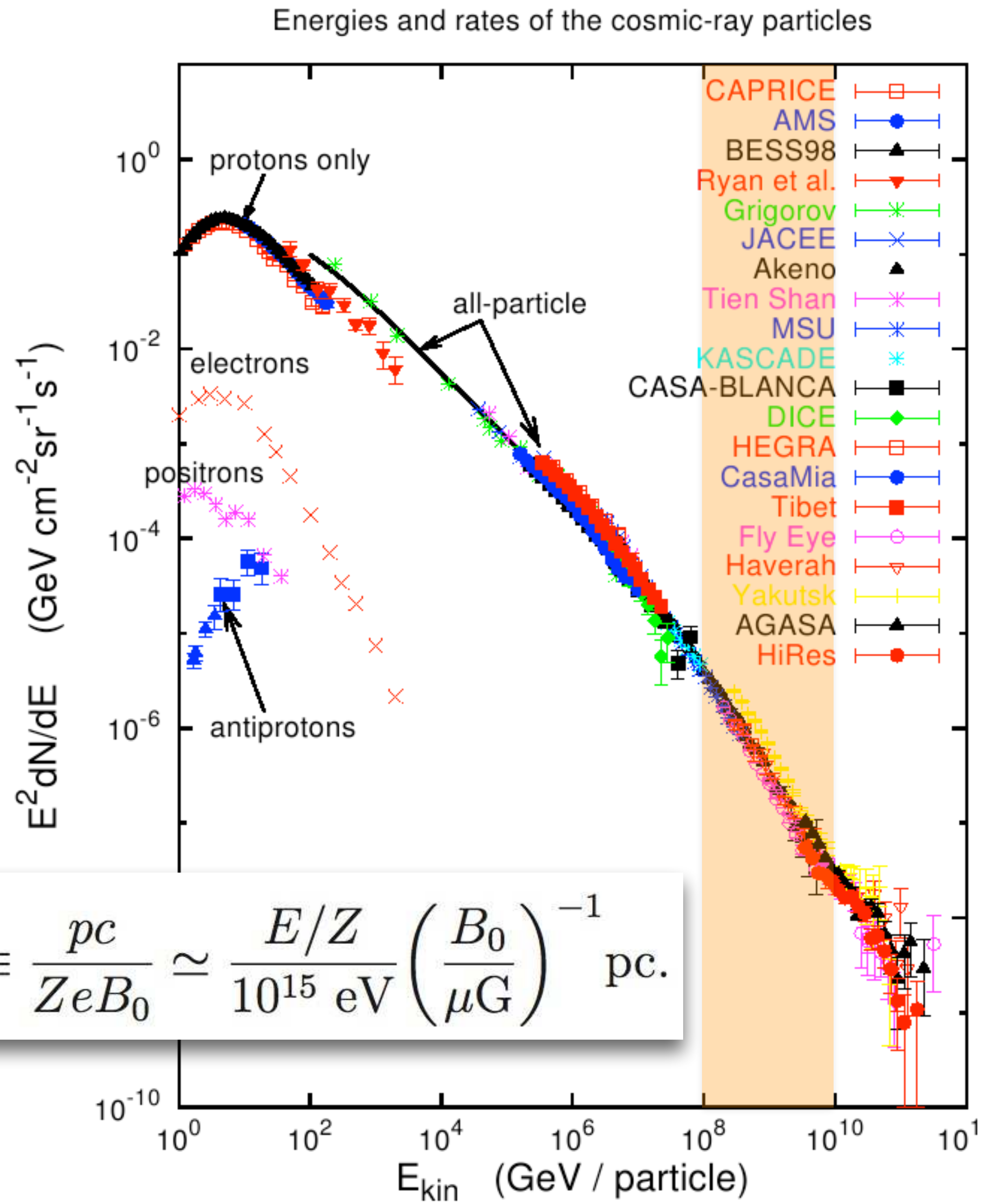
Understanding Cosmic Ray propagation in the Galaxy

Carmelo Evoli (Gran Sasso Science Institute)

Vulcano Workshop - 24th of May 2016

Cosmic-ray flux

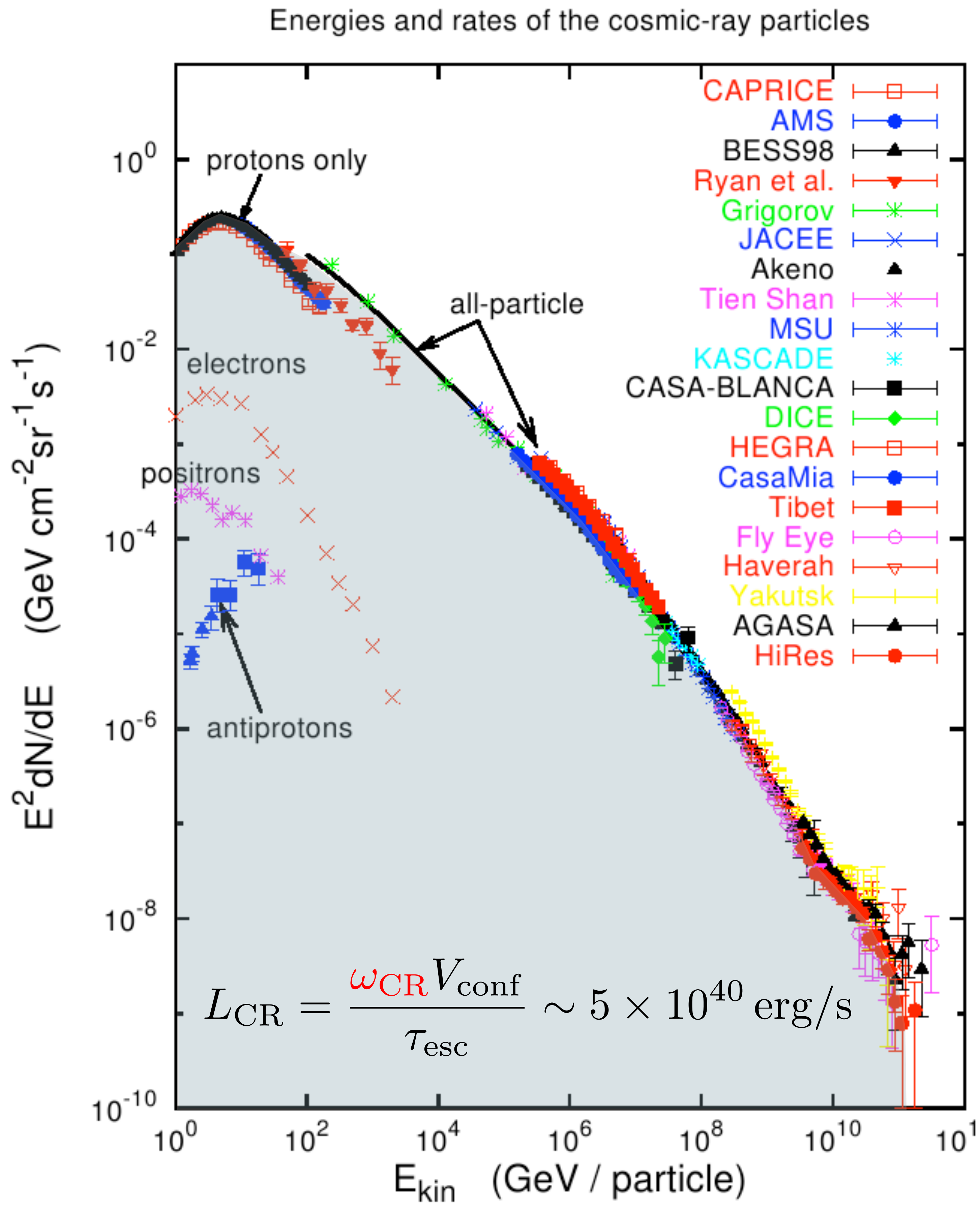
- Almost a perfect power-law over 12 energy decades.
- Observed at energy higher than terrestrial laboratories!
- Direct measurements versus air-cascade reconstructions.
- Anti-matter component.
- Transition from galactic to extra-galactic?



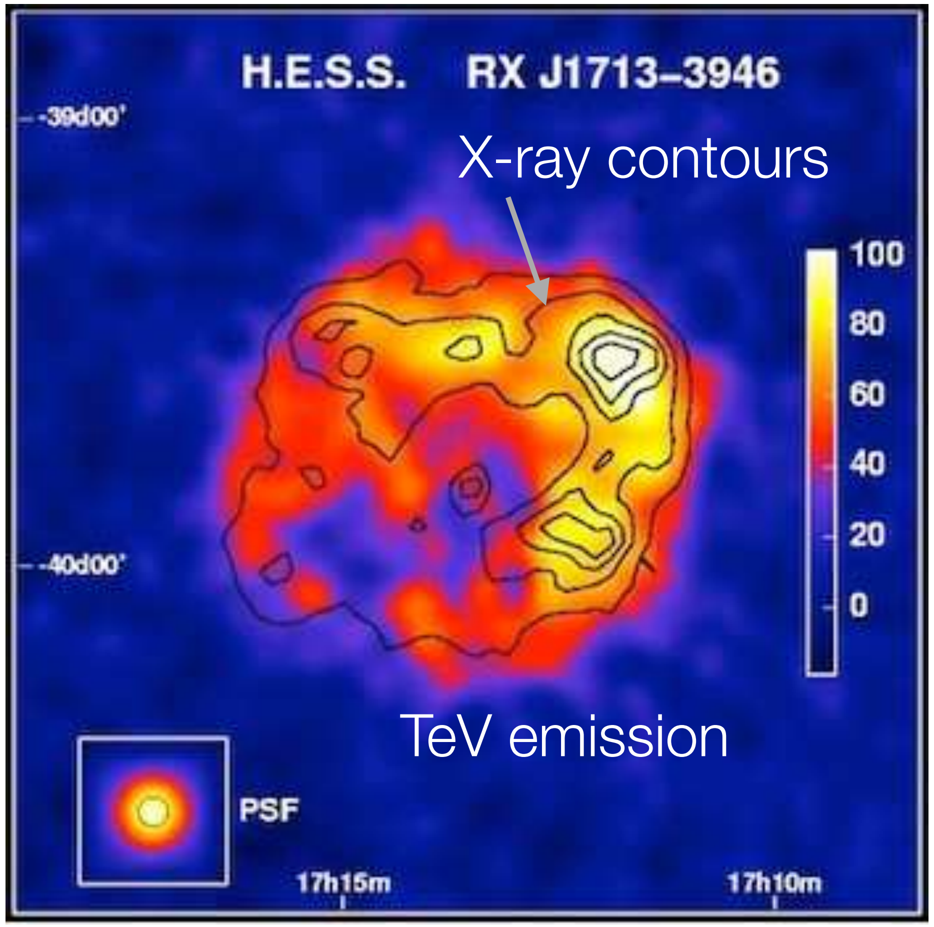
$$r_{\rm L} \equiv \frac{pc}{ZeB_0} \simeq \frac{E/Z}{10^{15}\ {\rm eV}} \left(\frac{B_0}{\mu{\rm G}}\right)^{-1} {\rm pc}.$$

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 “*SN paradigm*”



Aharonian et al., Nature, 2007

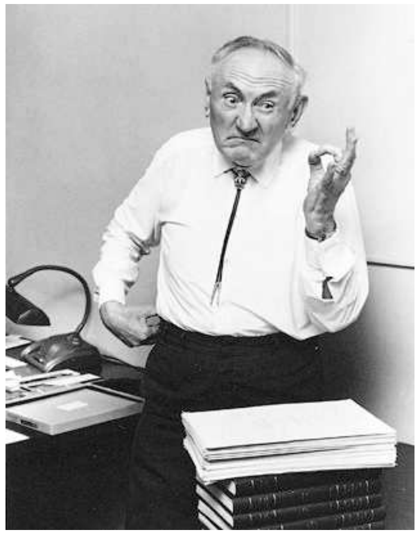
hadronic:

$$p\, p_{\rm ISM} \to \pi^0 \to \gamma\gamma$$

or leptonic:

$$e^-\, \gamma_{\rm ISRF} \to e^-\, \gamma$$

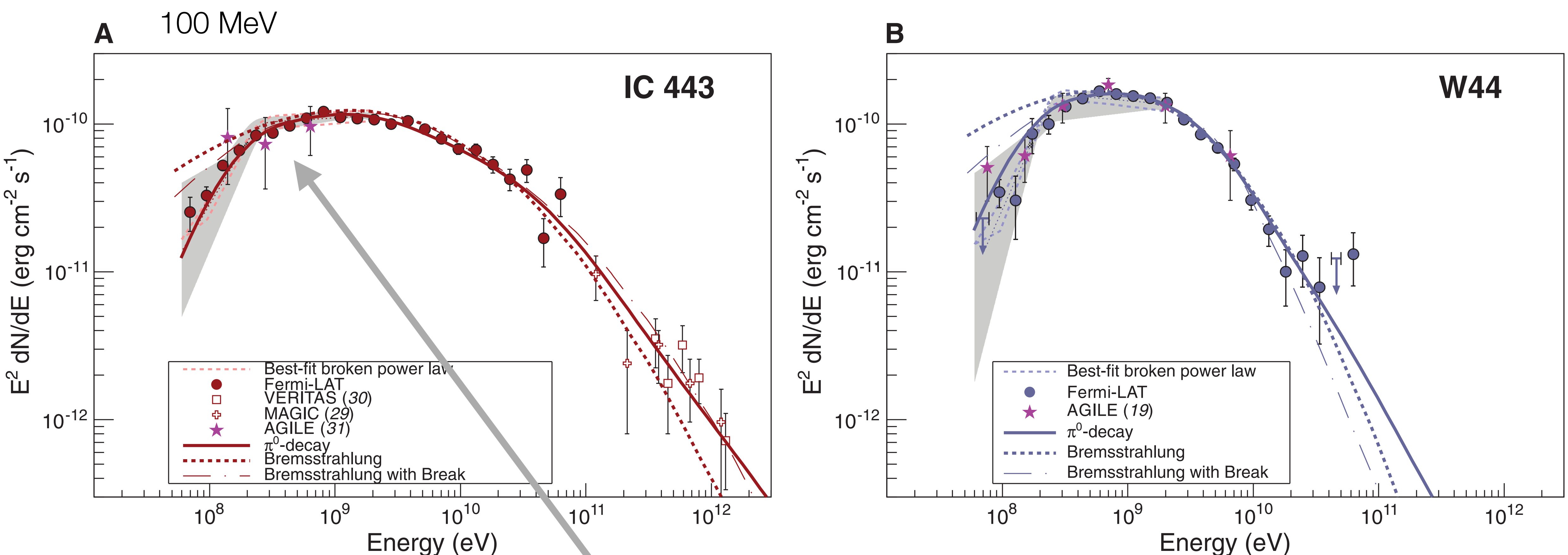
$$L_{\rm SN} \sim R_{\rm SN} E_{\rm kin} \sim 3 \times 10^{41}\,{\rm erg/s}$$

