Electric and magnetic field spectra from MHD to kinetic scales in space plasmas: Cluster data in Earth's magnetosheath

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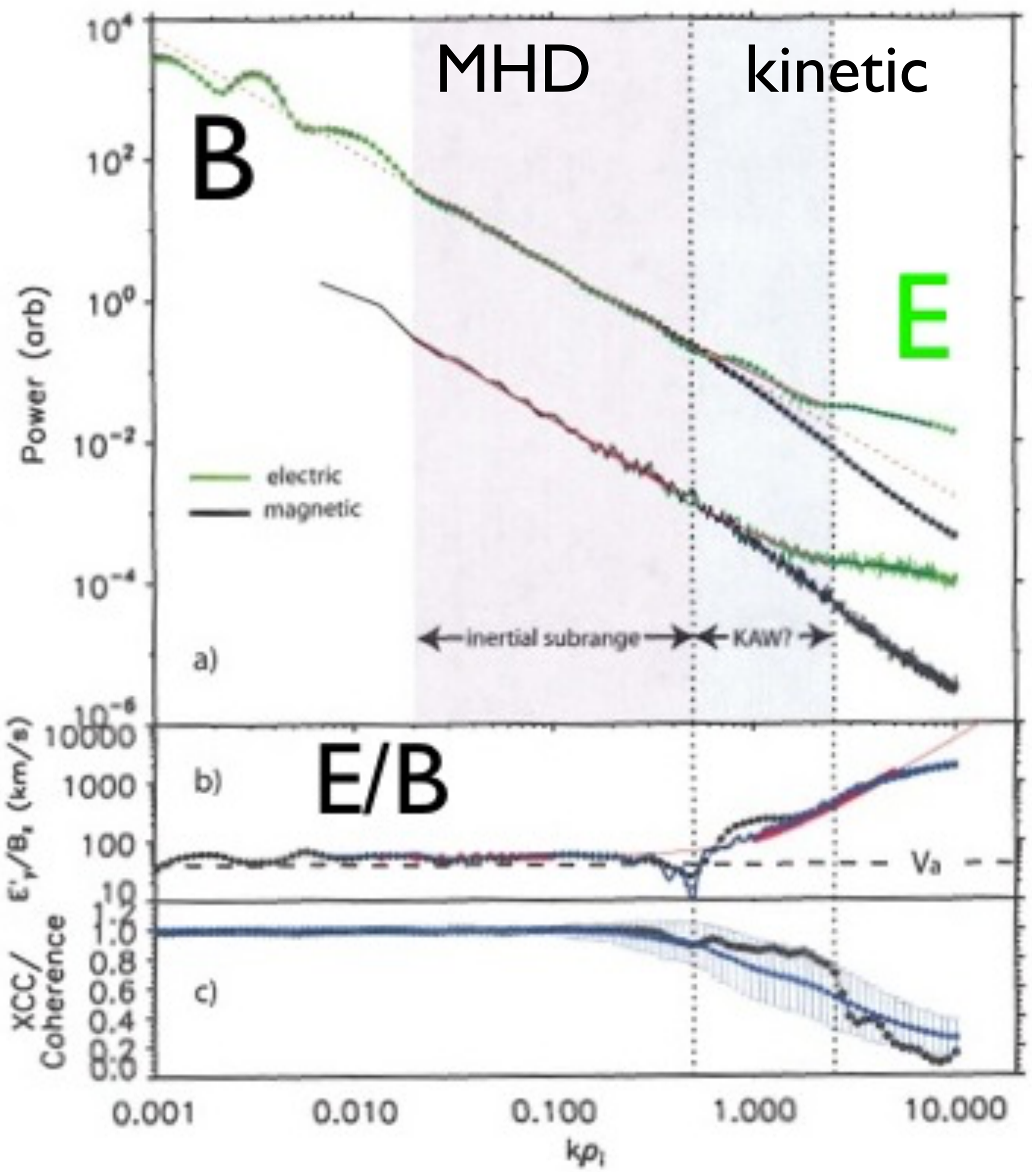
Matteini et al., "Electric and magnetic spectra from MHD to electron scales in the magnetosheath", MNRAS 2017

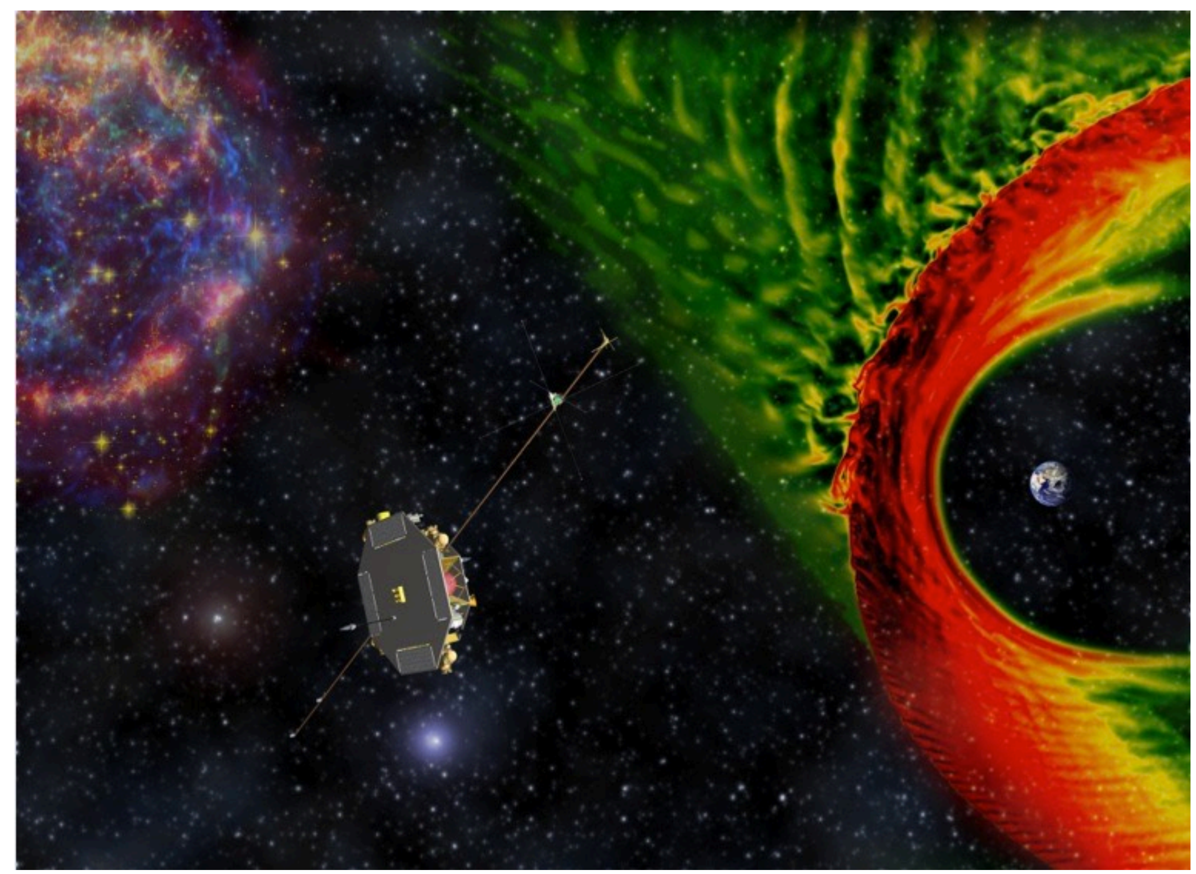
Motivation

The study of electric fields at kinetic scales is crucial for the understanding of particle energization in plasmas



