1st Solar Orbiter Summer School
"Towards a Deeper Understanding of the Sun and the Heliosphere with Solar Orbiter"

L'Aquila, September 22-25, 2014

RPW: Measuring Solar Radio and Plasma Waves

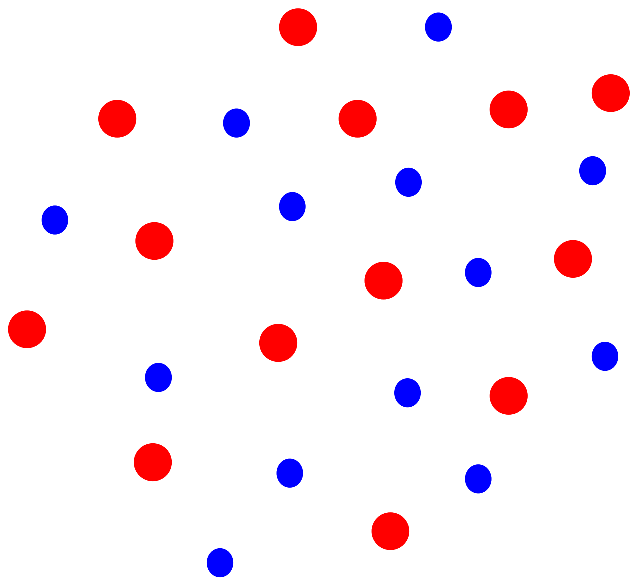
Milan Maksimovic
LESIA & CNRS, Paris Observatory - France
milan.maksimovic@obspm.fr

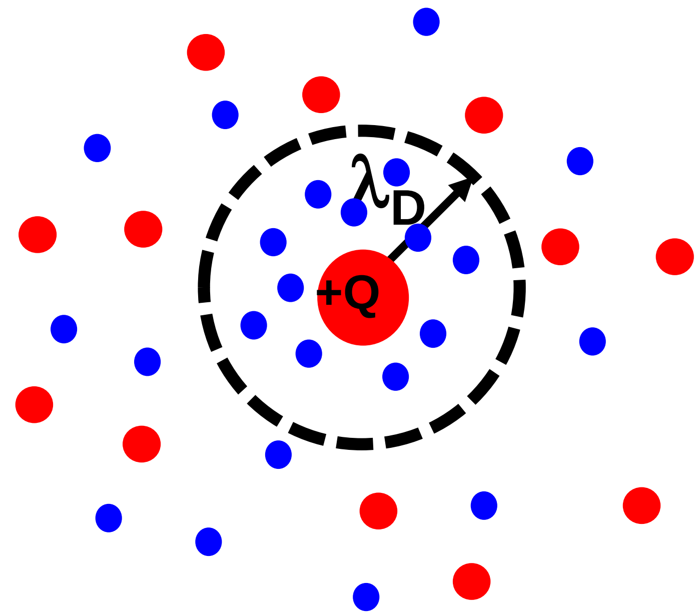
Outline

- Plasma waves versus Radio waves
- Plasma waves : what do we observed and understand ?
- Radio waves : what do we observed and understand ?
- « *Extra* » science : Dust measurements
- On the difficulty of measuring the DC/LF electric component of plasma waves
- RPW : a brief description

Plasma waves versus radio waves

Debye Screening





$$\lambda_D = \left(\frac{\varepsilon_0 k_B T}{n e^2}\right)^{1/2}$$

$$\Phi(r) = \frac{Q}{4\pi\varepsilon_0 r} e^{-r\sqrt{2}/\lambda_D}$$

$\lambda_D \approx 69\sqrt{T/n}$ **in S.I. units**

- $\lambda_D \approx$ **10 m @ 1 AU**
- $\lambda_D \approx$ **5 m @ 0.3 AU**
- $\lambda_D \approx$ **1 m @ 10 Rs**

What if the charge +Q moves at a speed v ?

- v must be compared to both $V_{thi} \approx \sqrt{k_B T/m_i}$ and $V_{the} \approx \sqrt{k_B T/m_e}$
- If $v < V_{thi} < V_{the}$ then both electrons and ions have time « *to participate* » to the screening of +Q
- If $V_{thi} < v < V_{the}$ then only the electrons have time « *to participate* » to the screening of +Q
- If $V_{thi} < V_{the} < v$ then there is no screening of +Q

Timescale for screening ?

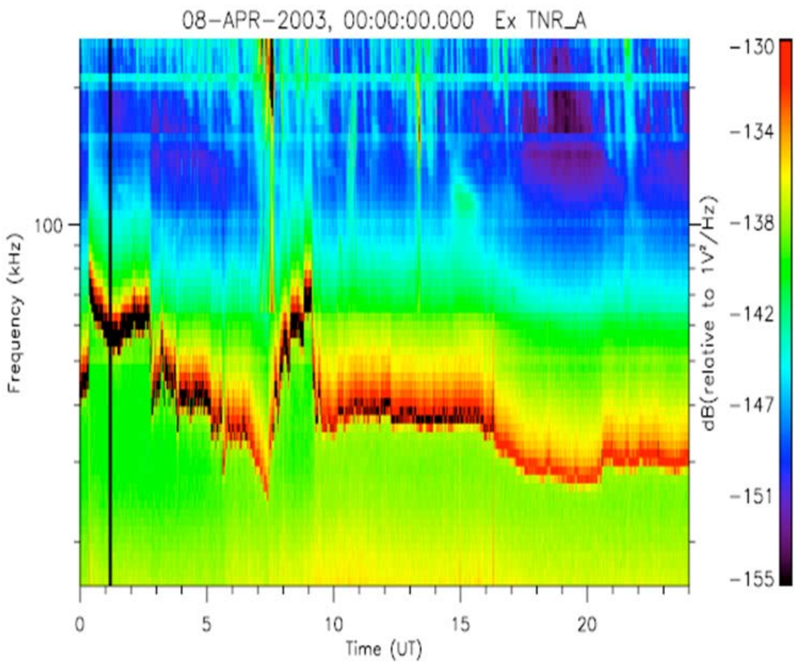
- Let's put suddenly a charge +Q in a plasma at equilibrium
- The electrons, which move faster, will need a time τ to travel a distance λ_D at the most probable speed V_{the}

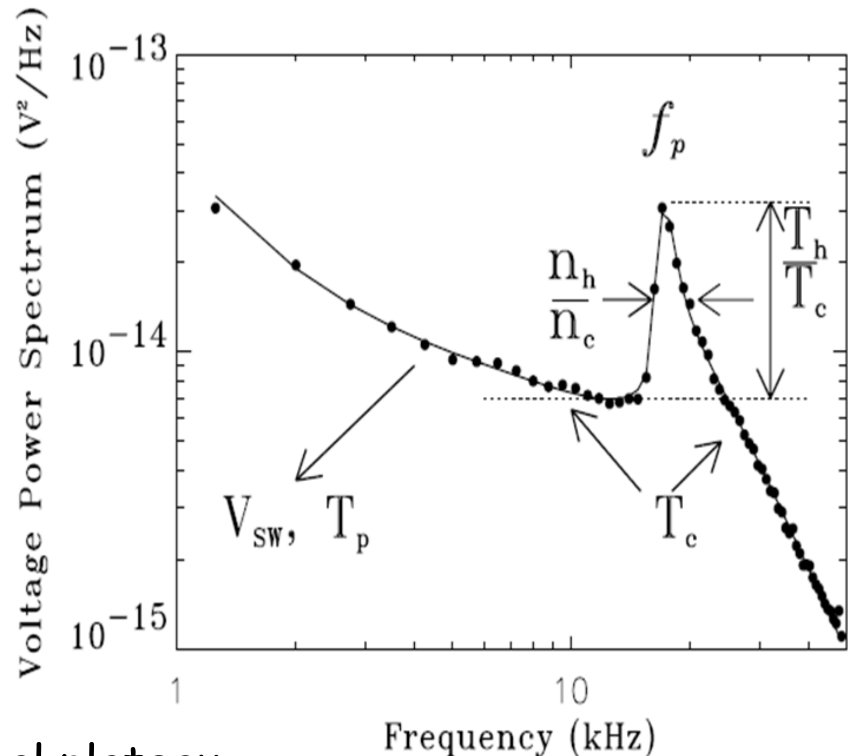
$$\tau \approx \left(\frac{\varepsilon_0 m_e}{ne^2}\right)^{1/2} \equiv \frac{1}{\omega_p}$$

$\omega_p = 2\pi F_p$ is the angular plasma frequency

- $F_p = 9\sqrt{n}$ in S.I. units
- $F_p \approx 20$ kHz @ 1 AU
- $F_p \approx 60$ kHz @ 0.3 AU
- $F_p \approx 0.5$ MHz @ 10 Rs

Electron Density and Temperature from Quasi-Thermal Noise Spectroscopy





Antenna geometry and size matter

- e^- passing closer than $\lambda_D \rightarrow F < F_P \rightarrow$ thermal plateau
- e^- passing further than $\lambda_D \rightarrow$ Langmuir waves @ $F < F_P$
  Power $\propto (F_P/F)^3$
- In practice $L/\lambda_D \geq 1$ is needed : satisfied at perihelion and in dense SW
- RPW should measure n_e & T_e with accuracies respectively of a few % and 10 %

2 Maxwellians:

cold : n_c, T_c

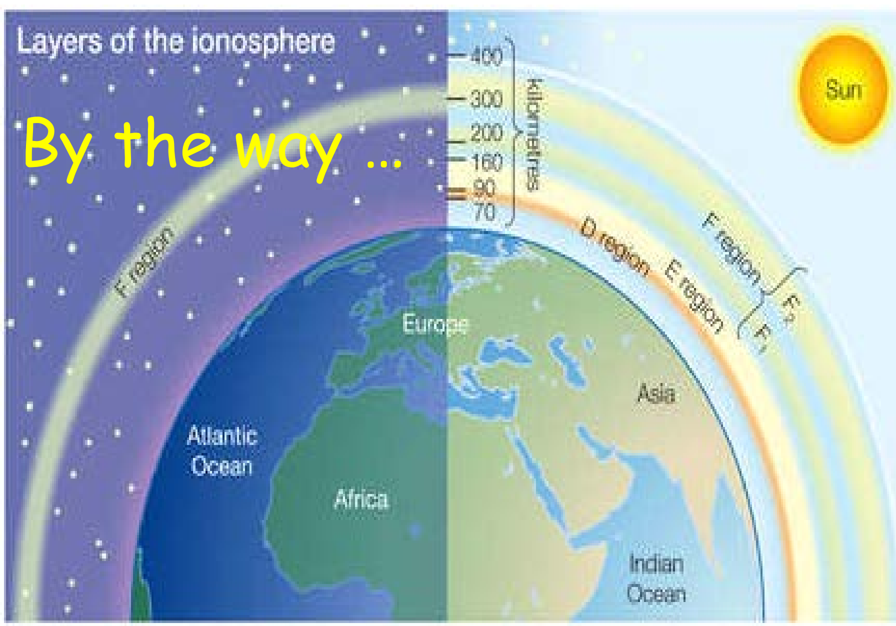
hot : n_h, T_h

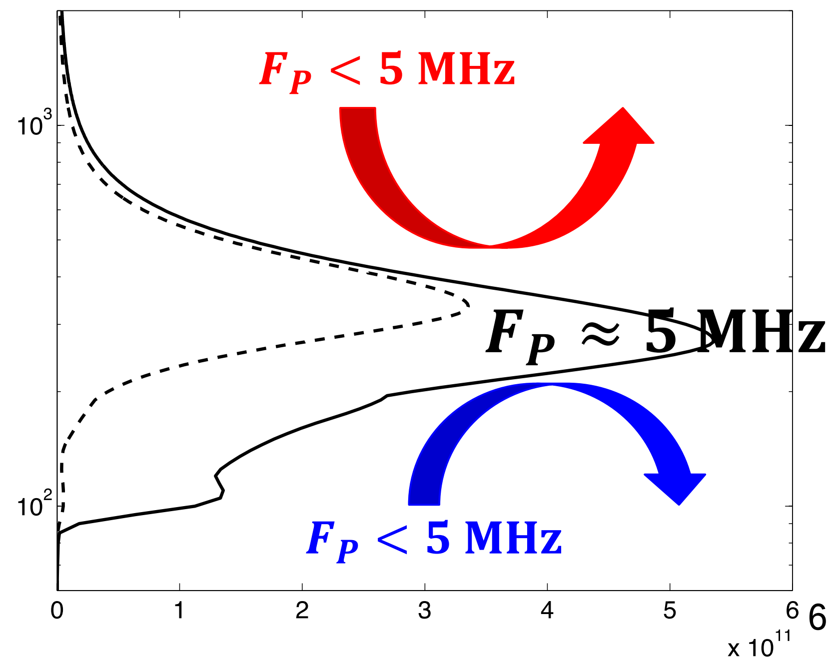
- Waves with $F < F_{Pi} < F_{Pe}$ are « *seen* » by both ions and electrons. They are screened and do not propagate
- Waves with $F_{Pi} < F < F_{Pe}$ are not « *seen* » by ions but are still screened by the electrons

} **Plasma Waves**

- Waves with $F_{Pi} < F_{Pe} < F$ are not seen by the plasma and propagate freely

} **Radio Waves**





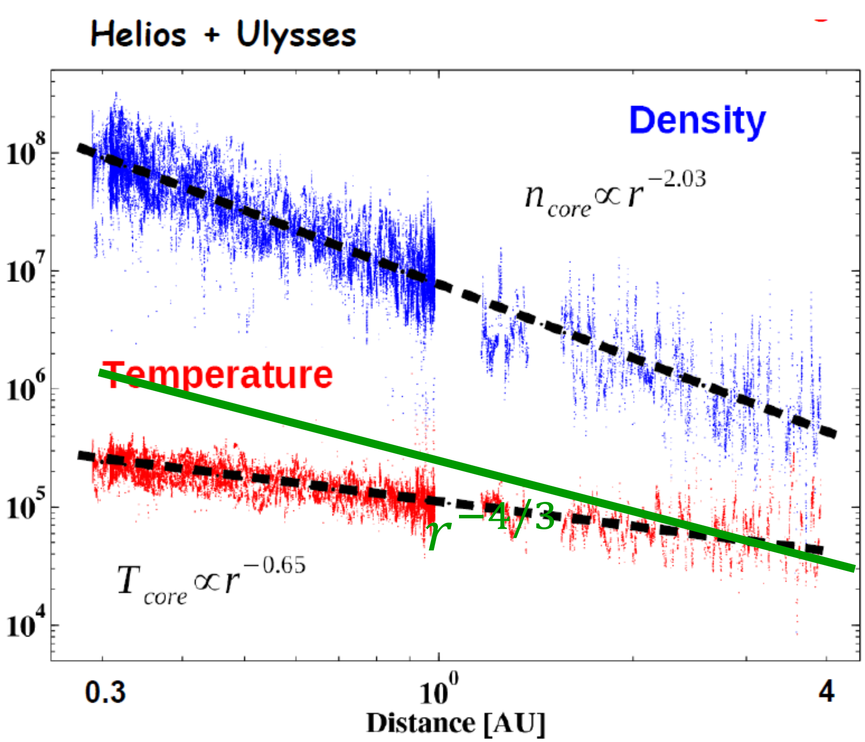
In practice it is more complicated …

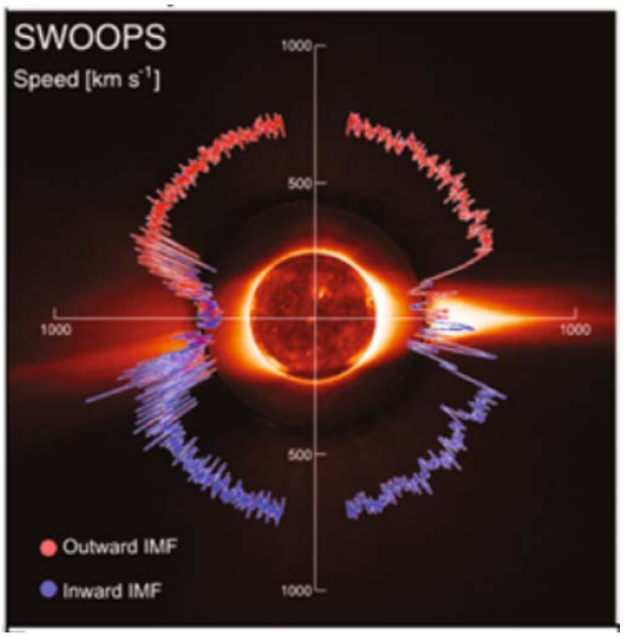
- There is a Magnetic Field Magnetic in the Solar Wind which imposes new time and length scales (gyro-radii and –frequencies)
- Full zoo of waves (see a good Plasma Physics textbooks)

EM character	oscillating species	conditions	dispersion relation	name
electrostatic	electrons	$\vec{B}_0 = 0$ or $\vec{k} \parallel \vec{B}_0$	$\omega^2 = \omega_p^2 + 3k^2 v_{th}^2$	plasma oscillation (or Langmuir wave)
		$\vec{k} \perp \vec{B}_0$	$\omega^2 = \omega_p^2 + \omega_c^2 = \omega_h^2$	upper hybrid oscillation
	ions	$\vec{B}_0 = 0$ or $\vec{k} \parallel \vec{B}_0$	$\omega^2 = k^2 v_s^2 = k^2 \frac{\gamma_e K T_e + \gamma_i K T_i}{M}$	ion acoustic wave
		$\vec{k} \perp \vec{B}_0$ (nearly)	$\omega^2 = \Omega_c^2 + k^2 v_s^2$	electrostatic ion cyclotron wave
		$\vec{k} \perp \vec{B}_0$ (exactly)	$\omega^2 = [(\Omega_c \omega_c)^{-1} + \omega_i^{-2}]^{-1}$	lower hybrid oscillation
electromagnetic	electrons	$\vec{B}_0 = 0$	$\omega^2 = \omega_p^2 + k^2 c^2$	light wave
		$\vec{k} \perp \vec{B}_0,\ \vec{E}_1 \parallel \vec{B}_0$	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$	O wave
		$\vec{k} \perp \vec{B}_0,\ \vec{E}_1 \perp \vec{B}_0$	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2} \frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2}$	X wave
		$\vec{k} \parallel \vec{B}_0$ (right circ. pol.)	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 - (\omega_c/\omega)}$	R wave (whistler mode)
		$\vec{k} \parallel \vec{B}_0$ (left circ. pol.)	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 + (\omega_c/\omega)}$	L wave
	ions	$\vec{B}_0 = 0$		none
		$\vec{k} \parallel \vec{B}_0$	$\omega^2 = k^2 v_A^2$	Alfvén wave
		$\vec{k} \perp \vec{B}_0$	$\frac{\omega^2}{k^2} = c^2 \frac{v_s^2 + v_A^2}{c^2 + v_A^2}$	magnetosonic wave

In-situ Plasma waves : what do we observed and understand ?

