Solar Wind electrons :

observations and basic physics

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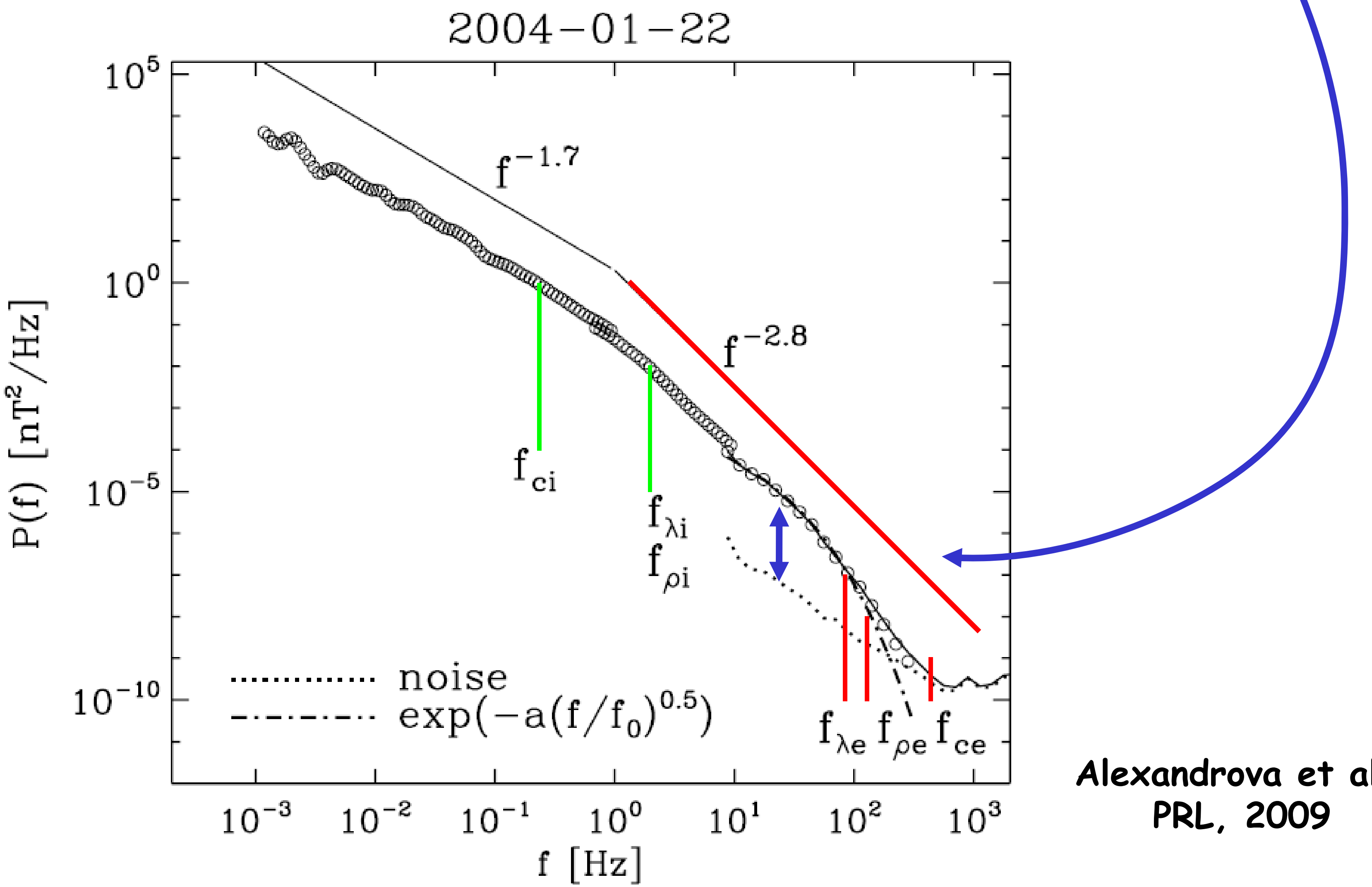
LESIA - Observatoire de Paris

Outline

- Observations
- Radial evolutions
- Basic physics & models
- Conclusions

GYPW01, Cambridge UK, 19-23 July 2010

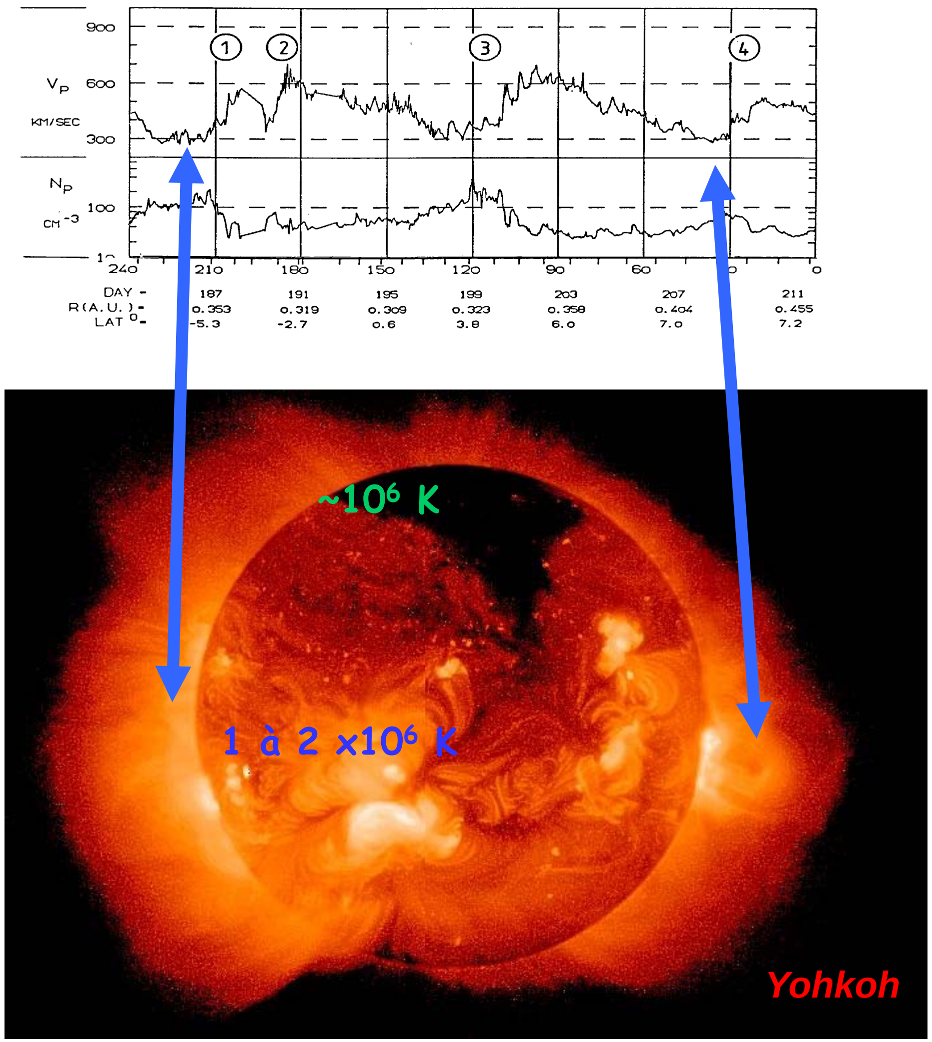
Turbulence in the Solar Wind : Evidence for slope break in the electron range



Alexandrova et al., PRL, 2009

The Solar Wind as Seen from the ecliptic

Helios, 1983



Ionized Hydrogen :

- e^-
- H^+ : ~95%
- He^{2+} : ~4%
- ~1% of heavy ions (C, N, O, Ne, Mg, Fe)

Slow Wind :

- V ~ 200 à 600 km/s
- N_e ~ 5 à 20 cm^{-3}
- ρV^2 ~ 2.1 x 10^{-9} Pa
- T_e ~ 1 à 3 x10^5 K → V_{the} ~ 2500 km/s
  E ~ 10-20 eV
- T_p ~ 0.5 à 3 x10^5 K → V_{thp} ~ 40 km/s
  E ~ 0.5-1.5 keV

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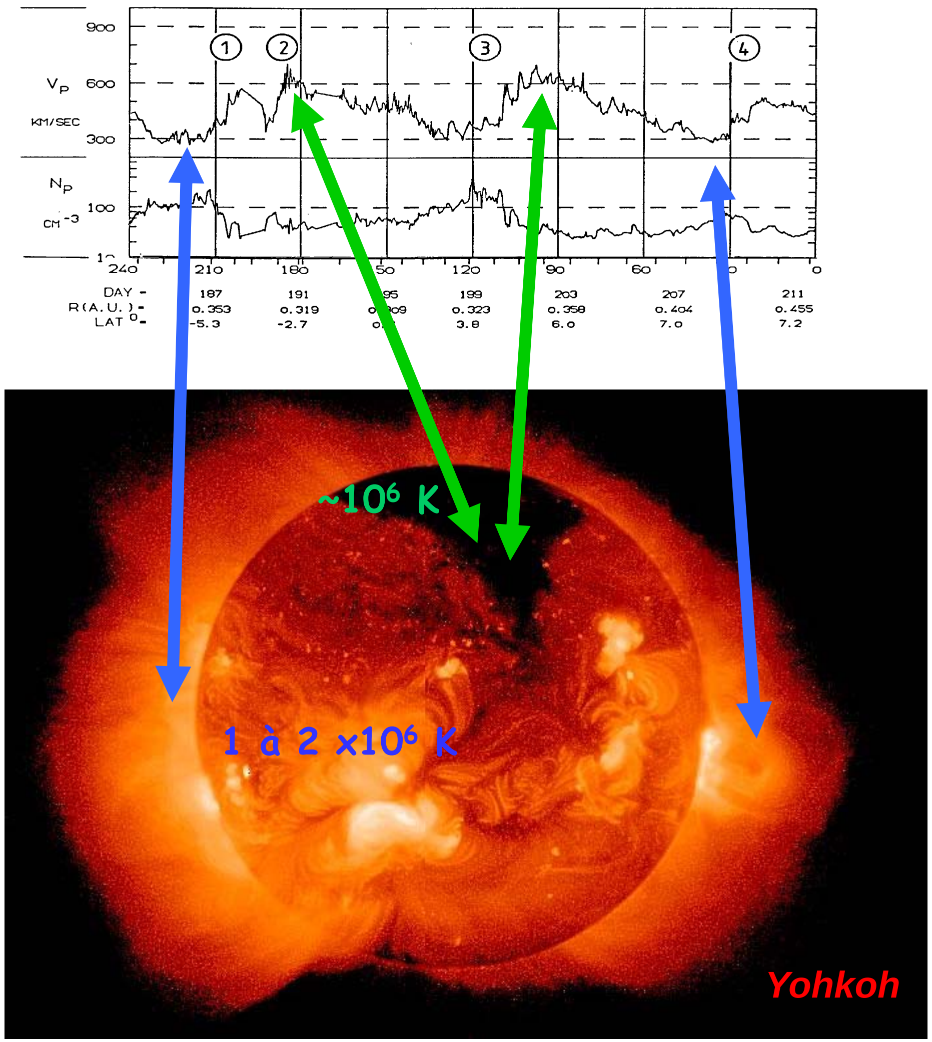

