Transport d'énergie multi-échelle dans le vent solaire et turbulence

Laboratoire de Physique des Plasmas

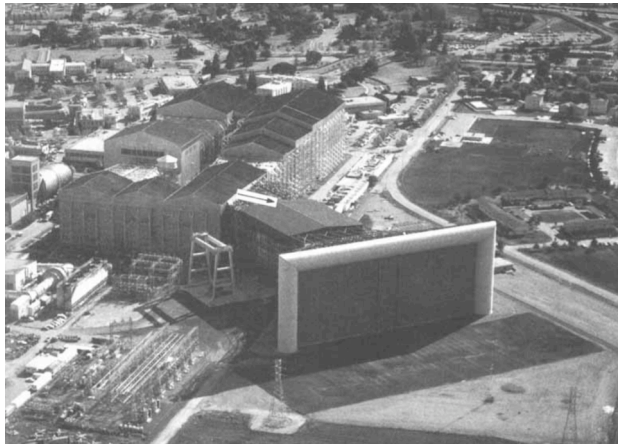
Colloque PNST 2016, Hendaye

Sébastien Galtier

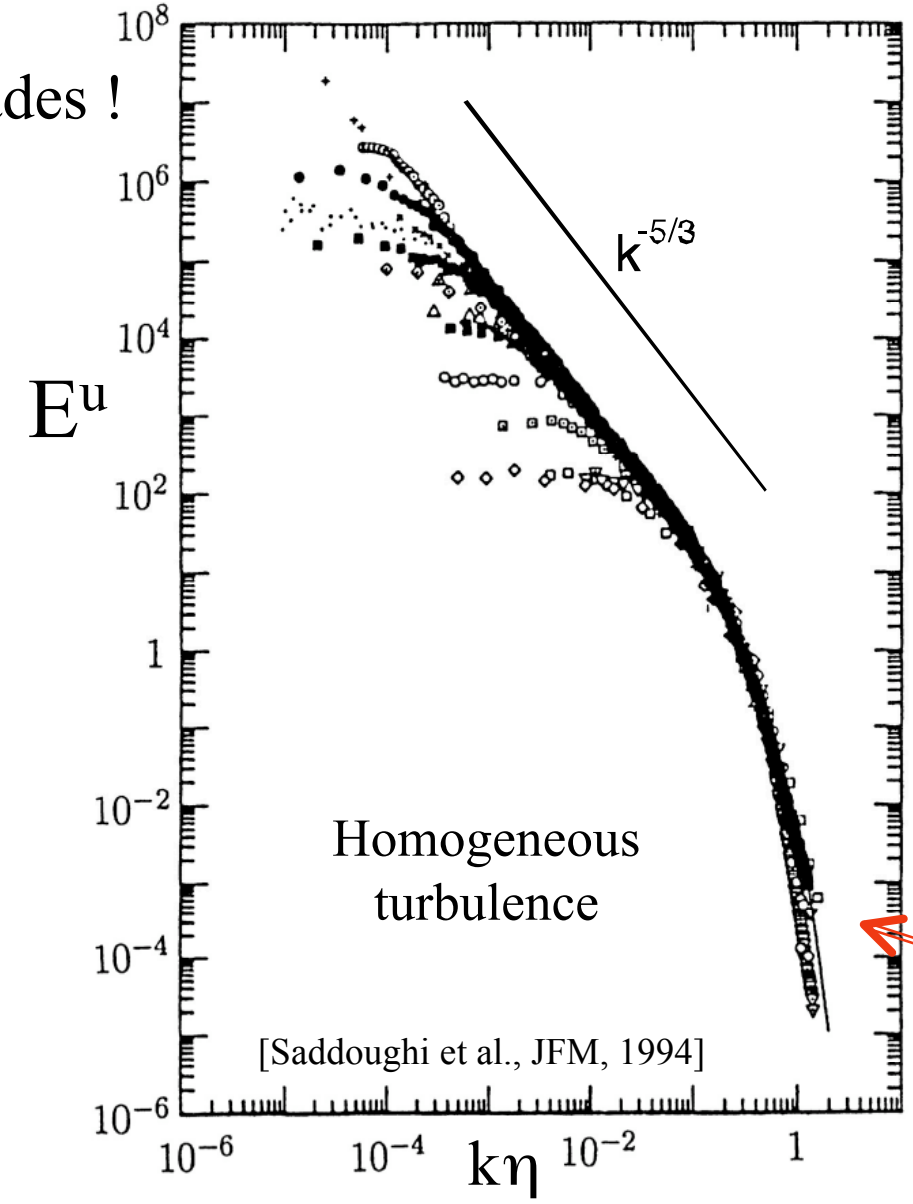
Laboratoire de Physique des Plasmas

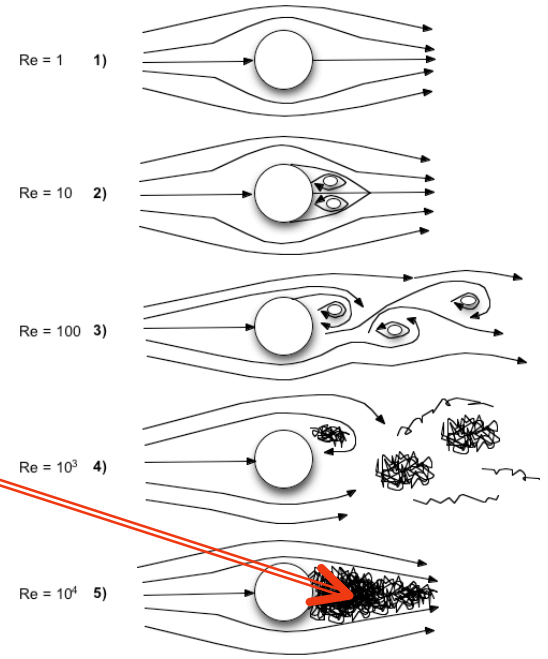
Vortex turbulence

Wind tunnel



3-4 decades !



