Future explorations of solar and space plasmas

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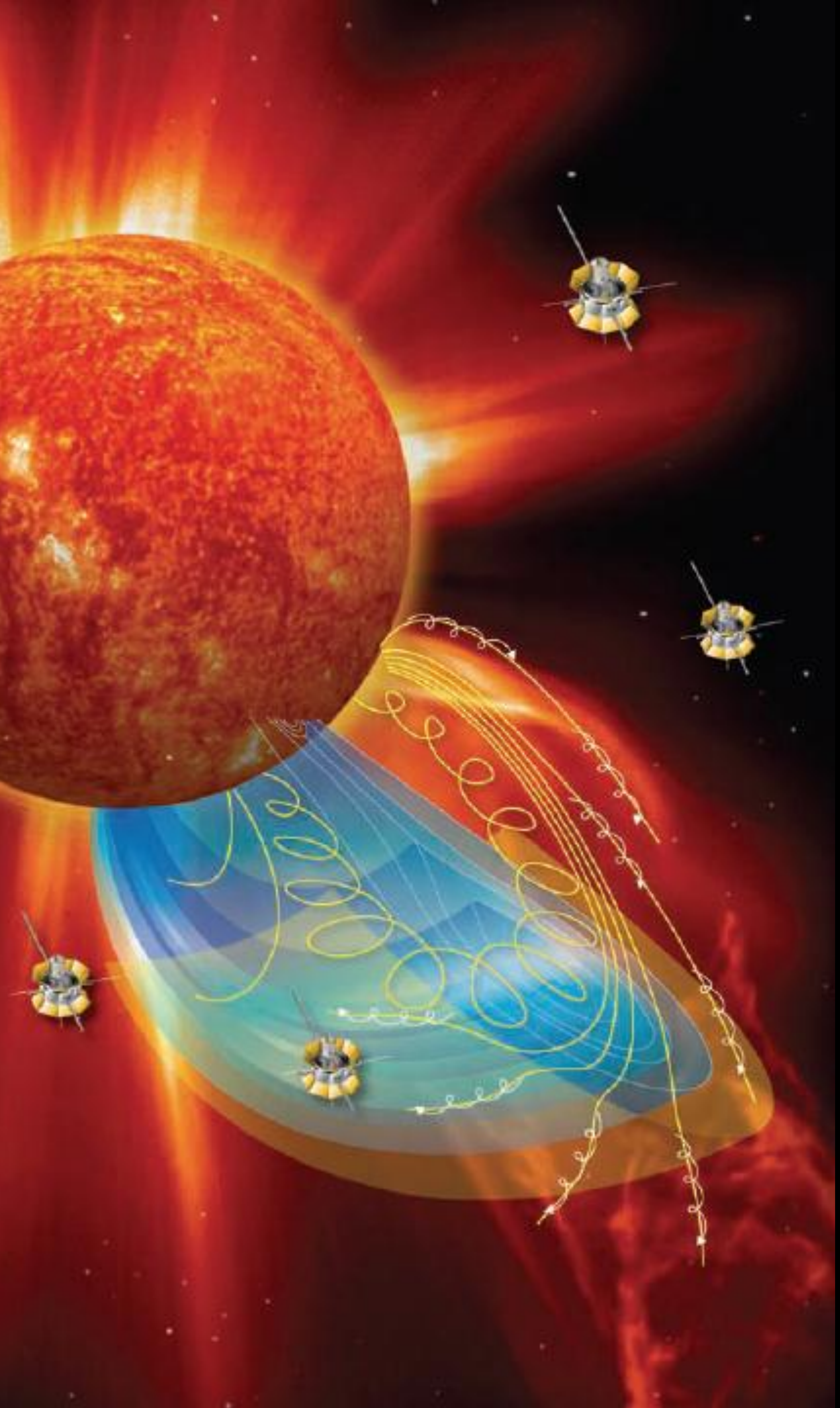
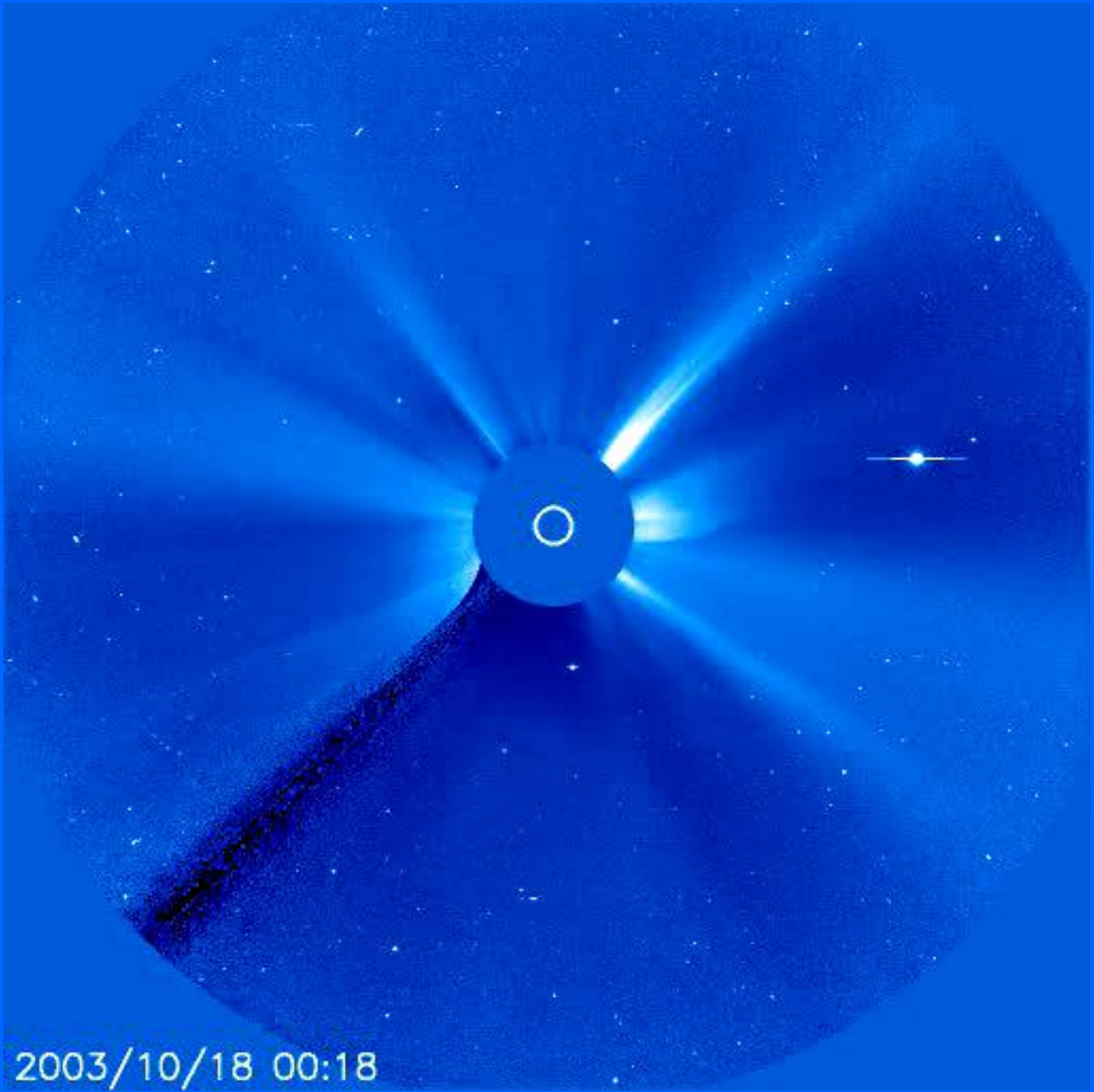
LESIA & CNRS, Observatoire de Paris

The future of plasma Astrophysics, March 8 2013, Les Houches, France



- How is the Solar Magnetic Field generated in the solar interior and what is the origin of the Solar Cycle?
  SoHO, SDO
- How does the Solar Magnetic Field emerge from the solar interior and what is its impact on the Solar atmosphere ?

  SoHO, TRACE, STEREO, SDO
- What are the physical mechanisms involved in the Corona & Solar Wind formations, heating & acceleration ?
  Yokho,Ulysses, SoHO, TRACE, STEREO
- What are the physical processes at the origin of the solar eruptive actvity (CMEs, Flares …) ?
  Yokho, Ulysses, SoHO, TRACE, STEREO, Rhessi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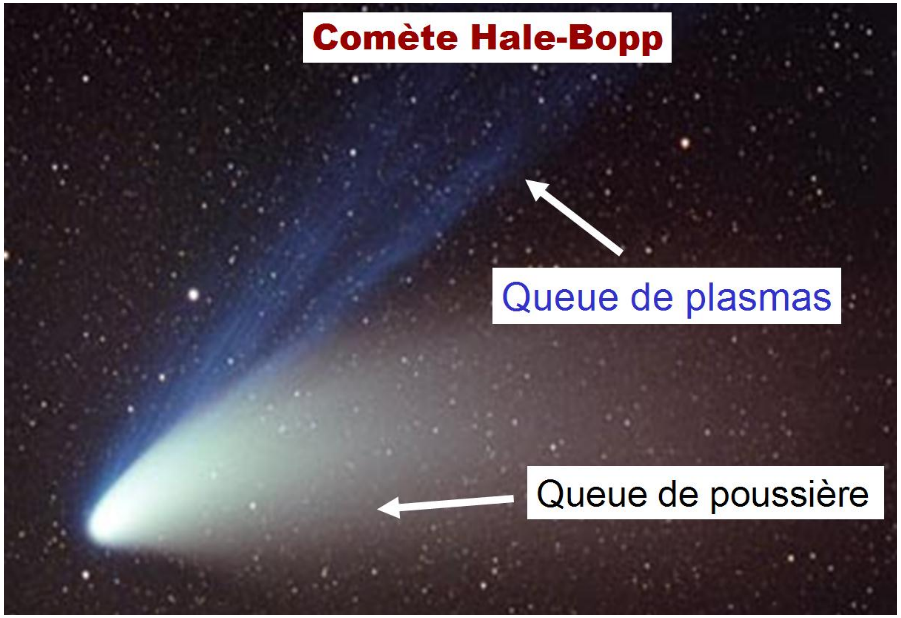
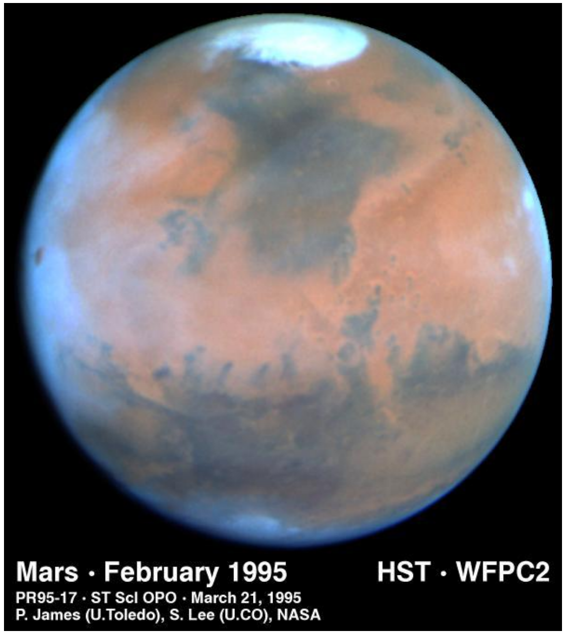
Interaction of the Solar WIND with …





The Heliosphere is an extraordinary laboratory for Plasma Physics …

… where it is possible to measure full particle distribution functions without perturbing the medium ?

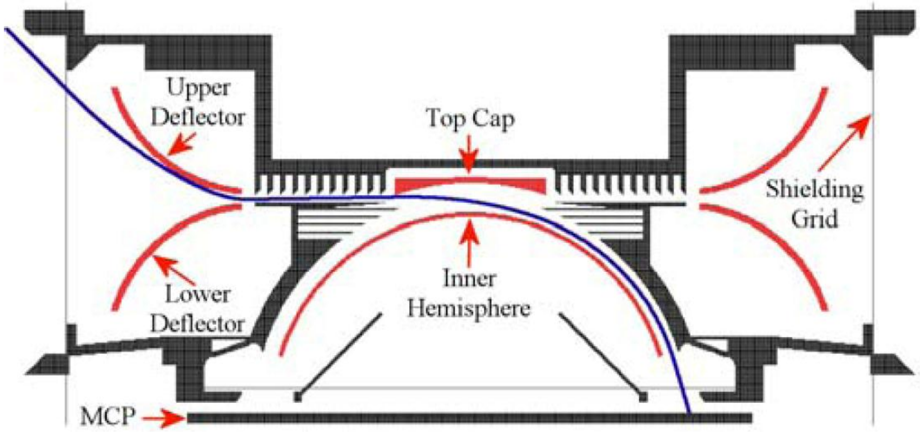
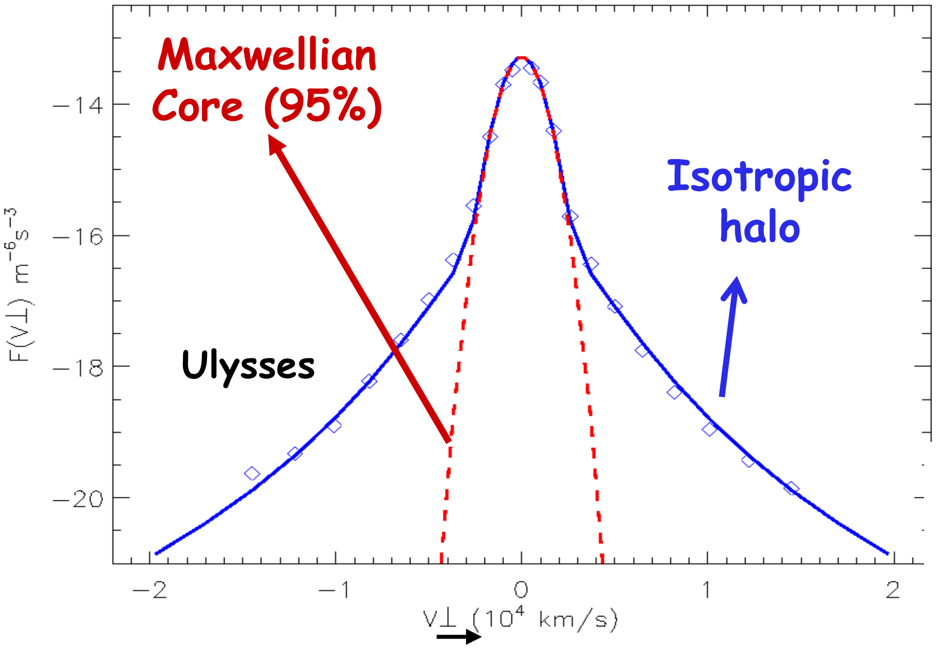


Figure 6.1-2: EAS Electro-optical Model

- Velocity (energy) selection set by entrance grid Φ
- Look direction set by electro-optical geometry or S/C spining

Electron velocity distribution functions : 3 components : core, halo & strahl



Maxwellian Core (95%)

Isotropic halo

Ulysses

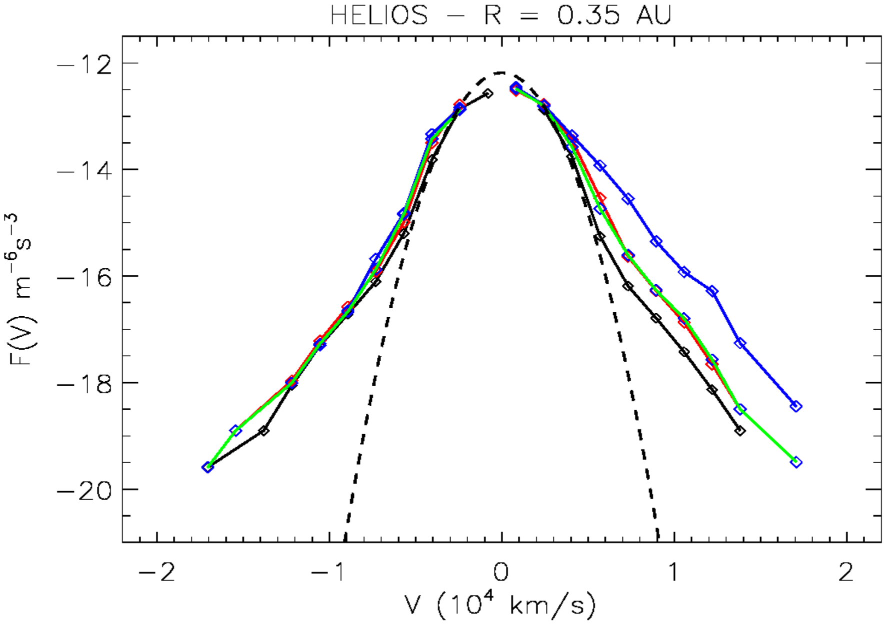
+ Strahl along $\vec{B}$

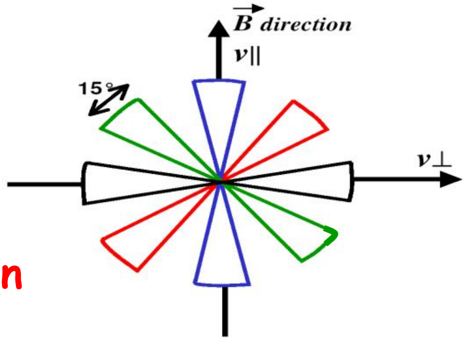
- Best model :

(bi-)Maxwellian for the core +
(bi-) Lorentzian (Kappa) :

