Quasi-thermal noise in the heliosphere

N. Meyer-Vernet & the QTN team(s)

International Workshop on solar, heliospheric and magnetospheric radioastronomy:

The legacy of Jean-Louis Steinberg (1922-2016)
6-10 Nov 2017, Observatoire de Paris, Meudon

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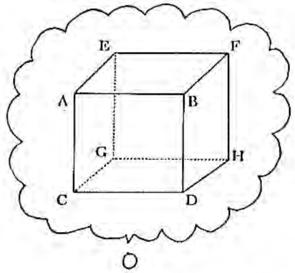
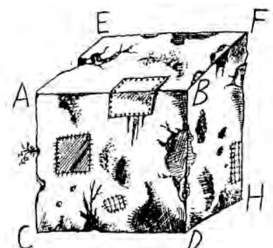
nicole.meyer@obspm.fr
www.lesia.obspm.fr/perso/nicole-meyer/

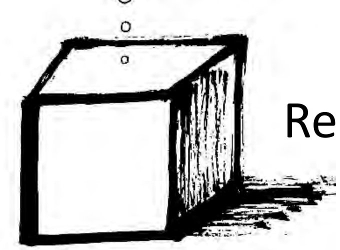
- What is quasi-thermal noise (QTN) spectroscopy?
- Theoretical bases: plasma/antenna
- Complications
- Further complications



Theoretician dream

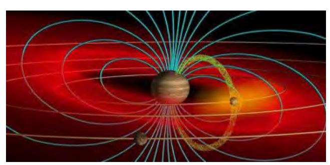


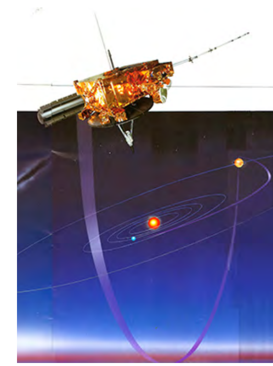
Reality of the space scientist



Real life

- Applications in various heliospheric environments

- The future



• What is quasi-thermal noise (QTN) spectroscopy?

The beginning

On Natural Noises Detected by Antennas in Plasmas *J. Geophys. Res. (1979)*

Received August 2, 1978

A noise that might serve to use a radio receiver as an *in situ* plasma sensor and should explain previous measurements

February 1979: Paper rejected because the theory was too simple and there was no detailed application to a geophysical plasma

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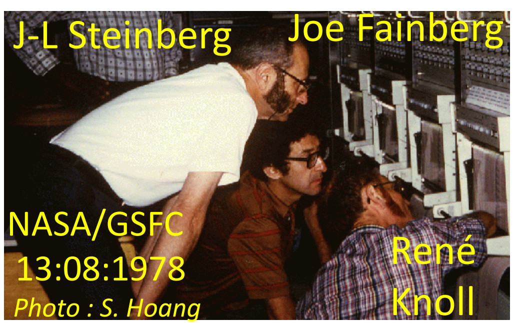

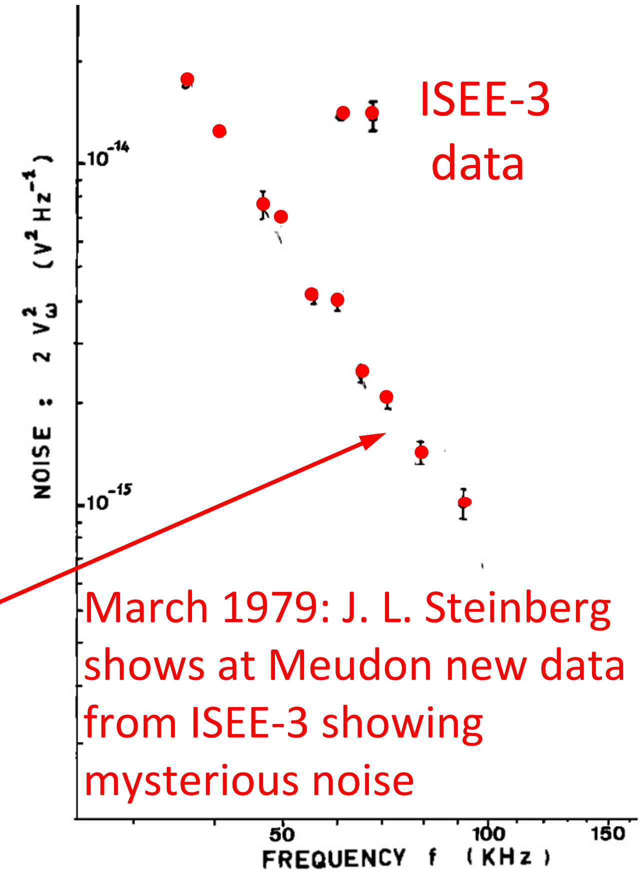

March 1979: J. L. Steinberg shows at Meudon new data from ISEE-3 showing mysterious noise

What is the origin of this noise?

The beginning

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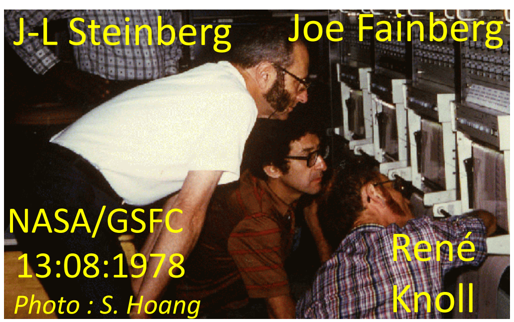
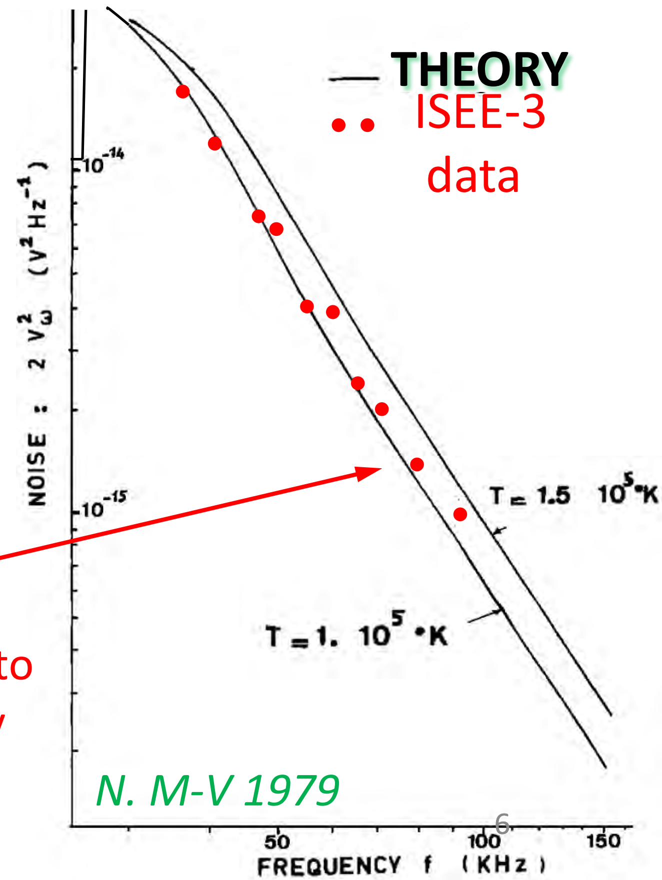


revised March 27, 1979
accepted March 28, 1979

This "mysterious noise" is similar to the value predicted by the theory of the paper rejected !



QTN spectroscopy was born

N. M-V 1979, Hoang et al 1980, Couturier et al 1981

It is not surprising that in 1978 the referee was doubtful about QTN use

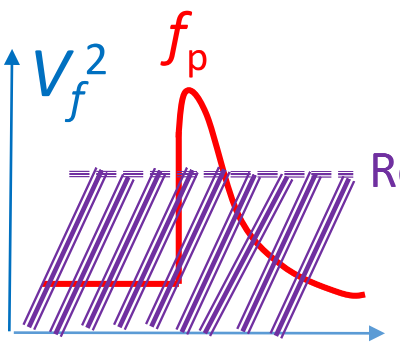
Context:
- Plasma **theory** dealed mainly with instabilities & turbulence
- Fashionable plasma wave **instruments:** relaxation sounder & quadrupolar probe.

Common view: *"the passive mode … is of relatively little interest"* *(XXX 1977)*

Despite several previous publications on plasma fluctuations & antennas in plasmas: Rostoker 1961, Balmain 1965, Sitenko 1967, Fejer & Kan 1969, Schiff 1970 ….

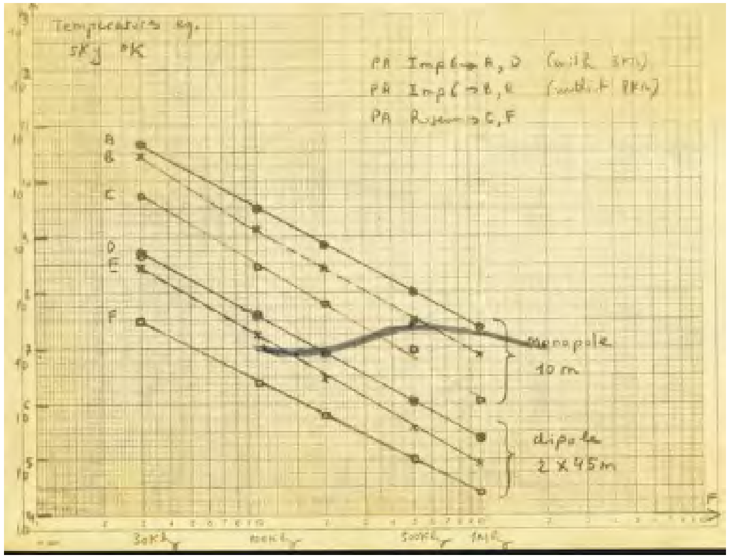
- QTN mainly **below receiver noise**

$\Rightarrow$ plasma frequency peak attributed to plasma instabilities



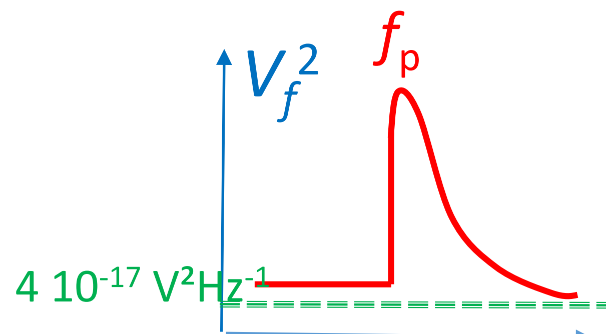
QTN spectroscopy was born

Receiver noise on ISEE-3: 4 10^{-17} V^2Hz^{-1}



from Gérard Epstein's 1974 notes

- QTN mainly **below receiver noise**

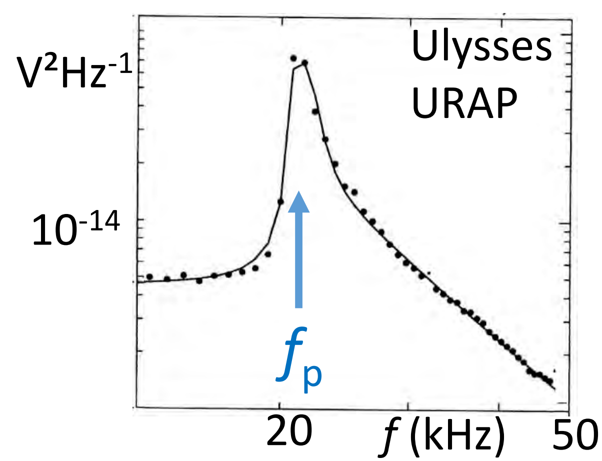


Except 3D radio mapping on ISEE-3 (Observatoire de Paris, NASA/GSFC):
The most sensitive radio receiver of these days (*Knoll et al 1978*)

• What is quasi-thermal noise (QTN) spectroscopy?

