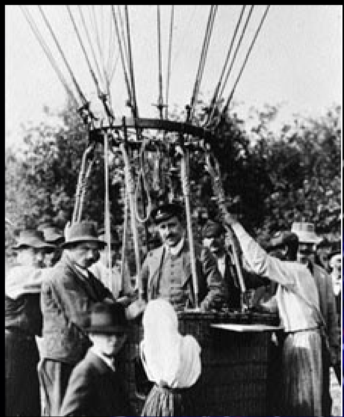
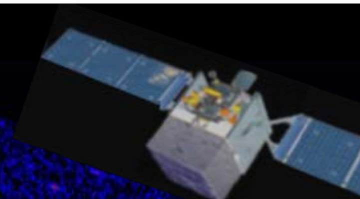


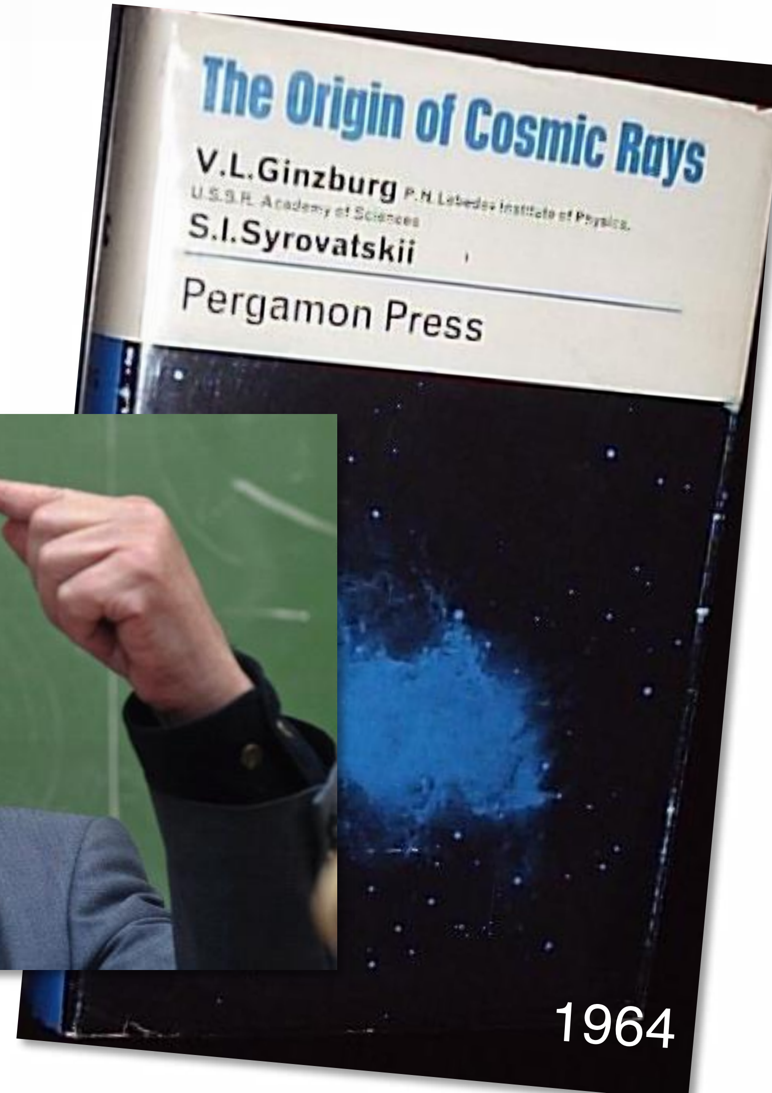


100 years

FERMI "GLOBAL INTERPRETATION"?

IGOR V MOSKALENKO – STANFORD

The Origin of Cosmic Rays



- ✧ Two years ago (2016) we celebrated a centennial anniversary of Vitaly Ginzburg's birth
- ✧ His famous textbook on astrophysics of cosmic rays is still in use and is cited very often

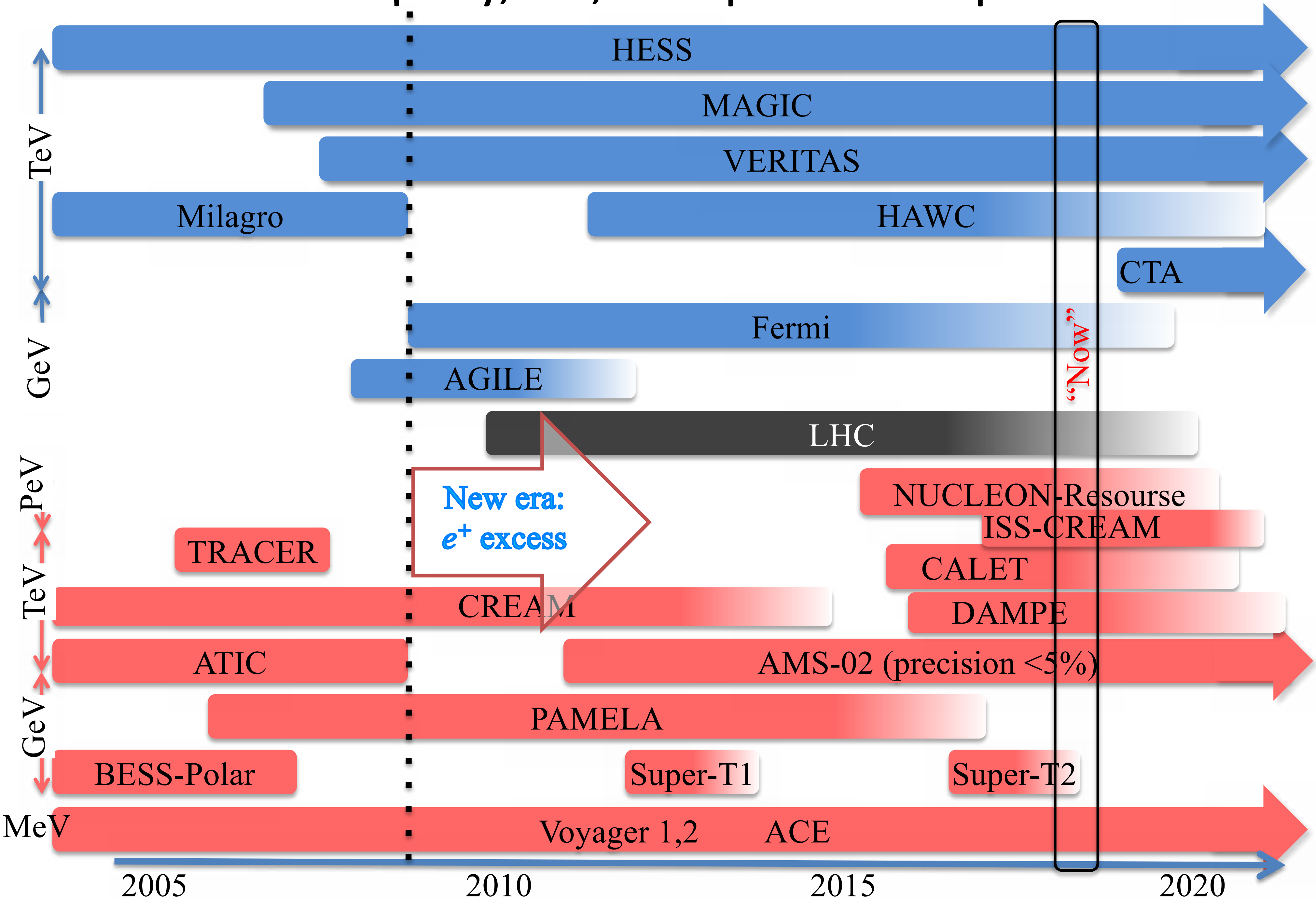
In respect of CR with $E_{CR}<10^{15}\div10^{16}$ eV there generally remain some vague points, but on the whole the picture is clear enough…

— V.L. Ginzburg, 1999

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

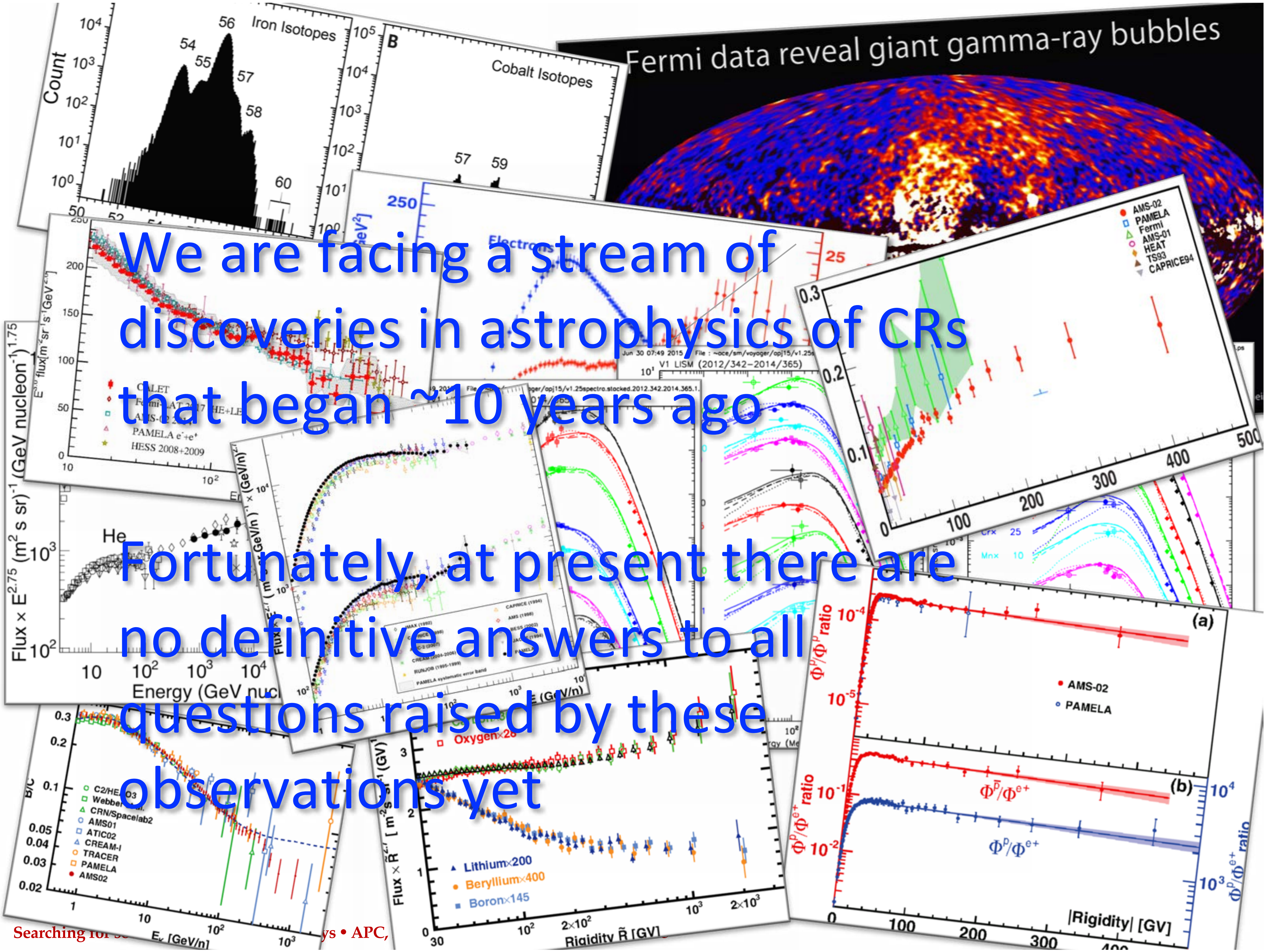
— Lord Kelvin, 1900

Timeline of γ-ray, CR, and particle experiments



We are facing a stream of discoveries in astrophysics of CRs that began ~10 years ago

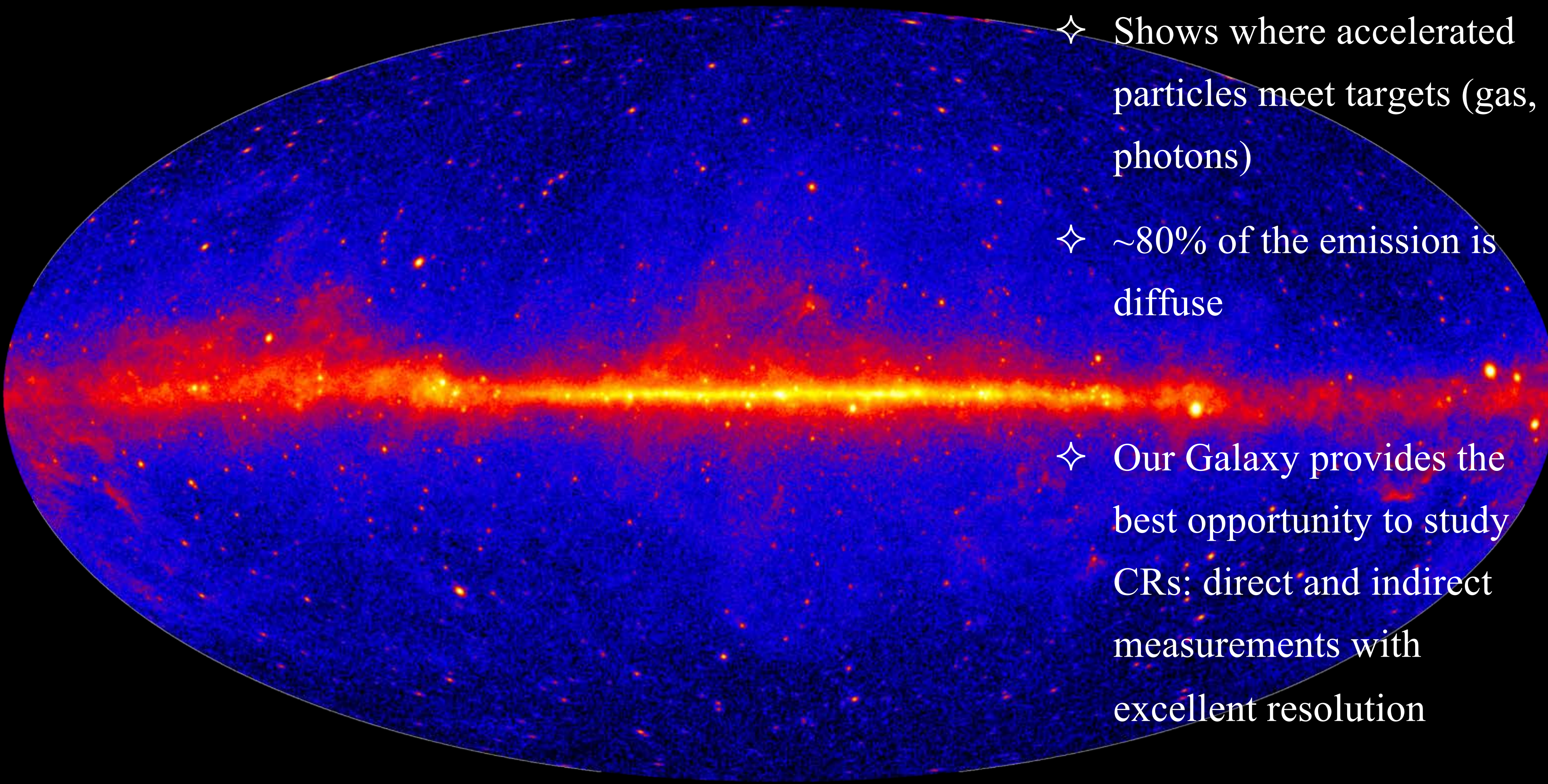
Fortunately, at present there are no definitive answers to all questions raised by these observations yet



What the heck does this all mean?

—Anonymous astrophysicist,
ca. 2018

Fermi-LAT skymap >1 GeV, 48 months

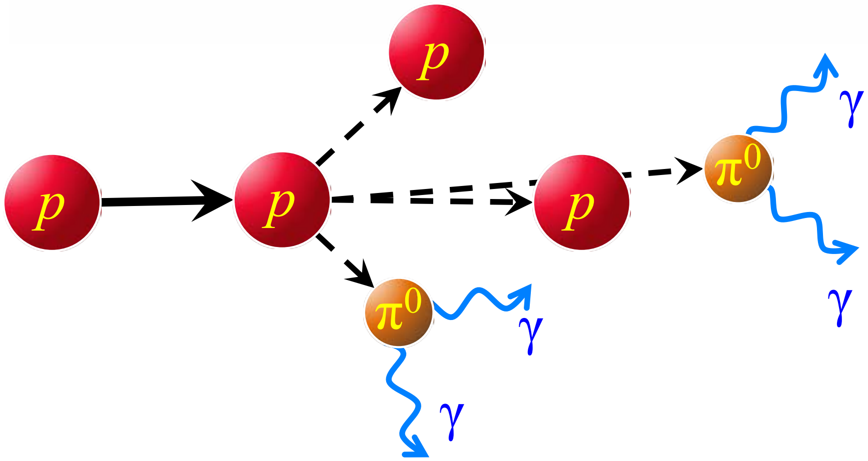


- ✧ Shows where accelerated particles meet targets (gas, photons)
- ✧ ~80% of the emission is diffuse
- ✧ Our Galaxy provides the best opportunity to study CRs: direct and indirect measurements with excellent resolution

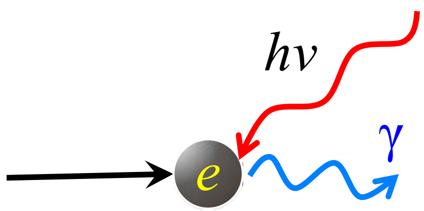
4-year sky map, >1 GeV, front converting (best psf) (4.52M events)

- ✧ LAT: ~275B triggers, 225M Source class events
- ✧ GBM: >1000 GRBs

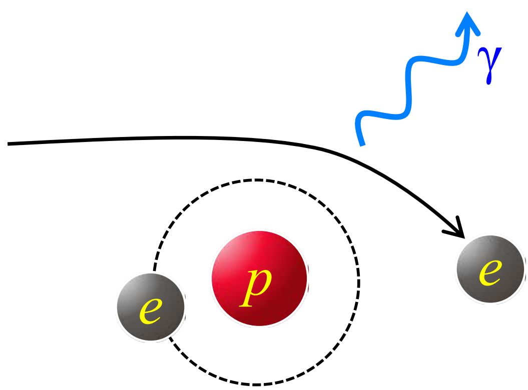
High energy gamma-ray emission processes



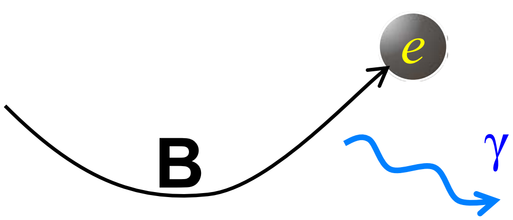
$pp \rightarrow \pi^0(2\gamma)+X$ – neutral pion production and decay



