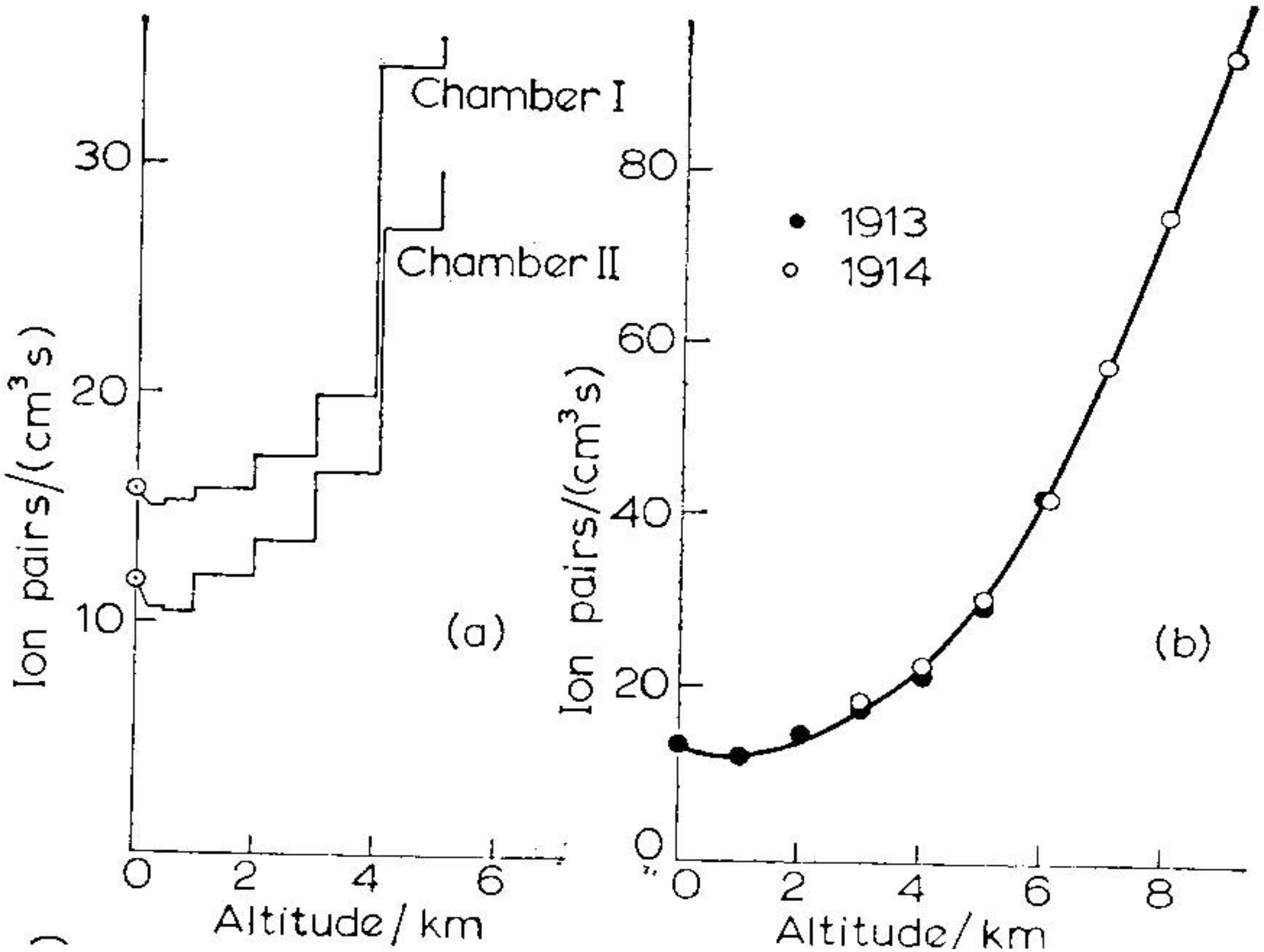
Galactic Cosmic rays as a dark matter probe

Carmelo Evoli (Universität Hamburg)

Oslo University - 22th of April 2015

A 100 years old discovery!



Victor Hess

W. Bothe

W. Kolhorster

High-energy photons or charged particles?

The New York Times

VOL. LXXXII...No. 27,370. December 31,1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

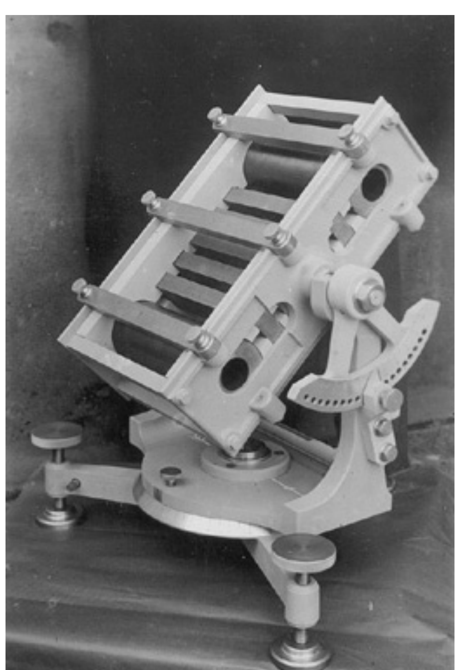
Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

High-energy photons or charged particles?

Bruno Rossi in his laboratory in Florence

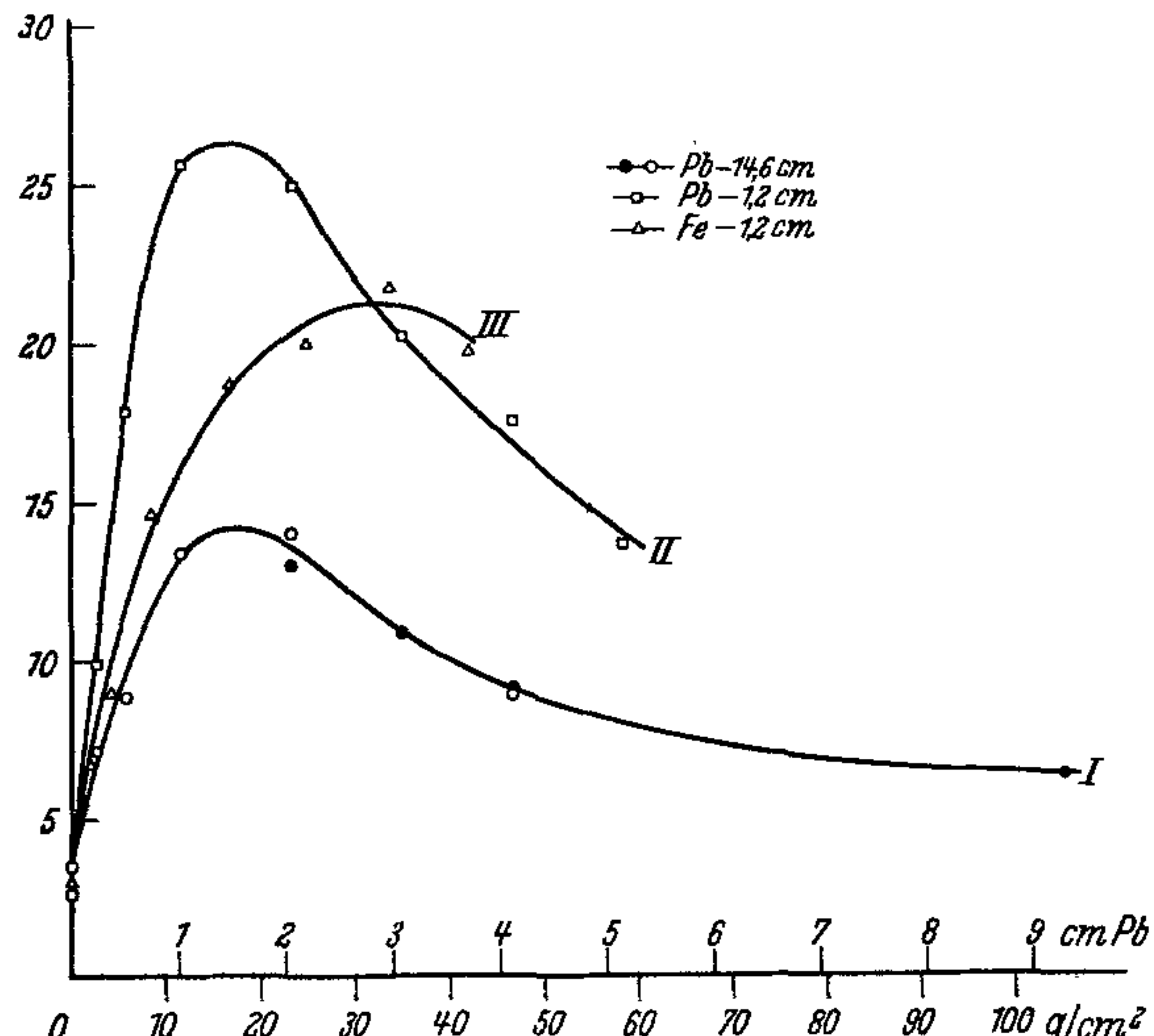


The CR telescope used by Bruno Rossi during the expedition in Eritrea

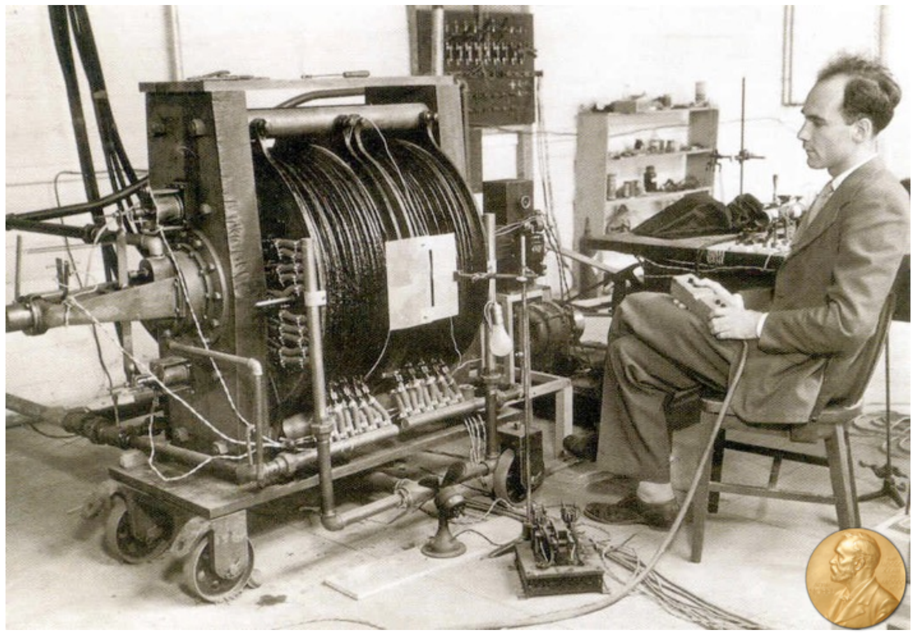
Über die Eigenschaften der durchdringenden Korpuskularstrahlung im Meeresniveau.

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

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

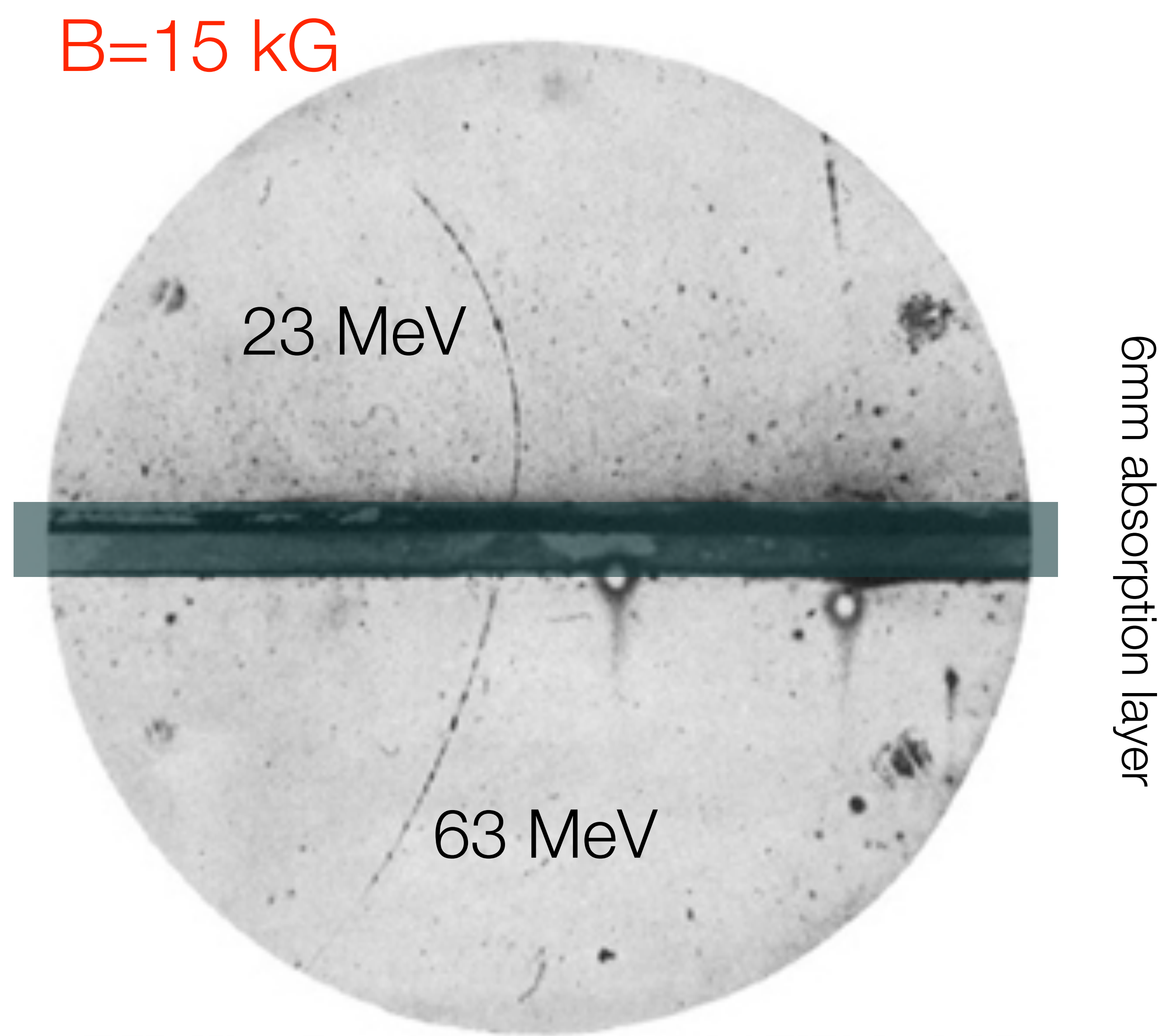


A unique particle physics laboratory



Carl D. Anderson

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

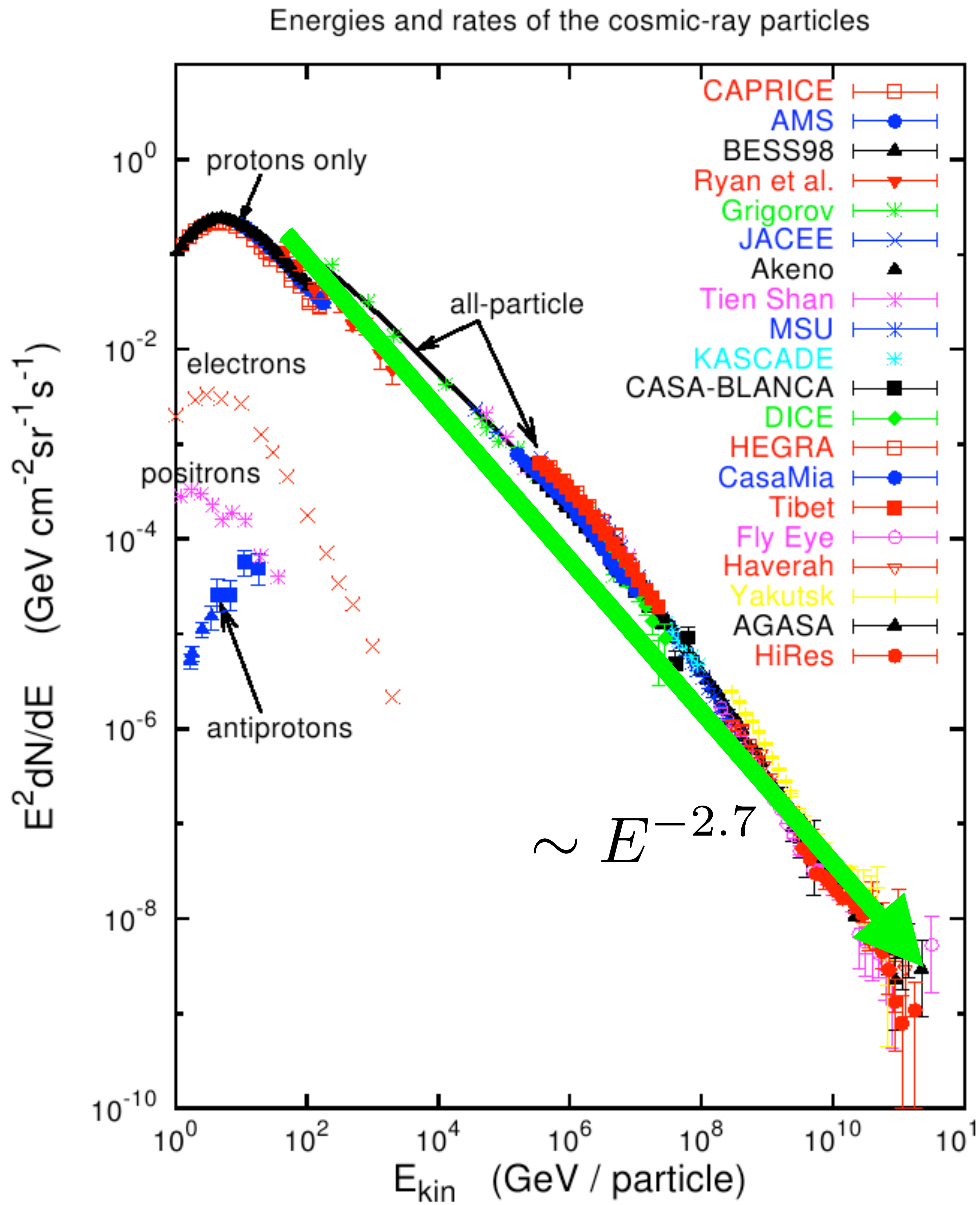


The first anti-matter evidence was found in the cosmic radiation in 1933.

Today

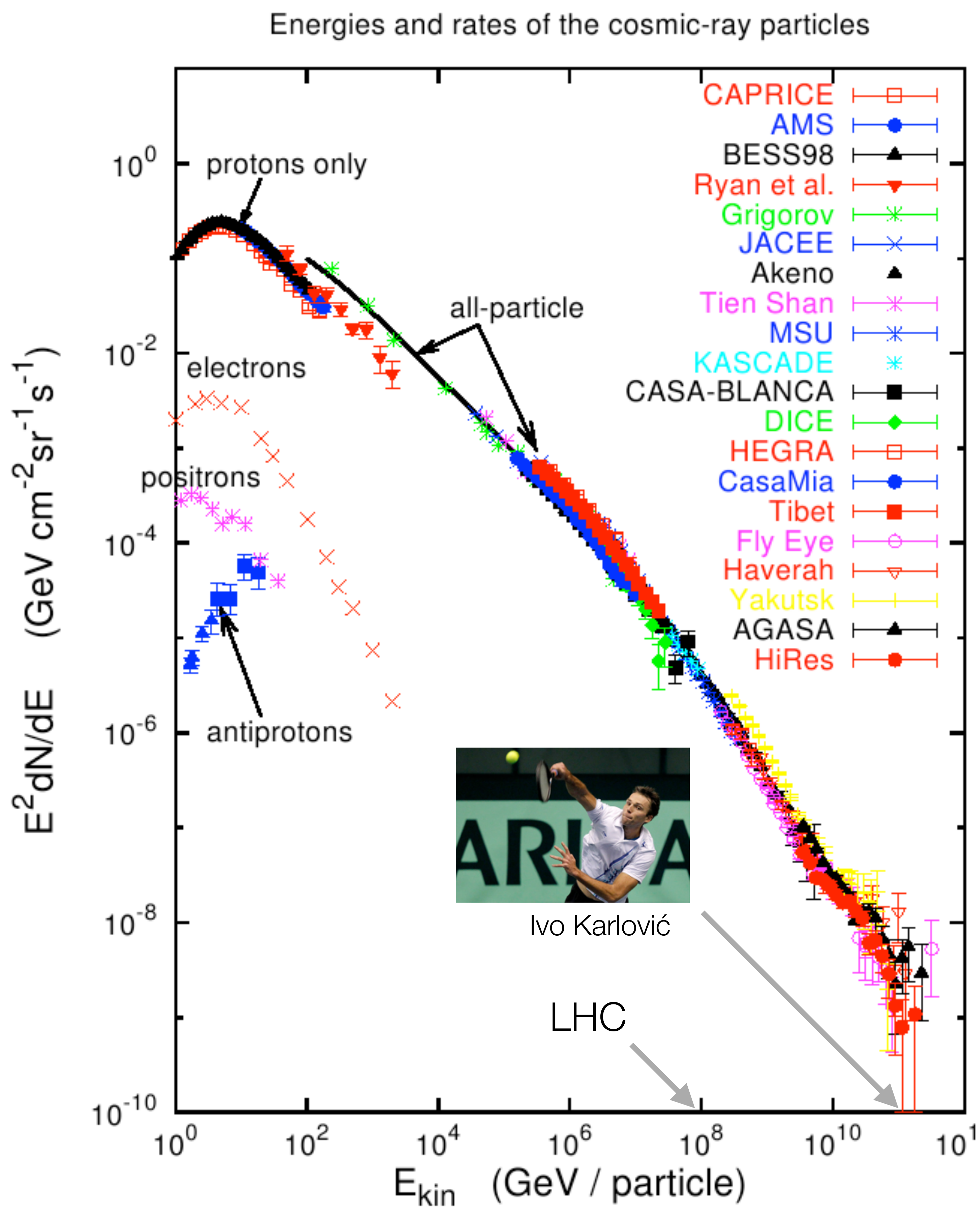
Cosmic-ray flux

- Almost a perfect power-law over 12 energy decades.



