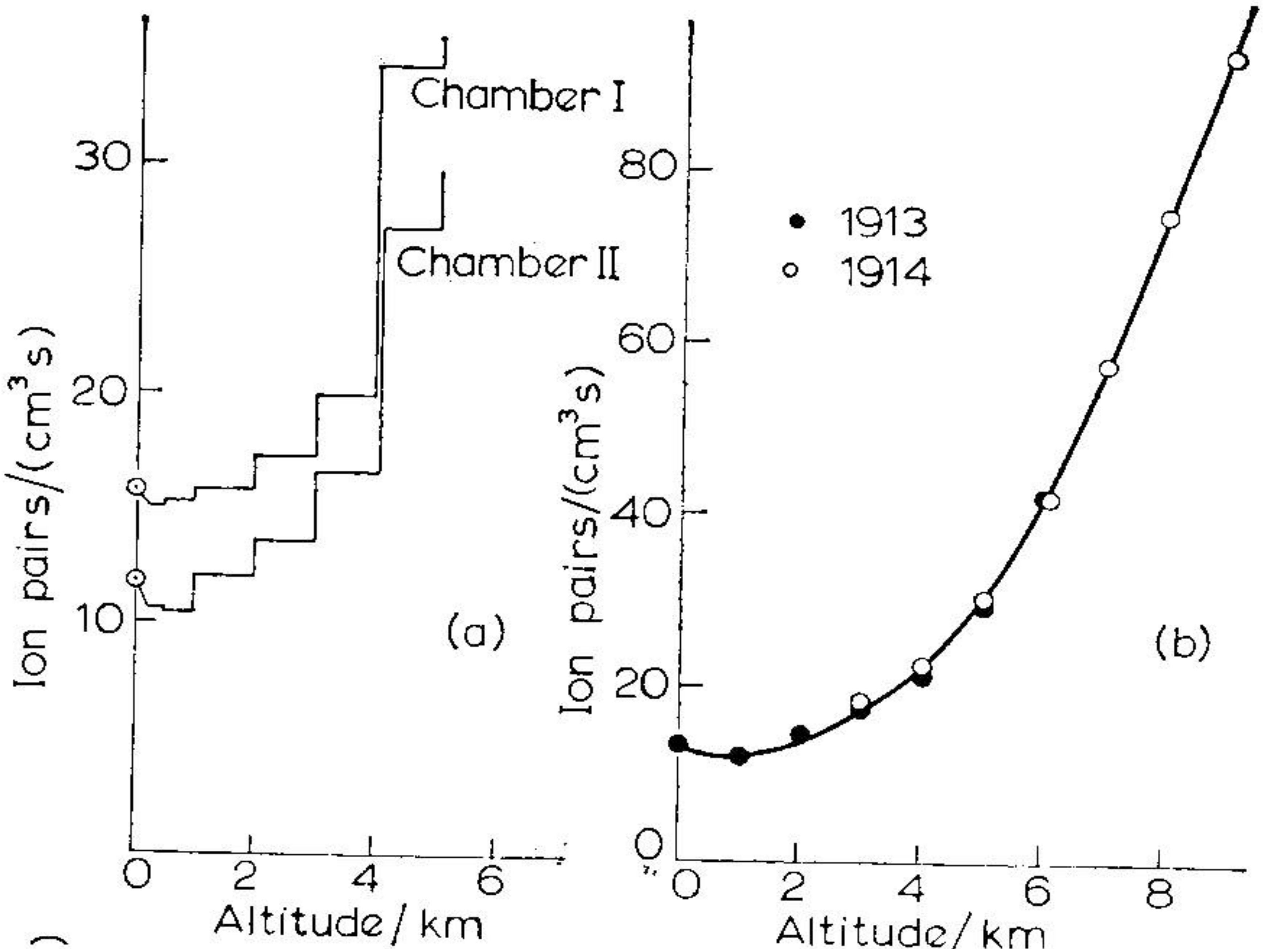
Recent results on Galactic Cosmic Rays and their interpretation

Carmelo Evoli (Gran Sasso Science Institute)

INFN Pisa - 28th of February 2017

A >100 years old discovery!



Victor Hess

W. Bothe

W. Kolhorster

A >100 years old discovery!

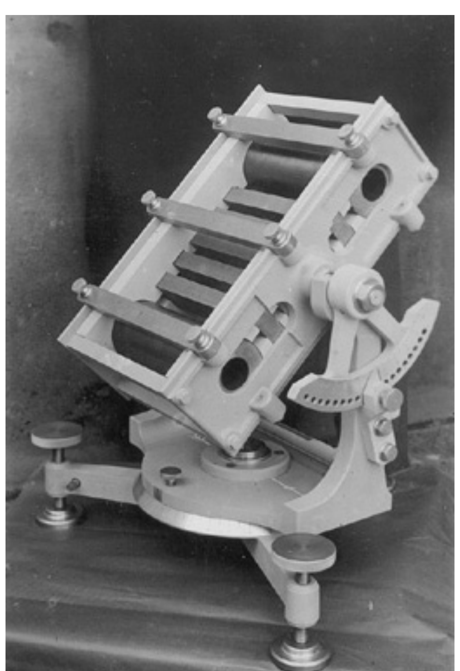
"Le osservazioni eseguite sul mare nel 1910 mi conducevano a concludere che una parte non trascurabile della radiazione penetrante che si riscontra nell'aria, avesse origine indipendente dall'azione diretta delle sostanze attive contenute negli strati superiori della crosta terrestre."
"[...] indicavano esistere, sulla superficie del mare, dove non è più sensibile l'azione del terreno, una causa ionizzante di tale intensità da non potersi spiegare esaurientemente considerando la nota distribuzione delle sostanze radioattive nell'acqua e nell'aria."


Domenico L. Pacini in Livorno

Tratto da La radiazione penetrante dalla superficie ed in seno alle acque, **Il Nuovo Cimento** Serie VI, Tomo 3: 93-100 (1912).

High-energy photons or charged particles?

Bruno Rossi in his laboratory in Florence

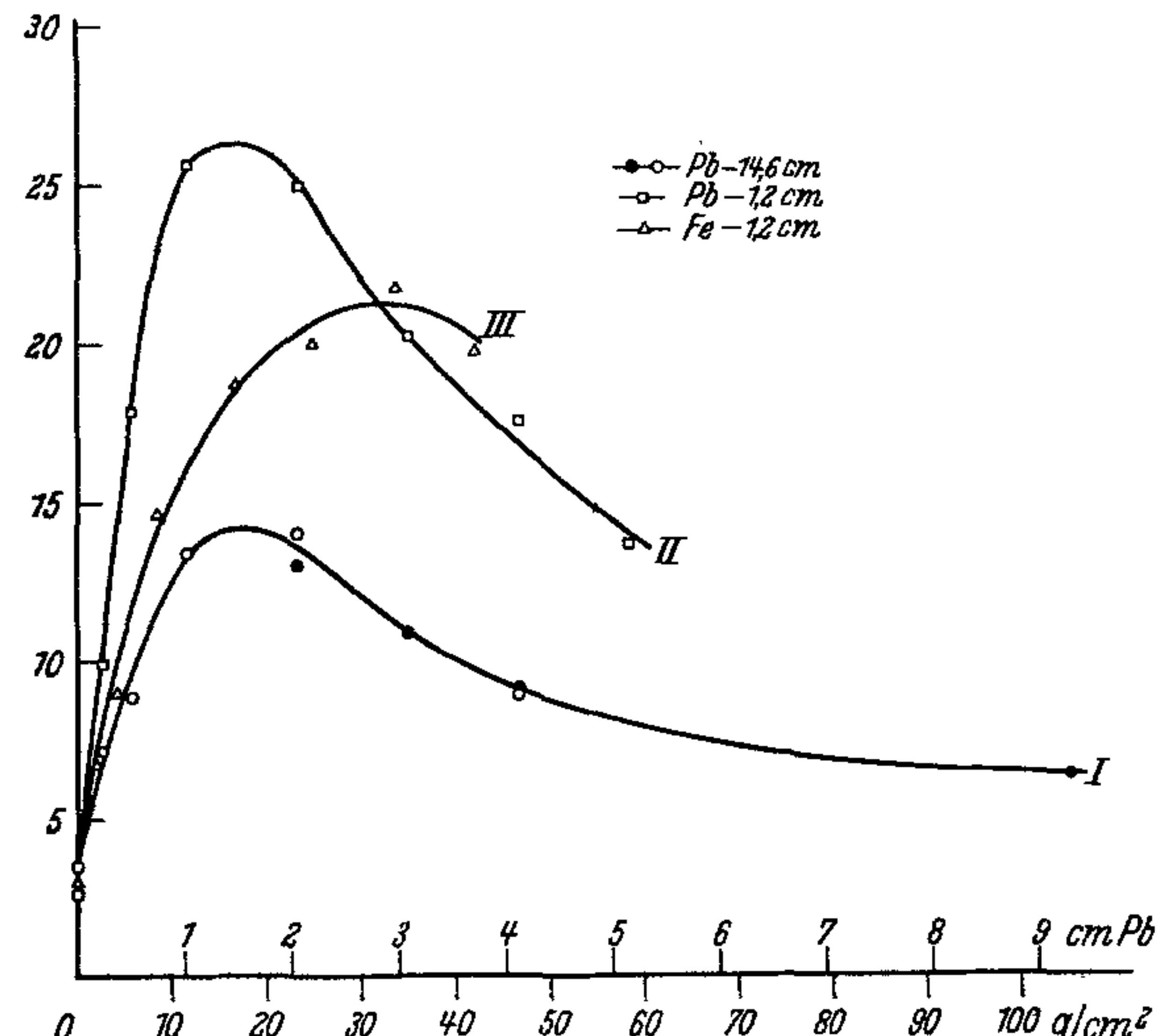


The CR telescope used by Bruno Rossi during the expedition in Eritrea

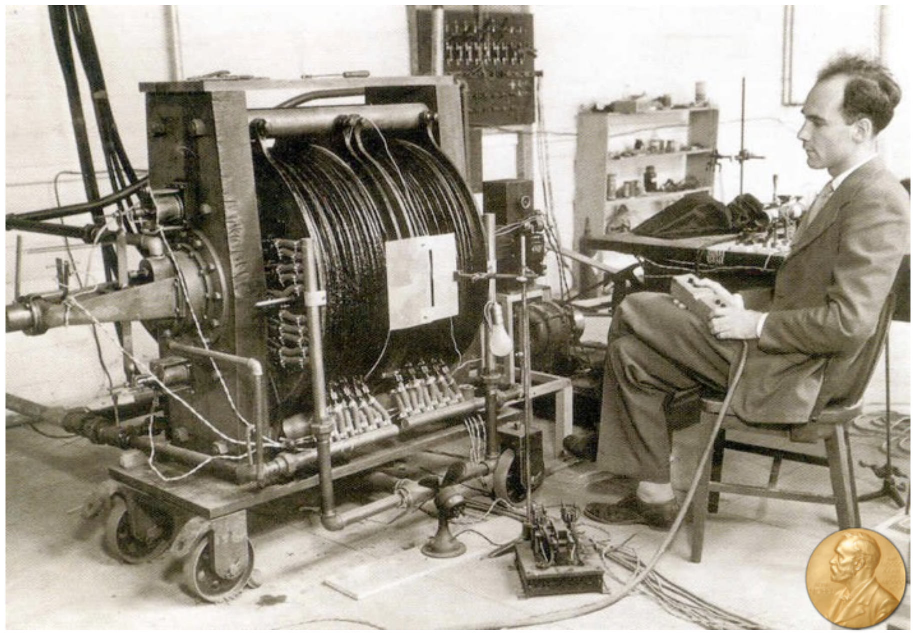
Über die Eigenschaften der durchdringenden Korpuskularstrahlung im Meeresniveau.

Von **Bruno Rossi** in Florenz, Arcetri.

Mit 16 Abbildungen. (Eingegangen am 24. Februar 1933.)

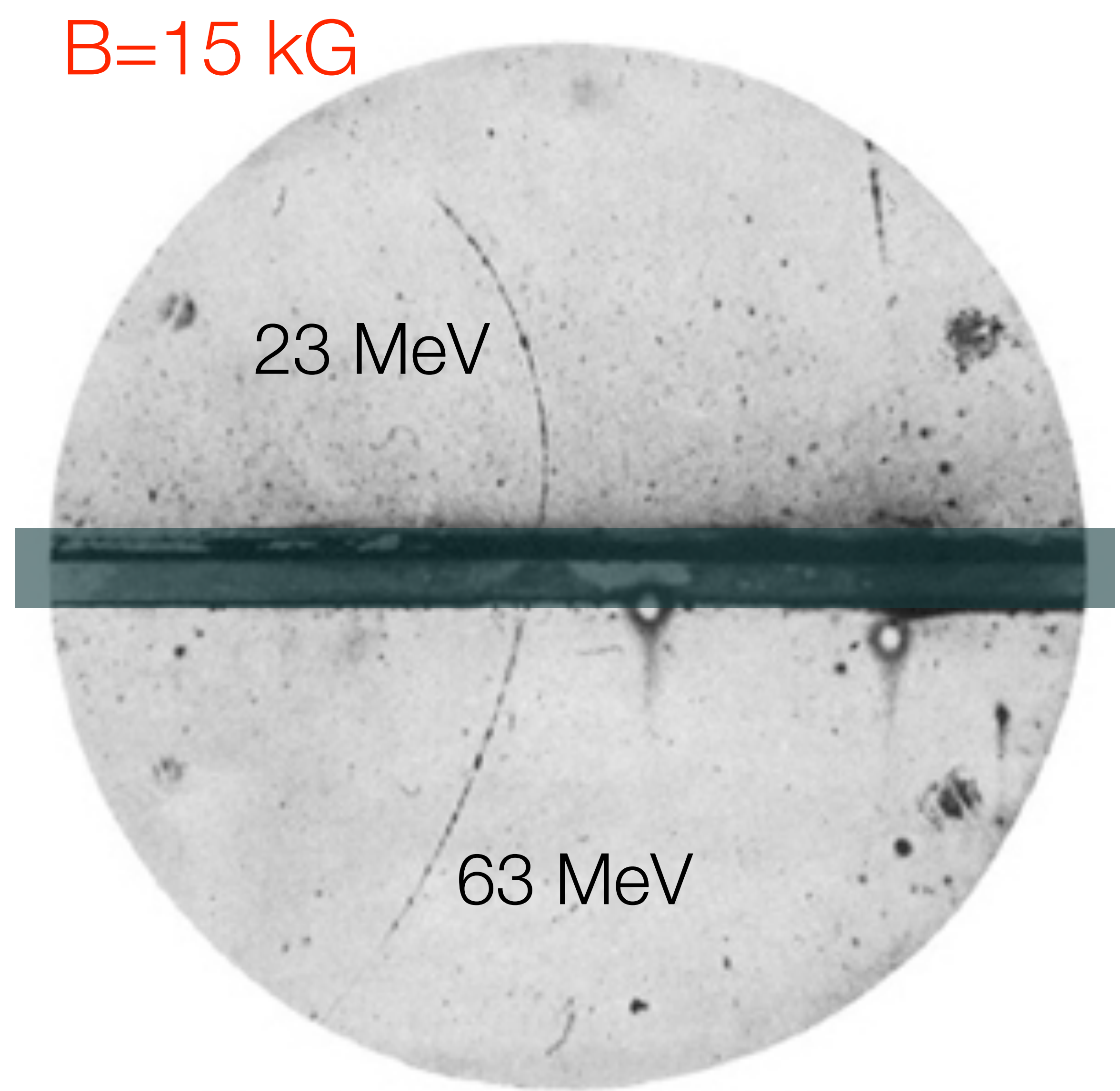


A unique particle physics laboratory



Carl D. Anderson

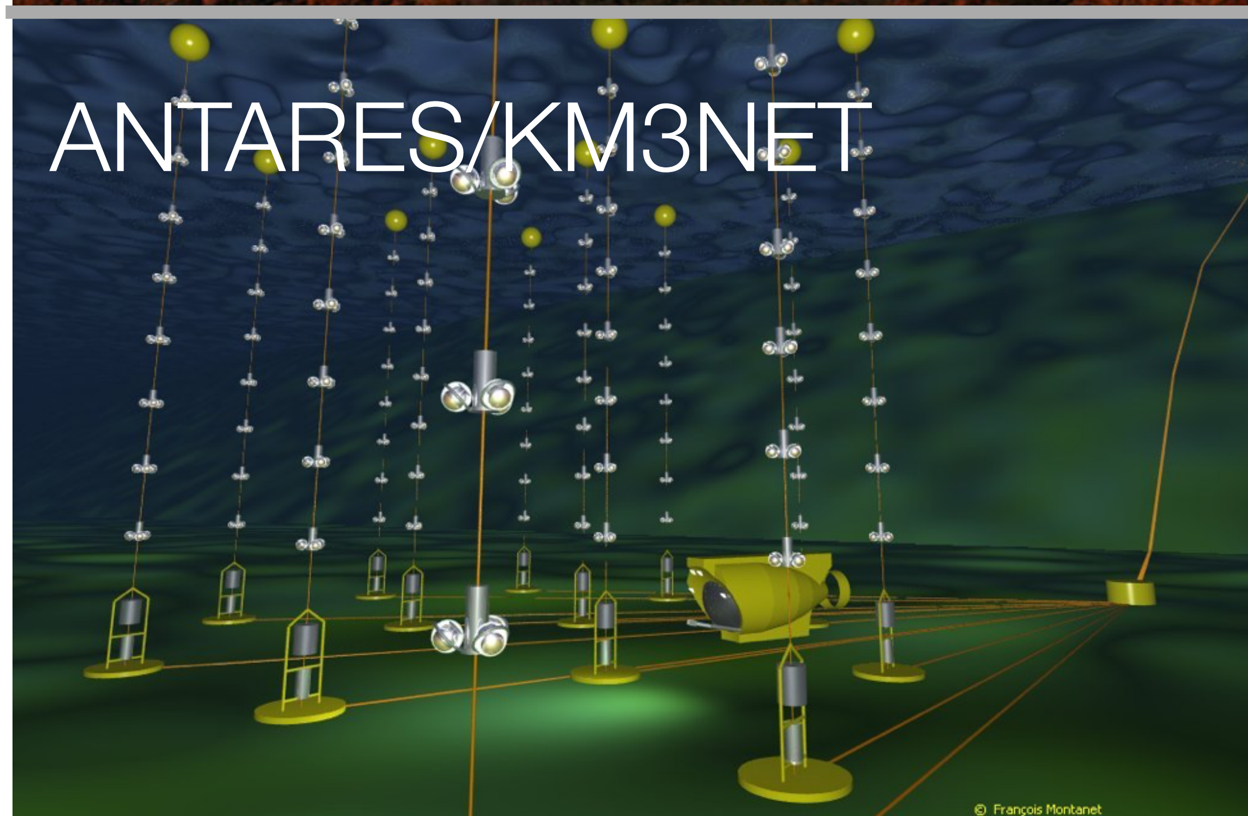
@ London's Westminster Abbey,
adjacent to Newton's grave.



The first anti-matter evidence was found in the cosmic radiation in 1933.

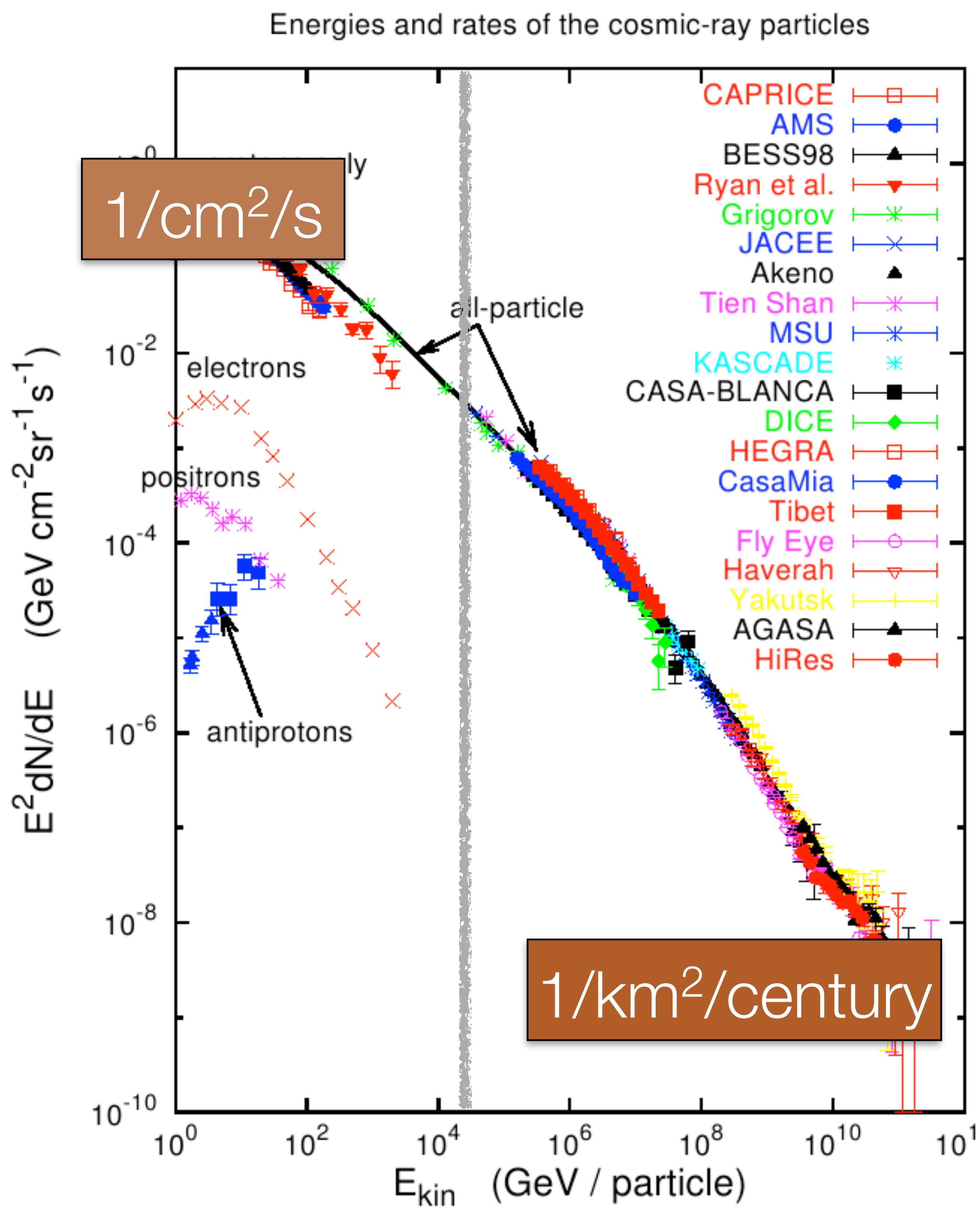
Today

Cosmic-ray experiments in Pisa in 2017



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.



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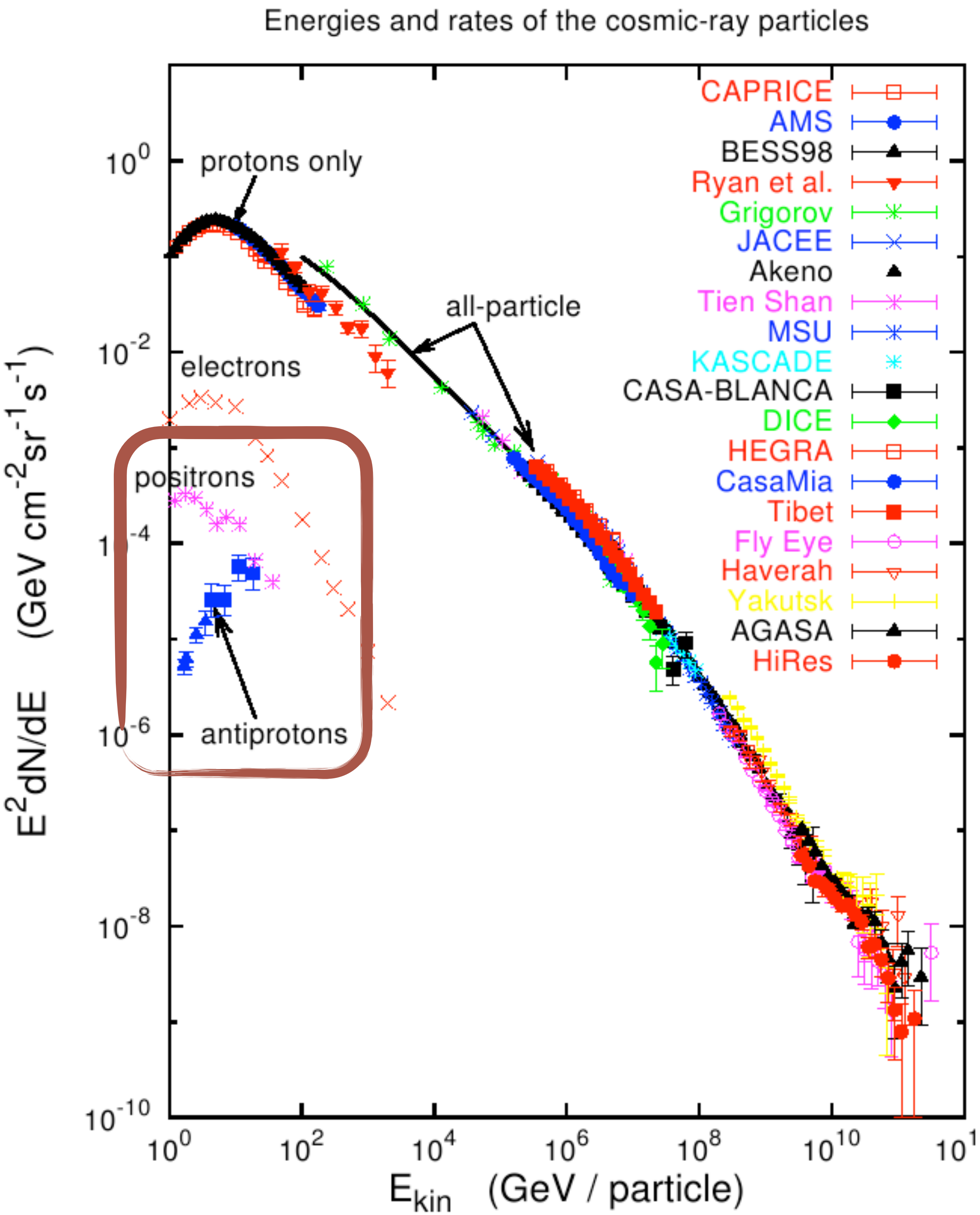

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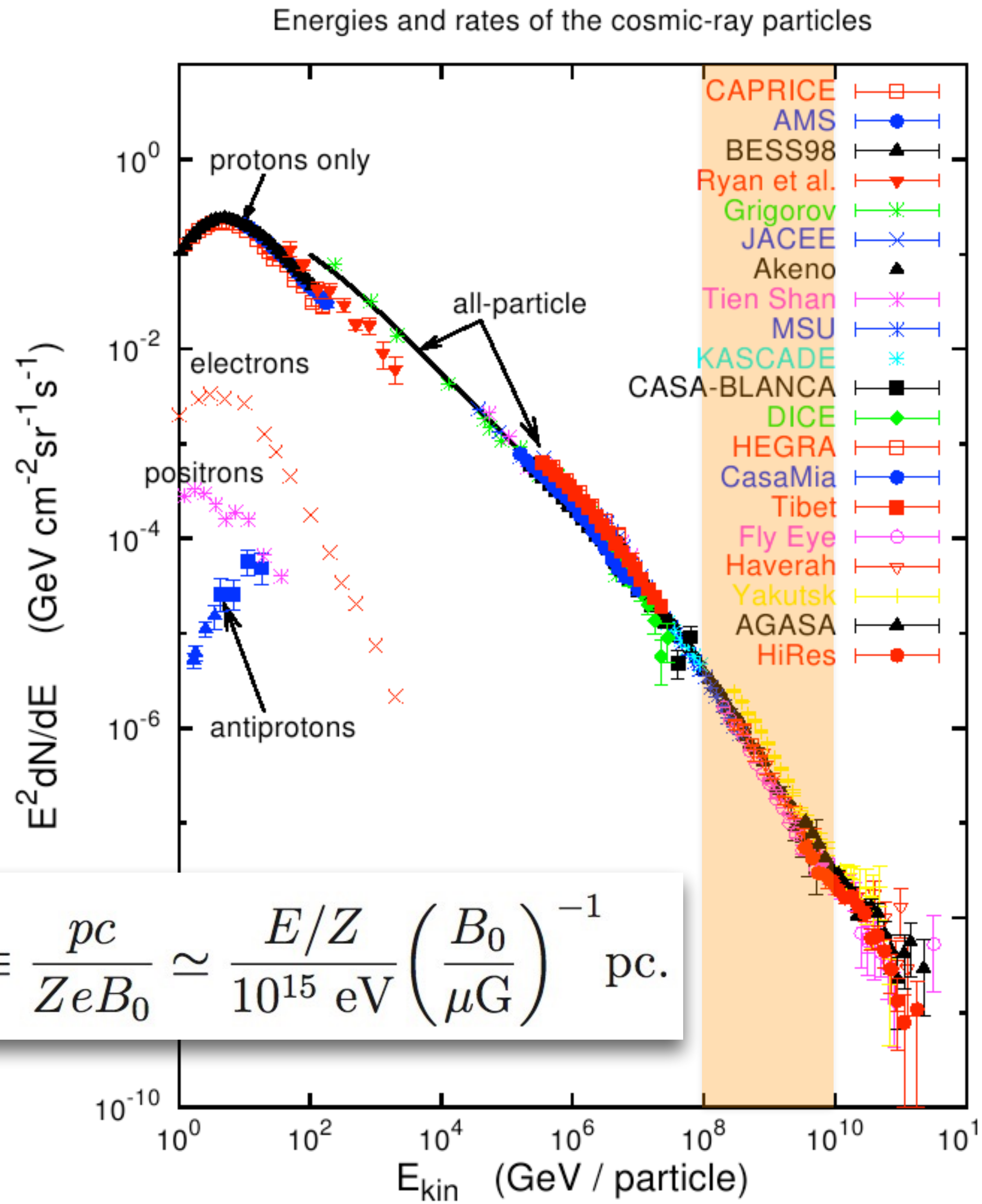
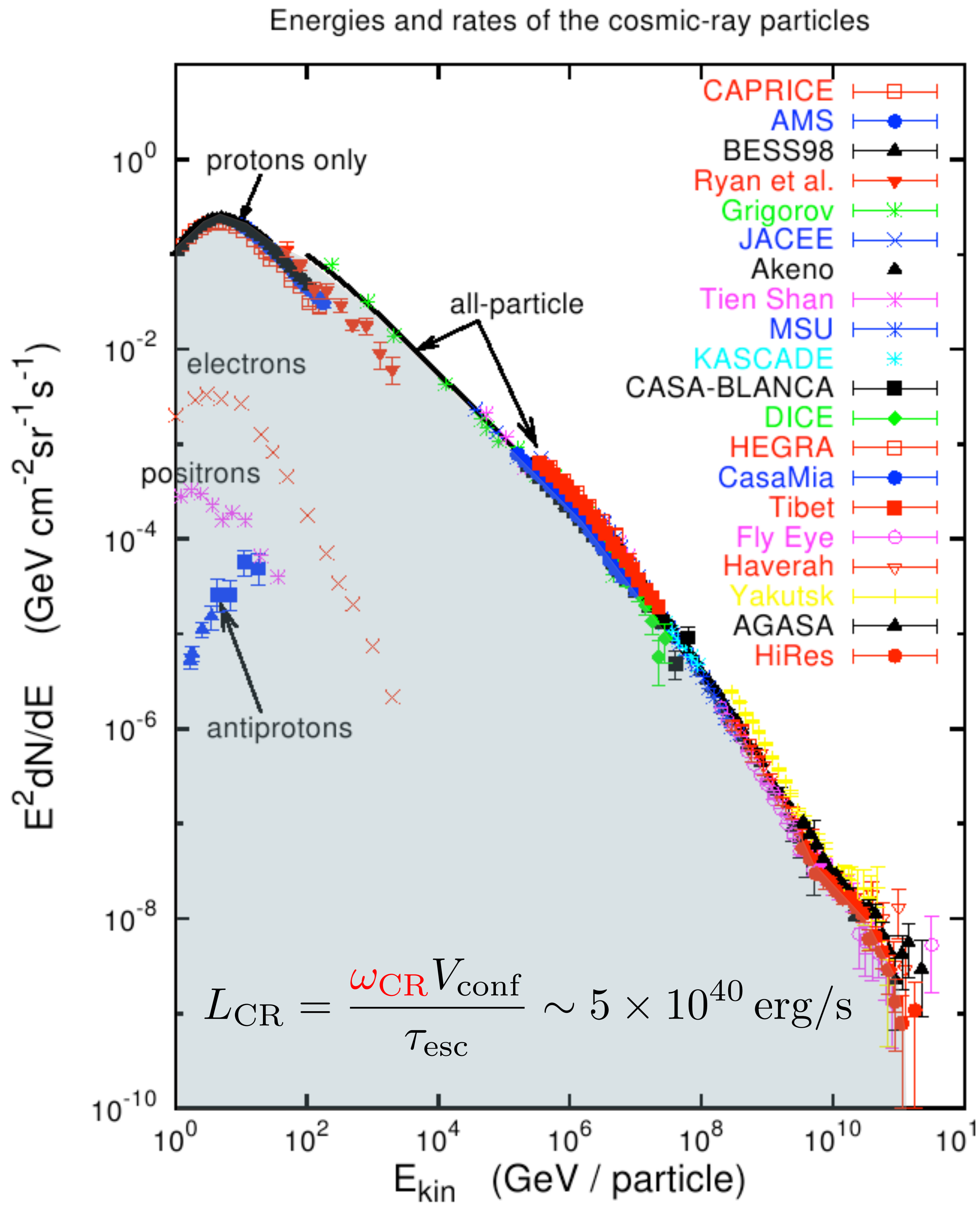