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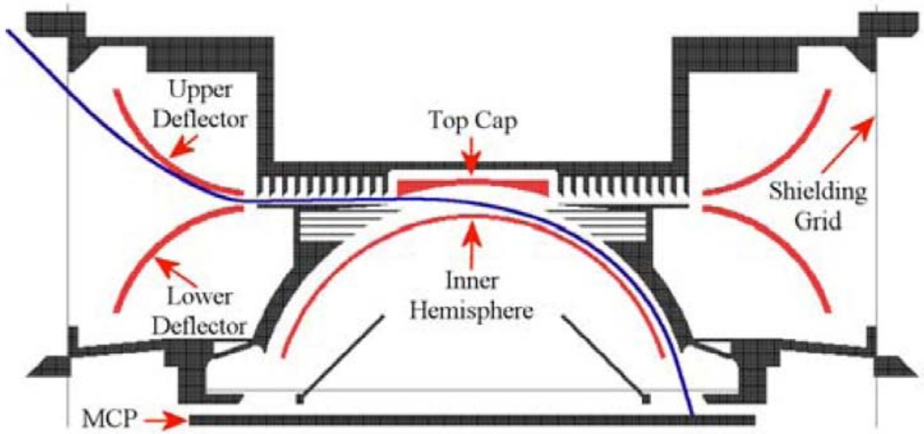
  E ~ 0.5-1.5 keV

Fast Wind :

- V ~ 600 à 800 km/s
- N_e ~ 1 à 5 cm^{-3}
- ρV^2 ~ 2.6 x 10^{-9} Pa
- T_e ~ 1 à 2 x10^5 K → V_{the} ~ 2100 km/s
  E ~ 10-20 eV
- T_p ~ 2 à 5 x10^5 K → V_{thp} ~ 80 km/s
  E ~ 1.5-3 keV

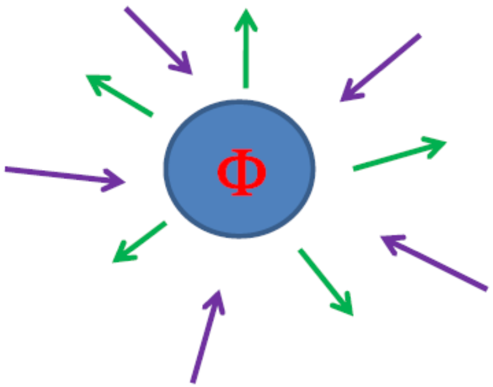
- Protons : transport moment, determine the viscosity
- Electrons : transport the heat & determine the conductivity

How do we measure particle distribution functions ?



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

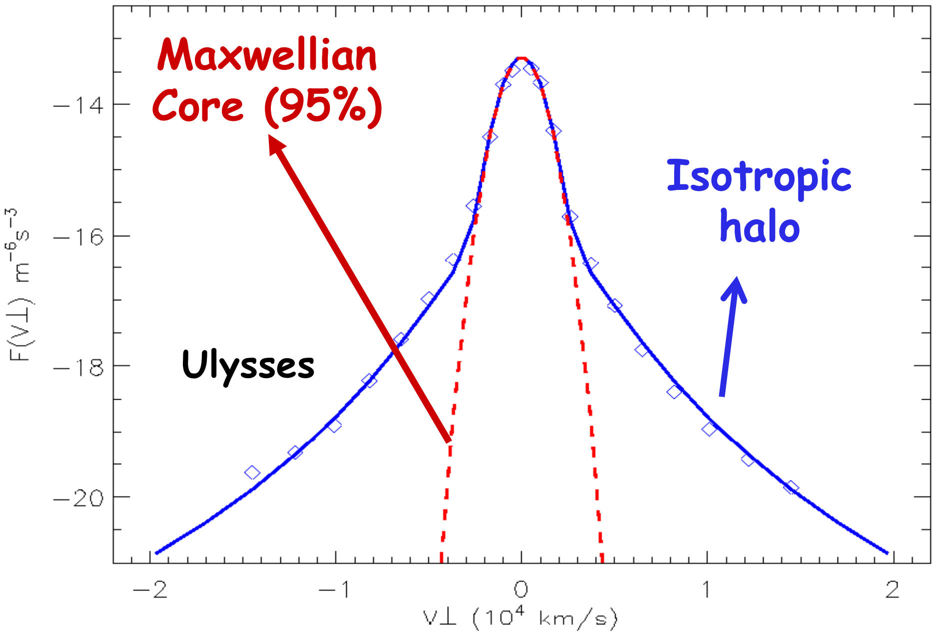
Spacecraft charging effects



- Photoelectrons
- SW electrons

Typical Φ ~ 2 to 10 Volts
Electrons affected
Ions not affected

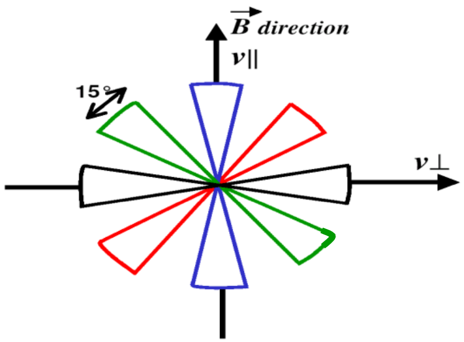
Electron velocity distribution functions :
3 components : core, halo & strahl

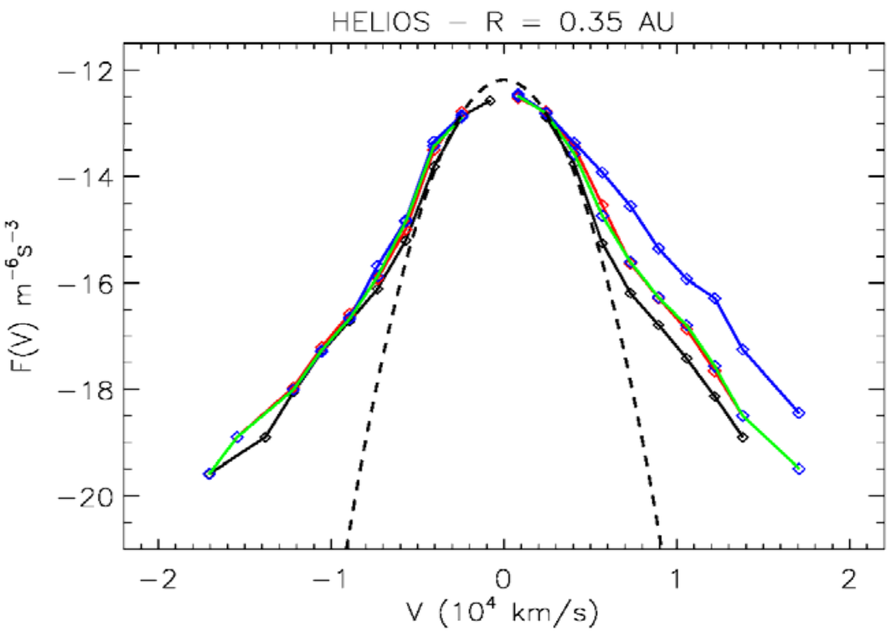


• Best model :
(bi-)Maxwellian for the core +
(bi-) Lorentzian (Kappa) :
Maksimovic et al., 1997, 2005