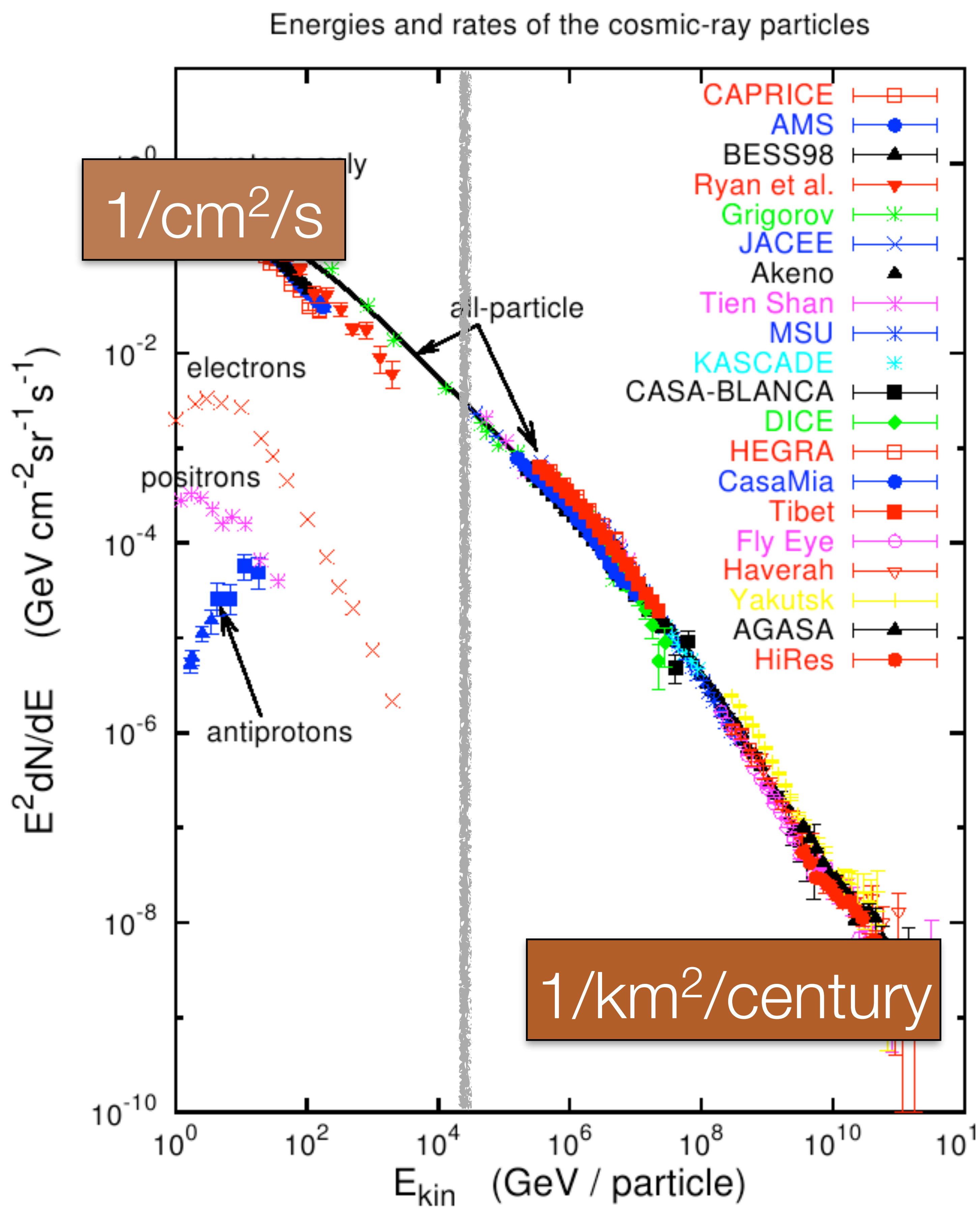
Cosmic-ray flux

- Almost a perfect power-law over 12 energy decades.
- Observed at energy higher than terrestrial laboratories!



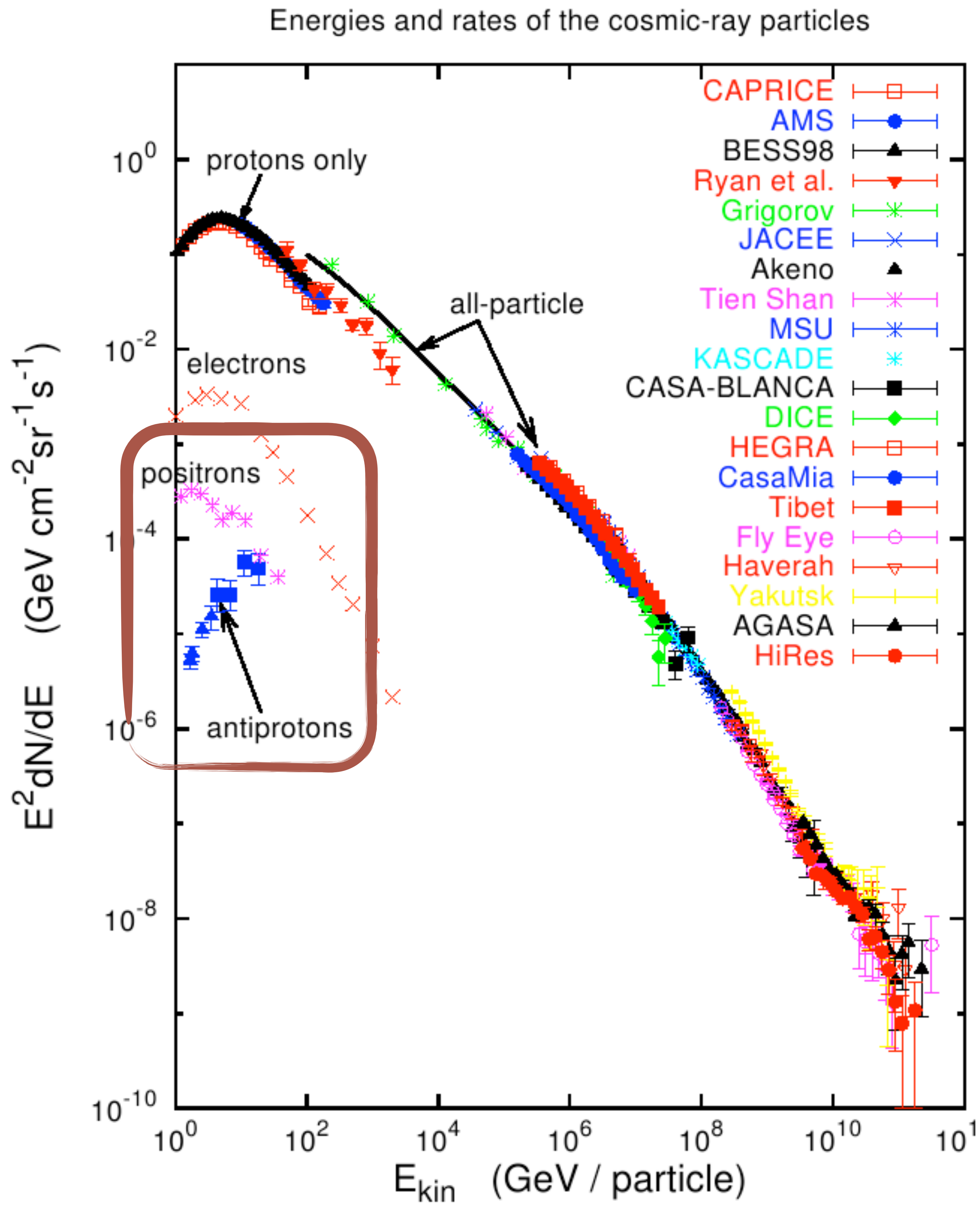
Cosmic-ray flux

- Almost a perfect power-law over 12 energy decades.
- Observed at energy higher than terrestrial laboratories!
- Direct measurements versus air-cascade reconstructions.



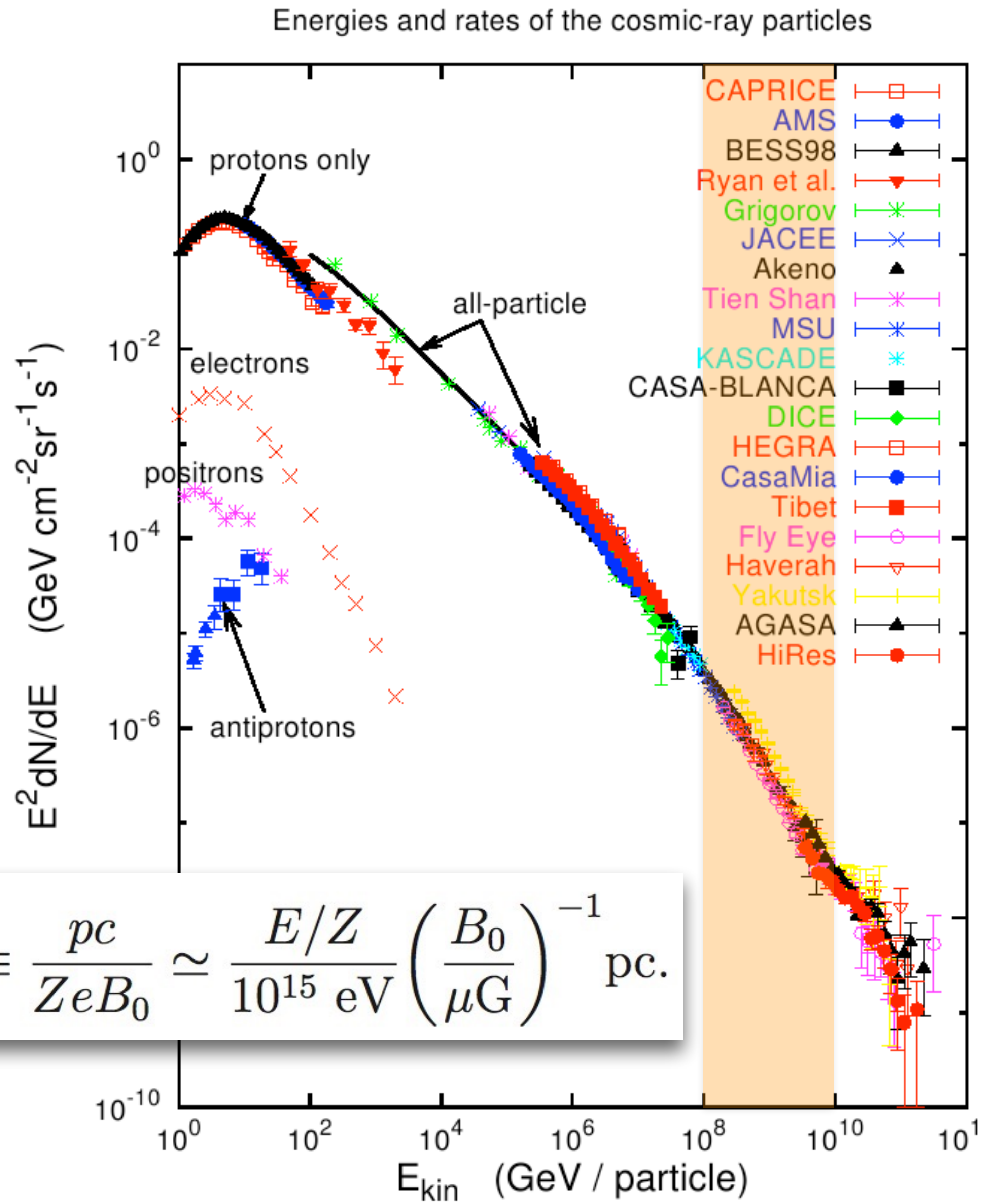
Cosmic-ray flux

- 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.



Cosmic-ray flux

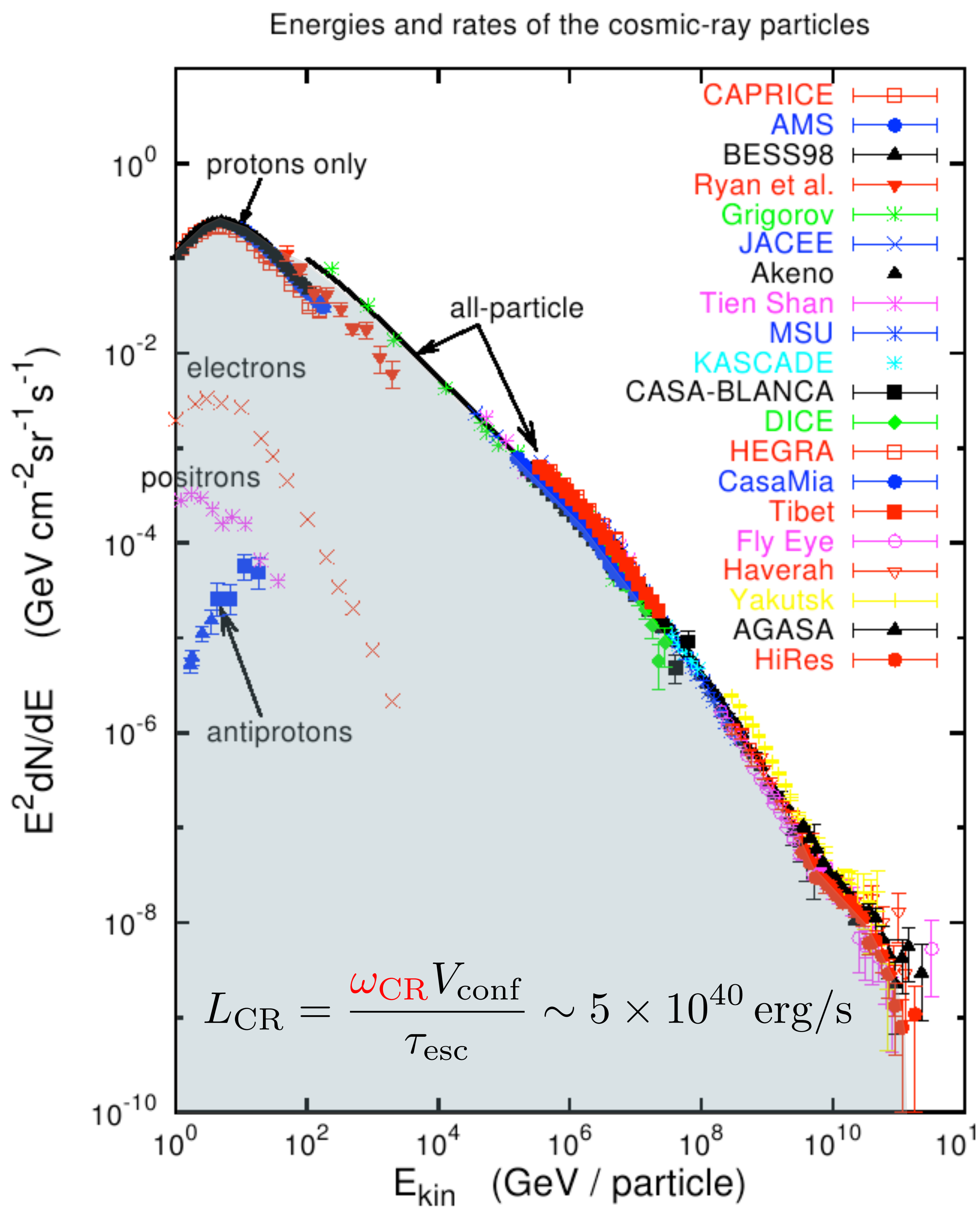
- Almost a perfect power-law over 12 energy decades.
- Observed at energy higher than terrestrial laboratories!
- Direct measurements versus air-cascade reconstructions.
- Anti-matter component.
- Transition from galactic to extra-galactic?



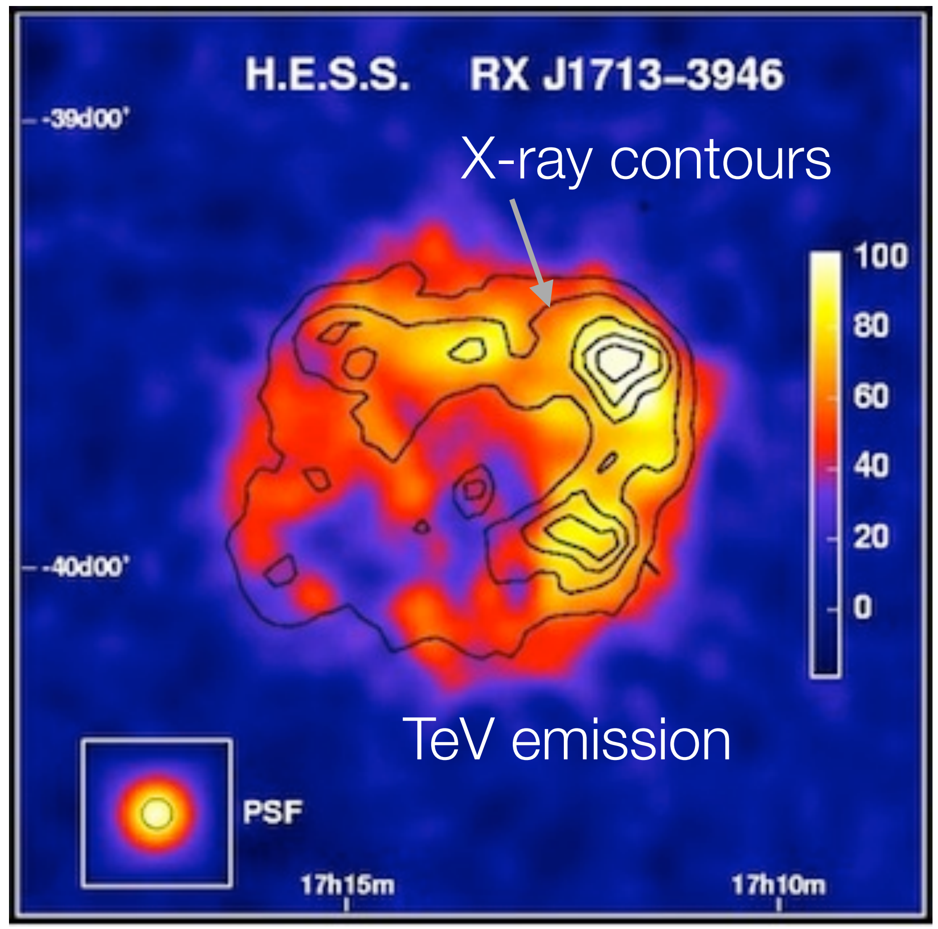
$$r_{\mathrm{L}} \equiv \frac{pc}{ZeB_0} \simeq \frac{E/Z}{10^{15}\ \mathrm{eV}} \left(\frac{B_0}{\mu\mathrm{G}}\right)^{-1} \mathrm{pc}.$$

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

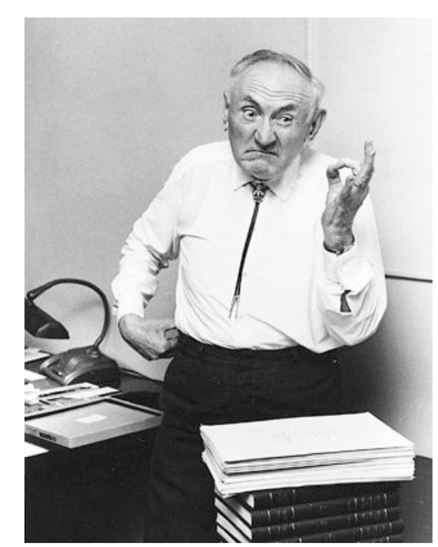
hadronic:

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

or leptonic:

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

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

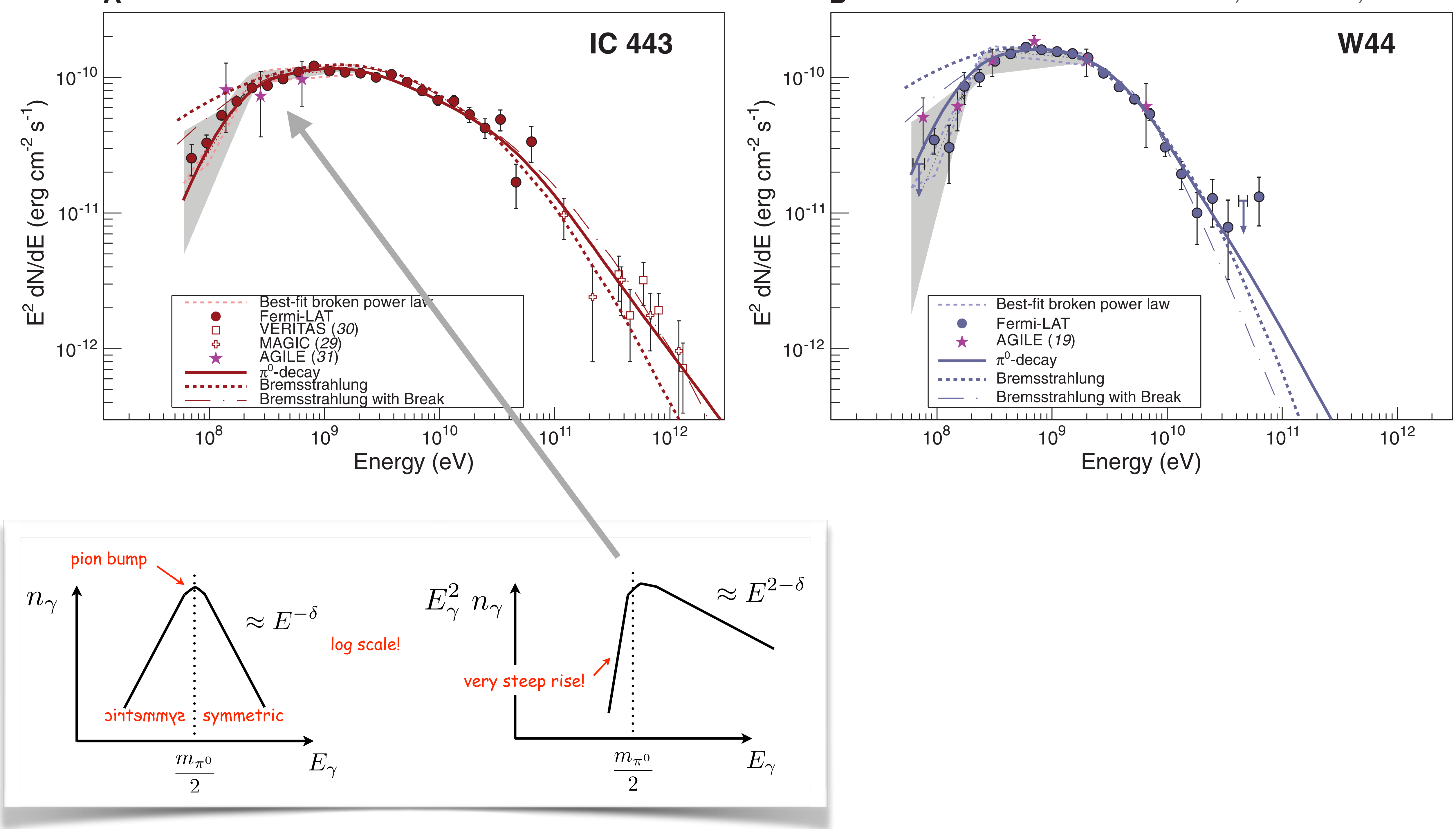


Fritz Zwicky

The pion-bump as hadronic signature

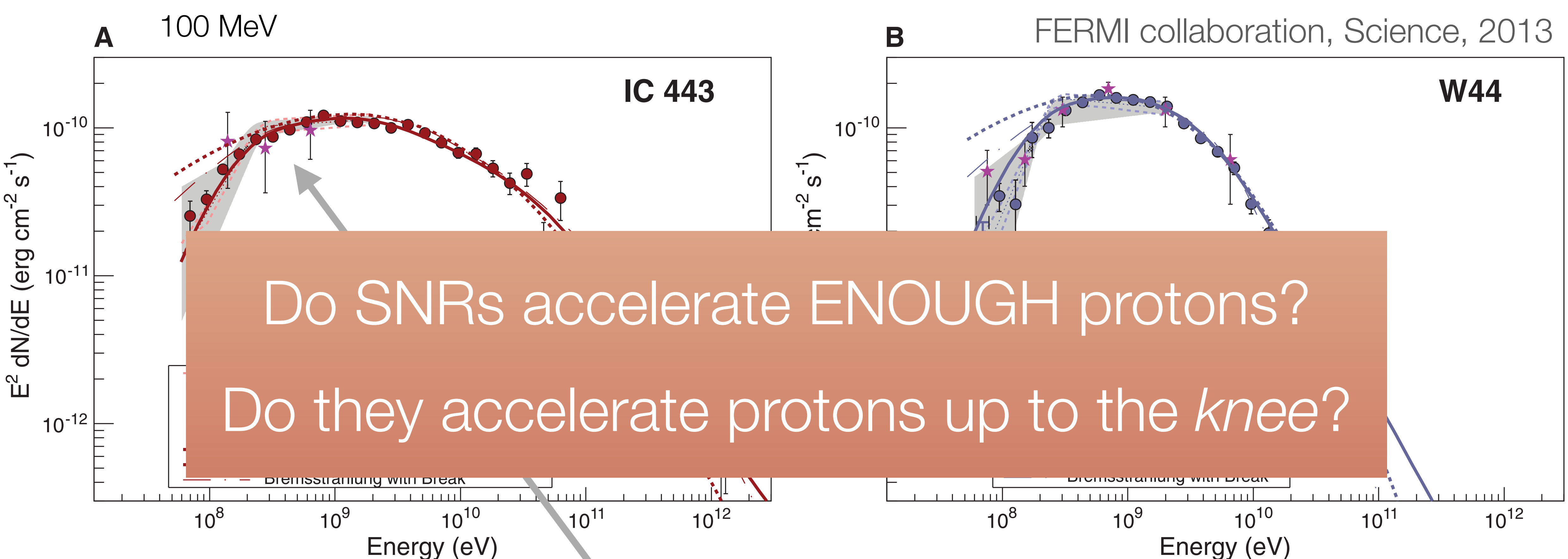
100 MeV

FERMI collaboration, Science, 2013



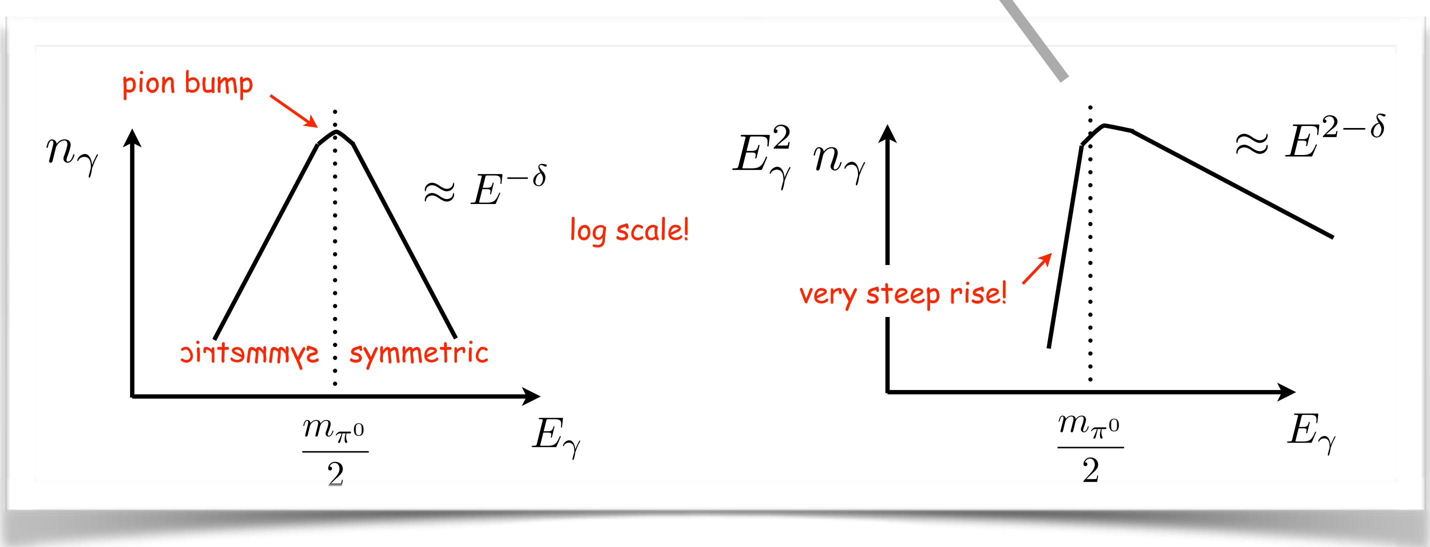
The pion-bump as hadronic signature

FERMI collaboration, Science, 2013

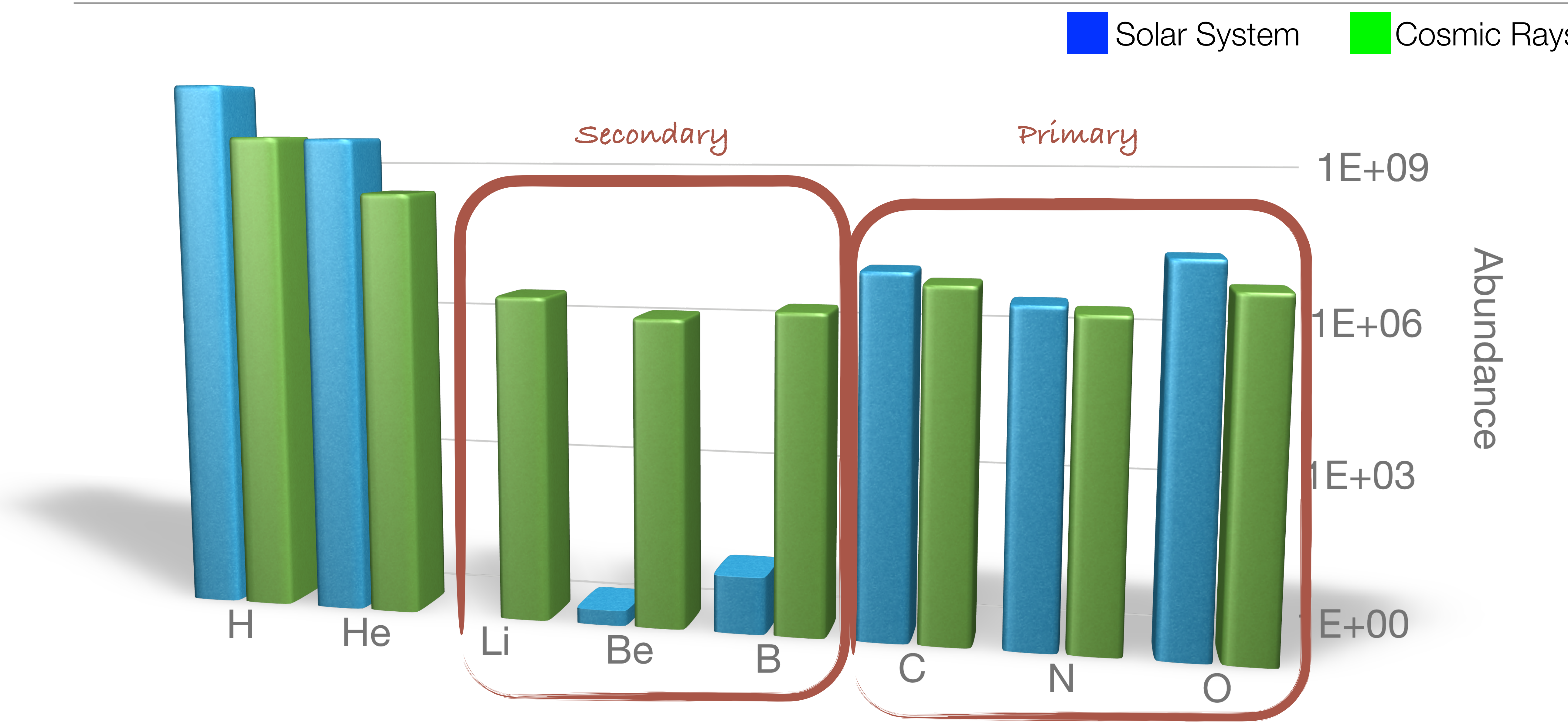


Do SNRs accelerate ENOUGH protons?

Do they accelerate protons up to the *knee*?

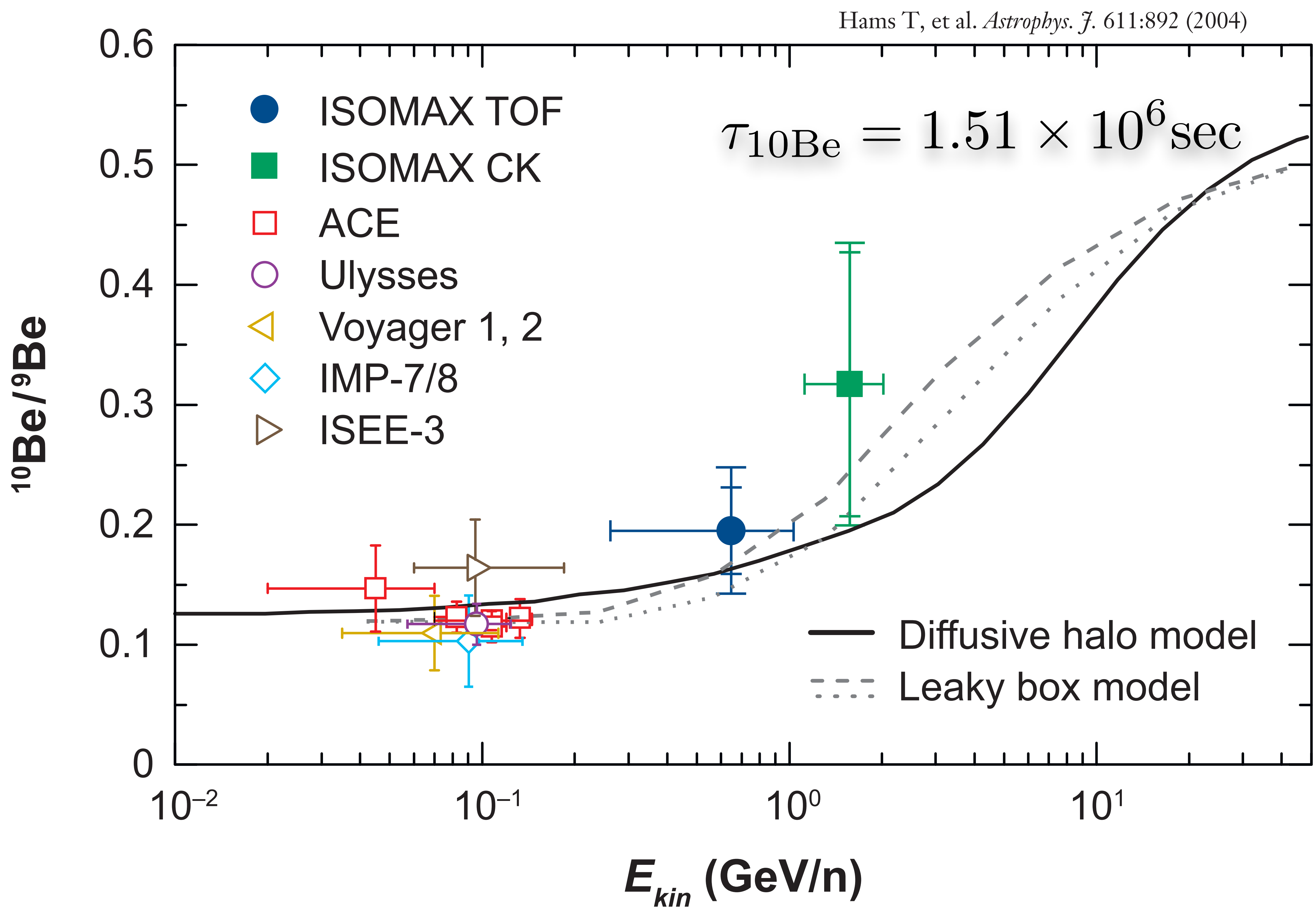


Cosmic-ray composition

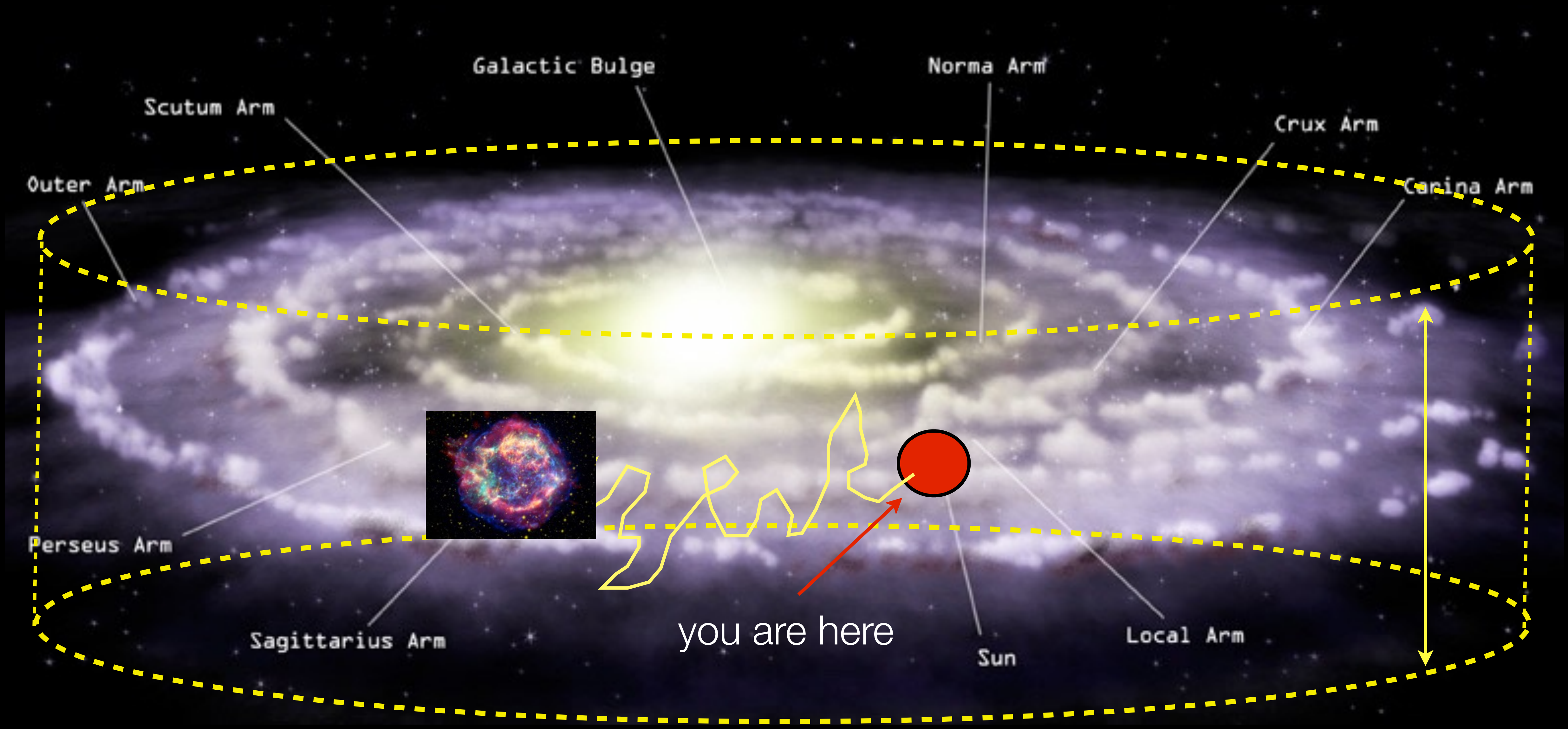


$$c\tau_{\rm esc} = \frac{X(E)}{\bar{n}_{\rm ISM}\mu} \sim 10^3\,{\rm kpc}$$ >> Galaxy size!

Cosmic-ray clocks

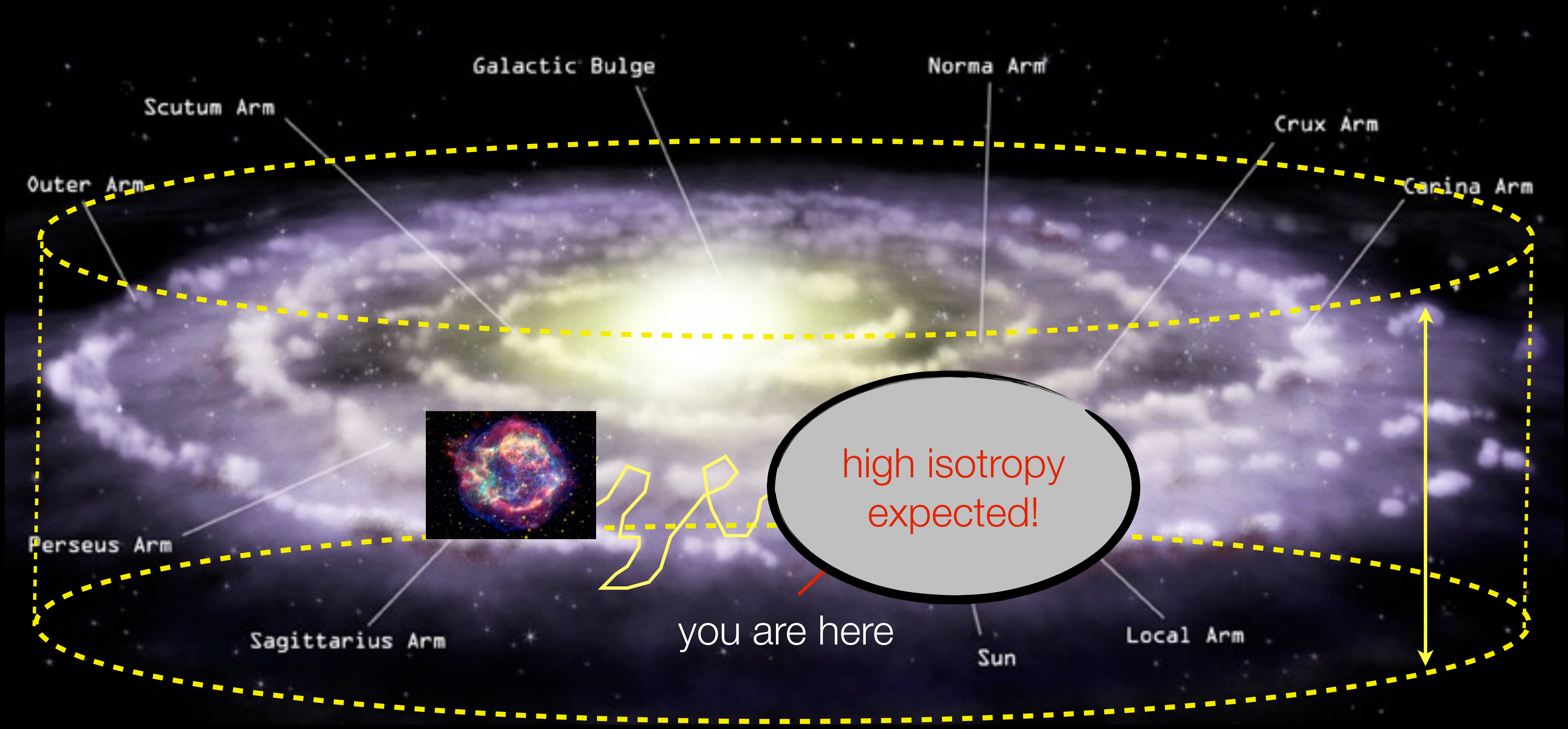


Galactic Propagation



L = 1-10 kpc

Galactic Propagation



L = 1-10 kpc

CR Diffusion in the MW

The diffusion equation:

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

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

Source term:

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

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

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

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

Spallation cross-section:

- appearance of nucleus i due to spallation of nucleus j

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

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

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

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:

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

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

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:

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

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

Energy losses:

- ionization, Coulomb, synchrotron
- adiabatic convection

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

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

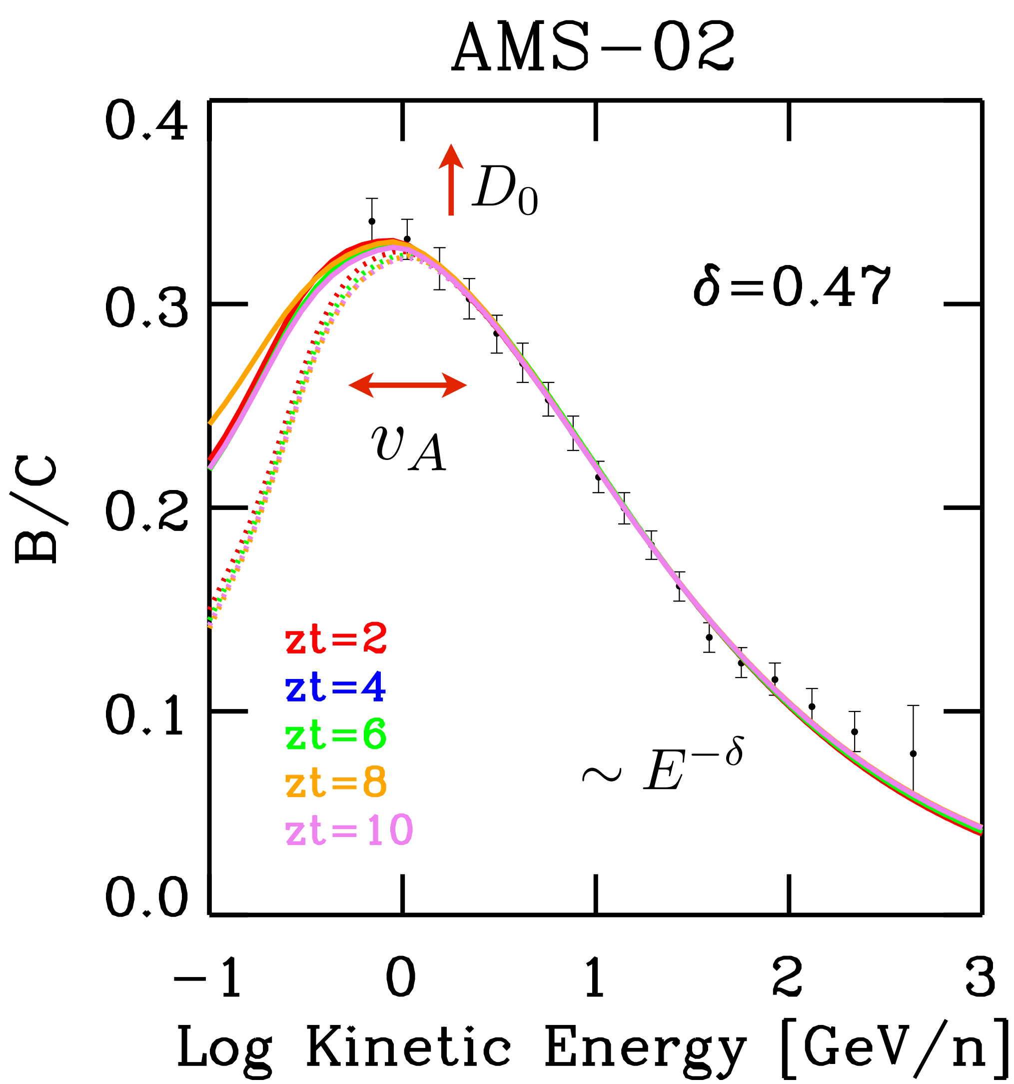
$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