Waves are believed to both heat & accelerate the Solar Wind





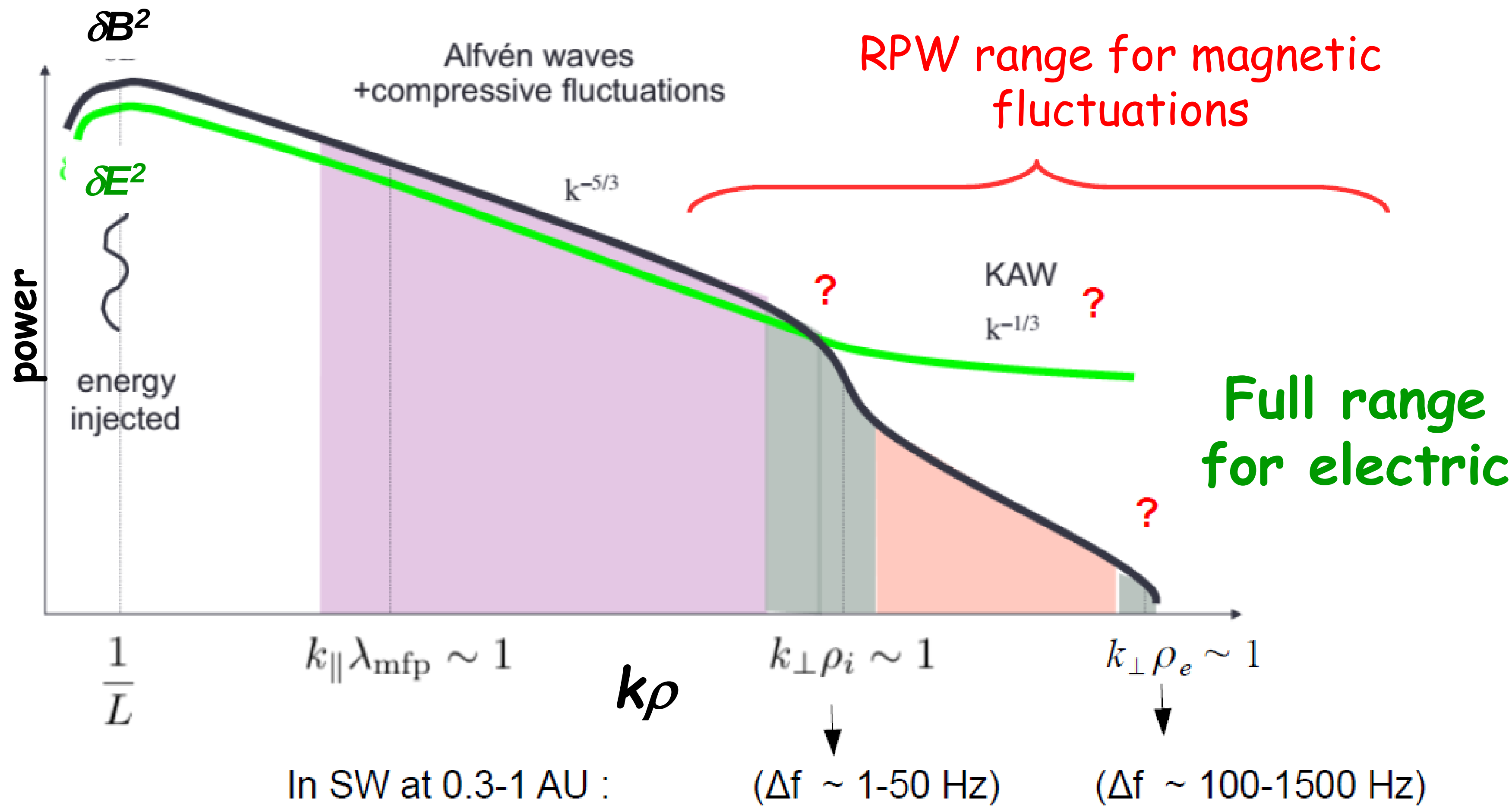
Stverak, PhD thesis

Turbulent heating/dissipation in the Solar Wind

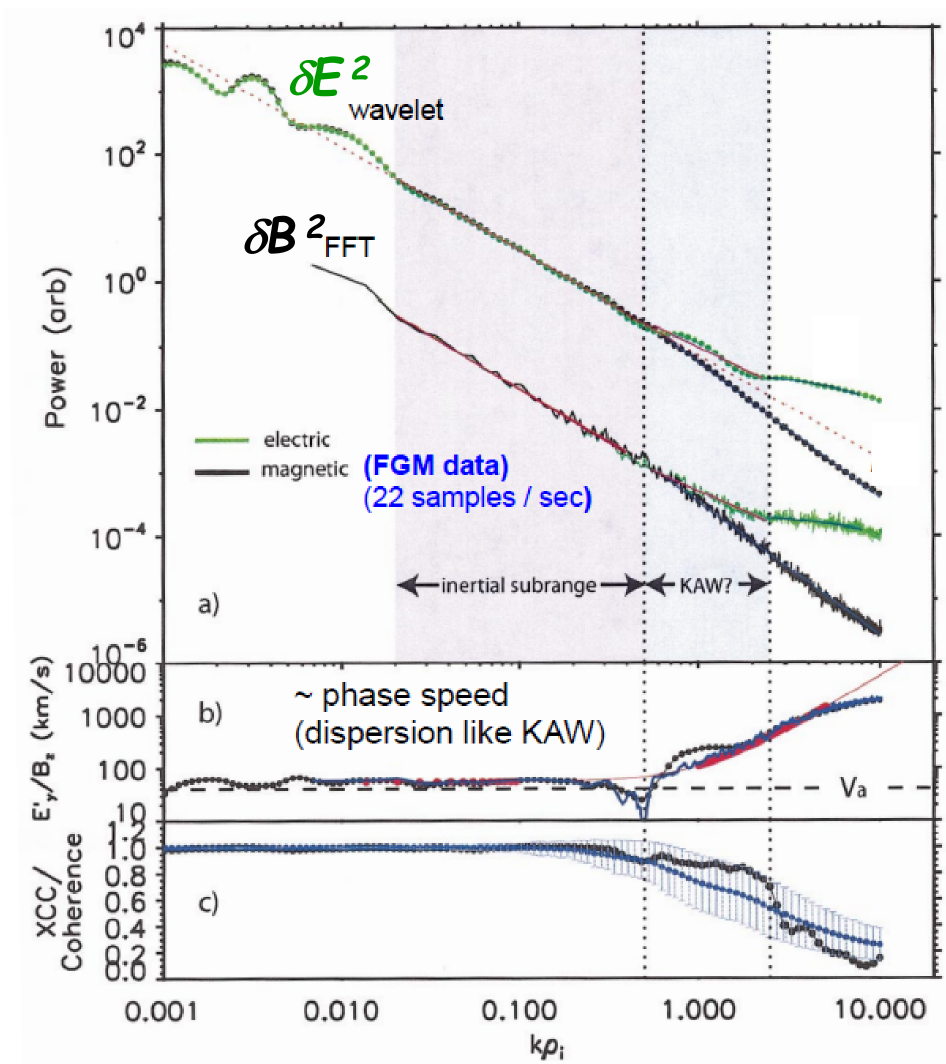
Kinetic Alvèn Waves ? Whistler Waves ?

Coherent structures ? Other ?

Turbulent energy cascade from large to small scales



Evidences for Kinetic Alven Waves turbulence ?



Cluster

- Phase speed is ~Alfven speed
- Dispersion at short wavelength is like Kinetic Alfvén Wave
- Strong evidence/consistency with KAW turbulence

Evidence for a turbulent dissipation at the proton gyroscale?

What above $k\rho_p \sim 1$?

Cascade up to the electron scale?

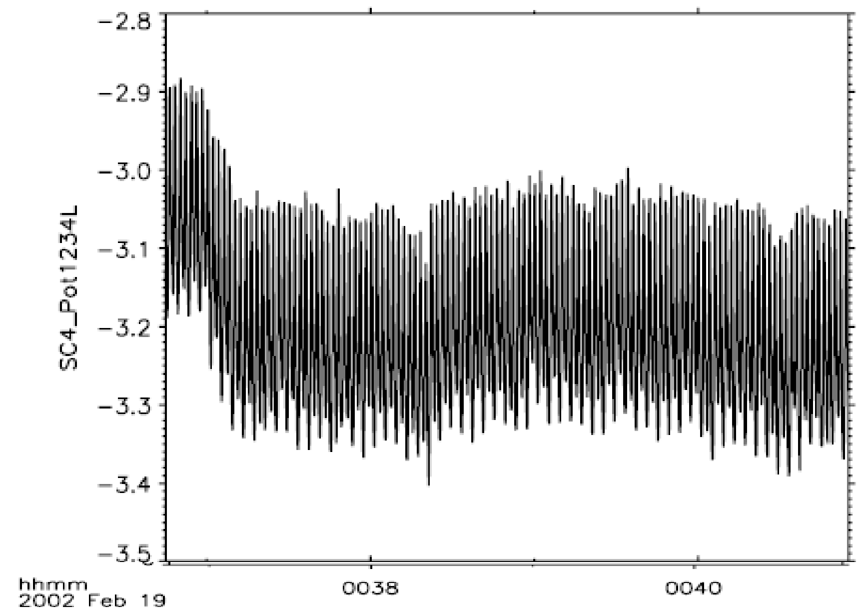
Bale et al., PRL, 2005
(also Sahraoui et al., PRL, 2009)

Caveats

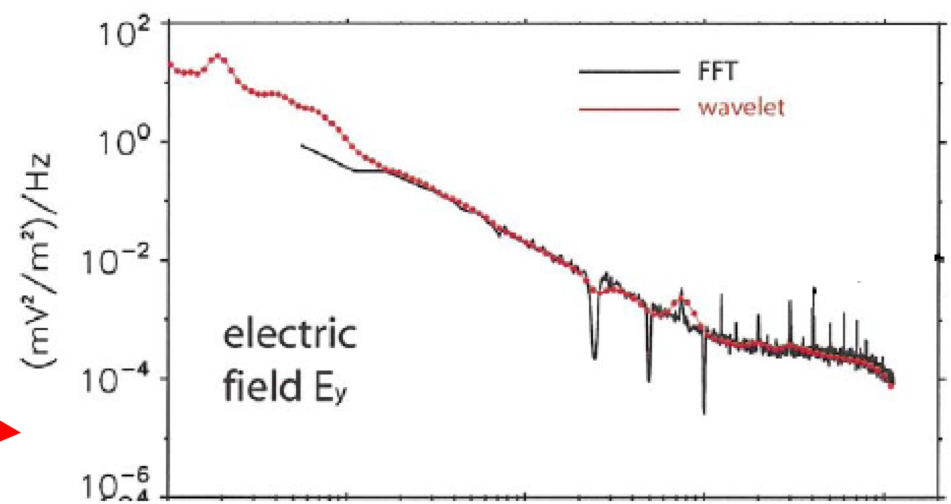
On Cluster electric measurements not easy because of S/C charging

Spin tone in the raw E data due to :

- **illumination variations on the probes**
- **wake effects**



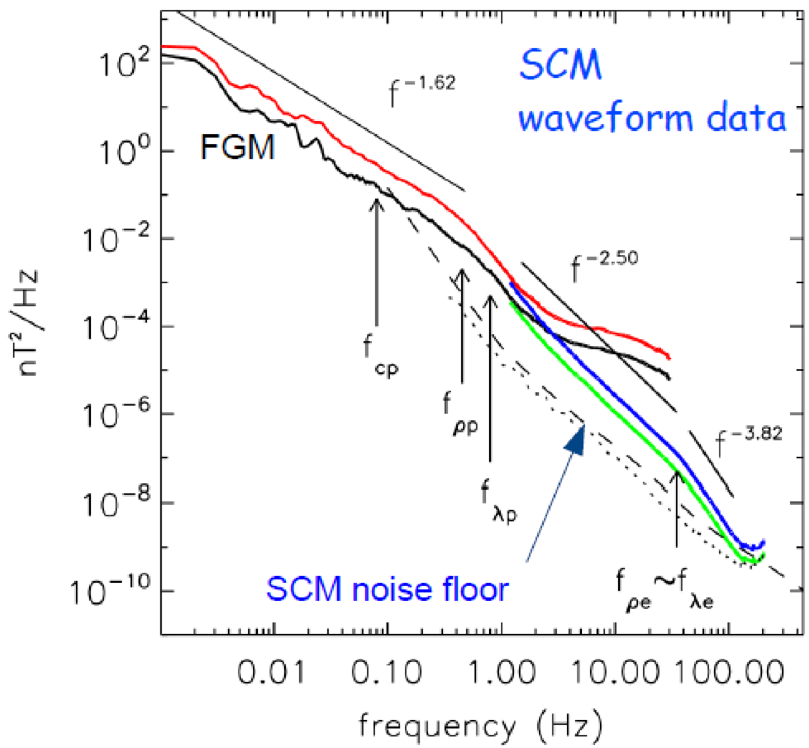
Spin tone needs to be filtered



Evidences for a Cascade well above the proton scales up to the electron typical scales (gyroscale and above ?)

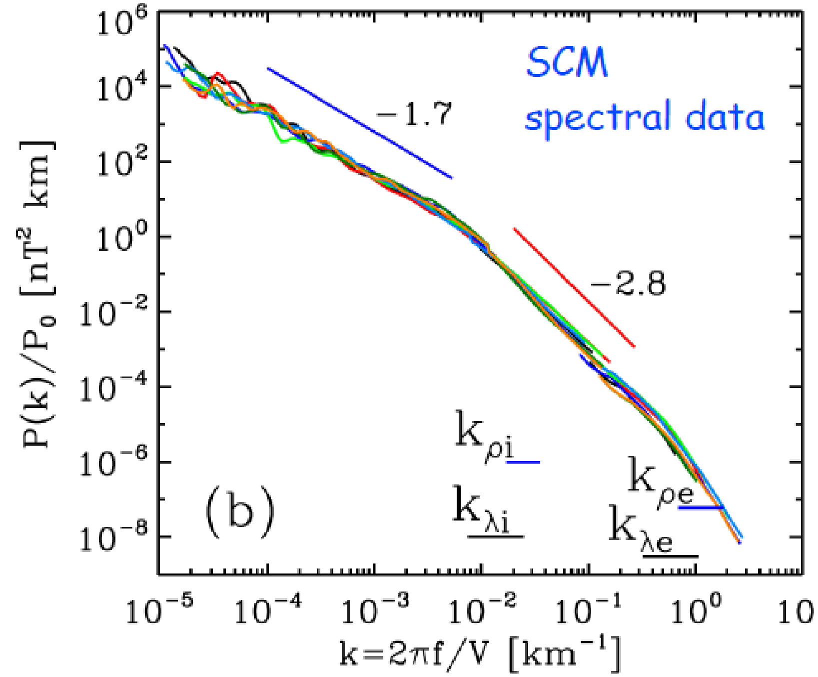
Cluster

A first case study



Sahraoui et al., PRL, 2009

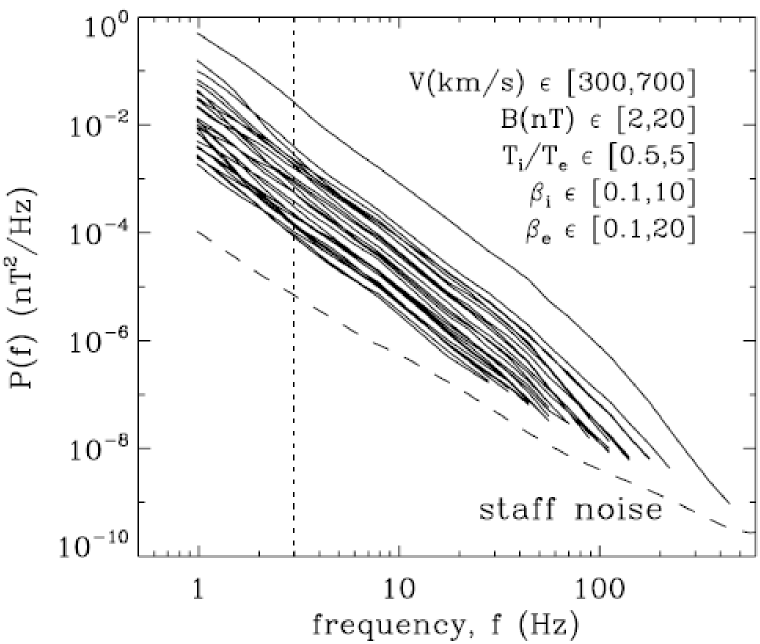
Another similar study (several cases)