The art of transforming a nuisance into a powerful sensor of space plasmas

Contrary to usual spectroscopy, based on **EM waves**, producing a **distant** diagnostic



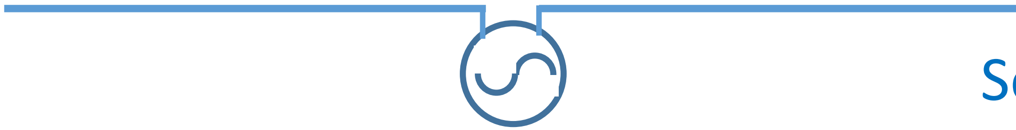
QTN based on **electrostatic plasma waves**
⇒ produces an ***in situ*** diagnostic

Receiver noise too small to be shown on the figure

Frequency of the line ⇒ electron **density**

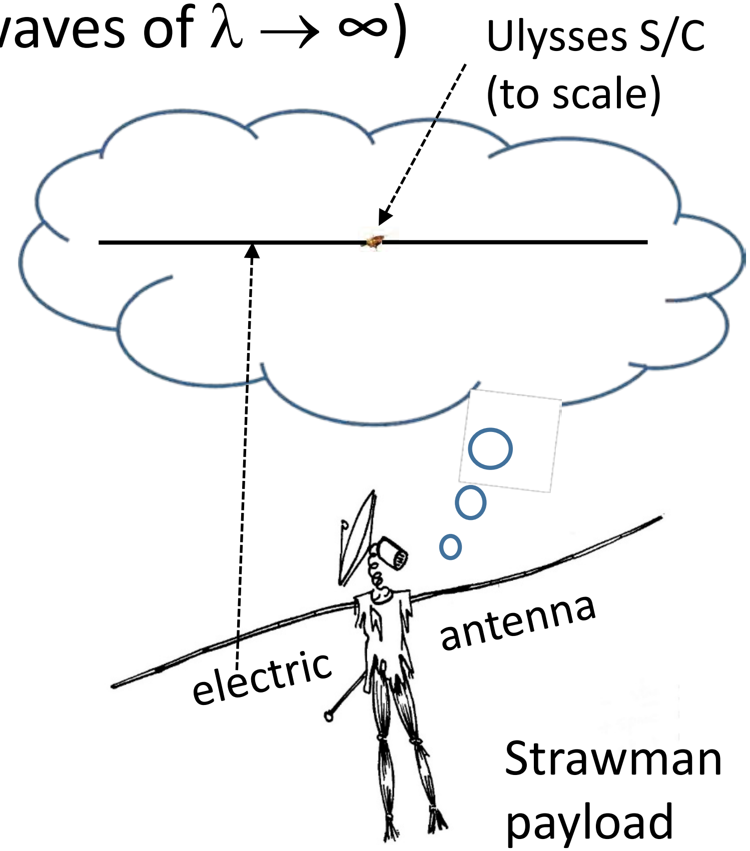
$f_{p\,(kHz)} = 9\, n^{1/2}{}_{(cm\text{-}3)}$ ⇒ radiofrequency range

Shape of the line ⇒ electron **temperature** & other properties



Electric antenna
Sensitive radio receiver

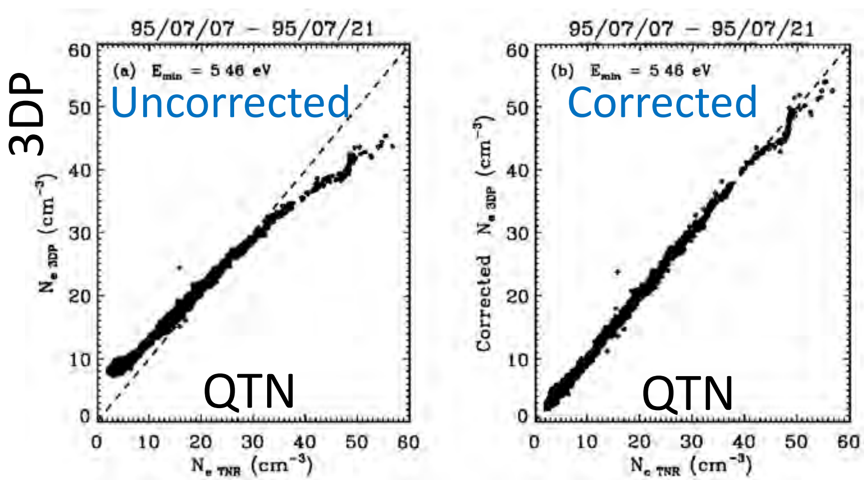
- **Senses a large plasma volume** (via waves of $\lambda \to \infty$)
  - ➢ Equivalent to detector of large cross-section
  - ➢ Immune to spacecraft perturbations (charging effects, photoelectrons …)
- **Passive** $\Rightarrow$ does not perturb the medium



➡ Complementary to particle detectors

Complementary to particle detectors

- Serves to calibrate them *(Maksimovic et al 1995, Issautier et al. 2001, Salem et al. 2001, 2016)*



Wind electron density data

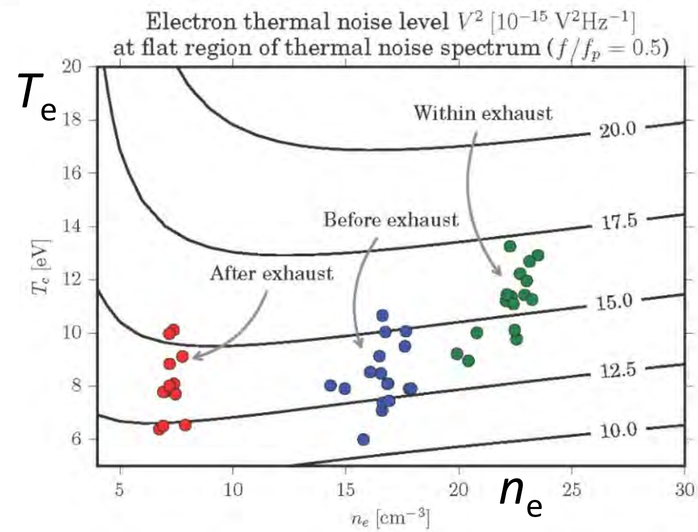
Salem et al. 2001

& talk by Salem et al.

- High rate measurements

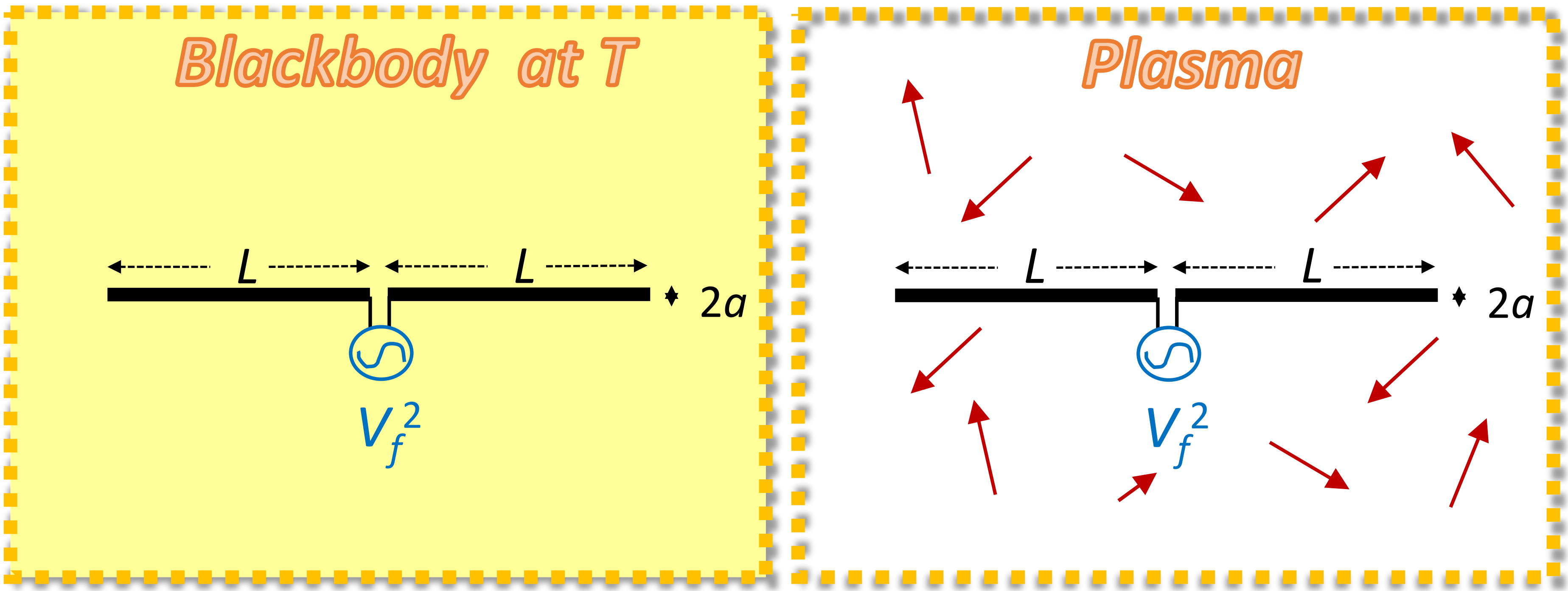
Electron heating at solar wind reconnection exhausts of short duration

