SOLAR WIND TURBULENCE

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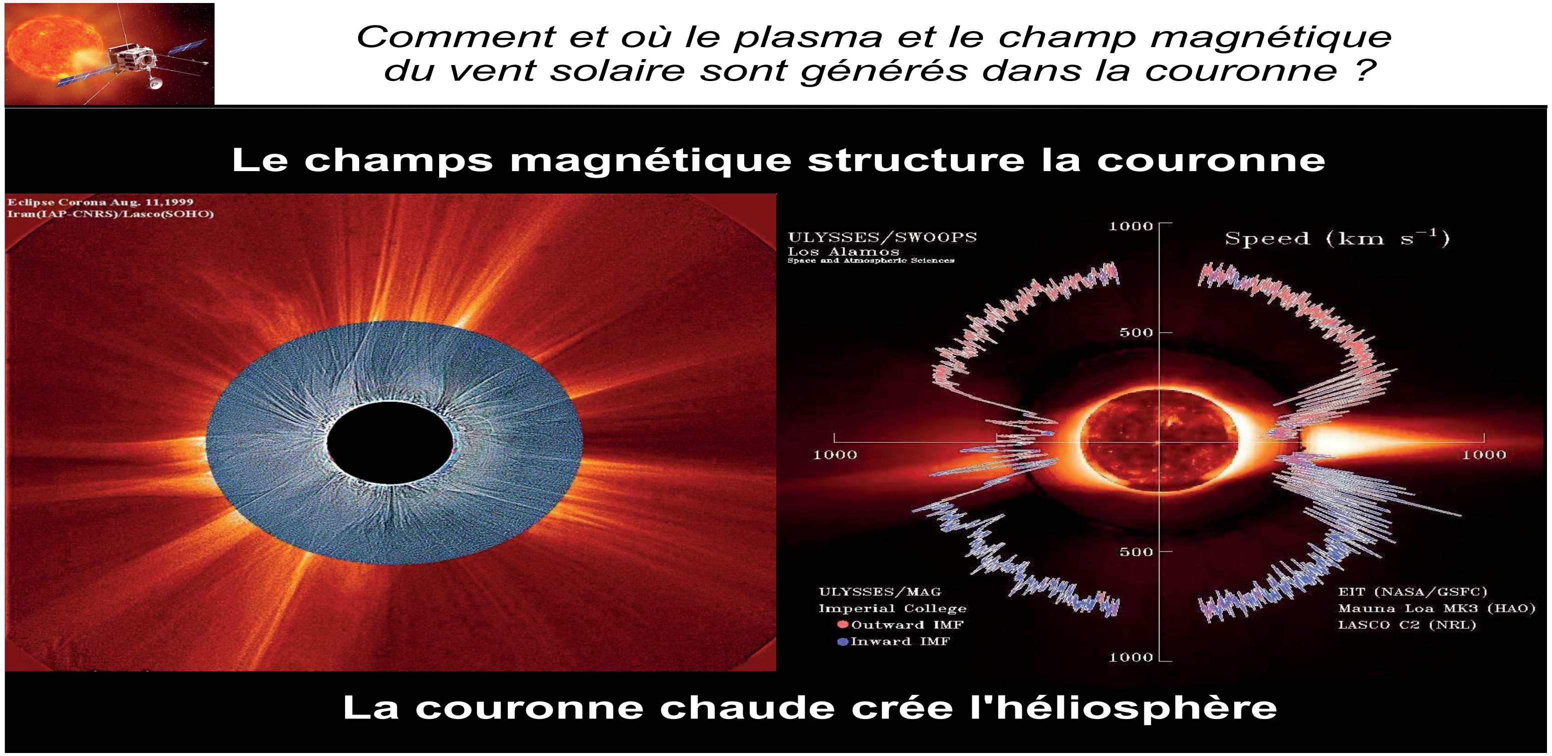
Points to discuss

- MHD turbulence:
  - Spatial anisotropy
  - Compressibility
- Kinetic turbulence: *sub-ion and sub-electrons scales*
  - Nature and dissipation mechanisms
  - Universality

The solar wind

The solar wind plasma is generally:

- Fully ionized (H^+, e^-)
- Non -relativistic ($V_A \ll c$), V~350-800 km/s
- *Collisionless*



Comment et où le plasma et le champ magnétique du vent solaire sont générés dans la couronne ?

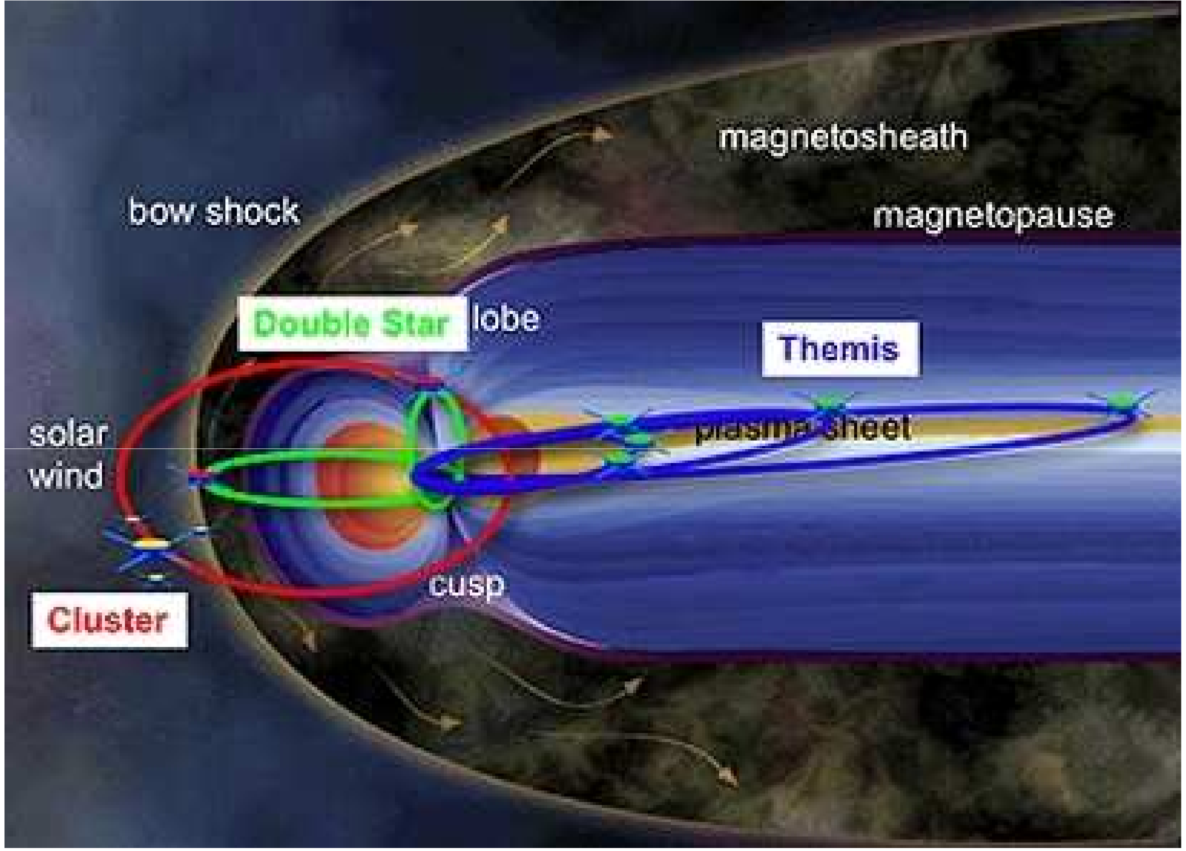
Le champs magnétique structure la couronne

La couronne chaude crée l'héliosphère

The magnetosphere

Fundamental plasma processes:

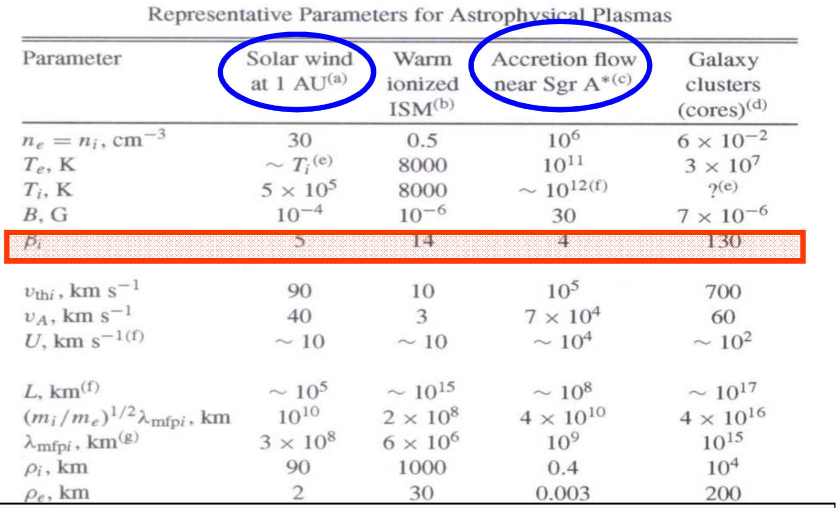
- Shocks
- Turbulence
- Magnetic reconnection
- Instabilities
- particle acceleration
- …



Near-Earth *vs* distant astrophysical plasmas

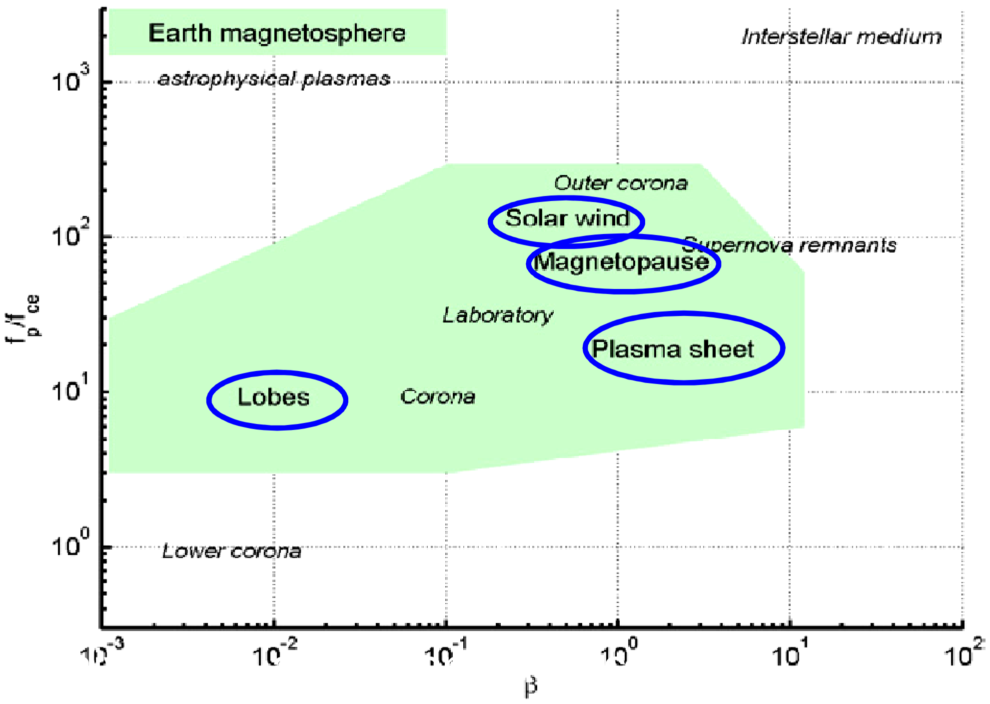
[Scheckochihin et al., ApJS, 2009]

$$\beta = \frac{\text{Thermal pressure}}{\text{Magnetic pressure}} \approx 0.4\frac{NT}{B^2}$$

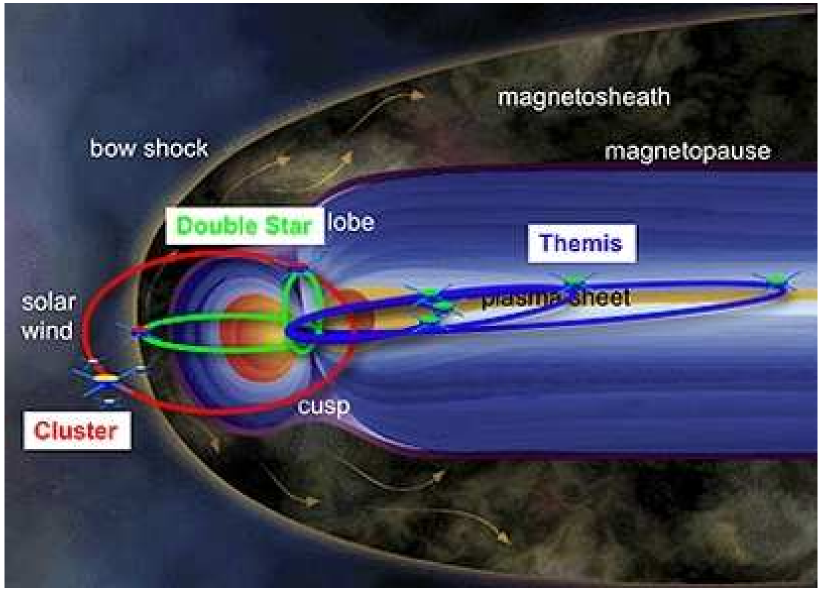


Representative Parameters for Astrophysical Plasmas

Parameter	Solar wind at 1 AU[(a)]	Warm ionized ISM[(b)]	Accretion flow near Sgr A*[(c)]	Galaxy clusters (cores)[(d)]
$n_e = n_i$, cm^{-3}	30	0.5	10^6	6×10^{-2}
T_e, K	$\sim T_i$[(e)]	8000	10^{11}	3×10^7
T_i, K	5×10^5	8000	$\sim 10^{12}$[(f)]	?[(e)]
B, G	10^{-4}	10^{-6}	30	7×10^{-6}
β_i	5	14	4	130
$v_{\mathrm{th}i}$, km s^{-1}	90	10	10^5	700
v_A, km s^{-1}	40	3	7×10^4	60
U, km s^{-1}[(f)]	~ 10	~ 10	$\sim 10^4$	$\sim 10^2$
L, km[(f)]	$\sim 10^5$	$\sim 10^{15}$	$\sim 10^8$	$\sim 10^{17}$
$(m_i/m_e)^{1/2}\lambda_{\mathrm{mfp}i}$, km	10^{10}	2×10^8	4×10^{10}	4×10^{16}
$\lambda_{\mathrm{mfp}i}$, km[(g)]	3×10^8	6×10^6	10^9	10^{15}
ρ_i, km	90	1000	0.4	10^4
ρ_e, km	2	30	0.003	200

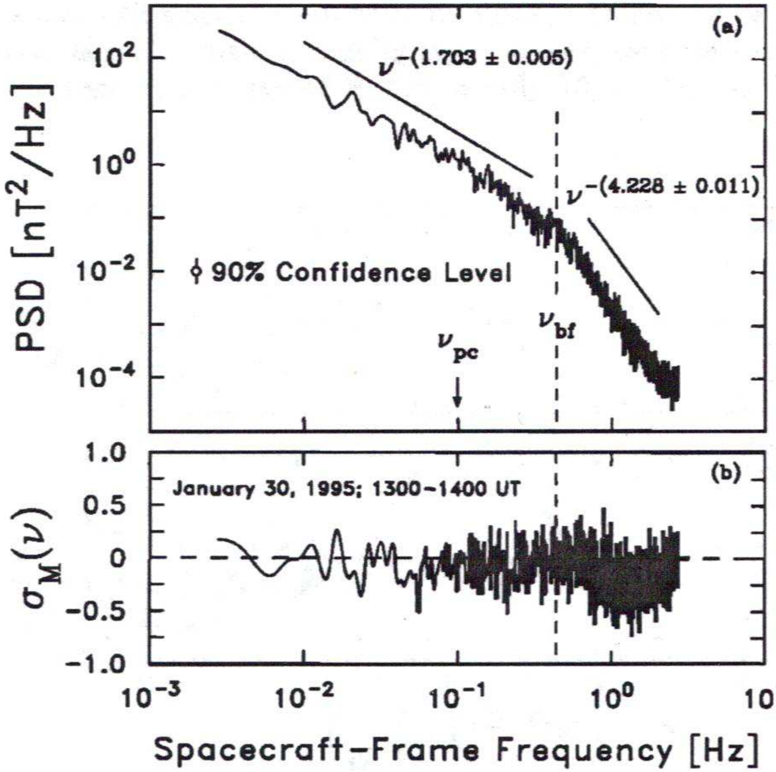


[Vaivads et al., Plasma Phys. Contr. Fus., 2009]