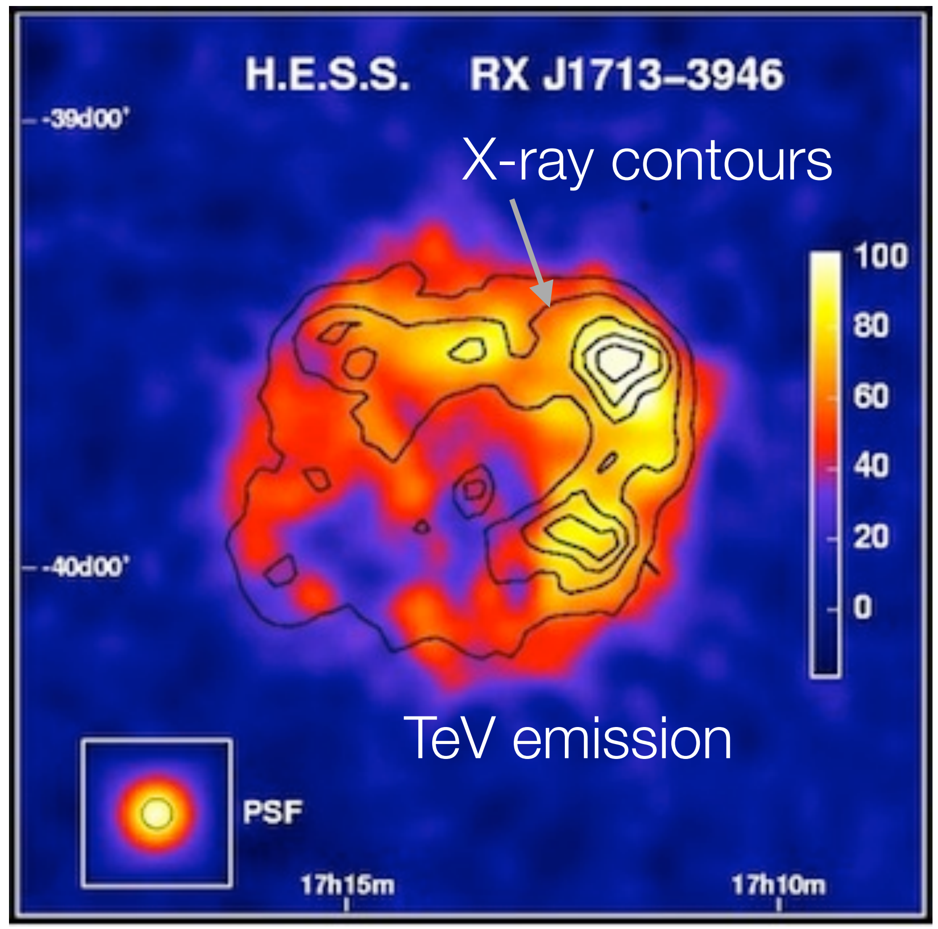
$$r_{\rm L} \equiv \frac{pc}{ZeB_0} \simeq \frac{E/Z}{10^{15}\ {\rm eV}} \left(\frac{B_0}{\mu{\rm G}}\right)^{-1} {\rm pc}.$$

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

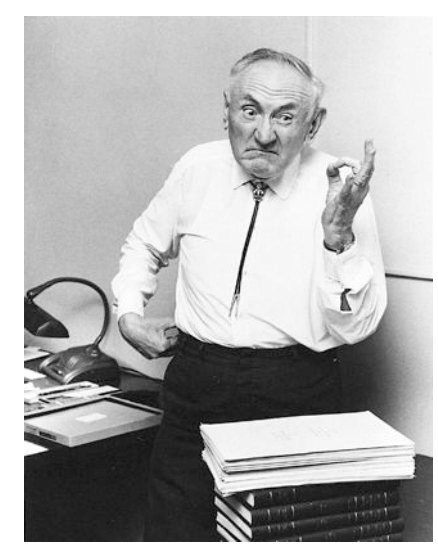
hadronic:

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

or leptonic:

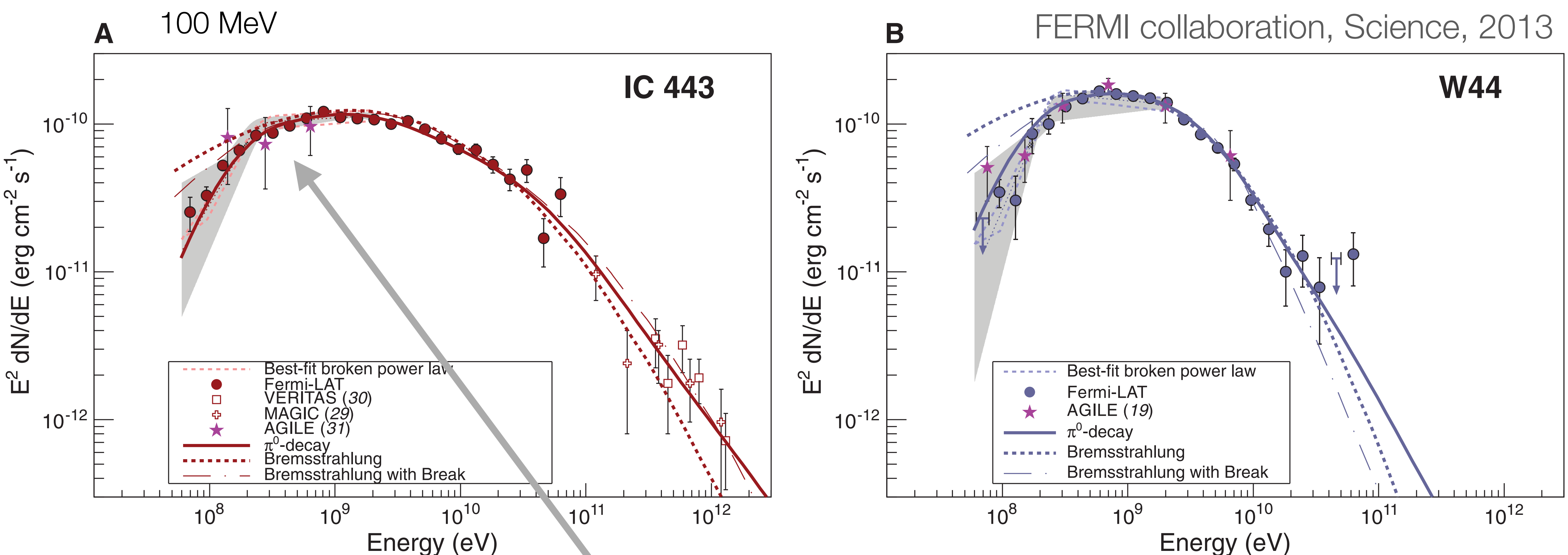
$$e^- \gamma_{\rm ISRF} \to e^- \gamma$$

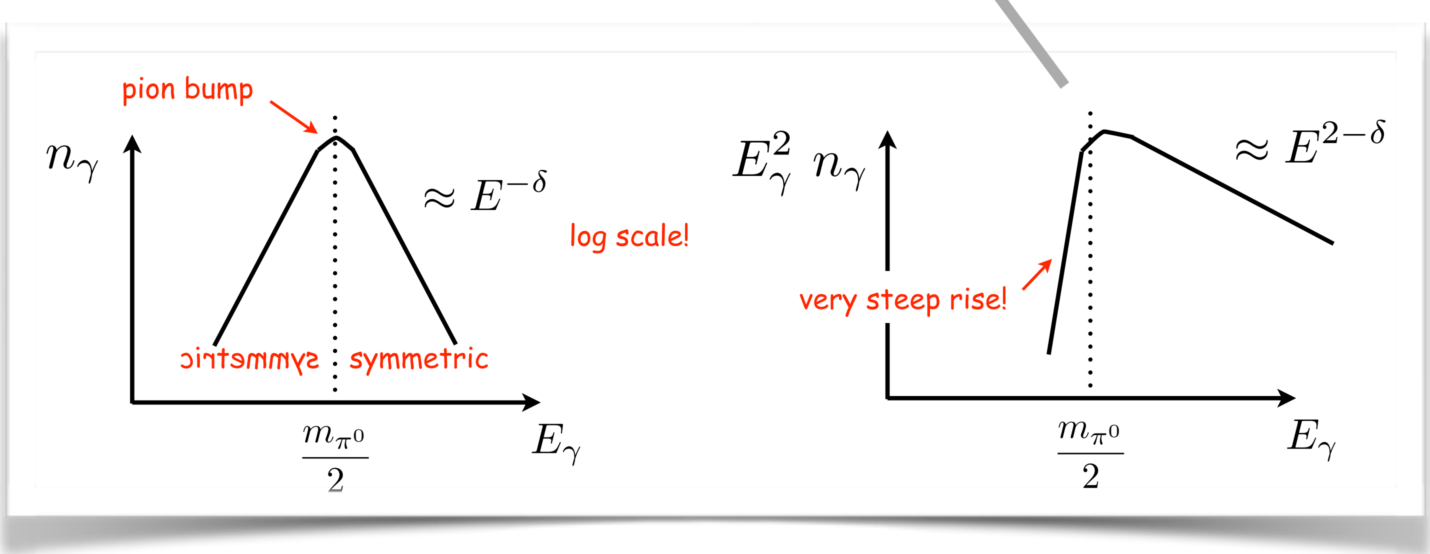
$$L_{\rm SN} \sim R_{\rm SN} E_{\rm kin} \sim 3 \times 10^{41}\, {\rm erg/s}$$



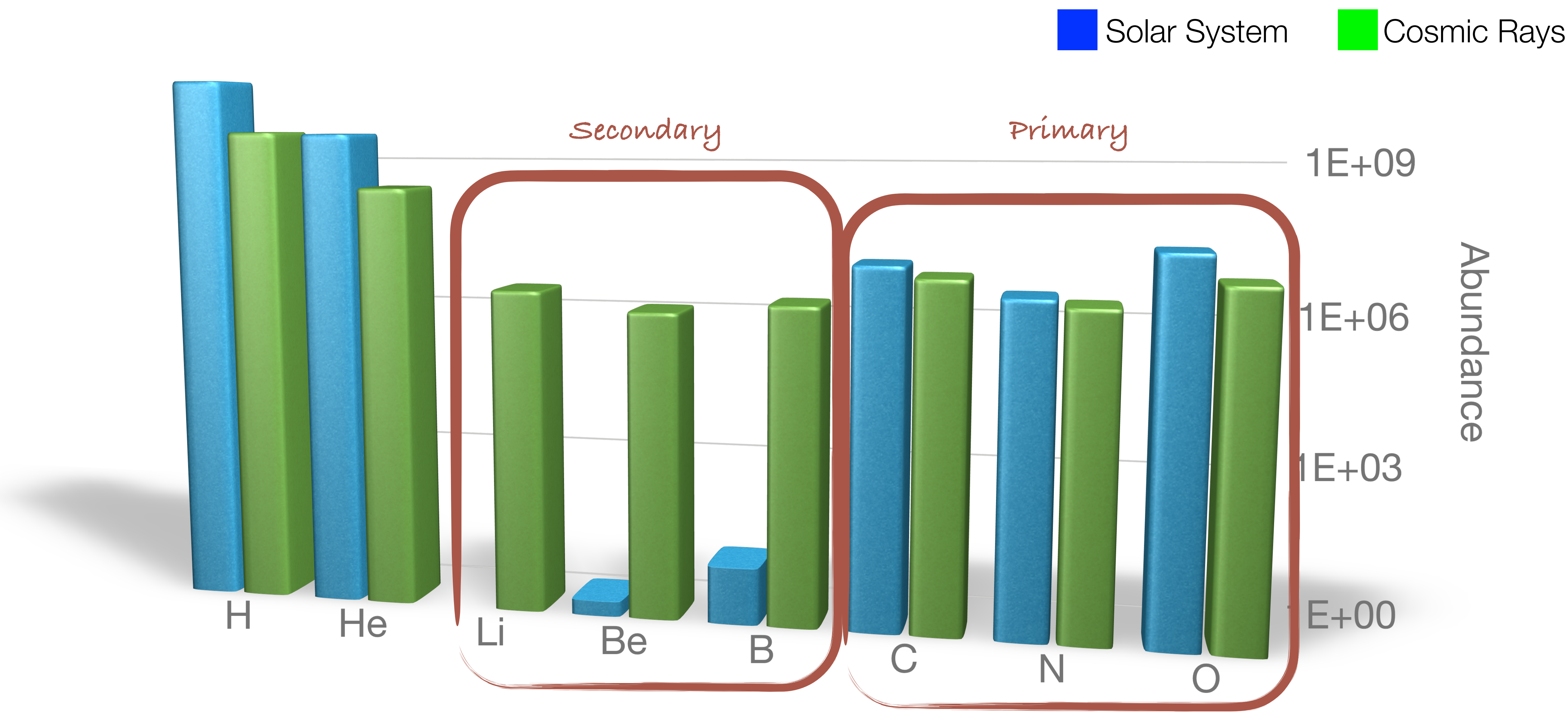
Fritz Zwicky

The pion-bump as hadronic signature





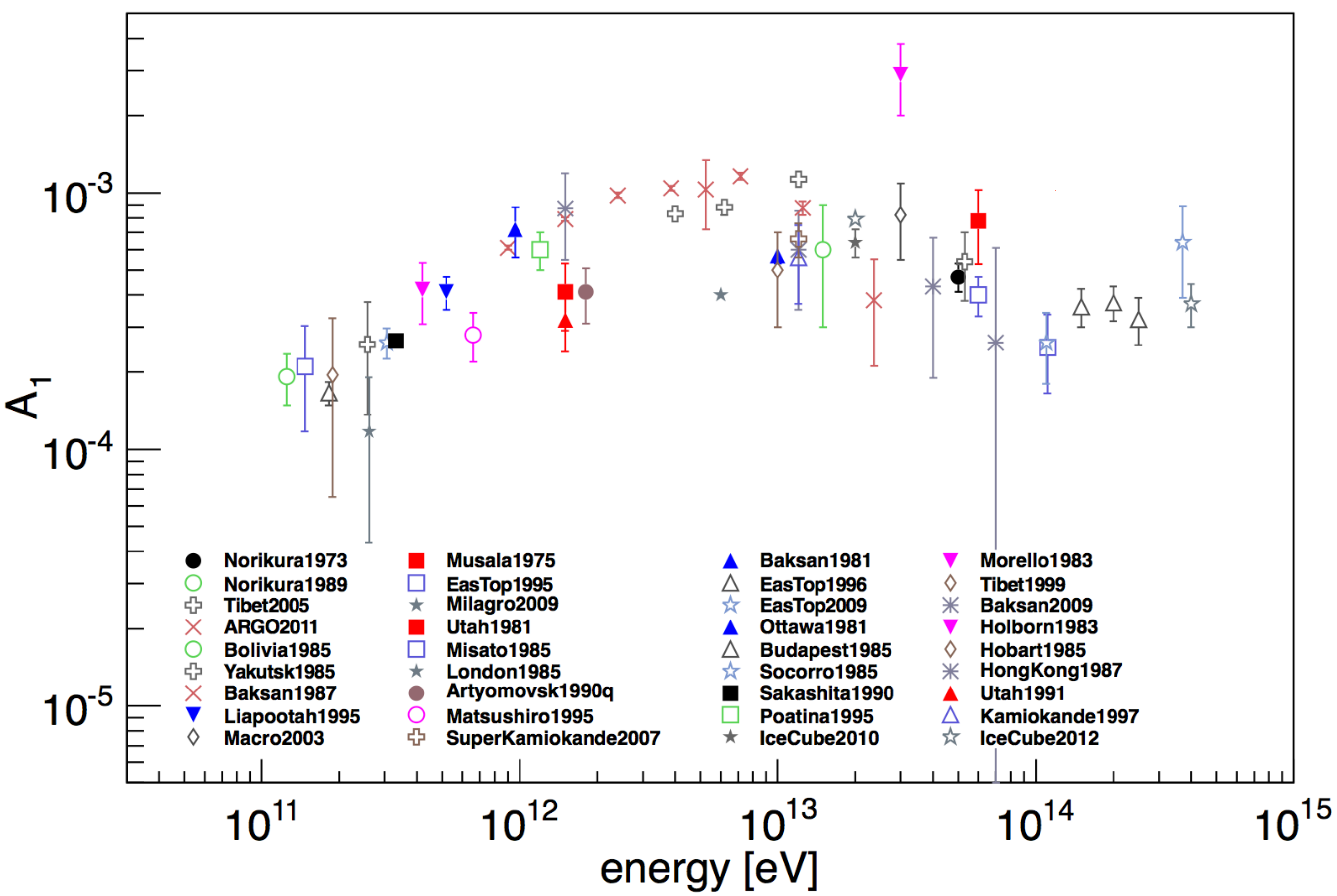
The cosmic-ray composition ***pillar***

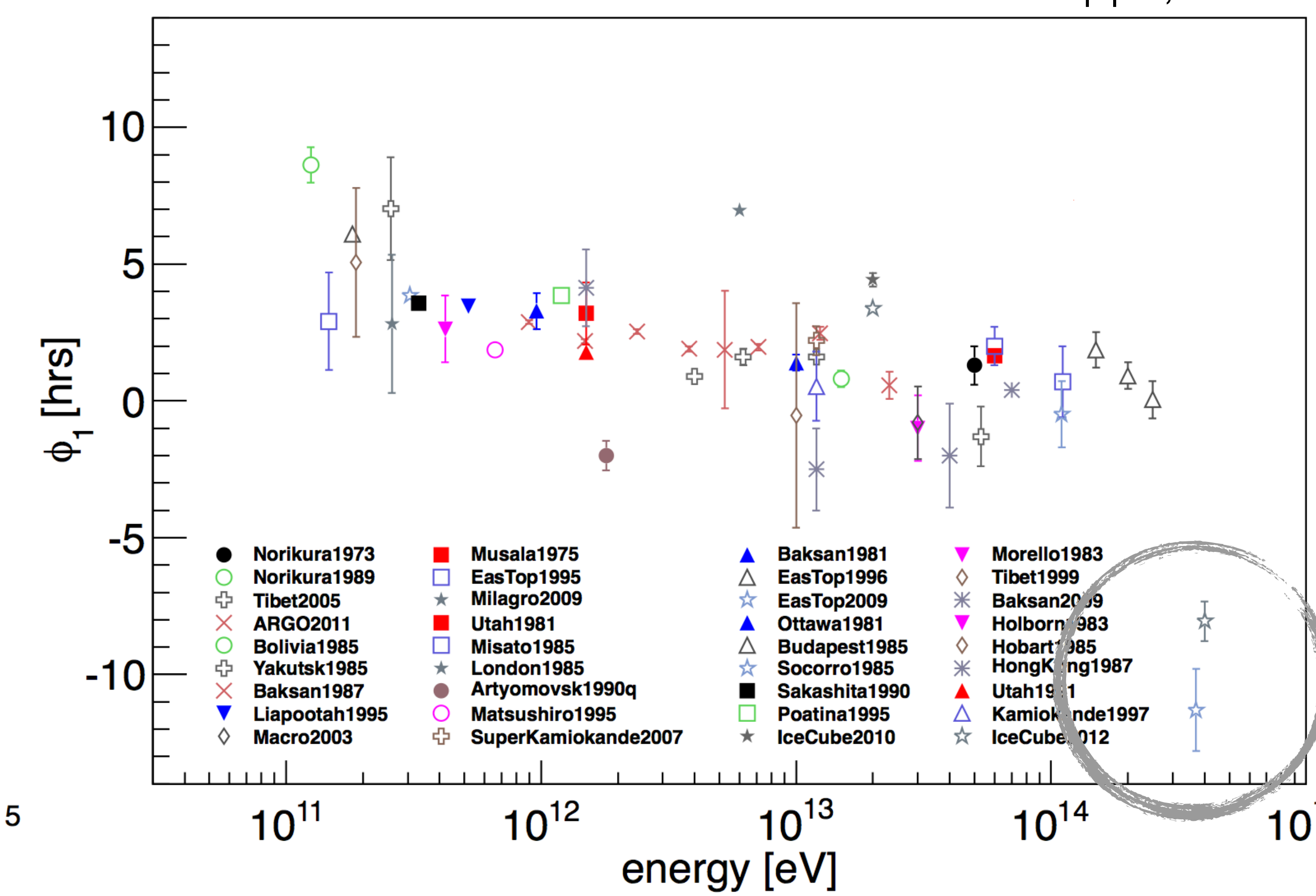


$$c\tau_{\rm esc} = \frac{X(E)}{\bar{n}_{\rm ISM}\mu} \sim 10^3\,{\rm kpc}$$ >> Galaxy size!

The cosmic-ray anisotropy ***puzzle***

Di Sciascio & Iuppa, 2014





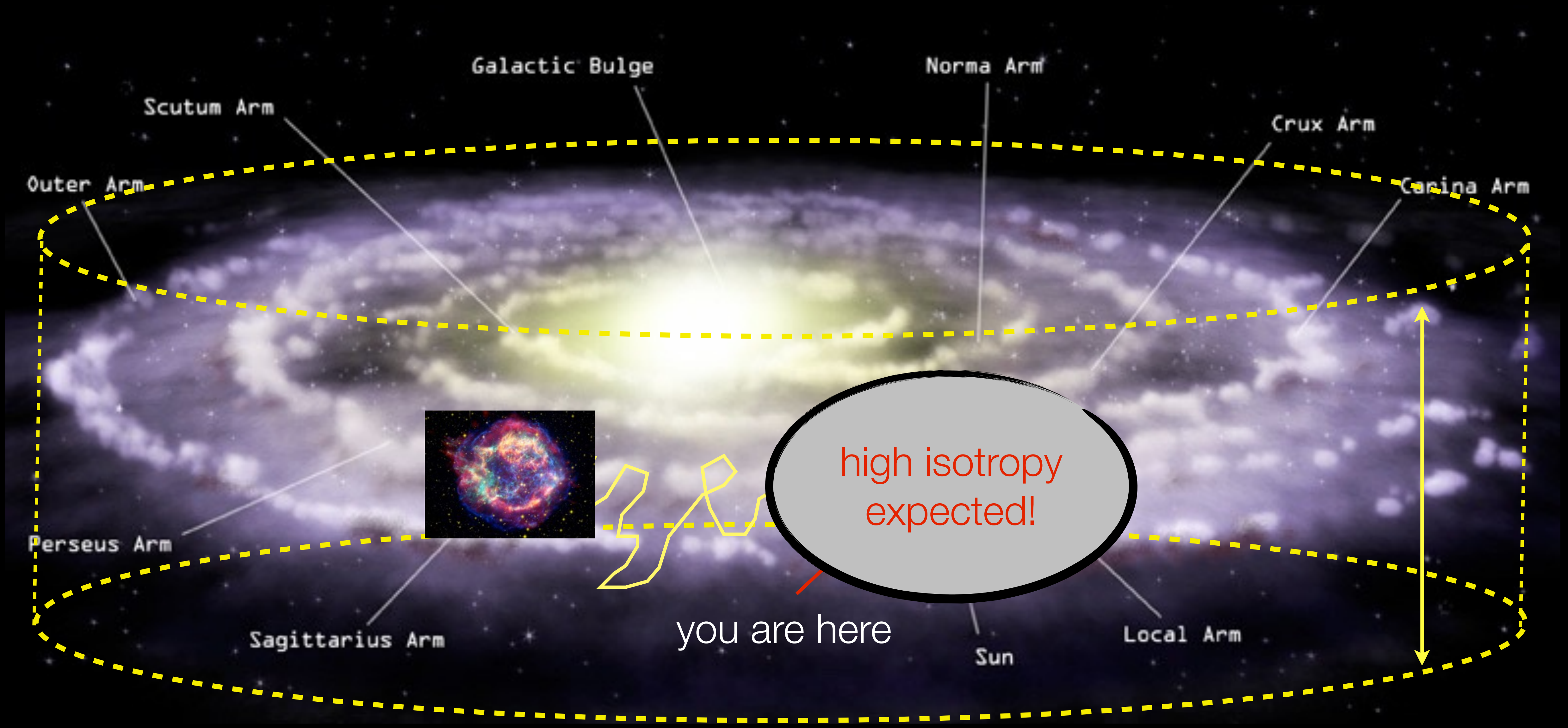
dipole amplitude increases up to ~10 TeV and then it decreases

phase of dipole steadily migrates and suddenly flips

$$A \sim \frac{v_A}{c} \sim 10^{-4} \frac{v_A}{30\,\mathrm{km/s}}$$

<< ballistic transport!

Galactic Propagation



L = 1-10 kpc

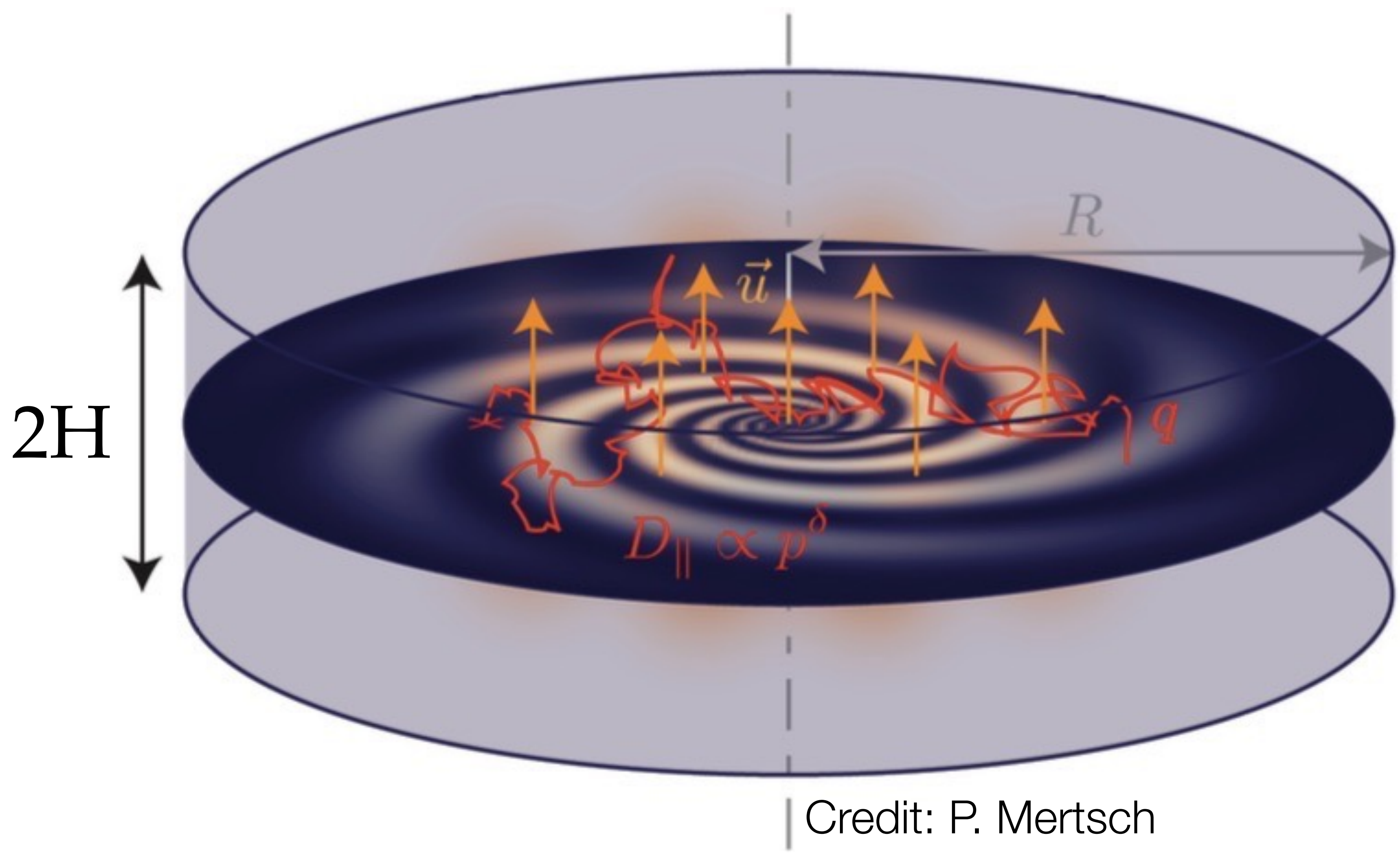
The Master equation

Berezinskii et al. (1990)

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

Transport

Sources/sinks



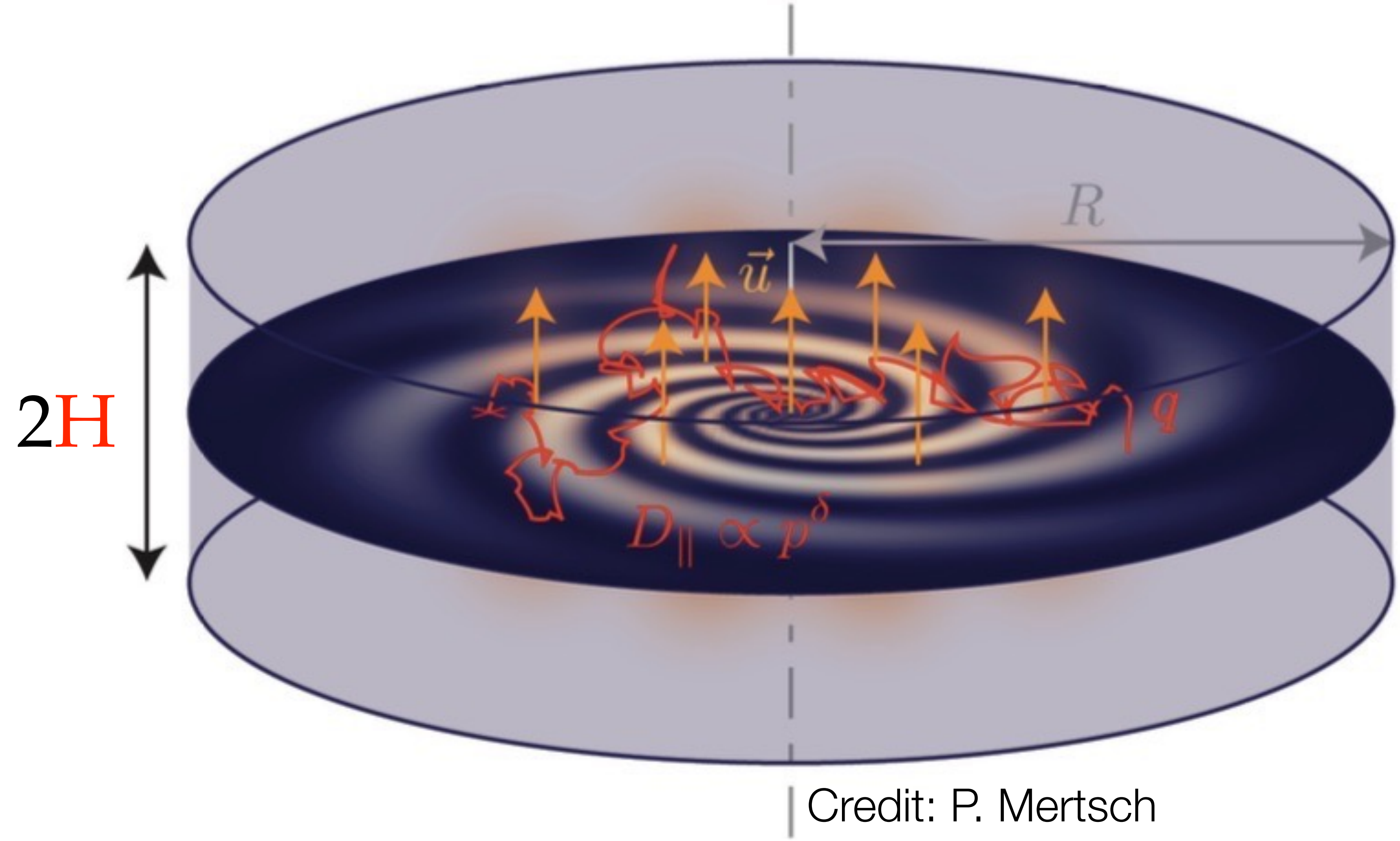
Credit: P. Mertsch

Minimal “5-parameters model”

Berezinskii et al. (1990)

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

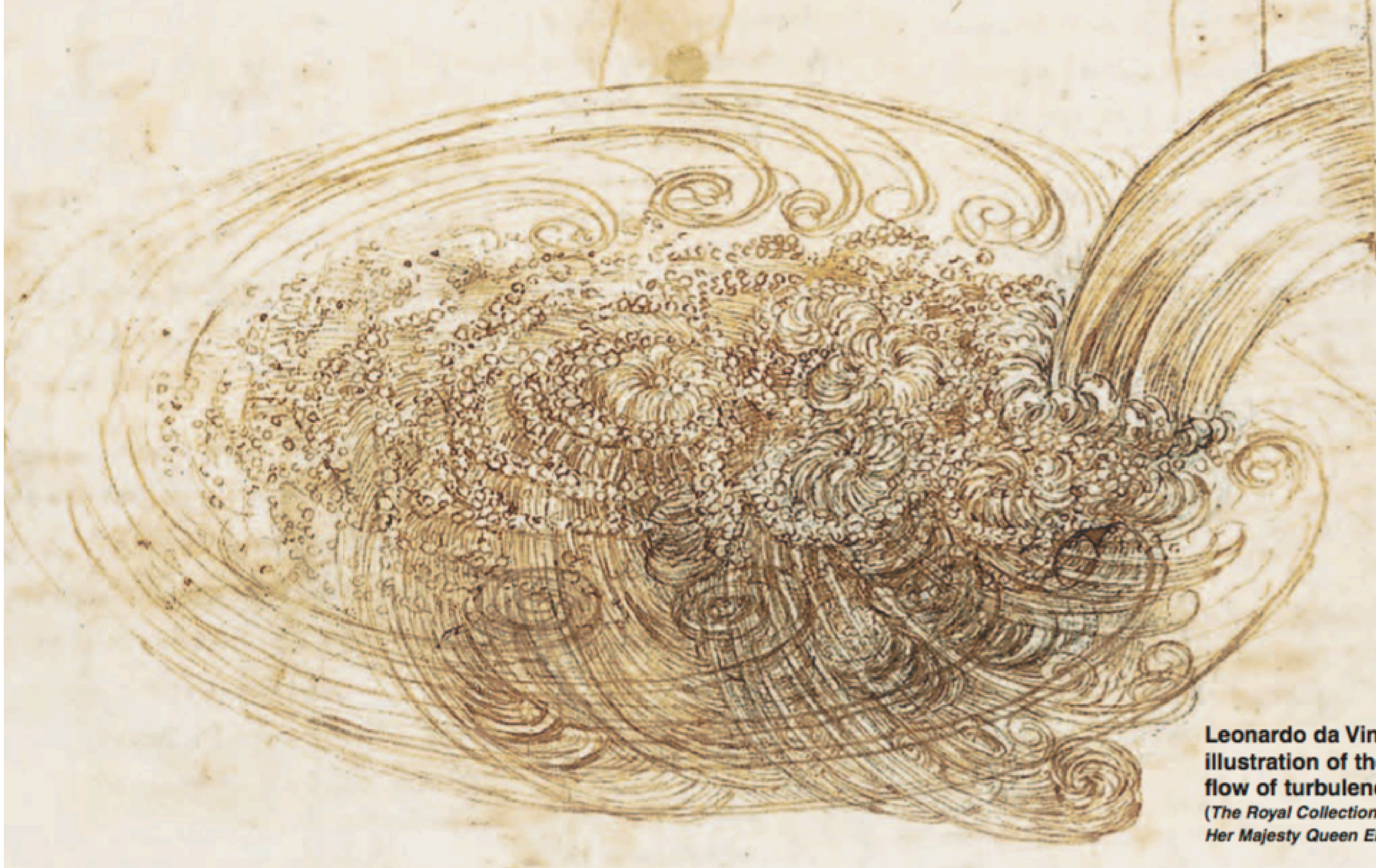
… far from reality even in QLT



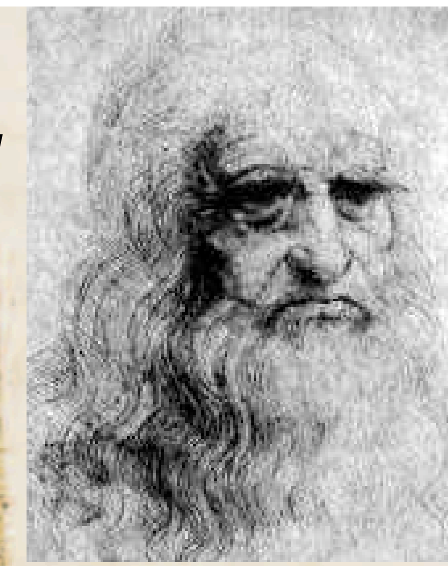
Credit: P. Mertsch

CR diffusion for the "poor physicist"