Pulupa et al. 2014, 2015, 2016



Isolevels of QTN $\propto T^{1/2}$

• Theoretical bases: plasma/antenna



Antenna in blackbody radiation at T

Nyquist: $V_f^2 = 4\, k_B T\, R_{EM}$

Antenna in plasma at T

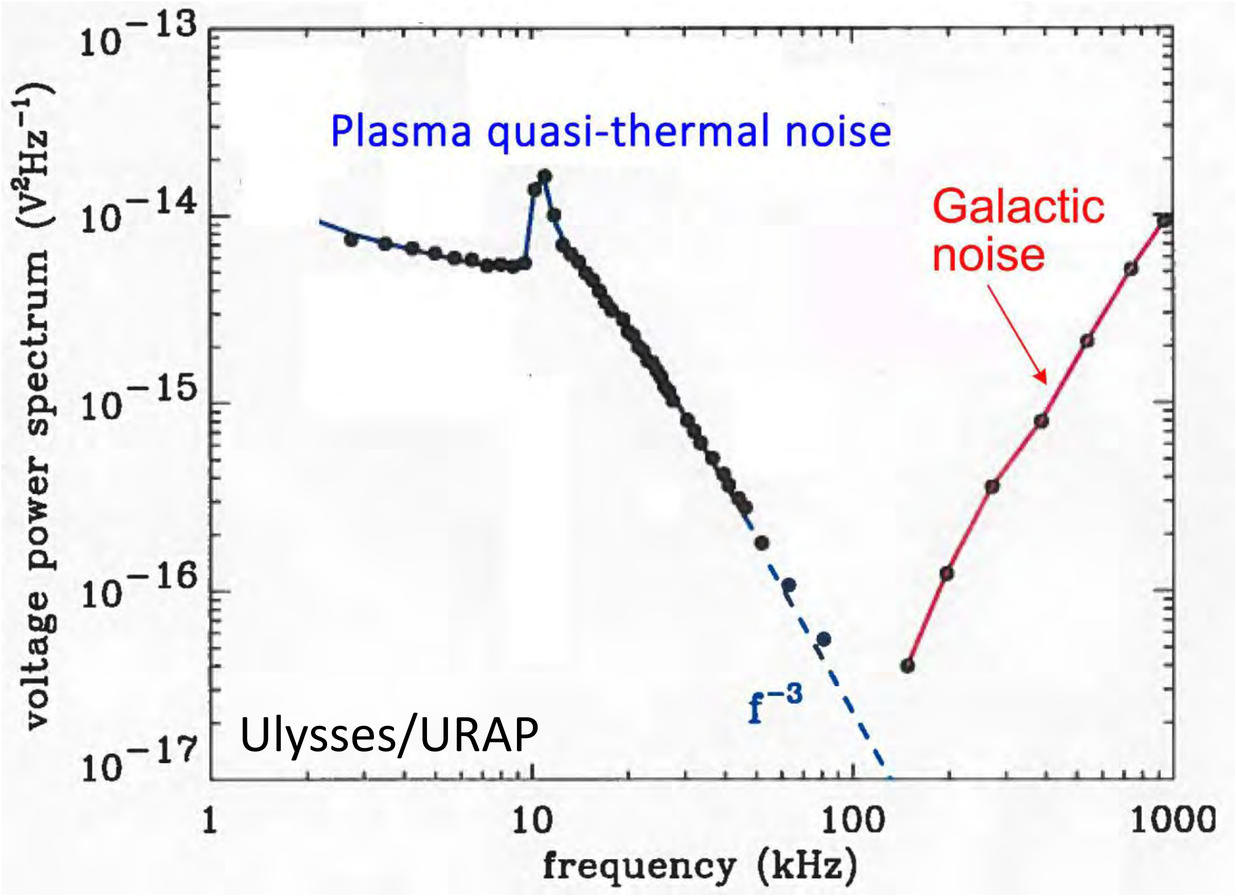
$V_f^2 = 4\, k_B T\, R_P$

Just below f_p, $R_P/R_{EM} = 10^{-2}\,(c/f\,L)^3 >> 1$ $\Rightarrow$ **Plasma thermal noise dominates**

- Theoretical bases: plasma/antenna

Plasma thermal noise dominates

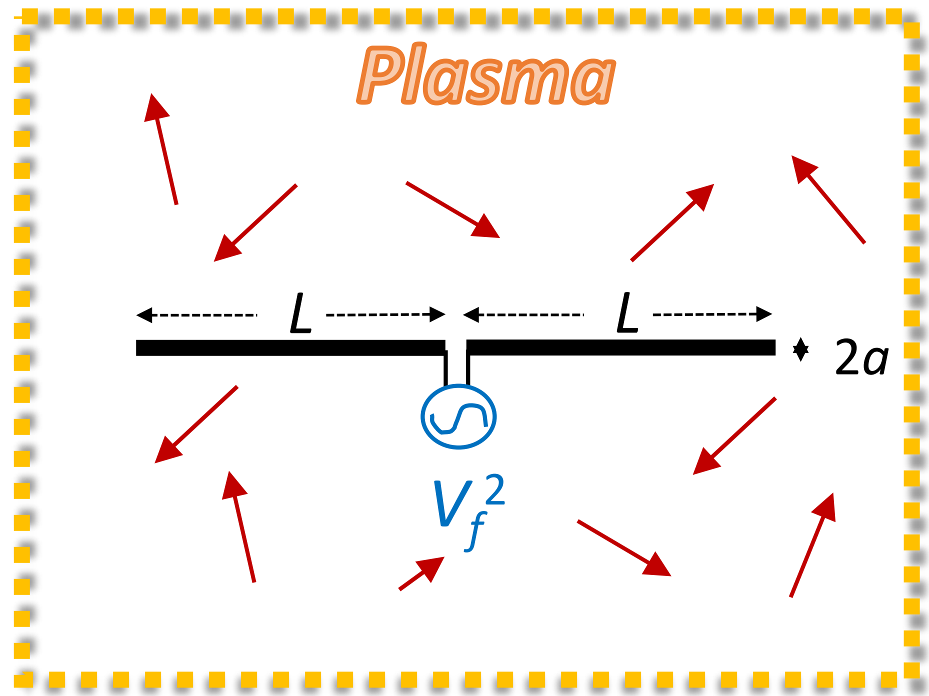
Except at very high frequencies



N. M-V, Hoang, Issautier, Moncuquet, Marcos 2001

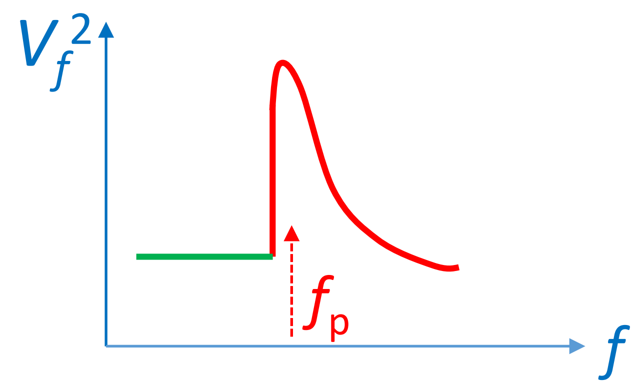
Theoretical bases: plasma/antenna

- QTN produced by motion of charged particles
- Electrostatic field ≠ Coulomb because plasma particles are dressed

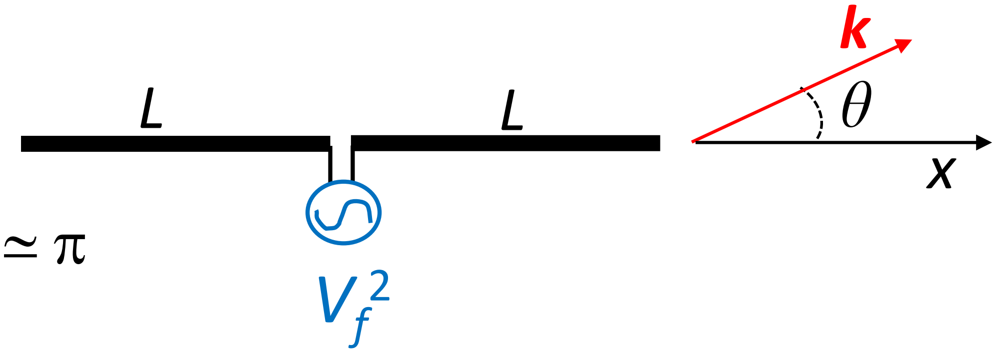


- $f < f_p$: electrons passing within Debye sheath
- $f \gtrsim f_p$: Langmuir waves

$k_L \simeq (1/3^{1/2} L_D)\,(1 - f_p^2/f^2)^{1/2}$

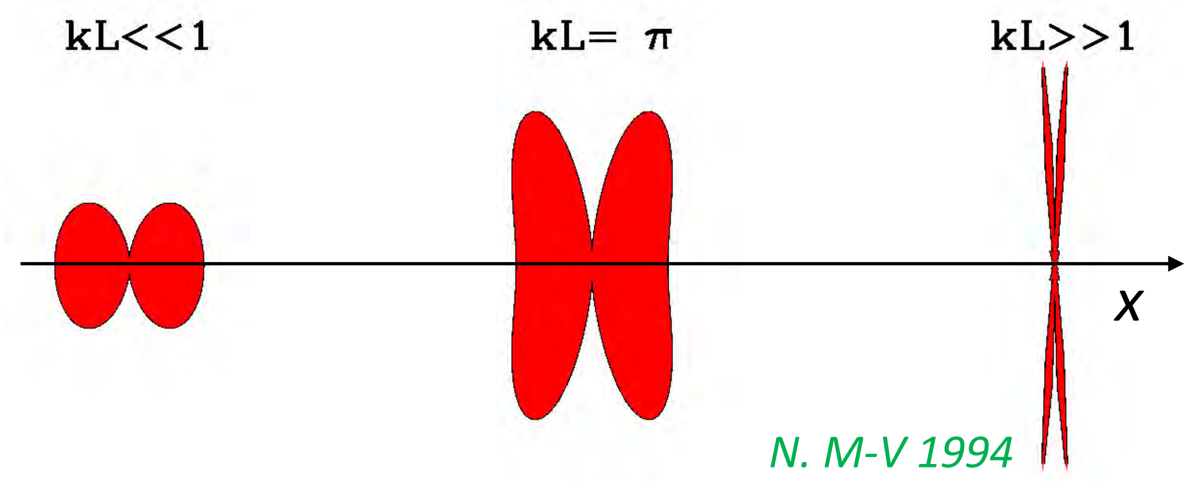


• Theoretical bases: plasma/antenna



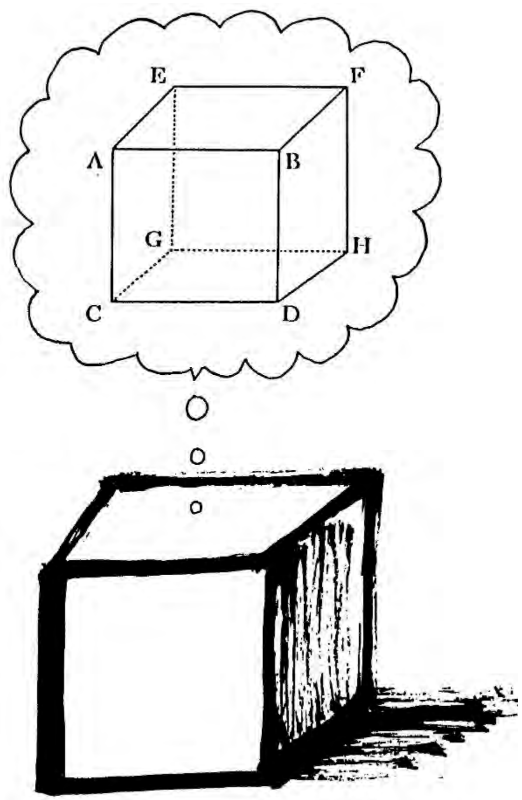
- ✓ Maximum sensitivity: $kL \simeq \pi$
  $\Rightarrow L \simeq \pi L_D$

- ✓ **E** ॥ **k** making angle θ with antenna: max. sensitivity $kL\cos\theta \simeq \pi$
  $\Rightarrow$ if $kL >> 1$ antenna favors $\theta \simeq \pi/2$



