The Milky Way high energy diffusion emissions.

The cosmic ray *"Knee"* and the Galactic / extragalactic transition.

Paolo Lipari
INFN Roma Sapienza

Catania Town Hall KM3NeT Meeting

Catania 22nd September 2022

Outline:

- Introduction to the Diffuse Fluxes
- Space Distribution of CR in the Galaxy
- Cosmic Ray Spectra at the Earth
- Galactic vs extragalactic Cosmic Rays
- The Magellanic Clouds

P. L. and S. Vernetto,
"Diffuse Galactic gamma ray flux
at very high energy",
Phys. Rev. D **98**, no.4, 043003 (2018)
[arXiv:1804.10116 [astro-ph.HE]].

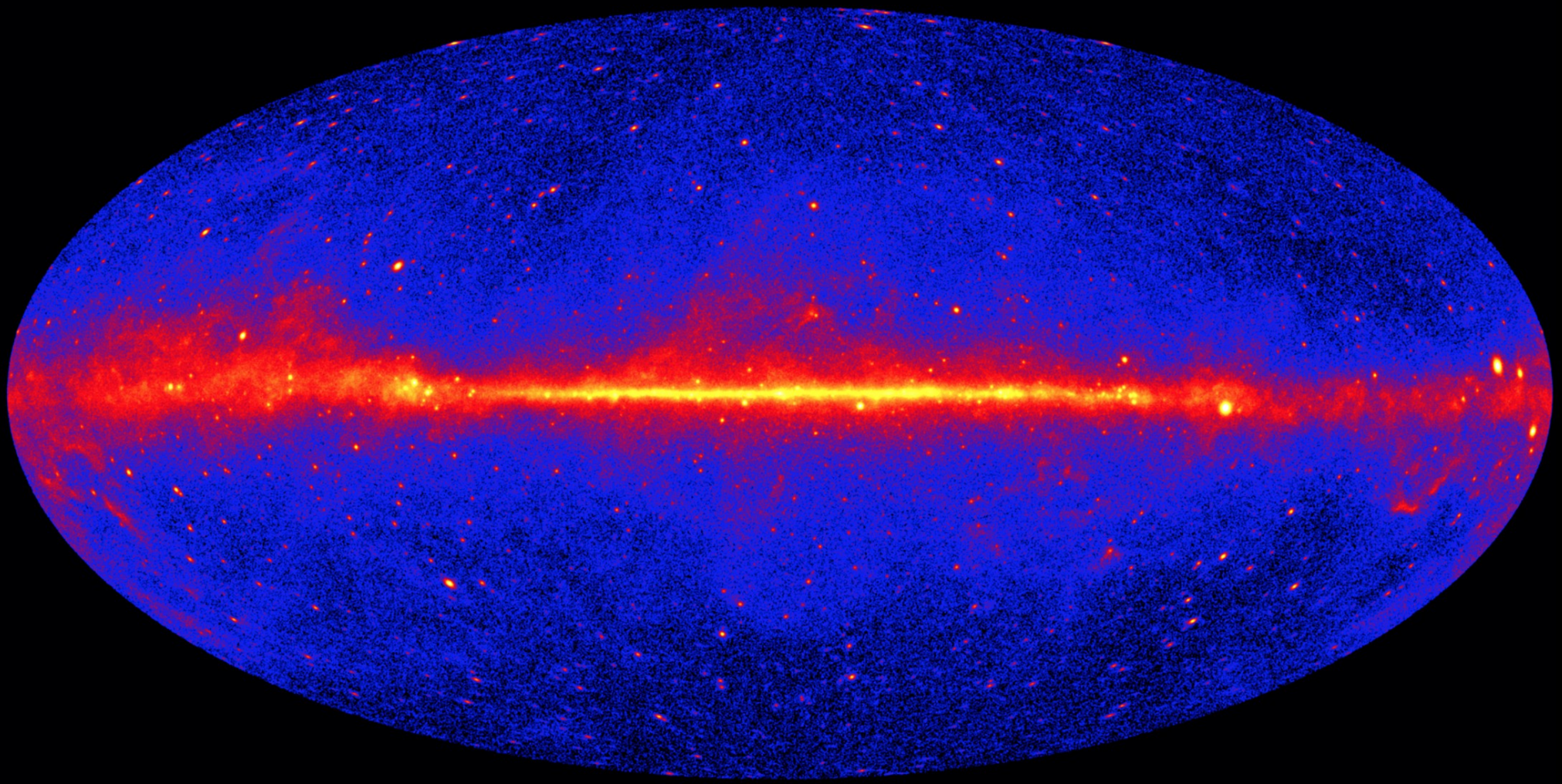
S. Vernetto and P. L.,
"Diffuse Galactic gamma-ray and neutrino fluxes
at very high energy and the Galactic/extragalactic
Cosmic Ray transition",
PoS **ICRC2021**, 923 (2021)

Gamma Ray Sky

FERMI-LAT (E > 100 MeV)

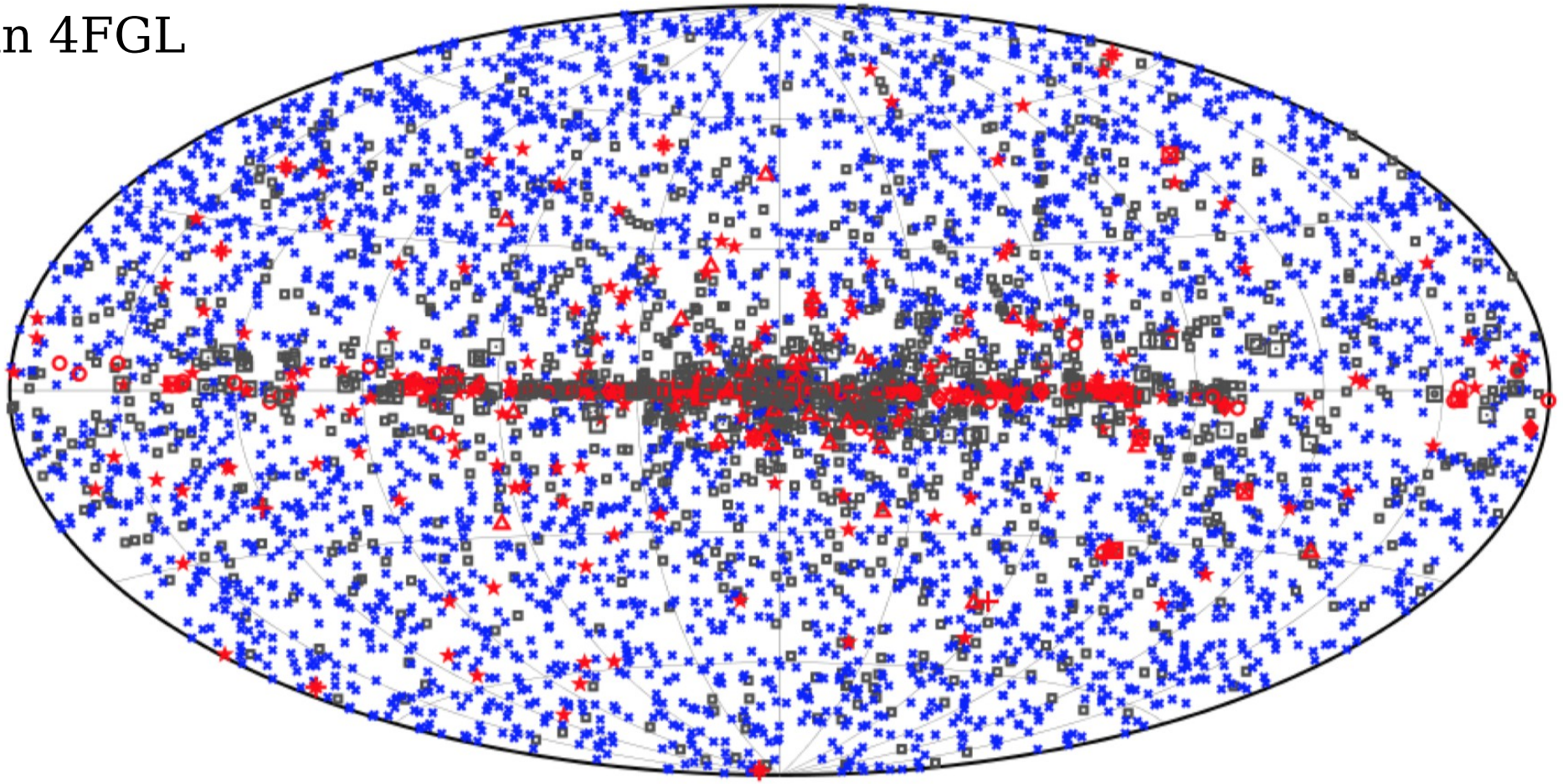
Ensemble of (quasi)-point-like sources [Galactic+extragalactic]

Diffuse Flux [Galactic + extragalactic (isotropic)]



FERMI 4th General Catalog 4FGL-DR3 (6658 sources)

5064 source
in 4FGL



No association
Pulsar
Binary
Star-forming region
Possible association with SNR or PWN
Globular cluster
Galaxy
Unclassified source
Starburst Galaxy
SNR
AGN
PWN
Nova

Note:

Separation between

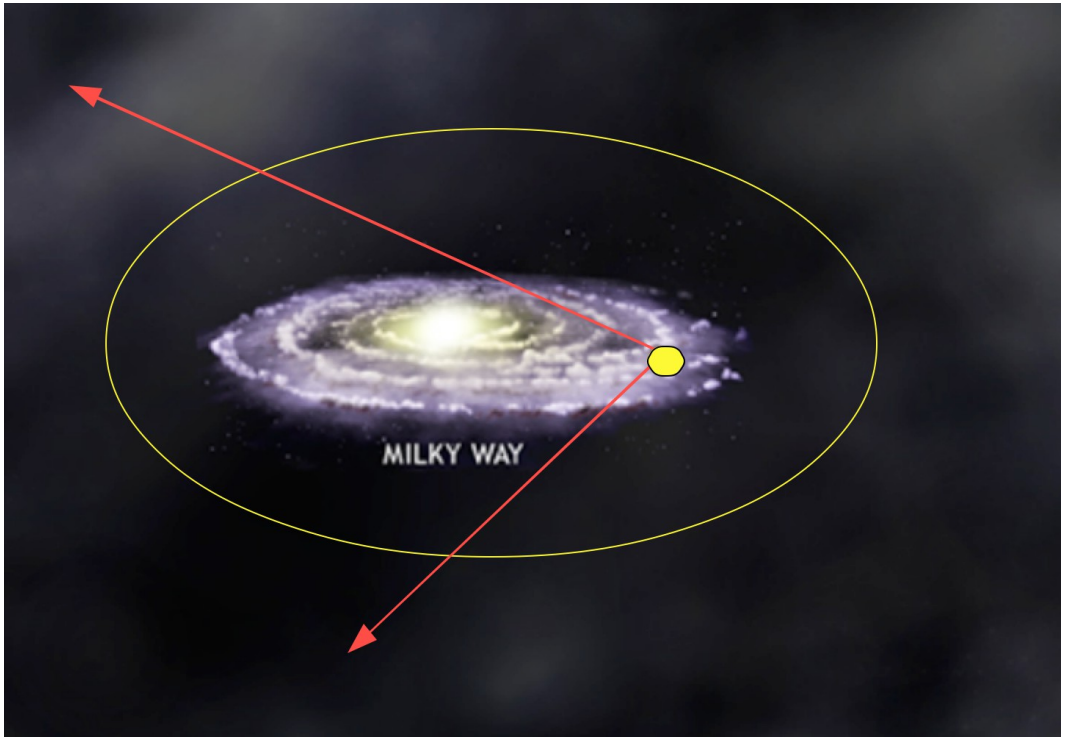
“Diffuse flux” and “Sources”
is a delicate problem

- Unresolved sources
- Extended halos

Diffuse Flux

in the direction Ω
obtained as the integral
of the emission along
the line of sight

[absorption effects
important at high energy
$E \gtrsim 100$ TeV]



Emission generated by Cosmic Rays distributed in Galactic space

absorption

$$\phi_\gamma(E,\Omega) = \frac{1}{4\,\pi} \int_0^\infty d\ell \; q_\gamma[E, \vec{x}_\odot + \ell\,\hat{\Omega}] \; e^{-\tau_\gamma(E,\Omega,\ell)}$$

$$\phi_\nu(E,\Omega) = \frac{1}{4\,\pi} \int_0^\infty d\ell \; q_\nu[E, \vec{x}_\odot + \ell\,\hat{\Omega}]$$

Emission mechanisms:

Interactions of CRs
(relativistic charged particles)
with targets in space

"Hadronic"

$$p + \mathrm{X} \rightarrow \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \rightarrow \gamma \; \gamma$$

$$\pi^+ \rightarrow \mu^+ \; \nu_\mu$$

$$\hookrightarrow \; e^+ \; \nu_e \; \overline{\nu}_\mu$$

Gamma-rays, Neutrinos
(emission of same order)

"Leptonic"

$$e^\pm \; \gamma_{\mathrm{soft}} \rightarrow \; e^\pm \; \gamma$$

$$e^\pm \; Z \rightarrow \; e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \rightarrow e^\pm \; \gamma_{\mathrm{syn}}$$

Only Photons

Dominant for $E \gtrsim 1$ GeV

Calculation of emission:

Leading (proton-proton) term for hadronic mechanism:

$$q_\gamma^{(pp)}(E_\gamma, \vec{x}) = n_p^{\rm ism}(\vec{x}) \times \int_{E_\gamma}^{\infty} dE_p \, [4\,\pi\ \phi_p(E_p, \vec{x})] \, \sigma_{pp}(E_p) \frac{dN_{pp\to\gamma}}{dE_\gamma}(E_\gamma, E_p)$$

Gas density in the Milky Way

Hadronic Interactions

Spectra of cosmic rays in the entire Galactic Volume

Study distribution of Cosmic Rays in the Galaxy

Sources of uncertainties in the calculation of the diffuse fluxes:

1. Modeling of hadronic interactions
   (good control, effects are only minor)

2. Description of matter (for hadronic mechanism)
   (+radiation and magnetic field for leptonic mech.)
   in the Milky Way.

3. Description of the Cosmic Ray spectra

   - Spectra at the Earth
   - Space dependence of the spectra

Observable fluxes: Source Spectra + Propagation

$$\phi_j(E, \vec{x}, t) \qquad q_j(E, \vec{x}, t)$$

Flux of particles of type j

Source spectrum of particles of type j

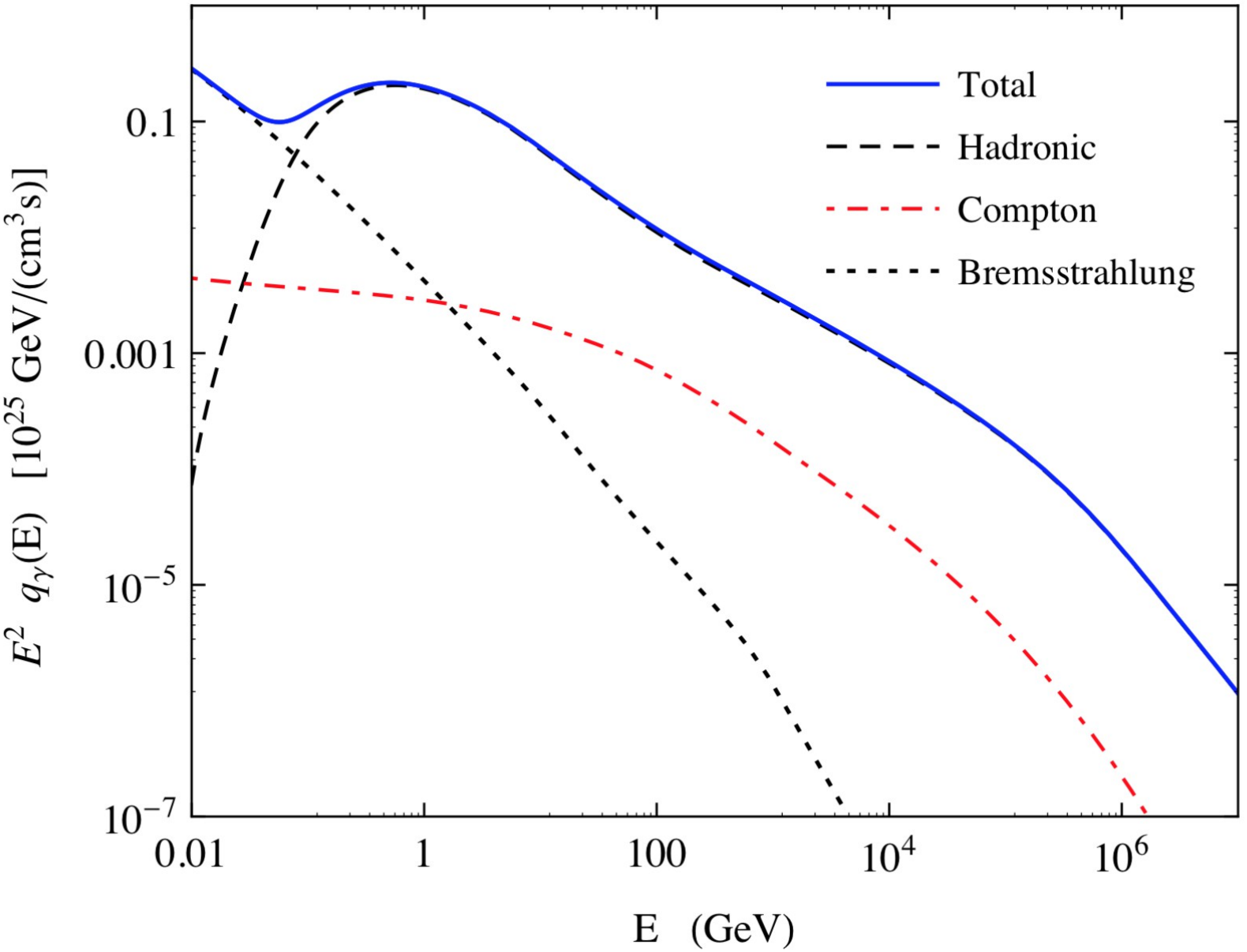
$$j \in \{p\ ,\ e^-\ ,\ e^+\ ,\ \overline{p}\ ,\ {}^3\mathrm{He}\ ,\ {}^4\mathrm{He}\ ,\ {}^6\mathrm{Li}\ ,\ \ldots\}$$

$$\phi_j = q_j \otimes \mathcal{P}_j$$

$$[\mathrm{Flux}]_\mathrm{j} = [\mathrm{Source\ spectrum}]_\mathrm{j} \otimes [\mathrm{Propagation}]_\mathrm{j}$$

Gamma-ray "Local emission"
(in the vicinity of the Solar system)

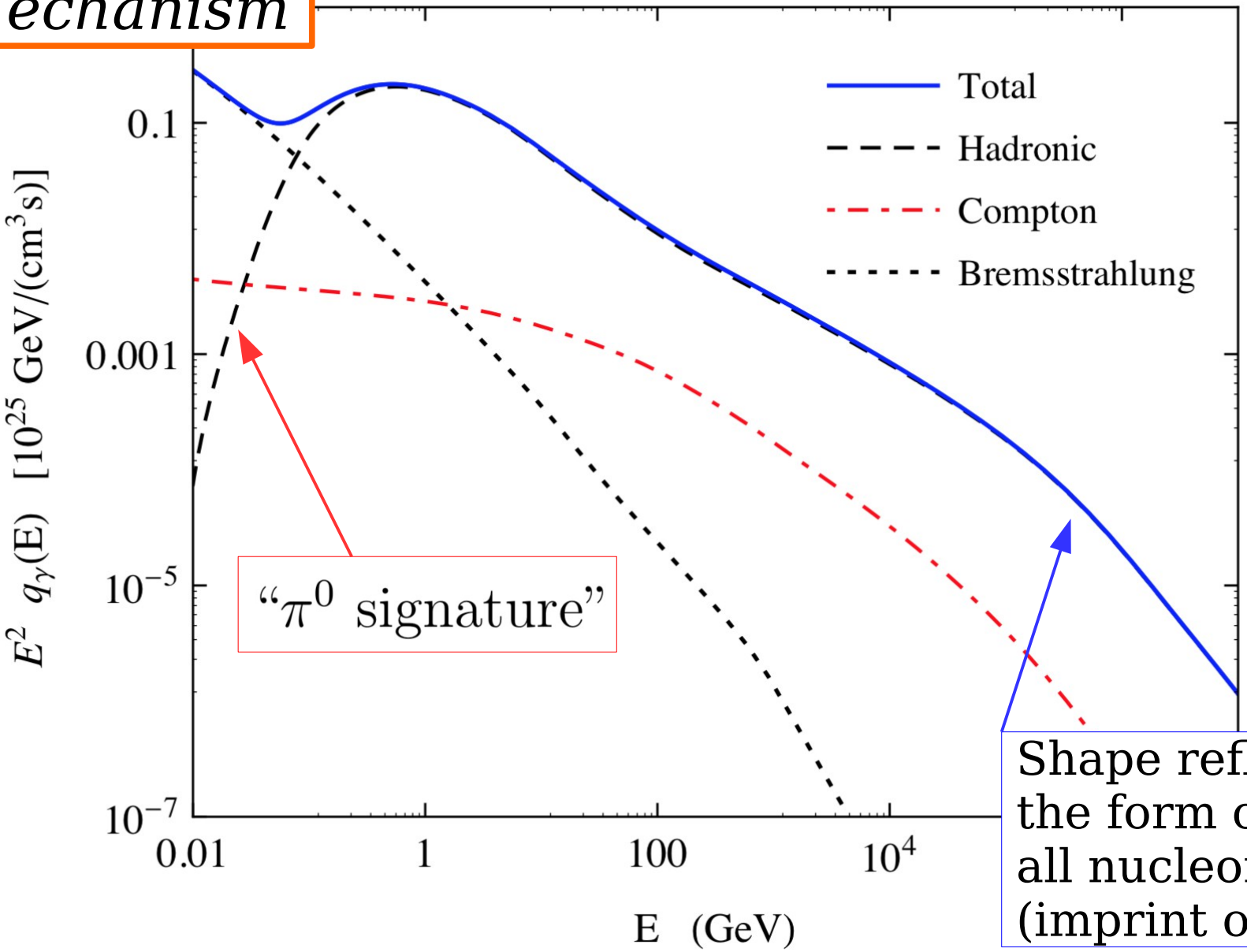
$$n_{p,\mathrm{ism}} = 1\ \mathrm{cm}^{-3}$$



