The microstate of the solar corona and the solar wind

- Radial gradients of kinetic temperatures
- Velocity distribution functions
- Ion composition and suprathermal electrons
- Coulomb collisions in the solar wind
- Waves and plasma microinstabilities
- Diffusion and wave-particle interaction

Length scales in the solar wind

Macrostructure - fluid scales

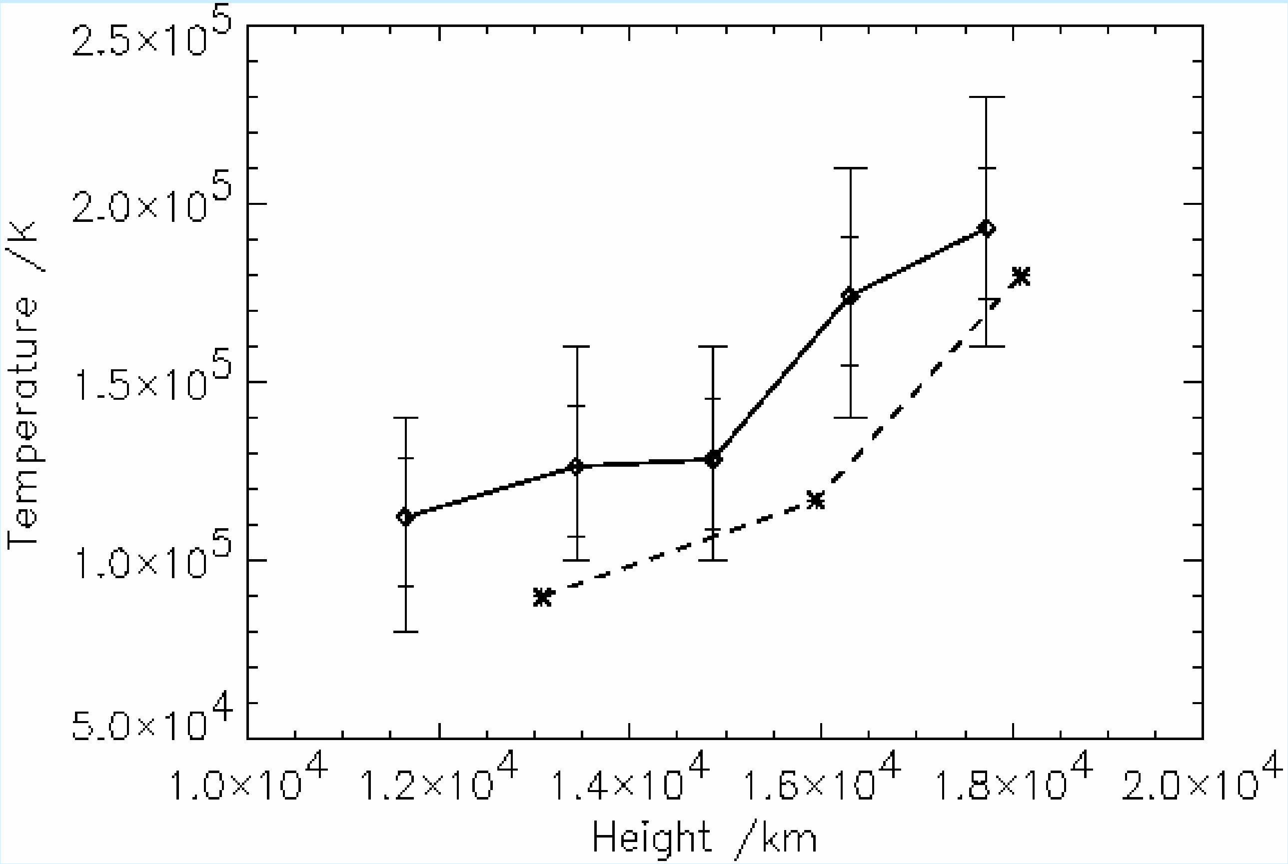
• Heliocentric distance:	r	150 Gm (1AU)
• Solar radius:	R_s	696000 km (215 R_s)
• Alfvén waves:	λ	30 - 100 Mm

Microstructure - kinetic scales

• Coulomb free path:	l	~ 0.1 - 10 AU
• Ion inertial length:	V_A / Ω_p (c / ω_p)	~ 100 km
• Ion gyroradius:	r_L	~ 50 km
• Debye length:	λ_D	~ 10 m
• Helios spacecraft:	d	~ 3 m

Microscales vary with solar distance!

