Semaine de l'Astrophysique Française

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Turbulence dans les plasmas héliosphériques (PNST)

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Turbulence: non resolved problem in classical mechanics

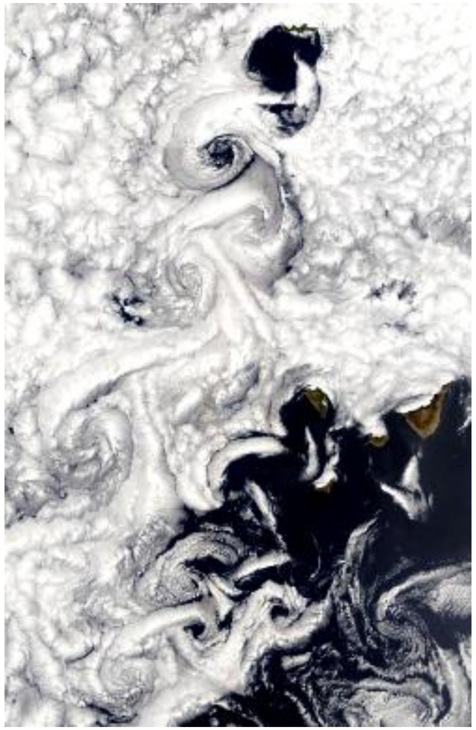
An external source of energy produces in the fluid all types of eddies at all scales…

[Leonardo da Vinci, 1452-1519]

Turbulent fluid is a fluid which (apparently) rebels against deterministic rules imposed by classical mechanics …

Turbulence is omnipresent

- Atmospheric flows
- Biological fluids
- Industrial flows
- Astrophysical flows
- …



Why does turbulence develop ?

"Navier-Stokes equation probably contains all of turbulence"
(Uriel Frisch, 1995)

ν → kinematic viscosity

$$\frac{\partial u}{\partial t} + (u.\nabla)u = -\nabla p + \nu \Delta u$$

non-linear term   dissipation

Non-linear term >> term of dissipation ⇒ Turbulence

Why does turbulence develop ?

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$\nu \rightarrow$ kinematic viscosity

$$\frac{\partial u}{\partial t} + (u.\nabla)u = -\nabla p + \nu \Delta u$$

non-linear term dissipation

Non-linear term >> term of dissipation ⇒ Turbulence

If the energy injection scale $L > L_d$ - scale of dissipation (~m.f.p.), turbulence develops !

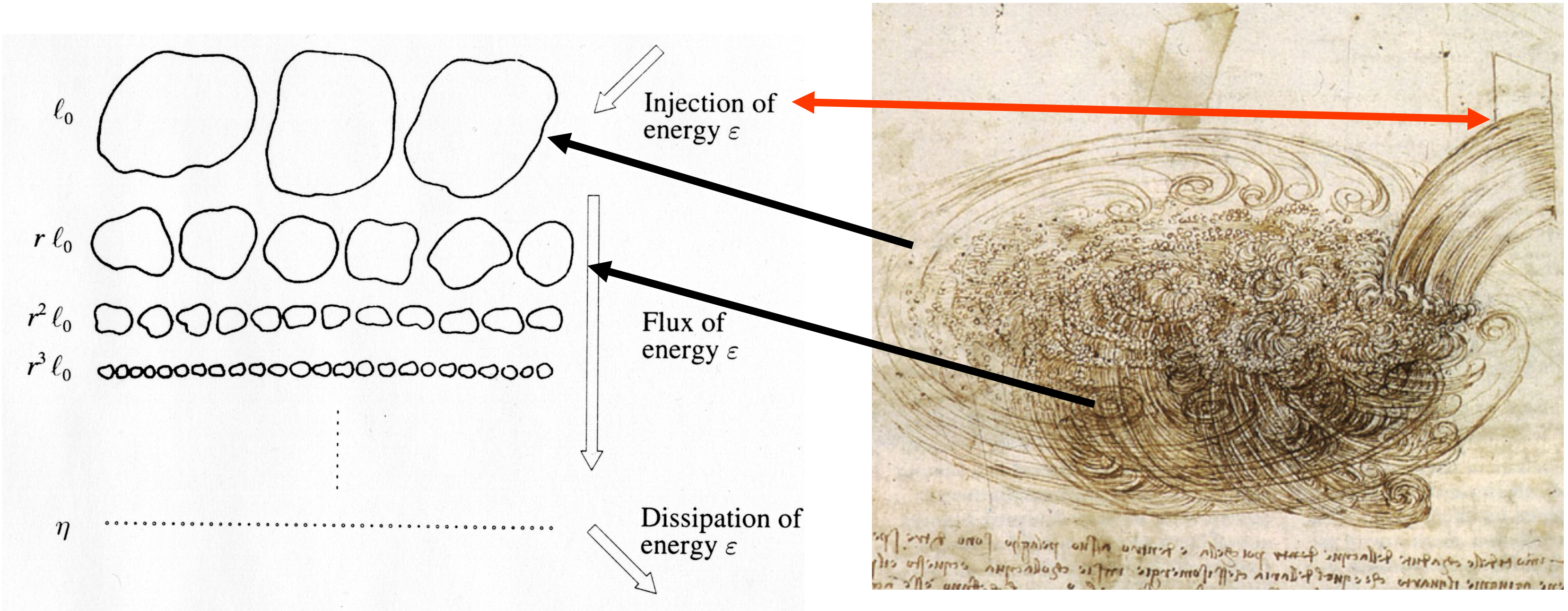
Reynolds number
[1883]

$$R = \left.\frac{(u.\nabla)u}{\nu \Delta u}\right|_{\text{At largest scale L}}$$

$$\boxed{R = \frac{UL}{\upsilon}}$$

How does this happen?

$$\frac{\partial u}{\partial t} + (u.\nabla)u = -\nabla p + \nu \Delta u$$



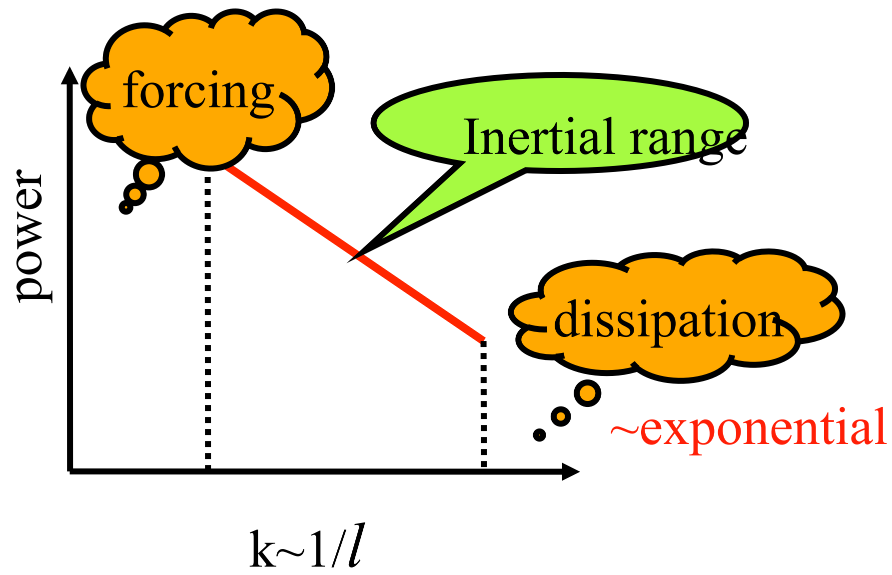
Since dissipation is efficient only at very small scales, there is an energy transfer to small scales:

nonlinear energy cascade

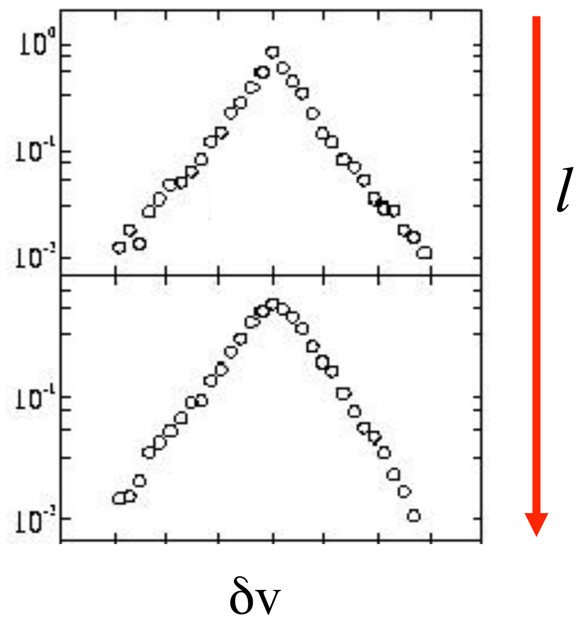
Turbulence

Locally unpredictable, but **statistical properties are predictable and universal**