Gamma-ray "Local emission"
(in the vicinity of the Solar system)

$$n_{p,\mathrm{ism}} = 1\ \mathrm{cm}^{-3}$$

Hadronic Mechanism

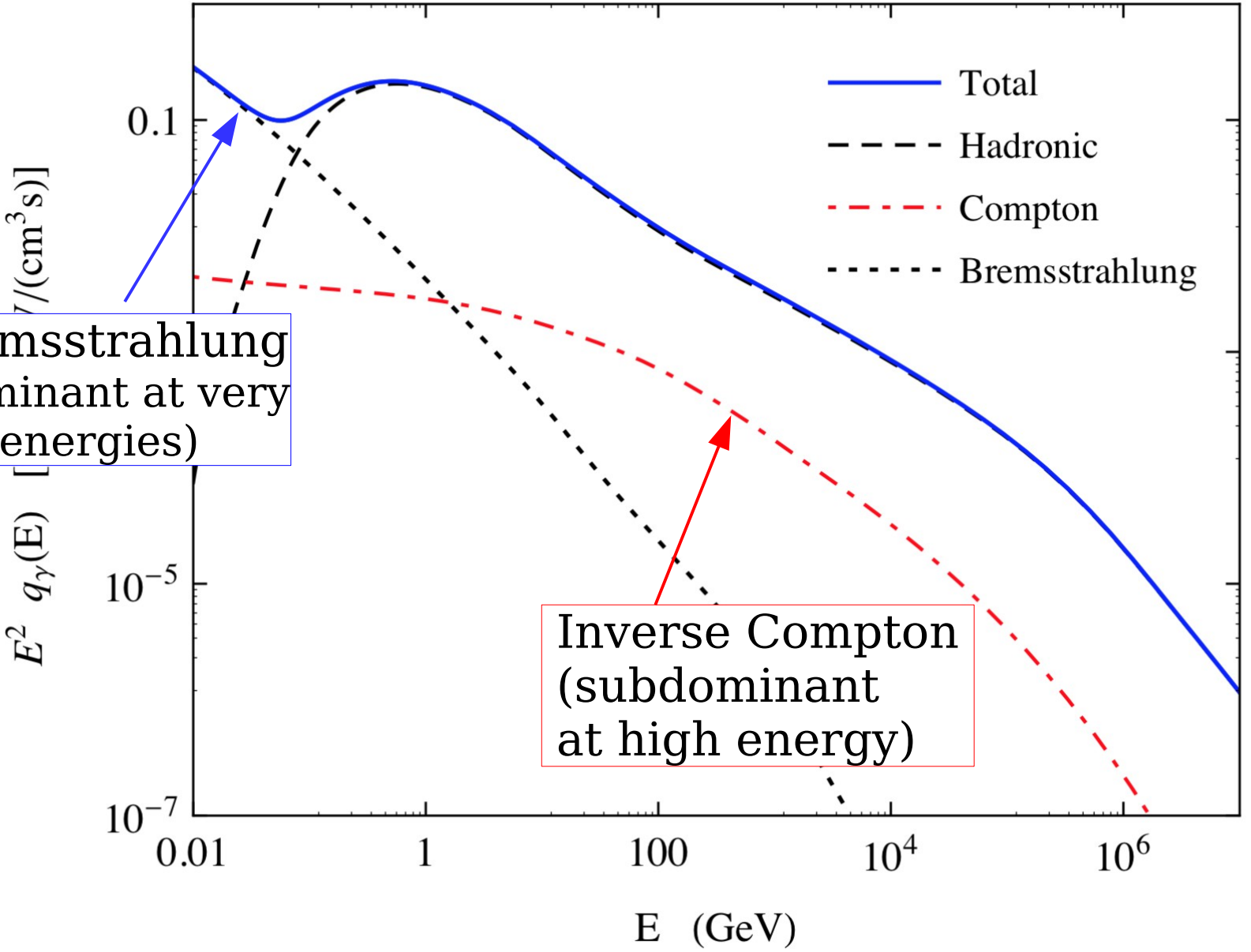


Shape reflects
the form of the
all nucleon spectrum
(imprint of the Knee)

Leptonic Mechanism Contributions

ocal emission"
of the Solar system)

$$n_{p,\mathrm{ism}} = 1\ \mathrm{cm}^{-3}$$



Bremsstrahlung (dominant at very low energies)

Inverse Compton (subdominant at high energy)

Comment: the study of:

The contributions of the
leptonic mechanism to the diffuse gamma-ray flux

The distribution of (radio waves)
synchrotron radiation
(generated by e-/e+ interactions
with magnetic fields)

$$\varepsilon_{\rm syn} = \frac{3}{2}\,\frac{q_e\,B}{m_e\,c^2}\,\gamma_e^2$$

$$\simeq 6.65\times 10^{-8}\;B_{\mu G}\;E^2_{\rm GeV}\quad {\rm eV}$$

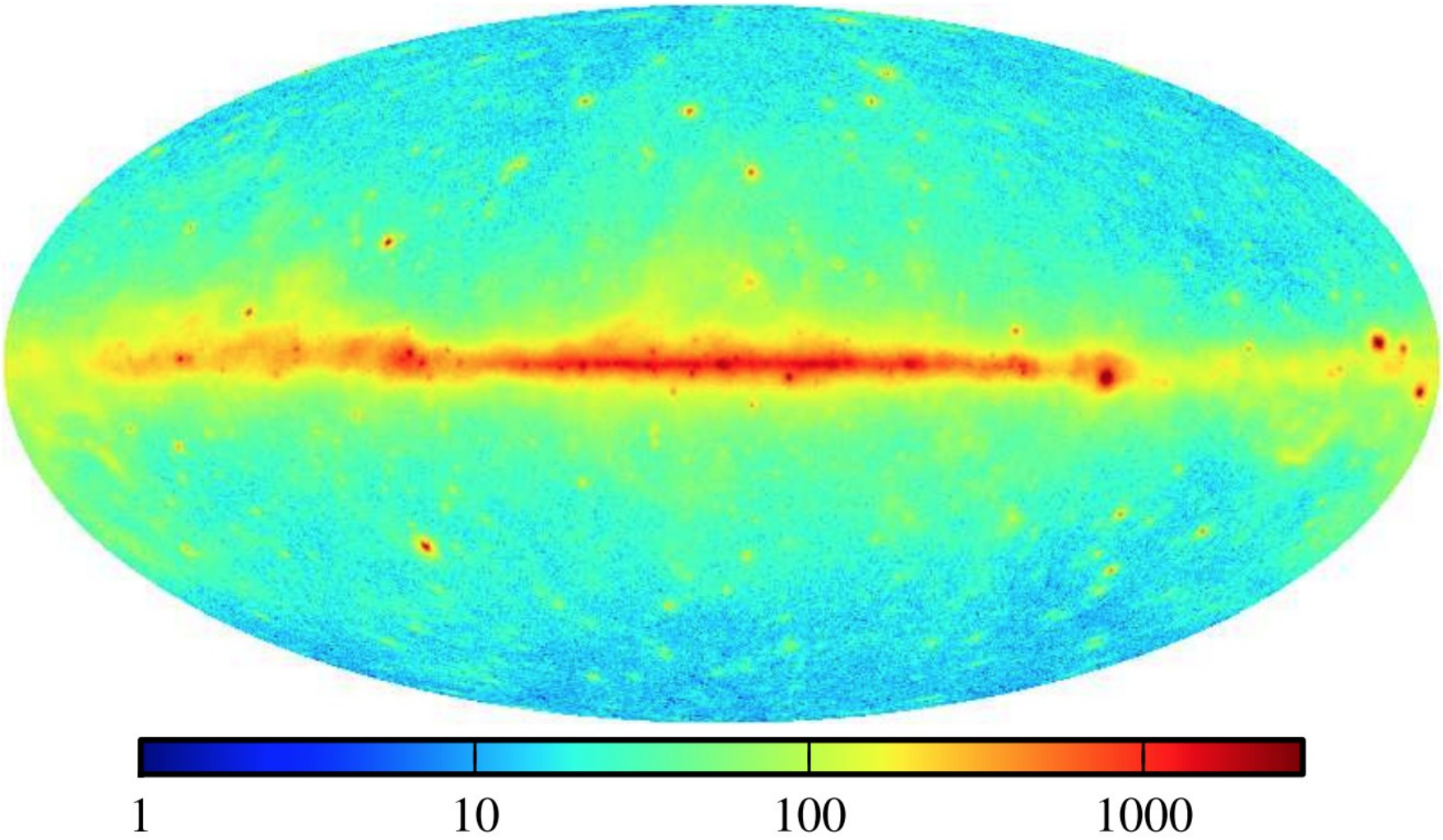
Are *very important* to determine the
space/energy dependence of the electron/positron
spectra and their propagation properties

[a*nd determine if and how electron propagation
differ from the propagation properties
of protons and nuclei.]*

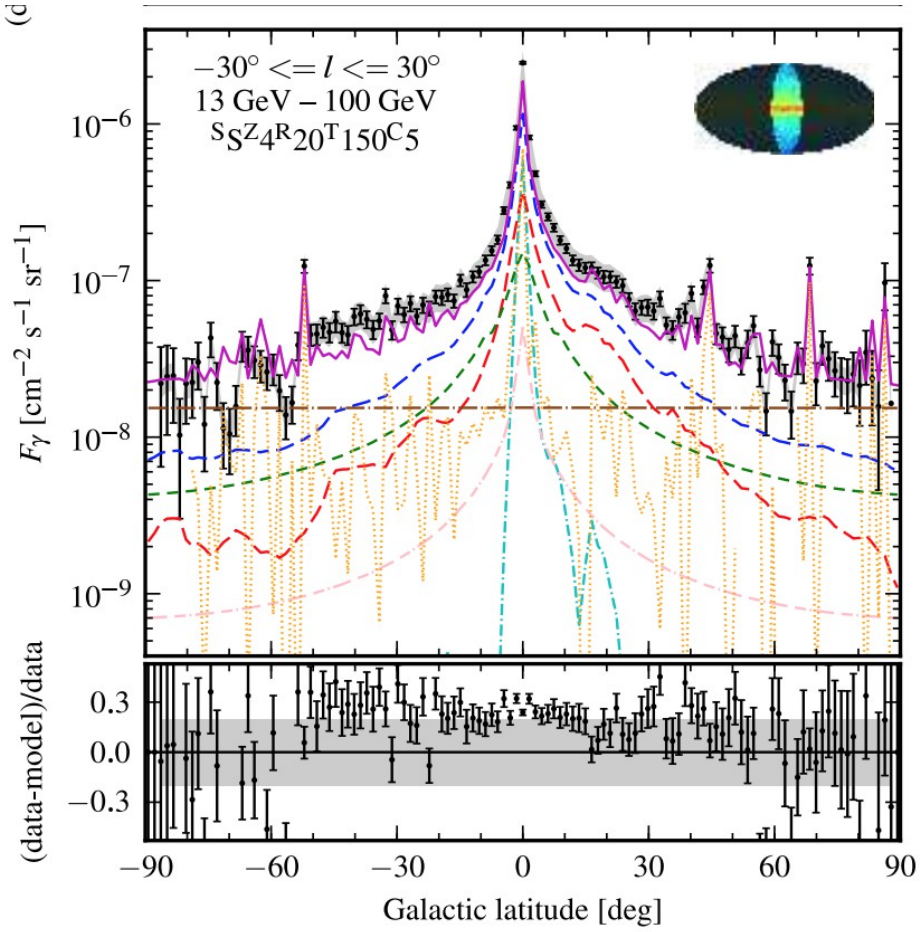
Topic not discussed here

Counts in
energy range 0.2 – 100 GeV

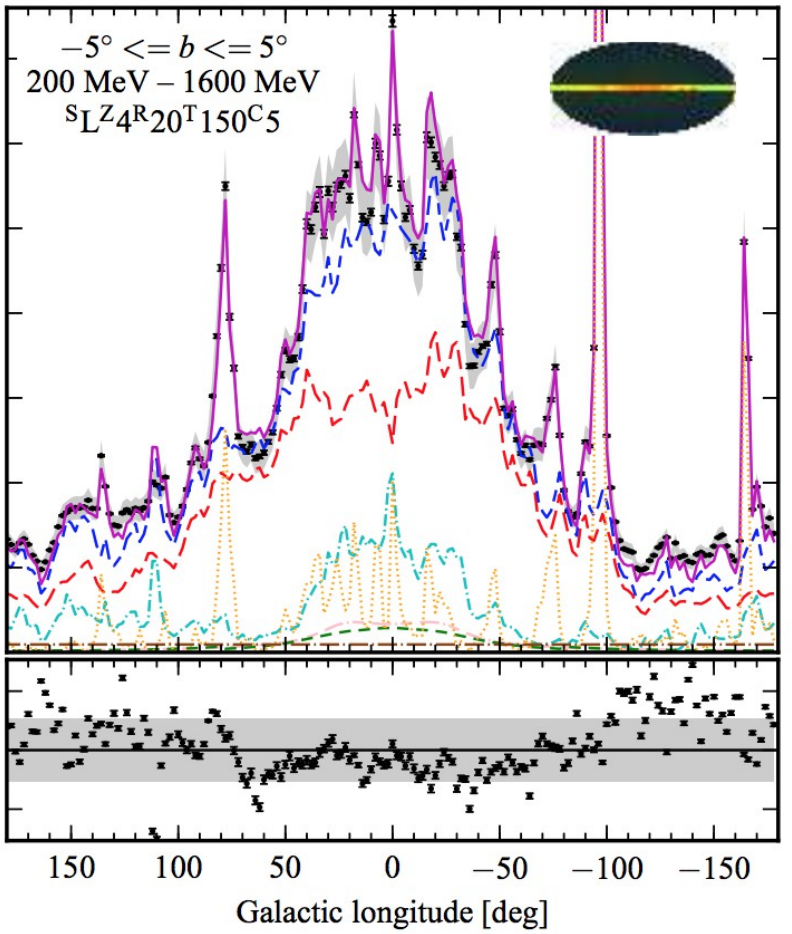
Gamma-ray all-sky map
obtained by FERMI-LAT



"Fermi-LAT Observations of the Diffuse Gamma-Ray Emission:
Implications for Cosmic Rays and the Interstellar Medium"
Astrophys. J. **750**, 3 (2012)
[arXiv:1202.4039 [astro-ph.HE]].



Galactic Latitude

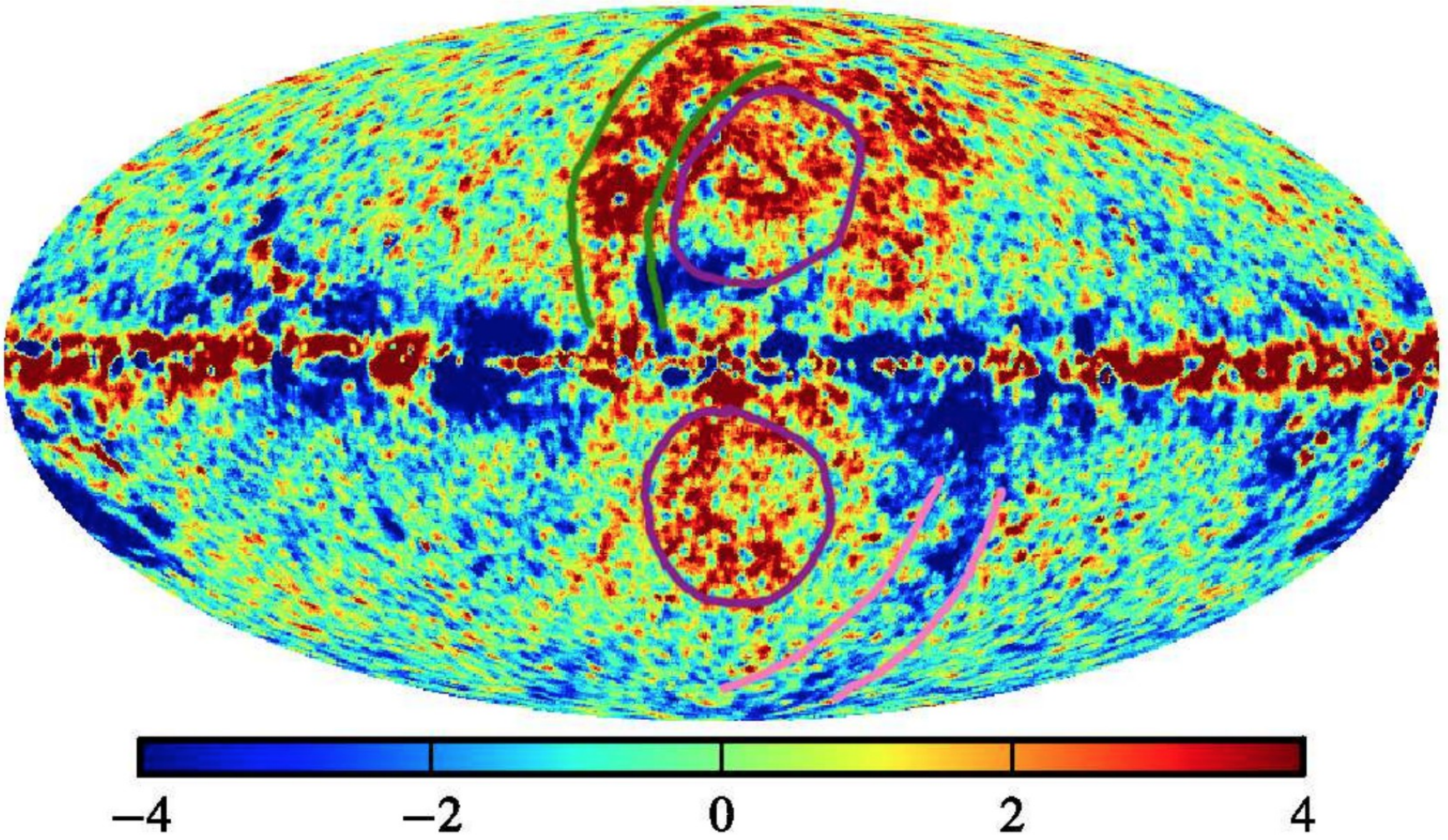


Galactic Longitude

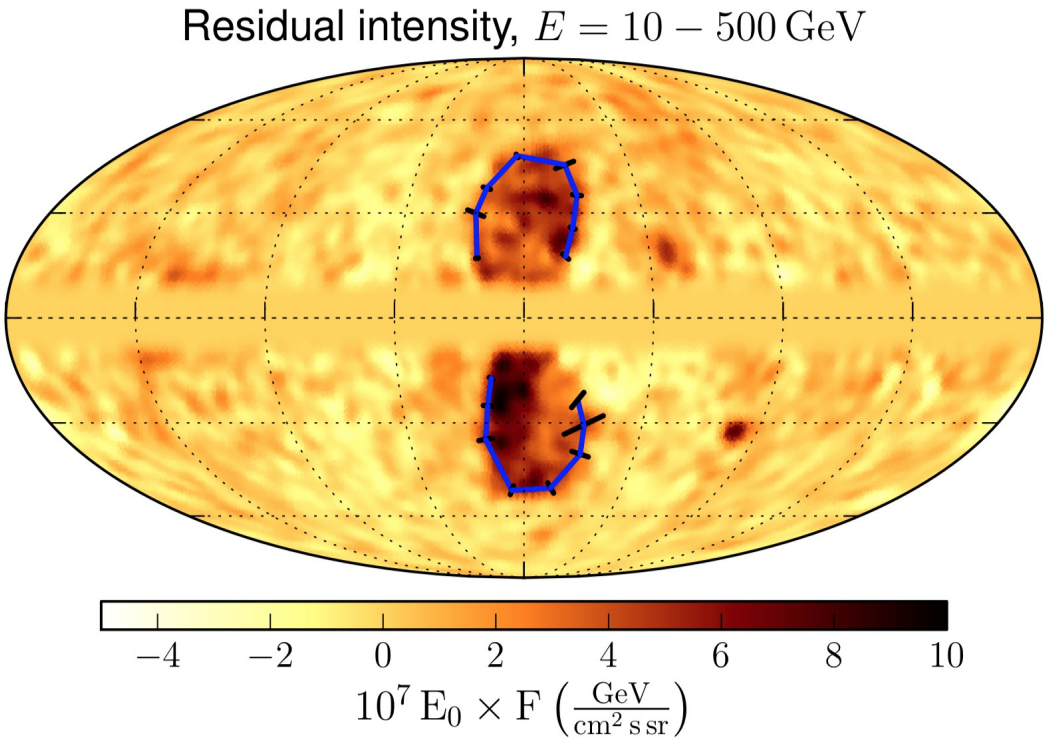
Results *approximately* consistent with "standard models where the spectra of protons and nuclei have the same shape in all points in the Galaxy

Intriguing and potentially very important “anomaly”

the *“Fermi bubbles”*



Residual Map (0.2-200 GeV) in units of Standard Deviations



Discovery of the

"FERMI bubbles"

Fascinating
(and poorly understood)

Large outflow from GC ?

....

