Gone with the Solar Wind: Turbulence, Intermittency, and Energy Dissipation in Space Plasmas
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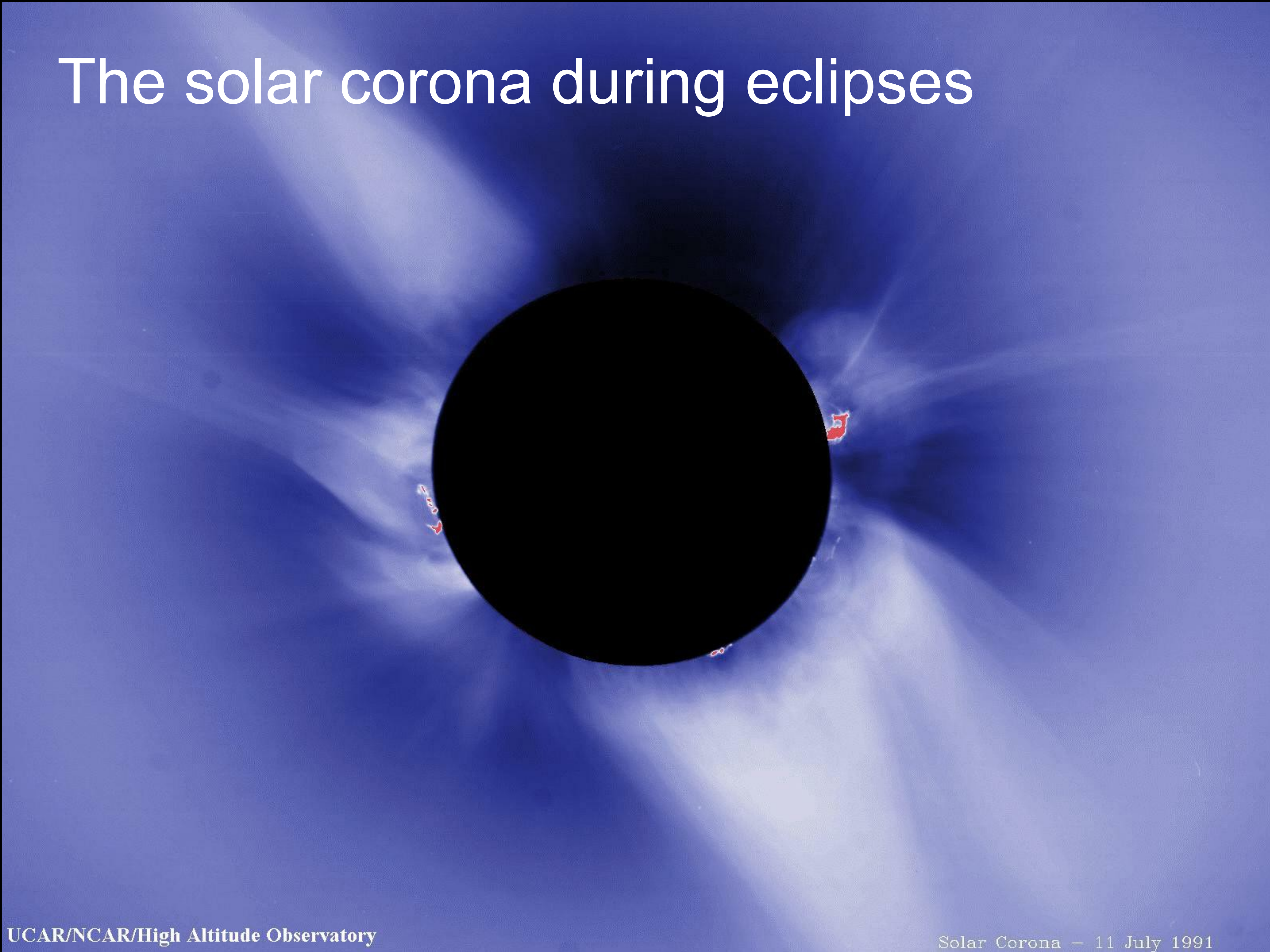
Outline

- Introduction: solar wind and turbulence
- Large scale turbulence: energy spectra, intermittency and exact laws
- Small-scale turbulence: distribution functions and the role of structures
- What strategy for the future?
- Examples
- New space mission proposal: THOR
- Conclusions

Main collaborations

UC Berkeley, University of Delaware, Observatoire de Meudon, LPP/Palaiseau, INAF/IAPS, Uppsala Univ., Observatoire de Nice, Imperial College of London, Queen Mary Univ., University College of London, UC San Diego, ESA/ESTEC

The solar corona during eclipses

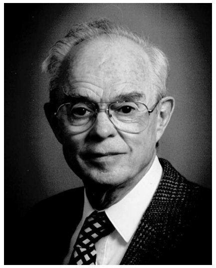


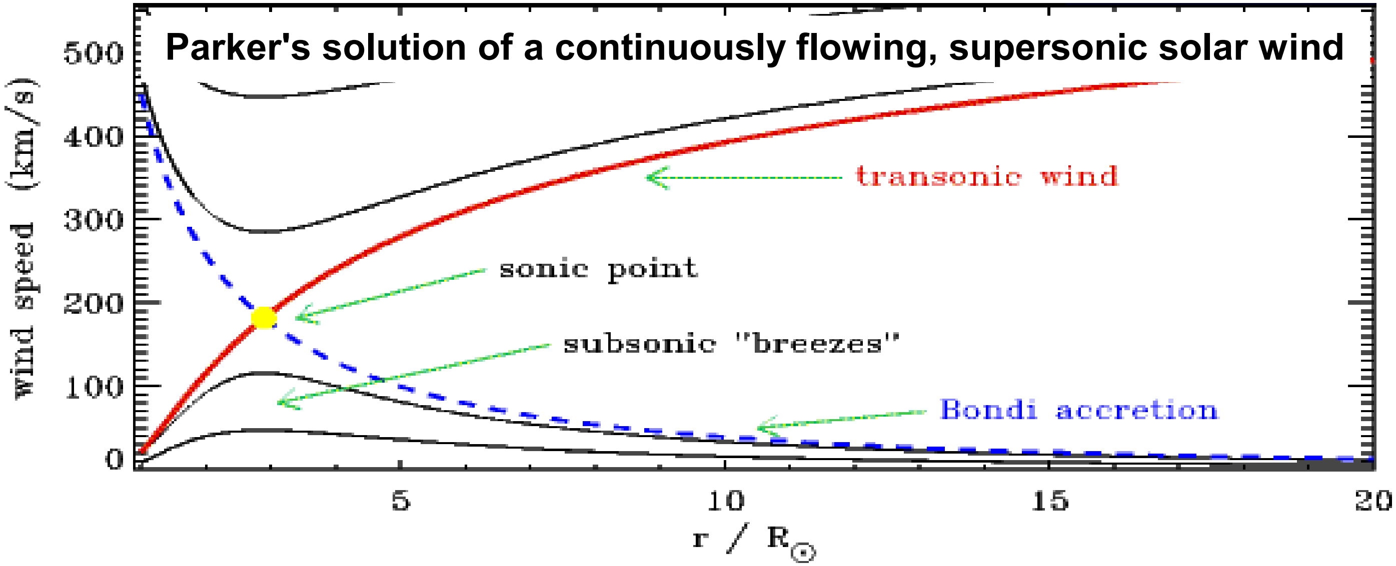
Comet tails

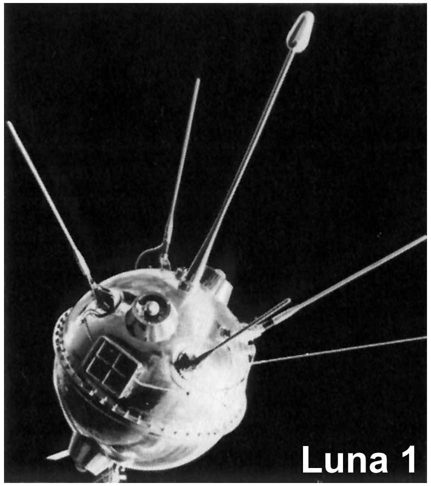
Polar aurorae

Discovering the Solar Wind

- 1859: Carrington (connected solar flare and geomagnetic storm)
- 1910: Eddington (while studying comets)
- 1916: Birkeland (continuous geomagnetic activity)
- 1950s: Chapman (calculated solar atmospheric extension)
- 1950s: Biermann, Ahnert (comet tails pointing anti-sunward)
- 1958: **Parker** (solar wind)
- 1959: Luna 1 (first direct measurement of the solar wind)

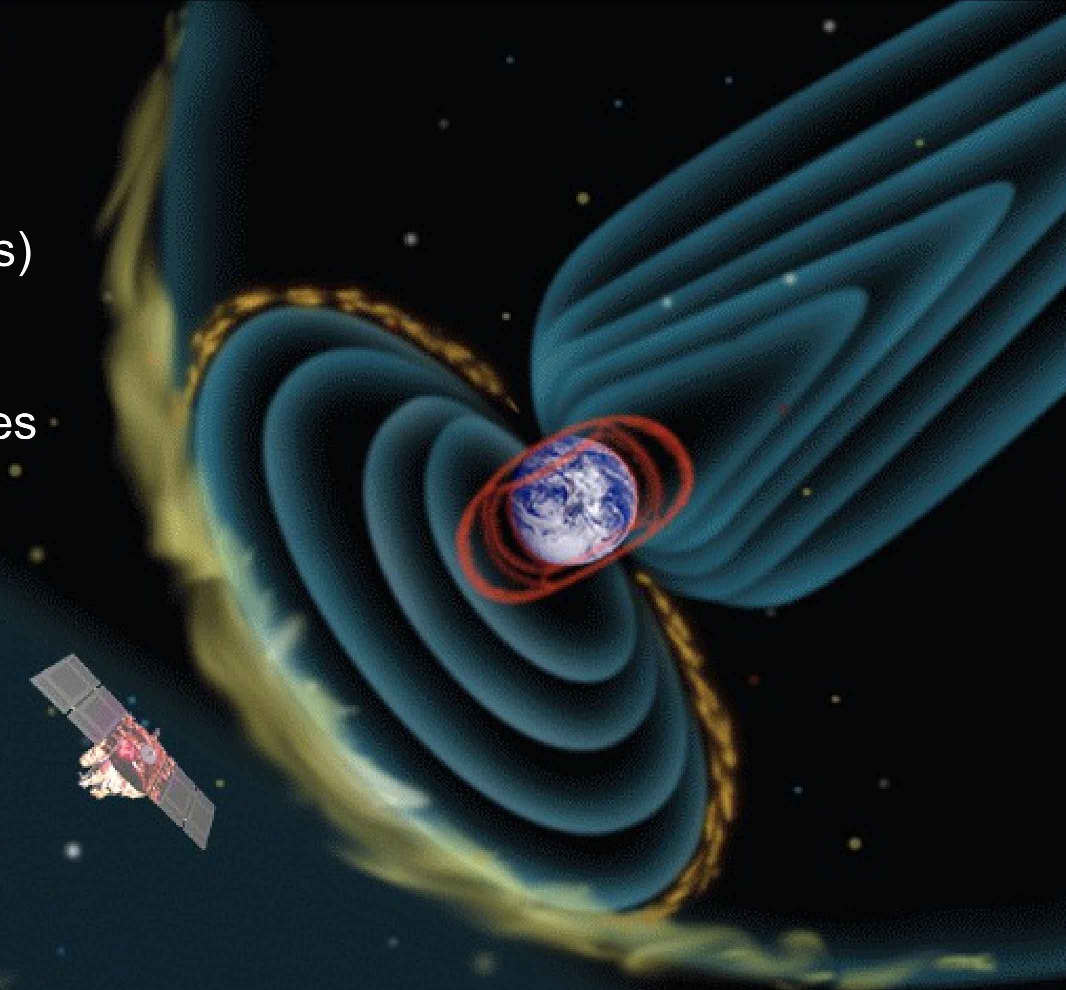






The solar wind

A weakly collisional, magnetized plasma (mainly protons and electrons) continuously blowing from the Sun, forming the Heliosphere while it interacts with planets and other bodies (e.g. shaping the magnetospheres).

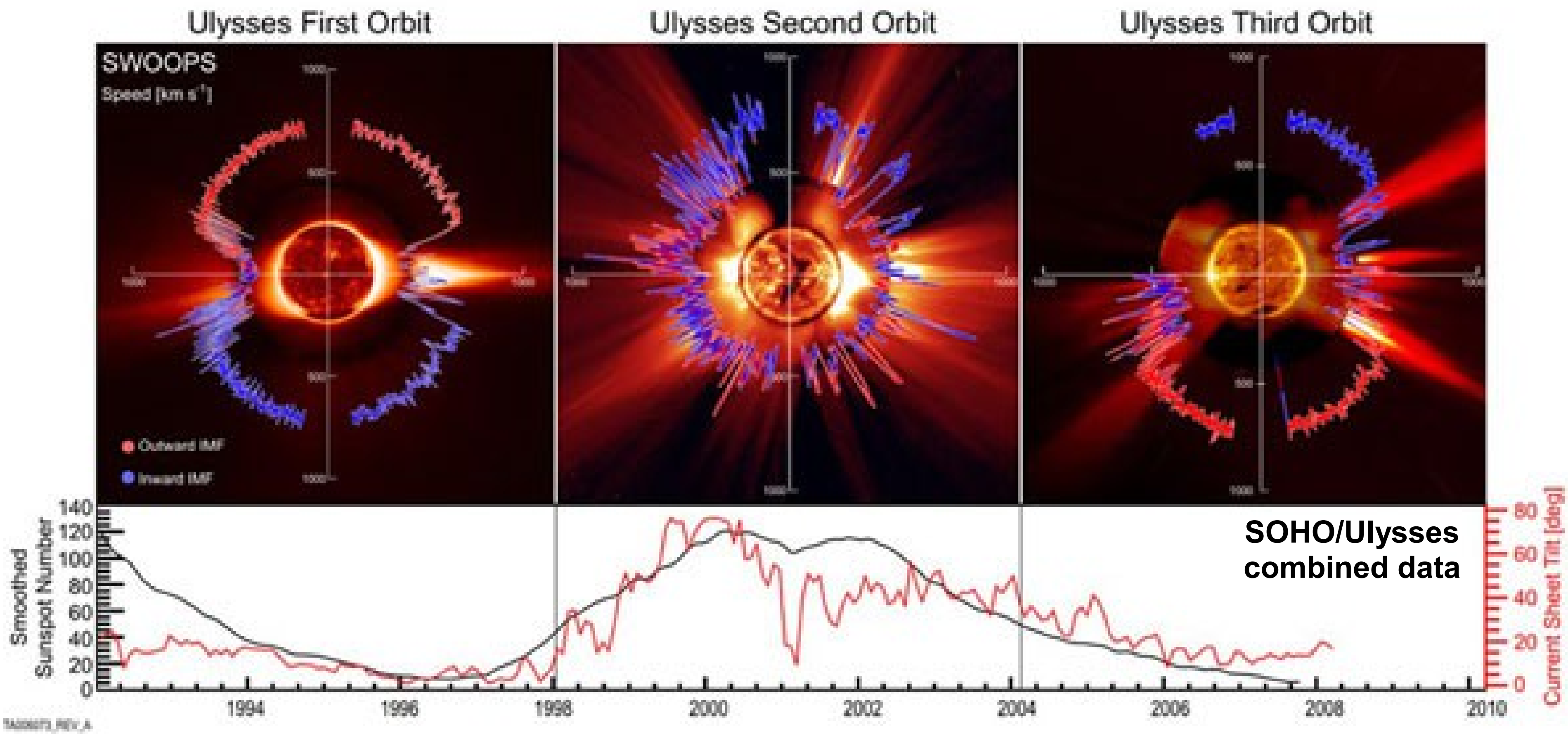


- **Rarefied:** few particles per cm^3 at Earth, in radial expansion
- **Highly supersonic** far from the Sun (V=300-700 Km/sec)
- **Hot**: $T>10^5$ K (kinetic temperature, not thermodynamic)
- **Magnetized** (B=1nT at Earth)
- **Complex,** due to solar variability and local processes
- **Variable** on all measured scales, from m-second to centuries

The solar wind variability

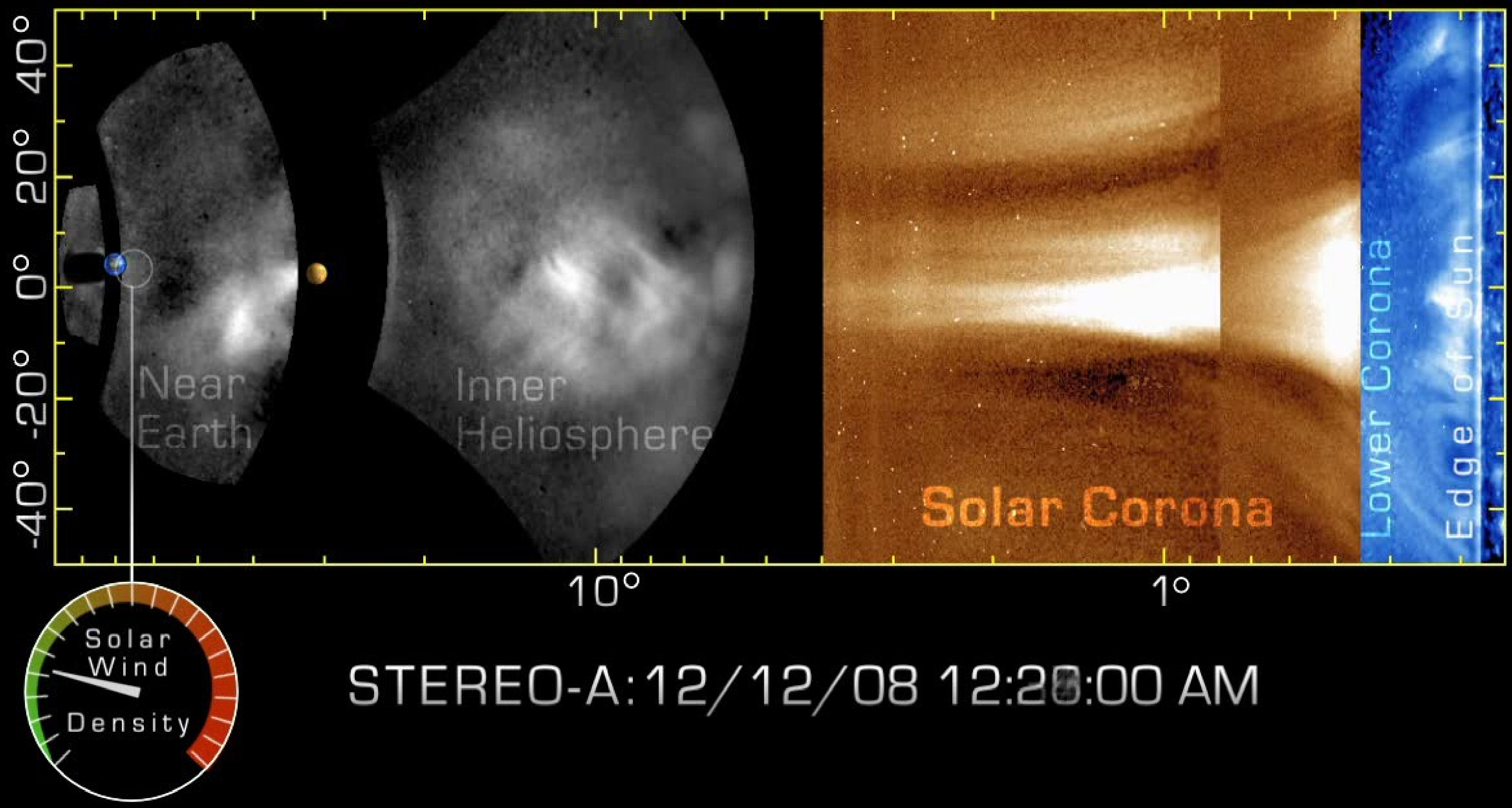
Low activity: steady wind, constant magnetic polarity

