Cosmic Ray propagation in the Galaxy with DRAGON2

Carmelo Evoli (Gran Sasso Science Institute)

Sources of Galactic cosmic rays - Paris - 8th of December 2016

DRAGON2 in the world

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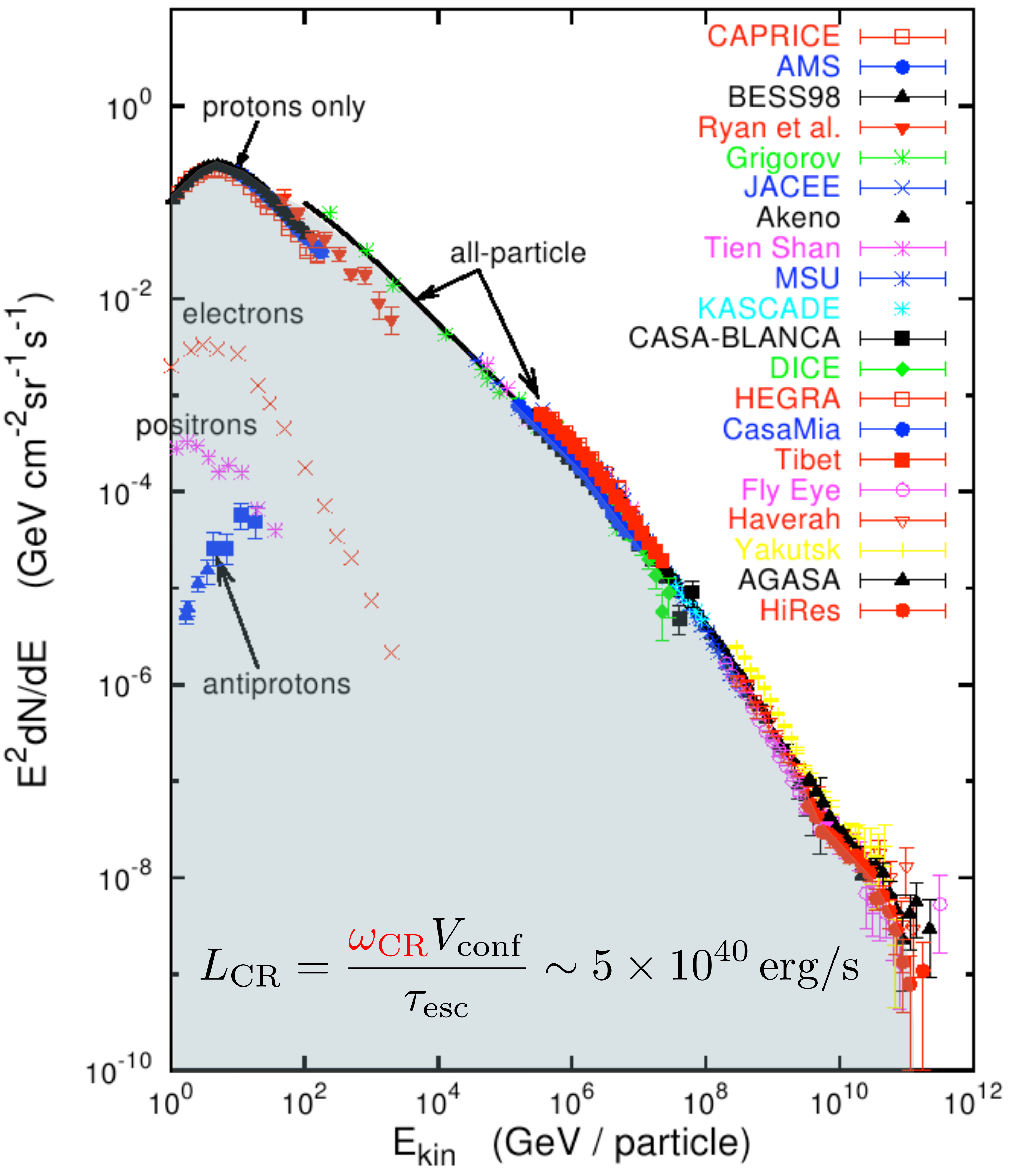
Cosmic-ray flux

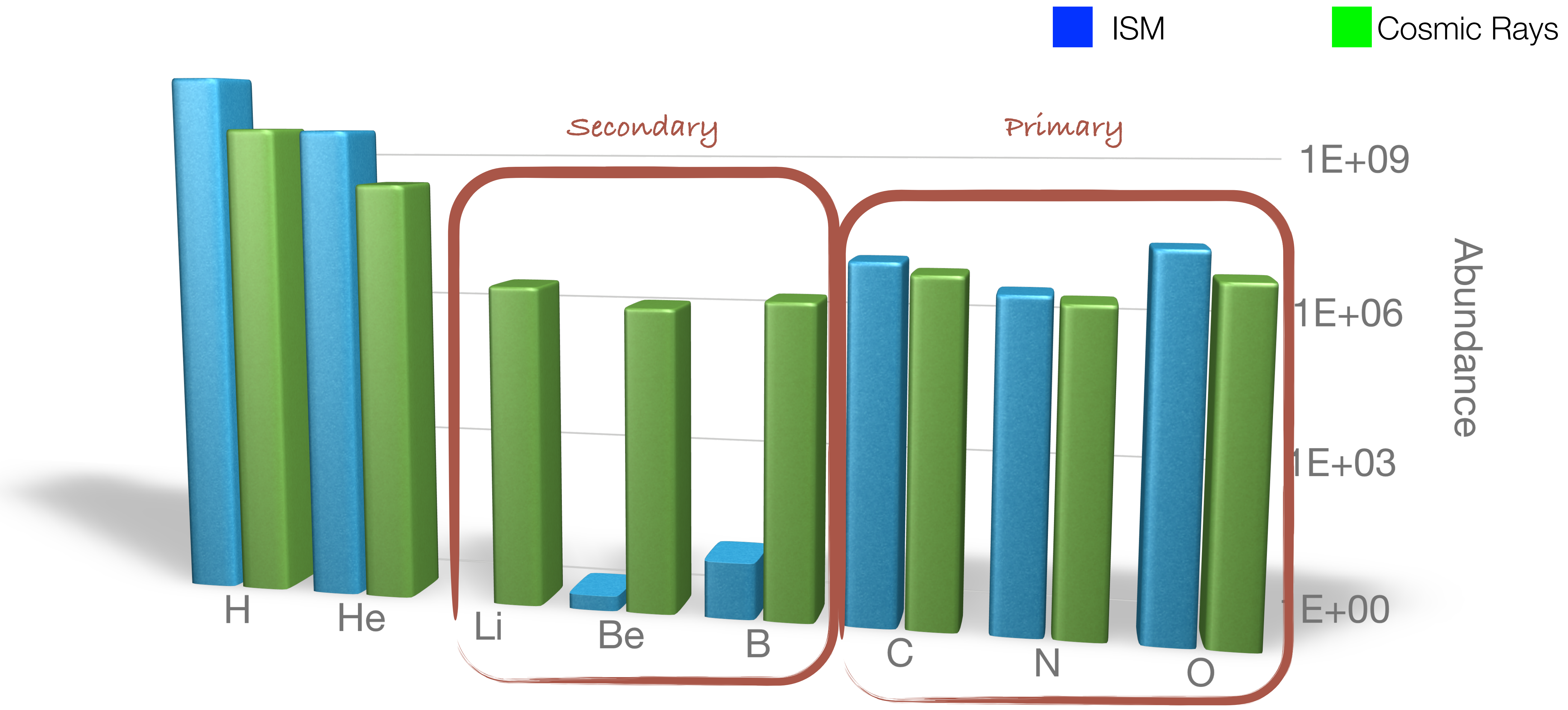
- Almost a perfect power-law over 12 energy decades.
- Observed at energy higher than terrestrial laboratories!
- Direct measurements versus air-cascade reconstructions.
- Anti-matter component.
- Transition from galactic to extra-galactic?
- Energy density in equipartition with starlight, turbulent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

Energies and rates of the cosmic-ray particles



$$L_{\rm CR} = \frac{\omega_{\rm CR} V_{\rm conf}}{\tau_{\rm esc}} \sim 5 \times 10^{40}\ {\rm erg/s}$$

Cosmic-ray composition as a probe of Galactic origin



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

>> Galaxy size!

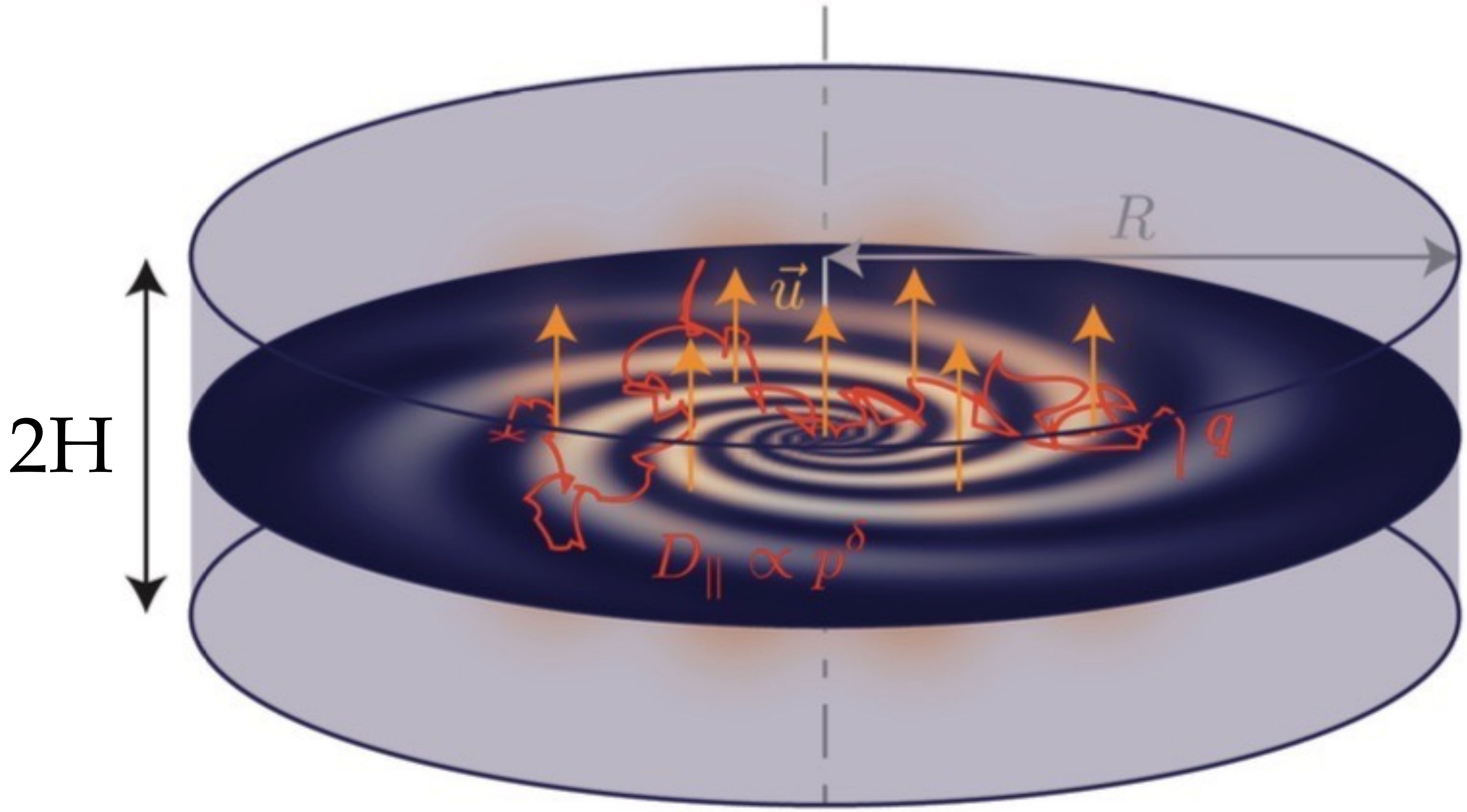
The Master equation

Berezinskii et al. (1990)

$$\boxed{\frac{\partial n_i}{\partial t} - \vec{\nabla} \cdot \left(D_{\mathrm{xx}} \cdot \vec{\nabla} n_i - \vec{u} n_i \right) - \frac{\partial}{\partial p} p^2 D_{\mathrm{pp}} \frac{\partial}{\partial p} \frac{1}{p^2} n_i} = \boxed{Q_{\mathrm{inj}} + Q_{\mathrm{losses}} + Q_{\mathrm{spall/dec}}}$$

Transport

Sources/sinks



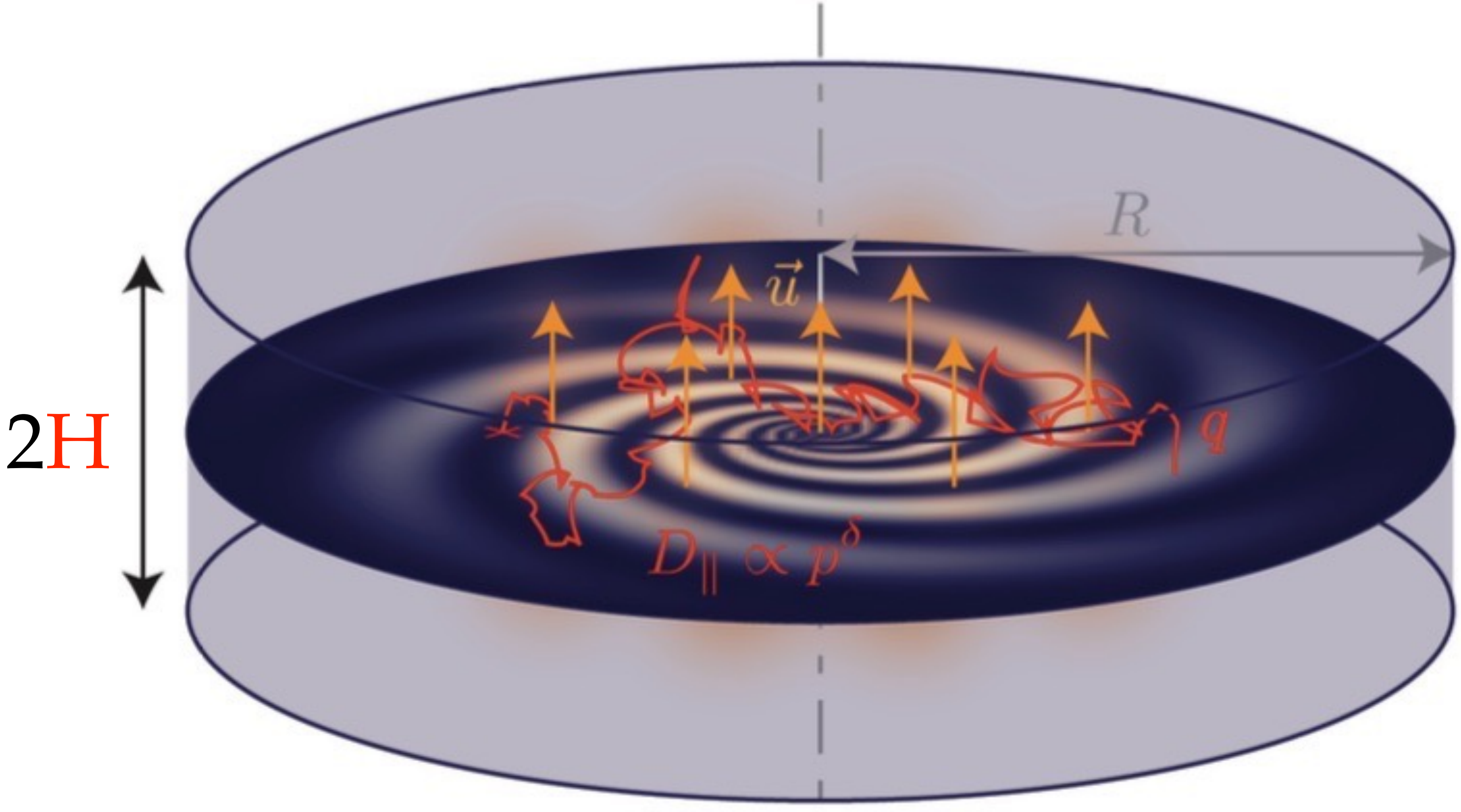
Credit: P. Mertsch

Minimal “5-parameters model”

Berezinskii et al. (1990)

$$-D_\odot \left(\frac{p}{p_0}\right)^{\delta} \frac{\partial^2}{\partial x^2} n_i - \frac{{v_A}^2\, p_0^4}{D_\odot} \frac{\partial}{\partial p} \left[\left(\frac{p}{p_0}\right)^{4-\delta} \frac{\partial}{\partial p} \left(\frac{n_i}{p^2}\right) \right] - v_z \frac{\partial n_i}{\partial z} = Q_{\mathrm{sources/sinks}}$$

… far from reality even in QLT



Credit: P. Mertsch

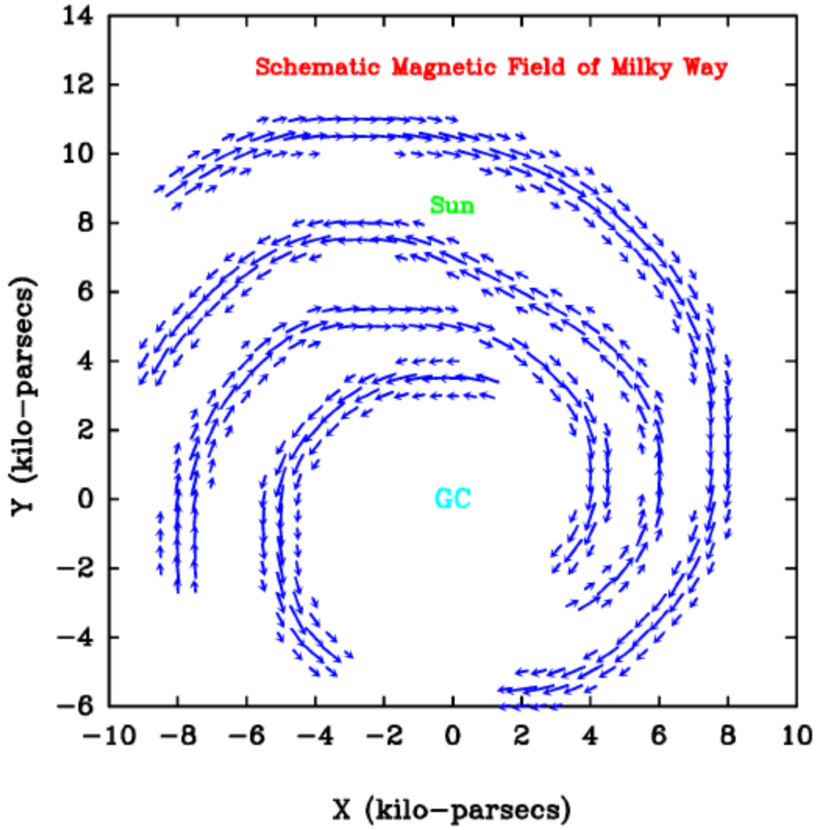
CR diffusion for the “poor physicist”