"Artist view"

Factorization of the CR spectral *shapes*

$$\phi_p(E,\vec{x}) = \phi_p^{\rm loc}(E) \times f_{\rm space}(\vec{x})$$

Property of the CR spectra
in a broad range of models
[including the commonly accepted ones]

1. Space independent injection
2. Stationary spectra
3. Diffusion dominated propagation

Factorization (of energy and space dependences)
of the CR spectra

$$\phi_p(E,\vec{x}) = \phi_p^{\rm loc}(E) \times f_{\rm space}(\vec{x})$$

Factorization of (energy and space)
for the gamma ray and neutrino source

$$q_{\nu,\gamma}(E,\vec{x}) = q_{\nu,\gamma}^{\rm loc}(E) \times f_{\rm space}(\vec{x}) \times \left(\frac{n_{\rm ism}(\vec{x})}{n_{\rm ism}(\vec{x}_\odot)} \right)$$

Factorization of (energy and angle)
of the gamma ray [no-absorption]
and neutrino diffuse fluxes

$$\phi_{\nu,\gamma}(E,\Omega) = \frac{q_{\nu,\gamma}^{\rm loc}(E)}{4\,\pi}\, T(\Omega)$$

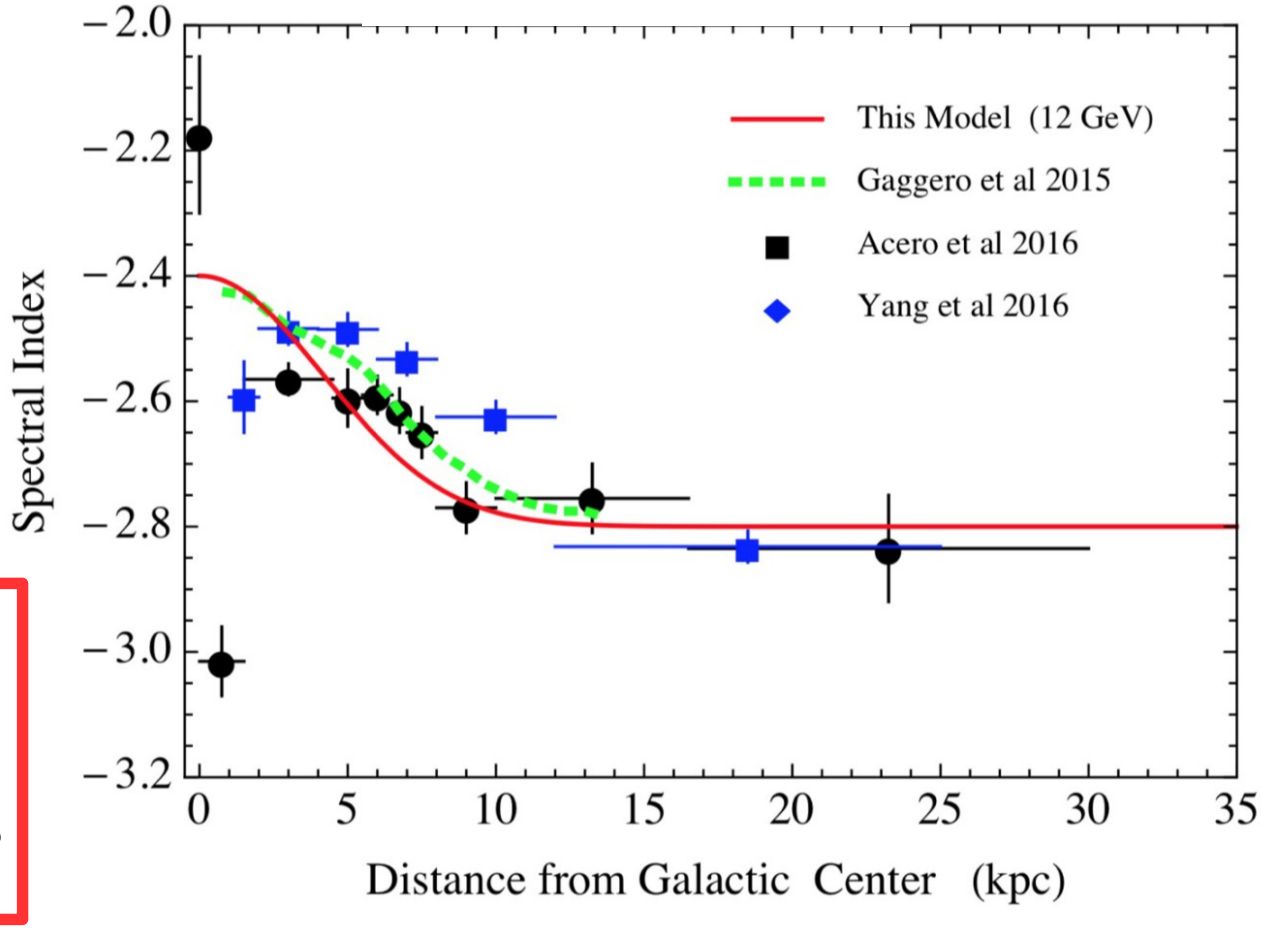
$$T(\Omega) = \frac{1}{n_{\rm ism}(\vec{x_\odot})} \int_0^\infty dt\; f_{\rm space}(\vec{x}_\odot + t\;\hat{\Omega}) \times n_{\rm ism}(\vec{x}_\odot + t\;\hat{\Omega})$$

Some indications that CR spectra in the central region of the Galaxy are harder than what is observed at the Sun (Earth).

Why ? [open problem with important implications]

$$\phi_{\text{nucleons}}(E) \propto E^{-\alpha} \qquad \alpha = \alpha(r)$$

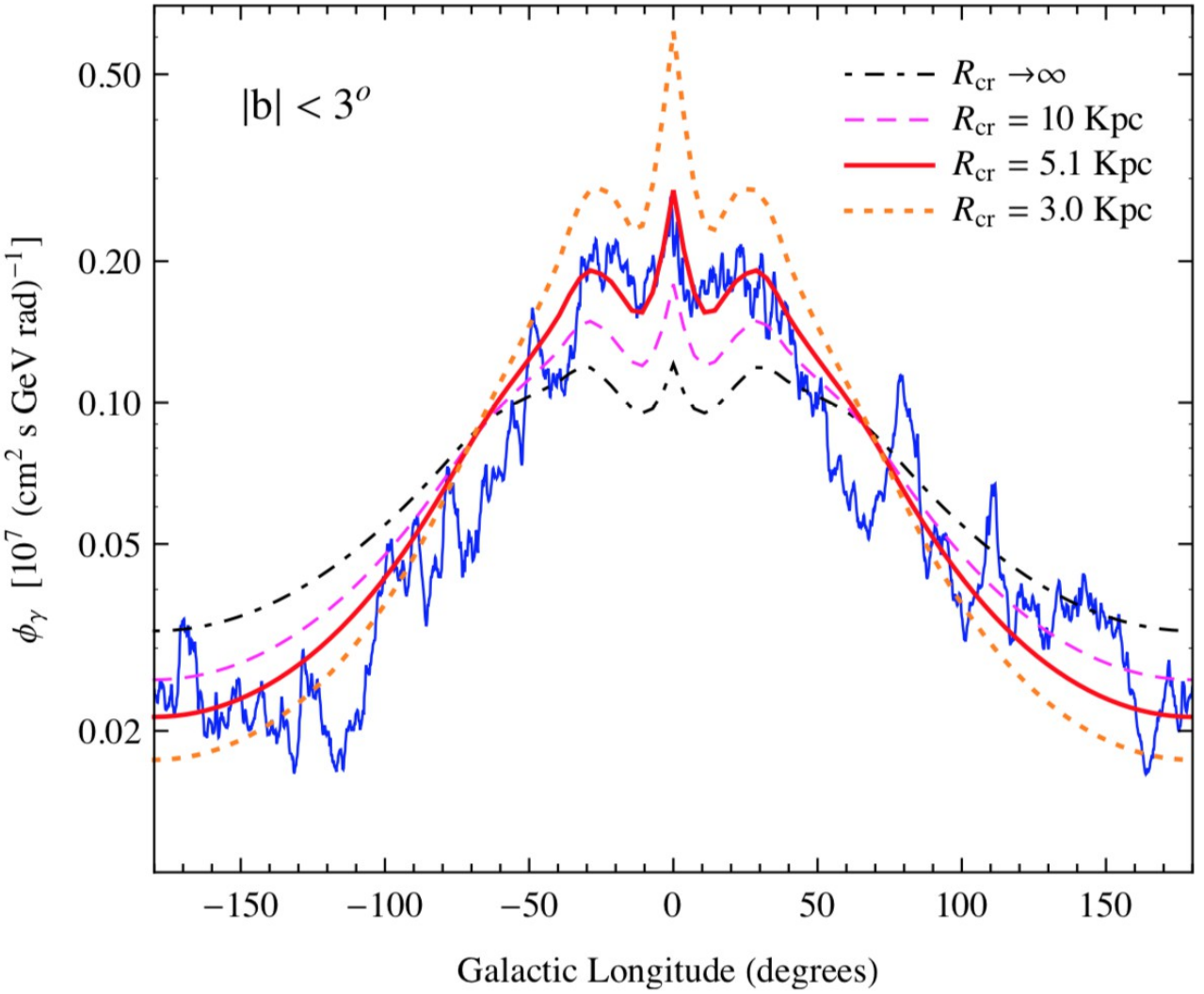
controversial result.



Study the diffuse flux in the PeV energy range

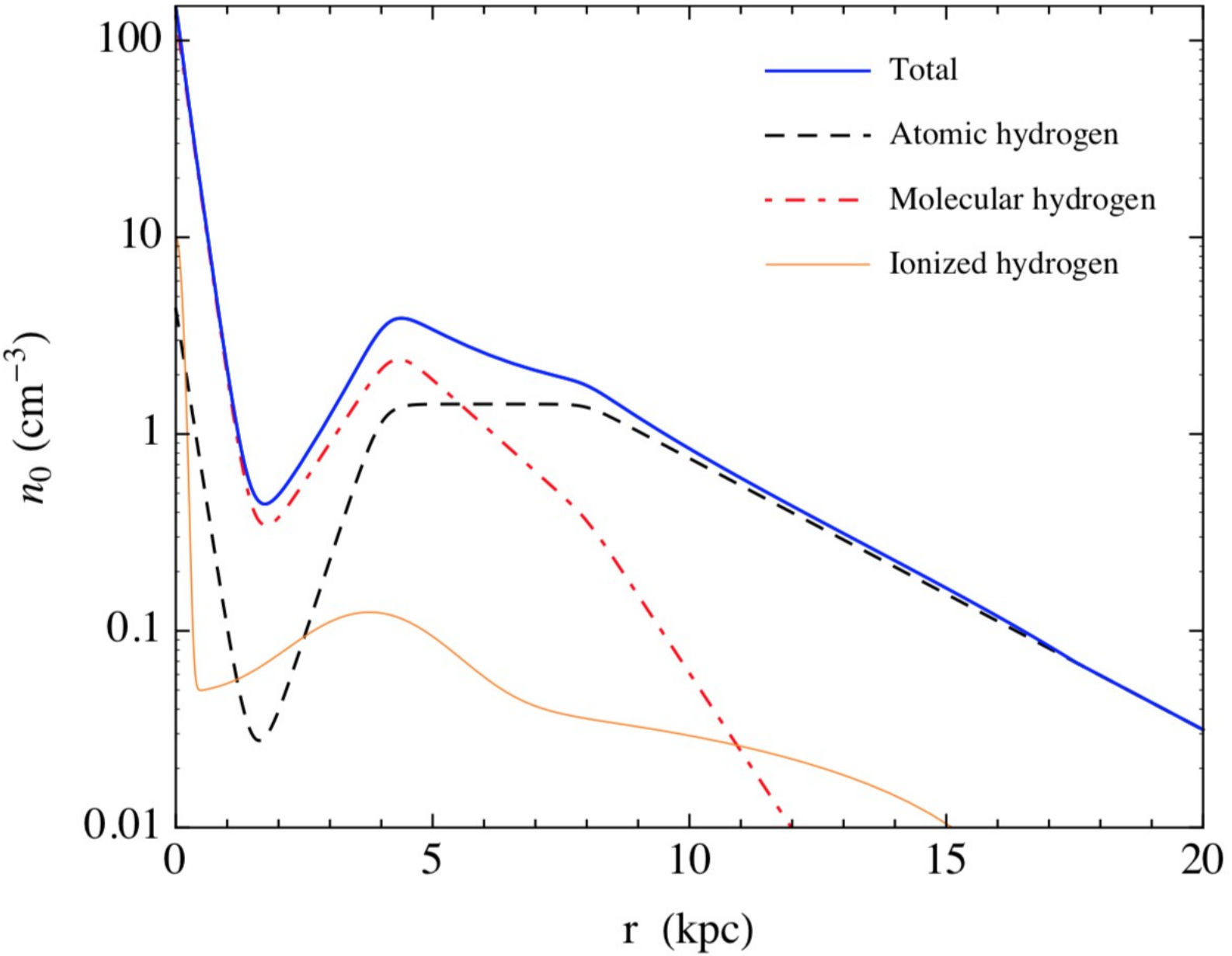
Sufficient for a first order description of the diffuse flux. Imply that the density falls exponentially with radius

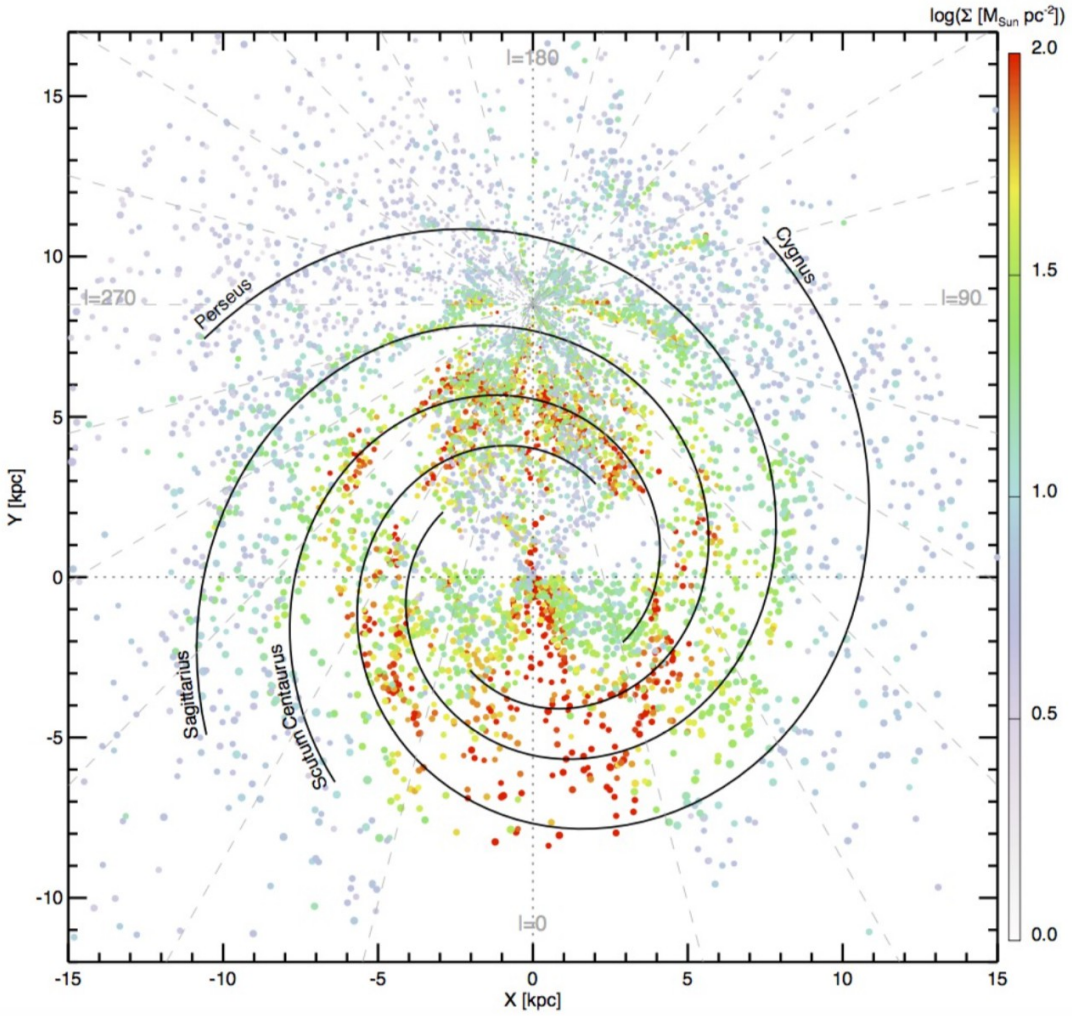
$$\phi(E,r) \propto e^{-r/R_{\rm cr}} \qquad R_{\rm cr} \approx 5.1 \text{ kpc}$$



Histogram FERMI

Description of the Interstellar gas in the Milky Way
Simple "smoothed" distribution (cylindrical symmetry)



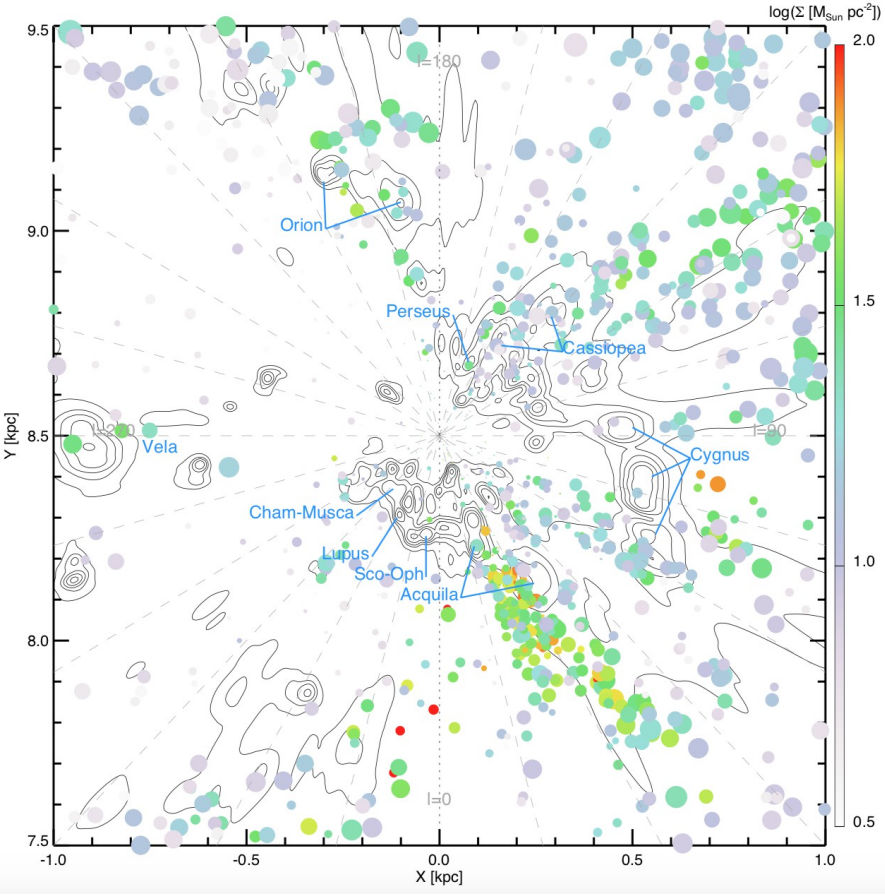


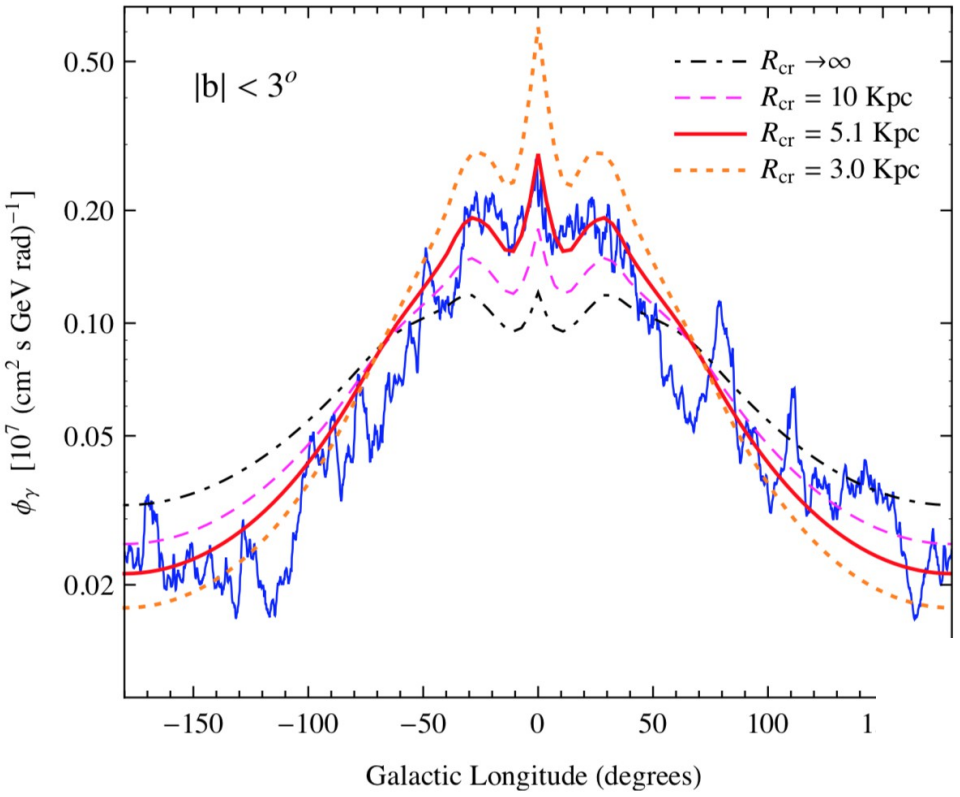
Miville-Deschêne,
Murray & Lee (2016)
Astrophysical Journal, 834, 57

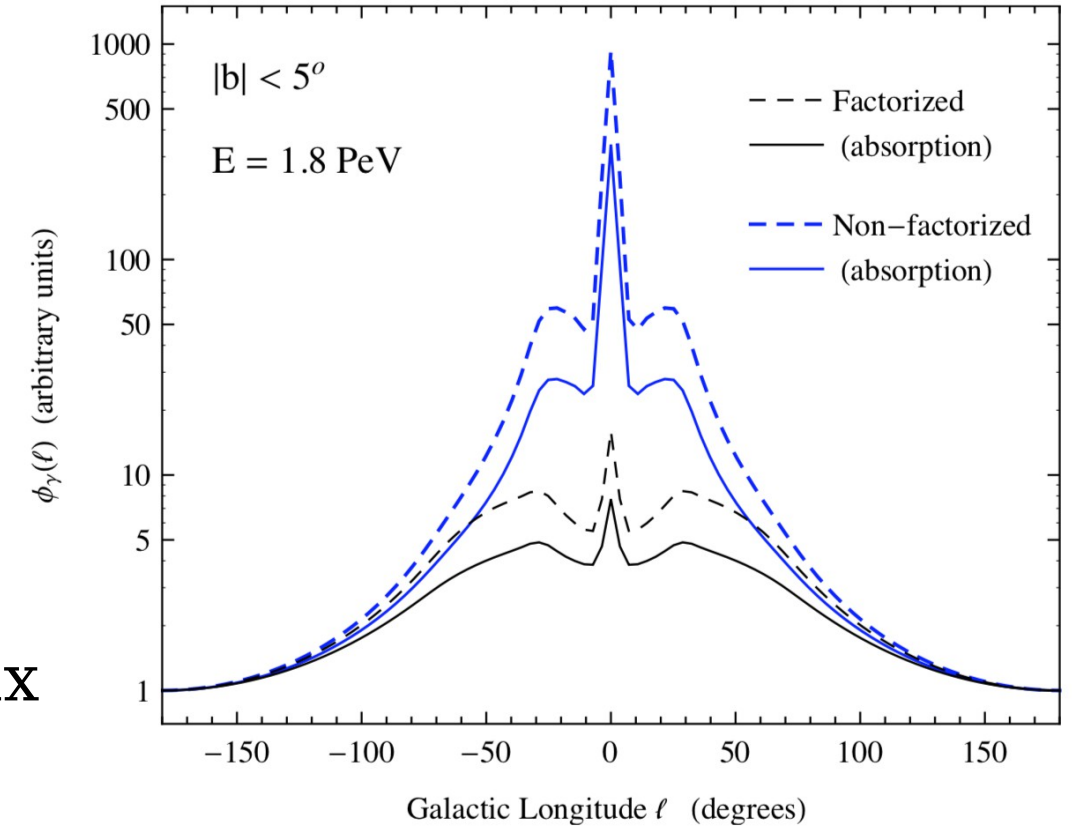
Physical properties of molecular clouds for the entire Milky Way disk"
[8107 molecular clouds]

Realistic distributions:

Ensemble of Molecular clouds.

