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A unified picture for different CR observables

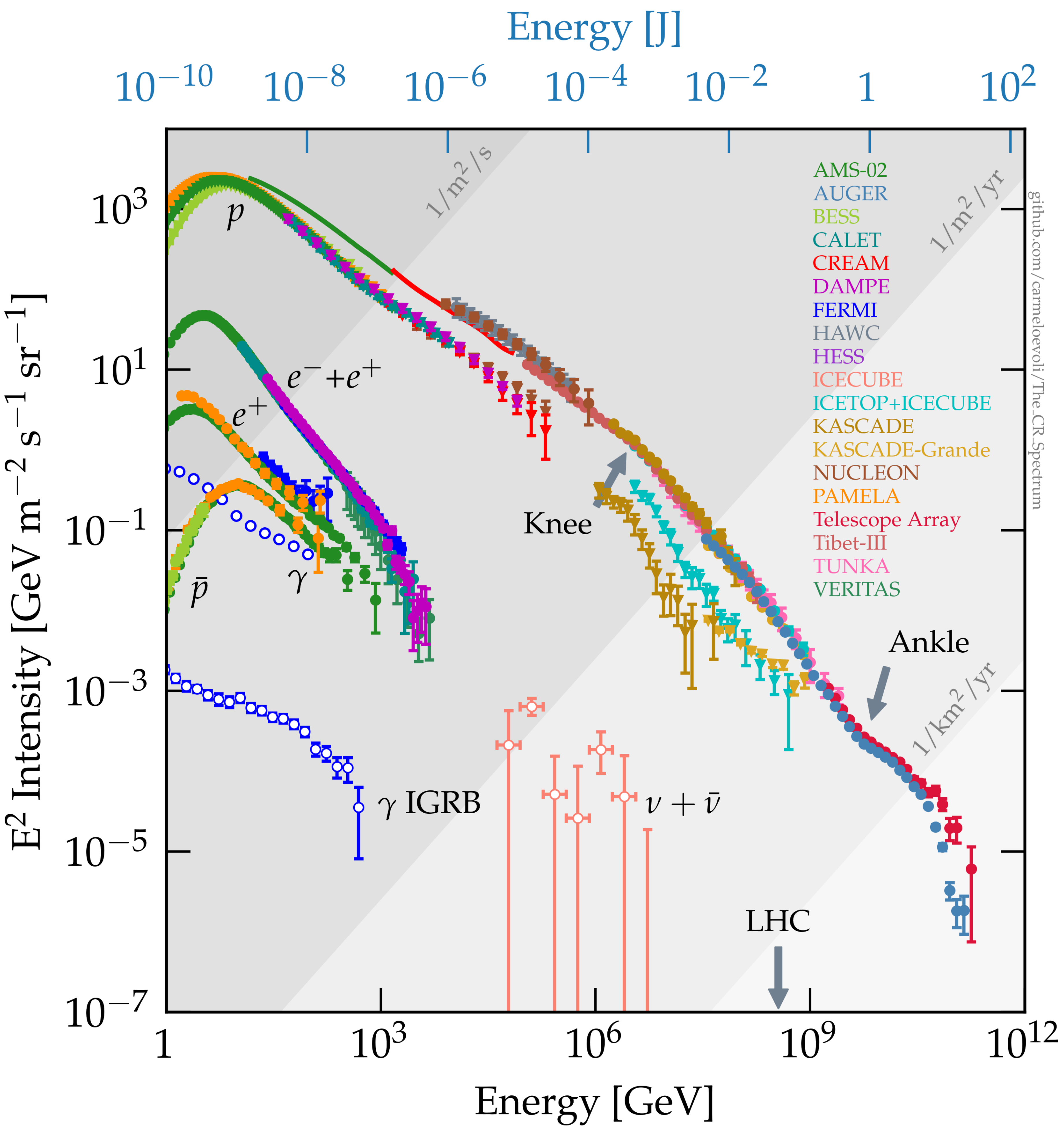
O.Fornieri, D.Gaggero, D.Guberman, P.De La Torre, L.Brahimi, A.Marcowith

[PRD 104 (10), 103013 (2021)]

Ottavio Fornieri

γ^{2022} 7th Heidelberg Symposium - Barcelona, 4-8 July 2022

The general picture



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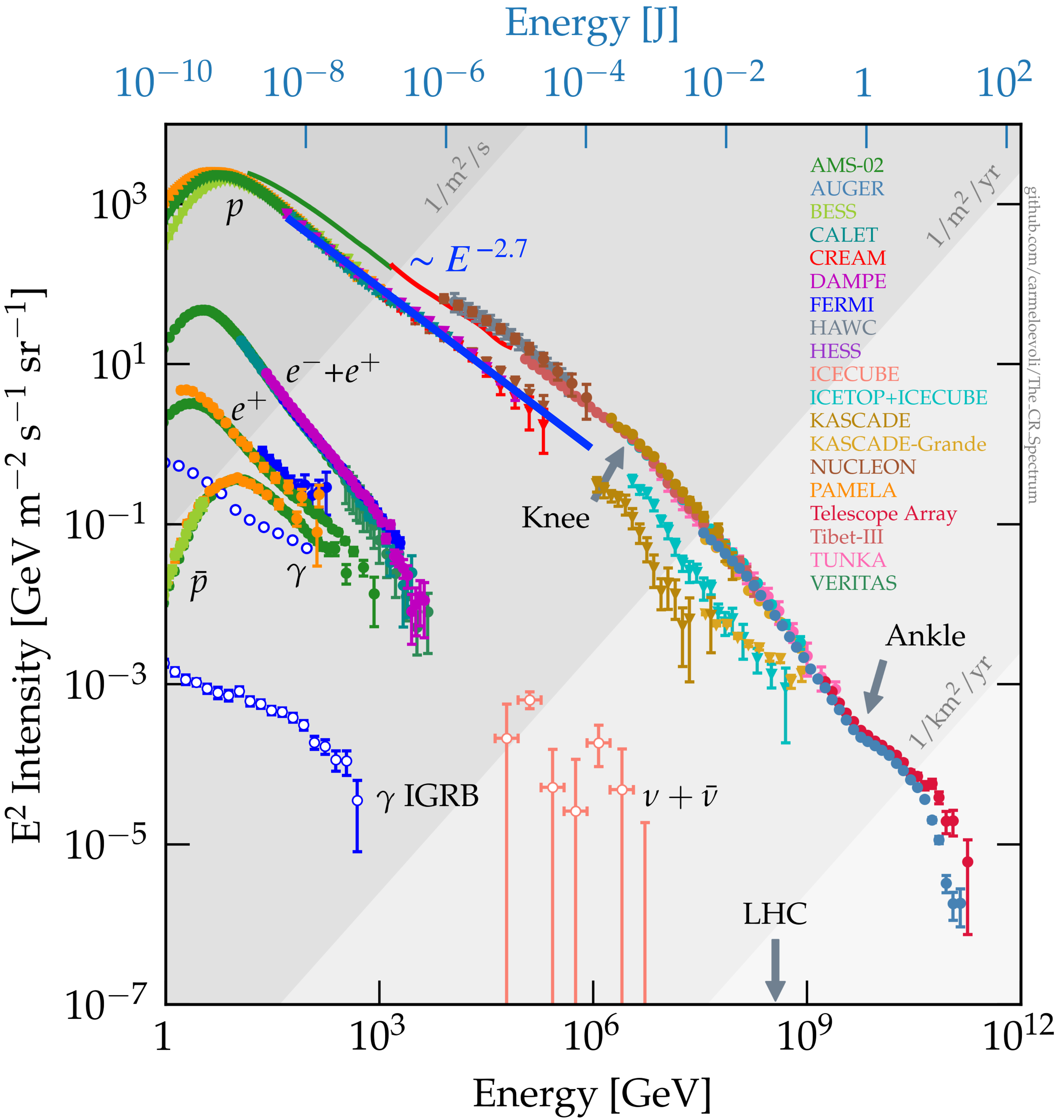
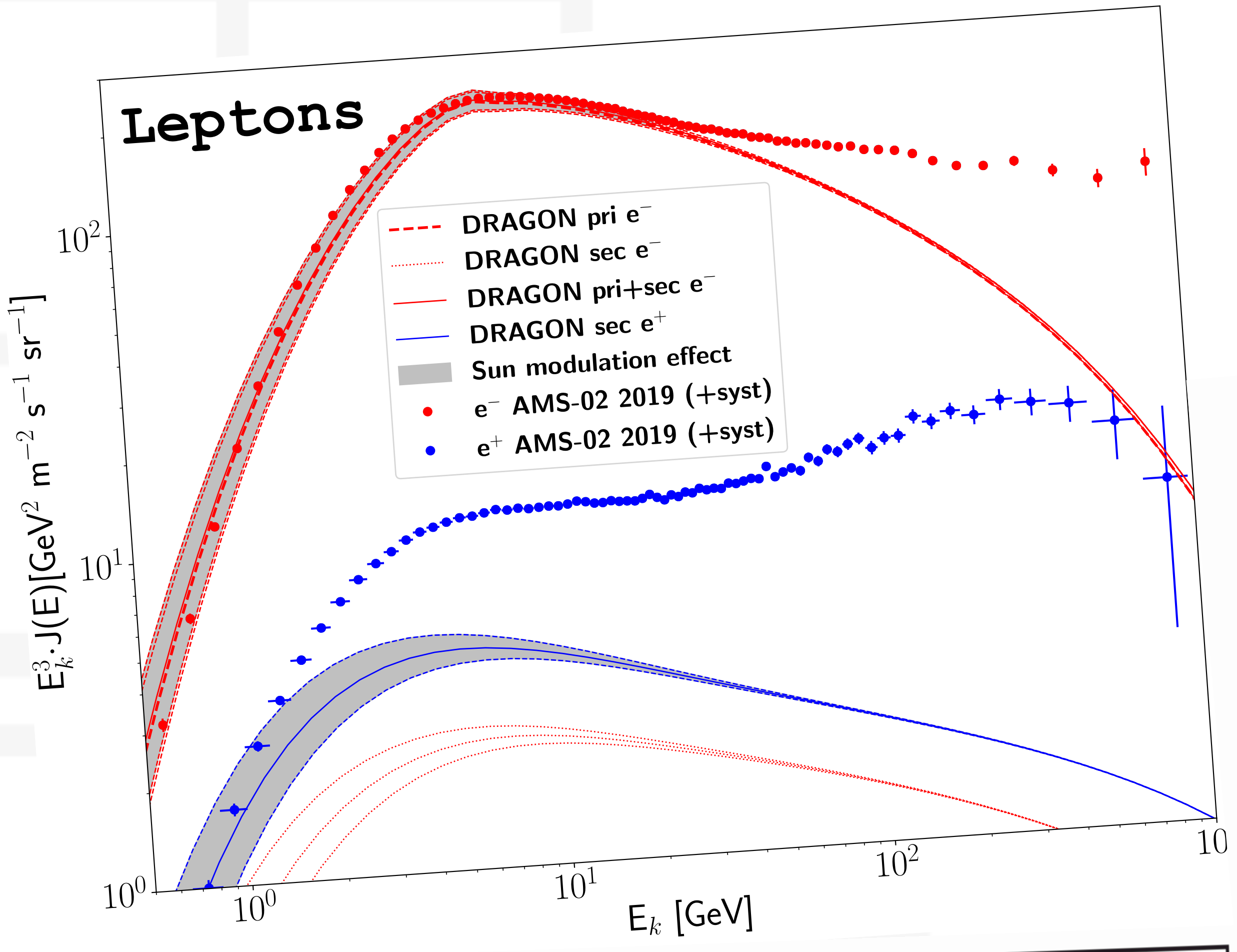
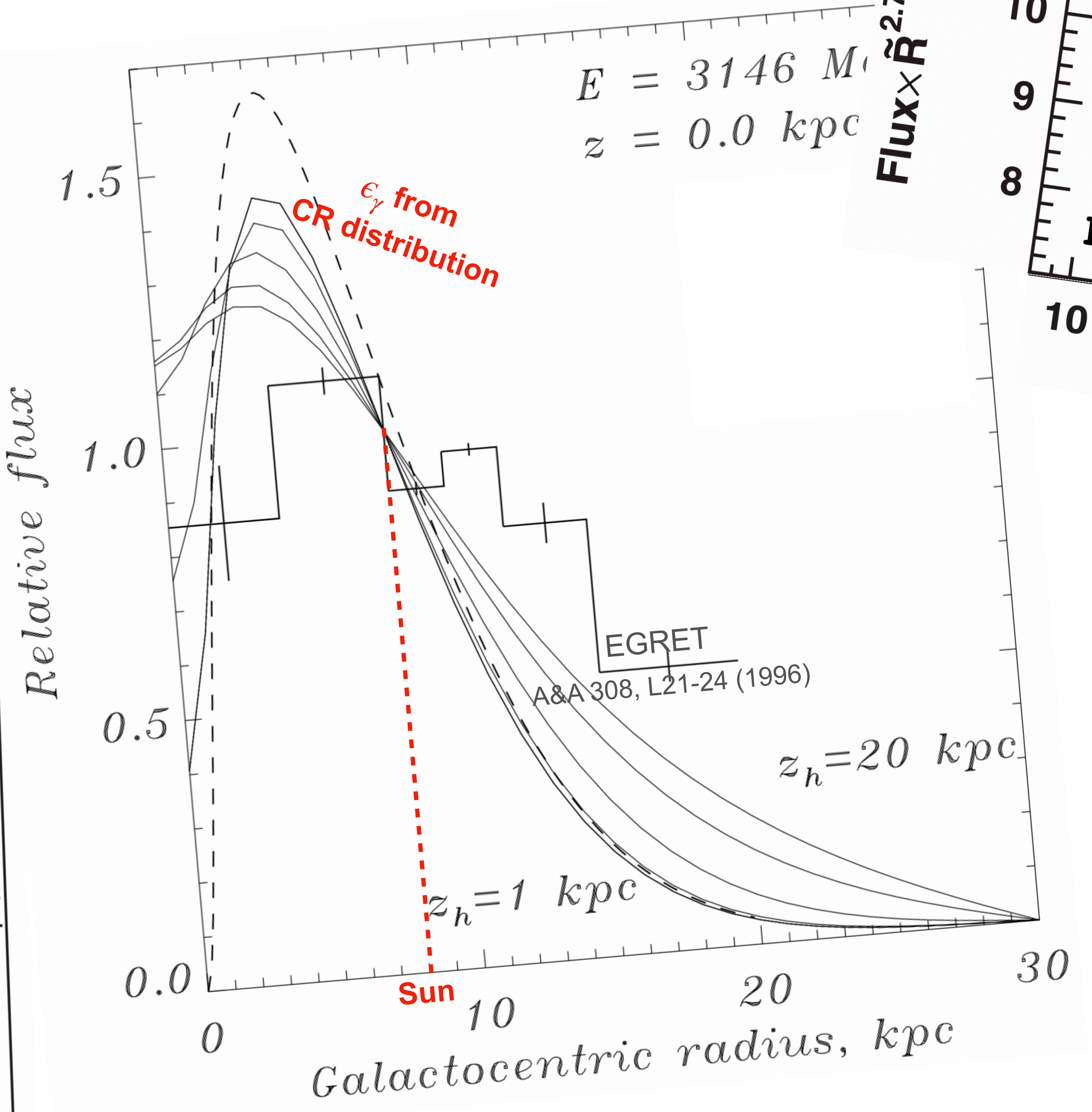
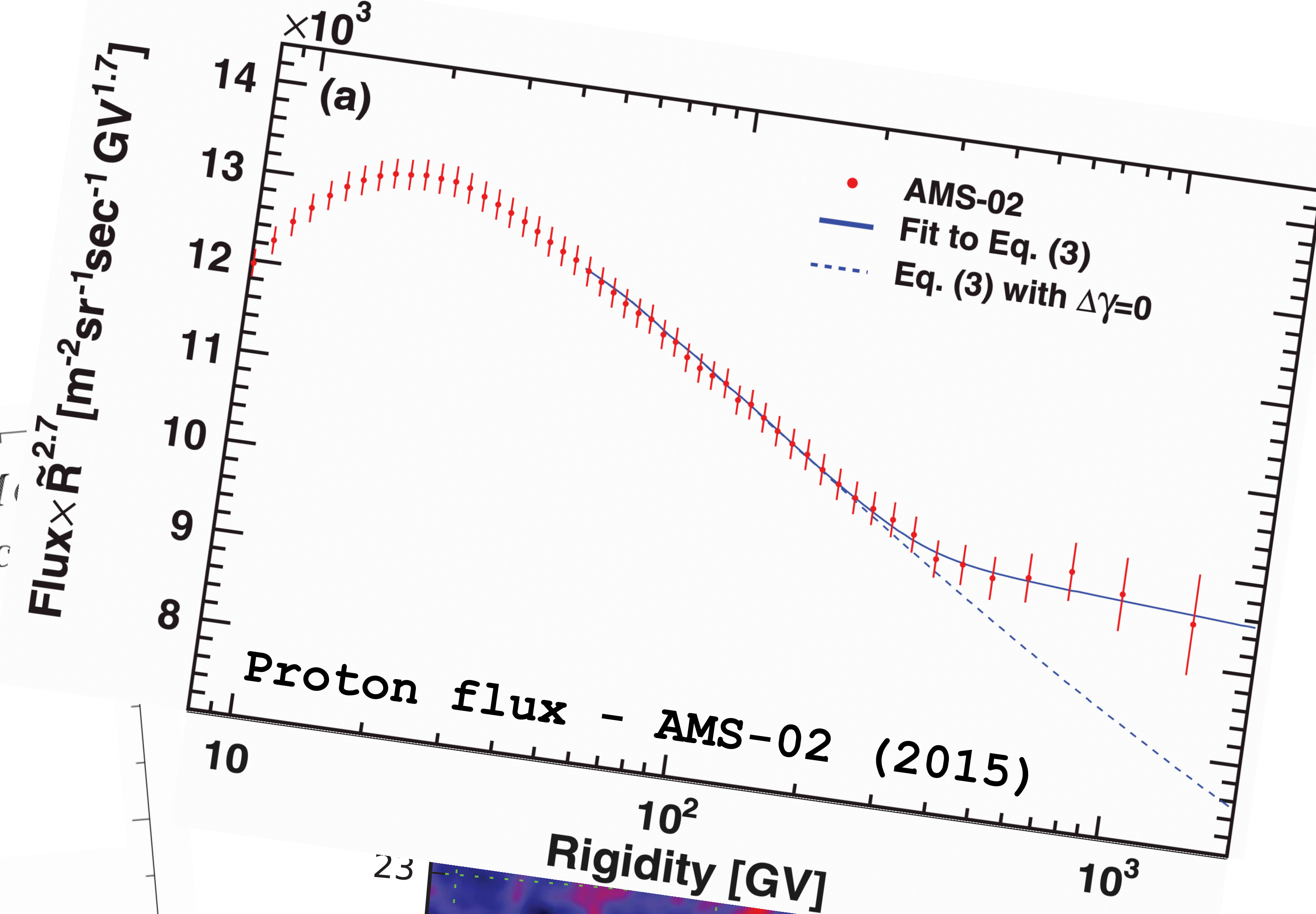
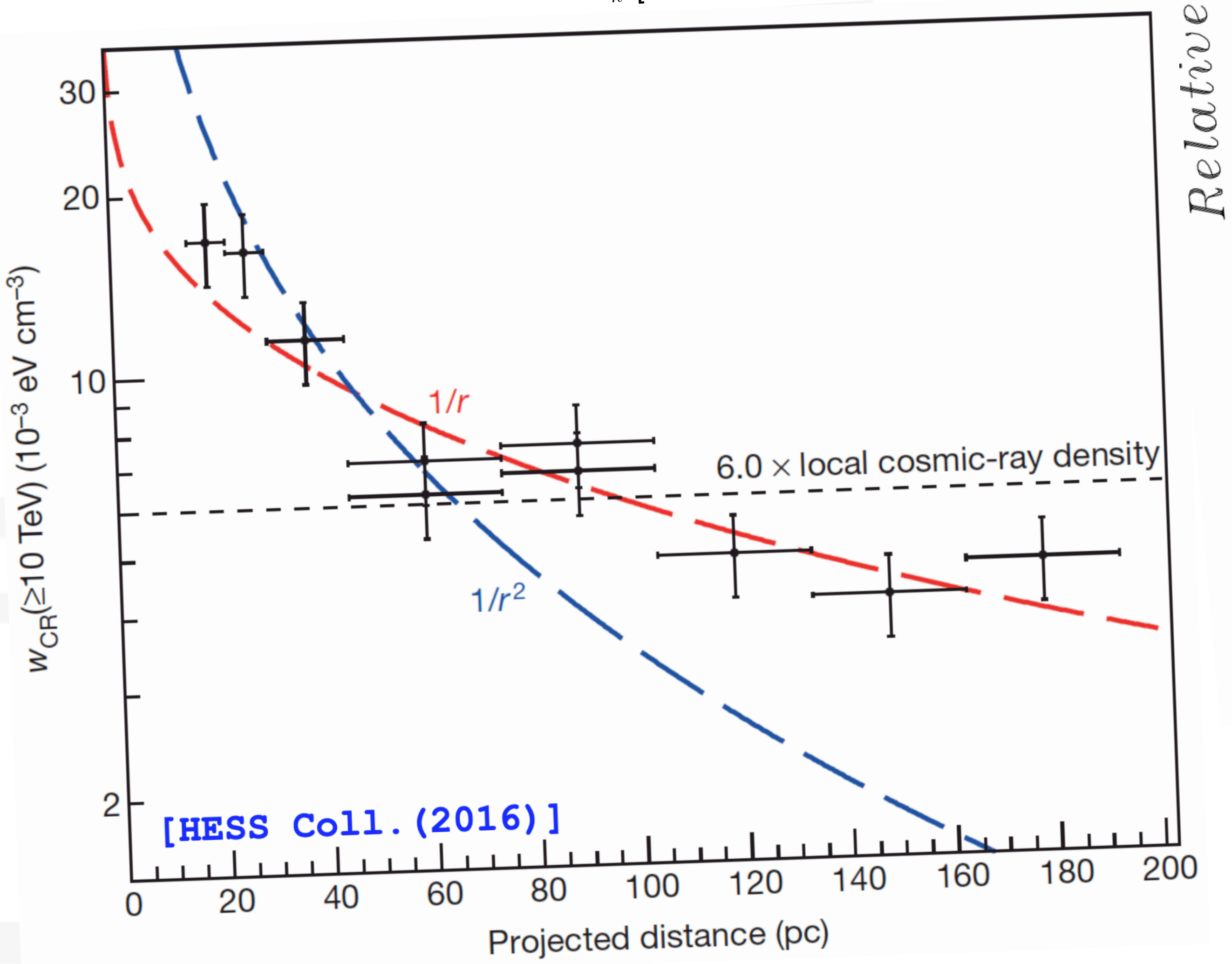


