Solar wind – magnetopshere coupling: small scales and large scales dynamics

Lina Hadid

Laboratoire de Physique des Plasmas
LPP, CNRS-École Polytechnique, France

Collaboratorsbb: F. Sahraoui, N. Andrés, S. Galtier, V. David, S. Y. Huang, N. Romanelli, G. DiBraccio, J. Halekas, M. W. Morooka, J.-E. Wahlund, A. M. Persoon, D. J. Andrews and O. Shebanits, L. Rezeau, D. Delcourt and many others

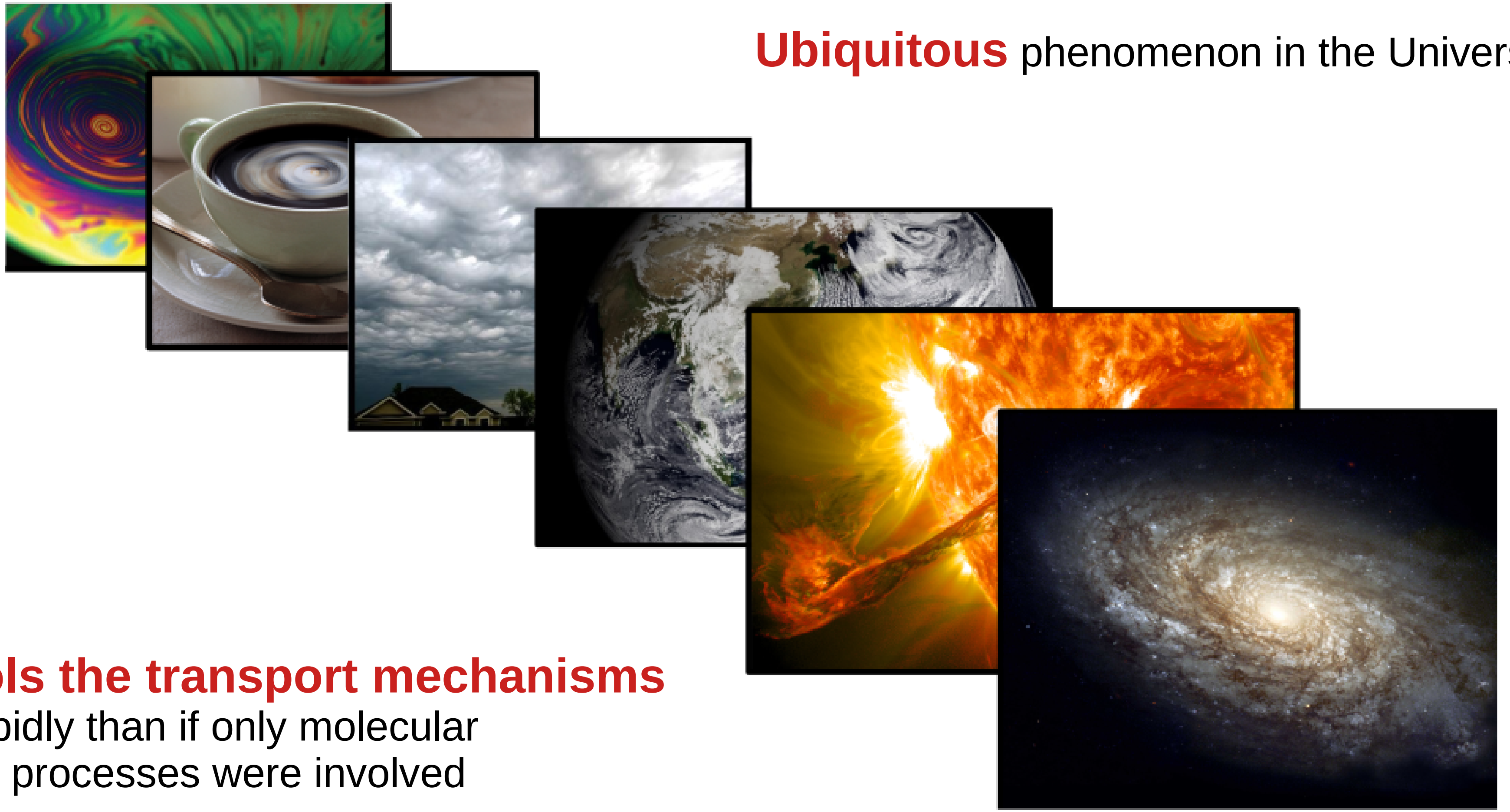
Part I: How do we observe space plasmas ?

Part II: Turbulence properties at the MHD scales

Part III: Planetary ionospheres - Saturn

Part II:
Turbulence properties at the MHD scales

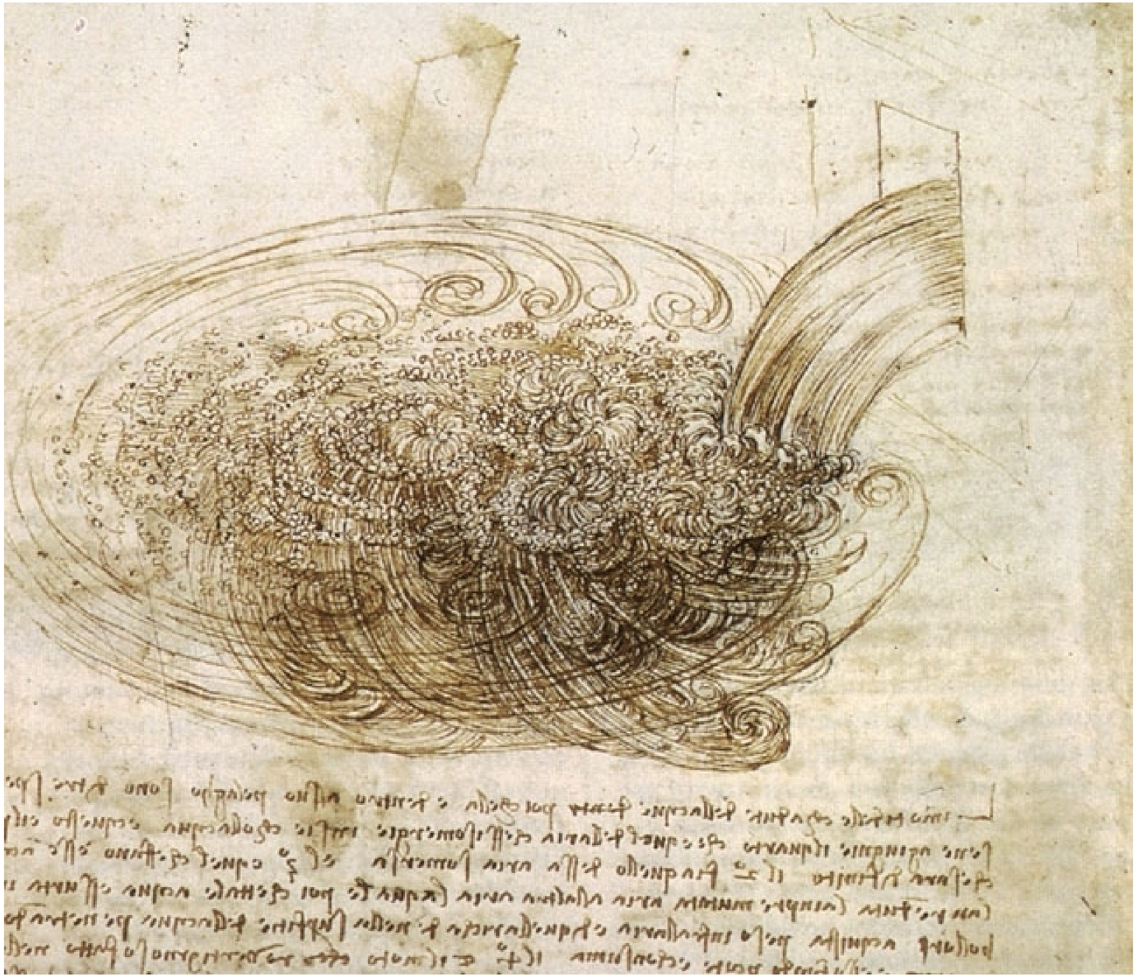
Turbulence overview



Ubiquitous phenomenon in the Universe

Controls the transport mechanisms
more rapidly than if only molecular
diffusion processes were involved

How it all started...



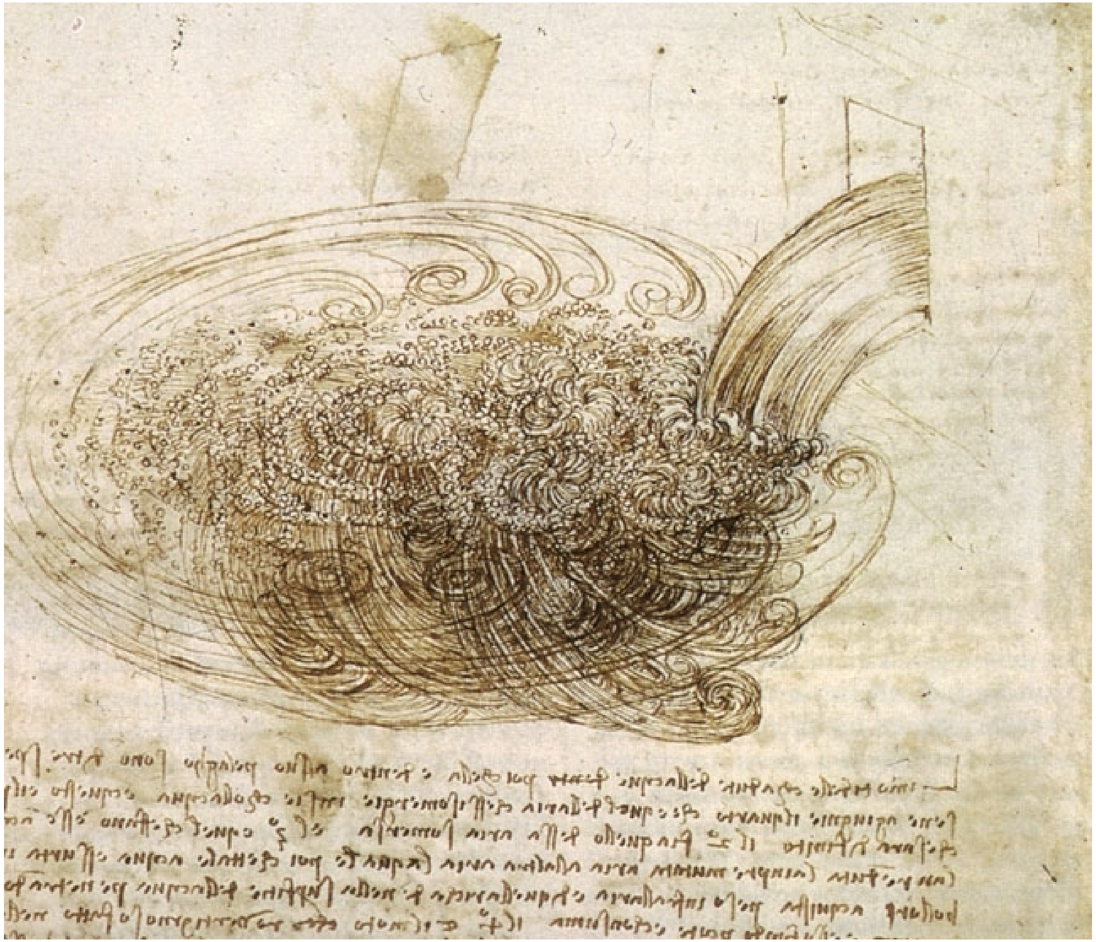
Leonardo da Vinci
(1452 - 1519)

How it all started...

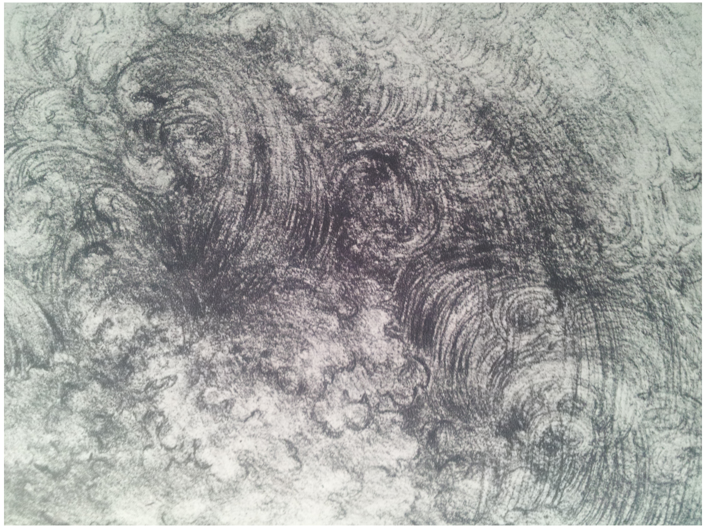
"Observe the motion of the surface of the water which resembles that of hair, and has two motions, of which one goes on with the flow of the surface, the other forms the lines of the eddies; thus the water forms eddying whirlpools one part of which are due to the impetus of the principal current and the other to the incidental motion and return flow."

P. 389 of Leonardo's manuscripts, the Codice Altantico

How it all started...



A mean, laminar flow that breaks up into a disordered eddy-like motions → it doesn't stay stable.

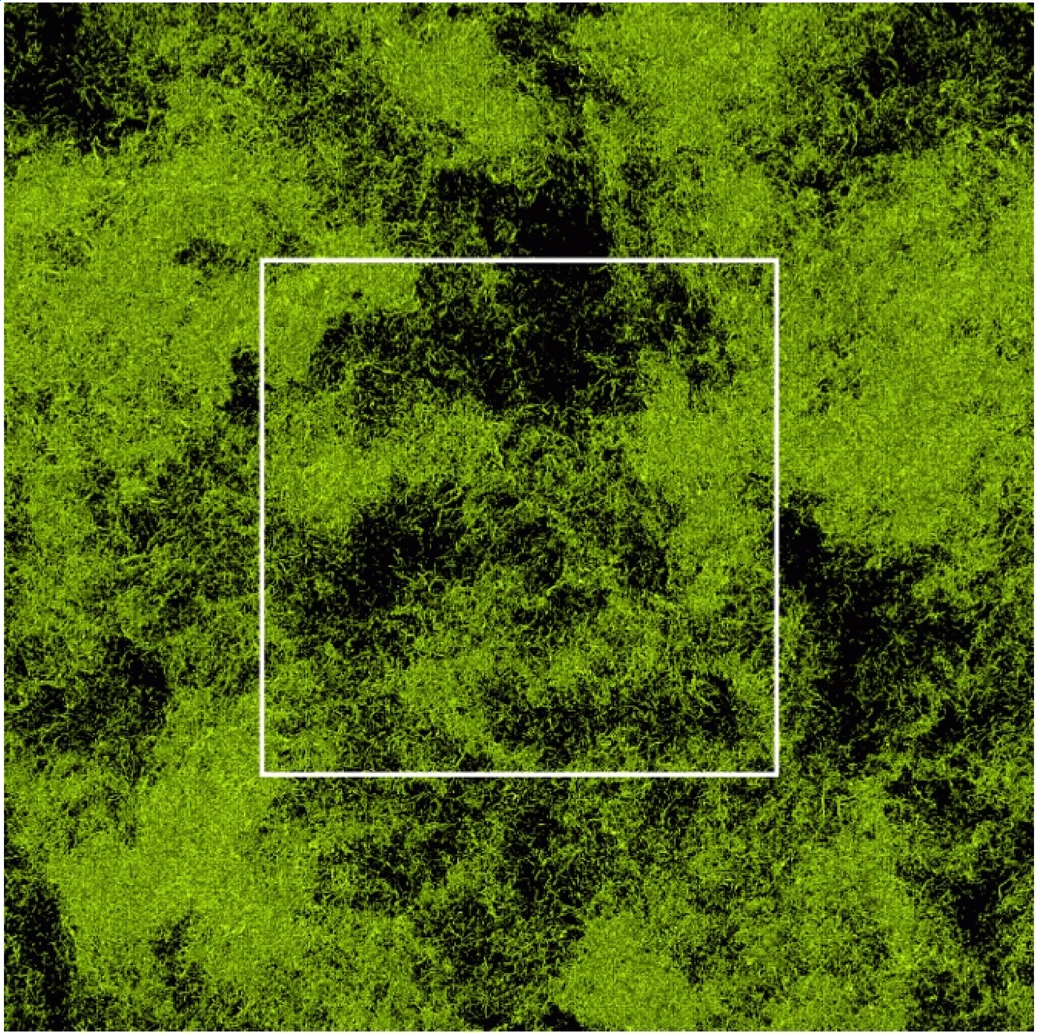


Eddy-like motion is universal

The Starry Night, June 1889, V. Van Gogh

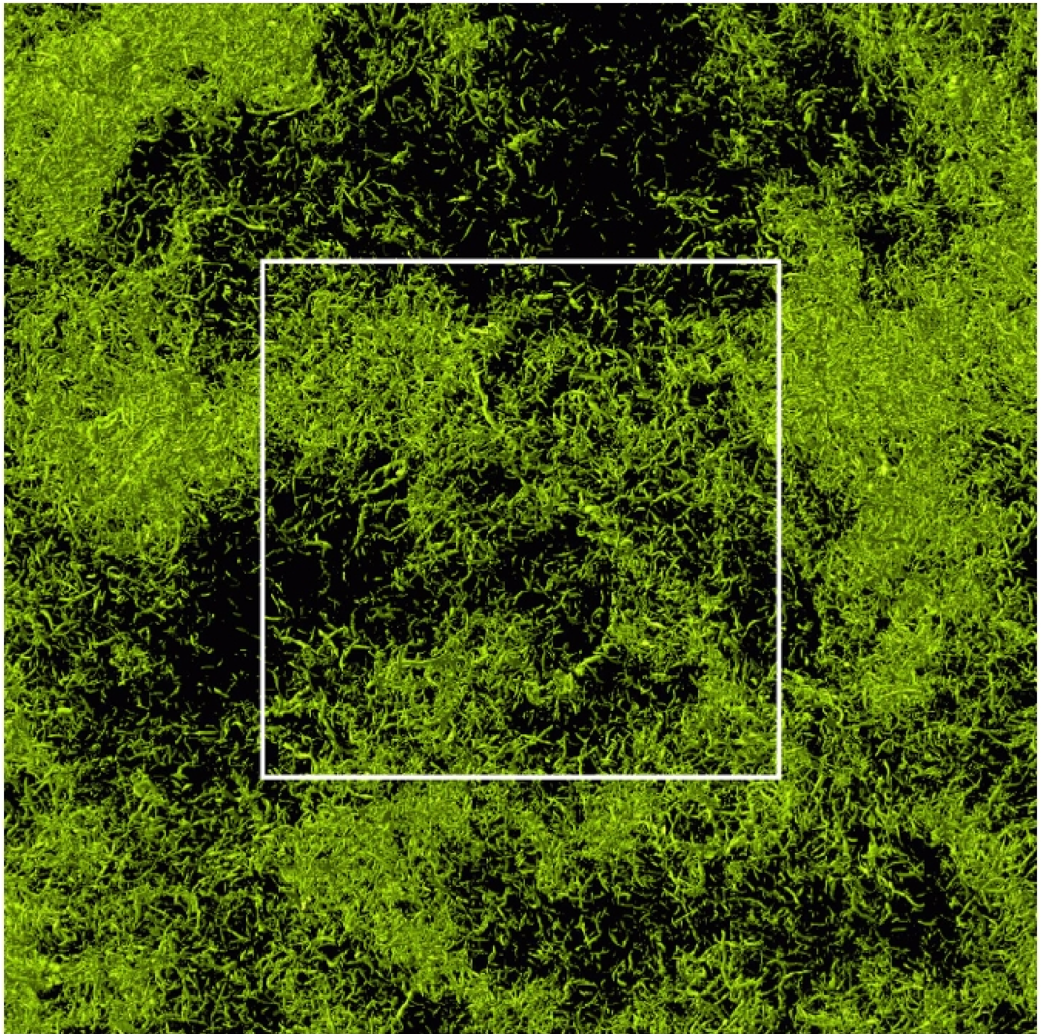
A mean, laminar flow that breaks up into a disordered eddy-like motions → it doesn't stay stable.

