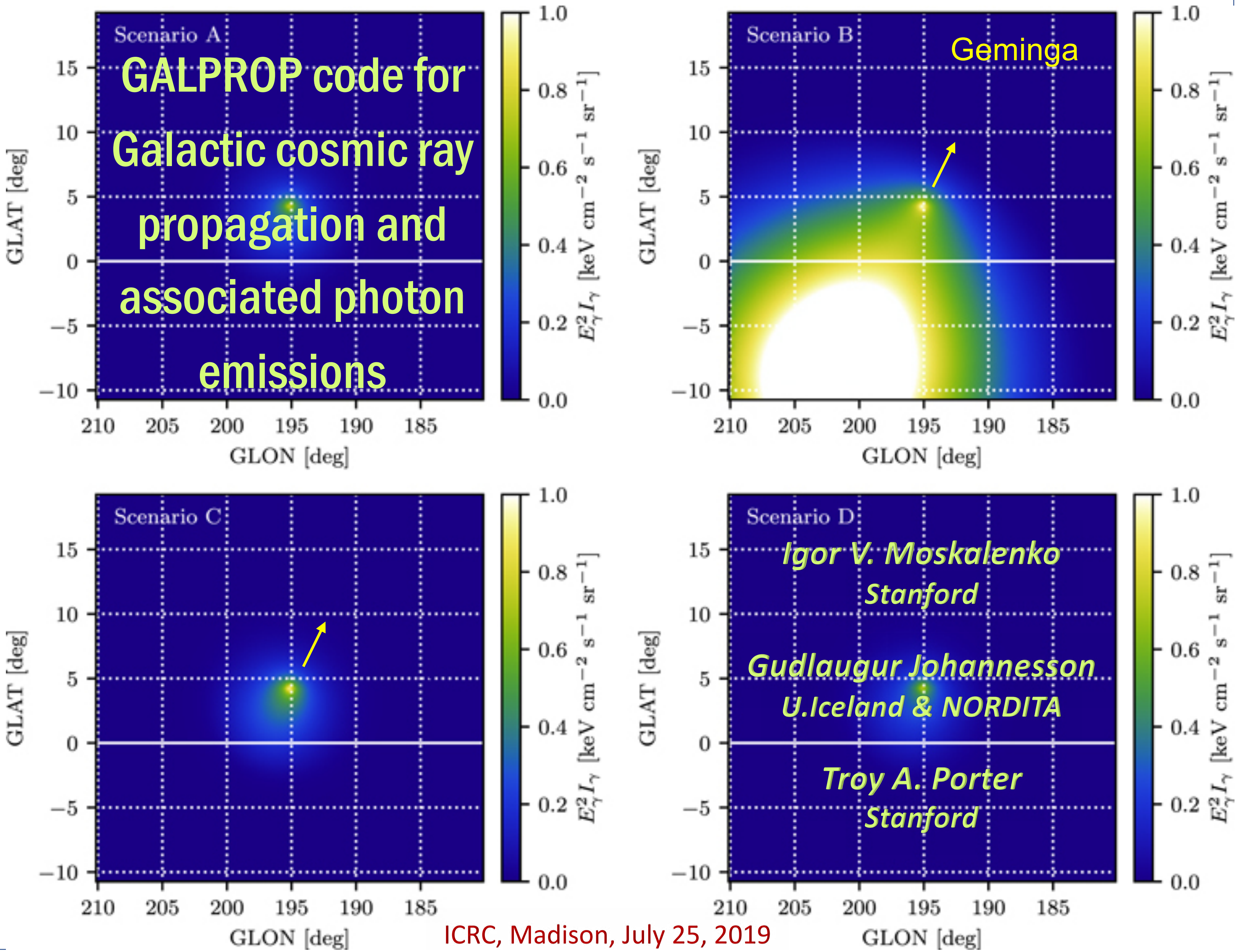
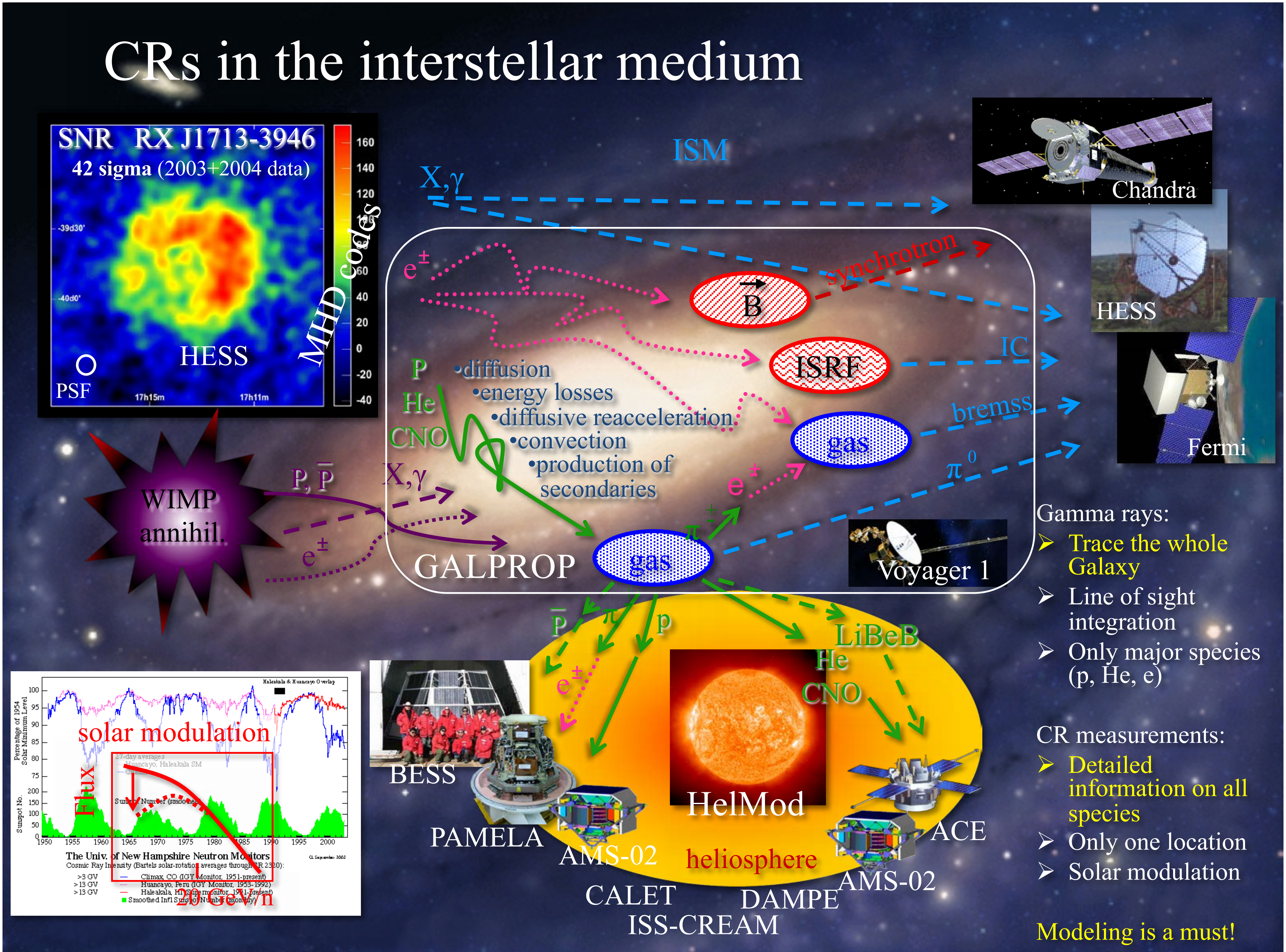
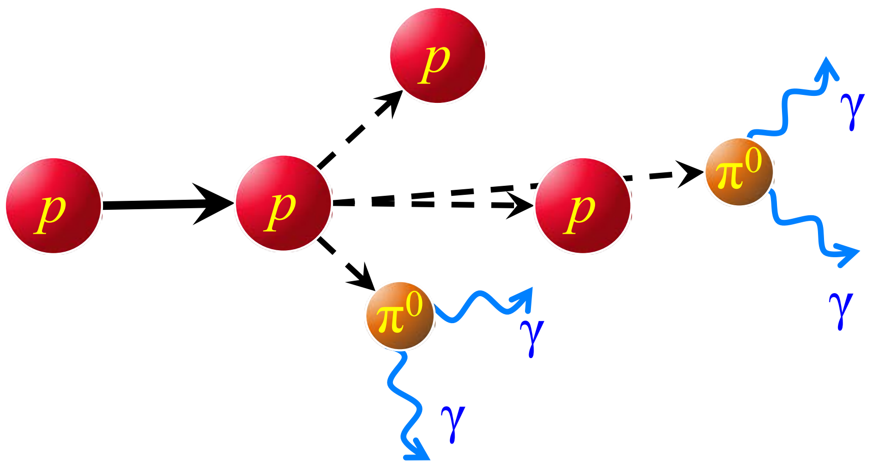

GALPROP code for Galactic cosmic ray propagation and associated photon emissions
Scenario A
Scenario B
Geminga
Scenario C
Scenario D
Igor V. Moskalenko
Stanford
Gudlaugur Johannesson
U.Iceland & NORDITA
Troy A. Porter
Stanford
GLAT [deg]
GLON [deg]
$E_\gamma^2 I_\gamma$ [keV cm^{-2} s^{-1} sr^{-1}]
ICRC, Madison, July 25, 2019

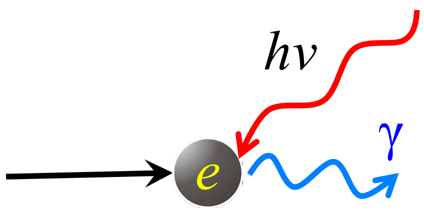


CRs in the interstellar medium
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
MHD codes
ISM
X,γ
e±
synchrotron
B
ISRF
IC
gas
bremss
π0
P
He
CNO
•diffusion
•energy losses
•diffusive reacceleration
•convection
•production of secondaries
WIMP annihil.
P, P̄
X,γ
e±
GALPROP
gas
π±
e±
Chandra
HESS
Fermi
Voyager 1
P̄
π
p
e±
LiBeB
He
CNO
solar modulation
Flux
20 GeV/n
BESS
PAMELA
AMS-02
HelMod
heliosphere
ACE
AMS-02
CALET
DAMPE
ISS-CREAM
Gamma rays:
Trace the whole Galaxy
Line of sight integration
Only major species (p, He, e)
CR measurements:
Detailed information on all species
Only one location
Solar modulation
Modeling is a must!