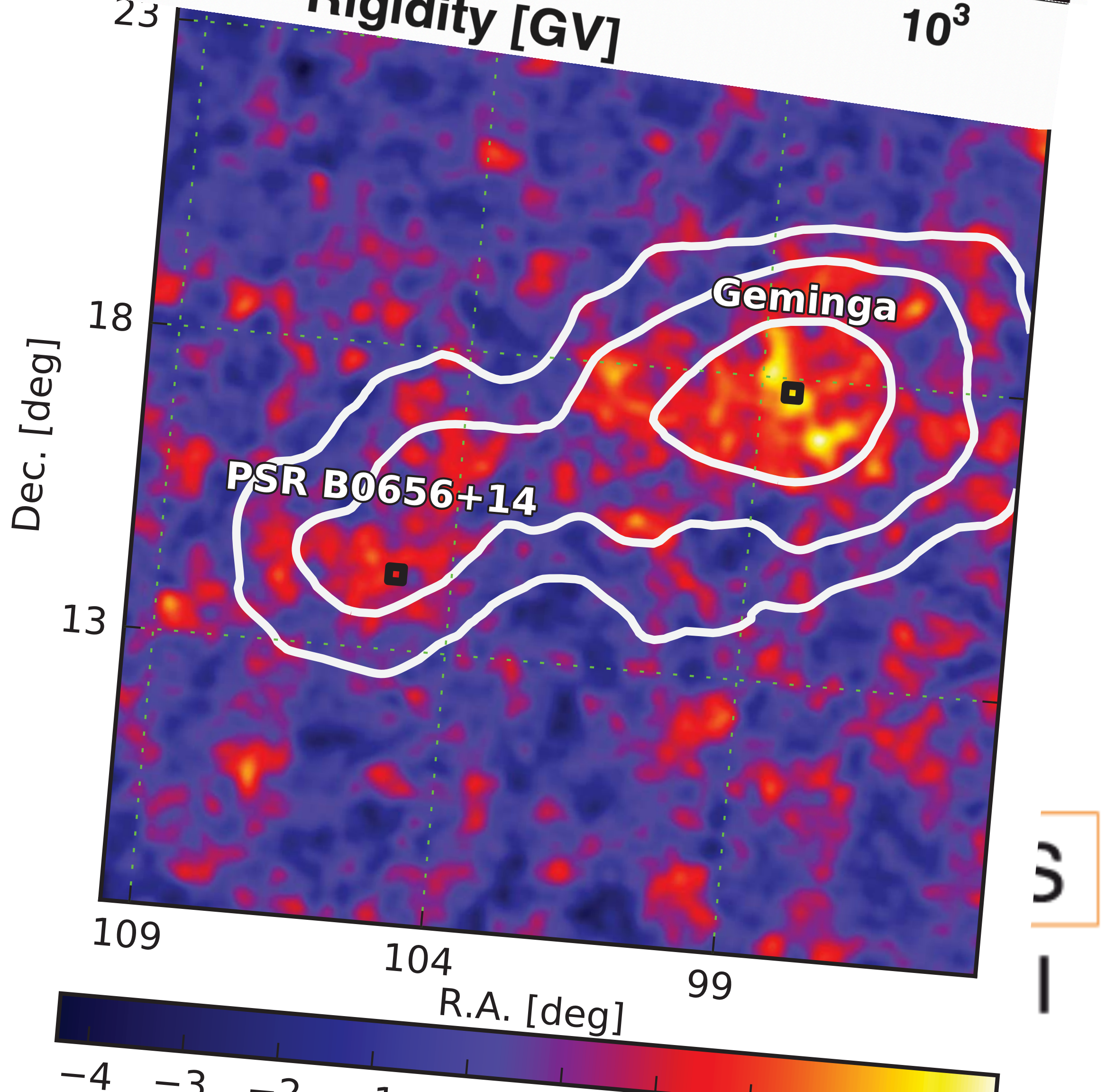
Anomalies in the details





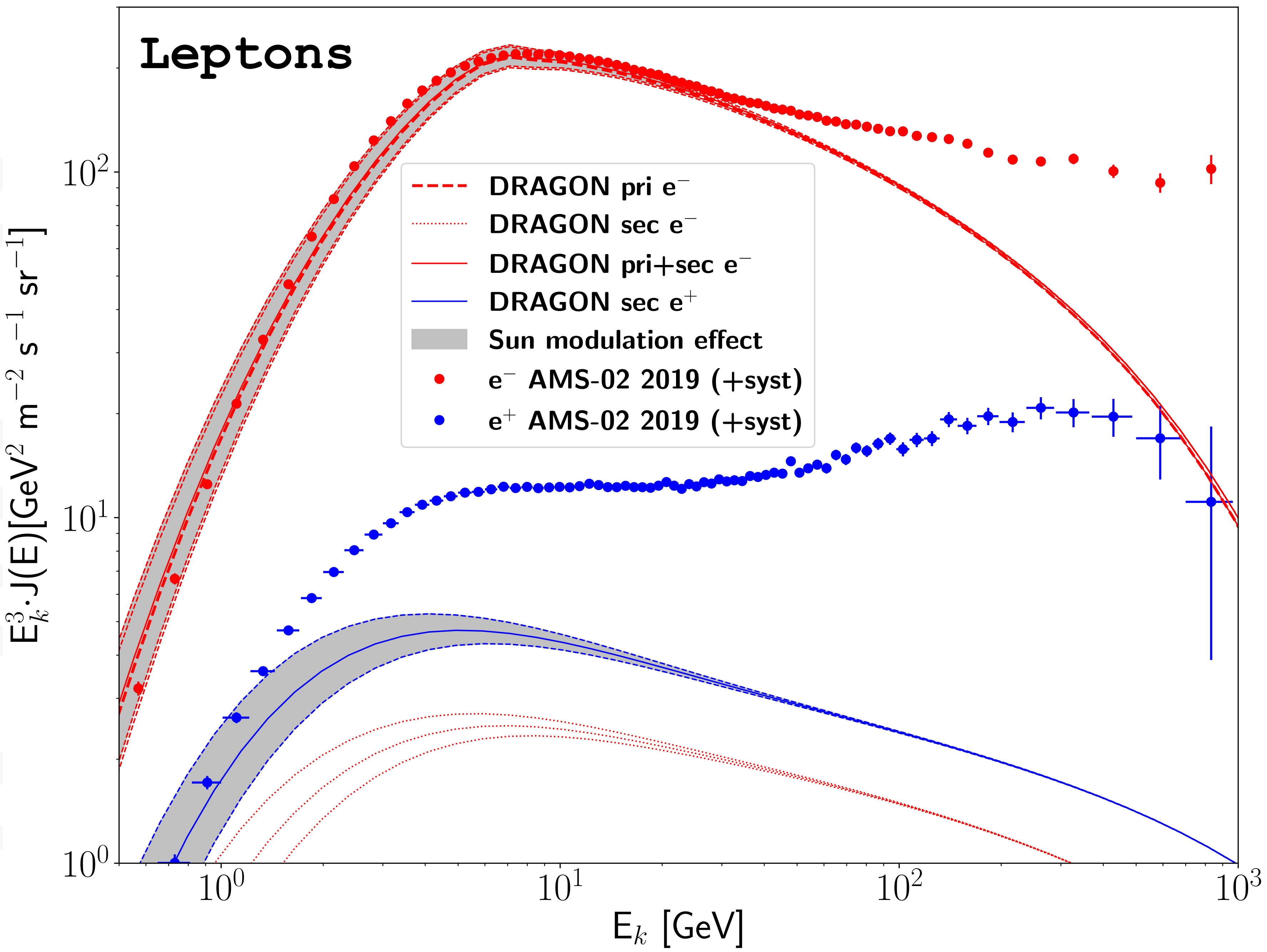


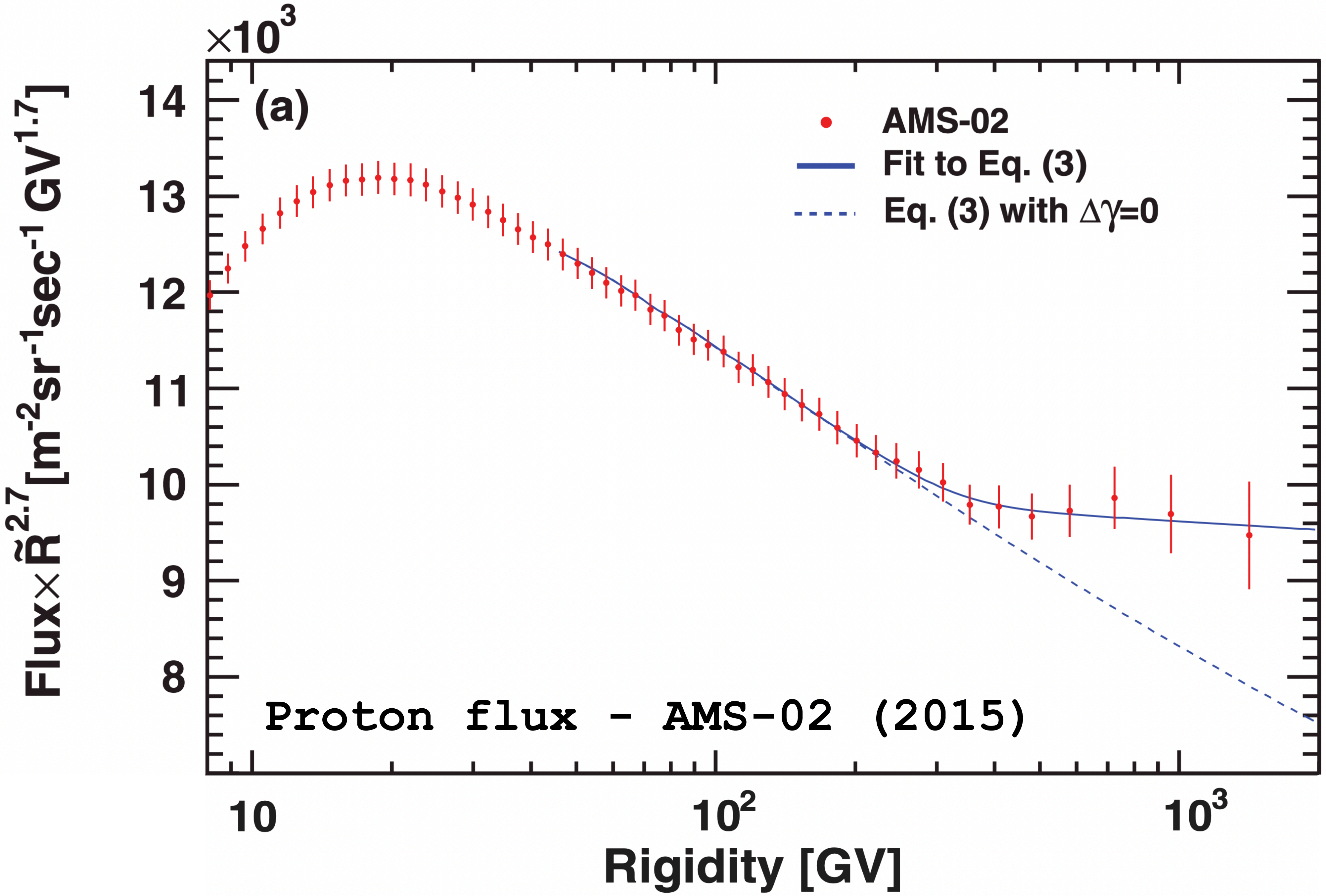




Standard expectation

Large-scale background





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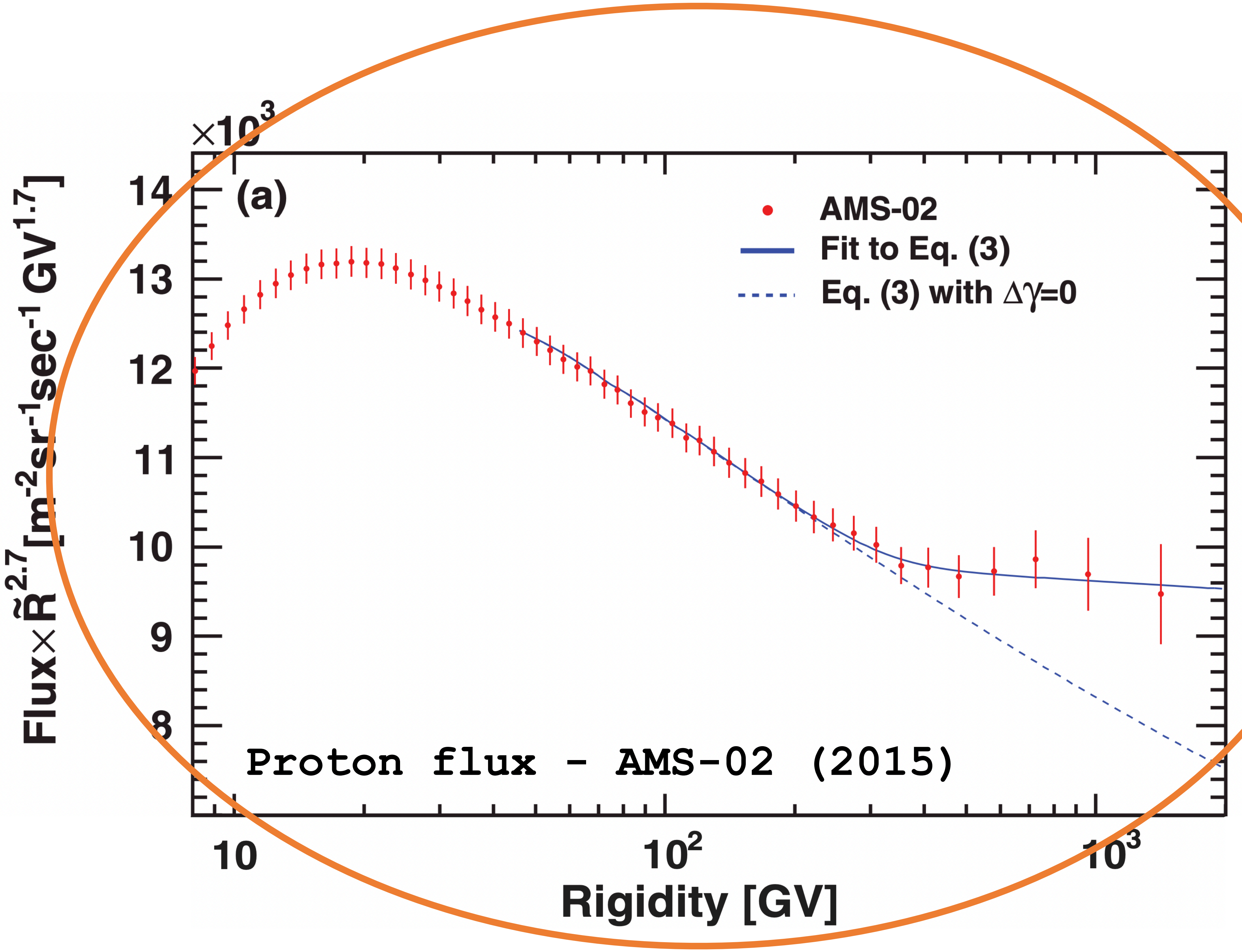

Diffusive origin of the hadronic hardening

- Propagated distribution function for primaries: $f_0 \sim N_0 \big/ D(E) \sim E^{-\Gamma_{\rm inj}-\delta}$
- Propagated distribution function for secondaries: $g_0 \sim N_0' \big/ D(E) \sim E^{-\Gamma_{\rm inj}-\delta} \big/ D(E) \sim E^{-\Gamma_{\rm inj}-2\delta}$

$D(E) \propto E^{\delta}$

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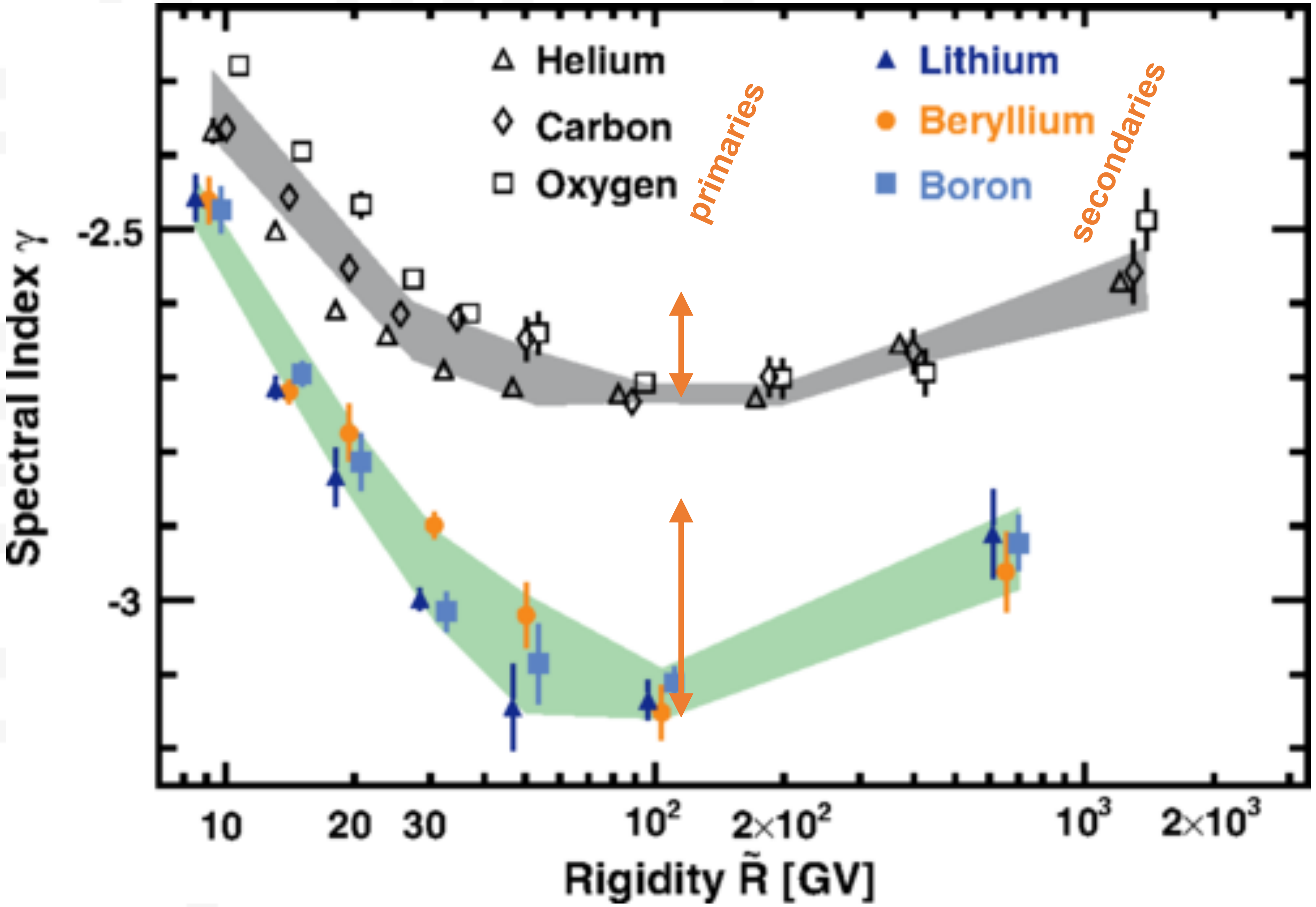
$D(E) \propto E^{\delta}$

[M.Aguilar *et al.* - PRL 120, 021101]