"The small eddies are almost numberless, and large things are rotated only by large eddies and not by small ones, and small things are turned by both small eddies and large"



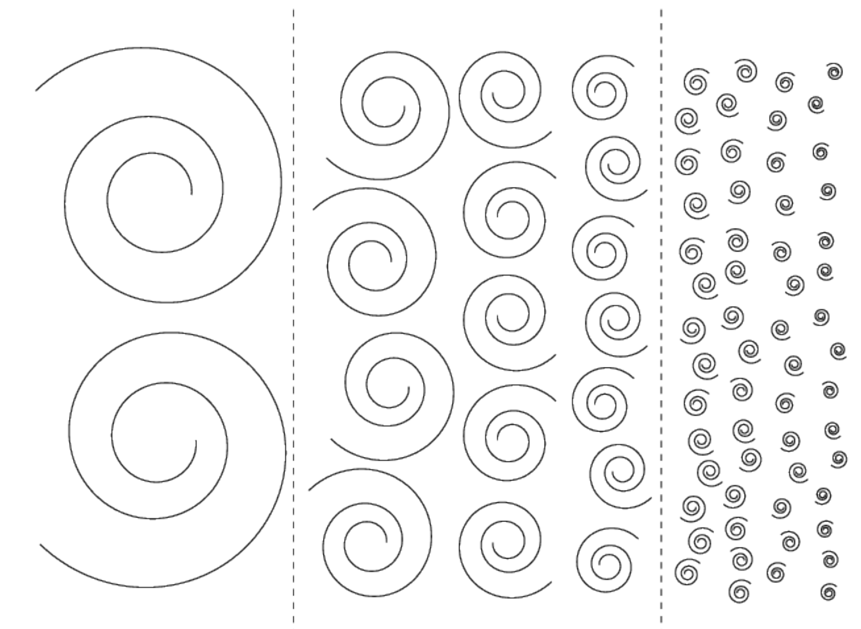
Leonardo da Vinci's illustration of the swirling flow of turbulence.
(The Royal Collection © 2004, Her Majesty Queen Elizabeth II)

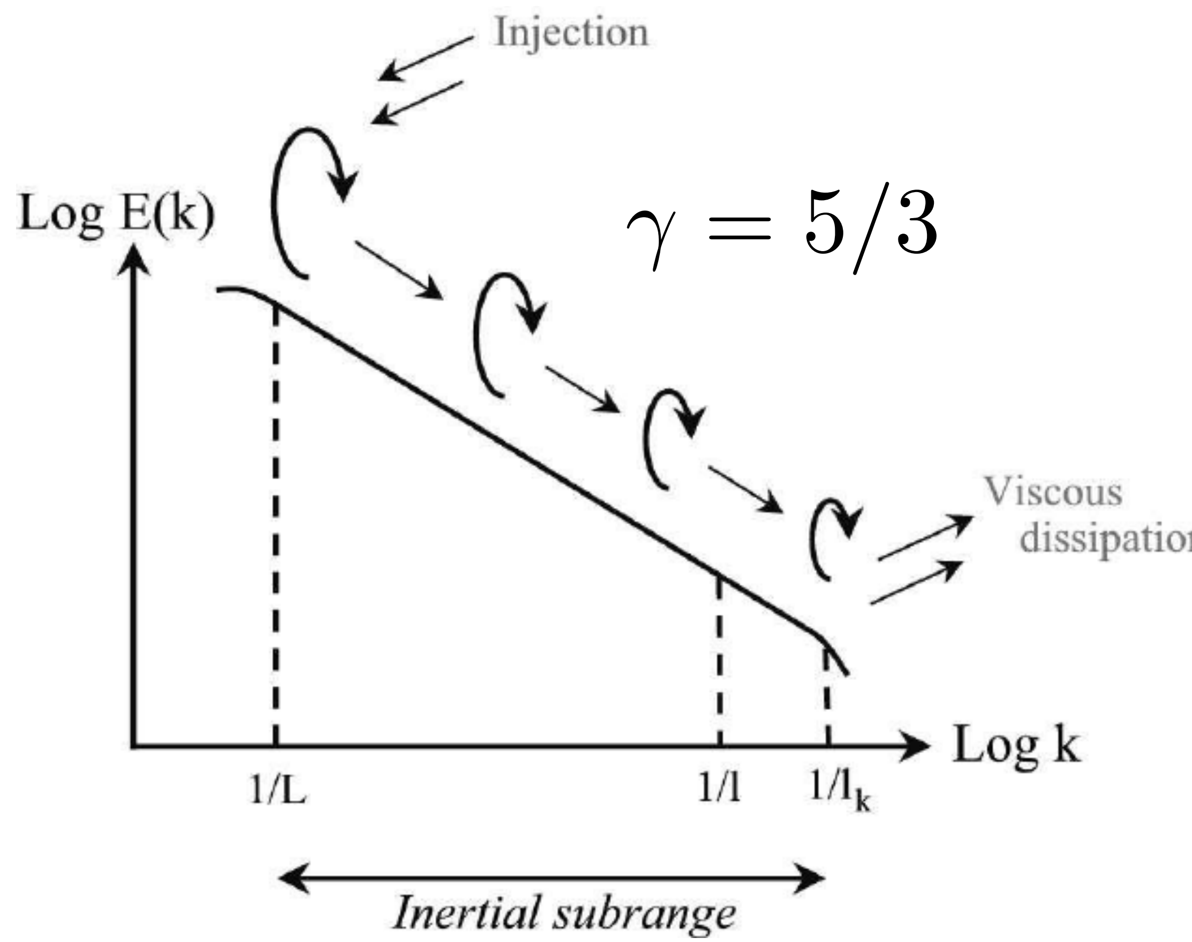


Leonardo da Vinci
(1452-1519)

CR diffusion for the "poor physicist"

The Richardson cascade

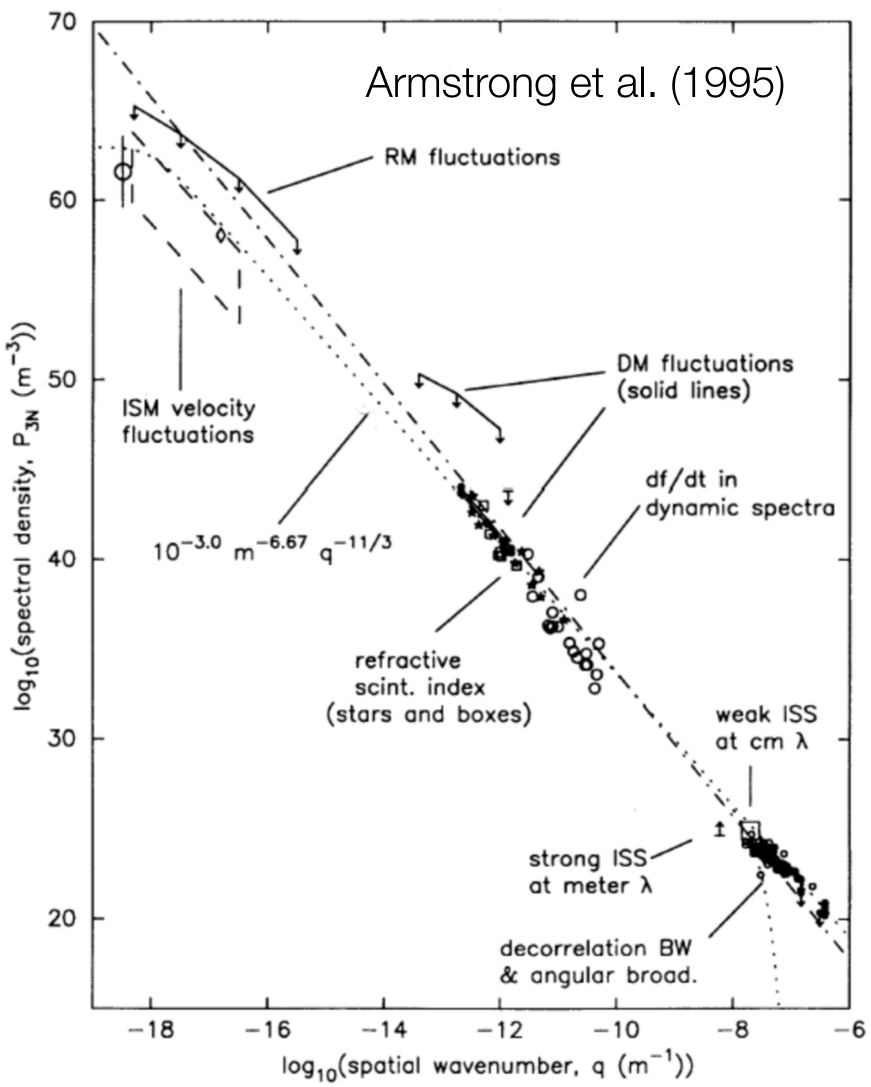




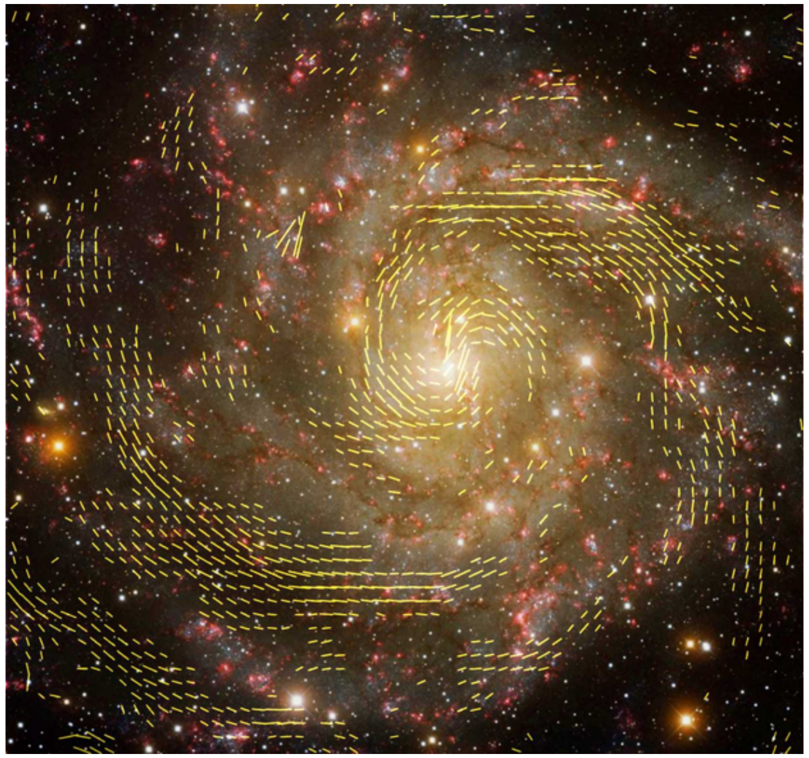
Big whorls have little whorls
That feed on their velocity
And little whorls have lesser whorls
And so on to viscosity

L.F. Richardson (1922)

CR diffusion for the "poor physicist"



IC 342, using data from both the VLA and the Effelsberg telescope



~0.1 - 0.01

Wave power-spectrum

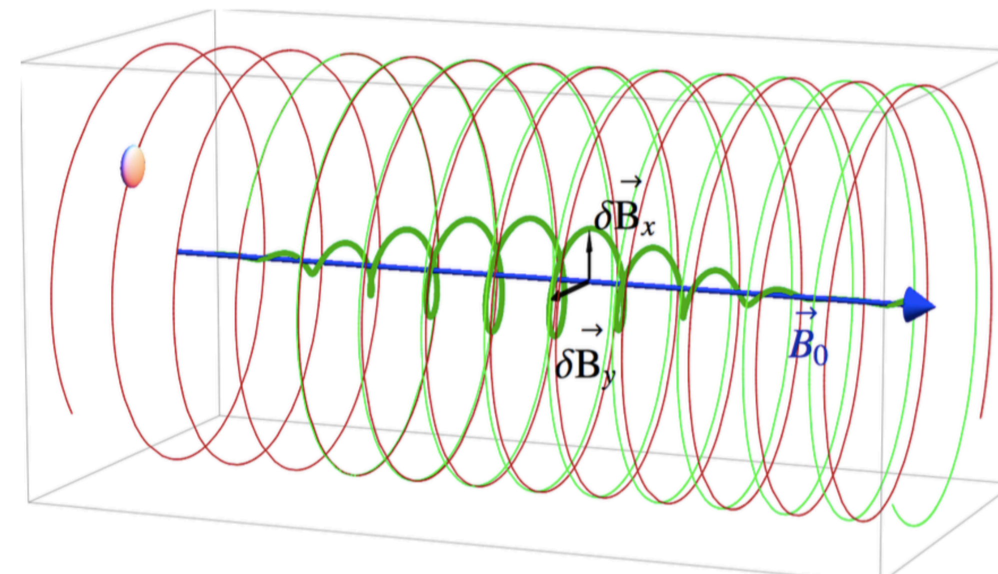
Kolmogorov

$$W(k)dk = \frac{\delta B^2(k)}{B_0^2} \rightarrow \int W(k)dk = \frac{\delta B_{tot}^2}{B_0^2} \equiv \eta_B$$

$$W(k) = \frac{2}{3}\frac{\eta_B}{k_0}\left(\frac{k}{k_0}\right)^{-5/3}$$

~1/100 pc

CR diffusion for the "poor physicist"



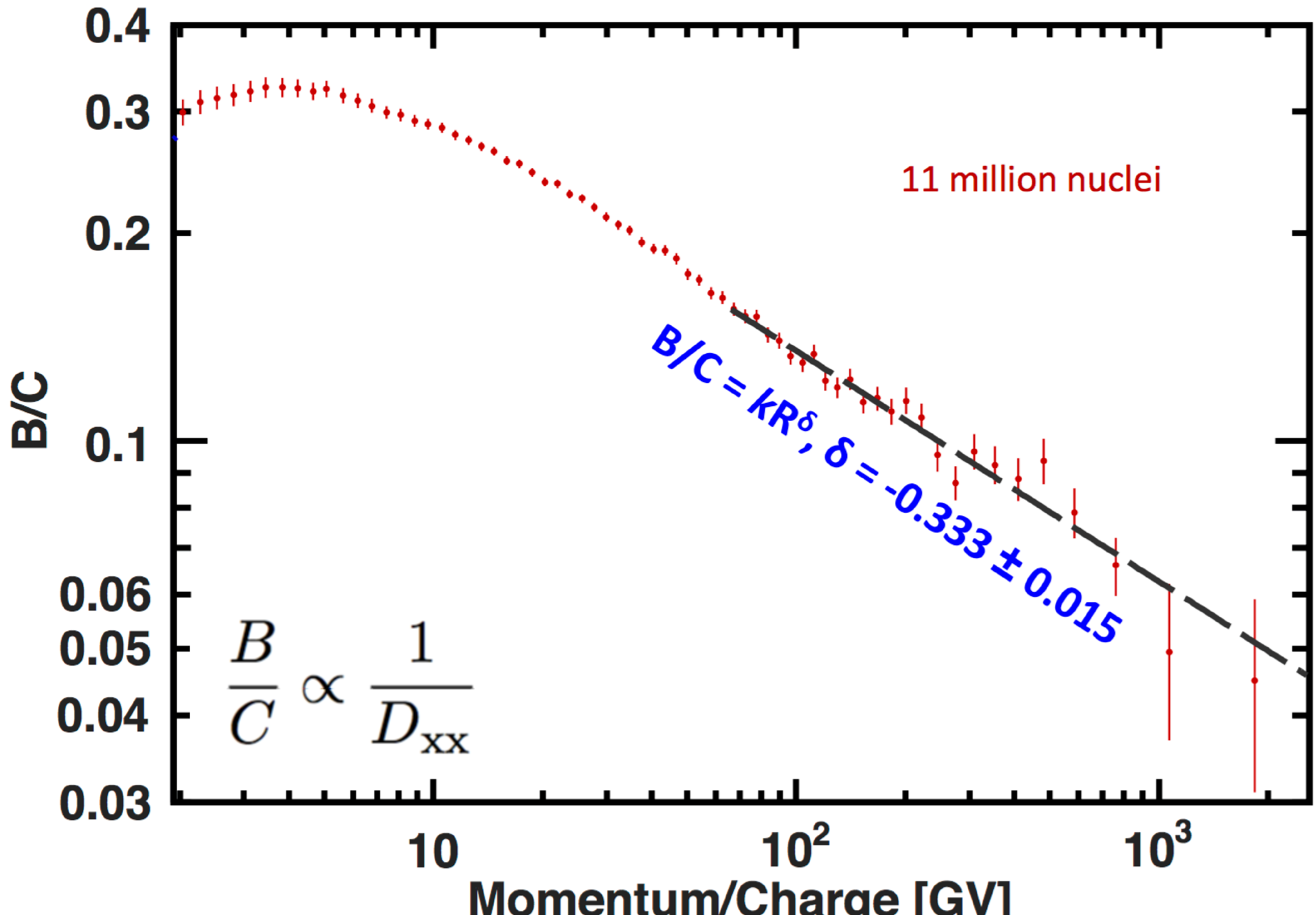
Assumptions:

- GCR diffuse in the ISM turbulent magnetic field
- The turbulent field can be described by 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 (~30 min at the blackboard):

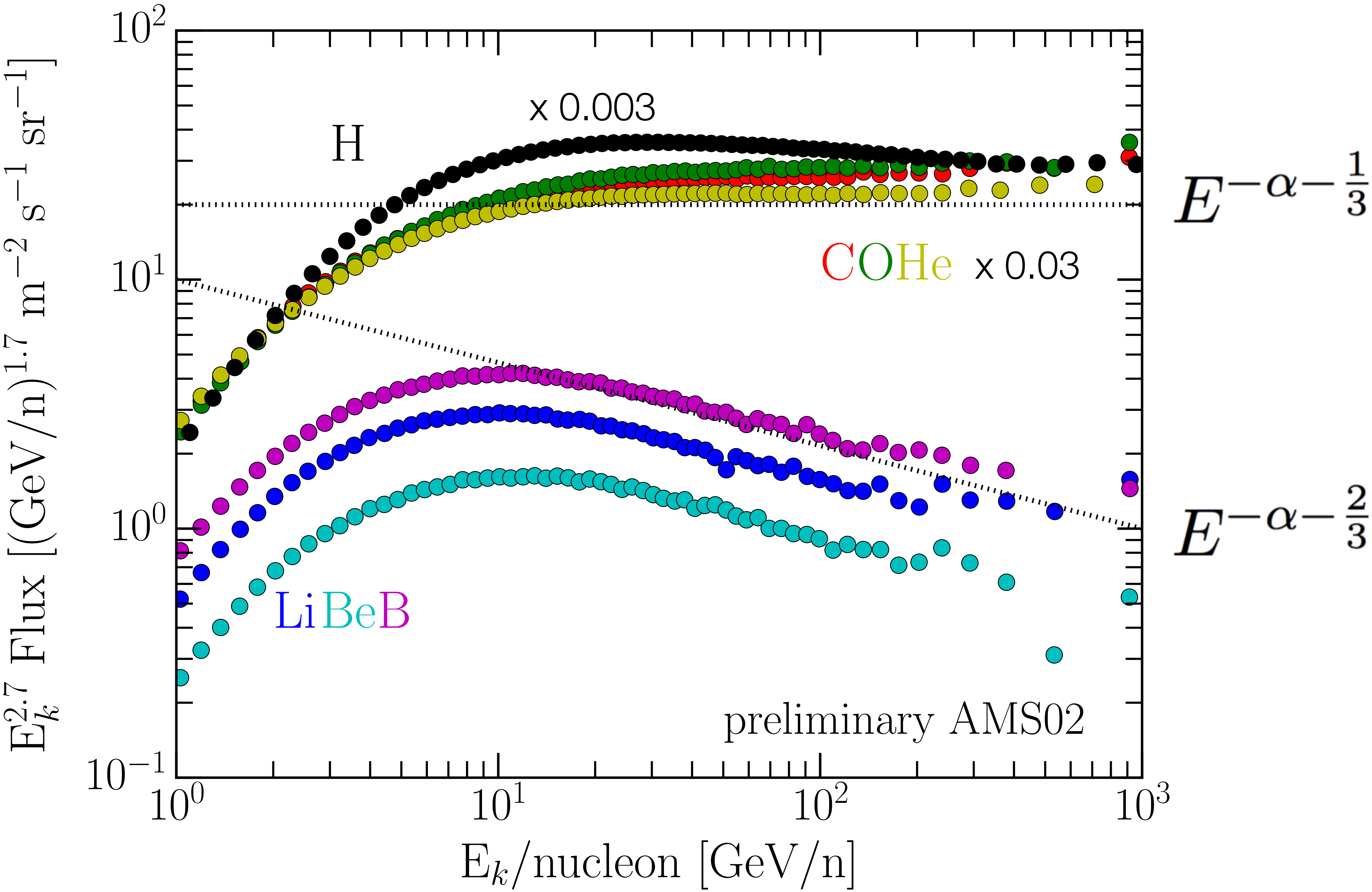
$$D_{\rm xx}(p) = \frac{c r_L}{3} \frac{1}{k_{\rm res} W(k_{\rm res})} \sim 3 \times 10^{28} {\rm cm}^2/{\rm s} \left(\frac{E}{\rm GeV}\right)^{1/3}$$

B/C by AMS-02

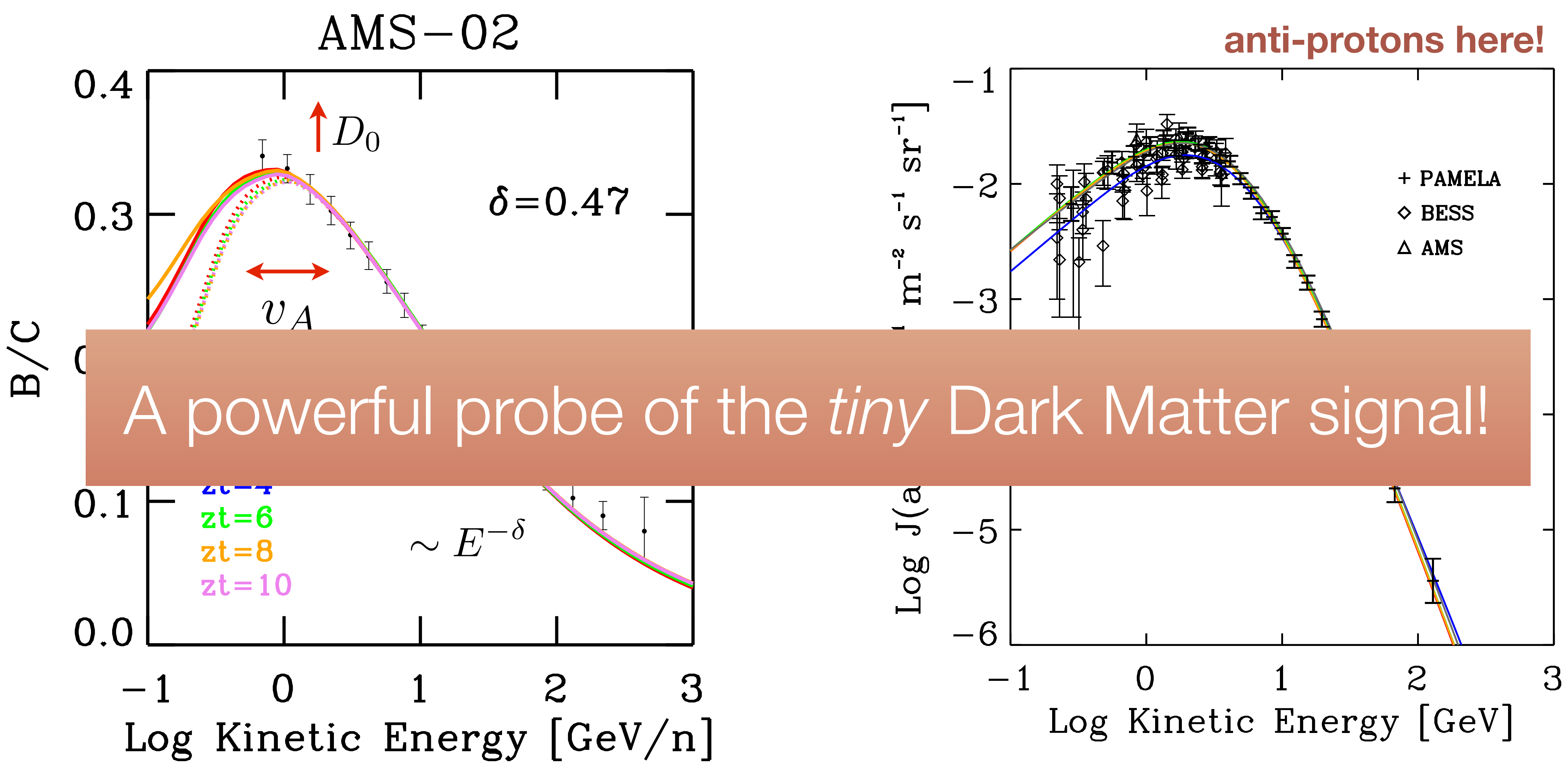


0.4
0.3
0.2
0.1
0.06
0.05
0.04
0.03
B/C
10
10^2
10^3
Momentum/Charge [GV]
11 million nuclei
B/C = kR$^\delta$, δ = -0.333 ± 0.015
$\frac{B}{C} \propto \frac{1}{D_{xx}}$

Primary and secondary nuclei by AMS-02



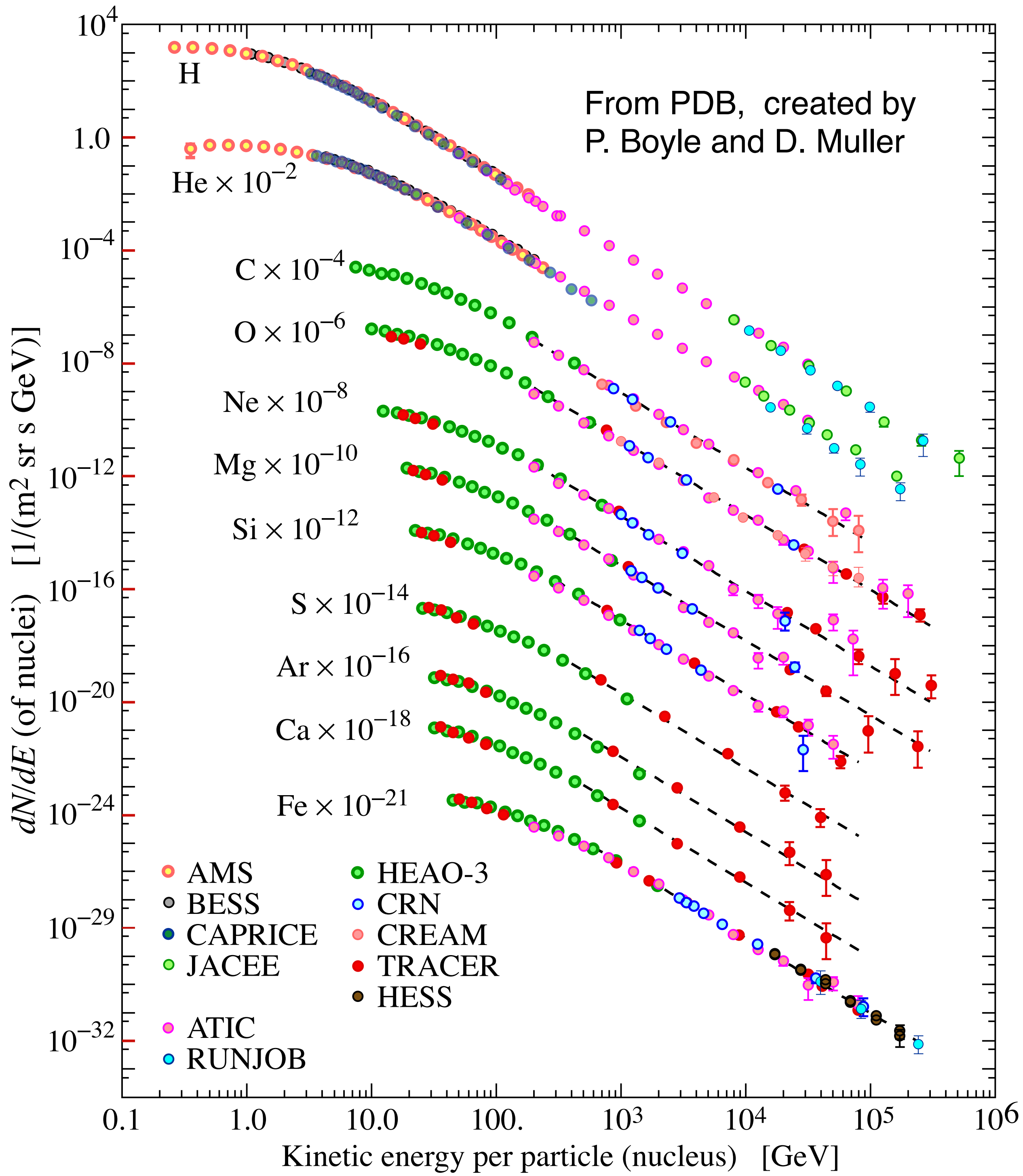
Fitting local observables



A powerful probe of the *tiny* Dark Matter signal!

