

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



Laboratoire de Physique des Plasmas

*Colloque PNST 2016, Hendaye*

Sébastien Galtier

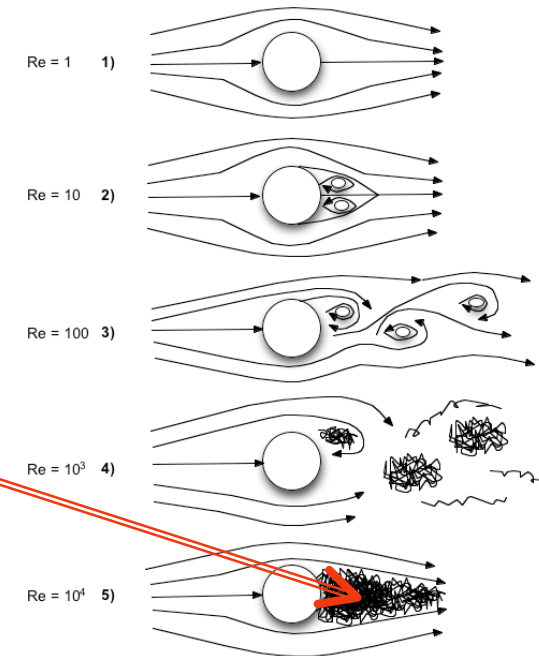
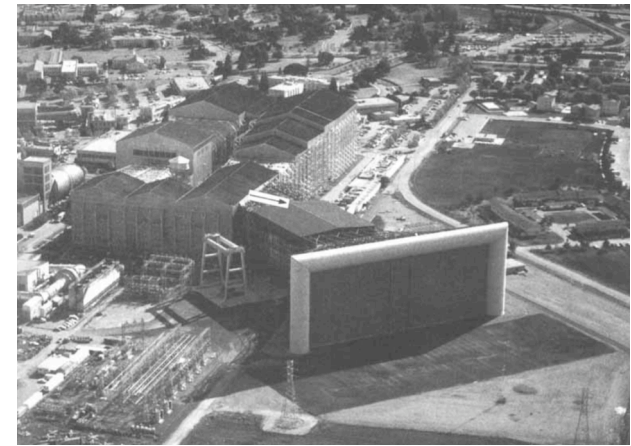
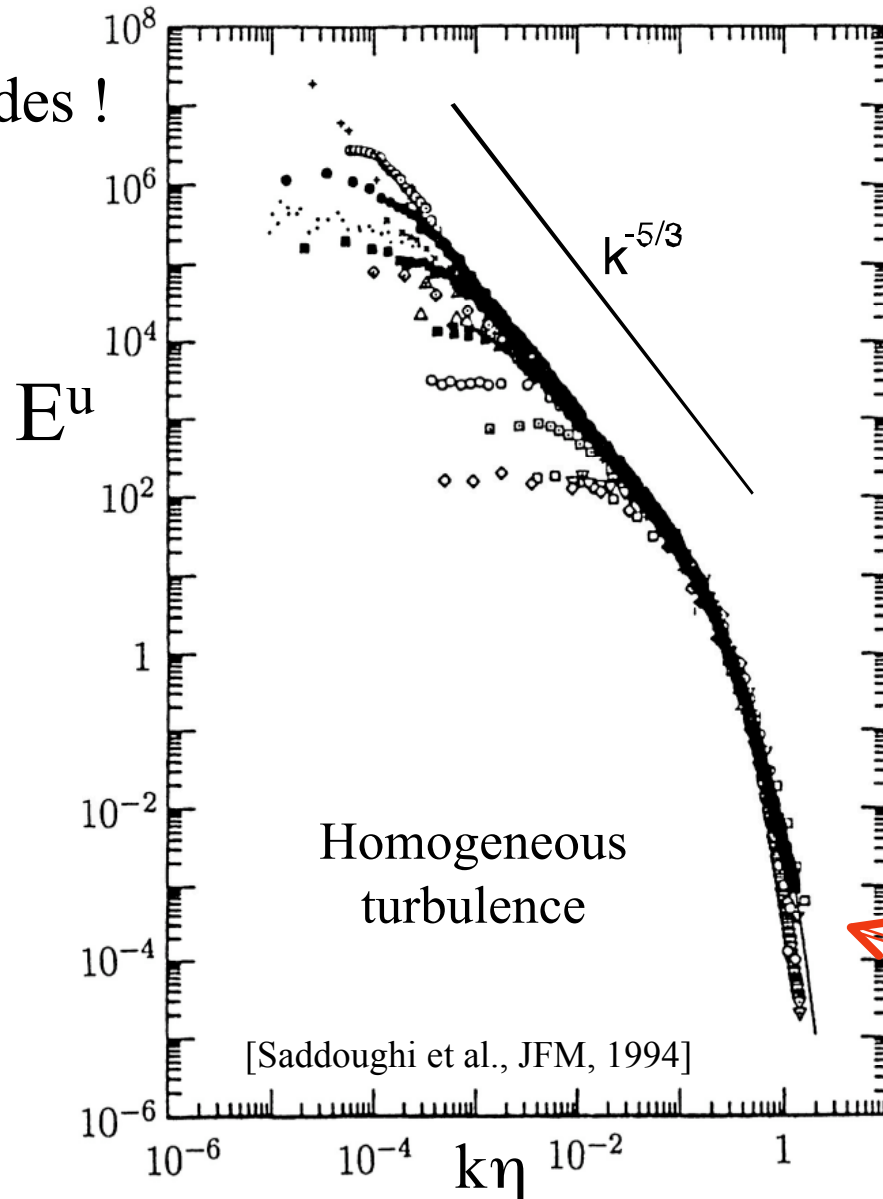
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# Vortex turbulence