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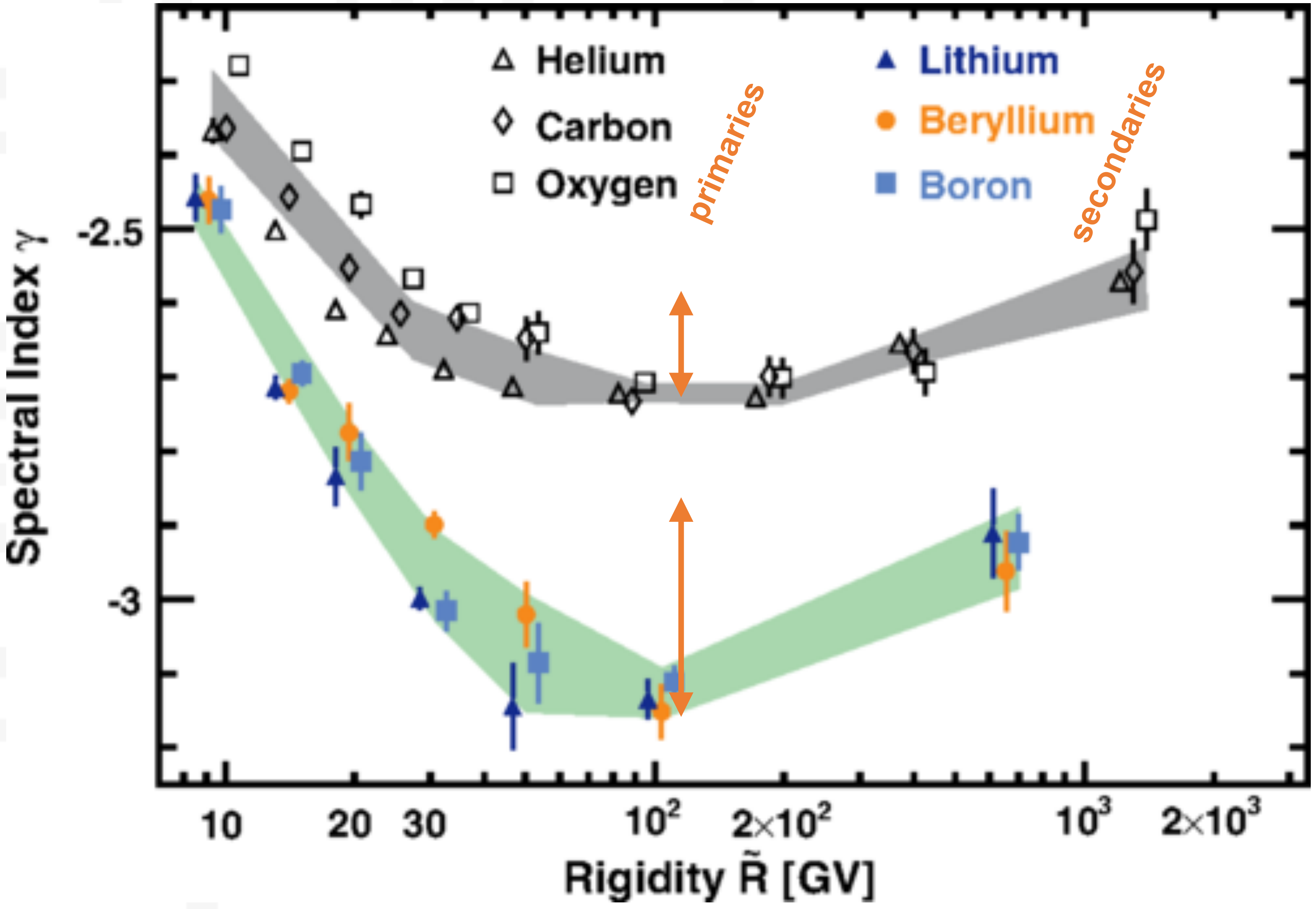
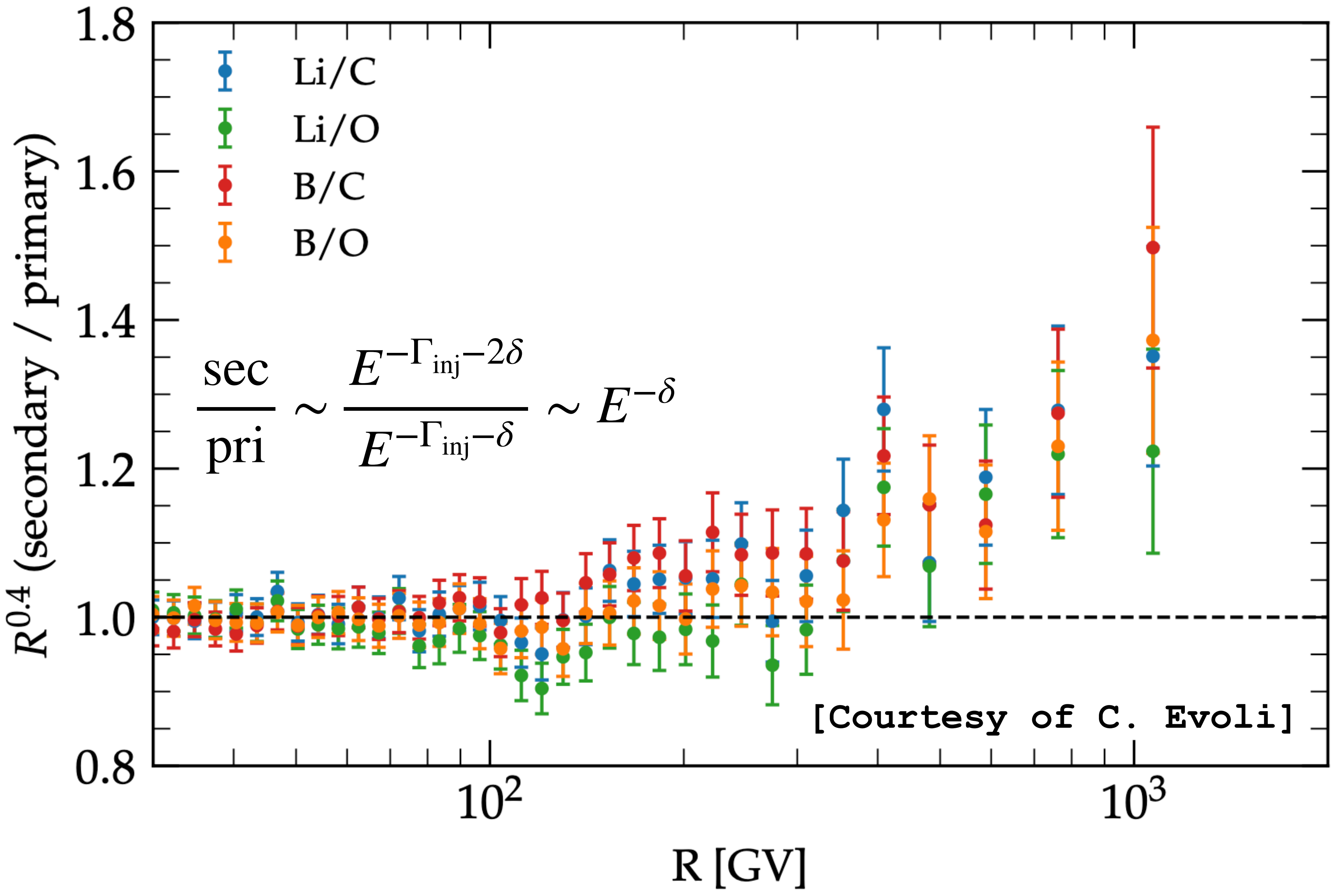
[M.Aguilar *et al.* - PRL 120, 021101]





Connecting protons and leptons

- Setup of the propagation model
- Cosmic-ray fluxes
- Cosmic-ray dipole anisotropy

GSSI

Variable-slope diffusion coefficient

A phenomenological interpretation of the hardening

The Astrophysical Journal Letters, 752:L13 (5pp), 2012 June 10
doi:10.1088/2041-8205/752/1/L13

ORIGIN OF THE COSMIC-RAY SPECTRAL HARDENING

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Received 2012 March 28; accepted 2012 April 16; published 2012 May 25

ABSTRACT

Recent data from ATIC, CREAM, and *PAMELA* indicate that the cosmic-ray energy spectra of protons and nuclei exhibit a remarkable hardening at energies above 100 GeV nucleon^{-1}. We propose that the hardening is an interstellar propagation effect that originates from a spatial change of the cosmic-ray transport properties in different regions of the Galaxy. The key hypothesis is that the diffusion coefficient is not separable into energy and space variables as usually assumed. Under this scenario, we can reproduce the observational data well. Our model has several implications for cosmic-ray acceleration/propagation physics and can be tested by ongoing experiments such as the Alpha Magnetic Spectrometer or *Fermi*-LAT.

G S S I

Variable-slope diffusion coefficient

A phenomenological interpretation of the hardening

Two-zone diffusion model

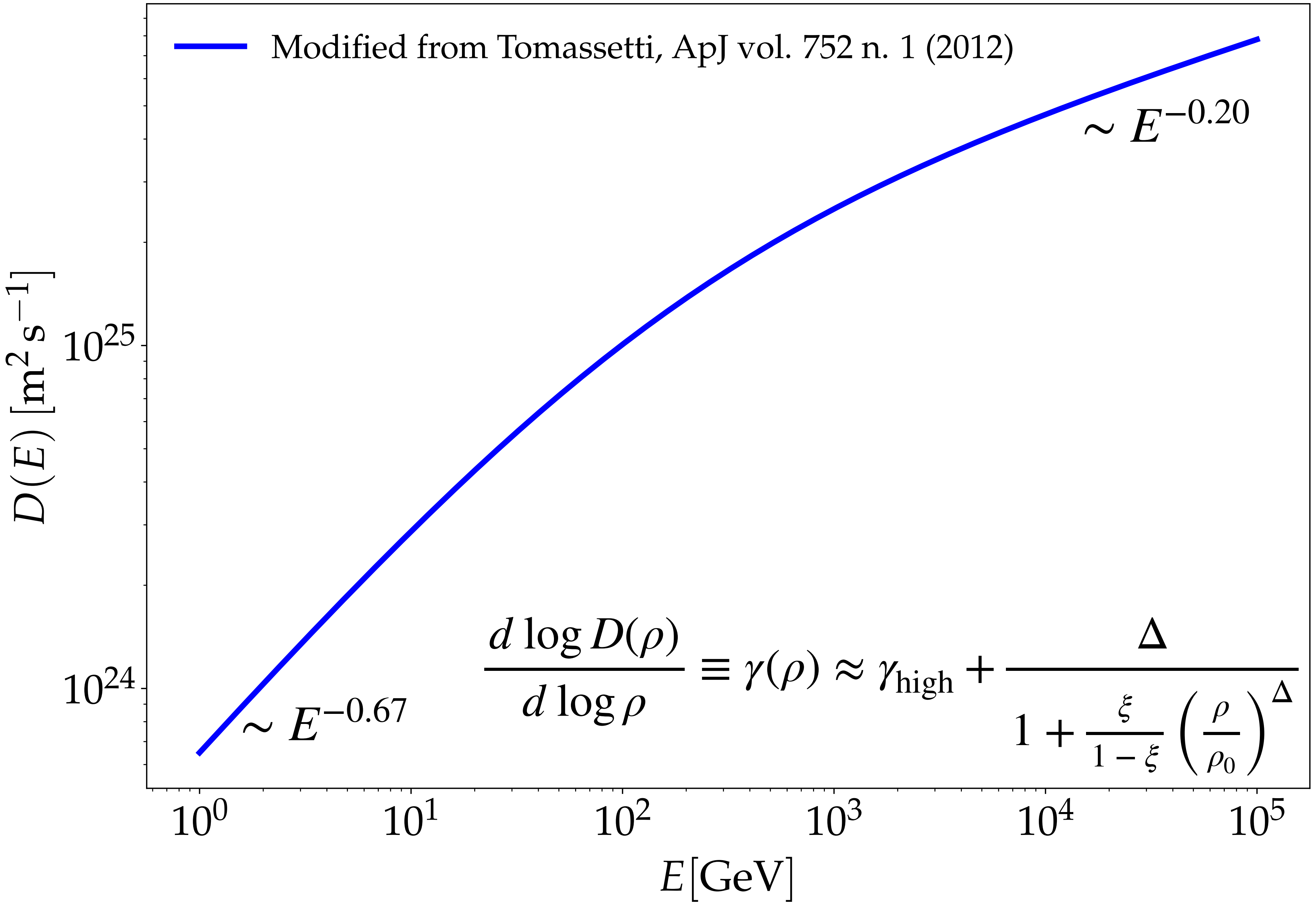
$D(E)\big|_{\text{Halo}} \propto E^{0.75}$ $\quad$ $D(E)\big|_{\text{WIM}} \propto E^{0.15}$

→ effectively

Smoothly broken-power-law

$D(E) \propto E^{\delta(E)}$

[Tomassetti: ApJ 752 1 (2012)]
[Fang et al.: PRD 94, 123007 (2016)]



Our recipe

We numerically compute the CR sea generated by a population of Galactic sources

$$\nabla \cdot (D\,\nabla N_i - \mathbf{u}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\nabla \cdot \mathbf{u}_w\right) N_i\right] =$$

$$S + \sum_{j>i}\left(c\beta n_{\rm gas}\,\sigma_{j\to i} + \frac{1}{\gamma\tau_{j\to i}}\right)N_j - \left(c\beta n_{\rm gas}\,\sigma_i + \frac{1}{\gamma\tau_i}\right)N_i$$

GS
SI

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We calculate the contribution of a nearby accelerator to p and e^-

$$\frac{\partial f(E,r,t)}{\partial t} = \frac{D(E)}{r^2}\frac{\partial}{\partial r} r^2 \frac{\partial f}{\partial r} + \frac{\partial}{\partial E}\left(b(E) f\right) + Q(E,r,t)$$

G S S I

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Same smoothly-broken power-law propagation setup

$D(E) \propto E^{\delta(E)}$

GSSI

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Same smoothly-broken power-law propagation setup

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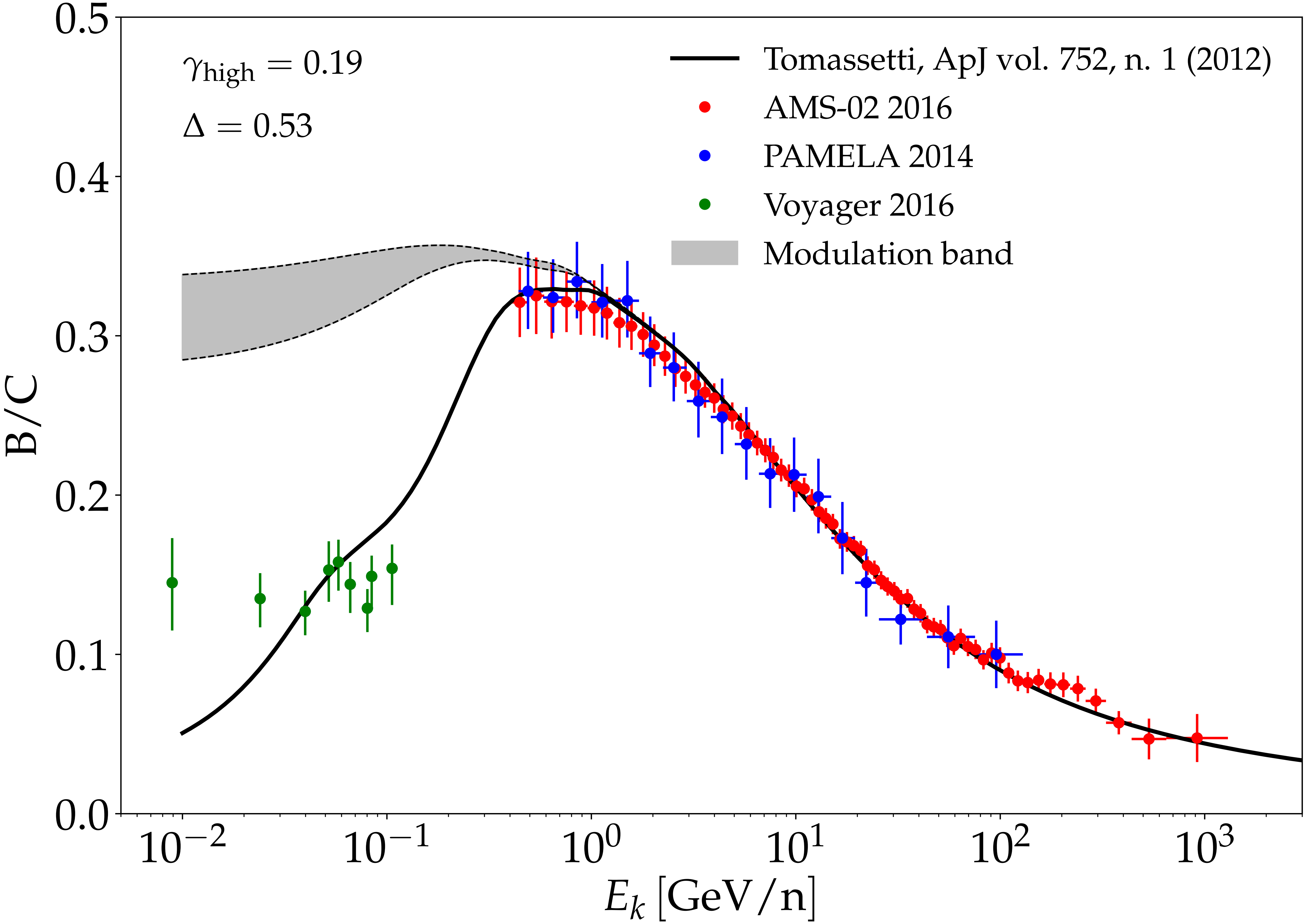
We cross-check our model with the small-scale anisotropy

B/C ratio for the $D(E) \propto E^{\delta(E)}$ model

Large-scale background



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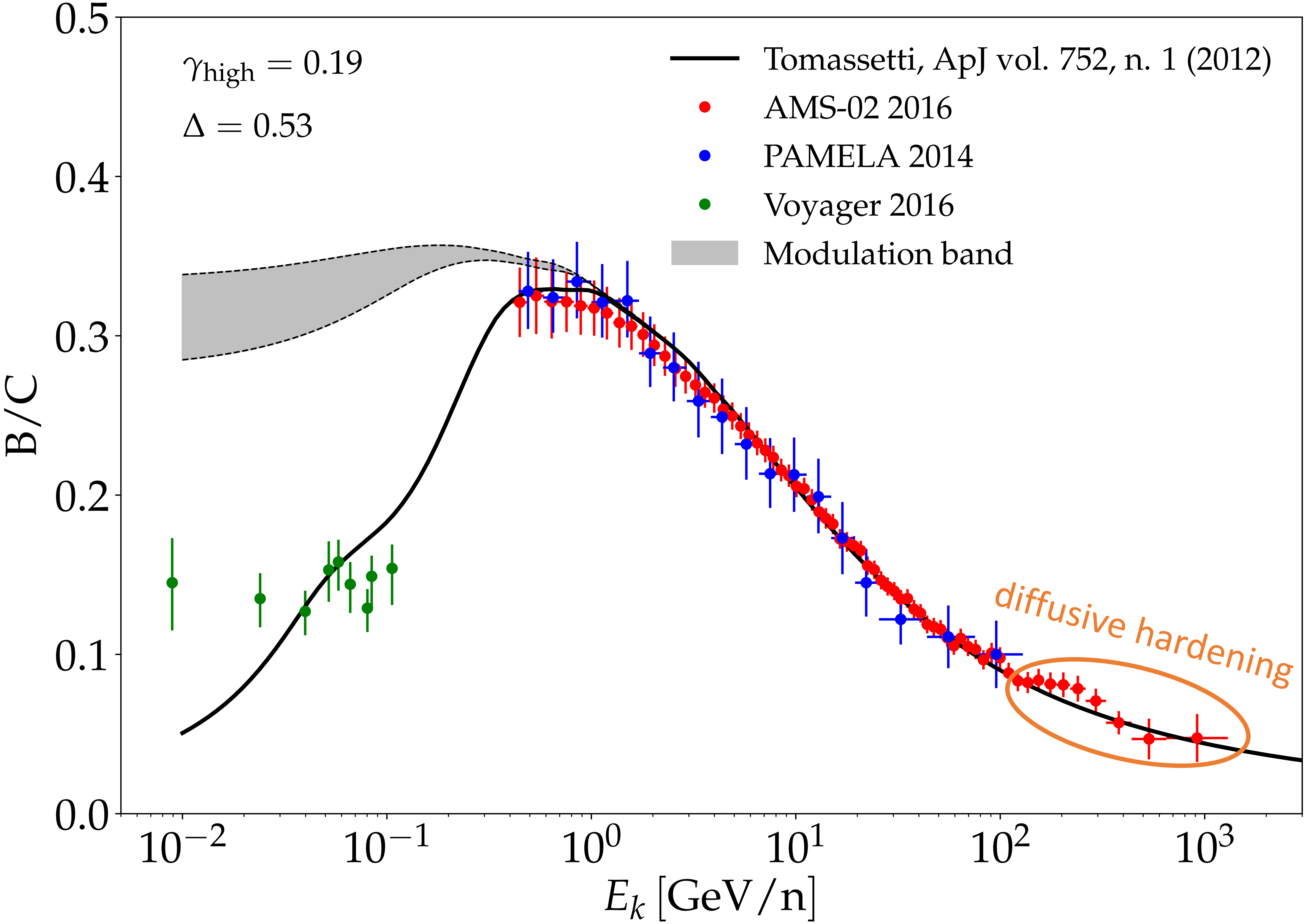

Connecting protons and leptons

- Setup of the propagation model
- Cosmic-ray fluxes
- Cosmic-ray dipole anisotropy