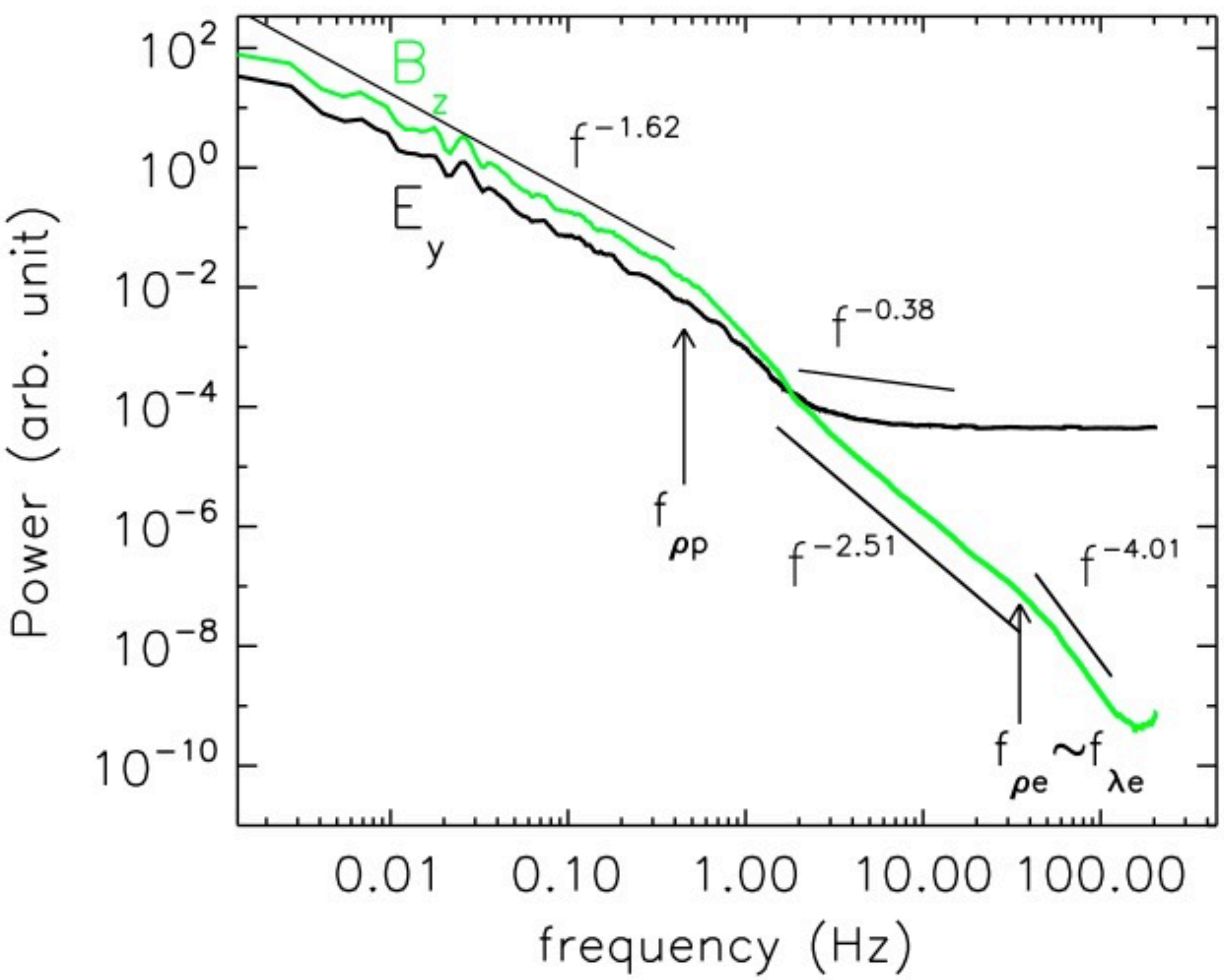
Bale et al. PRL 2005

THOR

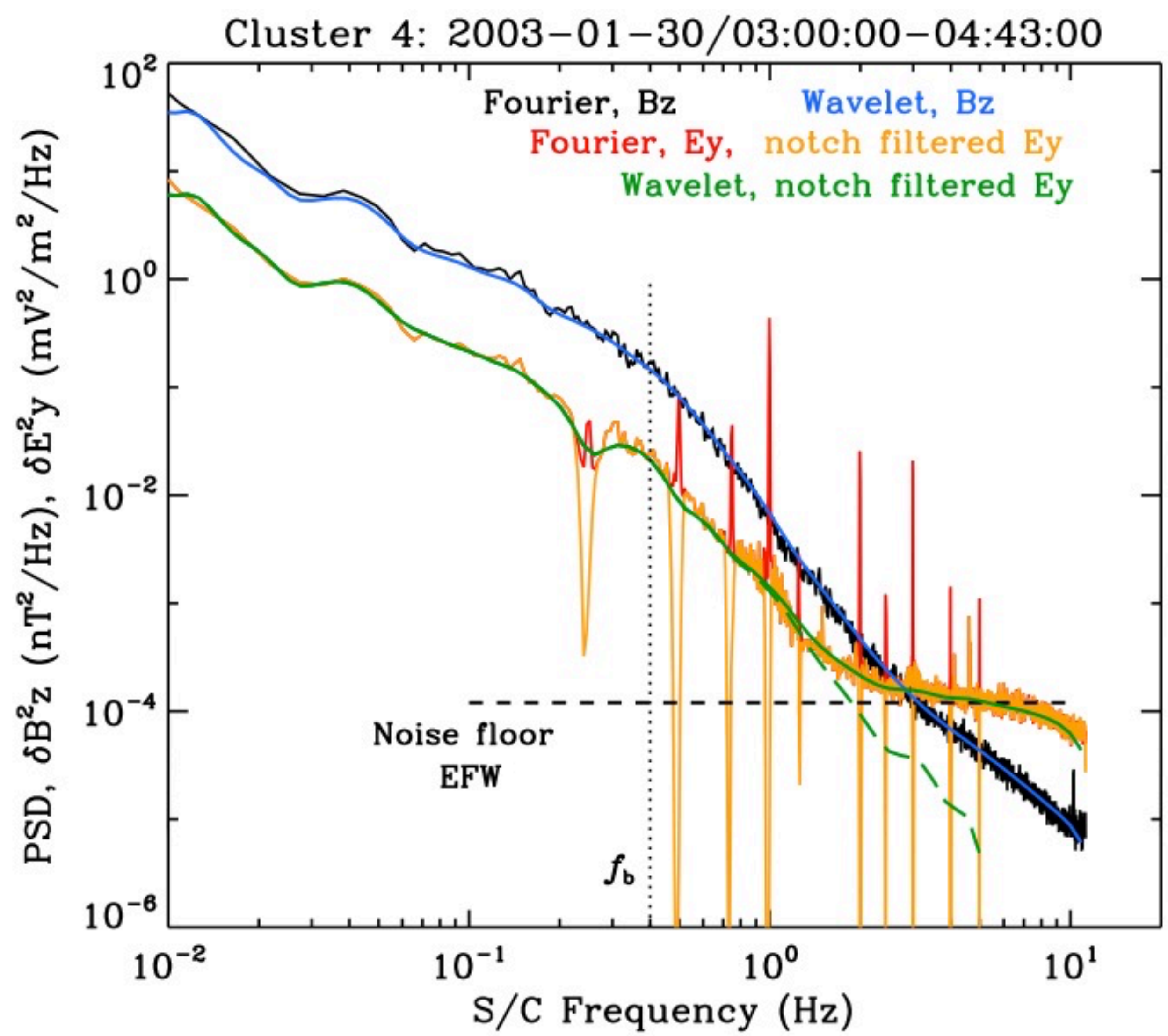


Electric field measurements in SW

While it is possible to follow the turbulent cascade down to electron scale with magnetic field observations, the same is not possible with electric field data due to current instrument limitations



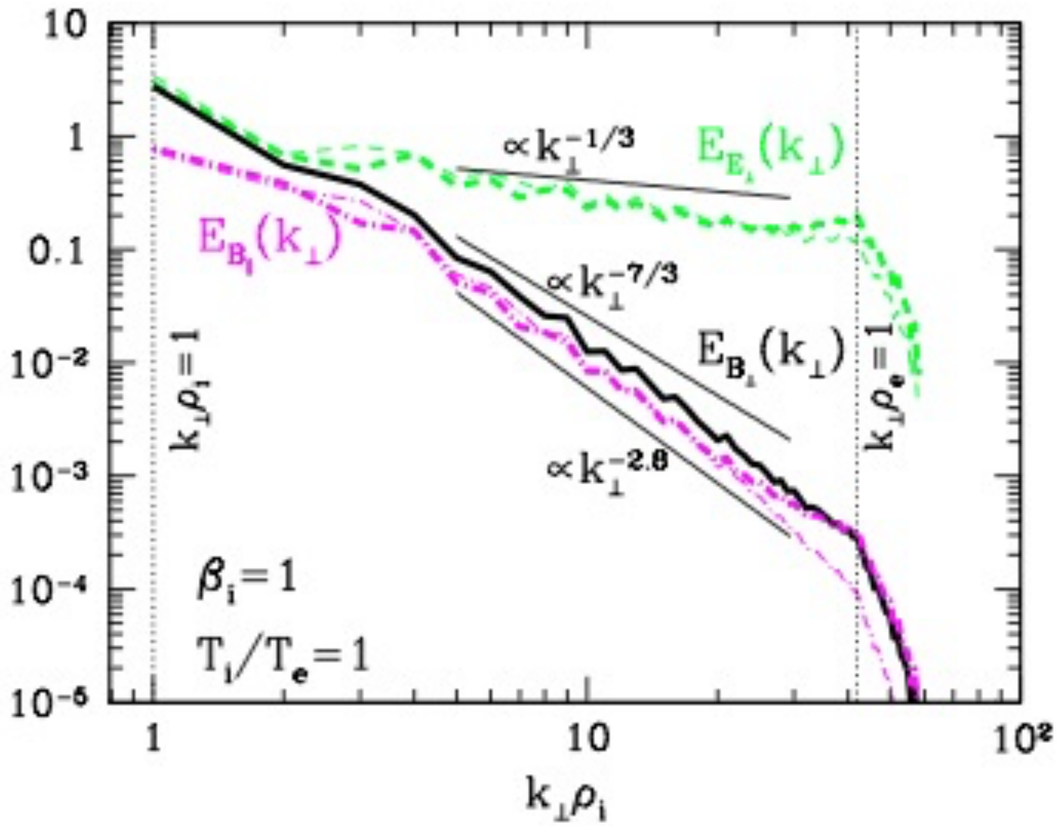
Sahraoui et al. 2009



Salem et al. 2012

Theoretical prediction

A shallower than magnetic electric field spectrum is observed in turbulence simulations of sub-ion scales