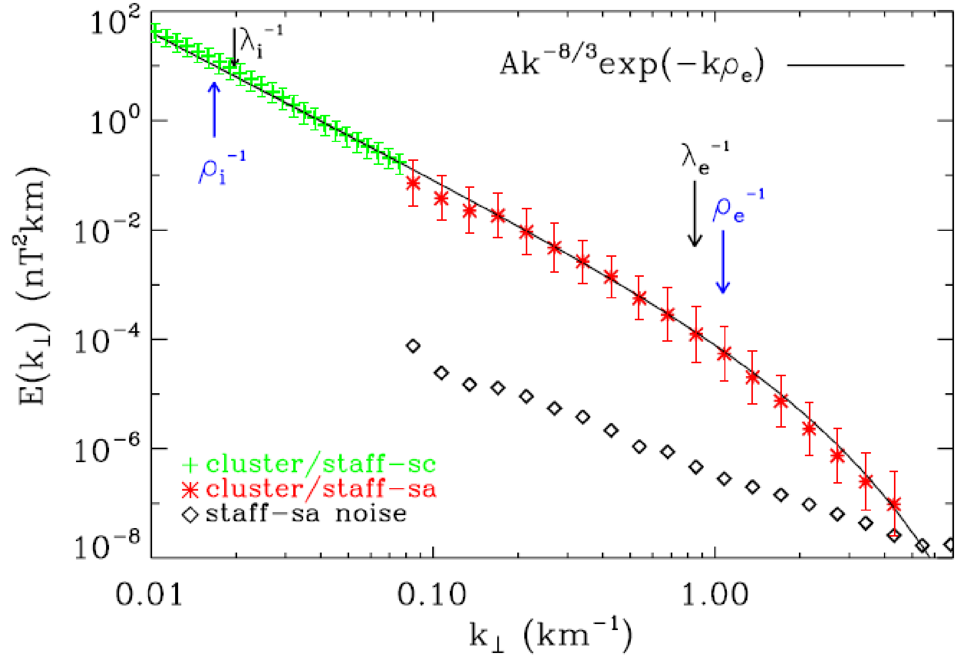


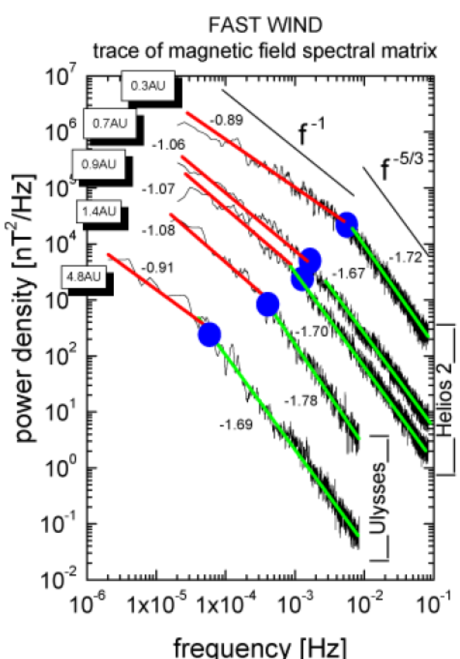
Alexandrova et al., PRL, 2009

- **Exponential decrease or power law ?**
- **Observational limitations : noise floor both for dE2 and dB2**

Alexandrova et al., ApJ 2012





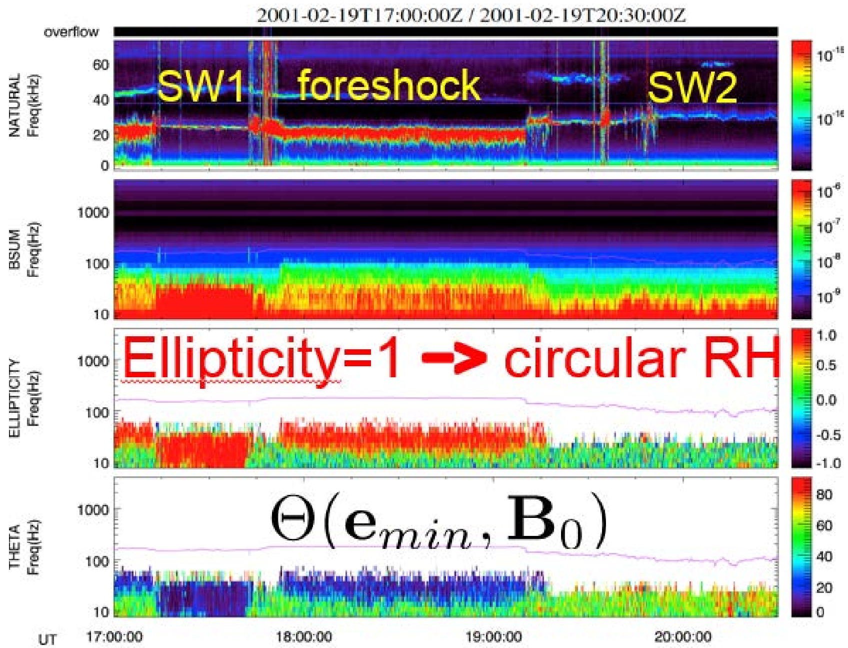


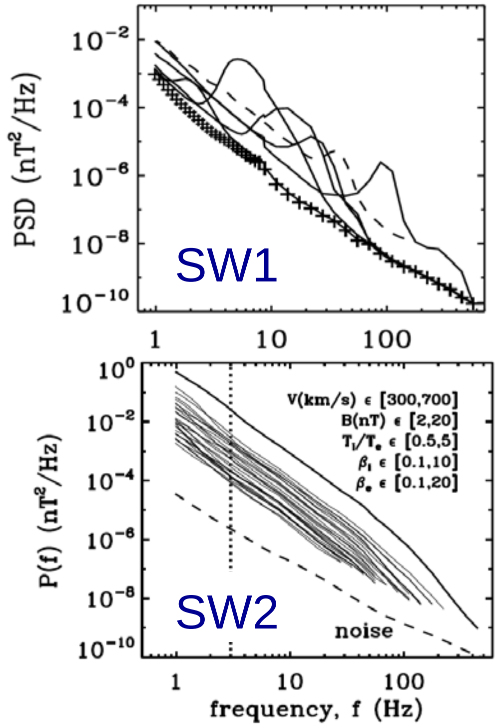
Even with the same search coil sensitivity as on Cluster, RPW will make important improvements

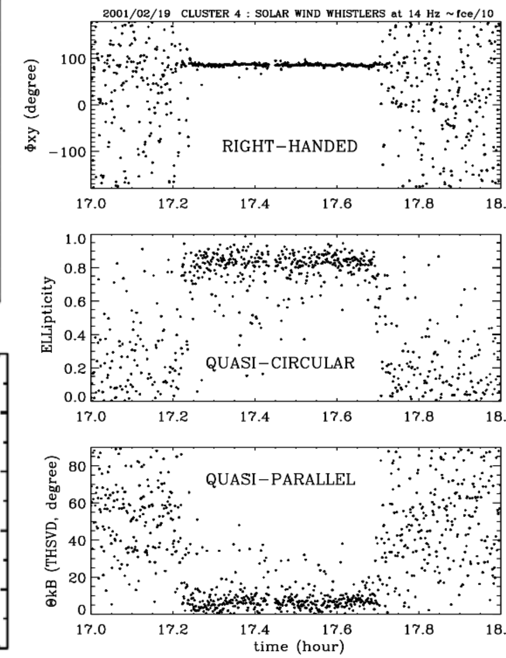
- A fonction of the ion thermal pressure
- Similar to the behaviour in the « far » dissipation range in usual fluid turbulence $E(k) \propto k^3 e^{-ckl_d}$?

Coherent waves are also observed

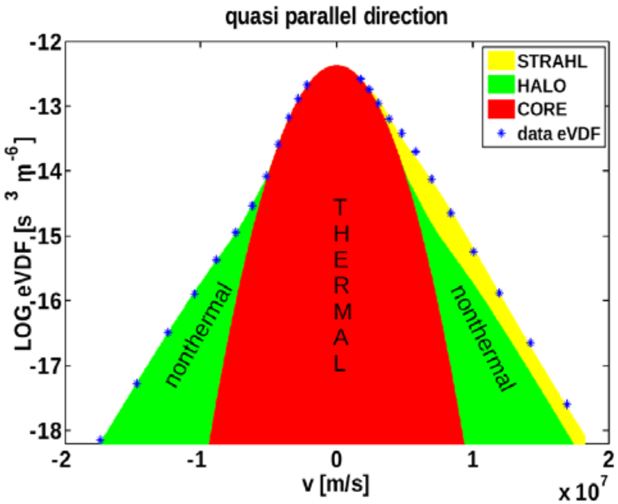
for e.g Whistler waves (Lacombe et al., 2014)





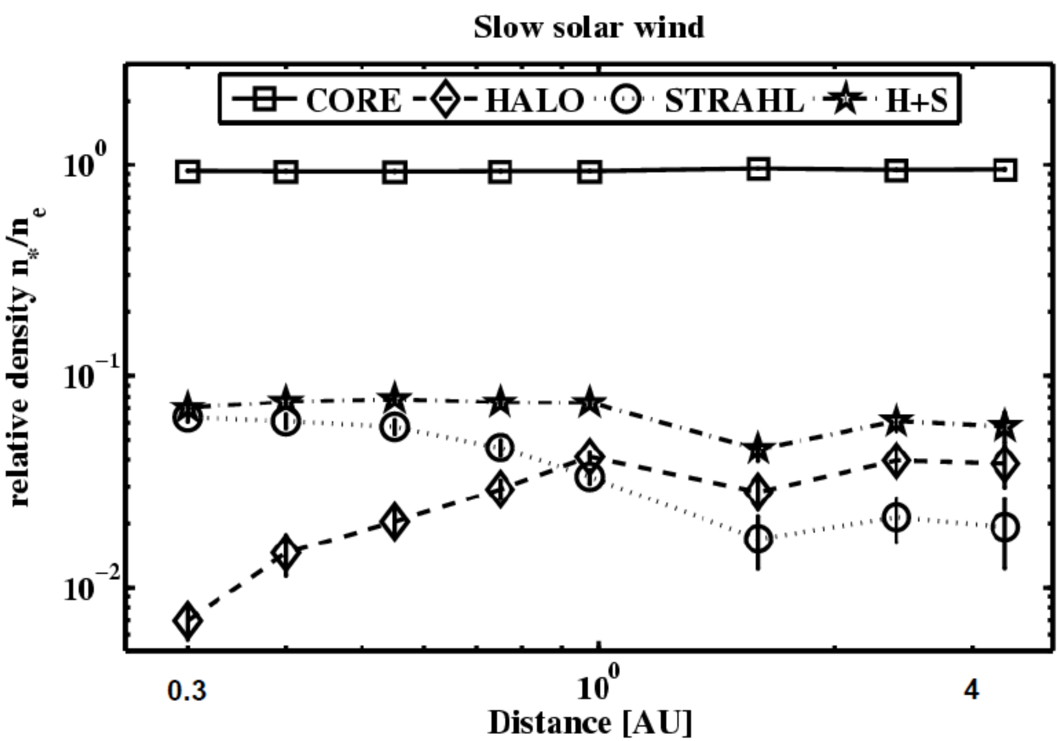


- Polarized fluctuations => spectra with bumps (10% of data)
- Non-polarized fluctuations => permanent (or background) turbulence (90% of data, Alexandrova et al. 2012, 2013)
- Permanent turbulence + sporadic polarized fluctuations => “intermediate” spectral shape (breaks, small bumps, …)



Can these Whistler waves explain the radial evolution of electron VDFs ?

Helios, Cluster, Ulysses



Data set : ~ 240,000 samples from 0.3 to 4 AU

Stverak et al., JGR, 2009

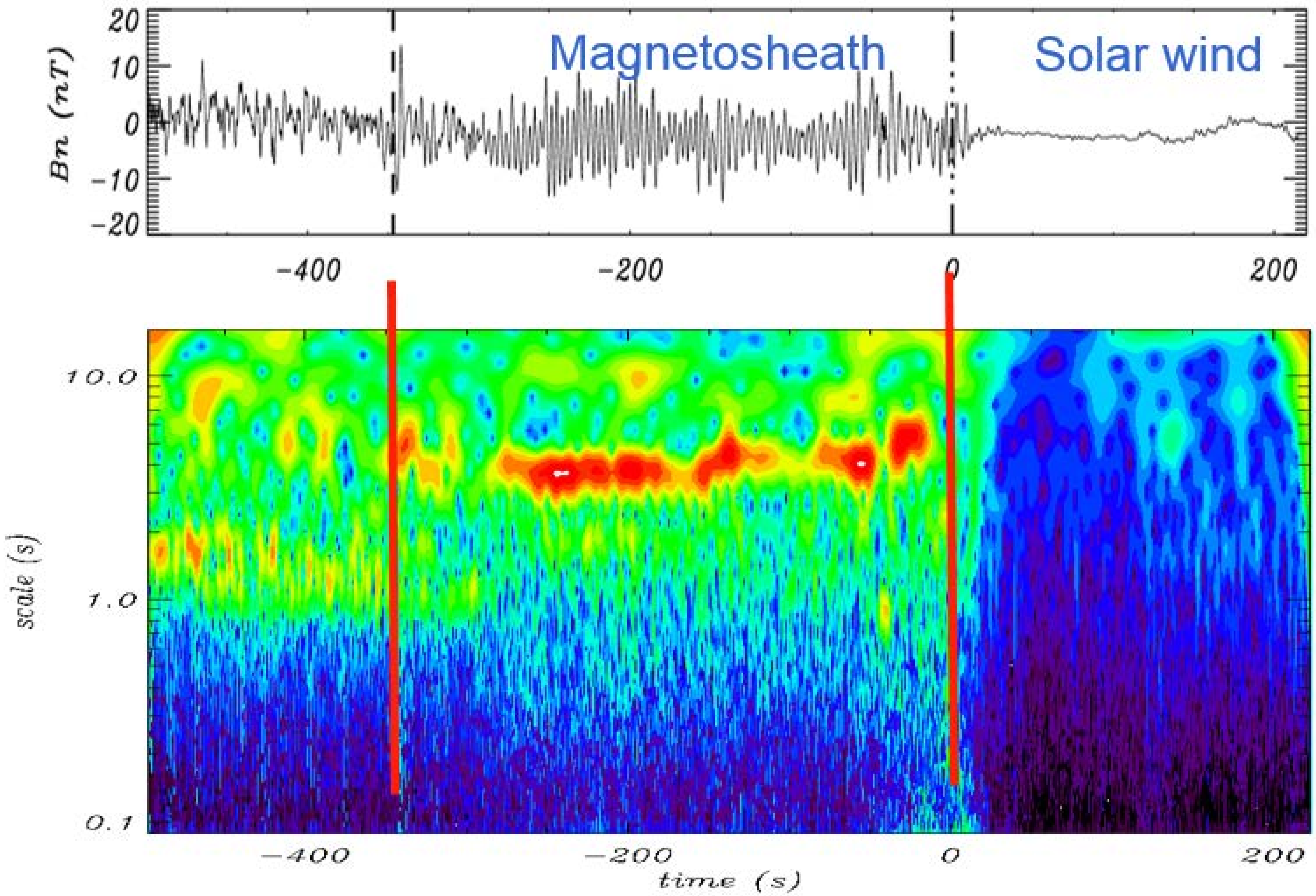
Maksimovic et al., 2005

During expansion, strahl is transformed into halo by wave-particle interactions ?

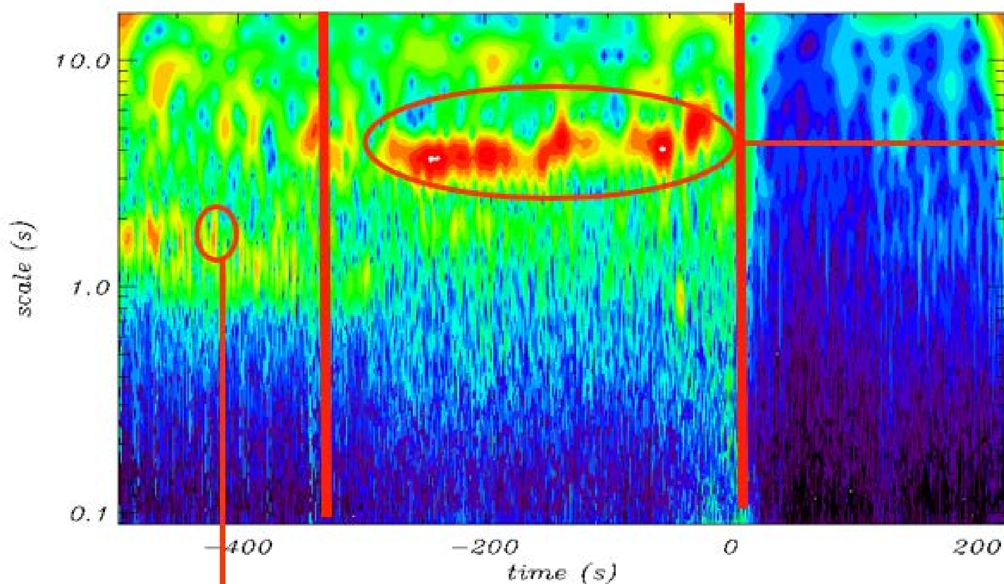
And even solitary structures …

For e.g. Alexandrova et al. 2006, JGR

Wavelet analysis of CLUSTER SCM waveforms



Presence of time-localized events in the vicinity of Alfvén Ion Cyclotron wave

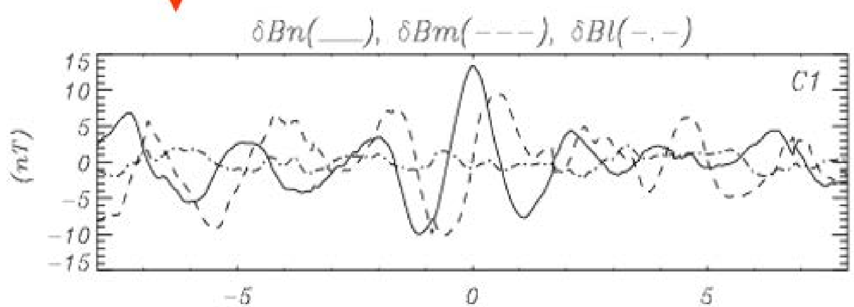


Alfvén Ion Cyclotron wave

$\lambda \propto 10\ c/\omega_{pi}$

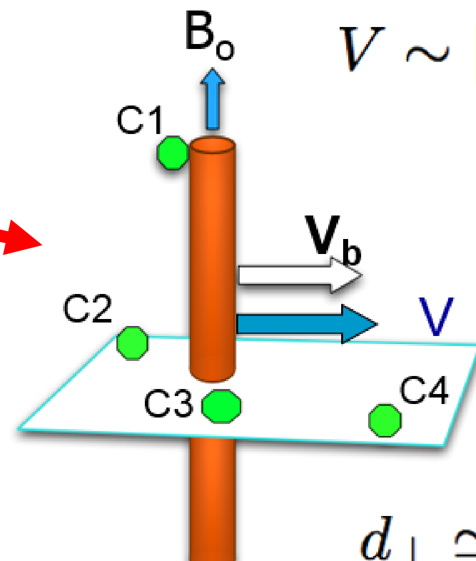
$f \propto 0.4\ f_{ci}$

Alexandrova et al. 2006, JGR



In plasma frame:

$V \sim [0, 0.3] V_A$



$d_\perp \simeq 500 km$

$d_\perp \sim 10 c/\omega_{pi}$

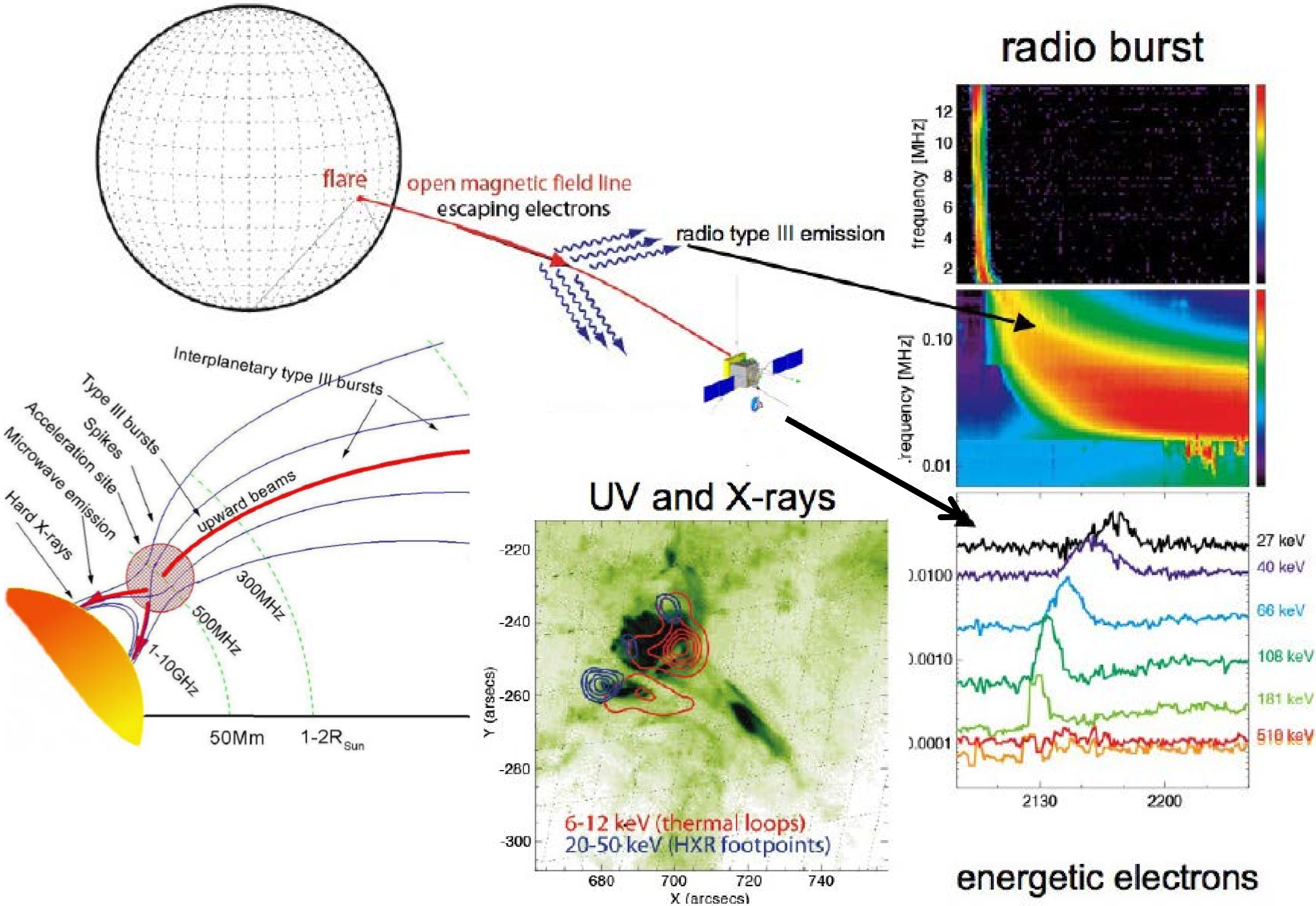
Full characterization with the 4 CLUSTER S/C of <u>localized Alvèn Vortices</u> : role for the dissipation ?

l'Observatoire de Paris LESIA

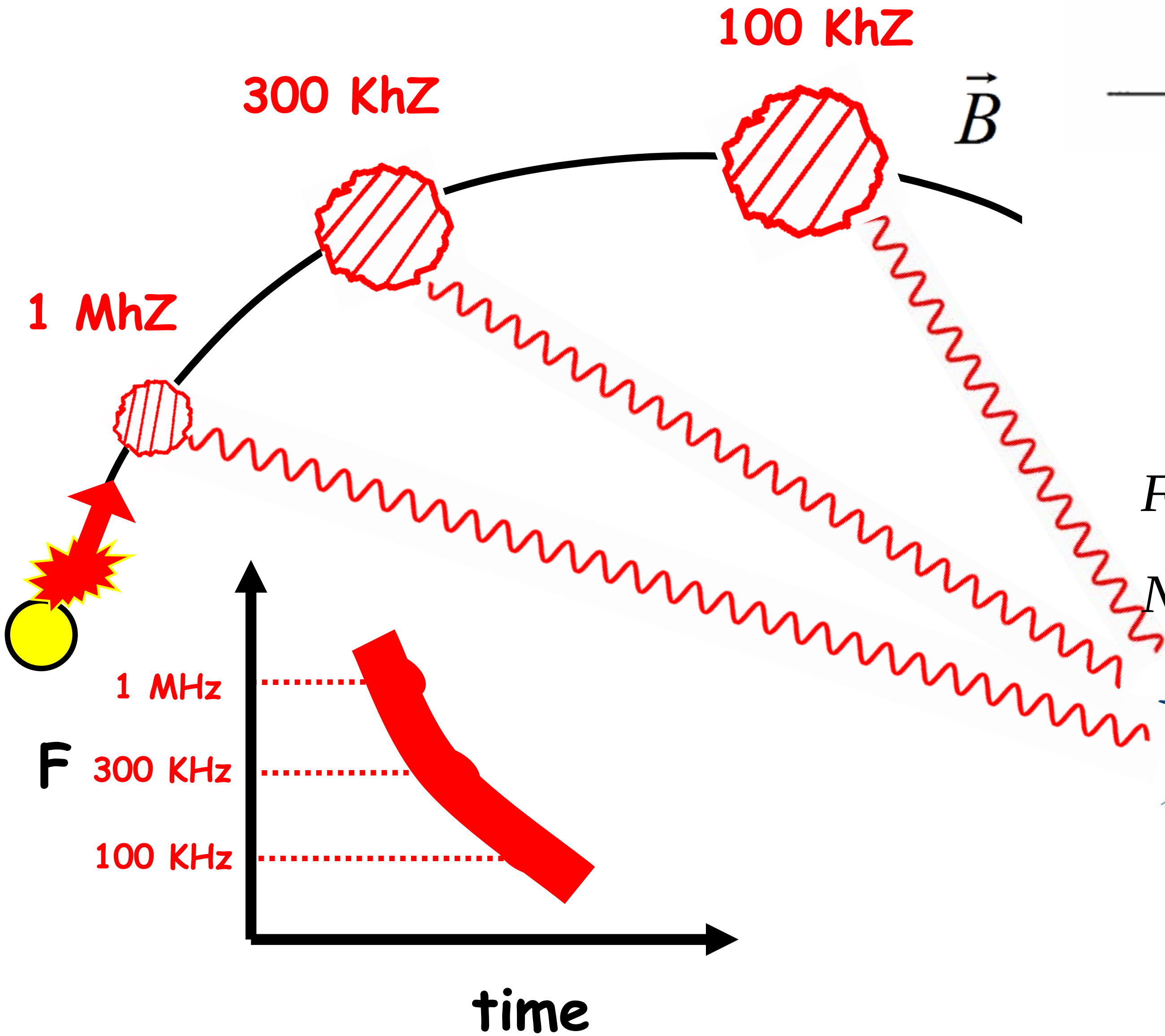
RPW

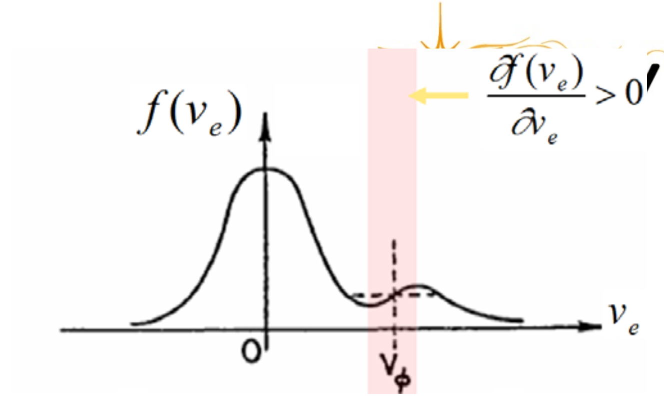
Radio waves :
what do we observed and understand ?

Solar Radio Bursts



Solar Type III radio emissions

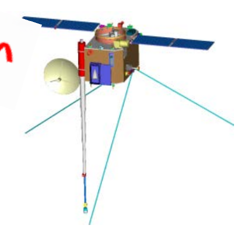




Electrostatic Langmuir waves → radio emission

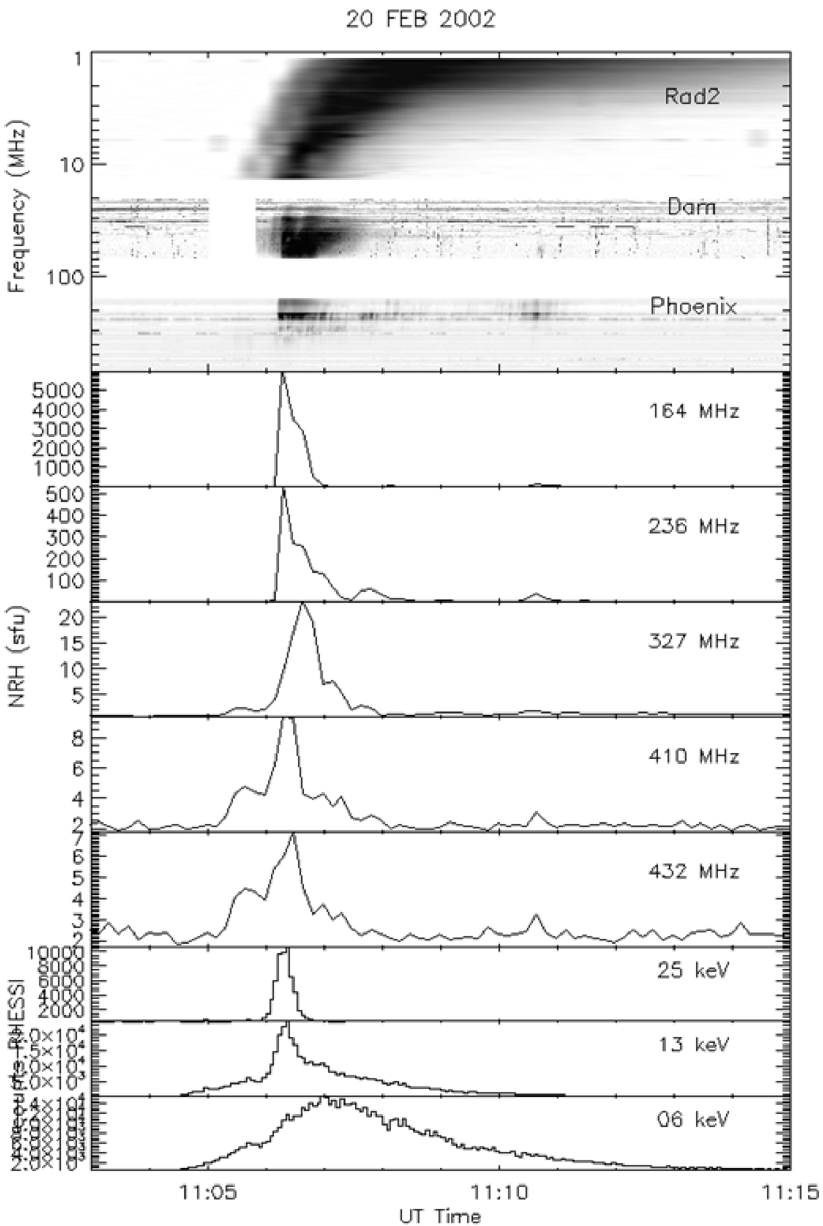
$$F_p(\text{kHz}) \propto \sqrt{N_e(\text{cm}^{-3})}$$