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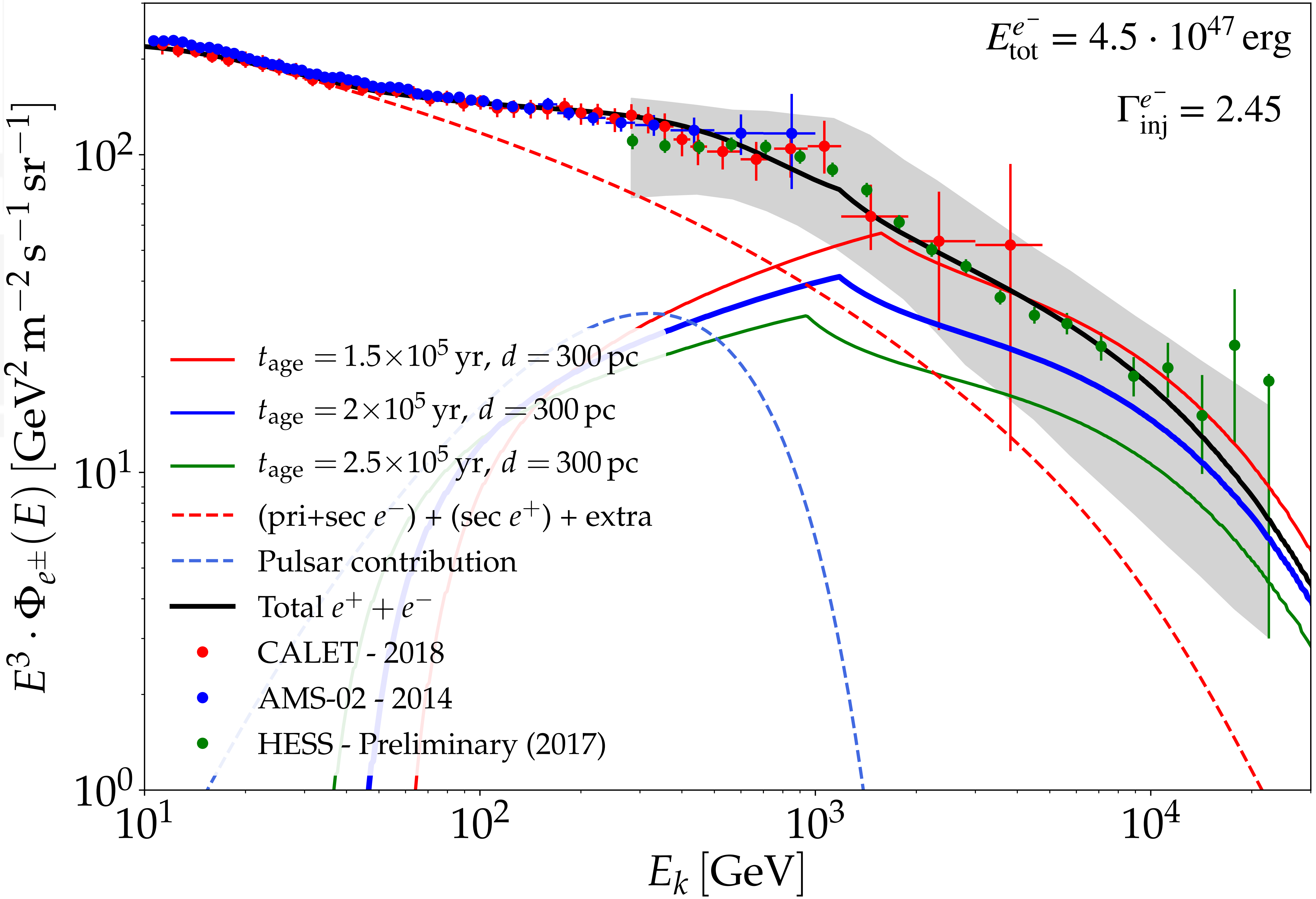
S I

The all-lepton flux



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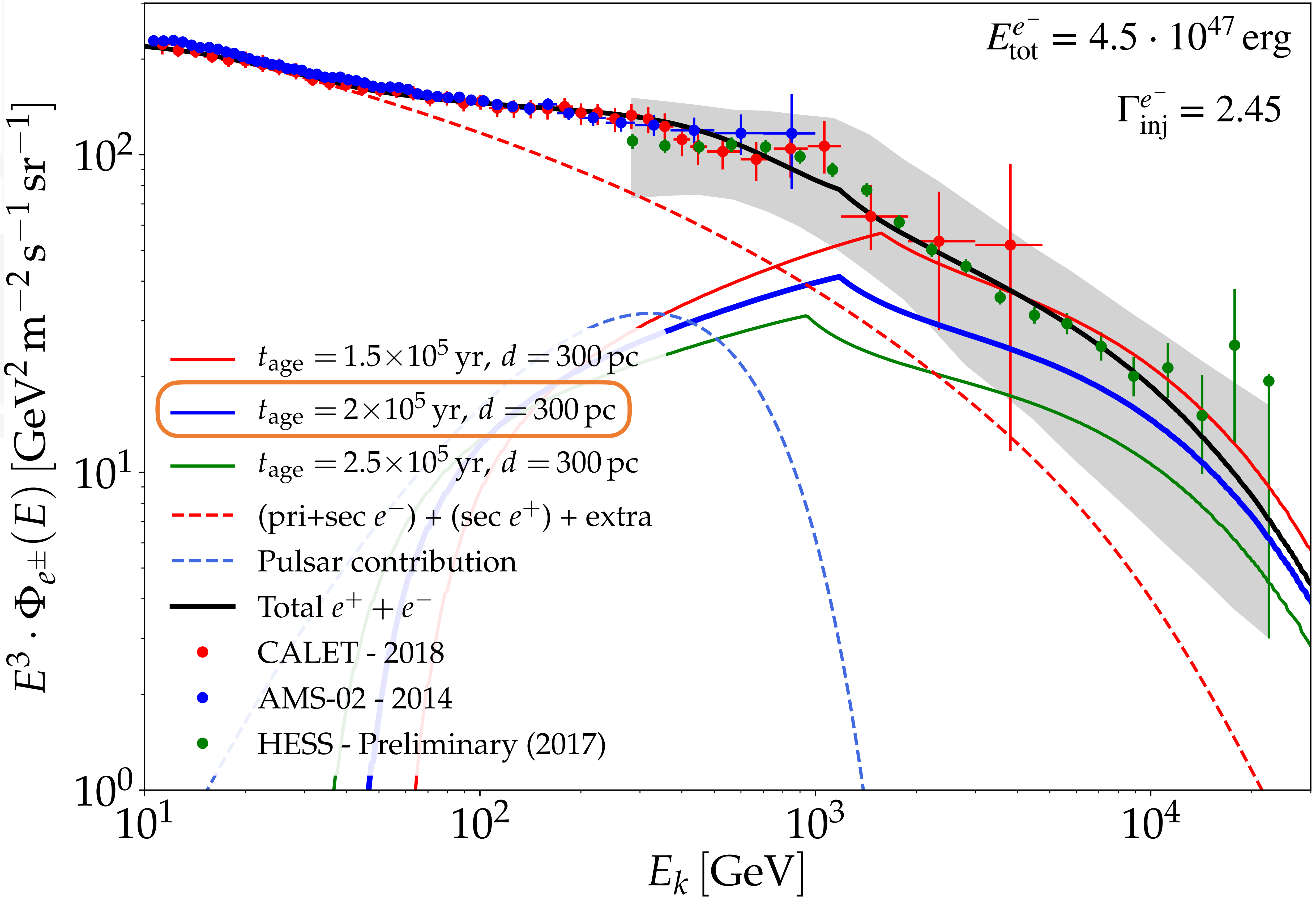

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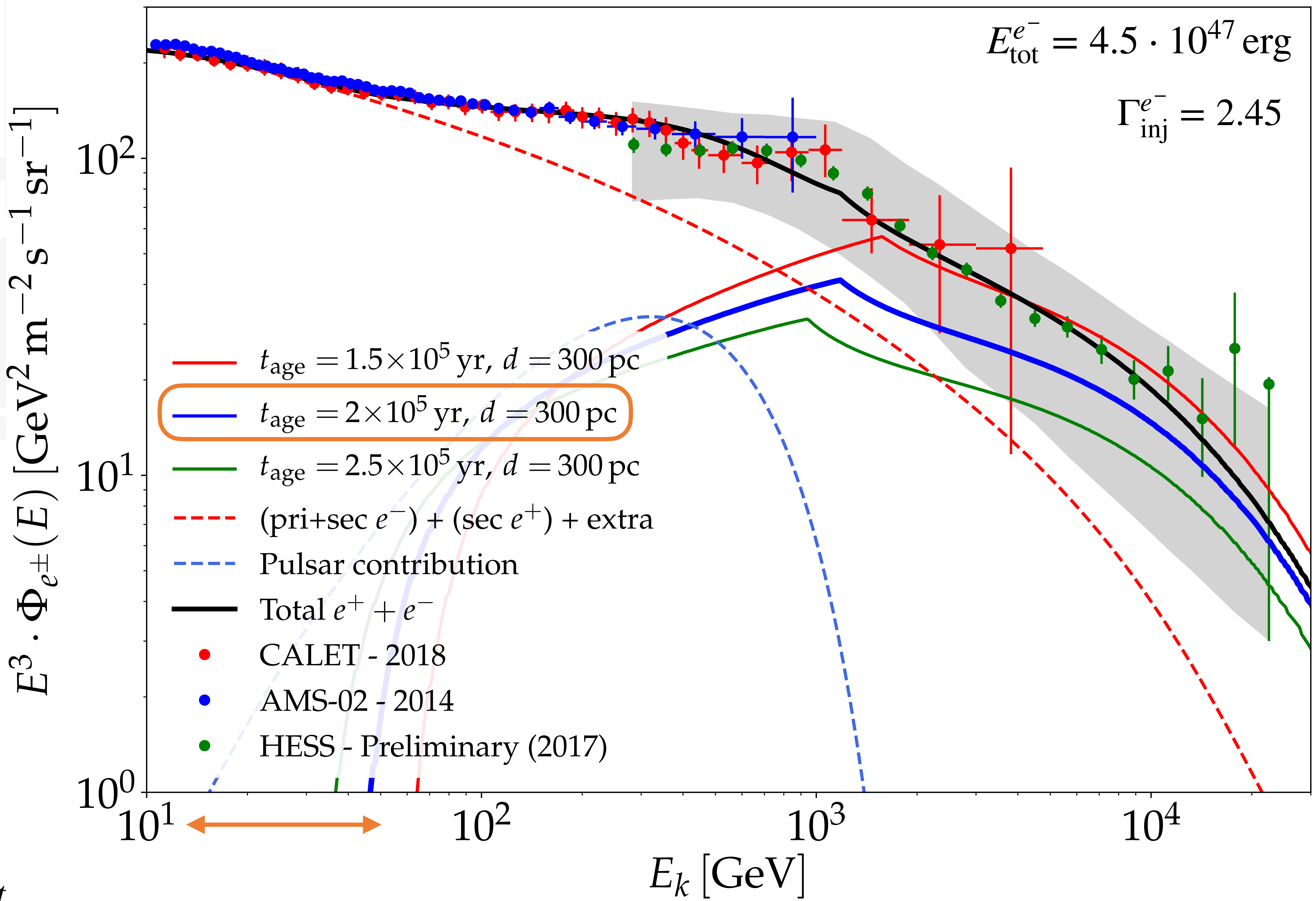

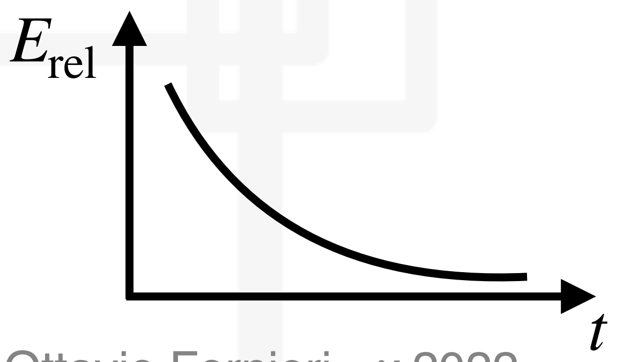

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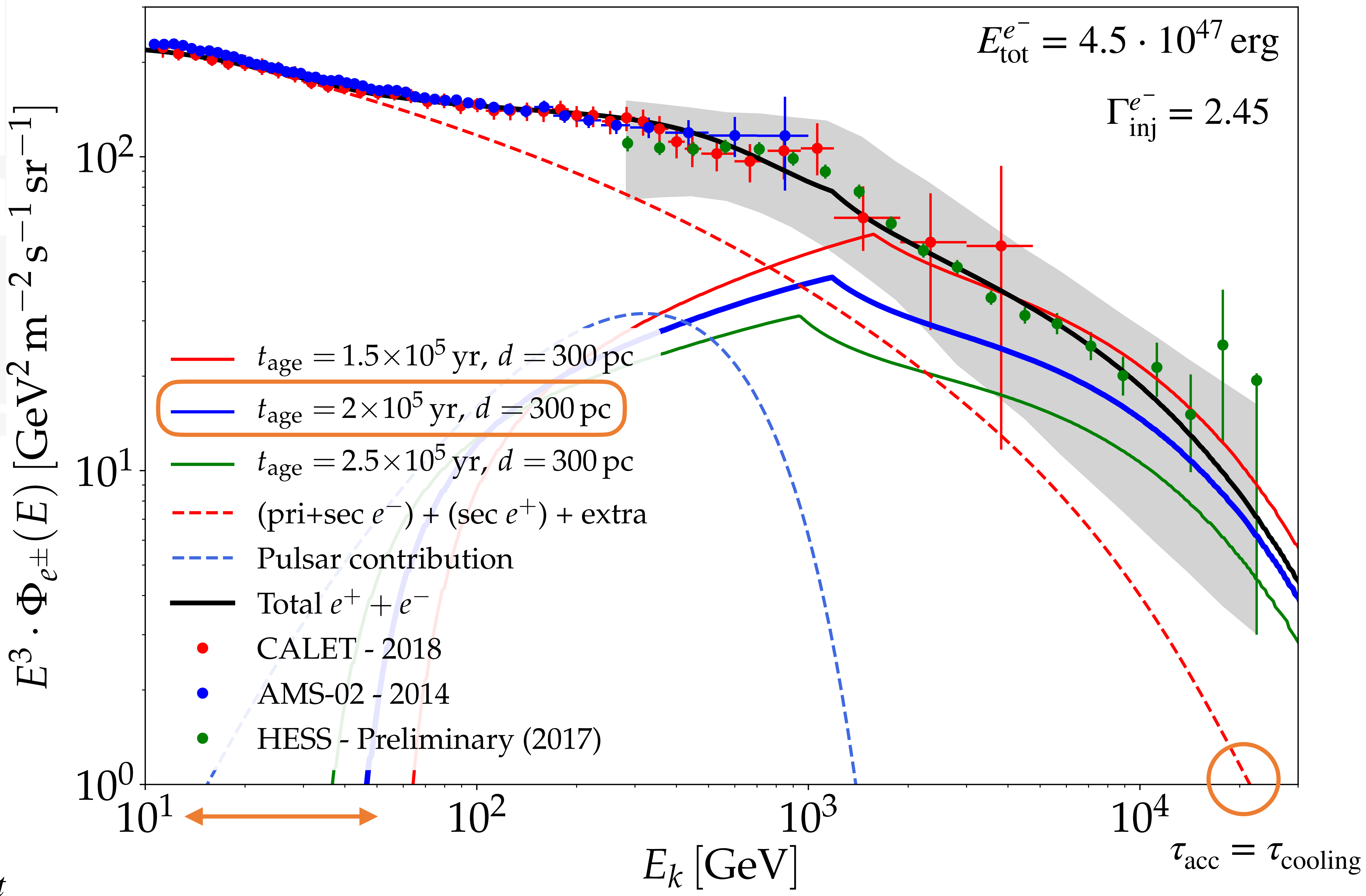
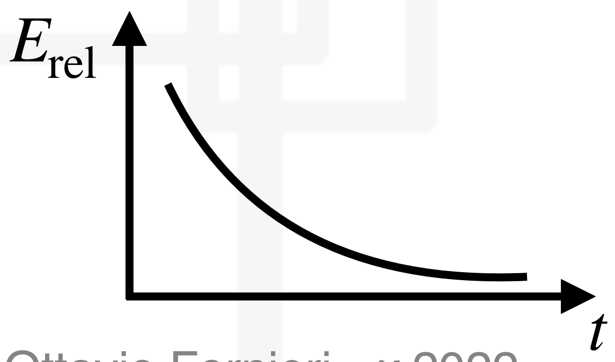
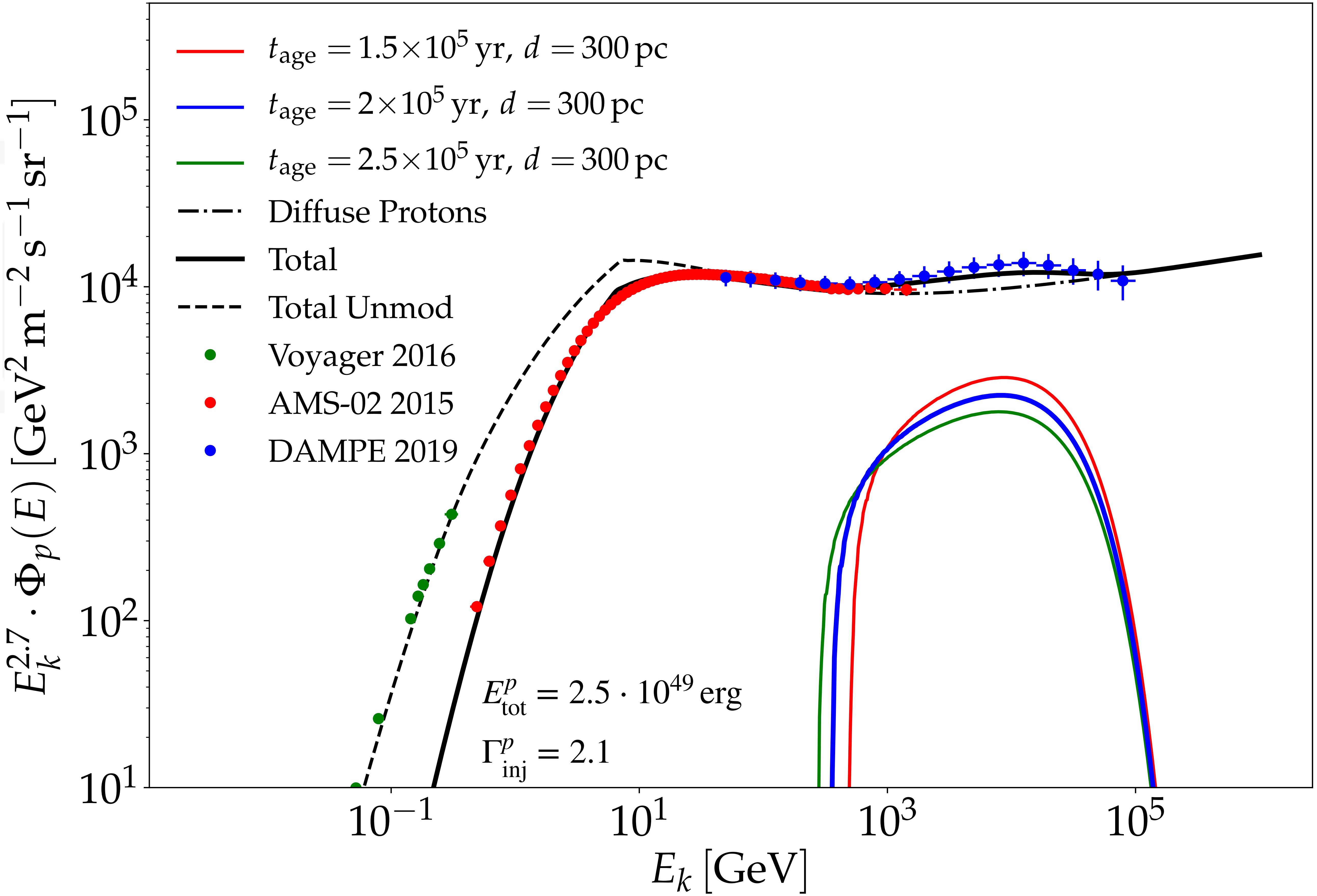




The proton flux

SNRs inject protons as well



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The proton flux

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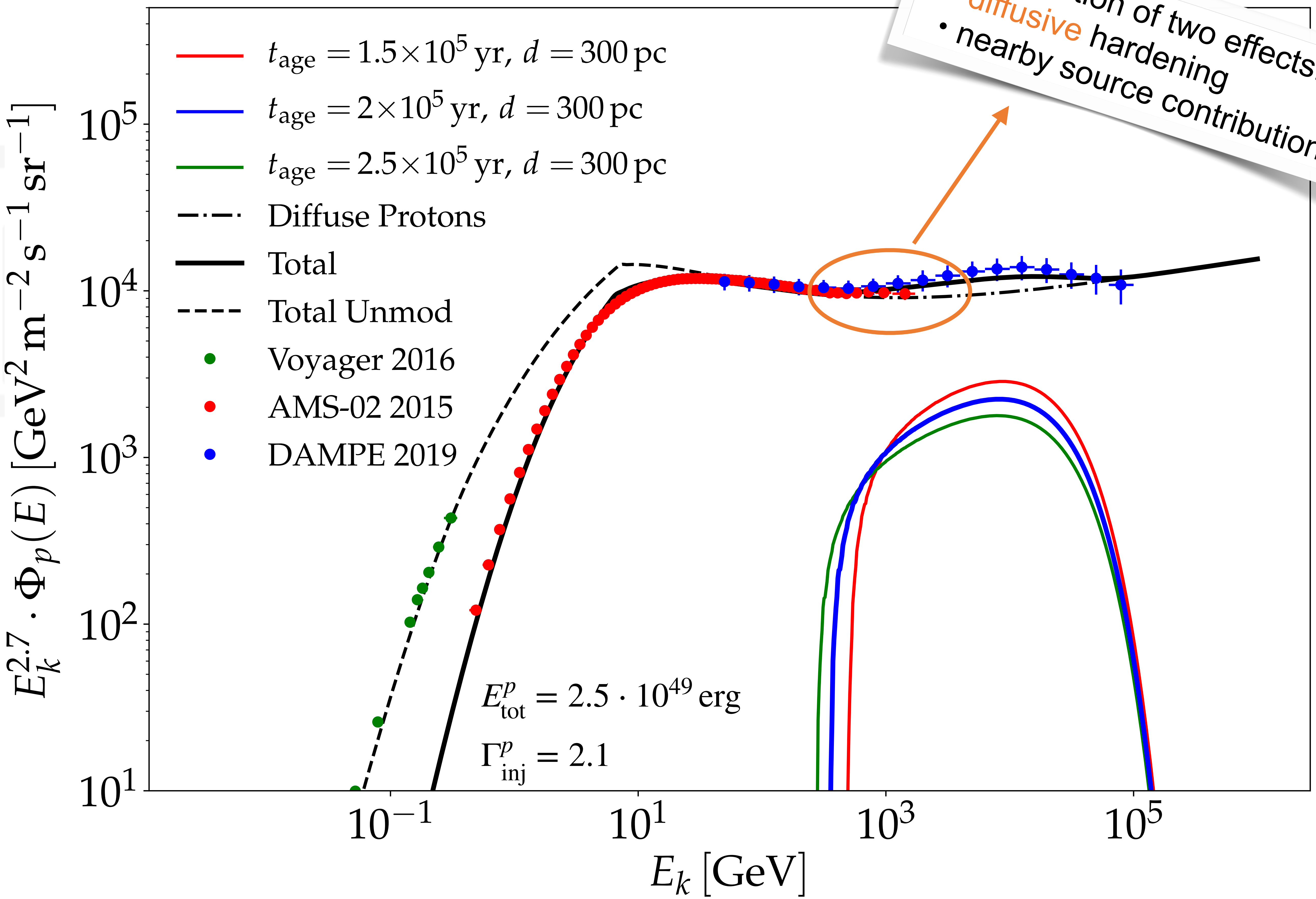