Proton temperature at coronal base



SUMER / SOHO

Hydrogen Lyman series

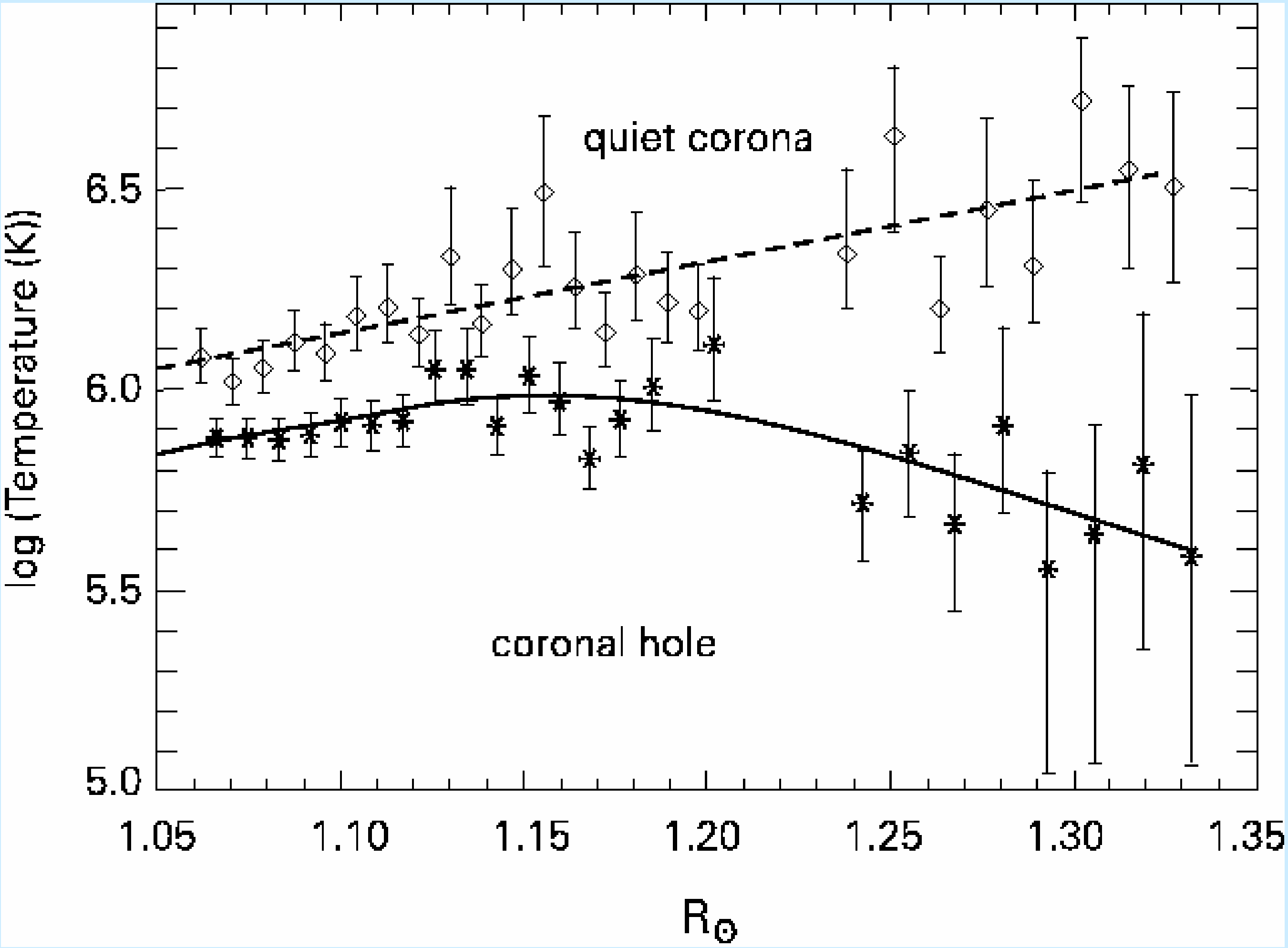
Off-limb transition region at the base of north polar CH