Beyond ion scale: $\delta E^2 \propto k^2 \delta B^2$

(see also *Schekochihin et al. 2009*, *Boldyrev et al. 2013* for a theoretical derivation)

Gyrokinetic simulations
Howes et al. PRL 2011

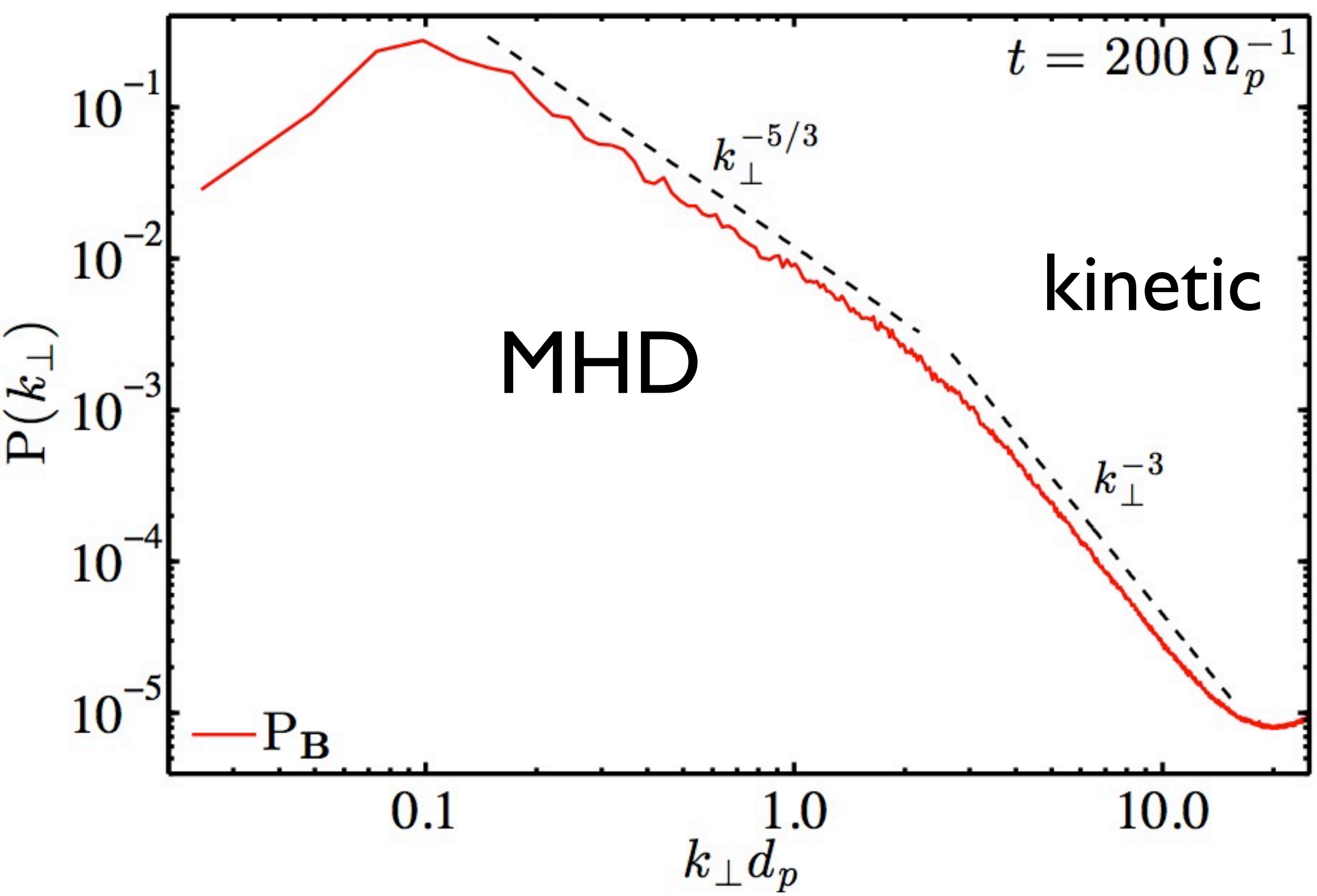
Analogous behavior also observed with other modeling, e.g.:
Hall-MHD (*Matthaeus et al. 2008*)
Landau-Fluid (*Passot et al. 2014*)
Hybrid-Vlasov (*Valentini et al. 2014, Cerri et al. 2016,...*)
Hybrid-PIC (*Franci et al. 2015a,b*)

Similar underlying treatment of electric field...

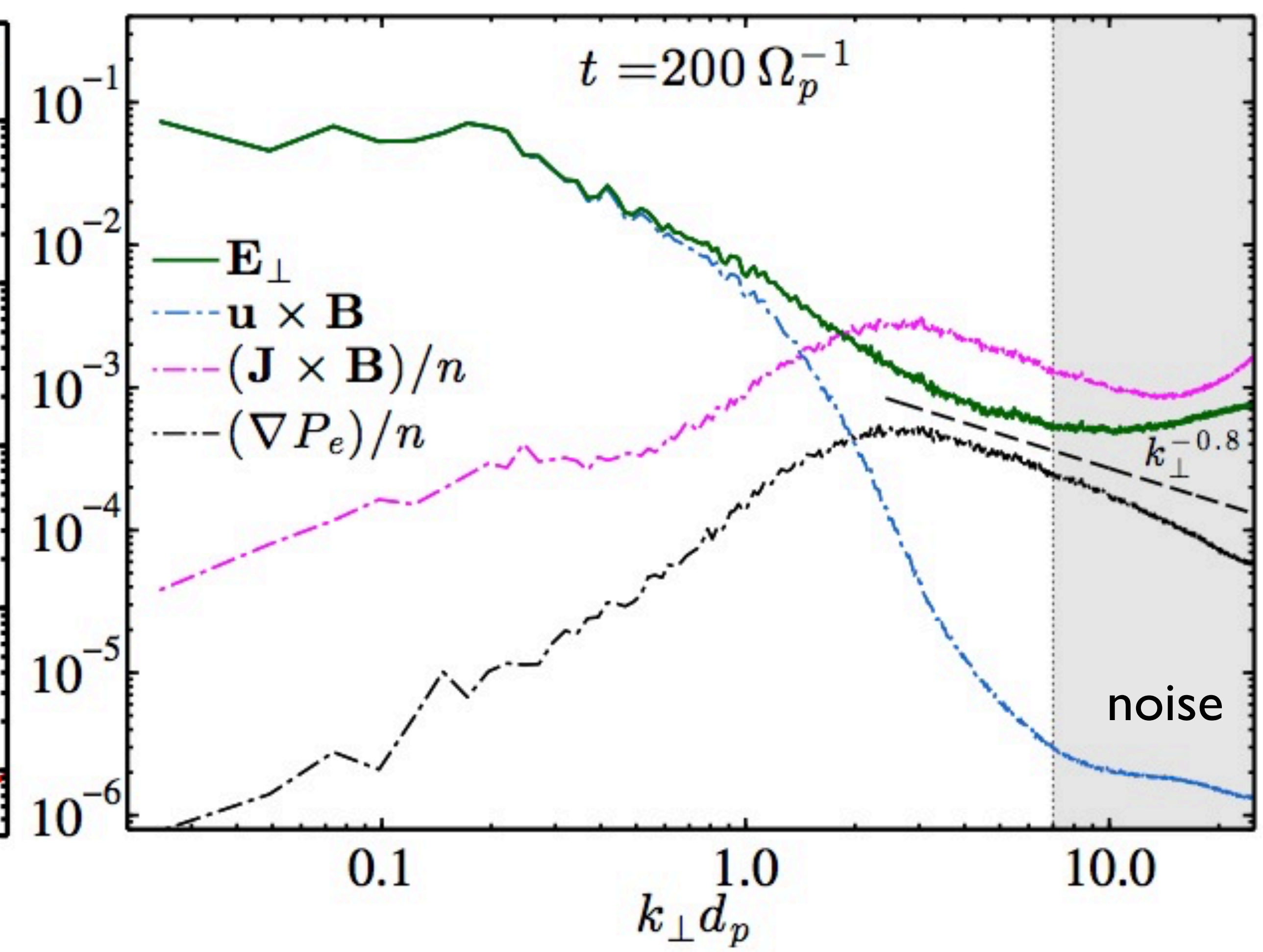
Electric field - Generalised Ohm's law

$$\boxed{\boldsymbol{E}} = \boxed{\underbrace{-\boldsymbol{u}\times\boldsymbol{B}}_{\boldsymbol{E}_{\mathrm{MHD}}}} + \boxed{\underbrace{\boldsymbol{J}\times\boldsymbol{B}/n}_{\boldsymbol{E}_{\mathrm{Hall}}}} - \boxed{\underbrace{\boldsymbol{\nabla}\mathrm{p}_e/n}_{\boldsymbol{E}_{\mathrm{pe}}}} + \underbrace{\eta\boldsymbol{J}}_{\boldsymbol{E}_\eta}$$