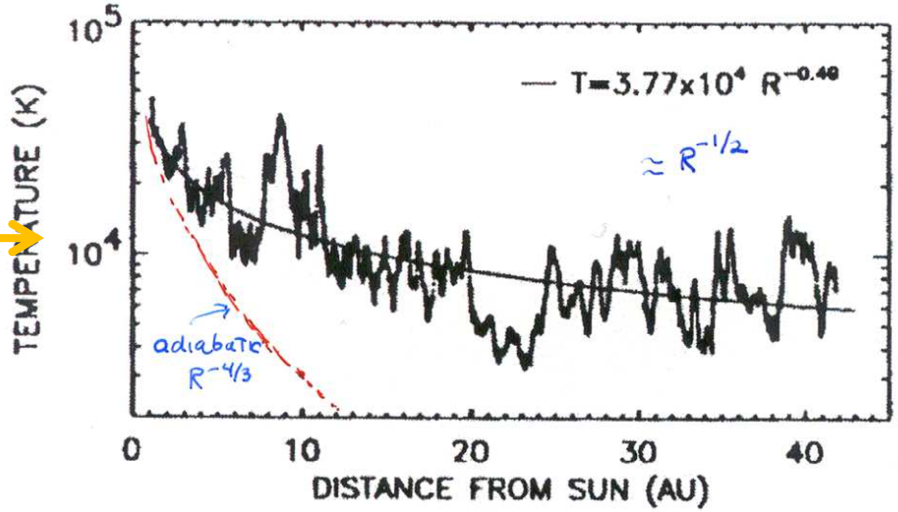


Solar wind turbulence

Steepening of the spectra near the ion scale → ion heating [Leamon+,1998]



Turbulence is proposed to explain local SW heating [Richardson & Paularena, 1995]



Dissipation mechanisms are still poorly understood

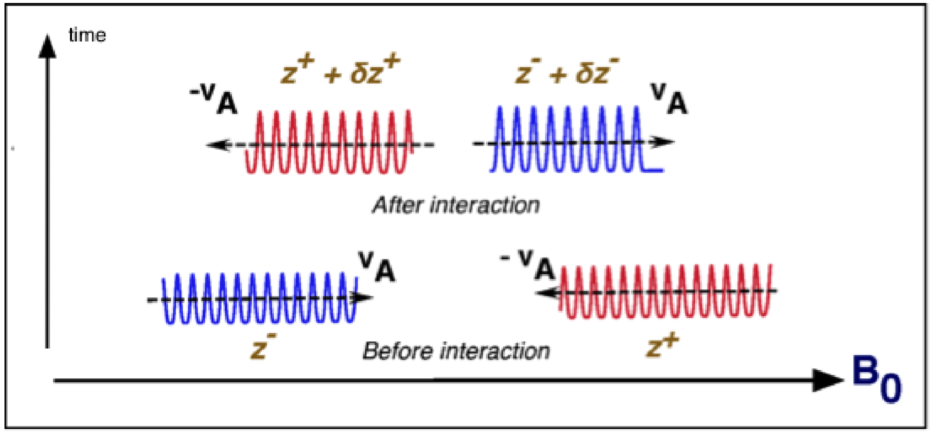
Incompressible MHD turbulence

Elsässer variables: $\mathbf{z}^{\pm} = v \pm \frac{b}{\sqrt{\mu_0 \rho}} \equiv v \pm V_A$

$$\partial_t z^{\pm} \mp v_A . \nabla z^{\pm} + z^{\mp} . \nabla z^{\pm} = -\nabla p$$

Linear term: $k_{//} v_A z^+$

Nonlinear term: $k_{\perp} u_{\perp} z^+$



$$\chi = \frac{k_{\perp} u_{\perp}}{k_{//} v_A}$$

Ratio of nonlinear to linear terms

χ~1 → Critically Balanced turbulence

Critical balance and spatial anisotropy

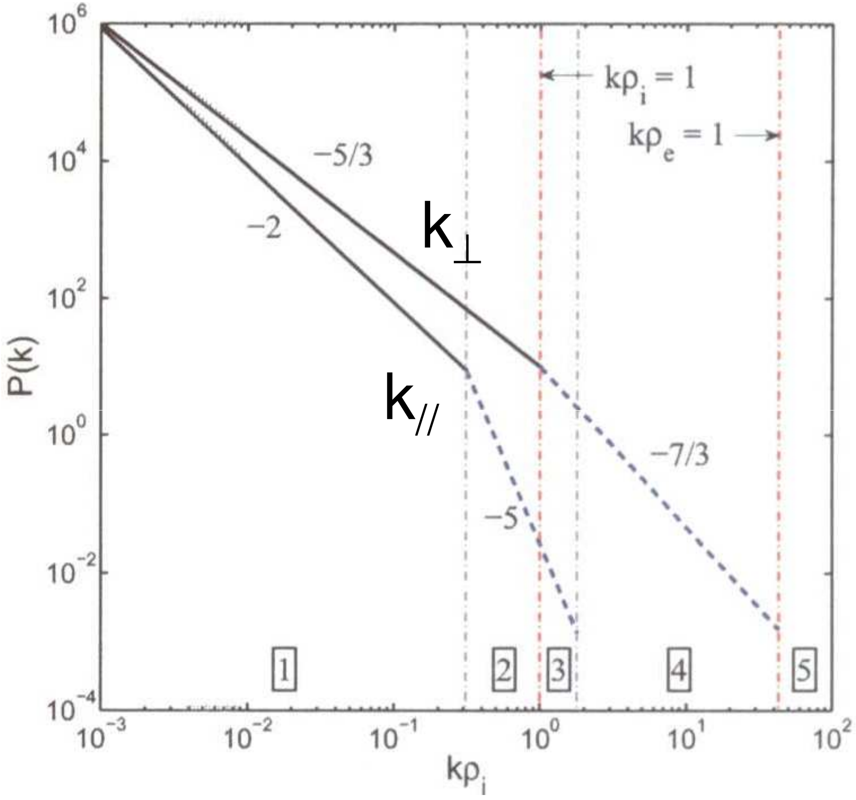
Critical balance [Goldreich & Sridhar, 1995]:

Linear (Alfvén) time ~ nonlinear (turnover) time $\Rightarrow \omega \sim k_{//} V_A \sim k_\perp u_\perp$

$\Rightarrow k_{//} \sim k_\perp^{2/3}$ (MHD scales)

$\Rightarrow k_{//} \sim k_\perp^{1/3}$ (sub-ion scales)

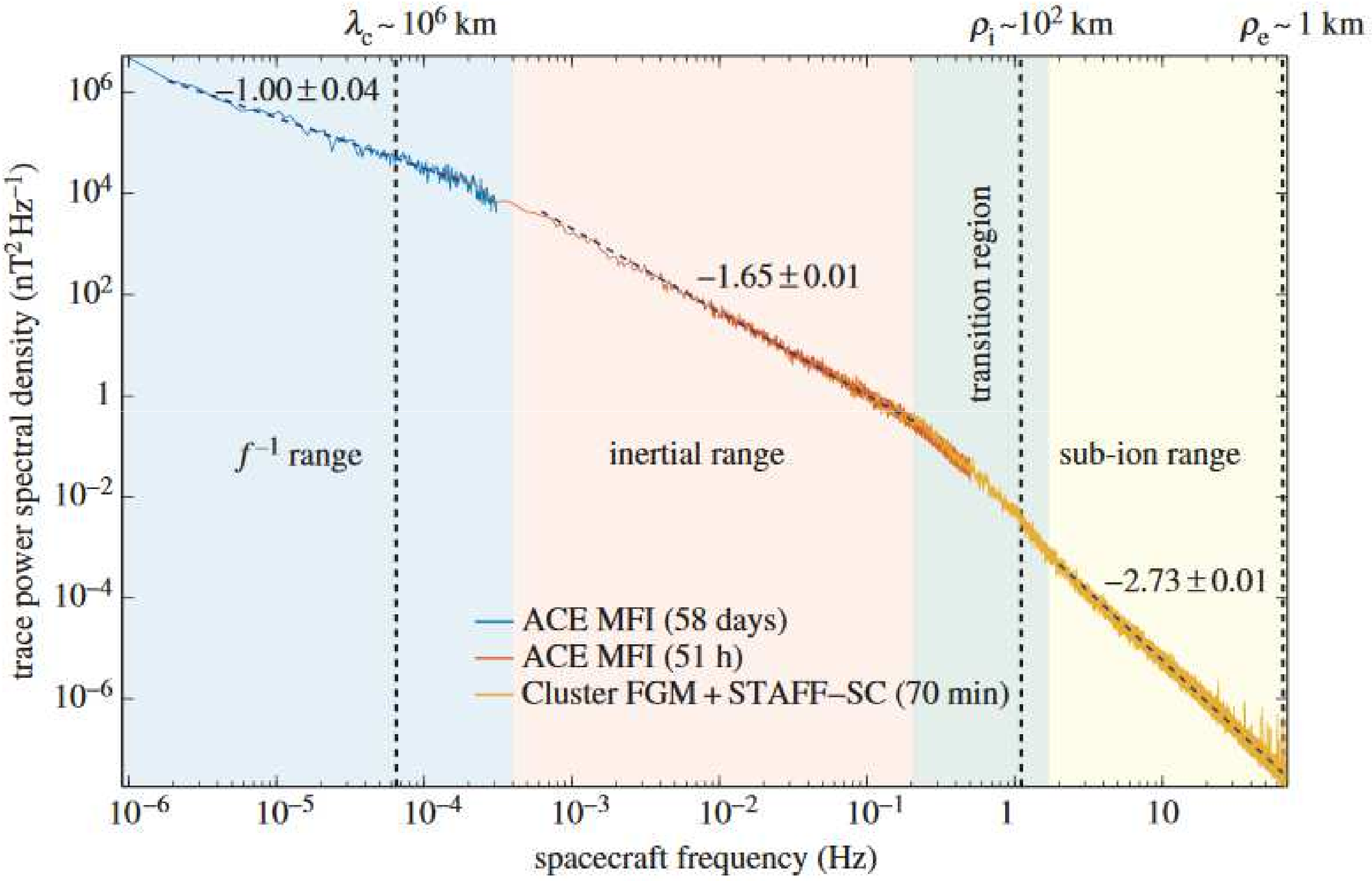
See also [Boldyrev, ApJ, 2005] and [Galtier et al., PoP, 2005]



[Chen et al., ApJ, 2010]

Theory *vs* measurements

Kiyani et al., Phil.Trans.R.Soc.A, 2015



Theories predict wavenumber (**k**) spectra
Observations provides frequency (ω_{sc}) spectra

$B^2 \sim \omega_{sc}^{-\alpha} \Rightarrow B^2 \sim k_{//}^{-\beta}\, k_{\perp}^{-\gamma}$??

The Taylor frozen-in flow hypothesis

- MHD turbulence in the solar wind: the Taylor's hypothesis can be valid

High SW speeds: V ~600km/s >> $V_\varphi \sim V_A \sim 50$km/s ⇒

$$\omega_{sc} = \omega_{plas} + \mathbf{k.v} \sim \mathbf{k.v} = \boxed{k_v v}$$

Inferring the k-spectrum is possible with one spacecraft, but only in one direction

- At sub-ion scales Vφ~k can be larger than V_{sw} (e.g. whistlers) ⇒ The Taylor's hypothesis can be violated

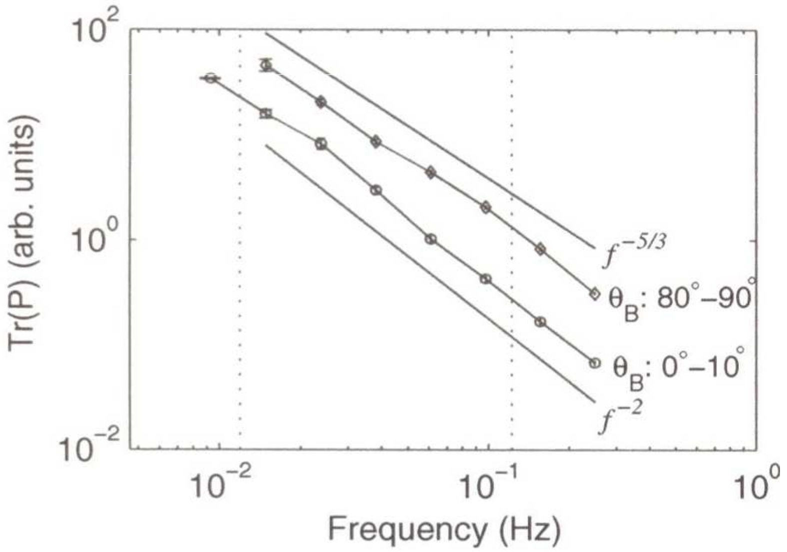
Single spacecraft analysis of turbulence anisotropy (I)

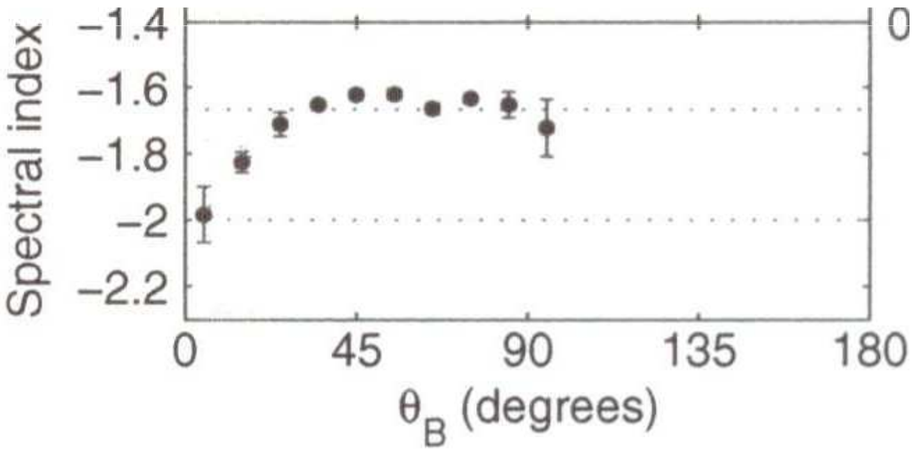
Single satellite analysis→ use of the Taylor assumption:

$\omega_{sc} \sim \mathbf{k}.\mathbf{V}_{sw} \sim k_v V_{sw}$

$\mathbf{V} // \mathbf{B} \rightarrow k_v = k_{//}$

$\mathbf{V} \perp \mathbf{B} \rightarrow k_v = k_{\perp}$





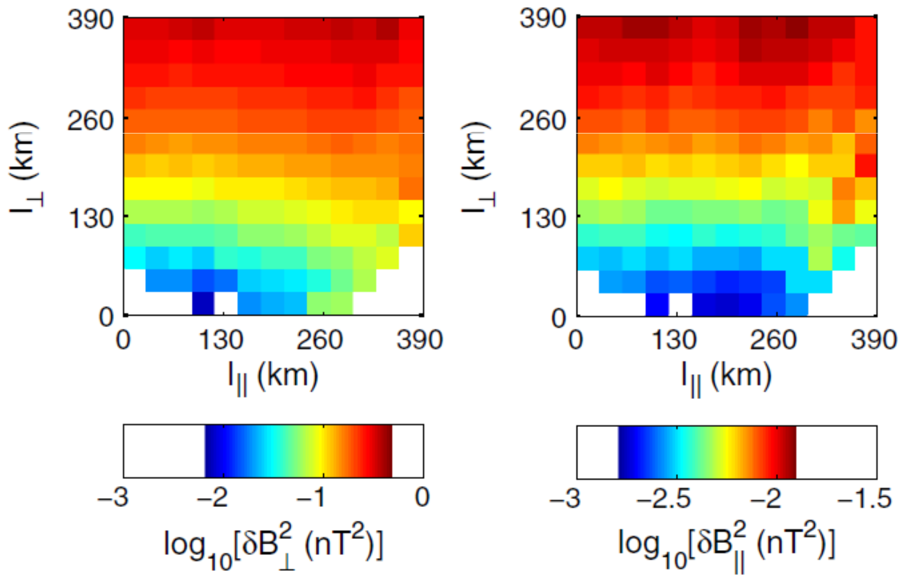
$\Theta_{BV} \rightarrow 0 \Rightarrow B^2 \sim k_{//}^{-2} \Rightarrow$ Consistent with the critical balance

[Horbury et al., PRL, 2008]

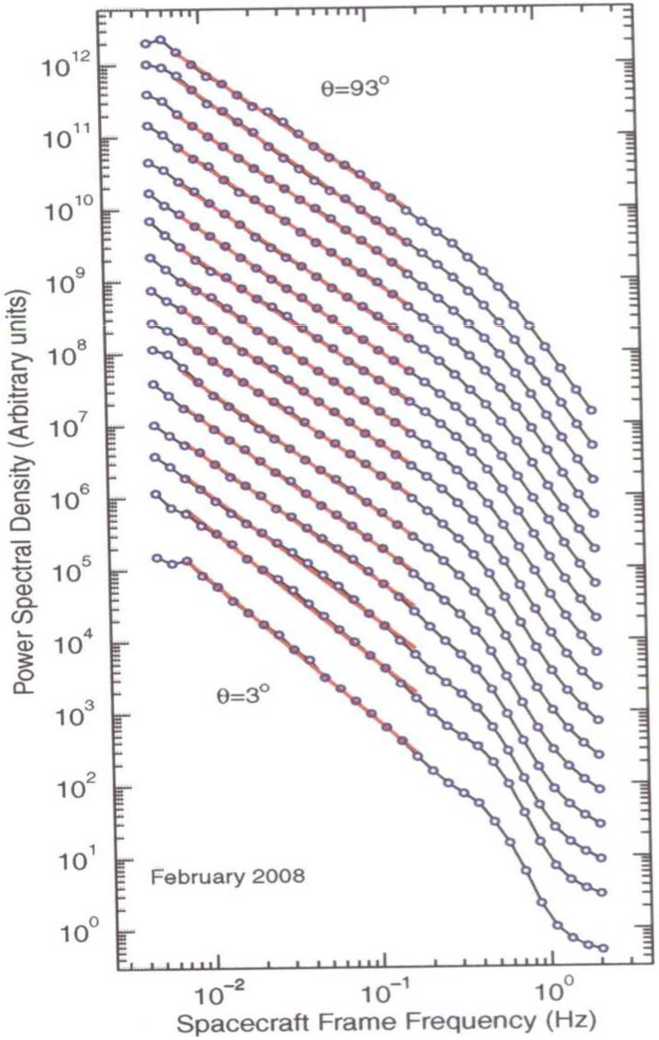
Single spacecraft analysis of turbulence anisotropy (II)

[Podesta, ApJ, 2009]

Results confirmed by other studies

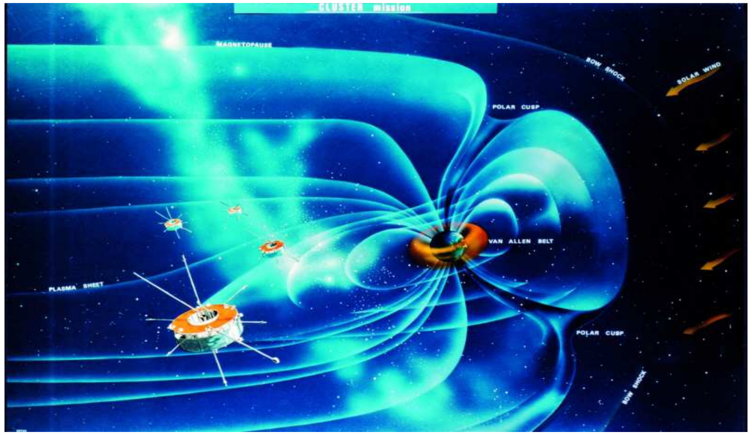


[Chen et al., PRL, 2010] (multi-spacecraft analysis but used Taylor hypothesis)

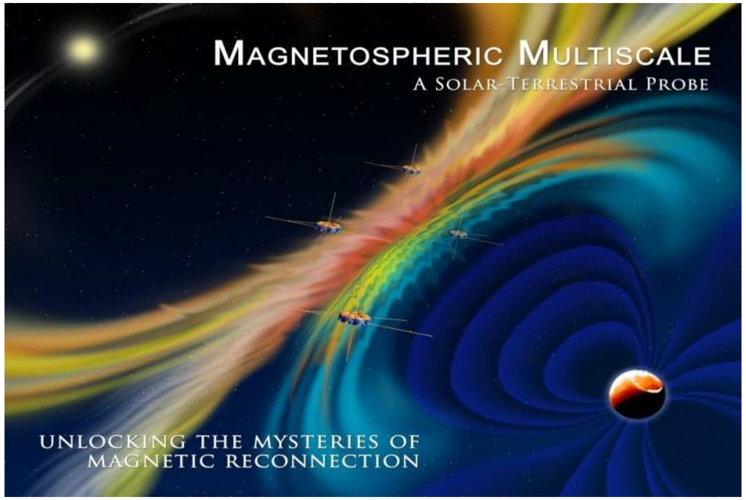


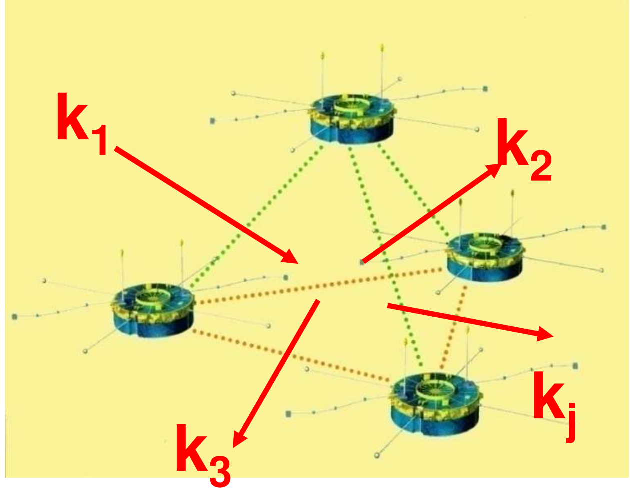
In situ measurements of anisotropy (I)
Multi-spacecraft analysis

ESA/Cluster (launched 2000)
separation >100km



NASA/MMS (launched 2015)
separation ~10km



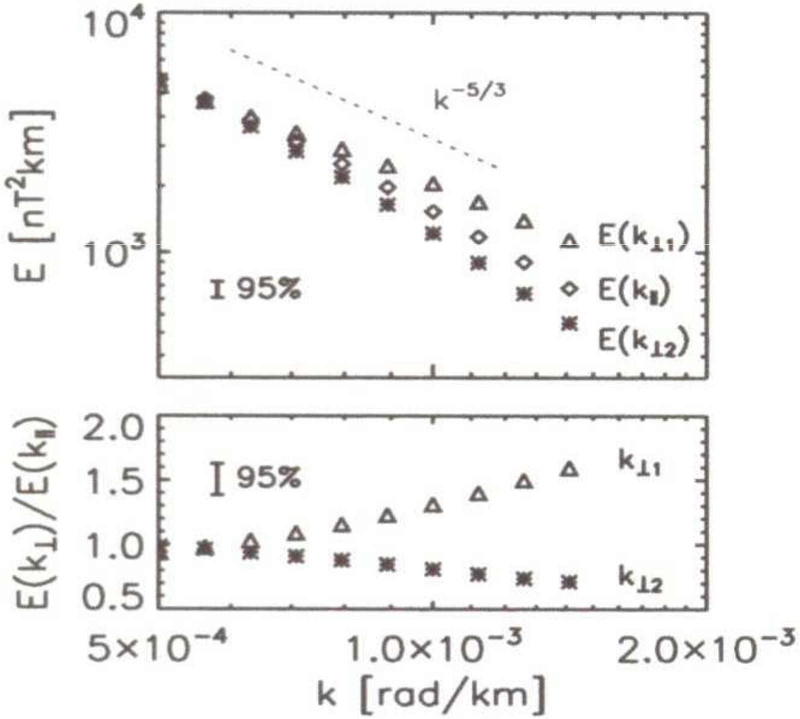


3D measurements of

- **gradients:** $\mathbf{J}=\nabla \times \mathbf{B}$, $\omega = \nabla \times \mathbf{v}$…
- ω-$\mathbf{k}$ spectra of turbulence → anisotropy, full "dispersion relations", …

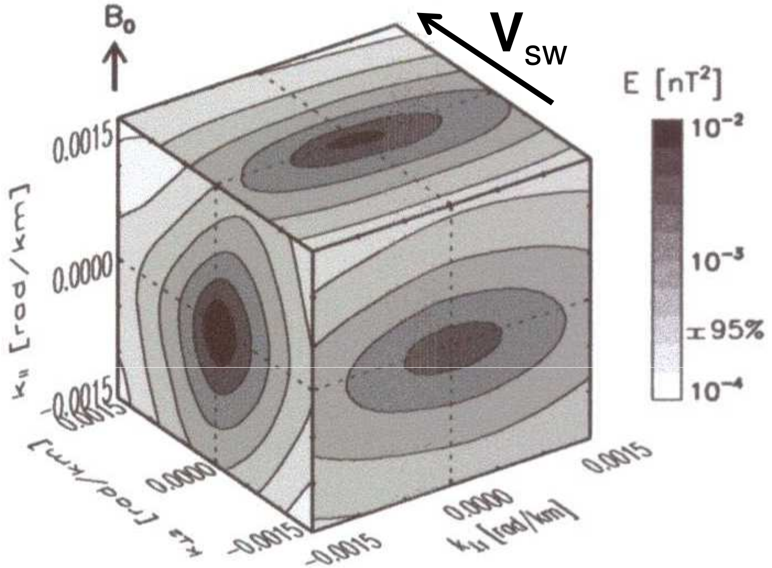
In situ measurements of anisotropy (II)
Multi-spacecraft analysis

Turbulence is anistropic and non-axisymmetric



[See also Sahraoui et al., PRL, 2006; 2010]

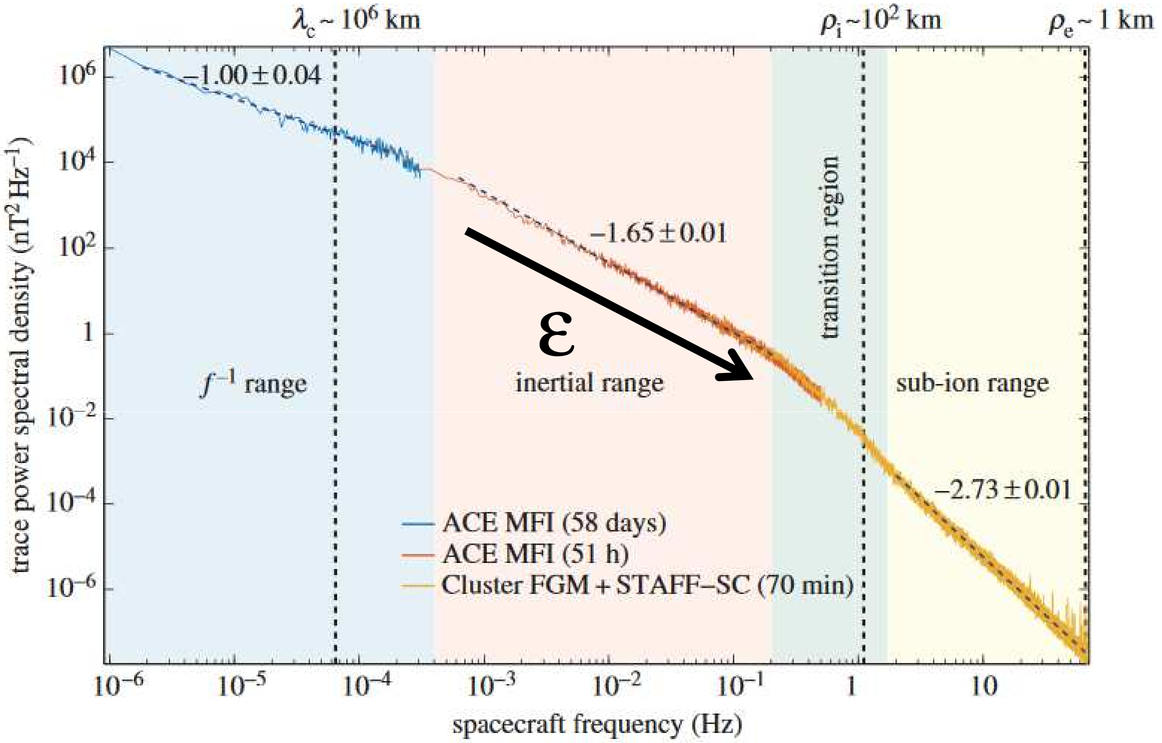
[Narita et al. , PRL, 2010]



The anisotropy (⊥ B) is along **V**$_{sw}$ → SW expansion effect?