Turbulence is a multiscale disorder



Earth simulator,
4096^3, isovorticity
Surfaces, Y. Kaneda

Turbulence is a multiscale disorder



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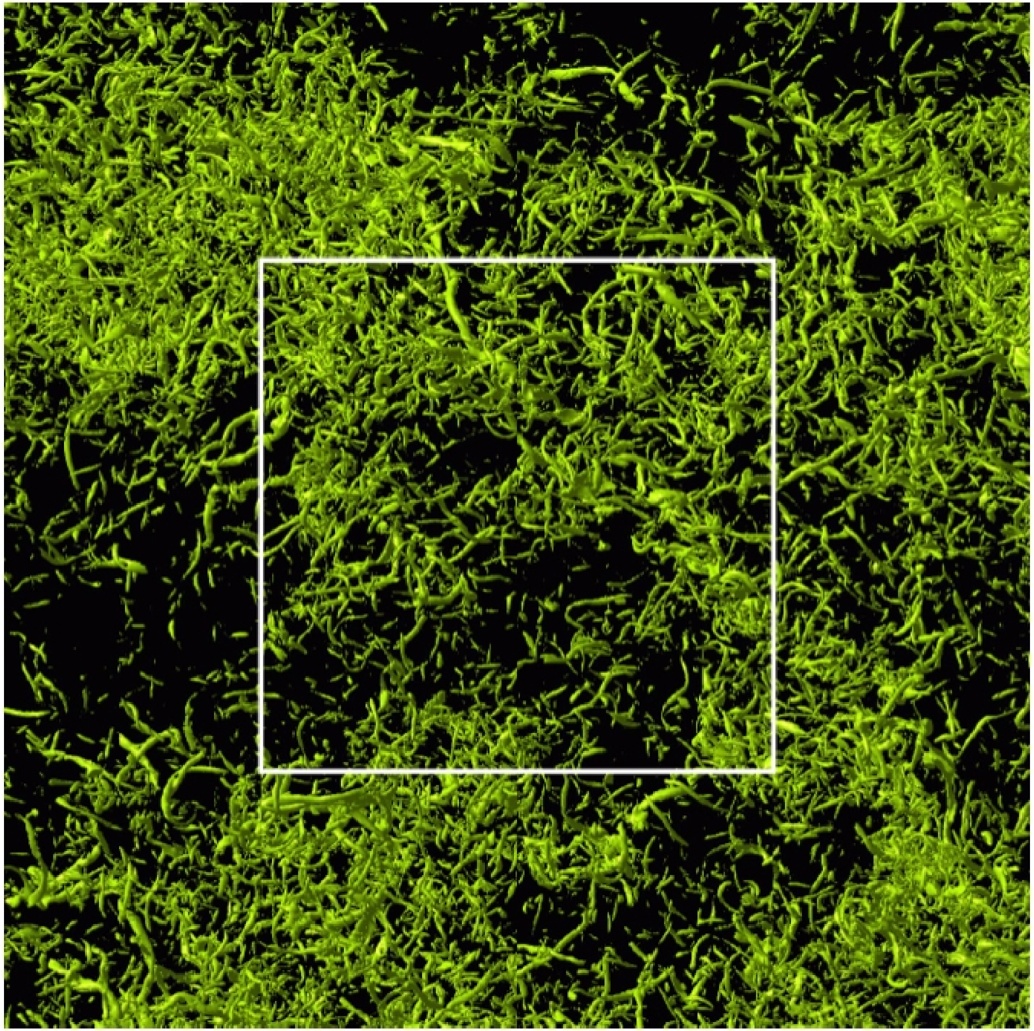

Earth simulator, 4096^3, isovorticity Surfaces, Y. Kaneda

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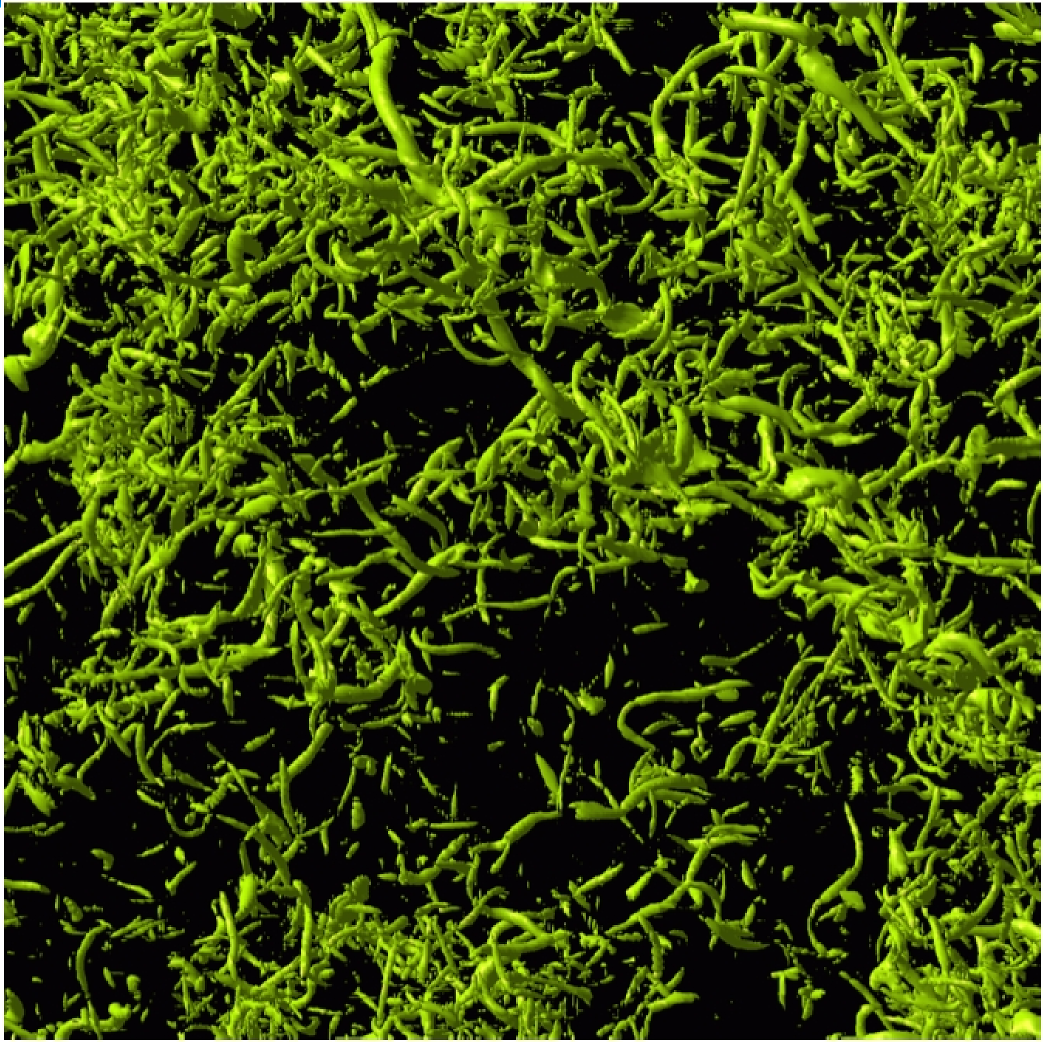

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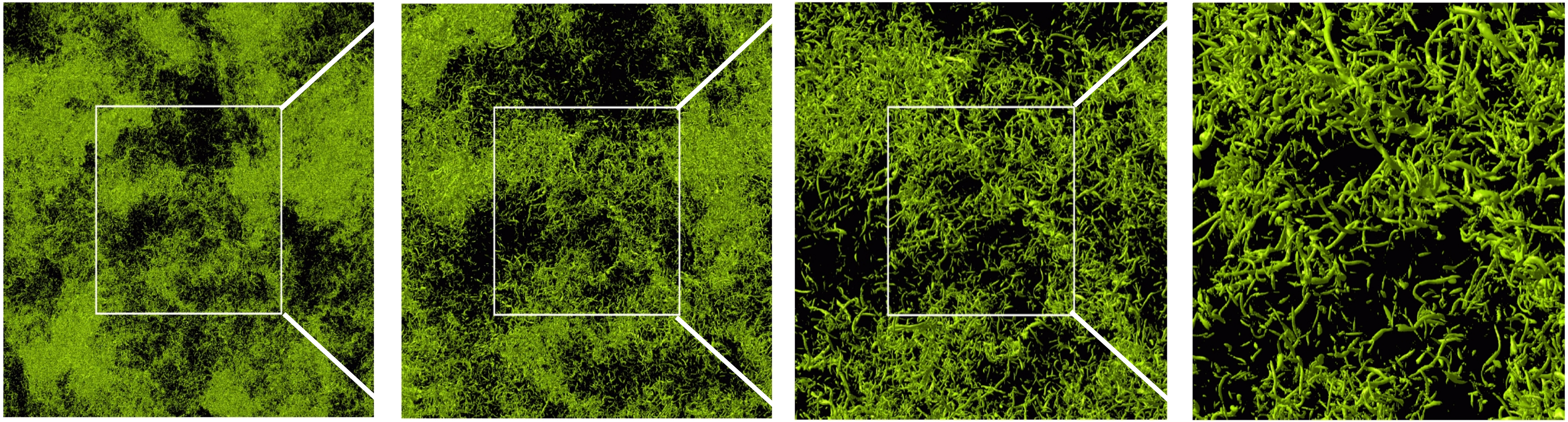
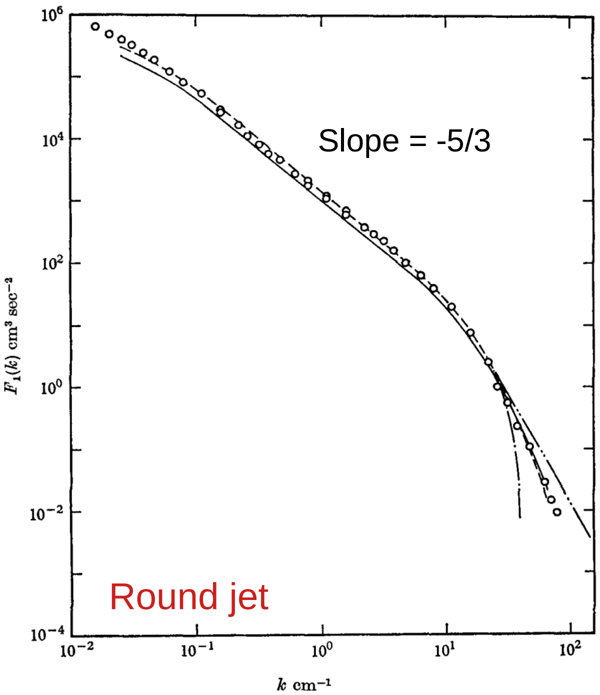
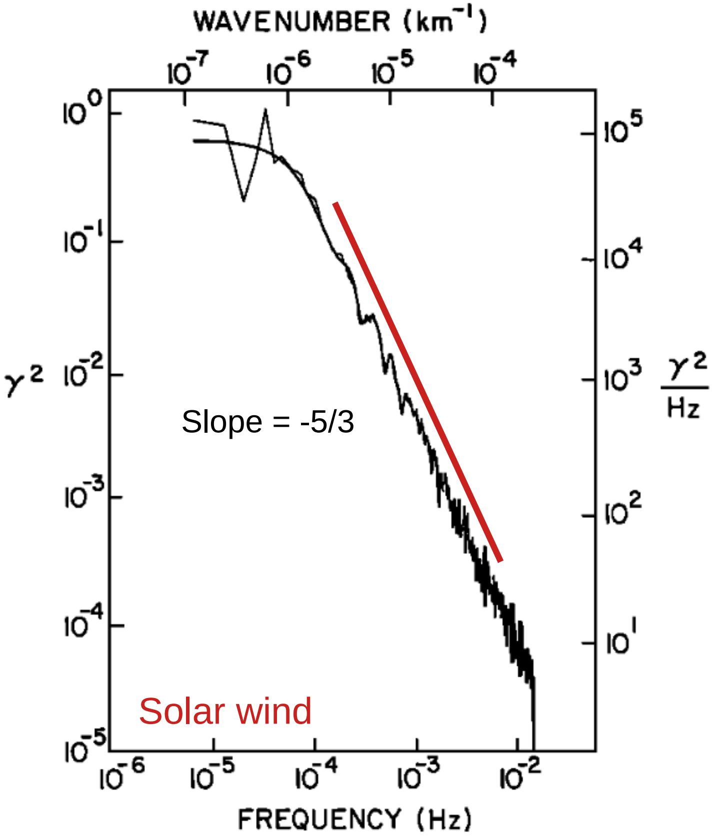


Earth simulator, 4096^3, isovorticity Surfaces, Y. Kaneda

Universal Kolmogorov power law of -5/3

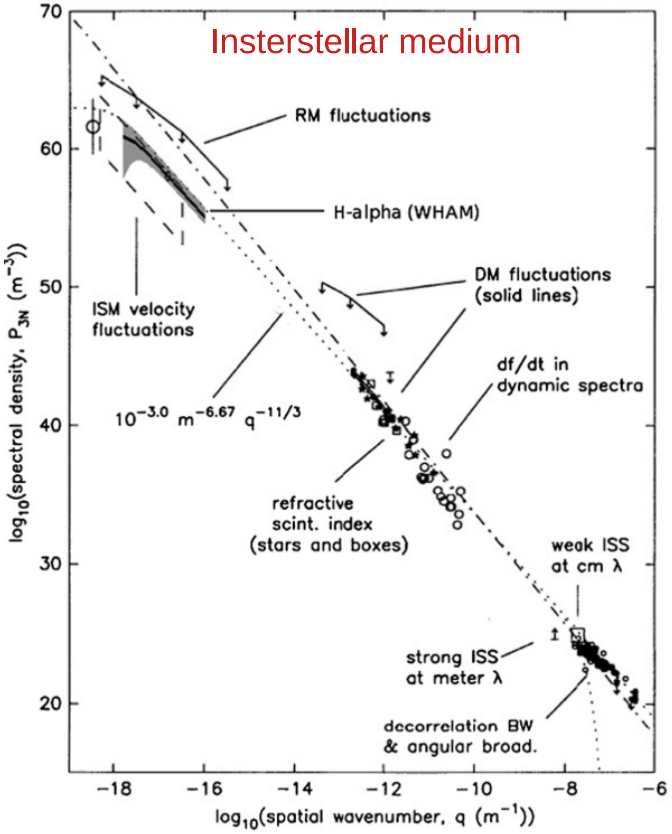


Gibson et al, 1962



Matthaeus & Goldstein, JGR, 1982

Great Power Law in the Sky



Armstrong et al., ApJ, 1995

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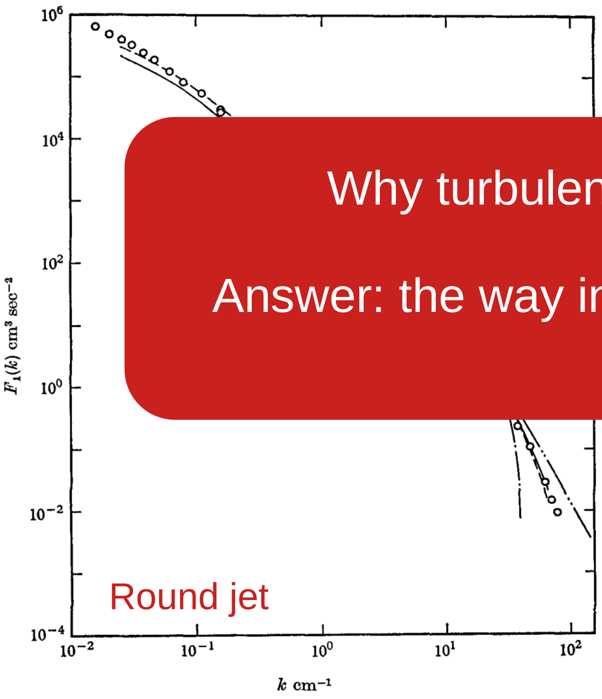
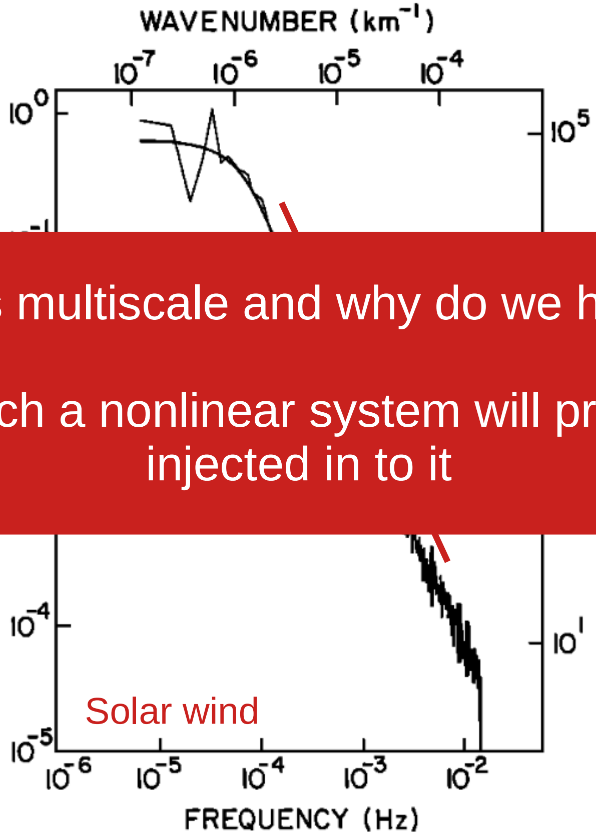


Gibson et al, 1962



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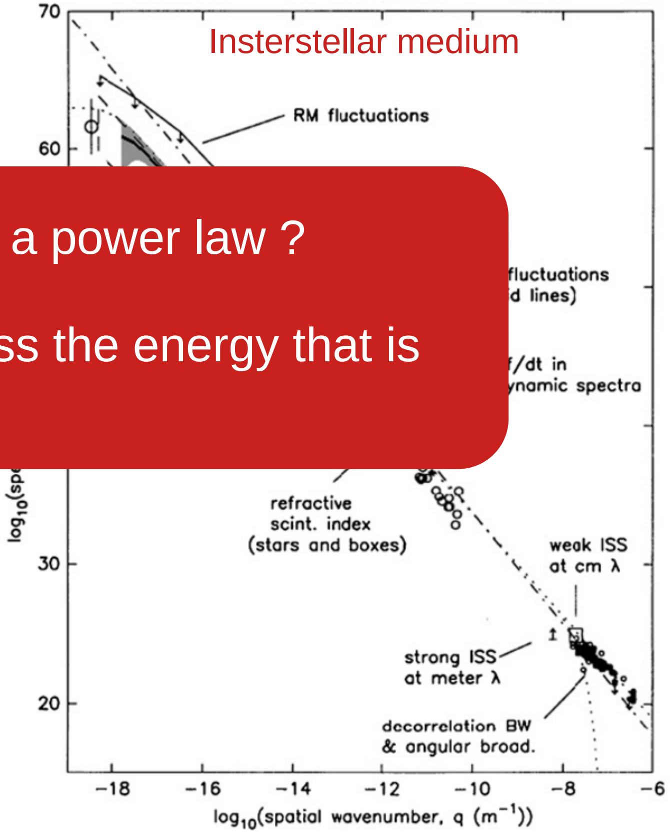

Armstrong et al., ApJ, 1995

Why turbulence is multiscale and why do we have a power law ?

