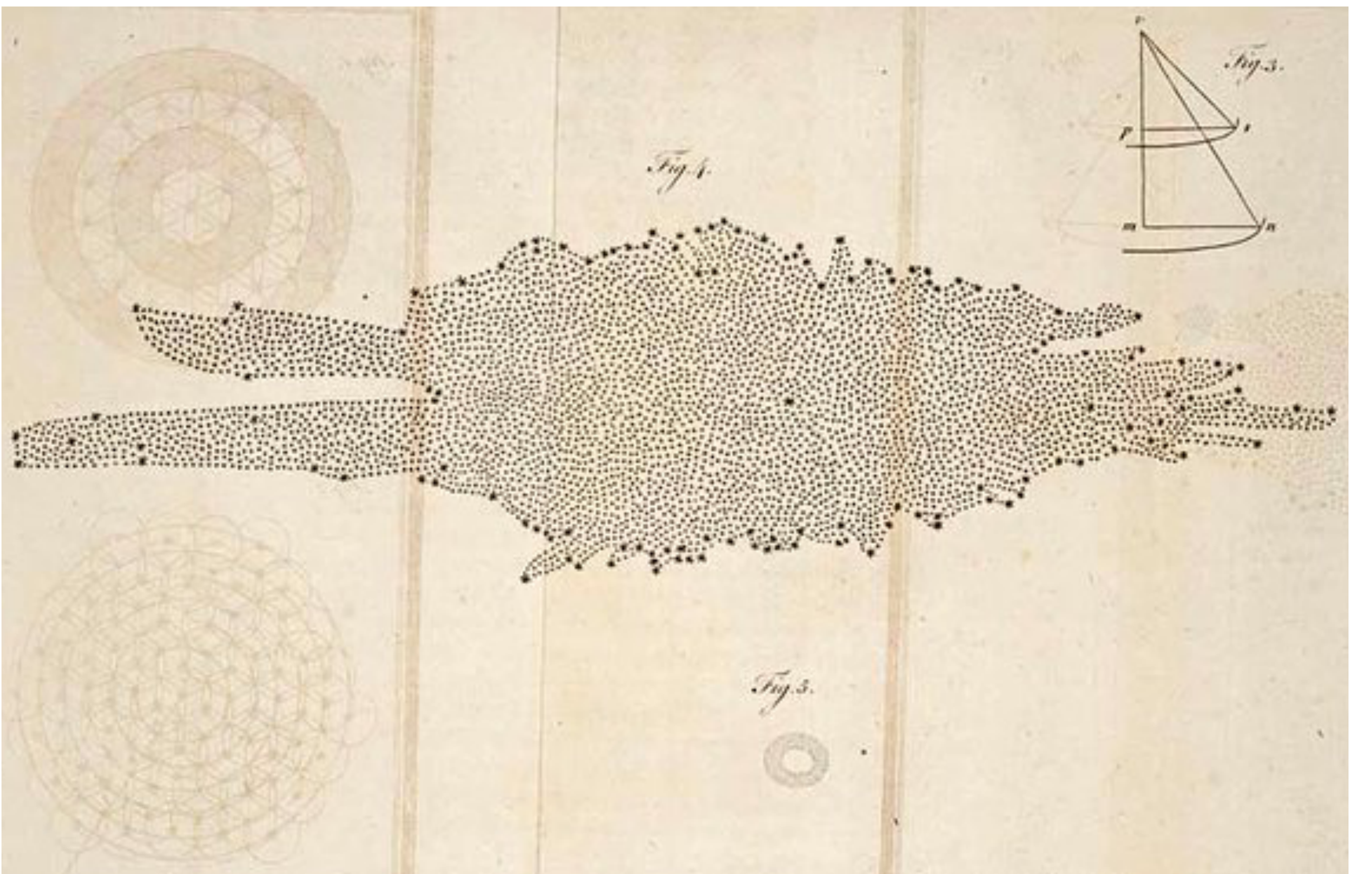
Galactic CRs: Lessons from diffuse gamma-ray observations

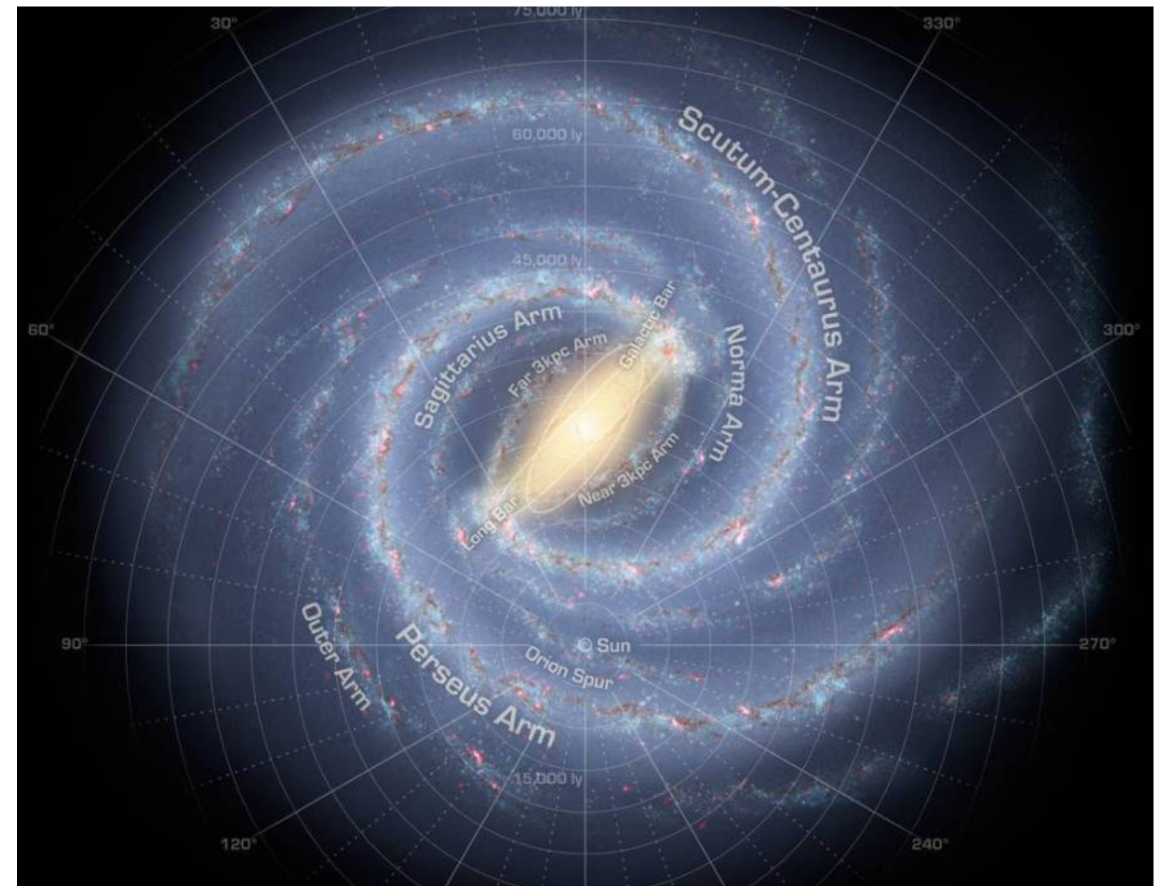
Carmelo Evoli (Gran Sasso Science Institute)

