SF2A 2022, S20 Cosmic Turbulence
8-9 juin 2022, Besançon

Introduction

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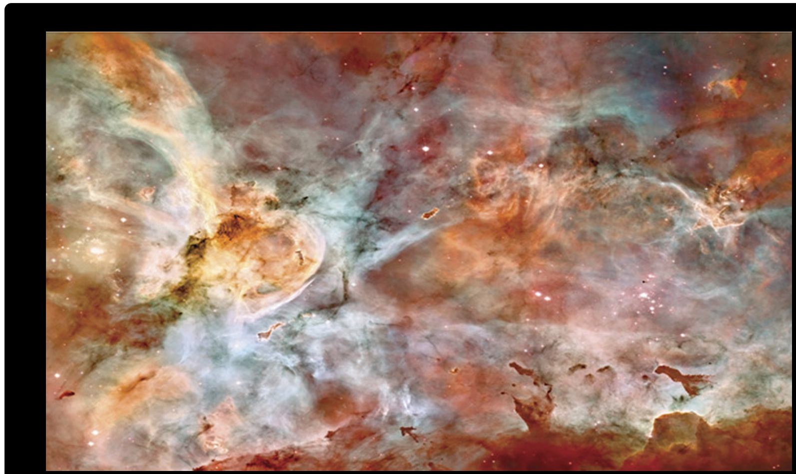
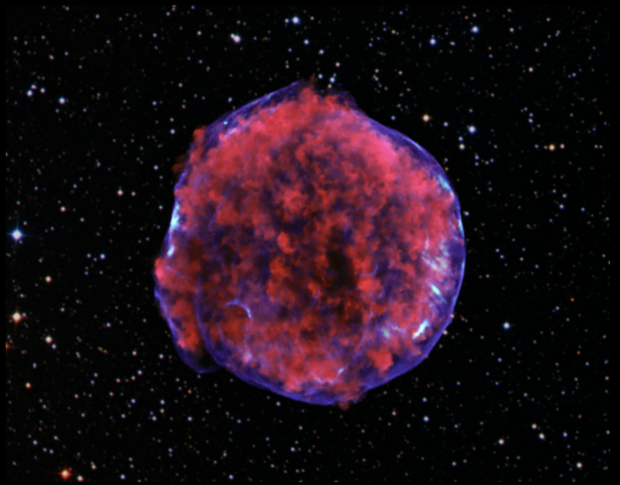
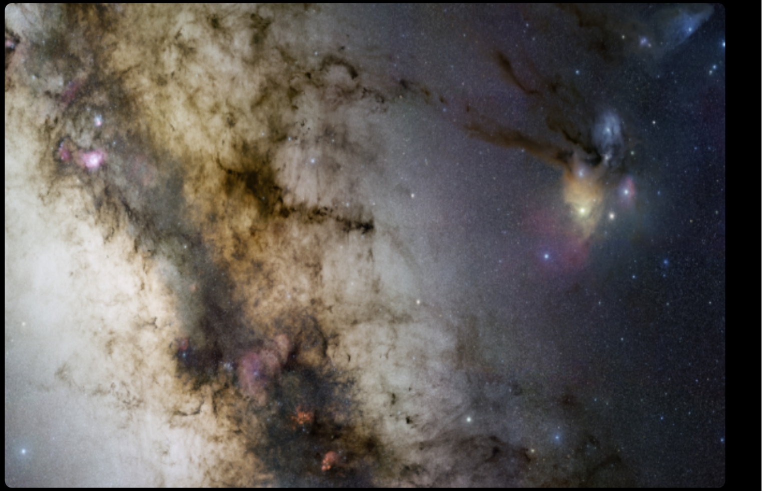
Atrophysical plasmas are generally turbulent


NASA, ESA, N. Smit (UC Berkley), HUBBLE Heritage team (STSCL/AURA), NOAO/AURA/NSF


2019 Miloslav Druckmuller, Peter Aniol


Chandra


ESO/VLT

Turbulence develops in any flow where energy is injected at scales L_0 >> the scale of dissipation L_d ($L_0/L_d = R_e^{3/4}$)

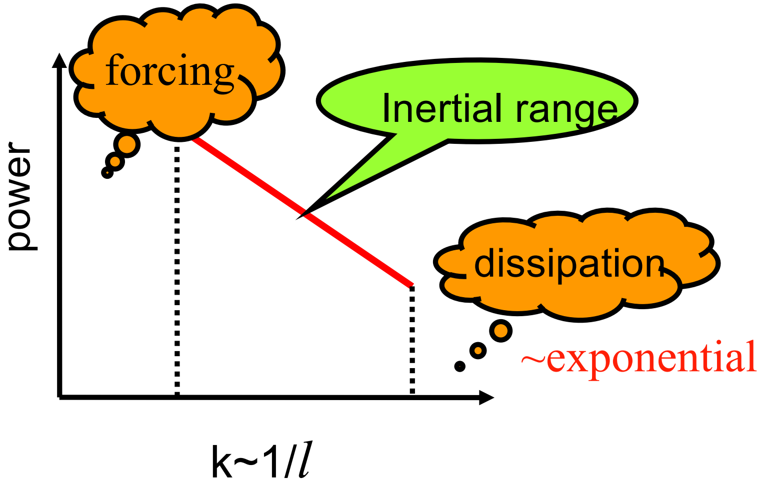
What kind of order emerges from this apparent chaos ?

Hydrodynamic Turbulence

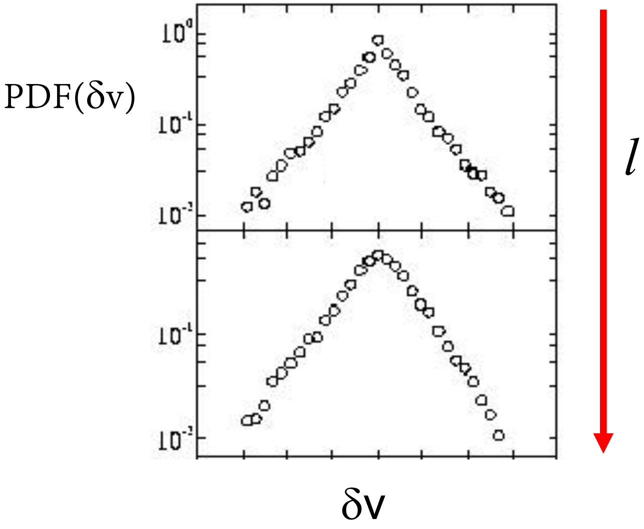
Leonardo da Vinci,
water studies
(1510-1512)

