Reconnection & ion heating

in low-β hybrid-kinetic plasma turbulence

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Séminaire Lagrange
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Outline

- Turbulence & heating in astrophysical and space plasmas
  - ☞ Why do we care about turbulence in “collisionless” plasmas?
  - ☞ The solar wind & space missions *(or, “where we can really learn something about plasma turbulence”)*
  - ☞ What (we think) we know about plasma turbulence and turbulent heating
  - ☞ The NASA Parker Solar Probe mission
- The hybrid-PIC code `PEGASUS` & simulation setup
- Magnetic reconnection & spectral features of quasi-steady state turbulence
- Ion heating

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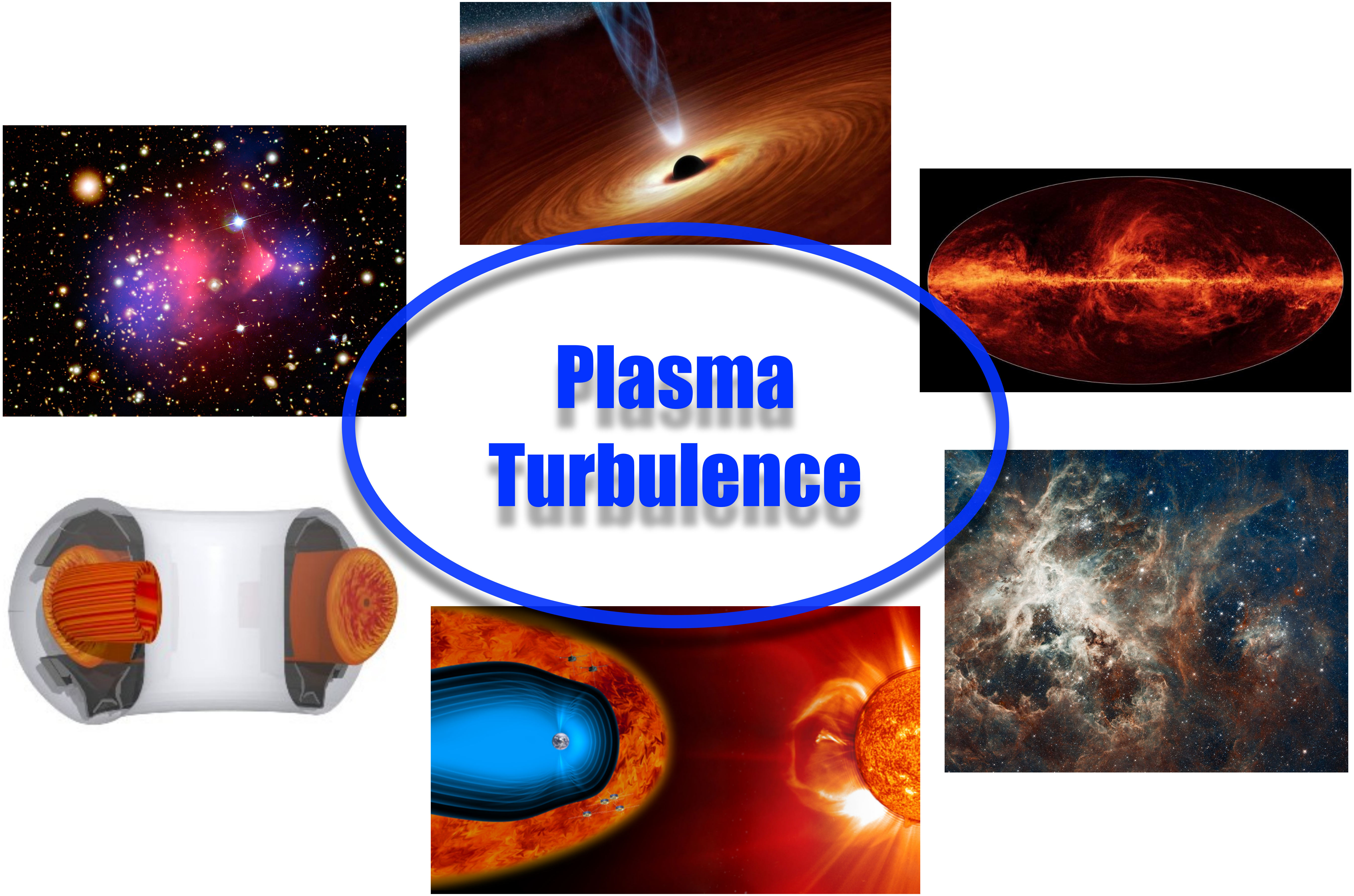
Turbulence in “collisionless” plasmas



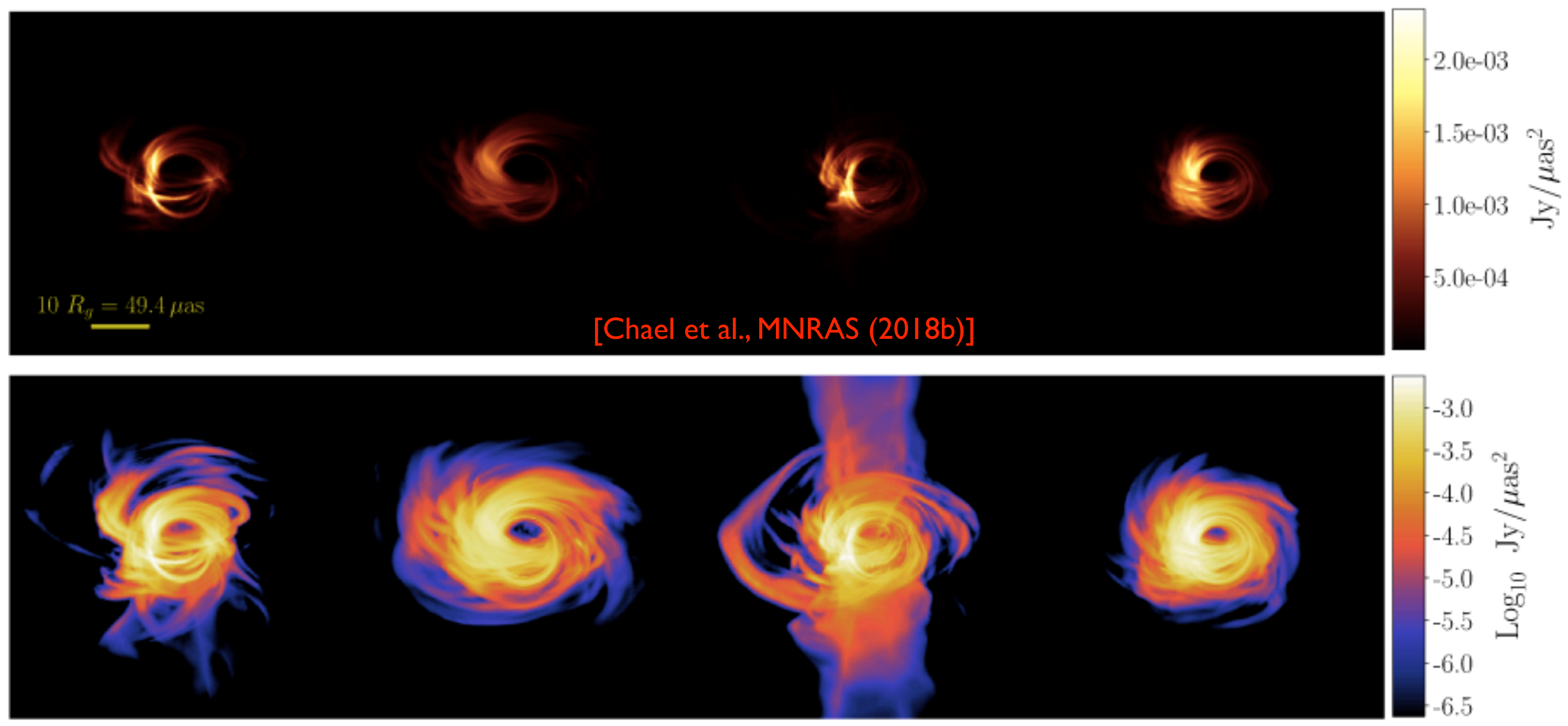
Plasma Turbulence

Turbulence in “collisionless” plasmas

[credit: Event Horizon Telescope Collaboration]

Turbulence in “collisionless” plasmas

[credit: Event Horizon Telescope Collaboration]



[Chael et al., MNRAS (2018b)]

Turbulent heating **+** ***energy partition among species***
➜ ***determine several emission features!***

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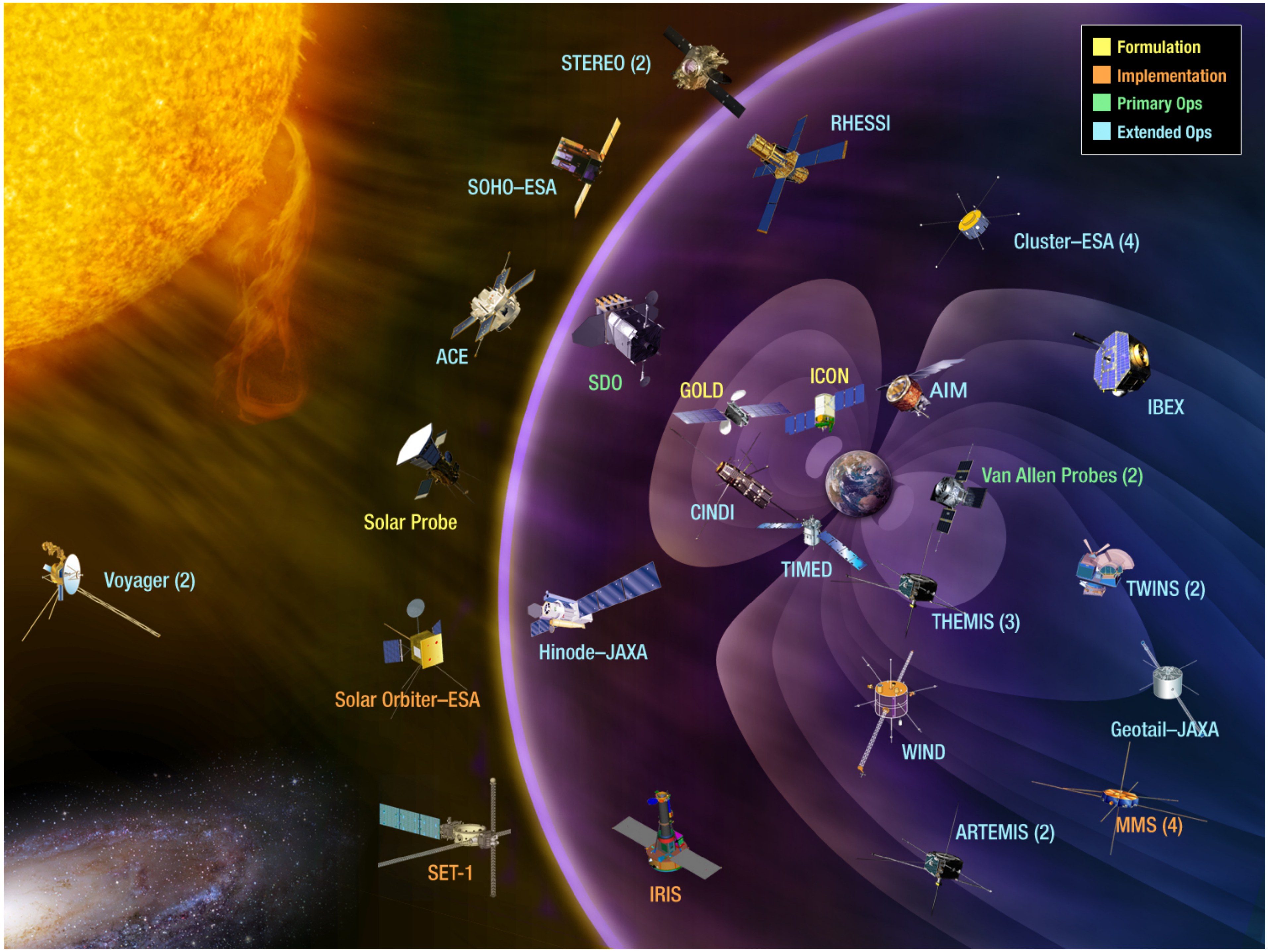
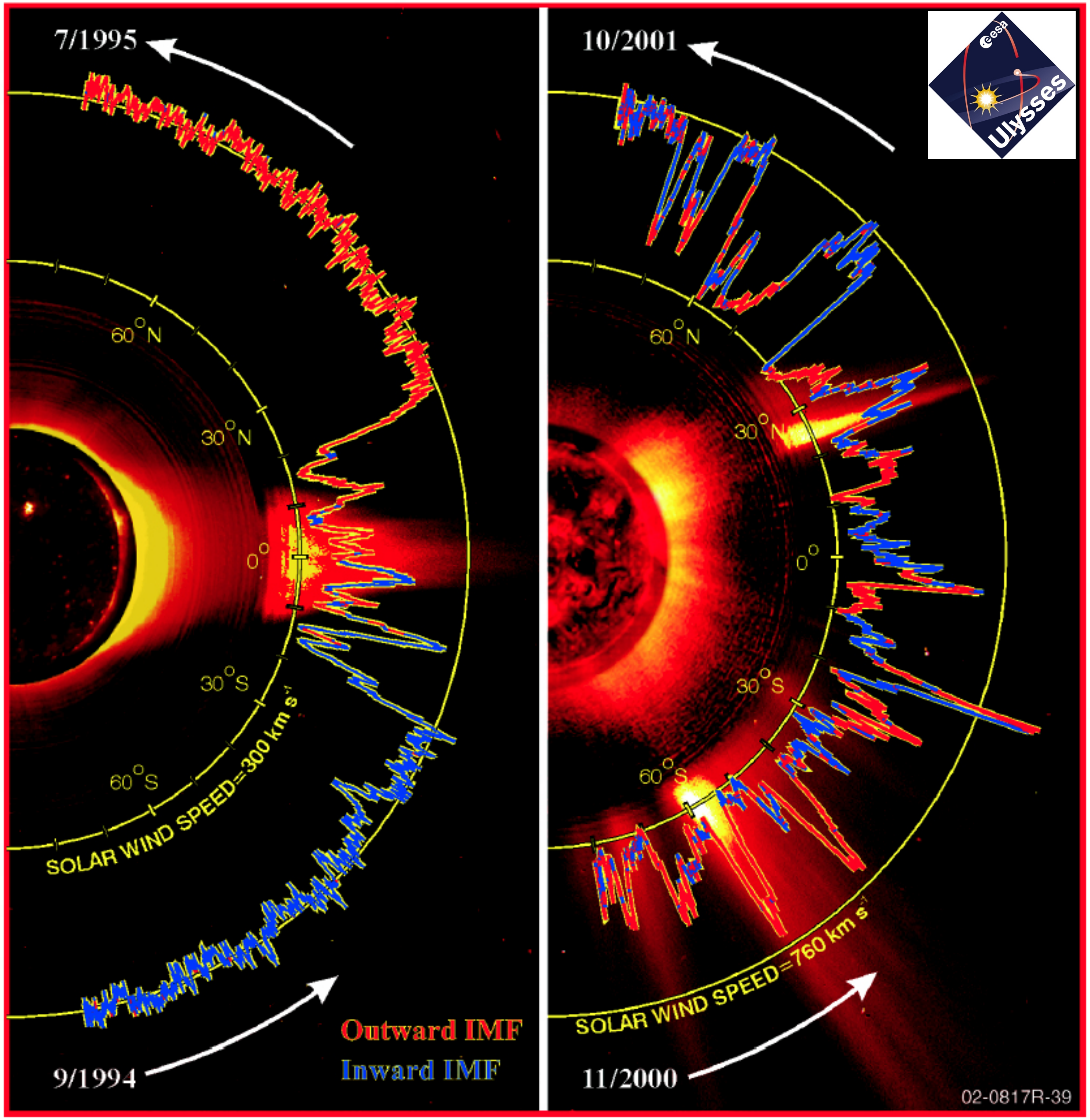
Near-Earth's environment & Solar Wind



[credit: NASA]

Increasingly accurate in situ measurements have become available

The Solar Wind (SW)



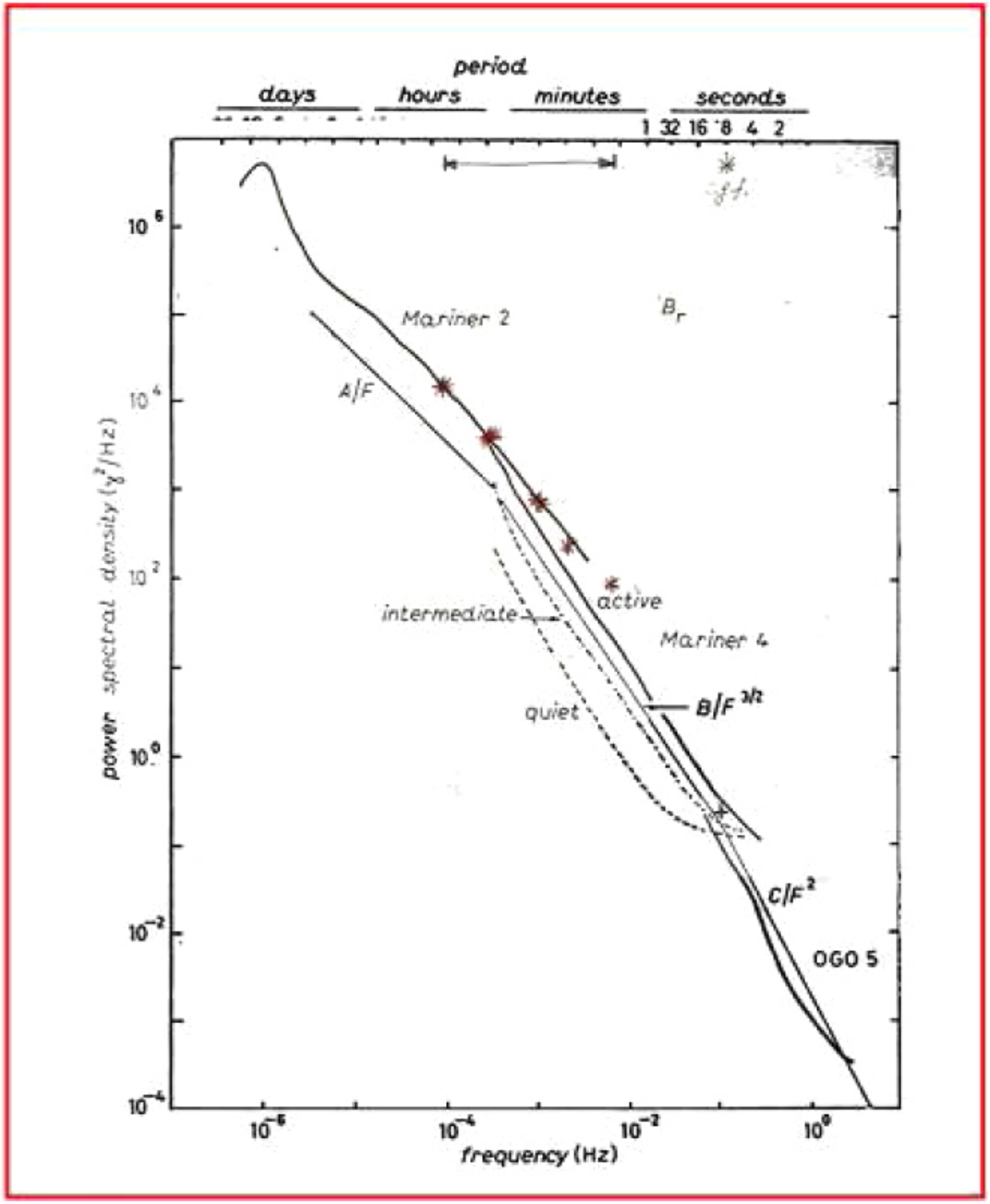
[credit: ESA]

- 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!

