CR scattering on MHD modes

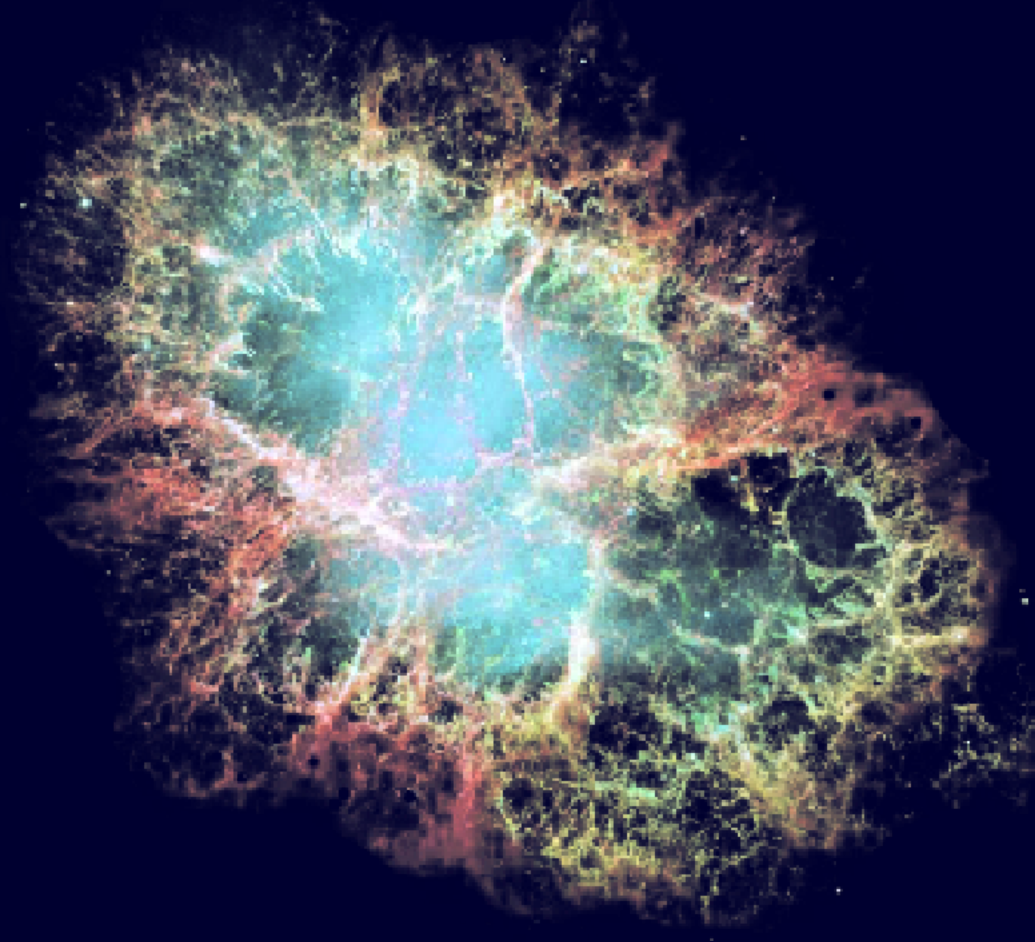
O. Fornieri *et al.* – MNRAS 502, 5821–5838 (2021)

Ottavio Fornieri
ICRC - Berlin, 12 July 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outline



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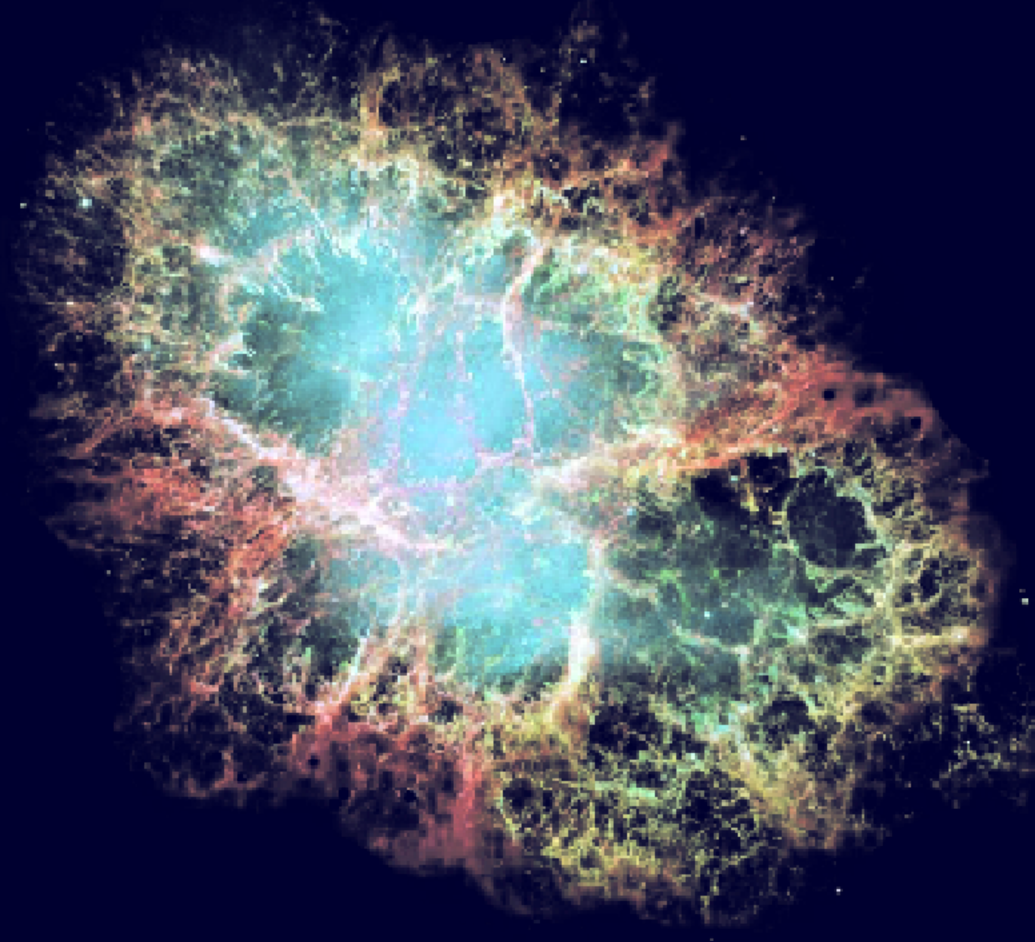
- Introduction and motivations



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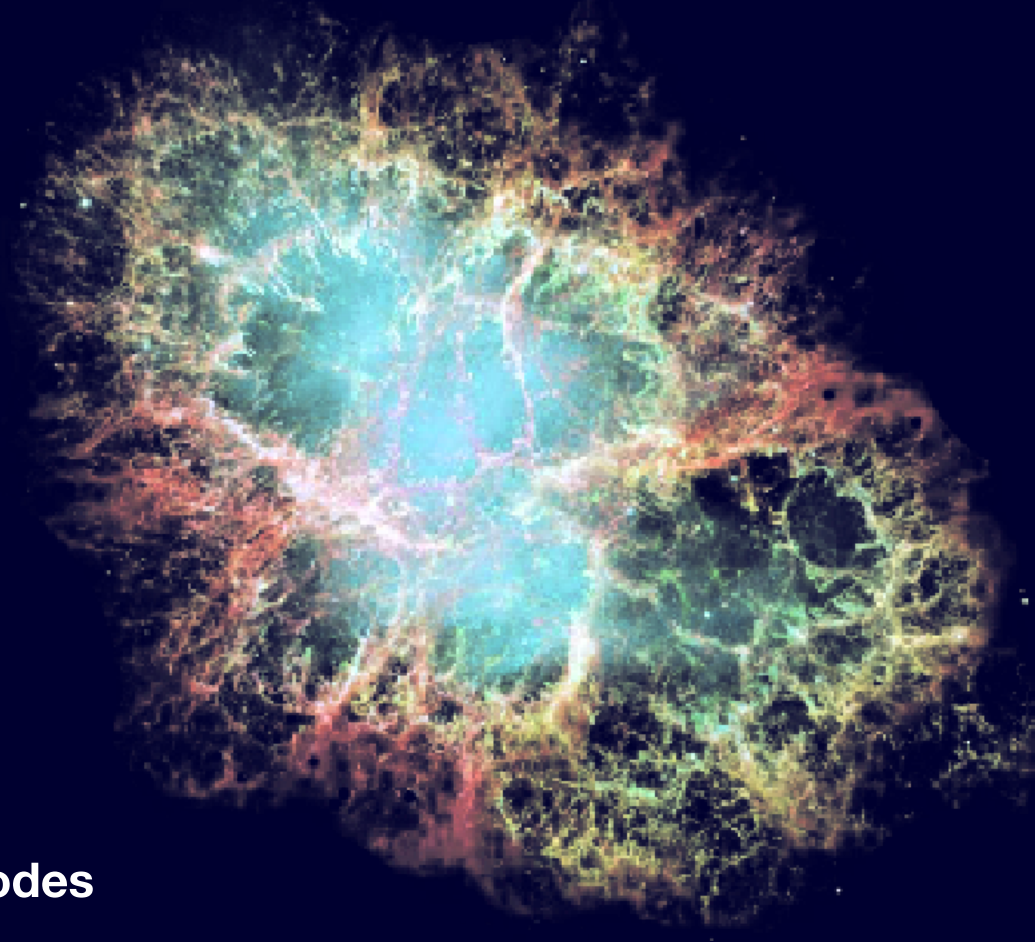

- Introduction and motivations

- Change in the standard paradigm of Alfvénic CR diffusion
  - The role of the **non-linear extensions** of the QLT
  - Diffusion coefficients resulting from the **compressible modes**

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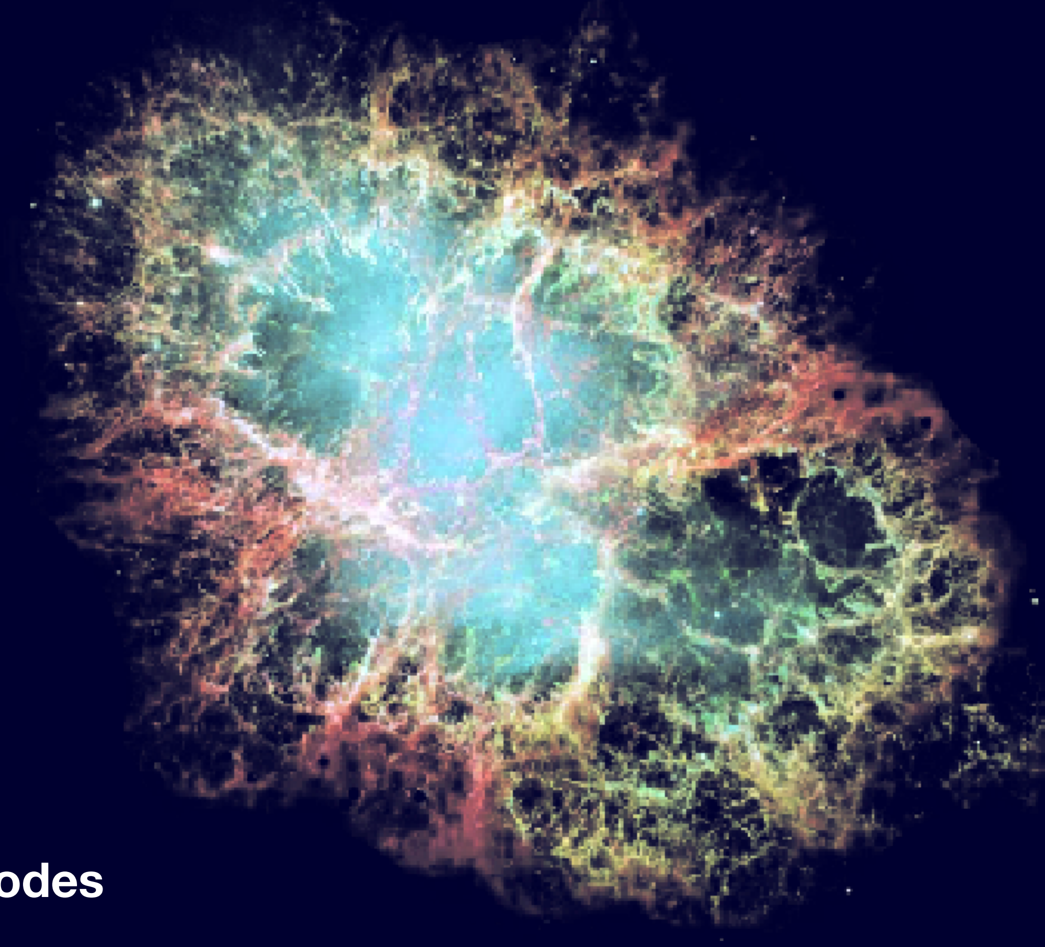


- Introduction and motivations

- Change in the standard paradigm of Alfvénic CR diffusion
  - The role of the **non-linear extensions** of the QLT
  - Diffusion coefficients resulting from the **compressible modes**

- Connecting the **micro-physics** of ISM turbulence with local CR observables
  - The role of *B/C* to constrain the **confining power** of the theory
  - A look at the hadronic species.

