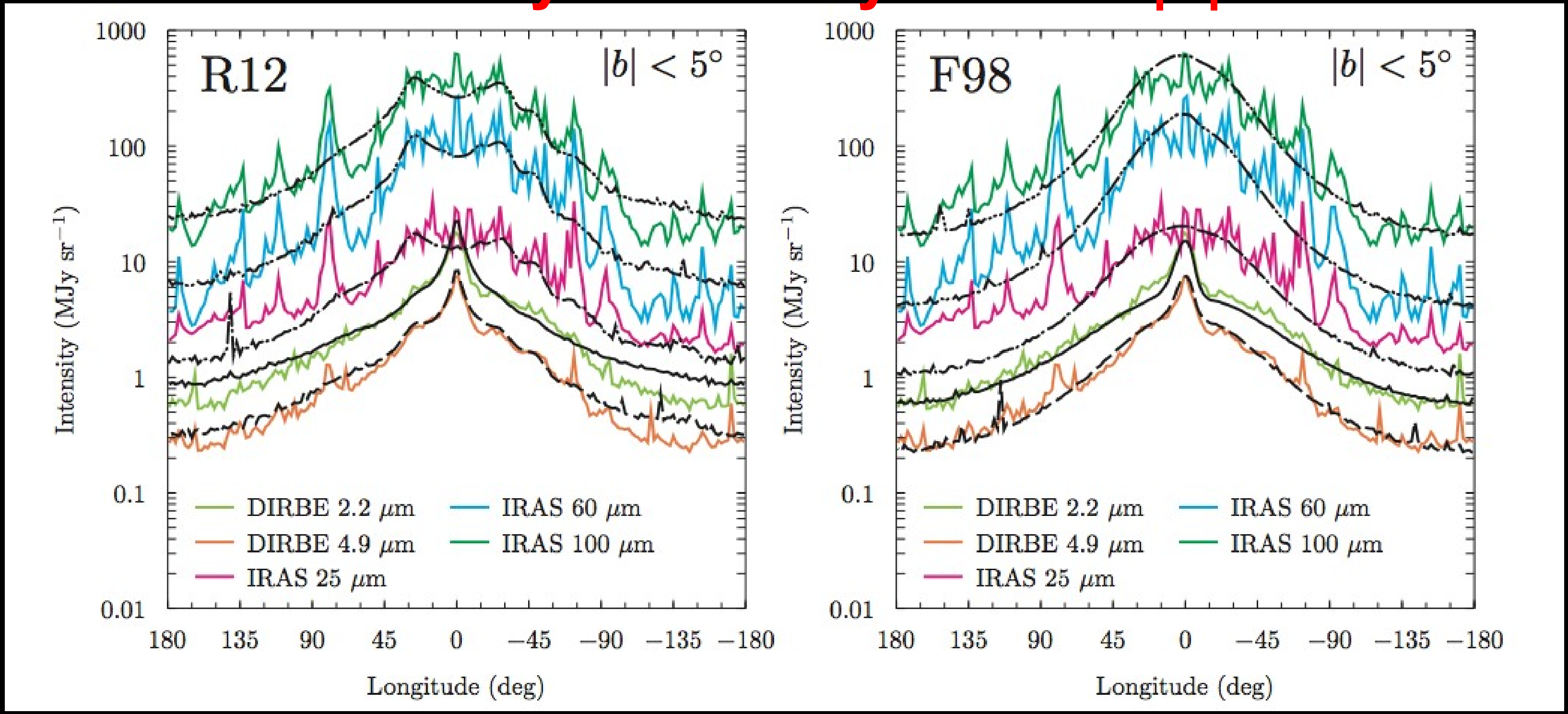
Cosmic-Ray Propagation in the ISM



Credit: I.V. Moskalenko

ISRF Models: R12 and F98

Intensity at Solar system for |b| < 5°



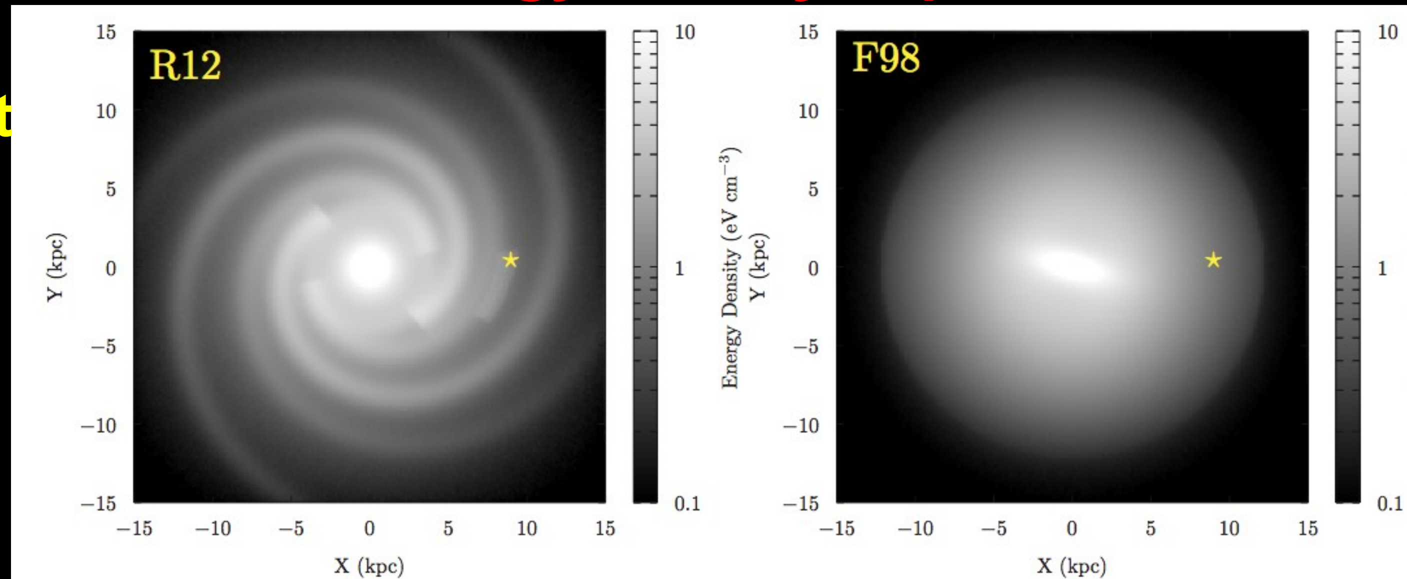
- Full radiation transport modelling using FRaNKIE code
- R12 includes stellar disc, ring, bulge, 4/2 major/minor arms + dust disc with inner hole toward GC
- F98 includes `old' and `young' stellar discs that are warped, spheroidal bar, and warped dust disc with inner hole toward GC
- R12 generally reproduces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