High activity: mixed slow and fast streams, frequent magnetic field reversals

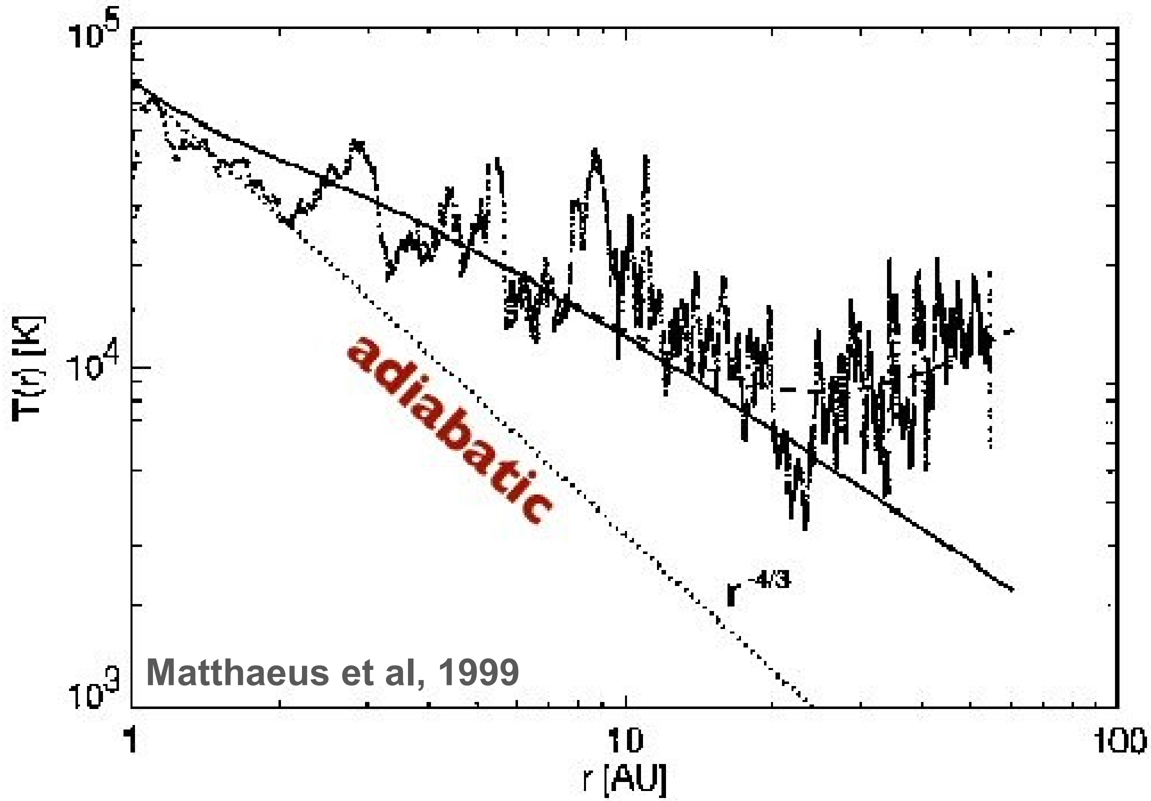


Seeing the solar wind

Credit: C. De Forest



The problem of solar wind heating: turbulence

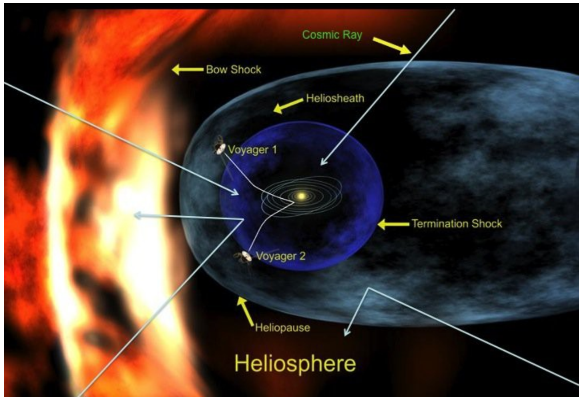


Temperature radial profile estimated using Voyager measurements

$$T \sim T_0 (r_0/r)^{\xi} \qquad \xi \in [0.7 \div 1]$$

Need some heat source: **turbulent dissipation?**

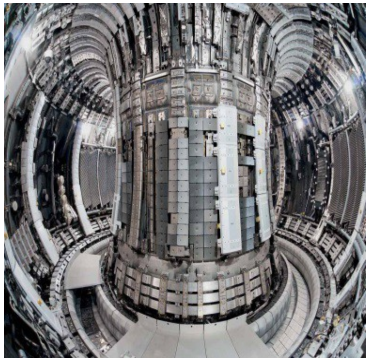
Why?



Unraveling fundamental plasma processes
Dissipation mechanisms, magnetic reconnection, waves, …

Understanding solar processes
Role of turbulence in coronal heating, flares…

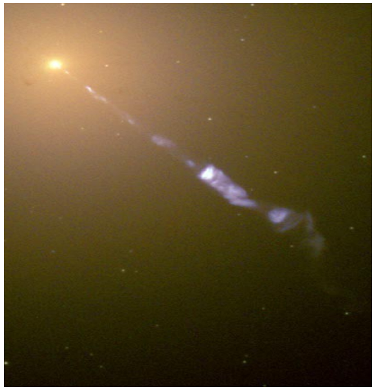
Understanding astrophysical plasmas
Stellar formation, jets, intergalactic medium, supernova remnants…



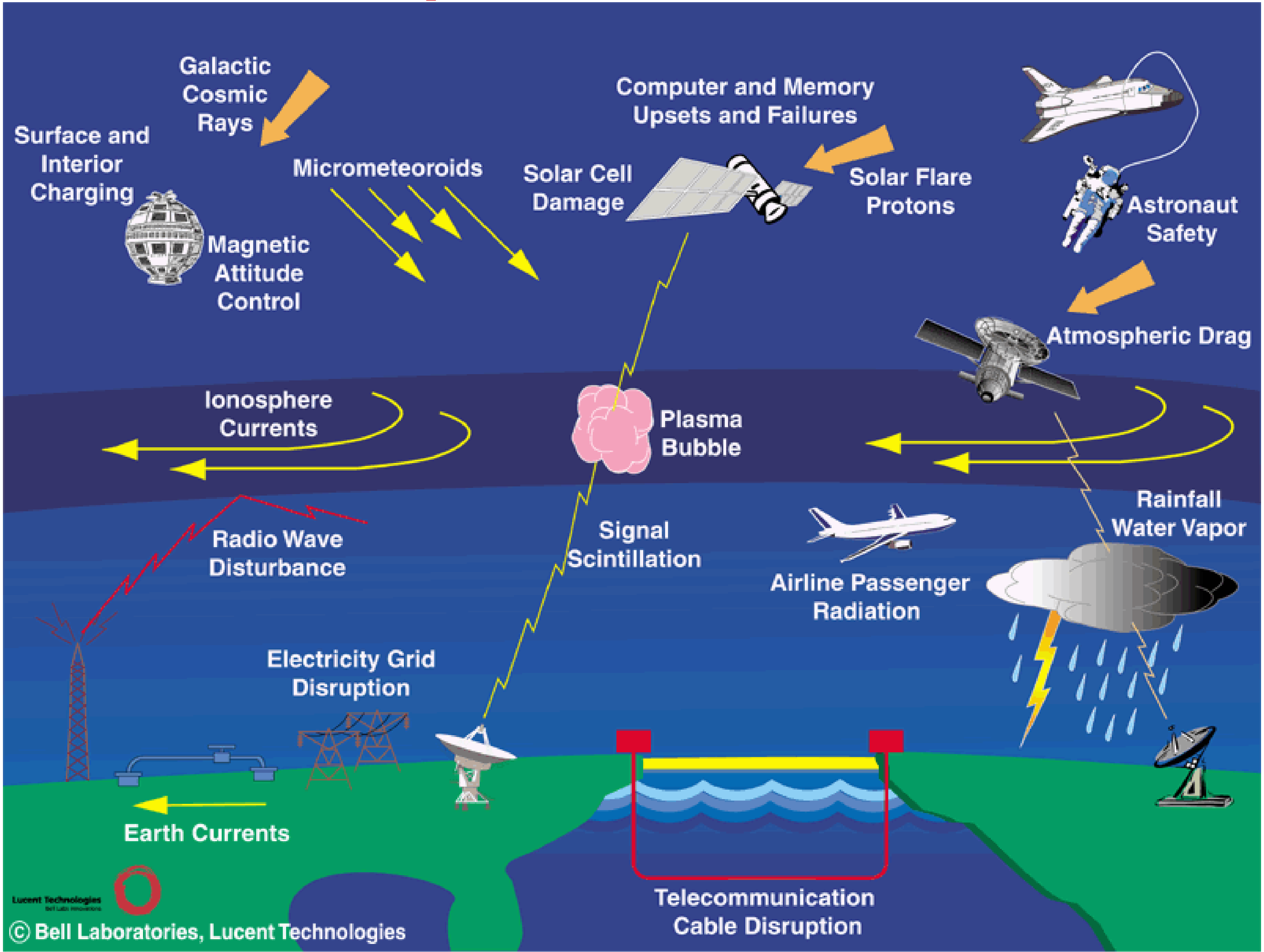
Relevant for energetic particle transport and acceleration
Controls cosmic rays throughout the solar system

Important for laboratory plasmas
May help confinement in fusion devices

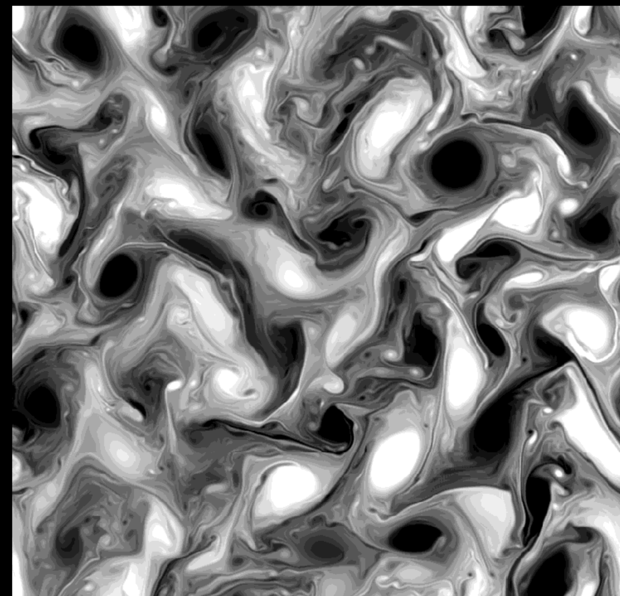
Connects the Sun with the Earth: Space Weather
Better knowledge of triggers = better prediction and protection

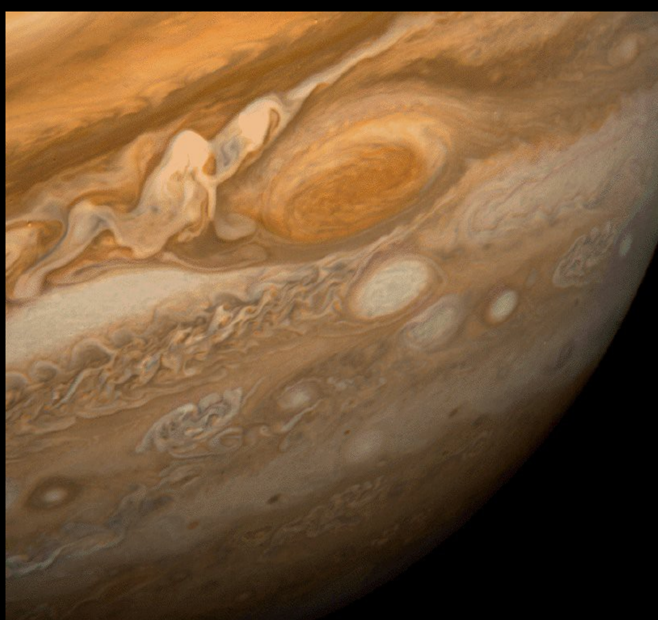


Space Weather



Turbulence: a universal phenomenon





Turbulence: an energy budget

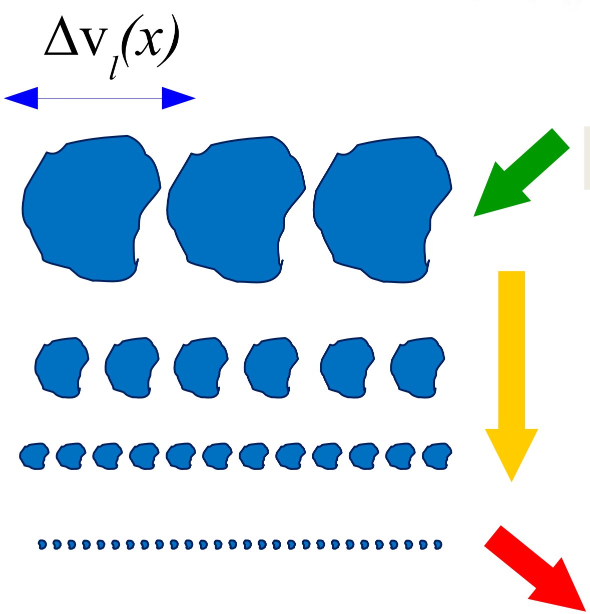
Small scale energy dissipation

Neutral fluids: Navier-Stokes $$\partial_t \mathbf{v} + \left(\mathbf{v}\cdot\nabla\right)\mathbf{v} = -\nabla P + \nu\,\nabla^2\mathbf{v} + \mathbf{F}$$

Cross scale energy transfer

Large scale forcing

$$Re = \frac{\mathrm{v}\,L}{\nu} = \frac{\text{Non-linear}}{\text{Dissipative}}$$



Energy injection (ε)

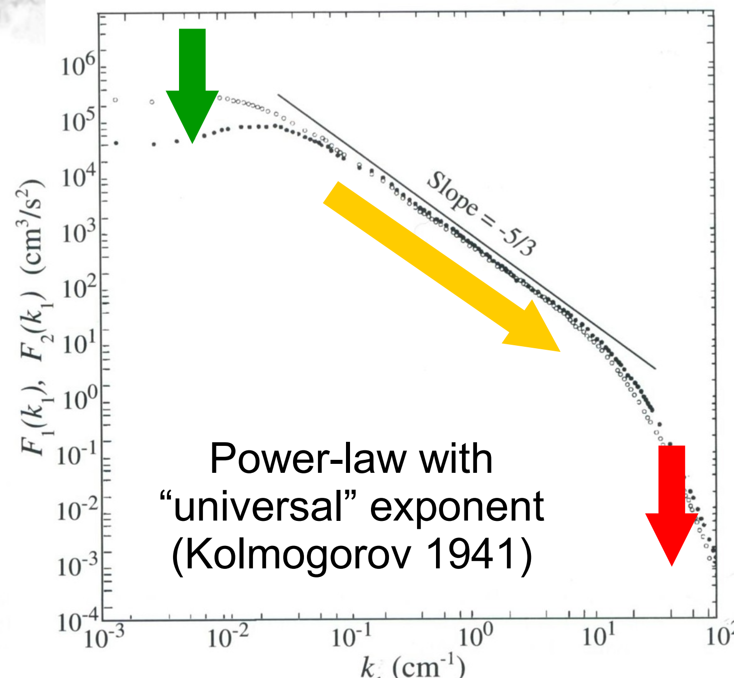
Integral scale L

Non-linear energy transfer (ε)

Inertial range

Energy dissipation (ε)

Dissipative scale l_d



Leonardo Da Vinci studies of turbulence, ca. 1500

L. Da Vinci, Codice Atlantico, f. 74v:
"Doue la turbolenza dellacqua rigenera, doue la turbolenza dellacqua simantiene plugho, doue la turbolenza dellacqua siposa" (where the turbulence of water is generated, where the turbulence of water keeps steady, where the turbulence of water dissipates)

Magnetohydrodynamic turbulence

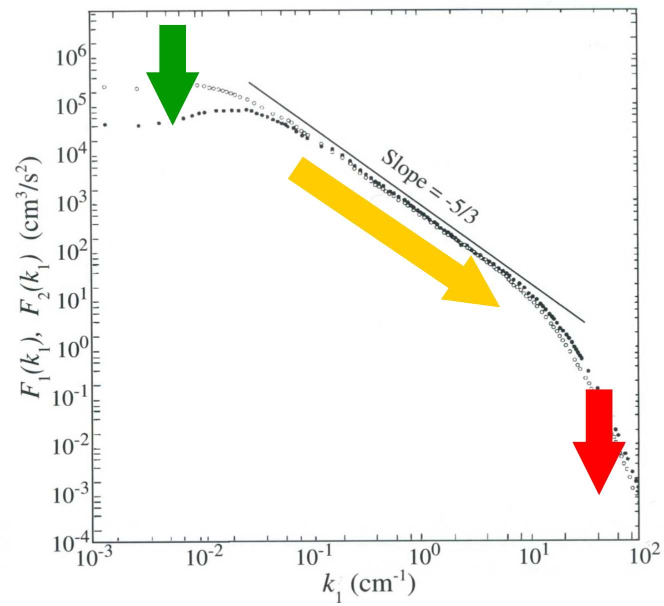
Plasma flows: incompressible Magnetohydrodynamics (MHD)

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

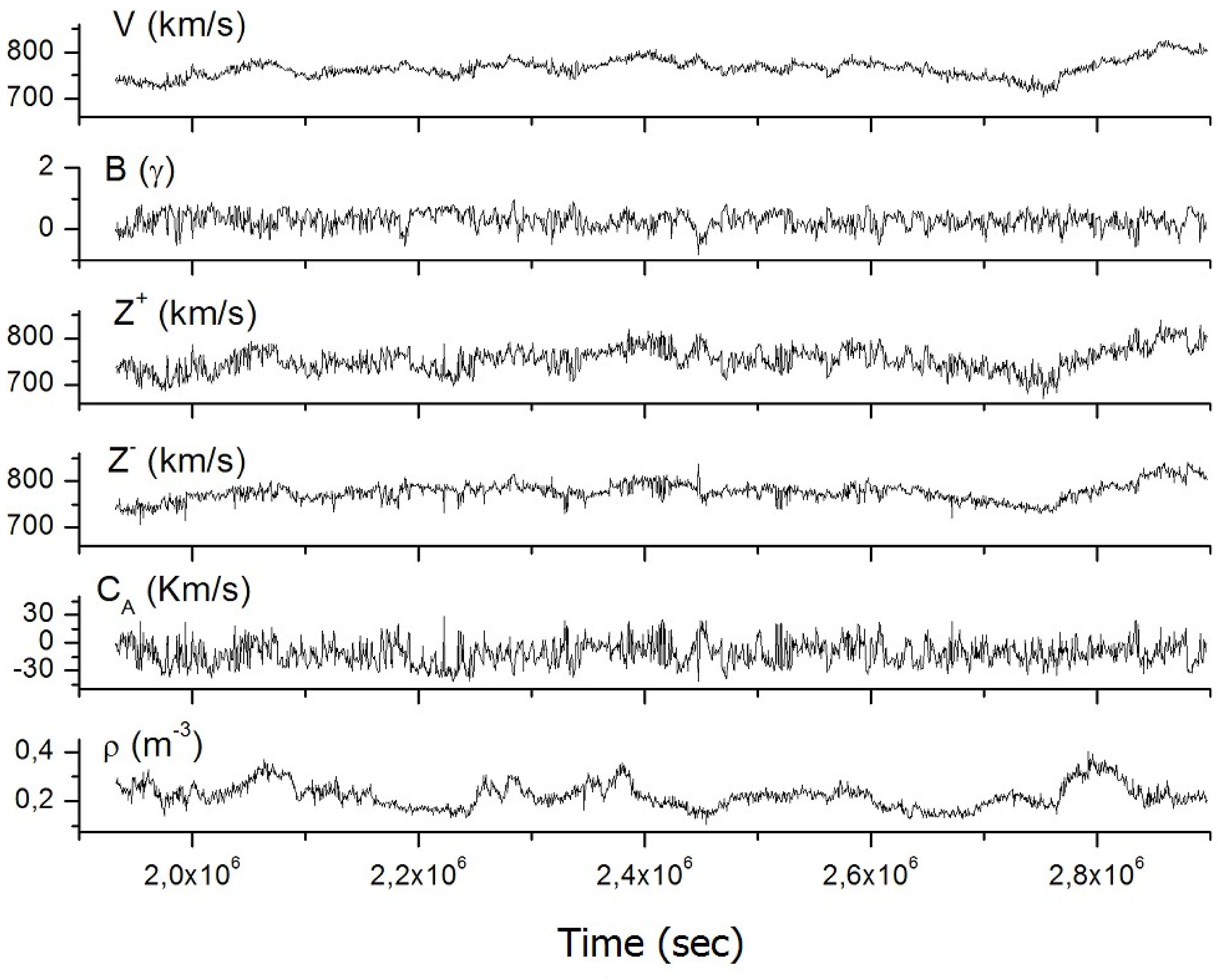
Elsasser fields: $z_i^{\pm} = v_i \pm b_i = v_i \pm \dfrac{B_i}{\sqrt{4\pi\rho}}$

$$\partial_t z_i^{\pm} + z_\alpha^{\mp}\partial_\alpha z_i^{\pm} = -\partial_i P + \nu\partial_\alpha^2 z_i^{\pm}$$

$$\partial_t \mathbf{v} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\nabla P + \nu\,\nabla^2\mathbf{v} + \mathbf{F}$$



