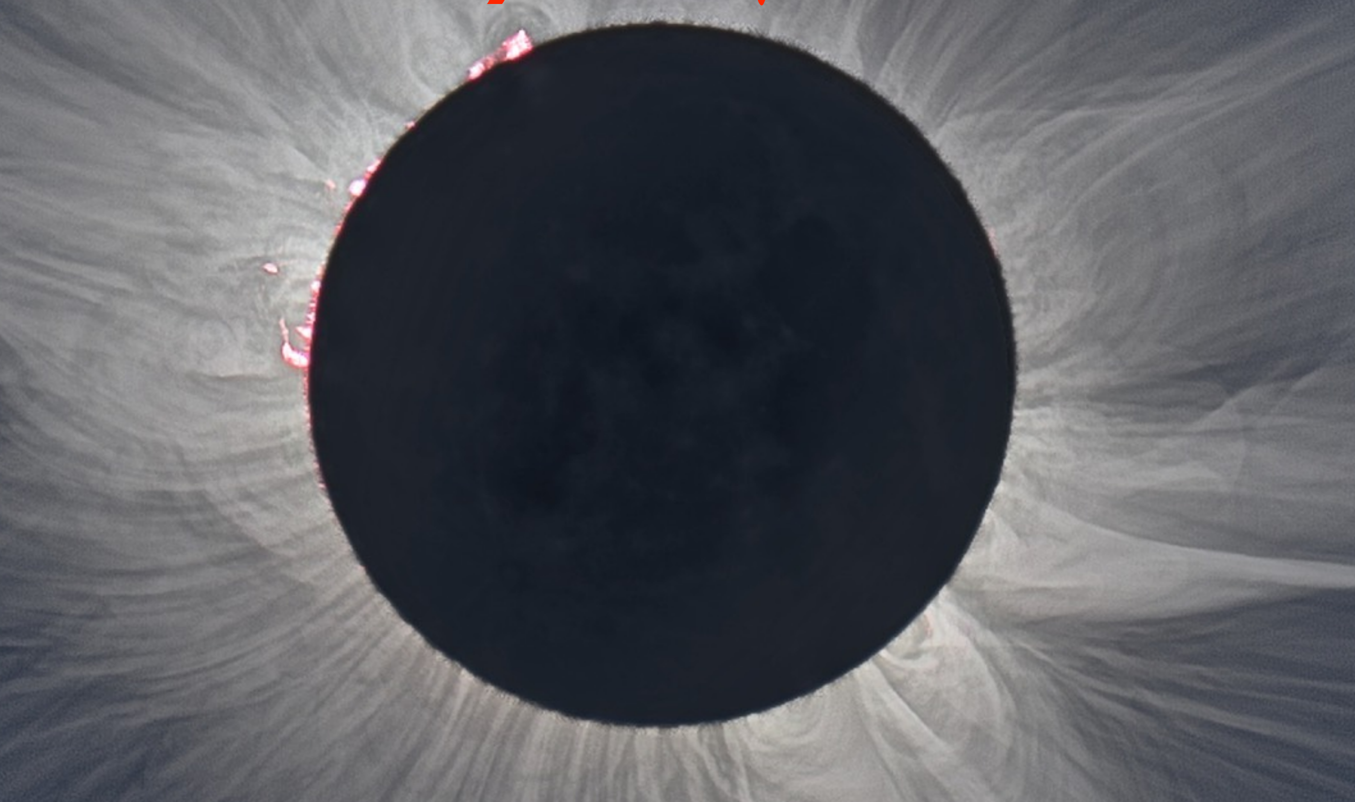
3D hybrid-kinetic turbulence and phase-space cascades

(in a $\beta = 1$ plasma)



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11th Plasma Kinetics Working Meeting

WPI Vienna, 23 July - 3 August, 2018

Thanks to main collaborators

M. W. Kunz
(Princeton U. & PPPL)

F. Califano
(University of Pisa)

Cerri, Kunz & Califano, Astrophys. J. Lett. **856**, L13 (2018)
"Dual phase-space cascades in 3D hybrid-Vlasov-Maxwell turbulence"

See also:

Cerri, Servidio & Califano, Astrophys. J. Lett. **846**, L18 (2017)
"Kinetic cascade in solar-wind turbulence: 3D3V hybrid-kinetic simulations with electron inertia"

Outline

- 3D3V Hybrid Vlasov-Maxwell (HVM) model *with electron inertia effects*

- Evidences that kinetic turbulence is anisotropic & intermittent… ok, but how much and how is it realised?

- Evidence that the turbulent cascade involves the entire phase space (simultaneous cascades in real and in velocity space) …*parallel* vs/and *perpendicular* phase mixing

- Theory vs Simulations: generalised theory of ion-entropy cascade or other approaches ?

3D3V HVM model + electron inertia

- **Fully kinetic ions** (Vlasov equation)
- **Electron fluid** (generalized Ohm's law w/ reduced electron inertia terms)
- **Maxwell's equations** (Faraday equation + Ampere's law w/o displacement current)

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{x}} + (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \frac{\partial f}{\partial \boldsymbol{v}} = 0,$$

$$(1 - d_e^2 \nabla_\perp^2)\boldsymbol{E} = -\boldsymbol{u} \times \boldsymbol{B} + \frac{\boldsymbol{J} \times \boldsymbol{B}}{n} - \frac{\boldsymbol{\nabla} p_e}{n},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \boldsymbol{E}, \quad \boldsymbol{\nabla} \times \boldsymbol{B} = \boldsymbol{J},$$

[**Cerri**, Servidio & Califano, ApJL (2017)]

- Reduced mass ratio: $m_i / m_e = 100$ ($d_e = 0.1\, d_i$)
- Quasi-neutrality is assumed ($n_i = n_e = n$)
- An isothermal closure for electrons' pressure
- $L_\perp \sim 31\, d_i$; $L_\parallel / L_\perp = 2$; $dx = dy \sim 0.08\, d_i$; $dz \sim d_i$; $dv = 0.2\, v_{th}$ (grid: $384^2 \times 64 \times 51^3 \rightarrow f \sim 10$ TB)

Anisotropic kinetic turbulence

[**Cerri**, Servidio & Califano, ApJL (2017)]

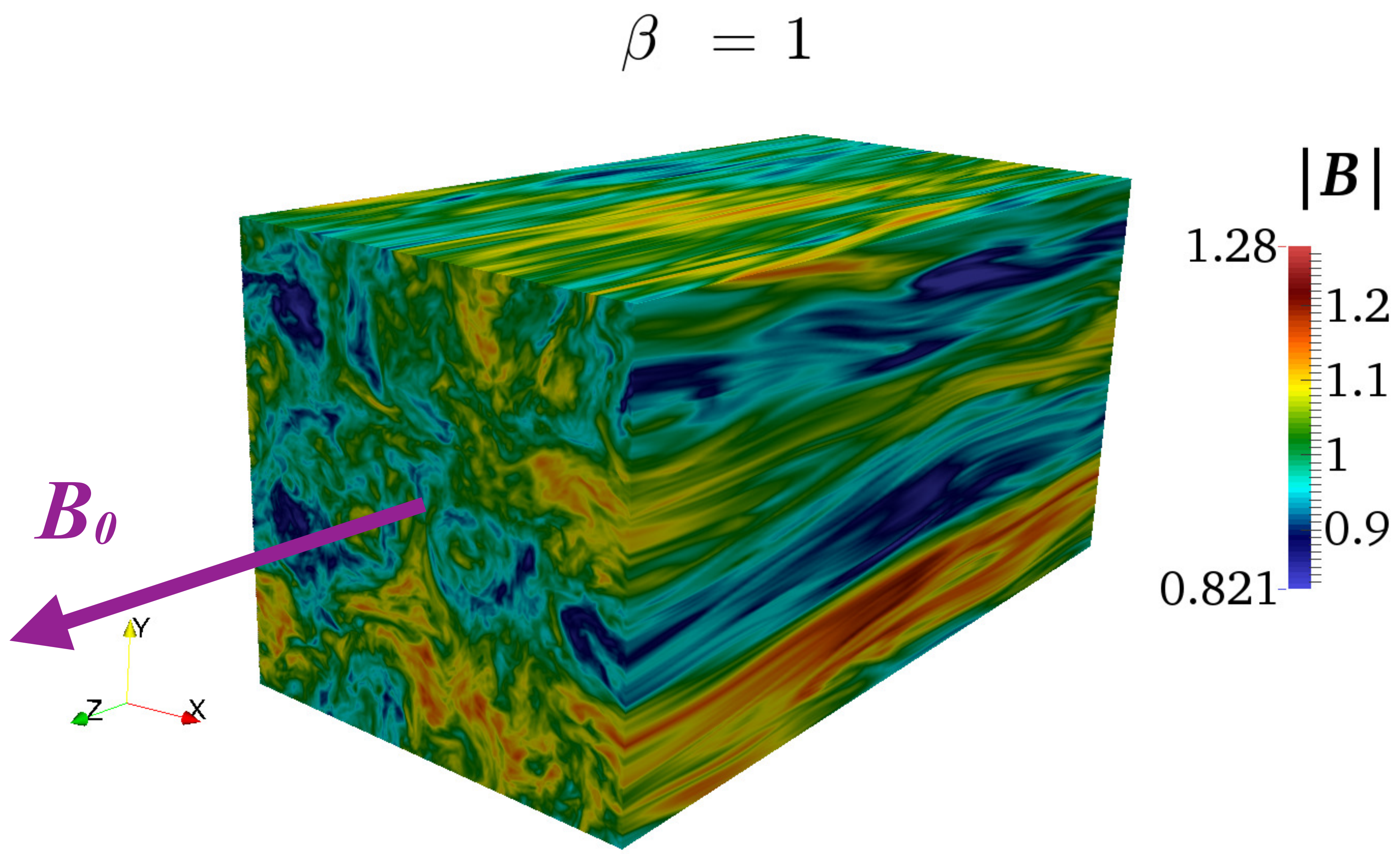


Figure: magnetic fluctuations (B_0 along z)

Intermittent kinetic turbulence (i)

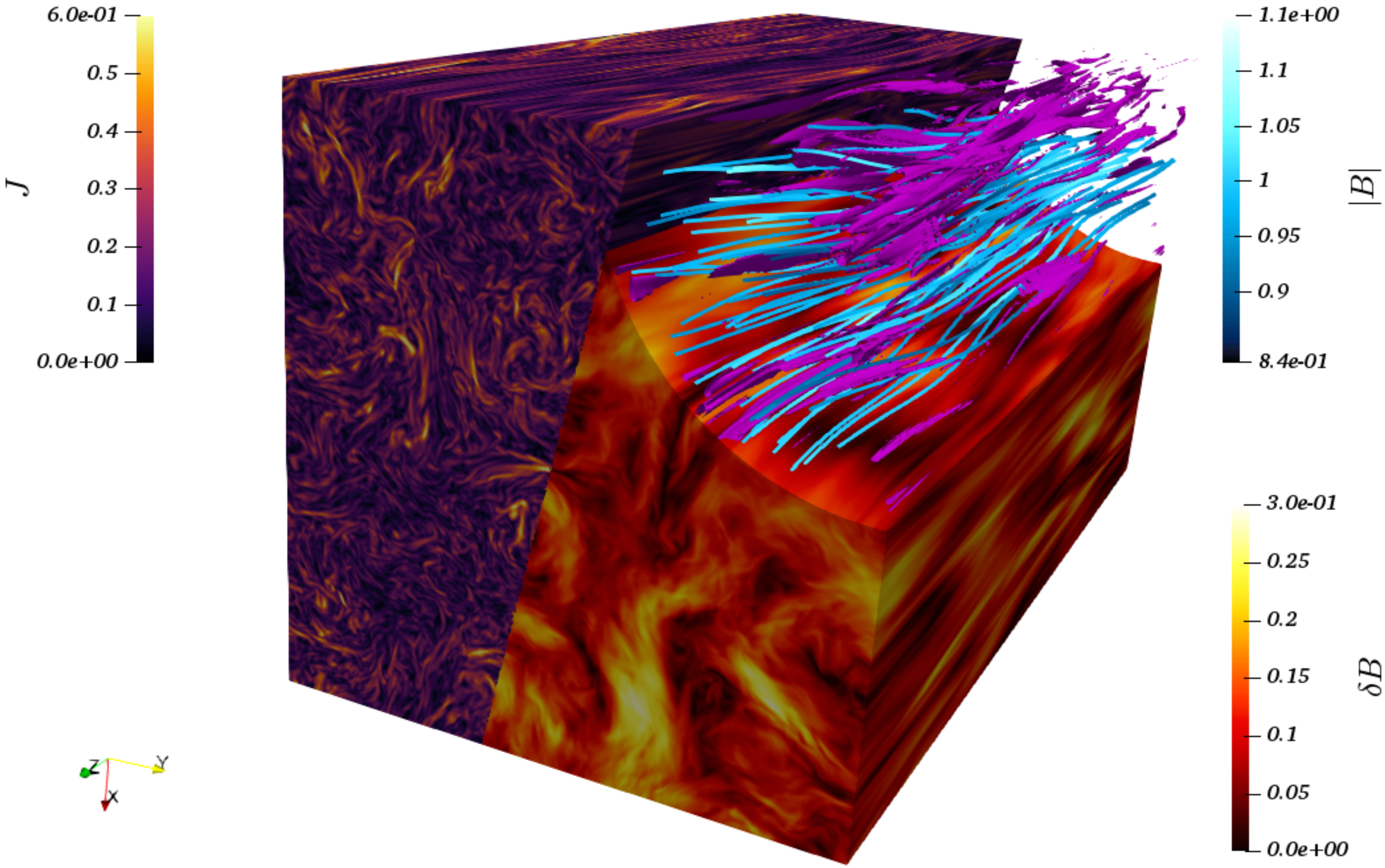
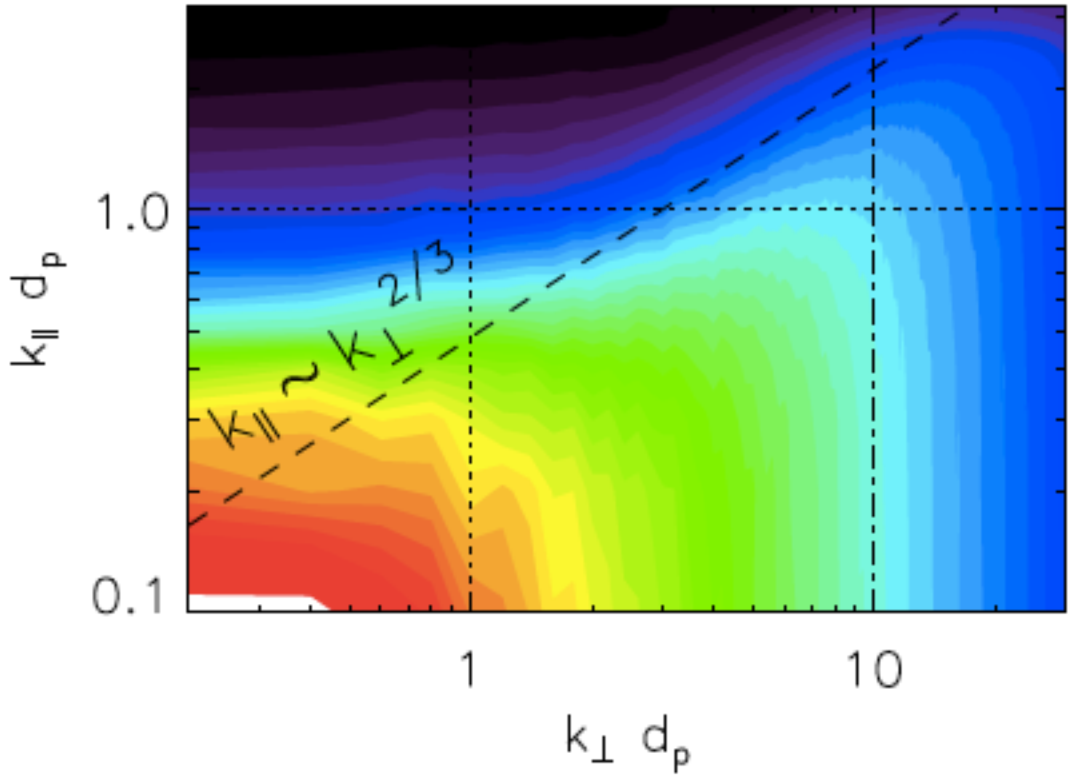