Marsch et al., A&A, **359**, 381, 2000

Charge-exchange equilibrium: $T_H = T_p$

Turbulence broadening: $\xi = 30\ \mathrm{km\ s^{-1}}$

Electron temperature in the corona



Streamer belt, closed

Coronal hole, open magnetically

David et al., A&A
336, L90, 1998

Heliocentric distance

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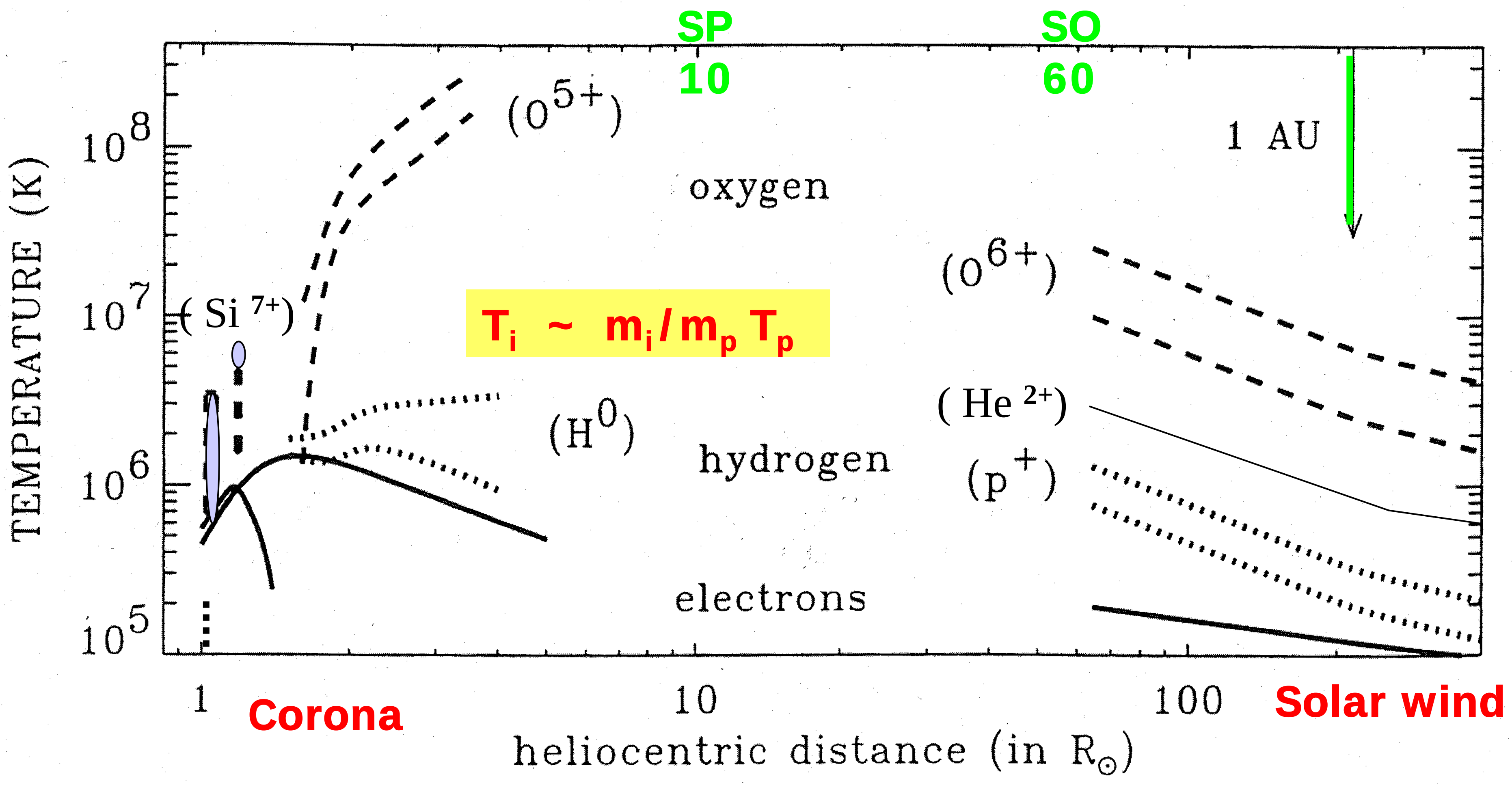
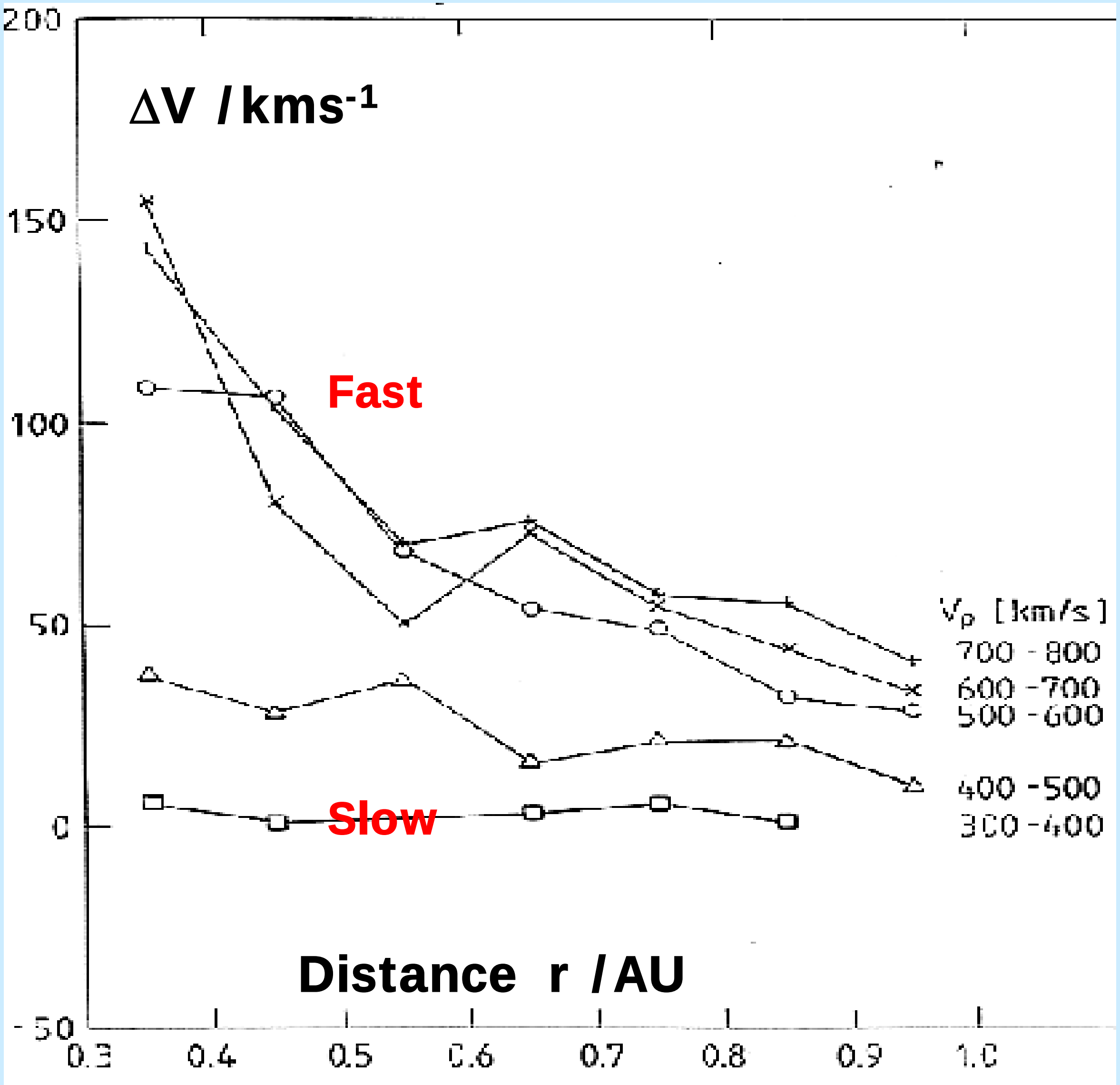
Temperature profiles in the corona and fast solar wind



$T_i \sim m_i / m_p \, T_p$

Cranmer et al., Ap.J., 2000; Marsch, 1991

Ion differential streaming



- **Helios:**

Alpha particles are faster than the protons!