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

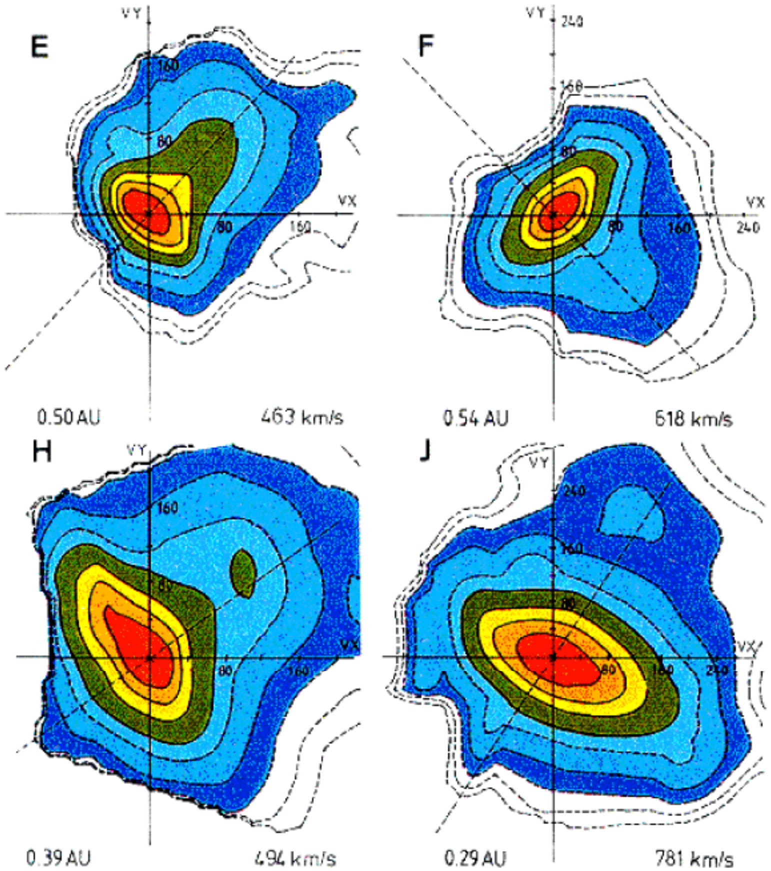
+ Strahl along $\vec{B}$

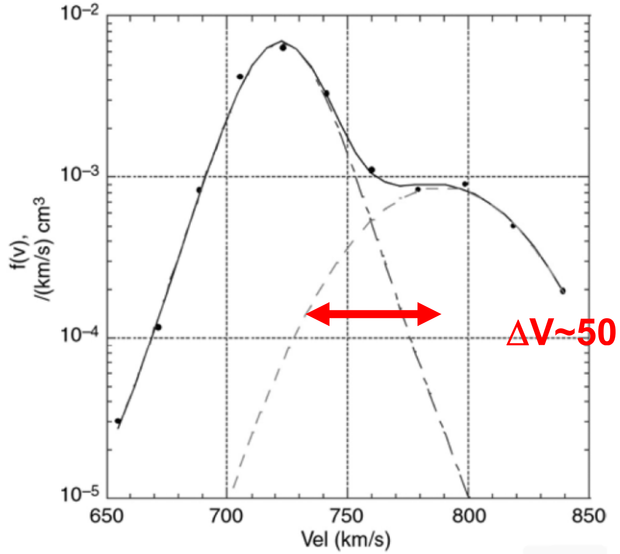




Proton distribution functions

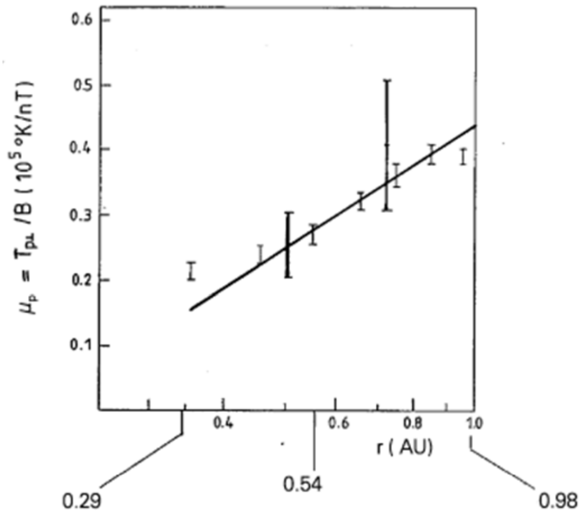
Helios





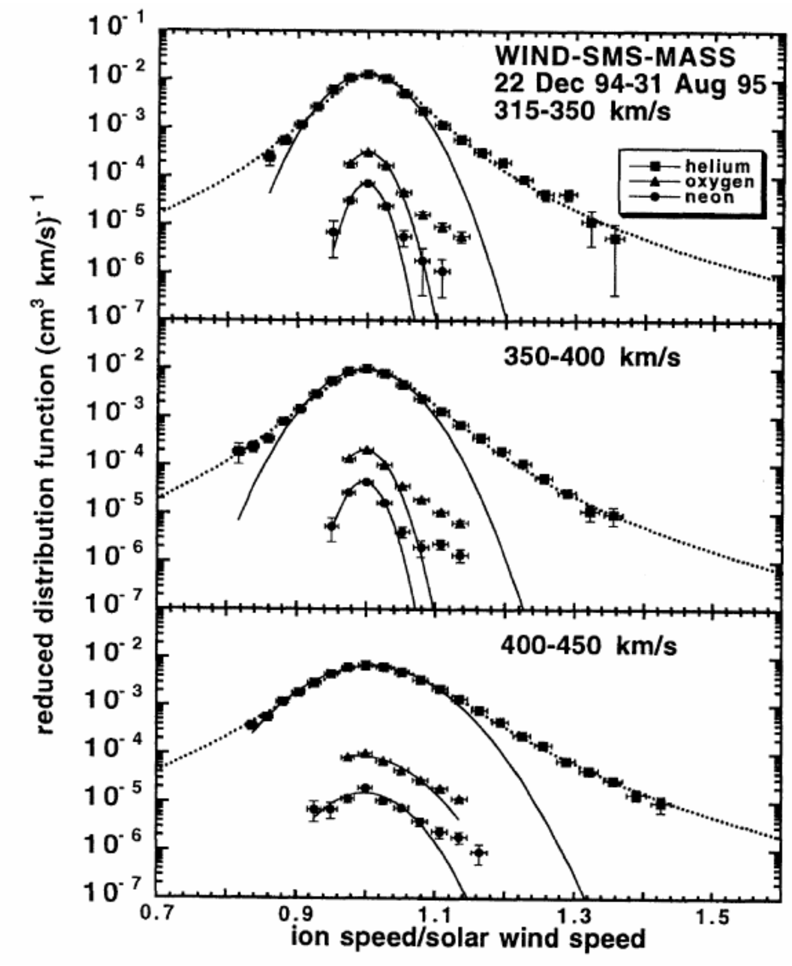
$\Delta V \sim 50$ km/s $\sim V_a$

non conservation of μ heating?



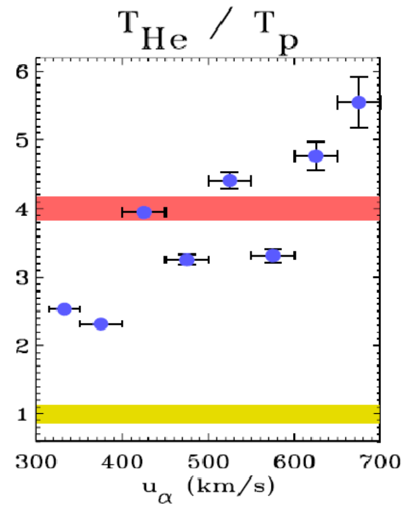
bi-Maxwellian + beam

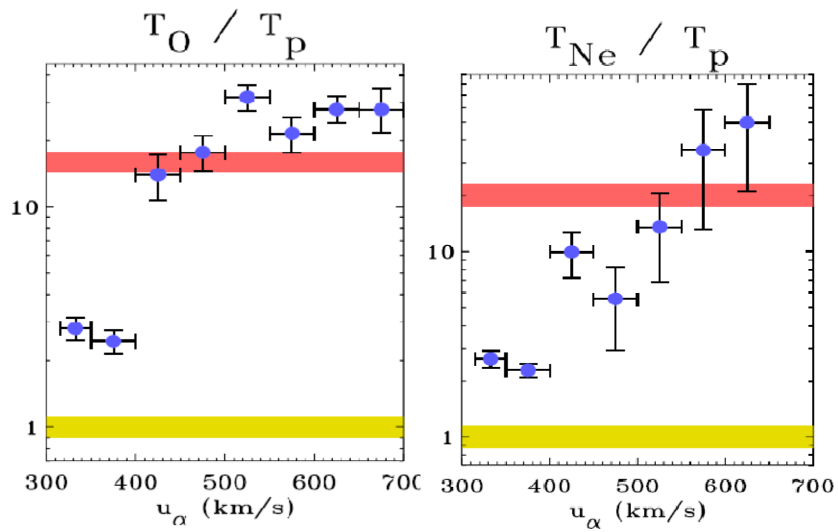
Heavy ions distribution functions



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

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

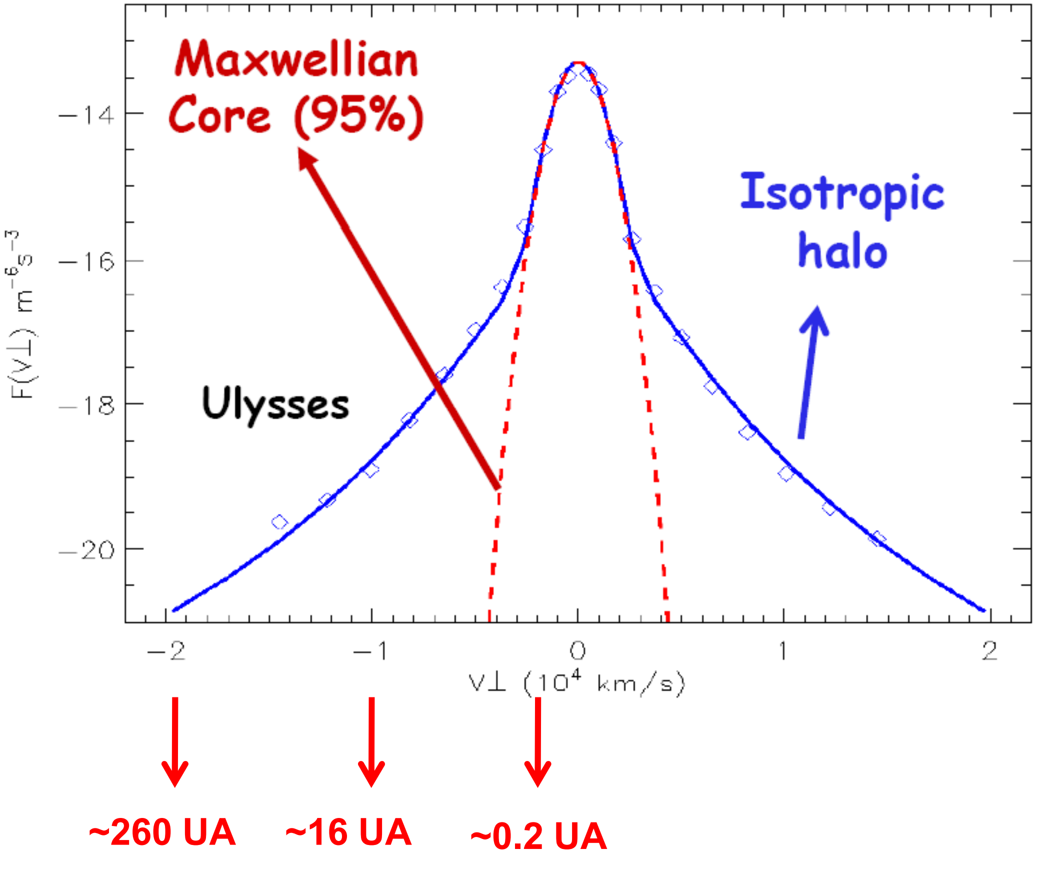




About Coulomb collisions in the SW

$$\frac{e^2}{4\pi\varepsilon_o r} \sim mv^2$$

coll. cross section $\propto r^2 \sim \left[\frac{e^2}{4\pi\varepsilon_o mv^2}\right]^2$



$$\text{free path} = v^4$$

$$\text{m.f.p.} = 9.10^7 \frac{T^2}{n} (\text{SI})$$

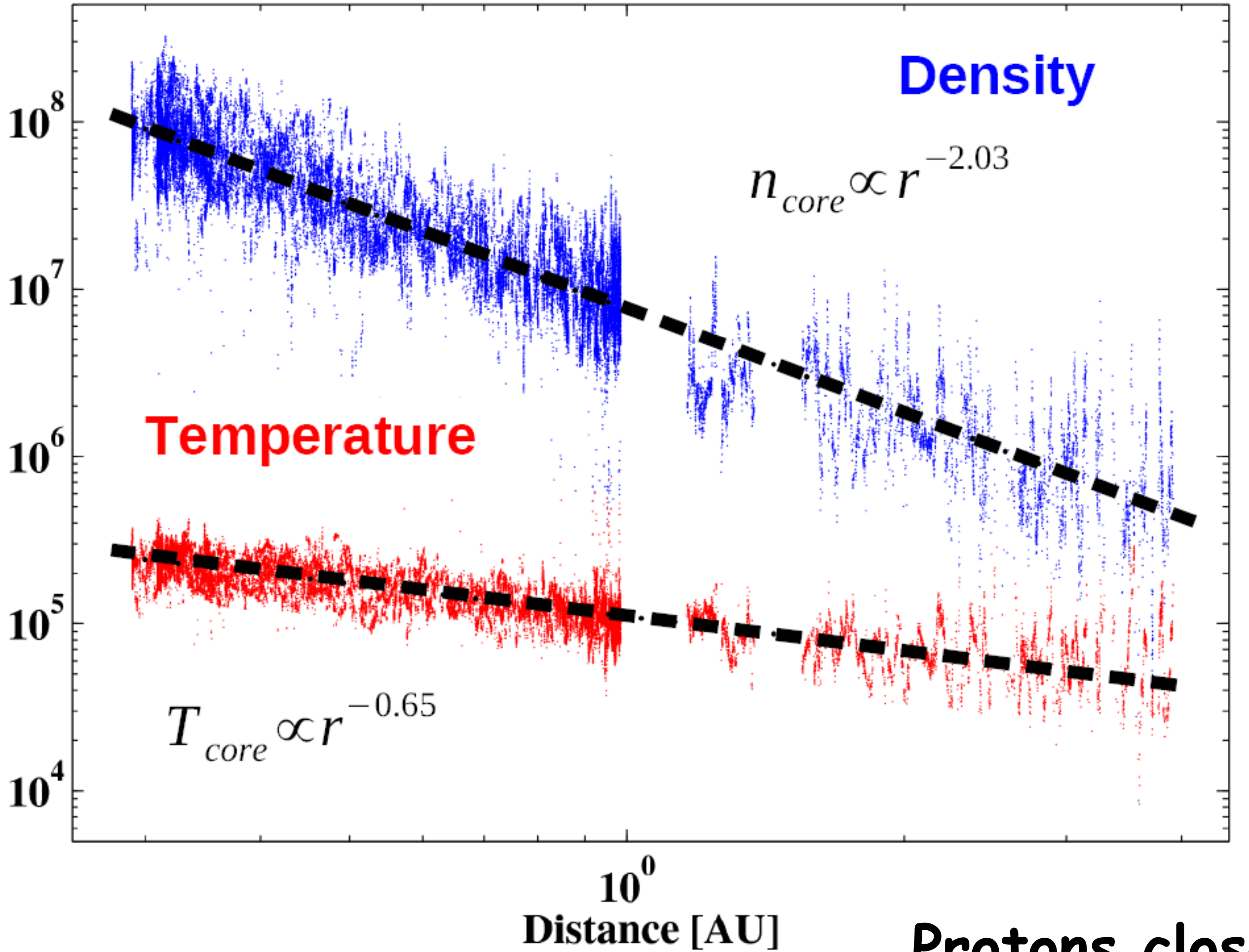
$\frac{\text{m.f.p.}}{\text{H}} \sim 1$ **corona, SW**