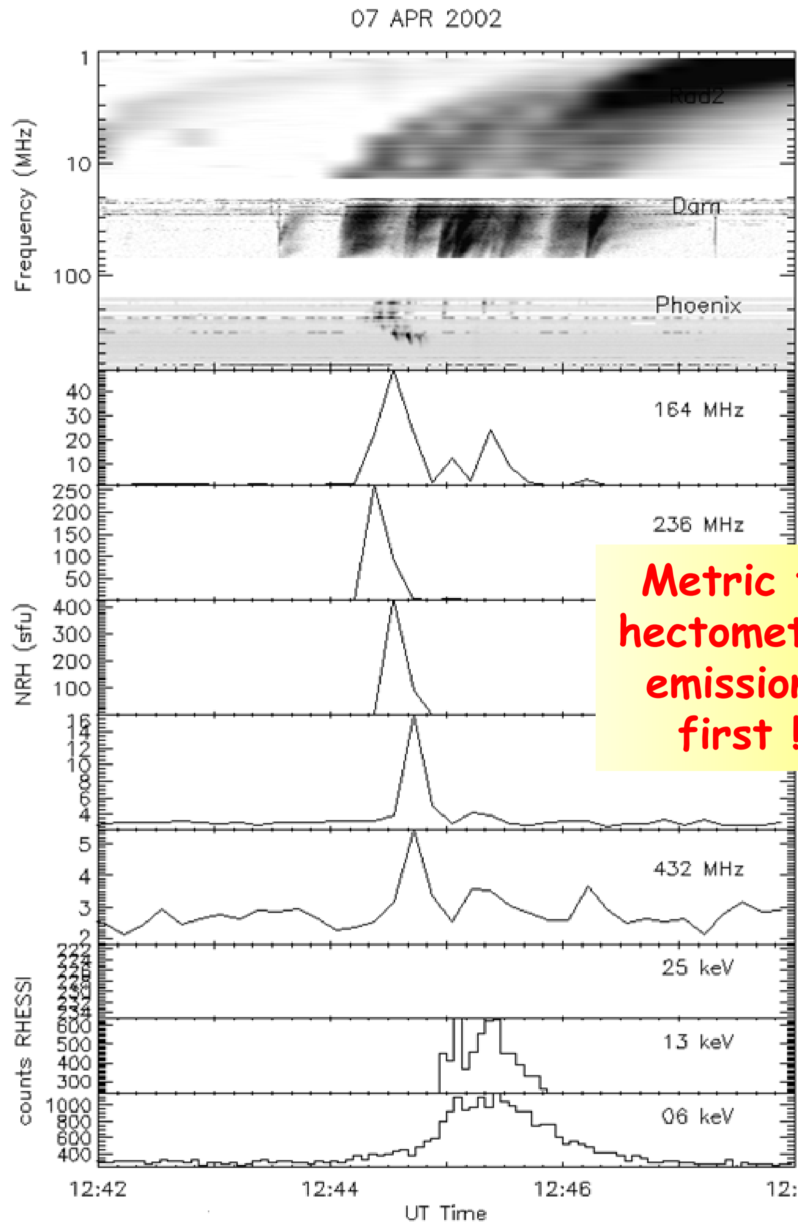
$$N_e \propto 1/R^2 \ (\text{au})$$



$$\rightarrow F_p \propto \frac{1}{\text{R}}$$

Combined RHESSI / NRH / Phoenix/Dam/WIND-WAVES observations



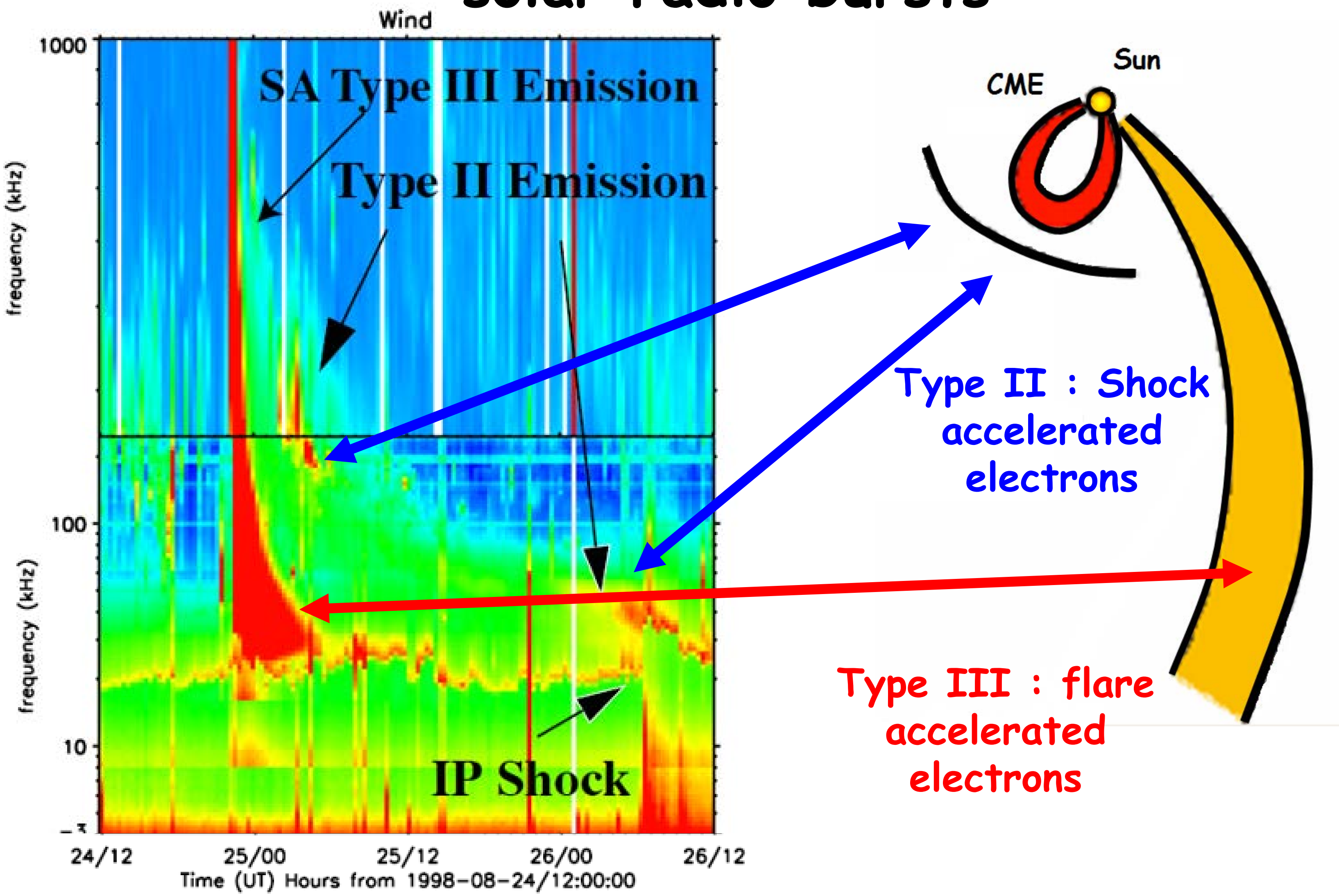


Metric to hectometric emissions first !

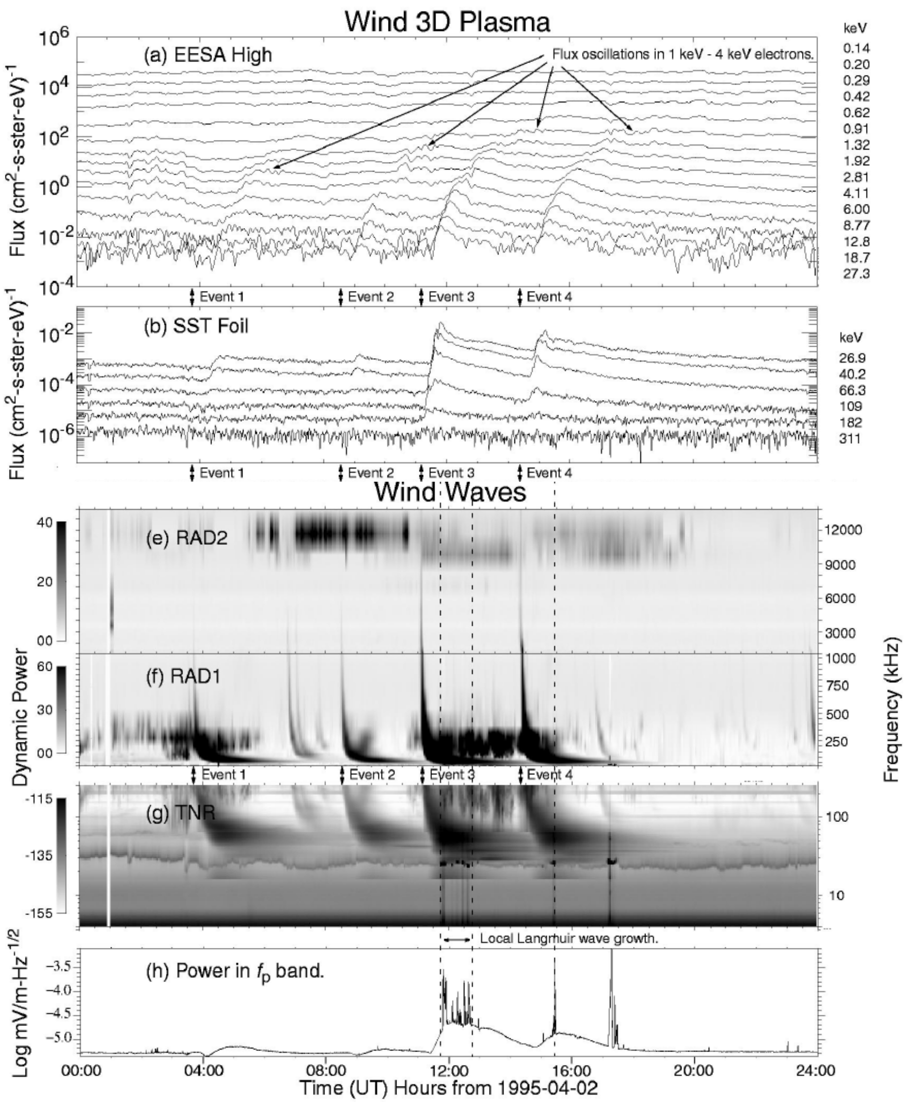
l'Observatoire de Paris | LESIA

RPW

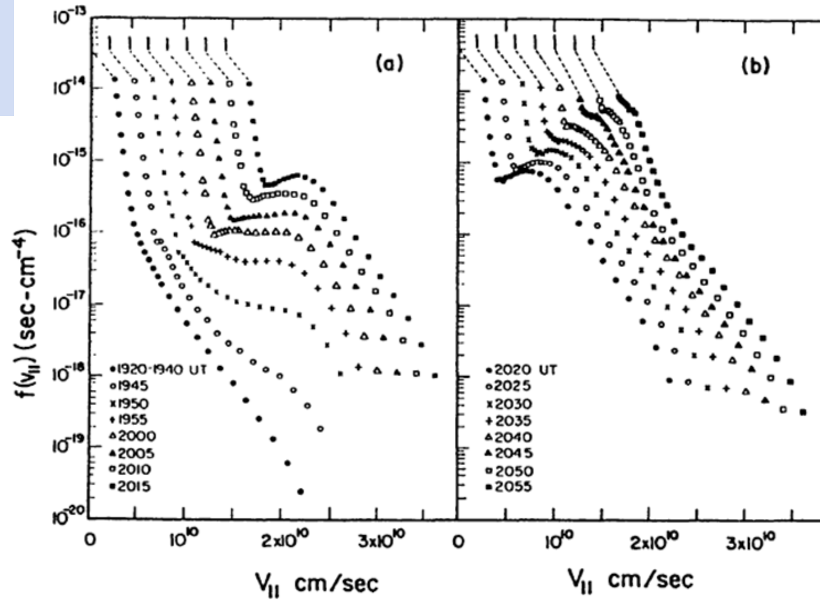
Type III & Type II solar radio bursts



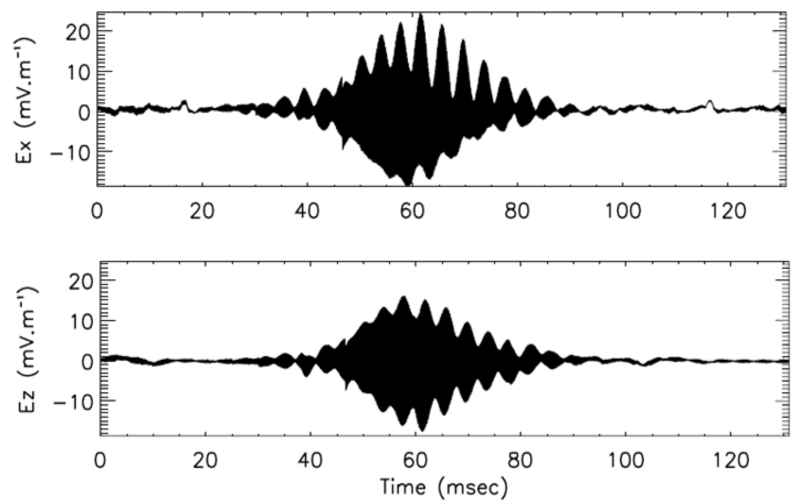
In-situ Type III and II measurements will be available on SO



Adapted from [Ergun et al., 1998]



Adapted from [Lin et al. 1981]



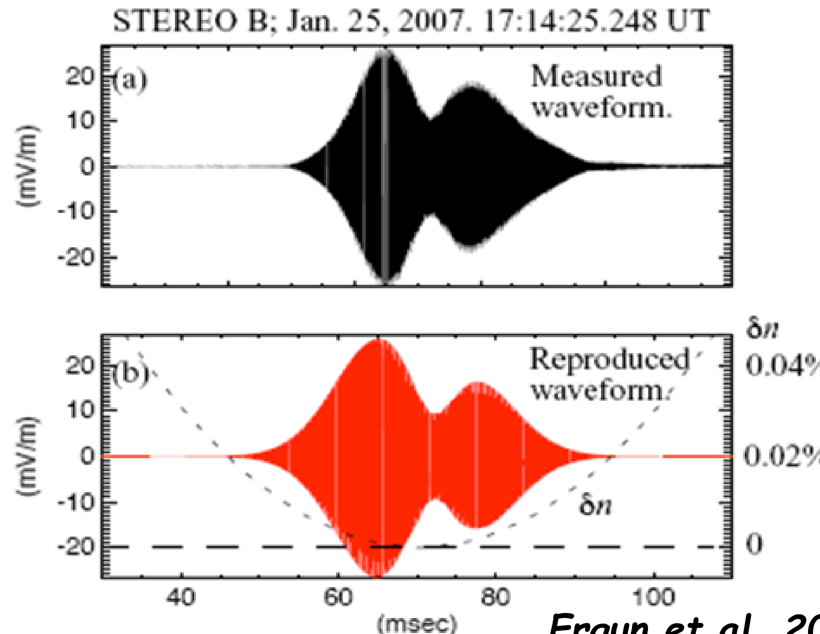
Swaves

RPW improvements for in-situ waves measurements

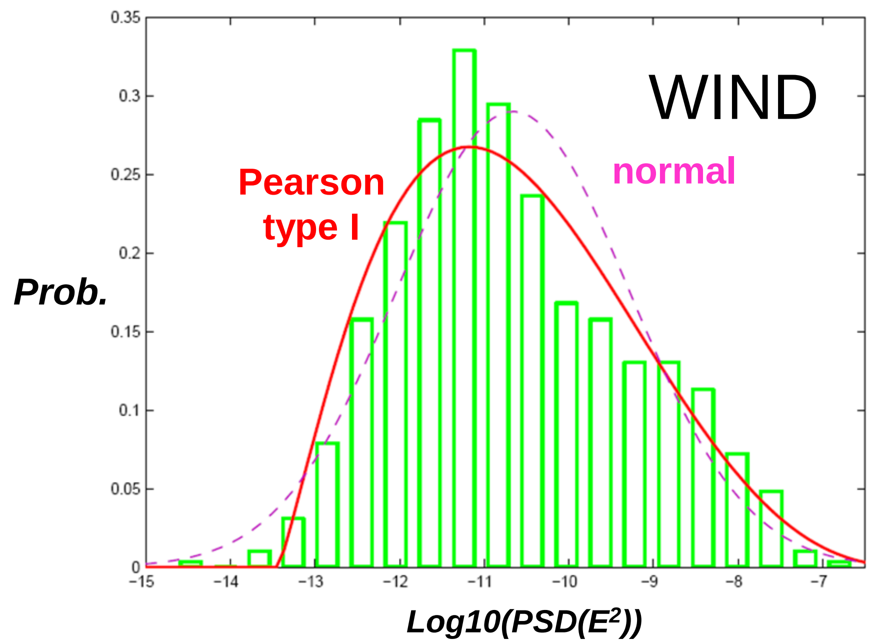
❑ RPW will measure both Langmuir waves and density fluctuations (from S/C pot. fluctuations, biased antennas) *DC E field and cross-shock potential*

❑ RPW will measure simultaneously 2-axis E + 1 axis B up to 500 kHz → mode conversion

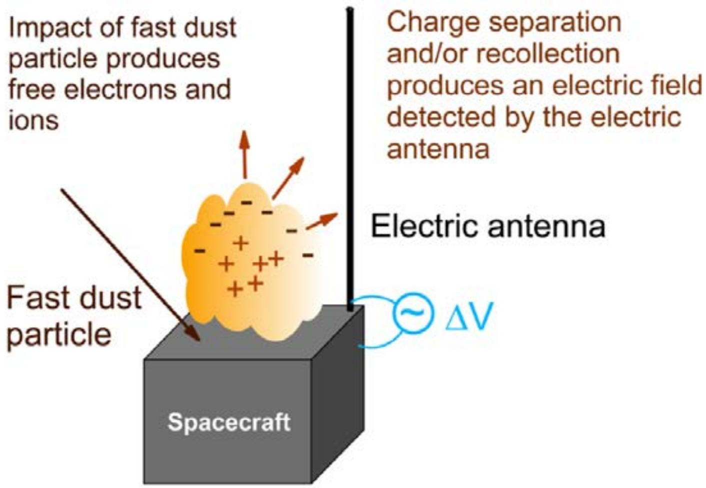
❑ Onboard statistics of LW power
Distribution of LW power more Pearson like than Normal ? (Vidojevic et al., 2010)