1) velocity field energy~$k^{-5/3}$ (scale invariance, same physics at all scales l) [Kolmogorov'41]

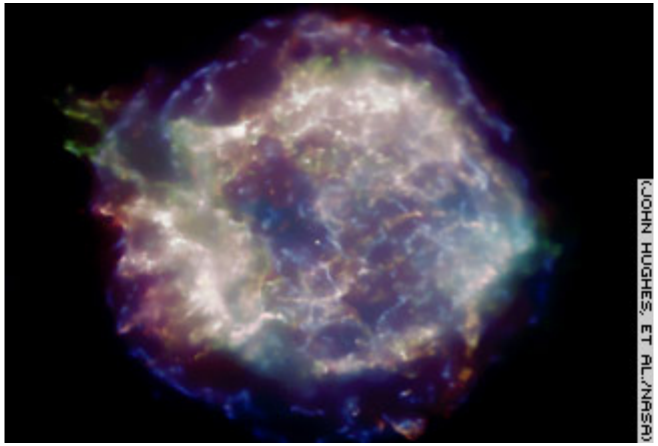


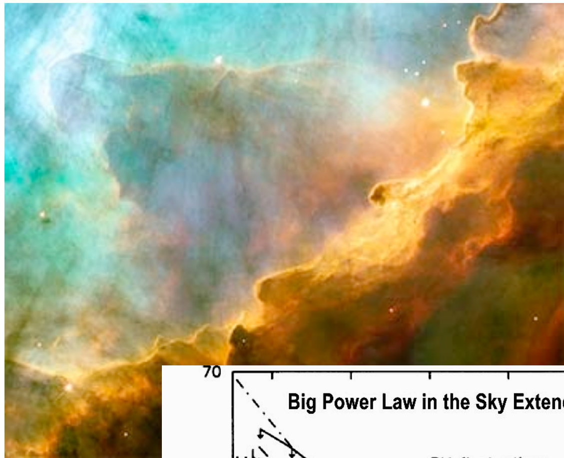
2) intermittency : deviation from the Gaussianity at small l



The Kolmogorov spectrum can be observed almost in all turbulent flows.

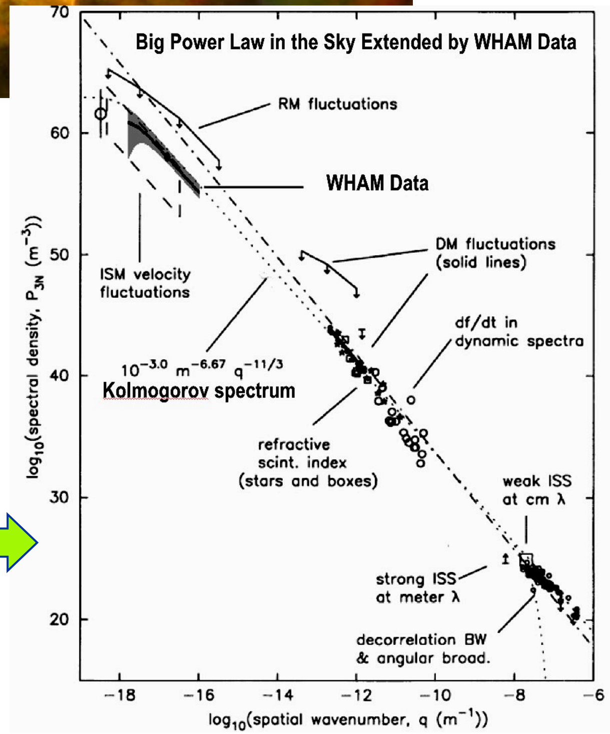
Astrophysical plasmas are generally turbulent





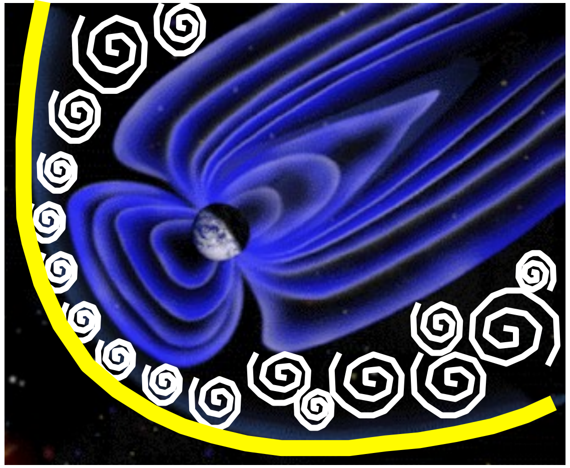
- Super Novae Remnants
- Interstellar medium
- Stellar winds
- Planetary magnetospheres…

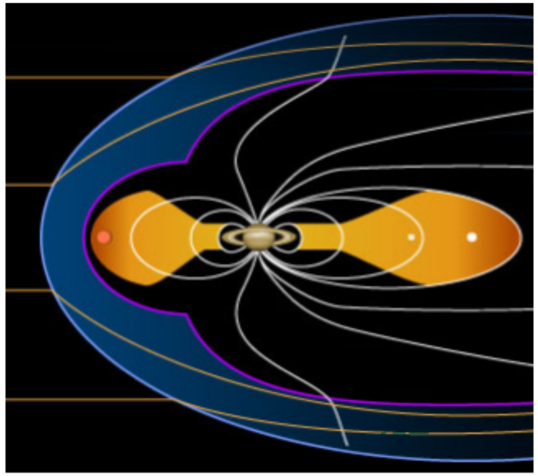
Turbulence in the interstellar gas as revealed by electron density fluctuations [Armstrong et al. 1995, Lazarian et al., 2012]

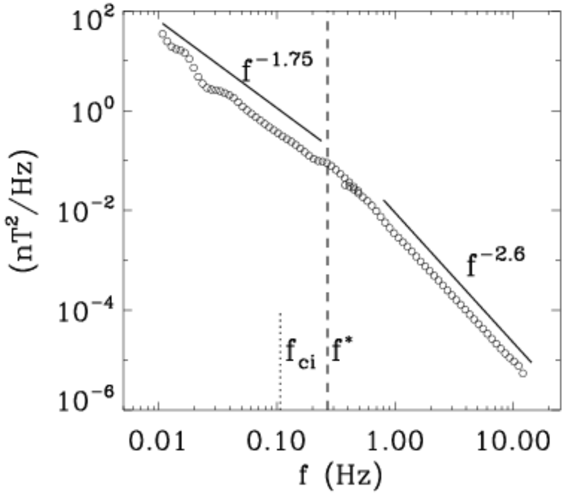


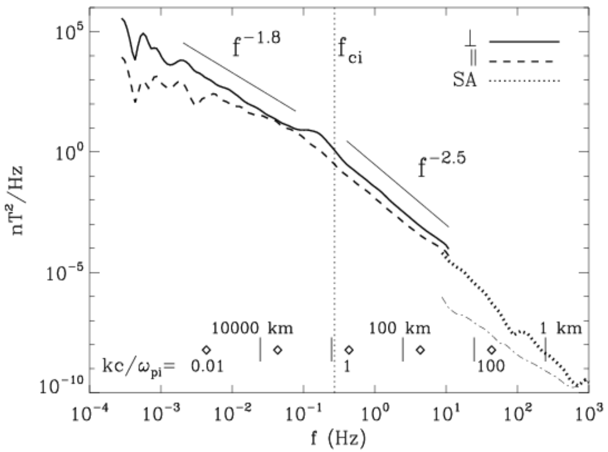
Plasma Turbulence in the Heliosphere

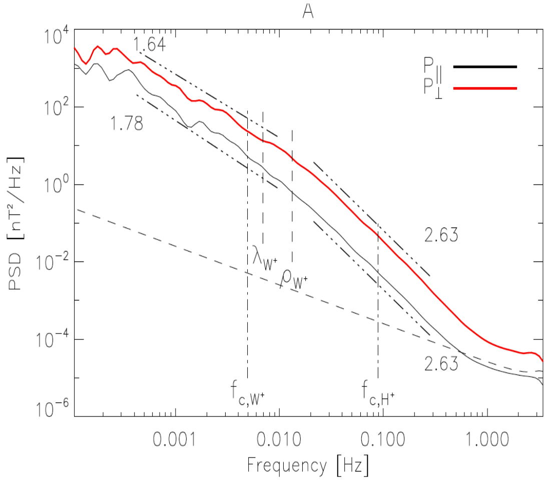
In situ measurements in the solar wind and planetary magnetospheres show omnipresence of plasma turbulence.