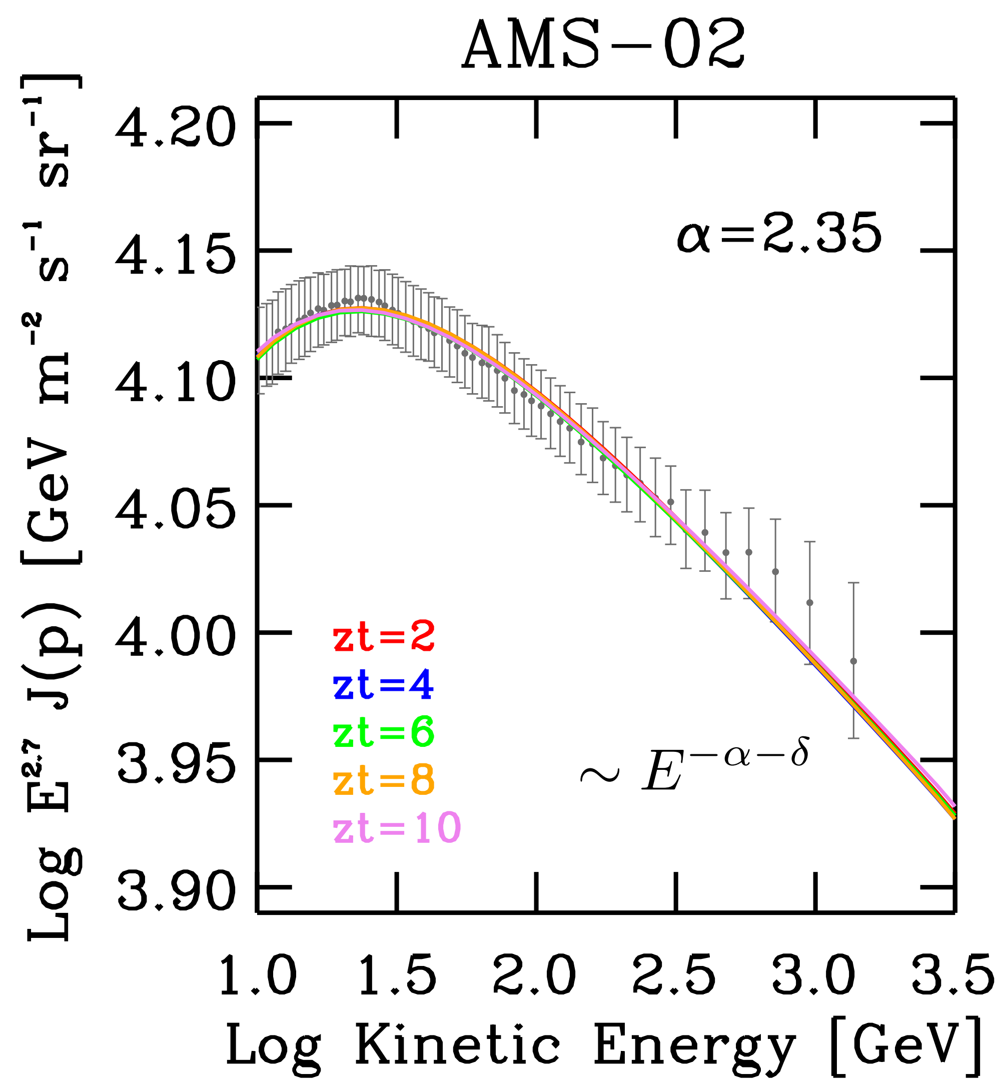
Reacceleration:

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

Ginzburg & Syrovatsky, 1964

Fitting local observables

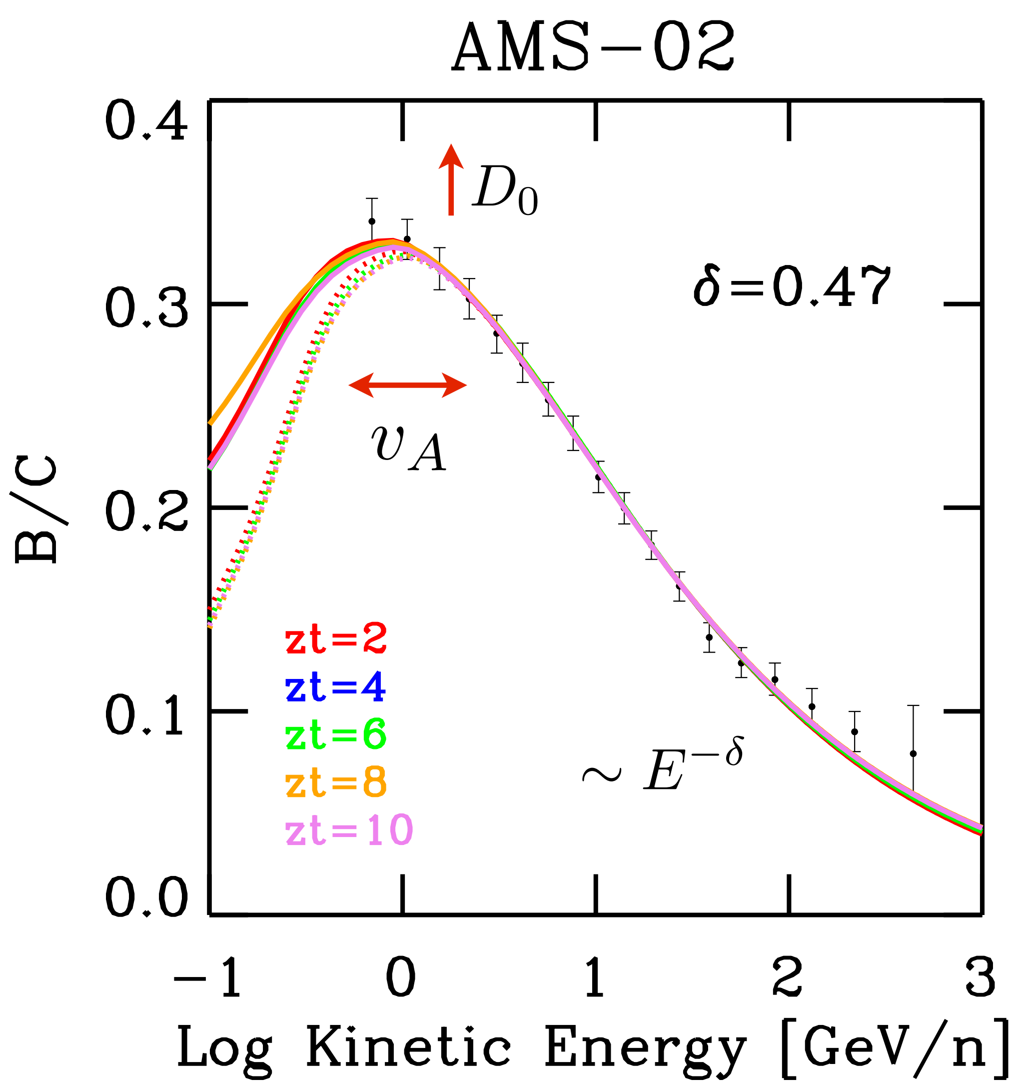


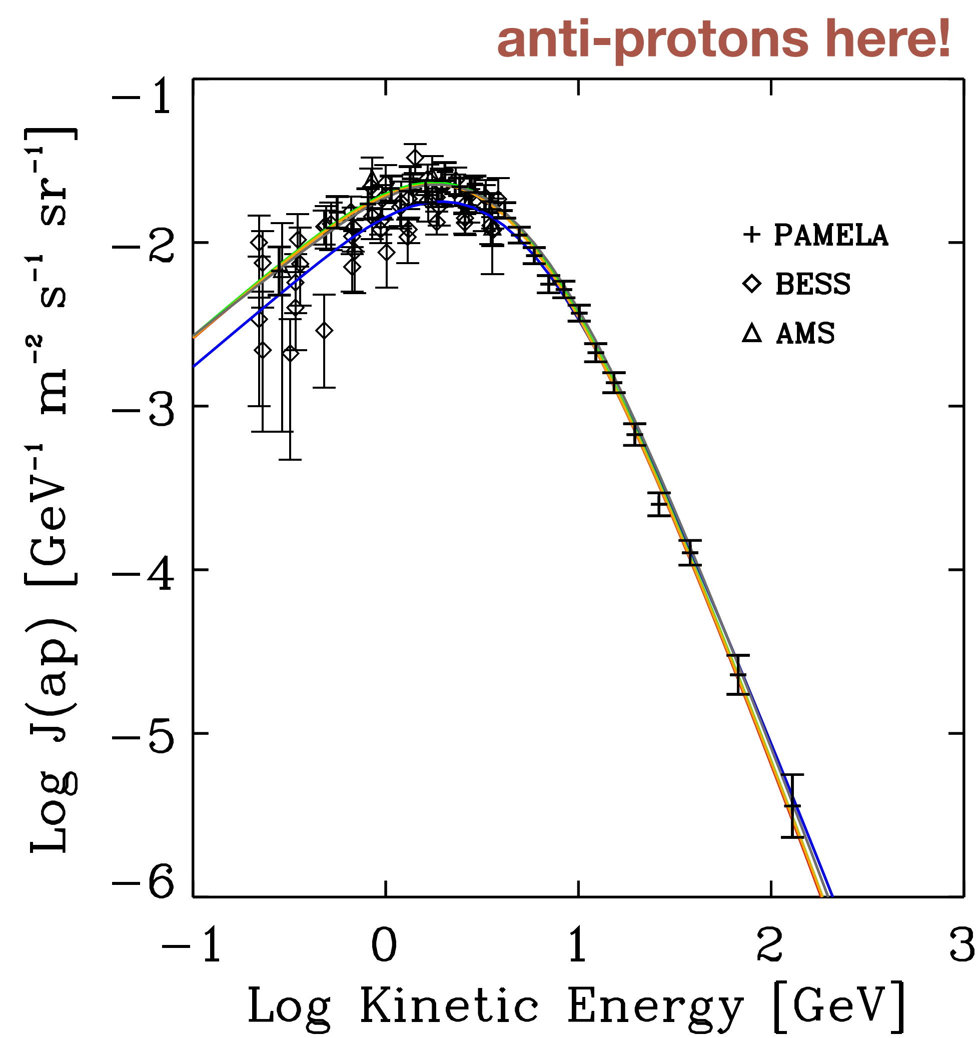


$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

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

Fitting local observables

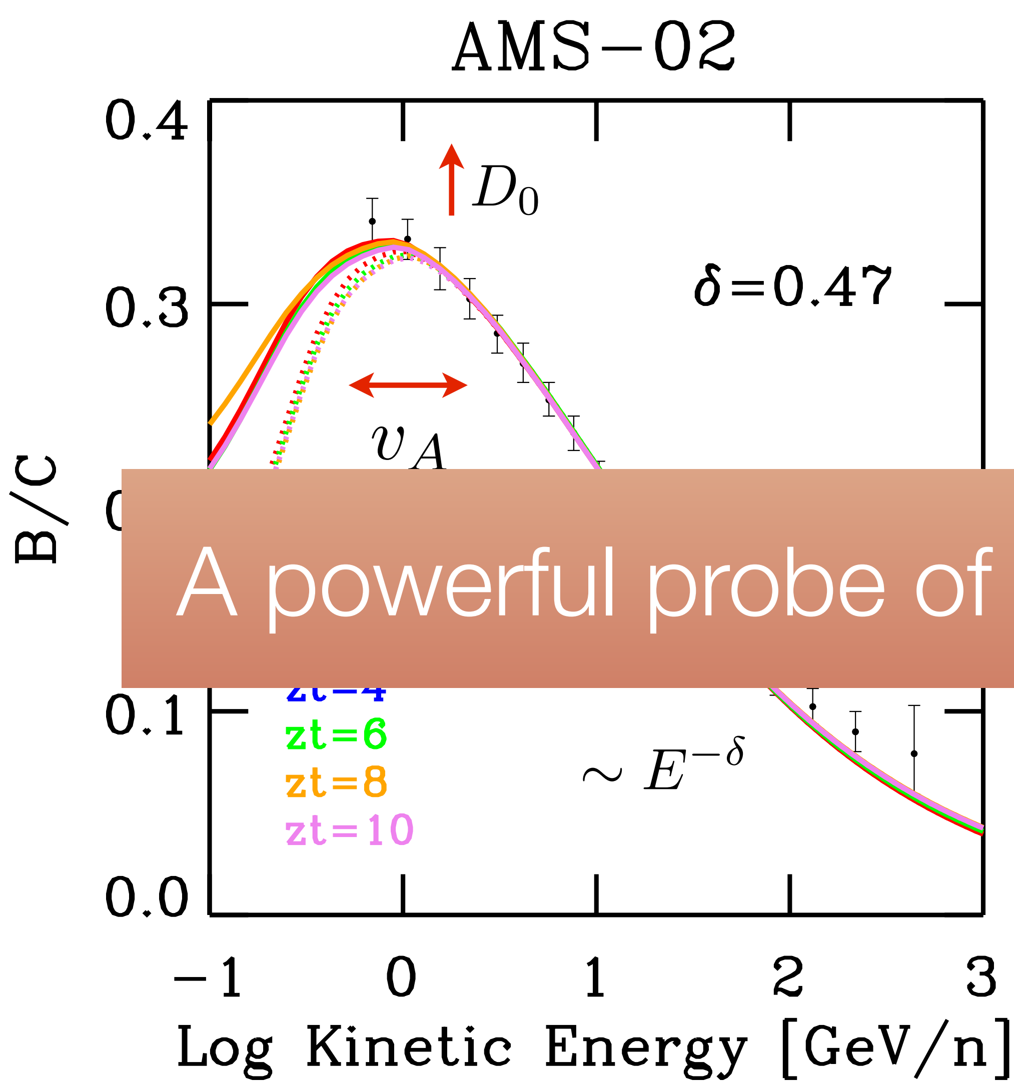


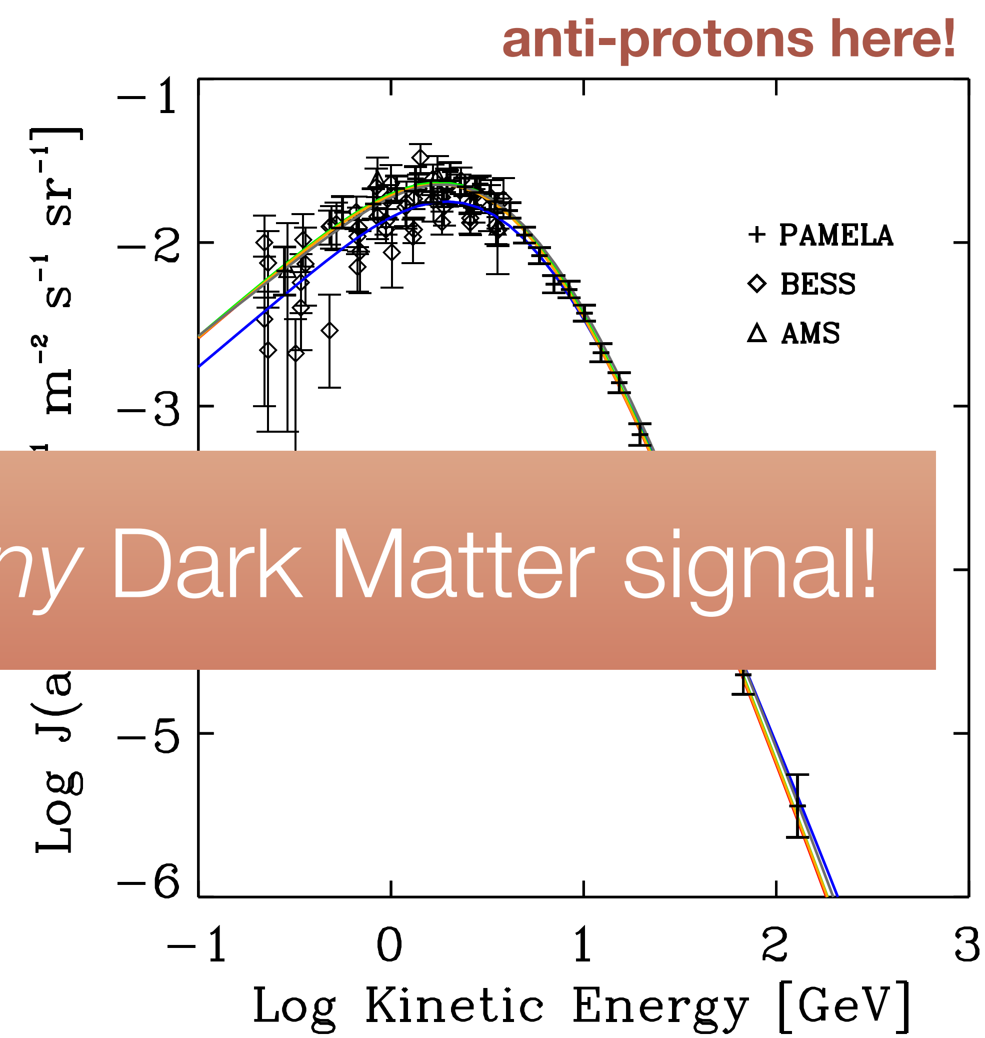


$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

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

Fitting local observables



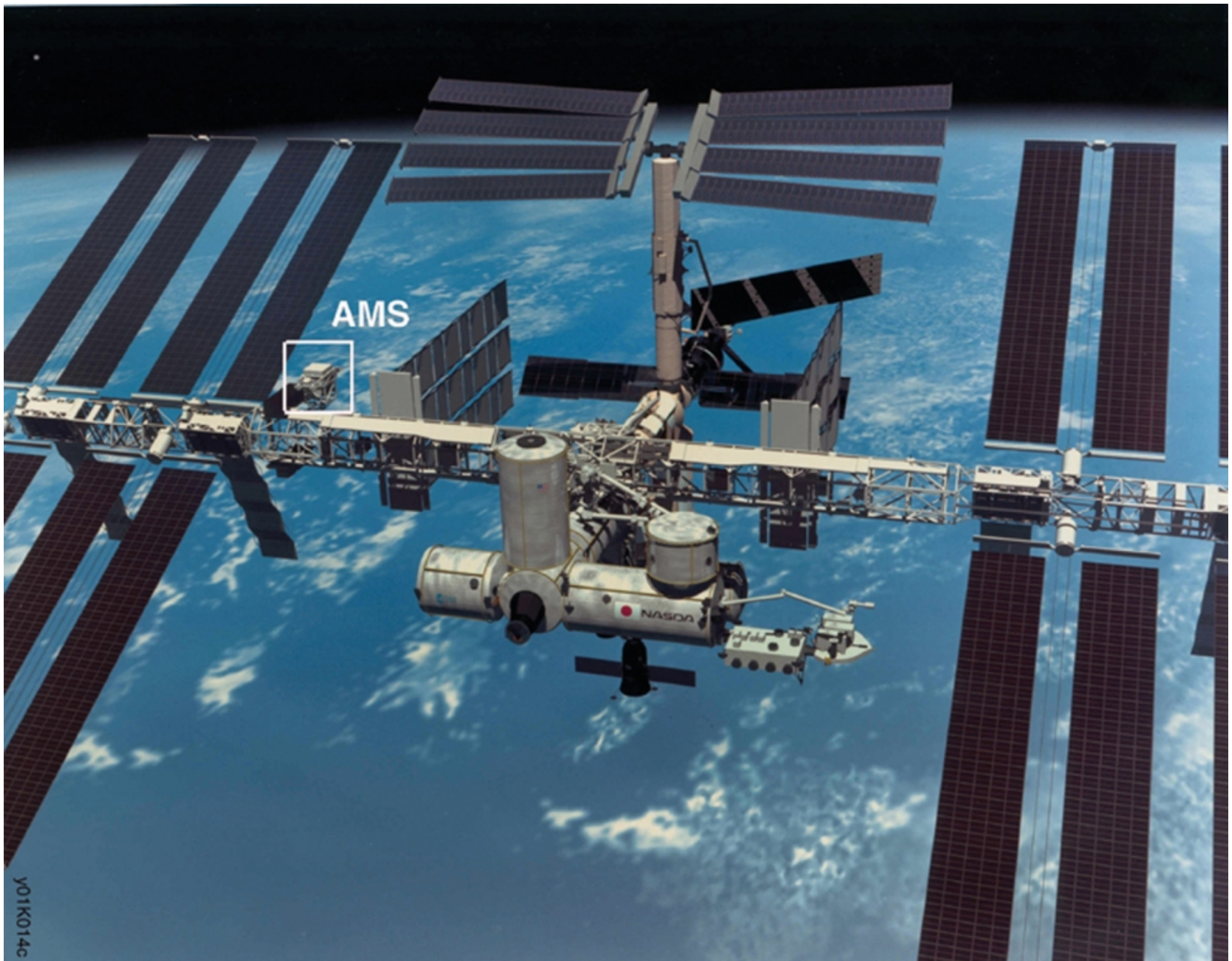


A powerful probe of the *tiny* Dark Matter signal!