The Ohm's law in 2D hybrid simulations of turbulence (*Franci et al. ApJ 2015*)



magnetic field



electric field

A simple scaling at sub-ion scales

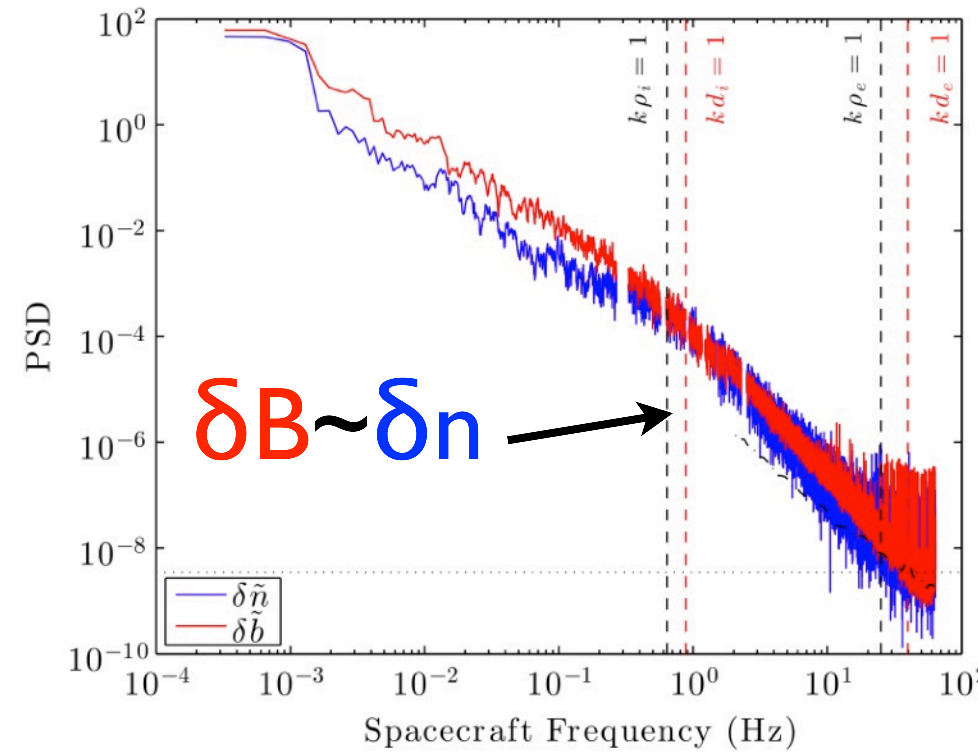
$$\boldsymbol{E} = \cancel{\underbrace{-\boldsymbol{u}\times\boldsymbol{B}}_{\boldsymbol{E}_{\mathrm{MHD}}}} + \underbrace{\boldsymbol{J}\times\boldsymbol{B}/n}_{\boldsymbol{E}_{\mathrm{Hall}}} \underbrace{-\boldsymbol{\nabla}\mathrm{p}_e/n}_{\boldsymbol{E}_{\mathrm{pe}}}$$

$$\mathbf{J}\times\mathbf{B} = (\nabla\times\mathbf{B})\times\mathbf{B} \propto B_0\nabla\delta B$$

$$\delta E \sim B_0\nabla_\perp\delta B + T_e\nabla_\perp\delta n \propto \nabla_\perp\left(\frac{\delta B}{B_0} + \beta_e\frac{\delta n}{n}\right)$$

as δB~δn at small scale: $\delta E \propto \nabla_\perp \delta B$

density and B scale with same power law (as expected for KAW)



Chen et al. 2013

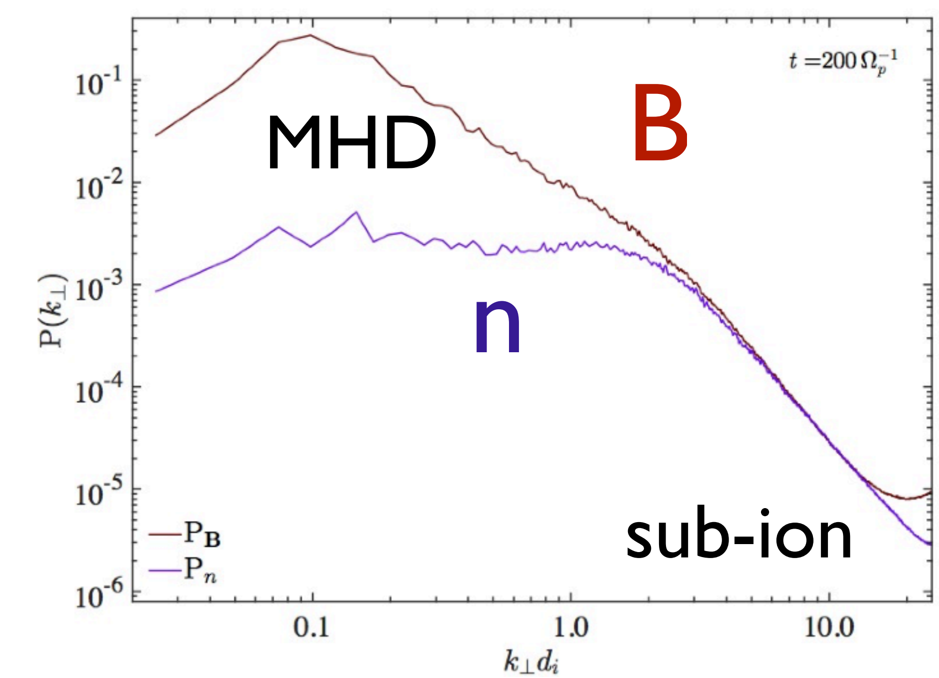
E/B ratio vs. k :

$$\boxed{\frac{\delta E^{kin}}{V_A} \propto k\rho_i\delta B}$$

sub-ion spectra:

$$\boxed{\delta E^2 \propto k^2\delta B^2}$$

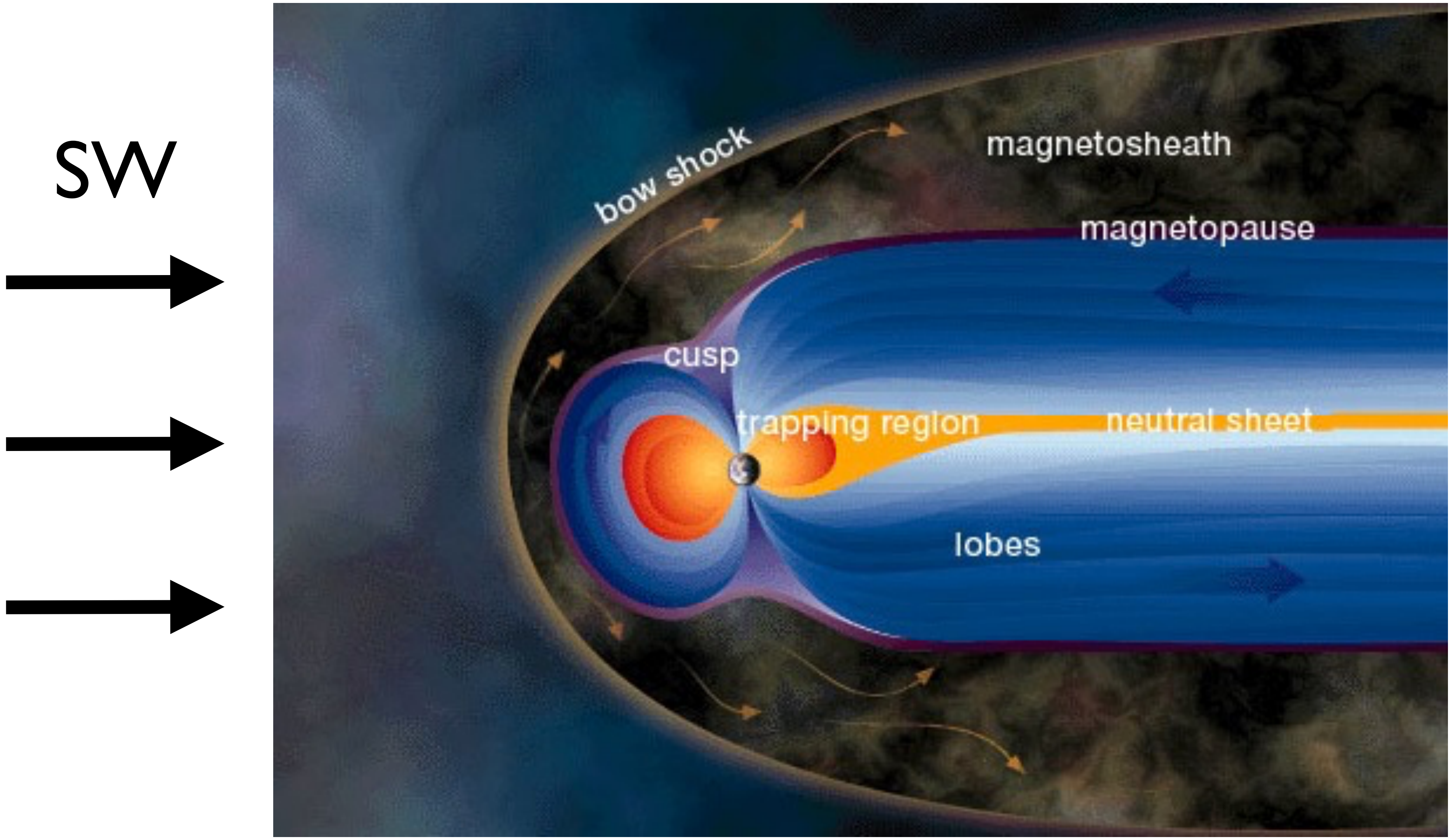
B	E
-7/3	-1/3
-8/3	-2/3
-2.8	-0.8



Franci et al. 2015a,b

Earth's Magnetosheath

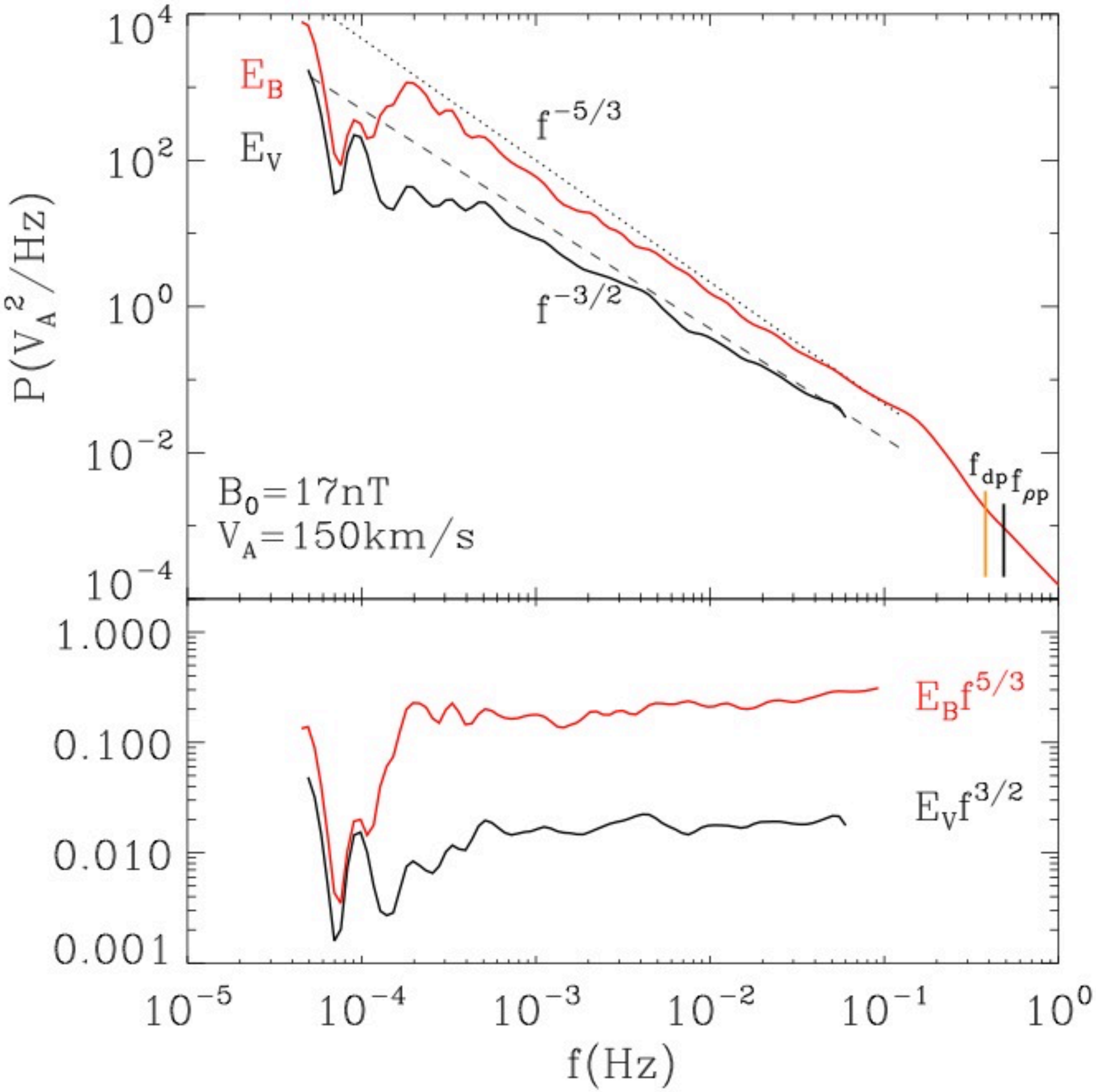
Downstream of Earth's bow shock, the turbulence has a higher power than in the solar wind



Cluster (STAFF-SA) can measure magnetic AND electric field at sub-ion scales in the magnetosheath (*Mangeney et al. 2006, Lacombe et al. 2006*)

Spectra in the Magnetosheath

fluid-MHD scales (FGM data)