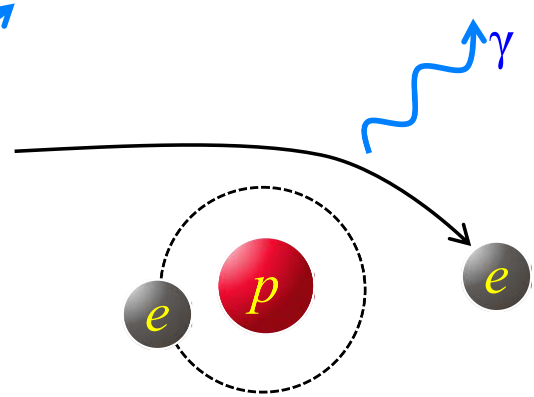
Production of high energy γ-rays



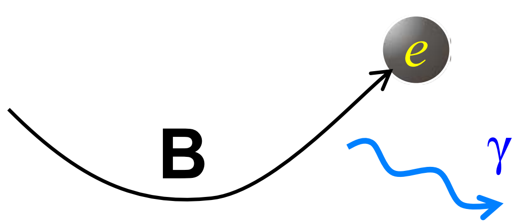
✧ *pp –> π⁰(2γ)+X* – production and decay of neutral pions *π⁰* and Kaons *K⁰*



✧ Inverse Compton Scattering

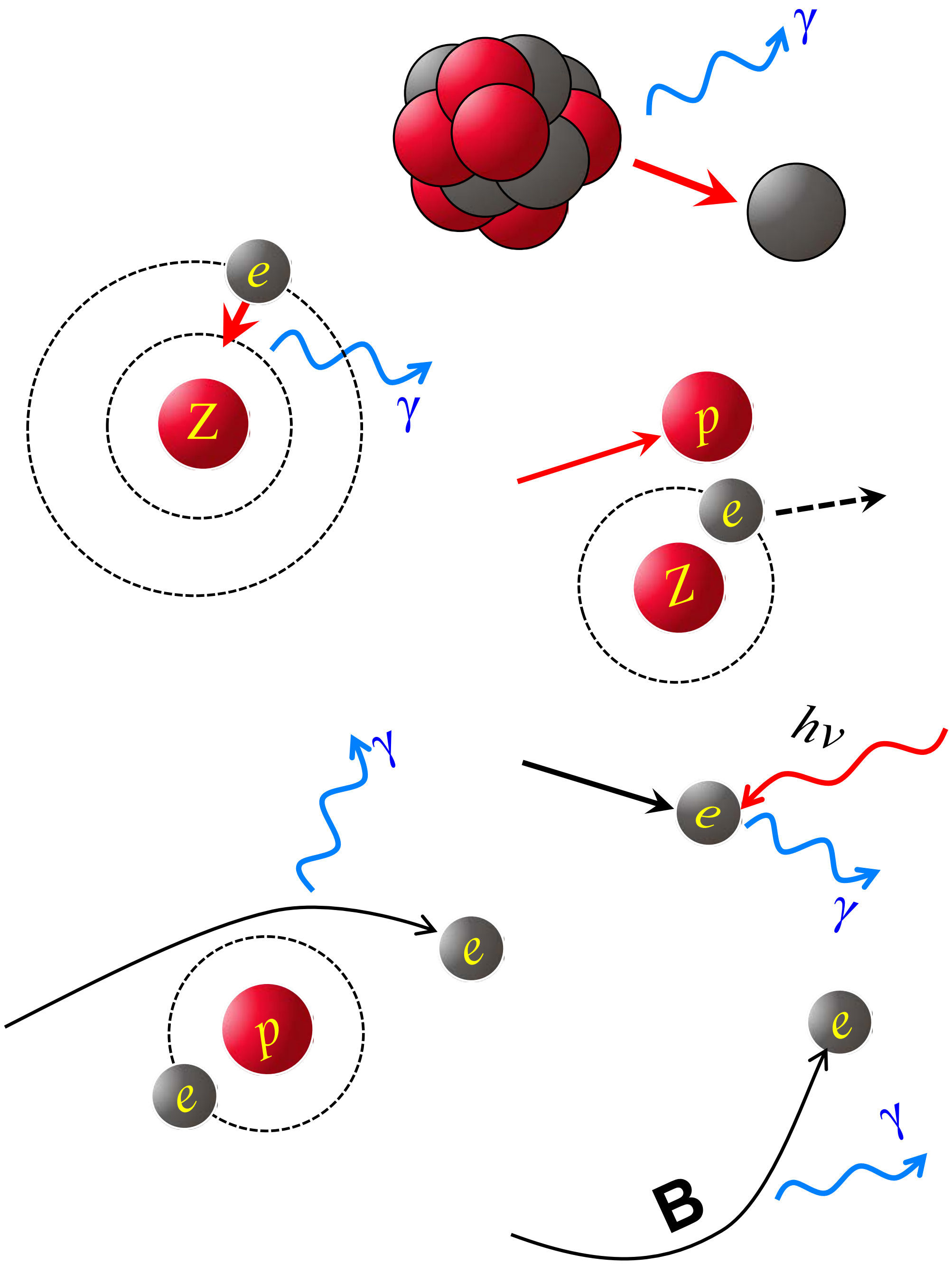


✧ Bremsstrahlung

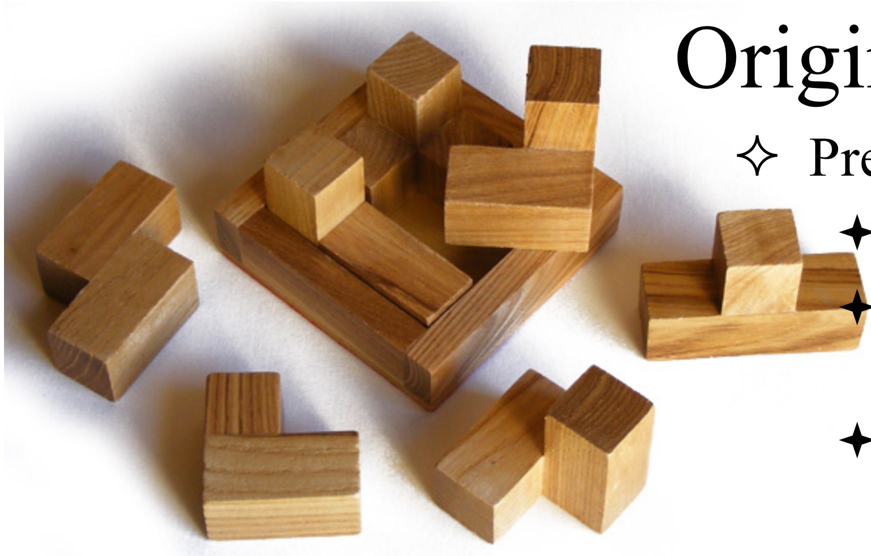


✧ Synchrotron emission

Low-energy processes and photons in the ISM



- ✧ – Radioactive decay lines (<10 MeV): SNR, spallation reaction
- ✧ – Atomic de-exitation lines (keV)
- ✧ Knock-on electrons (ICS, MeV)
- ✧ Electron stripping and pickup (K-capture)
- ✧ Inverse Compton Scattering
- ✧ Bremsstrahlung
- ✧ Synchrotron emission (radio-, X-ray)



Original motivation

- ✧ Pre-GALPROP (before ~1997)
  - ✦ Leaky-box type models: simple, but not physical
  - ✦ Many different simplifying assumptions – hard to compare
  - ✦ Many models, each with a purpose to reproduce data of a single instrument
  - ✦ No or few attempts to make a self-consistent model

✧ Two key concepts are forming the basis of GALPROP

I. One Galaxy – a self-consistent modeling:

Various kinds of data, such as direct CR measurements including primary and secondary nuclei, electrons and positrons, γ-rays, synchrotron radiation, and so forth, are all related to the same astrophysical components of the Galaxy and, therefore, have to be modeled self-consistently

II. As realistic as possible:

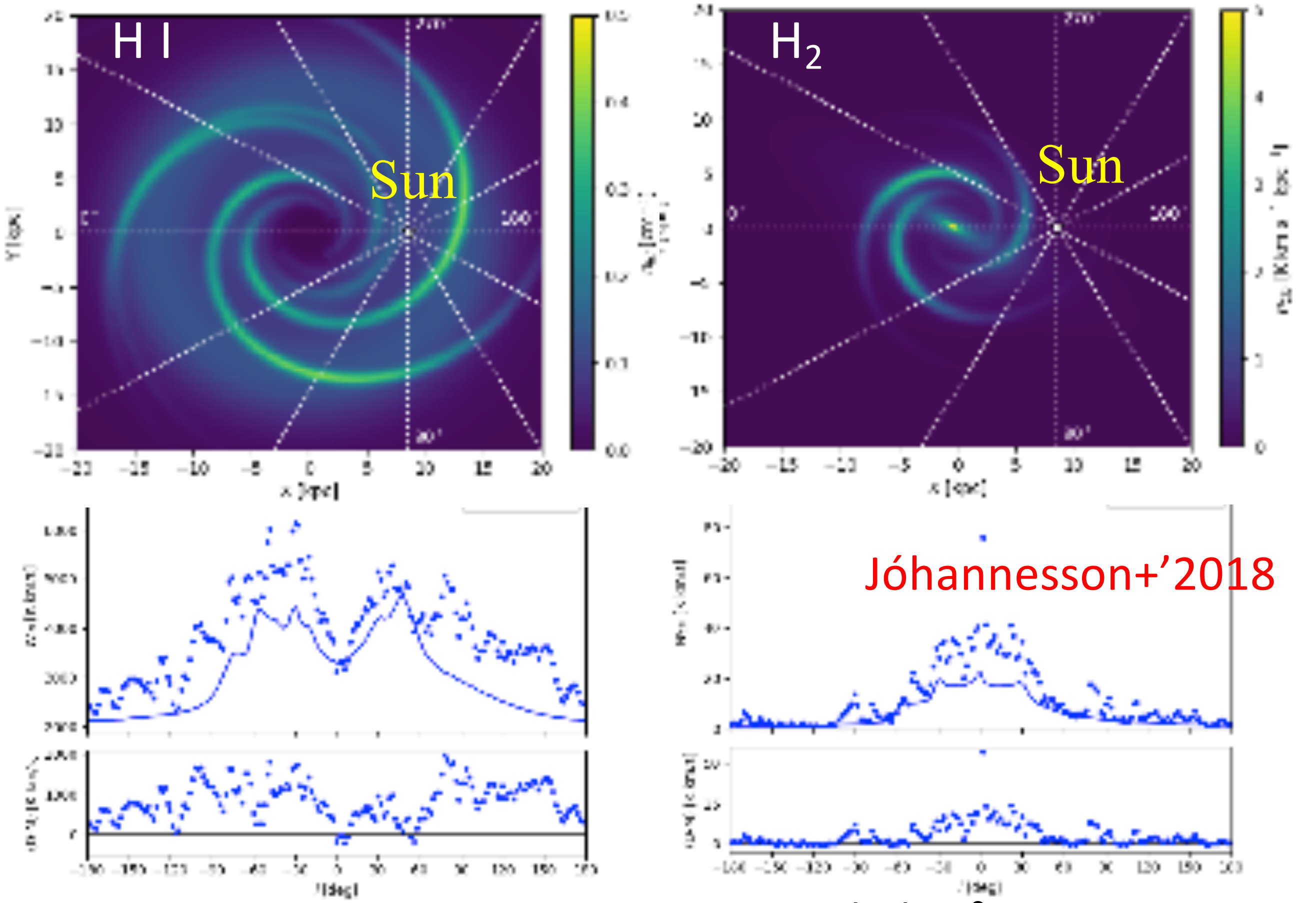
The goal for GALPROP-based models is to be as realistic as possible and to make use of all available astronomical and astrophysical information, nuclear and particle data, with a minimum of simplifying assumptions