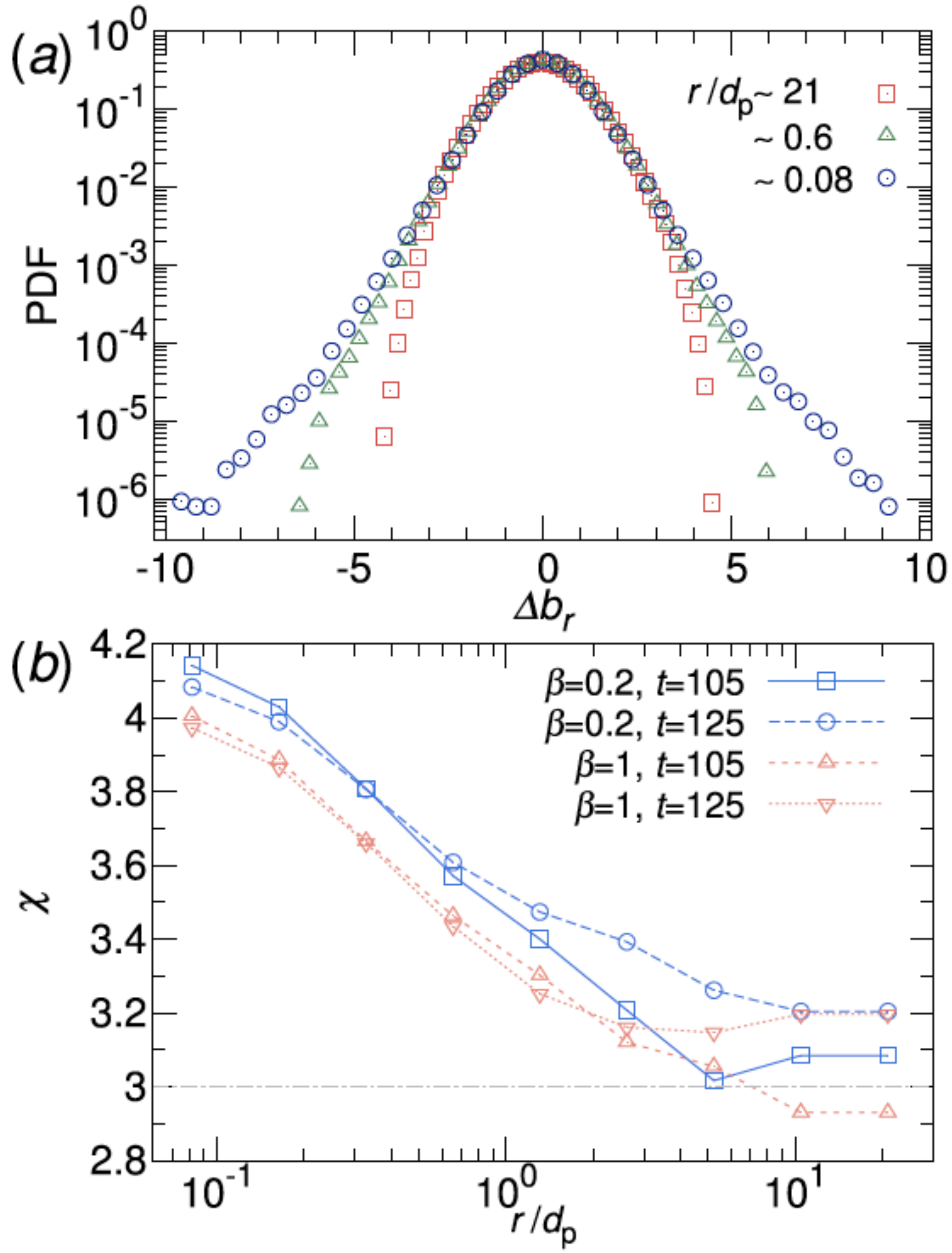
Figure: total magnetic fluctuations δB (red), current density J (purple & surfaces), magnetic field lines (light blue)

Intermittent kinetic turbulence (ii)

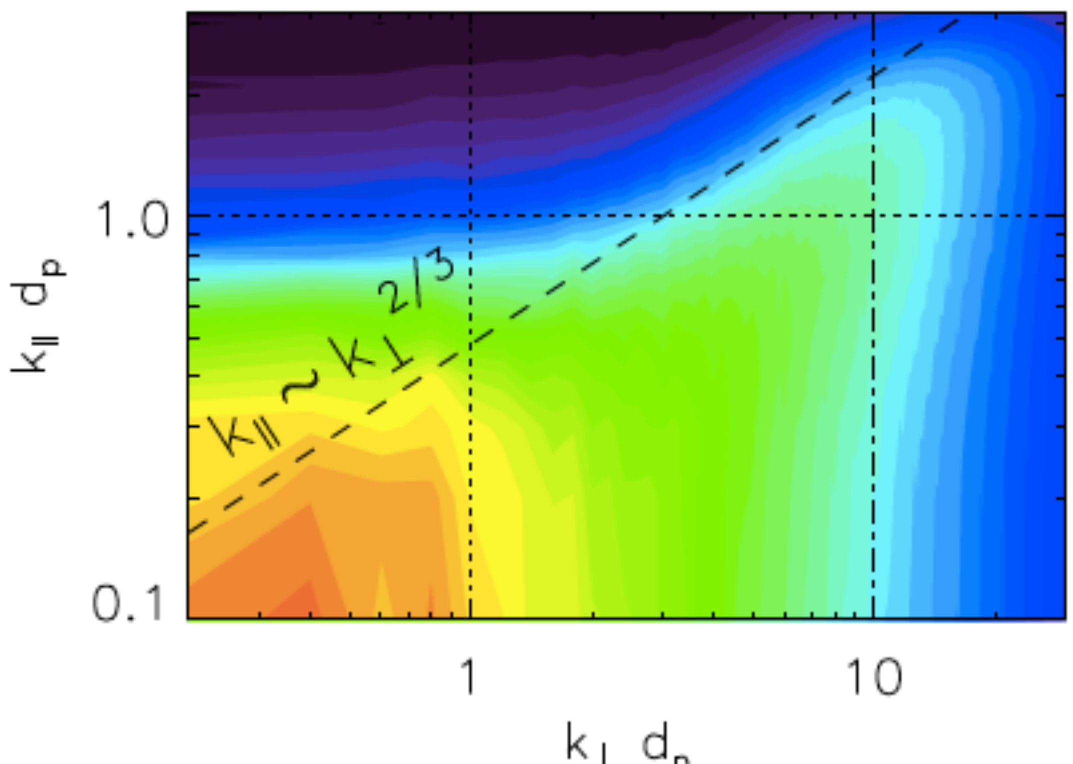
anisotropic and intermittent B fluctuations:

[**Cerri**, Servidio & Califano, ApJL (2017)]





anisotropic $E_\parallel$ fluctuations:

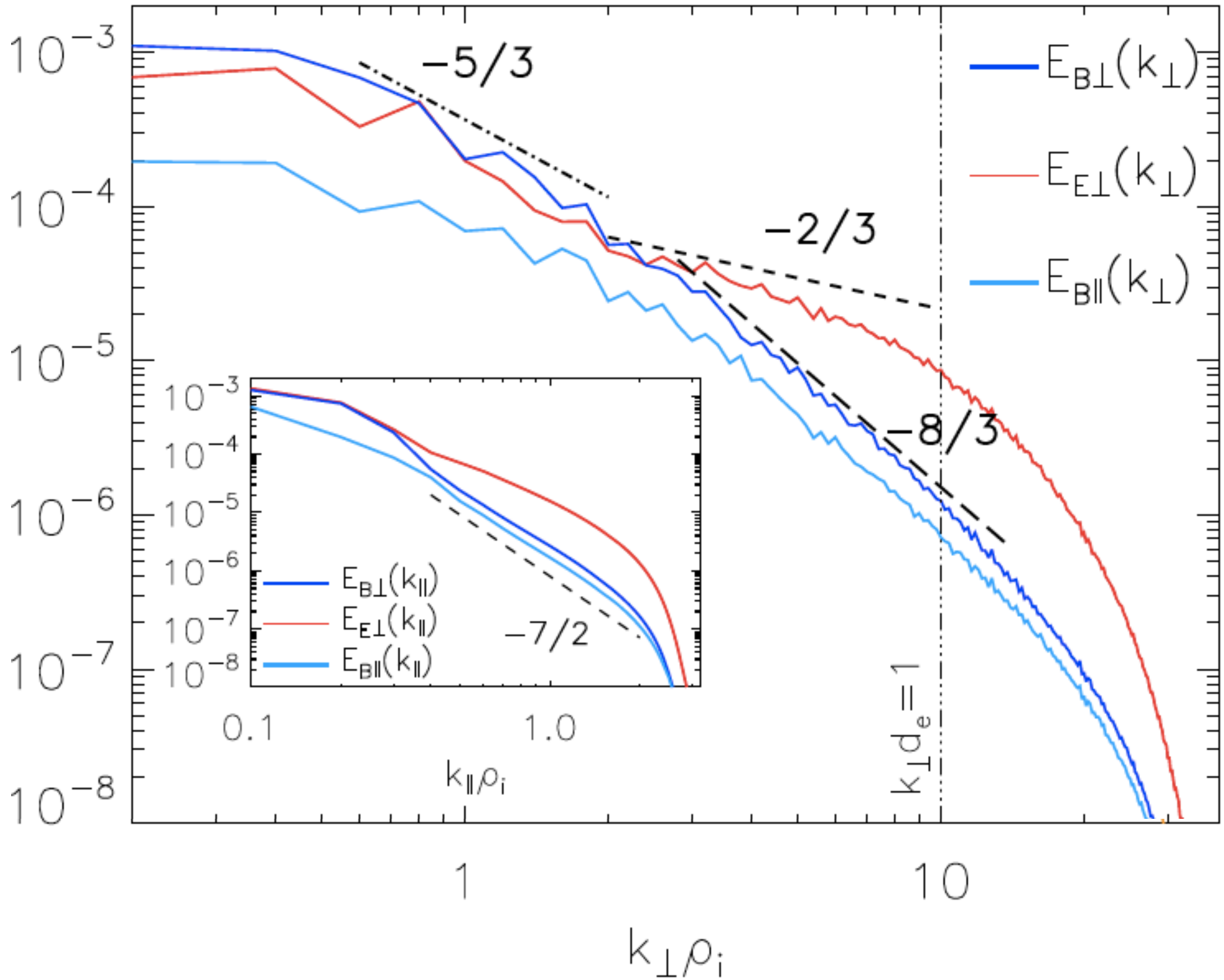


kinetic-scale anisotropy: $k_\parallel \sim k_\perp^{2/3}$

[consistent with Boldyrev & Perez, ApJL (2012)]

intermittent KAW turbulence ?

[**Cerri**, Kunz & Califano, ApJL (2018)]



intermittent KAW turbulence ?

[**Cerri**, Kunz & Califano, ApJL (2018)]

ion-scale turbulence:

☞ intermittency, current sheets, spectral anisotropy & -8/3 slope

☞ ***critically balanced, intermittent KAW turbulence*** *à la Boldyrev & Perez ?*

☞ **spectral anisotropy**: local vs global ?