Wind tunnel

3-4 decades !

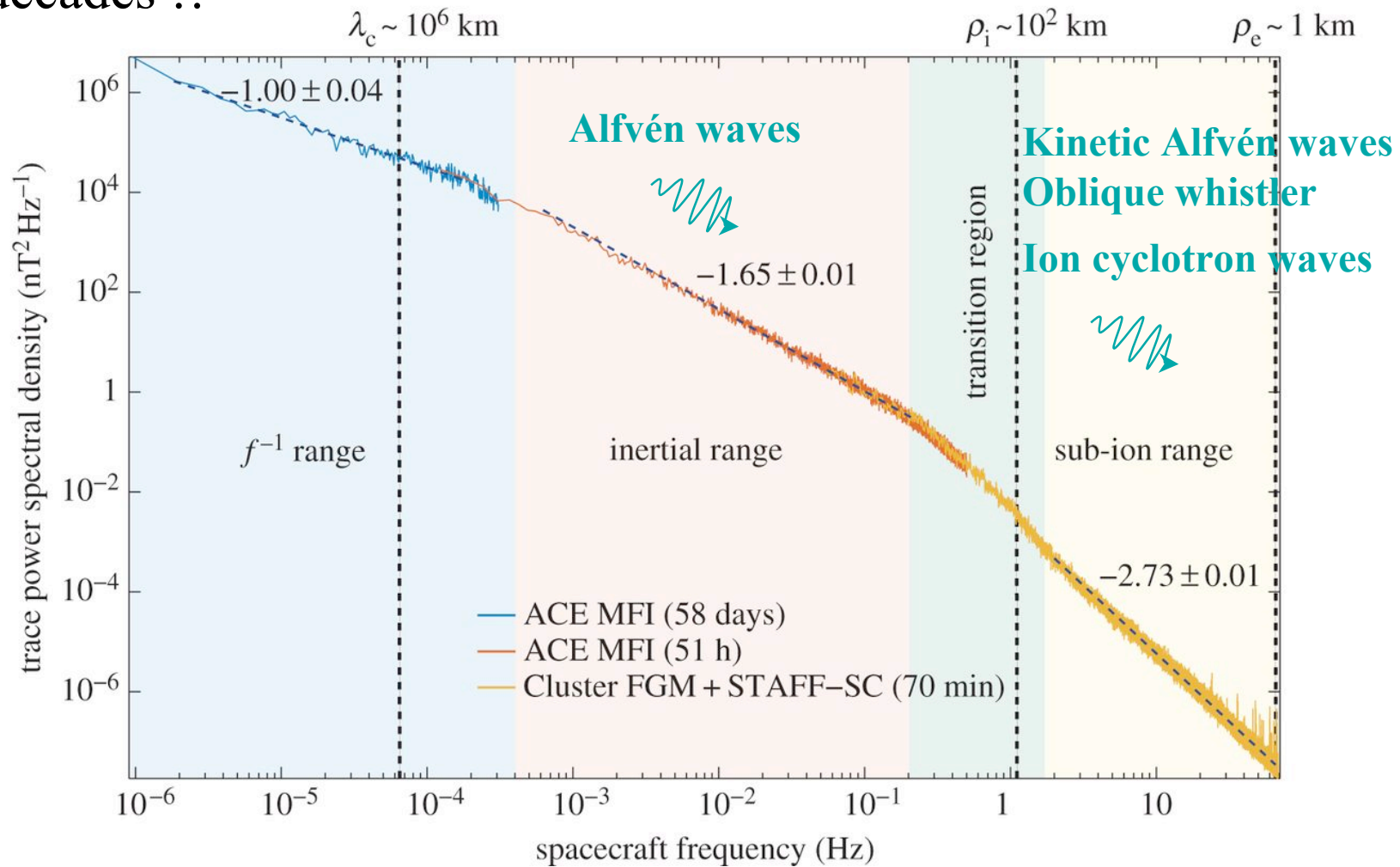


# Wave turbulence

Solar wind  
( $\sim 1$  AU)