CR scattering on MHD modes

[O. Fornieri *et al.* – **MNRAS 502, 5821–5838 (2021)**]

- Scattering rates of MHD modes
- Results on the observables

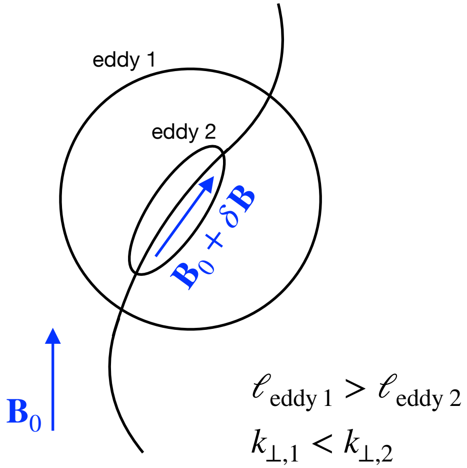
Motivation to dig into the micro-physics

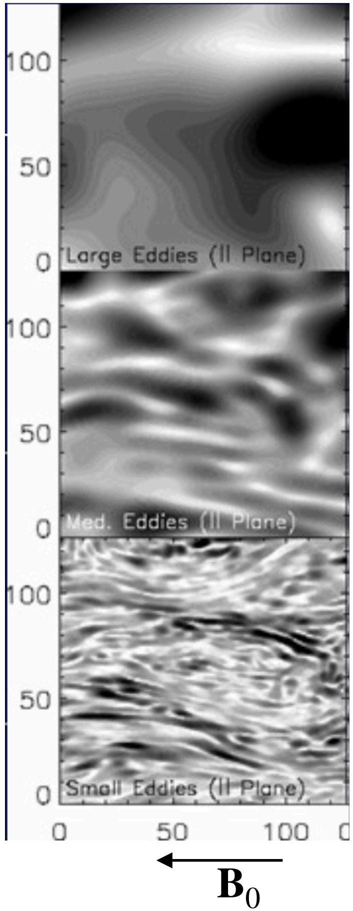
- **Conventional** diffusion based on **QLT from slab turbulence**
  - Resonant scattering only (δ-function resonance)
  - Scattering against **Alfvénic isotropic** turbulence only
  - $$D(E) = \frac{1}{3}\frac{cR_L}{kW(k)} \underset{R_L \sim E}{\sim} \frac{E}{k \cdot k^{-\alpha}} \underset{k \sim R_L^{-1}}{\sim} \frac{E}{E^{-1}E^{\alpha}} \propto E^{2-\alpha} \equiv E^{\delta}$$

- **MHD turbulence cascades in 3D** and is decomposed into **three propagating modes** (*fast* and *slow-magnetosonic*, *Alfvén*) [*e.g.* Kulsrud05]

- Alfvén modes are **anisotropic** $\left((k_{\parallel} \sim \ell_{\parallel}^{-1}) \neq (k_{\perp} \sim \ell_{\perp}^{-1}) \text{ wrt } \mathbf{B}_0\right)$ [Goldreich&Sridhar95, Cho&Lazarian03, Yan&Lazarian02,04,08]

$\Longrightarrow$ highly **inefficient in confining CRs** [Chandran00].





[Cho,Lazarian,Vishniac - ApJ 595:812-823 (2003)]

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- Results on the observables

Contribution to $D_{\mu\mu}$ from fast modes

1

Völk75, Yan&Lazarian08

$$D_{\mu\mu} = \Omega^2(1-\mu^2)\int d^3\mathbf{k} \sum_{n=-\infty}^{+\infty} \delta(k_\parallel v_\parallel - \omega + n\Omega) \left[\frac{n^2 J_n^2(z)}{z^2} I^{\mathrm{A}}(\mathbf{k}) + \frac{k_\parallel^2}{k^2} J_n'^2(z) I^{\mathrm{M}}(\mathbf{k}) \right]$$

QLT unperturbed orbits

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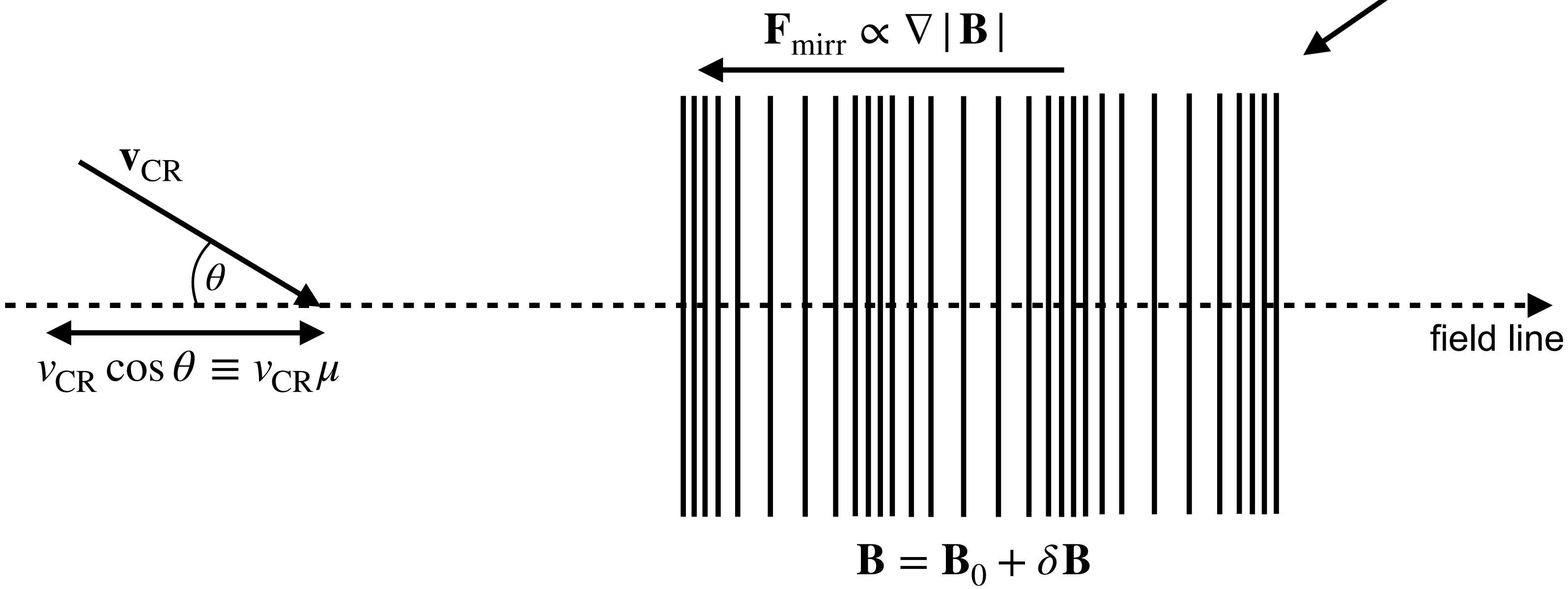

Efficient TTD interaction for

$v_{\mathrm{CR}}\mu \simeq \omega/k_\parallel$

⇩

Small μ range

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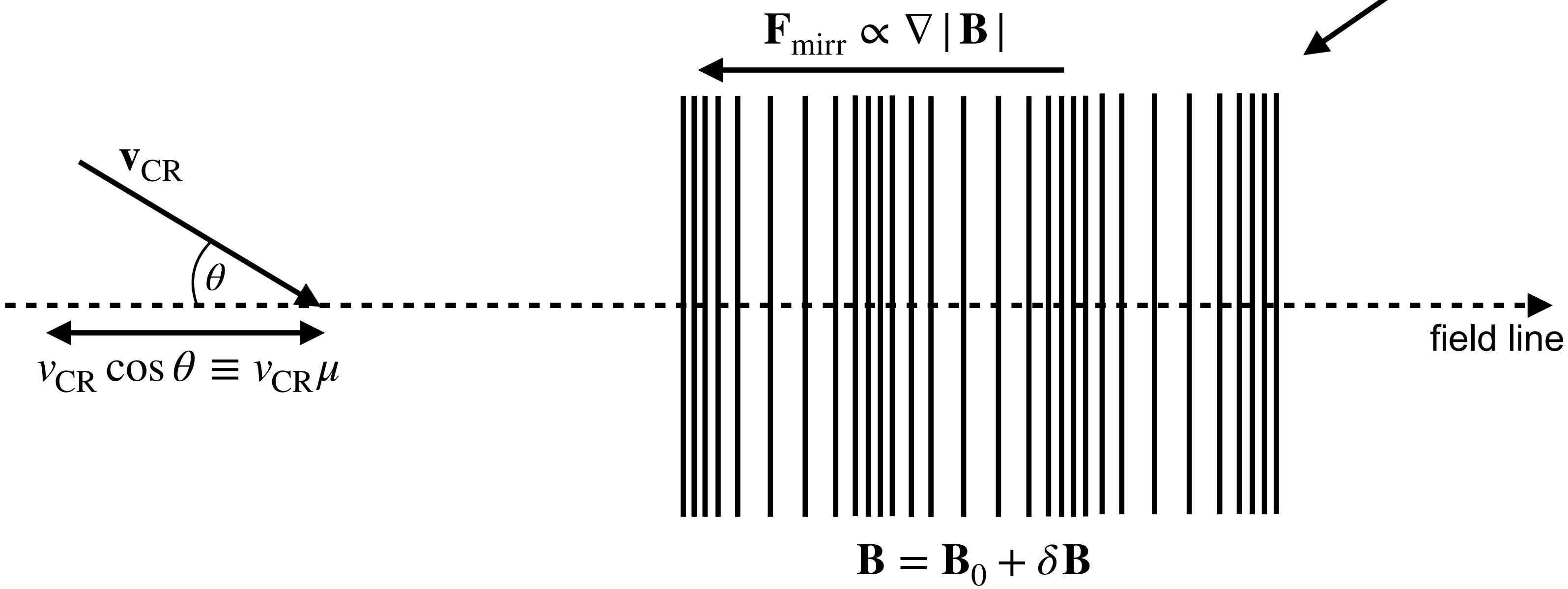

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Small μ range

Magnetosonic modes are present in QLT but not efficient!

Contribution to $D_{\mu\mu}$ from fast modes

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$$v_\perp^2 / |\mathbf{B}| = \text{constant}$$

Contribution to $D_{\mu\mu}$ from fast modes

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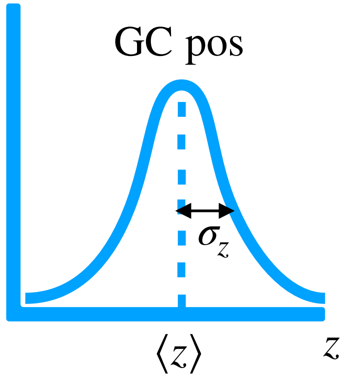
$\Downarrow$ $|\mathbf{B}|$ changes

$v_\parallel$ changes $\Rightarrow$ μ – range enhanced $\Rightarrow$ **guiding center** perturbed



$\Downarrow$

$$\delta B \xrightarrow{\mathcal{F}} \widetilde{\delta B} \cdot e^{i(k_\parallel z_{\text{pert}} - \omega t)}$$

$$e^{ik_\parallel z}\Big|_{\text{pert}} = \int_{-\infty}^{+\infty} dz\, e^{ik_\parallel z} \left(\frac{1}{\sqrt{2\pi\sigma_z}} e^{-\frac{(z-\langle z \rangle)^2}{2\sigma_z^2}} \right) = e^{ik_\parallel \langle z \rangle} \cdot e^{-k_\parallel^2 \frac{\sigma_z^2}{2}}$$

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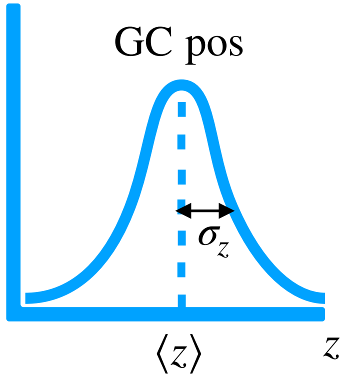

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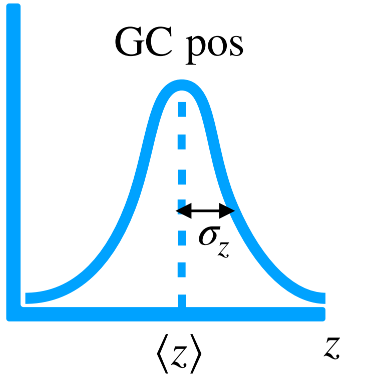