Early observations of SW turbulence

[credit: Bruno & Carbone, *LRSP* (2005); see Russel (1972) therein]



Early observations of ***magnetic fluctuations power spectrum*** as function of frequency from *Mariner 2*, *Mariner 4* and *OGO 5*:

- Injection range: $\sim f^{-1}$
- “intermediate” range: $\sim f^{-1.5}$
- “final” range: $\sim f^{-2}$

NOTE:

frequencies (f) in the spacecraft frame can be turned into wavenumbers (k) via ***Taylor hypothesis***: $2\pi f \approx \mathbf{k}\cdot\mathbf{V}_{\mathrm{sw}}$

Early observations of SW turbulence

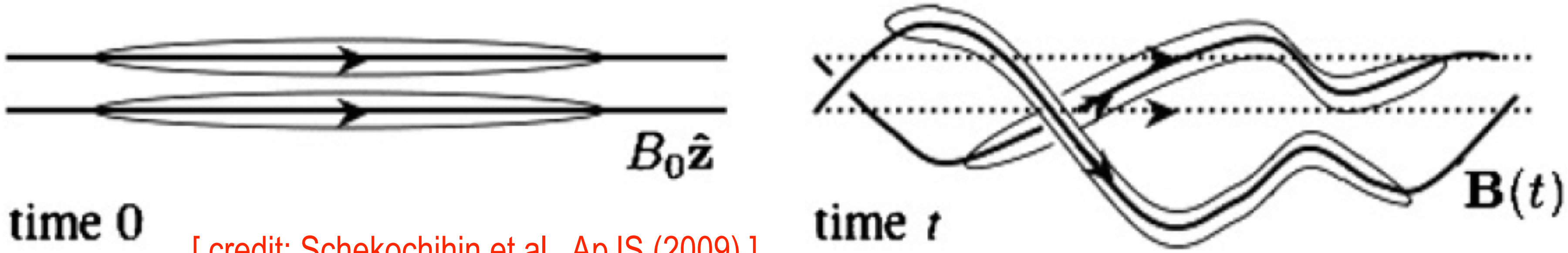
MHD turbulence in a nutshell

[neutral fluid case: $\sim k^{-5/3}$ (*Kolmogorov*: ***isotropic hydrodynamic turbulence***)]

- $\sim k^{-3/2}$ (*Iroshnikov & Kraichnan*: ***isotropic MHD turbulence***)
- $\sim k_{\perp}^{-5/3}$ & $\sim k_{||}^{-2}$ (parallel and perpendicular with respect to $\mathbf{B}$);

anisotropy from "***critical balance***": $k_{||} \sim k_{\perp}^{2/3}$

(*Goldreich & Sridhar*: ***anisotropic MHD turbulence***)



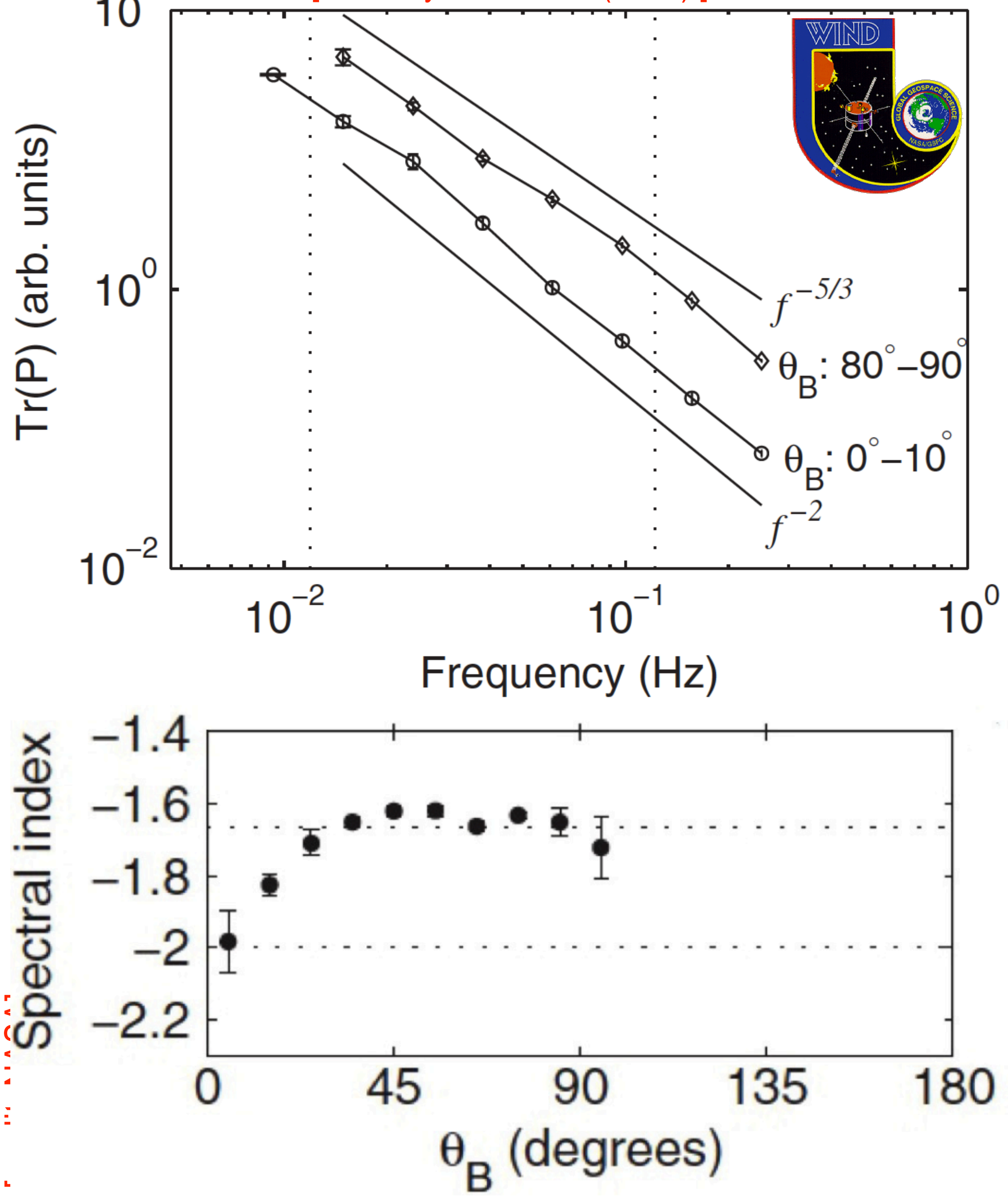
[credit: Schekochihin et al., ApJS (2009)]

[credit: Bruno & Carbone, LRSP (2005); see Russel (1972) therein]

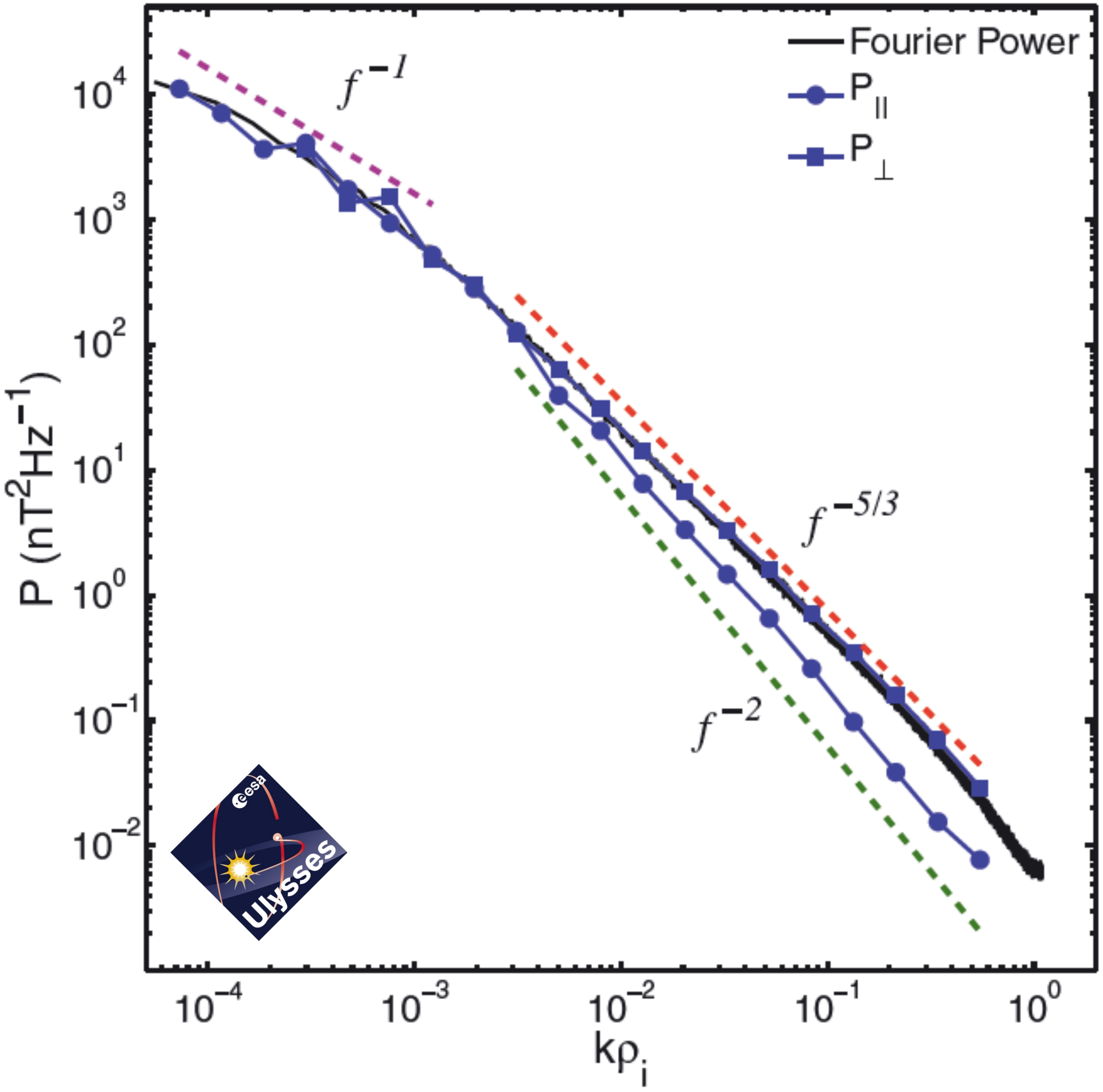
SW turbulence in the MHD range

Observations from WIND and Ulysses (and other spacecraft)

[Horbury et al., PRL (2008)]



[Wicks et al., MNRAS (2009)]



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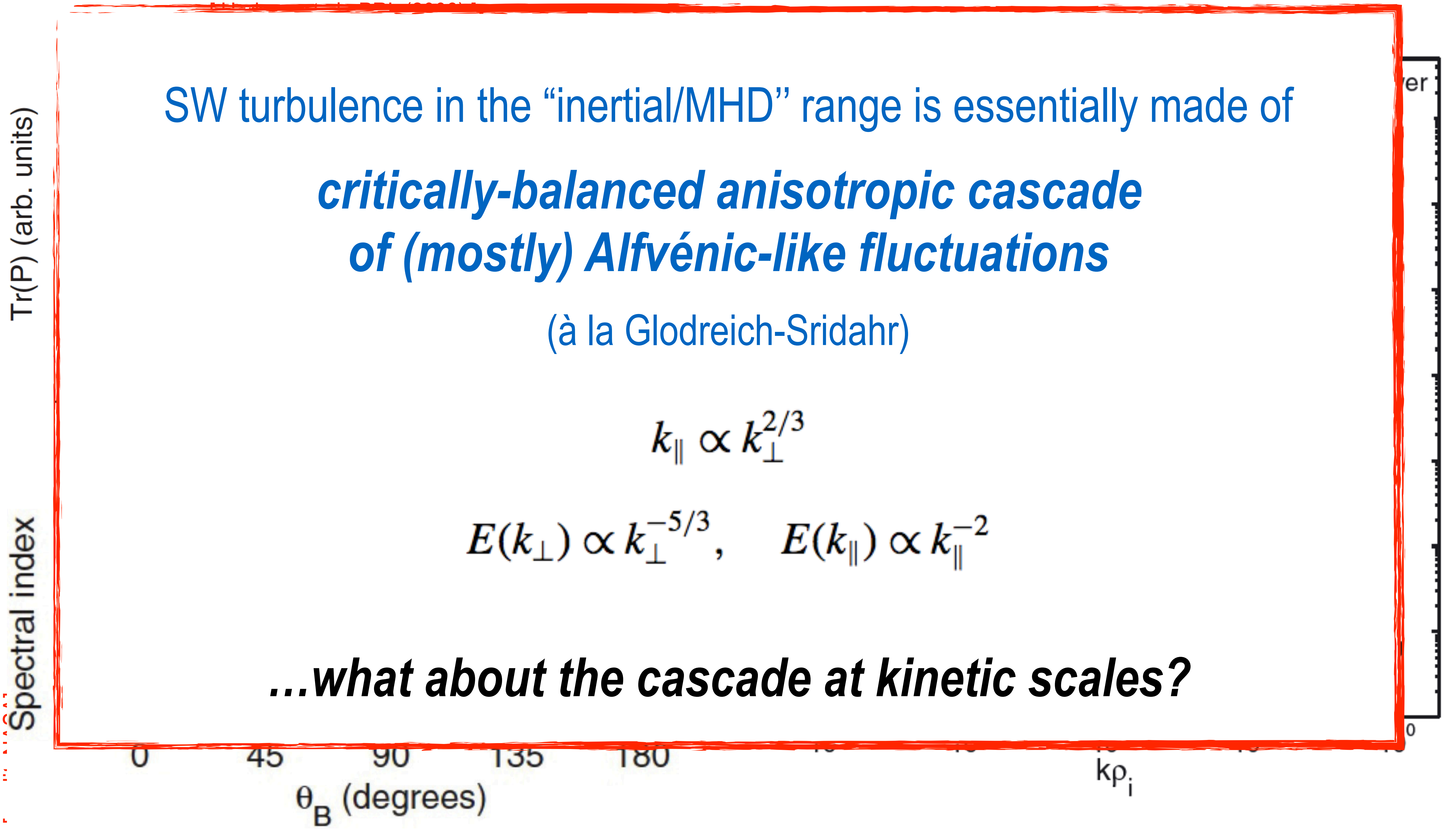


SW turbulence in the “inertial/MHD” range is essentially made of

critically-balanced anisotropic cascade
of (mostly) Alfvénic-like fluctuations

(à la Glodreich-Sridahr)

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

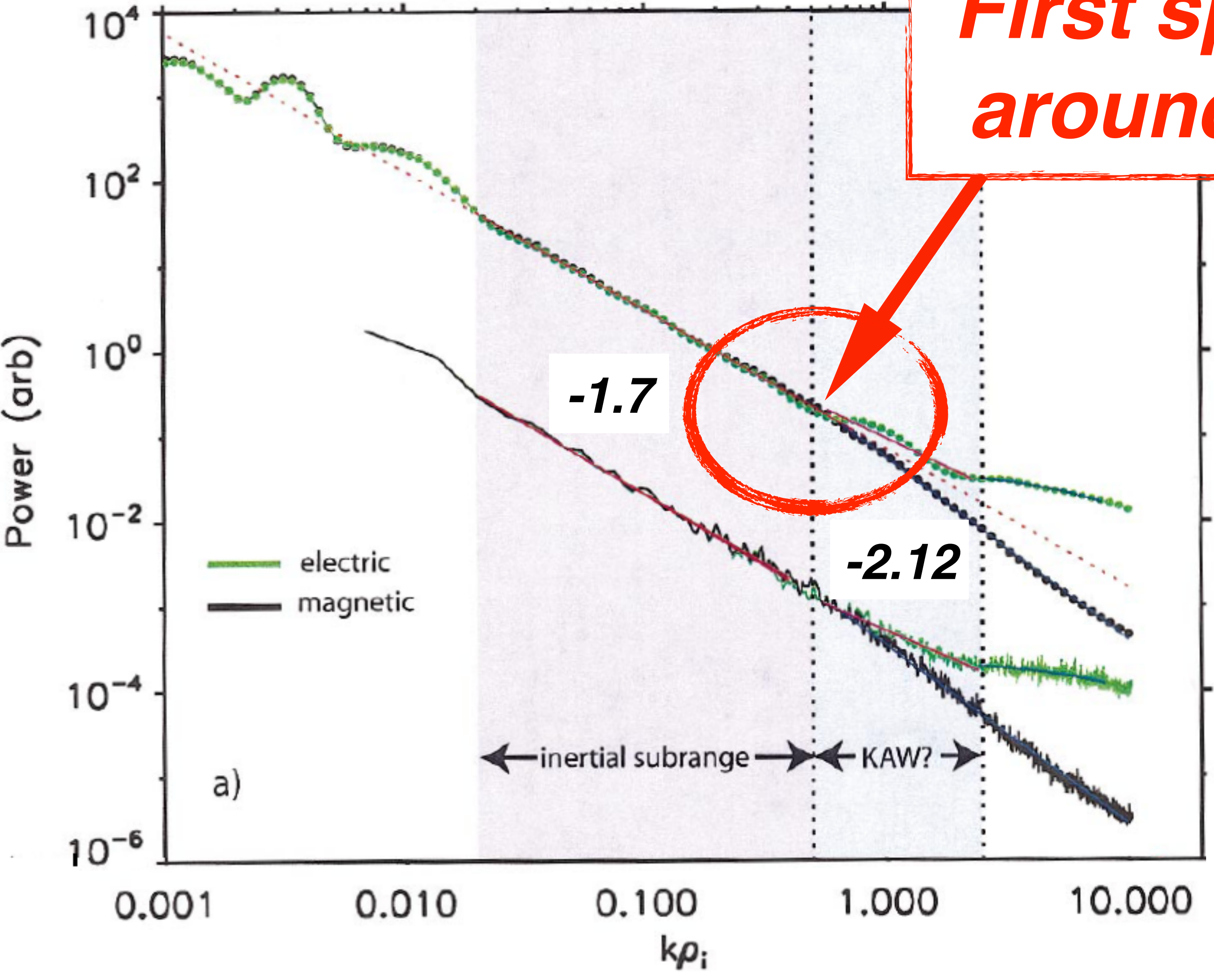
$$E(k_{\perp}) \propto k_{\perp}^{-5/3}, \quad E(k_{\parallel}) \propto k_{\parallel}^{-2}$$

…what about the cascade at kinetic scales?

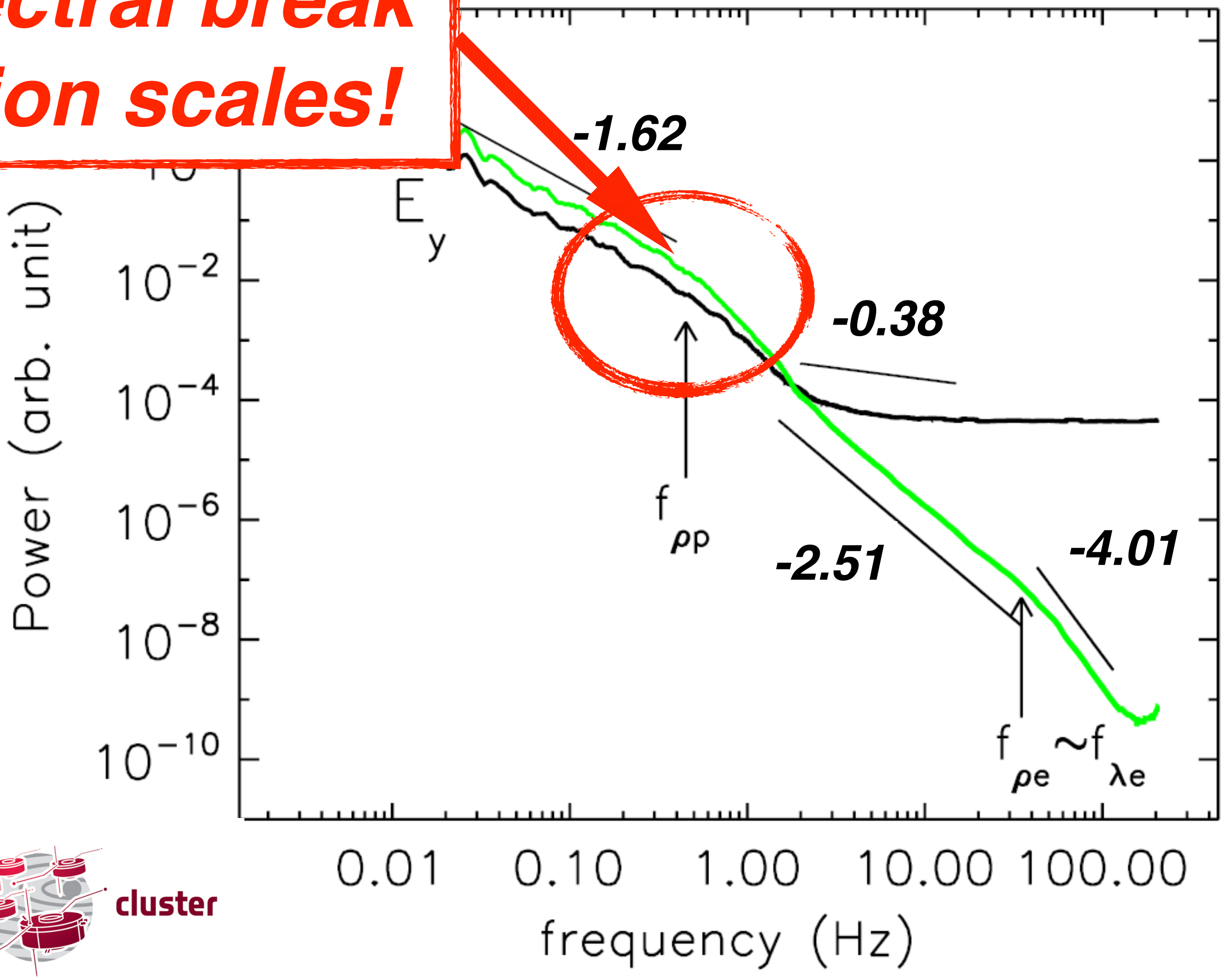
SW turbulence beyond the MHD range

First spectral break around ion scales!