Porter+ ApJ 846, 67 (2017)/arxiv:1708.00816

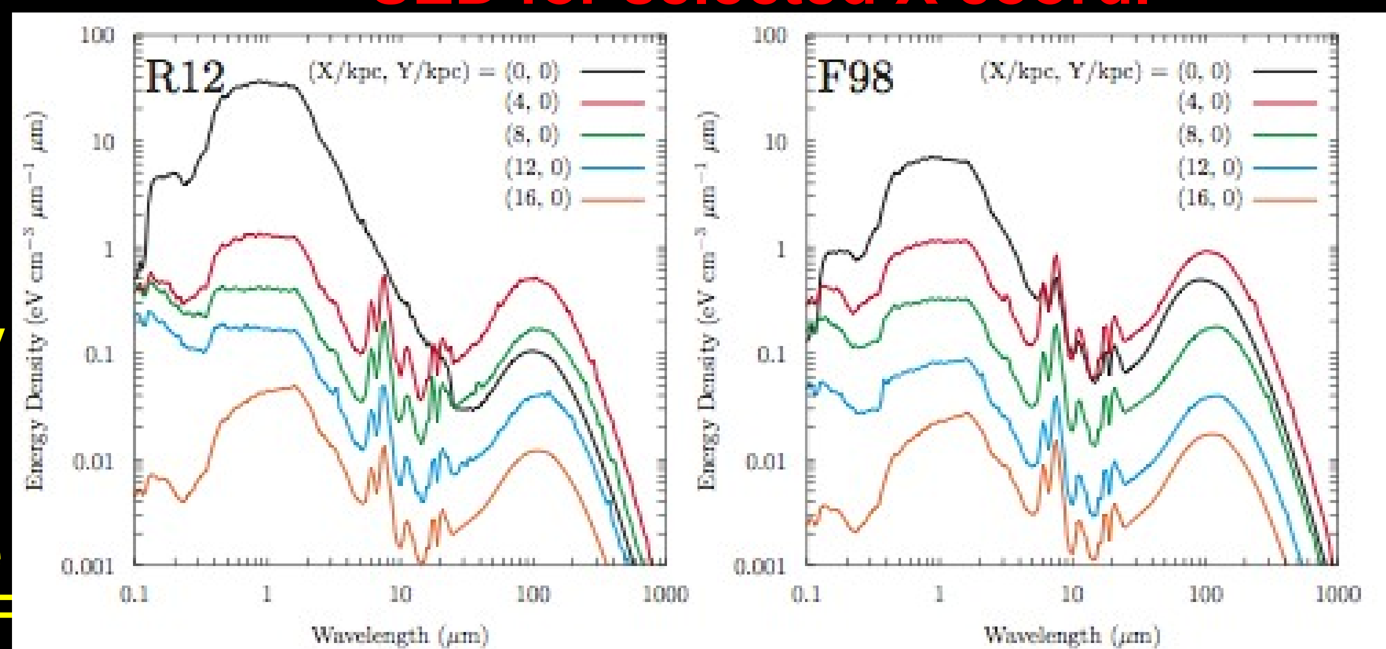
ISRF Models: R12 and F98

- 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



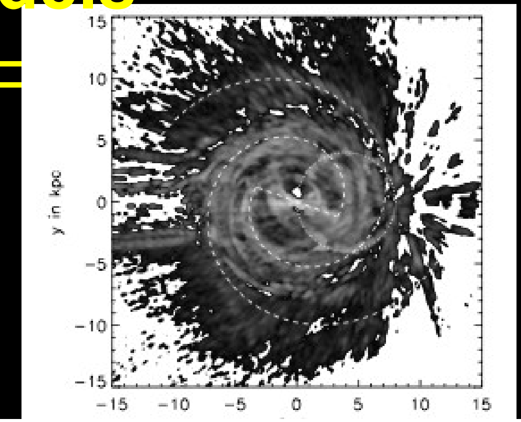
SED for selected X coord.