(some ongoing work with Lev and Daniel… 3 persons $\longrightarrow$ 3 different results ?)

v-space cascades of free energy

LINEAR PHASE MIXING

due to ballistic response of f :

$$\delta f \sim exp(-ik_{||}v_{||}t)$$

slower than its nonlinear counterpart
(at scales below the ion gyro-radius)

$\rightarrow$ mainly ***along*** $\boldsymbol{B_0}$ ("parallel")
and more important at "large" scales:

$$k_\perp \rho_i \lesssim 1$$

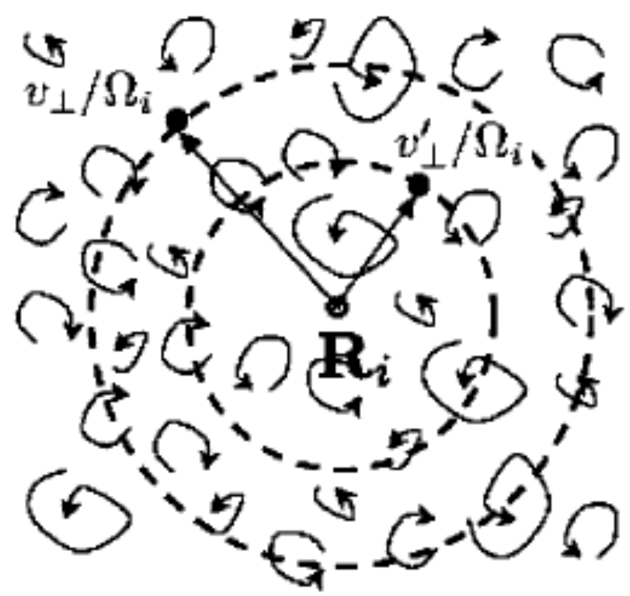
NON-LINEAR PHASE MIXING

de-correlation of $v_\perp$-structures of f
due to de-correlated $k_\perp$-fluctuations:

$$\frac{\delta v_\perp}{v_{\rm thi}} \sim \frac{1}{\rho_{\rm i}} \left| \frac{v_\perp}{\Omega_{\rm i}} - \frac{v'_\perp}{\Omega_{\rm i}} \right| \sim \frac{1}{k_\perp \rho_{\rm i}} \ll 1$$

faster than its linear counterpart,
but occurring only ***perpendicular to*** $\boldsymbol{B_0}$
and only below the ion gyro-radius:

$$k_\perp \rho_{\rm i} \gg 1$$



[Schekochihin et al., ApJS (2009)]

v-space cascades of free energy

Hermite representation of v-space cascades

$$\psi_m(v) \equiv \frac{H_m(v/v_{\rm th})}{\sqrt{2^m\, m!\, \sqrt{\pi}\, v_{\rm th}}}\, e^{-v^2/2v_{\rm th}^2}$$

basis function (H_m = Hermite polynomial of order m)

$$\int_{-\infty}^{\infty} \psi_m(v)\, \psi_n(v)\, {\rm d}v \;=\; \delta_{n\,m}$$

$$\delta f_{\mathbf{m}} \;=\; \int_{-\infty}^{\infty} \delta f(\boldsymbol{v})\; \psi_{\mathbf{m}}\, {\rm d}^3 v$$

3D decomposition of the **non-thermal entropy fluctuations**, δf

$$\delta f(\boldsymbol{v}) \;\equiv\; f(\boldsymbol{v}) \;-\; F_{\rm M}(\boldsymbol{v})$$

non-linear phase mixing physical argument:

de-correlation of $v_\perp$-structures due to de-correlated $k_\perp$-fluctuations (***does not need GK ordering***)

$$\boxed{\frac{\delta v_\perp}{v_{\rm thi}} \sim \frac{1}{\rho_{\rm i}} \left| \frac{v_\perp}{\Omega_{\rm i}} - \frac{v_\perp'}{\Omega_{\rm i}} \right| \sim \frac{1}{k_\perp \rho_{\rm i}} \qquad \longleftrightarrow \qquad m_\perp \propto k_\perp^2}$$

[**Cerri**, Kunz & Califano, ApJL (2018)]

v-space cascades of free energy

Hermite representation of v-space cascades

linear phase mixing $\rightarrow$ $\sim m_{\|}^{-1/2}$

[e.g. Watanabe & Sugama, PoP (2004); Zocco & Schekochihin, PoP 2011; Kanekar et al., JPP (2015)]

non-linear phase mixing $\rightarrow$ $\sim m_{\perp}^{-7/6}$

(GK theory of "ion-entropy cascade" in KAW turbulence)

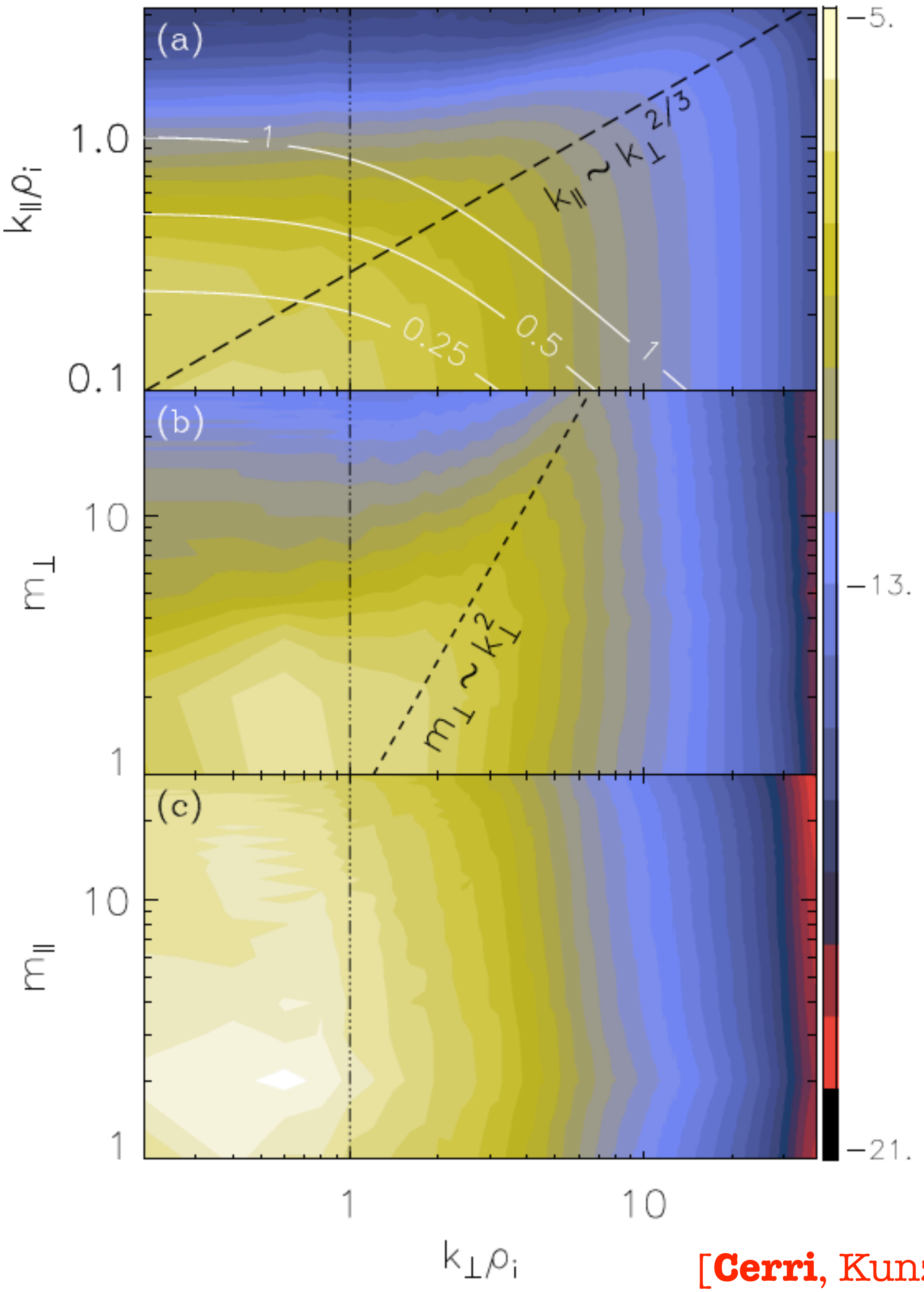
[e.g. Schekochihin et al., ApJS 2009; Cerri, Kunz & Califano, ApJ (2018)]

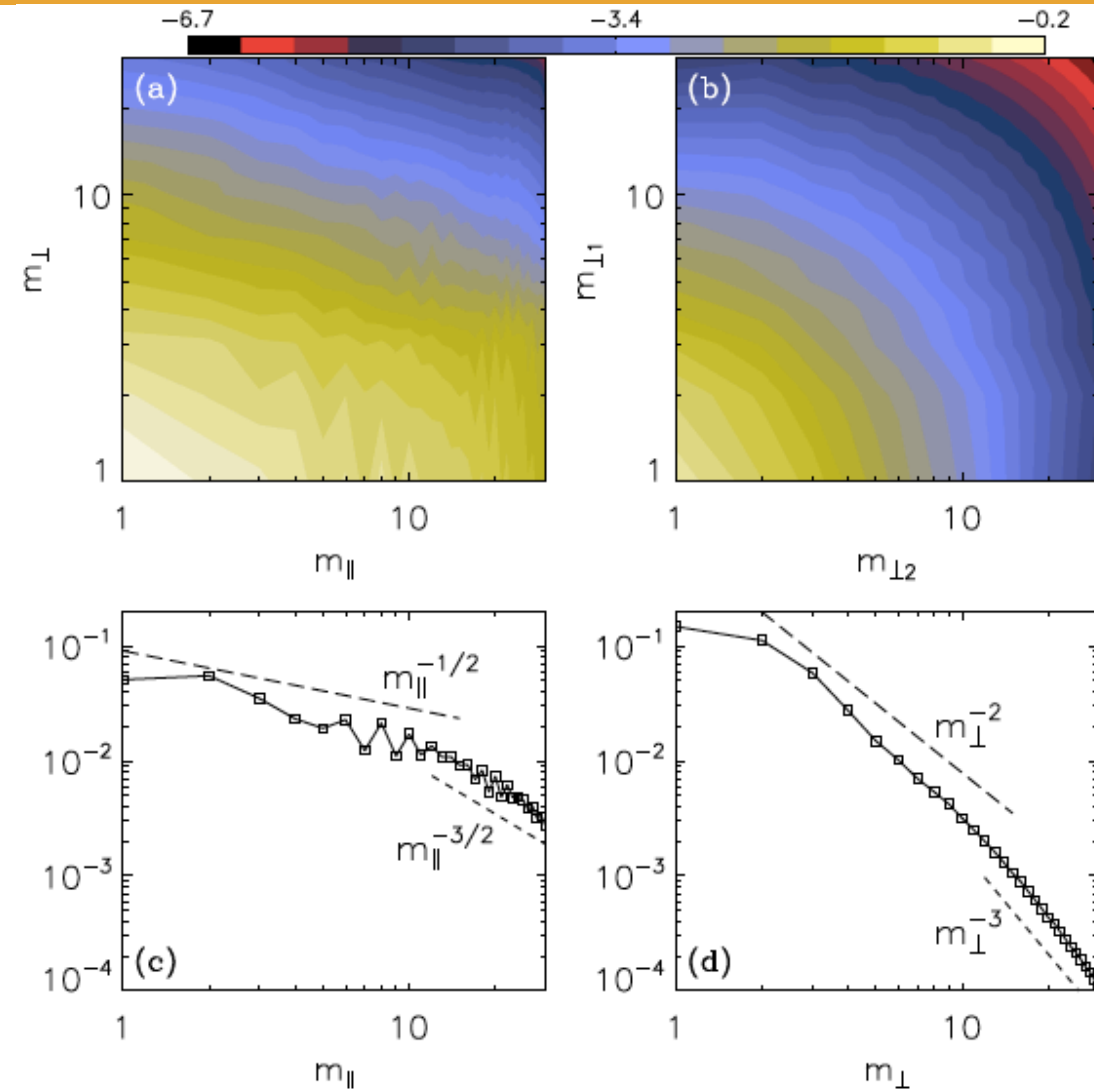
Kolmogorov-like arguments on Vlasov eqn $\rightarrow$ $\sim m^{-3/2}$ or m^{-2}

(only v-space cascades?)

[Servidio et al., PRL (2017)]

phase-space cascades of δf





Anisotropic 6D cascades!

[**Cerri**, Kunz & Califano, ApJL (2018)]

phase-space cascades of δf

phase-space turbulence:

☞ ***non-linear phase mixing*** argument, $m_\perp \sim k_\perp^2$, holds in perp phase space

☞ ***linear AND non-linear*** phase mixing are ***both active***: parallel vs perp

☞ ***spectral slopes*** not well understood: ***new theory or better simulations?***

[**Cerri**, Kunz & Califano, ApJL (2018)]

Generalised ion-entropy cascade (i)

Generalised theory of "ion-entropy cascade"

[**Cerri**, Kunz & Califano, ApJL (2018)]

☞ **underlying idea** *(Schekochihin et al., PPCF 2008)*:
$$\frac{\delta v_\perp}{v_{\rm thi}} \sim \frac{1}{\rho_{\rm i}}\left|\frac{v_\perp}{\Omega_{\rm i}} - \frac{v'_\perp}{\Omega_{\rm i}}\right| \sim \frac{1}{k_\perp \rho_{\rm i}} \qquad \longleftrightarrow \qquad m_\perp \propto k_\perp^2$$

de-correlation of $v_\perp$-structures

due to de-correlated $k_\perp$-fluctuations

☞ allow ***generalised spectral anisotropy***:
$$\boxed{\ell_{\|,\lambda} \propto \lambda^{\alpha/3}}$$

$\alpha = 1$ standard KAW anisotropy

$\alpha = 2$ intermittency-corrected case

$\alpha = 3$ constant anisotropy

☞ assume ***critically balanced KAW cascade***:
$$\tau_{{\rm nl},\lambda} \sim \tau^{(\alpha)}_{{\rm KAW},\lambda} \propto \lambda^{1+\alpha/3}$$

☞ ion-entropy non-linear timescale:
$$\tilde{\tau}_{h,\lambda} \sim \left(\frac{\rho_{\rm i}}{\lambda}\right)^{1/2} \tau^{(\alpha)}_{{\rm KAW},\lambda}$$

weighting of the nonlinear cascade time

due to ring-average in GK nonlinearity

☞ ***ion-entropy cascade time***:
$$\boxed{\tau^{(\alpha)}_{h,\lambda} \sim \left(\frac{\rho_{\rm i}}{\lambda}\right) \tau^{(\alpha)}_{{\rm KAW},\lambda} \sim \lambda^{\alpha/3}}$$

small changes in the non-adiabatic GK response (h_λ)

that accumulate as a random walk

to produce a change of order unity ($\Delta h_\lambda / h_\lambda \sim 1$)

Generalised ion-entropy cascade (ii)

Generalised theory of "ion-entropy cascade"

[**Cerri**, Kunz & Califano, ApJL (2018)]

☞ assume ***constant entropy flux through scales***: $h_\lambda^2/\tau_{h,\lambda} \sim \varepsilon_h = \mathrm{const}$

☞ derive ***scalings for non-adiabatic GK response***: $\boxed{h_\lambda^{(\alpha)} \propto \lambda^{\alpha/6}}$

accounting for "generalised" spectral anisotropy

☞ derive ***phase-space spectra of ion-entropy cascade***:

$$\boxed{E_h(k_\perp) \propto k_\perp^{-(3+\alpha)/3} \qquad E_h(k_\|) \propto k_\|^{-2} \qquad E_h(m_\perp) \propto m_\perp^{-(6+\alpha)/6}}$$

$\alpha = 1$ ***standard KAW anisotropy:***	$k_\| \propto k_\perp^{1/3}$	$E_h \propto k_\perp^{-4/3}$	$E_h(m_\perp) \propto m_\perp^{-7/6}$
$\alpha = 2$ ***intermittency-corrected case:***	$k_\| \propto k_\perp^{2/3}$	$E_h \propto k_\perp^{-5/3}$	$E_h(m_\perp) \propto m_\perp^{-4/3}$
$\alpha = 3$ ***constant anisotropy:***	$k_\| \propto k_\perp$	$E_h \propto k_\perp^{-2}$	$E_h(m_\perp) \propto m_\perp^{-3/2}$

Generalised ion-entropy cascade (ii)

ion-entropy cascade:

☞ ***generalisation*** to account for ***different spectral anisotropies*** provided

NOTE: in this theory, the non-adiabatic GK response is considered to be a scalar that is passively advected by the underlying KAW fluctuations (namely, by the ExB drift due to the KAW electric-field fluctuations)

☞ able to recover a $\mathbf{m}_\perp^{-3/2}$ ***spectrum for*** $\mathbf{k}_\parallel \sim \mathbf{k}_\perp$, but ***NOT*** the $\mathbf{m}_\perp^{-2}$

☞ theory of ion-entropy cascade:

electrostatic vs ***electromagnetic***?