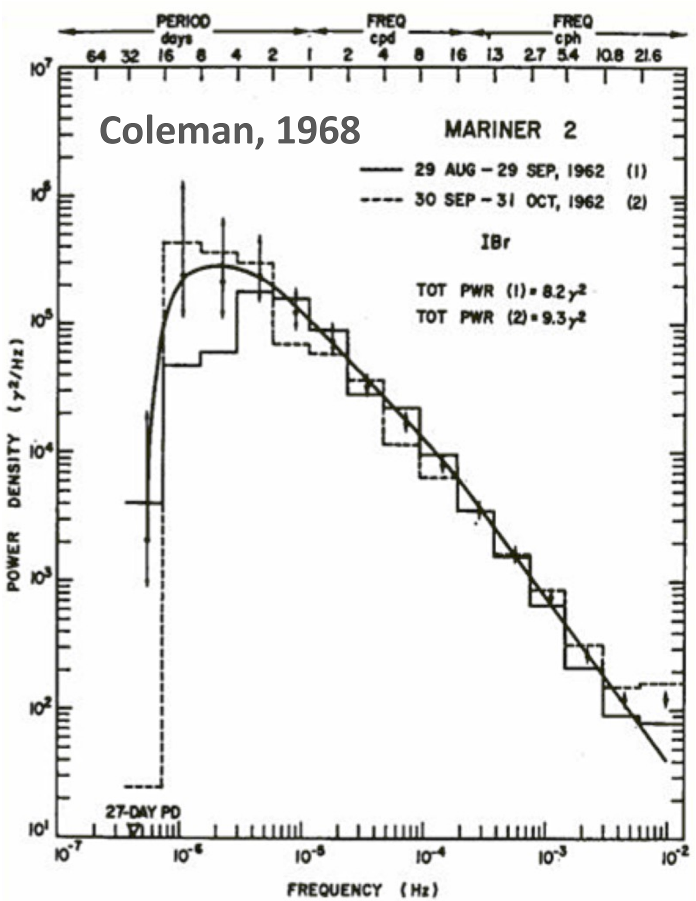
The solar wind as a wind tunnel

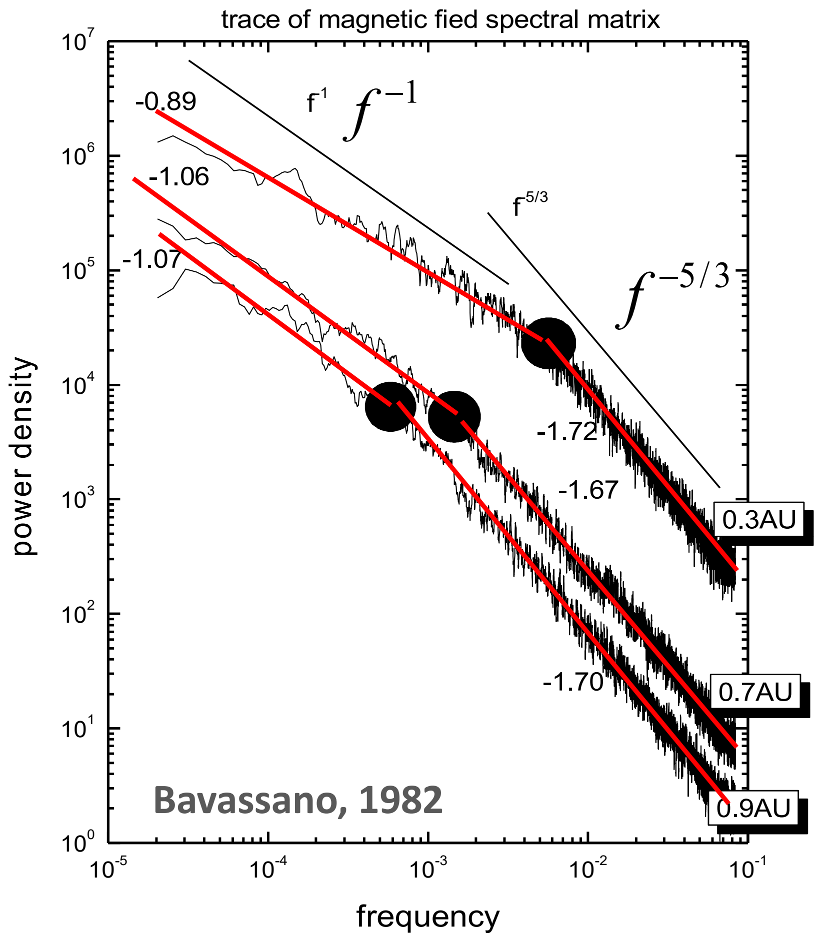


Bruno & Carbone, Liv. Rev. Solar Phys., 2005/2013; **Alexandrova et al., Space Sci. Rev., 2013**

Turbulence in the Solar Wind

Early observations of magnetic spectra with
“universal” power-law scaling exponent





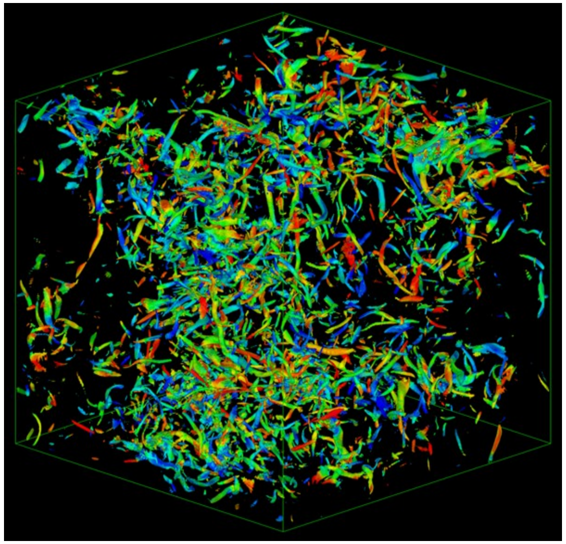
Intermittency in turbulence

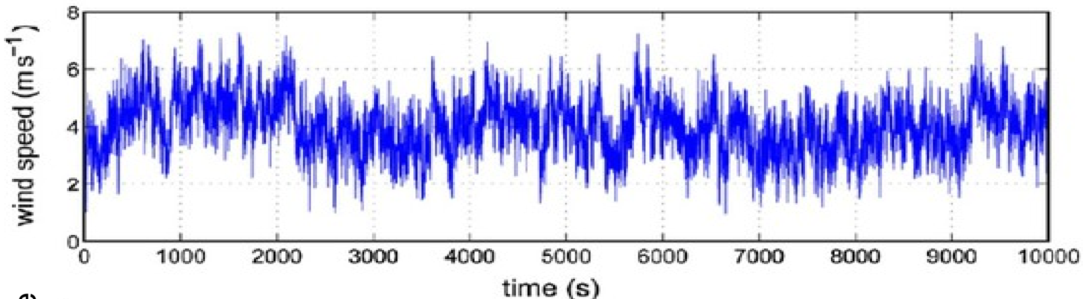
Universal feature of turbulence: **intermittency**

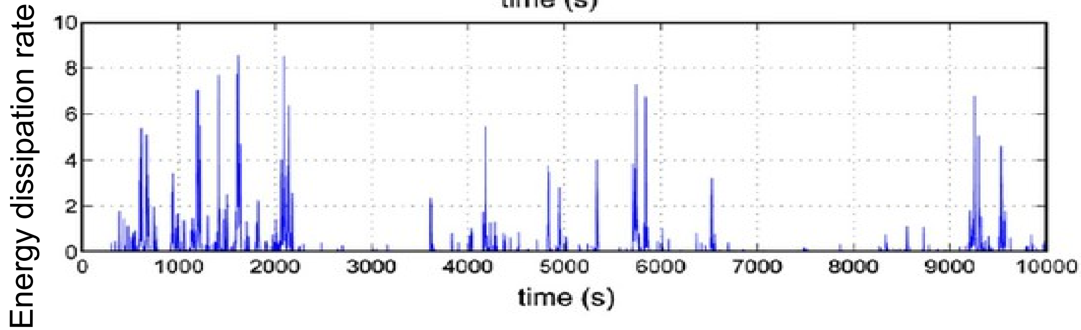
Energy dissipation is more efficient when it occurs in vortices distributed inhomogeneously in space.

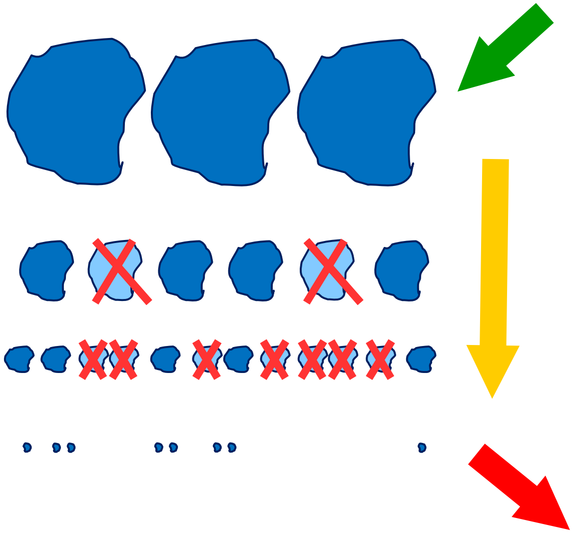
Experimental observation of intermittent, bursty, multifractal dissipation fields.

Turbulent dissipation in numerical simulations





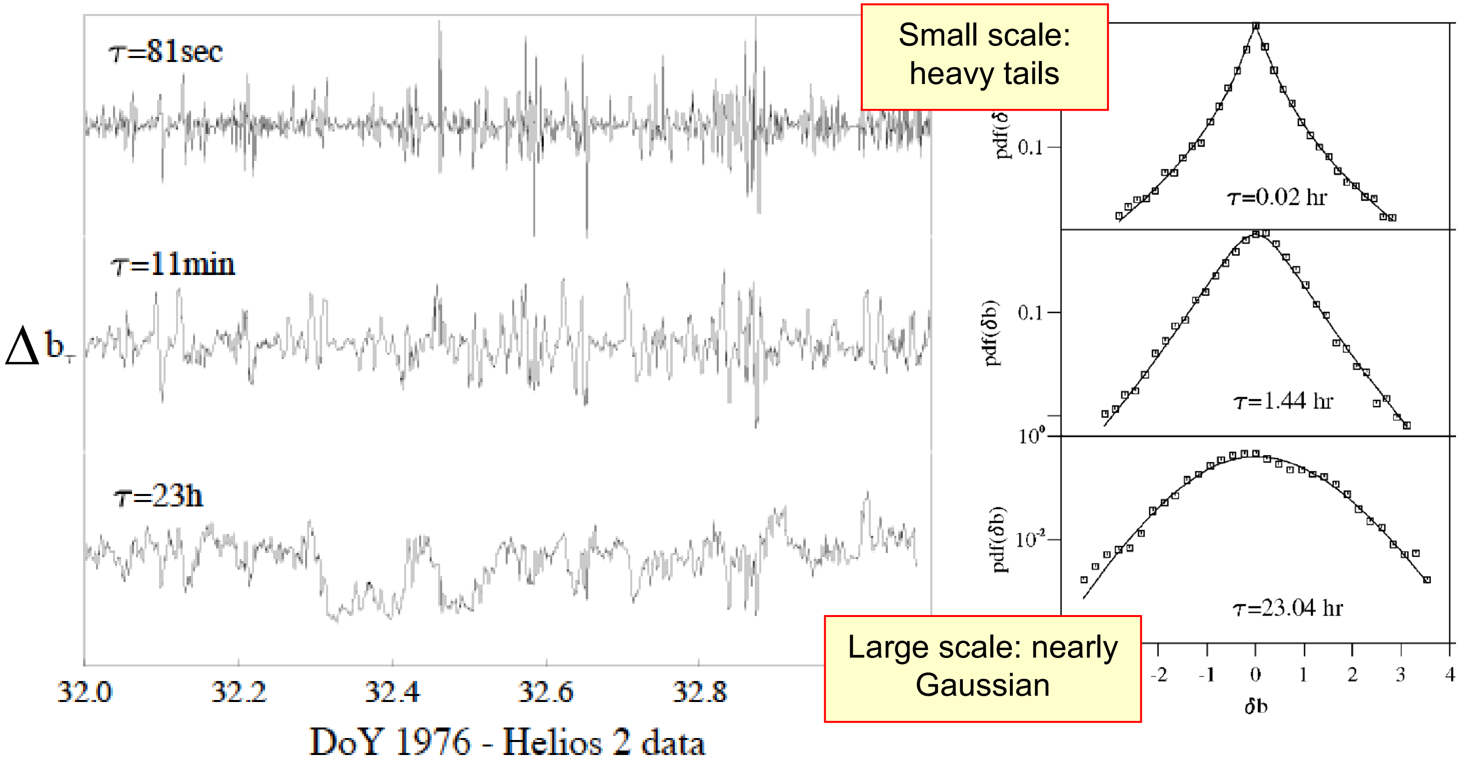




Intermittency in solar wind turbulence

Rare, bursty dissipative events dominate the small-scale statistics

Sorriso-Valvo et al., 1999, 2000, 2001, 2004, 2007, 2008, 2015, 2016…



- 15+ years work
- 30+ articles: thorough quantitative description of intermittency in different wind conditions, using spacecraft data and numerical simulations

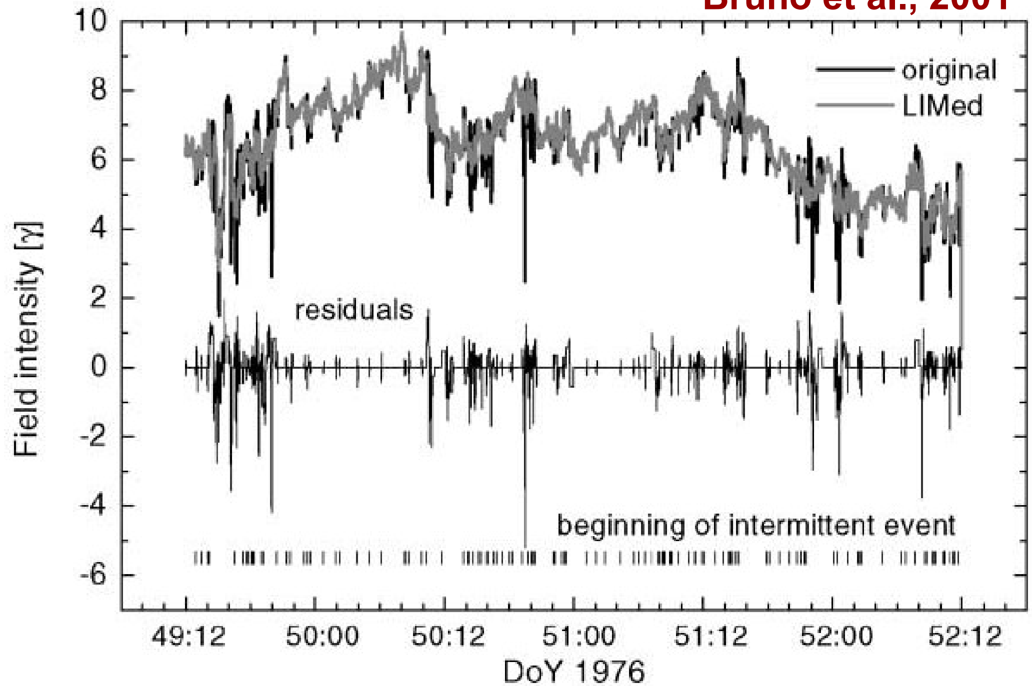
- Probability distribution Functions (PDFs) of velocity and magnetic field fluctuations have non-Gaussian, scale dependent fat tails. Quantitative diagnostics possible
- Dependence on wind speed, radial distance, solar activity...
- Good agreement with multifractal models of intermittent turbulence

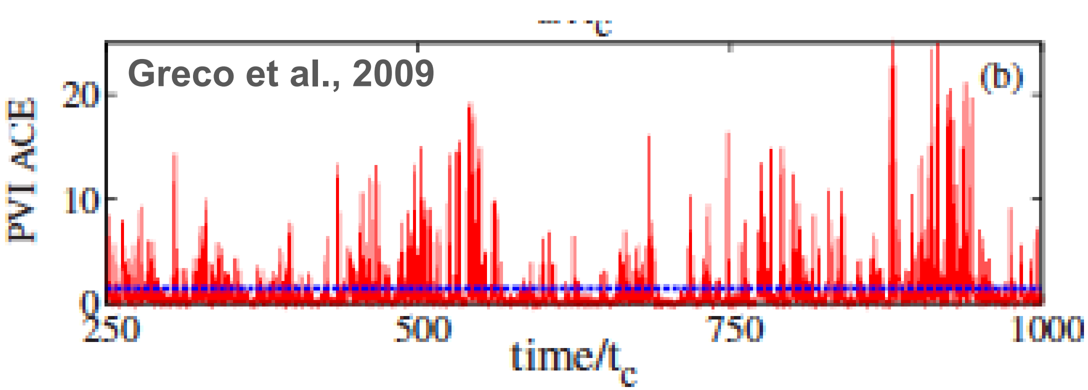
Identification of intermittent structures

In wavelets space

$$\mathrm{LIM}_{\Delta t,t} = \frac{|\tilde{b}_{\Delta t,t}|^2}{\langle|\tilde{b}_{\Delta t,t}|^2\rangle_t},$$

Bruno et al., 2001

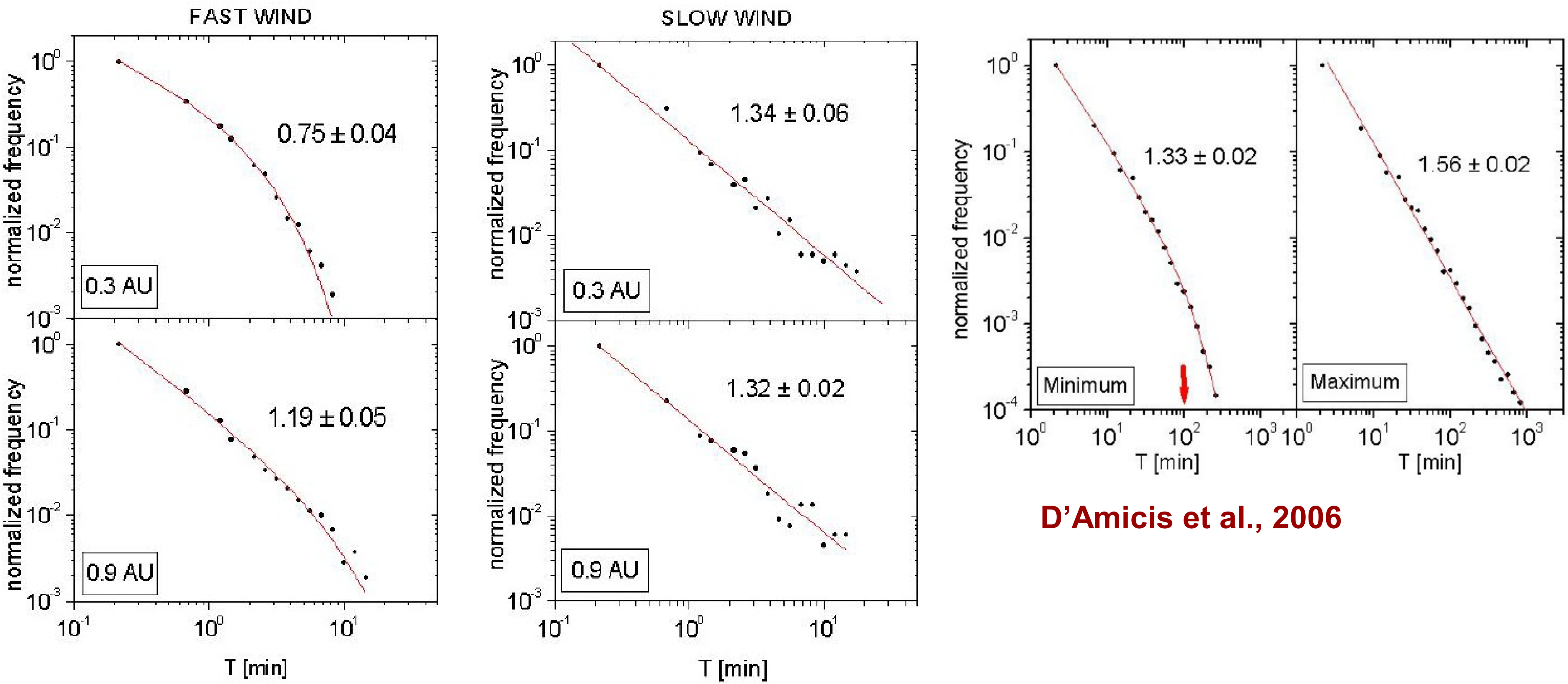




In physical space

$$\mathrm{PVI}_{\Delta t,t} = \frac{|\Delta \mathbf{B}(t,\Delta t)|^2}{\langle|\Delta \mathbf{B}(t,\Delta t)|^2\rangle},$$

Statistical properties of structures



D'Amicis et al., 2006

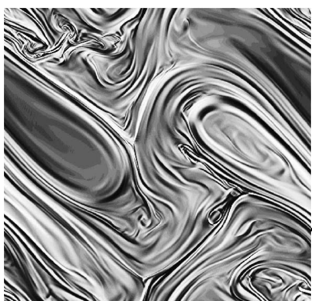
Power law WTD, quantitatively describing the state of turbulence
Less evident and evolving in fast wind. More evident near solar maxima.
Relationship with heating and acceleration?

