Journées de la SF2A, 7 - 10 juin 2022 à Besançon
S20 Cosmic Turbulence

Dissipation range of solar wind turbulence

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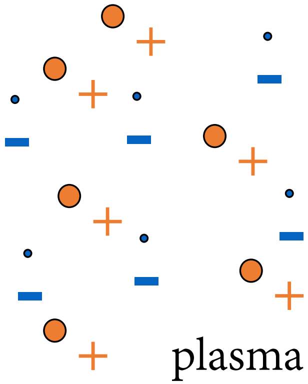
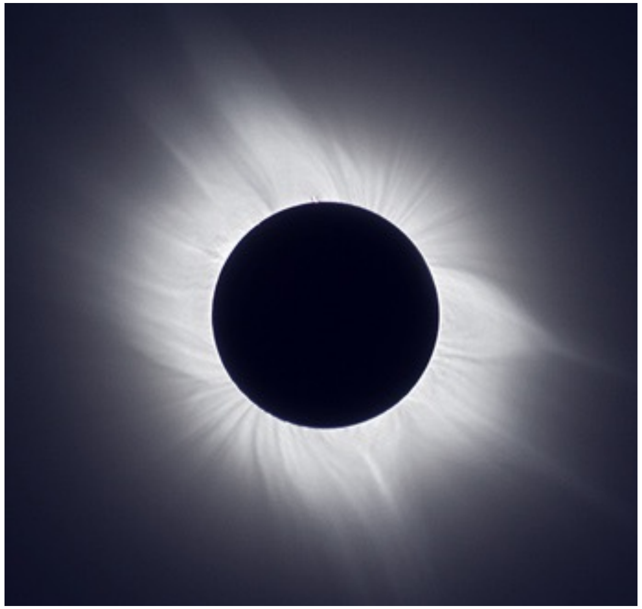
The solar wind

- Expansion of the solar corona in interplanetary space
- Best natural laboratory of astrophysical plasmas, which can be explored with space missions



plasma : ionized gas (e^- , p^+, α^+)

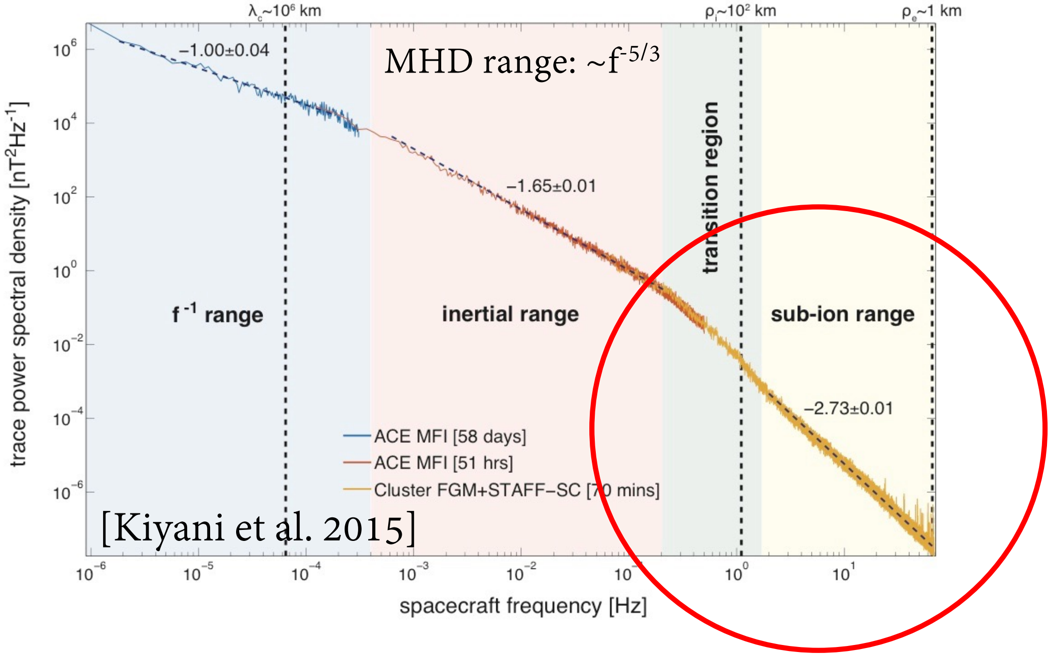


- Plasma: ionized gas, essentially electrons and protons
- Mean speed ~500 km/s (slow wind 300-400 km/s, fast wind 600-800 km/s)
- Mean temperature (e^-,p^+) at 1 AU ~ 10^5 K
- Mean density at 1 AU ~5 cm^{-3}
- Few collisions (1 collision/1 AU) ⇒ viscosity ~ 0 ⇒ magnetic field is frozen in plasma

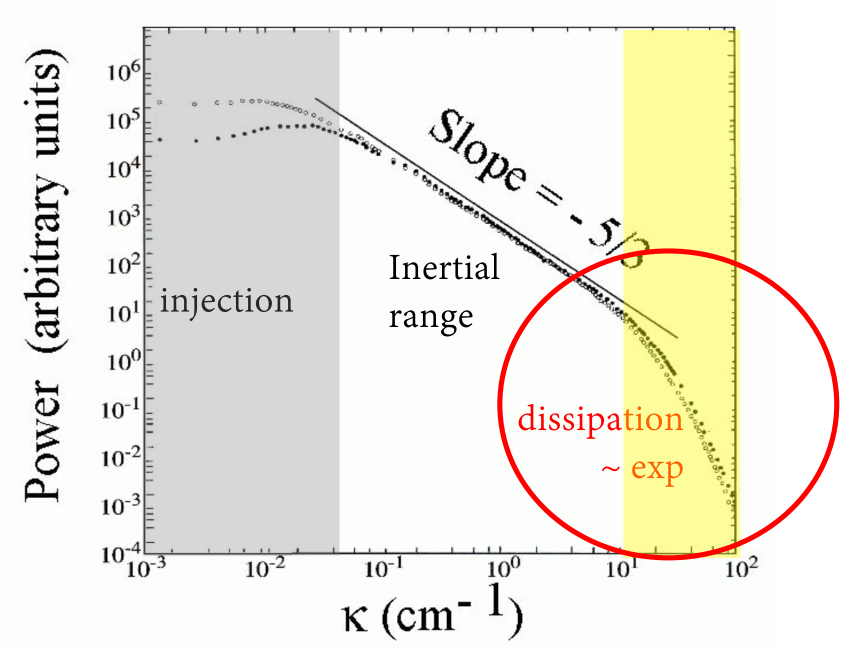
Dissipation range and ℓ_d in the solar wind ?

m.f.p.~ 1 AU= 1.5 10^8 km => cascade is at sub-collisional scales !