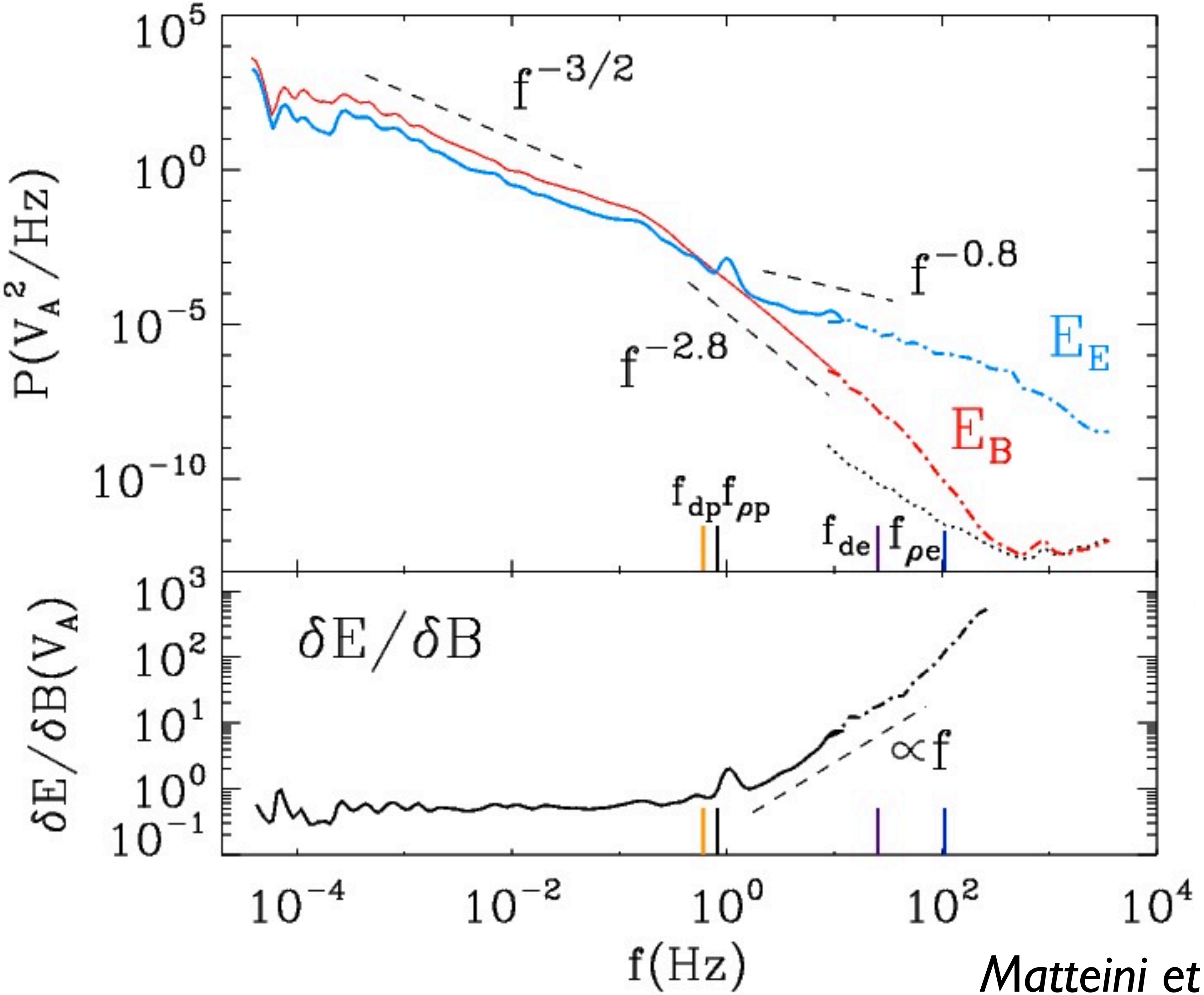


Well defined inertial range before ion break

Different spectral index in V and B, as often observed in solar wind

Electric and magnetic spectra

FGM/EFW (solid) + STAFF-SA (dash-dotted)



sub-ion spectra:

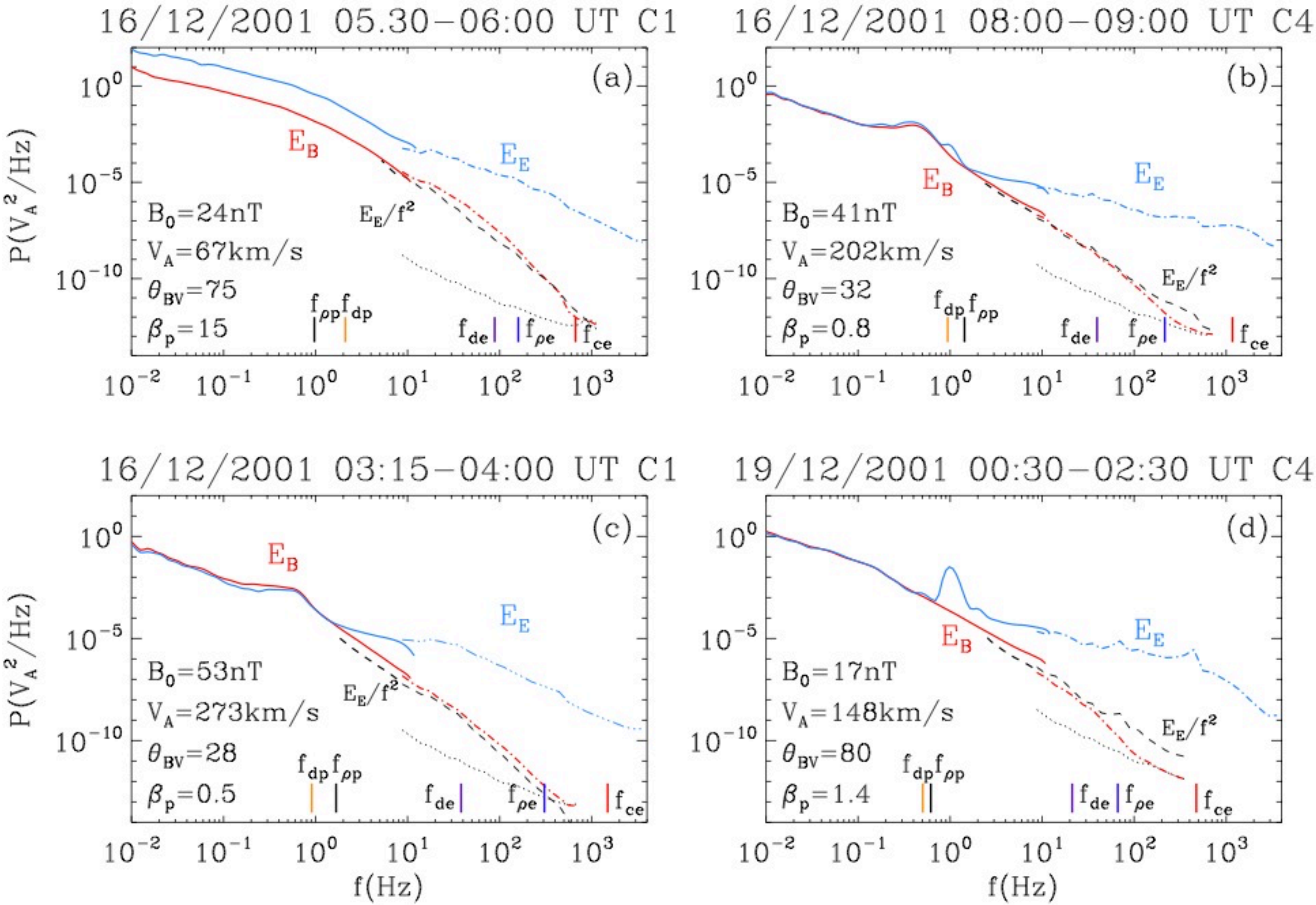
$$\boxed{\delta E^2 \propto k^2 \delta B^2}$$

E/B ratio vs. k :

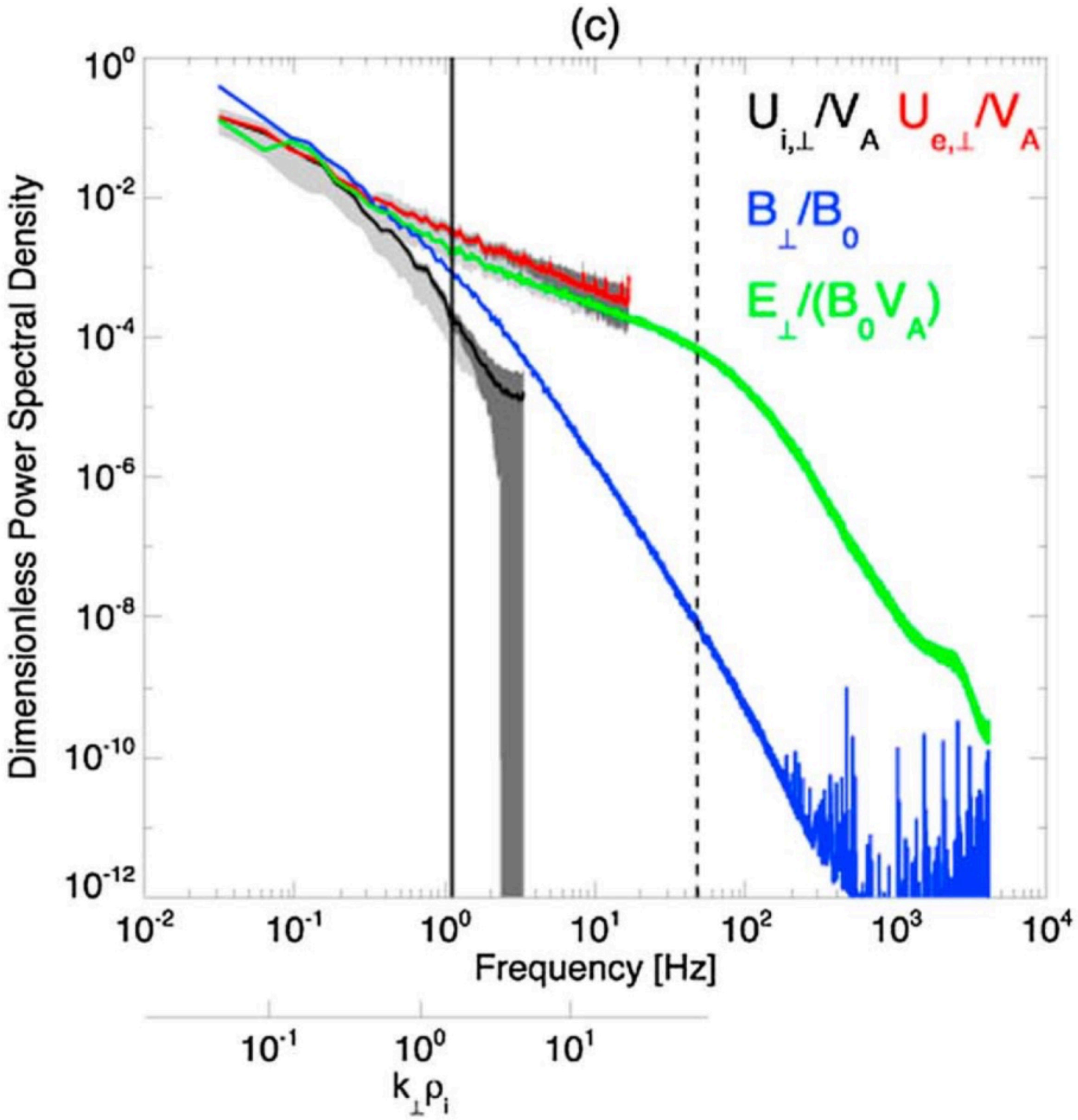
$$\boxed{\frac{\delta E^{kin}}{V_A} \propto k\rho_i \delta B}$$