NLT line

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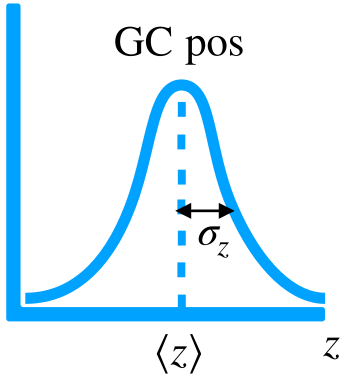

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$$k_\parallel^{\text{NLT}} \xrightarrow{\theta \approx 90^\circ} \frac{\Omega}{\Delta v_\parallel}$$

$$k_\parallel^{\text{QLT}} \sim \frac{\Omega}{v_\parallel} \xrightarrow{\theta \approx 90^\circ} +\infty$$

Our result for $D(E)$

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Inefficiency of the Alfvén modes

$$\mathscr{M}_{ij}^{\mathrm{F}} = \frac{M_\mathrm{A}^2\, L^{1/2}}{8\pi} J_{ij} k^{-7/2}$$

Fast modes (isotropic)

$$\mathscr{M}_{ij}^{\mathrm{A,sub}} = \frac{M_\mathrm{A}^{4/3}\, L^{-1/3}}{6\pi} I_{ij}\, k_\perp^{-10/3} \cdot \exp\left(-\frac{L^{1/3} k_\parallel}{M_\mathrm{A}^{4/3}\, k_\perp^{2/3}}\right)$$

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Evolution on the isosurfaces [GS95]

$$k_\parallel \sim k_\perp^{2/3}$$

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⇒ Little turbulent power on $k_\parallel$

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But $D_{\mu\mu} \propto R_n(k_\parallel v_\parallel - \omega + n\Omega) \ldots$

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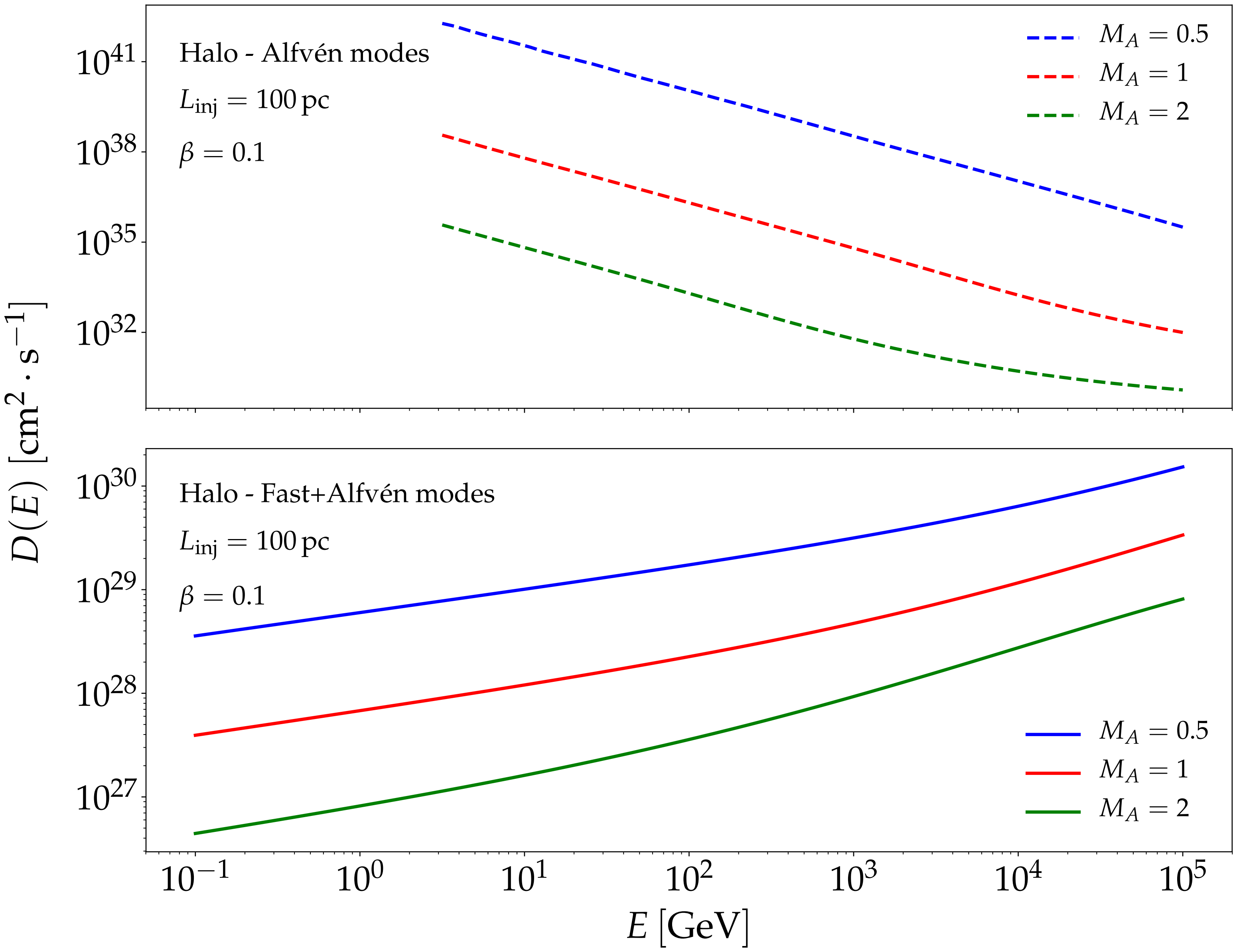

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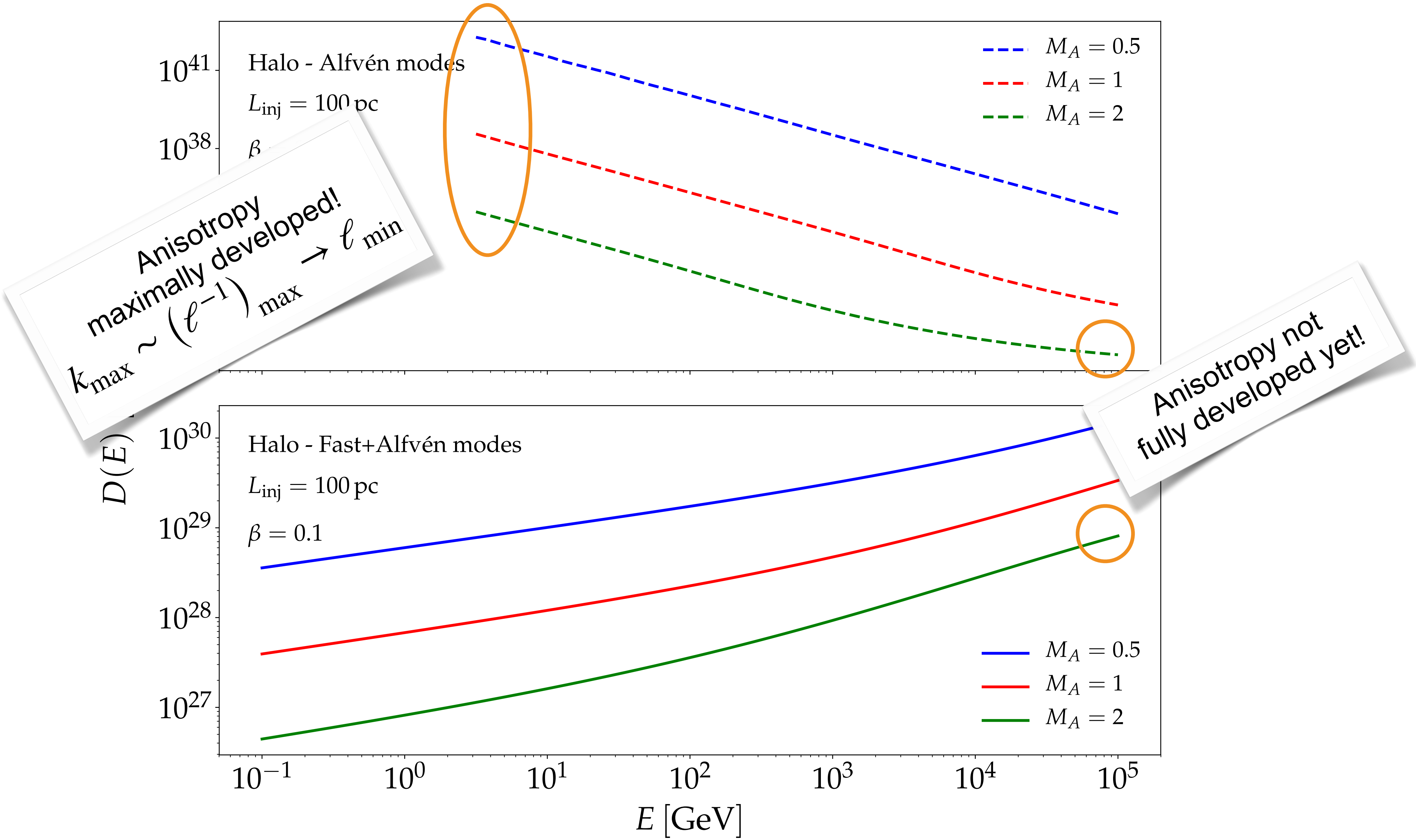
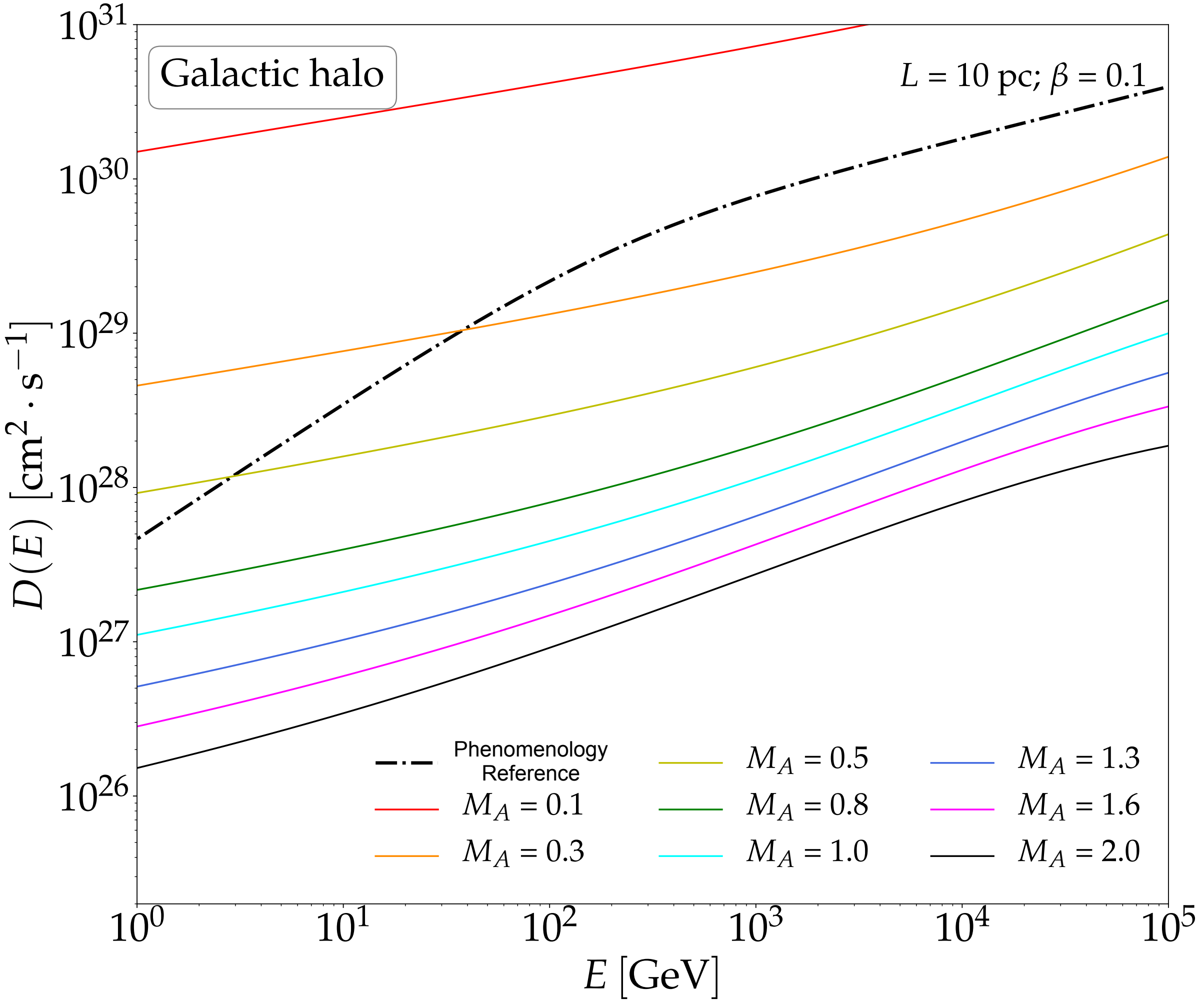
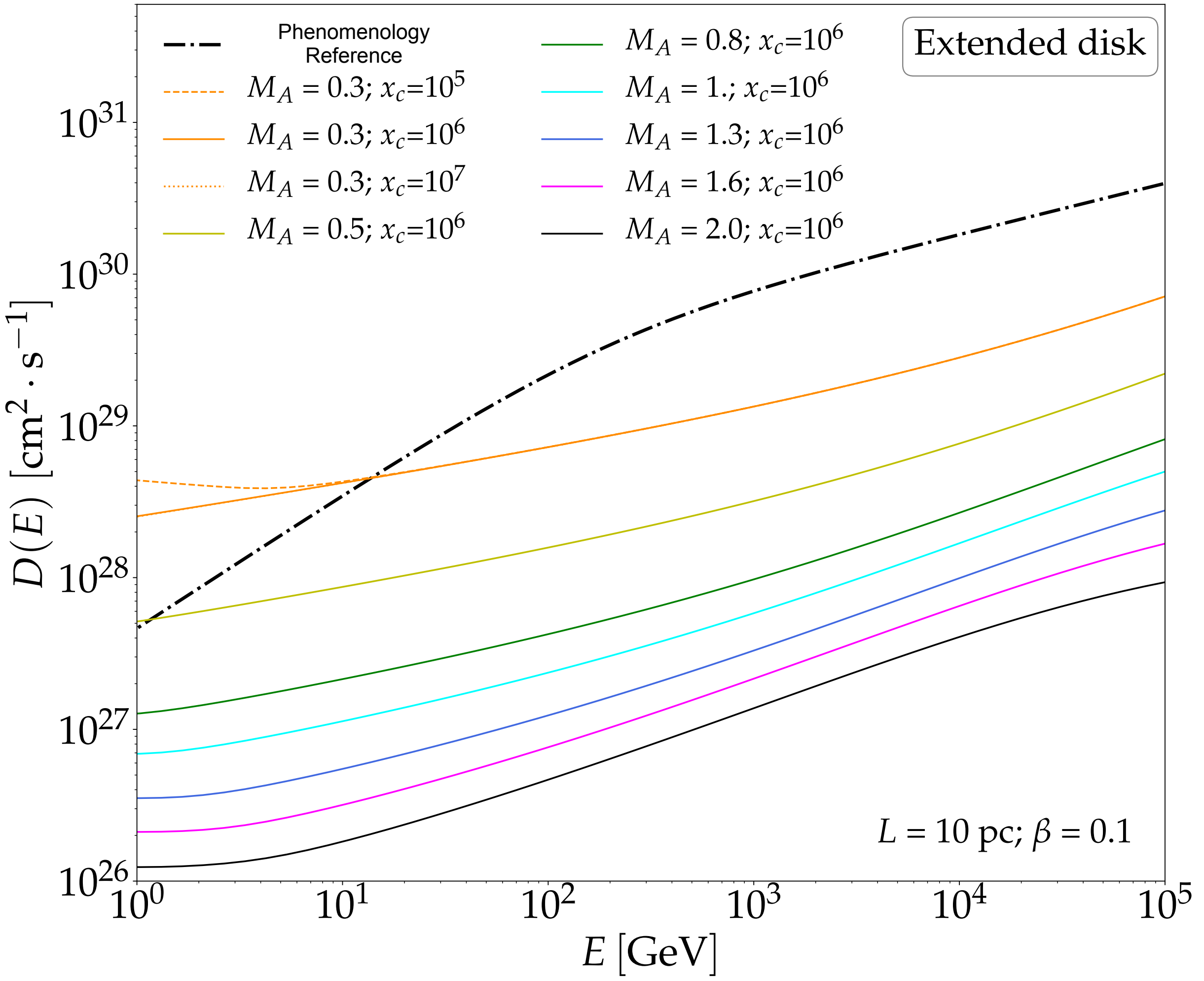