Taylor : $\ell = V_{sw}\tau,\ k = 2\pi f / V_{sw}$


MHD range: ~$f^{-5/3}$

[Kiyani et al. 2015]

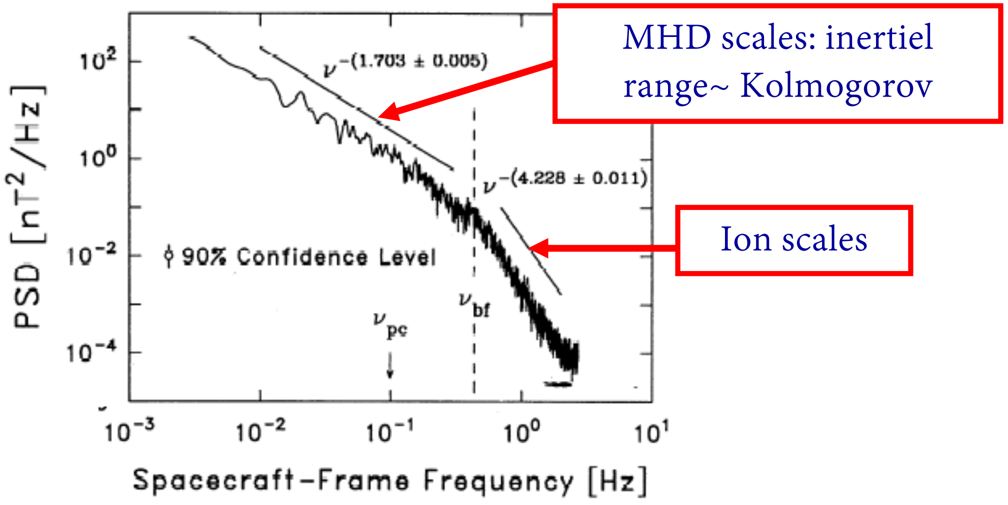

dissipation ~ exp

If the dissipation range starts at ion scales, why the spectrum is a power-law and not an exponential as is observed in HD turbulence ?

Magnetic turbulent spectrum
Transition to kinetic scales

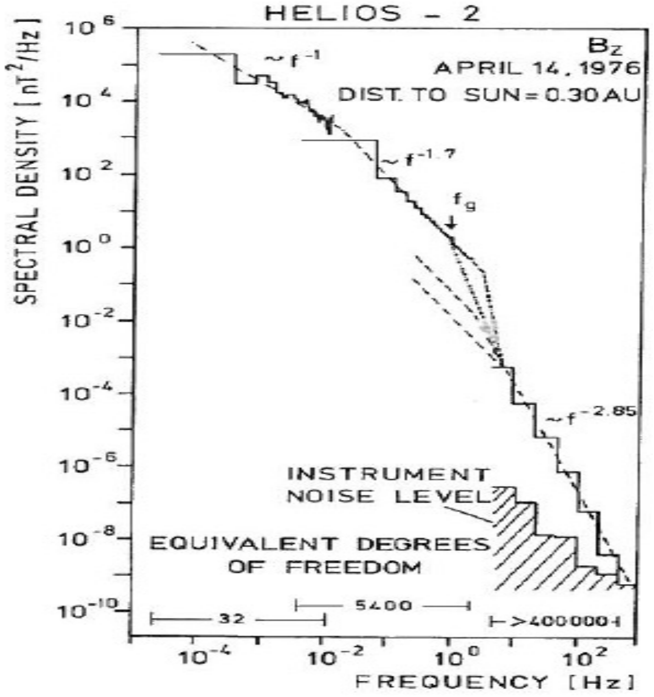
[Denskat et al., 1983]

[Leamon et al,1998] Wind/MAG



MHD scales: inertiel range~ Kolmogorov

Ion scales



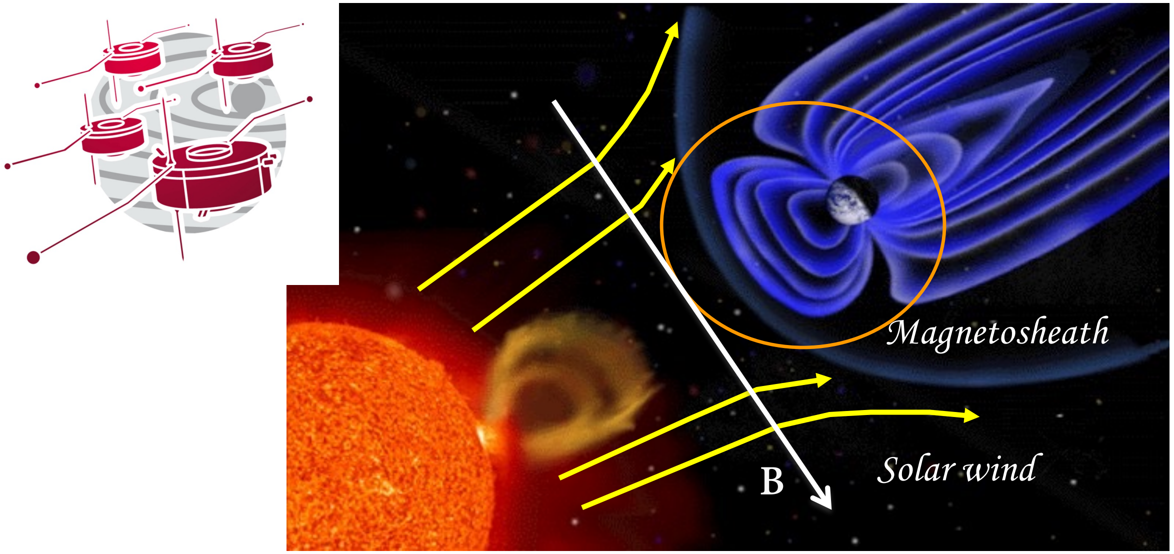
Magnetometers measurements (up to few Hz)