Power laws at MHD & sub-ion scales

8 decades !!



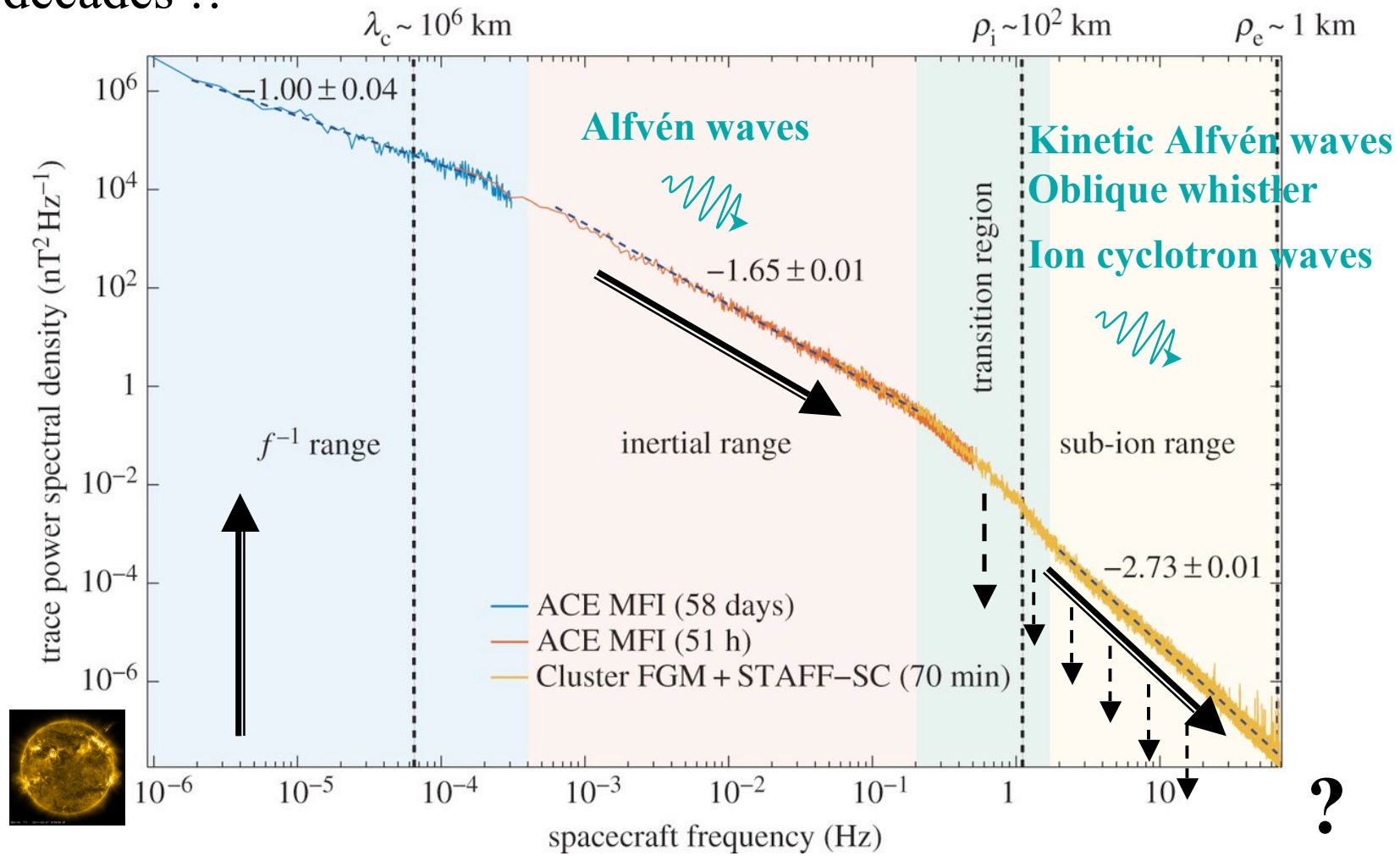
[Kiyani et al., Phil. Trans. R. Soc. A, 2015]