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

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



2) intermittency : deviation from the Gaussianity at small *l*



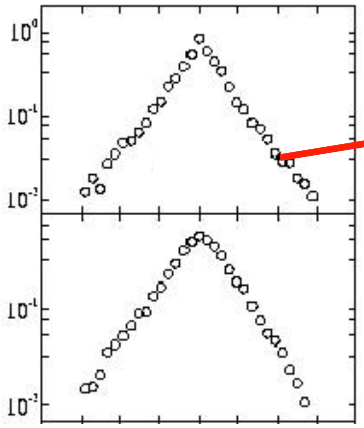
Intermittency in fluid turbulence

- Scale dependent non-Gaussianity of turbulent fluctuations
- Appearance of coherent structures

PDF(δv)

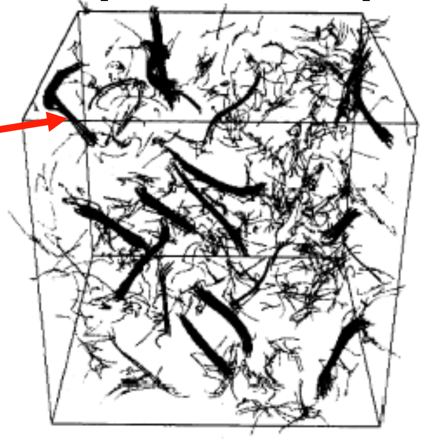
Small scale

Large scale

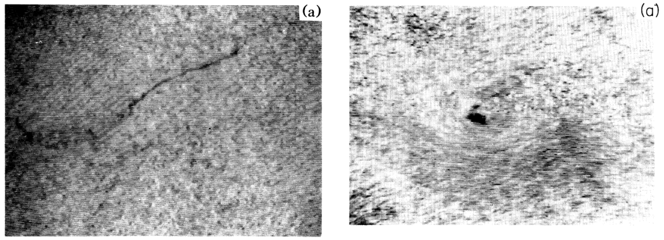


$\delta v_l = v(r+l) - v(r)$

[She et al., 1991]



[S. Douady, Y. Couder, and M. E. Brachet, PRL, 1991]

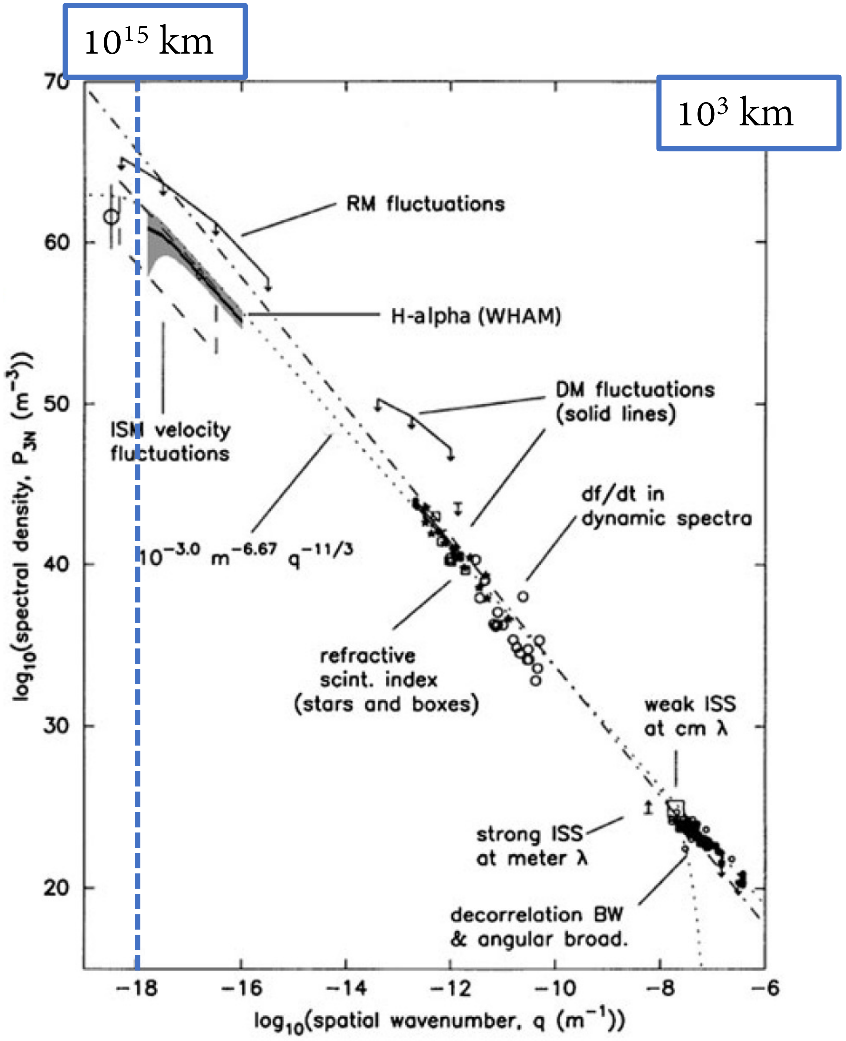


Filaments of vorticity (3D HD simulations & observations)

- length ~ $L_{injection}$ (L_0)
- cross-section ~ $L_{dissipation}$ (l_d)

=> dissipative structures

ISM plasma turbulence : electron density spectrum
Big Power Law in the Sky



Armstrong et al., 1995, Brandenburg & Lazarian 2013

Energy injection scales ~10^{15} km

Injection processes :

- Star's outflow (1 pc ~ 2 10^5 au ~ 3 10^{13} km);
- Explosion of Supernovae (scale ~ 100 pc ~ 3 10^{15} km);
- Shear motions in galaxy rotation (1 kpc ~ 3 10^{16} km);
- Infalling gas from intergalactic medium (from galaxy thickness scale ~3 10^{15} to 3 10^{17} km, close to galaxy size scale)

Inertial range: 10^5 - 10^{14} km

Ion scales (10^3-10^4 km) flattening?

Inner scale of the MHD inertial range:

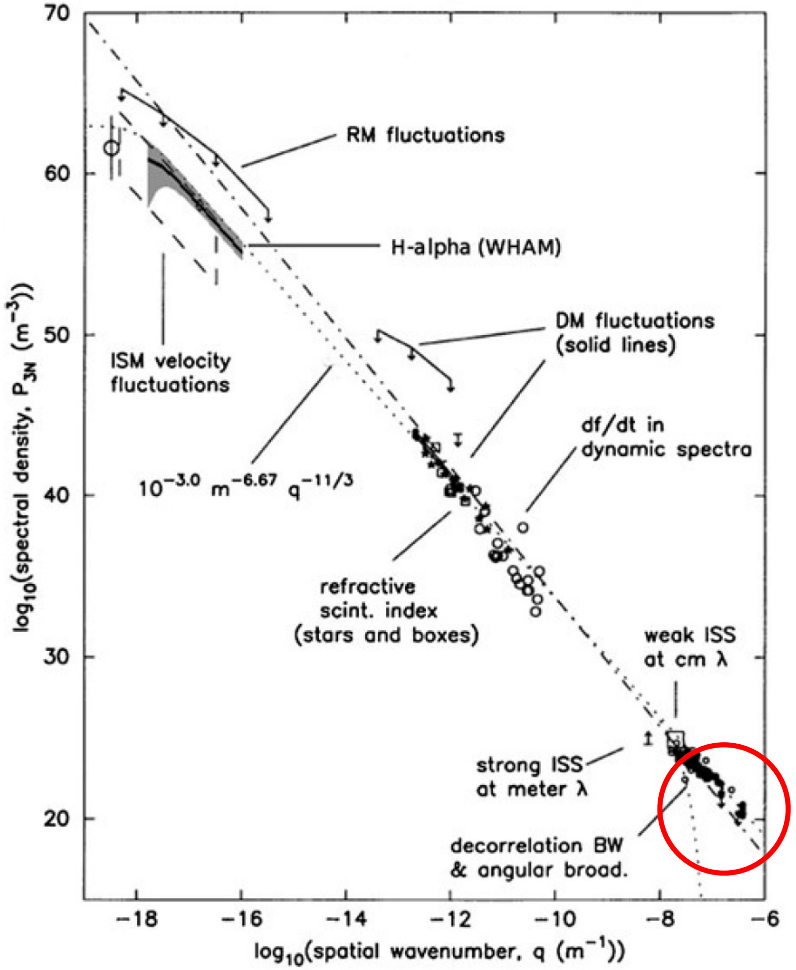
ion inertial length λ_i=c/ω_{pi} 10^3-10^4 km (?)

For plasma β=nkT/(B^2/8π) <<1, ion Larmor radius ρ_i << λ_i

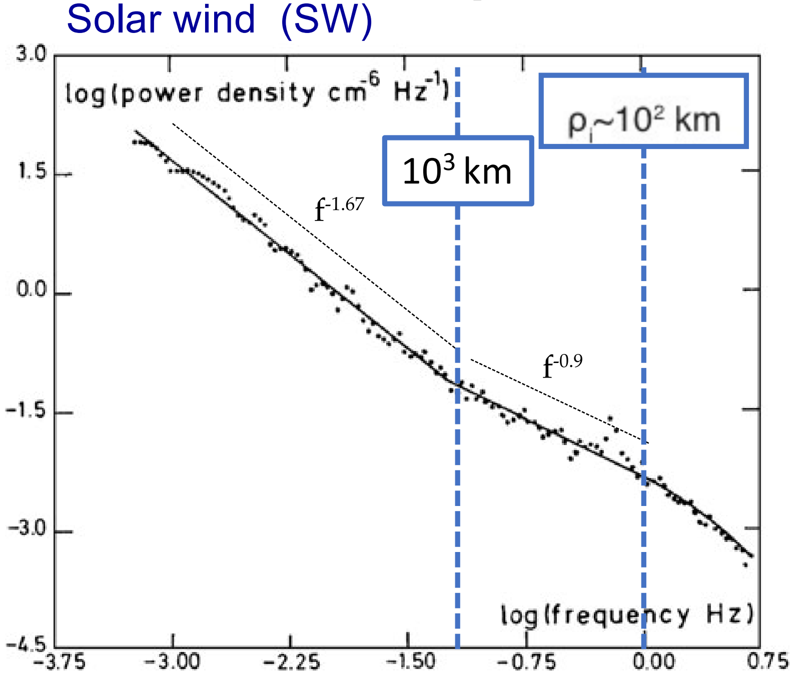
Dissipation processes ?

- Within coherent structures ? Of which shape ?

Solar wind & ISM electron density spectra

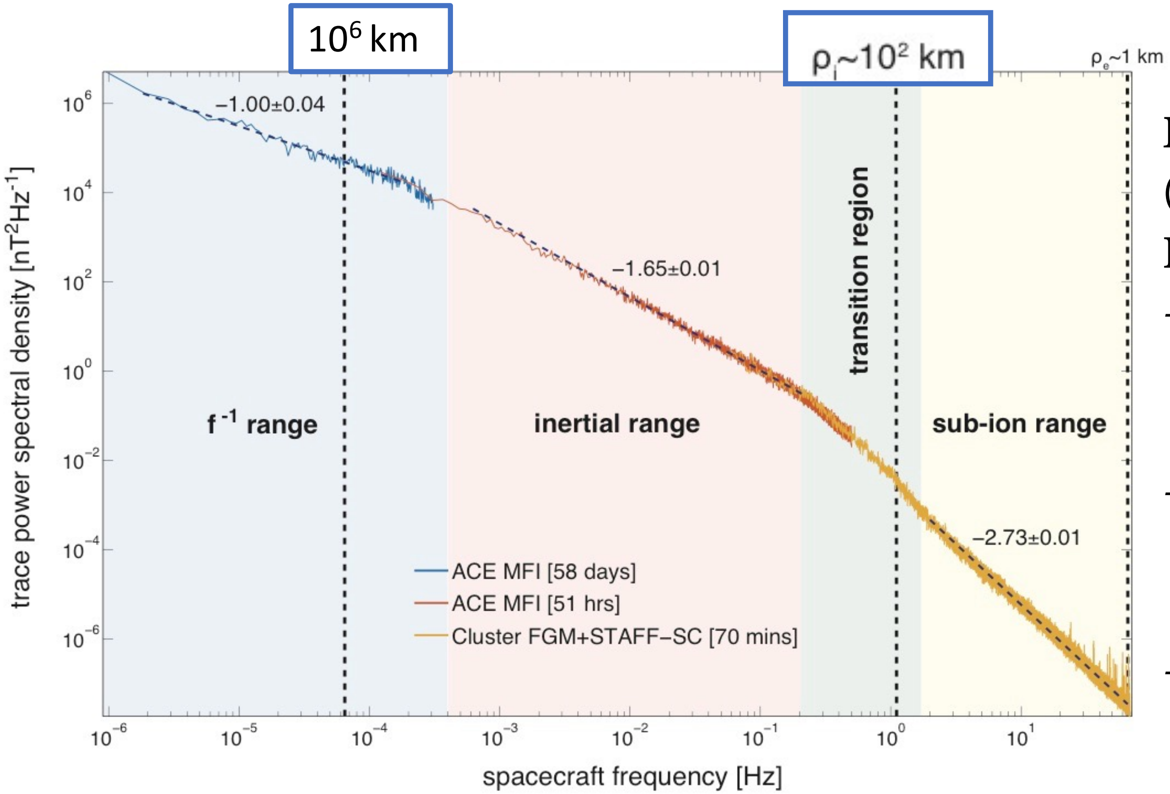


[Celnikier et al. 1983, A&A]



Flattening at ion scales ~ 100-1000 km in the SW density spectrum (due to kinetic Alfven waves ?).
The same in the ISM spectrum around 10^3 – 10^4 km scales ?

Solar wind turbulence: B-spectrum at 1 AU



Inertial range: K41 scaling at ~$[10^3,10^5]$ km

Inner scale of the MHD range: ion inertial length $\lambda_i=c/\omega_{pi}$ or ion Larmor radius $\rho_i \sim \lambda_i \sim 100$ km.