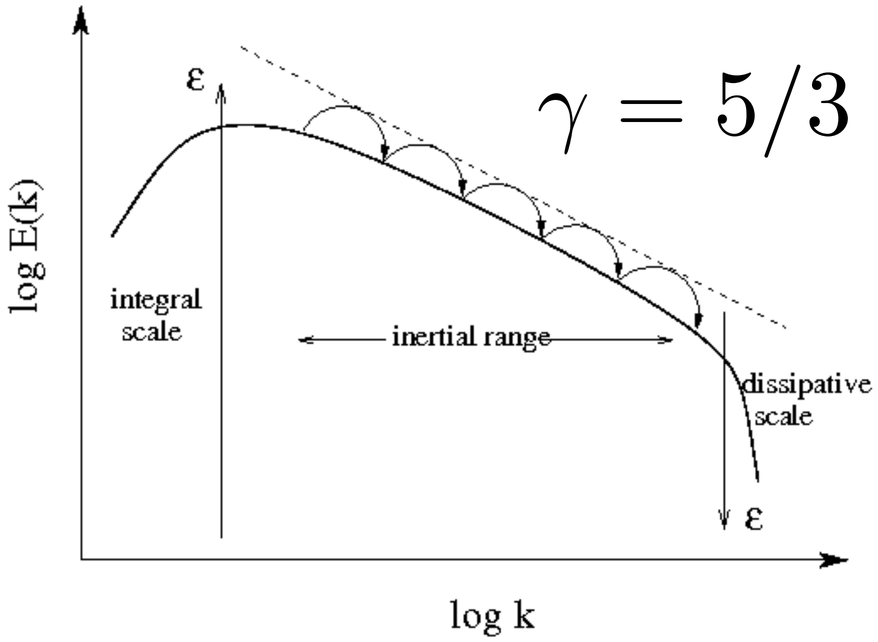
Assumptions:

- 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:

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





$$\gamma = 5/3$$

Diffusion in not-linear theory (NLT)

H. Yan & A. Lazarian, ApJ, 2008

- particle's pitch angle follows the variation of the *turbulent* magnetic field due to conservation of the adiabatic invariant:

$$\frac{\Delta v_{\parallel}}{v_{\perp}} = \frac{\left\langle (B - B_0)^2 \right\rangle^{1/4}}{B_0^{1/2}}$$

- resonance function has a Gaussian broadening:

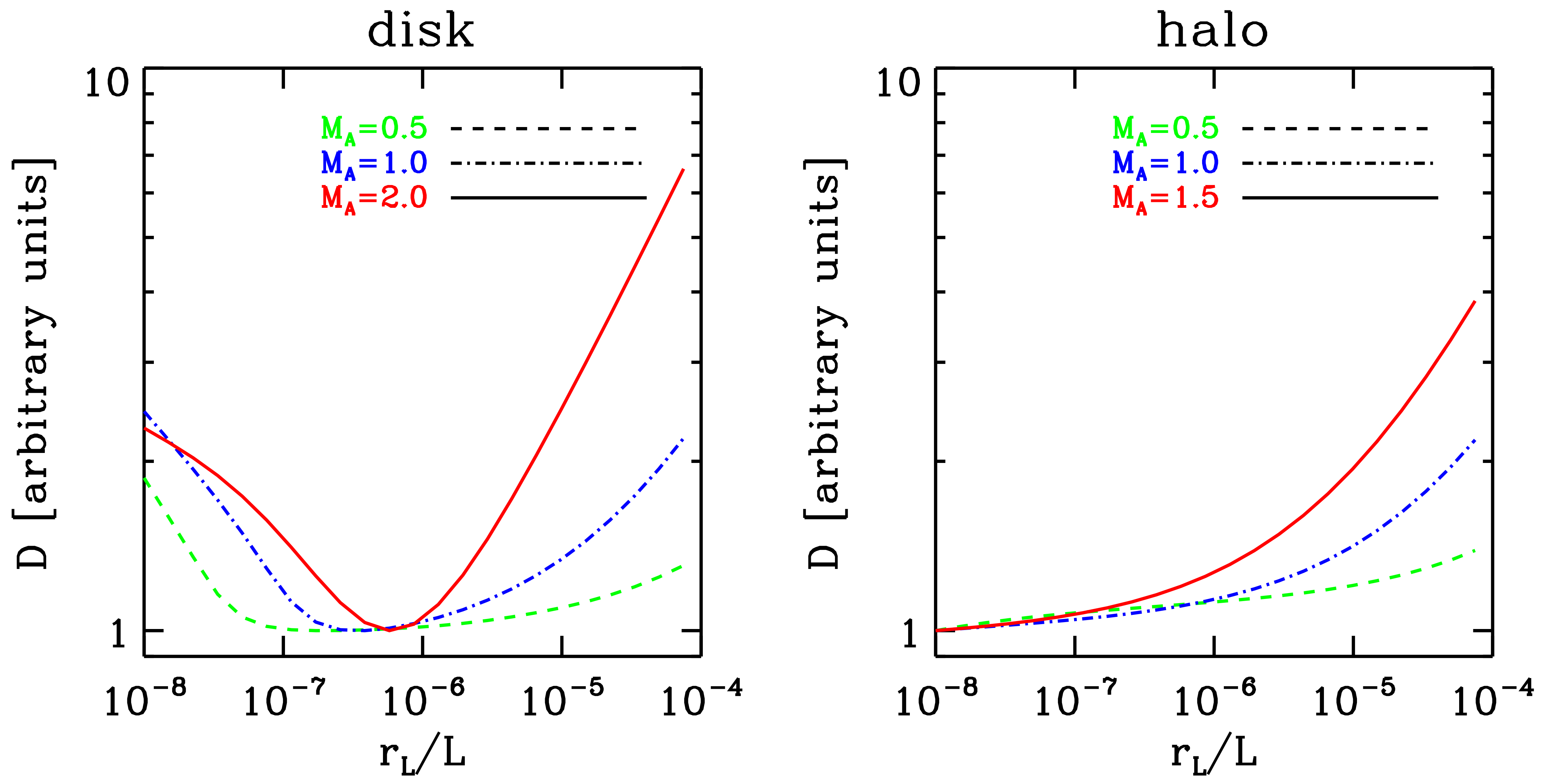
$$R_n^{\mathrm{NLT}}(k_{\parallel}v_{\parallel} - \omega \pm n\Omega) = \frac{\sqrt{\pi}}{k_{\parallel}\Delta v_{\parallel}} \exp\left[-\frac{(k_{\parallel} v\mu - \omega \pm n\Omega)^2}{k_{\parallel}^2 \Delta v_{\parallel}^2} \right]$$

- damping mechanisms make diffusion environment-dependent:

$$D_{\mu\mu} = \frac{\Omega^2(1-\mu^2)}{B_0^2} \int d^3k \, R_n^{\mathrm{NLT}}(\mathbf{k}) \left[\frac{k_{\parallel}^2}{k^2} J_n'^2(w) I^F(\mathbf{k}) \right]$$

Diffusion in NLT is environment dependent

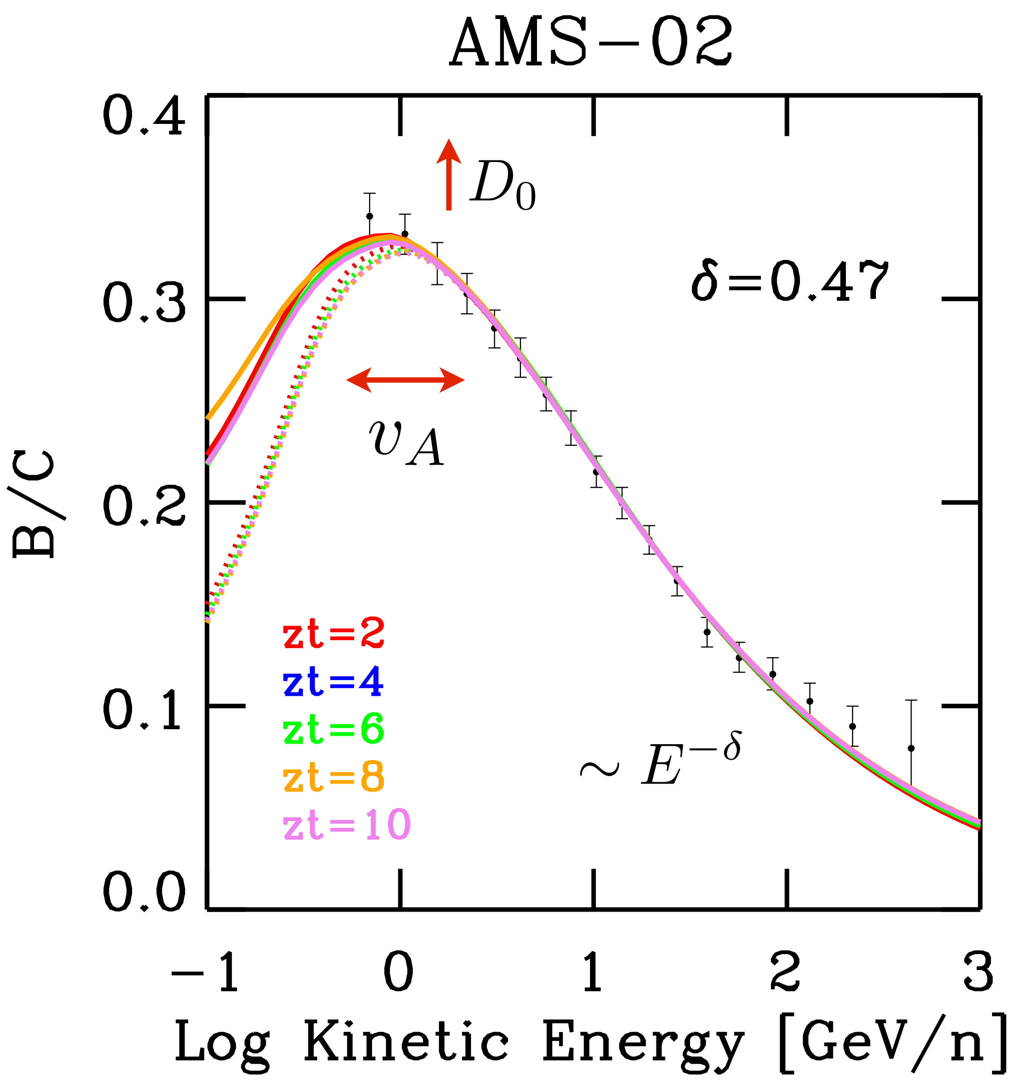
CE & H. Yan, ApJ, 2014

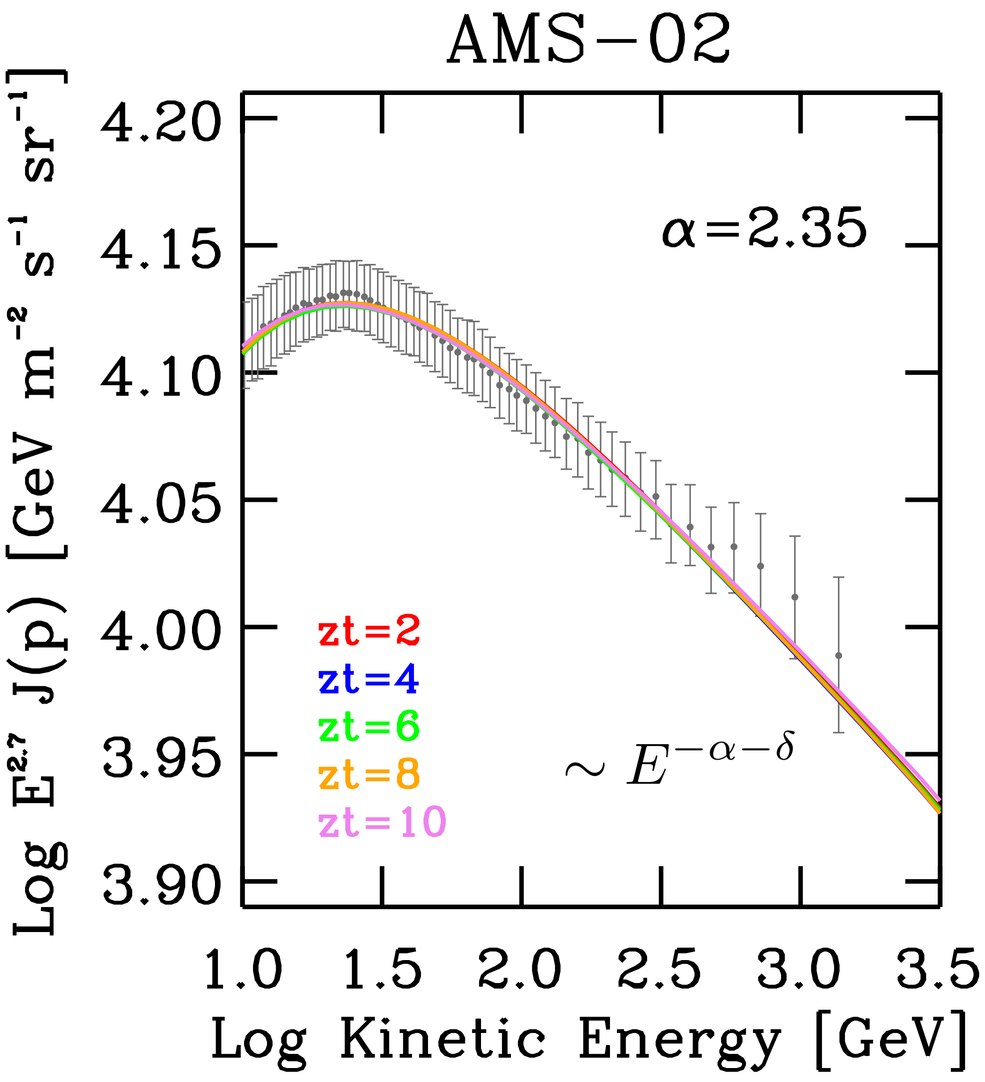


halo > collisionless damping

disk > collisionless + viscous damping

Fitting local observables

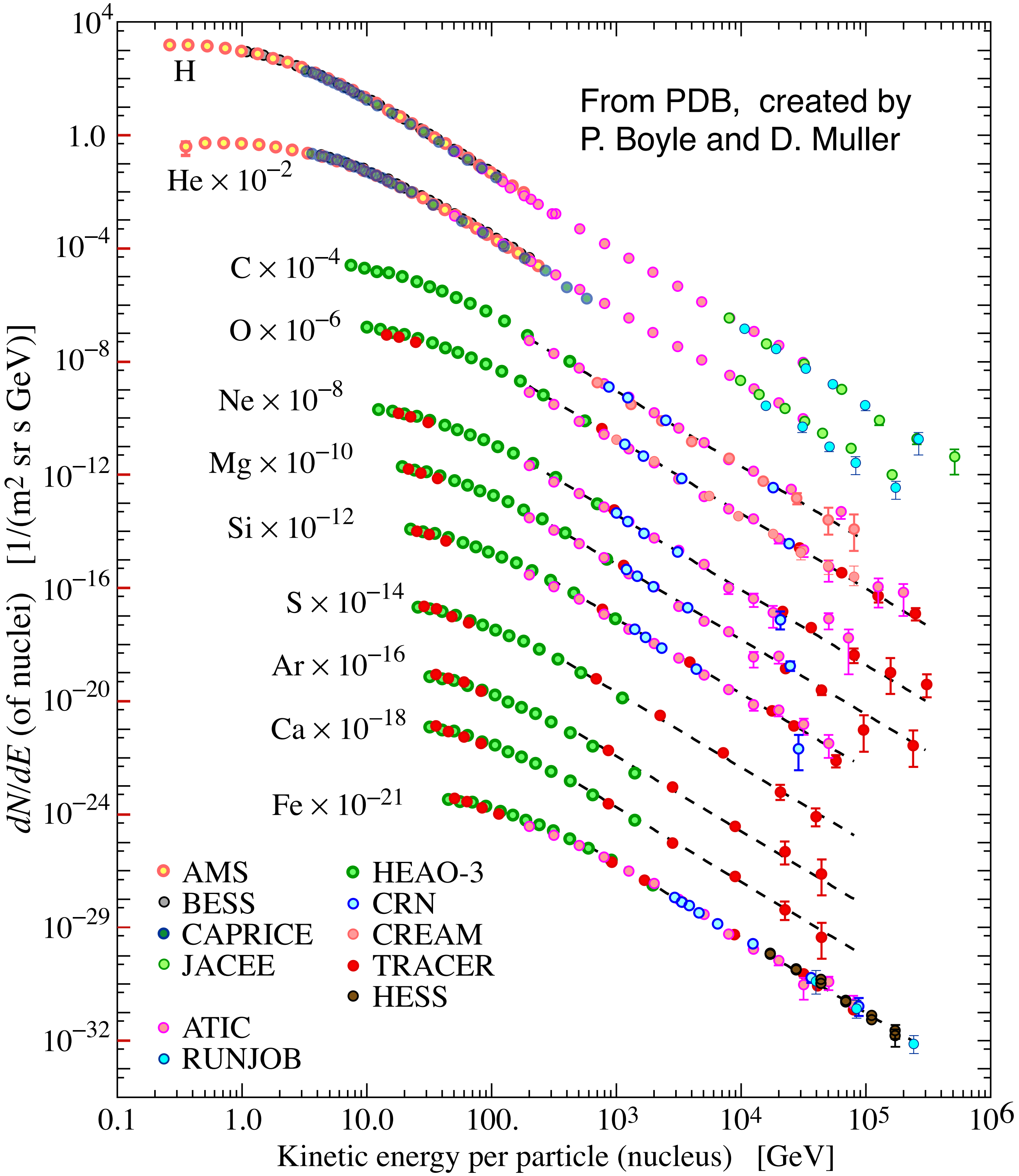




$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

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)