Answer: the way in which a nonlinear system will process the energy that is injected in to it

Turbulence in neutral fluid - Hydrodynamics

Motion is described by the **Navier-Stokes equation** (momentum equation for a moving incompressible fluid)

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\,\mathbf{u} = -\nabla P + \nu\nabla^2(\mathbf{u}) + F$$

- $\frac{\partial \mathbf{u}}{\partial t}$: Rate of change of velocity of a fluid
- $(\mathbf{u}\cdot\nabla)\,\mathbf{u}$: Moving fluid element advect each other
- $-\nabla P$: Pressure gradient
- $\nu\nabla^2(\mathbf{u})$: Viscosity (dissipation)
- F: External force (injection of energy)

Kinetic energy of the system:

$$\epsilon = \frac{1}{2}\int \frac{d^3\boldsymbol{r}}{V}\rho|\boldsymbol{u}|^2$$

The rate of change of the kinetic energy:

$$\frac{d\epsilon}{dt} = \int \frac{d^3\boldsymbol{r}}{V}\rho\,\boldsymbol{u}\cdot\boldsymbol{f} - \nu\int \frac{d^3\boldsymbol{r}}{V}\rho|\nabla\,\boldsymbol{u}|^2 = P_{inj} - P_{diss}$$

Steady state $\frac{d\epsilon}{dt} = 0 \rightarrow P_{inj} = P_{diss}$

$$P_{inj} \approx \frac{\rho u^3}{L} \qquad P_{dissip} \approx \frac{\rho\,\nu\,u^2}{L^2}$$

Where U and L are respectively a "typical" (average) velocity and scale (wavelength, 2π/k) of the flow, and ν is the kinematic viscosity of the flow.

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A necessary condition for turbulence: large Reynolds number!

$$P_{inj} \approx \frac{\rho u^3}{L}$$

$$P_{dissip} \approx \frac{\rho \nu u^2}{L^2}$$

$$\Rightarrow \quad \boxed{\frac{P_{inj}}{P_{dissip}} \approx \frac{u\,L}{\nu} = R_e \gg 1}$$

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→

$$\frac{P_{inj}}{P_{dissip}} \approx \frac{u L}{\nu} = R_e \gg 1$$

→

There is an imbalance between the injection and the dissipation and Nature has to correct for it!

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→

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→

The way to make dissipation large by making the scales Smaller (→ large *k*)

Kolmogorov spectrum and turbulence cascade

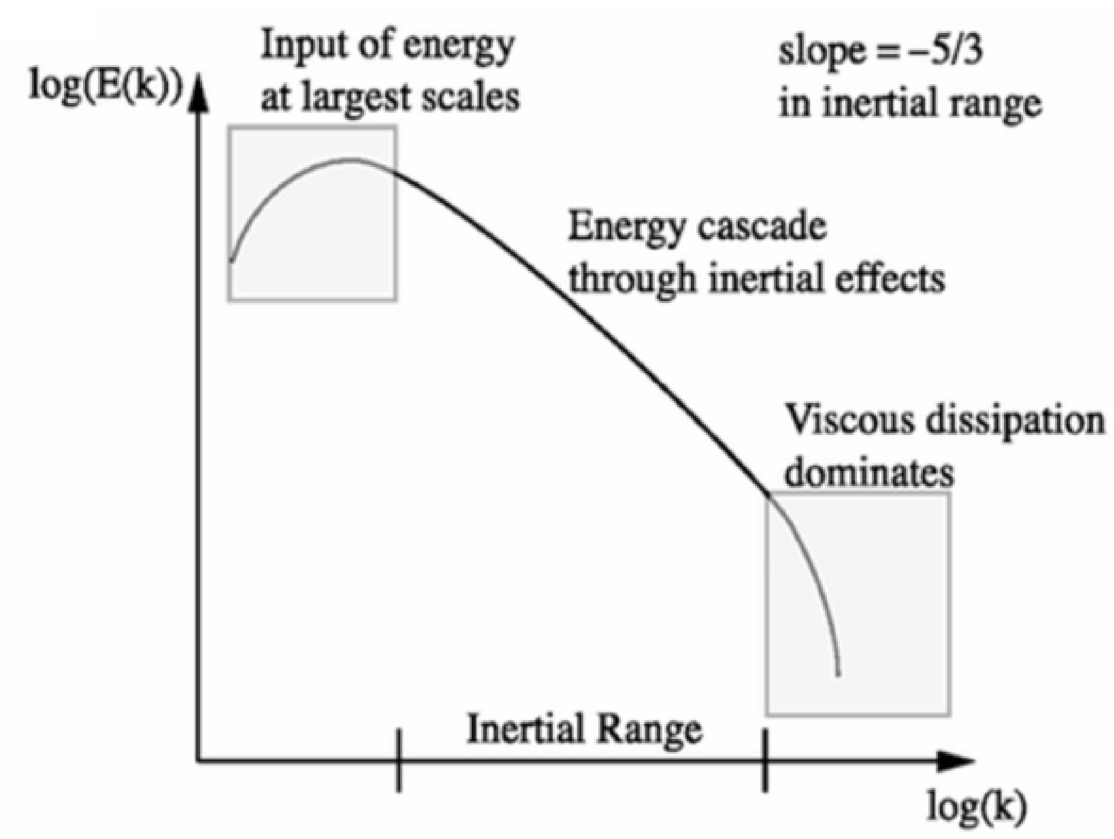
Kolmogorov’s theory describes how energy is transferred from larger to smaller eddies.

$$L_{inj} \gg l \gg l_{\nu}$$

Injection

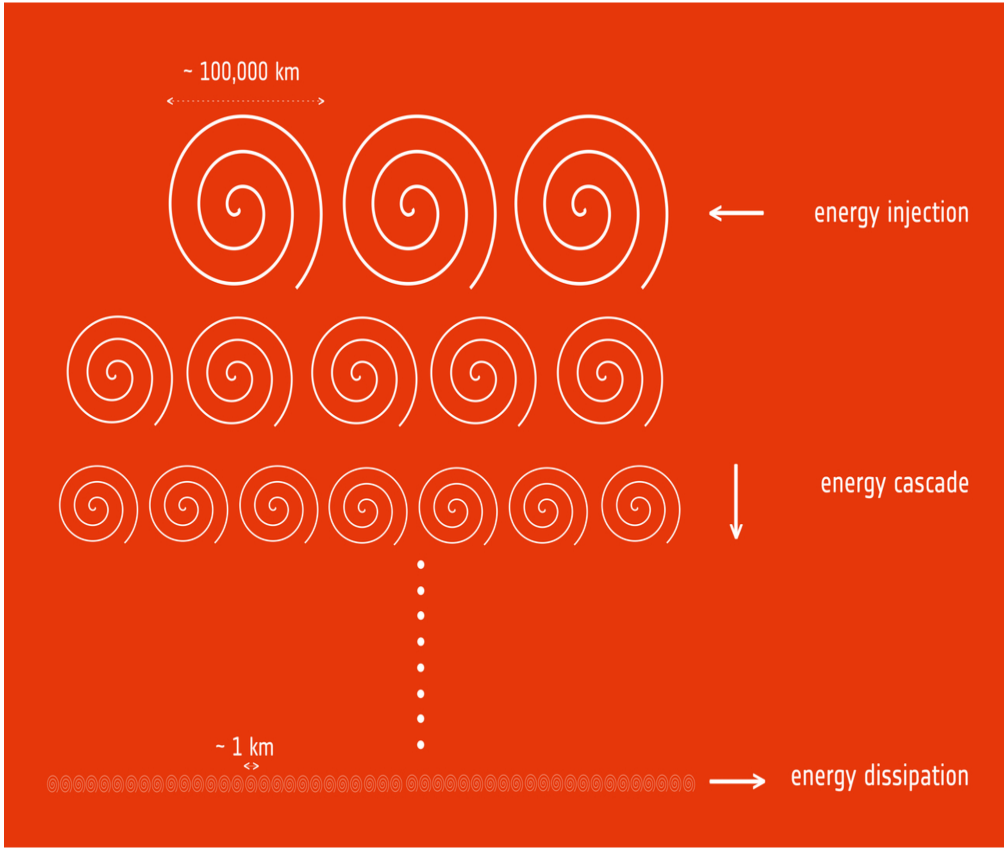
Dissipation

“Inertial range”

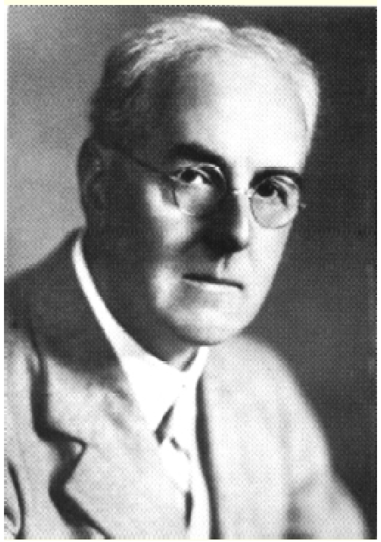


Phenomenological approach: Richardson picture

Lewis Fry Richardson (“Weather Prediction by Numerical Process.” Cambridge University Press, 1922) summarized this in the following often cited verse:



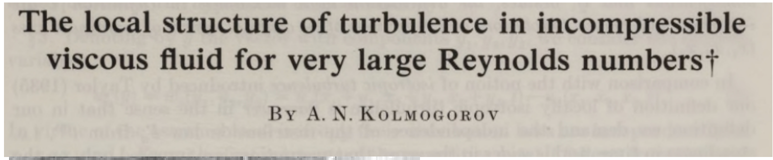
Big whirls have little whirls
Which feed on their velocity;
And little whirls have lesser whirls, And so on to viscosity
in the molecular sense



L. F. Richardson
(181 - 1953)

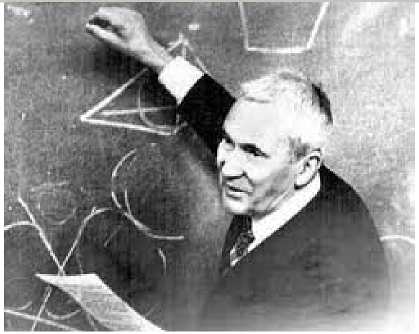
Exact law for incompressible HD turbulence

The first exact law of **a fully developed incompressible turbulence** was derived by Kolmogorov in 1941 [Kolmogorov, 1941], known as the 4/5 law.

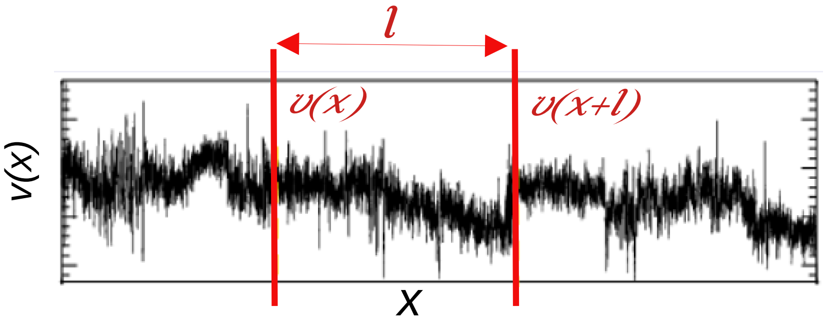


The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers†

By A. N. Kolmogorov



A. N. Kolmogorov (1903–1987)



Hypothesis:

- *Universality (no special systems)*
- *Homogeneity (no special locations)*
- *Isotropy (no special directions)*
- *Locality in scale space (no special scales)*

$$-\frac{4}{5}\varepsilon l = < (\delta v_l)^3 >$$

ε is the energy cascade (dissipation) rate

$$\delta v_\ell(t) = v_\ell(x+\ell) - v_\ell(x)$$

the velocity increments at scale l

$$E_k \sim {v_l}^2 k^{-1} \sim (\varepsilon k^{-1})^{2/3} k^{-f1} \sim \varepsilon^{2/3} k^{-5/3}$$

Turbulence in plasmas

On sufficiently large scales, we can treat the plasma as a fluid → **Magnetohydrodynamics**

Low frequencies and large scales (hypothesis in MHD)

$$\partial_t \approx 1/\tau \ll \omega_{ci}, \omega_{pe}$$
$$\partial_x \approx 1/L \ll \rho_{Li}, \lambda_{De}$$

Consequence of the slow variations:

1) Quasi-neutrality → $n_+ q_+ + n_- q_- \sim 0$ → $n_+ \sim n_- \sim n$
2) zero current → $n_+ q_+ v_+ + n_- q_- v_- \sim 0$ → $v_+ \sim v_- \sim v$

Key difference to neutral fluids:

→ Presence of a magnetic field → Breaks isotropy

Incompressible magnetohydrodynamics (MHD)

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mathbf{B} \cdot \nabla \mathbf{B} + \nu \nabla^2 \mathbf{u}$$

Magnetic tension

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

The ideal (resistivity = 0) version of the induction equation.

$$\nabla \cdot \mathbf{u} = 0$$

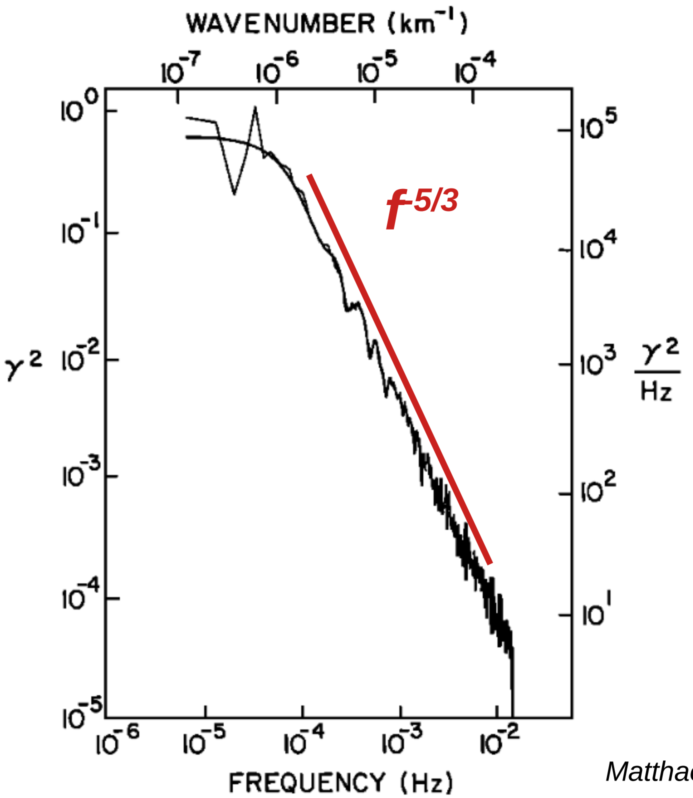
$$\nabla \cdot \mathbf{B} = 0.$$

“Fluid elements that lie on a field line initially will remain on this field line” → the magnetic field moves with the flow.

→ The total magnetic field can be split into two parts: $\mathbf{B} = \mathbf{B}_0 + \delta \mathbf{B}$ (mean + fluctuations).

Incompressible magnetohydrodynamics (MHD)

$$\frac{\partial \mathbf{z}^{\pm}}{\partial t} \mp (\mathbf{v_A} \cdot \nabla)\,\mathbf{z}^{\pm} + (\mathbf{z}^{\mp} \cdot \nabla)\,\mathbf{z}^{\pm} = -\nabla P_{\mathrm{tot}}{}^{*} + \nu^{\pm}\nabla^2\mathbf{z}^{\pm} + \nu^{\mp}\nabla^2\mathbf{z}^{\mp} + \mathbf{F}^{\pm}$$



Matthaeus & Goldstein, JGR, 1982

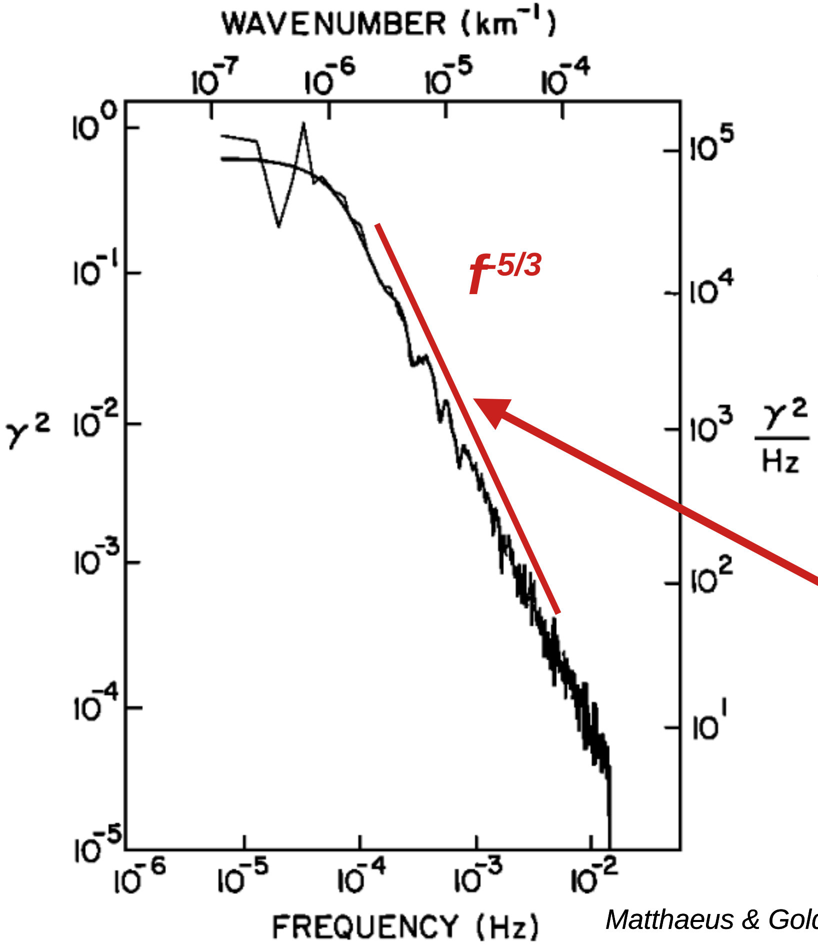
Elsasser variables:

$$\mathbf{z}^{\pm} = \mathbf{v} \pm \frac{\mathbf{B}}{\sqrt{4\pi\rho_0}} = \mathbf{v} \pm \mathbf{v}_A$$

$$-\frac{4}{3}\varepsilon^{\pm}\ell = < (\delta\mathbf{z}^{\pm} \cdot \delta\mathbf{z}^{\pm})\delta z_{\ell}^{\mp} >$$

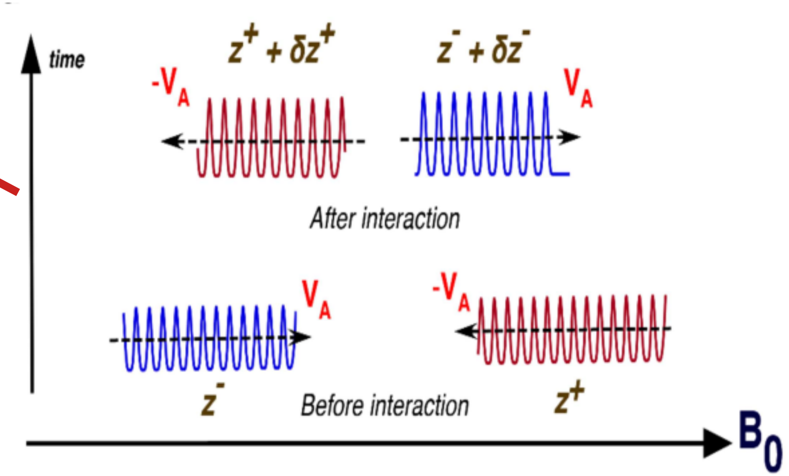
Politano & Pouquet, PRE, 1998

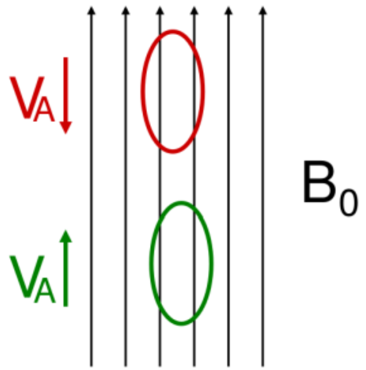
Incompressible magnetohydrodynamics (MHD)



Matthaeus & Goldstein, JGR, 1982

In order to have a better understanding of the multi-scale dynamics in a magnetized fluid, Iroshnikov [1964] and Kraichnan [1965] proposed independently a physical image of MHD turbulence known as the **"IK phenomenology"** based on the nonlinear interactions (collisions) between counter-propagating wavepackets moving at the Alfven speed.