$\frac{\text{m.f.p.}}{\text{H}} \sim 10^{-13}$ **chromosphere**

Collisions are not local
Part/waves interactions (turbulence, instabilities) provide the local energy transport

Radial evolutions

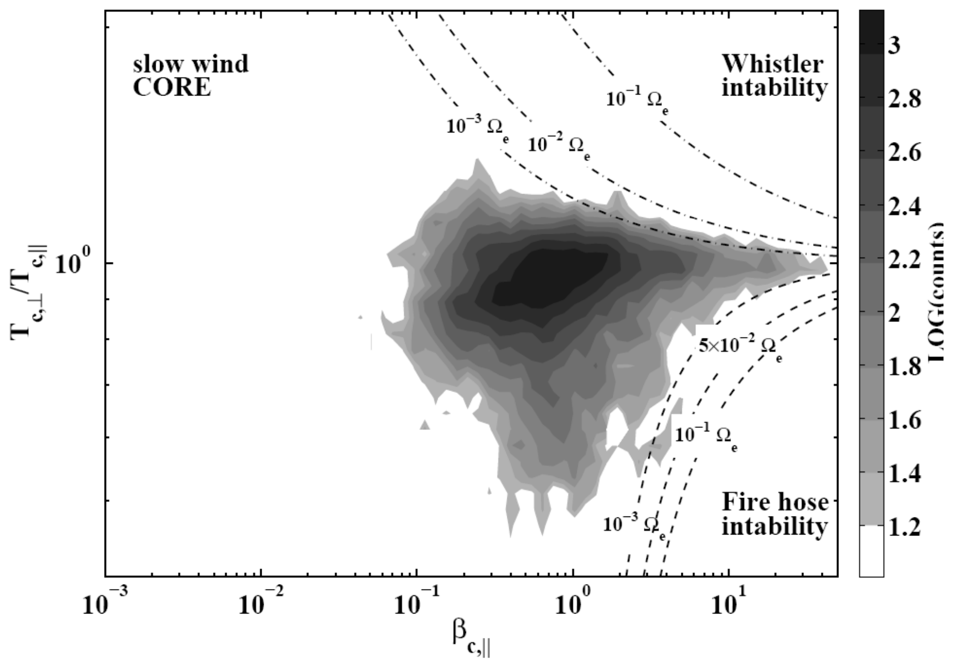
Helios + Ulysses

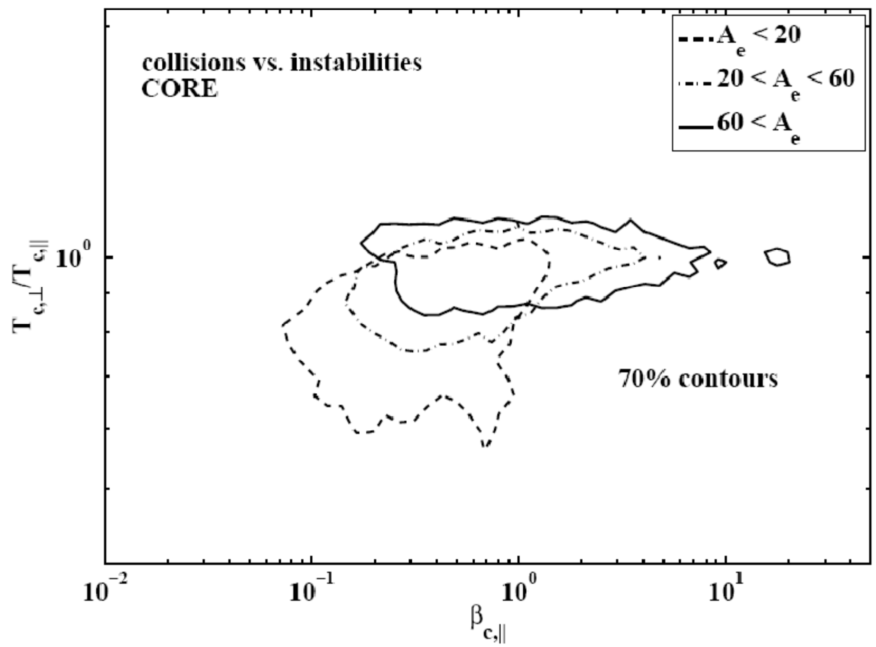


$T \propto R^{-4/3}$ adiabatic

Protons closer to adiabatic but extra heating needed for both e- and p+

Evidences for both collisions and instabilities shaping the eVDFs

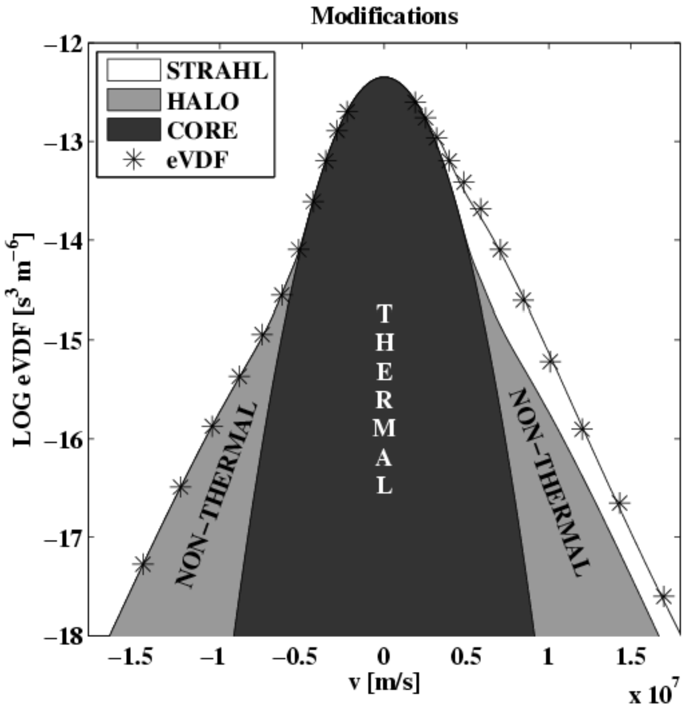




$$A_e = \upsilon_{ee} \frac{R}{V} \quad : \text{collisional age}$$

Stverak et al., JGR, 2008

Similar for protons : Kasper et al., Hellinger et al.



Radial evolution of electron distribution functions

Stverak et al., JGR, 2009

Core : bi-Maxwellian * flat-top

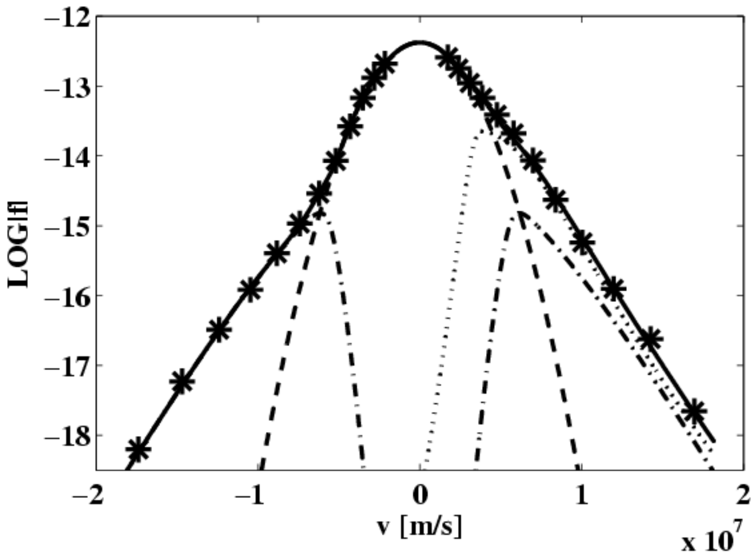
$$f_c = A_c \exp\left[-\frac{m}{2k}\left(\frac{1}{T_{c\perp}}v_\perp^2 + \frac{1}{T_{c\|}}(v_\| - \Delta_c)^2\right)\right],$$

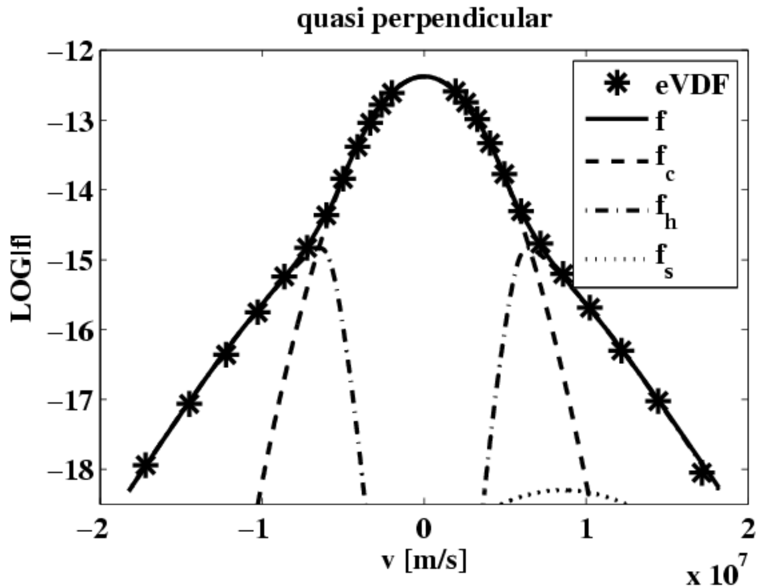
Halo : bi- Kappa * (1-flat-top)

$$f_{h,\kappa} = A_h\left(1 + \frac{m}{k(2\kappa_h - 3)}\left(\frac{v_\perp^2}{T_{h\perp}} + \frac{v_\|^2}{T_{h\|}}\right)\right)^{-\kappa_h - 1},$$