Primary spectra pre-PAMELA

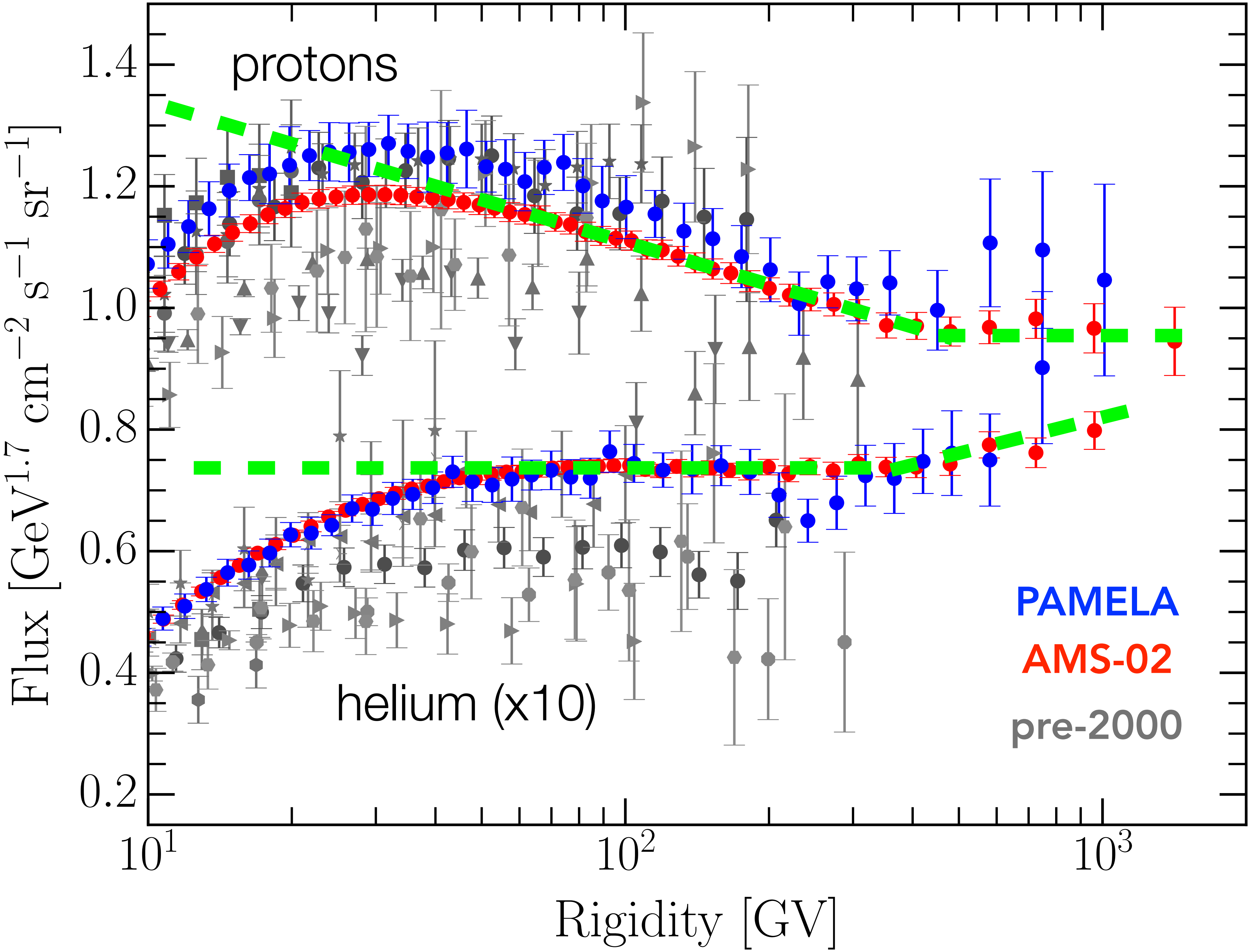


featureless and universal power-law energy spectra

prediction relying on many self-similarity assumptions: Fermi acceleration theory, Kolmogorov diffusion…

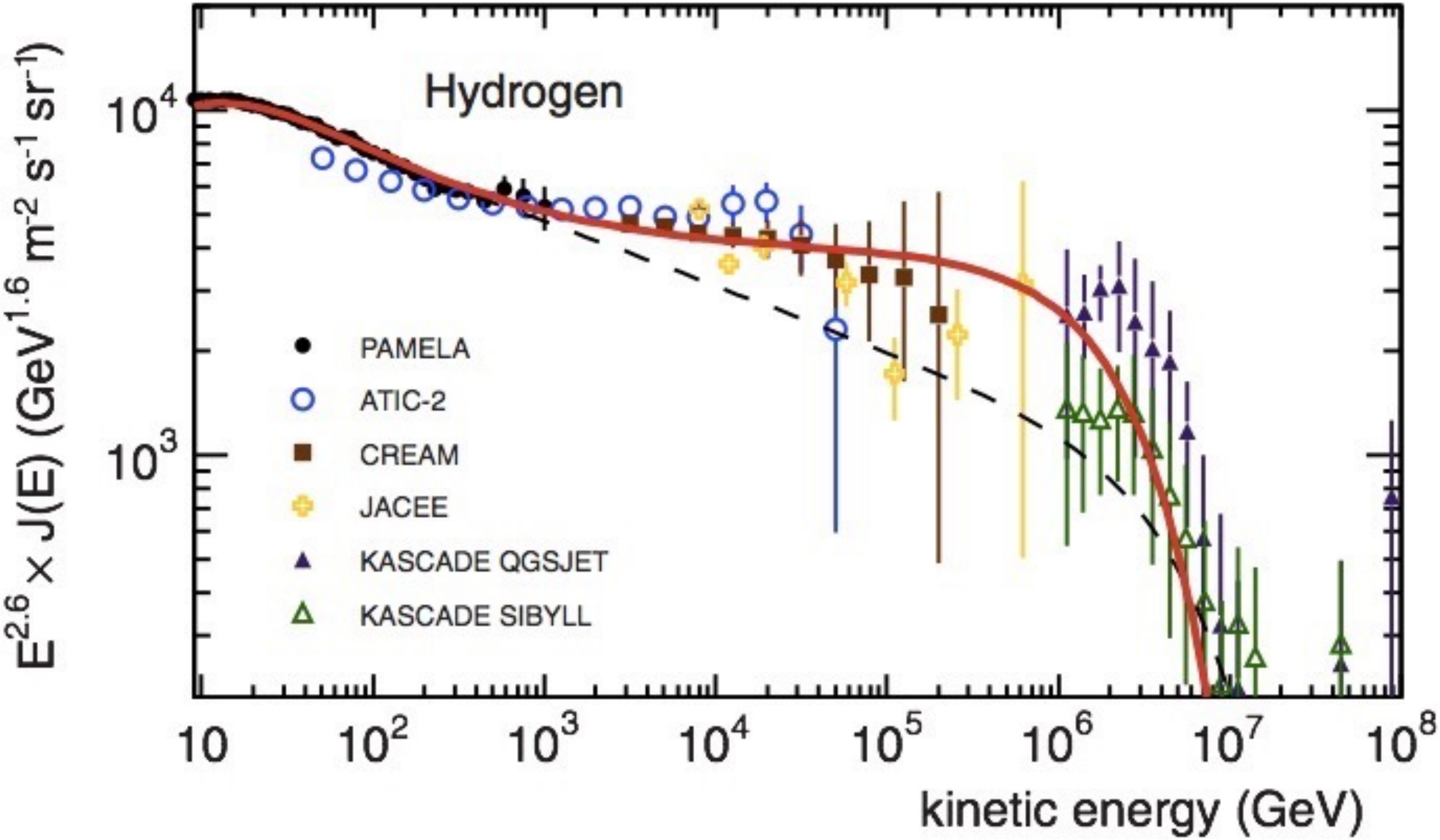
Today CR measurements reach remarkable precision

PAMELA Coll., Science, 2011 - AMS02 Coll., PRL, 2016



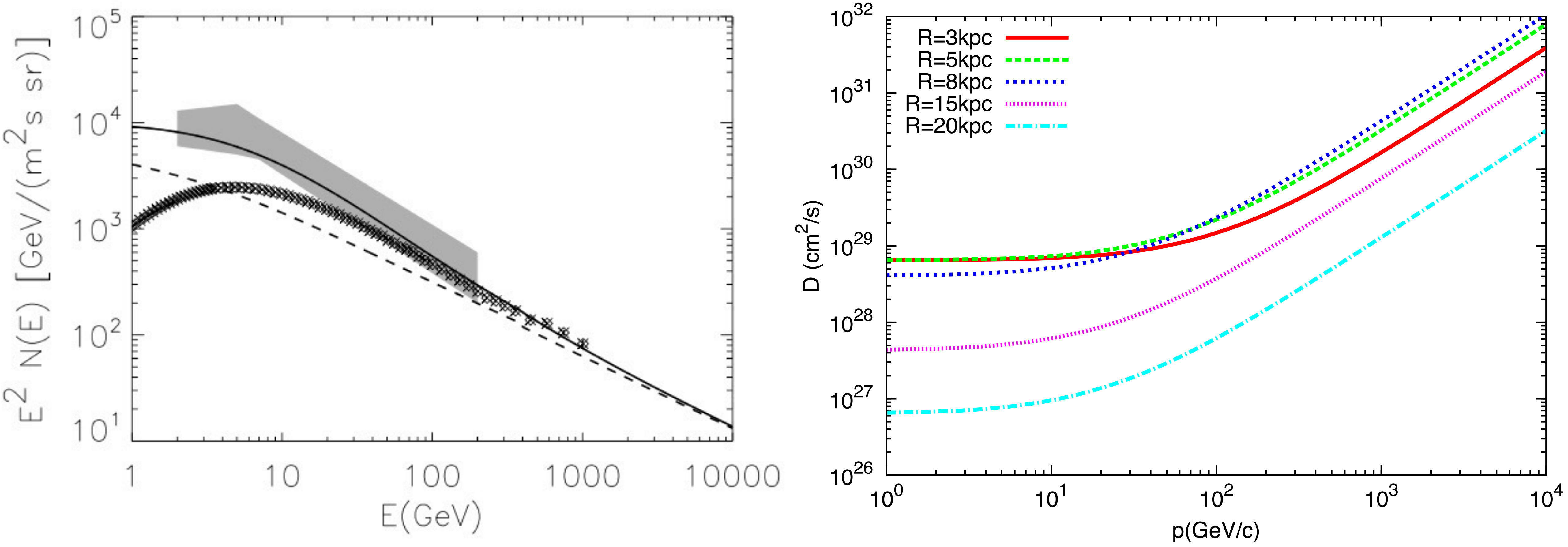
Diffusion in the halo different than in the disk

N. Tomassetti, ApJ, 2012



Non-linear CR propagation

Blasi et al., PRL, 2012; S. Recchia et al., arXiv:1604.07682

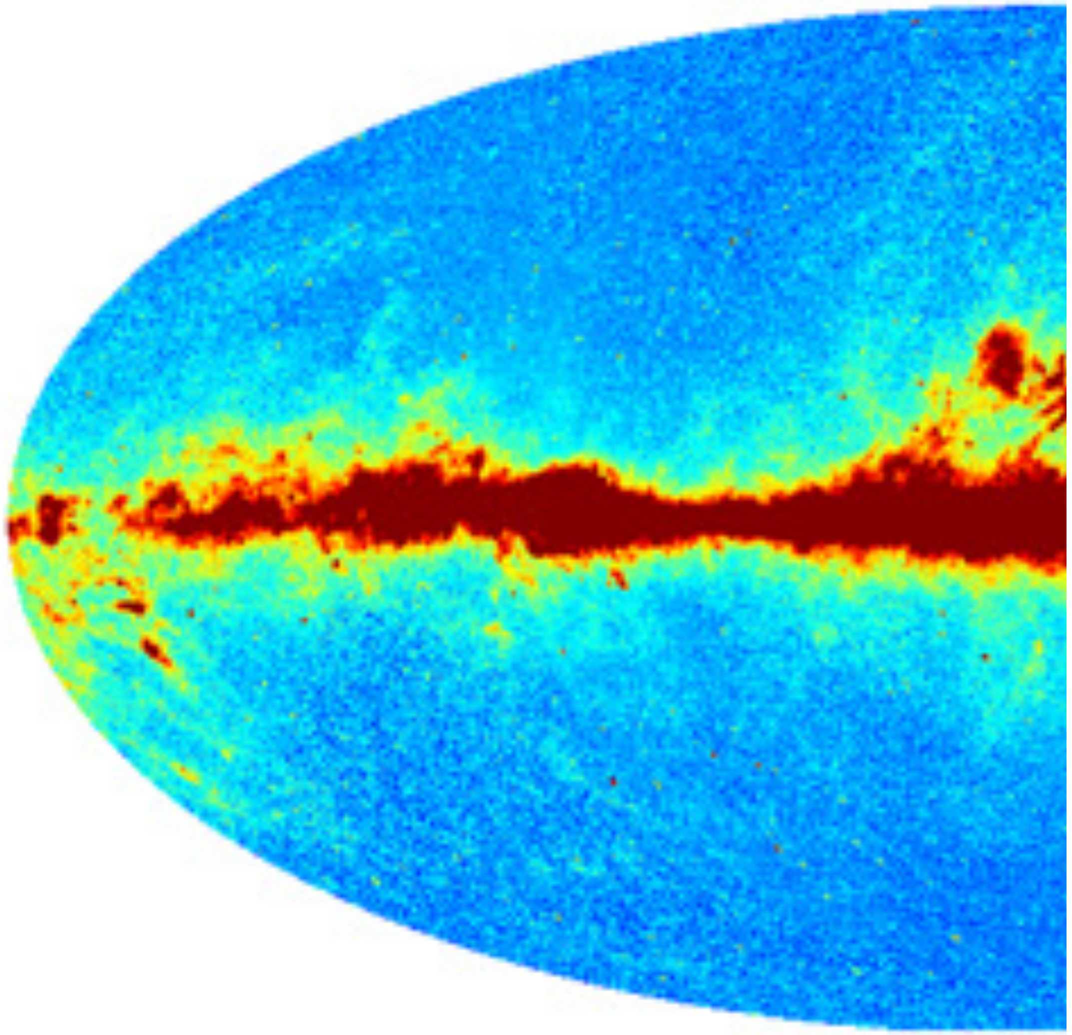


"we showed that both the gradient and the spectral shape can be explained in a simple model of non-linear CR transport: CRs excite waves through streaming instability in the ionized Galactic halo and are advected with such Alfvén waves. In this model, *the diffusion coefficient is smaller where the source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

You are here

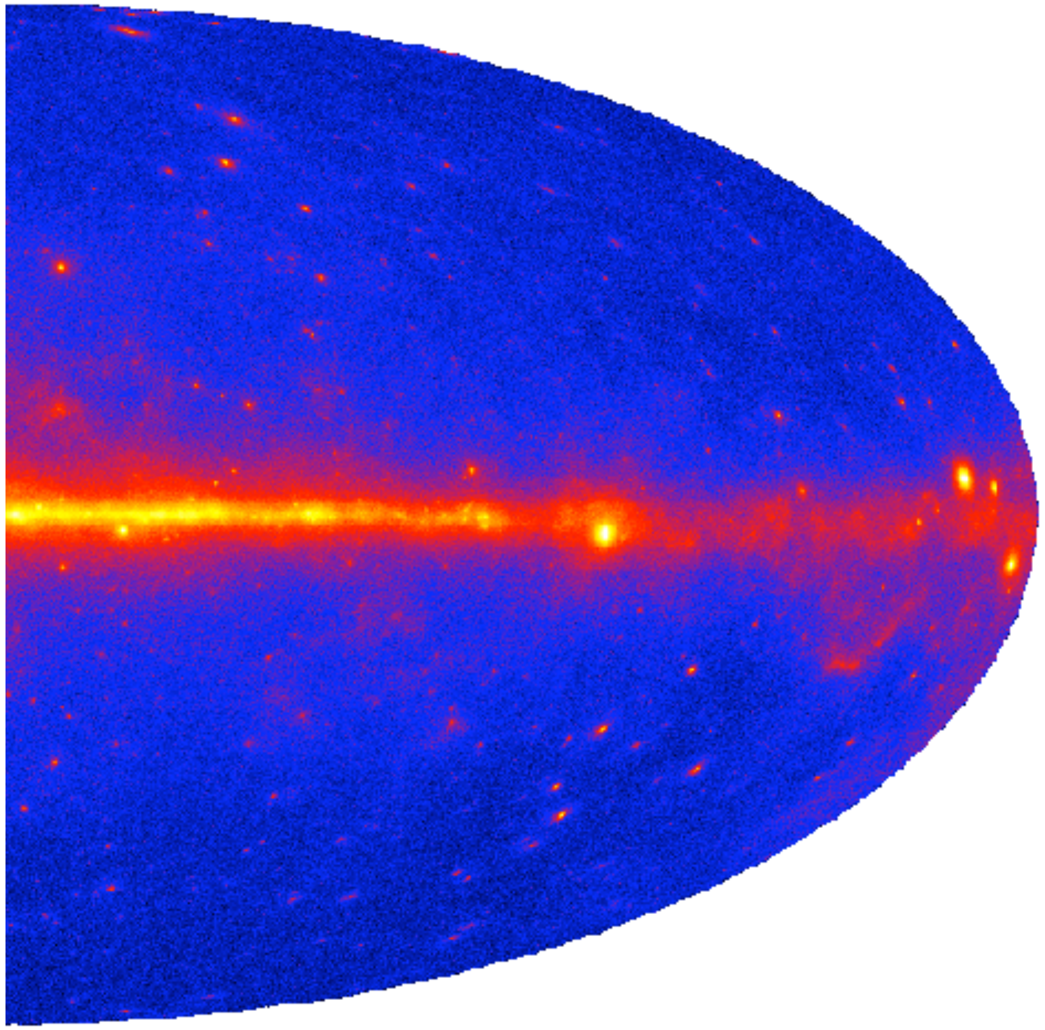
Diffuse emissions: from radio to gamma maps