- **In fast streams the differential velocity $\Delta \underline{V} \leq \underline{V}_A$**

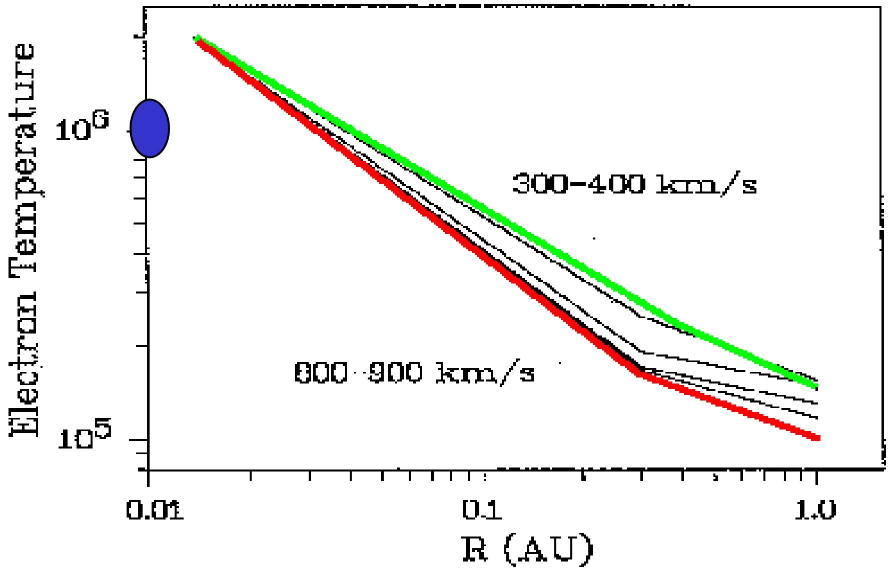
- **Ulysses:**

Heavy ions travel at alpha-particle speed!

Marsch et al., JGR, **87**, 52, 1982

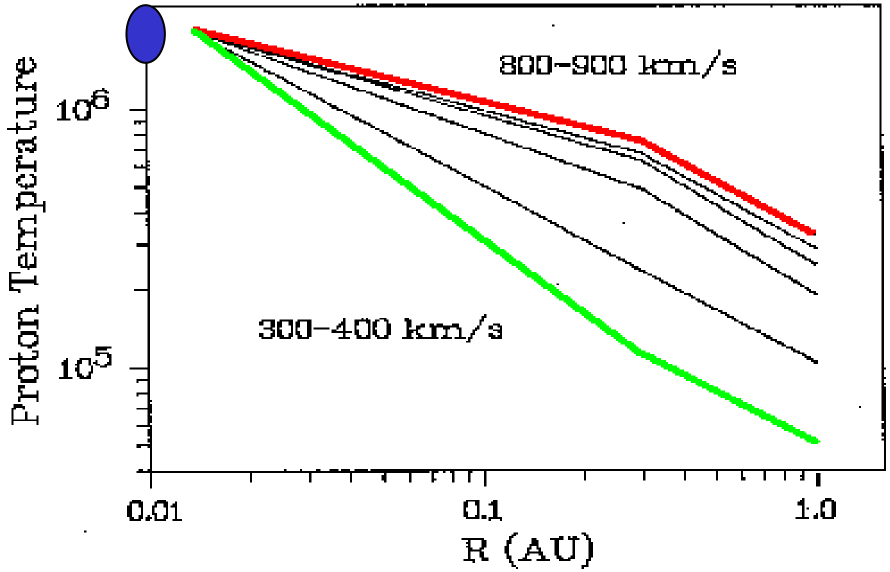
Proton and electron temperatures

Electrons
are cool!