Ergun et al, 2008

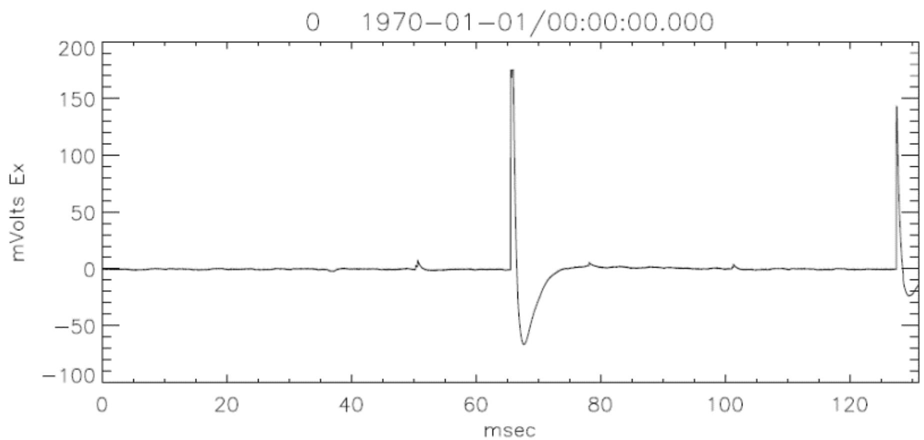


Interplanetary Dust

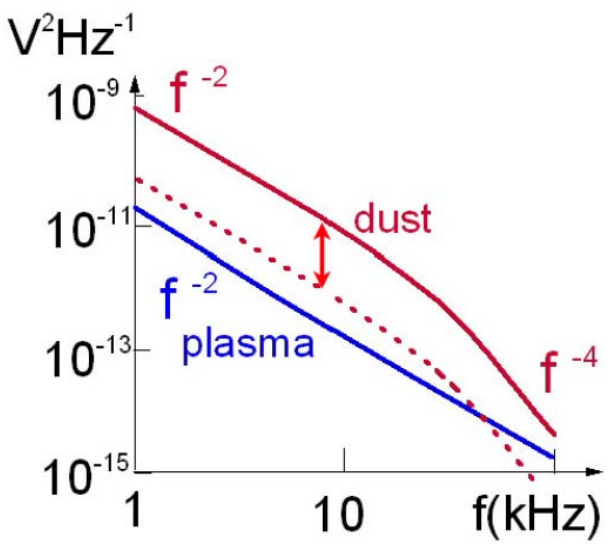


Released charge : $Q \simeq 0.7 m^{1.02} v^{3.48}$

Induced voltage pulse on S/C of capacitance C : $\delta V \sim -Q/C$

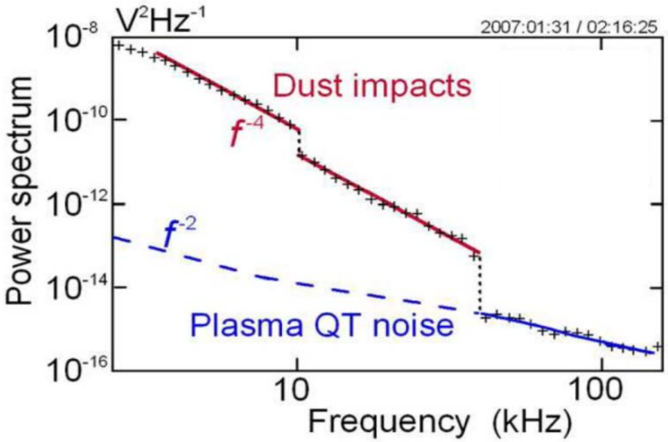


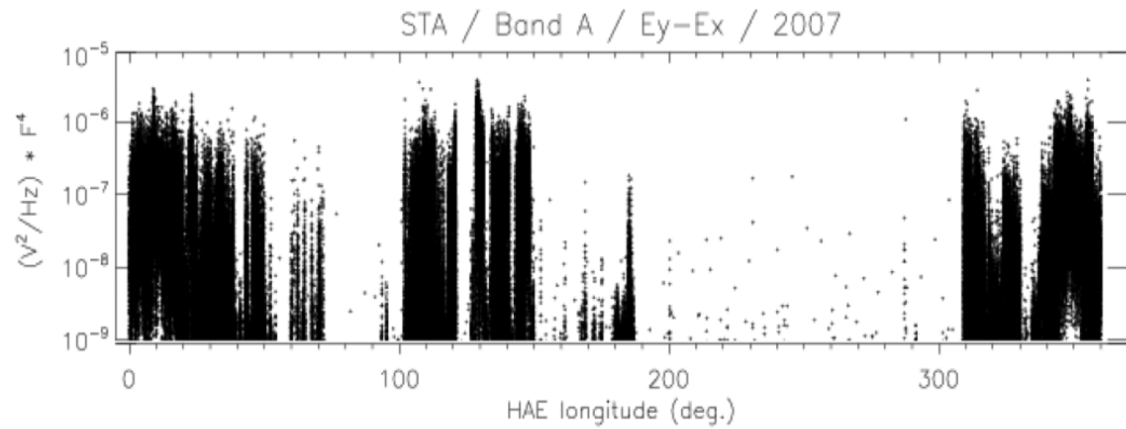
Temporal domain



Spectral domain

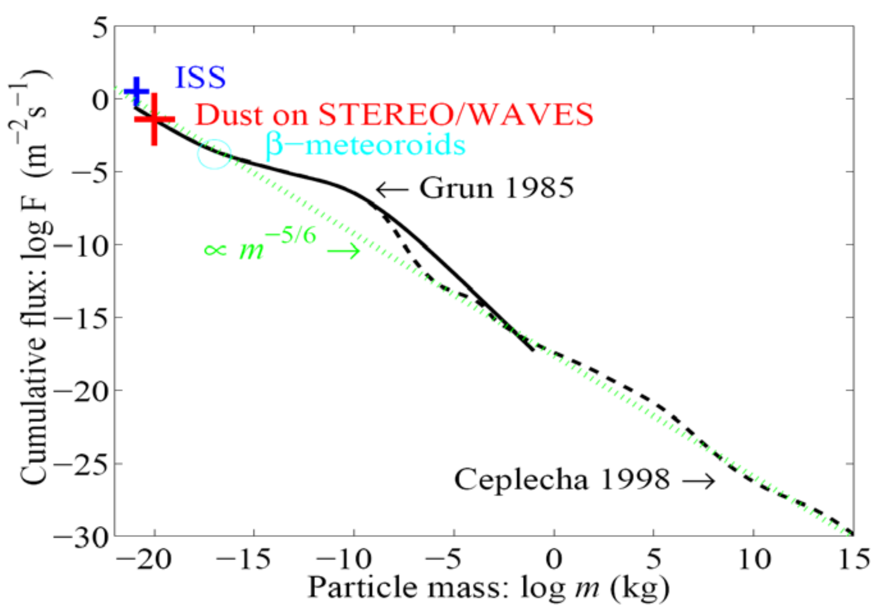
Discovery of a large flux of nanodust on Stereo *Meyer-Vernet et al., 2012*





Released charge : $Q \simeq 0.7 m^{1.02} v^{3.48}$

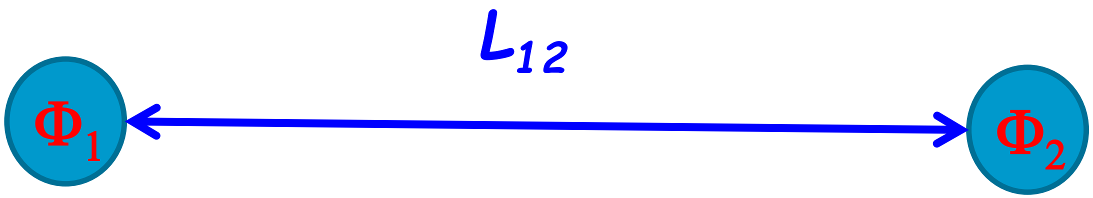
→*A nanoparticle @ 300 km/s* ~ *a grain of mass 10^4 greater @ 20 km/s*



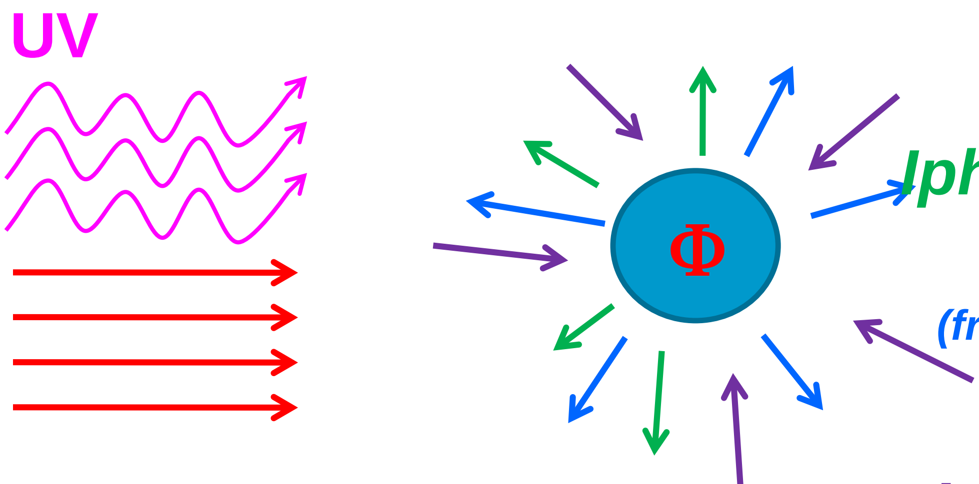
Picked-up by the -VXB field

On the difficulty of measuring the DC/LF electric component of plasma waves

Basics for measuring DC/LF E Field



$$|E| = | \Phi_2 - \Phi_1 | / L_{12}$$



Photoelectrons

Iph∝Nph Vph corrected for Φ

Secondary electrons

(from impact of external energetic electrons

SW electrons

Ie∝Ne Vthe corrected for Φ

Protons :

Ip∝Np Vp

Negligible at 0th order

Φ determined by *Ip + Ie + Iph = 0,*

actually Ie = - Iph (depending mostly on Ne)

Salem et al., 2001

$$J_{ph0} \approx \frac{10^{-5}\chi}{d_{AU}^2}$$

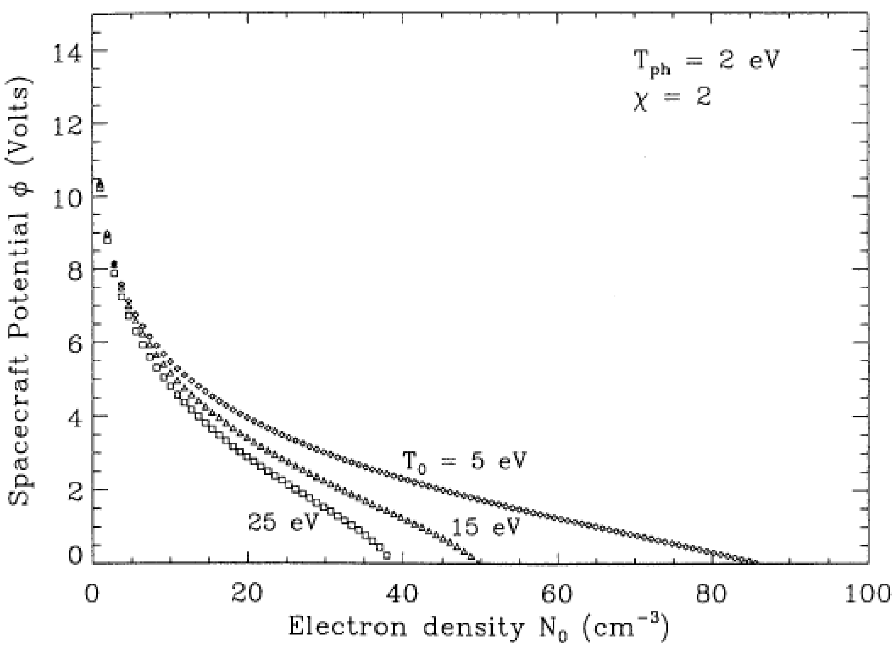
$$J_{ph} = J_{ph0}\,(1 + \frac{e\phi}{k_B T_{ph}})\, e^{-\,e\phi/k_B T_{ph}},$$

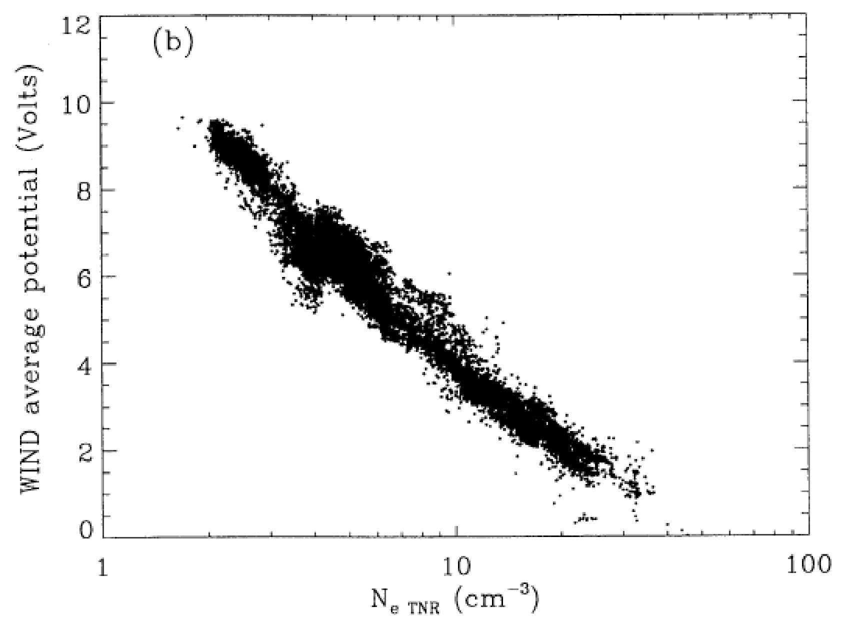
$$J_e = e\, N_e\, v_e,$$

$$J_e = J_{e0}\,(1 + \frac{e\phi}{kT_{e0}} \quad : 0,$$

Φ varies with Ne !!

We want to measure ~mV/m !!





We need to bias the antennas

Ie + Iph +Ibias= 0

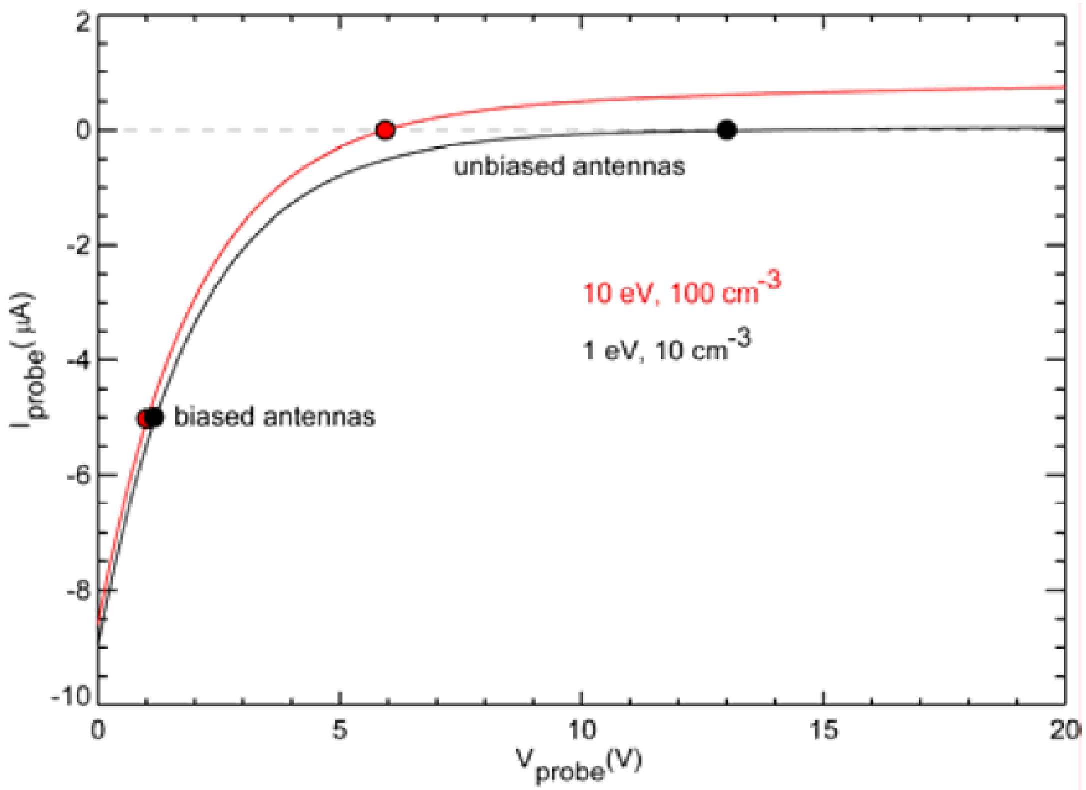
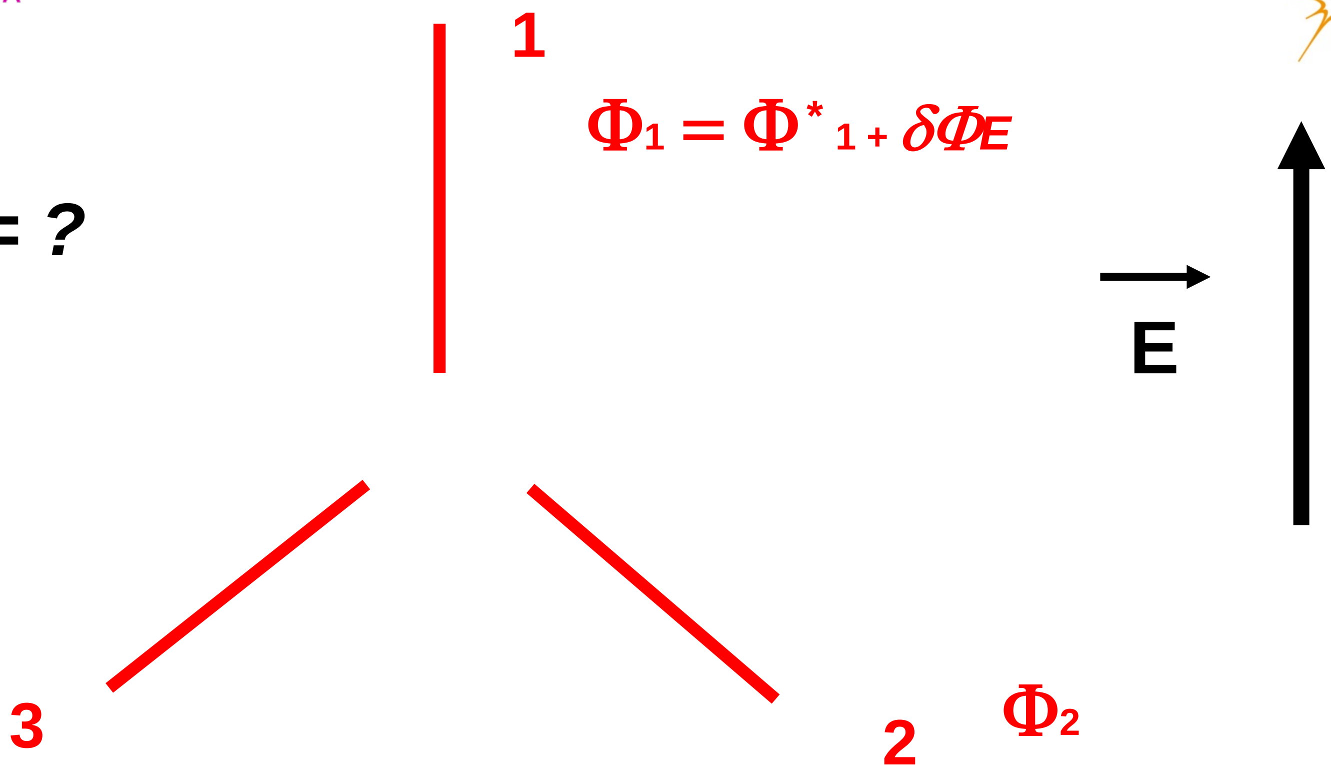


Figure 2.4 The simulated voltage-current curve of the antenna for two different plasma regimes. The potential variations of biased antenna are significantly less for different plasma parameters than for unbiased antenna.

courtesy C. Cully

$\delta\Phi_E = ?$



If $\Phi^*_1 = \Phi_2$ then $\Phi_2 - \Phi_1 = \delta\Phi_E$

For that we need :

- Equal illumination for 1 & 2
- Symmetry with respect to the S/C
- Biasing the probes