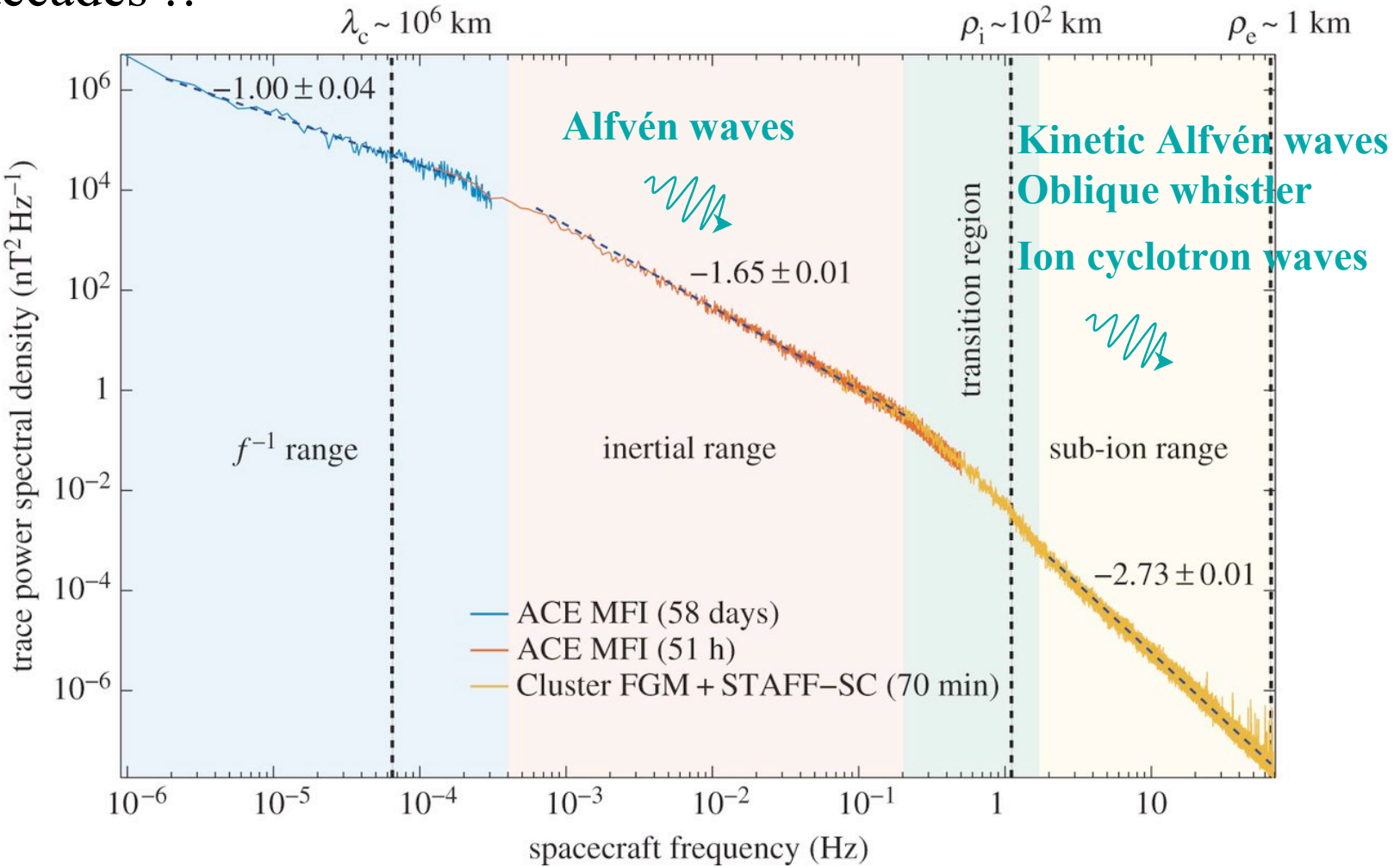


Wave turbulence

Solar wind
(~1 AU)

Power laws at MHD & sub-ion scales

8 decades !!



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