[Grappin et al., 1993; Saur & Bieber, 1999; Dong et al., 2014]

Energy dissipation rate: incompressible model



[Kiyani et al., Phil.Trans.R.Soc.A, 2015]

[Politano & Pouquet, 1998]

$$\boxed{\left\langle \left(\delta \mathbf{Y}^{\pm}\right)^{2} \delta Y_{r}{}^{\mp} \right\rangle = \frac{4}{3} \varepsilon^{\pm} r},$$

where $\mathbf{Y}^{\pm} = \left(\mathbf{v} \pm \frac{\mathbf{b}}{\sqrt{\mu_0 \rho}}\right)$

Exact law (BG13)

(3) Isothermal MHD turbulence

In the inertial zone we obtain (Banerjee & Galtier, PRE, 2013)

$$
\begin{aligned}
-2\varepsilon = \tfrac{1}{2}\nabla_{\mathbf{r}} \cdot & \overbrace{\left\langle \left[\frac{1}{2}\delta(\rho\mathbf{z}^-)\cdot\delta\mathbf{z}^- + \delta\rho\delta e\right]\delta\mathbf{z}^+ + \left[\frac{1}{2}\delta(\rho\mathbf{z}^+)\cdot\delta\mathbf{z}^+ + \delta\rho\delta e\right]\delta\mathbf{z}^- + \overline{\delta}(e+\frac{v_A^2}{2})\delta(\rho\mathbf{z}^- + \rho\mathbf{z}^+)\right\rangle}^{\text{Usual flux term}} \\
& \underbrace{-\frac{1}{4}\left\langle \frac{1}{\beta'}\nabla'\cdot(\rho\mathbf{z}^+e') + \frac{1}{\beta}\nabla\cdot(\rho'\mathbf{z}'^+e) + \frac{1}{\beta'}\nabla'\cdot(\rho\mathbf{z}^-e') + \frac{1}{\beta}\nabla\cdot(\rho'\mathbf{z}'^-e)\right\rangle}_{\text{New type of flux term}} \\
& + \left\langle(\nabla\cdot\mathbf{v})\left[R_E' - E' - \tfrac{\overline{\delta}\rho}{2}(\mathbf{v_A}'\cdot\mathbf{v_A}) - \tfrac{P'}{2} + \tfrac{P_M'}{2}\right]\right\rangle + \left\langle(\nabla'\cdot\mathbf{v}')\left[R_E - E - \tfrac{\overline{\delta}\rho}{2}(\mathbf{v_A}\cdot\mathbf{v_A}') - \tfrac{P}{2} + \tfrac{P_M}{2}\right]\right\rangle \\
& + \left\langle(\nabla\cdot\mathbf{v_A})\left[R_H - R_H' + H' - \overline{\delta}\rho(\mathbf{v}'\cdot\mathbf{v_A})\right]\right\rangle + \left\langle(\nabla'\cdot\mathbf{v_A}')\left[R_H' - R_H + H - \overline{\delta}\rho(\mathbf{v}\cdot\mathbf{v_A}')\right]\right\rangle
\end{aligned}
$$

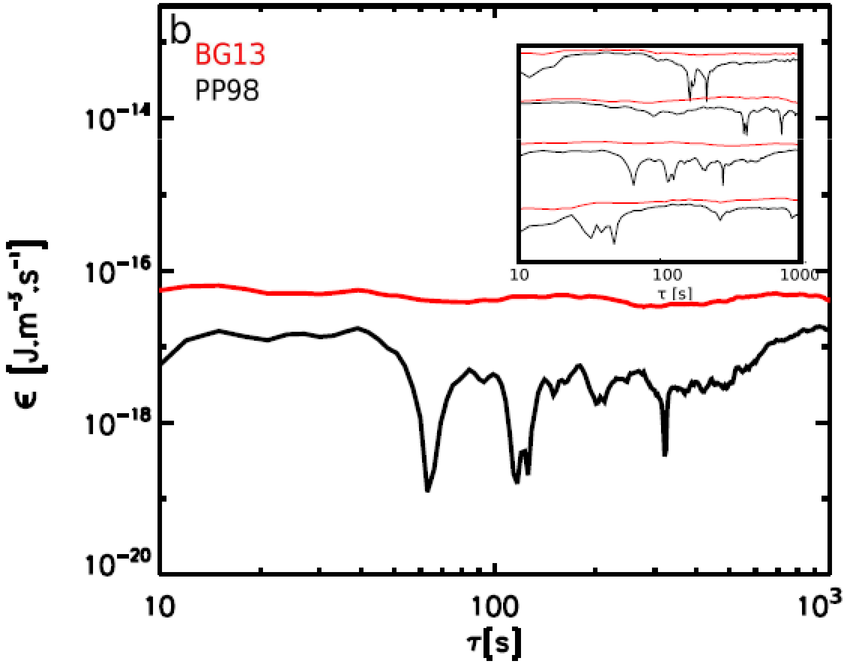
where

$$
\begin{aligned}
E &= \rho(\mathbf{v}\cdot\mathbf{v} + \mathbf{v}_A\cdot\mathbf{v}_A)/2 + \rho e,\ E' = \rho'(\mathbf{v}'\cdot\mathbf{v}' + \mathbf{v}_A'\cdot\mathbf{v}_A')/2 + \rho' e'; \\
R_E &= \rho(\mathbf{v}\cdot\mathbf{v}' + \mathbf{v}_A\cdot\mathbf{v}_A')/2 + \rho e',\ R_E' = (\rho'\mathbf{v}'\cdot\mathbf{v} + \mathbf{v}_A'\cdot\mathbf{v}_A)/2 + \rho' e; \\
R_H &= \rho(\mathbf{v}\cdot\mathbf{v}_A' + \mathbf{v}'\cdot\mathbf{v}_A)/2,\ R_H' = \rho'(\mathbf{v}'\cdot\mathbf{v}_A + \mathbf{v}\cdot\mathbf{v}_A')/2 \\
H &= \rho\mathbf{v}\cdot\mathbf{v}_A,\ H' = \rho'\mathbf{v}'\cdot\mathbf{v}_A';\ \beta = 2C_S^2/v_A^2;\ \beta' = 2{C_S}'^2/{v_A}'^2
\end{aligned}
$$

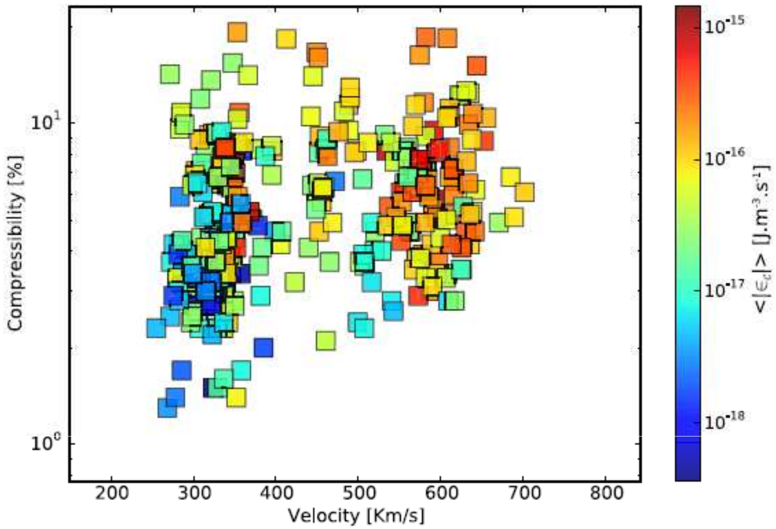
Compressible energy dissipation rate in the solar wind I

Low compressibility but significant enhancement of the dissipation rate

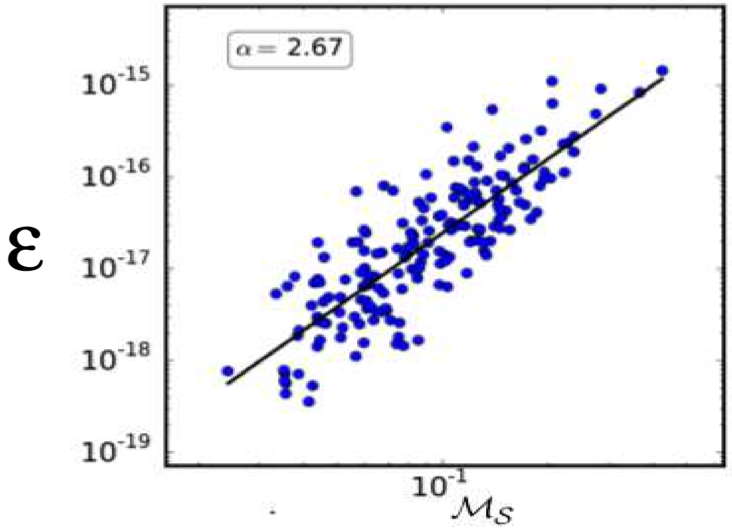
→ heating the solar wind



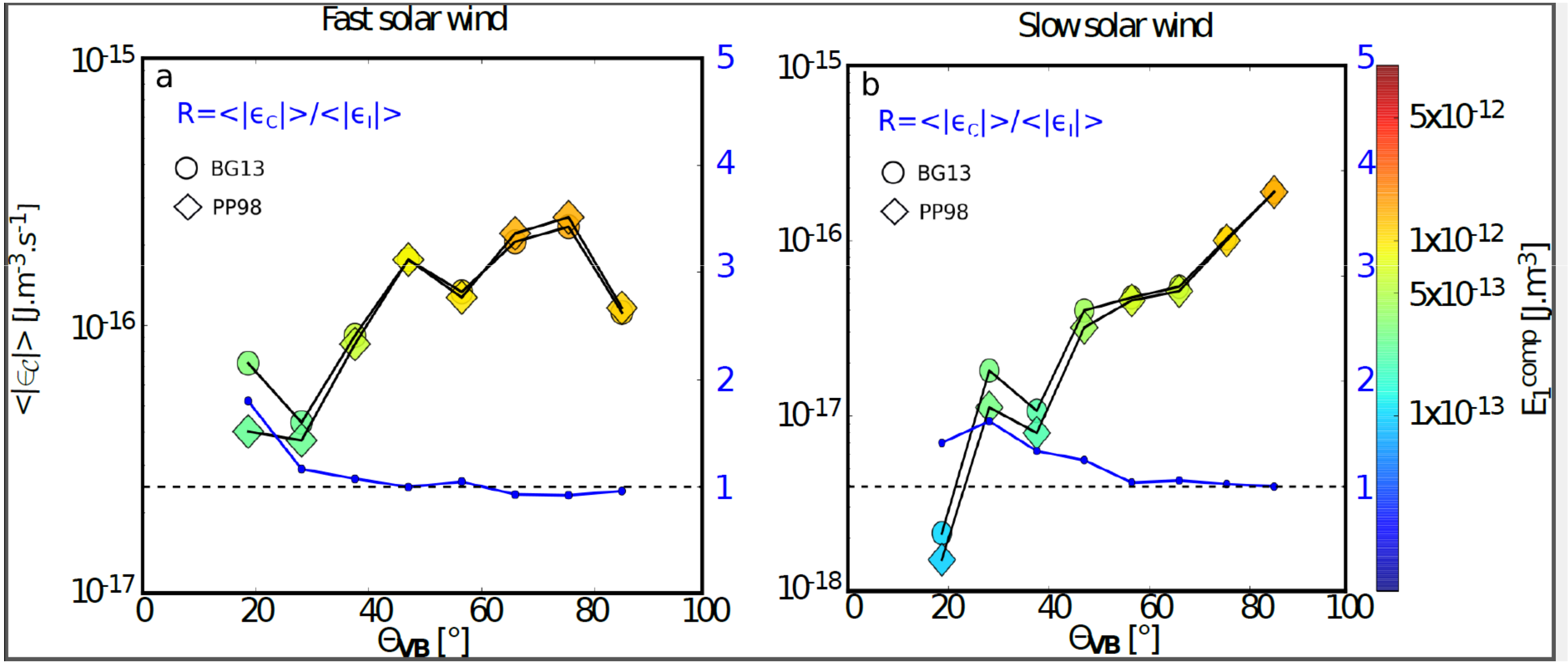
[Banerjee+, 2016, Hadid+, 2017a,b, Andrés+, 2017a,b]



Dissipation rate vs turbulent Mach number

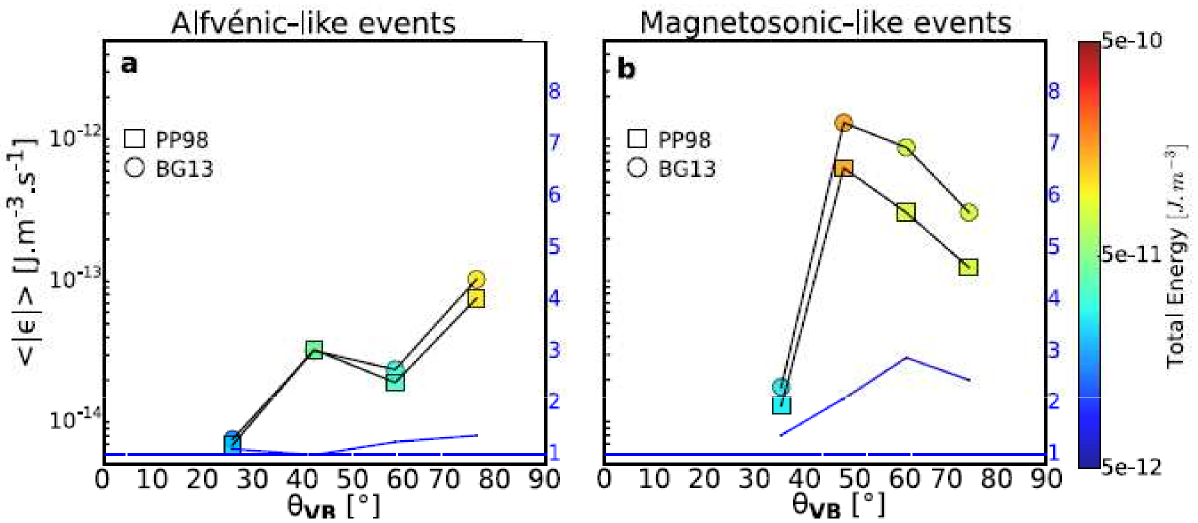


Compressible energy dissipation rate in the solar wind II



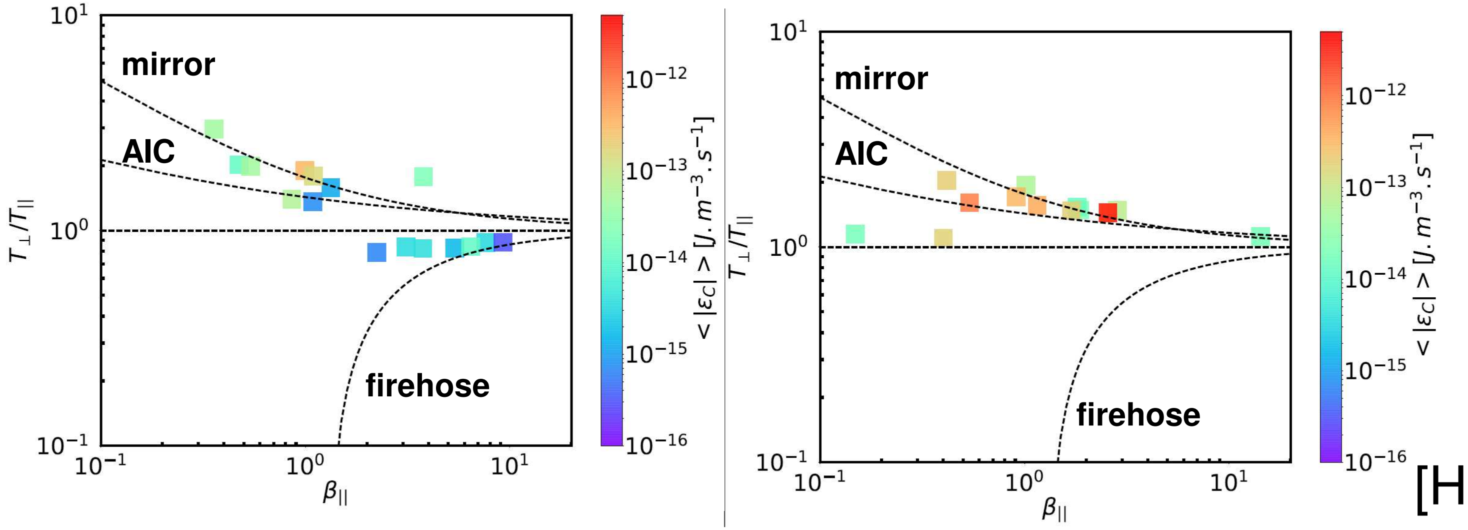
Stronger anisotropy in the slow solar wind

Compressible energy dissipation rate in the magnetosheath



Compressibility amplifies anisotropy.

ε_{max} is seen at Θ_{vB}~60° → mirror instability?



