Space plasmas measurement techniques

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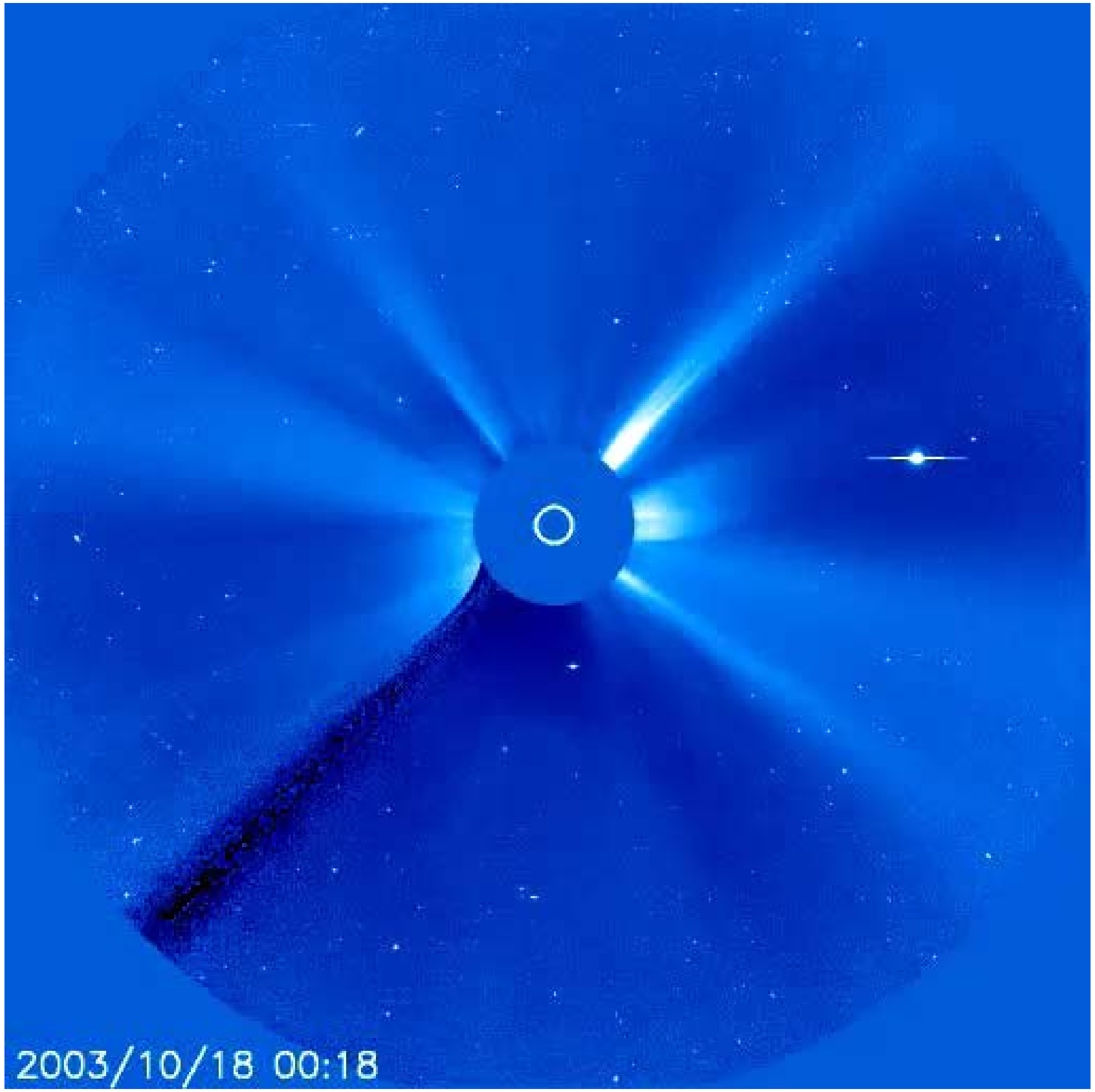
ÉCOLE DE PHYSIQUE des HOUCHES

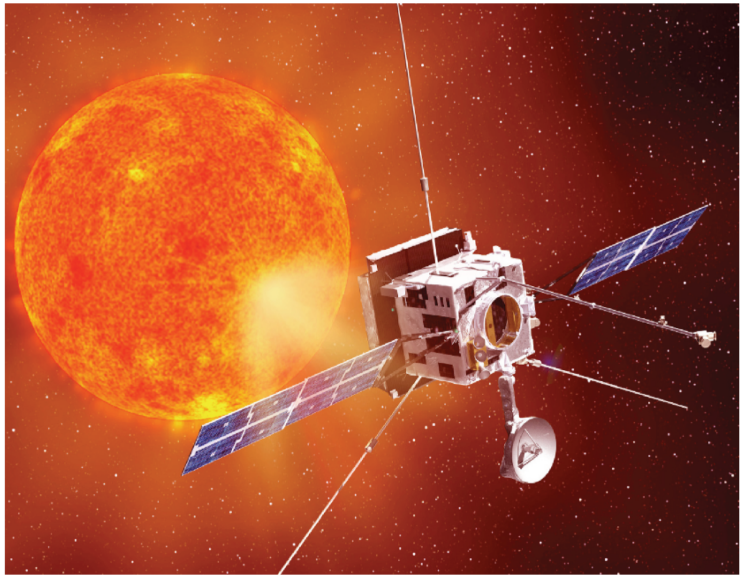
UNIVERSITÉ Grenoble Alpes

FROM LABORATORIES TO ASTROPHYSICS: THE EXPANDING UNIVERSE OF PLASMA PHYSICS



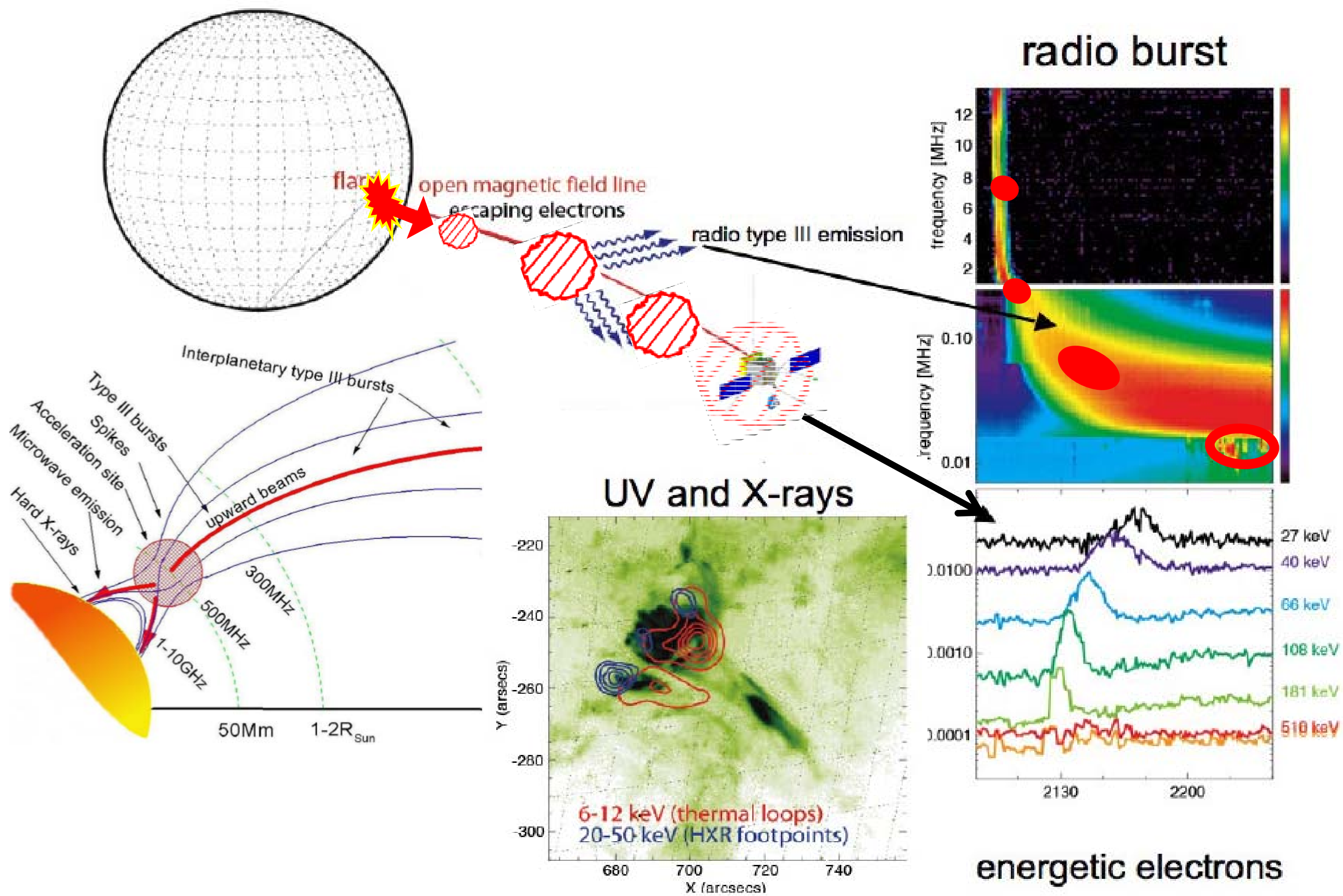
Solar Orbiter

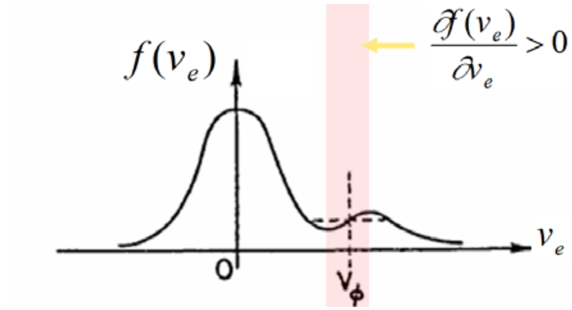
Exploring the Sun-heliosphere connection



- ESA mission with NASA participation (launcher + two instruments)
- Up to 0.28 AU with dedicated in-situ & remote sensing instrumentation closest approach possible)
- Out of ecliptic observations
- 1st M-class ESA Cosmic Vision (Launch ~Feb. 2019)

Interplanetary high energy electron & Solar Radio Bursts





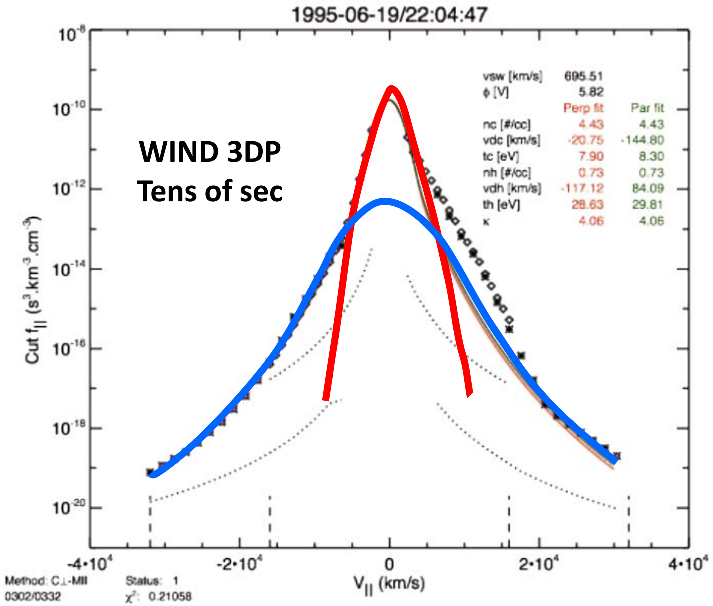
Electrostatic Langmuir waves → radio emission

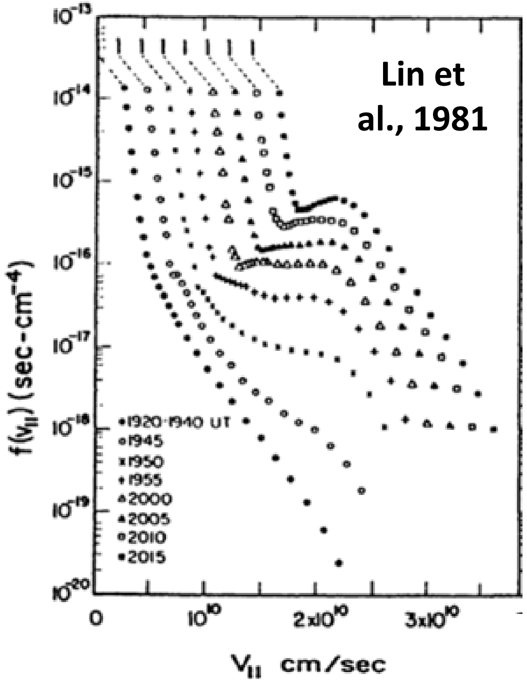
$$F_p(\mathrm{kHz}) \propto \sqrt{N_e(\mathrm{cm}^{-3})}$$

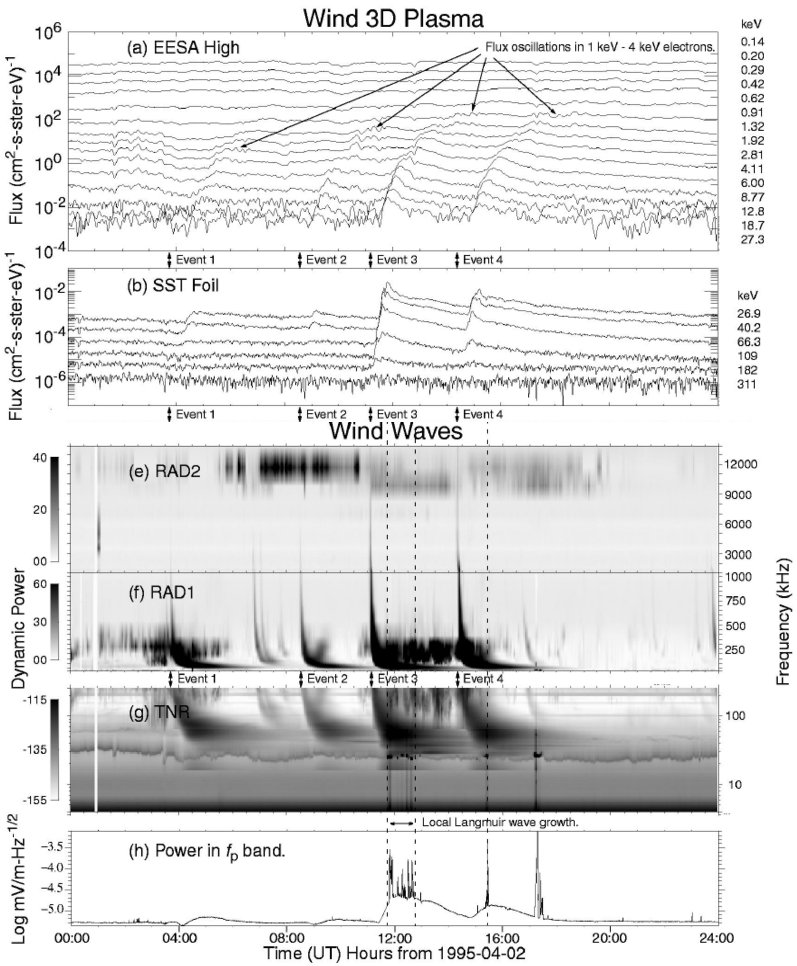
$$N_e \propto 1/R^2\ (\mathrm{au})$$

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

All necessary measurements will be available on Solar Orbiter



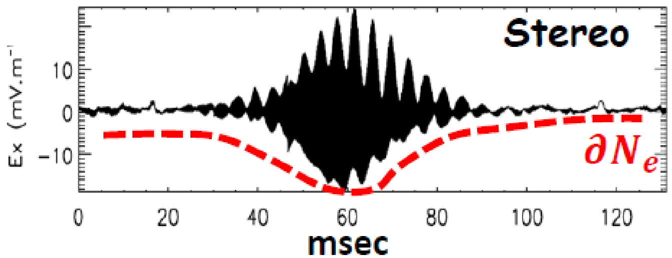




Adapted from [Ergun et al., 1998]

+ plasmas measurements

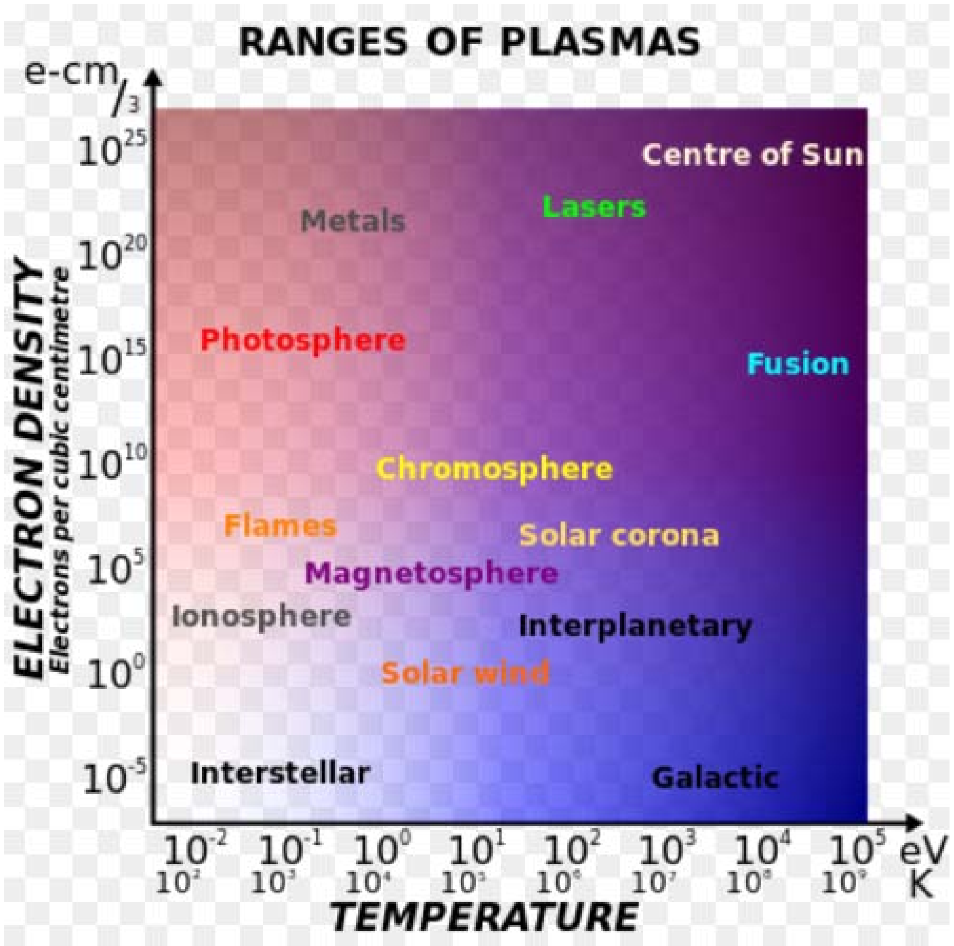
- Np, Tp, Vp (16Hz)
- High cadence Ne
- Bx, By, Bz DC & AC (up to the plasma frequency)