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

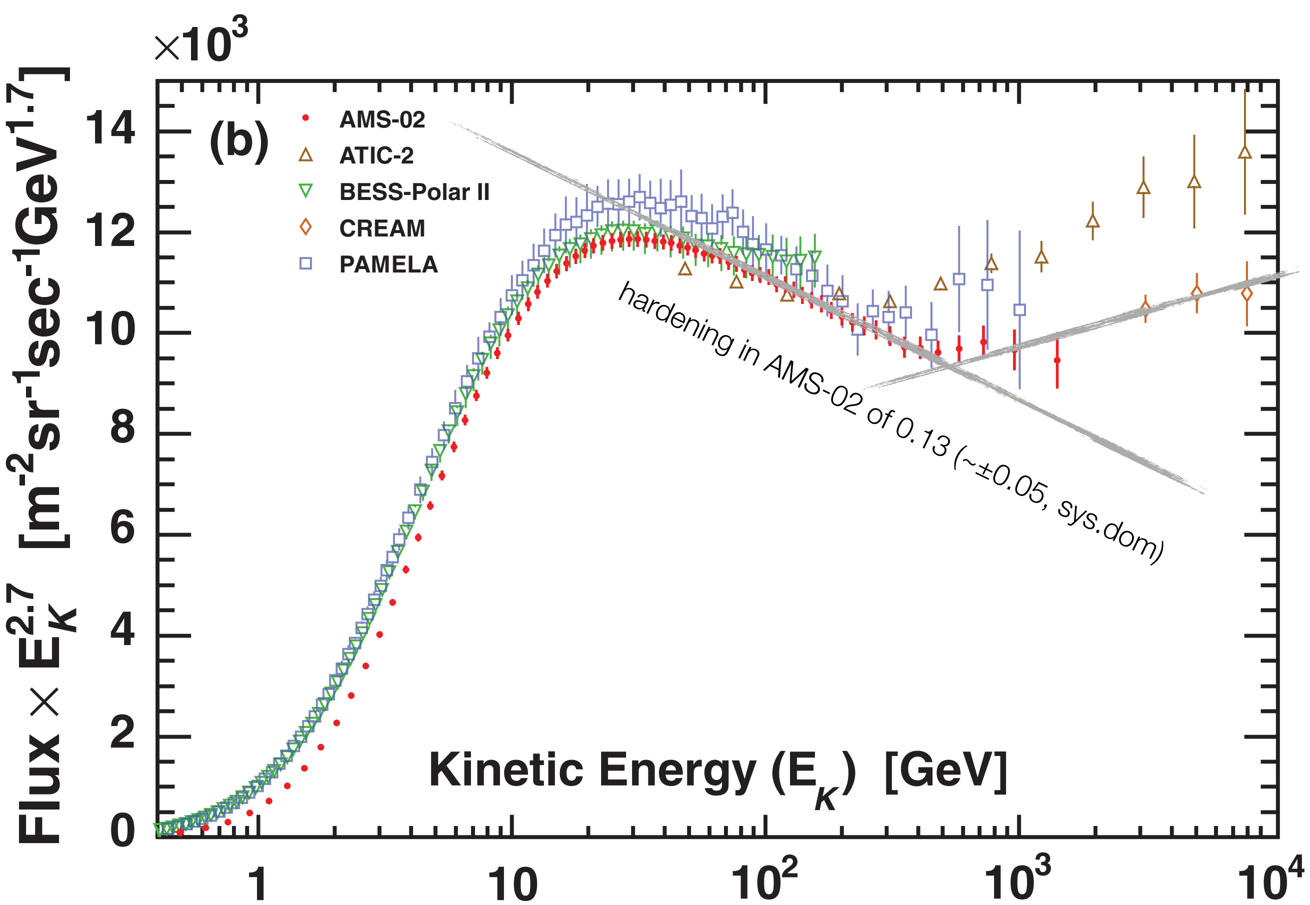
a simple (pre-modern data) picture

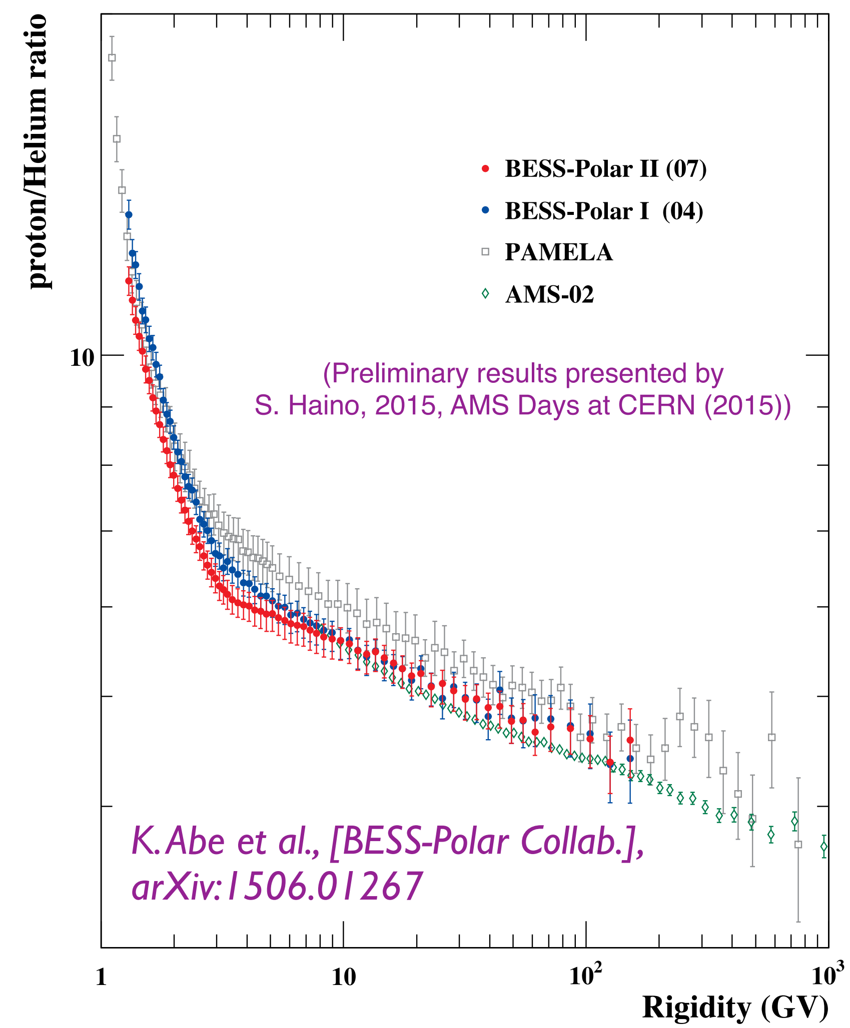


Probably the most obvious expectation about cosmic rays (0th order picture) is that, above a few GeV, they have a "**featureless and universal power-law energy spectra**" (lots of work rely on self-similarity: Fermi acceleration theory, Kolmogorov diffusion…)

Important to test for departures from basic features: may provide clues on specific scales and phenomena shedding light on non-universal features of injection, acceleration, escape, propagation.

is it the CR spectrum featureless and universal?



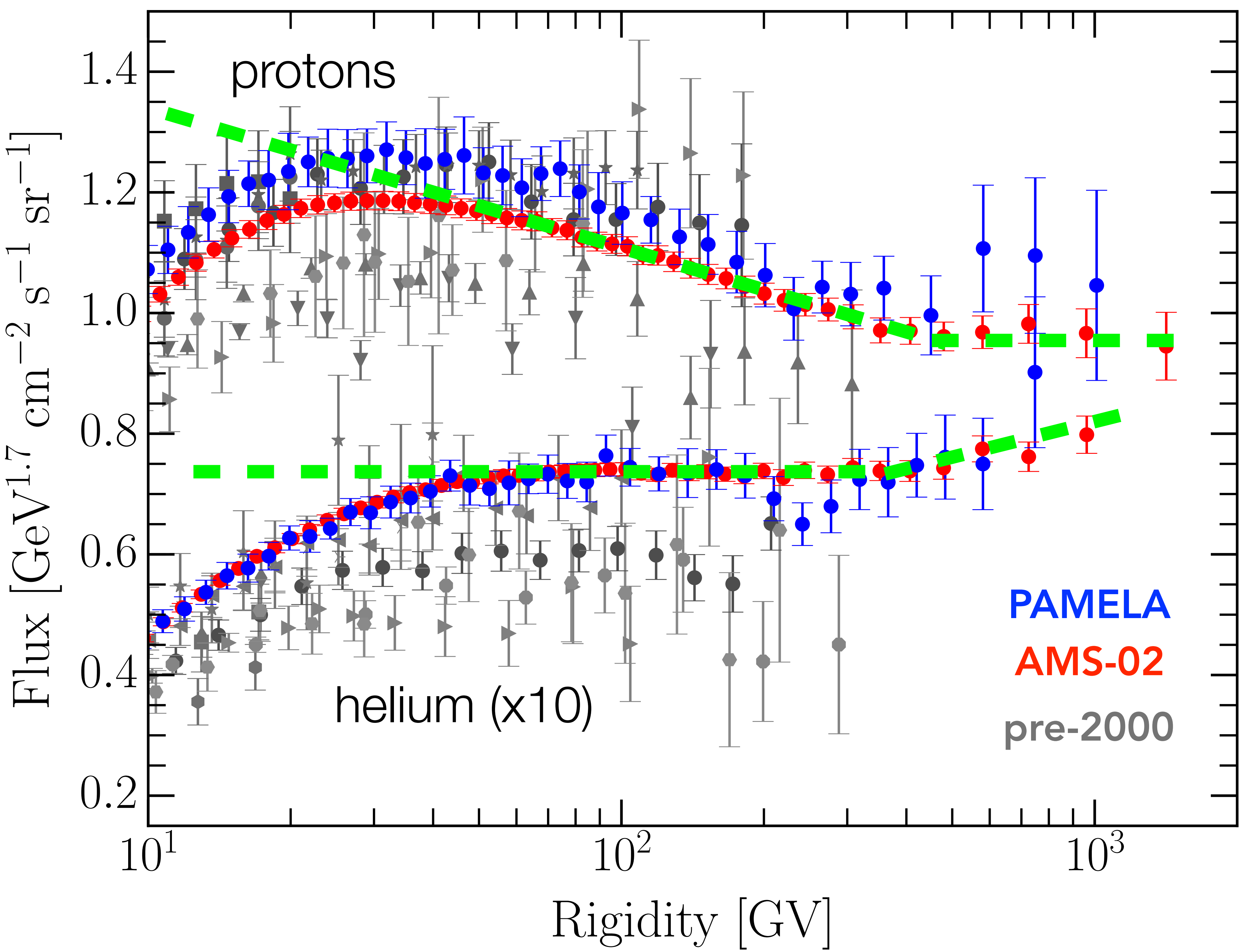


- local source?
- not-linear diffusion?
- two-zone diffusion?

- evolution in the Mach number?
- different acceleration zones?

Today CR measurements reach remarkable precision

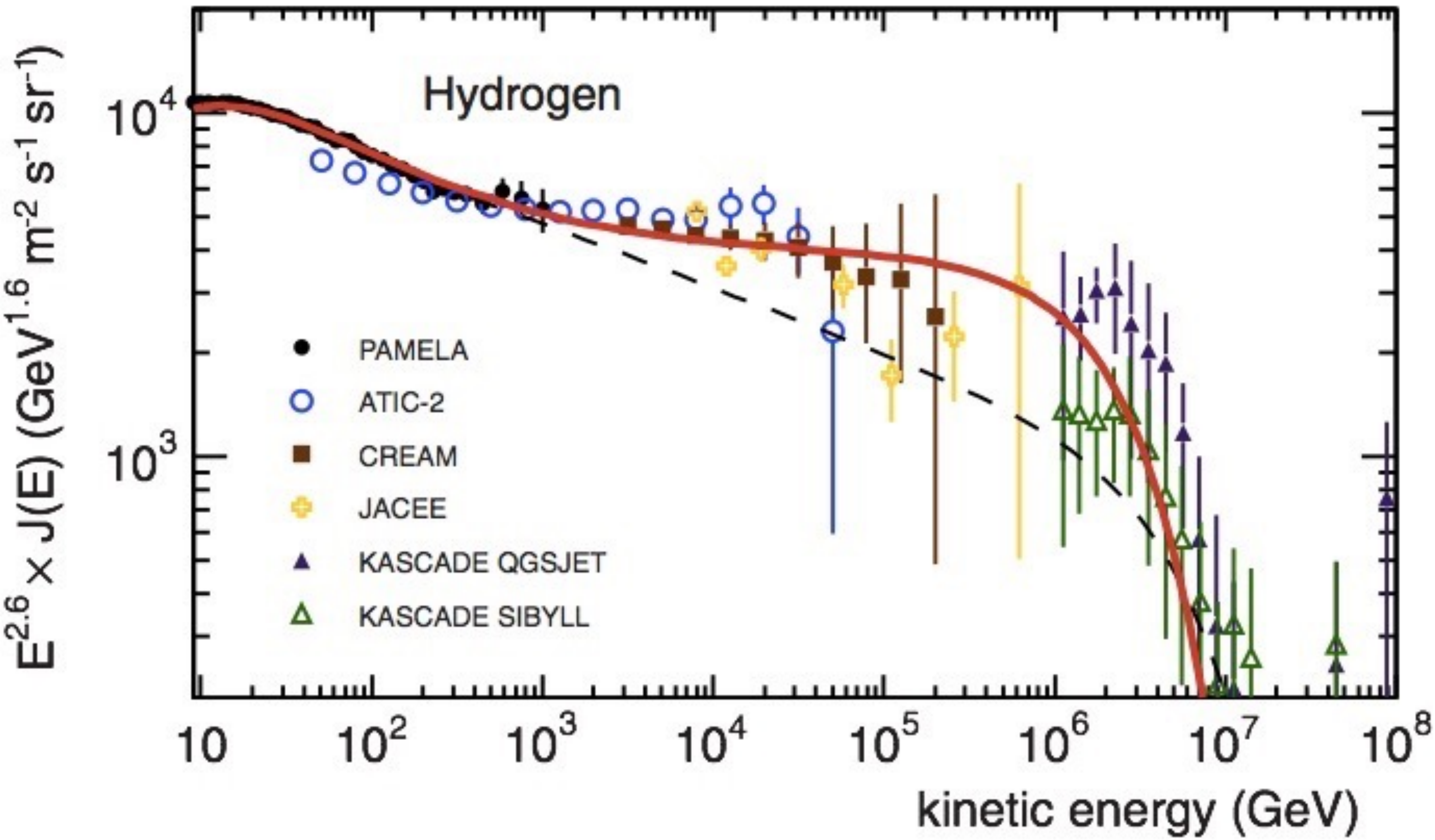
PAMELA Coll., Science, 2011 - AMS02 Coll., PRL, 2016



Diffusion in the halo different than in the disk

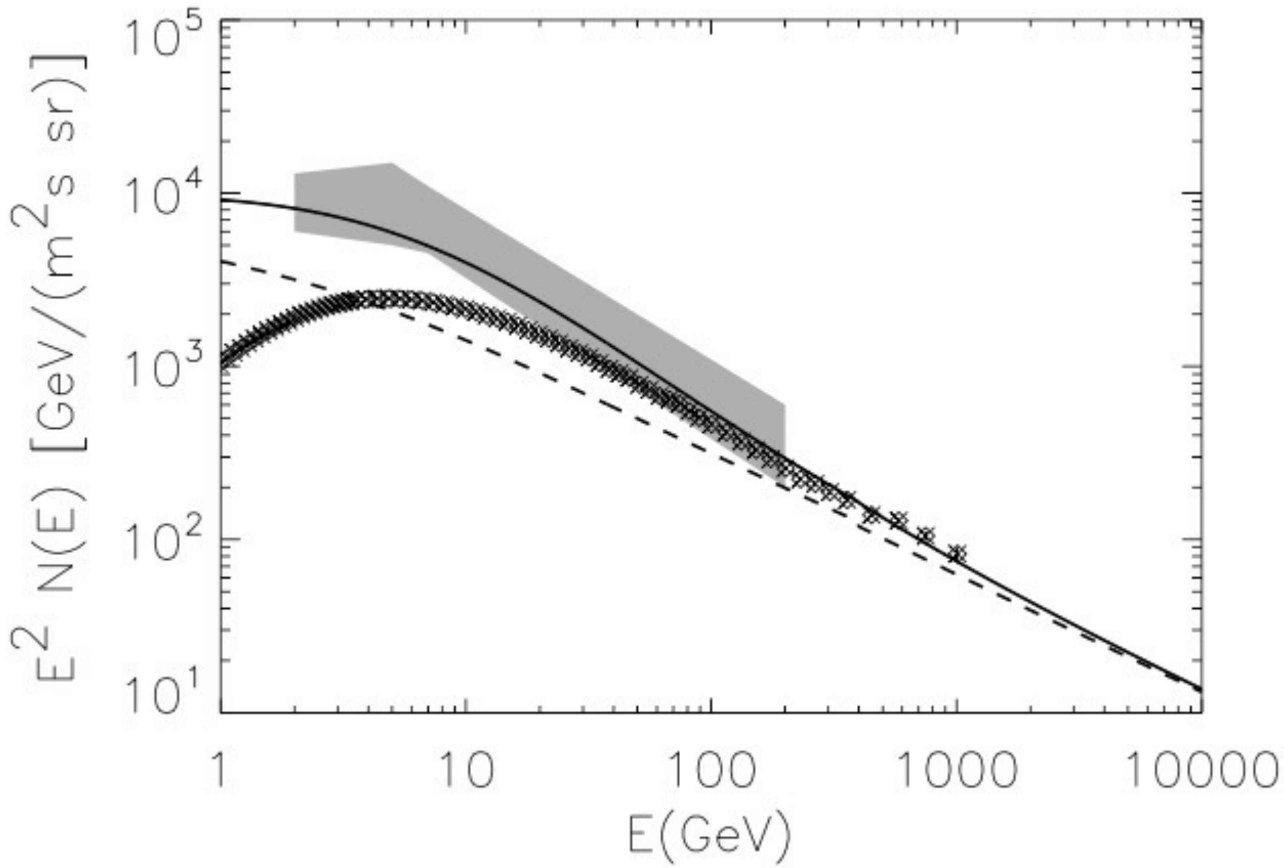
CE & H. Yan, ApJ, 2014

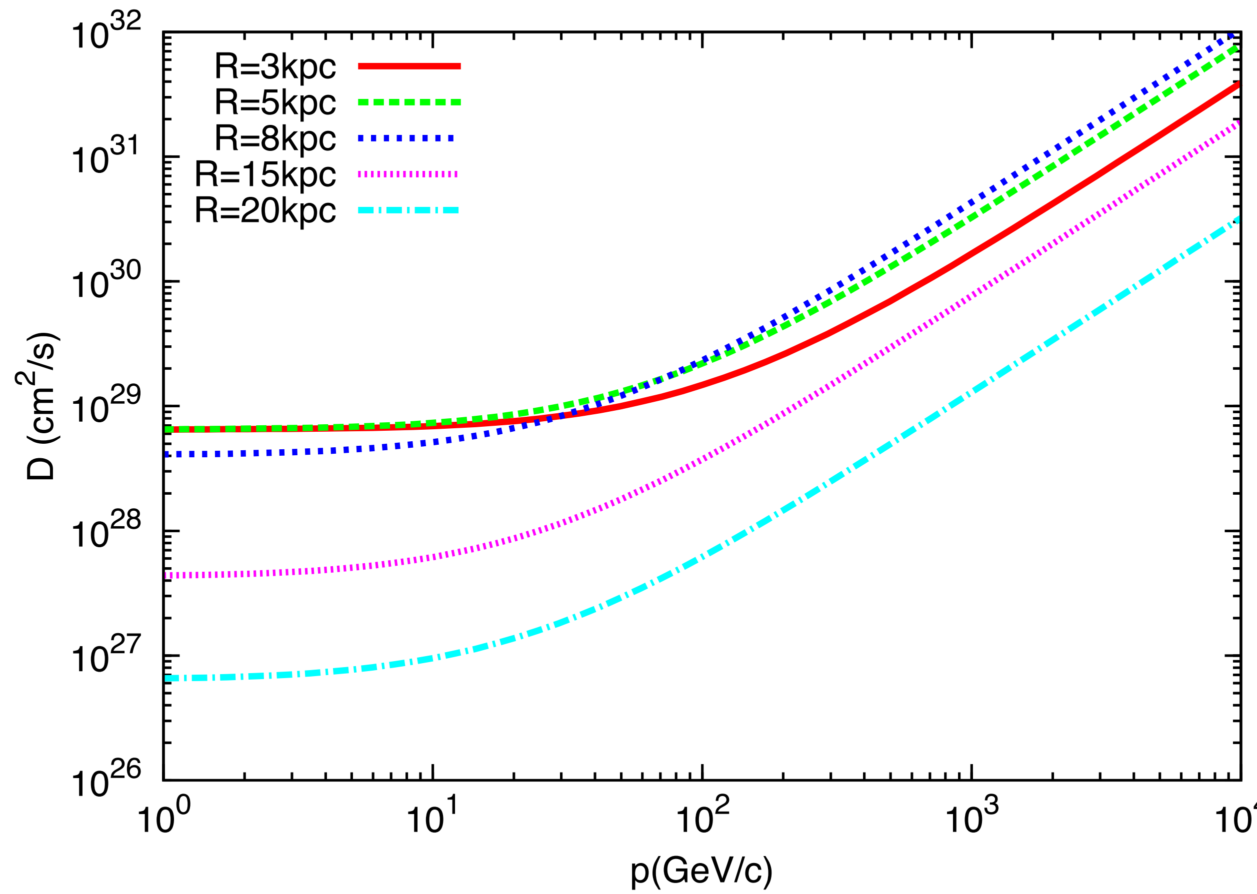
N. Tomassetti, ApJ, 2012



Non-linear CR propagation

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

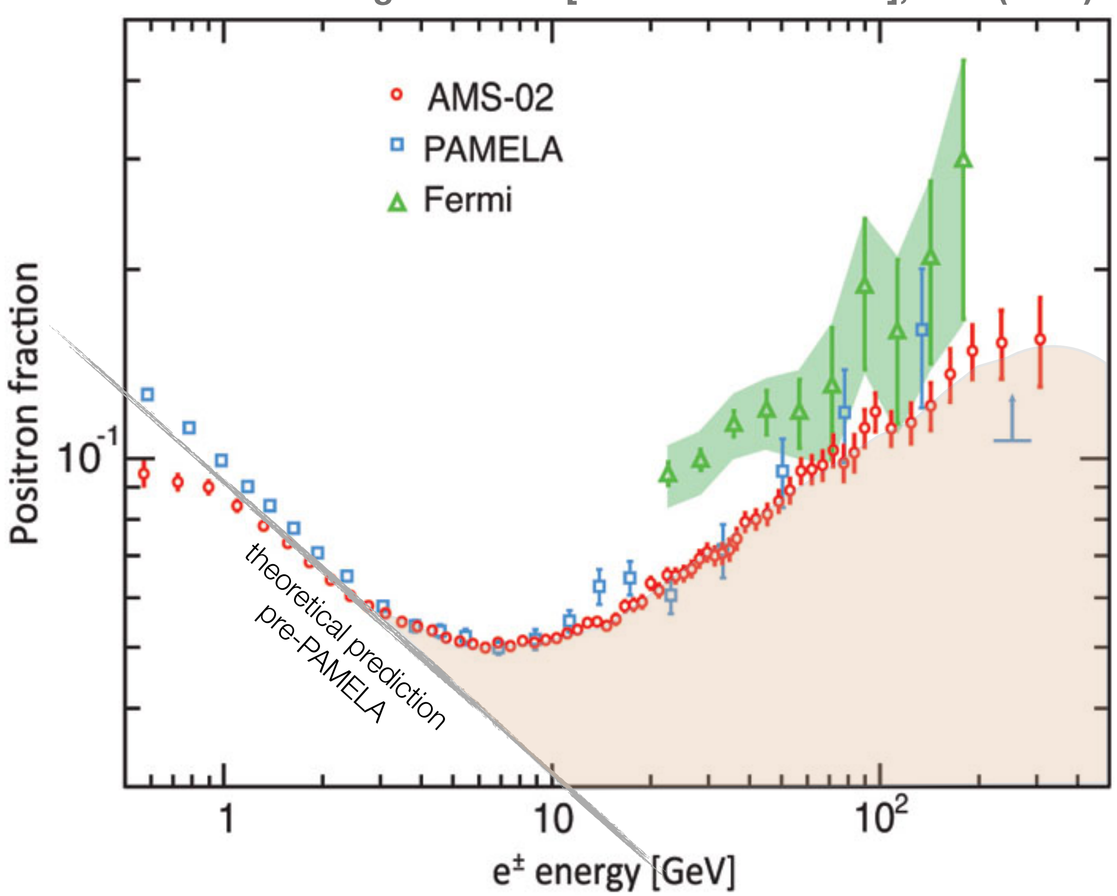




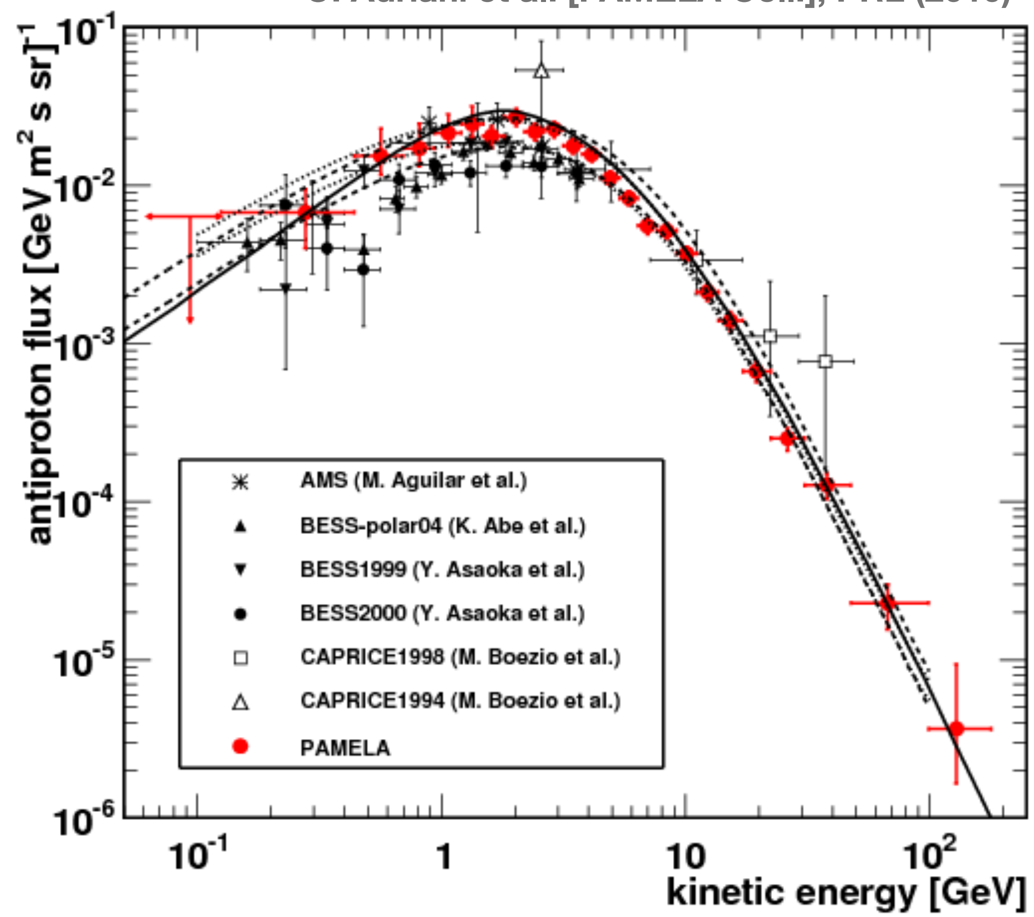
"we showed that both the gradient and the spectral shape can be explained in a simple model of non-linear CR transport: CRs excite waves through streaming instability in the ionized Galactic halo and are advected with such Alfvén waves. In this model, *the diffusion coefficient is smaller where the source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

is there any anti-matter excess?

M. Aguilar et al. [AMS Collaboration], PRL (2013)



O. Adriani et al. [PAMELA Coll.], PRL (2010)

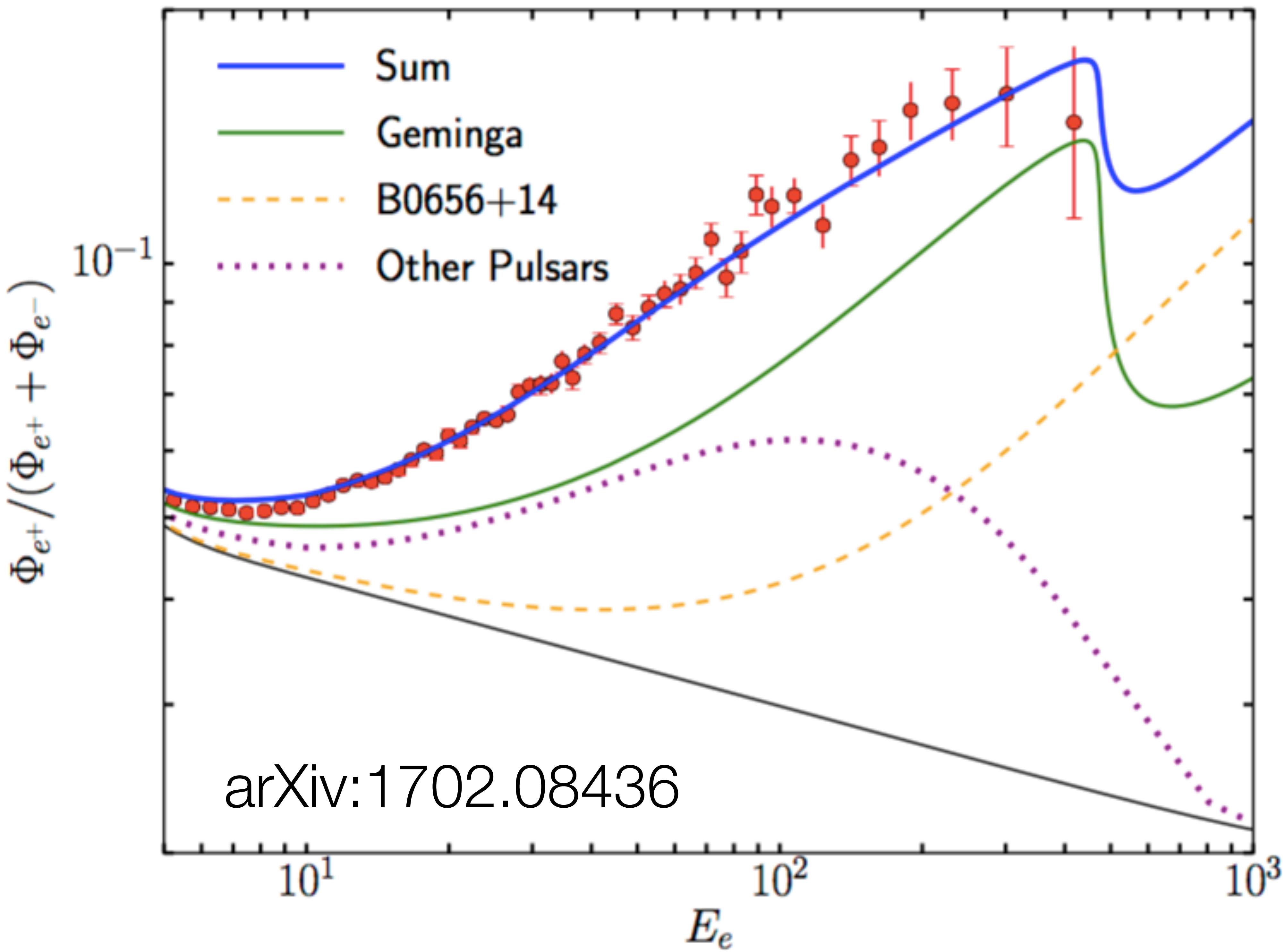


- secondary production in the sources?
- pulsars?
- dark matter?

- a powerful probe of secondary production in the ISM
- strong bound for annihilating dark matter

is there any anti-matter excess?

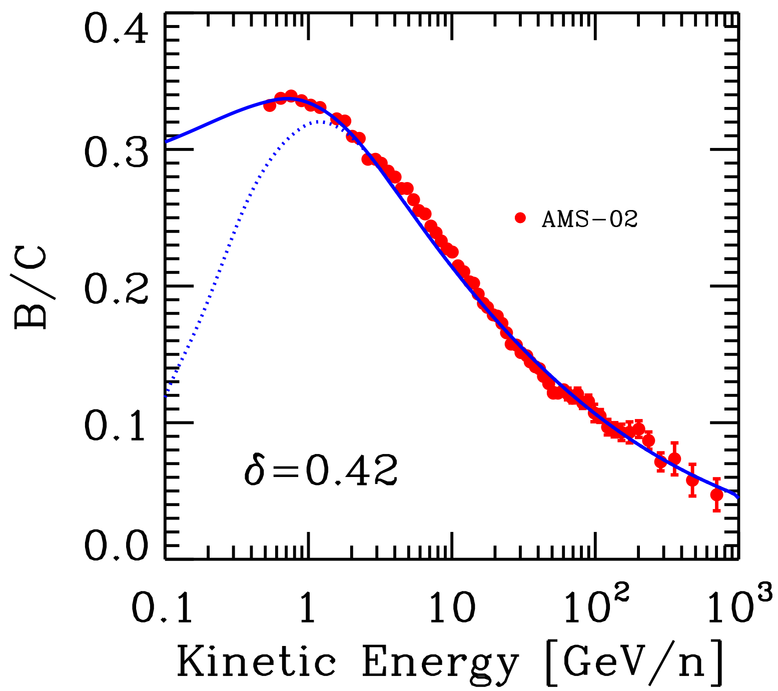
Di Bernardo, CE, et al., APh, 2011 - Di Mauro, et al., JCAP, 2016

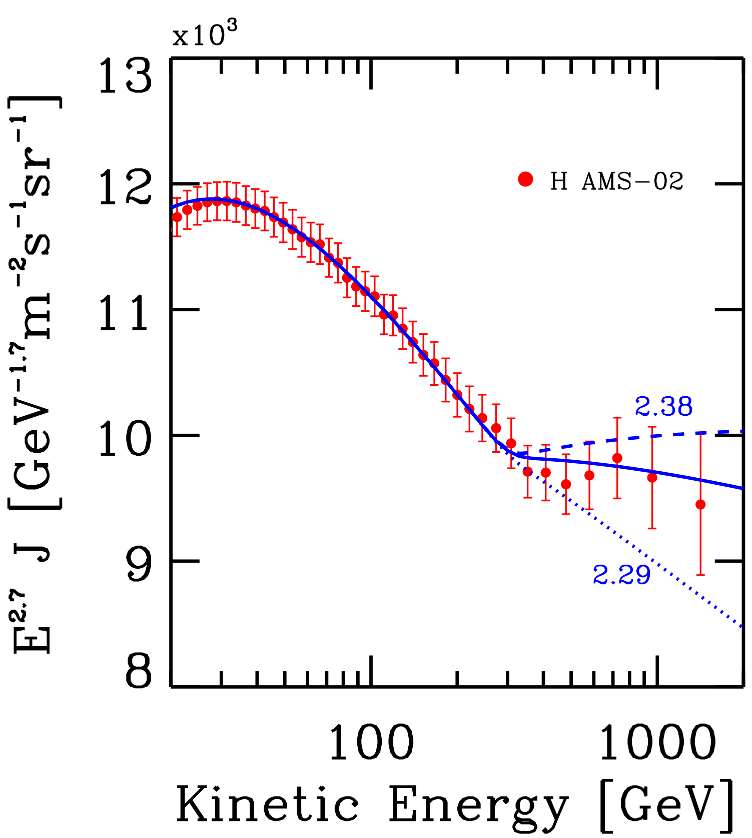


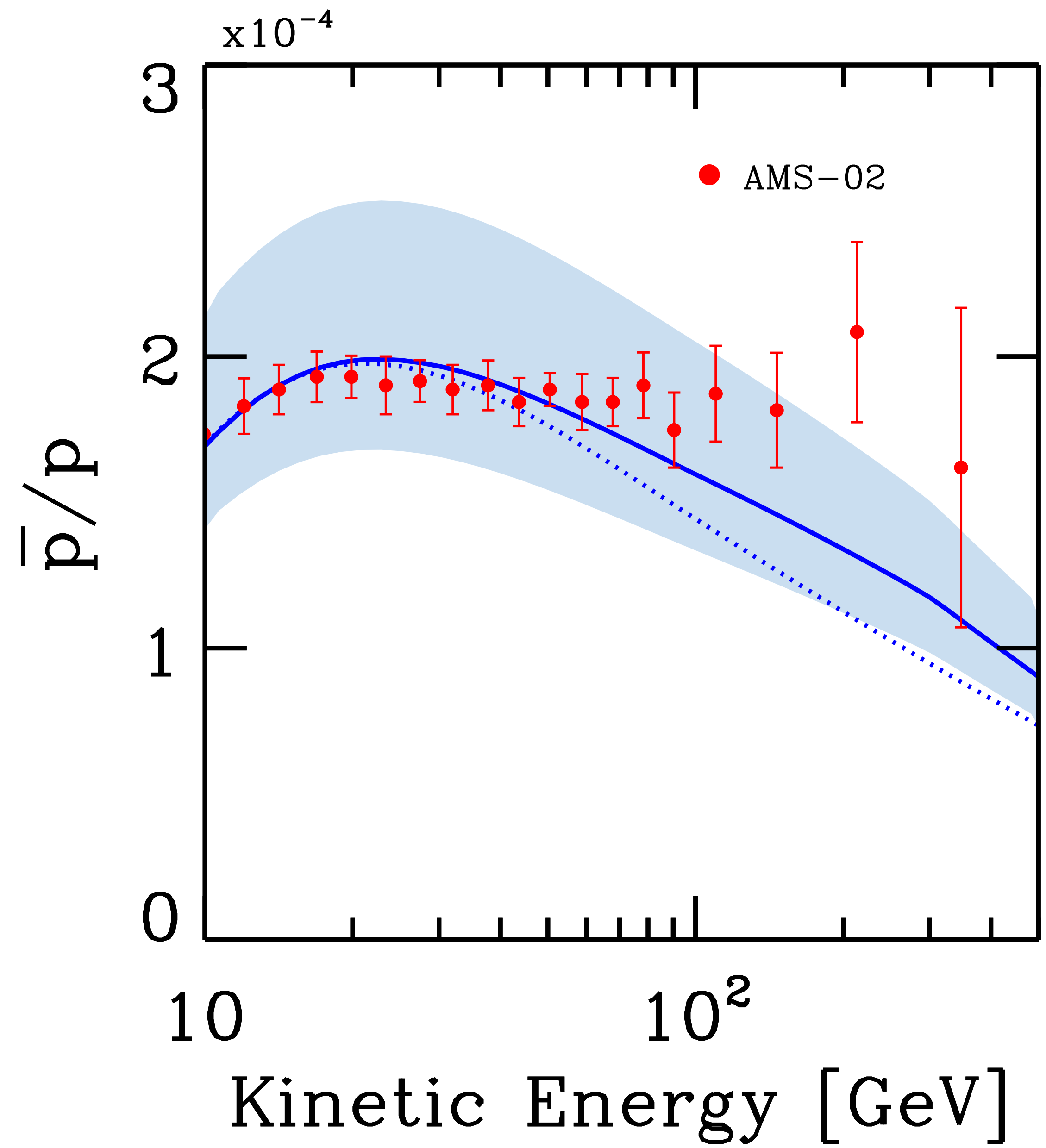
is there any anti-matter excess?