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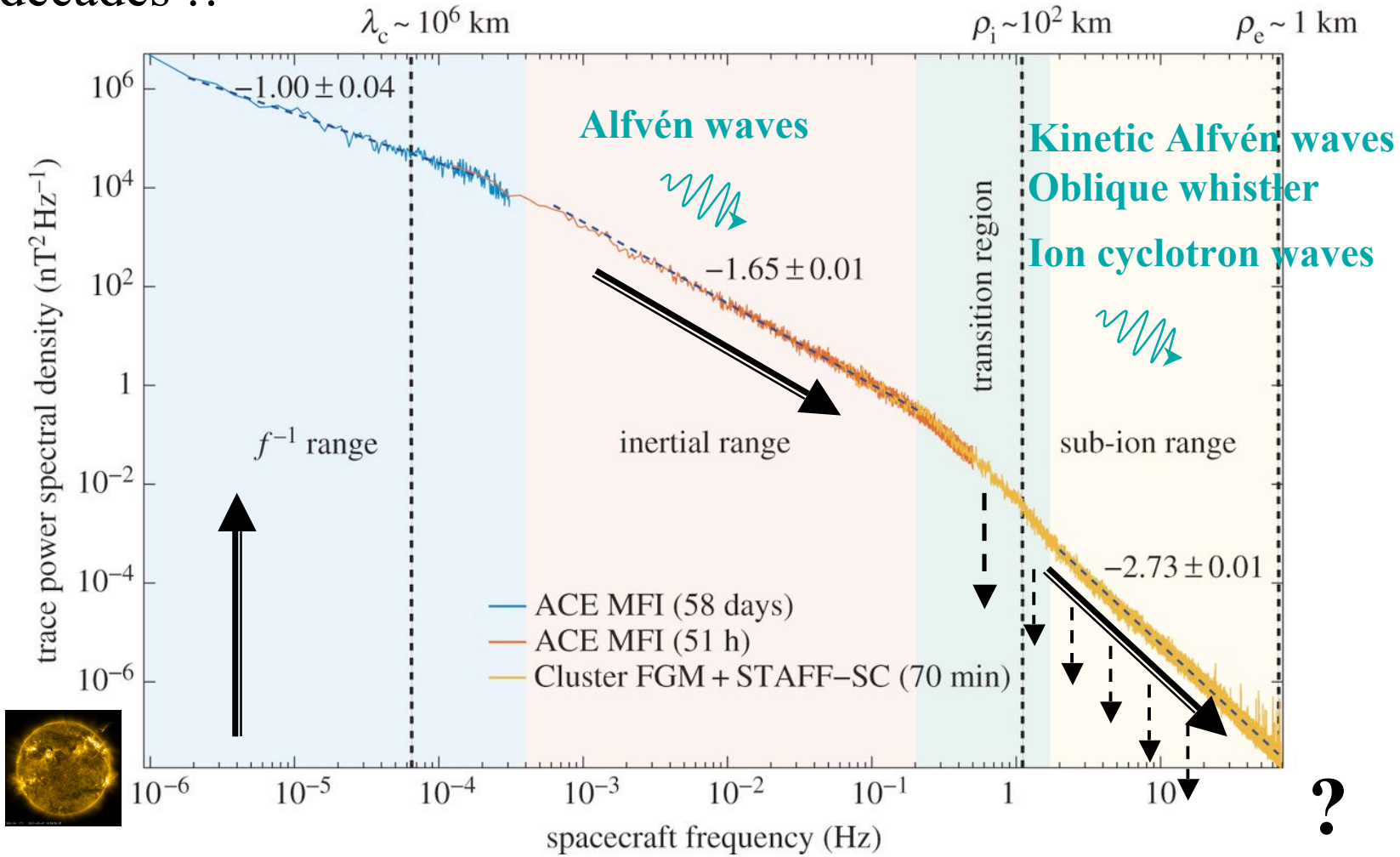
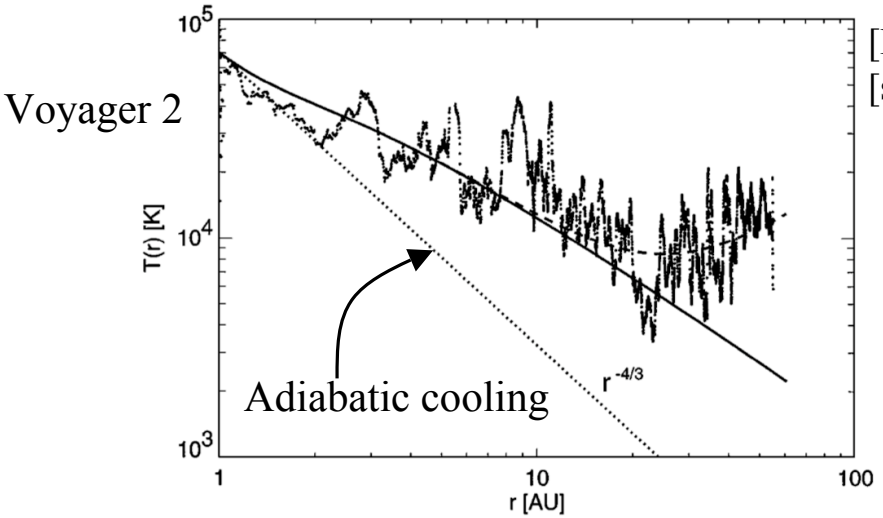