PLANCK all-sky foreground map



$$E_\gamma \sim 10^{-13}\,\mathrm{GeV}$$

Two year all sky Fermi-LAT map

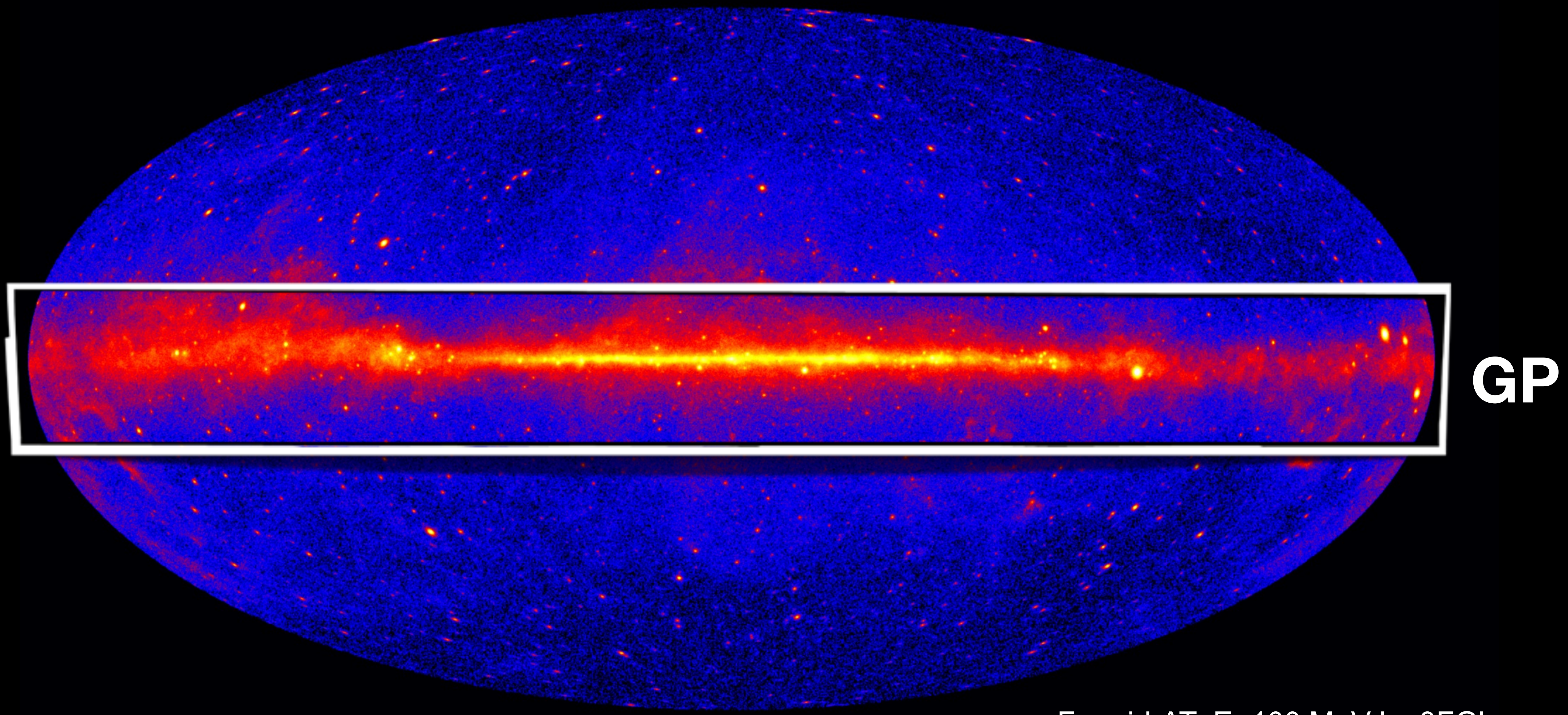


$$p\,p_{\mathrm{ISM}} \rightarrow \pi^0 \rightarrow \gamma\gamma$$

$$e^-\,\gamma_{\mathrm{ISRF}} \rightarrow e^-\,\gamma$$

$$E_\gamma > 1\,\mathrm{GeV}$$

The gamma-ray sky in 2016



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

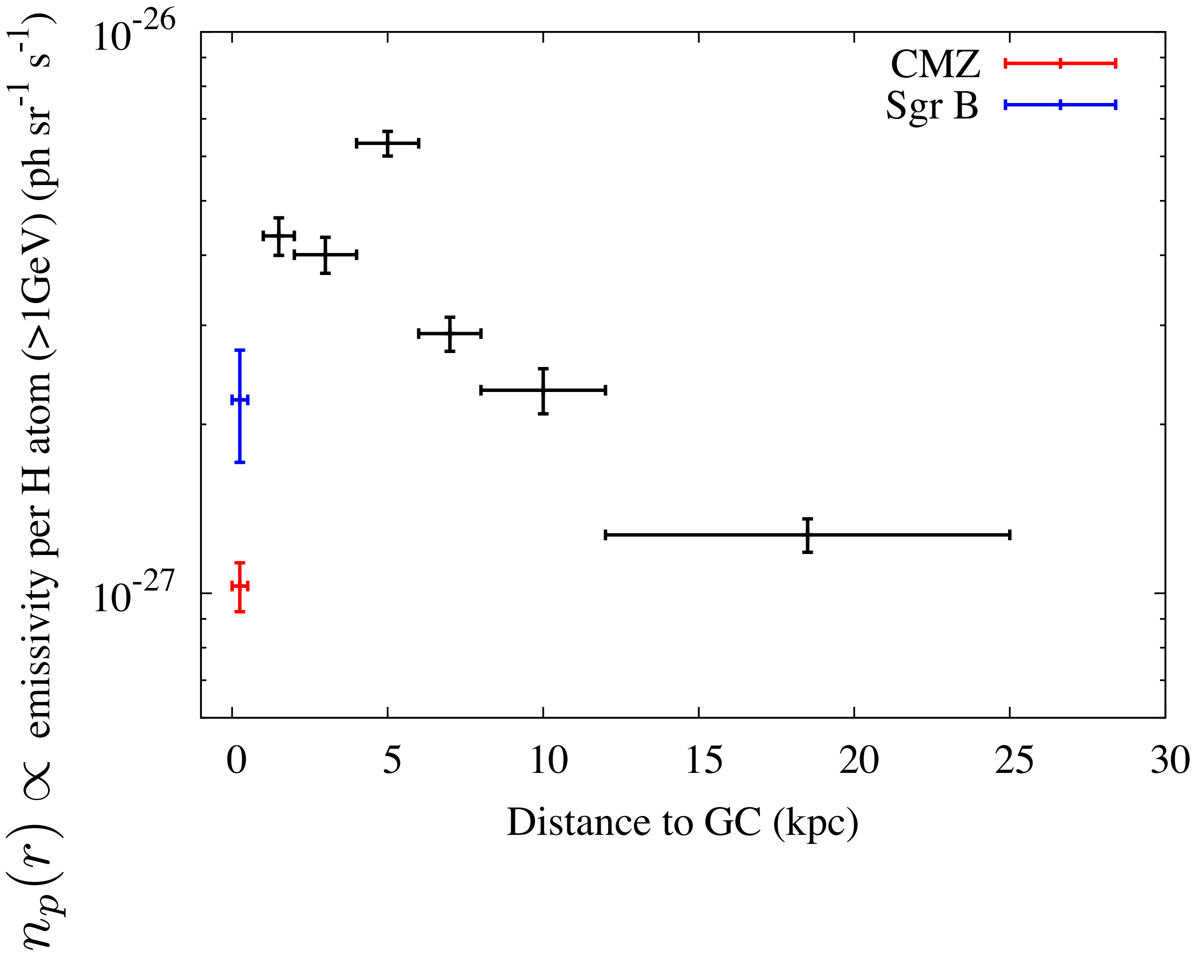
~ 70% of all observed photons coming from the diffuse Galactic emission

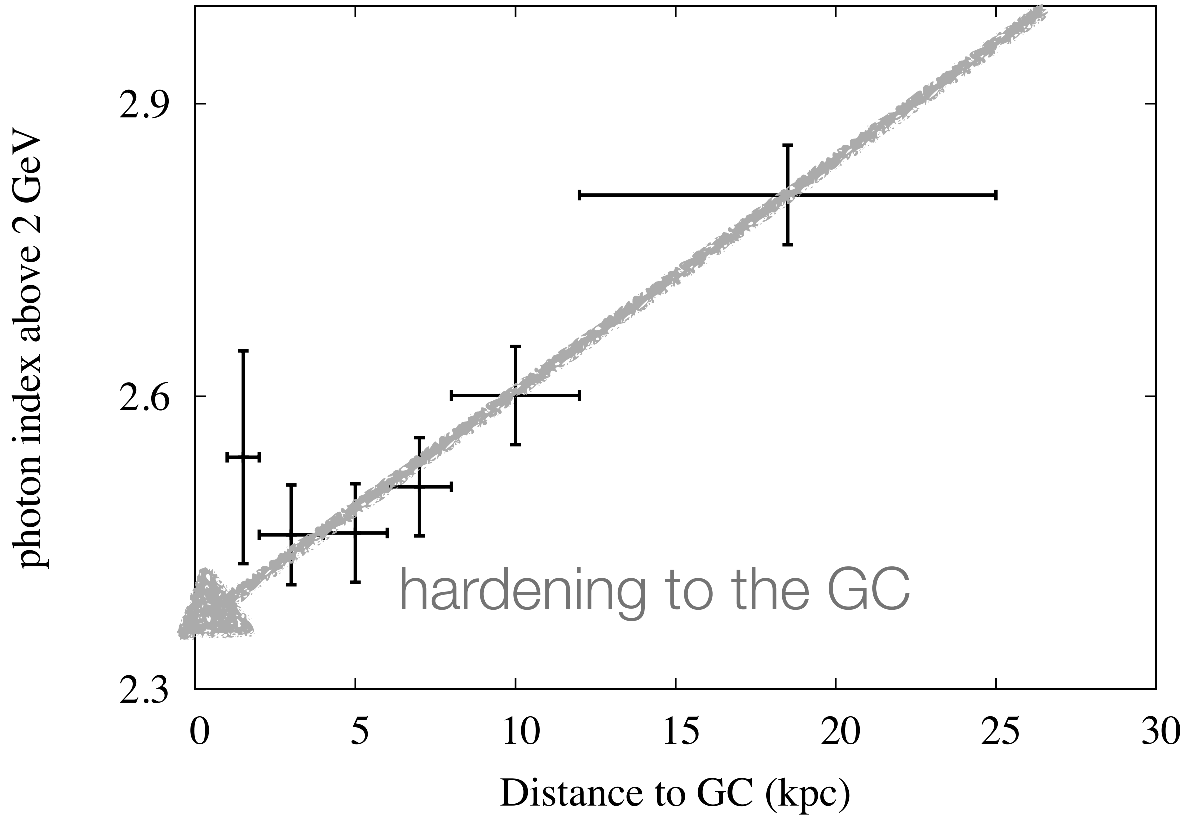
The extremely accurate gamma ray maps that FERMI is providing are useful to trace the CR distribution throughout all the Galaxy!

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

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

$|b| < 5^\circ$





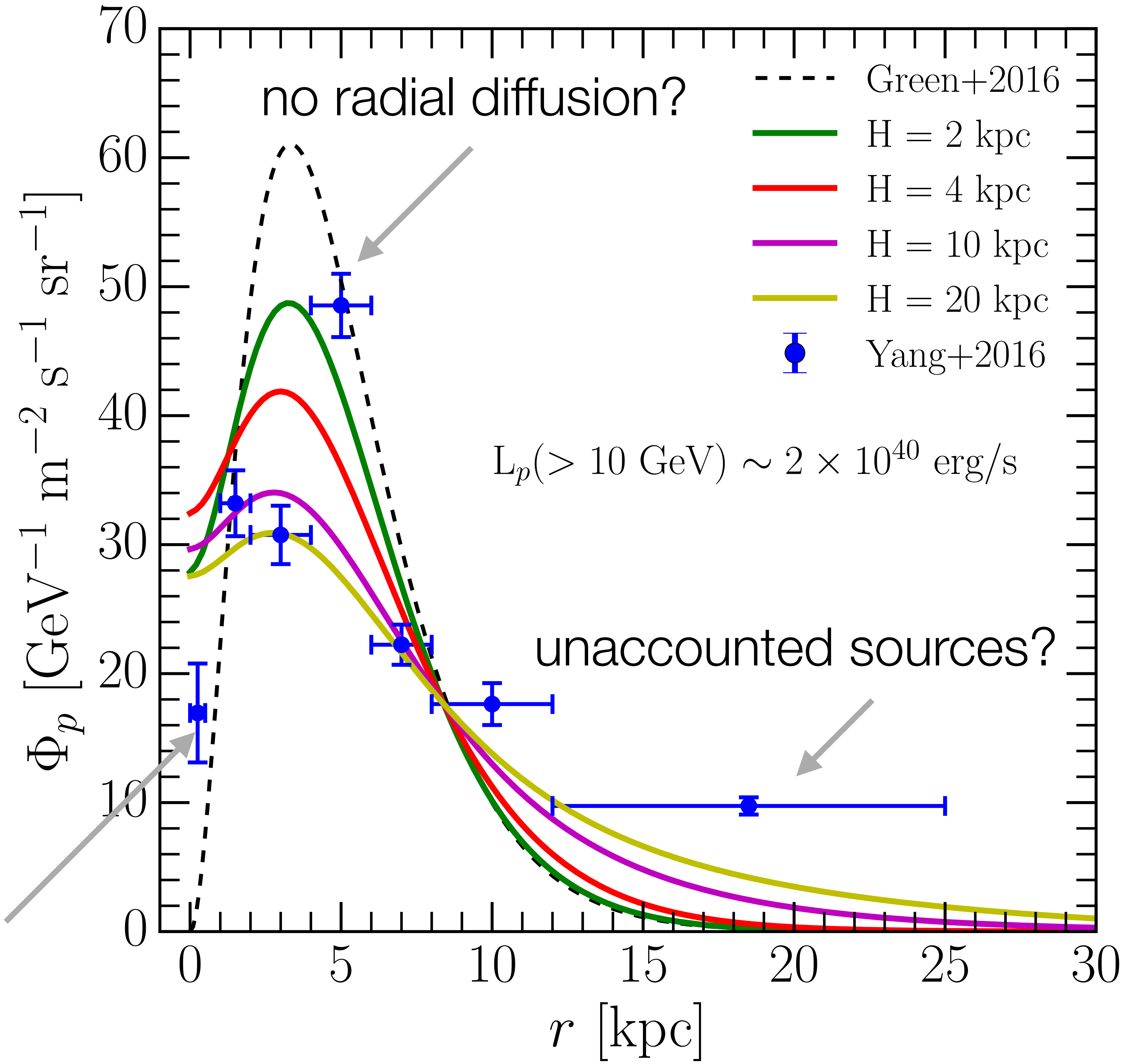
hardening to the GC

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*”

Comparison with a single zone model predictions

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



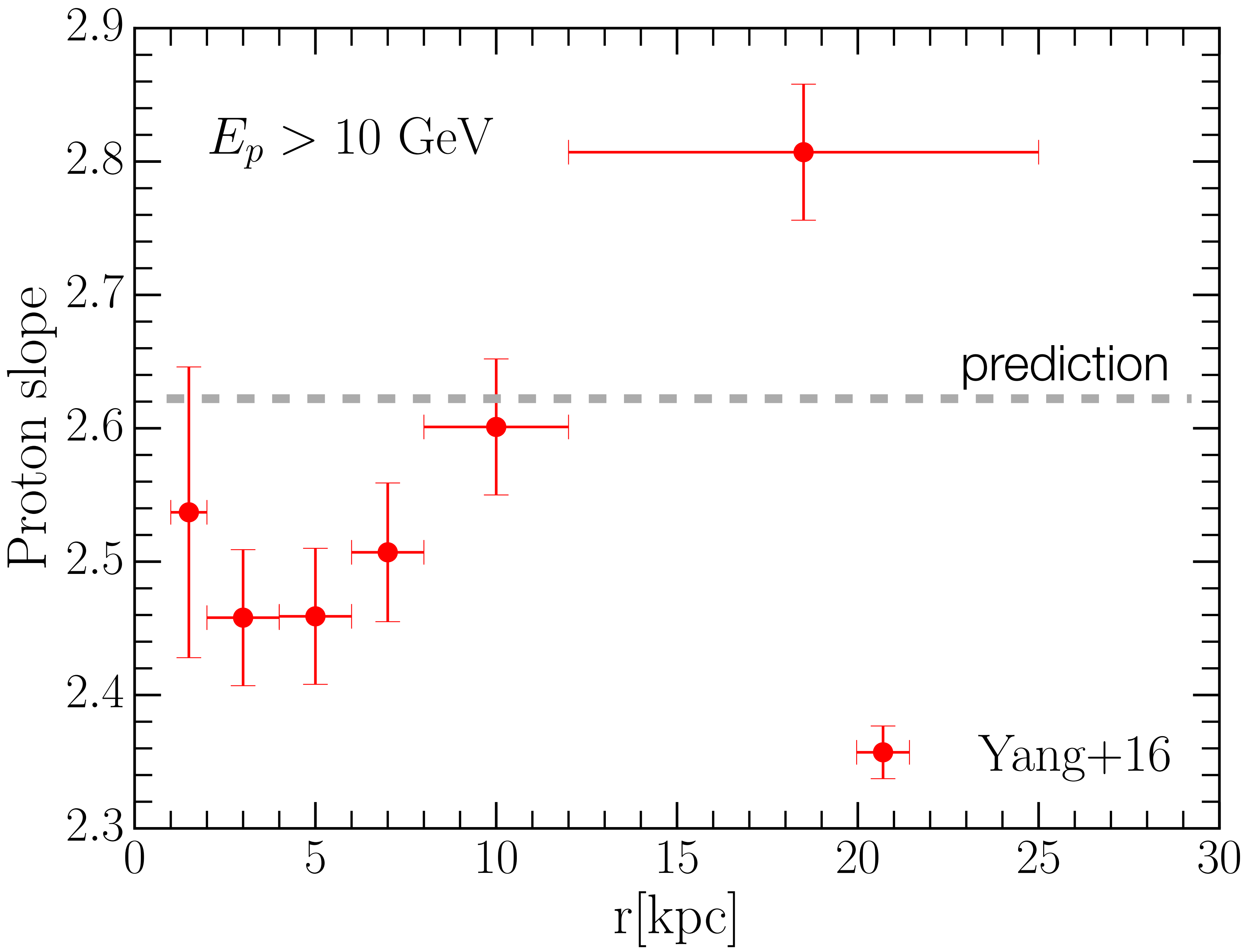
no radial diffusion?

unaccounted sources?

why so low?