There exist a spectral “break” close to ion scales ⇒

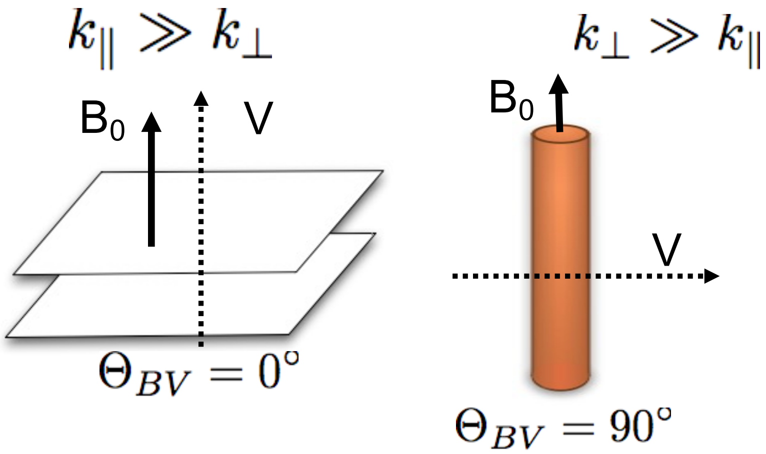
- onset of dissipation range (ion heating by turbulence)
- or a starting point of a small scale cascade ?
- Electron scales ?

Helios/Magnetometer + Search Coil (AC field) measurements, up to ~400 Hz.

Cluster mission ESA/NASA, 4 s/c, since 2000



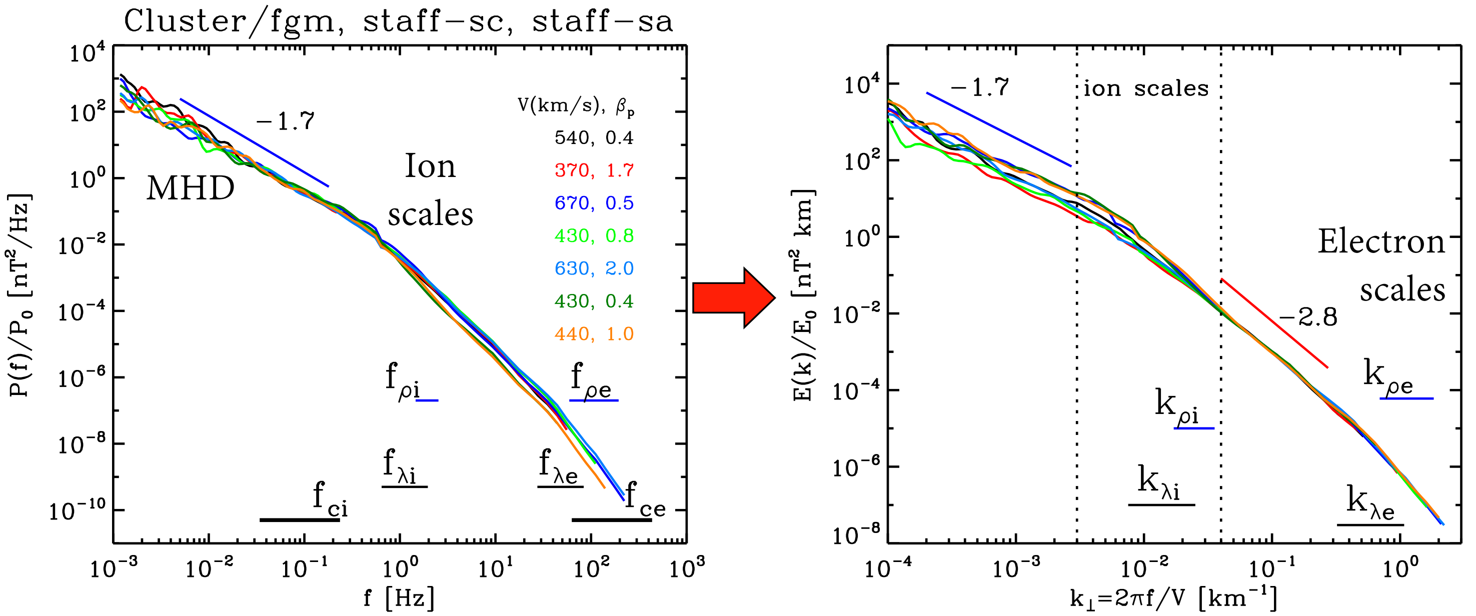
$$\omega_{obs} = \mathbf{k} \cdot \mathbf{V} = kV\cos(\Theta_{kV})$$



- Multi-satellite mission to study magnetosphere/solar wind connection
- Cluster is in the free solar wind when the field/flow angle is quasi-perpendicular ($Q_{BV} > 65^o$)
- Otherwise, Cluster is connected to the bow-shock => shock physics and not solar wind turbulence.
- Thus, with Cluster we can resolve k_{perp} fluctuations
- **STAFF (LPP/LESIA) is the most sensitive instrument by today to measure kinetic plasma scales**

Turbulent spectrum from MHD to electron scales (Cluster data)

[Alexandrova et al. 2009, PRL; 2013, SSR]