?

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

Solar wind heating



[Matthaeus et al., PRL, 1999]
[see also Marsch et al., JGR, 1982]

⇒ A local heating is needed

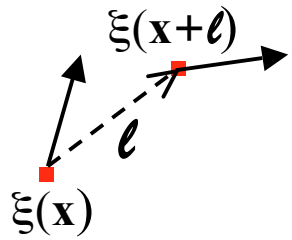
Incompressible MHD turbulence

$\mathbf{z}^{\pm} \equiv \mathbf{u} \pm \mathbf{b}$ $\qquad \delta\xi = \xi(\mathbf{x}+\boldsymbol{\ell}) - \xi(\mathbf{x})$

$$-\frac{4}{3}\varepsilon^{\pm}\ell = \overbrace{\langle(\delta\mathbf{z}^{\pm}\cdot\delta\mathbf{z}^{\pm})\delta z_{\ell}^{\mp}\rangle}^{Y^{\pm}},$$

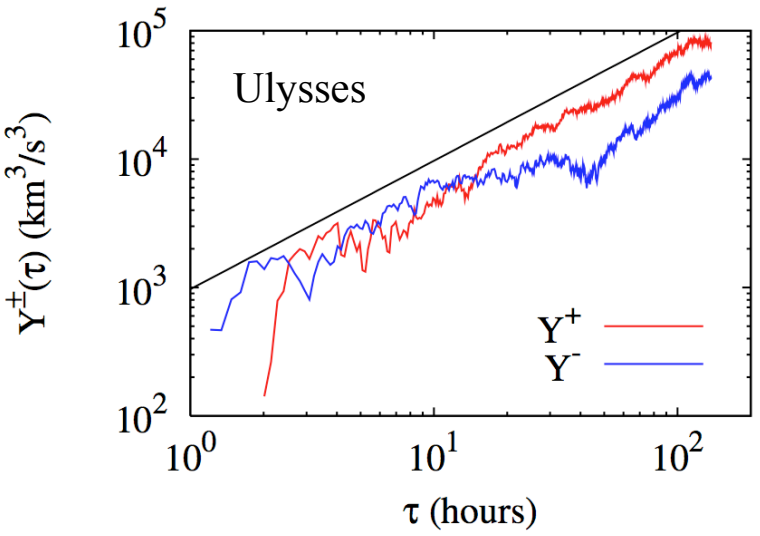
[Politano & Pouquet, PRE, 1998]

EXACT LAW



[Sorriso-Valvo et al., PRL, 2007]