Components of GALPROP

- ✧ Propagation, diffusive acceleration, convection, energy losses…
- ✧ Numerically solves transport equations for all cosmic ray species (stable + long-lived isotopes + pbars + leptons ~90) in 2D or 3D
- ✧ Derives the propagation parameters corresponding to the assumed transport phenomenology and source distribution
- ✧ Time-dependent solutions – Galactic evolution
- ✧ Detailed gas distribution from HI and CO gas surveys (energy losses from ionization, bremsstrahlung; secondary production; γ-rays from π^0-decay, bremsstrahlung)
- ✧ Interstellar radiation field (inverse Compton losses/γ-rays for $e^{\pm}$)
- ✧ B-field models
- ✧ Nuclear & particle production cross sections + the reaction network (cross section database + LANL nuclear codes + phenomenological codes)

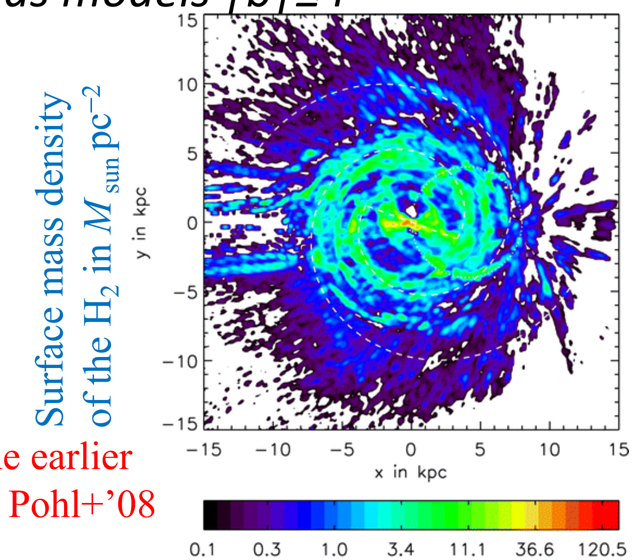
3D gas: H I & H_2

- ✧ Forward folding model fitting technique
- ✧ Max-likelihood fit to H I LAB and the DHT CO surveys
- ✧ Re-binned to HEALPix order 7 (H I) and 8 (CO), degraded to 2 km/s v-bins
- ✧ Built iteratively, starting with 2D disk, adding warping, central bulge/bar, flaring (outer Galaxy), and spiral arms



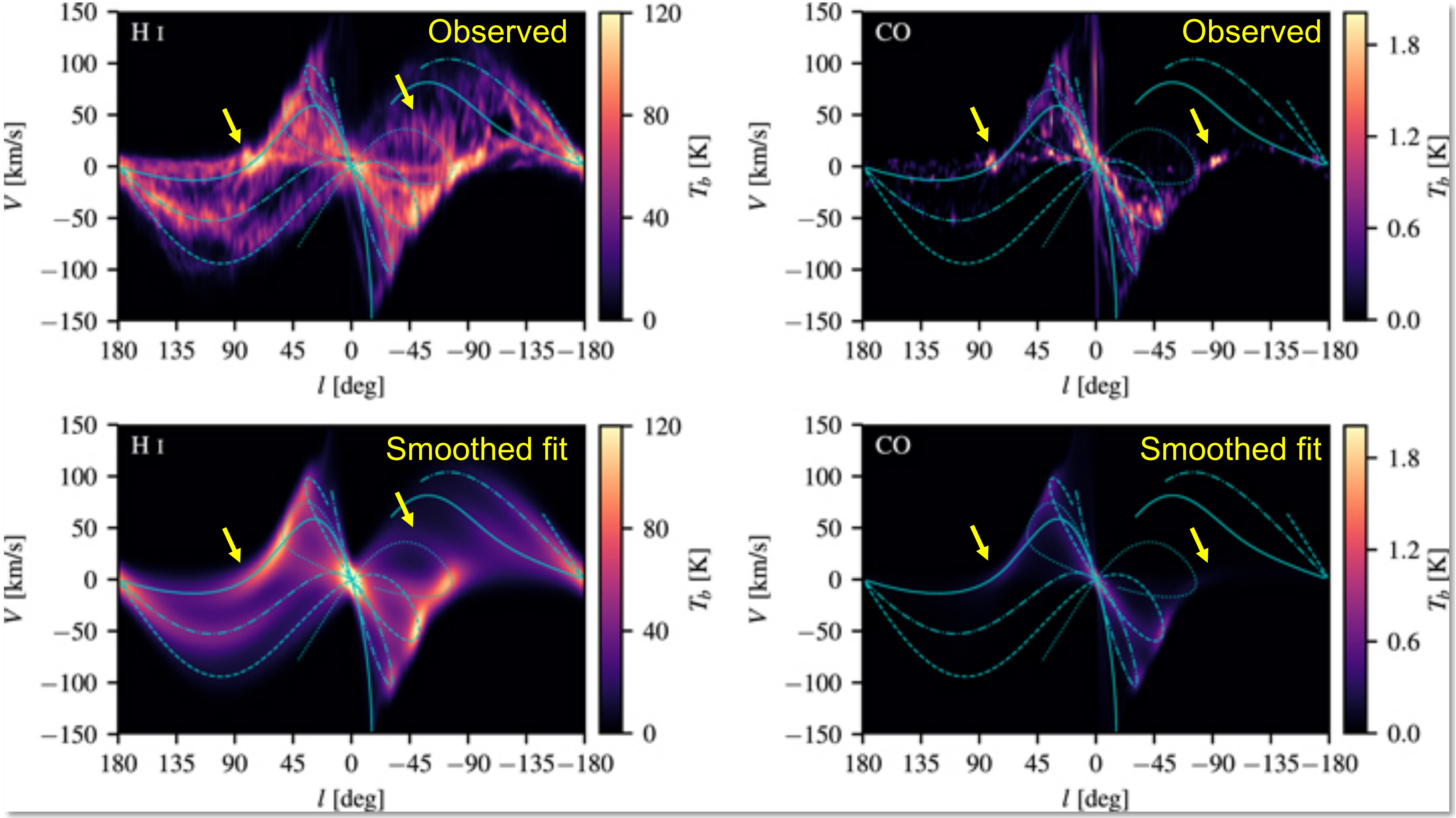
Longitude profiles of gas models |b|≤4°

- ✧ The location and shape of the spiral arms are identical between the H I and CO models, but the radial and vertical profiles differ
- ✧ Each spiral arm also has a free normalization



One of the earlier attempts: Pohl+’08

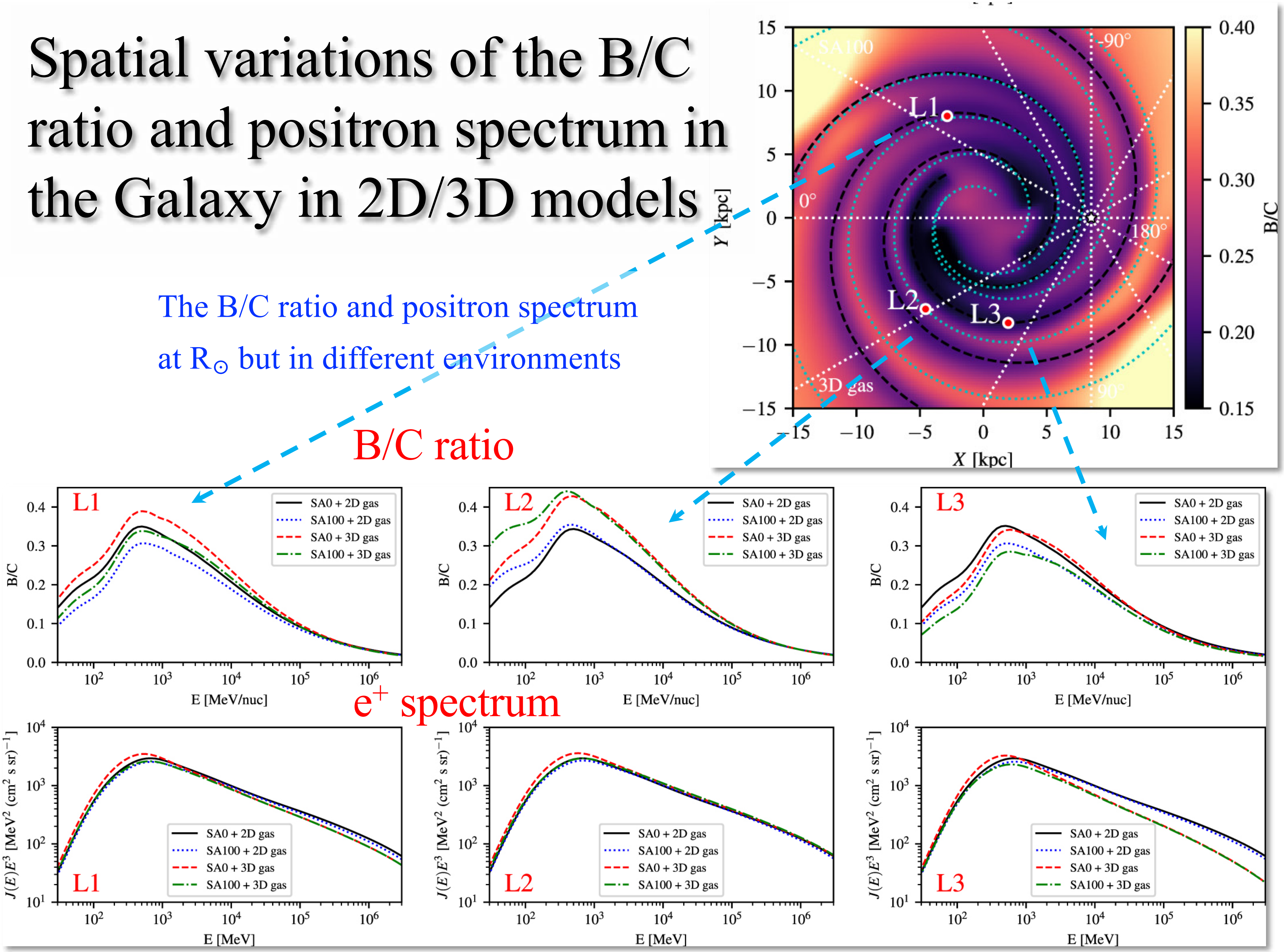
Velocity distribution of HI and CO (data vs. fit)



- ◇ Arrows show the features that are absent in the smoothed fit
- ◇ Lines are the spiral arms