Matteini et al., MNRAS 2017

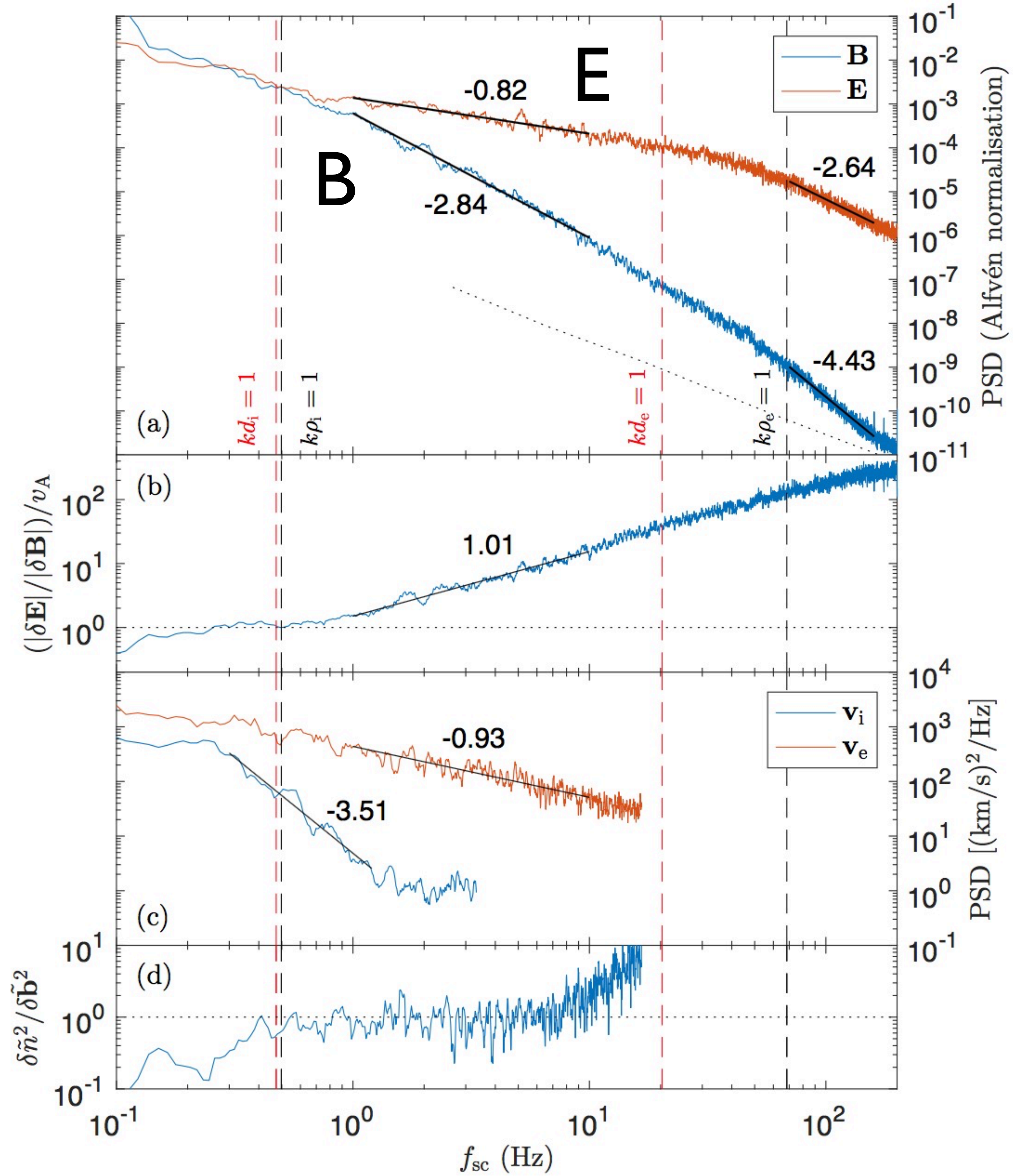
More examples at various beta and BV angle



MMS observations confirm these scalings



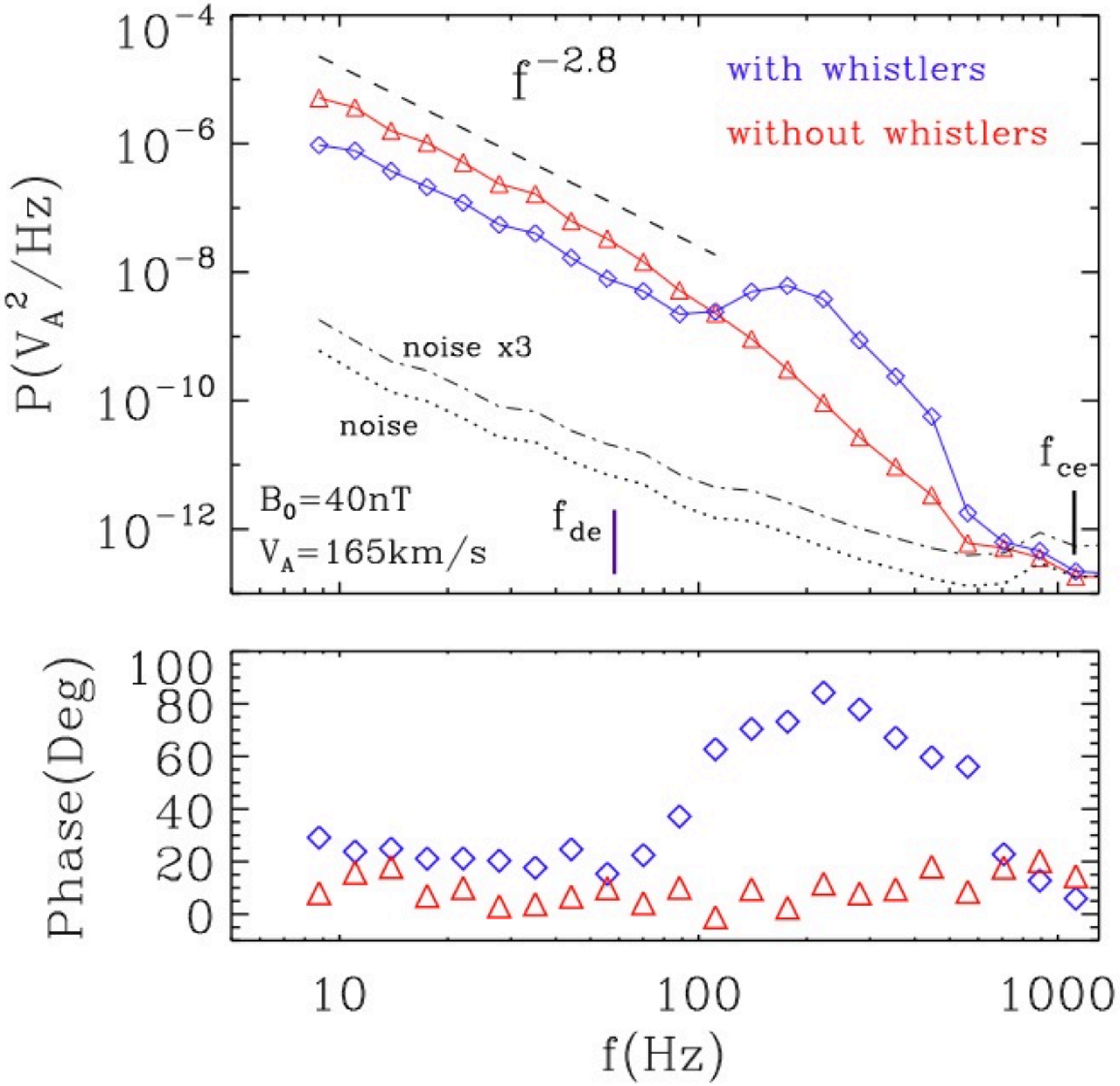
Stawarz et al. JGR 2016



Chen & Boldyrev ApJ 2017

Whistler waves at small scales

Small scale wave contribution to spectra has been removed by removing periods with whistler signatures (circular polarization)