Superposition of two effects:
- diffusive hardening
- nearby source contribution

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The proton flux

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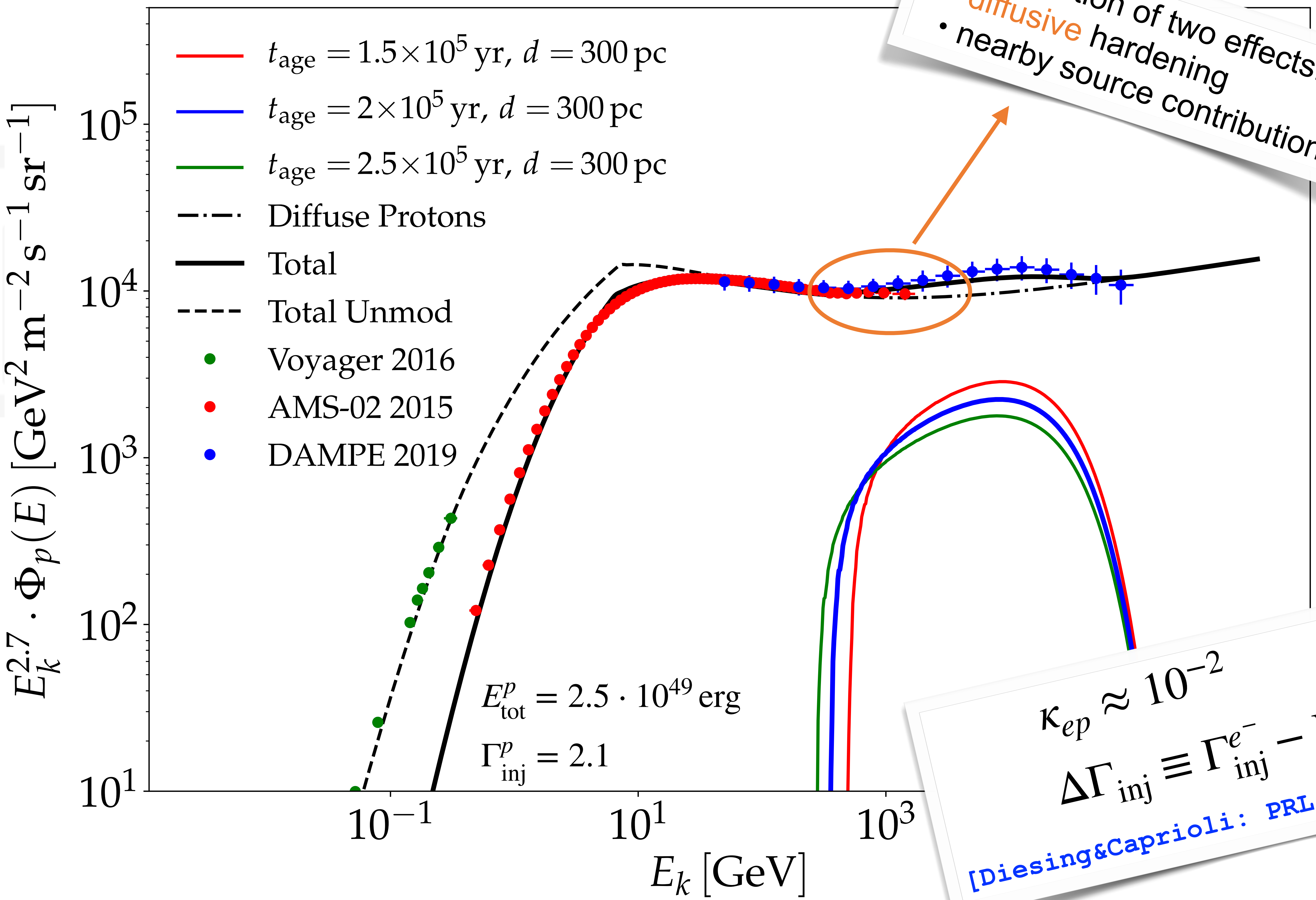

Superposition of two effects:
- diffusive hardening
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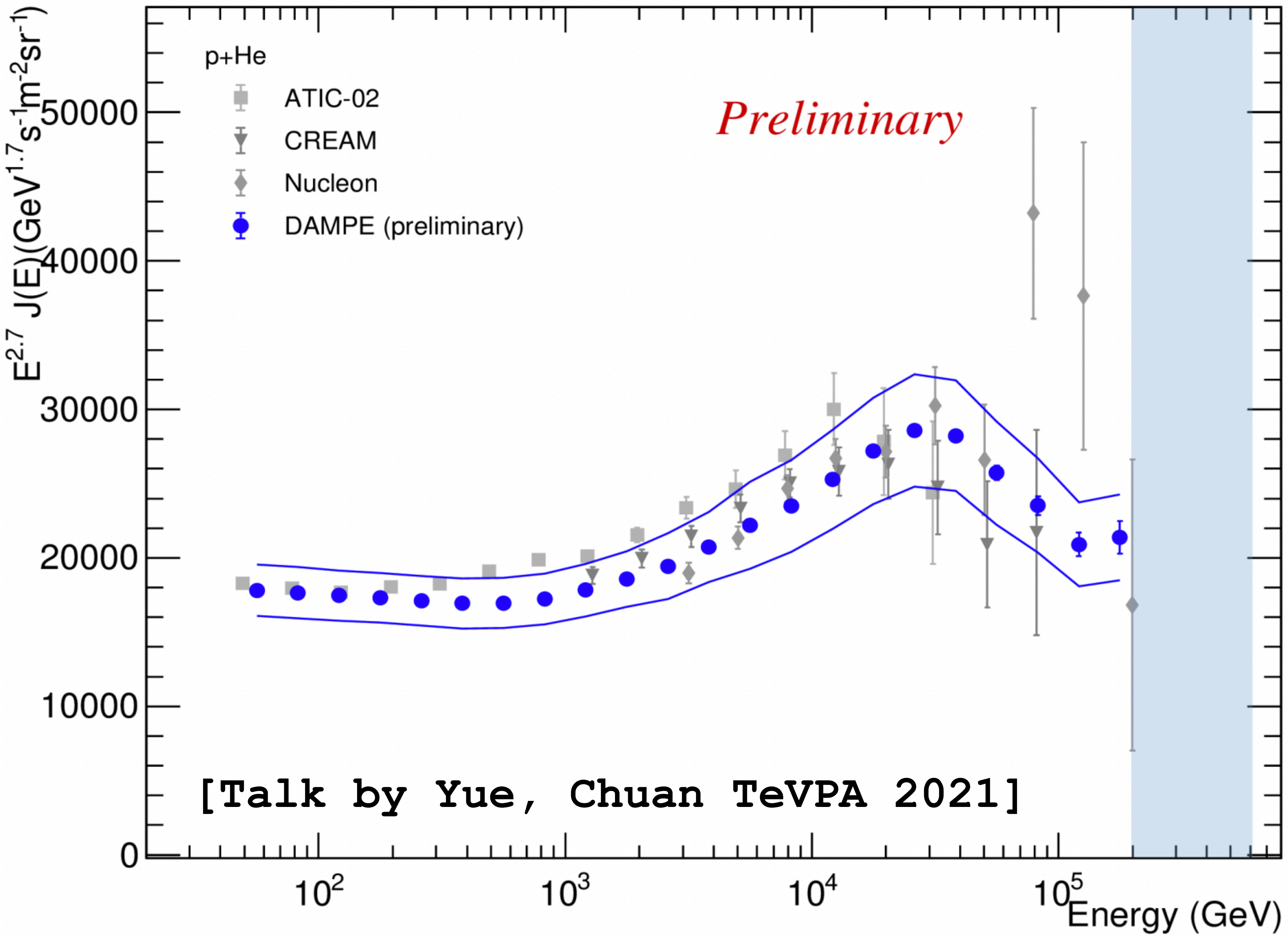
$\kappa_{ep} \approx 10^{-2}$

$\Delta\Gamma_{inj} \equiv \Gamma^{e^-}_{inj} - \Gamma^{p}_{inj} = 0.35$

[Diesing&Caprioli: PRL 123, 071101 (2019)]

The proton flux



Superposition of two effects:
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$\kappa_{ep} \approx 10^{-2}$

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$E^p_{tot} = 2.5 \cdot 10^{49}$ erg

$\Gamma^p_{inj} = 2.1$

[Diesing&Caprioli: PRL 123, 071101 (2019)]

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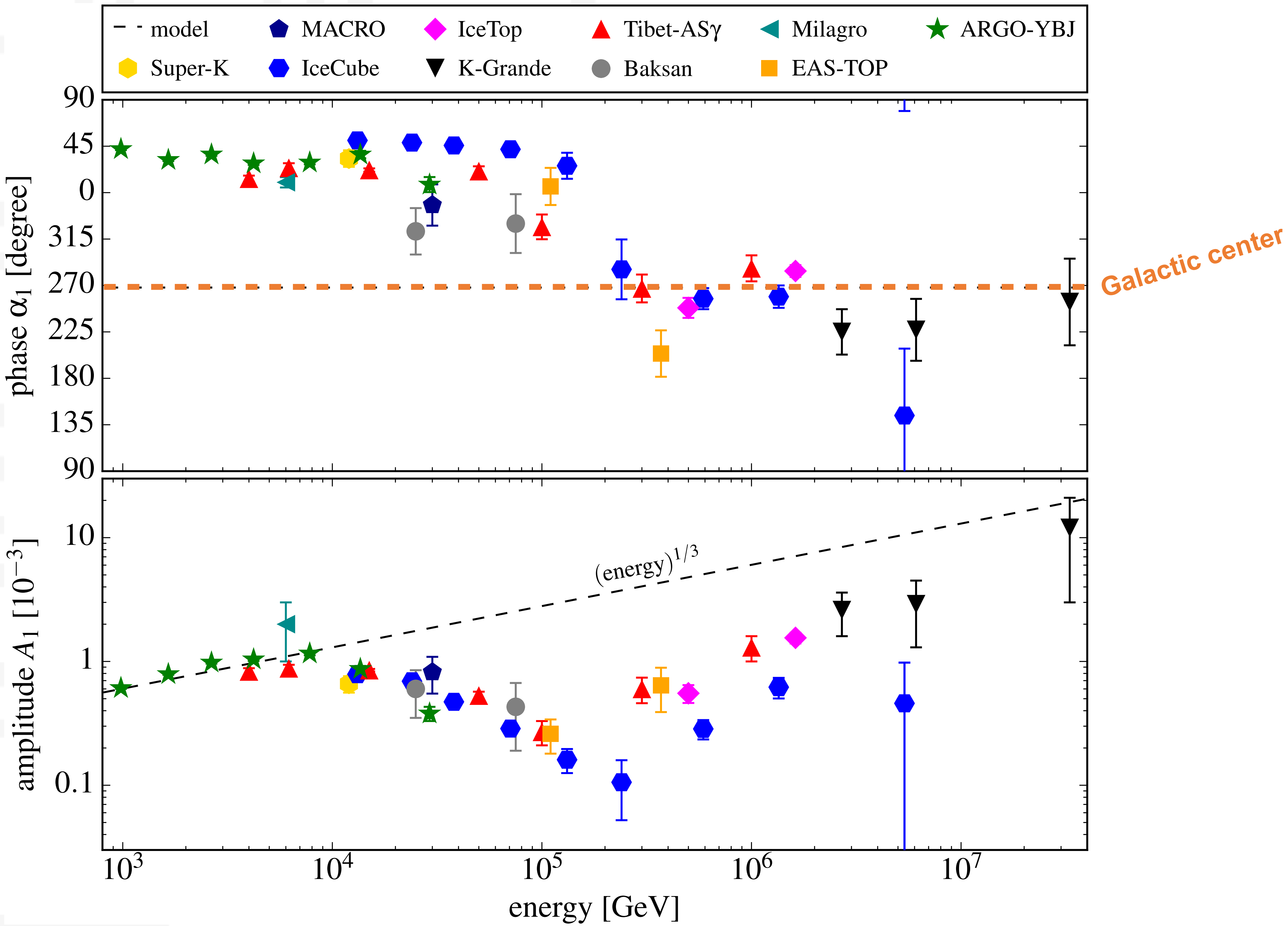
The dipole anisotropy

Measurement of the directional flux and phase

[Ahlers&Mertsch: Progr. in Part. and Nucl. Phys. 94 (2017)]



$$\Delta_{\mathrm{tot}} = \frac{\sum_i f_i \Delta_i \hat{r} \cdot \hat{n}_{\mathrm{max}}}{\sum_i f_i} \simeq \frac{f_i \Delta_i}{\sum_i f_i} + \frac{\left\langle \sum_i f_i \Delta_i \right\rangle}{\sum_i f_i}$$

$$\Delta_i \approx \Delta_{i,\mathrm{dipole}} = \frac{3D(E)}{c} \left| \frac{\nabla_{r,\theta,\phi} f_i}{f_i} \right|$$

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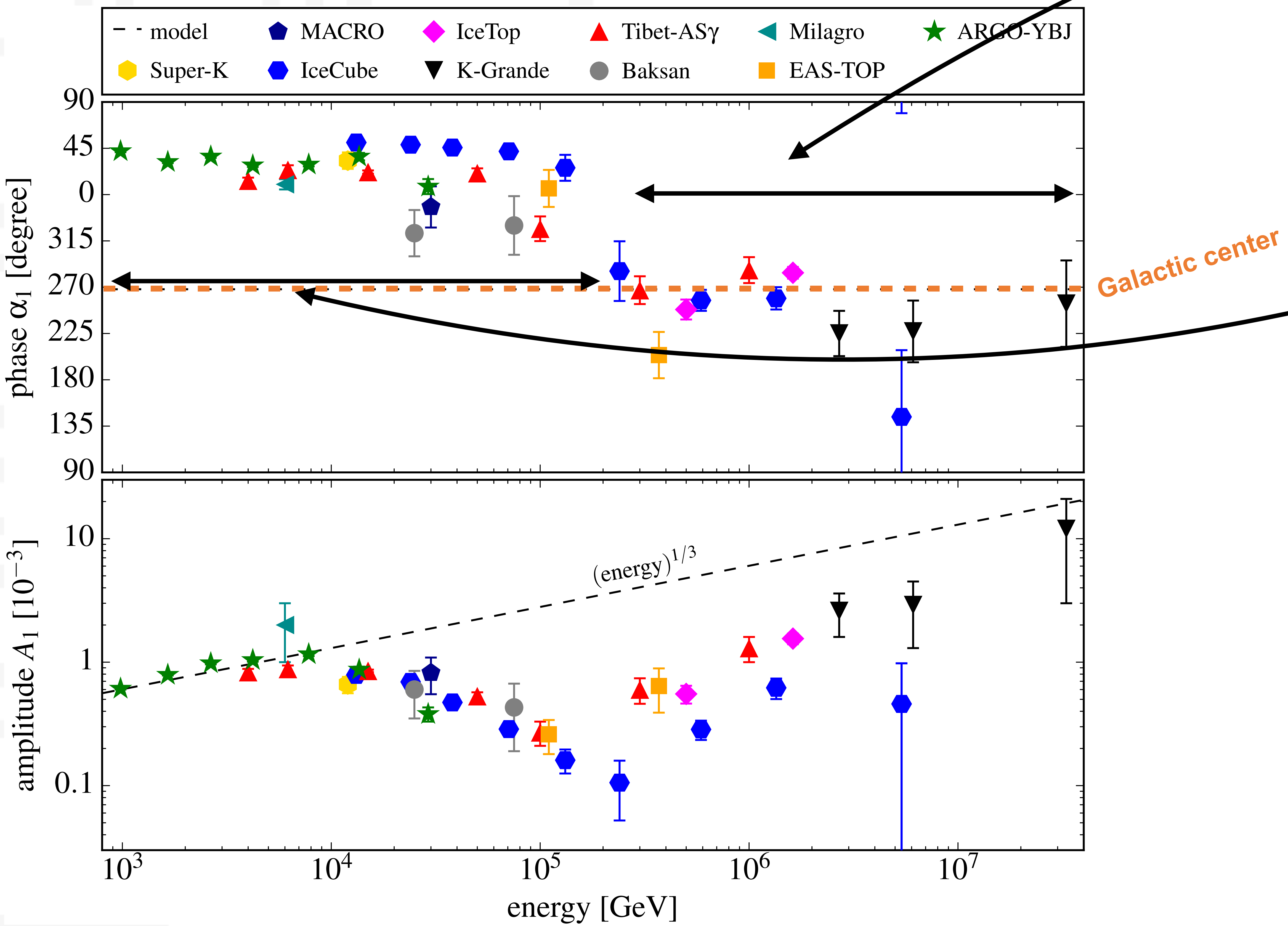

Single-source component

Large-scale component

$$\Delta_{\rm tot} = \frac{\sum_i f_i \Delta_i \hat{r}\cdot\hat{n}_{\rm max}}{\sum_i f_i} \simeq \frac{f_i \Delta_i}{\sum_i f_i} + \frac{\left\langle \sum_i f_i \Delta_i \right\rangle}{\sum_i f_i}$$

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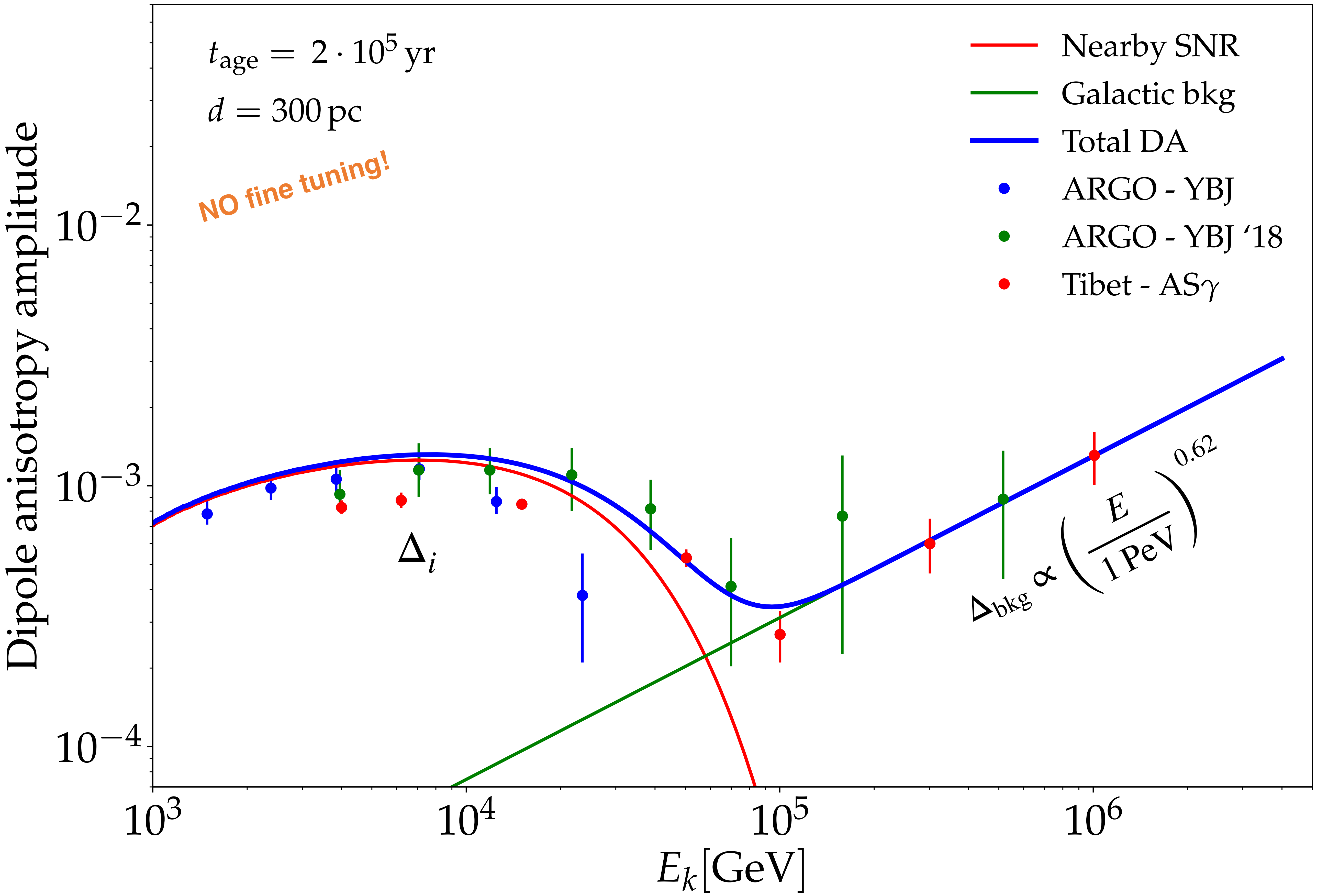
Dipole-anisotropy amplitude

Prediction from the GC + nearby source



Conclusions

- We have reproduced simultaneously **three different channels** with the **same nearby accelerator**

- The **key feature** is a transport setup that changes its properties with rigidity

  - Distinction *Halo* - *WIM* implies **two different scalings** $\Rightarrow$ $D(E)$ may **not** be **a single power-law**:

$$D(z,E) = \begin{cases} D_0 \left(\frac{E}{E_0}\right)^{\delta} & z \in [-L_{\rm WIM}, +L_{\rm WIM}] \\ D_0 \left(\frac{E}{E_0}\right)^{\delta+\Delta} & |z| \in [L_{\rm WIM}, L_{\rm Halo}] \end{cases} \quad \Longrightarrow \quad D(E) \propto E^{\delta(E)}$$

- Nearby sources experience the **same diffusion setup** as the large-scale CR sea.