Exact law for compressible isothermal MHD

$$-\frac{4}{3}\varepsilon_C \ell = \mathrm{F}_{1\mathrm{C}} + \mathrm{F}_{2\mathrm{C}} + \mathrm{Q}_{\mathrm{S_C}} + \mathrm{Q}_{\mathrm{S_H}} + \mathrm{Q}_{\mathrm{M}_\beta},$$

Nonflux terms

$$\mathbf{F}_{1\mathrm{C}} \equiv \langle [(\delta(\rho\mathbf{u}) \cdot \delta\mathbf{u} + \delta(\rho\mathbf{u}_\mathrm{A}) \cdot \delta\mathbf{u}_\mathrm{A}]\delta\mathbf{u} - [\delta(\rho\mathbf{u}) \cdot \delta\mathbf{u}_\mathrm{A} + \delta\mathbf{u} \cdot \delta(\rho\mathbf{u}_\mathrm{A})]\delta\mathbf{u}_\mathrm{A}\rangle$$

Compressible generalization of the Incompressible flux term (Monin & Yaglom 1975)

$$\mathbf{F}_{2\mathrm{C}} \equiv 2\langle \delta\rho\delta e\delta\mathbf{u}\rangle,$$

New purely compressible term

$$\mathrm{S_C} = \langle [R'_E - \frac{1}{2}(R'_B + R_B)](\boldsymbol{\nabla} \cdot \mathbf{u}) + [R_E - \frac{1}{2}(R_B + R'_B)](\boldsymbol{\nabla}' \cdot \mathbf{u}')\rangle + \langle [(R_H - R'_H) - \bar{\rho}(\mathbf{u}' \cdot \mathbf{u}_\mathrm{A})](\boldsymbol{\nabla} \cdot \mathbf{u}_\mathrm{A}) + [(R'_H - R_H) - \bar{\rho}(\mathbf{u} \cdot \mathbf{u}'_\mathrm{A})](\boldsymbol{\nabla}' \cdot \mathbf{u}'_\mathrm{A})\rangle.$$

$$\mathrm{S_H} = \langle (\frac{P'_M - P'}{2} - E')(\boldsymbol{\nabla} \cdot \mathbf{u}) + (\frac{P_M - P}{2} - E)(\boldsymbol{\nabla}' \cdot \mathbf{u}')\rangle + \langle H'(\boldsymbol{\nabla} \cdot \mathbf{u}_\mathrm{A}) + H(\boldsymbol{\nabla}' \cdot \mathbf{u}'_\mathrm{A})\rangle + \frac{1}{2}\langle (e' + \frac{{u_\mathrm{A}}'^2}{2})[\boldsymbol{\nabla} \cdot (\rho\mathbf{u})] + (e + \frac{{u_\mathrm{A}}^2}{2})[\boldsymbol{\nabla}' \cdot (\rho'\mathbf{u}')]\rangle,$$

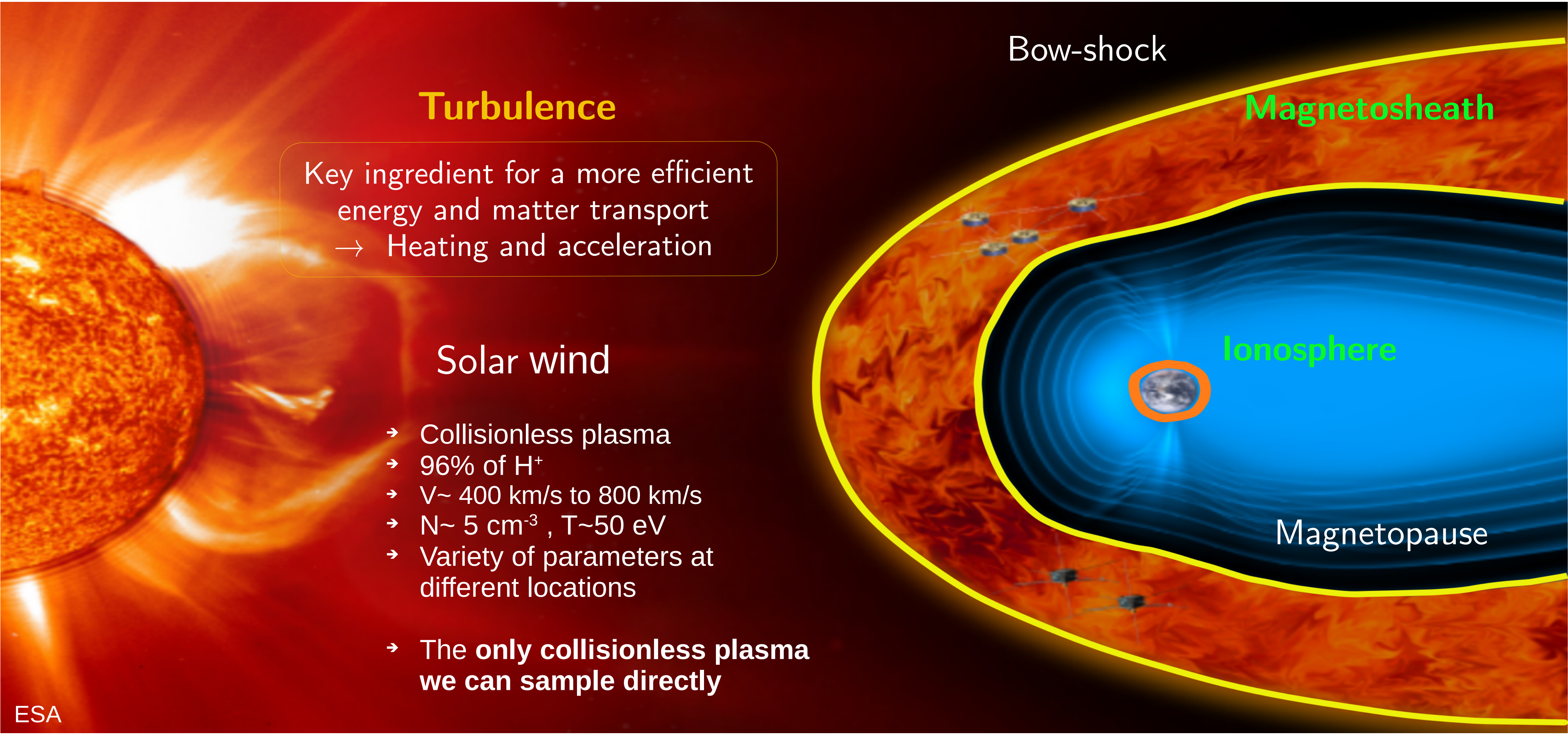
$$\mathrm{M} = -\frac{1}{2}\langle {\beta^{-1}}' \boldsymbol{\nabla}' \cdot (e'\rho\mathbf{u}) + \beta^{-1}\boldsymbol{\nabla} \cdot (e\rho'\mathbf{u}')\rangle.$$

Andrés & Sahraoui, PRE, 2017
Banerjee & Galtier PRE, 2013

Compressible exact law $$-\frac{4}{3}\varepsilon_C \ell = \mathrm{F}_{1\mathrm{C}} + \mathrm{F}_{2\mathrm{C}},$$

Incompressible exact law (Politano & Pouquet 1998) $$-\frac{4}{3}\varepsilon_I \ell = \mathrm{F}_I, \quad \boldsymbol{F}_I = \rho_0\langle [(\delta\boldsymbol{u})^2 + (\delta\boldsymbol{B})^2]\delta\boldsymbol{u} - 2(\delta\boldsymbol{u} \cdot \delta\boldsymbol{B})\delta\boldsymbol{B}\rangle$$

Solar wind – magnetosphere coupling



Turbulence

Key ingredient for a more efficient energy and matter transport
$\rightarrow$ Heating and acceleration

Solar wind

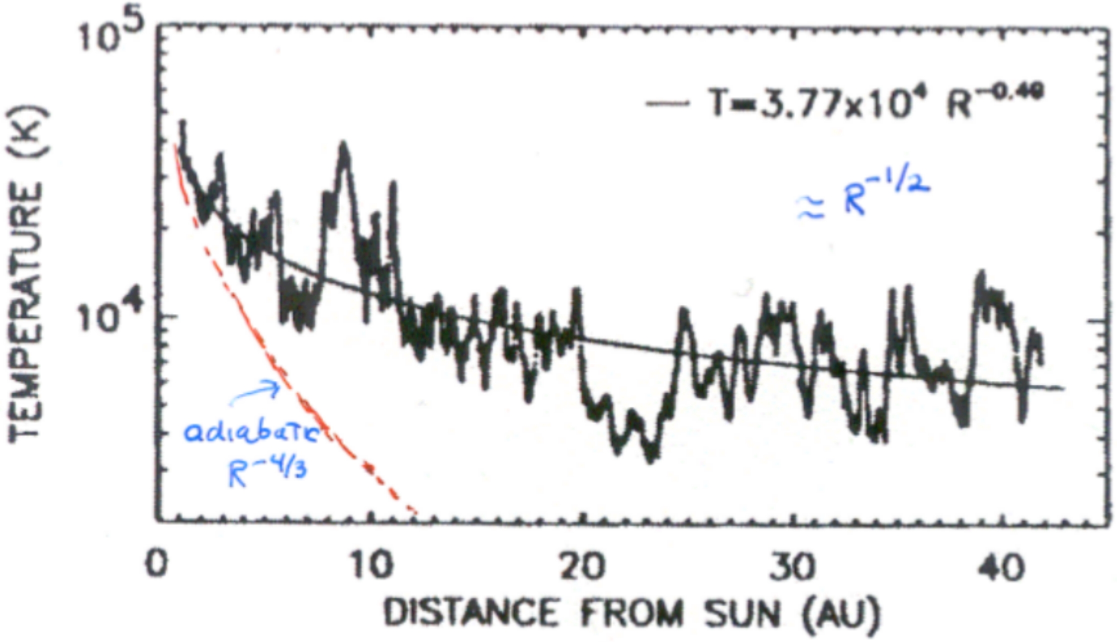
- Collisionless plasma
- 96% of H^+
- V~ 400 km/s to 800 km/s
- N~ 5 cm^{-3} , T~50 eV
- Variety of parameters at different locations

- The **only collisionless plasma we can sample directly**

Anomalous heating of the solar wind

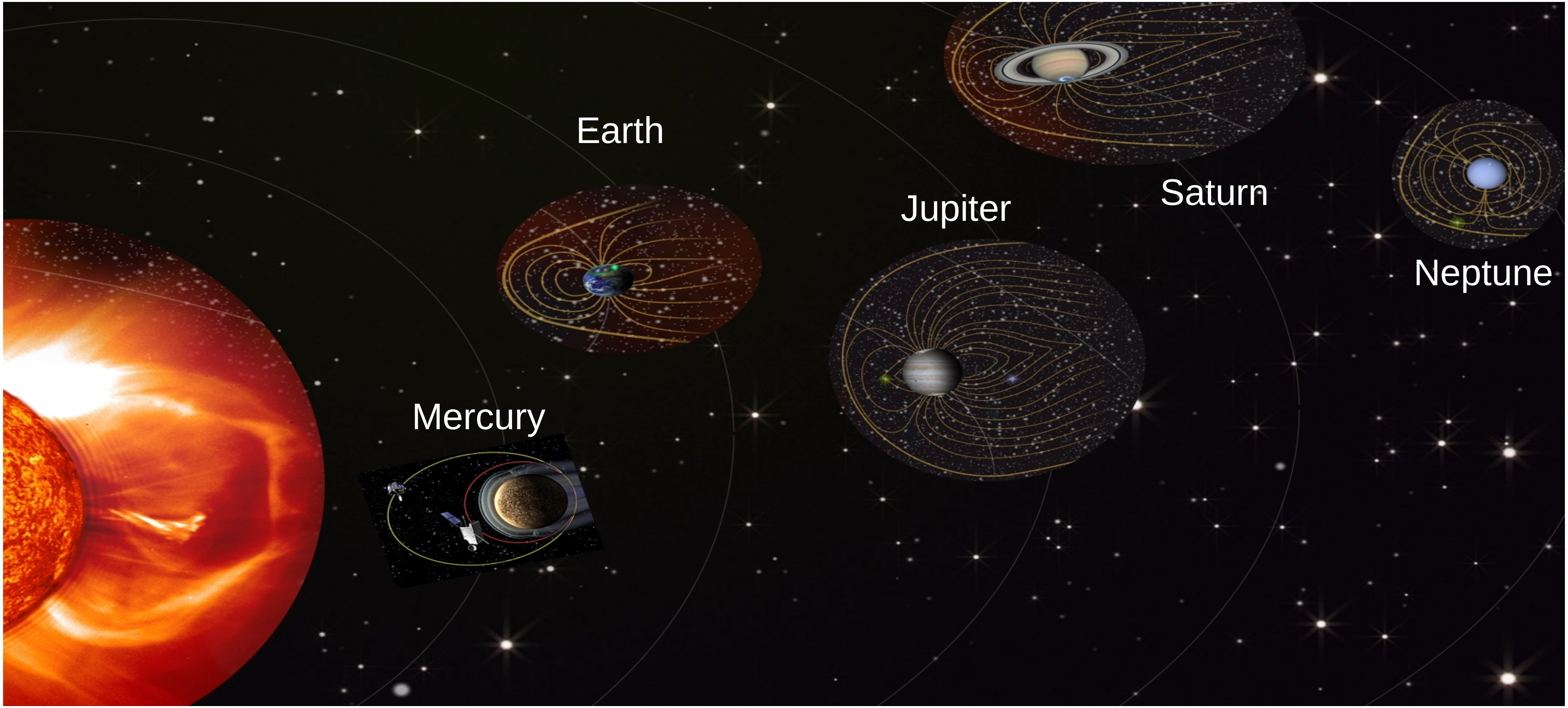
The solar wind plasma is known to cool down more slowly than expected from an a spherical adiabatic expansion model → **A source of local heating is needed!**

Energy dissipation rate needs to be measured!

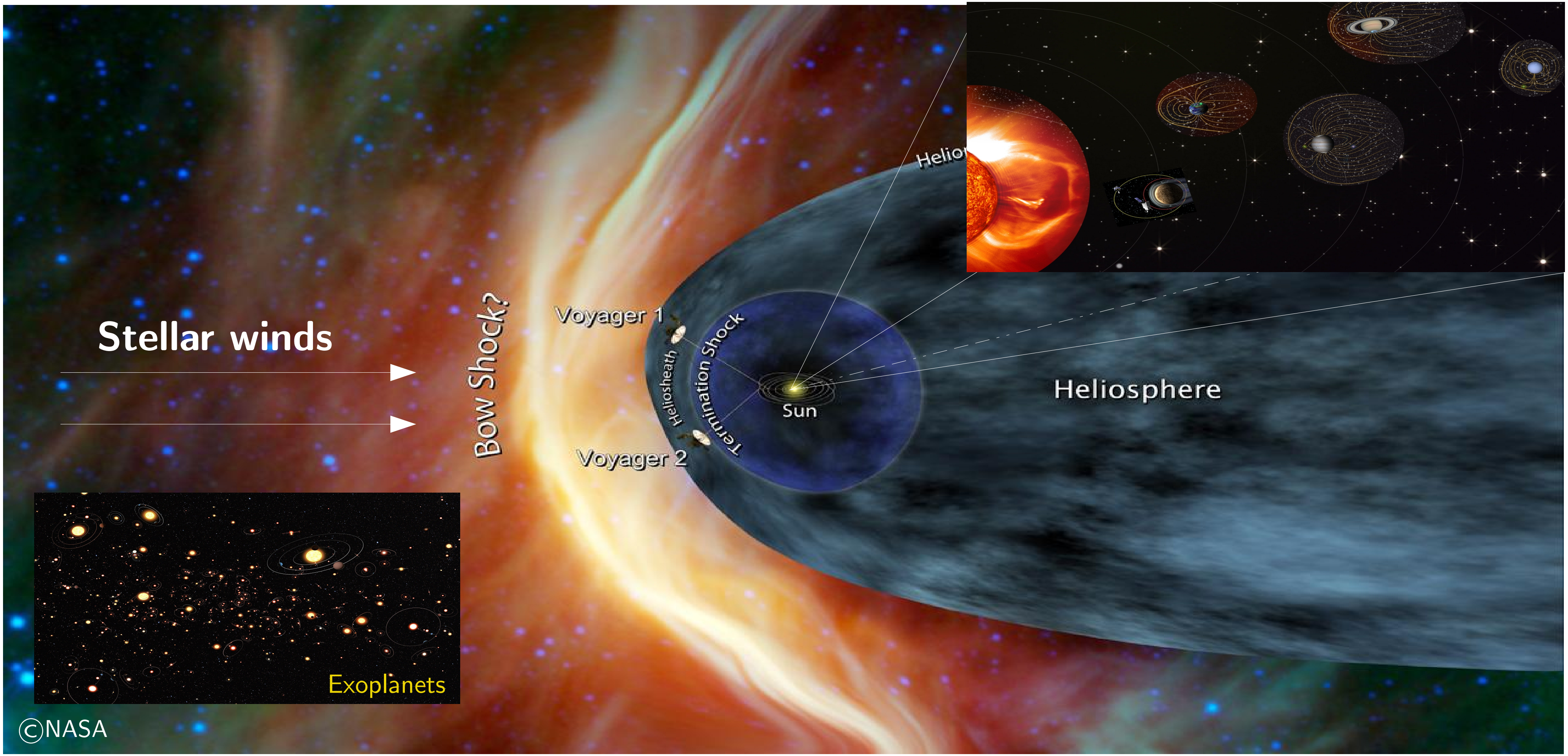


Richardson & Paularena, GRL, 1995

Analogous to other planetary magnetospheres

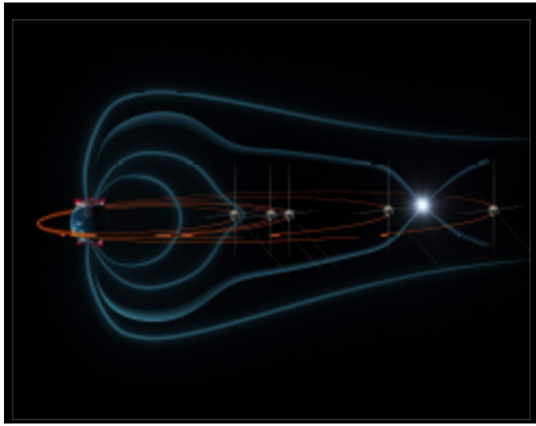


...and to the Heliosphere & beyond...