$\varepsilon \sim 10^2\ \mathrm{J\,kg^{-1}\,s^{-1}}$



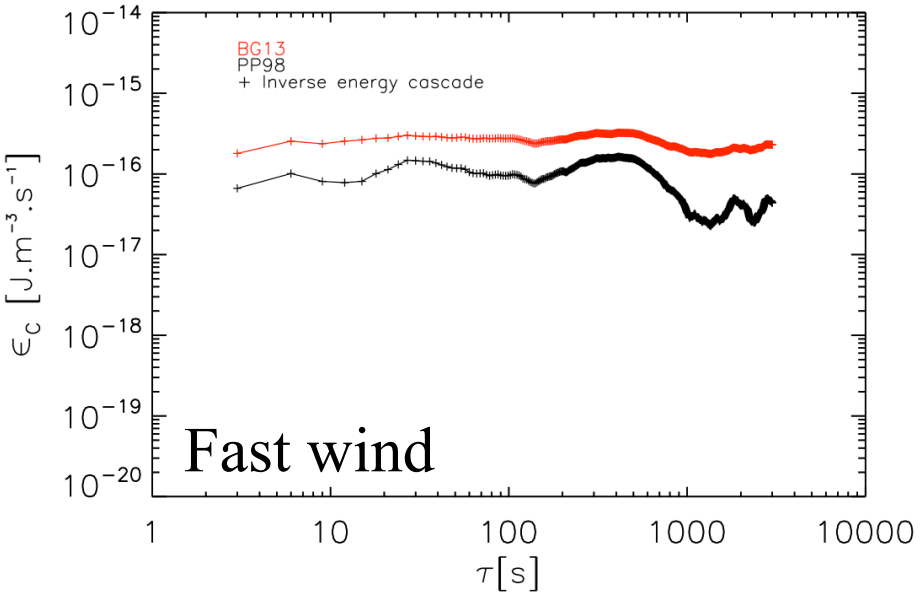
Compressible MHD turbulence

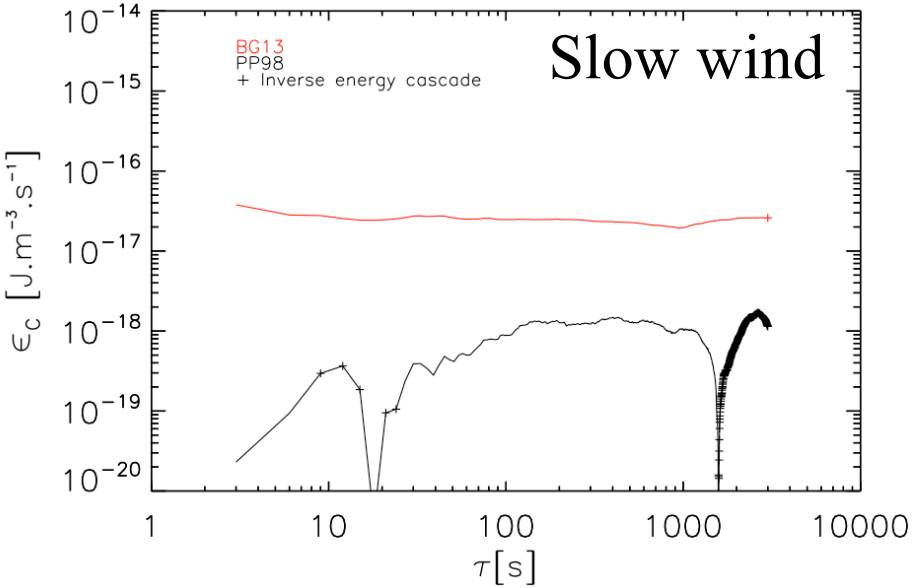
EXACT LAW

[Banerjee, PhD, 2014; Banerjee & SG, PRE, 2013]

$$-2\varepsilon = \frac{1}{2}\nabla_r \cdot \left\langle \left[\frac{1}{2}\delta(\rho\mathbf{z}^-)\cdot\delta\mathbf{z}^- + \delta\rho\delta e\right]\delta\mathbf{z}^+ + \left[\frac{1}{2}\delta(\rho\mathbf{z}^+)\cdot\delta\mathbf{z}^+ + \delta\rho\delta e\right]\delta\mathbf{z}^- + \bar{\delta}\left(e + \frac{v_A^2}{2}\right)\delta(\rho\mathbf{z}^- + \rho\mathbf{z}^+)\right\rangle$$
$$- \frac{1}{8}\left\langle \left(\frac{1}{\beta'}\nabla'\cdot(\rho\mathbf{z}^+e') + \frac{1}{\beta}\nabla\cdot(\rho'\mathbf{z}'^+e) + \frac{1}{\beta'}\nabla'\cdot(\rho\mathbf{z}^-e') + \frac{1}{\beta}\nabla\cdot(\rho'\mathbf{z}'^-e)\right)\right.$$
$$+ \left\langle (\nabla\cdot\mathbf{v})\left[R_E' - E' - \frac{\bar{\delta}\rho}{2}(\mathbf{v_A}'\cdot\mathbf{v_A}) + \frac{P_M' - P'}{2}\right]\right\rangle + \left\langle (\nabla'\cdot\mathbf{v}')\left[R_E - E - \frac{\bar{\delta}\rho}{2}(\mathbf{v_A}\cdot\mathbf{v_A}') + \frac{P_M - P}{2}\right]\right\rangle$$
$$+ \langle(\nabla\cdot\mathbf{v_A})[R_H - R_H' + H' - \bar{\delta}\rho(\mathbf{v}'\cdot\mathbf{v_A})]\rangle + \langle(\nabla'\cdot\mathbf{v_A}')[R_H' - R_H + H - \bar{\delta}\rho(\mathbf{v}\cdot\mathbf{v_A}')]\rangle\,,$$