TeVPA - Geneva - 15th of September 2016

Milky Way stars

artistic view by NASA/JPL



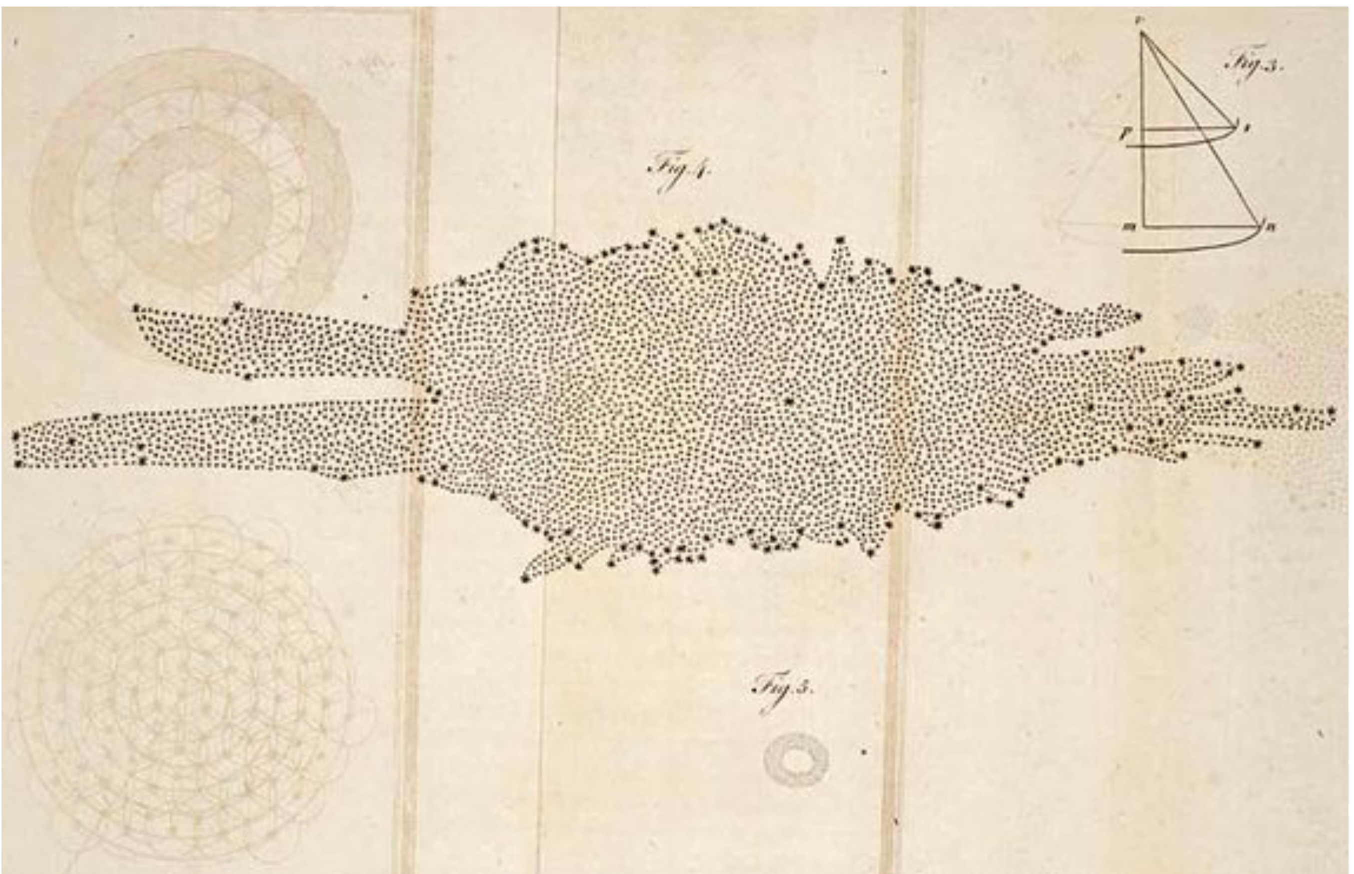


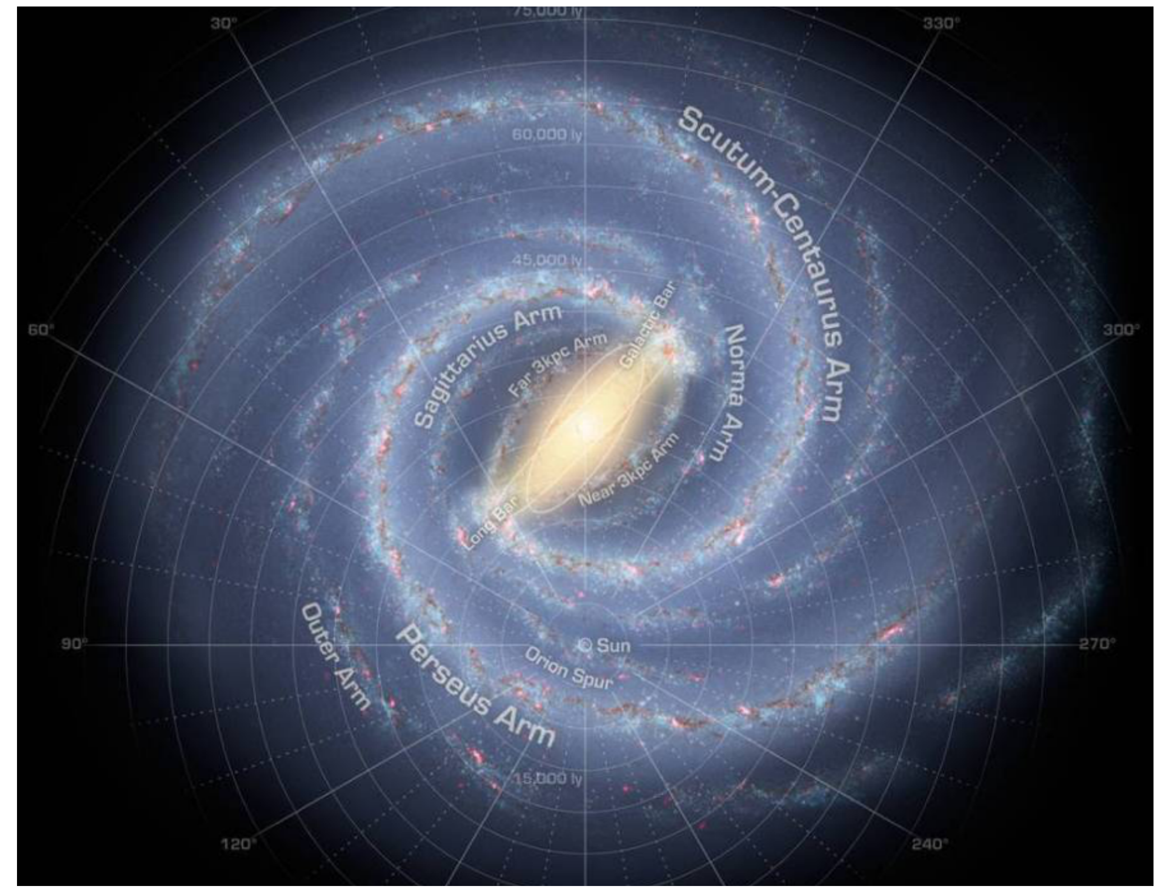
William Herschel in 1785

GAIA mission yesterday

Milky Way stars

artistic view by NASA/JPL





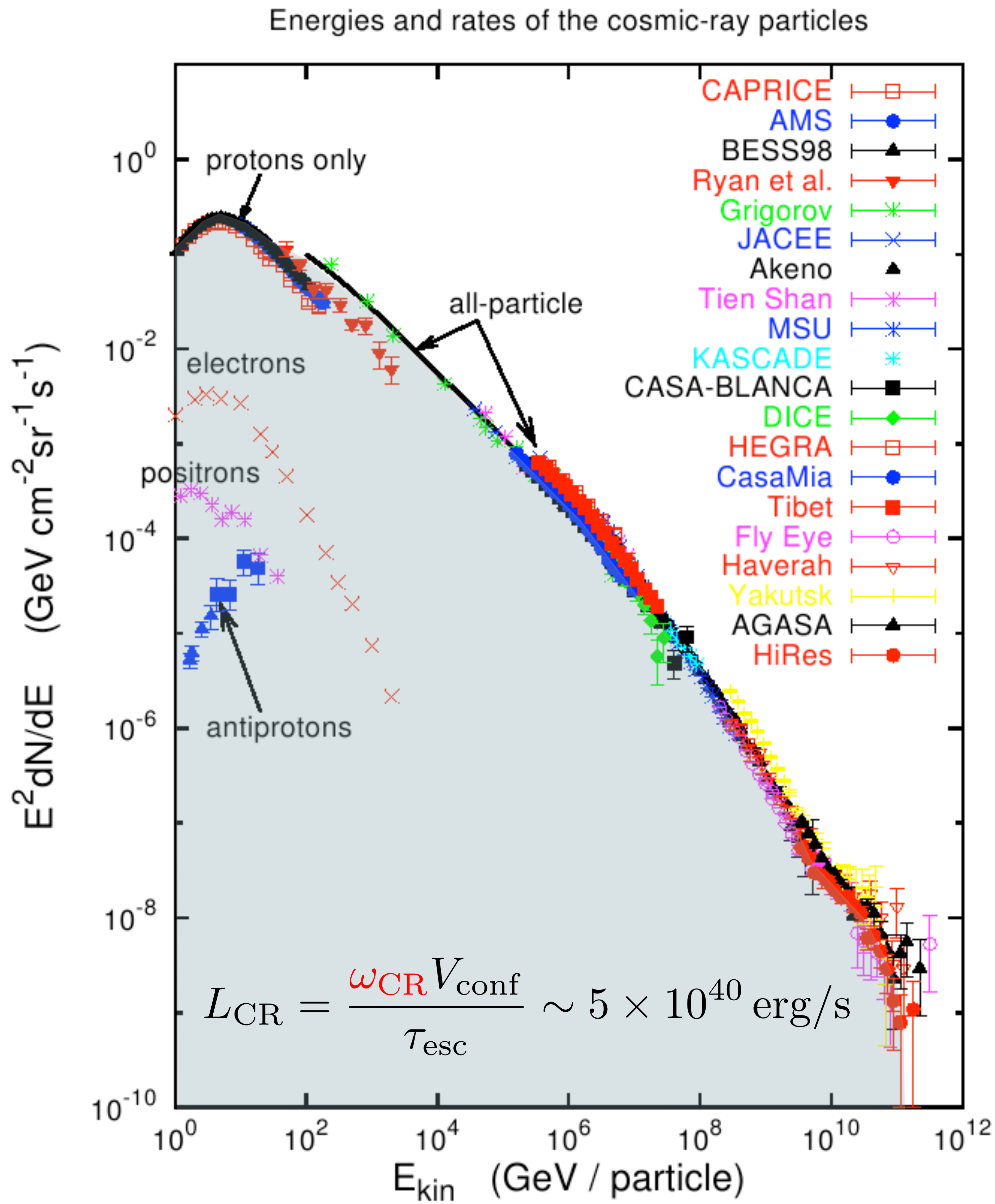
William Herschel in 1785

GAIA mission yesterday

constant *luminosity* was by far a bad assumption!

Cosmic-ray flux

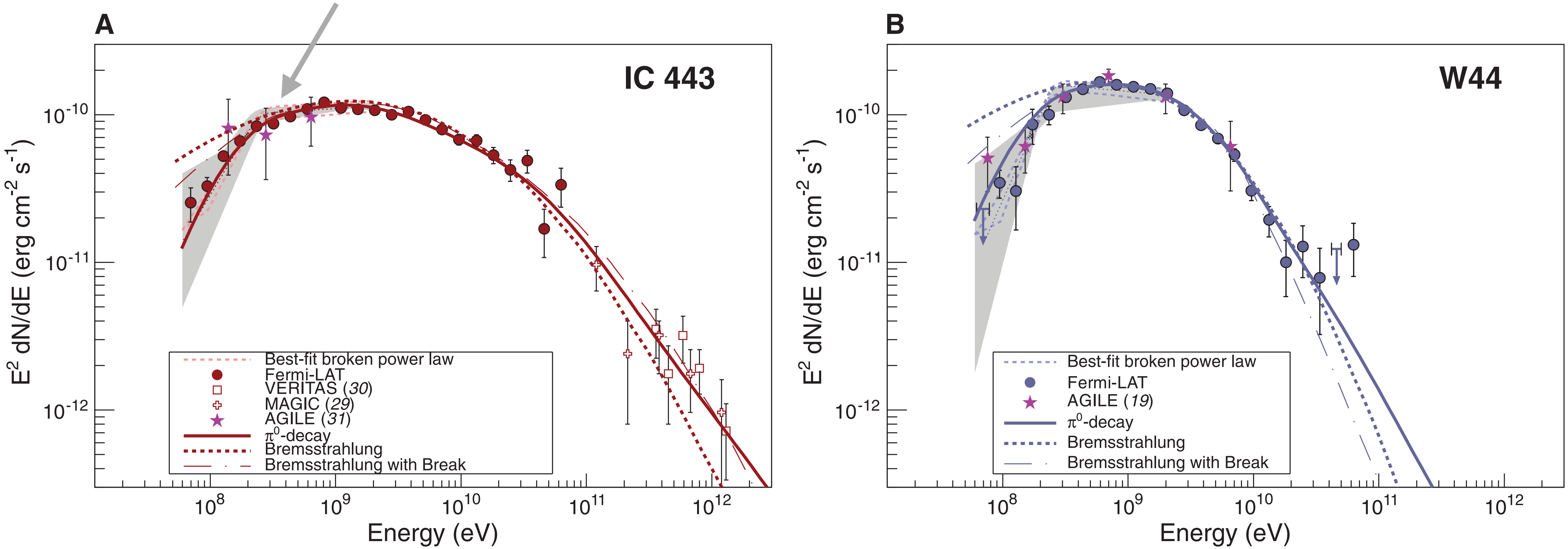
- Almost a perfect power-law over 12 energy decades.
- Observed at energy higher than terrestrial laboratories!
- Direct measurements versus air-cascade reconstructions.
- Anti-matter component.
- Transition from galactic to extra-galactic?
- Energy density in equipartition with starlight, turbulent gas motions and magnetic fields.



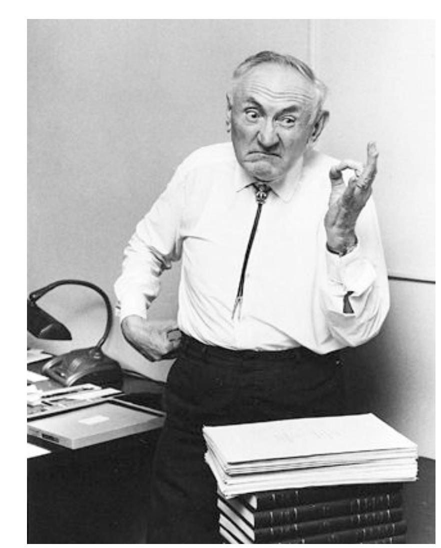
The SuperNova paradigm

S.Gabici, TeVPA2016

$$p\,p_{\mathrm{ISM}} \rightarrow \pi^0 \rightarrow \gamma\gamma$$



$$L_{\mathrm{SN}} \sim R_{\mathrm{SN}} E_{\mathrm{kin}} \sim 3 \times 10^{41}\ \mathrm{erg/s}$$



Fritz Zwicky

The SuperNova paradigm

S.Gabici, TeVPA2016

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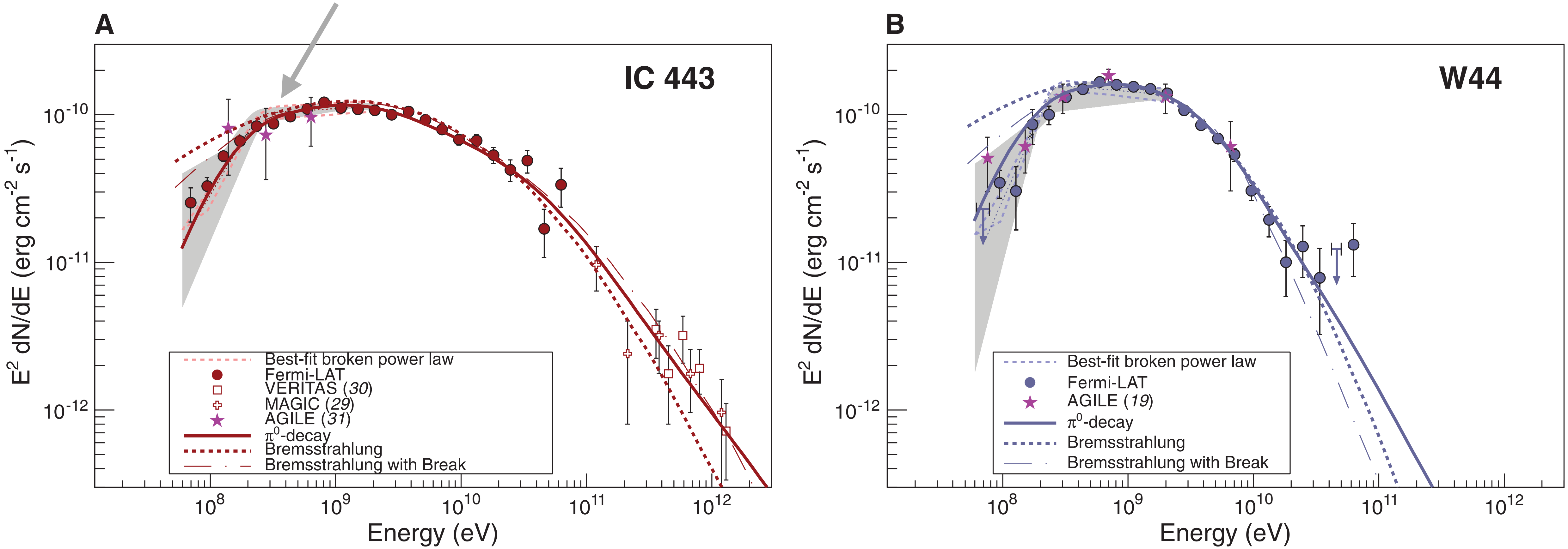
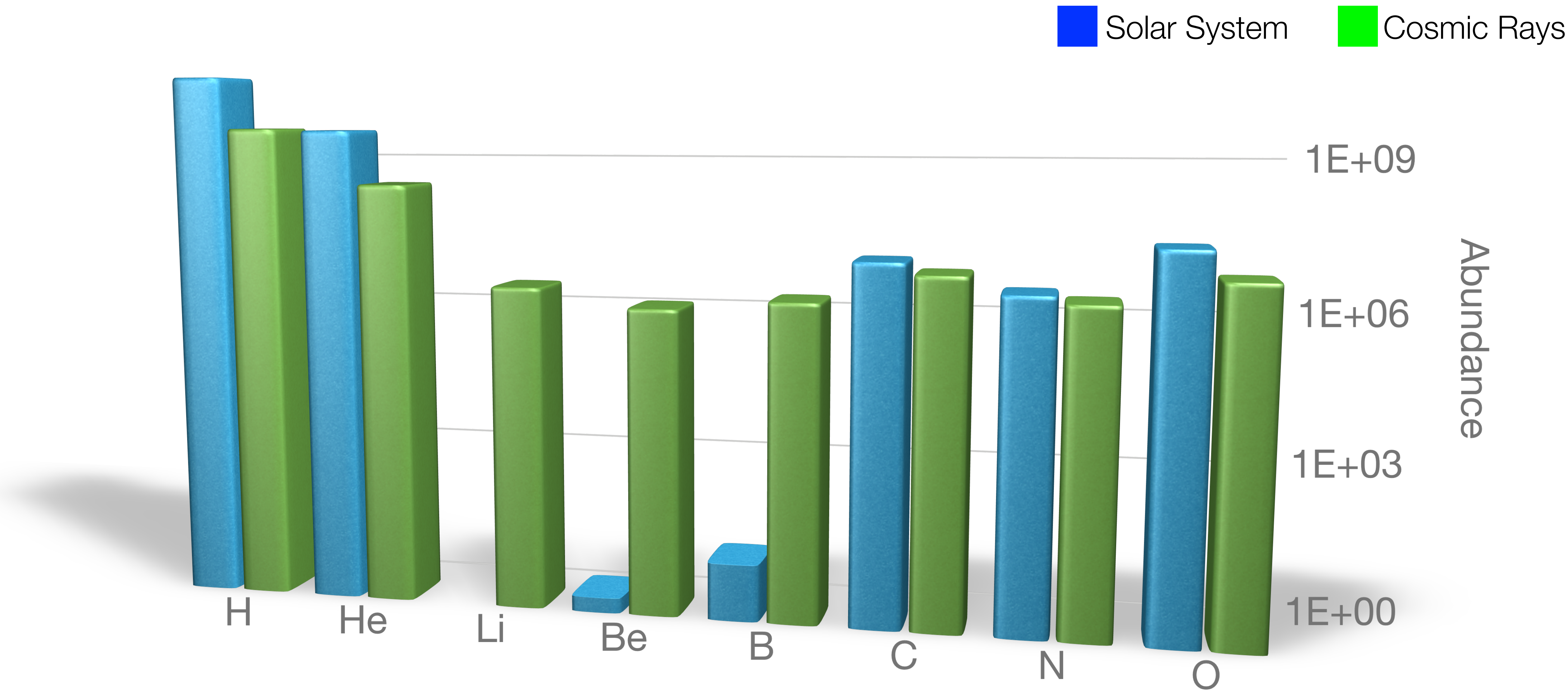


Do SNRs accelerate ENOUGH protons?