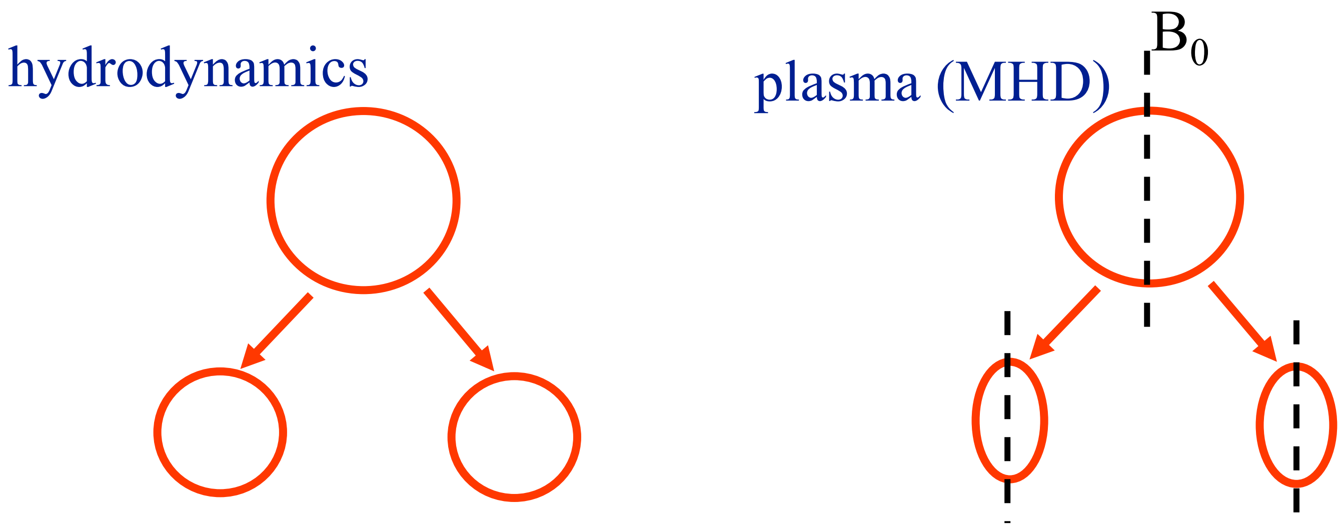






[Alexandrova et al. 2008, Von Papen et al. 2014]

Turbulence in space plasmas

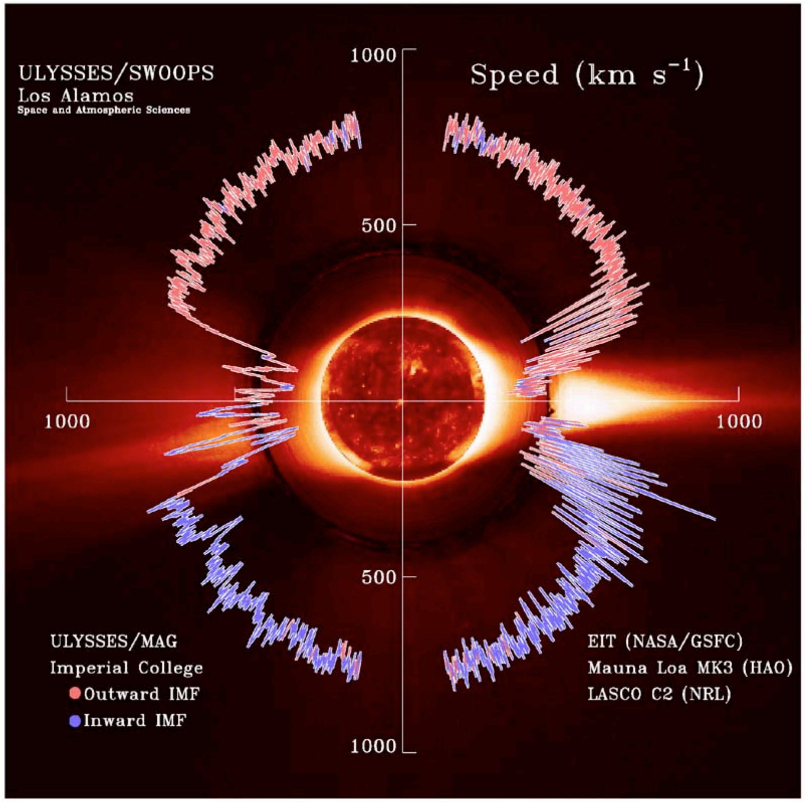


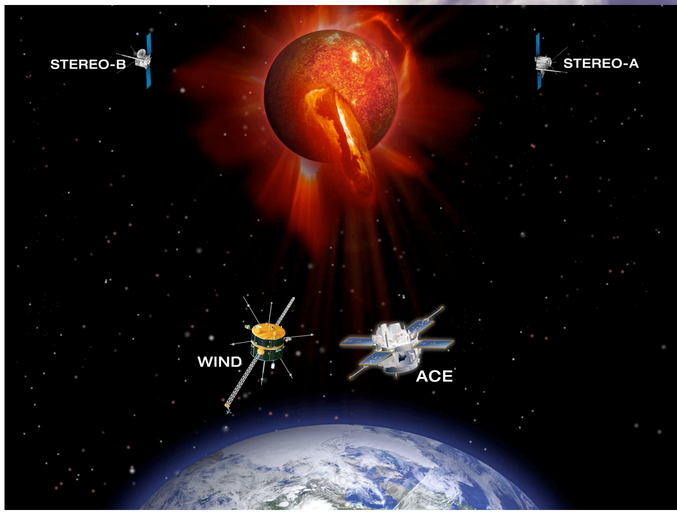
1. Presence of a mean magnetic field B_0 leads to an anisotropy of turbulent fluctuations
2. Plasma waves: Alfven, magnetosonic, mirror, wistlers, kinetic Alfven waves (KAW), etc… (wave turbulence)
3. No collisions : m.f.p. ~ 1 AU
4. In plasmas there is a number of characteristic space and temporal scales

$$f_{ci}, c/\omega_{pi}, R_{Li} \qquad f_{ce}, c/\omega_{pe}, R_{Le} \qquad \lambda_D$$

The solar wind

one of the best and the closest laboratory for astrophysical plasma turbulence.



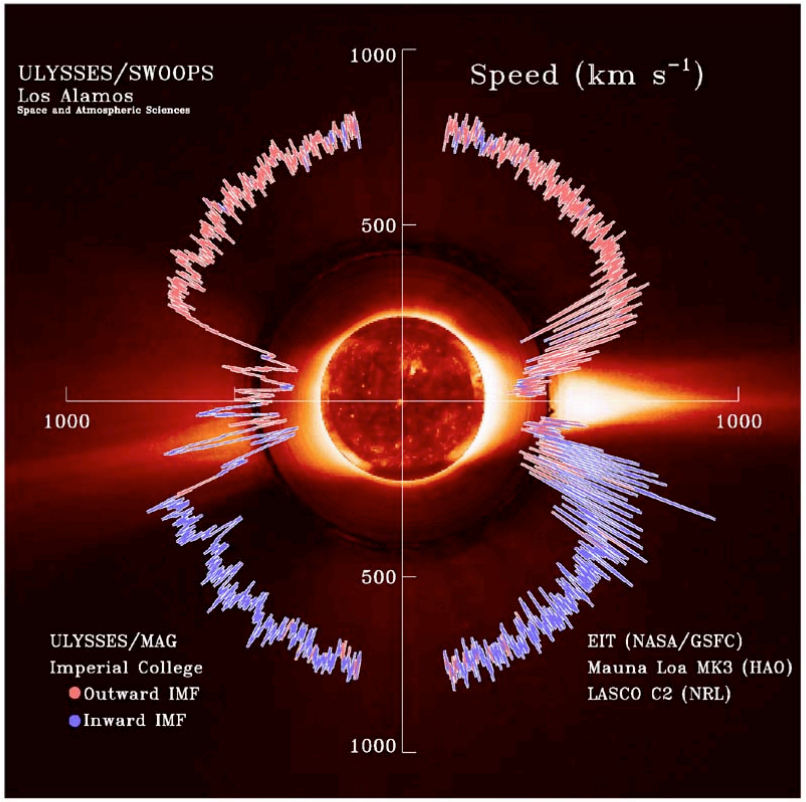


Two components, Slow and Fast streams.