slow wind
↓
fast wind

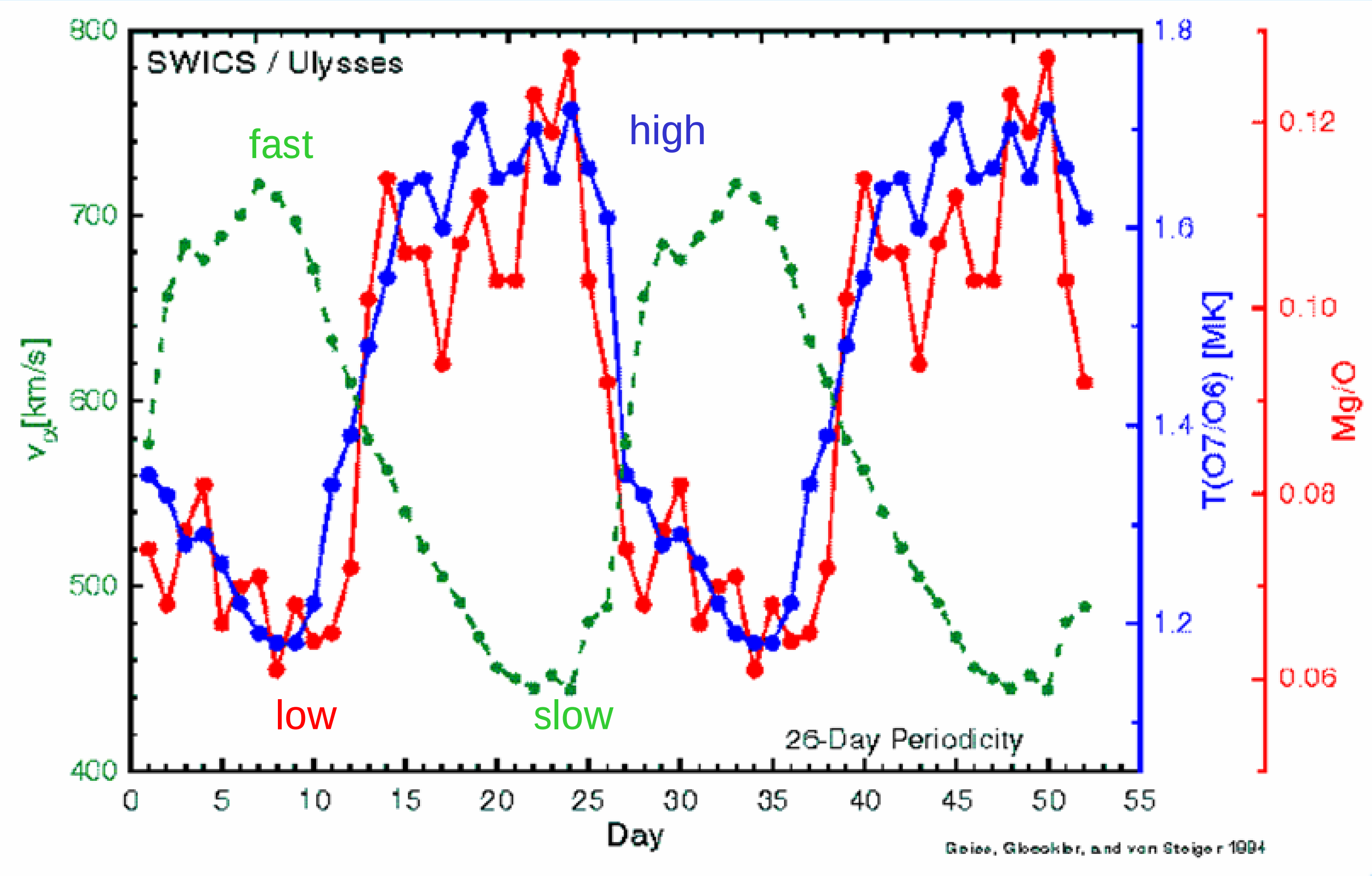
Protons
are hot!