Inverse Compton scattering



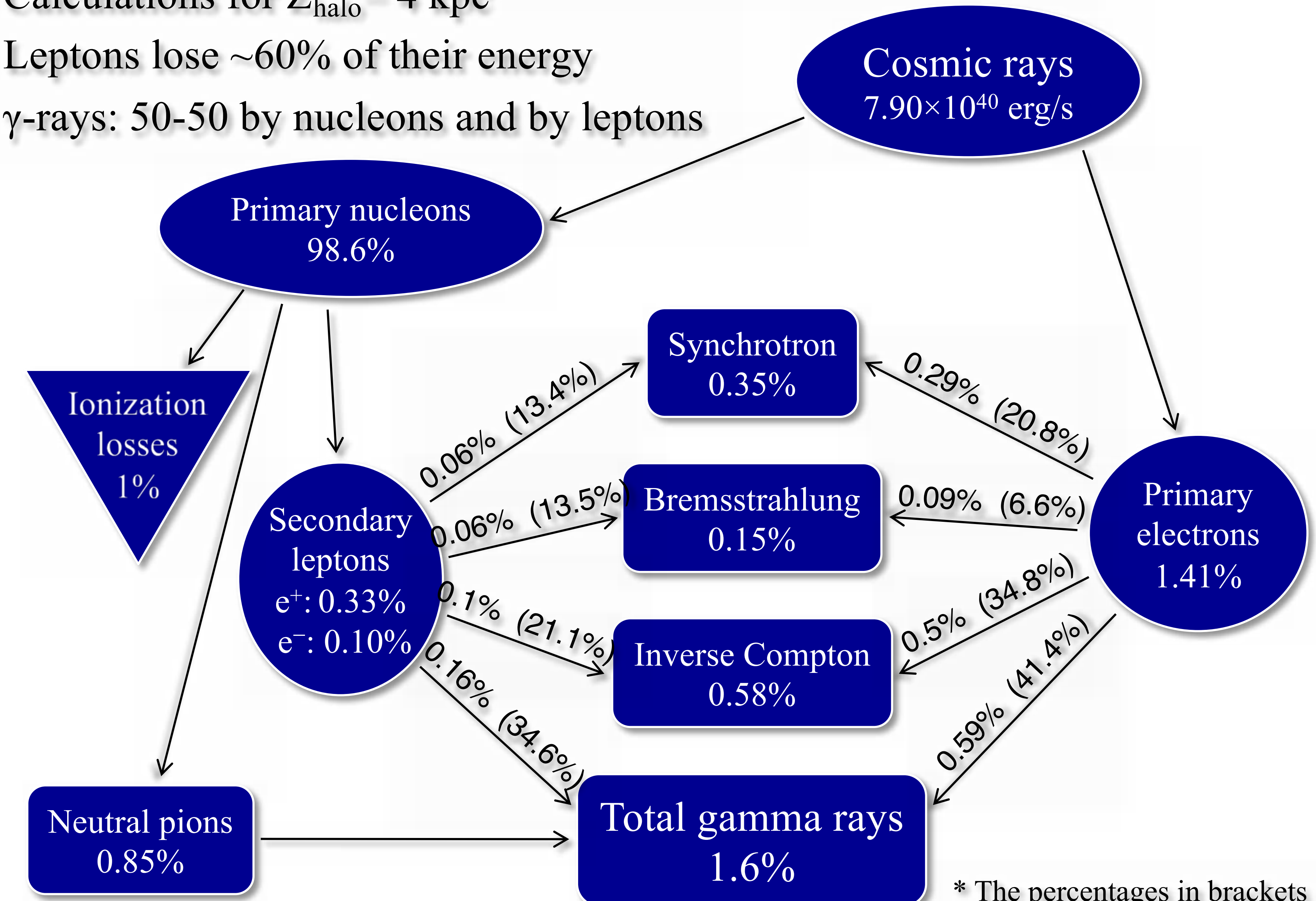
Bremsstrahlung



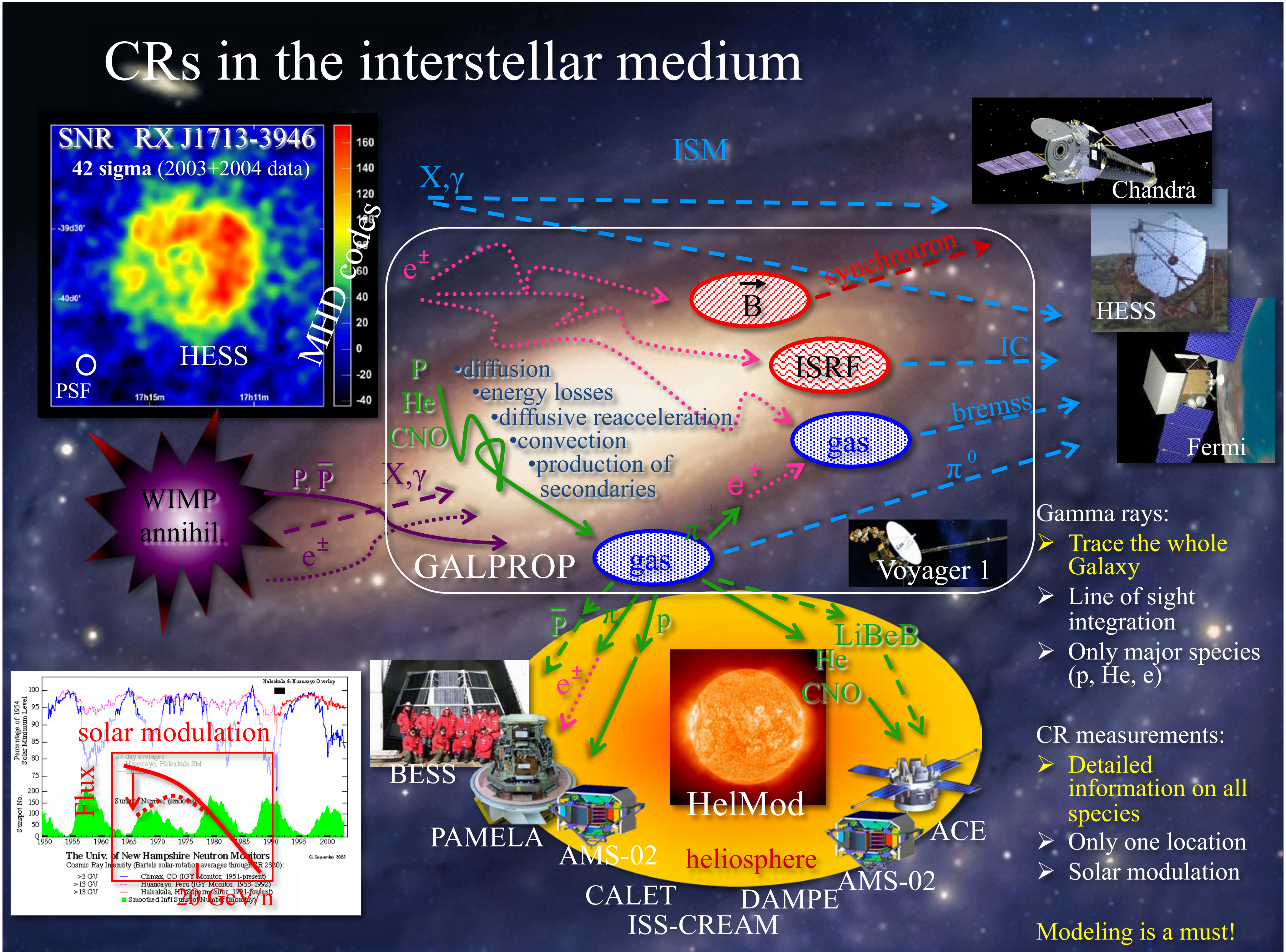
Curvature (or synchrotron) radiation

Milky Way as an electron calorimeter

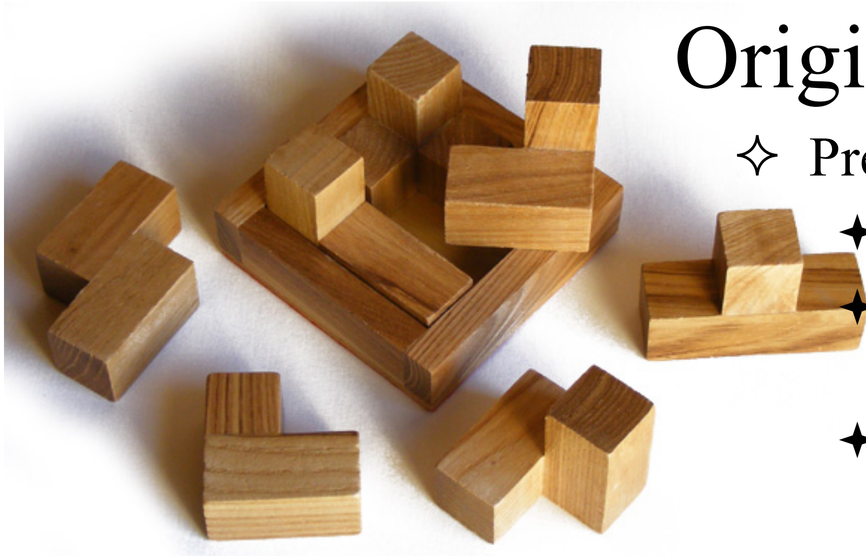
- ✧ Calculations for Z_{halo}= 4 kpc
- ✧ Leptons lose ~60% of their energy
- ✧ γ-rays: 50-50 by nucleons and by leptons



* The percentages in brackets show the values relative to the luminosity of their respective lepton populations



CRs in the interstellar medium
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
MHD codes
ISM
X,γ
Chandra
HESS
Fermi
e±
B
synchrotron
ISRF
IC
gas
bremss
π0
P
He
CNO
•diffusion
•energy losses
•diffusive reacceleration
•convection
•production of secondaries
e±
π±
gas
GALPROP
Voyager 1
WIMP annihil.
P, P̄
X,γ
e±
P̄
π
p
e±
LiBeB
He
CNO
BESS
PAMELA
AMS-02
HelMod
heliosphere
ACE
AMS-02
CALET
DAMPE
ISS-CREAM
solar modulation
Flux
20 GeV/n
The Univ. of New Hampshire Neutron Monitors
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!



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:

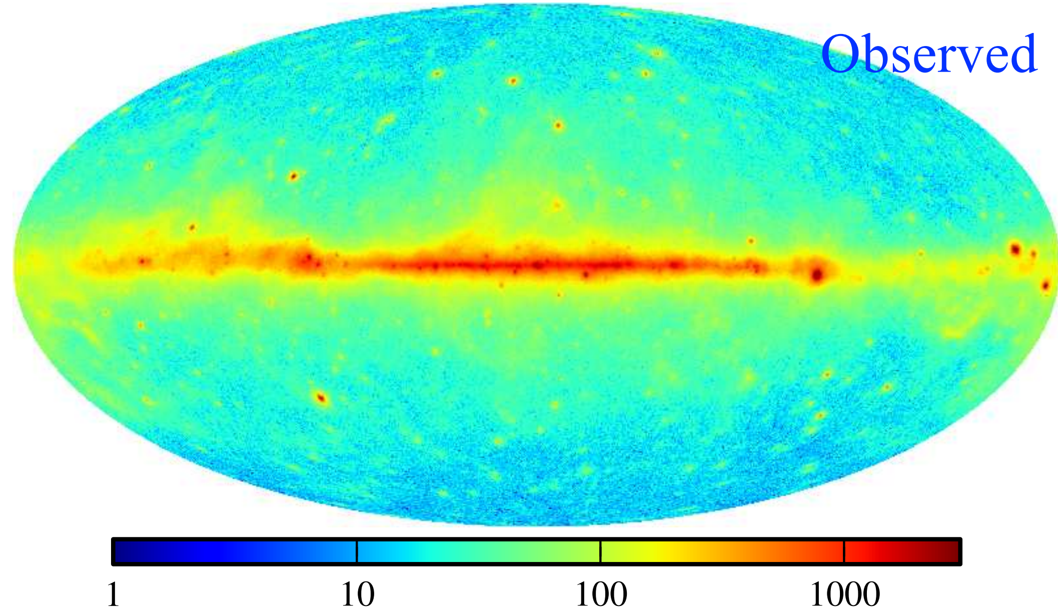
Various kinds of data, such as direct CR measurements including primary and secondary nuclei, electrons and positrons, γ-rays, synchrotron radiation, and so forth, are all related to the same astrophysical components of the Galaxy and, therefore, have to be modeled self-consistently

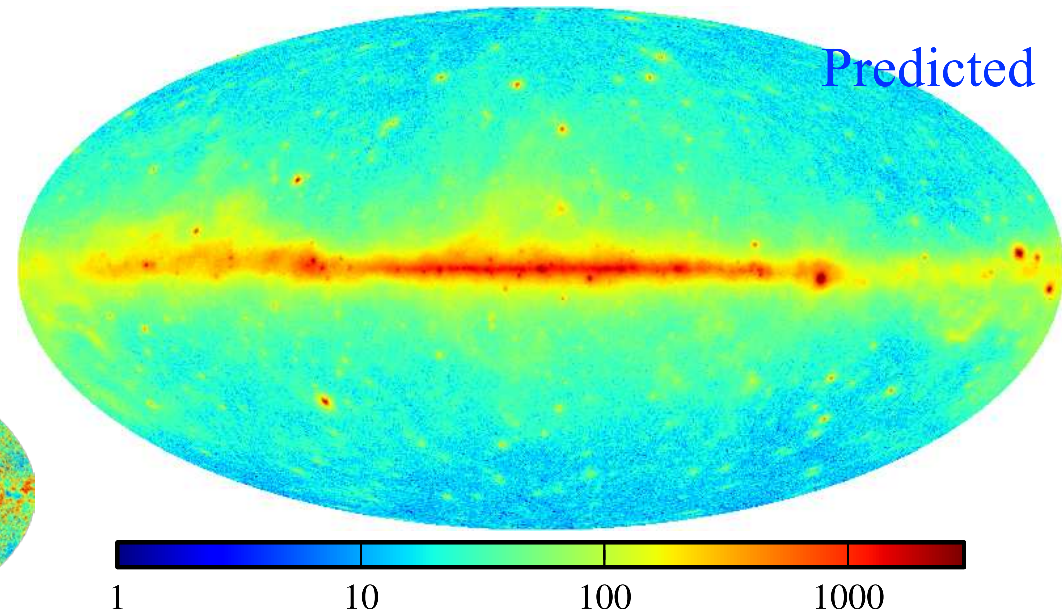
II. As realistic as possible:

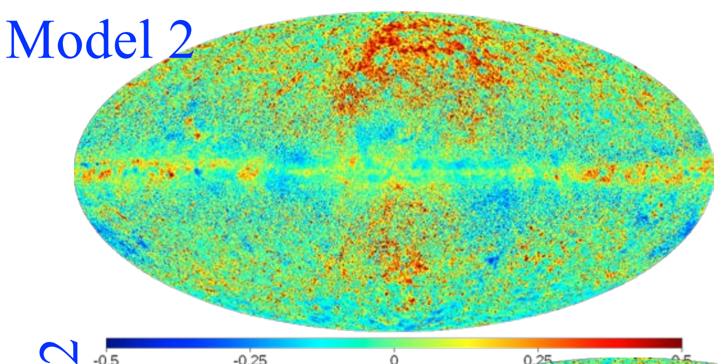
The goal for GALPROP-based models is to be as realistic as possible and to make use of all available astronomical and astrophysical information, nuclear and particle data, with a minimum of simplifying assumptions

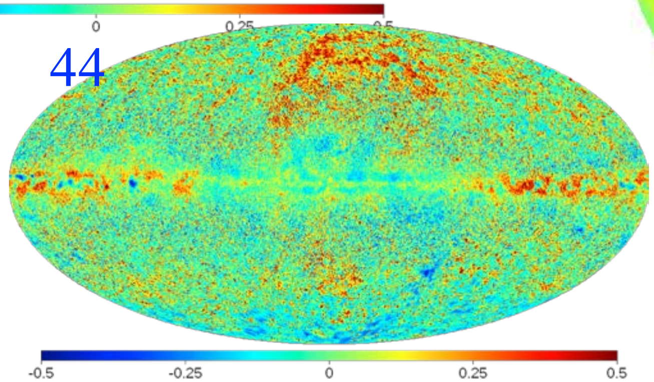
Diffuse emission skymap

- 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)









Ackermann+'12

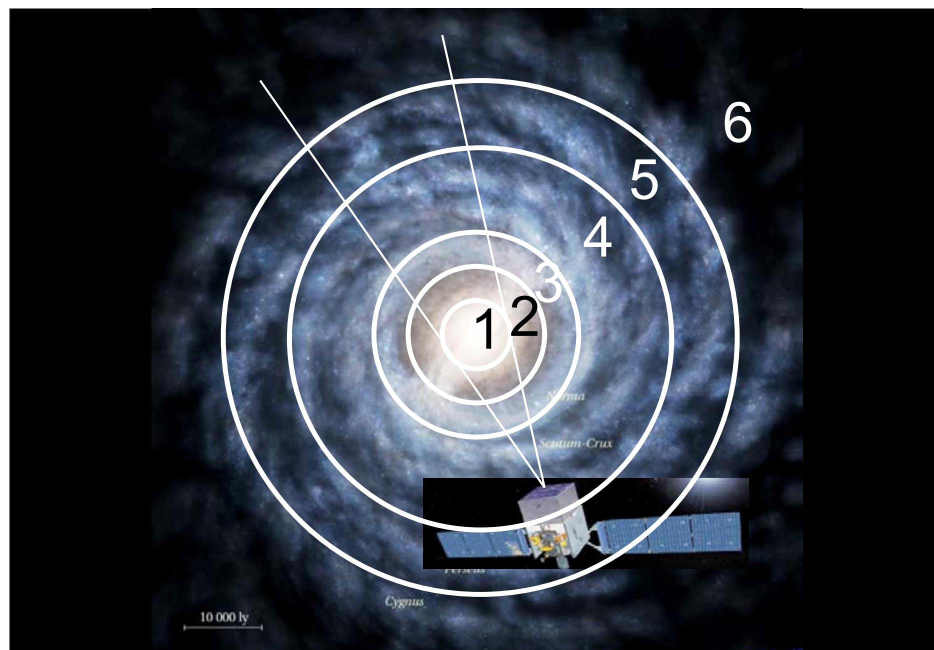
Fermi-LAT: Observations of the Inner Galaxy

- Cylindrically symmetrical model – GALPROP
- Gas-related (H_2, HI, HII) and inverse Compton emission components are divided into 6 Galactocentric rings and fitted to the observations
- Point sources, initially from 3FGL, isotropic emission, and Loop I are fitted to data in iterations
- Fit starts from the outer Galaxy
- Emission from the outer Galaxy is subtracted: inner Galaxy and projected sources remain

Ajello+, ApJ 819 [2016] 44A

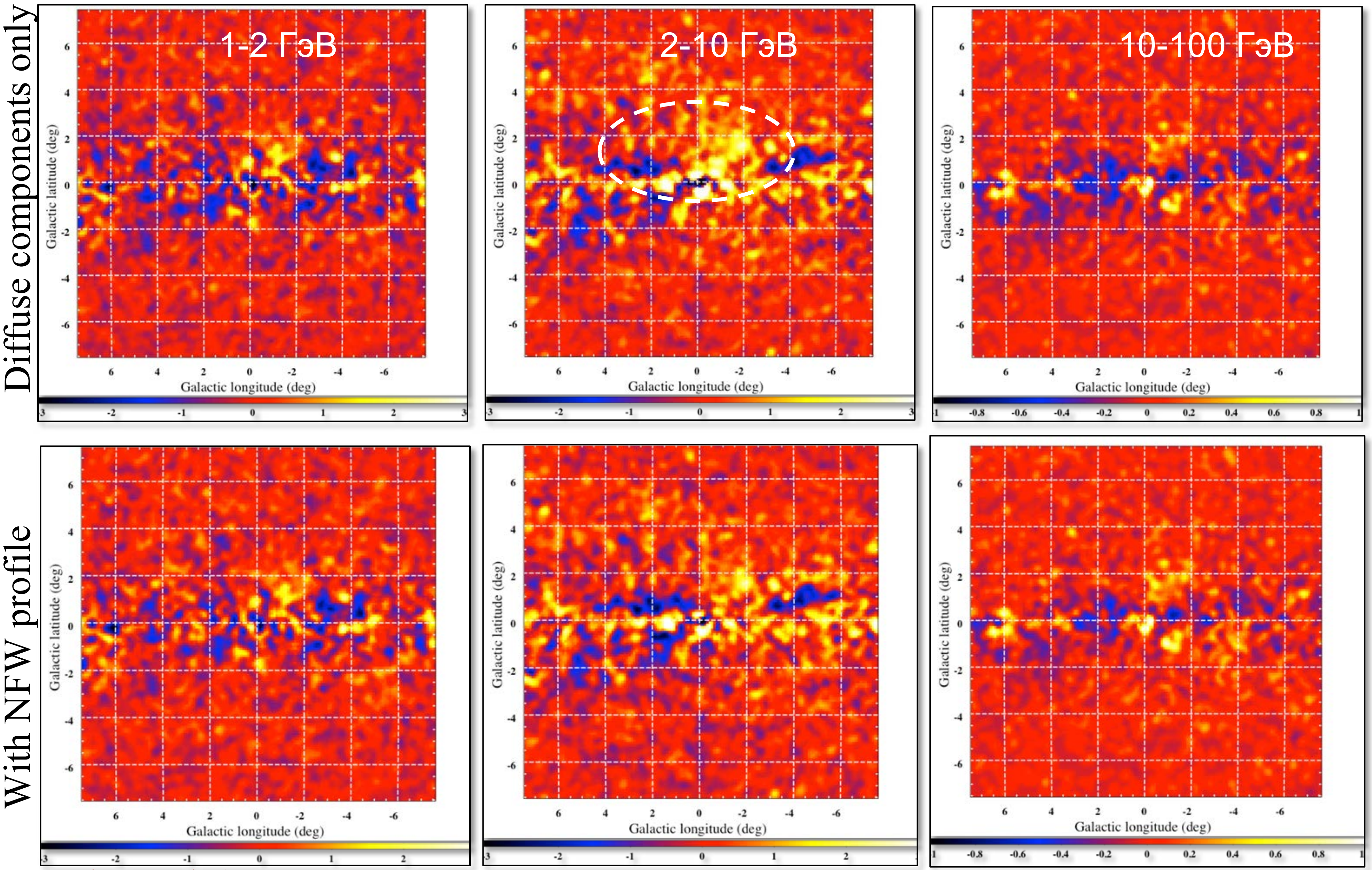
Table 1
Galactocentric Annular Boundaries

Annulus #	R_{min} (kpc)	R_{max} (kpc)	Longitude Range (Full)	Longitude Range (Tangent)
1	0	1.5	$-10° \leqslant l \leqslant 10°$	...
2	1.5	2.5	$-17° \leqslant l \leqslant 17°$	$10° \leqslant \|l\| \leqslant 17°$
3	2.5	3.5	$-24° \leqslant l \leqslant 24°$	$17° \leqslant \|l\| \leqslant 24°$
4	3.5	8.0	$-70° \leqslant l \leqslant 70°$	$24° \leqslant \|l\| \leqslant 70°$
5	8.0	10.0	$-180 \leqslant l \leqslant 180°$	...
6	10.0	50.0	$-180 \leqslant l \leqslant 180°$	...