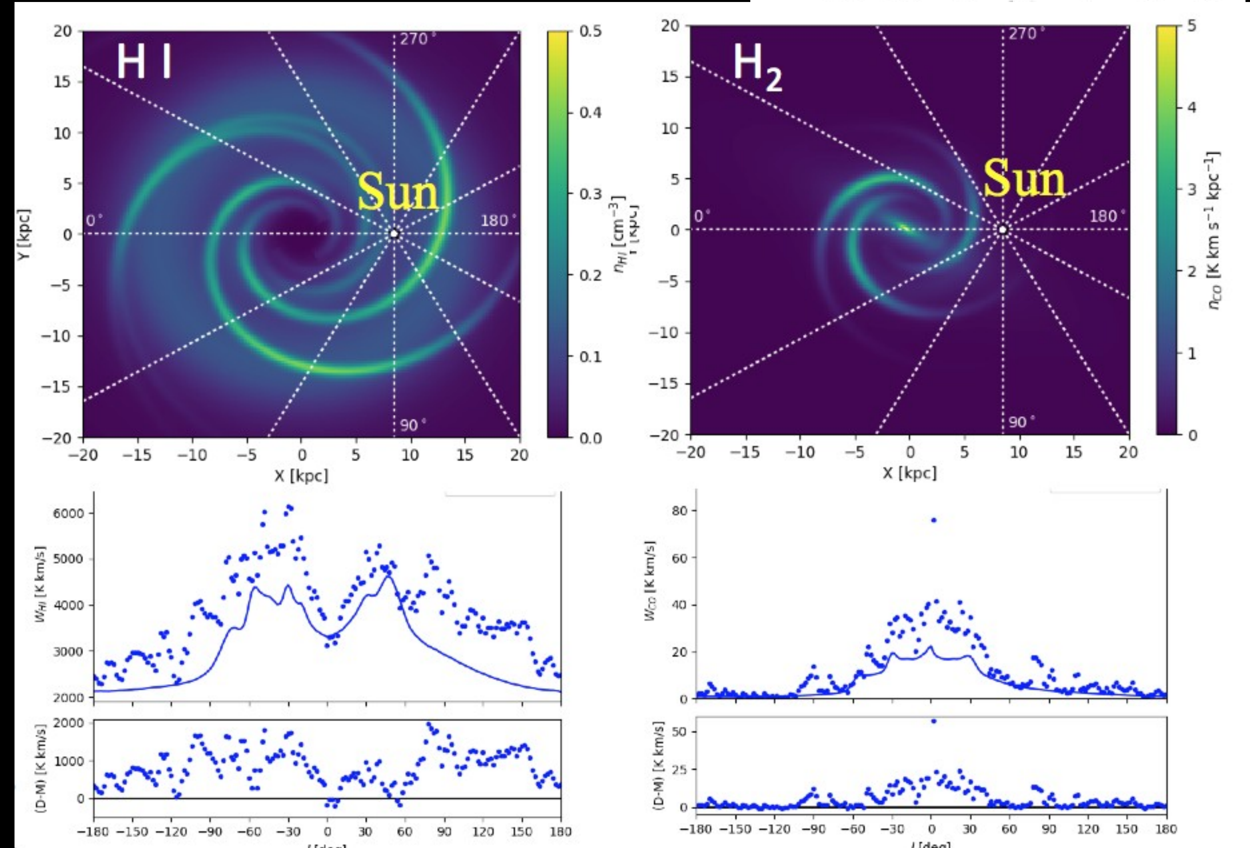


3D atomic and molecular gas models

- Deconvolution studies produce results not suitable for CR propagation calculations, e.g., Pohl+ 2008
- Use forward-folding 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

H_2 surface density Pohl+ 2008





Longitude profiles of gas models |b|≤4°

Johannesson+ ApJ 856, 45 (2018)/arxiv:1802.08646

Discretised Time/Space Modelling of Interstellar Emission

DECIPHERING RESIDUAL EMISSIONS: TIME-DEPENDENT MODELS FOR THE NON-THERMAL INTERSTELLAR RADIATION FROM THE MILKY WAY

T. A. Porter[1,†], G. Jóhannesson[2,3], and I. V. Moskalenko[1]

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ABSTRACT

Cosmic rays (CRs) in the Galaxy are an important dynamical component of the interstellar medium (ISM) that interact with the other major components (interstellar magnetic and radiation fields, and gas) to produce broadband interstellar emissions that span the electromagnetic spectrum. The standard modelling of CR propagation and production of the associated emissions is based on a steady-state assumption, where the CR source spatial density is described using a smoothly varying function of position that does not evolve with time. While this is a convenient approximation, reality is otherwise where primary CRs are produced in and about highly localised regions, e.g., supernova remnants, which have finite lifetimes. In this paper we use the latest version of the GALPROP CR propagation code to model time-dependent CR injection and propagation through the ISM from a realistic three-dimensional discretised CR source density distribution, together with full three-dimensional models for the other major ISM components, and make predictions of the associated broadband non-thermal emissions. We compare the predictions for the discretised and equivalent steady-state model, finding that the former predicts novel features in the broadband non-thermal emissions that are absent for the steady-state case. Some of features predicted by the discretised model may be observable in all-sky observations made by WMAP and *Planck*, the recently launched eROSITA, the *Fermi*–LAT, and ground-based observations by HESS, HAWC, and the forthcoming CTA. The non-thermal emissions predicted by the discretised model may also provide explanations of puzzling anomalies in high-energy γ-ray data, such as the *Fermi*–LAT north/south asymmetry and residuals like the so-called "Fermi bubbles".

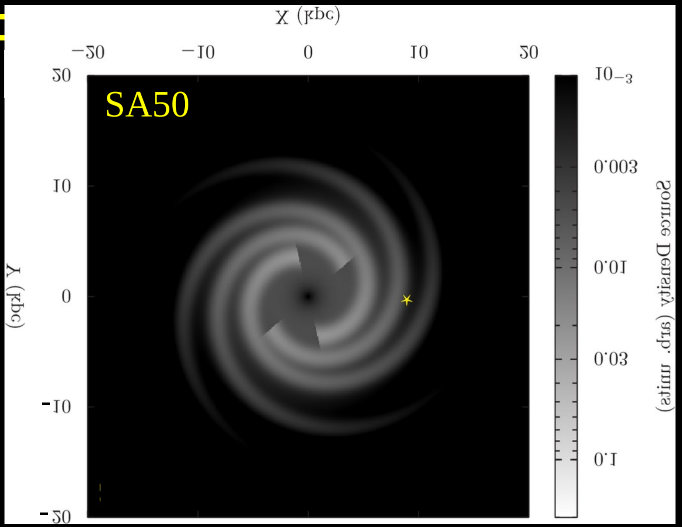
Keywords: astroparticle physics — Galaxy: general — Gamma rays: general — Gamma rays: ISM — (ISM:) cosmic rays — radiation mechanisms: nonthermal

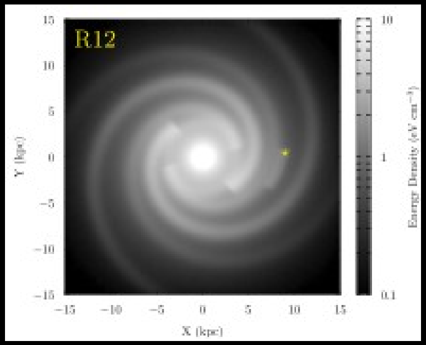
arXiv:1909.02223

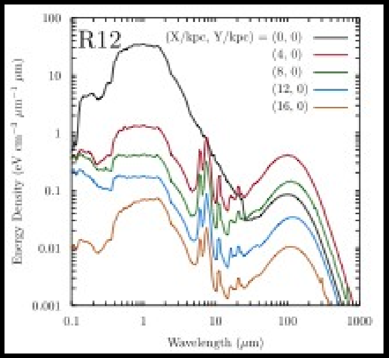
ApJ in press

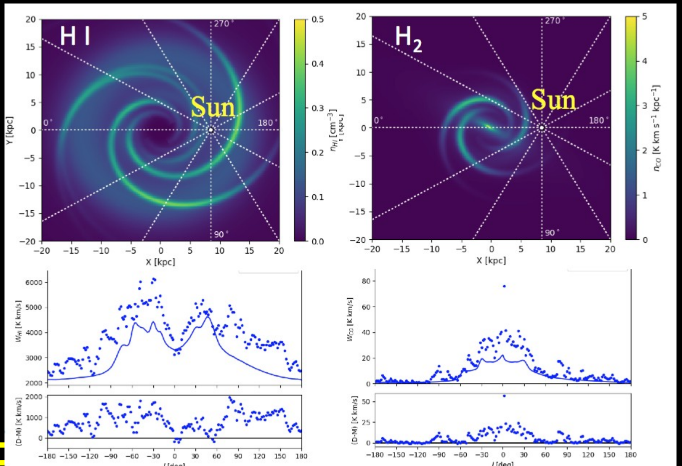
Time/Space Discretised CR Injection and Propagation Across Milky Way