Not easy to explain !





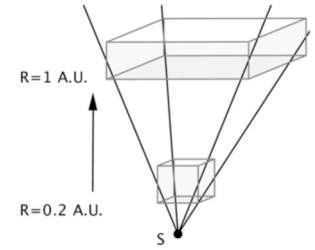
[Hadid et al., 2016]

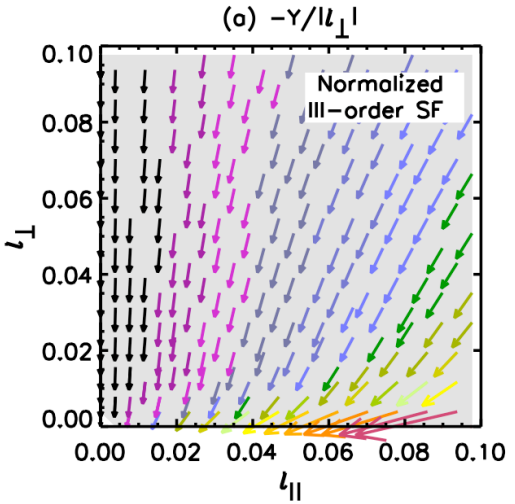
THEMIS

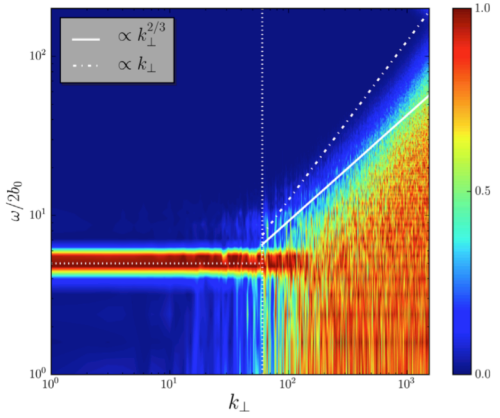
Fundamental works on MHD turbulence

→ Numerical simulations

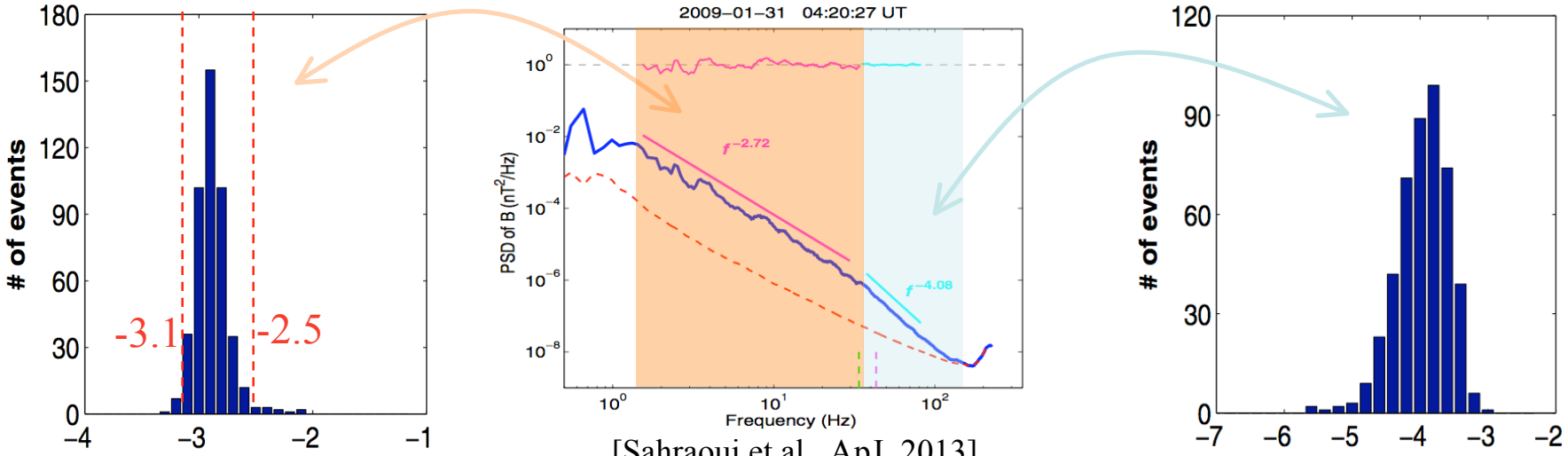
- ✓ Imprints of expansion of the local anisotropy (Verdini et al., poster) [Verdini & Grappin, ApJ, 2015] [Dong et al., ApJ, 2014]
- ✓ Anisotropy of the 3rd order structure functions in MHD turbulence [Verdini et al., ApJ, 2015]
- ✓ Direct evidence of the transition from weak to strong MHD turbulence [Meyrand et al., PRL, 2016]