Fermi-LAT observations of the inner Galaxy: residuals

(Data–Model): CR sources – pulsar distribution, point sources removed

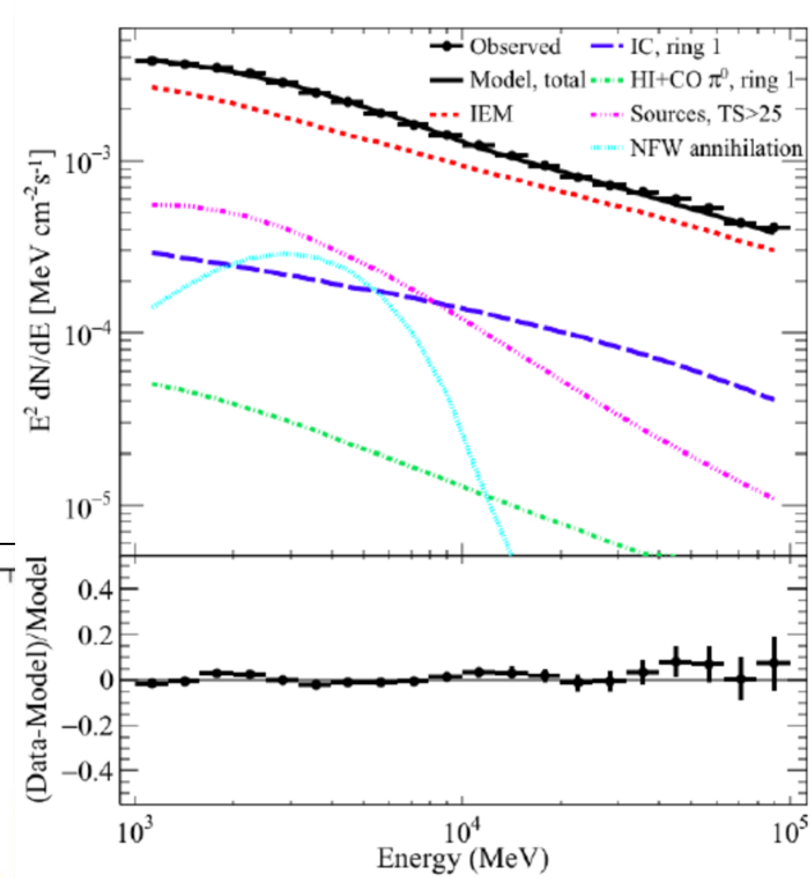


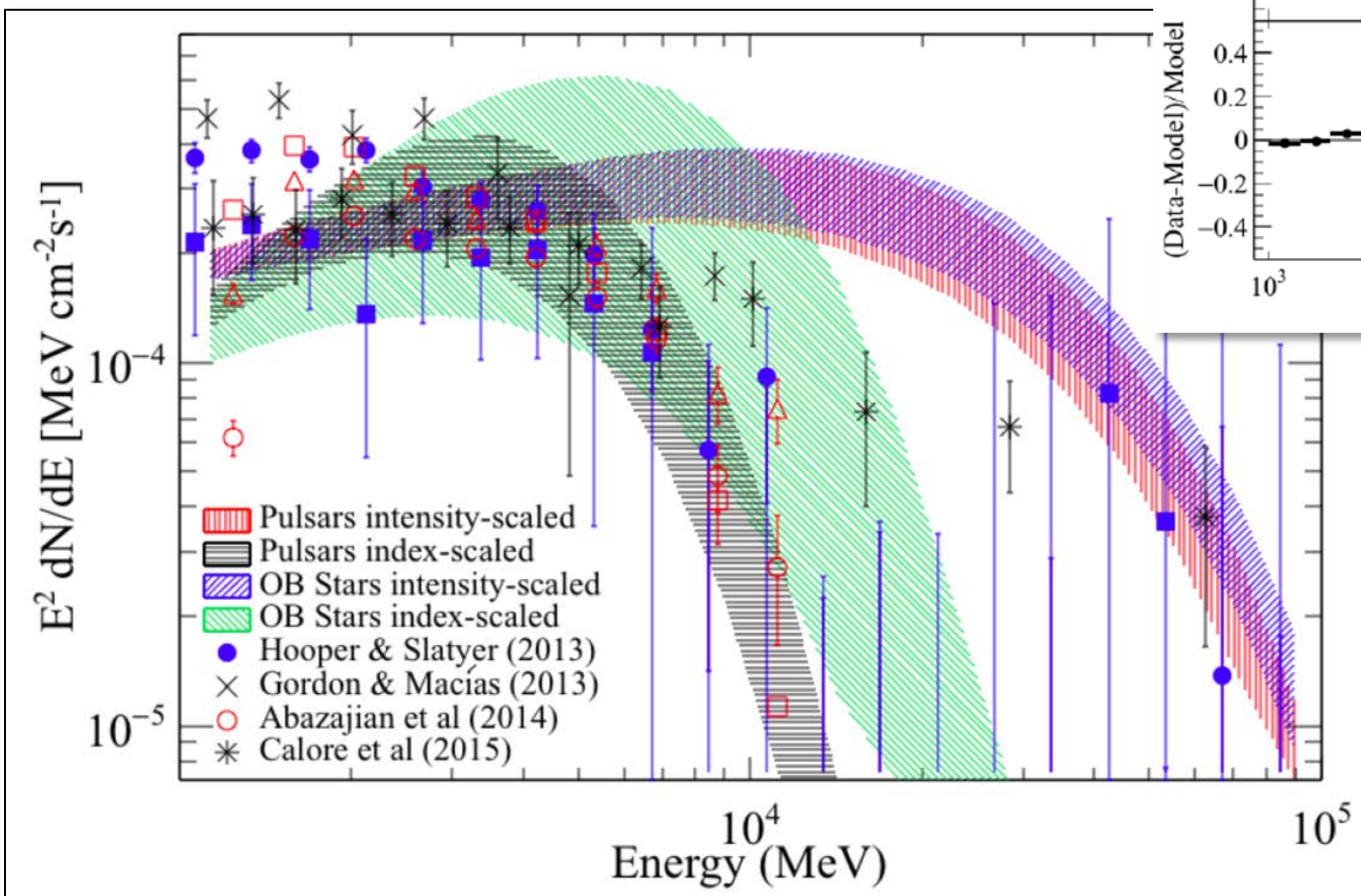
Events per pixel 0.1° × 0.1°

Spectrum of NFW component

✧ NFW profile:

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$



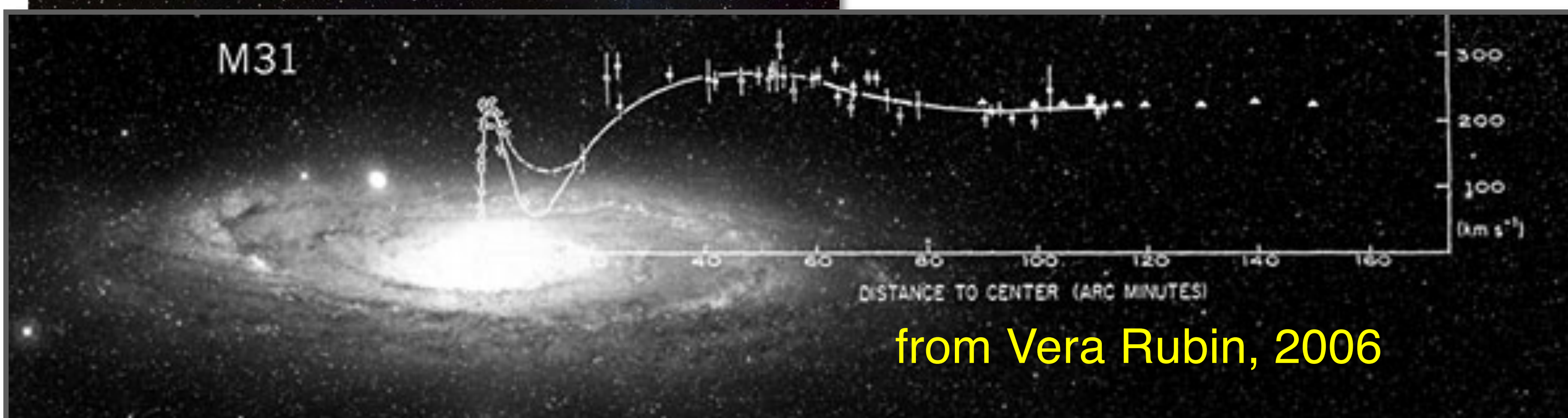


✧ Components of the emission from ROI 15° × 15° at the Galactic center

✧ Spectrum of NFW component for different CR source distributions

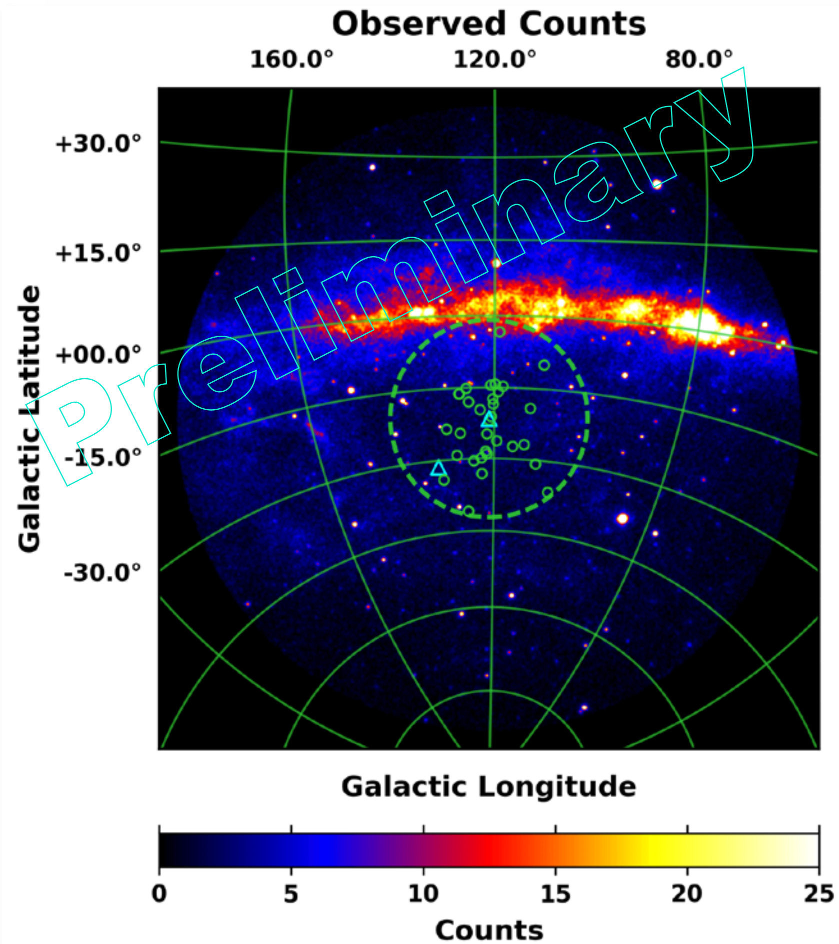
Andromeda galaxy M31 – a closest spiral

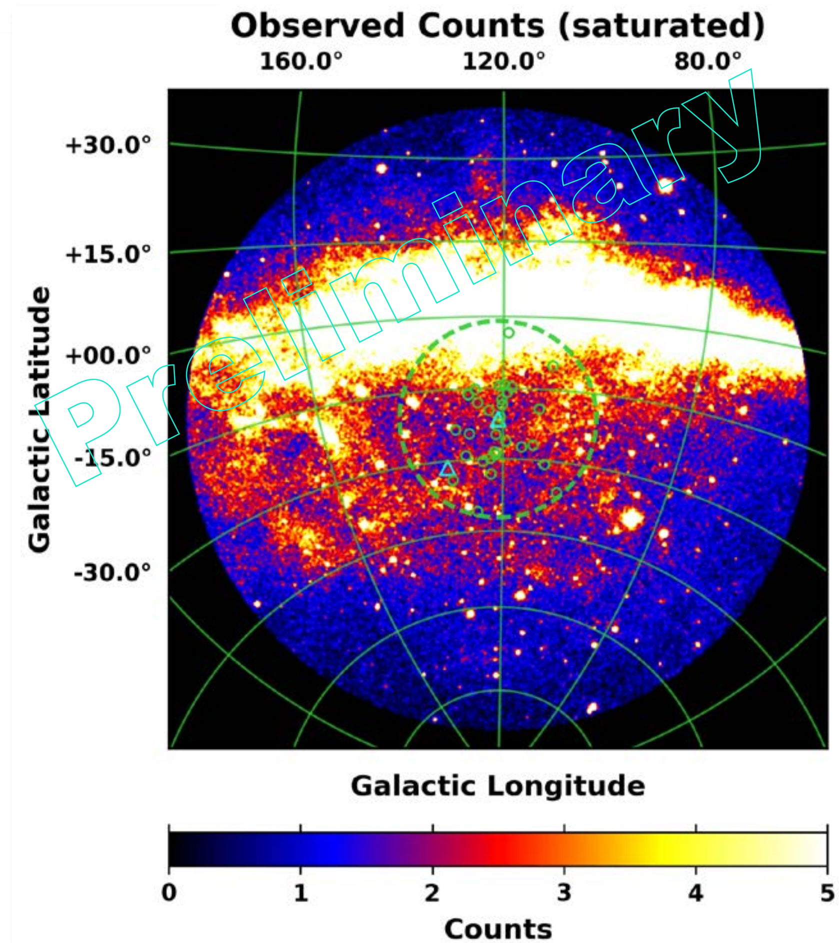
- ✧ Similar to the Milky Way at 778 kpc
- ✧ Provides an external view on our own Galaxy
- ✧ Large size on the sky 3°×1° – easy to resolve
- ✧ The rotation curve remains constant over large distances – large content of DM
- ✧ Virial radius ~300 kpc



Fermi-LAT: region of interest

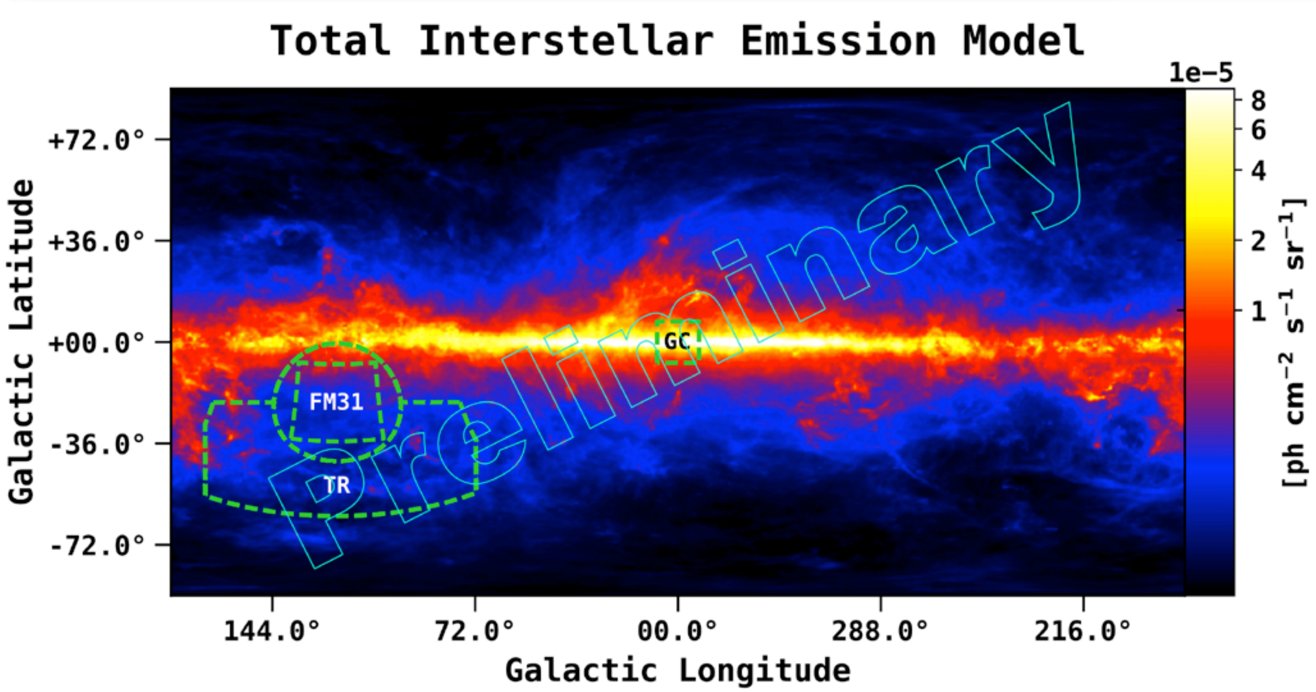
8th Fermi Symp.
Karwin+,arXiv: 1812.02958

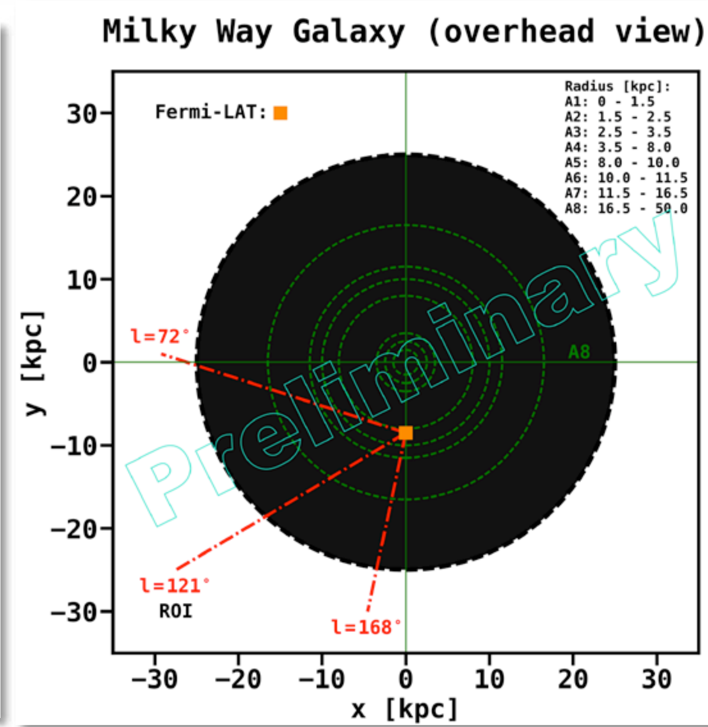




- ✧ Observed counts and saturated counts for a 60° radius centered at M31
- ✧ The green dashed circle is ~21° in radius and corresponds to a 300 kpc projected radius for a MW-M31 distance – the canonical virial radius of M31