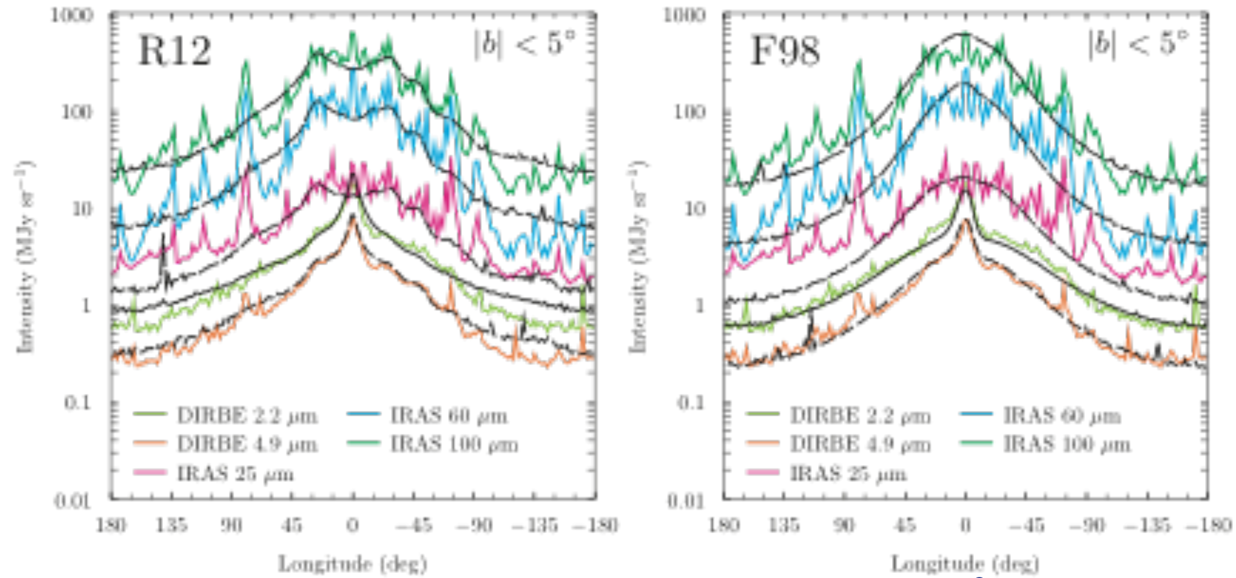
Spatial variations of the B/C ratio and positron spectrum in the Galaxy in 2D/3D models

The B/C ratio and positron spectrum at $R_\odot$ but in different environments

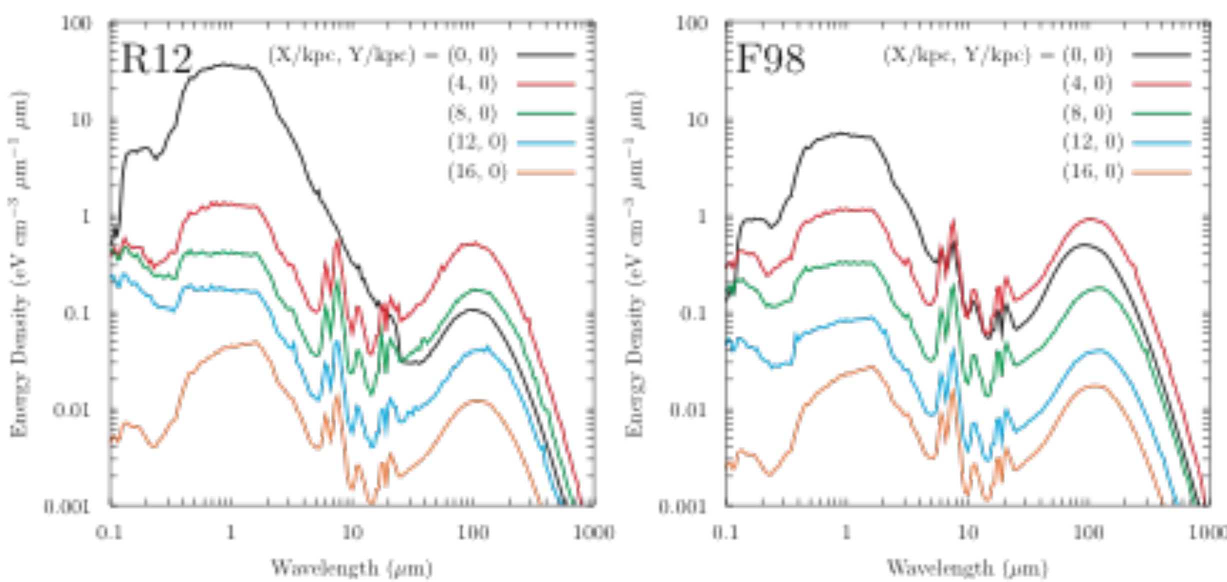


3D interstellar radiation field

- ✧ Monte Carlo radiation transfer code FRaNKIE
- ✧ Two models for the stellar and dust distributions are chosen from the literature:
  - ✦ R12 = Robitaille+’2012
  - ✦ F98 = Freudenreich’1998
- ✧ The simulation volume for the radiation transfer: a box X,Y=±15 kpc, Z=±3 kpc
- ✧ λ-grid = 0.0912–10000 μm



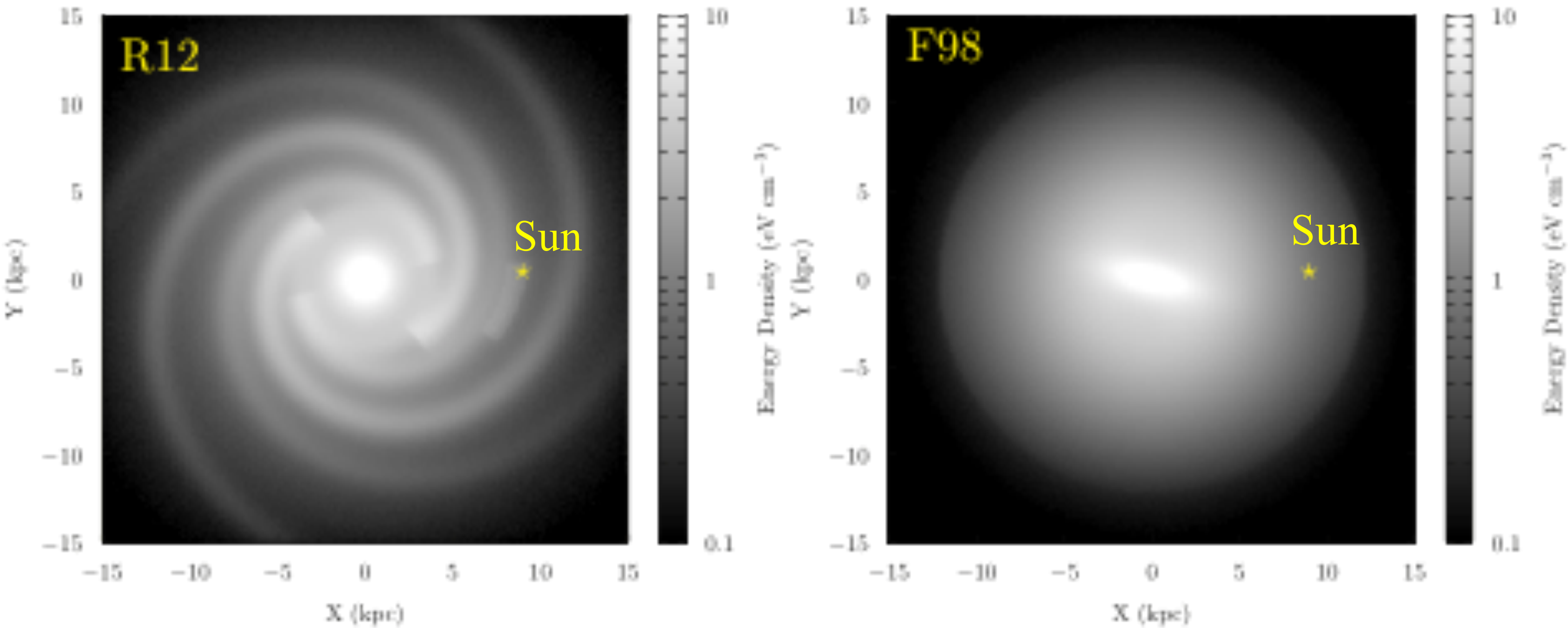
Longitude profile averaged over |b|<5°



Energy density for distances X=0,4,8,12,16 kpc

Porter+’2017

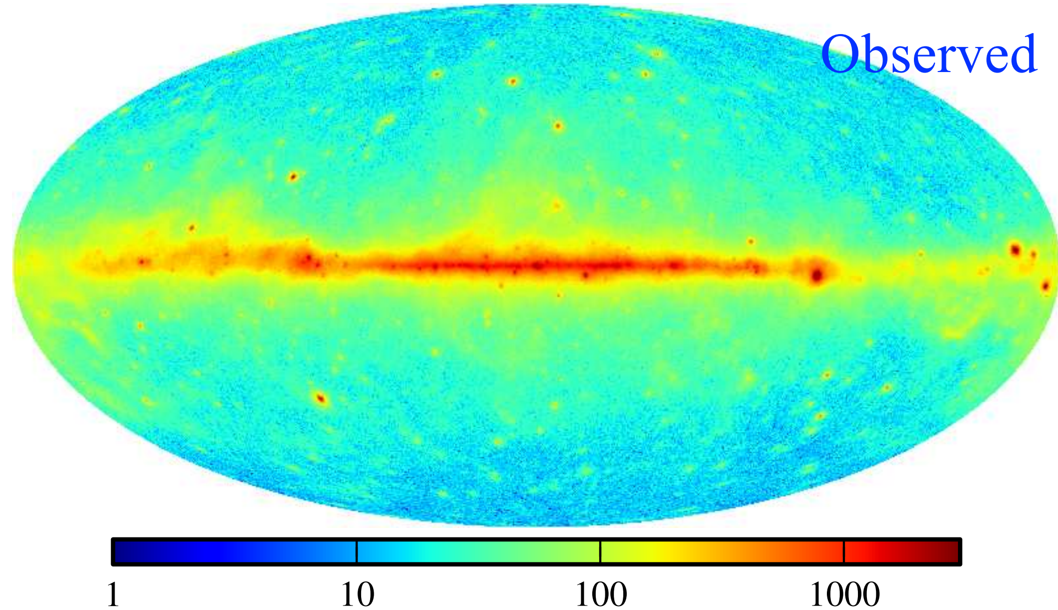
Energy density of interstellar radiation field

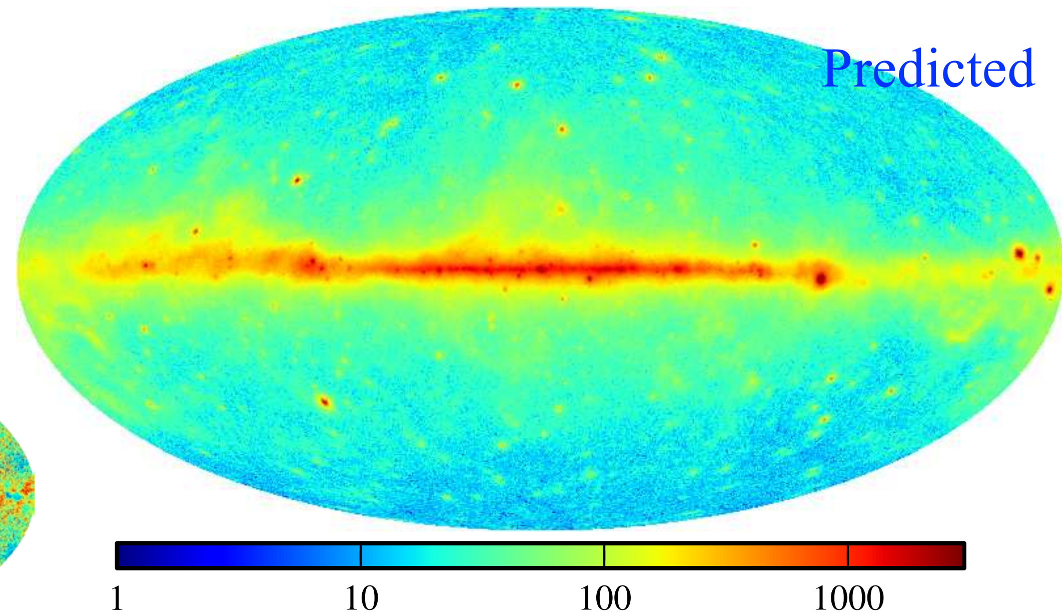


- ✧ Integrated ISRF energy densities in the Galactic plane
- ✧ The ISRF structure will translate into the structure in the inverse Compton
- ✧ A comparison with the Fermi-LAT data is not made yet
- ✧ Affects spectra of electrons/positrons at HE and diffuse emission

