Turbulent regimes in collisions of 3D Alfvén-wave packets

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Journées SF2A, "Comsic Turbulence" — 8 June 2022, Besançon

Outline

1. **Introduction**

   ☞ Turbulence in space and astrophysical plasmas

   ☞ Phenomenology of Alfvénic turbulence: from weak to strong

   ☞ Dynamic alignment and reconnection-mediated regime

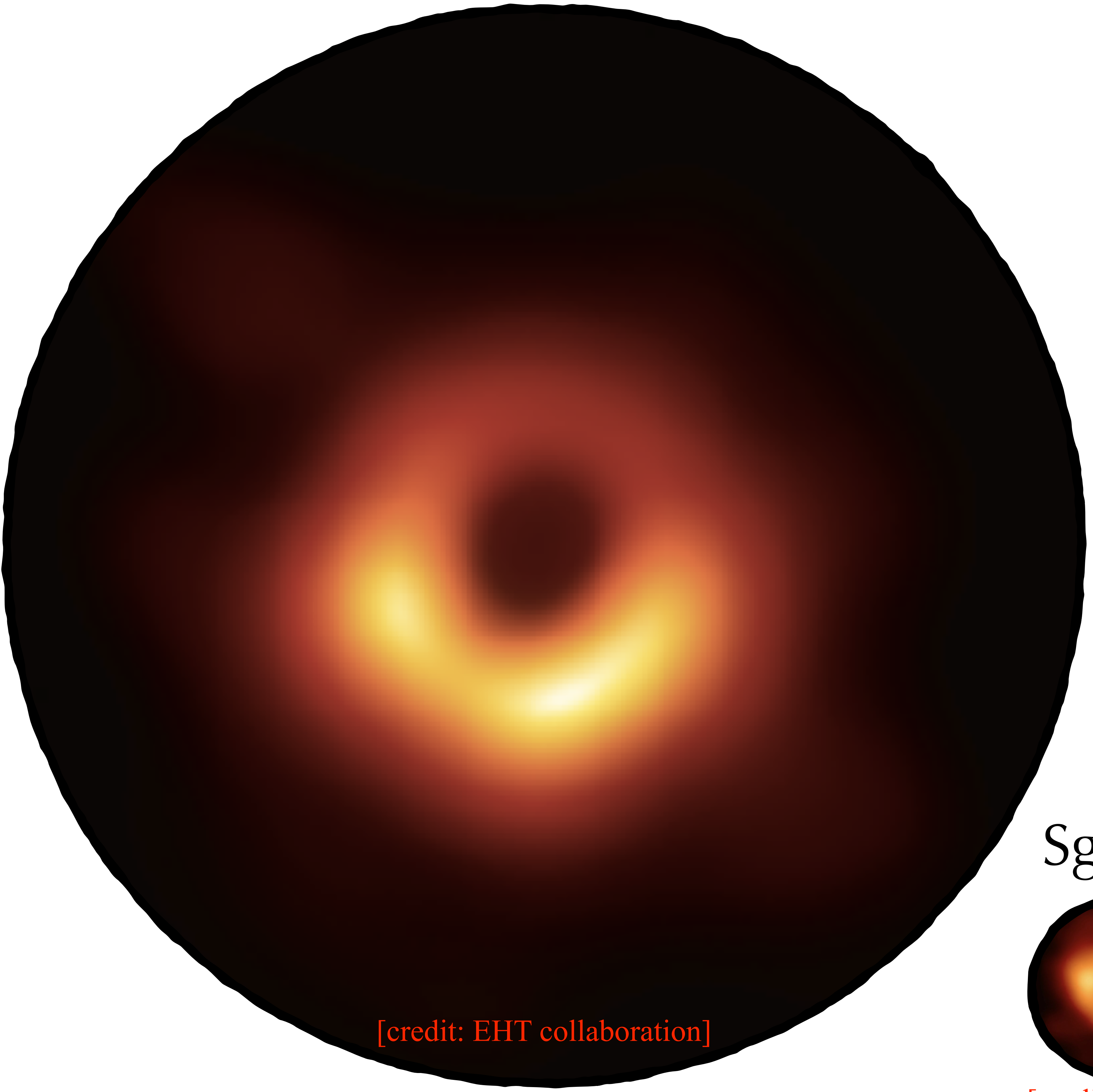
2. **Results**

   ☞ A new theory: dynamic alignment and reconnection in weak turbulence

   ☞ 3D simulations: collisions of Alfvén-wave packets in reduced MHD

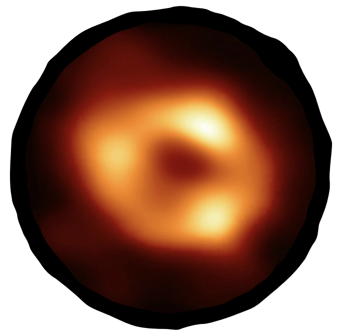
Turbulence in space and astrophysical plasmas

M87*



[credit: EHT collaboration]

Sgr A*



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Turbulence in space and astrophysical plasmas

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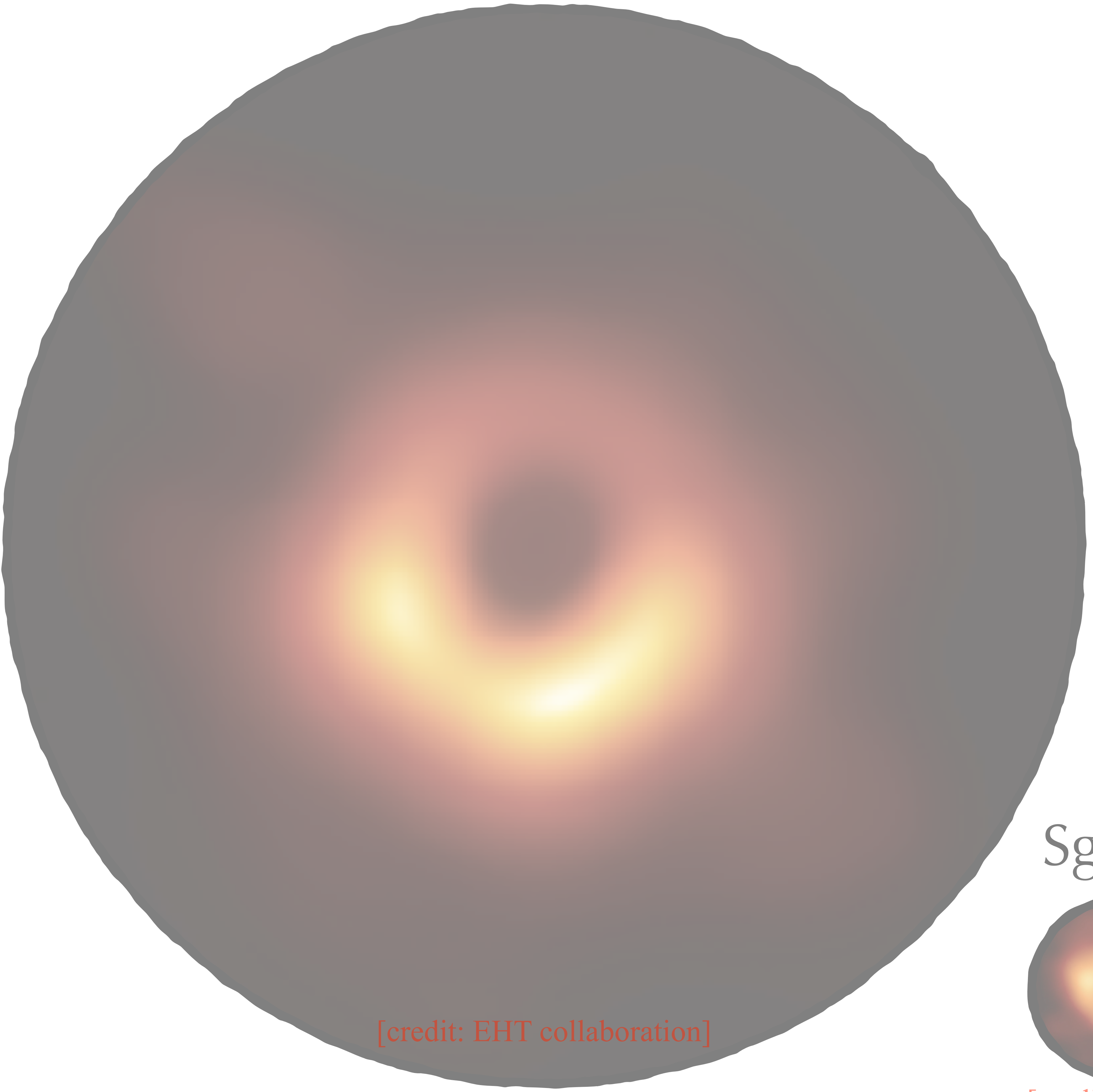

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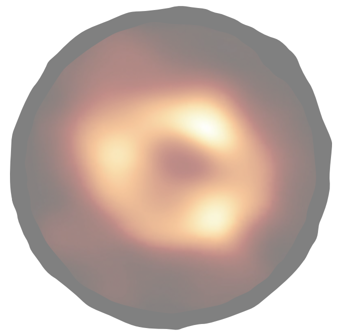

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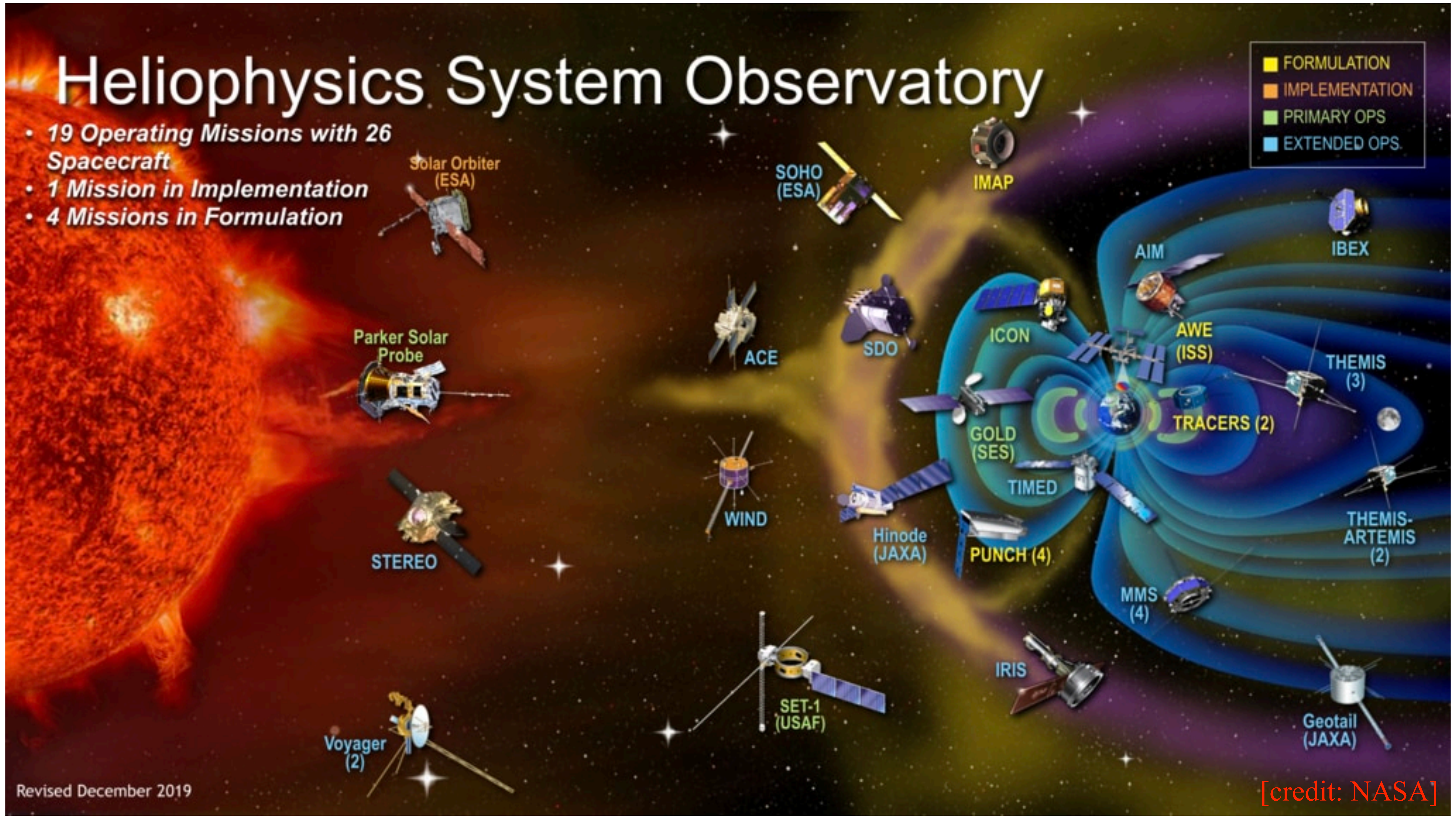
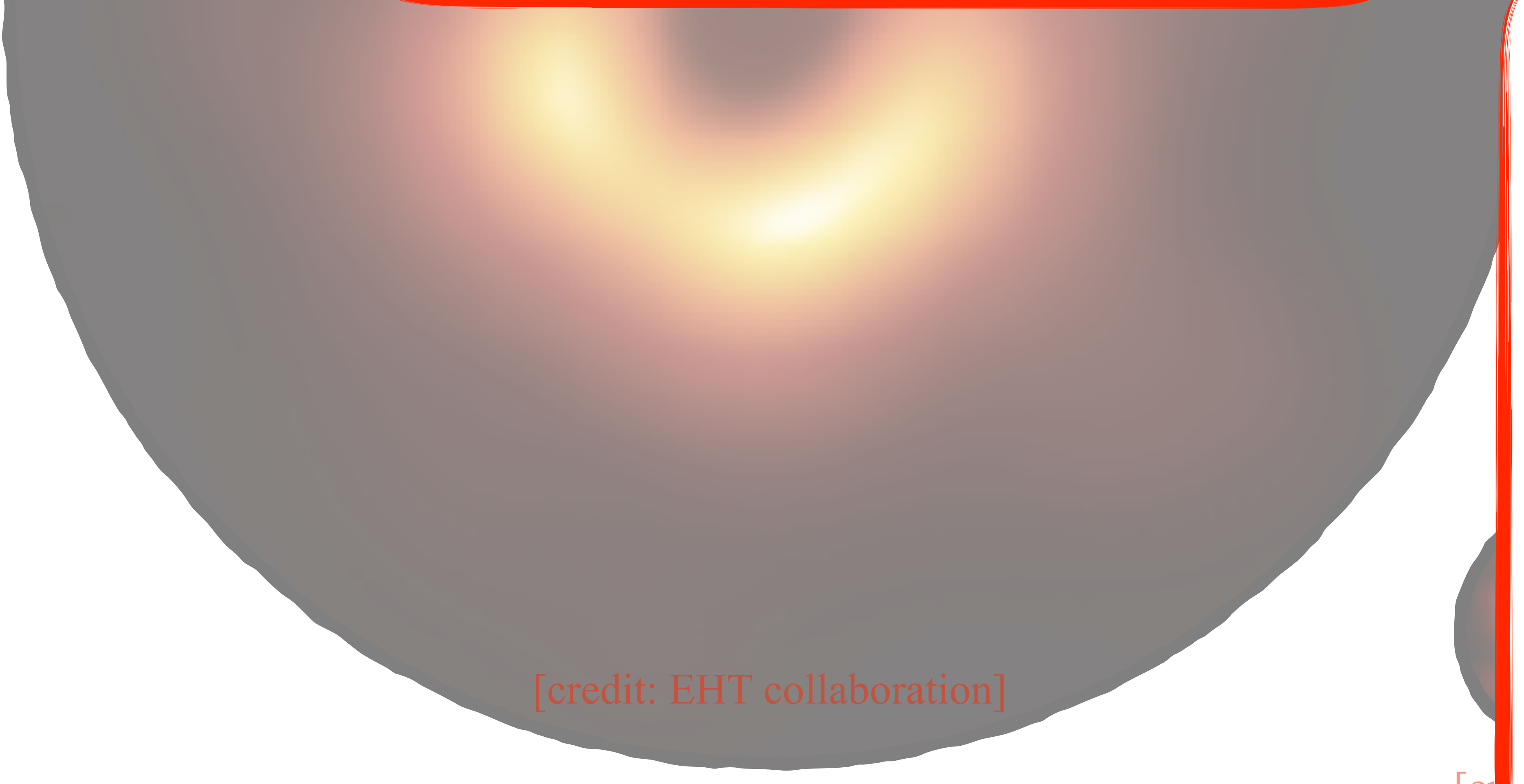
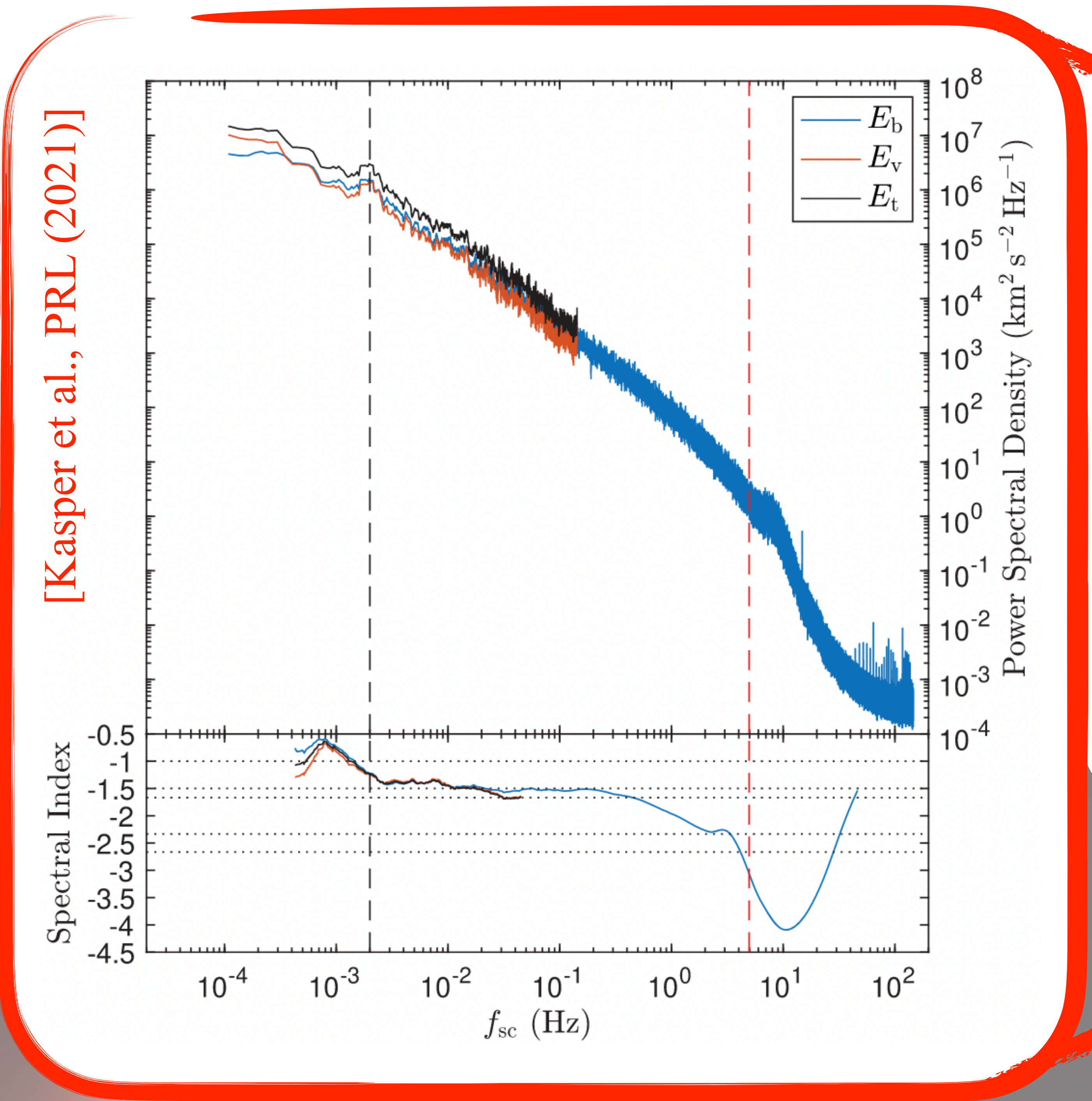
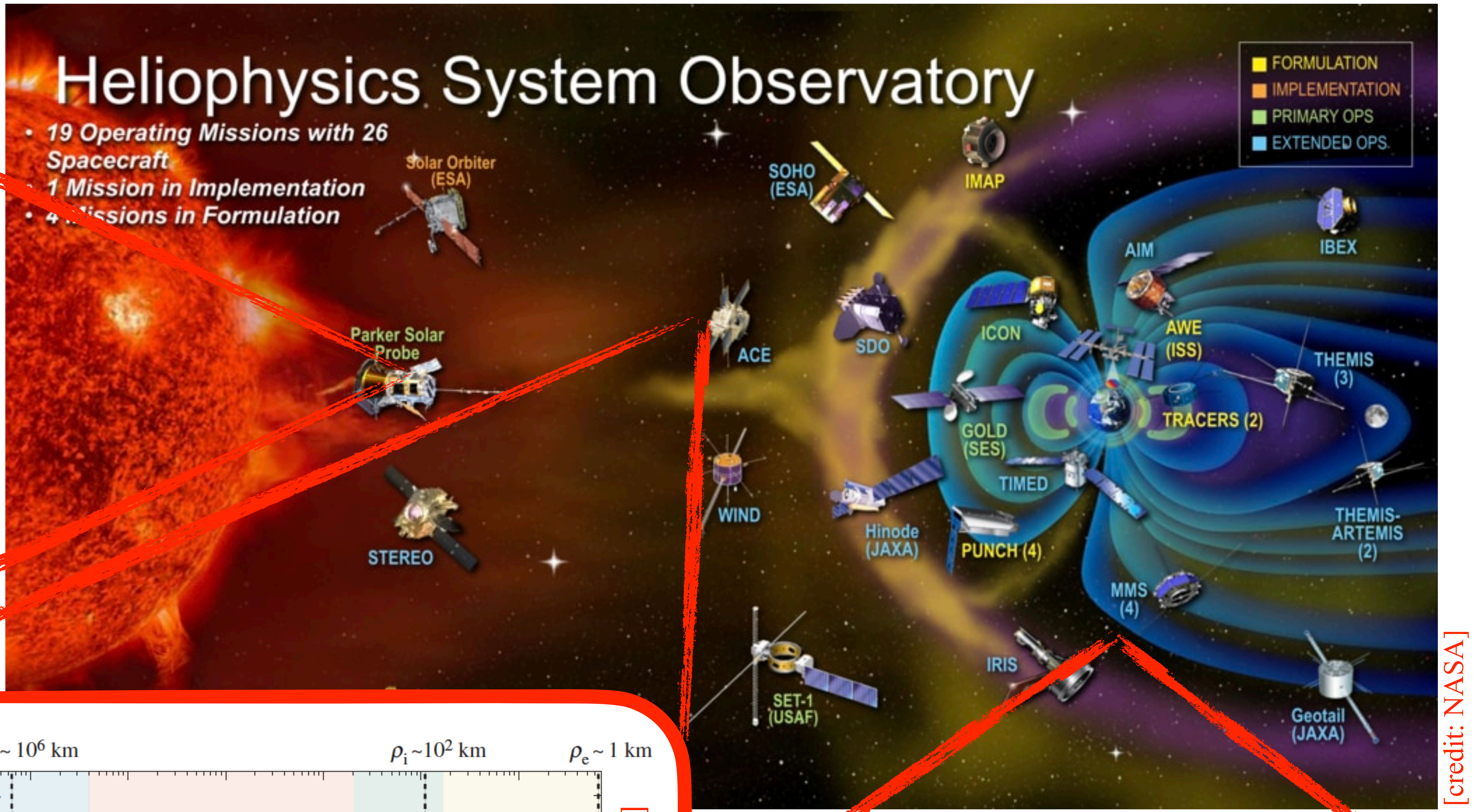