Maksimovic et al., 1997, 2005

$$f_\kappa(v) \sim \left[1 + \frac{v^2}{\kappa v_{th}^2} \right]^{-\kappa}$$

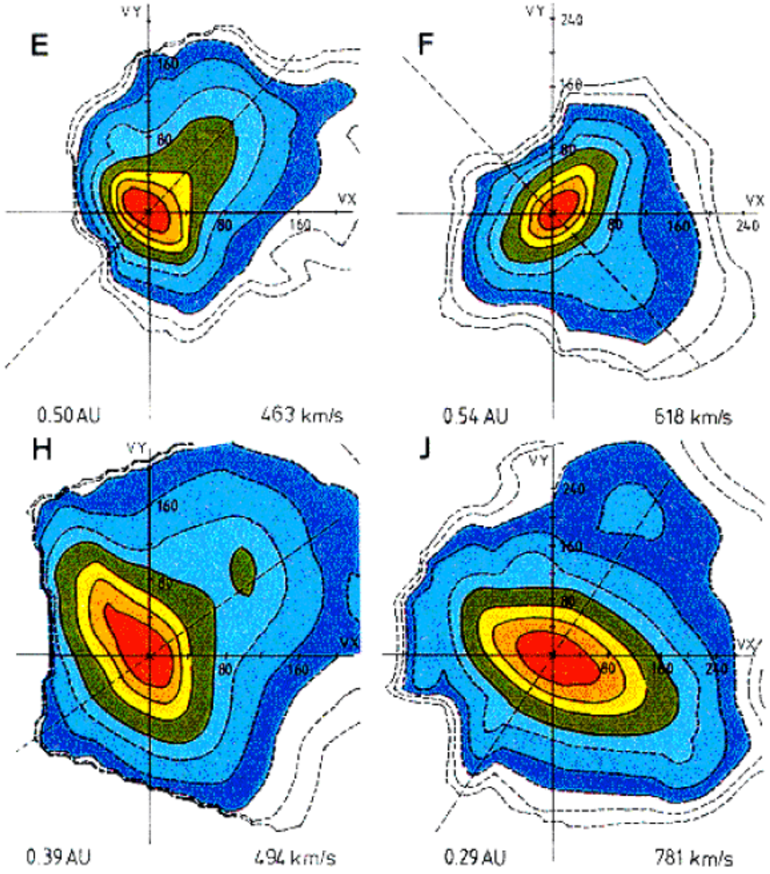


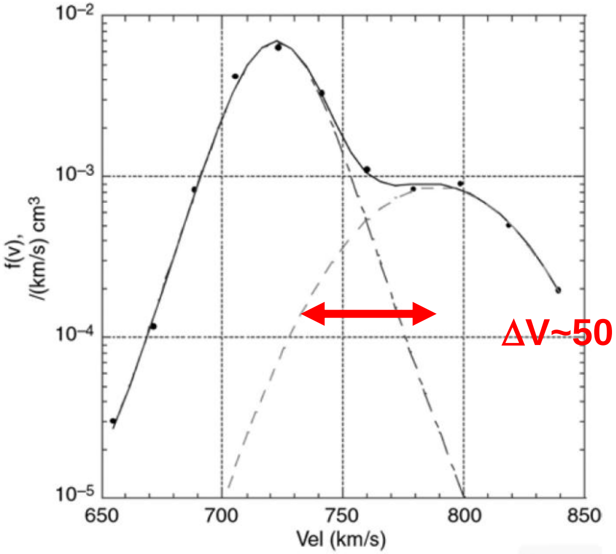


Where do these VDFs originated ? In the corona ?

Proton distribution functions

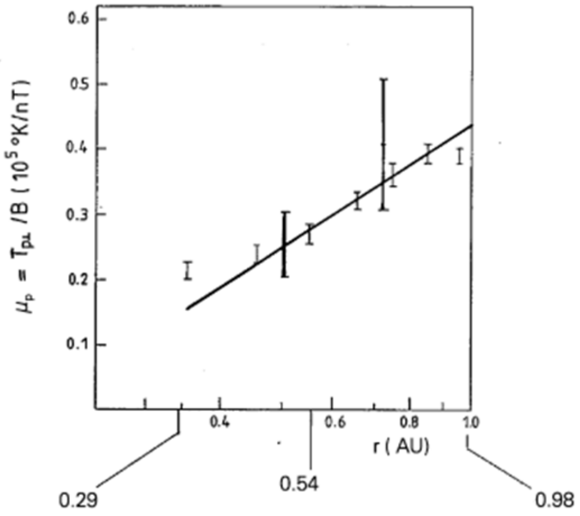
Helios





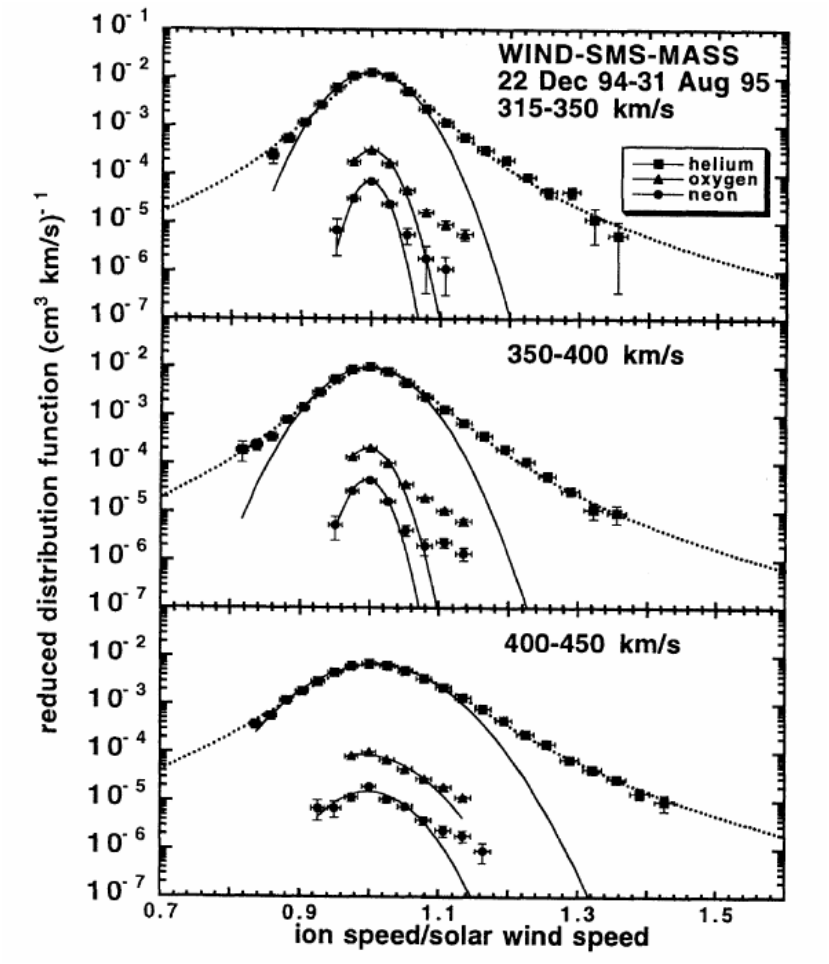
ΔV~50 km/s ~*Va*

non conservation of μ heating?



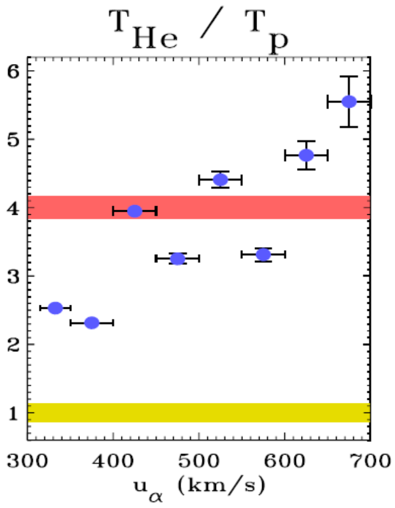
bi-Maxwellian + beam

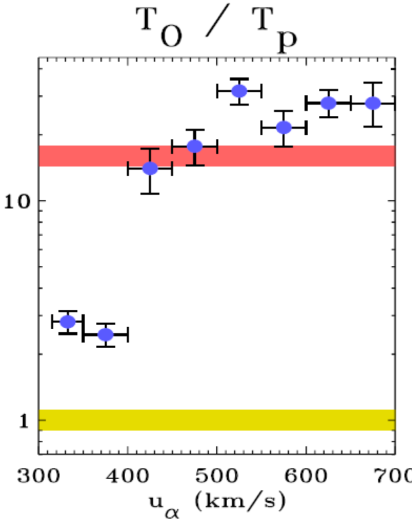
Heavy ions distribution functions

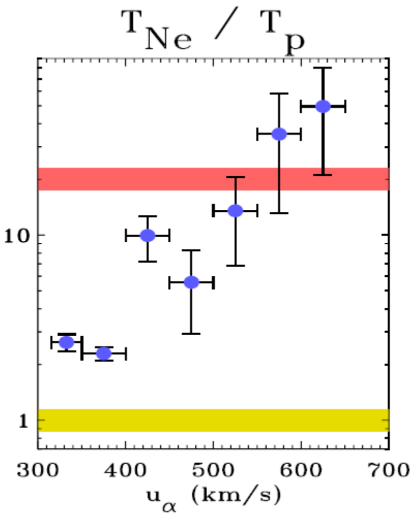


$$(\Delta V \approx V_A)$$

$$(T_{\text{ion}}/T_{\text{p}}) \gtrsim (m_{\text{ion}}/m_{\text{p}})$$



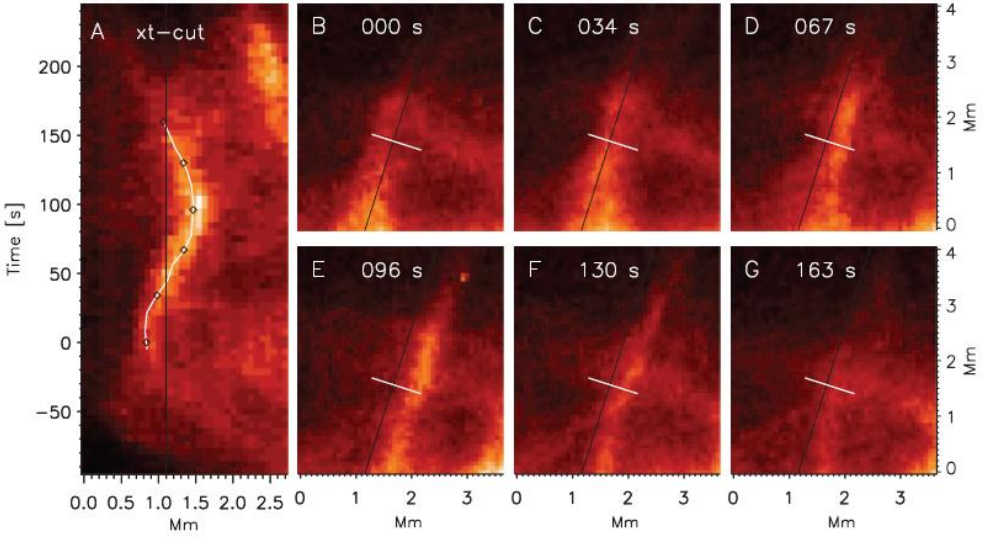


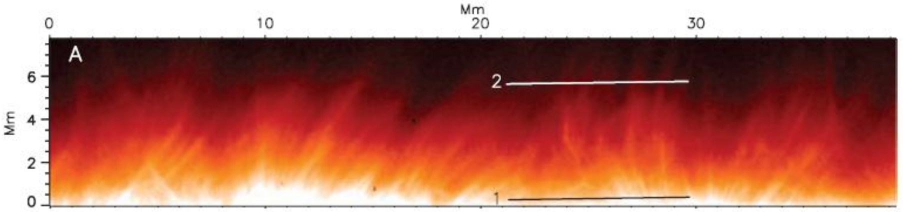


… where it is possible to measure magnetic & electric plasma waves ?

Do we observed Chromospheric Alfvénic Waves that are Strong enough to Power the Solar Wind ?

De Pontieu et al., Science, 2007





- Hinode SOT Ca II H 3968 Å images

- Displacements of spicules that are compatibles with the propagation of Alvén Waves *(10-25 km/s and T~100-500s)*

- Estimates of the energy flux carried by MHD simulations seem sufficient

… but we see photons, not plasma

In the Solar wind we directly observe Alvén Waves *(courtesy T. Horbury)*

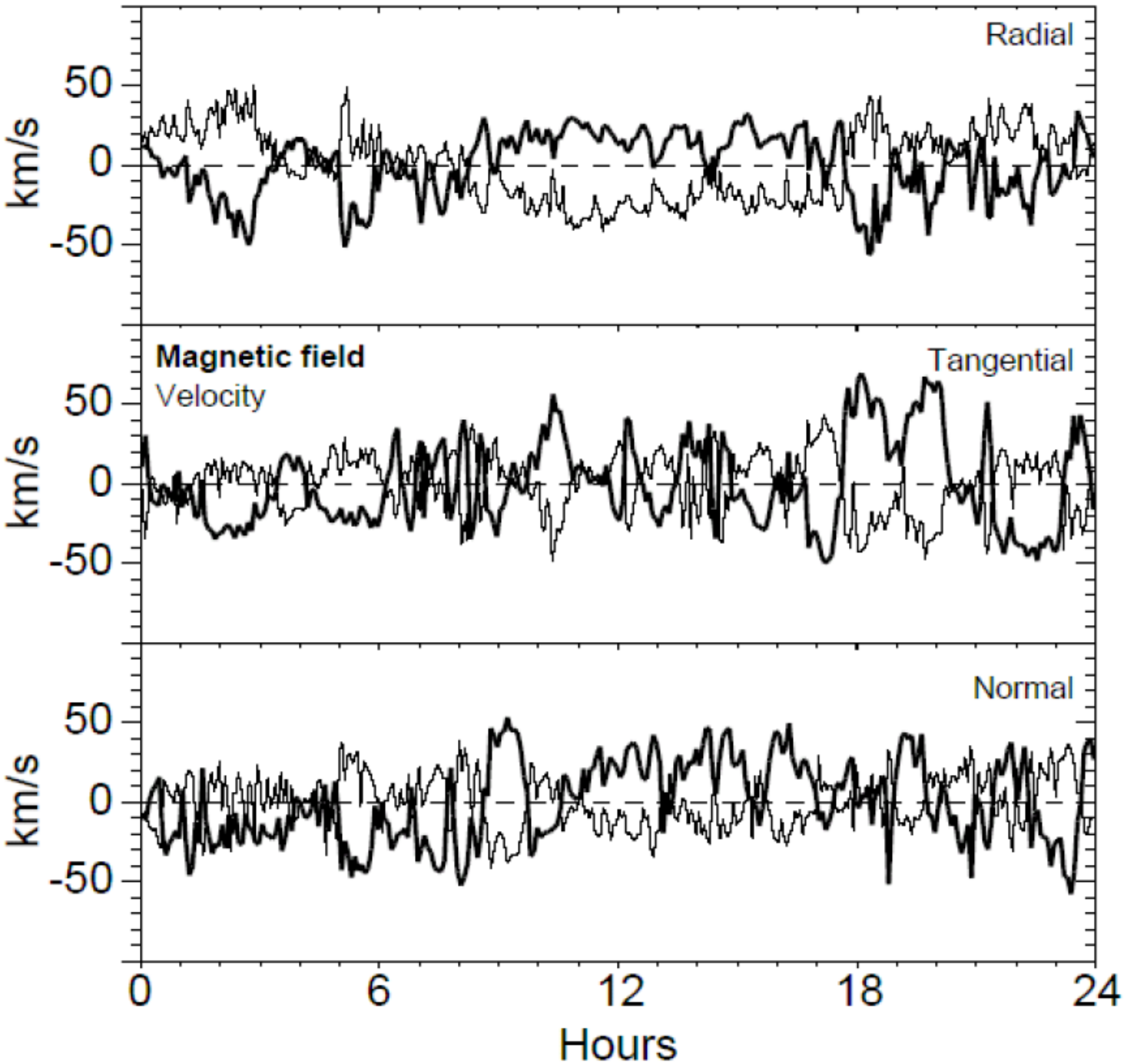
Field-parallel Alfvén wave:

- B and V variations anti-correlated

Field-anti-parallel Alfvén wave:

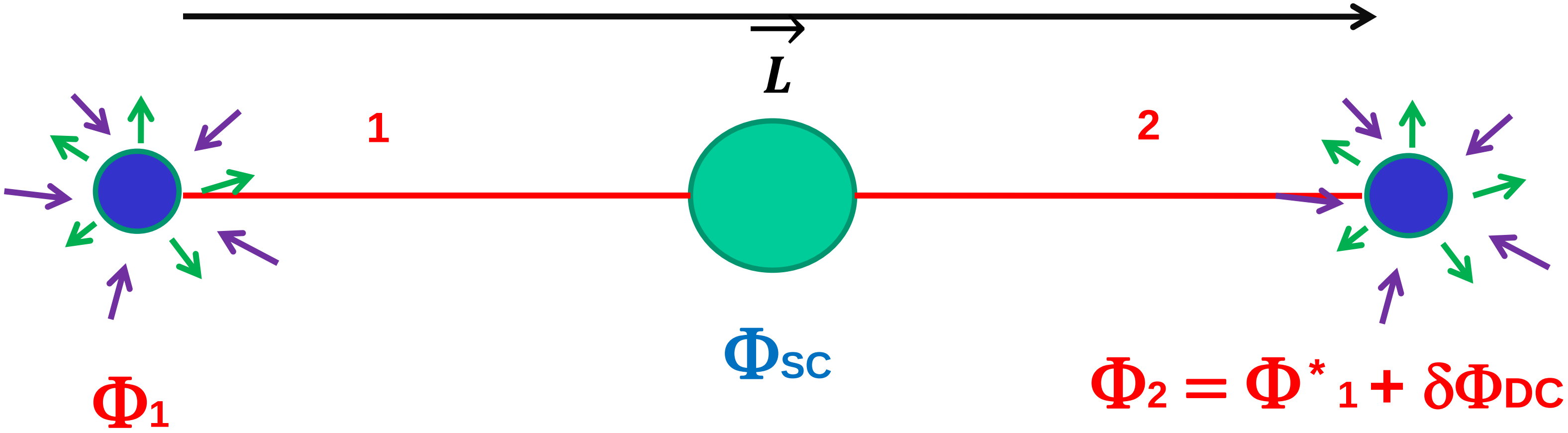
- B and V variations correlated

- See this very clearly in the solar wind
- Most common in high speed wind



adding the measurements DC electric fields

$$\overrightarrow{E_{DC}} \cdot \overrightarrow{L} = \delta\Phi_{DC}$$



If equal illumination for 1 & 2
& symmetry with respect to the S/C

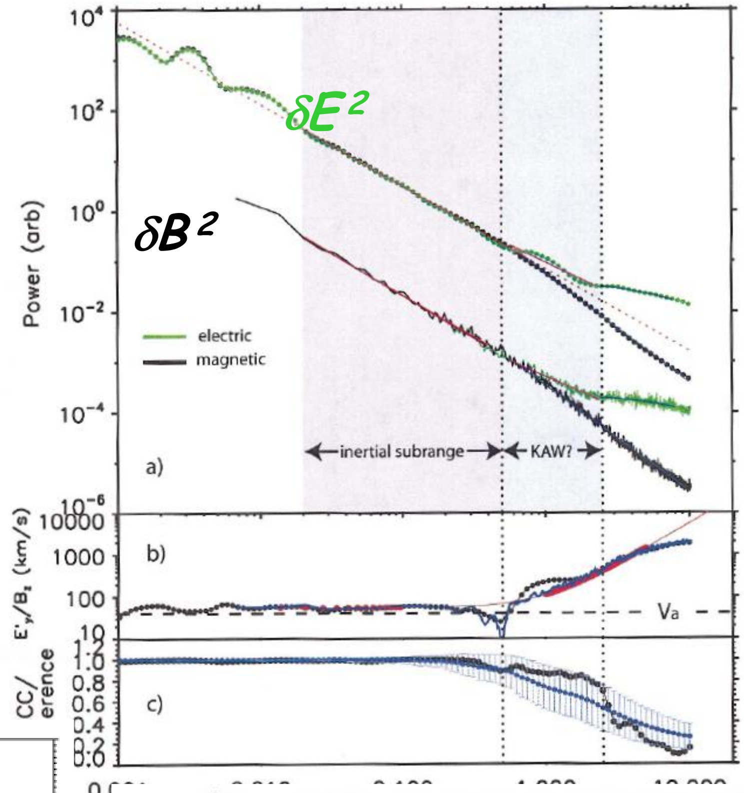
then $\Phi^*_1 = \Phi_1$ and $\Phi_2 - \Phi_1$ will provide $\delta\Phi_{DC}$

can provide the Poynting flux $S = \delta E \times \delta B/\mu_0$

Courtesy S. Bale

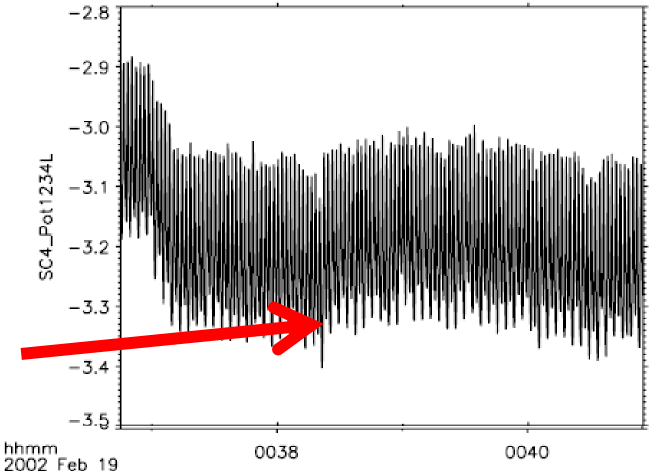
Cluster measurements of the E field of solar wind turbulence show that:

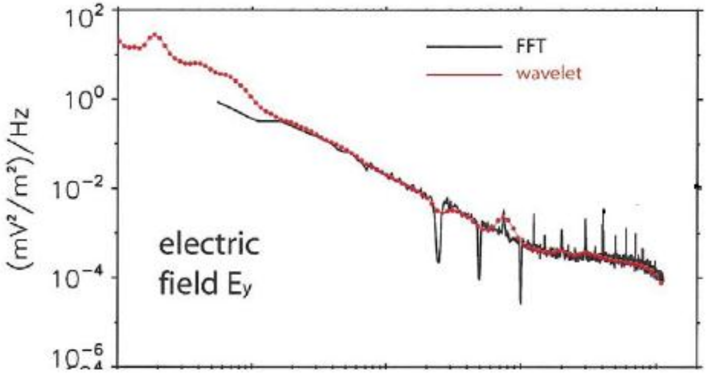
1. The cascade is Alfénic, E & B strongly correlated
2. Short λ E field power is enhanced
3. E/B ratio is consistent with Alfénic inertial range and evolution to KAW at short λ
4. Density (S/C pot.) spectrum is $k^{-5/3}$



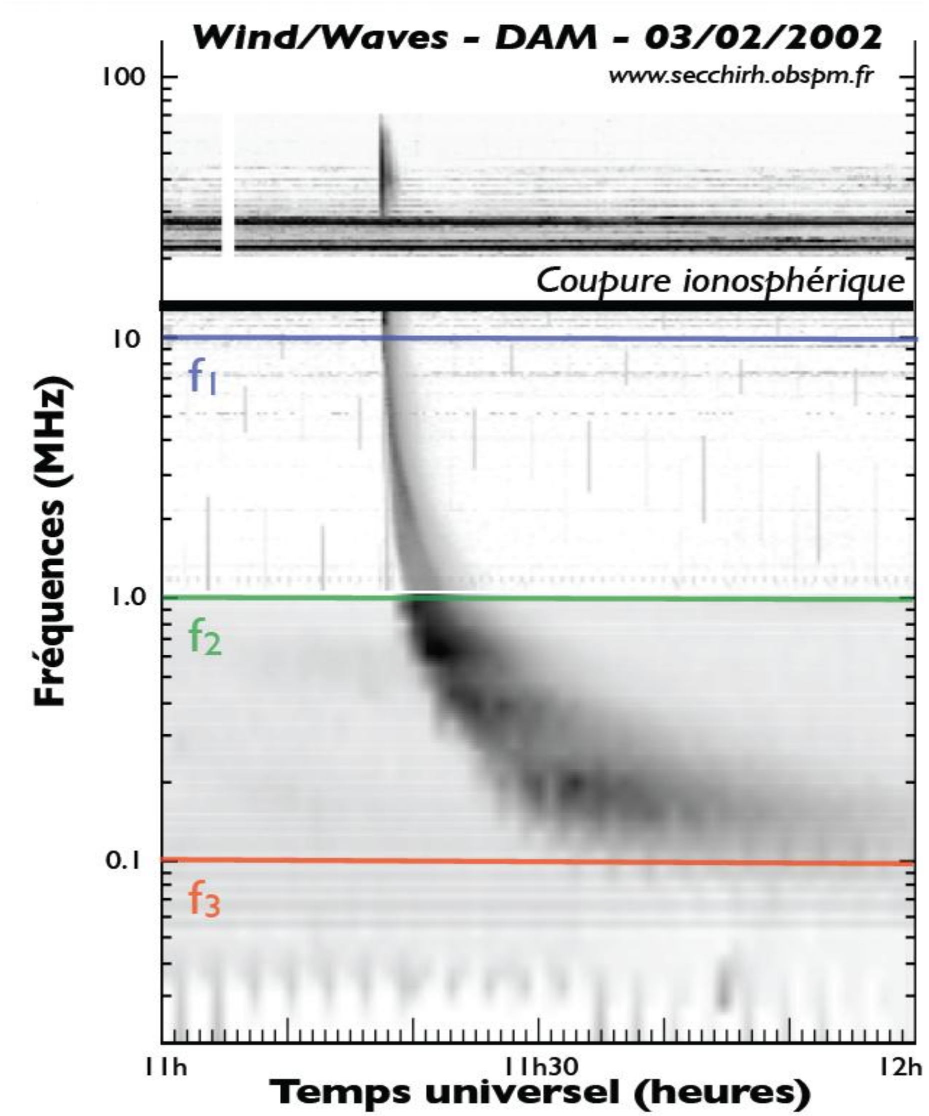
Measurements not easy because of S/C charging

Spin tone in the raw E data





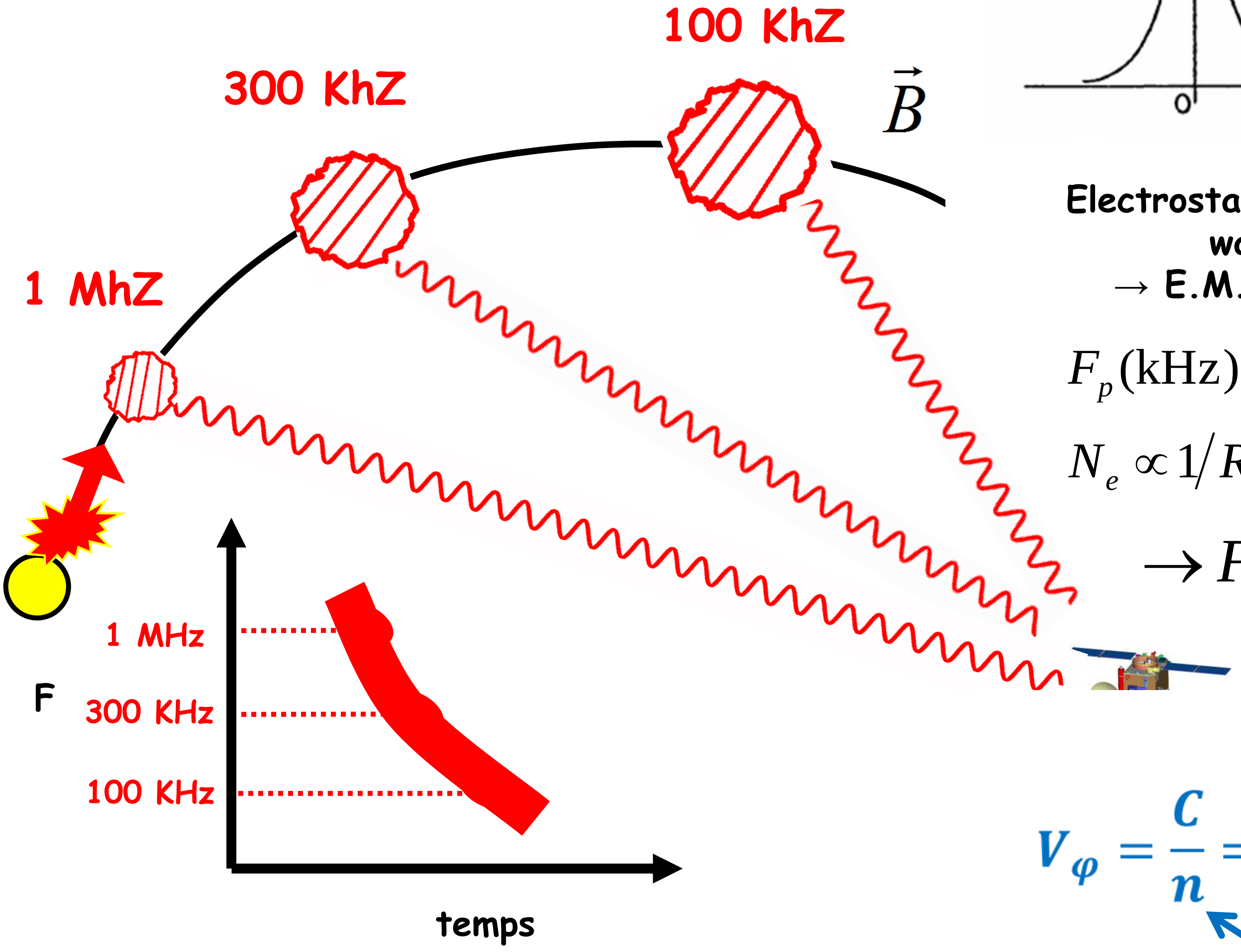
… where it is possible to do cool plasma physics involving particles, waves, density fluctuations … *(lecture by Zarka)*

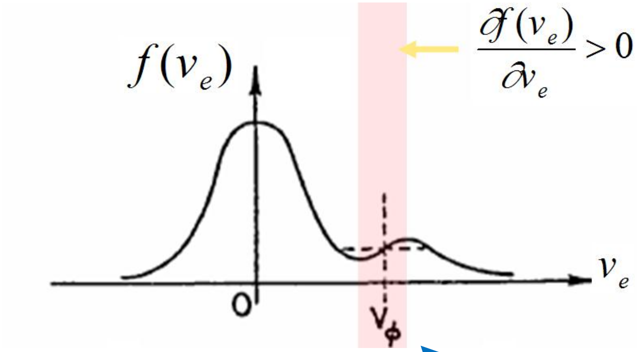


Solar Type III bursts, *Wild, 1950*

- Short (sec → hrs) & intense (→10^{-14} $W.m^{-2}.Hz^{-1}$) radio bursts
- Decrease rapidly from high to low frequencies (GHz → kHz).
- Emmited at the Fundamental or/and the Harmonic of the local Fp
- Low level of polarization (@ high freq)
- Most of the time associated with Solar Flares
- Associated with the propagation of supra-thermal electrons (c/10 → c/3)

Type III radio Burst





Electrostatic Langmuir waves
→ E.M. emission

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

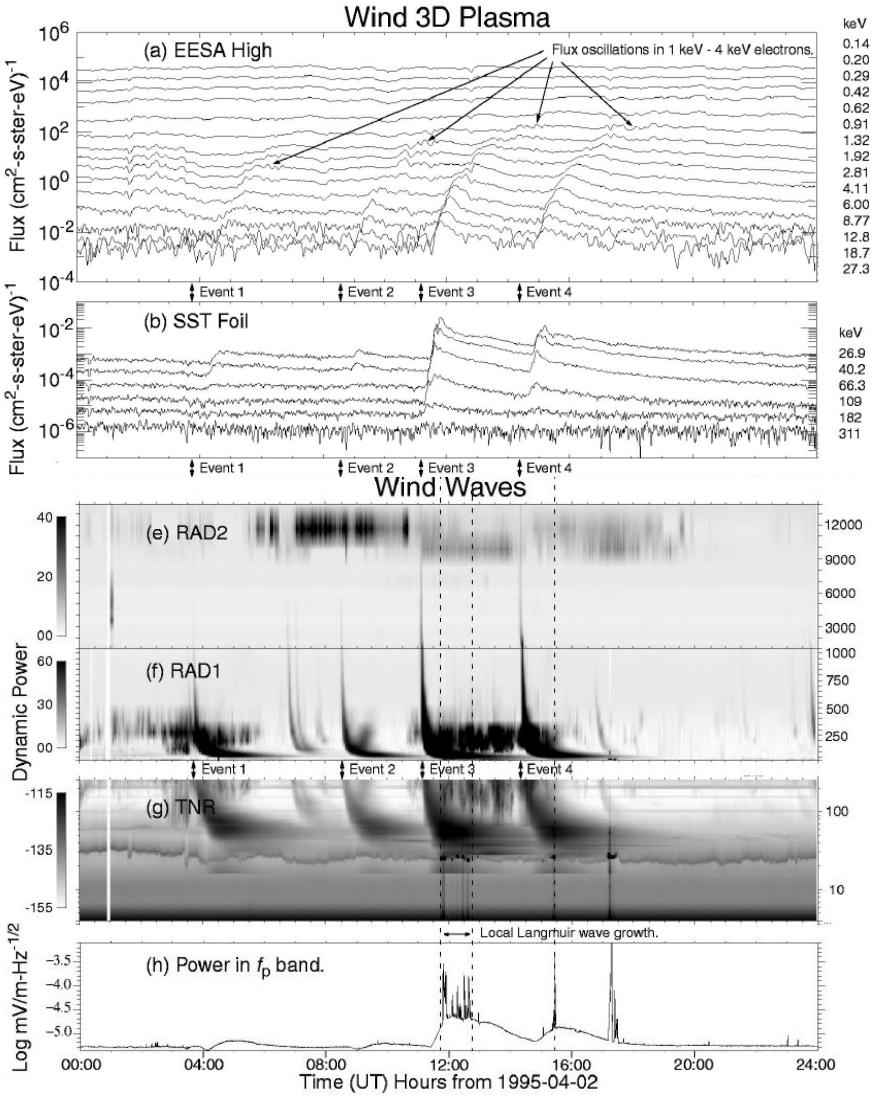
$$N_e \propto 1/R^2 \ (\mathrm{au})$$

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

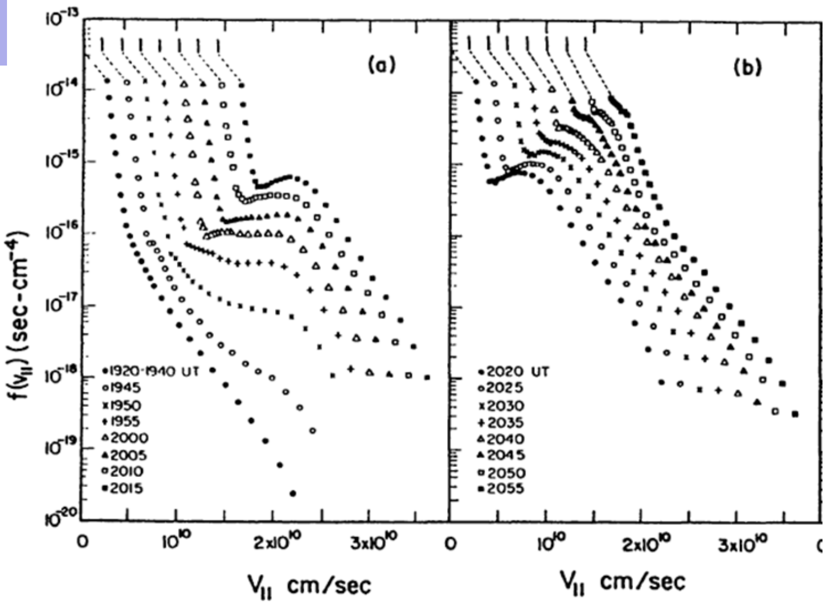
$$V_\varphi = \frac{c}{n} = V_{Beam}$$

fluctuating

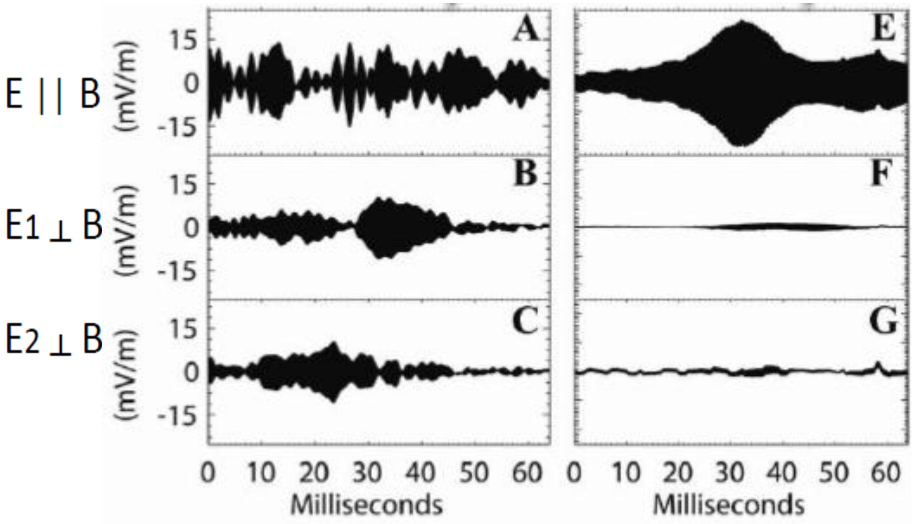
In-situ Type III observations



Adapted from [Ergun et al., 1998]