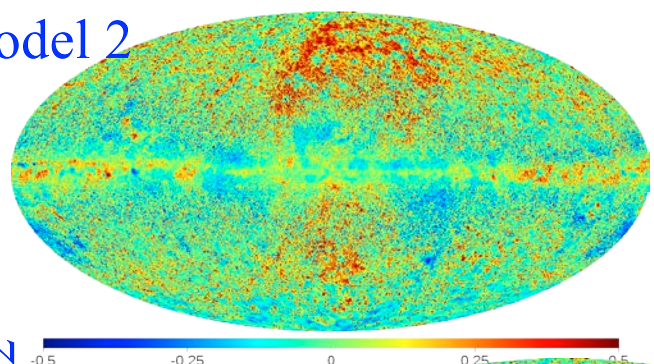
Diffuse emission skymap

- Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV
- Predicted counts calculated using GALPROP reacceleration model tuned to CR data (+ sources)
- Residuals (Obs-Pred)/Obs ~ % level, ~10% in some places (details of the Galactic structure and/or freshly accelerated CRs)



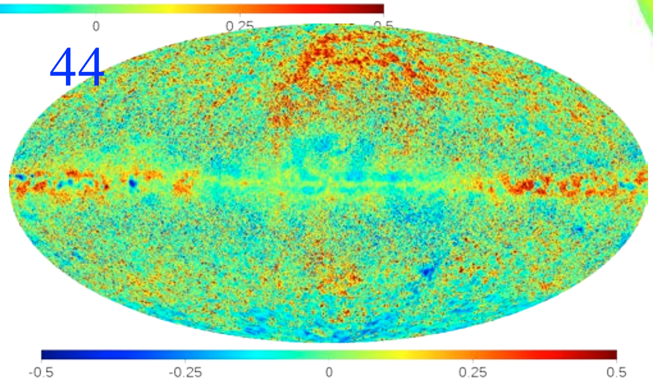


Model 2



Ackermann+'12

44



PHYSICAL REVIEW C **98**, 034611 (2018)

Editors' Suggestion

Current status and desired precision of the isotopic production cross sections relevant to astrophysics of cosmic rays: Li, Be, B, C, and N

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Igor V. Moskalenko‡

W. W. Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, California 94305, USA

Michael Unger§

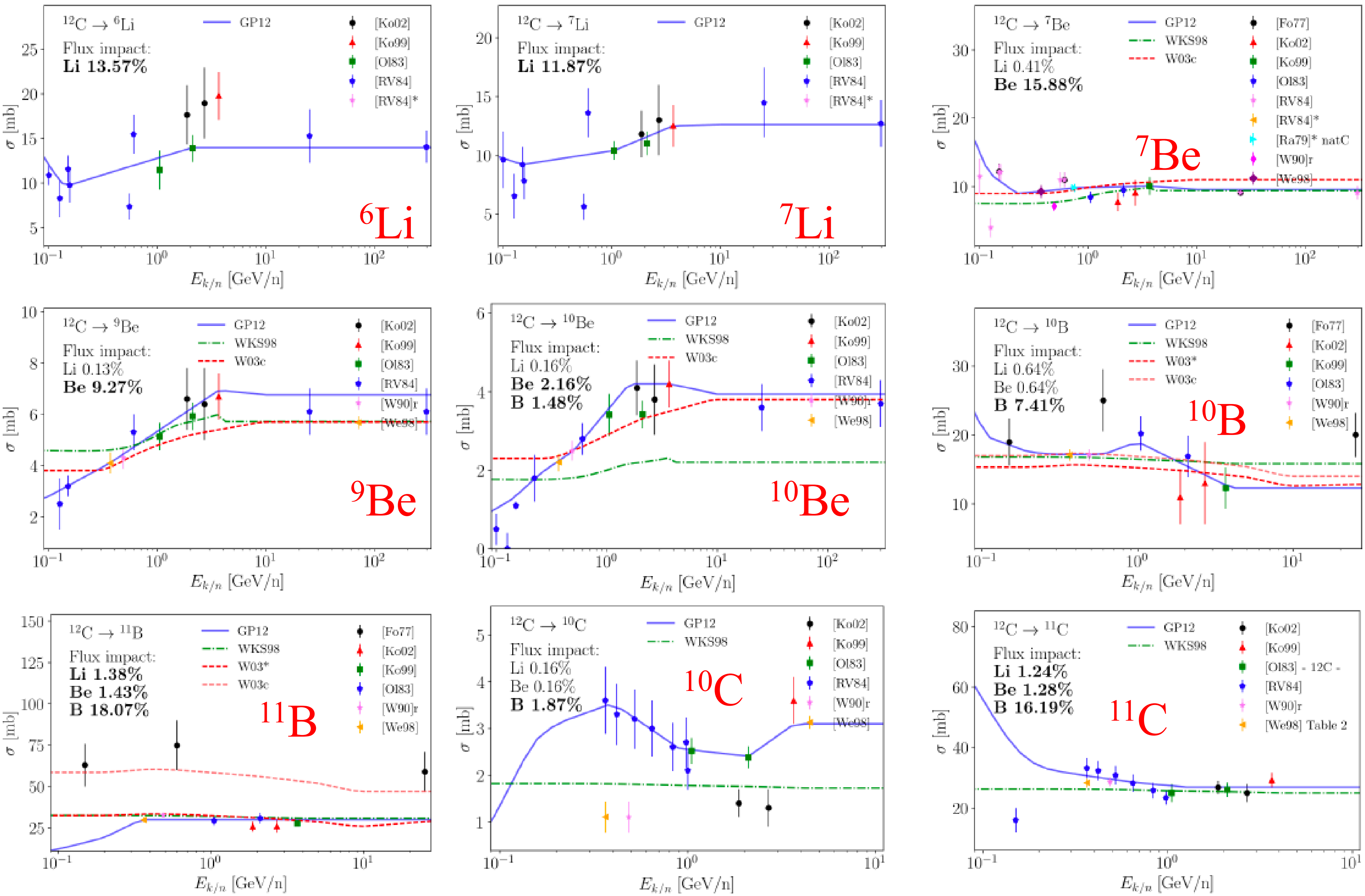
Karlsruhe Institute of Technology, Karlsruhe, Germany

- Provided a motivation for a NA61 proposal
- New measurements of Li, Be, B, C, N, O were done on CERN SPS in Dec. 2018, using secondary beams from Pb nuclei fragmentation
- Momentum 13A GeV/c at different A/Z settings
- Results are being analyzed

Examples of Xsections ^{12}C+H

GP12 = GALPROP, option 12

WKS98, W03 = Webber et al.

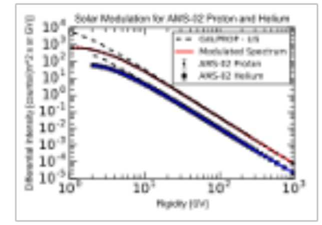


HelMod:

The Heliospheric Modulation Model

Online Calculator

(version 3.5.0)