Comparison with a single zone model predictions

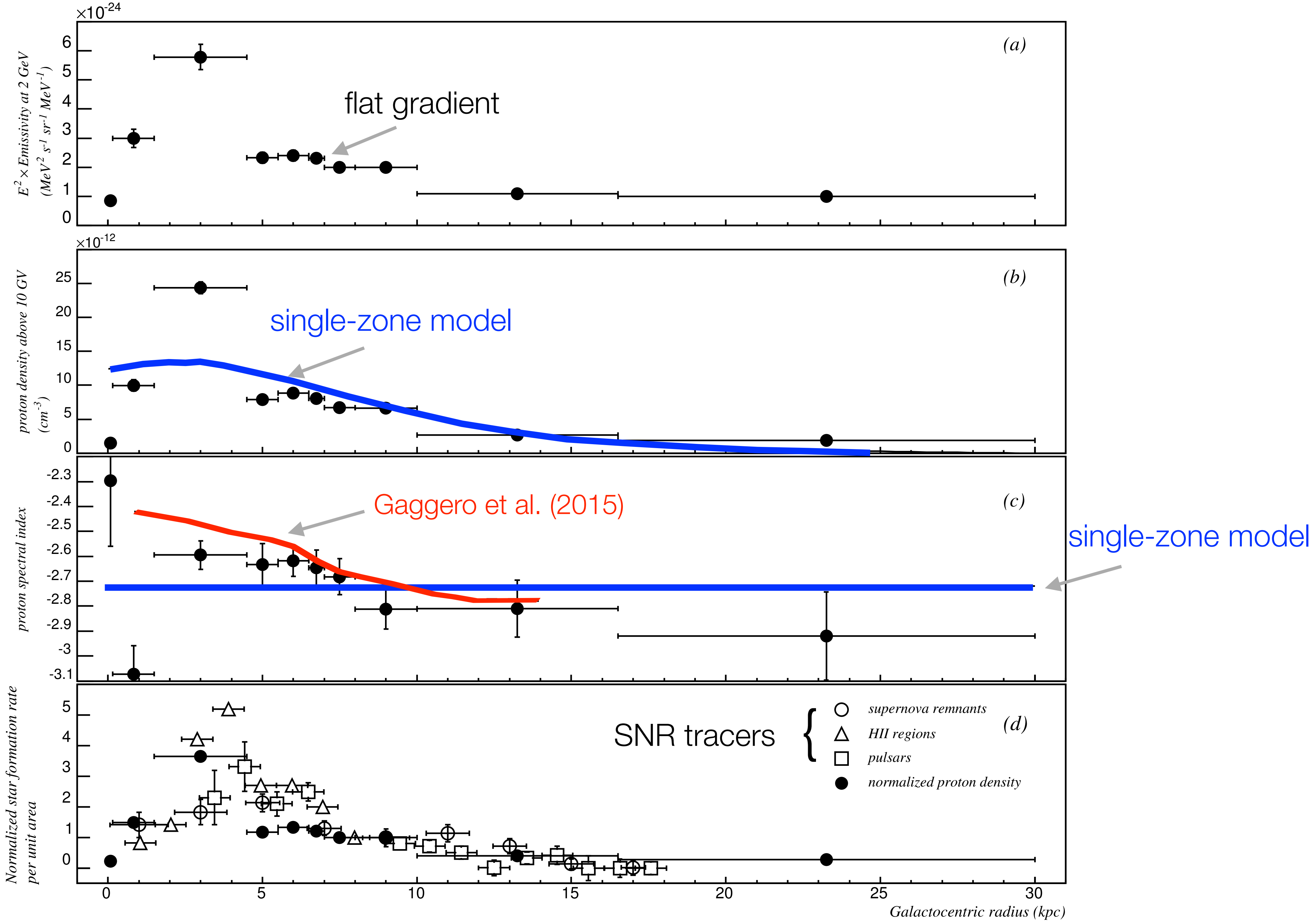
R. Yang, F. Aharonian, **CE**, PRD, 2016



see also Gaggero et al., PRD, 2015 (also known as KRA**g**)

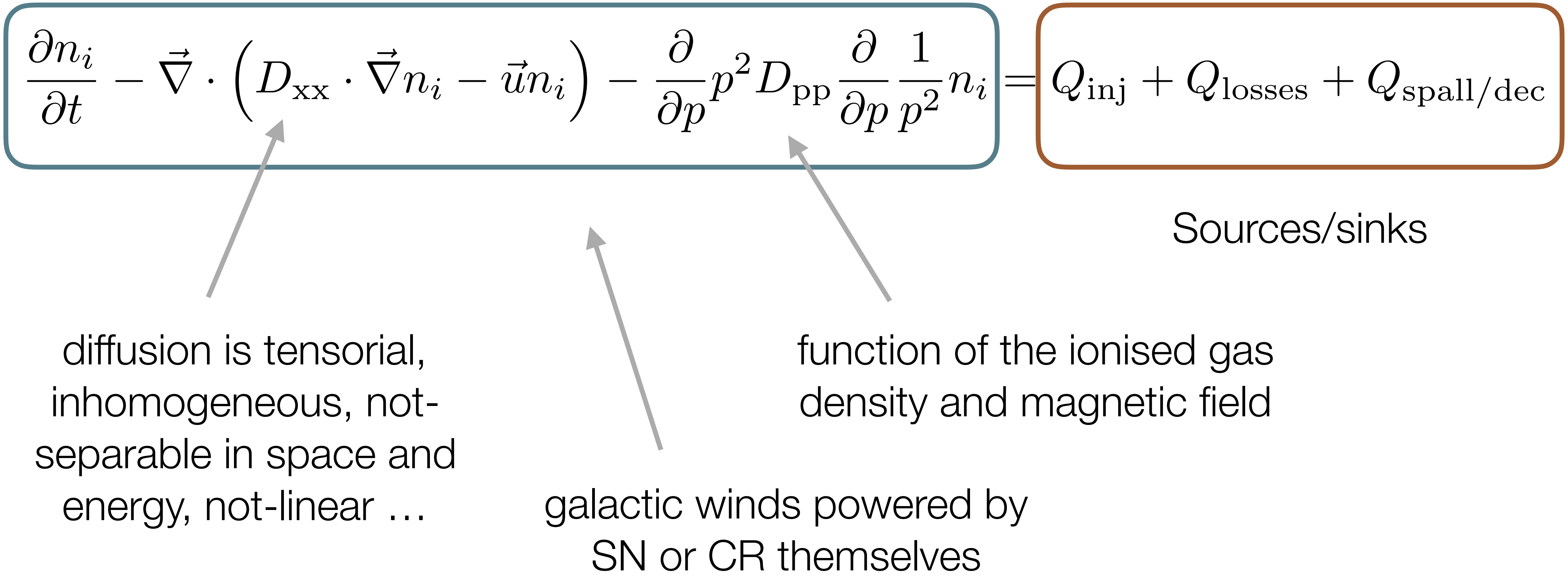
FERMI galactic interstellar emission model (GEIM)

FERMI Collaboration, arXiv:1602.07246



The Master equation

Berezinskii et al. (1990)



$$\boxed{\frac{\partial n_i}{\partial t} - \vec{\nabla}\cdot\left(D_{\mathrm{xx}}\cdot\vec{\nabla} n_i - \vec{u}\, n_i\right) - \frac{\partial}{\partial p} p^2 D_{\mathrm{pp}} \frac{\partial}{\partial p}\frac{1}{p^2} n_i} = \boxed{Q_{\mathrm{inj}} + Q_{\mathrm{losses}} + Q_{\mathrm{spall/dec}}}$$

Sources/sinks

diffusion is tensorial, inhomogeneous, not-separable in space and energy, not-linear …

function of the ionised gas density and magnetic field

galactic winds powered by SN or CR themselves

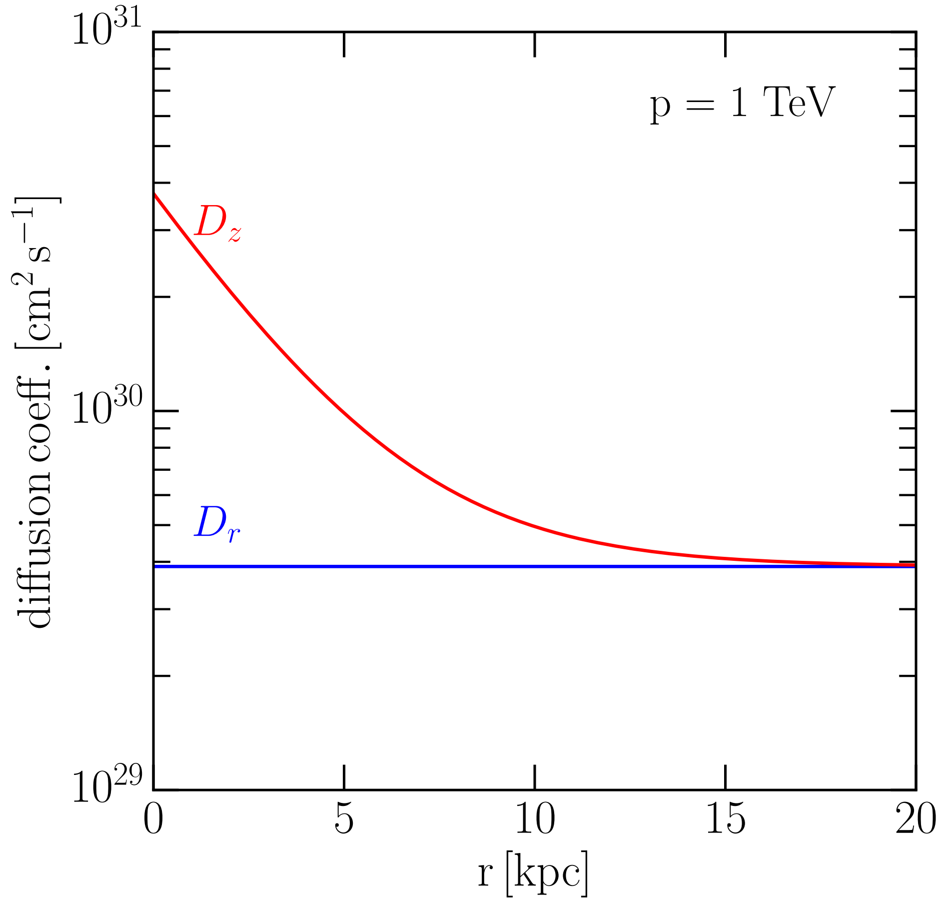
what is the impact on the diffuse emissions or on the local spectra of the physical effects we averaged out?

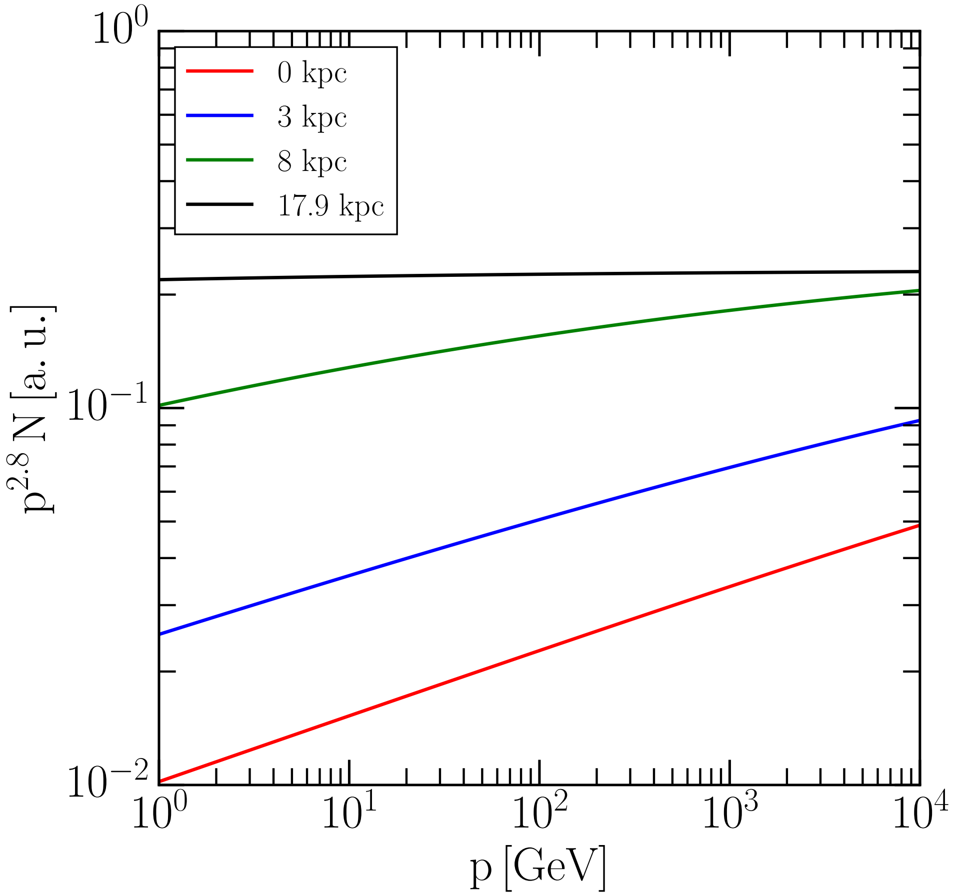
DRAGON2

- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion

$$D_r = D_{0,\perp} \left(\frac{p}{p_0}\right)^{\delta_\perp}$$

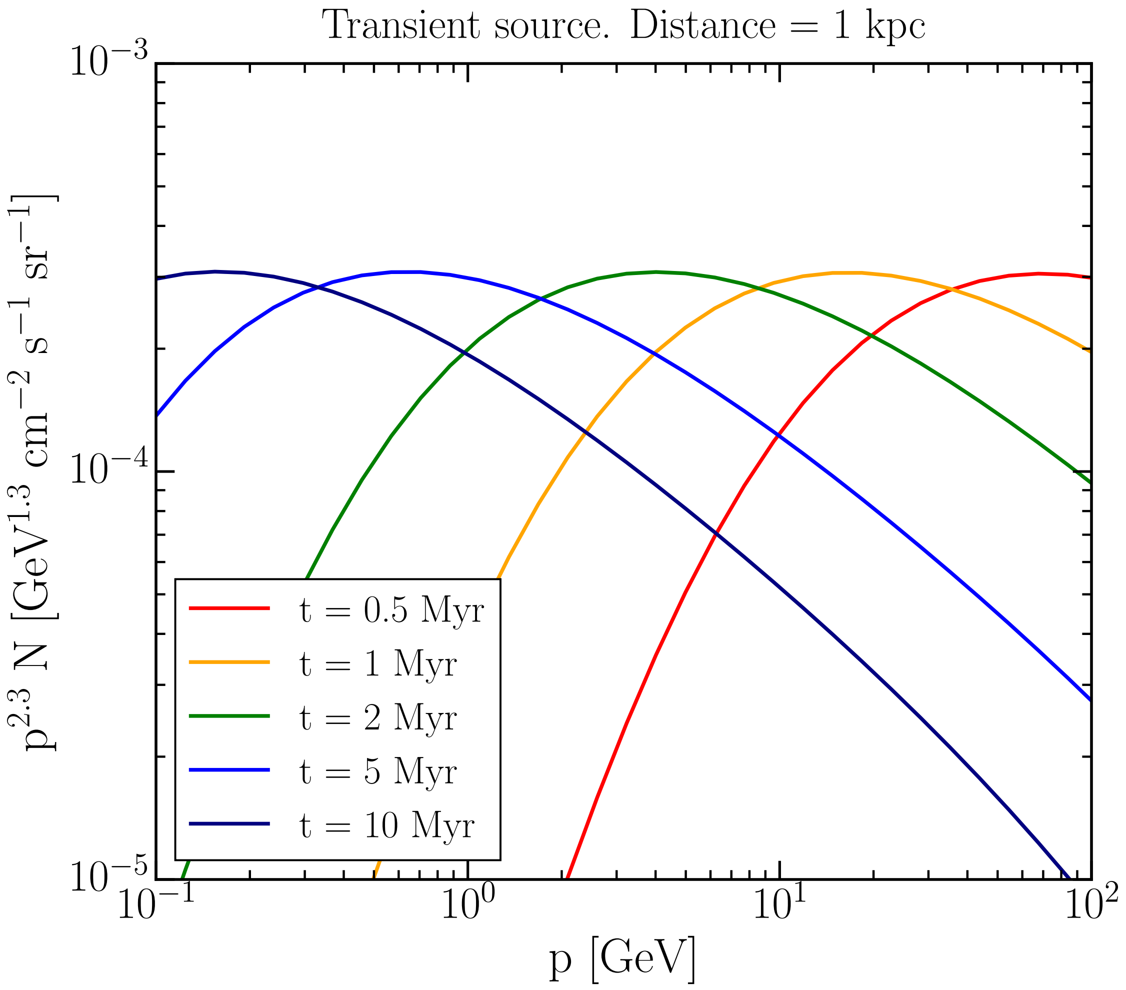
$$D_z = D_{0,\perp} \left(\frac{p}{p_0}\right)^{\delta_\perp} + D_{0,\parallel} \exp\left(-\frac{r}{R_0}\right) \left(\frac{p}{p_0}\right)^{\delta_\parallel}$$