The turbulent cascade in the solar wind

Fluids - Yaglom law: linear scaling of the 3rd order moment: $\Delta v_l^3 = -4/5\varepsilon l$

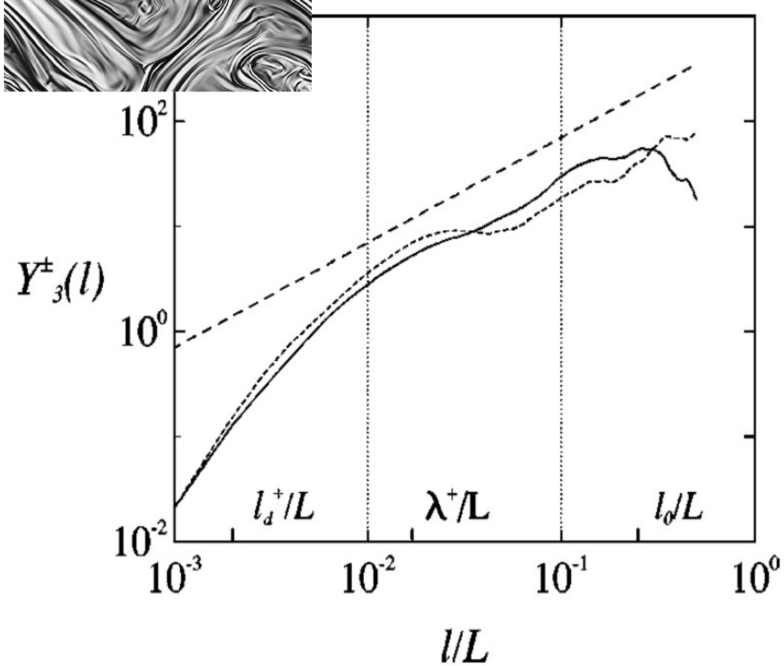
MHD - Politano-Pouquet law: linear scaling of the *mixed* 3rd order moment.

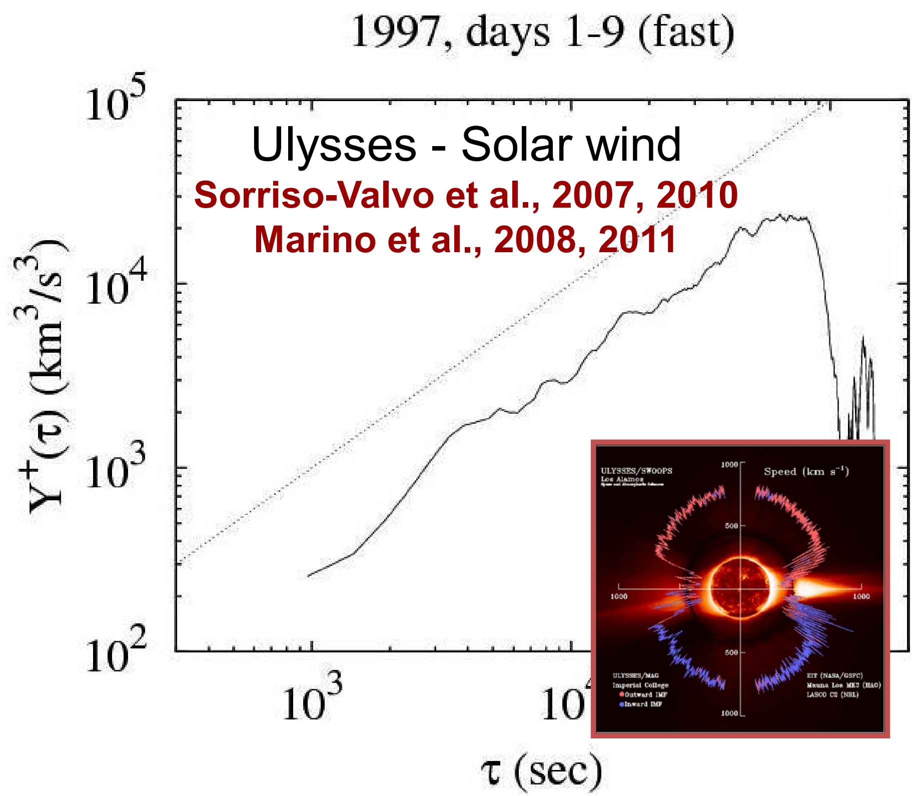
$$Y^{\pm}(\ell) = \langle |\Delta \mathbf{z}^{\pm}(\ell;\mathbf{x})|^2 \Delta z_R^{\mp}(\ell;\mathbf{x}) \rangle = -\frac{4}{3}\varepsilon^{\pm}\ell$$



2D-MHD simulations

Sorriso-Valvo et al., 2002



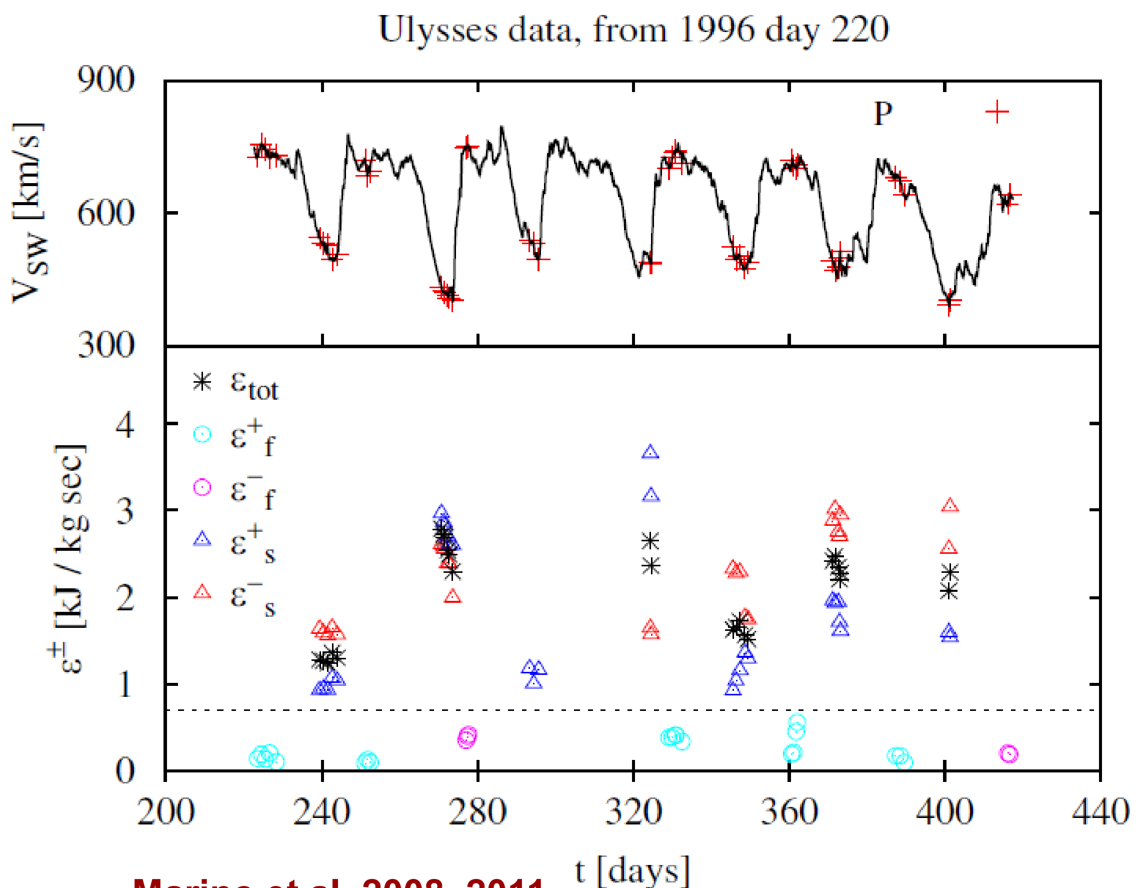


Turbulent energy transfer rate

Politano-Pouquet: first measurement of the mean energy transfer rate ε

$$Y^{\pm}(\ell) = \langle |\Delta \mathbf{z}^{\pm}(\ell;\mathbf{x})|^2 \Delta z_R^{\mp}(\ell;\mathbf{x}) \rangle = -\frac{4}{3}\varepsilon^{\pm}\ell$$

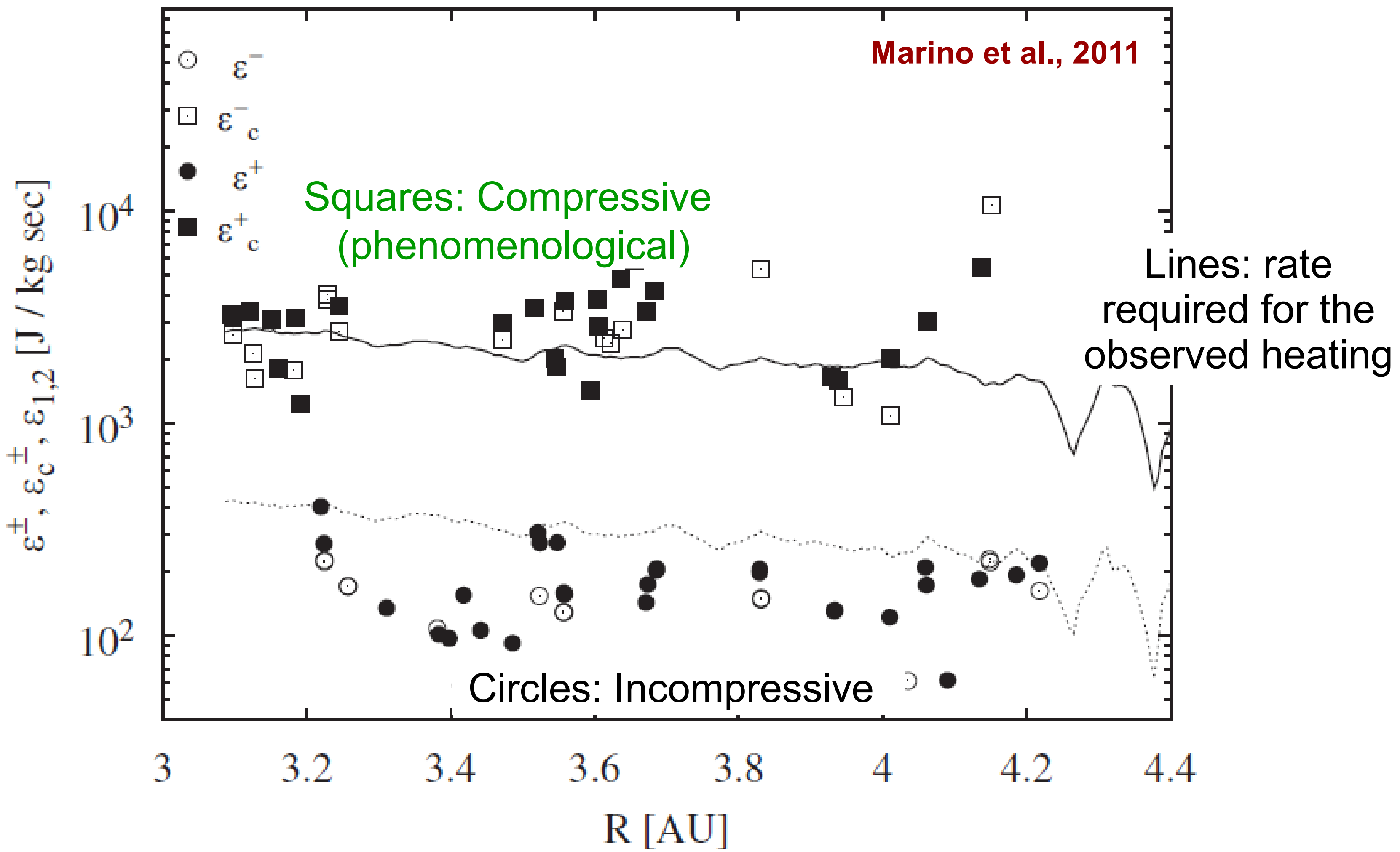
- Not always observed: identification of "clean" turbulence solar wind intervals.
- Correlations with wind speed, solar activity, radial distance, heliolatitude, cross-helicity, velocity shears.



Marino et al, 2008, 2011

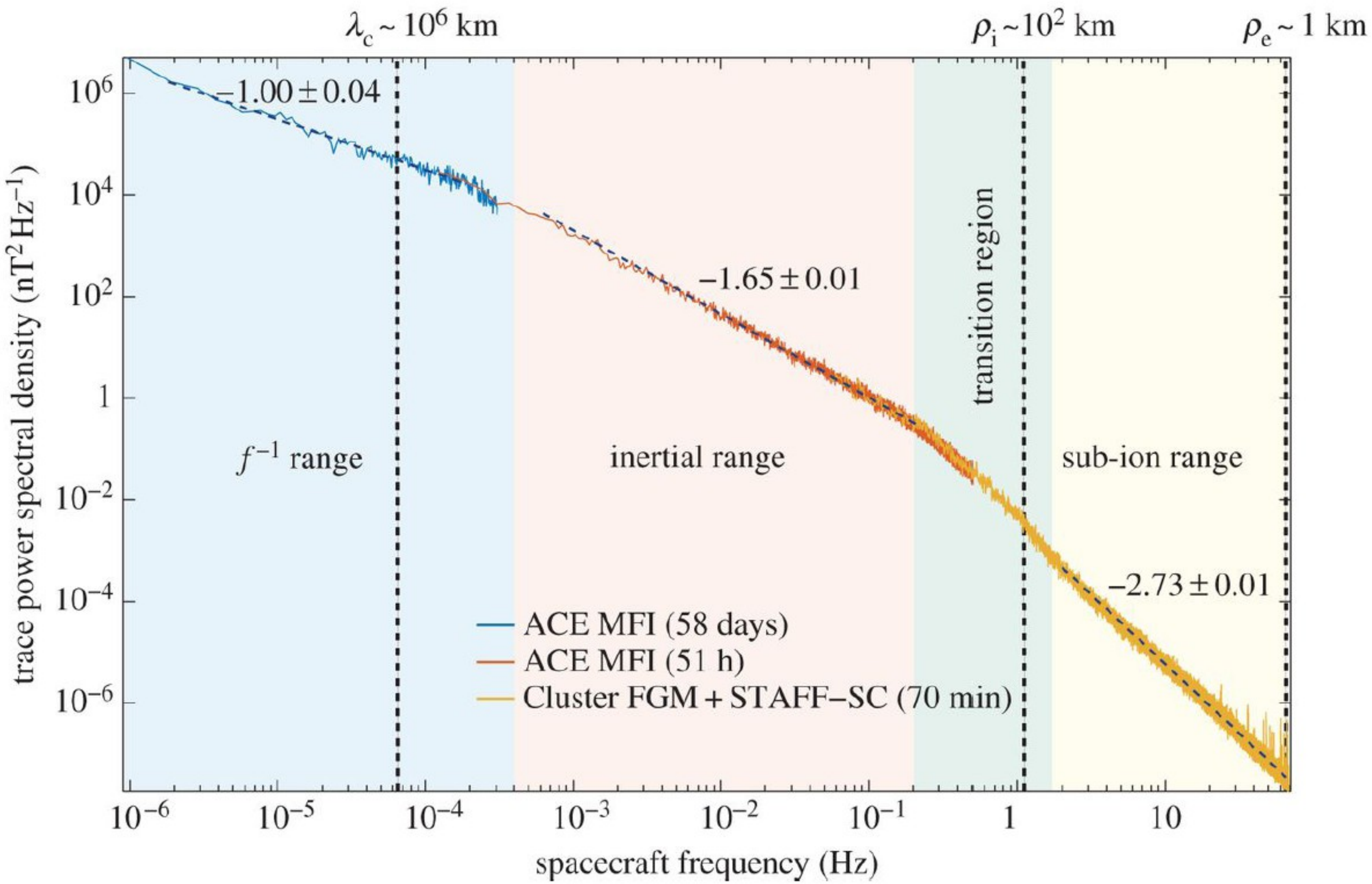
Turbulent heating in the solar wind

Energy available for heating: compatible with temperature observations.