HelMod Forecasting of the Intensities of Ion Cosmic Rays

M. J. Boschini, S. Della Torre, M. Gervasi, D. Grandi, G. La Vacca, S. Pensotti, P.G. Rancoita, D. Rozza and M. Tacconi

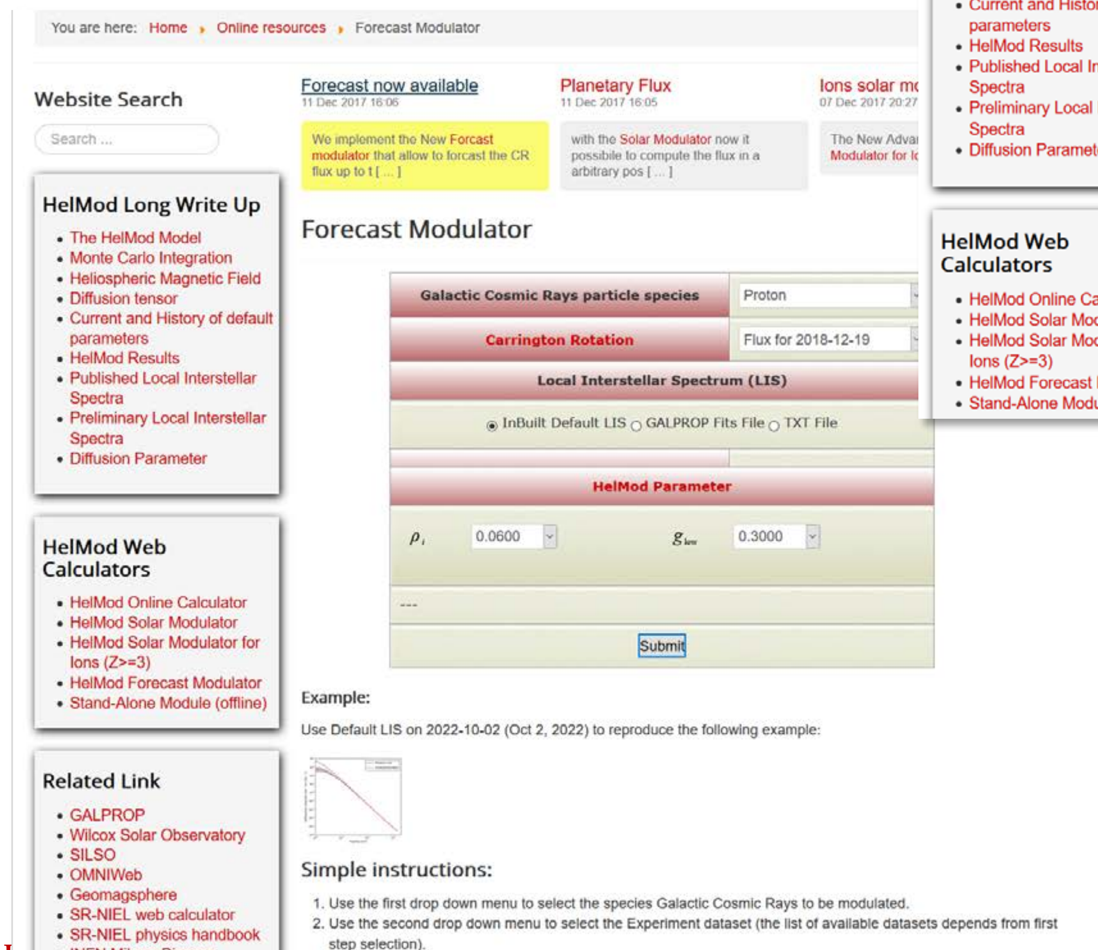
INFN Sezione Milano-Bicocca

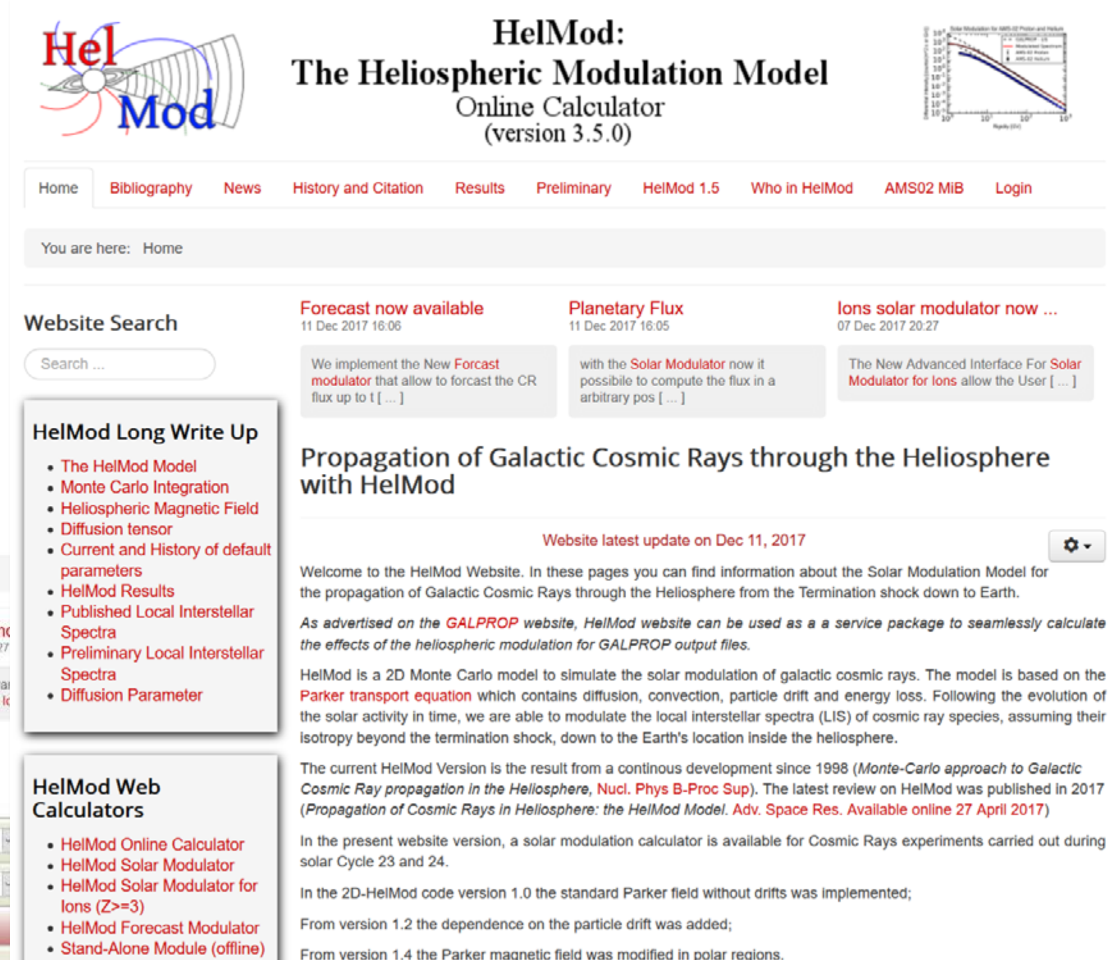
N. Masi, L. Quadrani

INFN Sezione Bologna

GALPROP/HelMod

- Goal #1: reliable local interstellar spectra of all CR species (>100 MeV/n)
- Goal #2: reliable heliospheric modulation for an arbitrary epoch in the past
- GALPROP/HelMod
  - Boschini, et al., ApJ 840 (2017) 115 (p, He, $\bar{p}$)
  - – – – ApJ 854 (2018) 94 (e^-)
  - – – – ApJ 858 (2018) 61 (He, C, O)
  - – – – ApJ 2019, in preparation



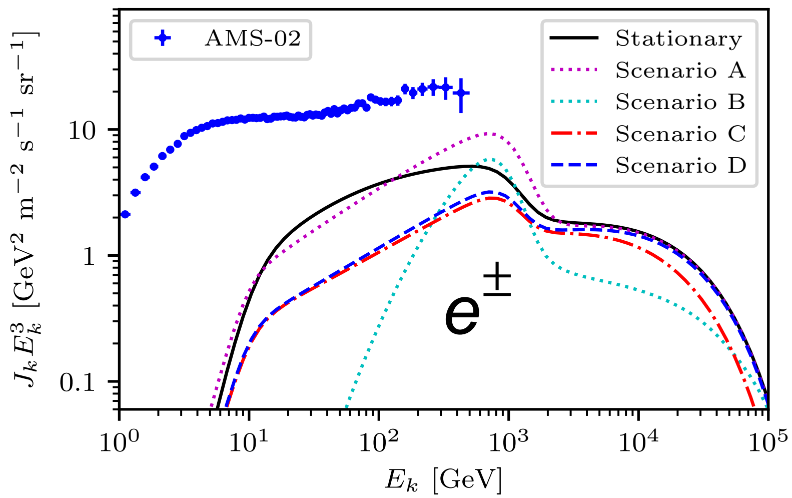


- Time dependent Parker (1965) equation
- 2D Monte Carlo, backward in time
- Convection, energy loss, full description of the diffusion tensor (charge sign effect)
- http://www.helmod.org

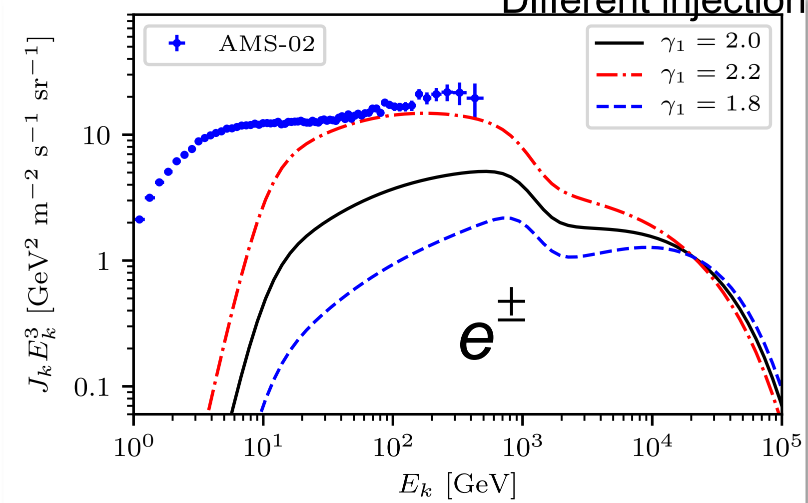
e^+ and γ from Geminga

- HAWC – slow diffusion zone
- 2-zone model
- Fine non-uniform grid
- Proper motion
- Evolution of the slow diffusion zone