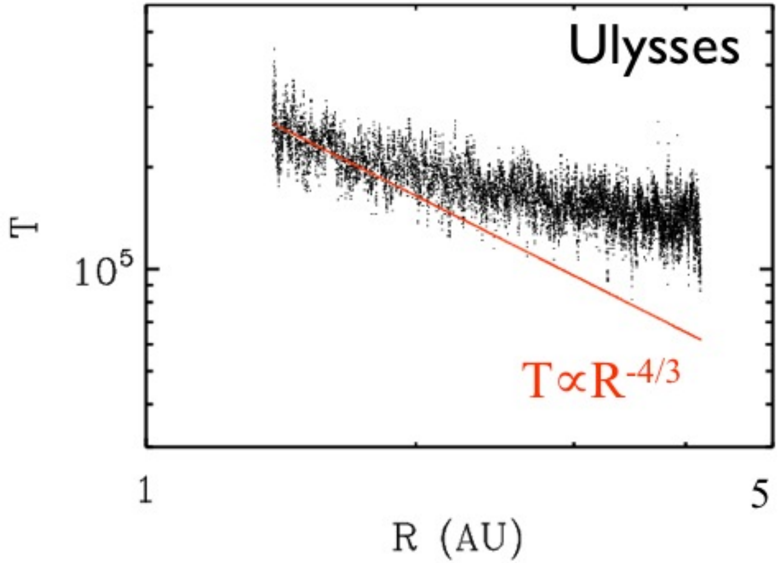
Slow wind: V = 300-400 km/s, n=7 cm-3, Tp=2.10^{5}K

Fast wind: V = 600-800 km/s, n=3 cm-3, Tp=5.10^{5}K

The solar wind



[Image credit: Lorenzo Matteini]

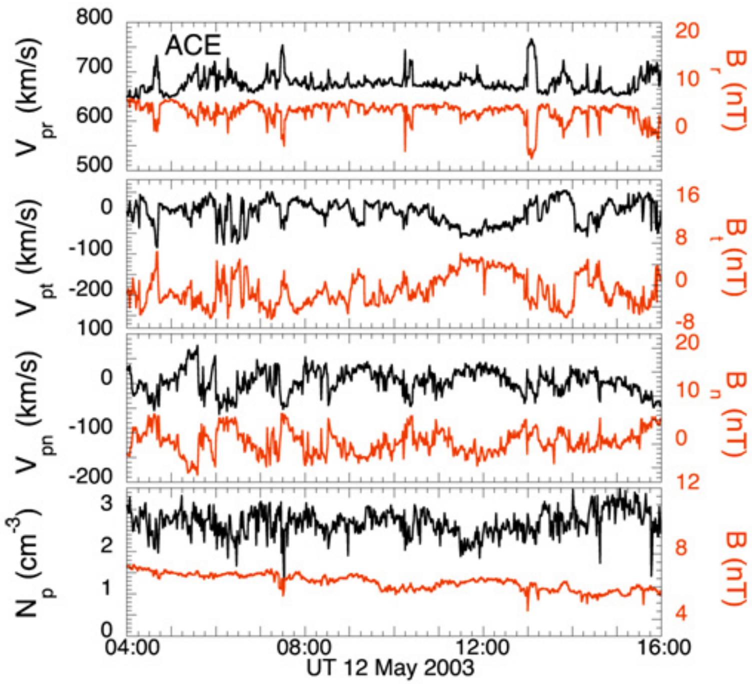


Wind temperature decays less than adiabatic (~$R^{-4/3}$)

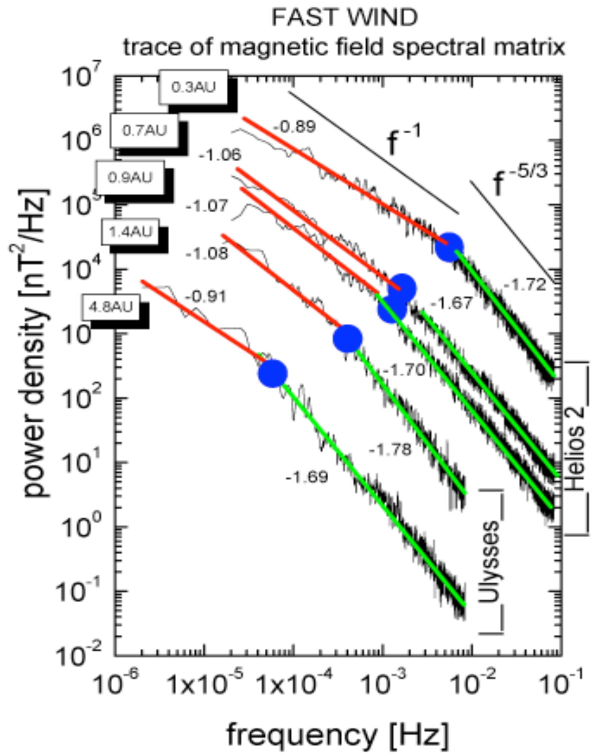
Turbulence dissipation may explain the solar wind heating [e.g. Vasquez et al. 2007; Sorriso-Valvo et al. 2007; Macbride et al. 2008; Smith et al. 2009; Cranmer et al. 2009; Marino et al. 2012; Wu et al. 2013, …]

Solar wind Turbulence and Alfven waves

[Gosling et al., 2009; Balcher & Davis 1977]

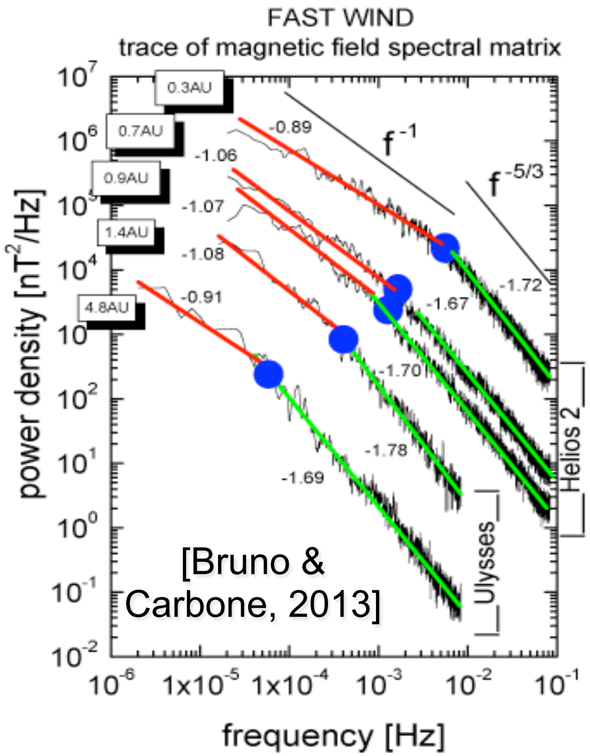


[Bruno & Carbone, 2013]



- Strong correation between V and B fluctuations at 1 AU (Alfven waves)
- These waves belongs to f^{-1} spectral range.
- Kolmogorov turbulence at smaller scales (MHD) is observed.

Starting point of the Kolmogorov spectrum

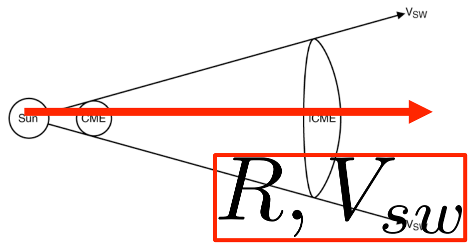


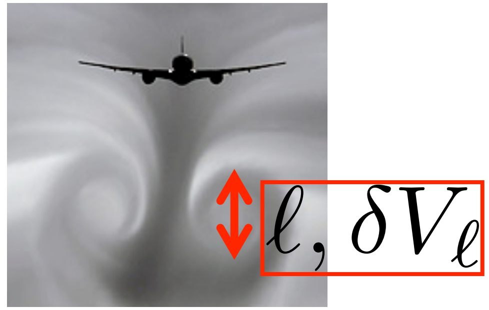
- The solar wind expansion time:

$$\tau_{exp} = R/V_{sw}$$

- The eddy-turnover time:

$$\tau_{NL} = \ell/\delta V_\ell$$

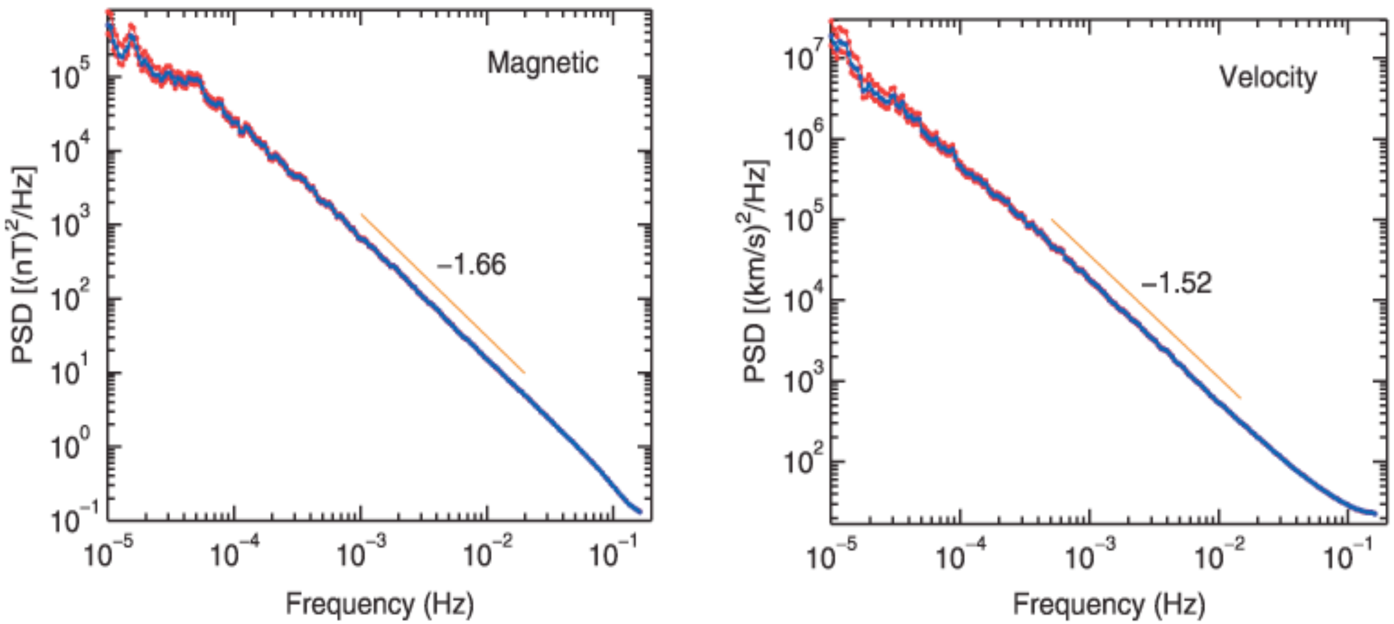




- Transition between f^{-1} and f$^{-5/3}$ spectrum corresponds to a scale where these 2 characteristic times are of the same order [Mangeney et al. 1991; Meyer-Vernet 2007]: $\tau_{exp} \simeq \tau_{NL}$

Solar wind Turbulence and Alfven waves

In a case of a pure alfvenic turbulence magnetic and velocity spectra should be the same, but in the solar wind it is not the case:



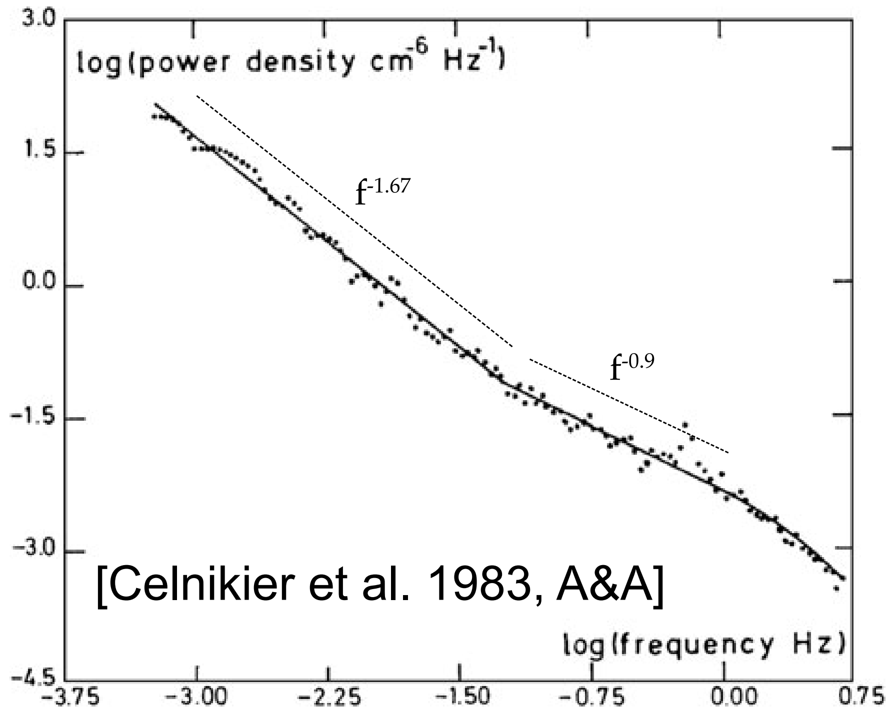
[Podesta et al., 2007; Salem 2000]

Why?

- Local dynamo process (Grappin et al., 1983) ?
- Solar wind expansion ?
- Compressibility ?

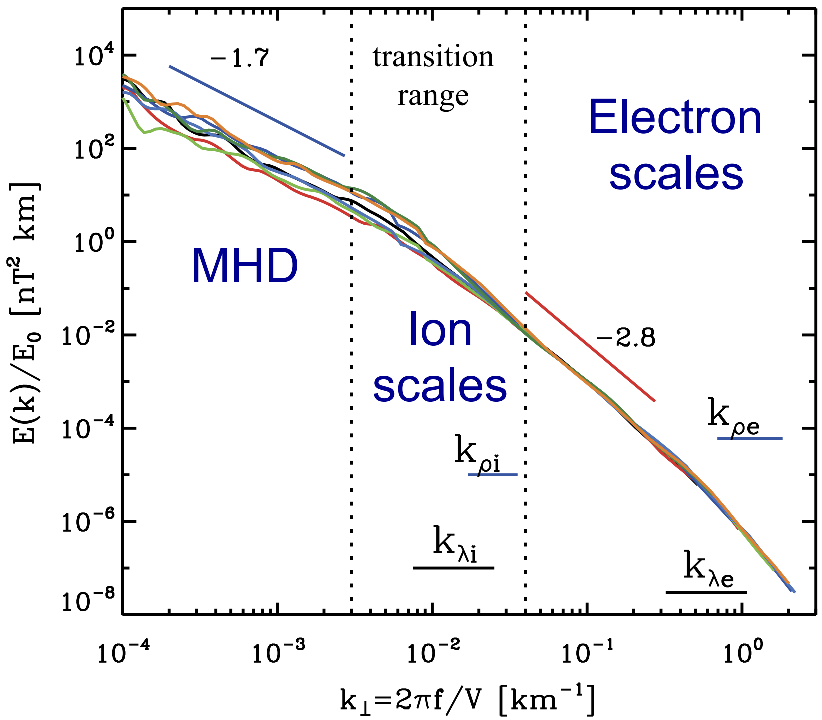
Solar wind turbulence is compressible

Spectrum of electron density fluctuations in the solar wind as measured by ISEE 1 & 2. See as well Chen et al. 2013.



Can the compressibility be the source of the non-alfvenisity of the inertial range in the solar wind turbulence?

Solar wind turbulent spectrum of magnetic fluctuations at MHD-Ion-Electron scales



[Alexandrova, Chen, Sorriso-Valvo, Bale, Horbury, 2013 Space Science Rev.]

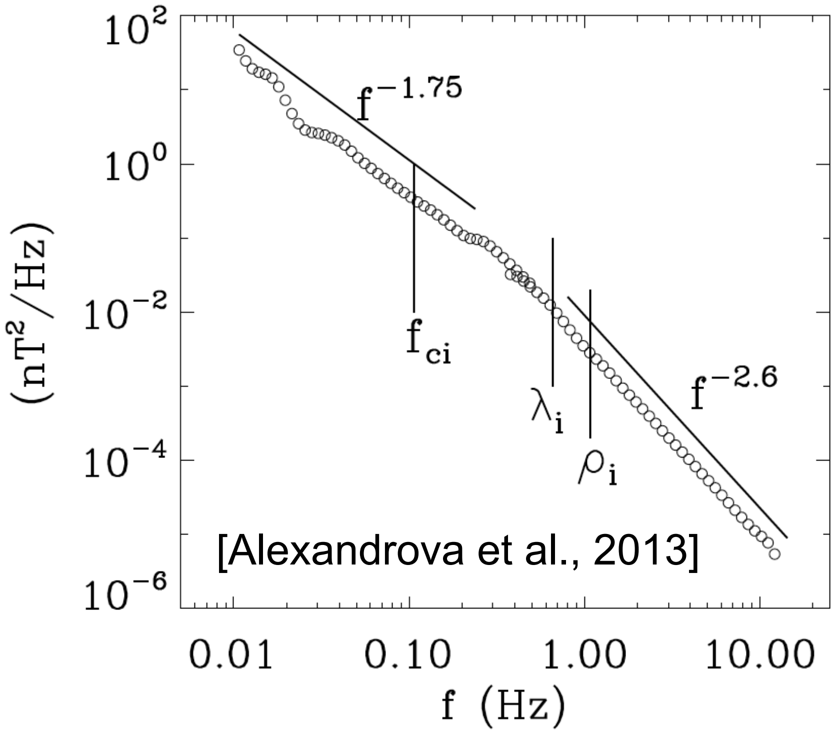
1. What is going on close to ion and electron scales?
2. Which plasma scale is responsible for the ion break?
3. Which plasma scale plays the role of the dissipation scale?
4. Physical mechanisms?
5. Nature of turbulent fluctuations : waves or strong turbulence?
6. …

Turbulence at kinetic scales

1. Ion scales

$$f_{ci} = \frac{eB_0}{2\pi m_i c}, \;\; k\rho_i \sim 1, \;\; kc/\omega_{pi} \sim 1$$

Which ion scale is responsible for the break?