$$\beta_p = \frac{nkT_p}{B^2/8\pi}$$

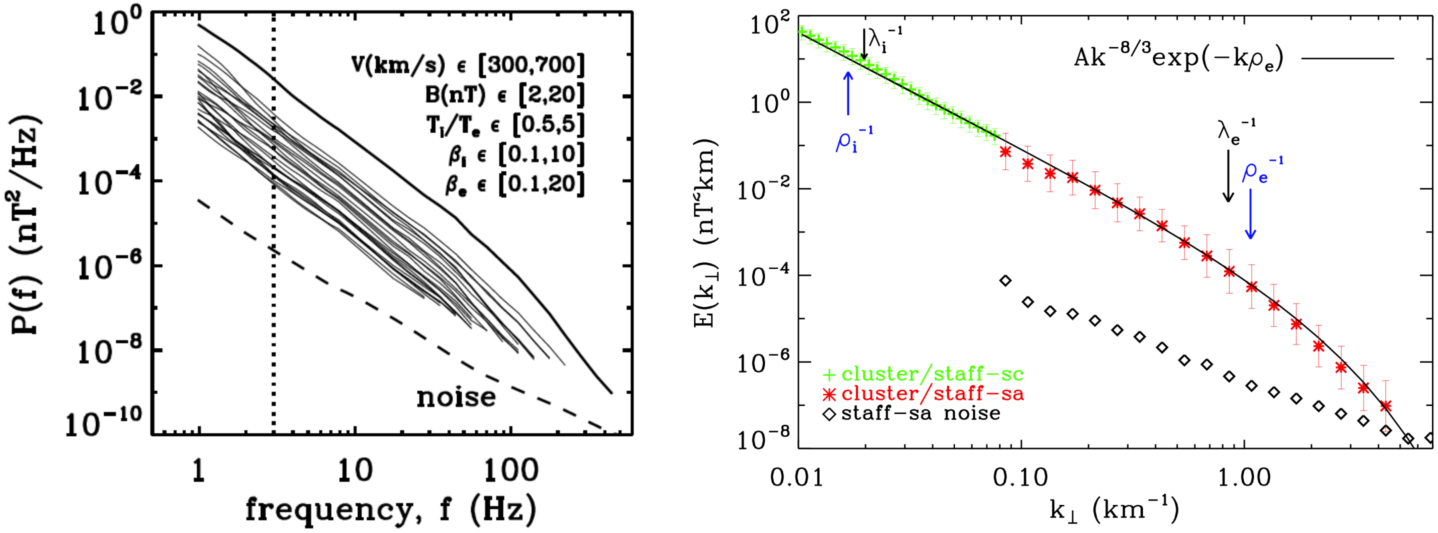
$$f_{\rho_e} = V/2\pi\rho_e$$

$$\rho_e = \frac{V_{th,e}}{2\pi f_{ce}}$$

$$k_{\rho_e} = 1/\rho_e$$

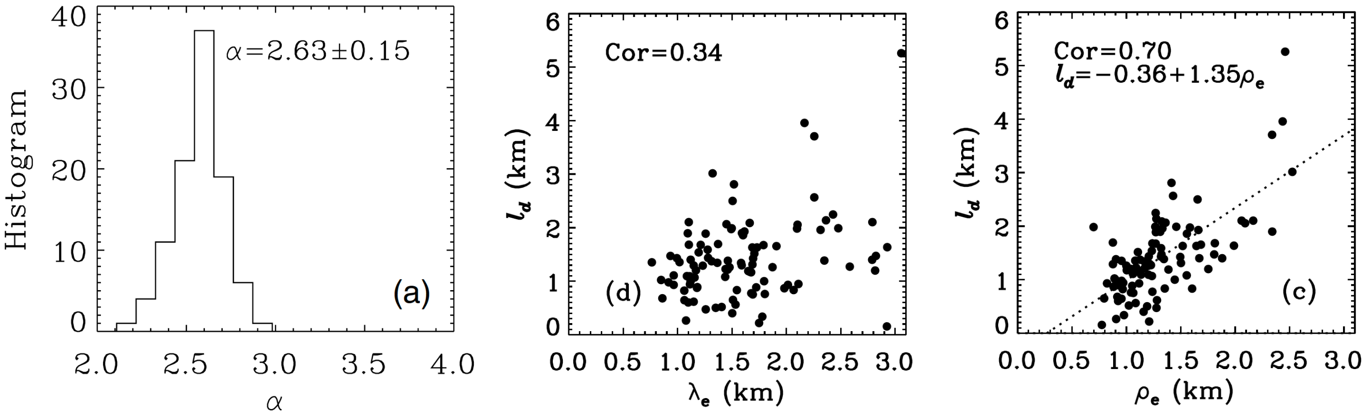
- Superposition of different spectra at sub-ion scales seems to indicate general behaviour : spectrum ~$k_{perp}^{-2.8}$ => small scale cascade
- End of the cascade ? Dissipation scales ?

100 kinetic spectra in the solar wind (Cluster/STAFF)



[Alexandrova et al., 2012]

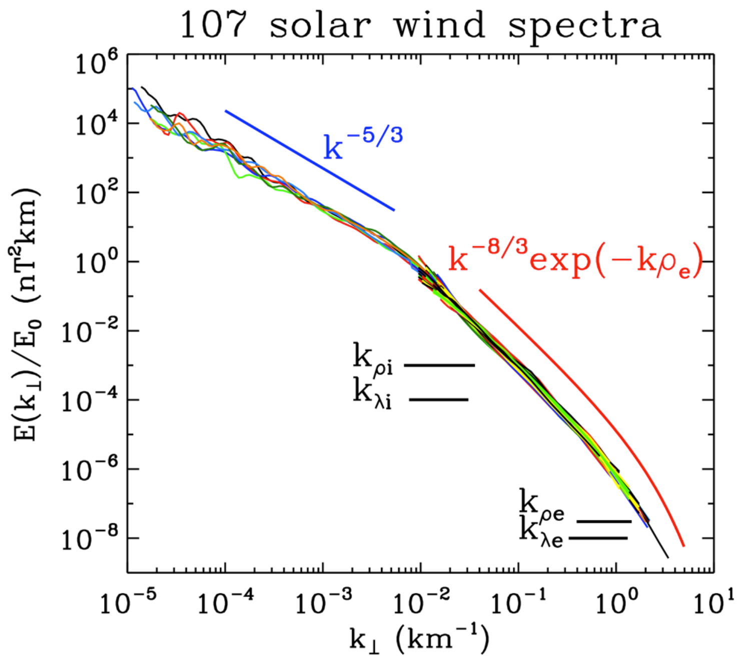
Dissipation range spectrum in fluids: $\boxed{E(k) = Ak^{-\alpha}\exp\left(-k\ell_d\right)}$ [Chen, et al., 1993, PRL]

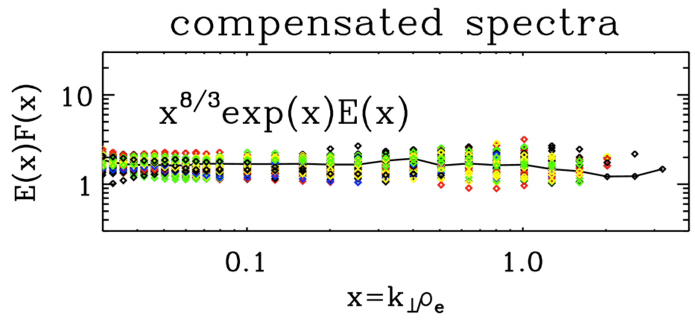


➡ $\boxed{\ell_d \sim \rho_e}$

$$\boxed{\begin{array}{l} E(k) = Ak^{-8/3}\exp\left(-k\ell_d\right) \\ \ell_d \simeq \rho_e = \sqrt{2k_B T_e m_e}/eB \end{array}}$$

General magnetic spectrum at kinetic scales at 1 AU from the Sun





- For different solar wind conditions we find a general spectrum with "fluid-like" roll-off spectrum at electron scales