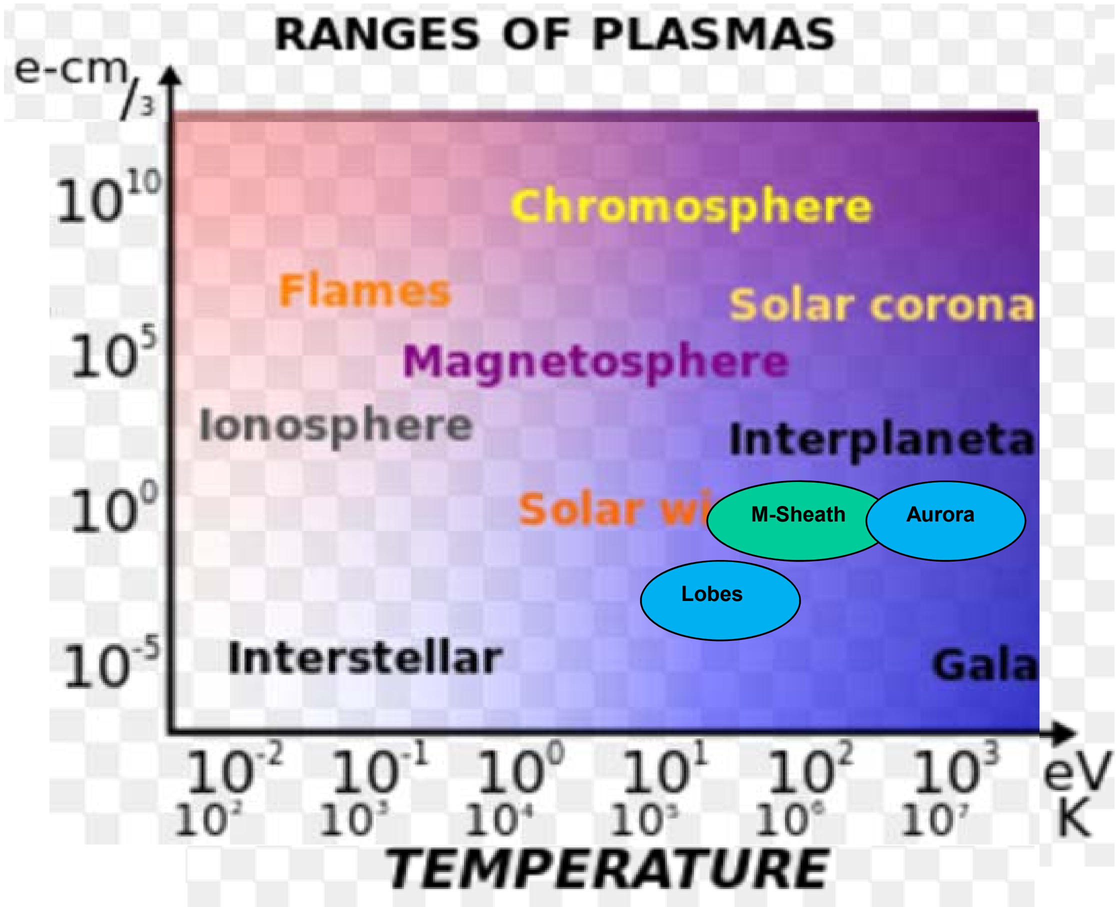


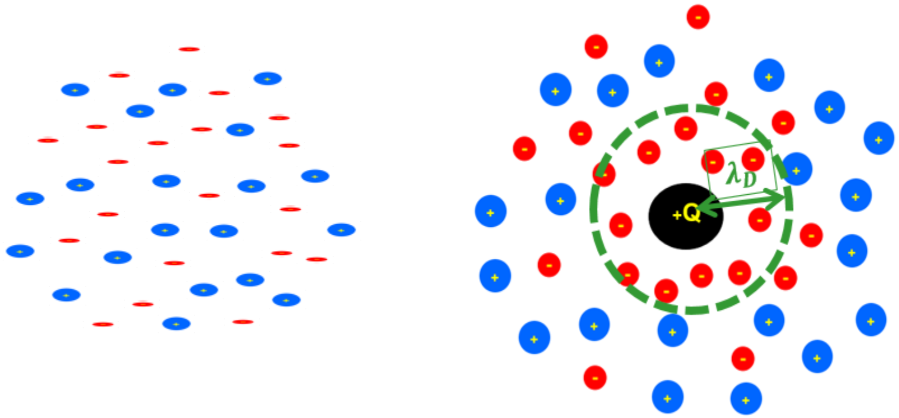
Outline

- ❑ **Particles measurements**
  - **Electrons**
  - **Ions & composition**
  - **Energetic particles**
- ❑ **Waves measurements**
  - **Magnetic DC & AC sensors**
  - **Measuring DC-LF electric fields**
  - **Measuring AC Electric Field: The Thermal Noise as an example**
- ❑ **Surprises, tricky data corrections and future challenges**

Astrophysical Plasmas accessibe to in-situ measurements







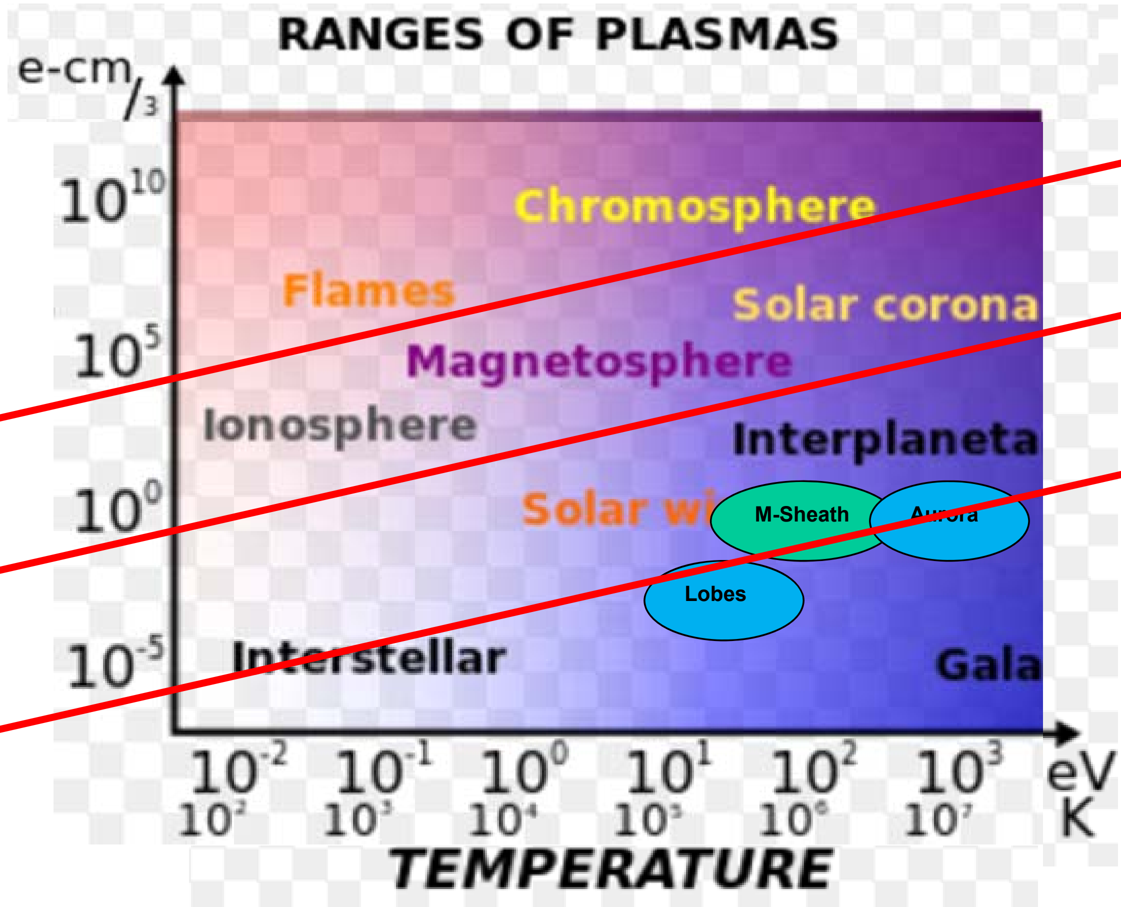
$$\Phi(r) = \frac{Q}{4\pi\varepsilon r}\, e^{-r/\lambda_D}$$

$$\lambda_D = \sqrt{\frac{\epsilon_0 kT}{ne^2}} \sim 69 \sqrt{\frac{T\ [\mathrm{K}]}{n\ [\mathrm{m}^{-3}]}}$$

$\lambda_D = 2\ 10^{-3}\mathrm{m}$

$\lambda_D = 0.7\ \mathrm{m}$

$\lambda_D = 218\ \mathrm{m}$

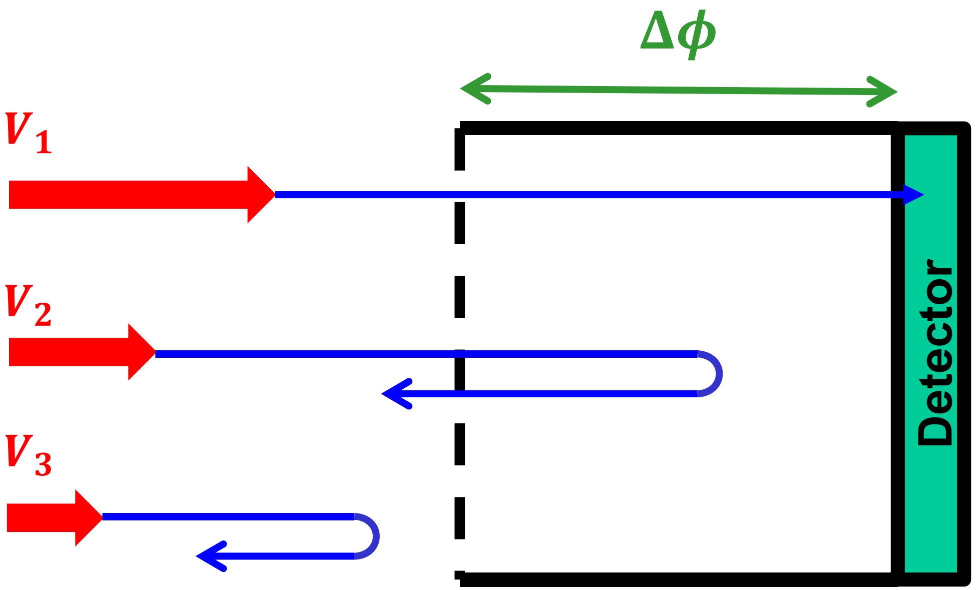


Particle Energy Distributions

A plasma particle is defined by

- a mass
- an electric charge
- a speed or kinetic energy

$$\frac{1}{2}mV(r)^2 + Ze\phi(r) = \frac{1}{2}mV_\infty^2$$



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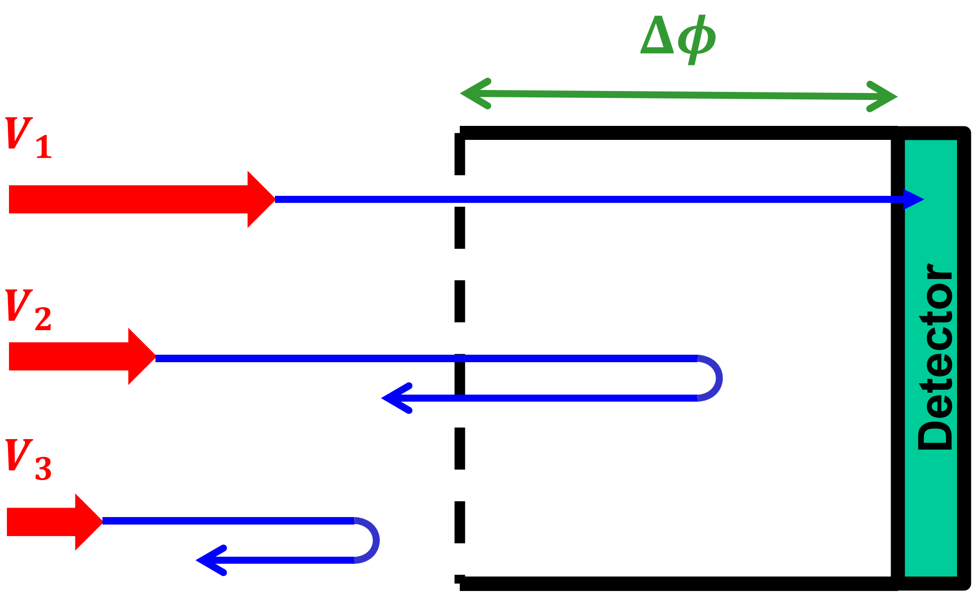
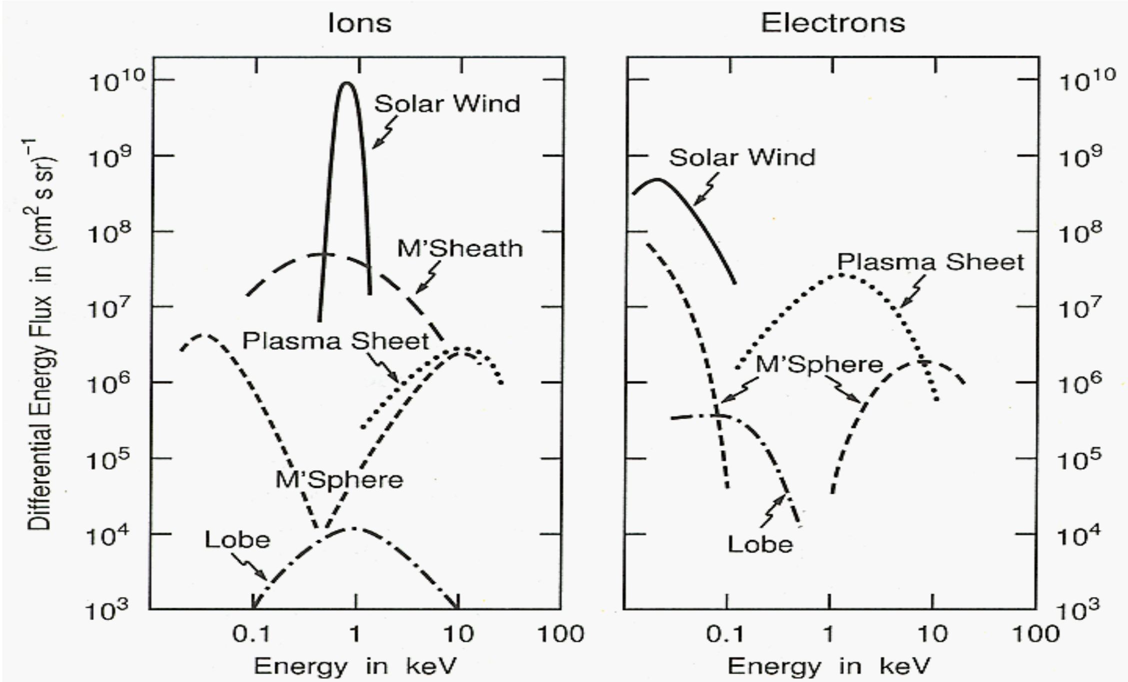
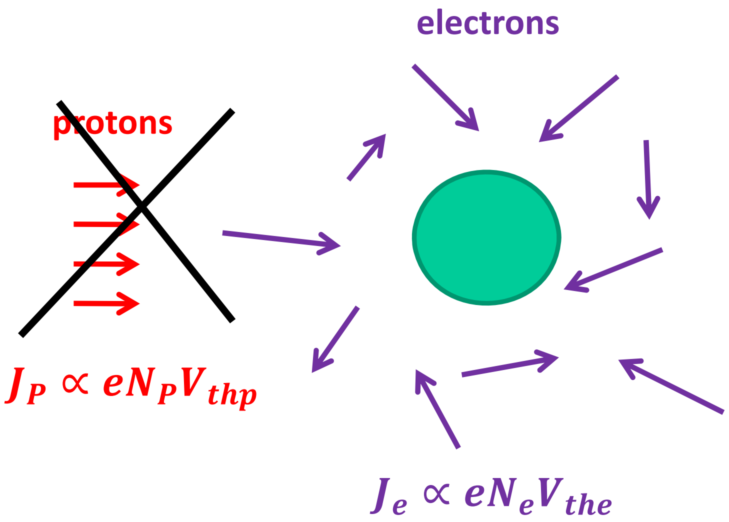




The broad range of energies and fluxes require different instruments

← Faraday cup principle

Electric charging in space : an example in the Solar Wind



For a plasma in quasi-equilibrium with $T_e \sim T_i$

- $V_{the} = \sqrt{\frac{2kT_e}{m_e}} \gg V_{thi} = \sqrt{\frac{2kT_i}{m_i}}$
- **In the Solar Wind $T_e \sim T_p \sim 10^5 K$**

  $\rightarrow V_{the} \sim 1740 \text{ km/s} \gg V_{thp} \sim 40 \text{ km/s}$

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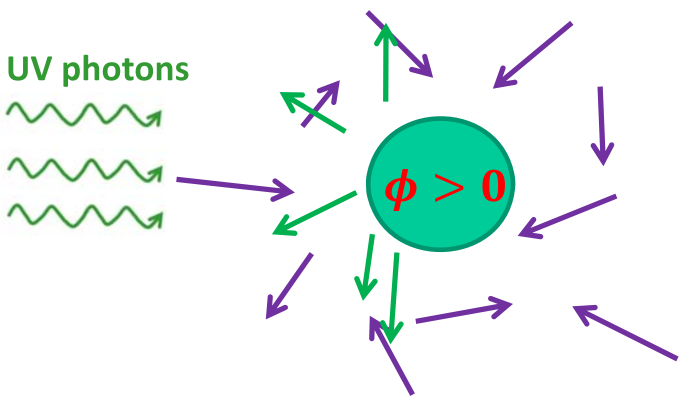

What are the average electron velocity V_e^* and density N_e^* at the surface of the Sphere?