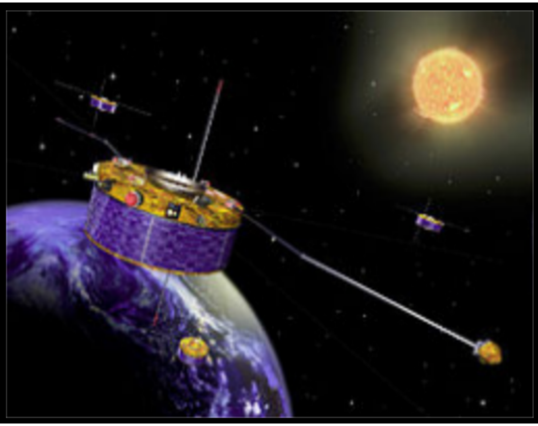


In-situ fields and particles spacecraft data

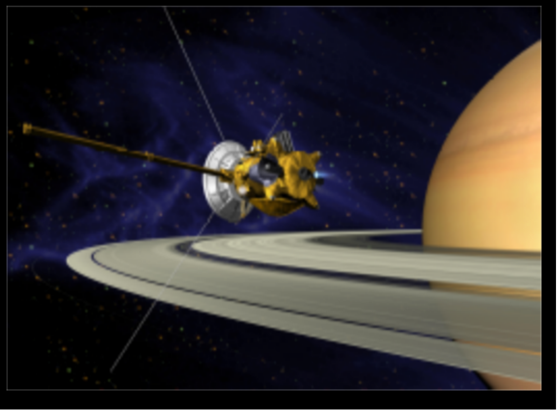
Themis/Artemis (1AU)
NASA



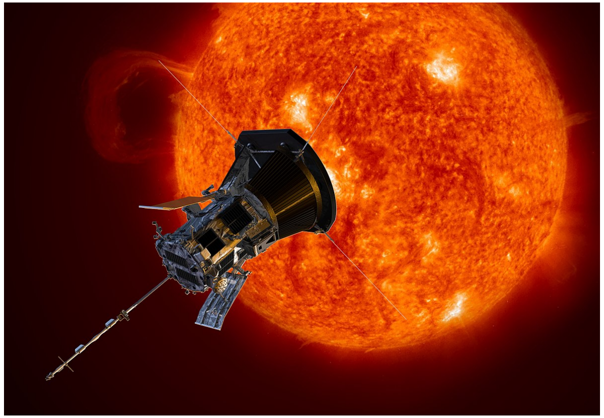
Cluster (1AU)
ESA



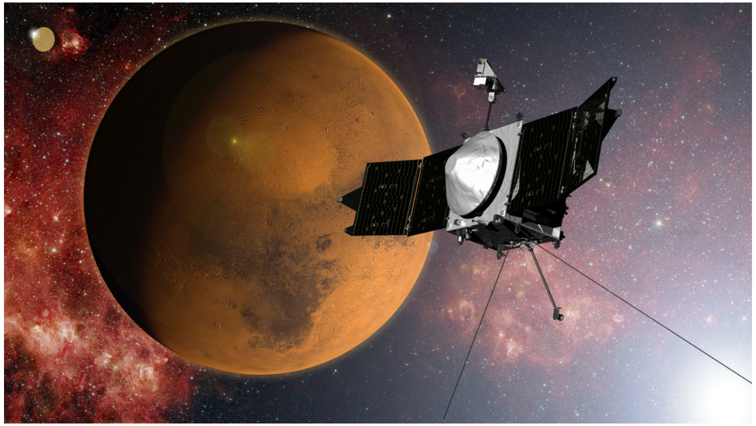
Cassini/Huygens (10 AU)
ESA/NASA/ASI



PSP (0.2 AU)
NASA



MAVEN (1.5 AU)
NASA



Solar wind and planetary magnetosheaths

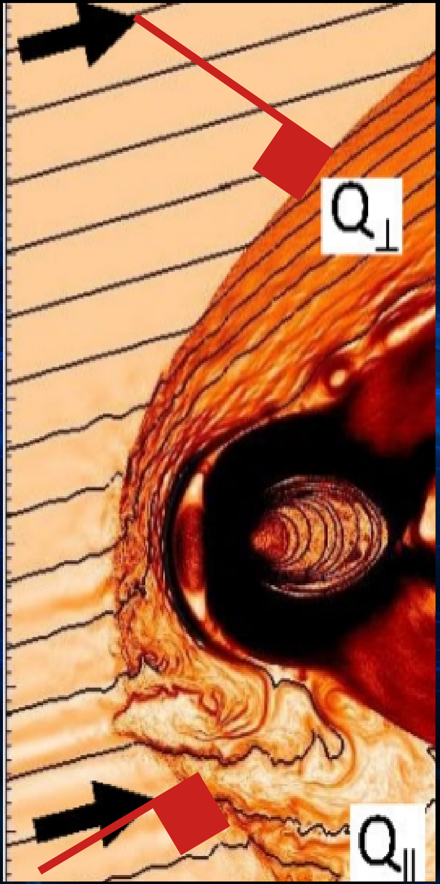
V~200 km/s
n~20 cm^{-3}
T~250 eV

Solar wind

- Collisionless plasma
- 96% of H^+
- V~ 400 km/s to 800 km/s
- N~ 5 cm^{-3} , T~50 eV

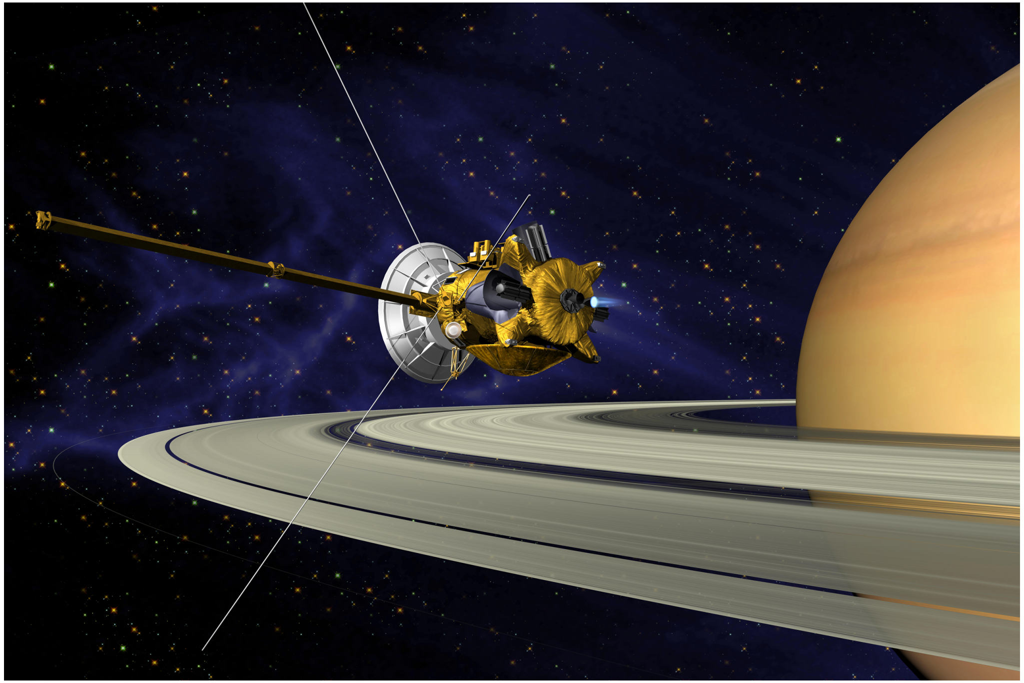
Magnetosheath:
A more Complex space plasma.

- Bounded region:
  Shock + magnetopause
- More Complex: highly disturbed, temperature anisotropies → Kinetic instabilities.
- Large scales inhomogeneities: Kelvin-Helmholtz instabilities.



Karimabadi, et al.,
Phys. Plasmas, 2014

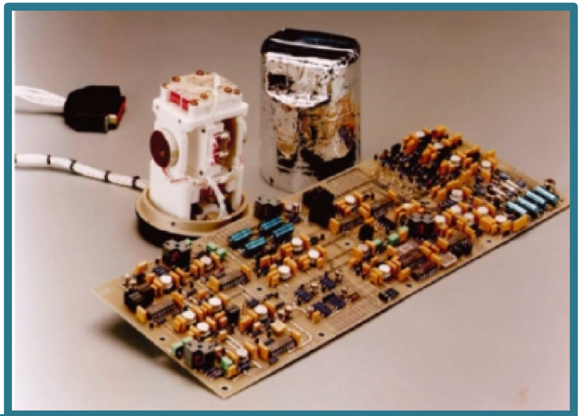
Spectral properties of turbulence



Launched: 1997
End: 2017
Goal: Explore Saturn and its plasma environment.

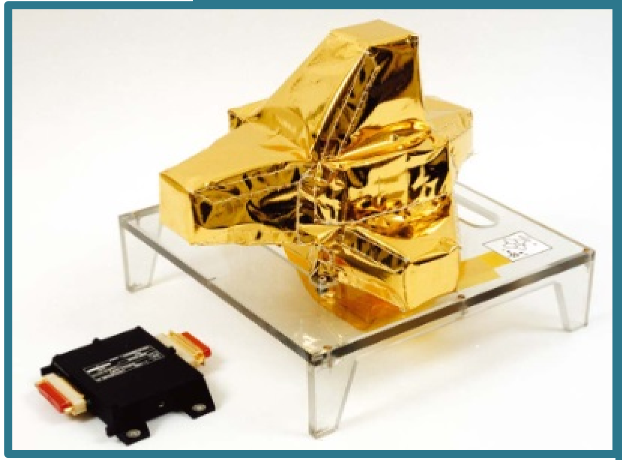
Cassini in situ fields and particles data

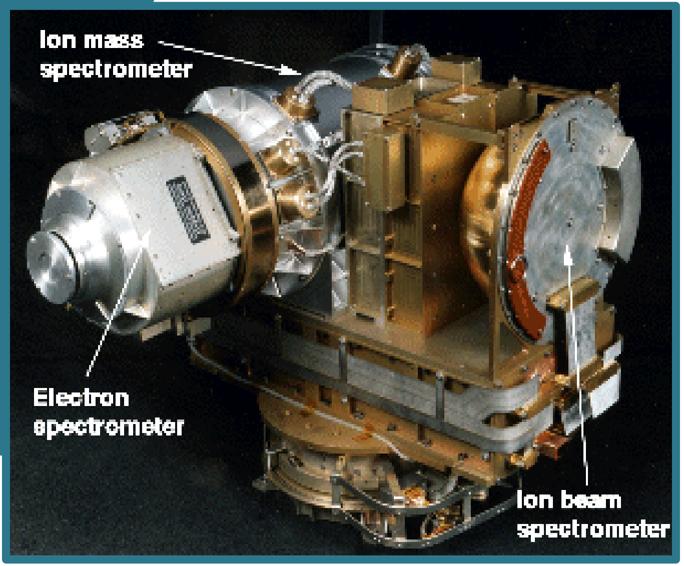
MAG: Low frequency measurements [DC-1Hz]



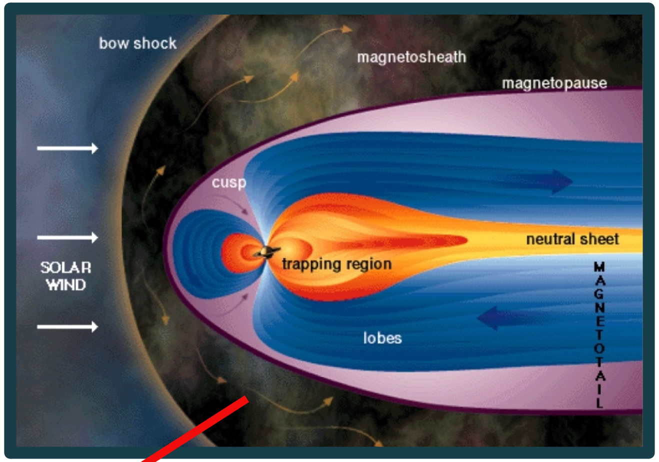
CAPS: Cassini Plasma Spectrometer
VDF of ions and electrons: n,V,T

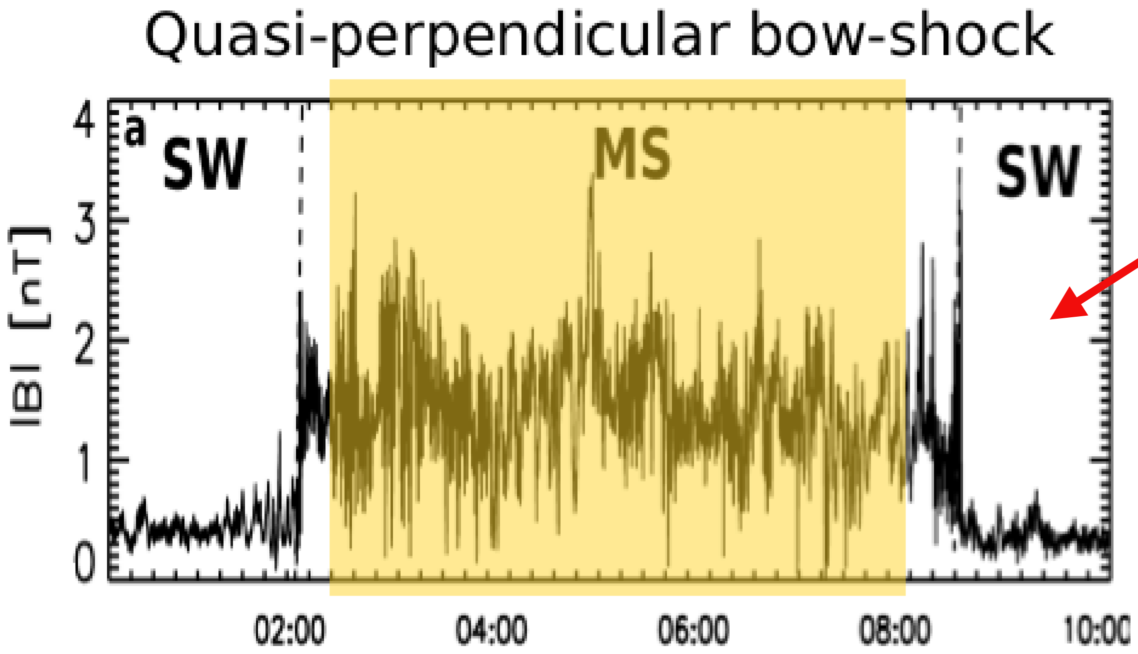
Search Coils: High frequency magnetic field fluctuations [1Hz-20KHz]