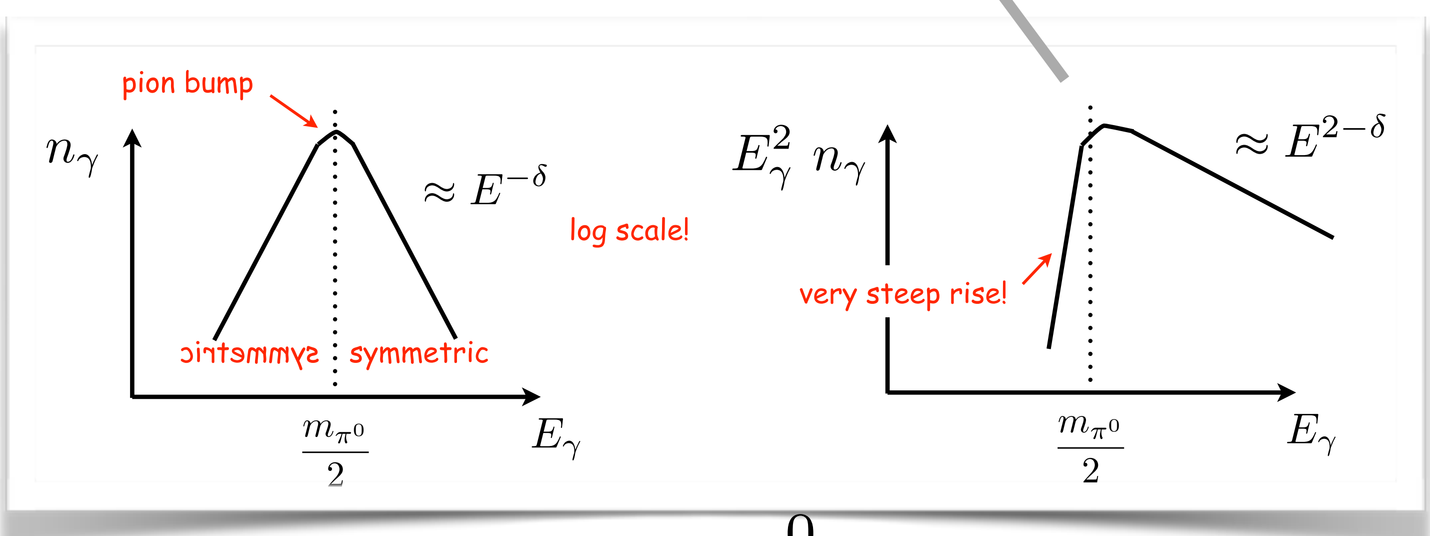


Baade W, Zwicky F, Phys Rev (1934)

The pion-bump as hadronic signature

FERMI collaboration, Science, 2013





$$p\, p_{\rm ISM} \to \pi^0 \to \gamma\gamma$$

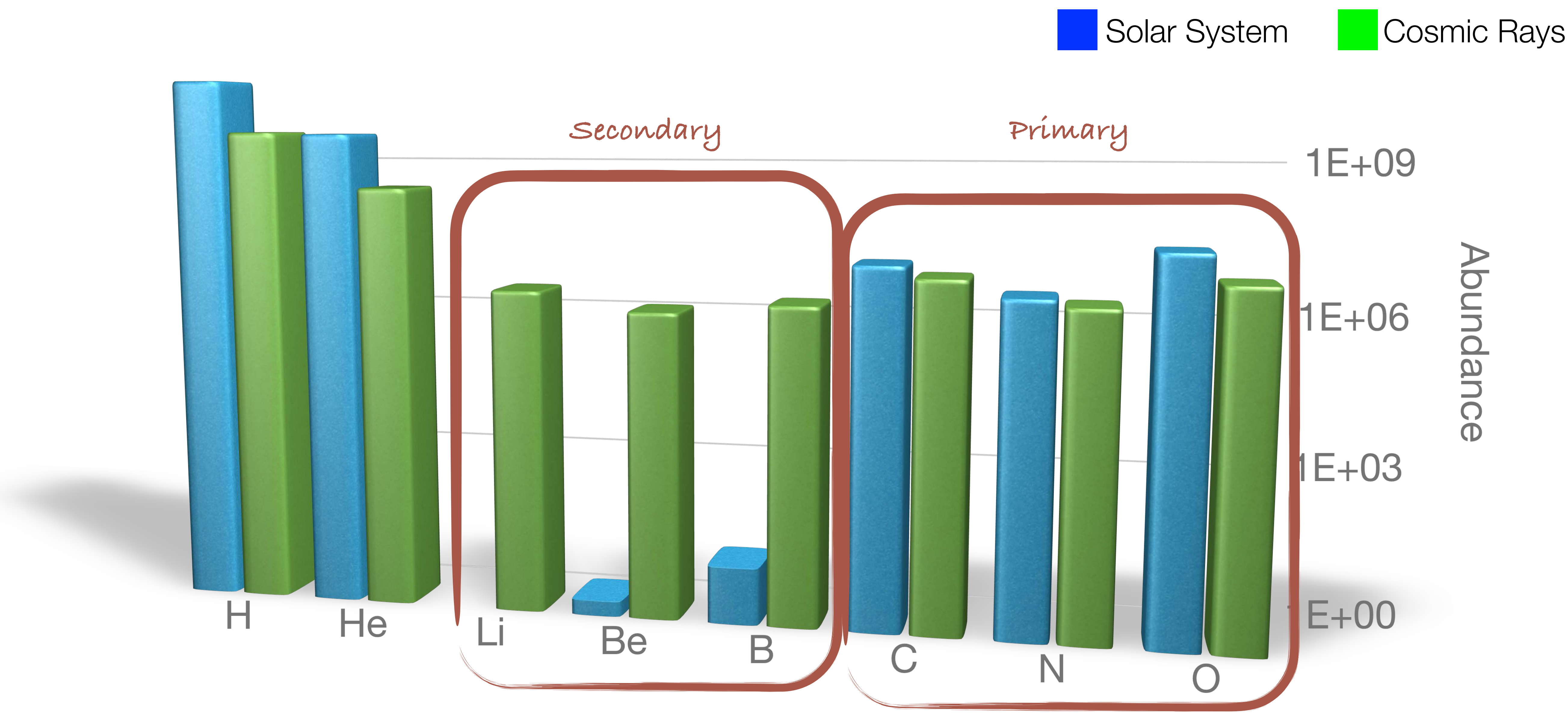
but…

Do SNRs accelerate ENOUGH protons?

Do they accelerate protons up to the *knee*?

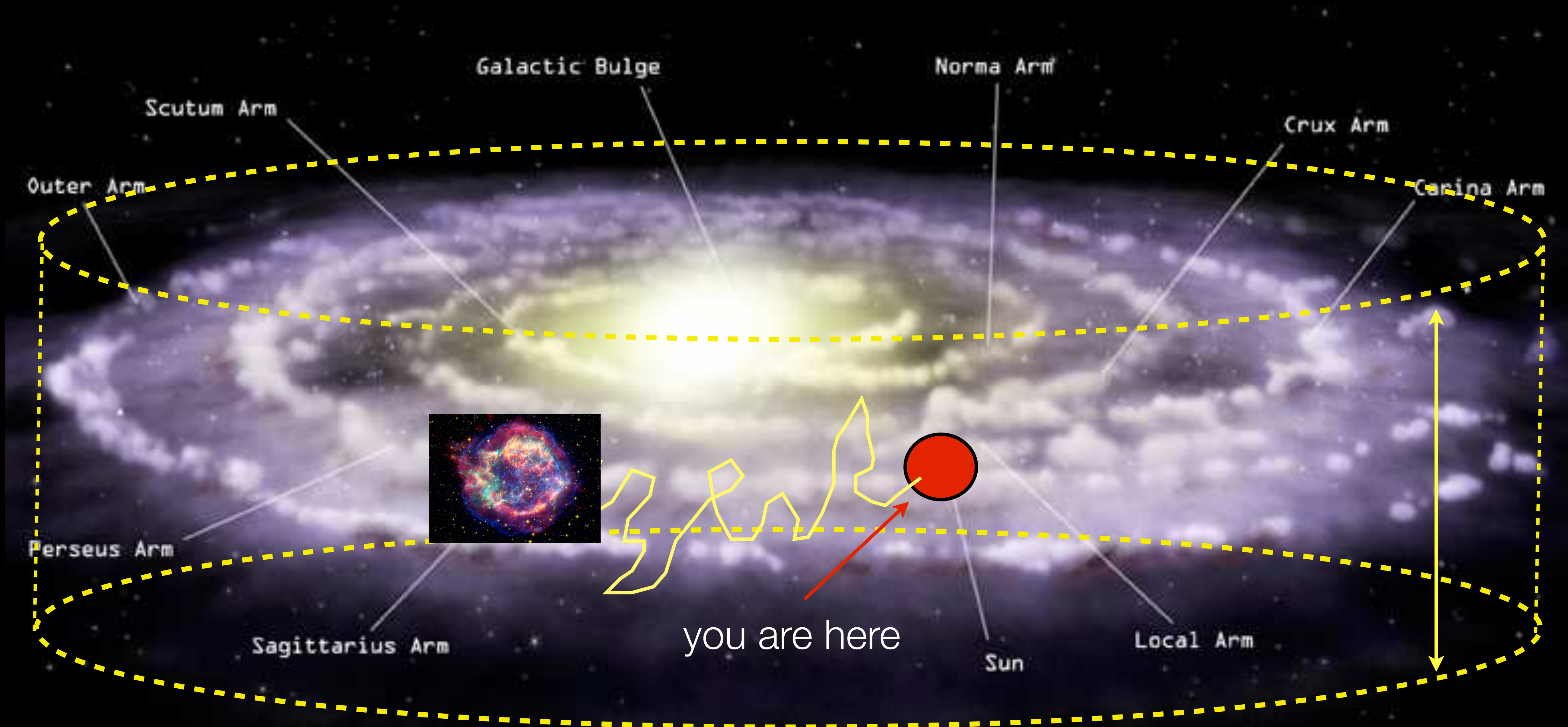
see also Tavani et al., 2010, Astrophys J Lett 710

Cosmic-ray composition



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

Galactic Propagation



L = 1-10 kpc

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla\cdot(D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Source term:

- assumed to trace the SNR in the Galaxy
- assumed the same power-law everywhere

Ginzburg & Syrovatsky, 1964

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$$Q^i(p,r,z) + \sum_{j>i} c\,\beta\, n_{gas}(r,z)\sigma_{ij}N^j - c\,\beta\, n_{gas}\sigma_{in}(E_k)N^i$$

Spallation cross-section:

- appearance of nucleus i due to spallation of nucleus j
- total inelastic cross-section: disappearance of nucleus i

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

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$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Diffusion tensor:

- $D(E) = D_0(\rho/\rho_0)^\delta \exp(z/z_t)$

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

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$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Energy losses:

- ionization, Coulomb, synchrotron
- adiabatic convection

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla \cdot (D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Reacceleration:

- $D_{pp} \propto \frac{p^2 v_A^2}{D}$

Ginzburg & Syrovatsky, 1964

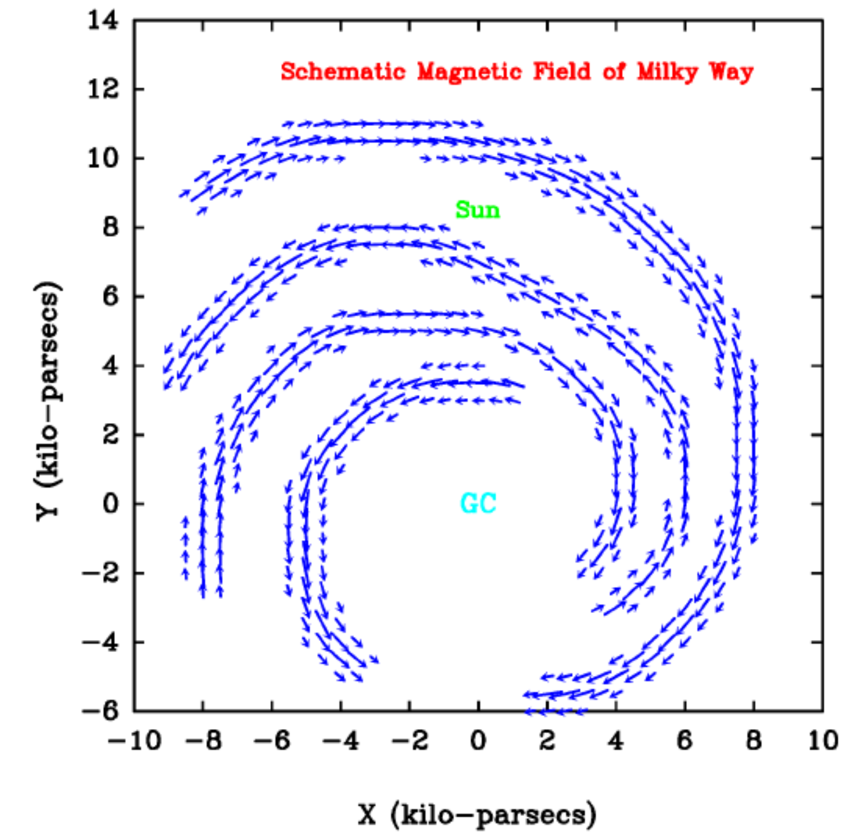
CR diffusion for the "poor physicist"

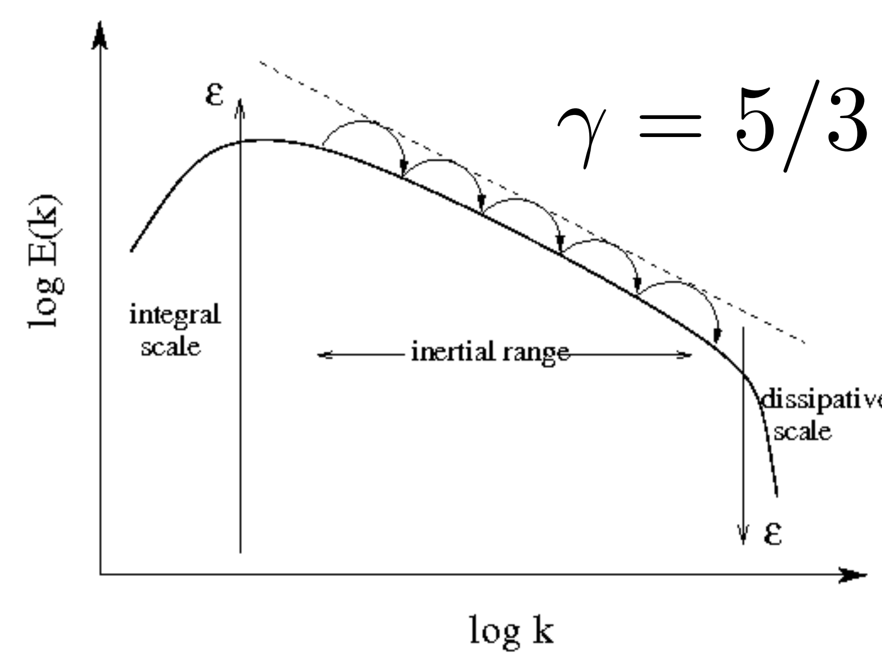
Assumptions:

- GCR diffuse in the ISM turbulent magnetic field
- The turbulent field can be modeled with a Kolmogorov isotropic power-spectrum
- The turbulent field amplitude is a small fluctuation with respect to the regular component
- Resonant interaction wave-particle

It follows:

$$D = D_0 \rho^{\delta} \quad \text{where} \quad \delta = 2 - \gamma = 1/3$$





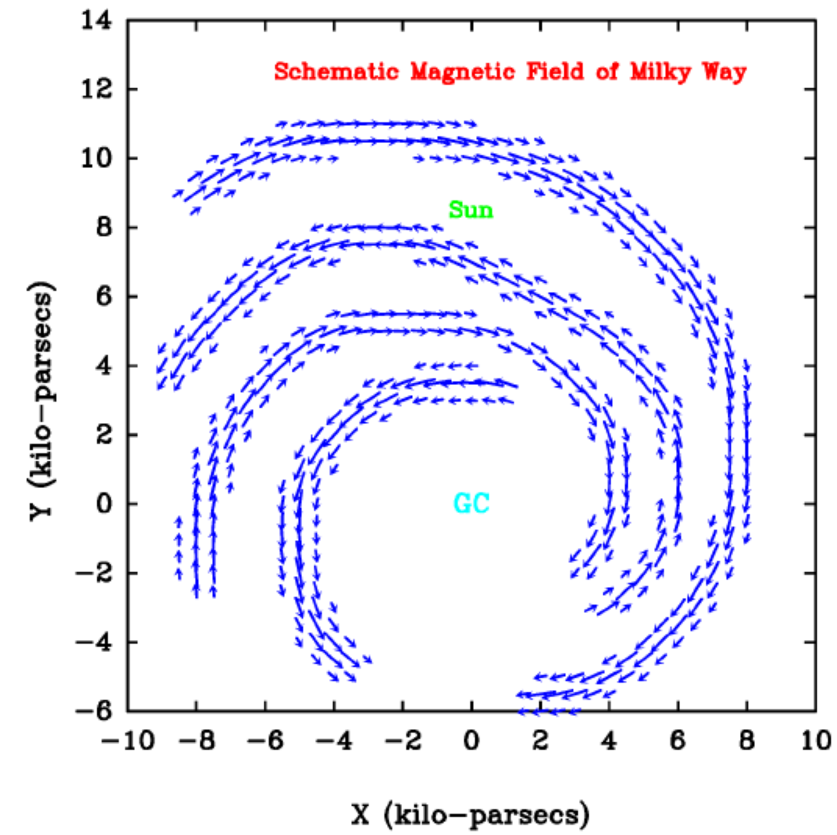
CR diffusion for the “poor physicist”

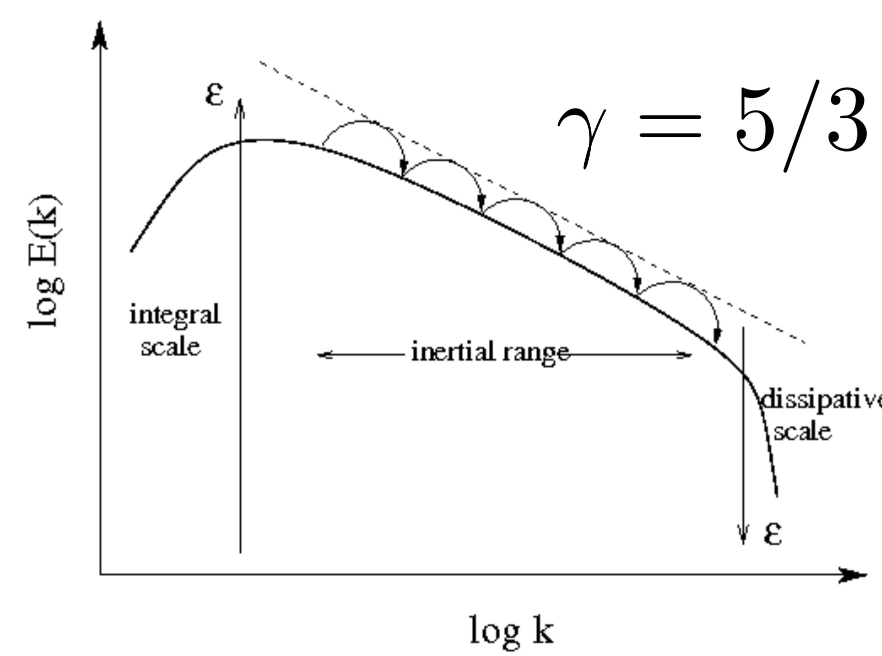
Assumptions:

- ~~GCR diffuse in the ISM turbulent magnetic field~~
  see Wentzel, 1974; Cesarsky 1980; Blasi, Amato & Serpico, 2012
- ~~The turbulent field can be modeled with a Kolmogorov isotropic power-spectrum~~
  see GS95, Cho & Lazarian, PRL, 2002
- ~~The turbulent field amplitude is a small fluctuation with respect to the regular component~~
  see Planck intermediate results. XIX. (A&A sub.)
- ~~Resonant interaction wave-particle~~
  see Yan & Lazarian, 2002; Tautz,, Shalchi & Schlickeiser, 2008

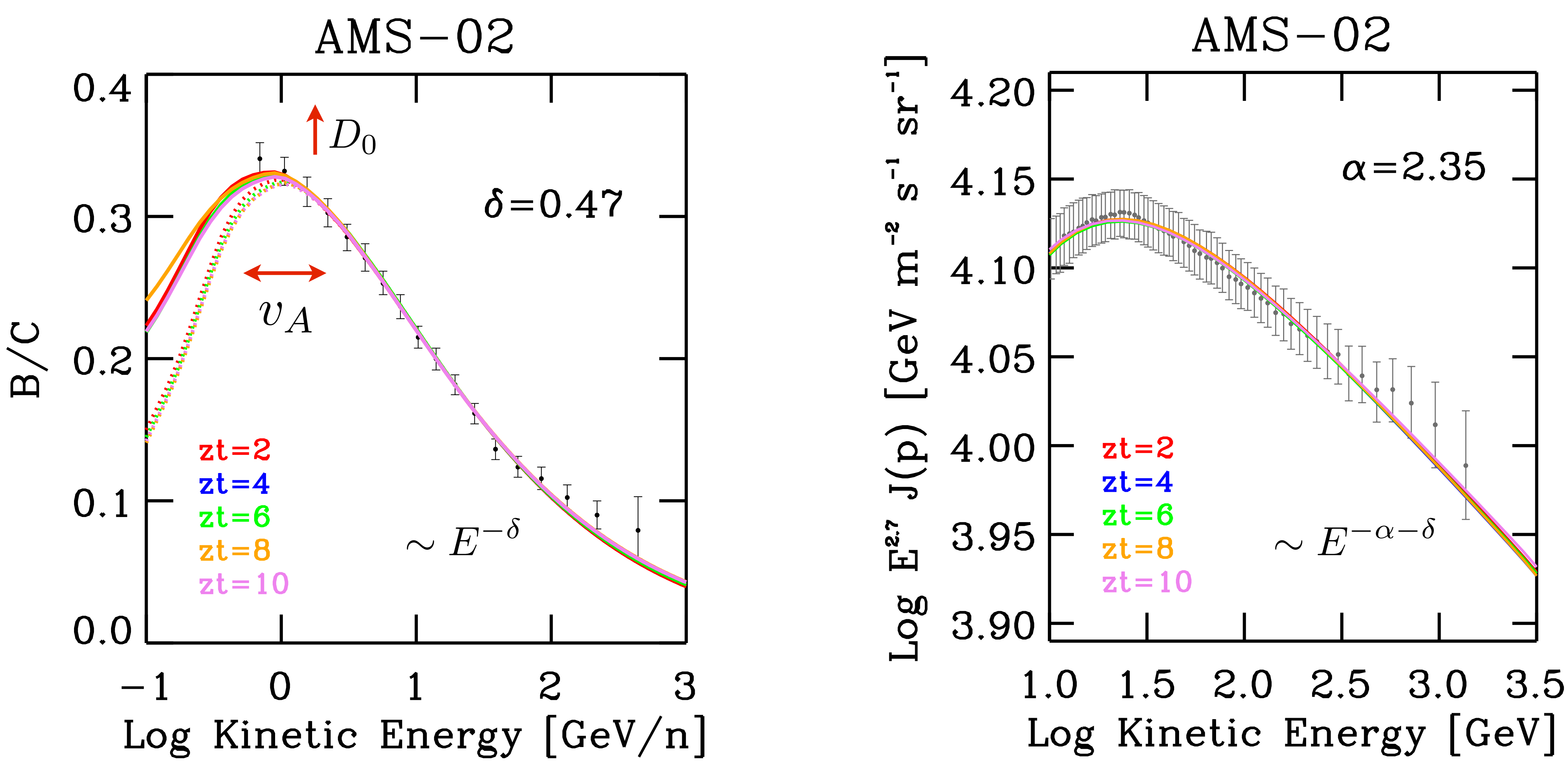
It follows:

$$D = D_0 \rho^{\delta} \quad \text{where} \quad \delta = 2 - \gamma = 1/3$$





Fitting local observables

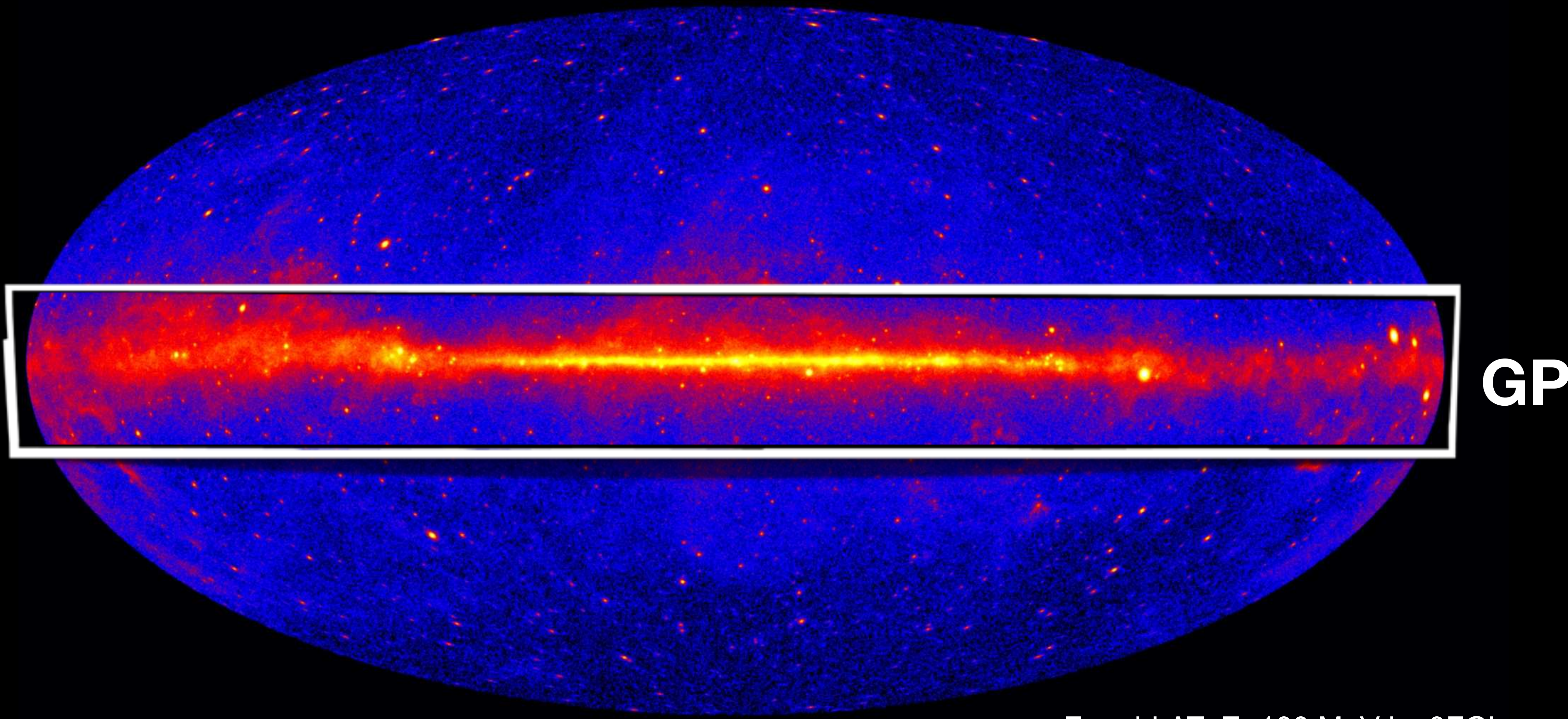


$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

The best constraints on the halo scale height (z_t > 2 kpc) are obtained from the galactic diffuse synchrotron emission (G.Di Bernardo, CE, et al., JCAP, 2013)


You are here

The gamma-ray sky in 2016 (for the future see Luca Latronico's talk)

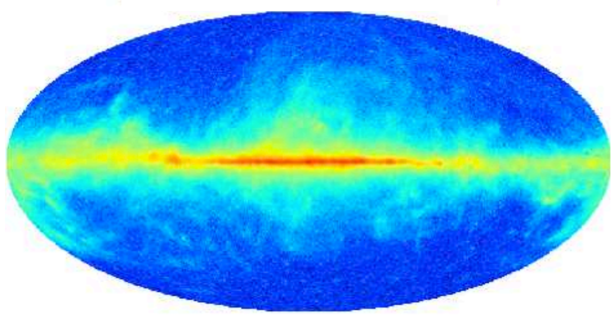


Fermi-LAT E>100 MeV by 3FGL
[LAT collaboration 2015]

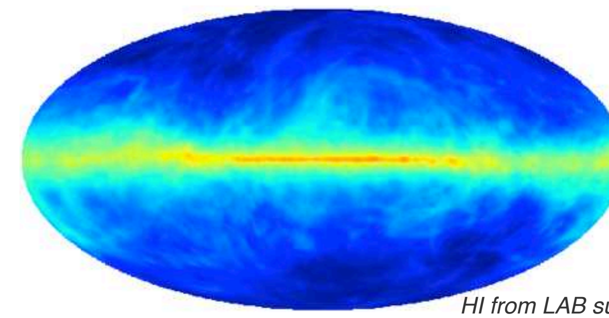
~ 70% of all observed photons coming from the diffuse Galactic emission

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

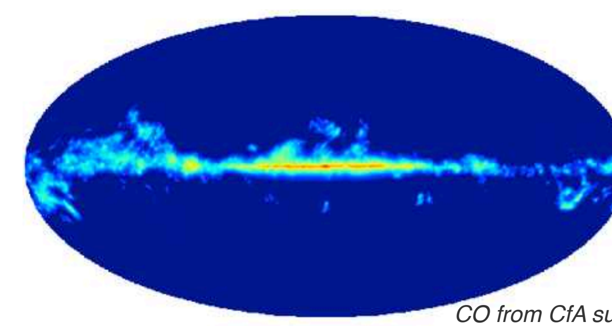


$$= \int_{\mathrm{los}} dl \; n_p(r) \times$$



HI from LAB survey

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



CO from CfA survey

H2

MW Hydrogen is ~75% in terms of mass fraction.