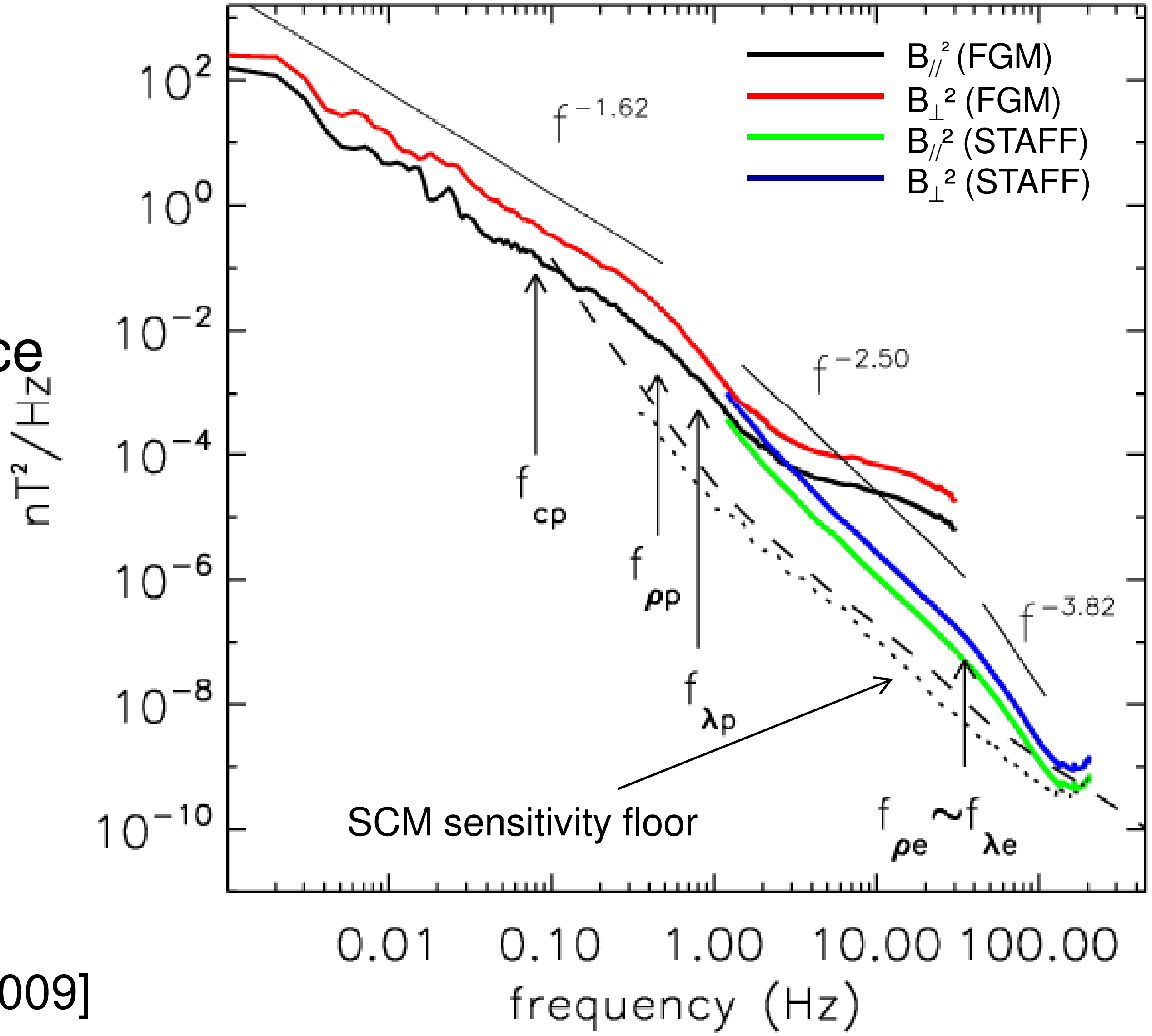
[Hadid et al., 2017b]

Sub-ion scale turbulence

First evidence of

- Cascade from MHD to sub-electron scales in solar wind turbulence
- New sub-electron

Dissipation range

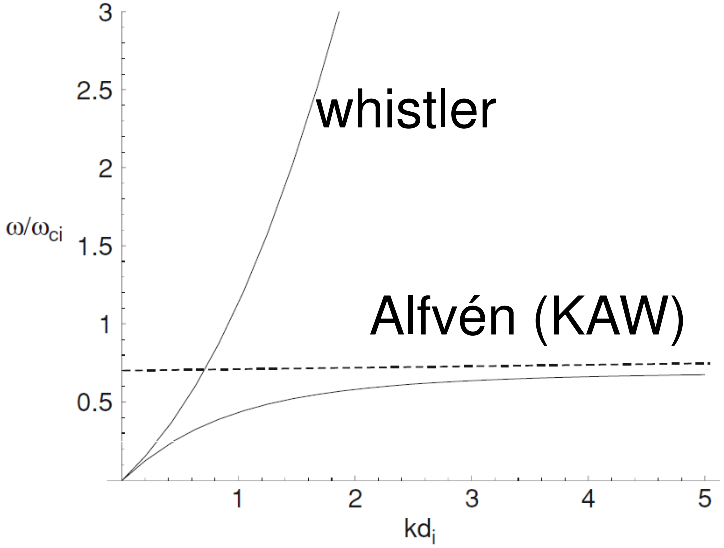


[Sahraoui et al., PRL, 2009]

Cascade Channels vs theories

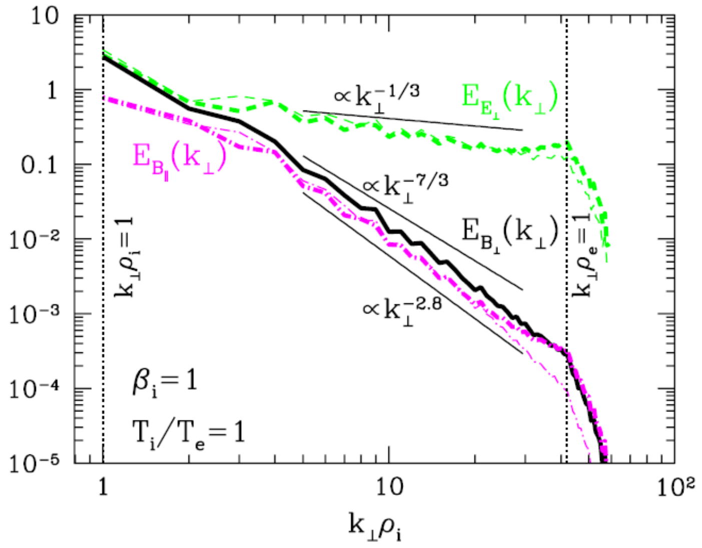
1. Fluid models: Hall-MHD, EMHD, Two-fluid [e.g., Biskamp 1997, Galtier 2006]

$$\mathbf{E}+\mathbf{V}\times\mathbf{B}=\frac{1}{en}\mathbf{J}\times\mathbf{B}-\frac{\nabla P_e}{en}+\ldots$$



2. Landau-fluid models [e.g., Snyder & Hammett, Passot & Sulem, 2006]

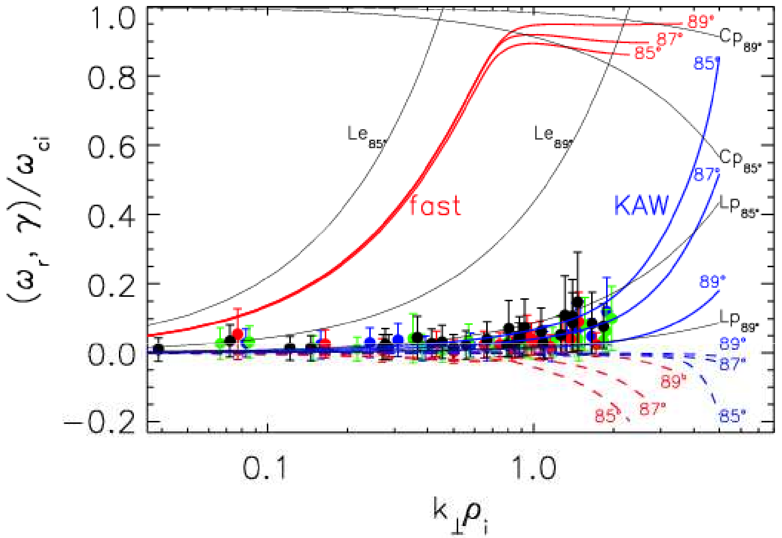
3. Gyrokinetic theory ($k_{//} << k_\perp$, $\omega << \omega_{ci}$) [Schekochihin et al. 2006; Howes et al., 2011]



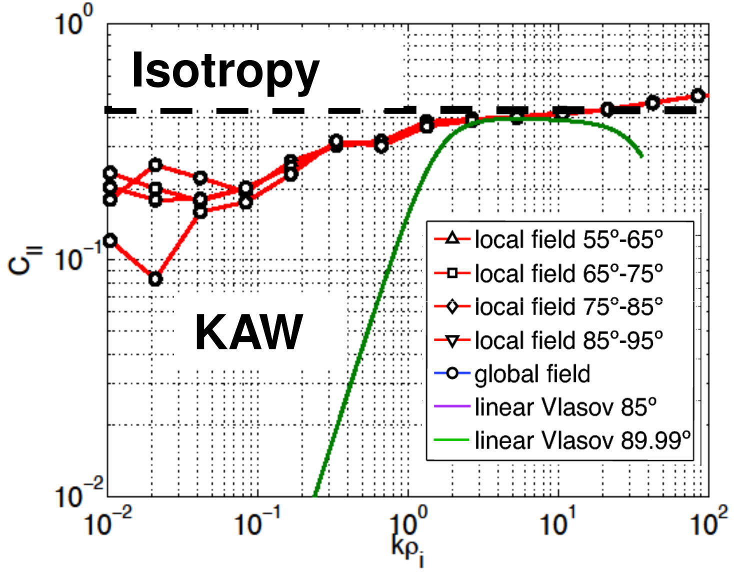
4. Hybrid, Full PIC & Vlasov [Gary et al. 2011; Servidio 2011, Valentini 2012, Califano]

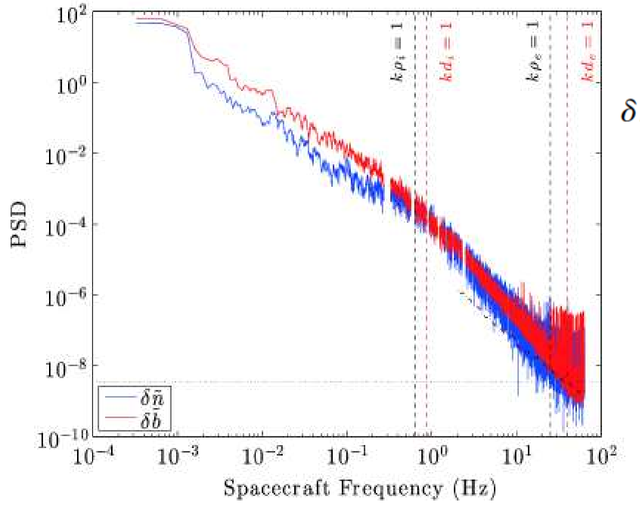
KAW *vs* whistler turbulence

[Sahraoui+, PRL, 2010]



[Kiyani+, ApJ, 2013; Salem+, 2012; Podesta+, 2012]





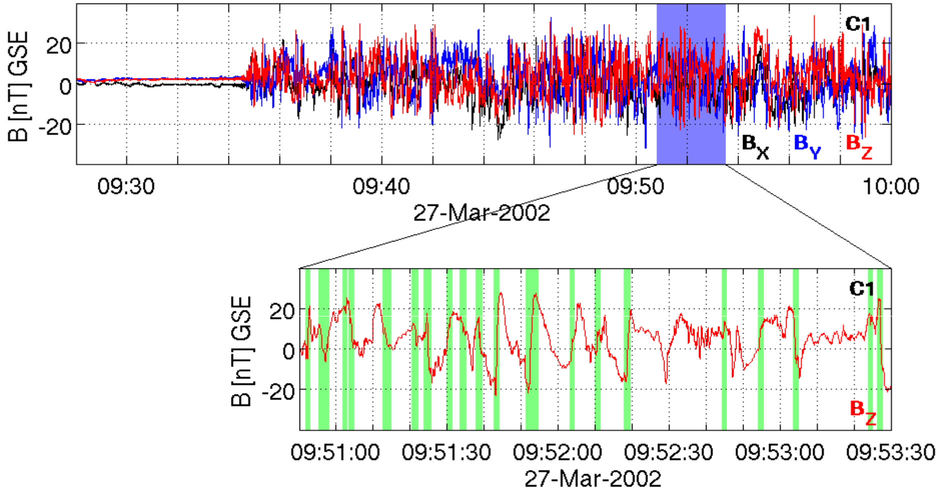
$$\delta\tilde{n} = \left(1 + \frac{T_i}{T_e}\right)^{1/2} \frac{v_s}{v_A}\left[1 + \left(\frac{v_s}{v_A}\right)^2 \left(1 + \frac{T_i}{T_e}\right)\right]^{1/2} \frac{\delta n}{n_0},$$

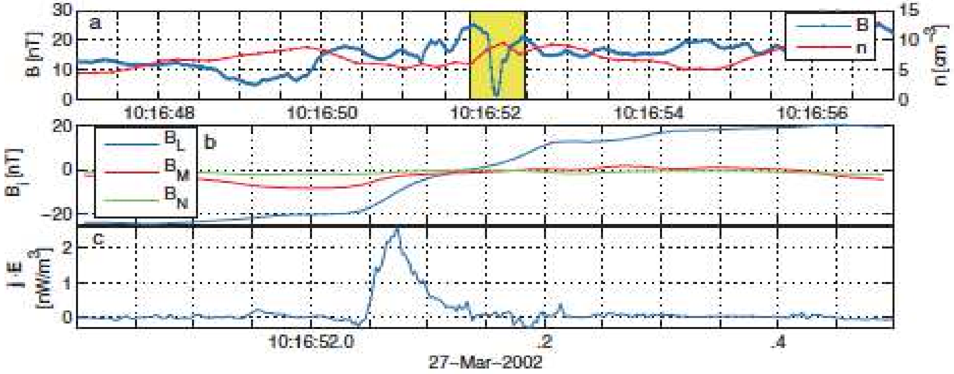
$$\delta\tilde{\mathbf{b}} = \frac{\delta \mathbf{B}}{B_0},$$

- Dominance of KAW
- Whistler turbulence exists [Hamilton+, 2008; Gary & Smith; 2009; Smith+, 2012; He+,2012; Cerri et al., 2016]

Current sheets vs waves

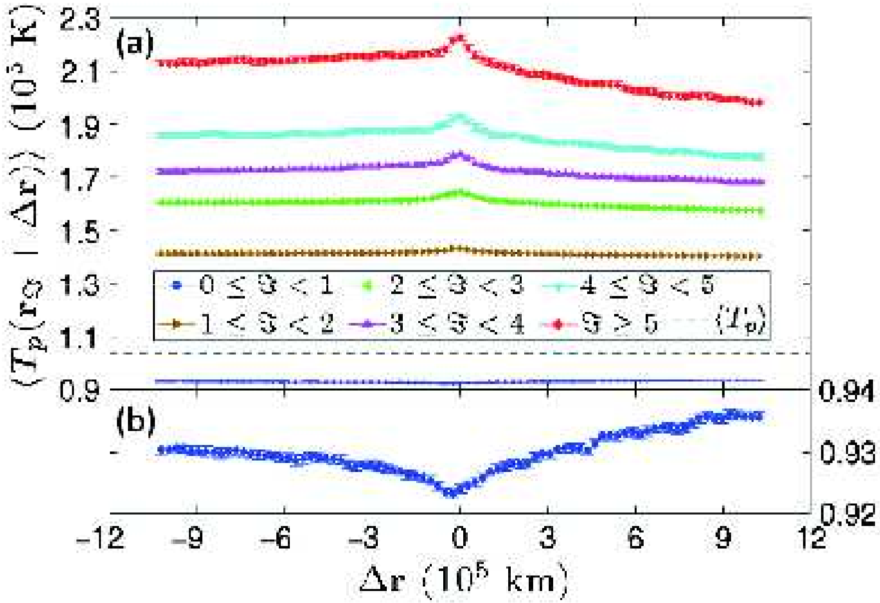
Ion scale CS in the magnetosheath





[Sundkvist+, 2007; Retinò+, 2007, Chasapis+, 2015]