Parametric study in the two-zone model

$D(E)$ changing with the properties of the turbulence





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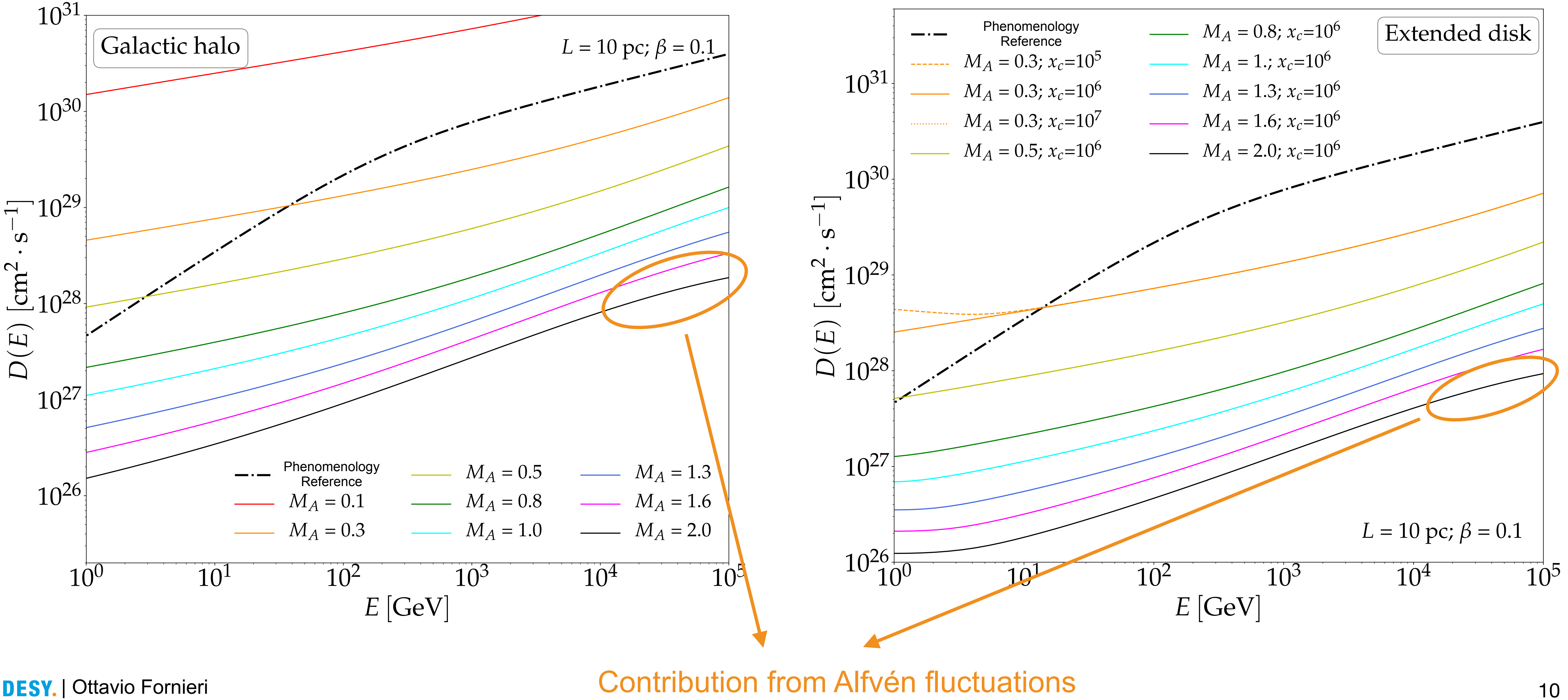

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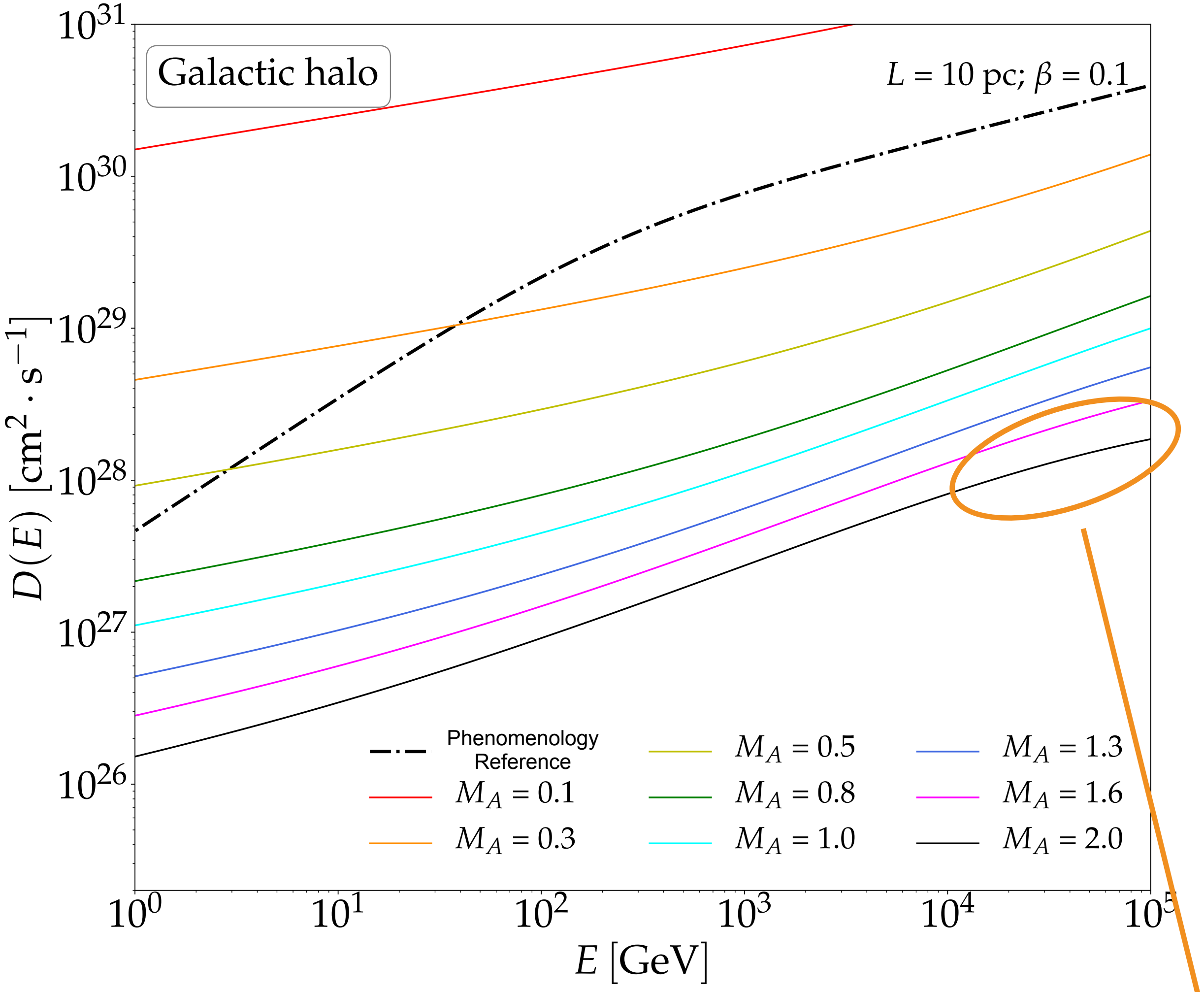