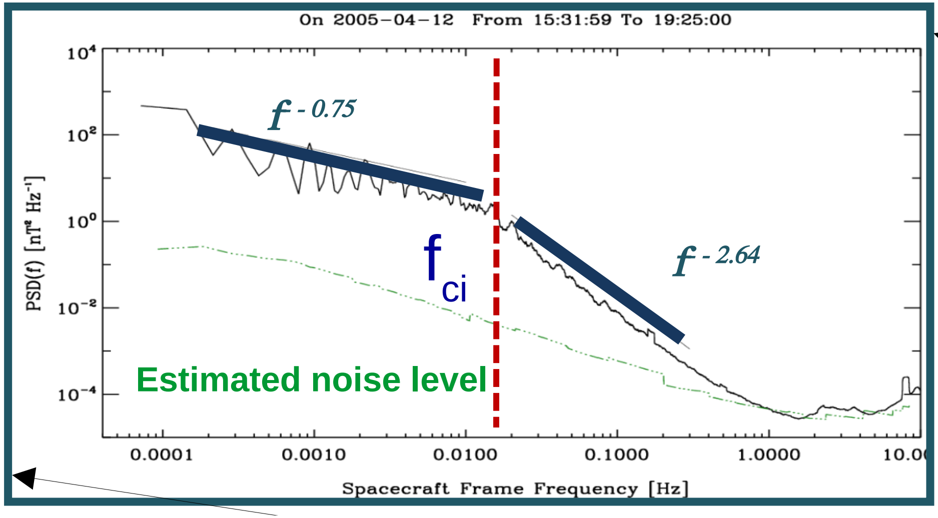
Example of magnetic energy spectrum

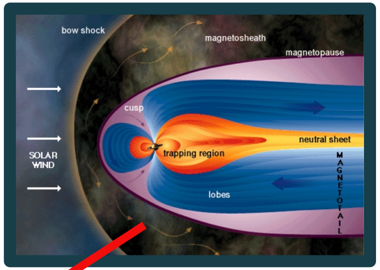


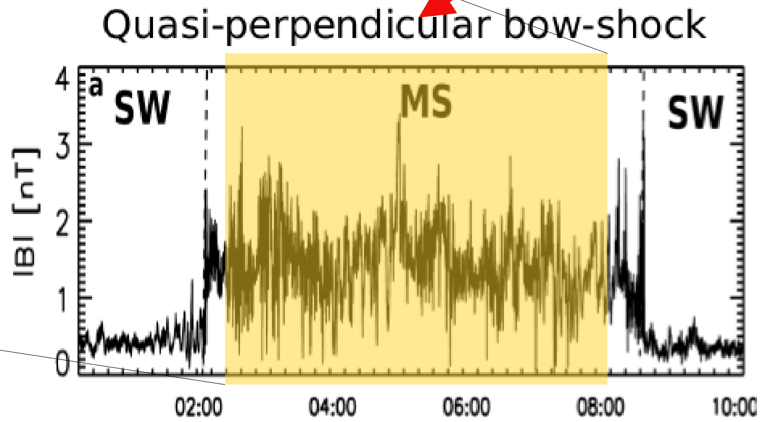


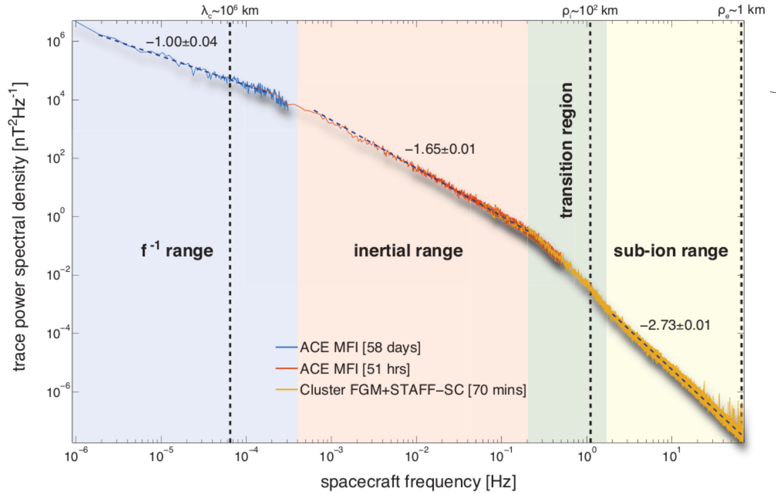
Hadid et al., ApJl, 2015

Example of magnetic energy spectrum





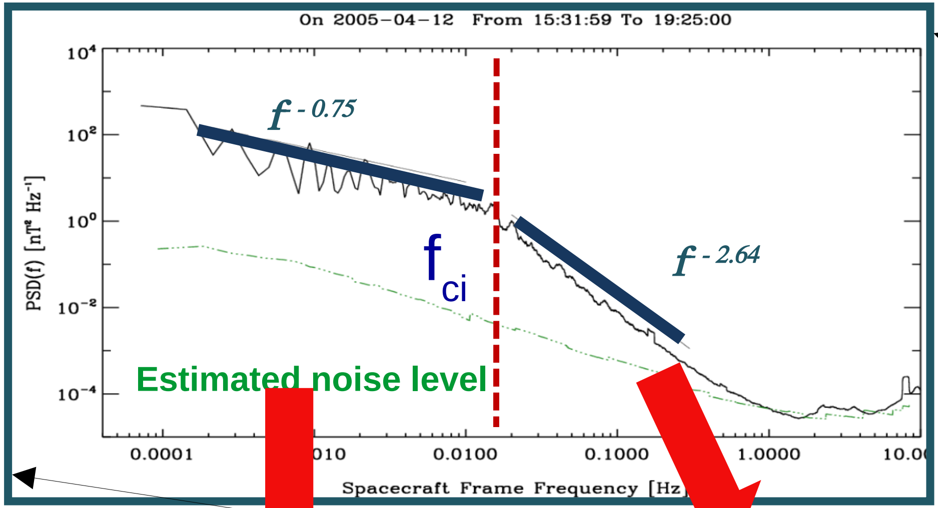


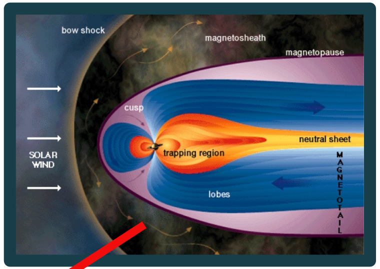


Kiyani et al., ApJl, 2015

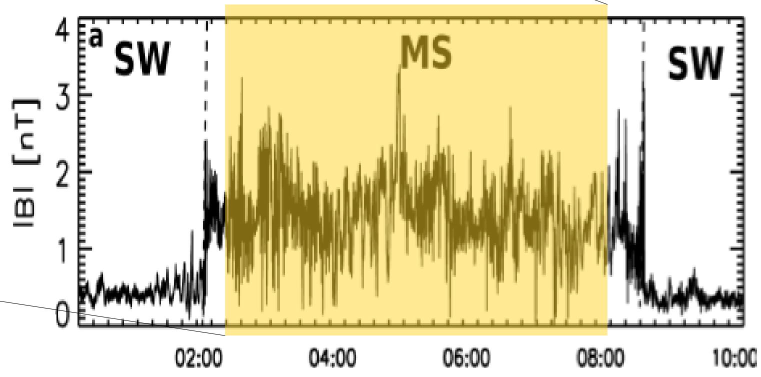
Hadid et al., ApJl, 2015

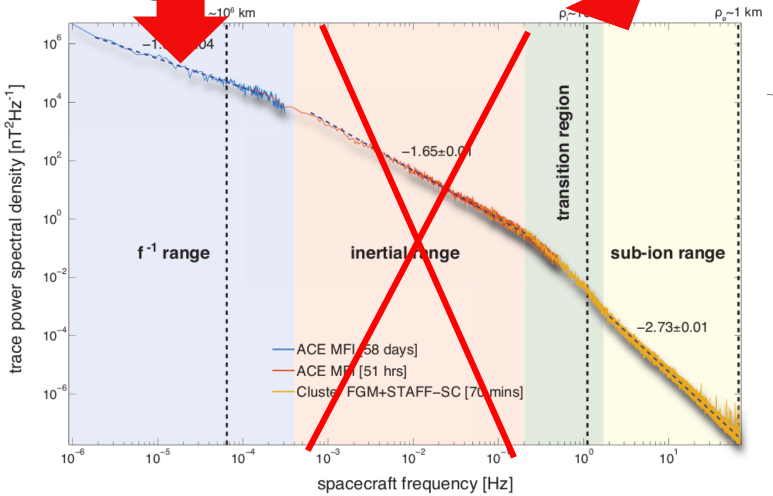
Example of magnetic energy spectrum





Quasi-perpendicular bow-shock

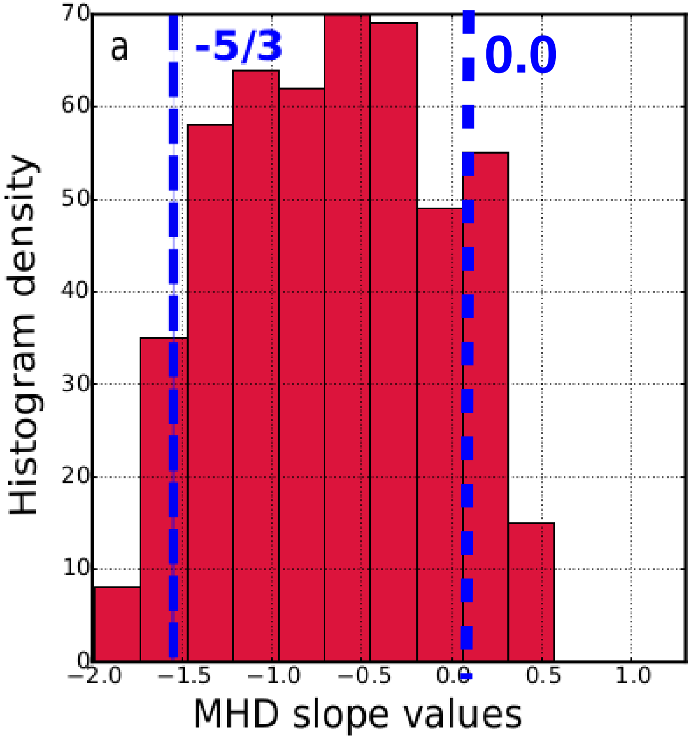


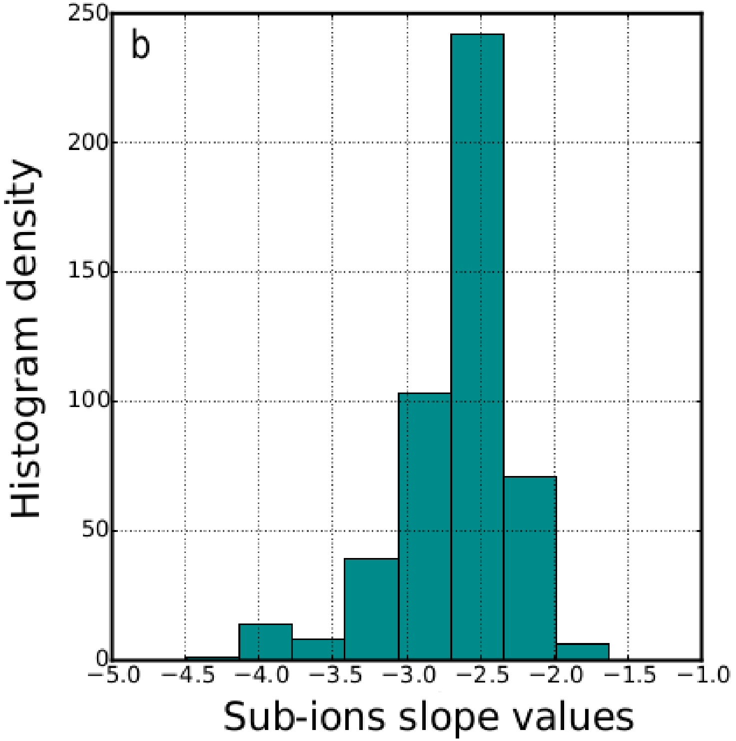


A fundamental difference with the SW:
Absence of the 5/3 Kolmogorov law

Slope distribution in Saturn's magnetosheath

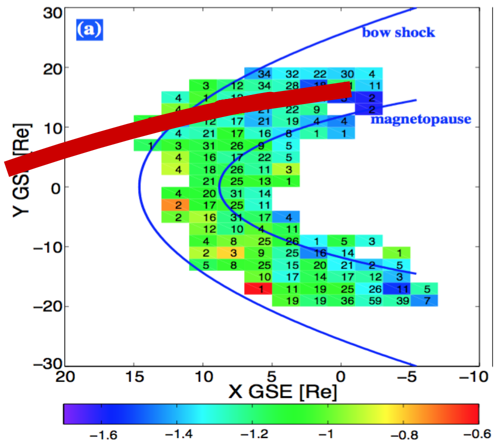
Statistical study: 400 time intervals (2h each) between 2004-2014



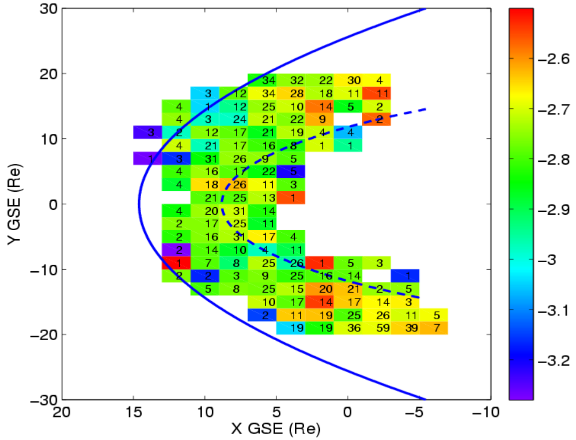


Slope distribution in the magnetosheath of Earth

MHD scales

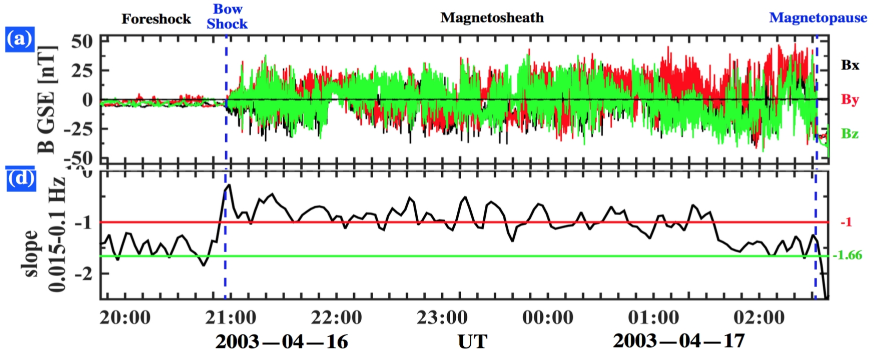


Sub-ions scales



MHD scales:
Dependence on the location within the Magnetosheath

Sub-ion scales:
No dependence on the location within the magnetosheath

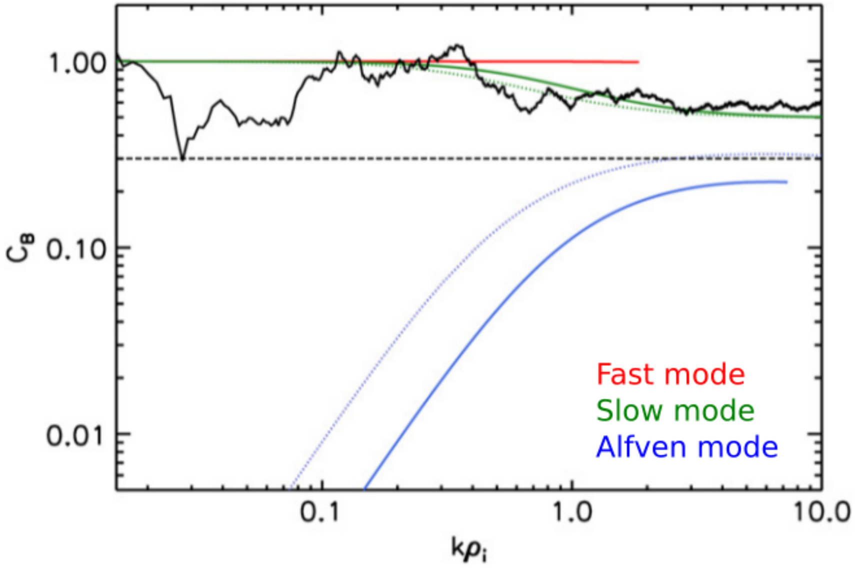


Local slope variation at MHD scales:
solar wind → bow shock → magnetopause.

S. Huang et al., ApJ, 2017

Nature of the fluctuations at the MHD scales

Magnetosheath Cassini Data

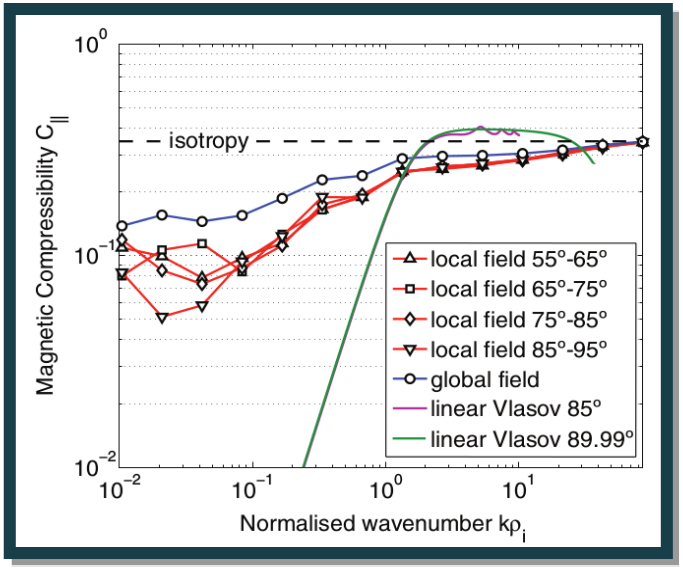


Theoretical Magnetic compressibilities

$$C_{||} = \delta B_{||}^2 / \delta B^2$$

Lacombe & Belmont, Adv. Space Res., 1995
Gary & Smith, JGR, 2009

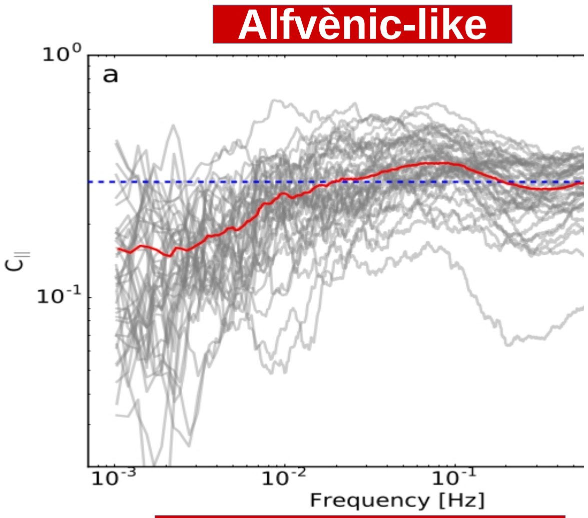
Solar Wind Cluster Data

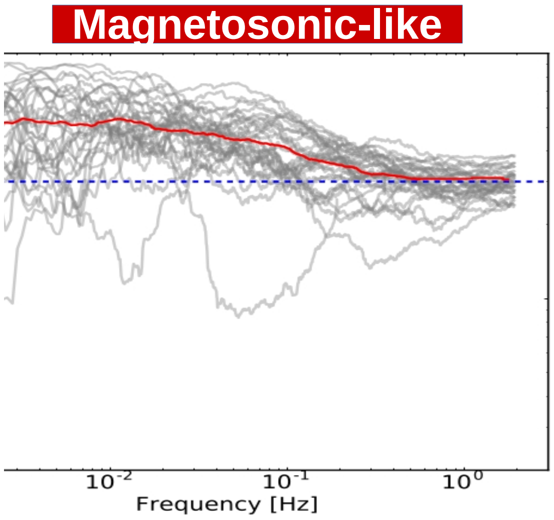


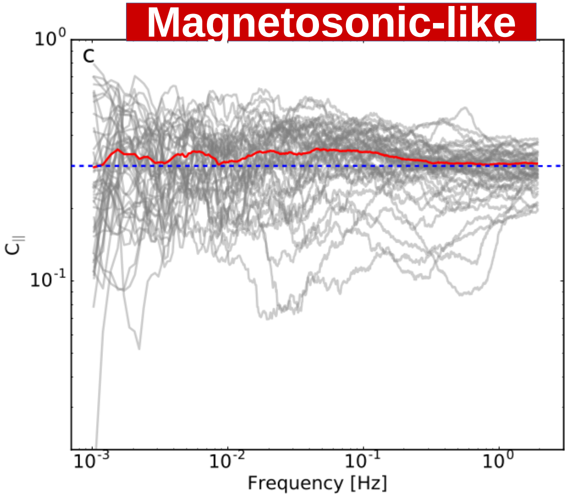
Kiyani et al. ApJ, 2013

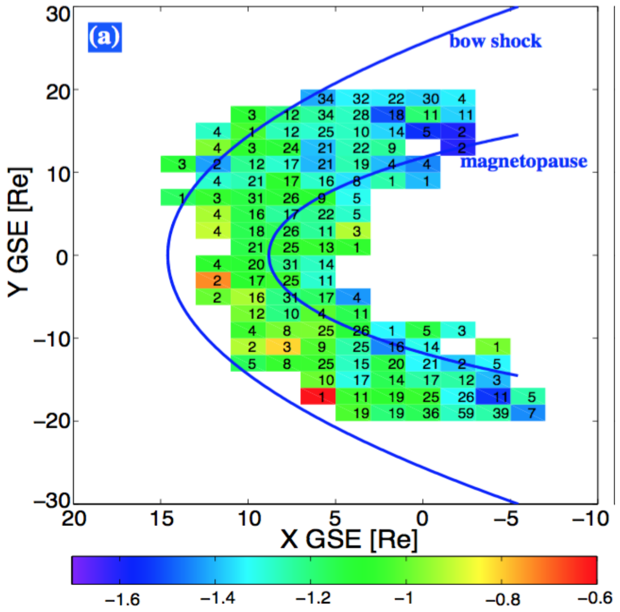
Highly compressible turbulence at MHD scales.

Nature of the fluctuations at the MHD scales









Dominance of the magnetosonic-like modes at the MHD scales

S. Huang et al., ApJ, 2017

Estimation of the energy/disspation rate

Exact law for incompressible MHD (PP98) *[Politano & Pouquet, PRE, 1998]*

$$\mathbf{z}^{\pm} = \mathbf{v} \pm \frac{\mathbf{B}}{\sqrt{4\pi\rho_0}}$$

$$\left\langle \left(\delta \mathbf{z}^{\pm}\right)^2 \delta z_l{}^{\mp} \right\rangle = -\frac{4}{3}\varepsilon^{\pm} l$$

Incompressible cascade/heating rate

Exact law for compressible MHD *[Andrés & Sahraoui, PRE, 2017, Banerjee & Galtier, PRE, 2013]*

$$\frac{4}{3}\varepsilon_C \ell = \mathrm{F}_{1\mathrm{C}} + \mathrm{F}_{2\mathrm{C}} + \mathrm{Q}_{\mathrm{S_C}} + \mathrm{Q}_{\mathrm{S_H}} + \mathrm{Q}_{\mathrm{M}_\beta},$$

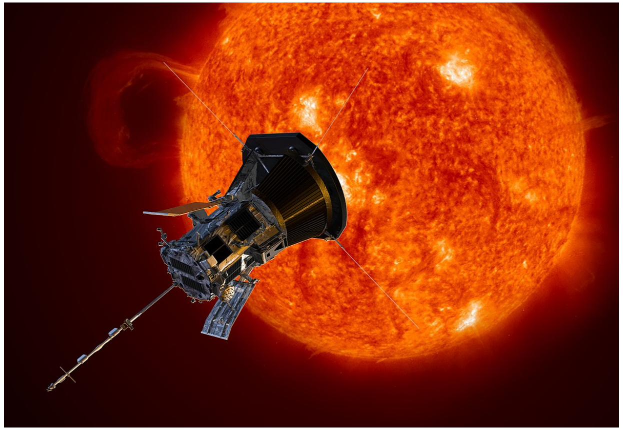
Compressible cascade/heating rate

$$\mathbf{F}_{1\mathrm{C}} \equiv \langle [(\delta(\rho\mathbf{u}) \cdot \delta\mathbf{u} + \delta(\rho\mathbf{u}_\mathrm{A}) \cdot \delta\mathbf{u}_\mathrm{A}]\delta\mathbf{u} - [\delta(\rho\mathbf{u}) \cdot \delta\mathbf{u}_\mathrm{A} + \delta\mathbf{u} \cdot \delta(\rho\mathbf{u}_\mathrm{A})]\delta\mathbf{u}_\mathrm{A}\rangle$$

$$\mathbf{F}_{2\mathrm{C}} \equiv 2\langle \delta\rho\delta e\delta\mathbf{u}\rangle$$

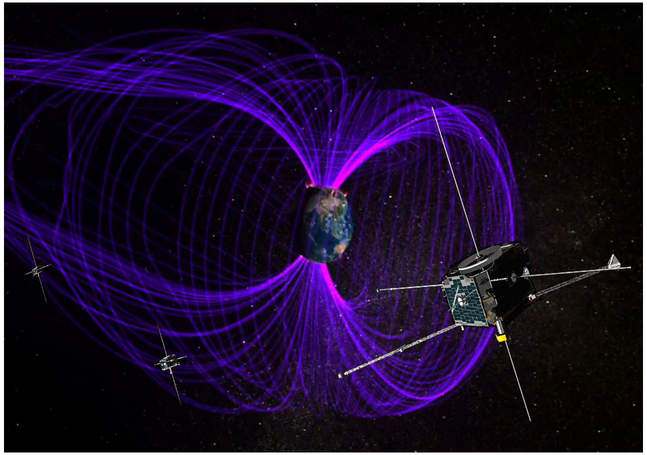
Estimation of the energy/disspation rate

PSP



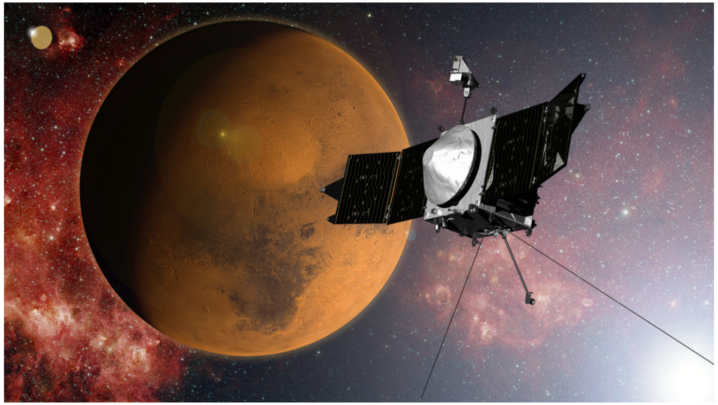
Sun (~ 0.2 A.U.)