$J_e = eN_e^* V_e^*$ can be obtained applying Louville Theorem

$$\frac{1}{2} m_e v'^2 + Ze\phi = \frac{1}{2} m_e v'^2$$

$$v'_{\min} = \sqrt{2e\phi/m_e} \sim V_{the}/\sqrt{2}$$

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$$V_e^* = \frac{4\pi}{N_e^*} \int_{v_\phi}^{\infty} v' f'(v') v'^2 dv'$$

$$J_e = \frac{2e}{\sqrt{\pi}} N_e V_{the} \left(1 + \frac{e\phi}{kT_e}\right)$$

And the photoelectron current ?

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

- Depends on the photo-electric properties of the material

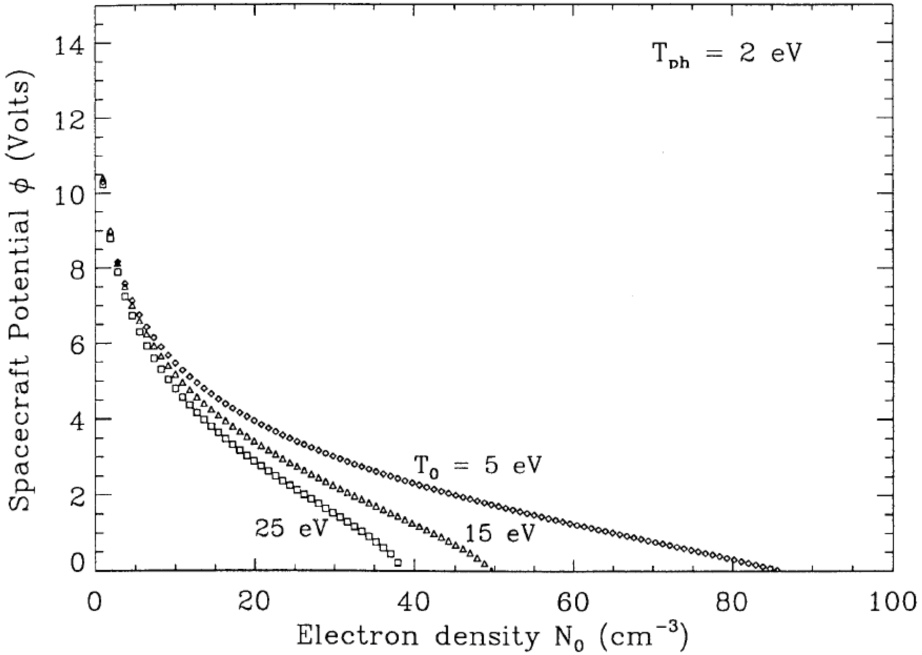
$- \; T_{ph} \sim 2 \text{ to } 3 \text{ eV and } J_{ph} \sim \text{few } \mu\text{A/m}^2$

Finally the potential is obtained by assuming $J_e(\phi) = J_{ph}(\phi)$

$$\frac{e\phi}{k_B T_{ph}} - \ln\left[\frac{1 + \frac{e\phi}{k_B T_{ph}}}{1 + \frac{e\phi}{k_B T_e}} \frac{K J_{ph0}}{N_e \sqrt{T_e}}\right] = 0$$

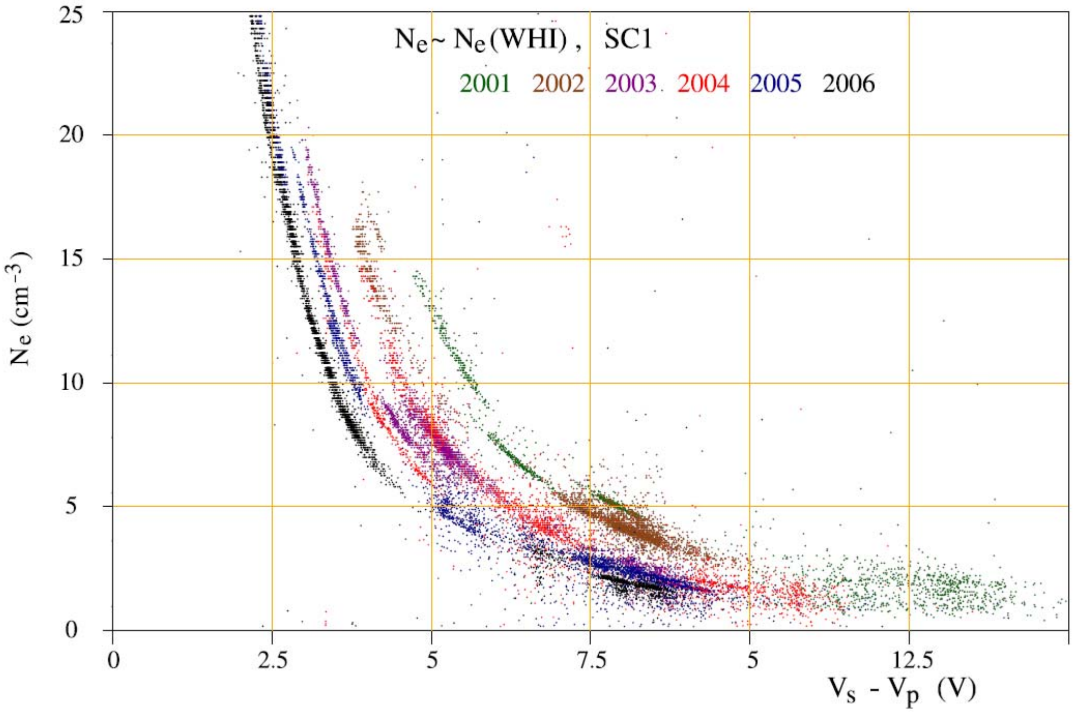
To be fully exhaustive one shall include the secondary electrons currents (important closer to the Sun)

$$\frac{e\phi}{k_B T_{ph}} - \ln\left[\frac{1+\frac{e\phi}{k_B T_{ph}}}{1+\frac{e\phi}{k_B T_e}} \frac{K J_{ph0}}{N_e\sqrt{T_e}}\right] = 0$$



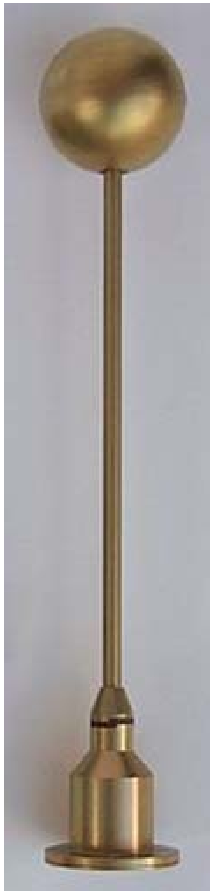
Salem et al., 2001

Cluster data

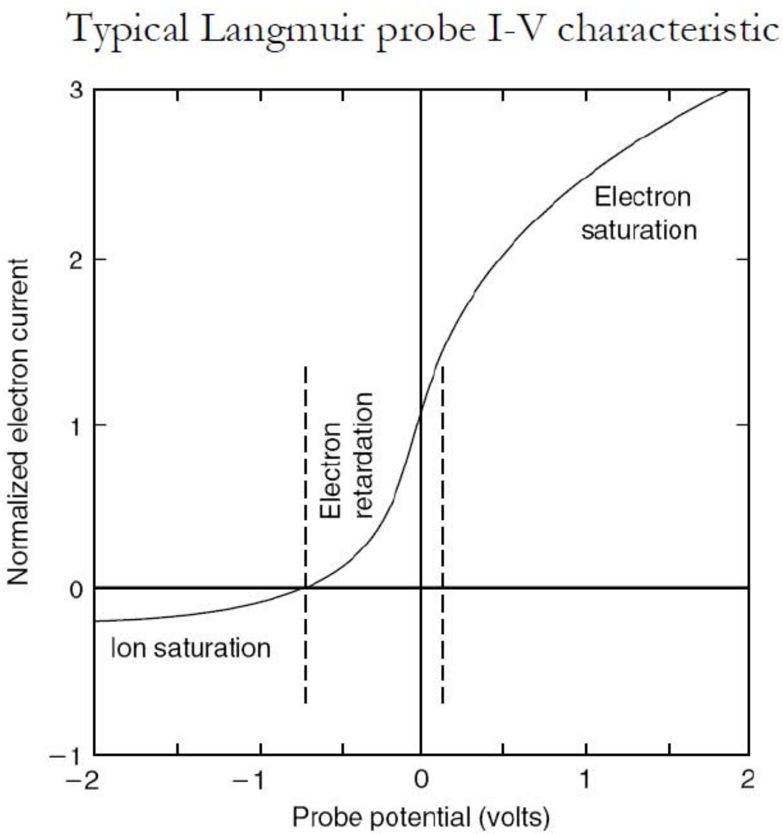


Pedersen et al., 2008

Electron diagnostic in cold plasmas – The Langmuir Probe



Sweeping *V* and measuring *I*



Maksimovic : Space plasmas measurement techniques

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$$V_{te} = \sqrt{\frac{2kT_e}{m_e}} \gg V_{ti} = \sqrt{\frac{2kT_i}{m_e}}$$

- **in the retardation region**

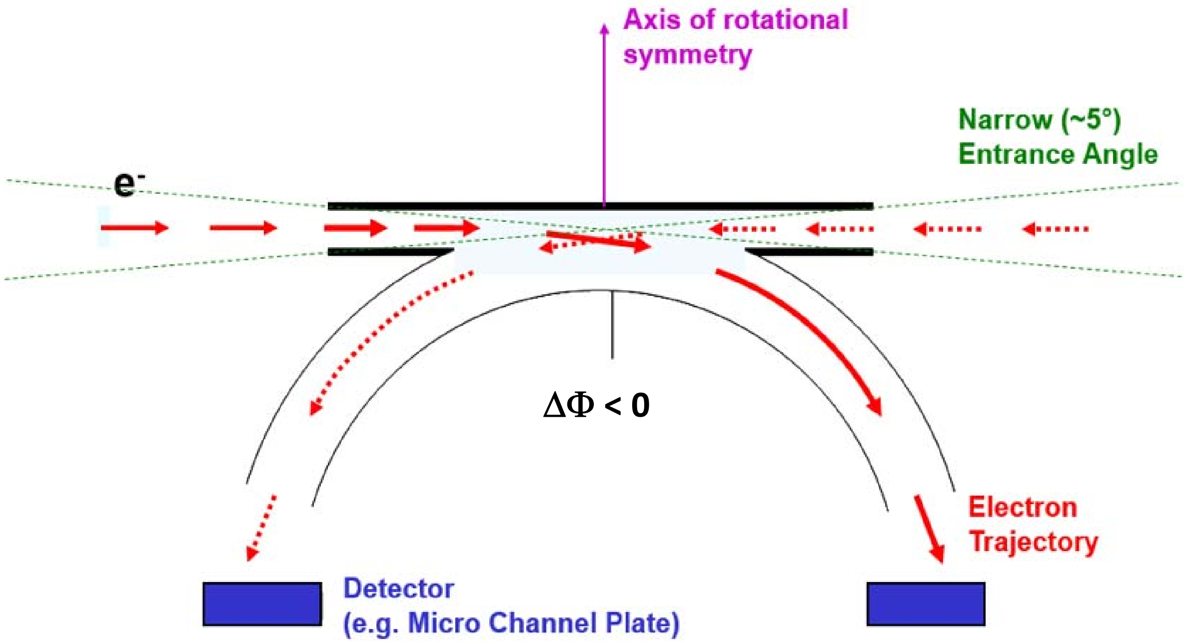
$$I_e \propto N_e e V_{the} e^{-eV/k_B T_e}$$

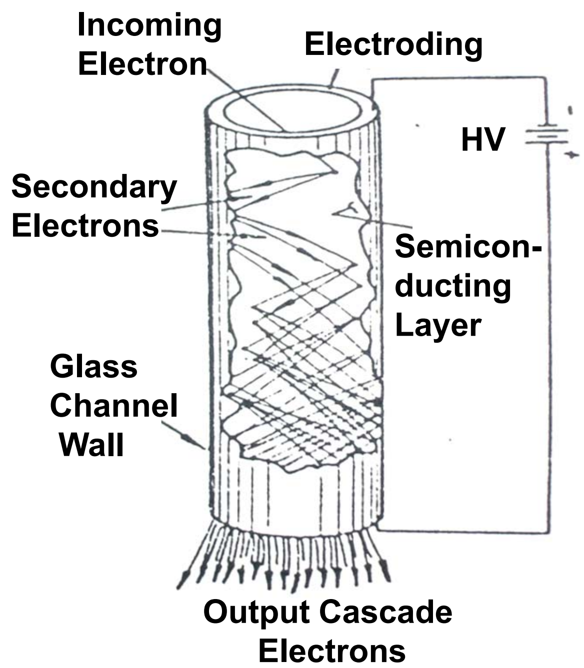
- **In the saturation region**

$$I_e \propto N_e e V_{the} \left(1 + \frac{eV}{k_B T_e}\right)^{1/2}$$

Segmented langmuir probe in order to measure the ion bulk speed

Measuring the full 3D VDF
'Top Hat' detectors – Principles of Operation





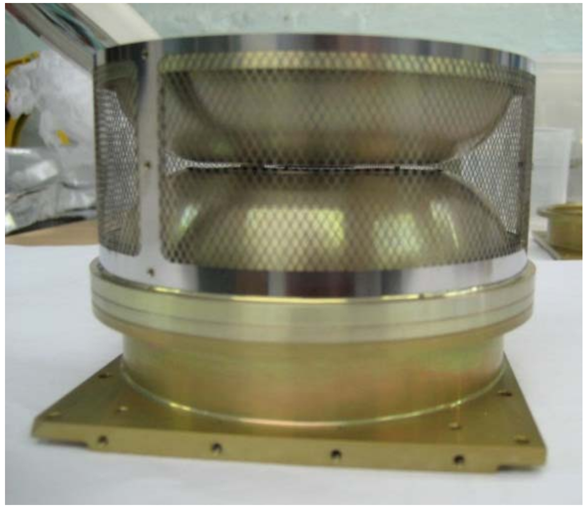
Hollow cylinders

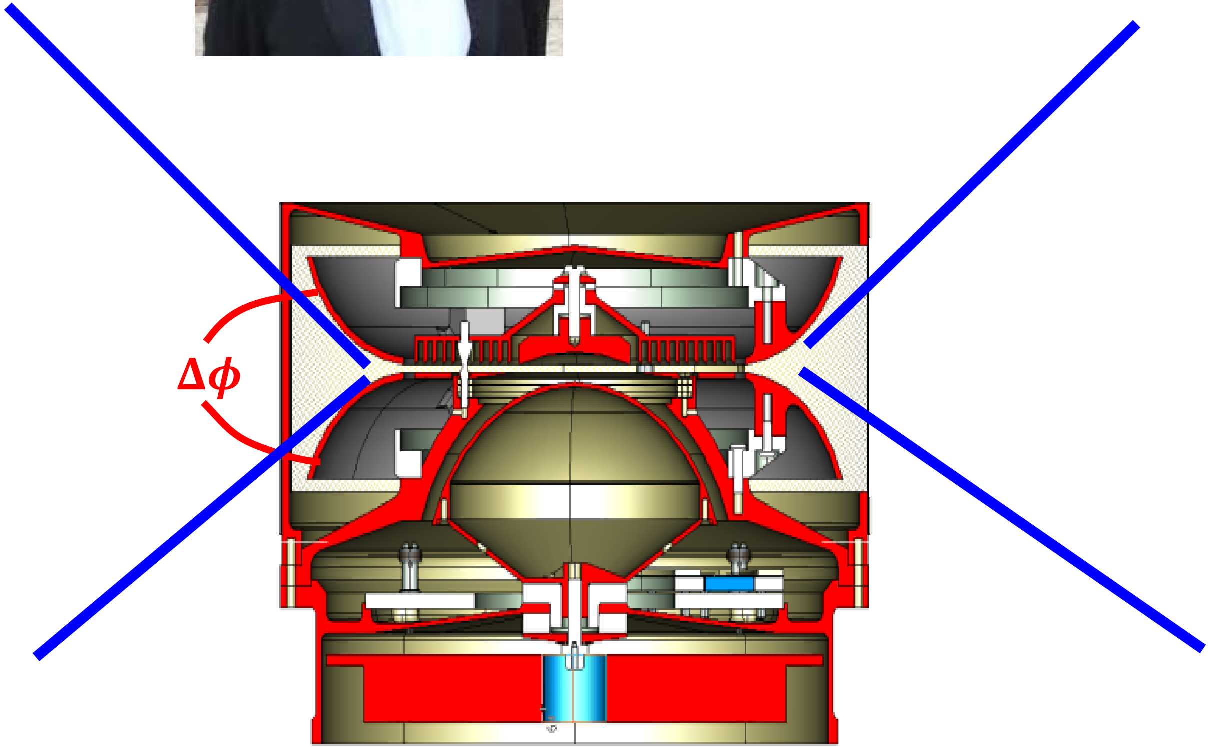
A full 3D Velocity Distribution function is obtained by