KAW-driven vs ***non-KAW-driven***?

GK vs non-GK regimes?

Summary

☞ what is the actual ***spectral anisotropy of kinetic turbulence*** ?

how it is ***realised*** ?
how do we ***properly measure it*** ?
how is it ***correctly included in the theory*** ?

☞ how do we correctly describe ***kinetic plasma turbulence in phase space*** ?

electromagnetic effects needed ?
new theory ***outside GK regime*** ?

+ *other questions about the role of* ***reconnection*** *and of* ***structures****…*

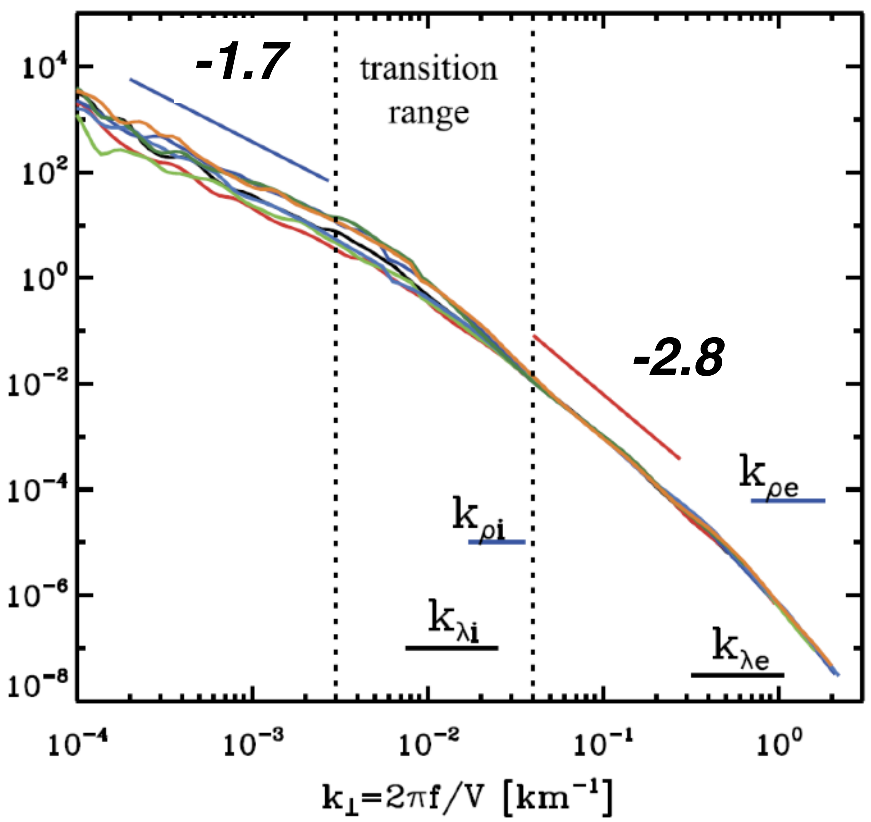
The journey just started…
there is some fundamental work to be done here!

Thank you!

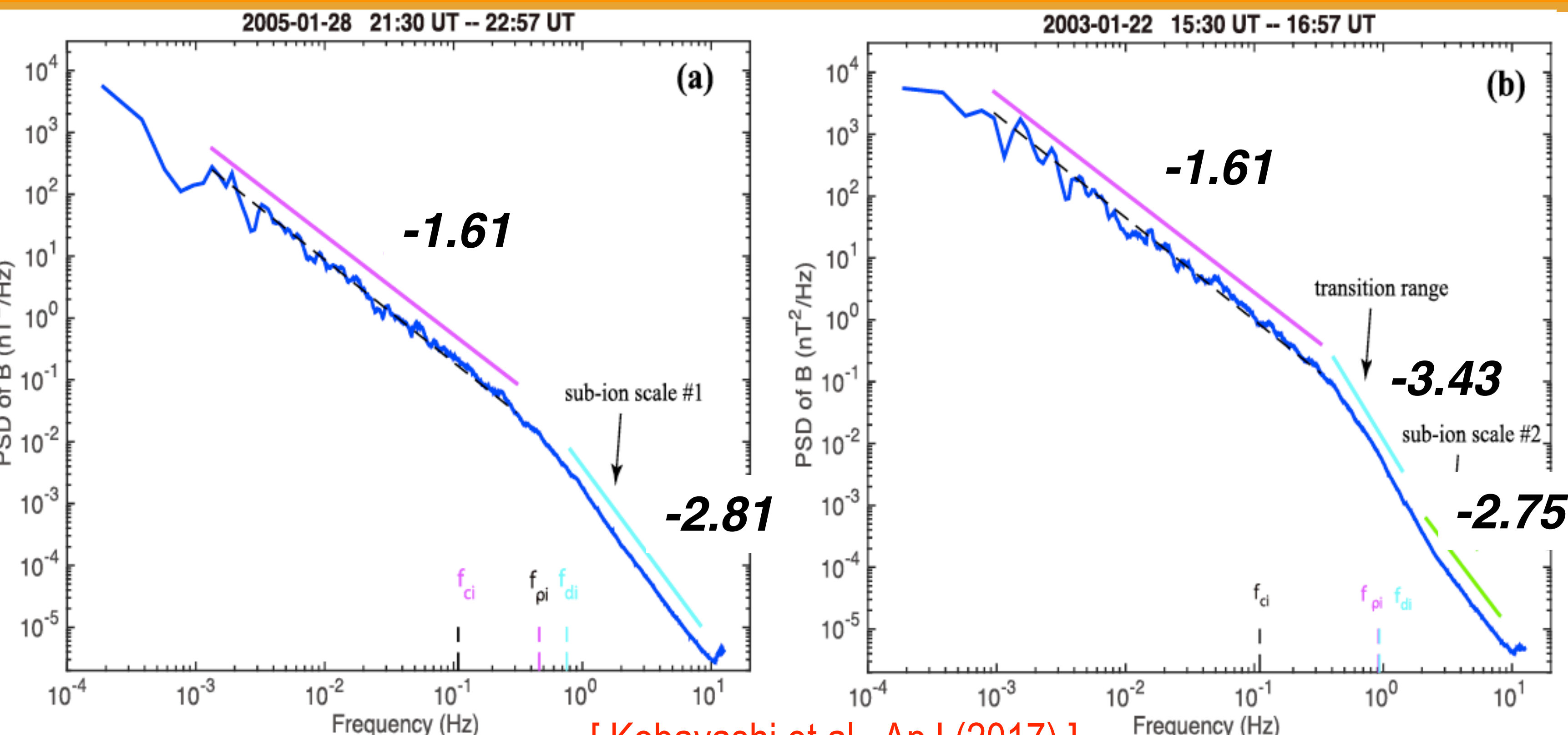
BACKUP SLIDES

Universality of kinetic-range spectrum?

Solar Wind



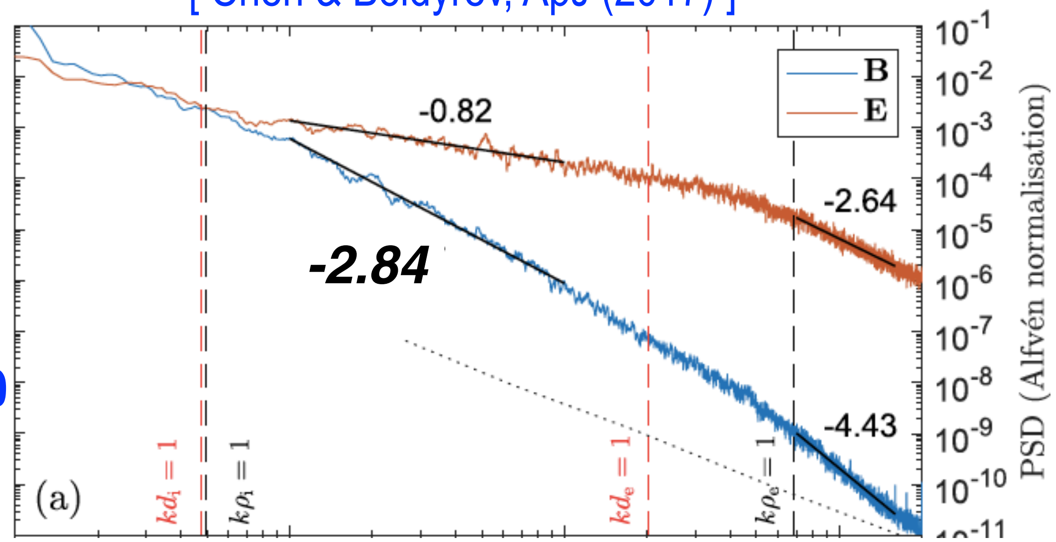
[Alexandrova et al., SSR (2013)]



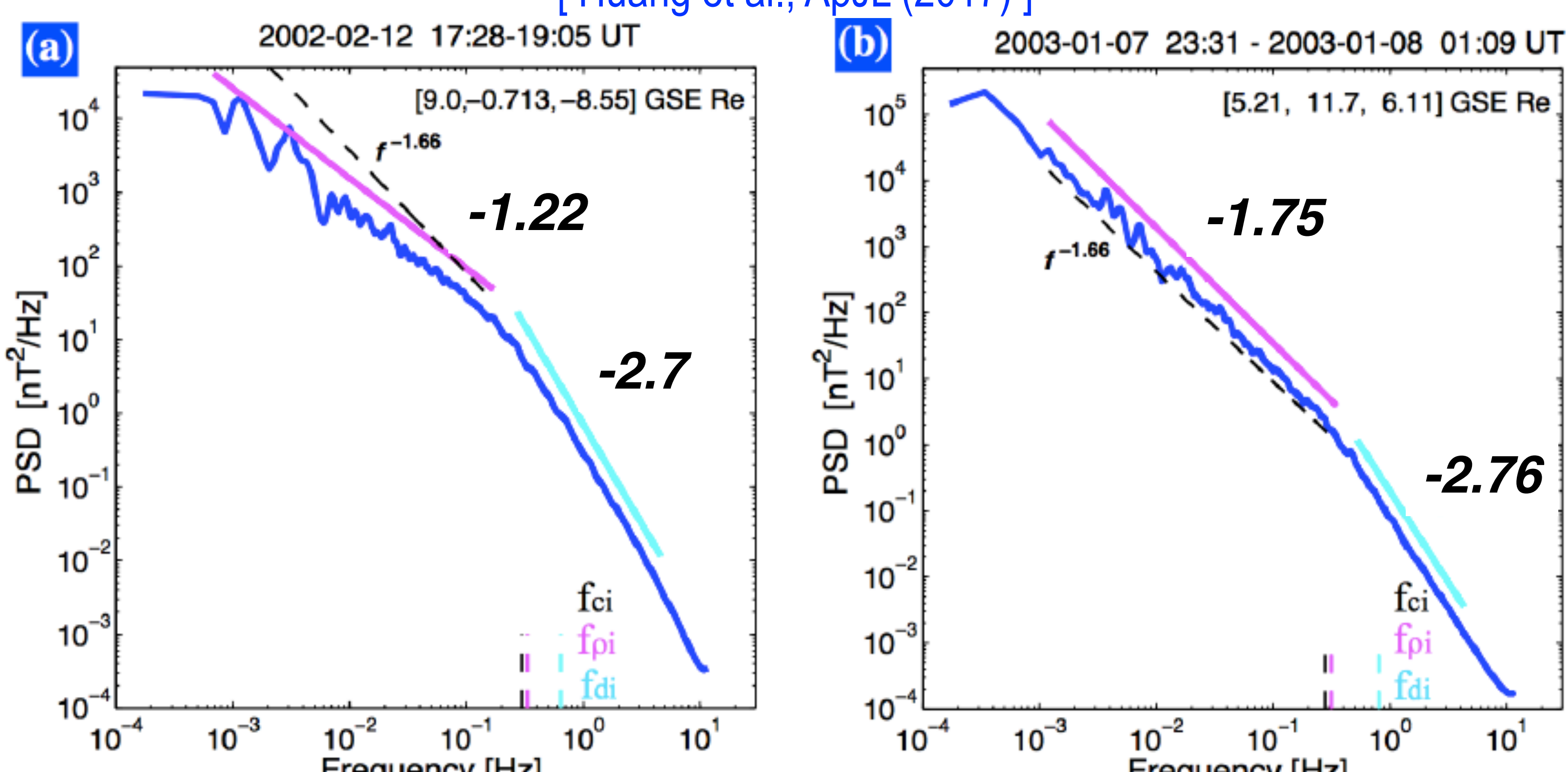
[Kobayashi et al., ApJ (2017)]

Magnetosheath

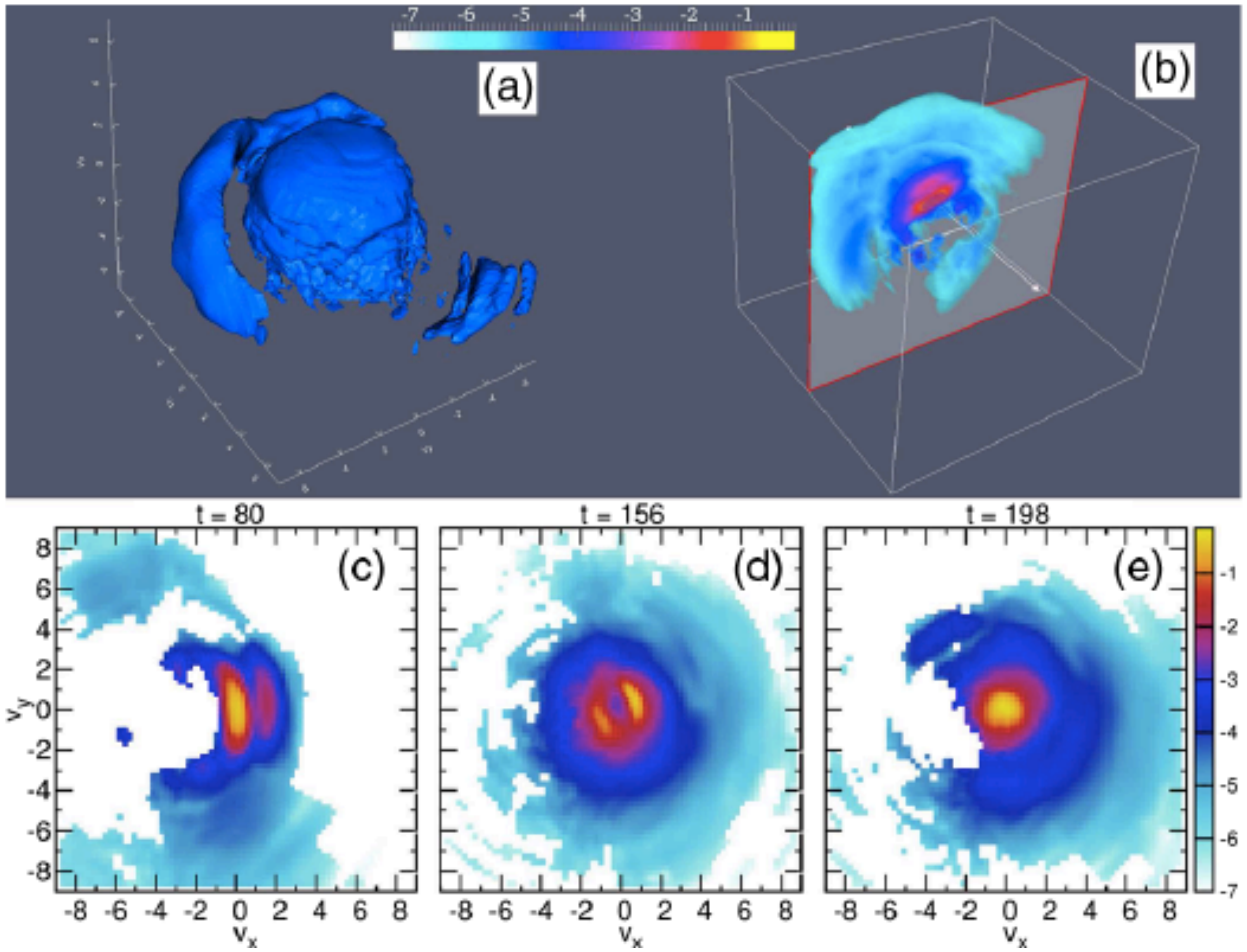
[Chen & Boldyrev, ApJ (2017)]