- **Atomic** (HI): The most massive phase with a large filling factor (h ~ 200 pc).
- **Molecular** (H2): The densest phase, very clumpy (h ~ 100 pc).
- **Ionized** (HII): Much smaller density and with the largest scale height (h ~1 kpc).

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

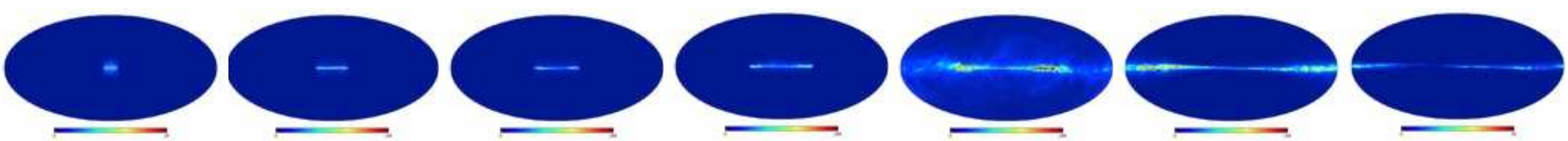
Template analysis for the GDE

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

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

from a propagation one-zone model

free parameters



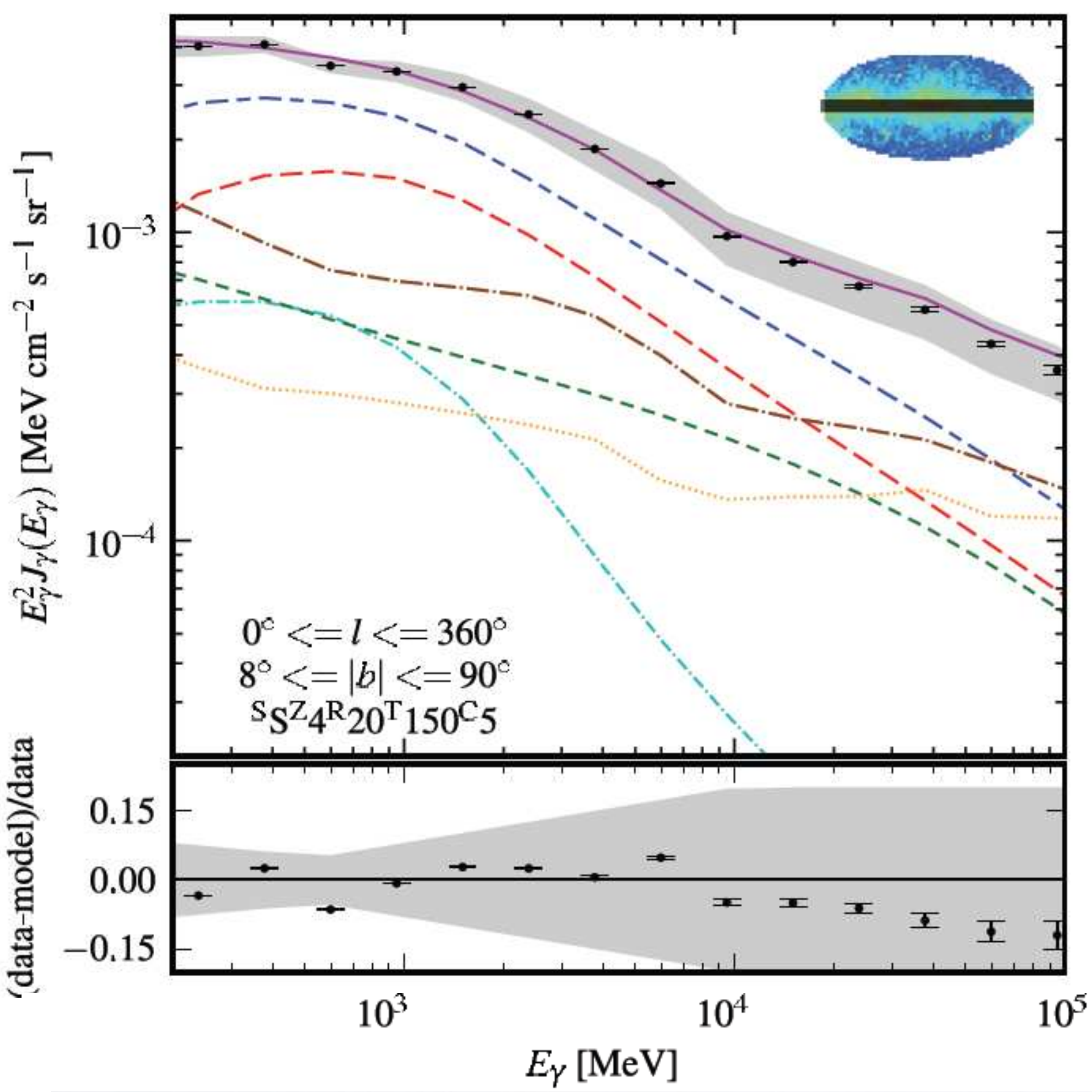
Galactocentric HI rings

Ackermann et al., ApJ, 750 (2012)