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

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

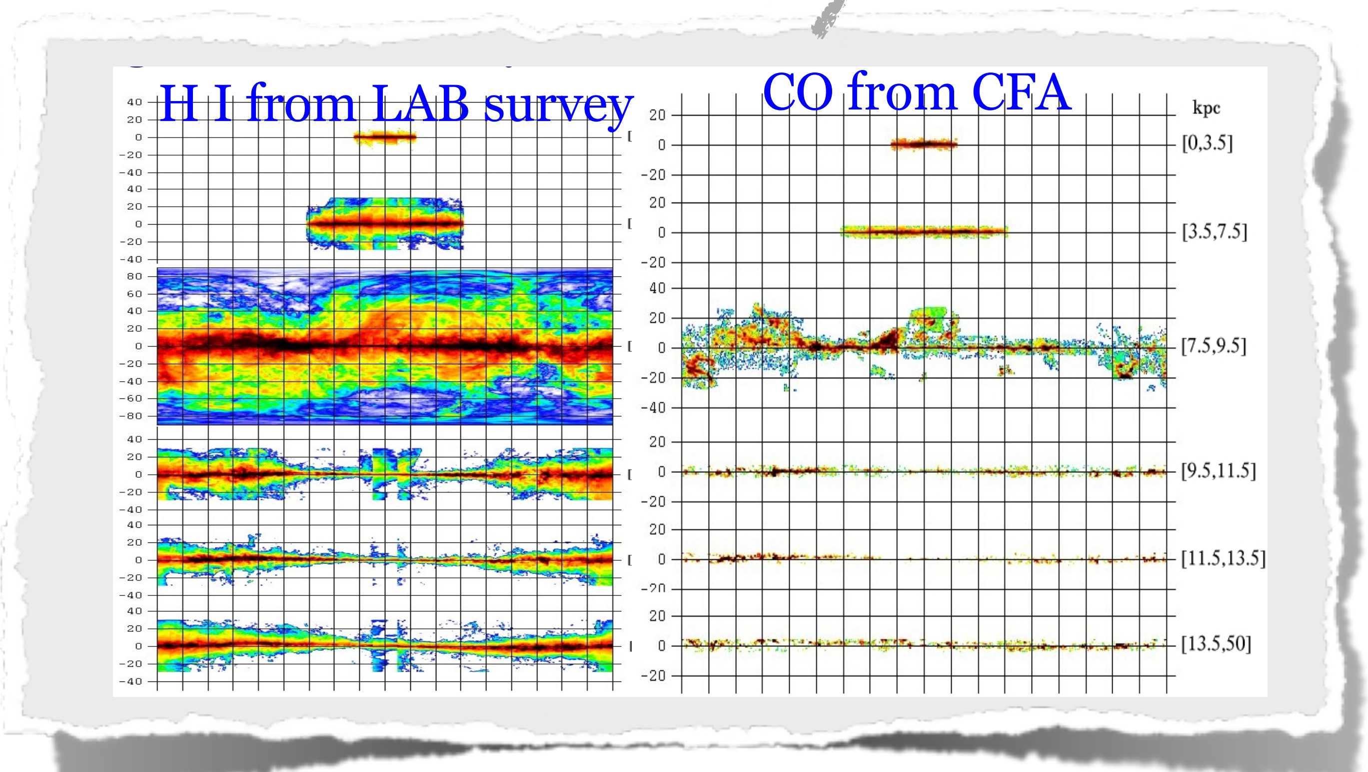
AMS-02 (2011-2021)




You are here

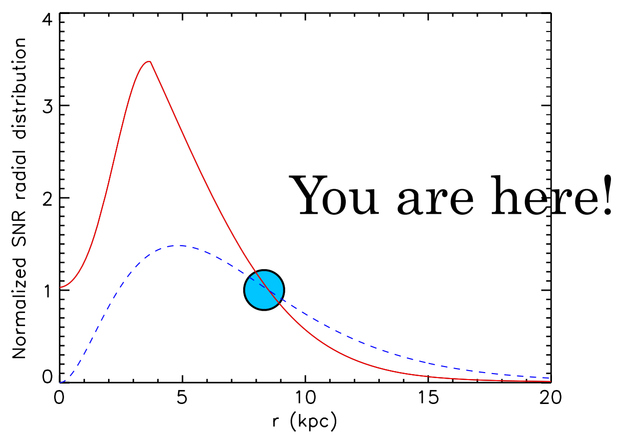
Is it possible being not-local?

- we can measure the anisotropy: $\delta \propto \nabla n_{\rm cr}$
- we can observe diffuse emissions: $\phi_\gamma \propto \int_{los} n_{\rm cr} \cdot n_{\rm gas} \, dr$



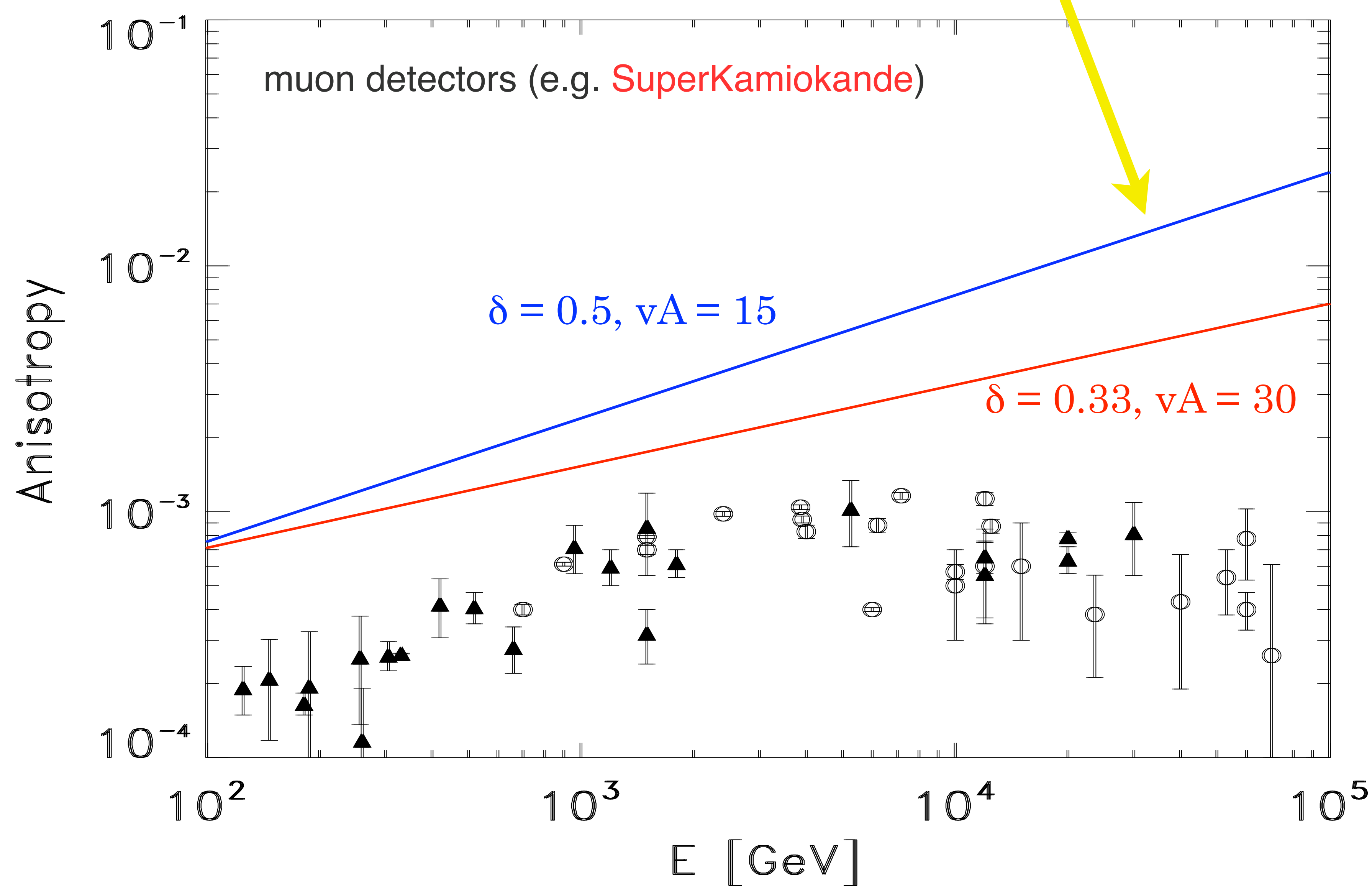
The *anisotropy* problem

Macro Collaboration, PRD, 2003; Super-Kamiokande Collaboration, PRD, 2007



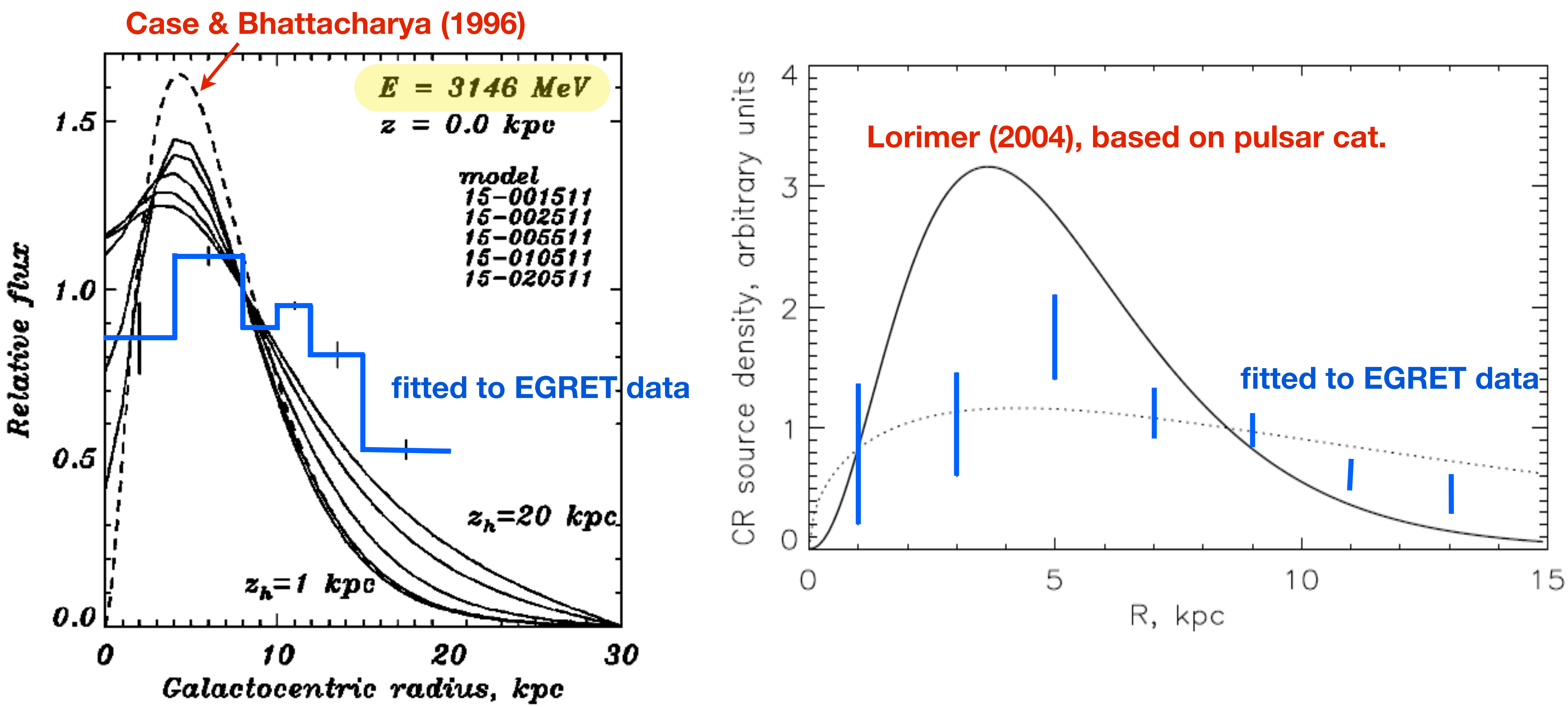
Since CR sources are more abundant in the inner Galaxy, a dipole anisotropy is expected towards the Galactic center:

$$\delta_{\vec{x}} = \frac{3D(E)}{c} \frac{\nabla_{\vec{x}} n_{CR}(E, \vec{r}, t)}{n_{CR}}$$



The *gradient* problem

Strong & Mattox, A&A, 1996; Strong et al., ApJ, 2000

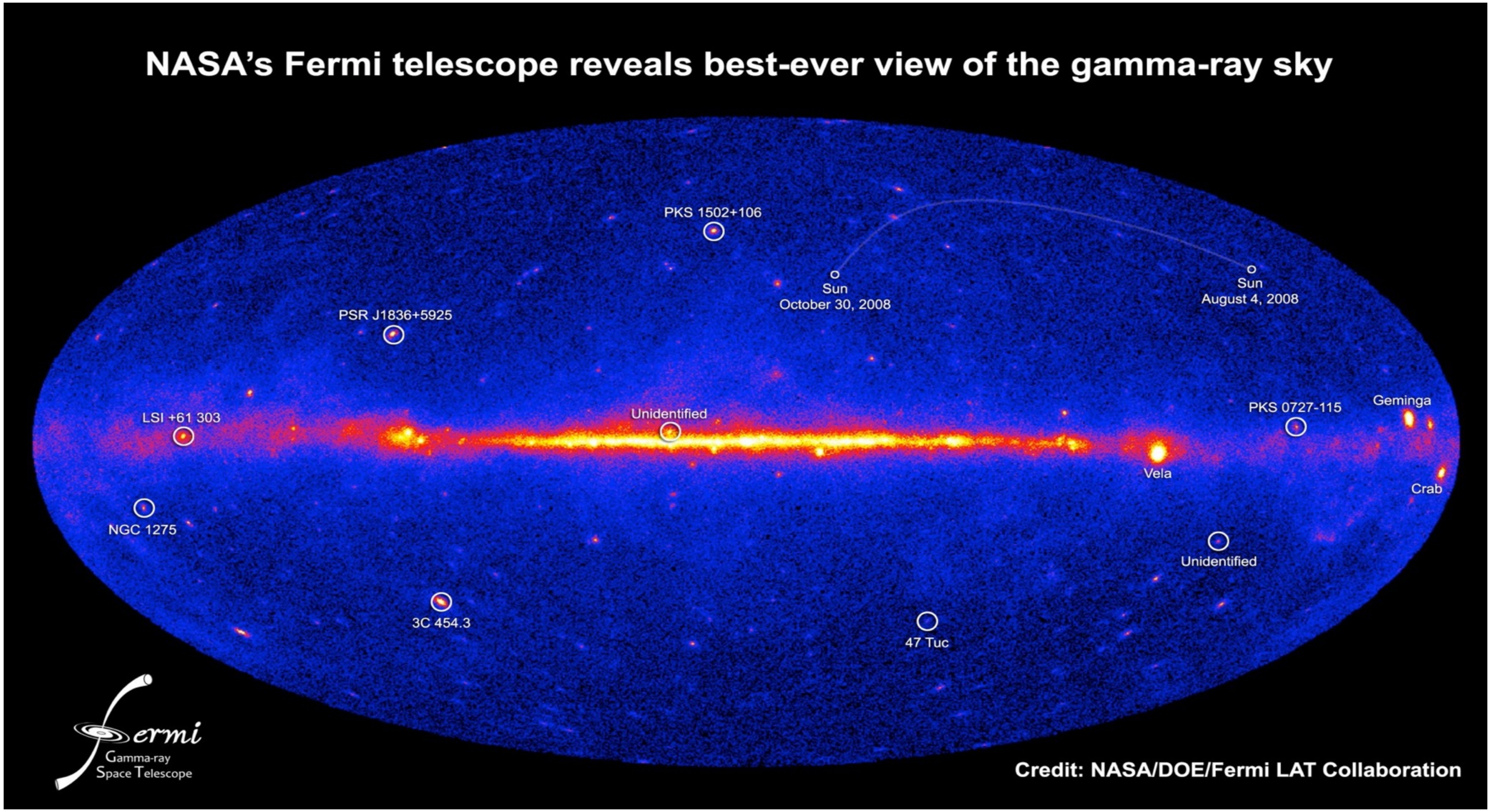


- CR distribution inferred from gamma-ray data (method goes back to SAS-2/COS-B era) is **flatter** than that computed assuming the observed **SNR** (source) profile.

FERMI (2008-2018)

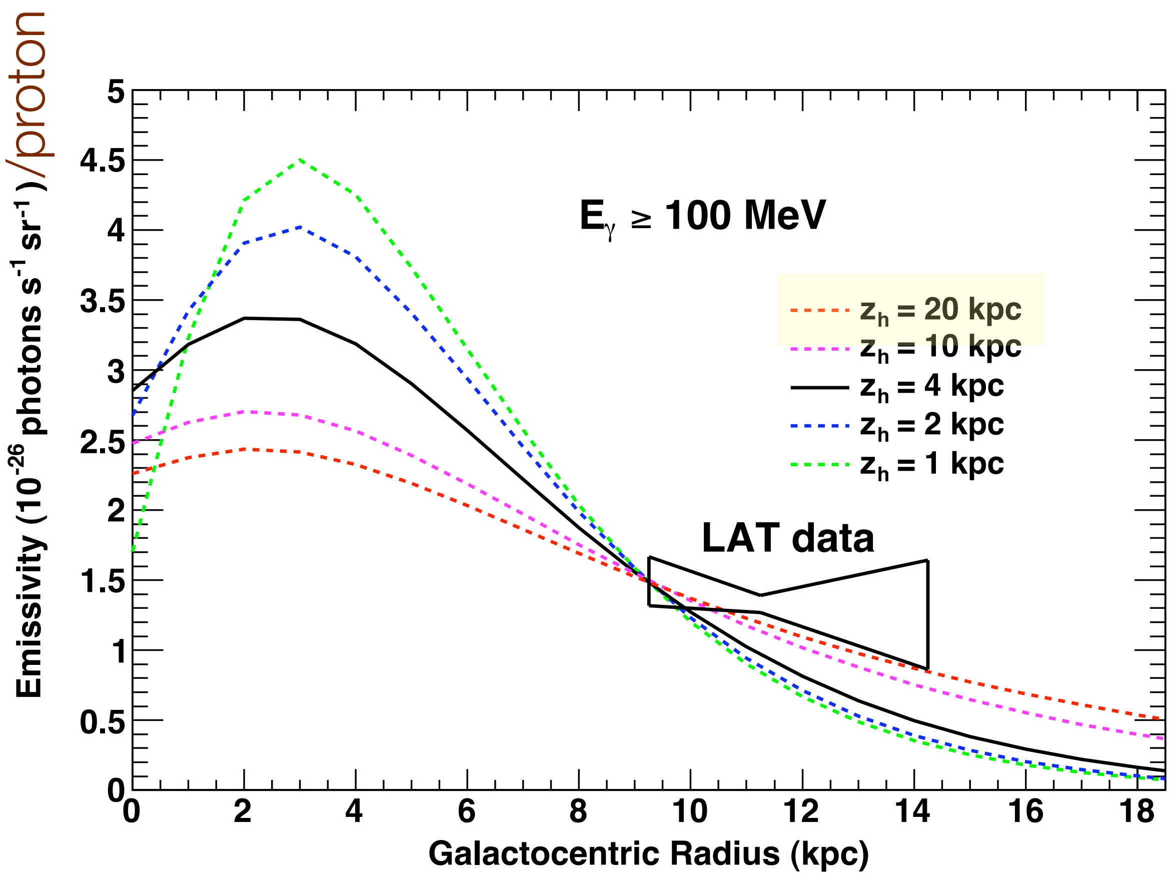
The *gradient* problem in the FERMI era

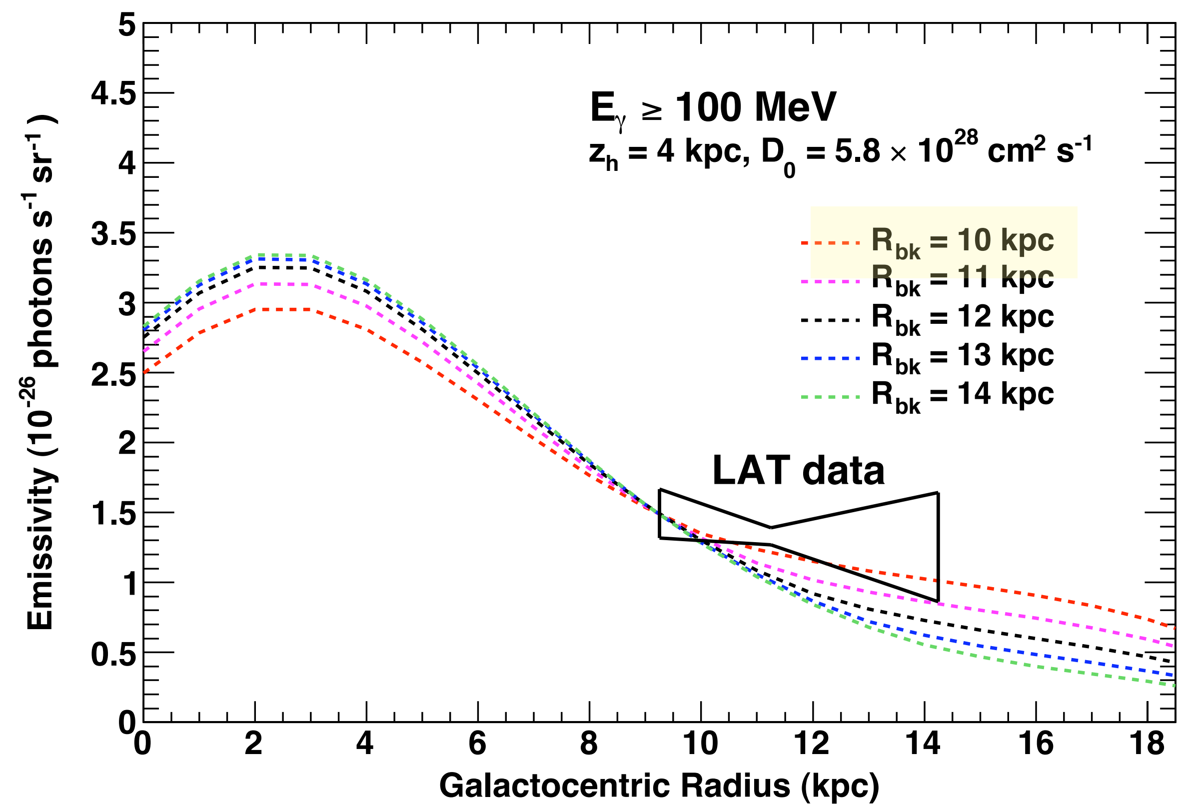
- The extremely accurate gamma ray maps that Fermi is providing are useful to trace the CR distribution throughout all the Galaxy!