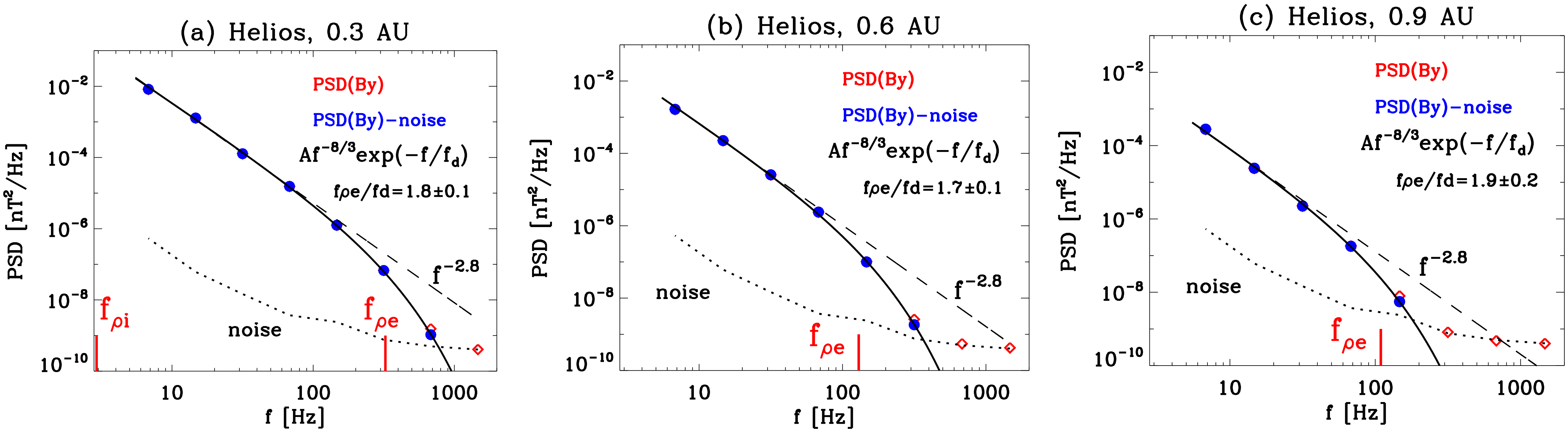
- "fluid-like" roll-off => no more spectral self-similarity, **dissipation range of e/mag turbulence.**

- Electron Larmor radius seems to play a role of the dissipation scale in collisionless solar wind [Alexandrova et al., 2009 PRL, 2012 APJ]

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

- General in the Heliosphere ?

Helios (1976) measurements at 0.3, 0.6 and 0.9 AU

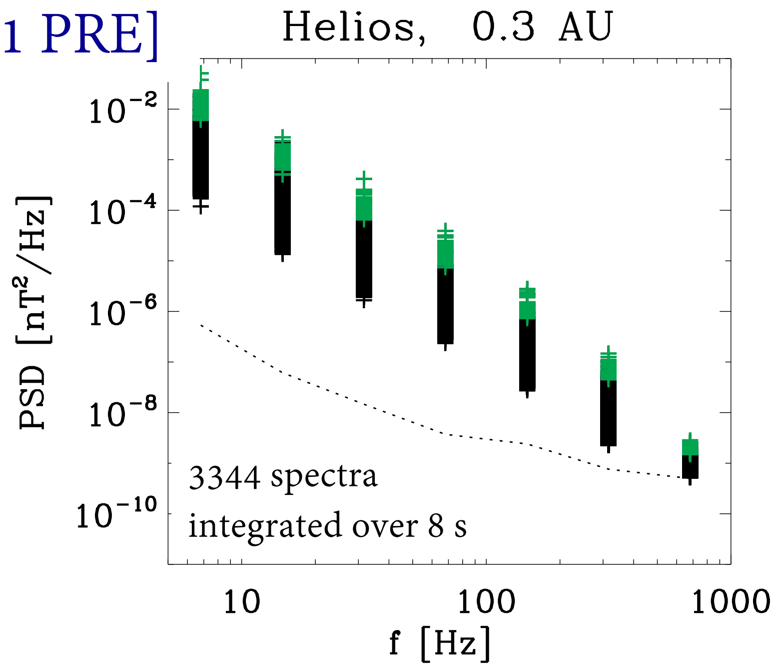


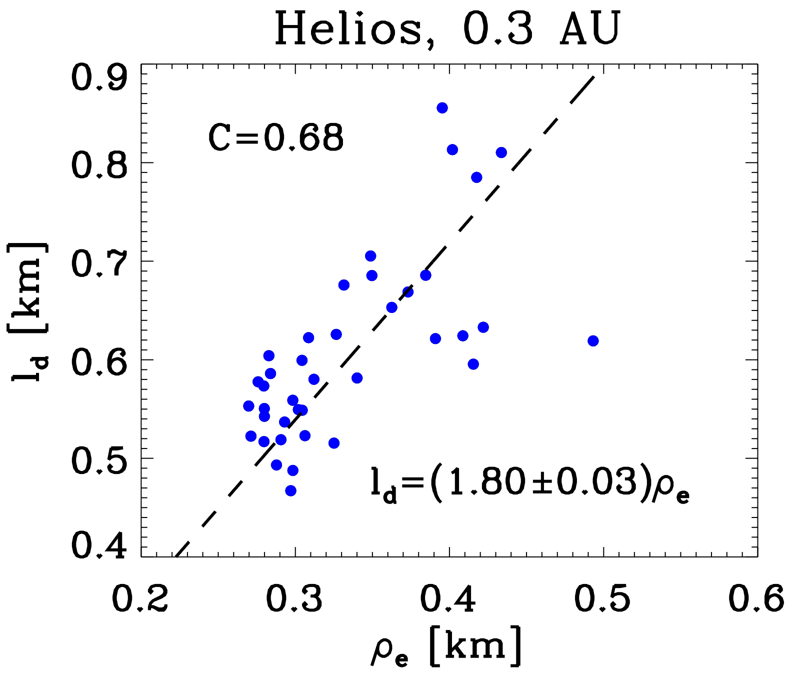
$$P_{\text{model}}(f) = Af^{-8/3}\exp\left(-f/f_d\right)$$

- At 3 radial distances the model function fits well the data.
- As turbulence level goes down with radial distance, the number of resolved frequencies (3 times over the noise) decreases.
- Better to stay at 0.3 AU to have maximal number of resolved frequencies (7).