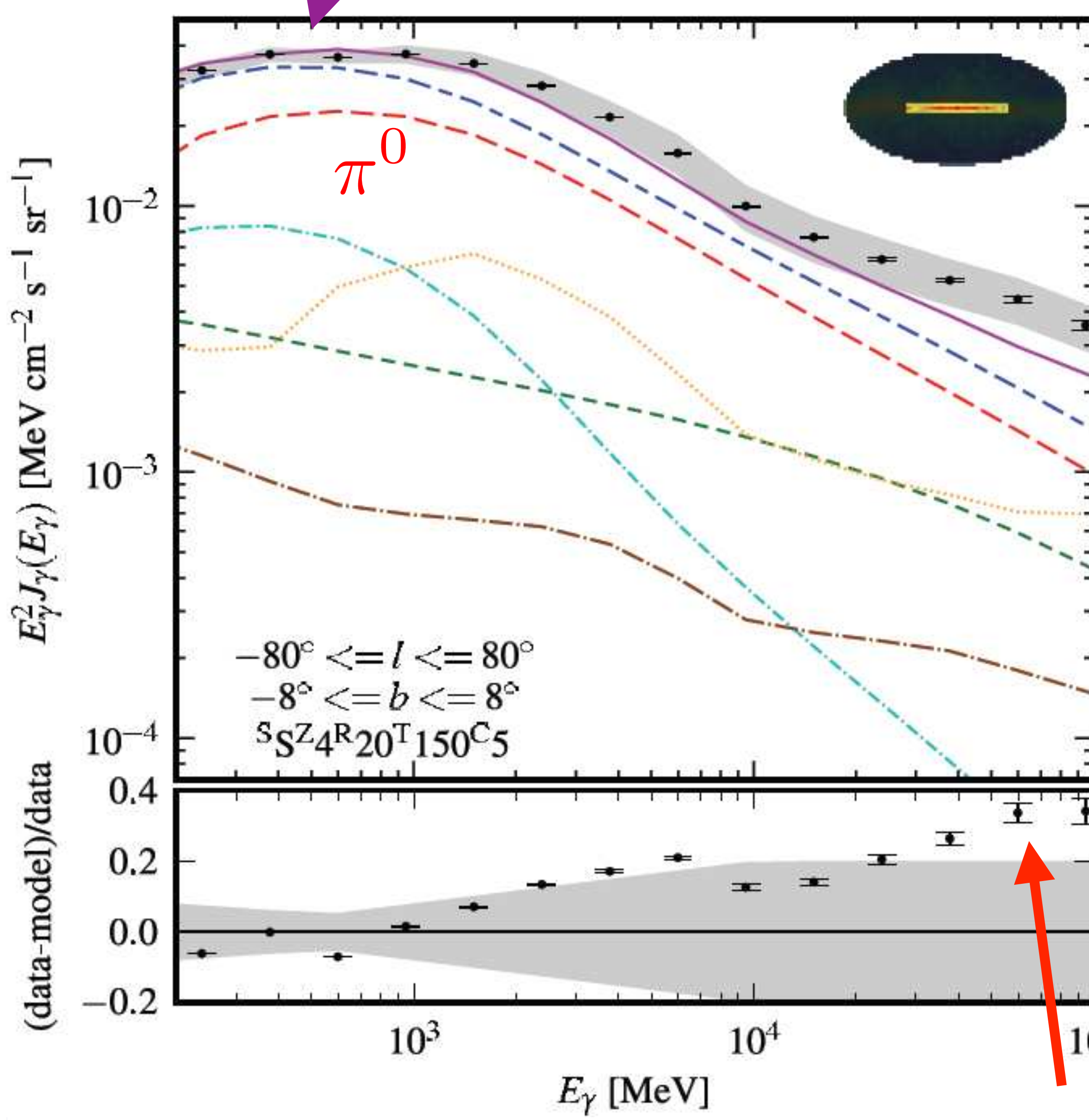
FERMI galactic diffuse emission

FERMI reference model for the galactic emission

full sky, without the GP



inner GP



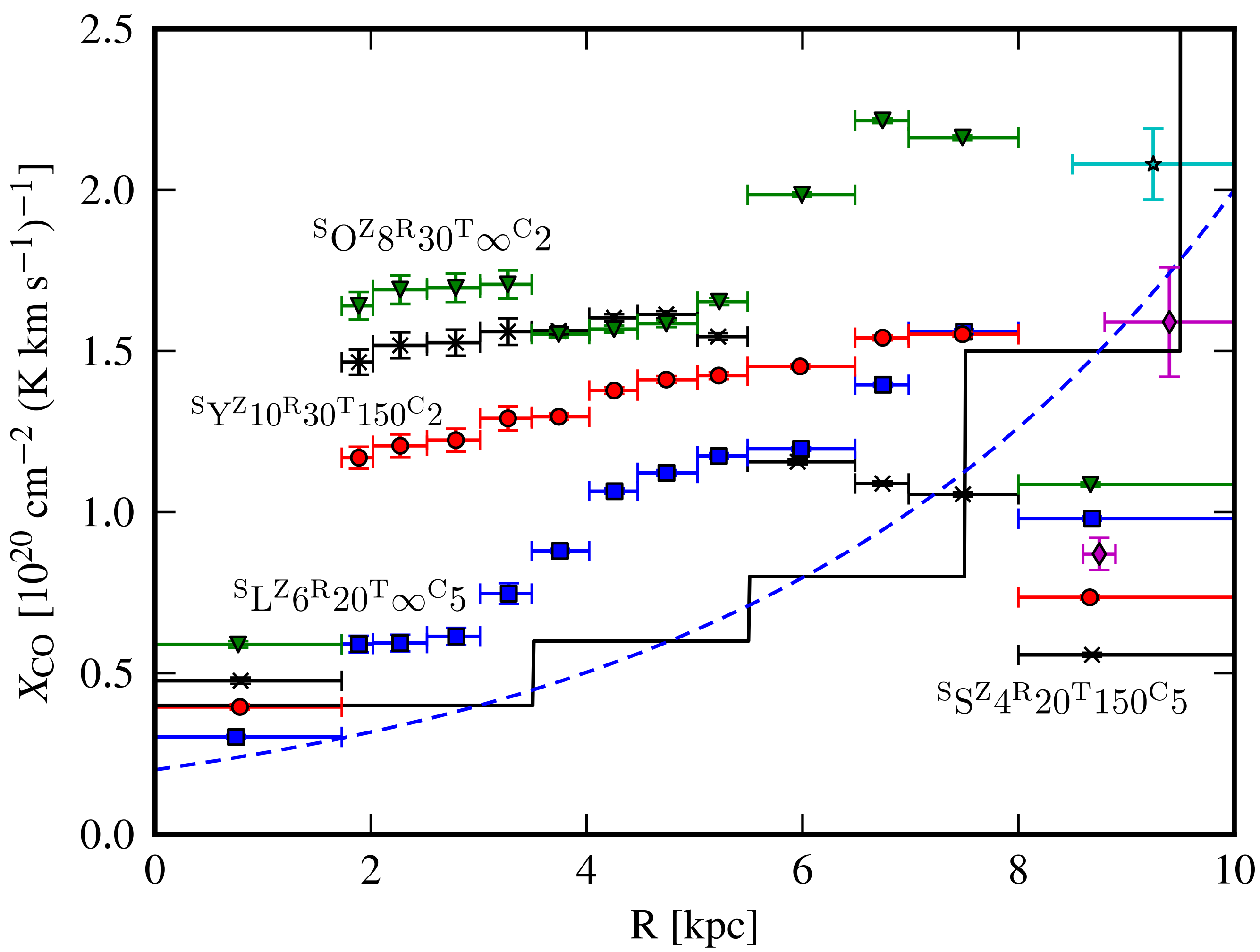
DGE

@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

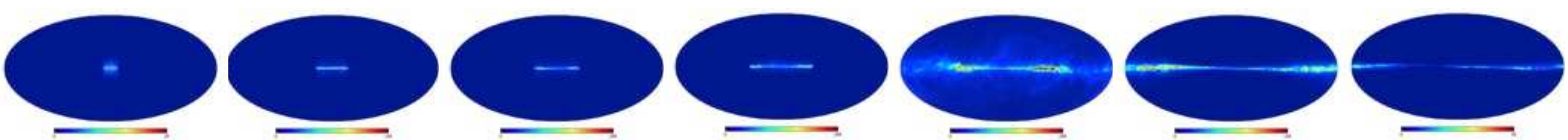
Fermi Collaboration, ApJ, 2011

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

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

free parameters

free parameters

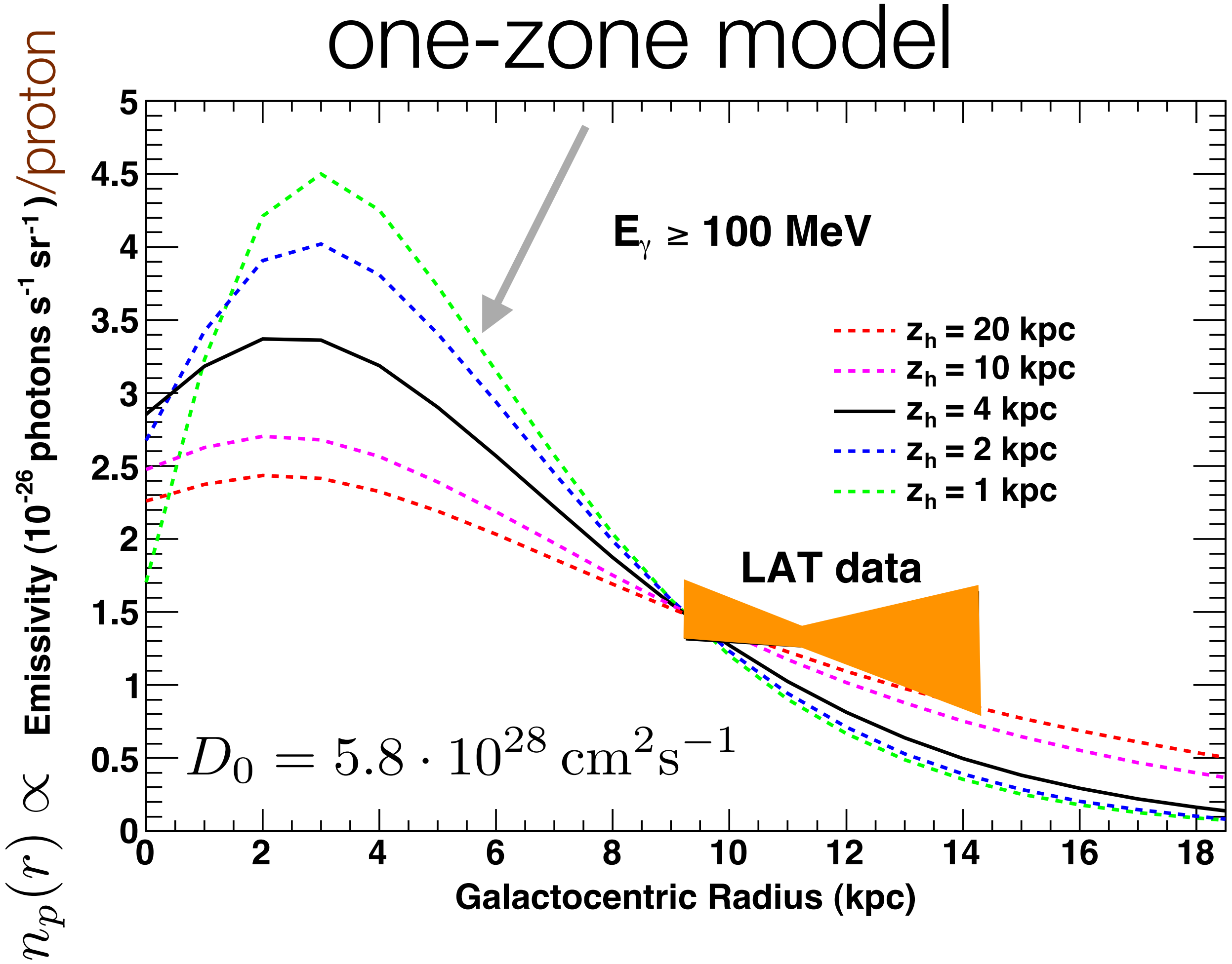


Galactocentric HI rings

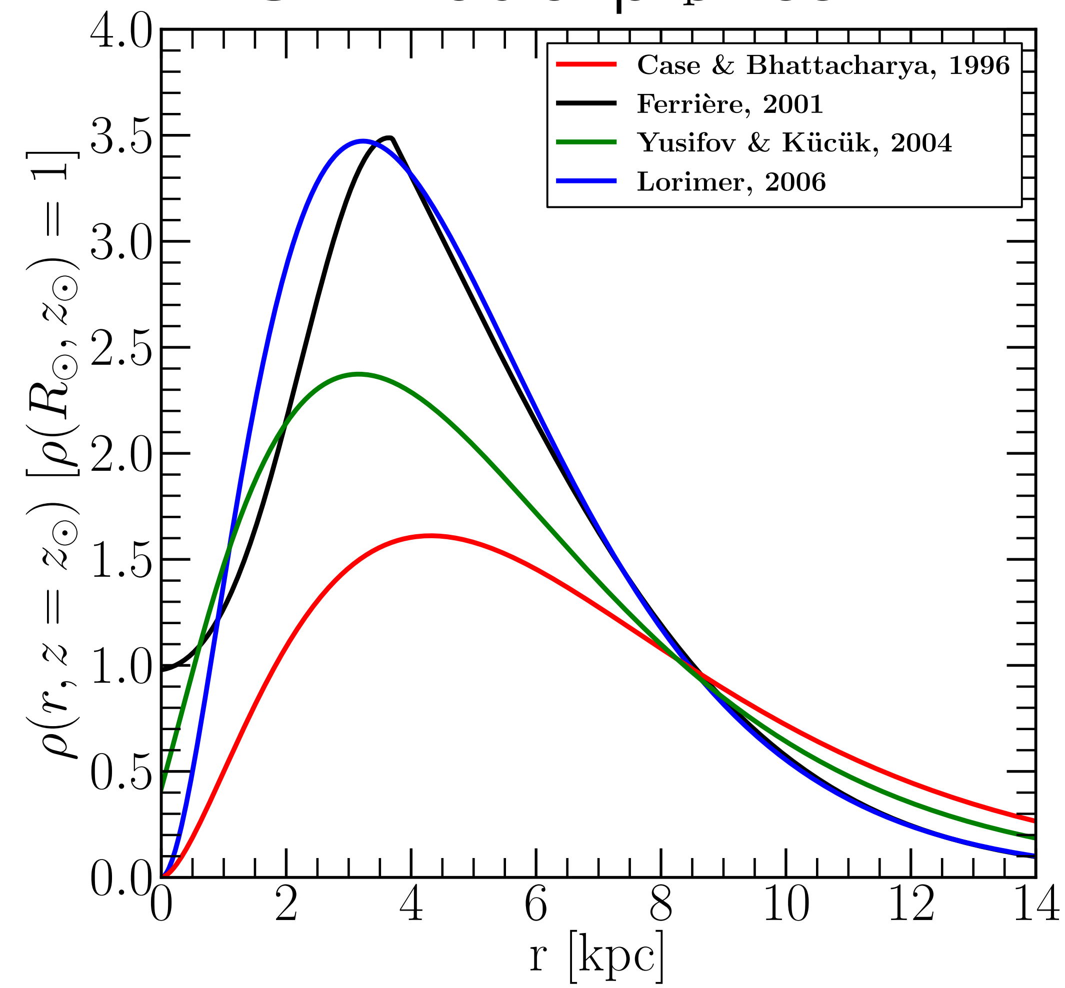
The *gradient* problem in the FERMI sky

Fermi Collaboration, ApJ, 2011

one-zone model



SNR radial profiles



Results: FERMI detected **more** γ's than predicted based on sources following SNR distribution and one-zone model for diffusion.

Disclaimer: let me skip some subtle details given the broad audience, more in the discussion session.

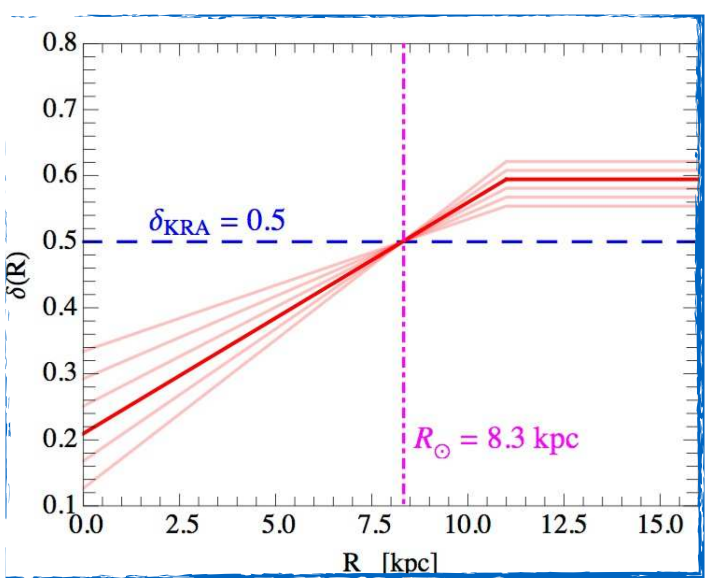
A new view on diffuse galactic modelling

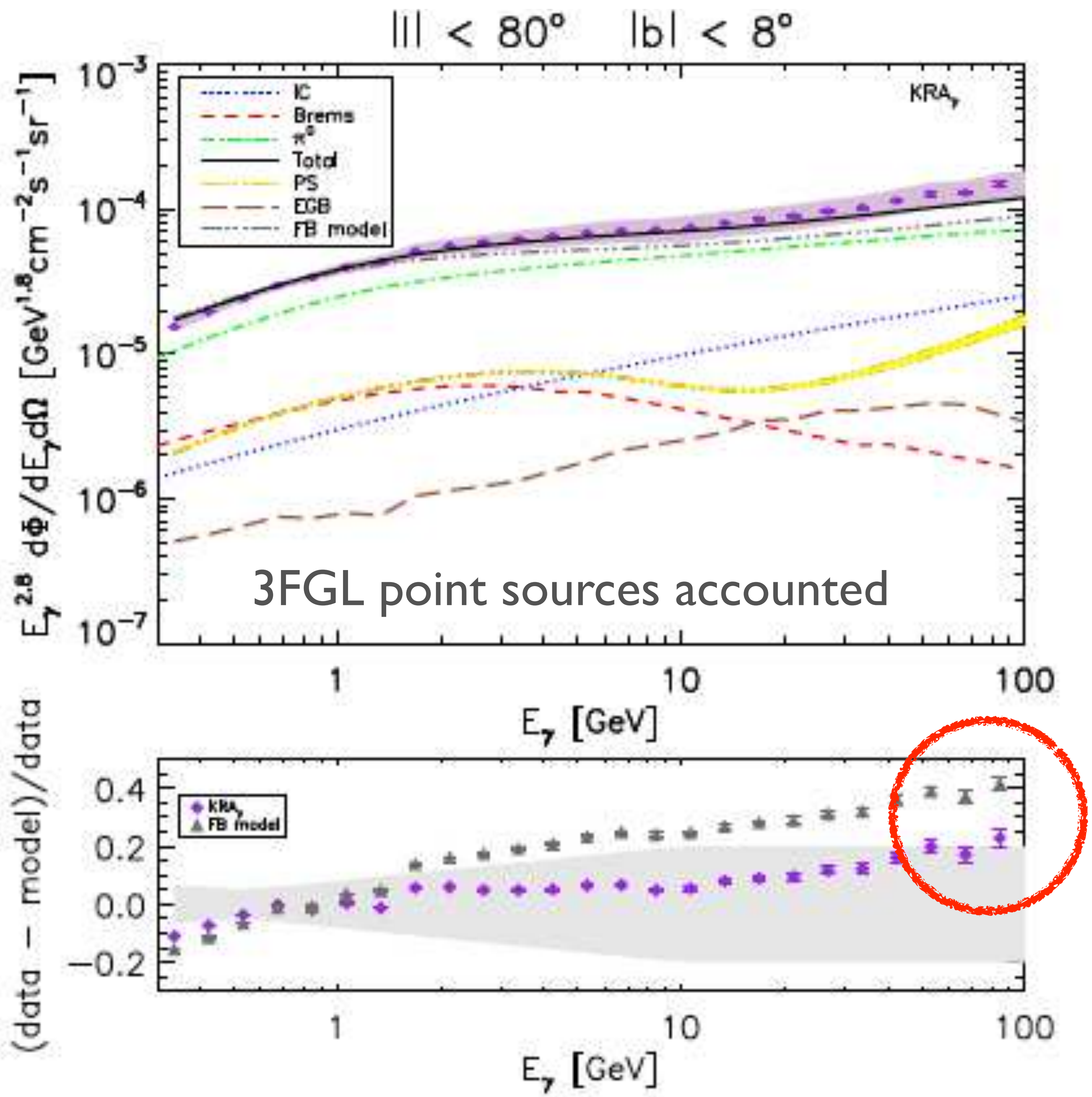
D. Gaggero et al., PRD, 91 (2015)

how to change my propagation model to reproduce γ data?

