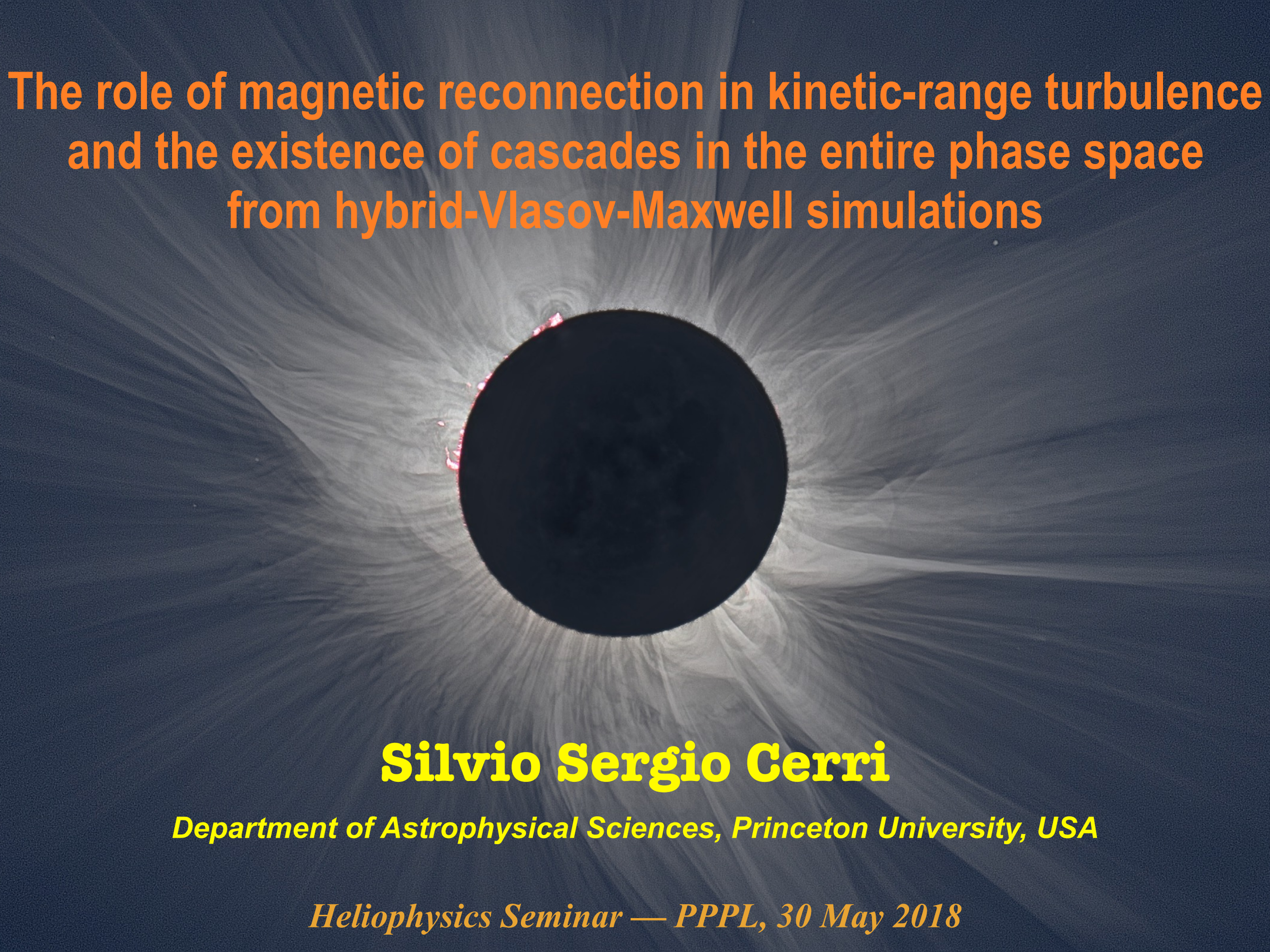
The role of magnetic reconnection in kinetic-range turbulence and the existence of cascades in the entire phase space from hybrid-Vlasov-Maxwell simulations



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Heliophysics Seminar — PPPL, 30 May 2018

Thanks to main collaborators

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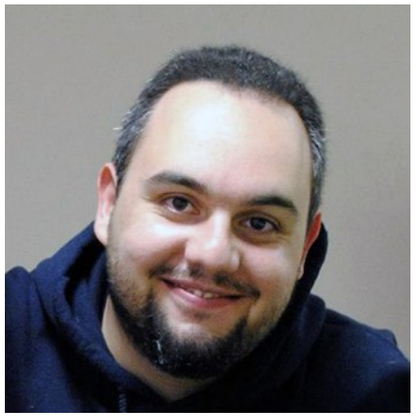
M. W. Kunz
(Princeton U. & PPPL)



L. Franci
(Queen Mary London)

Cerri & Califano, New J. Phys. **19**, 025007 (2017)
"Reconnection and small-scale fields in 2D-3V hybrid-kinetic driven turbulence simulations"

Franci, **Cerri**, Califano, *et al.*, Astrophys. J. Lett. **850**, L16 (2017)
"Magnetic reconnection as a driver for sub-ion scale cascade in plasma turbulence"

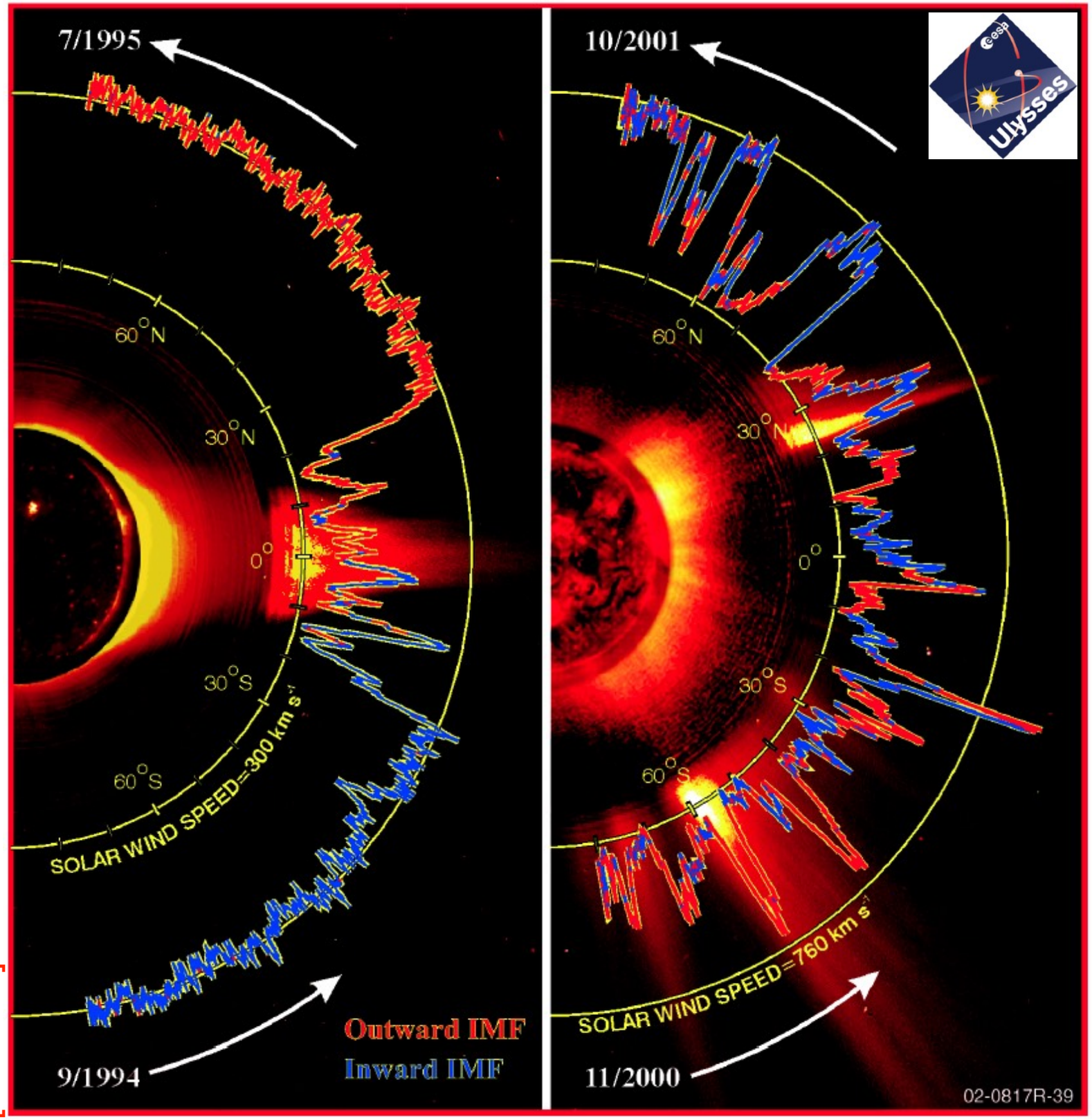
Cerri, Kunz & Califano, Astrophys. J. Lett. **856**, L13 (2018)
"Dual phase-space cascades in 3D hybrid-Vlasov-Maxwell turbulence"

Also: ***F. Rincon*** *(IRAP Toulouse),* ***S. Servidio*** *(U. of Calabria),* ***E. Papini*** *&* ***S. Landi*** *(U. of Florence)*

Outline

- Turbulence in the Solar Wind
- Hybrid Vlasov-Maxwell (HVM) model
- The role of **magnetic reconnection** in kinetic-range turbulence: a new paradigm for energy transfer (2D-3V)
- The next frontier of kinetic plasma turbulence: **cascades in a six-dimensional phase space**

The Solar Wind

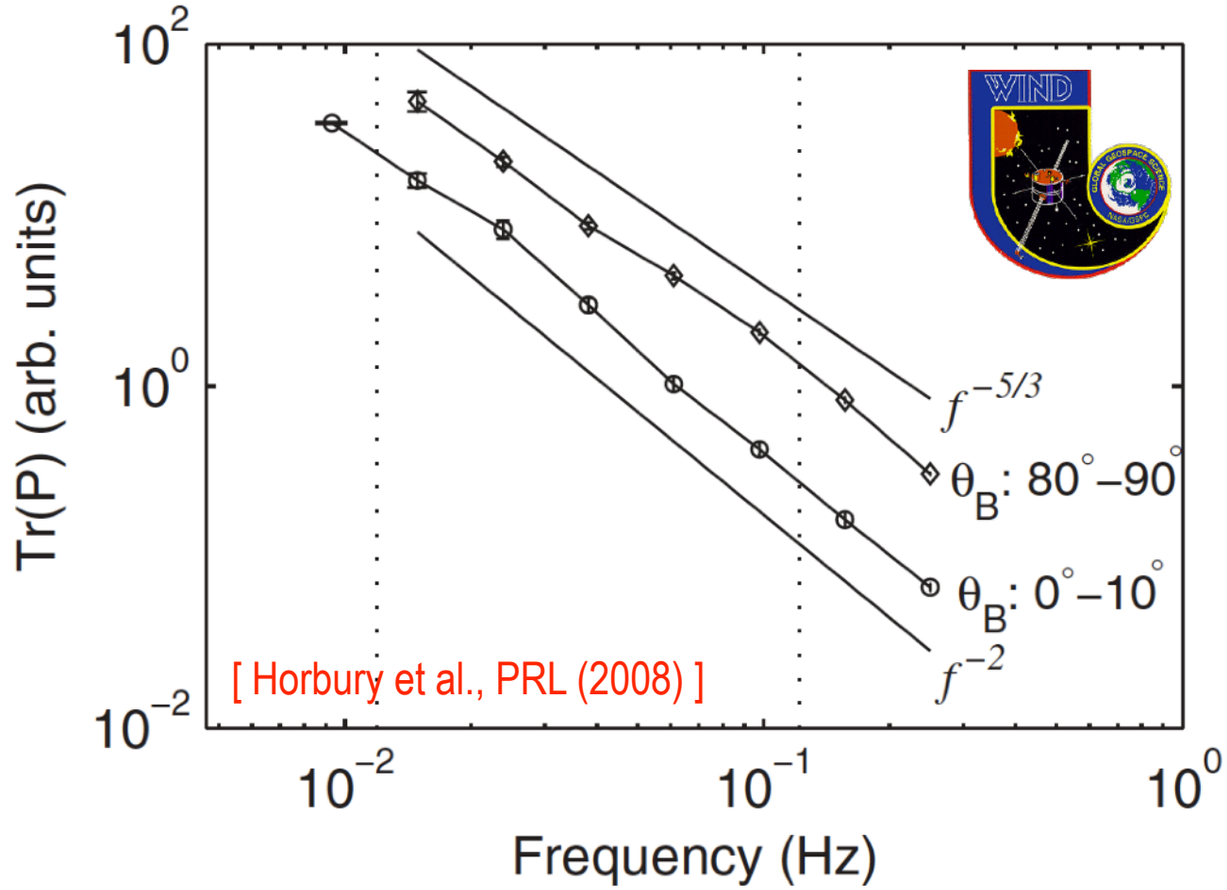


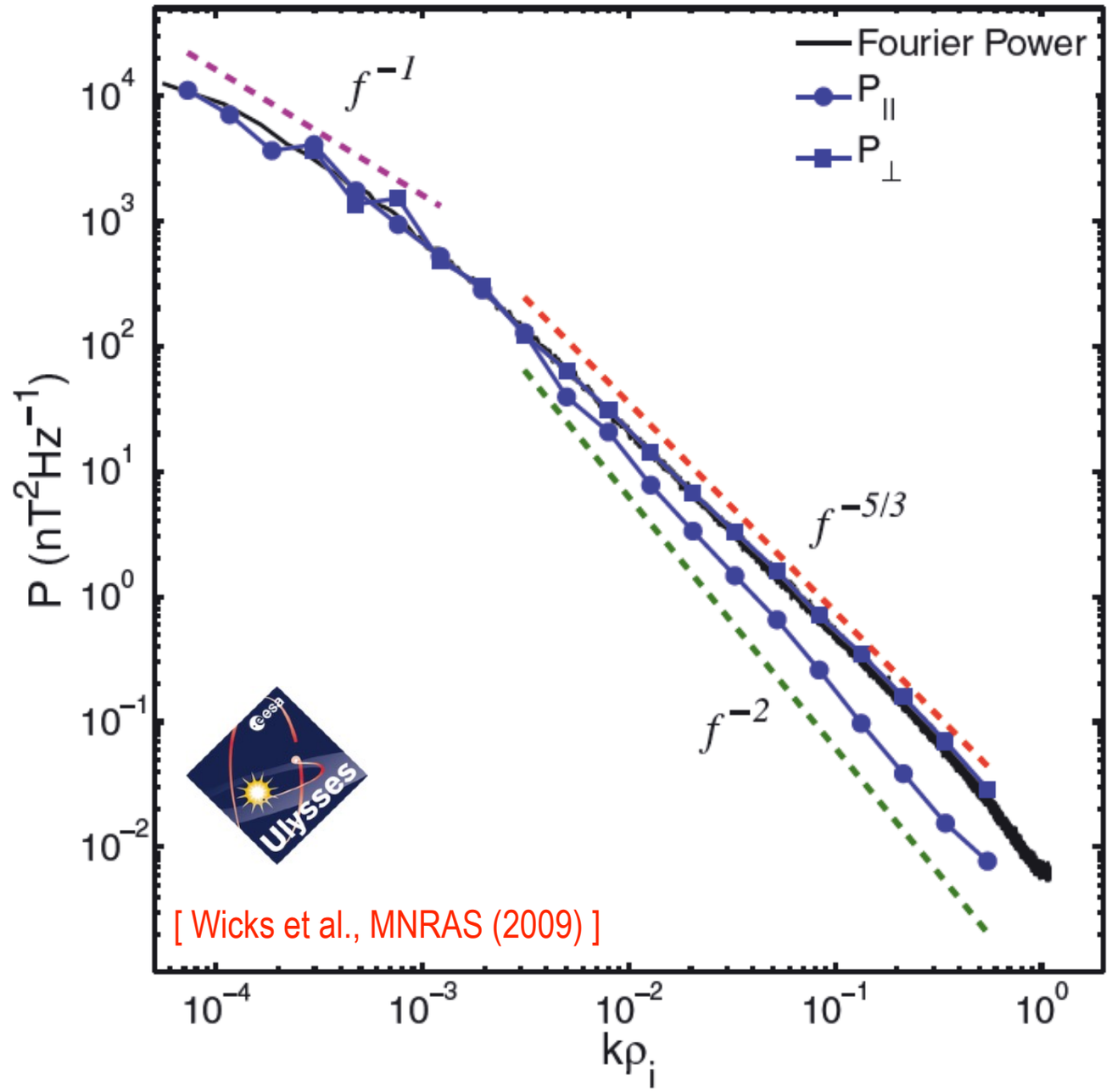
[credit: ESA]

- Continuous flow of (globally neutral) charged particles from our star: Solar Wind (SW)
- SW is mostly found in a **turbulent state**
- Time and space variability due to solar cycles and turbulent evolution: quite large parameter space
- SW plasma is **collisionless**

kinetic treatment is eventually necessary!