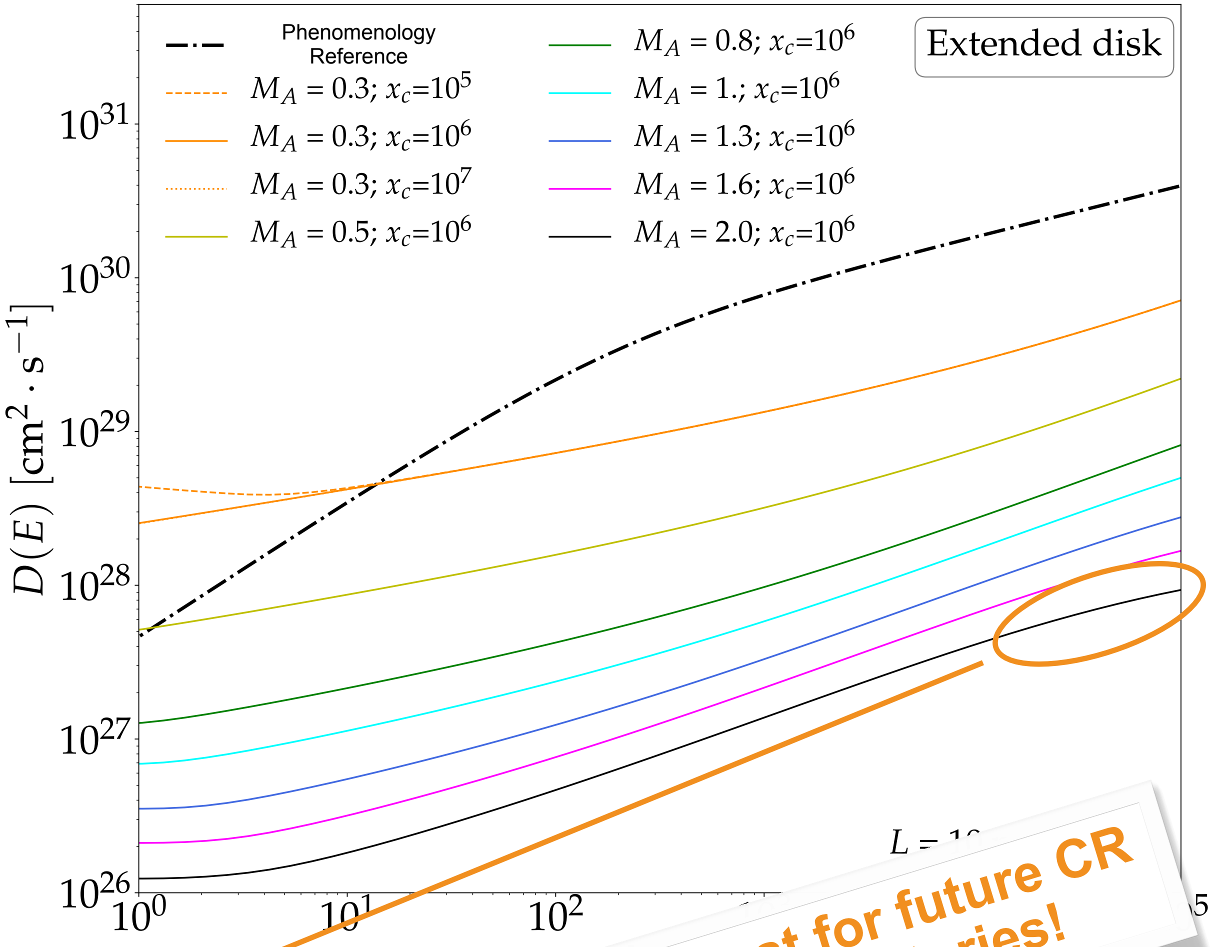

Interest for future CR observatories!

Contribution from Alfvén fluctuations

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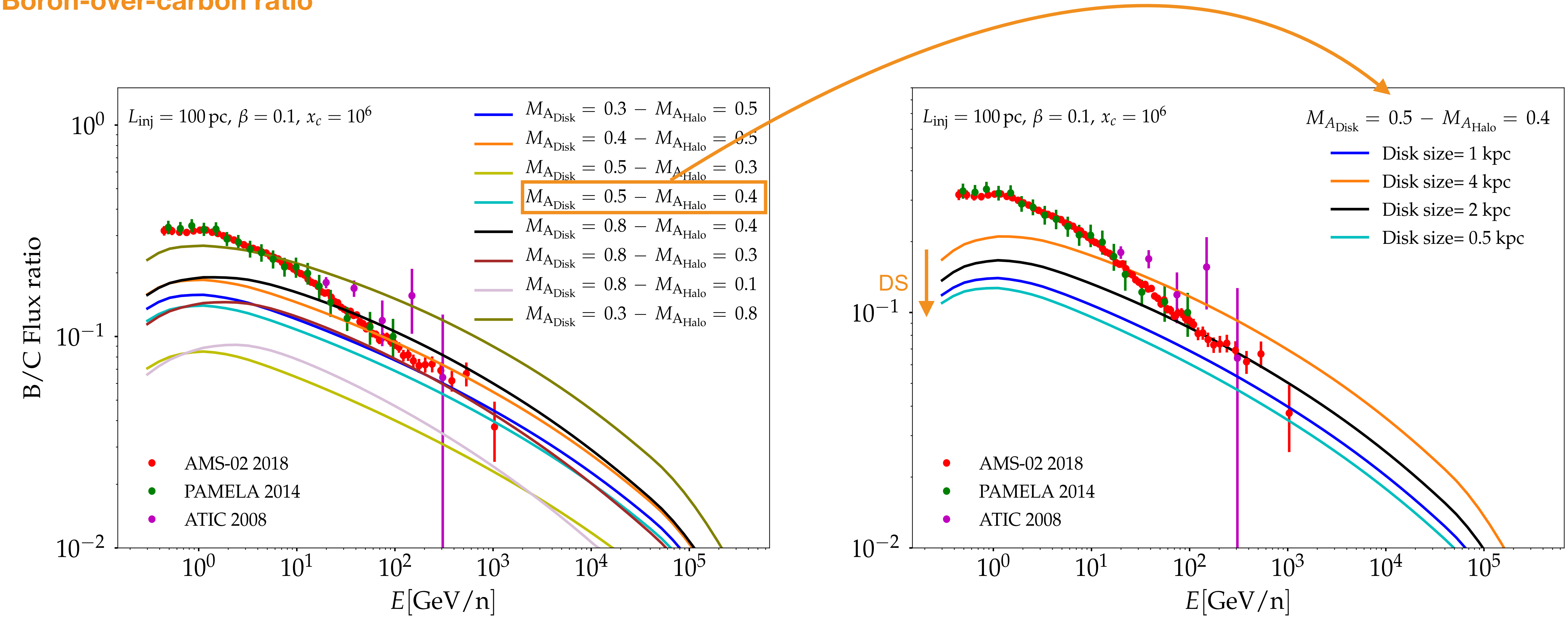
Non-linear extension implemented in DRAGON2

Boron-over-carbon ratio



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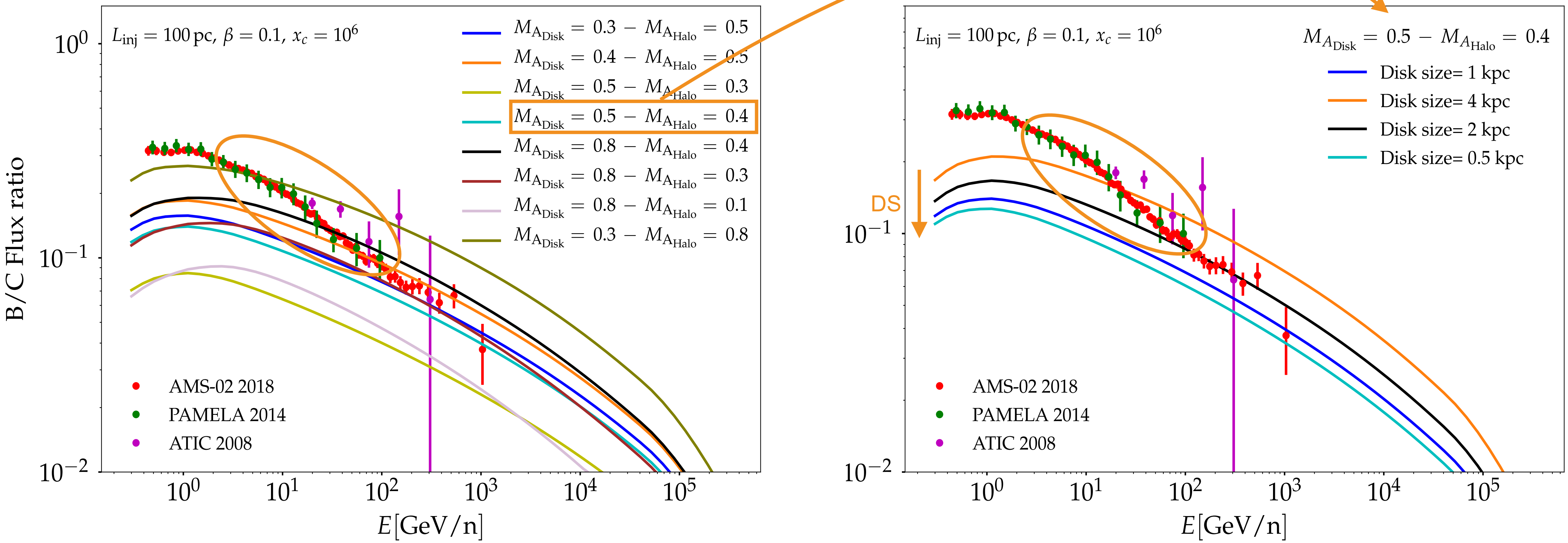
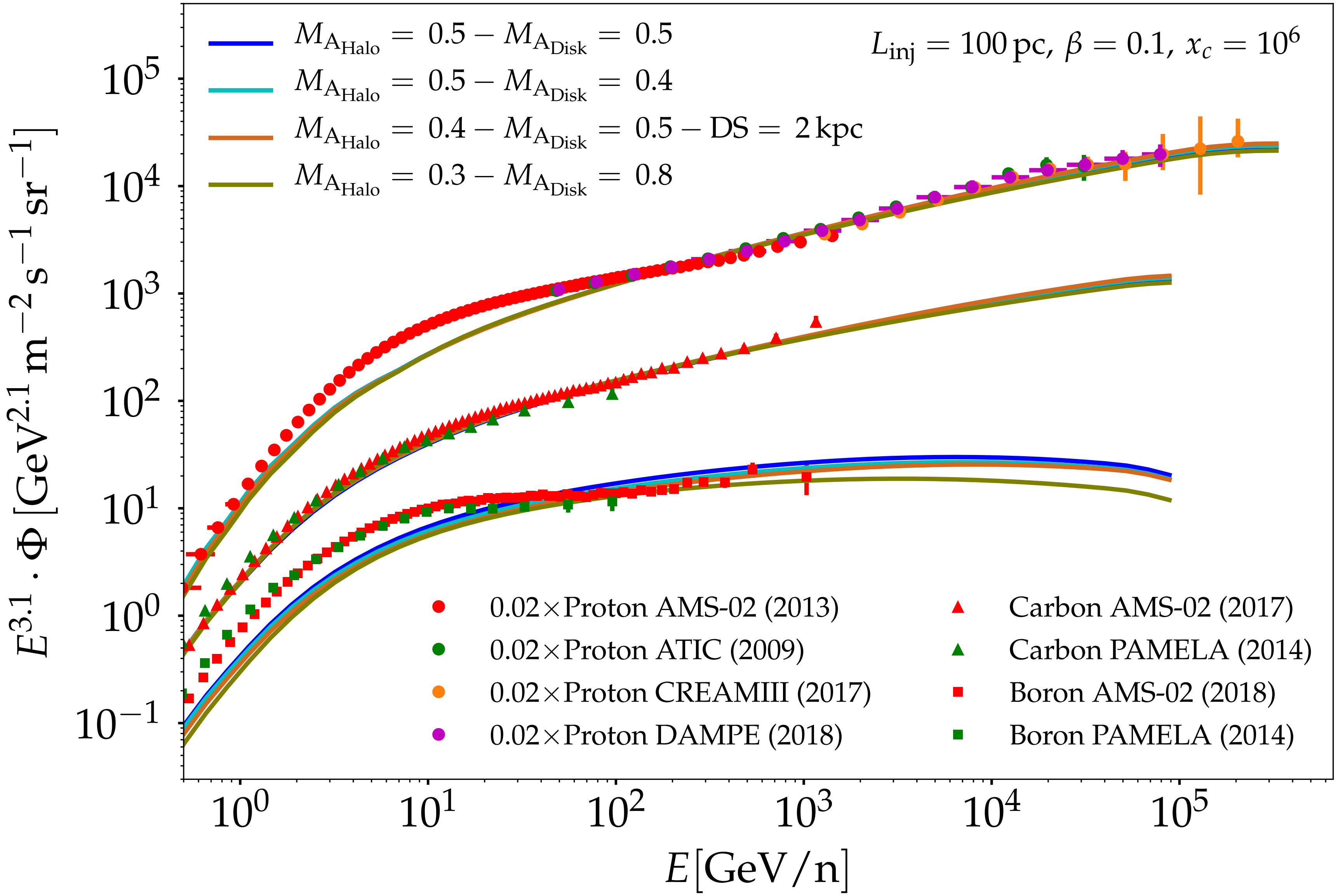


- Turbulence strength (M_A) & disk-size constrained by the production of boron
- High-energy slope and normalization reproduced **without *ad hoc* tuning**!
- **Iroshnikov-Kraichnan scaling of B/C not reproduced** $\Rightarrow$ transition to another process!