Time scale

$$f_{ci} = \Omega_{ci}/2\pi \; ; \; \Omega_{ci} = eB/m_i c$$

Spatial scales

$$\rho_i = \frac{V_{\perp i}}{\Omega_{ci}} \; ; \; \lambda_i = \frac{c}{\omega_{pi}} = \frac{V_A}{\Omega_{ci}}$$

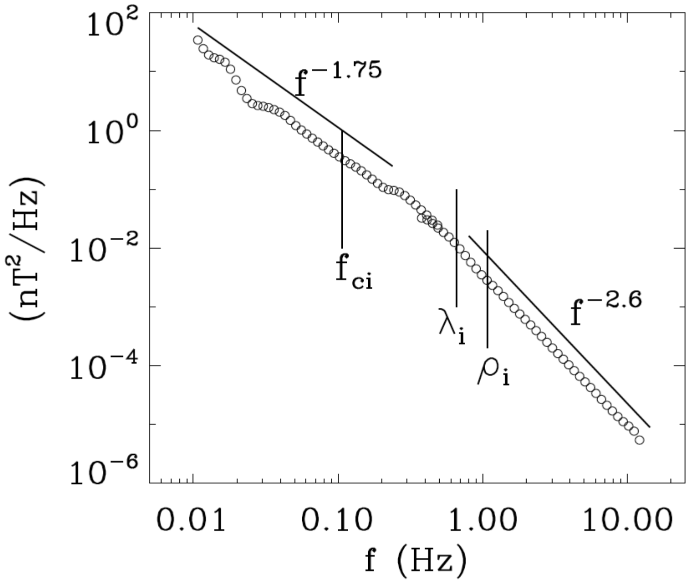
In frequency spectrum, these scales appear at Doppler shifted frequencies:

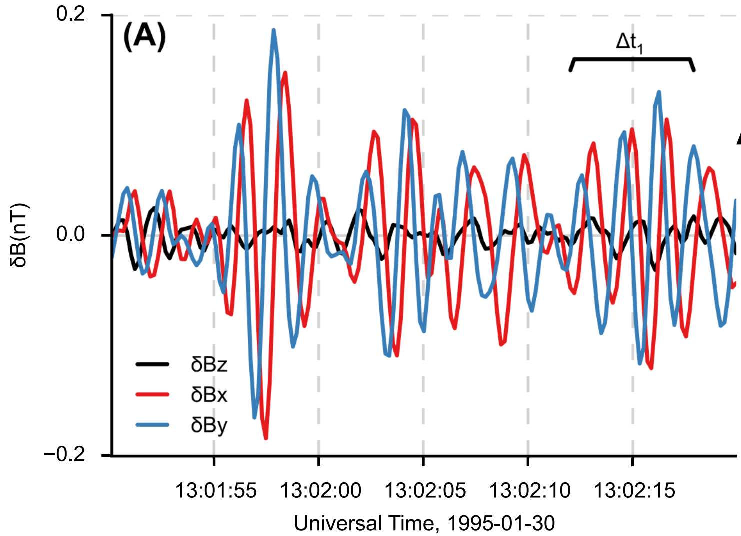
$$f_{\rho_i} \simeq \frac{V_{solar\ wind}}{\rho_i} \; ; \; f_{\lambda_i} \simeq \frac{V_{solar\ wind}}{\lambda_i}$$

- All characteristic time and spatial ion scales are observed close to the spectral break point…
- How can we distinguish between different scales?
- Important in order to understand which physical mechanisms “break the spectrum” (e.g., if it is f_{ci} => damping of Alfven waves).
- Plasma beta dependent [Chen et al. 2014]

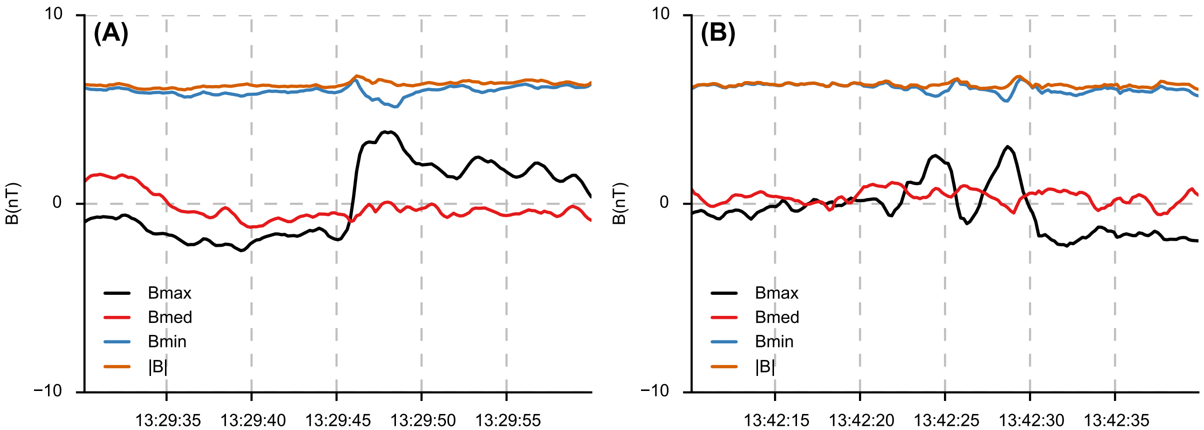
$$\boxed{\beta_i = 2\mu_0 n k_B T_i / B^2 = \rho_i^2/\lambda_i^2.}$$

Ion scales: superposition of different phenomena

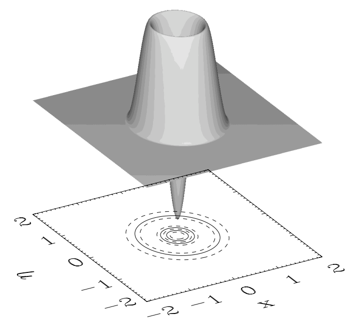




Monochromatic Alfven waves at freq~f_{ci}



Localized spatial structures at scale ~ ion Larmor Radius

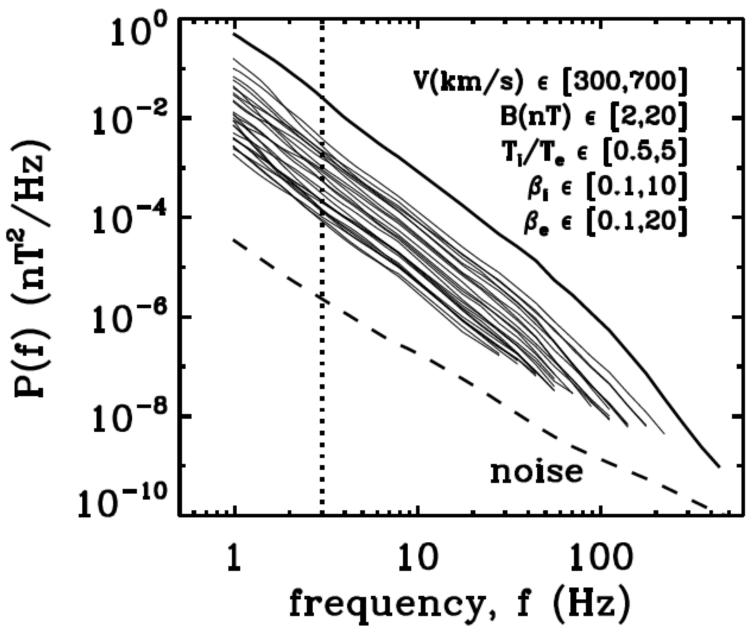


[Lion et al, 2015, to be submitted]