CE, D.Gaggero & D.Grasso, 1504.05175

see also Giesen *et al.*, 1504.04276
Kappl, Reinert and Winkler, 1506.04145



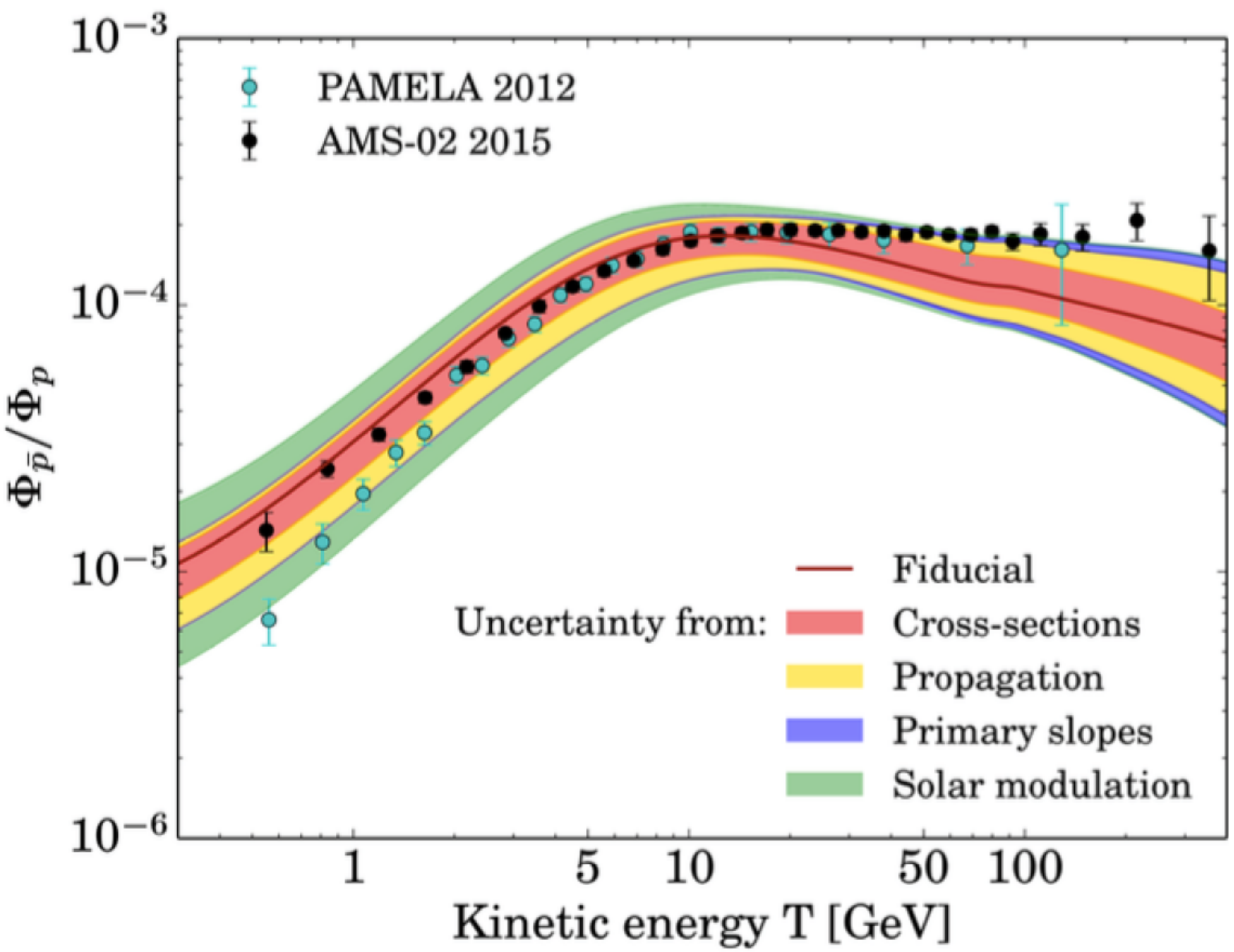


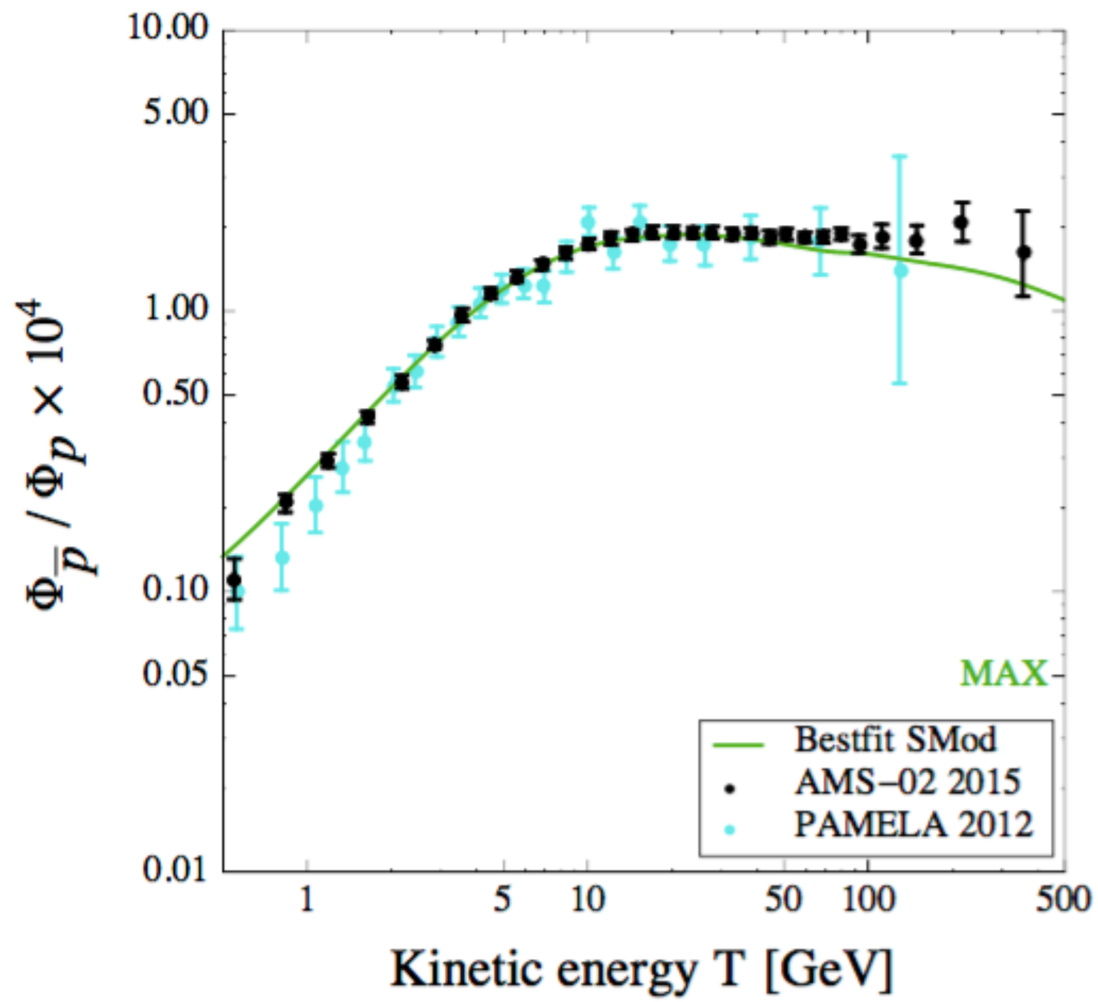


production
cross-sections

is there any anti-matter excess?

Giesen *et al.*, 1504.04276

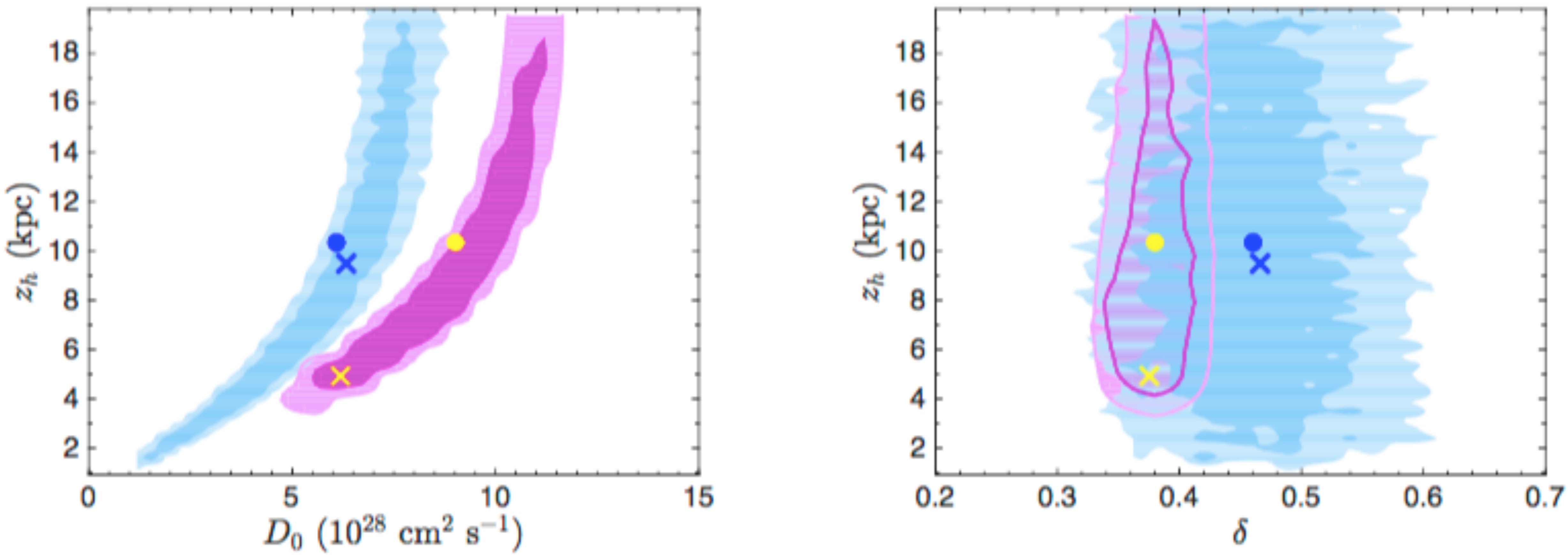




No model selection based on B/C

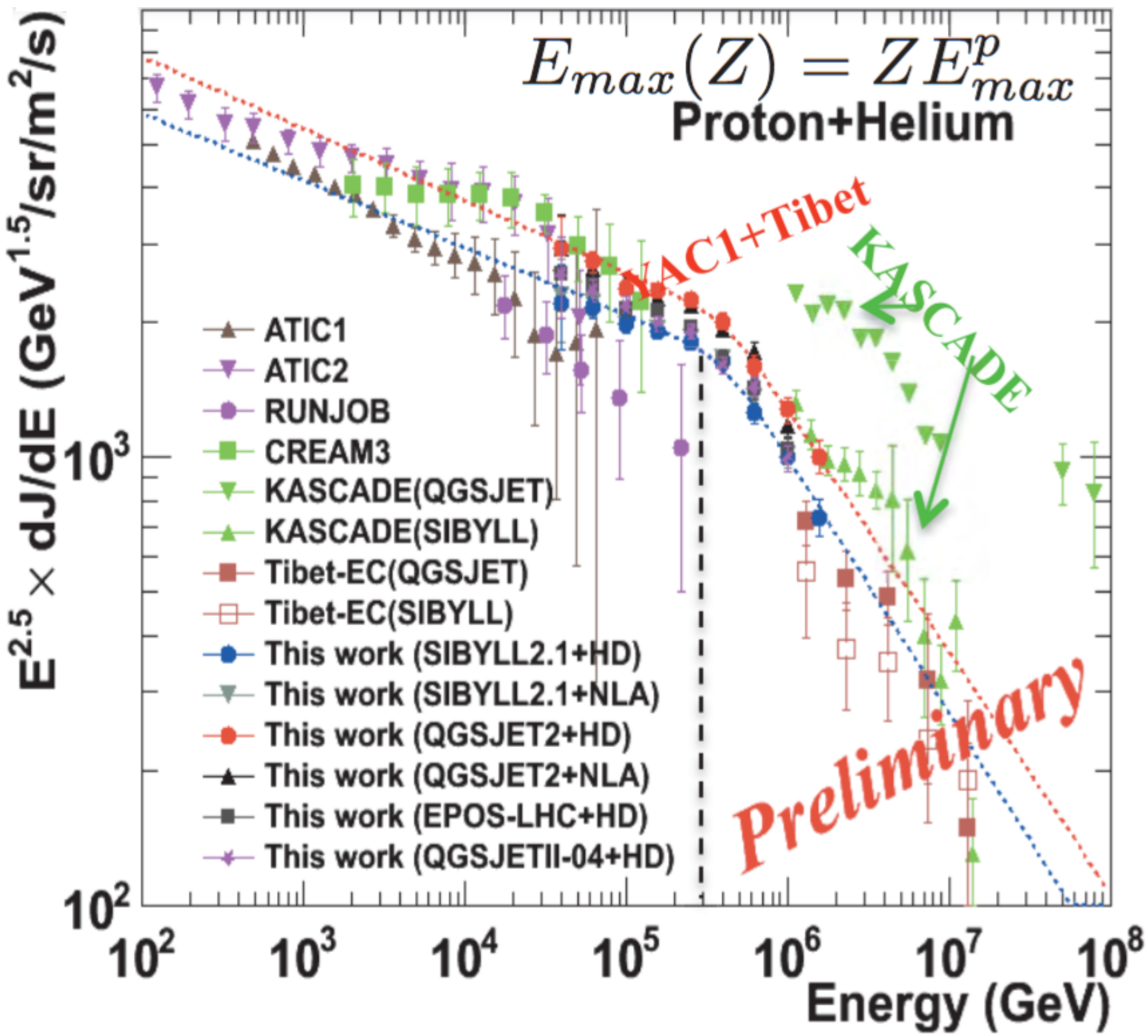
is there any anti-matter excess?

Johannesson et al.,1602.02243



Two-dimensional posterior distributions, showing 1 and 2-sigma credible intervals for the p, ap and He scan (blue), and for the light elements (magenta).

what is the maximum galactic CR energy?

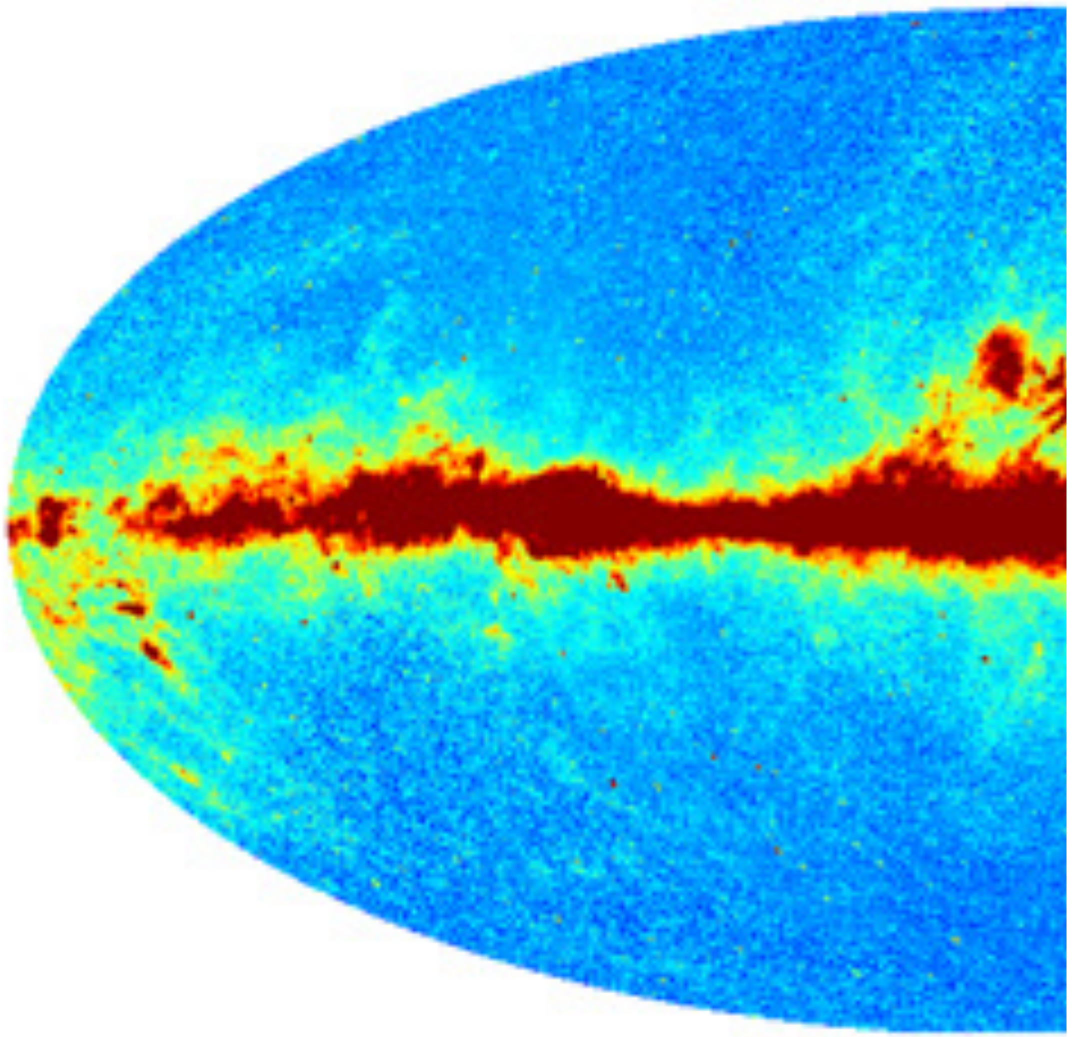


the end of the galactic spectrum as a superposition of cutoffs?

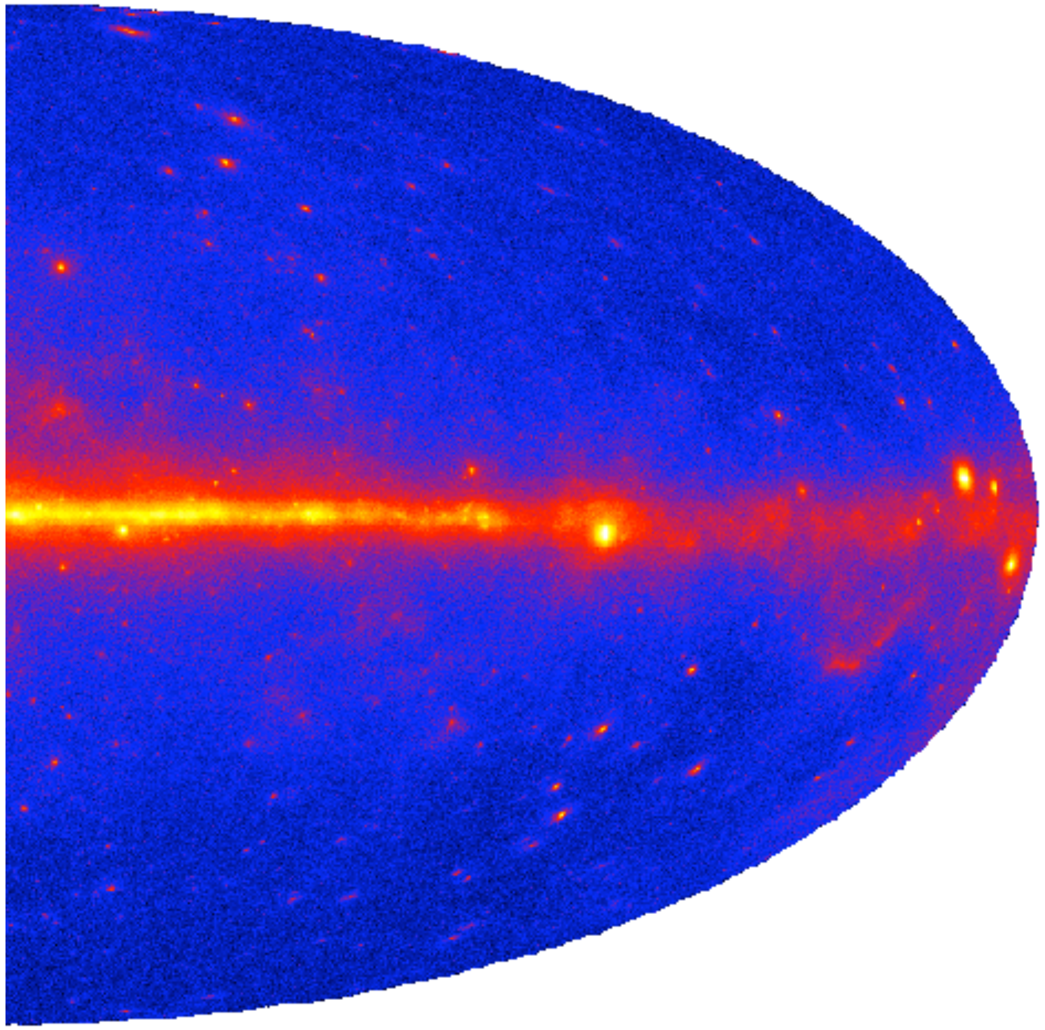

You are here

Diffuse emissions: from radio to gamma maps

PLANCK all-sky foreground map



Two year all sky Fermi-LAT map



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

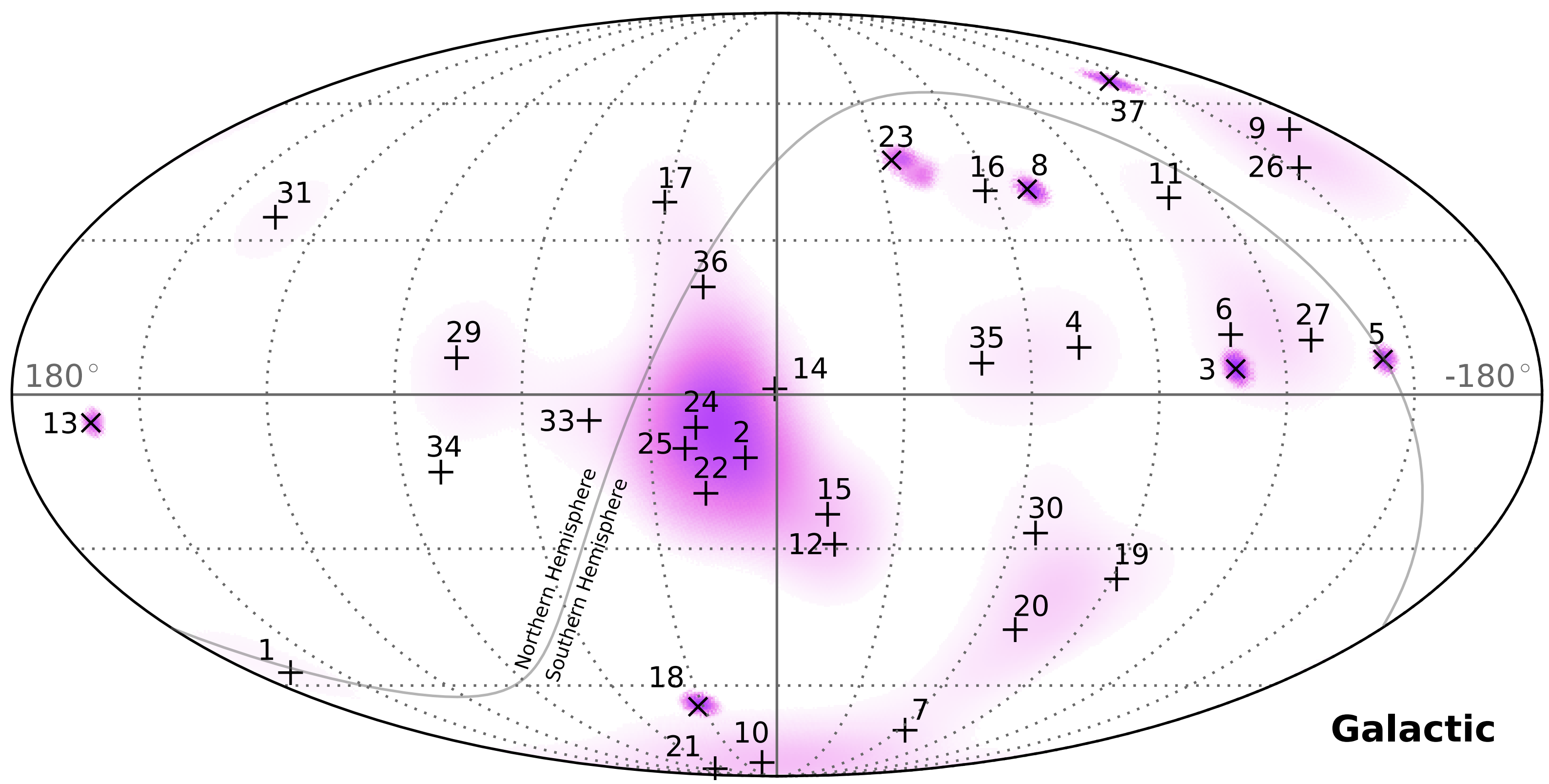
$$p\,p_{\rm ISM} \to \pi^0 \to \gamma\gamma$$

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

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

Diffuse emissions: from radio to gamma maps

Ice-Cube 3yrs



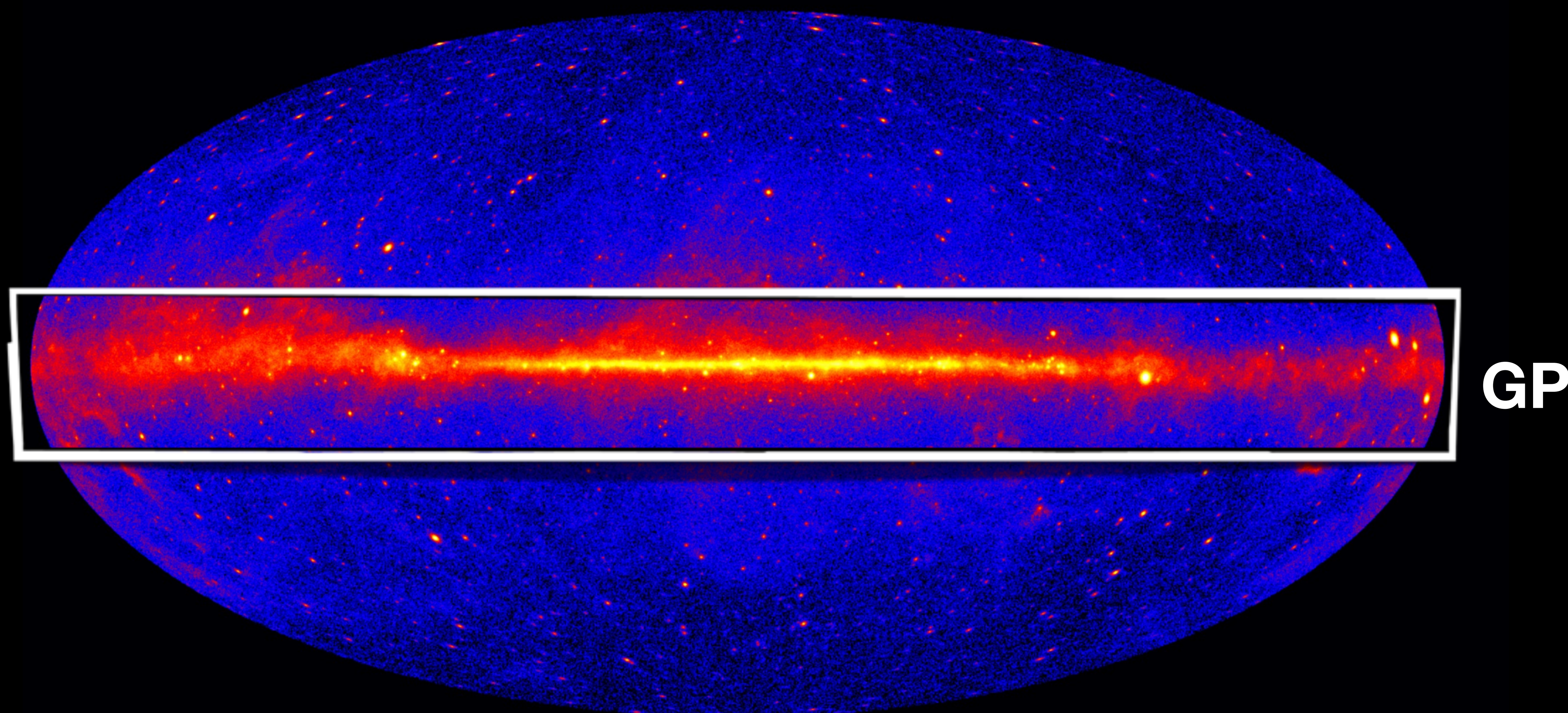
?

$$N + p_{\rm ISM} \to \pi^{\pm} + X$$

$$\hookrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

$$\hookrightarrow {\rm e}^{\pm} + \overset{(-)}{\nu}_{\mu} + \overset{(-)}{\nu}_{\rm e}$$

The gamma-ray sky in 2016

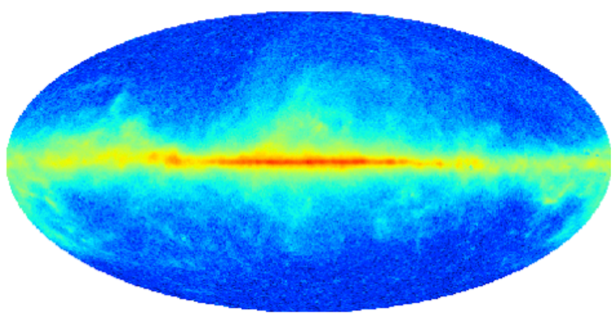


Fermi-LAT E>100 MeV by 3FGL
[LAT collaboration 2015]

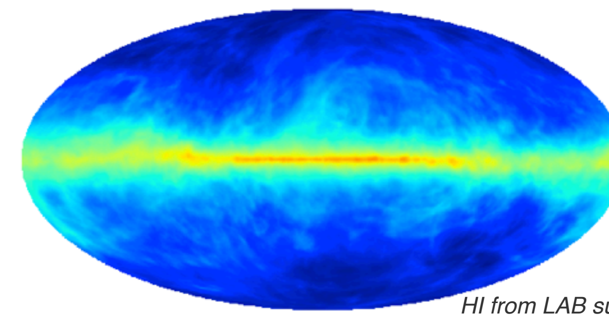
~ 70% of all observed photons coming from the diffuse Galactic emission