Long antenna sensitive to ***k*** perpendicular to its direction

• Complications



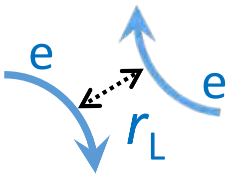
Theoretician dream

Real life

Drawings by Saul STEINBERG

- Complications

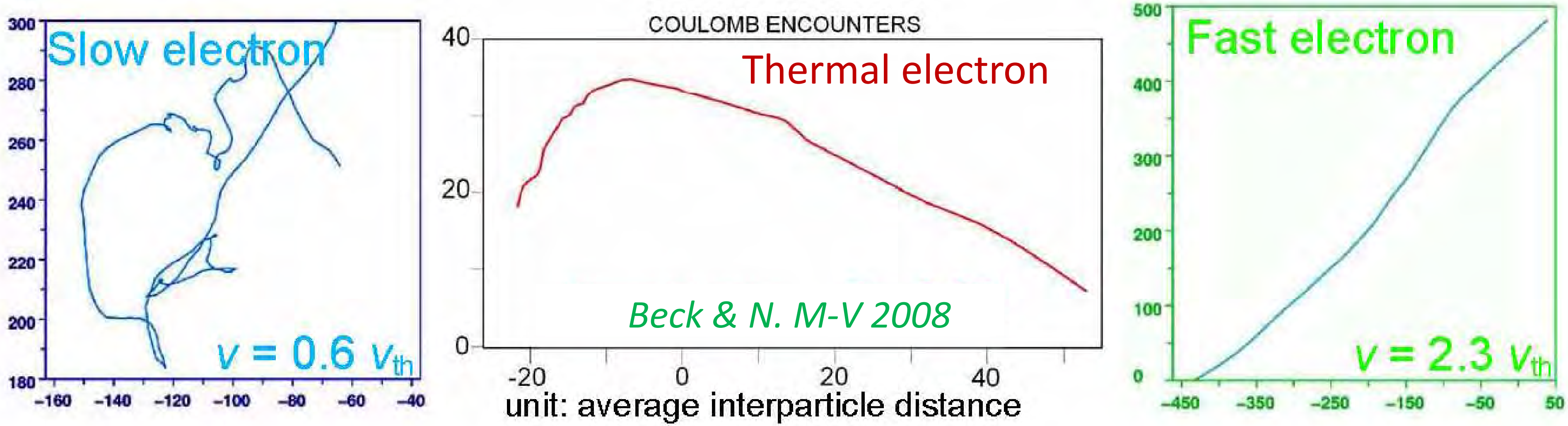
- ***Space plasmas are NOT in thermal equilibrium!***



Fundamental reason: Coulomb cross-section $\propto r_L^2 \Rightarrow$ free path $\propto$ energy squared

Coulomb energy = kinetic energy at distance r_L = $e/(4\pi\varepsilon_0 T_{eV})$

Trajectory of an electron (N-body simulation)



Fast particles are collisionless, even when most particles (core of distribution) are collisional

$\Rightarrow$ **Velocity distributions have suprathermal tails**

- *Space plasmas are NOT in thermal equilibrium!*

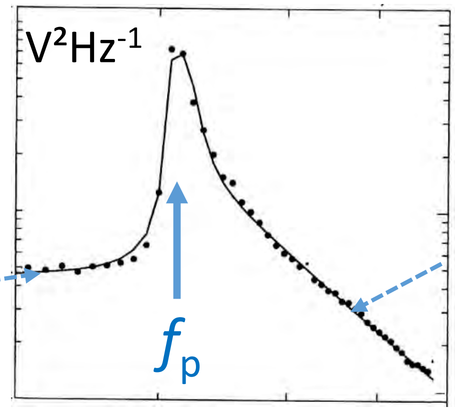
What kind of « **temperature** » does QTN spectroscopy measure?

Define « temperatures » from moments of distribution $T_p \propto \langle v^p \rangle^{2/p}$

- **kinetic temperature T_2** $\propto \langle v^2 \rangle$
- **Debye length** $L_D^2 \propto T_{-2} \propto 1/\langle v^{-2} \rangle$ depends on core of distribution

- $f < f_p$: QTN determined by electrons passing closer than $L_D \Rightarrow$ low-energy electrons

$V_f^2 \propto T_{-2}/T_{-1}^{1/2} \simeq T_{core}^{1/2}$

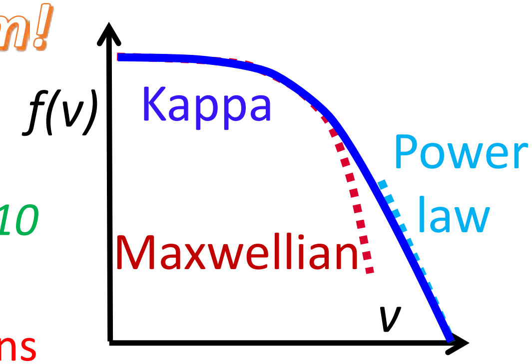


- $f >> f_p$: $V_f^2 \propto T_2$
Kinetic temperature

- Particles of speed v interact with waves of phase speed $\omega/k = v$

$\omega/k \to \infty$ for $f \to f_p$ ⇒ Peak shape determined by **suprathermal** electrons

- ***Space plasmas are NOT in thermal equilibrium!***

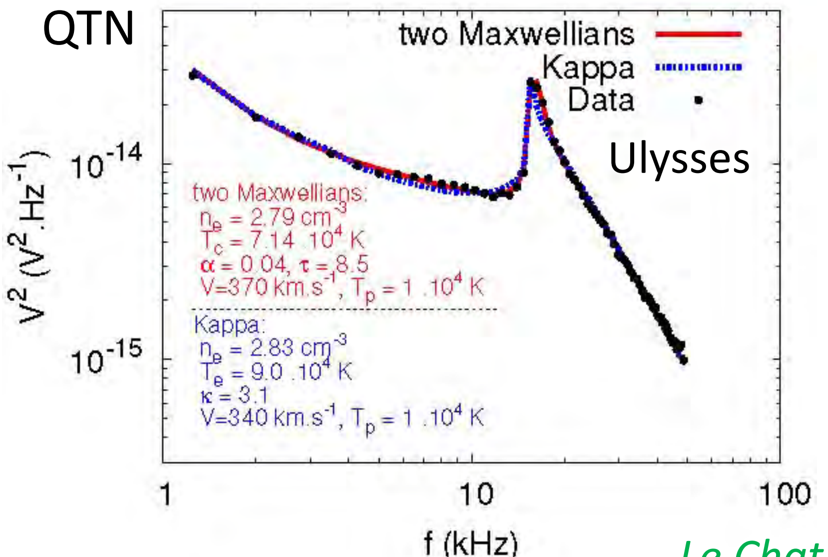


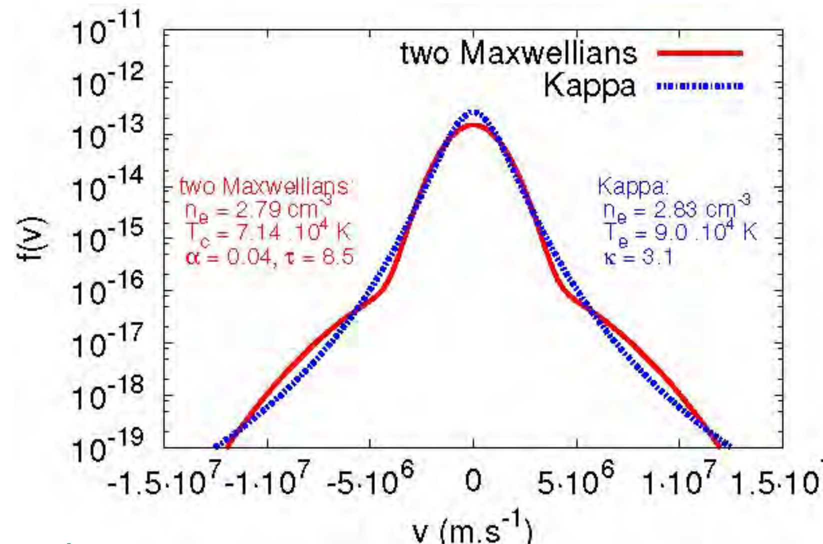
QTN with a Kappa electron distribution

Chateau & N M-V 1991 Zouganelis 2008 Le Chat et al. 2009, 2010

Comparison between Kappa and sum of Maxwellians

QTN





Le Chat et al. 2010

n and *T* agree within a few %

If $2 < L/L_D < 7$ QTN plateau $\propto T_{-2}/T_{-1}^{1/2}$ $\simeq T_c^{1/2}$ for two Maxwellians