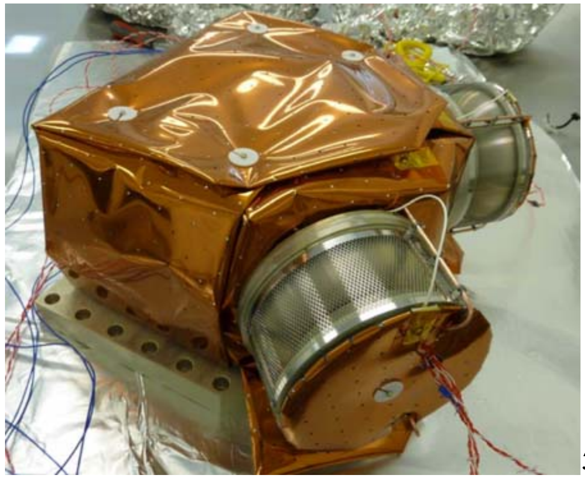
- Scaning the energy ($\Delta\Phi$)
- Using the Top hat axis of symmetry and the spacecraft spin

The Solar Orbiter EAS instrument

Christopher « Chris » Owen,
Mullard Space Sciences Lab., UK

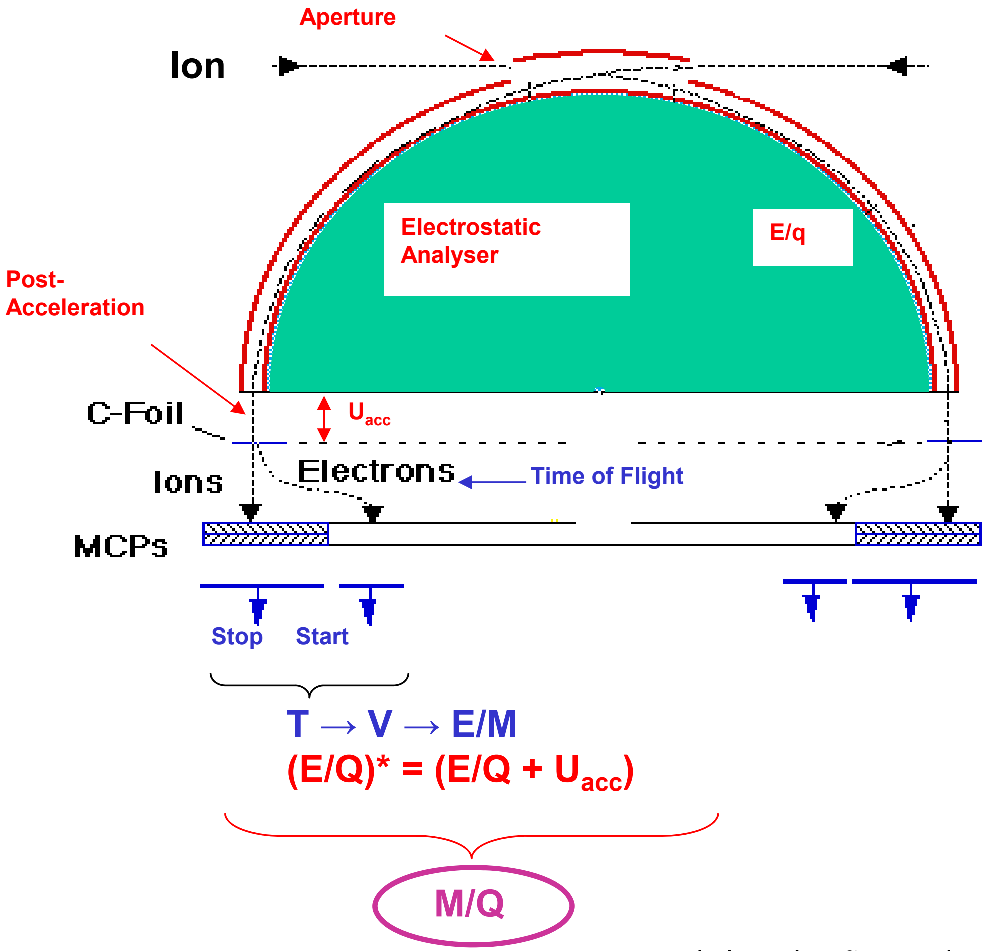






Particle Composition :

Add a time-of-flight detector beneath the top hat analyser:



- Top hat section makes E/q selection as before : $E/Ze \propto \Delta\Phi$
- Ions are then accelerated by an electric field into a thin carbon foil
- On passing through the foil the ion knocks out an electron
- The difference in travel time to the detector between the ion and electron can be used to determine the ions velocity, and hence E/M for the ion;
- Combining the two measurements gives M/Q

Particle Composition :

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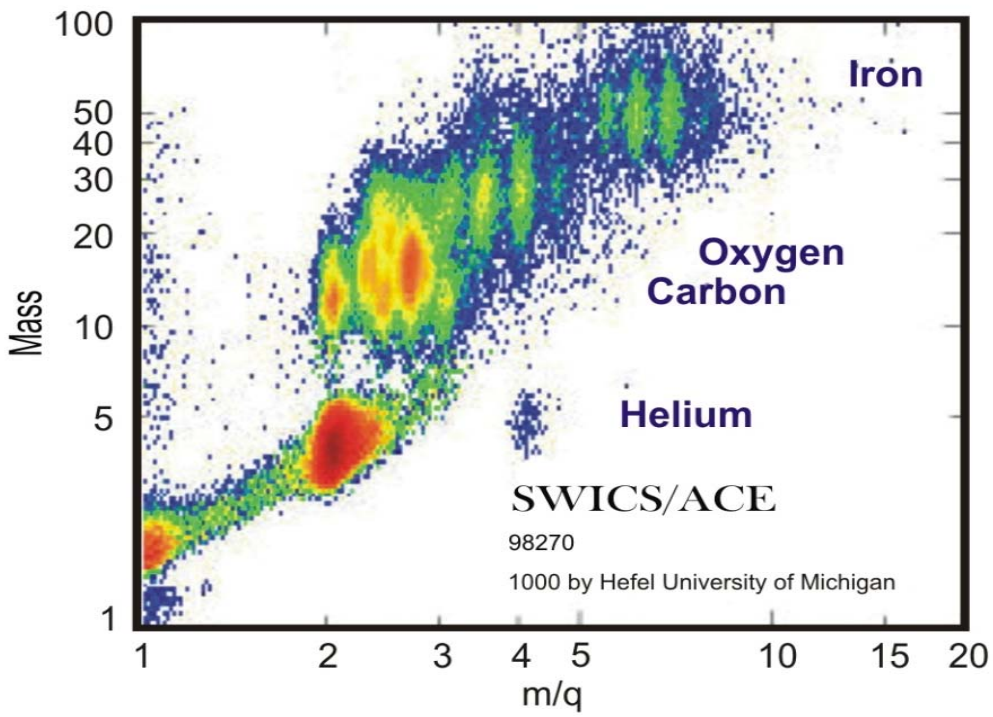
Composition Plot – colours represent relative abundance of ions



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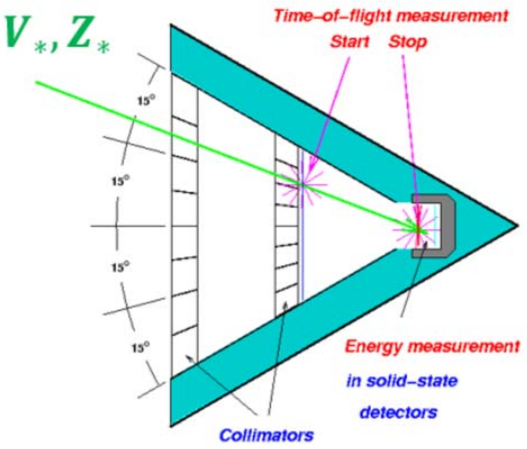
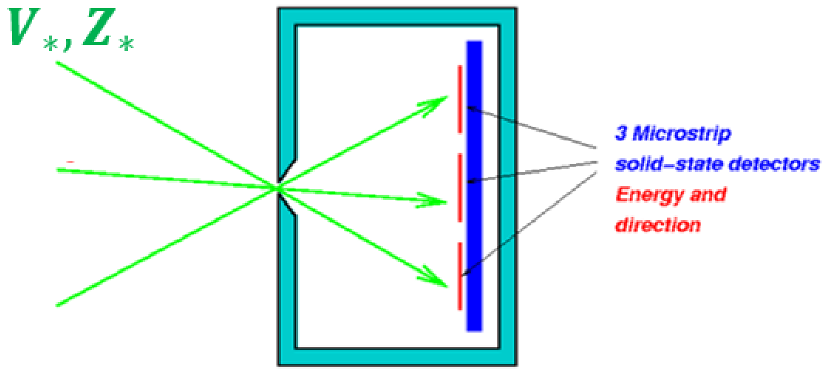
High-Energy Particle Telescopes





Robert "Bob" Wimmer-Schweingruber
University of Kiel, Germany

Energy loss Bethe-Block equation

Javier Rodríguez-Pacheco
University of Alcala, Spain

$$\frac{dE}{dx} = -\frac{Z_*^2 e^4 n_e}{4\pi\varepsilon_0^2 V_*^2 m_e}\left[\ln\left(\frac{2eV_*^2}{\langle E_B\rangle}\right) - \ln(1-\beta^2) - \beta^2\right] \text{with } \beta = \frac{V_*}{c}$$

$\langle E_B \rangle$ is the « first energy ionization » of the target

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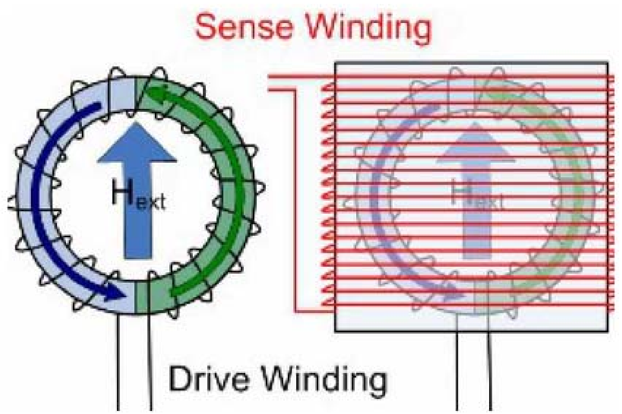
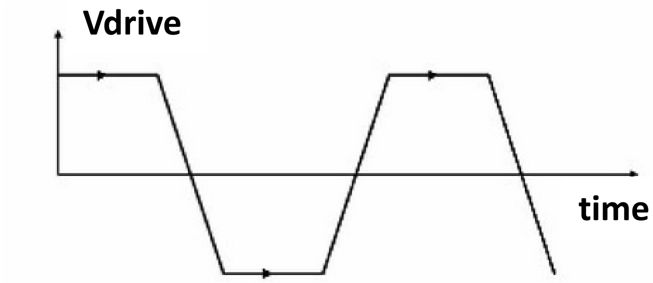
Measuring DC/LF Magnetic Fields in space

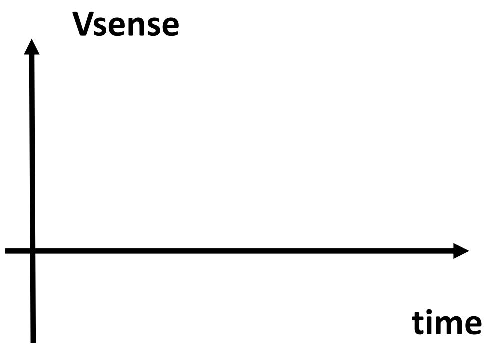
Flux Gate Magnetometer

Nobody knows... best theory is that it is little pixies inside the cores.

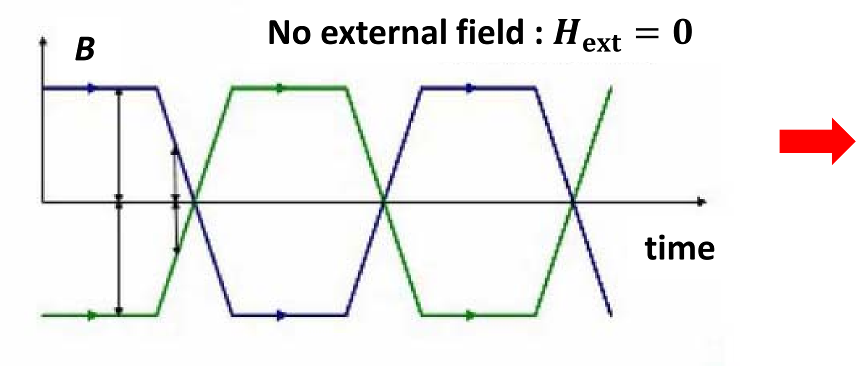
Timothy "Tim" Horbury
Imperial College, UK







ring cores of a highly magnetically permeable alloy around which are wrapped two coil windings



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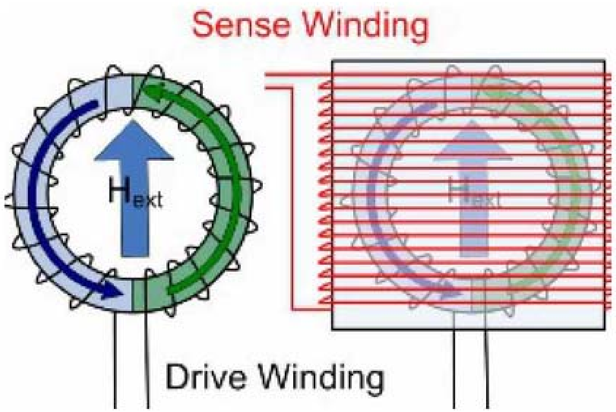

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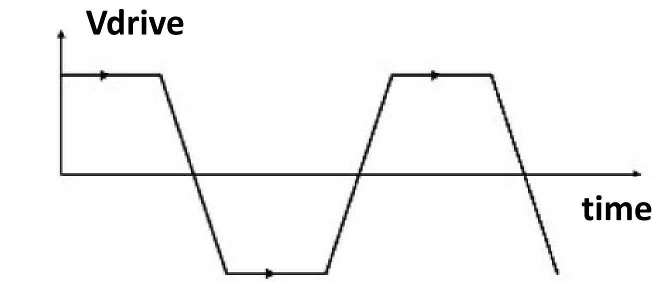
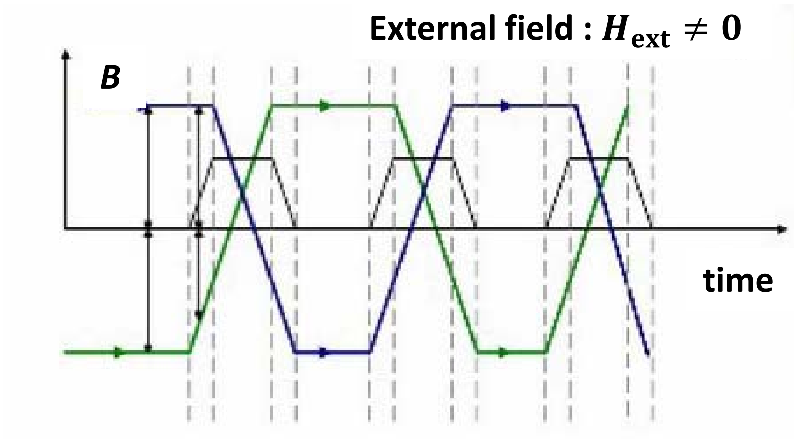
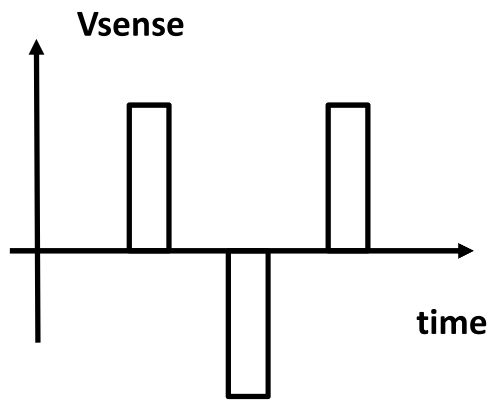