SW turbulence in the MHD range





critically-balanced anisotropic cascade of (mostly) Alfvénic-like fluctuations (à la Glodreich-Sridahr)

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

$$E(k_{\perp}) \propto k_{\perp}^{-5/3}, \quad E(k_{\parallel}) \propto k_{\parallel}^{-2}$$

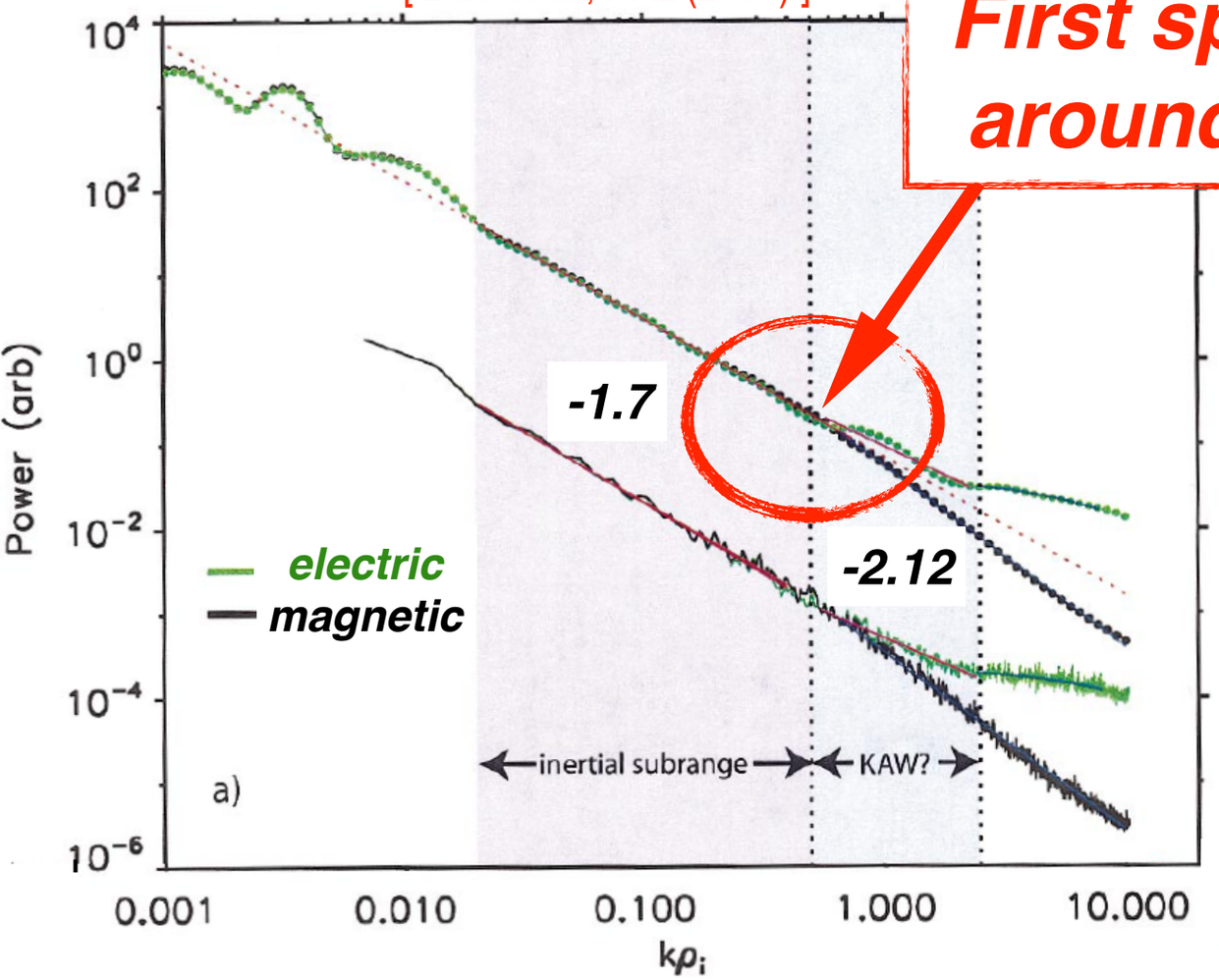
...what about the cascade at kinetic scales?

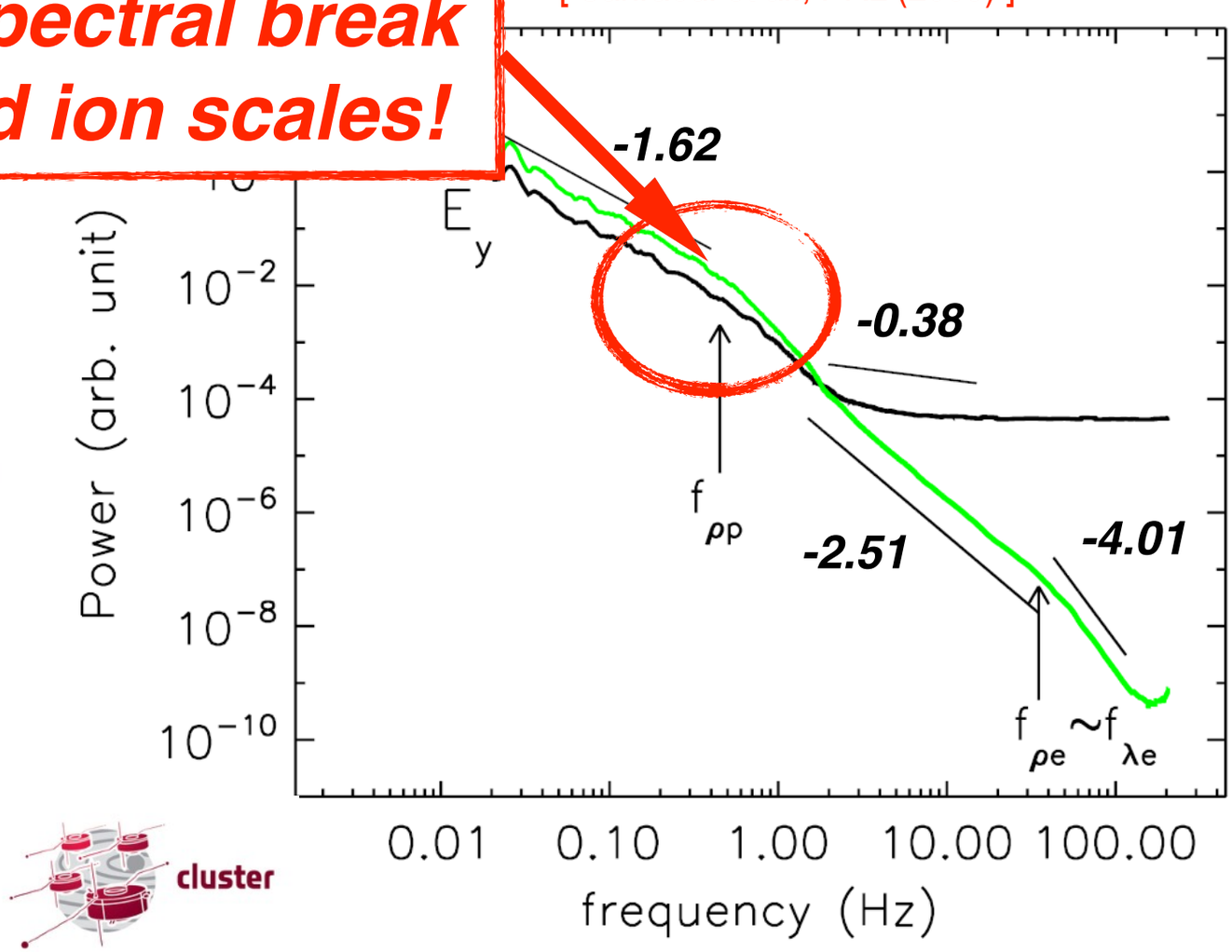
Observations beyond the MHD range

[Bale et al., PRL (2005)]

First spectral break around ion scales!

[Sahraoui et al., PRL (2009)]





cluster

First observations of electromagnetic turbulent cascade at kinetic scales:

- **Spectral breaks at kinetic scales**
- **Steepening of magnetic spectrum**
- **Flattening of electric spectrum**

Kinetic-range turbulence theories

Kinetic Alfvén wave (KAW) cascade

[see e.g. Schekochihin et al., ApJS (2009); Boldyrev et al., ApJ (2013)]

- B-spectrum ~ $k_\perp^{-7/3}$
- E-spectrum ~ $k_\perp^{-1/3}$
- Spectral anisotropy: $k_\parallel \sim k_\perp^{1/3}$

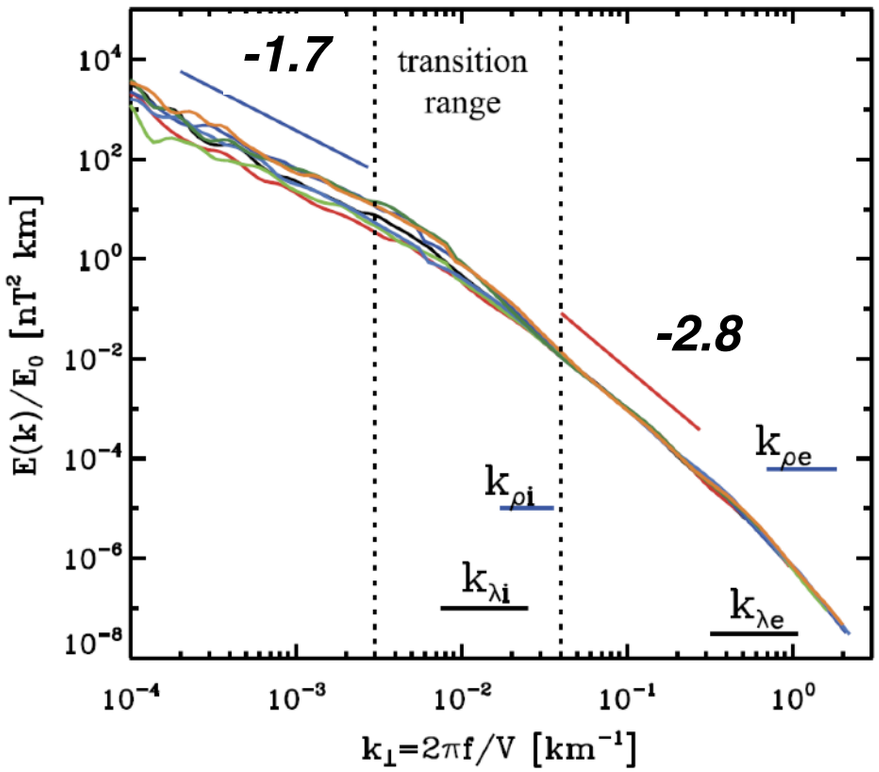
Whistler wave (WW) cascade

[see e.g. Galtier & Bhattacharjee, PoP (2003); Cho & Lazarian, ApJL (2004)]

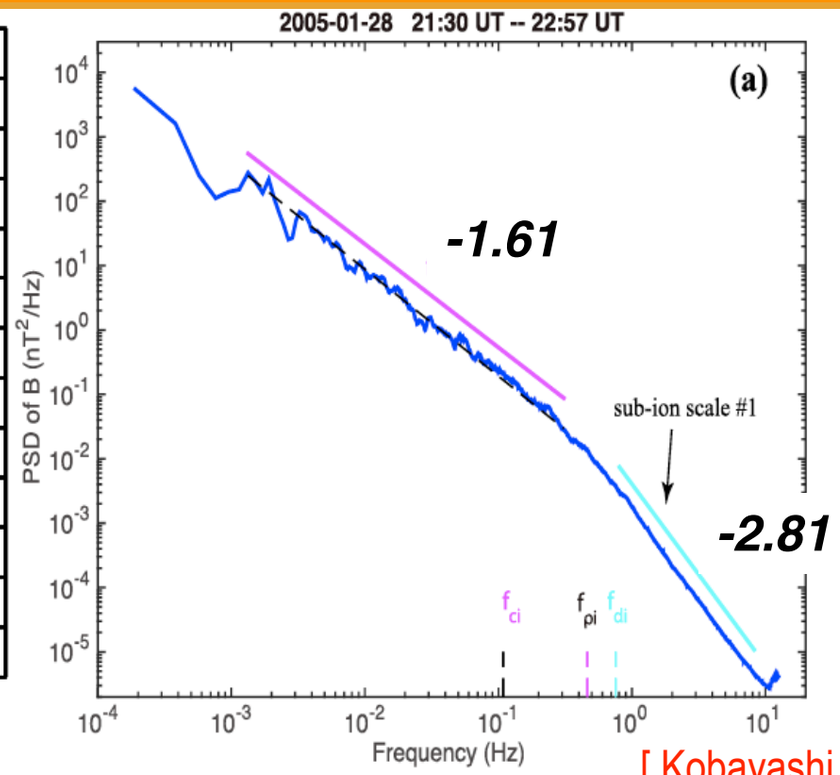
- B-spectrum ~ $k_\perp^{-7/3}$
- E-spectrum ~ $k_\perp^{-1/3}$
- Spectral anisotropy: $k_\parallel \sim k_\perp^{1/3}$

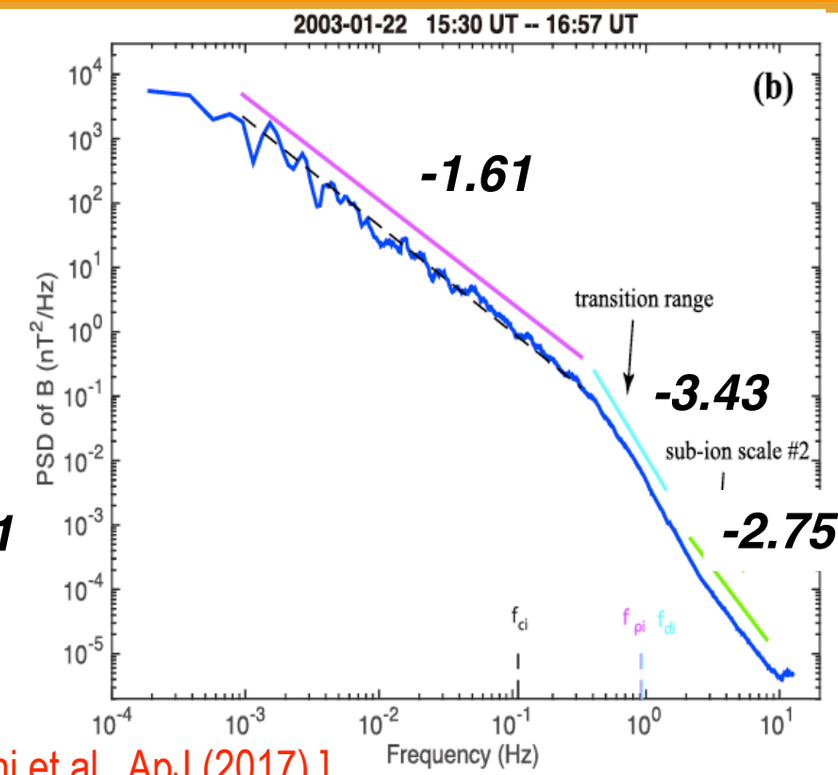
Universality of kinetic-range spectrum?

Solar Wind



[Alexandrova et al., SSR (2013)]

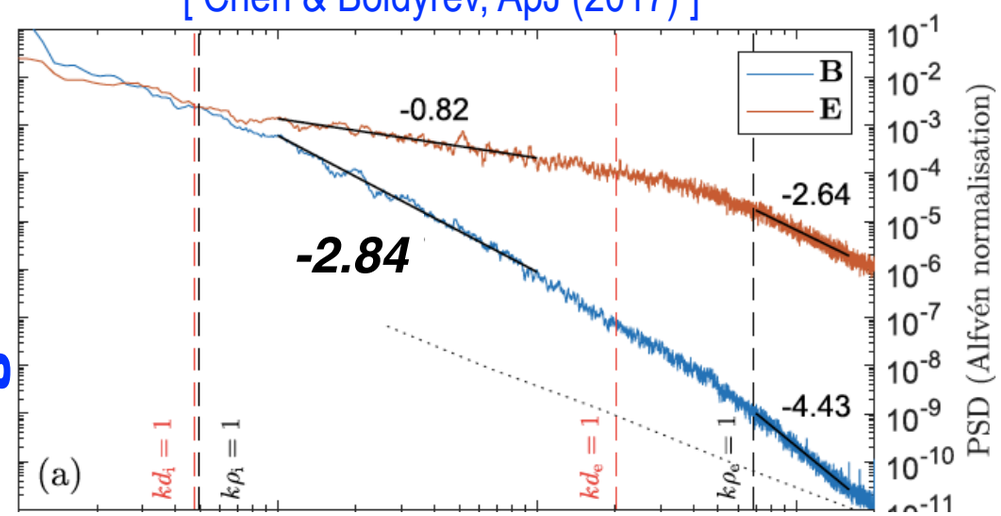




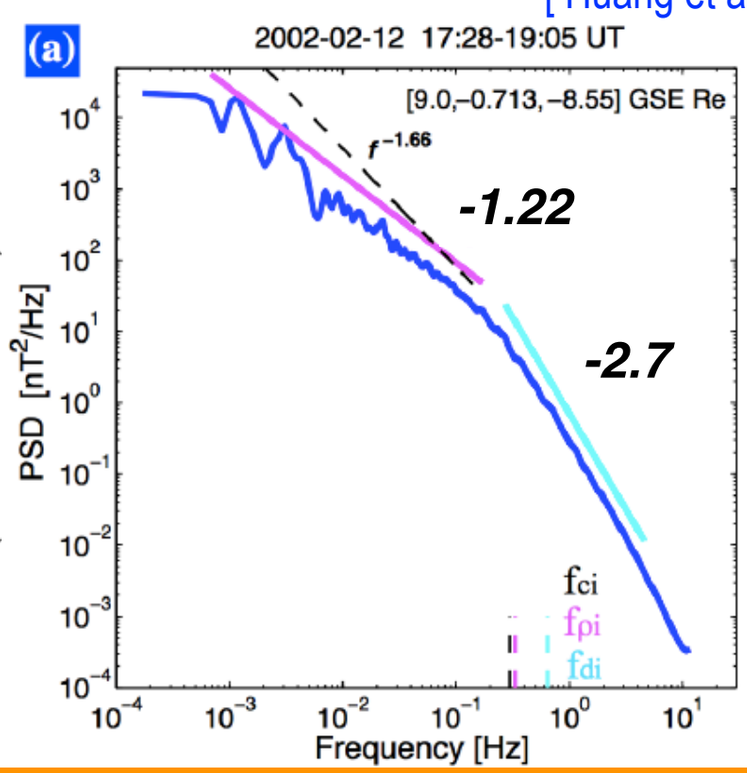
[Kobayashi et al., ApJ (2017)]