[Bale et al., PRL (2005)]



[Sahraoui et al., PRL (2009)]

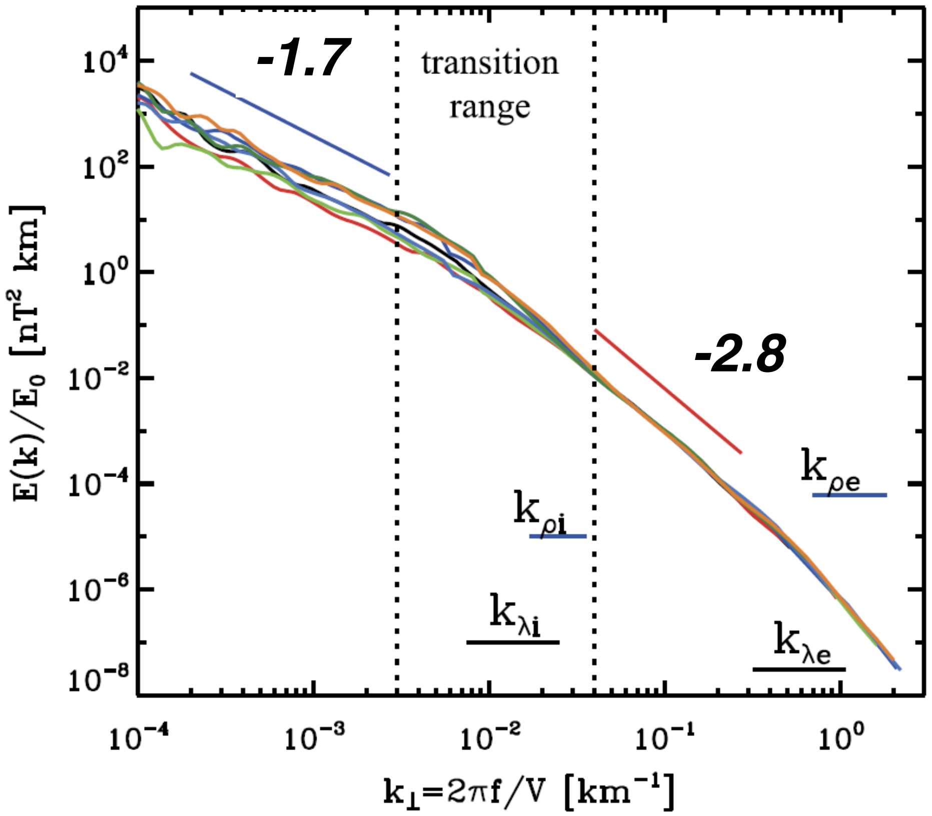


First observations of electromagnetic turbulent cascade at kinetic scales by Cluster:

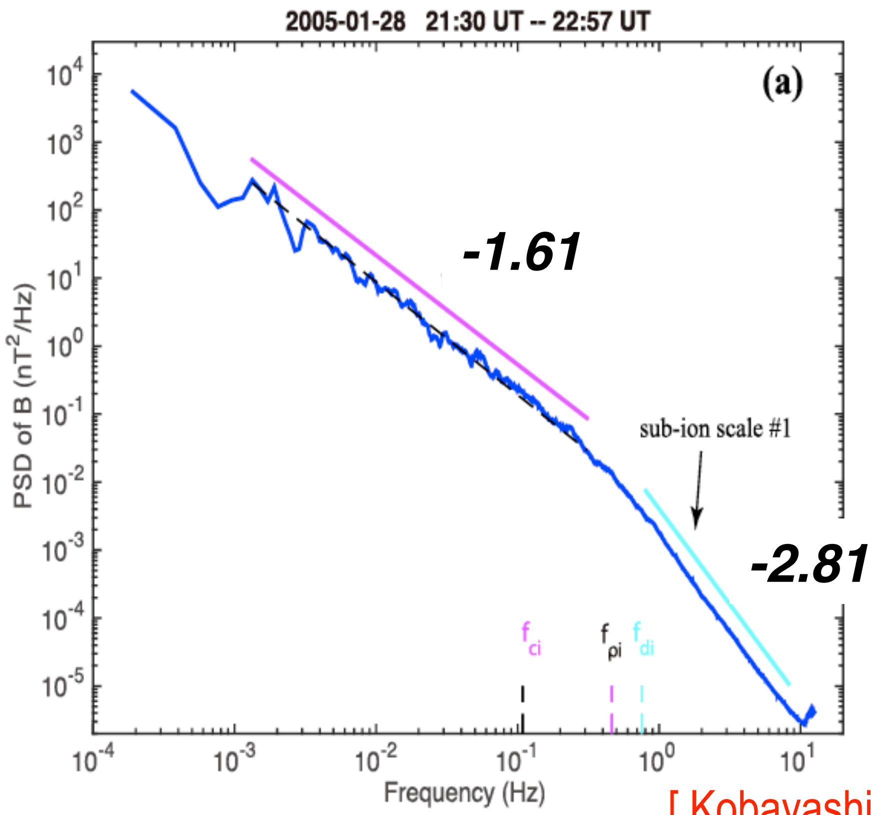
- ***Spectral breaks at kinetic scales***
- ***Steepening of magnetic spectrum***
- ***Flattening of electric spectrum***

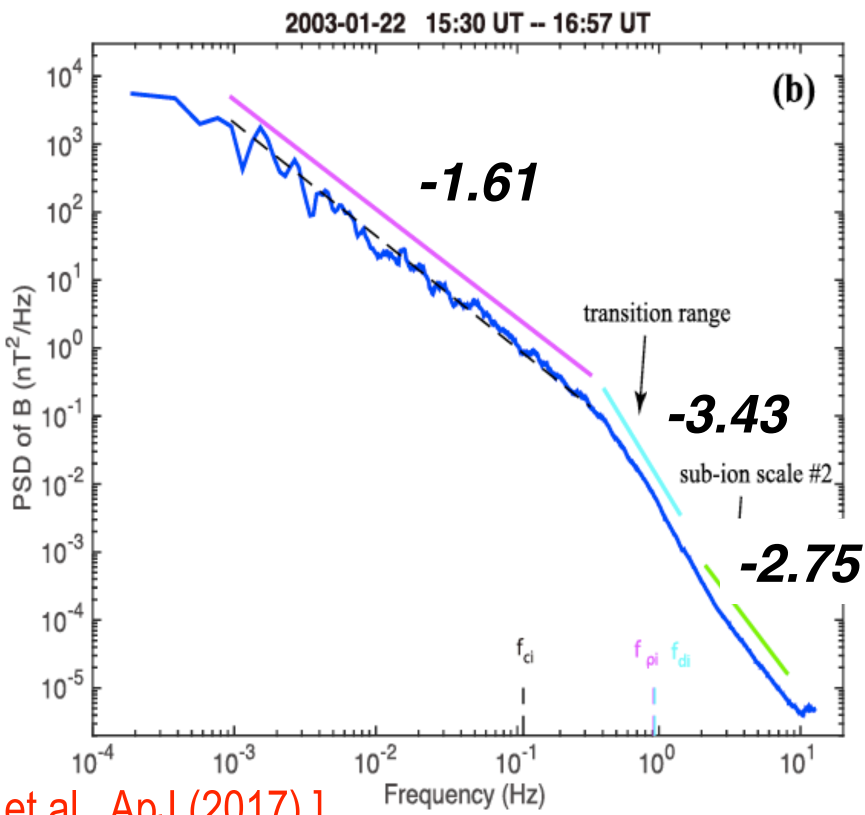
Universality of kinetic-range spectrum?

Solar Wind



[Alexandrova et al., SSR (2013)]

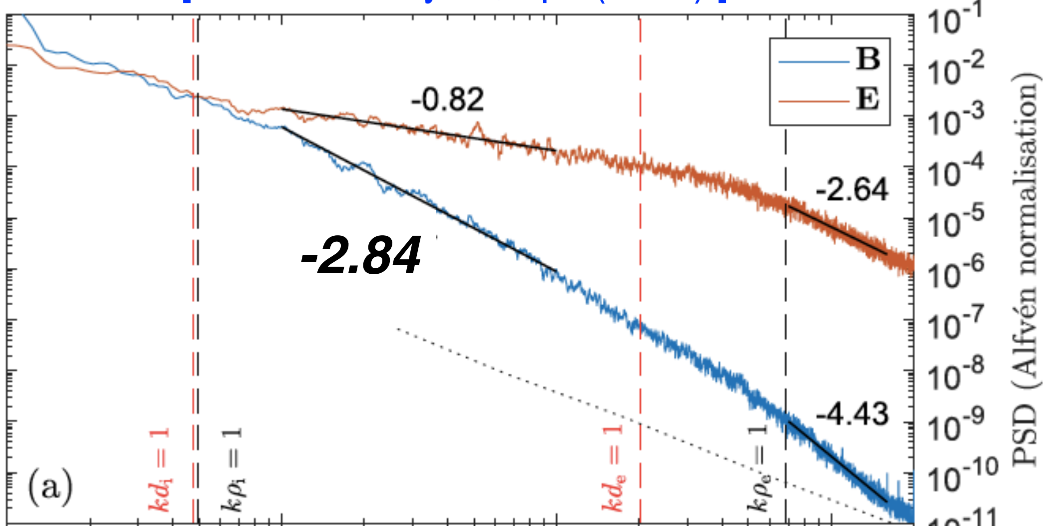




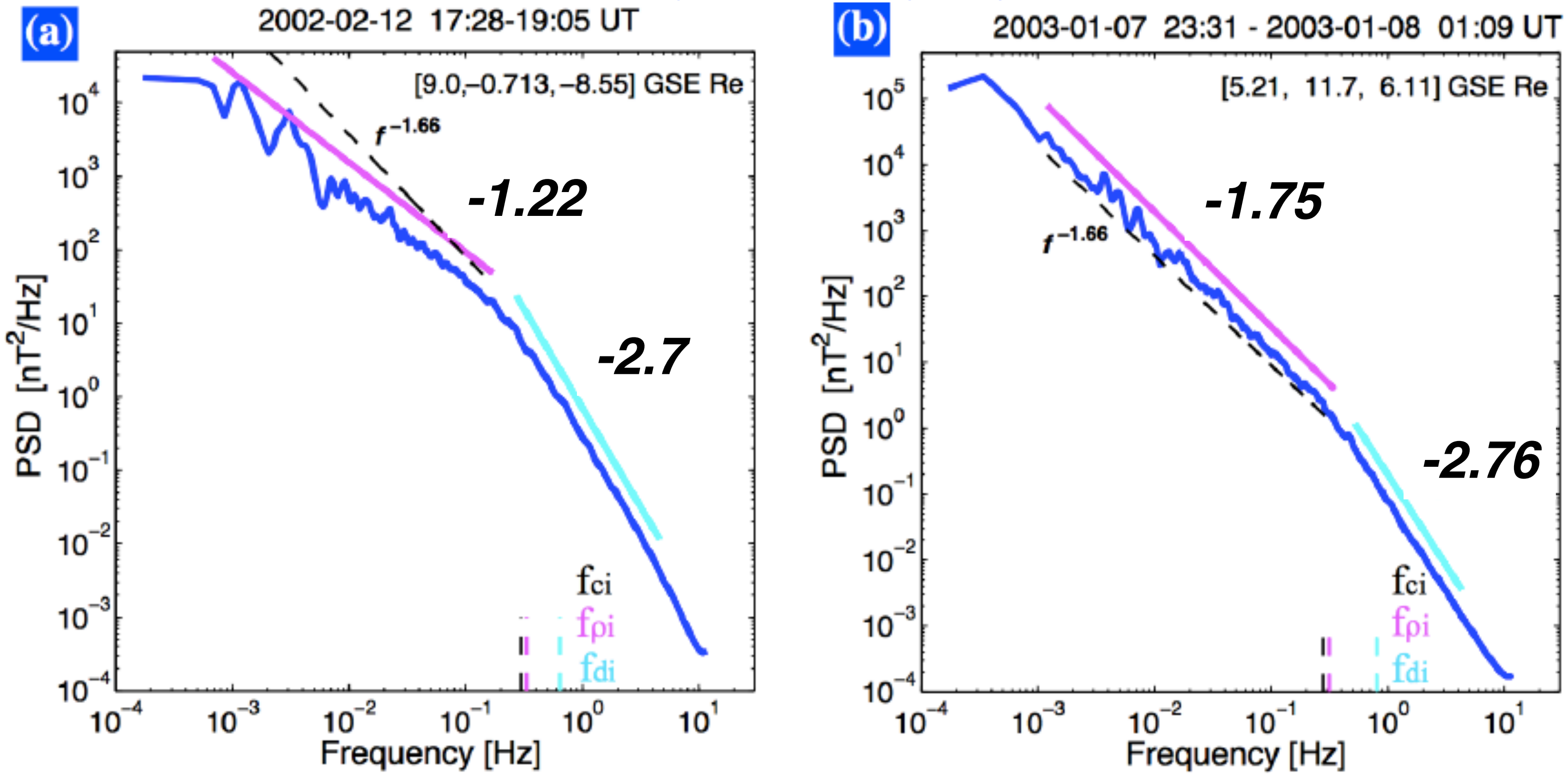
[Kobayashi et al., ApJ (2017)]

Magnetosheath

[Chen & Boldyrev, ApJ (2017)]



[Huang et al., ApJL (2017)]



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: $k_{||} \sim k_\perp^{1/3}$

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: $k_{||} \sim k_\perp^{1/3}$

Kinetic-range turbulence theories

Additional possible sources of steepening

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

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

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

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

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

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

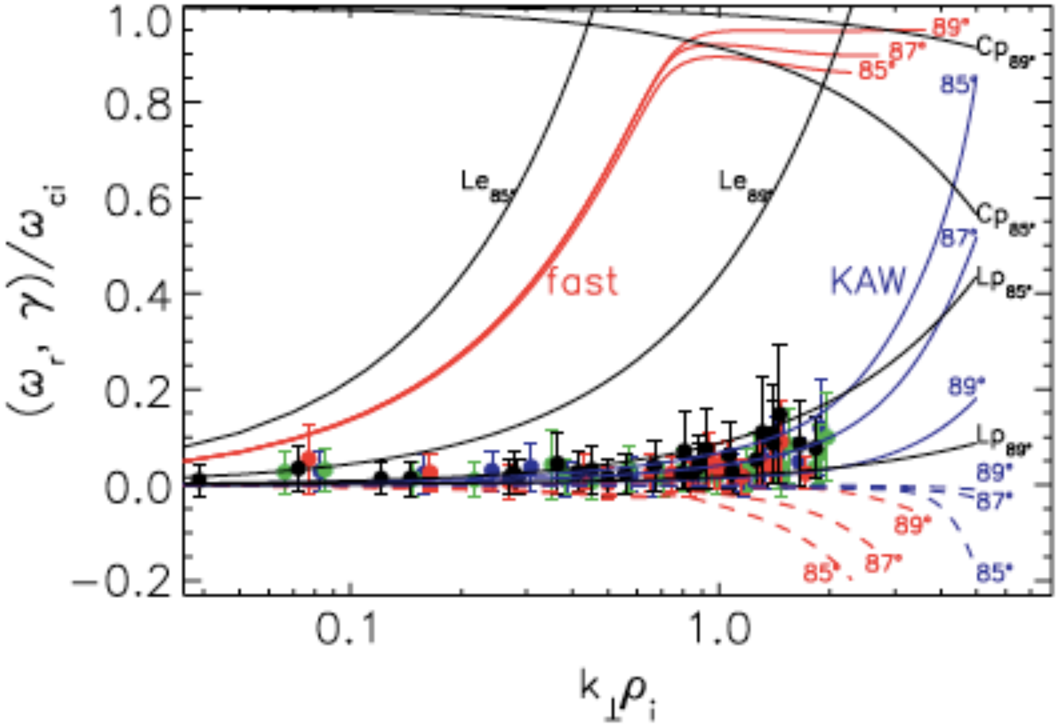
- Nonlinearity parameter saturation ("weak vs strong..er") [Passot & Sulem, ApJL (2015)]

- B
- E
- S

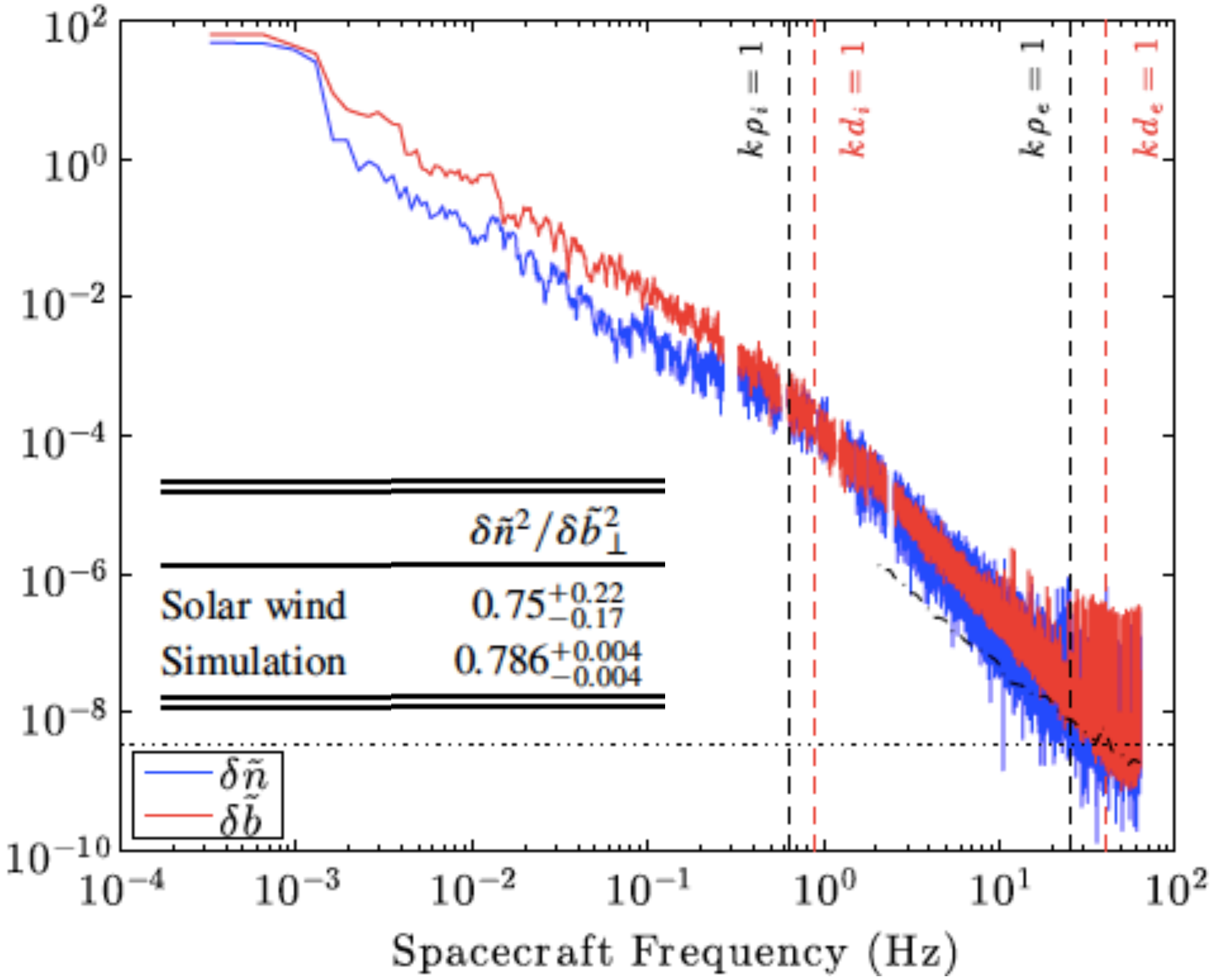
- B
- E
- S

More kinetic-range turbulence observations

[Sahraoui et al., PRL (2010)]

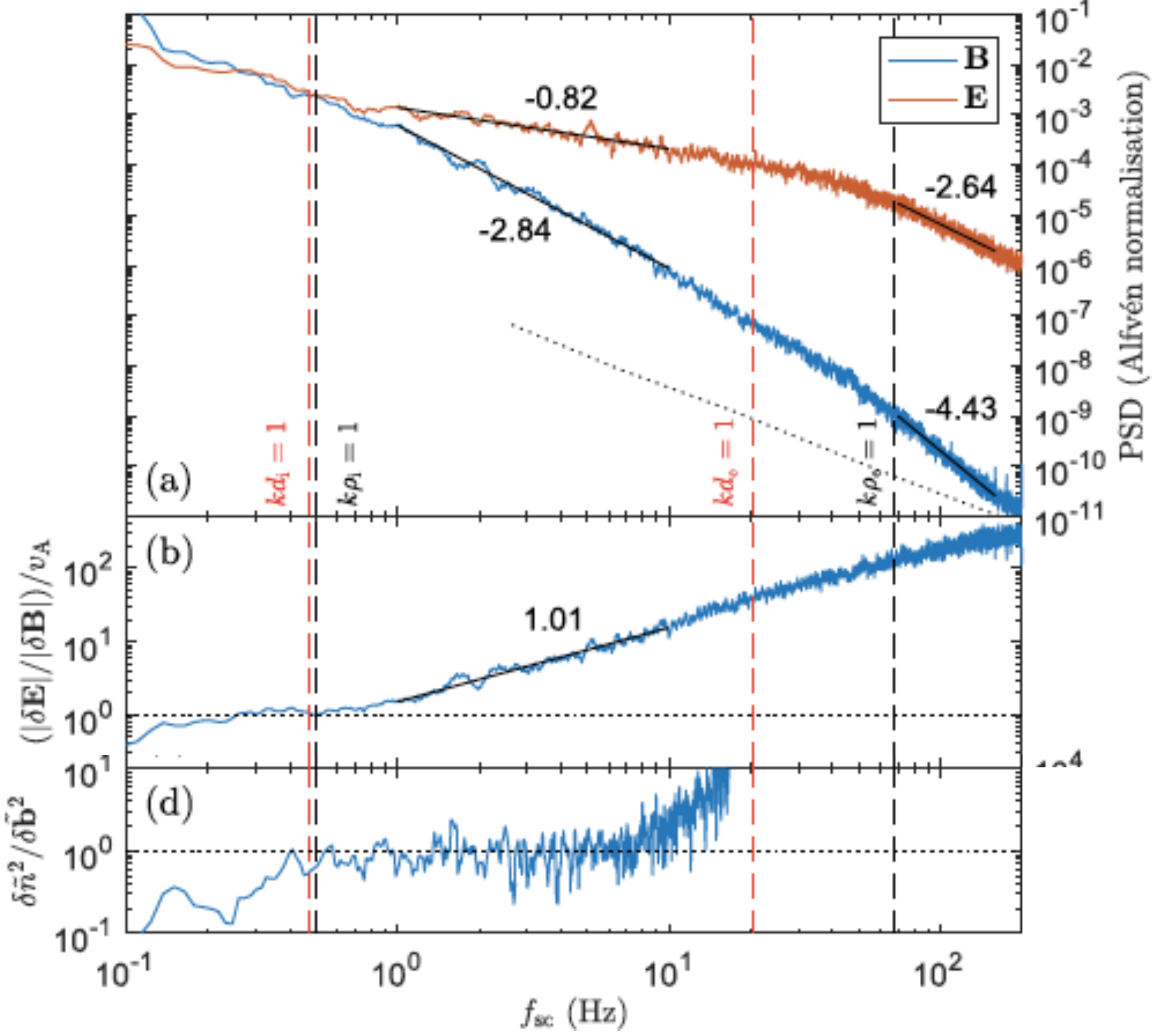


[Chen et al., PRL (2013)]