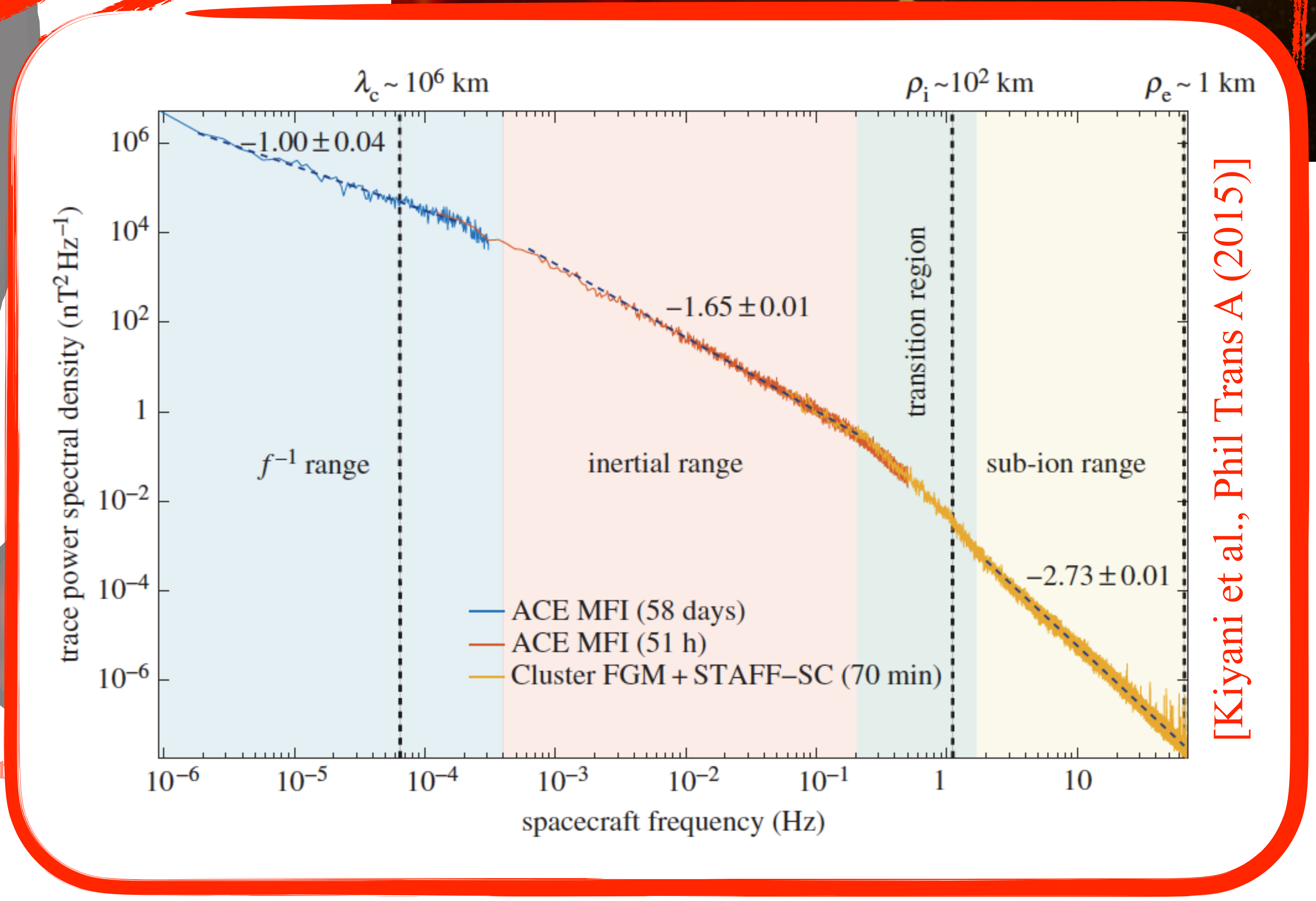
[credit: NASA]

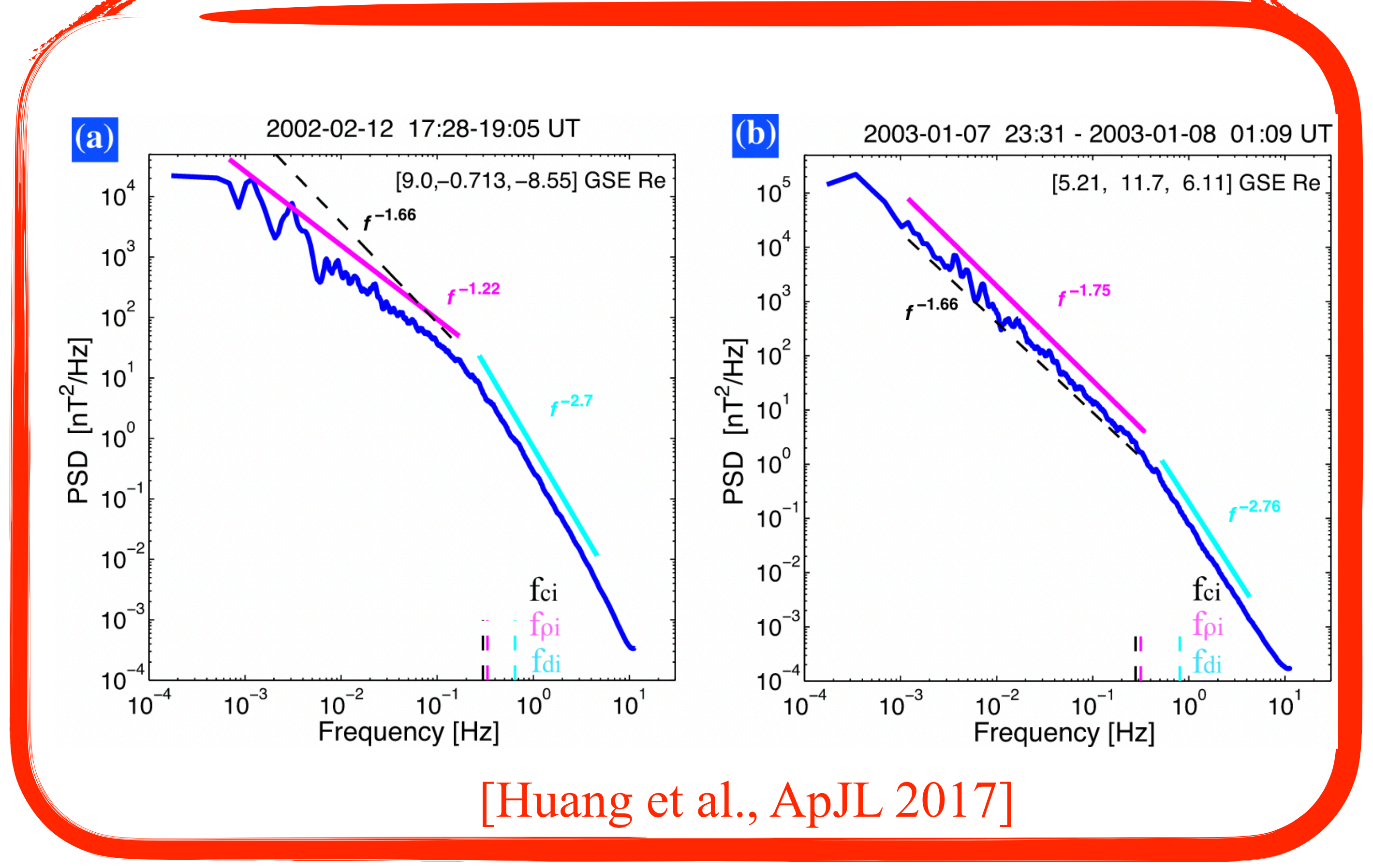
Turbulence in space and astrophysical plasmas











Turbulence in space and astrophysical plasmas

Introduction

Alfvénic Turbulence

☞ incompressible MHD equations:

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} = -\frac{\boldsymbol{\nabla} P_{\rm tot}}{\varrho_0} + \frac{(\boldsymbol{B} \cdot \boldsymbol{\nabla})\boldsymbol{B}}{4\pi \varrho_0} + \nu \nabla^2 \boldsymbol{u}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{B} = (\boldsymbol{B} \cdot \boldsymbol{\nabla})\boldsymbol{u} + \eta \nabla^2 \boldsymbol{B}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$$

Alfvénic Turbulence

☞ incompressible MHD in the Elsässer formulation ($\eta = \nu$):

$$\frac{\partial \boldsymbol{z}^+}{\partial t} + (\boldsymbol{z}^- \cdot \boldsymbol{\nabla})\boldsymbol{z}^+ = -\boldsymbol{\nabla}\widetilde{P}_{\rm tot} + \eta\,\nabla^2\boldsymbol{z}^+$$

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$$\boldsymbol{z}^\pm \doteq \boldsymbol{u} \pm \frac{\boldsymbol{B}}{\sqrt{4\pi\rho_0}}$$

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Alfvén waves traveling "up" or "down" the magnetic field **B**

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non-linear interaction only between counter-propagating Alfvén waves

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Alfvén waves traveling “up” or “down” the magnetic field **B**

Alfvénic turbulence ~ interaction of counter-propagating AWs

Alfvénic Turbulence

☞ split into "background + Alfvénic fluctuations":

$$\boldsymbol{B} = \boldsymbol{B}_0 + \delta\boldsymbol{B}_\perp$$

$$\boldsymbol{u} = \not{\boldsymbol{u}}_0 + \delta\boldsymbol{u}_\perp$$

$$\boldsymbol{v}_\mathrm{A} = \frac{\boldsymbol{B}_0}{\sqrt{4\pi\varrho_0}}$$

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$$\Rightarrow \quad \left(\frac{\partial}{\partial t} \mp \boldsymbol{v}_\mathrm{A} \cdot \boldsymbol{\nabla} \right) \delta \boldsymbol{z}^\pm + (\delta \boldsymbol{z}^\mp \cdot \boldsymbol{\nabla}) \delta \boldsymbol{z}^\pm = \ldots \text{ (!) turbulence needs finite dissipation!}$$

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(!) turbulence needs finite dissipation!

linear frequency: $\omega_\mathrm{A} = k_\parallel v_\mathrm{A}$

non-linear frequency: $\omega_\mathrm{nl} = k_\perp \delta z^\mp$

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linear frequency: $\omega_\mathrm{A} = k_\| v_\mathrm{A}$

non-linear frequency: $\omega_\mathrm{nl} = k_\perp \delta z^\mp$

$\Rightarrow$ non-linearity parameter: $\chi \doteq \dfrac{\omega_\mathrm{nl}}{\omega_\mathrm{A}} = \dfrac{k_\perp \delta z^\mp}{k_\| v_\mathrm{A}}$

- $\ll 1$ ("WEAK")
- ~ 1 ("STRONG")

Phenomenology of Alfvénic Turbulence

weak Alfvénic turbulence: a quick phenomenological derivation of the spectrum

☞ *for a formal derivation, see, e.g.,*

[Ng & Bhattacharjee, PoP 1996]
[Galtier, Nazarenko, Newell, Pouquet, JPP 2000]
[Schekochihin, arXiv:2010.00699]

Phenomenology of Alfvénic Turbulence

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$$\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3$$
$$\omega(k_{\parallel,1}) + \omega(k_{\parallel,2}) = \omega(k_{\parallel,3})$$

$\Rightarrow$ *no parallel cascade ($k_{//}$ = cst.), only a cascade in $k_\perp$!*

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How many interactions are needed to produce a significant change in counter-propagating Alfvén-wave packets?
(i.e., $\Delta(\delta z)/\delta z \sim 1$)

crossing time ~ linear propagation time: $\tau_A = (k_\parallel v_A)^{-1}$

distortion time ~ non-linear time: $\tau_{nl} = (k_\perp \delta z)^{-1}$

$$\Rightarrow \quad \Delta(\delta z) \sim \left(\frac{\tau_A}{\tau_{nl}}\right)\delta z = \chi\,\delta z$$

(change during one collision)

$\Rightarrow$ assume changes accumulates as a random walk:

$$N_{\text{inter.}} \sim \left(\frac{\delta z}{\Delta(\delta z)}\right)^2 \sim \frac{1}{\chi^2}$$

$$\Rightarrow \quad \tau_{\text{casc}} \sim N\,\tau_A \sim \frac{\tau_{nl}^2}{\tau_A} = \frac{\tau_{nl}}{\chi}$$

CASCADE TIME

Phenomenology of Alfvénic Turbulence

weak Alfvénic turbulence: a quick phenomenological derivation of the spectrum

☞ fluctuations' scaling and energy spectrum from constant energy flux through scales:

$$\frac{\delta z^2}{\tau_{\rm casc}} \sim \varepsilon = \text{const.} \quad \Rightarrow \quad \delta z \propto k_\perp^{-1/2} \quad \Rightarrow \quad \mathcal{E}_{\delta z} \propto k_\perp^{-2}$$

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⚠️ A very important consequece of these scalings is that **an initially weak Alfvénic cascade will not remain weak!**

non-linear frequency increases with decreasing scales,
while linear frequency is constant because there is no parallel cascade:

$$\omega_{\rm nl} = k_\perp \delta z \sim k_\perp^{1/2}$$

$$\omega_{\rm A} = k_{\|,0} v_{\rm A} = \text{const.}$$

$$\Rightarrow \quad \chi \sim k_\perp^{1/2} \quad \Rightarrow \quad \boxed{\frac{\lambda_\perp^{\rm CB}}{\ell_{\|,0}} \sim \left(\frac{\varepsilon\, \ell_{\|,0}}{v_{\rm A}^3}\right)^{1/2} \sim \left(\frac{\delta z_0}{v_{\rm A}}\right)^{3/2} \approx \chi_0^{3/2}} \; (\ll 1)$$

transition to critical balance ($\chi \sim 1$)

Phenomenology of Alfvénic Turbulence

critically balanced (strong) Alfvénic turbulence: a quick phenomenological derivation

☞ *for furhter details, see, e.g.,*

[Goldreich & Sridhar, ApJ 1995]
[Oughton & Matthaeus, ApJ 2020]
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Phenomenology of Alfvénic Turbulence