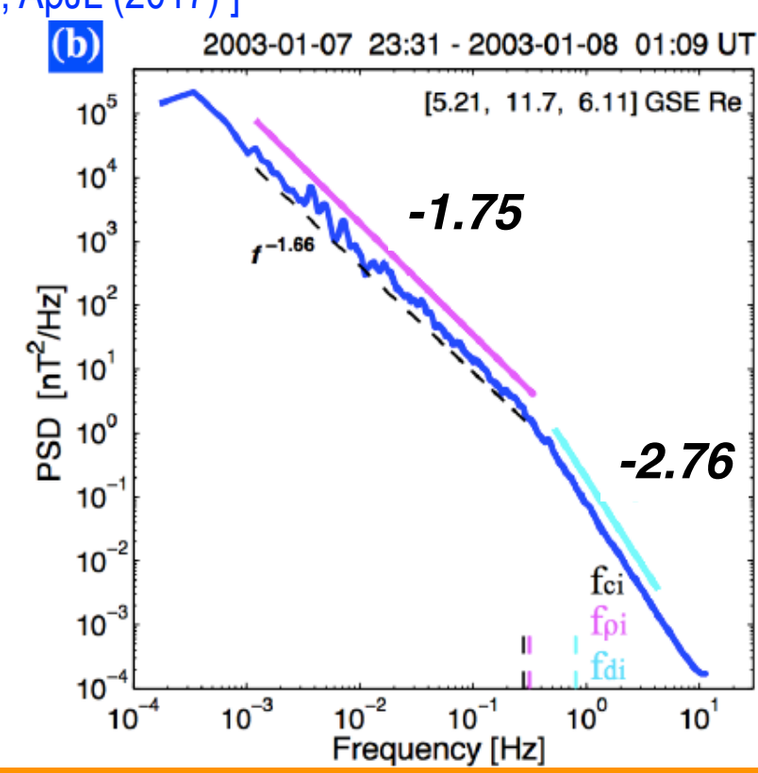
Magnetosheath

[Chen & Boldyrev, ApJ (2017)]

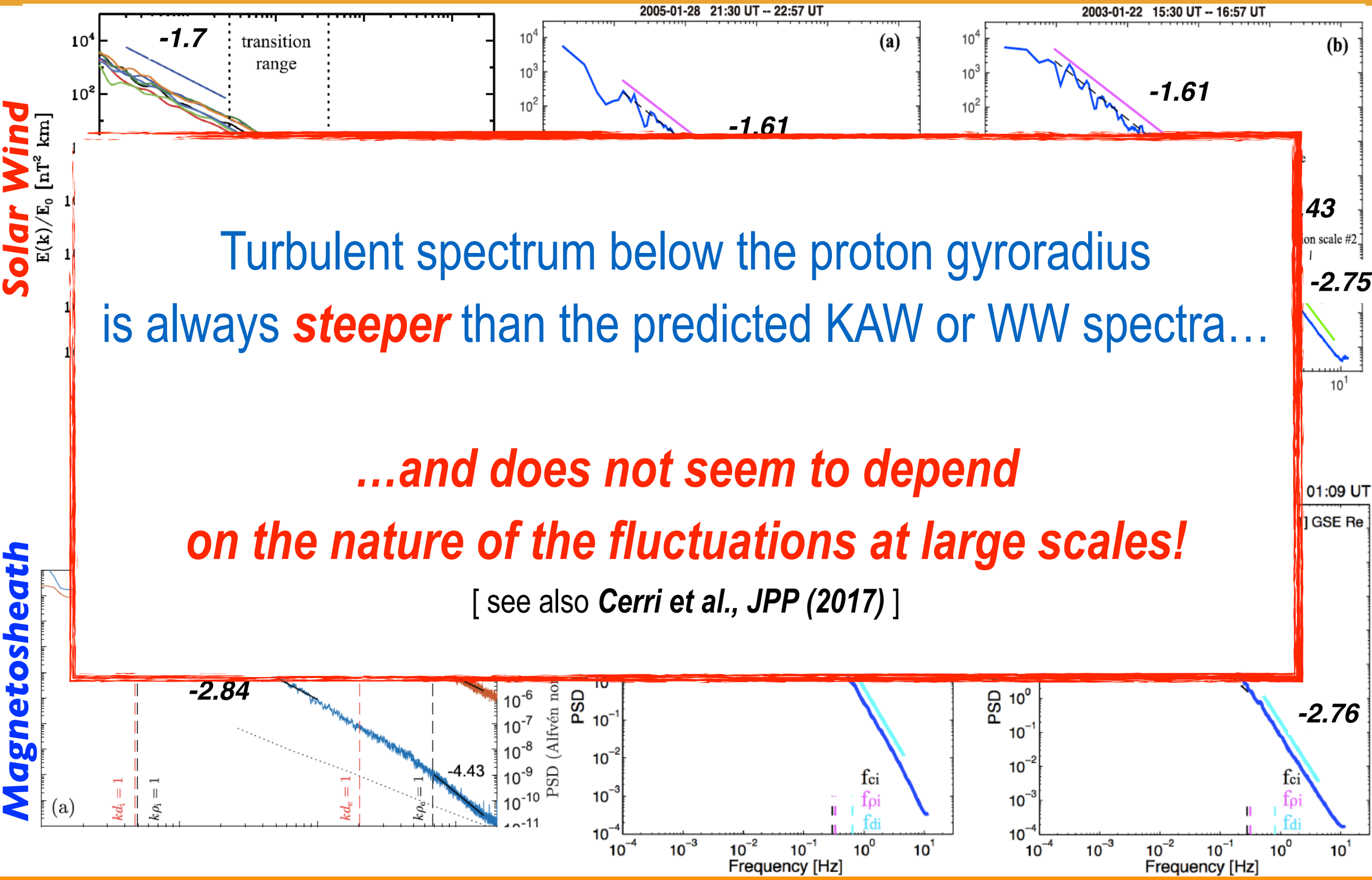


[Huang et al., ApJL (2017)]





Universality of kinetic-range spectrum?



Turbulent spectrum below the proton gyroradius is always ***steeper*** than the predicted KAW or WW spectra…

…and does not seem to depend on the nature of the fluctuations at large scales!

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

Universality of kinetic-range spectrum?

Additional possible sources of steepening

- Landau damping effects (within GK theory) [Howes et al., JGR (2008)]

exponential corrections ~ $k_\perp^{-7/3}\exp(-F[\omega(k),\gamma(k)])$

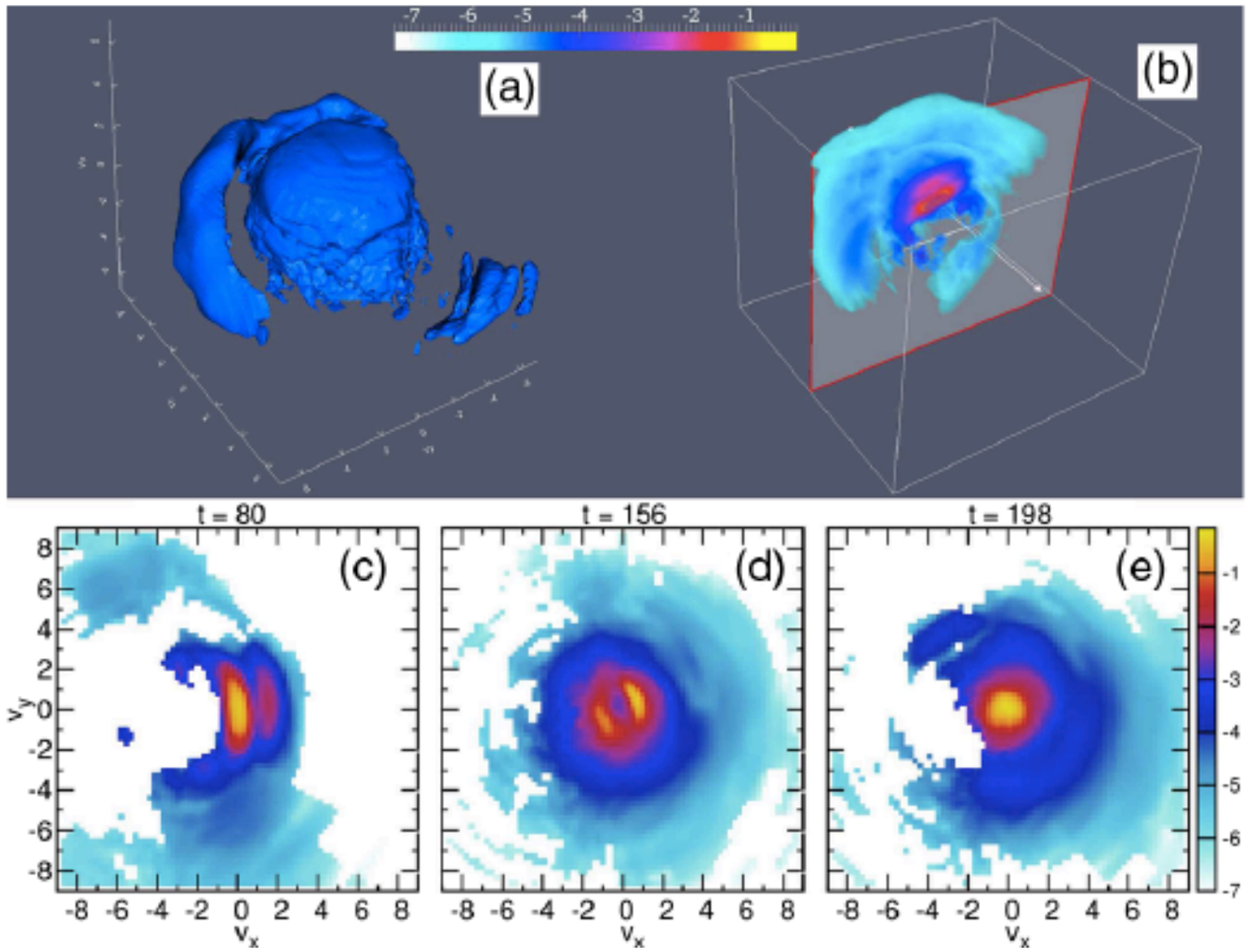
- Compressibility effects [Alexandrova et al., ApJ (2008)]

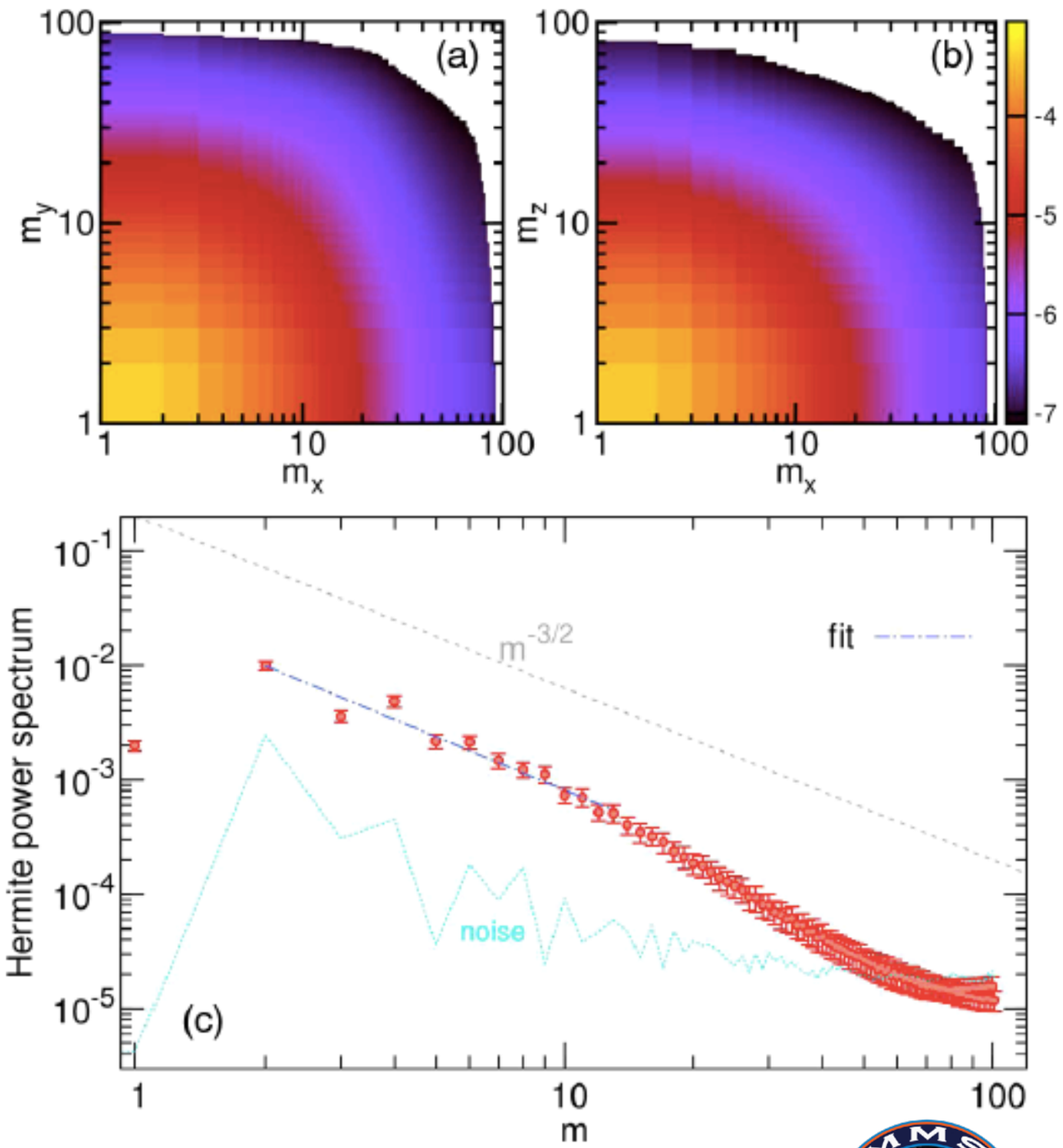
B-spectrum ~ $k_\perp^{-7/3-2\xi}$

- Intermittency effects [Boldyrev & Perez, ApJ (2012)]

B-spectrum ~ $k_\perp^{-8/3}$; E-spectrum ~ $k_\perp^{-2/3}$; anisotropy $k_{||} \sim k_\perp^{2/3}$

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)]

Plasma turbulence at kinetic scales

Fundamental questions:

☞ **What is the nature of the turbulent cascade at kinetic scales?**

☞ **How the turbulent energy is eventually dissipated in a "collisionless" plasma?**

we are going to focus on the ***scales above electron scales***
→ ***ion kinetic range*** *and* ***ion entropy cascade***

Meanwhile, on the simulations side…

- ***Gyrokinetic*** *simulations of driven Alfvén-wave turbulence* (3D-2V)
  Howes et al., PRL (2011); TenBarge & Howes, ApJL (2013); Told et al., PRL (2015)

- ***Hybrid-PIC*** *simulations of freely decaying Alfvénic turbulence* (2D & 3D) *and of driven Alfvénic turbulence* (3D)
  Franci et al., ApJ (2015; 2018); Arzamasskiy et al., in preparation

- ***Hybrid-Vlasov*** *simulations of freely decaying turbulence* (2D-3V & 3D-3V) *and driven compressible turbulence* (2D-3V)
  Valentini et al., PRL (2010); Servidio et al., PRL (2012); Servidio et al., JPP (2015); Cerri et al., ApJL (2016; 2017; 2018)

- ***Full-PIC*** *simulations of freely decaying Alfvénic turbulence* (3D)
  Groselj et al., PRL (2018)

- ***Full-Vlasov*** *simulations of freely decaying turbulence* (2D-3V Orszag-Tang)
  Juno et al., JCP (2018)

HVM model with 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)

[**Cerri** et al., ApJL (2016)]

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f + \left(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} + \boldsymbol{F}_{\rm ext}\right)\cdot\frac{\partial f}{\partial \boldsymbol{v}} = 0,$$

$$\left(1 - d_{\rm e}^2\nabla_\perp^2\right)\boldsymbol{E} = -\boldsymbol{u}\times\boldsymbol{B} + \frac{\boldsymbol{J}\times\boldsymbol{B}}{n} - \frac{\boldsymbol{\nabla} p_{\rm e}}{n},$$

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

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

- External random forcing (2D version only; injects momentum fluctuations; δ-correlated in time)
- 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