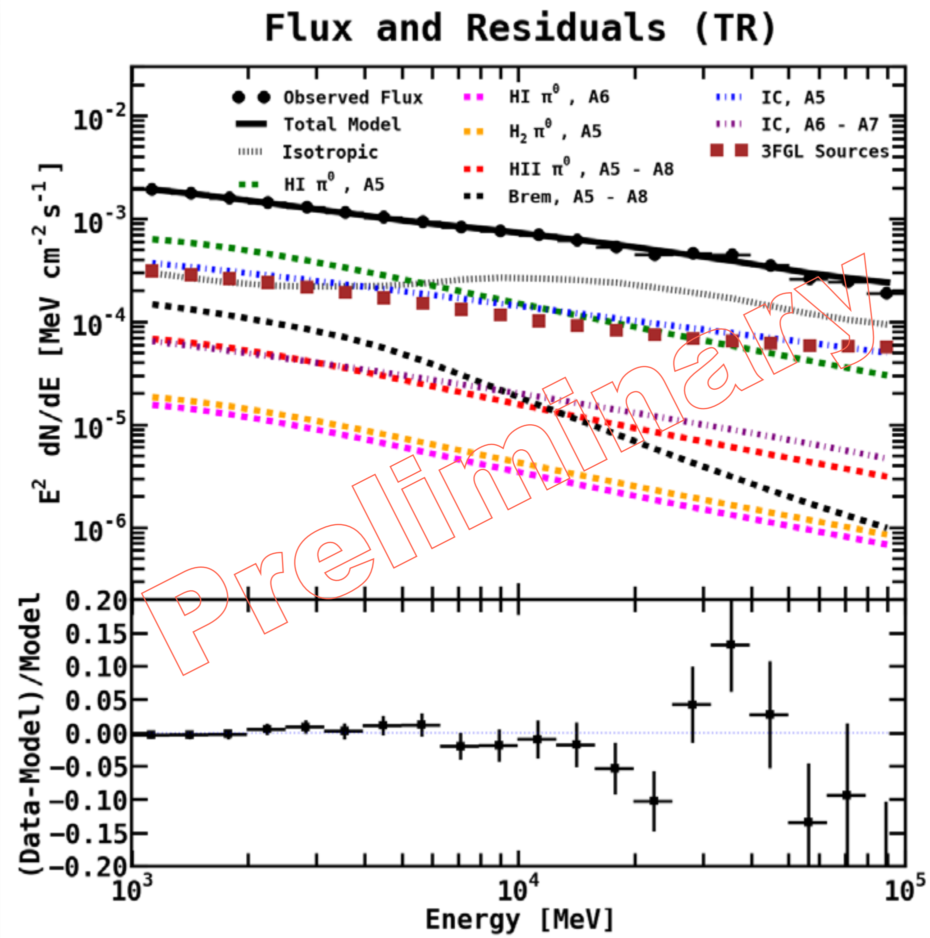
Test region and M31 field

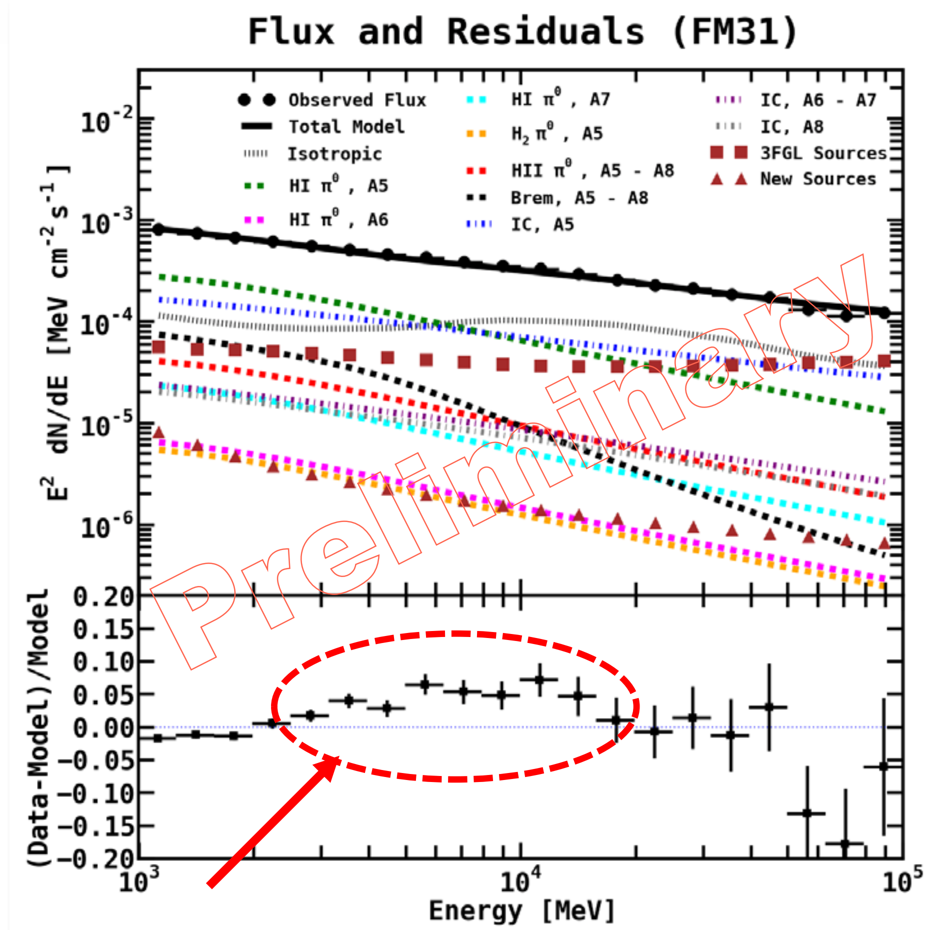




- ✧ The interstellar emission model for the MW (1-100 GeV):
  π^0-decay + (anisotropic) inverse Compton + Bremsstrahlung
- ✧ "Square" region is M31 field
- ✧ "TR" labels the test region
- ✧ Schematic of the eight concentric circles which define the annuli (A1-A8) in the MW foreground model. Only A5-A8 contribute to the Galactic foreground emission for the field used in this analysis.

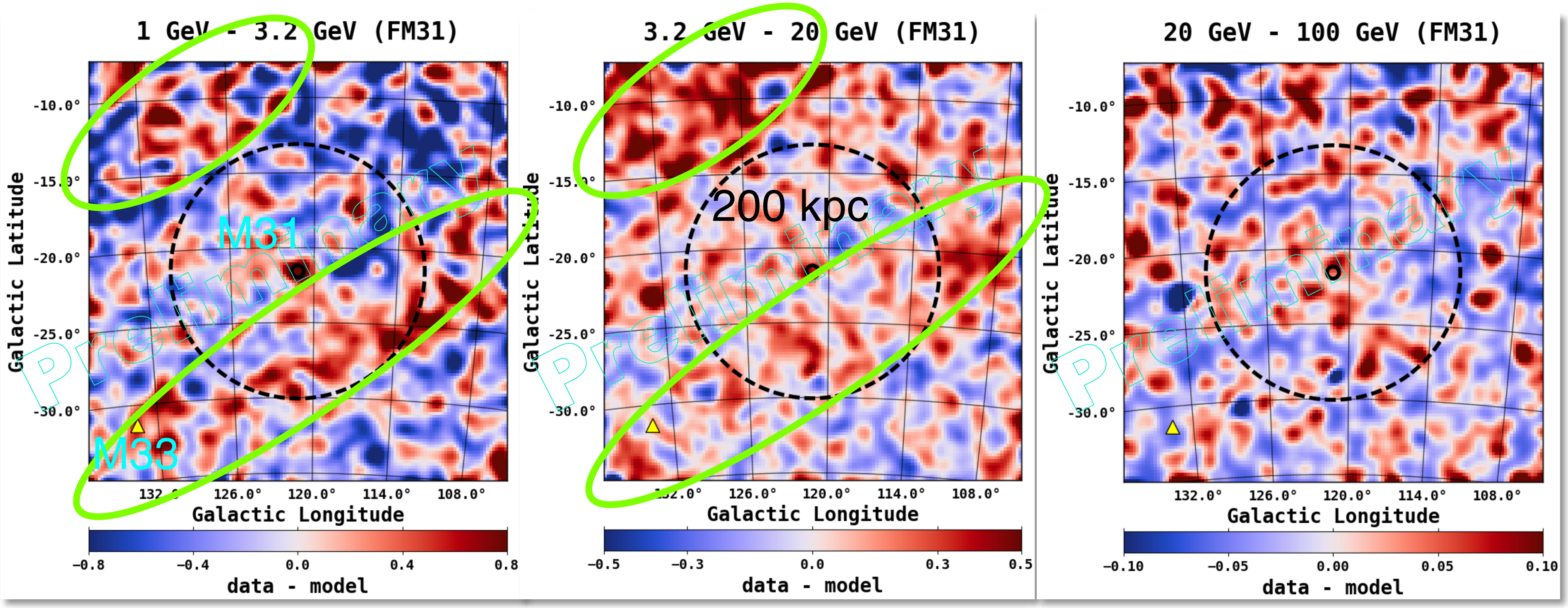
Spectral fits in TR and FM31





- ✧ Flux and fractional count residuals for the fit in the TR and FM31
- ✧ The fractional residuals (FM31) show an excess between 3-20 GeV reaching a level of 4%

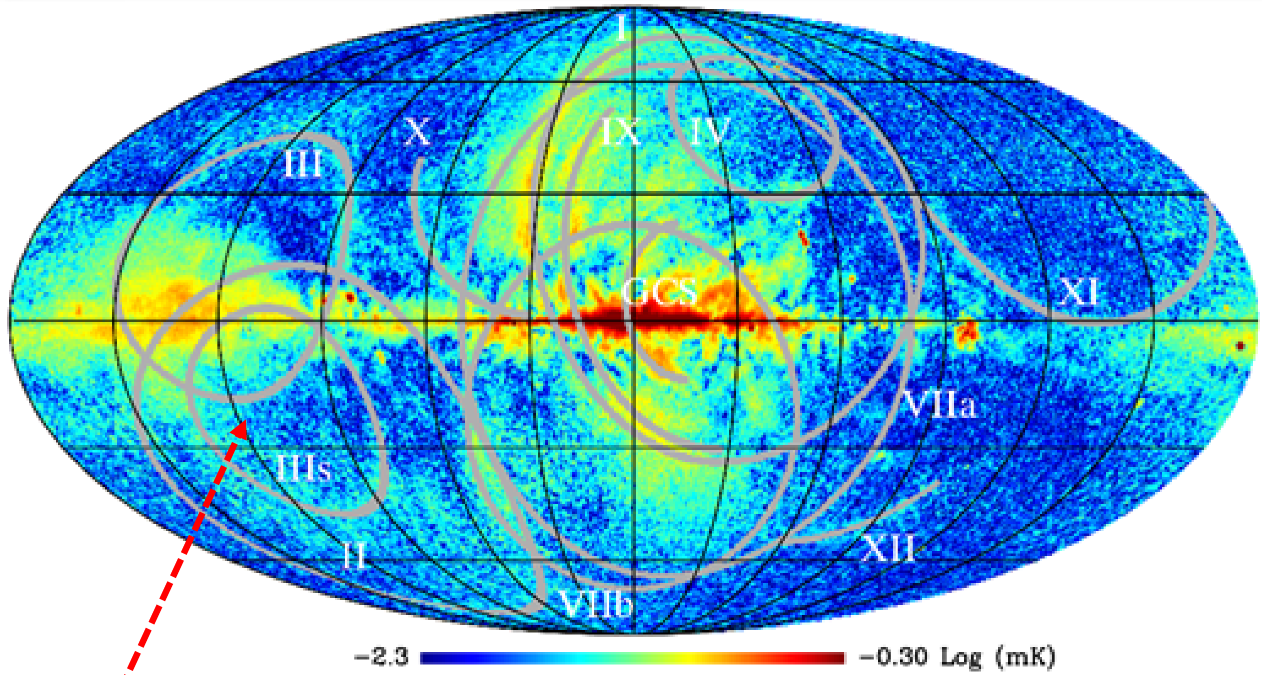
FM31: Spatial residuals



- ✧ Spatial count residuals (data – model) resulting from the baseline fit in FM31 for three different energy bands. Smoothed using 1° Gaussian kernel. The pixel size is 0.2°×0.2°
- ✧ The “arc” structure is clearly seen in the 1st and 2nd pixels
- ✧ M33 is in the bottom left angle
- ✧ Dashed circle – “spherical halo” of 200 kpc radius

The Arc & Galactic Loops

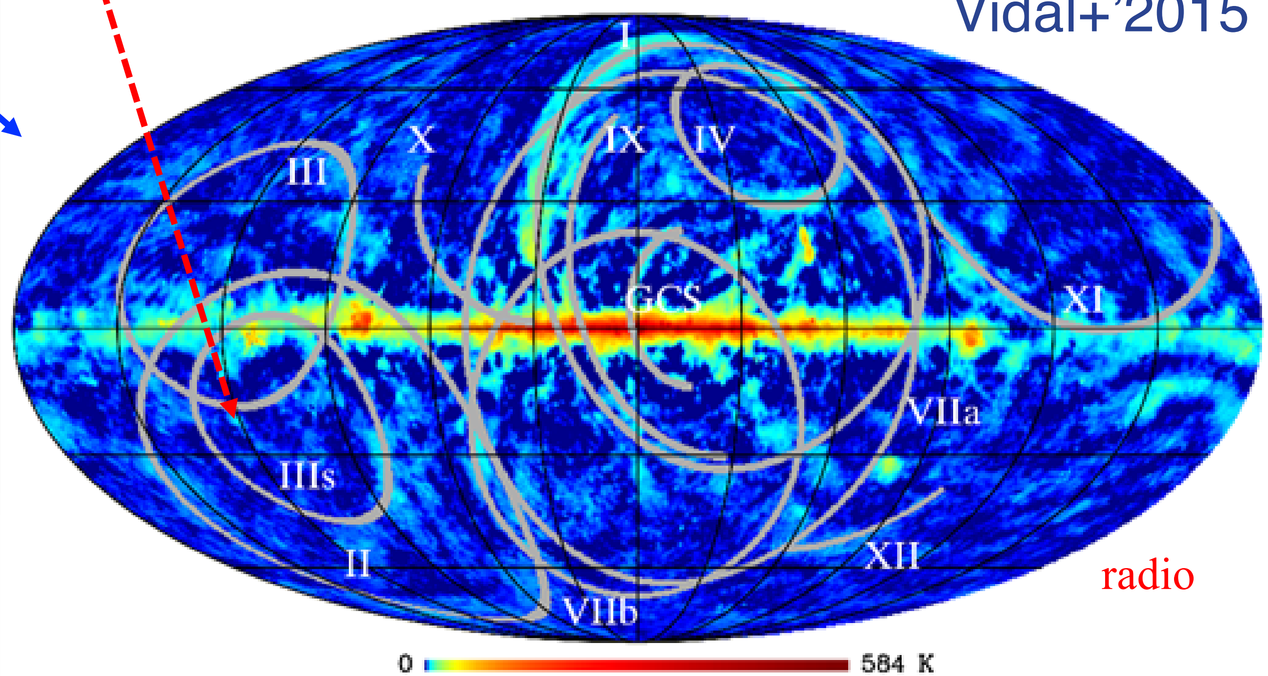
- ✧ WMAP *K*-band polarization intensity map
- ✧ Unsharp mask version of the Haslam et al. (1982) map
- ✧ The origin of the Loops is unknown
- ✧ If these are old SNRs, accelerated particles may still be present in the shell
- ✧ FM31: Loops III, II, IIIs



WMAP *K*-band polarization intensity map

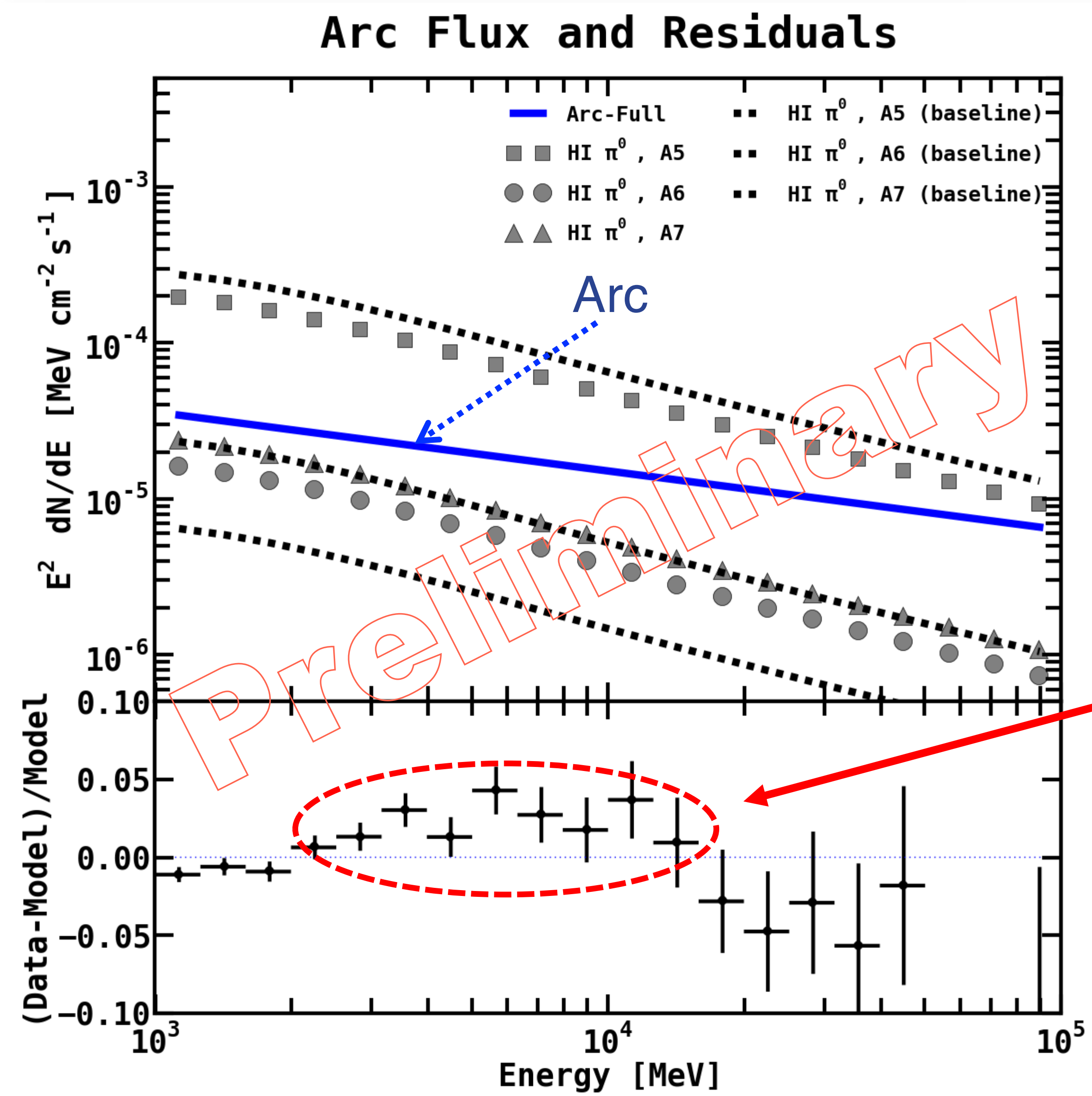
M31

Vidal+'2015



radio

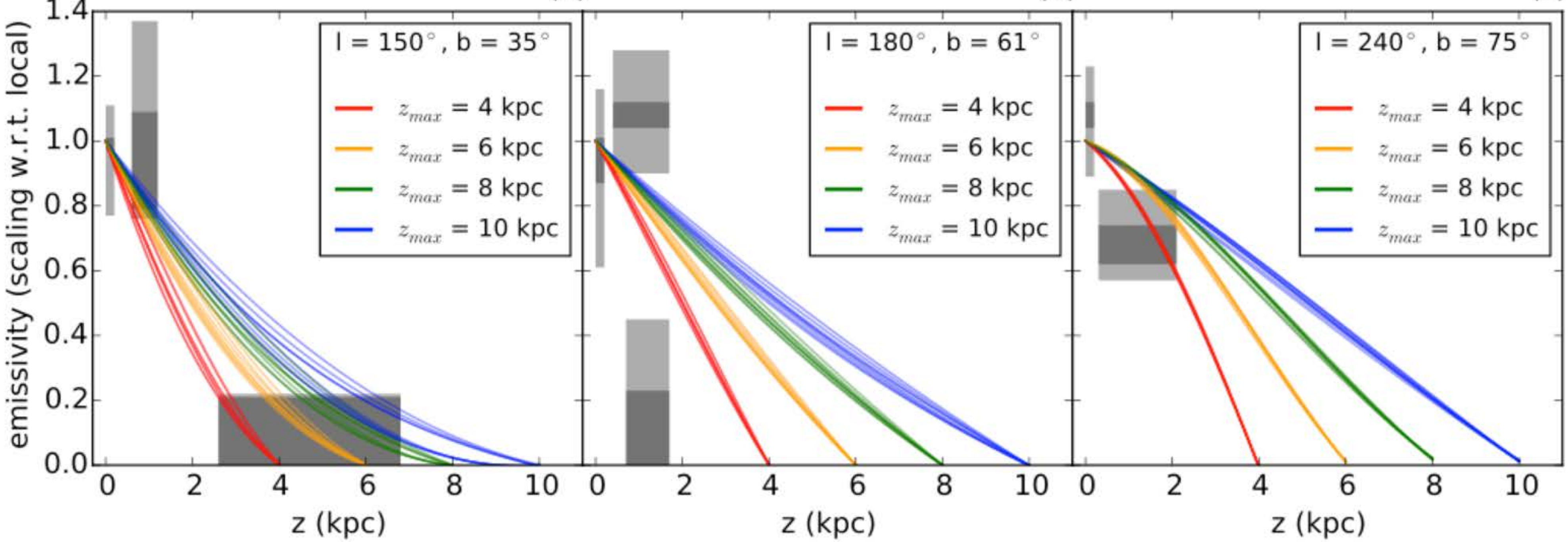
Fit with the arc template



- Spectrum of the arc structure is harder than the rest of the gas
- A fit with the arc template removes structured spatial residuals
- The spectral excess is still present and significant

Interpretation: Cosmic Rays in the halo

Low-latitude Intermediate Velocity Arch and Complex A (a) | Lower and Upper Intermediate Velocity Arch (b) | Intermediate Velocity Spur (c)



models from Ackermann et al 2012 ApJ 750 3

CRs in High Velocity Clouds, Tibaldo+'2015

- broad agreement with propagation model
- hint at 50% decrease within 2 kpc from the disk ↚→ large halos