- Latest release of GALPROP (v56) with enhancements + 3D CR source density models + 3D ISRF models + 3D gas models
- Define SA50 smooth source density (disc+ R12 arms) and new sampler facility to discretise in space and time
- Propagation parameters (halo size, etc.) obtained by tuning to CR data for the source distribution using the 3D gas model
- Energy losses/interstellar emission production using full 3D gas, ISRF (R12), and magnetic field (Pshirkov+11)









Longitude profiles of gas models |b|≤4°

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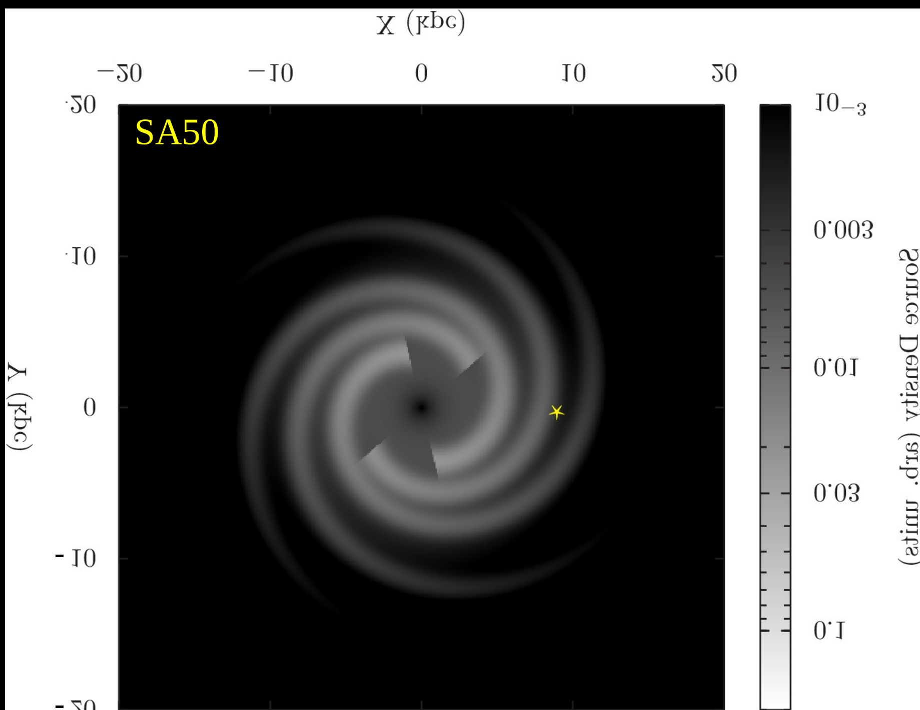
Propagation of Cosmic Rays: Steady-State

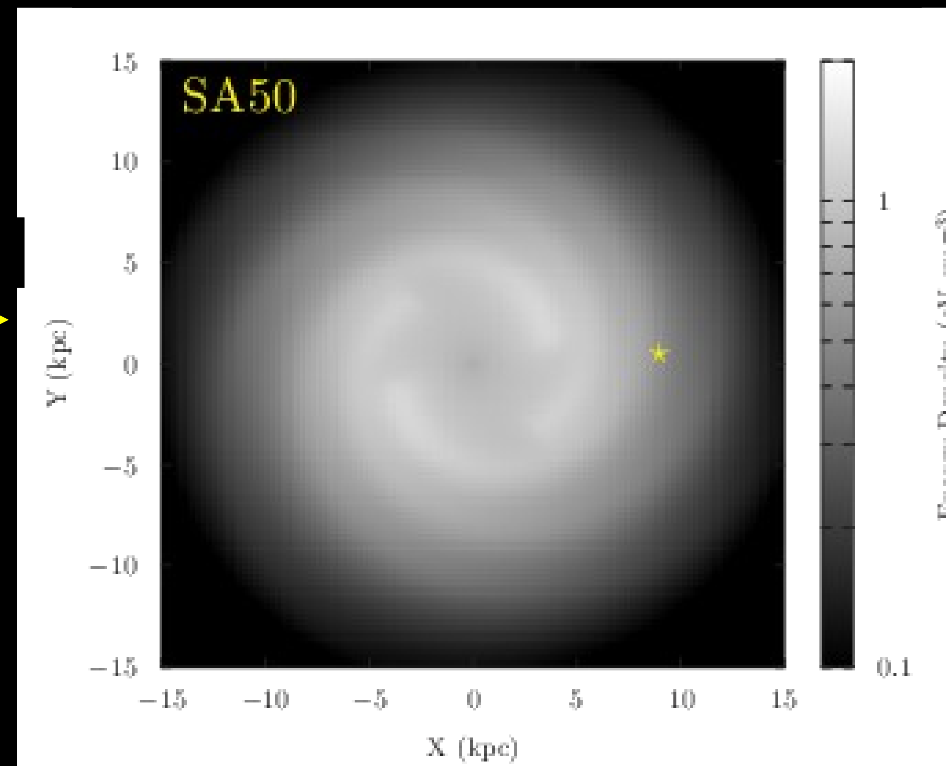
SA50 continuous source density model with 50% of CR luminosity in arms and 50% in disc – total luminosity ~ 5e40 erg/s