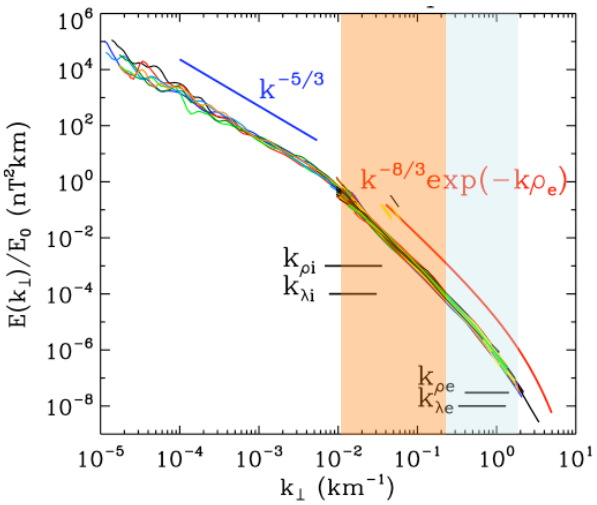




Is there universality at sub-ion scales ?



[Sahraoui et al., ApJ, 2013]

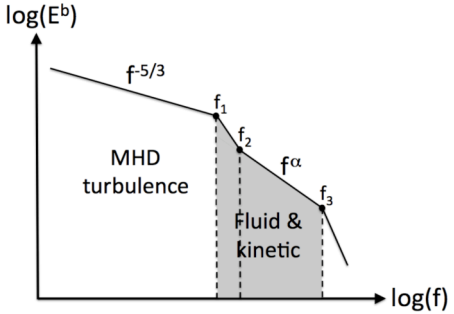


[Alexandrova et al., ApJ, 2012]

[Lacombe et al., ApJ, 2014]