Non-linear extension implemented in DRAGON2

Hadronic species



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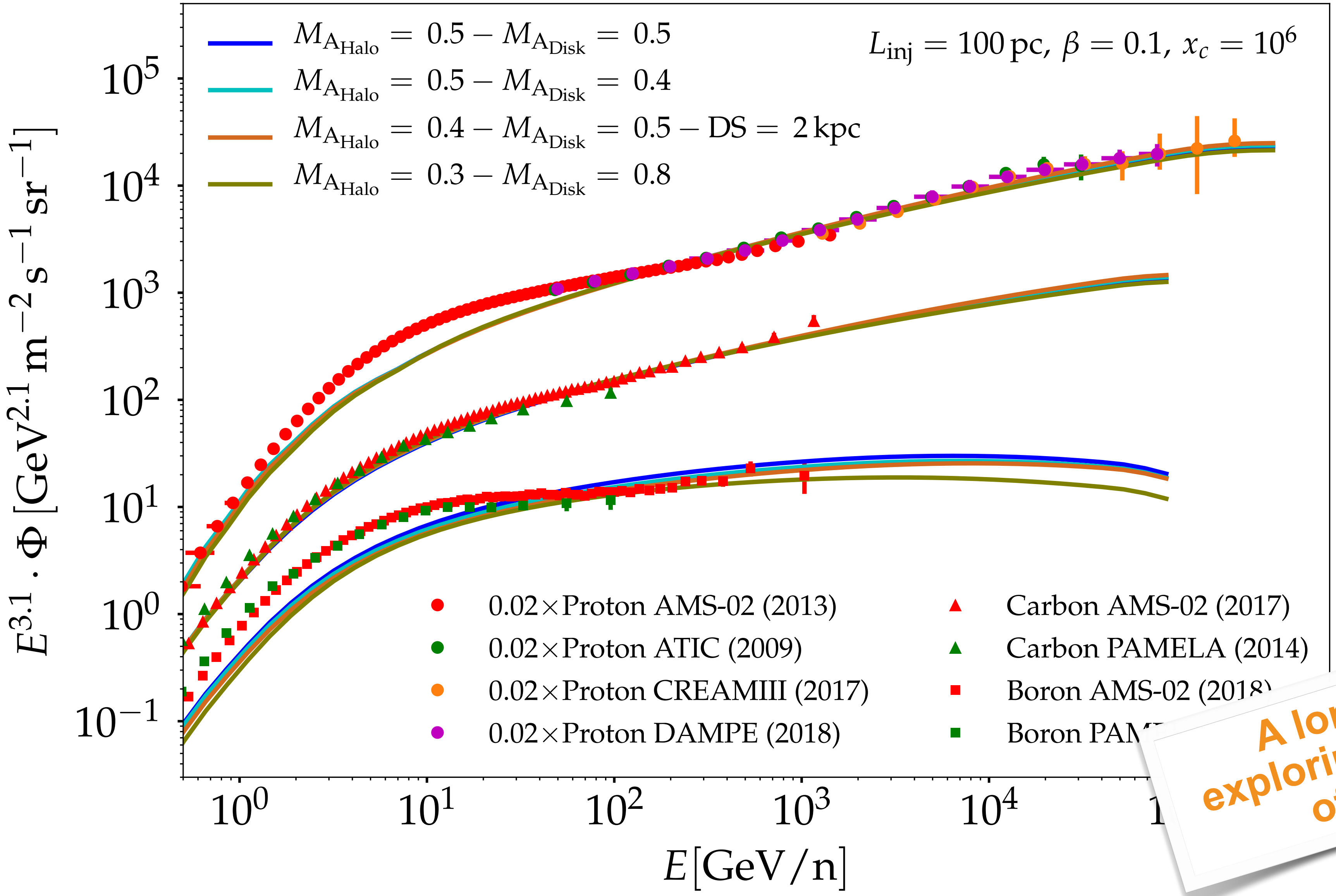
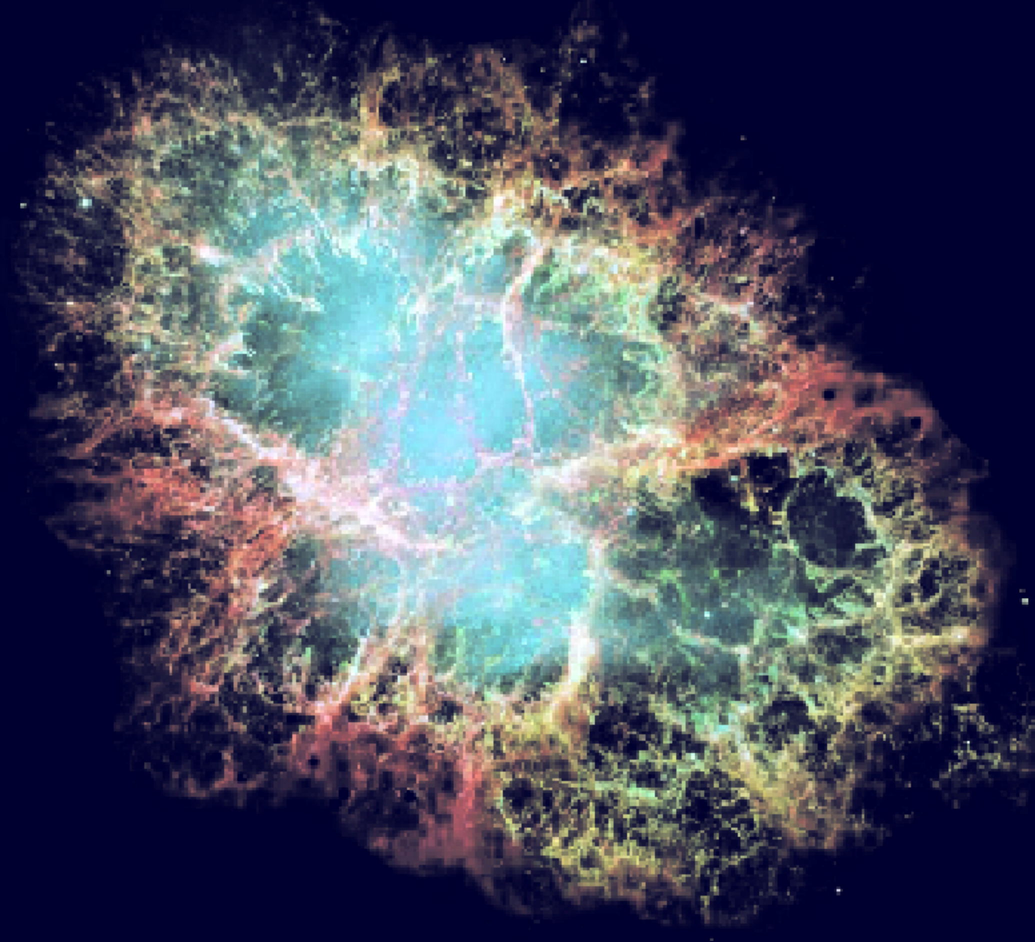


A long way to go exploring other aspects of the theory!

Conclusions



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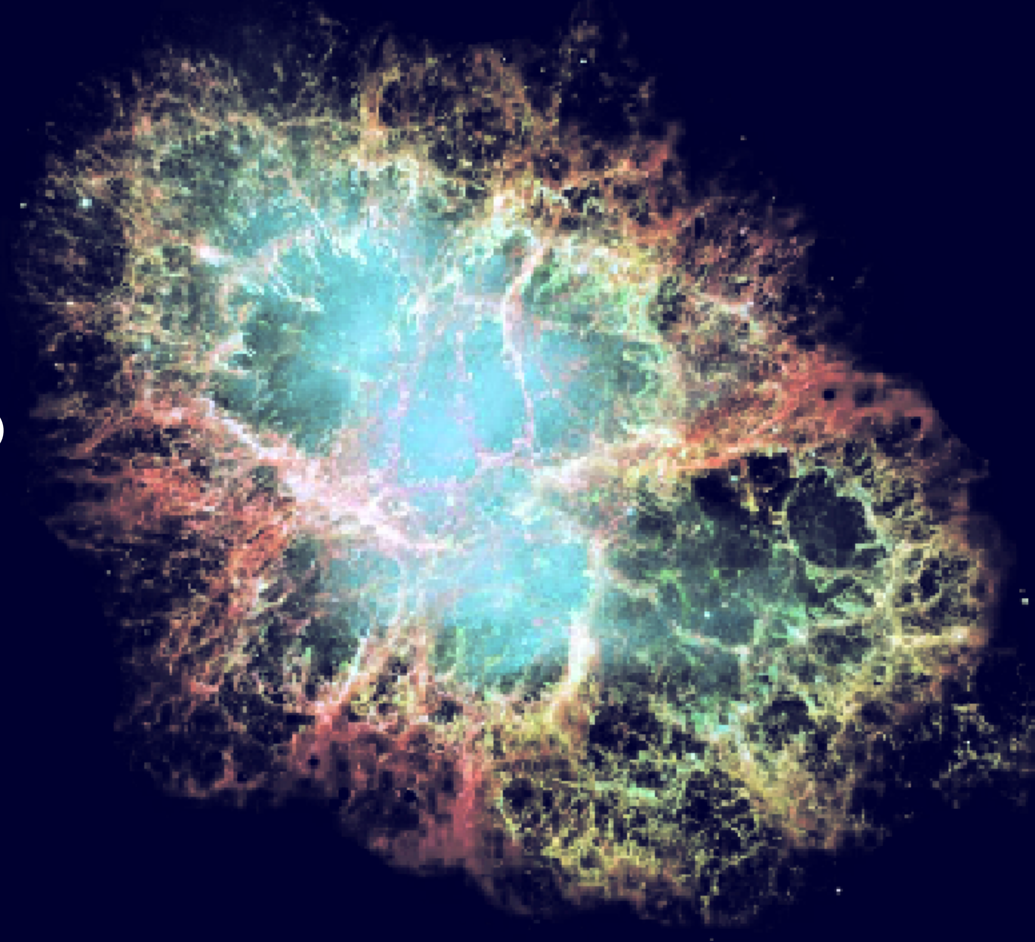

- **Alfvén modes are inefficient** plus they show the **opposite trend** for $D(E)$

Conclusions

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- NLT developed in YL08 explains CR confinement **above** $\sim 200\,\mathrm{GeV}$
  - Below this energy, *streaming instabilities* may dominate [**Farmer&Goldreich04, Yan&Lazarian11**]
  - *B/C* **IK-like scaling** might be a **coincidence**

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- Characteristic features of such paradigm are to be investigated by the **future CR and γ-ray telescopes**.

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Thanks for your attention!

Backup slides

3D correlation tensors from 1D scalings

$$\int E_{1D}(k)\,dk = \int E_{3D}(\mathbf{k})\,d^3\mathbf{k}$$

Iroshnikov-Kraichnan (isotropic) spectrum

$$E_{1D}^{IK}(k) \sim k^{-3/2}$$

$$\int E_{1D}(k)\,dk = \int E_{3D}(\mathbf{k})\,d^3\mathbf{k} = \int E_{3D}(k)\,4\pi k^2\,dk$$

$$\Rightarrow \quad E_{3D}^{IK}(k) \sim k^{-3/2-2} \sim k^{-7/2}$$

Goldreich-Sridhar (anisotropic) spectrum

$$E_{1D}^{GS}(k) \sim k_\perp^{-5/3}$$

$$k_\parallel \sim k_\perp^{2/3}$$

$$\begin{aligned} d^3\mathbf{k} &= dk_x \wedge dk_y \wedge dk_z = k_\perp dk_\perp \wedge dk_\parallel \wedge d\phi \\ &= k_\perp dk_\perp \wedge d(k_\perp^{2/3}) \wedge d\phi = k_\perp dk_\perp \wedge \left(\frac{d(k_\perp^{2/3})}{dk_\perp}\right) dk_\perp \wedge d\phi \\ &= \frac{2}{3} k_\perp dk_\perp \wedge k_\perp^{-1/3}(dk_\perp \hat{k}_\parallel) \wedge d\phi = \frac{2}{3} k_\perp^{2/3}\, k_\perp dk_\perp \wedge d\phi = \frac{2}{3} k_\perp^{5/3} dk_\perp \wedge d\phi \end{aligned}$$

$$\Rightarrow \quad E_{3D}^{GS}(k) \sim k^{-5/3-5/3} \sim k^{-10/3}$$

Little turbulent power in $k_{\parallel}$

1D calculation

$$\int dk_{\parallel}\, E(k_{\parallel}) = \int dk_{\perp}\, E(k_{\perp})$$

$$E^{\rm GS}(k_{\perp}) \sim k_{\perp}^{-5/3}$$

$$k_{\parallel} \sim k_{\perp}^{2/3} \;\Rightarrow\; k_{\parallel}^{3/2} \sim k_{\perp}$$