Turbulence at kinetic scales

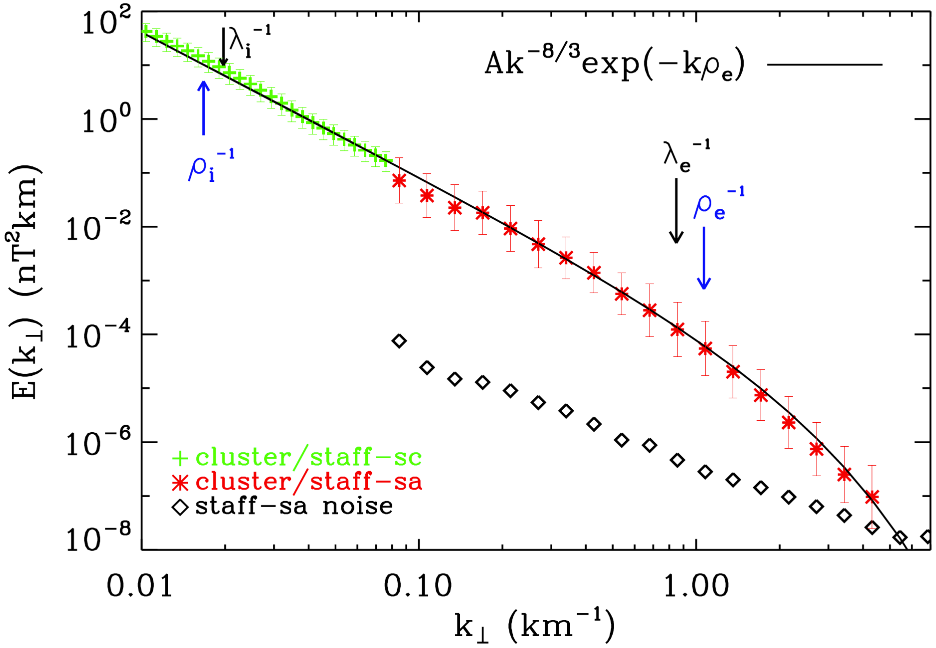
2. Electron scales

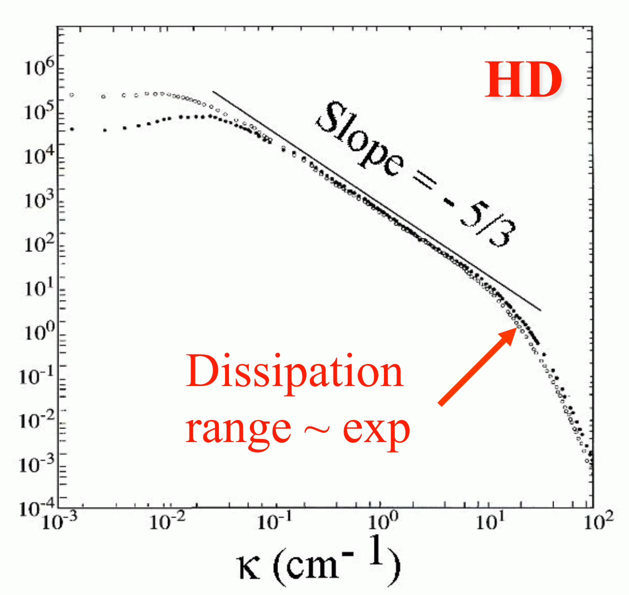
Cluster mission : the most sensitive instrumentation (magnetic spectrum up to 400 Hz).



Turbulent spectrum at electron scales: dissipation range?!

[Alexandrova et al., 2012, APJ]





- In HD turbulence, dissipation range can be described by [Chen et al., 1993, PRL] :

$$\boxed{E(k) = Ak^{-\alpha}\exp(-k/k_d)}$$

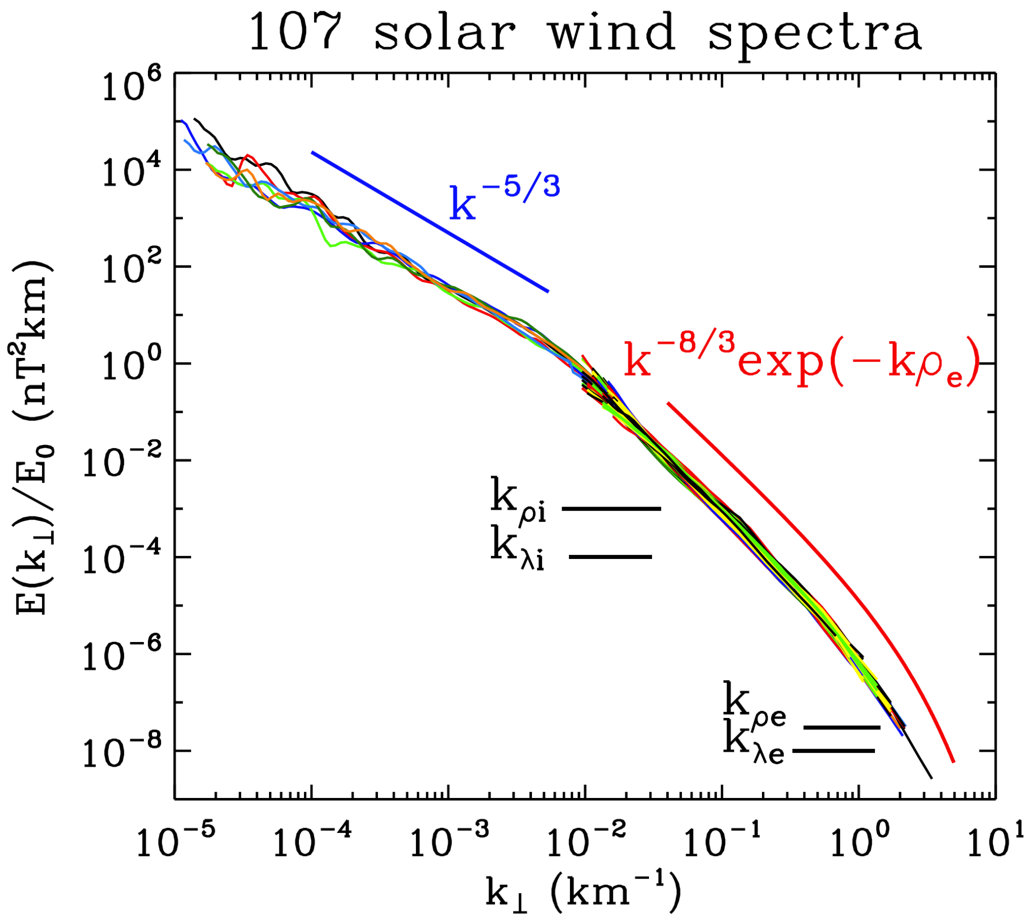
- In solar wind turbulence, we find a similar law :

$$\boxed{E(k) = Ak^{-8/3}\exp(-k\rho_e)}$$

General spectrum at electron scales

[Alexandrova et al., 2012, APJ]

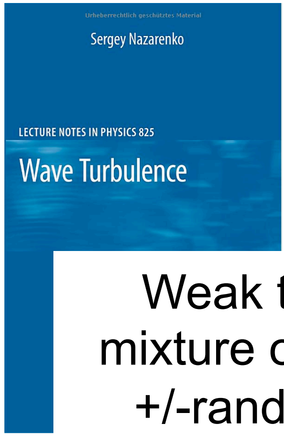
$$\boxed{E(k) = Ak^{-8/3}\exp(-k\rho_e)}$$

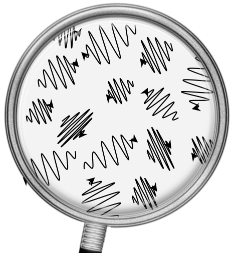


Nature of turbulent fluctuations : waves or strong turbulence ?

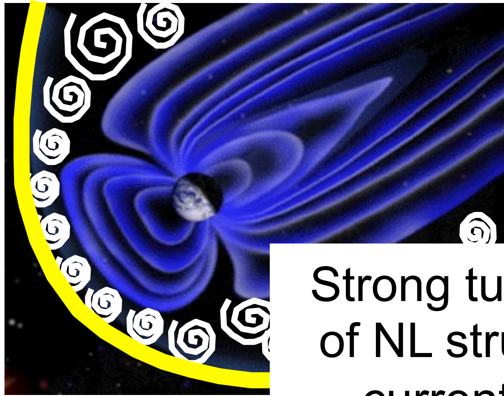
Turbulence nature: weak (or wave) vs strong