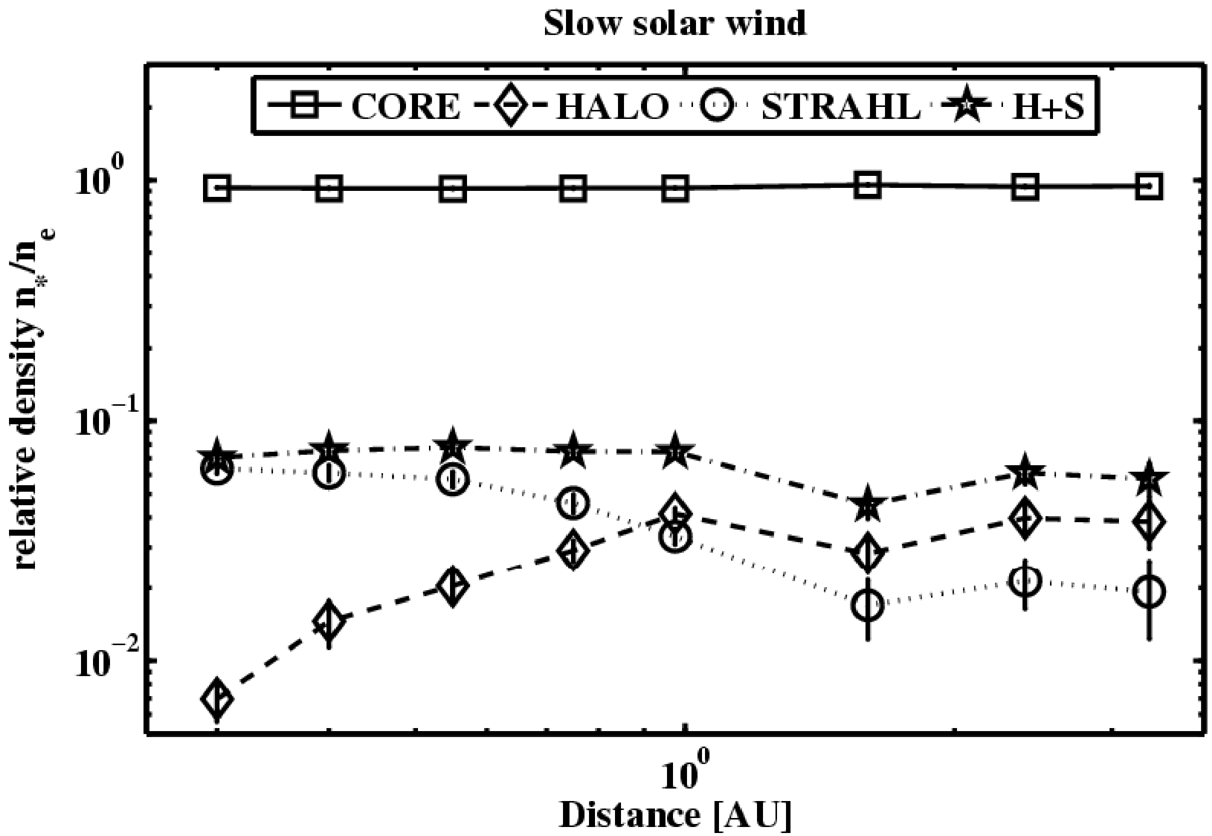
Strahl : bi- Kappa * (1-flat-top) from antisunward dir.

$$f_s = A_s\left(1 + \frac{m}{k(2\kappa_s - 3)}\left(\frac{v_\perp^2}{T_{s\perp}} + D\frac{(v_\| - \Delta_s)^2}{T_{s\|}}\right)\right)^{-\kappa_s - 1}$$





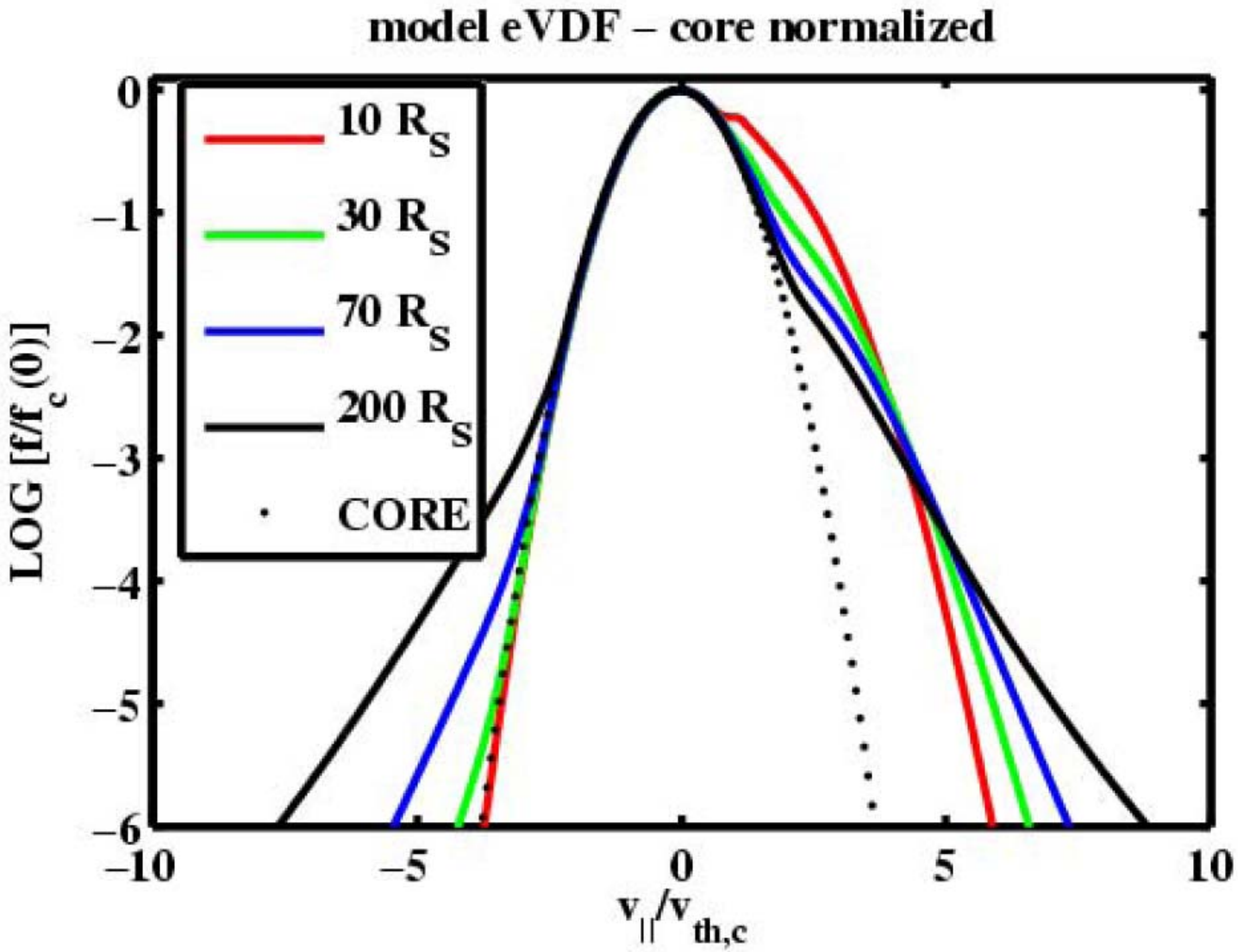
Helios, Cluster, Ulysses



Strahl is transformed into halo with distance by particle/wave interactions ?

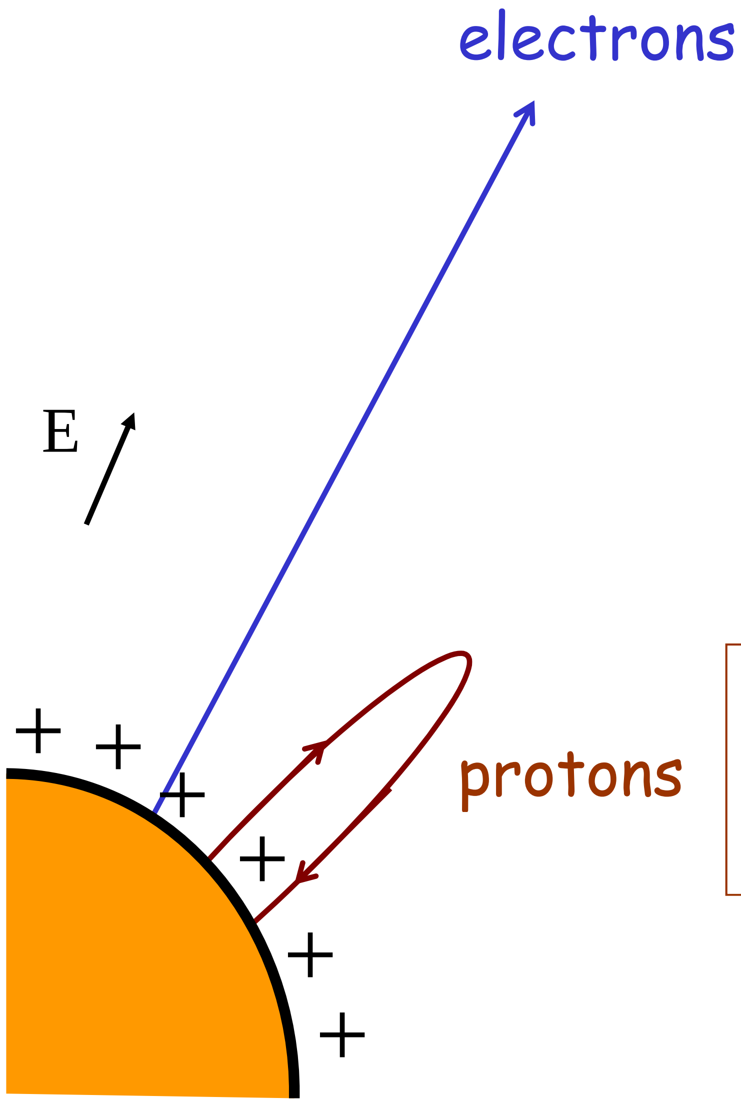
Similar to fast wind (Maksimovic et al. 2005)