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

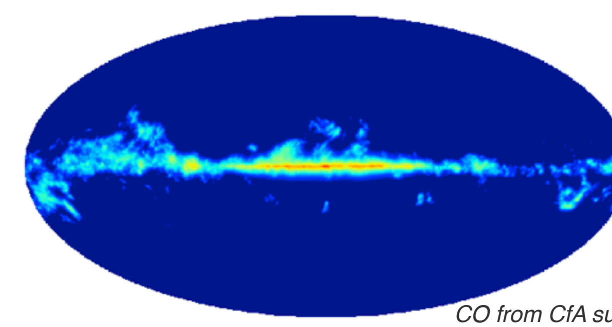


$$= \int_{\mathrm{los}} dl \; n_p(r) \times$$



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

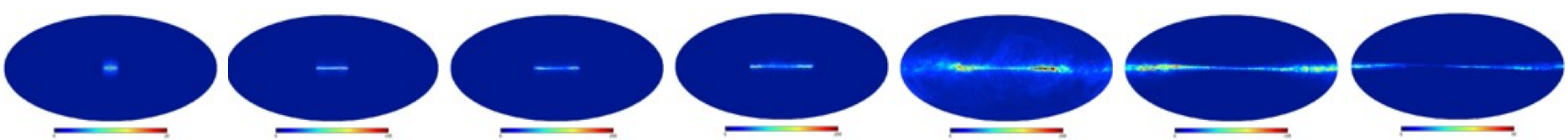
Template analysis for the GDE

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

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

from a propagation one-zone model

free parameters



Galactocentric HI rings

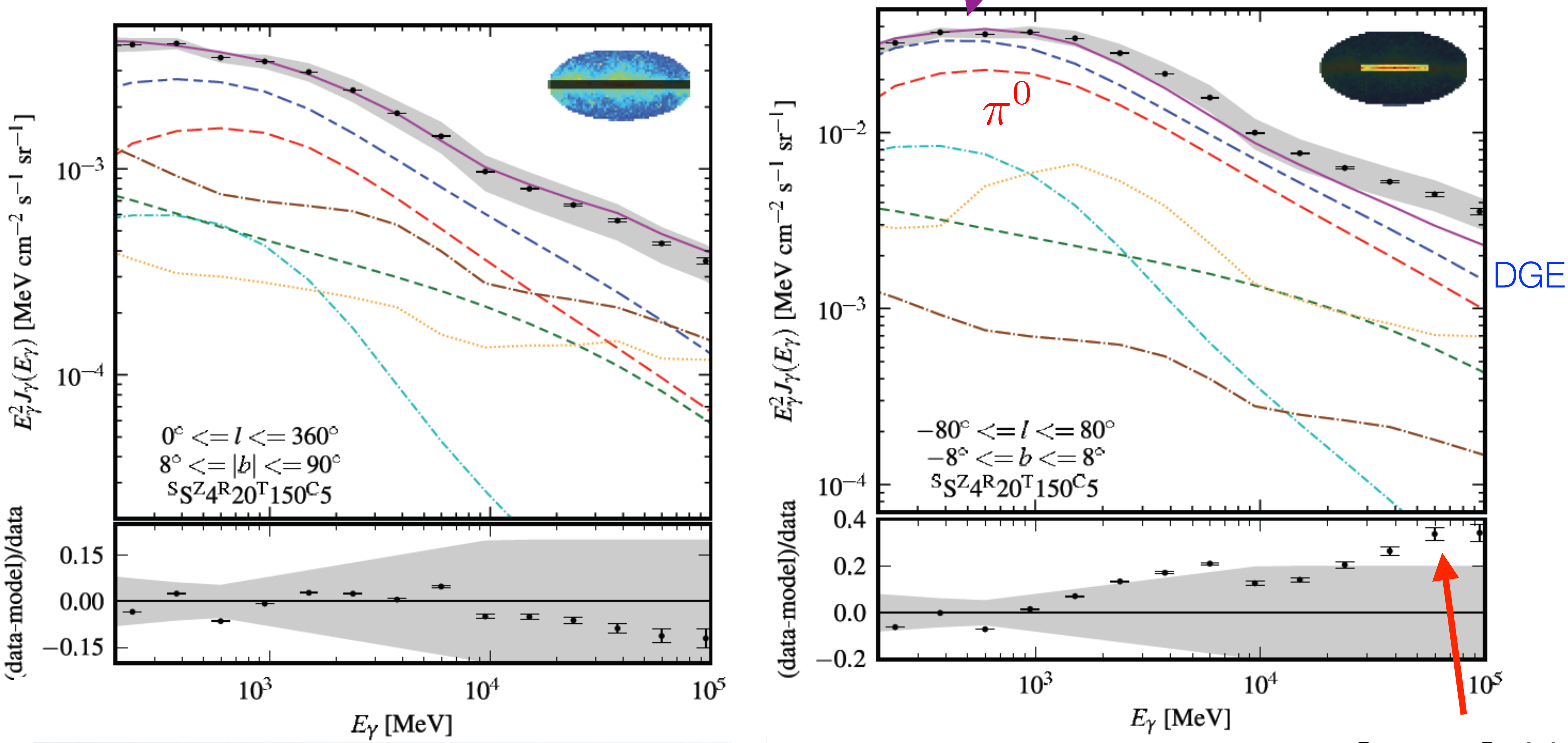
Ackermann et al., ApJ, 750 (2012)

FERMI galactic diffuse emission

FERMI reference model for the galactic emission

full sky, without the GP

inner GP

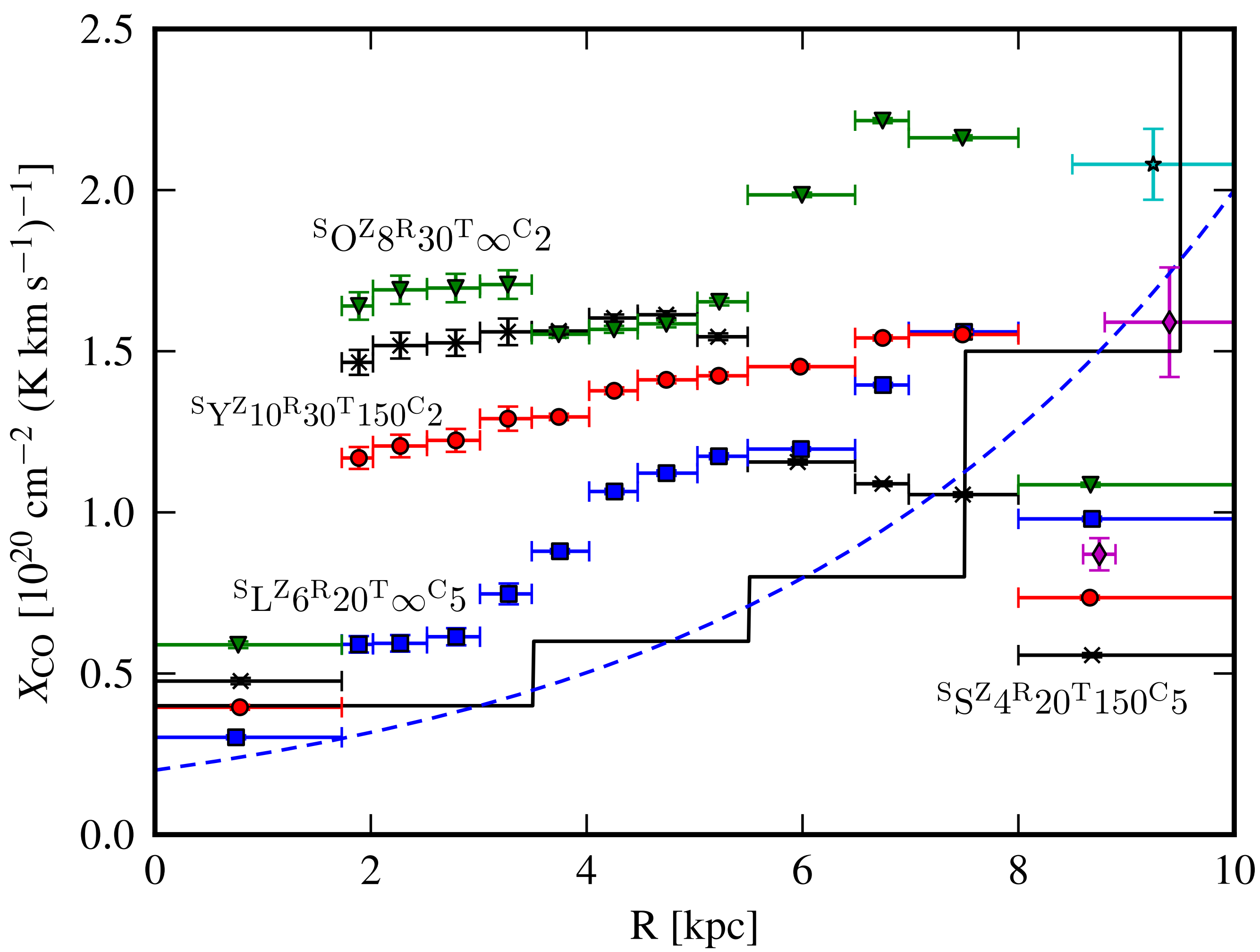


@100 GeV

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"!

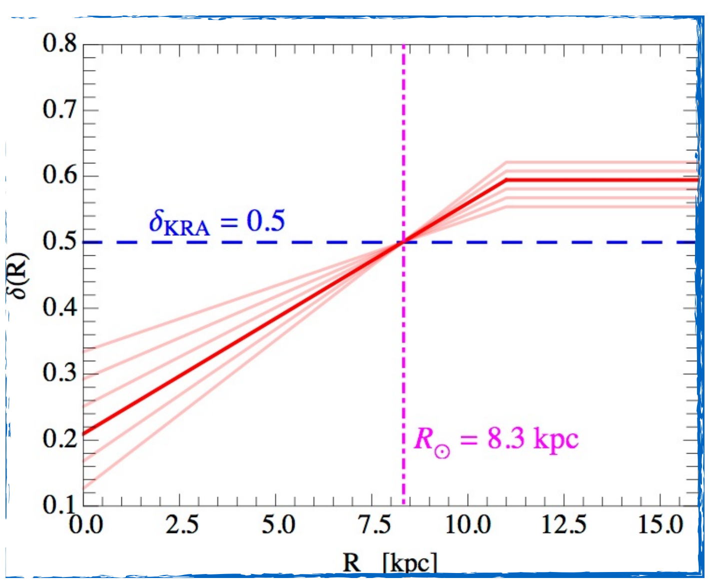
A new view on diffuse galactic modelling

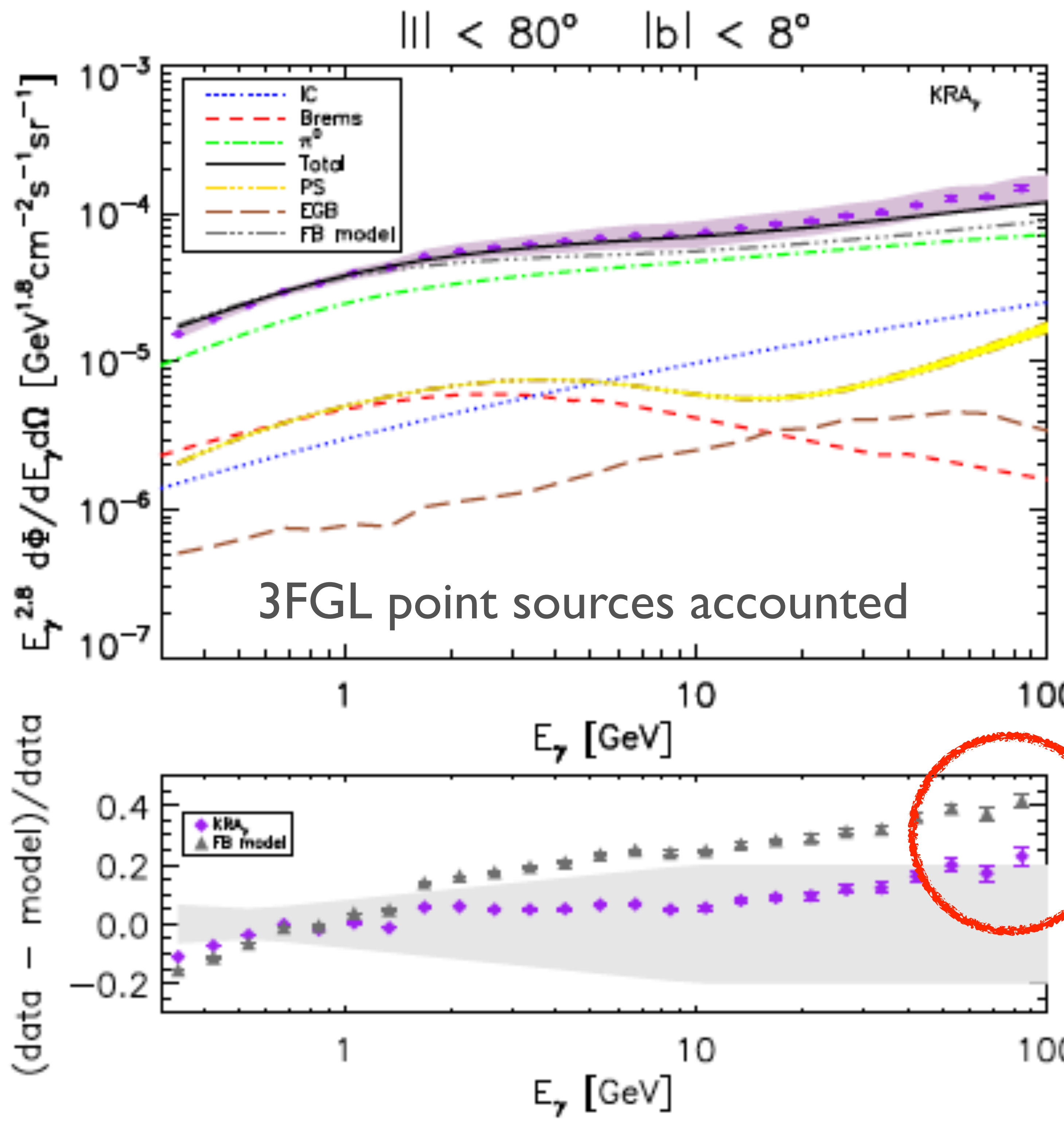
D. Gaggero et al., PRD, 91 (2015)

how to change my propagation model to reproduce γ data?

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

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





Model *independent* template analysis

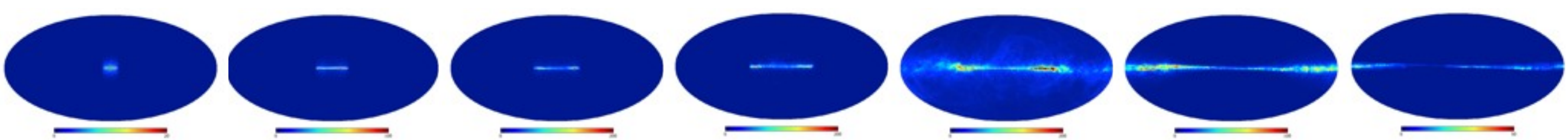
Fermi Collaboration, ApJ, 2011

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

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

free parameters

free parameters

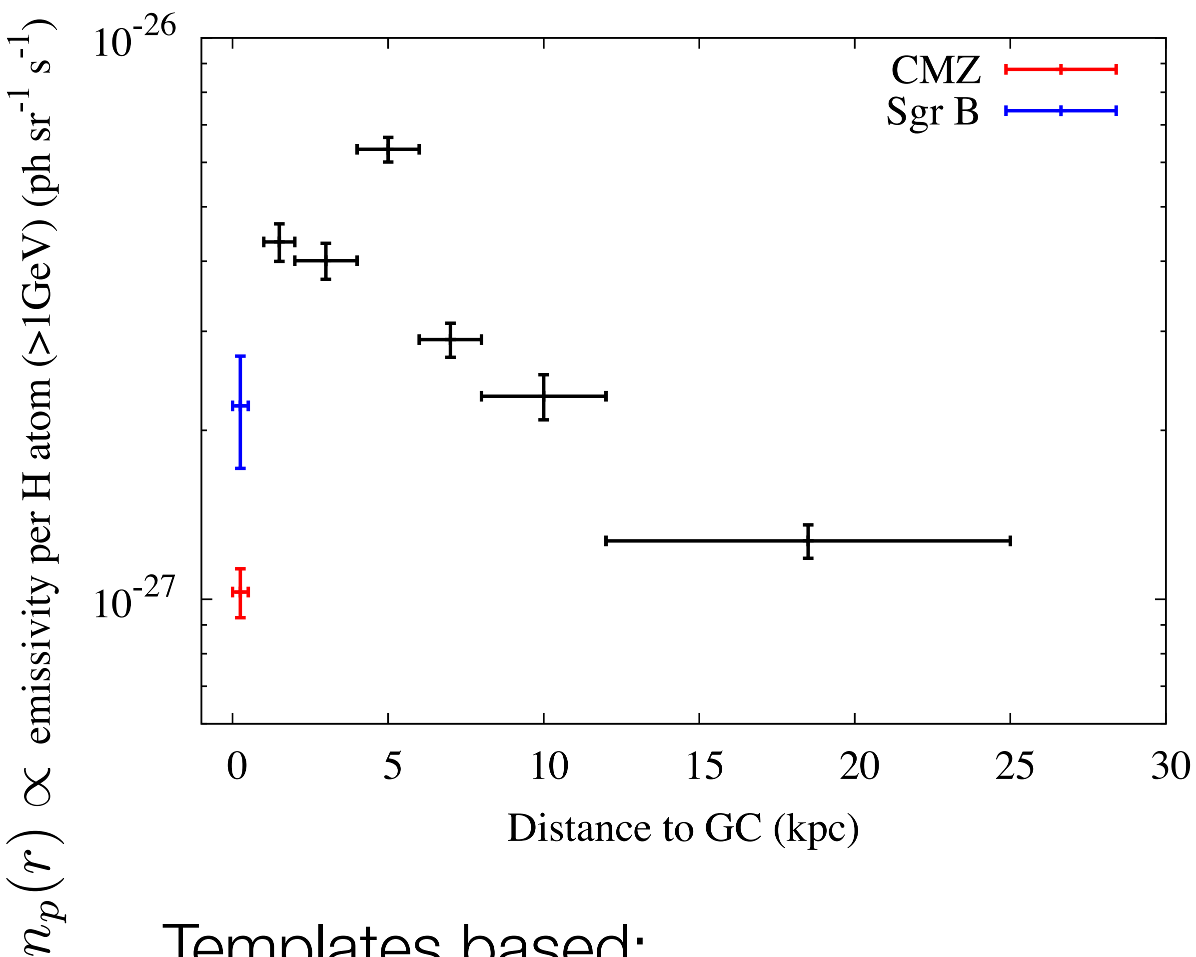


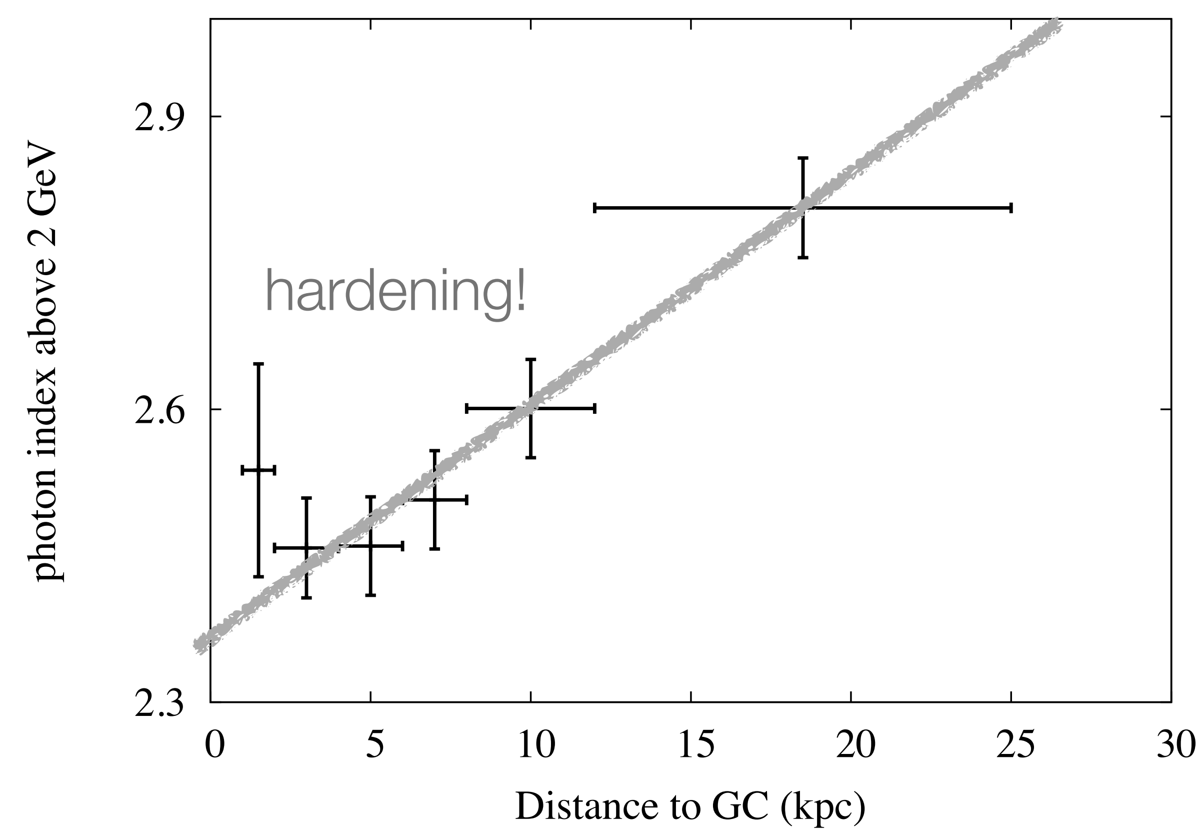
Galactocentric HI rings

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

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

$|b| < 5^\circ$





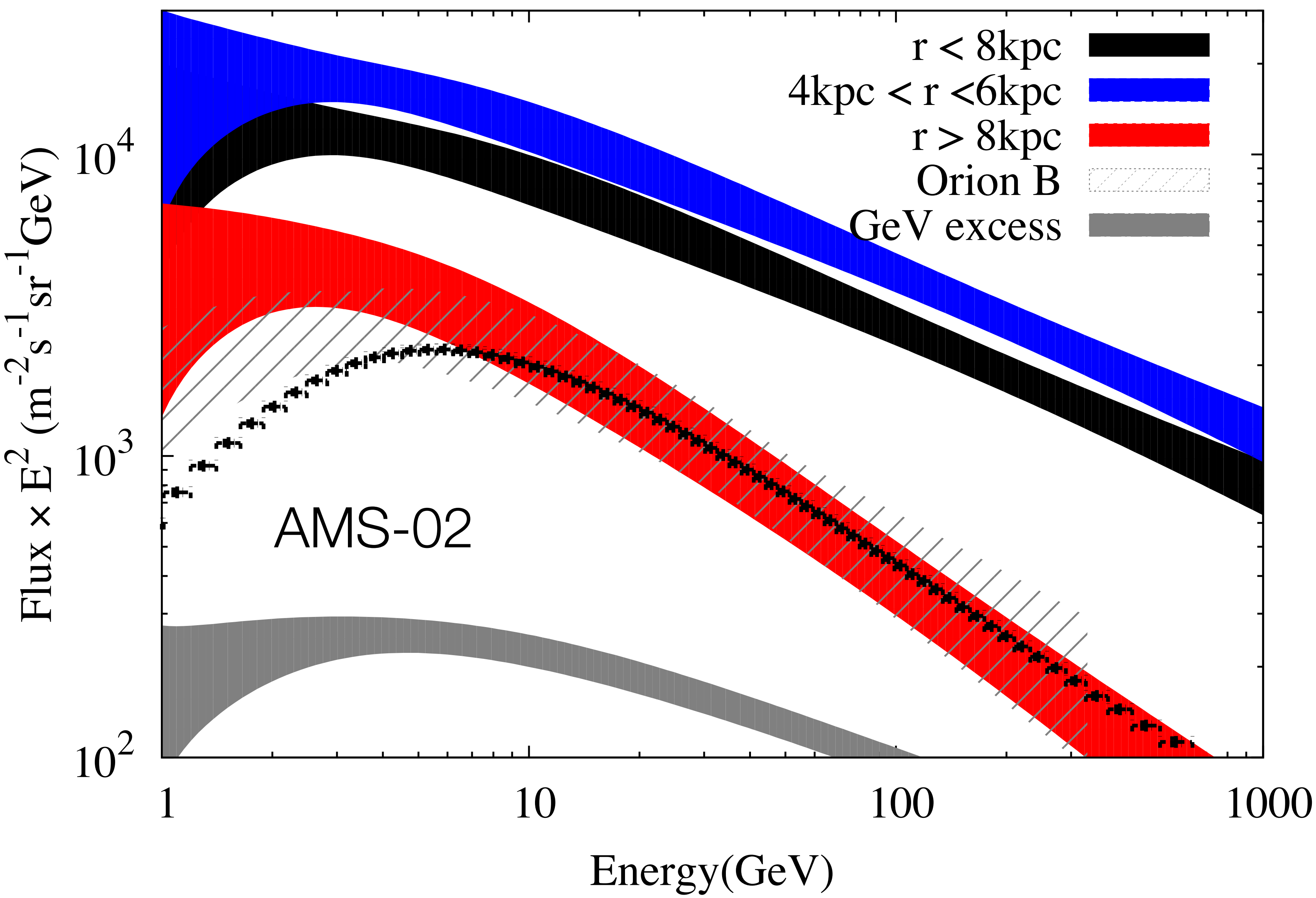
Templates based:

- 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

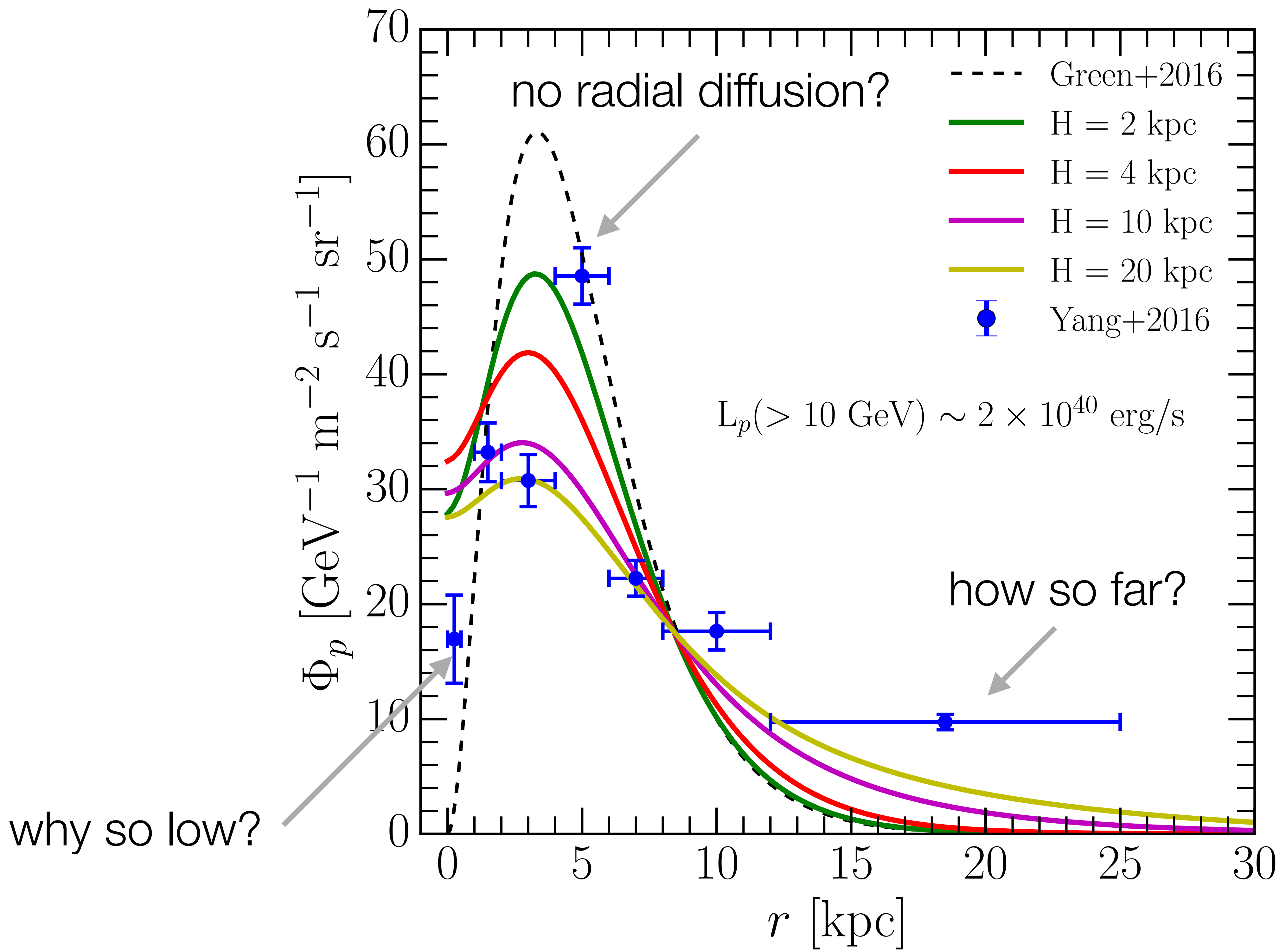
R. Yang, F. Aharonian, **CE**, PRD, 2016



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.

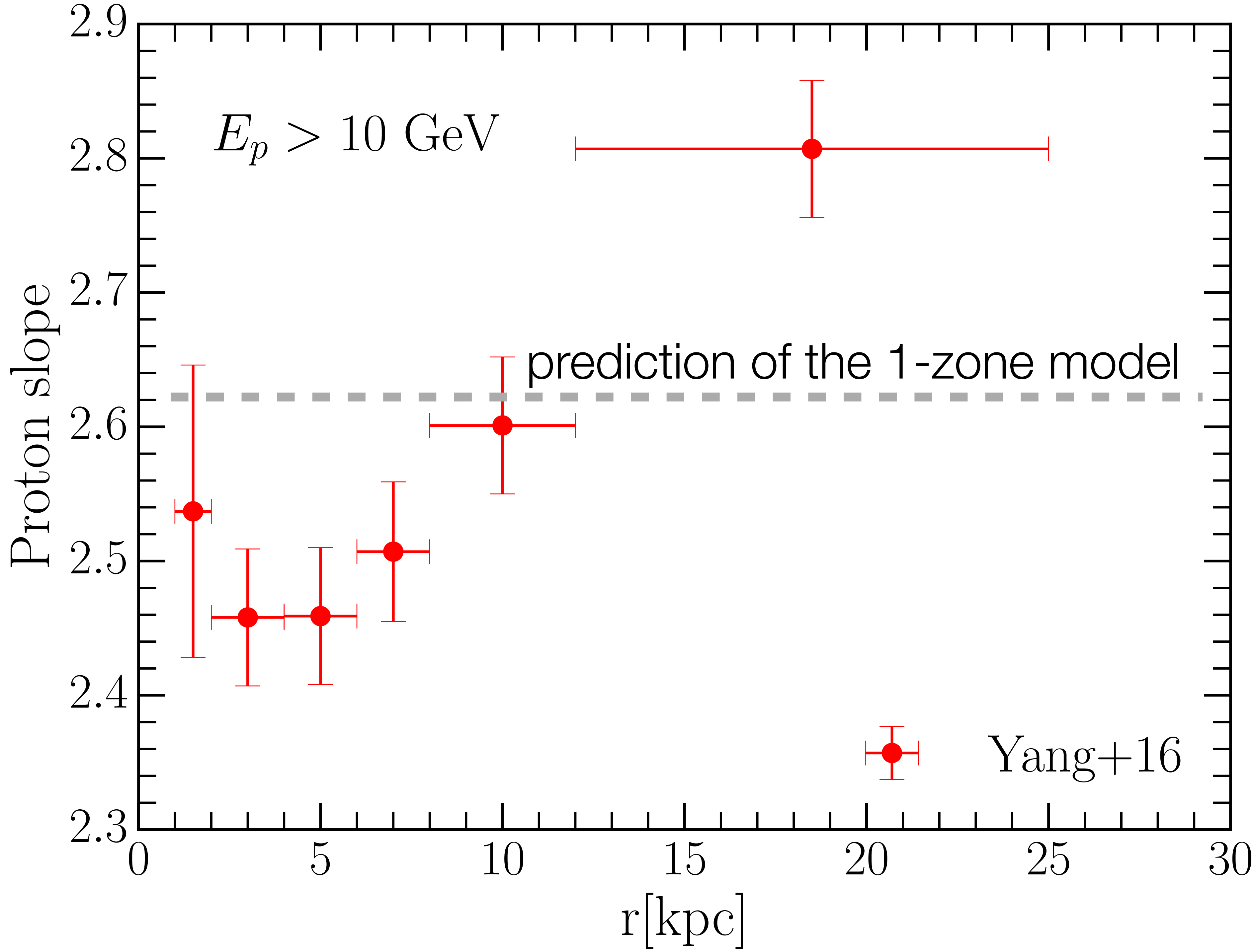
Comparison with one-zone model predictions

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



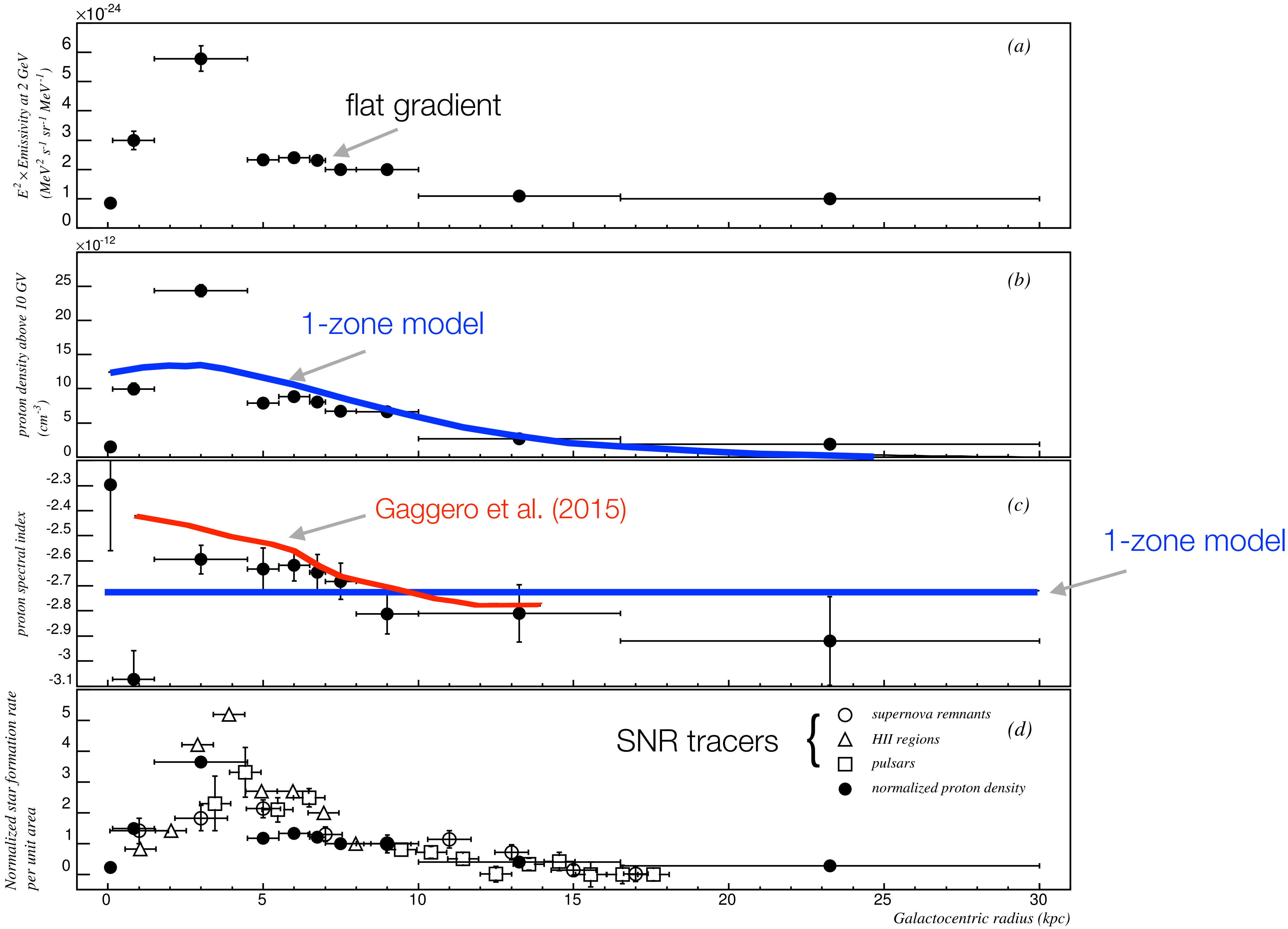
Comparison with one-zone model predictions