	$\delta\tilde{n}^2/\delta\tilde{b}_\perp^2$
Solar wind	$0.75^{+0.22}_{-0.17}$
Simulation	$0.786^{+0.004}_{-0.004}$

[Chen & Boldyrev., ApJ (2017)]



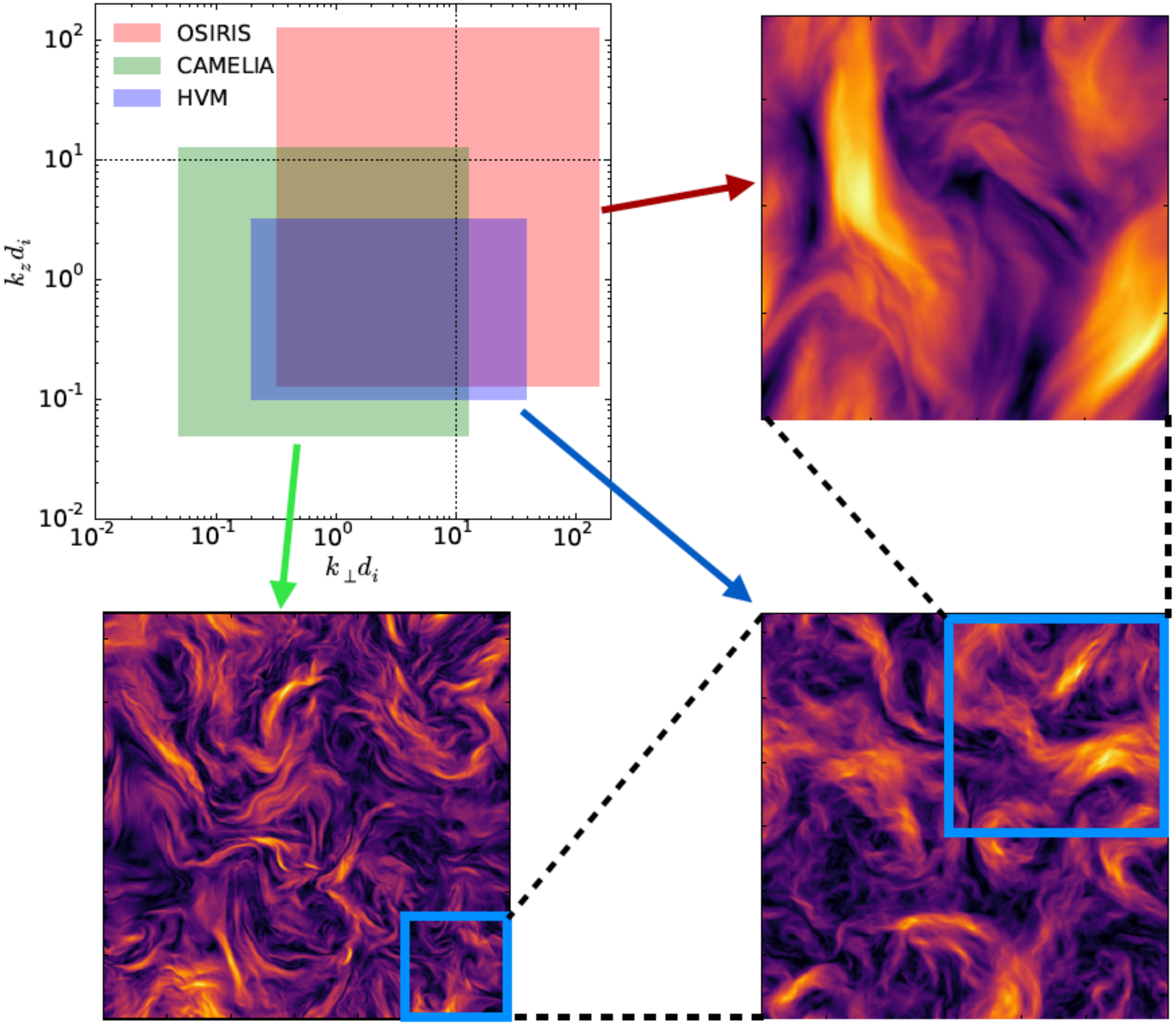
$$\delta\tilde{b} = \frac{\delta B}{B_0} \qquad \delta\tilde{n} = \sqrt{\frac{\beta_i}{2}\left(1+\frac{T_e}{T_i}\right)\left[1+\frac{\beta_i}{2}\left(1+\frac{T_e}{T_i}\right)\right]}\,\frac{\delta n}{n_0}$$

observations are overall consistent
with ***kinetic-Alfvén-wave (KAW) turbulence***

Spectral anisotropy: a solution, after all?

Understanding sub-ion-range turbulence: a multi-model, collaborative effort

[**Cerri**, Groselj & Franci, FSPAS (2019)]



☞ **Different injection properties at “MHD scales”:**

- freely decaying Alfvénic fluctuations
- freely decaying compressive B fluctuations
- continuous Alfvénic injection (“driven”)

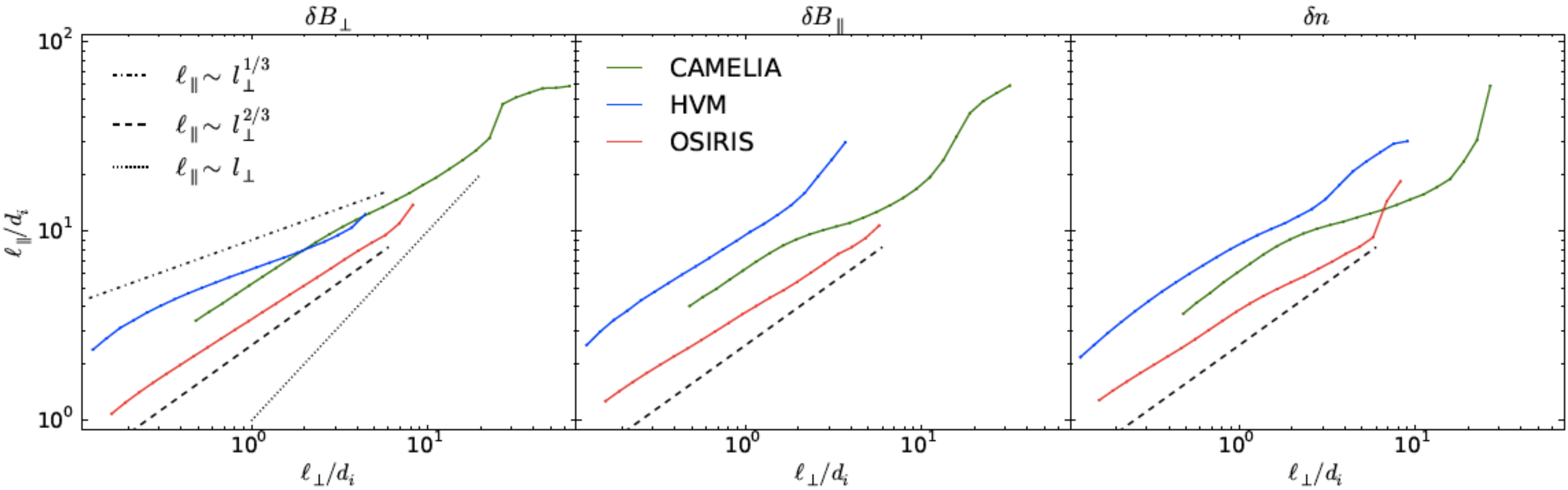
☞ **Different models and numerical methods employed:**

- hybrid-PIC w/o electron inertia
- hybrid-Vlasov w/ electron inertia
- full PIC

Spectral anisotropy: a solution, after all?

With high-angular-resolution, multi-point structure functions every simulation eventually agrees on the spectral anisotropy of (almost) each quantity!

[**Cerri**, Groselj & Franci, FSPAS (2019)]



sub-ion-scale anisotropy: $l_\parallel \sim l_\perp^{2/3}$

(polarisation properties of sub-ion-scale fluctuations are also consistent with kinetic-Alfvén-wave turbulence — not shown here)

Spectral anisotropy: a solution, after all?

Observations & simulations of turbulent fluctuations in the “sub-ion range” are overall consistent with

“intermittency corrected” kinetic-Alfvén-wave (KAW) turbulence

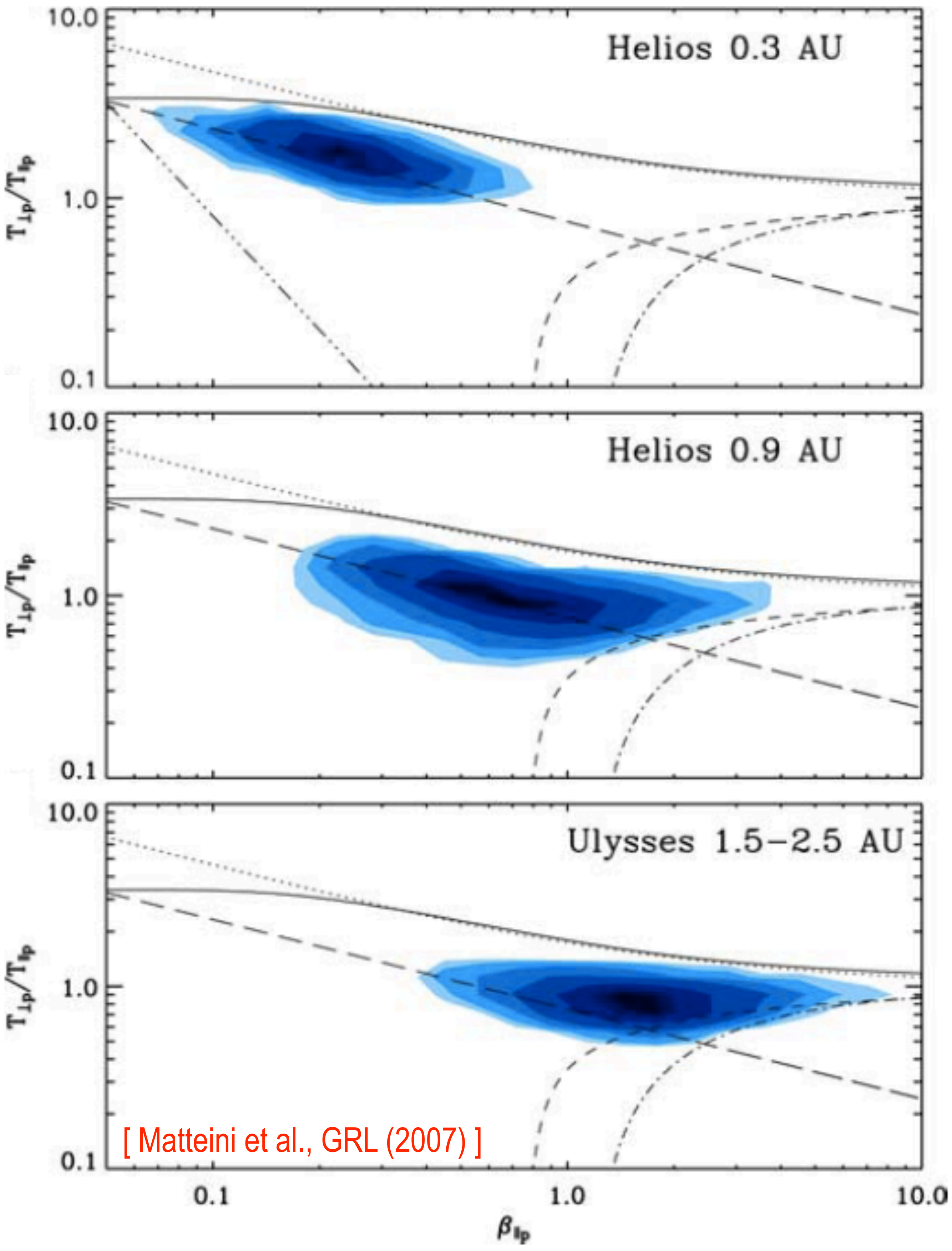
<u>BUT</u> this is not the end of the story:

Reconnection & turbulence as tightly entwined processes
→ ***idea of “reconnection-mediated turbulence” for sub-ion range***

see, e.g.,
Cerri *& Califano, NJP (2017)* [simulations]
Franci, ***Cerri****, et al., ApJL (2017)* [simulations]
Loureiro & Boldyrev, ApJ (2017) [theory]
Mallet, Schekochihin & Chandran, JPP (2017) [theory]
Vech et al., ApJL (2018) [observations]

…what about turbulent heating?

Temperature evolution in turbulent SW



[Matteini et al., GRL (2007)]

- Proton temperature parallel and perpendicular to the local magnetic field **does not follow an adiabatic evolution**

- Other processes must dominate the thermal evolution of the turbulent SW plasma (**“turbulent heating”**)

- Turbulent heating seems to **preferentially heat the protons in the direction perpendicular to B**

How turbulent energy finds its path to dissipation in a “collisionless” plasma?

Turbulent cascades in velocity space

A “collisionless” plasma enjoys the whole phase-space playground!

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)

→ presumably <u>mainly</u> ***along B_0*** (“parallel”)
and more important at ***“large” perpendicular scales***:

$$k_\perp \rho_\mathrm{i} \lesssim 1$$

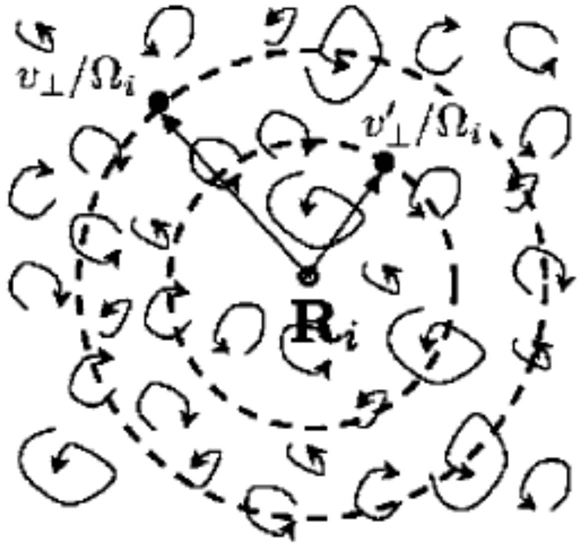
NON-LINEAR PHASE MIXING

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

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

(typically) faster than its linear counterpart, when active:
→ occurring <u>only</u> ***perpendicular to B_0***
and <u>only</u> ***below the ion gyro-radius***:

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

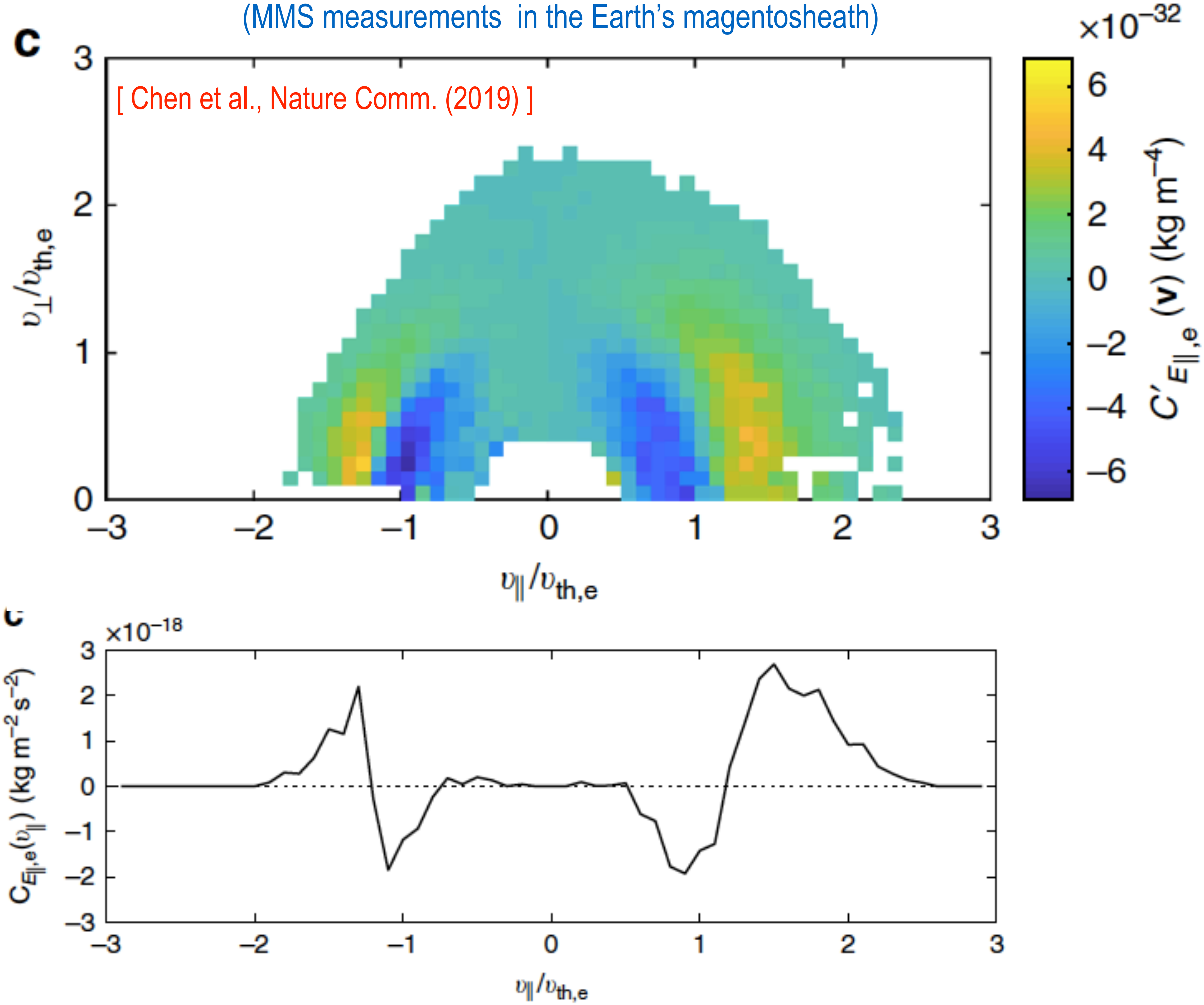


[Schekochihin et al., ApJS (2009)]

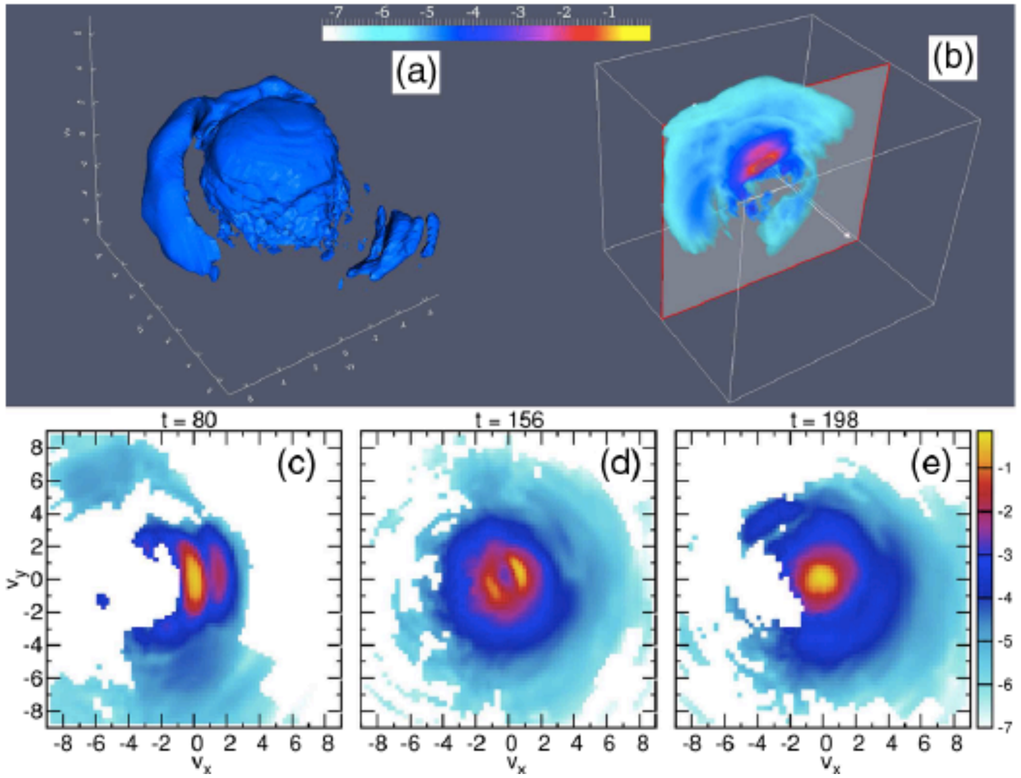
Landau damping of turbulent fluctuations