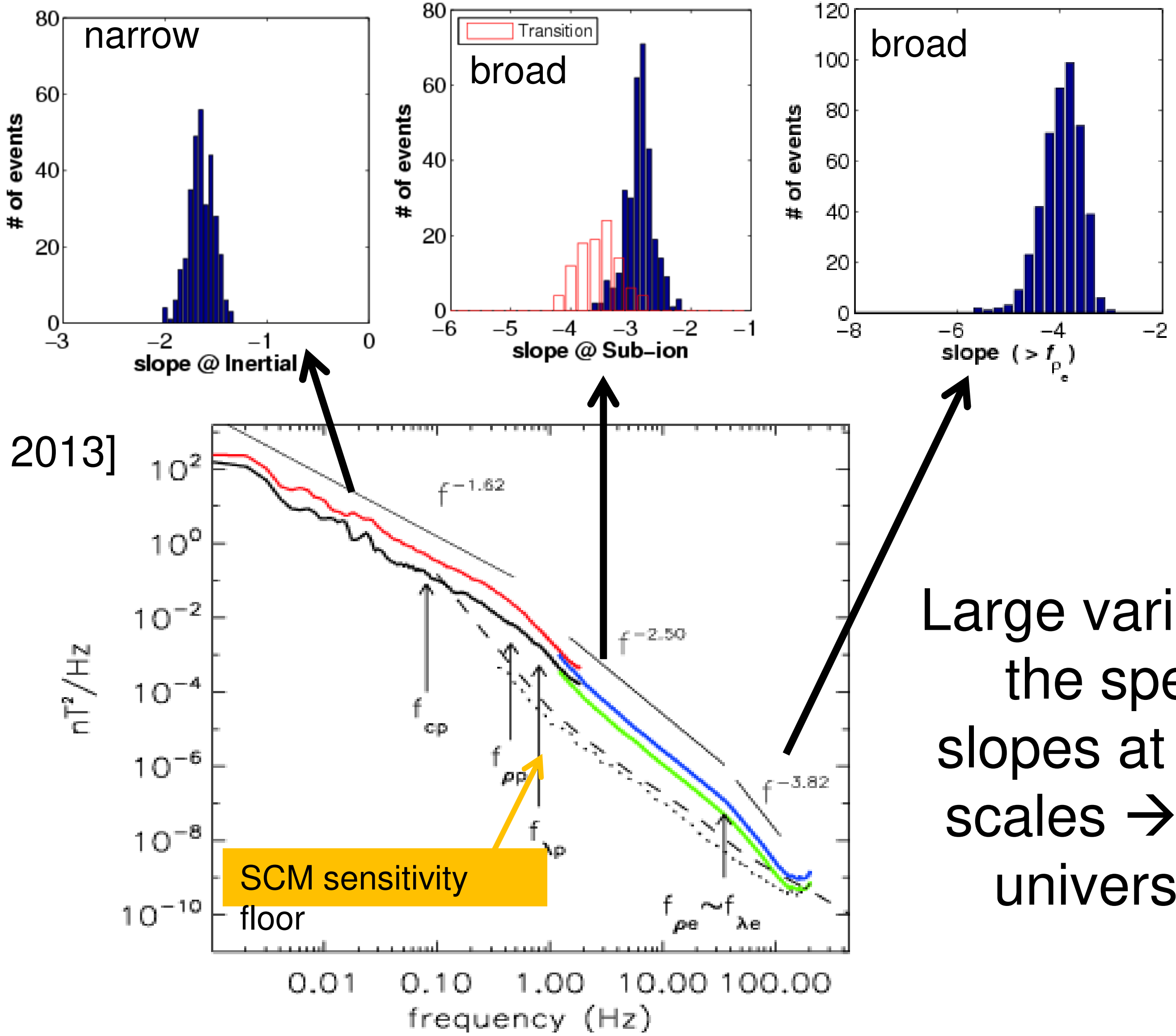
MHD scale CS in the SW



[Osman+, PRL, 2012]

See also Gosling+, ApJL,2007 in fast solar wind; Chian+, ApJL,2011 in CMEs, and many more others

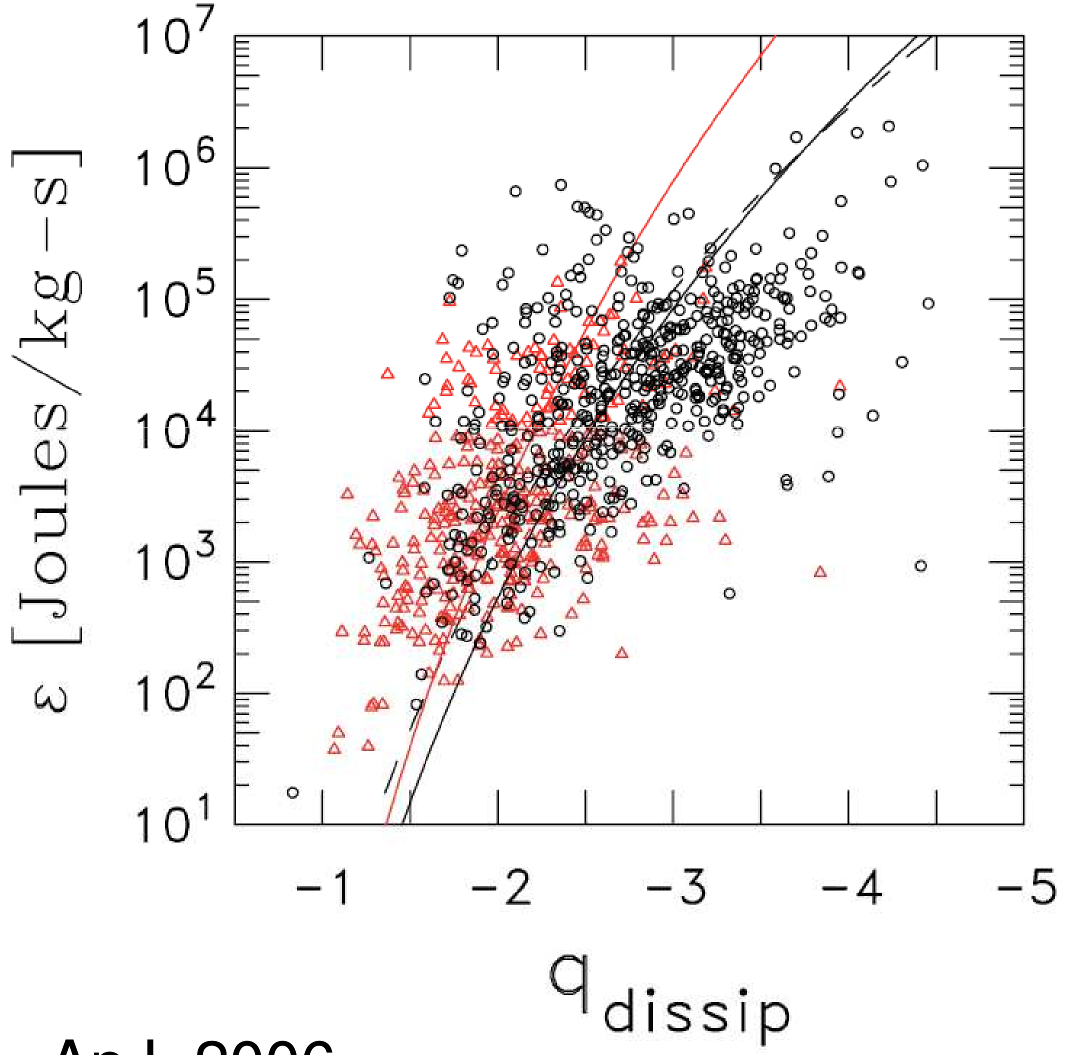
Universality?



[Sahraoui, ApJ, 2013]

Large variability of the spectral slopes at sub-ion scales → lack of universality?

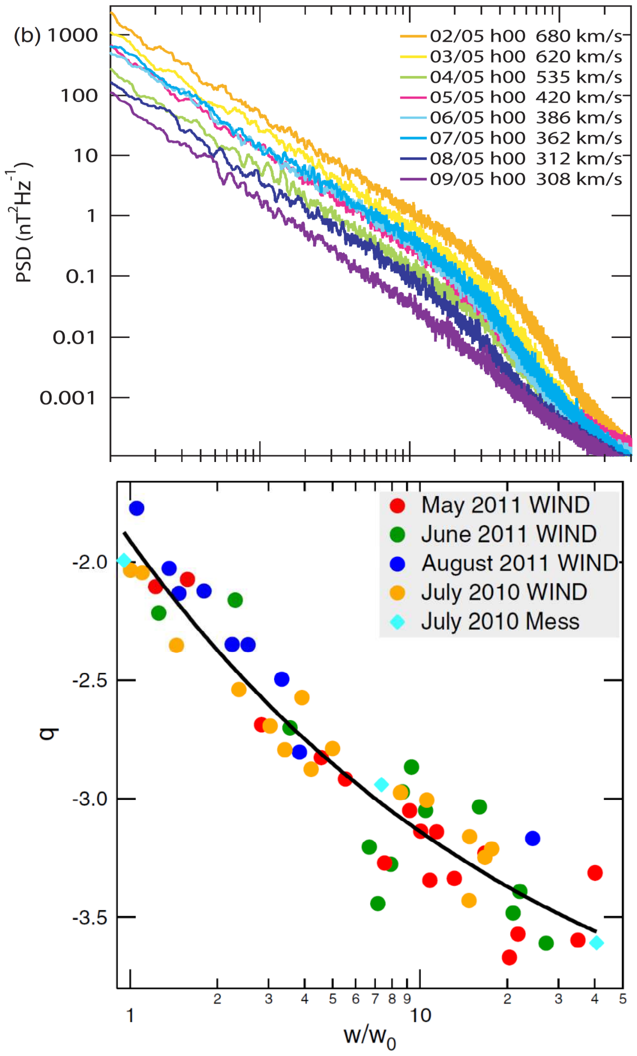
Dissipation rate vs slopes



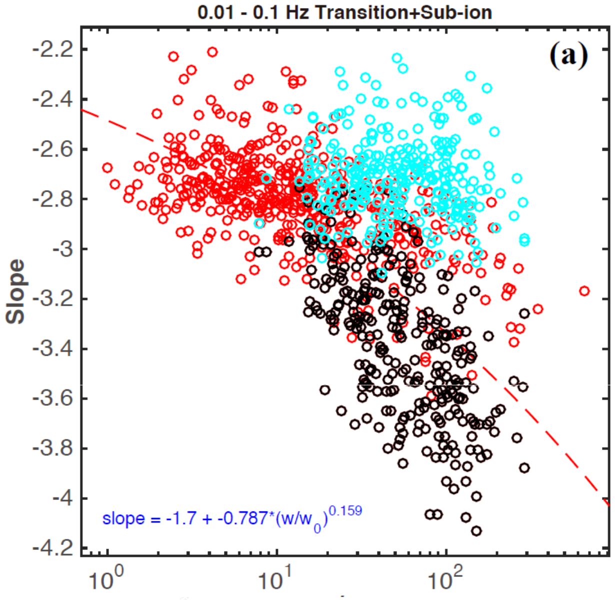
Smith et al., ApJ, 2006

Amplitude fluctuation vs slopes

[Bruno et al., ApJ, 2014]

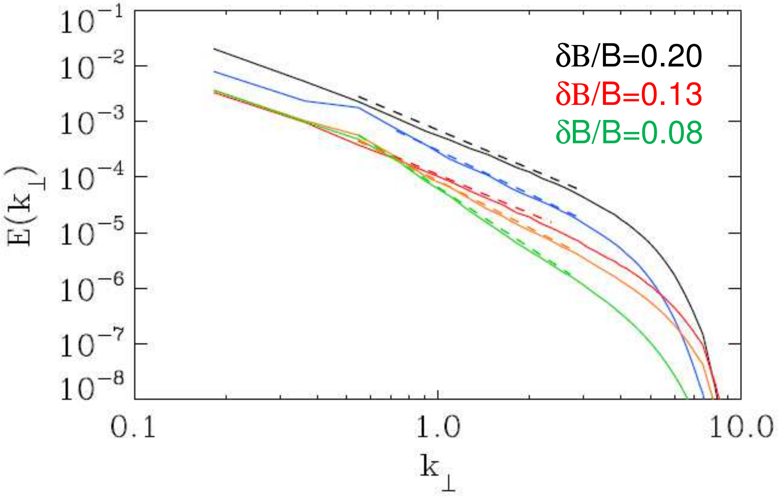


[Kobayashi et al., ApJ, 2017]



Landau-fluid simulations

[Passot+, ApJ, 2015; Sulem+, ApJ, 2016]



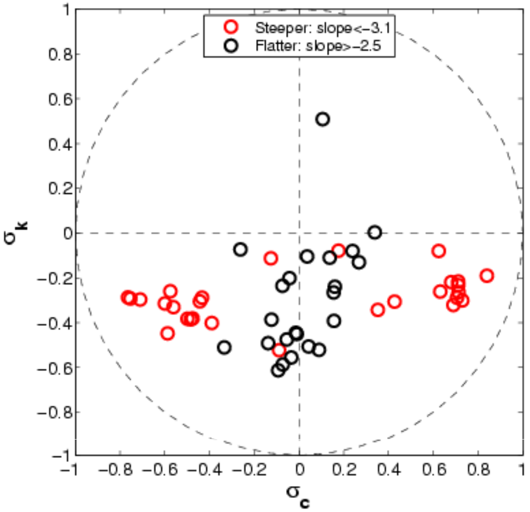
Cross helicity vs slopes

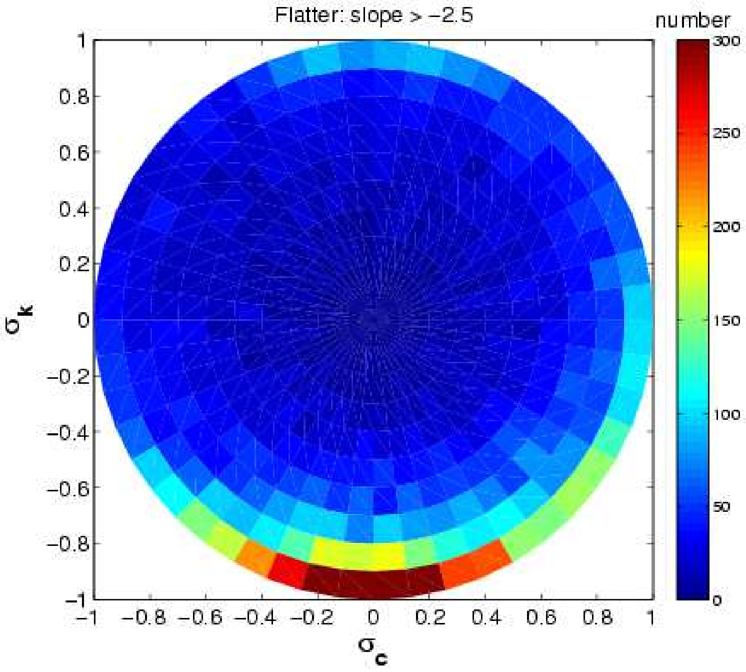
$$\sigma_C = \frac{<\delta z^{+2}> - <\delta z^{-2}>}{<\delta z^{+2}> + <\delta z^{-2}>} \qquad \delta z^{\pm} = \delta v \pm \delta v_A$$