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



FERMI galactic interstellar emission model (GEIM)

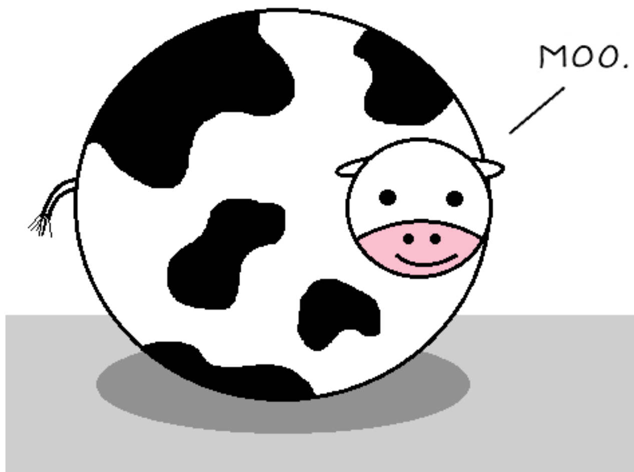
FERMI Collaboration, arXiv:1602.07246

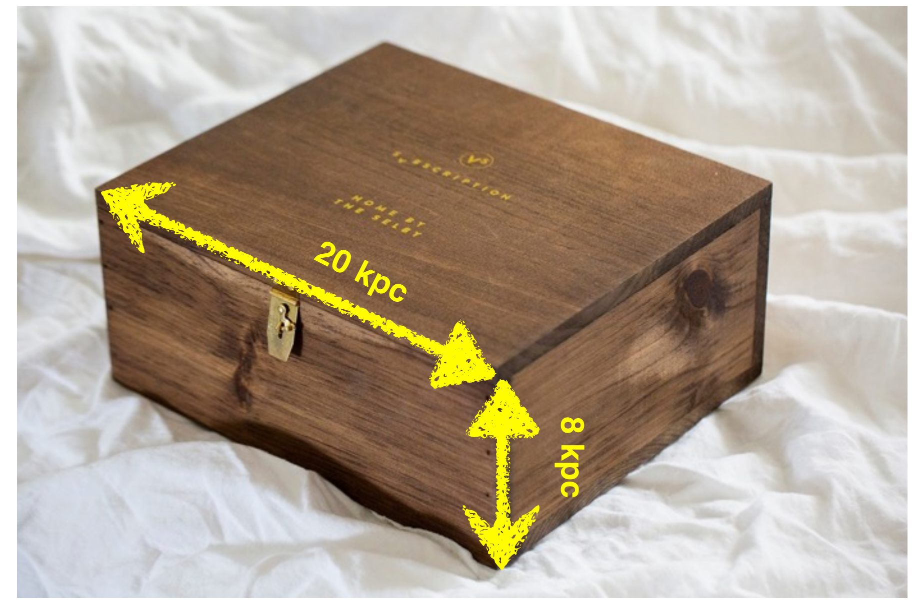


understanding galactic propagation

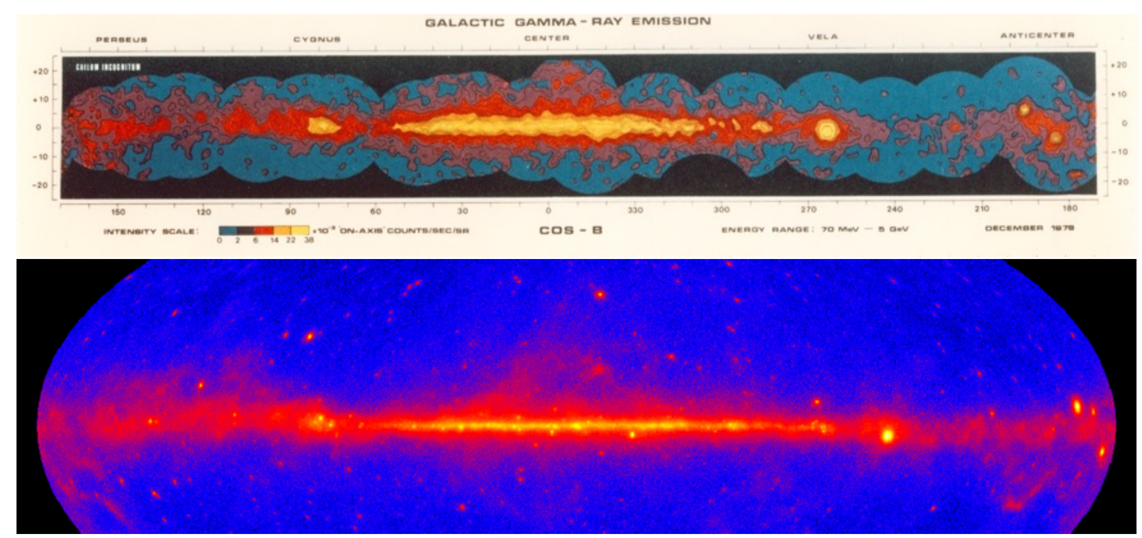
anomalies with respect to what?

Models:





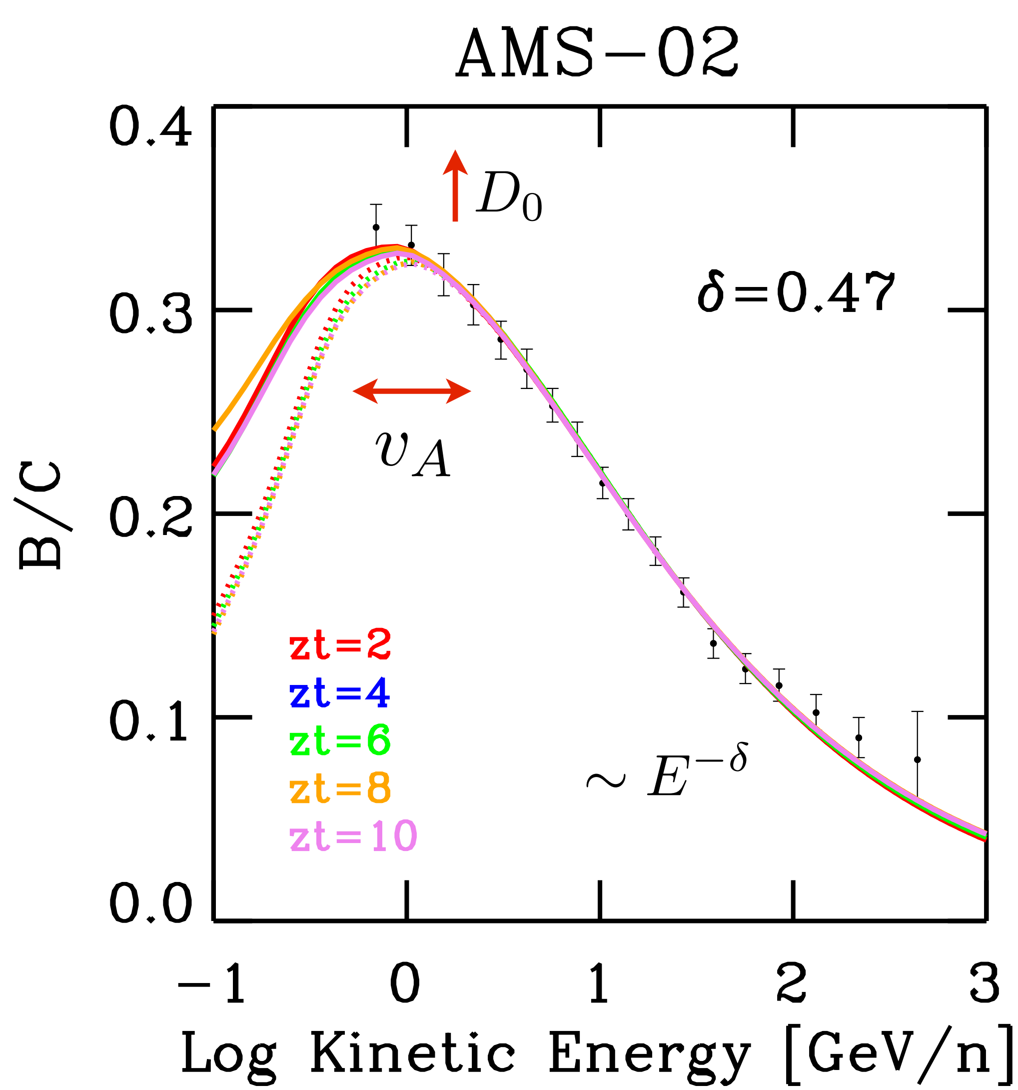
Data:

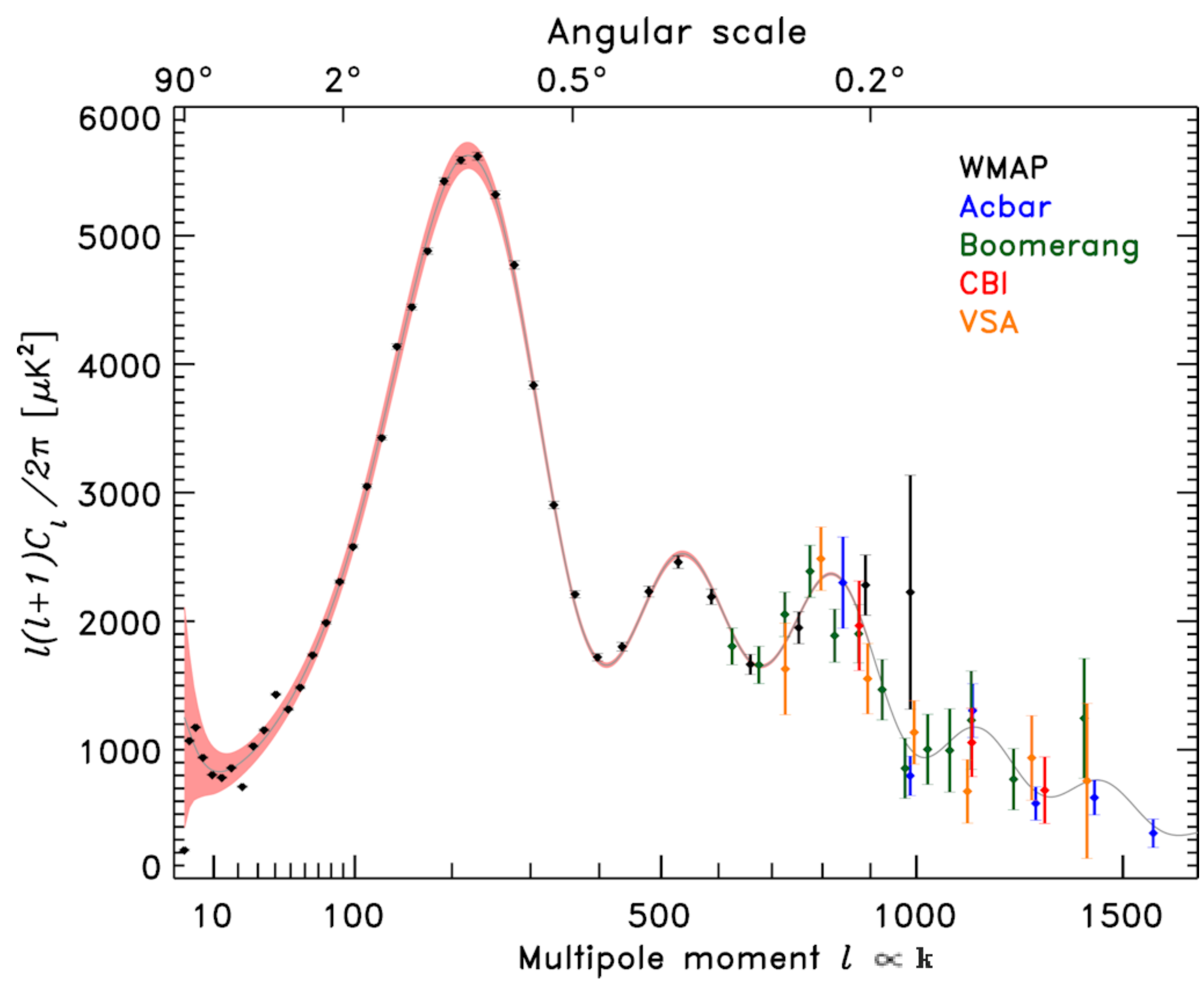


1978

today

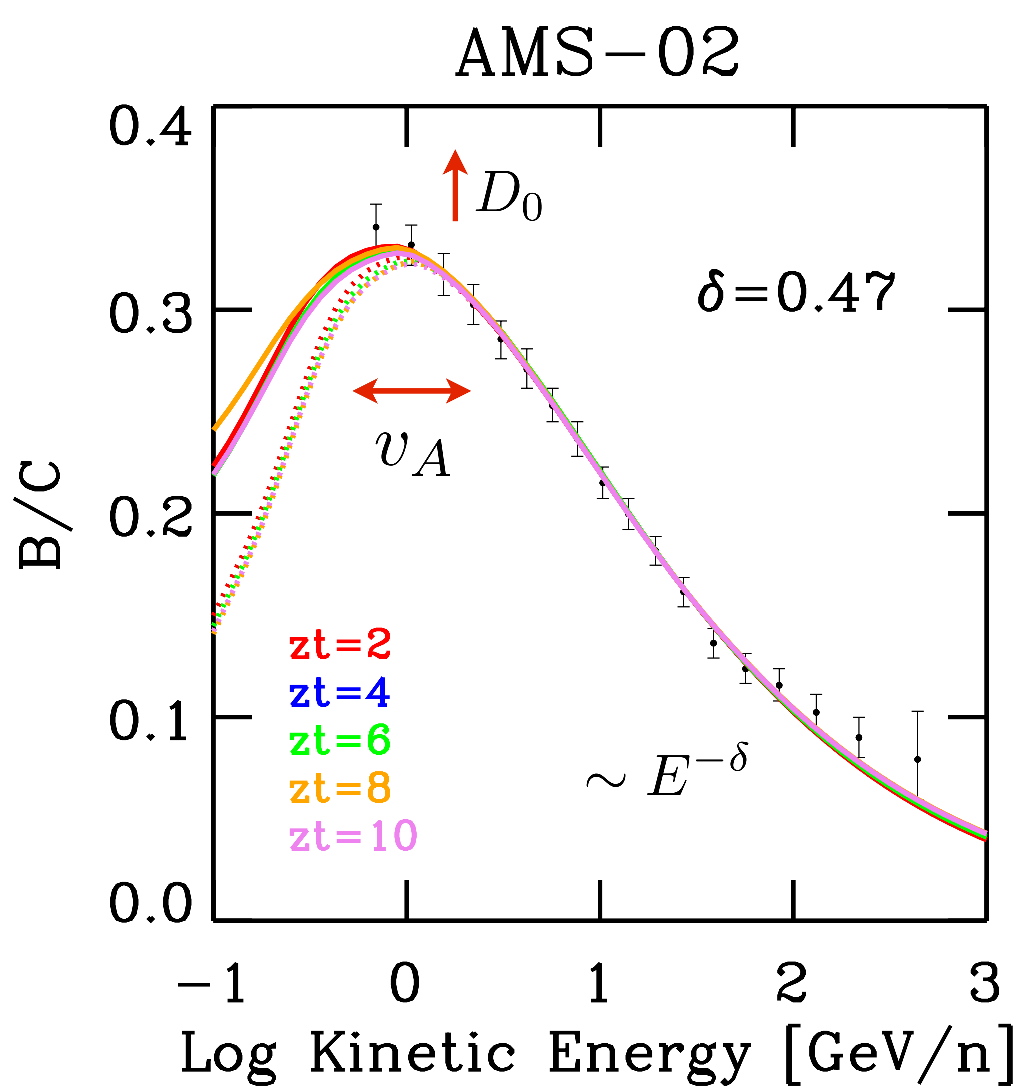
Fitting local observables: an analogy

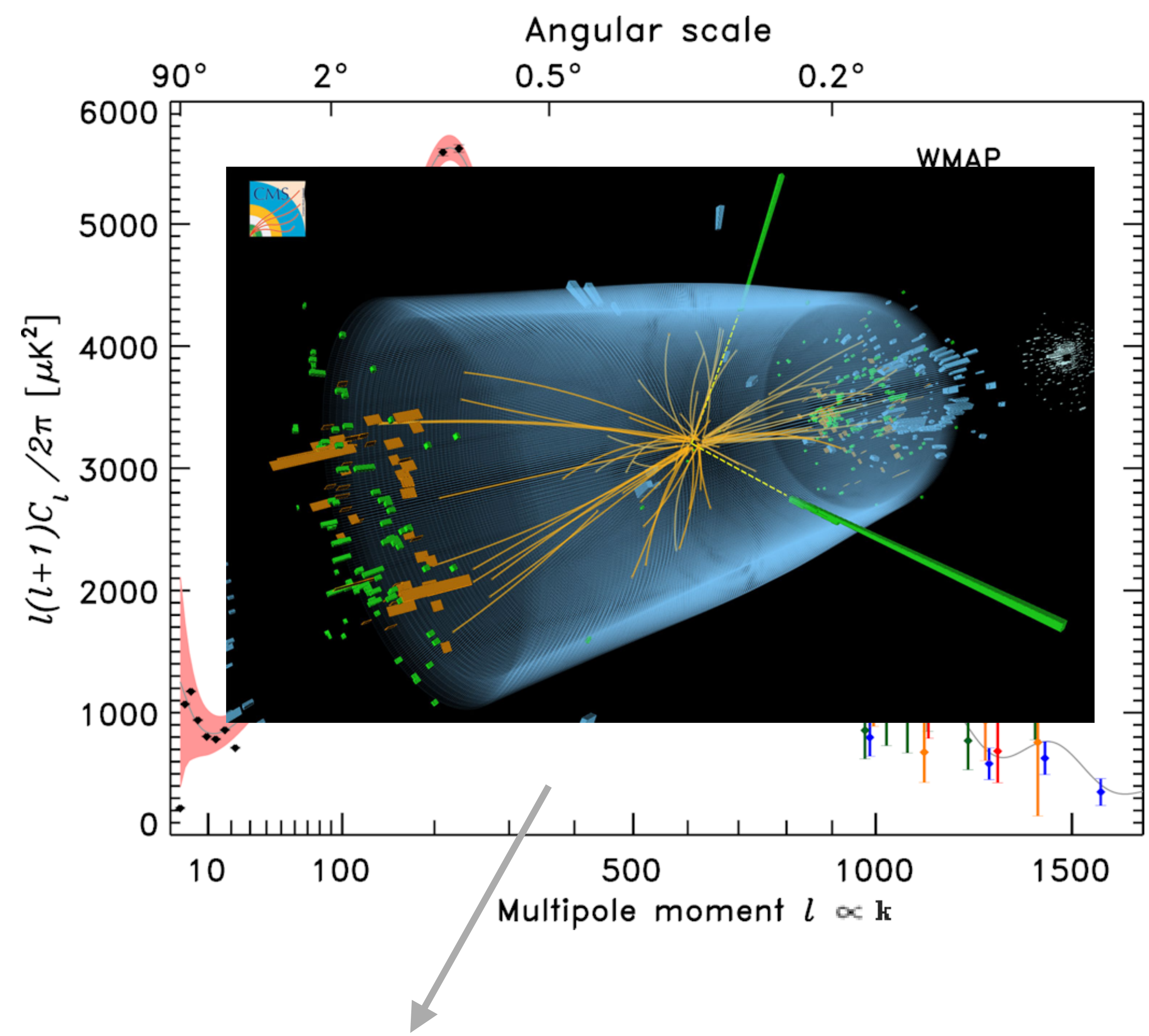




$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t) \qquad f(\Omega_m, \Omega_\Lambda, \Omega_b \ldots)$$

Fitting local observables: an analogy



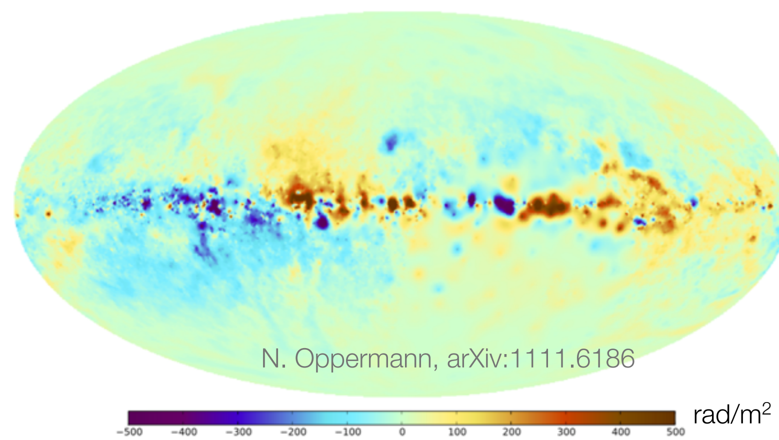


$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

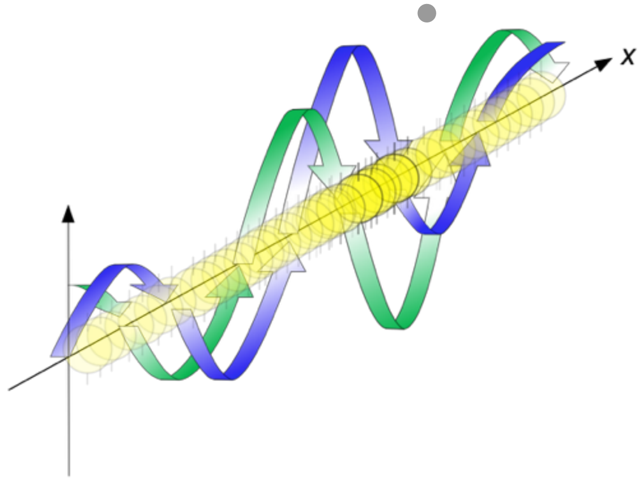
$$f(\Omega_m\,,\ \Omega_\Lambda\,,\ \Omega_b\ \ldots)$$

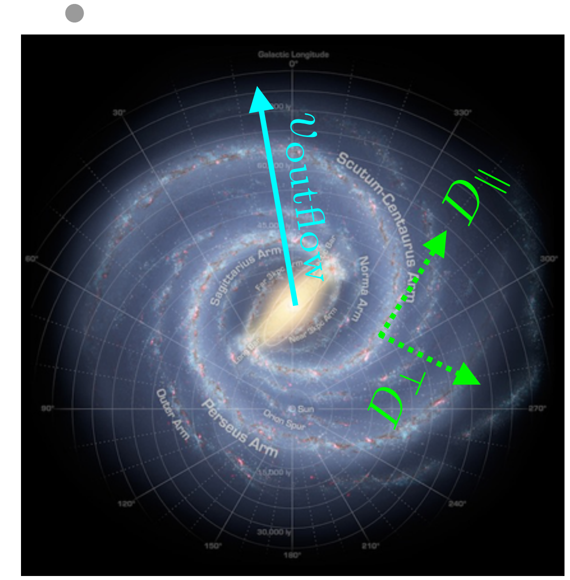
towards a “physical" consistent global picture

improved knowledge
of ISM turbulence



realistic simulation of
global CR transport





new developments of particle-wave
interaction formalism

The Master equation

Berezinskii et al. (1990)

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

Sources/sinks

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

galactic winds powered by SN or CR themselves

function of the ionised gas density and magnetic field

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

DRAGON2

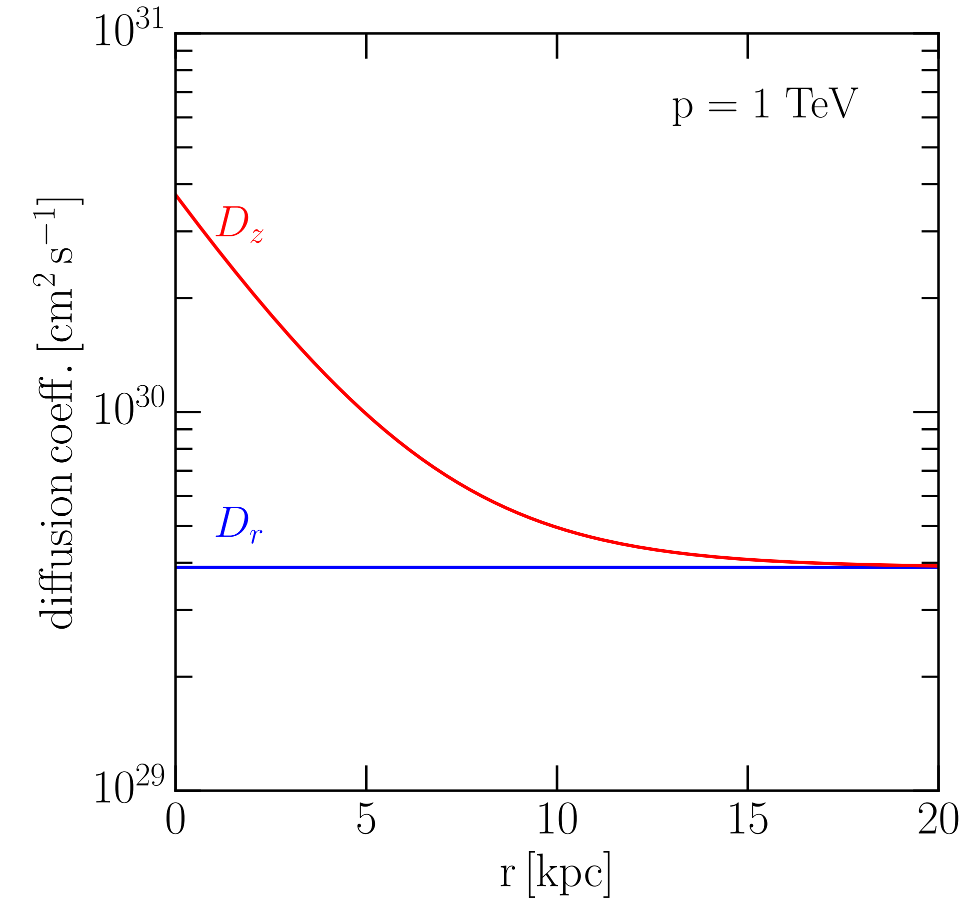
- C. Evoli et al., arXiv:1607.07886

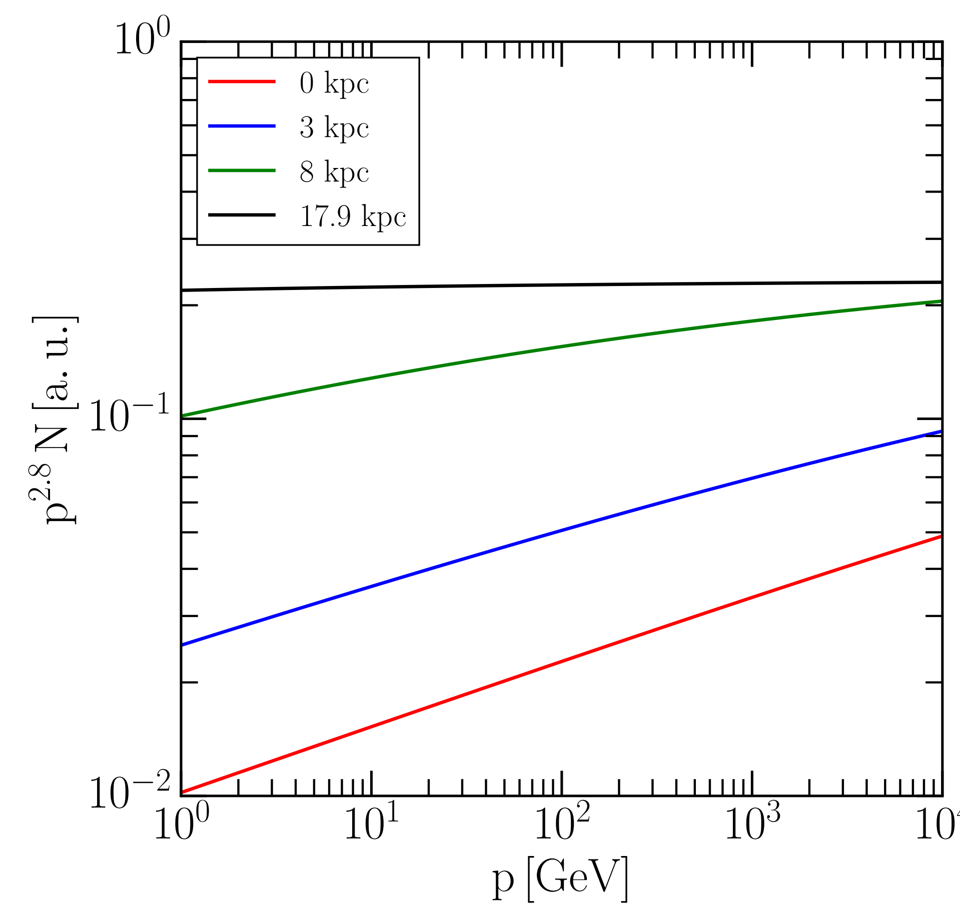
DRAGON2

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

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

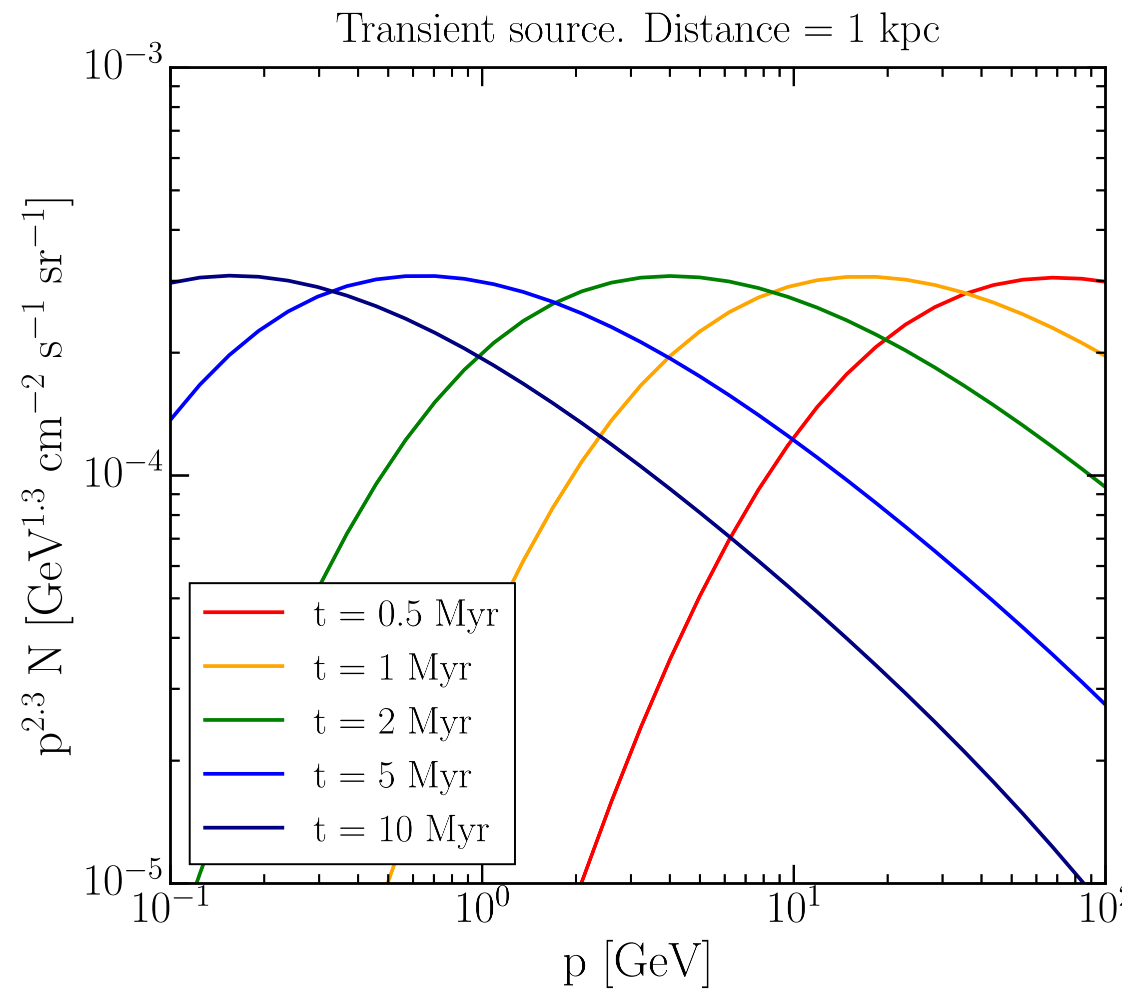
$$D_z = D_{0,\perp} \left(\frac{p}{p_0} \right)^{\delta_\perp} + D_{0,\parallel} \exp \left(-\frac{r}{R_0} \right) \left(\frac{p}{p_0} \right)^{\delta_\parallel}$$