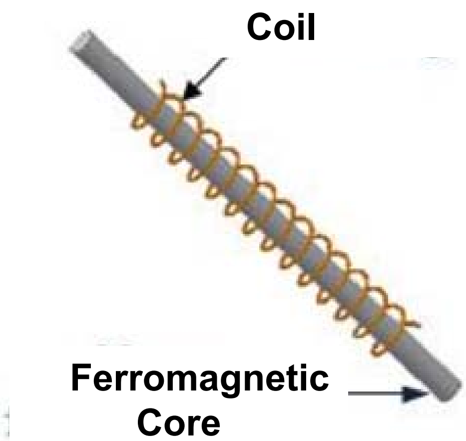
Measuring AC Magnetic Fields in space

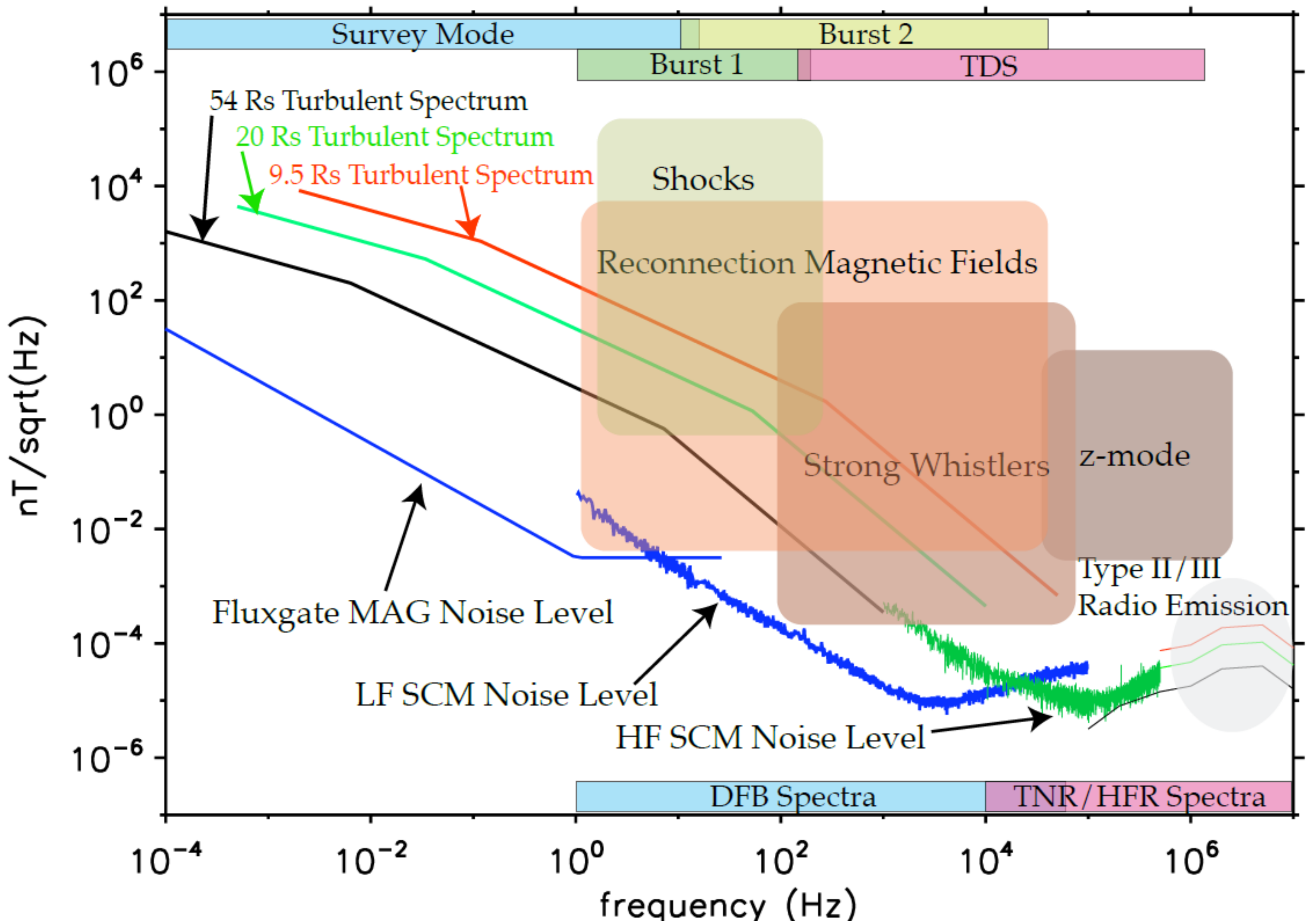
Vladimir "Volodya" Krasnoselskikh
LPC2E Orléans, France

The Search Coil Magnetometer (SCM) is an inductive sensor is based on Faraday's law of induction.

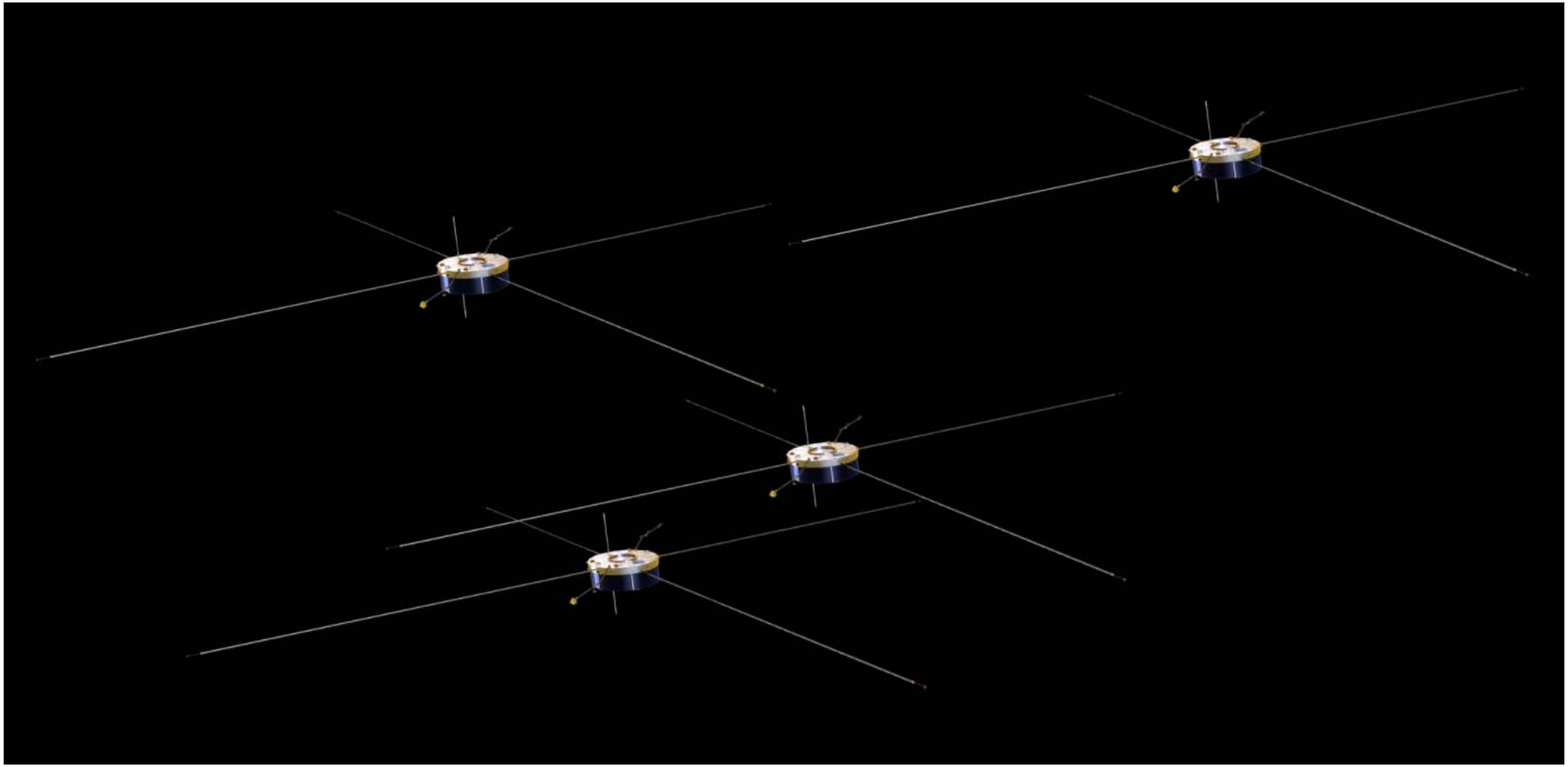
$$\mathcal{E} = -N\frac{d\phi}{dt} = -NS\frac{dB}{dt}$$

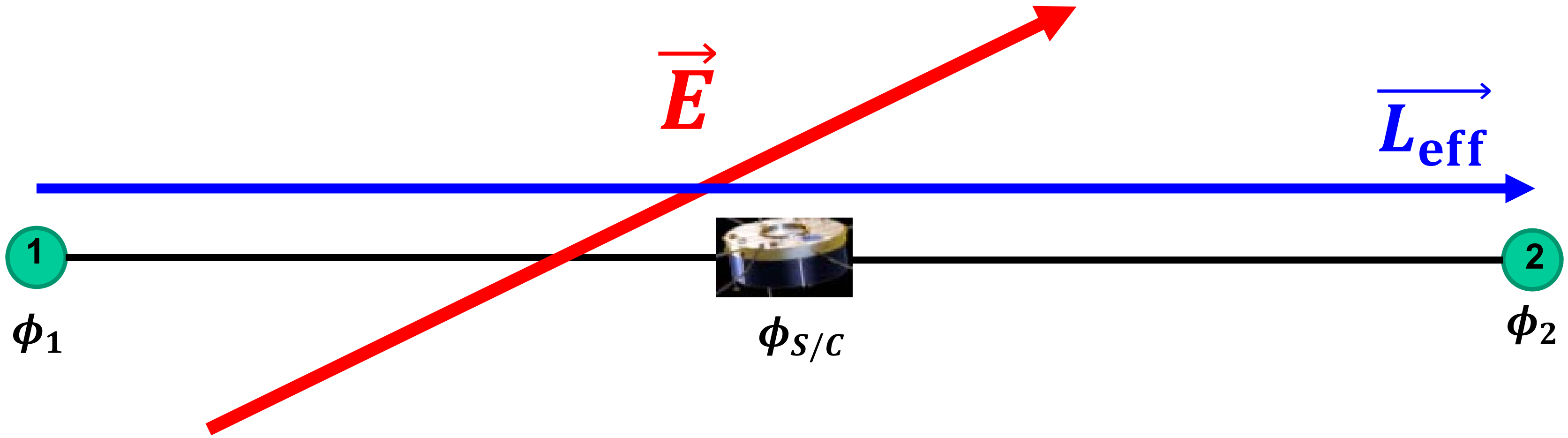
SCMs On Solar Orbiter and Solar Probe Plus




Survey Mode
Burst 2
Burst 1
TDS
54 Rs Turbulent Spectrum
20 Rs Turbulent Spectrum
9.5 Rs Turbulent Spectrum
Shocks
Reconnection Magnetic Fields
Strong Whistlers
z-mode
Type II/III
Radio Emission
Fluxgate MAG Noise Level
LF SCM Noise Level
HF SCM Noise Level
DFB Spectra
TNR/HFR Spectra
nT/sqrt(Hz)
frequency (Hz)
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}

Measuring DC/LF Electric Field in space

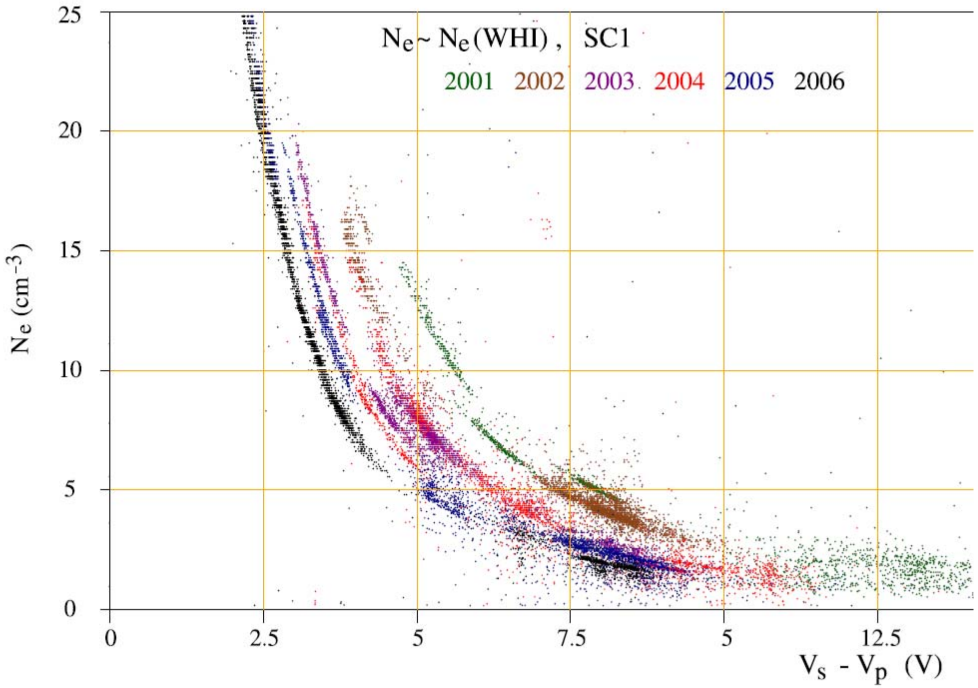


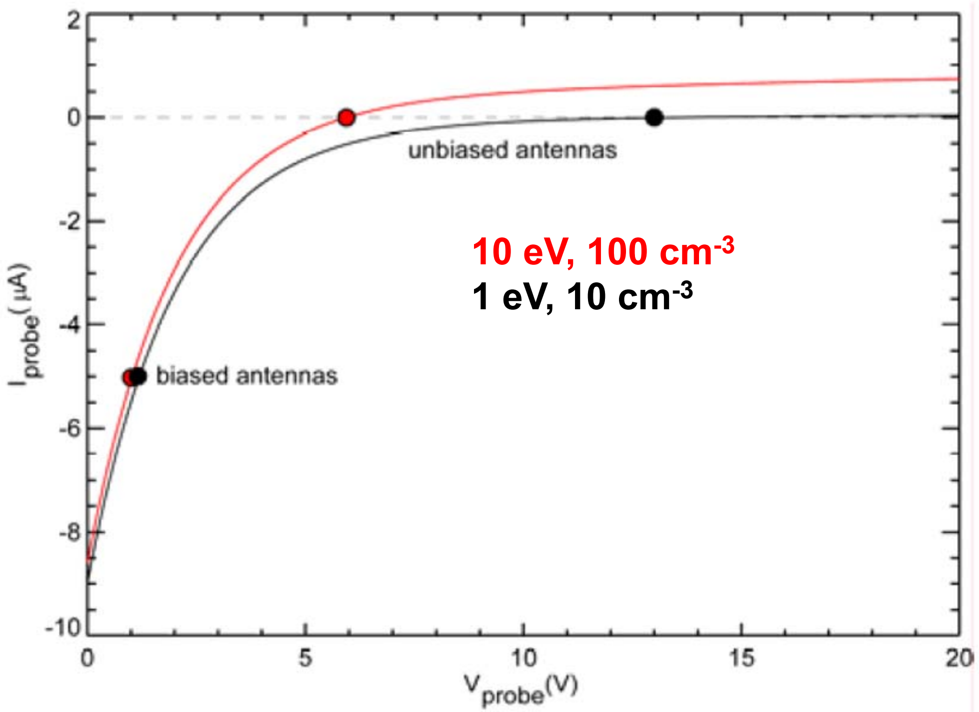


- If the two probes are equally illuminated then $\phi_1 = \phi_2$ and not necessarily equal to $\phi_{S/C}$
- Actually we do not measure ϕ_1 and ϕ_2 but rather $V_1 = \phi_{S/C}$ - ϕ_1 and $V_2 = \phi_{S/C}$- ϕ_2 where we use the S/C as the potential ground
- If the ground is the same for the two probes then $V_1 - V_2 = \phi_2$- $\phi_1 = 0$

- If an external $\vec{E}$ is applied then $\phi_1 \neq \phi_2$
- Actually $\phi_2 - \phi_1 = \delta_{\phi_E} = \vec{E} \cdot \overrightarrow{L_{\text{eff}}}$
- So if the experimental setup is appropriate then :
  - ➢ $V_1 - V_2 = \delta_{\phi_E} = \vec{E} \cdot \overrightarrow{L_{\text{eff}}}$!

But life is not so simple because typical electric fields are tiny (a few mV/m) !