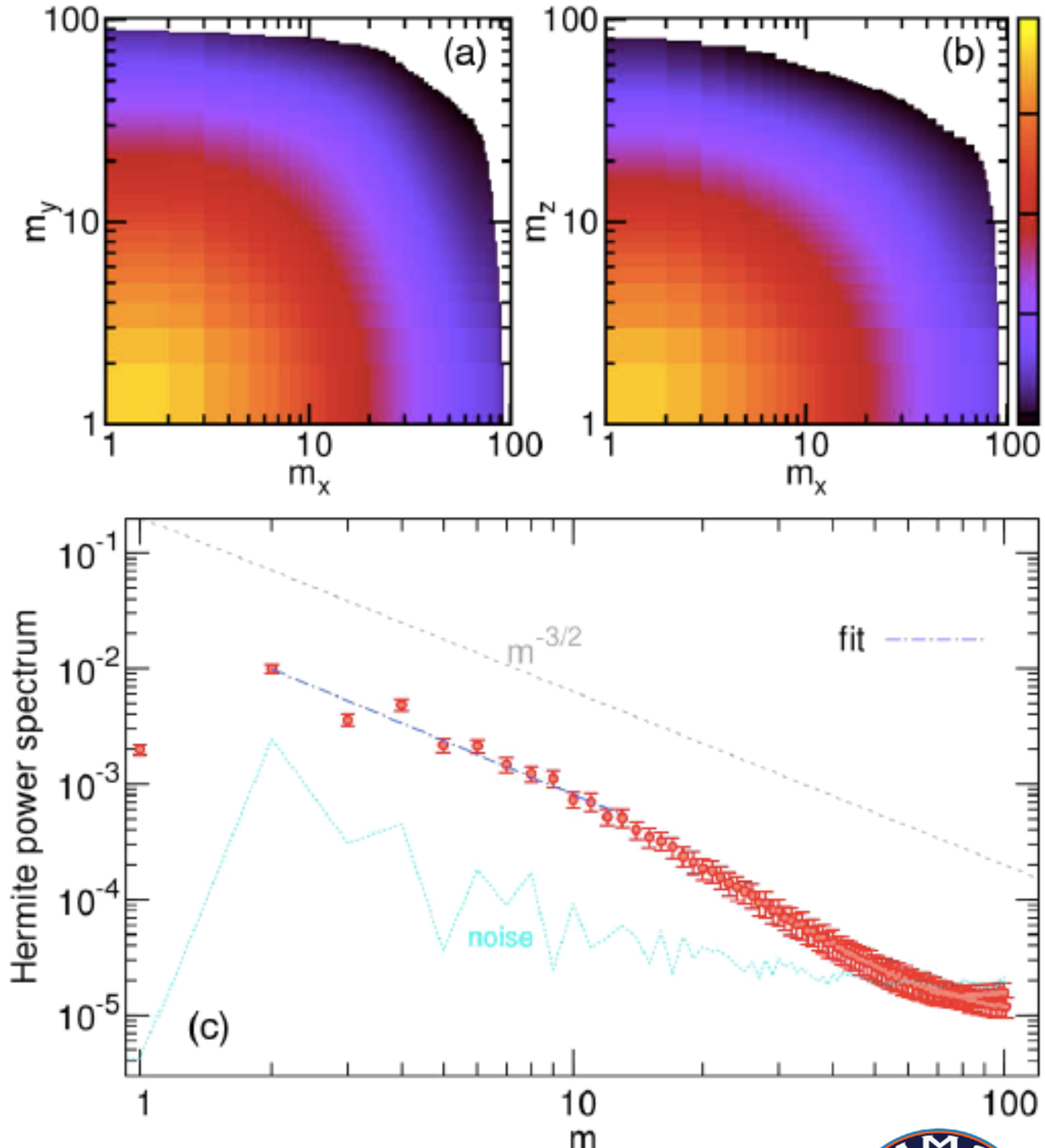


[Huang et al., ApJL (2017)]



electron entropy cascade



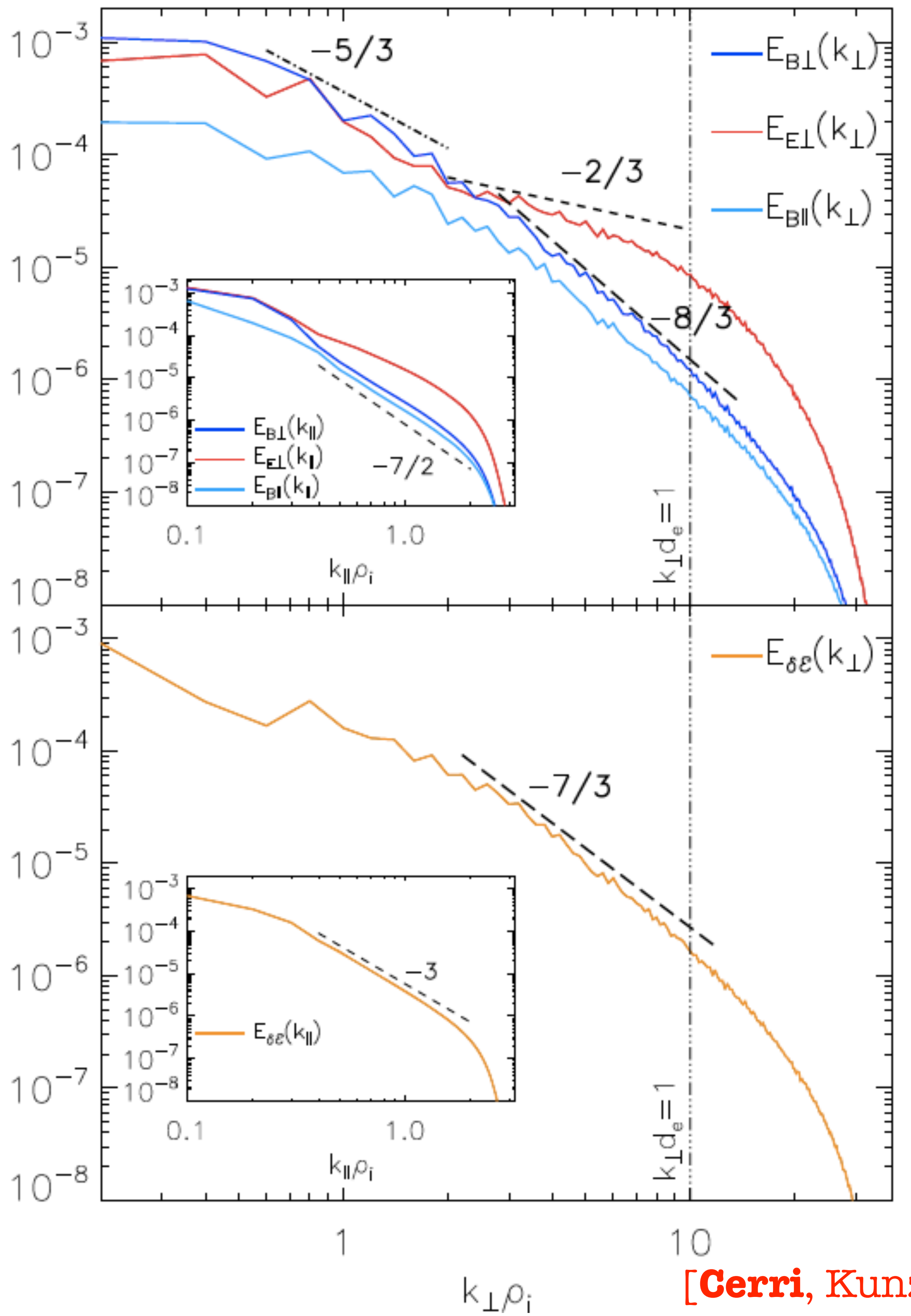


First evidence of a cascade
in velocity space from in-situ data!

(electron distribution function
measured by MMS
in the Earth's magentosheath)

[Servidio et al., PRL (2017)]

real-space cascade of ion entropy



$$\delta\mathcal{E} \equiv -\int d^3v\,(f\ln f - F_M \ln F_M)$$

$$\delta f \approx h \text{ and } \delta\mathcal{E} \approx \int d^3v\,(Th^2/2F_M) \text{ for } k_\perp\rho_i \gg 1$$

δE effectively behaves as a passive scalar…

…derive generalised scalings for δE spectrum:

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

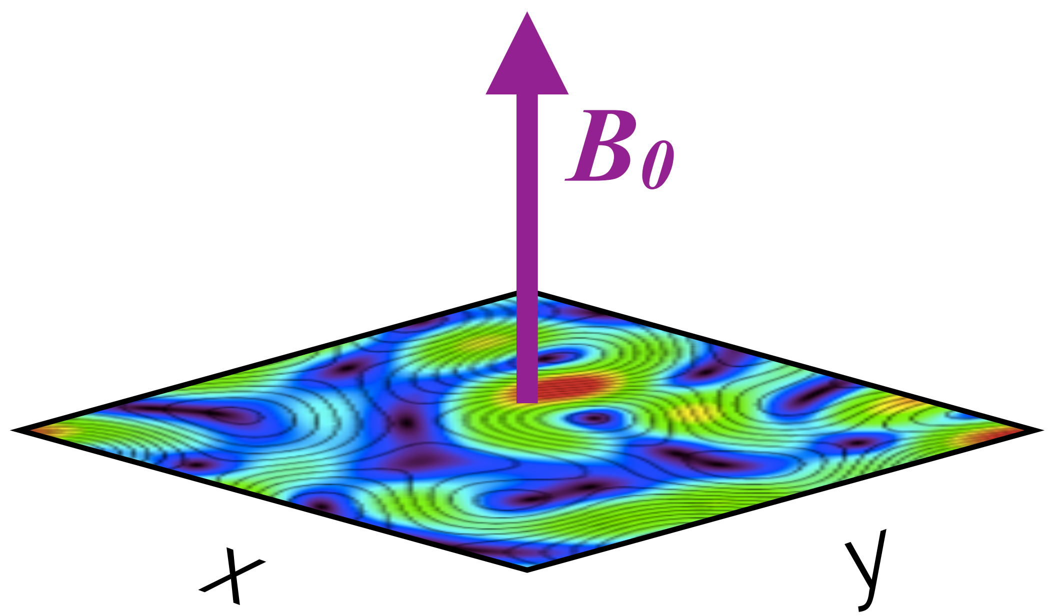
$$E_{\delta\mathcal{E}}(k_\parallel) \propto k_\parallel^{-3}$$

$$\alpha = 2 \qquad E_{\delta\mathcal{E}} \propto k_\perp^{-7/3}$$

[**Cerri**, Kunz & Califano, ApJL (2018)]

2D-3V turbulence

☞ *going back to 2D-3V → role of reconnection*



Why different large-scale properties end up in the same kinetic-range spectrum ?

Is this "universality" a signature of the same physical process that underlies the turbulent transfer at kinetic scales?