# Wave turbulence

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Power laws at MHD & sub-ion scales

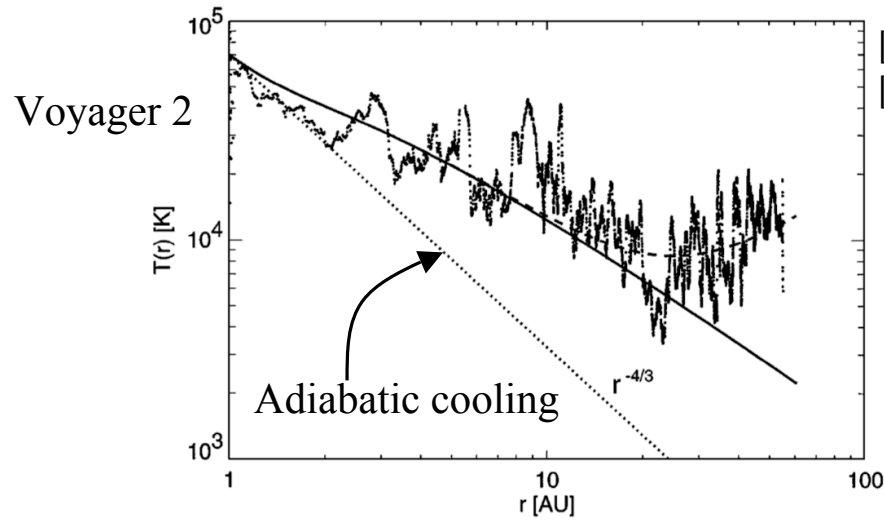
8 decades !!



[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

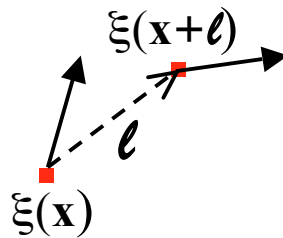
## Incompressible MHD turbulence

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

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

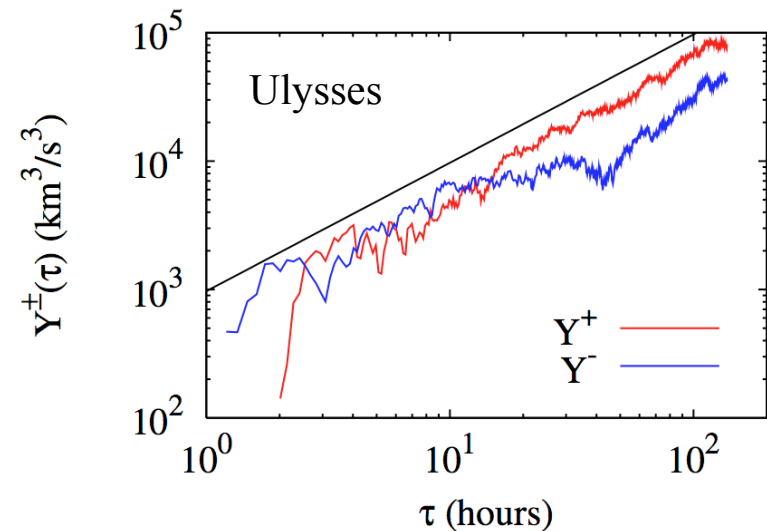
[Politano & Pouquet, PRE, 1998]