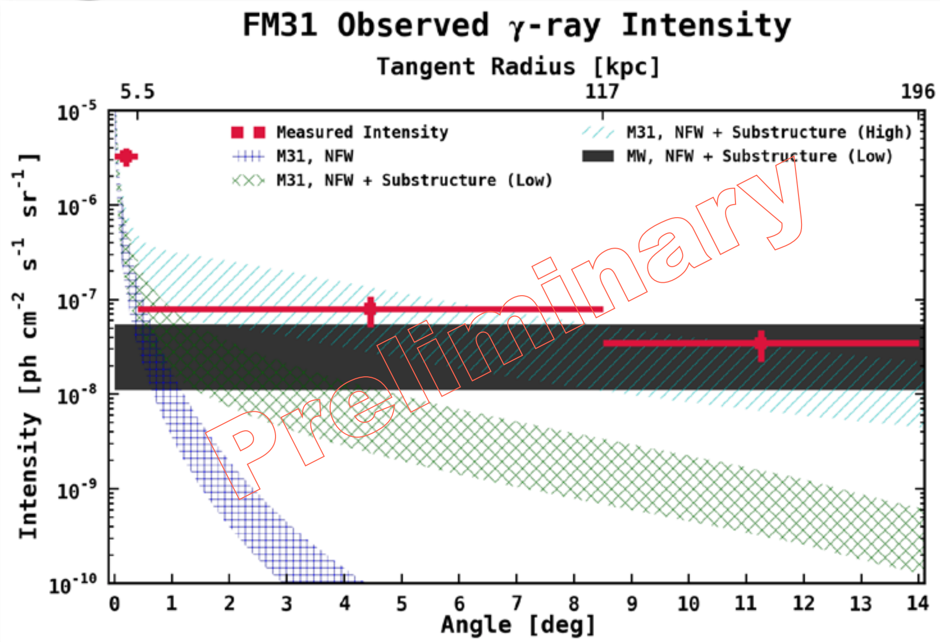
✧ First direct evidence of CR intensity in the Galactic halo

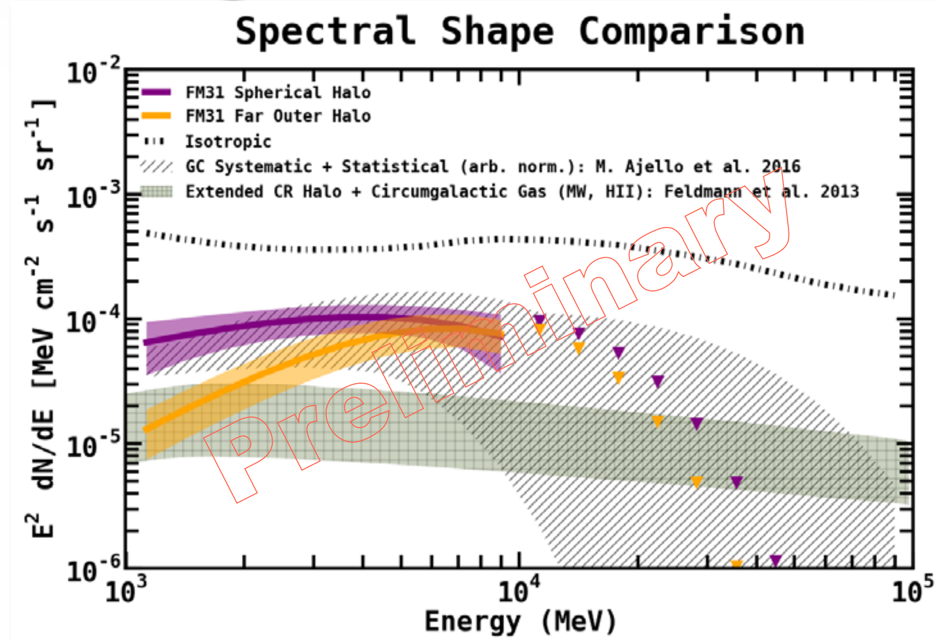
∧ first direct evidence of Galactic origin of CRs

L.Tibaldo

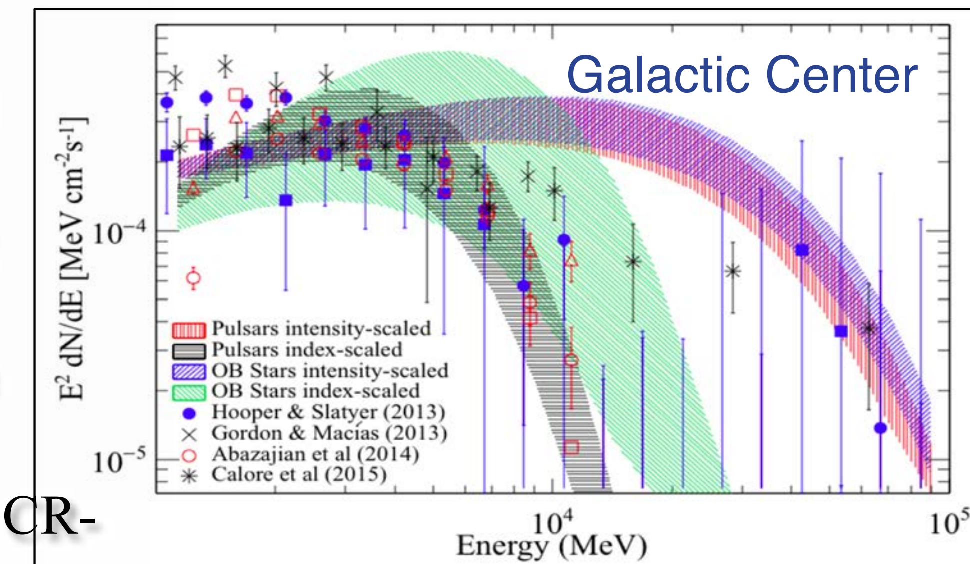
s

Spectrum of the excess and interpretation

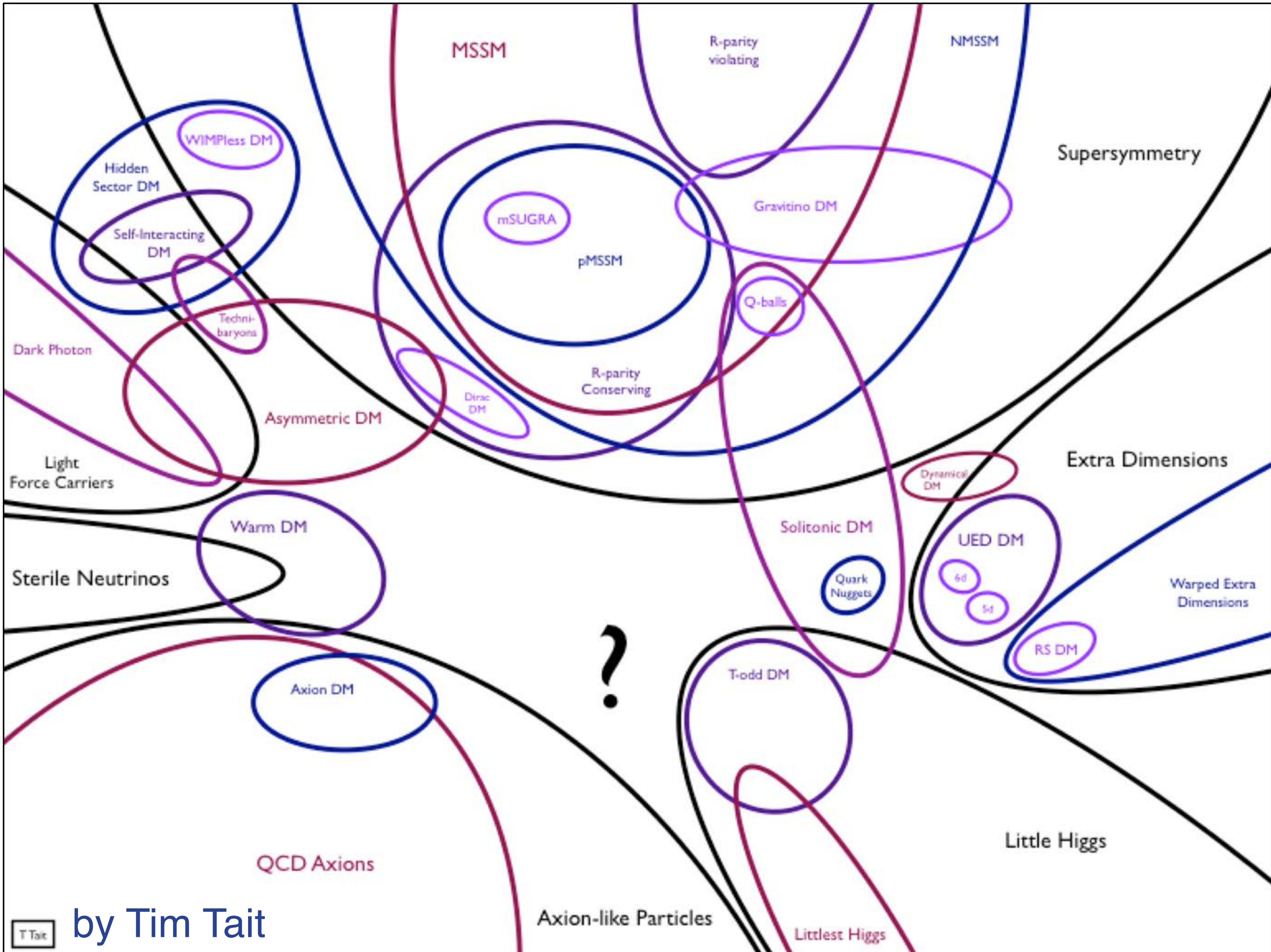




- ✧ FM31:
  - ✦ Inner galaxy: <0.4° (5.5 kpc projected radius) – 7σ
  - ✦ Spherical halo: 0.4° < r <8.5° (117 kpc projected radius) – 7σ
  - ✦ Far outer halo: 8.5° < r <14° (~200 kpc projected radius) – 5σ
- ✧ Spectral shape is not resembling other CR-related components

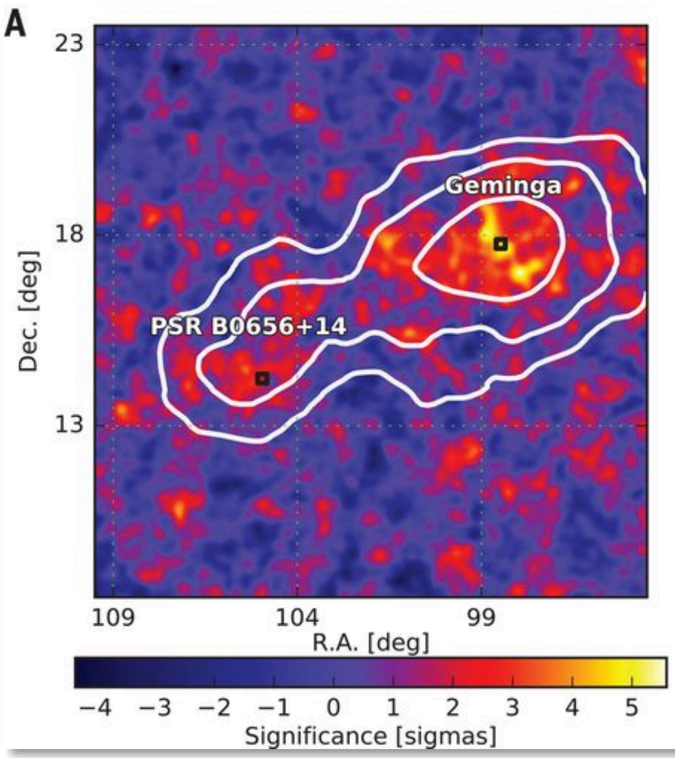


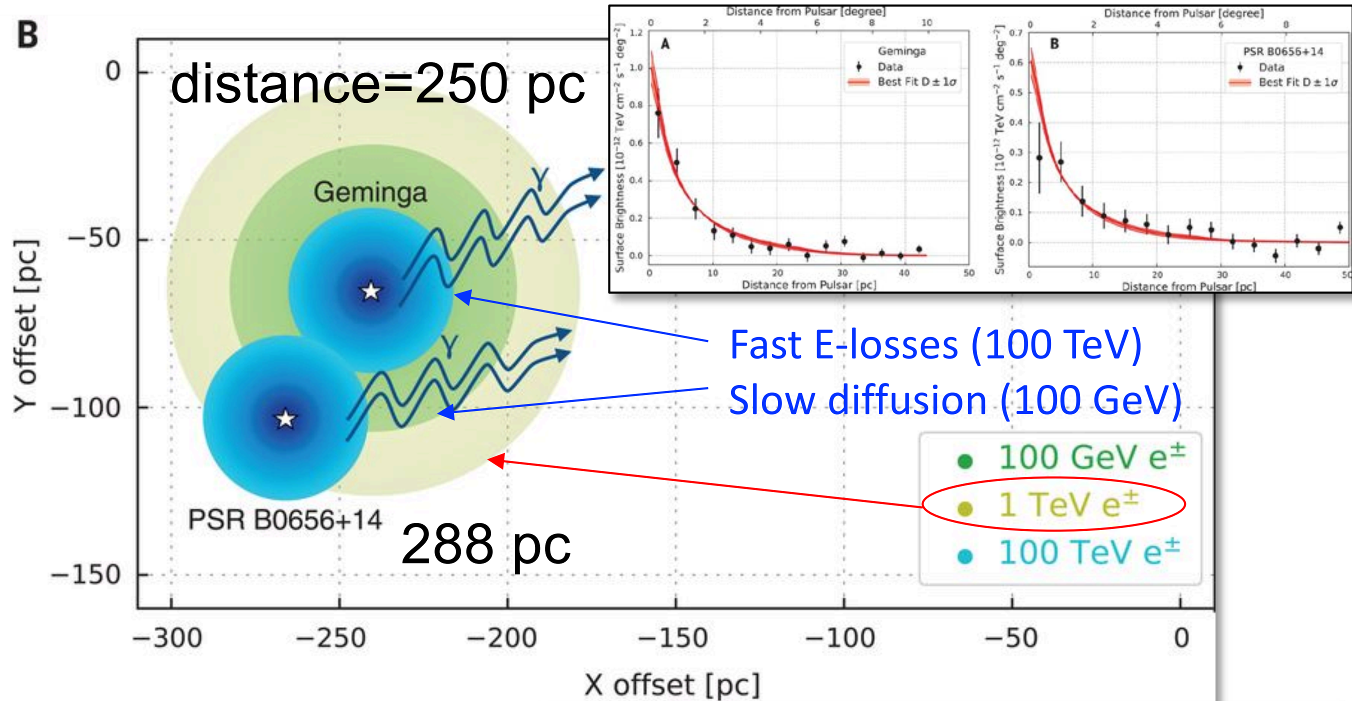
The problem of dark matter (hidden mass) and its detection



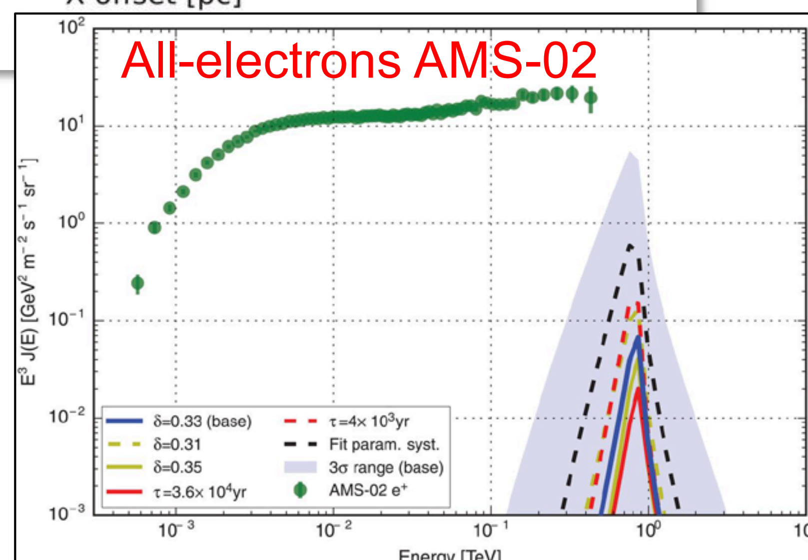
by Tim Tait

HAWC observations of the extended emission from Geminga & PSR B0656





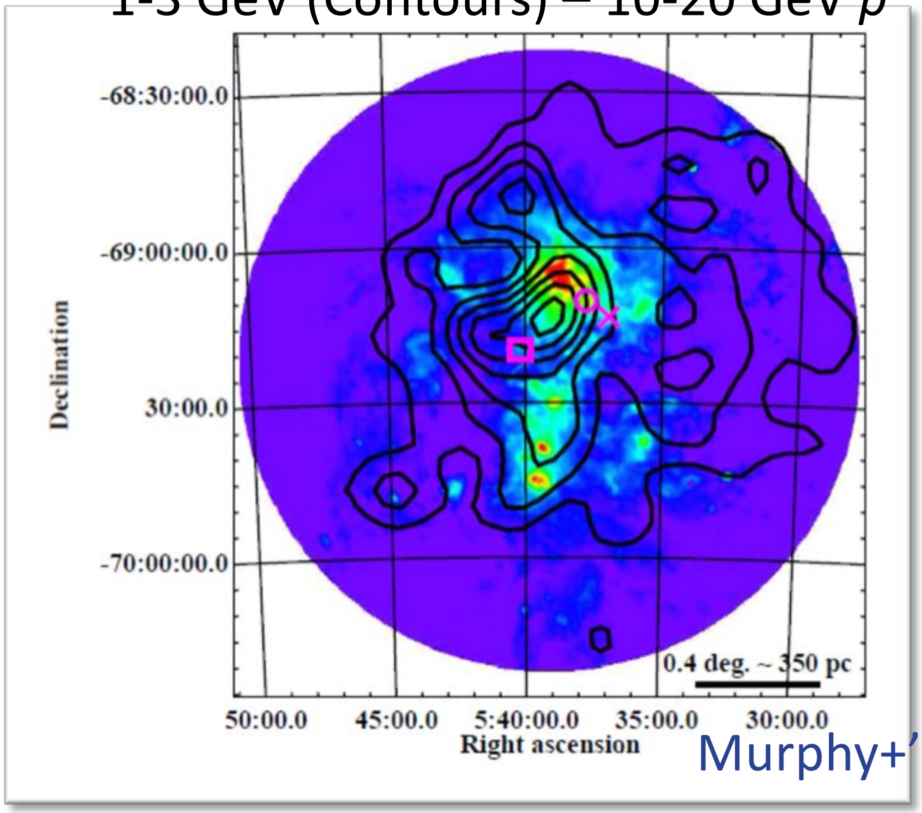
Abeysekara+'2017



- ✧ Evidence of a non-uniform diffusion near the sources of CRs
- ✧ Fast E-losses (100 TeV) vs slow diffusion (100 GeV)
- ✧ The local value ~4.5×10^{27} cm^2 s^{-1} @100 TeV is << the average from the B/C ratio
- ✧ Proper motion ~60 pc since SN (Geminga)

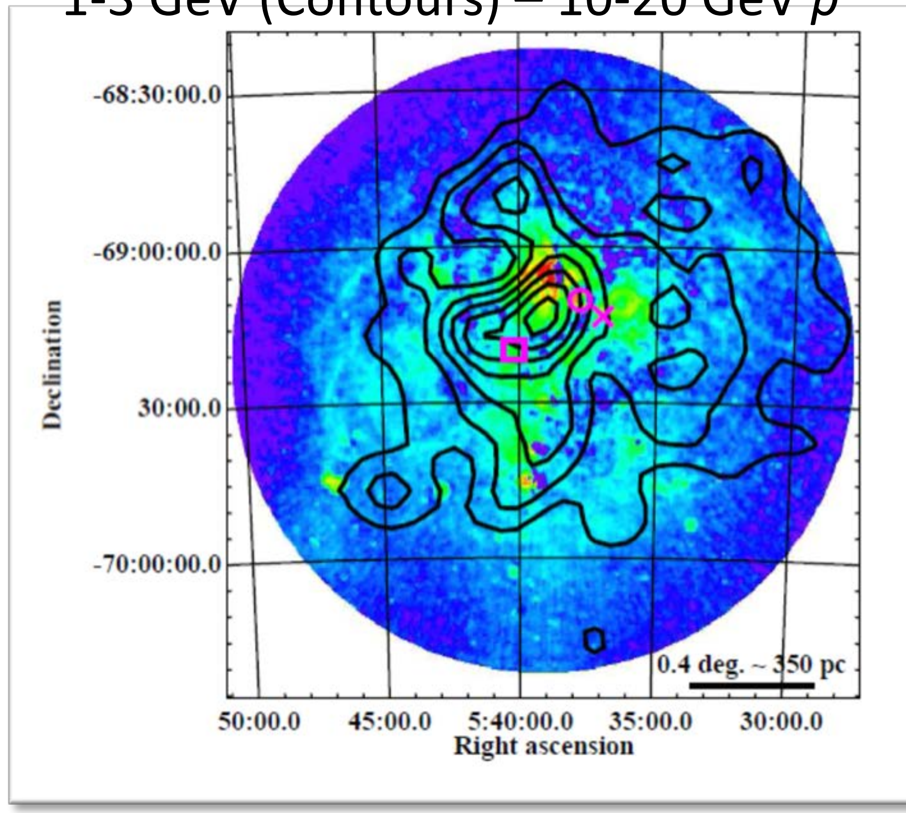
Spatially Resolved CR diffusion in LMC: 30 Doradus