Reconnection-mediated turbulence

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PAPER

Reconnection and small-scale fields in 2D-3V hybrid-kinetic driven turbulence simulations

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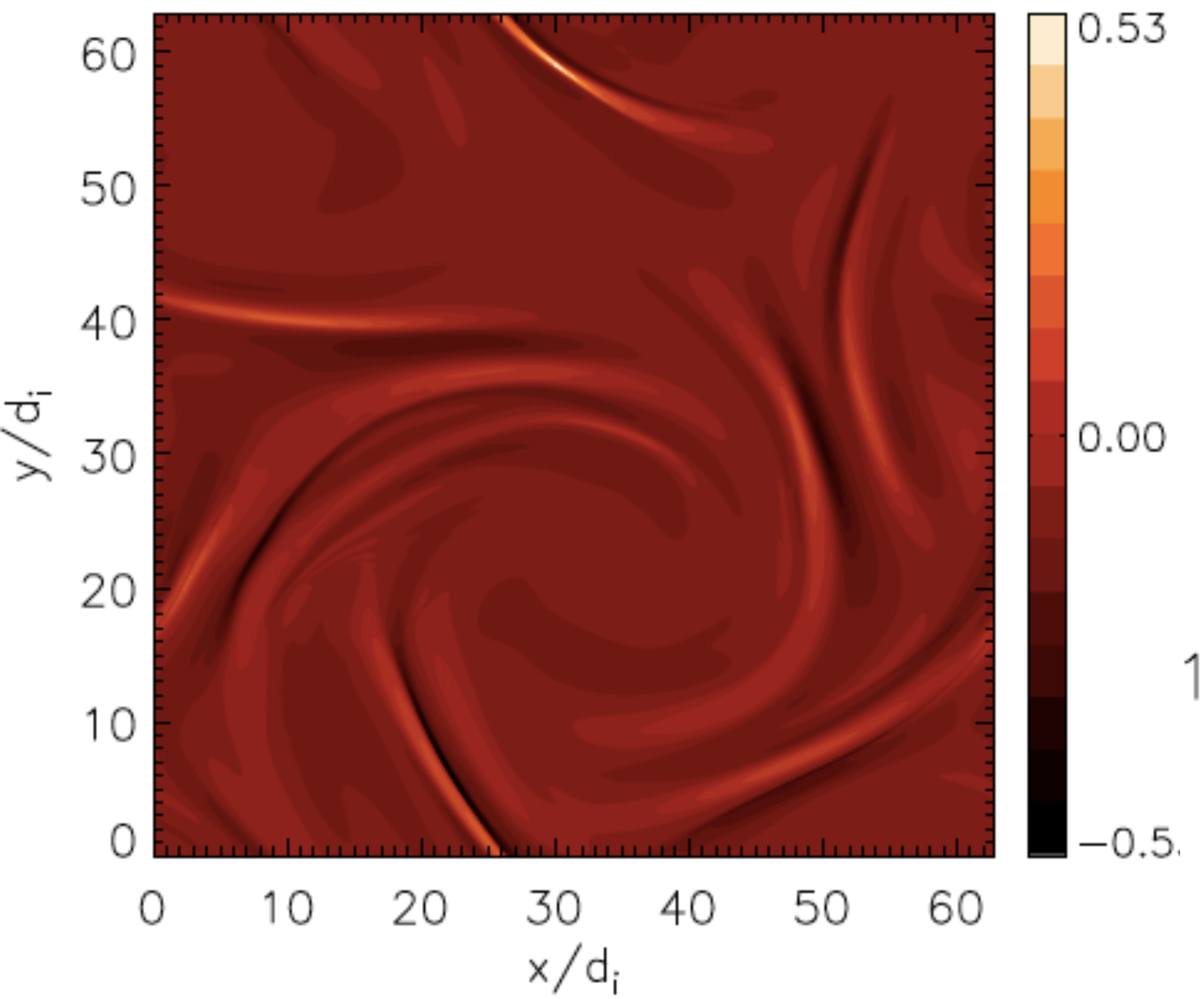
Keywords: plasma turbulence, space plasmas, magnetic reconnection, Vlasov simulations

scales which then cascade towards smaller and smaller scales. We have therefore identified the fast magnetic reconnection processes as the preferred (or concurrent) mediators for the cascade at small-scales, thus picturing turbulence and magnetic reconnection as tightly entwined self-regulating processes that feed on each other. In our opinion, such a mechanism is crucial for developing a self-regulated turbulent state across and below the ion kinetic scale lengths.

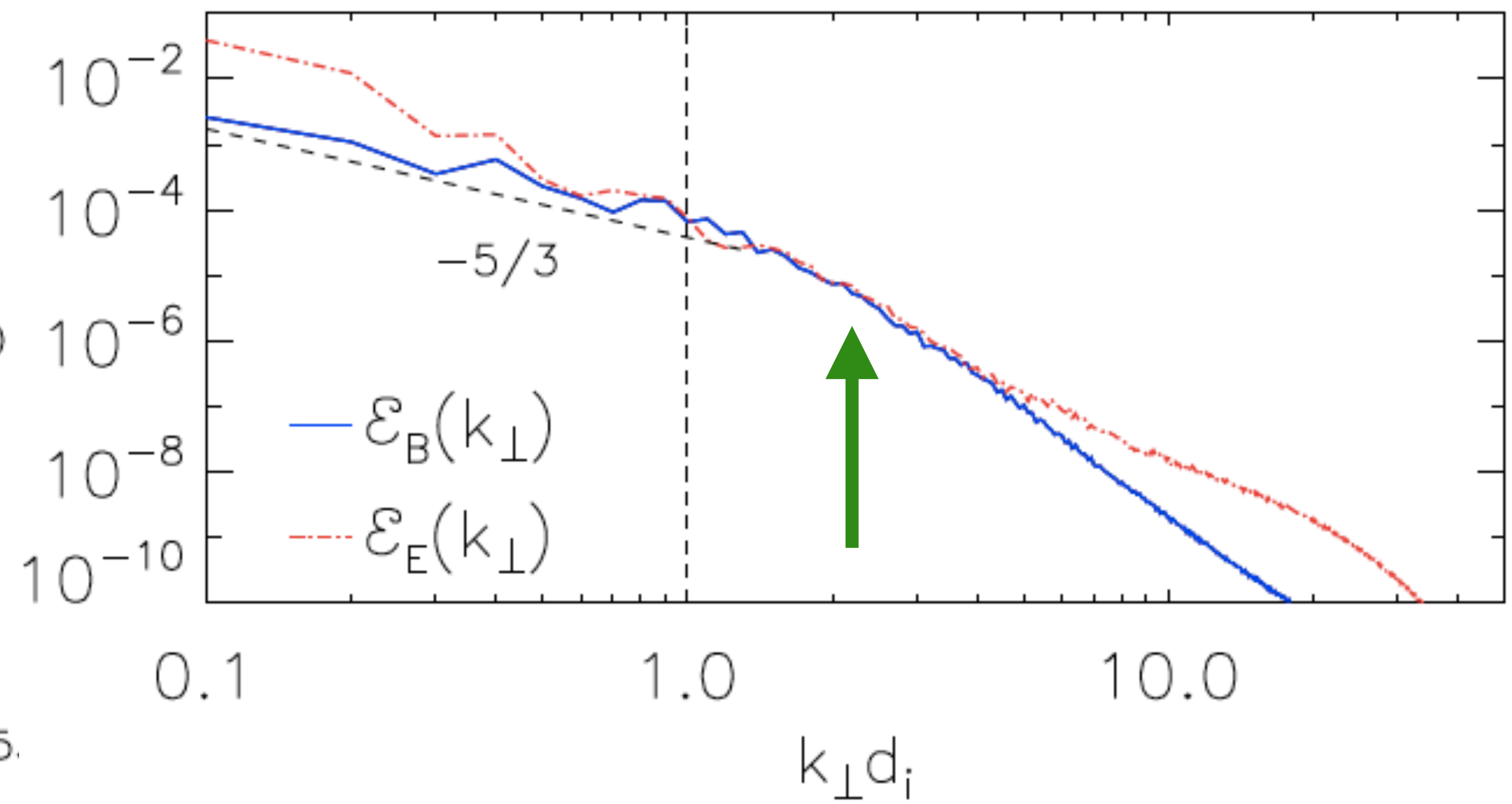
In summary, the transition between the inertial and the subproton-scale spectrum is mediated by the formation of coherent structures and by the associated small-scale non-ideal electric field emerging from the destabilization of 'large-scale' current sheets by fast magnetic reconnection. The coherent structures formation

Reconnection-mediated turbulence

[**Cerri** & Califano, NJP (2017)]



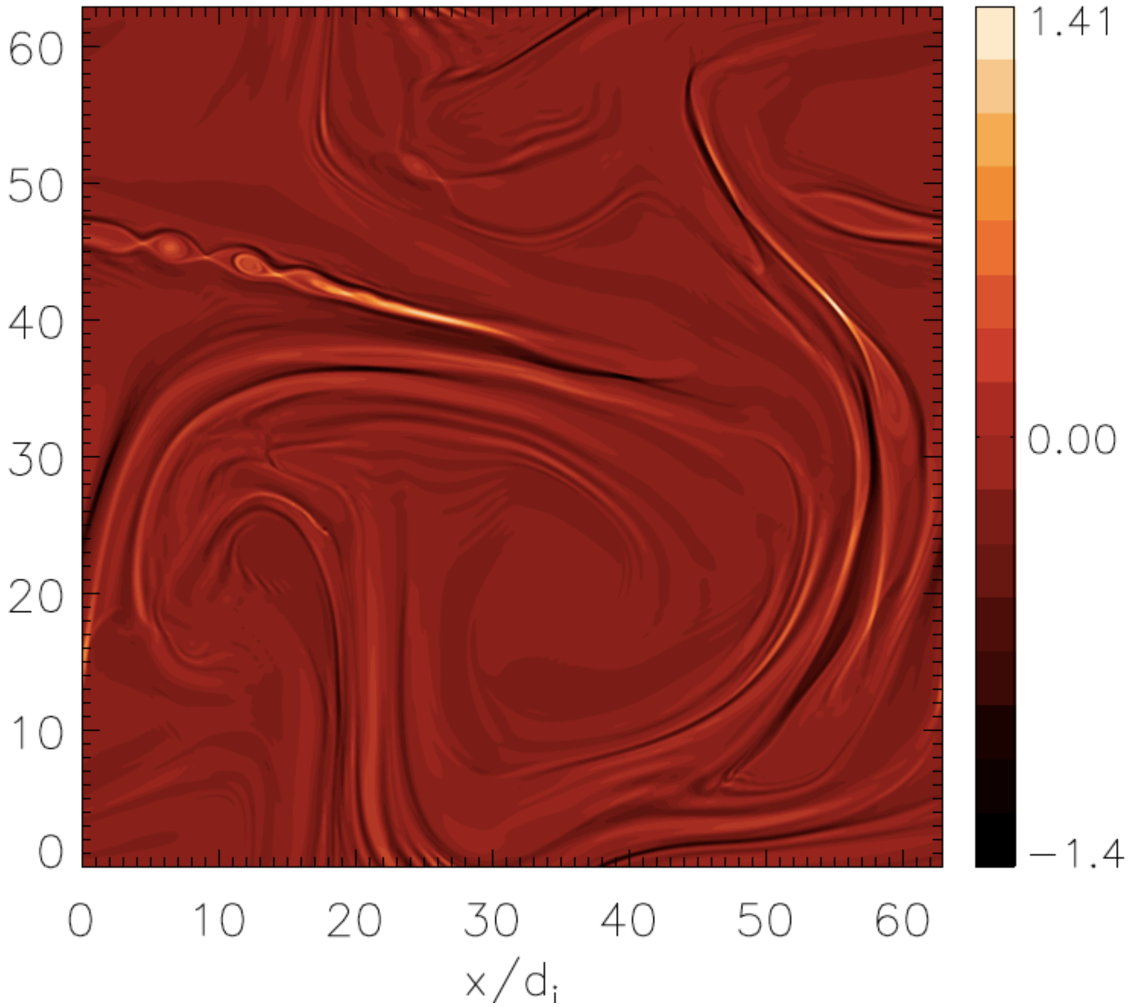
Colors: $J_{||}$ (out-of-plane current density)

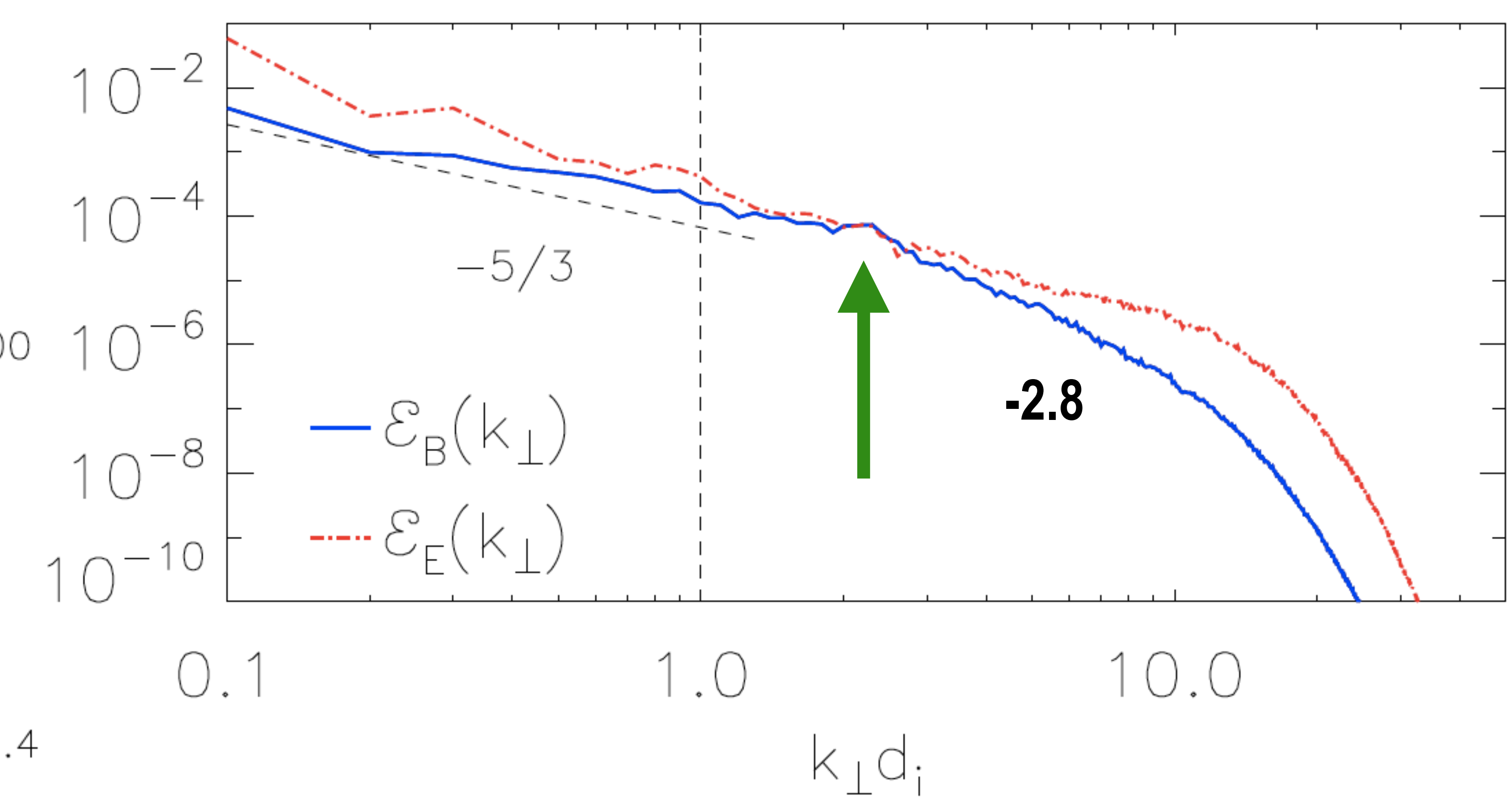


First suggestion that **magnetic reconnection may mediates** the formation of the **spectral break at ion scales** and the **energy transfer of the turbulent cascade below the ion gyro-radius!**

Reconnection-mediated turbulence

[Cerri & Califano, NJP (2017)]





Colors: $J_{||}$ (out-of-plane current density)

First suggestion that **magnetic reconnection may mediates** the formation of the **spectral break at ion scales** and the **energy transfer of the turbulent cascade below the ion gyro-radius!**

Reconnection-mediated turbulence

[**Cerri** & Califano, NJP (2017)]