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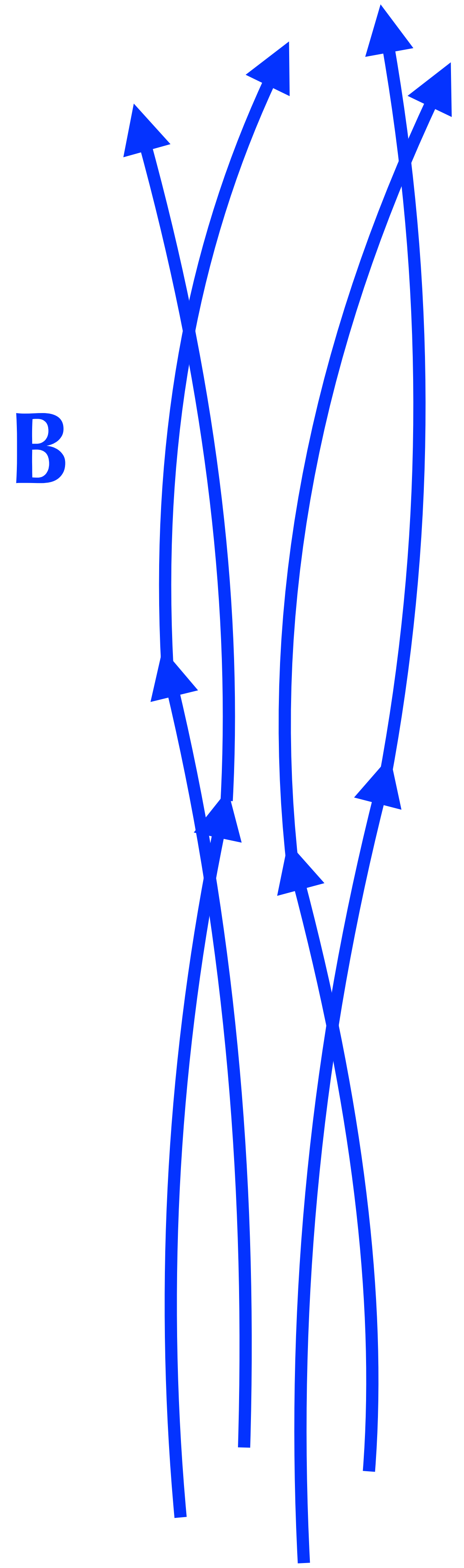

☞ At this point, linear, non-linear, and cascade timescales match each other:

$$\tau_{\rm nl} \sim \tau_{\rm A} \quad \Rightarrow \quad \tau_{\rm casc} \sim \tau_{\rm nl}$$

Phenomenology of Alfvénic Turbulence

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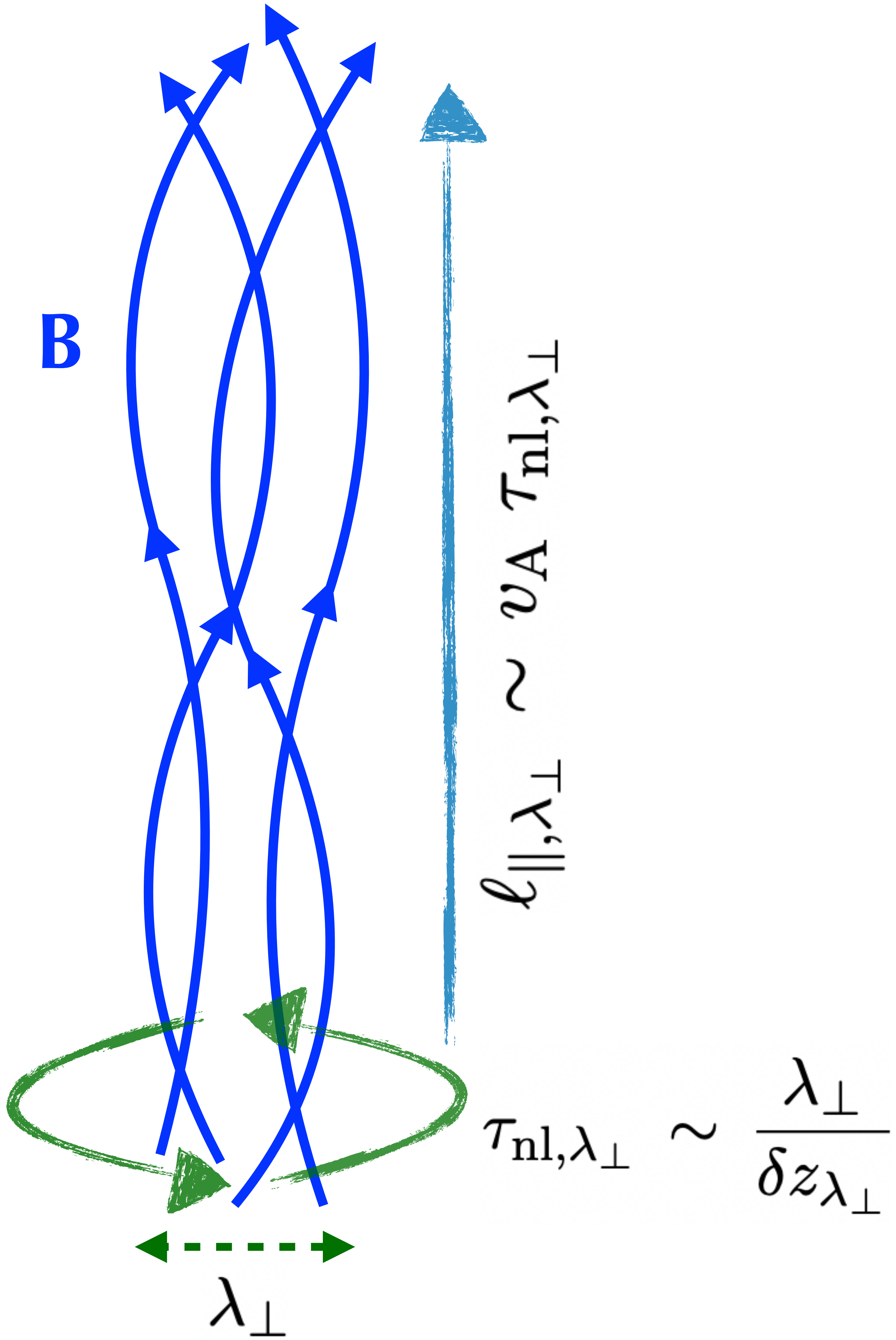


☞ At this point, linear, non-linear, and cascade timescales match each other:

$$\tau_{nl} \sim \tau_A \quad \Rightarrow \quad \tau_{casc} \sim \tau_{nl}$$

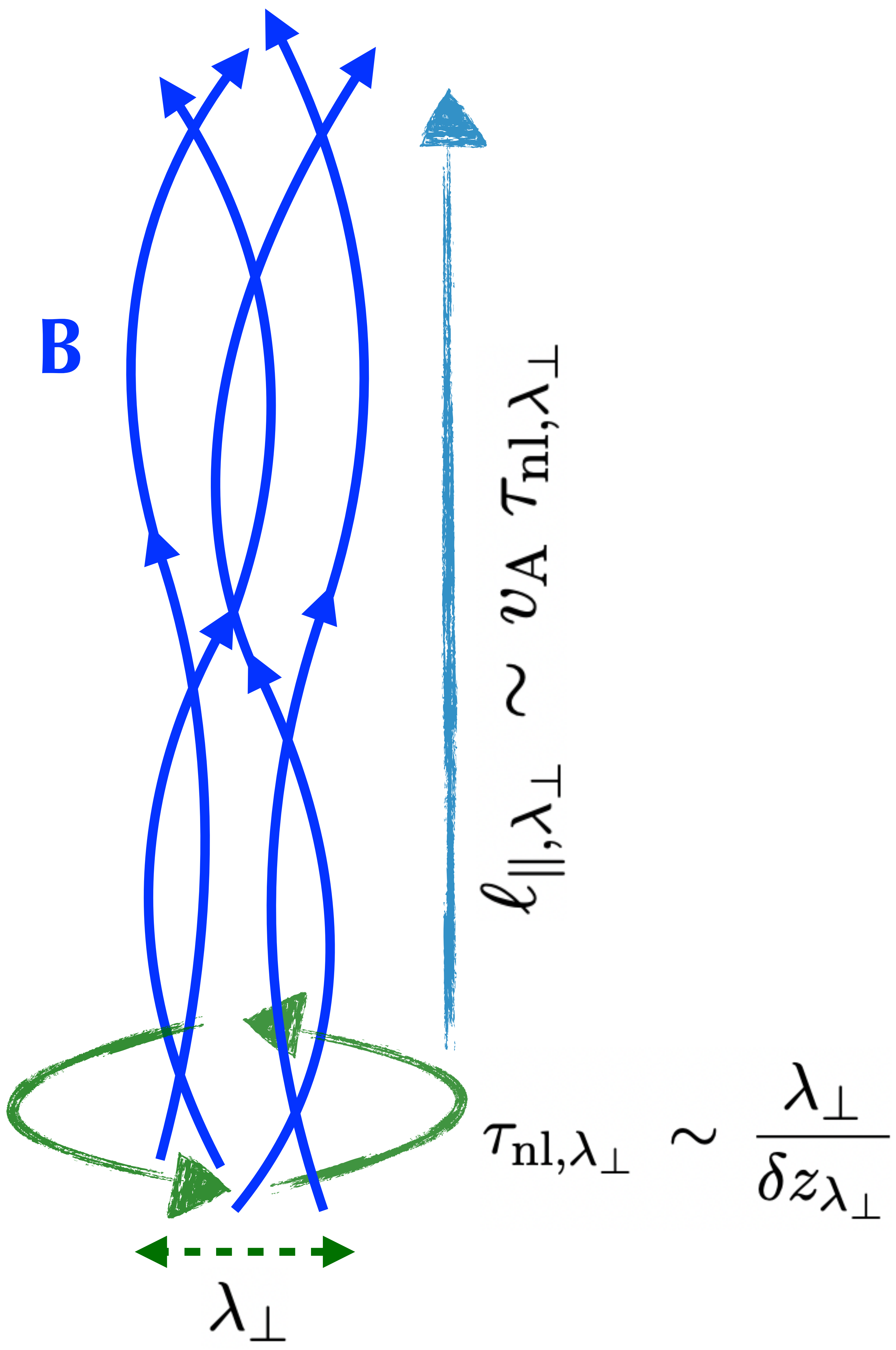
you can see the ***``critical-balance condition" as the result of causality***:

the information about Alfvénic fluctuations decorrelating in the perpendicular plane over an eddy turn-over time τ_{nl} can only propagate along the field for a length $\ell_{\|}$ at maximum speed v_A.

"So… CB is essentially AWs trying to keep up with the turbulent eddies…"

Phenomenology of Alfvénic Turbulence

critically balanced (strong) Alfvénic turbulence: a quick phenomenological derivation



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the information about Alfvénic fluctuations decorrelating in the perpendicular plane over an eddy turn-over time τ_{nl} can only propagate along the field for a length $\ell_{||}$ at maximum speed v_A.

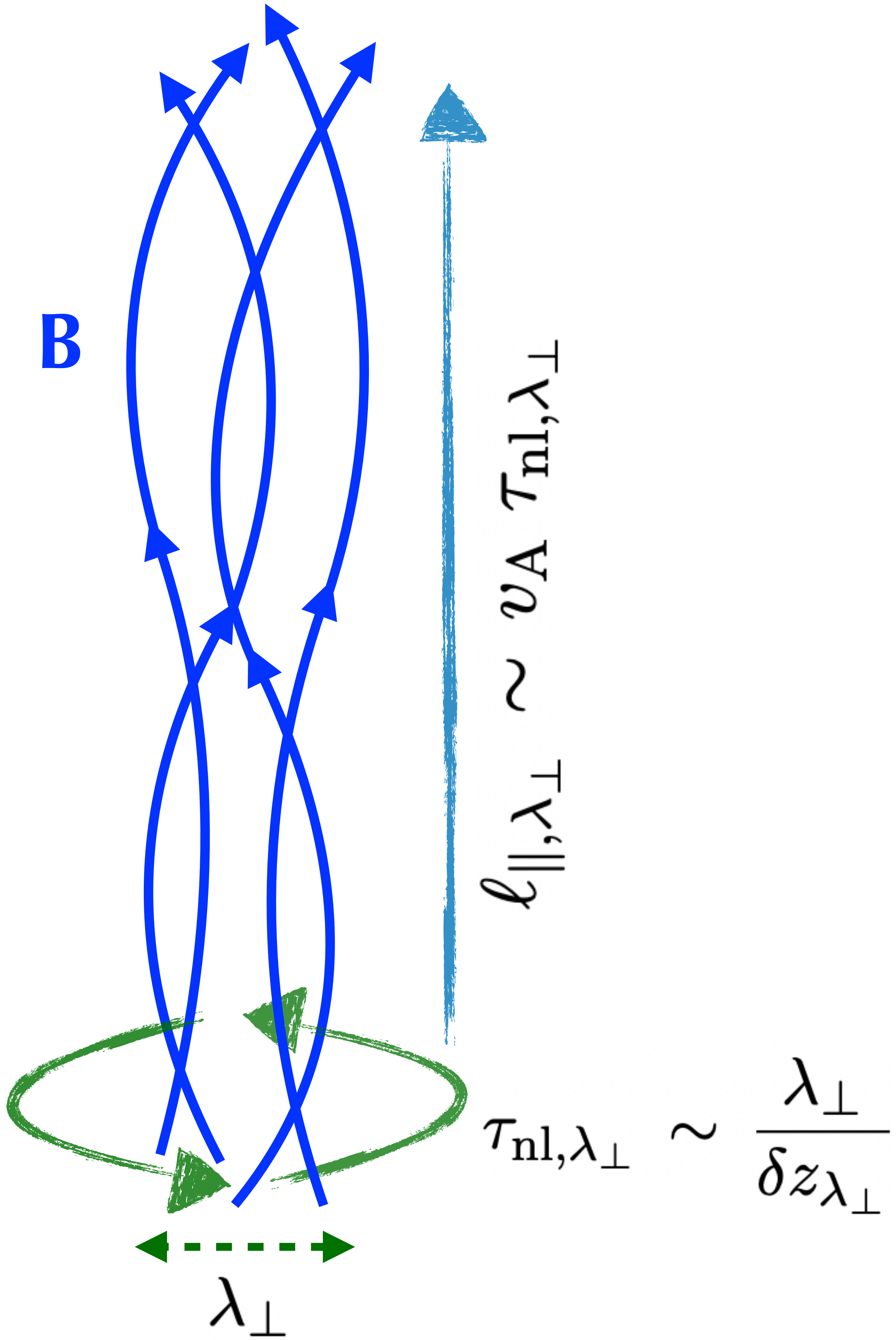
"So… CB is essentially AWs trying to keep up with the turbulent eddies…"

Therefore, once $\tau_{nl} \sim \tau_A$ is reached, the balance is mantained.

(In principle, this could be done by continuing the cascade with τ_{nl} = const., or by generating smaller $\ell_{||}$ such that $\tau_A \sim \ell_{||}/v_A \sim \tau_{nl}$ keeps holding… it is the latter)

Phenomenology of Alfvénic Turbulence

critically balanced (strong) Alfvénic turbulence: a quick phenomenological derivation



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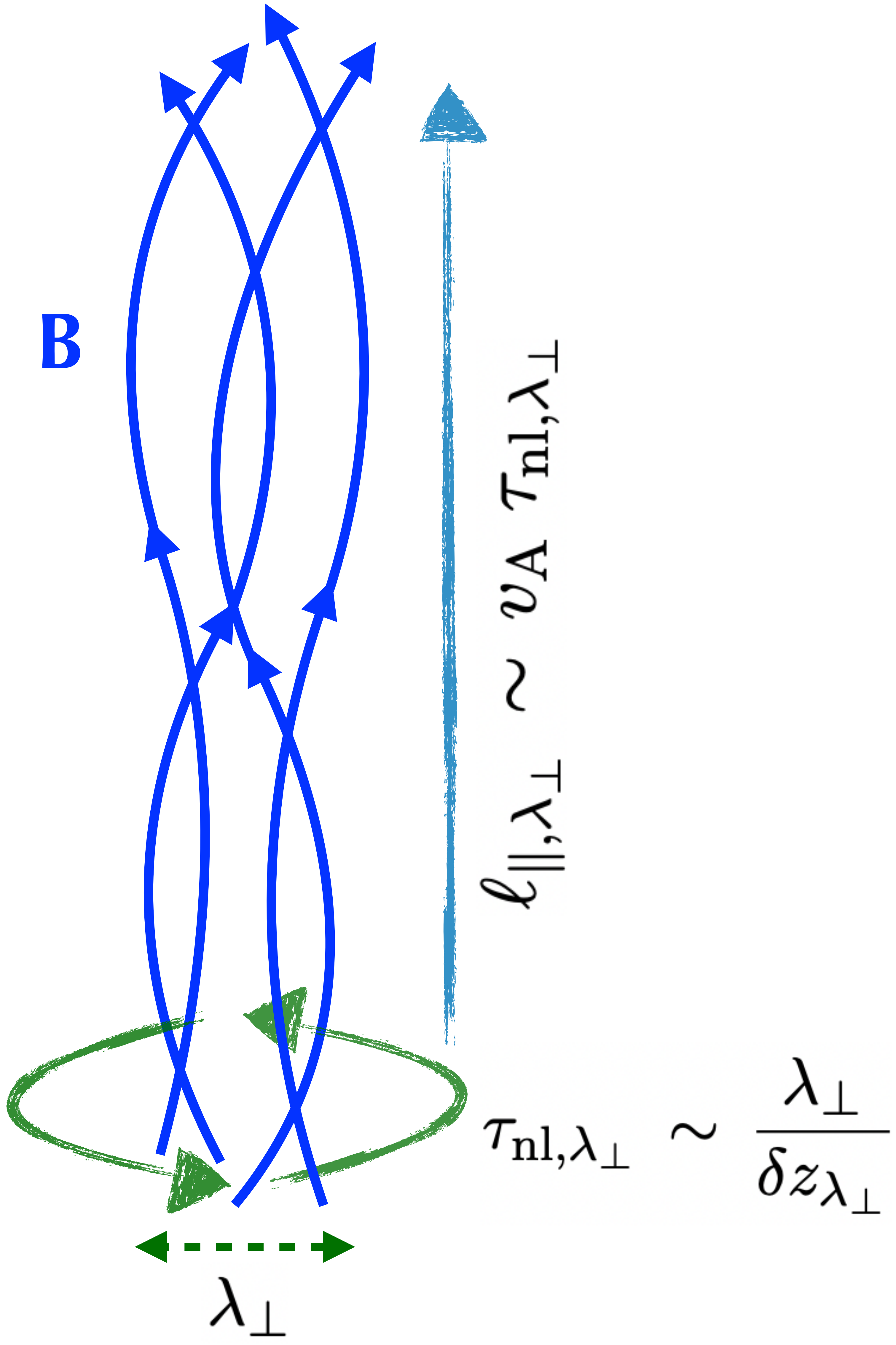

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$$\tau_{\mathrm{nl}} \sim \tau_{\mathrm{A}} \quad \Rightarrow \quad \tau_{\mathrm{casc}} \sim \tau_{\mathrm{nl}}$$

☞ fluctuations' scaling + spectum from **ε** = const. (*you know the drill*):