★ = solar system location

Propagation

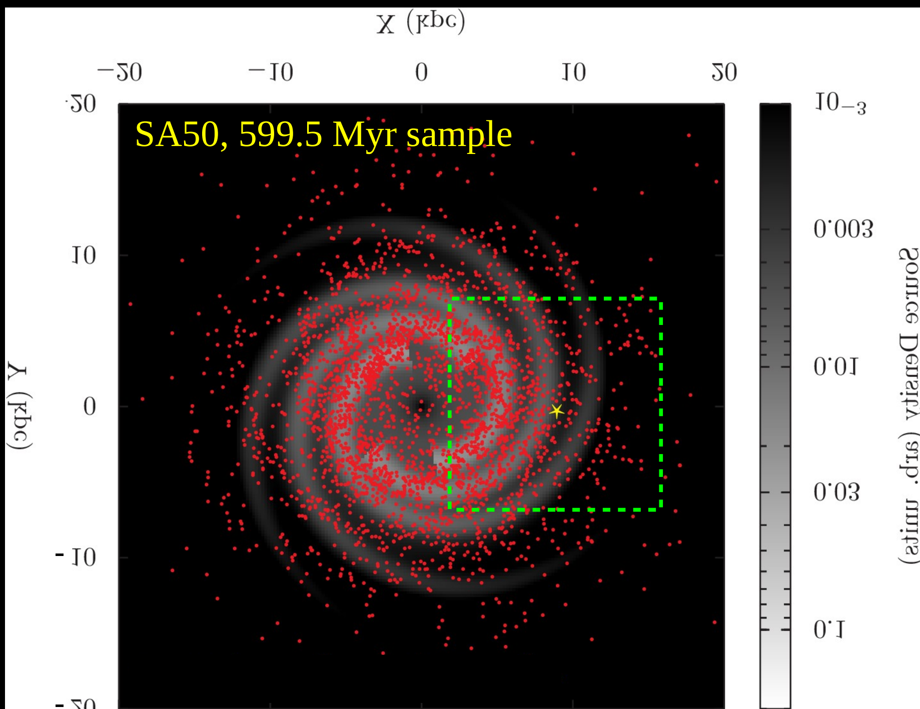
Total integrated energy density at Galactic plane – dominated by protons, but both proton and electron distributions are smooth



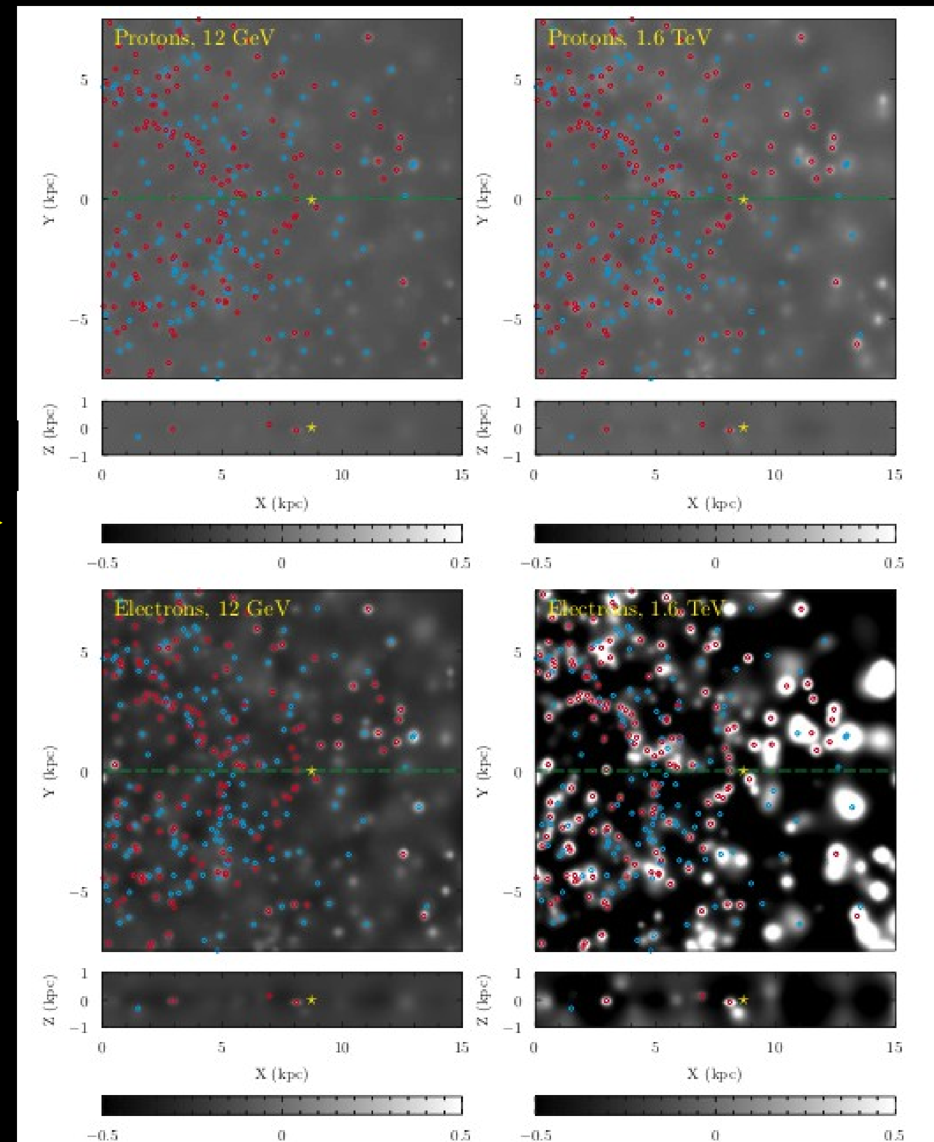
Propagation of Cosmic Rays: Discretised

Simulation: 600 Myr with 0.01 yr^-1 frequency, 50 pc^3 volume/region, 100 kyr active time, constant luminosity, sources sampled from SA50, evolved using GALPROP t-dep,100 MeV to 10 TeV CR p and e with 32 energy planes