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

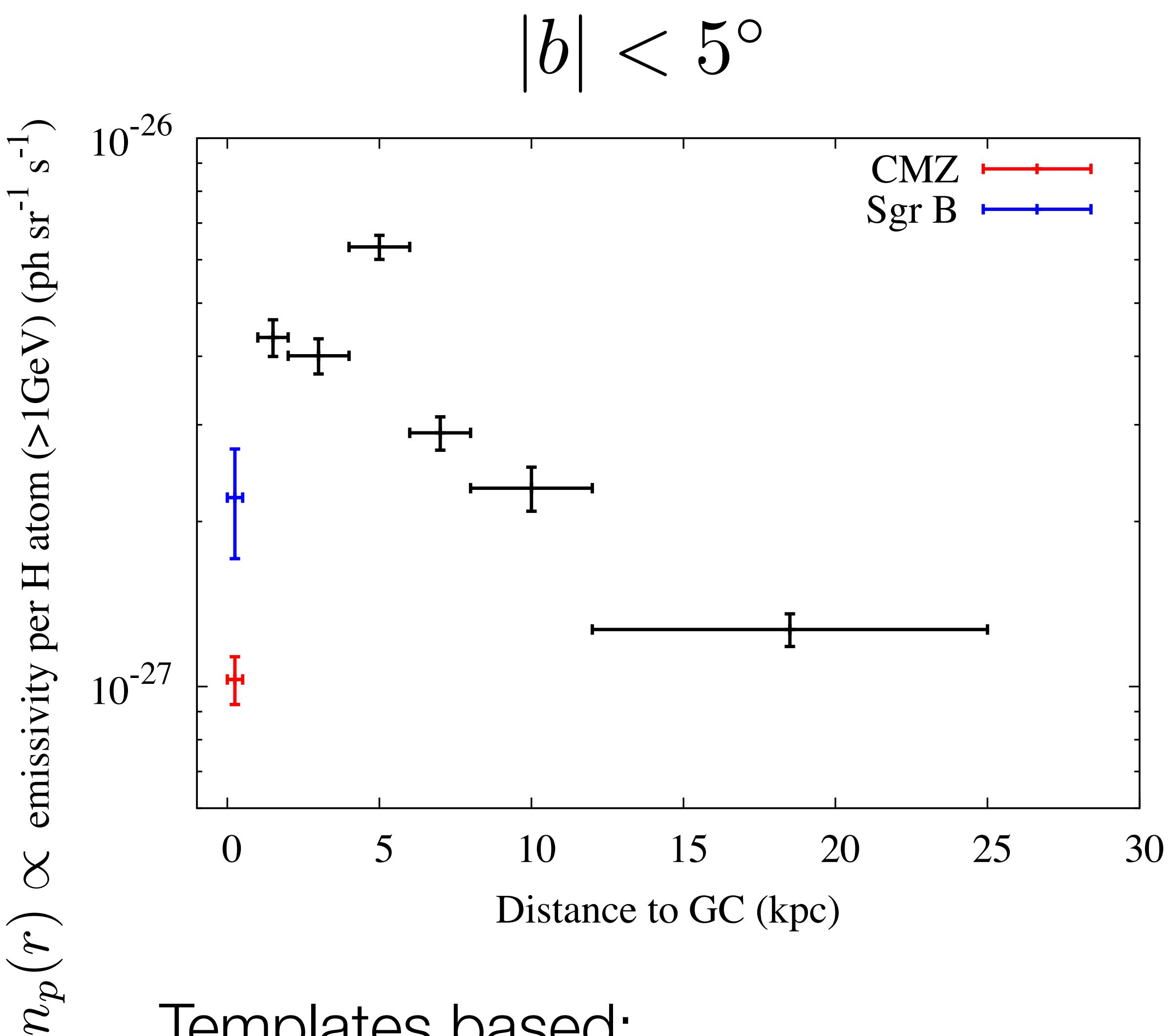
$$D = D_0 \rho^\delta$$

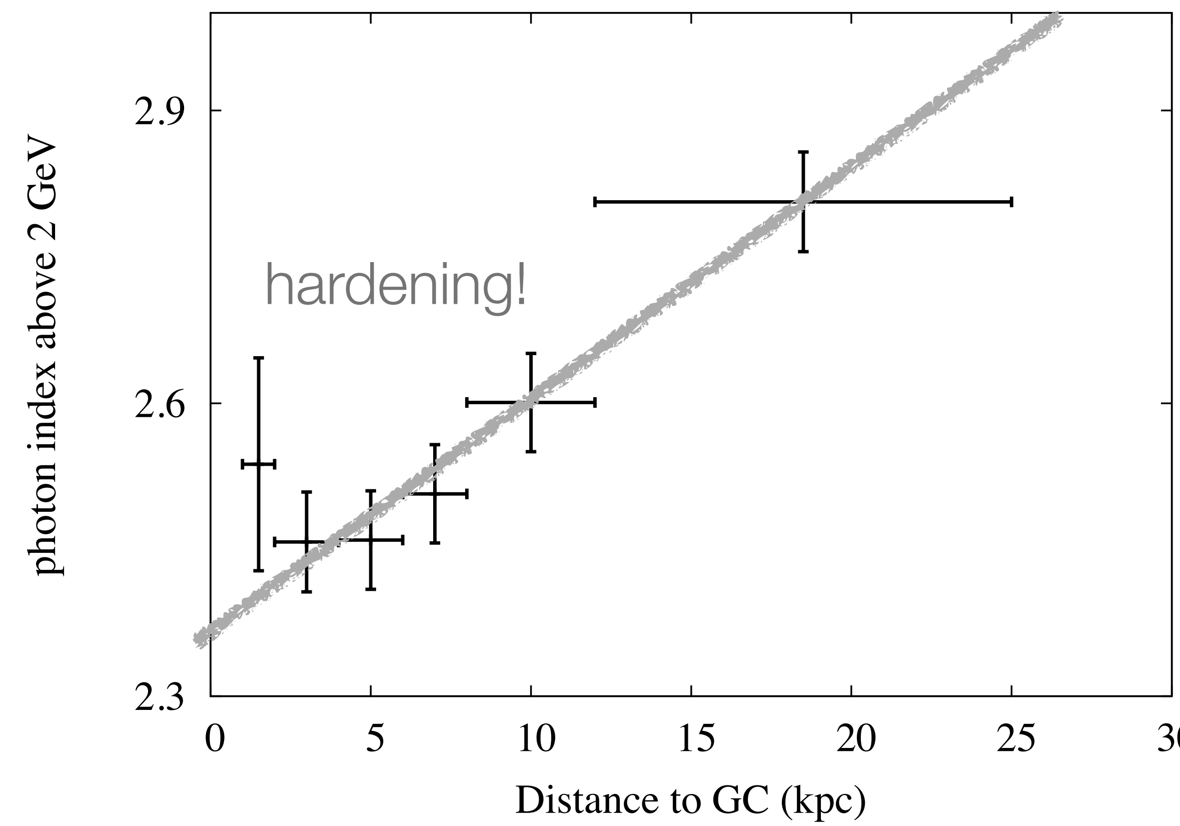




The radial distribution of the diffuse γ-ray emissivity in the GP

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





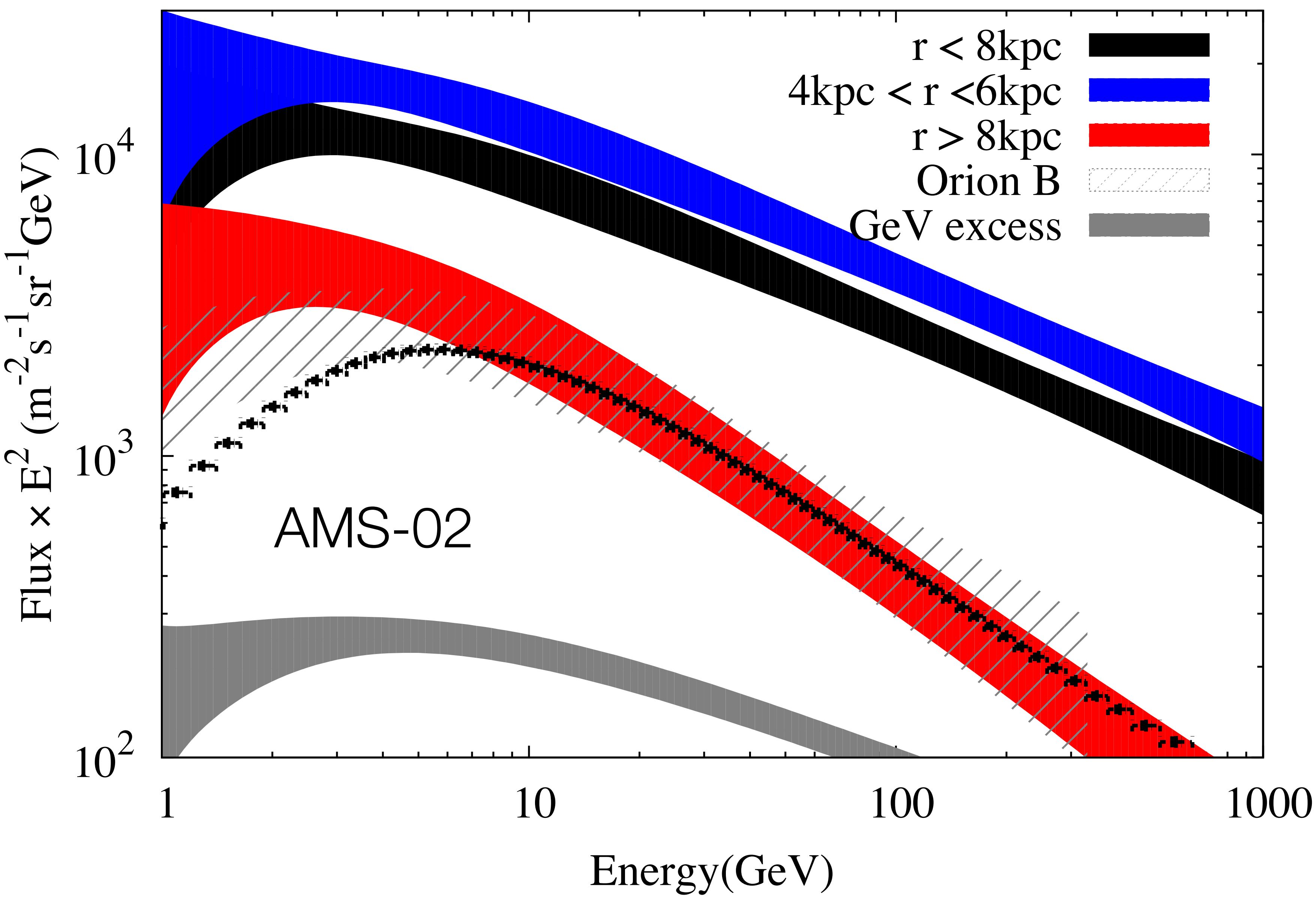
Templates based:

- 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*"

Results: 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

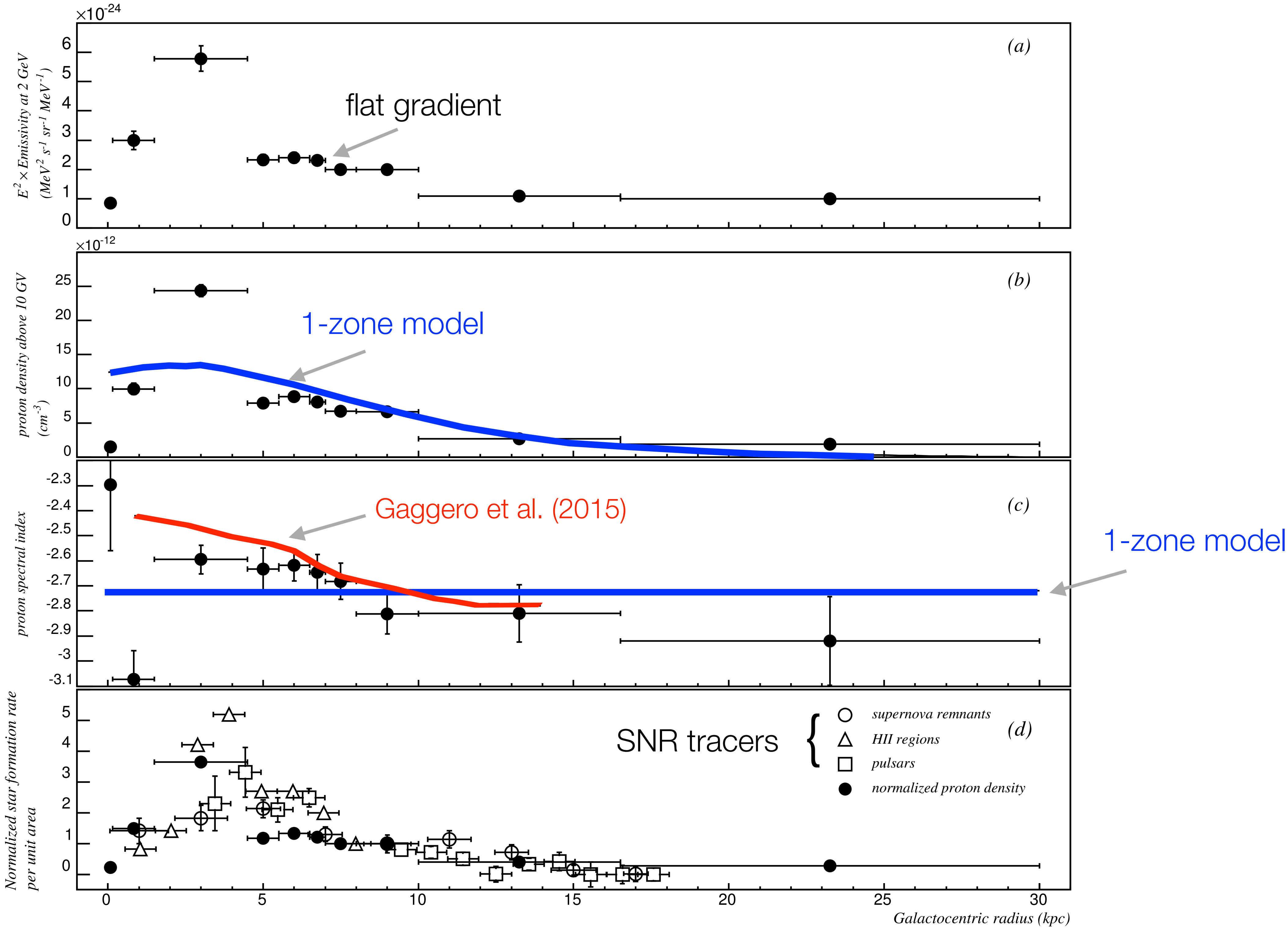
R. Yang, F. Aharonian, **CE**, PRD, 2016



The energy spectrum of multi-GeV protons derived from γ-ray data in the outskirts of the Galaxy is quite close to the measurements of local CRs.