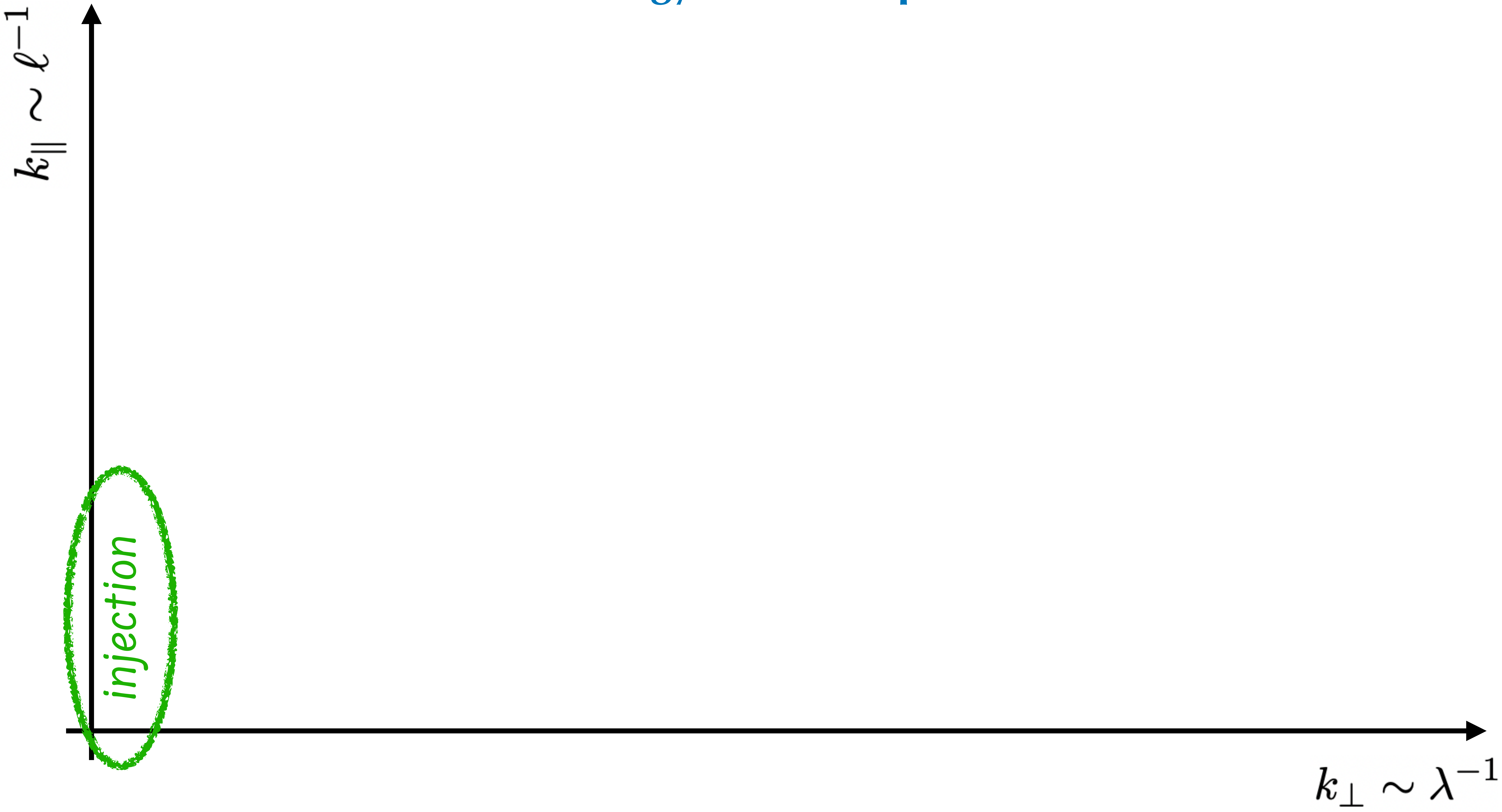
$$\frac{\delta z_{k_\perp}^2}{\tau_{\mathrm{nl},k_\perp}} \sim \varepsilon = \mathrm{const.} \quad \Rightarrow \quad \boxed{\delta z_{k_\perp} \propto k_\perp^{-1/3} \quad \Rightarrow \quad \mathcal{E}_{\delta z}(k_\perp) \propto k_\perp^{-5/3}}$$

☞ now, you can also compute the fluctuations' wavenumber anisotropy:

$$k_\perp \delta z_{k_\perp} \sim k_\| v_{\mathrm{A}} \quad \Rightarrow \quad \boxed{k_\| \propto k_\perp^{2/3}} \quad \left(\Rightarrow \quad \mathcal{E}_{\delta z}(k_\|) \propto k_\|^{-2} \right)$$

Phenomenology of Alfvénic Turbulence

Energy flux in k space



Phenomenology of Alfvénic Turbulence

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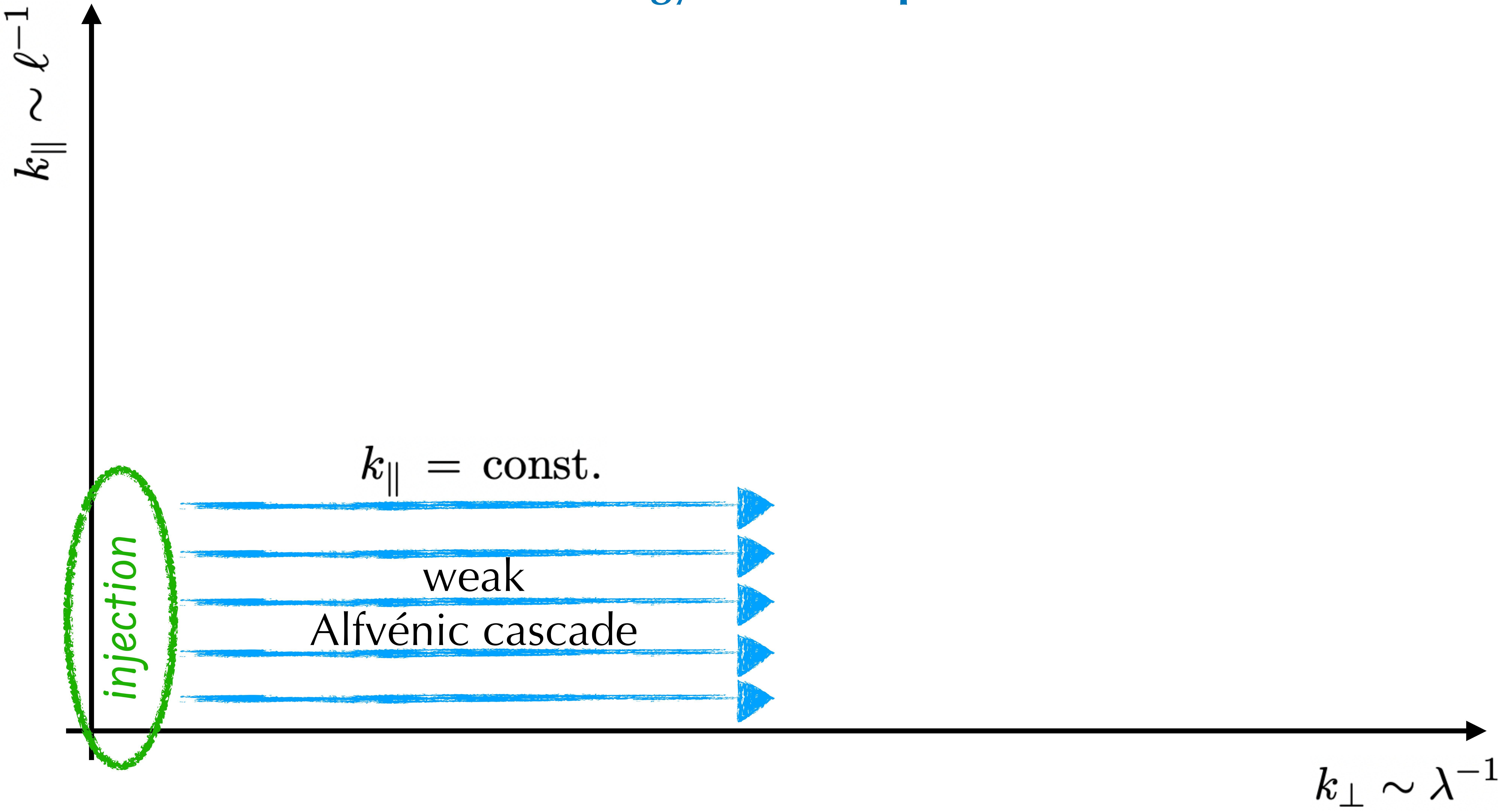

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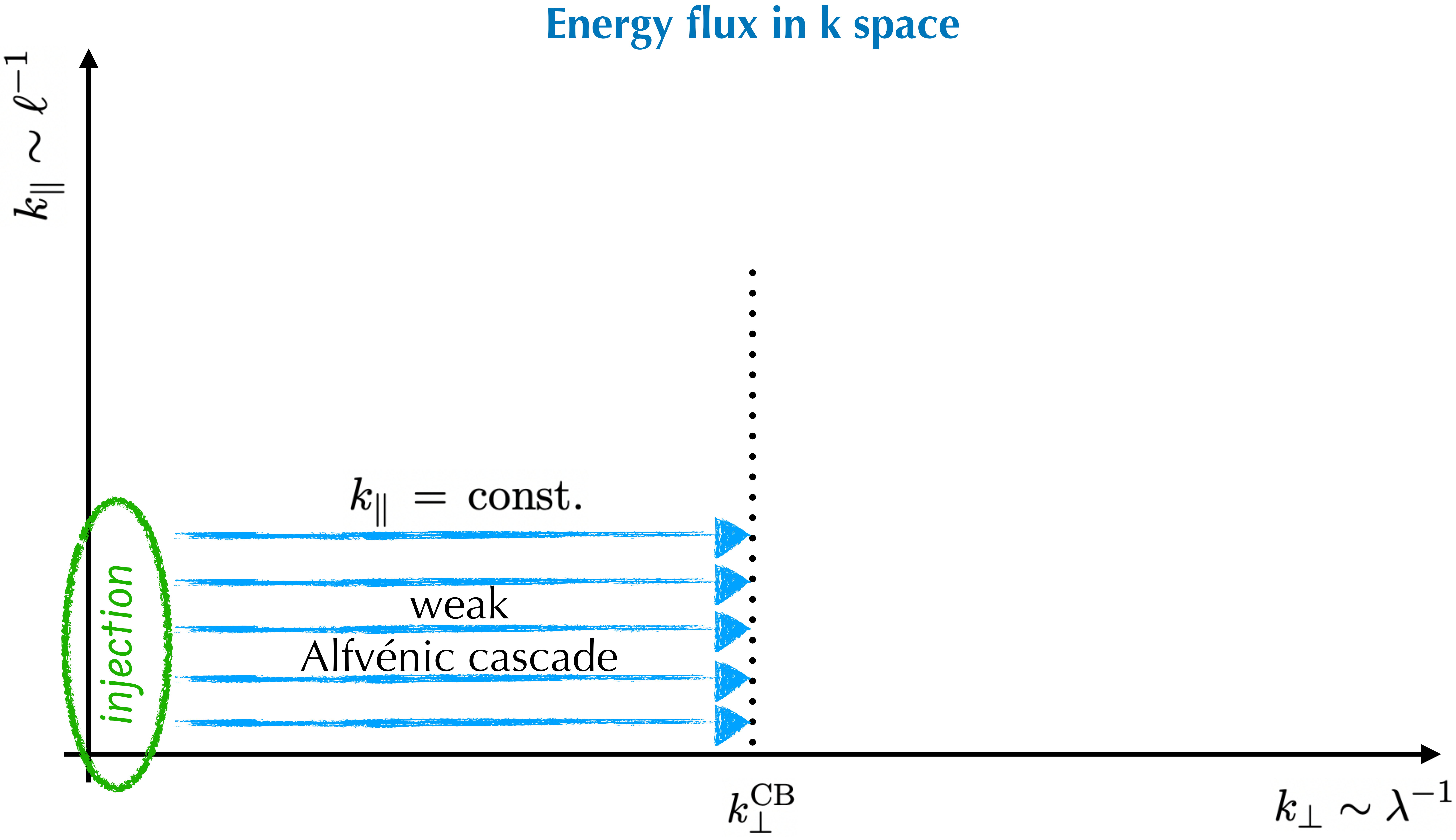

Phenomenology of Alfvénic Turbulence

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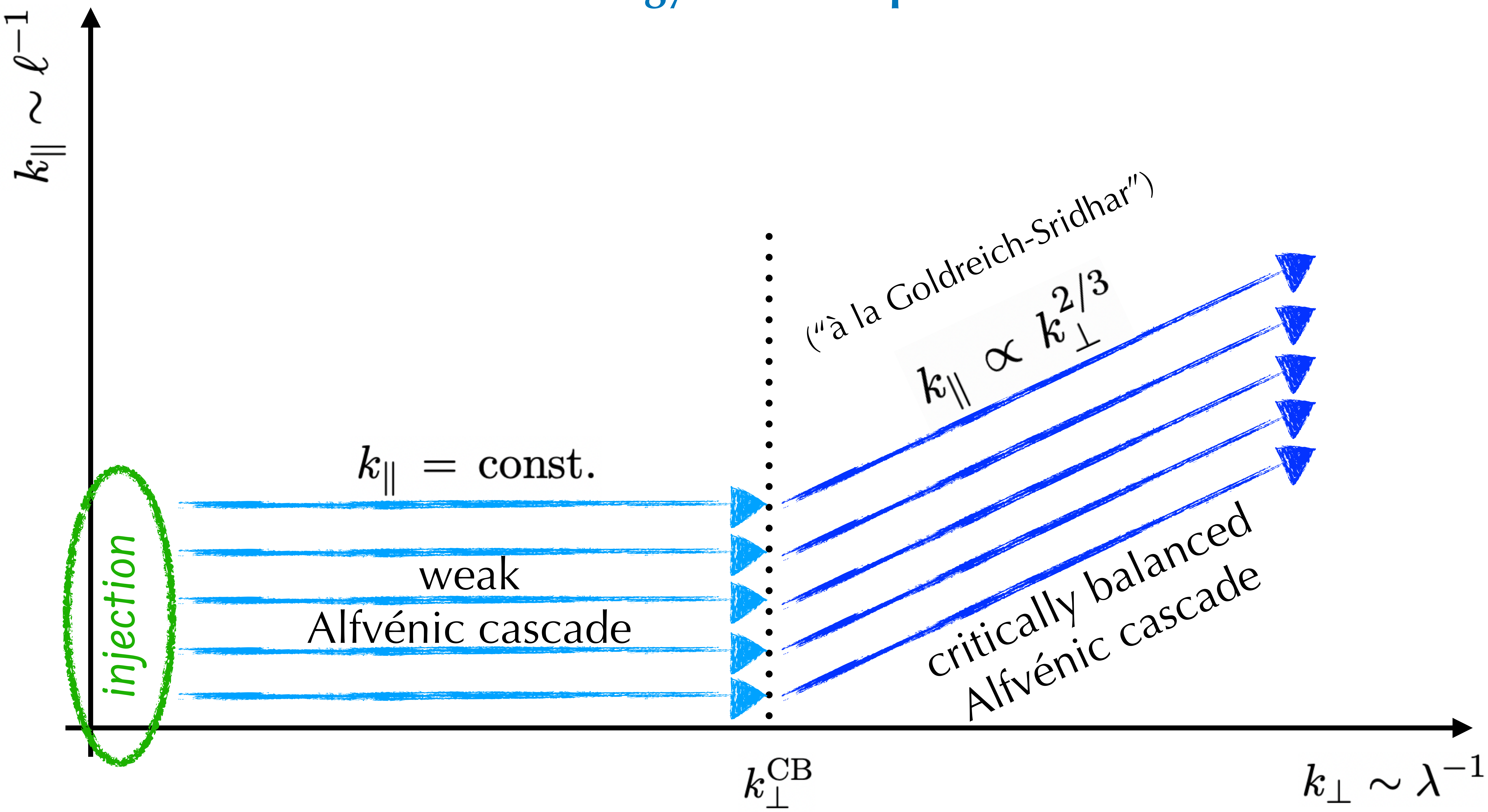

Further Developments in Theoretical Models

dynamic alignment in Alfvénic turbulence: three-dimensional anisotropy

☞ *for furhter details, see, e.g.,*

[Boldyrev, PRL 2006]
[Schekochihin, arXiv:2010.00699]

reconnection-mediated regime in Alfvénic turbulence

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[Boldyrev & Loureiro, ApJ 2017]
[Mallet, Schekochihin, Chandran, MNRAS 2017]
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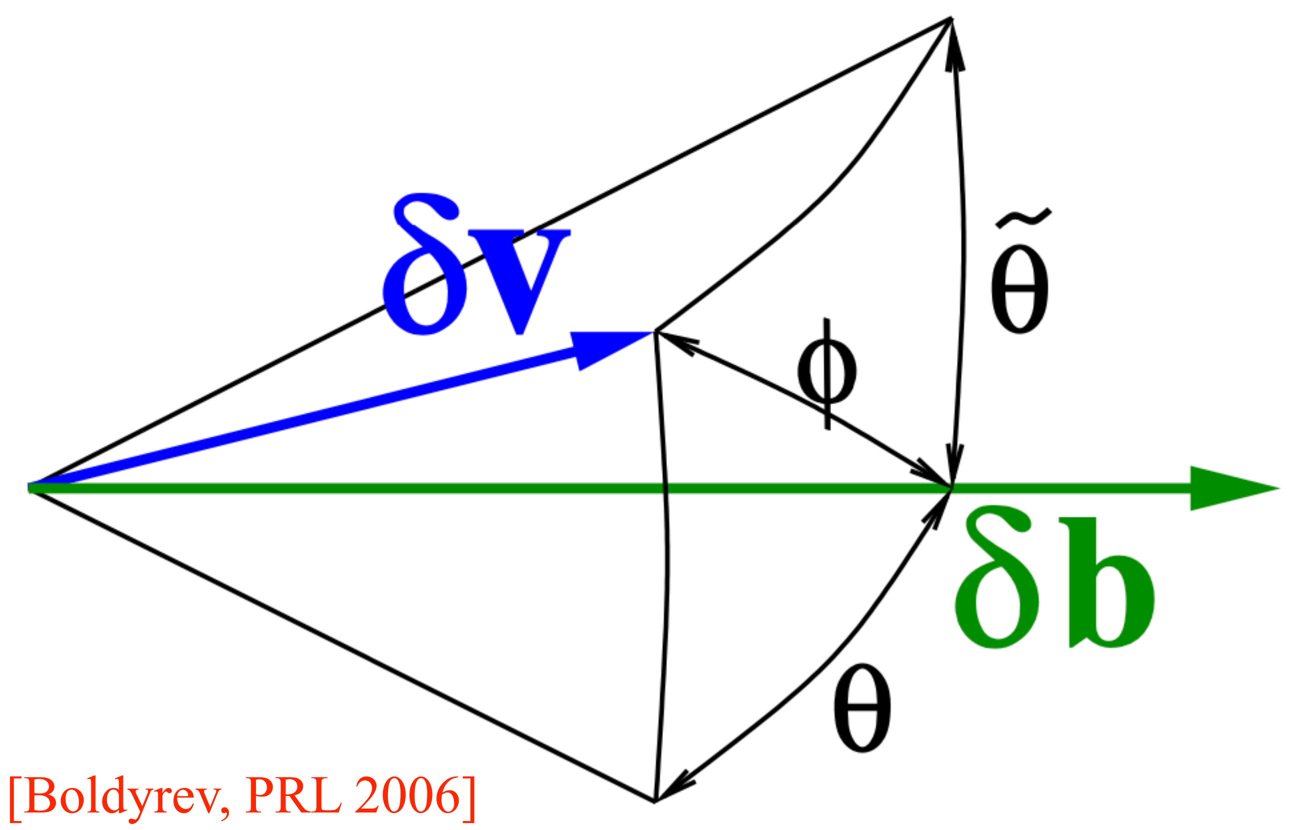

[Boldyrev, PRL 2006]