eVDF extrapolated back to the sun



Some basic physics and models

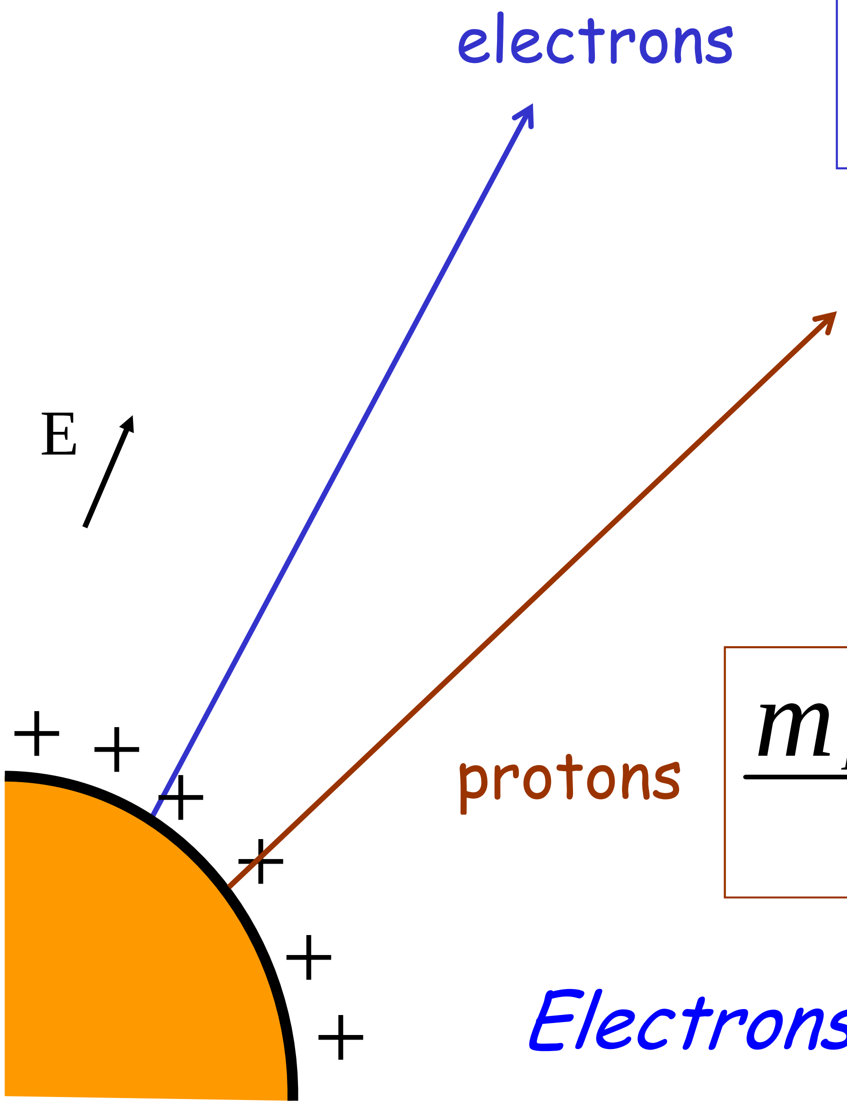
- *Interplanetary electric potential*



$$\frac{m_e MG}{r_o} << kT$$

$$\frac{m_p MG}{r_o} > kT$$

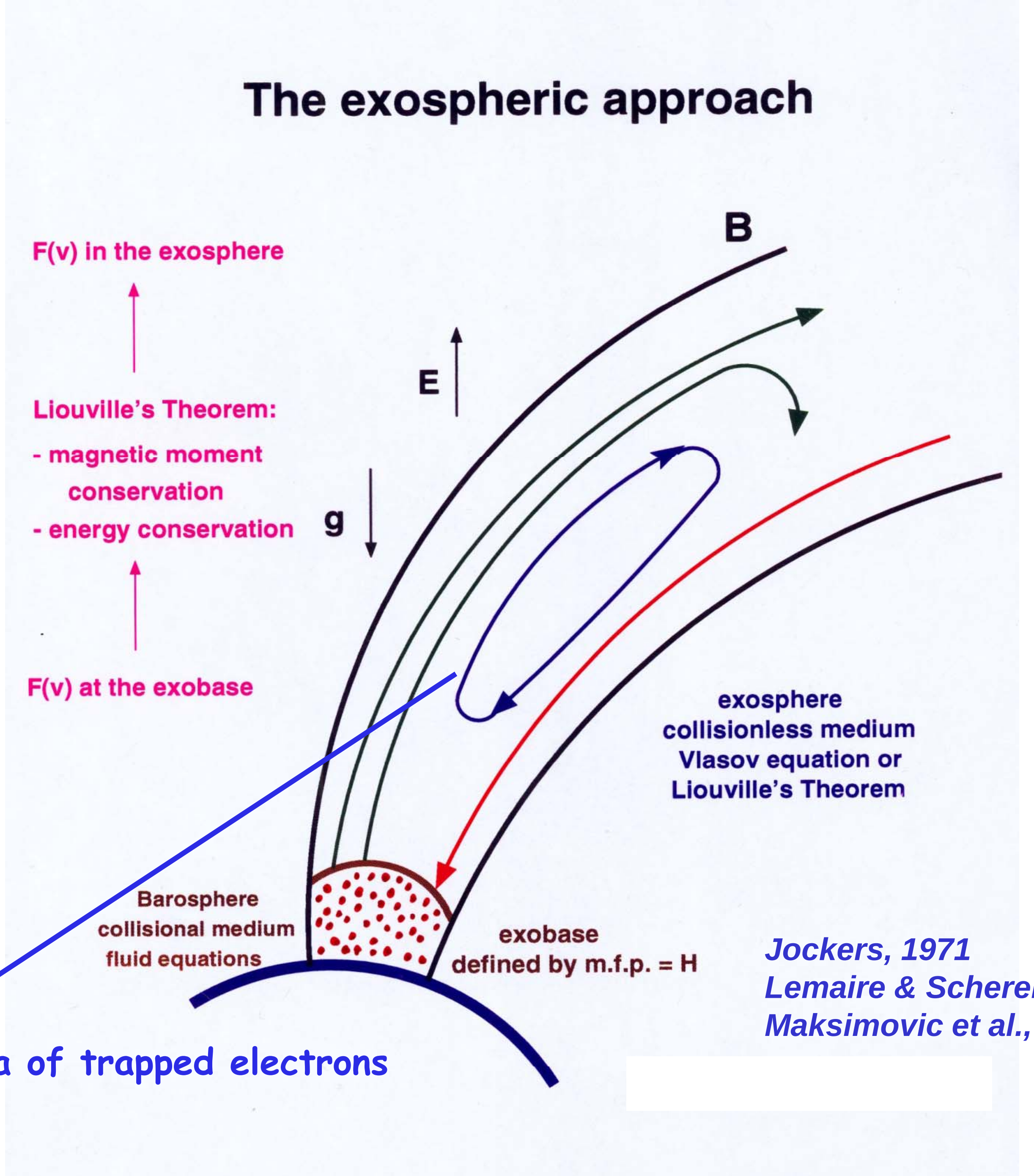
• *Interplanetary electric potential*



$$\frac{m_e M G}{r_o} << kT$$

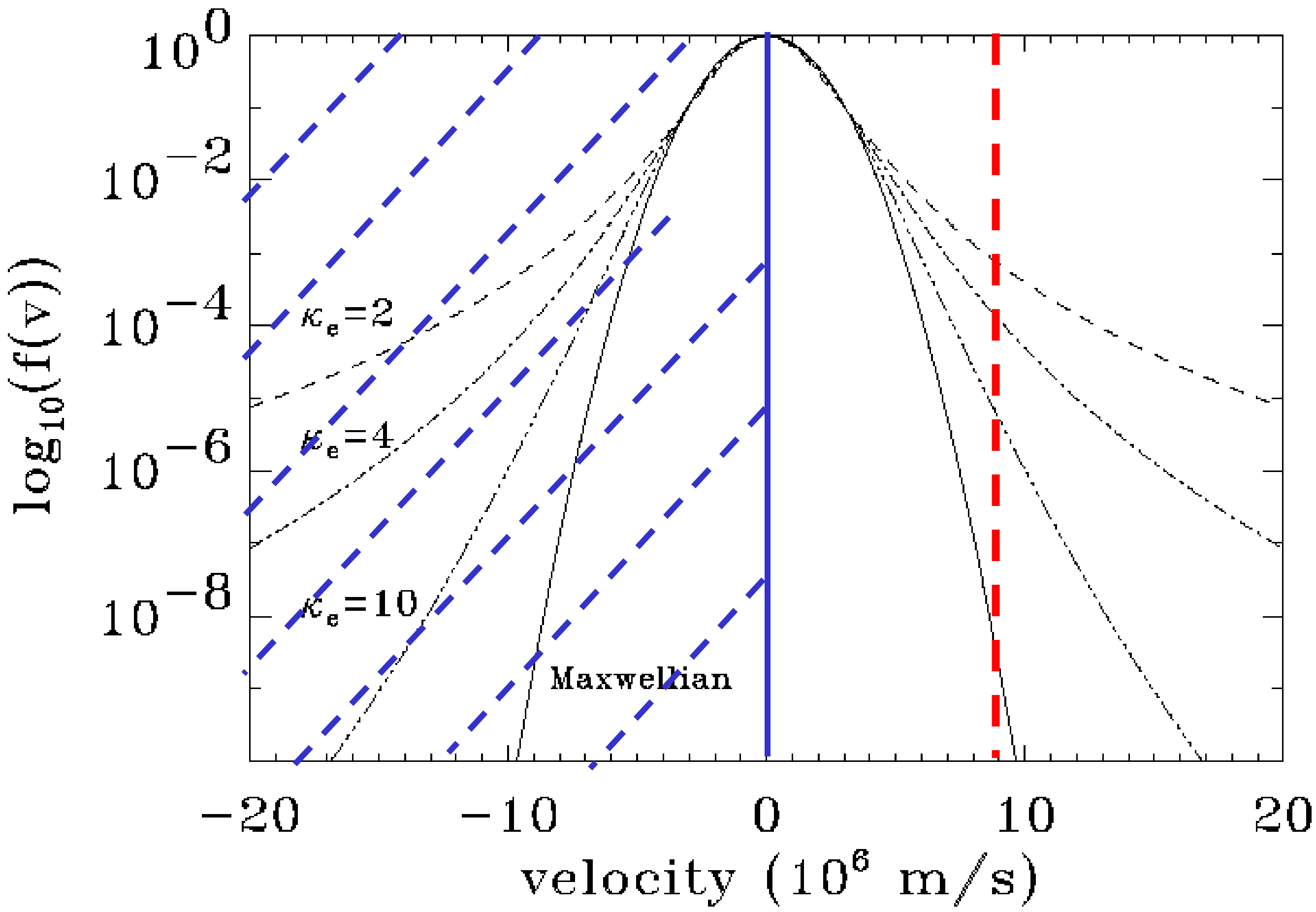
$$\frac{m_p M G}{r_o} > kT$$

Electrons are pulling the wind



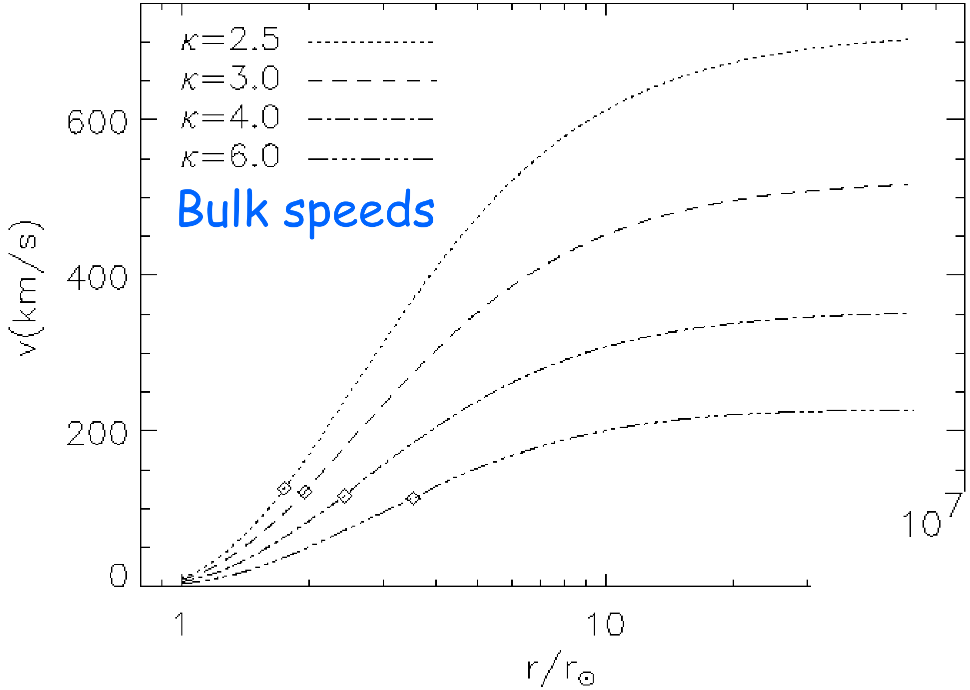
Jockers, 1971
Lemaire & Scherer, 1971
Maksimovic et al., 1997