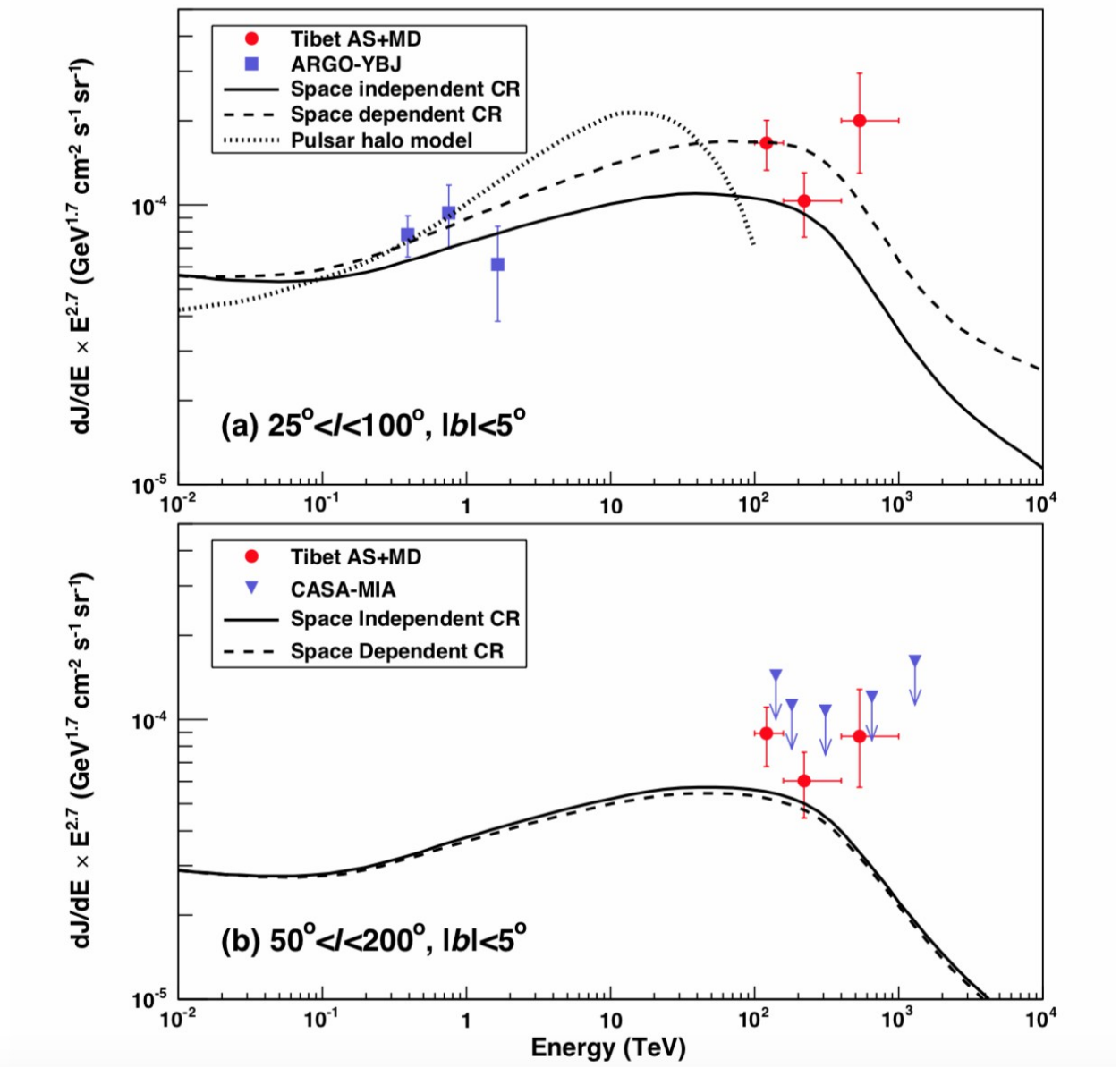






Predictions for the shape in longitude of the diffuse flux in the PeV energy range

Recent measurement of the Gamma Ray diffuse flux by the Tibet Asg collaboration



M. Amenomori *et al.* [Tibet ASγ Coll.], "First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies" Phys. Rev. Lett. **126**, no.14, 141101 (2021) [arXiv:2104.05181 [astro-ph.HE]].

Measurements of the Cosmic Ray spectra (at the EARTH):

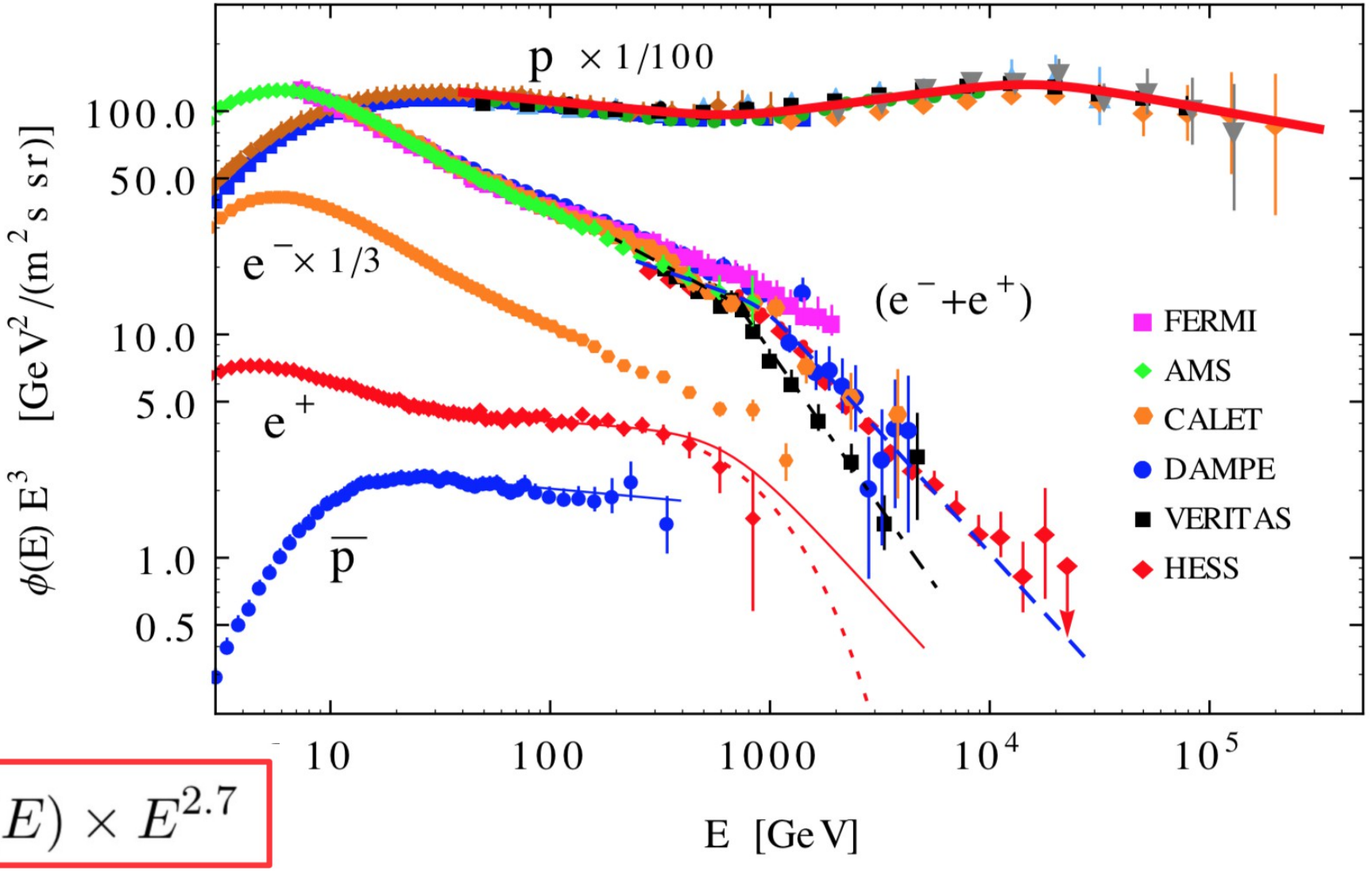
- Direct Measurements
- Air Shower Observations (higher energy)

Precision measurements of the
Cosmic Ray Spectra [*at the Earth*]

p e^-

$\overline{p}$ e^+

Why these spectral shapes ?

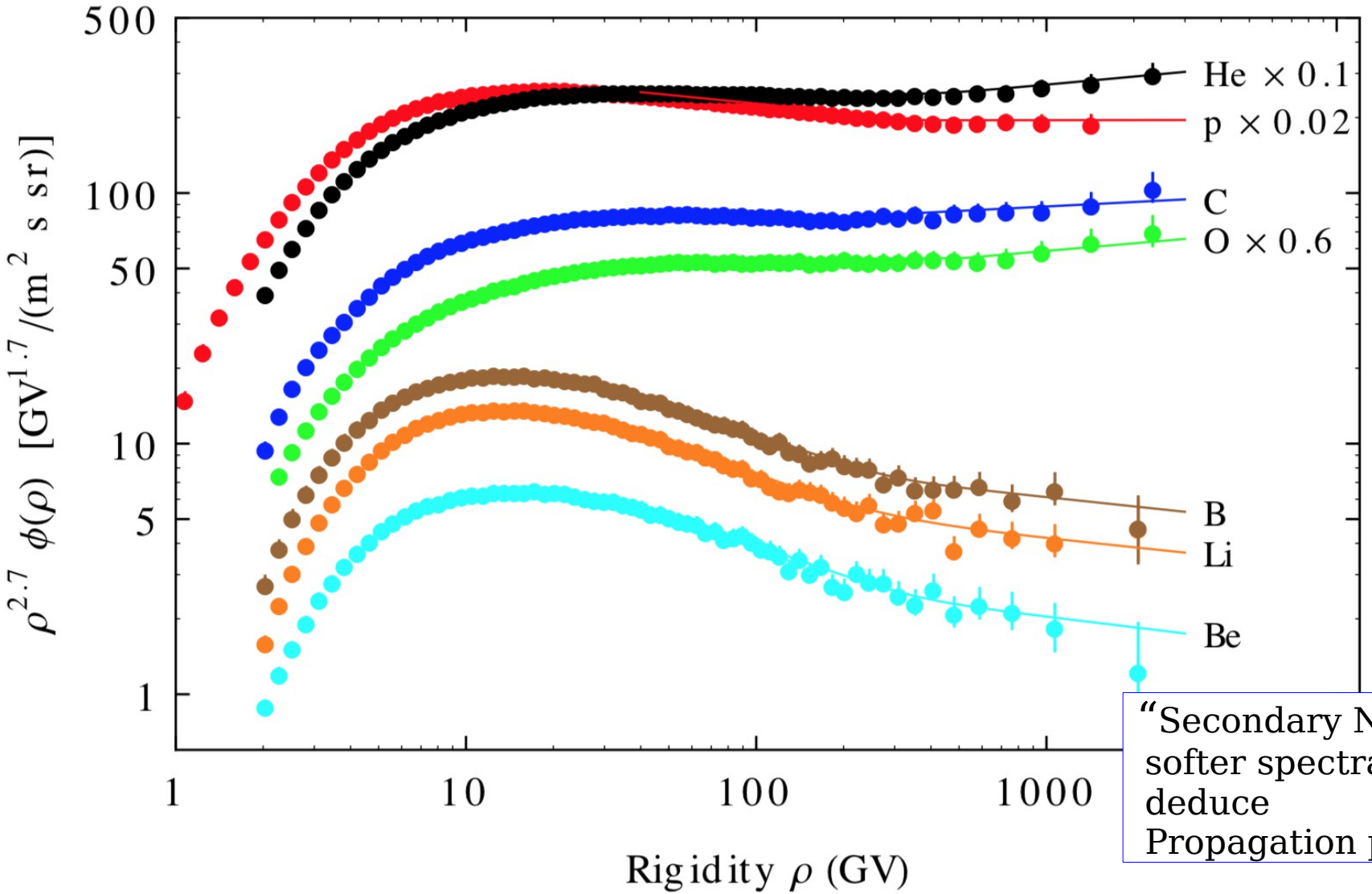


$\phi(E) \times E^{2.7}$

Precision measurements of the Cosmic Ray Spectra [*at the Earth!*]

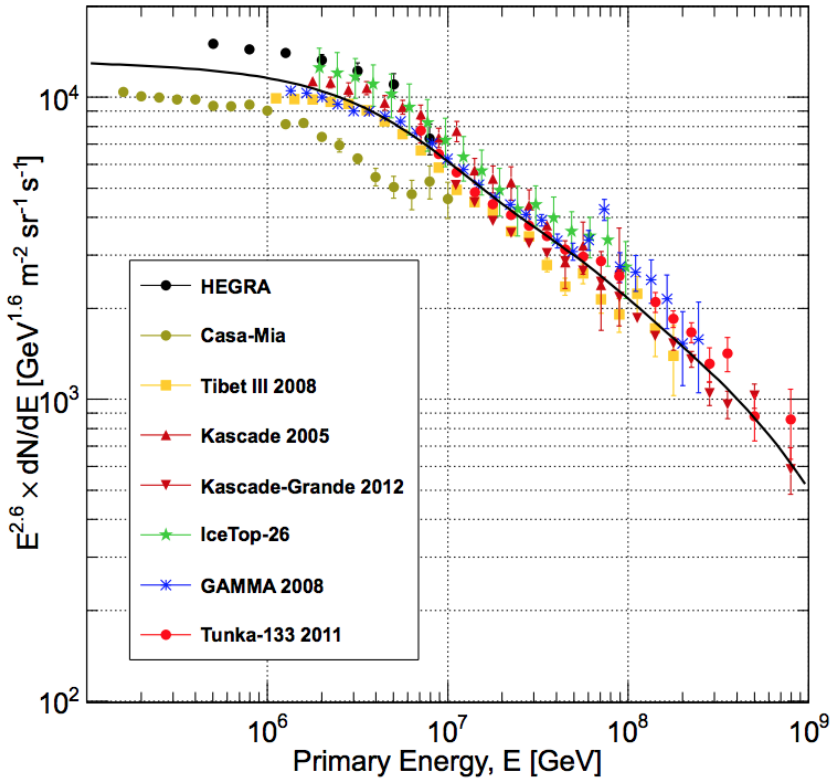
p
He
C, O
Li, Be, B

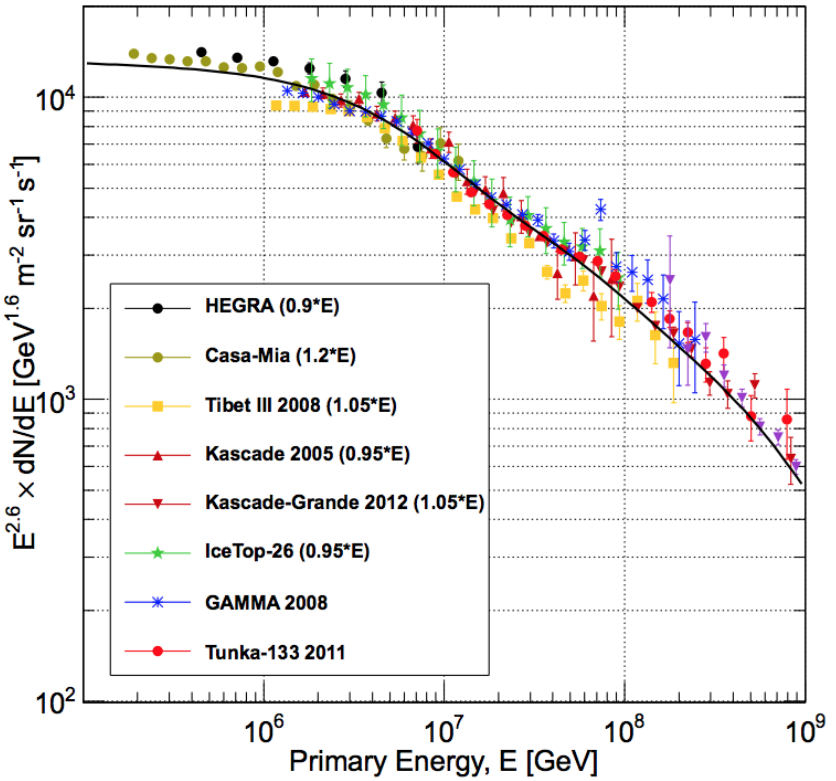
Nuclei (AMS02)



"Secondary Nuclei"
softer spectra
deduce
Propagation properties

*Significant uncertainties i*n the description of the cosmic ray spectrum and *composition* in the energy range where only indirect (air shower) observations are available





All-particle spectra from Air-shower experiments

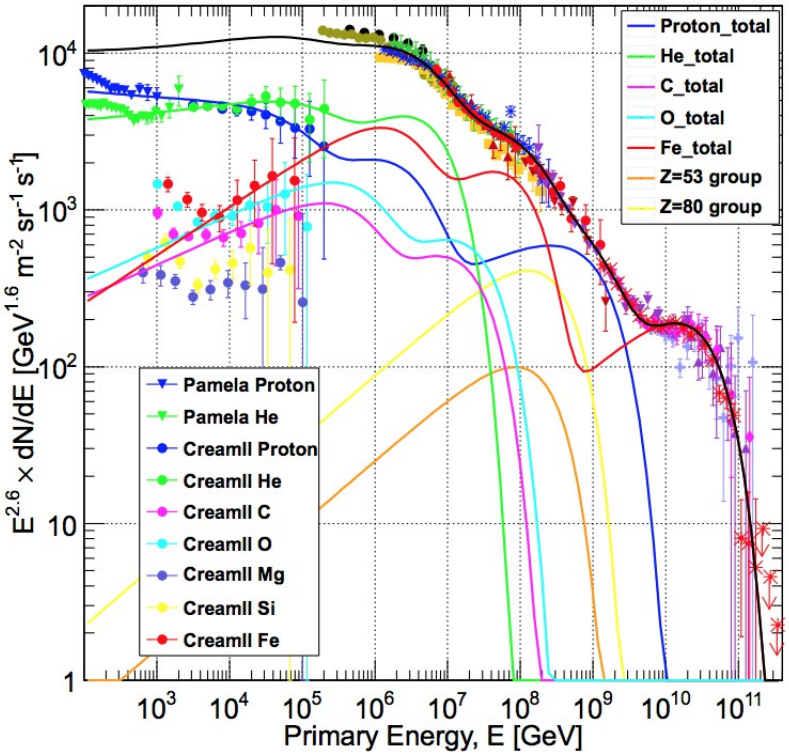
Data after readjusting the energy scale of detectors

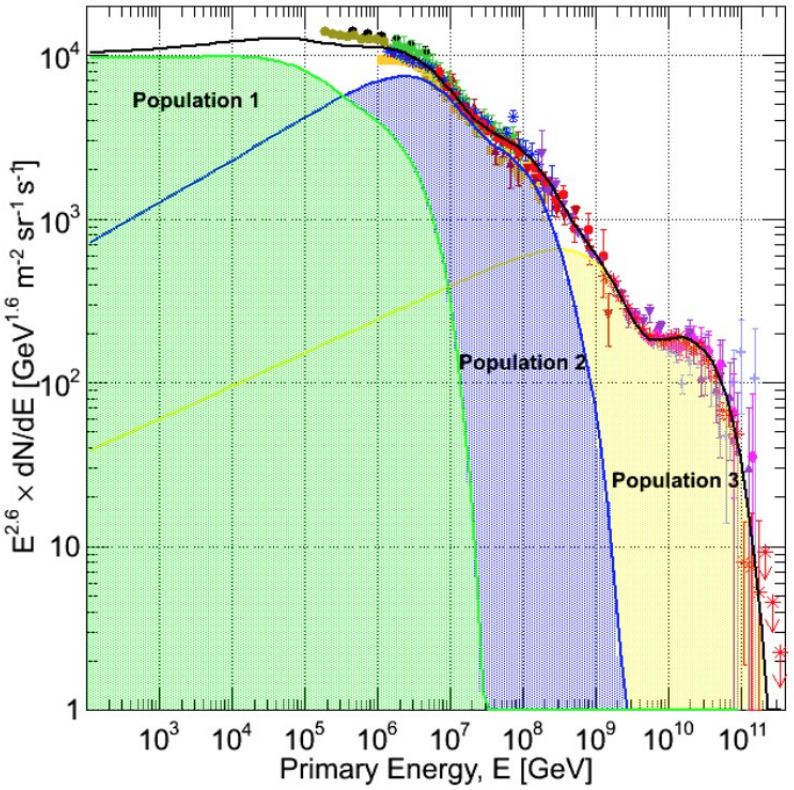
GST: Gaisser, Stanev, Tilav (2013)

GST Model

T. K. Gaisser, T. Stanev and S. Tilav,
"Cosmic Ray Energy Spectrum from Measurements of Air Showers",
Front. Phys. (Beijing) **8**, 748-758 (2013)
[arXiv:1303.3565 [astro-ph.HE]].