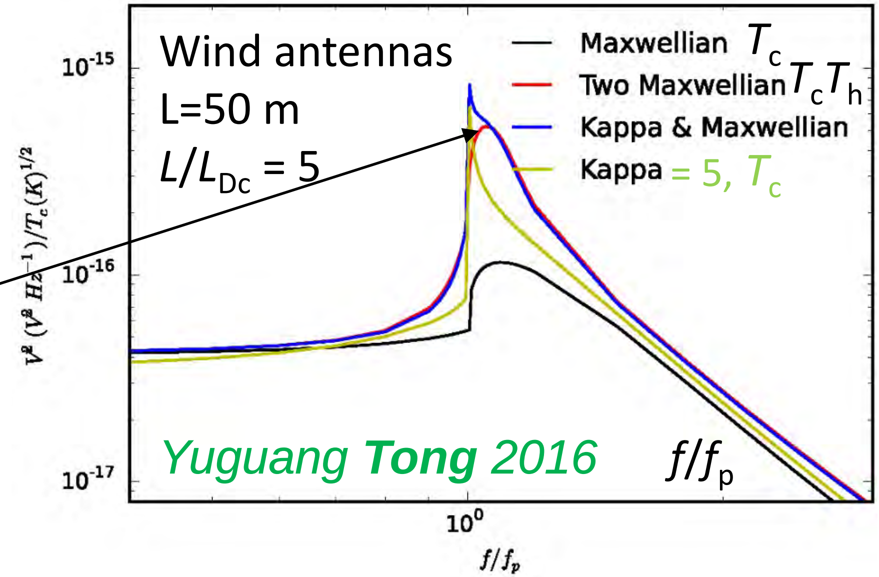
$\simeq 0.96\, T_{-2}^{1/2}$ for Kappa

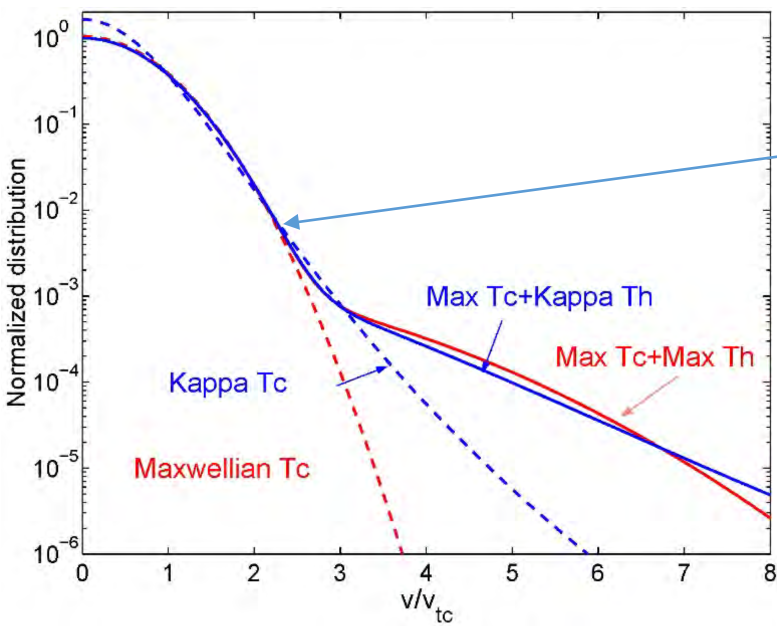
N. M-V et al. 2017

- ***Space plasmas are NOT in thermal equilibrium!***

QTN with a cold Maxwellian
+ a hot Kappa

same QTN as cold + hot
maxwellian if $f > 1.06\,f_p$





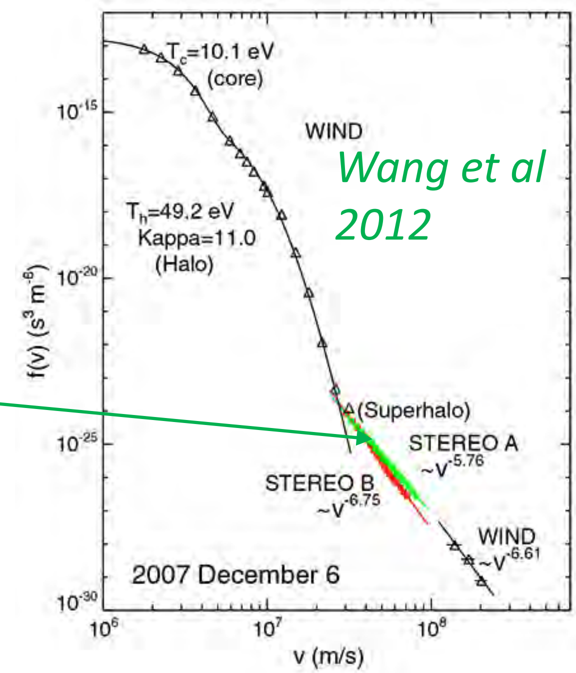
Because both distributions are similar at energies < $(3k_BT/4)\,f_p/(f-f_p)$ which determine the QTN

- ***Space plasmas are NOT in thermal equilibrium!***

Fine structure of the f_p peak reveals high-energy electrons

- Could QTN spectroscopy be used to measure super-halo electrons in the solar wind ?

Energy $E \gtrsim 2$ keV



- Revealed at frequencies $(f - f_p)/f_p \simeq$ (3/4) T/E

  $\Rightarrow$ between f_p and 1.004 f_p if $T \simeq$ 10 eV

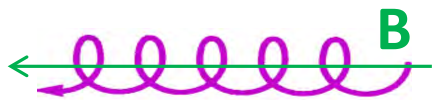
- QTN power $V_f^2 \simeq 10^{-12}$ V²Hz⁻¹ with frequency resolution $\simeq 4\ 10^{-3}$

N. M-V, Issautier, Moncuquet. 2017

Might be erroneously interpreted as due to a plasma instability

- Complications

- ***Magnetic field***



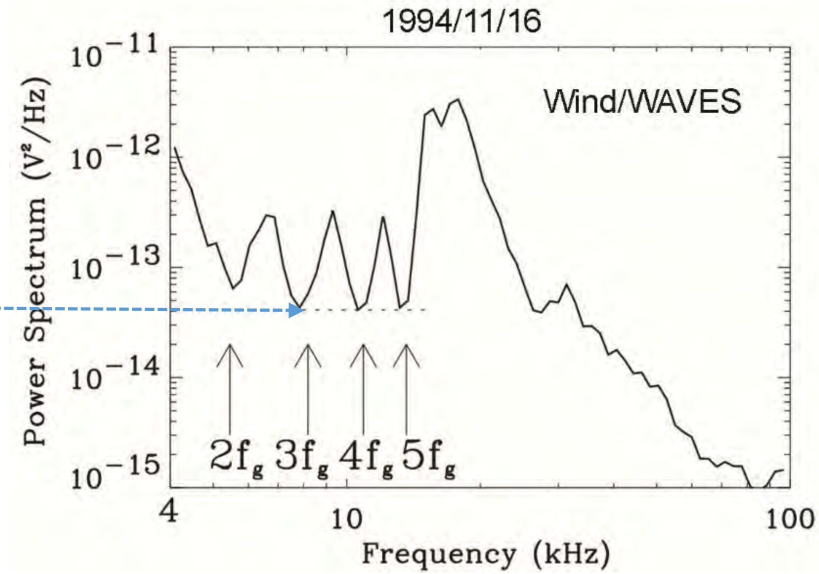
✓ Changes resonance frequencies

✓ Bernstein waves …

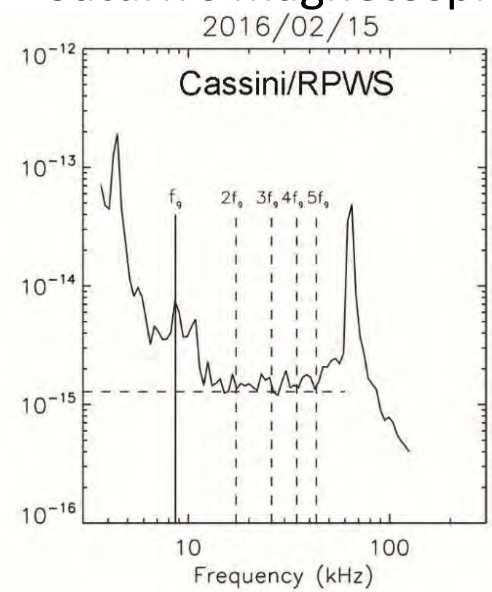
- At gyroharmonics: QTN unchanged
- Between gyroharmonics: maximum QTN reveals suprathermal electrons

Minima at nf_g

Earth's magnetosphere



Saturn's magnetosphere

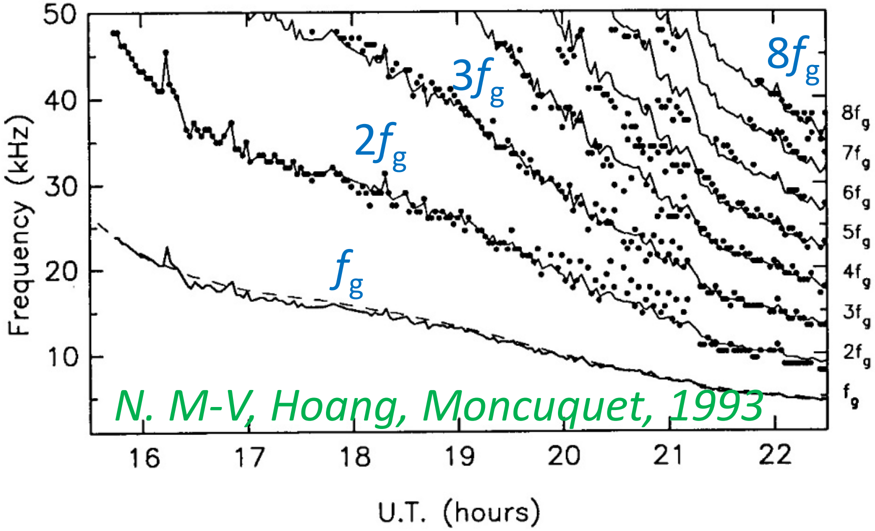


N. M-V, Issautier, Moncuquet 2017

- *Magnetic field*

Frequencies of QTN minima (nf_g) reveal magnetic field

Ulysses/URAP in Io plasma torus



Agrees with in board magnetometer within 2%

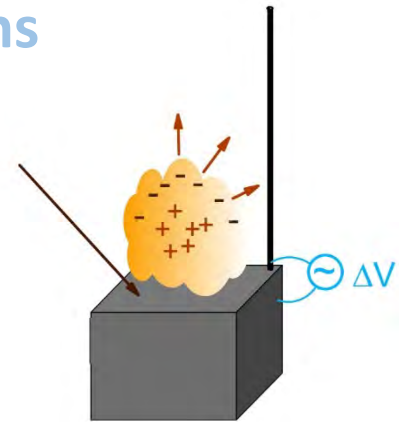
QTN spectroscopy can serve as a cheap magnetometer!

- Complications

- ***Space plasmas may be dusty***

✓ High-speed impacts

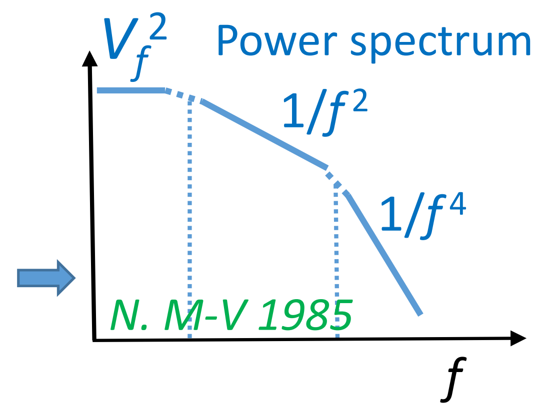
$\Rightarrow$ Voltage pulse δv



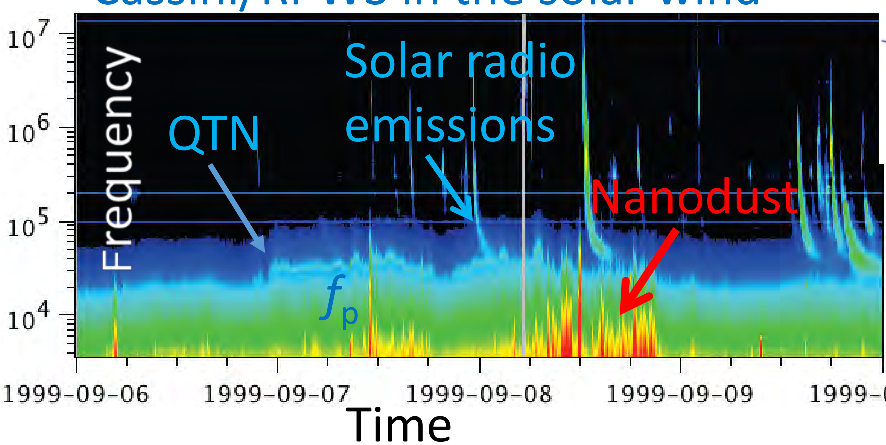
Impact ionization

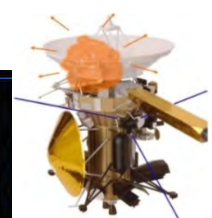
$Q \propto m_{dust}\, v^{3\text{-}4}$

- Micrometer grain at v = 10 km/s $\Rightarrow \delta v = Q/C$ = 10 mV
- Nanometer grain at v = 300 km/s $\Rightarrow$ *same amplitude*