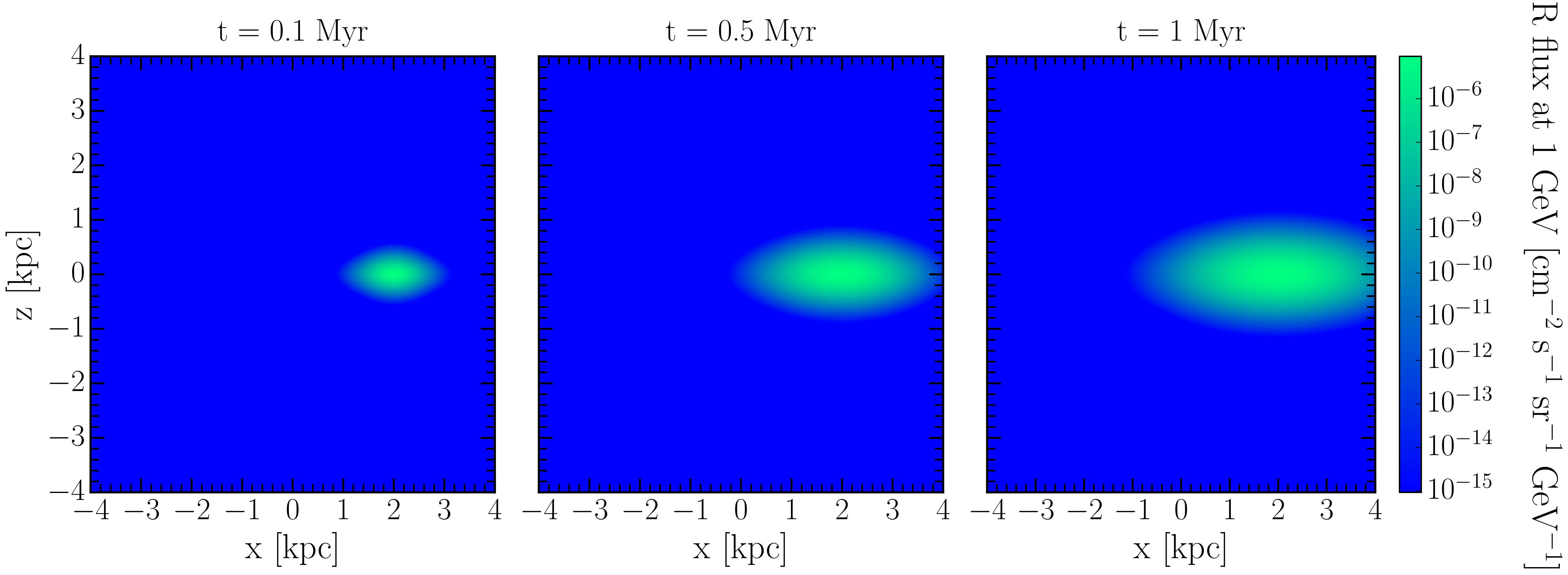




DRAGON2

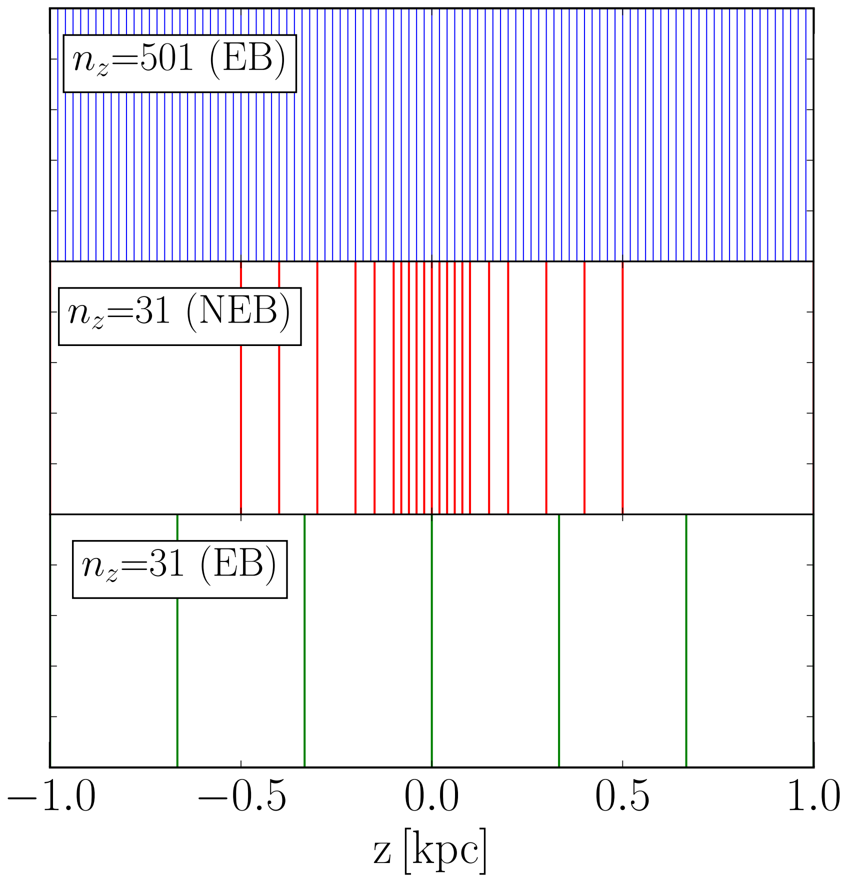
- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources

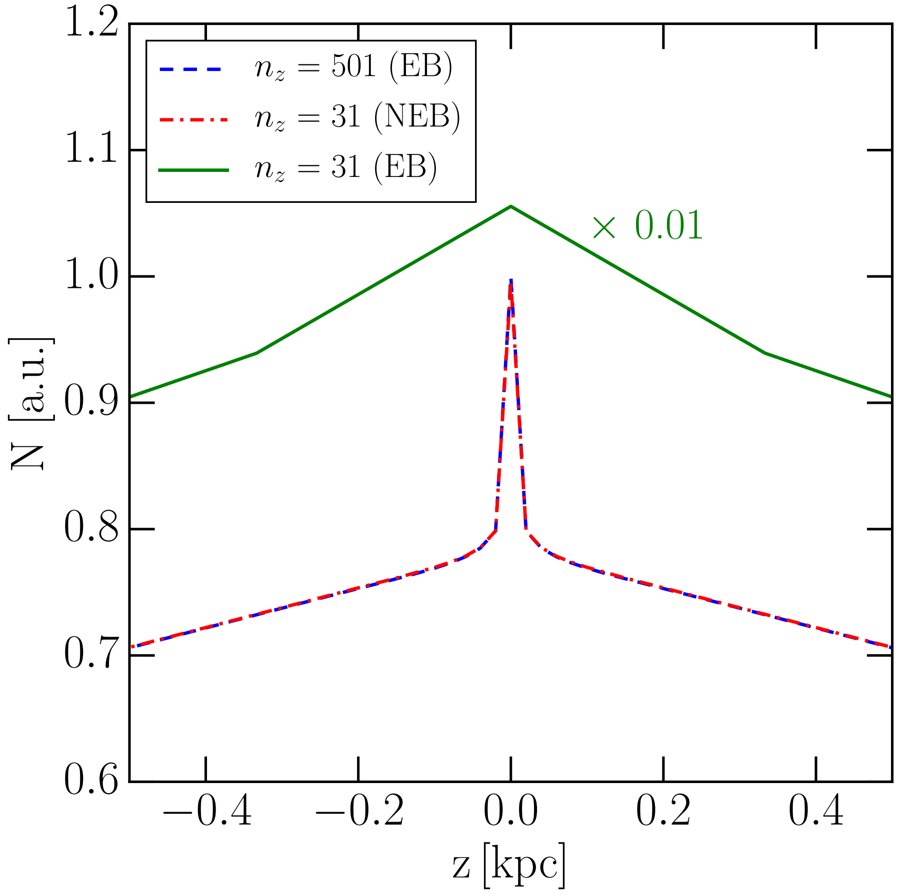




DRAGON2

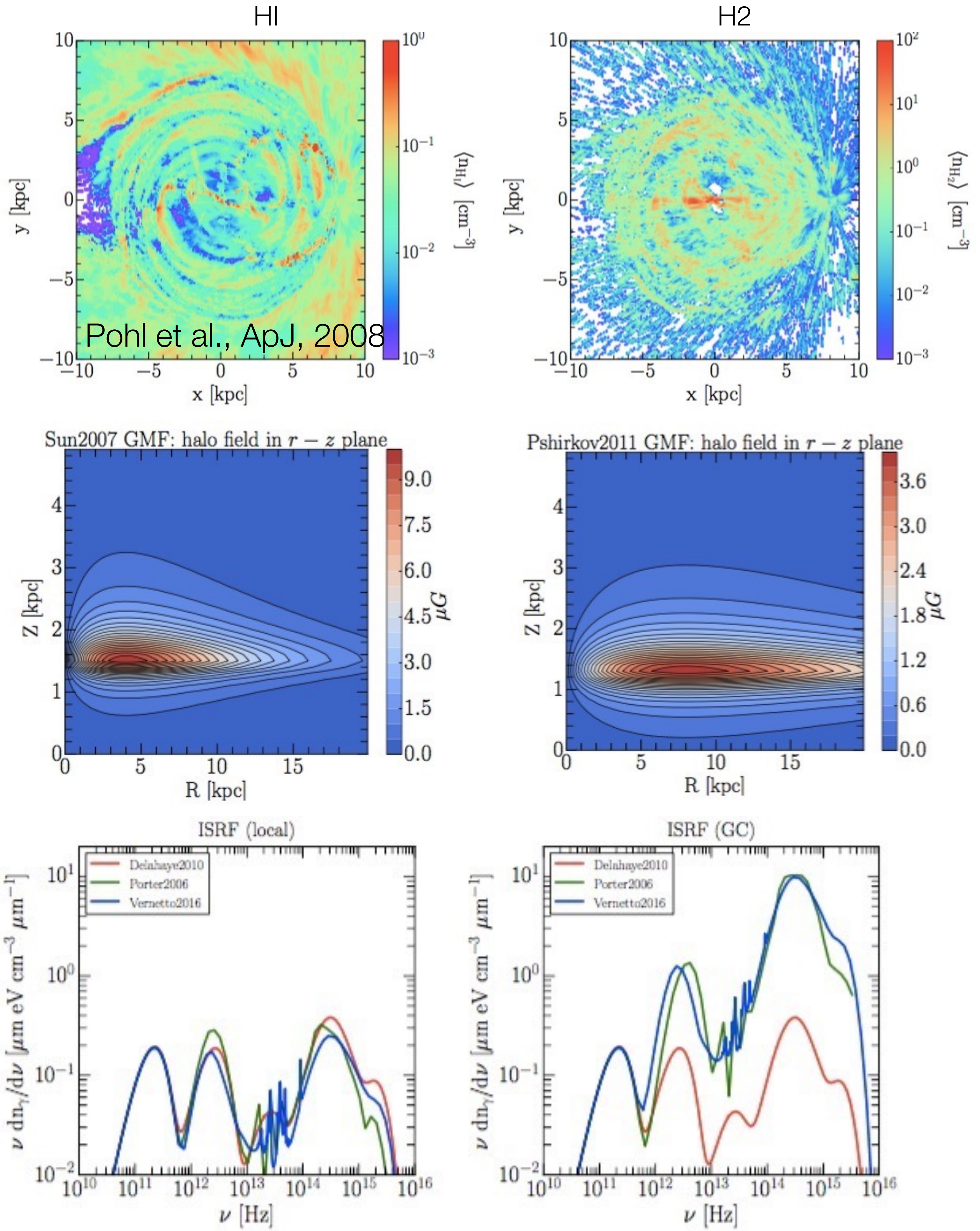
- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources
- non-equidistant binning





DRAGON2

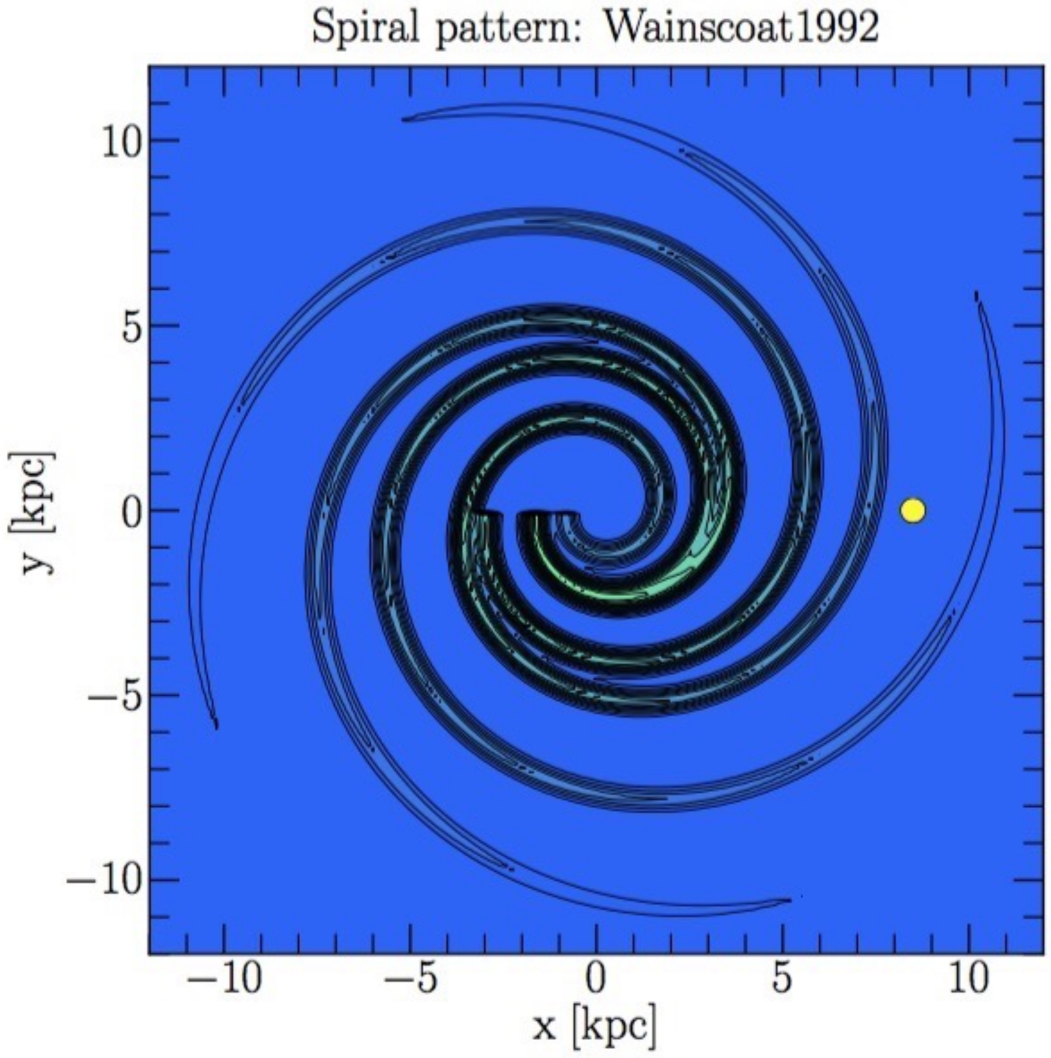
- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources
- non-equidistant binning
- a complete set of astrophysical ingredients

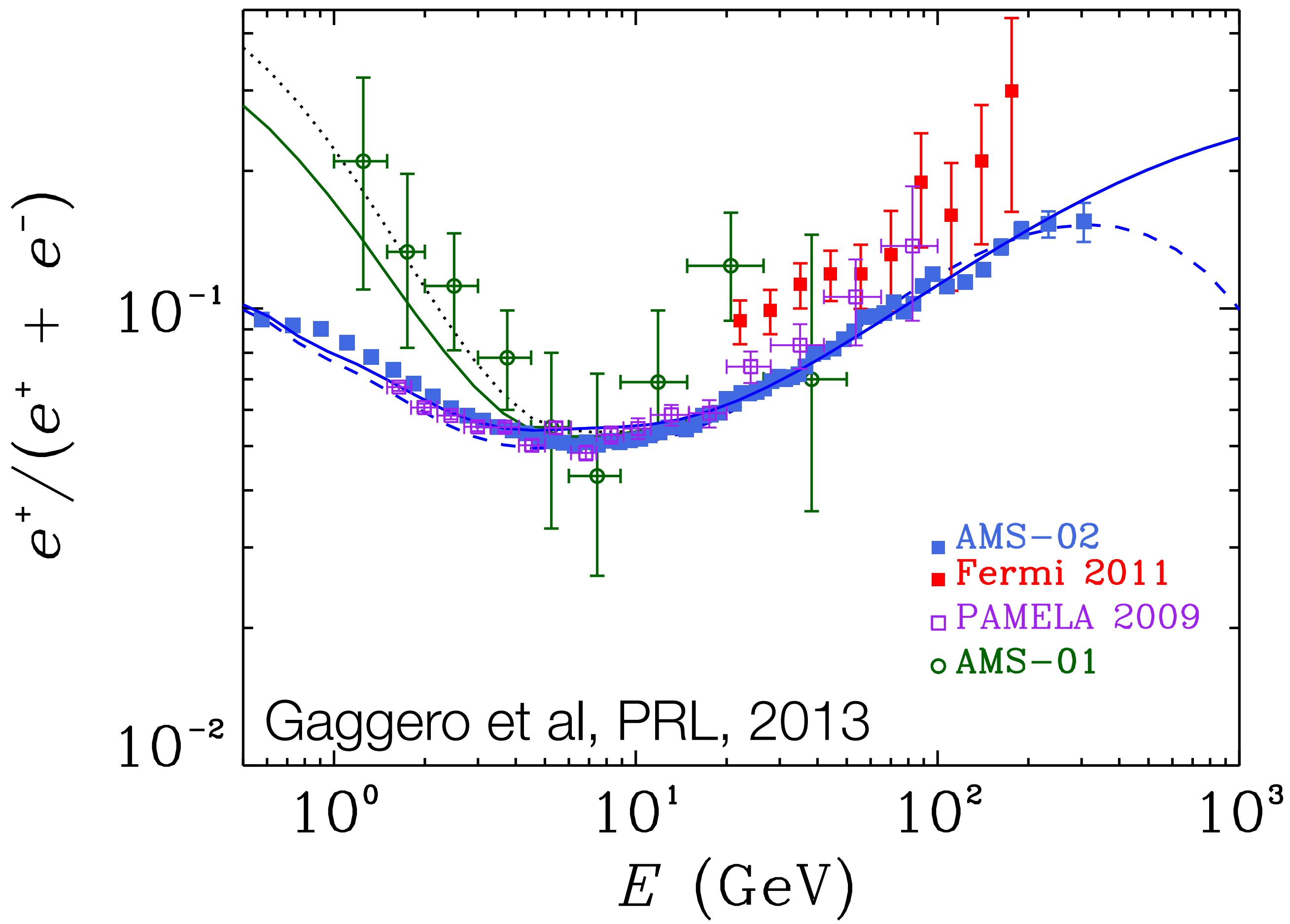


Pohl et al., ApJ, 2008

DRAGON2

- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources
- non-equidistant binning
- a complete set of astrophysical ingredients
- primary leptons