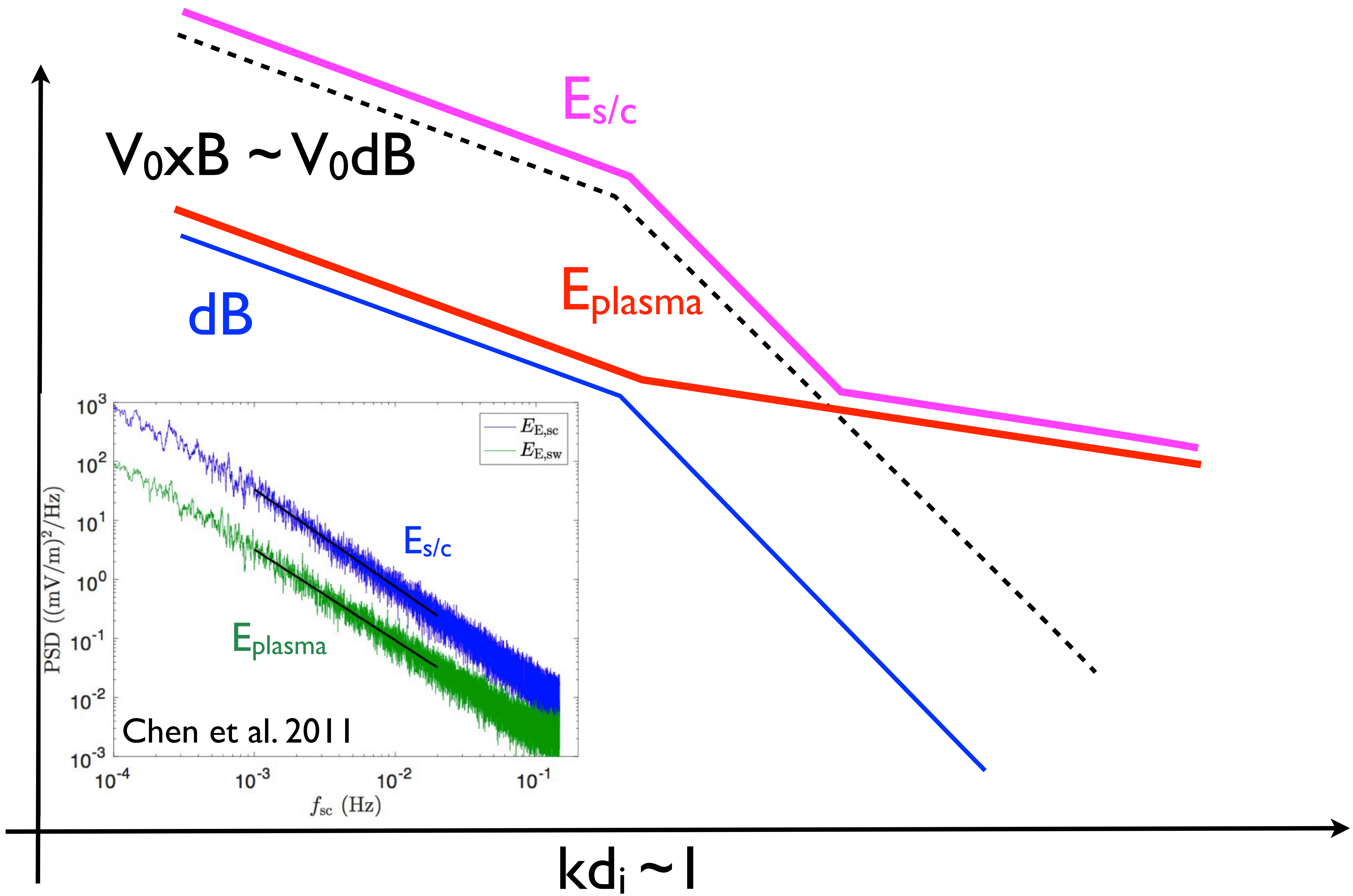


In SW whistlers are associated with heat flux (carried by strahl electrons)

see *Lacombe et al. ApJ 2014, Stansby et al. ApJL in press*

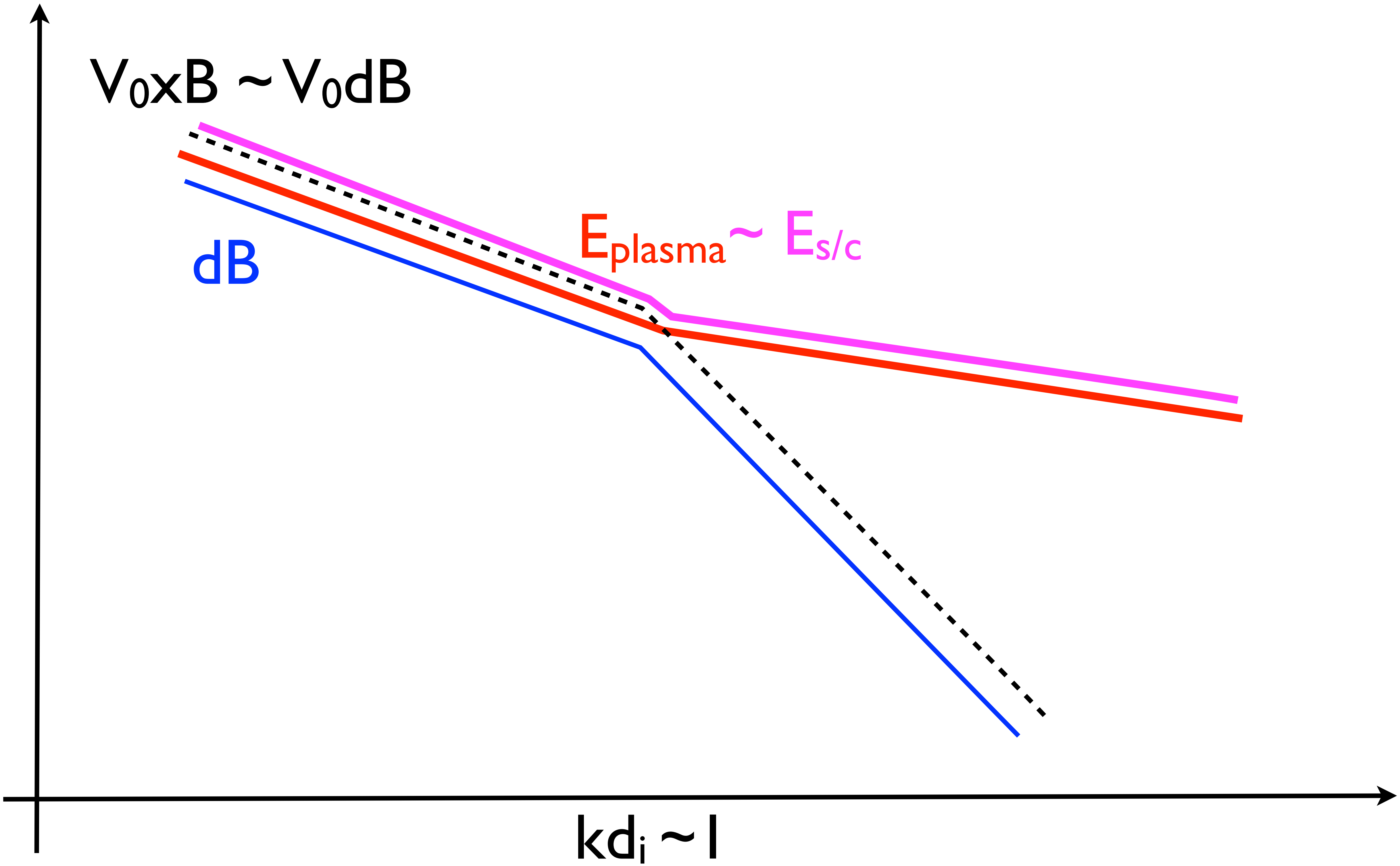
Plasma vs. Spacecraft frame electric field

(solar wind-like case, $V_0 \gg V_A$)



Plasma vs. Spacecraft frame electric field

(magnetosheath-like case, $V_0 \sim V_A$)



Conclusion

- First analysis of E and B spectra from MHD to electron scales in space plasmas. Spectrum of E is shallower than B beyond ion scale ($\delta E \sim k \delta B$). NB. <u>here E is measured in s/c frame, however at small scales, to a good approximation, it corresponds to E computed in the plasma frame!</u>
(see next couple of slides)

- At present, this can not be tested in SW (next future: SPP, Orbiter, MMS) However, such an investigation is possible in the magnetosheath (Cluster)

- Between ion and electron scales turbulent spectra are well described by the generalized Ohm's law:
- fluid description of electrons in the cascade
- turbulent fluctuations are electromagnetic in this range
- Fluctuations in E, B and plasma are in equilibrium (self-consistent):
at this stage, no clear excess of E for plasma heating!

- THOR will need to measure departures from this scaling of the background turbulence in order to capture energy dissipation and particle energization