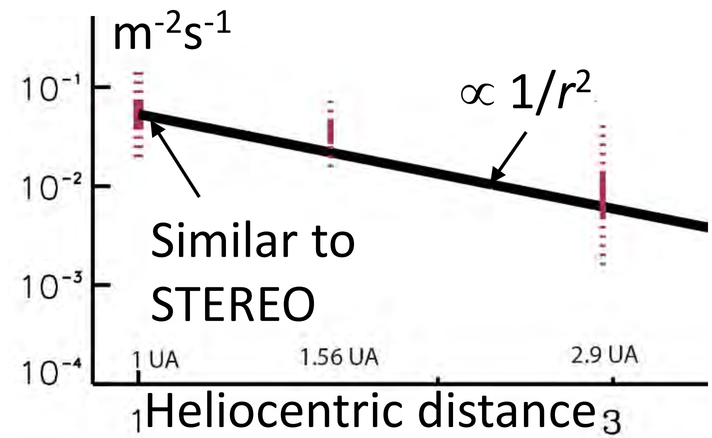
Cassini/RPWS in the solar wind





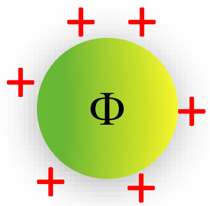
Schippers et al. 2014, 2015

Average nanodust flux (> 10 nm) between 1 and 3 AU:



- *Space plasmas may be dusty*

✓ Low-speed impacts

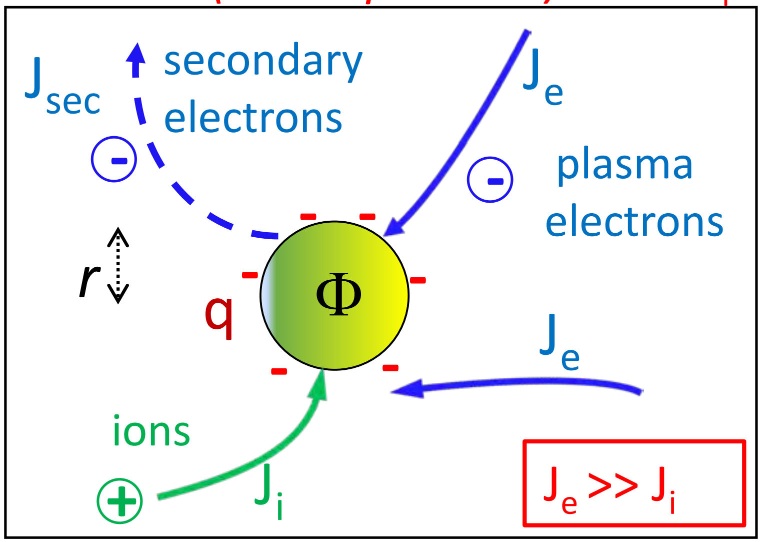


Dust grains carry an electric charge

→ QTN of moving charged dust grains is dominant

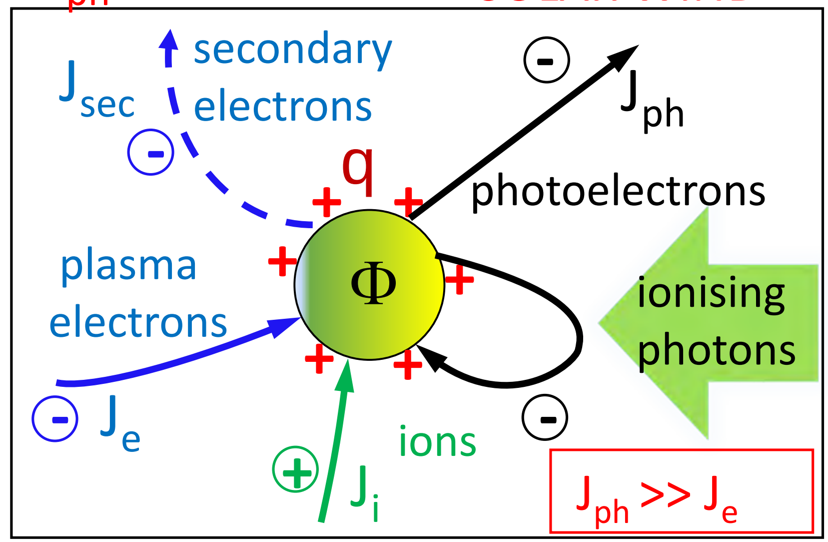
Basics of electric charging in space

PLANETS (dense plasmas) J_{ph} X



Charging governed by incoming plasma electrons until grain **negative** charge repels them sufficiently to balance other currents

J_{ph} dominates *SOLAR WIND*



Charging governed by escaping photoelectrons until grain **positive** charge binds them sufficiently to balance plasma currents

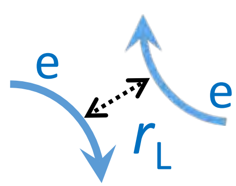
Grain of radius *r* carries electric charge $q = 4\pi\varepsilon_0 r \Phi$ ← a few T_{eV}

capacitance of sphere of radius r

Temperature of main charging process

$\Rightarrow |q/e| =$ a few r/r_L

Landau radius = $e/(4\pi\varepsilon_0 T_{eV})$

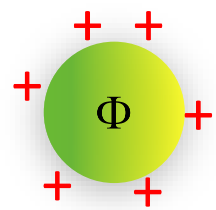


If $r > r_L$

Mann, N. M-V, Czechowski 2013

- *Space plasmas may be dusty*

Grain of radius r carries electric charge q



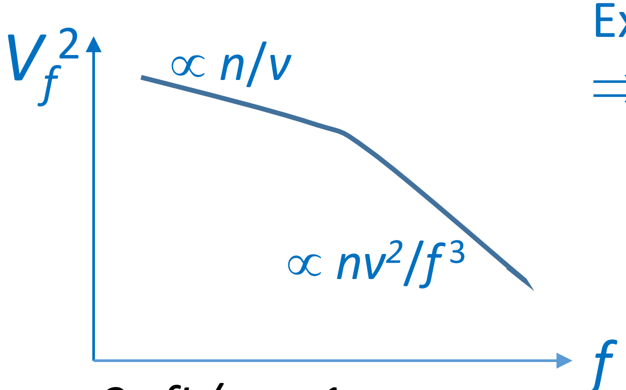
✓ Low-speed impacts

Impact ionisation

$\Rightarrow q/Q \simeq 0.05\, r_{\mu m}^{-2}\ v_{km/s}^{-3.5}\ T_{eV}$

>> 1 for low-speed nanodust

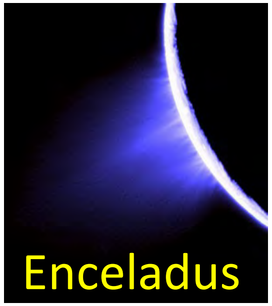
➡ QTN of moving charged dust grains



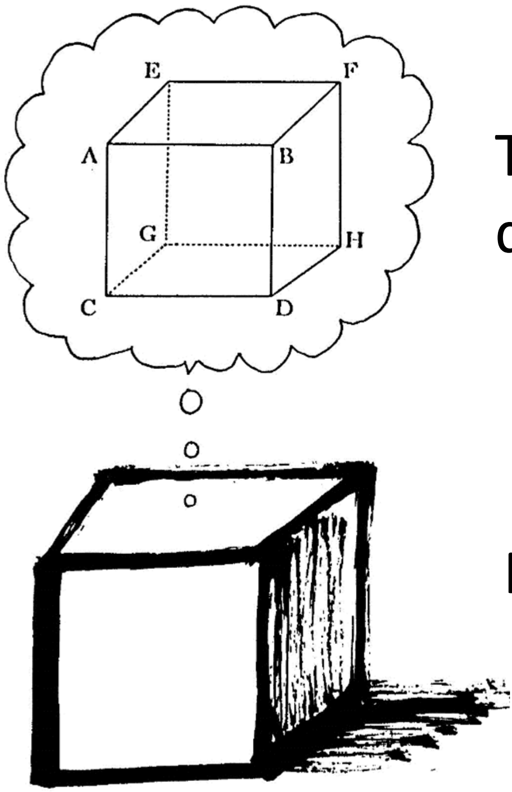
$2\pi f L/v << 1$

Example: $n = 10^3\ \mathrm{cm}^{-3}$ nanograins (10 nm) at 15 km/s

$\Rightarrow V_f^2 \simeq 10^{-10}\ \mathrm{V^2 Hz^{-1}}$ near 1 kHz

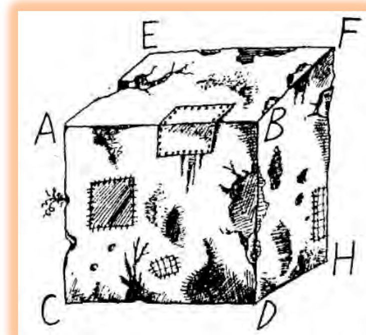


• Further complications



Theoretician dream

Real life

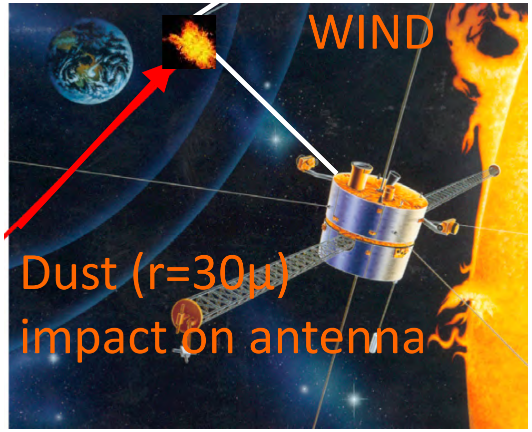


The reality of the space scientist

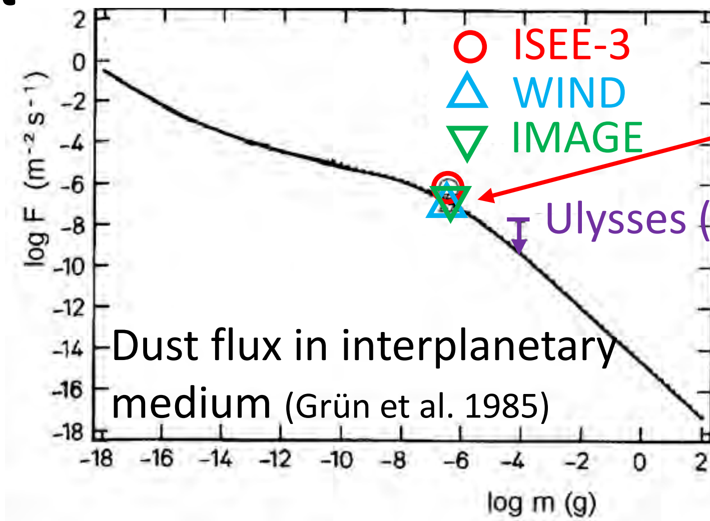
Drawings by *Saul*

✓ Unequal antenna booms

Antenna broken by dust impact



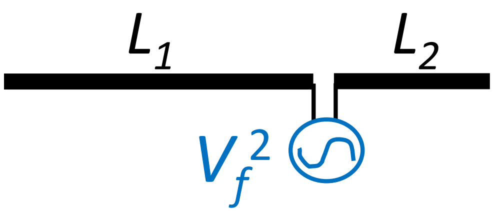
Dust impacts on thin antennas ($r \simeq 0.2$ mm)



Dust flux deduced from the rate of antenna break-up

N. M-V 2001

Agrees with Grün's model



⇒ Use thin antenna break-ups as dust detector (albeit expensive) !