The dilema of trapped electrons



Flux e^- ↗ with κ_e ↘

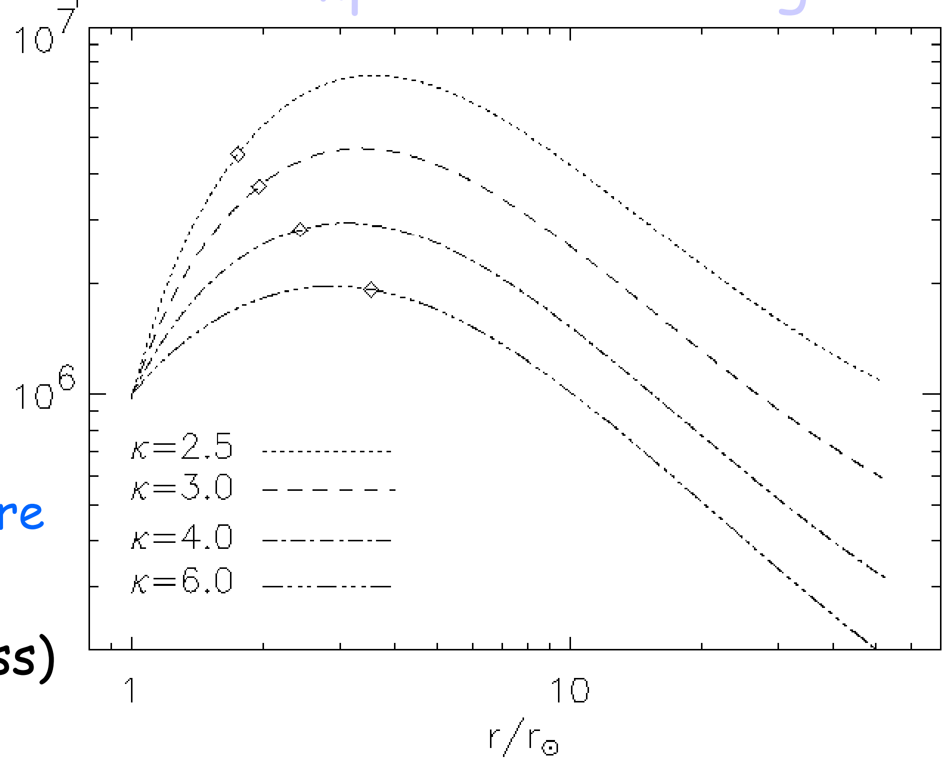
Transsonic exospheric model



r_0=1.0 R_s
T_{eo}=10^6 K
T_{po}=2•10^6 K
maxwellian protons
non-maxwellian electrons

Important heating...

important acceleration before 10Rs

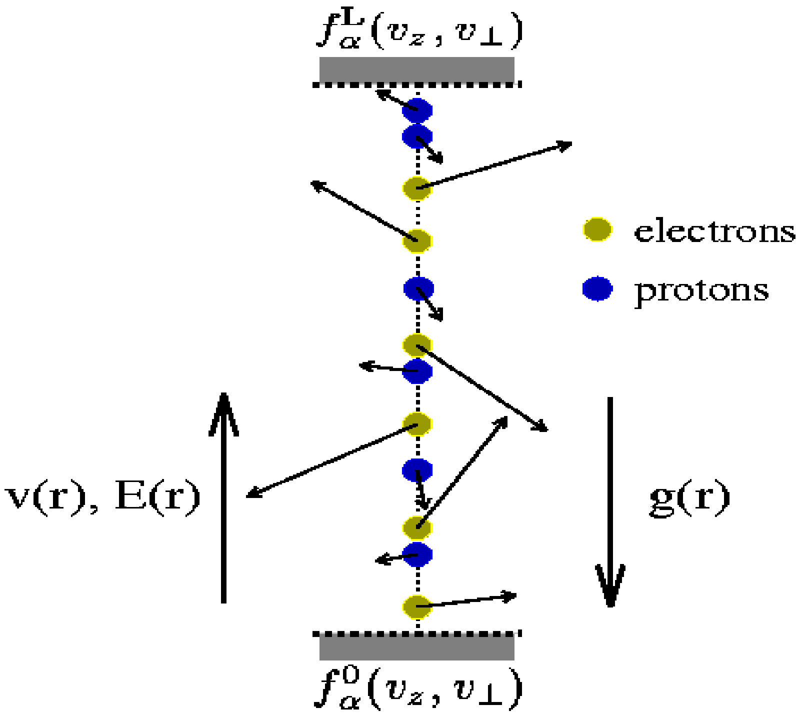


electron temperature

(Zouganelis et al., 2004, ApJ, in press)

Particule simulation

Landi & Pantellini, A&A, 2001 & 2003



* Spatially 1D, 3D particle velocities
* Self-consistent E(r) field
* Collisions with Coulombian cross section
* "Thermostats" at r=0 and r=L

Analytical model

Pierrard et al., JGR, 1999

Dorelli & Scudder, GRL1999 & JGR 2003

$$\frac{\partial f_e}{\partial t} + \mathbf{v} \cdot \nabla f_e + \frac{\mathbf{F_e}}{m_e} \cdot \nabla_{\mathbf{v}} f_e = C_e$$

External (g,E) forces

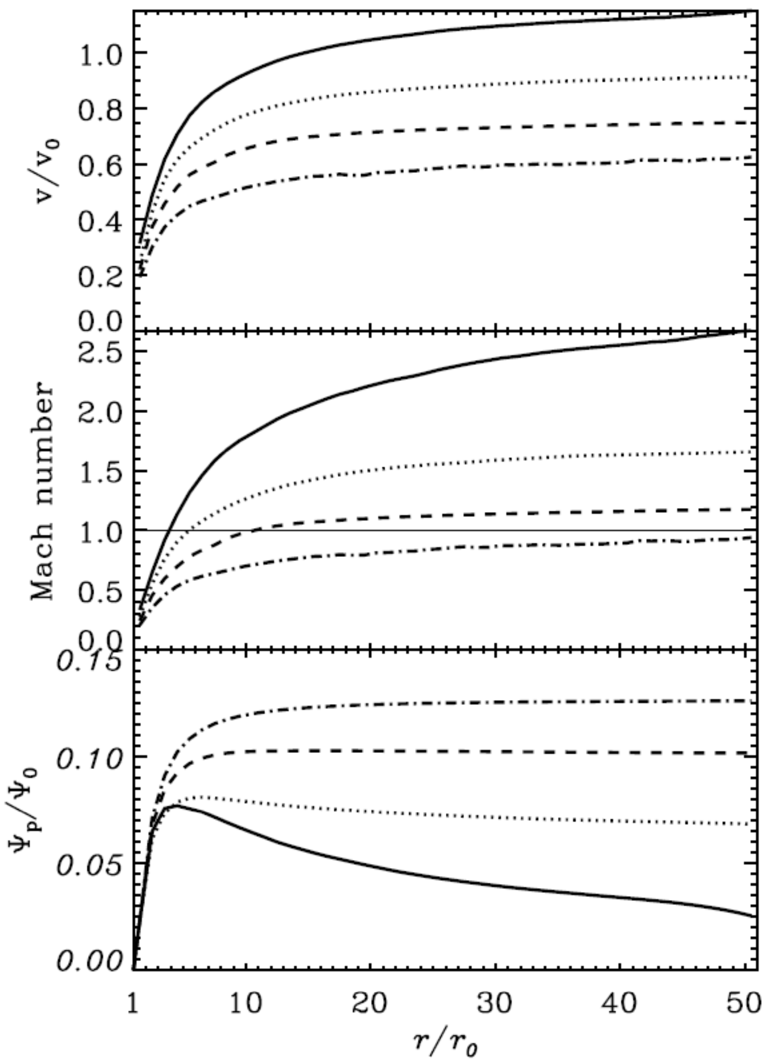
Rosenbluth et al. [1957]
Coulomb coll. operator

- The protons are treated as an infinitely massive, charge neutralizing background

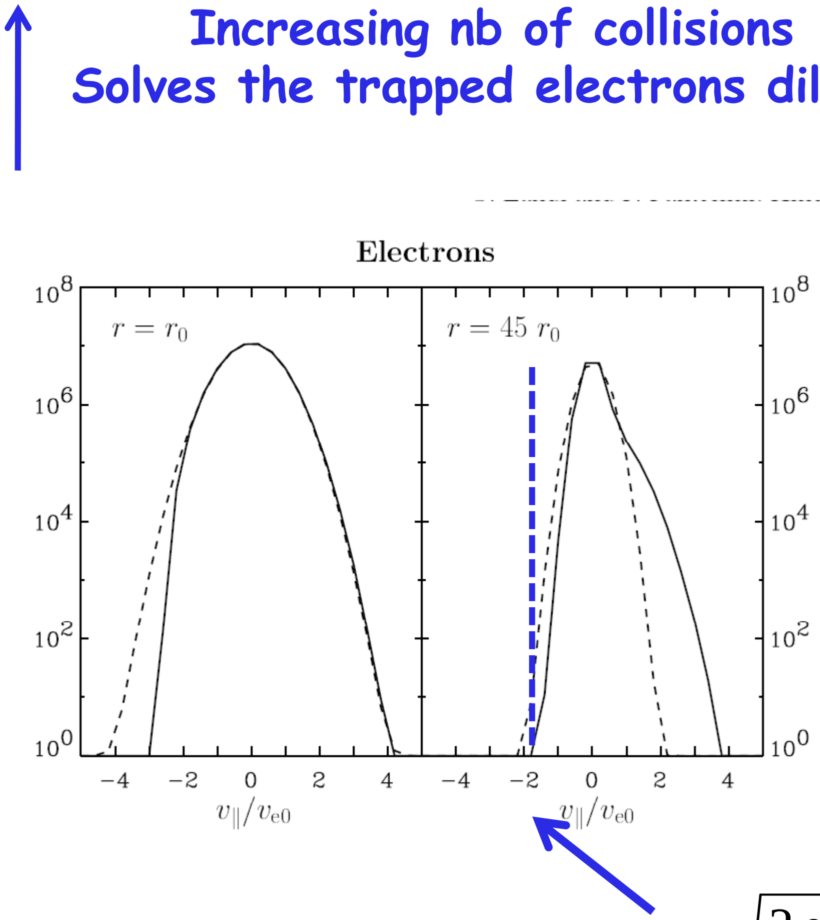
- The heat flux is constant and carried entirely by the electrons.