The *gradient* problem in the FERMI era

Fermi Collaboration, ApJ, 2011



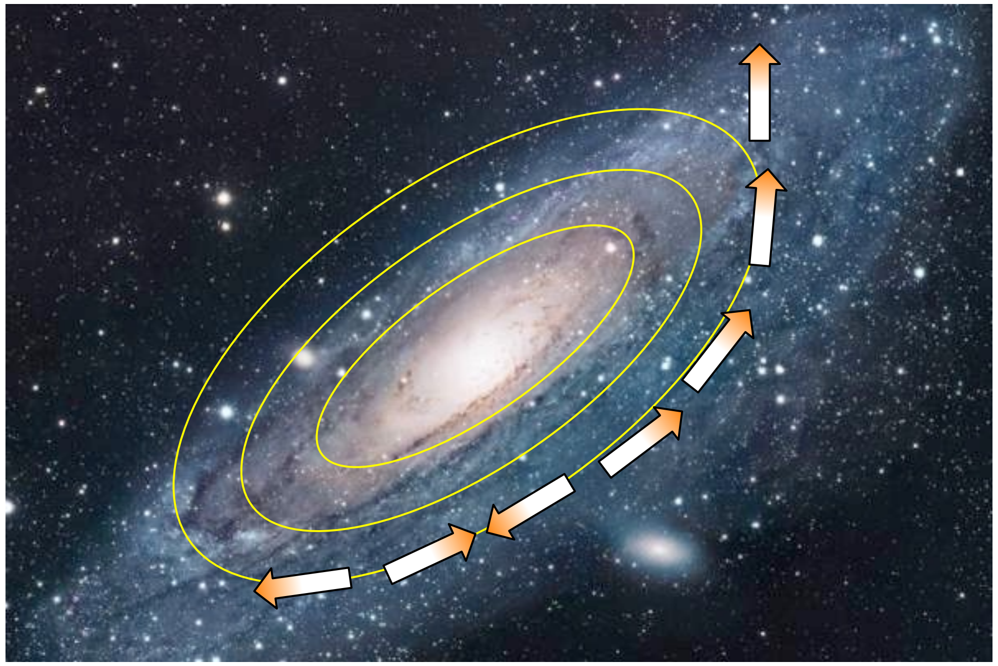


FERMI detected **more** γ's than a prediction based on SNR distribution and standard CR halo: more CR sources, more "dark gas" or larger CR halo?

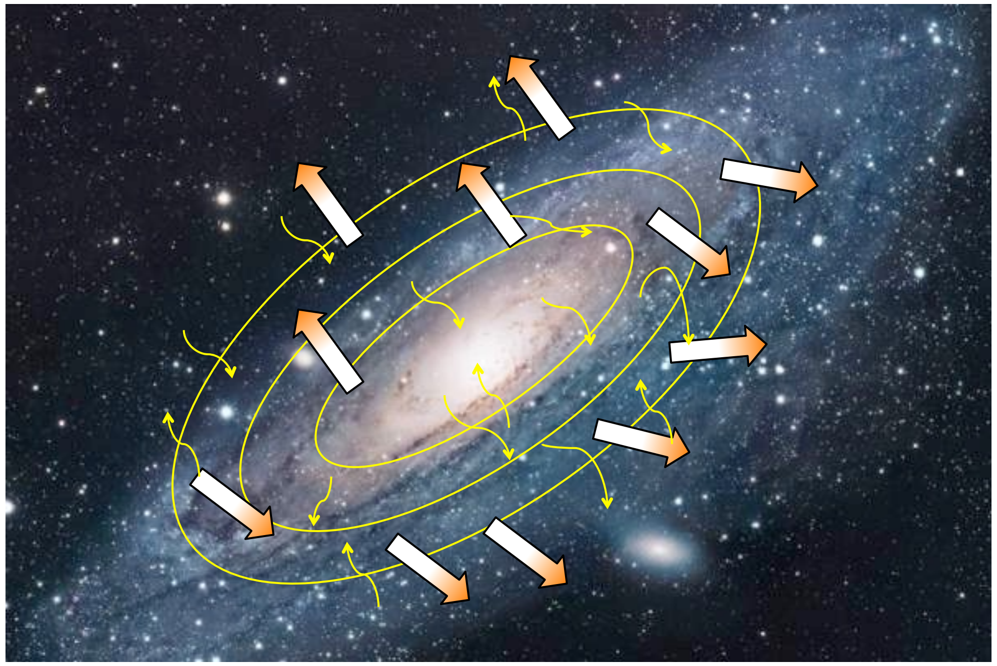
Diffusion is more complicate than that!

- How do the diffusion coefficient depends on turbulence?

If the turbulent field is very low:



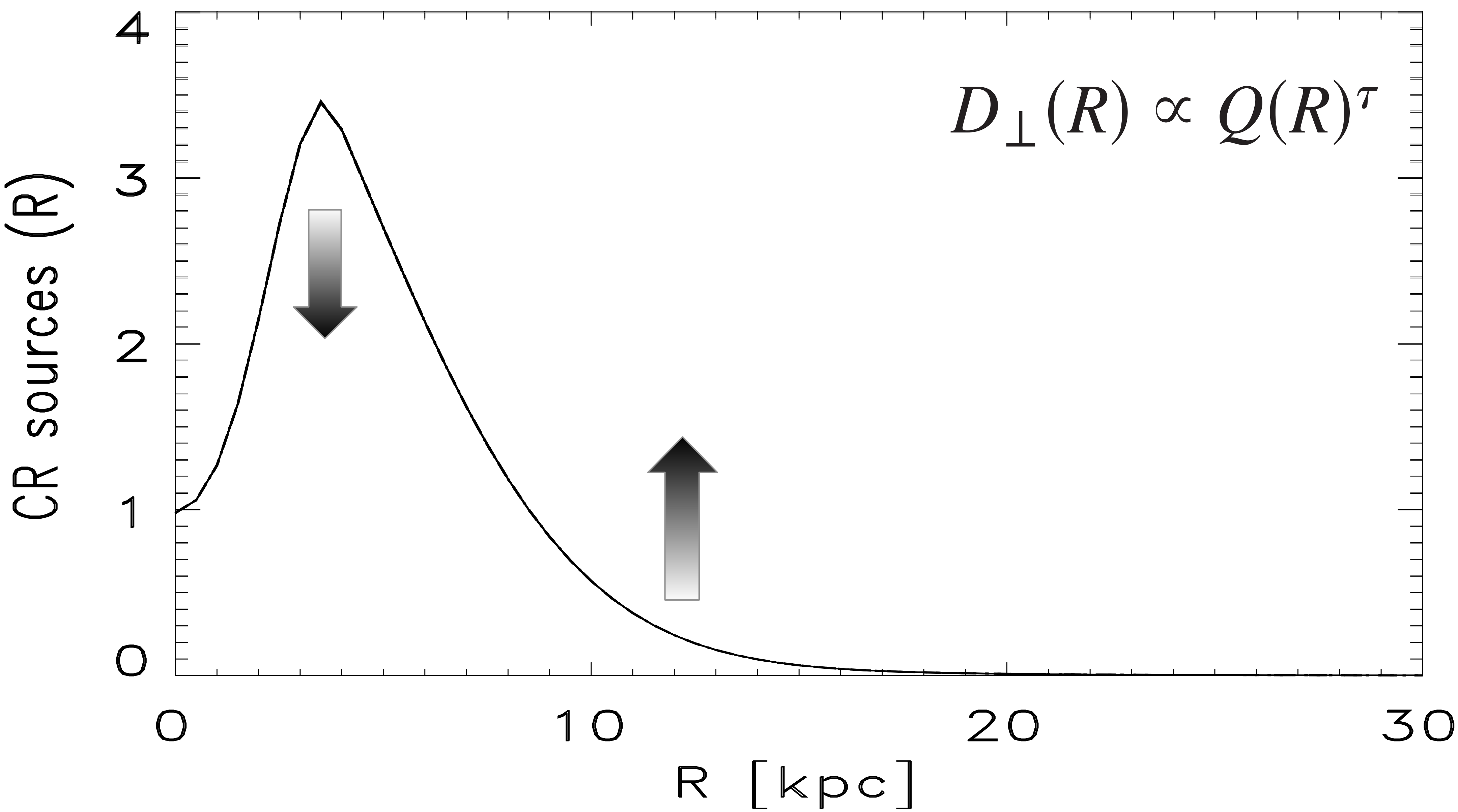
If the turbulent component is comparable to the regular field:



- In the inner galaxy, where turbulence is high, the parallel and perp. diffusion are similar values and the perpendicular escape is the dominant one:

$$\frac{T_{\|}}{T_{\perp}} \simeq \left(\frac{R_{\mathrm{arm}}}{H}\right)^2 \frac{D_{\perp}}{D_{\|}} \simeq 4 \times 10^2 \left(\frac{H}{4\ \mathrm{kpc}}\right)^{-2} \frac{D_{\perp}}{D_{\|}}$$

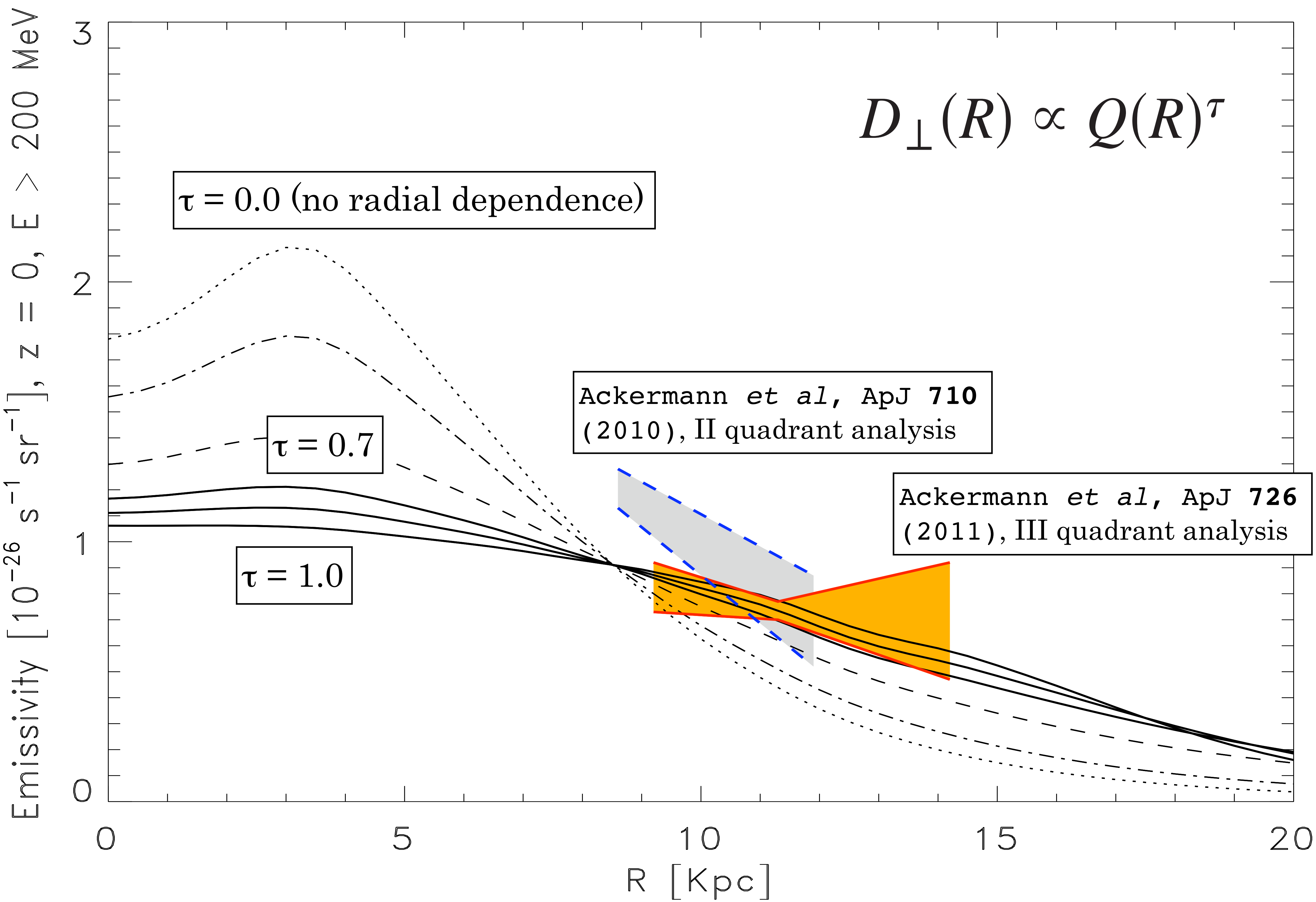
How to solve the gradient problem



- In the regions where CR sources are more abundant turbulence is higher then perpendicular escape is faster, more CR are removed.

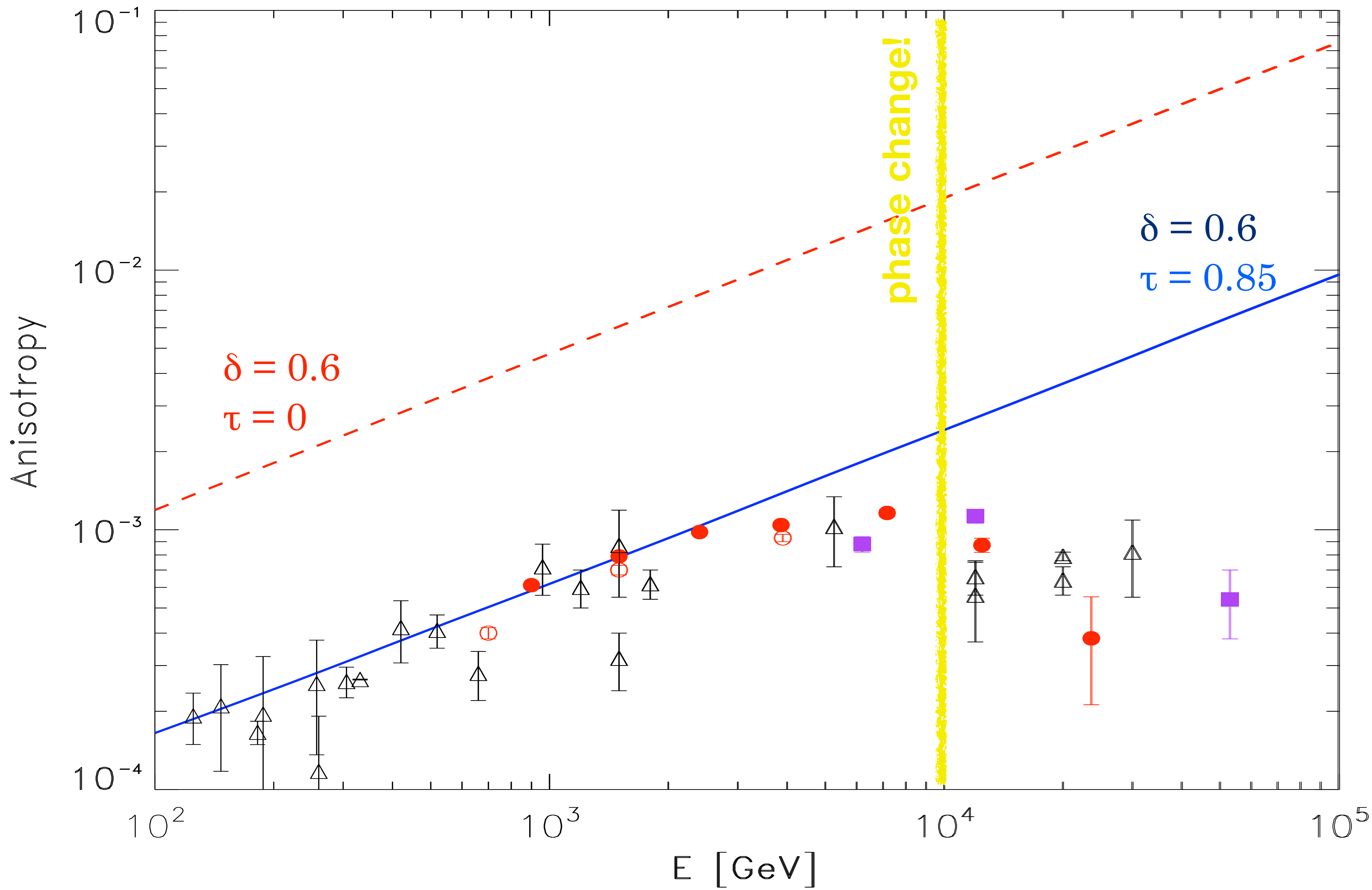
Results

CE, D. Gaggero, D. Grasso & L. Maccione, PRL, 2012



Anisotropy prediction

CE, D. Gaggero, D. Grasso & L. Maccione, PRL, 2012

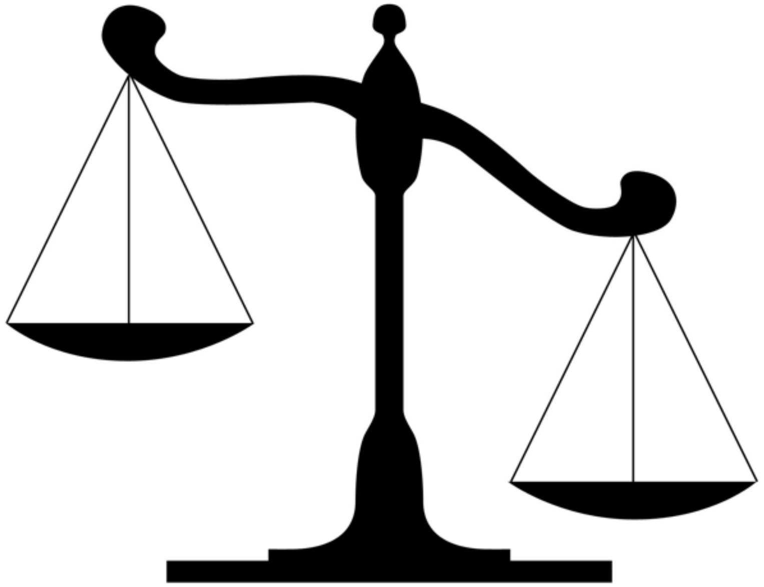


The dark side

The challenge!

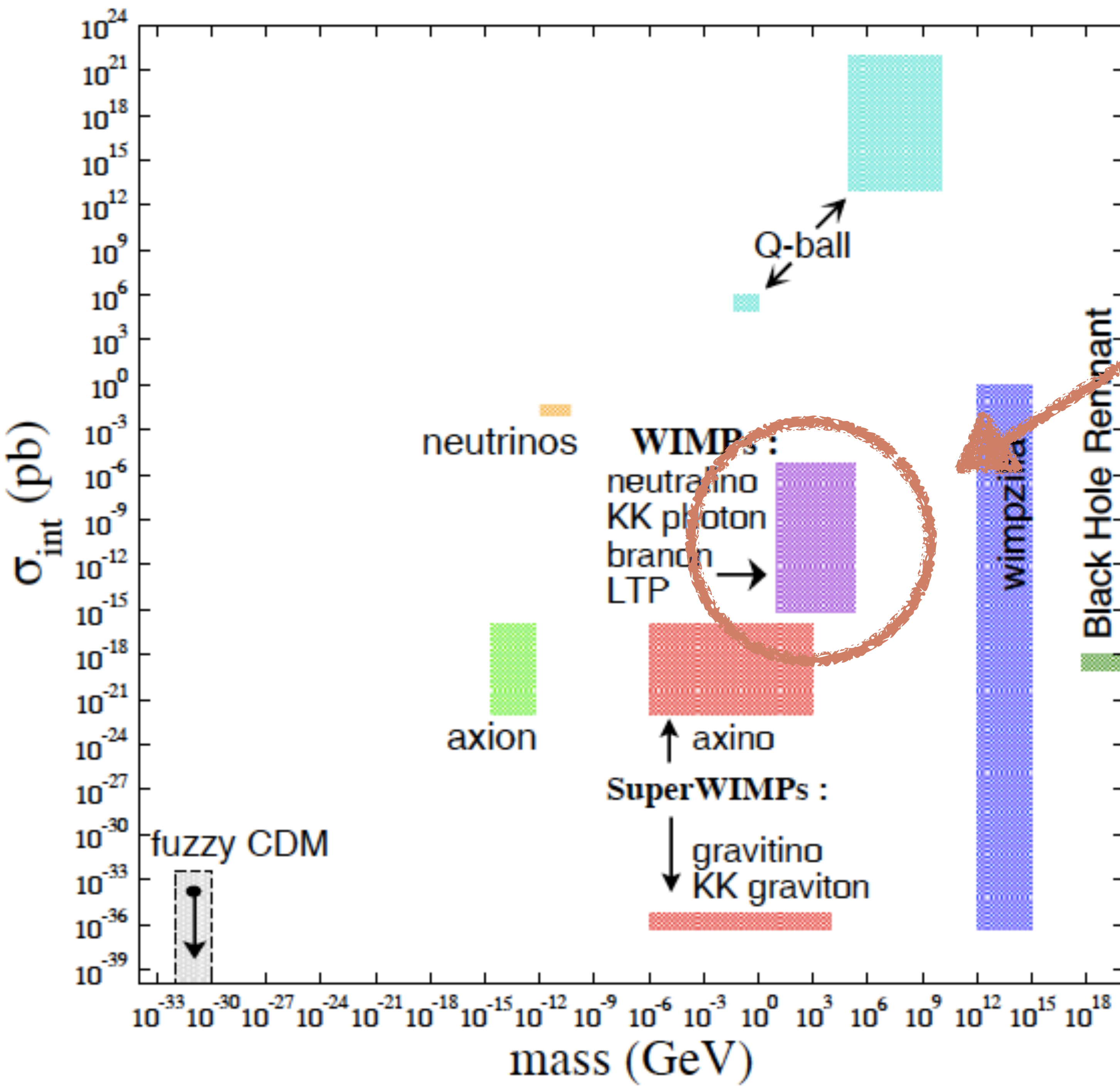
Andromeda : a MW-like galaxy

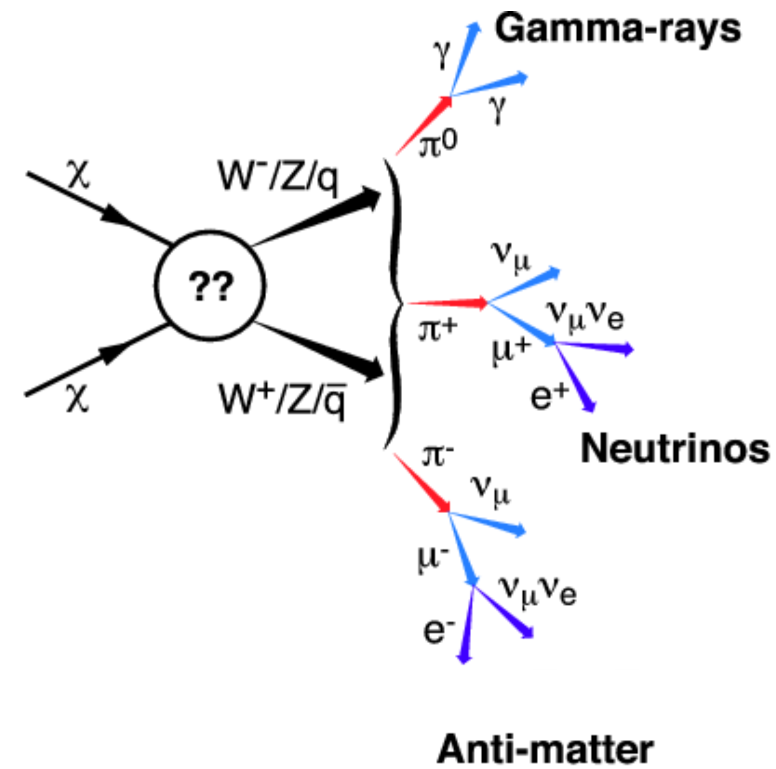
1



5

The importance of being WIMP





$$\epsilon_\chi \sim \frac{\rho_\chi^2}{m_\chi}\langle\sigma v\rangle \sim 5\times 10^{-29}\,\mathrm{GeV\,cm^{-3}\,s^{-1}}$$