$L_1 \neq L_2$ changes antenna response

- EM waves: if L_1, $L_2 << \lambda_{EM}$ ⇒ Power depends on $(L_1 + L_2)$
- QTN : if L_1, $L_2 >> L_D$ ⇒ Power depends on $L_1 L_2/(L_1 + L_2)$

➡ Measuring EM waves & QTN reveals L_1 and L_2

✓ Fat antennas DC- current $\Rightarrow$ shot noise

Plasma electrons impacting antenna
$\Rightarrow$ voltage pulse $\delta V = e/C$ $\Rightarrow$ $V_f^2 \propto S\, e^2/C^2 f^2$

Antenna surface

Shot noise generally small with thin wire antennas

Beware! ⚠

✓ Biased antennas

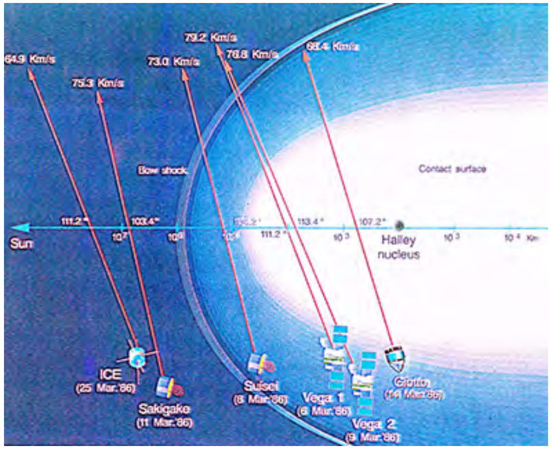
Solar wind: photoelectron current ~ 20 X plasma electron current
$\Rightarrow$ antenna floats at $\Phi > 0$ (enables current balance by reducing escaping photoelectron current)

If antenna biased to $\Phi = 0$: full photoelectron current $\Rightarrow$ shot noise X 20 !

• Applications: QTN in a comet's plasma tail

September 11, 1985 First encounter of a spacecraft with a comet

6 months before a fleet of spacecraft encountered Halley comet

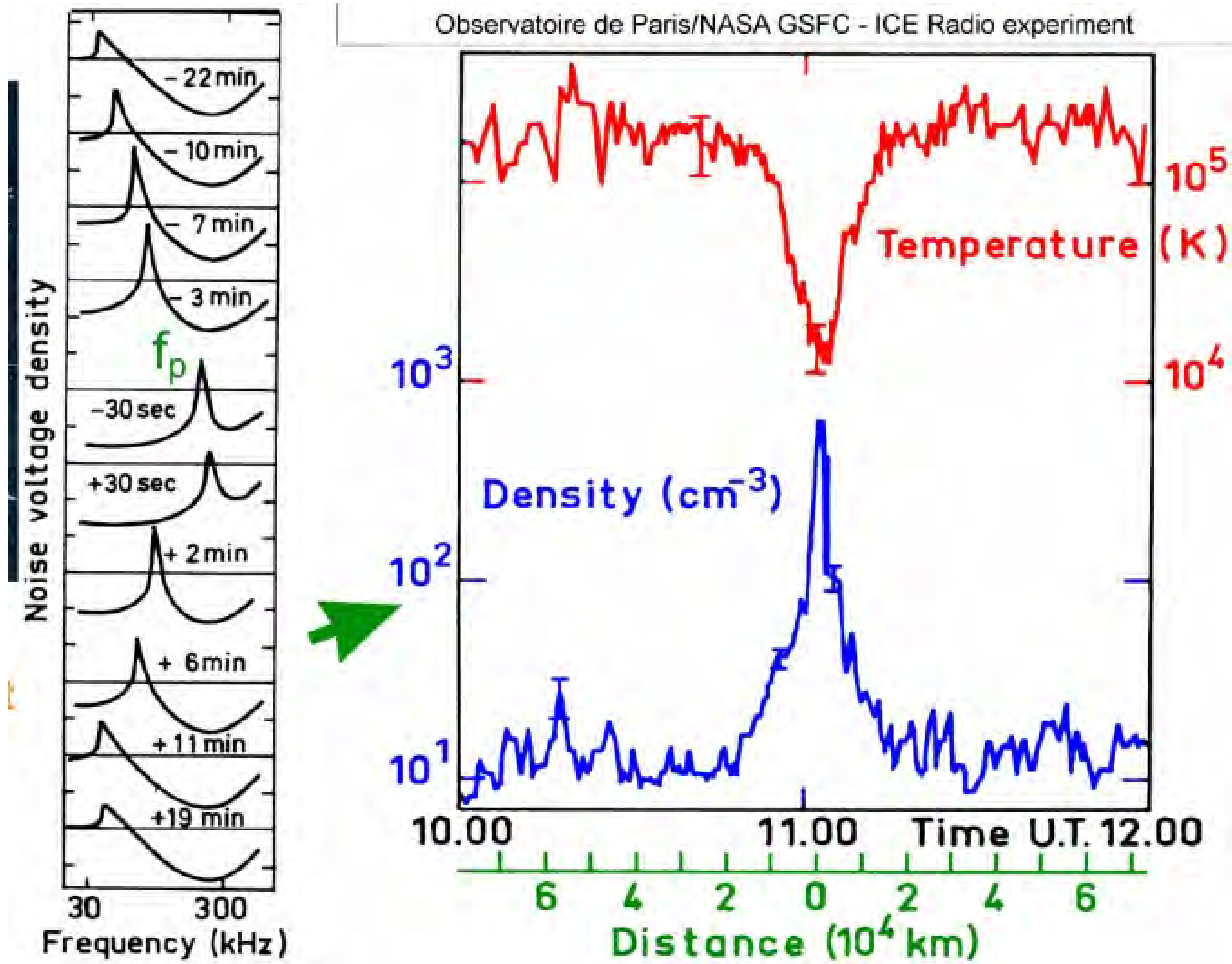


ICE crossed the plasma tail

Plasma too cold for the plasma electron experiment (Bame et al. 1986) to measure correctly the electron density and temperature within the tail

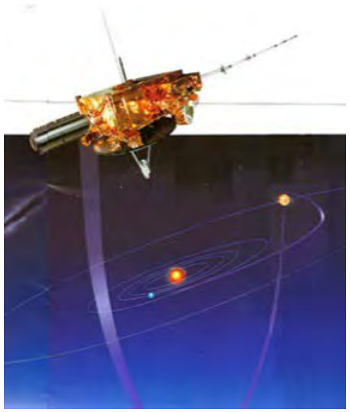
QTN spectroscopy was well adapted ($L/L_D >> 1$)