☞ Observations and simulations show that $\delta\mathbf{v}_\lambda$ and $\delta\mathbf{b}_\lambda$ have a spontaneous tendency to align in the plane perpendicular to the local mean field $\langle\mathbf{B}\rangle_\lambda$, within an angle θ_λ

(e.g., Podesta et al., JGR 2009; Hnat et al., PRE 2011; Mason et al., ApJ 2011; Wicks et al., PRL 2013; Mallet et al., MNRAS 2016; …)

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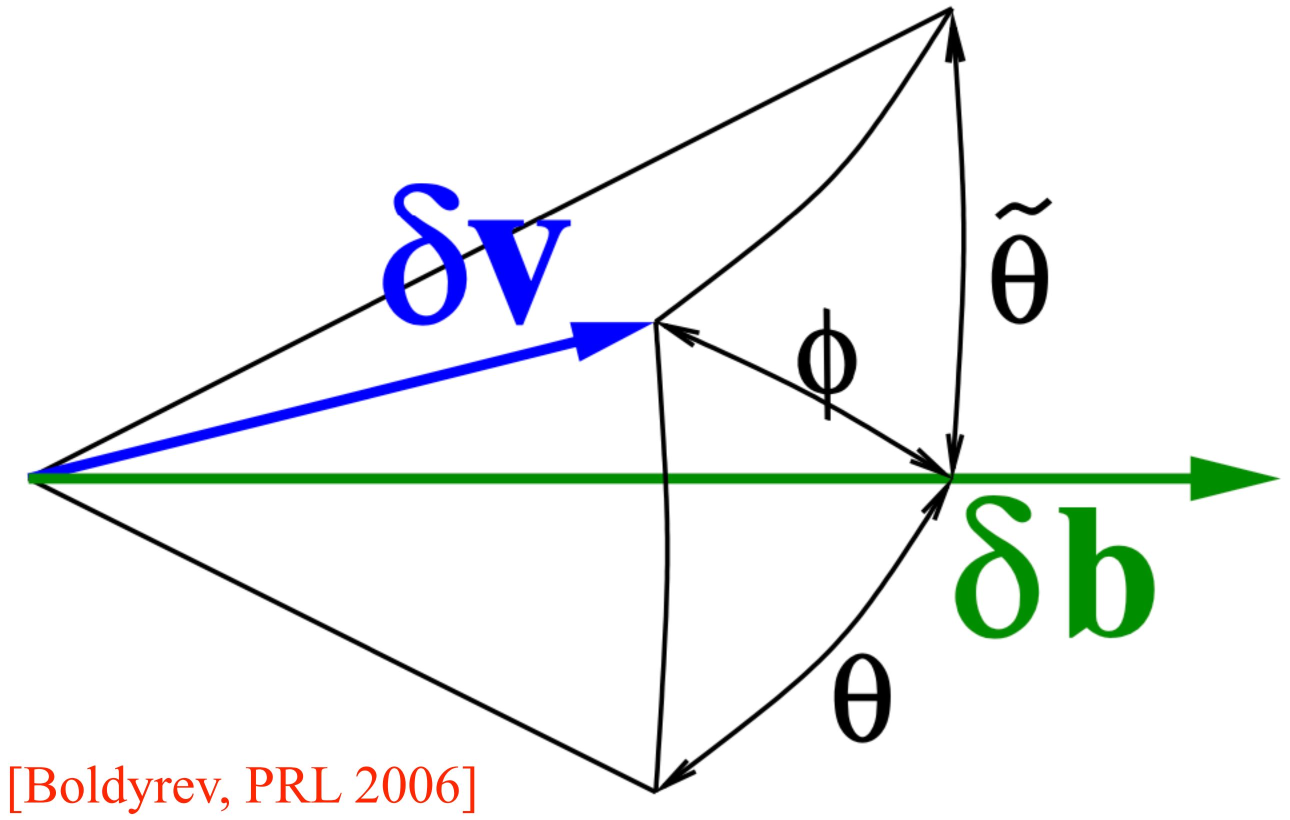

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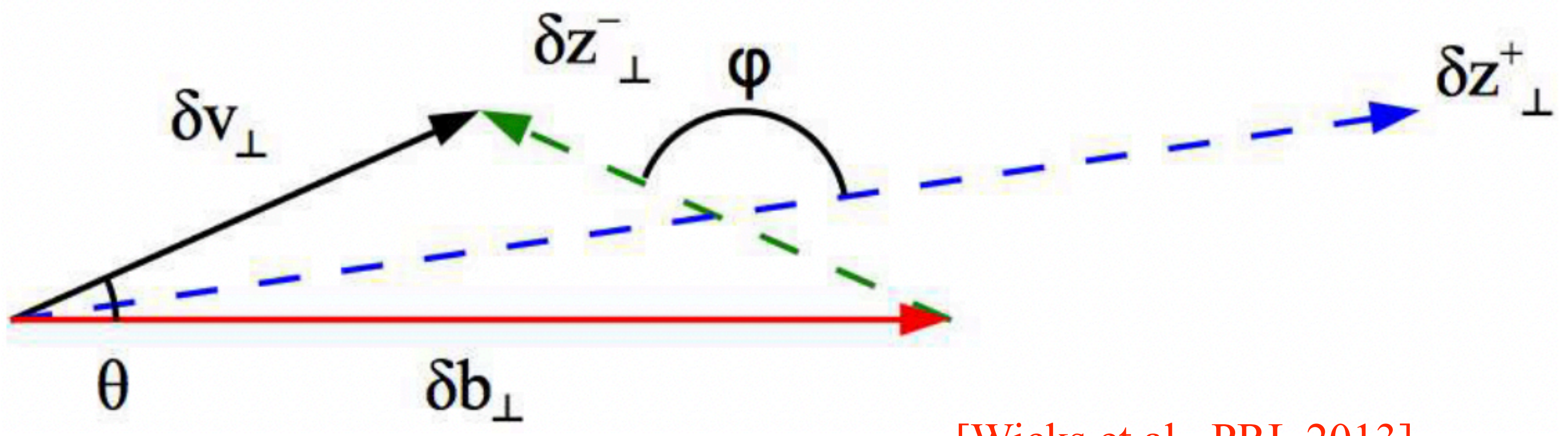
⚠ the alignment between $\mathbf{\delta v}_\lambda$ and $\mathbf{\delta b}_\lambda$ is *not the same* as the alignment between $\mathbf{\delta z}^+_\lambda$ and $\mathbf{\delta z}^-_\lambda$!

(but they are related: see Schekochihin arXiv:2010.00699)



[Wicks et al., PRL 2013]

alignment ⇒ depletion of non-linearities: $\delta\mathbf{z}^{\mp}\cdot\boldsymbol{\nabla}\delta\mathbf{z}^{\pm}\sim\sin\varphi_\lambda\,\frac{\delta z_\lambda^2}{\lambda}\approx\varphi_\lambda\,\frac{\delta z_\lambda^2}{\lambda}\quad\longleftrightarrow\quad\theta_\lambda\,\frac{\delta v_\lambda^2}{\lambda}$

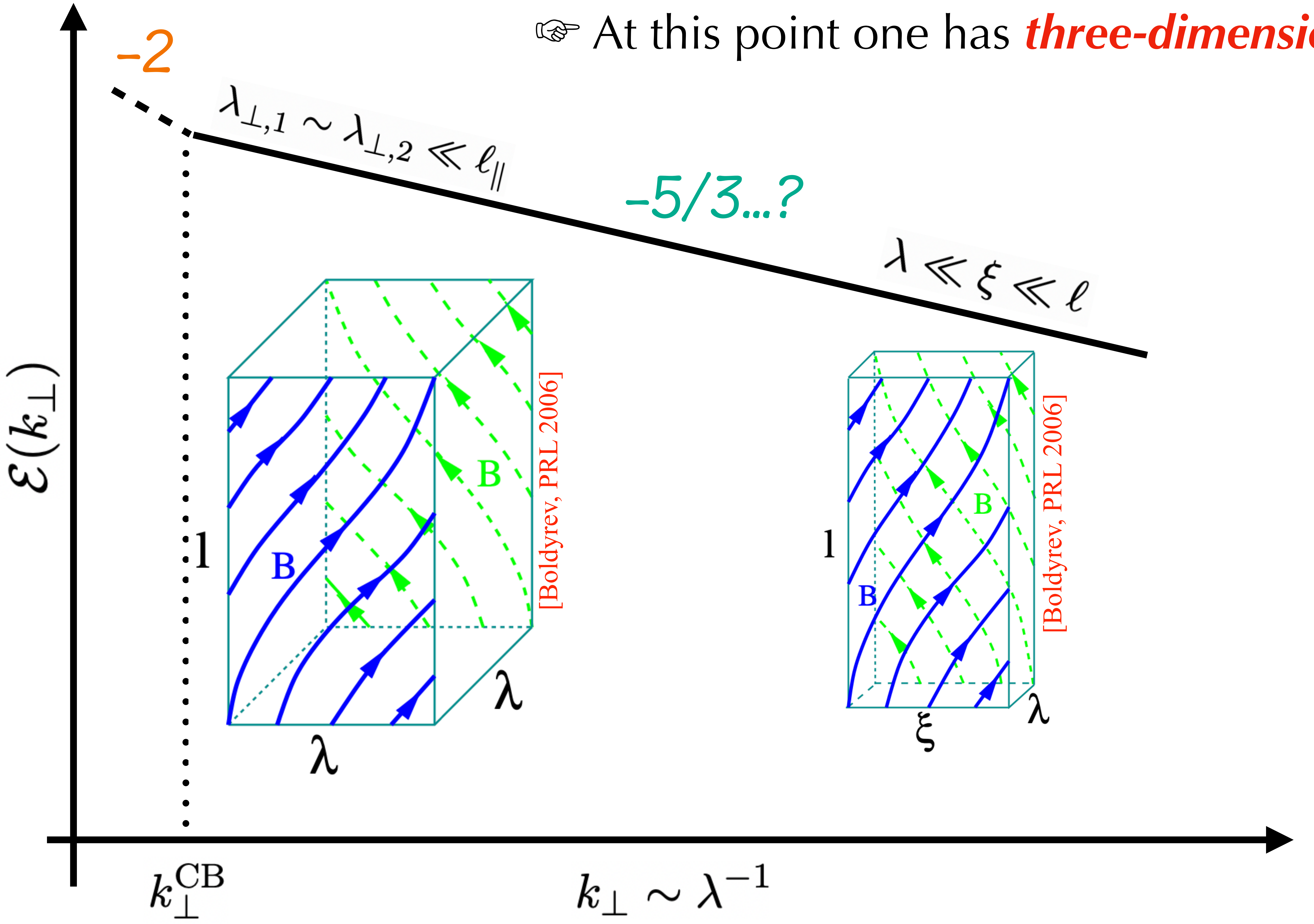
⚠ but remember that *fluctuations cannot be perfectly aligned* ($\theta_\lambda = 0$) in order to have a non-linear cascade

Further Developments in Theoretical Models

dynamic alignment in Alfvénic turbulence: three-dimensional anisotropy

The effect of alignment is not only to *make the non-linear interactions weaker*, but also to *induce anisotropy in the plane perpendicular to the magnetic field **B***

☞ At this point one has ***three-dimensional anisotropy of the fluctuations***!



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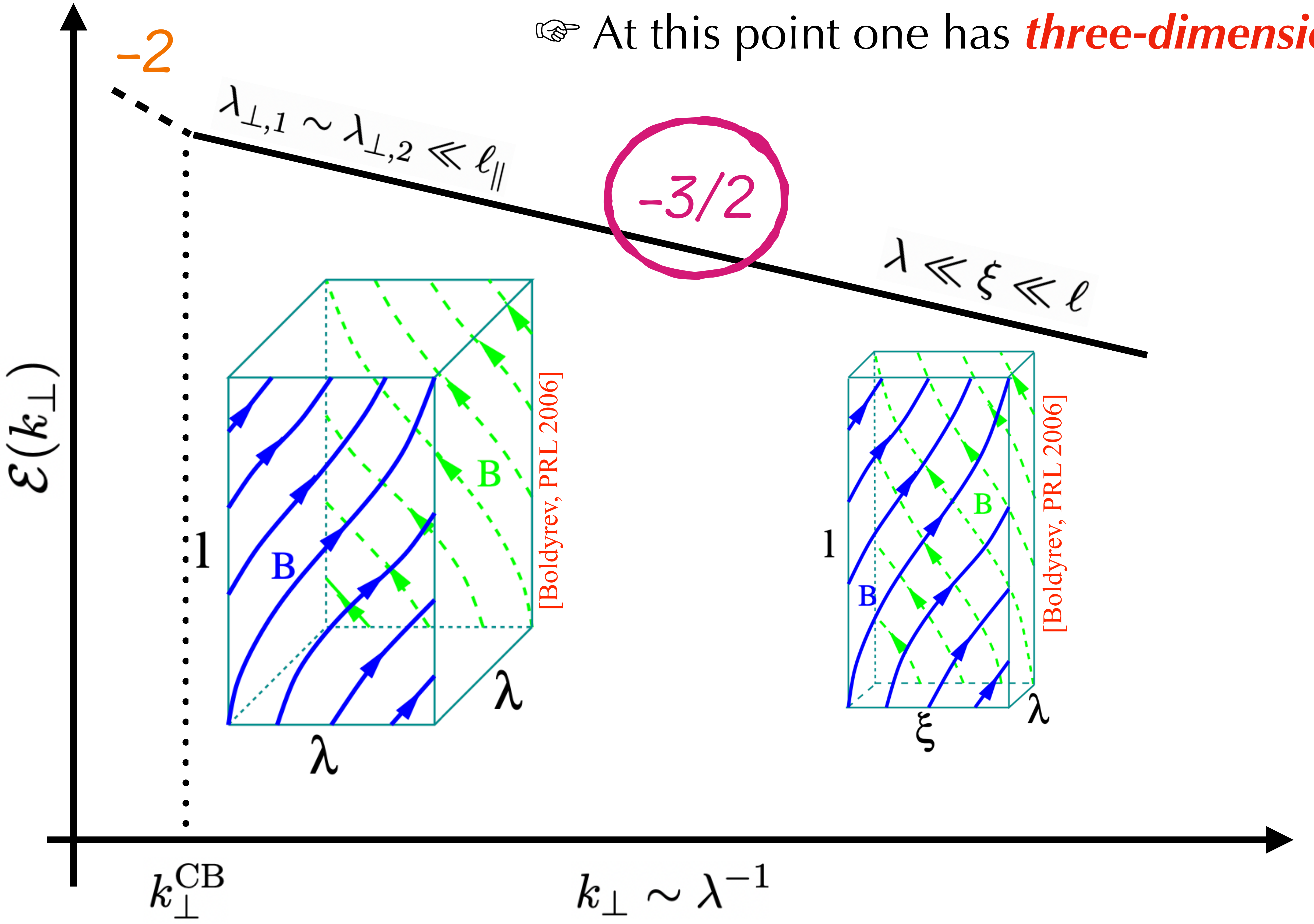


☞ long story short:

(see Boldyrev, PRL 2006 for the derivation)

$$\theta_{k_\perp} \propto k_\perp^{-1/4} \quad \Rightarrow \quad \delta v_{k_\perp} \propto k_\perp^{-1/4} \quad \Rightarrow \quad \mathcal{E}(k_\perp) \propto k_\perp^{-3/2}$$

$$\left(\text{also, now } \; k_\parallel \propto k_\perp^{1/2}\right)$$

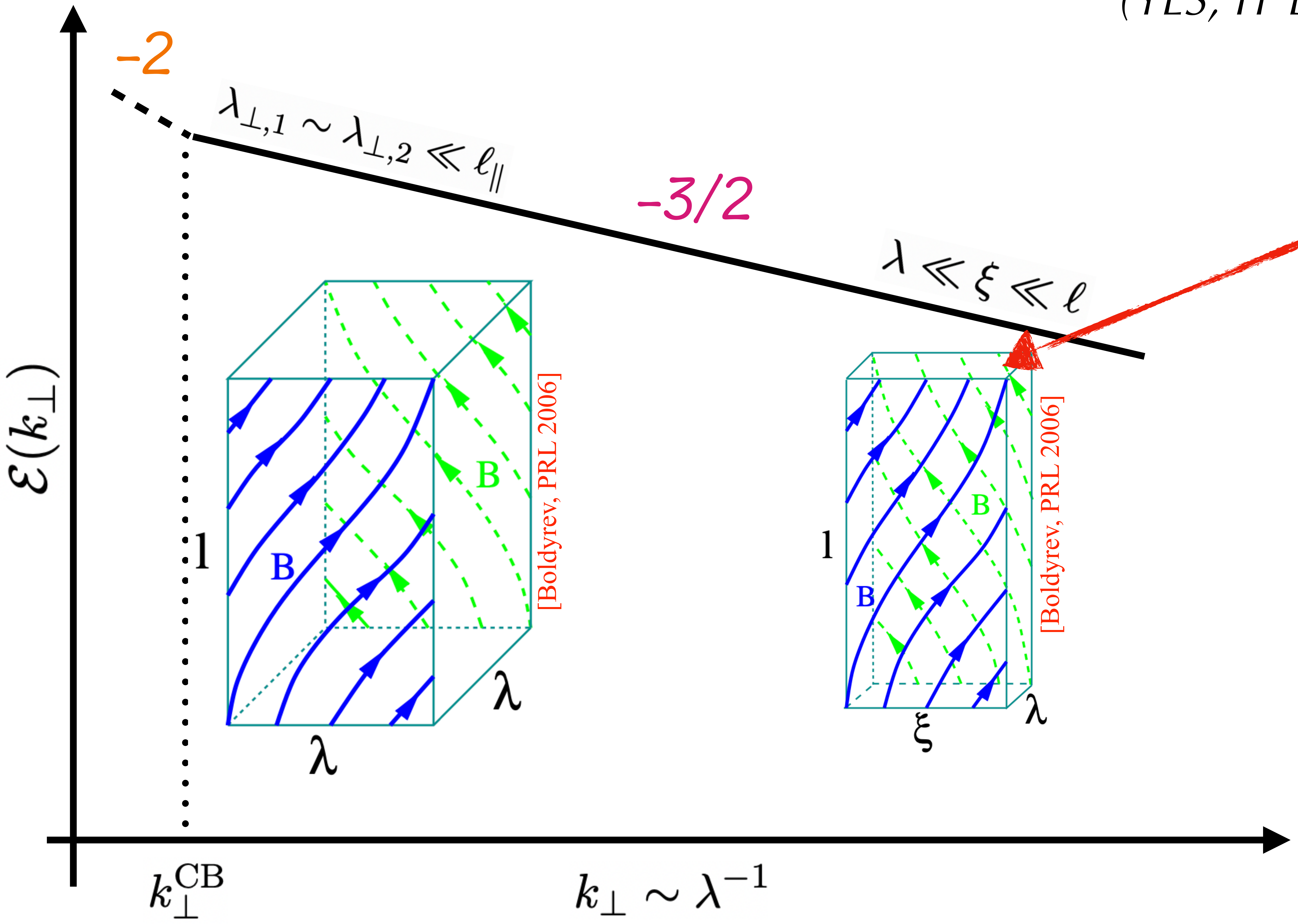
Further Developments in Theoretical Models

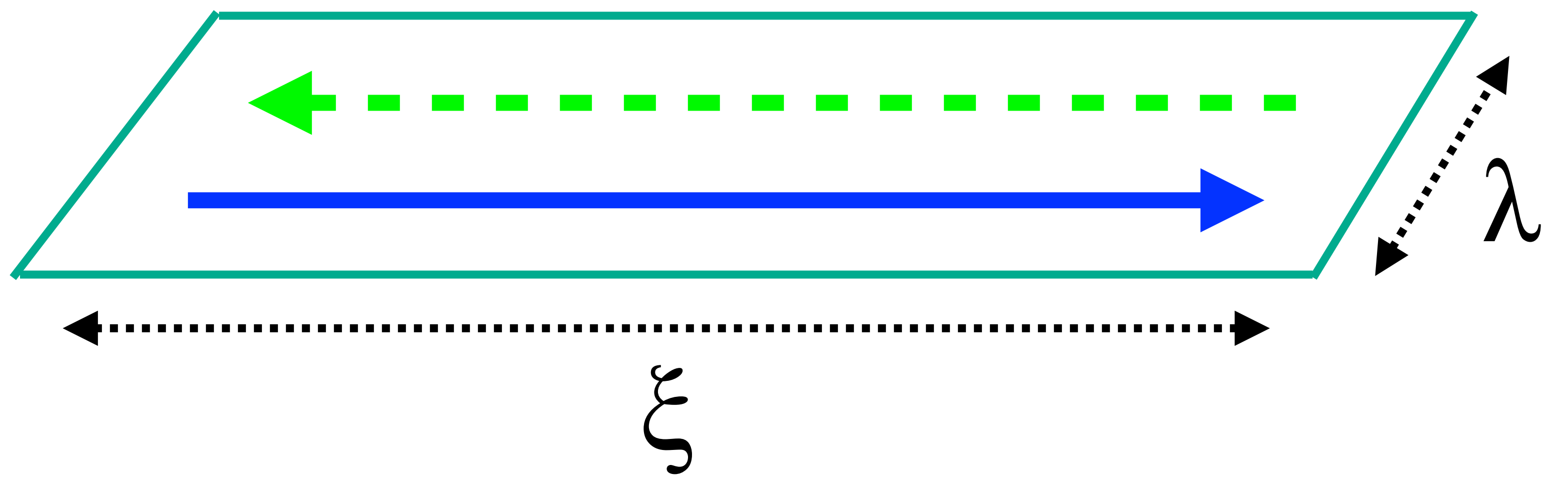
reconnection-mediated regime in Alfvénic turbulence

So, we had *three-dimensional anisotropy, right?* … wait a minute!

doesn't *3D anisotropy of the turbulent eddies look line a **current sheet in the plane perpendicular to B**?!*

(YES, IT DOES!)