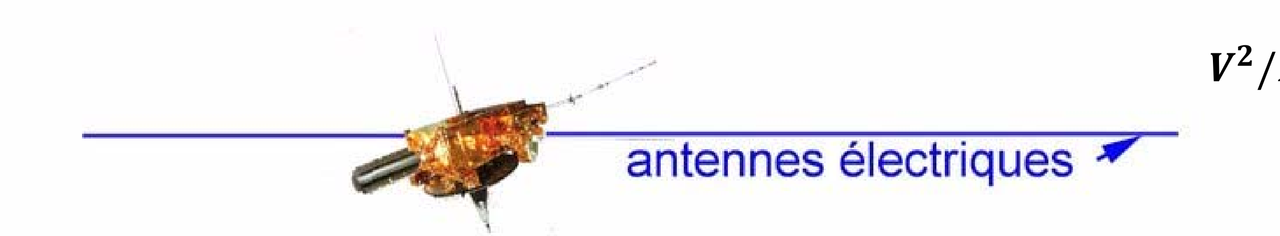


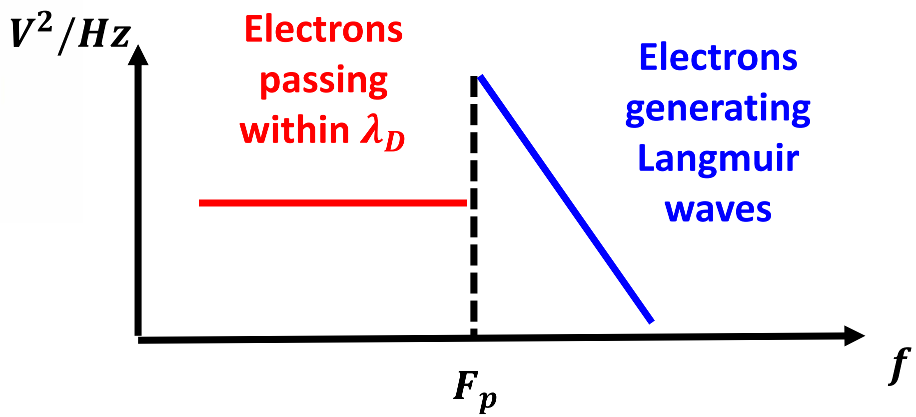
Adding a Biasing current on the probe will solve the problem of the density fluctuations in the medium

$$J_e(\phi) = J_{ph}(\phi) + J_{\mathrm{BIAS}}$$

- **So if the experimental setup is appropriate and if <u>one injects a BIAS current in the probes</u> then**
- $V_1 - V_2 = \delta_{\phi_E} = \vec{E} \cdot \overrightarrow{L_{\mathrm{eff}}}$ **!**
- $\frac{V_1+V_2}{2} = \phi_{S/C} - \cancel{\phi_2} + \cancel{\frac{\delta_{\phi_E}}{2}} \sim \phi_{S/C}$

Measuring AC Electric Field: The Thermal Noise as an example





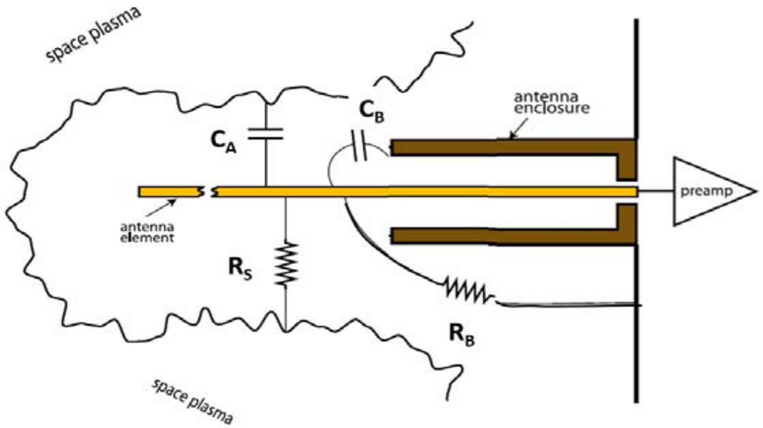
In drifting plasma, spectral density at the antenna ports:

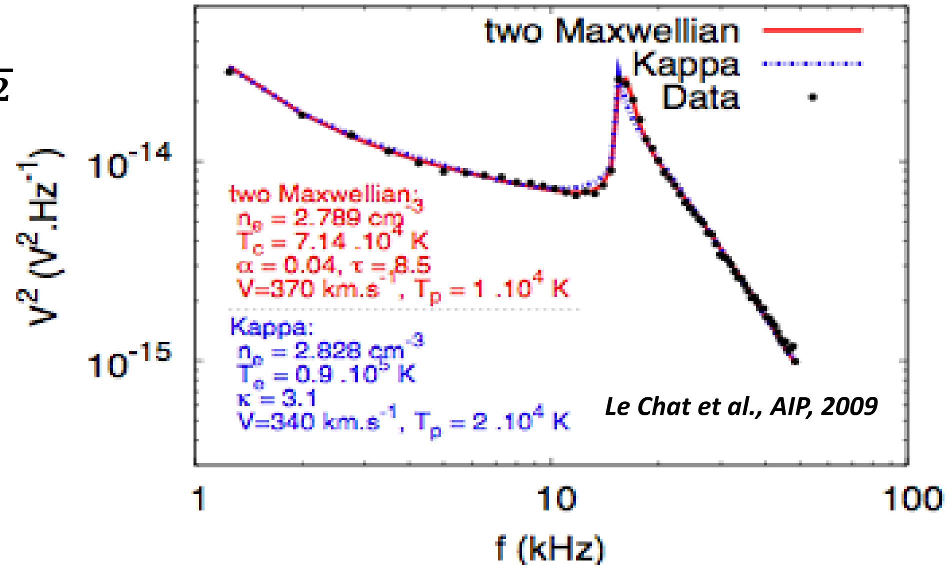
$$V_\omega^2 = \frac{2}{(2\pi)^3}\int d^3k \left|\frac{\mathbf{k.J}}{k}\right|^2 E^2(\mathbf{k},\omega-\mathbf{k.V})$$

antenna plasma

Resistive $G = \frac{1}{(1+R_S/R_B)^2}$

$$V_R^2(\omega) = \frac{V_\omega^2}{(1+C_B/C_A)^2}$$





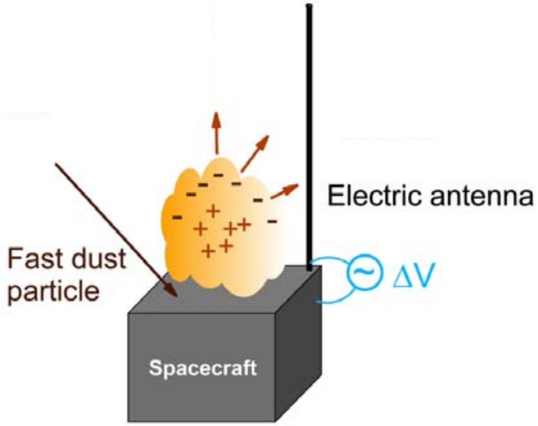
Le Chat et al., AIP, 2009

Outline

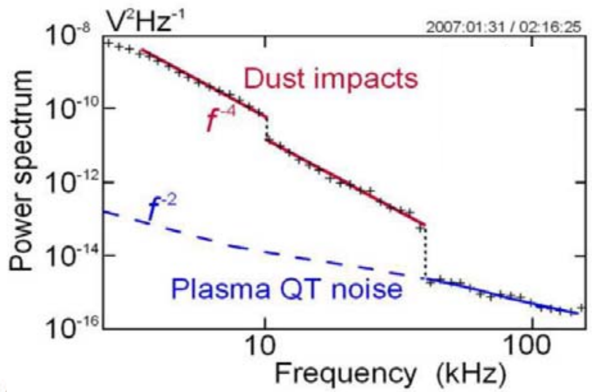
- Particles measurements
  - Electrons
  - Ions & composition
  - Energetic particles
- Waves measurements
  - Magnetic DC & AC sensors
  - Measuring DC-LF electric fields
  - Measuring AC Electric Field: The Thermal Noise as an example
- **Surprises, tricky data corrections and future challenges**

Surprises : when an instrument allow unexpected observations

Nanodusts with STEREO



Spectral domain

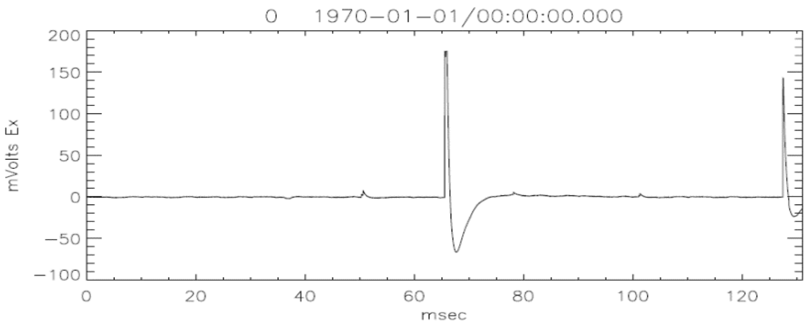


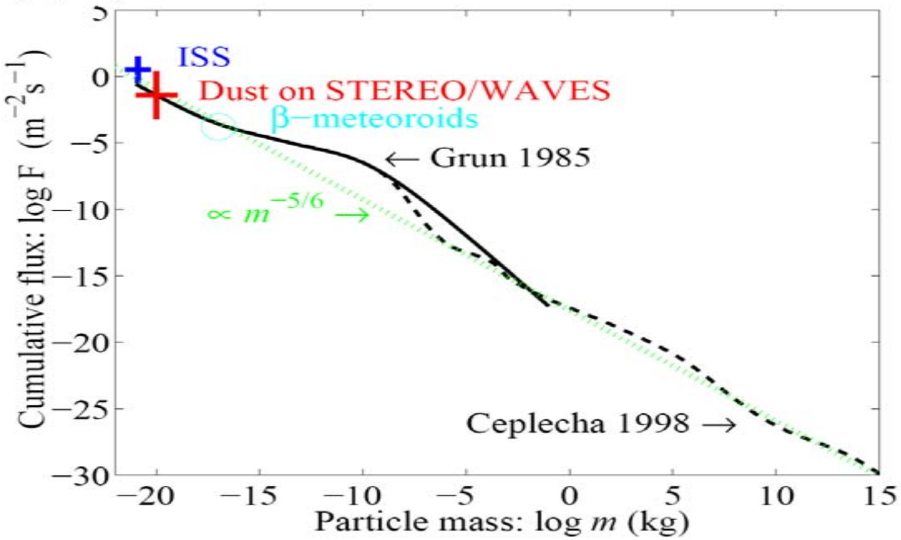
→A nanoparticle @ 300 km/s **~** *a grain of mass 10^4 greater @ 20 km/s*

Picked-up by the VXB field

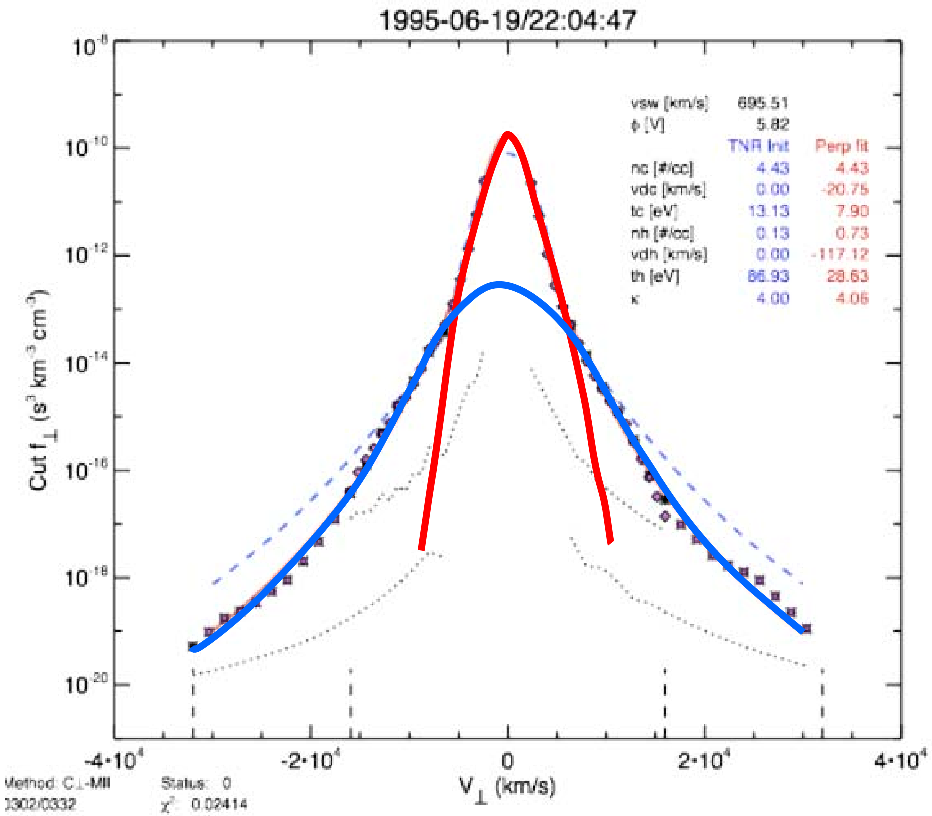
Released charge : $Q \simeq 0.7 m^{1.02} v^{3.48}$

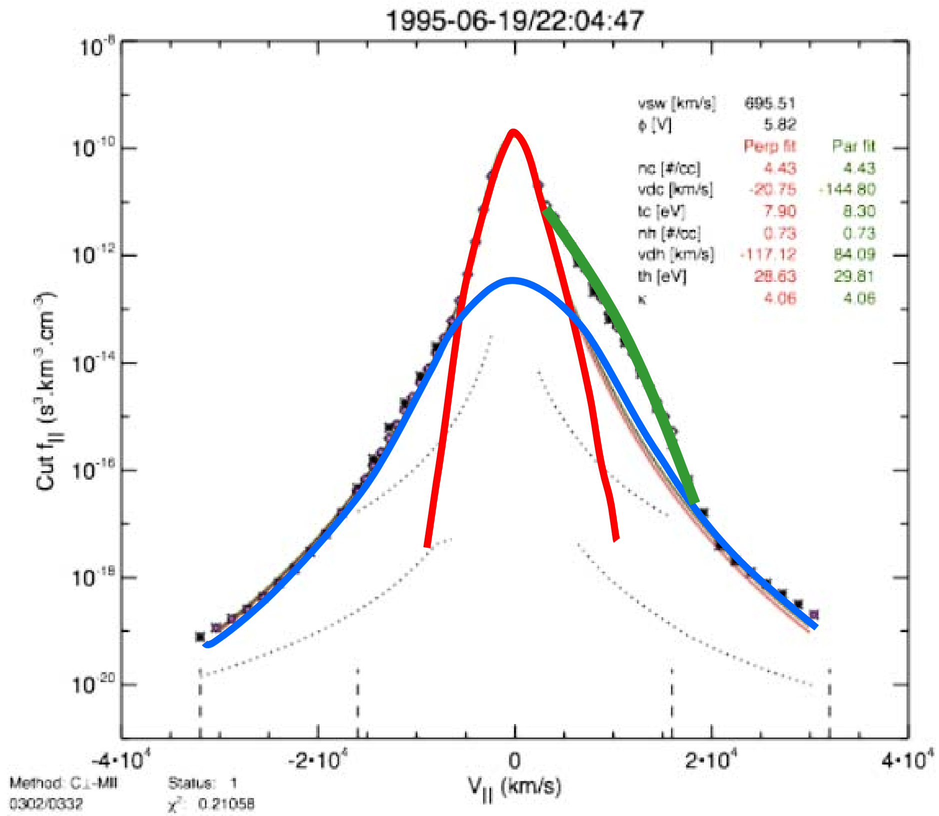
Induced voltage pulse on S/C of capacitance C : $\delta V \sim -Q/C$