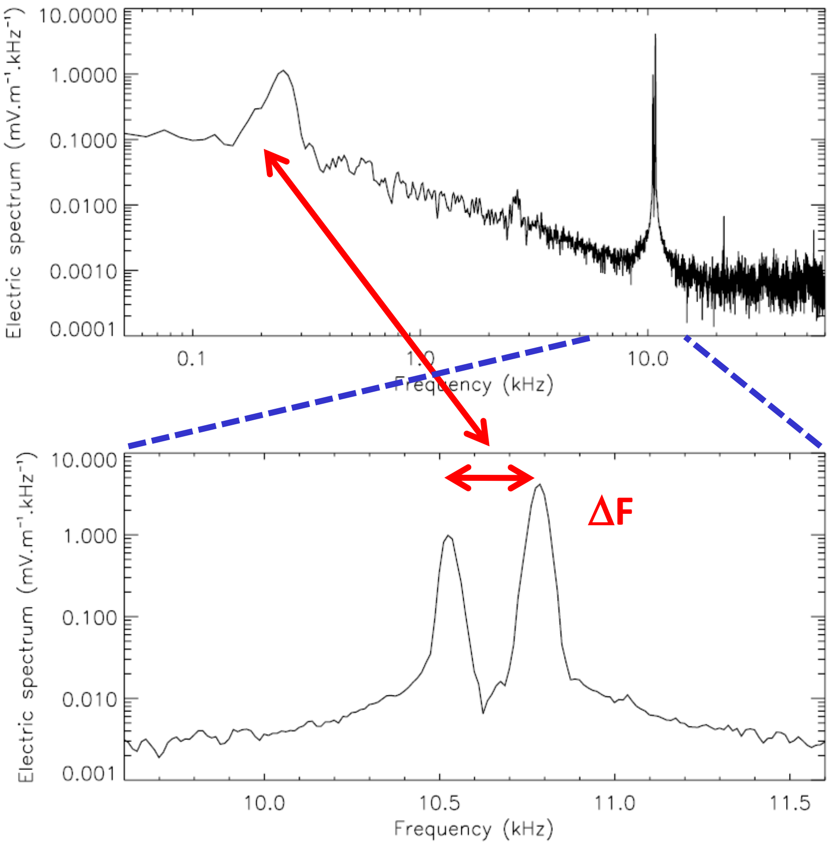


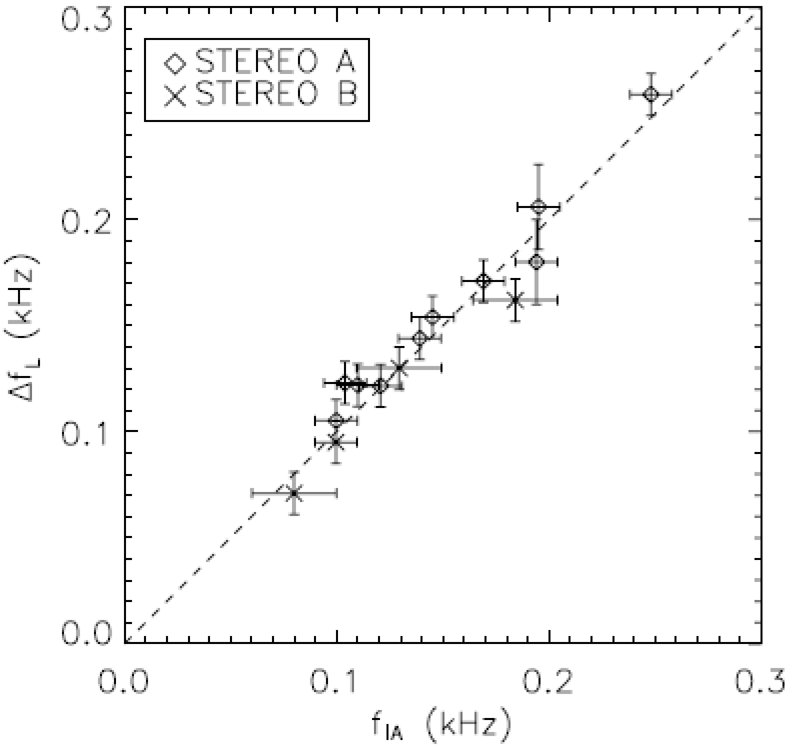
Adapted from [Lin et al. 1981]



Stereo/Waves (from Malaspina, 2011)
localized Langmuir Waves packets

What are the mechanisms responsible for the Mode Conversion Electrostatic → Electro-Magnetic ?





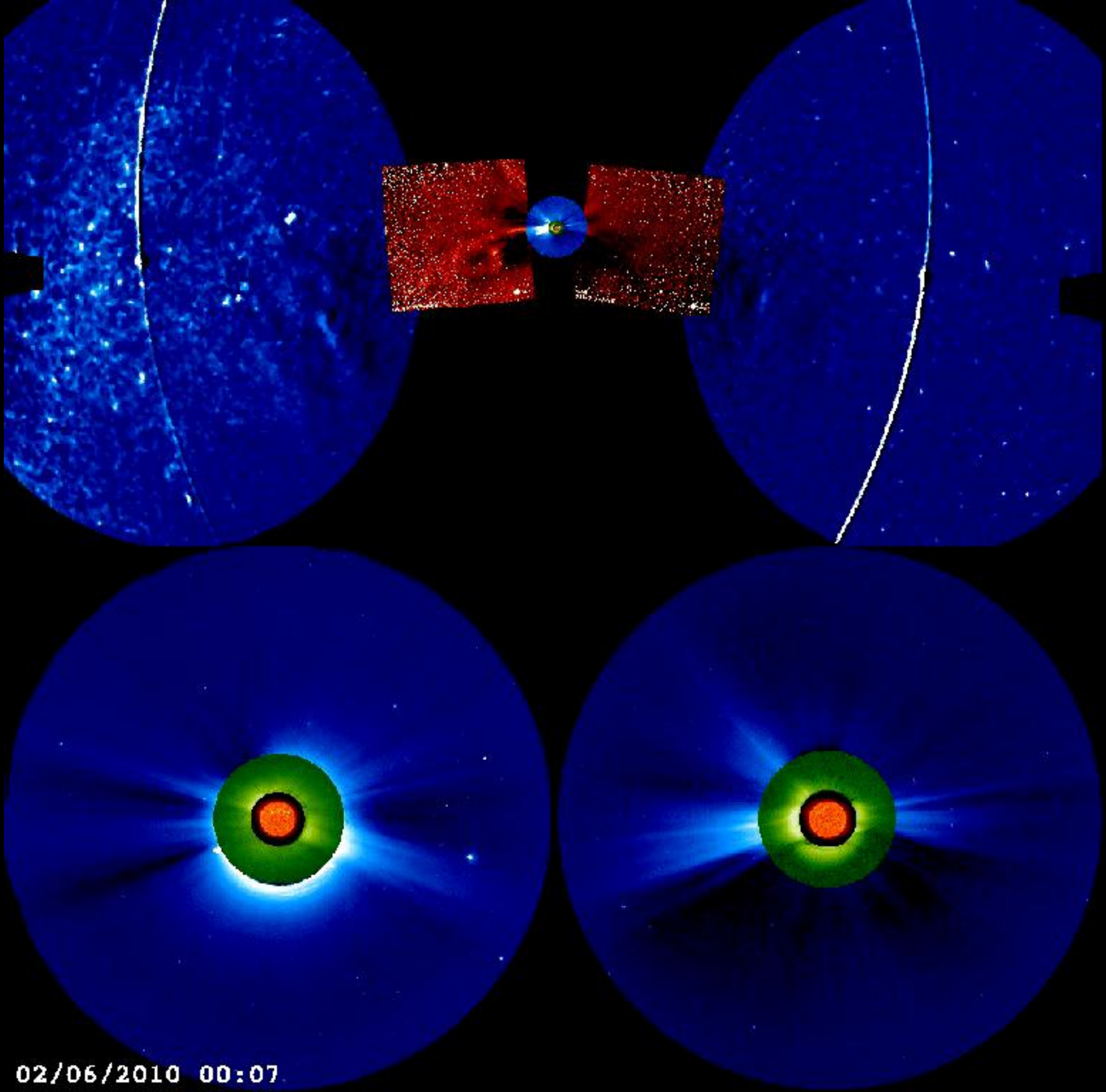
Henri et al. 2008, 2009

- Direct evidence for three-wave coupling (Langmuir and Ion acoustic waves)

$$\begin{cases} L + S \longrightarrow F(f_p) \\ L + S \longrightarrow L' \\ L + L' \longrightarrow H(2f_p) \end{cases}$$

Solar Orbiter

Exploring the Sun-heliosphere connection with dedicated remore-sensing and in-situ instrumentation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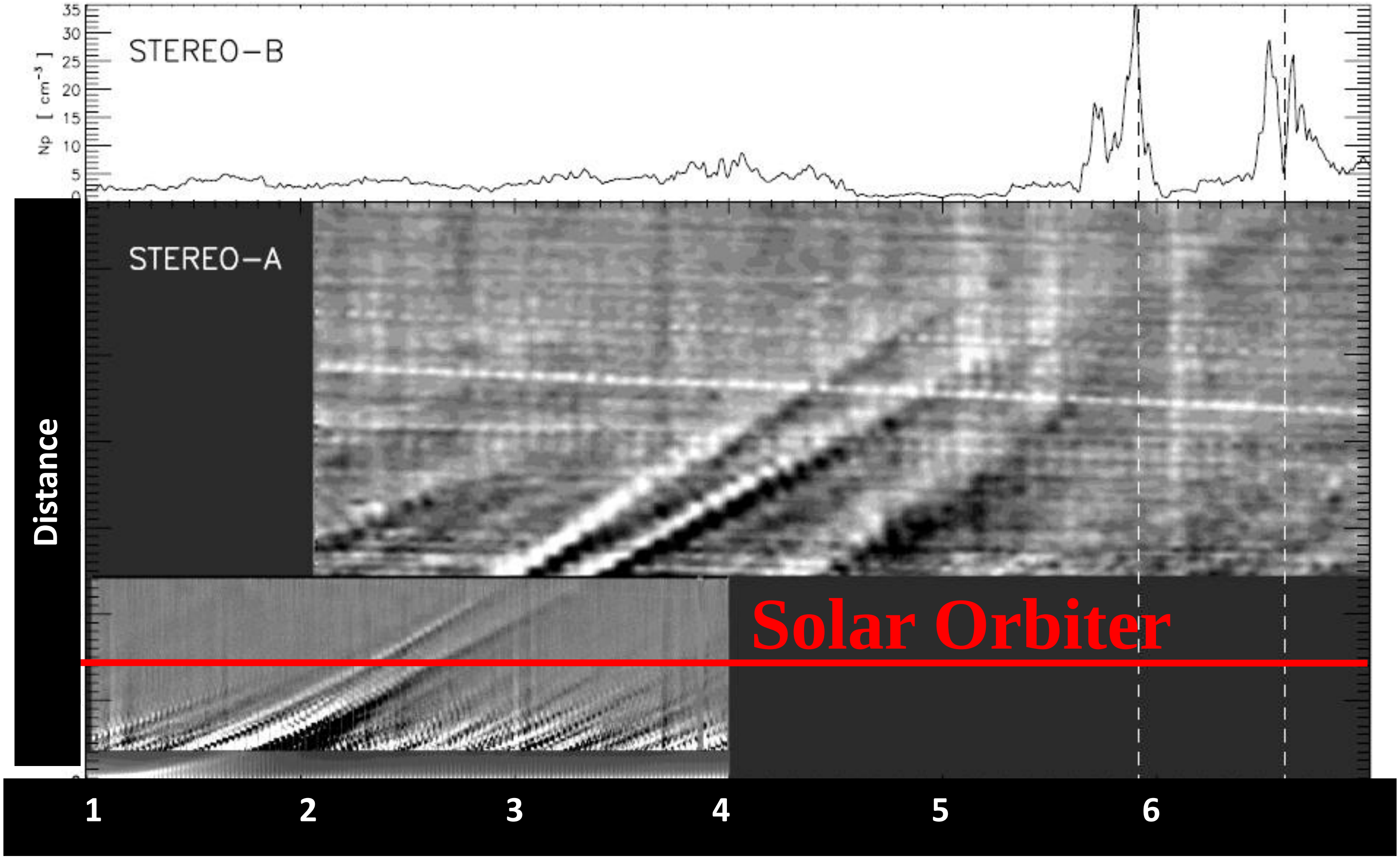
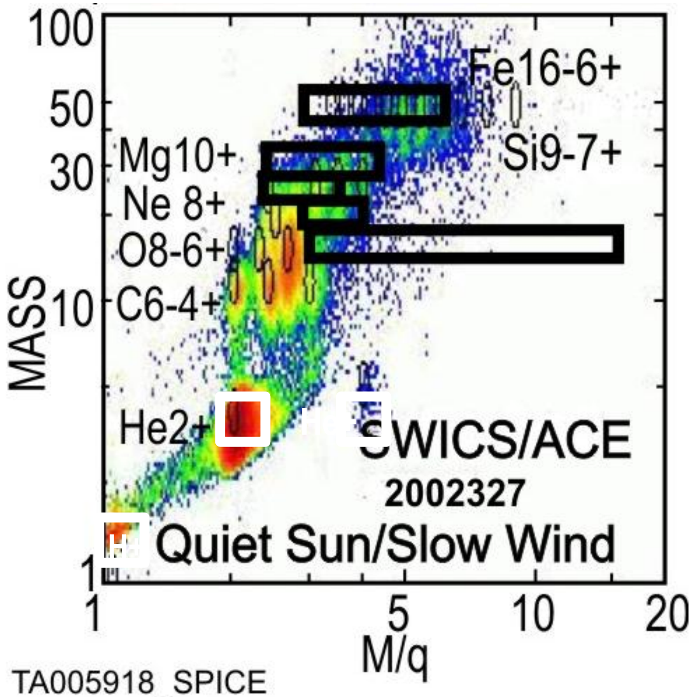
The need for near-Sun observations



Days

Linking the Sun and the solar wind

- Need to measure the same parameter on the Sun and in space to make the link
  - Heavy ion charge states and composition
  - Magnetic polarity
  - Energetic particles