Sub-ion scales: electron fluid cascade (EMHD)

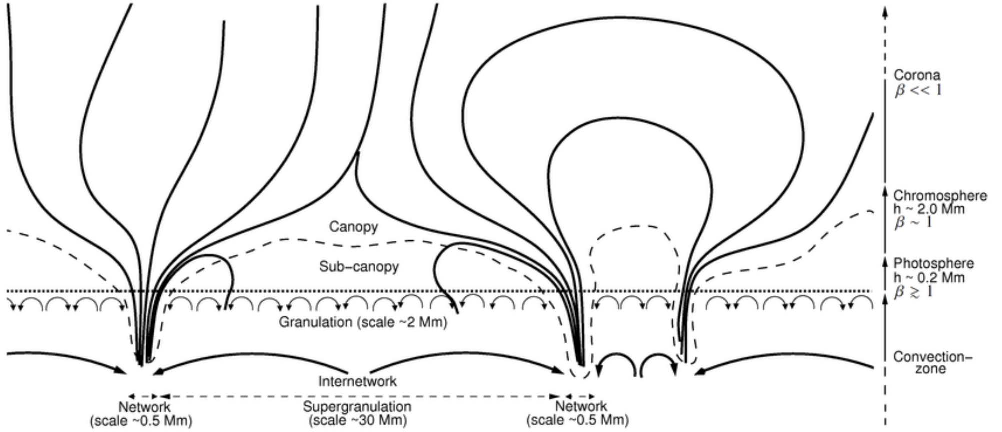
Dissipation scale: electron Larmor radius ~1 km (0.3 - 1 AU)

Energy injection scales: $[10^6,10^8]$ km

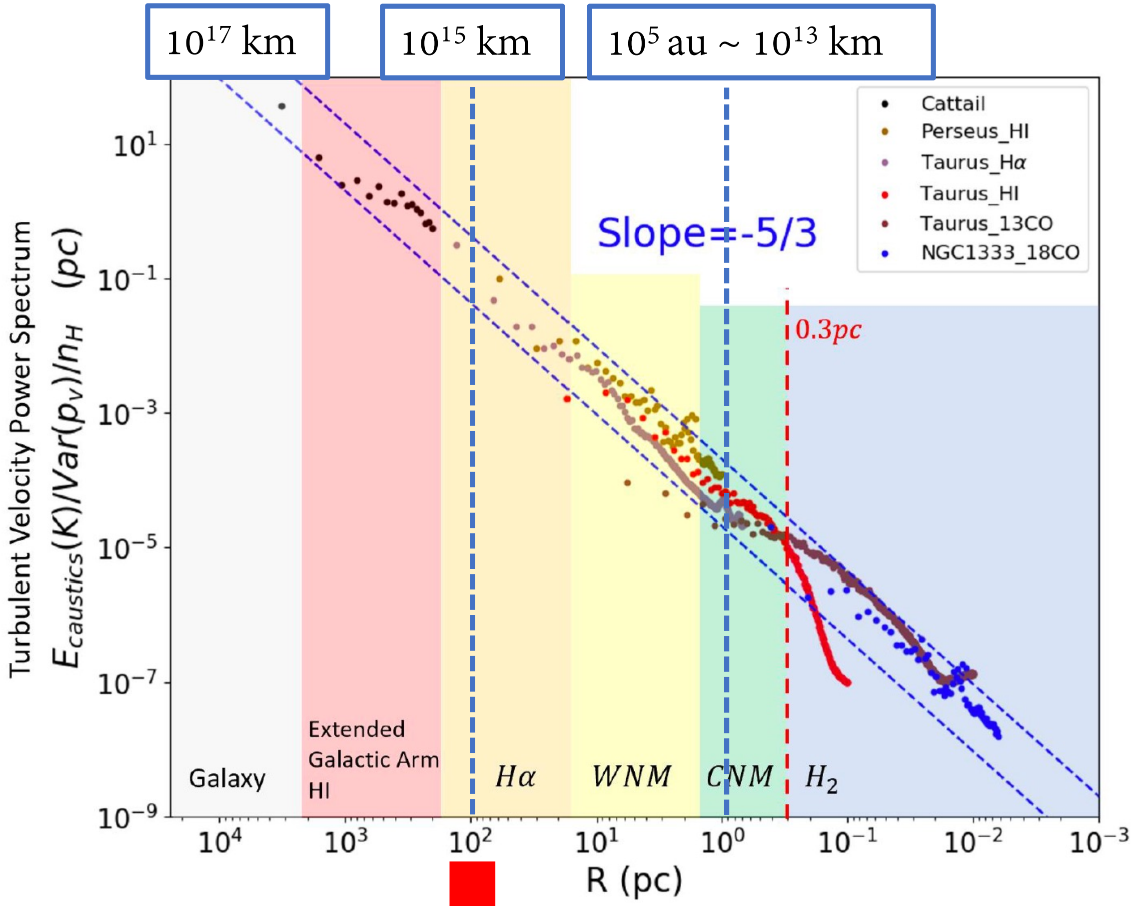
(1 AU= 1.5 10^8 km)

Injection processes :

- Slow/Fast wind streams interactions – corotation interaction regions; size of the open field regions during max of activity ~ 5 10^6 km
- Super-granulation: size at the surface of the Sun~3 10^4 km, which increases with expansion to ~ 6 10^5 km, at 20 R_{sun} (1 R_{sun} = 7 10^5 km ~ 10^6 km)
-



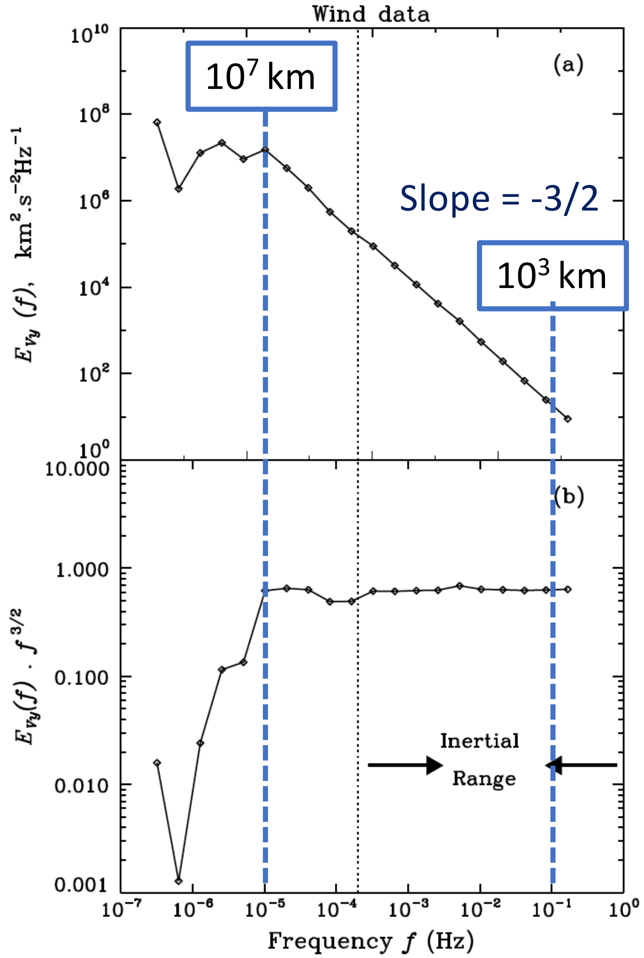
ISM & solar wind turbulence: velocity-spectra