3D-3V turbulence

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

$\beta = 1$

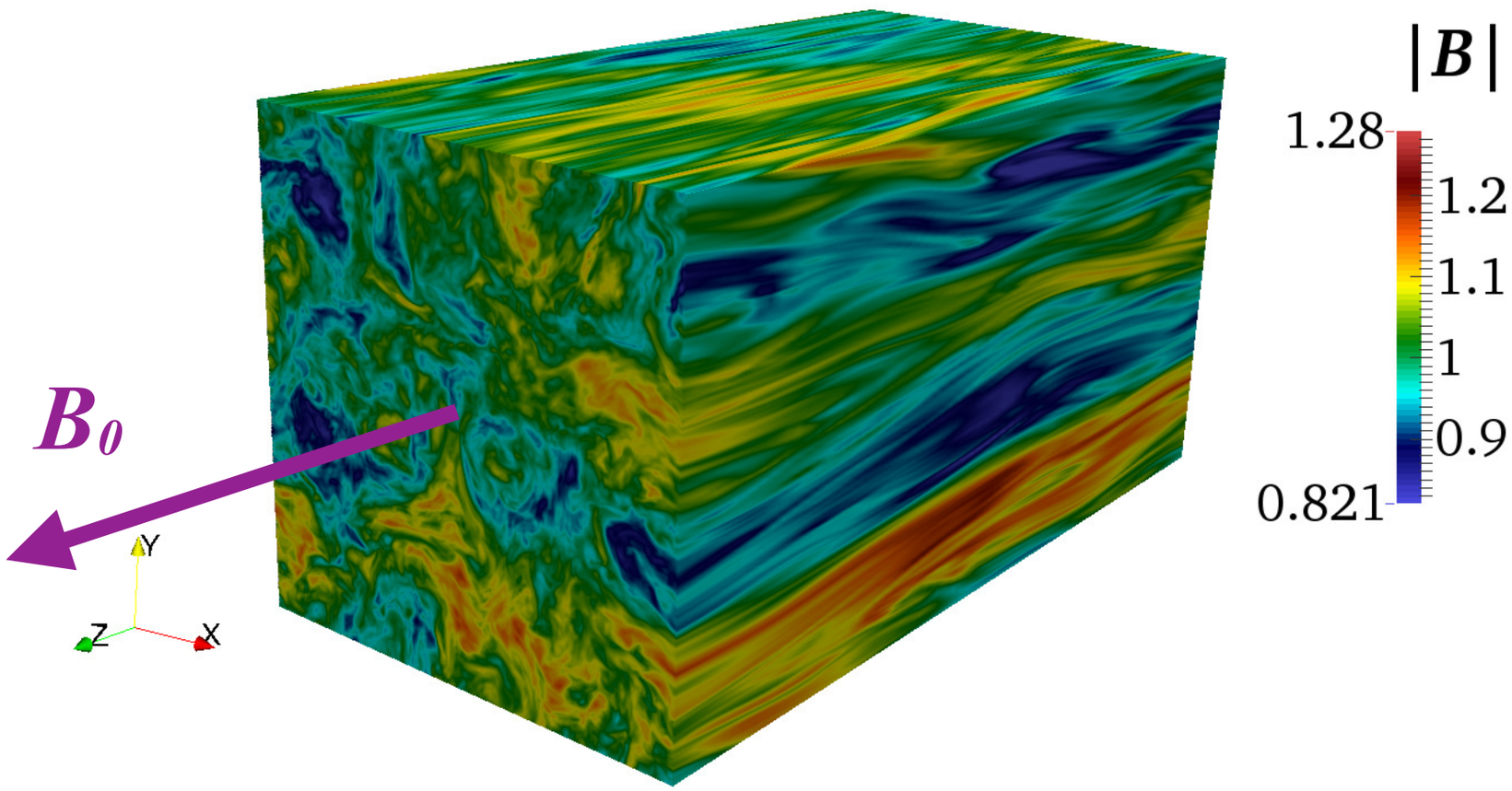
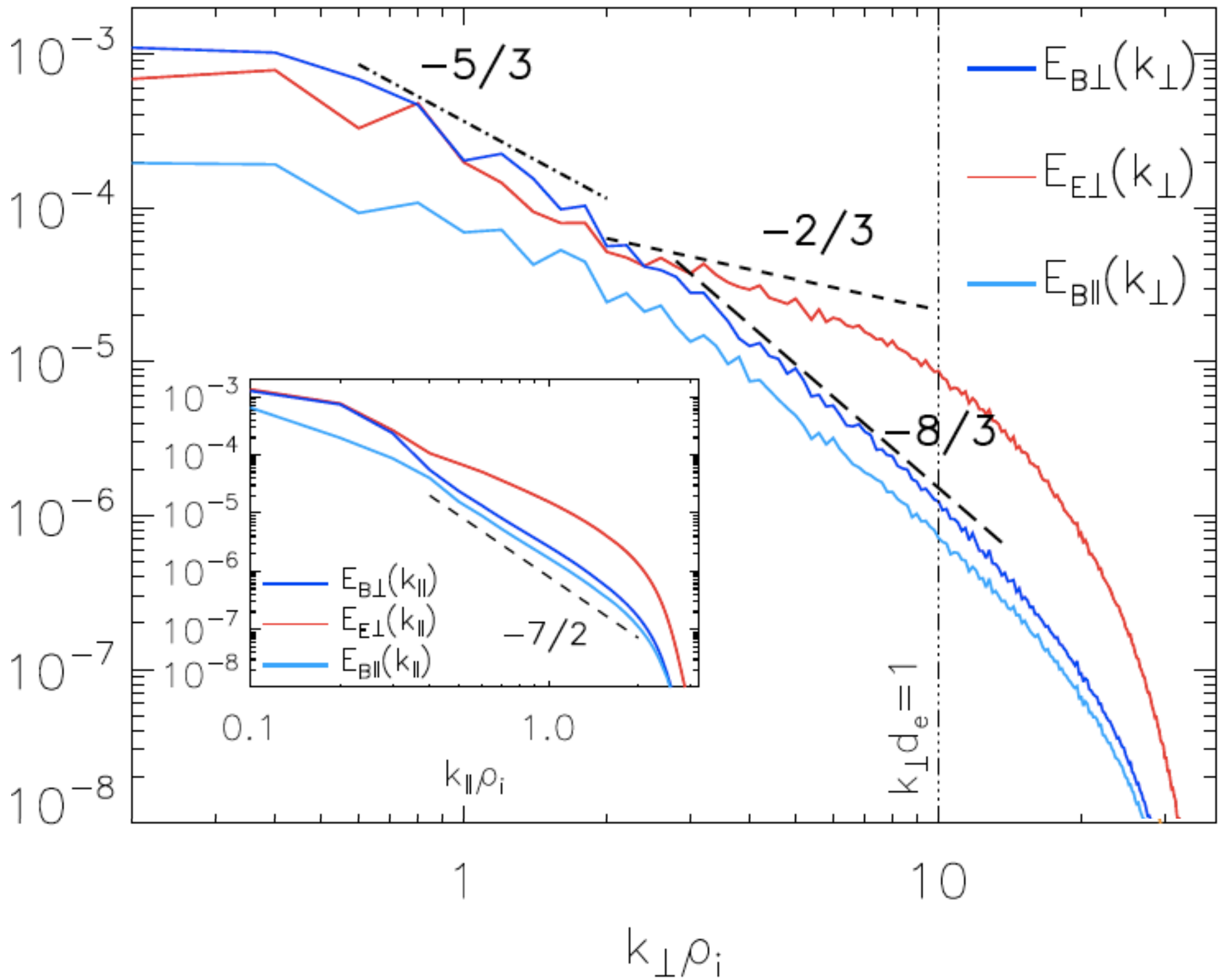


Figure: magnetic fluctuations (B_0 along z)

Properties of turbulent fluctuations

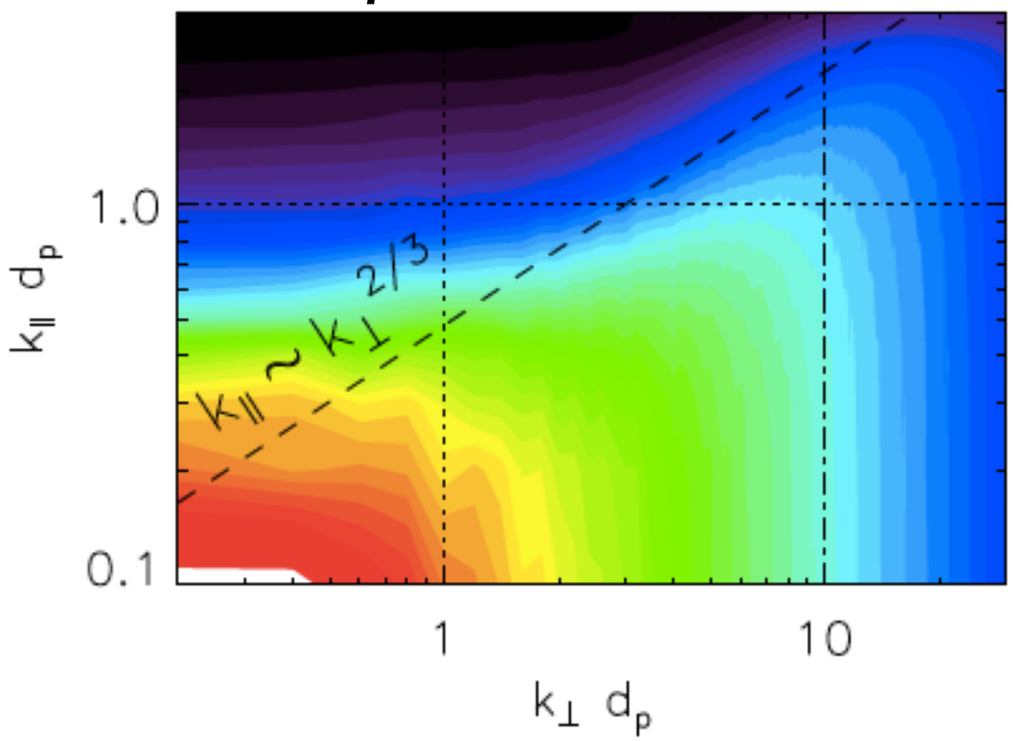
[**Cerri**, Kunz & Califano, ApJL (2018)]

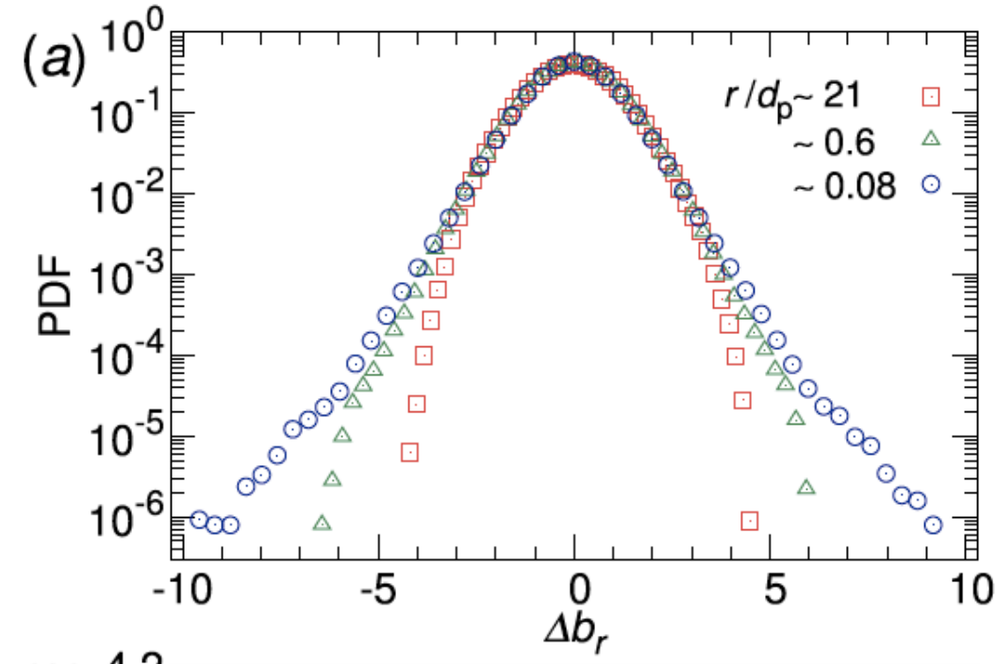


Properties of turbulent fluctuations

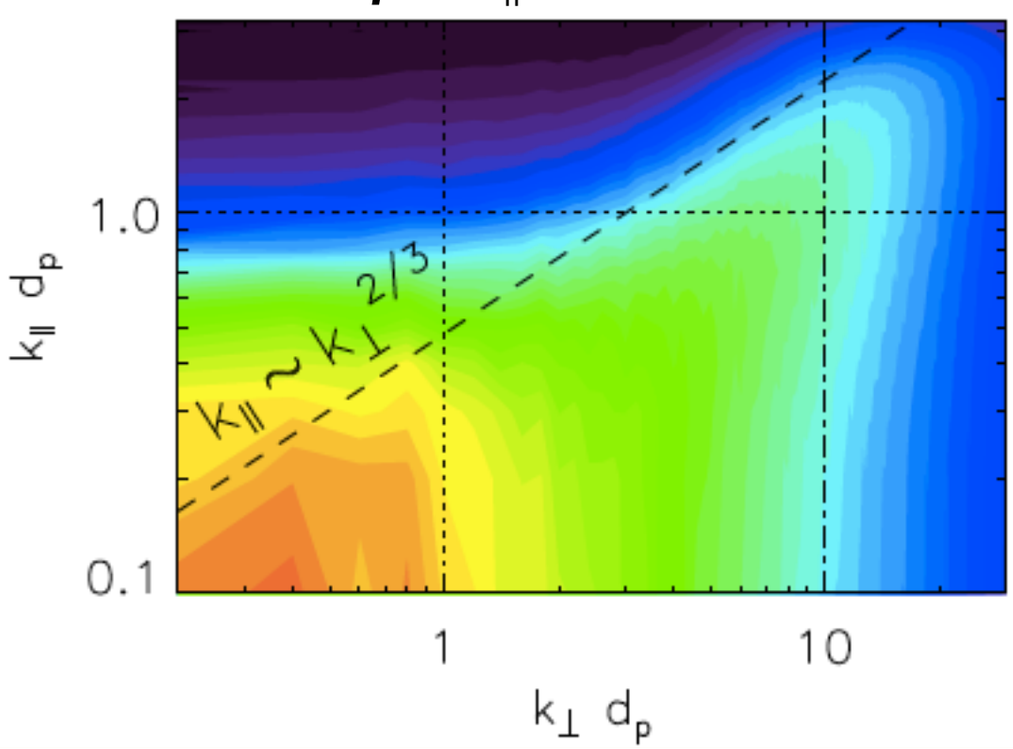
anisotropic and intermittent B fluctuations:

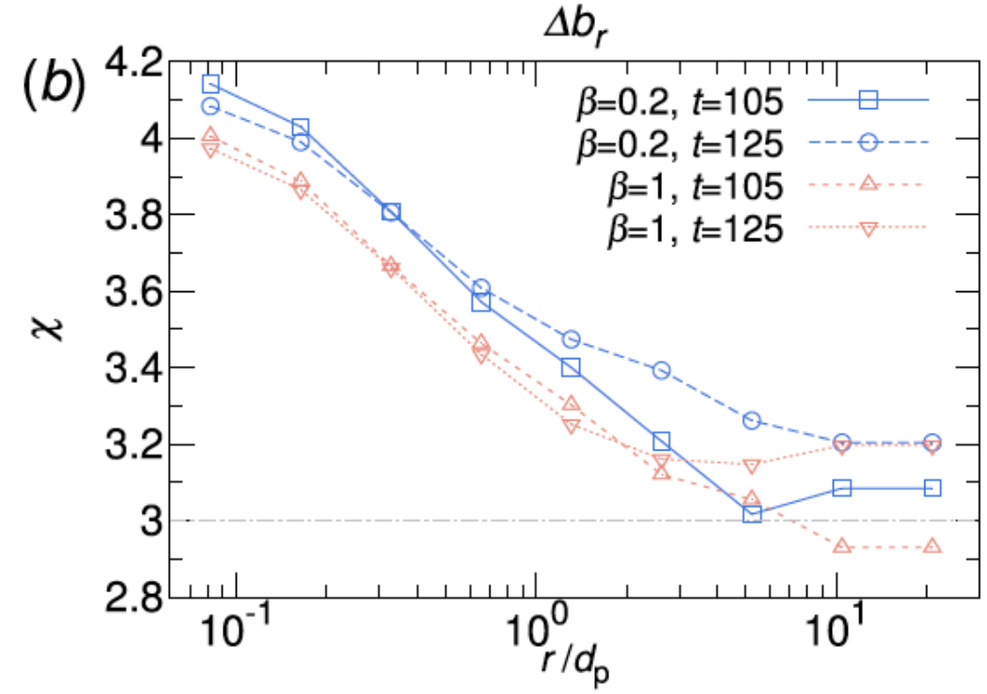
[**Cerri**, Servidio & Califano, ApJL (2017)]





anisotropic $E_\parallel$ fluctuations:





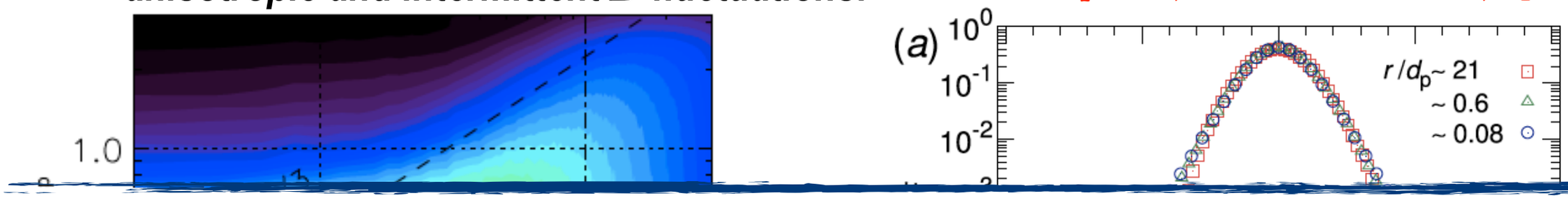
kinetic-scale anisotropy: $k_\parallel \sim k_\perp^{2/3}$

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

Properties of turbulent fluctuations

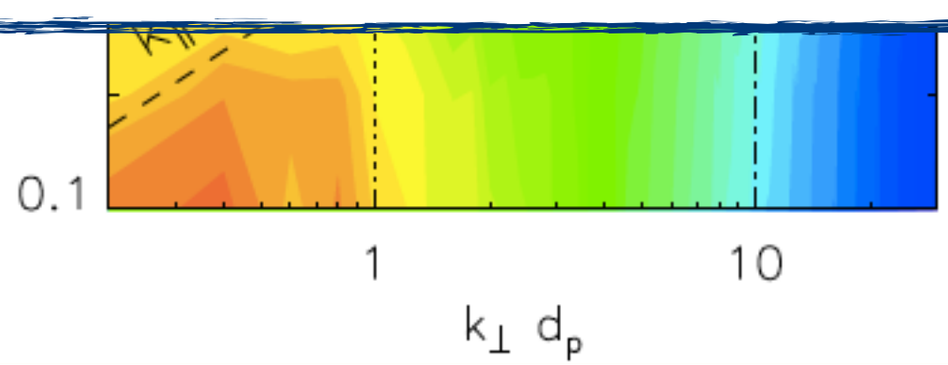
anisotropic and intermittent B fluctuations:

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



Electromagnetic fluctuations in 3D hybrid-kinetic turbulence at β = 1 are consistent with ***critically balanced, intermittent KAW turbulence***

see ***Cerri, Servidio & Califano, ApJL (2017)***

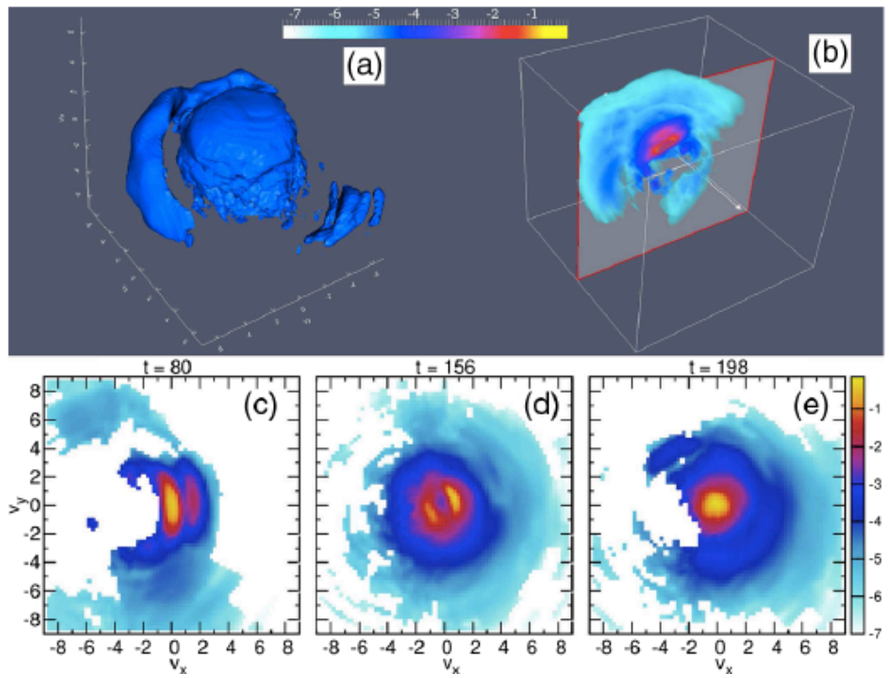


kinetic-scale anisotropy: $k_{\|} \sim k_{\perp}^{2/3}$

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

3D-3V turbulence

☞ ***3D-3V → turbulence in a six-dimensional phase space!***



How kinetic-range turbulence affects the distribution in phase space ?

Is there an ion entropy cascade ?

v-space cascades of free energy

linear (parallel) 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)
→ mainly along B_0 ("parallel")
and perhaps occurring at "large" scales:

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

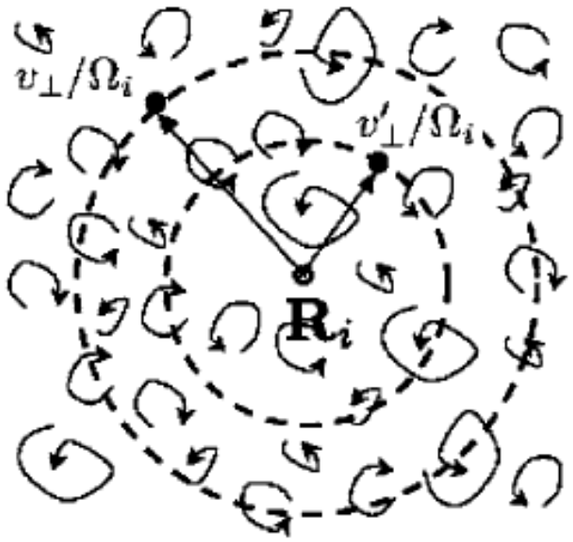
non-linear (perpendicular) phase mixing

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

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

faster than its linear counterpart,
but occurring only perpendicular to B_0
and below the ion gyro-radius:

$$k_\perp \rho_i \gg 1$$



[Schekochihin et al., ApJS (2009)]

v-space cascades of free energy

Hermite representation of v-space cascades

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

basis function (H_m = Hermite polynomial of order m)

$$\int_{-\infty}^{\infty} \psi_n(x)\psi_m(x)\,{\rm d}x = \delta_{nm}$$

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

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

non-linear phase mixing (GK theory of "ion-entropy cascade" in KAW turbulence) $\rightarrow$ ~ $m_{\perp}^{-7/6}$

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

Kolmogorov-like arguments on Vlasov equation (only v-space cascades?) $\rightarrow$ ~ $m^{-3/2}$ or m^{-2}

[Servidio et al., PRL (2017)]

v-space cascades of free energy

Generalized theory of "ion-entropy cascade"

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

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

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

allow for different spectral anisotropy (i.e., standard KAW anisotropy, intermittency-corrected case, constant anisotropy):

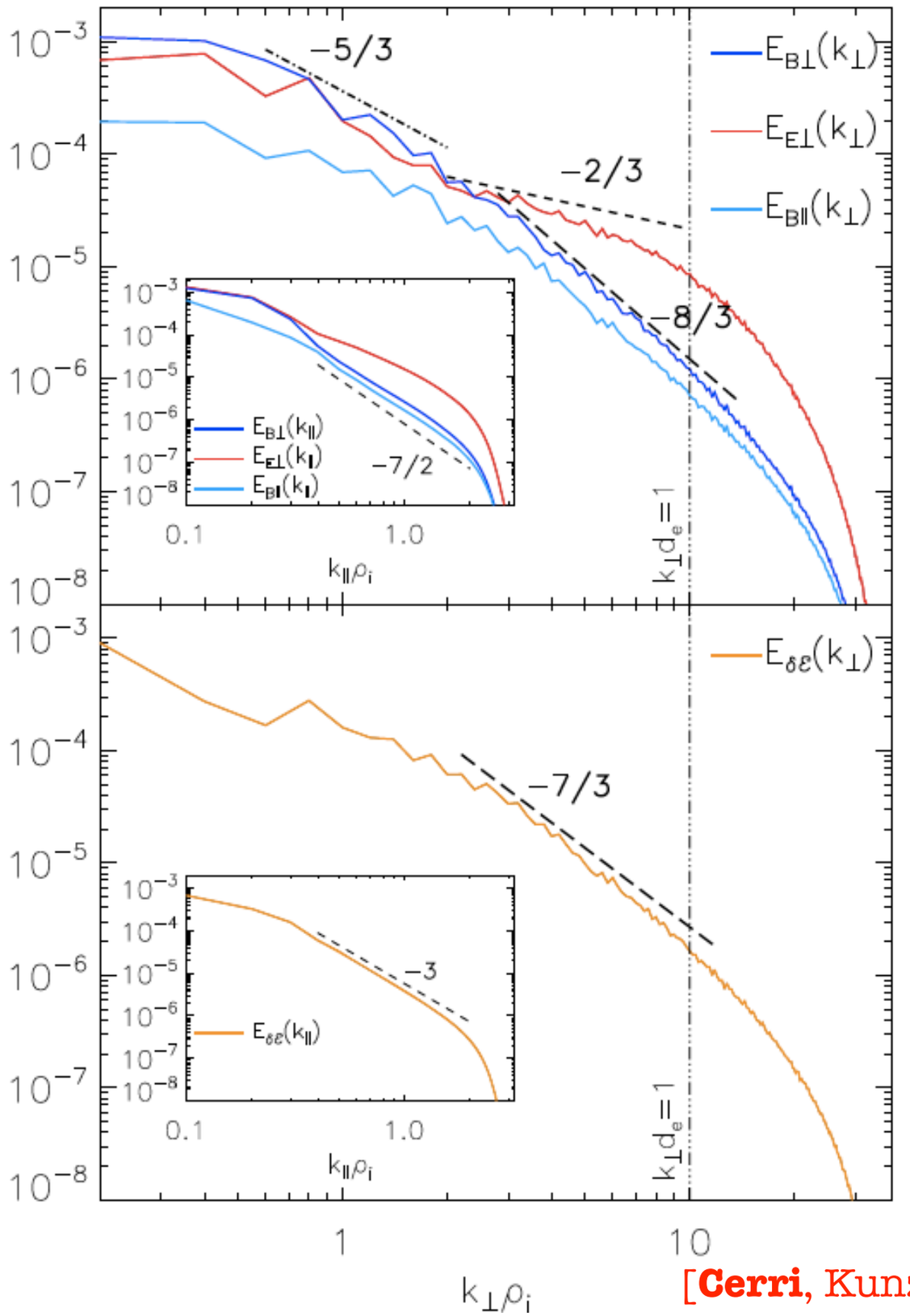
$$\ell_{\parallel,\lambda} \propto \lambda^{\alpha/3}$$

NOW use GK arguments (gyro-averaging) to derive scalings of non-adiabatic gyrokinetic response h: $h_\lambda^{(\alpha)} \propto \lambda^{\alpha/6}$

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

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

real-space cascade of ion entropy



All the scalings for electromagnetic fields
are consistent with the intermittency-corrected scenario
[Boldyrev & Perez, ApJL (2012)]

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

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

δE effectively behaves as a passive scalar…

…derive scalings for δE spectrum:

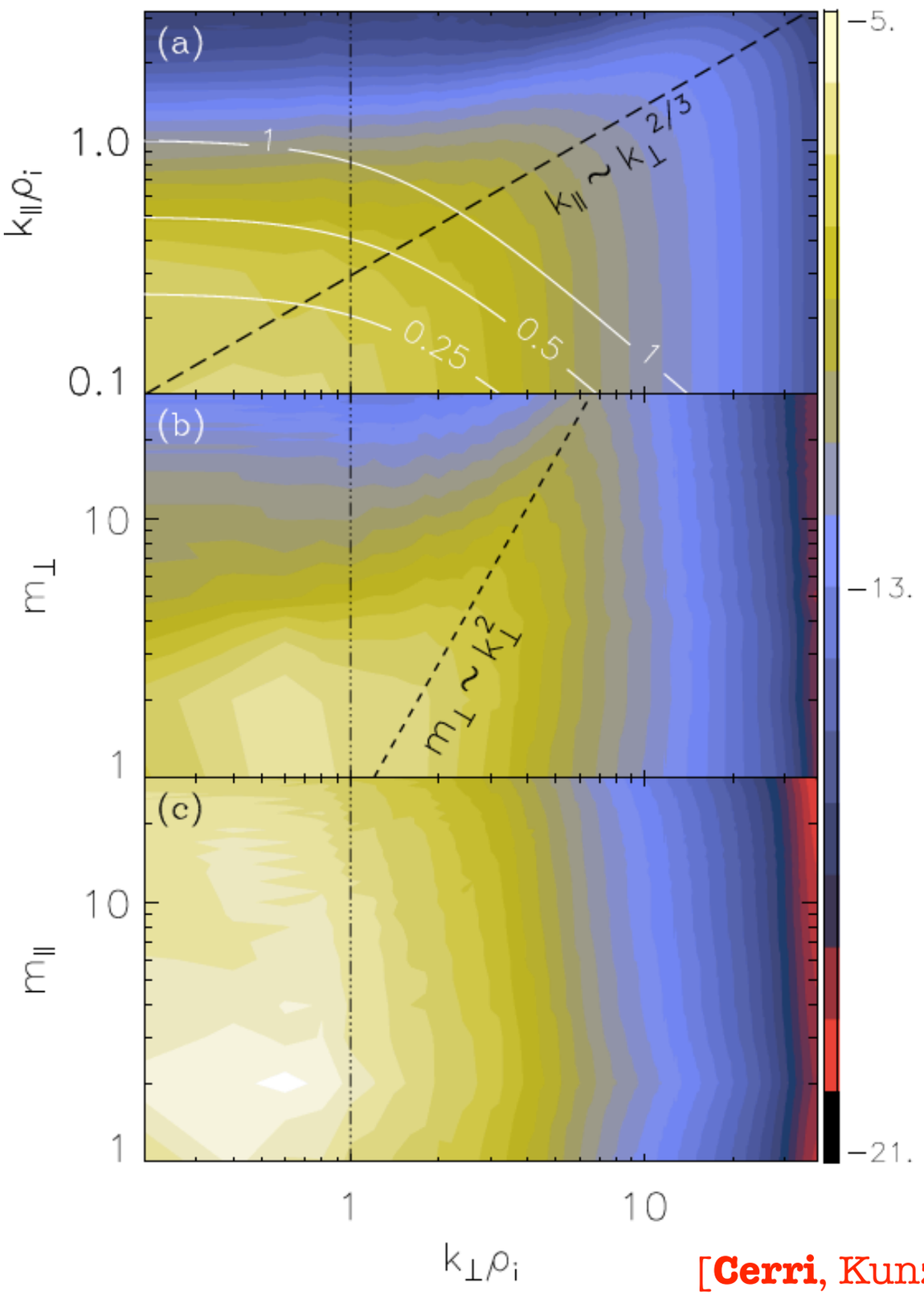
$$E_{\delta\mathcal{E}}(k_\perp) \propto k_\perp^{-(3+2\alpha)/3}$$

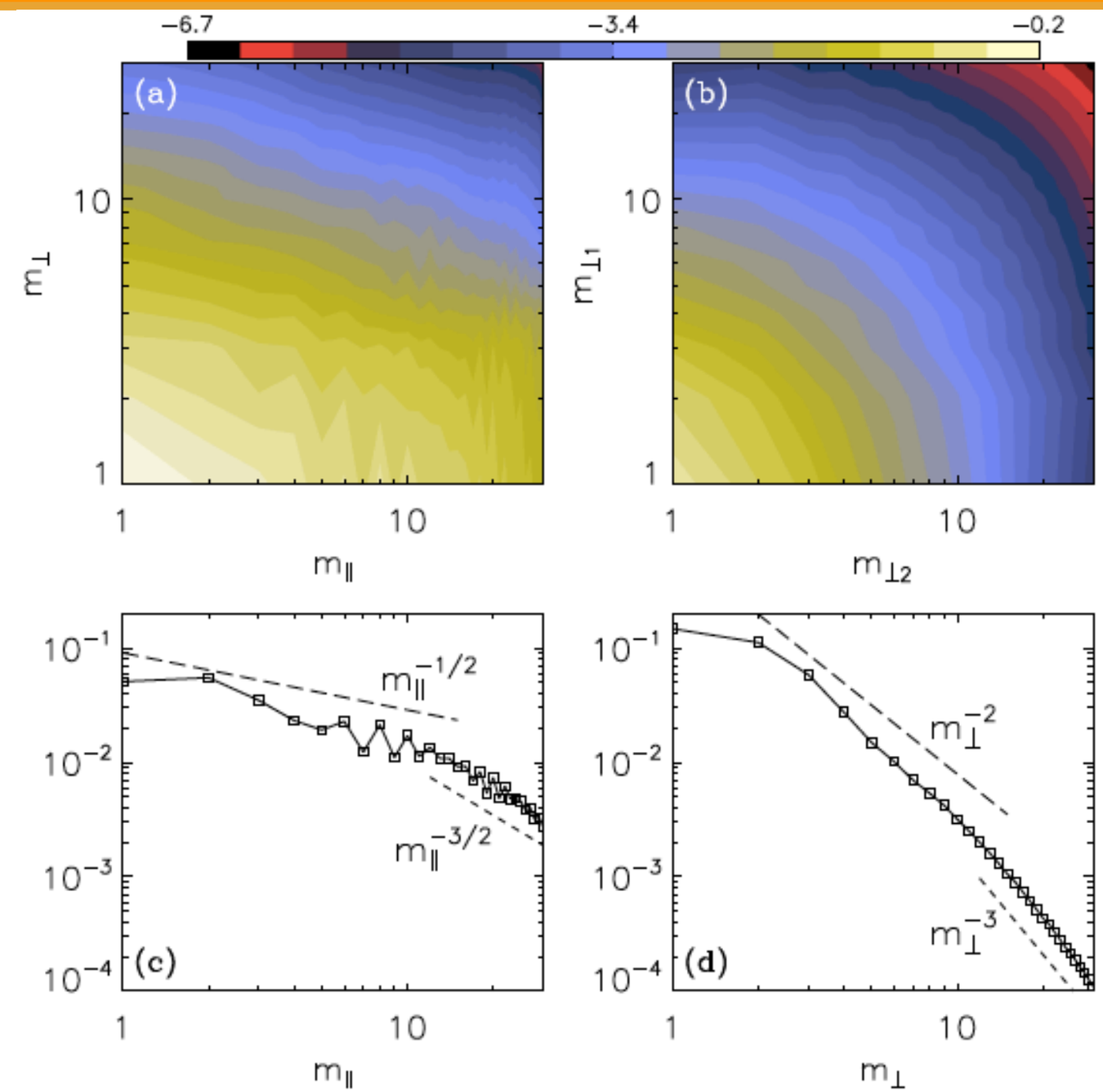
$$E_{\delta\mathcal{E}}(k_\parallel) \propto k_\parallel^{-3}$$