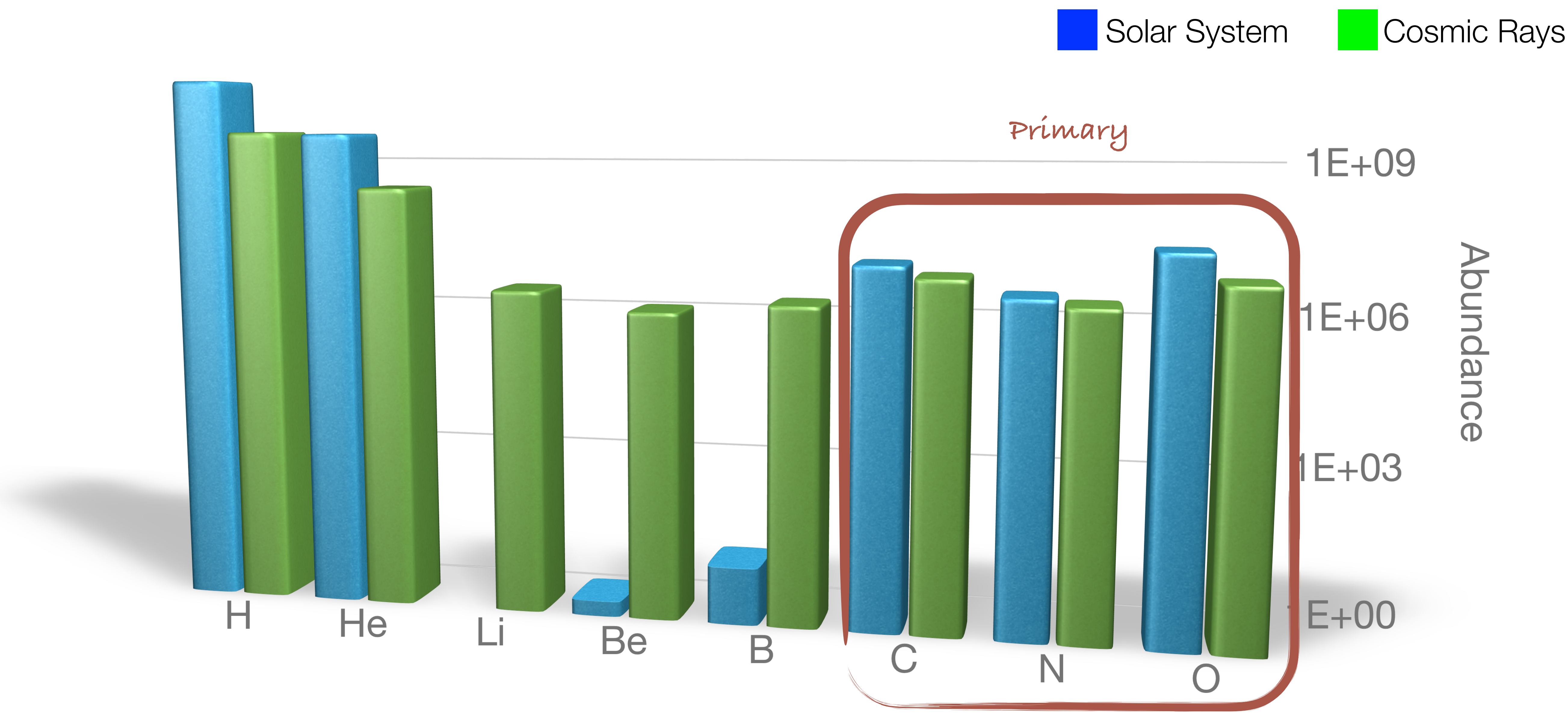
Do they accelerate protons up to the knee?

Cosmic-ray composition



$$c\tau_{\rm esc} = \frac{X(E)}{\bar{n}_{\rm ISM}\mu} \sim 10^3\,{\rm kpc}$$

Cosmic-ray composition



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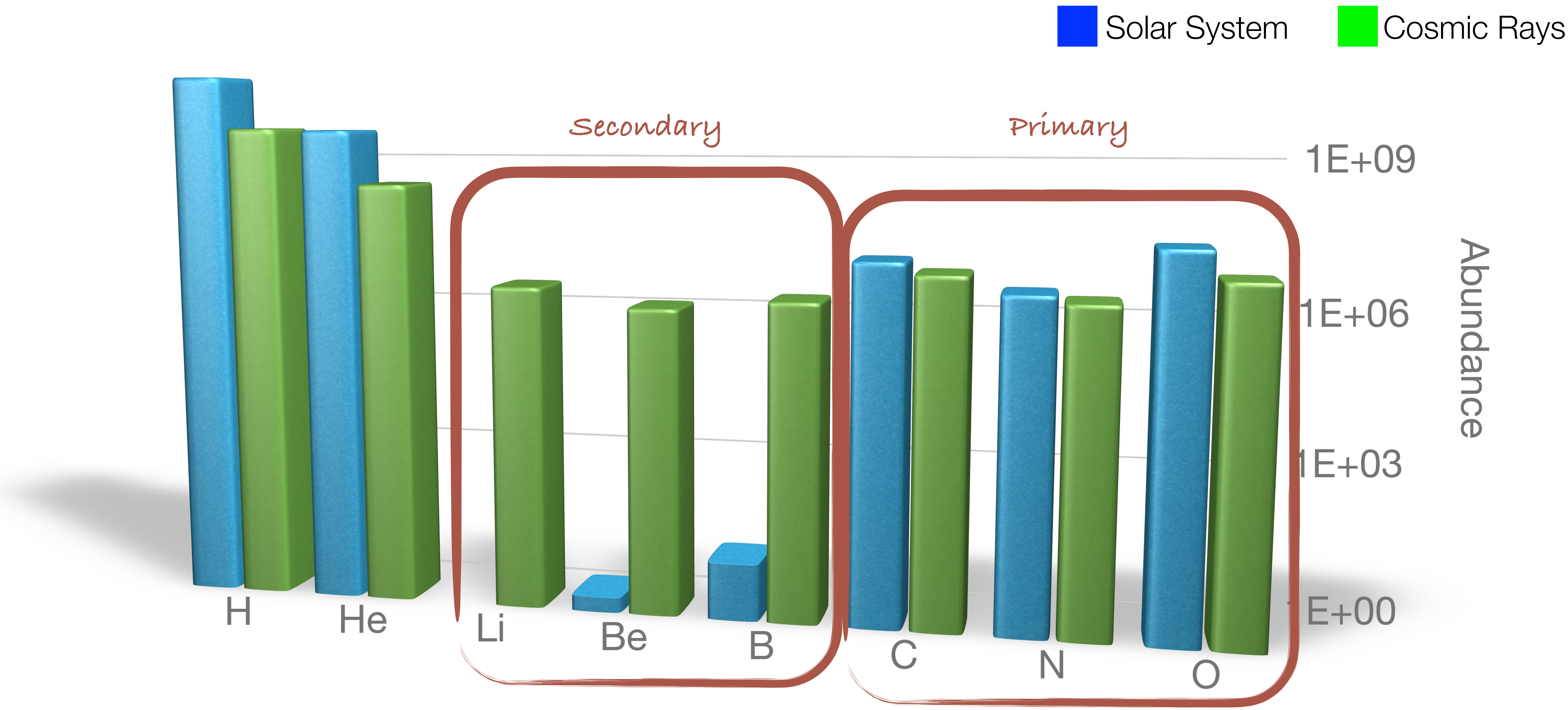
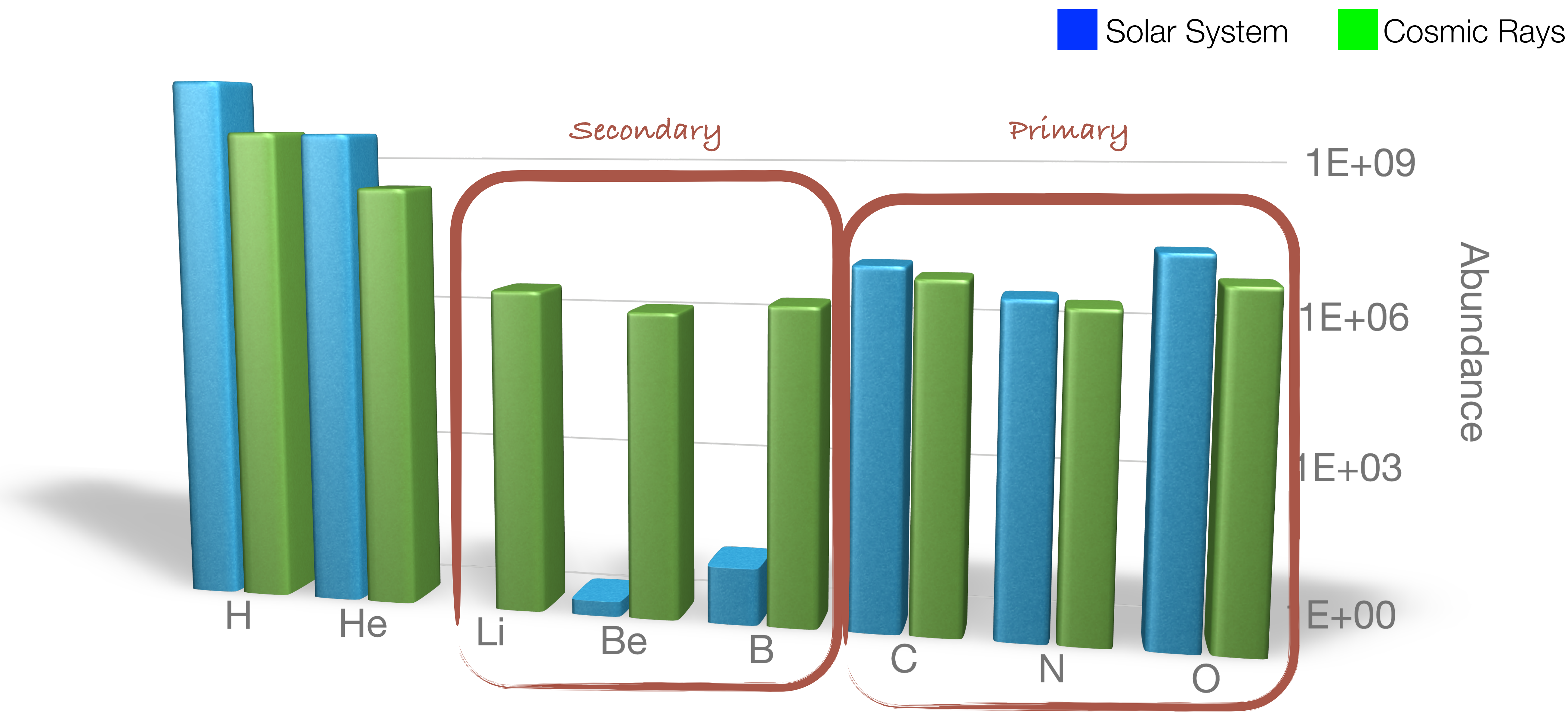
Cosmic-ray composition



$$c\tau_{\mathrm{esc}} = \frac{X(E)}{\bar{n}_{\mathrm{ISM}}\mu} \sim 10^3\,\mathrm{kpc}$$