24 µm (Color) – starforming
1-3 GeV (Contours) – 10-20 GeV *p*



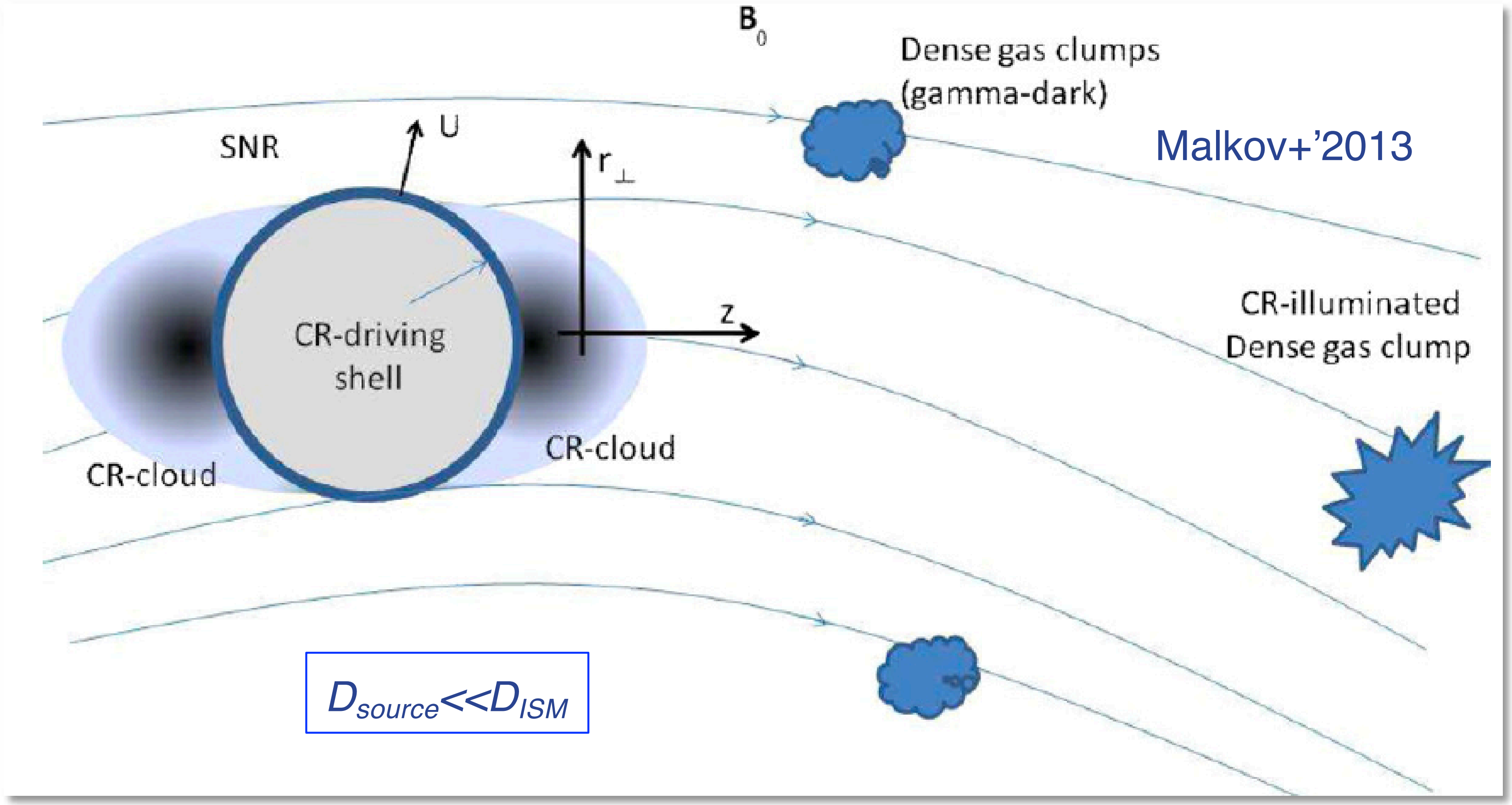
Murphy+'2012

1.4 GHz (Color) – 3 GeV e^-
1-3 GeV (Contours) – 10-20 GeV *p*



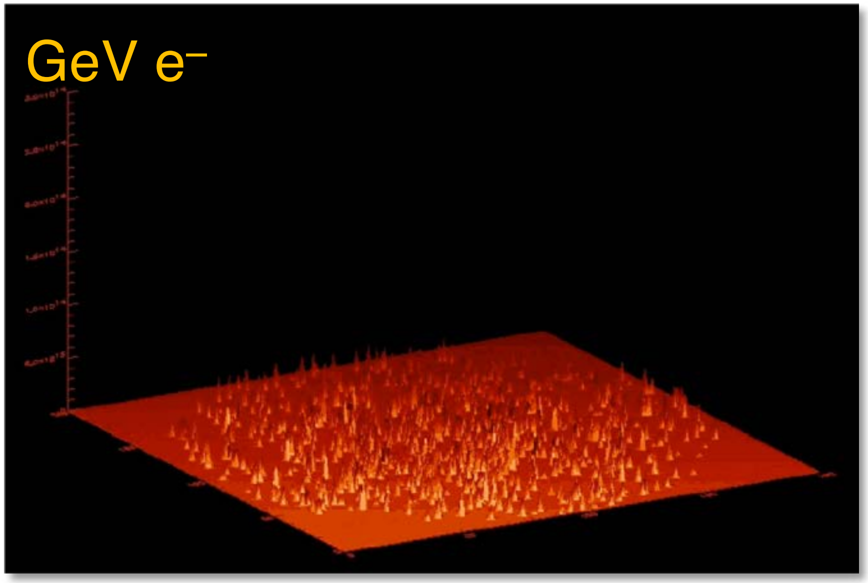
- ✧ IR – proxy for the star forming region (SNR)
- ✧ Radio – synchrotron emission from electrons (100-140 pc at ~3 GeV)
- ✧ Gamma rays – emission from π^0-decay (CR protons, 200-320 pc at ~20 GeV)
- ✧ Diffusion coefficient ~$10^{27}(R/GV)^{0.7}$ cm^2 s^{-1} (~20 times lower than average in the MW)

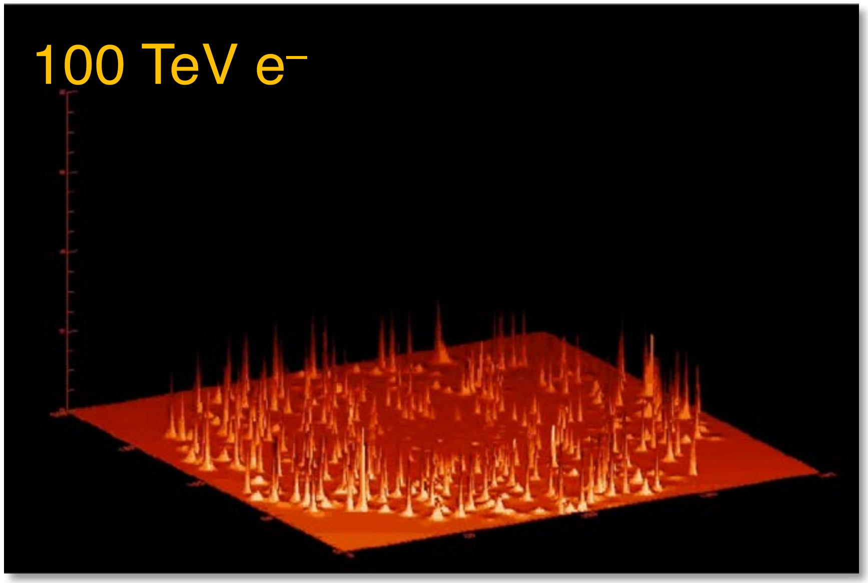
Excitation of turbulence by the leaking particles



- Escaping CRs excite the Alfvén waves
- The diffusion coefficient is strongly suppressed compared to its background ISM value

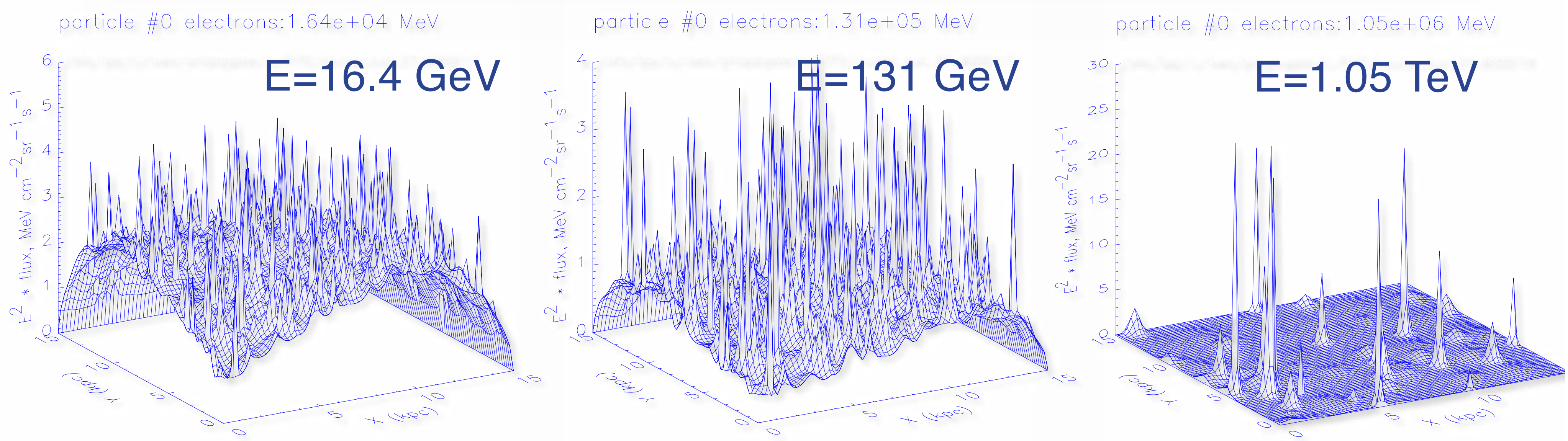
GALPROP animations ~2003

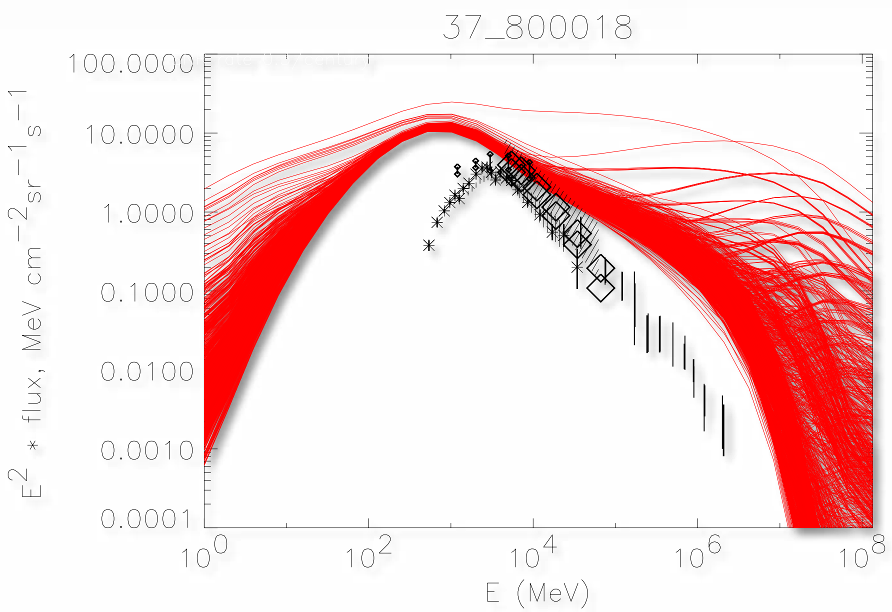




- A couple of animations made by Simon Swordy (Chicago U.) are using time dependent solutions with stochastic SN generated by GALPROP
- Electron energy loss timescale:
  - 1 TeV: ~300 kyr
  - 100 TeV: ~3 kyr
- Compare with CR lifetime ~10 Myr

Time-dependent 3D calculations – electrons



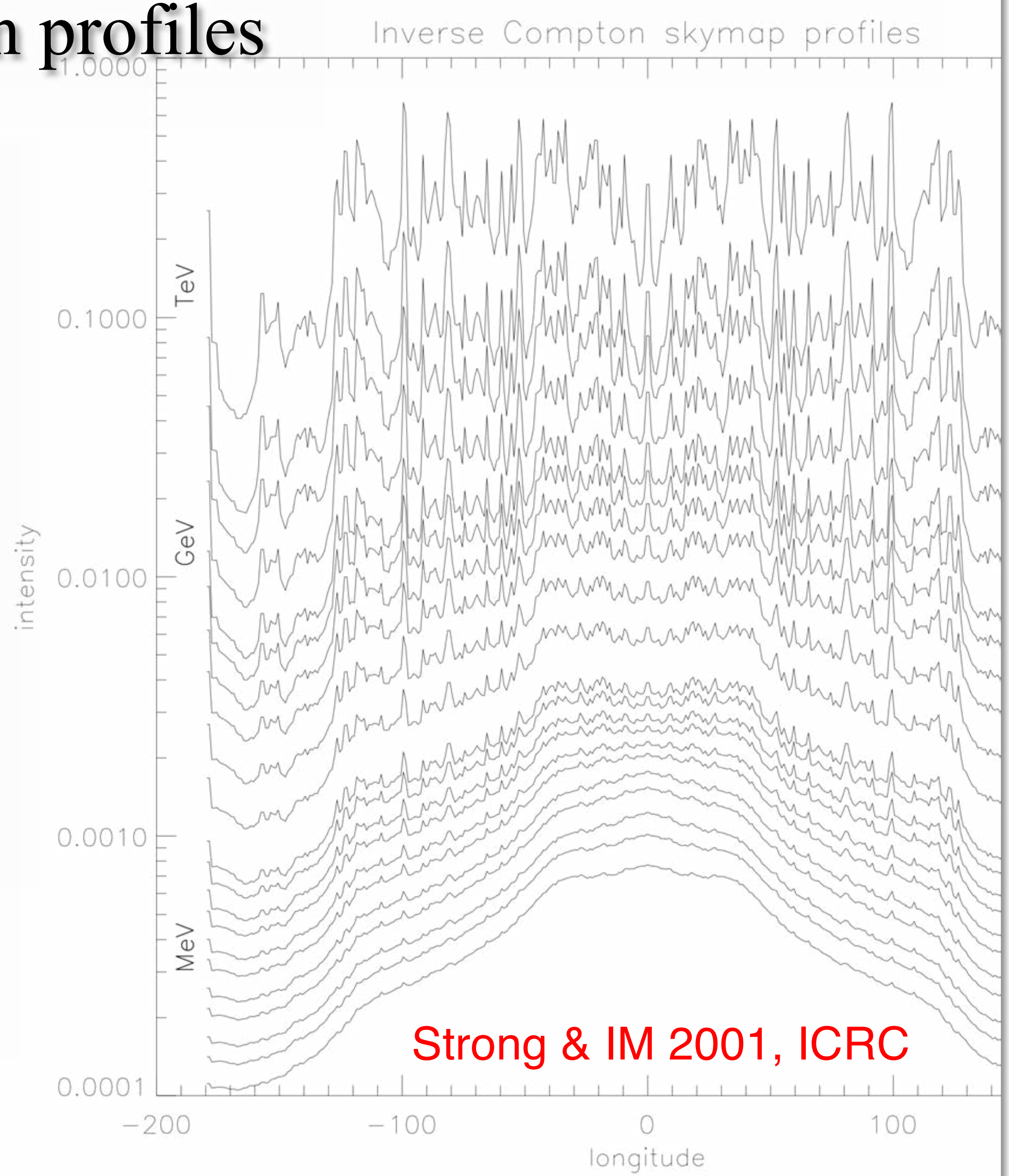


Time-dependent 3D solutions with stochastic SN generated by GALPROP

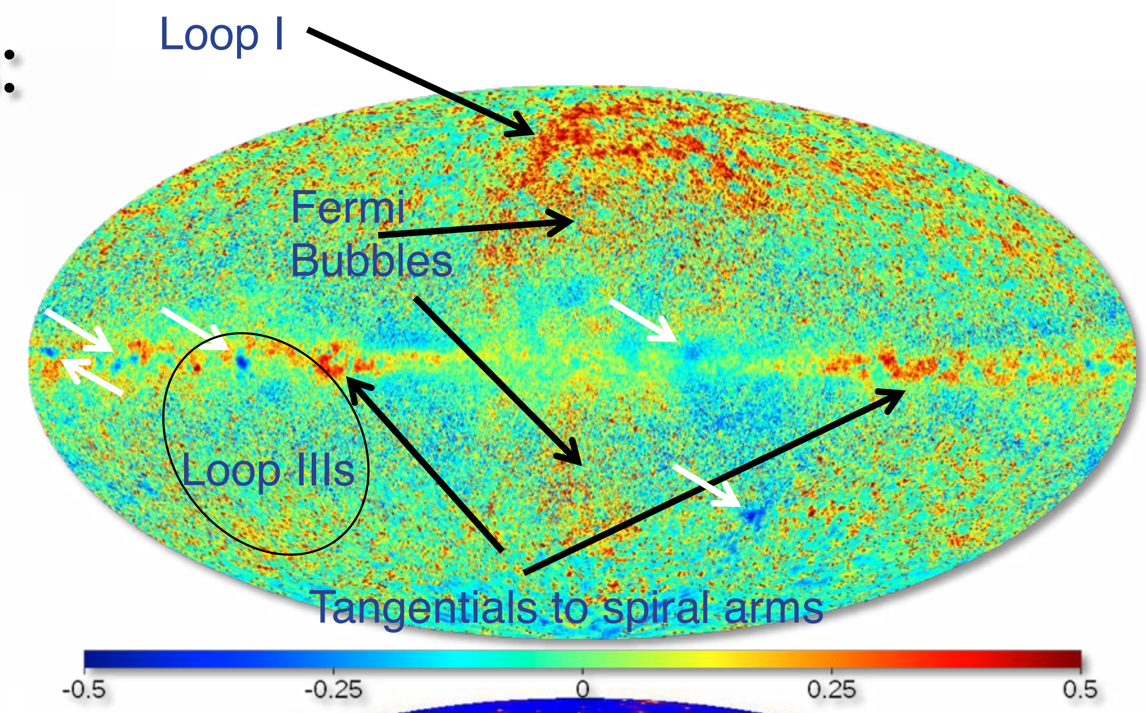
Strong & IM 2001, ICRC

Inverse Compton profiles

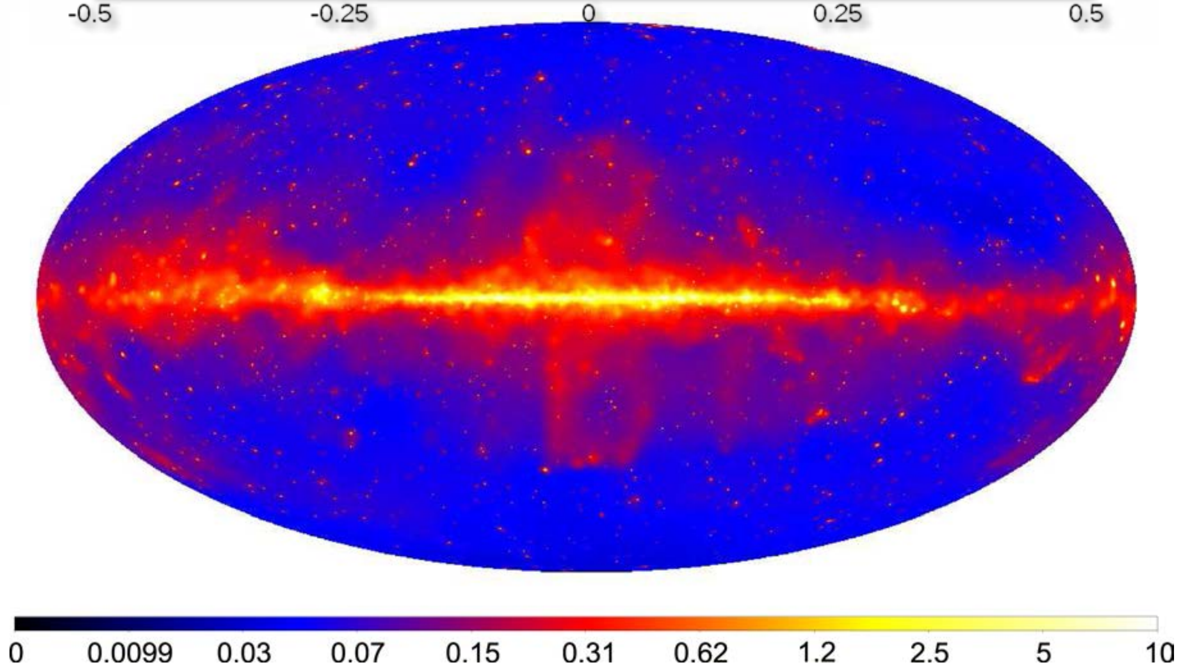
- ✧ Longitude profiles of IC emission in MeV, GeV, and TeV energy ranges
- ✧ Most significant fluctuations can be seen at VHE
- ✧ At that time we thought it is a useful exercise, but not practical due to large errors in electron data and diffuse emission – was not submitted to a journal