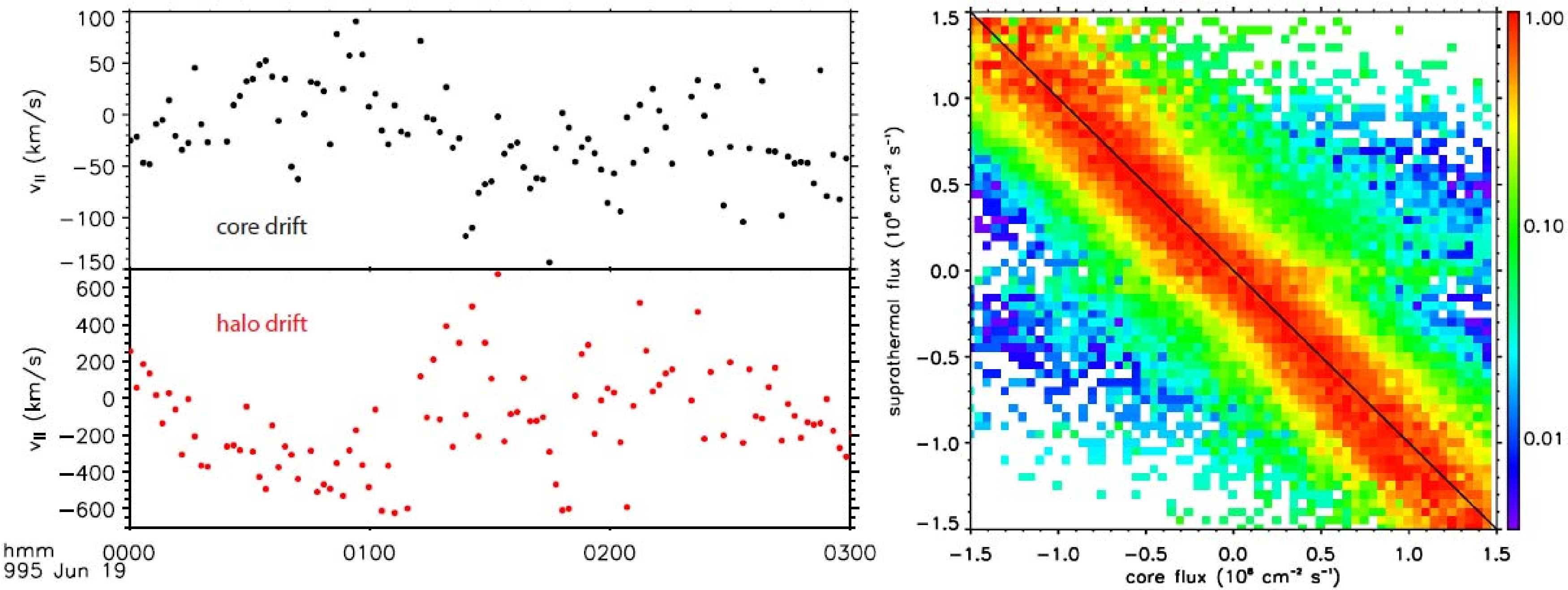


Tricky data corrections techniques



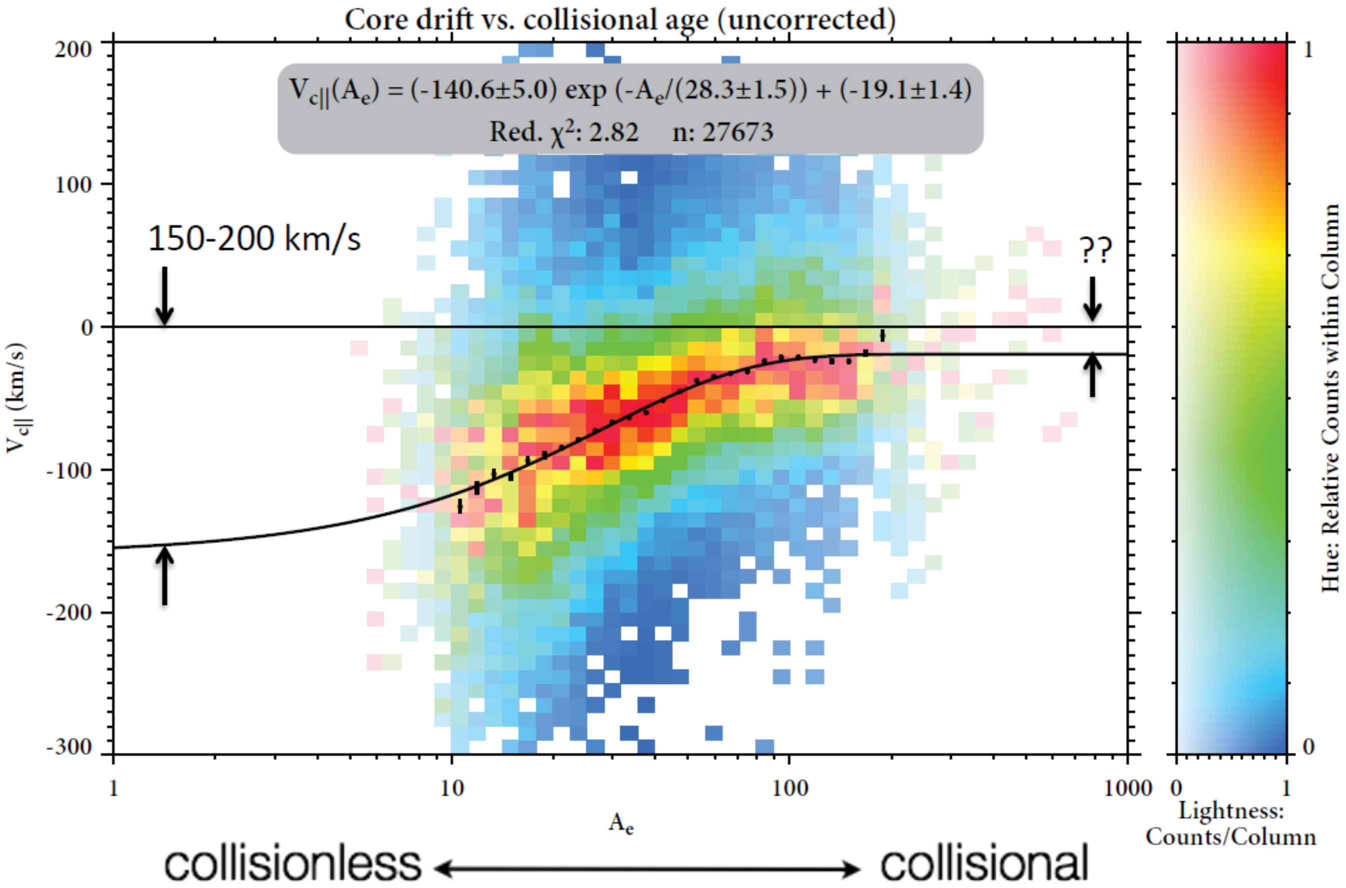


Current balance in the proton frame

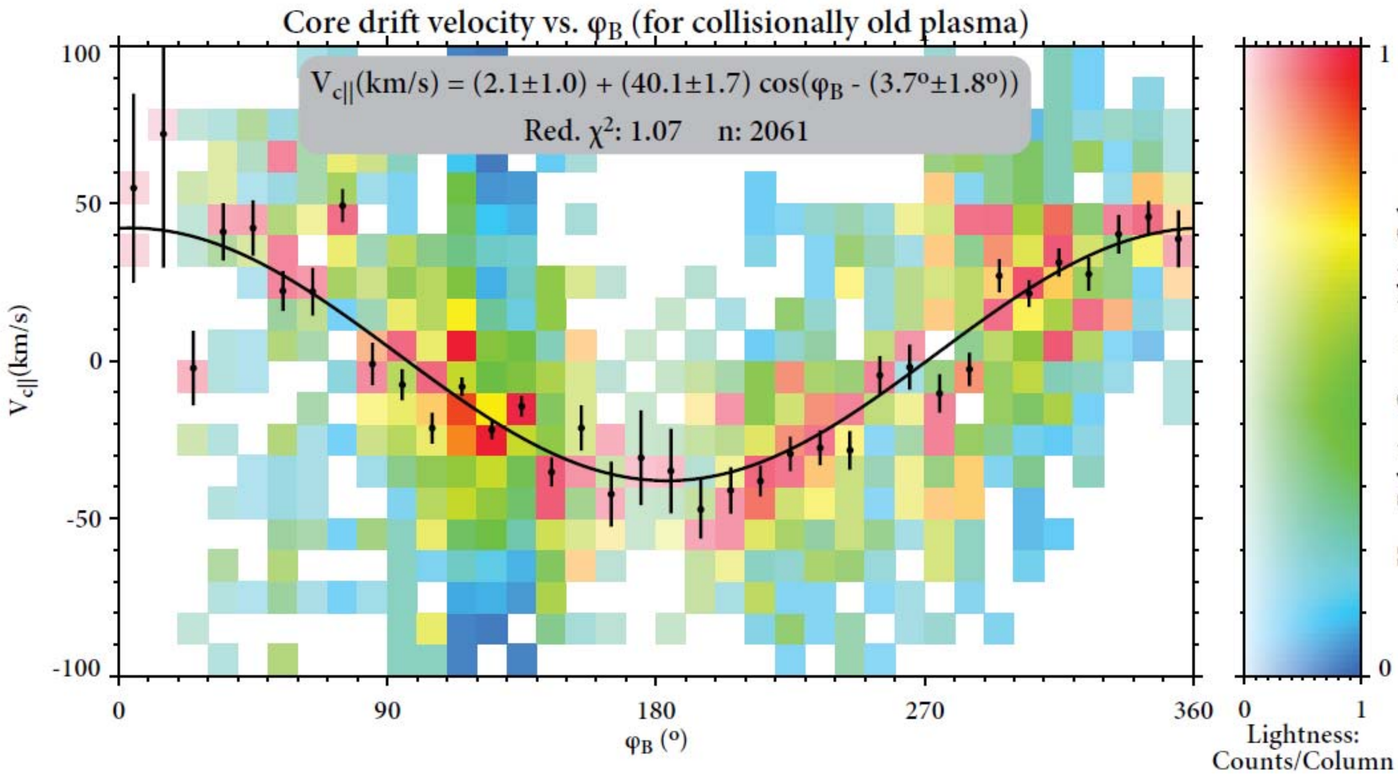


In the charge-center (~cm) frame, we expect zero net current: $n_c\, v_c + n_h\, v_h + n_s\, v_s = 0$, which seems to be so...

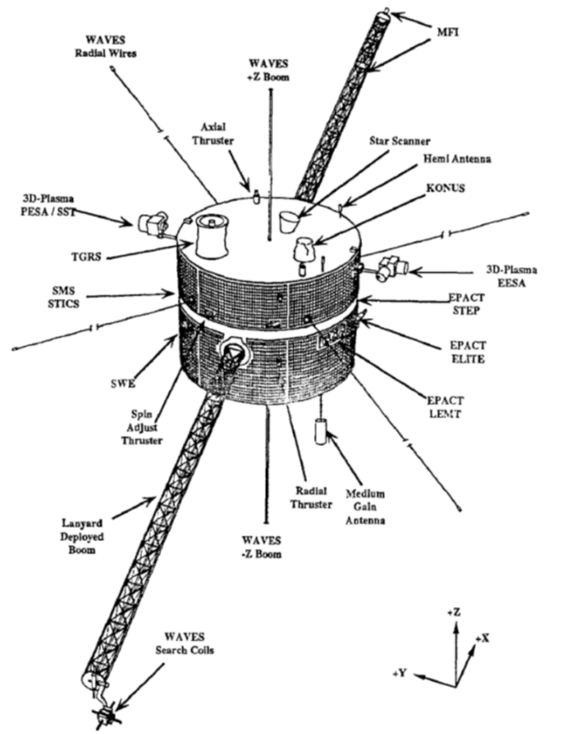
Core electron-proton (||) drift



Sunward drift in collisional regime



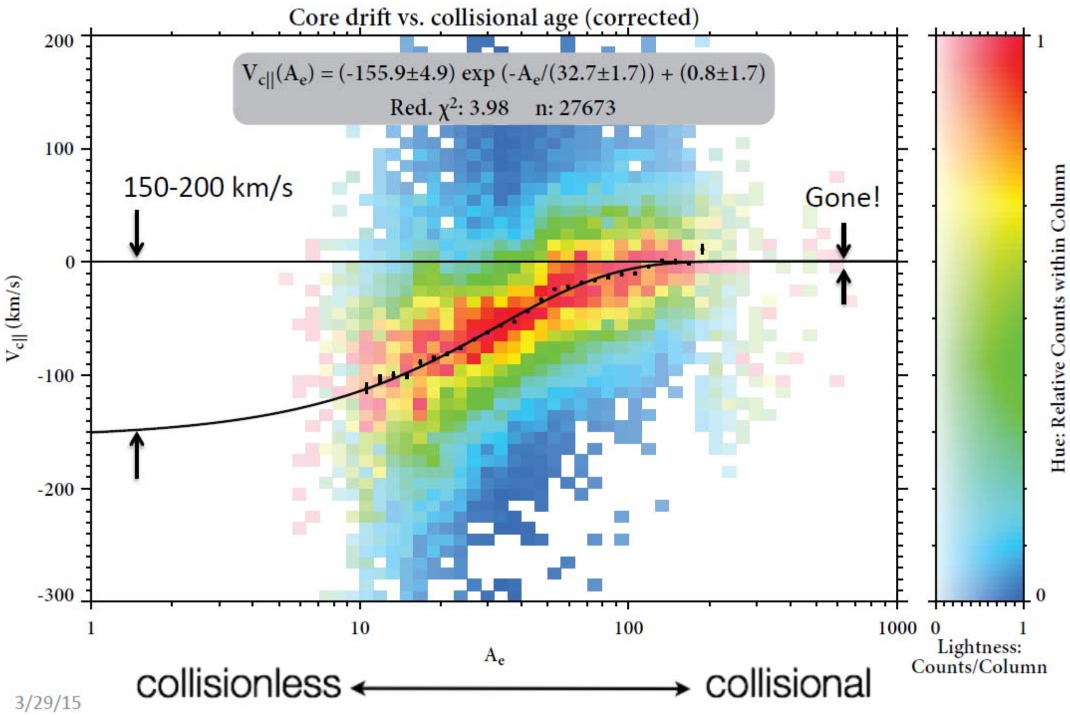
Dipolar S/C potential correction

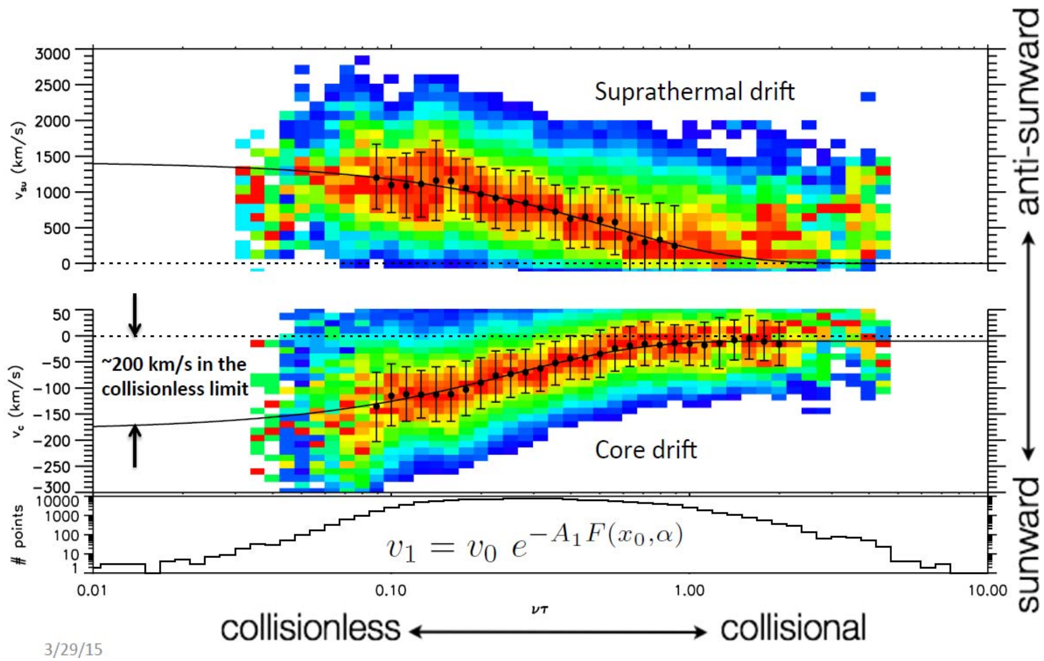


$$\phi(\varphi, R) = K\left(\frac{1}{R} - \frac{A\cos\varphi}{R^2}\right)$$

$$\phi(\varphi) = \phi_0 - \phi_1 \cos\varphi$$

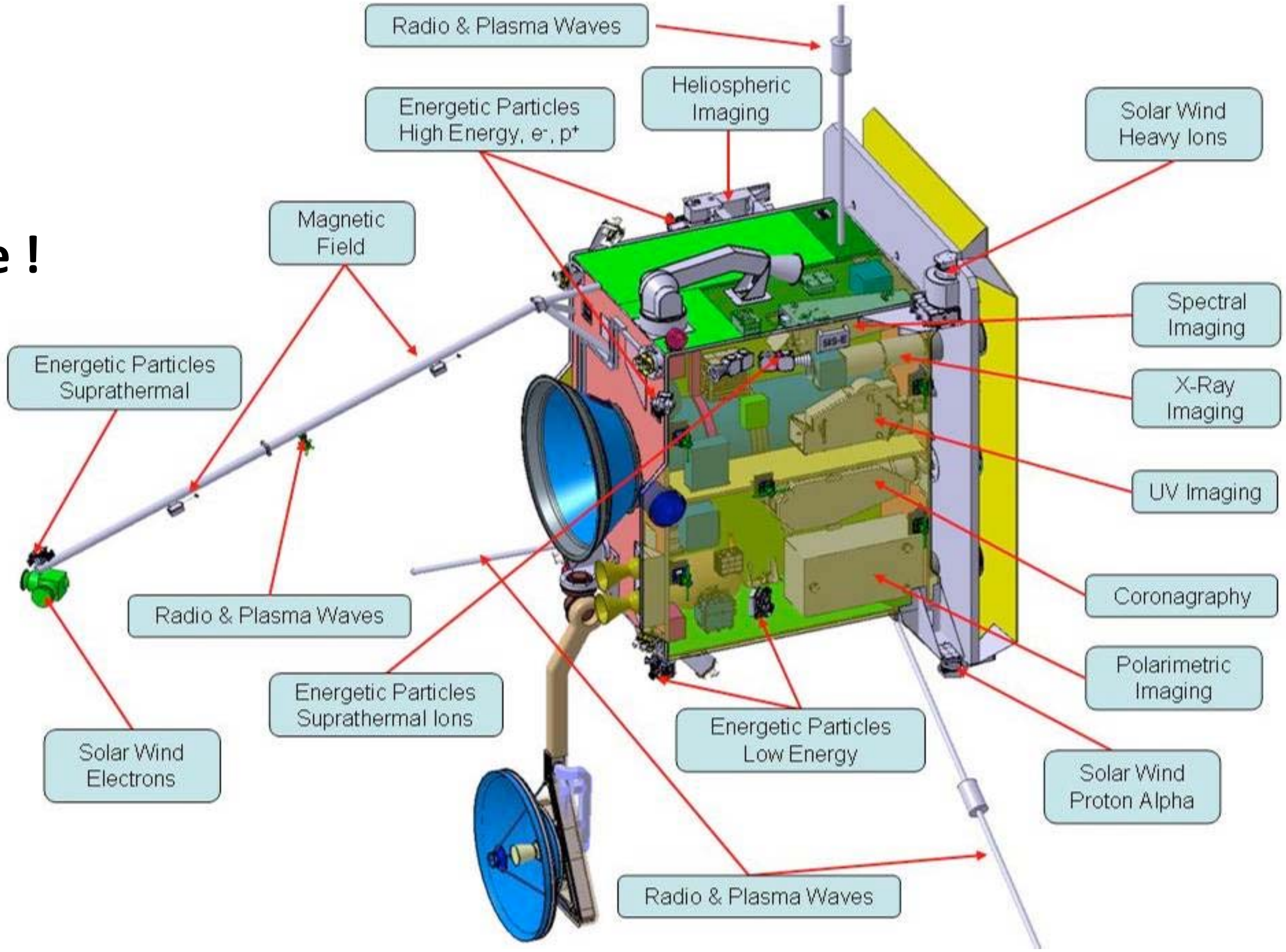
Core electron-proton (||) drift



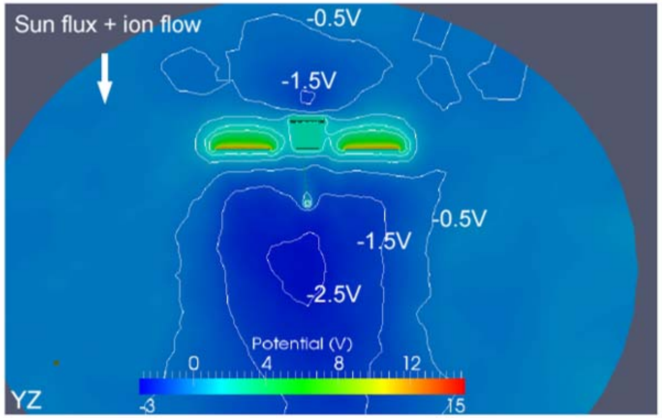


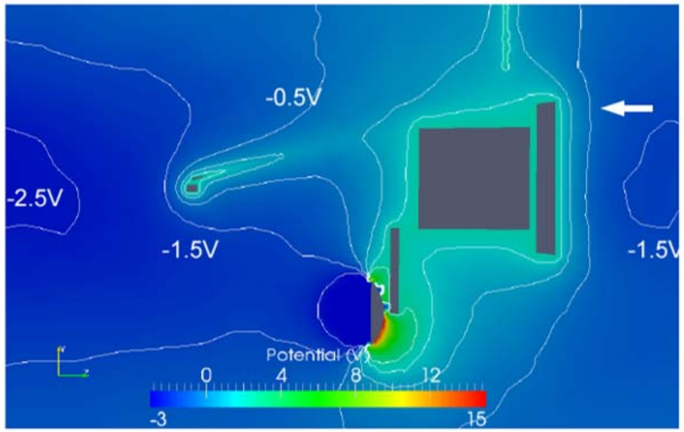
Some Challenges with Solar Orbiter

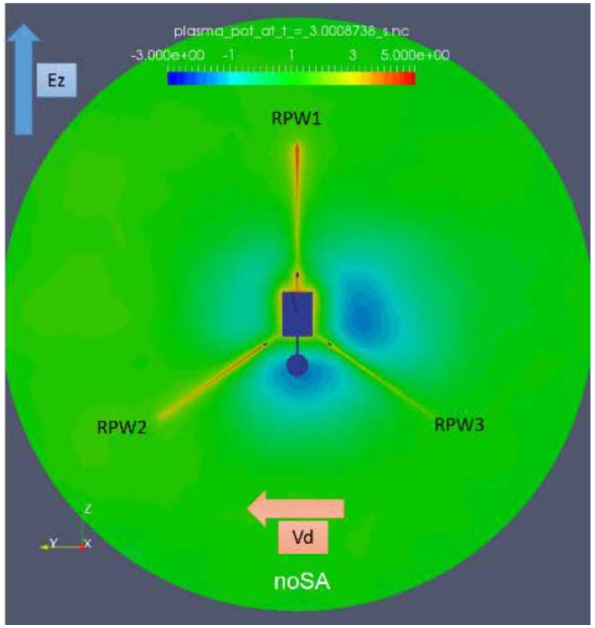
Integrating all 10 instruments on the S/C platform is a real chalenge !