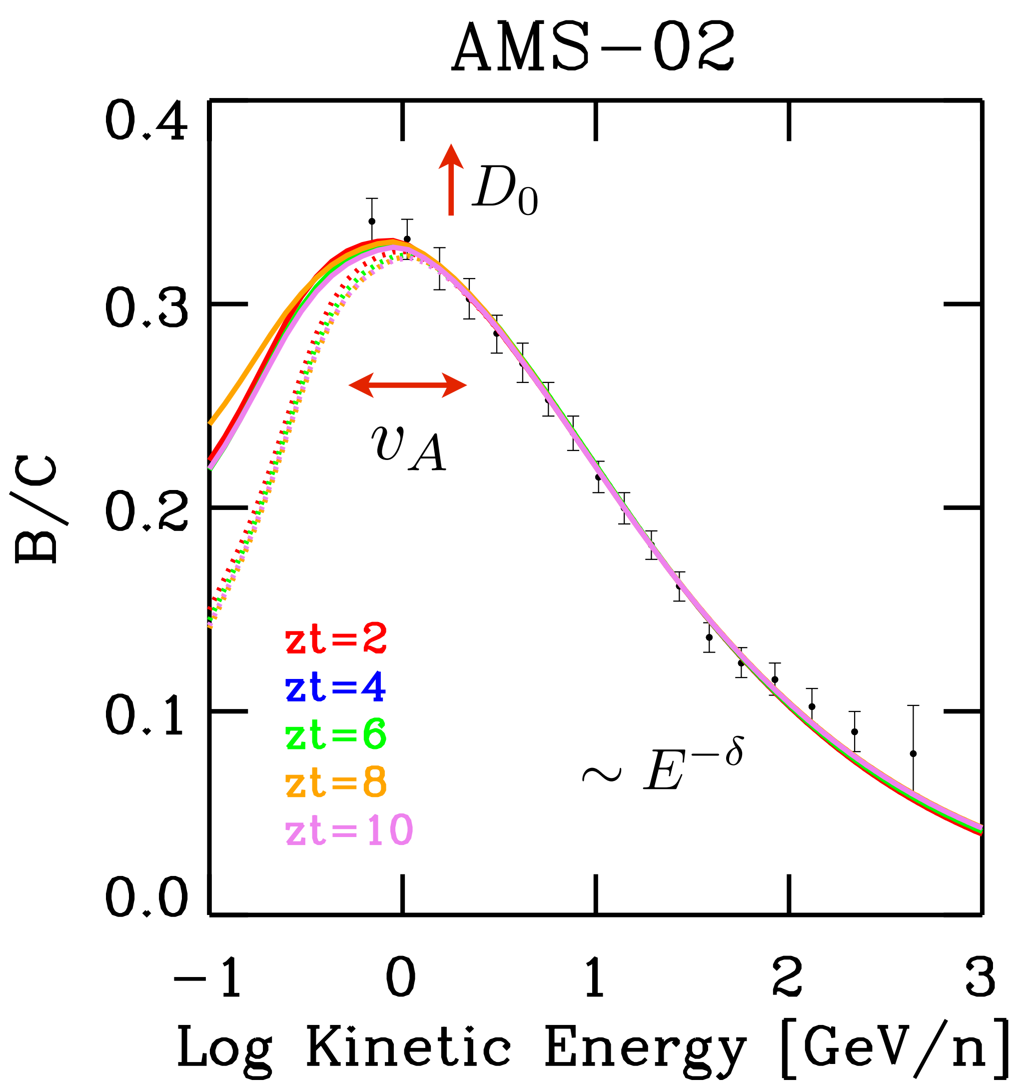
Cosmic-ray composition

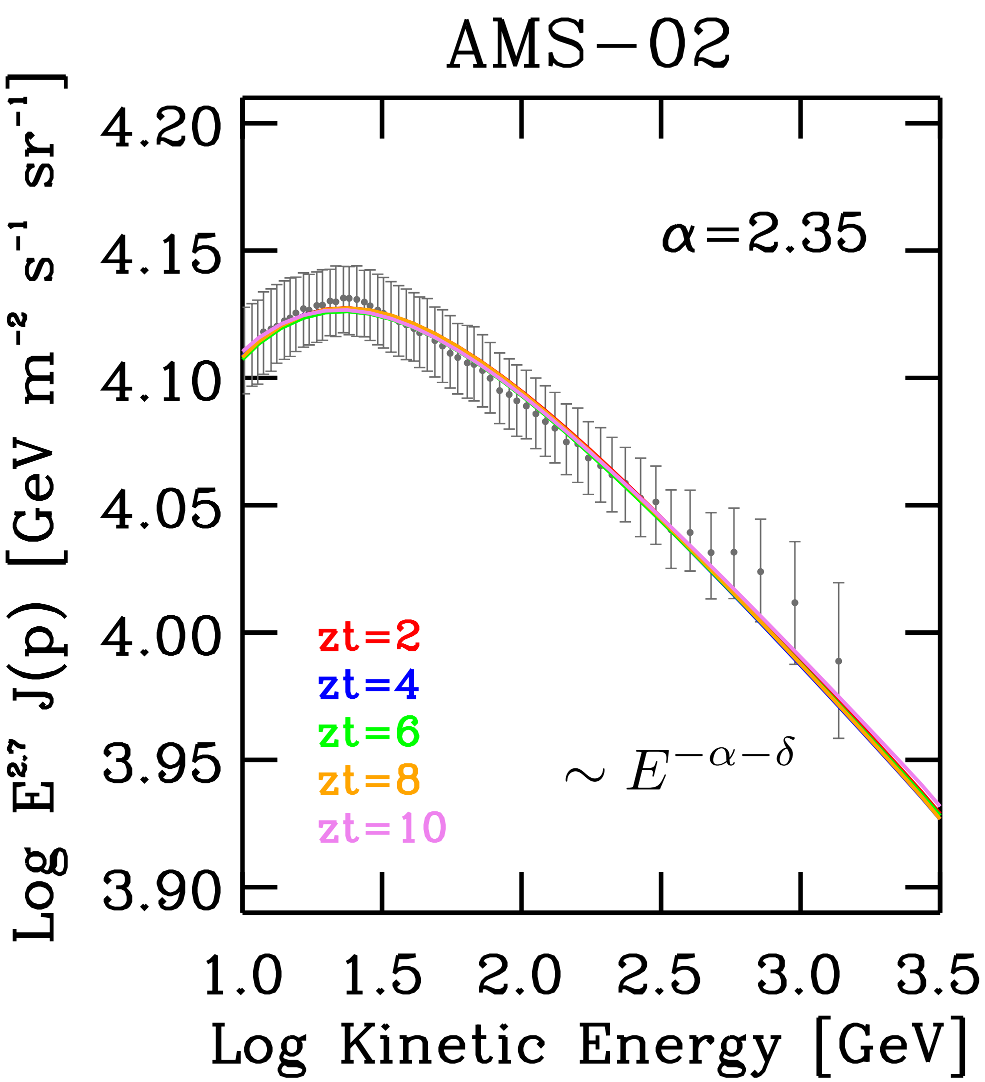


$$c\tau_{\rm esc} = \frac{X(E)}{\bar{n}_{\rm ISM}\mu} \sim 10^3\,{\rm kpc}$$ >> Galaxy size!

Fitting local observables

CE, D. Gaggero, D.Grasso, JCAP, 2016





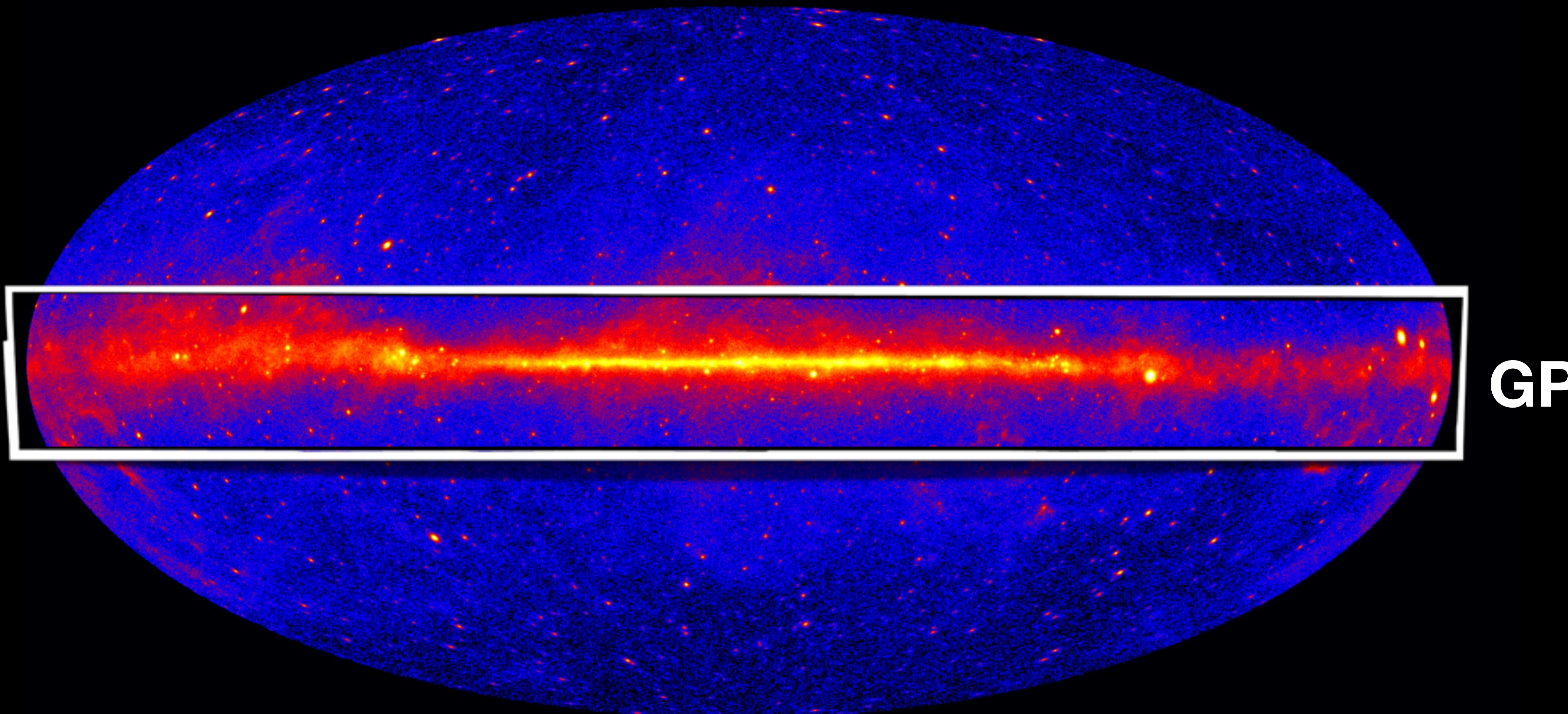
$$D(E) = D_0(E/E_0)^{\delta}$$

$$\frac{D_0}{H} \sim 0.75\, \frac{10^{28}\,\mathrm{cm}^2/\mathrm{s}}{\mathrm{kpc}}$$

$$\delta \sim 0.42$$


You are here

The gamma-ray sky in 2016

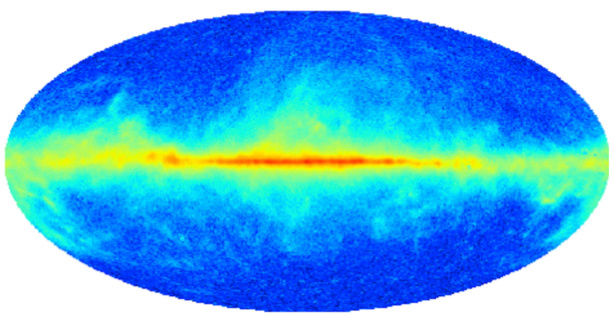


Fermi-LAT E>100 MeV by 3FGL
[LAT collaboration 2015]

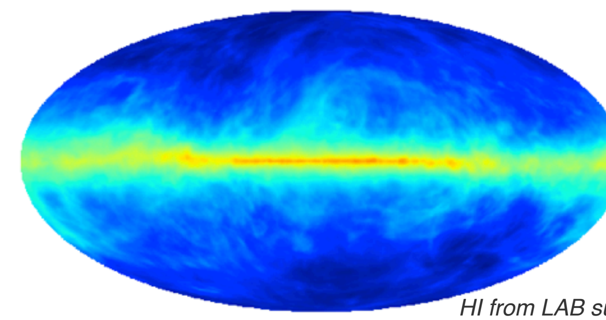
~ 70% of all observed photons coming from the diffuse Galactic emission

The extremely accurate gamma ray maps that FERMI is providing
are useful to trace the CR distribution throughout all the Galaxy!

Most of the GP γ emission is the decay of π^0 produced in CR/gas collisions

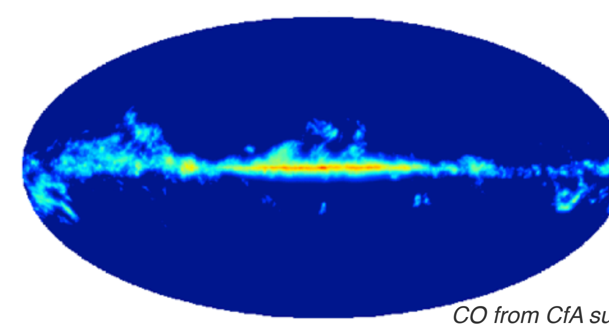


$$\leftarrow \int_{\mathrm{los}} dl \; n_p(r) \times$$



HI from LAB survey

$$+ \; n_p(r) \times \boxed{X_{\mathrm{CO}}(r) \times}$$



CO from CfA survey

H2

more details and results in Luigi Tibaldo’s talk

for a review see I.Grenier, J.Black and A.Strong, ARA&A 2015

Template analysis for the GDE

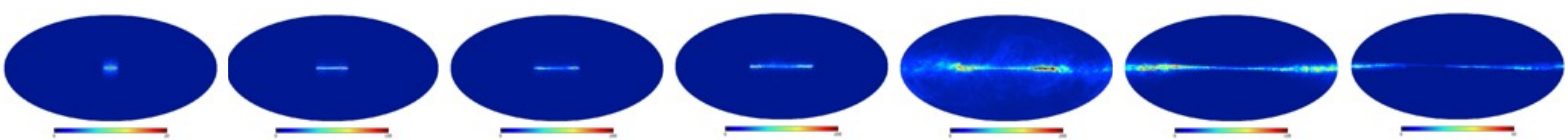
$$\Phi_\gamma = \sum_i g^i_{\rm HI} N_{\rm HI}(r_i) + \sum_i g^i_{\rm CO} W_{\rm CO}(r_i) + \sum_i g^i_{\rm IC} I_{\rm IC}(r_i) + I_{\rm iso}$$

from radio observations

$$\Phi_\gamma \sim \sum_i n_{\rm p}(r_i) N_{\rm HI}(r_i) + \sum_i n_{\rm p}(r_i) X_{\rm CO}(r_i) W_{\rm CO}(r_i)$$