Sample at 599.5 Myr, source regions active within 200 kyr



Propagation



★ = solar system location

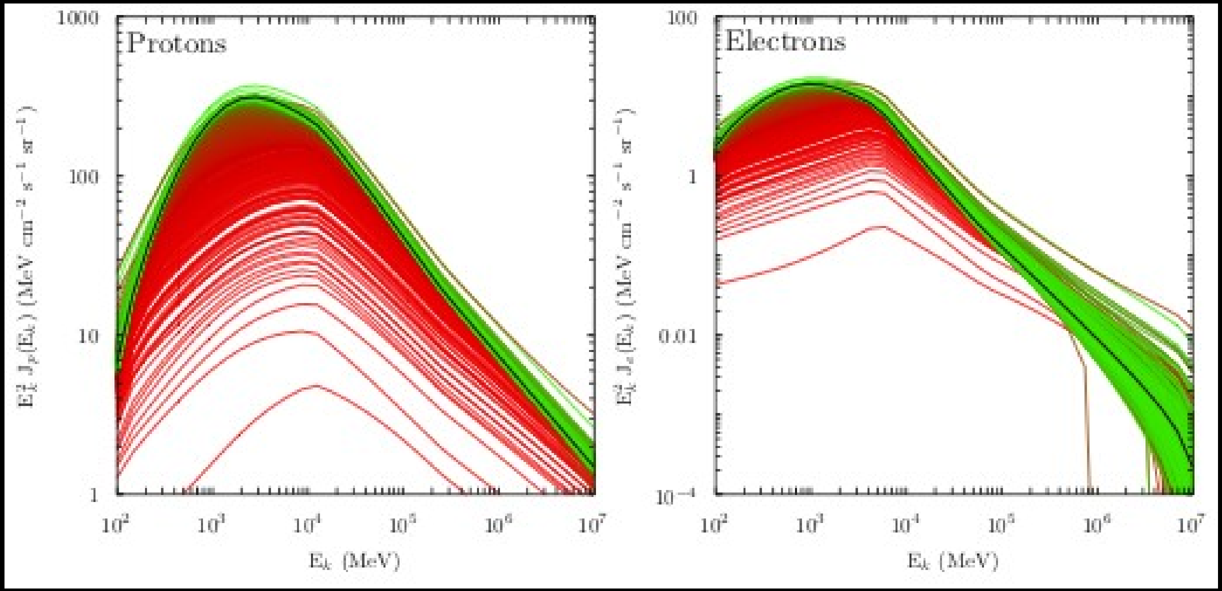
TD = time-dependent/discretised

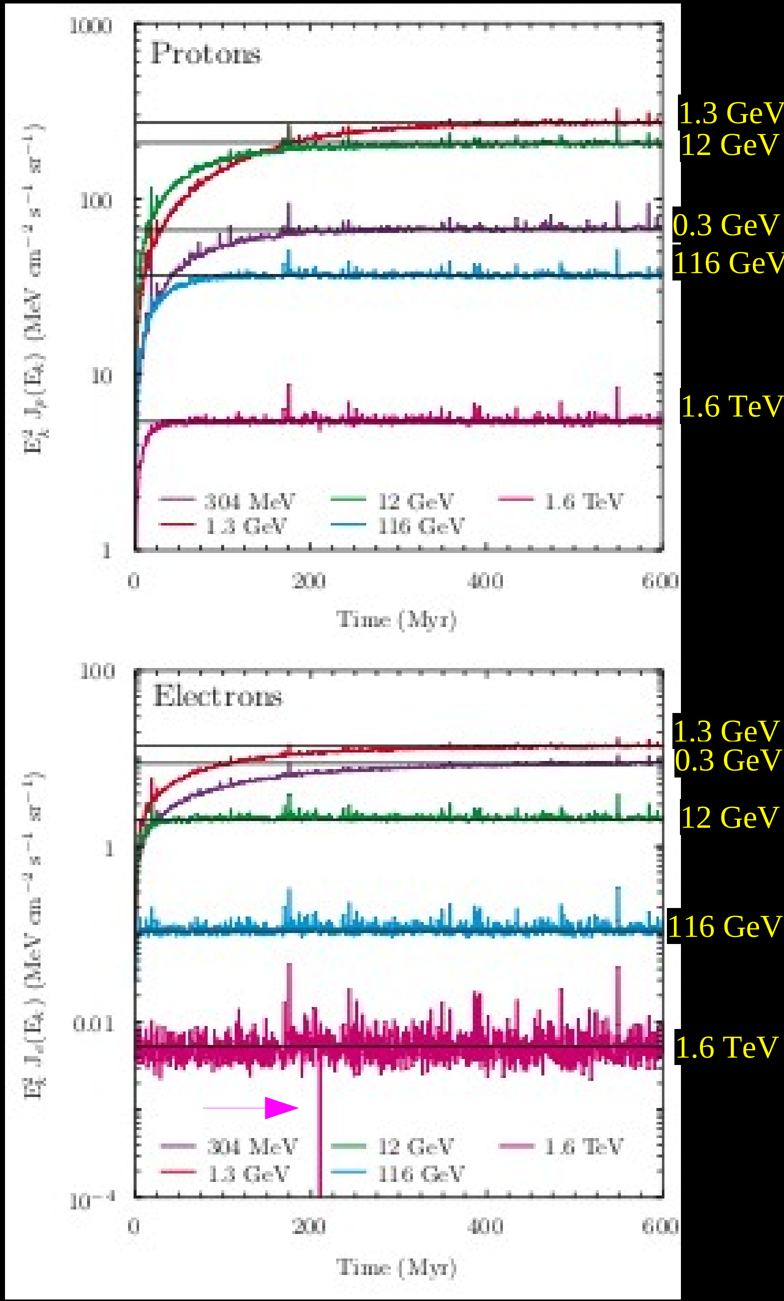
SS = steady-state/baseline

(TD-SS)/SS – fractional energy density

Cosmic Ray Intensities at Solar System

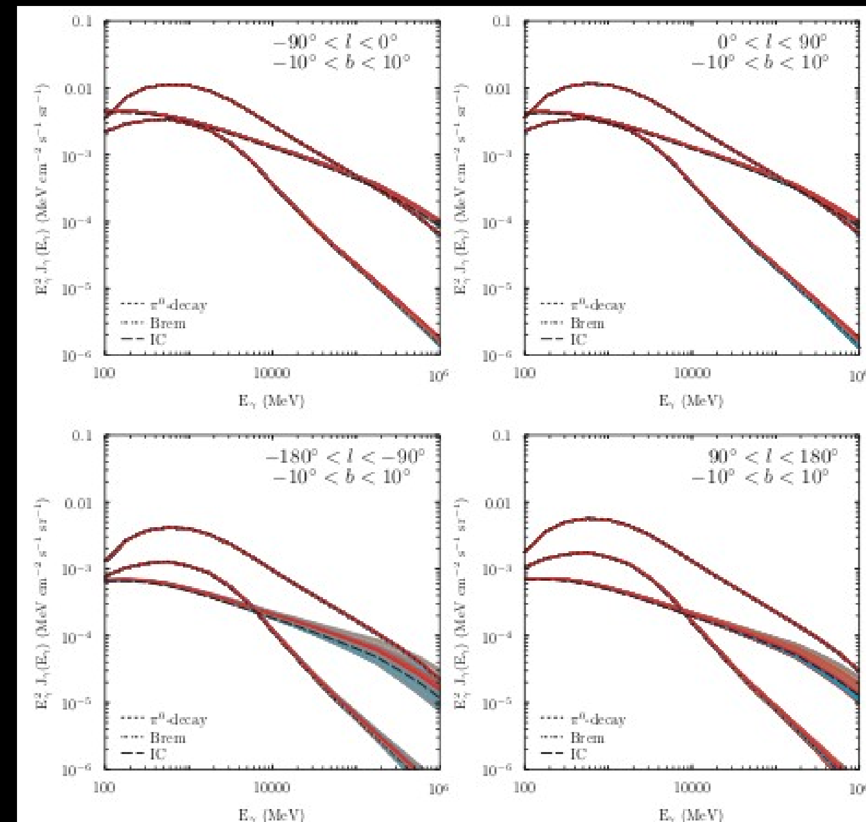
- Discretised solution approaches steady state for long times (> few times 60-70 Myr propagation time scale at GeV energies)
- Fluctuations ~ 20-30% mostly, with some anomalies
- Envelope for high-energy electron intensity spectrum → fluctuates significantly over ~100s kyr sampling