**EXACT LAW**



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

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



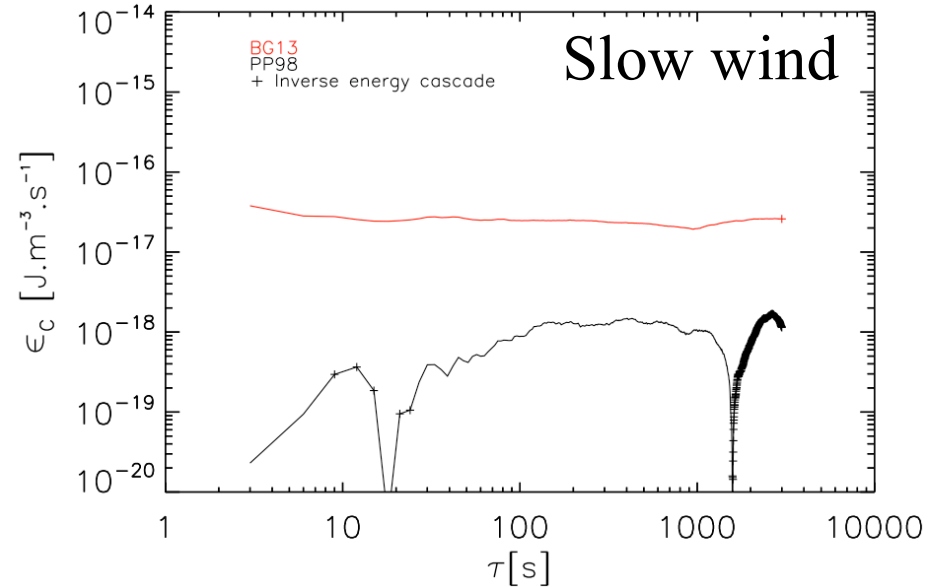
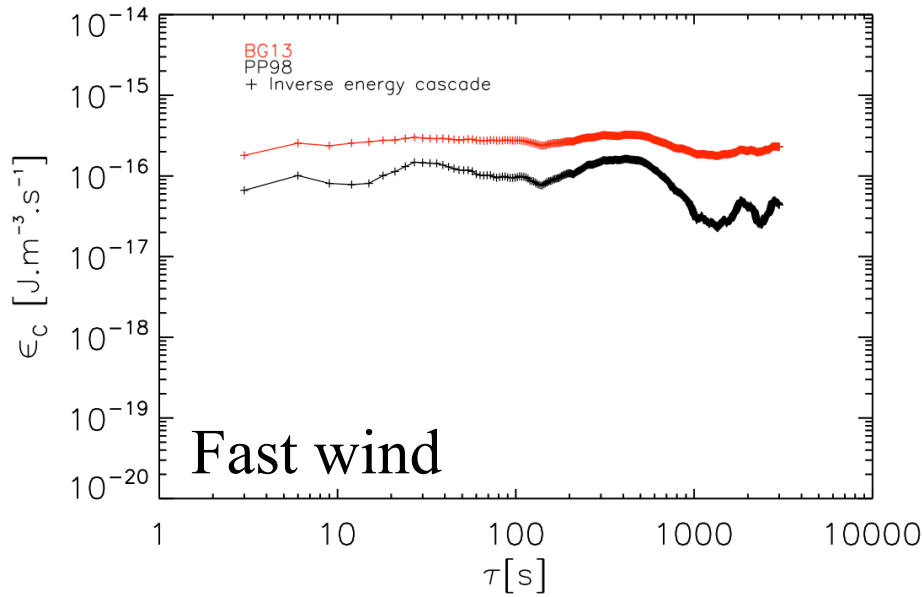
# Compressible MHD turbulence

## EXACT LAW

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

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

Not easy to explain!



[Hadid et al., 2016]

THEMIS

# Fundamental works on MHD turbulence

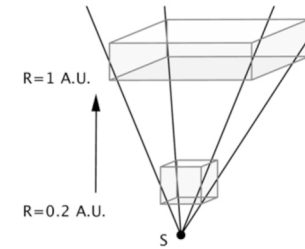
## → Numerical simulations

- ✓ Imprints of expansion of the local anisotropy (Verdini et al., poster) [Verdini & Grappin, ApJ, 2015]

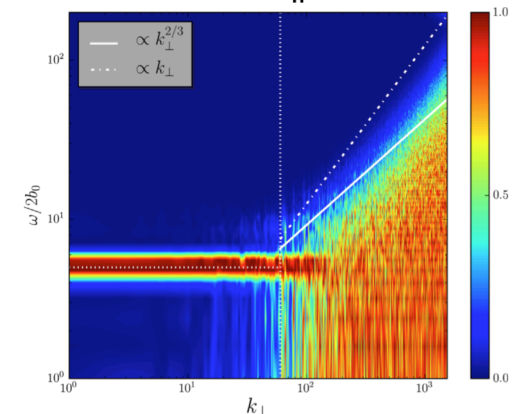
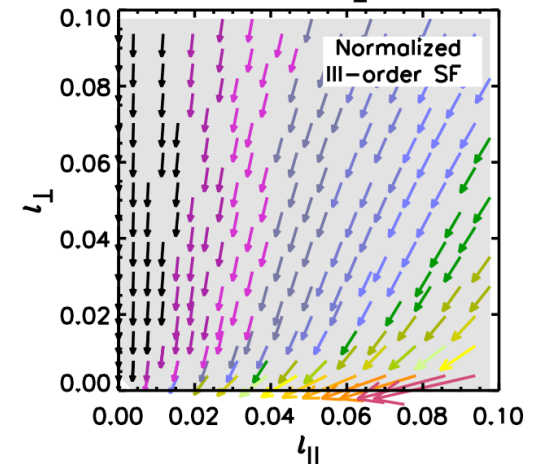
[Dong et al., ApJ, 2014]