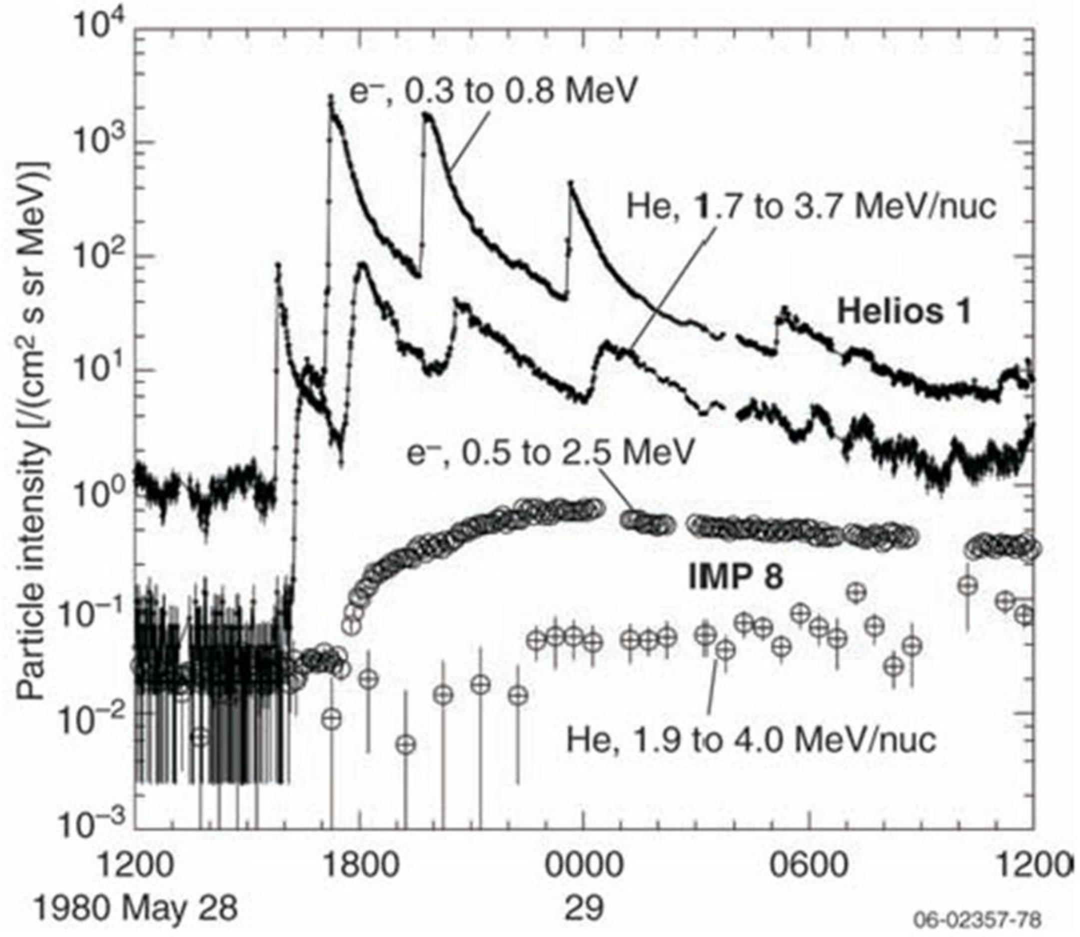


TA005918_SPICE

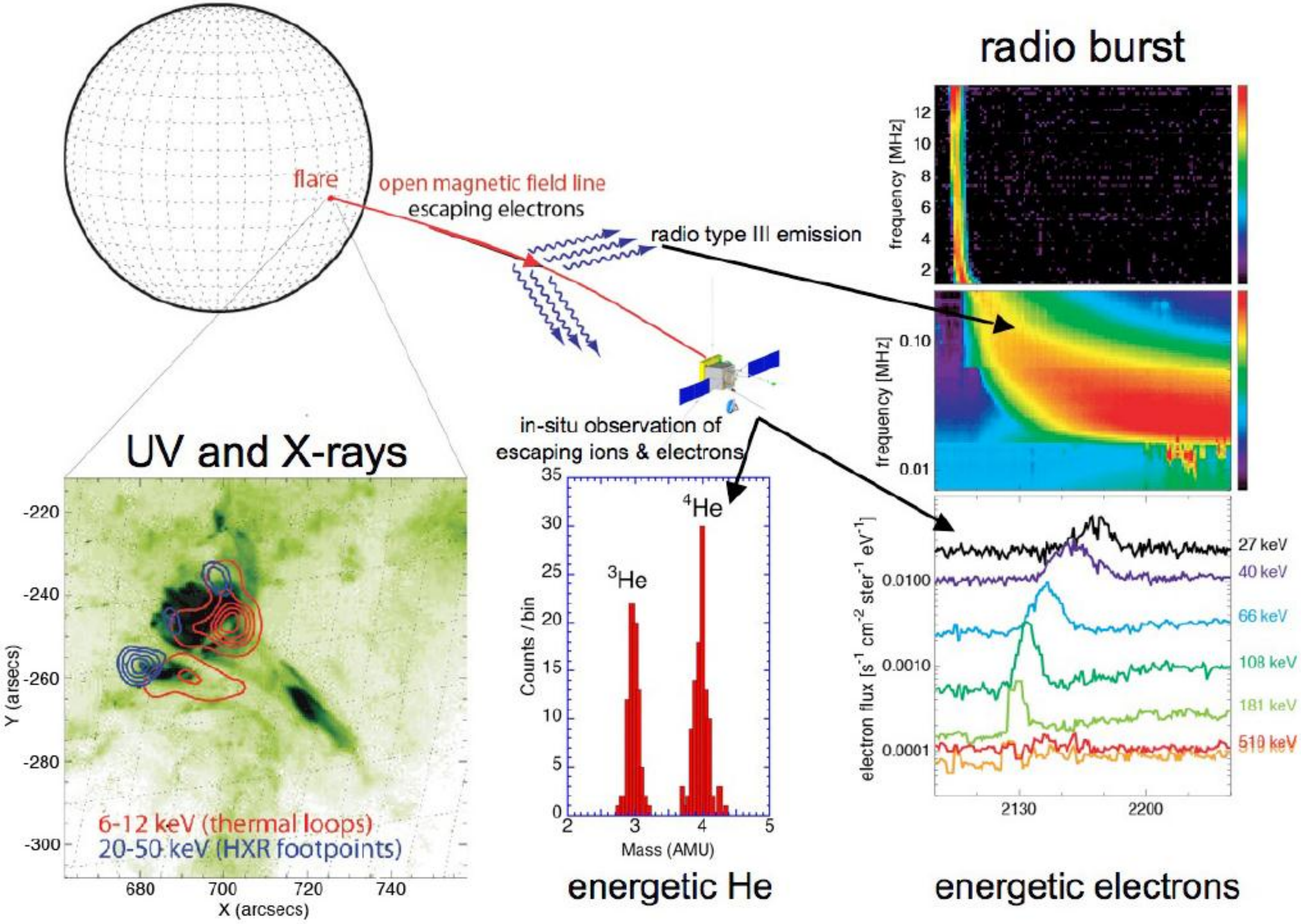
- Solar Orbiter will make all o these measurements with both remote sensing and in situ instruments

How do solar eruptions produce energetic particle ?

- Around 10% of coronal mass ejection energy is in accelerated particles
- Understanding release and transport mechanisms requires going close to the Sun
- Solar Orbiter will measure energetic particles within a mean free path of their acceleration site

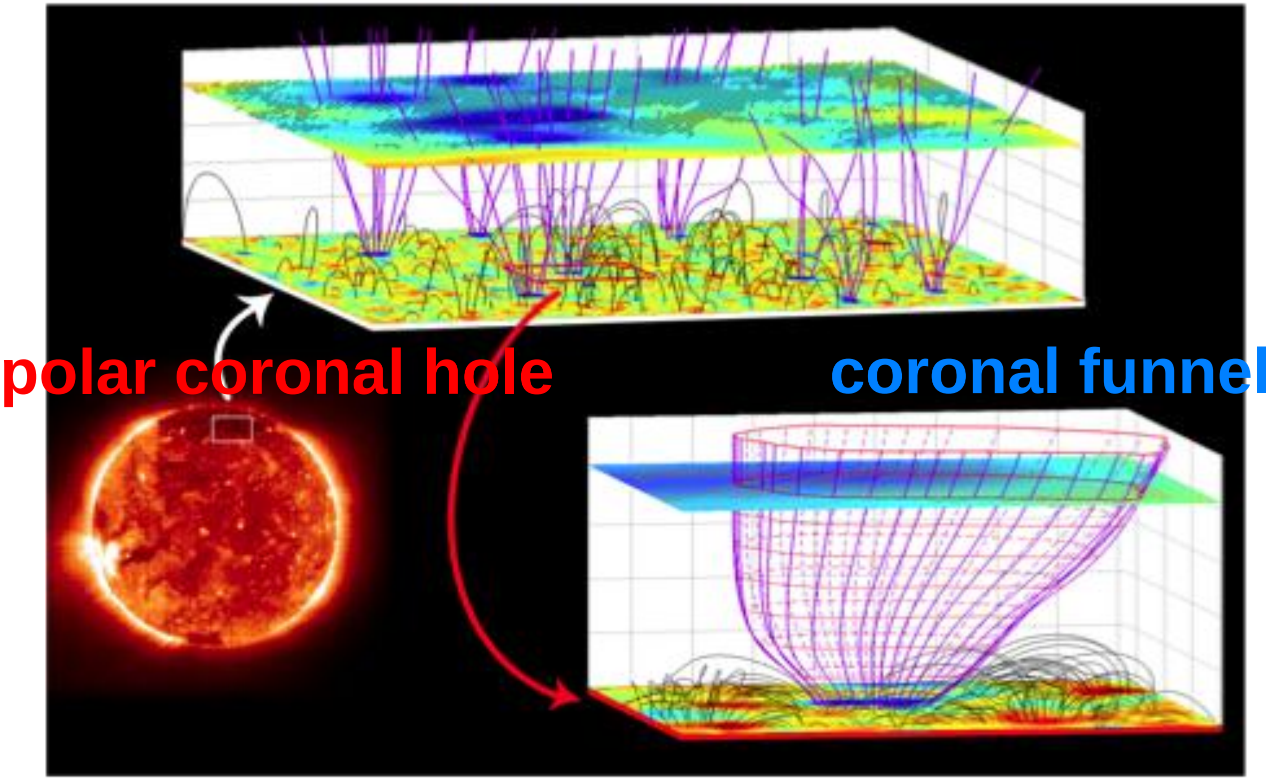


Coordinated remote and in-situ observations of a flare source : Tracing the magnetic connectivity from the solar surface to the inner heliosphere



How and where do the solar wind plasma and magnetic field originate in the corona?

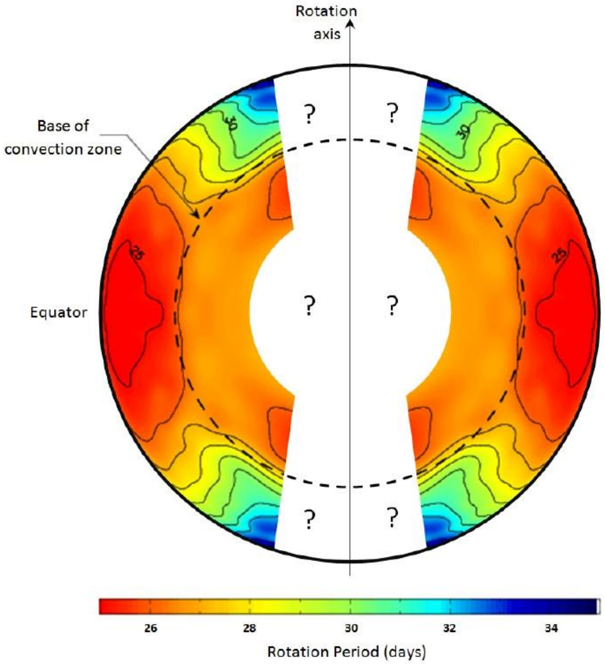
- Solar wind is variable and structured
- Originates in complex magnetic "carpet"
- Small scale transient jets are common

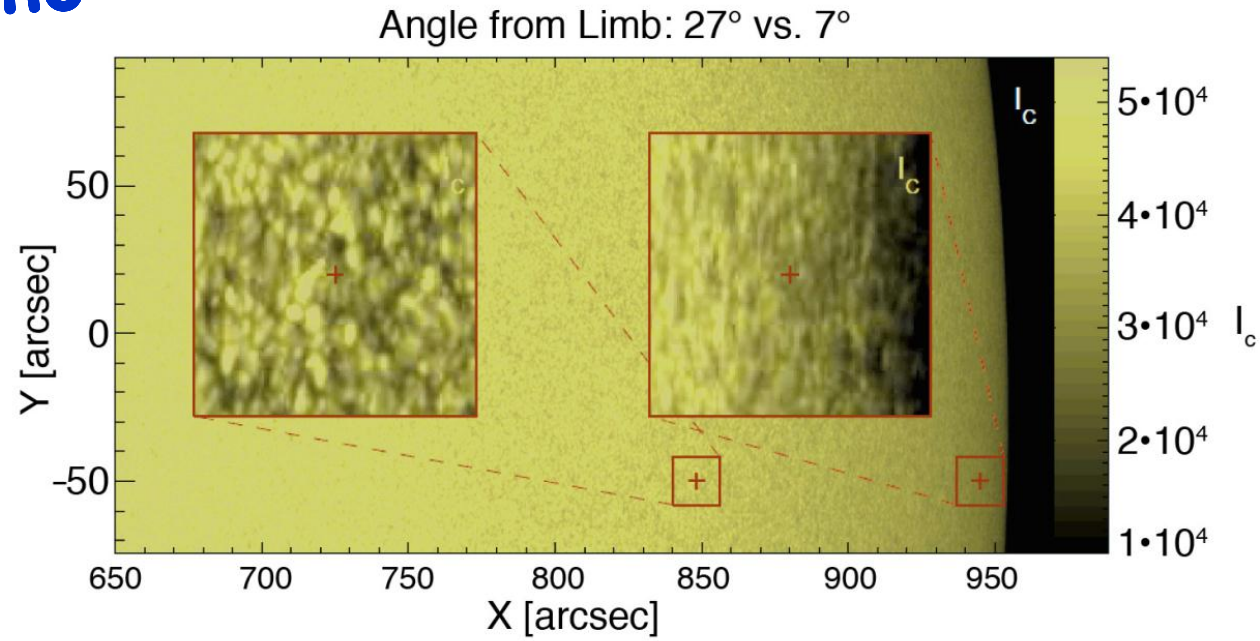


Tu, Zhou, Marsch et al., Science 2005

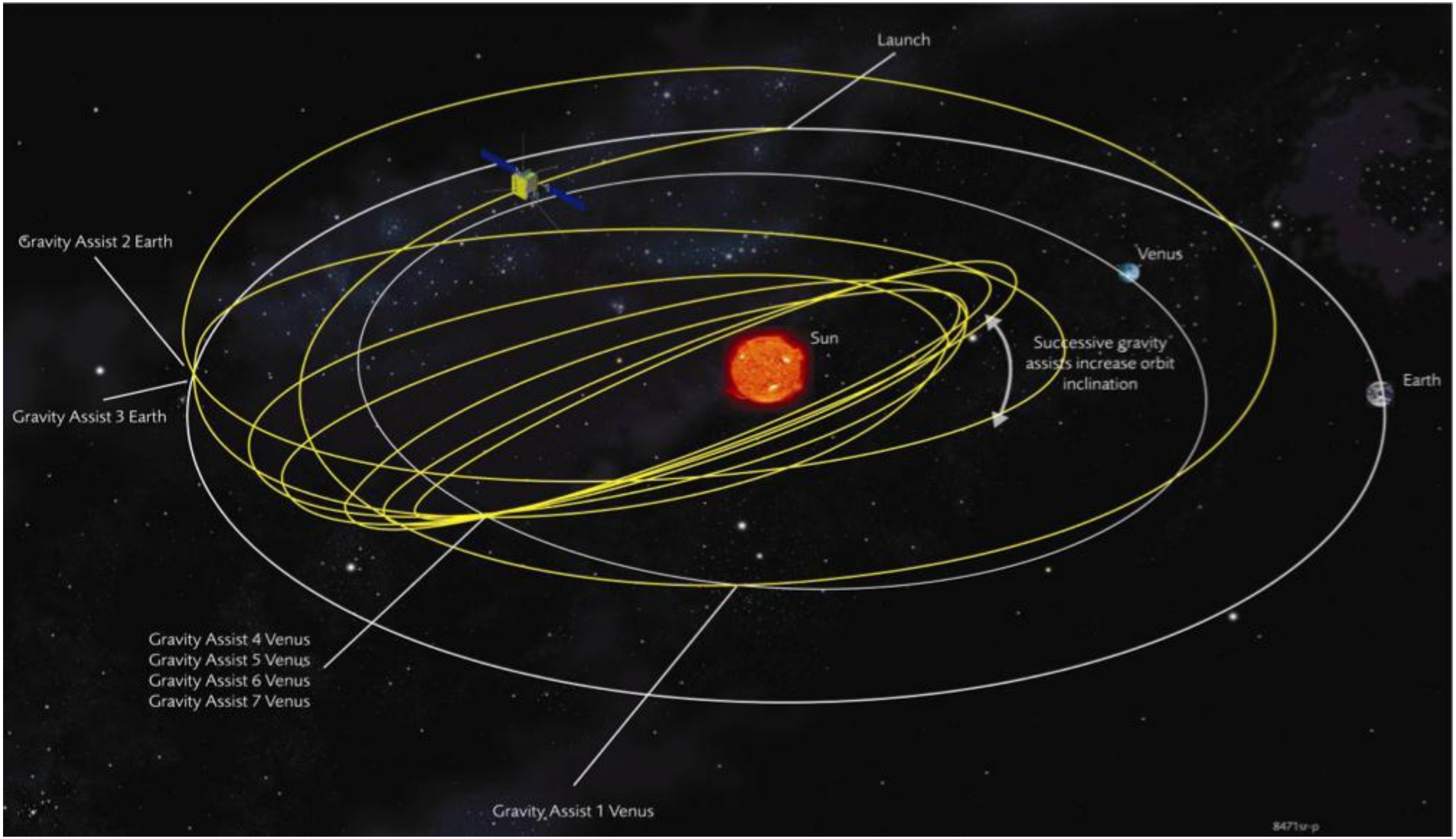
How does the solar dynamo work?

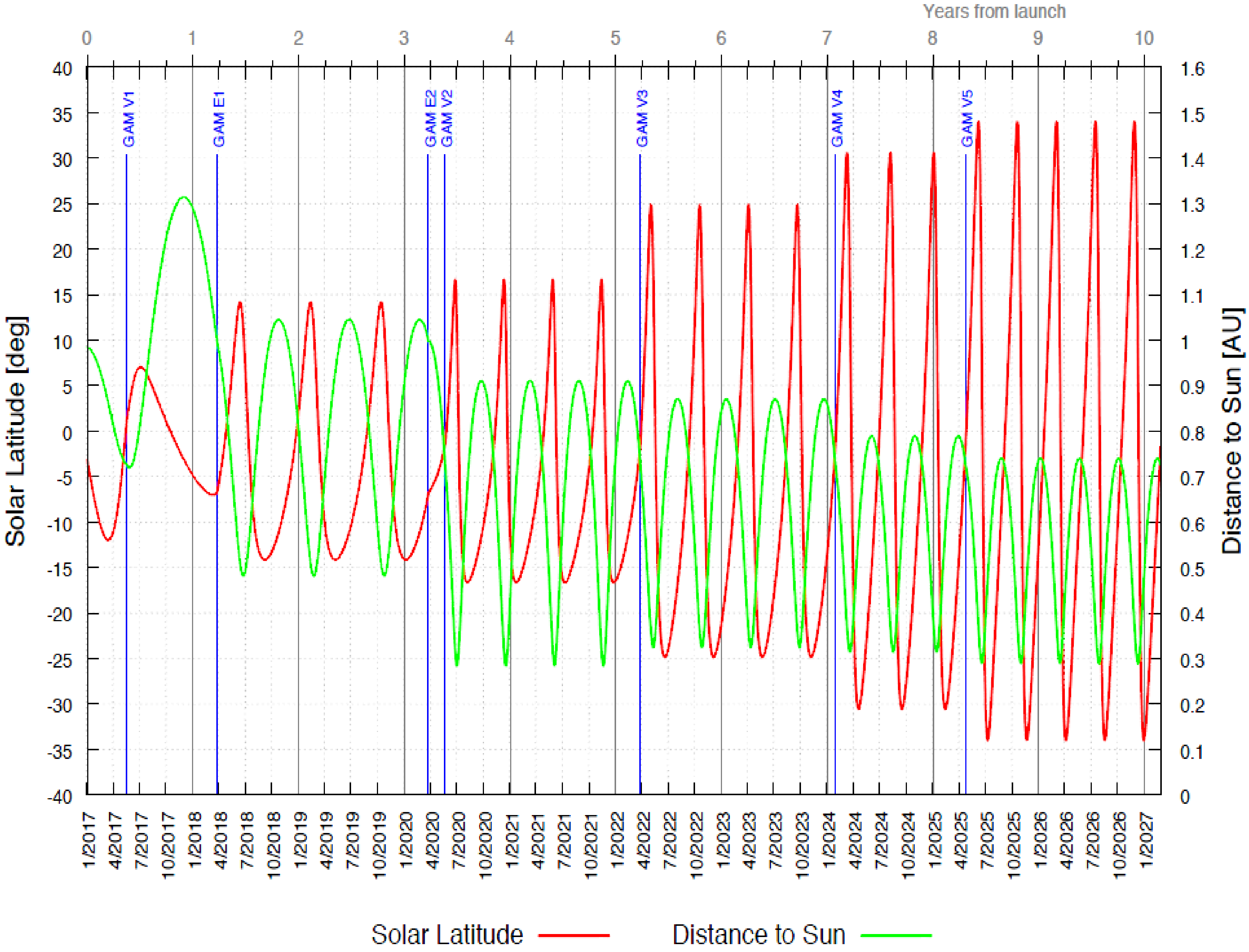
- The unexplored poles are central to the operation of the Sun's dynamo