First evidence of Landau damping from in-situ data

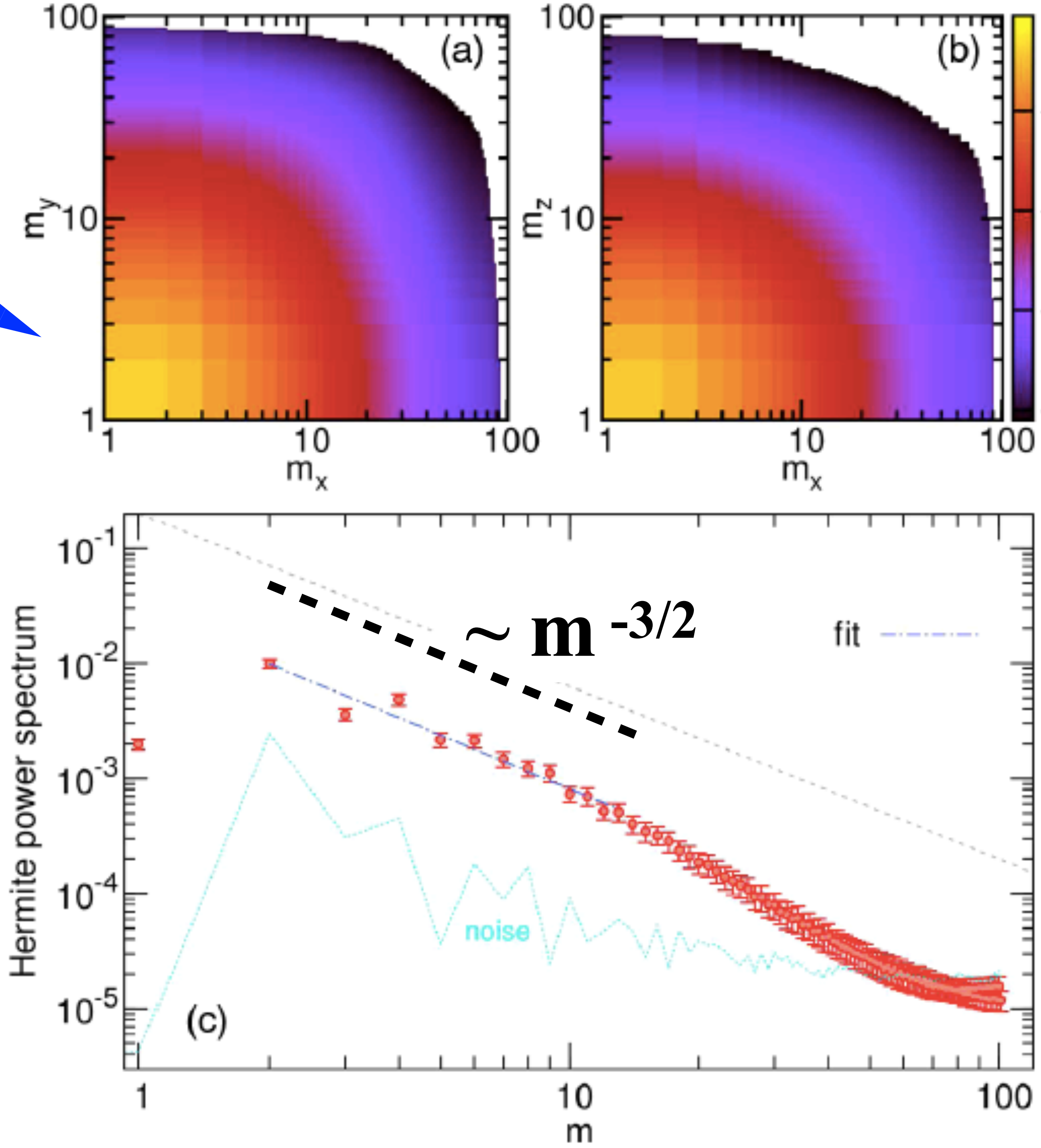
(MMS measurements in the Earth's magentosheath)



MMS observation of v-space cascades



[Servidio et al., PRL (2017)]

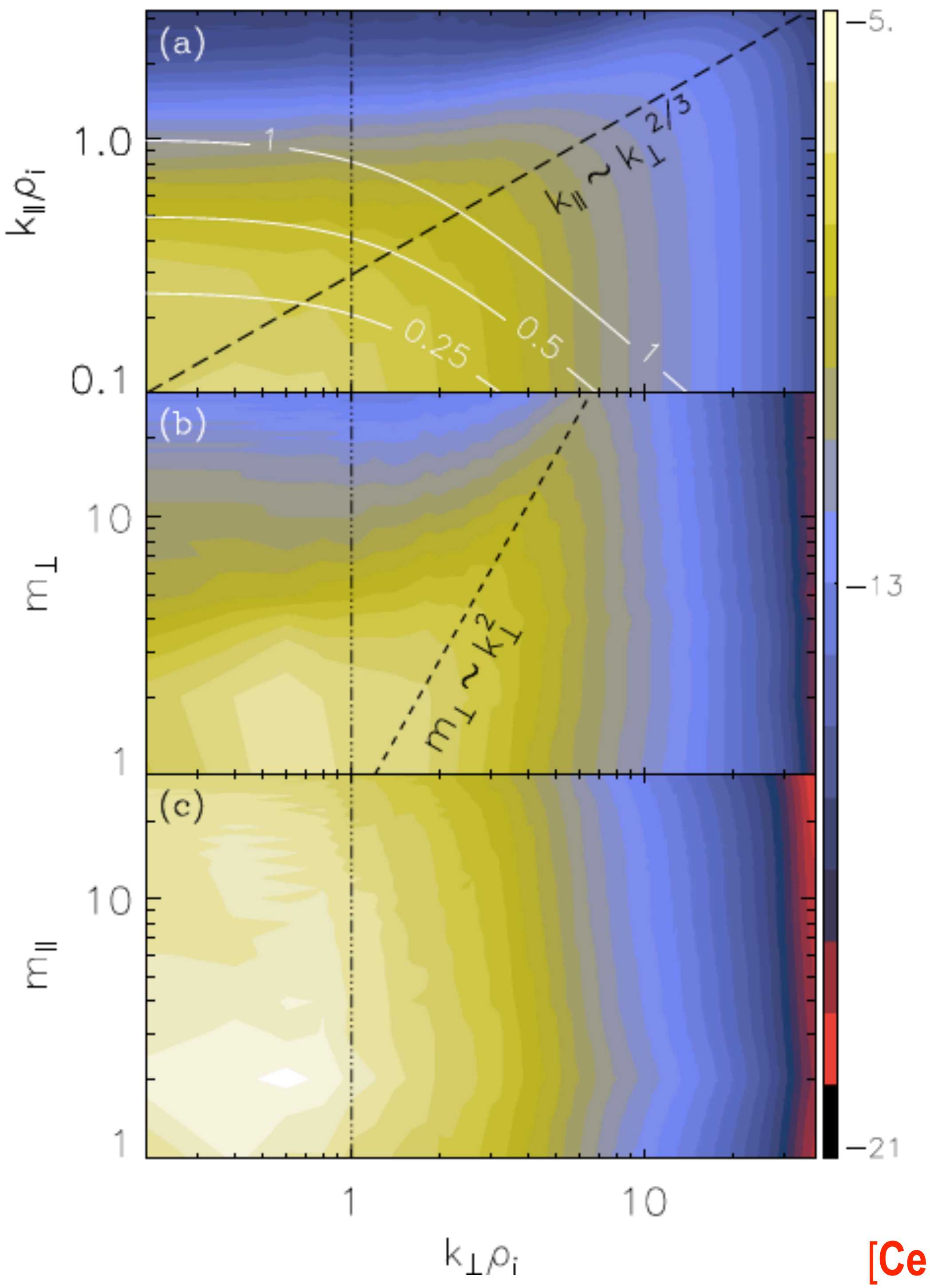


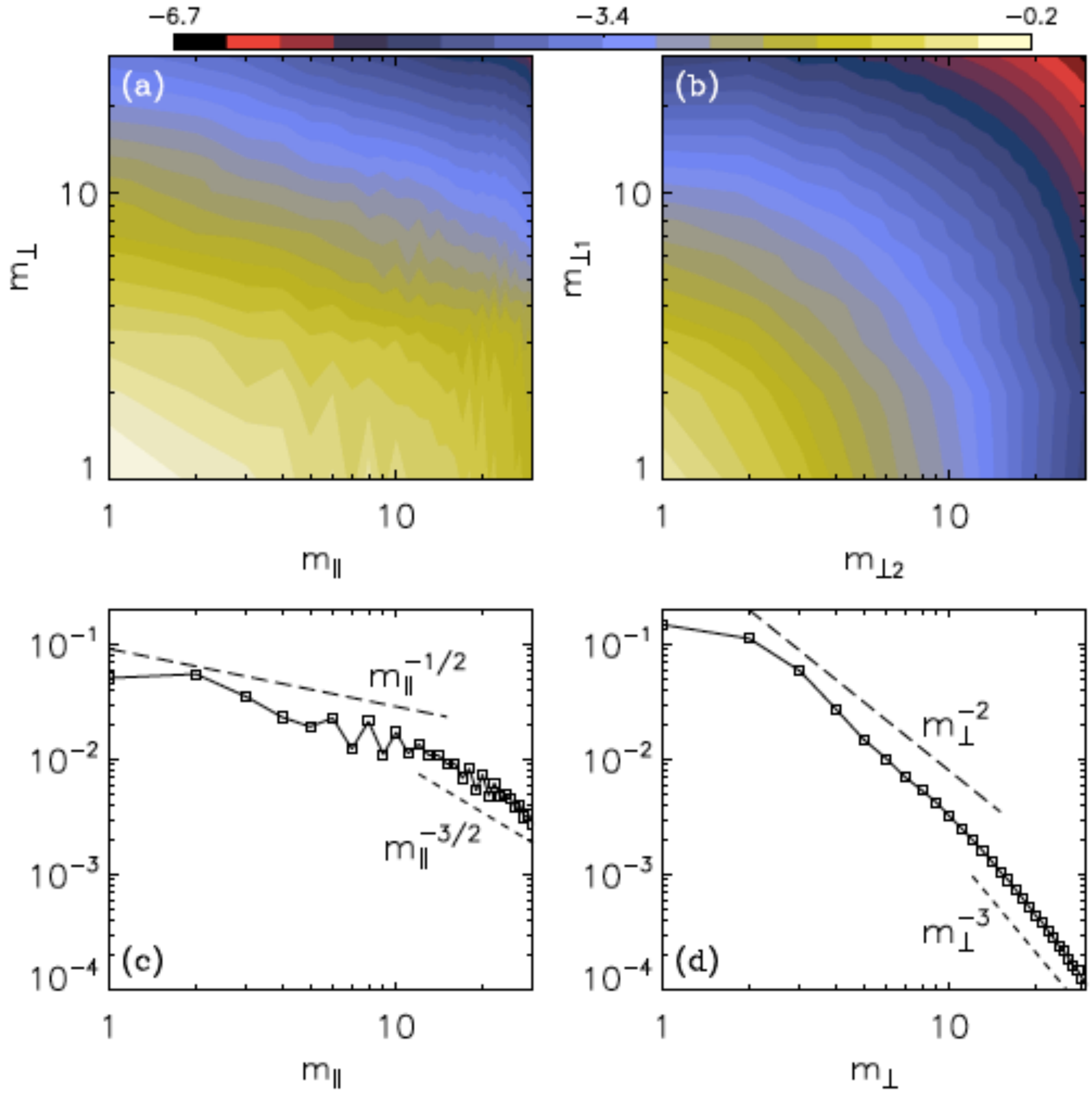
First evidence of a cascade in velocity space from in-situ data!

(measured by MMS in the Earth's magentosheath)

Multiple players are allowed!

Anisotropic cascade of ion free-energy fluctuations in 6D phase space





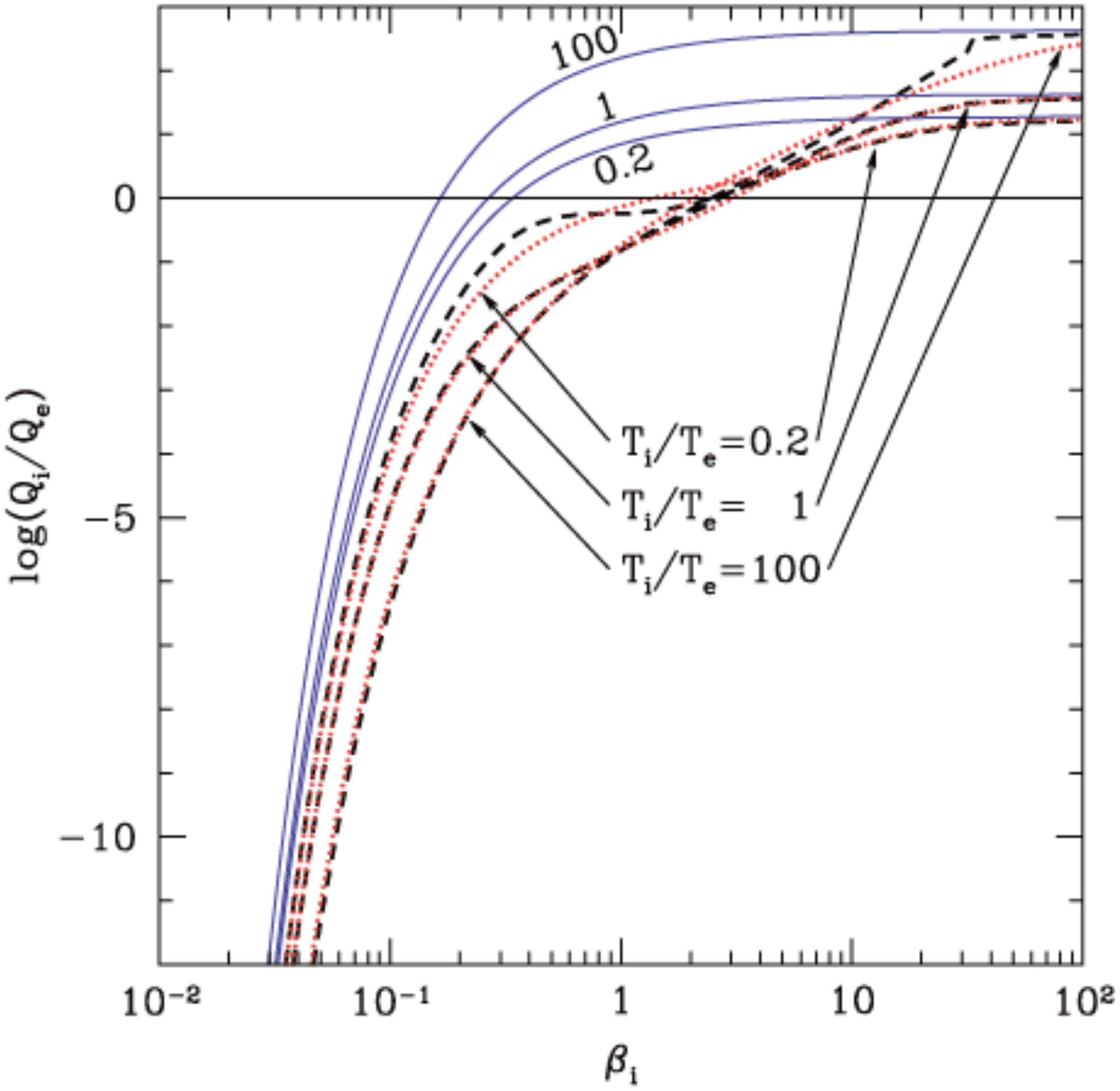
[**Cerri**, Kunz & Califano, ApJL (2018)]

→ ***different mechanisms can be simultaneously at play***

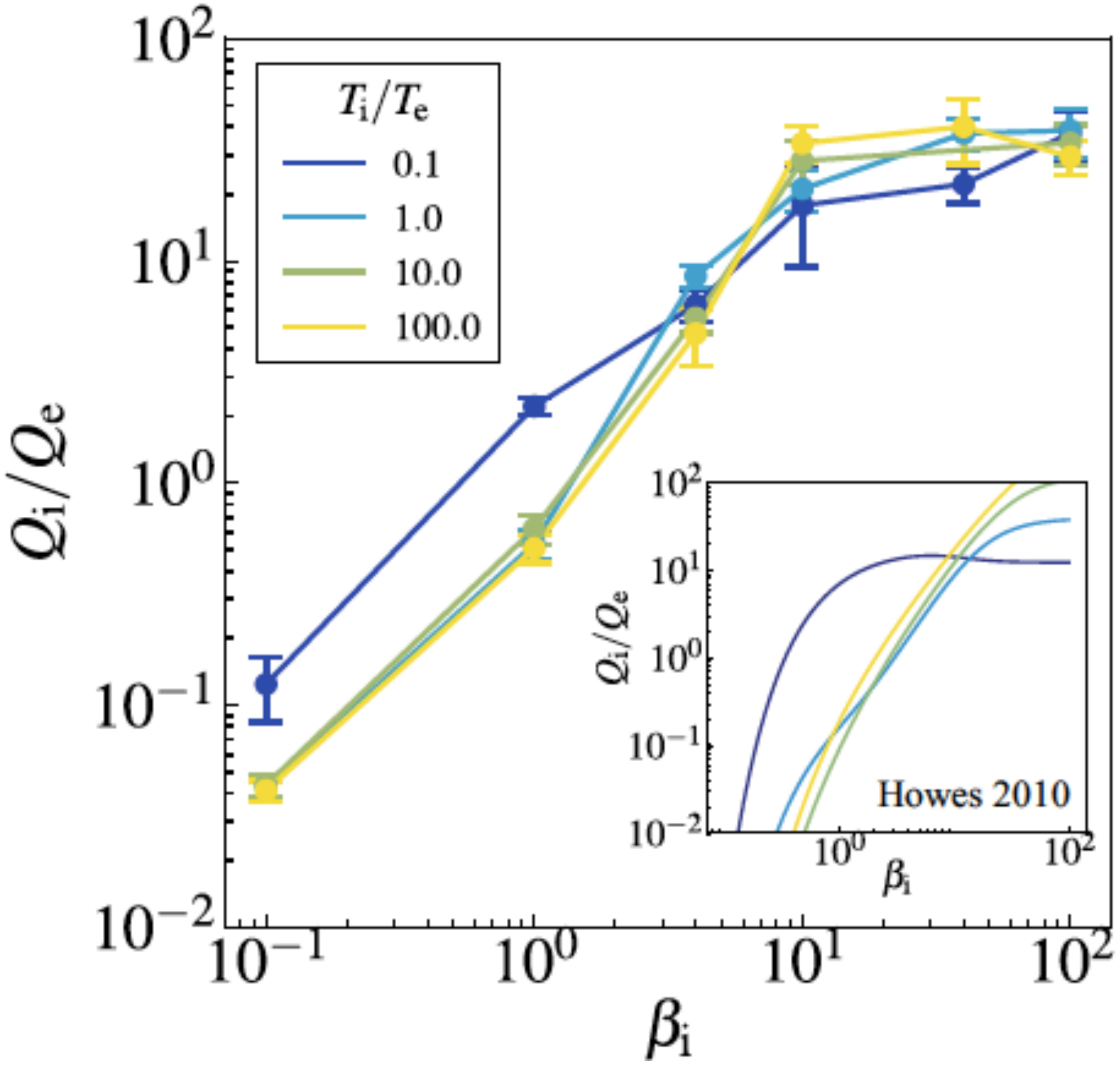
Landau damping of turbulent fluctuations

Turbulent heating from gyro-kinetic (GK) damping rates

$$Q_s(k_\perp) = 2C_1^{3/2} C_2(\overline{\gamma}_s/\overline{\omega})\epsilon(k_\perp)/k_\perp$$



[Howes, MNRAS (2010)]



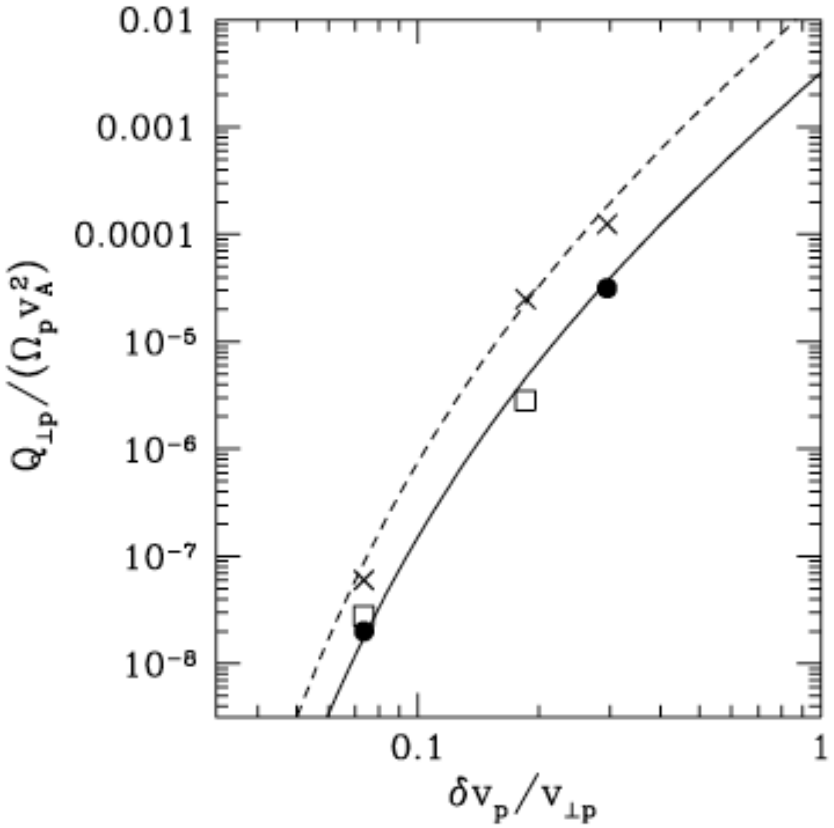
[Kawazura et al., PNAS (2019)]