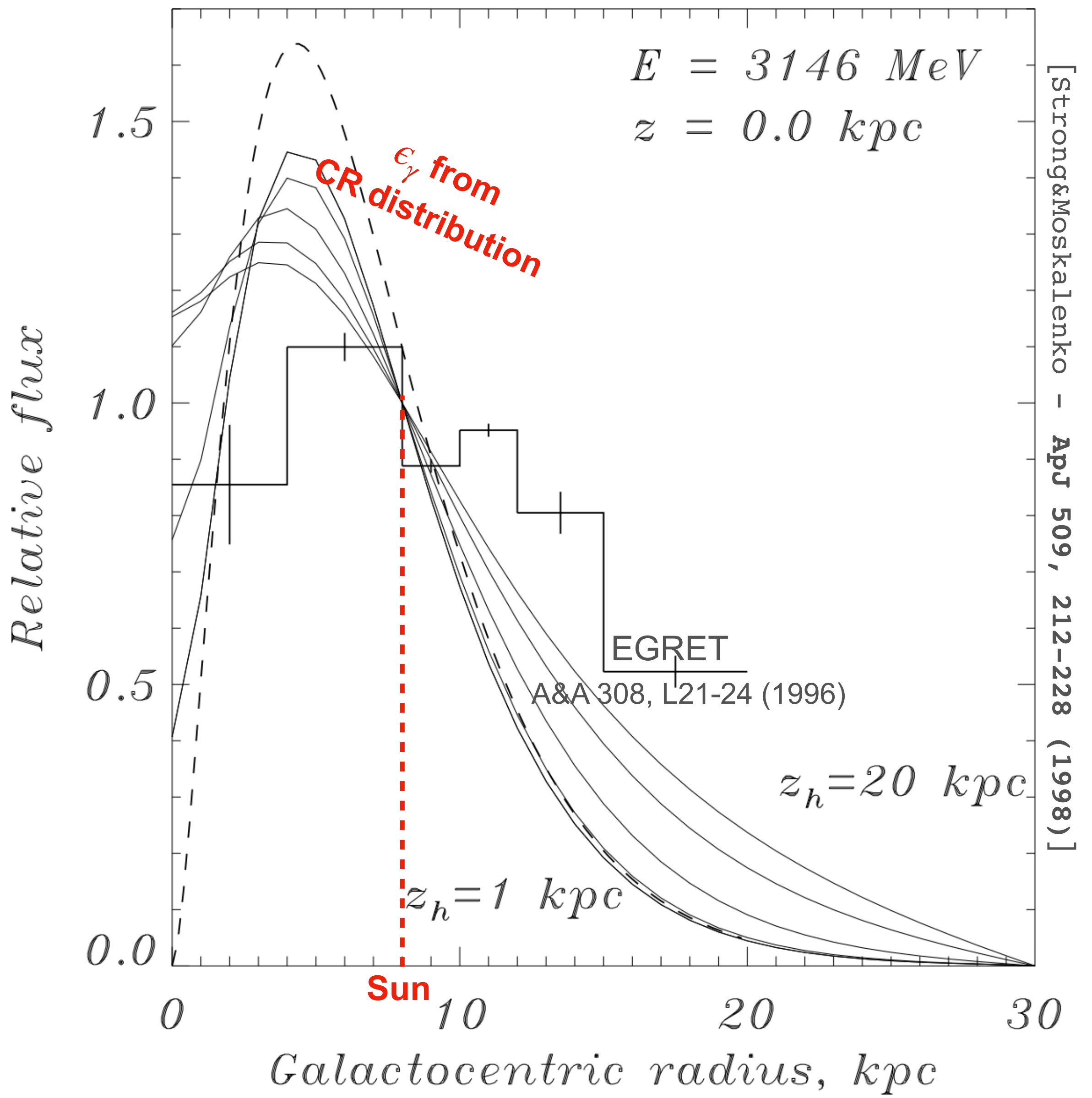
$$\rightarrow\; \frac{dk_{\perp}}{dk_{\parallel}} = \frac{3}{2} k_{\parallel}^{3/2-1} = \frac{3}{2} k_{\parallel}^{1/2}$$

$$\int dk_{\perp}\, E(k_{\perp}) = \int \frac{3}{2} k_{\parallel}^{1/2}\, dk_{\parallel}\, E(k_{\perp}) =$$

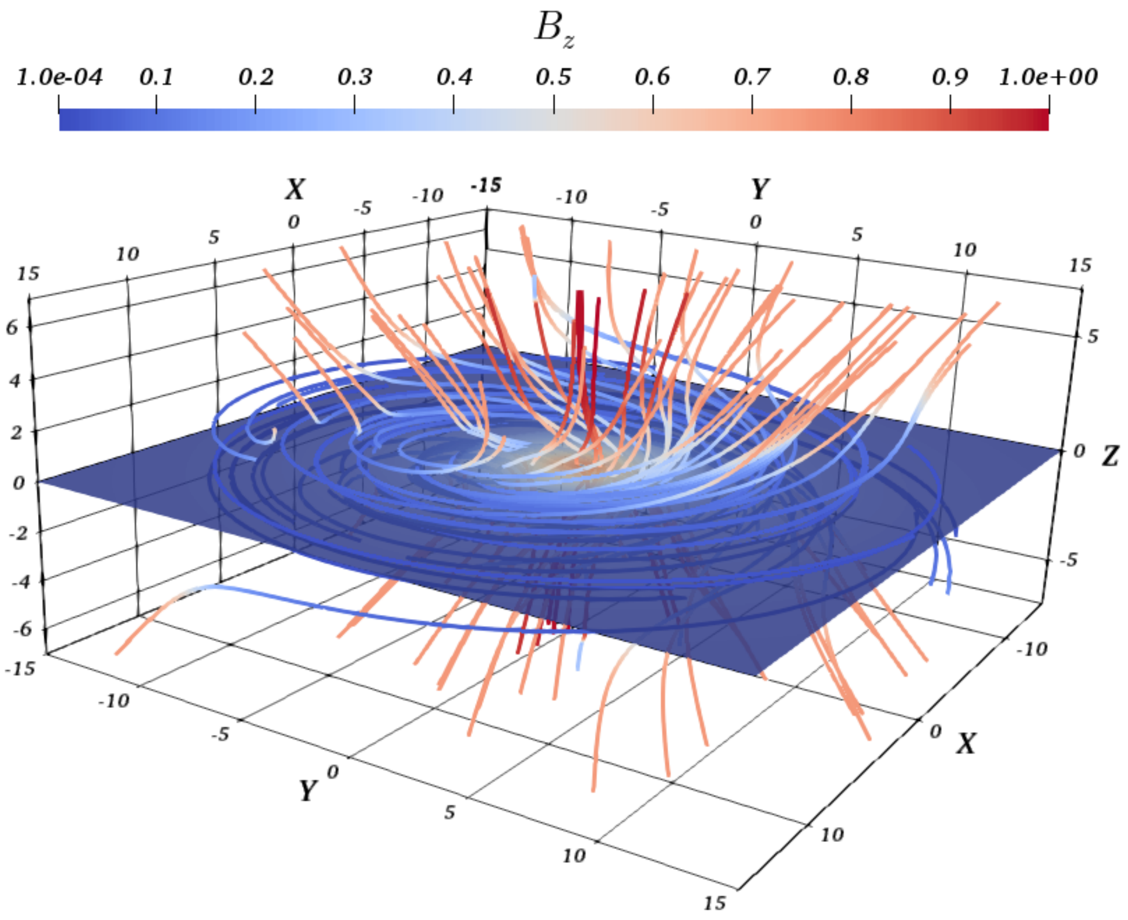
$$= \frac{3}{2} \int k_{\parallel}^{1/2}\, dk_{\parallel}\, k_{\perp}^{-5/3} = \frac{3}{2} \int dk_{\parallel}\, k_{\parallel}^{1/2} \left(k_{\parallel}^{3/2}\right)^{-5/3}$$

$$E^{\rm GS}(k_{\parallel}) \sim k_{\parallel}^{-2}$$

An enlightening issue?

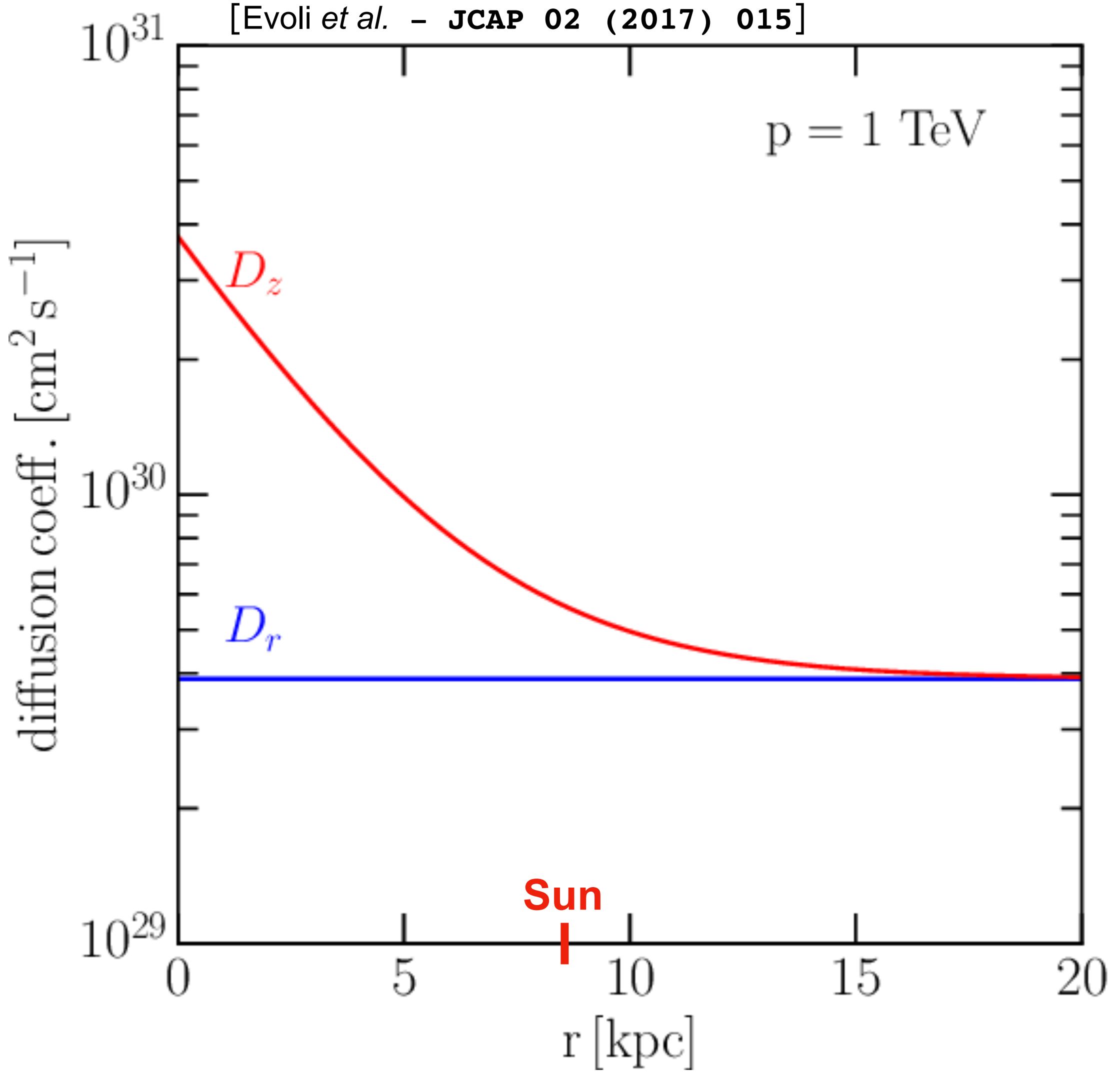


Connections with the propagation models



[Cerri *et al.* – **JCAP 10 (2017) 019**]

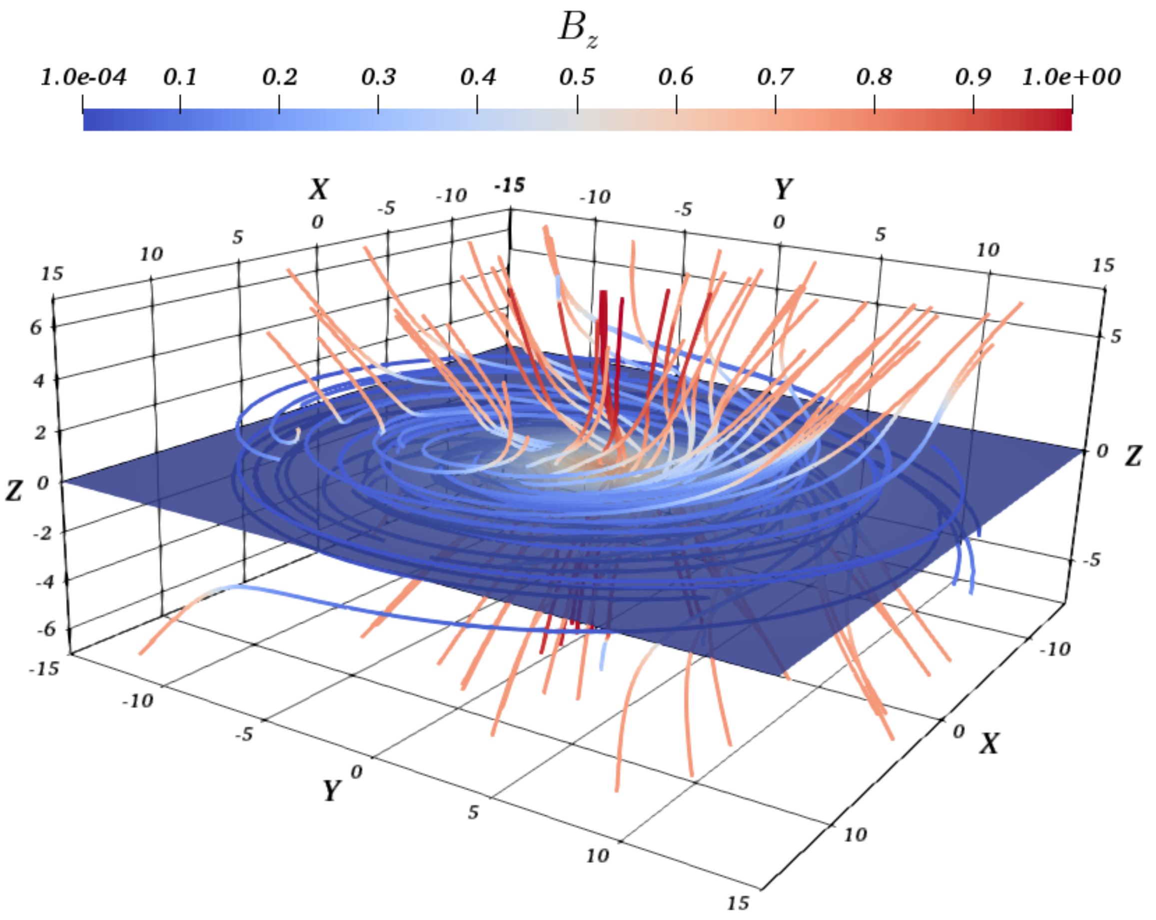
[Evoli *et al.* – **JCAP 02 (2017) 015**]