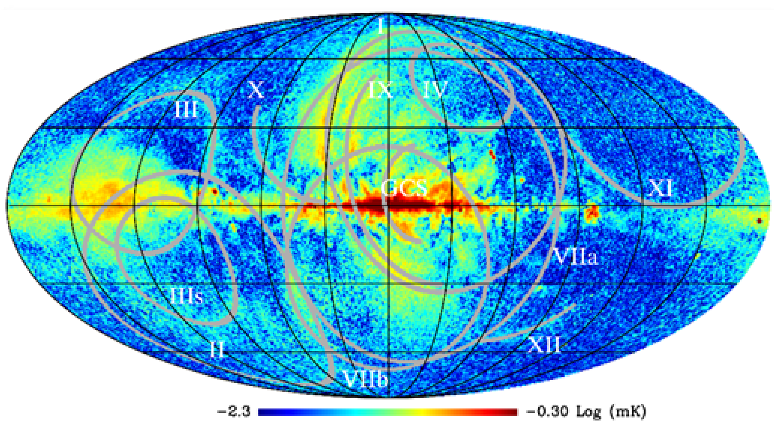


Gamma-ray skymaps: Residuals



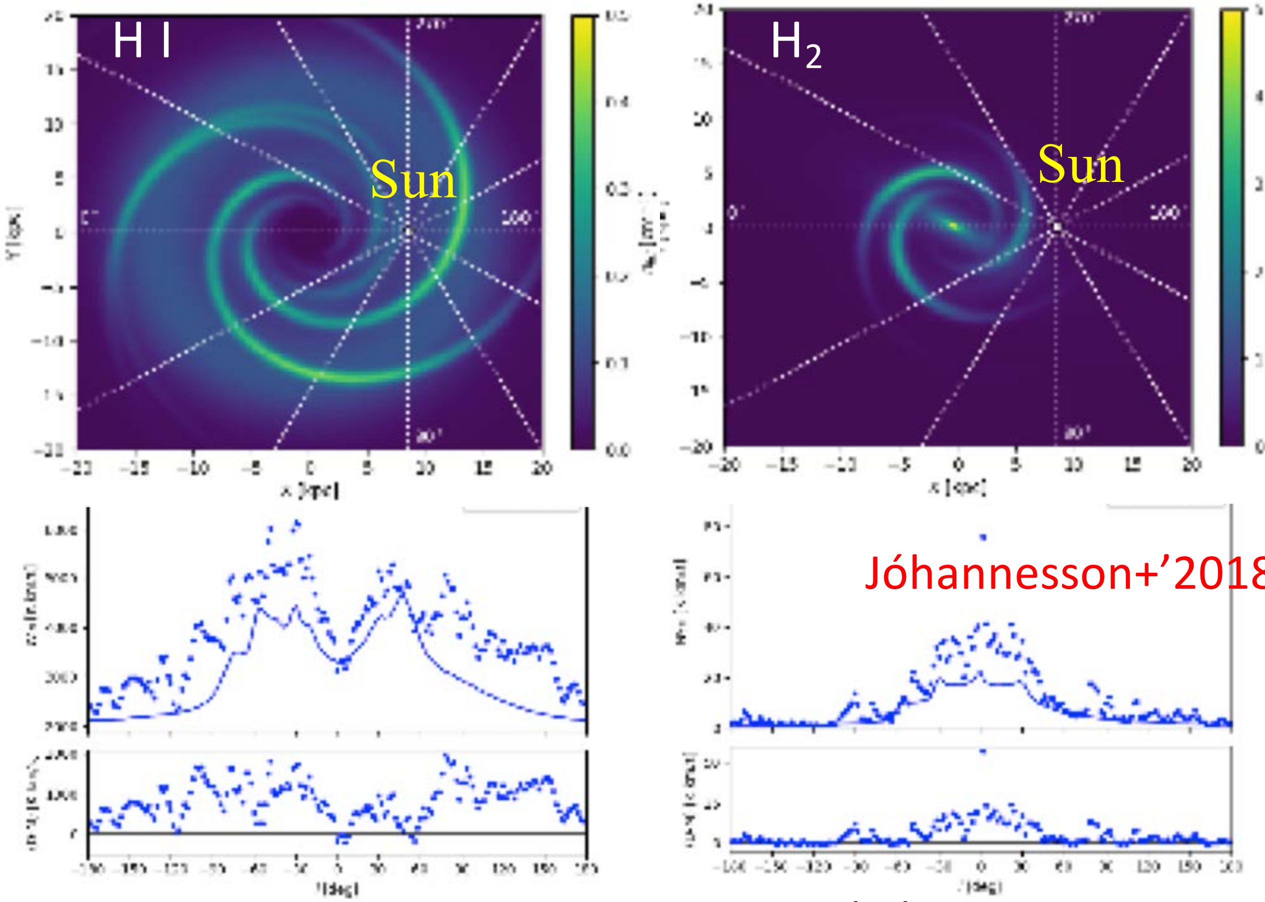
- ✧ Details of the Galactic structure are clearly see in residual maps:
  - ✦ Spiral arms
  - ✦ Fermi Bubbles
  - ✦ Excesses & Deficits
  - ✦ Loops & Spurs





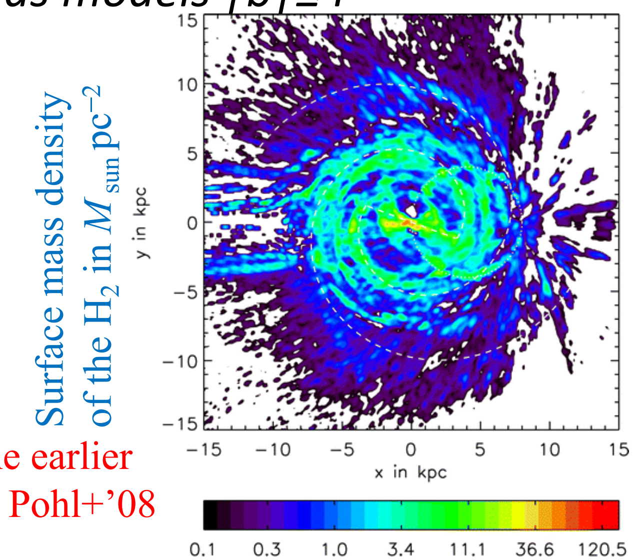
3D gas: H I & H_2

- ✧ 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°

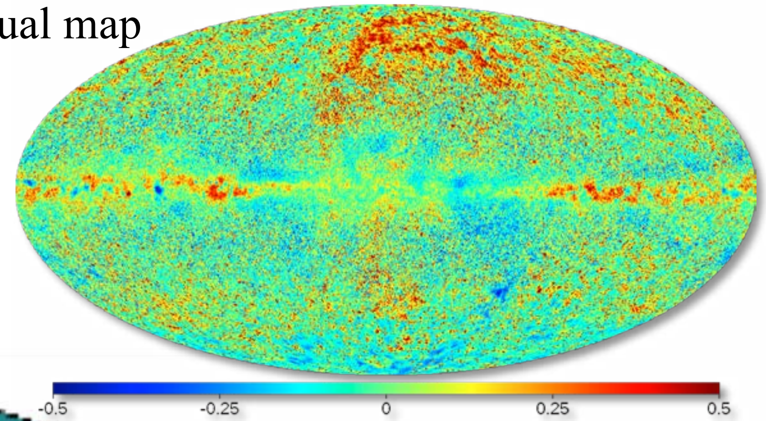
- ✧ The location and shape of the spiral arms are identical between the H I and CO models, but the radial and vertical profiles differ
- ✧ Each spiral arm also has a free normalization

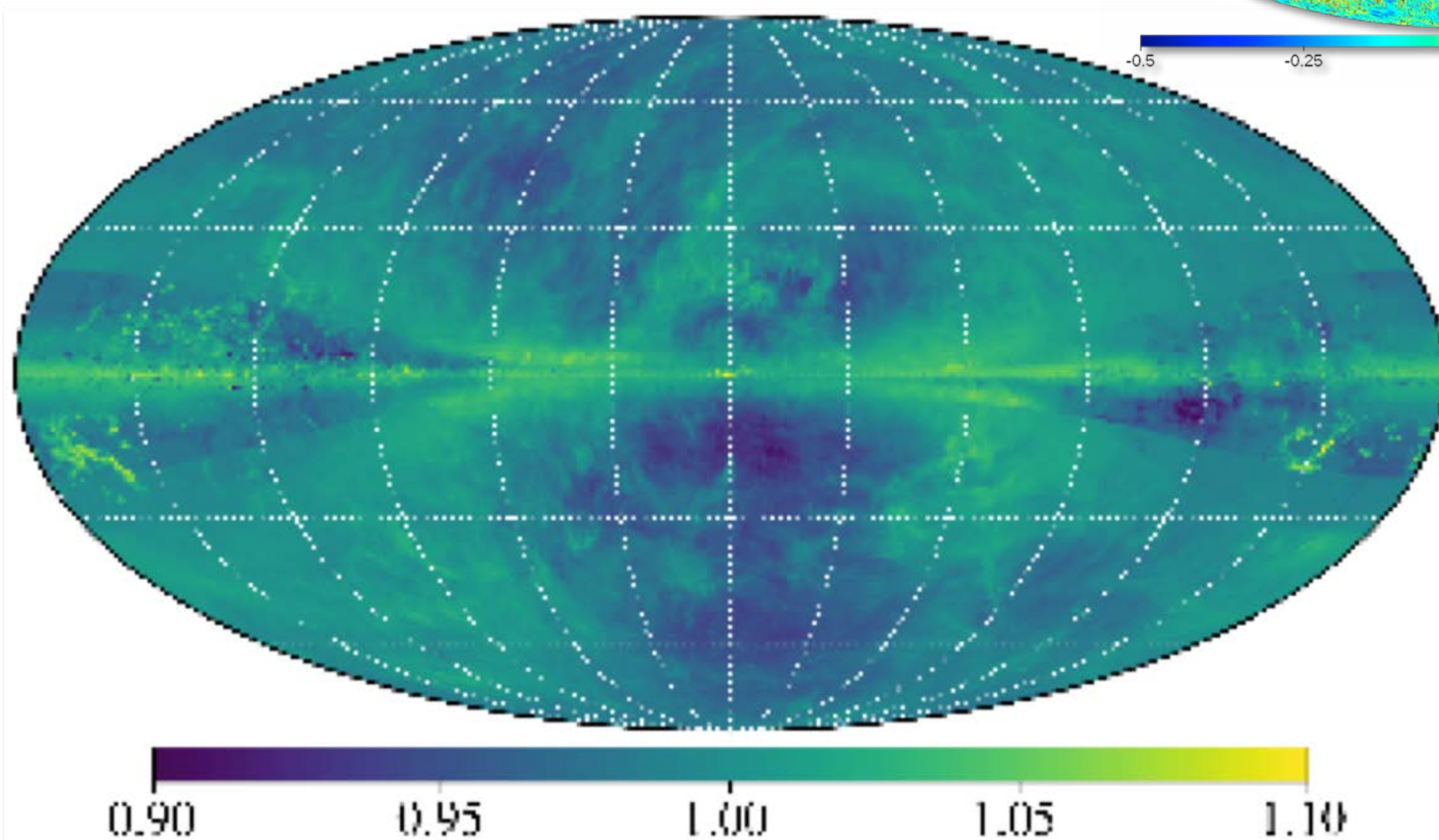


One of the earlier attempts: Pohl+'08

Effect of 3D gas on gamma-ray skymaps

Fermi-LAT residual map

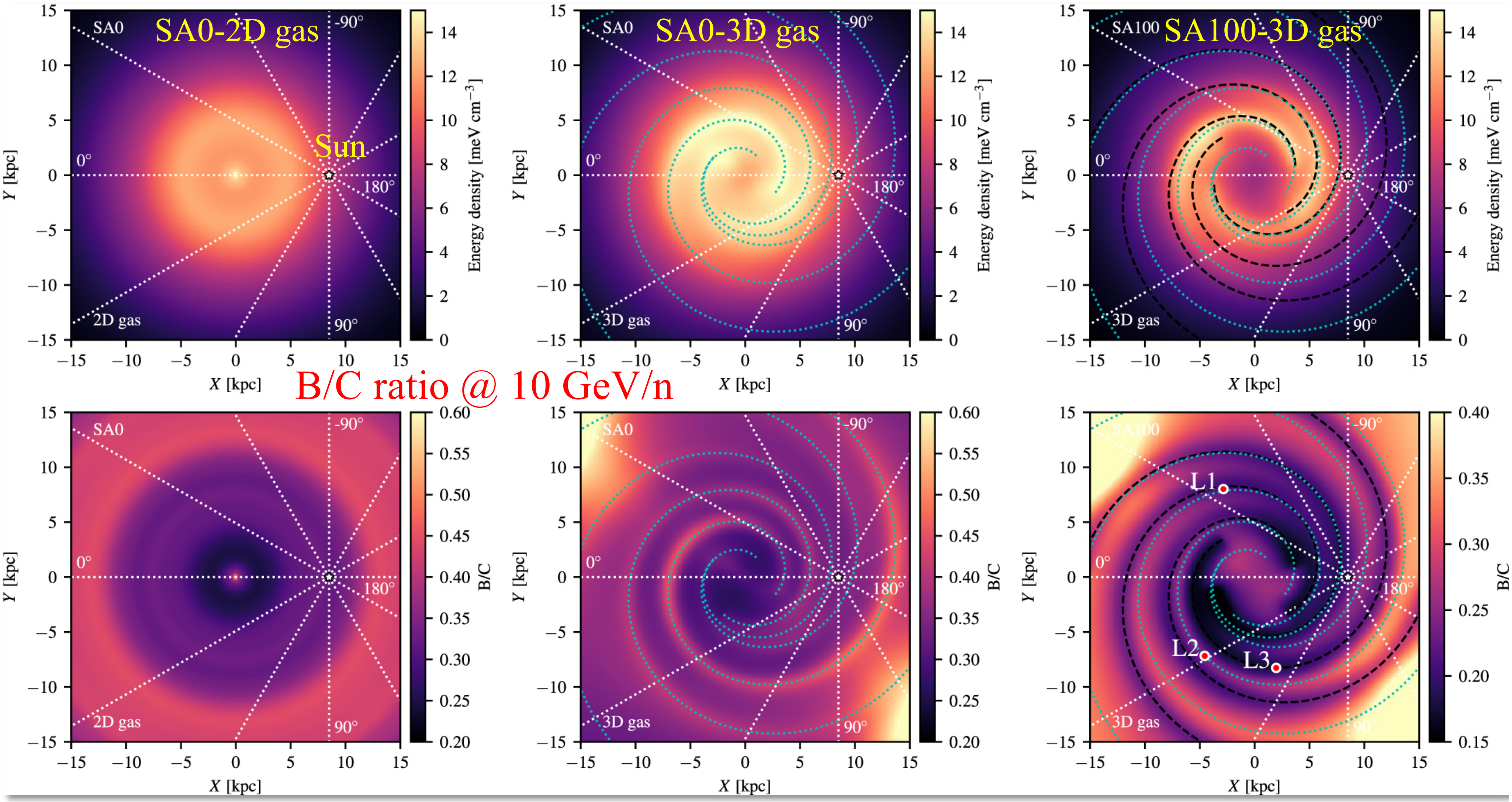




- ✧ Ratio of the total gamma-ray skymaps at 1 GeV for 3D/2D models
- ✧ The 3D/2D ratio demonstrates features similar to the Fermi-LAT residual map

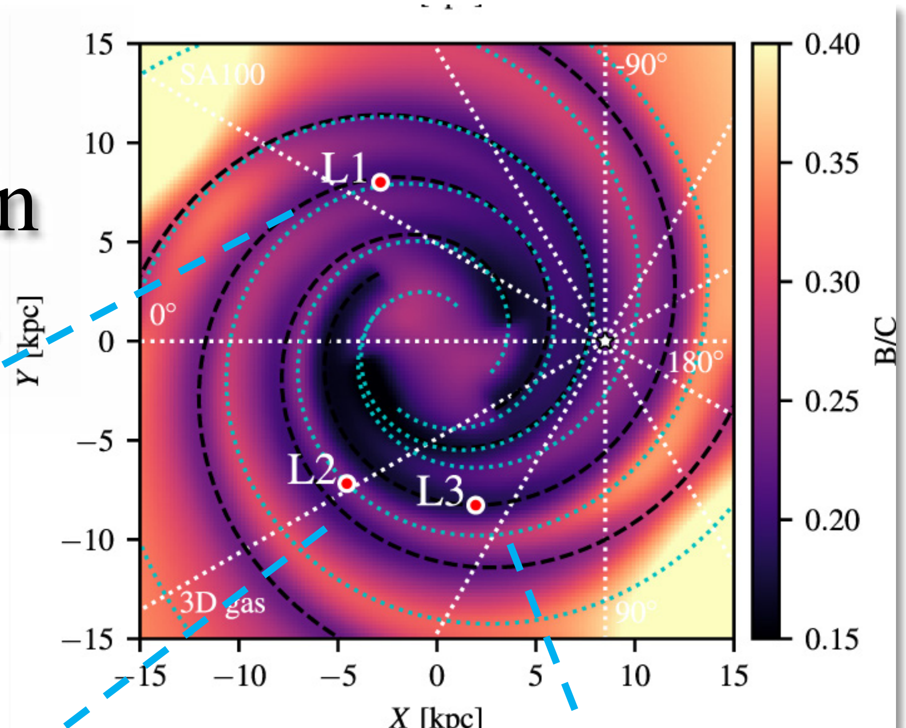
Secondary e$^+$ and B/C ratio in models with CR sources in spiral arms

Energy density of secondary positrons in the mid-plane of the MW

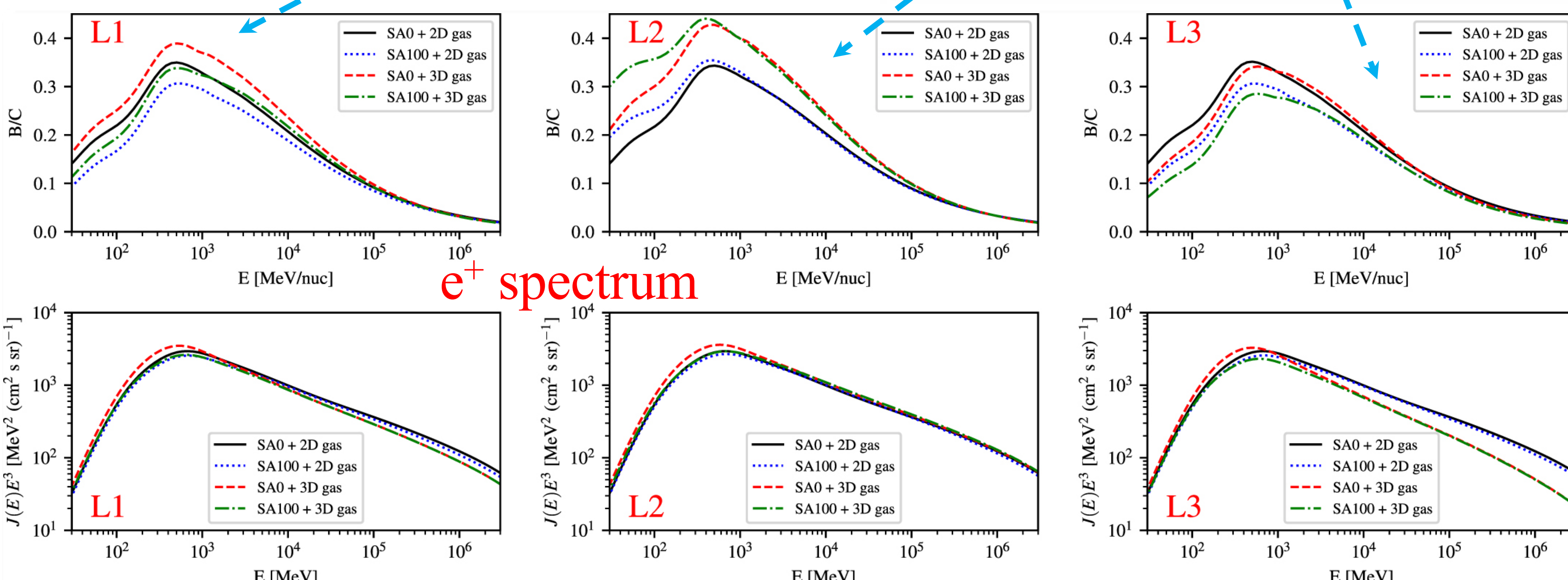


Spatial variations of the B/C ratio and positron spectrum in the Galaxy in 2D/3D models