Magnetic spectrum at sub-ion scales (Helios at 0.3 AU)

[Alexandrova+, 2021 PRE]





Fitting of 39 most intense spectra (see green points) with the 2-parameter model:

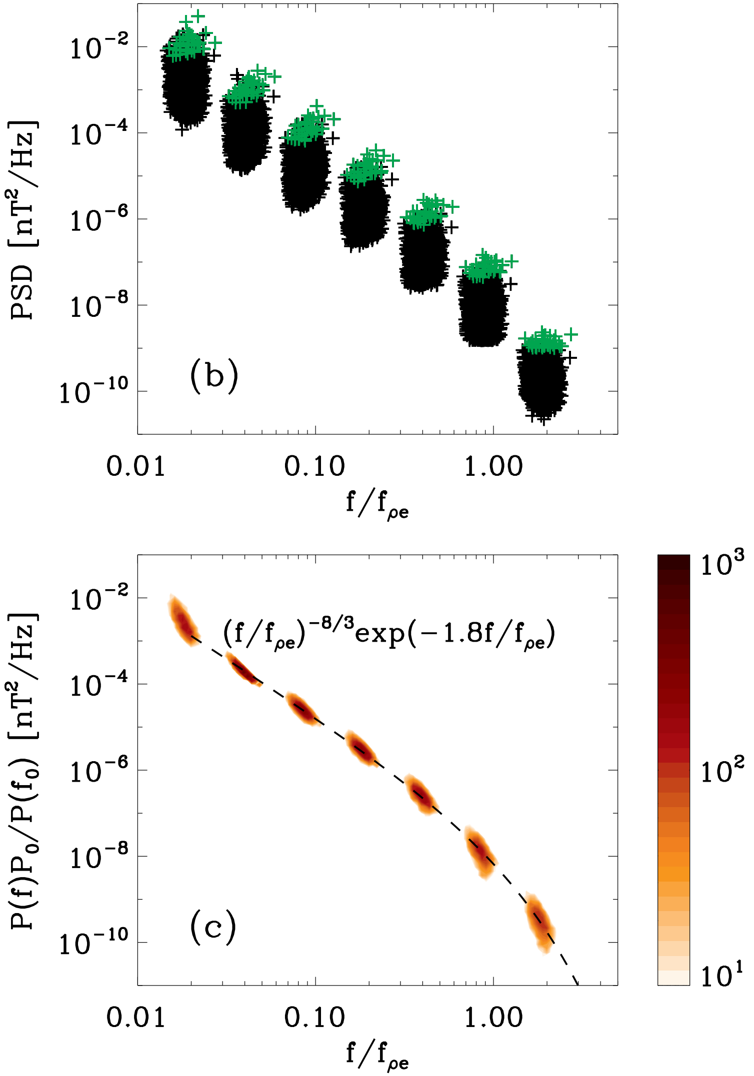
$$\boxed{\begin{aligned} E(k) &= Ak^{-8/3}\exp\left(-k\ell_d\right) \\ \ell_d \simeq \rho_e &= \sqrt{2k_BT_em_e}/eB \end{aligned}}$$

Dissipation scale correlates with electron Larmor radius as at 1 au.

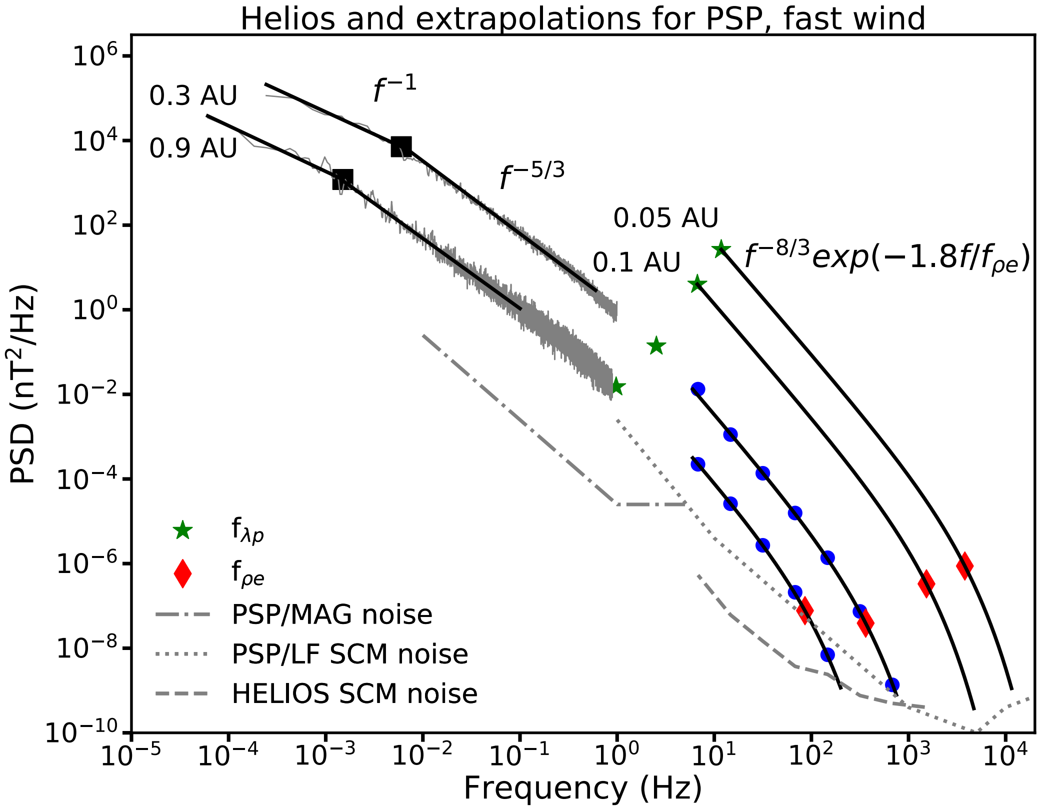
Magnetic spectrum at sub-ion scales (Helios at 0.3 AU)

$$\boxed{P_{\text{model}}(f) = A f^{-8/3} \exp\left(-1.8 f / f_{\rho e}\right)}$$

- Taking-off dependence on A by collapsing 3344 spectra in amplitude (in 1 point), all spectra can be described by this model function (without free parameters).
- The same function describes kinetic spectrum at 1 AU, just the coefficient 1.8 differs…(why?)
- Parker Solar Probe closer to the Sun?