from a propagation model

free parameters



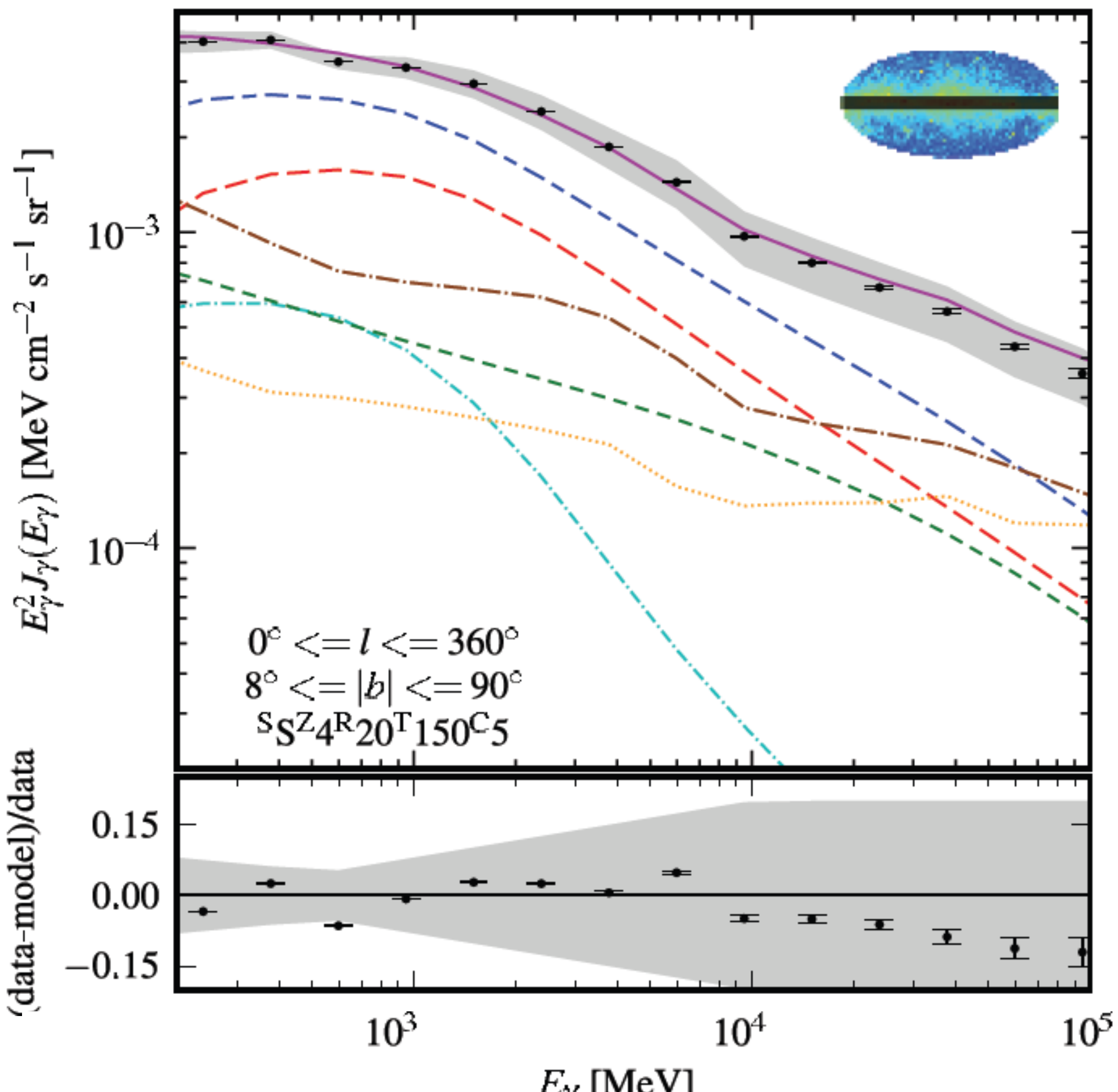
Galactocentric HI rings

Ackermann et al., ApJ, 750 (2012)

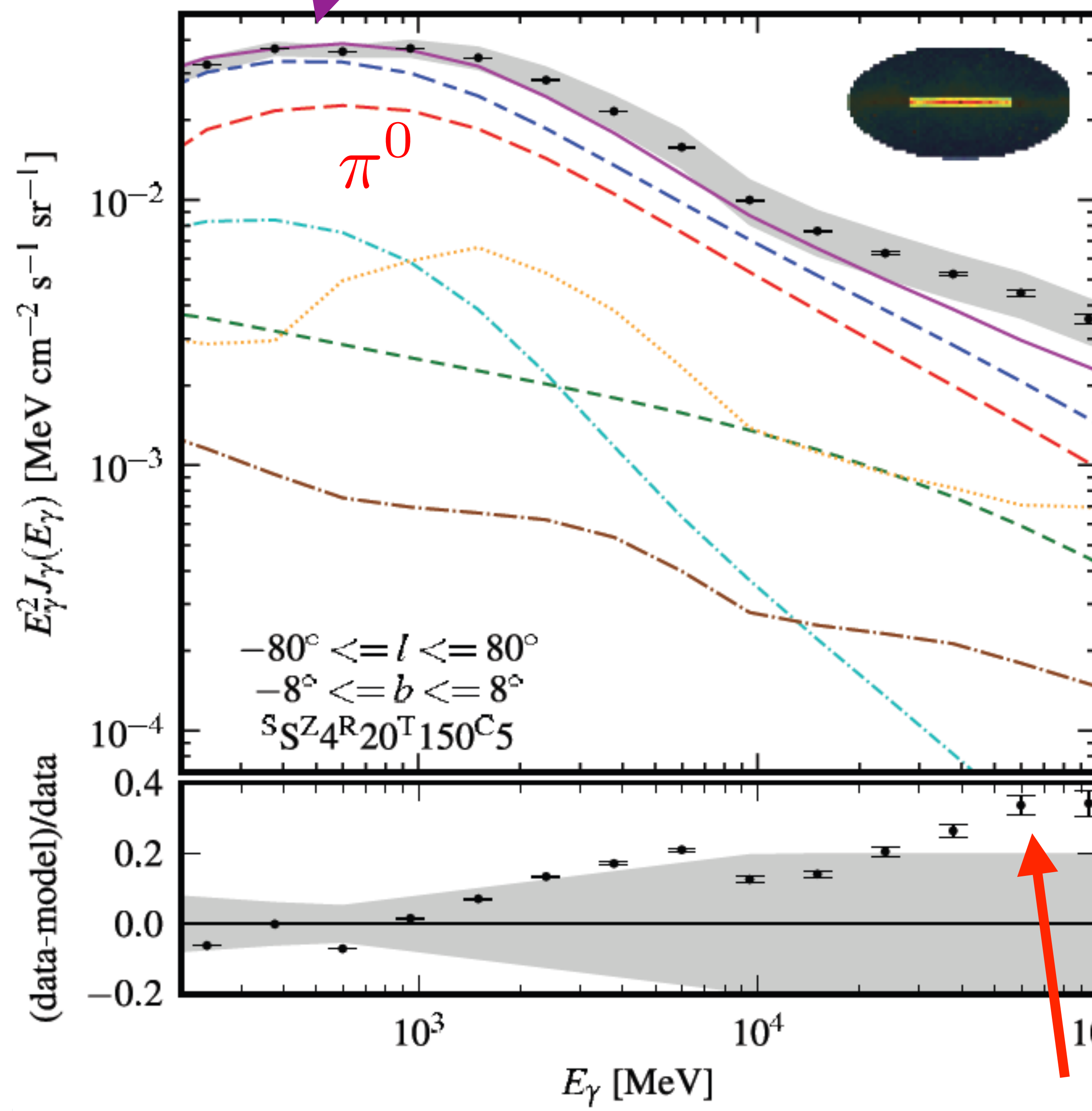
FERMI galactic diffuse emission

FERMI reference model for the galactic emission

full sky, without the GP



inner GP



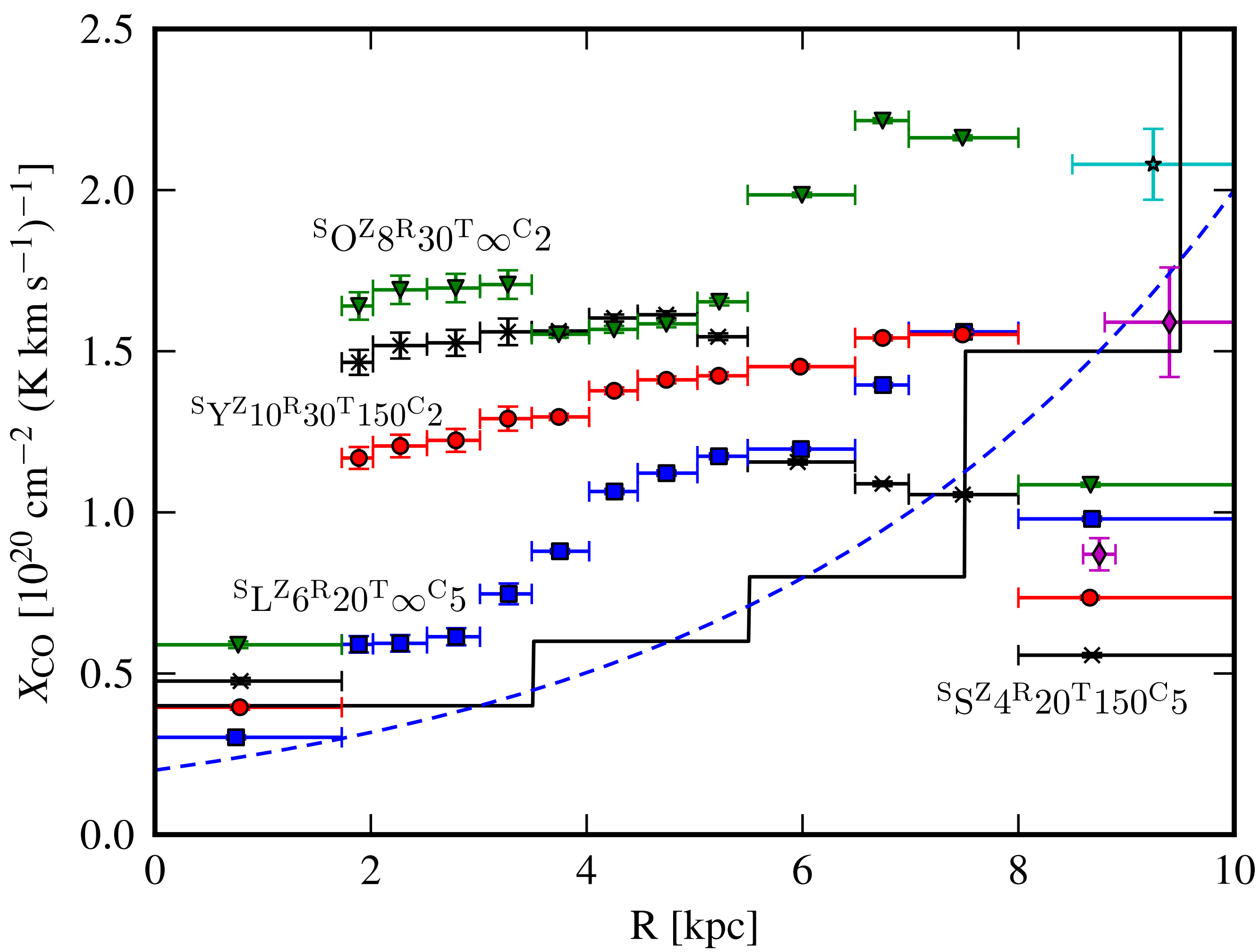
DGE

@100 GeV

Ackermann et al., ApJ, 750 (2012)

What do we learn about galactic CR?

see Olaf Reimer's talk at TeVPA2015



- standard CR propagation/interaction models adequate for local measurements
- diffuse emissions are reproduced at the expenses of consistent physics (i.e., normalisations "here & then")
- FERMI DGE became "a point-source analysis model"!

Model *independent* template analysis

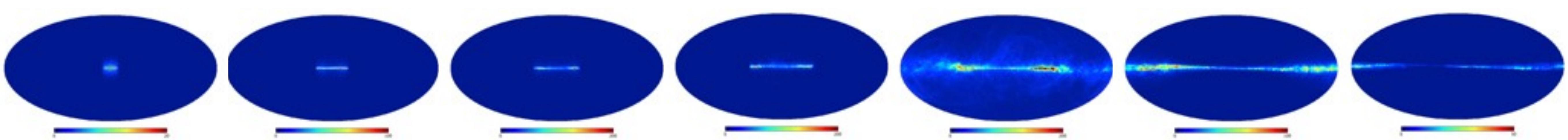
R. Yang, F. Aharonian, **CE**, PRD, 2016

$$\Phi_\gamma = \sum_i g^i_{\rm HI} N_{\rm HI}(r_i) + \sum_i g^i_{\rm CO} W_{\rm CO}(r_i) + \sum_i g^i_{\rm IC} I_{\rm IC}(r_i) + I_{\rm iso}$$

$$\Phi_\gamma \sim \sum_i n_{\rm p}(r_i) N_{\rm HI}(r_i) + \sum_i n_{\rm p}(r_i) X_{\rm CO}(r_i) W_{\rm CO}(r_i)$$