Finite-amplitude fluctuations at ion gyroscale

Stochastic heating in low-frequency turbulent fluctuations

$$Q_\perp = \frac{c_1(\delta v_\mathrm{i})^3}{\rho_\mathrm{i}} \exp\left(-\frac{c_2}{\varepsilon_\mathrm{i}}\right) \qquad \varepsilon_\mathrm{i} = \frac{\delta v_\mathrm{i}}{v_{\perp\mathrm{i}}} \simeq \beta^{-1/2}\delta B_\mathrm{p}/B_0$$

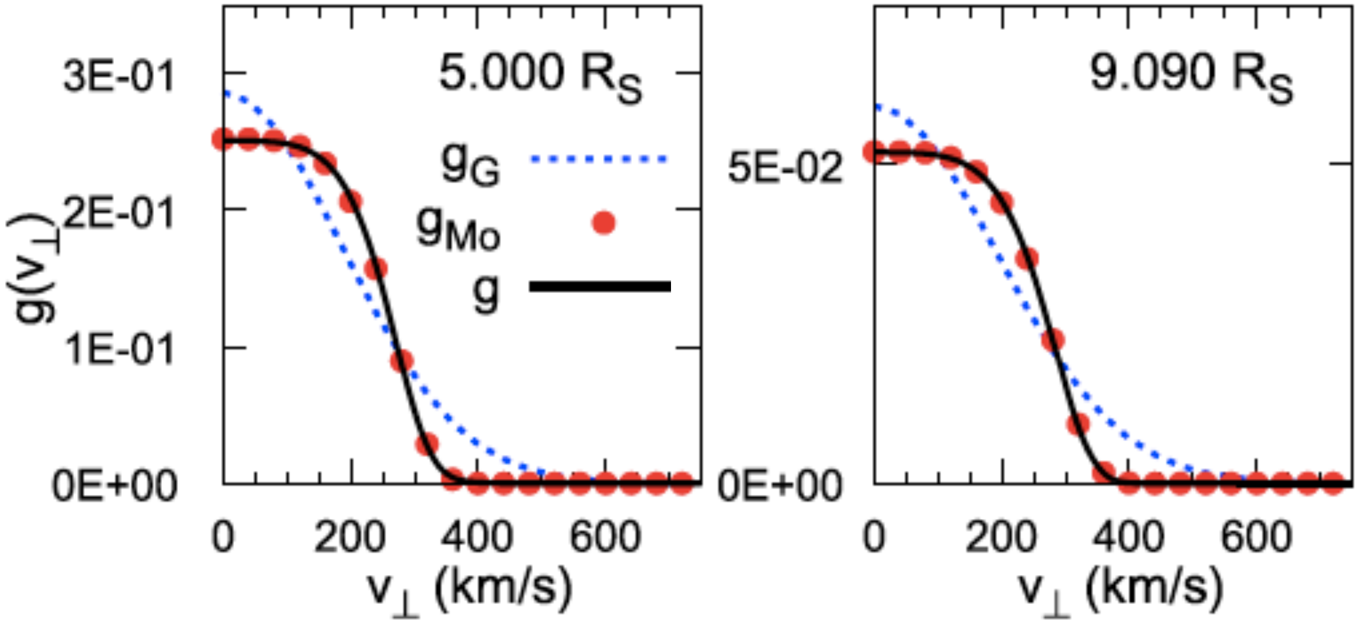
[Chandran et al., ApJ (2010)]



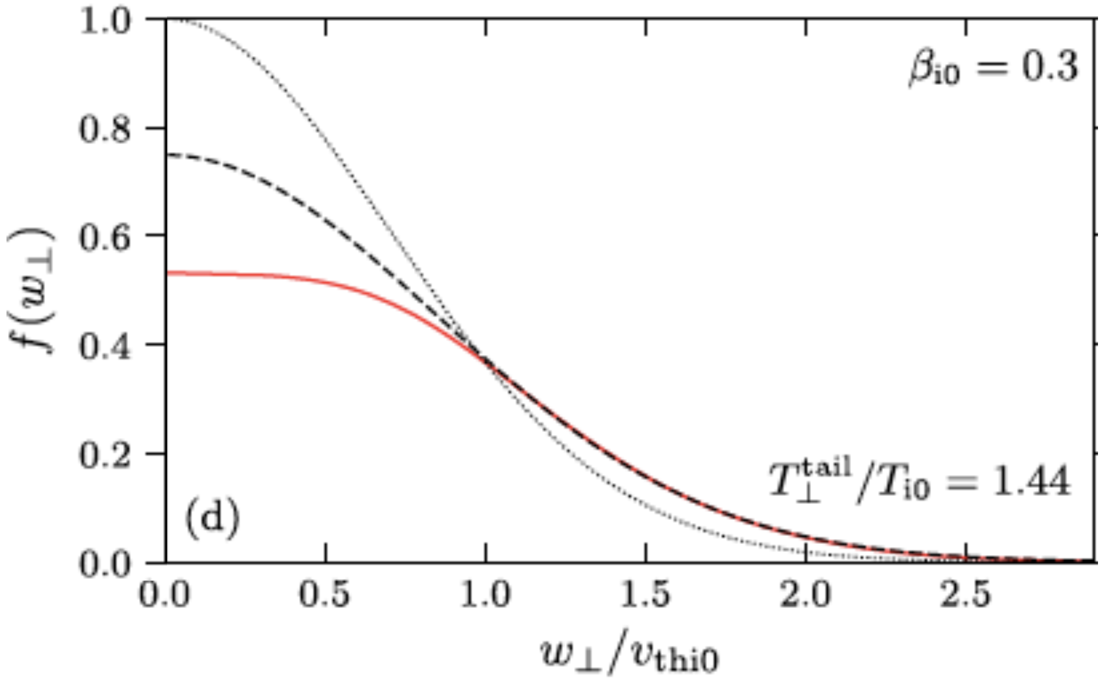
$$\Gamma = C_K^{-3/2}\left(\frac{\delta v_\mathrm{p}}{\rho_\mathrm{p}}\right)\left(\frac{\delta B_\mathrm{p}}{B_0}\right)^2 v_A^2$$

$$\frac{Q_{\perp\mathrm{p}}}{\Gamma} = 3.0\exp\left(-\frac{0.34}{\varepsilon_\mathrm{p}}\right)$$

[Klein & Chandran, ApJ (2016)]

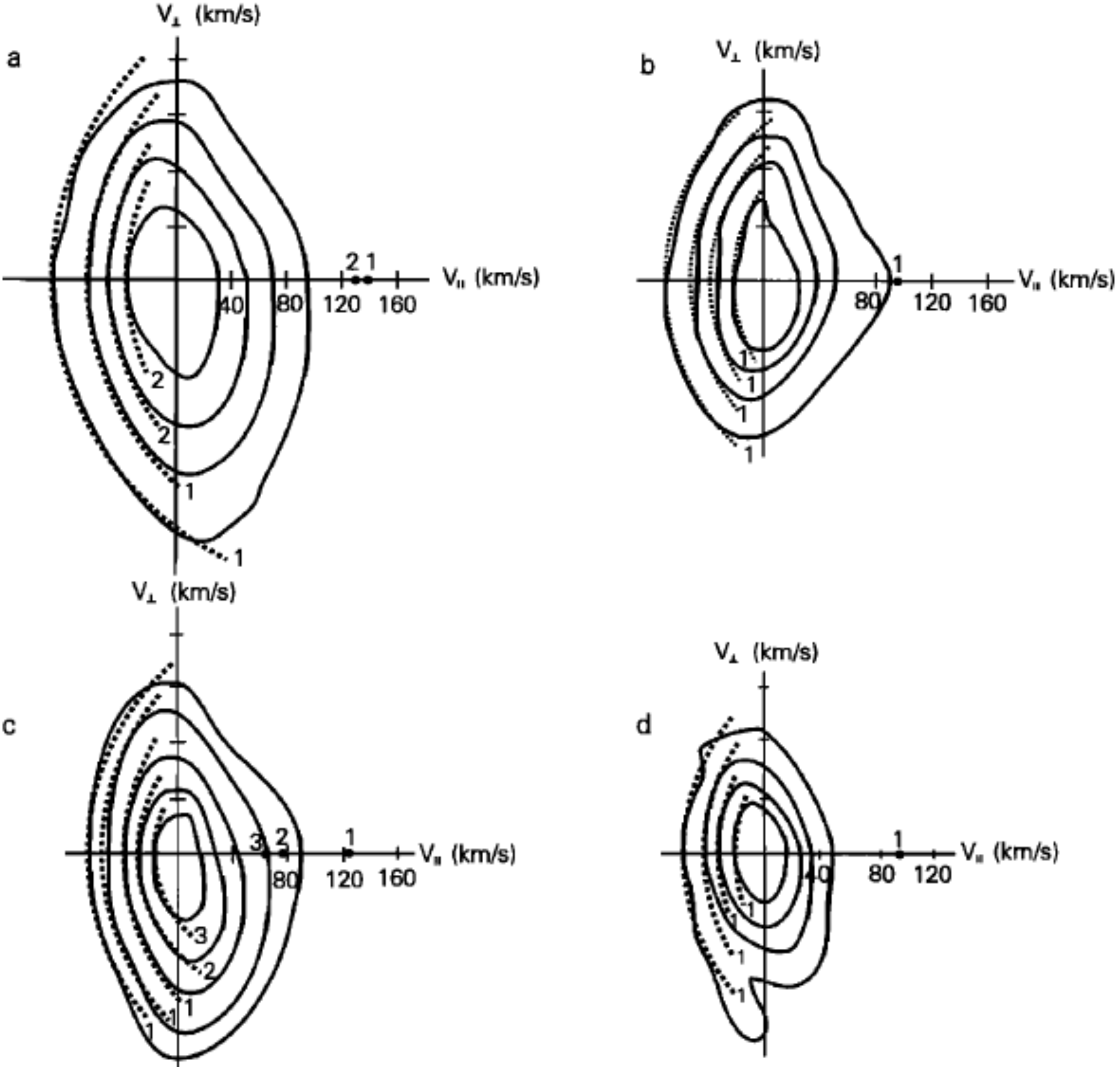


[Arzamasskiy et al., ApJ (2019)]

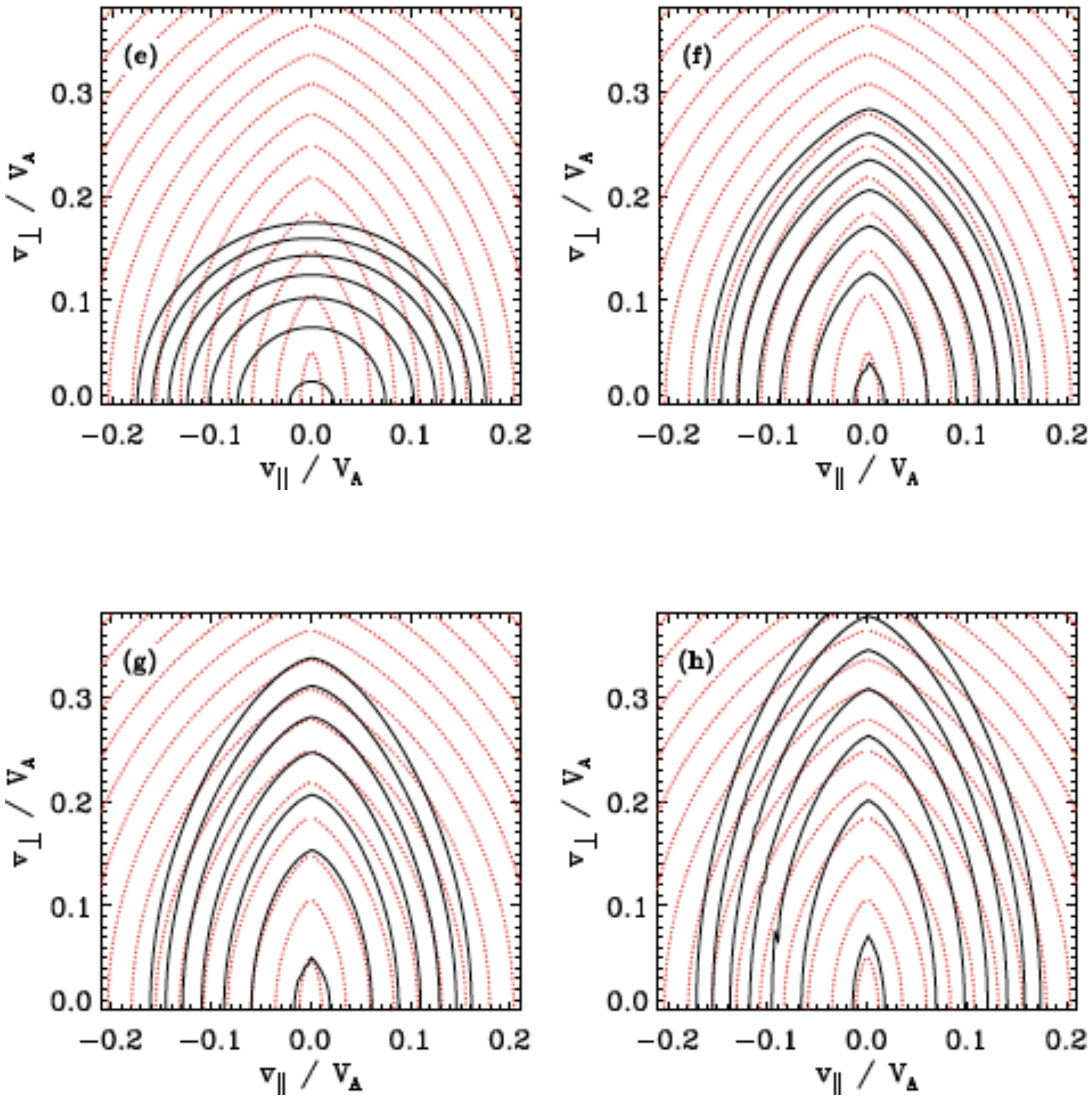


“high-frequency” fluctuations

Ion-cyclotron heating



[Marsch & Tu, JGR (2001)]



[Cranmer, ApJS (2014)]

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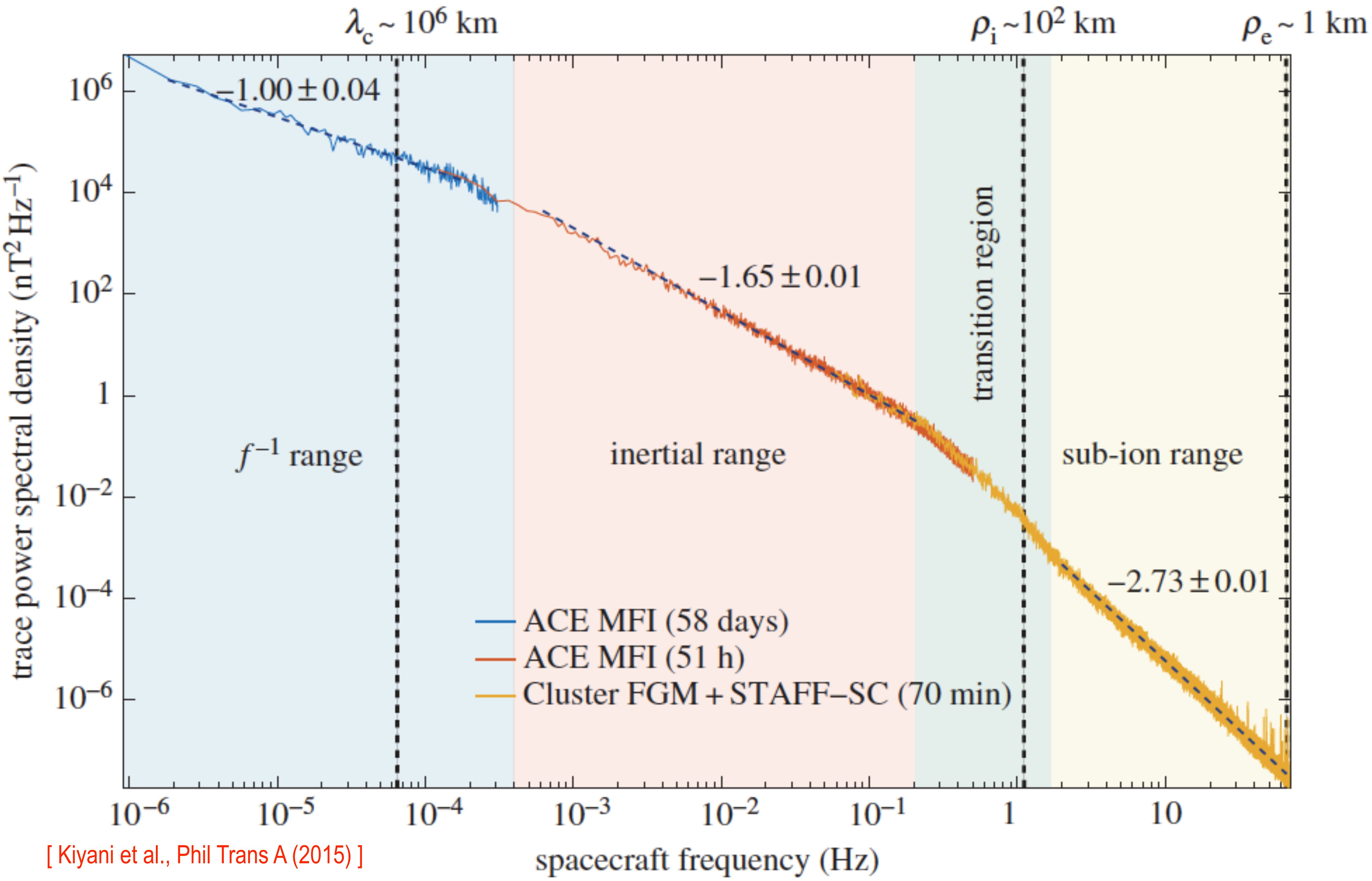
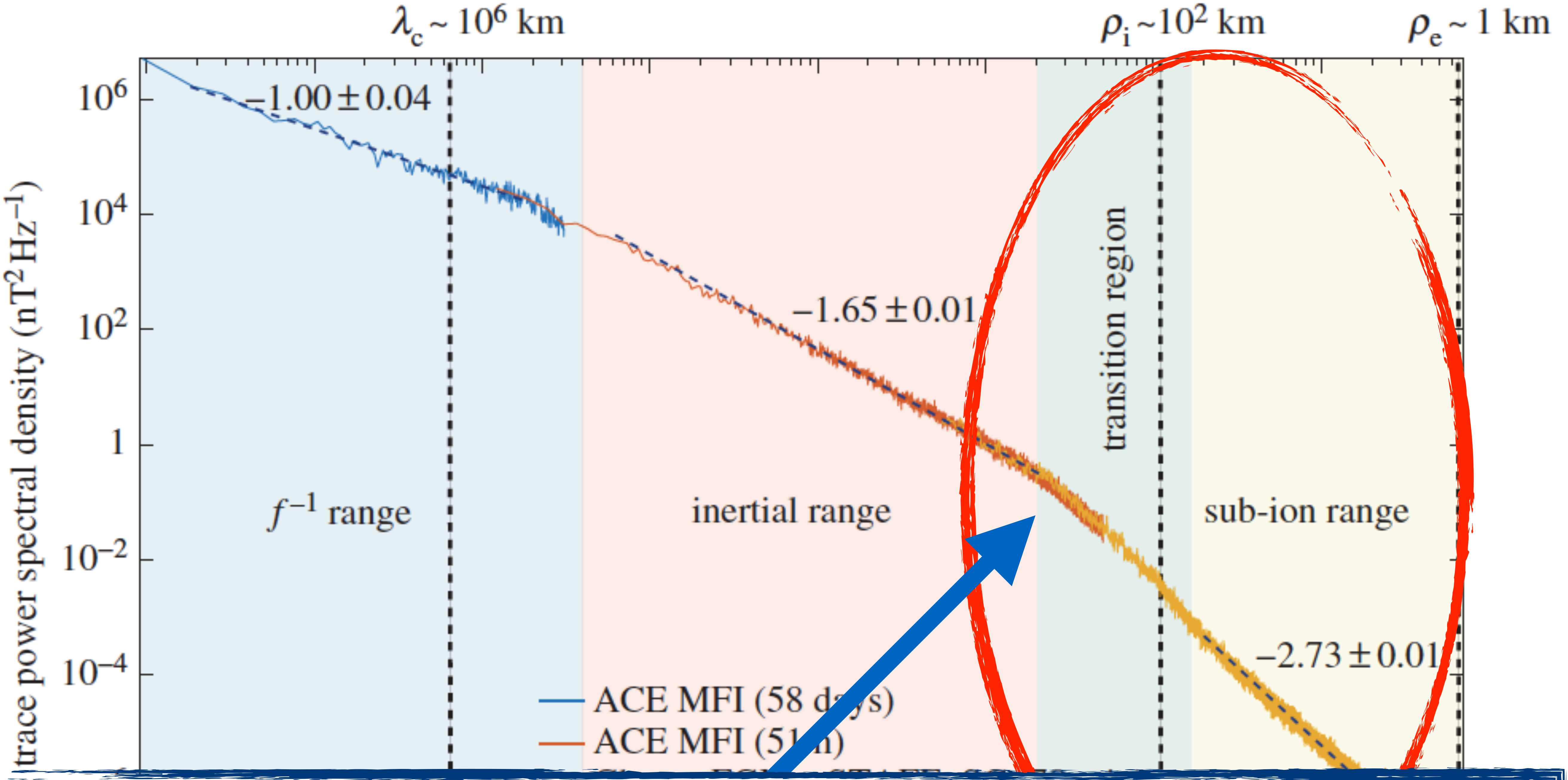
The standard picture of SW turbulence