☞ *if the eddies at a scale live "long enough" for the tearing instability (i.e., reconnection) to grow, then we can imagine that this process will be responsible for the production of small-scale magnetic fluctations*

Further Developments in Theoretical Models

reconnection-mediated regime in Alfvénic turbulence

So, we had *three-dimensional anisotropy*, *right?* … wait a minute!

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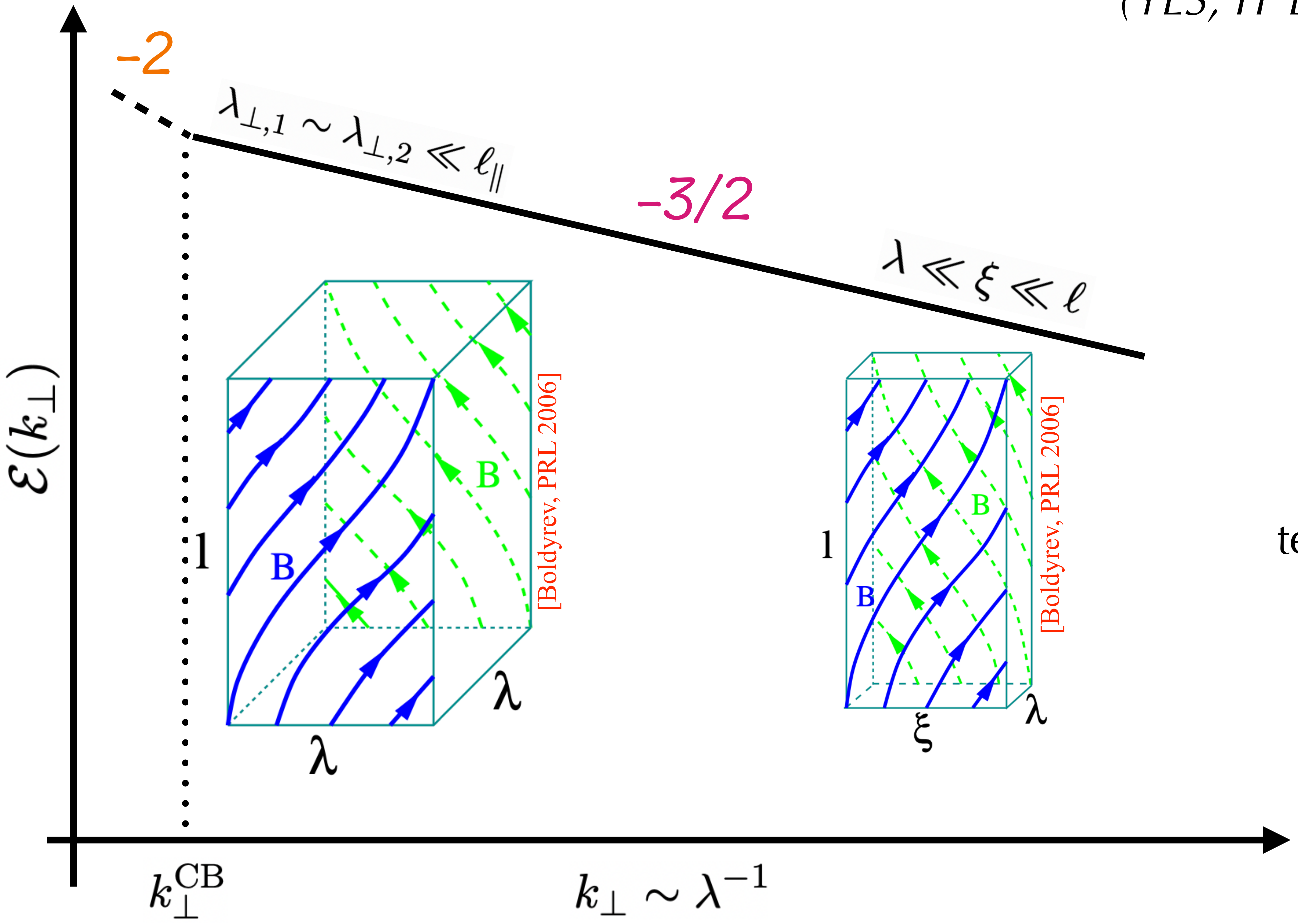

eddy lifetime: $\tau_{{\rm nl},k_\perp} \sim (\theta_{k_\perp} k_\perp \delta v_{k_\perp})^{-1} \propto k_\perp^{-1/2}$

tearing growth rate: $\gamma^{\rm rec}_{k_\perp} \sim k_\perp \delta v_{k_\perp} \left(\frac{\delta v_{k_\perp}}{k_\perp \eta}\right)^{-1/2} \propto S_0^{-1/2} k_\perp^{11/8}$

$$\left(\eta : \ \text{resistivity}\,, \quad S \doteq \frac{v_{\rm A}\,\ell_0}{\eta} : \ \text{Lundquist number}\right)$$

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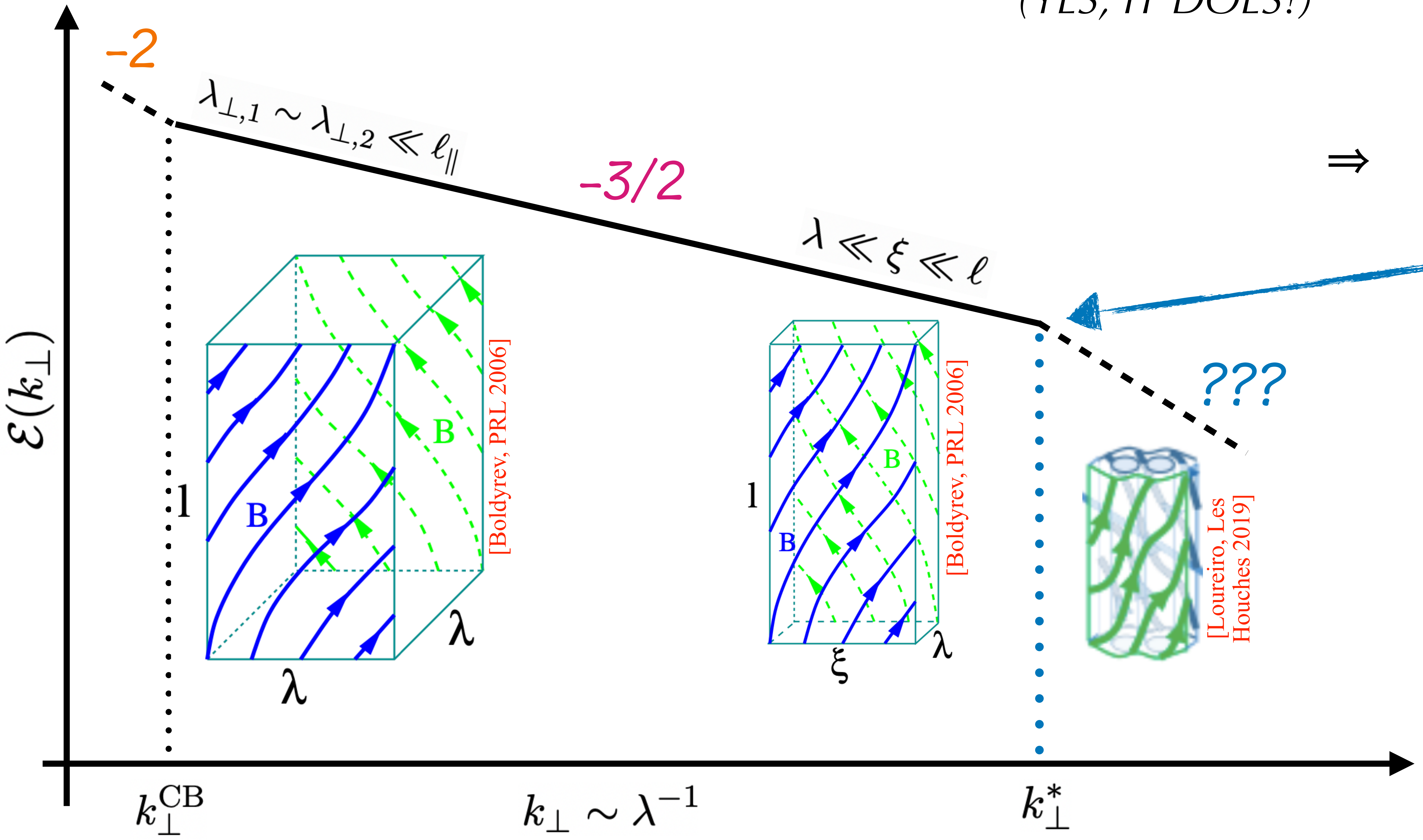

$\Rightarrow \quad \gamma^{\rm rec}\,\tau_{\rm nl} \sim 1 \quad \text{at} \quad \dfrac{\lambda_*}{\ell_0} \sim S_0^{-4/7}$

transition to reconnection-mediated cascade

⚠️ this regime exists if the Lundquist number is large enough to separate such transition scale from the actual dissipation scale!

(see references at the beginning of this part)

Further Developments in Theoretical Models

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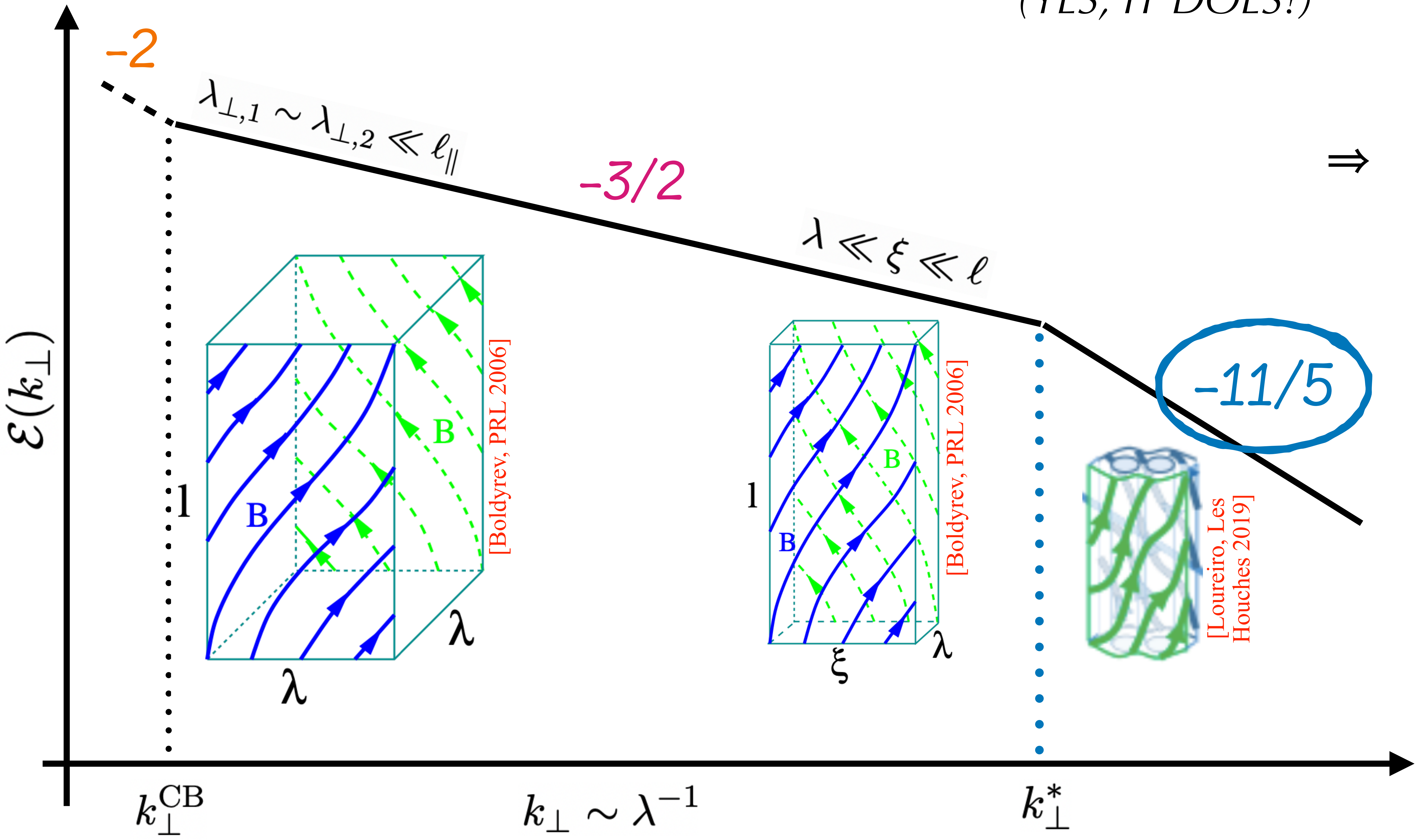


$$\Rightarrow \quad \gamma^{rec}\,\tau_{nl} \sim 1 \quad \text{at} \quad \frac{\lambda_*}{\ell_0} \sim S_0^{-4/7}$$

☞ reconnection now defines the cascade time:

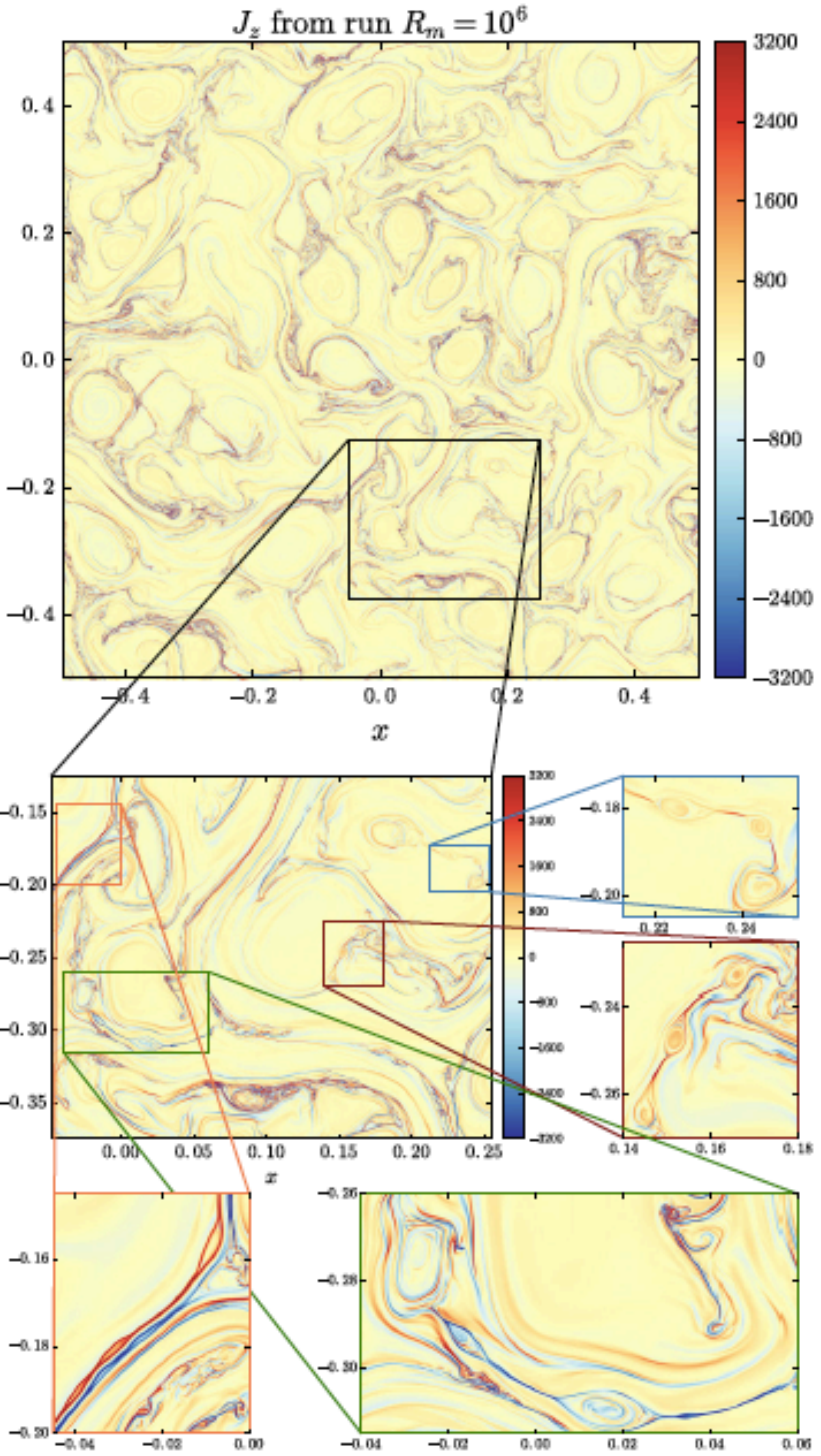
$$\tau_{nl} \longrightarrow \tau_{rec} \sim 1/\gamma^{rec}$$