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

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

phase-space cascades of δf

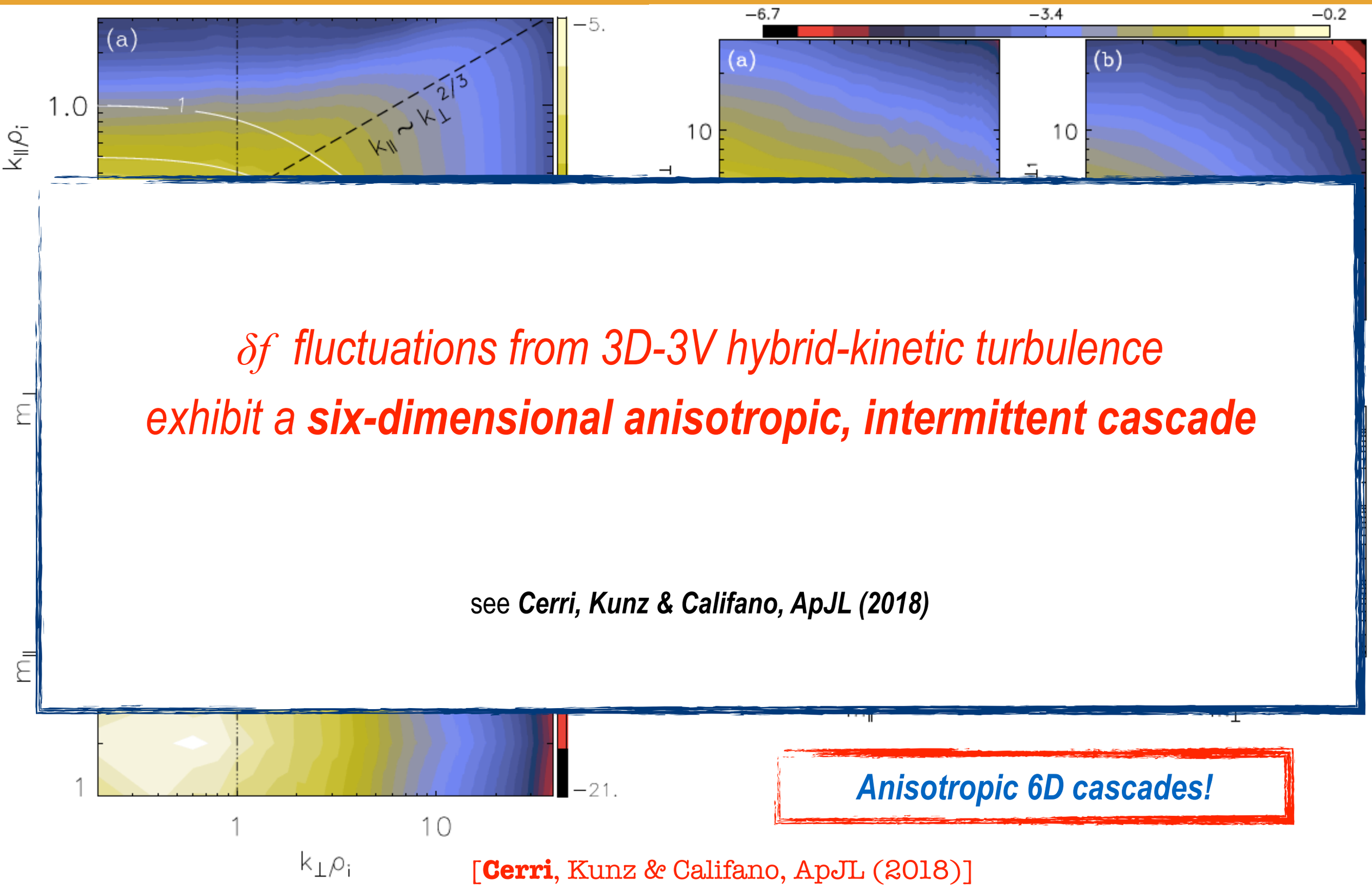




Anisotropic 6D cascades!

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

phase-space cascades of δf



*δf fluctuations from 3D-3V hybrid-kinetic turbulence exhibit a **six-dimensional anisotropic, intermittent cascade***

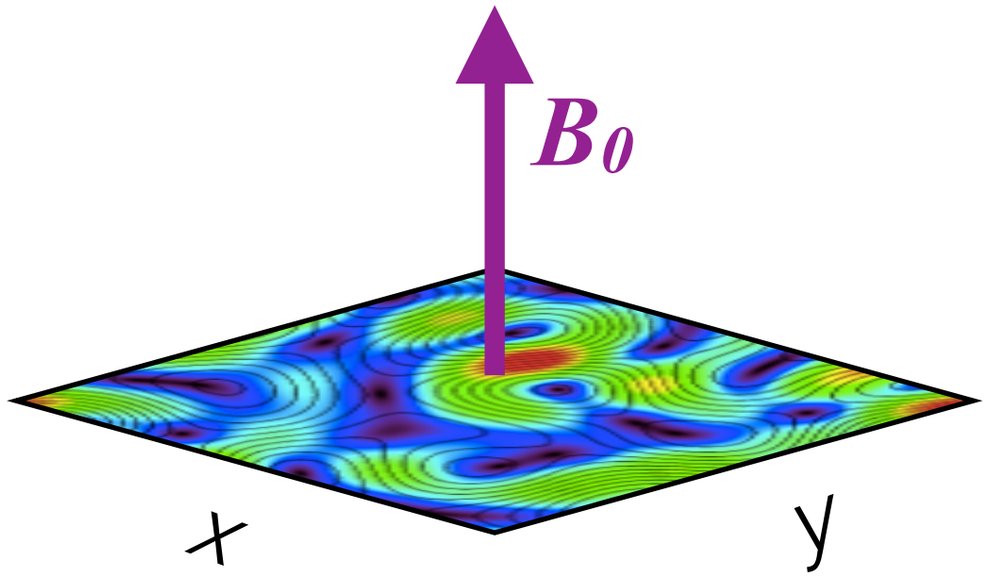
see ***Cerri, Kunz & Califano, ApJL (2018)***

Anisotropic 6D cascades!

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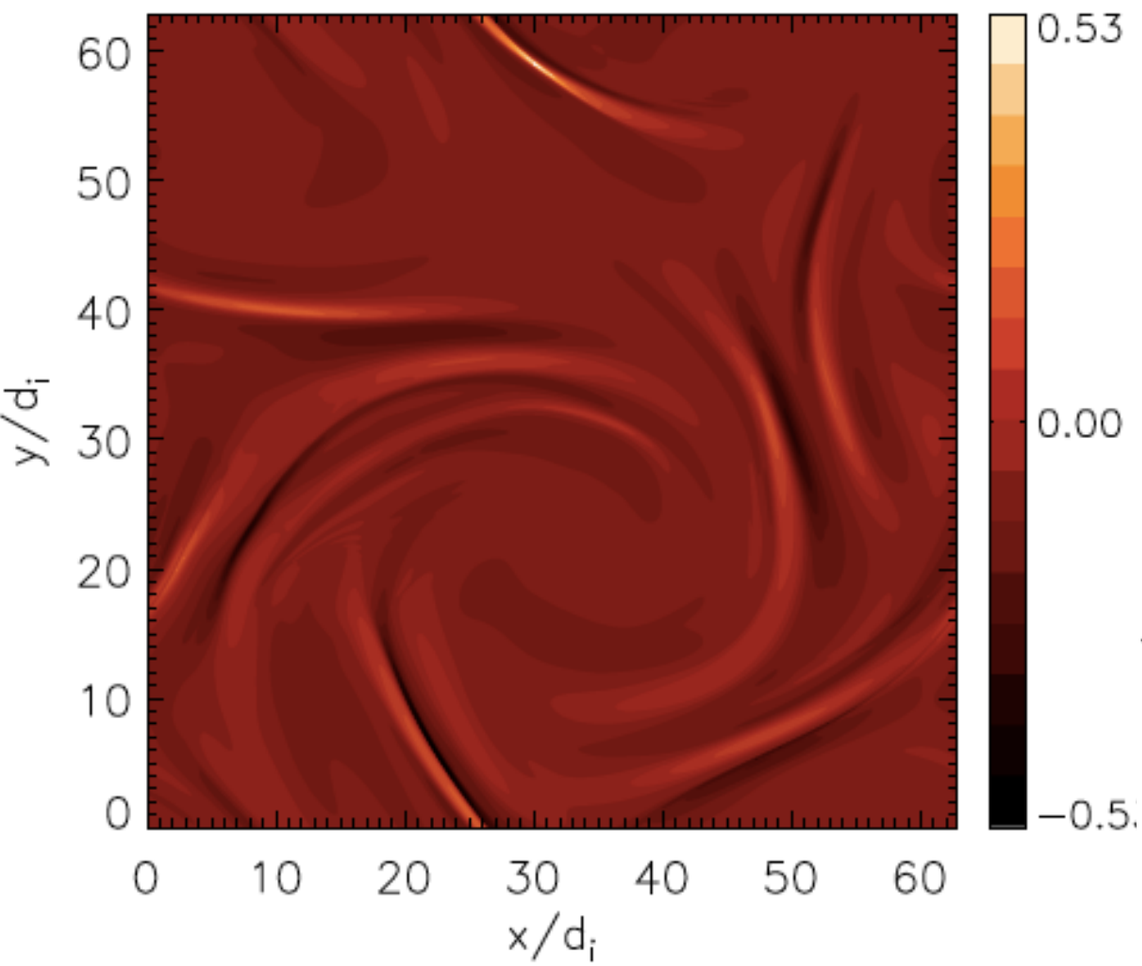
Keywords: plasma turbulence, space plasmas, magnetic reconnection, Vlasov simulations

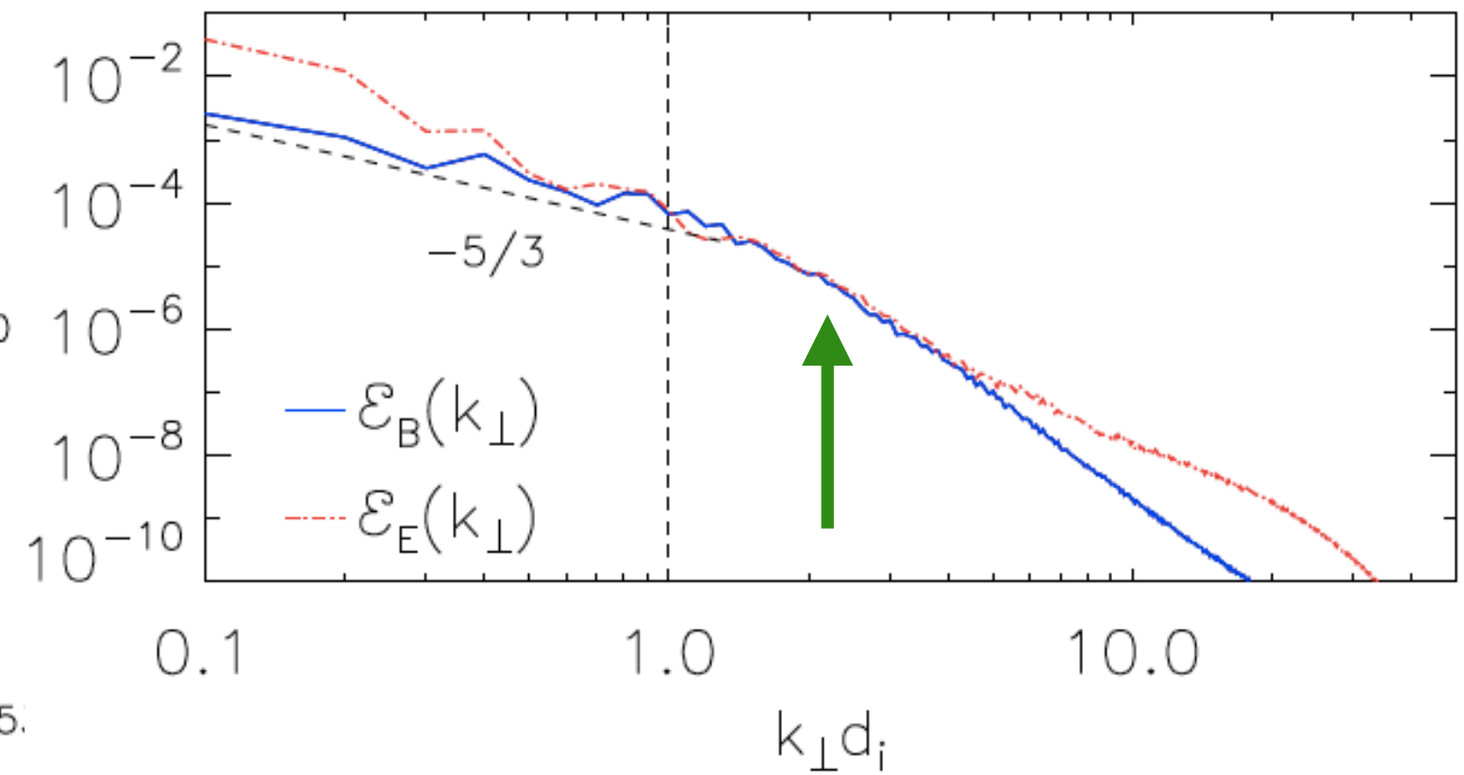
scales which then cascade towards smaller and smaller scales. We have therefore identified the fast magnetic reconnection processes as the preferred (or concurrent) mediators for the cascade at small-scales, thus picturing turbulence and magnetic reconnection as tightly entwined self-regulating processes 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

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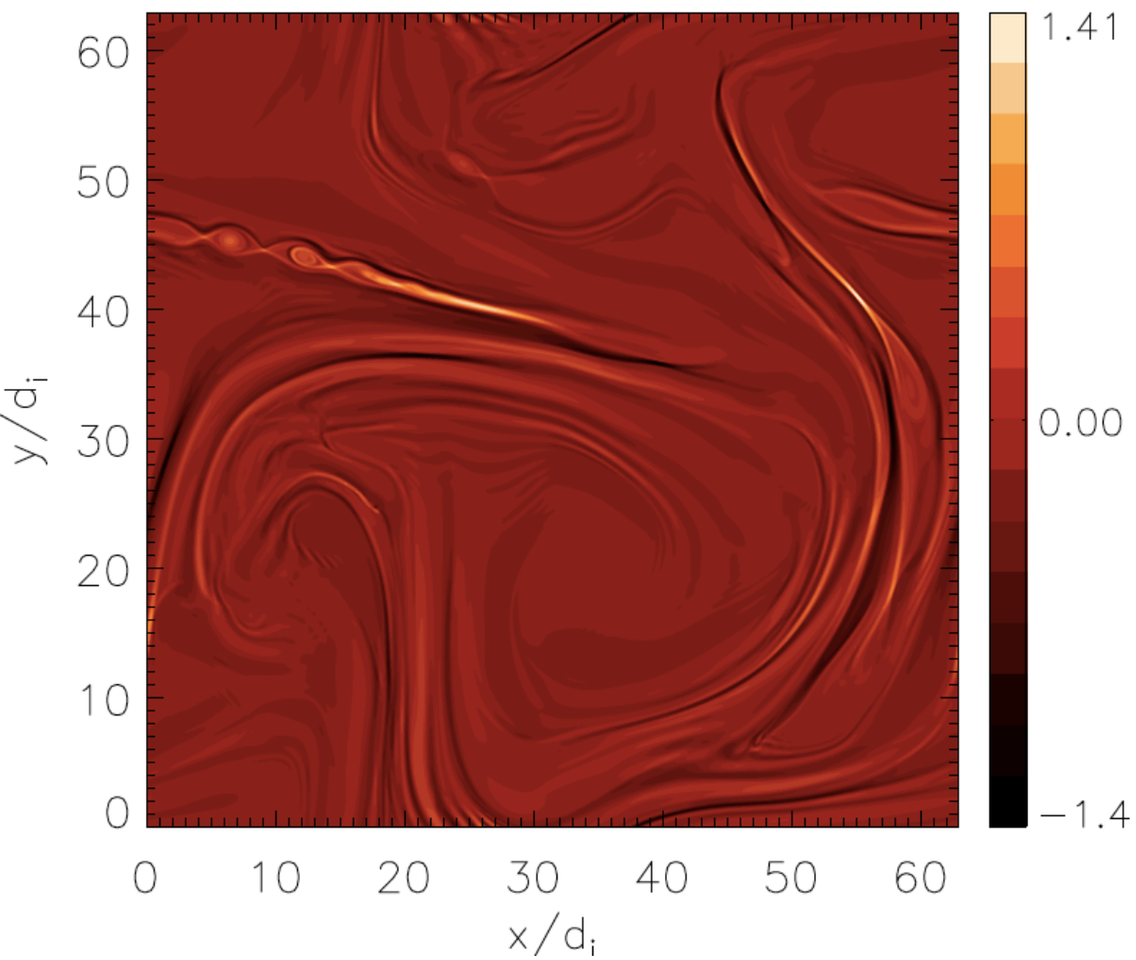