Solar wind turbulence: beyond MHD

Break at ion scales: MHD approximations no longer valid: plasma physics

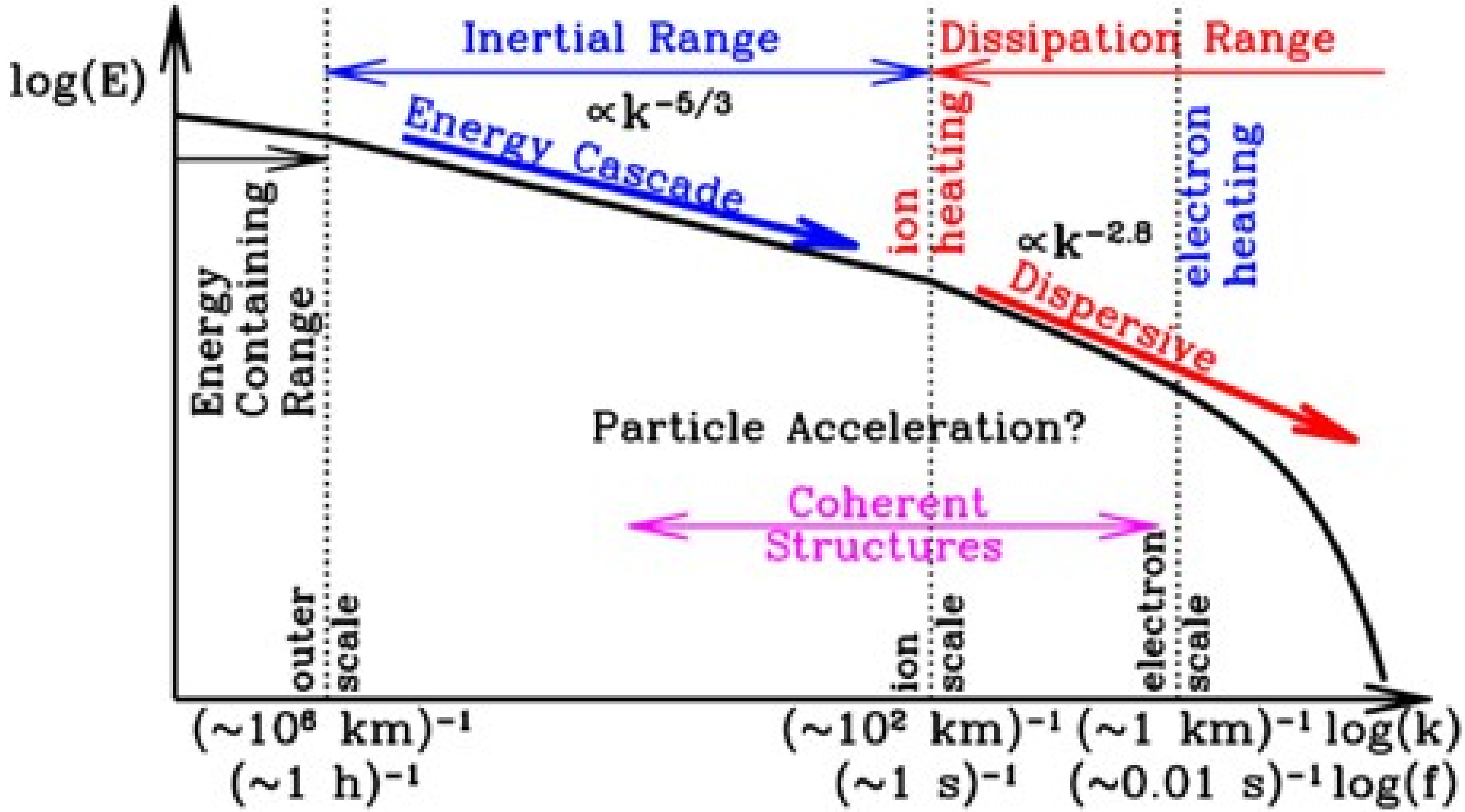


Khurom H. Kiyani et al. Phil. Trans. R. Soc. A
2015;373:20140155

Kinetic effects in plasmas

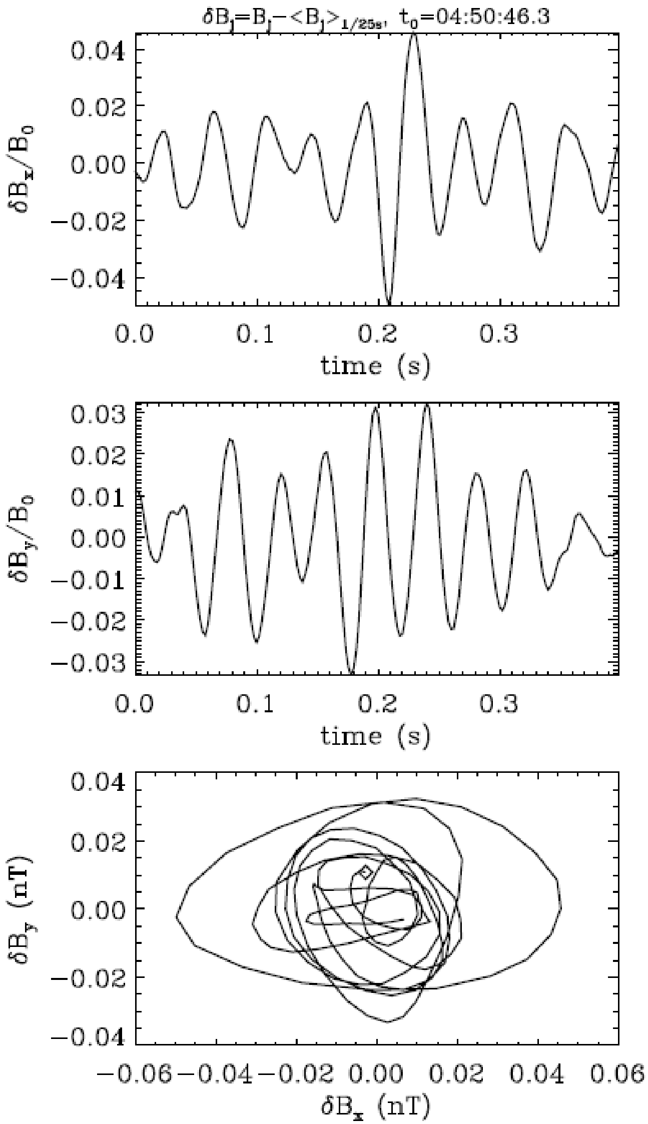
Field-particle interactions: resonance, damping, plasma instabilities, magnetic reconnection, particle acceleration, heating, collisions...

Fluid range: MHD **Kinetic range: Vlasov**

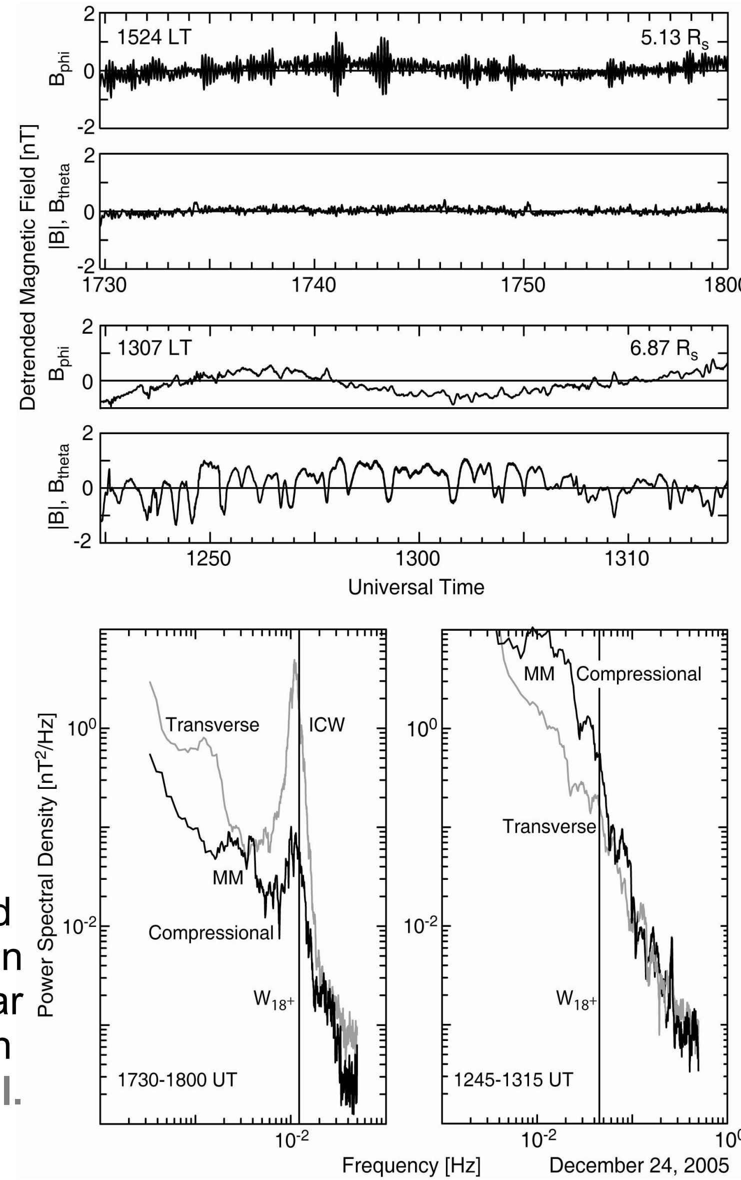


Solar wind small-scale waves

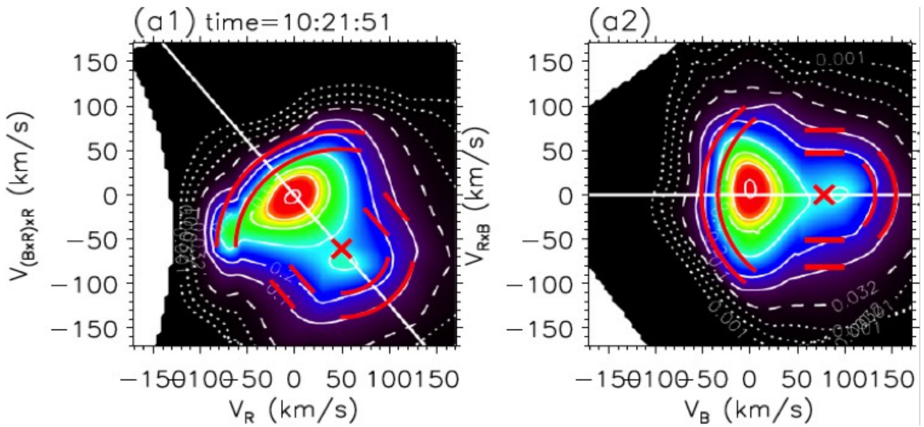
Mirror modes near the Earth
Lacombe et al., 2014

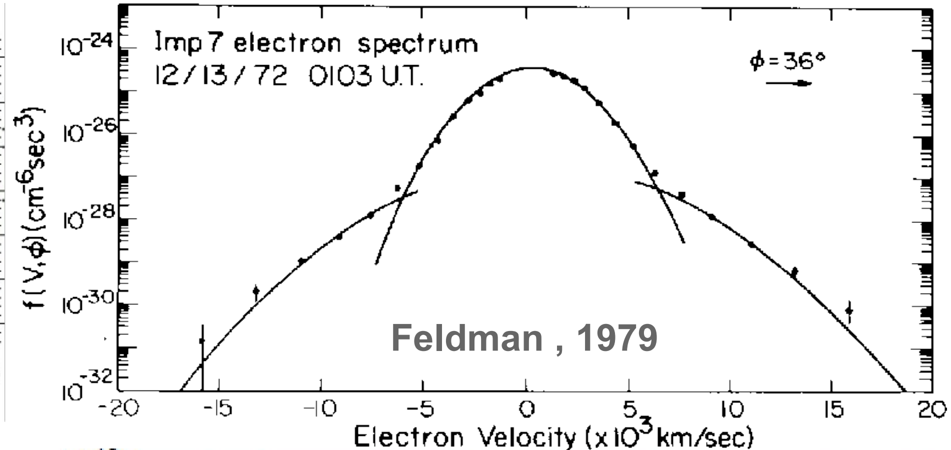


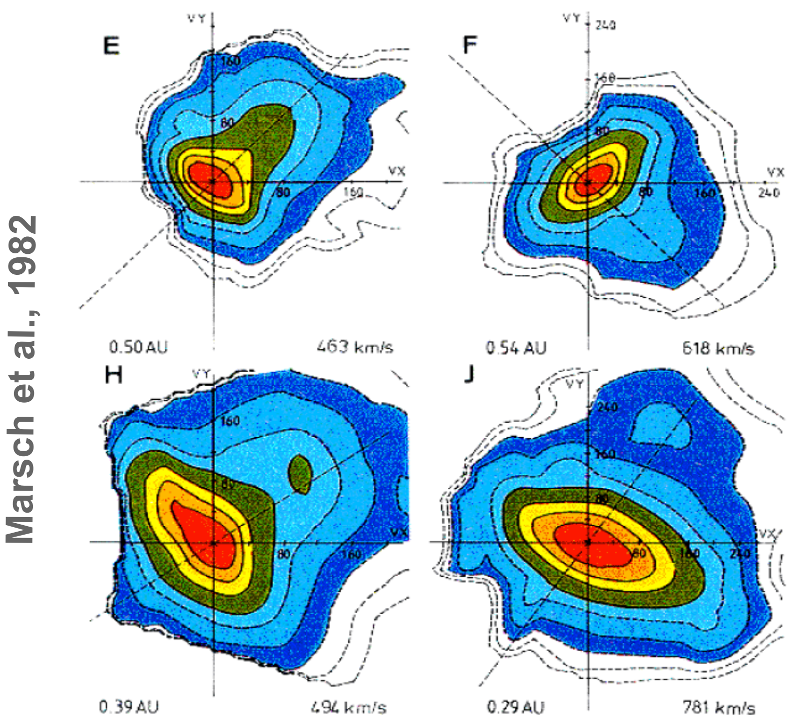
Mirror and ion-cyclotron modes near Saturn
Russel et al.

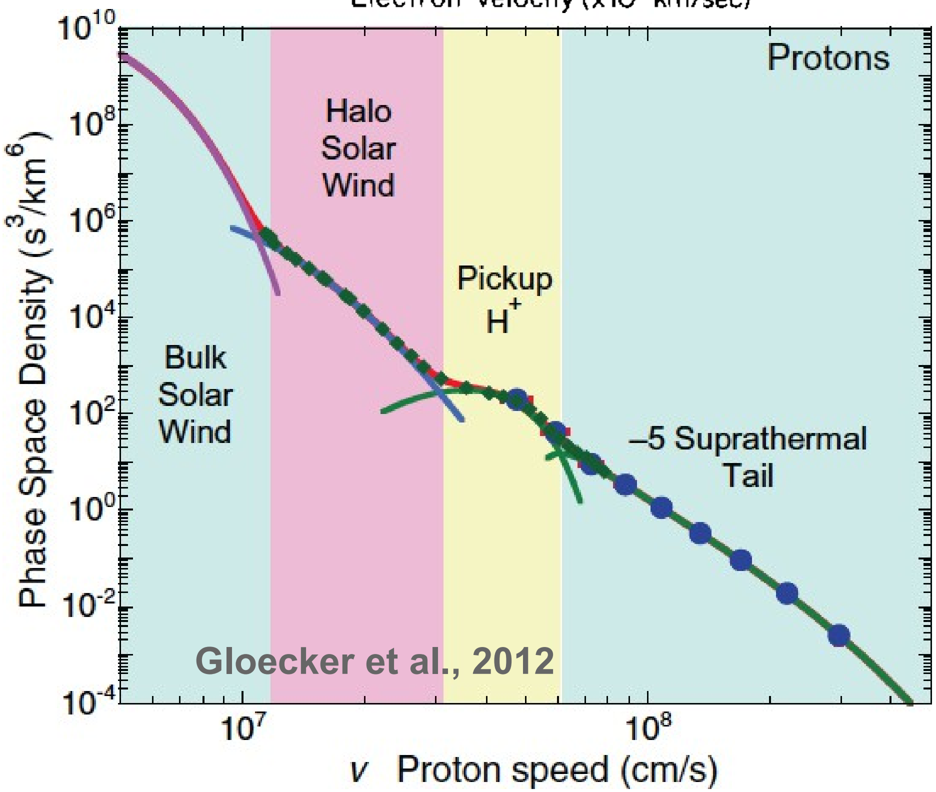


Non-Maxwellian velocity distribution









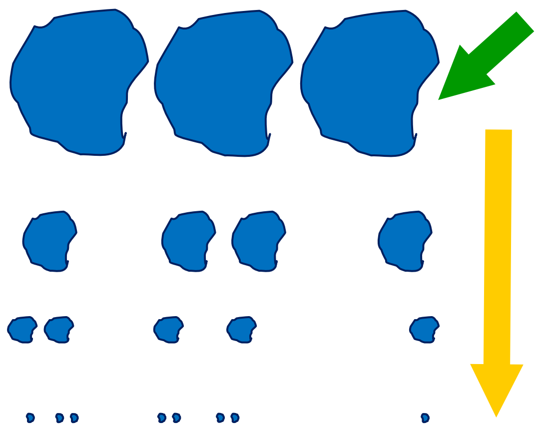
Vlasov-Maxwell equations

Evolution of the particle distribution functions *in the absence of collisions*

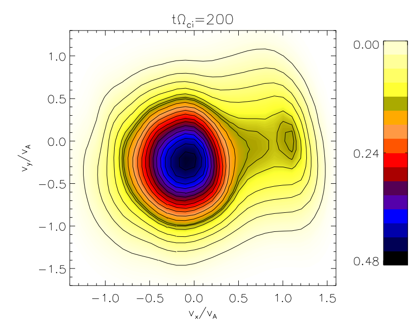
$$\frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \nabla f_e - e\left(\mathbf{E} + \frac{\mathbf{v_e}}{c} \times \mathbf{B}\right) \cdot \frac{\partial f_e}{\partial \mathbf{p}} = 0$$

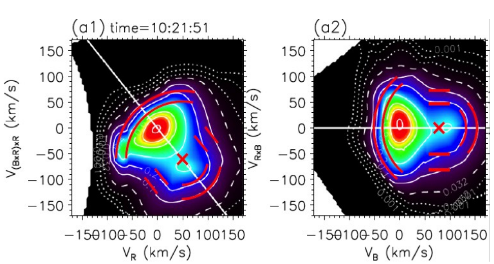
$$\frac{\partial f_i}{\partial t} + \mathbf{v}_i \cdot \nabla f_i + Z_i e\left(\mathbf{E} + \frac{\mathbf{v_i}}{c} \times \mathbf{B}\right) \cdot \frac{\partial f_i}{\partial \mathbf{p}} = 0$$

+ Maxwell

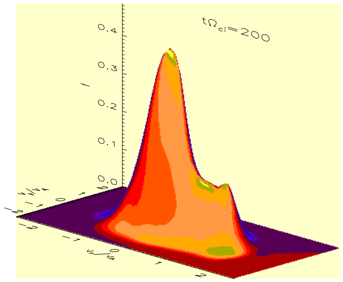


Fluid range: nonlinear cascade for the moments (n, v,...), structures...



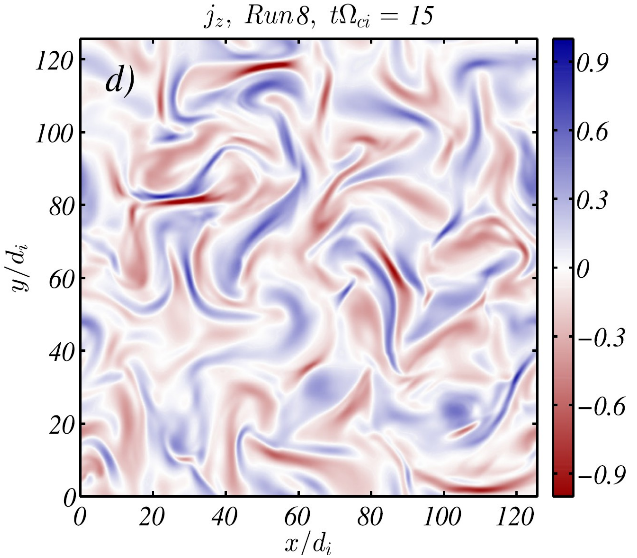


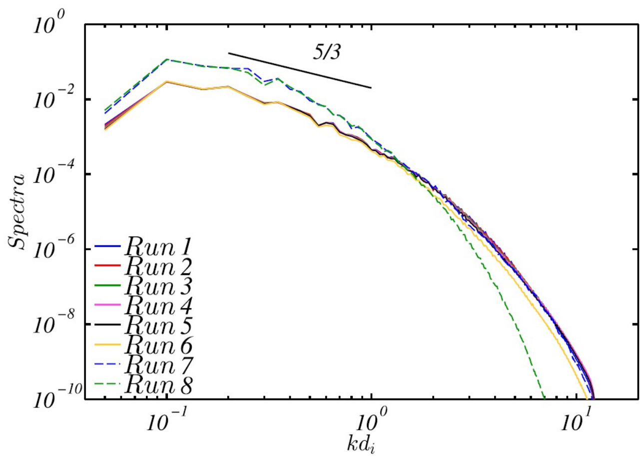
Kinetic range: nonlinear cascade for the distribution functions, waves...

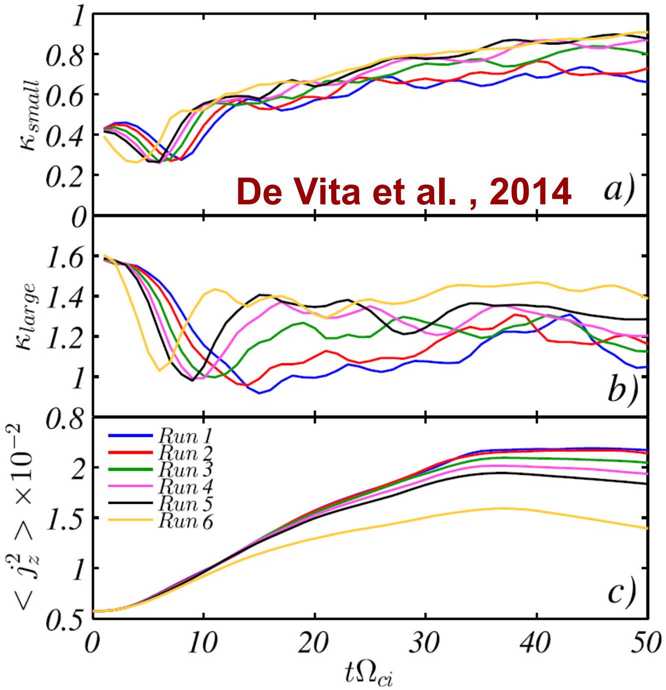


Vlasov-Maxwell turbulence

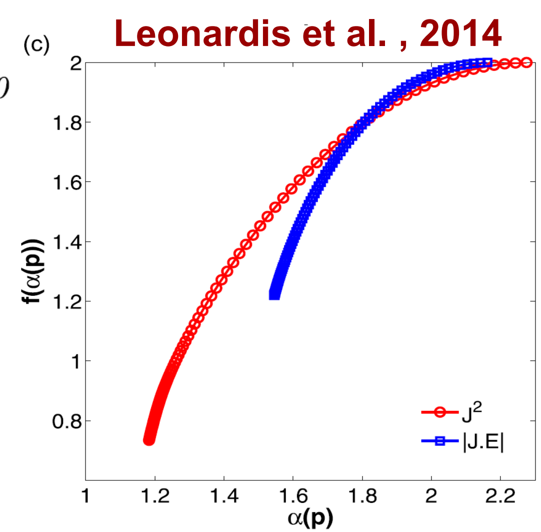
Numerical simulations: large computational requirements
Only recently: transition to turbulence and intermittency







Determine the complexity of current structures to describe the transition to turbulence: cancellation analysis



Quantitative measure of intermittency: multifractal analysis of the energy dissipation

Turbulent Heating & Acceleration

How is turbulent energy dissipated in space plasmas?

linear

waves in coherent structures:
- wave generation & damping
- secondary instabilities

waves:
- cyclotron damping
- Landau damping
- stochastic heating

non-linear

coherent structures:
- reconnection
- scattering & acceleration
- trapping & betatron
- vortex dynamics

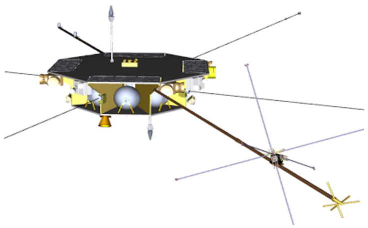
non-linear waves:
- steepened waves
- phase space holes
- nonlinear Landau damping

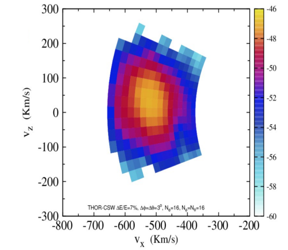
localized *uniform*

Individually studied for simple approximations and under ideal conditions

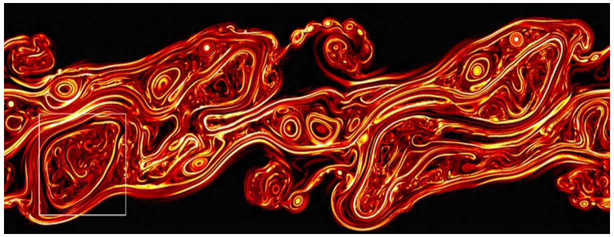
What strategy?