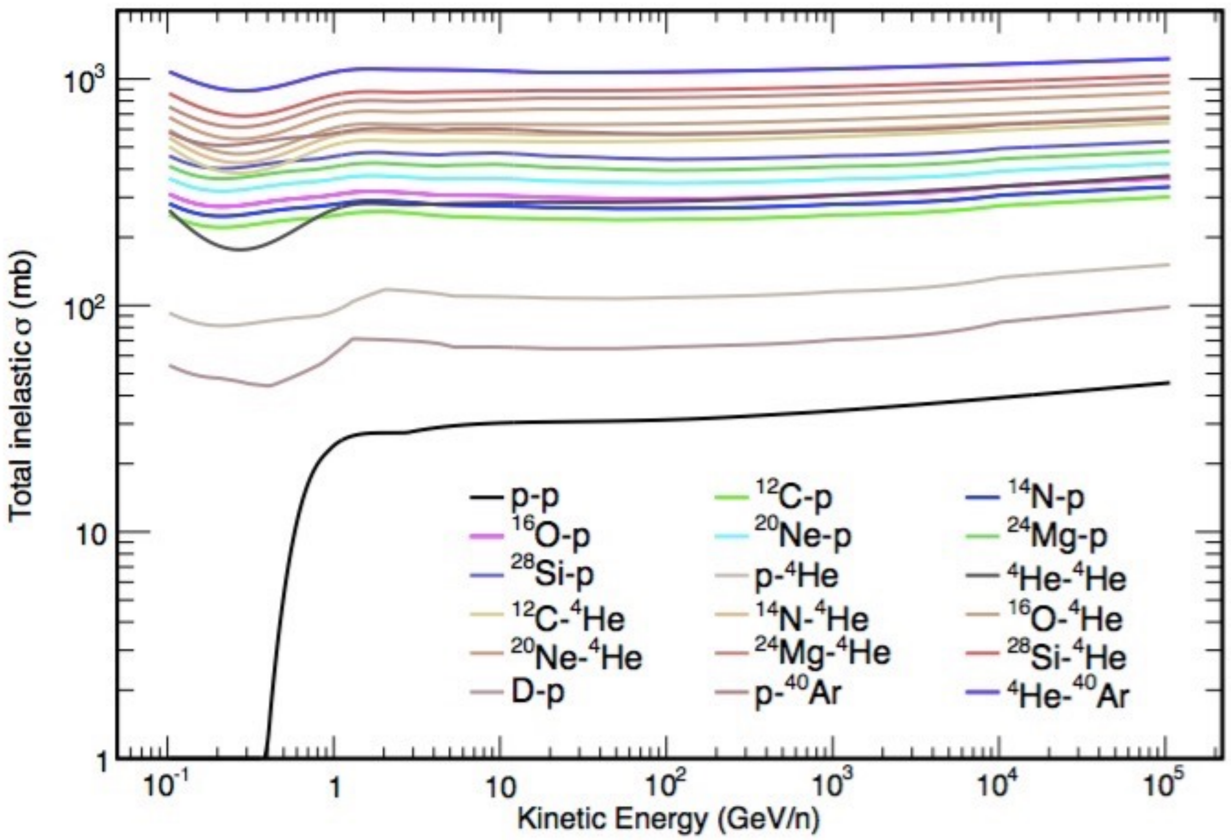


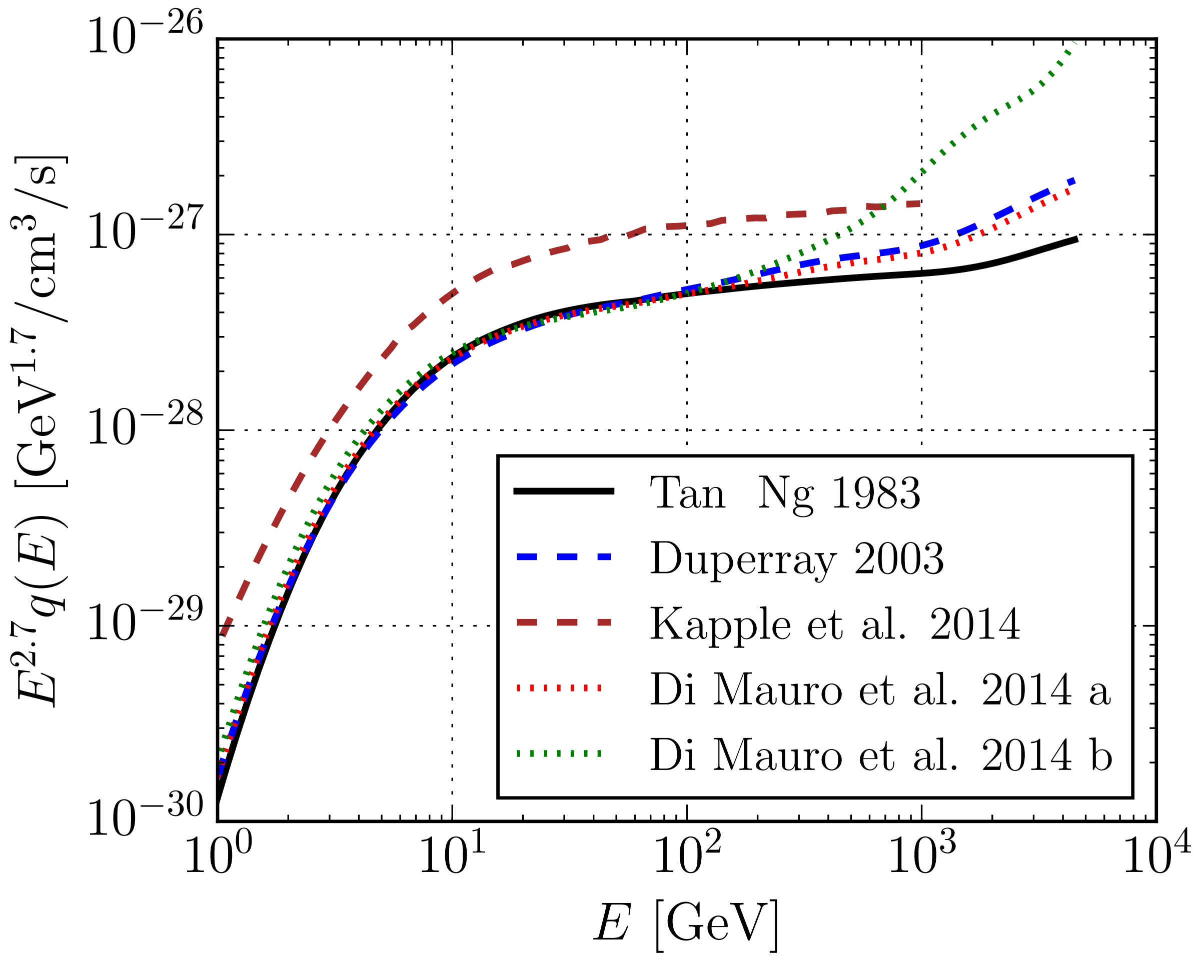

Gaggero et al, PRL, 2013

DRAGON2

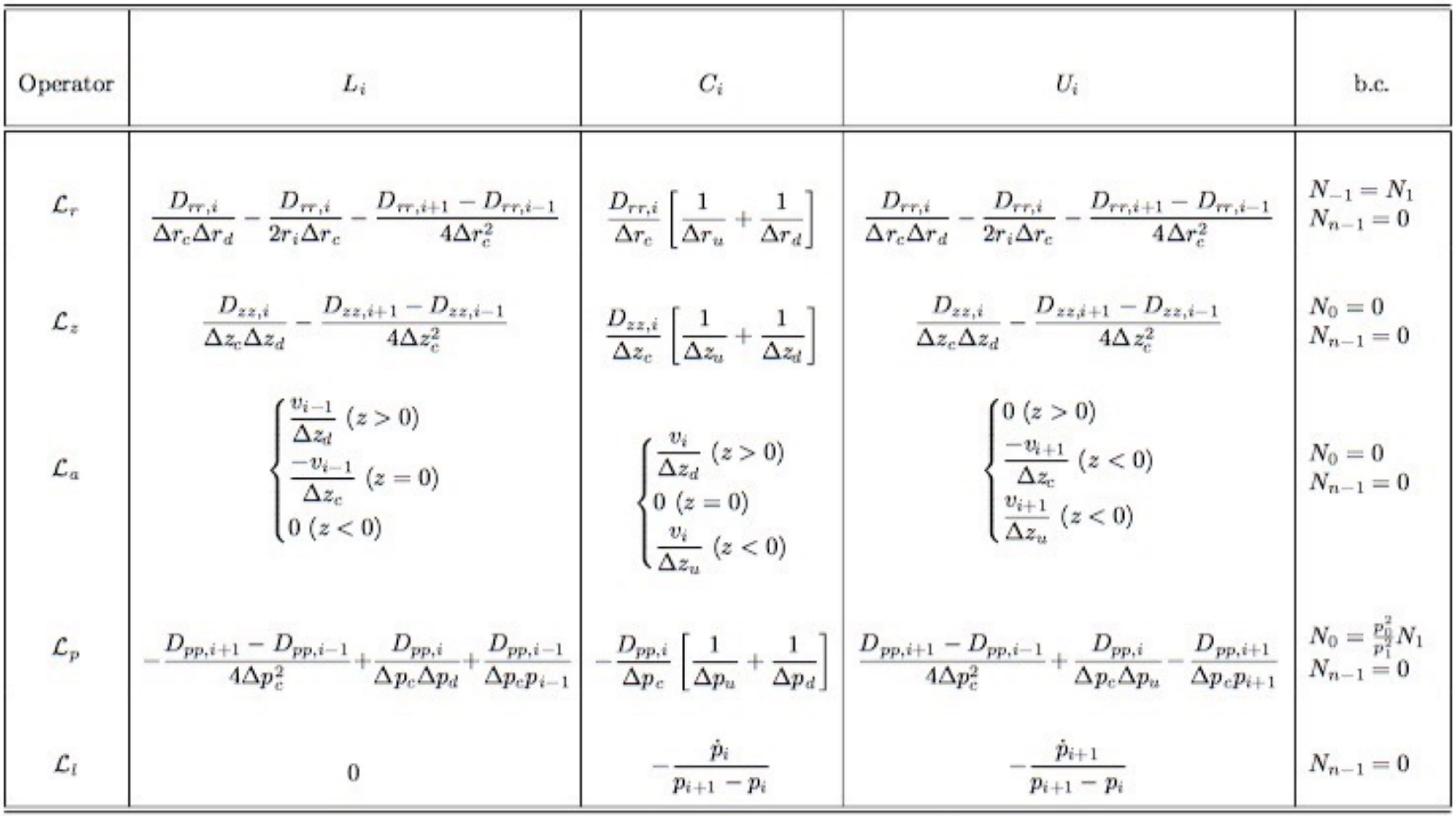
- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources
- non-equidistant binning
- a complete set of astrophysical ingredients
- primary leptons
- improved nuclear network model (in preparation)

FLUKA M.N. Mazziotta et al., APP, 2016





DRAGON2 solver in Operator Spitting

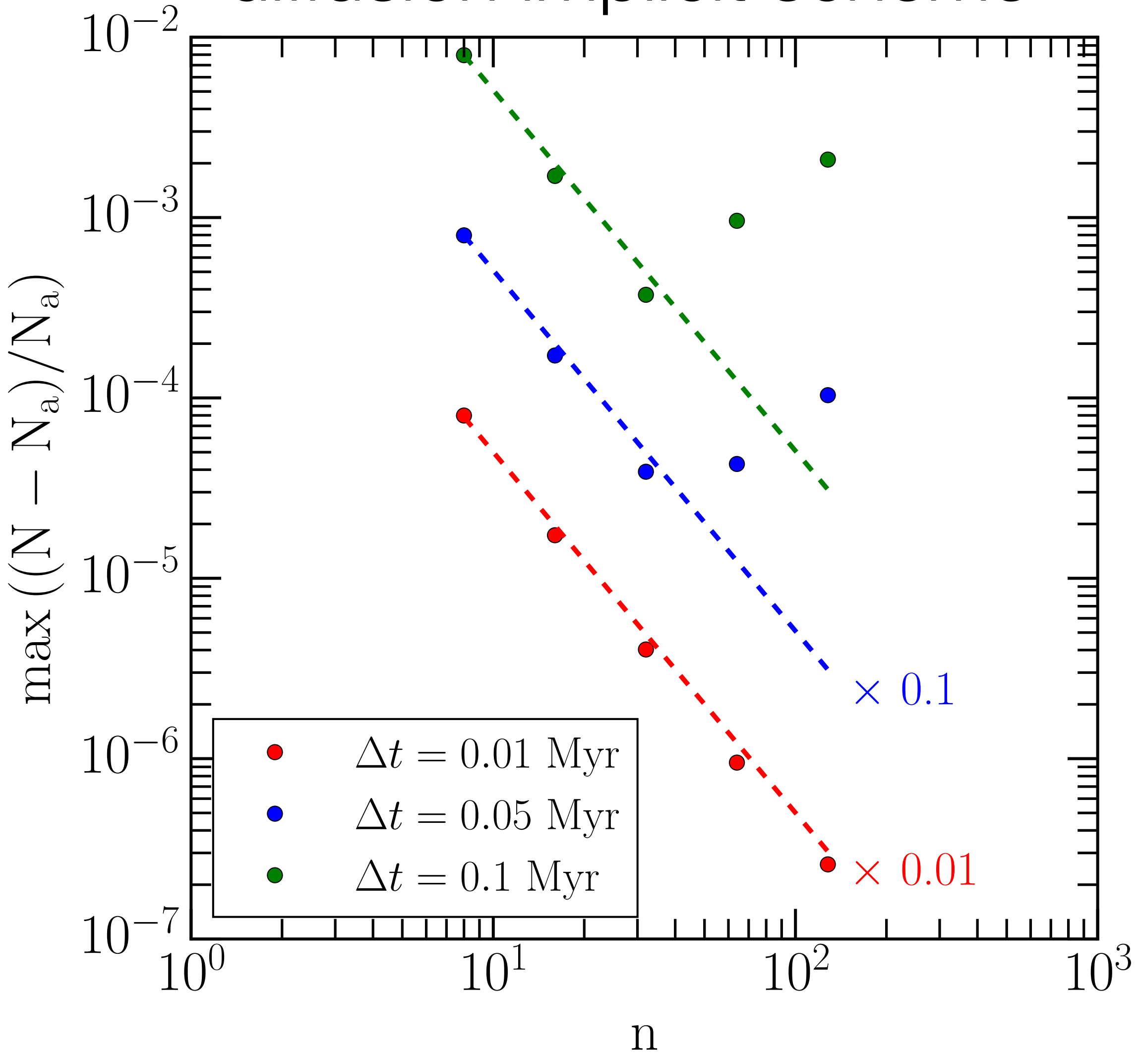


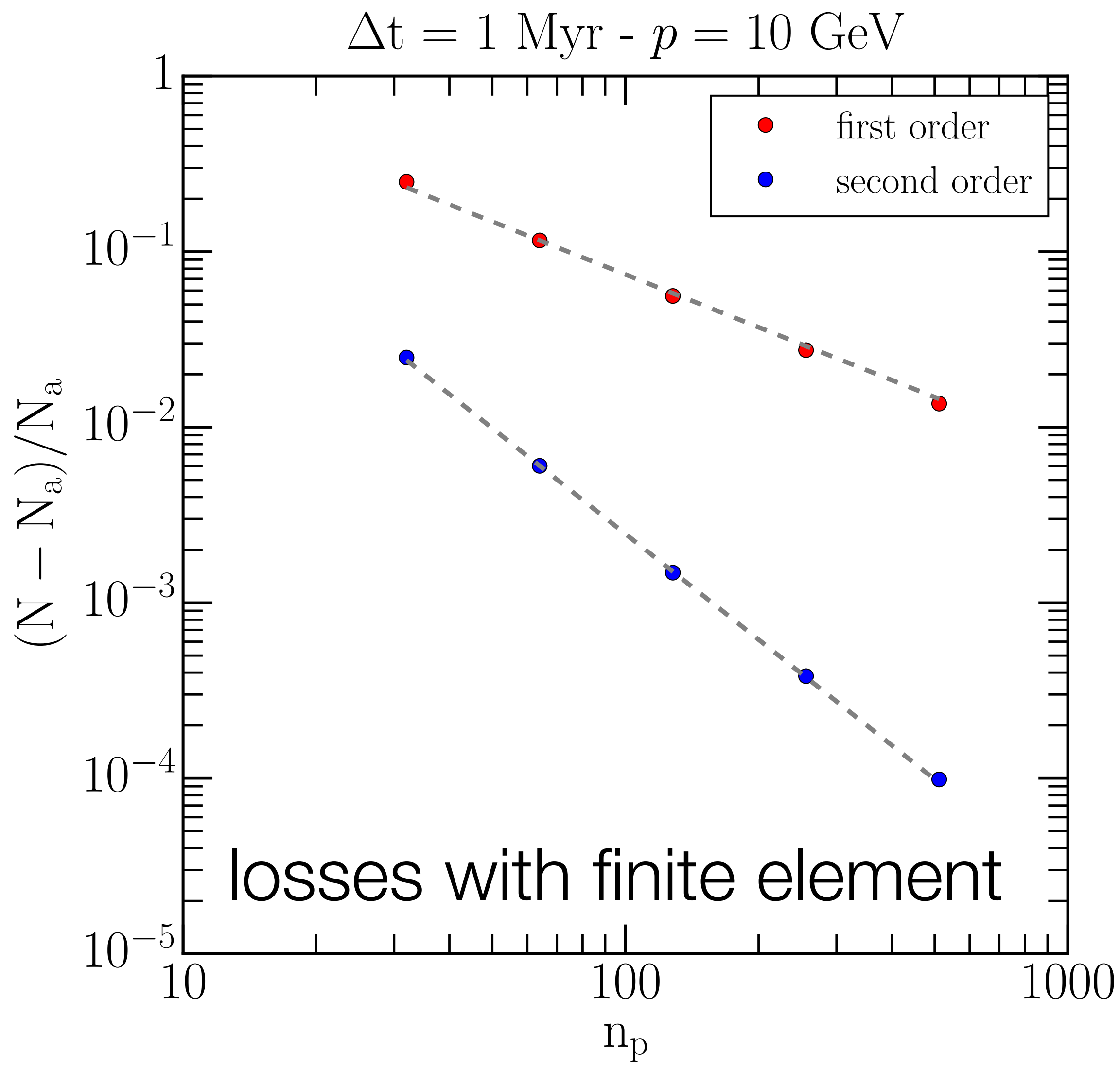
Operator	L_i	C_i	U_i	b.c.
$\mathcal{L}_r$	$\frac{D_{rr,i}}{\Delta r_c \Delta r_d} - \frac{D_{rr,i}}{2 r_i \Delta r_c} - \frac{D_{rr,i+1} - D_{rr,i-1}}{4 \Delta r_c^2}$	$\frac{D_{rr,i}}{\Delta r_c}\left[\frac{1}{\Delta r_u} + \frac{1}{\Delta r_d}\right]$	$\frac{D_{rr,i}}{\Delta r_c \Delta r_d} - \frac{D_{rr,i}}{2 r_i \Delta r_c} - \frac{D_{rr,i+1} - D_{rr,i-1}}{4 \Delta r_c^2}$	$N_{-1} = N_1$ $N_{n-1} = 0$
$\mathcal{L}_z$	$\frac{D_{zz,i}}{\Delta z_c \Delta z_d} - \frac{D_{zz,i+1} - D_{zz,i-1}}{4 \Delta z_c^2}$	$\frac{D_{zz,i}}{\Delta z_c}\left[\frac{1}{\Delta z_u} + \frac{1}{\Delta z_d}\right]$	$\frac{D_{zz,i}}{\Delta z_c \Delta z_d} - \frac{D_{zz,i+1} - D_{zz,i-1}}{4 \Delta z_c^2}$	$N_0 = 0$ $N_{n-1} = 0$
$\mathcal{L}_a$	$\begin{cases} \frac{v_{i-1}}{\Delta z_d}\ (z > 0) \\ \frac{-v_{i-1}}{\Delta z_c}\ (z = 0) \\ 0\ (z < 0) \end{cases}$	$\begin{cases} \frac{v_i}{\Delta z_d}\ (z > 0) \\ 0\ (z = 0) \\ \frac{v_i}{\Delta z_u}\ (z < 0) \end{cases}$	$\begin{cases} 0\ (z > 0) \\ \frac{-v_{i+1}}{\Delta z_c}\ (z < 0) \\ \frac{v_{i+1}}{\Delta z_u}\ (z < 0) \end{cases}$	$N_0 = 0$ $N_{n-1} = 0$
$\mathcal{L}_p$	$-\frac{D_{pp,i+1} - D_{pp,i-1}}{4 \Delta p_c^2} + \frac{D_{pp,i}}{\Delta p_c \Delta p_d} + \frac{D_{pp,i-1}}{\Delta p_c p_{i-1}}$	$-\frac{D_{pp,i}}{\Delta p_c}\left[\frac{1}{\Delta p_u} + \frac{1}{\Delta p_d}\right]$	$\frac{D_{pp,i+1} - D_{pp,i-1}}{4 \Delta p_c^2} + \frac{D_{pp,i}}{\Delta p_c \Delta p_u} - \frac{D_{pp,i+1}}{\Delta p_c p_{i+1}}$	$N_0 = \frac{p_0^2}{p_1^2} N_1$ $N_{n-1} = 0$
$\mathcal{L}_l$	0	$-\frac{\dot{p}_i}{p_{i+1} - p_i}$	$-\frac{\dot{p}_{i+1}}{p_{i+1} - p_i}$	$N_{n-1} = 0$

Table 1. Crank-Nicolson coefficients and boundary conditions for the 2D case ($\Delta x_c \equiv \frac{x_{i+1} - x_{i-1}}{2}$, $\Delta x_{\mathrm{u}} \equiv s x_{i+1} - x_i$, $\Delta x_{\mathrm{d}} \equiv x_i - x_{i-1}$).