[Yuen et al. 2022, arXiv]

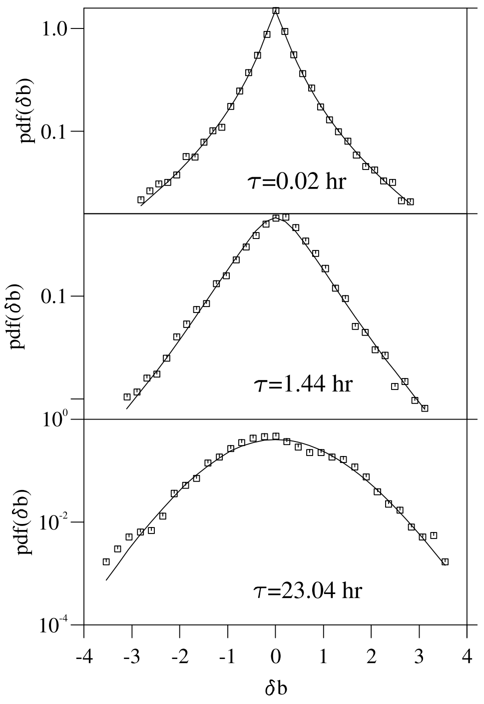
‘Big Power Law in the Sky’

Fig. 2 (**a**) Spectrum of velocity fluctuations of V_y (GSE) component, measured by *Wind* as a function of the frequency in the spacecraft frame, the data have been published in Salem et al. (2009). (**b**) Compensated spectrum by an $f^{3/2}$ law: the resulting function is flat for $f > 10^{-4}$ Hz. Courtesy of C. Salem

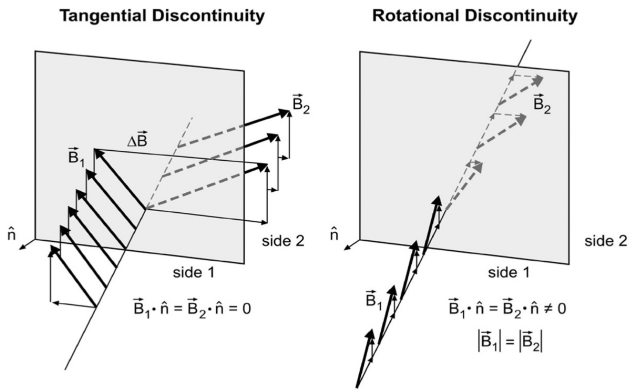


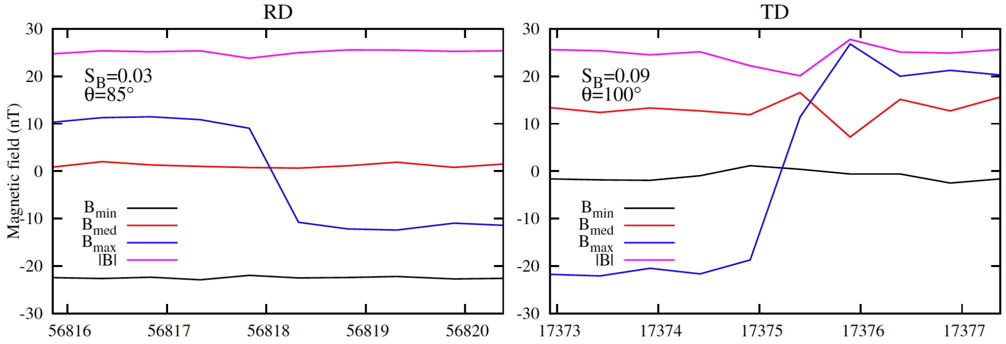
Intermittency of solar wind turbulence

Scale dependent non-Gaussianity is observed within the MHD inertial range [Sorriso-Valvo et al. 1999]
Examples of structures: planar discontinuities (current sheets and magnetosonic shocks)



B.T. Tsurutani et al. / Journal of Atmospheric and Solar-Terrestrial Physics 73 (2011) 5–19





[e.g., Veltri & Mangeney 1999, Servidio, et al. 2008, Greco, et al. 2009, 2012, 2014, Perri et al. 2012]

Intermittency of solar wind turbulence

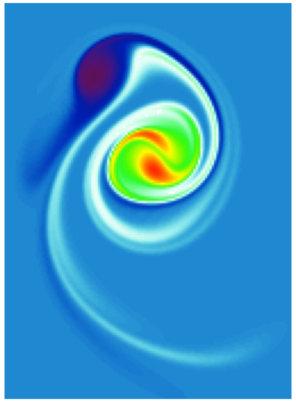
More complex topologies [e.g., Lion et al. 2016, Perrone 2016, 2017, Roberst 2016]:

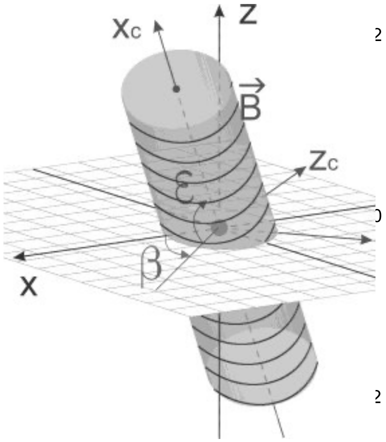
- Magneric holes
- Alfven vortices
- Magnetosonic solitons

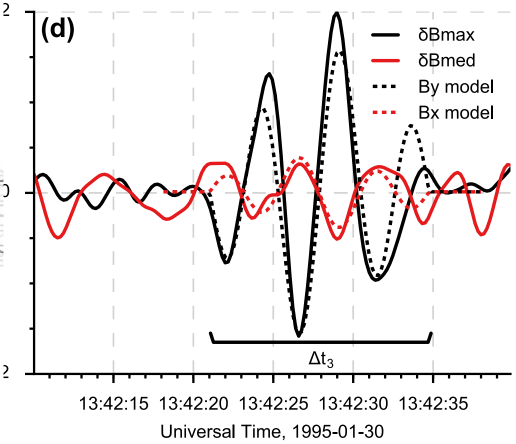
Magnetic holes [Karlsson et al. 2021]