• Applications: QTN in a comet's plasma tail

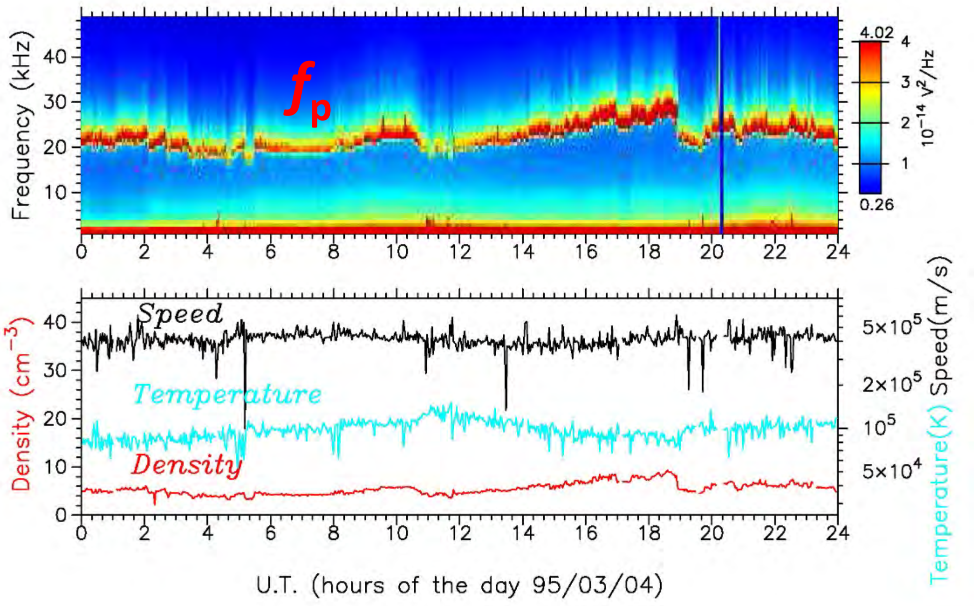


N. M-V, Couturier, Hoang, Perche, Steinberg, Fainberg, Meetre (Science, 1986)

• QTN in 3-D solar wind

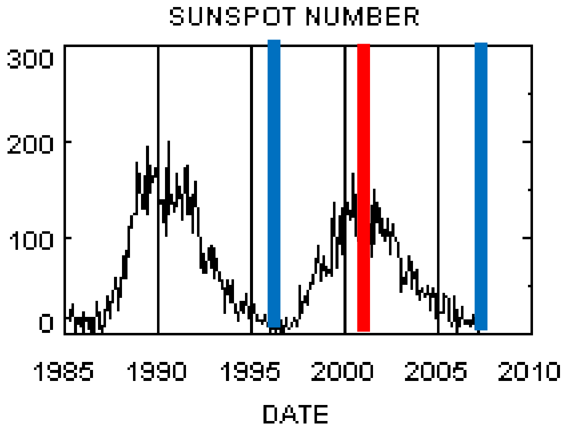


Ulysses/URAP

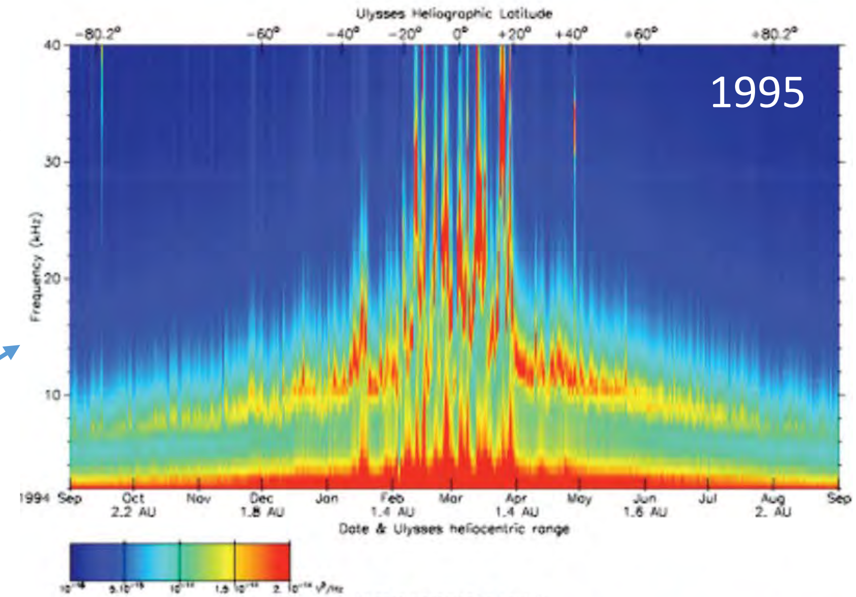


Issautier et al., 1998

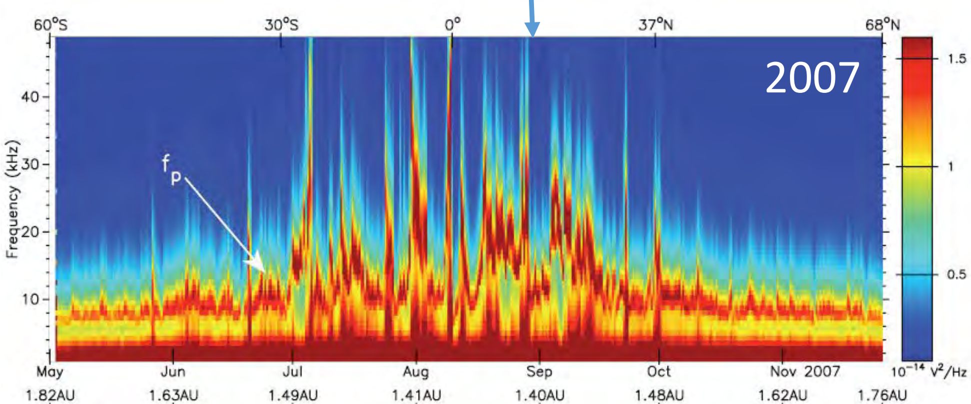
• QTN in 4-D solar wind

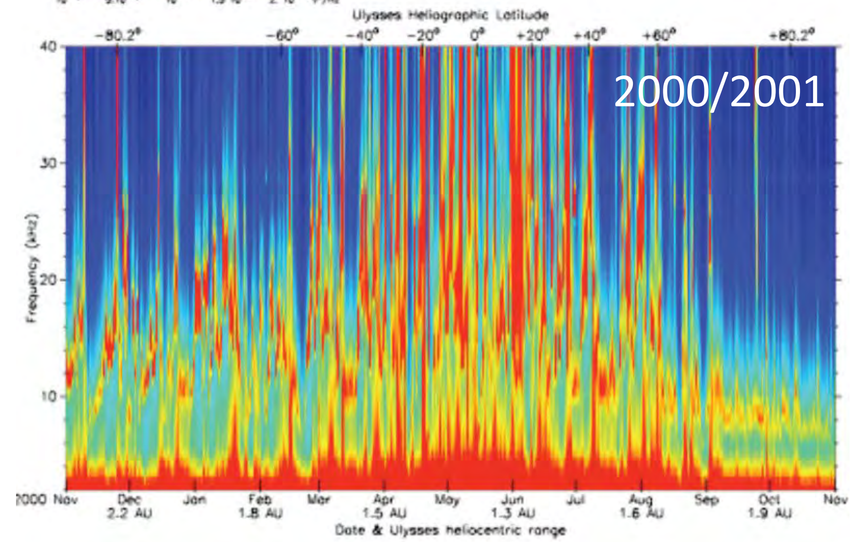


Ulysses/URAP



Solar cycle minimum

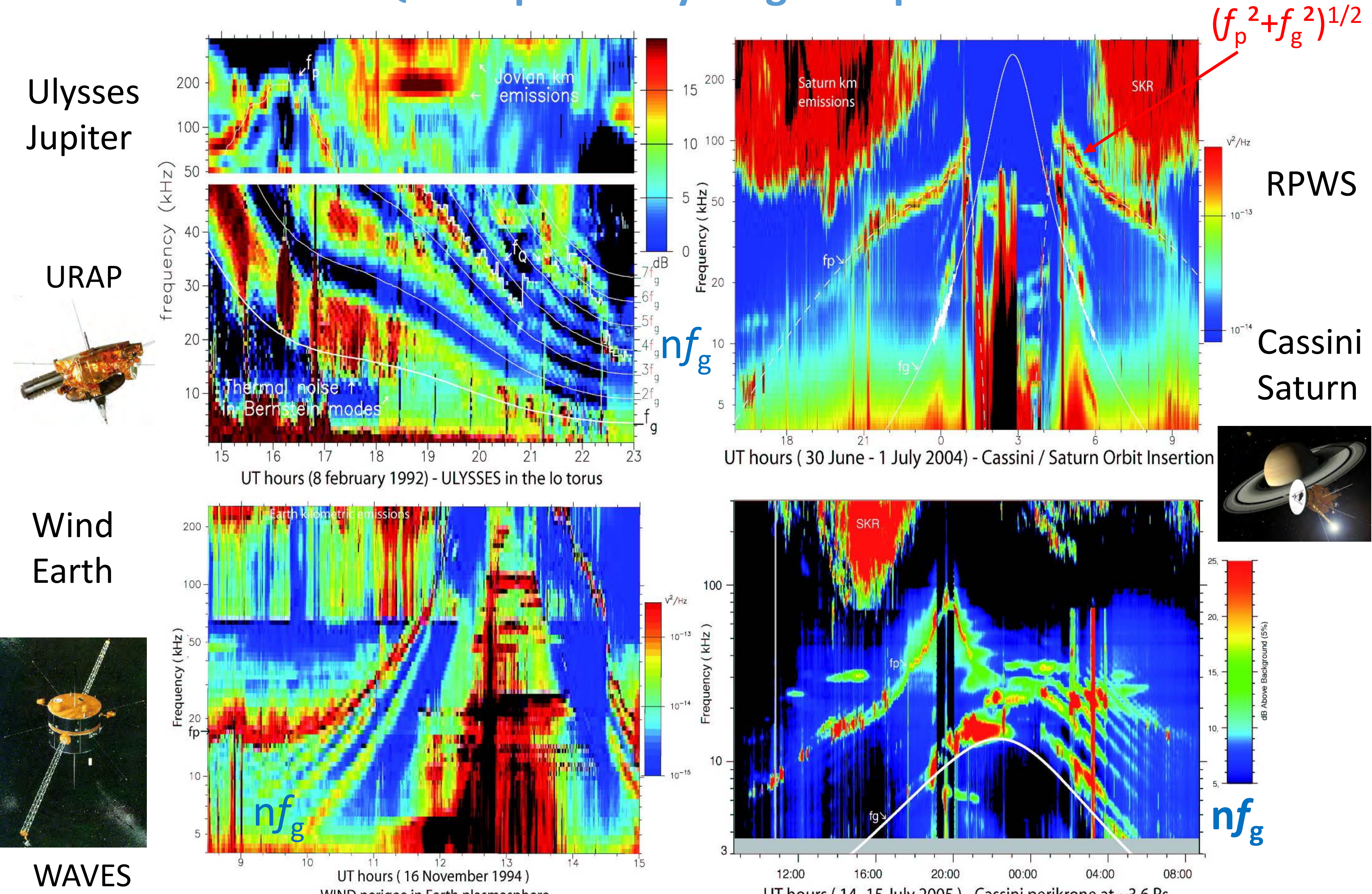




Issautier et al., 1998, 2008

Solar cycle maximum

• QTN in planetary magnetospheres

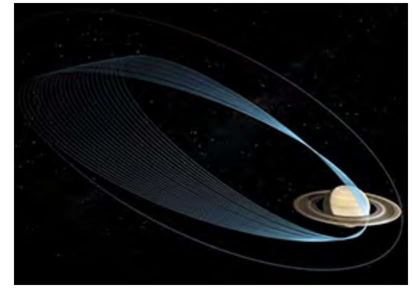


Moncuquet et al., 2006 (PRE VI)

- **Future**

➢ Ionospheres

- Saturn's ionosphere (Cassini grand finale 2017)
  Lecacheux et al. 2018



- Earth's ionosphere CubeSats projects

❖ Debye length $\sim$ cm $\lesssim$ antenna radius

Antenna impedance and QTN: integrals over **k** involving the antenna current distribution in Fourier space

o Current distribution

$$|\mathbf{k}.\mathbf{J}| = \left|\frac{4\sin^2(k_\parallel L/2)}{k_\parallel L} J_0(k_\perp a)\right|$$

radius of the antenna

$k \sim 1/L_D$

$\Rightarrow J_0 \neq 1$

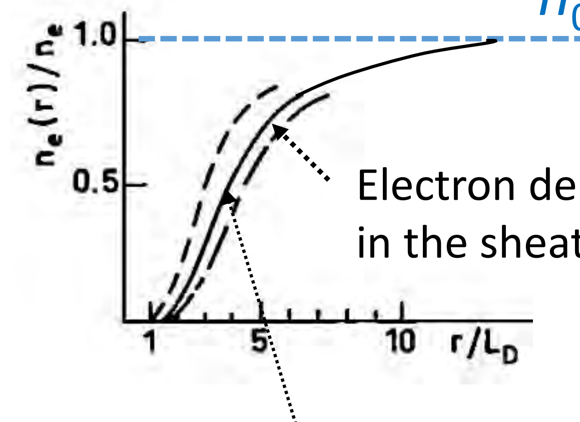
Reactive antenna impedance $\Rightarrow$ changes the receiver gain

- Charging governed by ambient electrons $\Rightarrow$ Antenna's potential is negative

  $\Rightarrow$ Debye sheath with depleted electrons $> L_D$ around antenna

$\Rightarrow$ f_p in the sheath $< f_p$ in the plasma

$\Rightarrow$ at $f < f_{p(plasma)}$ *there is a* region in the sheath where $f = f_{p(sheath)}$



n_0 Electron density of ambient plasma

Electron density in the sheath

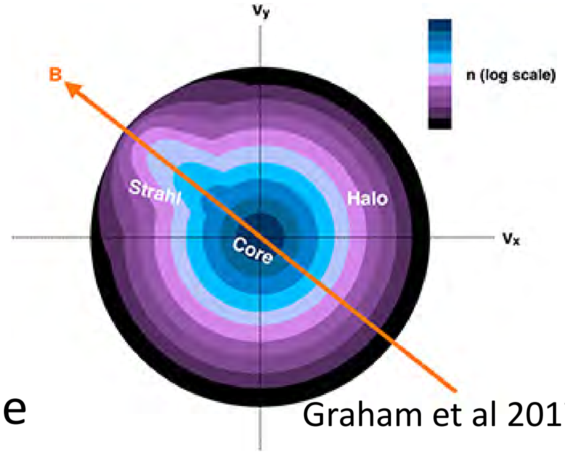
Example: where $n/n_0 = 0.5$, we have $f = f_p$ at $f = 0.5^{1/2} f_{p0}$

Plasma resonances in the sheath increase QTN by orders of magnitude

N. M-V et al. 1977, 1978 (calculated and observed)

• **Future**

➢ **Inner solar wind and corona**



Graham et al 2017

❖ Anisotropy of the velocity distributions

Strahl: mirror force (focusing $\Rightarrow$ beam-like) + pitch-angle scattering (collisions + ..)

- Expected to decrease with distance at low and medium speeds Stverak et al. 2009
- Expected to increase with distance at higher speeds ($v \gtrsim 5\ v_{th}$) Horaites et al. 2017

Should affect QTN near the f_p peak

Parker Solar Probe / FIELDS (Bale et al. 2016, Pulupa et al. 2017)