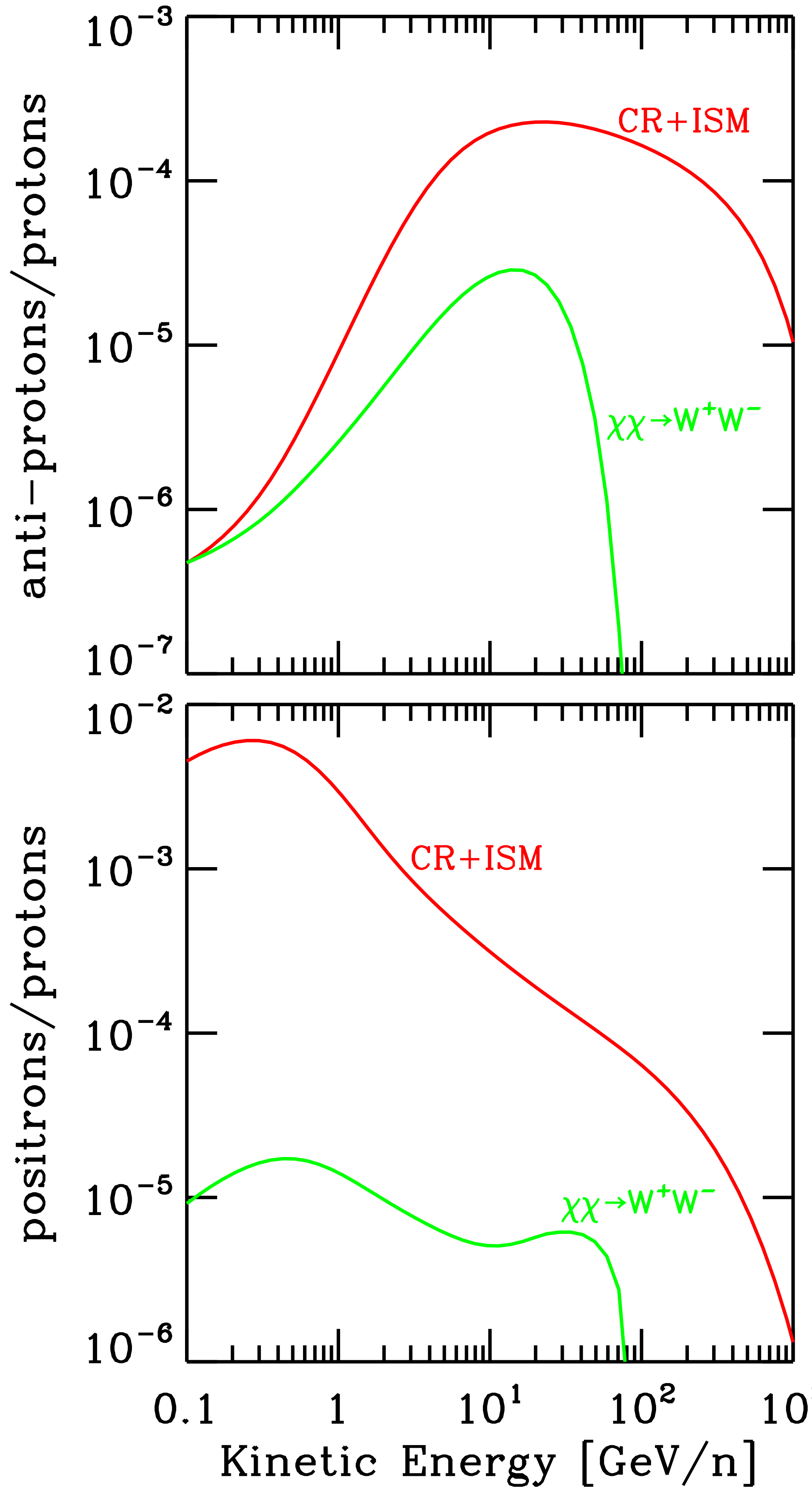
$$\epsilon_{\rm CR} \sim E^2\phi_{\rm CR}\, n_{\rm ISM}\,\sigma_{pp} \sim 5\times 10^{-25}\,\mathrm{GeV\,cm^{-3}\,s^{-1}}$$

problem!

astrophysical emissivity is much larger than Dark one

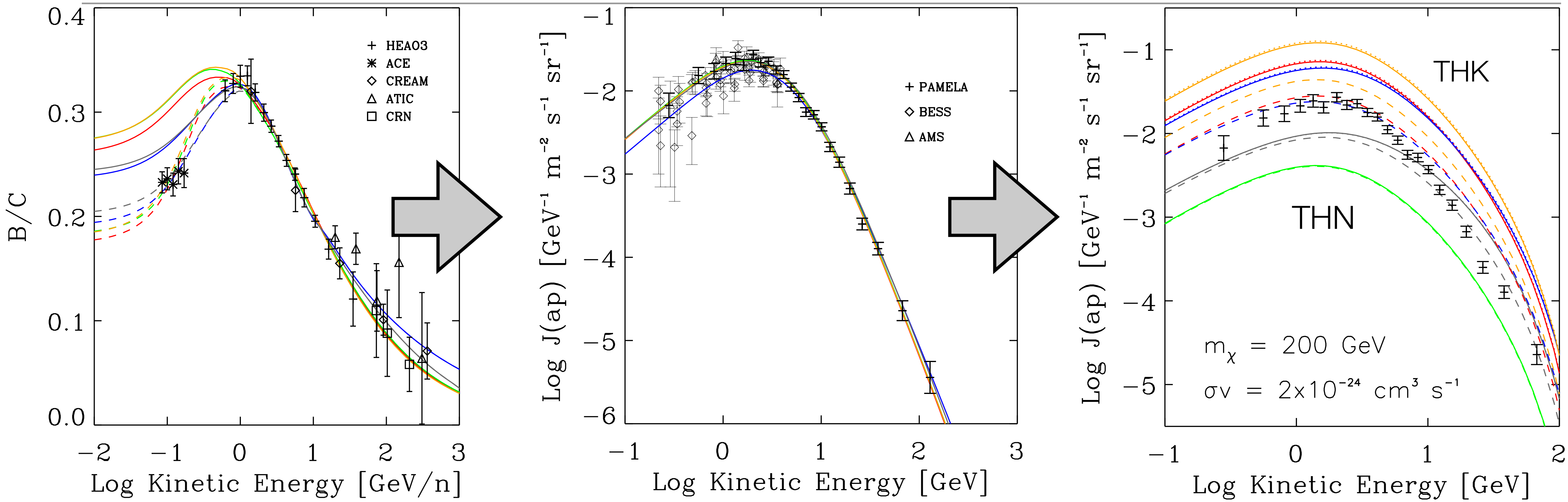
Why antiprotons?

- we know the **background** with good accuracy
- in a **democratic** WIMP model the ratio between DM signal and background from standard astrophysical sources is usually much larger in the **antiproton** channel with respect to all other indirect detection methods.



Playing with anti-protons from DM

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664

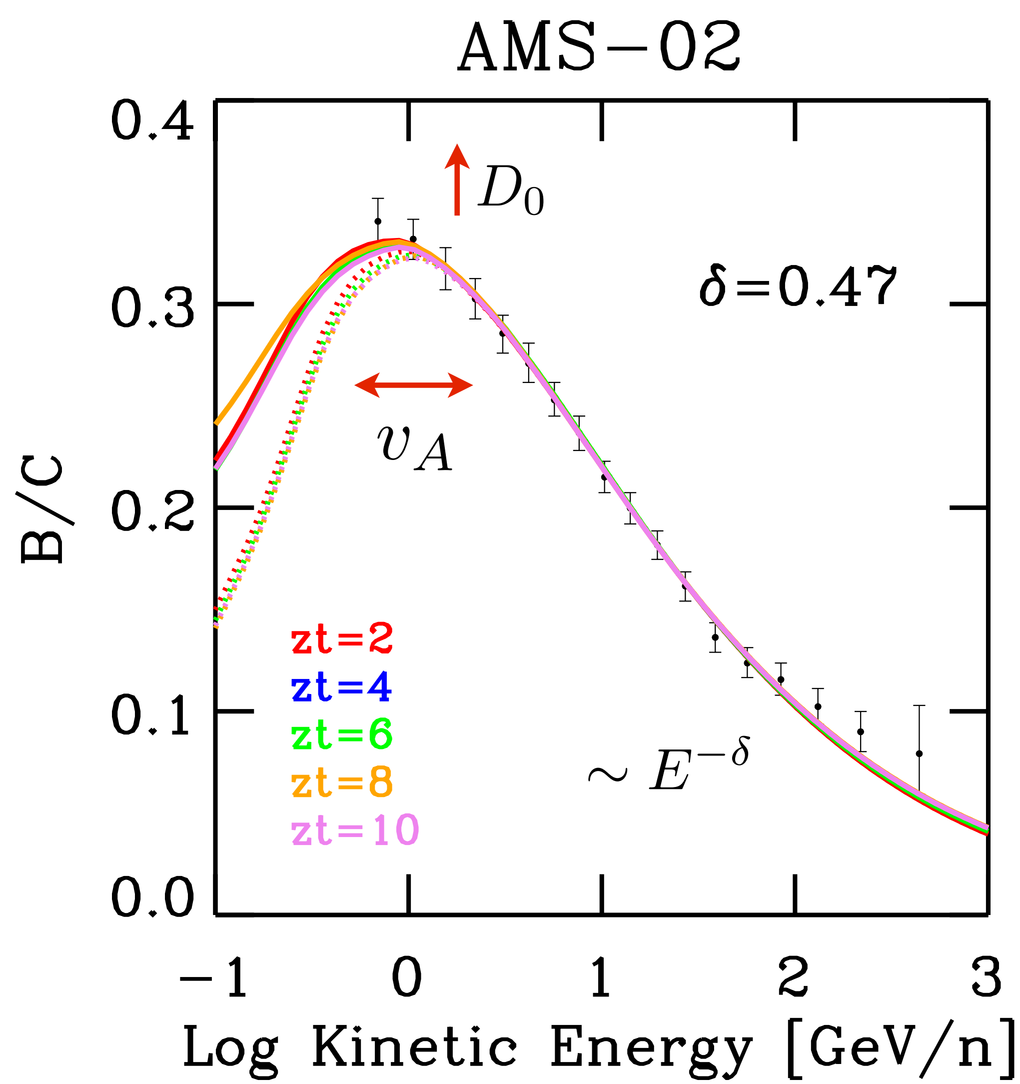


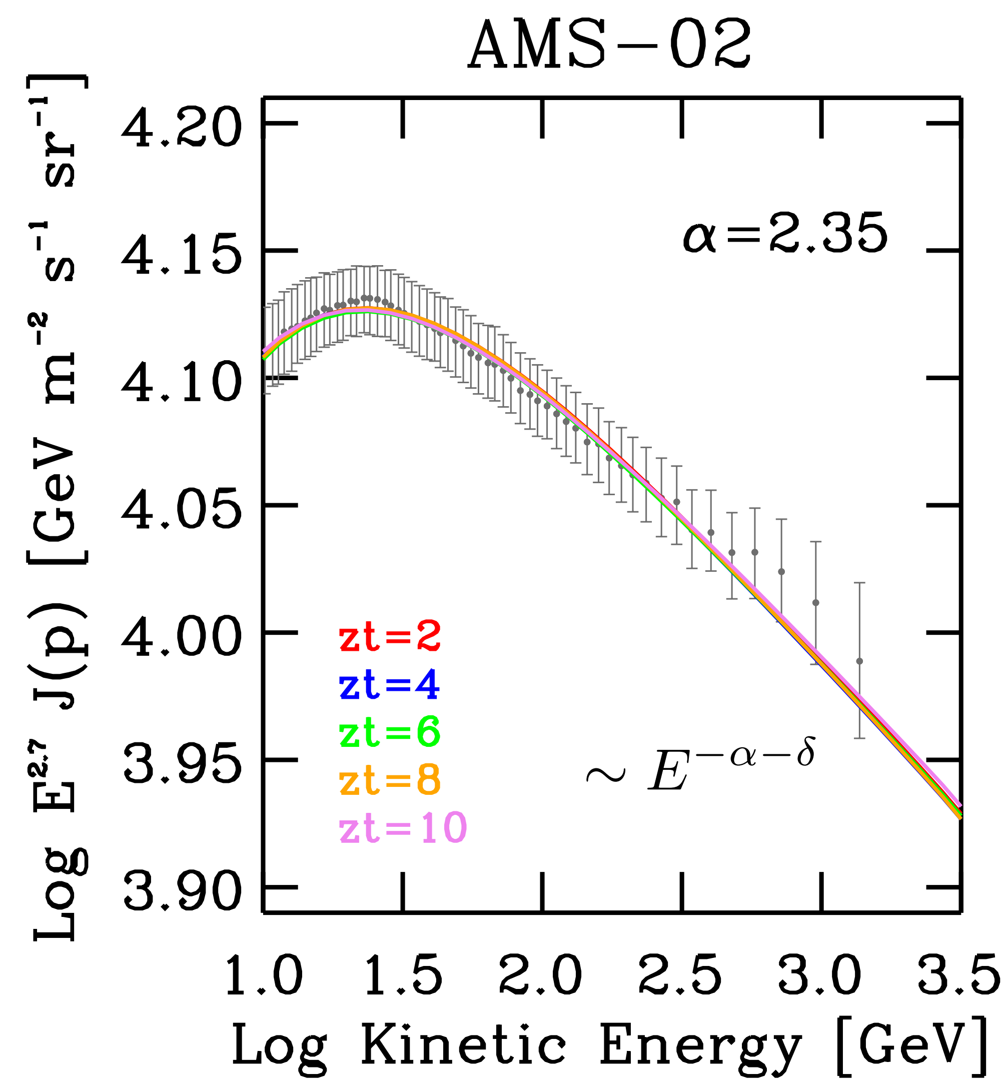
30%

~1 oom

Model	z_t (kpc)	δ	$D_0(10^{28}$ cm^2/s)	η	v_A (km/s)	γ	dv_c/dz (km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)	$\chi^2_{\bar{p}}$	Color in Figs.
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67	0.59	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36	1.84	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	0.7	0.46	0.70	0.73	Green
THK	10	0.50	4.75	−0.15	14.1	2.35	0	0.7	0.55	0.69	0.62	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.4	0.53	0.21	1.32	Gray

Varying the halo size in the range 2 - 10 kpc



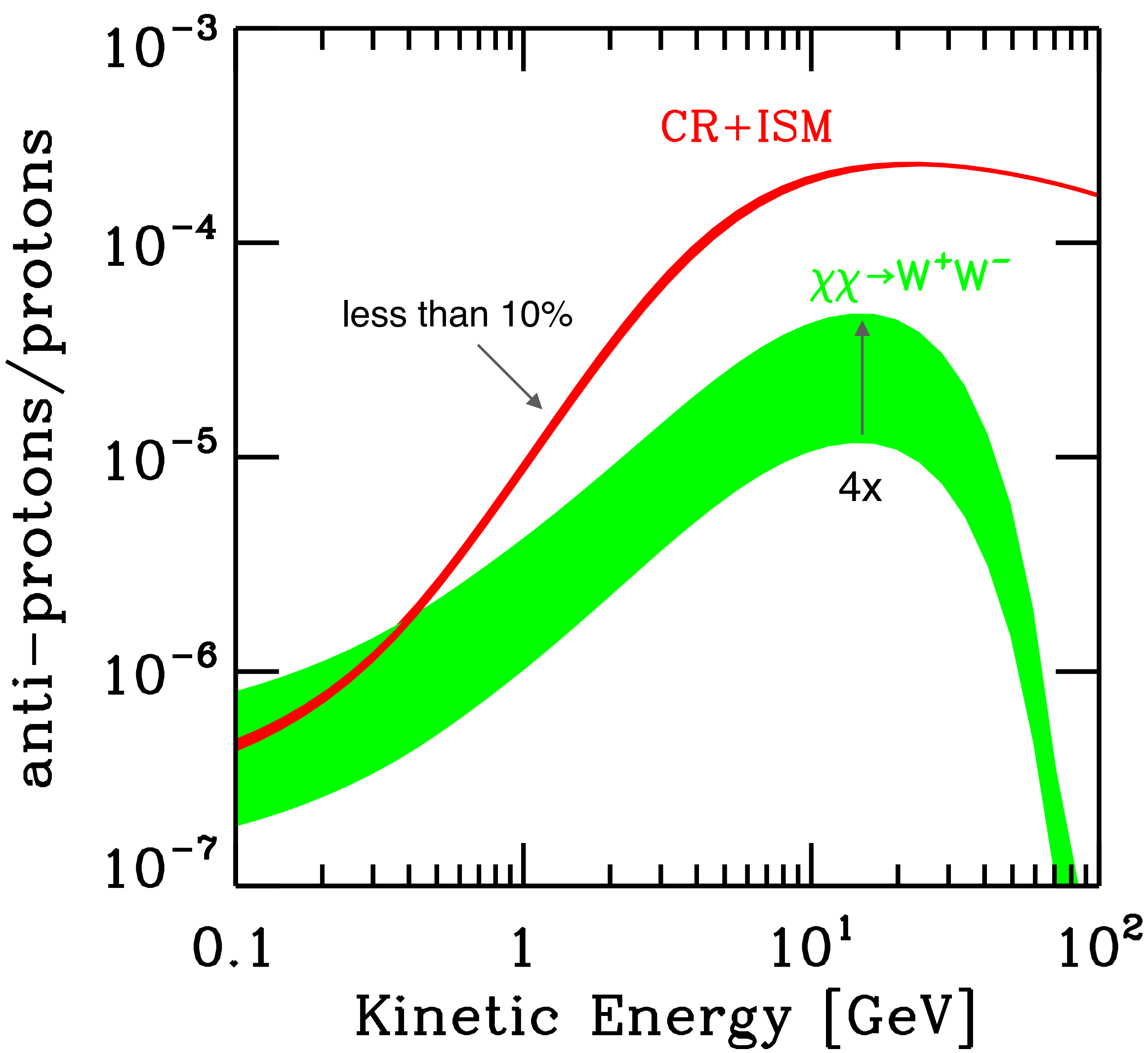


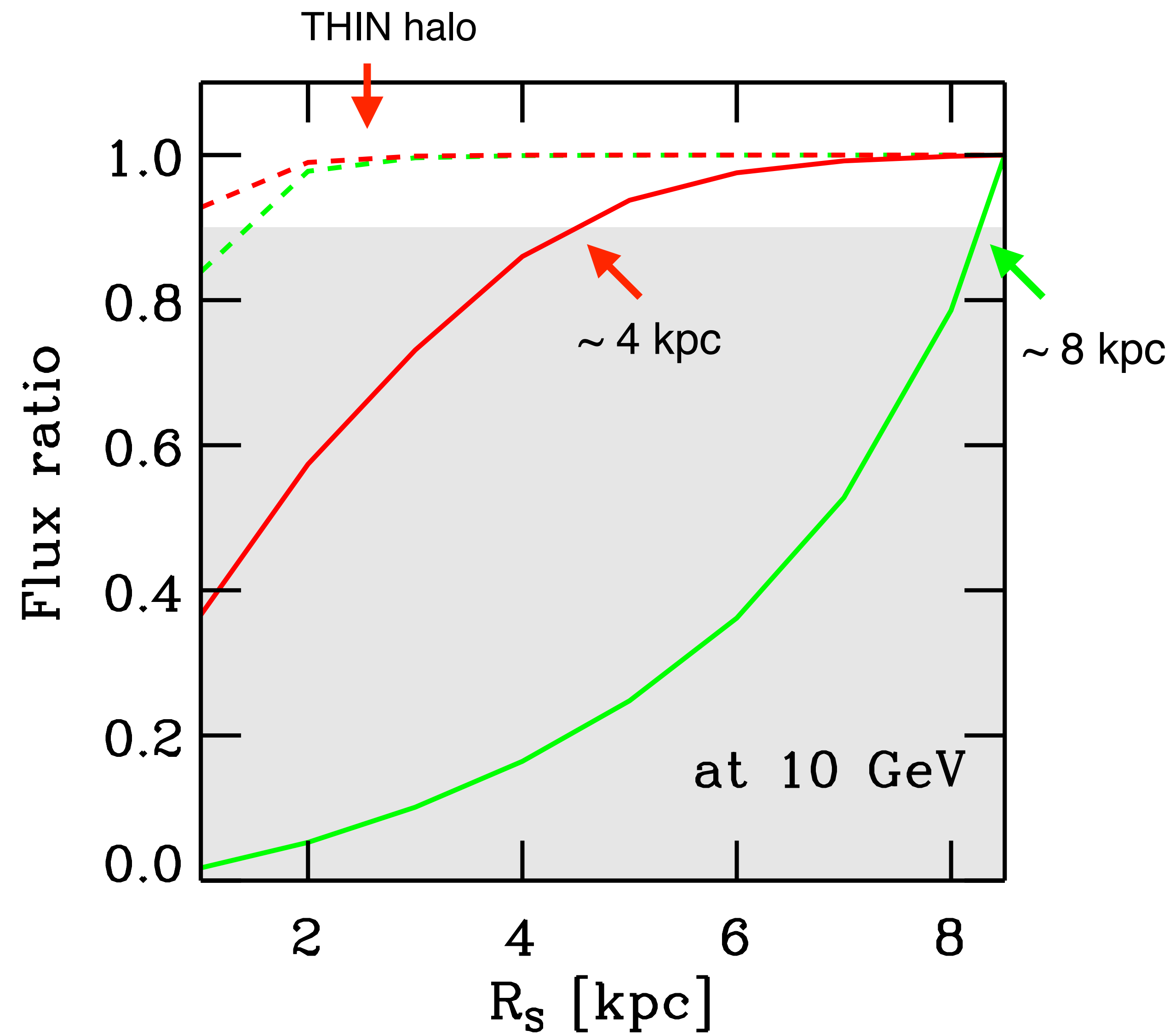
$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