[Kiyani et al., Phil Trans A (2015)]

The standard picture of SW turbulence



(We think that) What the system "chooses" in terms of turbulent cascade and turbulent heating is occurring across the transition region, and perhaps in part of the sub-ion range

(e.g., what kinetic cascade and heating "channels" get activated)

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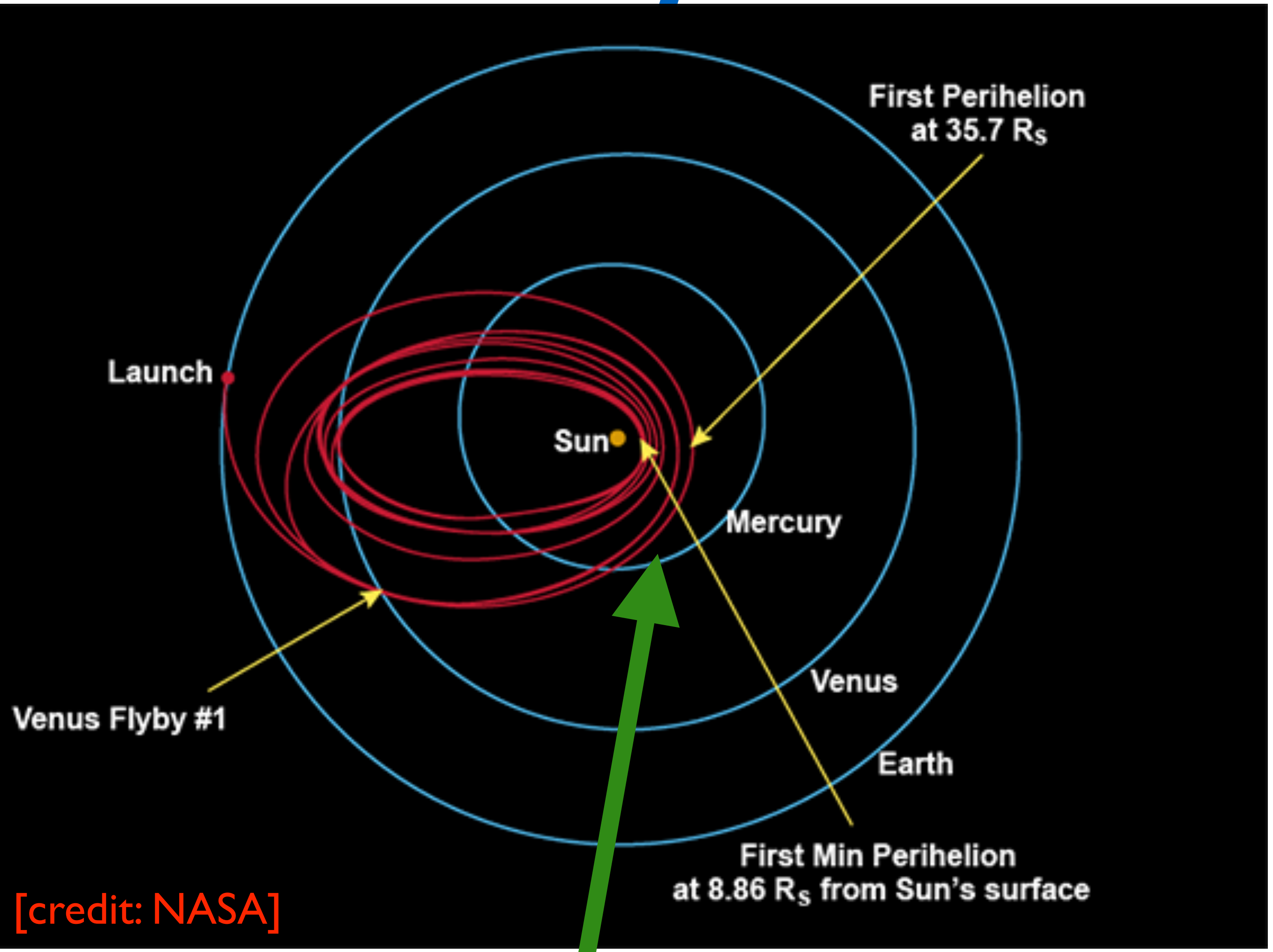
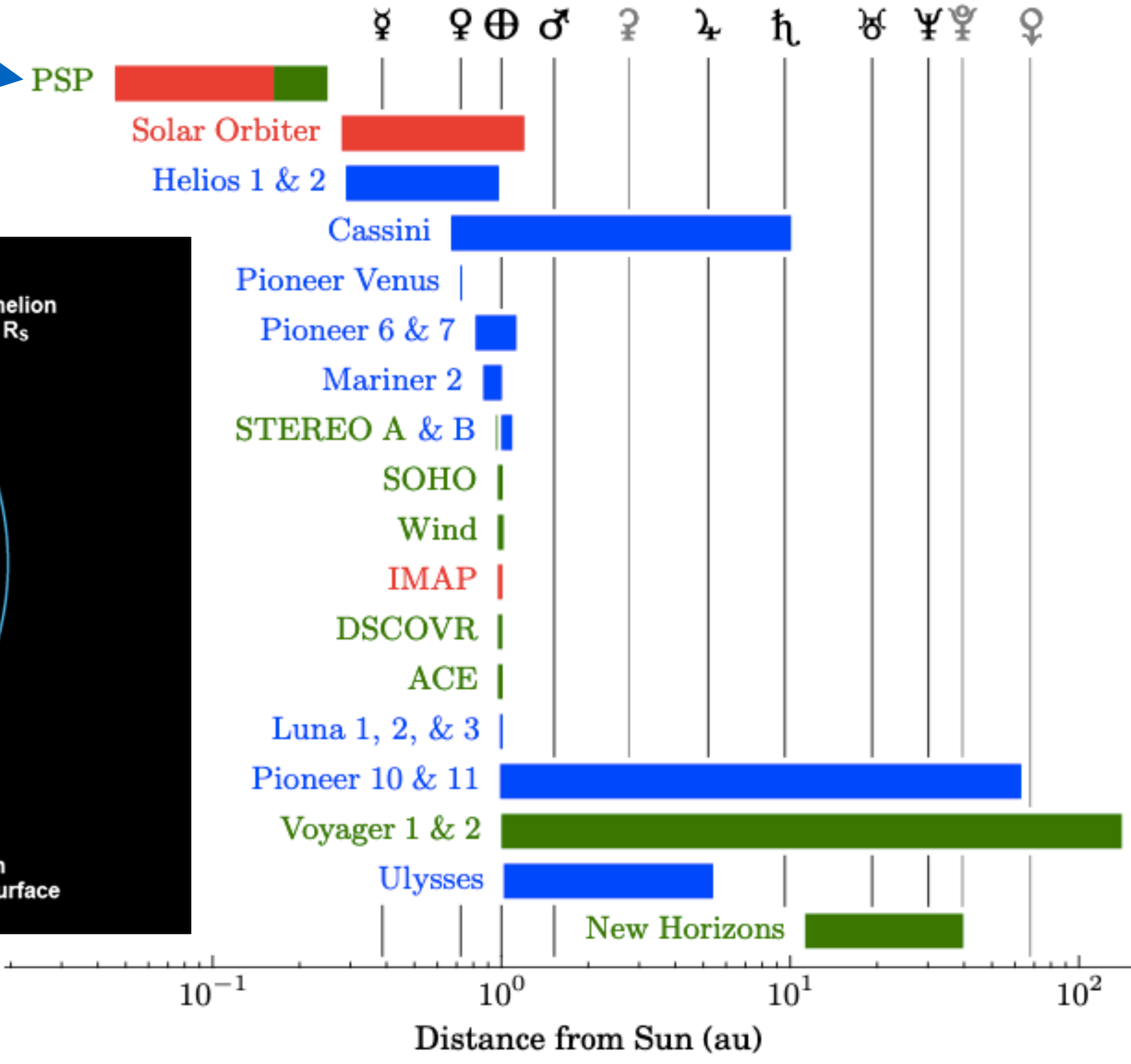
NASA Parker Solar Probe (PSP) mission

Parker Solar Probe: a mission to “touch” the Sun



[credit: NASA]

typically β << 1 regime



[credit: Verscharen, Klein & Maruca (arXiv:1902.03448)]

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  - ☞ The solar wind & space missions *(or, “where we can really learn something about plasma turbulence”)*
  - ☞ What (we think) we know about plasma turbulence and turbulent heating
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- The hybrid-PIC code PEGASUS & simulation setup
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- Ion heating

The hybrid-PIC code PEGASUS++

[Kunz et al., JCP (2014)]

- **Fully kinetic ions** (Vlasov equation through Lagrangian approach)
- **Massless electron fluid** (generalized Ohm's law)
- **Maxwell's equations** (Faraday equation + Ampere's law w/o displacement current)

$$\frac{\partial f_{\mathrm{i}}}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f_{\mathrm{i}} + \frac{e}{m_{\mathrm{i}}}\left[\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B} + \frac{\boldsymbol{F}_{\mathrm{ext}}}{m_{\mathrm{i}}}\right]\cdot\frac{\partial f_{\mathrm{i}}}{\partial \boldsymbol{v}} = 0,$$

$$\boldsymbol{E} = -\frac{\boldsymbol{u}_{\mathrm{i}}}{c}\times\boldsymbol{B} + \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{e n_{\mathrm{i}} c} - \frac{T_{\mathrm{e},0}\boldsymbol{\nabla} n_{\mathrm{i}}}{e n_{\mathrm{i}}},$$

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

- Quasi-neutrality is assumed ($n_e = n_i$)
- Time-correlated external forcing injecting momentum fluctuations at a prescribed power input rate
- An isothermal closure for electrons' pressure is adopted
- Small-scale dissipation: hyper-resistivity + numerical filters (only on the first two moments of f_i, i.e., n_i and $n_i\boldsymbol{u}_i$)

Simulation setup

$\beta_{\mathrm{i},0} = 1/9 \simeq 0.11$ $\quad T_{\mathrm{e},0}/T_{\mathrm{i},0} = 1$

$L_{\parallel} = 6L_{\perp} = 48\pi d_{\mathrm{i}} \simeq 151 d_{\mathrm{i}}\ (\simeq 452\rho_i)$

$N_x = N_y = 288$ $\quad N_z = 1728$

$\Delta \simeq 0.087 d_{\mathrm{i}}\ (\simeq 0.26\rho_{\mathrm{i}})$

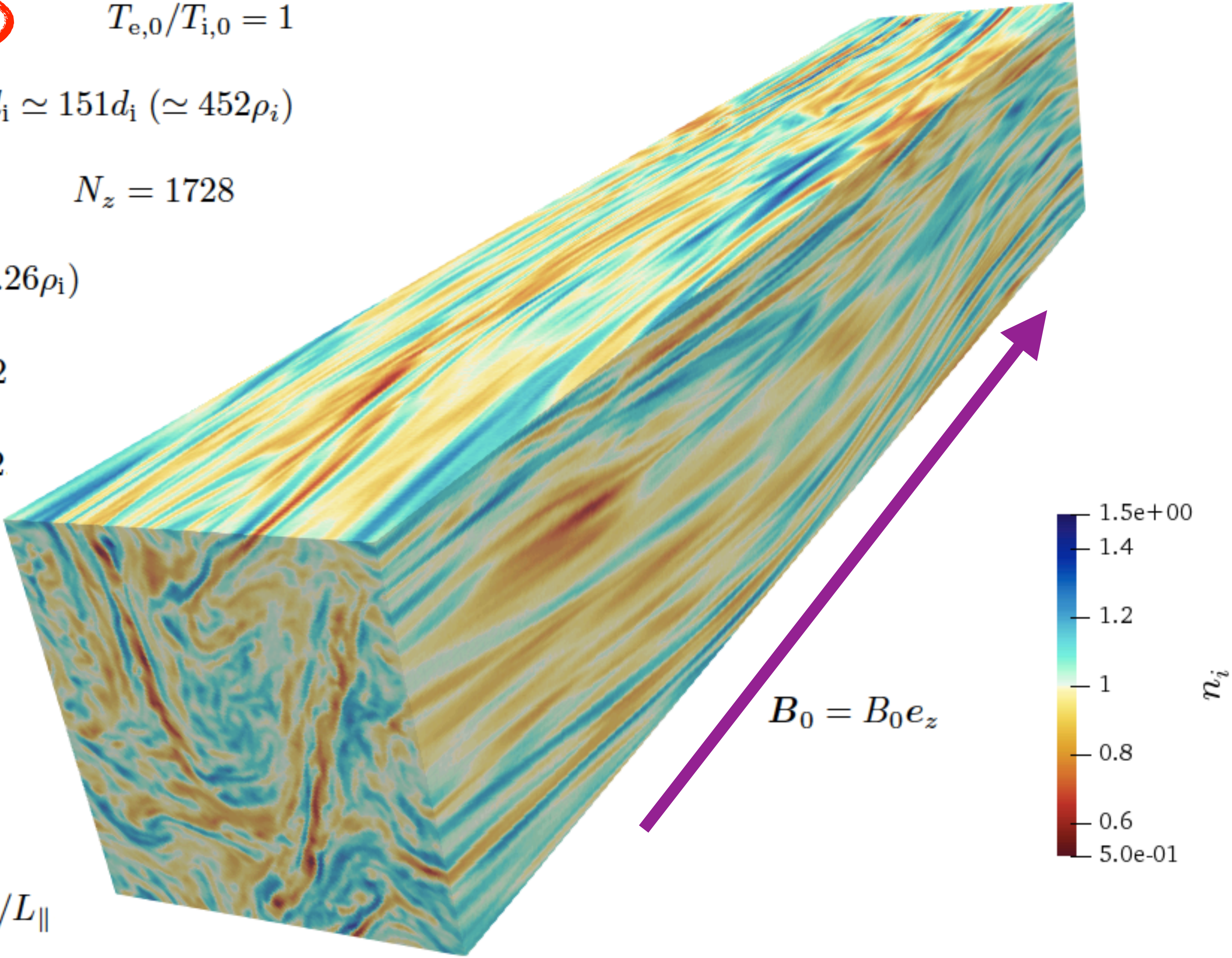
$0.083 \lesssim k_{\perp}\rho_{\mathrm{i}} \lesssim 12$

$0.014 \lesssim k_{\parallel}\rho_{\mathrm{i}} \lesssim 12$

512 ppc

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

$\delta u_{\perp}^{(\mathrm{rms})}/v_A \approx L_{\perp}/L_{\parallel}$



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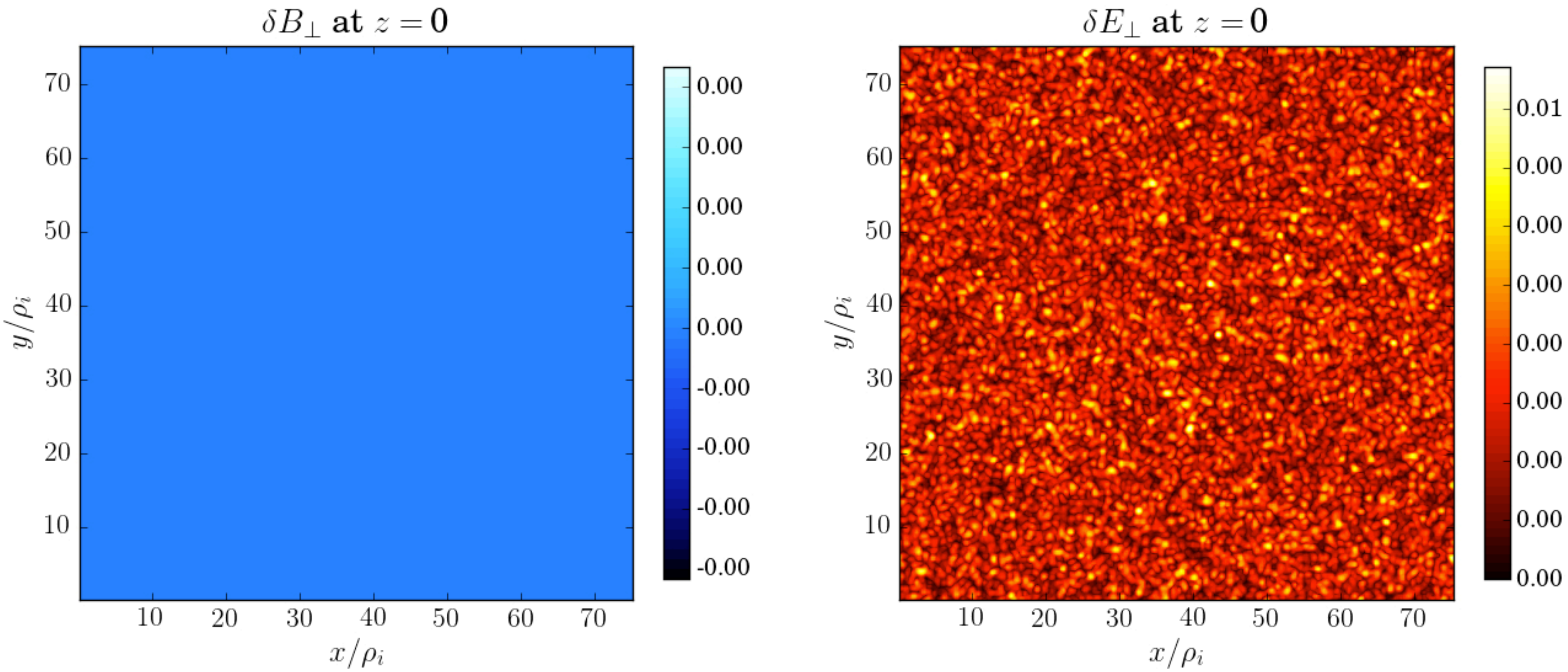
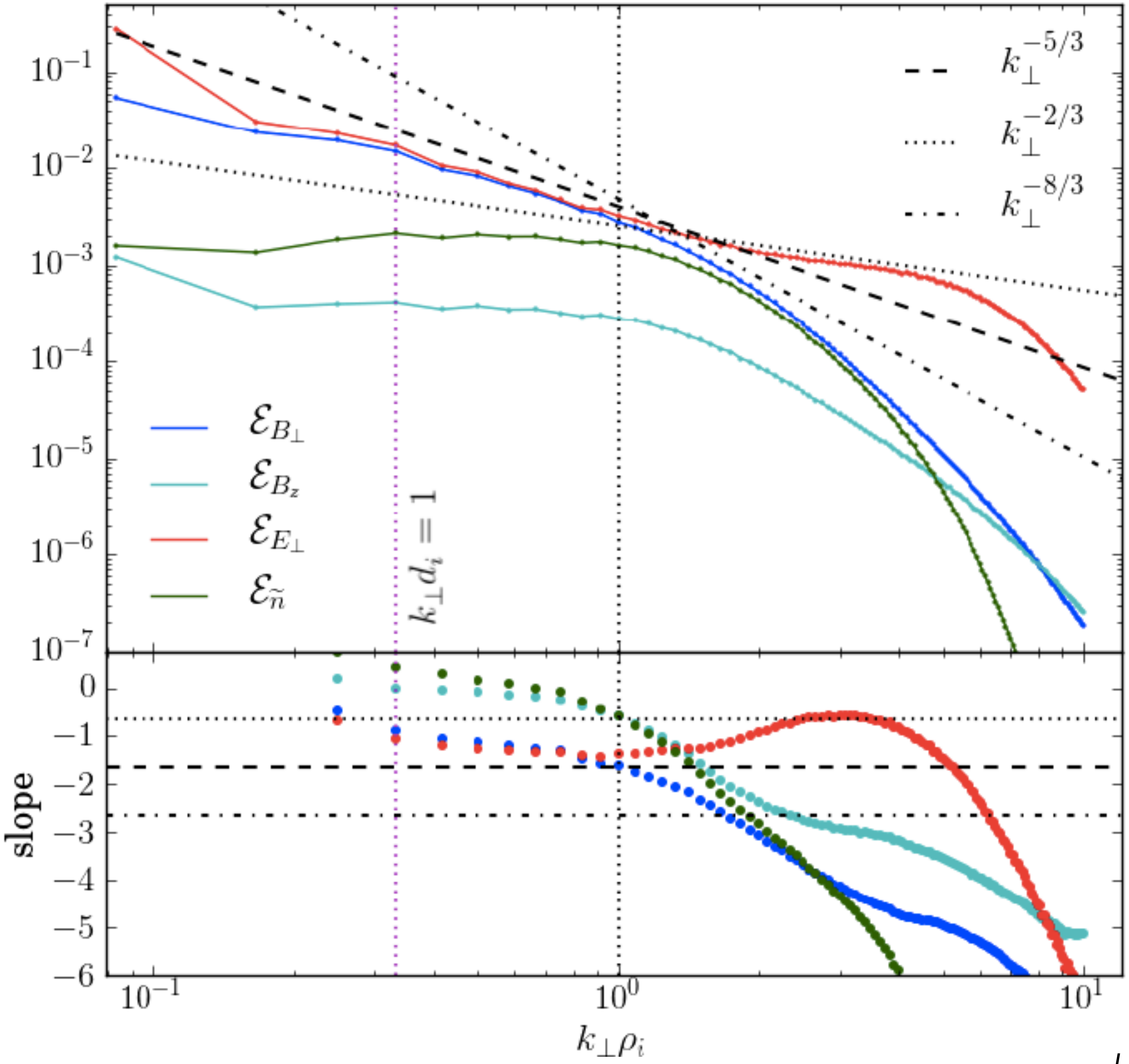
An impression of reconnection