Mission profile




Years from launch
0
1
2
3
4
5
6
7
8
9
10
GAM V1
GAM E1
GAM E2
GAM V2
GAM V3
GAM V4
GAM V5
Solar Latitude [deg]
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
Distance to Sun [AU]
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1/2017
4/2017
7/2017
10/2017
1/2018
4/2018
7/2018
10/2018
1/2019
4/2019
7/2019
10/2019
1/2020
4/2020
7/2020
10/2020
1/2021
4/2021
7/2021
10/2021
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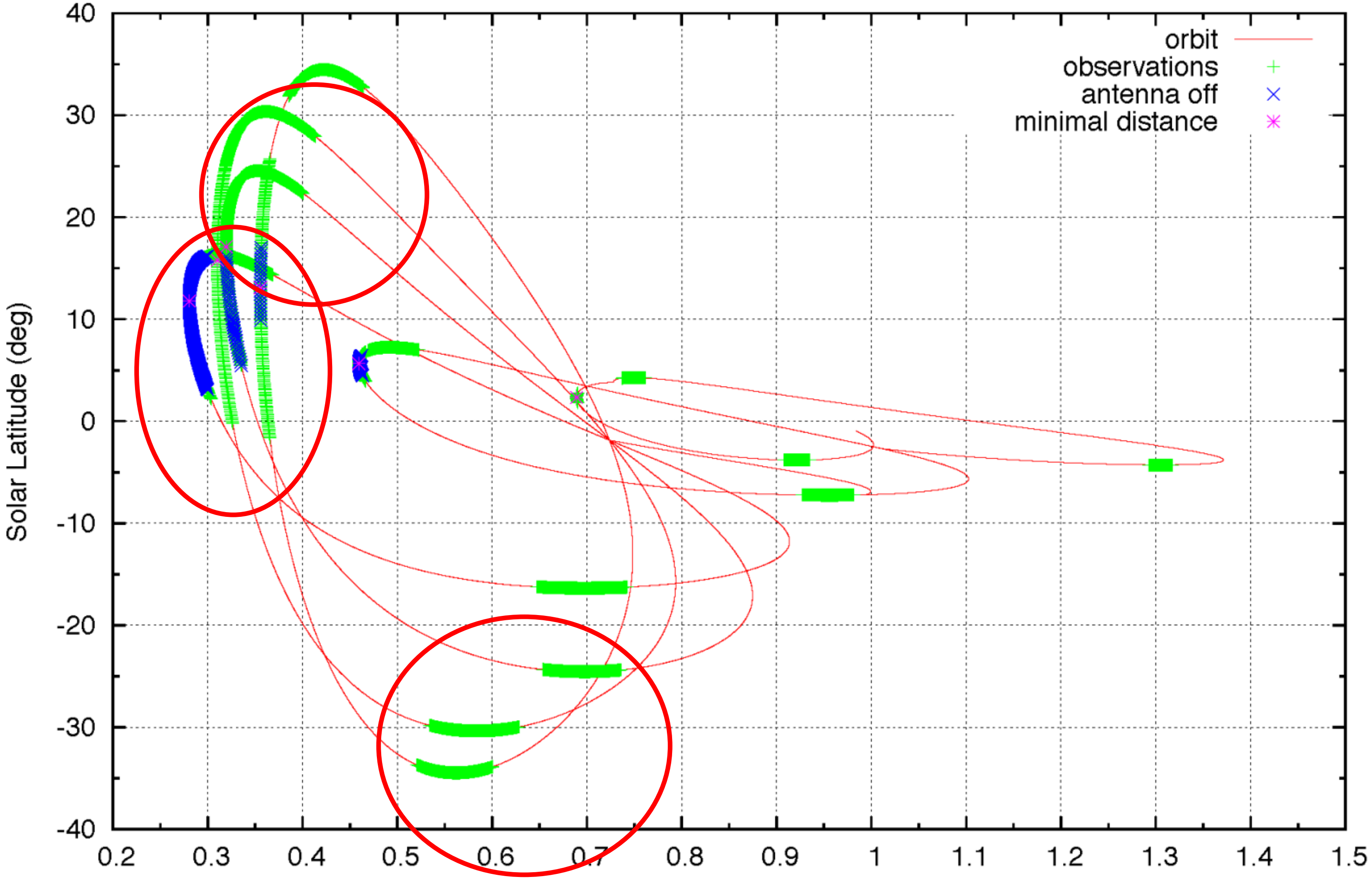
4/2022
7/2022
10/2022
1/2023
4/2023
7/2023
10/2023
1/2024
4/2024
7/2024
10/2024
1/2025
4/2025
7/2025
10/2025
1/2026
4/2026
7/2026
10/2026
1/2027
Solar Latitude
Distance to Sun



orbit
observations
antenna off
minimal distance
Solar Latitude (deg)
Distance (AU)
40
30
20
10
0
-10
-20
-30
-40
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5

In situ instruments			
SWA	Solar wind analyser	C. Owen, UK	Sampling protons, electrons and heavy ions in the solar wind
EPD	Energetic particle detector	J. Rodriguez-Pacheco, Spain	Measuring timing and distribution functions of accelerated energetic particles
MAG	Magnetometer	T. Horbury, UK	High-precision measurements of the heliospheric magnetic field
RPW	Radio and plasma wave analyser	M. Maksimovic, France	Studying local electromagnetic and electrostatic waves and solar radio bursts
Remote sensing instruments			
PHI	Polarimetric and heliospheric imager	S. Solanki, Germany	Full-disc and high-resolution visible light imaging of the Sun
EUI	Extreme ultraviolet imager	P. Rochus, Belgium	Studying fine-scale processes and large-scale eruptions
STIX	Spectrometer/telescope for imaging X-rays	S. Krucker, Switzerland	Studying hot plasmas and accelerated electrons
METIS	Multi-element telescope for imaging and spectroscopy	E. Antonucci, Italy	High-resolution UV and extreme UV coronagraphy
SoloHI	Solar Orbiter heliospheric imager	R.Howard, US	Observing light scattered by the solar wind over a wide field of view
SPICE	Spectral imaging of the coronal environment	ESA provided	Spectroscopy on the solar disc and corona

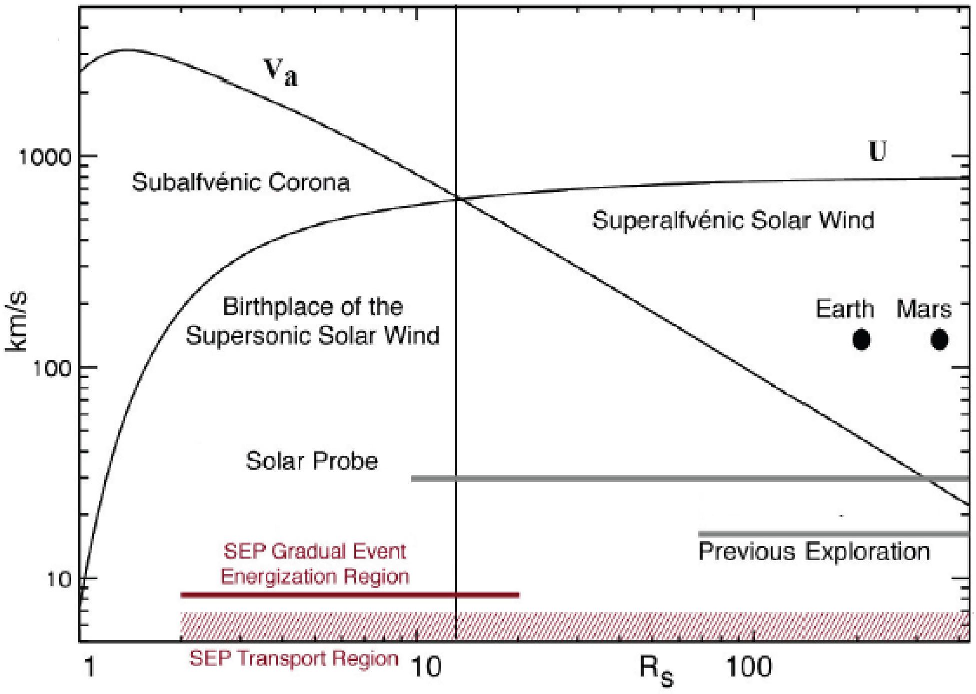
Solar Probe Plus

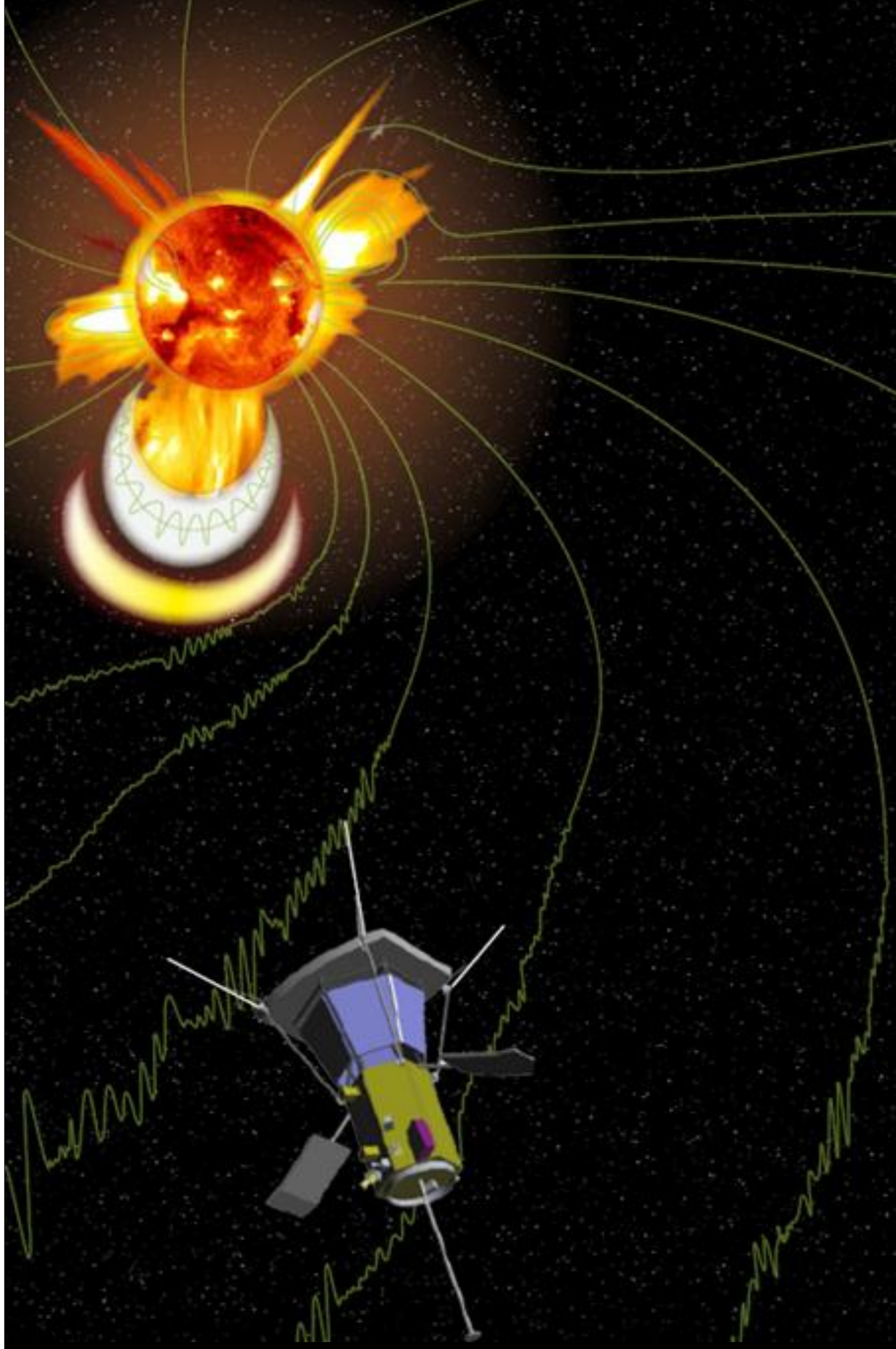
☐ 9.5 Rs to 30 RS : primary science

☐ Focussed in-situ instrumentation

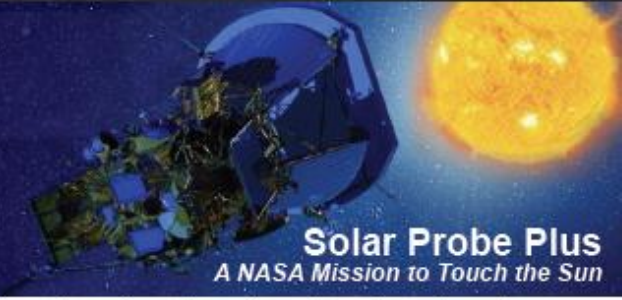
☐ instruments under selection

☐ Launch ~2018

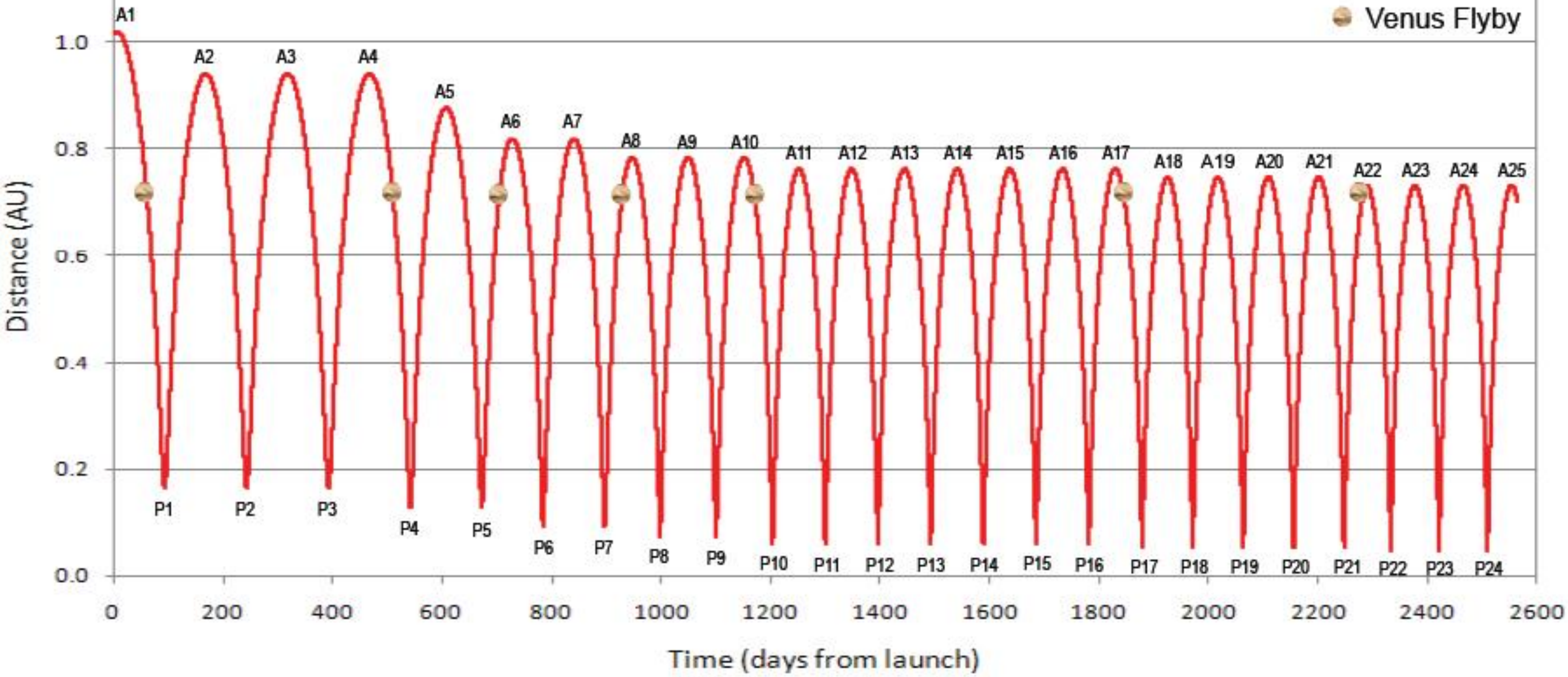




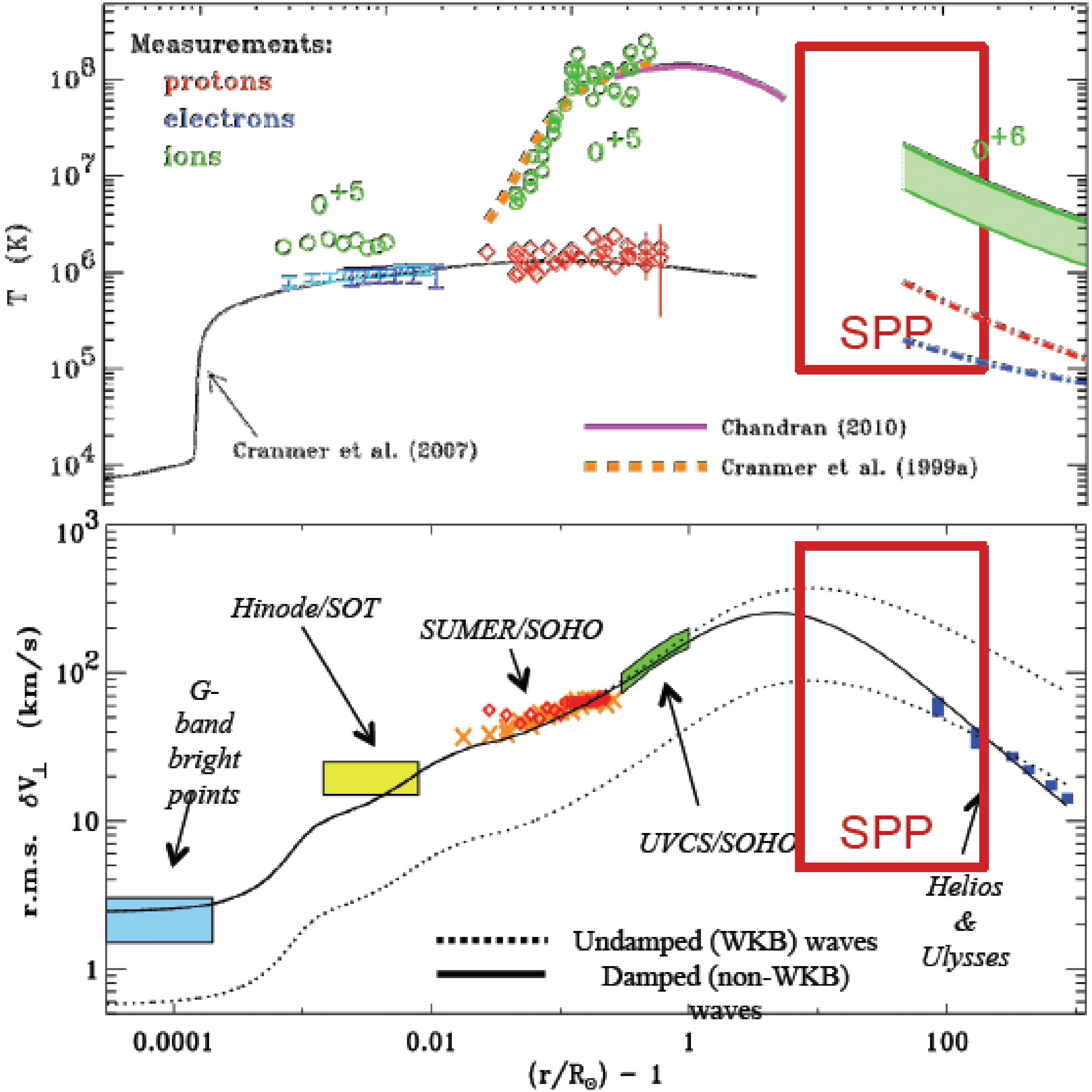
Reference Mission Design
Solar Distance Profile