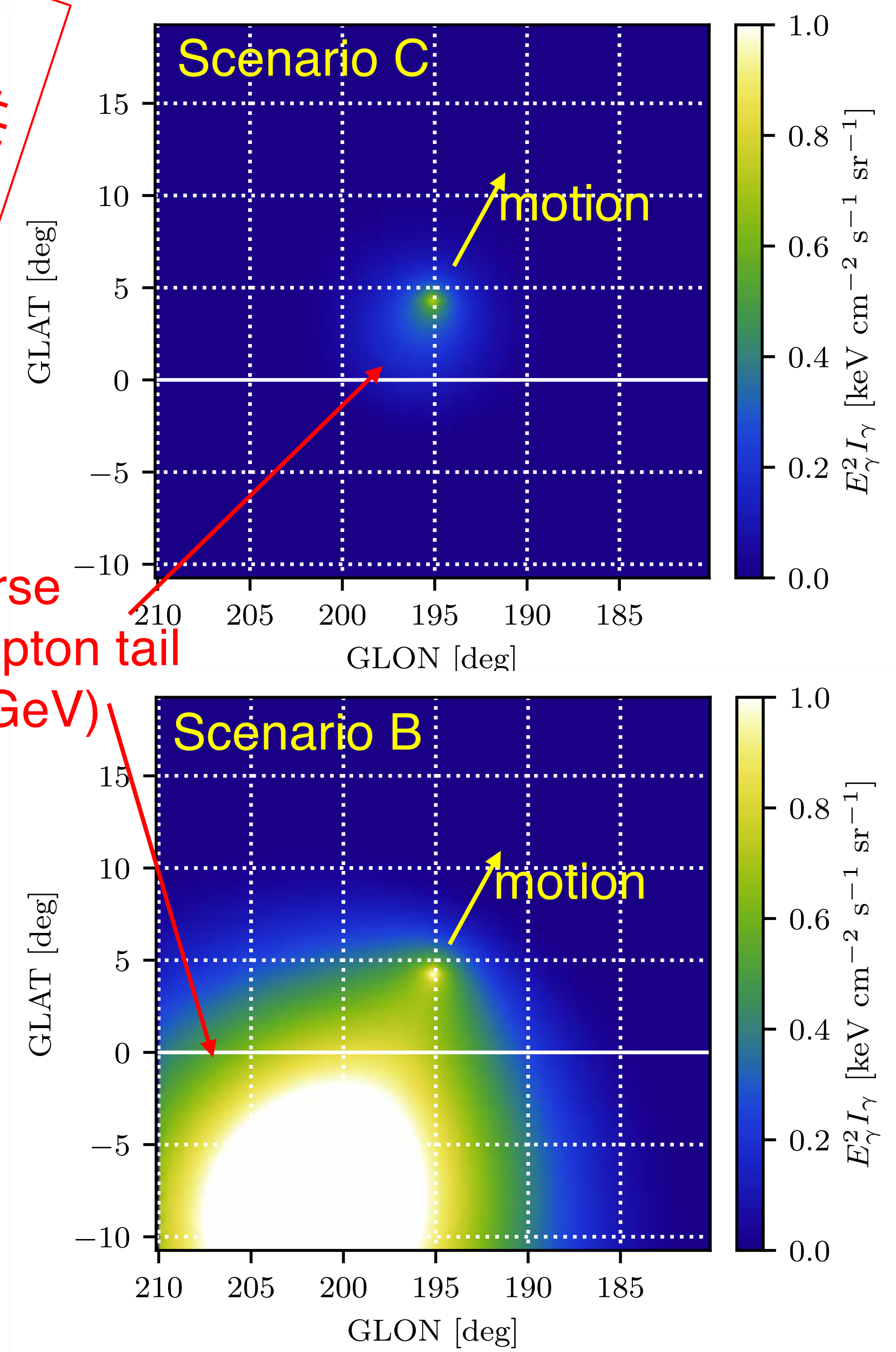
See the poster by Johannesson+



Different injection



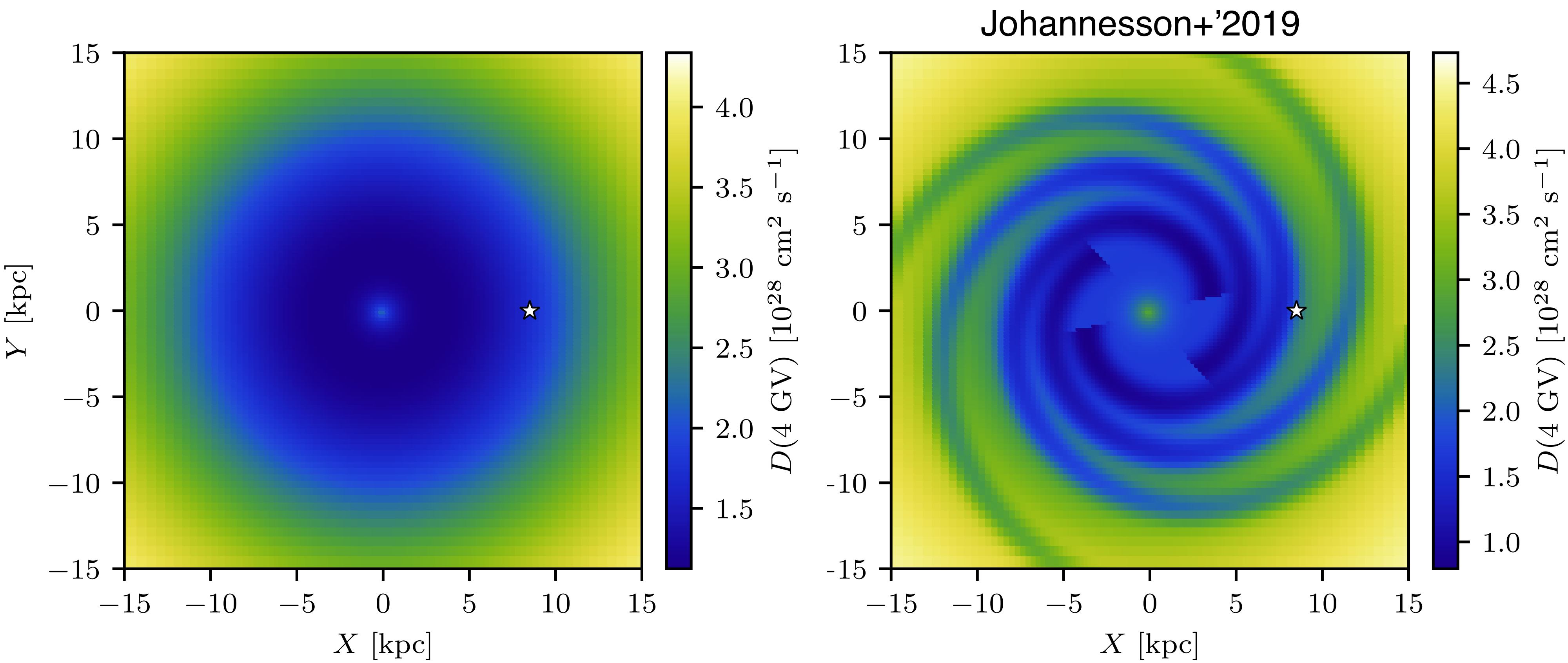
Inverse Compton tail (10 GeV)



Johannesson+'2019

Generalization to the whole MW galaxy

Distribution of the effective diffusion coefficient in 2D and 3D model

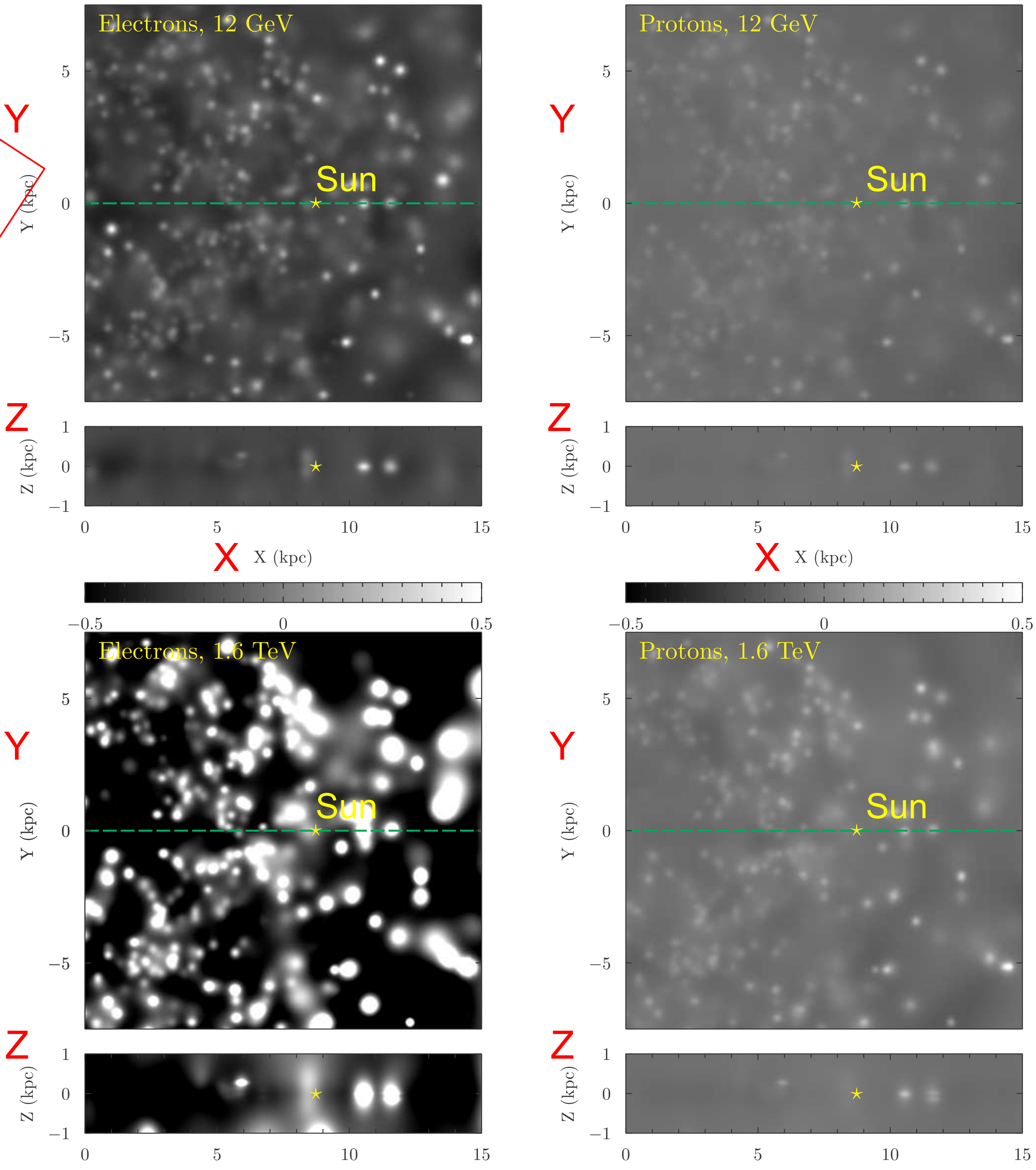


- ✧ Assuming the slow diffusion zone around each CR source, the effective diffusion coefficient in the plane may vary by a factor of 2-3
- ✧ Produces relatively small effect on CR spectra – diffusion coefficient in the halo remains unaltered
- ✧ Effect on the diffuse emission is still being evaluated

Time-dependent solutions. I

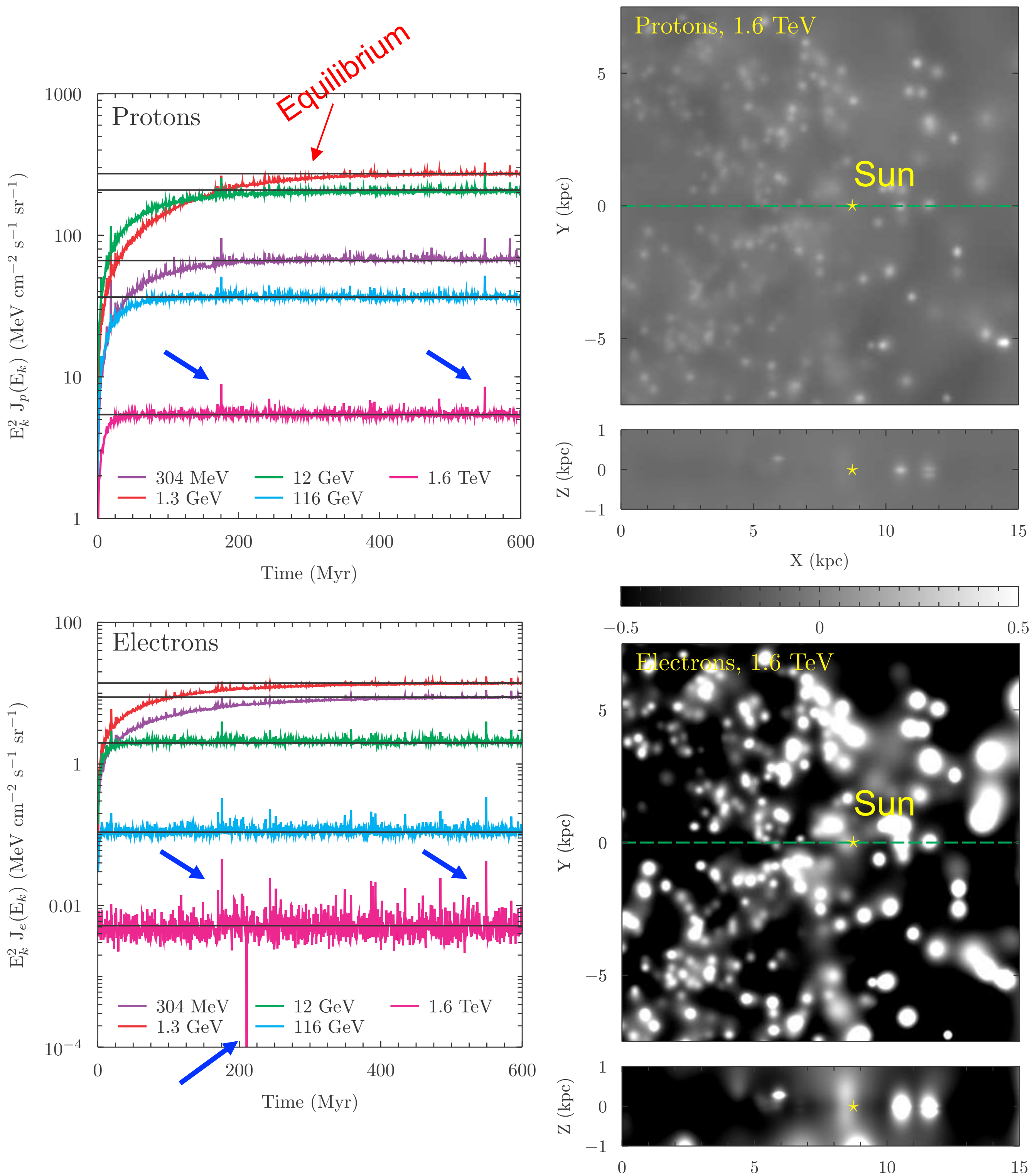
See the talk by Porter+

- ✧ Fractional residuals vs. steady state solutions
- ✧ CR source distribution is not smooth (X,Y,Z)
- ✧ *e, p*: 12 GeV, 1.6 TeV
- ✧ Discretized sources add to the CR distribution
- ✧ Local sources cause fluctuations of CR fluxes
- ✧ Delay between the source-on time and effect on the environment (gammas)