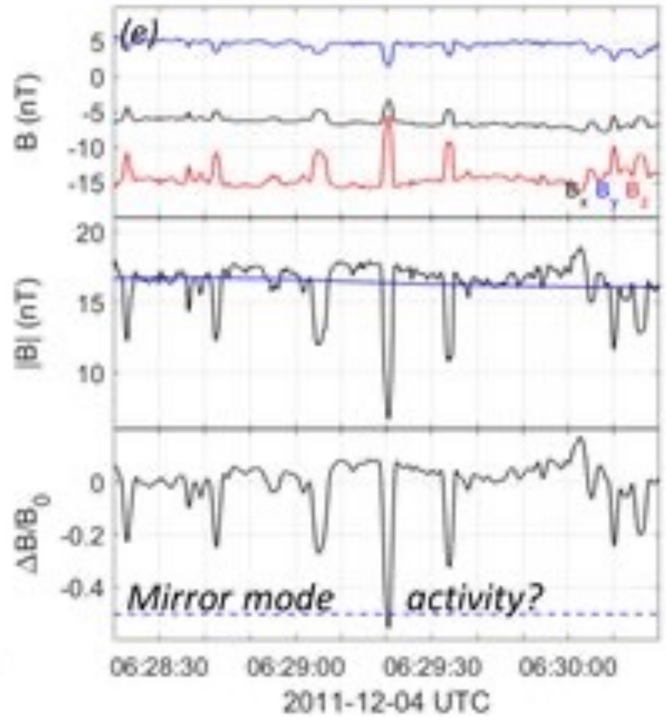
Alfven Vortex: cylindrical NL Alfven wave [Petviashvilli & Pokhotelov 1992]

$$\boxed{\delta V_\perp / V_A = \xi \delta B_\perp / B_0}$$



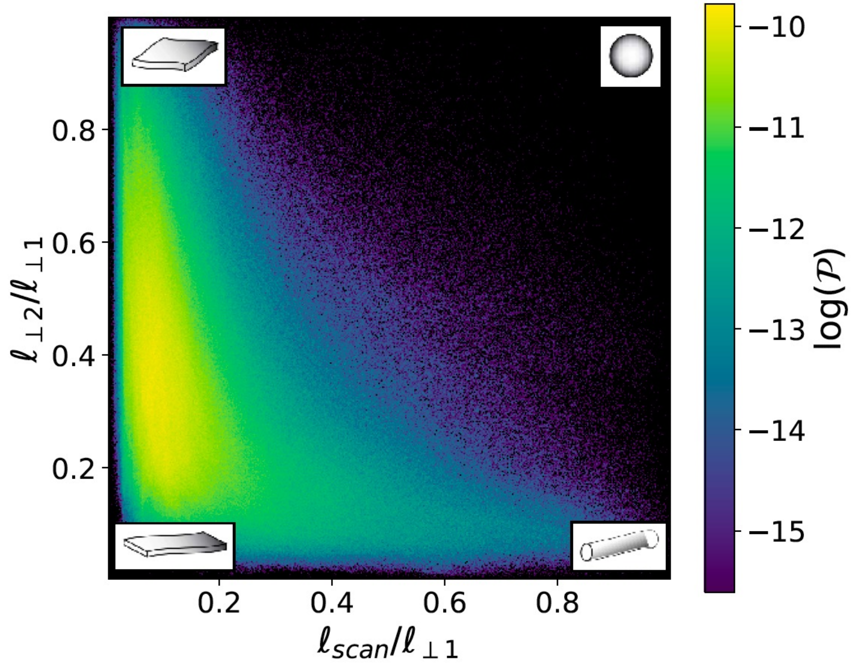






Intermittency in the ISM ?

PHD thesis of Thibaud Richard (2022)
On dissipative structures in ISM: compressible MHD numerical simulations



Aspect ratio measurements => sheets, ribbons, tubes

Galactic ISM filaments: LOFAR vs. Planck L47

[Zaroubi et al. 2015]

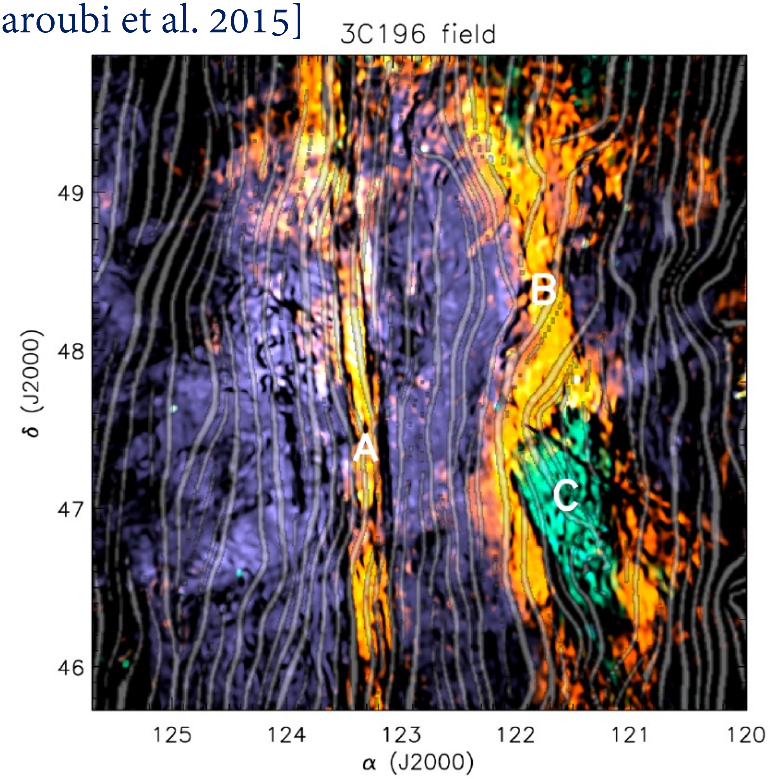
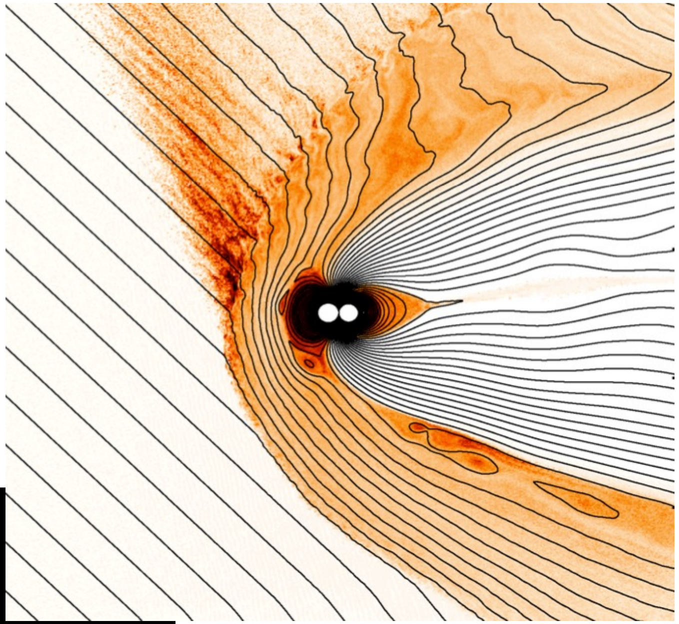