- ✓ Anisotropy of the 3rd order structure functions in MHD turbulence [Verdini et al., ApJ, 2015]

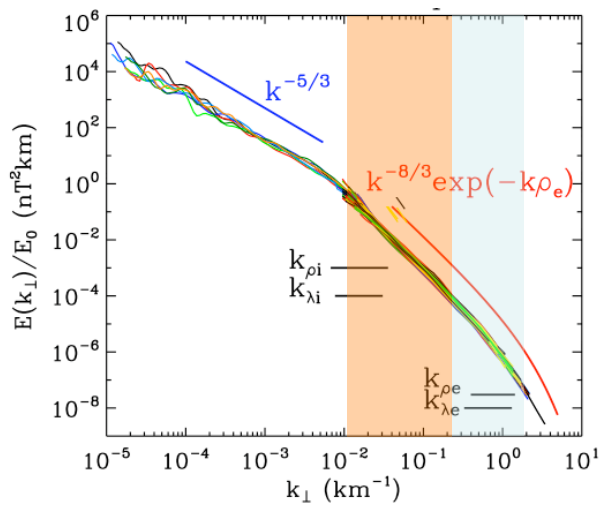
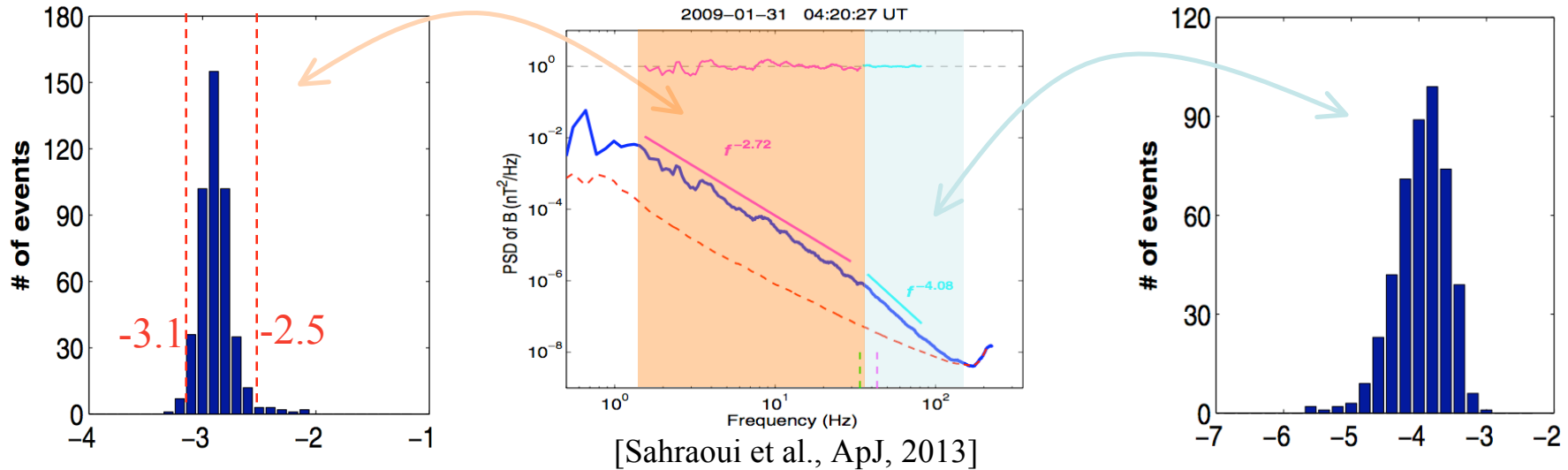
- ✓ Direct evidence of the transition from weak to strong MHD turbulence [Meyrand et al., PRL, 2016]