Helios turbulent spectrum (fast wind) and extrapolations for PSP



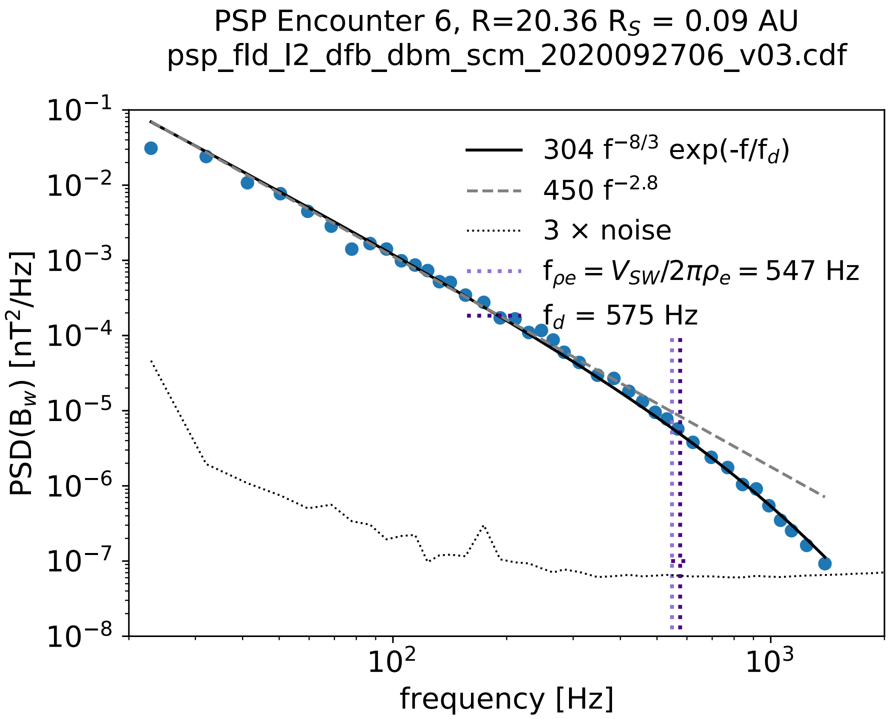
Assumptions for extrapolations:

- The turbulence level goes together with the mean field: $\delta B/B_0 \sim$ const
- $f^{-1} - f^{-5/3}$ break goes as $R^{-1.52}$ [Bruno & Carbone, 2013]
- The density matches both the 0.3 to 1 au Helios density observations and the coronal density observations obtained remotely by Sittler and Guhathakurta [1999];
- The conservation of the mass flux

$$n_e(R)V(R)R^2 = \text{const.}$$

[Alexandrova, Jagarlamudi, Hellinger, Maksimovic et al. 2021 PRE]

Parker Solar Probe: observations at 0.09 UA



[Master-1 diploma thesis of Jessica Martin, June 2021]

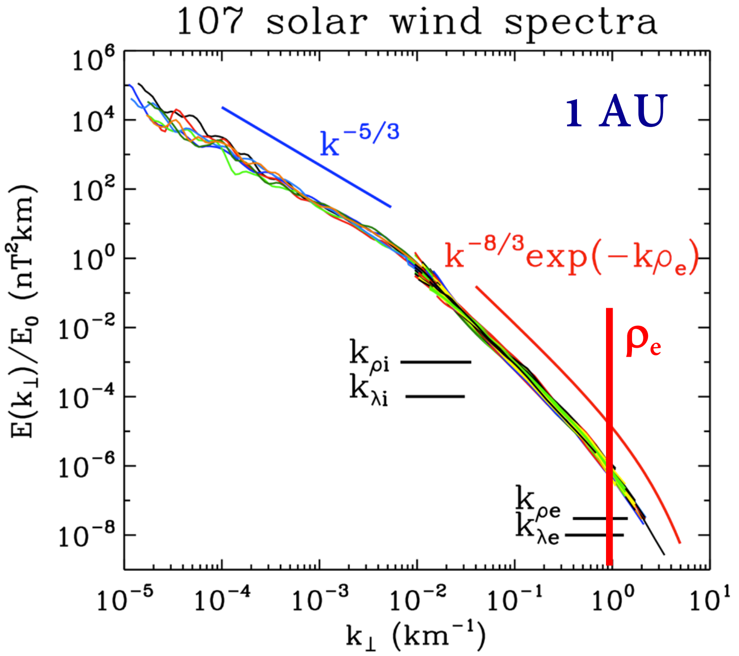
$$E(f) = A_0 f^{-8/3} \exp\left(-f/f_d\right)$$
$$E(k) = A k^{-8/3} \exp\left(-k\ell_d\right)$$
$$k = 2\pi f / V_{SW}$$
$$\ell_d/\rho_e = f_{\rho_e}/f_d = 0.84$$

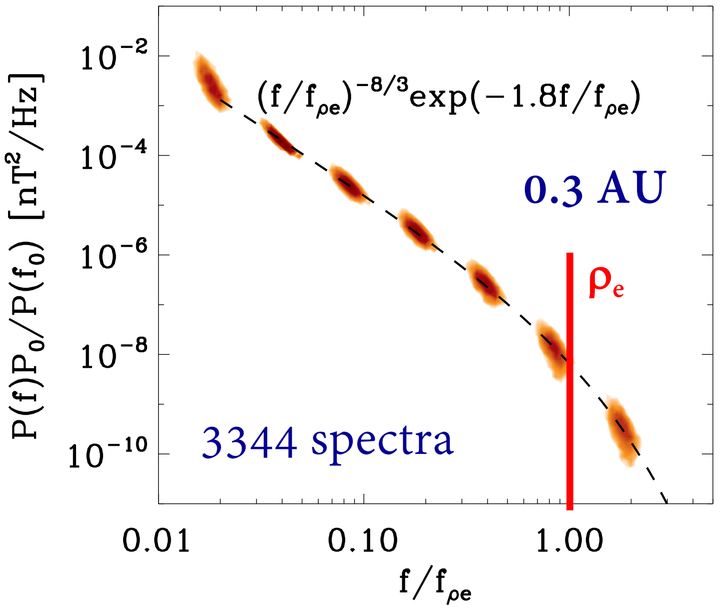
Observations of Cluster & Helios :