Some models

$$E^b(k_\perp) \sim k_\perp^{-x}$$

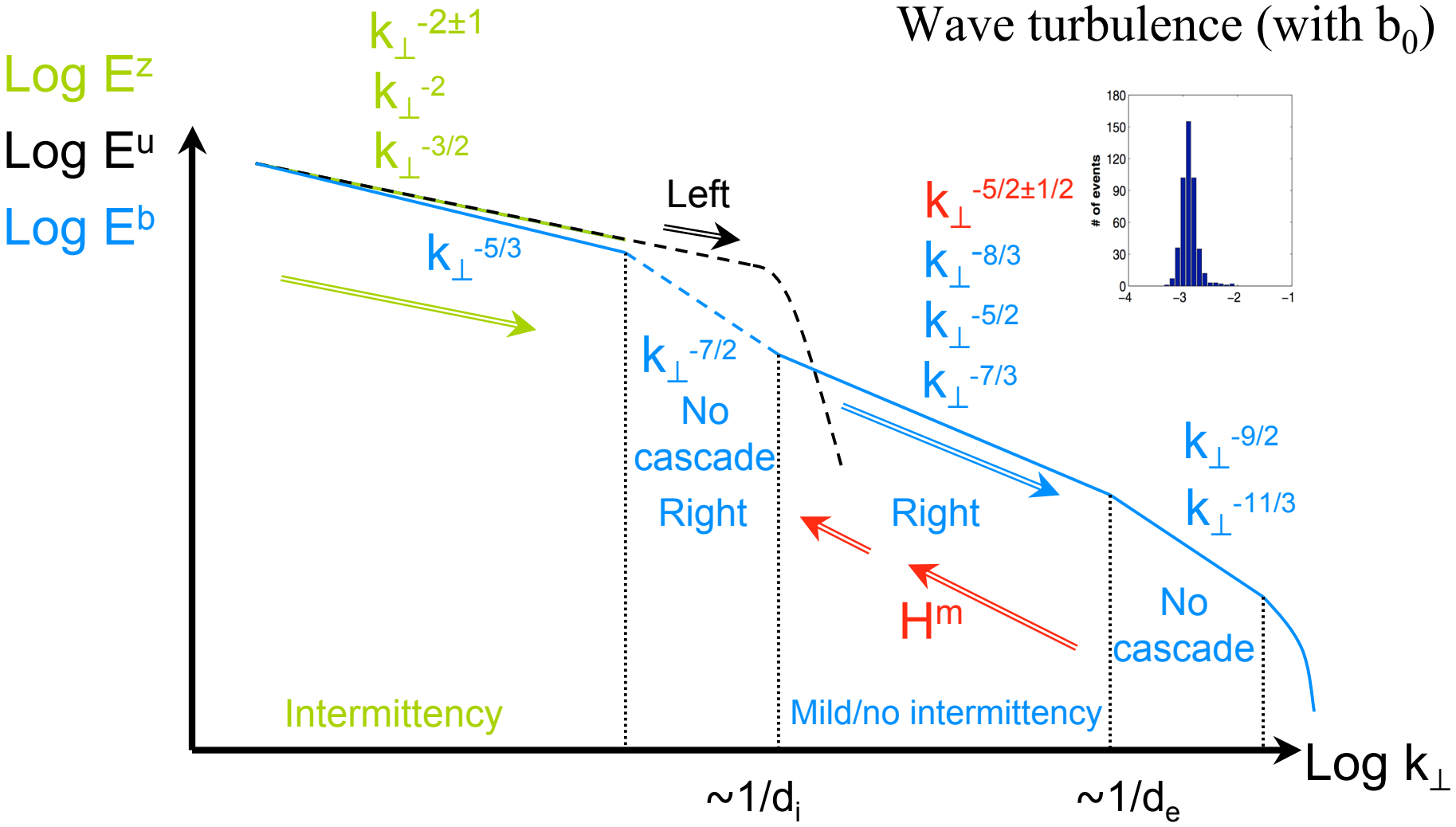


- ✓ Electron MHD (simulation, model, analytic): x=7/3; 8/3; 5/2±1/2

[Meyrand et al., PRL, 2012, 2013]

- ✓ Hall MHD (simulation): x=7/3; 5/2; 11/3

Anisotropic fluide-plasma turbulence



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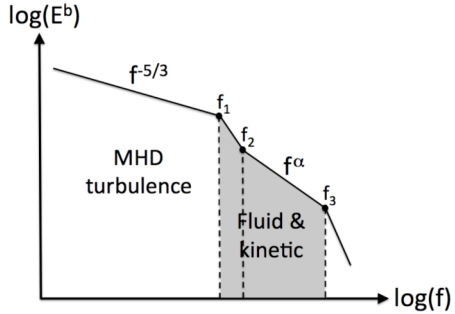

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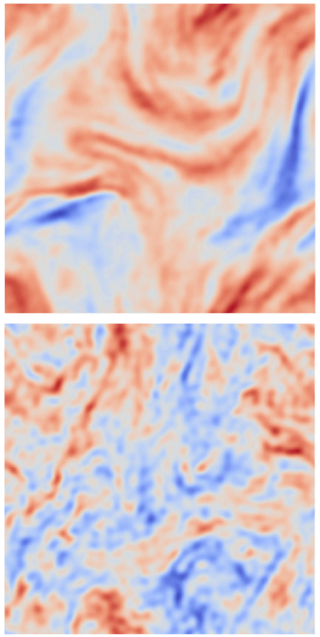
[Meyrand et al., PRL, 2012, 2013]

✓ Hall MHD (simulation): x=7/3; 5/2; 11/3

✓ Landau damping (FLR fluid simulation): x≥7/3

→ energy is not transferred conservatively along the cascade; filaments of density

[Passot et al., EPJD, 2014; Passot et al., ApJ, 2015; Sulem et al., ApJ, 2016]



✓ Gyrokinetic: dissipation over a broad range of scales

[Told et al., PRL, 2015]

✓ Theory of coherent electron-scale magnetic structures

[Jovanovic et al., PS, 2015]

Final word

✓ Very active community !

→ 36 refereed papers in 2013-2016; 228 citations

✓ 2 workshops in 2015 (60 participants)

CIAS-Meudon in May

Cargèse in September

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[© Romain Meyrand]

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…and Cargèse in 2016 :