1. Improve space data quality

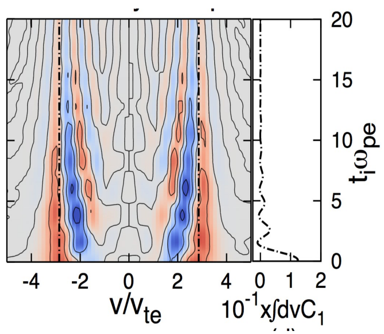




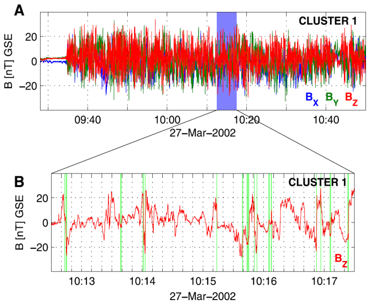
2. Increase performance of fluid and fully kinetic numerical simulations

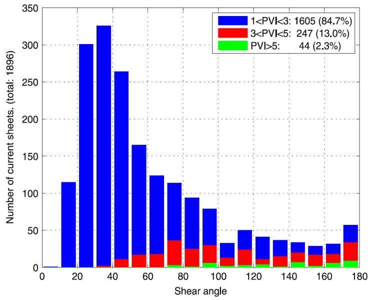


3. Develop more precise diagnostic tools



4. Perform extensive data analysis - measurements and numerical simulations





Example of specific approach

- **Dissipation and dispersion: various mechanisms**
  Which processes occur under specific conditions? What triggers them?

- **Solar wind extremely complex system**
  Complexity: solar origin (activity, speed, composition, structures...) and turbulence origin (expansion, anisotropy, waves, cross-helicity...)

- **Even under “quiet” conditions**
  Intermittency and inhomogeneous dissipation (see Castaing)

Accurate data conditioning
to isolate different processes

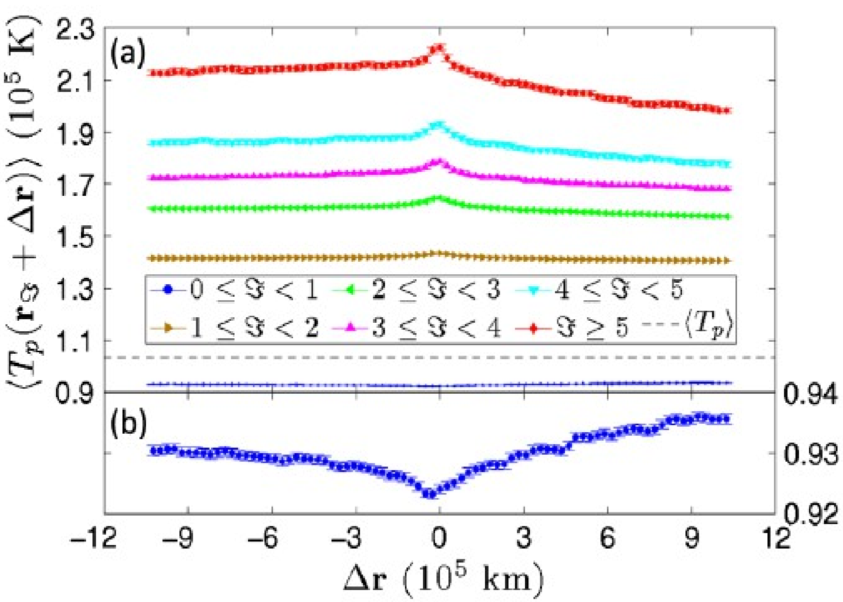
Study of "dissipative" processes

- Collect samples from **space measurements** and **numerical simulations**
- Accurately describe all possible properties and phenomena

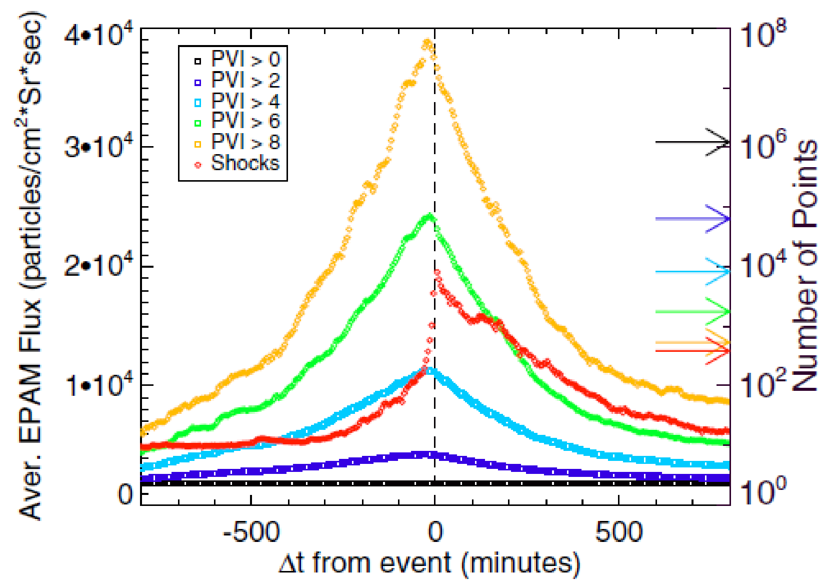
Plasma properties		**Diagnostics for dissipation**	
Global and statistical	**Local**	**Global and statistical**	**Local**
Plasma conditions (composition, speed, cross-helicity, β, region...)	Shocks, reconnection, structures, collisions...	Heating, energetic particles...	Heating, particle beams, modified VDF...
Turbulence (spectra, energy flux, intermittency, anisotropy...)	Structure topology, field singularity...	Waves, differential energization...	Reconnection, wave packets
Look for correlations to discriminate dissipation mechanisms **Constrain theoretical models for dissipation** **Exploit numerical simulations and support space mission design**			

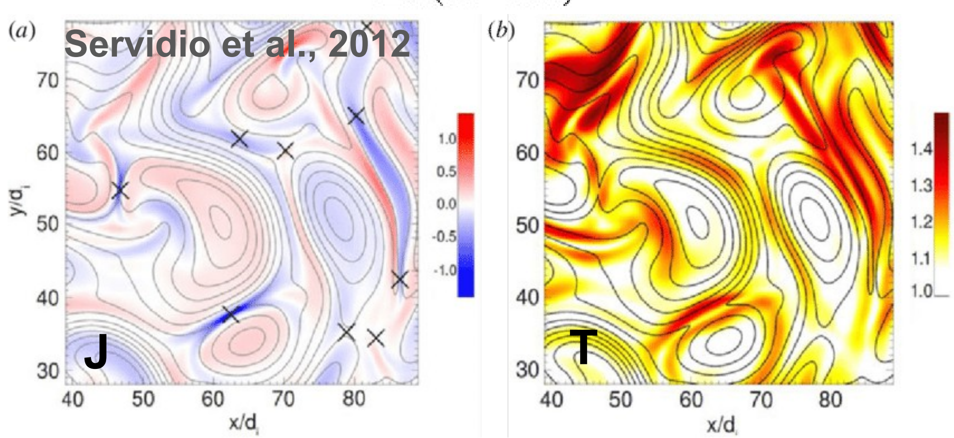
Examples: heating and acceleration near intermittent structures

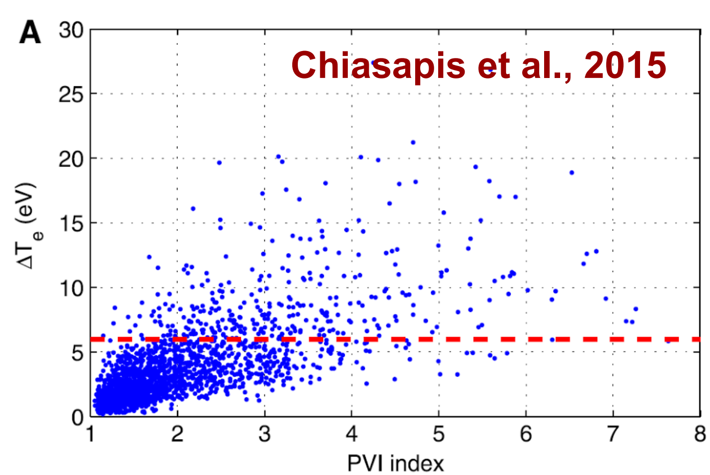
Enhanced heating near PVI detected structures [Osman et al., 2012]



Enhanced SEP flux observation near PVI detected structures [Tessein et al., 2013]



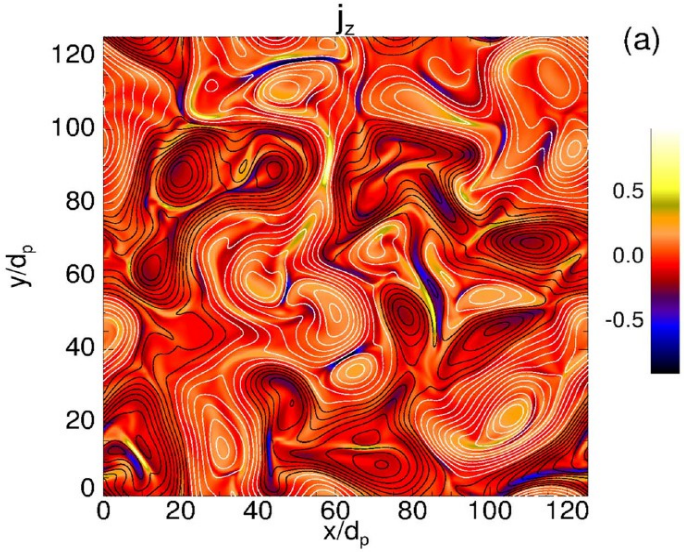


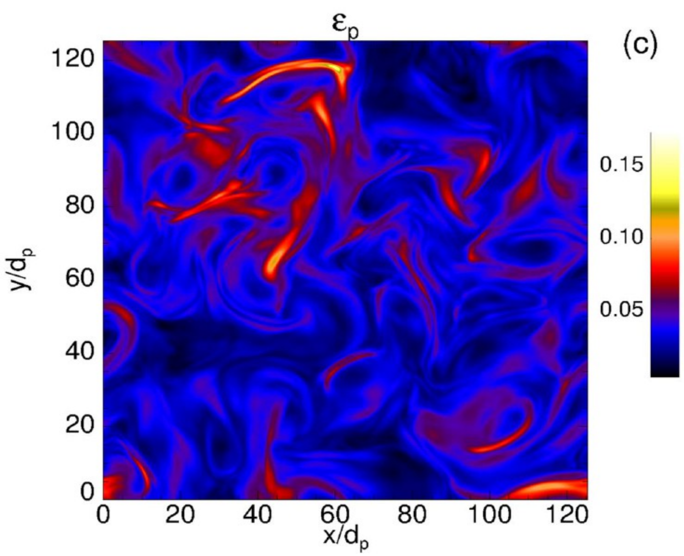


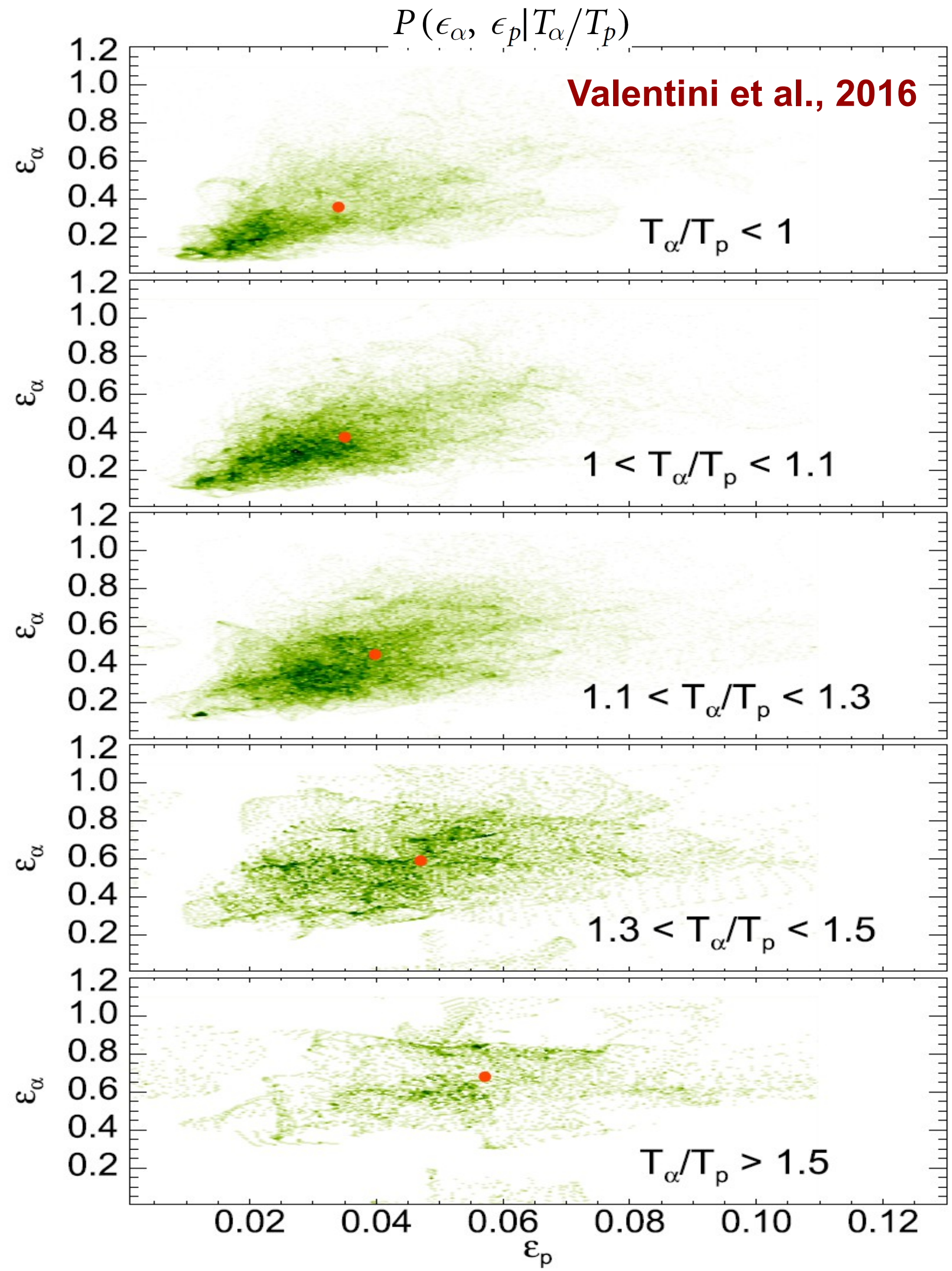
Examples: heating of α-particles

Protons and α heated differentially:
info about heating mechanism?

Deviation from maxwellian: ε



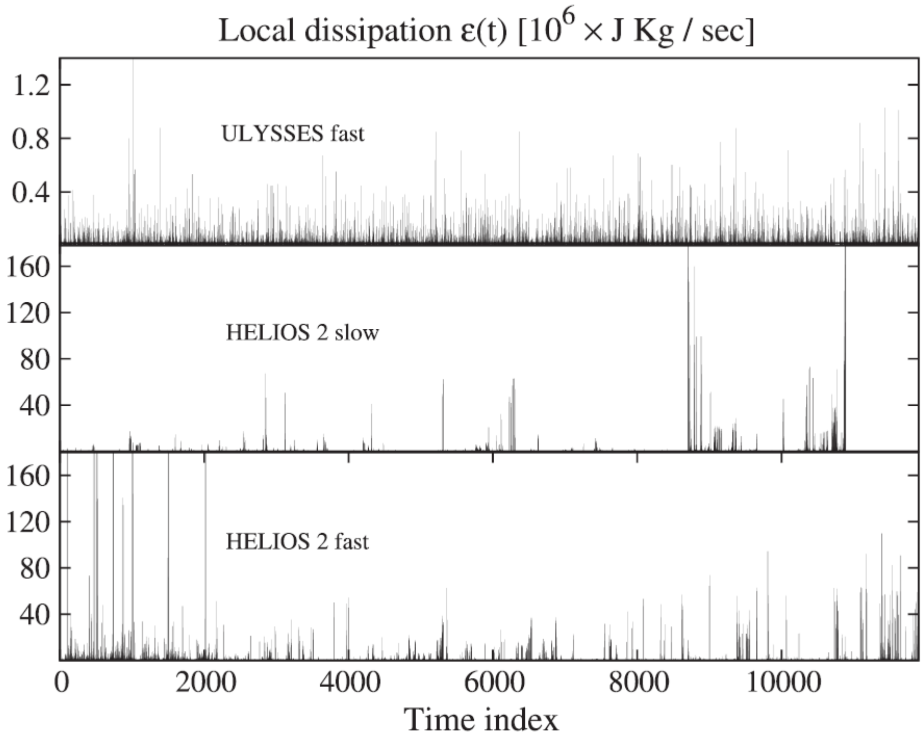


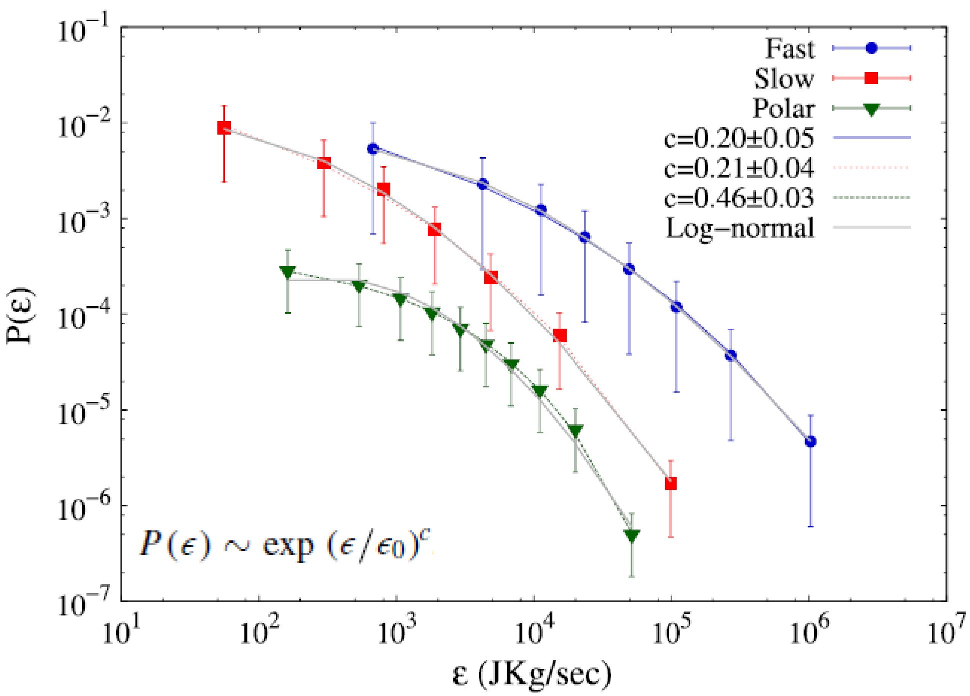


Local dissipation rate in solar wind

Politano-Pouquet law: proxy for the local energy transfer rate:

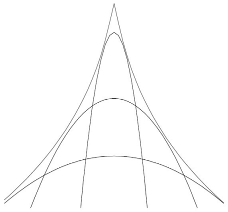
$$Y^{\pm}(\ell) = \langle |\Delta \mathbf{z}^{\pm}(\ell;\mathbf{x})|^2 \Delta z_R^{\mp}(\ell;\mathbf{x}) \rangle = -\frac{4}{3}\varepsilon^{\pm}\ell \quad \Rightarrow \quad \epsilon_{\tau}^{\pm}(t) = \frac{|\Delta z^{\pm}(t)|^2 \Delta z_R^{\mp}(t)}{\tau \langle v \rangle}$$



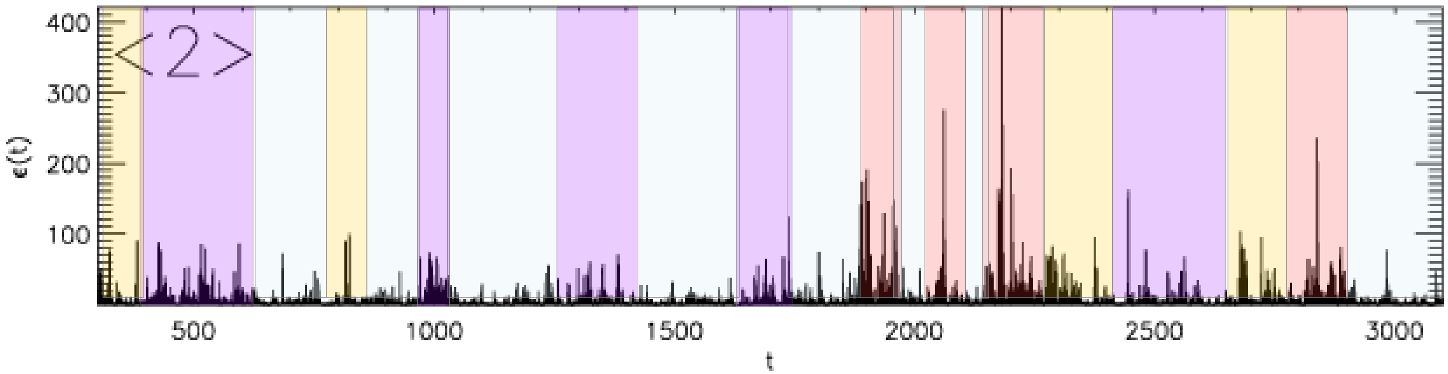


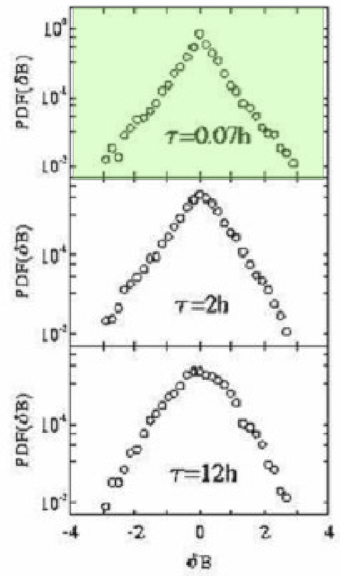
Sorriso-Valvo et al, APJ 2015

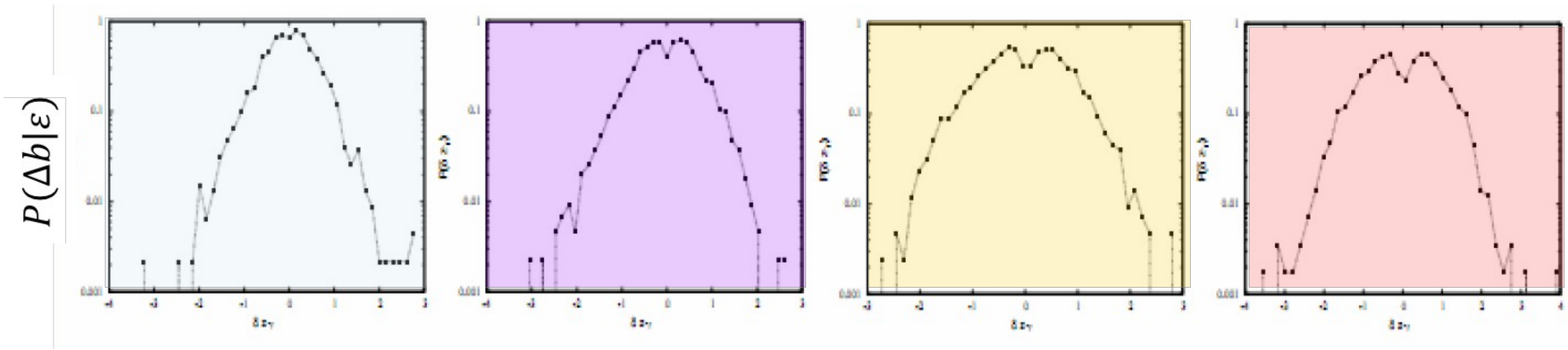
Conditioned PDFs



PDFs conditioned to given ε: Gaussian PDFs at all scales:
Multifractal model of intermittency







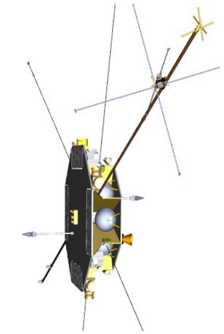
Helios 2, slow

Sorriso-Valvo et al, 2002, 2015


THOR
Turbulence Heating ObserveR
www.thor.irfu.se
esa
European Space Agency

THOR

Exploring plasma energization in space turbulence

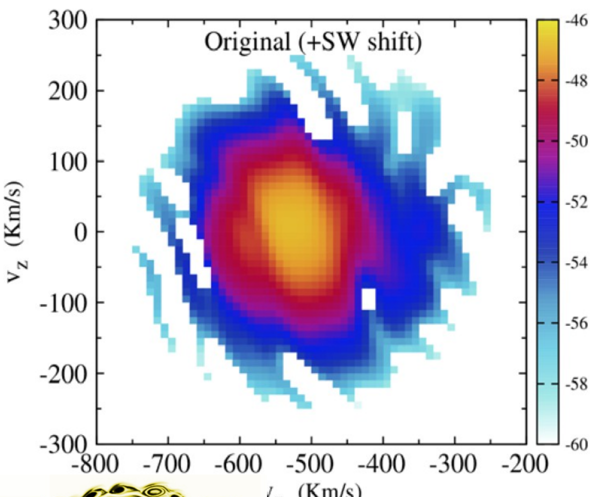


Science questions

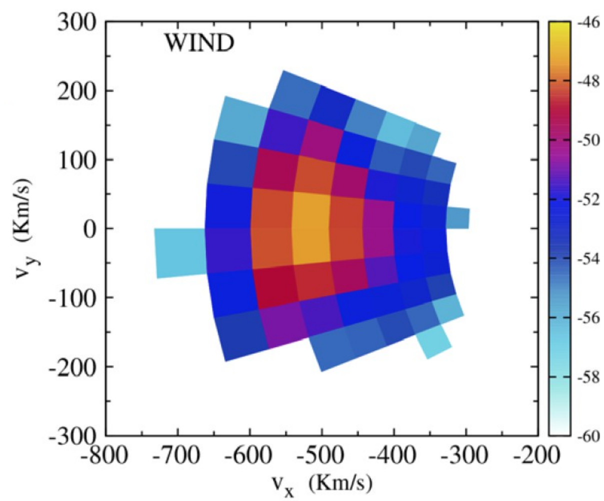
- How is plasma heated and particles accelerated?
- How is the dissipated energy partitioned?
- How does dissipation operate in different regimes of turbulence?

Particle measurements requirements

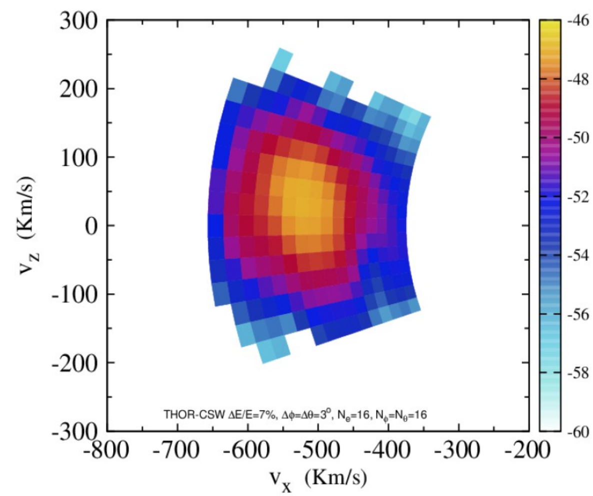
Vlasov Simulation



Virtual
Previous Spacecraft

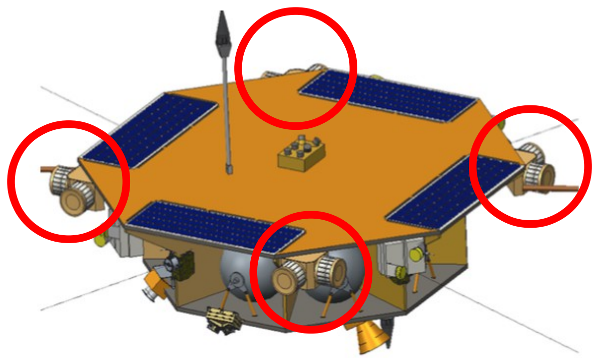


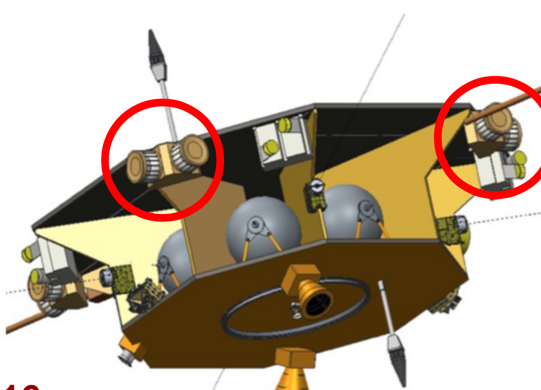
Virtual - THOR

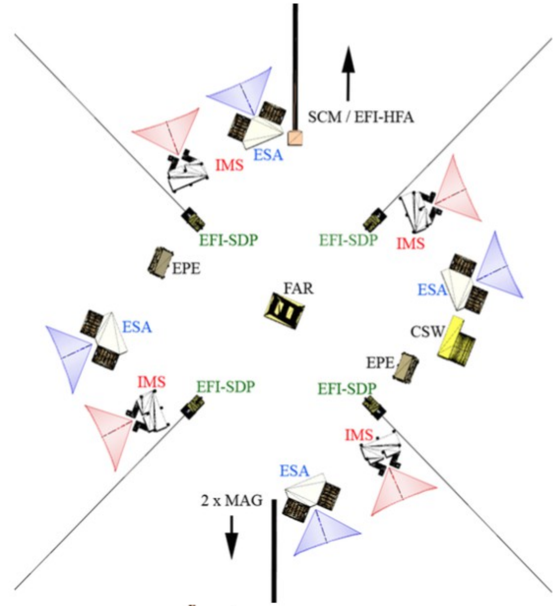


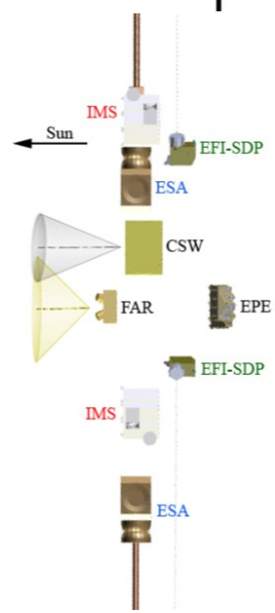
Vaivads et al., 2016

THOR payload





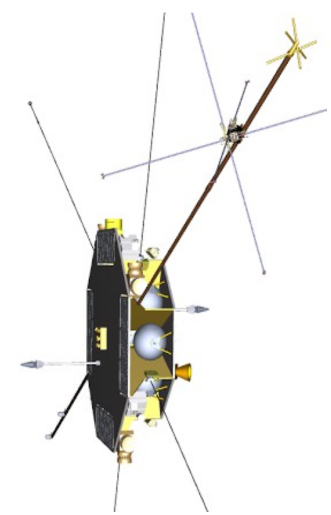




Vaivads et al., 2016

THOR timeline

✓ 2015-01-15 proposal submitted to ESA M4
✓ 2015-06-04 THOR selected for study phase
✓ 2015-06-11 kick-off of ESA phase 0 study
✓ 2015 fall end of phase 0
✓ 2016 phase A study
✓ 2016 kick-off workshop of THOR
2017 fall final down-selection
2026 launch?



Summary

- Solar wind offers a great opportunity to study plasma physics
- Fluid-scale turbulence & intermittency have been deeply studied
- Small-scale turbulence has been recently addressed
- There are many proposed mechanisms for dissipation of plasma turbulence
- Multiple approach: space missions, data, theory, and numerical simulations
- Important to understand what triggers different dissipation mechanisms
- Collateral gain: astrophysical and laboratory plasma dissipation processes, implications for space weather

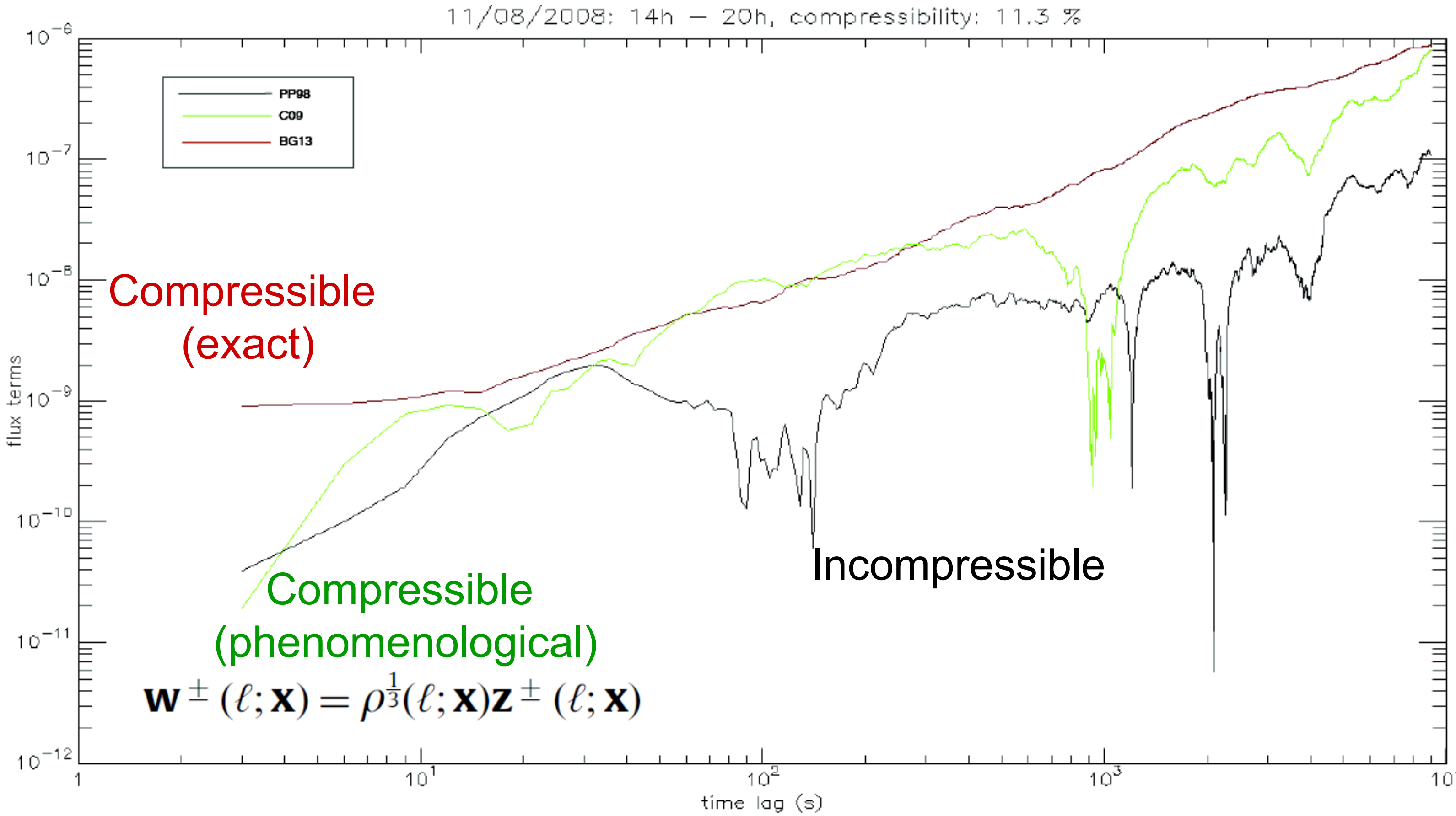
Thank you

Short CV

- **PhD** at Calabria University (Italy) & Observatoire de Nice (France)
- **Post-doctoral** researcher at Calabria University (Italy)
- Since 2004: Staff **Researcher** at National Council of Research (Italy)
- 2012-2013: **Researcher** at UC Berkeley
- **Visiting** researcher: Observatoire de Nice; Technical University of Barcelona; Ocean Science Institute, Barcelona; National Institute of Astrophysics, Rome; Torino Observatory; Observatoire de Paris; Plasma Physics Laboratory, Palaiseau; University College of London; Queen Mary University of London.
- 78 published **articles**, 1500+ citations, h-index=21
- 18 **invited talks**, 100+ conferences and workshops
- **Convener** of conference sessions: EGU, AOGS
- **Organizer** & co-organizer of international Workshops and schools
- **Coordinator** of one EU Marie Curie Project (4 years, 300k€)
- Several national research **grants** and projects (Italy)
- 10+ years **teaching** experience (Italy and Spain)
- Italian national **qualification** as full professor
- **Supervisor** of 2 PhD and several Master students
- ESA astronaut **instructor**
- **Panelist** for NASA and Italian Ministry of University and Research

Compressive cascade in the solar wind

Include compressive effects in the P-P law:
better scaling and higher energy transfer rate



$$\mathbf{w}^{\pm}(\ell;\mathbf{x}) = \rho^{\frac{1}{3}}(\ell;\mathbf{x})\mathbf{z}^{\pm}(\ell;\mathbf{x})$$

Carbone et al., PRL 2009; Banerjee, PhD thesis; Banerjee & Galtier, PRE 2013.

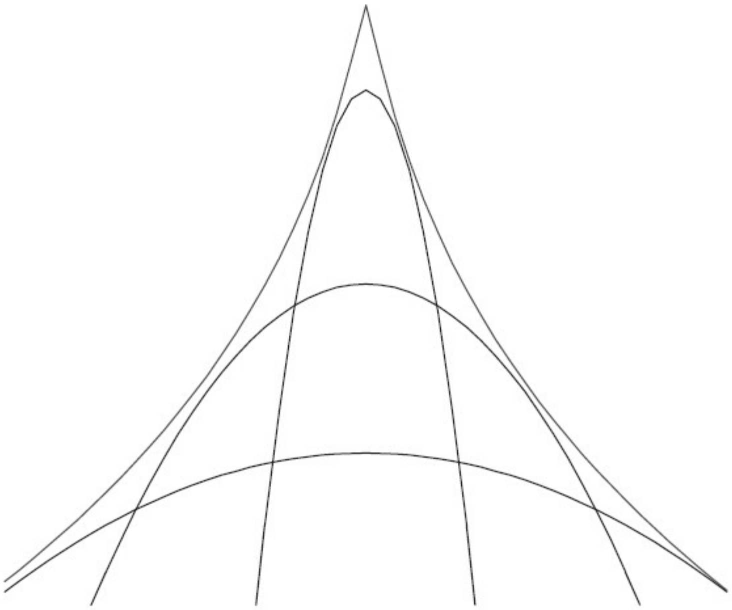
Castaing multifractal model

Multifractal picture: different subsets with different energy transfer rate have Gaussian fluctuations (e.g. Δb), at all scales.

Intermittent PDF: superposition of those Gaussians, each with given variance σ and weight L, proportional to the size of each subset.