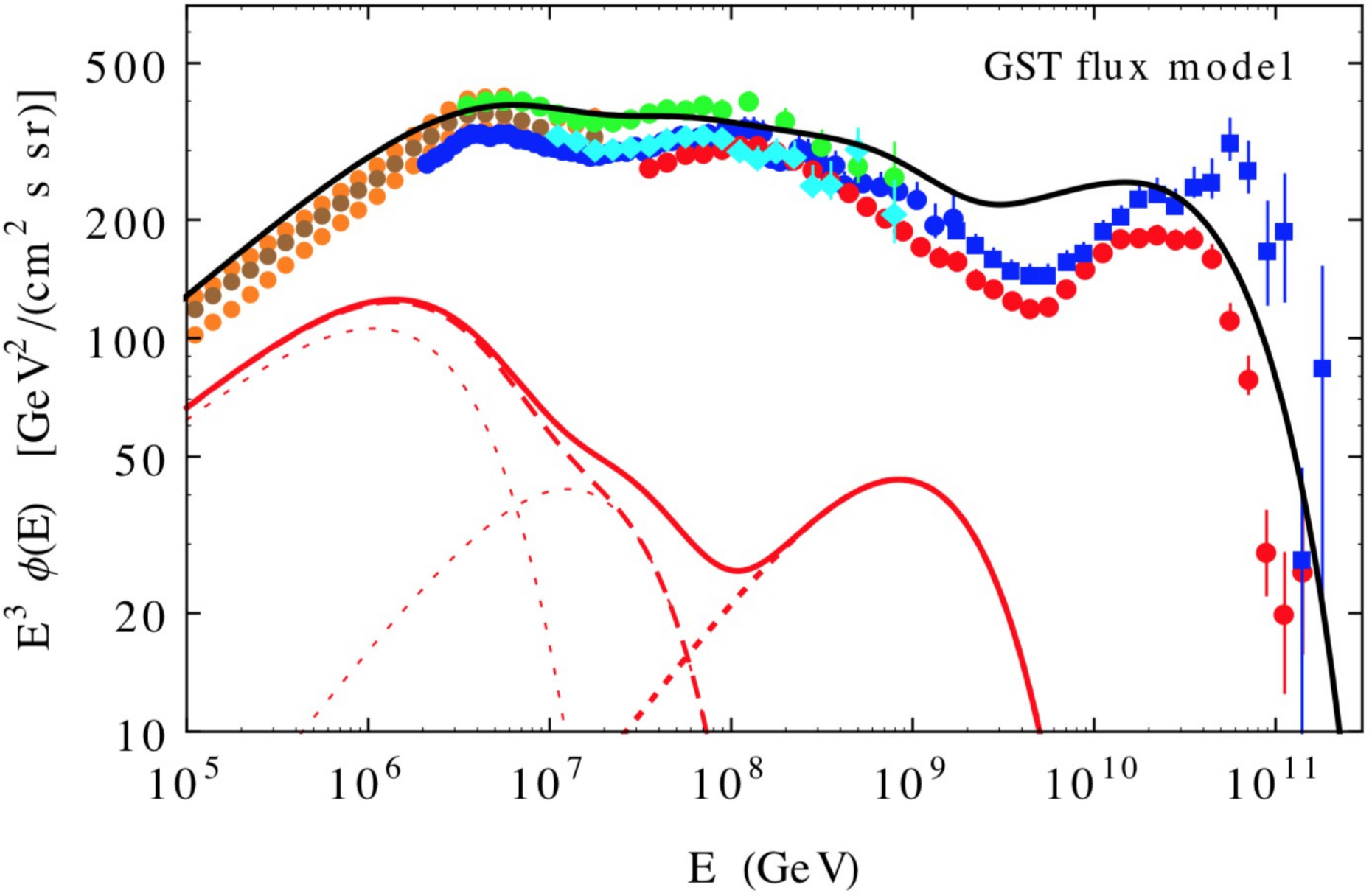
3 populations of sources
generating spectra that are power laws
with exponential cutoffs ["Peter's cycles"] $E_{\max}(Z) = Z\,E_{\max}(p)$



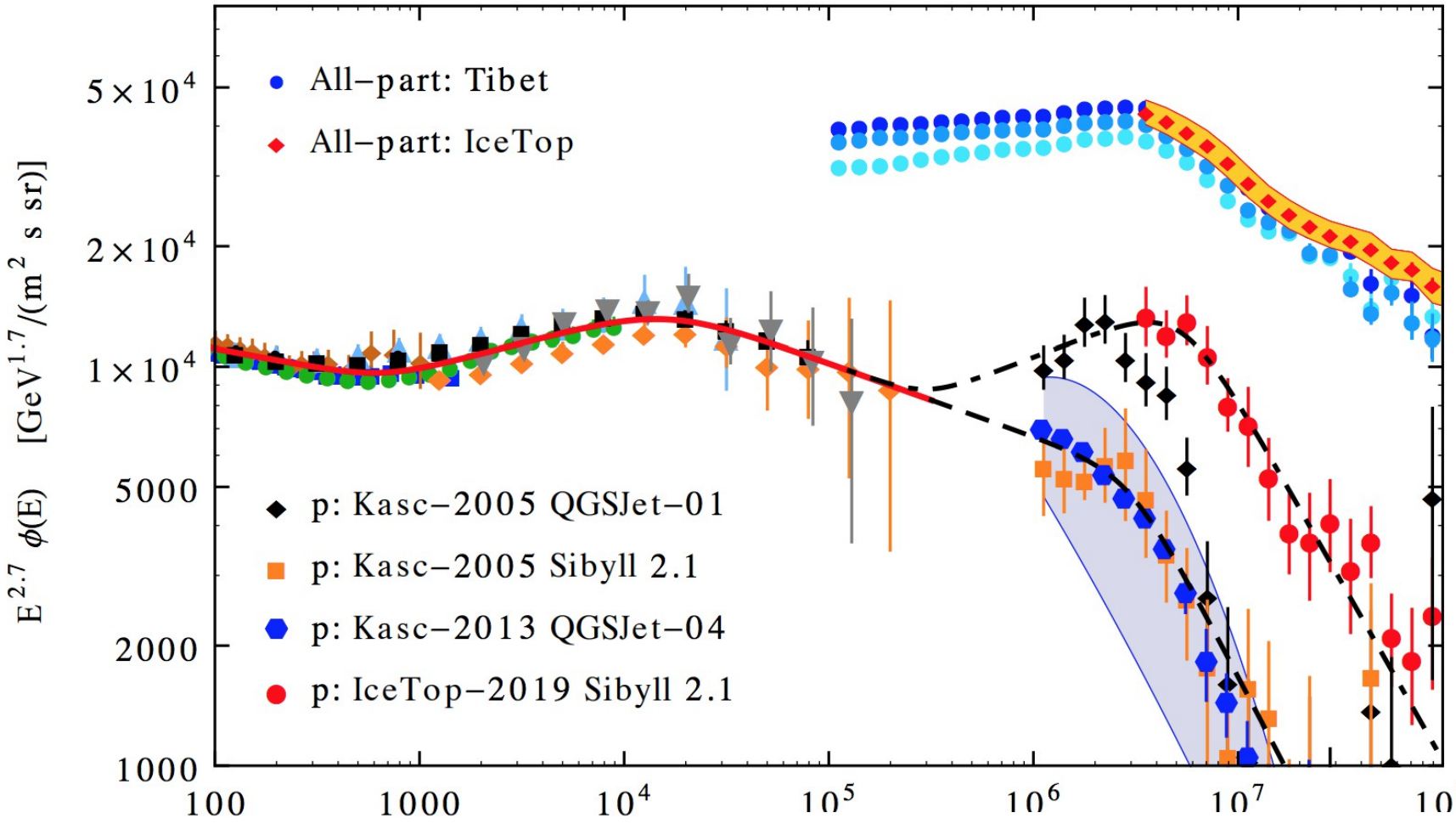


All particle
All Nucleon spectra

GST (Gaisser., Stanev, Tilav) Model



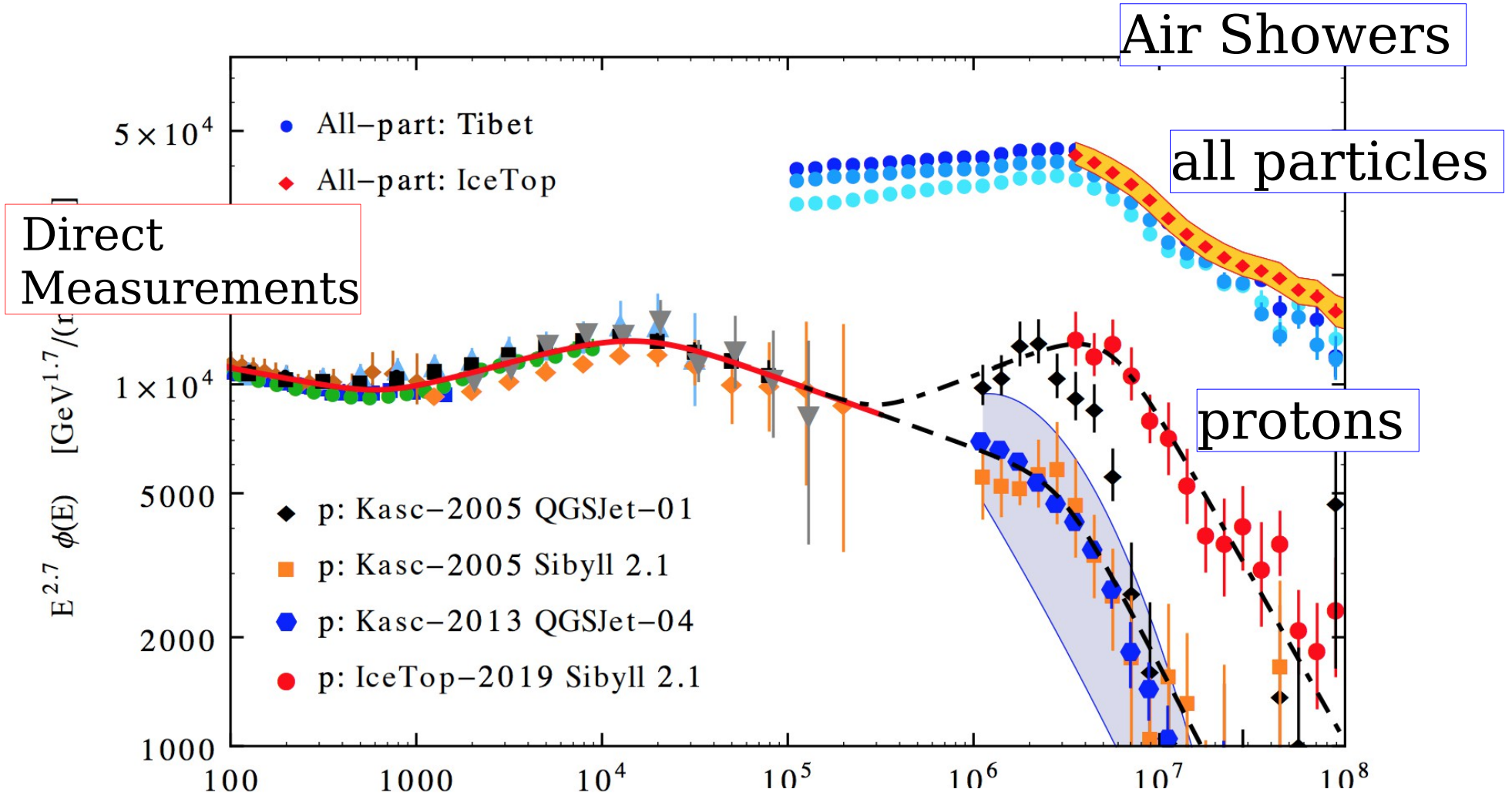
The composition measurements have very large uncertainties
[Associated to the modeling of CR showers (hadronic interactions)
and also to analysis algorithms]



P. L. and S. Vernetto,
"The shape of the cosmic ray proton spectrum"
Astropart. Phys. **120**, 102441 (2020)
[arXiv:1911.01311 [astro-ph.HE]].

Proton flux:

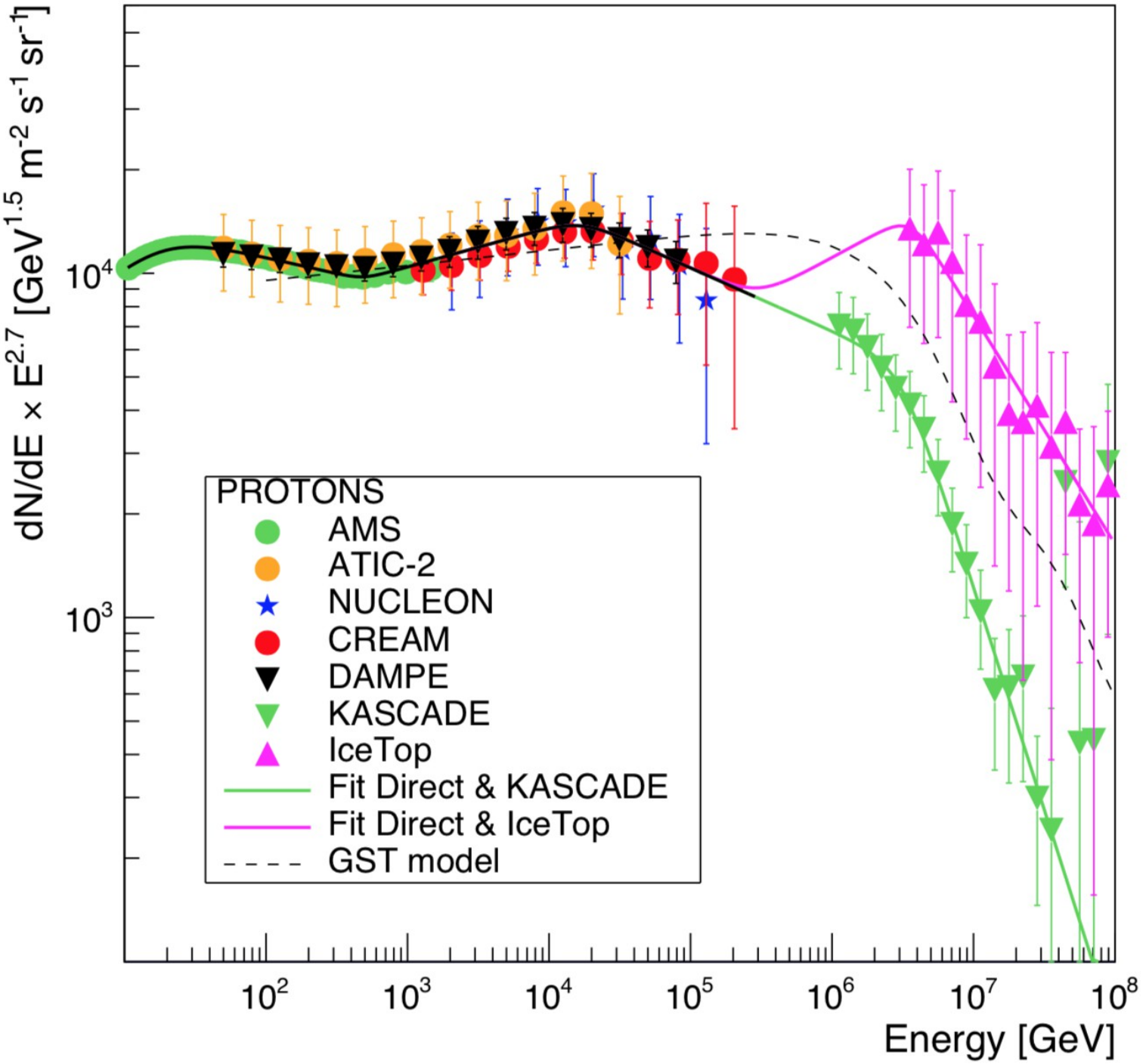
The composition measurements have very large uncertainties
[Associated to the modeling of CR showers (hadronic interactions)
and also to analysis algorithms]



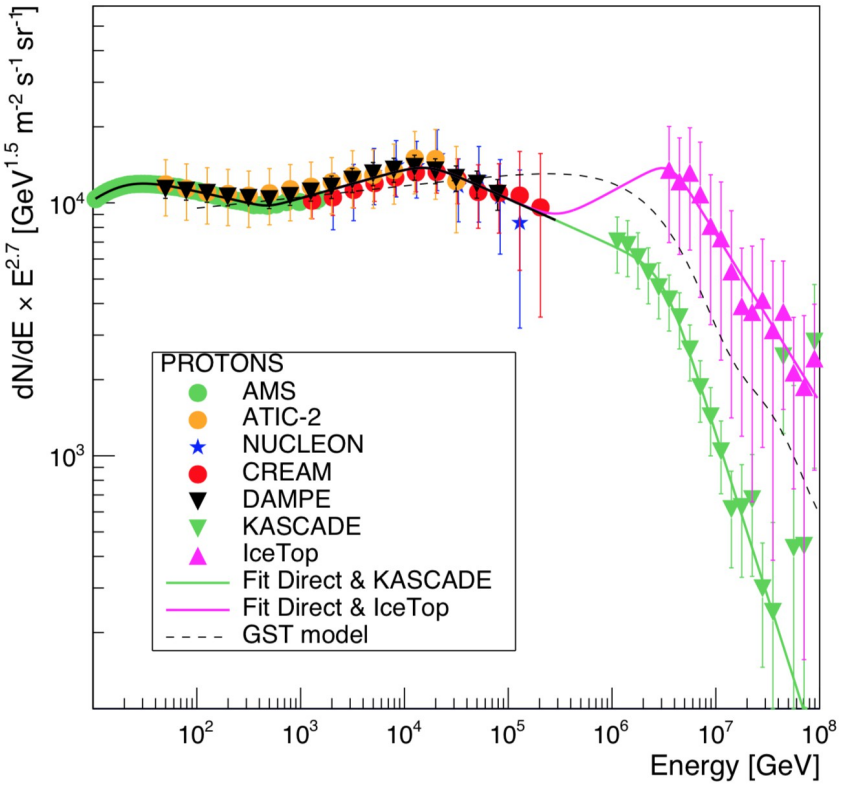
P. L. and S. Vernetto,
"The shape of the cosmic ray proton spectrum"
Astropart. Phys. **120**, 102441 (2020)
[arXiv:1911.01311 [astro-ph.HE]].