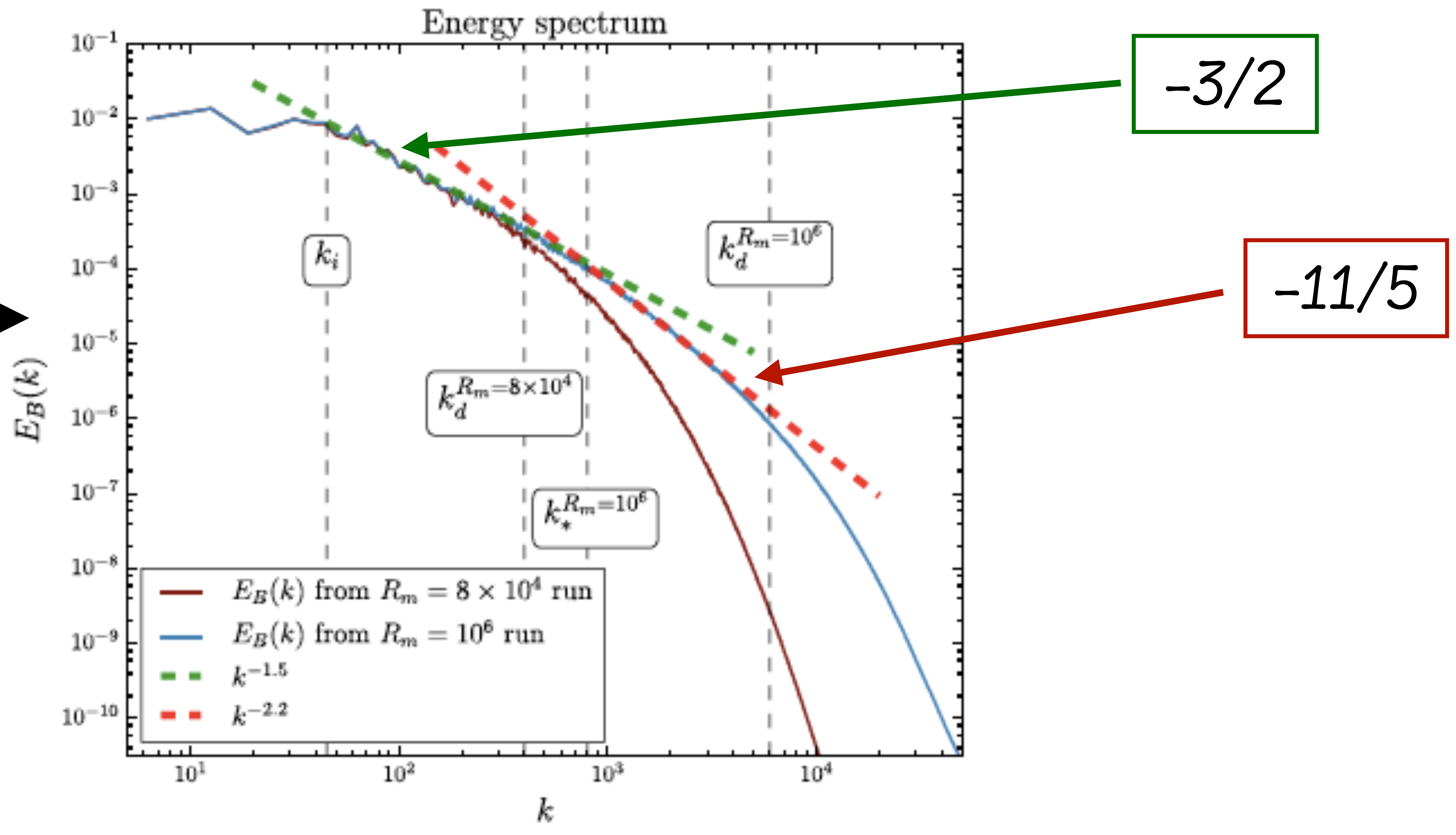
$$\Rightarrow \quad \mathcal{E}(k_\perp) \propto k_\perp^{-11/5}$$

spectrum of reconnection-mediated turbulence

Reconnection-mediated turbulence in simulations

[Dong et al., PRL (2018)]





☞ so far, the only evidence of reconnection-mediated turbulence in MHD

- only in **2D geometry**
- requires ***extremely large Lundquist numbers*** (grid: 64000^2 !!!)

Results

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

Can we do better, and can it be done in 3D?

YES!

just go back to a basic 3D setup: start from the ***building blocks of the Alfvénic cascade***!

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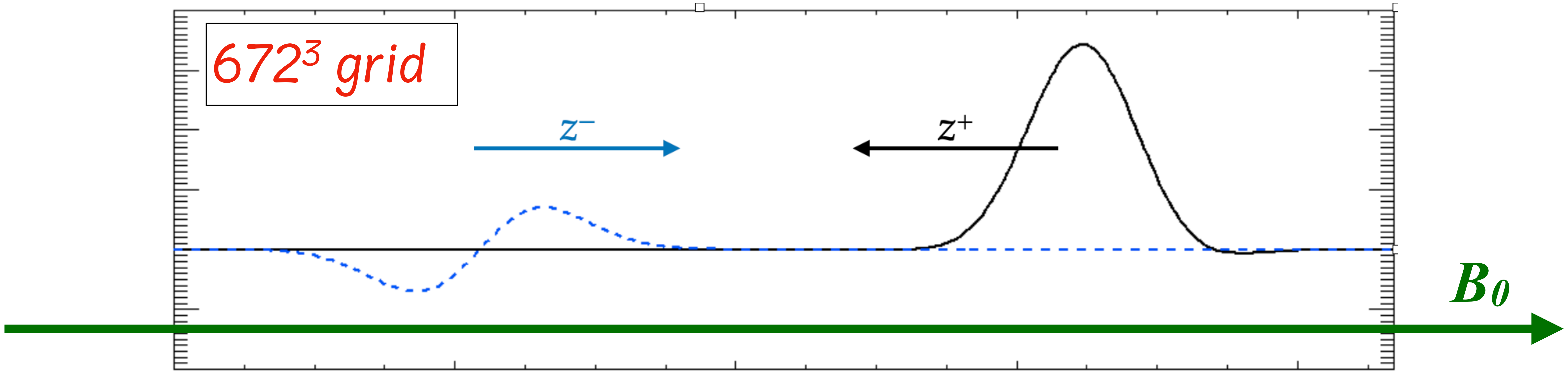

Simulations performed with the ***Hamiltonian 2-fields gyro-fluid*** model/code by Passot, Tassi, Sulem, and Laveder

☞ *model retains **only Alfvén & kinetic-Alfvén modes**, assumes **strong anisotropy*** ($k_\parallel << k_\perp$), …

Results

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

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But we do it "WISELY", i.e., with a "trick":

$$\gamma^{\rm rec}\,\tau_{\rm nl} \sim 1$$

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$$\gamma^{\rm rec}\tau_{\rm nl} \sim 1$$

Usually, one tries to increase $\gamma^{\rm rec}$ by achieving large S: requires extreme resolution!

Results

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

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$$\gamma^{\rm rec}\tau_{\rm nl} \sim 1$$

Let's increase the non-linear time instead! (by considering a smaller non-linear parameter, $\chi < 1$)

Results

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

A new theory

dynamic alignment and reconnection in weak turbulence

Dynamic Alignment and Reconnection in Weak Turbulence

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

☞ [WI] ***"Asymptotically weak"*** regime ($\chi << 1$):

$$\delta b_k \sim \text{const.}$$

$$\theta_k \propto k_\perp^{-1} \quad \Rightarrow \quad \mathcal{E}(k_\perp) \propto k_\perp^{-1}$$

⚠️ A very important consequece of these scalings is that ***$\chi(k) \sim const.$***, so **the cascade would remain weak…**
…however, instead of standard transition to CB, one gets a **transition to reconnection-mediated (strong) turbulence**

$$\frac{\lambda_*^{(\mathrm{WI})}}{\ell_0} \sim \left(\frac{\varepsilon \ell_0}{v_\mathrm{A}^3}\right)^{-1/12} S_0^{-1/3} \sim \chi_0^{-1/12} M_{\mathrm{A},0}^{-1/4} S_0^{-1/3}$$

Dynamic Alignment and Reconnection in Weak Turbulence

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

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☞ [WII] ***"Transitional"*** regime ($\chi < 1$):

$$\theta_k \propto k_\perp^{-1/2} \quad \Rightarrow \quad \delta b_k \propto k_\perp^{-1/4}$$

$$\mathcal{E}(k_\perp) \propto k_\perp^{-3/2}$$

⚠️ In this regime **the cascade can either transition to standard CB or to reconnection-mediated (strong) turbulence**

$$\lambda_\mathrm{CB}^{(\mathrm{WII})}/\ell_0 \sim \varepsilon \ell_0 / v_\mathrm{A}^3 \sim \chi_0 \, M_{\mathrm{A},0}^3$$

$$\frac{\lambda_*^{(\mathrm{WII})}}{\ell_0} \sim \left(\frac{\varepsilon \ell_0}{v_\mathrm{A}^3}\right)^{-1/9} S_0^{-4/9} \sim \chi_0^{-1/9} M_{\mathrm{A},0}^{-1/3} S_0^{-4/9}$$

$$\lambda_*^{(\mathrm{WII})}/\lambda_\mathrm{CB}^{(\mathrm{WII})} \sim \chi_0^{-10/9} M_{\mathrm{A},0}^{-10/3} S_0^{-4/9}$$

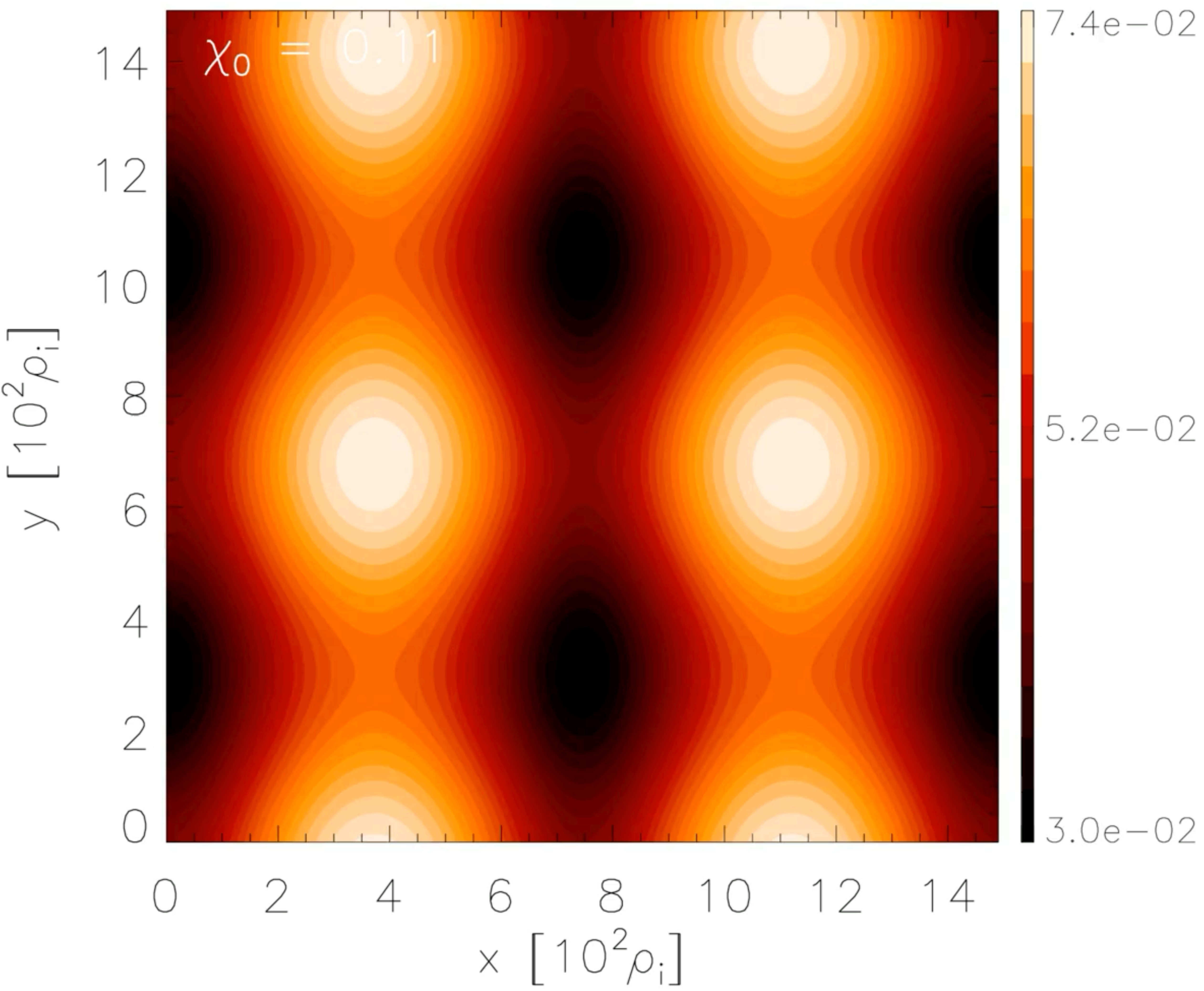
3D Simulations

collisions of Alfvén-wave packets in reduced MHD

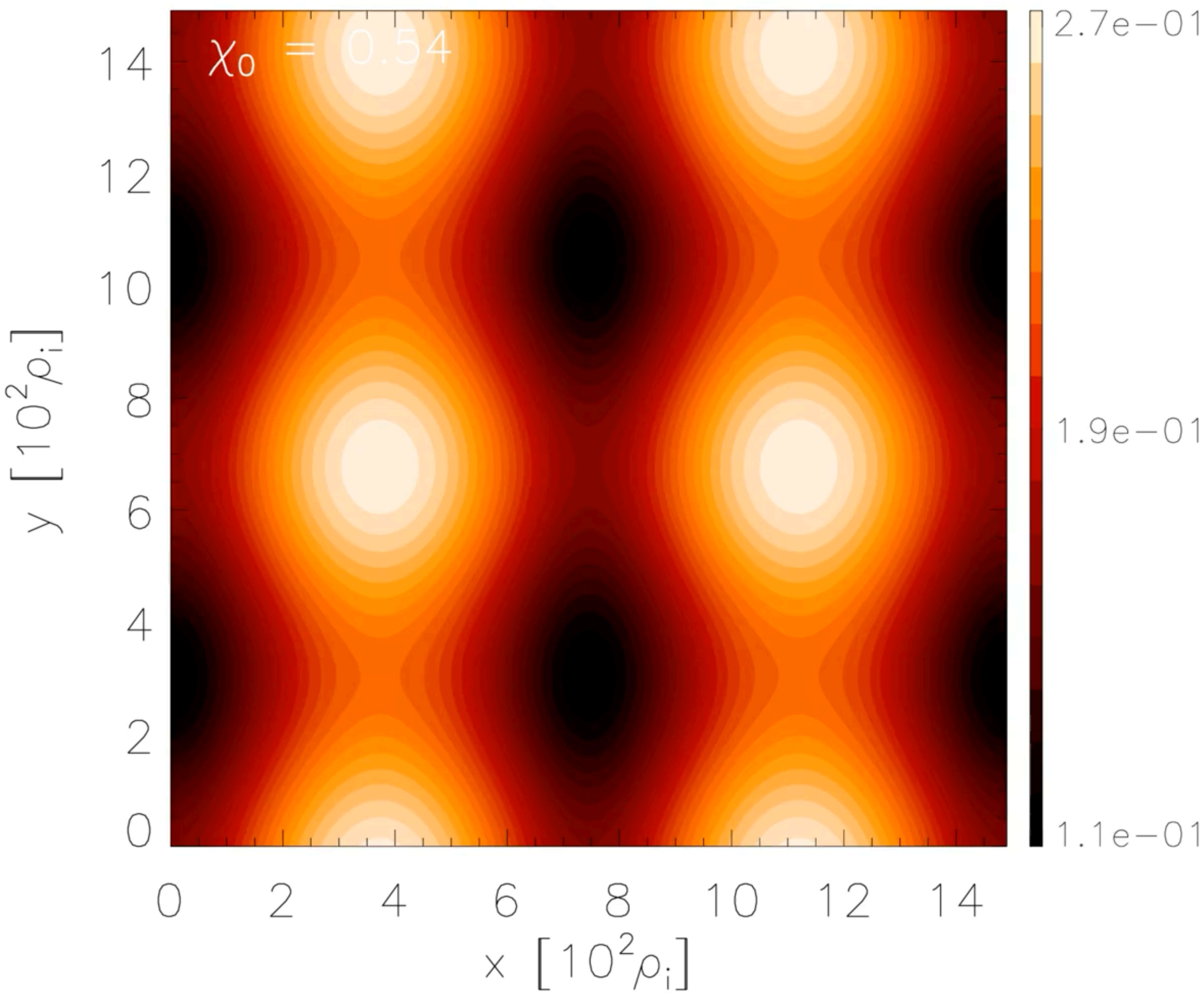
3D simulations of colliding AW packets

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

$<\delta \mathbf{b}_\perp>_z / \mathbf{B}_0$ ($\chi_0 \sim 0.1$)



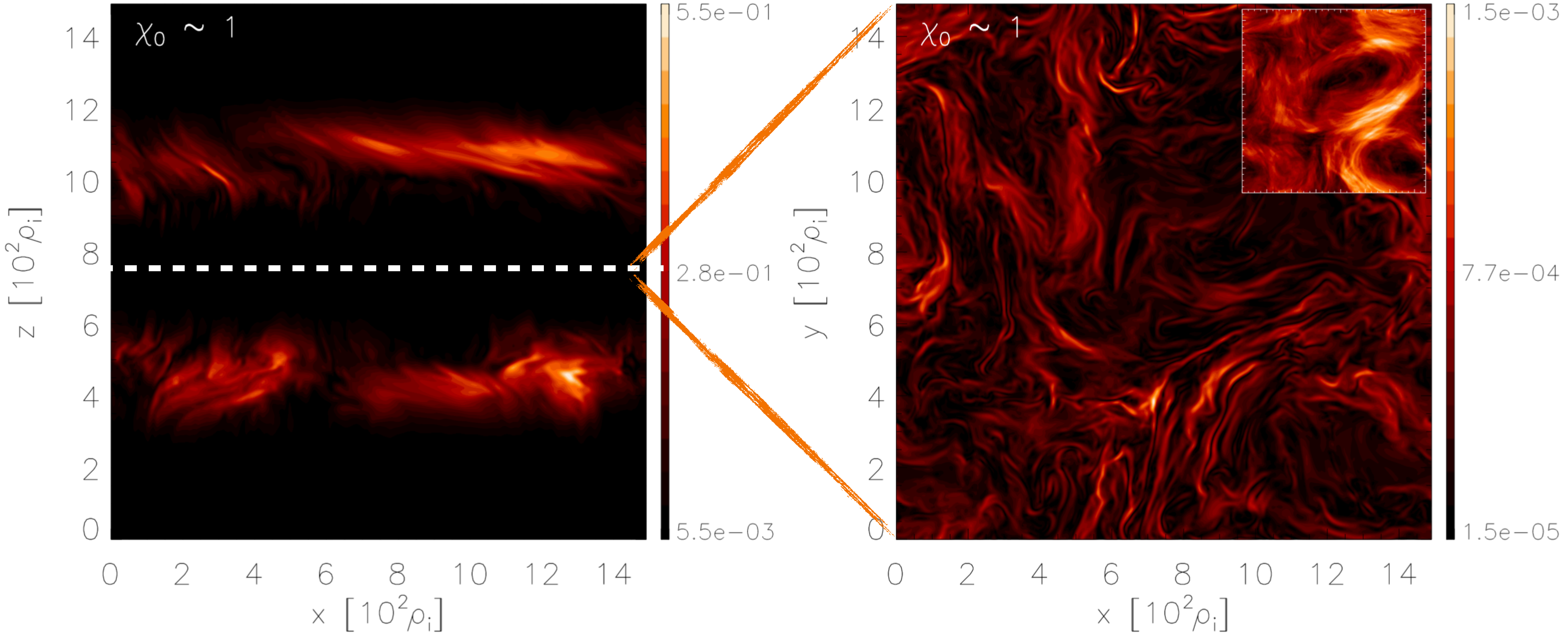
$<\delta \mathbf{b}_\perp>_z / \mathbf{B}_0$ ($\chi_0 \sim 0.5$)