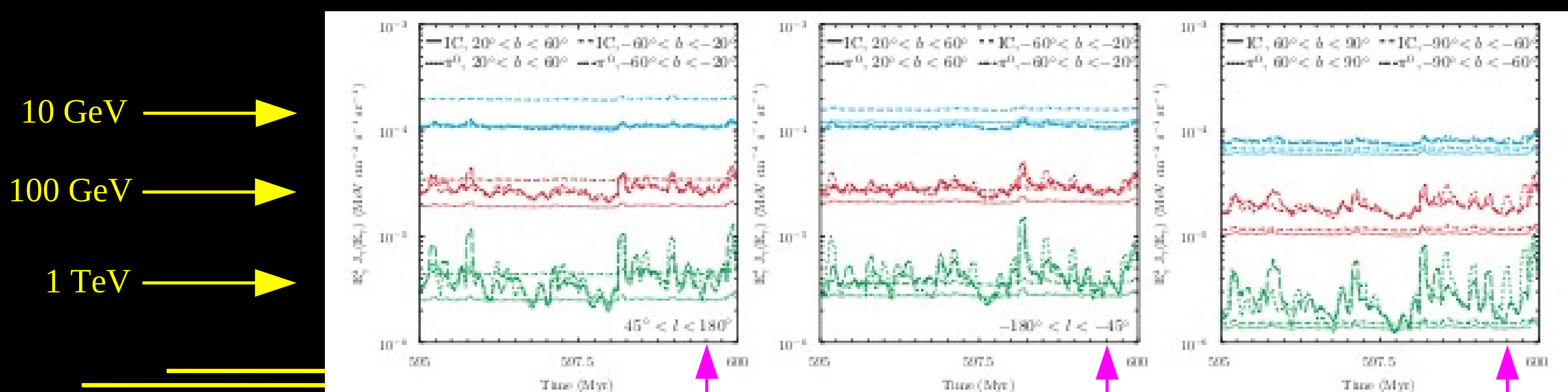




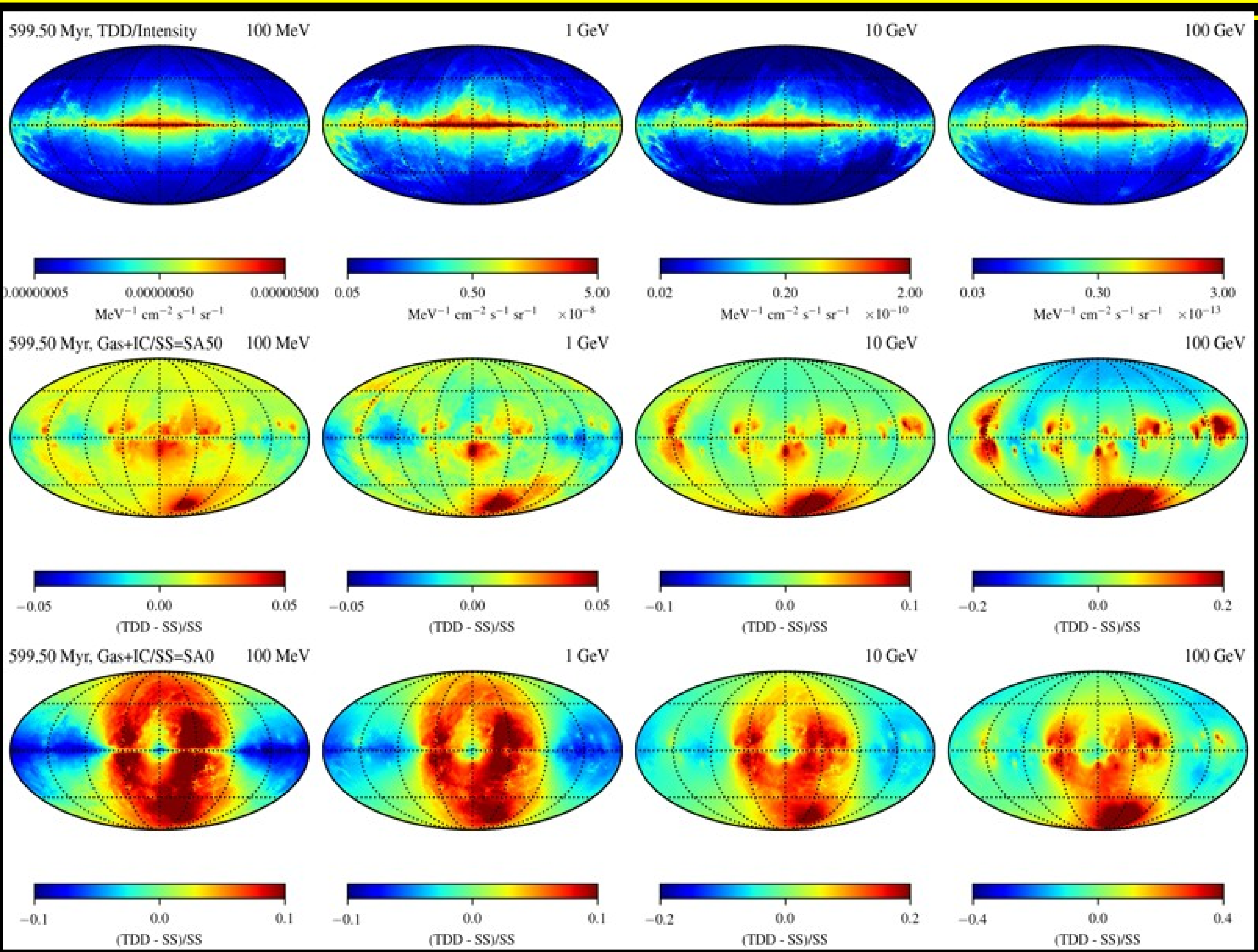
Gamma Ray Intensities

- Discretised/steady-state intensities consistent about plane for quadrants 1 and 4
- IC > 100 GeV hardens/softens with evolution of discretised solution
- Out of plane intensities show significant variability and directionality due to distribution of discrete regions out of plane (even though sampled from symmetric distribution) – feature not seen for the steady-state case
- Epoch shown 595 → 600 Myr





High-Energy Gamma Rays @ 599.5 Myr



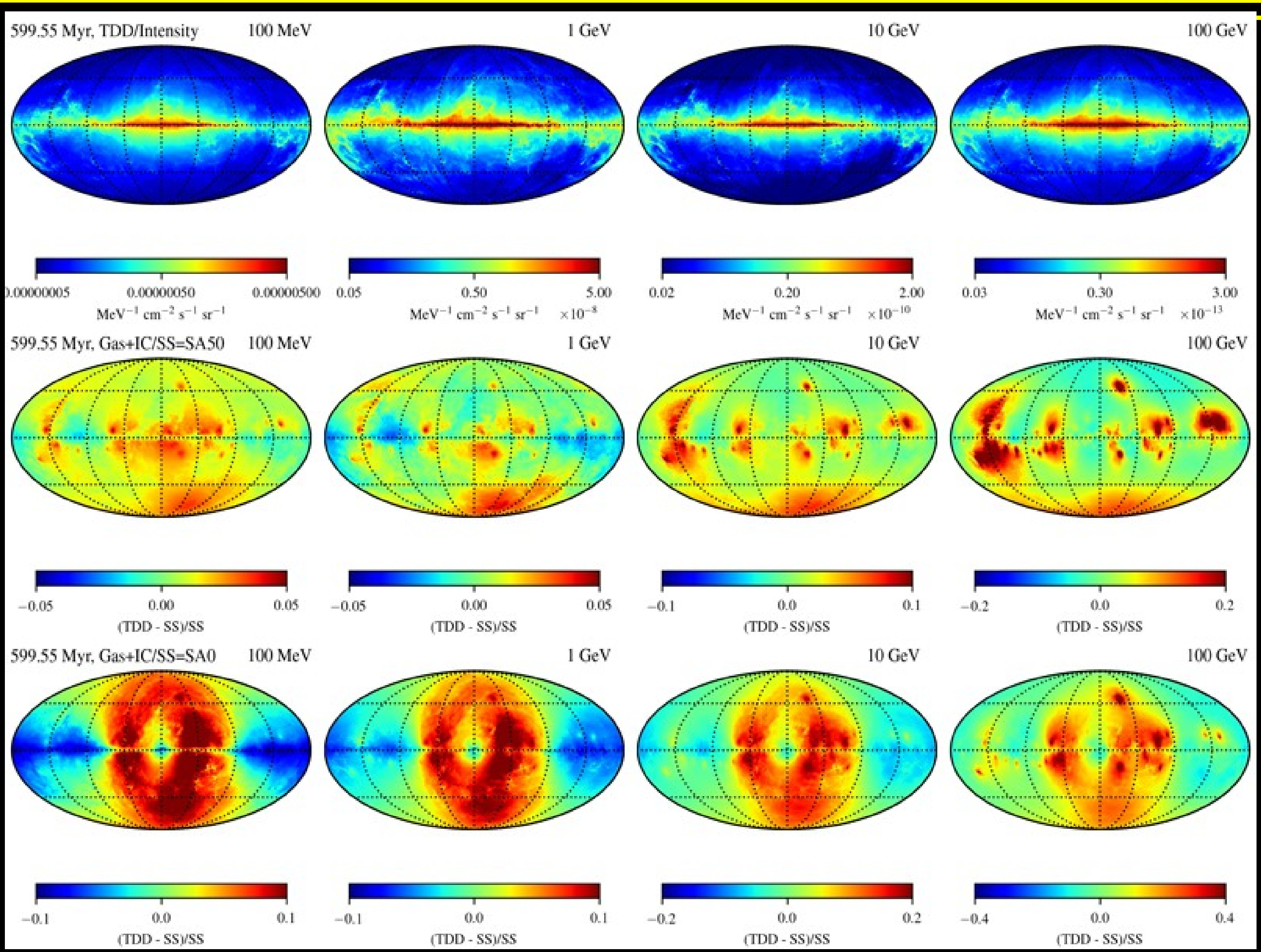
Top row is the total intensity for the discretised solution sampled from SA50 continuous model

Middle row are the fractional residuals for the discretised solution using SA50 steady-state as baseline/denominator

Bottow row are the fractional residuals for discretised solution using SA0 (pure 2D disc) steady-state for baseline

All models are tuned to give same local CR spectra (SA50 and SA0 parameters given in ApJ 879, 91 [2019])

High-Energy Gamma Rays @ 599.55 Myr



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Summary

- CTA improvements in sensitivity and resolution → details of interstellar emission are very important for maximising scientific return
- Steady-state CR propagation models are unlikely to provide the best description of the VHE sky but can provide useful starting point
- GeV energies are suited for understanding global distribution of CR sources and ISM components → can use this information for discrete ensemble approach for the VHE sky
- Ongoing work to further improve ISM models, high-res gas maps including DNM with spatial information, more coming including statistical ensemble optimised with Fermi+ data → first GeV/TeV interstellar emission models that can be used for simulations, analysis (common formats for, e.g., 3ML, gammapy)
- Can download GALPROP code for your own investigations with 3d, time/space-discretised calculations: galprop.stanford.edu