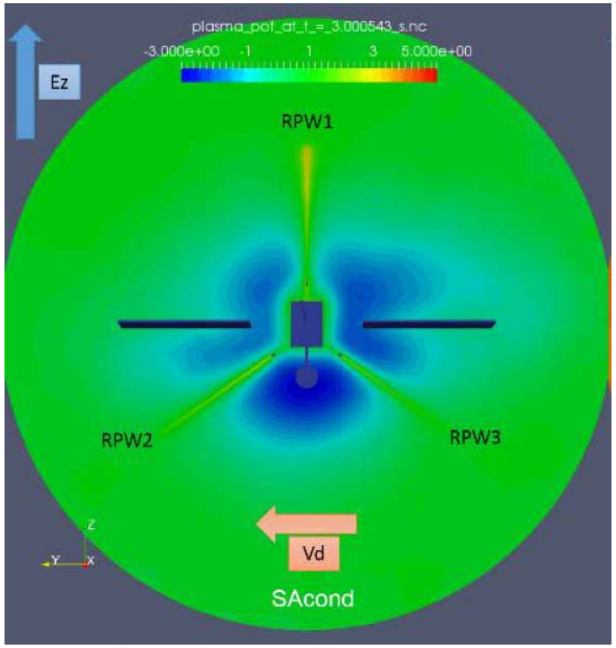


Undertanding the electrostaic environment will be a challenge

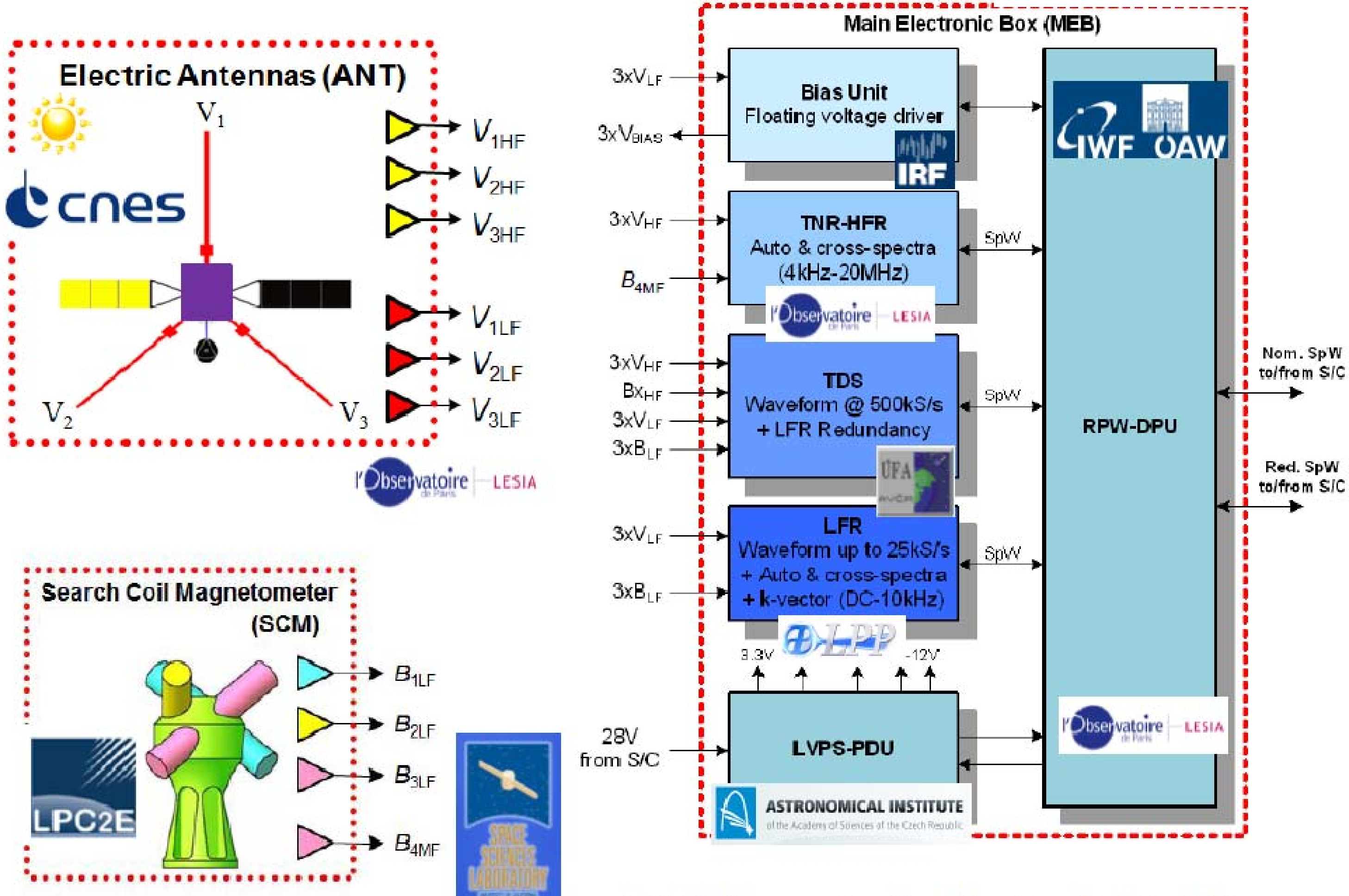




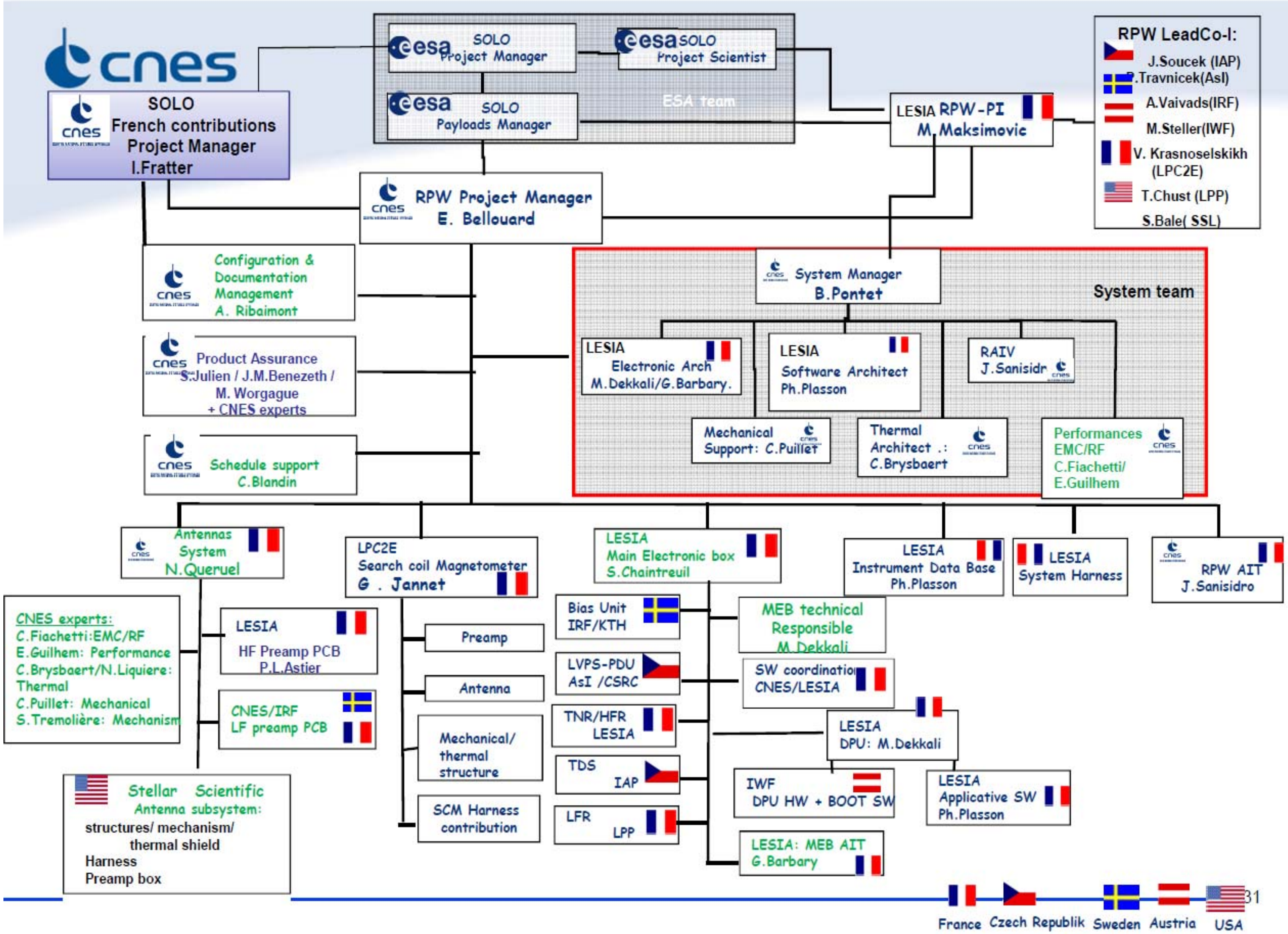




The Radio & Plasmas Waves instrument



DC Efield expertise & calibration, link to SPP


cnes
SOLO French contributions Project Manager I.Fratter
esa SOLO Project Manager
esa SOLO Project Scientist
esa SOLO Payloads Manager
ESA team
LESIA RPW-PI M. Maksimovic
RPW LeadCo-I:
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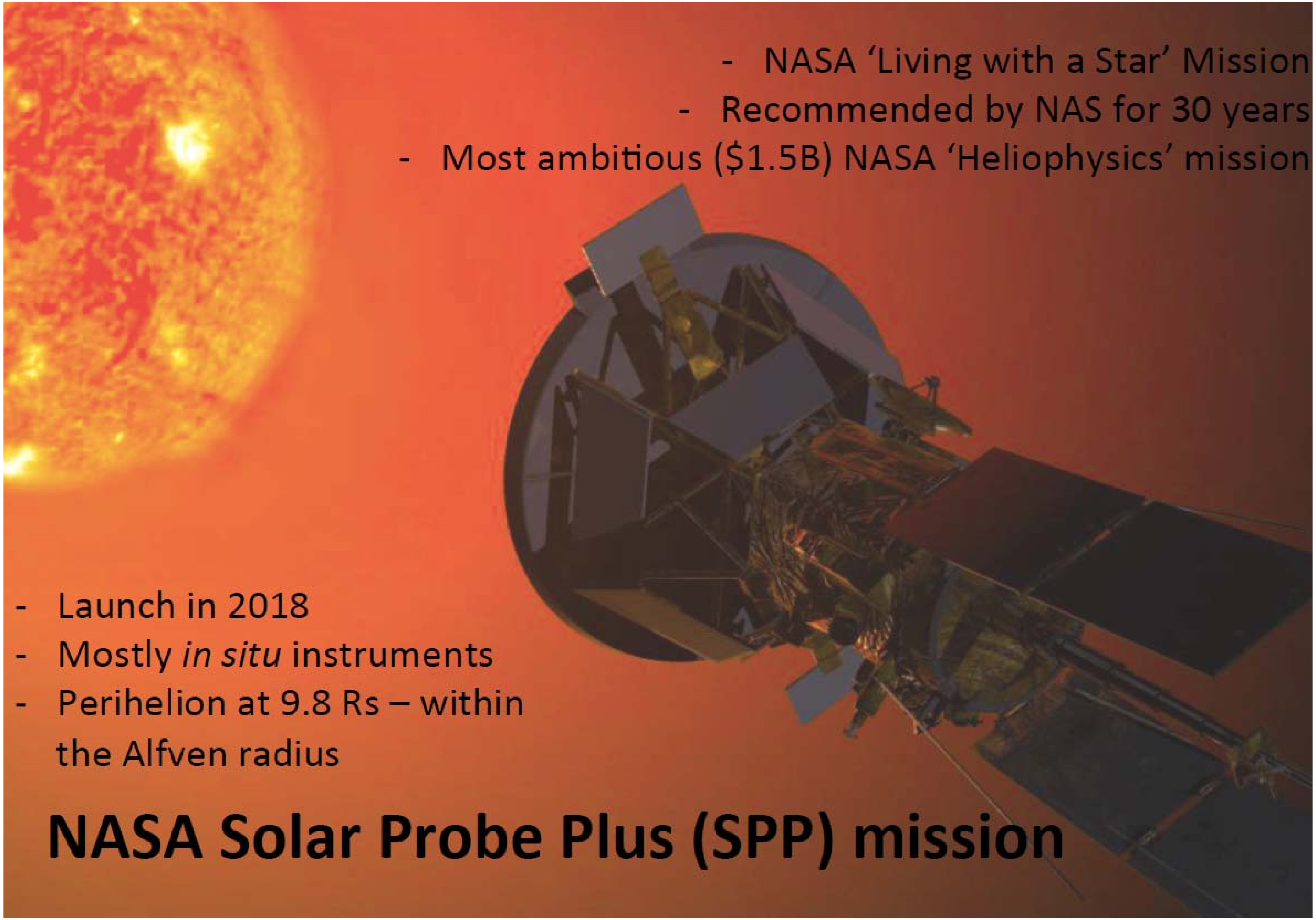
P.Travnicek(AsI)
A.Vaivads(IRF)
M.Steller(IWF)
V. Krasnoselskikh (LPC2E)
T.Chust (LPP)
S.Bale(SSL)
RPW Project Manager E. Bellouard
Configuration & Documentation Management A. Ribaimont
Product Assurance S.Julien / J.M.Benezeth / M. Worgague + CNES experts
Schedule support C.Blandin
System Manager B.Pontet
System team
LESIA Electronic Arch M.Dekkali/G.Barbary.
LESIA Software Architect Ph.Plasson
RAIV J.Sanisidr
Mechanical Support: C.Puillet
Thermal Architect .: C.Brysbaert
Performances EMC/RF C.Fiachetti/ E.Guilhem
Antennas System N.Queruel
LPC2E Search coil Magnetometer G . Jannet
LESIA Main Electronic box S.Chaintreuil
LESIA Instrument Data Base Ph.Plasson
LESIA System Harness
RPW AIT J.Sanisidro
CNES experts:
C.Fiachetti:EMC/RF
E.Guilhem: Performance
C.Brysbaert/N.Liquiere: Thermal
C.Puillet: Mechanical
S.Tremolière: Mechanism
LESIA HF Preamp PCB P.L.Astier
CNES/IRF LF preamp PCB
Stellar Scientific Antenna subsystem: structures/ mechanism/ thermal shield Harness Preamp box
Preamp
Antenna
Mechanical/ thermal structure
SCM Harness contribution
Bias Unit IRF/KTH
LVPS-PDU AsI /CSRC
TNR/HFR LESIA
TDS IAP
LFR LPP
MEB technical Responsible M.Dekkali
SW coordination CNES/LESIA
LESIA DPU: M.Dekkali
IWF DPU HW + BOOT SW
LESIA Applicative SW Ph.Plasson
LESIA: MEB AIT G.Barbary
France
Czech Republik
Sweden
Austria
USA
31



- NASA 'Living with a Star' Mission
- Recommended by NAS for 30 years
- Most ambitious ($1.5B) NASA 'Heliophysics' mission
- Launch in 2018
- Mostly *in situ* instruments
- Perihelion at 9.8 Rs – within the Alfven radius
NASA Solar Probe Plus (SPP) mission