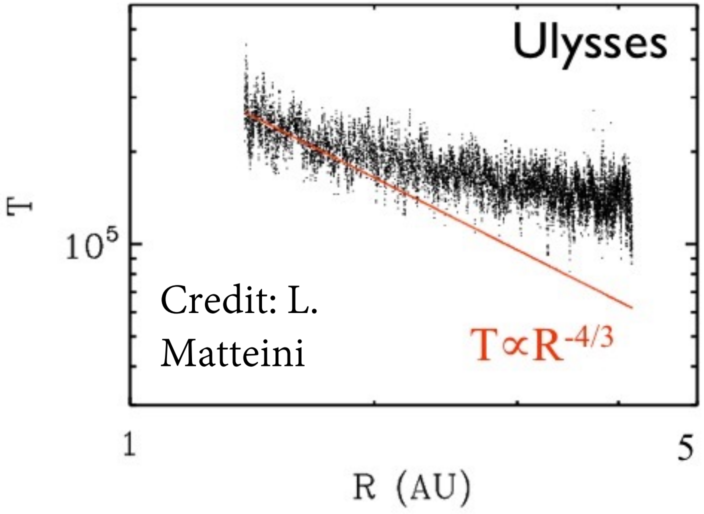
Figure 1. A composite image of morphological features of the 3C196 field detected with LOFAR at different Faraday depths and the magnetic field lines orientation (grey lines) inferred from the *Planck* dust polarization maps at 353 GHz. A ‘triangular’ feature displayed in green (marked with C) is emission at negative Faraday depths (-3 to $-0.5\,\mathrm{rad\,m^{-2}}$), the filamentary structures at Faraday depth of $+0.5\,\mathrm{rad\,m^{-2}}$ are given in yellow (marked with A and B). The violet shows the prominent diffuse background emission arising at Faraday depths from $+1.0$ to $+4.5\,\mathrm{rad\,m^{-2}}$. The resolution of the LOFAR image is 3 arcmin.

Why turbulence is important ?

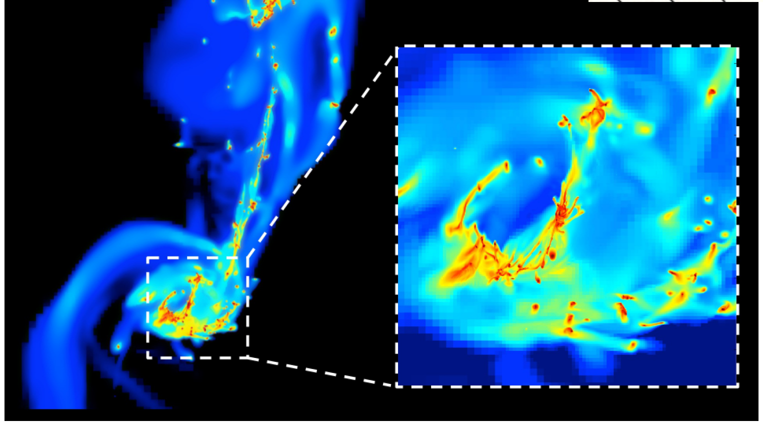
- Cosmic Rays diffusion and acceleration
- Important ingredient for star formation process
- Important for collissionless shocks
- Best candidate to explain solar wind non-adiabatic expansion
- Dissipation processes & magnetic reconnection



Solar wind ion temperature decays less than adiabatic (~$R^{-4/3}$) => heating !

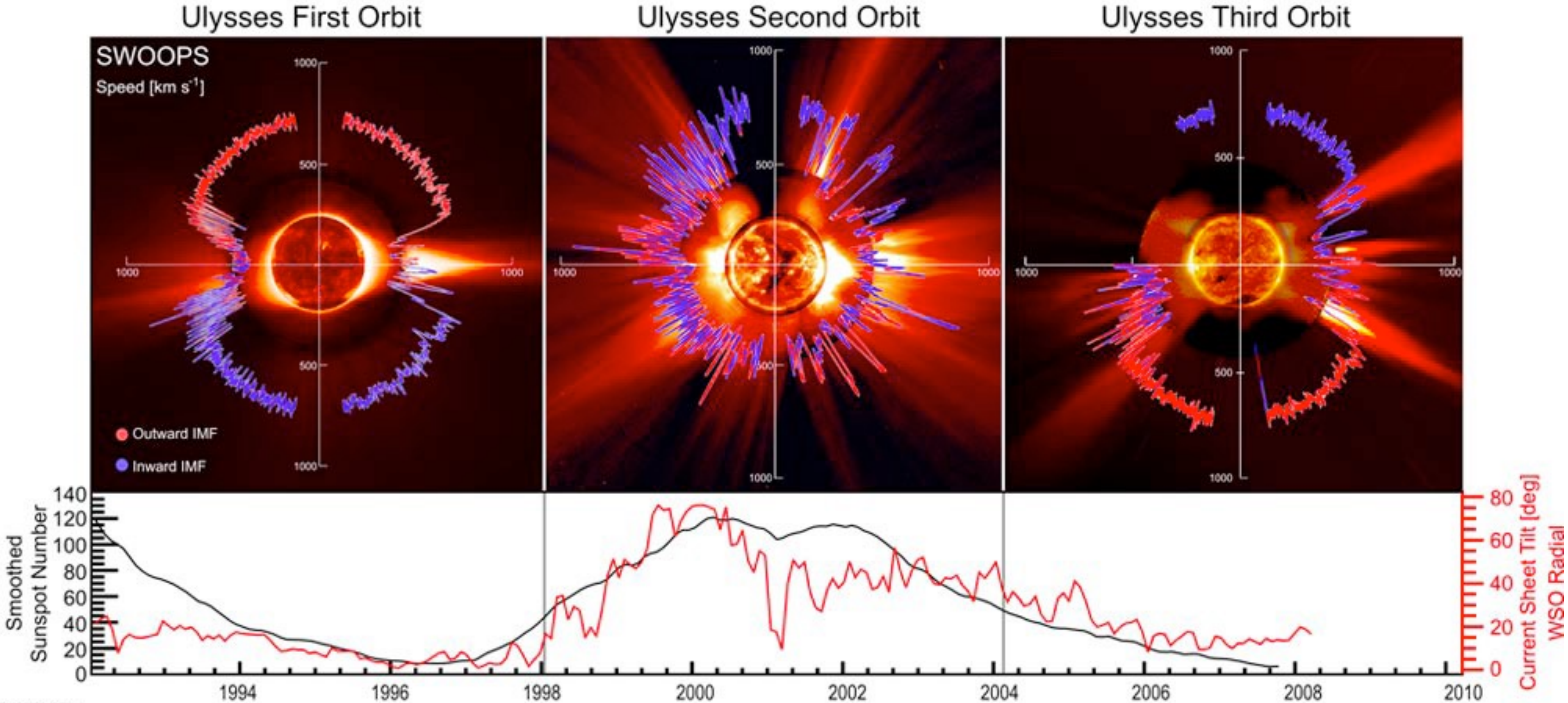


Credit: L. Matteini



Gas density in galaxy collisions. The stars are formed in dense regions under "compressive turbulence". Credit: CEA-SAp