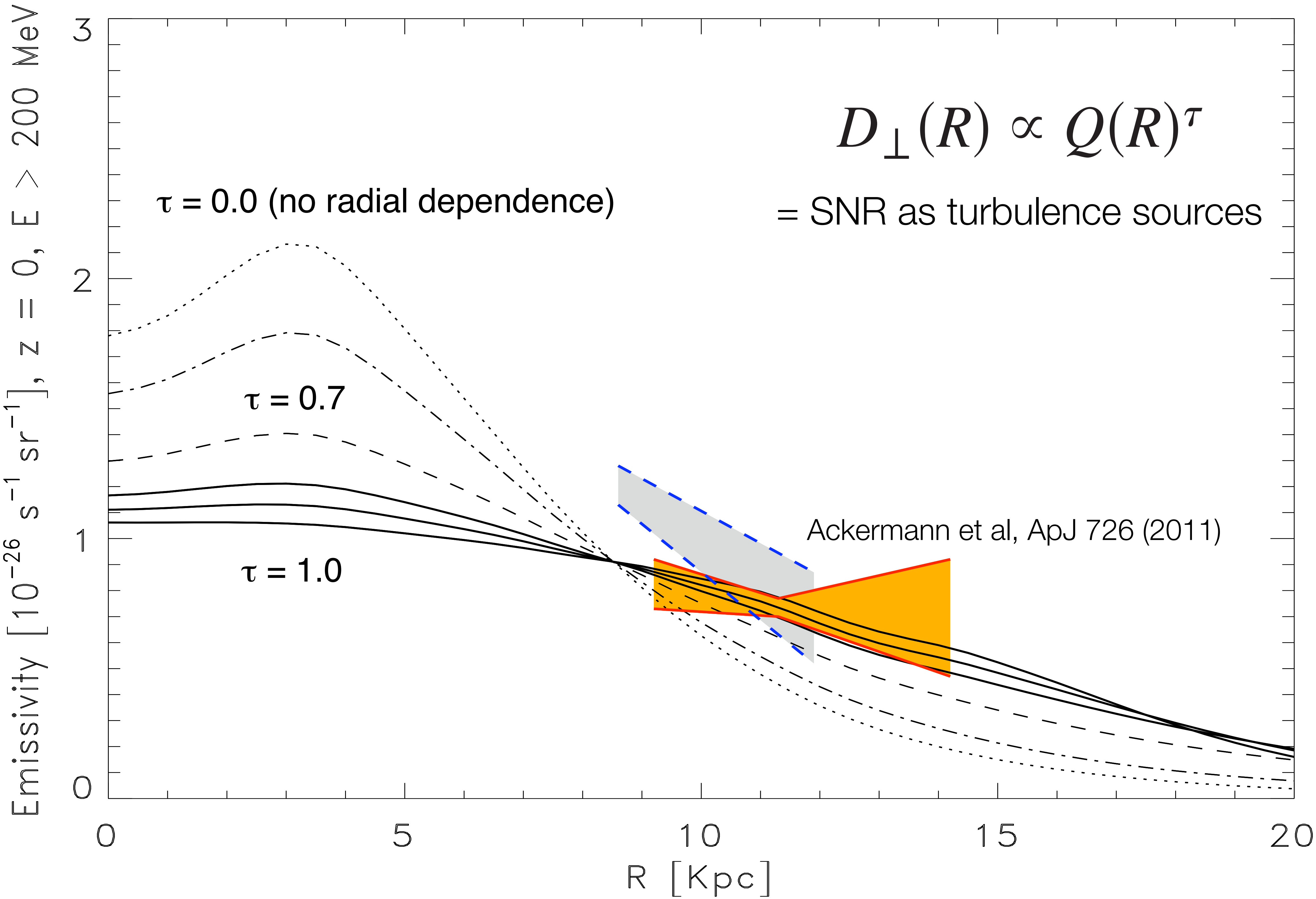
FERMI galactic interstellar emission model (GEIM)

FERMI Collaboration, arXiv:1602.07246



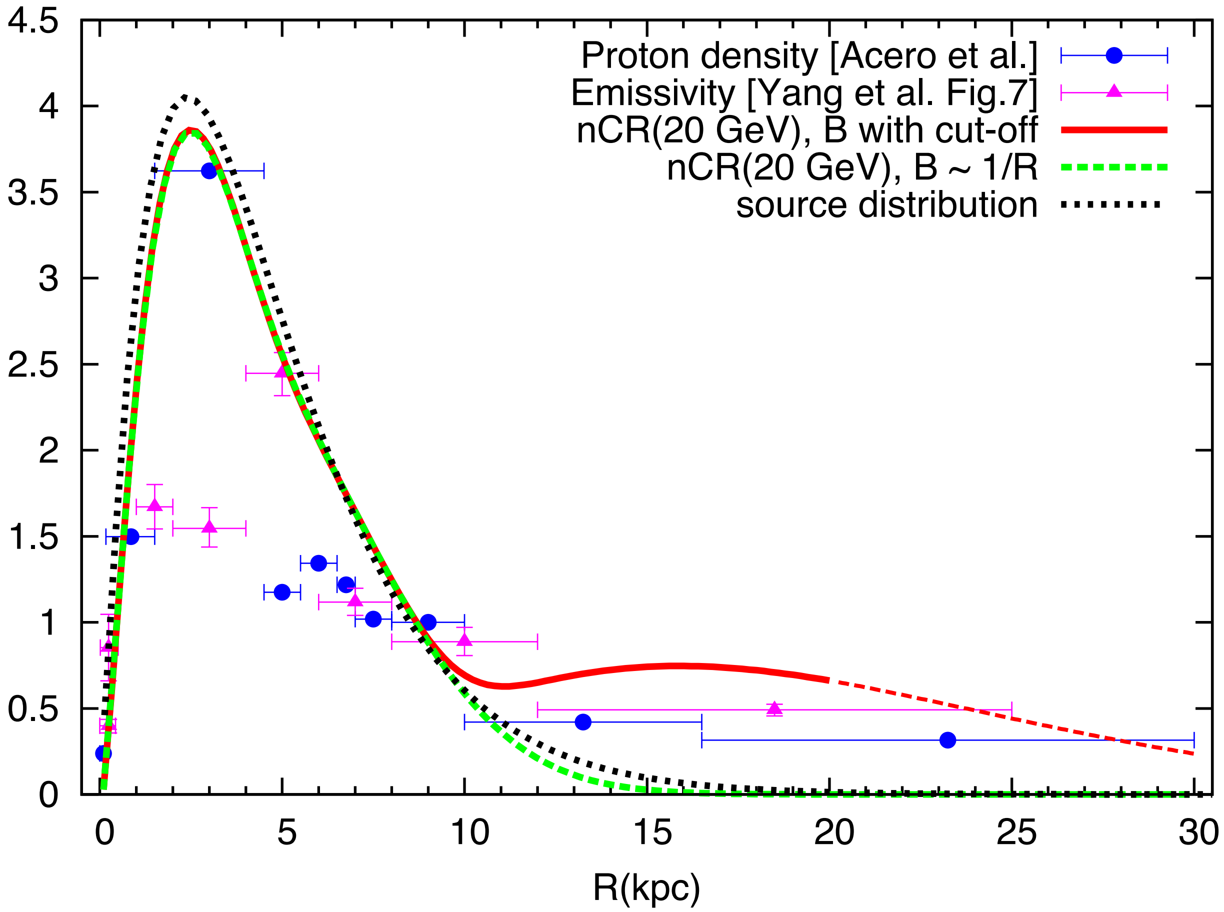
The gradient problem in terms of inhomogeneous diffusions

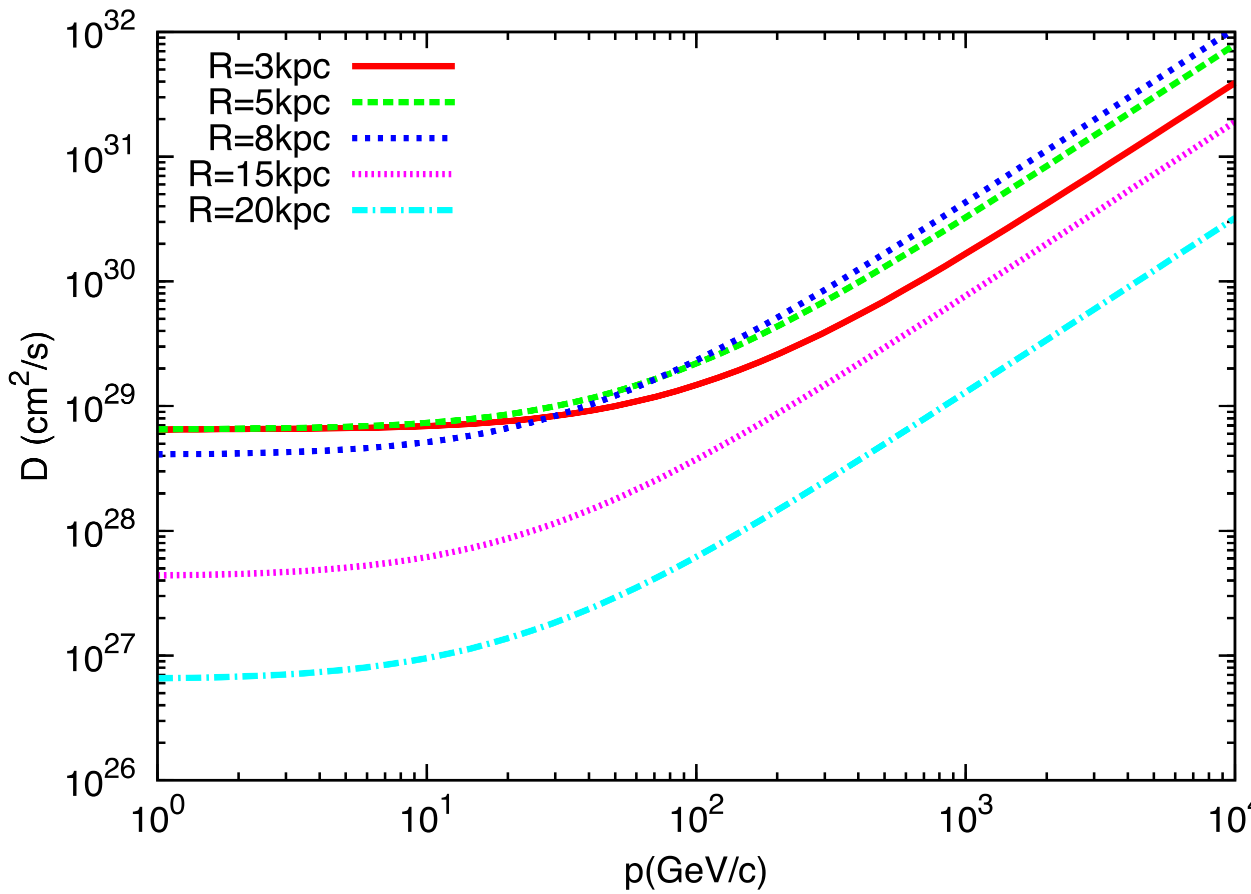
CE et al., PRL, 2012



Non-linear CR propagation

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





"we showed that both the gradient and the spectral shape can be explained in a simple model of non-linear CR transport: CRs excite waves through streaming instability in the ionized Galactic halo and are advected with such Alfvén waves. In this model, *the diffusion coefficient is smaller where the source density is larger and this phenomenon enhances the CR density in the inner Galaxy."*

Diffusion-Reacceleration-Advection Equation

Ginzburg & Syrovatsky (1964)

$$\underbrace{\partial_t N}_{\to 0} - \partial_x (D_x \partial_x) N - \partial_p \left[p^2 D_p \partial_p \left(\frac{N}{p^2} \right) \right] =$$

+ Sources
- Losses
- Spallation

$D_x = D_\odot g(p) f(x)$ $\qquad$ $D_p \sim p^2 v_A^2 / D_x$

$$-D_\odot g(p) \partial_x \left[f(x) \partial_x \right] N - \frac{v_A^2}{D_\odot f(x)} \partial_p \left[\frac{p^4}{g(p)} \partial_p \left(\frac{N}{p^2} \right) \right] = [\ldots]$$

$$-D_\odot g(p) \partial_x^2 N - \frac{v_A^2}{D_\odot} \partial_p \left[\frac{p^4}{g(p)} \partial_p \left(\frac{N}{p^2} \right) \right] = [\ldots]$$

1-zone model

Diffusion-Reacceleration-Advection Equation

Ginzburg & Syrovatsky (1964)

$$\partial_t N - \partial_x (D_x \partial_x) N - \partial_p \left[p^2 D_p \partial_p \left(\frac{N}{p^2} \right) \right] =$$

+ Sources
- Losses
- Spallation

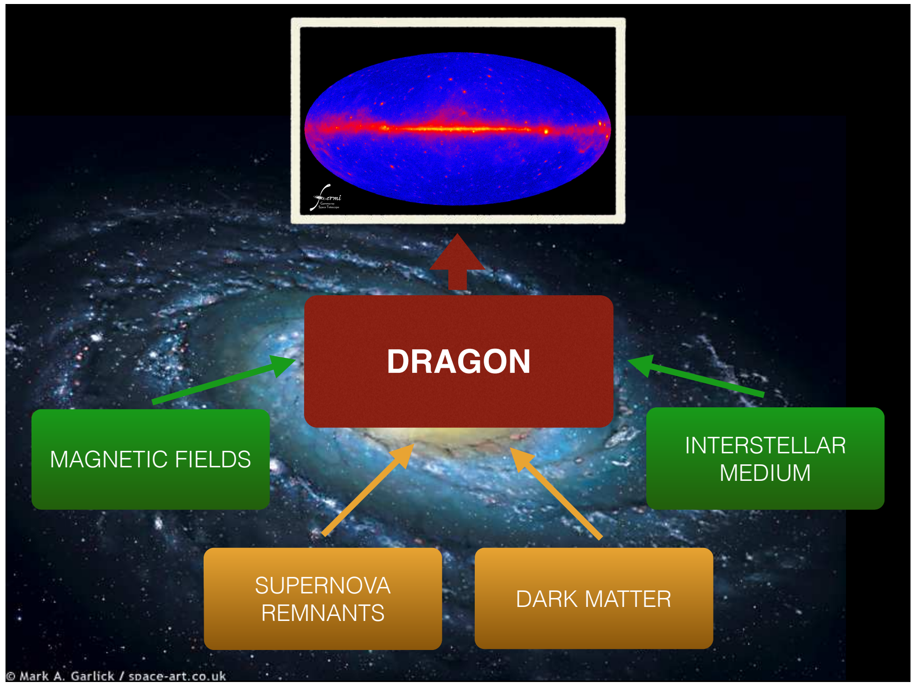
$$D_\odot g(p) \partial_x \left[f(x) \partial_x \right] N \quad \frac{v_A^2}{D_\odot f(x)} \partial_p \left[\frac{p^4}{g(p)} \partial_p \left(\frac{N}{p^2} \right) \right] = [\ldots]$$

$$D_\odot g(p) \partial_x^2 N \quad \frac{v_A^2}{D_\odot} \partial_p \left[\frac{p^4}{g(p)} \partial_p \left(\frac{N}{p^2} \right) \right] = [\ldots]$$

The DRAGON numerical package

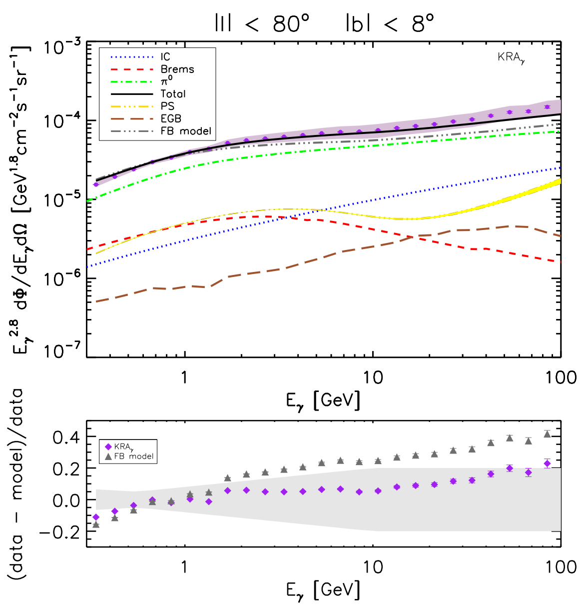
DRAGON code has been under development since *2008* following two main ideas:

- going beyond the 1-zone model for diffusion, implementing inhomogeneous + drifts
- the solution of the diffusion equation depends on a number of assumptions (**gas**, **magnetic field**, **ISRF**, **cross-sections**, **algorithm**…). Our approach allows quantitative estimates of the uncertainties induced by different assumptions.