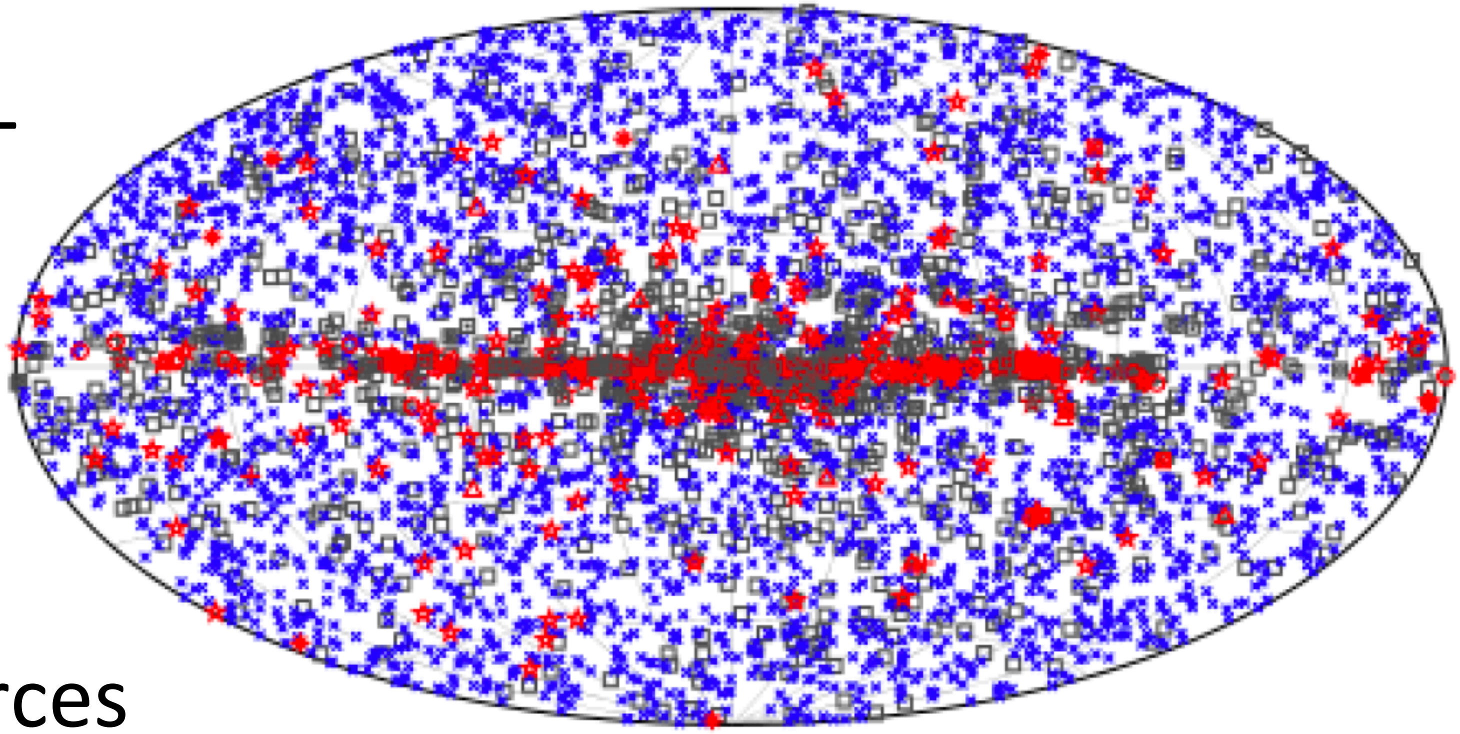


Time-dependent solutions. II

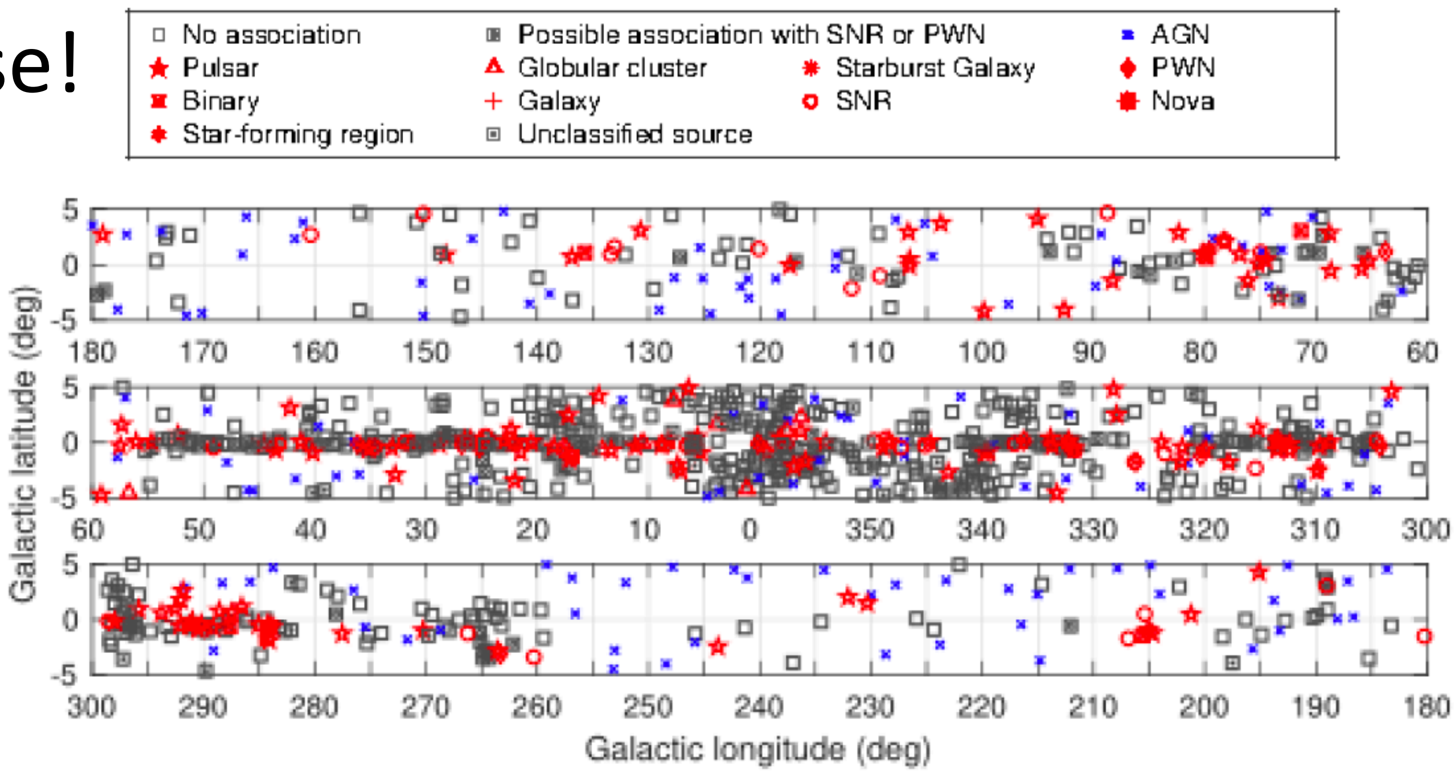
- The local CR proton and electron number densities
- Fluctuations increase with energy
- Electron fluctuations are generally larger
- Mostly positive spikes
- Sometime the spikes are negative
- Fluctuations are mostly at ~20% level
- Affect diffuse emission



Fermi-LAT
4FGL



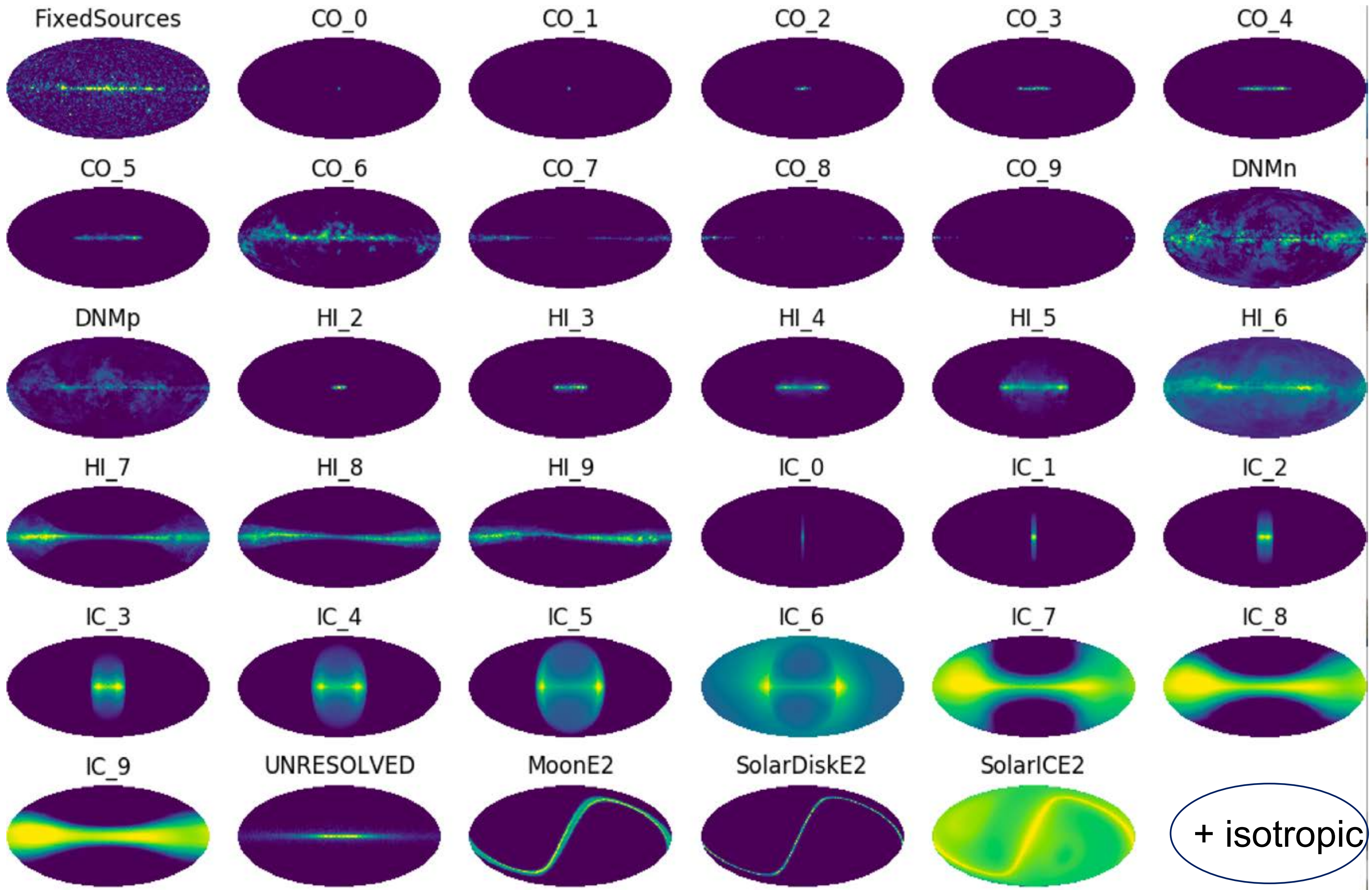
5500 sources
Very dense!



Example Templates – 36 (one energy band)

- **These have been processed into predicted counts maps**

independently scaled



GALPROP + Moon + Solar disk + Solar IC + fixed sources + unresolved sources + isotropic

In place of a conclusion

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement

— Lord Kelvin, 1900

In respect of CR with $E_{CR}<10^{15}\div10^{16}$ eV there generally remain some vague points, but on the whole, the picture is clear enough…

— V.L. Ginzburg, 1999