THEMIS



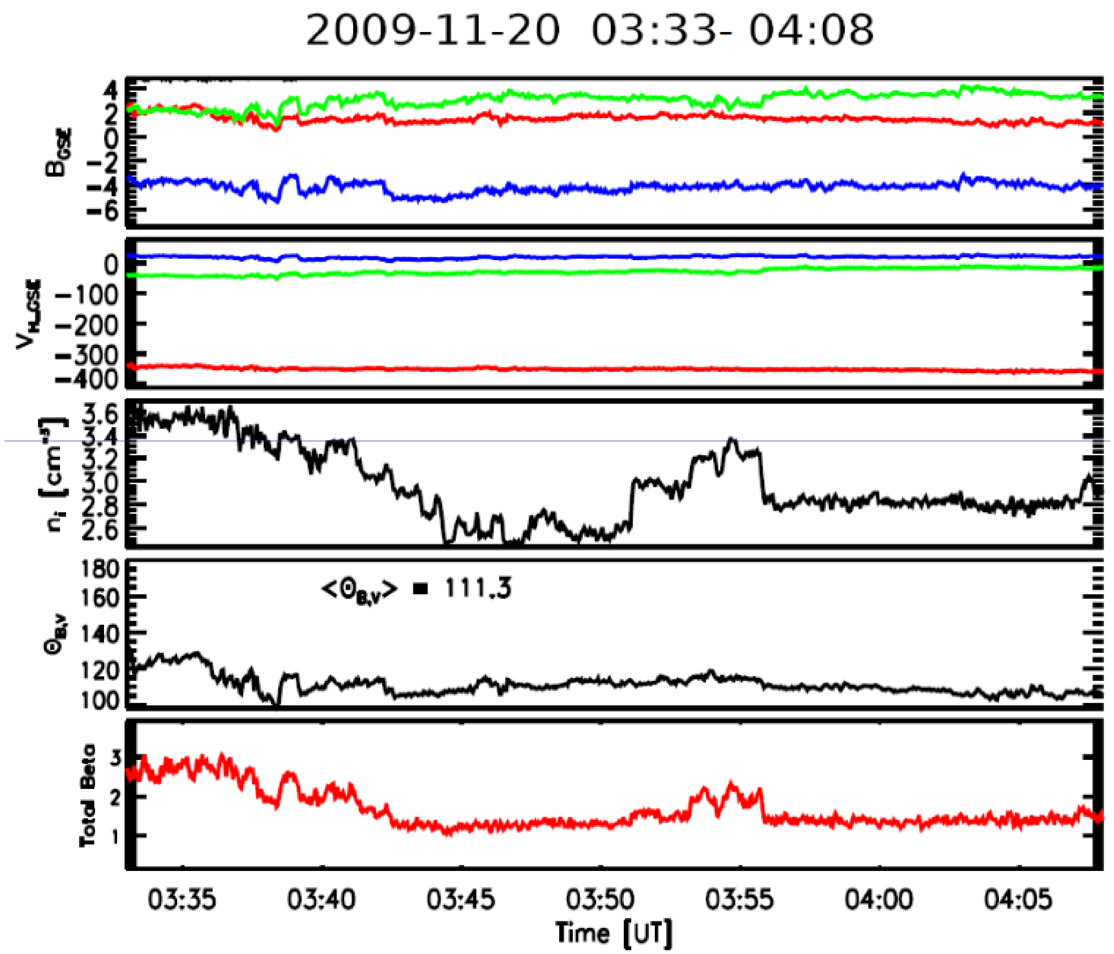
Earth (~ 1 A.U.)

MAVEN



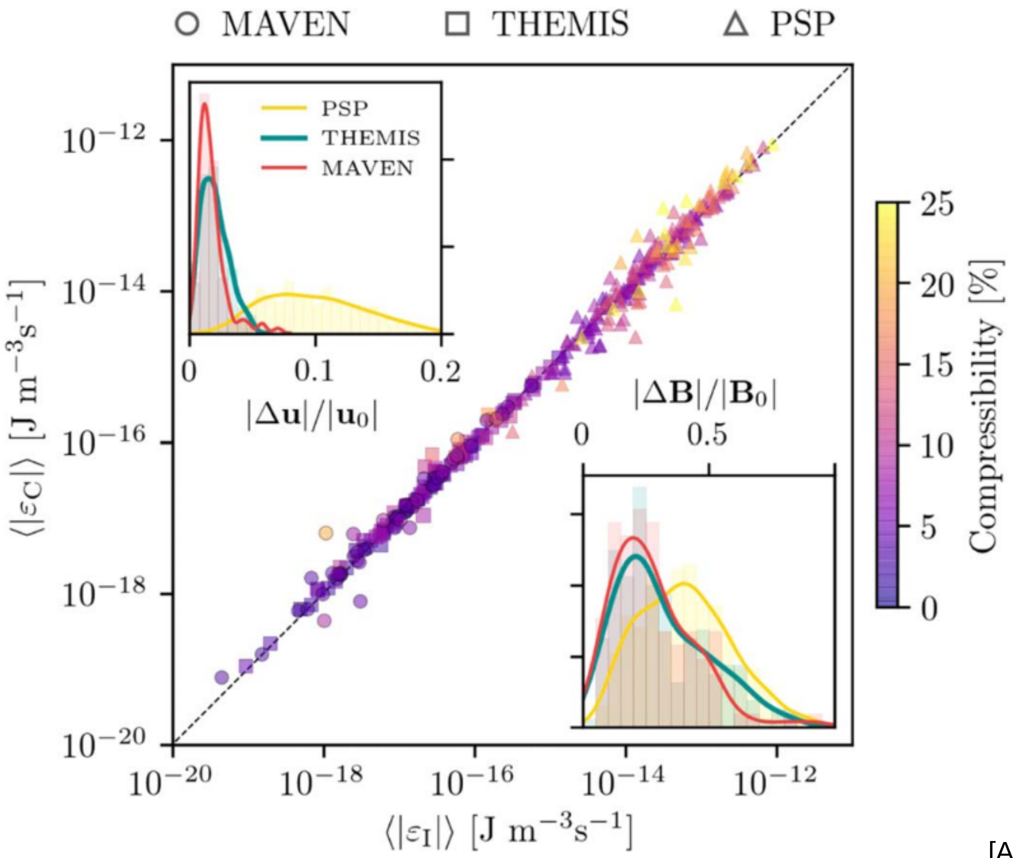
Mars (~ 1.5 A.U.)

Estimation of the energy/disspation rate



Hadid et al., ApJL, 2017

Radial evolution of the compressible ε in the SW



The density, velocity, and magnetic fluctuations increase as we approach the Sun (e.g., Bruno &Carbone 2005; Matthaeus & Velli 2011).

Moderate increases of the total compressible cascades with respect to the incompressible cascades (Banerjee et al. 2016, Hadid et al. 2017; Andrés et al. 2019; Huang & Sahraoui 2019).

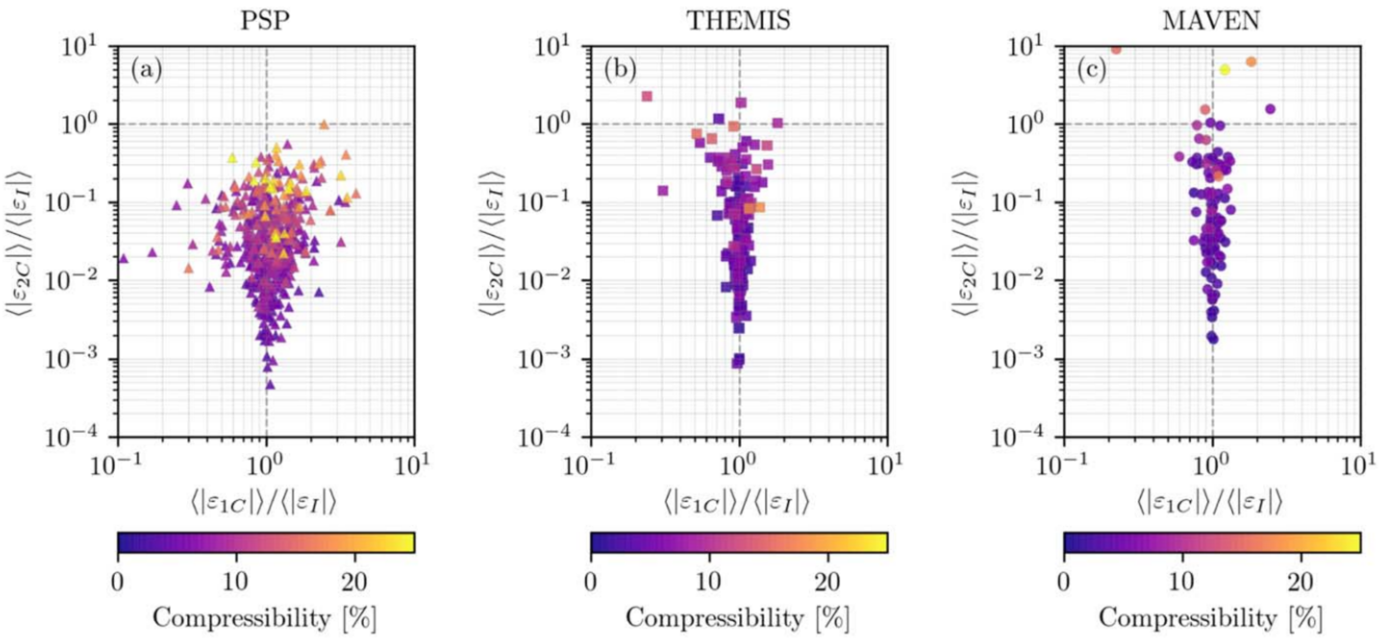
[Andrés+, *ApJ, 2021*]

Contribution of the different terms

$$\boldsymbol{F}_{1\mathrm{C}} \equiv \langle[(\delta(\rho\boldsymbol{u})\cdot\delta\boldsymbol{u} + \delta(\rho\boldsymbol{u}_\mathrm{A})\cdot\delta\boldsymbol{u}_\mathrm{A}]\delta\boldsymbol{u} - [\delta(\rho\boldsymbol{u})\cdot\delta\boldsymbol{u}_\mathrm{A} + \delta\boldsymbol{u}\cdot\delta(\rho\boldsymbol{u}_\mathrm{A})]\delta\boldsymbol{u}_\mathrm{A}\rangle,$$

$$\boldsymbol{F}_{2\mathrm{C}} \equiv 2\langle\delta\rho\delta e\delta\boldsymbol{u}\rangle,$$

$$\boldsymbol{F}_I = \rho_0\langle[(\delta\boldsymbol{u})^2 + (\delta\boldsymbol{B})^2]\delta\boldsymbol{u} - 2(\delta\boldsymbol{u}\cdot\delta\boldsymbol{B})\delta\boldsymbol{B}\rangle$$

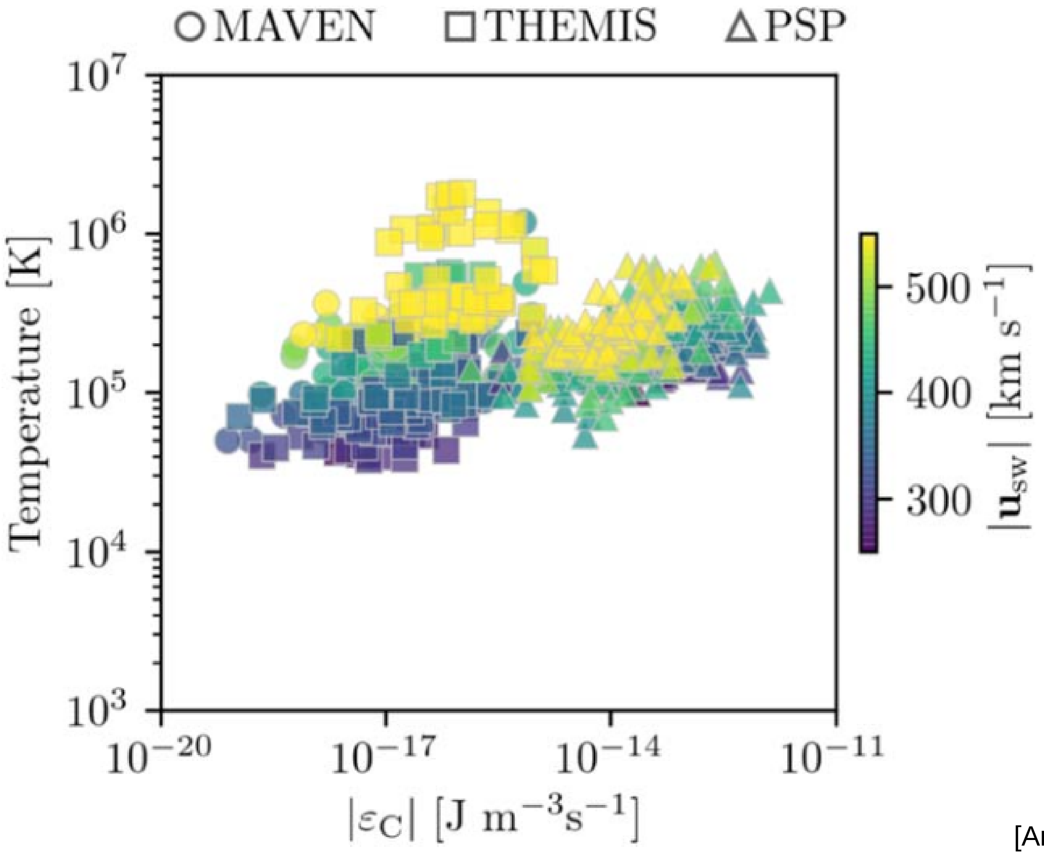


[Andrés+, *ApJ, 2021*]

Density fluctuations are small (‹5%) → the compressible Yaglom-like component, ε1C, coincides with the incompressible component, εI, while the compressible term, ε2C, is negligible.

Density fluctuations increase (up to 25%) → the dominant component is given by a competition between ε1C and ε2C.

Relation between ε and the temperature

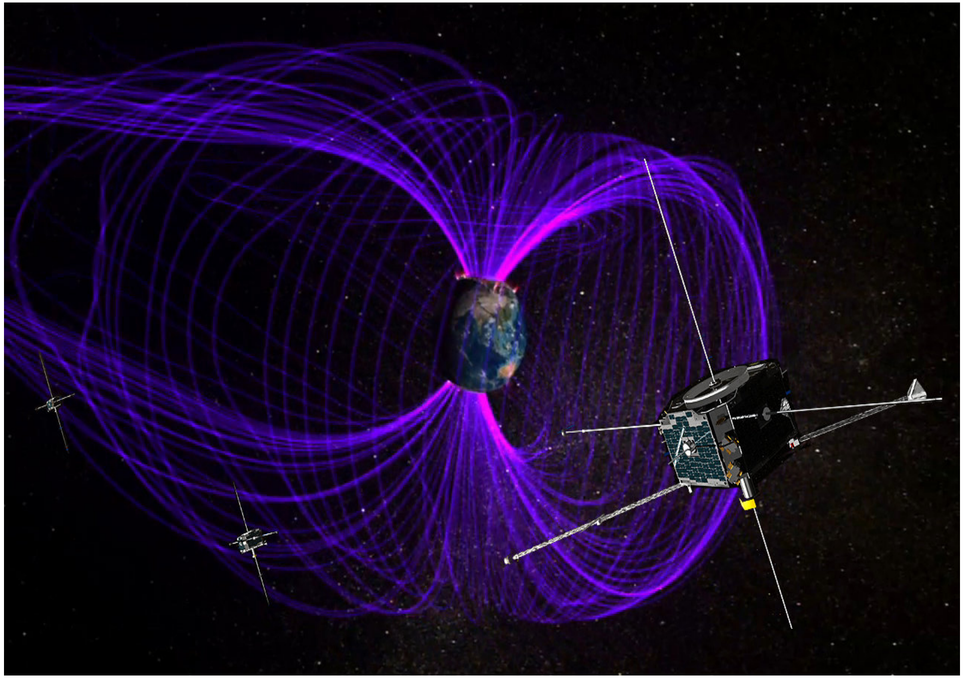


A clear correlation between the solar-wind temperature and the compressible energy cascade rate:
→ the larger the cascade rate, the higher the temperature.

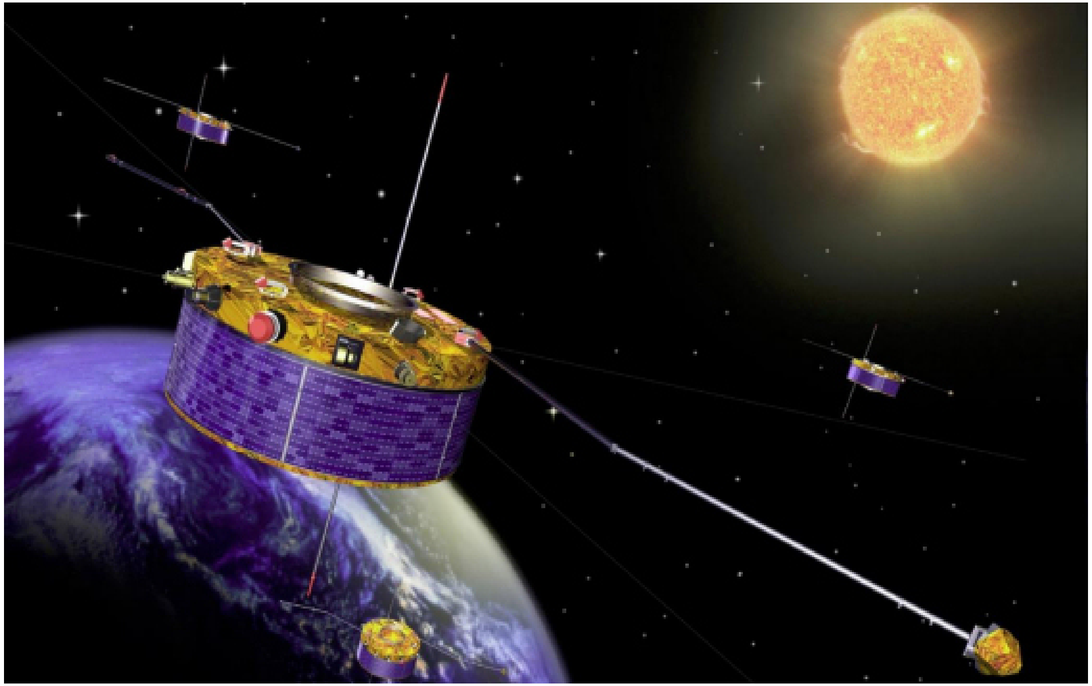
[Andrés+, *ApJ, 2021*]

How about the magnetosheath ?