GSSI

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Thank you!

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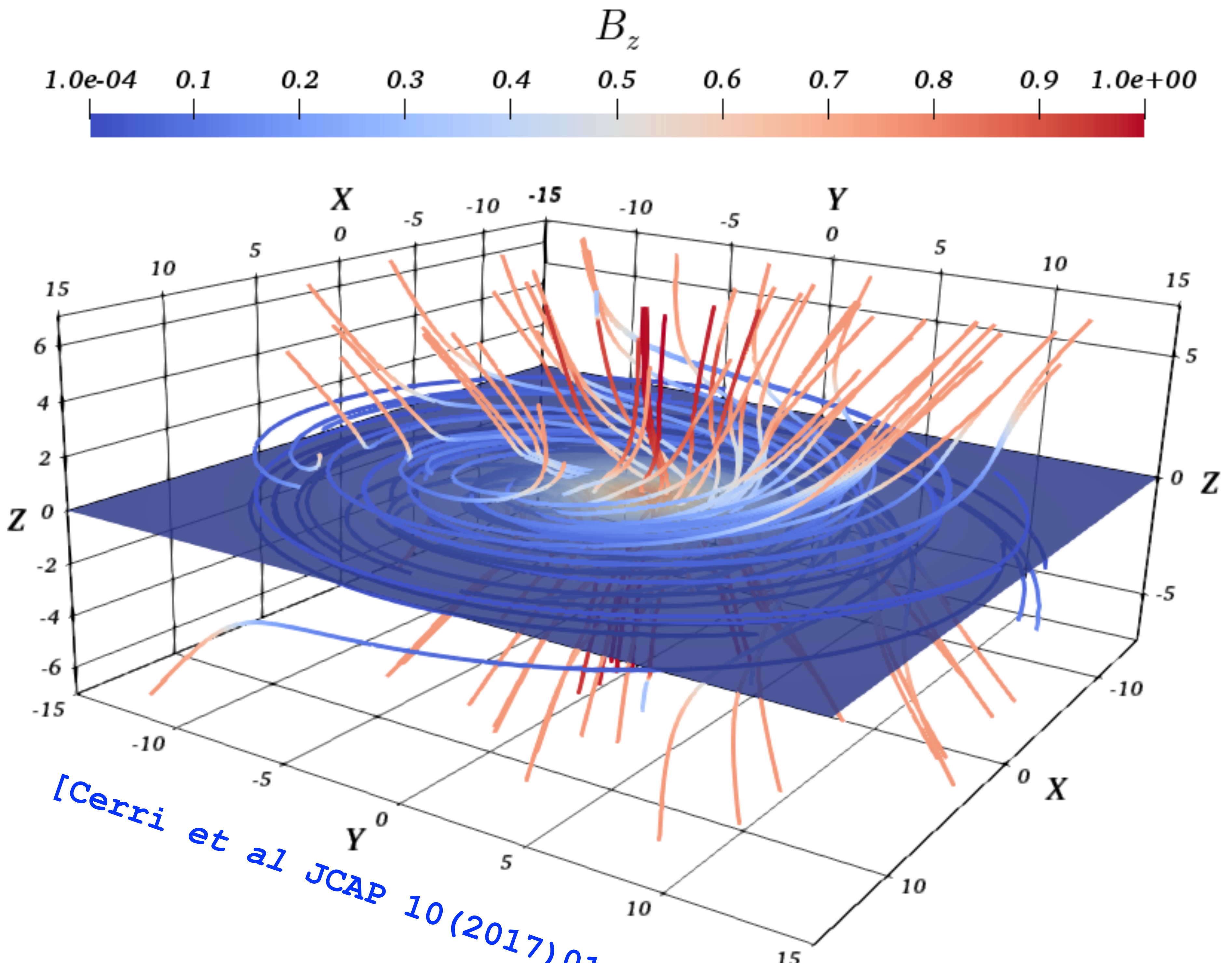
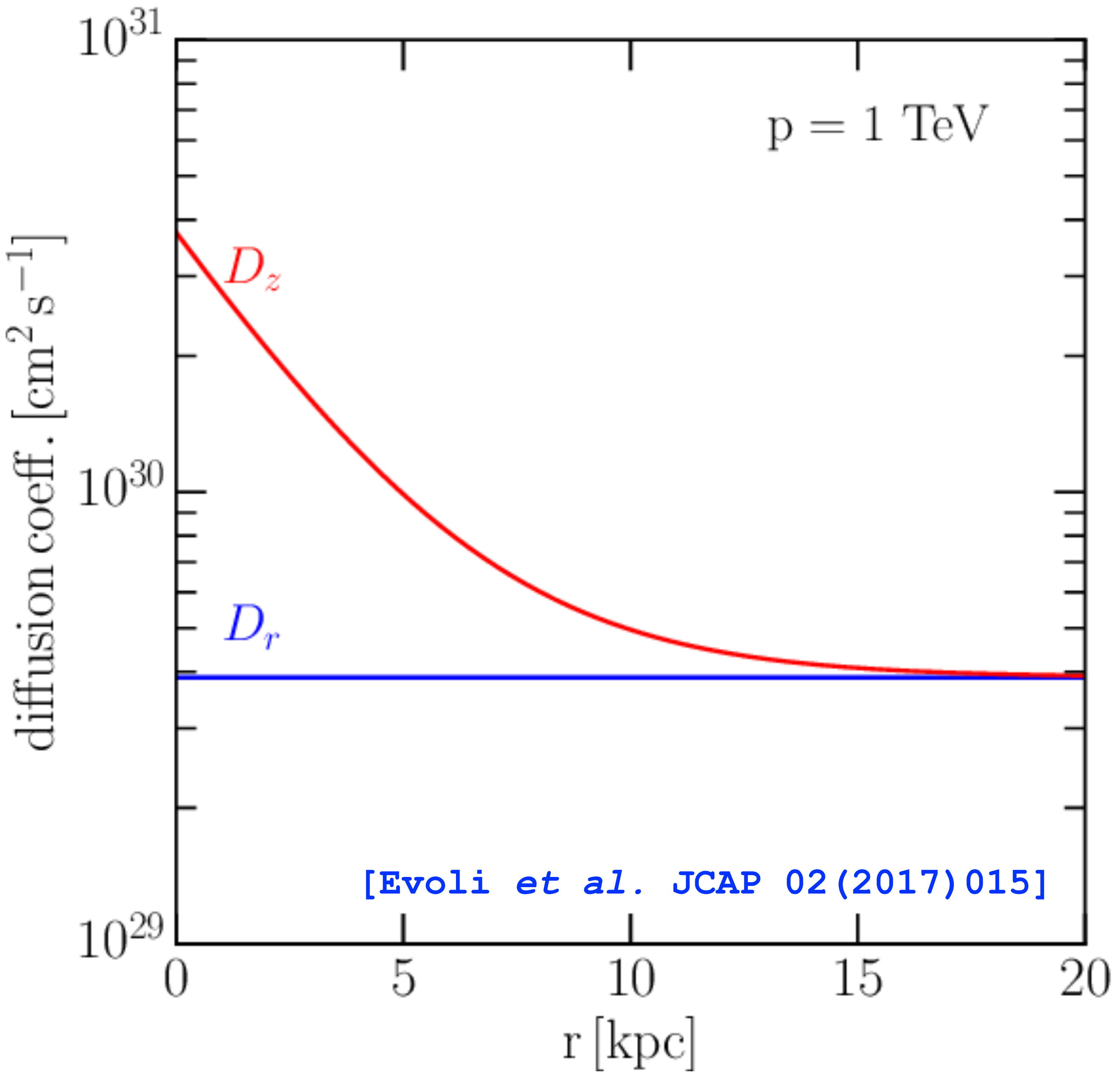
Backup slides

Need for perpendicular diffusion $D_\parallel \neq D_\perp$



[Cerri et al JCAP 10(2017)019]



[Evoli et al. JCAP 02(2017)015]

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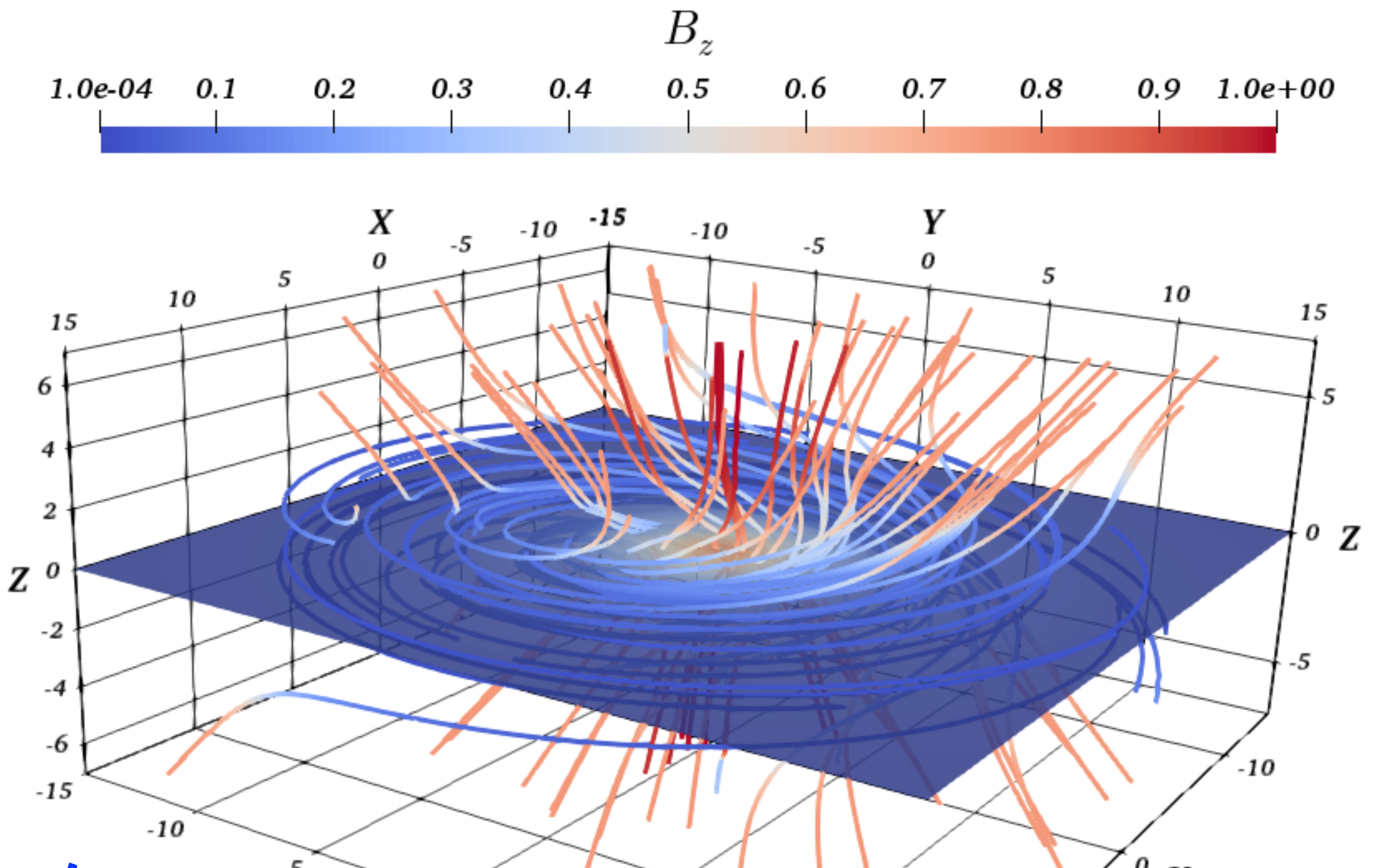

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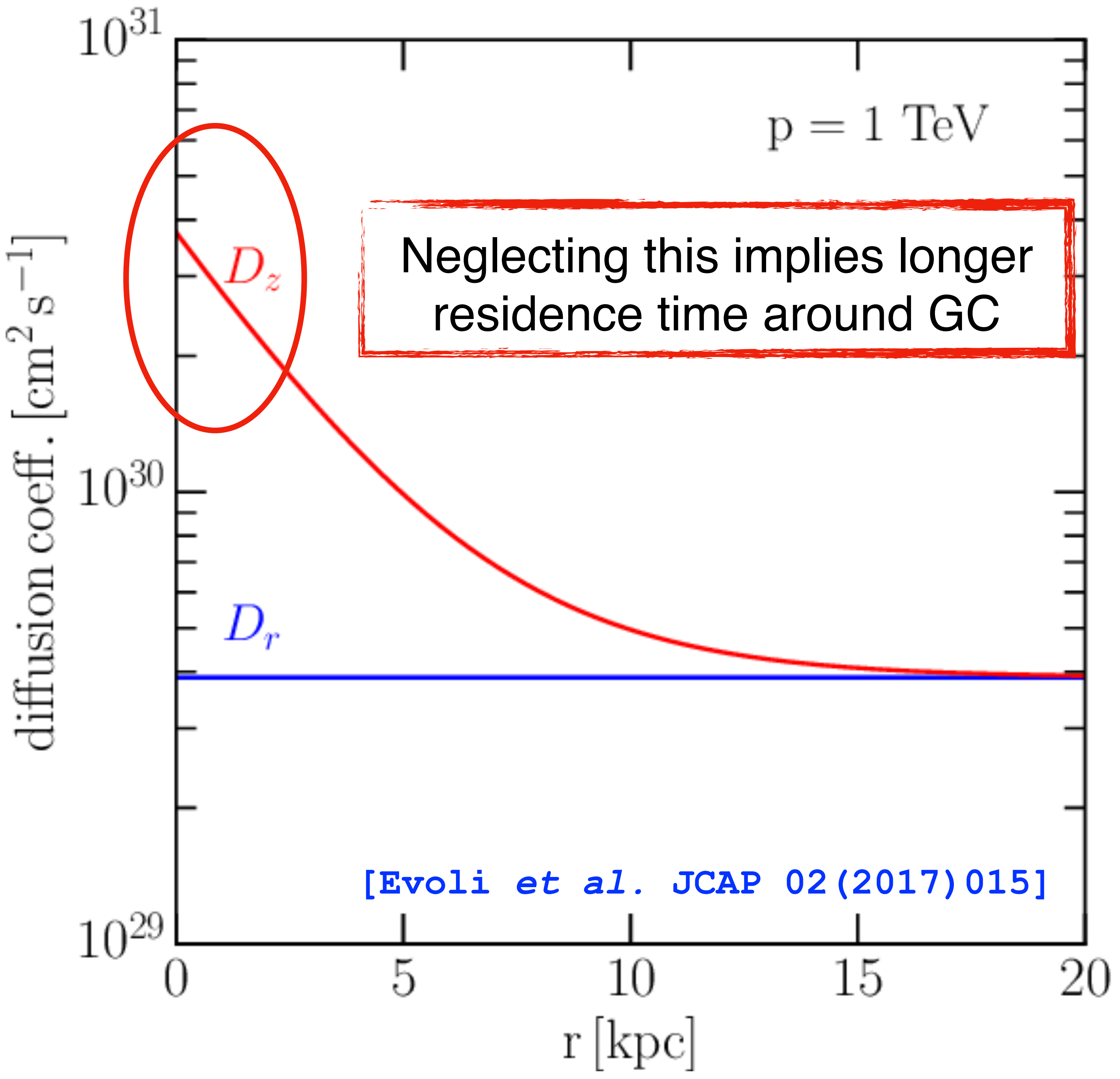
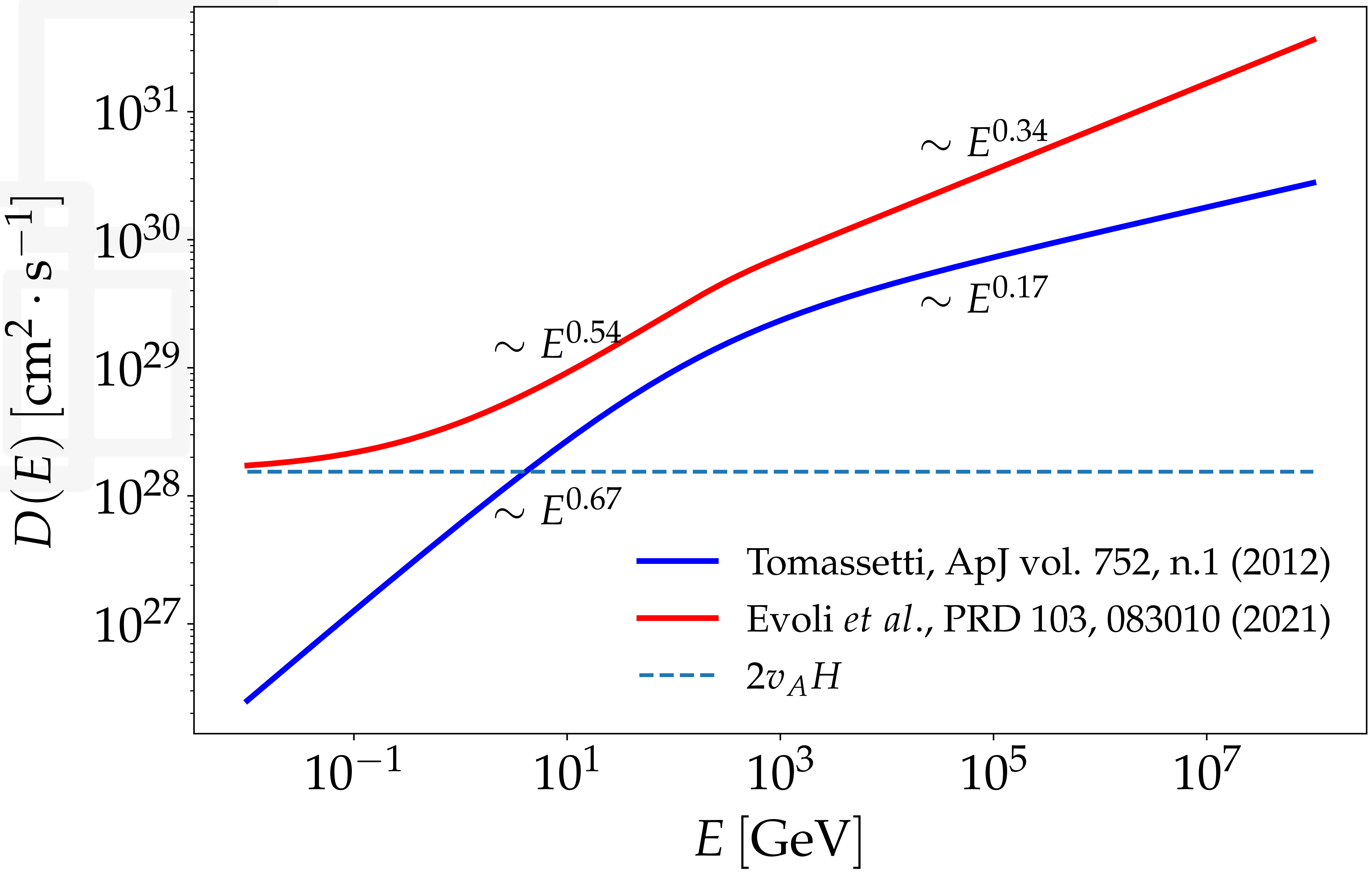


[Evoli et al. JCAP 02(2017)015]