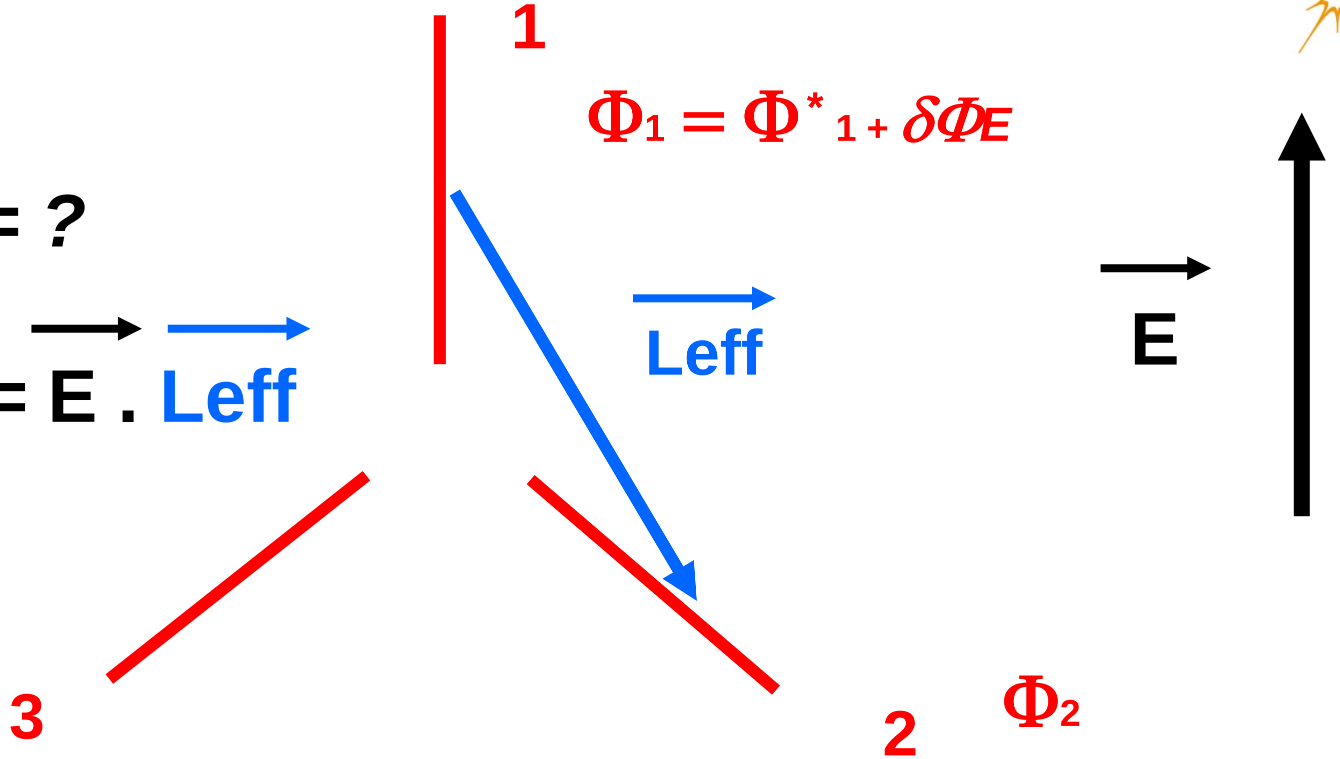
Typically

If $\Phi^*_1 = \Phi_2$ *~ 0 to 10 Volts*

E ~ few to few 100s of mV/m

$\delta\Phi_E = ?$

$\delta\Phi_E = \vec{E} \cdot \vec{L}_{eff}$



If $\Phi^*_1 = \Phi_2$ then $\Phi_2 - \Phi_1 = \delta\Phi_E$

For that we need :

- Equal illumination for 1 & 2
- Symmetry with respect to the S/C
- Biasing the probes

Typically

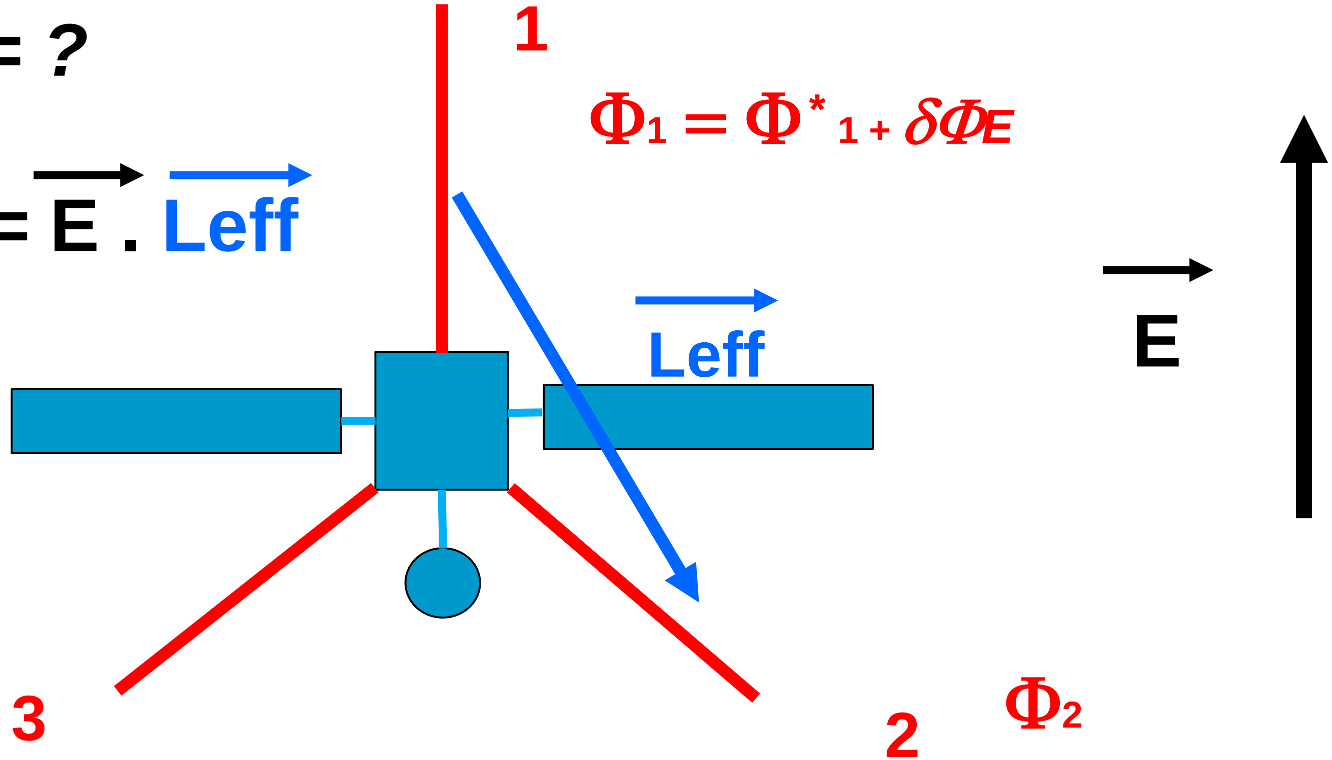
If $\Phi^*_1 = \Phi_2$ ~ *0 to 10 Volts*

E ~ few to few 100s of mV/m

$\vec{L}_{eff}$ can only be determined by simulation

$\delta\Phi_E = ?$

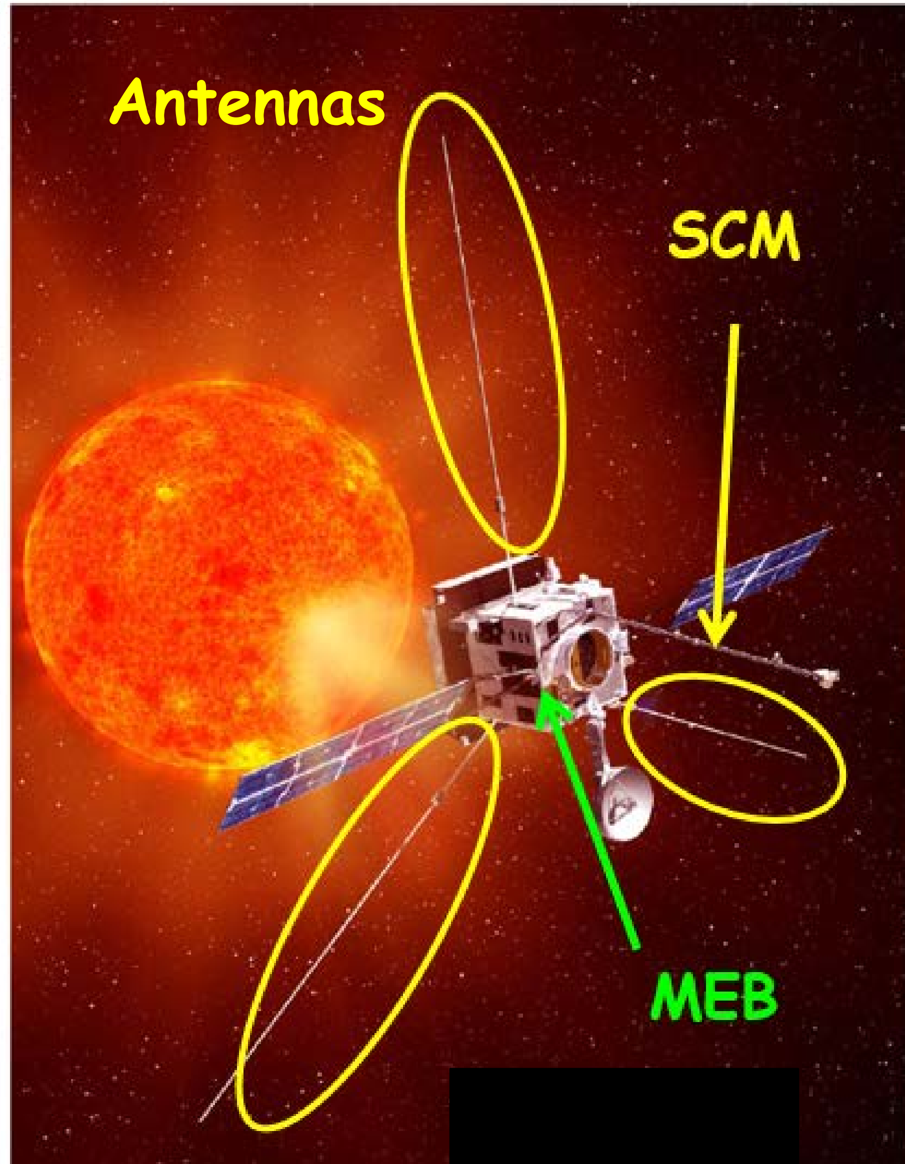
$\delta\Phi_E = \vec{E} \cdot \vec{Leff}$

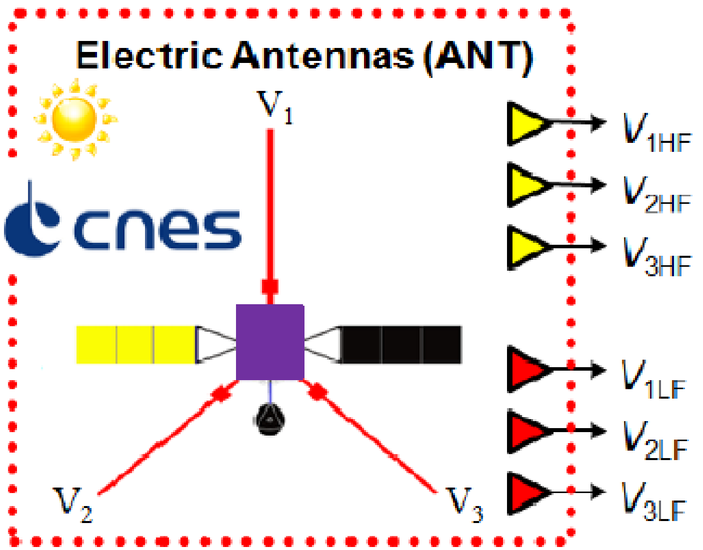


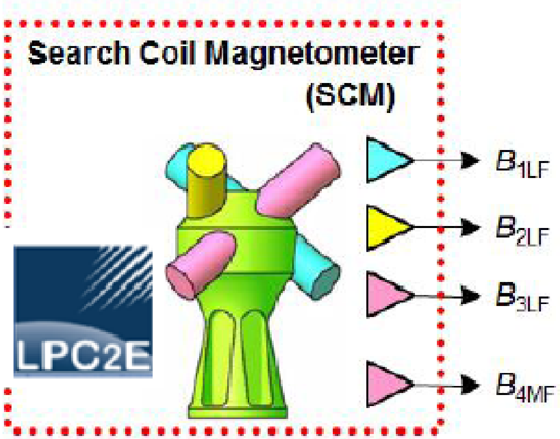
The problem is that there is a S/C in addition to the RPW antennas !!