Point #1

*The formation of a **spectral break** and of a **kinetic-range spectrum** is extremely fast and coincides with the time at which **ion-scale current sheets** undergo **fast magnetic reconnection***

see ***Cerri & Califano, NJP (2017)***

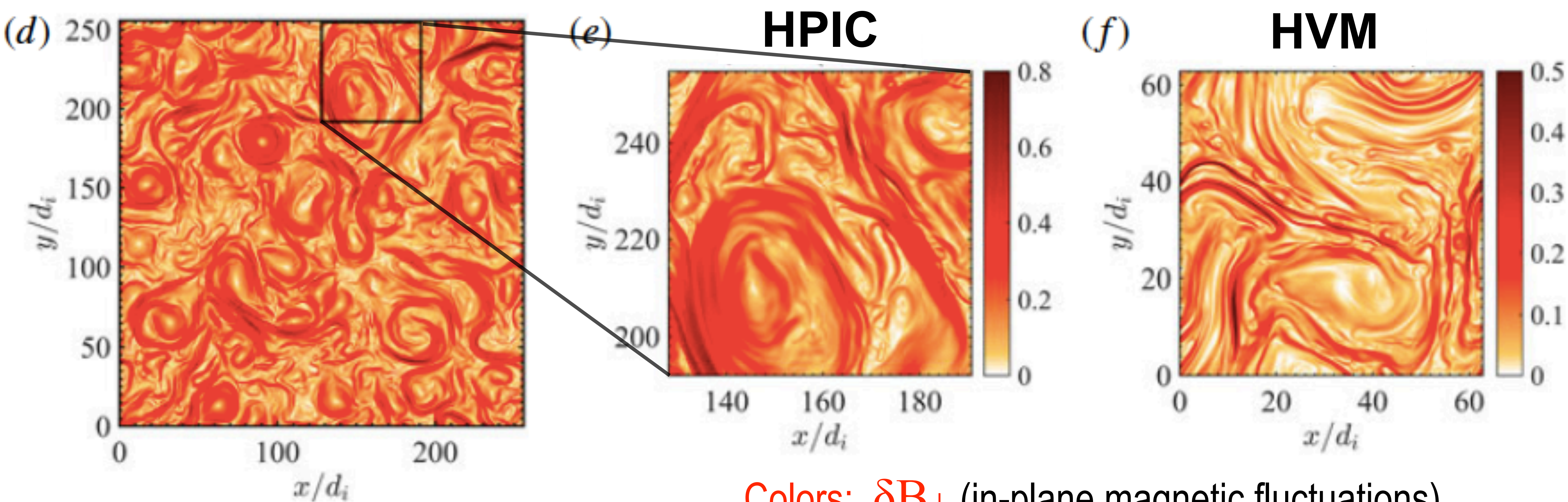
Does this depend on large-scale details ?

HPIC	HVM
2048^2 x 64000ppc	1024^2 x 51^3
L = 256 d_i ; dx = 0.125 d_i	L ~ 63 d_i ; dx ~ 0.06 d_i ; dv = 0.2 $v_{th,i}$
freely-decaying large-scale large-amplitude **Alfvénic fluctuations** (magnetic + velocity incompressible fluctuations)	**continuously-driven** large-scale small-amplitude **partially-compressible fluctuations** (only momentum fluctuations are injected)

[**Cerri** et al., JPP (2017)]

- Out-of-plane ambient magnetic field $\boldsymbol{B_0}$
- Comparison made for $\beta_i = 0.2$, 1, and 5
- Same energy-containing scales: $(k_\perp d_i)_{inj} \leq 0.3$
- No initial density fluctuations, no initial anisotropy
- Isothermal electrons with $T_e = T_i$

Does this depend on large-scale details ?



Colors: $\delta B_{\perp}$ (in-plane magnetic fluctuations)

Very similar structures when considering the same scales

Key ingredient for small-scales turbulence:

reconnecting current sheets & coherent structures

[**Cerri** et al., JPP (2017)]

Does this depend on large-scale details ?

Point #2

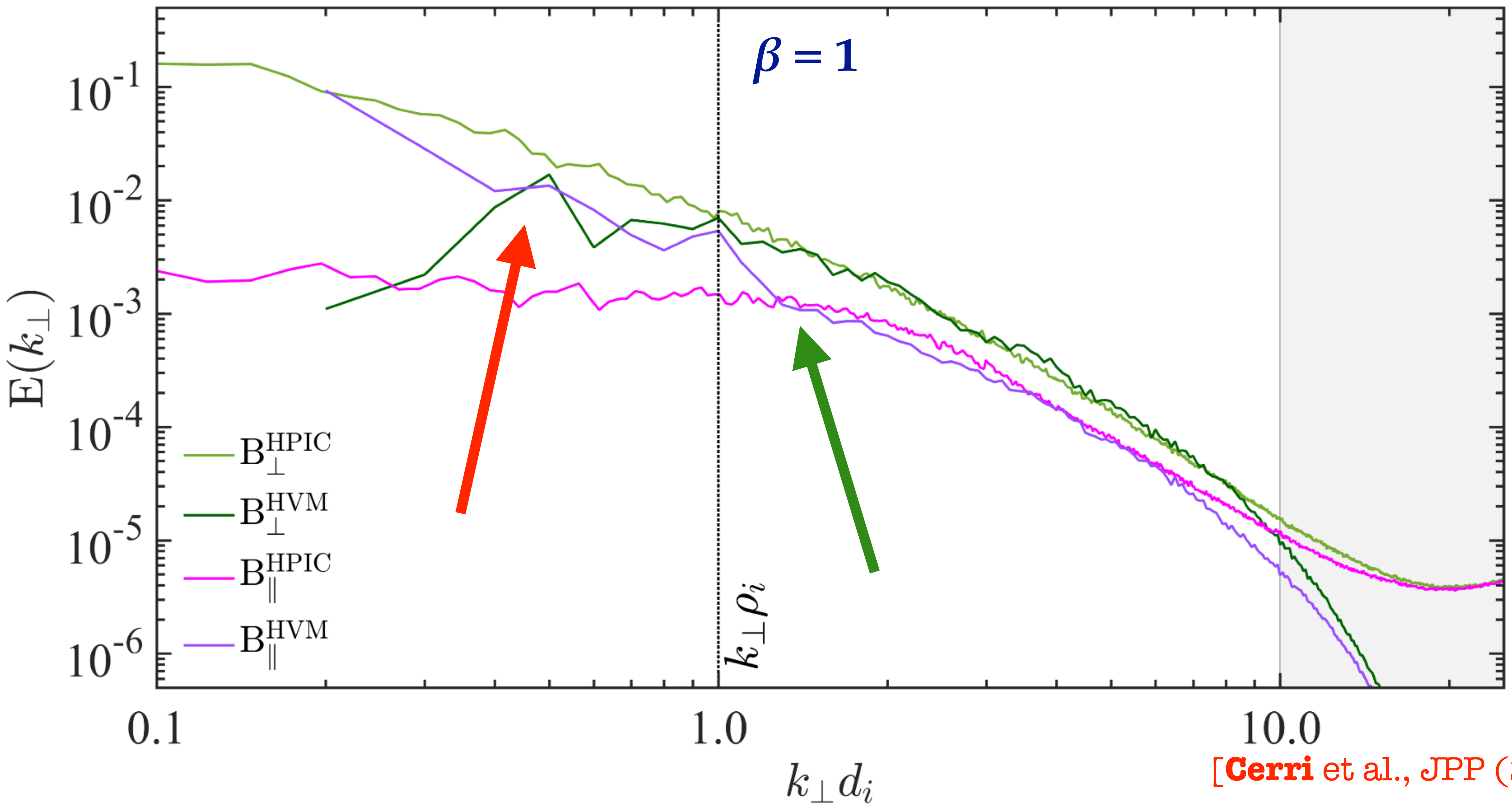
In the turbulent stage we see the same formation
*of **coherent structures via magnetic reconnection**…*
…despite completely different large-scale properties!

see ***Cerri et al., JPP (2017)***

[**Cerri** et al., JPP (2017)]

Does this depend on large-scale details ?

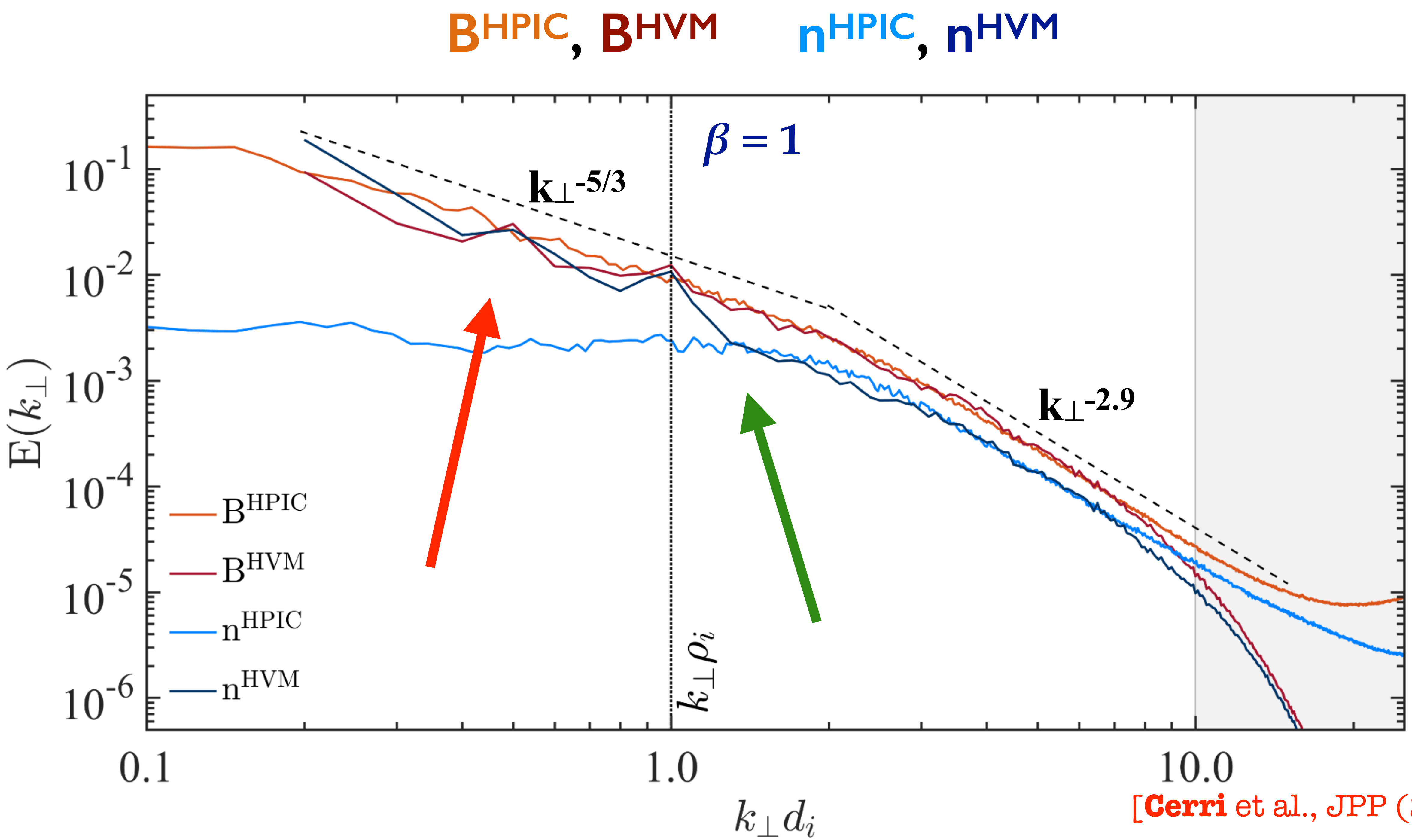
$B_\perp^{HPIC}$, $B_\perp^{HVM}$ $B_{//}^{HPIC}$, $B_{//}^{HVM}$



[**Cerri** et al., JPP (2017)]

- Different spectral behaviour at large scales (different setup, inizialization & forcing)
- Very good agreement at smaller scales (***self-consisent plasma response***)
- Numerical effects at the smallest scales (ppc-noise in HPIC, filters in HVM)

Does this depend on large-scale details ?



[**Cerri** et al., JPP (2017)]

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- Very good agreement at smaller scales (***self-consisent plasma response***)
- Numerical effects at the smallest scales (ppc-noise in HPIC, filters in HVM)

Does this depend on large-scale details ?

Point #3

Self-consistent re-processing of fluctuations *while they cascade…*

… perhaps …

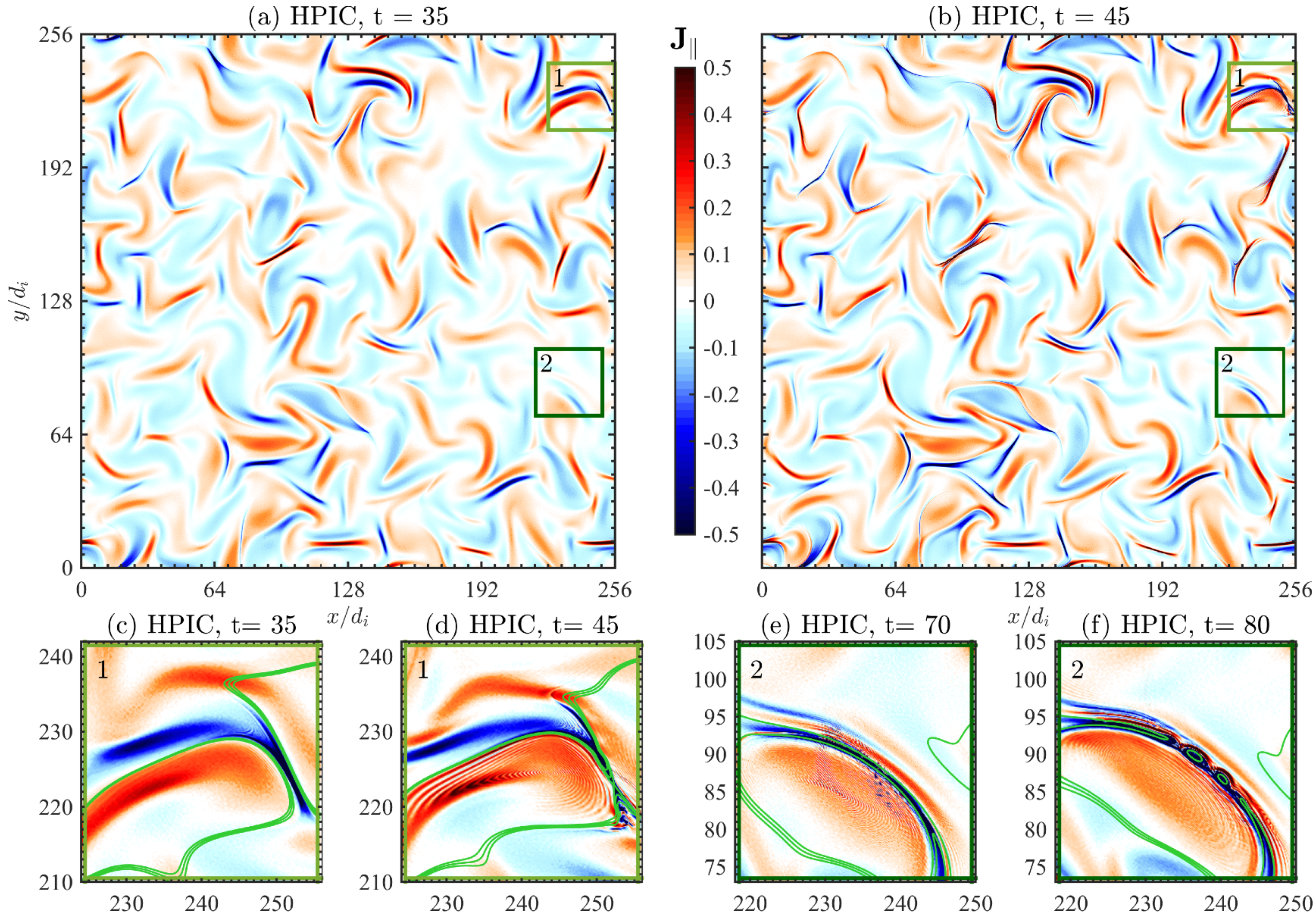
… ***same underlying process allows/mediates the kinetic cascade****!*