(a)  $-\gamma/l_{\perp 1}$



# Is there universality at sub-ion scales ?



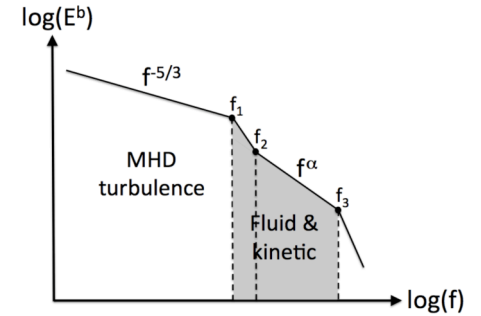
[Alexandrova et al., ApJ, 2012]



[Lacombe et al., ApJ, 2014]

# Some models

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

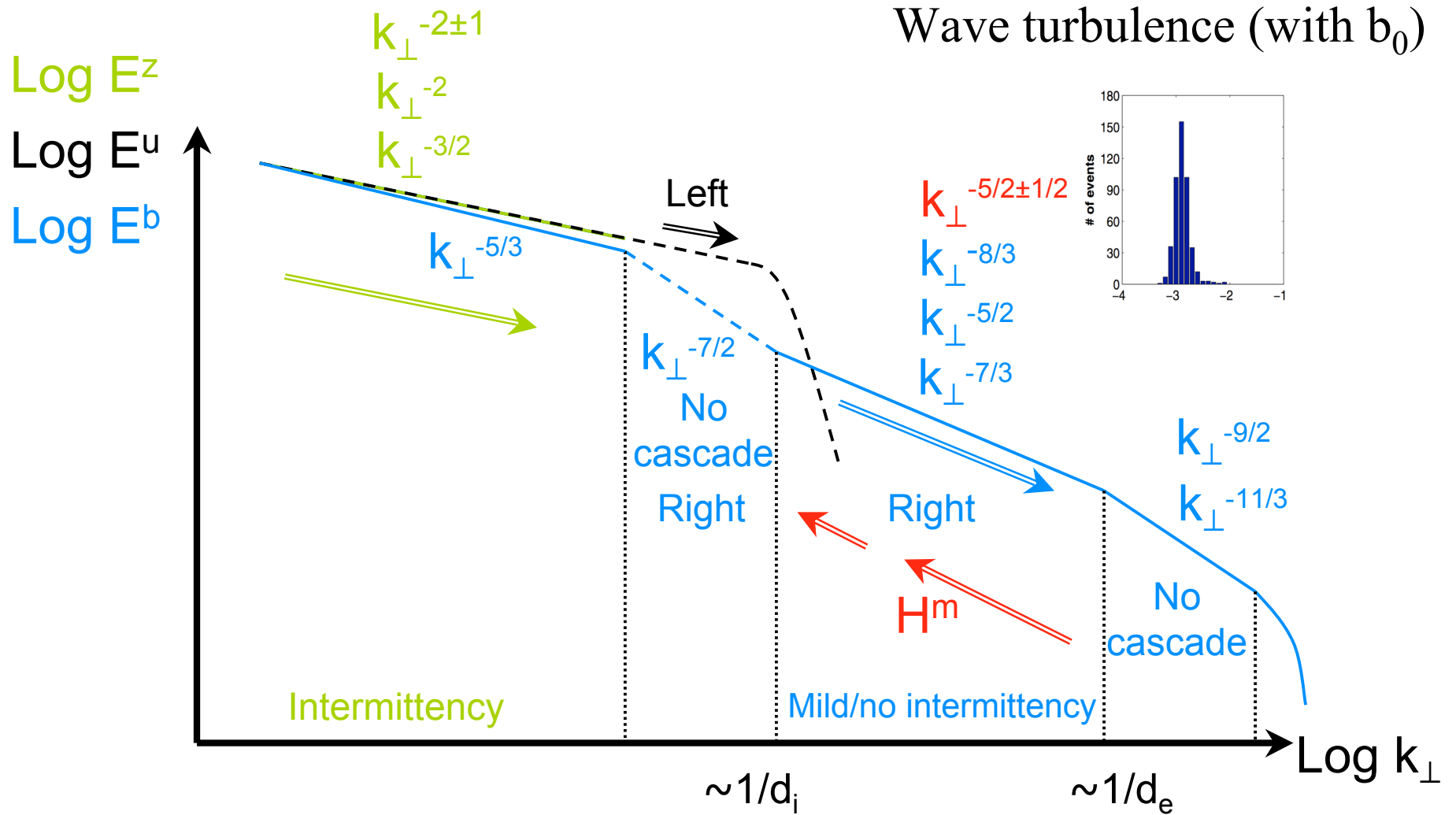


- ✓ Electron MHD (simulation, model, analytic):  $x=7/3; 8/3; 5/2 \pm 1/2$

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

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

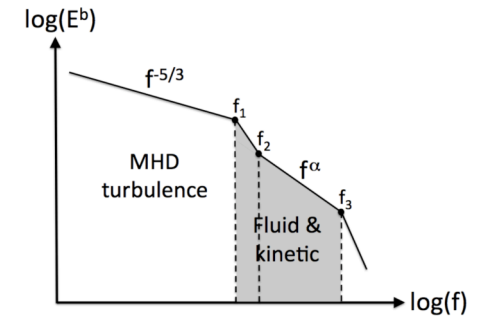
# Anisotropic fluid-plasma turbulence





# Some models

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



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

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

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

- ✓ Landau damping (FLR fluid simulation):  $x \geq 7/3$   
→ energy is not transferred **conservatively** along the cascade; **filaments** of density

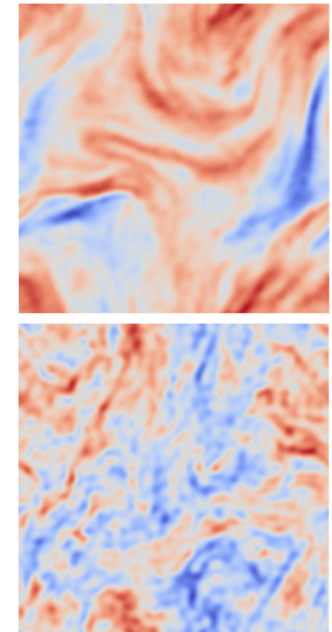
[Passot et al., EPJD, 2014; Passot et al., ApJ, 2015; Sulem et al., ApJ, 2016]

- ✓ 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*



[© Romain Meyrand]

- ✓ Very active community !
  - 36 refereed papers in 2013-2016; 228 citations
- ✓ 2 workshops in 2015 (60 participants)
  - CIAS-Meudon in May
  - Cargèse in September



# Final word



✓ Very active community !

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...and Cargèse in 2016 :

[© Romain Meyrand]

**INSTITUT D'ETUDES SCIENTIFIQUES DE CARGÈSE**  
Cargèse International School 2016

**Advances in Geophysical and Astrophysical Turbulence**  
July 25 - August 5, 2016

**Web site**

**Sébastien GALTIER**  
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**Hélène POLITANO**  