Landi & Pantellini, A&A 2003

Lani et al., SW12, 2009

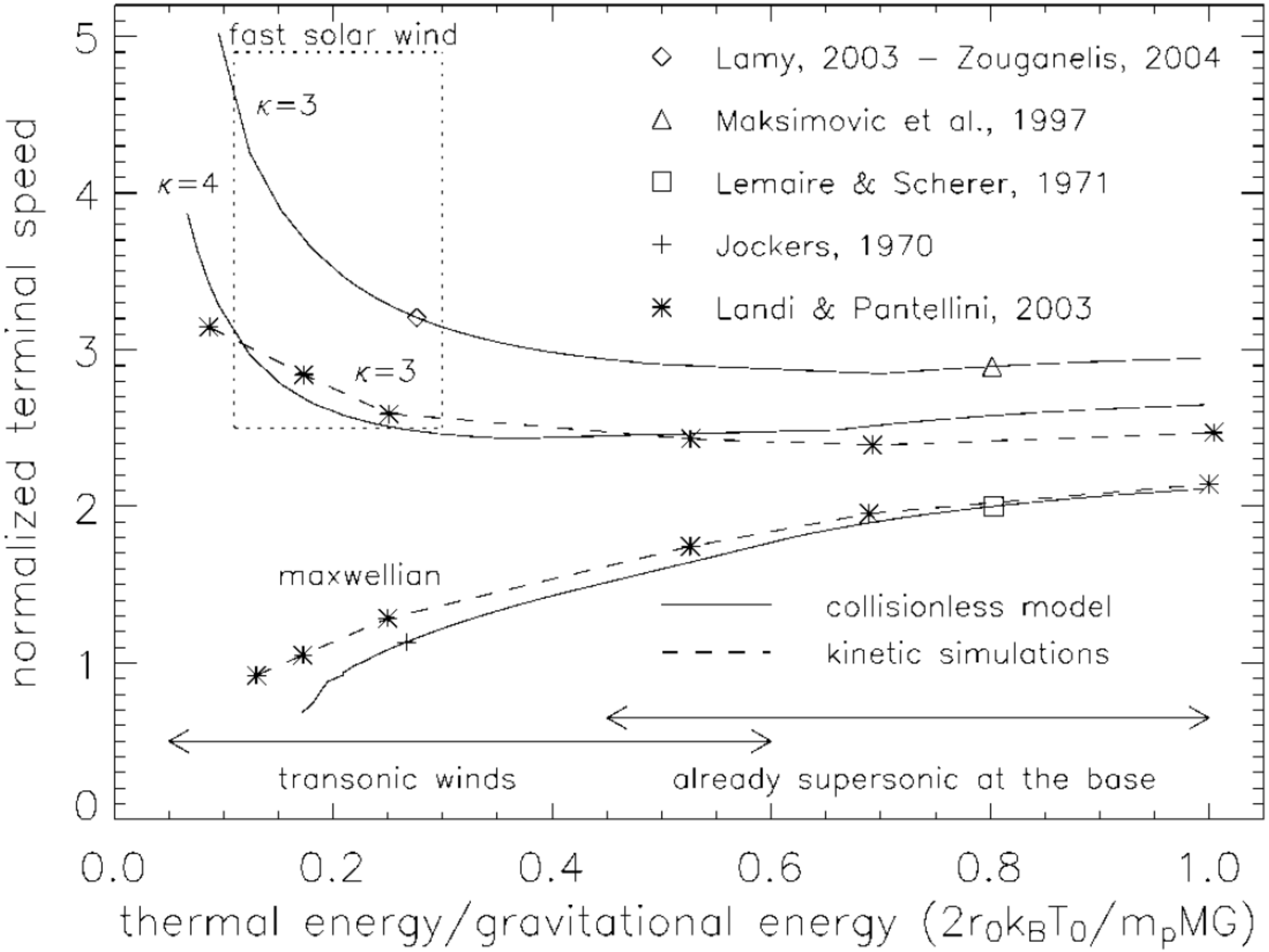


Increasing nb of collisions
Solves the trapped electrons dilema

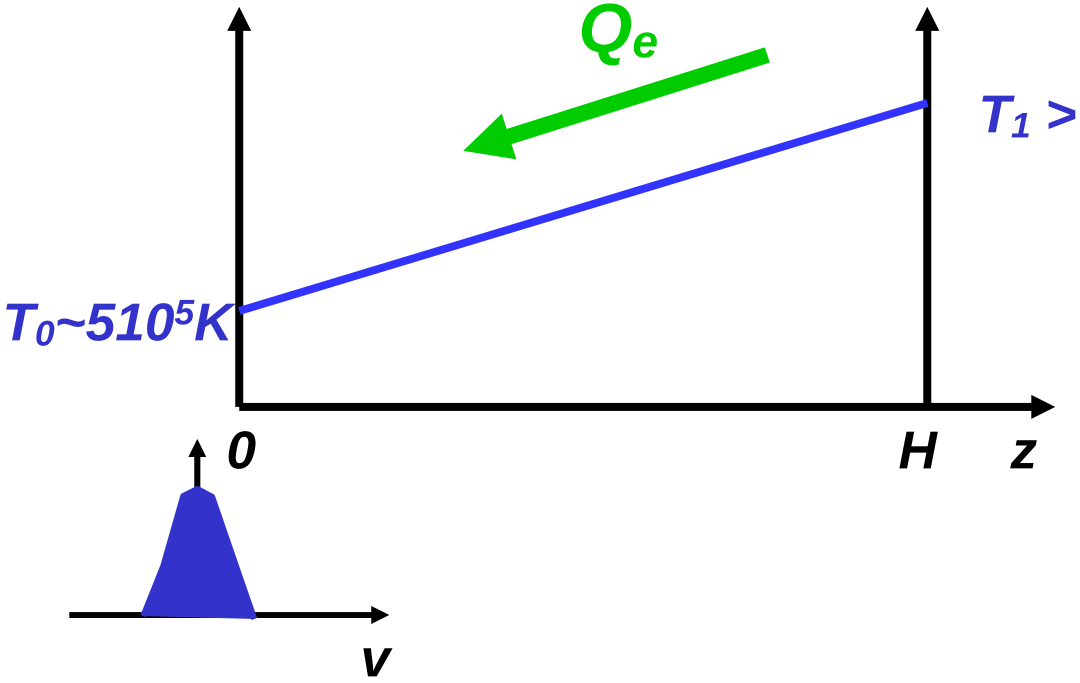


$$\sim \sqrt{\frac{2e\Phi}{m_e}}$$

Extensive comparison between exospheric and kinetic collisional models
Zouganelis et al., APJL 2005



Non-thermal distributions and heat flux in the corona

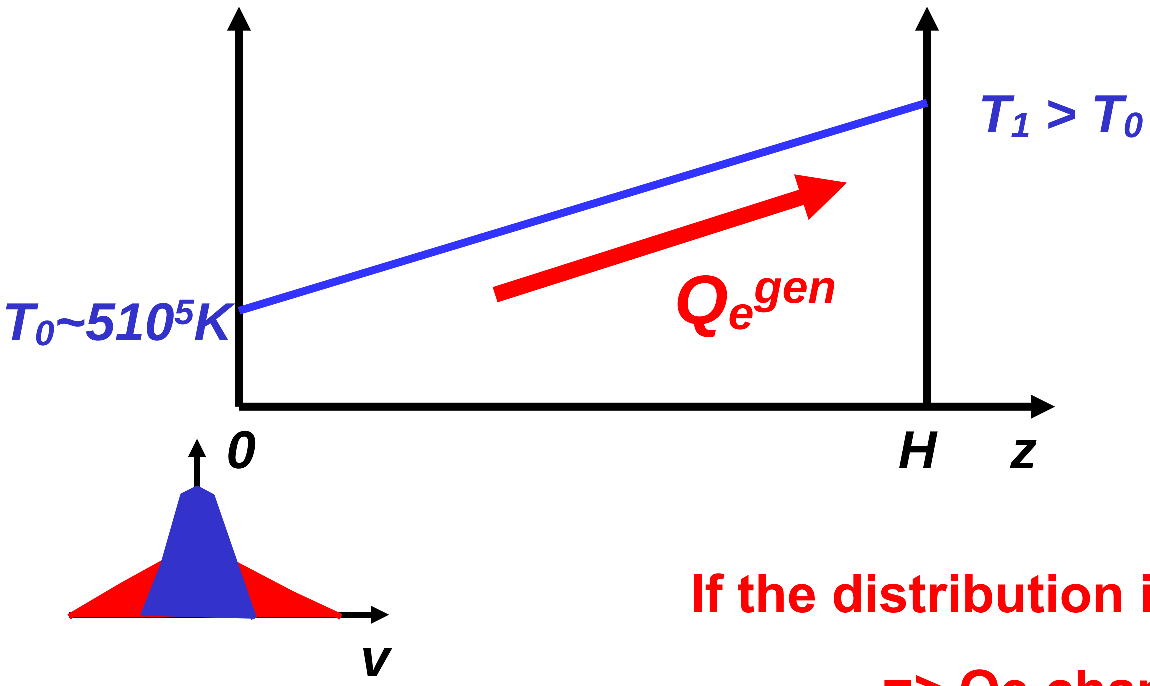


Classical Spitzer-Harm heat flux

$$Q_e = -K \nabla T_e$$

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

Non-thermal distributions and heat flux in the corona



Classical Spitzer-Harm heat flux

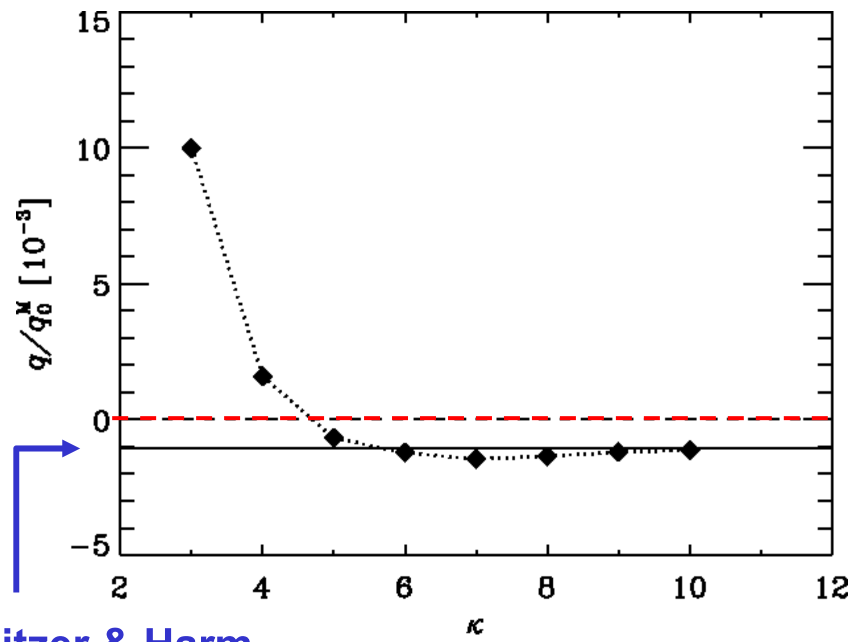
$$Q_e = -K \nabla T_e$$

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

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

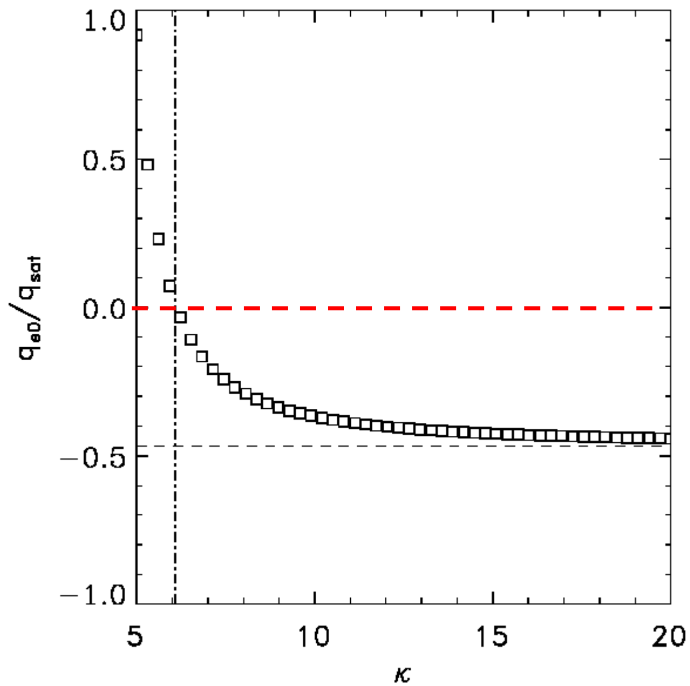
=> Qe changes direction

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

Conclusions:

- Non Maxwellian e VDFs are always present in the Solar Wind
- The core / strahl structure seems to results from natural expansion in a ambipolar interplanetary electric field and Coulomb collisions for the core
- The halo part seems to come from scaterred strahl electrons and develops with radial distance
- Both electrons and ions need additional heating processes (dissipation of turbulence, instabilities)
- The equations for the transport of energy are not obvious

- **We need to go closer to the Sun**