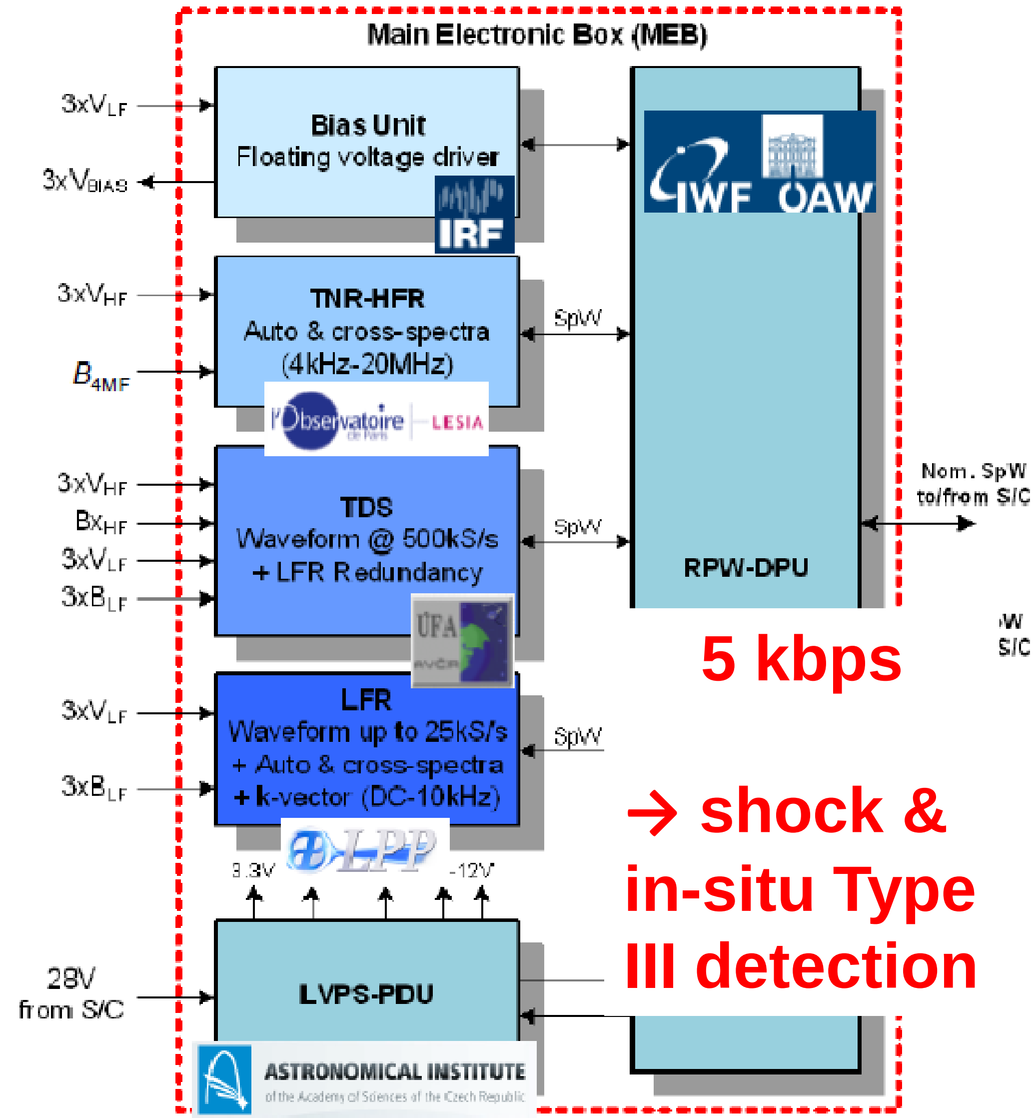
Need to simulate the effect of the S/C

RPW : a (very) brief description









5 kbps

→ shock & in-situ Type III detection

DC Efield expertise & calibration, link to SPP

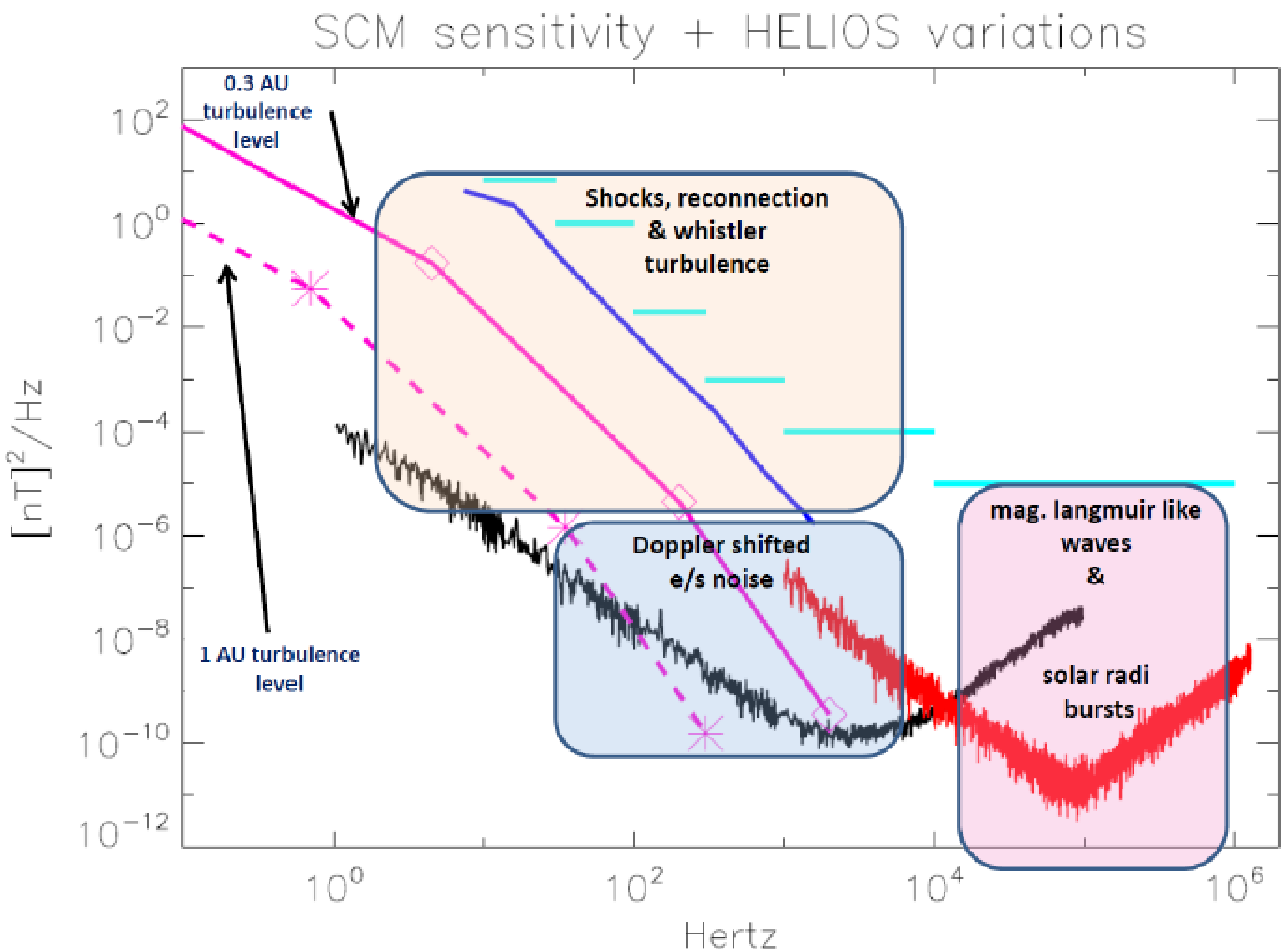
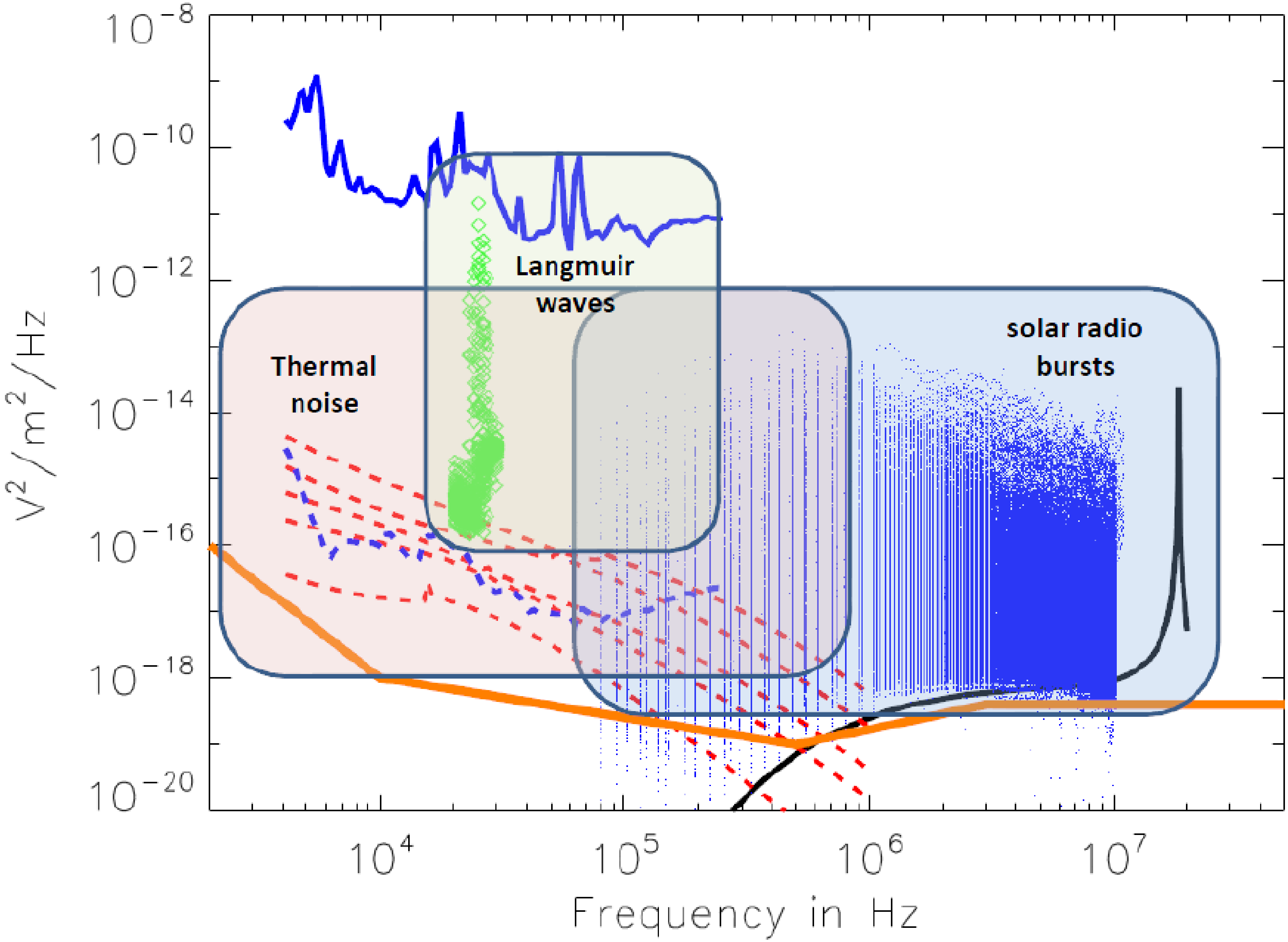


Figure 10: Magnetic field fluctuations of various natural phenomena that will be observed by the RPW instrument


Langmuir
waves
solar radio
bursts
Thermal
noise
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
$V^2/m^2/Hz$
10^4
10^5
10^6
10^7
Frequency in Hz

Bibliography (1/2)

- Alexandrova O.., A. Mangeney, M. Maksimovic, N. Cornilleau-Wehrlin, J.-M. Bosqued, M. André & E.A. Lucek, Alfvén vortex filaments observed in the magnetosheath downstream of quasi-perpendicular bow-shock,Journal of Geophysical research, 111, A12208, doi:10.1029/2006JA011934, 2006

- Alexandrova O., J. Saur, C. Lacombe, A. Mangeney, J. Mitchell, S. J. Schwartz, and P. Robert, Universality of Solar-Wind Turbulent Spectrum from MHD to Electron Scales, Phys. Rev. Lett. 103, 165003 – Published 14 October 2009

- Alexandrova O., C. Lacombe, A. Mangeney, R. Grappin, M. Maksimovic, Solar Wind Turbulent Spectrum at Plasma Kinetic Scales, Astrophysical Journal, 760, DOI:10.1088/0004-637X/760/2/121, 2012.

- Bale S.D., P. J. Kellogg, F. S. Mozer, T. S. Horbury, and H. Reme, Measurement of the Electric Fluctuation Spectrum of Magnetohydrodynamic Turbulence, Phys. Rev. Lett. 94, 215002 – Published 2 June 2005

- Ergun R.E. et al., WIND SPACECRAFT OBSERVATIONS OF SOLAR IMPULSIVE ELECTRON EVENTS ASSOCIATED WITH SOLAR TYPE III RADIO BURSTS, THE ASTROPHYSICAL JOURNAL, 503:435È445, 1998

- Lacombe C., O. Alexandrova, L. Matteini, O. Santolik, N. Cornilleau-Wehrlin, A. Mangeney Y. de Conchy and M. Maksimovic, Whistler mode waves and the electron heat flux in the solar wind: Cluster observations, Journal of Geophysical Research, in press 2014

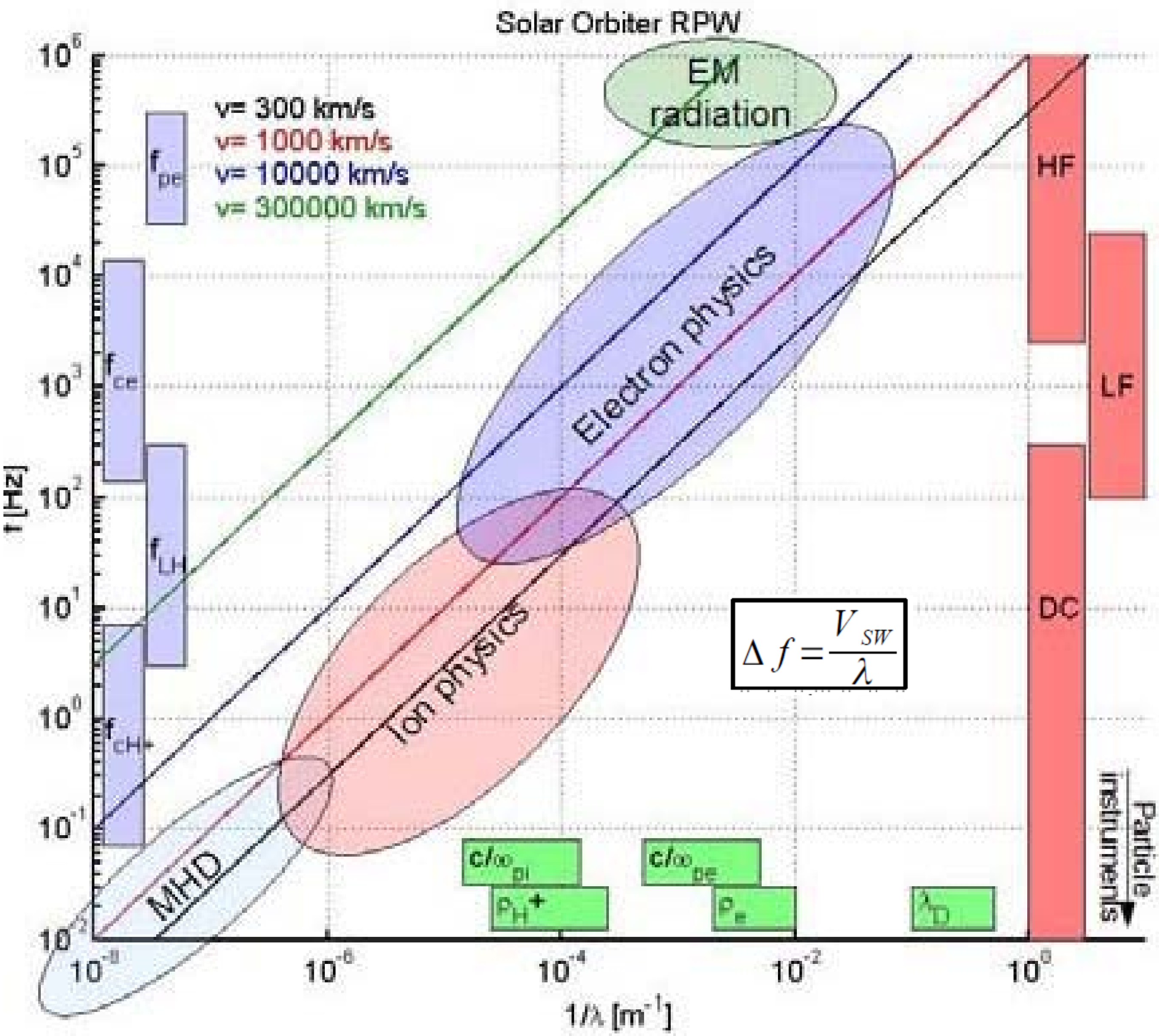
- Lin R.P., et al., Energetic electrons and plasma waves associated with a Solar Type III radio burst, The Astrophysical journal, 251:364-373, 1981

- Maksimovic M., S. Hoang, N. Meyer-Vernet, M. Moncuquet, J.-L. Bougeret, P. Canu and J. L. Phillips, The Solar Wind Electron Parameters from Quasi-Thermal Noise Spectroscopy and Comparison with other Measurements on Ulysses, Journal of Geophysical Research, 100, 19,881-19,891, 1995.

- Maksimovic M., K. Issautier, S.D. Bale, N. Vilmer, M. Moncuquet, N. Meyer-Vernet and J.-L. Bougeret, Solar Wind Electron Temperature and Density Measurements for the Solar Orbiter using the Thermal Noise spectroscopy, Solar encounter, Proceedings of the First Solar Orbiter Workshop, 14 - 18 May 2001, Puerto de la Cruz, Tenerife, Spain, ESA SP-493, ISBN 92-9092-803-4, p. 285, 2001.

Bibliography (2/2)

- Maksimovic M., I. Zouganelis, J.-Y. Chaufray, K. Issautier, E.E. Scime, J. Littleton, E. Marsch, D.J. McComas, C. Salem, R.P. Lin, and H. Elliott , Radial Evolution of the Electron Distribution Functions in the Fast Solar Wind between 0.3 and 1.5 AU, J. Geophys. Res., 110, A09104, doi:10.1029/2005JA011119, 2005.
- Meyer-Vernet & Perche, Tool kit for antennae and thermal noise near the plasma frequency, Journal of Geophysical Research: Space Physics, Volume 94, Issue A3, pages 2405–2415, DOI: 10.1029/JA094iA03p02405, 1989
- Meyer-Vernet N., S. Hoang, K. Issautier, M. Maksimovic, R. Manning, M. Moncuquet and R.G. Stone, Measuring plasma parameters with thermal noise spectroscopy, AGU Monograph on Measurements Techniques in Space Plasmas, Geophysical Monograph 103, 1998.
- Meyer-Vernet N., M. Maksimovic, A. Czechowski, I. Mann, I. Zouganelis, K. Goetz, M.L. Kaiser, O.C. St. Cyr, J.-L. Bougeret, S.D. Bale, Dust detection by the wave instrument on STEREO: nanoparticles picked-up by the solar wind?, Solar Physics, 256: 463-474, DOI 10.1007/s11207-009-9349-2, 2009.
- Sahraoui F., M. L. Goldstein, P. Robert, and Yu. V. Khotyaintsev, Evidence of a Cascade and Dissipation of Solar-Wind Turbulence at the Electron Gyroscale, Phys. Rev. Lett. 102, 231102 – Published 10 June 2009
- Salem C., et al., Determination of accurate solar wind electron parameters using particle detectors and radio wave receivers, Journal of Geophysical research, 106, 21,701, 2001
- Stverak S., M. Maksimovic, P. Travnıcek, E. Marsch, A.N. Fazakerley and E.E. Scime, Radial Evolution of Non-thermal Electrons in the Low-latitude Solar Wind: Helios, Cluster and Ulysses observations, J. Geophys. Res., 114, A05104, doi:10.1029/2008JA013883, 2009.
- Vidojevic S., A. Zaslavsky, M. Maksimovic, O. Atanackovic, S. Hoang and Q. N. Nguyen, LangmuirWaves and Type III Bursts Observed by the Wind Spacecraft, in: (M. Maksimovic, K. Issautier, N. Meyer-Vernet, M. Moncuquet, F. Pantellini, Eds.) Proceedings of the 12th Solar Wind Conference, Saint Malo, France, 22 - 26 June 2009,, AIP CP. 1216, 284, 2010.


Solar Orbiter RPW
v= 300 km/s
v= 1000 km/s
v= 10000 km/s
v= 300000 km/s
EM radiation
Electron physics
Ion physics
MHD
HF
LF
DC
Particle instruments
$\Delta f = \frac{V_{SW}}{\lambda}$
f_{pe}
f_{ce}
f_{LH}
f_{cH+}
c/ω_{pi}
c/ω_{pe}
ρ_{H^+}
ρ_e
λ_D
f [Hz]
1/λ [m^{-1}]

"Instantaneous" 5 x 5 spectral matrix (256 FFT points)

$$\mathbf{SM}\left(\omega_j^{(m)}\right)=\begin{bmatrix} B_1B_1^* & B_1B_2^* & B_1B_3^* & B_1E_1^* & B_1E_2^* \\ cc & B_2B_2^* & B_2B_3^* & B_2E_1^* & B_2E_2^* \\ cc & cc & B_3B_3^* & B_3E_1^* & B_3E_2^* \\ cc & cc & cc & E_1E_1^* & E_1E_2^* \\ cc & cc & cc & cc & E_2E_2^* \end{bmatrix}$$

Time Averaged Spectral Matrix (ASM)

$$\mathbf{ASM}\left(\omega_j^{(m)}\right)=\frac{1}{N_{SM}^{(m)}}\sum_{k=1}^{N_{SM}^{(m)}}\mathbf{SM}_k\left(\omega_j^{(m)}\right)=\langle\mathbf{SM}\rangle_{time}$$

***Frequency* average ...**

$$\mathbf{S}\left(\omega_j^{(m)}\right)=\langle\mathbf{ASM}\rangle_{frequency}$$

... before computations of the BPs (i.e. wave parameters)

Mono-**k** assumption :

	BP1 set 1:	Power spectrum of the magnetic field (***B***)
	BP1 set 2:	Power spectrum of the electric field (***E***)
(Means, JGR, 1972)	**BP1** set 3:	Wave normal vector (from ***B***)
(Means, JGR, 1972)	**BP1** set 4:	Wave ellipticity estimator (from ***B***)
(Samson & Olson, GJRA, 1980)	**BP1** set 5:	Wave planarity estimator (from ***B***)
	BP1 set 6:	X_{SO}(radial)-component of the Poynting vector
$\mathbf{n}\times\mathbf{E}=\frac{\omega}{k}\mathbf{B}$ →	**BP1** set 7:	Phase velocity estimator
$\frac{S_{ij}}{\sqrt{S_{ii}S_{jj}}}$ →	**BP2** set 1:	Autocorrelations
$\frac{S_{ij}}{\sqrt{S_{ii}S_{jj}}}$ →	**BP2** set 2:	Normalized cross correlations