Proton flux:

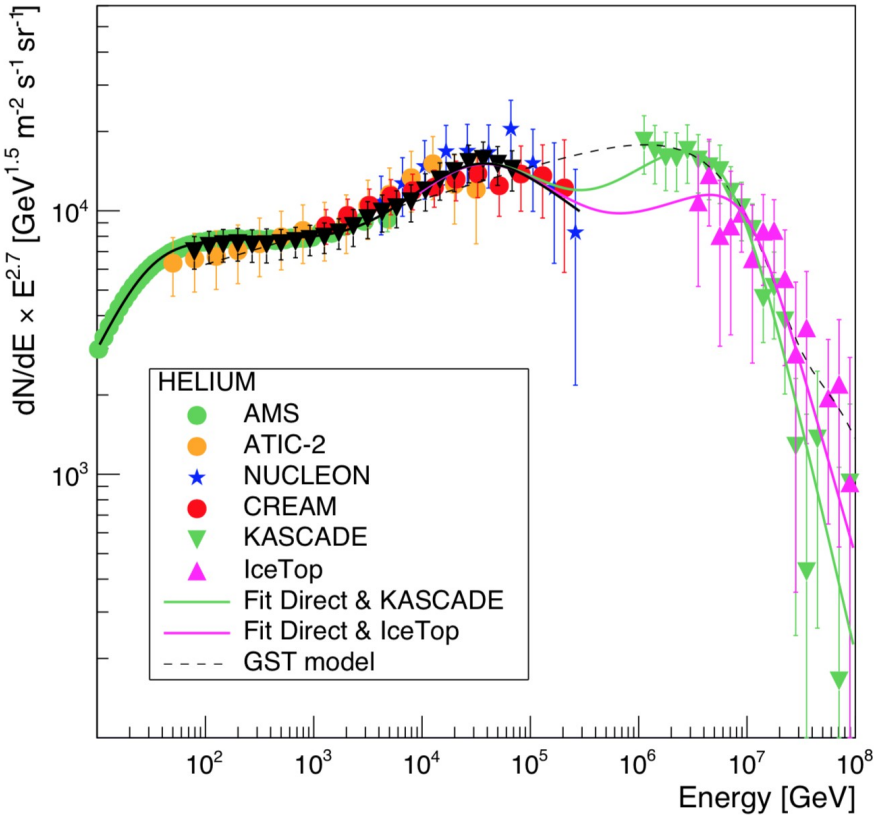
Proton flux estimates



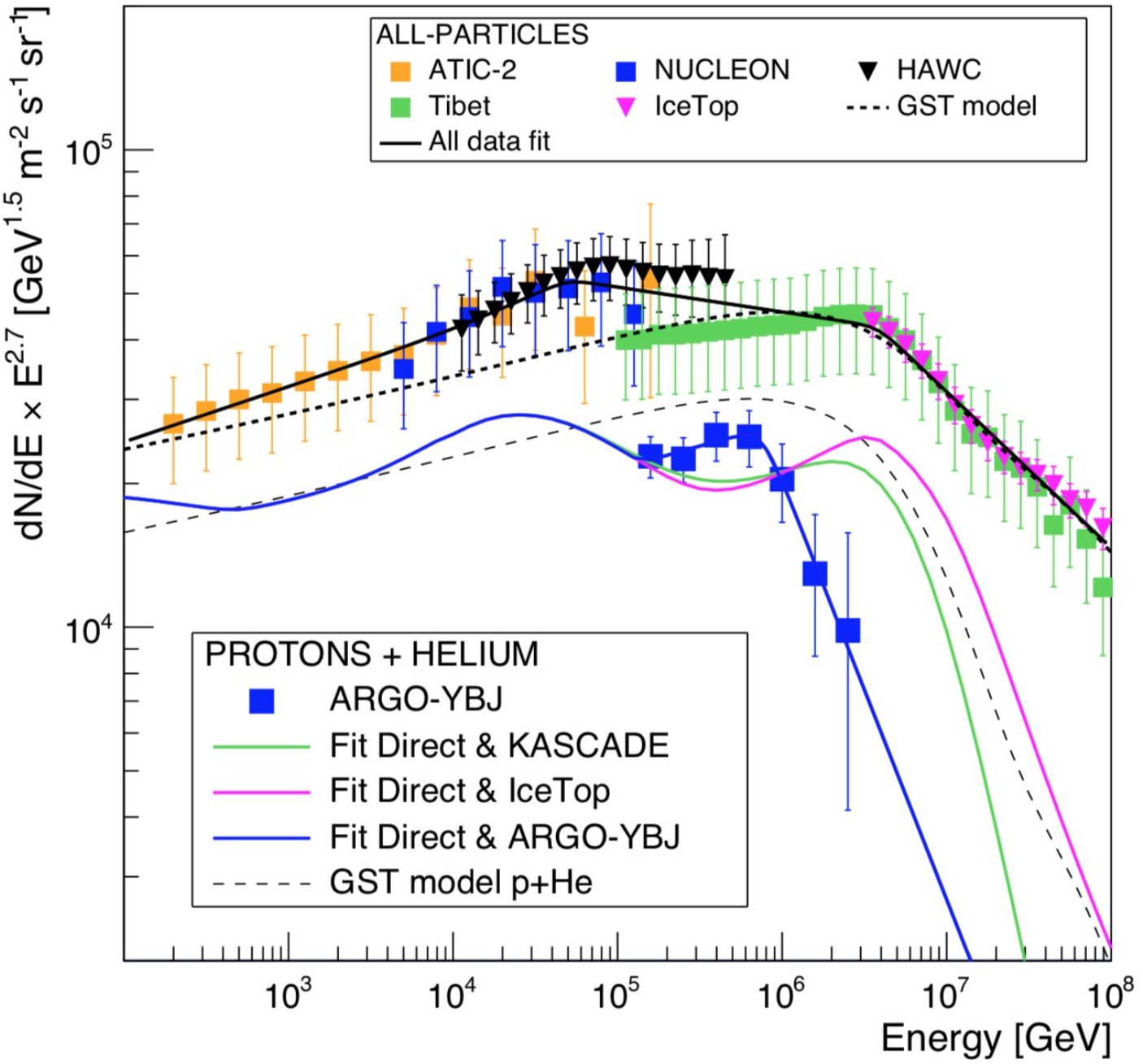
Proton flux



Helium flux

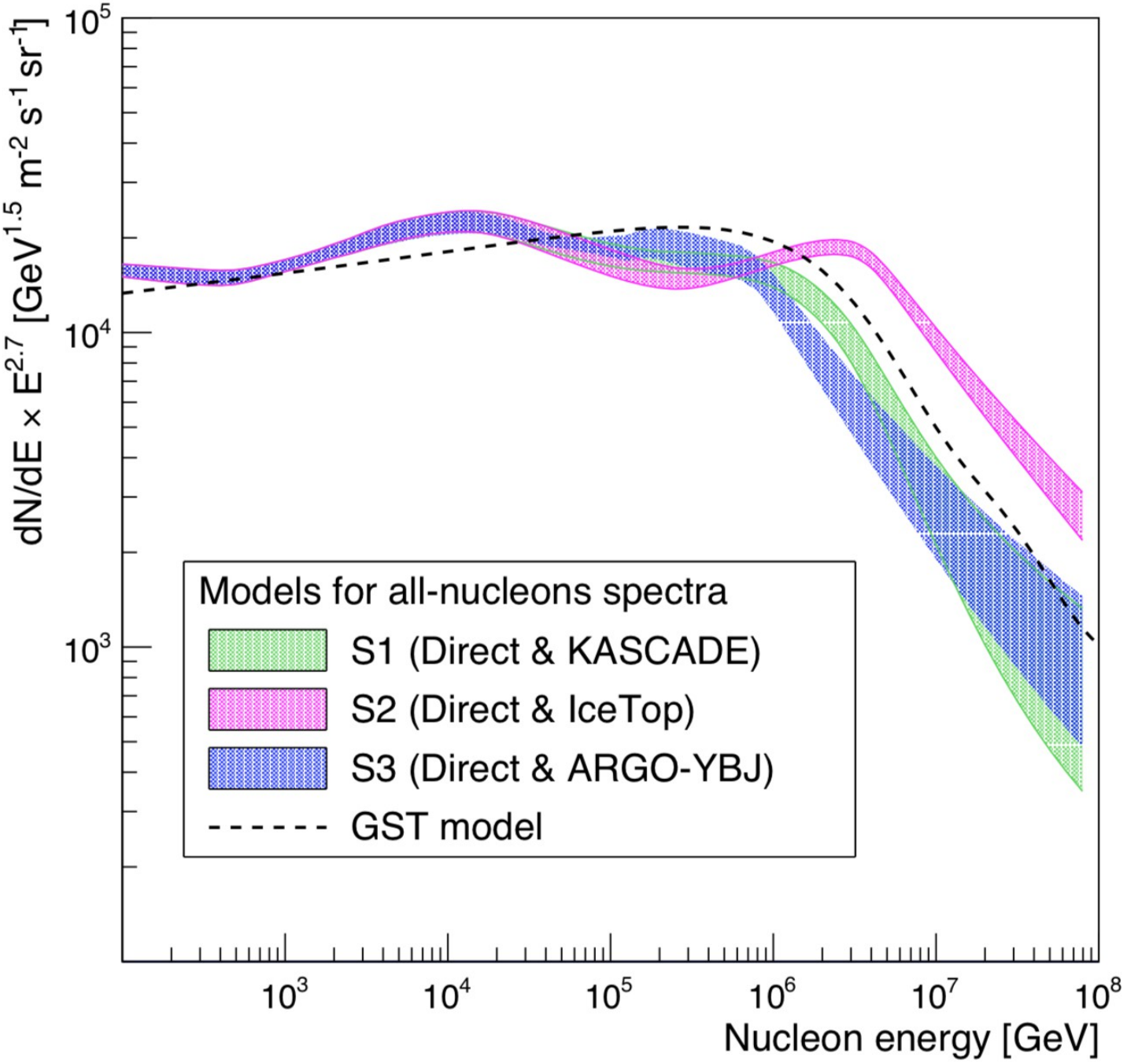


Proton + Helium flux



All Nucleon Spectra

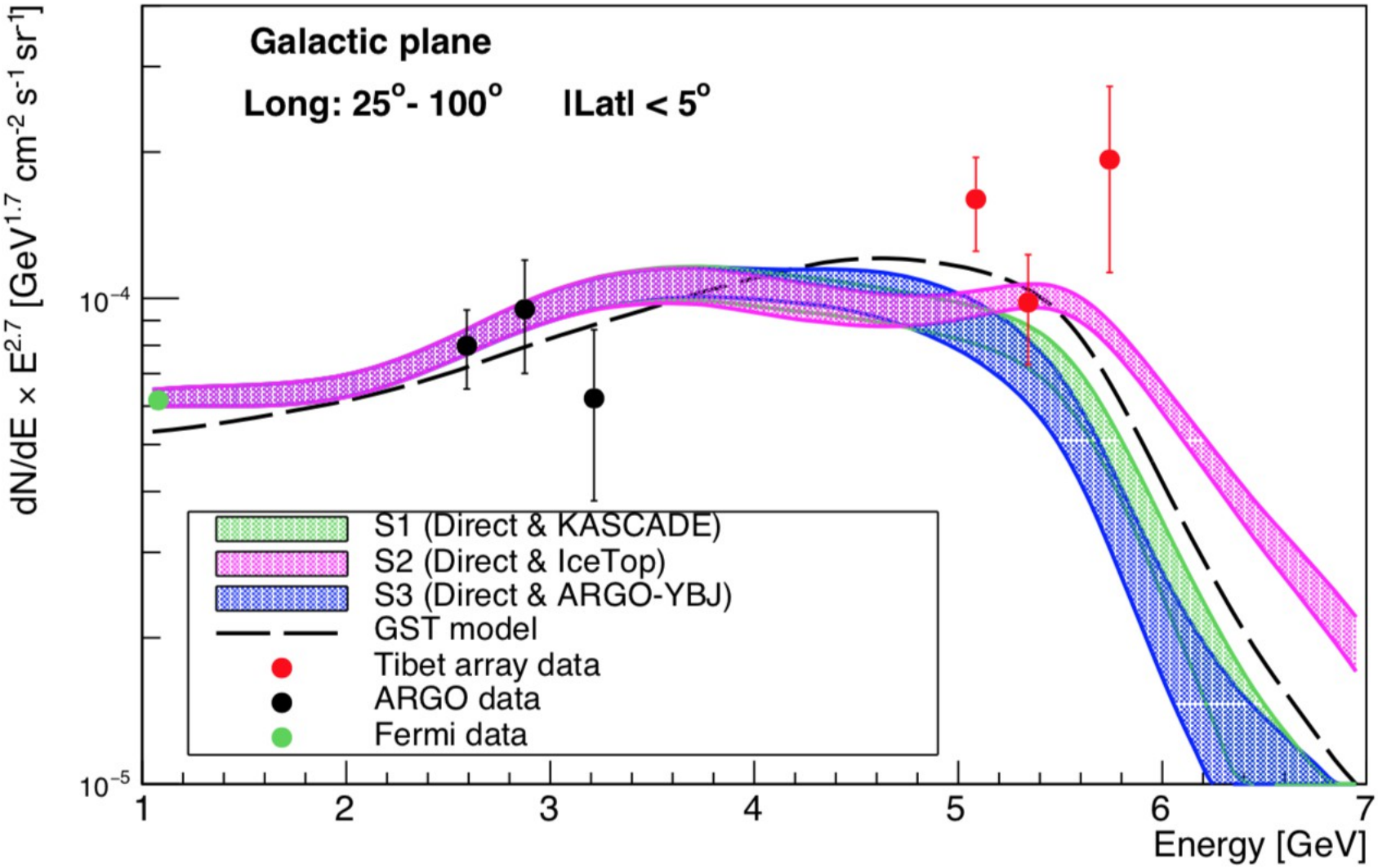
3 models



Comparison of calculations with data
diffuse gamma ray measurements

ARGO
Tibet ASgamma

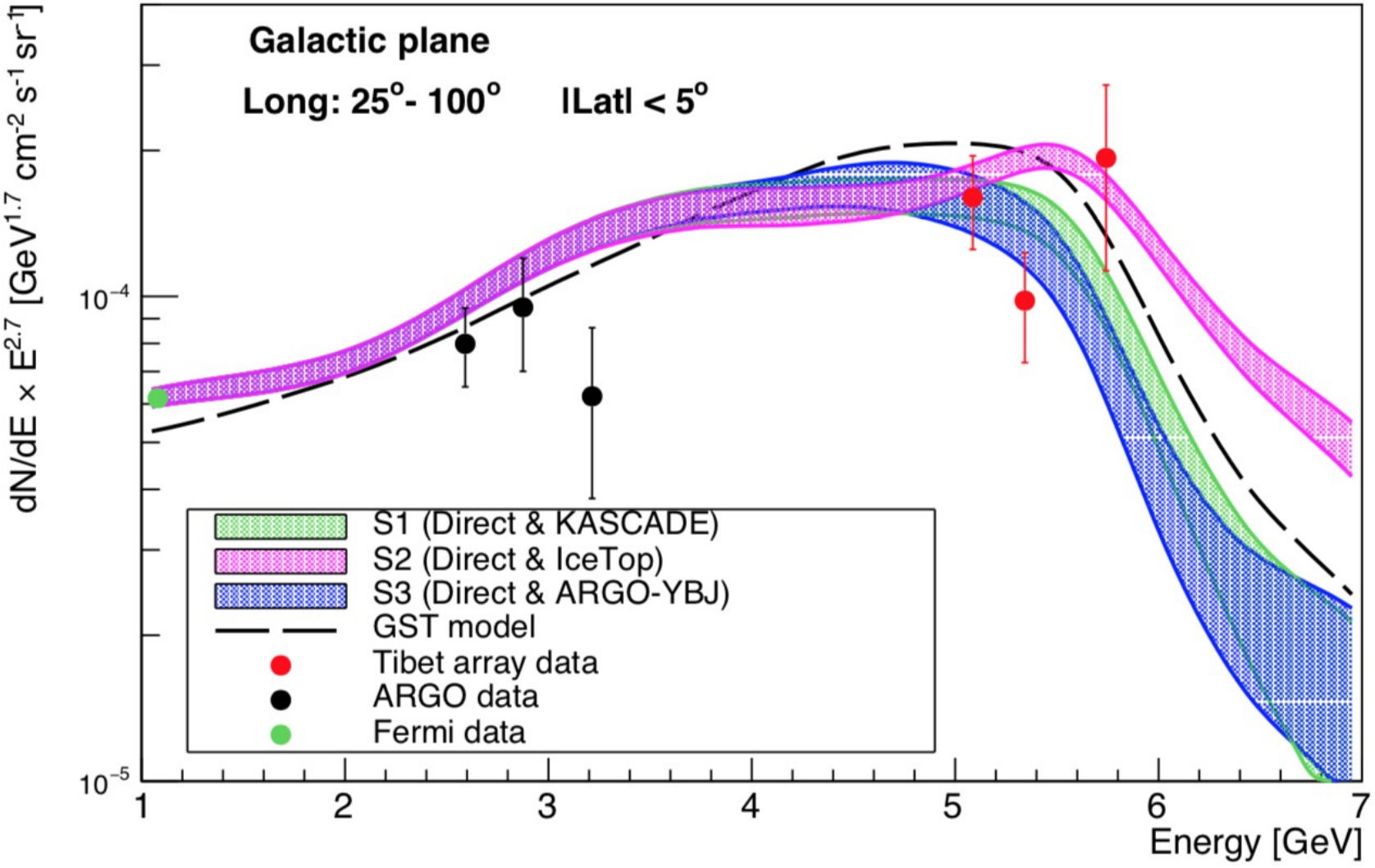
[Identical spectra in the entire Galaxy]



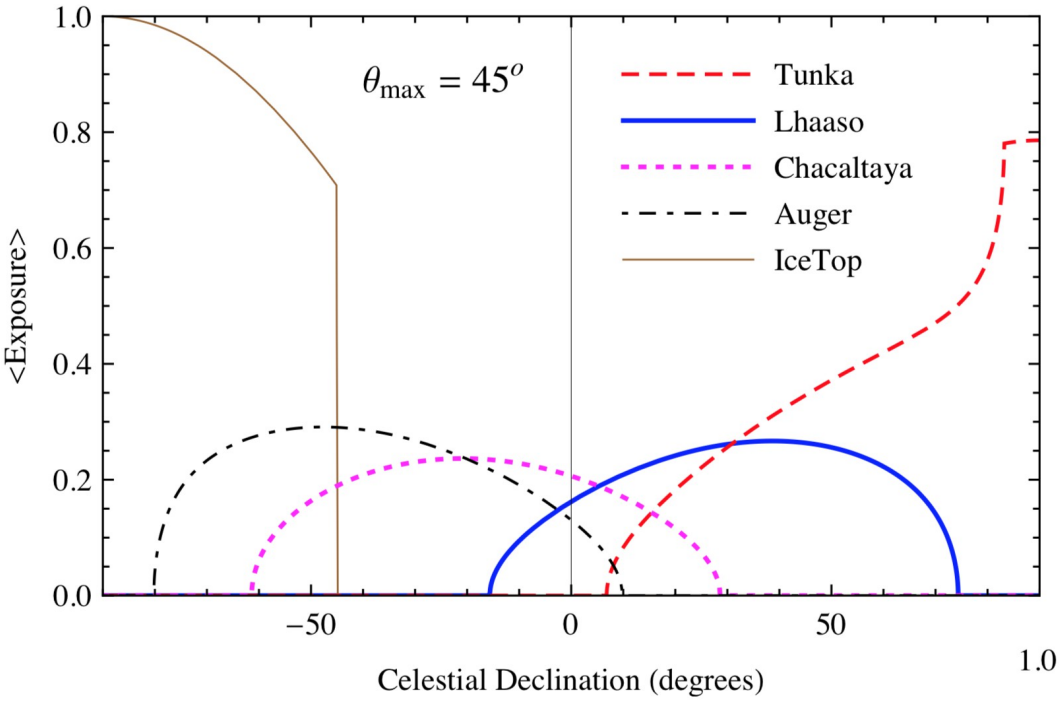
Comparison of calculations with data
diffuse gamma ray measurements

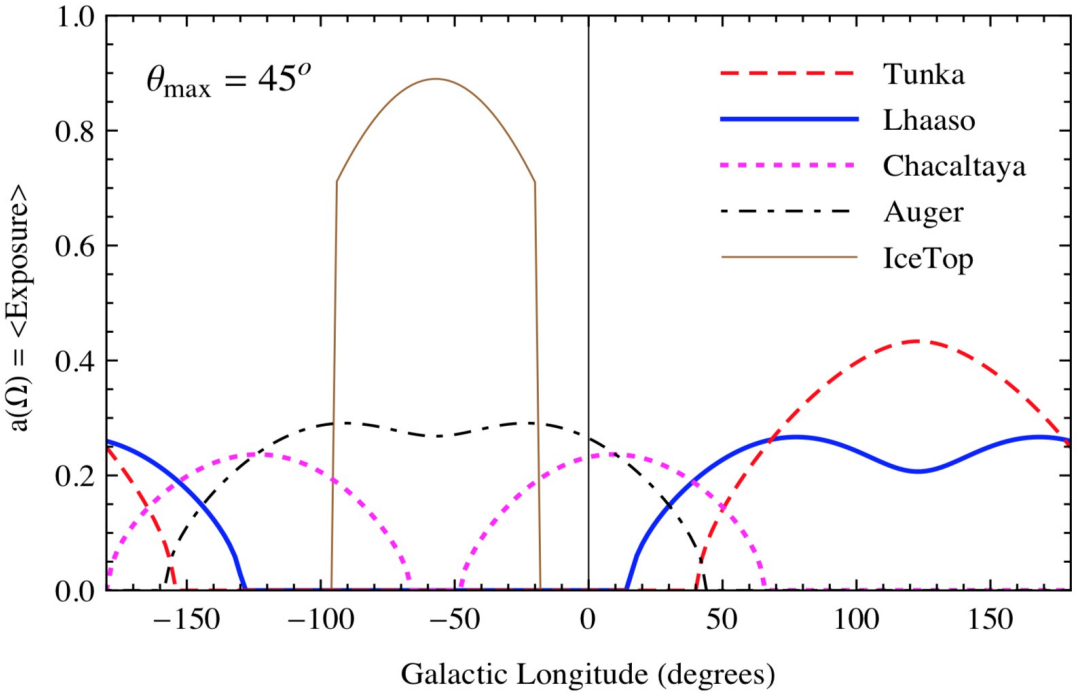
ARGO
Tibet ASgamma

[Hardening of spectrum toward central part of Galaxy]



Study the Galactic distribution of the diffuse flux for all Galactic Longitudes (Galactic center/anticenter)_