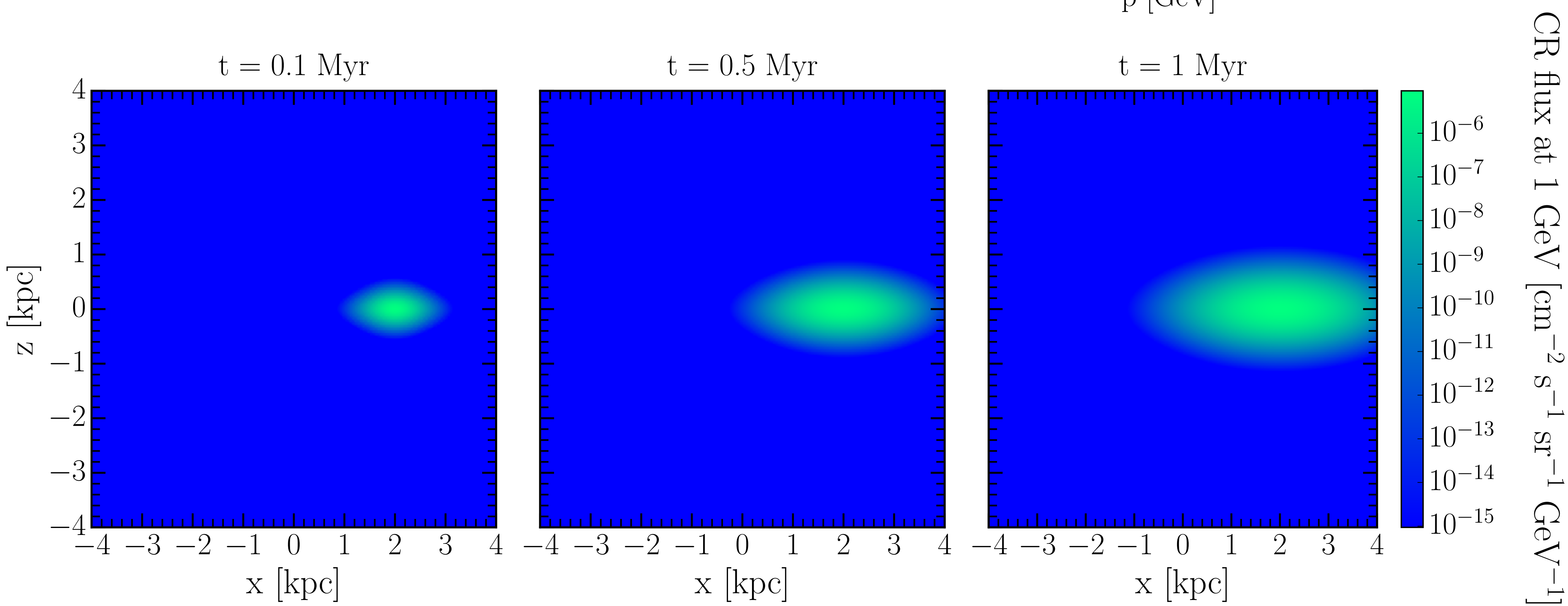




DRAGON2

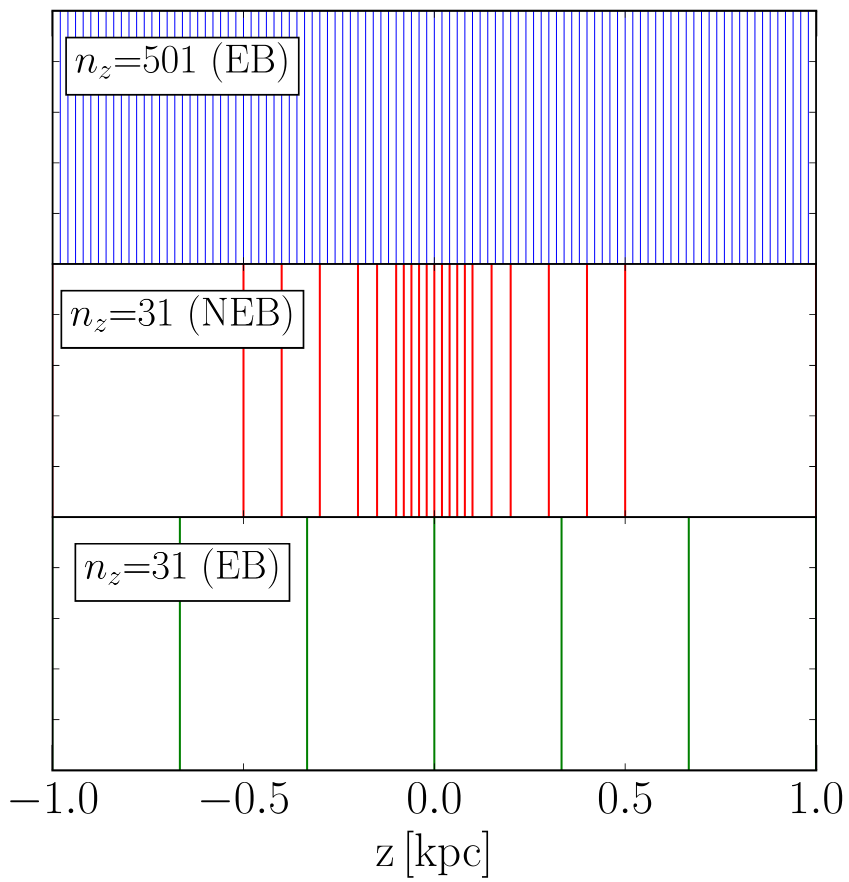
- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources

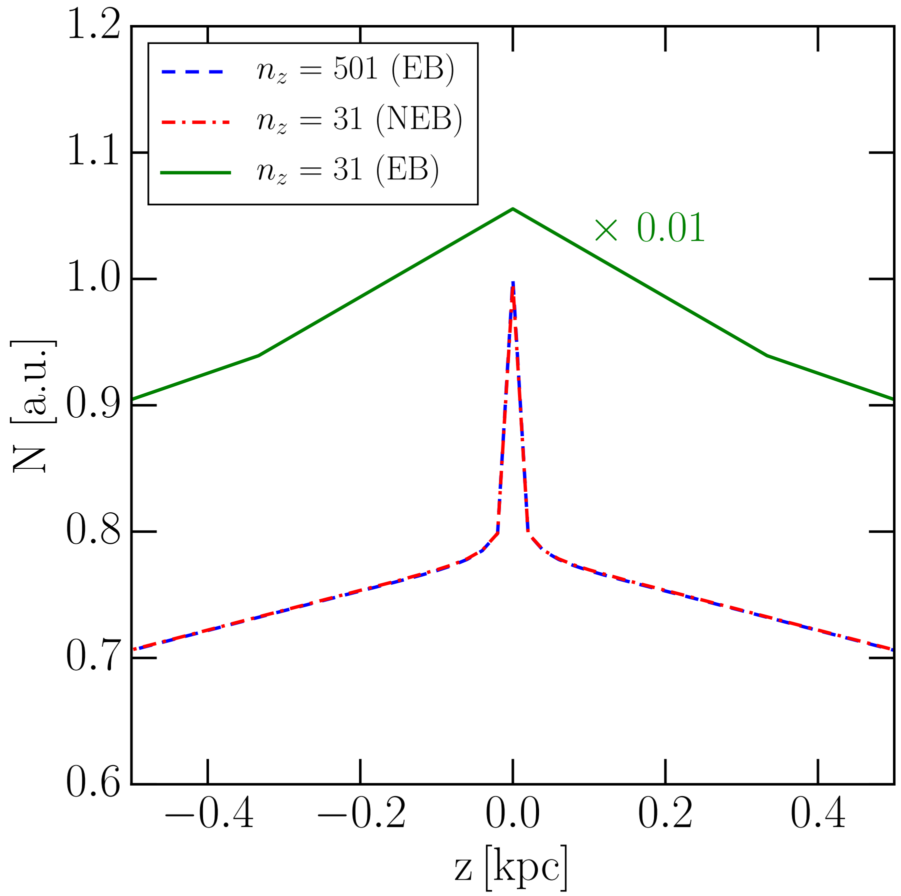




DRAGON2

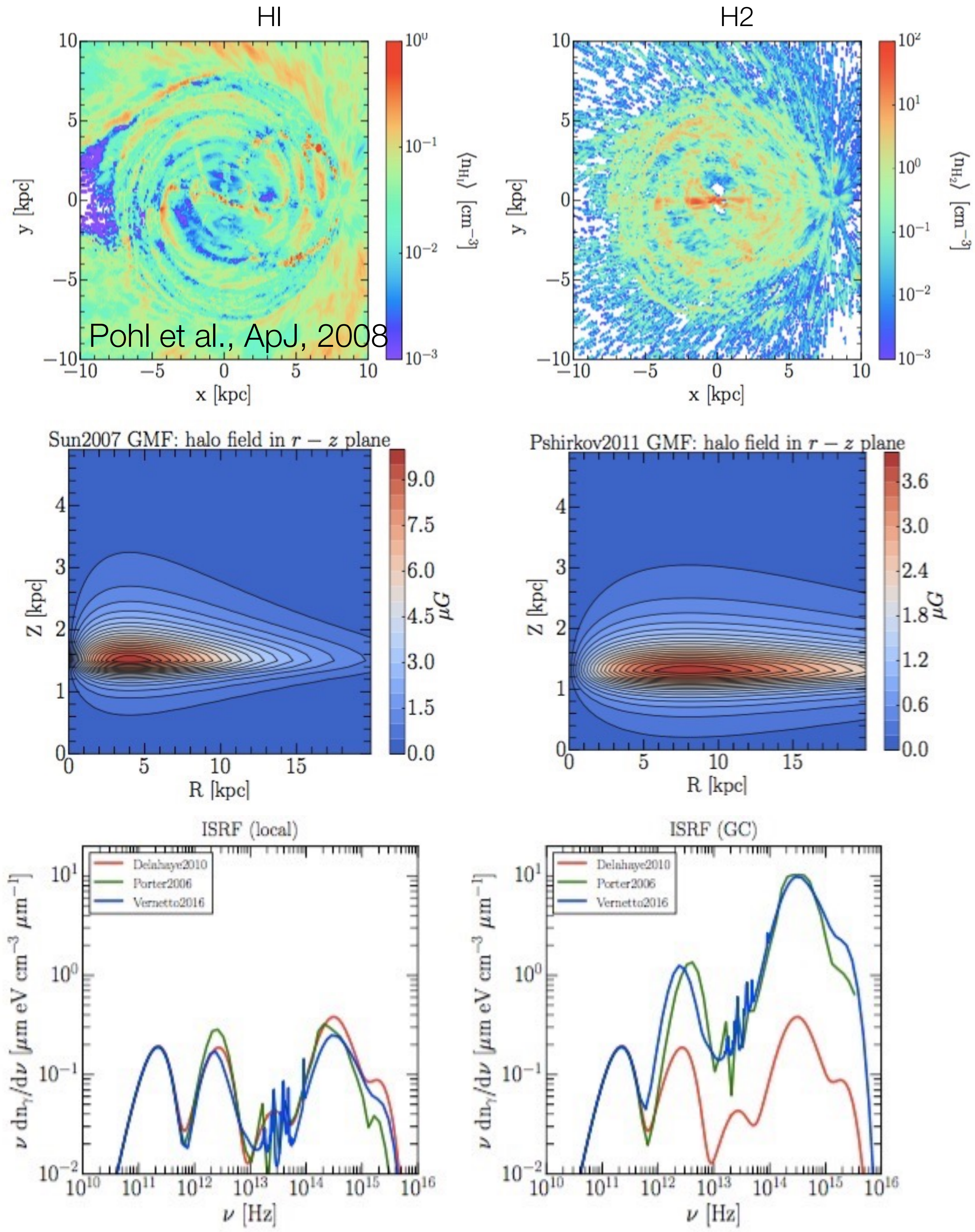
- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources
- non-equidistant binning





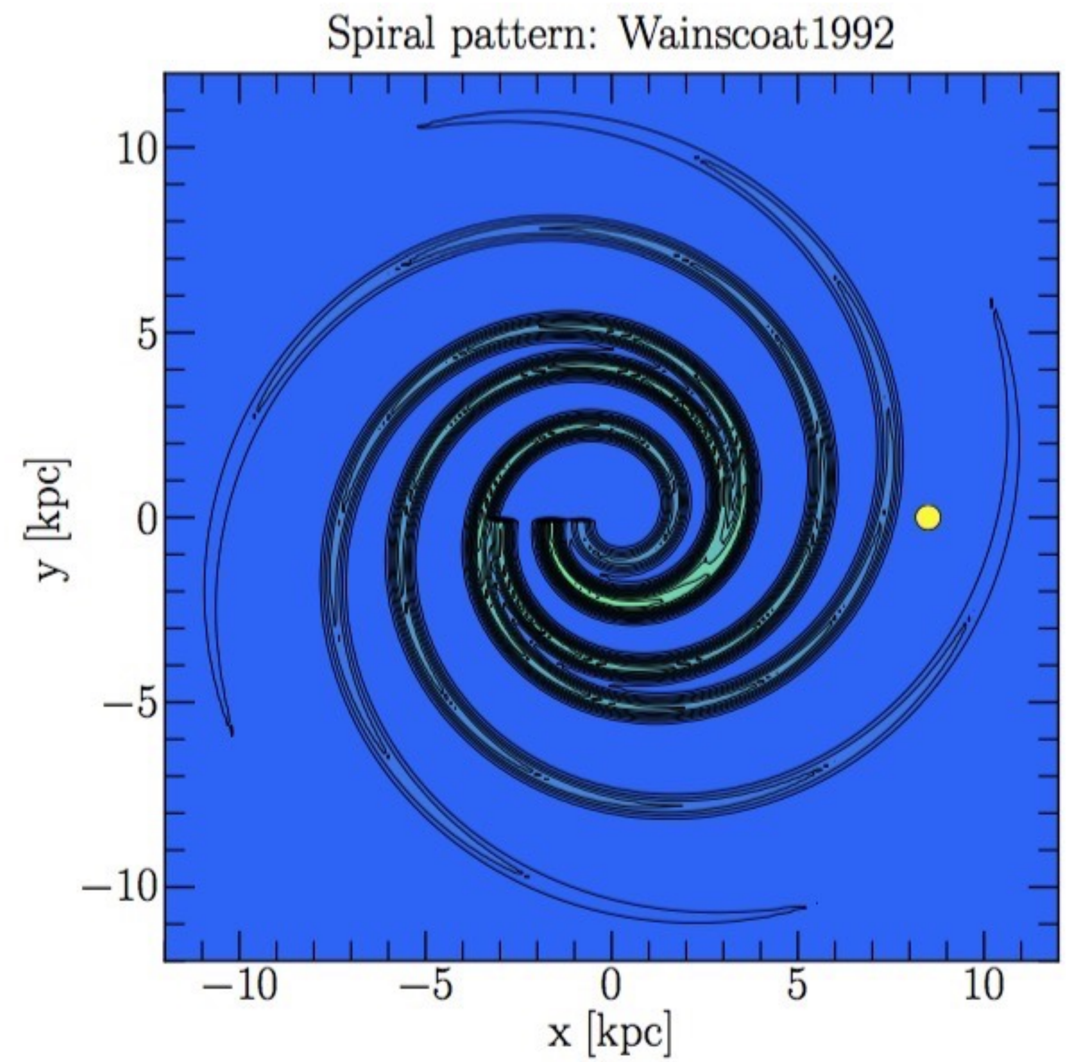
DRAGON2

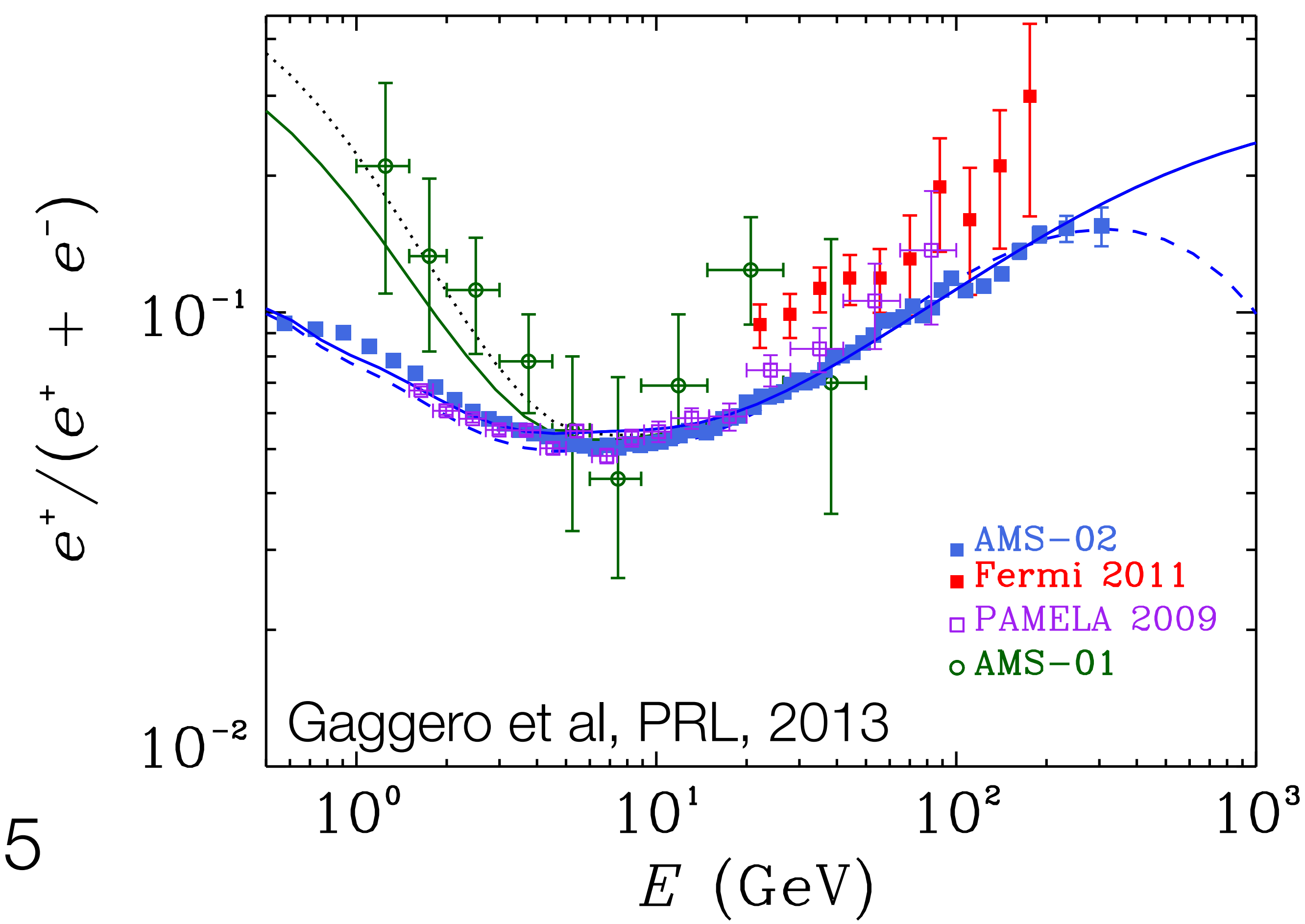
- C. Evoli et al., arXiv:1607.07886
- anisotropic diffusion
- modeling transient sources
- non-equidistant binning
- a complete set of astrophysical ingredients



DRAGON2

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



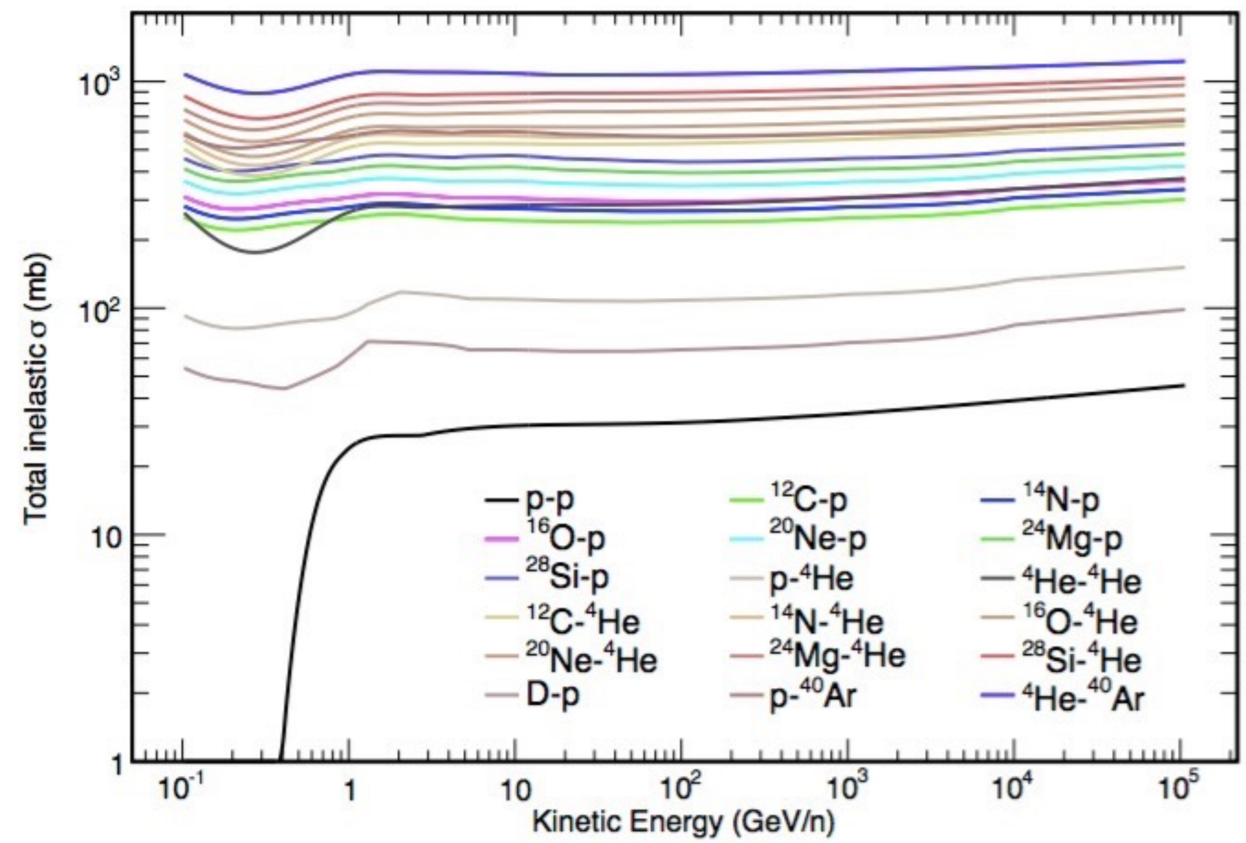


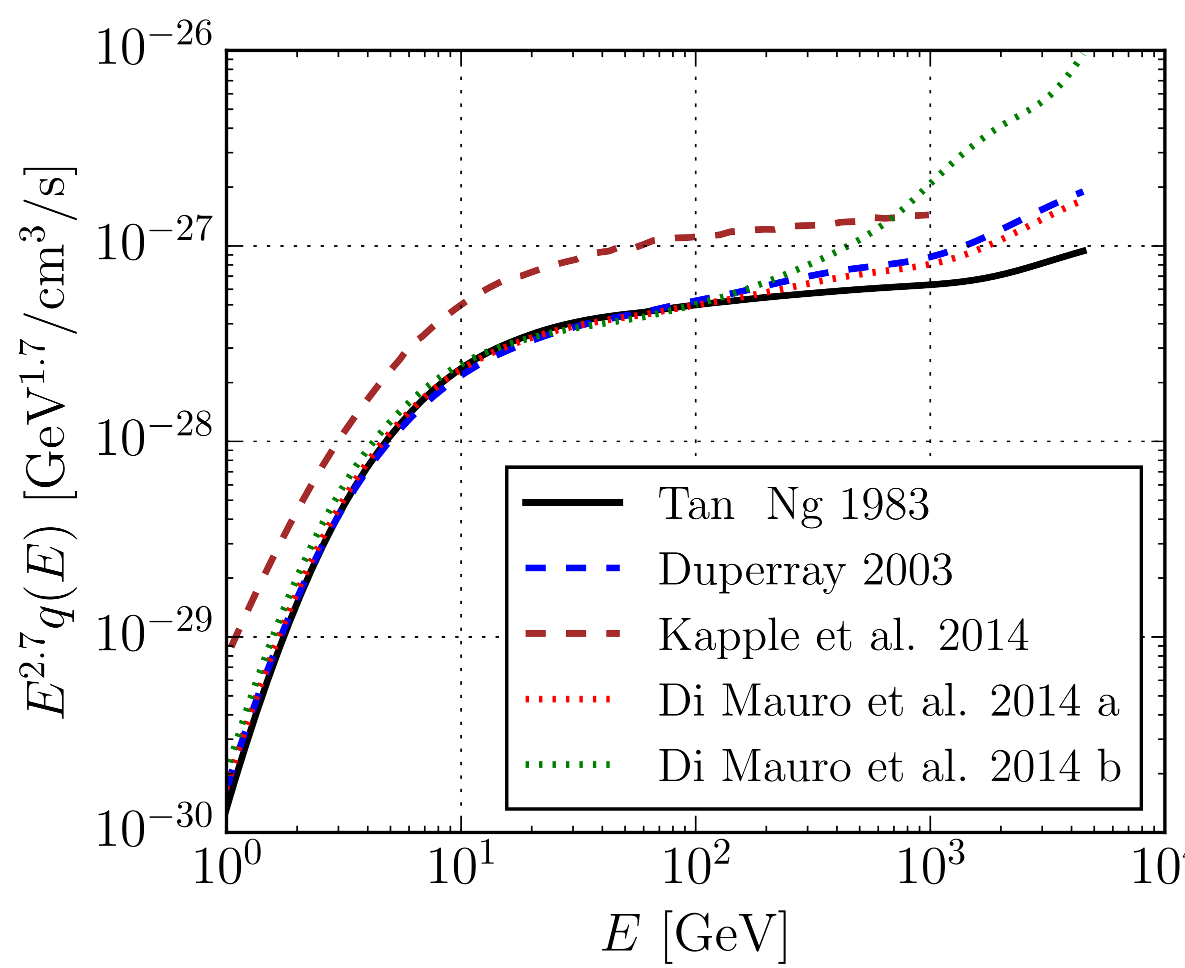
see also Kissmann, R. et al., APh, 2015

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



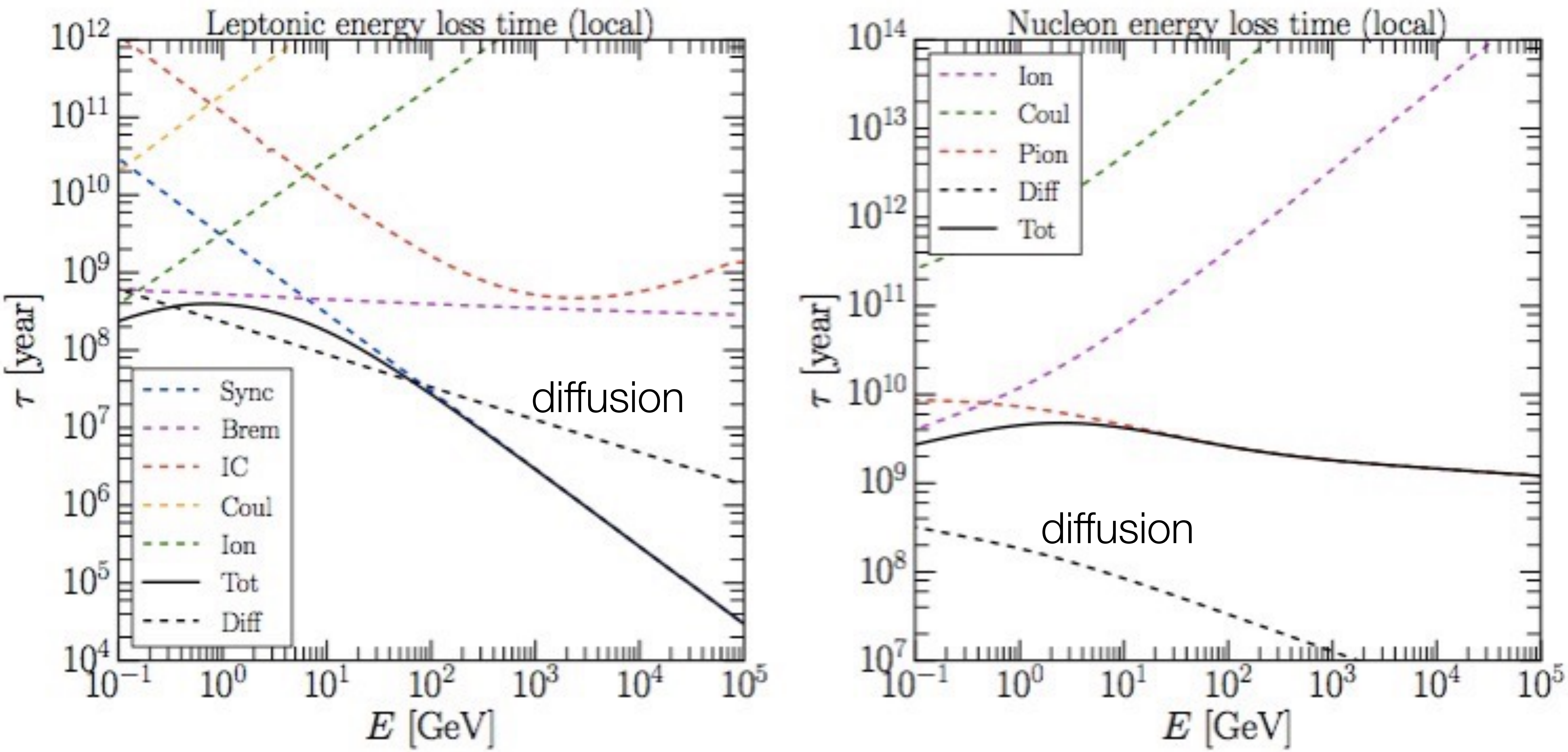


DRAGON2 solver in Operator Spitting

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

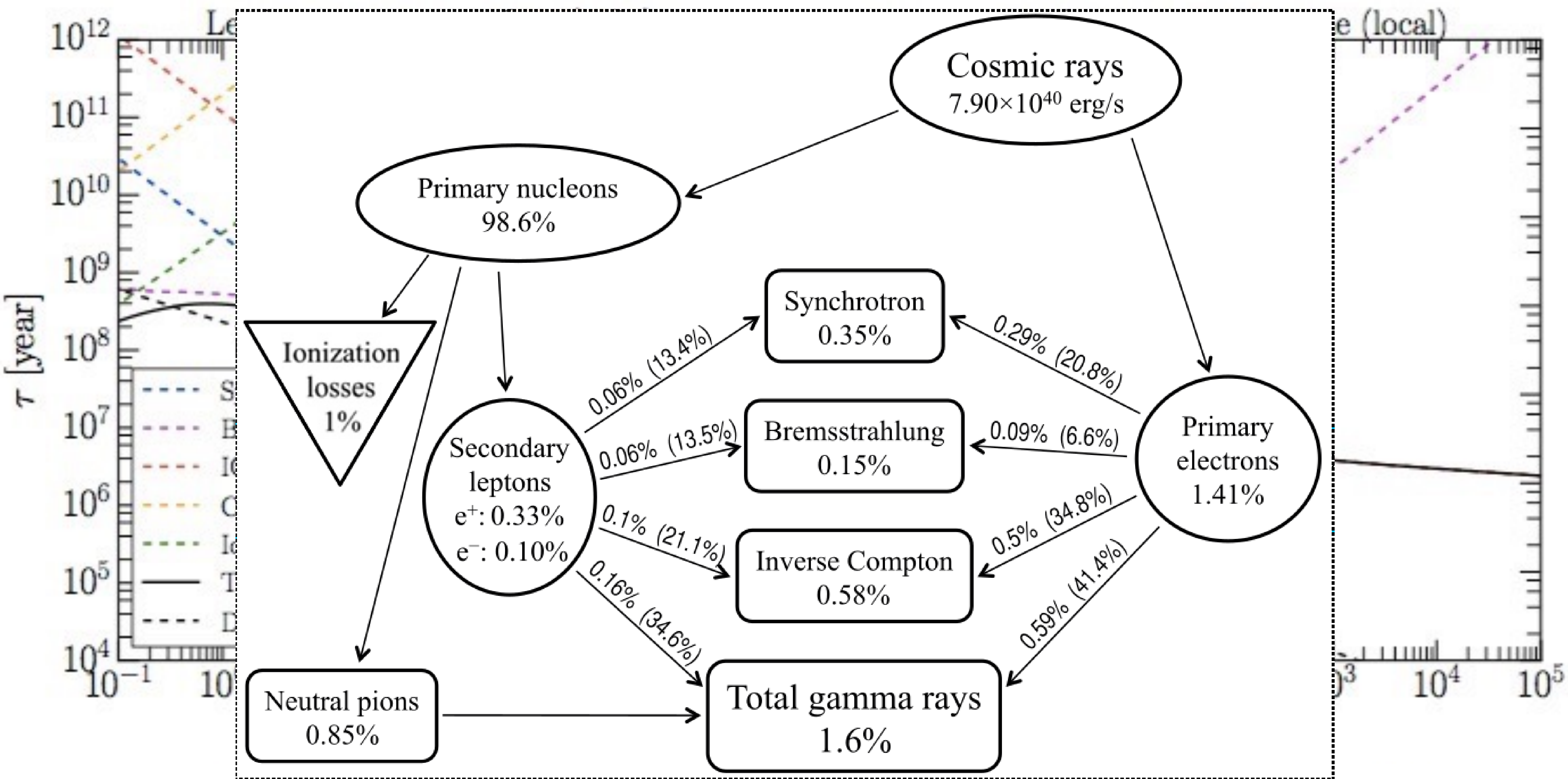
Table 1. Crank-Nicolson coefficients and boundary conditions for the 2D case ($\Delta x_c \equiv \frac{x_{i+1} - x_{i-1}}{2}$, $\Delta x_u \equiv sx_{i+1} - x_i$, $\Delta x_d \equiv x_i - x_{i-1}$).

DRAGON2 energy losses in the ISM



DRAGON2 energy losses in the ISM

Strong et al., ApJ 722 (2010) L58



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

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**