DRAGON2 numerical tests

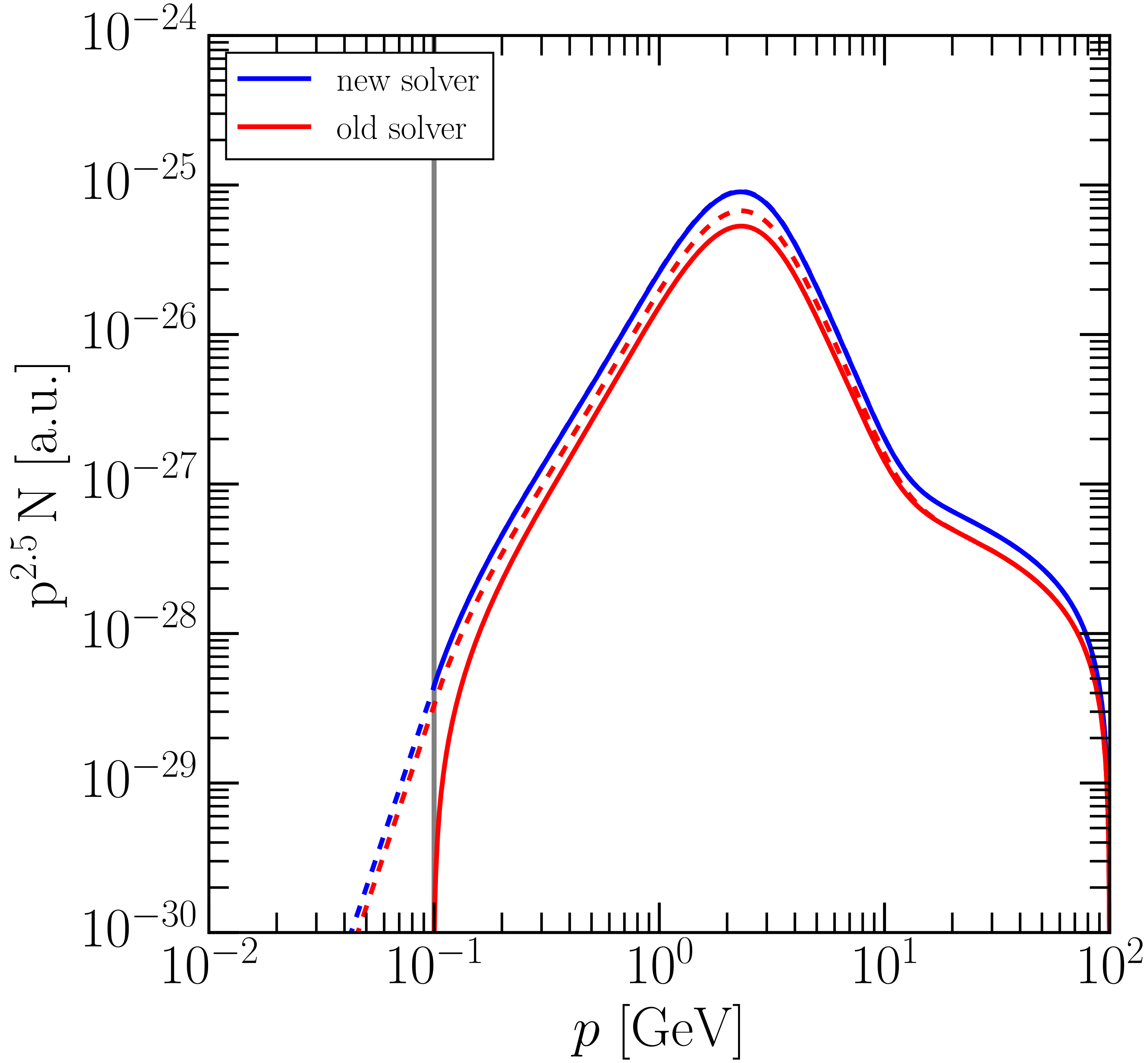
diffusion implicit scheme





each operator is 2nd order discretised
and tested against an analytical solution

DRAGON2 numerical tests: b.c. in momentum

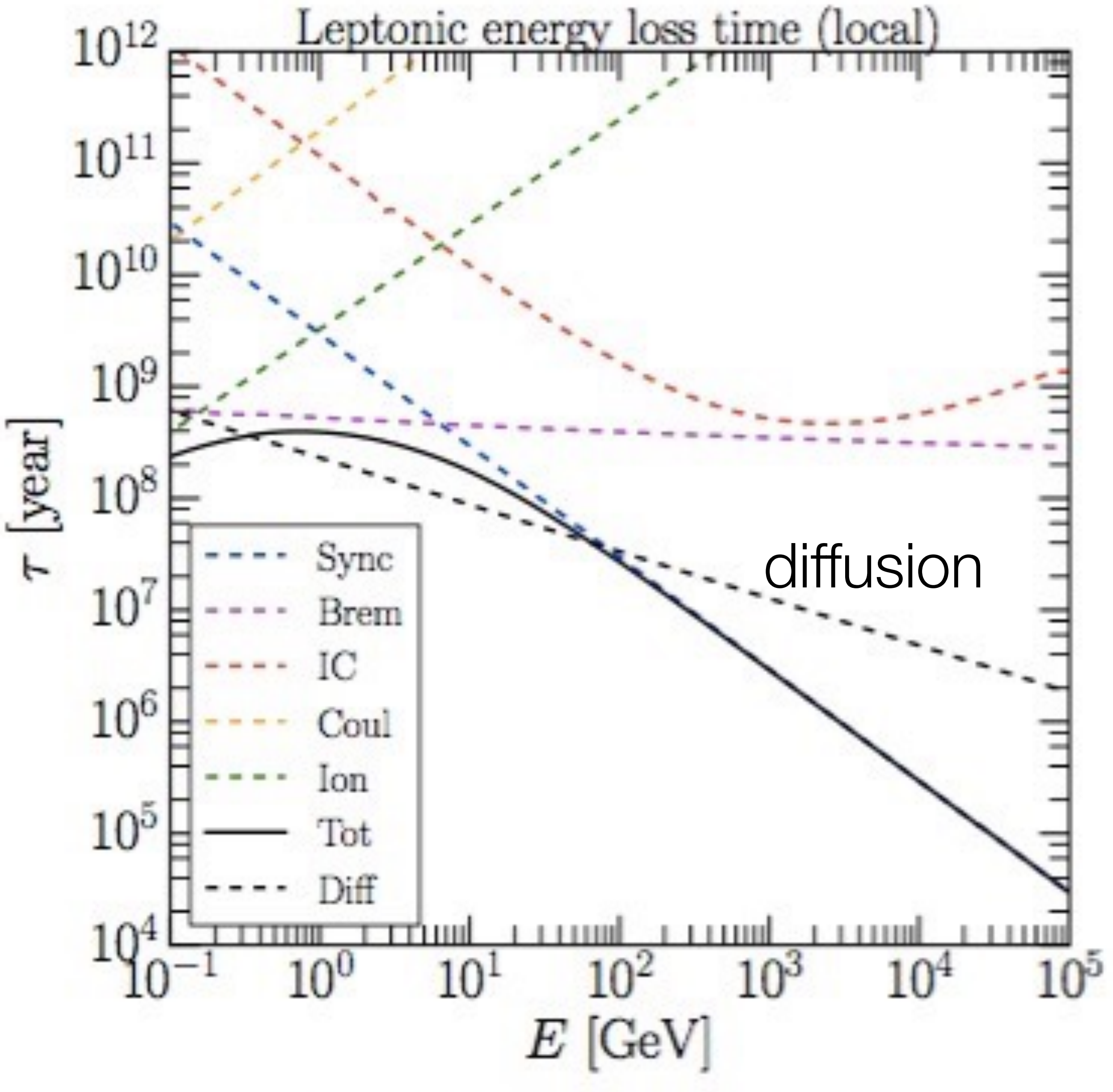


$$\frac{\partial}{\partial p}\left(\frac{N}{p^2}\right)_{p_{\min}} = 0$$

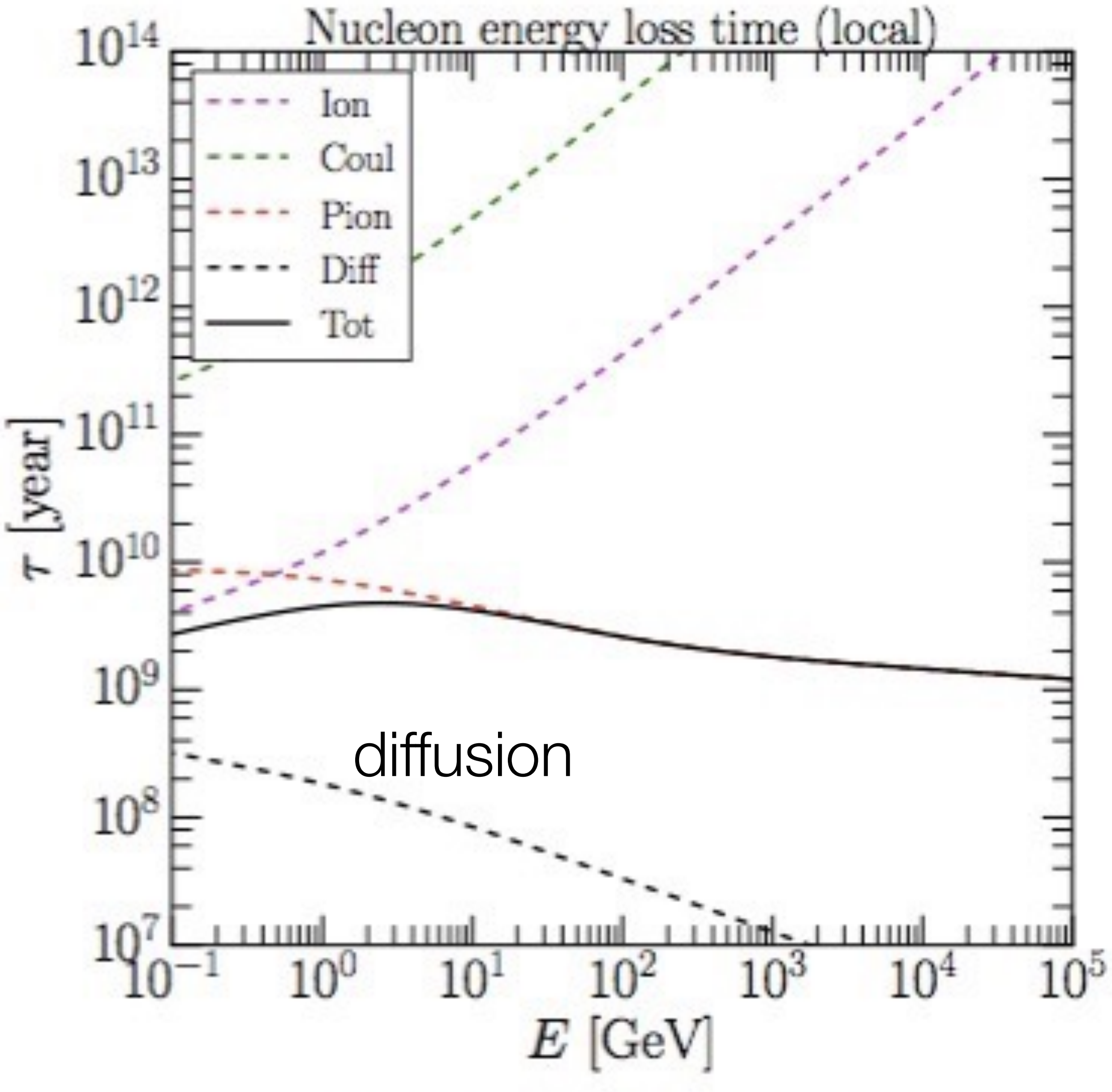
is equivalent to

$$N(p=0) = 0$$

DRAGON2 energy losses in the ISM



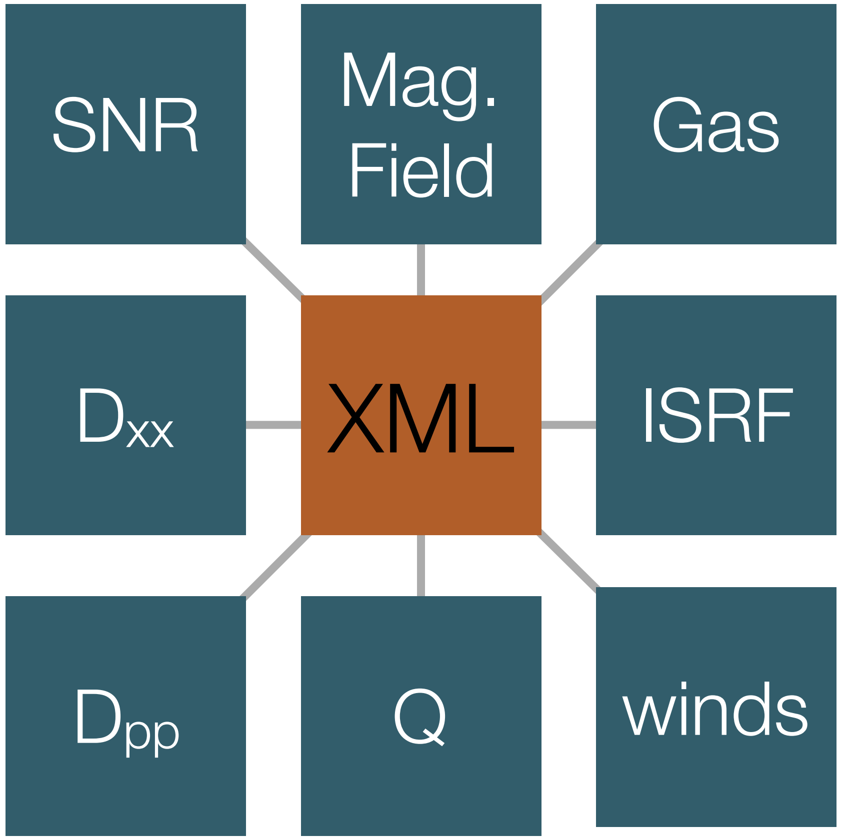
diffusion



diffusion

A new modular code

```
#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

Techniques/codes to solve the transport problem

	(Semi-)analytical	*Numerical*	*Monte Carlo*
Approach	Simplify the problem: • keep dominant effects only • simplify the geometry	Finite difference scheme: • discretise the equation • scheme (e.g., Crank-Nicholson)	Follow each particle: • N particles at t=0 • evolve each of them to t+1 $1\mathrm{D}: \Delta z = \pm \sqrt{2D\Delta t}$
Tools	• Green functions, • Fourier/Bessel expansion • Differential equations	• Numerical recipes/solvers (NAG, GSL libraries)	• Stochastic differential equations (Markov process) + MPI
Pros	• Useful to understand the physics • Fast (MCMC analyses "simple")	• Very simple algebra • Any new input easily included	• Statistical properties (along path) • No grid but t step (for/back)-ward
cons	• Only solve approximate model • New solution for new problem	• Slower, memory for high res. • "Less" insight in the physics	• Even slower (+ statistical errors) • Massively parallel problem
Codes and/or references	Webber (1970+) Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)	GALPROP (Strong et al. 1998) DRAGON (Evoli et al. 2008) PICARD (Kissmann et al., 2013)	Webber & Rockstroh (1997) Farahat et al. (2008) Kopp, Büshing et al. (2012)

Credit: David Maurin (LPSC)

DRAGON2 goals and future work…

- DRAGON2 aims at solving the kinetic transport equation for CR in the Galaxy under very general assumptions
- unavoidable to match local observables **and** diffuse emissions (or other not-local observables, e.g., anisotropy) in a consistent model
- or to test non-uniform diffusion: what would be the profile for a D ~ exp(-r / 100 pc) at the GC?

DRAGON2 goals and future work…

- The solution of the diffusion equation depends on a number of assumptions (gas, magnetic field, ISRF, diffusion coefficients, cross-sections,…). Our approach allows quantitative estimates of the uncertainties associated by assuming different models.
- Next step will be to model the feedback *by* ISM (e.g., self-generated diffusion, CR driven wind) and *on* ISM (e.g., heating by ionisation and waves damping)

Conclusions

- quality of gamma and CR flux data are progressively exceeding the realism of current CR propagation models

- simple recipes (scale invariant injection, diffusion, or unlimited breaks) do not work anymore to explain the global galactic picture

- Theory (read: microphysics) driven improvements in the numerical modelling of CR propagation are desirable at this point