BONUS



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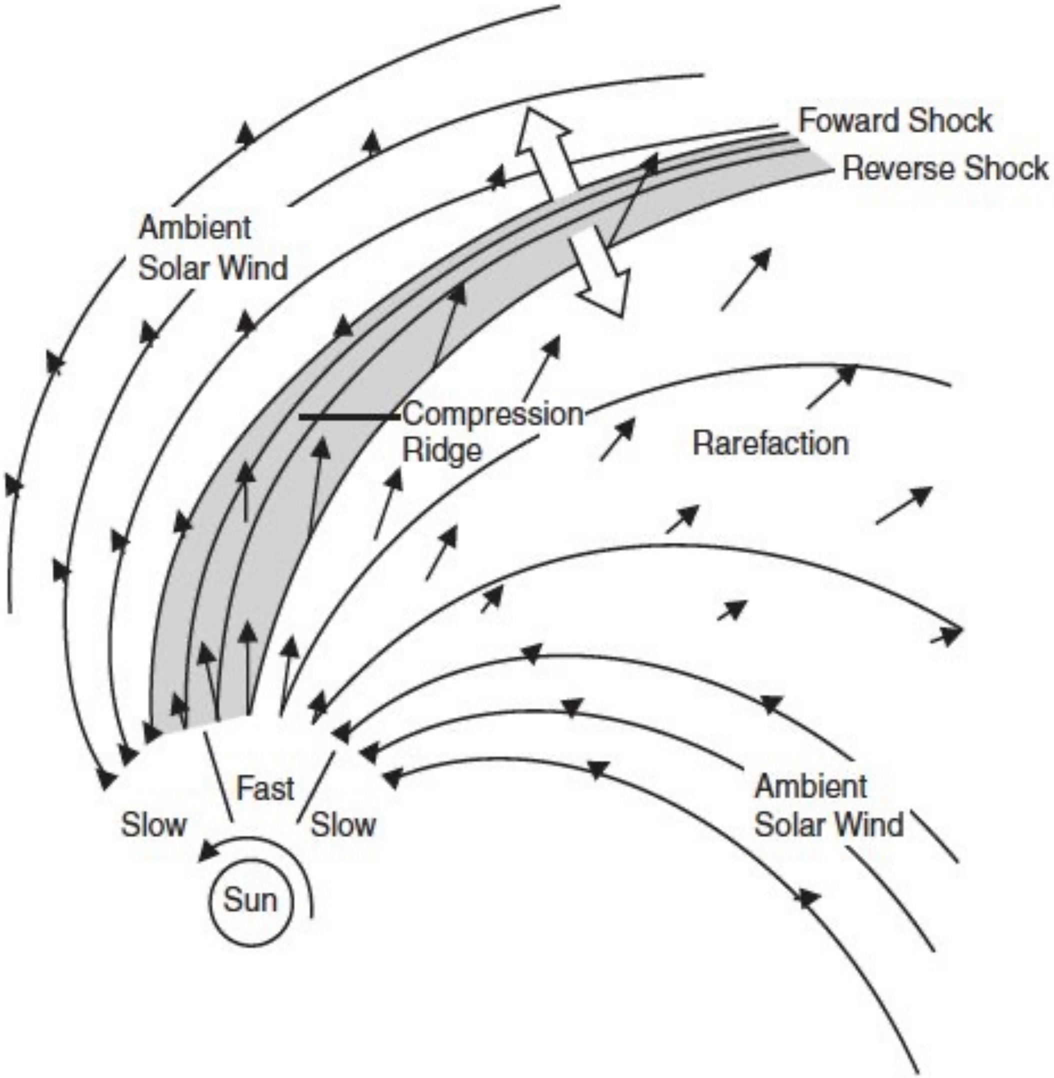
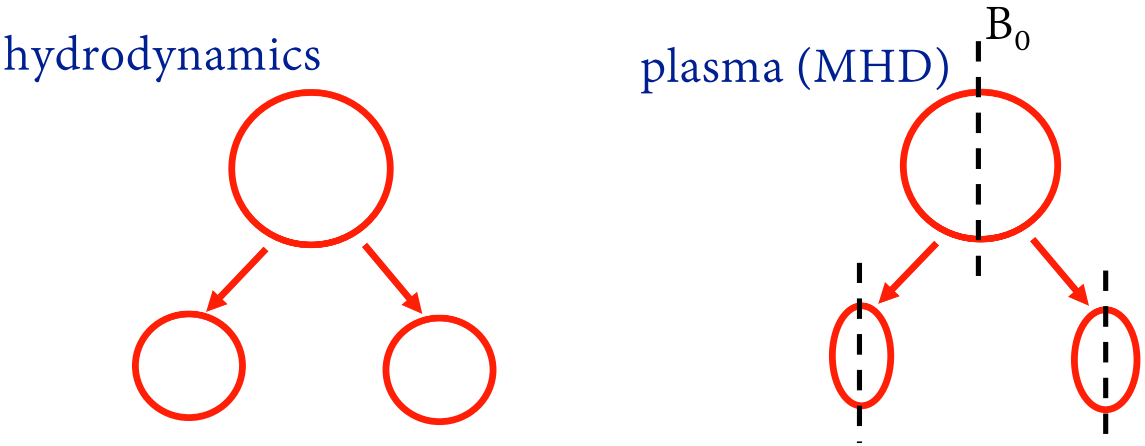

Foward Shock
Reverse Shock
Ambient
Solar Wind
Compression
Ridge
Rarefaction
Fast
Slow
Slow
Sun
Ambient
Solar Wind

Turbulence in magnetized plasmas



hydrodynamics

plasma (MHD)

B_0

1. Presence of a mean magnetic field B_0 ⇒ anisotropy of turbulent fluctuations
2. Plasma waves: Alfvén, magnetosonic, mirror, whistlers, kinetic Alfvén waves (KAW), etc… (wave turbulence)
3. Nearly no collisions : mean free path ~ 1 AU
4. In plasmas there is a number of characteristic space and temporal scales

$$\Omega_{ci}, \rho_i, \lambda_i; \quad \Omega_{ce}, \rho_e, \lambda_e; \quad \lambda_D$$

- Is there a certain degree of generality in space plasma turbulence ?
- Similarities with HD (spectra & intermittency) ?