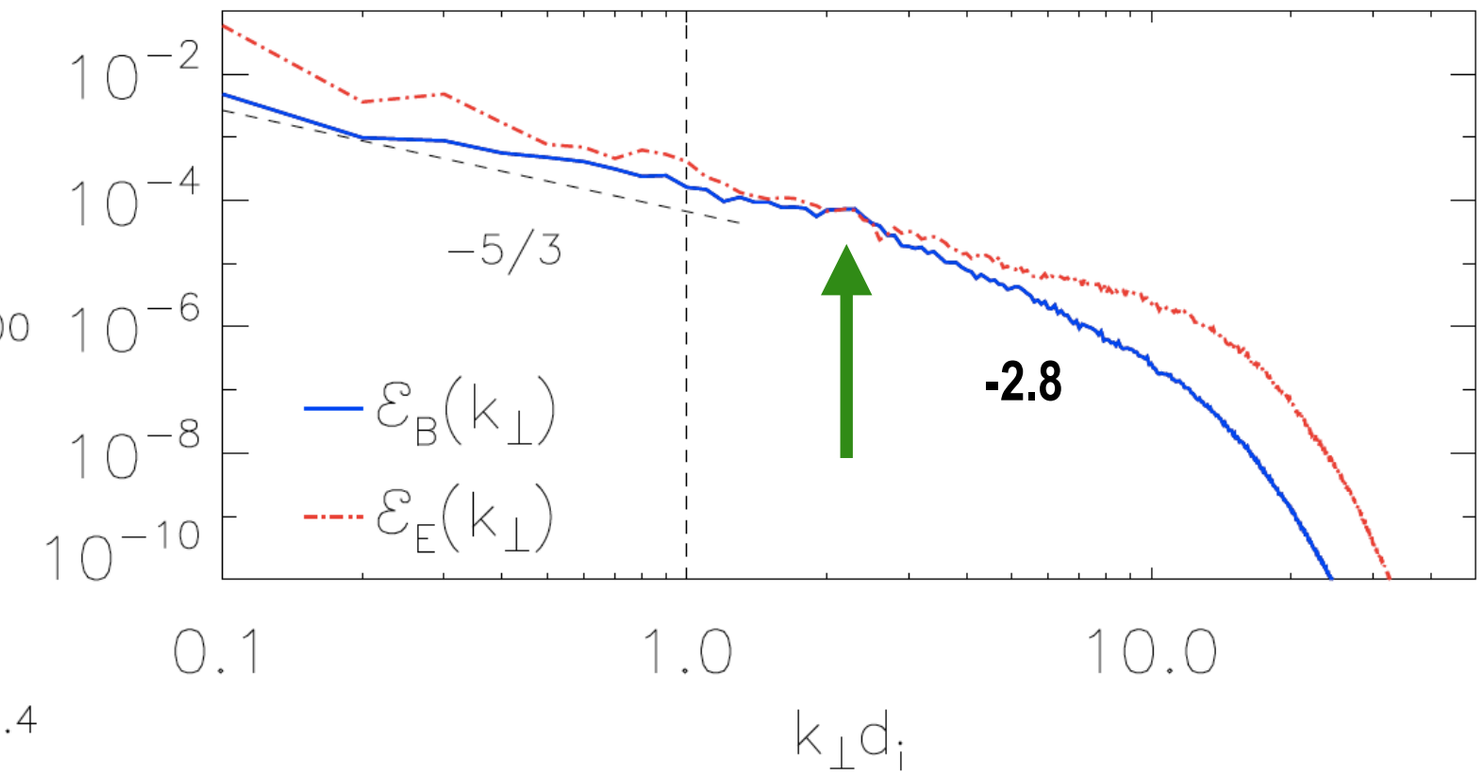

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Reconnection-mediated turbulence

[**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)***

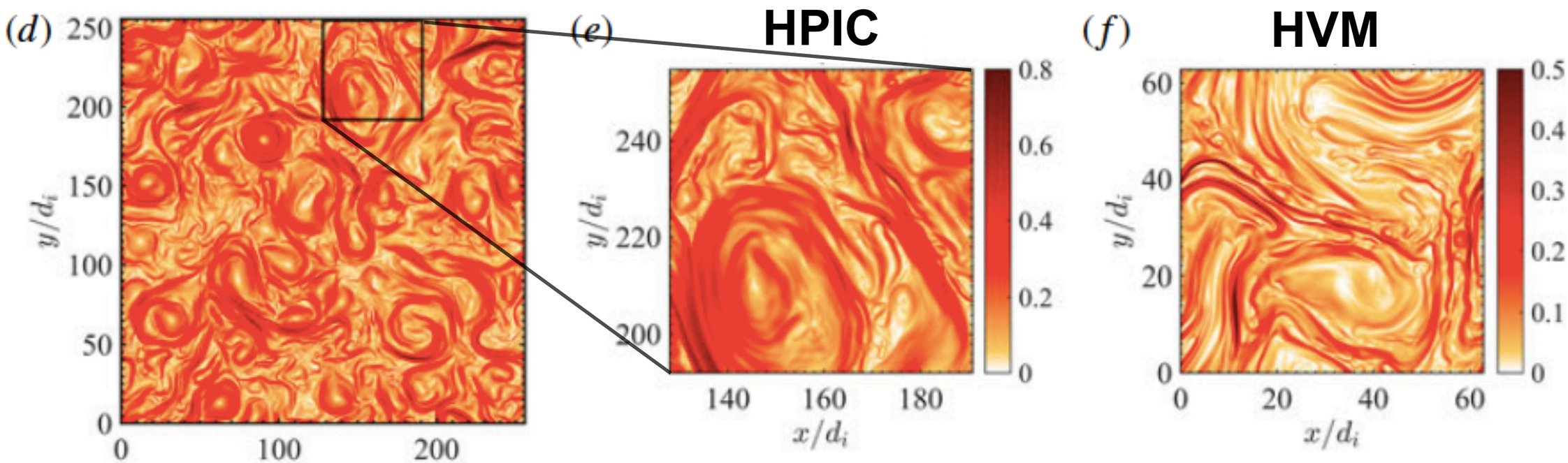
Does this depend on large-scale details ?

HPIC	HVM
2048^2 x 64000ppc	1024^2 x 51^3
$L = 256\ d_i$; $dx = 0.125\ d_i$	$L \sim 63\ d_i$; $dx \sim 0.06\ d_i$; $dv = 0.2\ v_{th,i}$
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

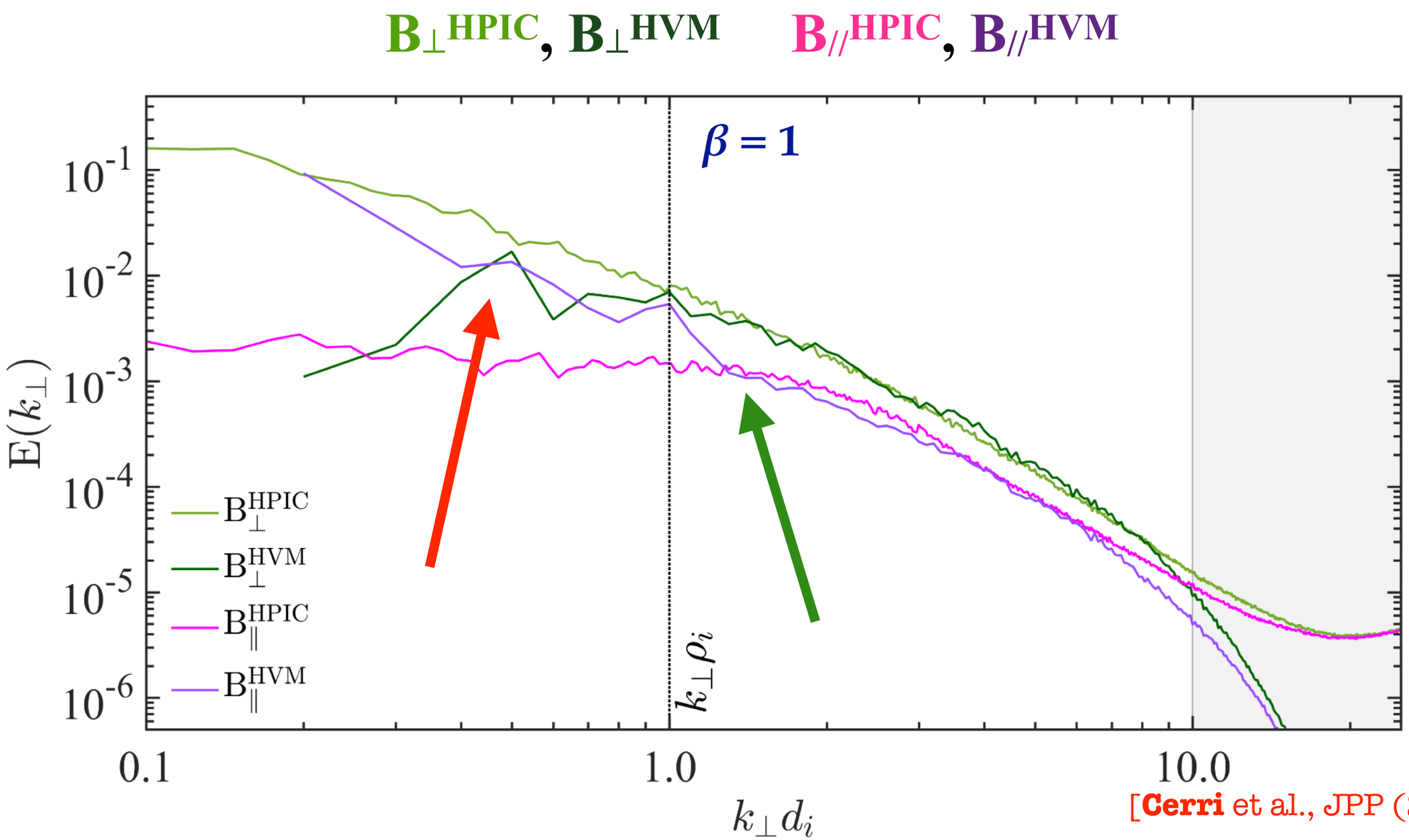
of ***coherent structures via magnetic reconnection****…*

…despite completely different large-scale properties!

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

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

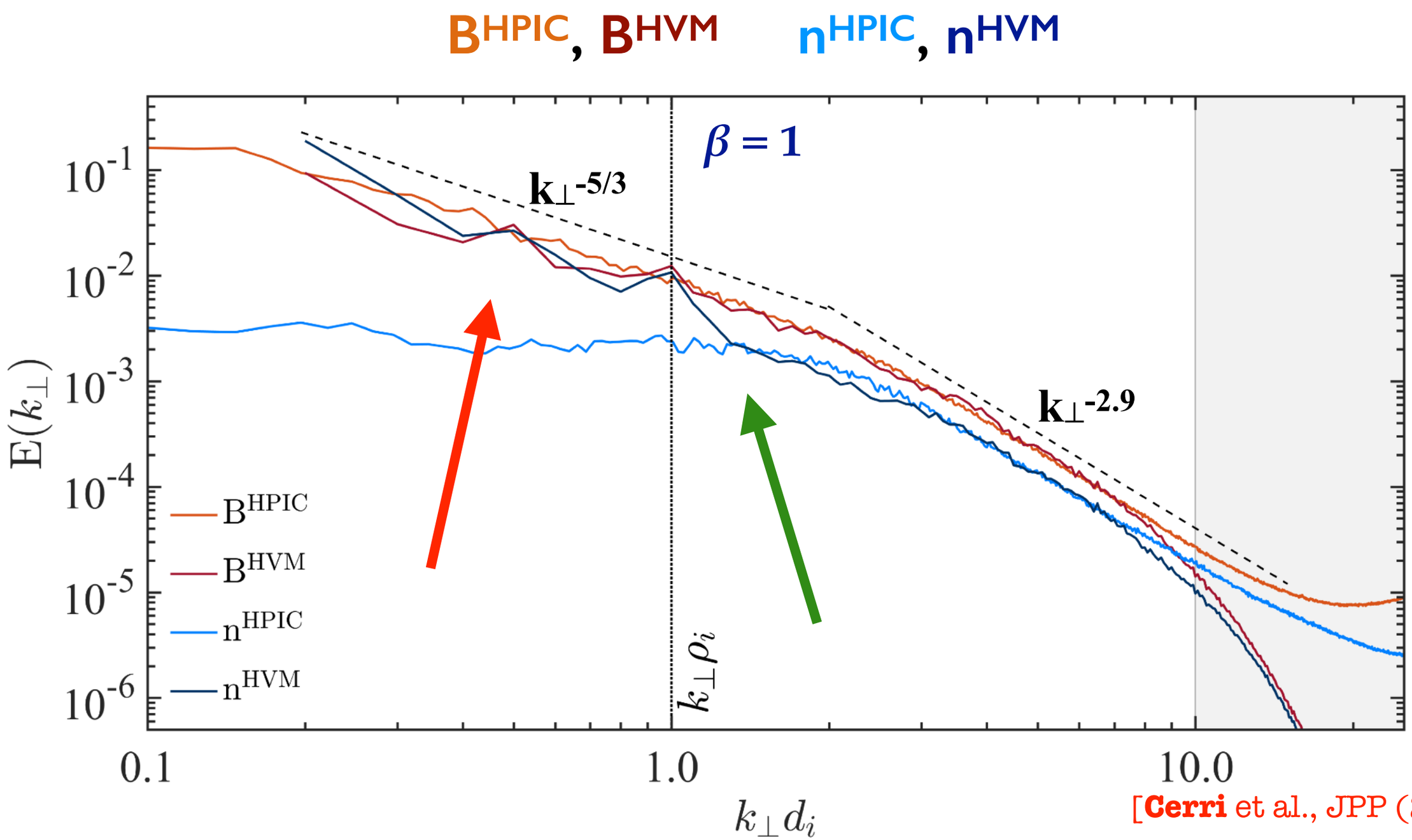
Does this depend on large-scale details ?



[**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 ?



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Does this depend on large-scale details ?

B^{HPIC}, B^{HVM} n^{HPIC}, n^{HVM}

Point #3

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

… perhaps …

… same underlying process allows/mediates the kinetic cascade!

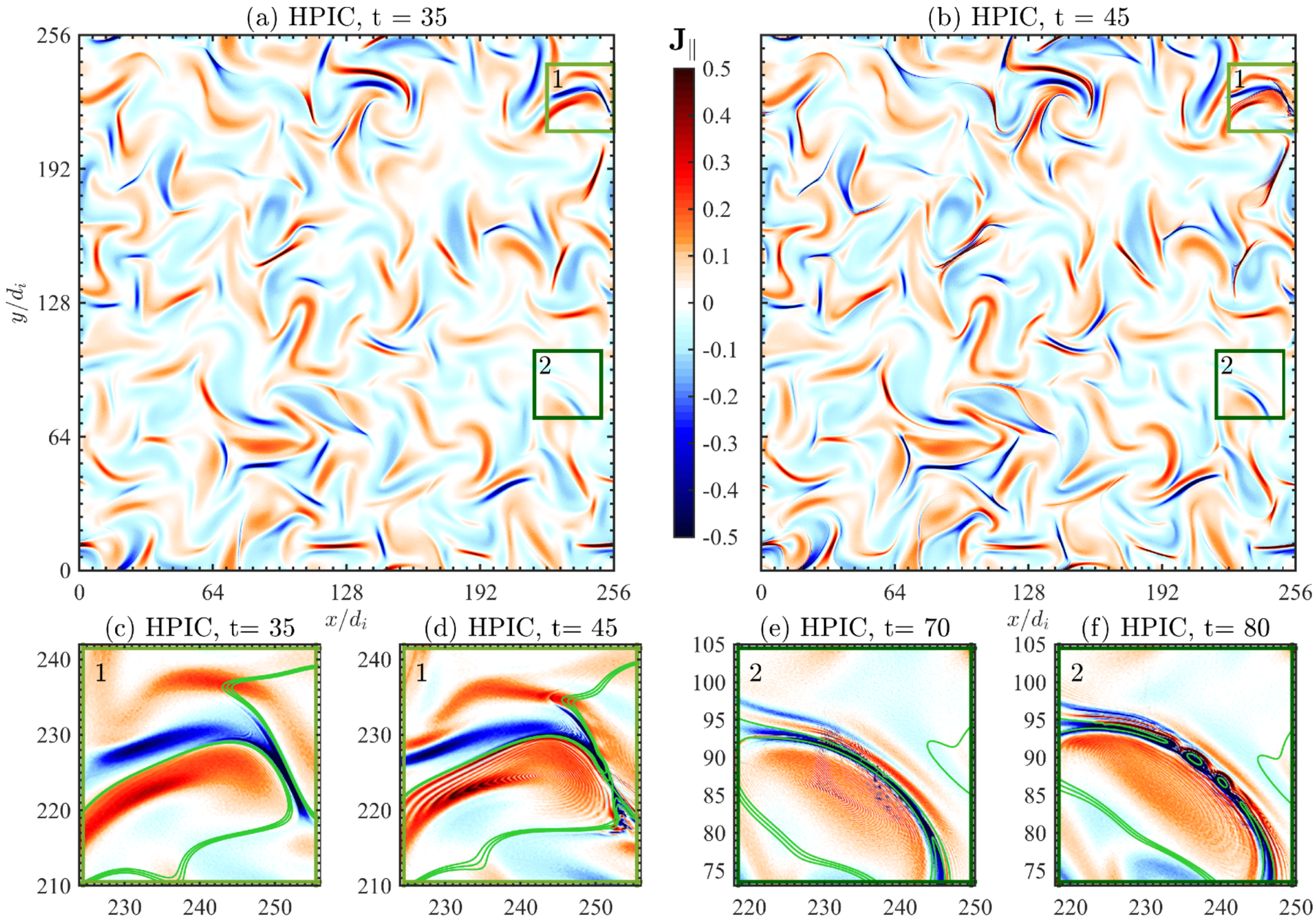
[☞ ***reconnection***]

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

- Numerical effects at the smallest scales (ppc-noise in HPIC, filters in HVM)