Courtesy S. Galtier

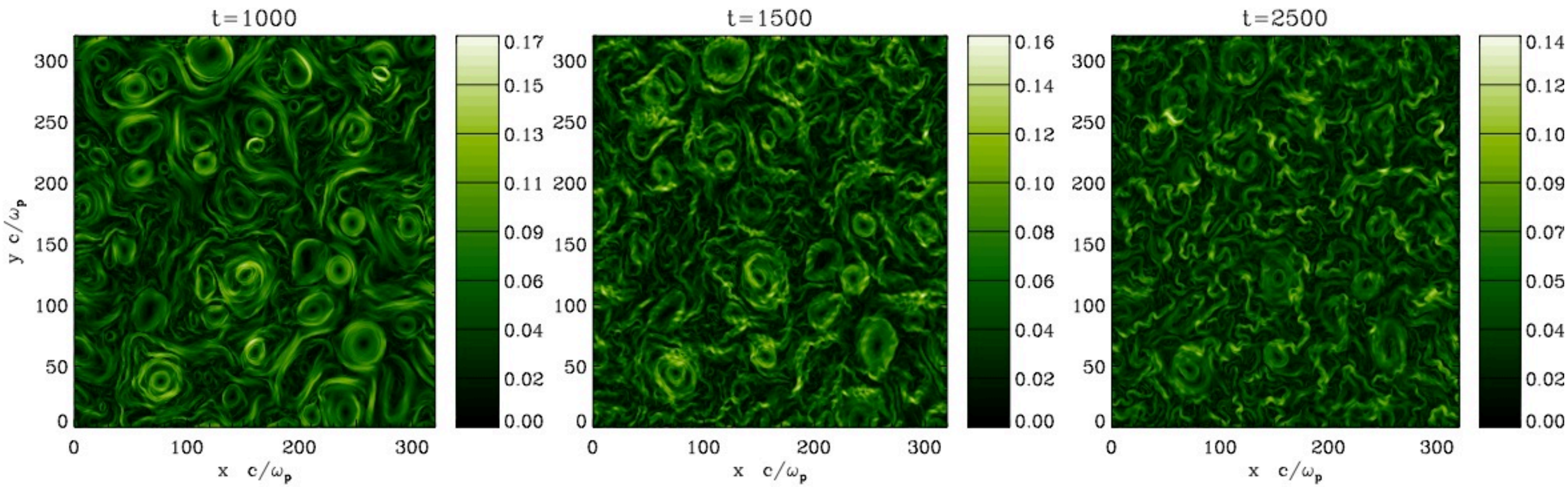




Weak turbulence: mixture of waves with +/-random phases



Strong turbulence: mixture of NL structures (vortices, current sheets, ect…)

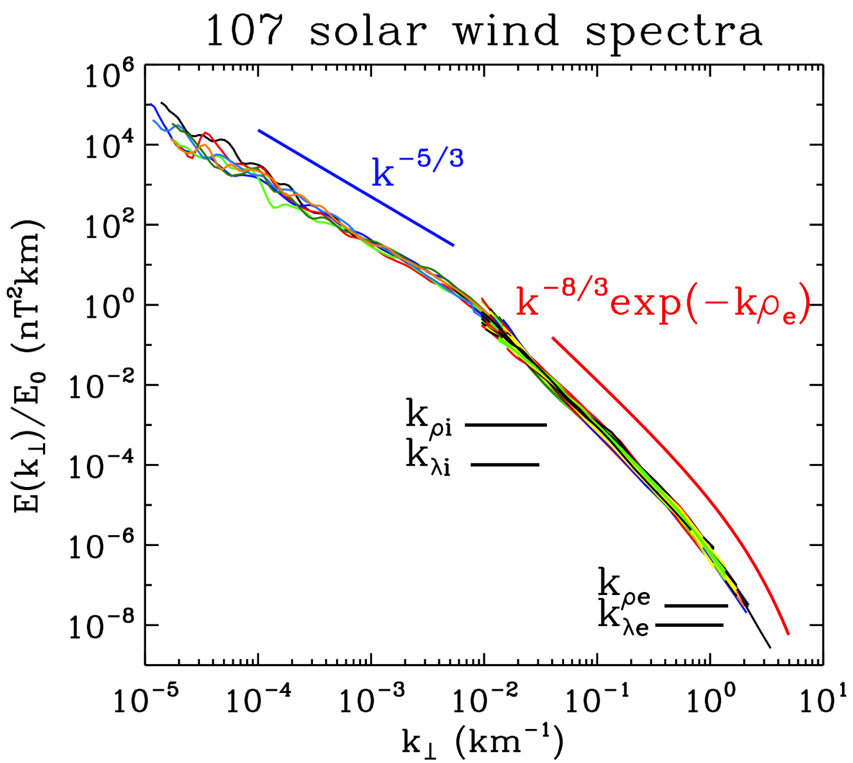


Courtesy of Lorenzo Matteini: 2D Hybrid numerical simulations showing developpment of strong turbulence (vortices) with superposed waves.

Discussion and Conclusion

- Plasma turbulence is an important ingradient in many astrophysical systems.
- Stellar wind/planet interaction: boundary lays are turbulent => impact on the energy and plasma transport, acceleration of energetic particles, ect…

- Solar wind is one of the best laboratories of space plasma turbulence.
- We resolve turbulent fluctuations from MHD (10^7 km) to sub-electron scales (300 m).



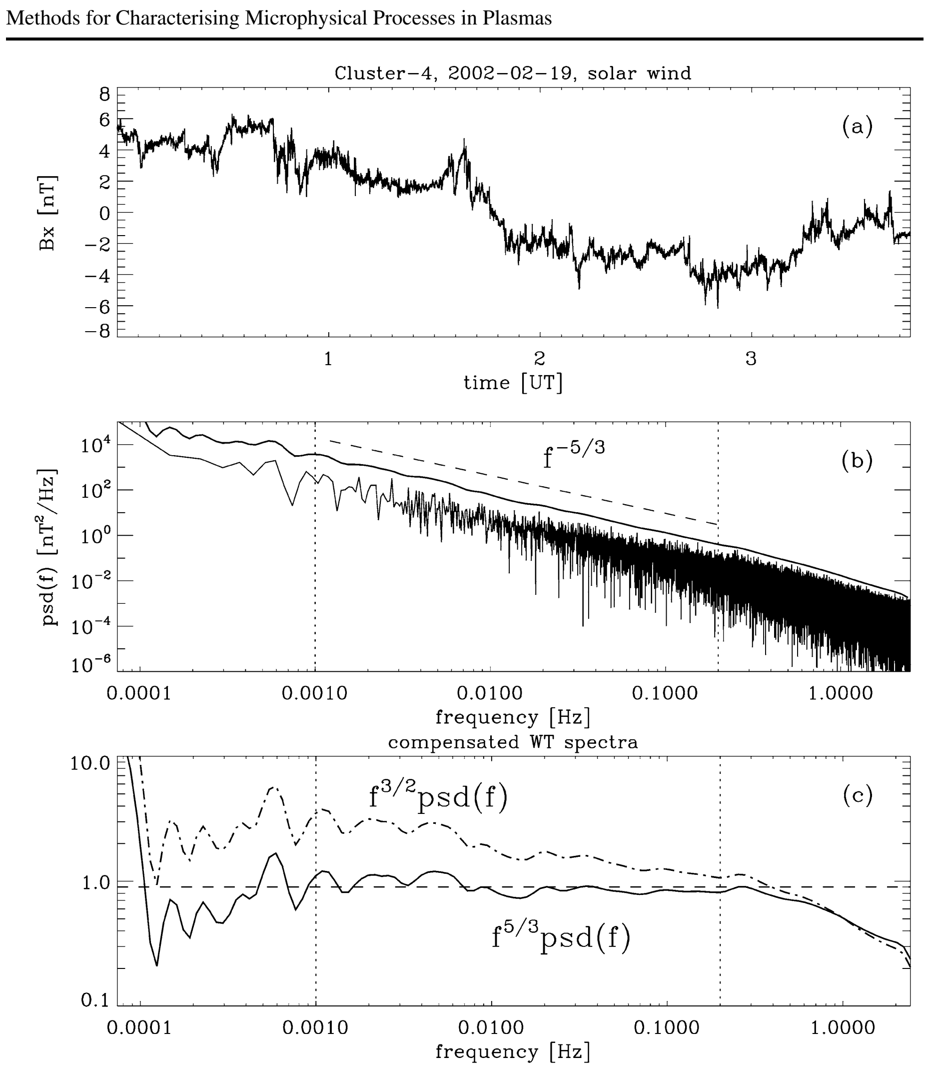
Open questions

- Nature of Kolmogorov like turbulence ? Role of compressibility ?
- Physical processes at ion scales ?
- Final dissipation at electron scales ?
- Plasma heating and particle acceleration by turbulence ?
- Dissipation without collisions ?
- …

Bonus

How do we measure turbulent spectra?

Satellites in-situ measurements are time series =>
Fourier (or Wavelet) transform => frequency spectra



[Dudok de Wit et al. 2013, SSR]

- example of Cluster/FGM
(5 vectors/sec measuremets)

How do we get k-spectra?

Taylor hypothesis:

$$\boxed{\begin{aligned} \ell &= V_{sw}\tau = V_{sw}/f \\ k &= 2\pi/\ell = 2\pi f/V_{sw} \end{aligned}}$$