Orbit #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Period (d)	168	150	150	140	121	112	107	102	102	100	96	96	96	96	96	96	96	92	92	92	87	88	88	88



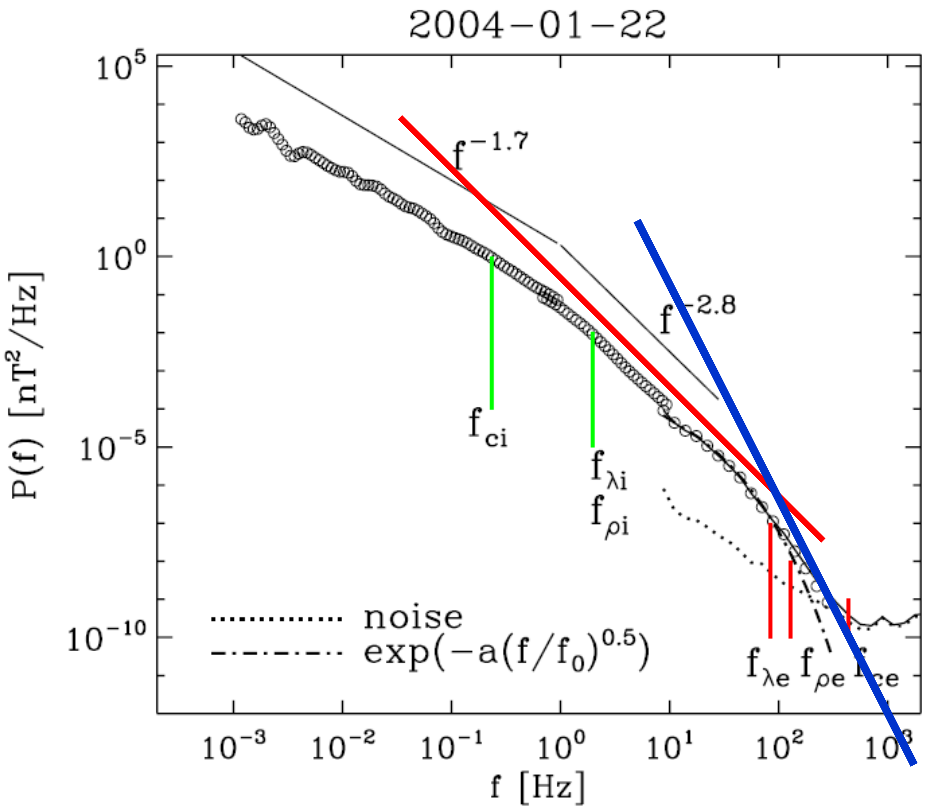
- **Max solar distance is1.018 AU, and min solar distance is 0.0442 AU (9.5 R_S)**
- **Total of 25 aphelia (A1 through A25) and 24 perihelia (P1 through P24)**
- **Perihelia gradually decreases**

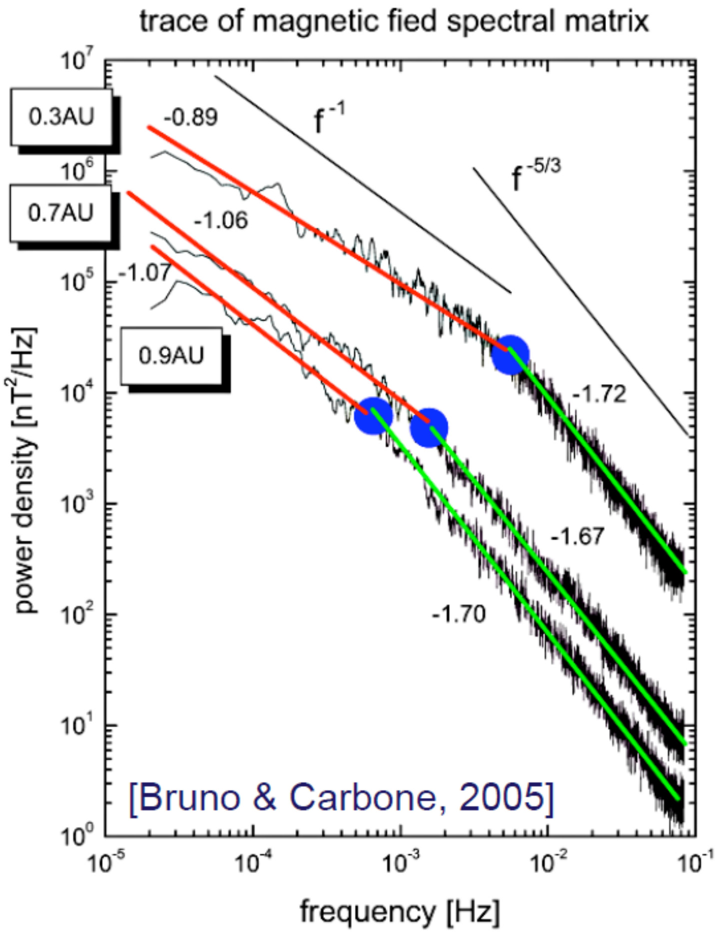

Measurements:
protons
electrons
ions
O+5
O+5
O+6
SPP
Cranmer et al. (2007)
Chandran (2010)
Cranmer et al. (1999a)
T (K)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
G-band bright points
Hinode/SOT
SUMER/SOHO
UVCS/SOHO
SPP
Helios & Ulysses
Undamped (WKB) waves
Damped (non-WKB) waves
r.m.s. δV⊥ (km/s)
0.0001
0.01
1
100
(r/R⊙) − 1

Evidence of a second break @ electronic scales in the Solar Wind turbulence

Alexandrova et al., PRL, 2009
(See lecture by Sahraoui)

Problem: both δE^2 & δB^2 close to noise levels





[Bruno & Carbone, 2005]

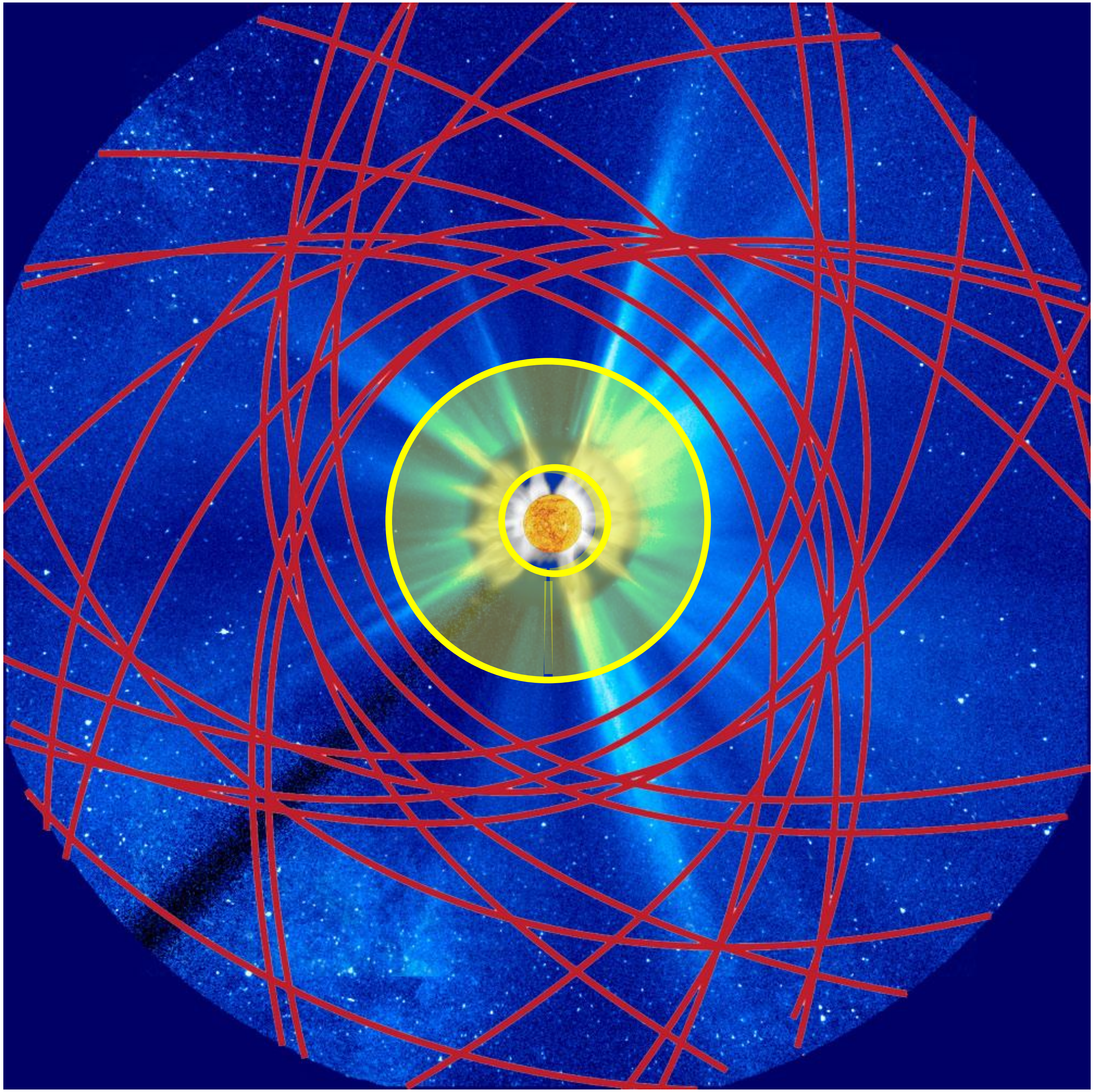
The Turbulence level ↑ with R ↓
@ 10 Rs : close to saturation ?

Exemple of Synergy

Solar Orbiter METIS field-of-view at ~0.28 AU (yellow).

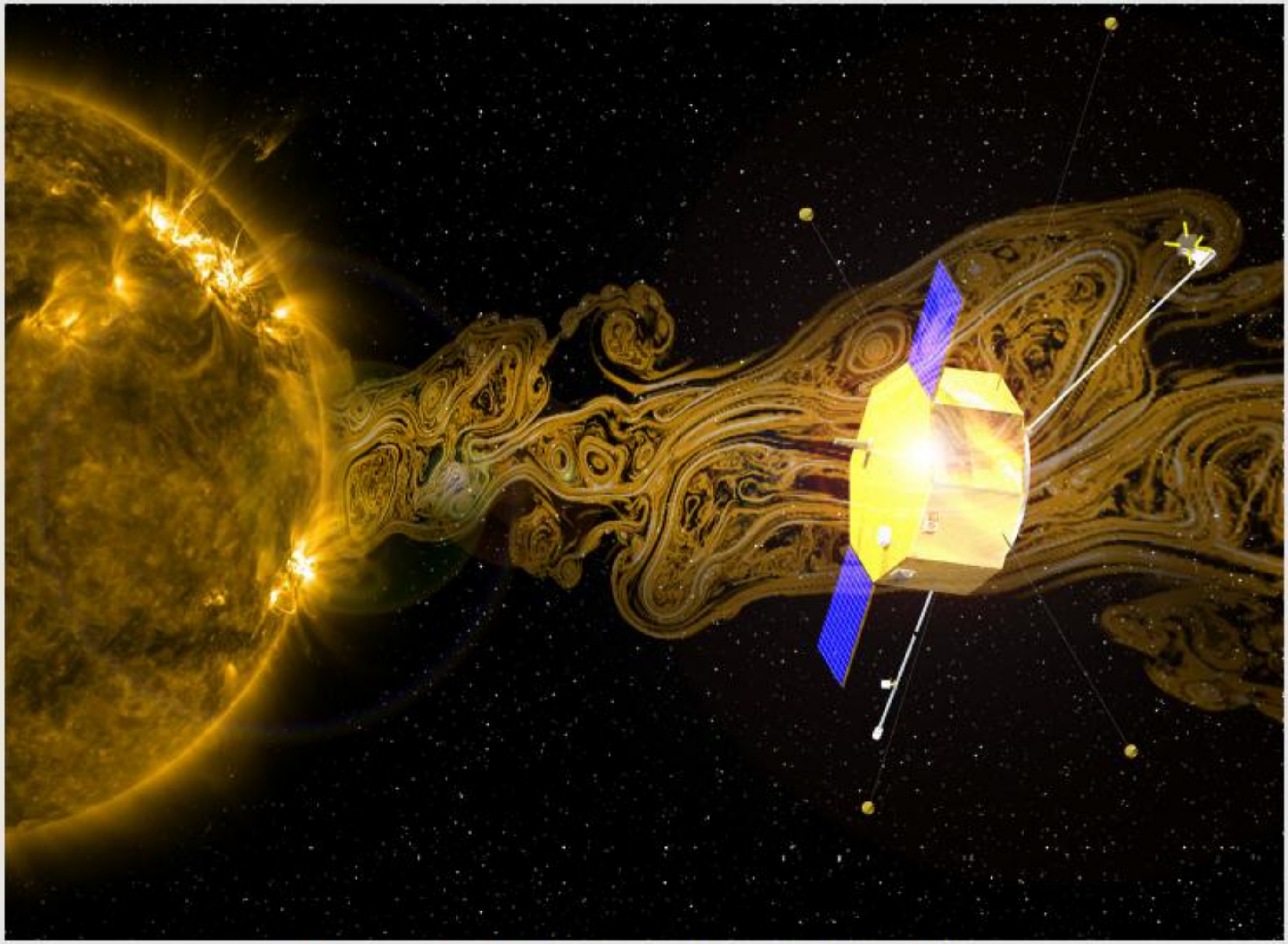
Solar Probe + trajectory projected on the plane of the sky (red)

courtesy E. Antonucci



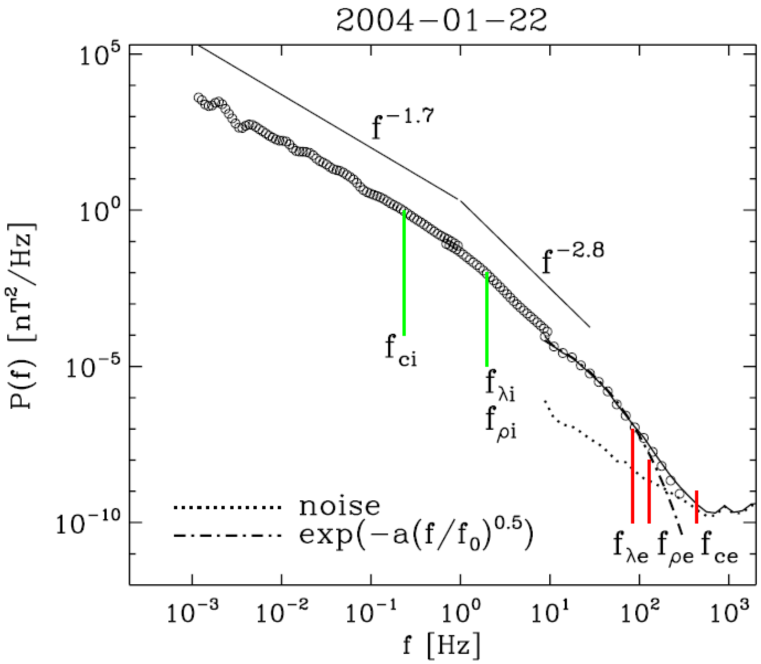
The Future ?