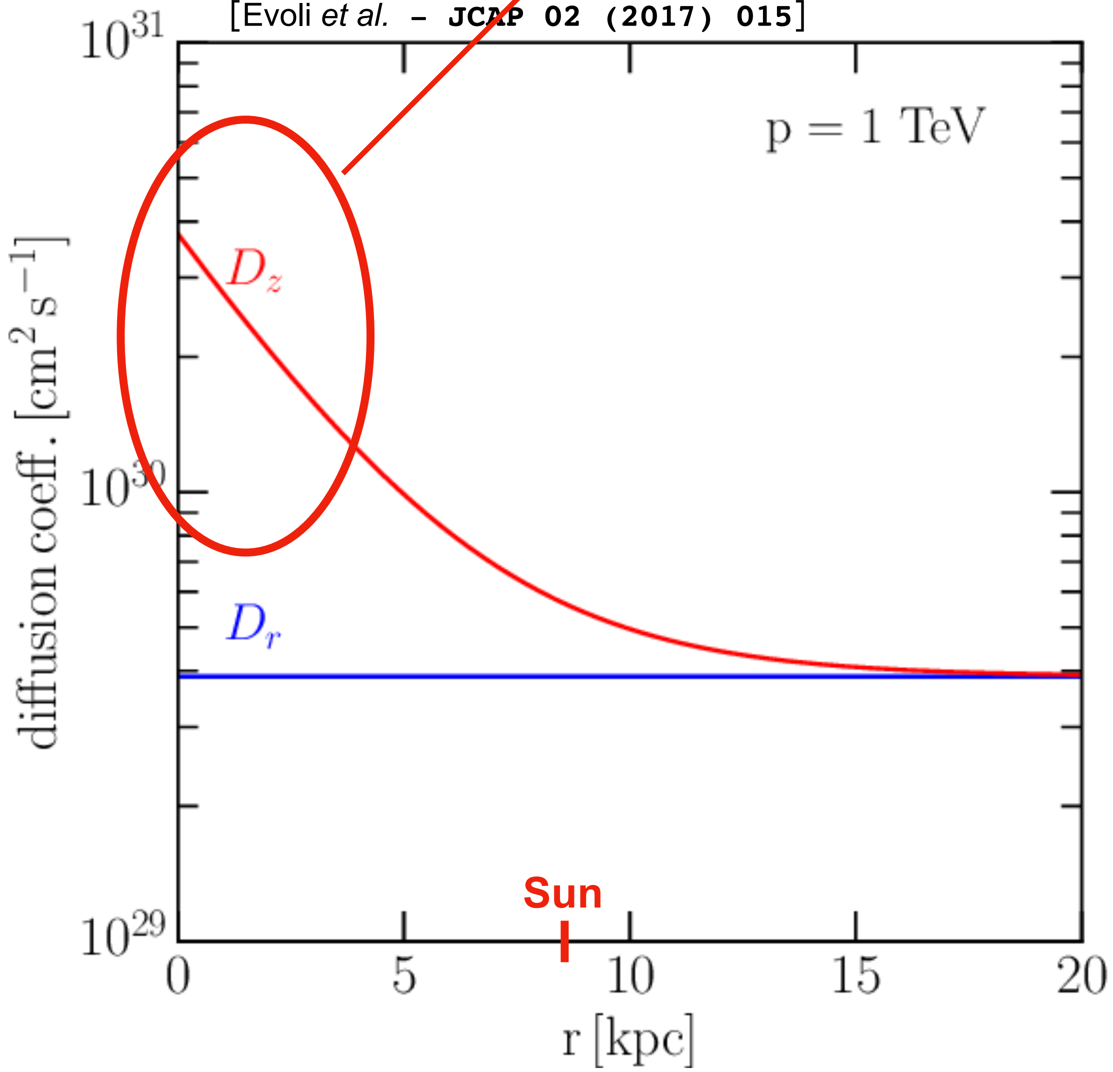
Connections with the propagation models

Neglecting this implies longer residence time around GC

[Cerri *et al.* – JCAP 10 (2017) 019]



[Evoli *et al.* – JCAP 02 (2017) 015]



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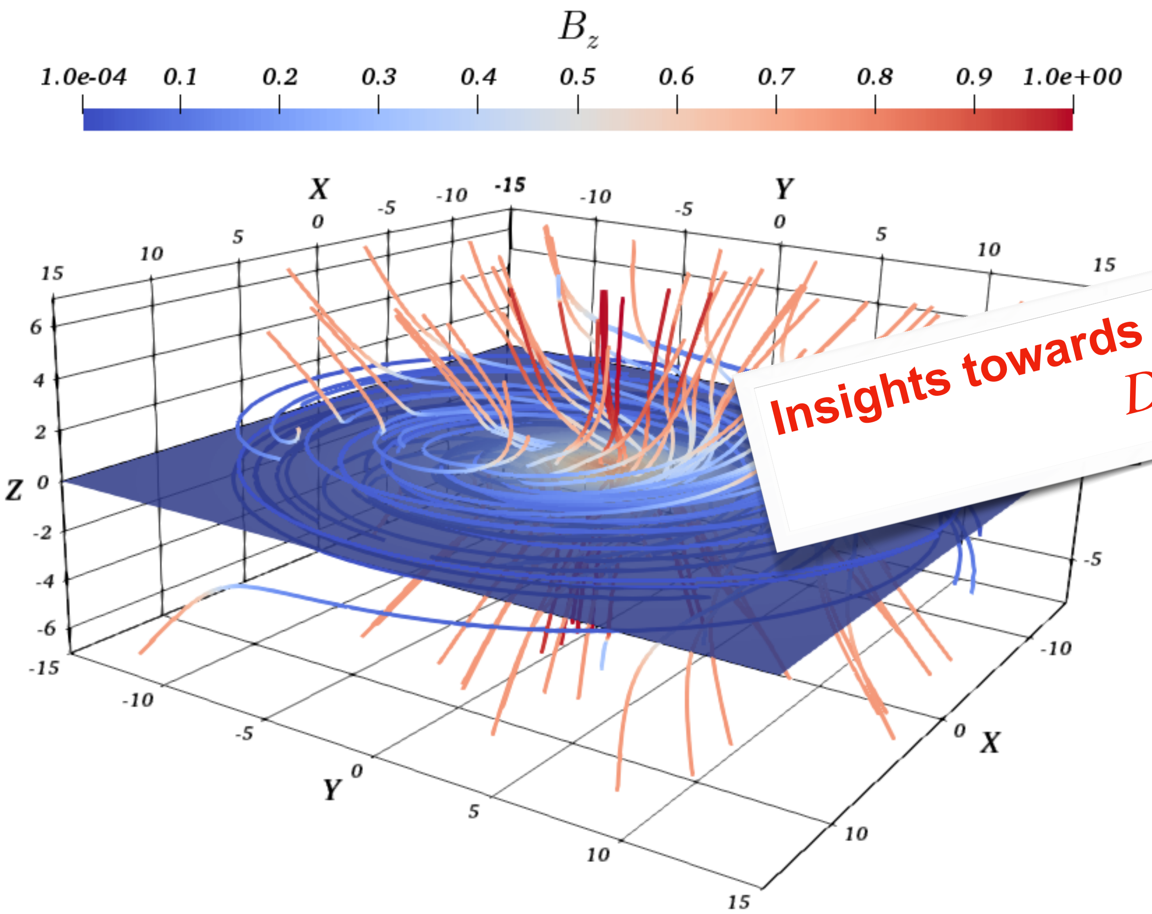
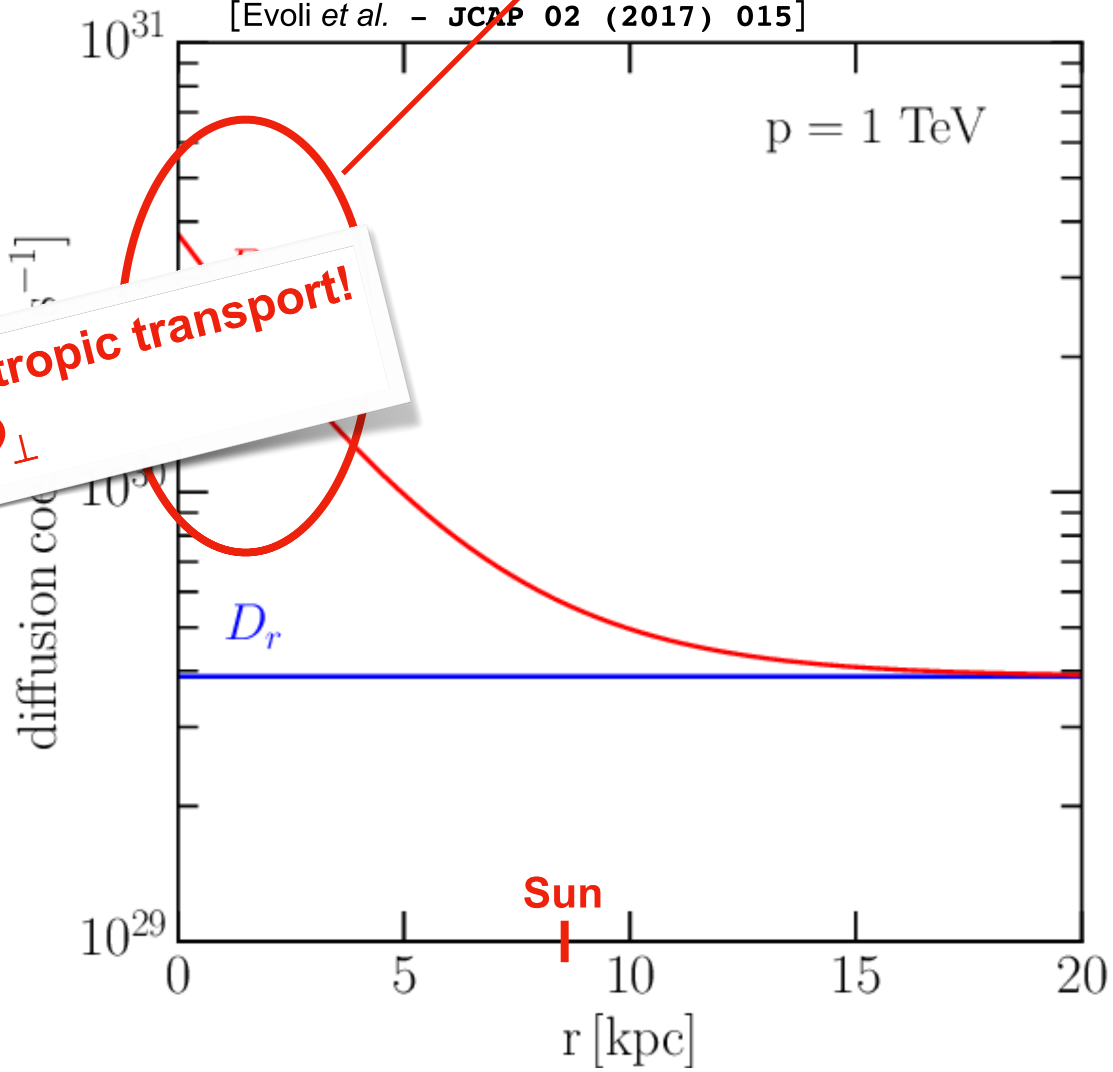


[Evoli *et al.* – JCAP 02 (2017) 015]



Insights towards anisotropic transport!
$D_{\parallel} \neq D_{\perp}$