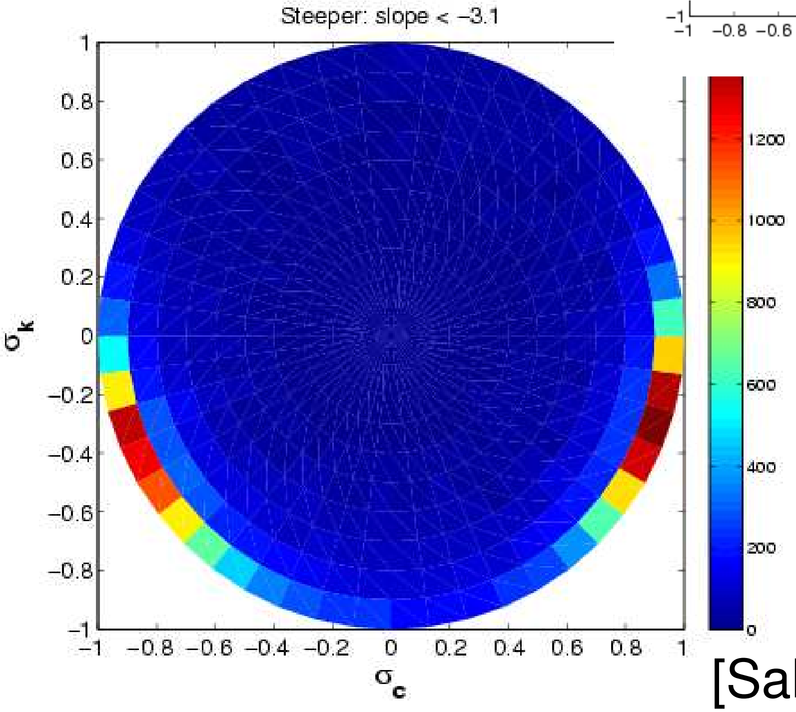
$$\sigma_k = \frac{<\delta v^2> - <\delta v_A^2>}{<\delta v^2> + <\delta v_A^2>}$$

$\sigma_c \sim 1 \rightarrow \delta z^- \sim 0 \rightarrow$

$$NL \equiv z^{\mp}.\nabla z^{\pm} \approx 0???$$





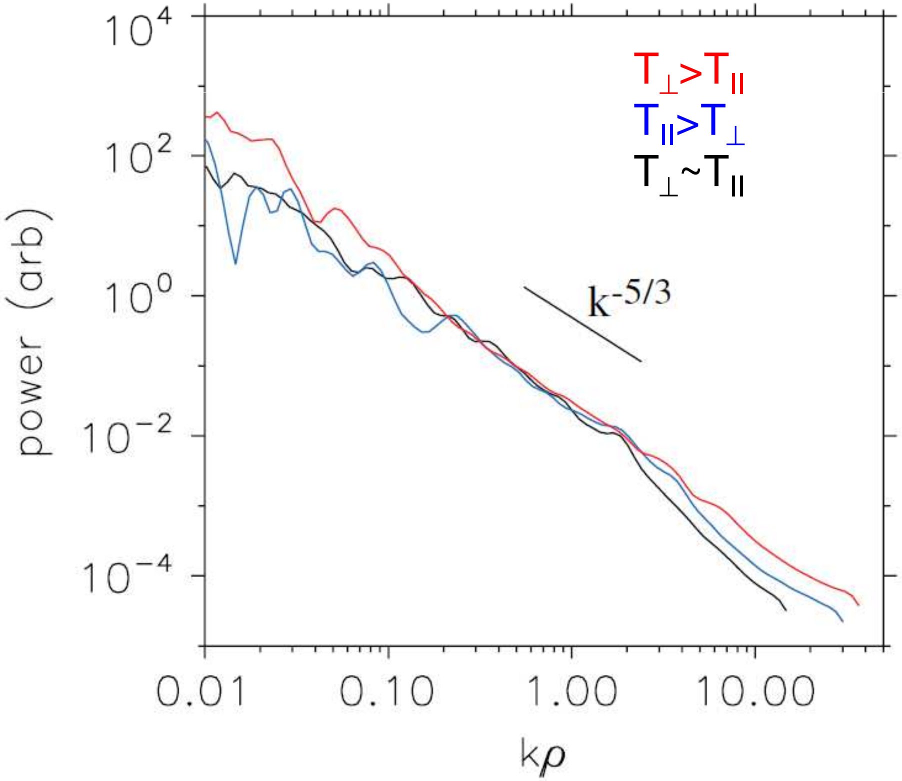


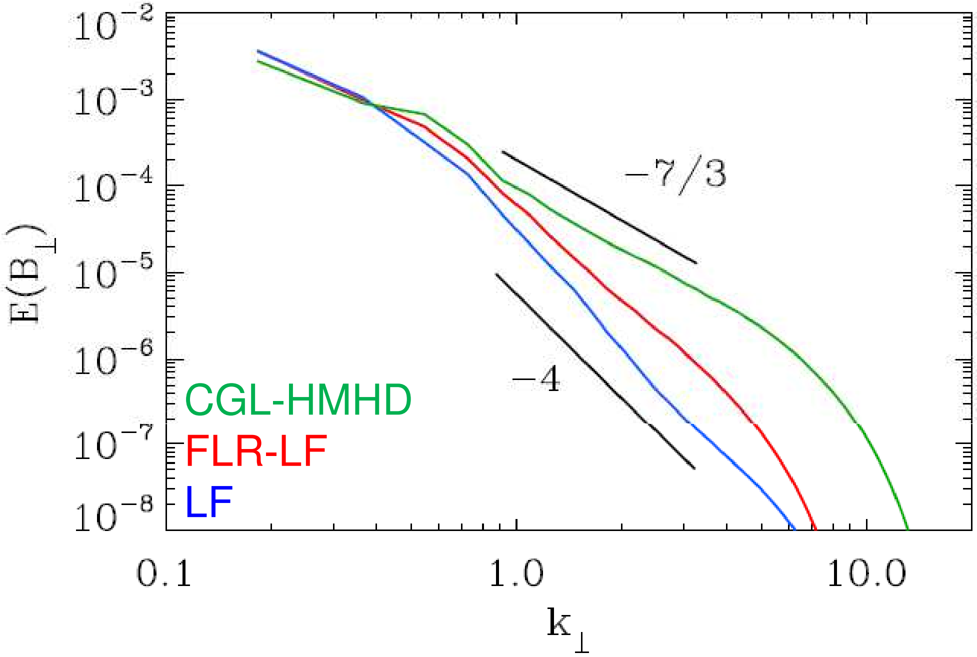
[Sahraoui, 2017b]

Other possible explanations

Plasma instabilities

[Bale et al., PRL, 2009]

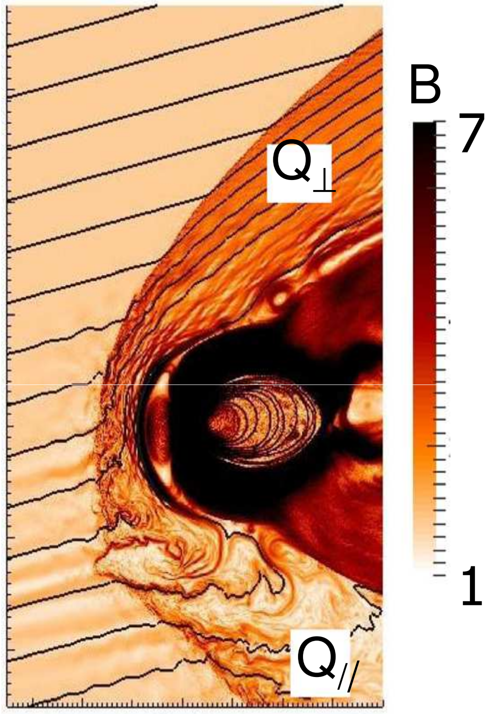




Landau damping (LF simulation)

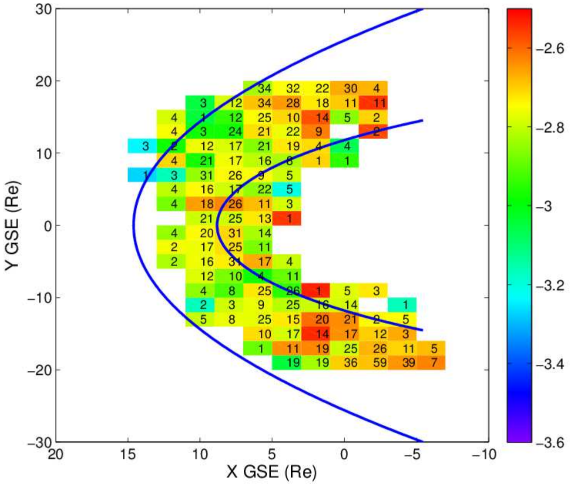
[Kobayashi et al., ApJ, 2017]

Magnetosheath turbulence

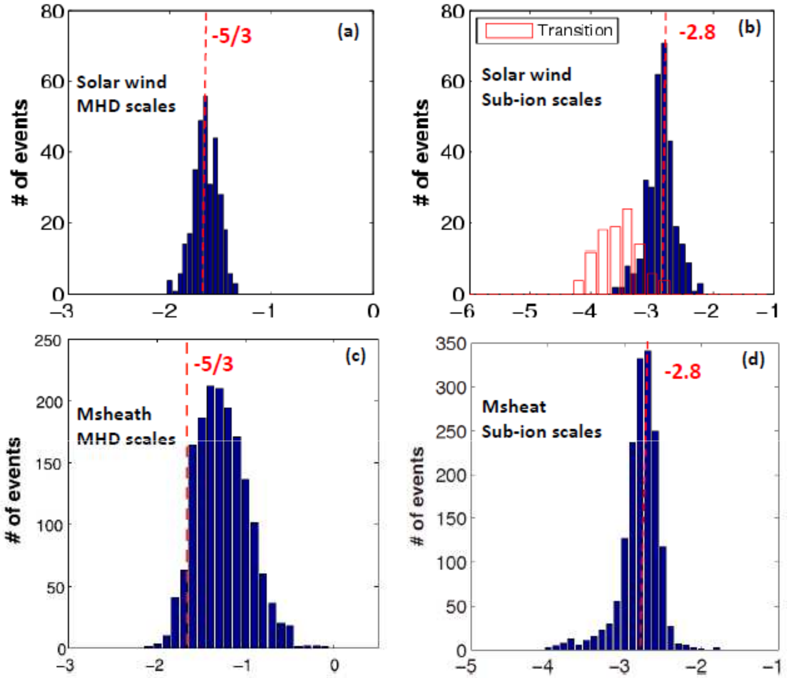


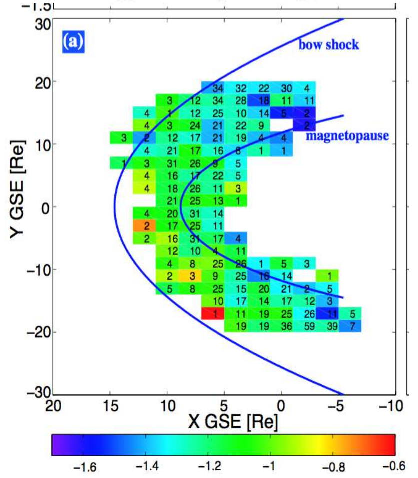
Karimabadi et al., 2014

Sub-ion scales



Huang et al., 2016

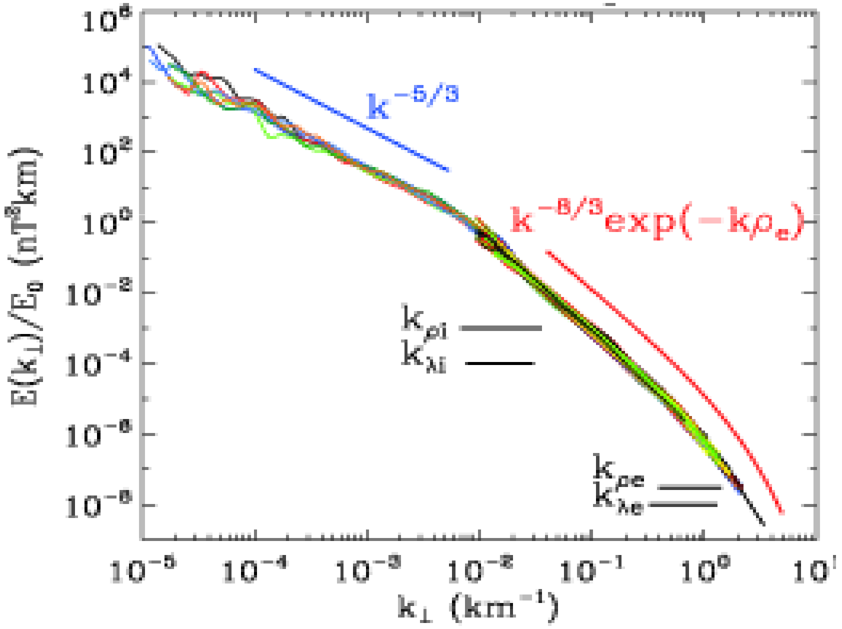




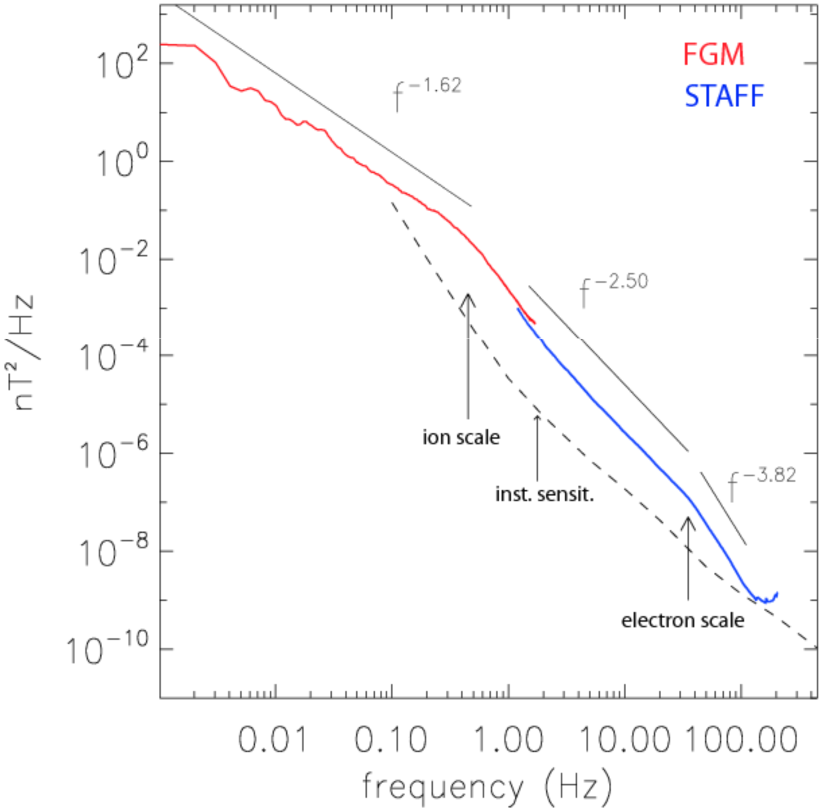
MHD scales

Sub-electron scale turbulence I

[Alexandrova, ApJ, 2012]