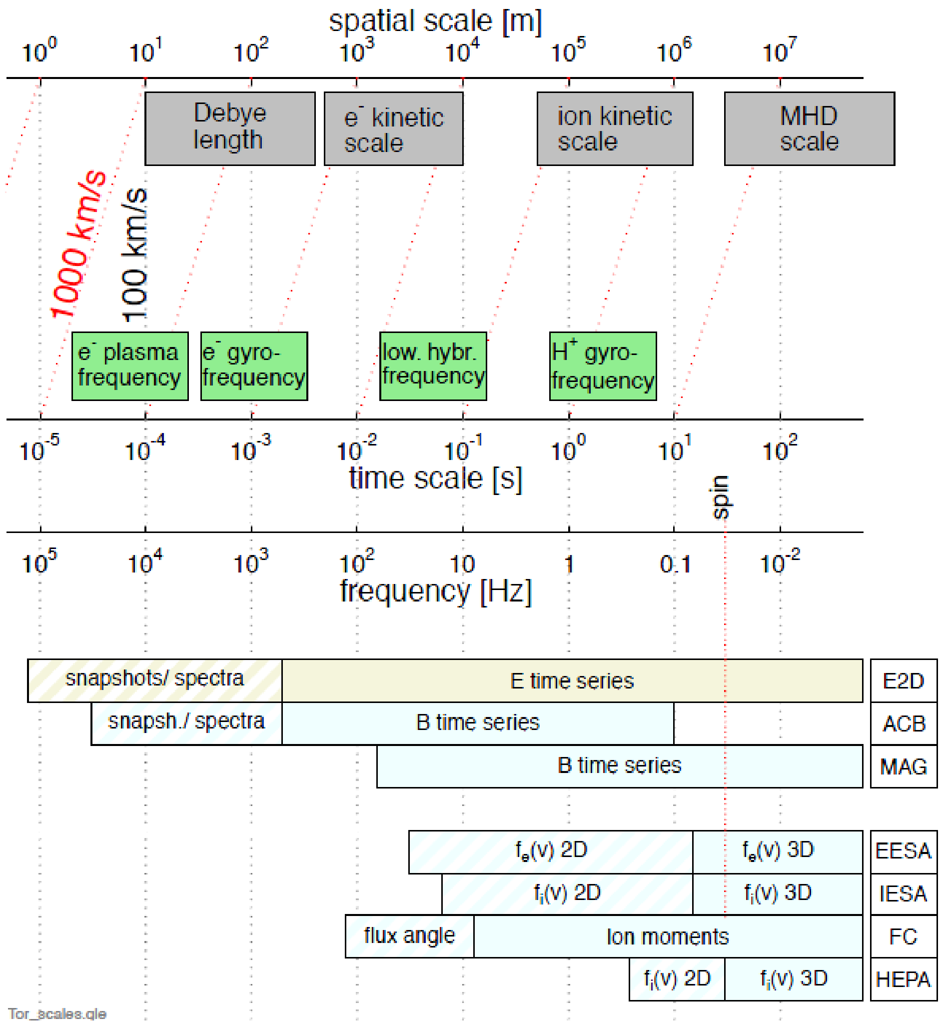
Tor



Exploring dissipation in solar wind turbulence

Both fast Waves & particle measurements

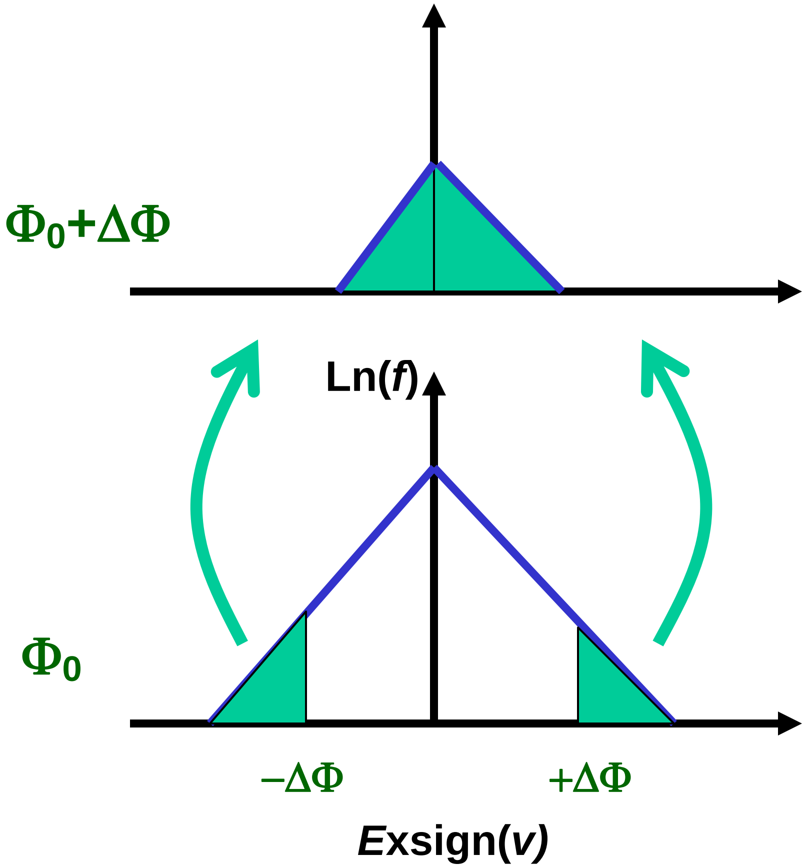




Conclusions

- **The Heliosphere is a very exciting laboratory for plasma physics**
- **Solar Orbiter & Solar Probe will improve our knowledge of the Sun & Heliosphere (solar wind heating and acceleration) …**
- **… & will also improve our knowledge of weakly collisional plasmas**
- **Future space projects (for instance TOR) science objectives should be discussed by a wider community such as the one attending this school**

Collisionless model for the Transition Region : Scudder's (1992) velocity filtration mechanism



Liouville's Theorem

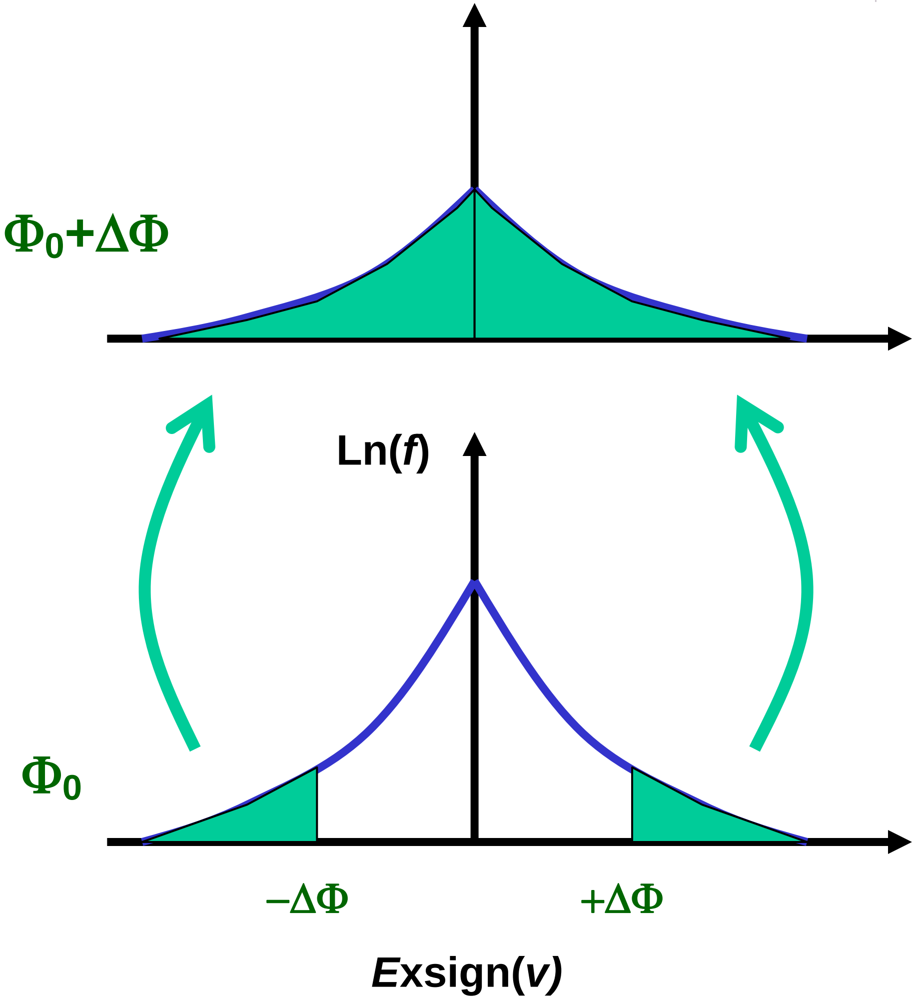
$$\mathbf{f(v^2, r) = f_0(v_0^2, r_0) = f_0(v^2 + U^2(r))}$$

$$\mathbf{with\ U^2(r) = 2\Delta\Phi/m}$$

$$\mathbf{f(v^2, r) = f_0(v_0^2) \times \exp\left(-\frac{U^2(r)}{v_{M0}^2}\right)}$$

$\longrightarrow$ ***T(r)=cst***

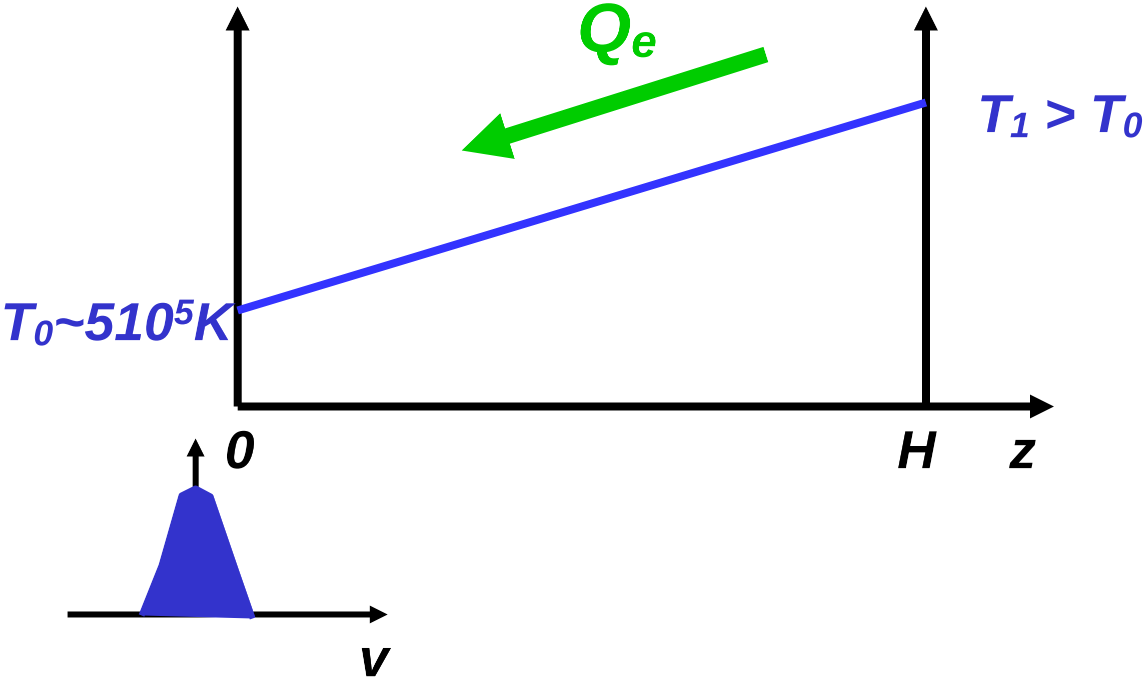
$$f^{\kappa}(v) = \frac{n}{2\pi(\kappa v_{\kappa}^{2})^{3/2}}\,\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)\Gamma(3/2)}\left(1+\frac{v^{2}}{\kappa v_{\kappa}^{2}}\right)^{-(\kappa+1)}$$



$$\mathbf{f}(\mathbf{v}^{2},\mathbf{r}) = \mathbf{f}_{0}\left(\frac{\mathbf{v}^{2}}{\mathbf{1}+\mathbf{U}^{2}(\mathbf{r})/\kappa\mathbf{v}_{\kappa 0}^{2}}\right) \times \left(\mathbf{1}+\frac{\mathbf{U}^{2}(\mathbf{r})}{\kappa\mathbf{v}_{\kappa 0}^{2}}\right)^{-(\kappa+\mathbf{1})}$$

→ ***T(r)* ↗ *with r***

Non-thermal distributions and heat flux in the corona

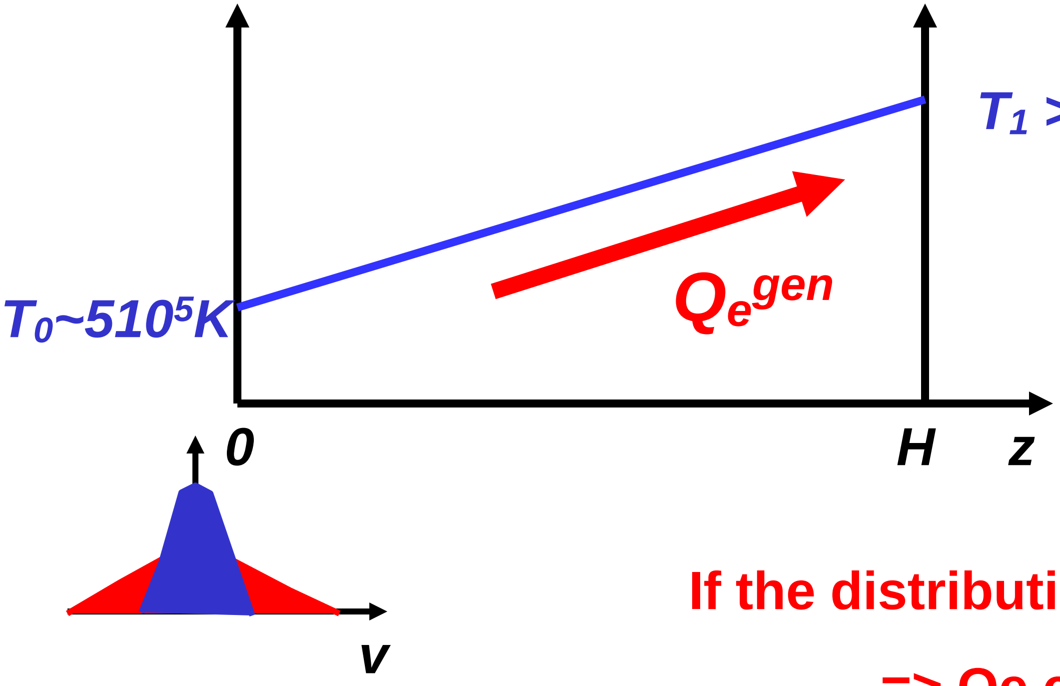


Classical Spitzer-Harm heat flux

$$Q_e = -K \nabla T_e$$

$$Q_e \propto -T_e^{5/2} \frac{\partial T_e}{\partial z}$$

Non-thermal distributions and heat flux in the corona



Classical Spitzer-Harm heat flux

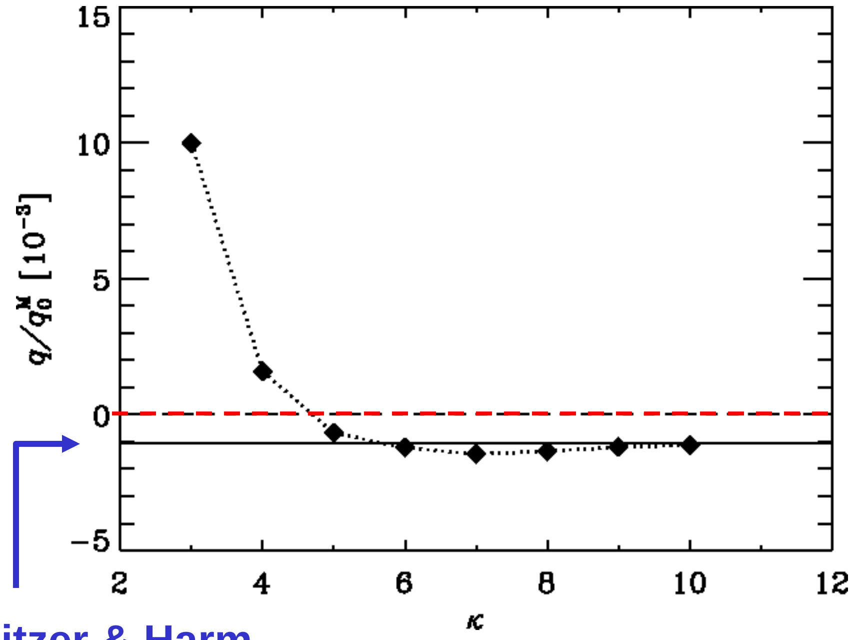
$$Q_e = -K \nabla T_e$$

$$Q_e \propto -T_e^{5/2} \frac{\partial T_e}{\partial z}$$

If the distribution is non-thermal at *z=0* :

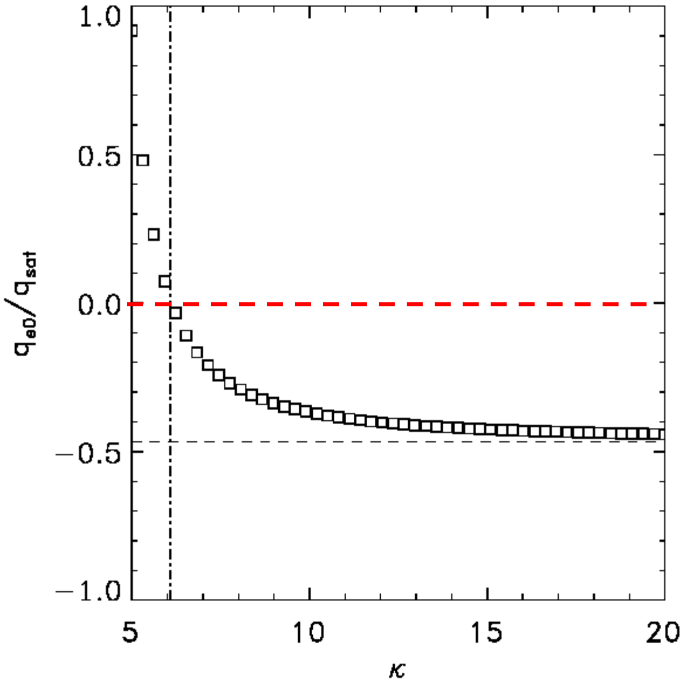
=> Qe changes direction

Landi & Pantellini, 2001 & 2003



Spitzer & Harm

Dorelli & Scudder, 1999 & 2003



Even with a weak Knundsen number (10^{-2} à 10^{-4})

→ **e^- VDF with supra-thermal tails still exist at $z = 0.1$ Rs**

→ **The classical Spitzer & Harm heat flux is not valid**