[☞ ***reconnection***]

see ***Cerri et al., JPP (2017)***

Short-circuiting the cascade

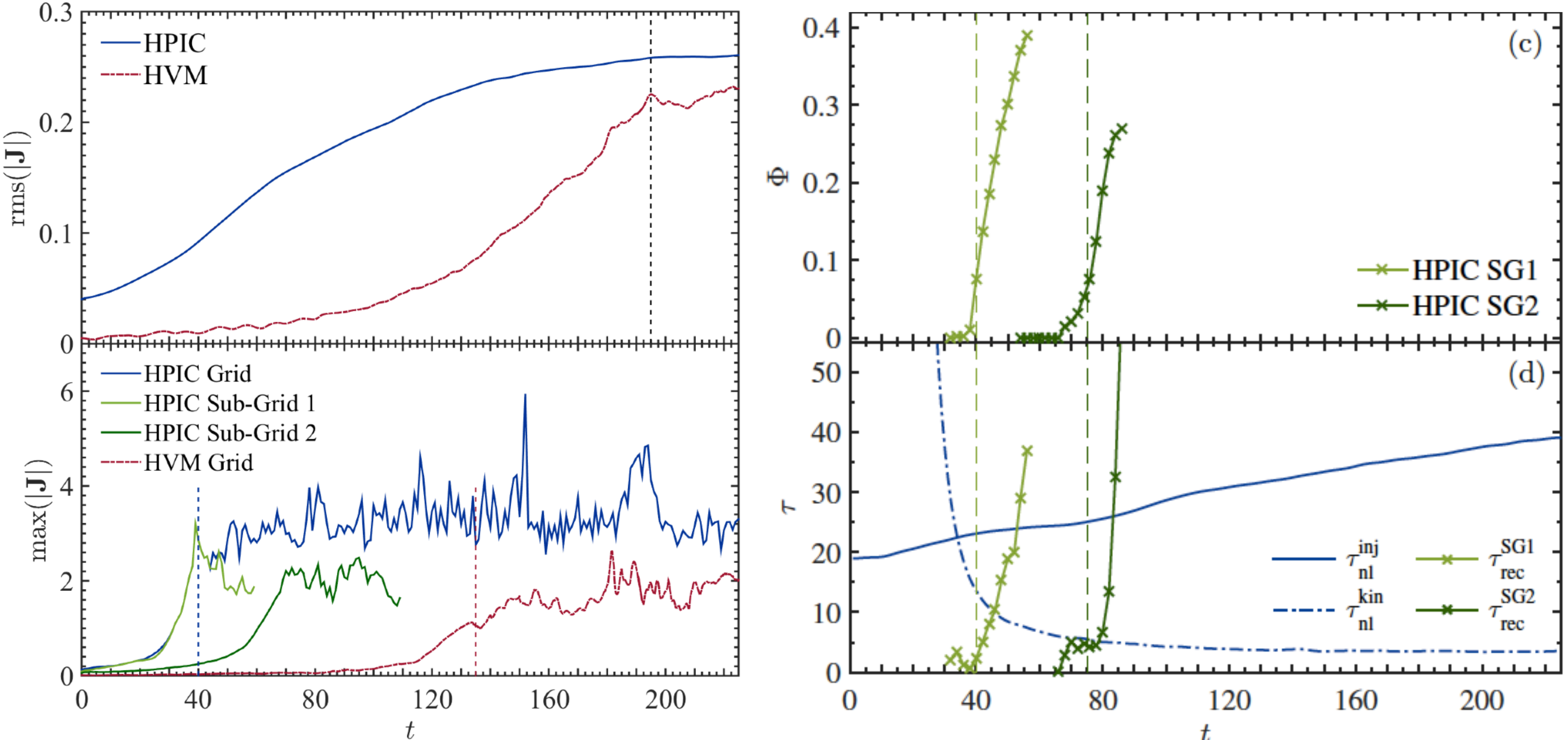
Tracking local current intensity increase and reconnection events



[Franci, **Cerri**, Califano et al., ApJL (2017)]

Short-circuiting the cascade

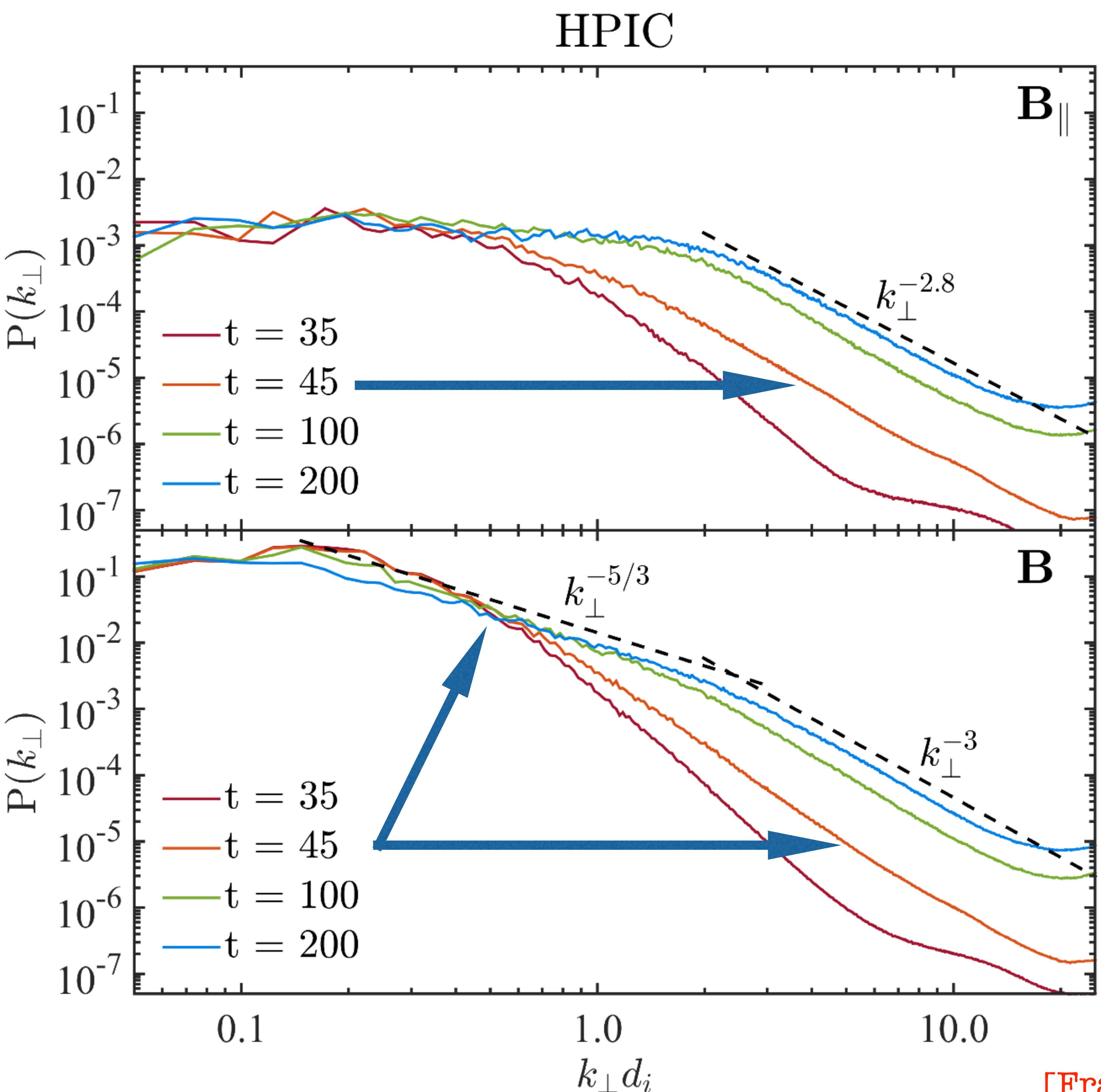
Tracking local current intensity increase and reconnection events



[Franci, **Cerri**, Califano et al., ApJL (2017)]

The associated kinetic-range turbulent nonlinear time scale quickly adjust to the local reconnection time scale!

Short-circuiting the cascade

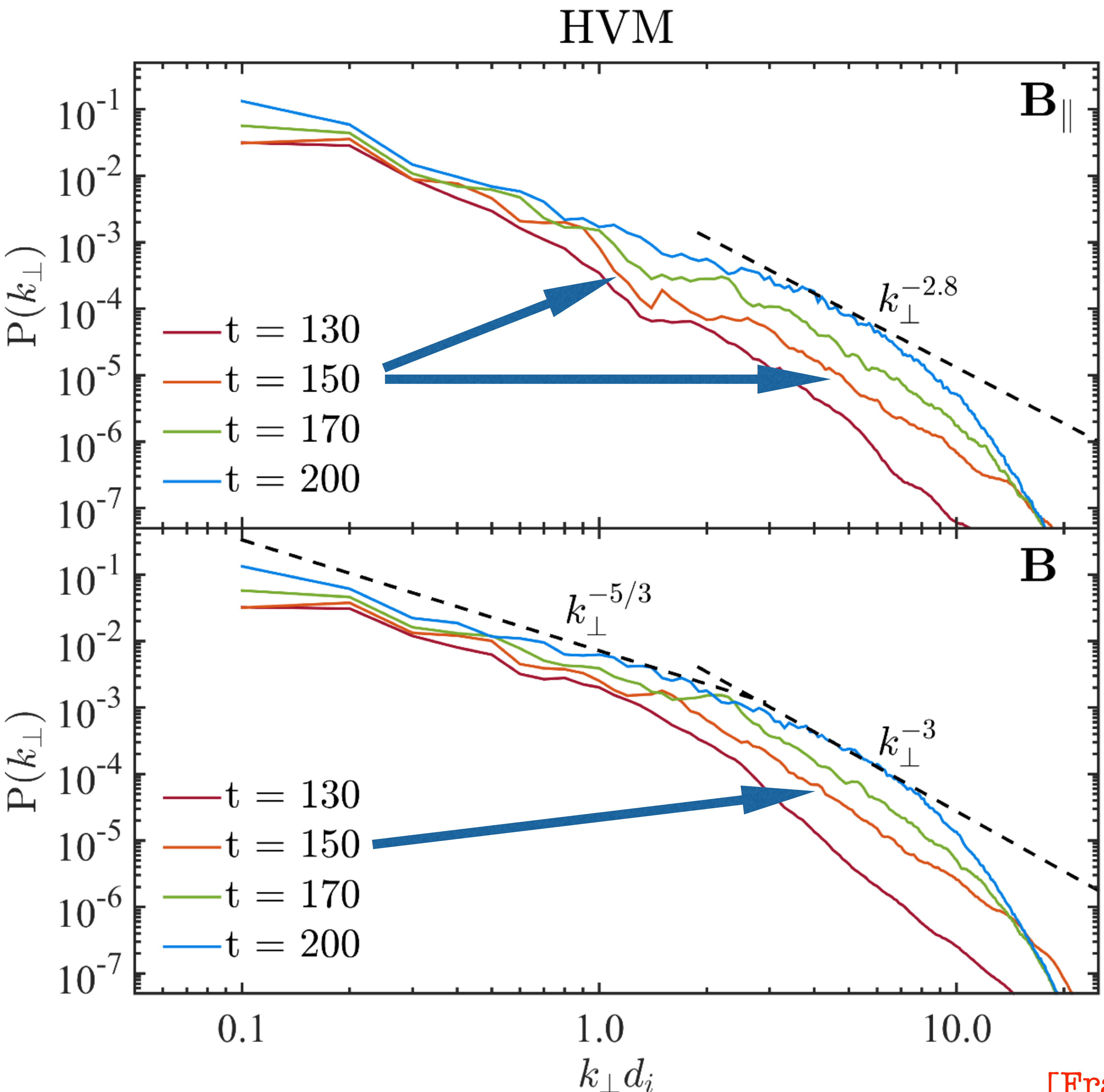


Kinetic-scale spectrum forms before the formation of a developed "MHD specturm"

The slopes does not change while the MHD cascade develops (amplitude just "rises")

[Franci, **Cerri**, Califano et al., ApJL (2017)]

Short-circuiting the cascade



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Connecting the dots…

- Kinetic spectrum does not strongly depend on the large-scale properties
- Reconnection can allows/enhance energy transfer of turbulent fluctuations from MHD to kinetic scales
- (Possible non-local structure-mediated energy transfer picture? standard local nonlinear energy transfer simultaneously active?)
- Enhanced total energy transfer affects spectral slopes in a way consistent with SW observations
- Magnetic intermittency and structures observed in the SW plasma as an intrinsic element of kinetic-scale turbulence

Reconnection & turbulence as tightly entwined processes

any theory of the turbulent cascade should perhaps take into account magnetic reconnection as an effective channel for energy transfer

Just 2 take-away messages…

- ***Reconnection-mediated scenario for kinetic-range turbulence gets stronger***
  (supported by an increasing number of simulations & observations)

  ☞ first suggestion in: ***Cerri & Califano, NJP (2017)***

  + more (explicit) numerical evidences in: ***Franci, Cerri, Califano et al., ApJL (2017)***

  + some theory: ***Loureiro & Boldyrev, ApJ (2017); Mallet, Schekochihin & Chandran, JPP (2017)***

- ***Kinetic turbulence intrinsically involves the entire phase space and is anisotropic both in real- and in velocity-space!***
  (now also supported by simulations outside GK theory & observations by MMS)

  ☞ first 6D anisotropic turbulent cascade in: ***Cerri, Kunz & Califano, ApJL (2018)***