3D simulations of colliding AW packets

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

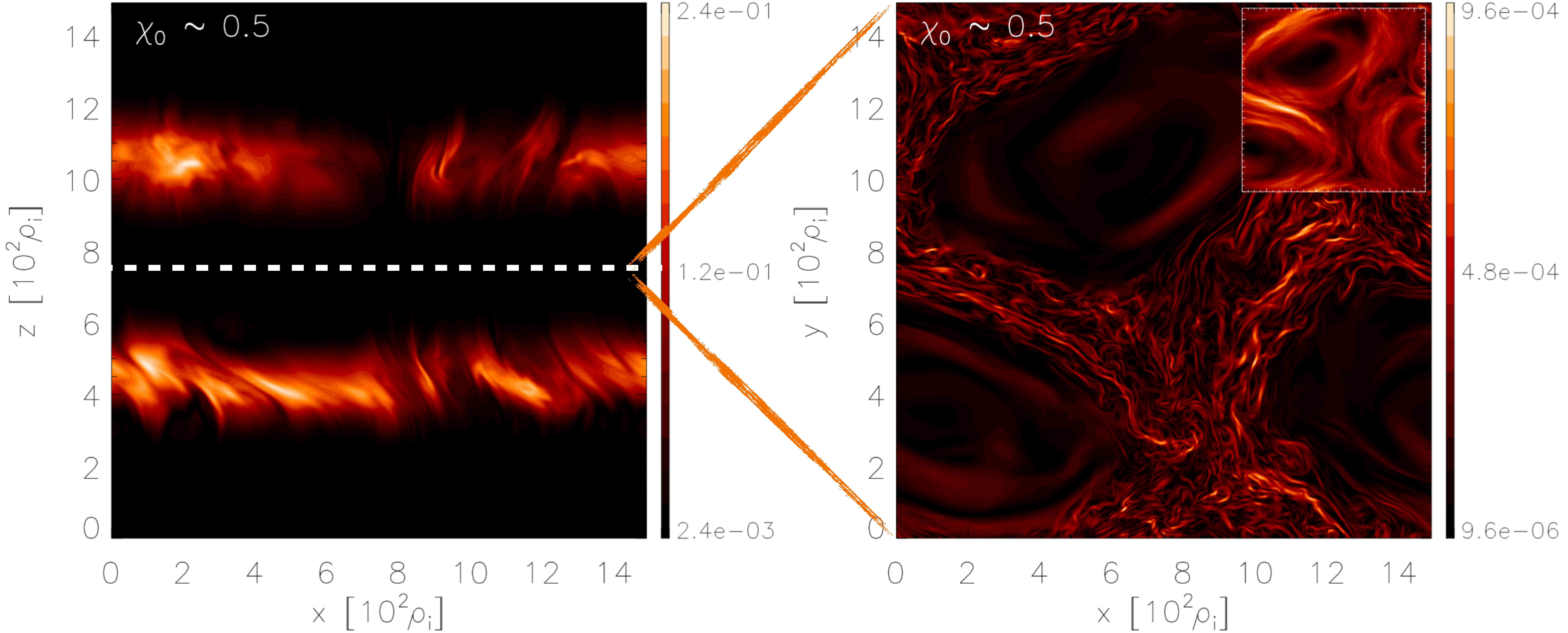
$\delta \mathbf{b}_\perp / \mathbf{B}_0 \ (\chi_0 \sim 1)$



3D simulations of colliding AW packets

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

$\delta b_\perp / \mathbf{B}_0 \;\; (\chi_0 \sim 0.5)$



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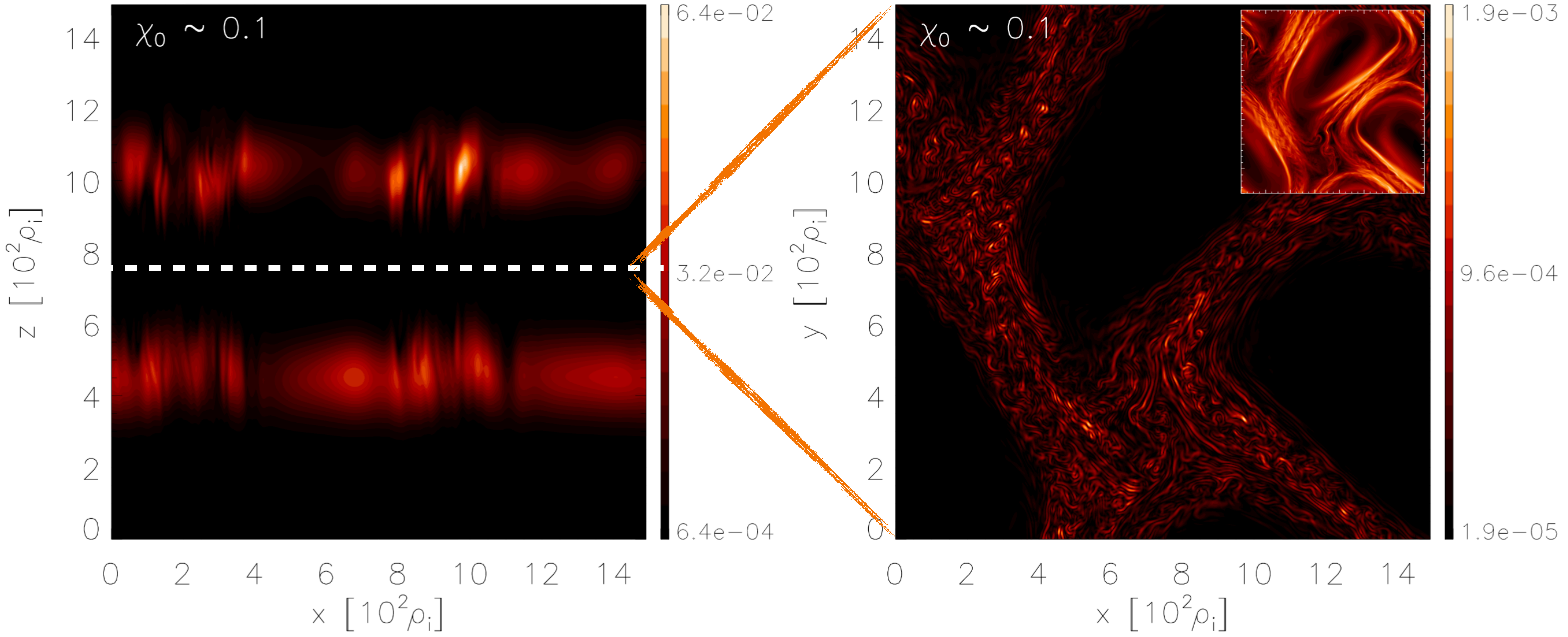

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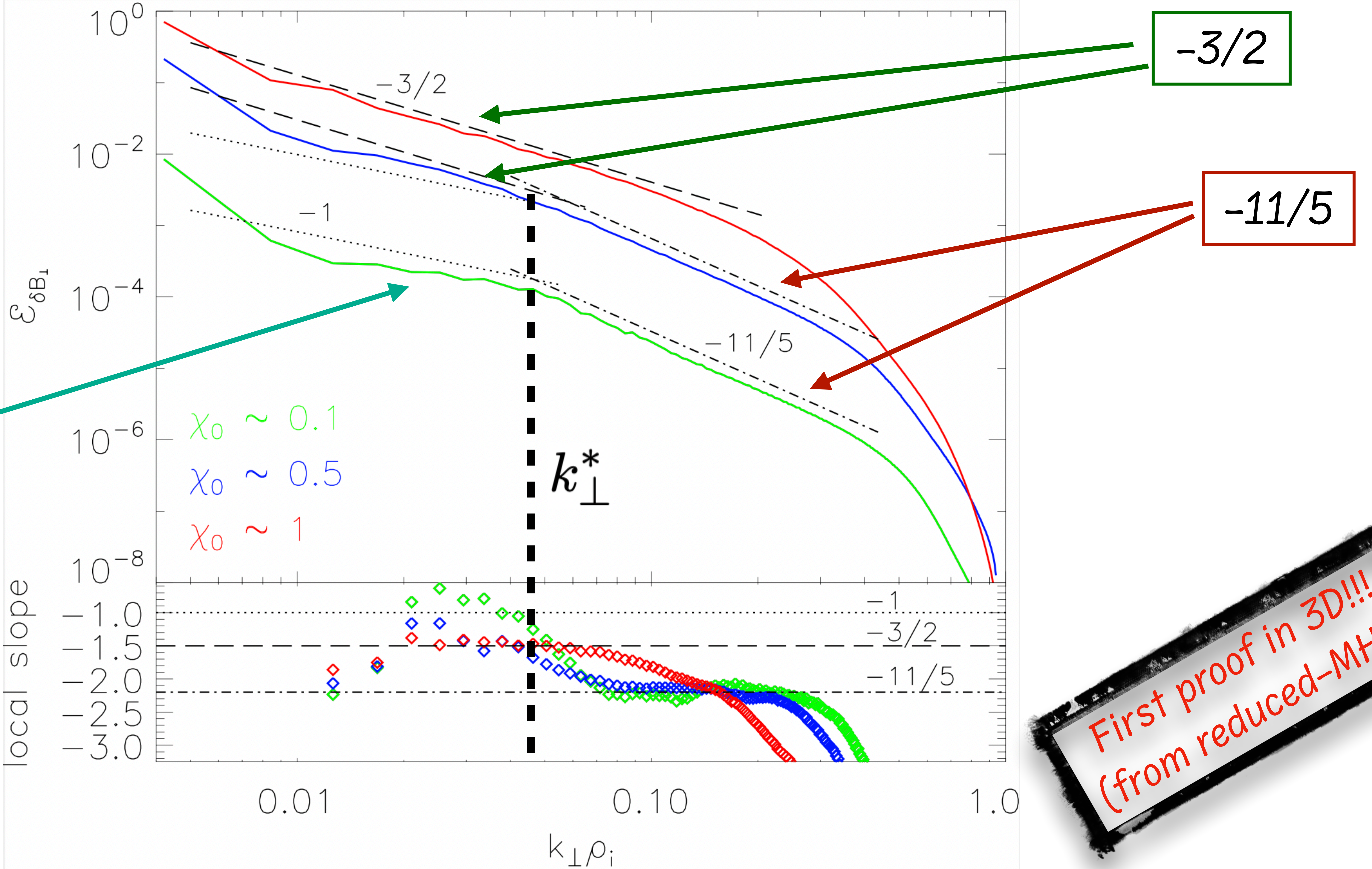
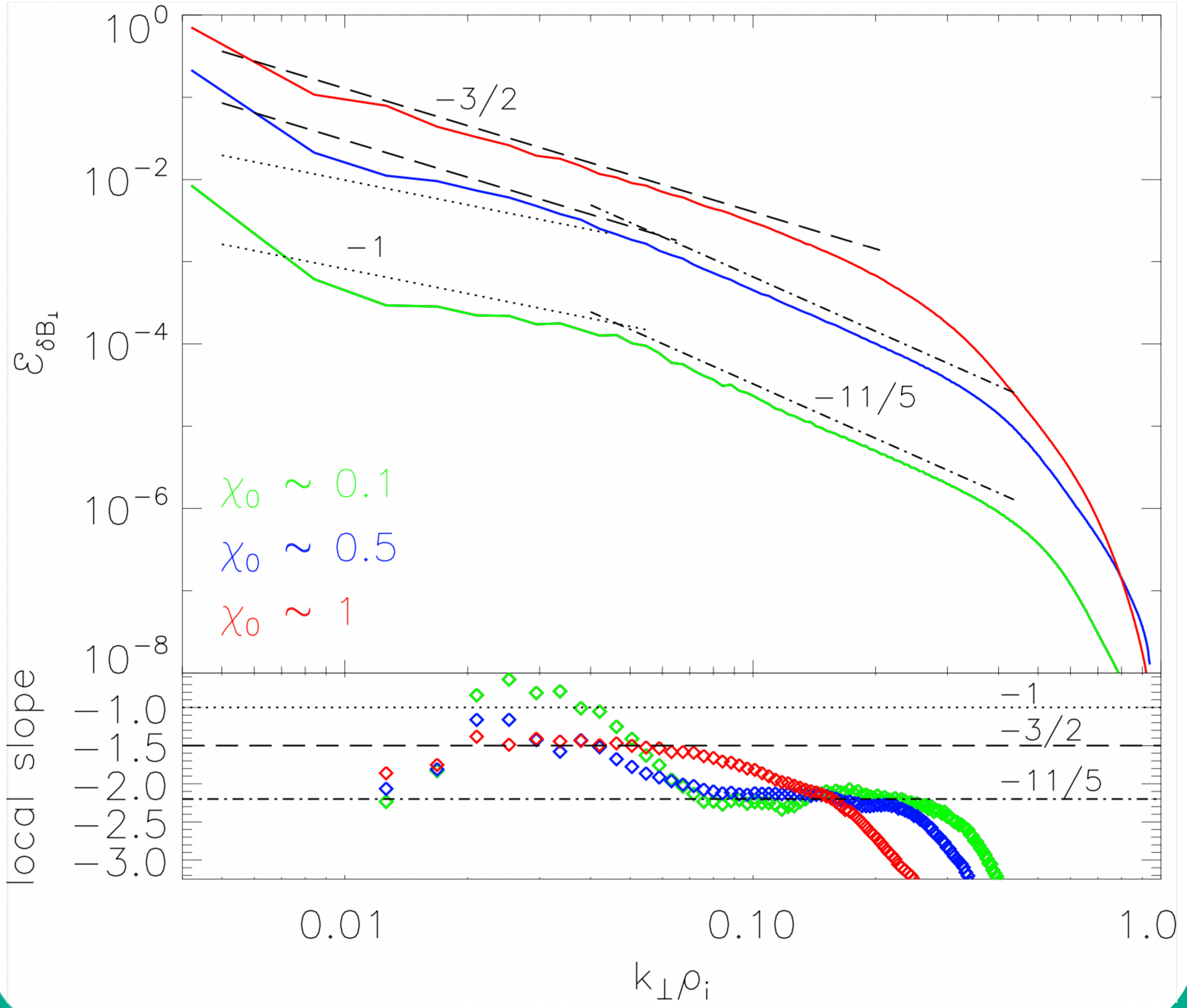


First proof in 3D!!!
(from reduced-MHD)

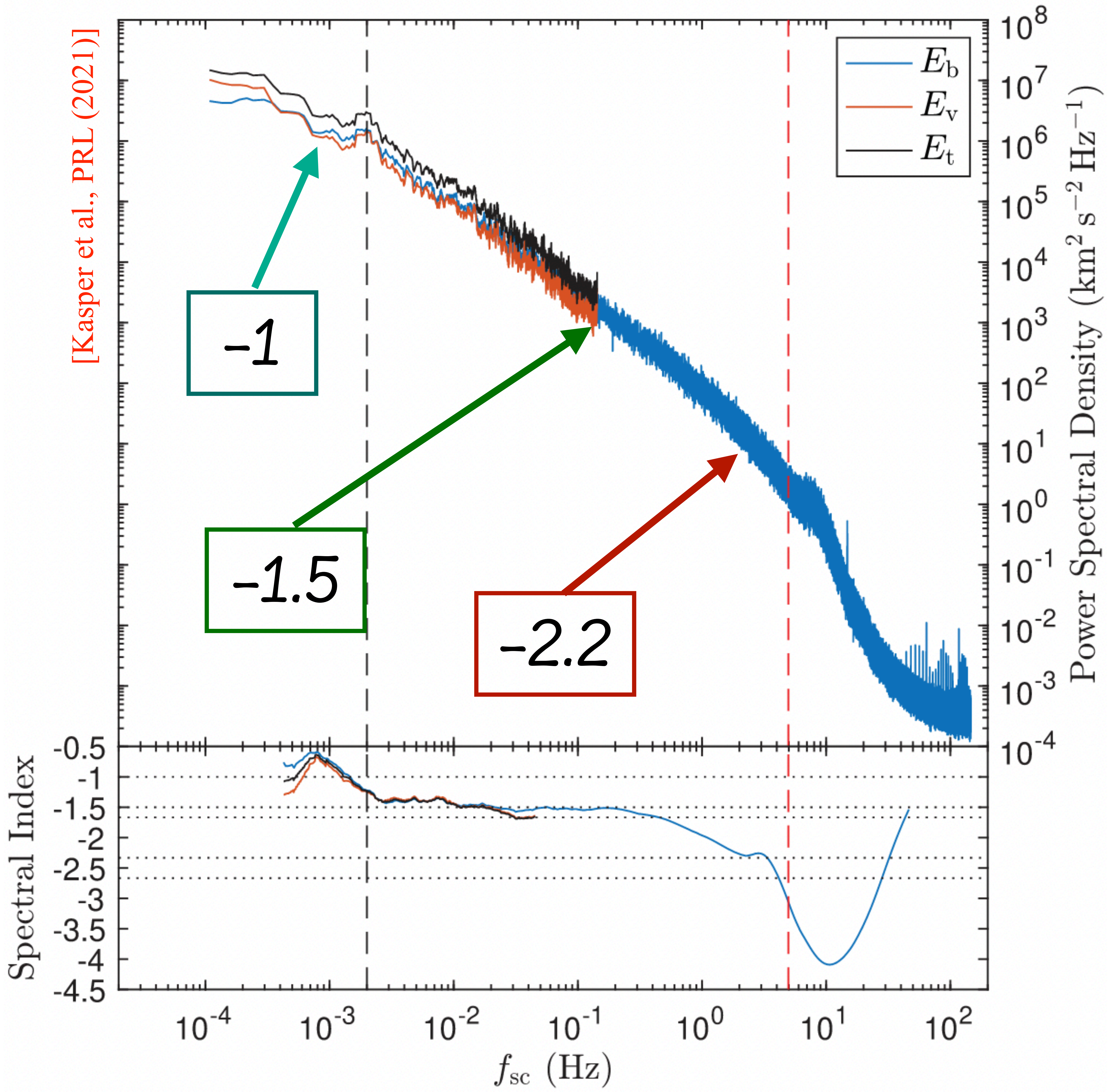
3D simulations of colliding AW packets

[Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)]

Simulations



PSP observations



Take home message(s)

☞ ***Derived new scalings of weak turbulence with dynamic alignment***

new transition scales depend on M_A and S

☞ ***The fate of weak MHD turbulence is to become strong… but which type of strong MHD turbulence?***

emergence of reconnection-mediated turbulence depends on S and χ

☞ ***First proof of reconnection-mediated turbulence in 3D simulations***

(from a first-principle setup and with reduced MHD)

➥ **COMING SOON:** Cerri, Passot, Laveder, Sulem, Kunz, ApJL (*to be submitted*)

Thank you for your attention!