Short-circuiting the cascade

Tracking local current intensity increase and reconnection events



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

Short-circuiting the cascade

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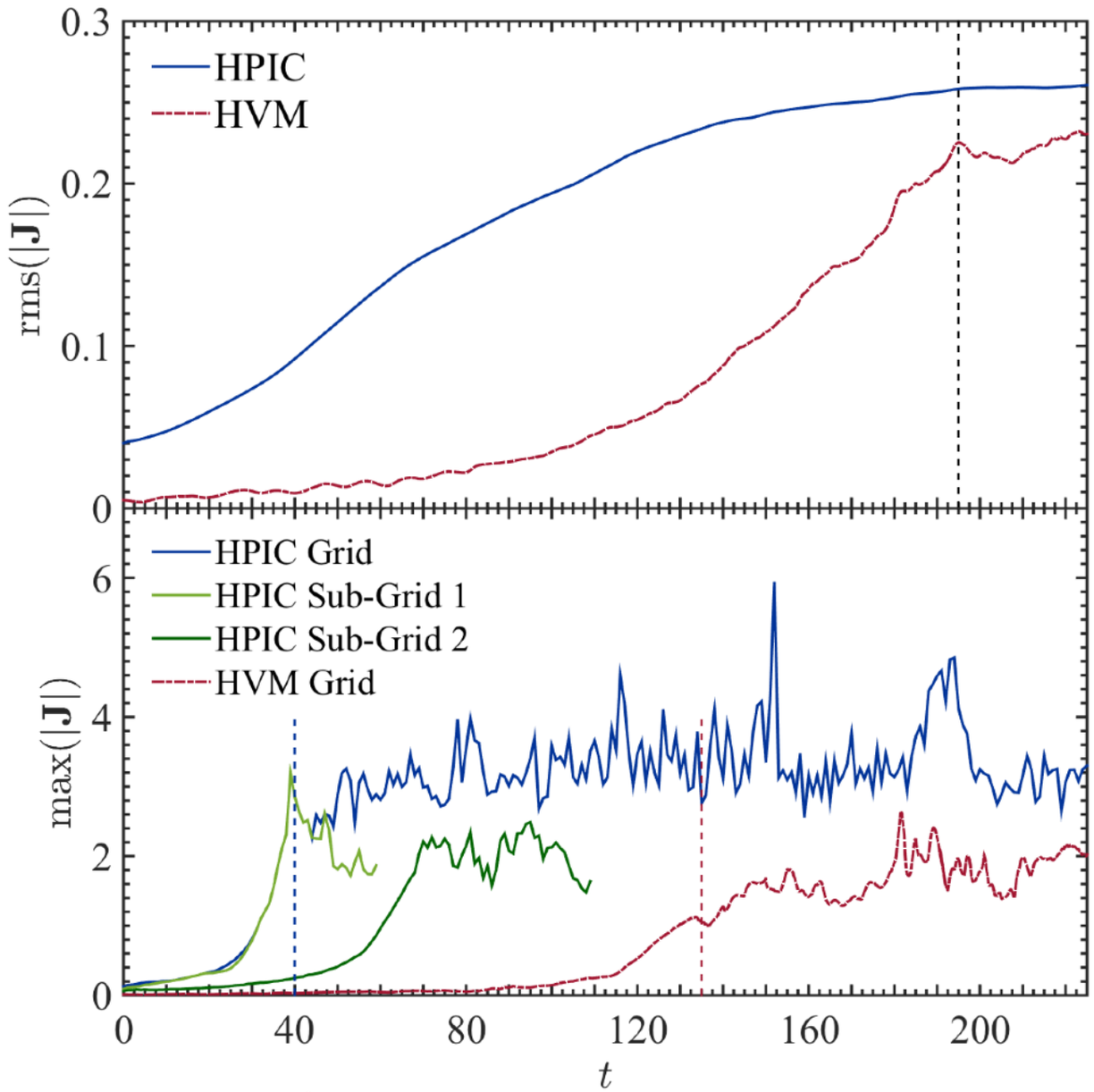
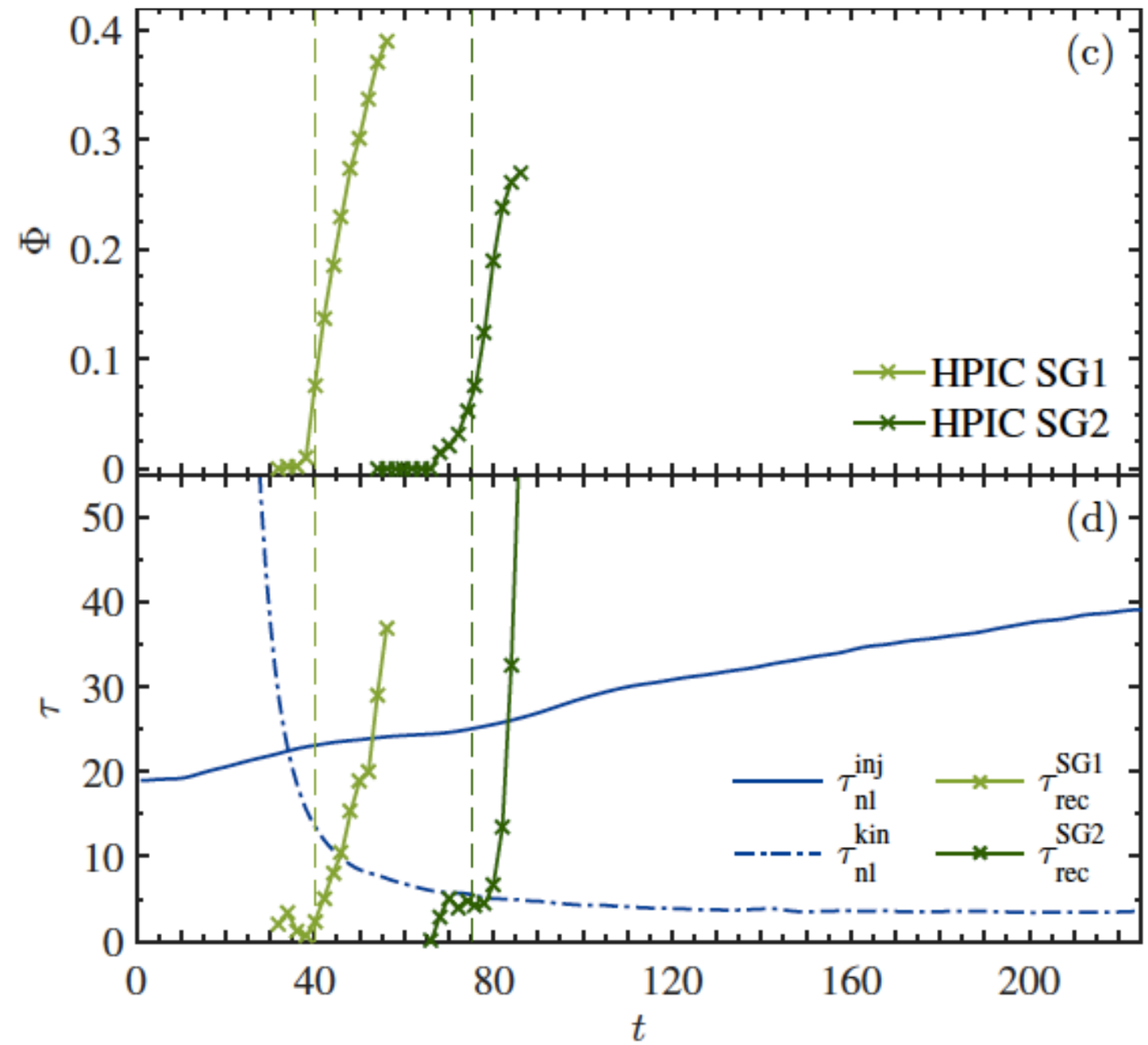
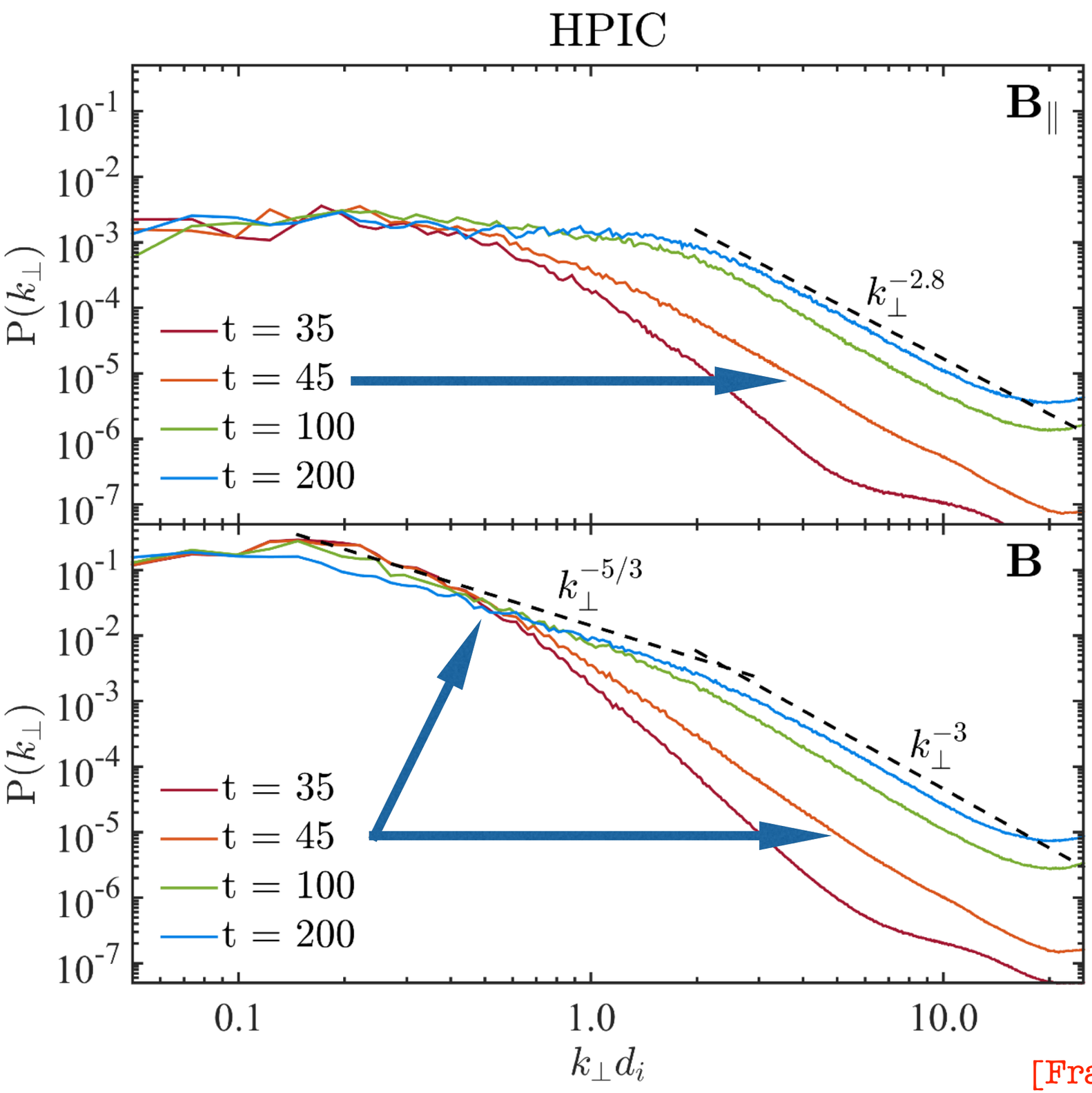




[Franci, **Cerri**, Califano et al., ApJL (2017)]

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

Short-circuiting the cascade

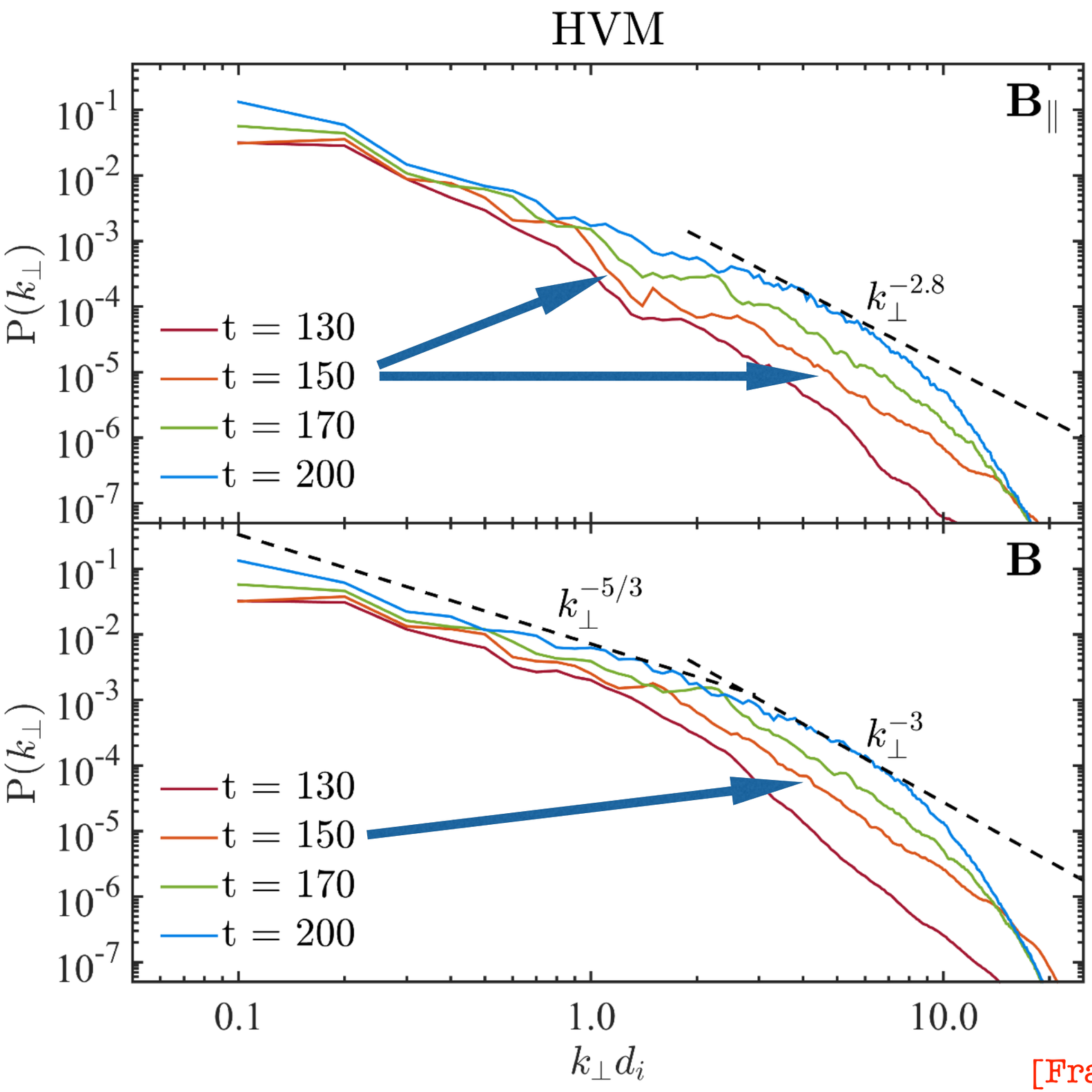


Kinetic-scale spectrum forms before the formation of a developed "MHD specturm"

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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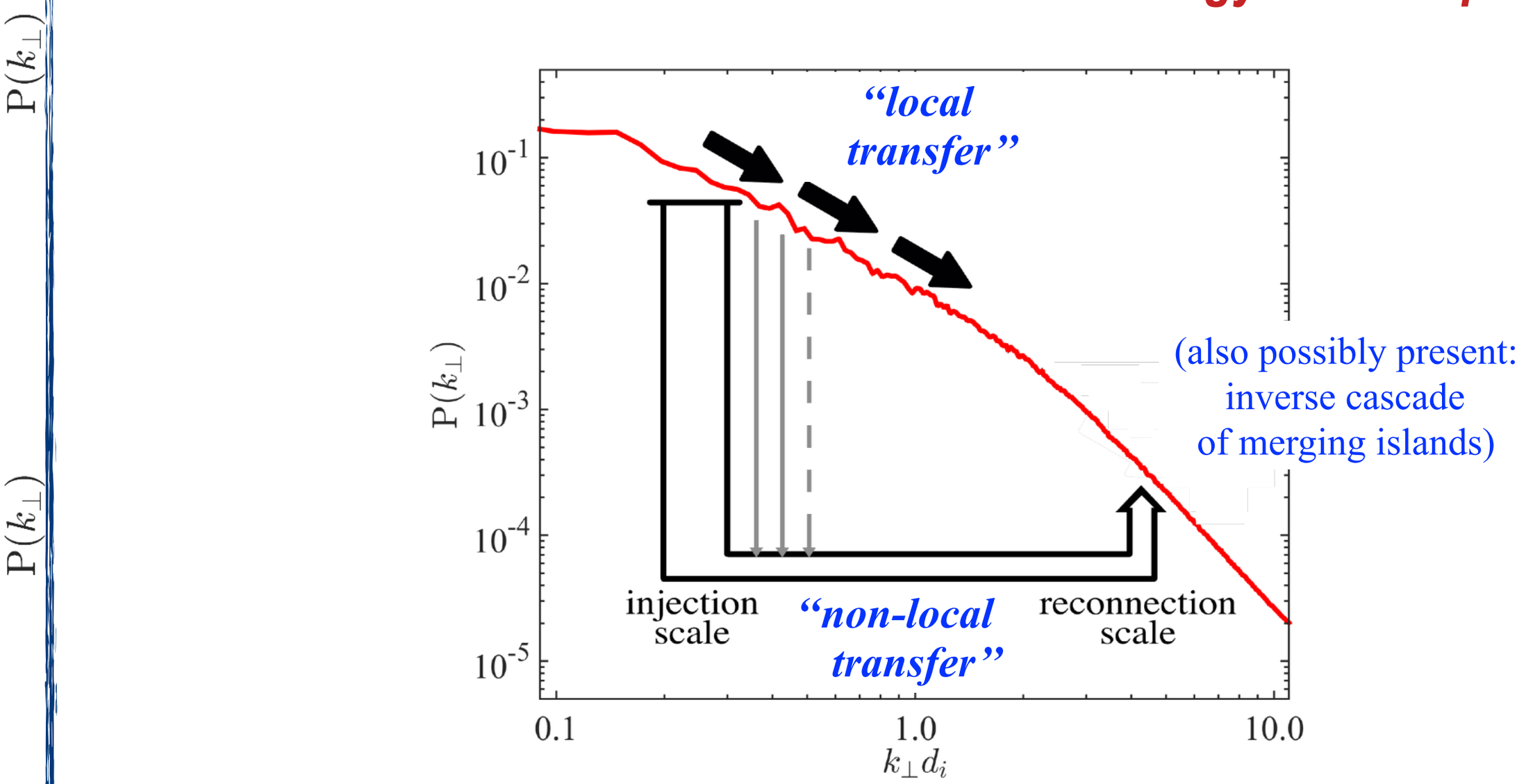
Short-circuiting the cascade

Point #4

Possible non-local reconnection-mediated energy transfer picture?



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

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 and 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)***

- ***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)***

Thank you!