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**Yannick PONTY**  
Obs. Côte d'Azur, Nice, France  
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**Main topics include:**

- \* MHD Turbulence
- \* High-Performance Computing (HPC)
- \* Stratified Turbulence
- \* Magnetic Reconnection
- \* Electron MHD Lagrangian
- \* Magnetic Field Generation and Turbulent
- \* Modeling Turbulent Flows
- \* Rotating Turbulence
- \* Vertical Transport and Mixing

- \* Helicity and Topology
- \* Space Plasmas
- \* Waves and Intermittency
- \* Landau Fluids
- \* Lagrangian Tracers
- \* Dynamo
- \* Multi-scale Interactions
- \* Generation Waves and Eddies
- \* Zonal Flows

**Eminent scientists in the field will animate the workshop. These include:**  
Olga Alexandrova (LESIA, Paris FR), Jérémie Bec (Lagrange, OCA Nice FR), Marc E. Brachet (LPS, ENS Paris FR), François Daviaud (CEA, Saclay, FR), Bérengère Dubrion (CEA, Saclay, FR), Edm. Falgarone (LERMA, ENS Paris FR), Sébastien Galtier (LPP Paris FR), Pablo Mininni (Univ. Buenos Aires, AR), Sergey Nazarenko (Univ. Warwick UK), Caroline Koen (LJMU, Paris 11 FR), Hélène Politano (LJAD, Univ. Nice- Sophia, FR), Thierry Passot (Lagrange, OCA Nice FR), Jean-François Pinton (LPP, ENS Lyon FR), Anick Pouquet (UCAR, Boulder US), Leslie M. Smith (Univ. Wisconsin Madison, US)

**Organization Committee**  
Sébastien Galtier (LLP, Paris FR), Hélène Politano (Univ. Côte d'Azur (UCA) Nice, FR), Yannick Ponty (Univ. Côte d'Azur UCA Nice FR)

**Application and registration**  
<http://www.oca.eu/ags2016>  
Contact : yannick.ponty@oca.eu  
Deadline Registration : 2016, April 30th  
Registration Fees : 650 € - 850 €