Different parametrisations of the $D(E)$

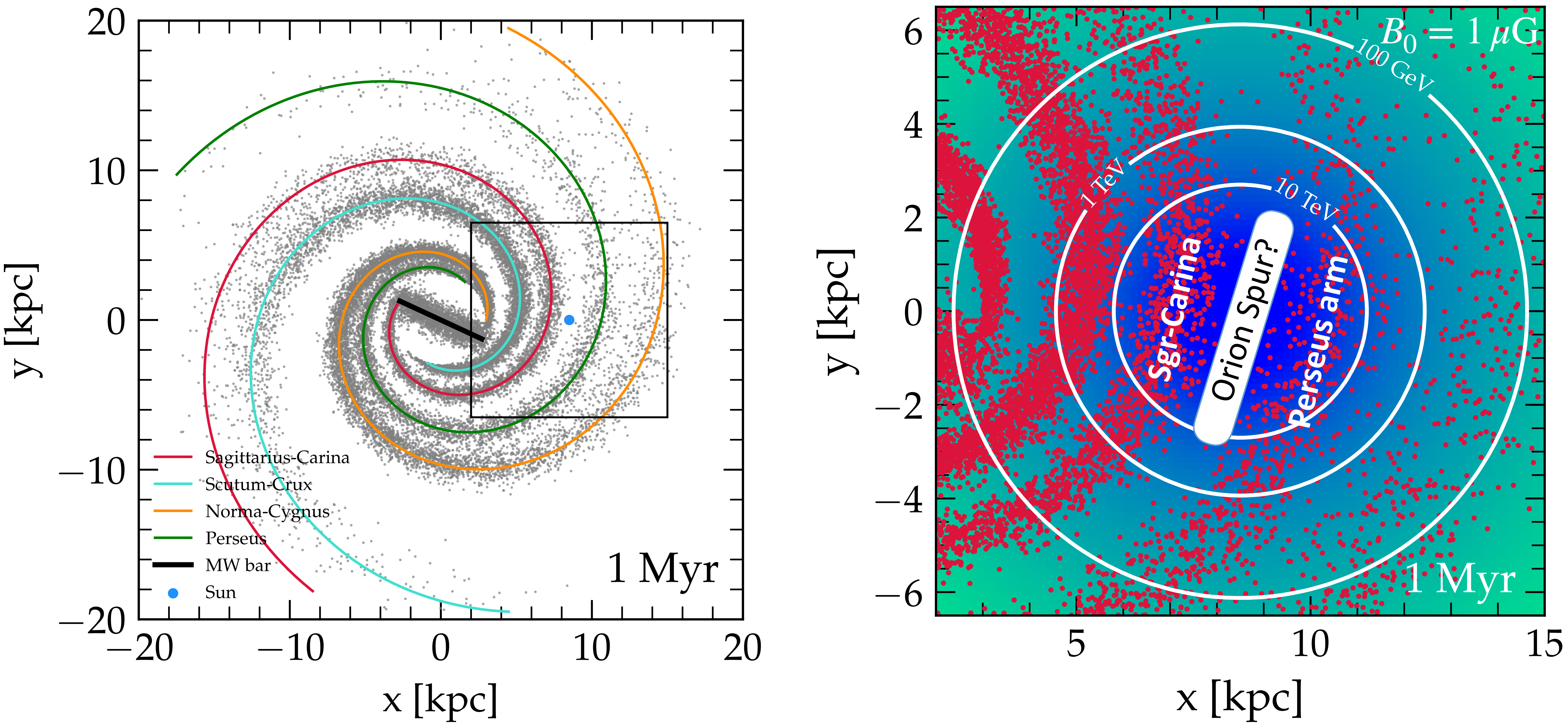


Lepton horizon, for $B = 3.2\ \mu$G: $\Delta x_{\rm horizon} = 1.3$ kpc

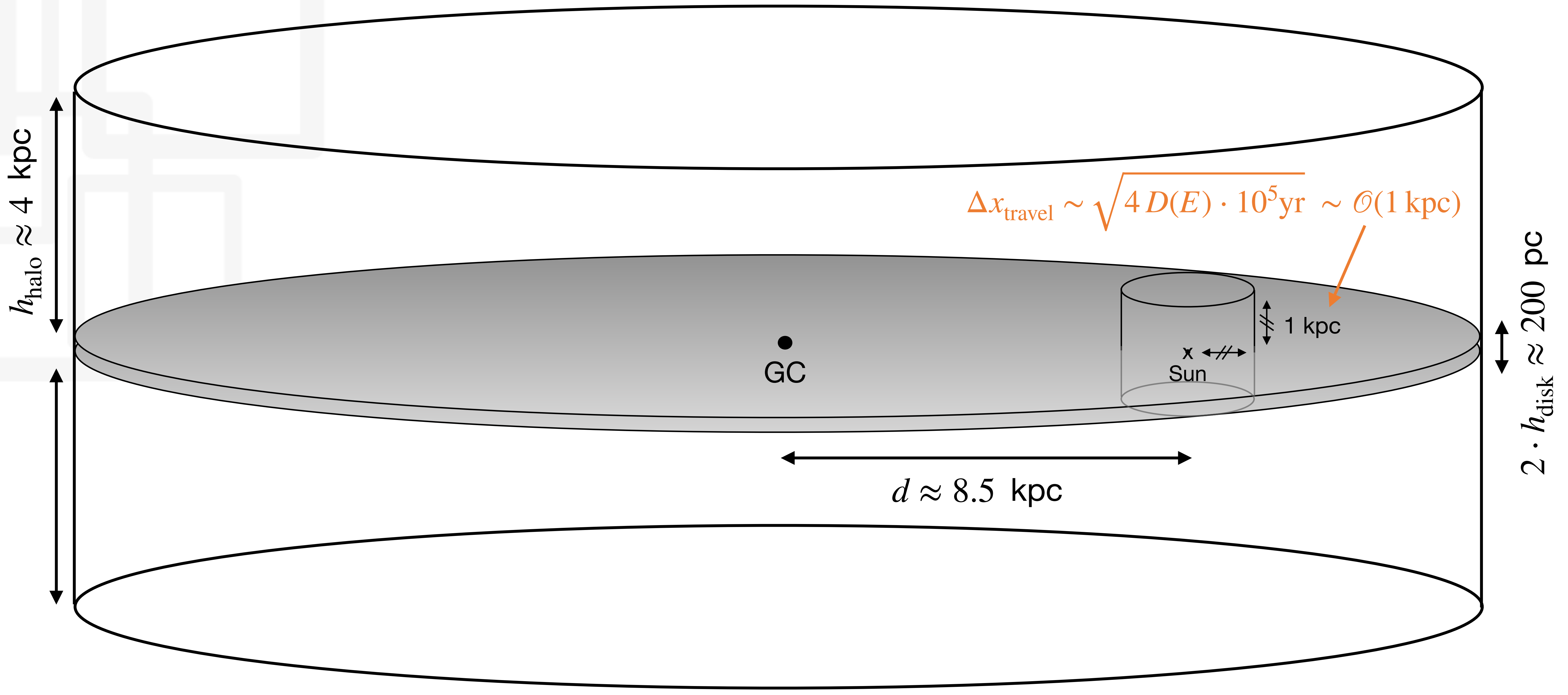
[*K. Ferrière:* 2015 J. Phys. Conf. Ser. 577 012008]

GS SI

Galactic population



Expected SN events



Rates of SN explosions around the solar system from [*K.Ferrière: Rev. Mod. Phys. 73, 1031*]

Expected SN events

$$n_{\rm events}\ \left[{\rm kpc}^{-2}\cdot{\rm Myr}^{-1}\right] = \int_{-1\,{\rm kpc}}^{+1\,{\rm kpc}} dz \left(\mathscr{R}^S_{\rm Ia}(z) + \mathscr{R}^S_{\rm II}(z) \right)$$

If:

- uniform rate inside the disk of radius $r = 1\,{\rm kpc}$
- constant rate over the age of the oldest SN accelerating CRs, $t_{\rm age} \sim 5\cdot 10^5\,{\rm yr}$

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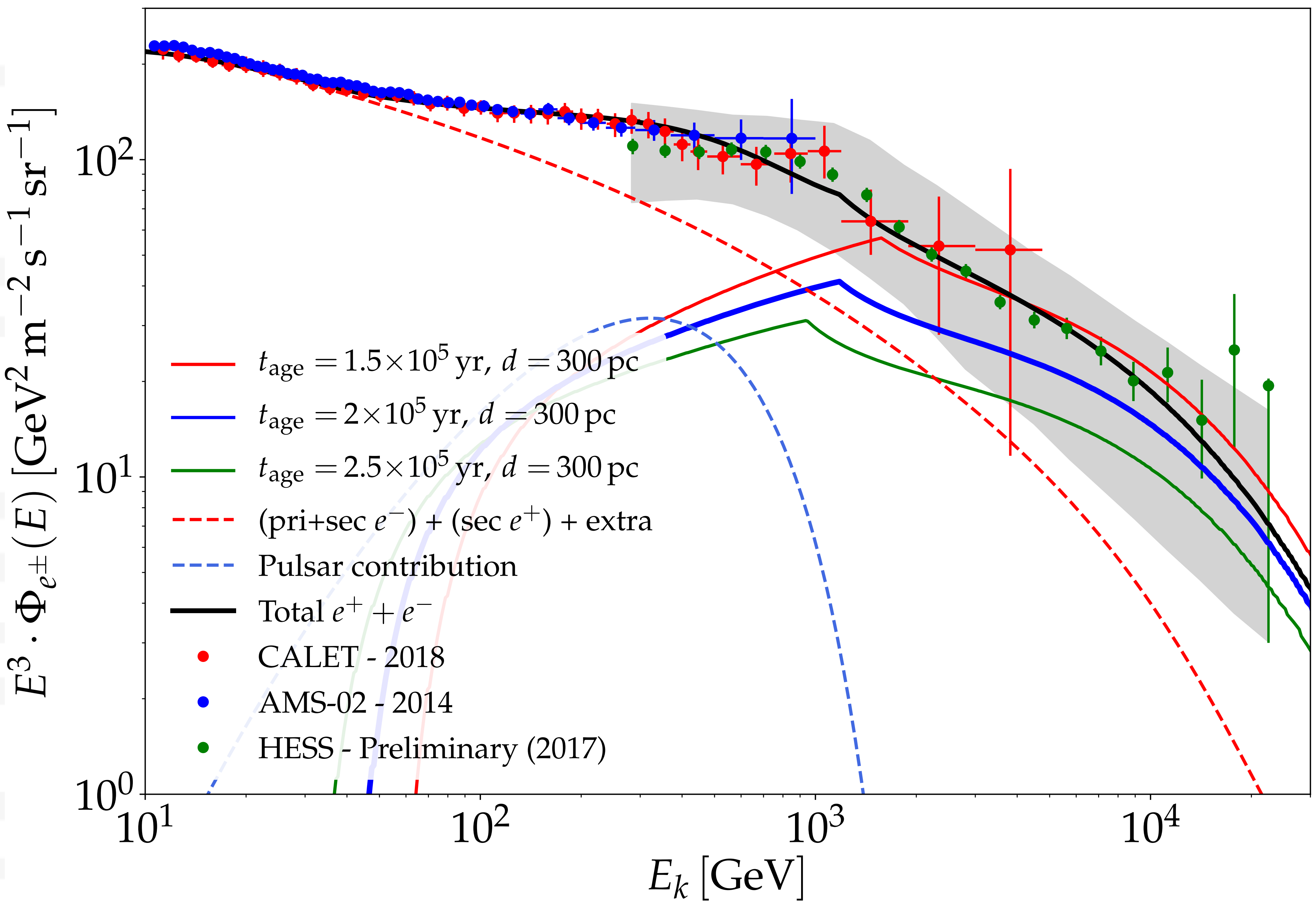
$$\Rightarrow\ N_{\rm events} = n_{\rm events} \cdot \pi r^2 \cdot t_{\rm age} \approx 2.2 \sim \mathcal{O}(\underbrace{1 - 10})$$

We already see some of them

We consider the lowest possible number of hidden sources

[*Recchia&Gabici:* PRD 99, 103022]



$t_{age} = 1.5\times10^5$ yr, $d = 300$ pc
$t_{age} = 2\times10^5$ yr, $d = 300$ pc
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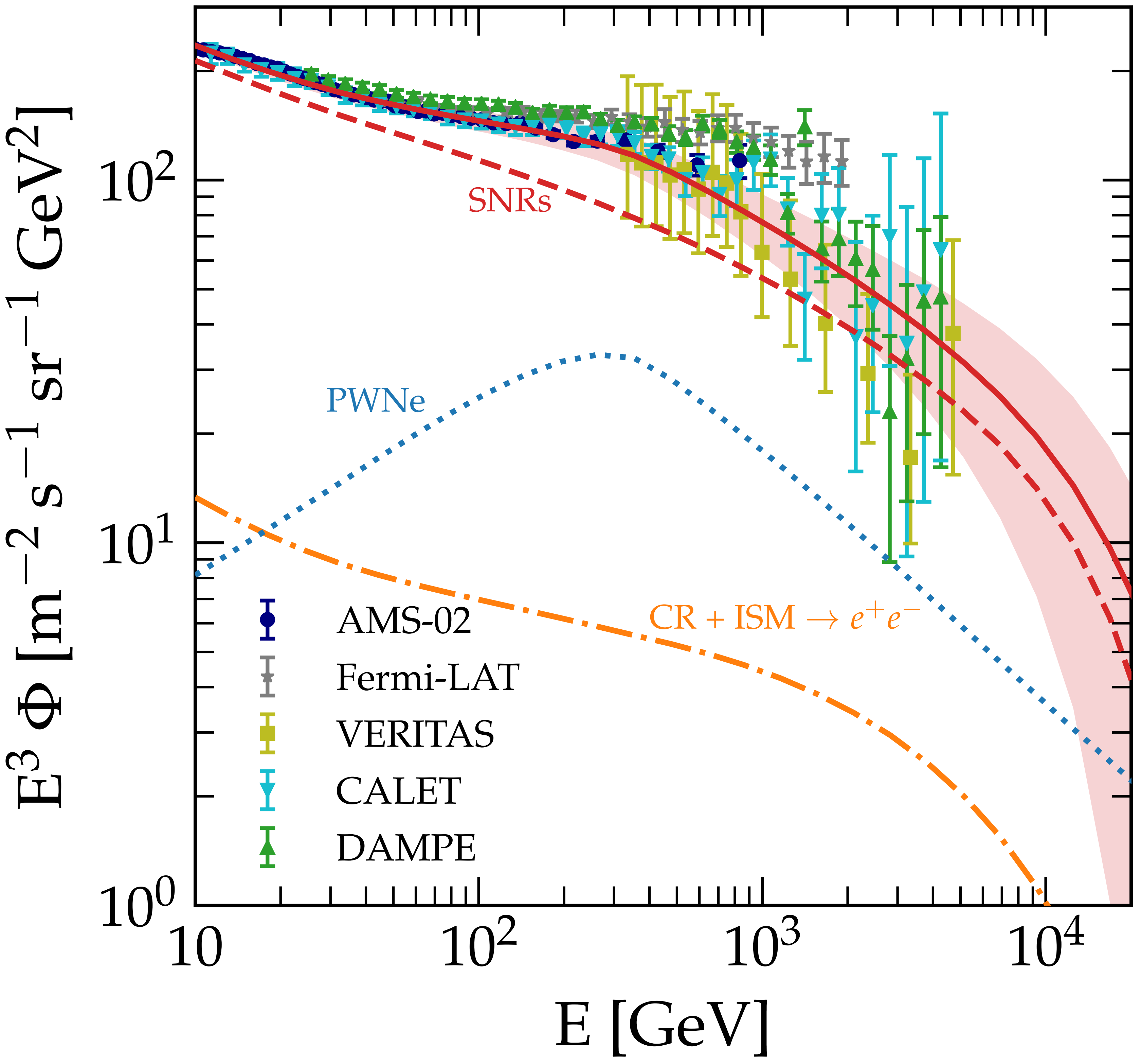
(pri+sec e^-) + (sec e^+) + extra
Pulsar contribution
Total $e^+ + e^-$
CALET - 2018
AMS-02 - 2014
HESS - Preliminary (2017)
$E^3 \cdot \Phi_{e^\pm}(E)$ [GeV^2 m^{-2} s^{-1} sr^{-1}]
E_k [GeV]



SNRs
PWNe
CR + ISM → e^+e^-
AMS-02
Fermi-LAT
VERITAS
CALET
DAMPE
$E^3\ \Phi$ [m^{-2} s^{-1} sr^{-1} GeV^2]
E [GeV]

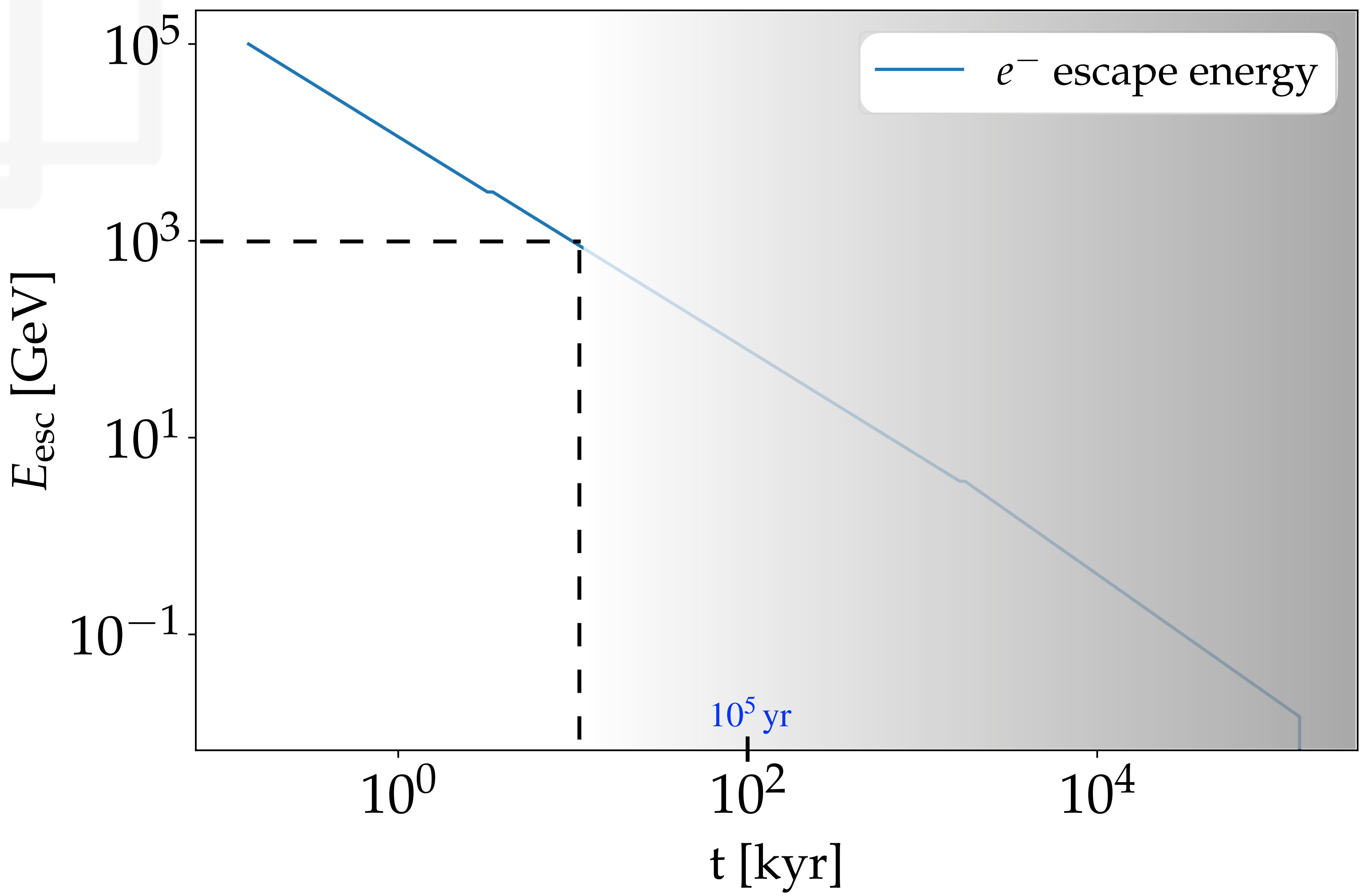
On the age of the electron source

$$t_{\rm age} = t_{\rm rel} + \Delta t_{\rm travel}$$

$\Delta t_{\rm travel} \simeq 10^5$ yr is fixed by the break at ~ 1 TeV

- $t_{\rm rel} > \Delta t_{\rm travel}$ $\Rightarrow$ we wouldn't observe those electrons

- $t_{\rm rel} \leq \Delta t_{\rm travel}$



$\Rightarrow$ $t_{\rm rel} \ll \Delta t_{\rm travel}$

$\Downarrow$

$$t_{\rm age} \simeq \Delta t_{\rm travel}$$

Energy-dependent release time

$$t_{\text{Sed,kyr}} = 0.3 E_{\text{SNR},51}^{-1/2} M_{\text{ej},\odot} n_{T,1}^{-1/3}$$

$$t_{\text{PDS,kyr}} = \frac{36.1 e^{-1} E_{\text{SNR},51}^{3/14}}{\xi_n^{5/14} n_{T,1}^{4/7}}$$

$$t_{\text{MCS,kyr}} = \min\left[\frac{61 v_{\text{ej},8}^3}{\xi_n^{9/14} n_{T,1}^{3/7} E_{\text{SNR},51}^{3/14}}, \frac{476}{(\xi_n \Phi_c)^{9/14}}\right] t_{\text{PDS,kyr}}$$

$$t_{\text{merge,kyr}} = 153 \left(\frac{E_{\text{SNR},51}^{1/14} n_{T,1}^{1/7} \xi_n^{3/14}}{\beta C_{06}}\right)^{10/7} t_{\text{MCS,kyr}}$$

Protons

- $\ln\left(\frac{E_{\text{esc,Cur}}(t)}{m_p c^2}\right) E_{\text{esc,Cur}}(t) = \ln(E_M(t_{\text{Sed}}))\left(\frac{t}{t_{\text{Sed}}}\right)^{-6/5}$

  such that $E_M \equiv E_{p,\max}(t_{\text{Sed}}) = 1\,\text{PeV}$

- $E_{\text{esc,Geo,1}}(t) = E_{\text{M}}(t_{\text{PDS}})\left(\frac{t}{t_{\text{PDS}}}\right)^{-11/10} = E_{\text{esc,Cur}}(t_{\text{PDS}})\left(\frac{t}{t_{\text{PDS}}}\right)^{-11/10}$

- $E_{\text{esc,Geo,2}}(t) = E_{\text{M}}(t_{\text{MCS}})\left(\frac{t}{t_{\text{MCS}}}\right)^{-5/4} = E_{\text{esc,Geo,1}}(t_{\text{MCS}})\left(\frac{t}{t_{\text{MCS}}}\right)^{-5/4}.$