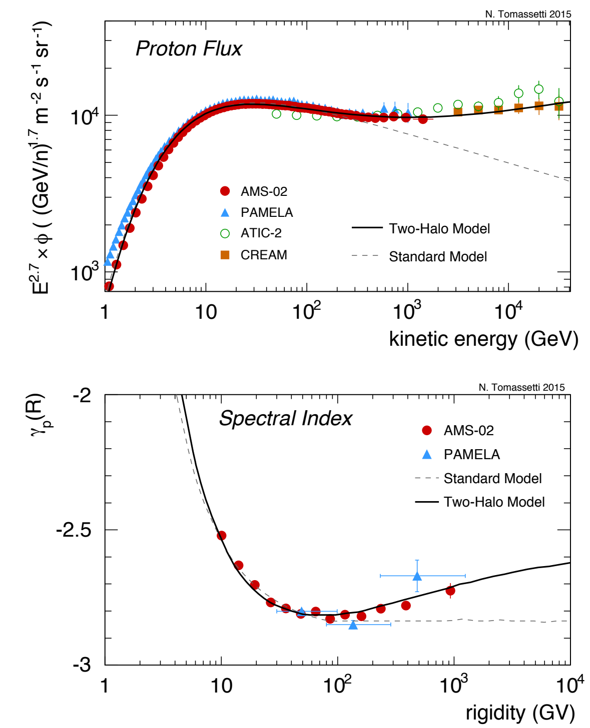


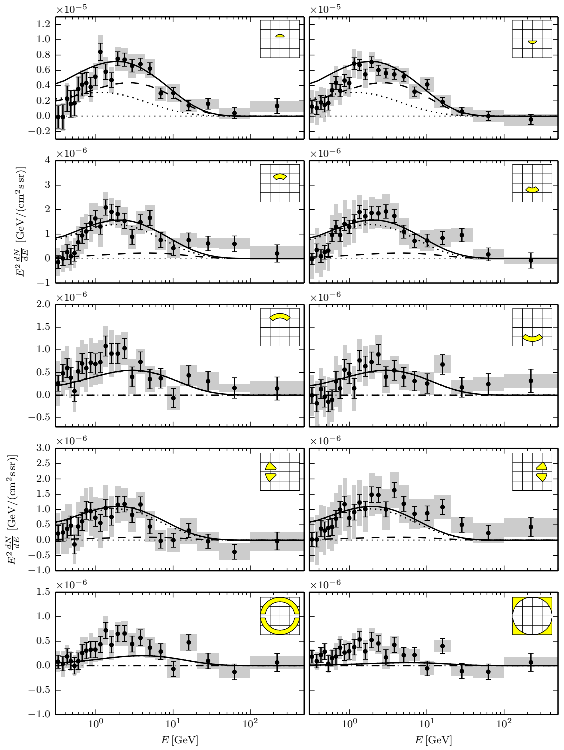
- **D**iffusing **R**eaccelerating **A**dvecting **G**alactic CRs: an **O**pen **N**ew code.

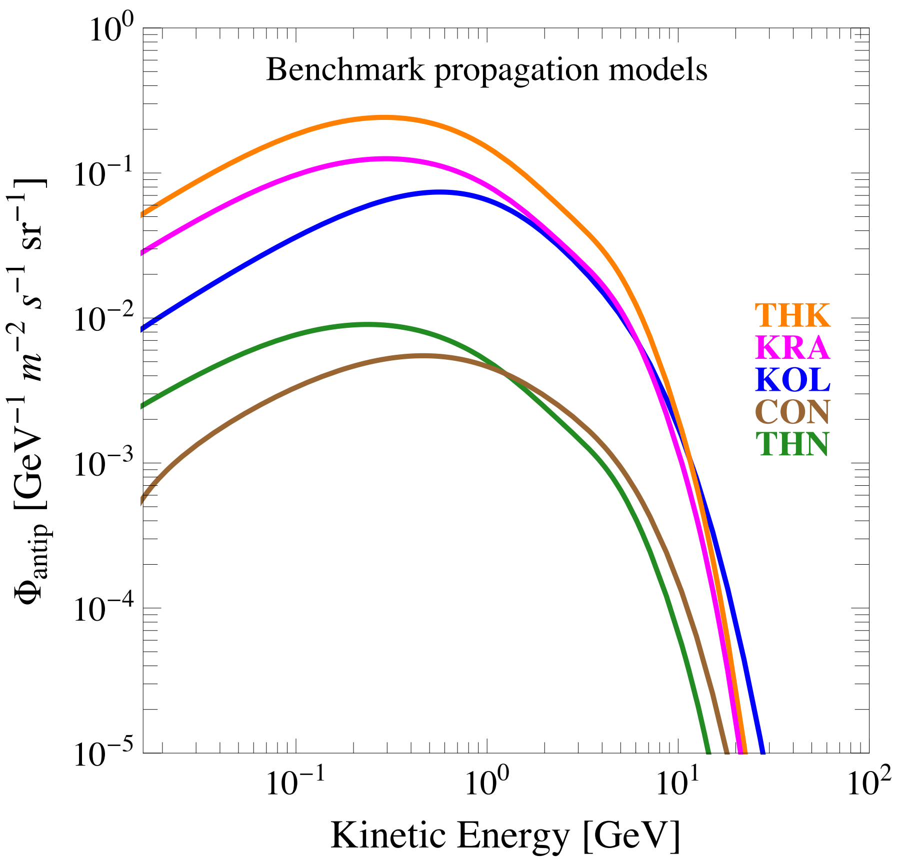
Ready for the v2…

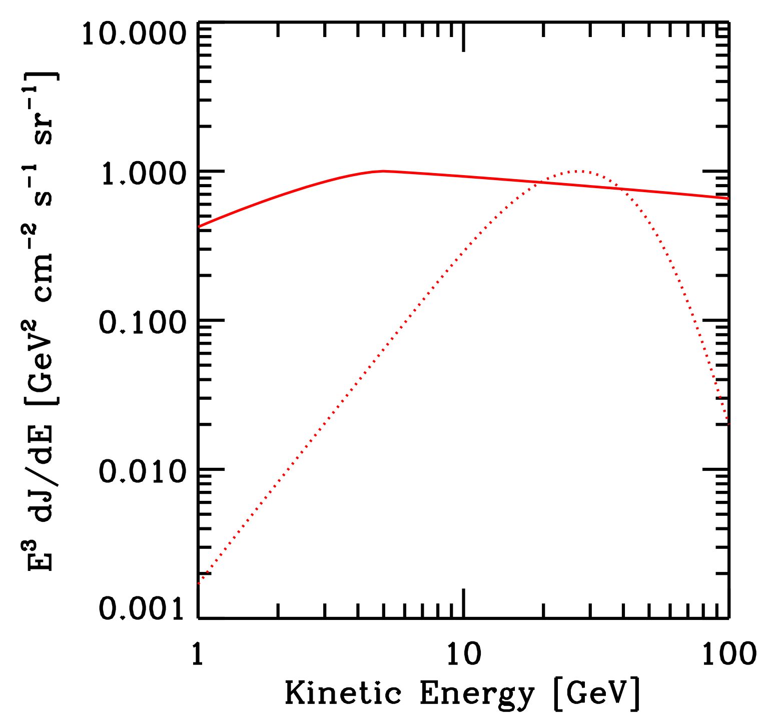


- inhomogeneous and anisotropic diffusion
- transients
- more DM models
- inhomogeneous reacceleration
- halo vs disk



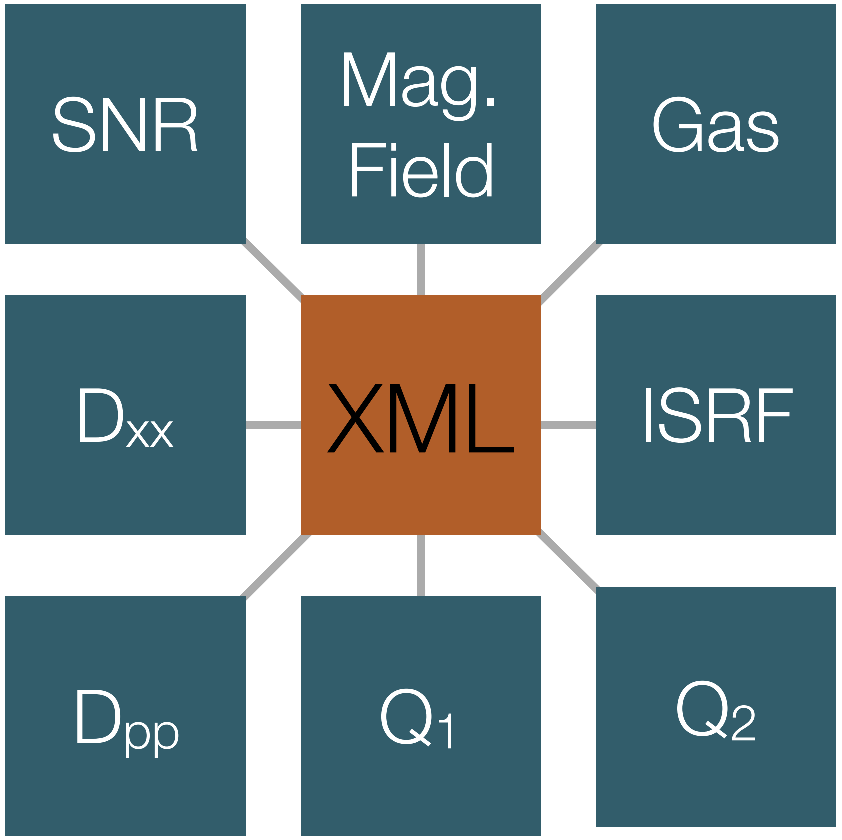






… really modular!

```
#include "TGalaxyGrid.h"

namespace DRAGON {

   class THIDensityNakanishi03 : public TGalaxyGrid
   {
      double h0;
      double n0;
   public:
      THIDensityNakanishi03();
      double distribution(const TVector3d& pos);
   };


   THIDensityNakanishi03::THIDensityNakanishi03() : TGalaxyGrid()
   {
      h0 = 1.06 * pc;
      n0 = 0.94 * (1./cm3);
   }

   double THIDensityNakanishi03::distribution(const TVector3d& pos)
   {
      double rKpc = pos.getR() / kpc;
      double exp1 = exp(-rKpc / 2.4);
      double exp2 = exp(-pow((rKpc - 9.5) / 4.8, 2));
      double densityOnPlane = n0 * (0.6 * exp1 + 0.24 * exp2);
      double scaleHeight = h0 * (116.3 + 19.3 * rKpc + 4.1 * rKpc *
   rKpc - 0.05 * rKpc * rKpc * rKpc);

      return (densityOnPlane * exp(-M_LN2 * pow(pos.z / scaleHeight,
   2)));
   }

} // namespace
```

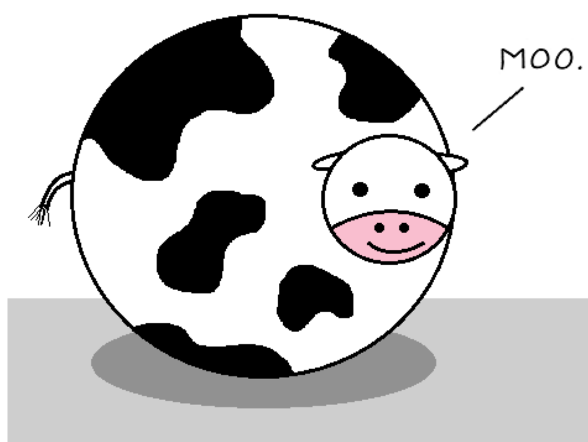


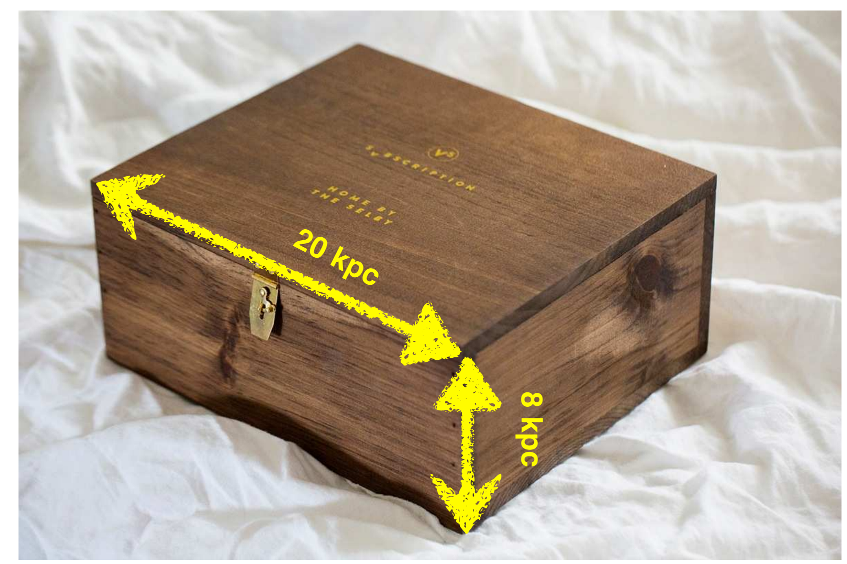
DRAGON2 Libraries

Take home message!

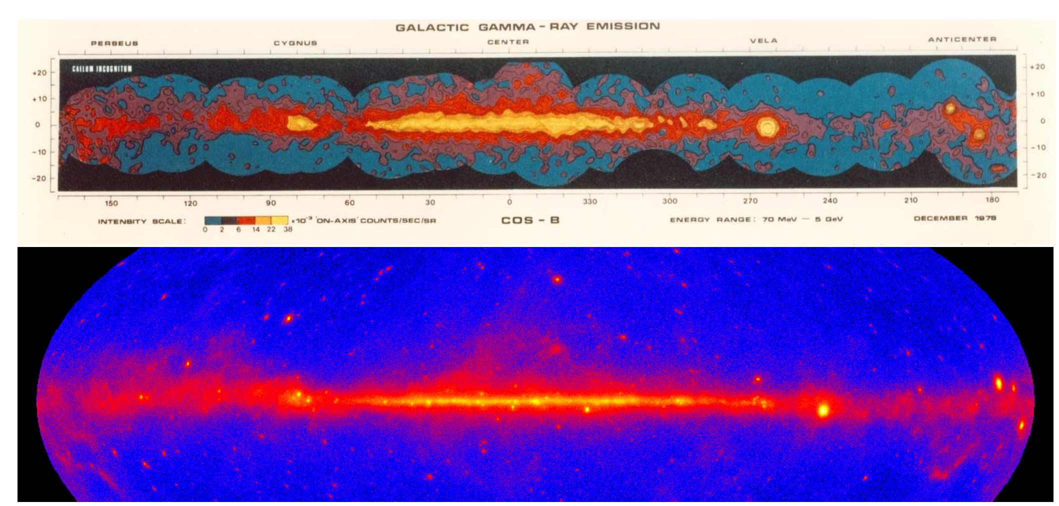
- quality of gamma data exceeded progressively realism of CR propagation model!

Models:





Data:



1978

today