- Introducing the distribution of weights $L(\sigma)$;
- Computing the convolution of Gaussians of width σ, $G(\sigma,\Delta b)$:

$$P(\Delta b) = \int L(\sigma)\ G(\Delta b,\sigma)\ d\sigma$$

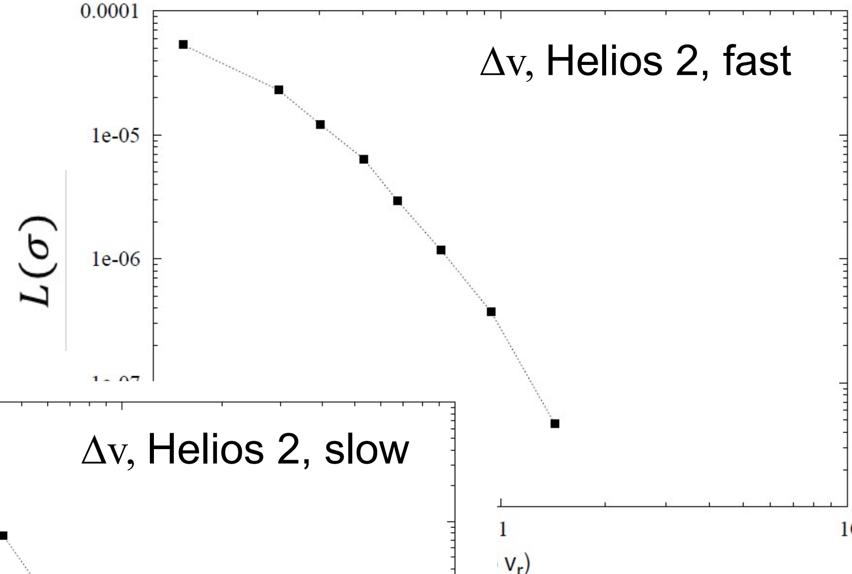


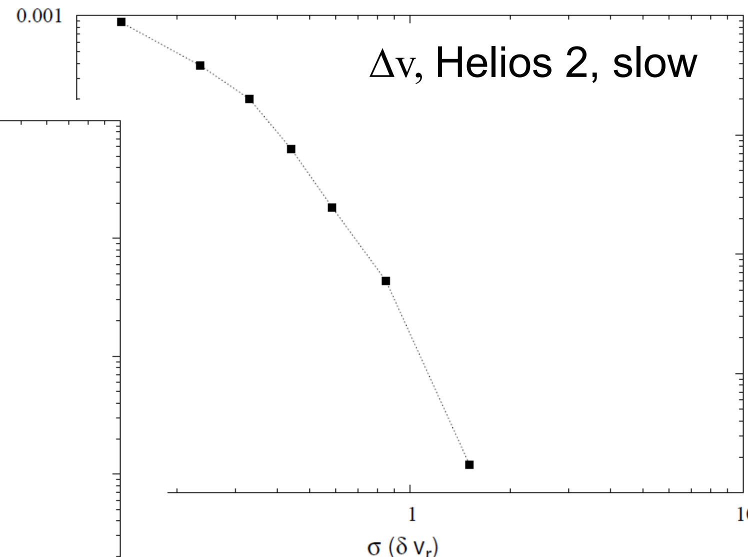
Castaing et al., Phys. D 1990; Carbone et al., Riv. Nuovo Cimento 2004

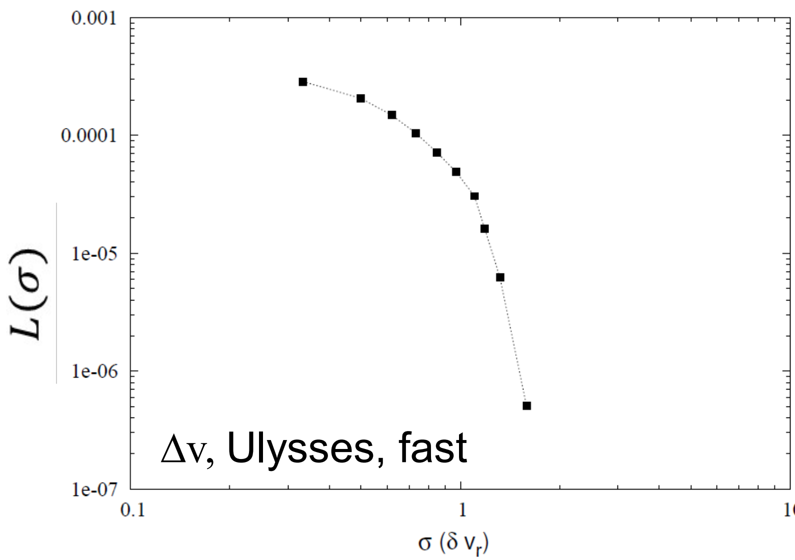
Self-consistent L(σ)

- Standard deviations of conditioned PDFs computed through Gaussian fit.

- Distribution of variances L(σ) estimated self-consistently from the data: roughly stretched exponential.





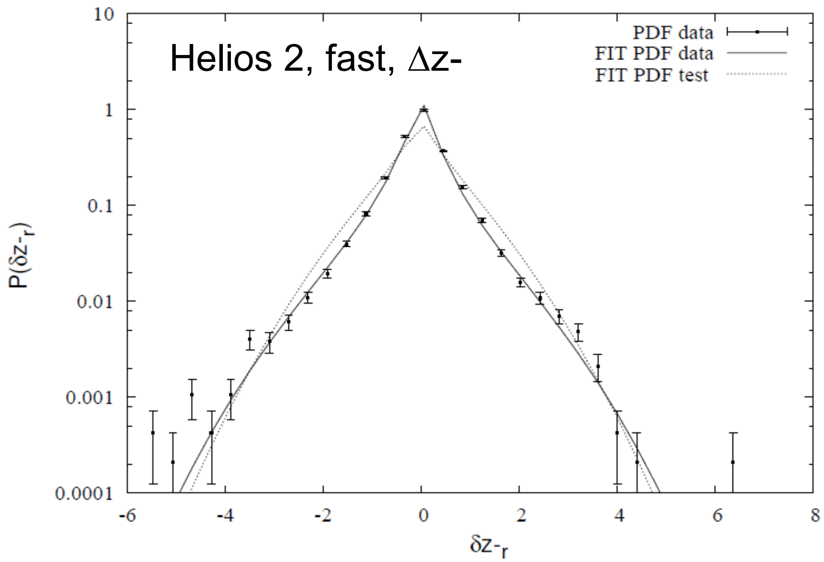


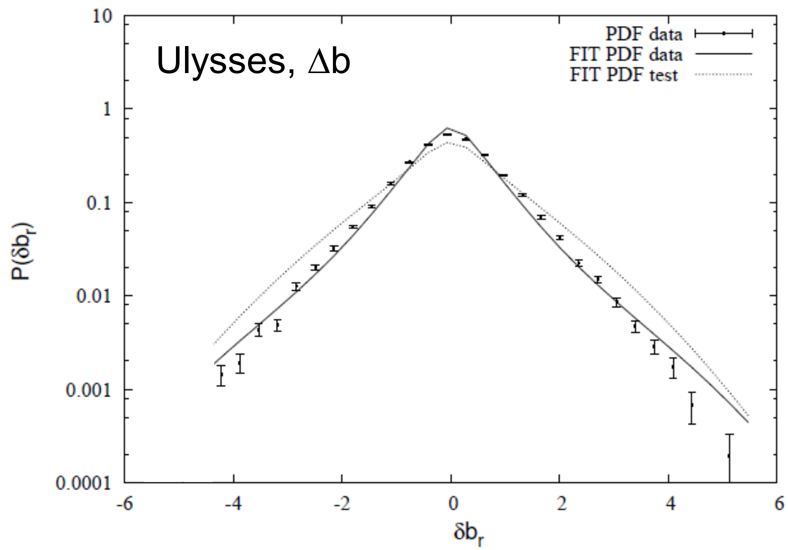
$$P(\Delta v) = \int L(\sigma)\ \ G(\Delta v,\sigma)\ d\sigma$$

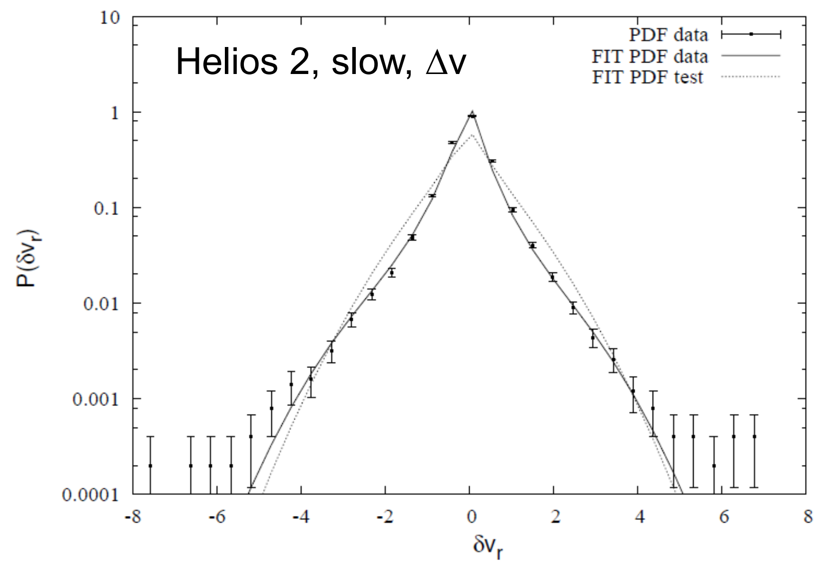
Self-consistent Castaing PDF

The parameter-free Castaing convolution fits the experimental PDFs: validation of the multifractal model of solar wind intermittency

Sorriso-Valvo et al, APJ 2015

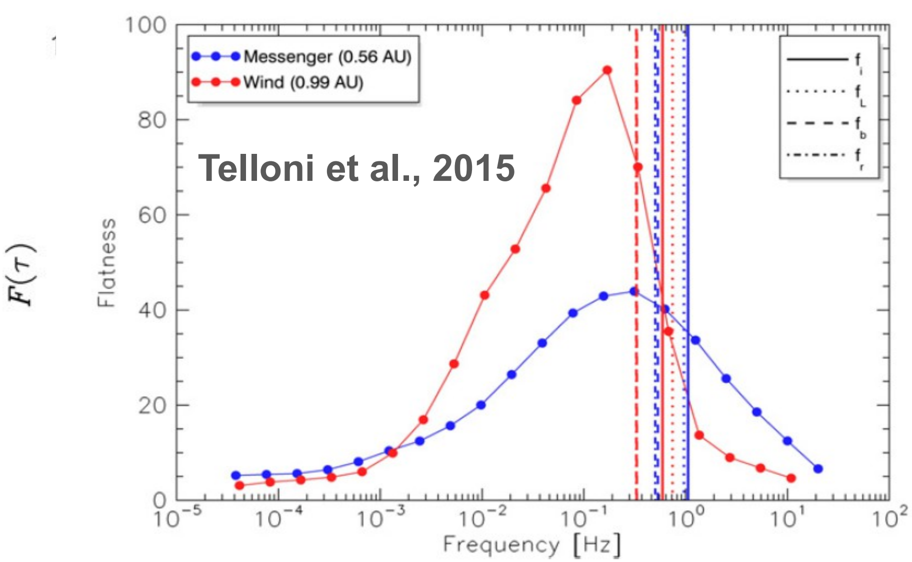


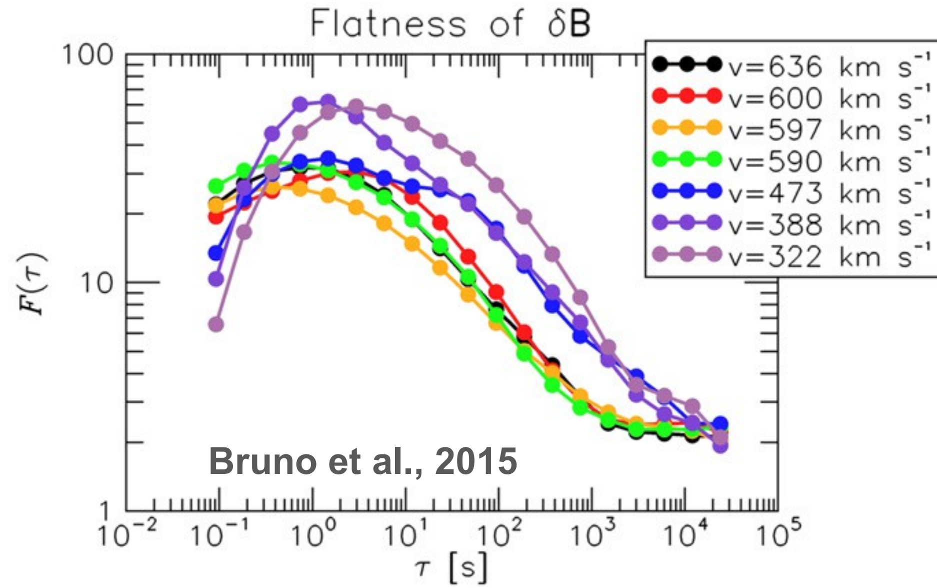


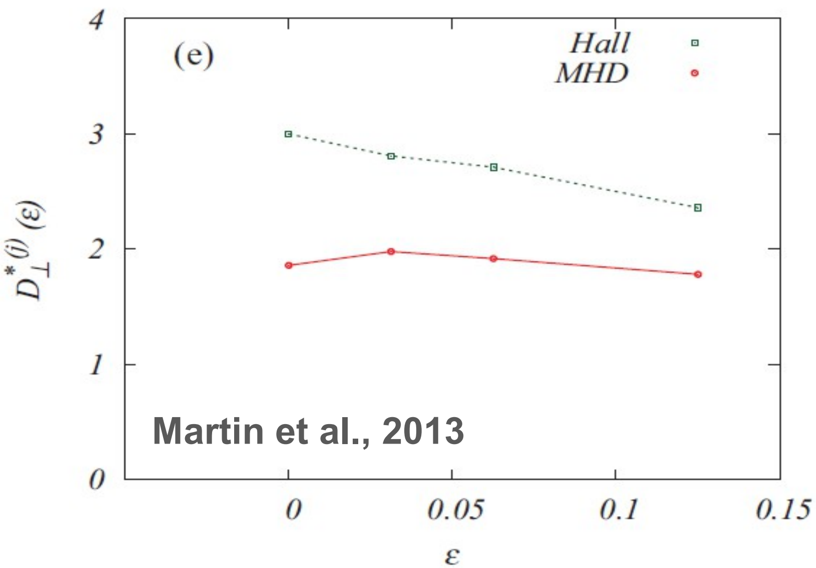


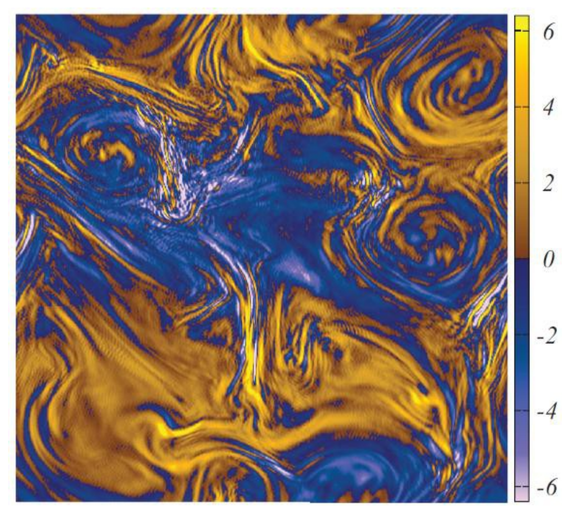
Small-scale fluctuations: intermittency?

Evidences from data and simulations: current sheets reach minimum size, then filament

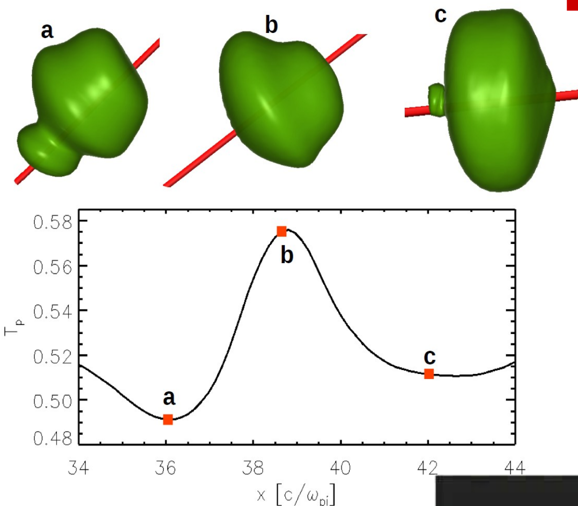






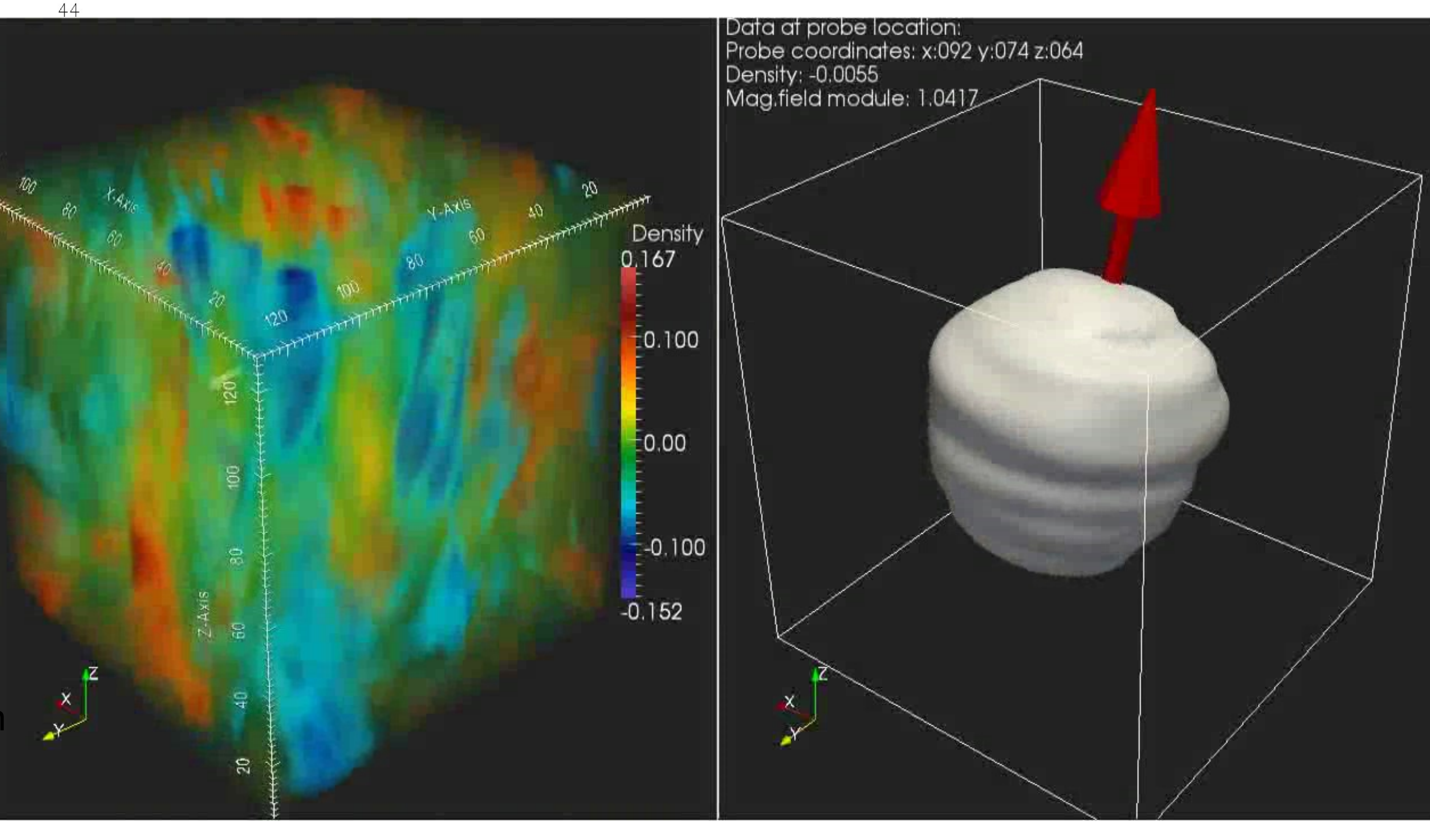


Example: Virtual spacecraft



Numerical simulations reproduce spacecraft time series to test diagnostics tools and help defining space mission payload requirements

The VDF shape responds to field fluctuations



Vlasov numerical simulations and relative proton distribution function