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



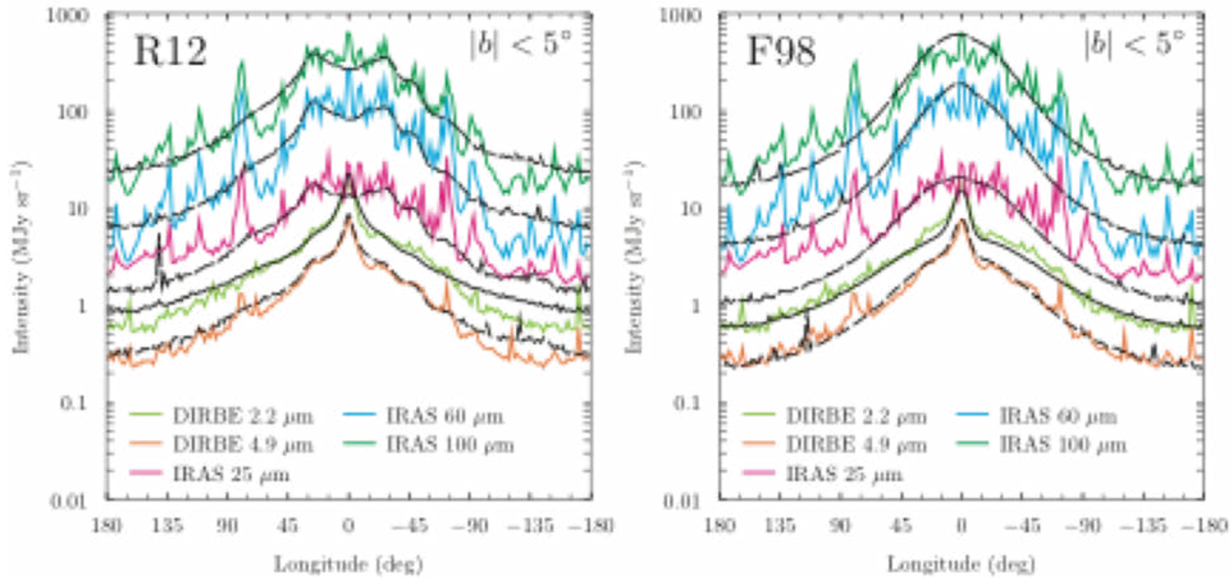
B/C ratio



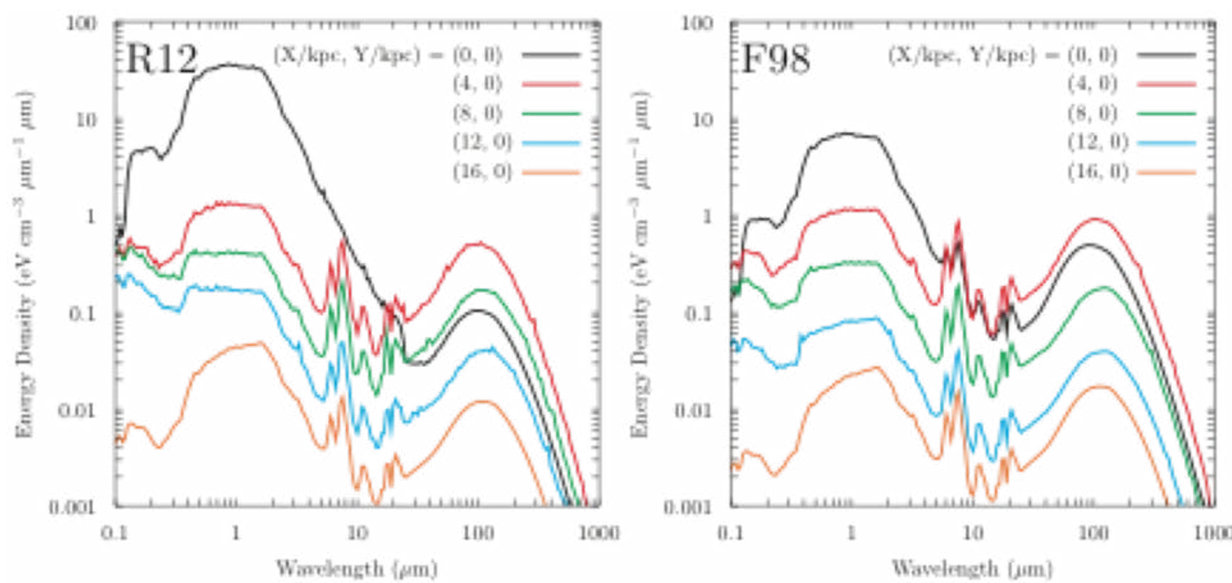
e^+ spectrum

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



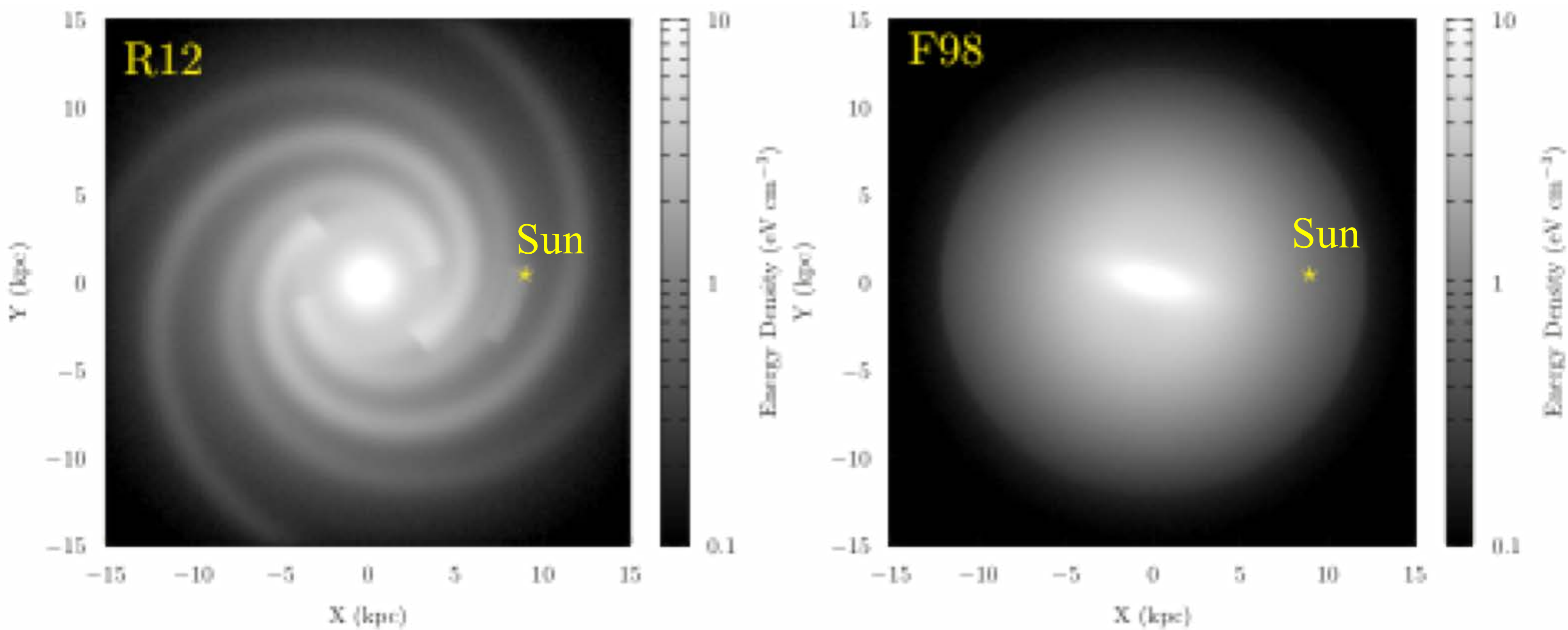
Longitude profile averaged over |b|<5°



Porter+'2017

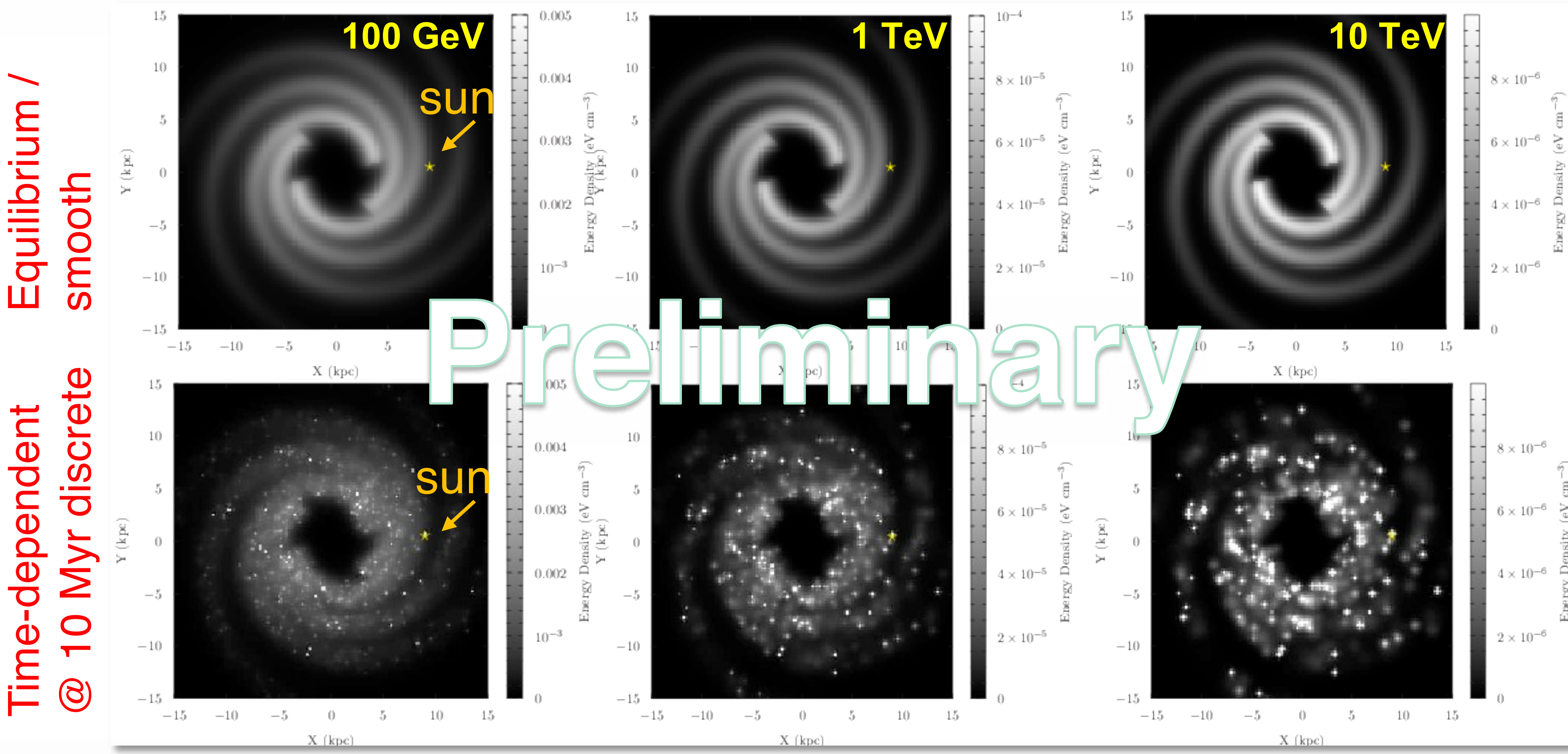
Energy density for distances X=0,4,8,12,16 kpc

Energy density of the interstellar radiation field



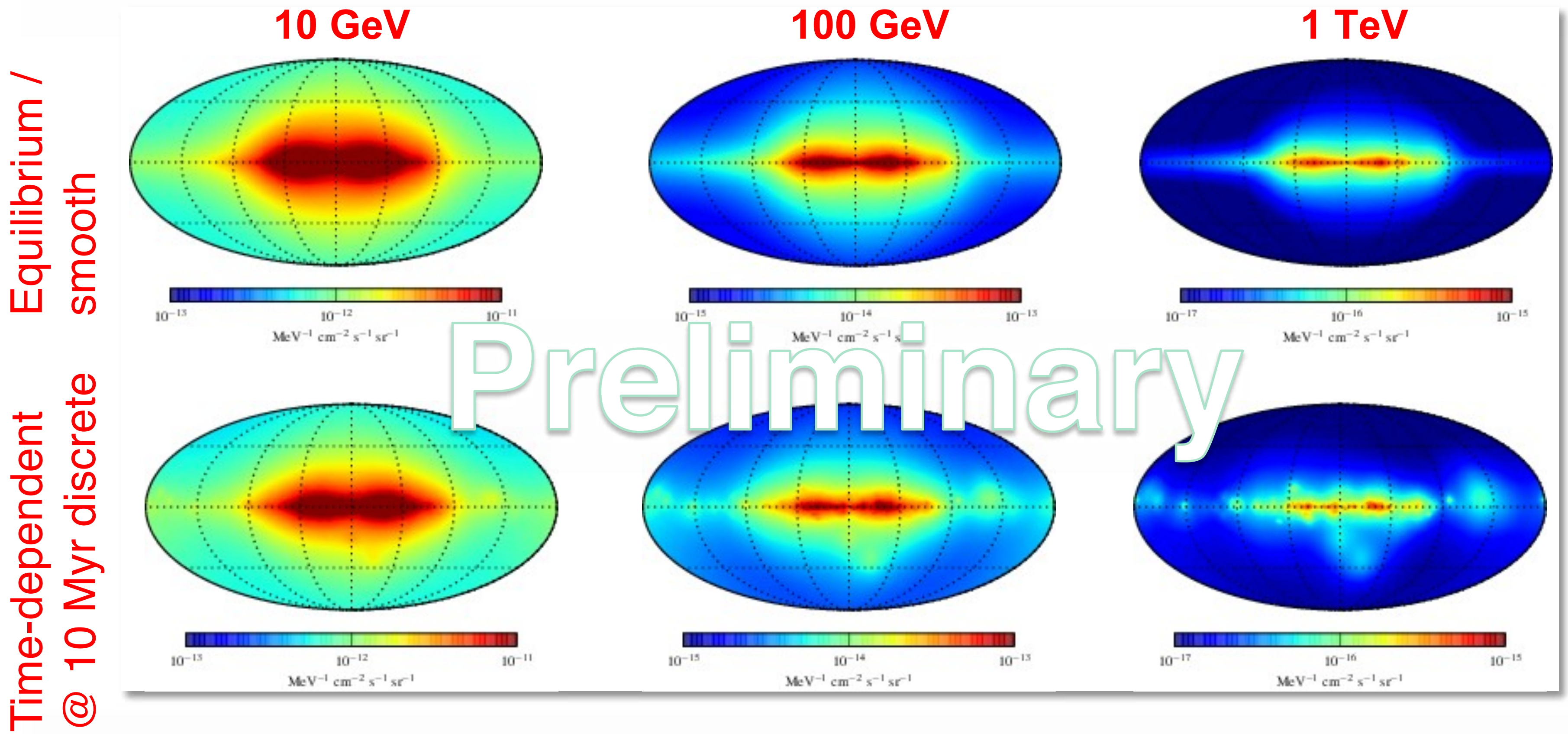
- ✧ Integrated ISRF energy densities in the Galactic plane
- ✧ The ISRF structure will translate into the structure in the inverse Compton
- ✧ A comparison with the Fermi-LAT data is not made yet
- ✧ Affects spectra of electrons/positrons at HE and diffuse emission

Time-dependent energy densities of CR electrons

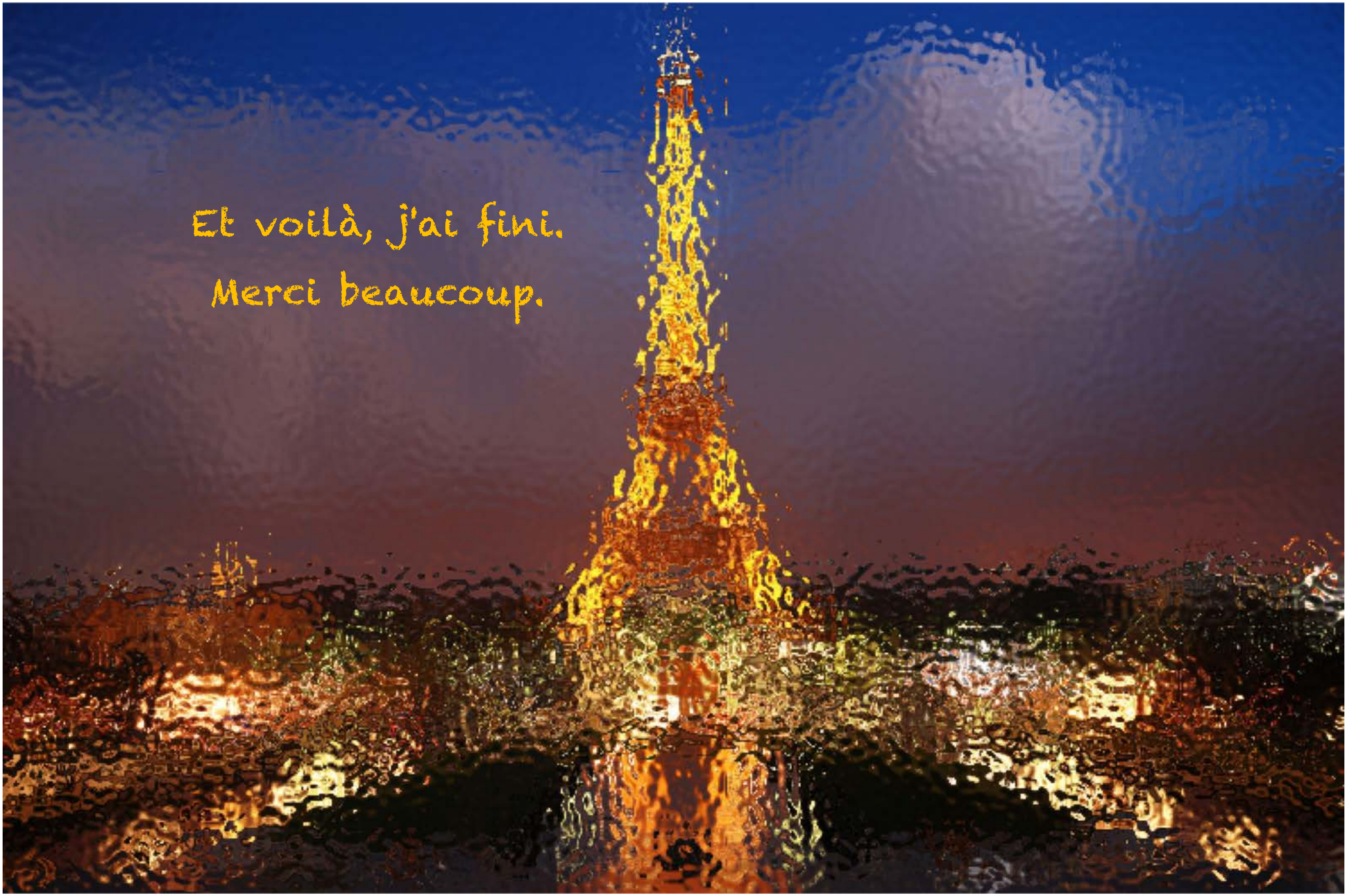


- ✧ SA100 model with propagation parameters determined using smooth source/equilibrium solution and compare with corresponding time-dependent/discrete sampler calculation normalized accordingly (same average injected CR power, normalized to local CR data for t→long times)
- ✧ Showing examples of CR electron energy densities, but protons, nuclei, secondaries also calculated (generally have smoother spatial distribution)

Time-dependent interstellar emission intensities



- ✧ SA100 model with propagation parameters determined using smooth source/equilibrium solution and compare with corresponding time-dependent/discrete sampler calculation normalized accordingly (same average injected CR power, normalized to local CR data for t→long times)
- ✧ Showing examples of inverse Compton emission – propagation + interstellar emission calculation uses the R12 ISRF model (full 3D with arms)


Et voilà, j'ai fini.
Merci beaucoup.