- First current sheets and reconnection events clearly recognisable
- Several relevant features in spectra and ion heating emerge only after these first events
- Continuous formation and disruption of current sheets via reconnection in quasi-steady turbulent phase

Spectrum of turbulent fluctuations



[**Cerri**, Arzamasskiy & Kunz (in preparation)]

- Spectral break between d_i and ρ_i
- Polarisation of sub-ion scale fluctuations roughly consistent with KAW-like turbulence (not shown)
- Spectral slopes steeper than the ones predicted by standard KAW turbulence
- Sub-ion-scale spectrum consistent with the picture of "***reconnection-mediated" kinetic turbulence***

see, e.g., for
<u>kinetic case</u>:
***Cerri** & Califano, NJP (2017)*
*Franci, **Cerri** et al., ApJL (2017)*

+ <u>"fluid" case</u>:
Loureiro & Boldyrev, ApJ (2017); Mallet et al., JPP (2017), Comisso et al., ApJ (2018); Dong et al., PRL (2018),…

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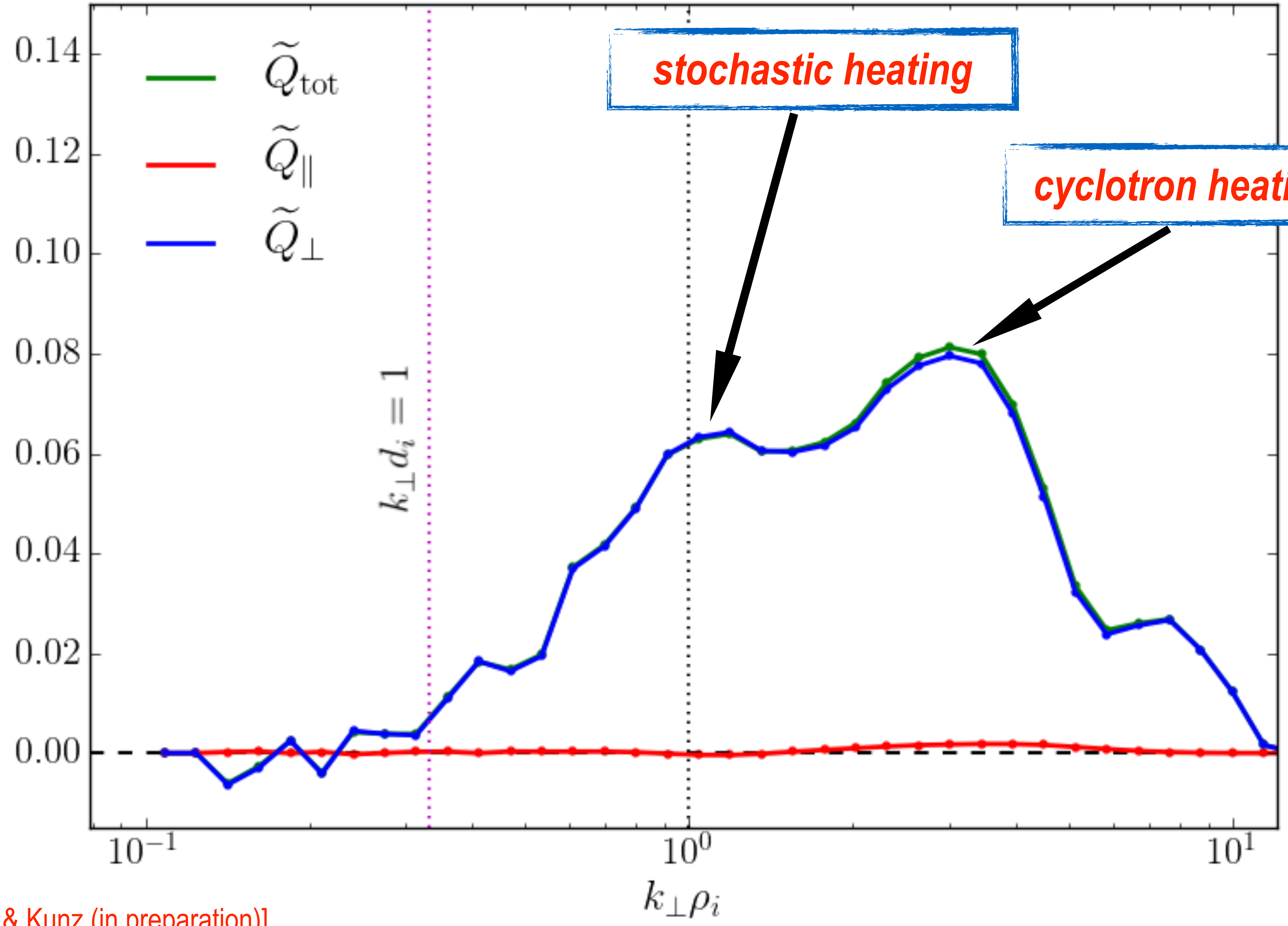
Ion heating in k-space

Ion heating averaged over the quasi-steady turbulent phase

$$\widetilde{Q}_{\|,\perp} = \frac{1}{Q_{\rm tot}} \sum_{\rm particles} \boldsymbol{w}_{\|,\perp} \cdot \boldsymbol{E}_{\|,\perp}(k_\perp)$$

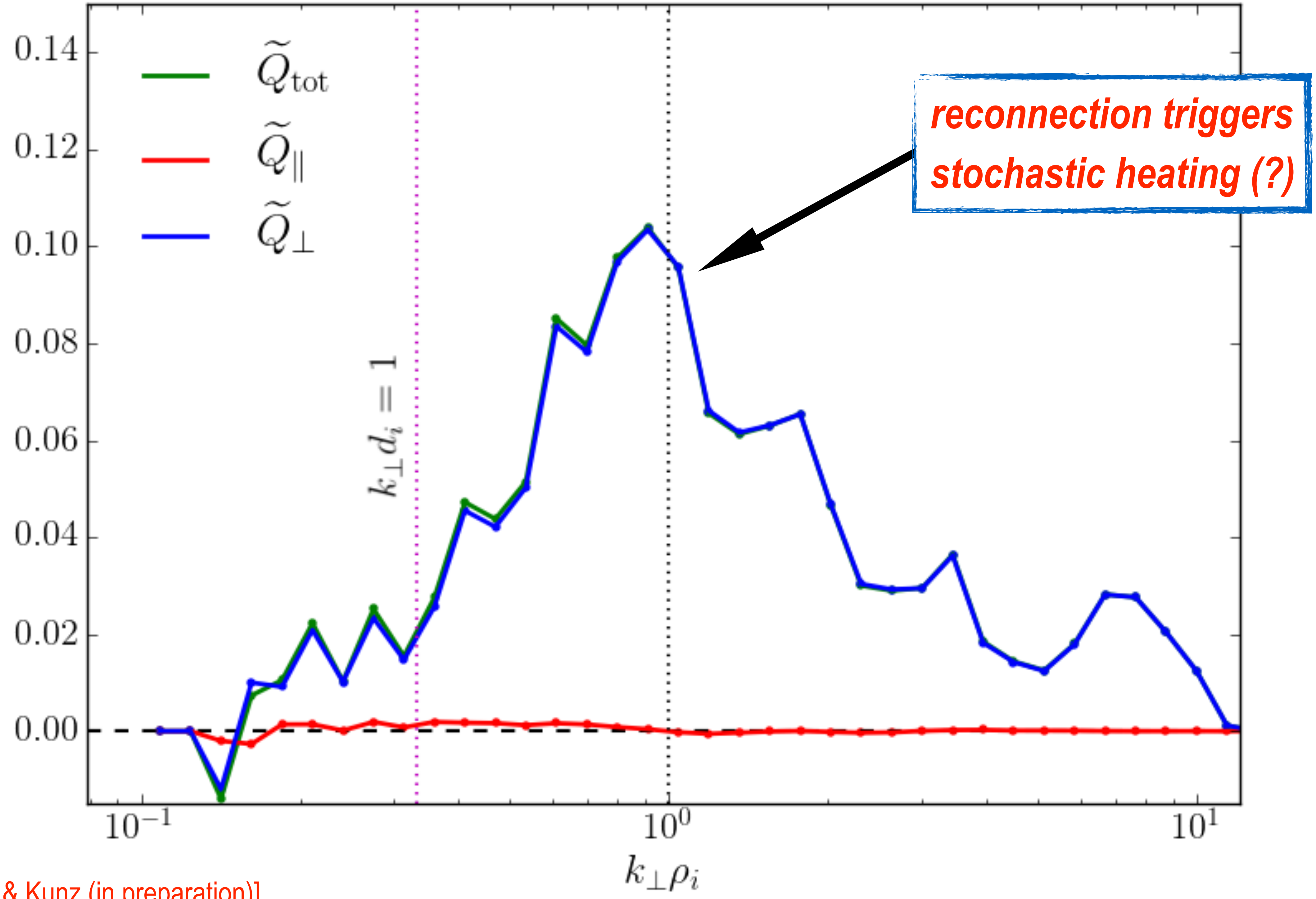


[**Cerri**, Arzamasskiy & Kunz (in preparation)]

Ion heating in k-space

Ion heating averaged over the onset of the first reconnection events

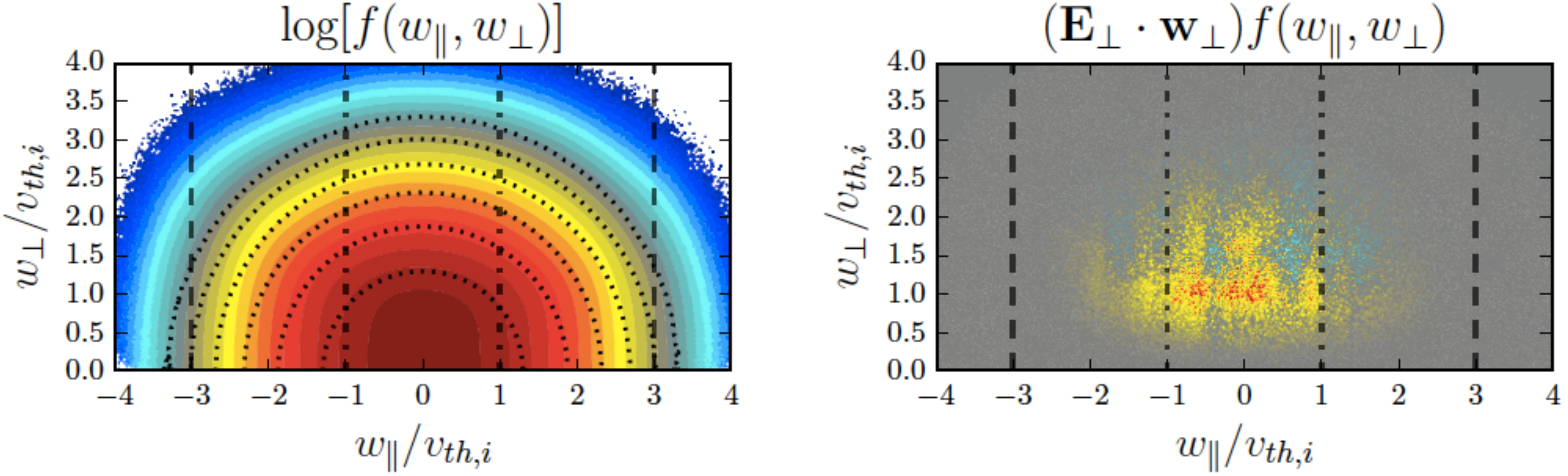
$$\widetilde{Q}_{\|,\perp} = \frac{1}{Q_{\rm tot}} \sum_{\rm particles} \boldsymbol{w}_{\|,\perp} \cdot \boldsymbol{E}_{\|,\perp}(k_\perp)$$

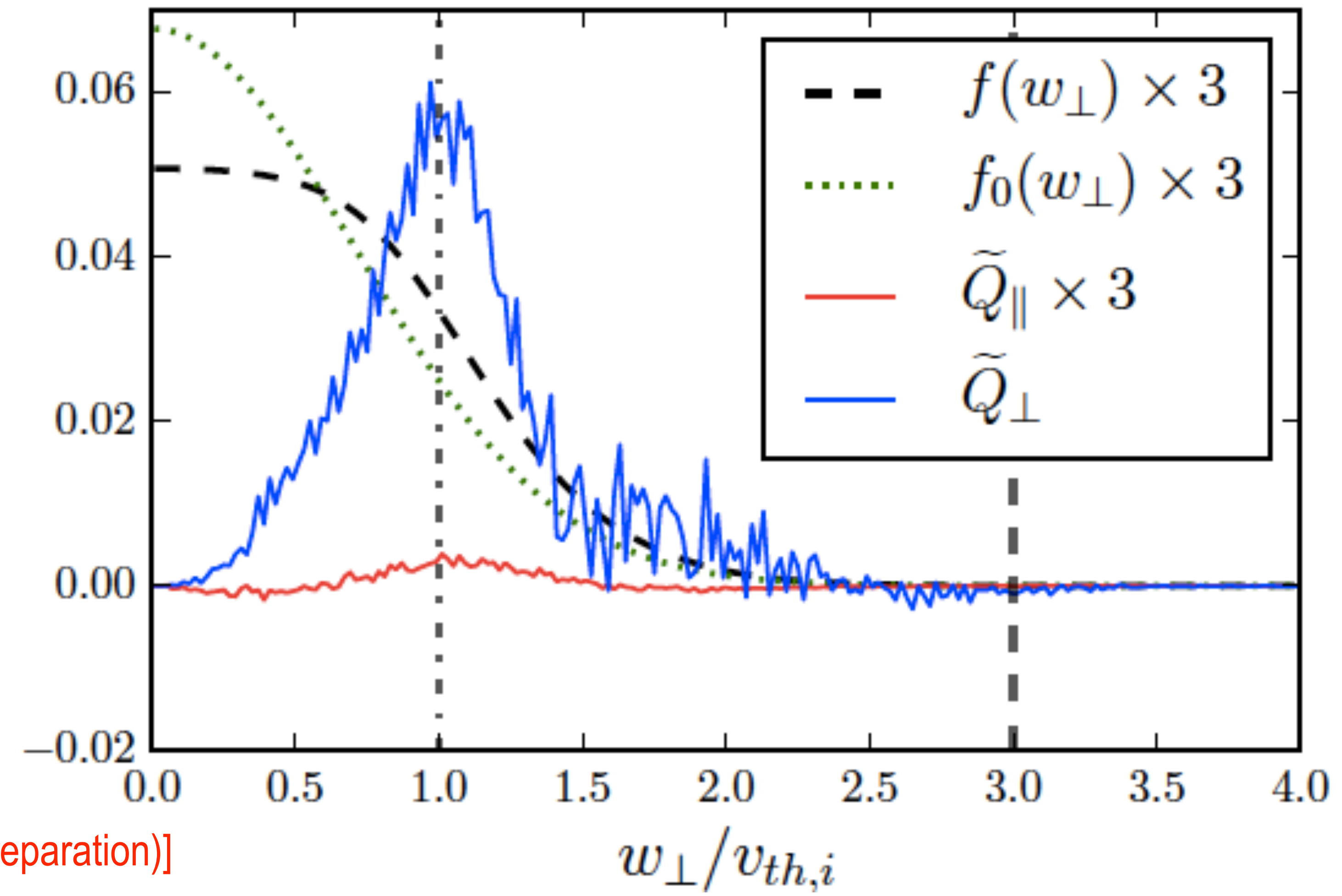


reconnection triggers stochastic heating (?)

[**Cerri**, Arzamasskiy & Kunz (in preparation)]

Ion heating in velocity space

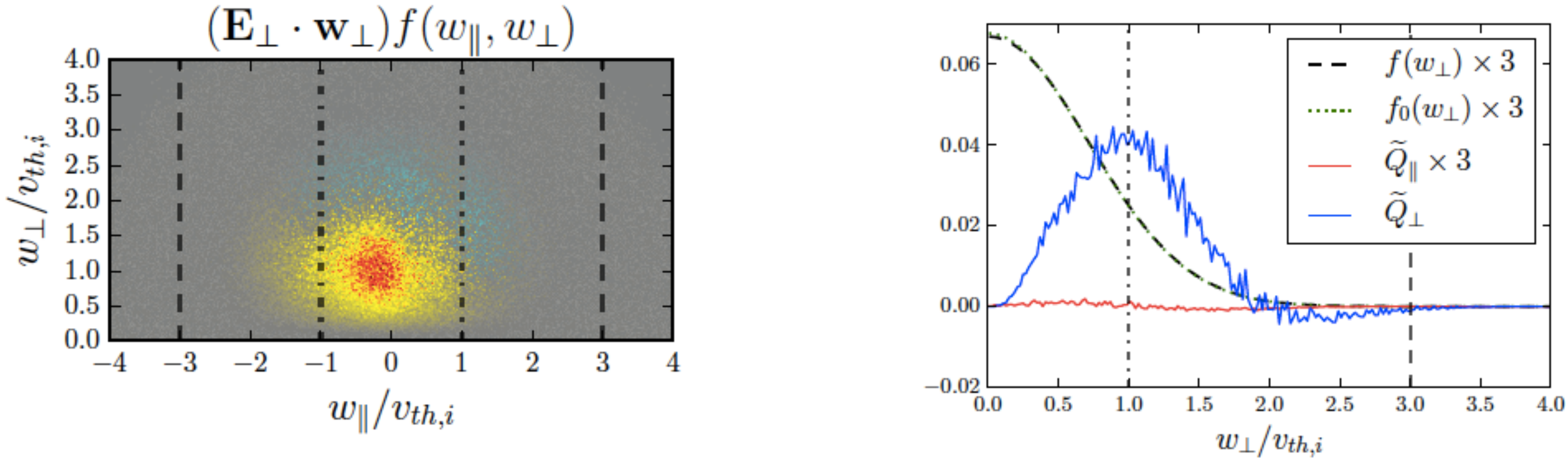




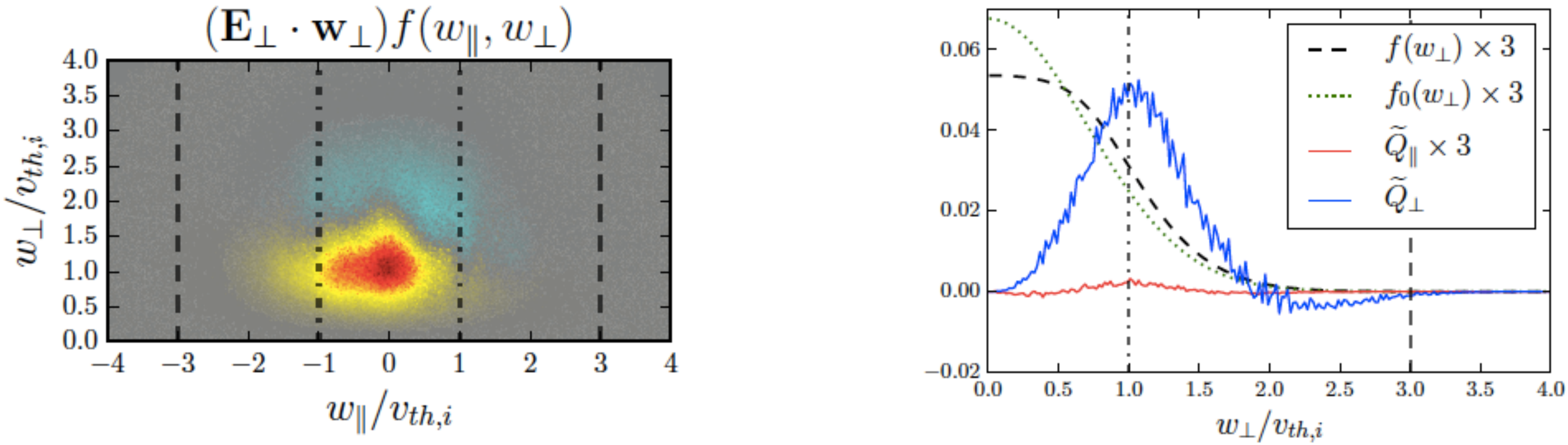
[**Cerri**, Arzamasskiy & Kunz (in preparation)]

Ion heating in velocity space

☞ ***averaged over the onset of the first reconnection events:***



☞ ***averaged over the entire quasi-steady turbulent phase:***



[**Cerri**, Arzamasskiy & Kunz (in preparation)]

Conclusions

- *In low-β (hybrid-kinetic) turbulence,* ***ion heating is predominantly perpendicular to $\boldsymbol{B}$***
  ($Q_{||} / Q_{tot} \sim 1.5$ %)

- ***Magnetic reconnection*** *seems to play a relevant role in determining the* ***transition to quasi-steady state turbulence*** *and in* ***"activating" (some of the) ion-heating mechanisms***

- ***Simultaneous presence of stochastic ion heating and (possibly) ion-cyclotron heating***
  (to be further investigated — very intermittent behaviour in time!)

- *From this simulation we estimate that only* ***~40% of the injected power goes into ion heating***
  (still about an order of magnitude larger than GK prediction)

☞ *This regime is particularly relevant for* ***Parker Solar Probe****, so… let's see!*

Thank you!