Tibet/Lhaaso observe Galactic anti-center

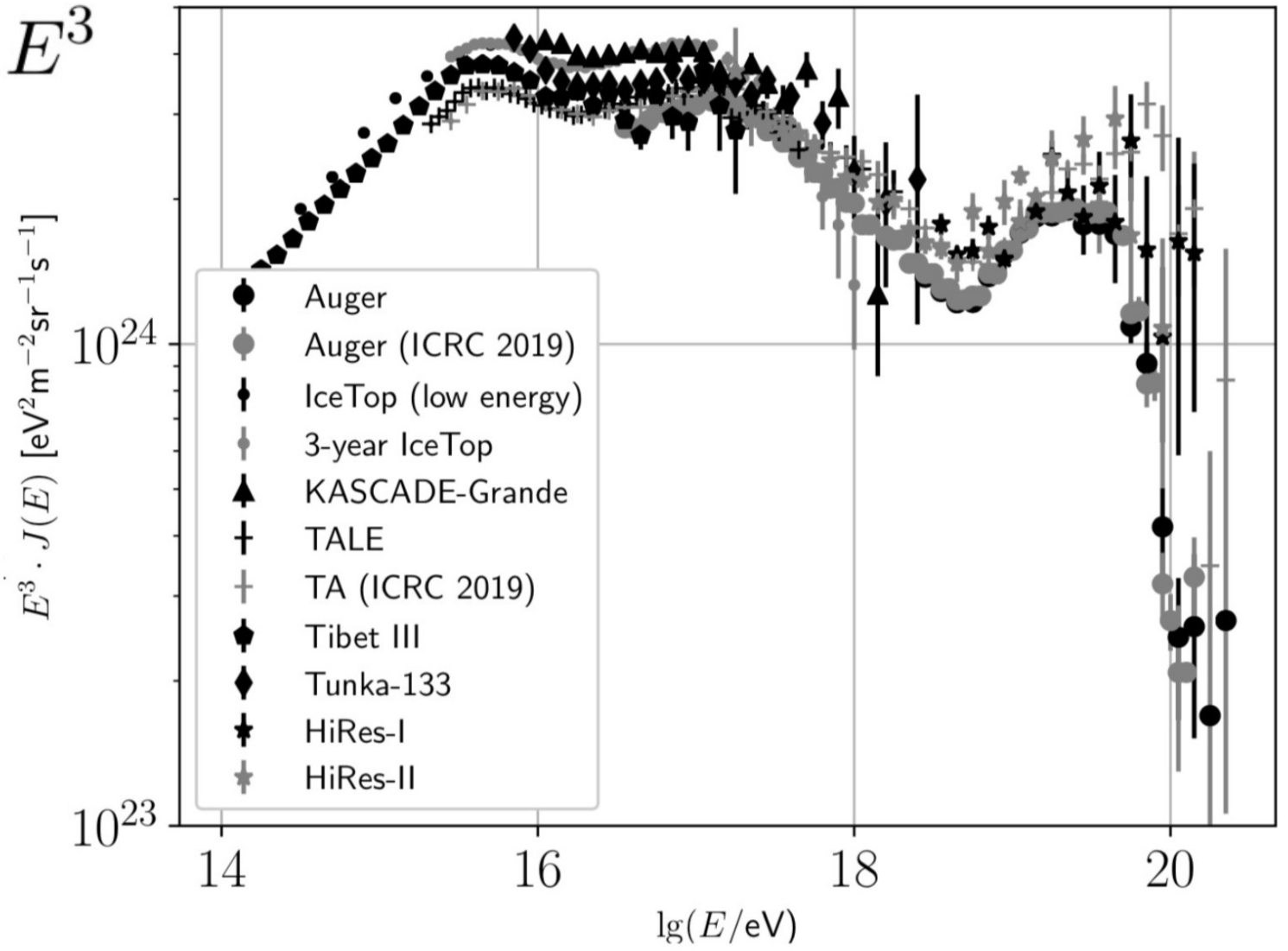
Galactic

versus

Extragalactic Cosmic Rays

Fundamental problem for High Energy Astrophysics

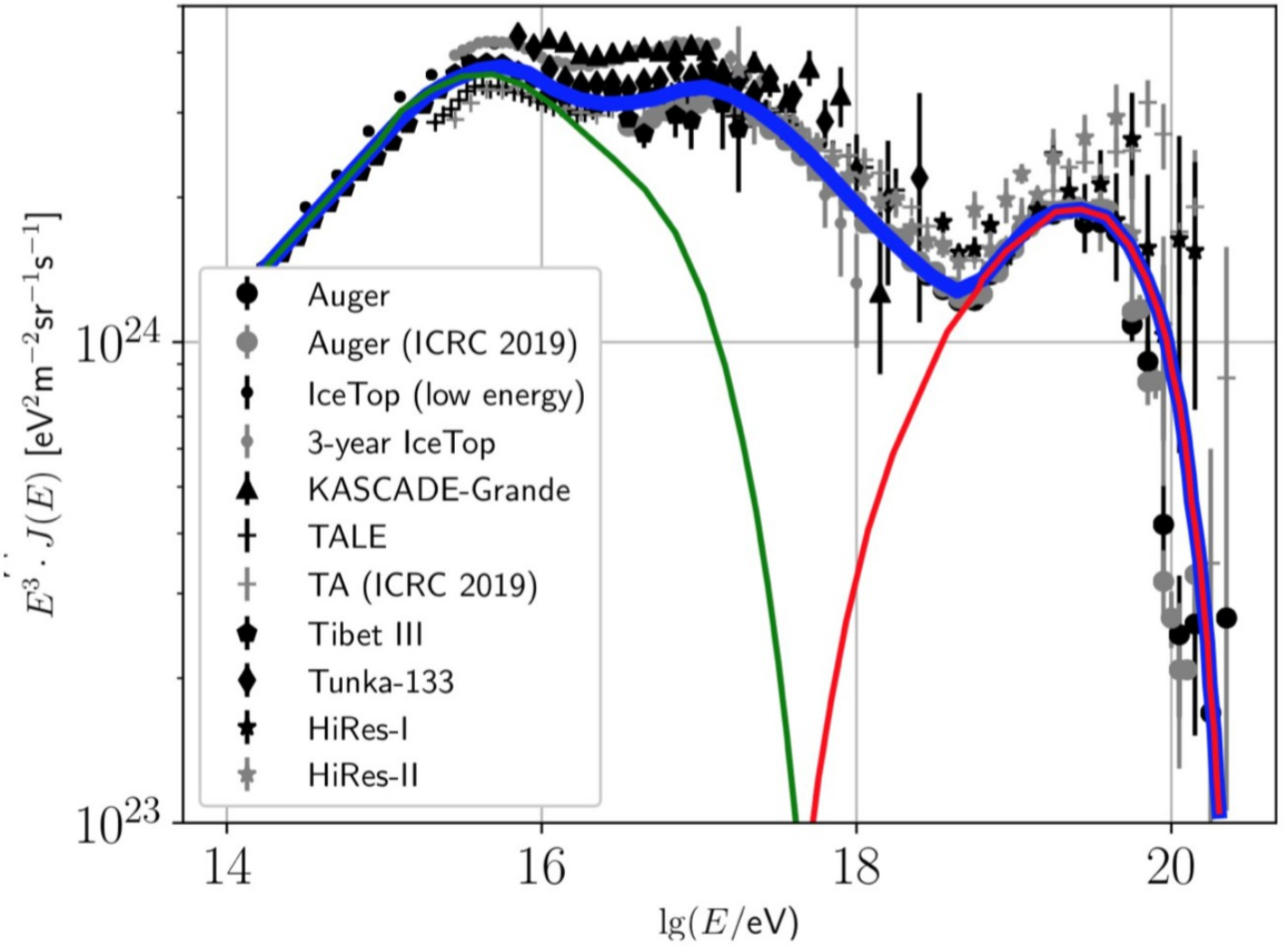
Cosmic ray spectra measured by
Extensive Air Shower (EAS) experiments (E > 100 TeV)



$\phi(E) \times E^3$

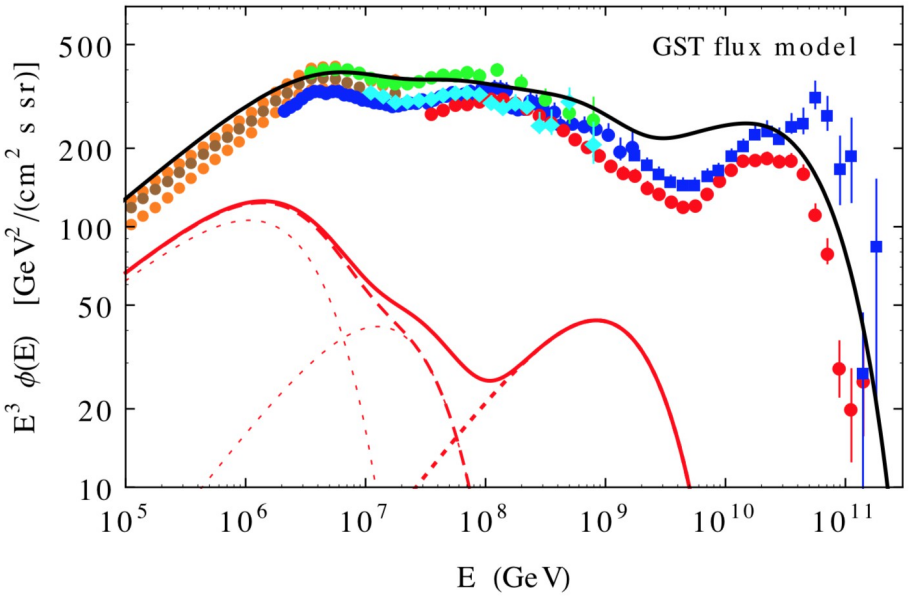
Alex Kääpä (ICRC 2021. Highlight talk
"On the transition between Galactic and extragalactic CR"

[common (but not universally) accepted interpretation]



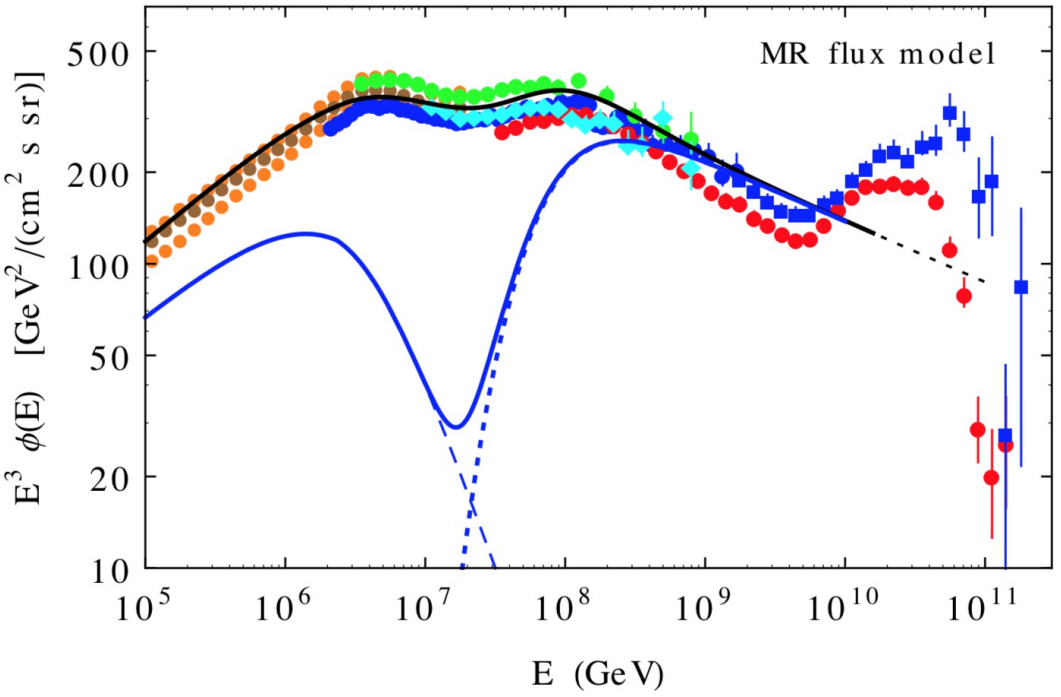
Galactic *"unexplained"* Extragalactic

GST Model All particle All Nucleon spectra

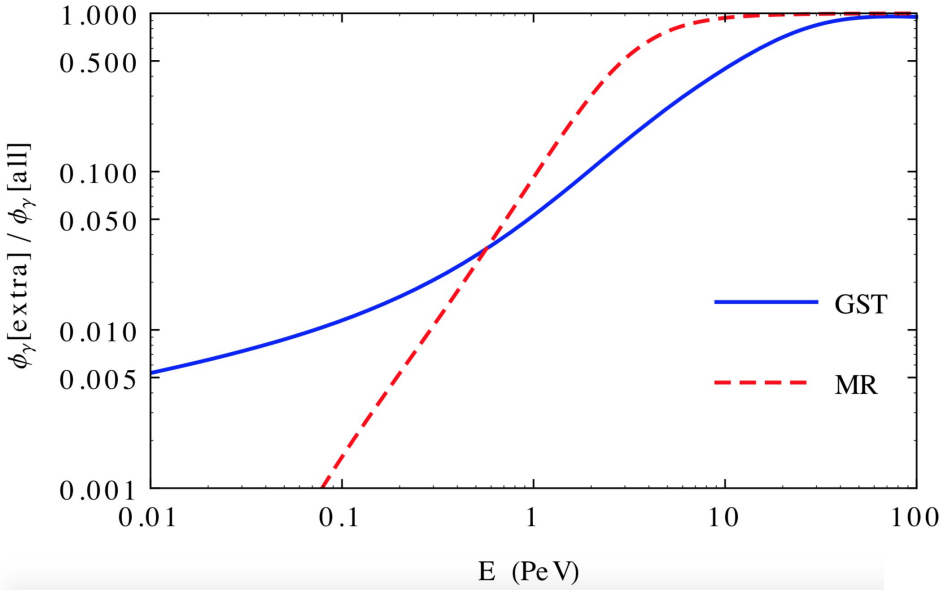


Model where CR above the 2nd Knee are extragalactic (and pure protons)

S. Mollerach and E. Roulet,
"A scenario for the Galactic cosmic rays between the knee and the second-knee"
JCAP **03**, 017 (2019)
[arXiv:1812.04026 [astro-ph.HE]].

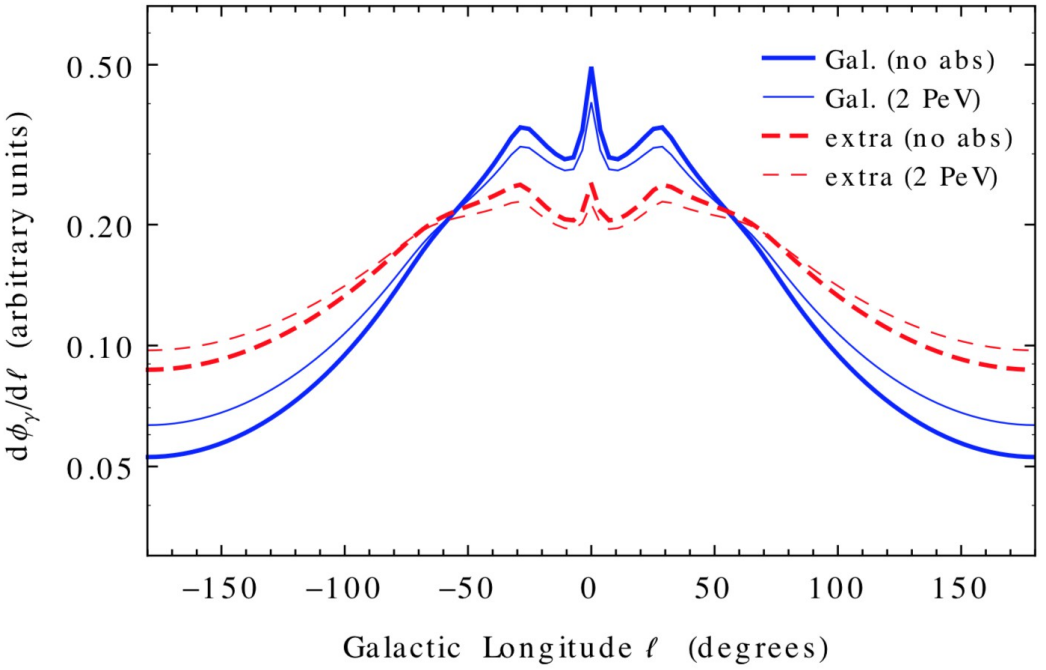


Fraction of diffuse Galactic gamma ray flux generated by extragalactic cosmic rays



S. Vernetto and P. L.,
"Diffuse Galactic gamma-ray and neutrino fluxes at very high energy and the Galactic/extragalactic Cosmic Ray transition",
PoS **ICRC2021**, 923 (2021)

Galactic Longitude distribution at 2 Pev

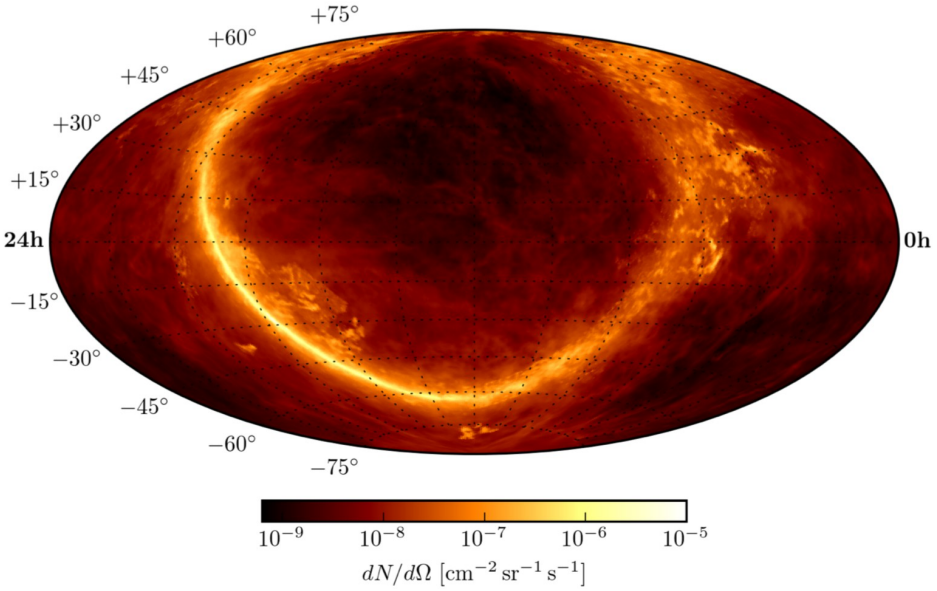


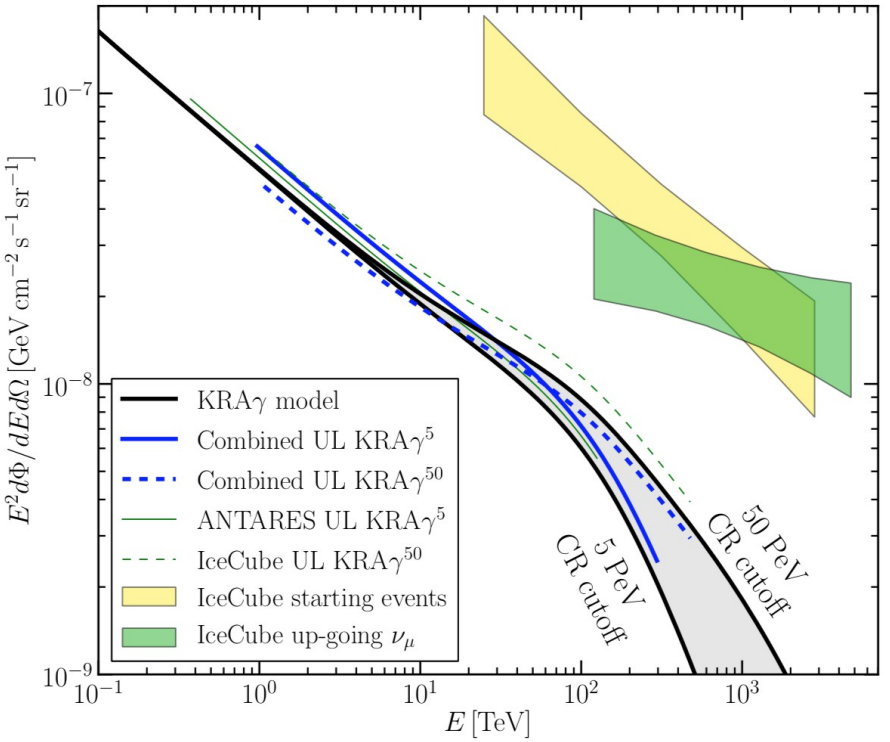
What fraction of the IceCube neutrino signal comes from the Milky Way ?

Joint paper of the ANTARES and IceCube Collaborations

ANTARES and IceCube Collaborations,
"Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes,"
Astrophys. J. Lett. **868**, no.2, L20 (2018)
[arXiv:1808.03531 [astro-ph.HE]].