free parameters

free parameters

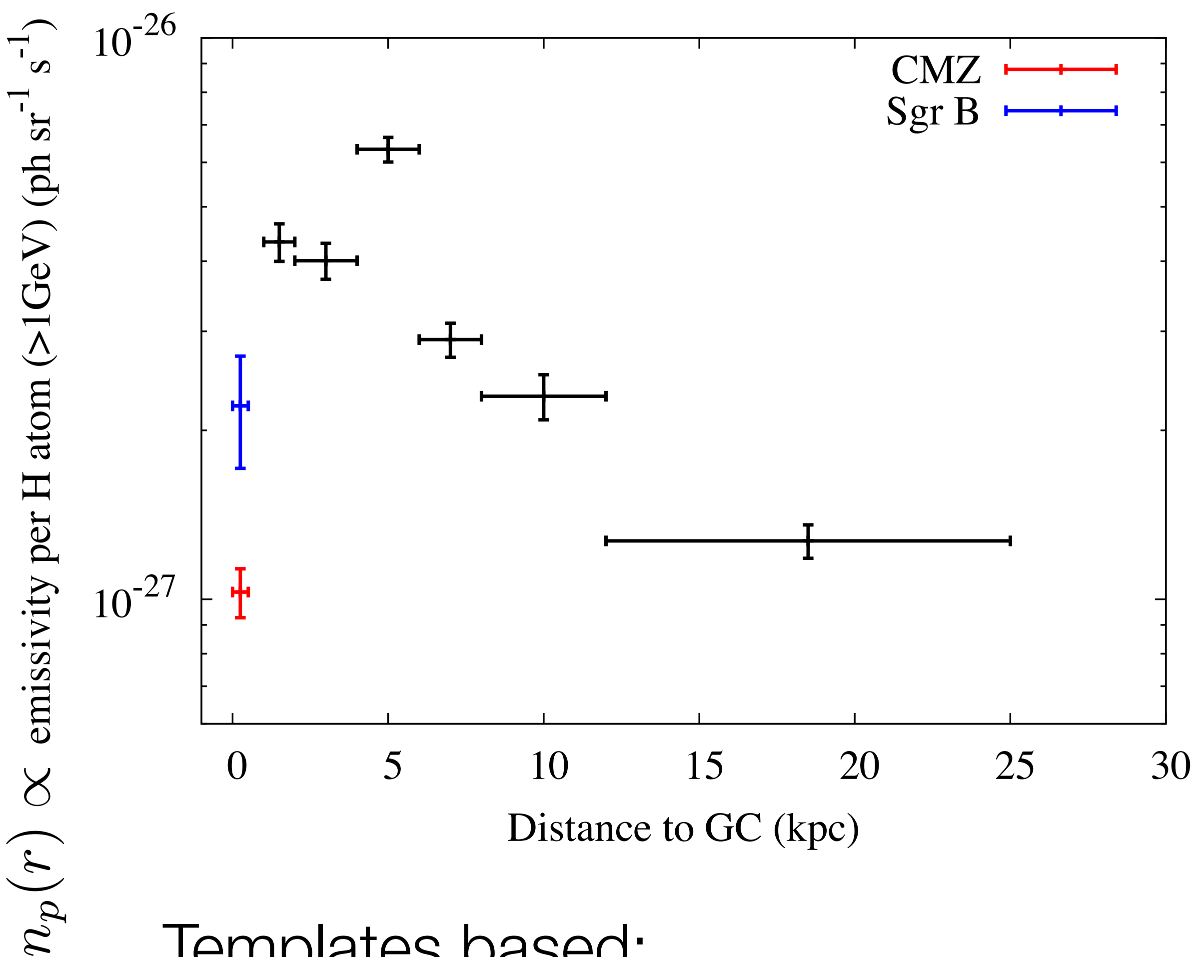


Galactocentric HI rings

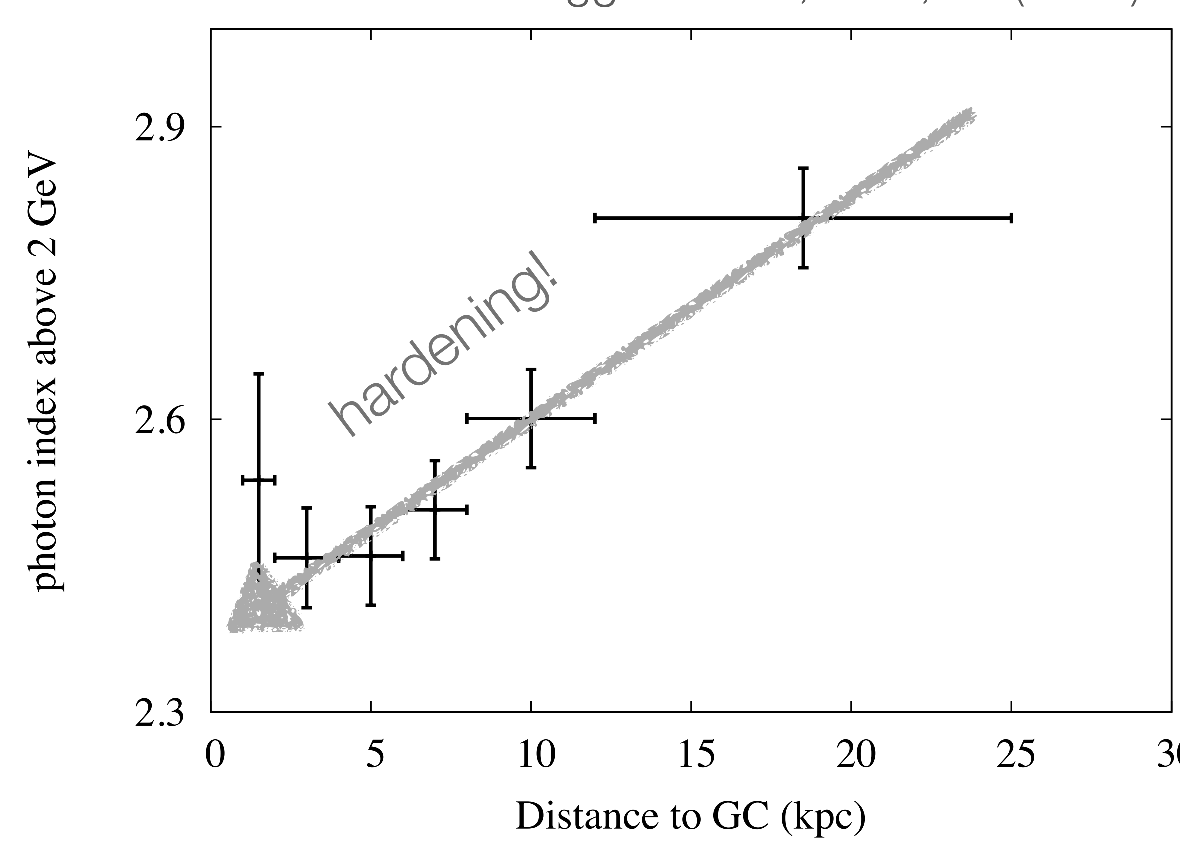
The radial distribution of the diffuse γ-ray emissivity in the GP

R. Yang, F. Aharonian, **CE**, PRD, 2016

$|b| < 5^\circ$



see also D. Gaggero et al., PRD, 91 (2015)



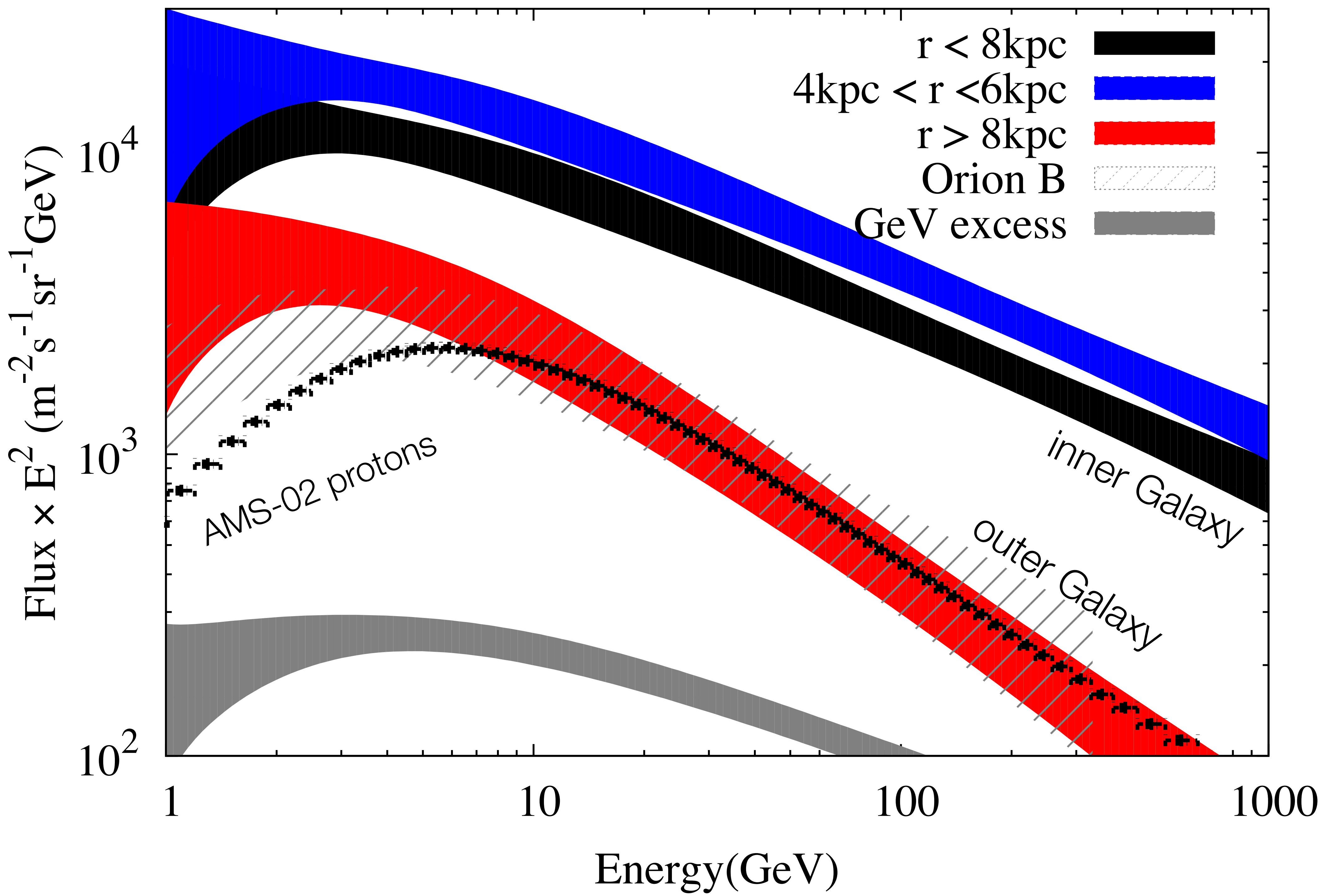
Templates based:

- on CO galactic survey of with the CfA 1.2m millimetre-wave Telescope
- the Leiden/Argentine/Bonn (LAB) Survey on HI gas
- dust opacity maps from PLANCK for "*dark gas*"

Main result: Both the absolute emissivity and the energy spectra of γ-rays derived in the interval 0.2-100 GeV show significant variations along the galactic plane.

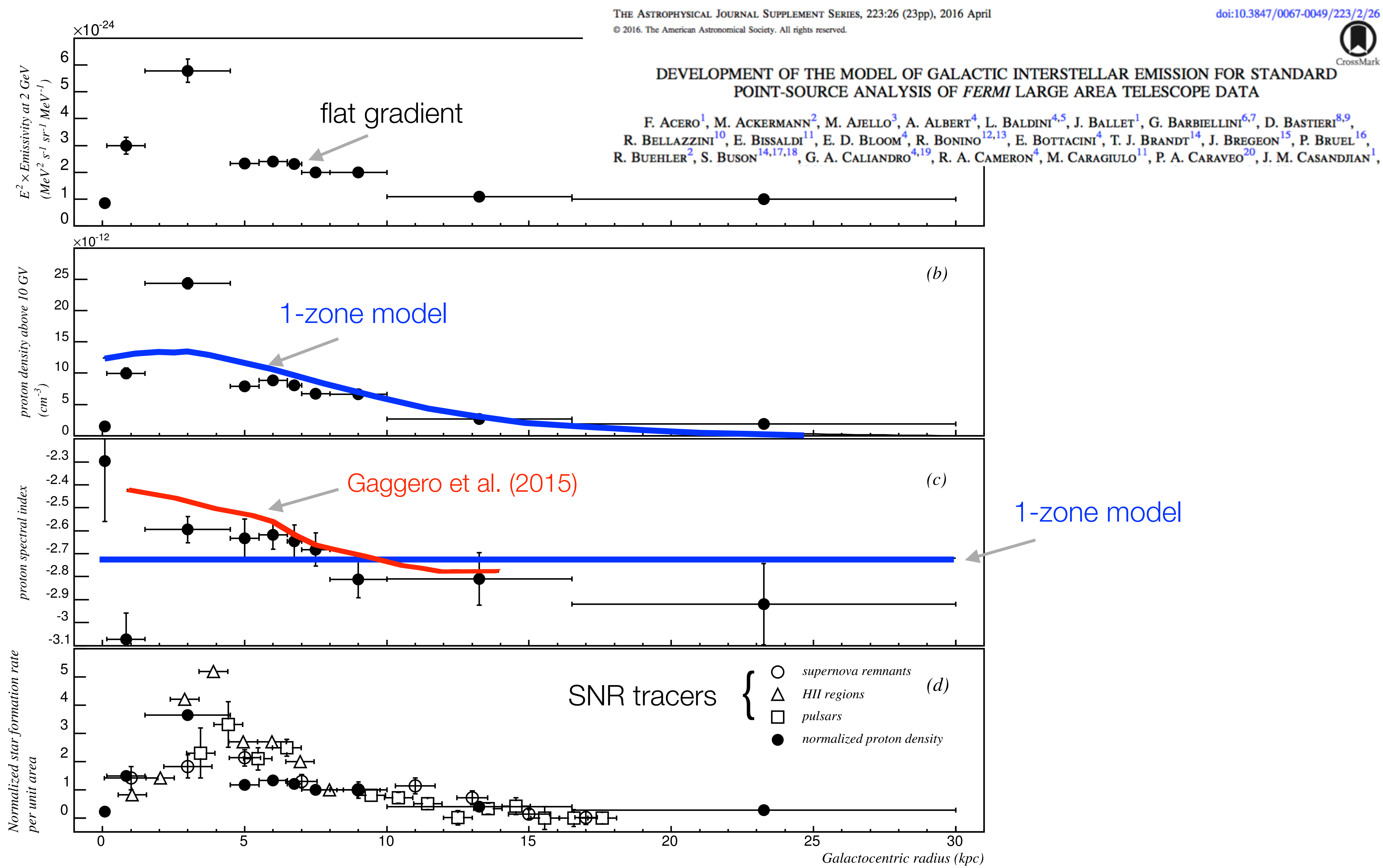
Comparison with local proton spectrum

R. Yang, F. Aharonian, **CE**, PRD, 2016



FERMI galactic interstellar emission model (GEIM)

FERMI Collaboration, APJS, 2016



Disclaimer:

Ginzburg & Syrovatsky (1964)

diffusion-reacceleration-advection transport equation:

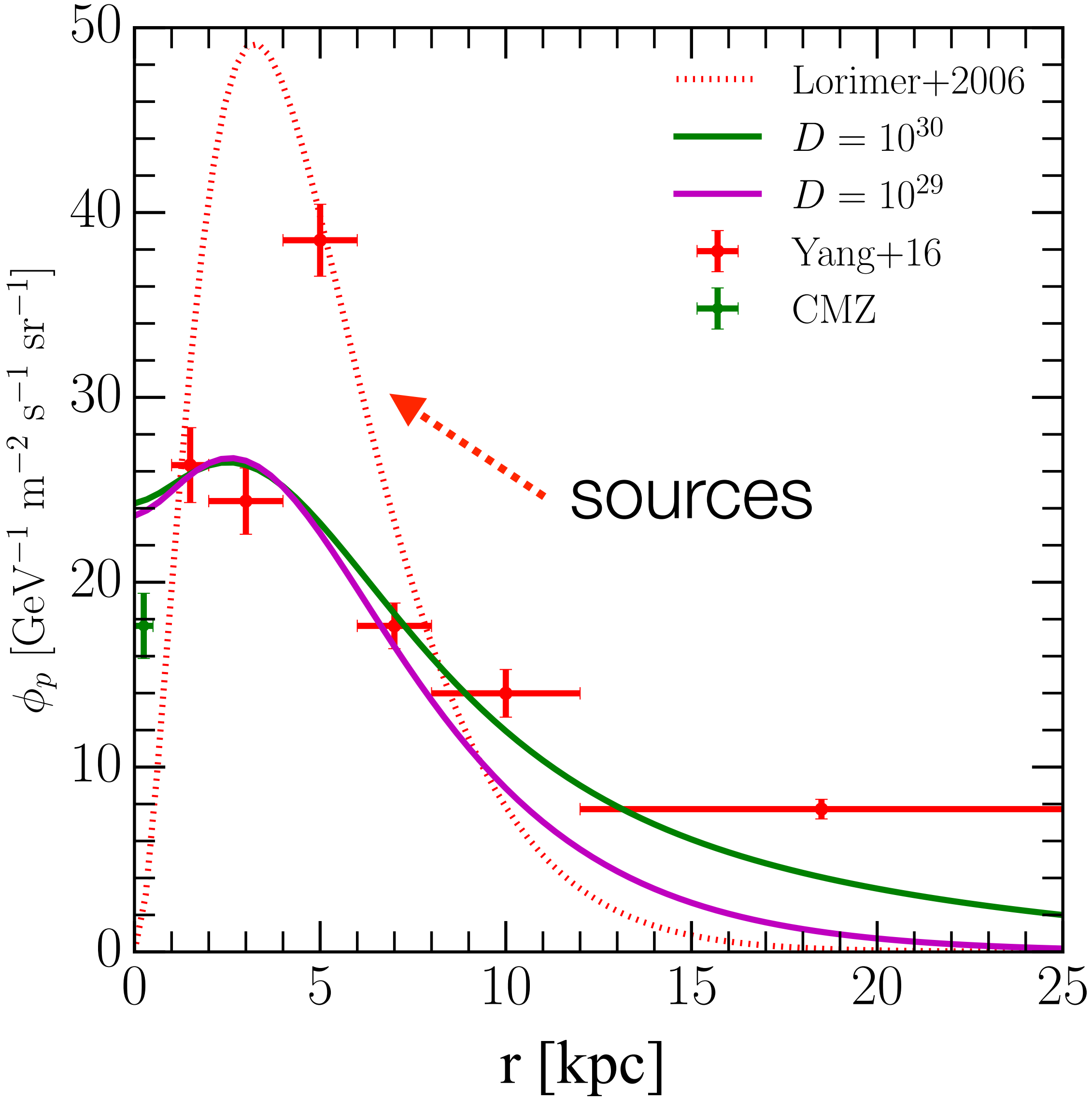
$$\underbrace{\partial_t N}_{\text{time ev.}}^{\to 0} - \underbrace{\nabla \cdot (D_{\vec{x}} \nabla N)}_{\text{spatial diffusion}} - \underbrace{\nabla \cdot (\vec{v}_w N)}_{\text{advection}} - \underbrace{\partial_p \left[p^2 D_p \partial_p \left(\frac{N}{p^2} \right) \right]}_{\text{re-acceleration}} =$$

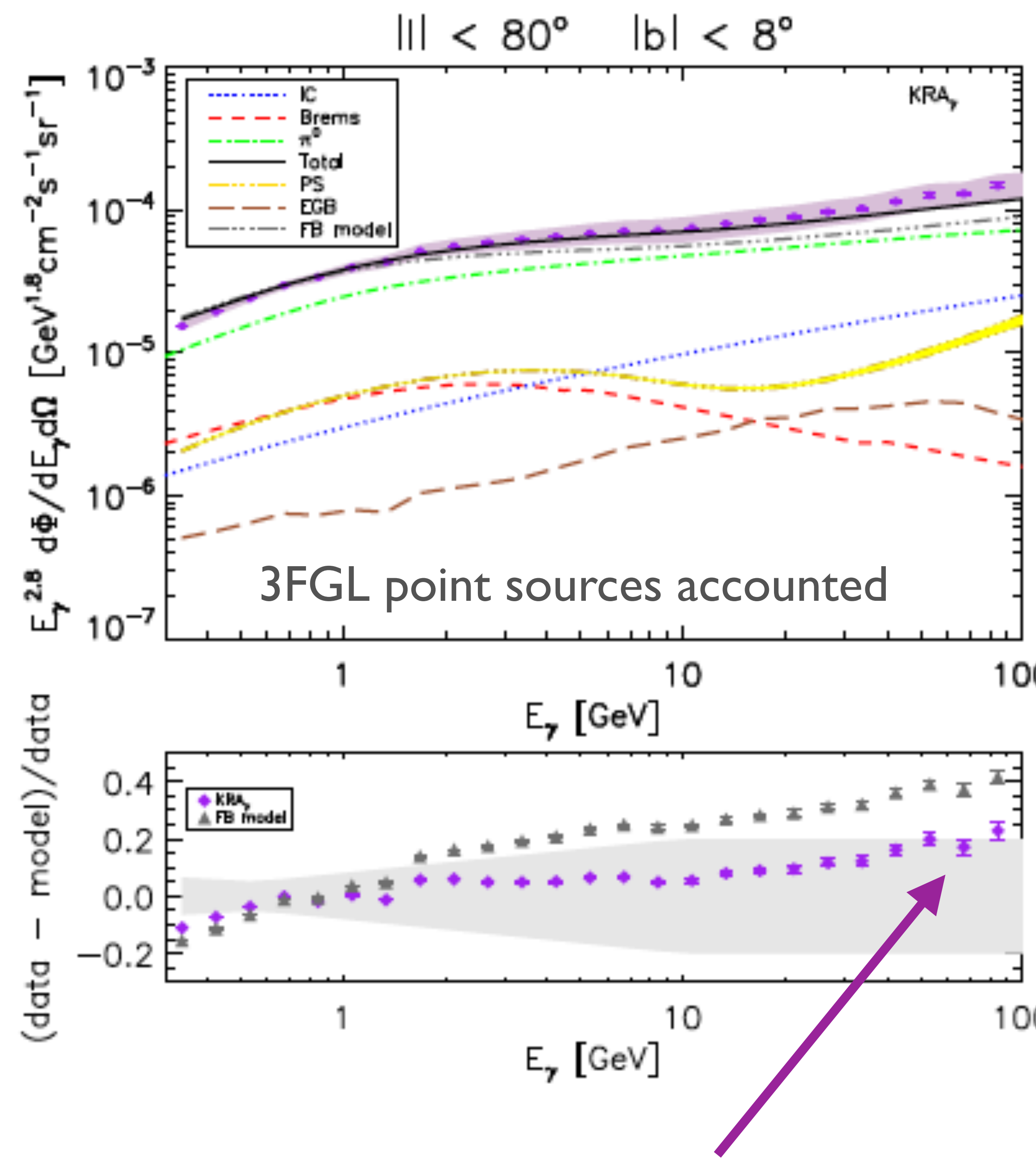
+ Sources
- Losses
- Spallation

in **OneZoneModel**s these 3 operators are *constant* in space!

In tension with the SN paradigm?

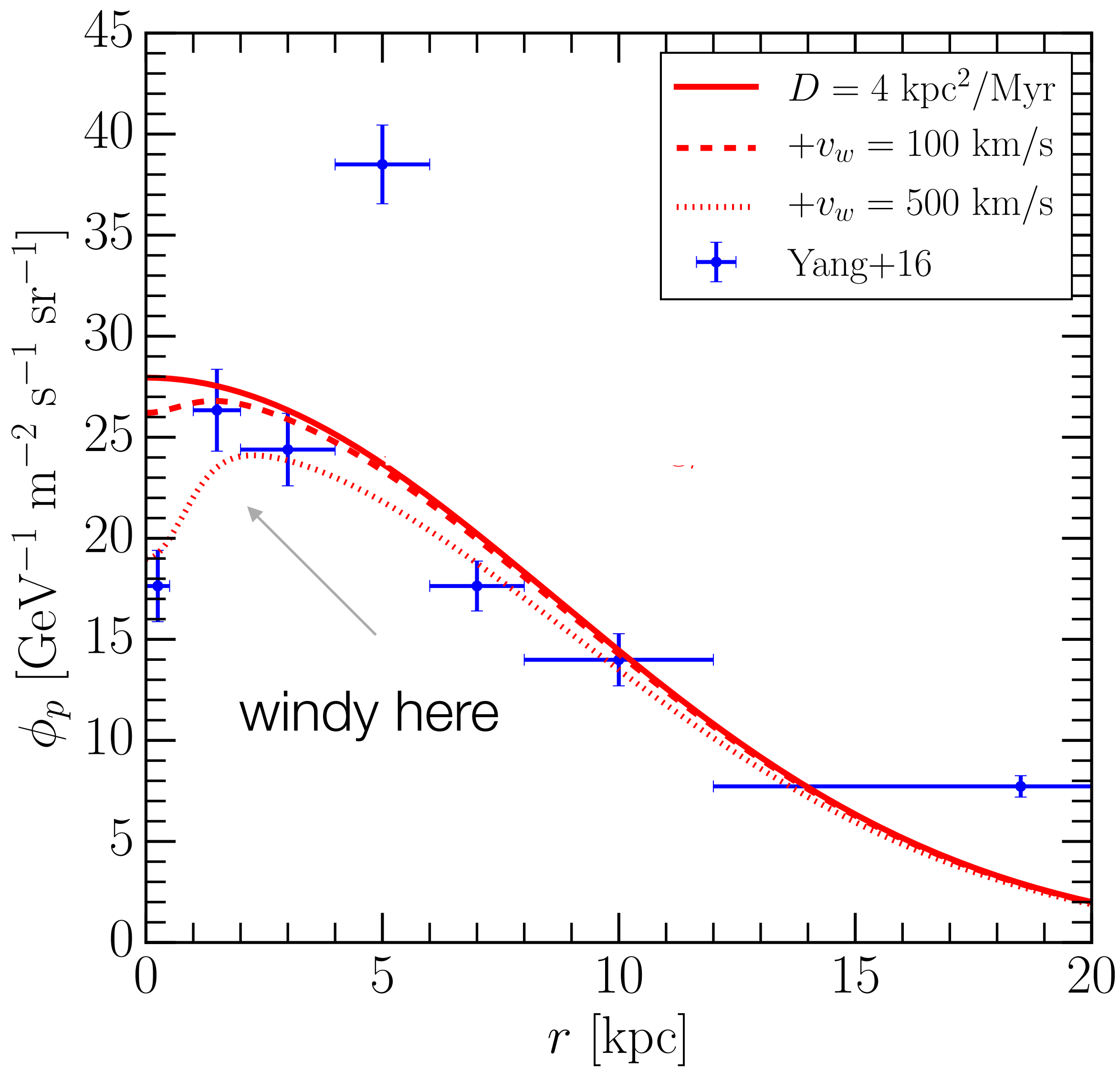
see Daniele Gaggero's talk



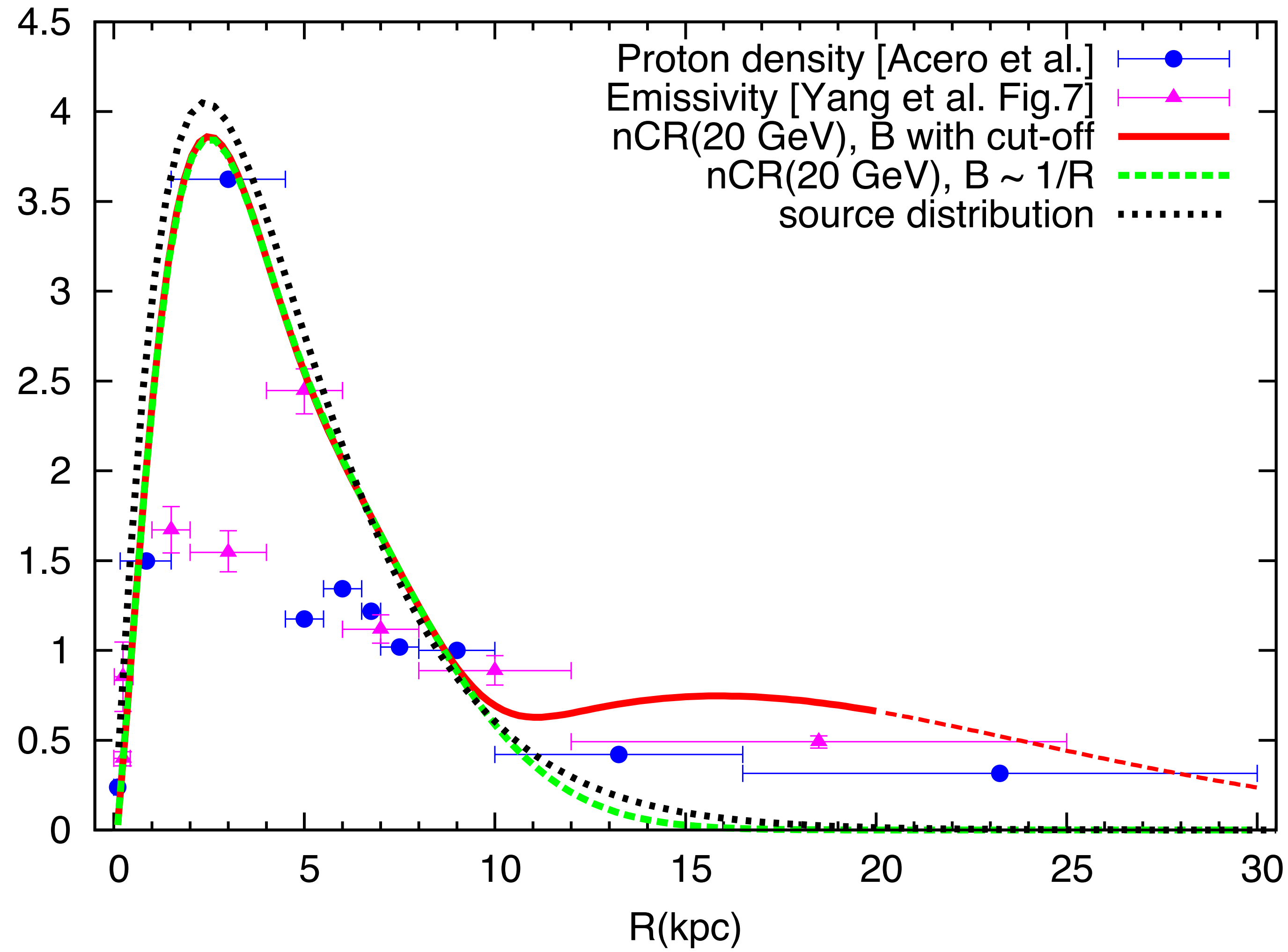


$$\delta(r) = A + B \cdot \left(\frac{r}{r_\odot}\right)$$

looking for alternative scenarios: sources or propagation?