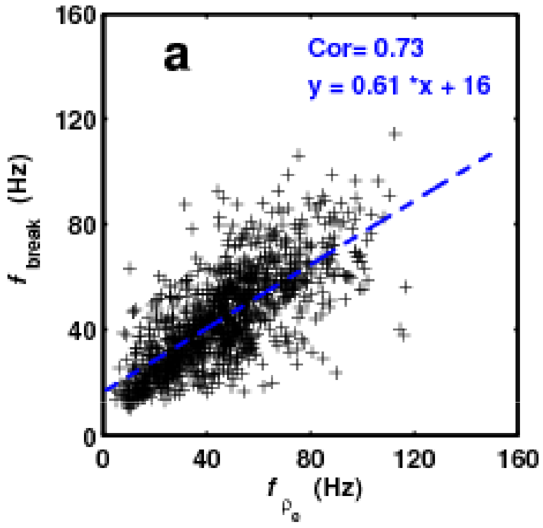
[Sahraoui, PRL, 2009]

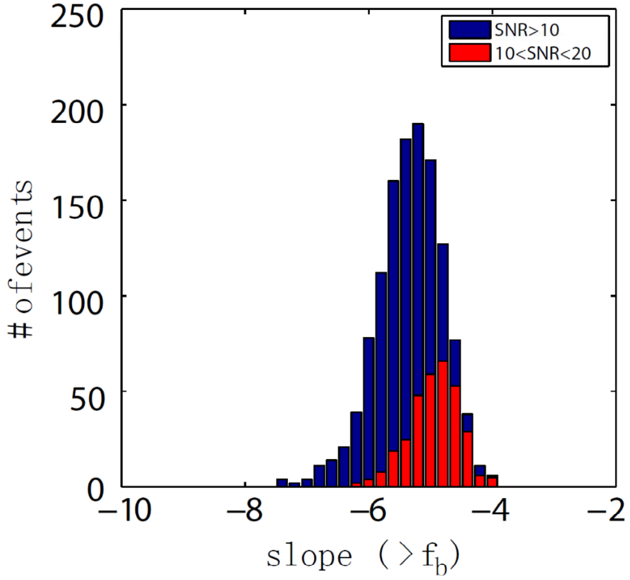


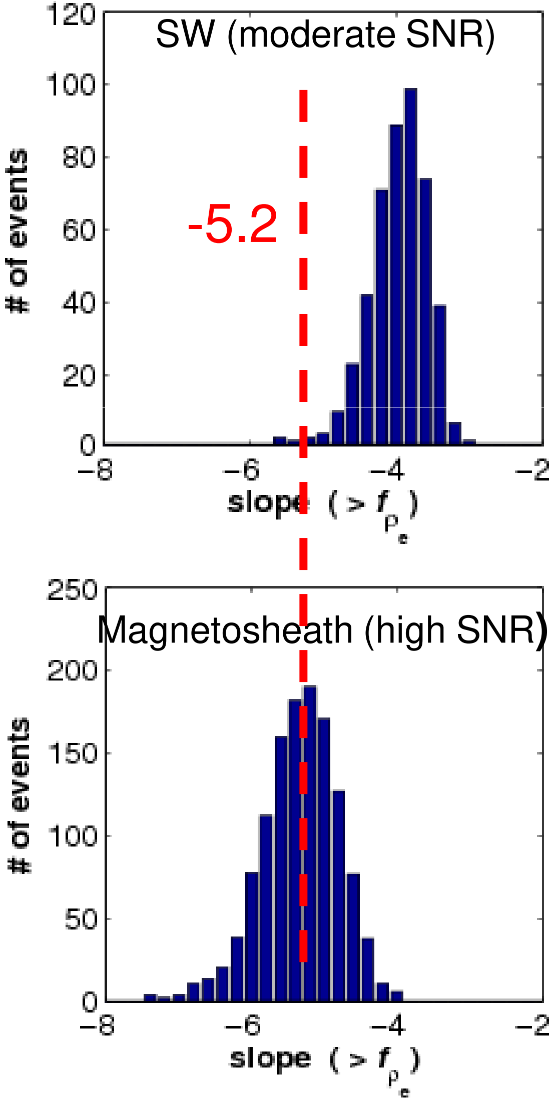
Ultimate (KAW) cascade below ρ_e?
Exponential dissipation ?
Universal scaling ?

See Alex's talk

Sub-electron scale turbulence II







[Sahraoui+, ApJ, 2013;
Huang+, ApJL, 2014]

THOR mission (Phase A, ESA/M4)

Main targets:
- Solar wind,
- IP shocks,
- Foreshock,
- Shock,
- Magnetosheath

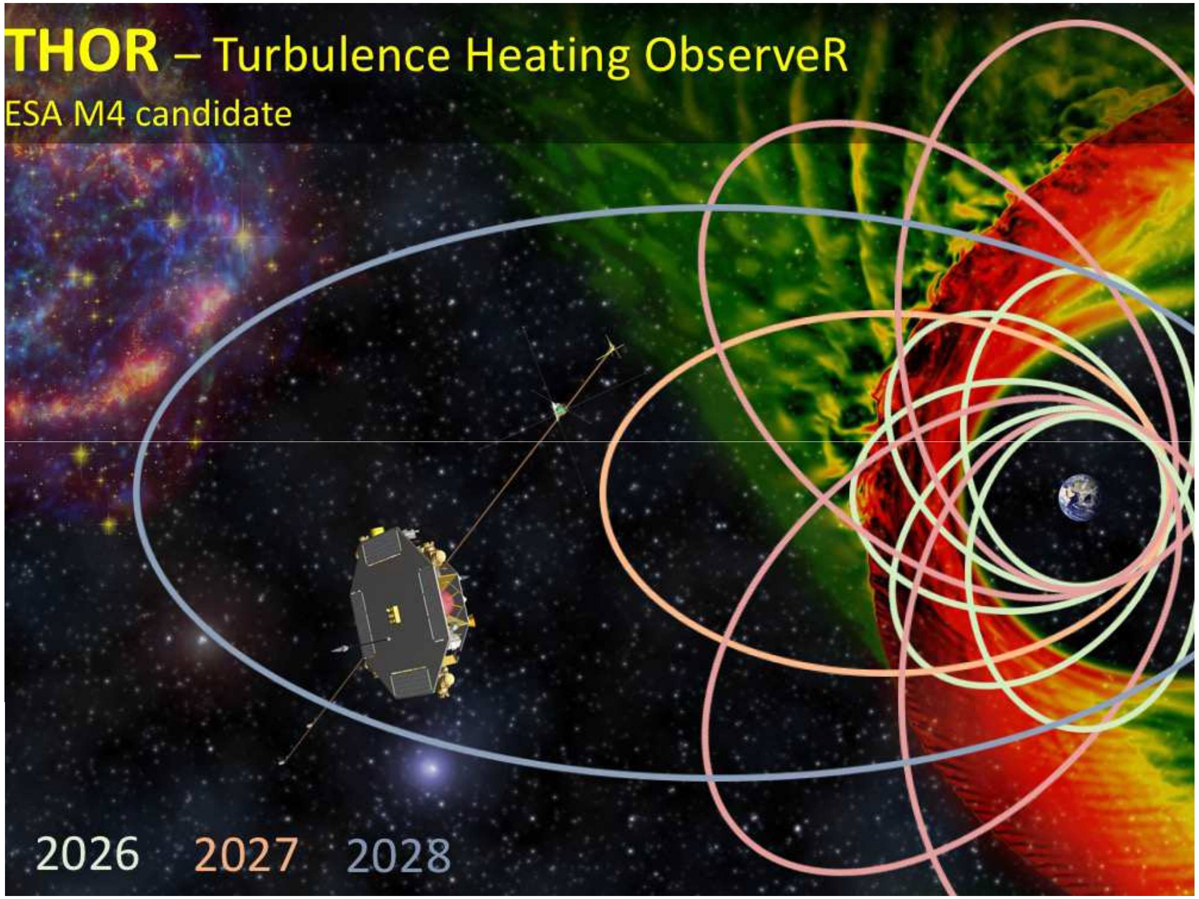


Table 22: THOR mission phases

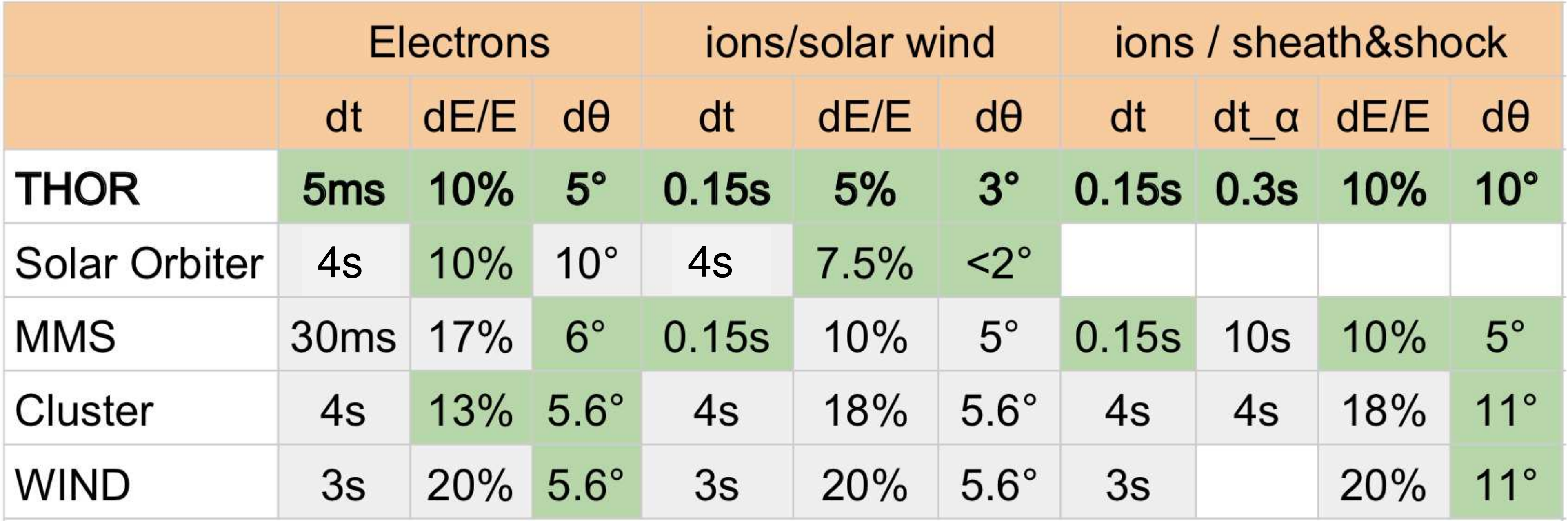
Phase	Orbit	T [h]	ΔV to next orbit
1	4 x 16 R_E	44.53	204 m/s
2	4 x 26 R_E	81.81	214 m/s
3	4 x 61 R_E 14 x 61 R_E	330.37	260 m/s

Each of the mission phases lasts one full year. The total ΔV needed for orbital maneuvers is 678 m/s. Phase 3 involves Moon flybys to save ΔV.

Nominal mission: 3 years

THOR particle payload vs other missions

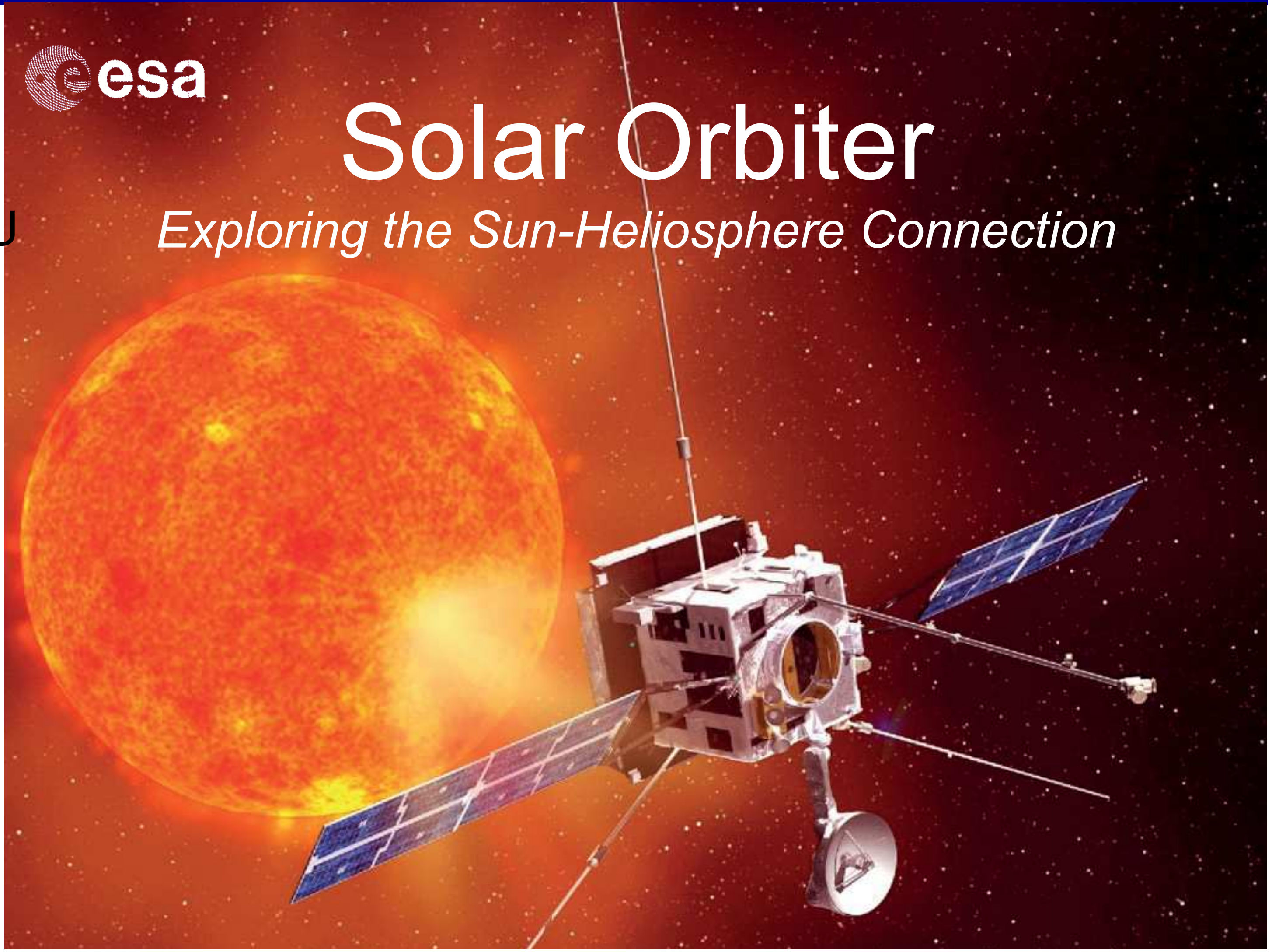
3D velocity distributions functions (VDFs)



	Electrons			ions/solar wind			ions / sheath&shock			
	dt	dE/E	dθ	dt	dE/E	dθ	dt	dt_α	dE/E	dθ
THOR	**5ms**	**10%**	**5°**	**0.15s**	**5%**	**3°**	**0.15s**	**0.3s**	**10%**	**10°**
Solar Orbiter	4s	10%	10°	4s	7.5%	<2°				
MMS	30ms	17%	6°	0.15s	10%	5°	0.15s	10s	10%	5°
Cluster	4s	13%	5.6°	4s	18%	5.6°	4s	4s	18%	11°
WIND	3s	20%	5.6°	3s	20%	5.6°	3s		20%	11°

ESA/Solar Orbiter

- Launch 2018
- Distance : 0.28 AU
- In-situ data & remote sensing



NASA/Solar Probe Plus

- Launch 2018
- Distance : 0.03 AU
- In-situ data & remote sensing

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771