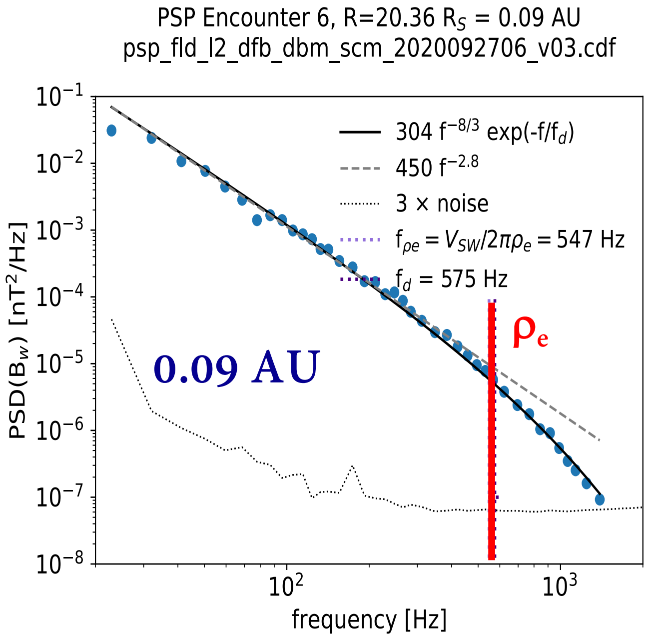
$$E(k) = A k^{-8/3} \exp\left(-k\ell_d\right)$$
$$\ell_d = 1.4\rho_e,\ \text{R=1 UA (Cluster)}$$
$$\ell_d = 1.8\rho_e,\ \text{R=0.3 UA (Helios)}$$

PSP/SCM analysis (preliminary results)

Conclusions
Dissipation range and ℓ_d in the solar wind



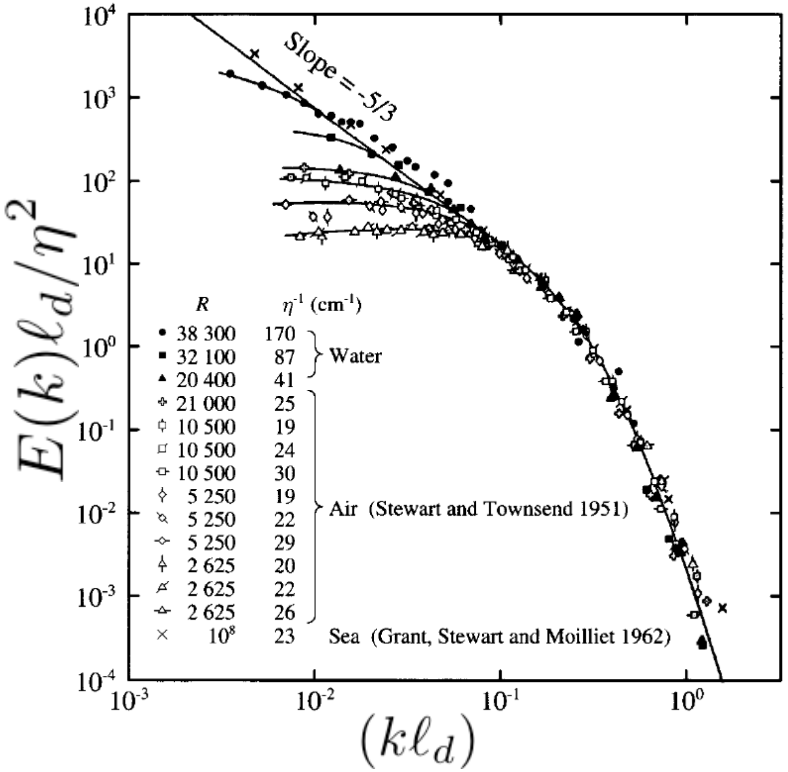




- The same form of spectrum at 1 au (Cluster), 0.3 (Helios) and at 0.09 au (PSP) in the Heliosphere => generality !
- The e/m cascade ends onto the electrons with ρ_e ~ dissipation scale ℓ_d.

Universal Kolmogorov’s function

[Frisch, Turbulence: the legacy of Kolmogorov, 1995]



$$E(k)\ell_d/\eta^2 = F(k\ell_d)$$

ℓ_d: dissipation scale

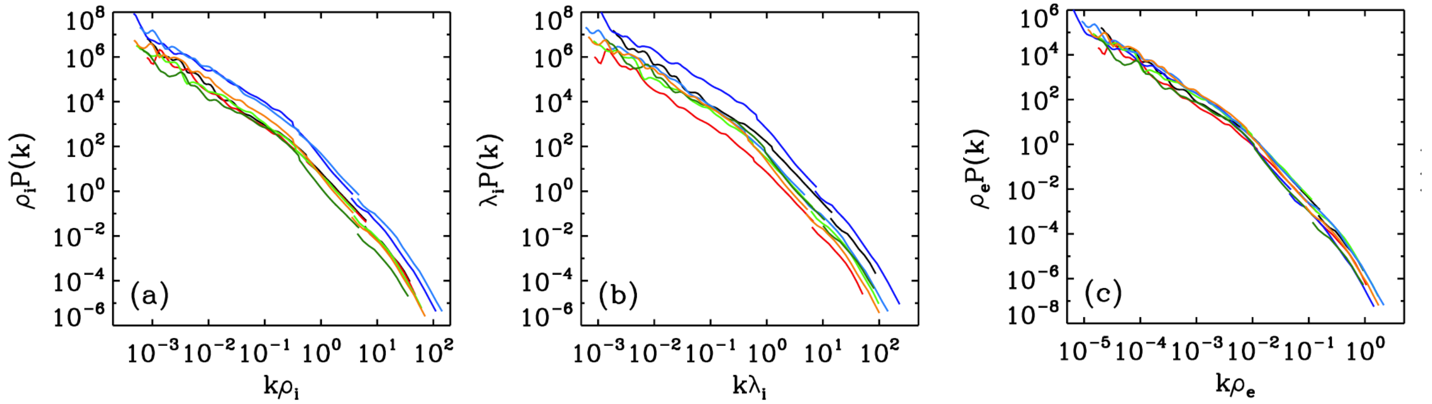
η: viscosity

In HD turbulence, this normalization collapses spectra measured under different conditions.

Dissipation scale?

Universal Kolmogorov's function: $\boxed{E(k)\ell_d/\eta^2 = F(k\ell_d)}$

Let us try to apply this kind of normalization for solar wind spectra and for different candidates for the dissipation scale: $\ell_d = \rho_{i,e}, \lambda_{i,e}$



- Assumption: η=Const
- $k\rho_i$ & $k\lambda_i$ - normalizations are not efficient for collapse
- $k\rho_e$ normalization bring the spectra close to each other

➡ $\boxed{\ell_d \sim \rho_e}$

[Alexandrova et al., 2009, PRL]