S. Recchia, P. Blasi and G. Morlino, arXiv:1604.07682



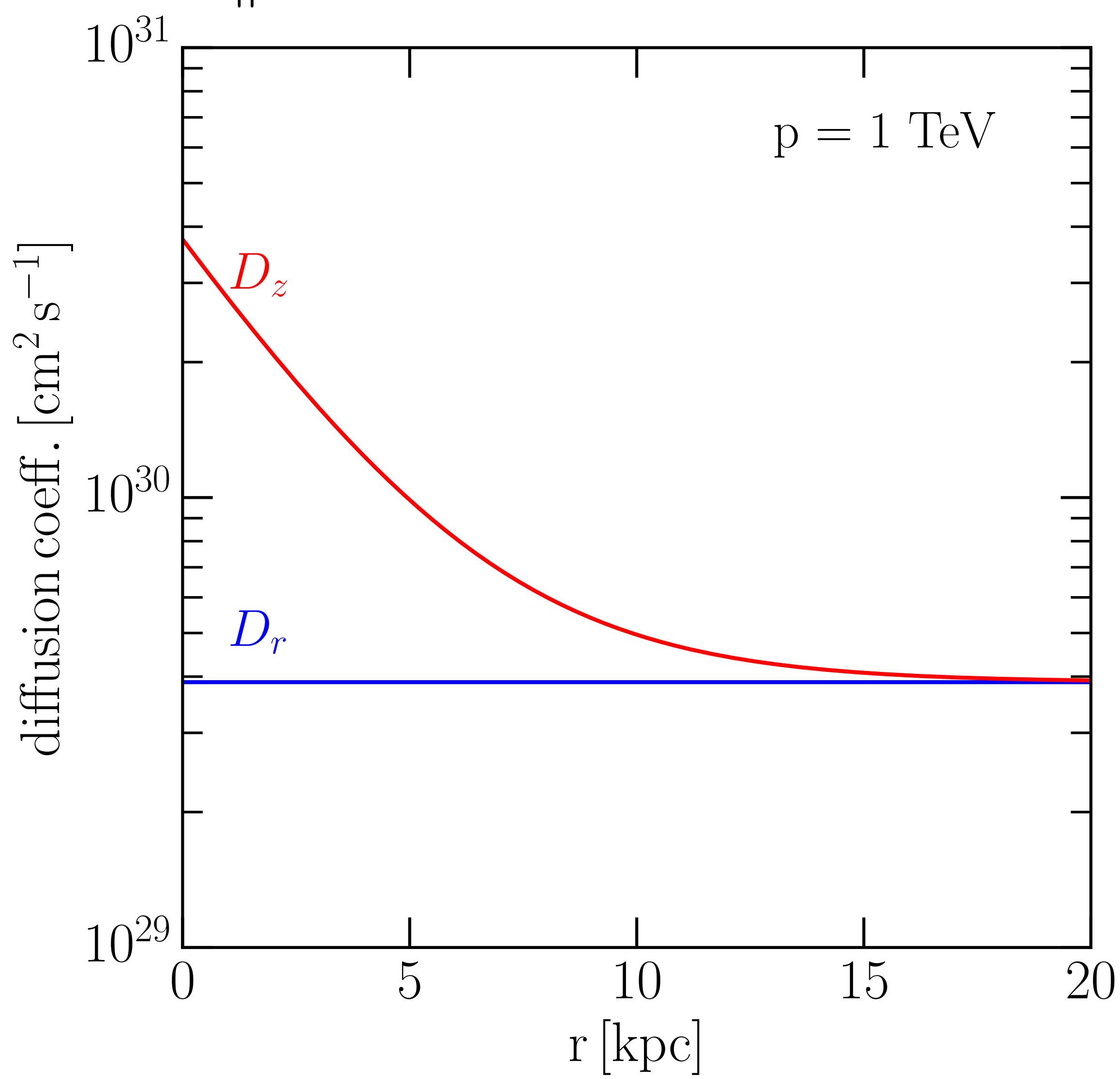
a single source at the GC active ~10 Myr ago

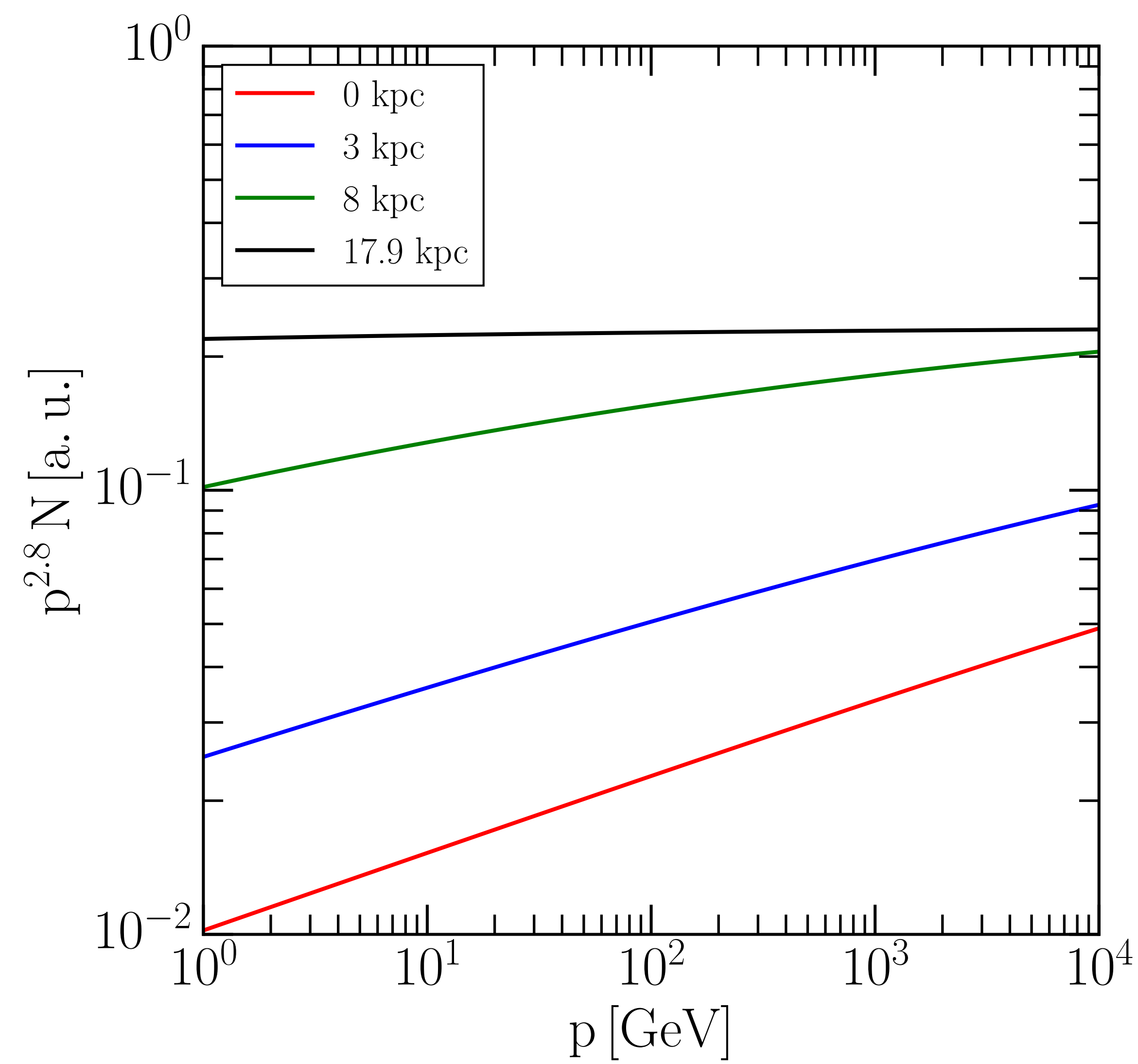
non-linear effects during propagation

hints of anisotropic diffusion?

CE+, arXiv:1607.07886

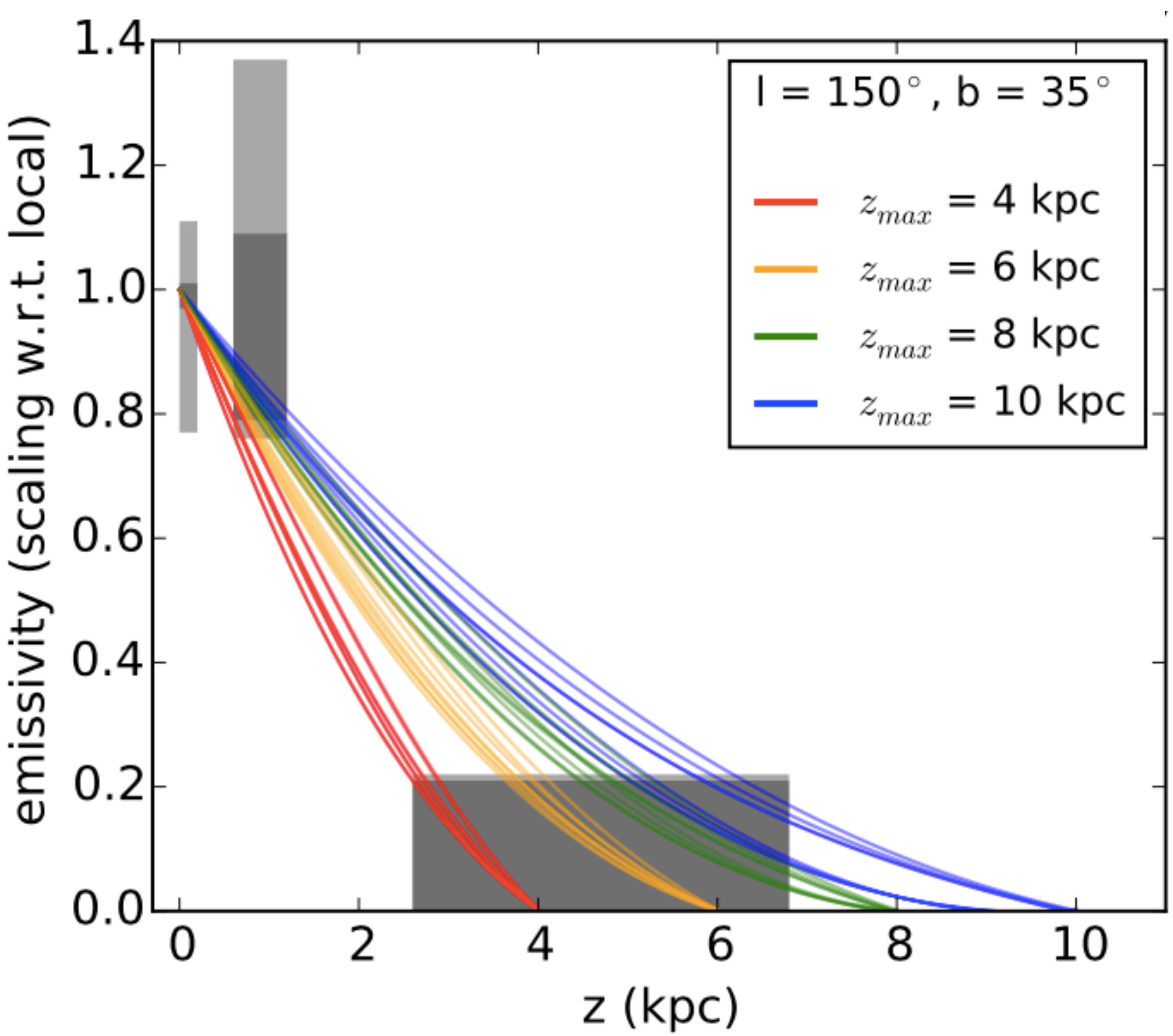
$$\delta_{\parallel} = 0.33 \text{ and } \delta_{\perp} = 0.5$$





CRs in the halo

Tibaldo+, ApJ, 2015



from the gamma-ray emission in high- and intermediate-velocity molecular clouds

CRs at ~GeV originate in the Galactic disk: proved!

but: what is the *physical* meaning of the halo?

conclusions

- assuming constant properties can be dangerous if one aims at understanding how stars or CRs are distributed in our Galaxy
- recent model-independent analysis of the gamma-ray emissivity profiles provide strong evidence for inhomogeneous and/or anisotropic diffusion in the different galactic environments
- propagation models are challenged to reproduce these new exciting results and confirm/rule out the SN paradigm.

arXiv:1607.07886