Magnetosheath of Earth (2 years of Cluster + THEMIS data)



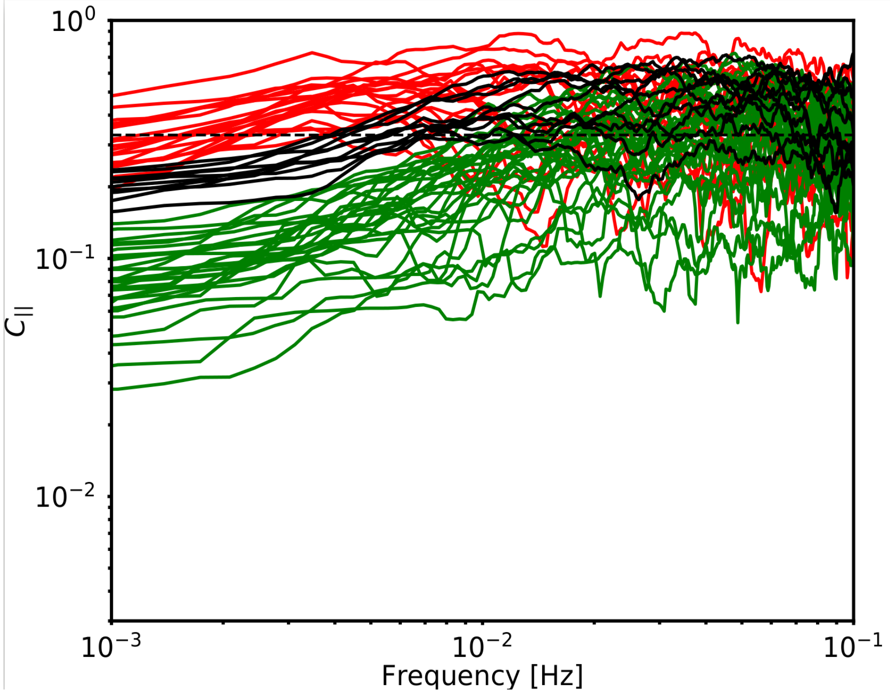
©NASA

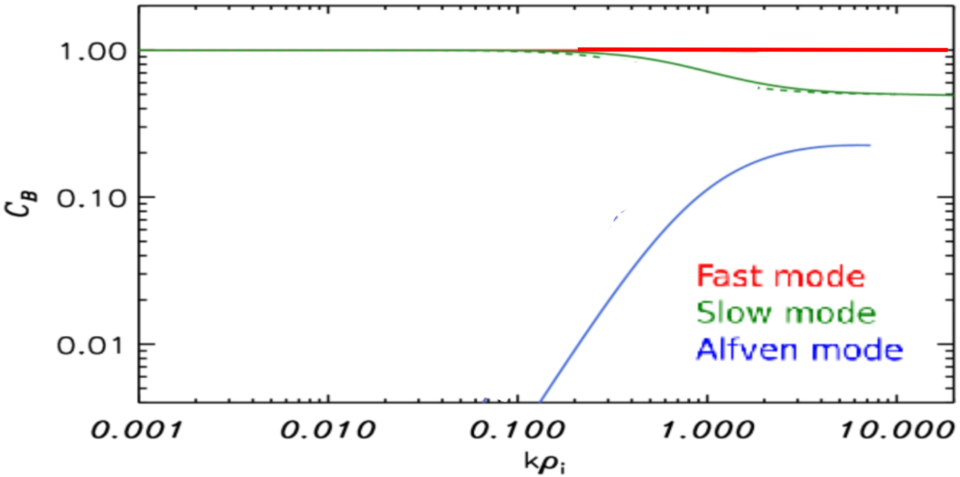


©ESA

Magnetosheath of Earth

- Presence of the inertial range
- Uniformity of the plasma beta
- Stationnarity of the velocity field
- Uniformity of the energy cascade rate
- Magnetic compressibility



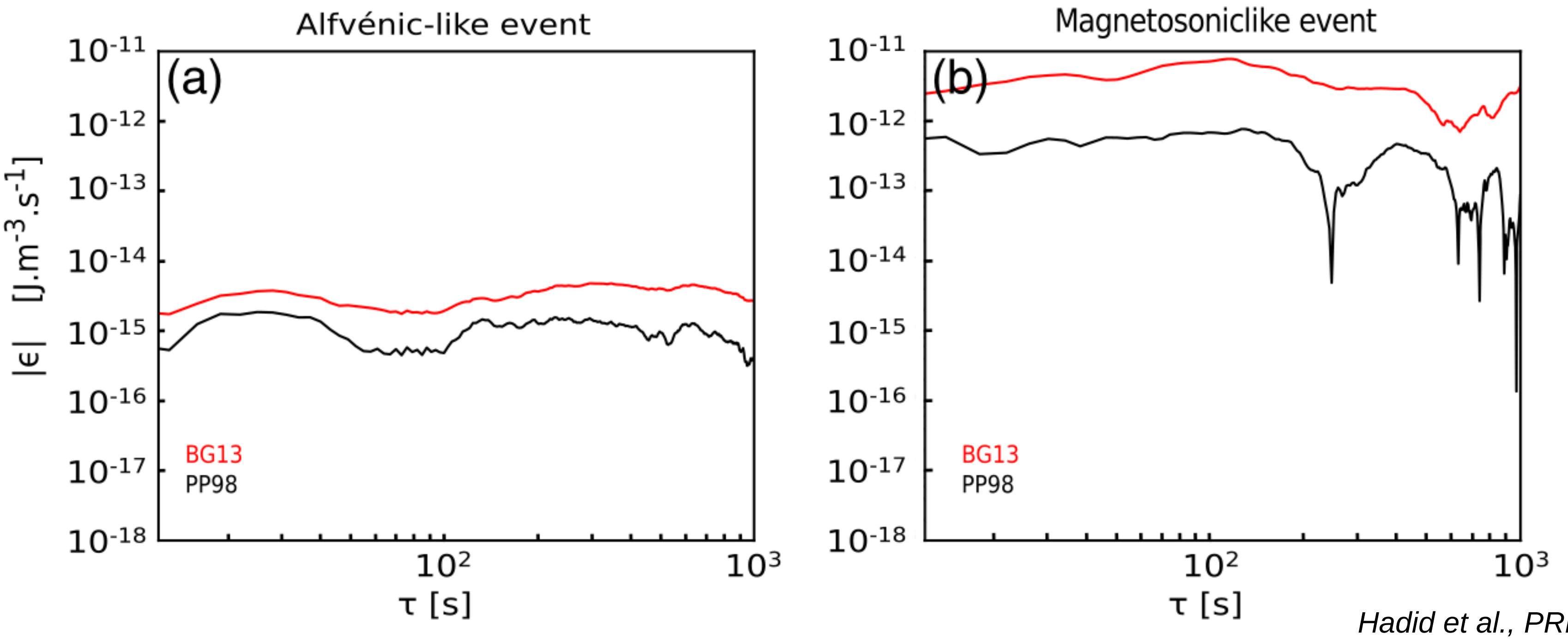


$$C_{||} = \delta B_{||}^2 / \delta B^2$$

Distinguish between **Alfvenic-like ($\langle C_{||} \rangle < 0.2$)** and magnetosonic like ($\langle C_{||} \rangle > 0.3$) fluctuations

Hadid et al., PRL, 2018

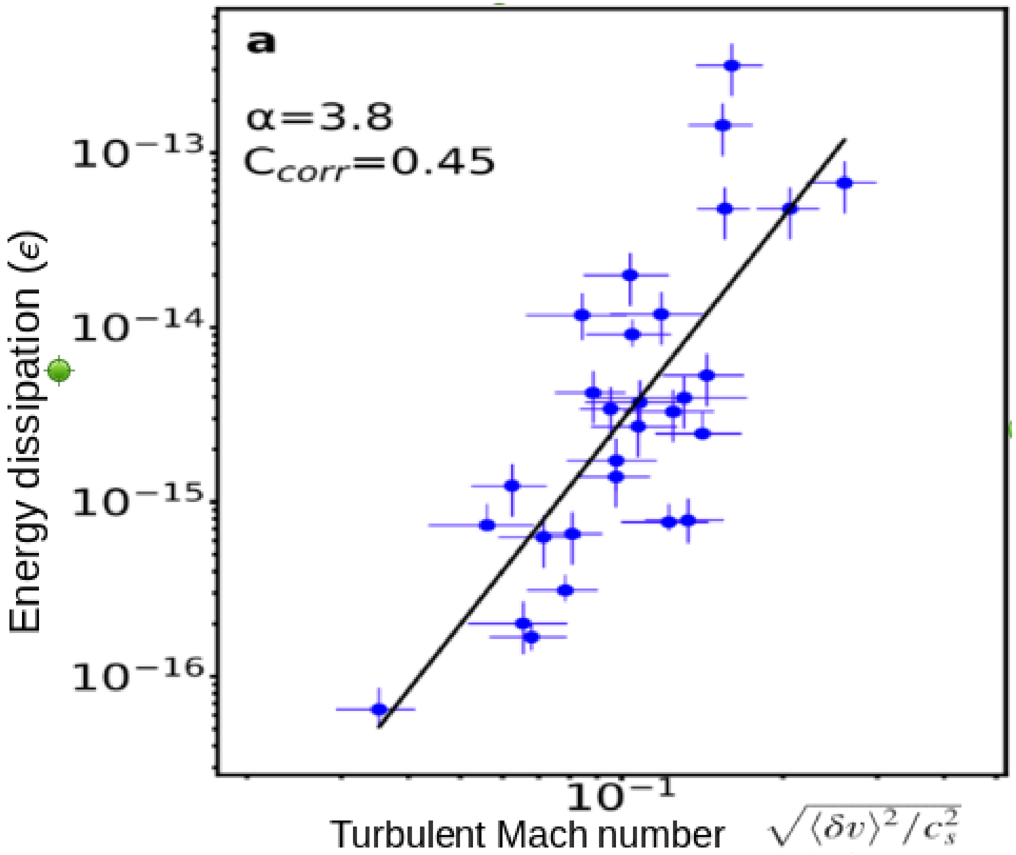
Magnetosheath of Earth



Hadid et al., PRL, 2018

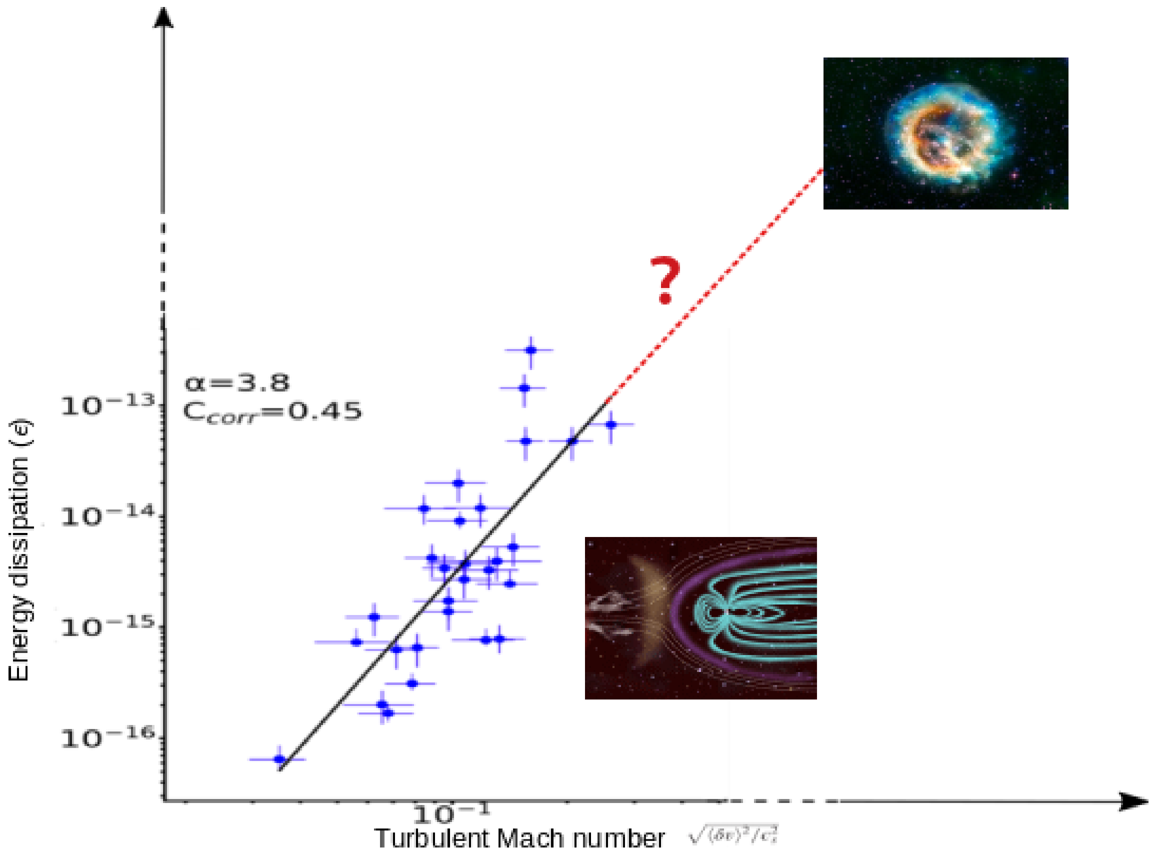
Compressibility amplifies > ϵx100 !
New empirical law relating ϵ to the turbulent Mach number → application for interstellar medium

Energy cascade rate vs. turbulent Mach number



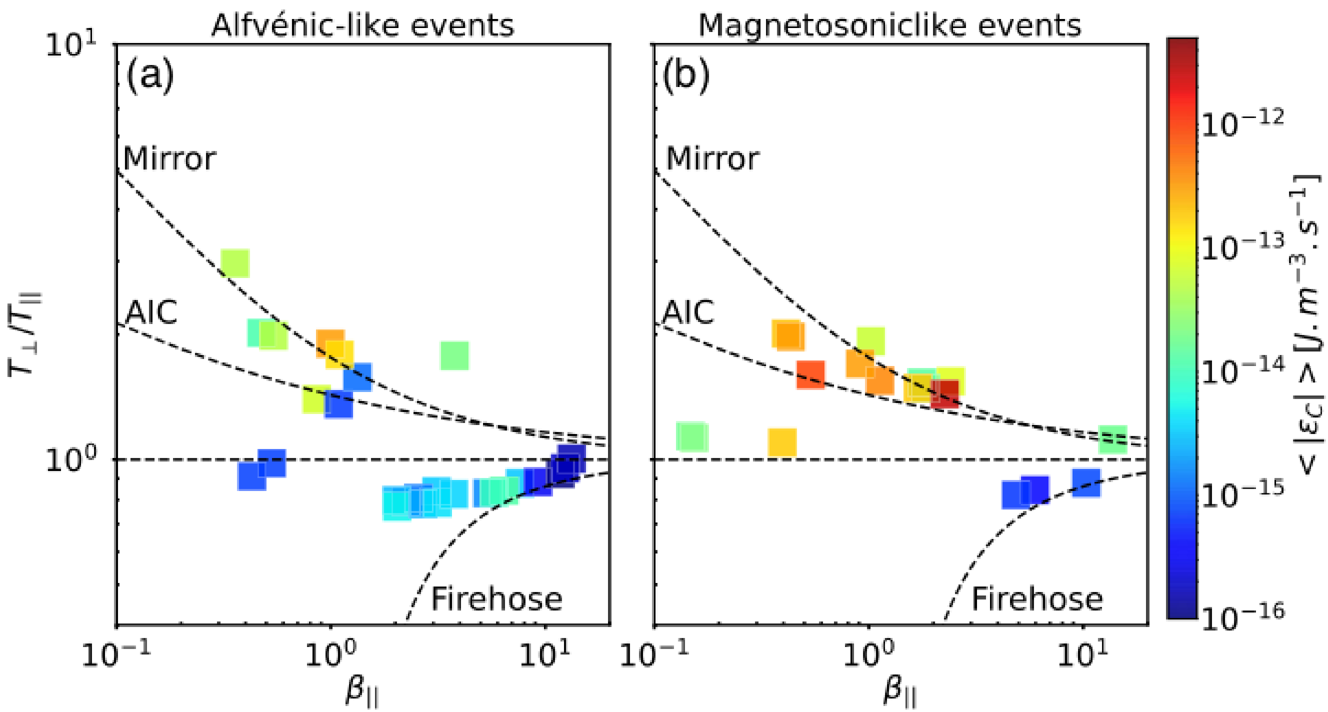
Hadid et al., PRL, 2018

Energy cascade rate vs. turbulent Mach number



Hadid et al., PRL, 2018

Role of the kinetic instabilities



Alfvenic-like events: large fraction of low <|ϵ_C|> lie around the stabiblity condition
Magnetosonic-like events: the highest <|ϵ_C|> lie around the mirror instability -> energy injection through the mirror instability which enhances the energy cascade rate (similar to the solar wind observations [Osman+ PRL, 2013]).

Interpreting spacecraft measurements

Taylor hypothesis: consists in assuming that the measurements taken on board the spacecraft correspond to one-dimensional spatial sample.

The general formula relating the frequency of the wave (or any other characteristic time scale if it is turbulence) in the plasma rest frame ω to the measured one onboard the spacecraft ωsc is given by:

$$\omega_{sc} = \omega + kV \cos \Theta_{\mathbf{kV}}$$

If the phase speed of the wave is negligible w.r.t the flow speed (i.e., $V_\Phi = \omega/k \ll V$), then the Taylor frozen-in-flow assumption should be valid →

$$\omega_{sc} \sim kV \cos \Theta_{\mathbf{kV}}$$

The solar wind:

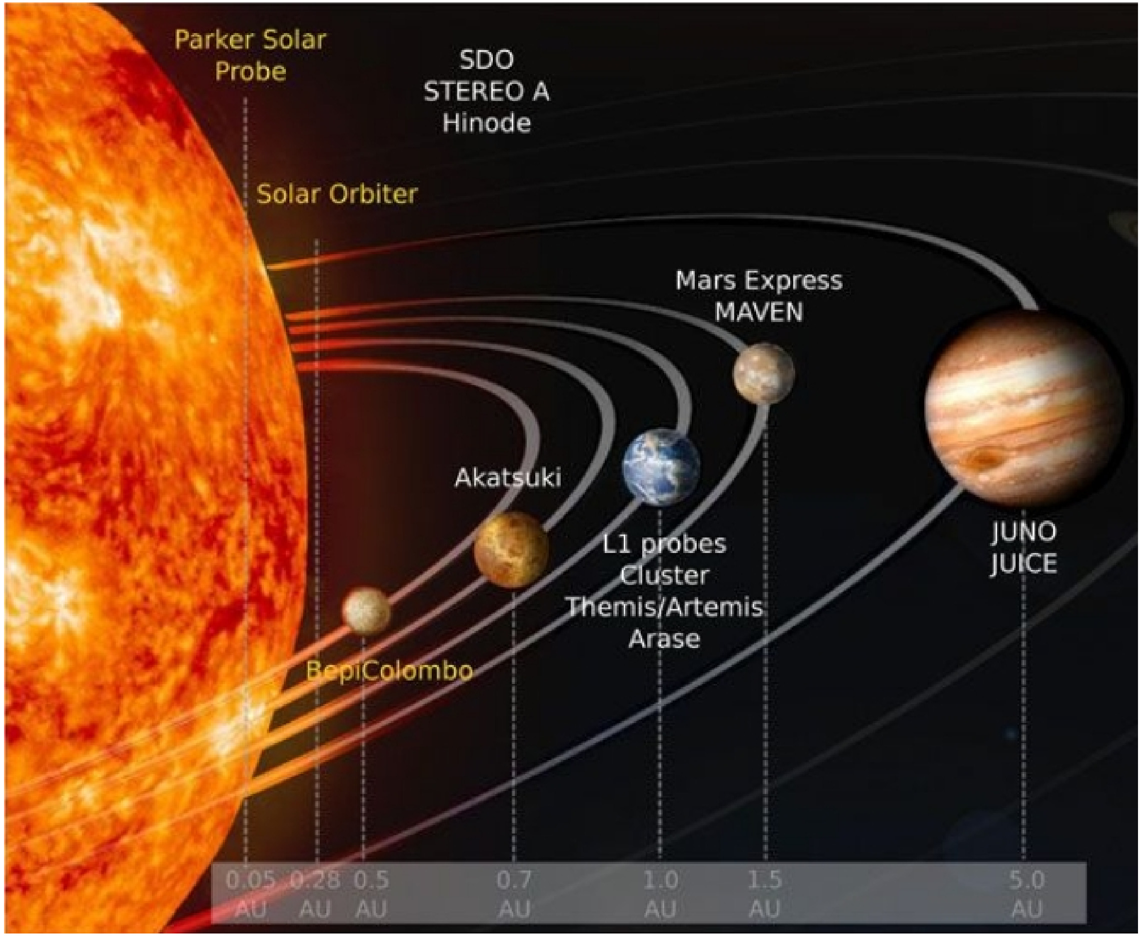
At MHD scales since $V_\Phi \equiv V_A \sim 50$ km/s $\sim V/10$ → Taylor hypothesis almost always valid

Magnetosheath:

The Taylor hypothesis **is thought** to be violated since $V_\Phi \sim V_A \sim C_s \sim 100 - 200$ km/s where V_A and C_s represent respectively the Alfvén and the sound speeds considered to be the typical phase speed of the fluctuations. It is valid in at least two conditions (strongly anisotropic turbulence and stationary fluctuations)

PSP – SO -BC coordinated observations

Excellent opportunity to perform multi-point, multi-instrument synergic studies of heliospheric phenomena



Velli et al., ApJ, 2020

Hadid et al., Frontiers, 2021

Alberti et al., ApJ, 2021

Telloni et al., ApJ, 2022

End of Part II