The best constraints on the halo scale height (L > 2 kpc) are obtained from the galactic diffuse synchrotron emission (G.Di Bernardo, CE, D.Gaggero, D.Grasso and L.Maccione, JCAP, 2013)

Varying the halo size in the range 2 - 10 kpc

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664



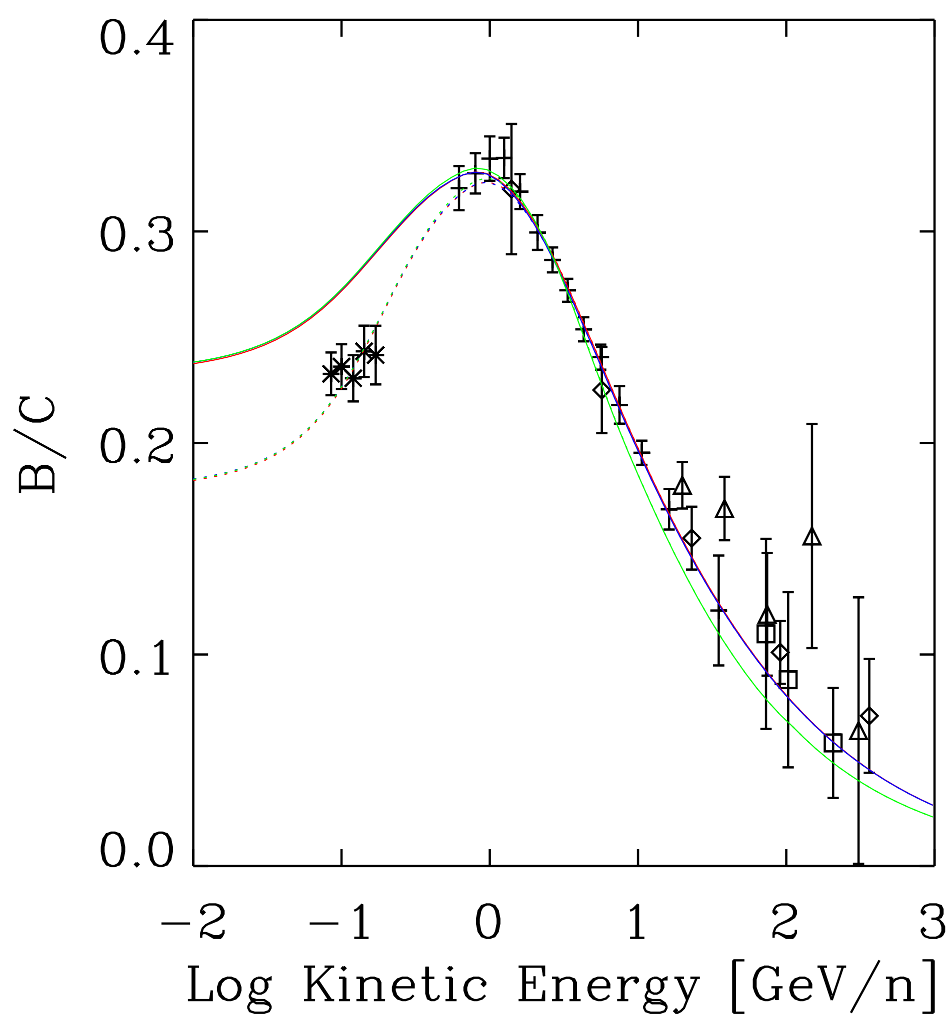


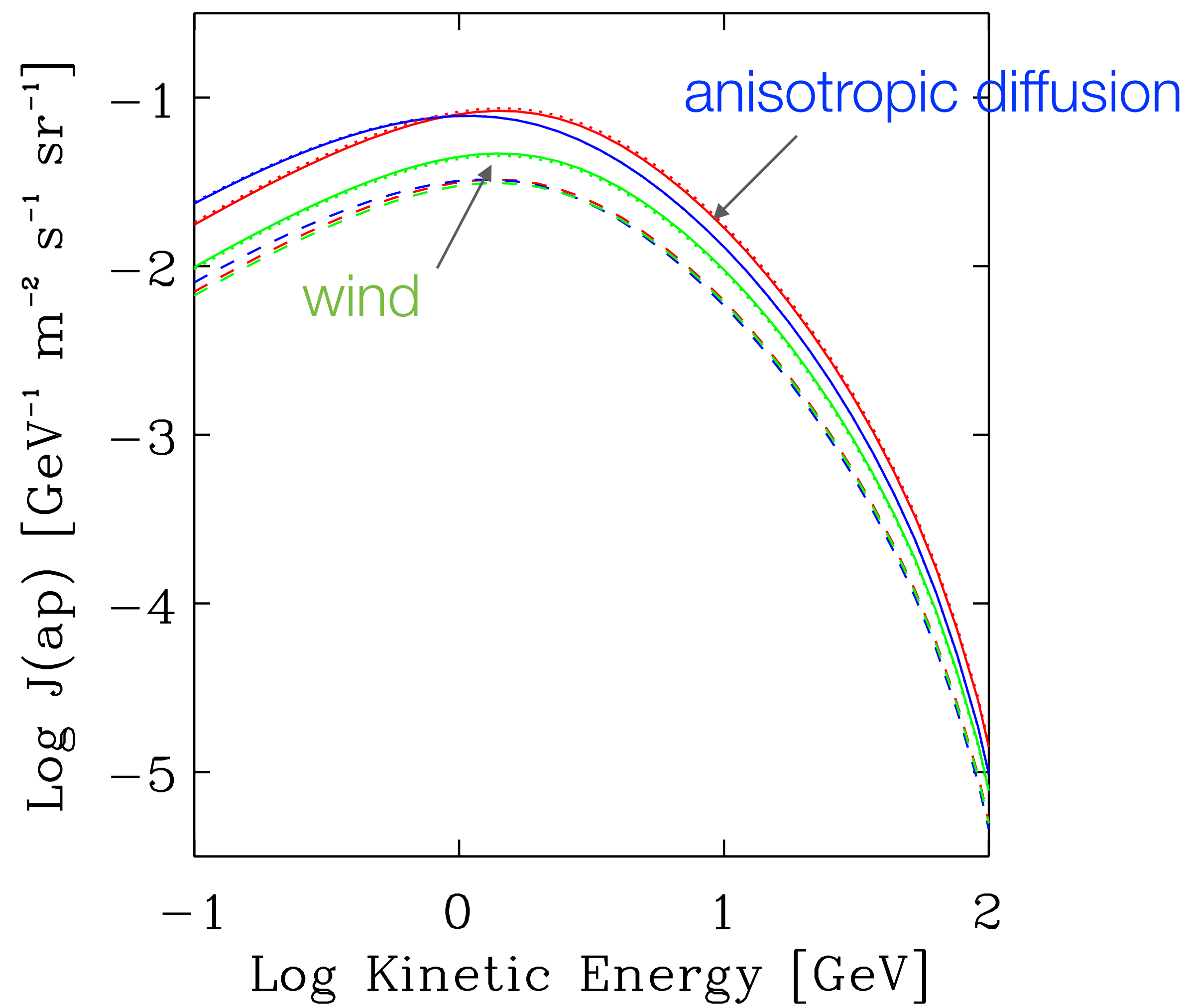
Much larger uncertainty in the DM fluxes!

The ratio of the local flux obtained considering sources with distance smaller than R_S to that obtained with $R_S = \infty$
(see also R. Taillet & D. Maurin, A&A, 2003)

Unavoidable uncertainties?

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664

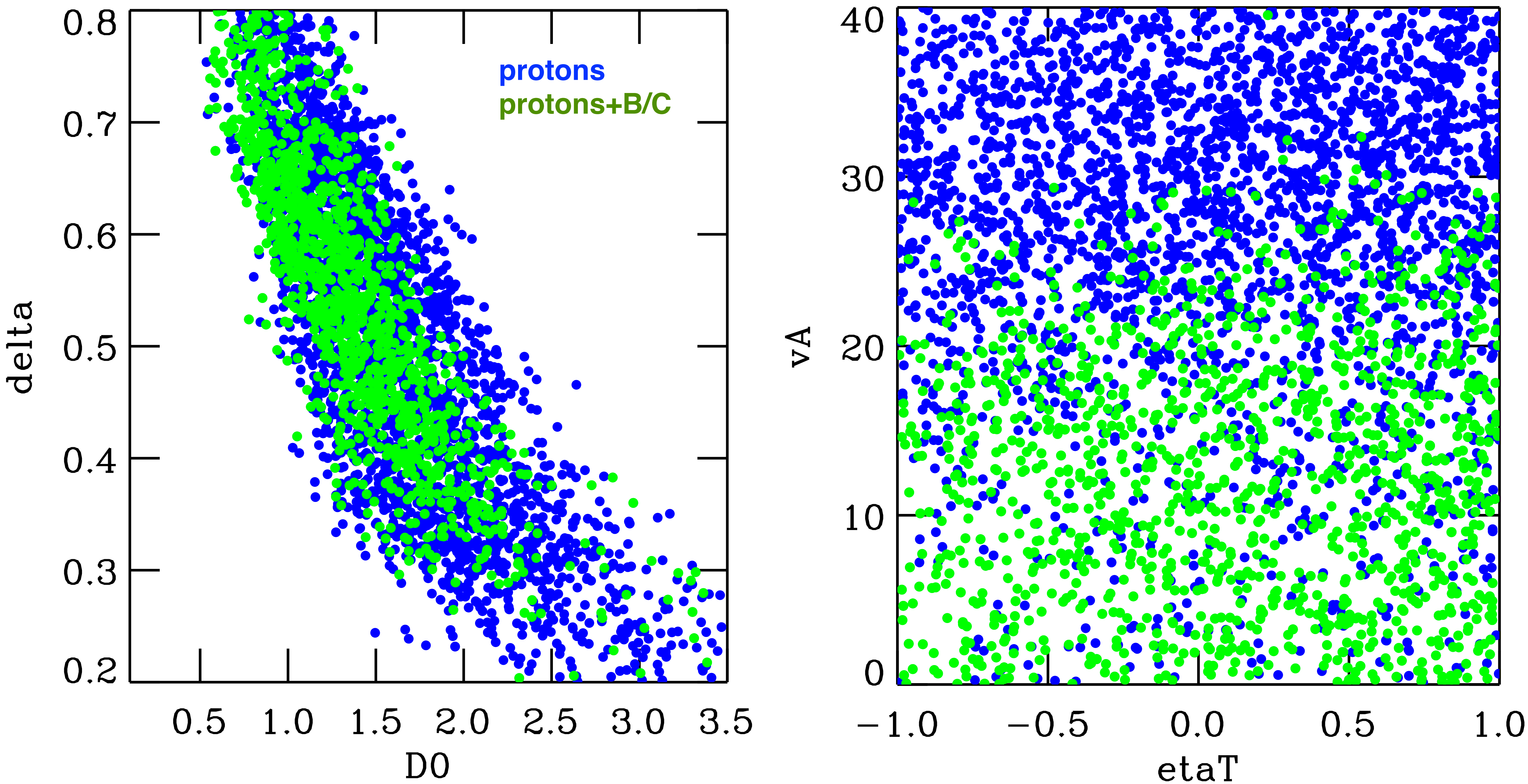




Changing diffusion conditions in the inner Galaxy gives significant effect on the DM contribution without affecting the local observables

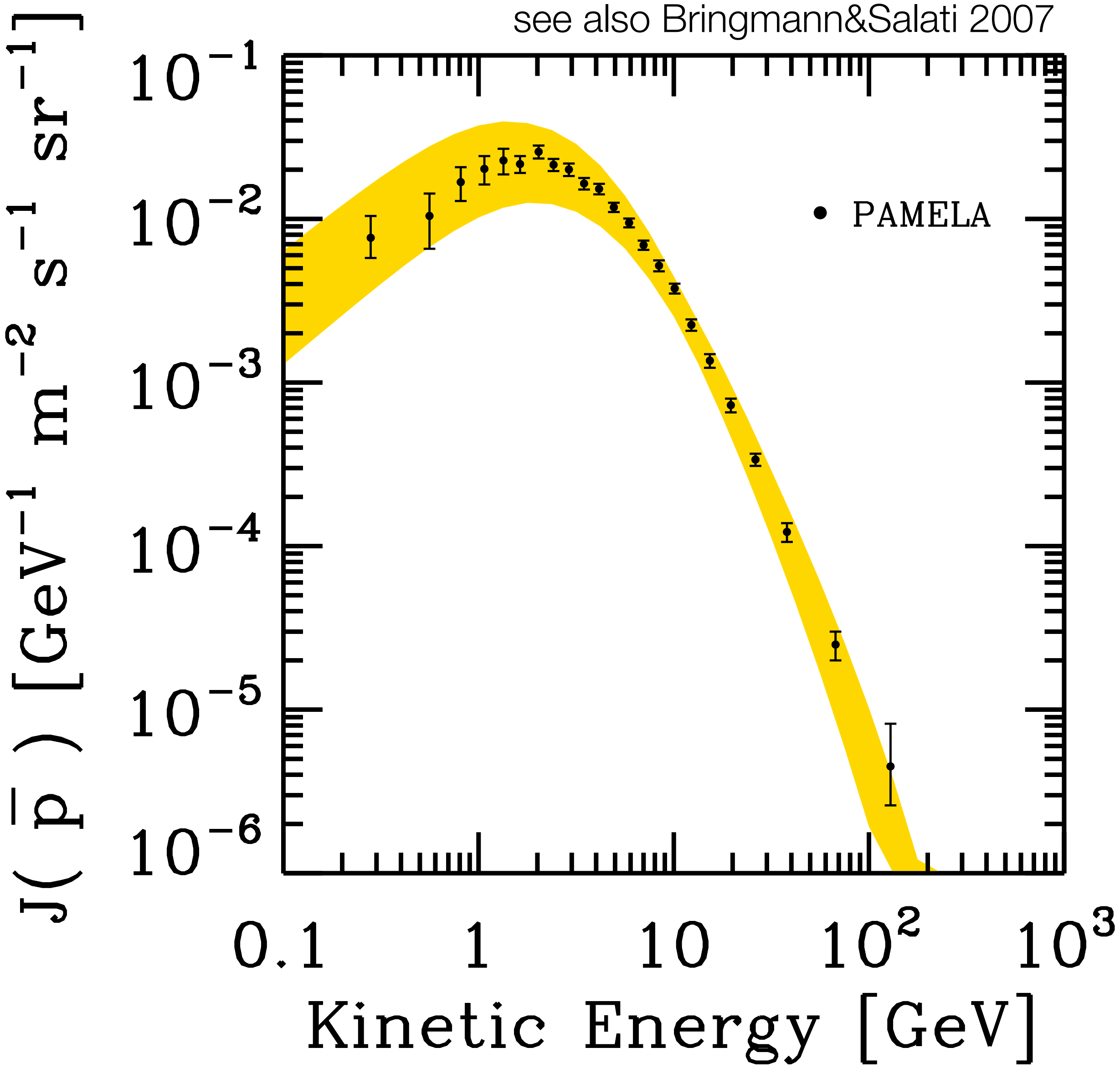
Only a comprehensive study including local and non-local observables may succeed in reducing safely the propagation uncertainties.

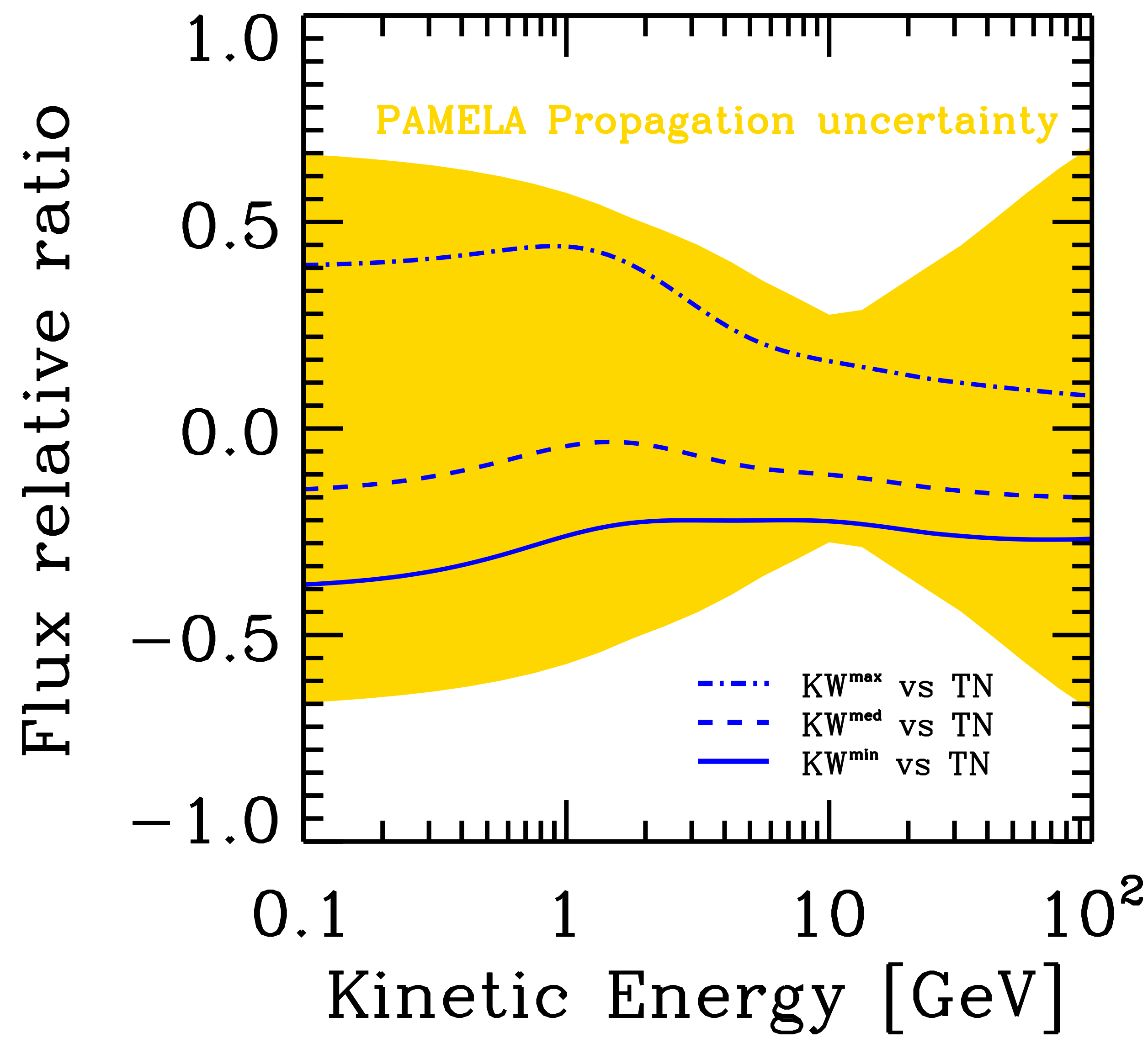
How to bracket the propagation uncertainties?



How to bracket the propagation uncertainties?

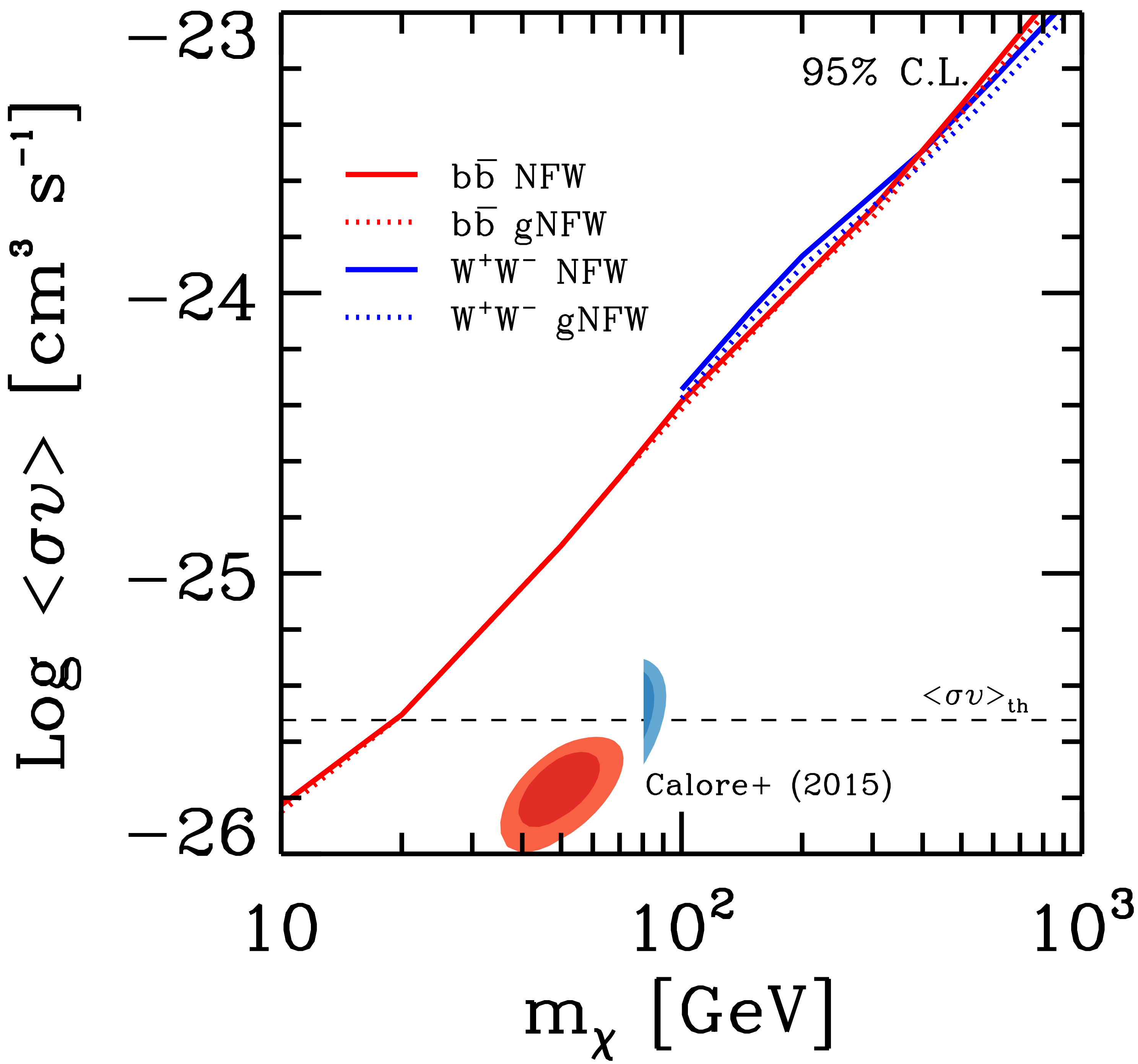
see also Bringmann&Salati 2007





DM bounds after PAMELA data

CE, D.Gaggero & D.Grasso, 1504.05175



AMS-02 anomaly?

CE, D.Gaggero & D.Grasso, 1504.05175