Leptons

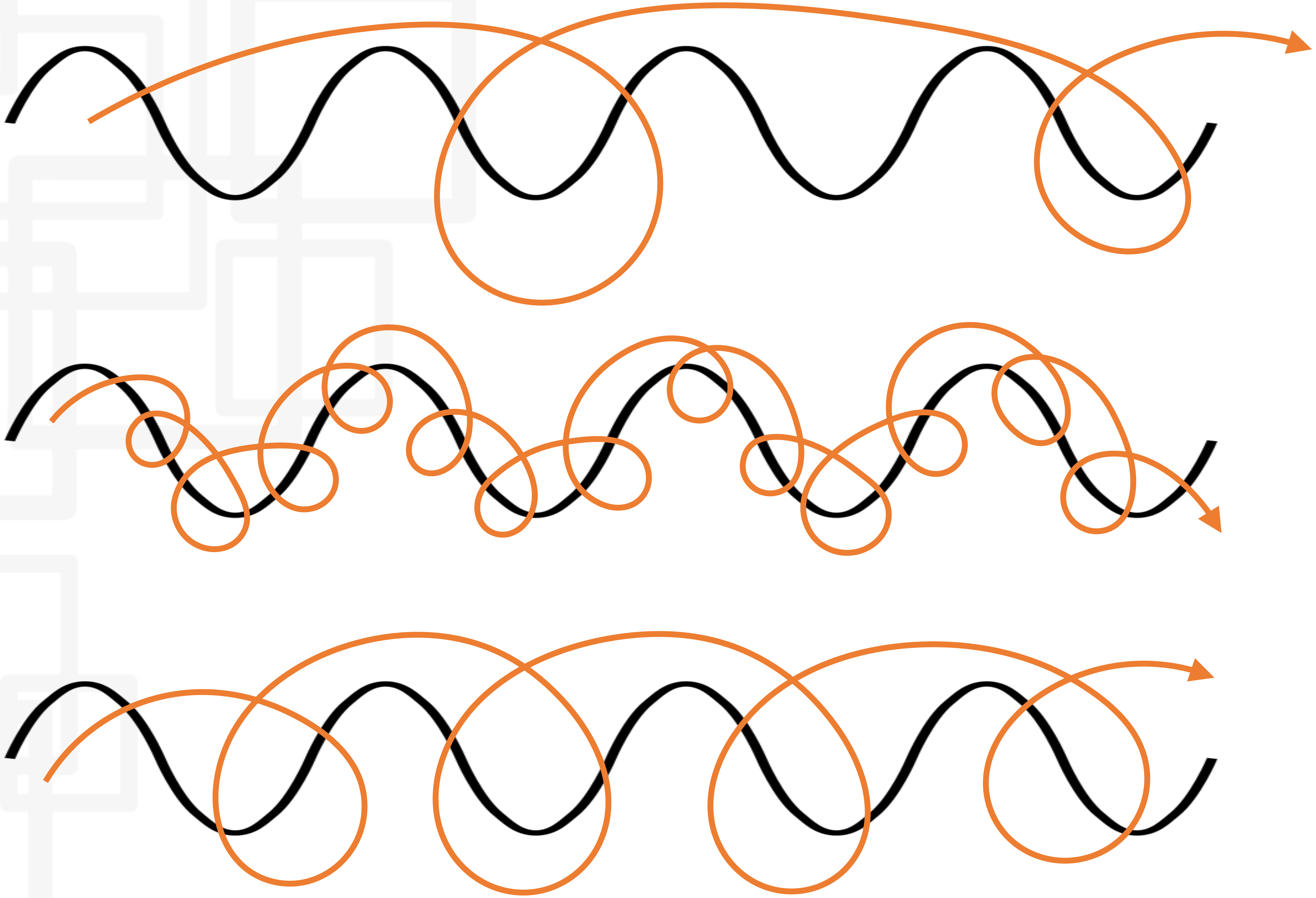
- $E_{\text{esc,Geo,0}}(t) = E_{\text{M}}(t_{\text{Sed}})\left(\frac{t}{t_{\text{Sed}}}\right)^{-11/10}$

  such that $E_M \equiv E_{e,\max}(t_{\text{Sed}}) = 100\,\text{TeV}$

- $E_{\text{esc,Geo,1}}(t) = E_{\text{M}}(t_{\text{PDS}})\left(\frac{t}{t_{\text{PDS}}}\right)^{-11/10} = E_{\text{esc,Geo,0}}(t_{\text{PDS}})\left(\frac{t}{t_{\text{PDS}}}\right)^{-11/10}$

- $E_{\text{esc,Geo,2}}(t) = E_{\text{M}}(t_{\text{MCS}})\left(\frac{t}{t_{\text{MCS}}}\right)^{-5/4} = E_{\text{esc,Geo,1}}(t_{\text{MCS}})\left(\frac{t}{t_{\text{MCS}}}\right)^{-5/4}.$

Pitch-angle scattering on $\mathbf{B}$-fluctuactions

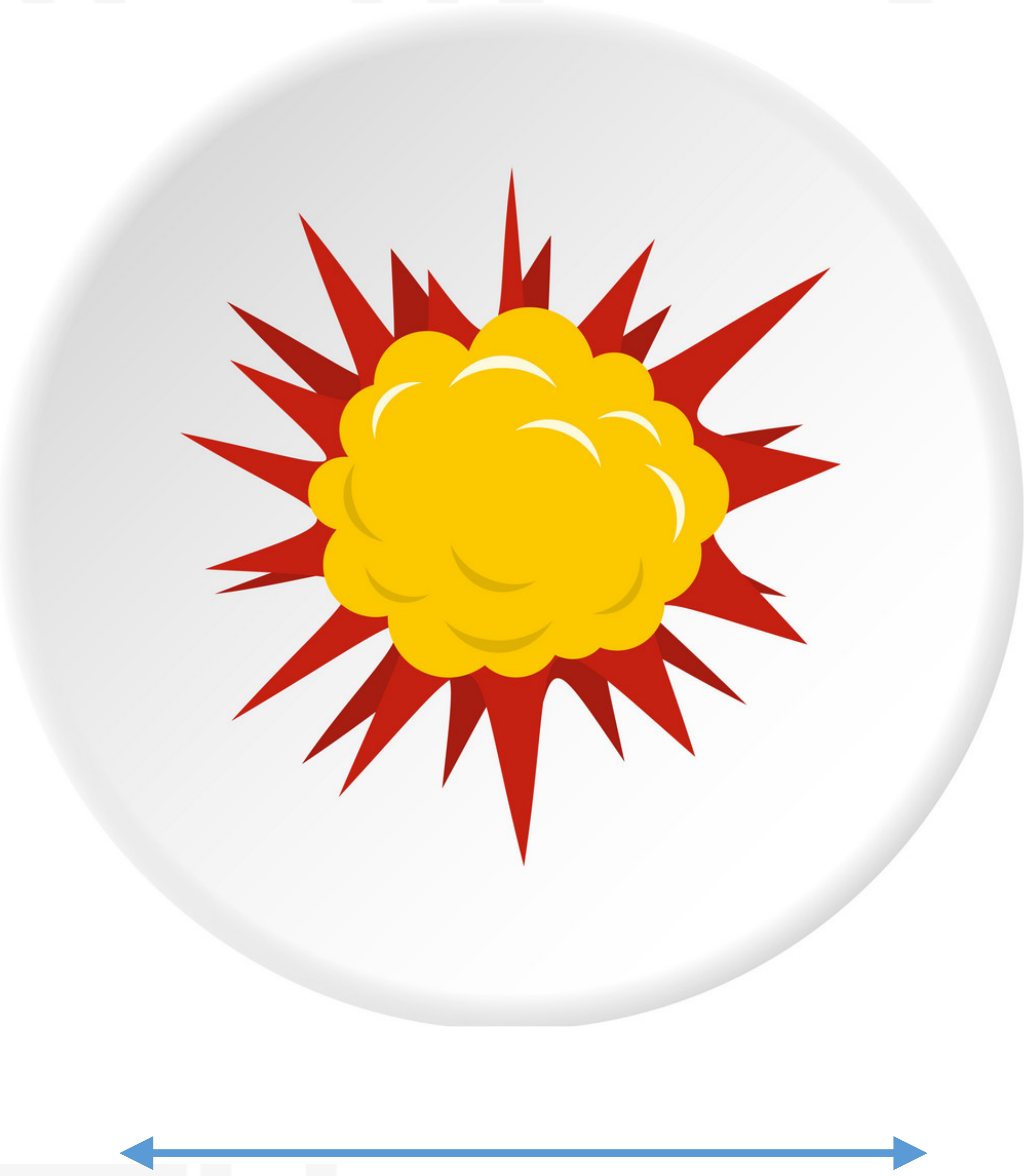


$$r_L \gg \frac{1}{k_{\text{fluctuation}}} \quad \rightarrow \quad \mathbf{B}_0$$

$$r_L \ll \frac{1}{k_{\text{fluctuation}}} \quad \rightarrow \quad \delta\mathbf{B}$$

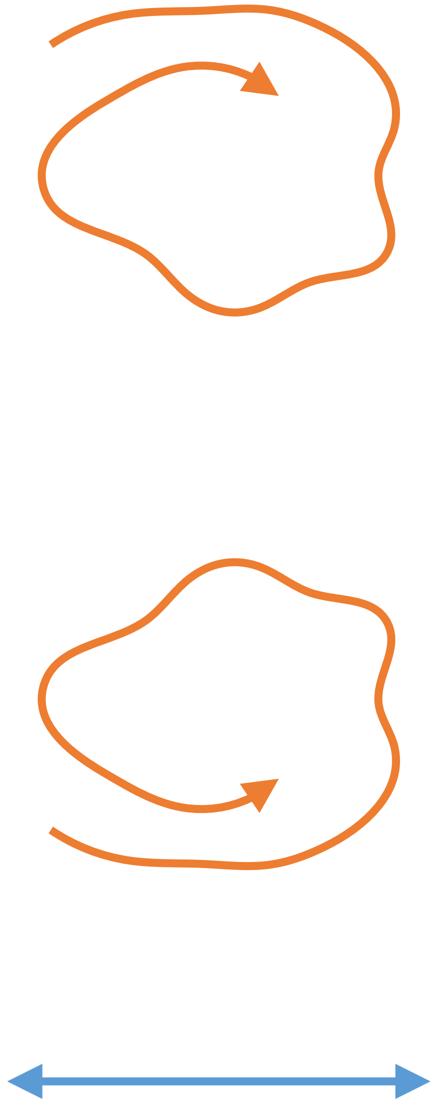
$$r_L \sim \frac{1}{k_{\text{fluctuation}}} \quad \rightarrow \quad \mathbf{B}_0 + \delta\mathbf{B}$$

Turbulent cascade in the inertial range



$$L_{\rm inj} \sim \frac{1}{k_{\rm inj}}$$

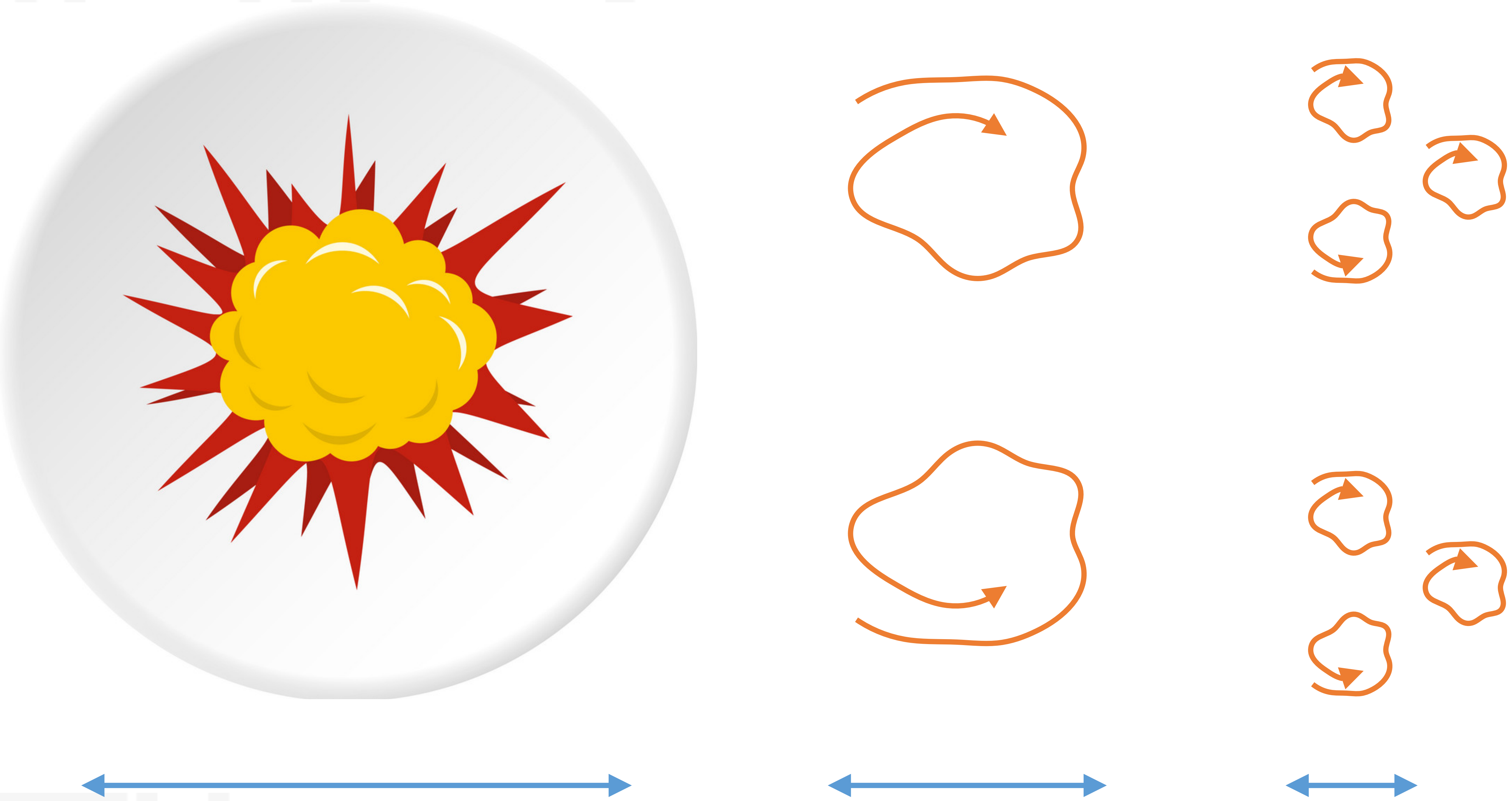
Turbulent cascade in the inertial range



$$L_{\text{inj}} \sim \frac{1}{k_{\text{inj}}}$$

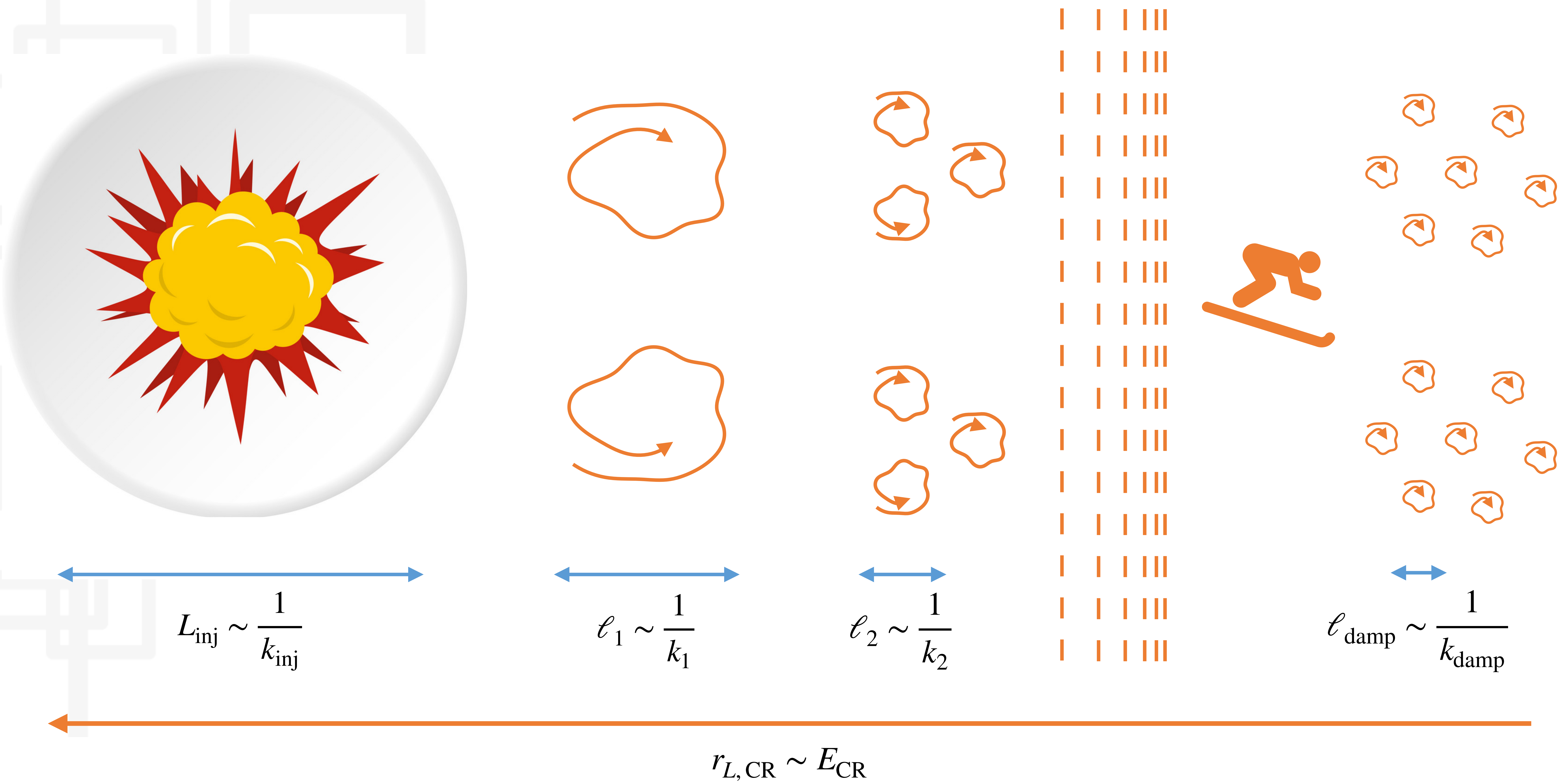
$$\ell_1 \sim \frac{1}{k_1}$$

Turbulent cascade in the inertial range



$L_{\text{inj}} \sim \frac{1}{k_{\text{inj}}}$ $\ell_1 \sim \frac{1}{k_1}$ $\ell_2 \sim \frac{1}{k_2}$

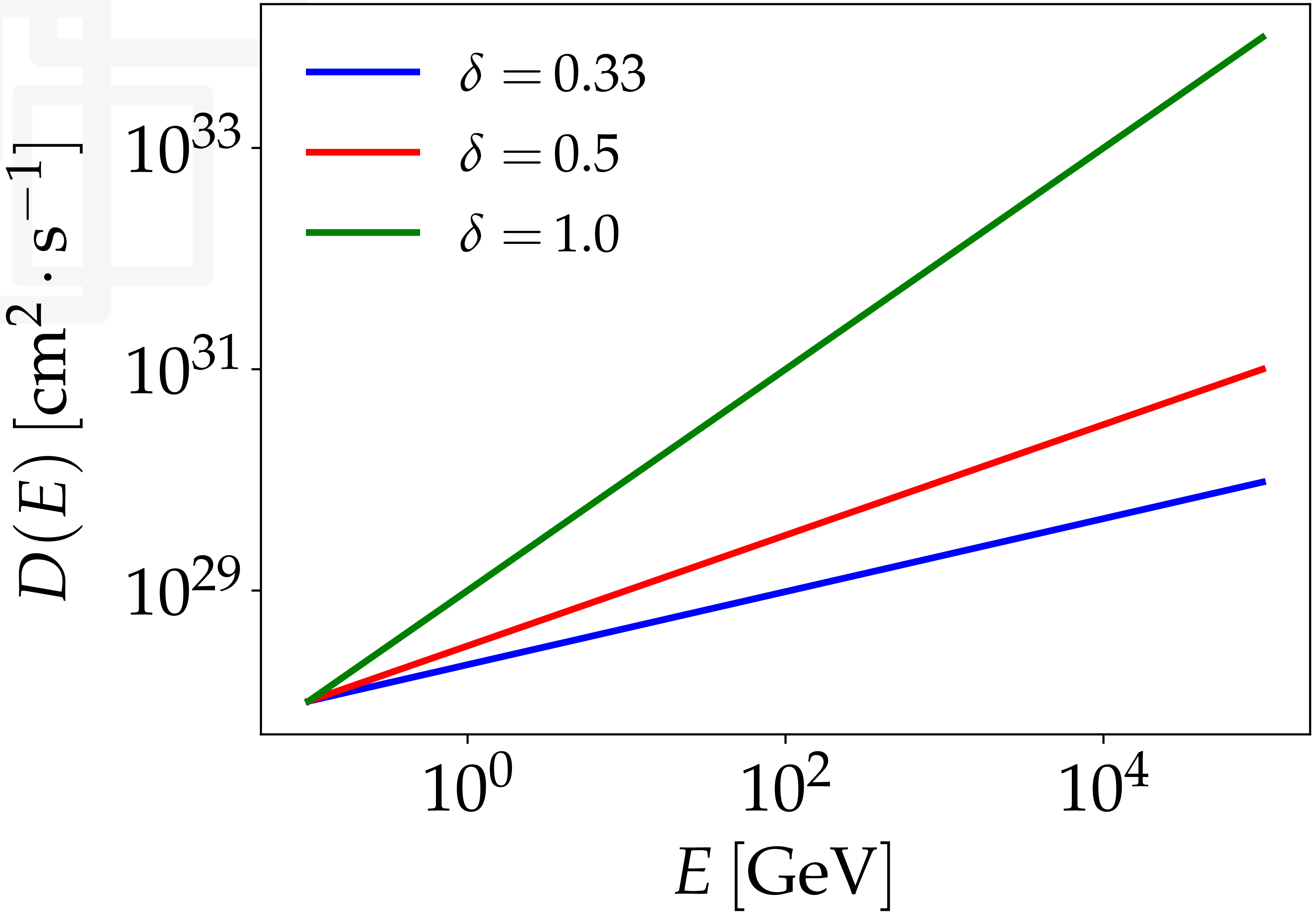
Turbulent cascade in the inertial range



From turbulence to CR diffusion

$$D(E) = \frac{1}{3} \cdot \frac{c\, r_L}{k_{\rm res} \cdot E(k_{\rm res})} \quad \Rightarrow \quad D(E) \sim \frac{r_L}{r_L^{-1} \cdot r_L^{\alpha}}$$

$$D(E) \sim E^{2-\alpha} \equiv E^{\delta}$$



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Take-home message

Accurate *measurements require detailed knowledge of the* ***microphysics of CR transport*** *in our Galaxy.*

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