No excess
(based on template)





Template

for the Angular distribution of the Galactic diffuse flux

The upper limit on Galactic diffuse component close to predictions

(that are however model dependent)

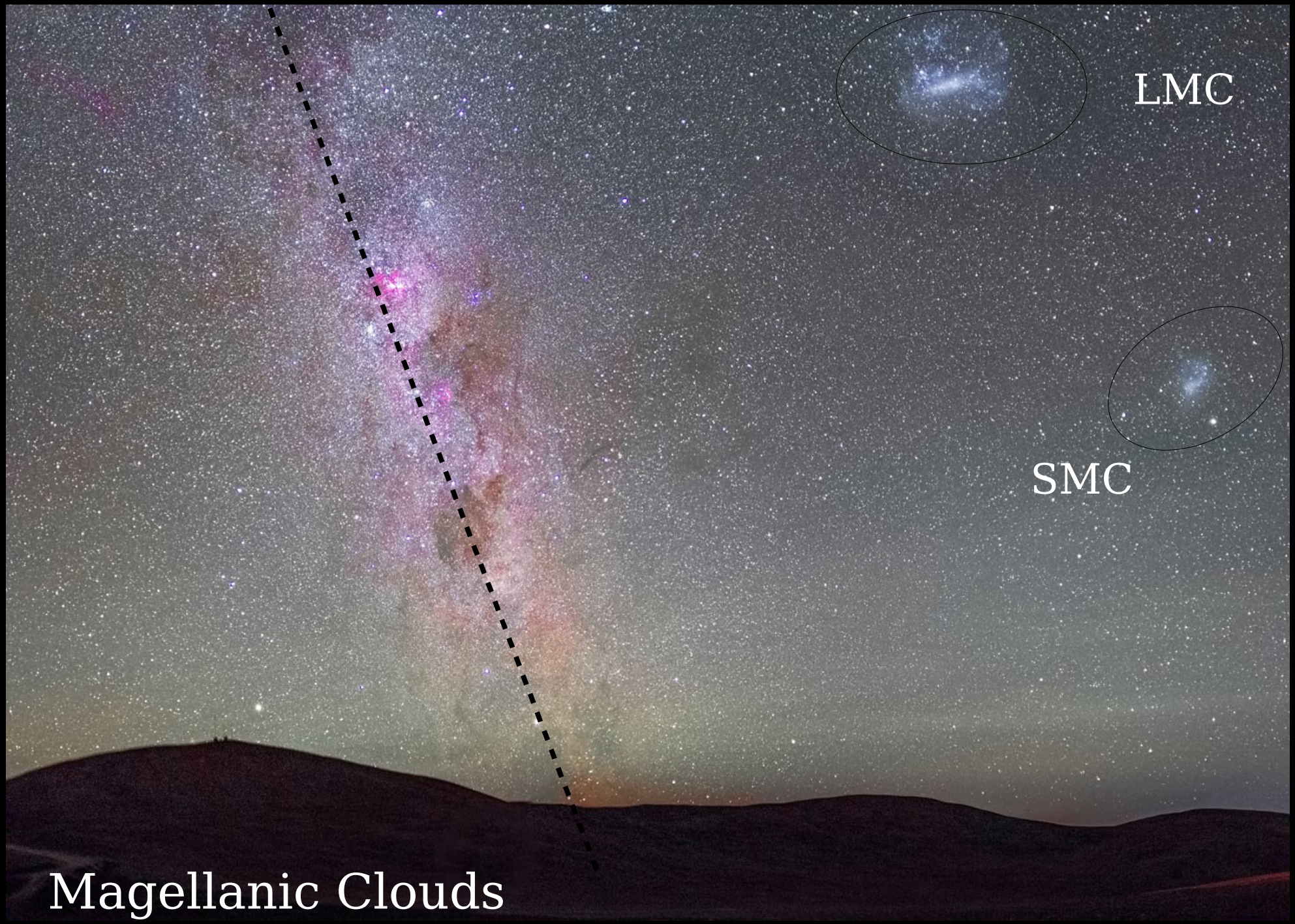
An historical note:

There was an epoch in the development of cosmic ray studies where the hypothesis that cosmic ray filled homogeneously the entire universe was seriously considered
[The SuperNova model of Zwicky was an early example].

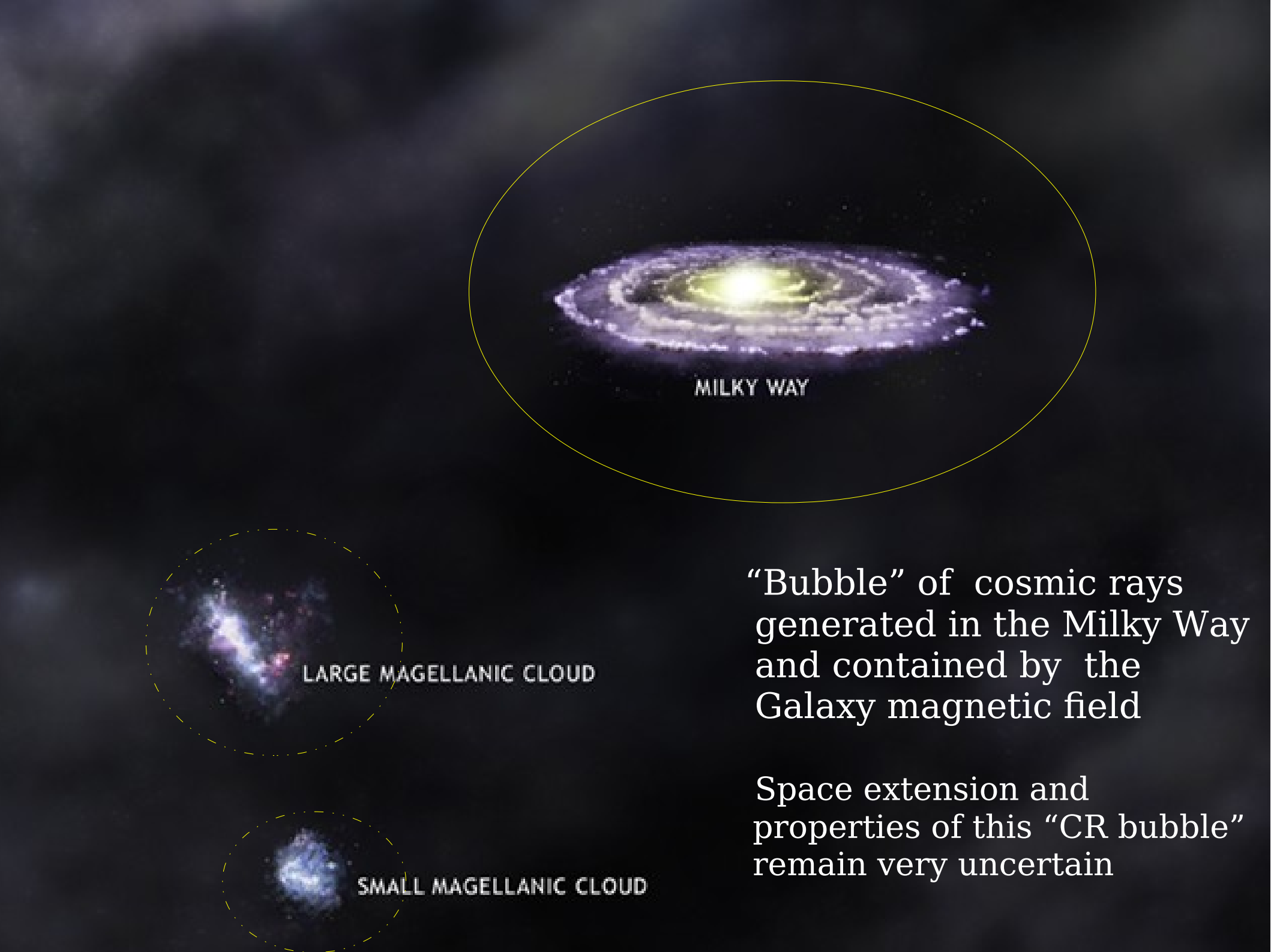
Vitaly Ginzburg suggested to use observations of the Magellanic Clouds to prove/disprove "Metagalactic Models"
(where CR fill the entire universe)

Gamma Radiation of Magellanic Clouds and Metagalactic Origin of Cosmic Rays

V. L. GINZBURG *Nature Physical Science* **239**, 8–9 (1972)



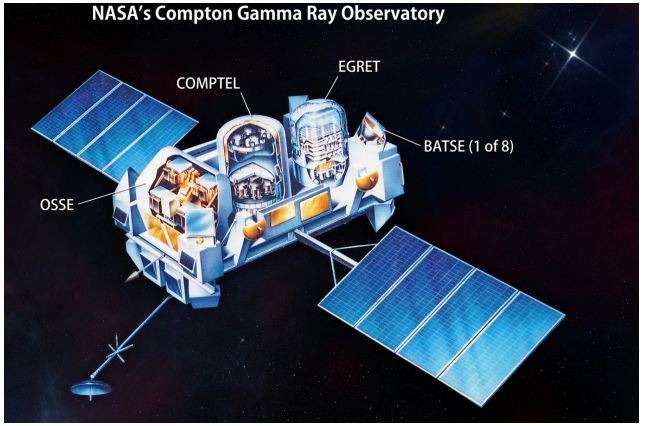
Magellanic Clouds



"Bubble" of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field

Space extension and properties of this "CR bubble" remain very uncertain

The program of Ginzburg
has been completed
Upper Limit of the Small Magellanic
Cloud by EGRET (1993)

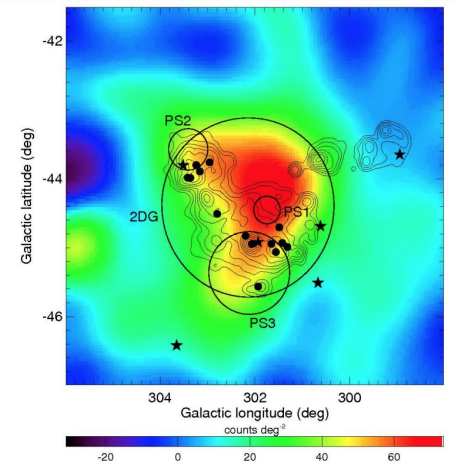


EGRET Collaboration,
"Constraints on the cosmic rays in the Small Magellanic Cloud"
Phys. Rev. Lett. **70**, 127-129 (1993)

$$\phi_{\rm SMC}(E \geq 100\ {\rm MeV}) \lesssim \frac{1}{5}$$

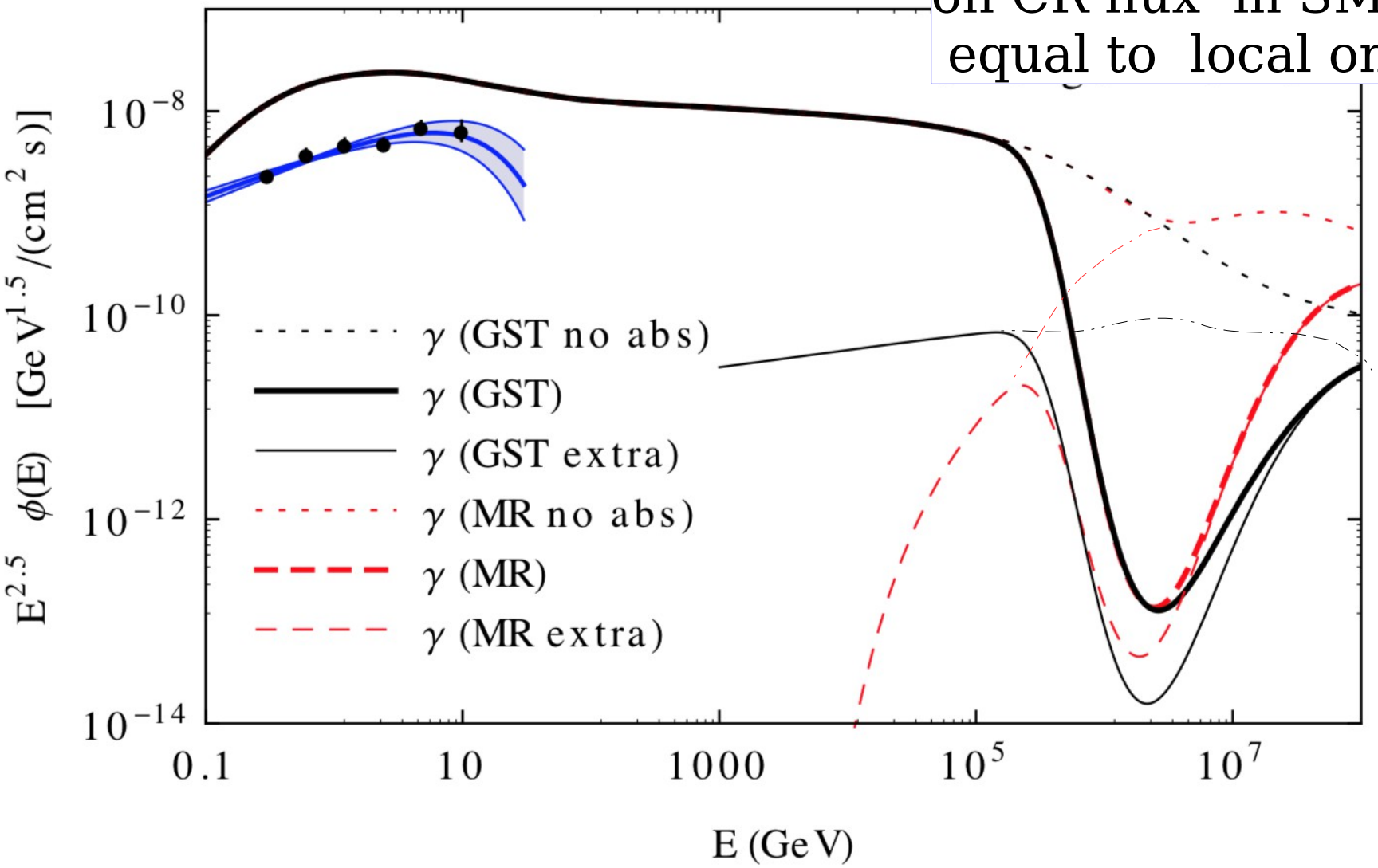
Prediction
based on the
assumption
SMC CR pop. = local one

Measurements of the LMC
and SMC by FERMI-LAT



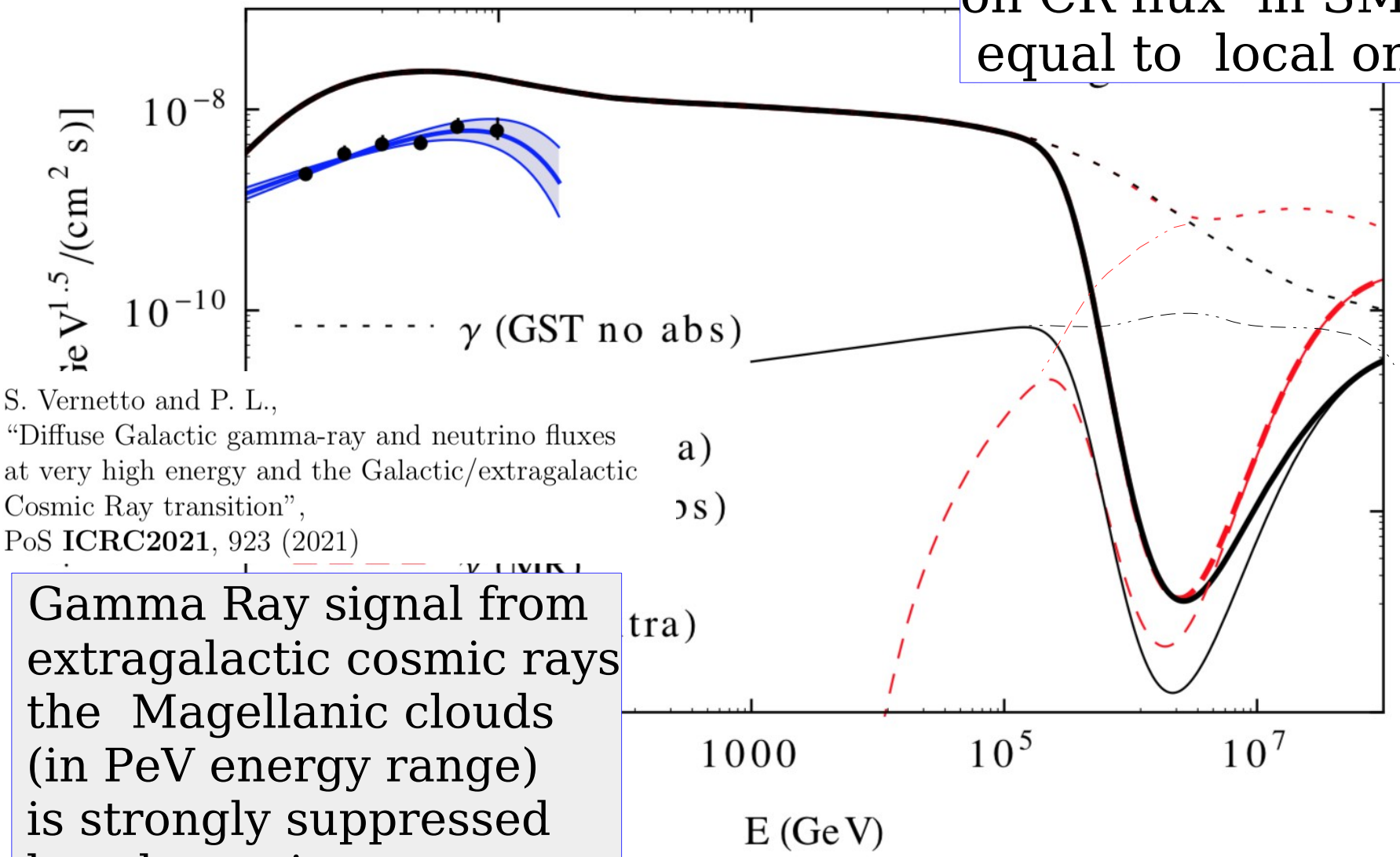
Gamma-Ray flux from the SMC (Small Magellanic Cloud)

Prediction based on CR flux in SMC equal to local one



Gamma-Ray flux from the SMC (Small Magellanic Cloud)

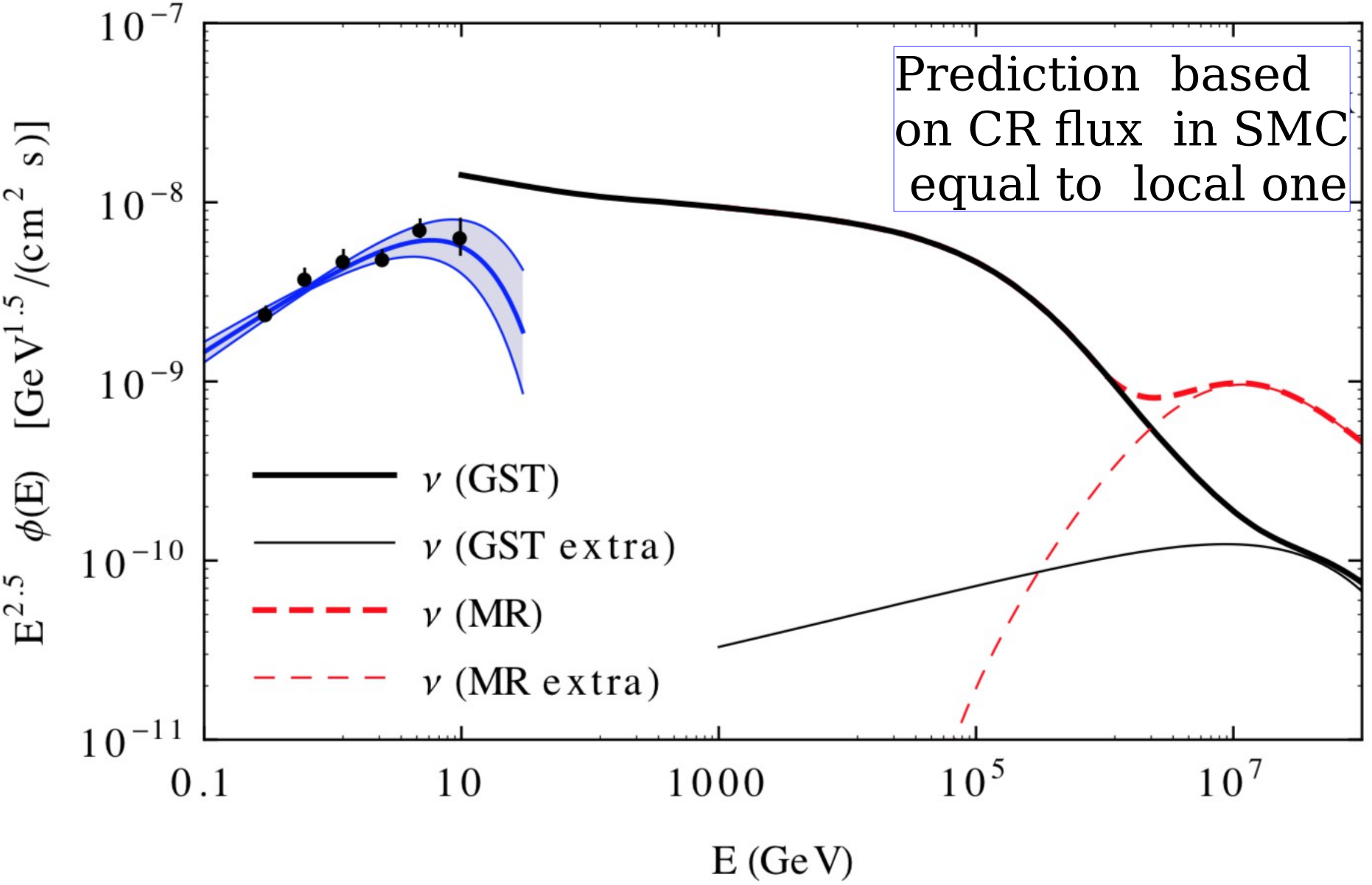
Prediction based on CR flux in SMC equal to local one



S. Vernetto and P. L.,
"Diffuse Galactic gamma-ray and neutrino fluxes at very high energy and the Galactic/extragalactic Cosmic Ray transition",
PoS **ICRC2021**, 923 (2021)

Gamma Ray signal from extragalactic cosmic rays the Magellanic clouds (in PeV energy range) is strongly suppressed by absorption

Neutrino flux from the SMC (Small Magellanic Cloud)



Final Considerations:

The study of very high energy (PeV range and beyond) diffuse fluxes of gamma rays and neutrinos is a very powerful tool to solve some of the crucial problems in cosmic ray astrophysics.

- Understand CR propagation
- Determine the CR source spectra
- The origin of the Knee
- The Galactic/Extragalactic transition

Observations at very high energy (10 PeV range) and with very broad sky coverage are difficult but very desirable