fast wind
↓
slow wind

Marsch, 1991

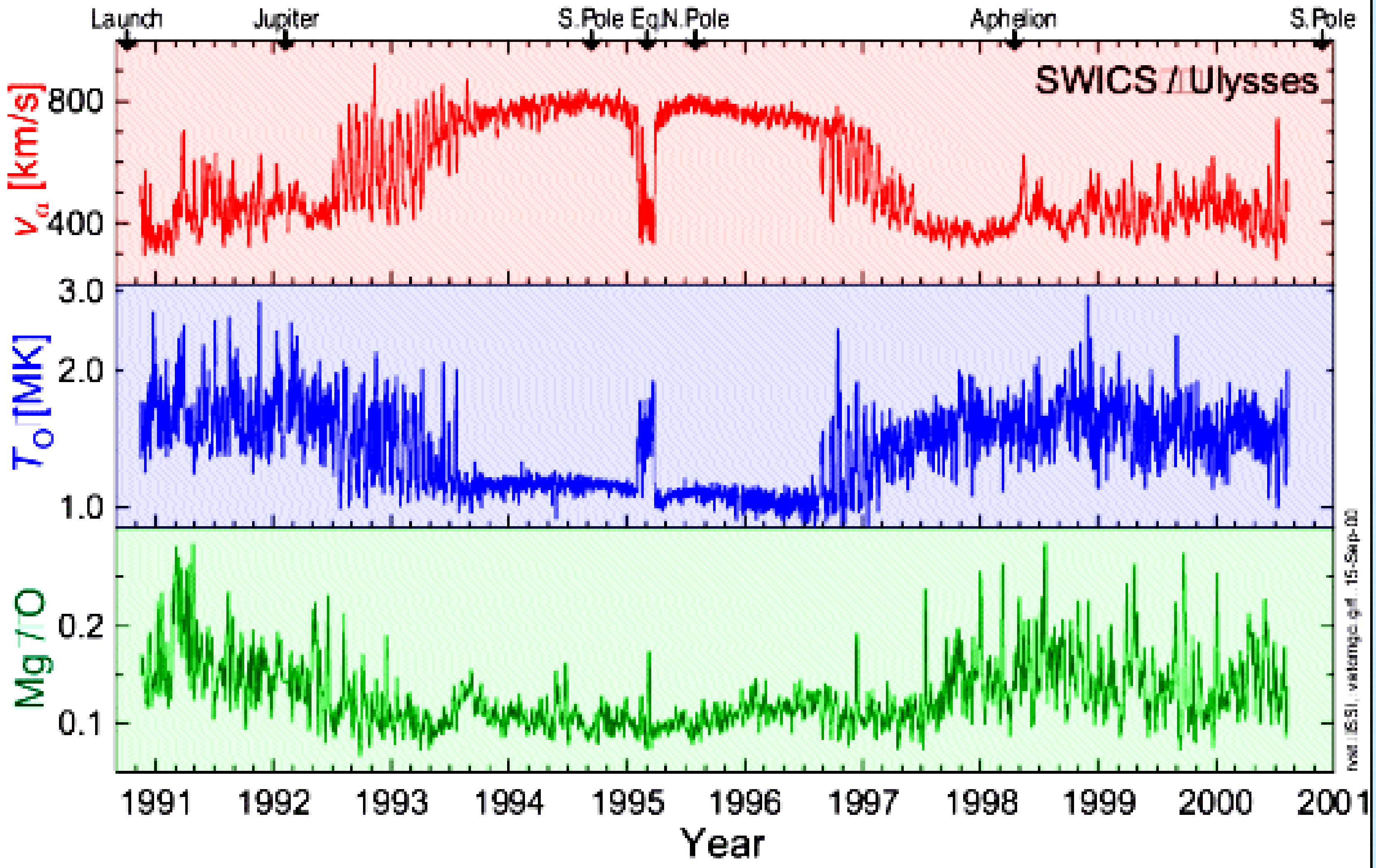
Oxygen freeze-in temperature



Geiss et al., 1996

Ulysses SWICS

Correlations between wind speed and corona temperature



Velocity distribution functions

Statistical description: $f_j(\mathbf{x},\mathbf{v},t)d^3xd^3v$,

gives the probability to find a particle of species j with a velocity **v** at location **x** at time t in the 6-dimensional phase space.

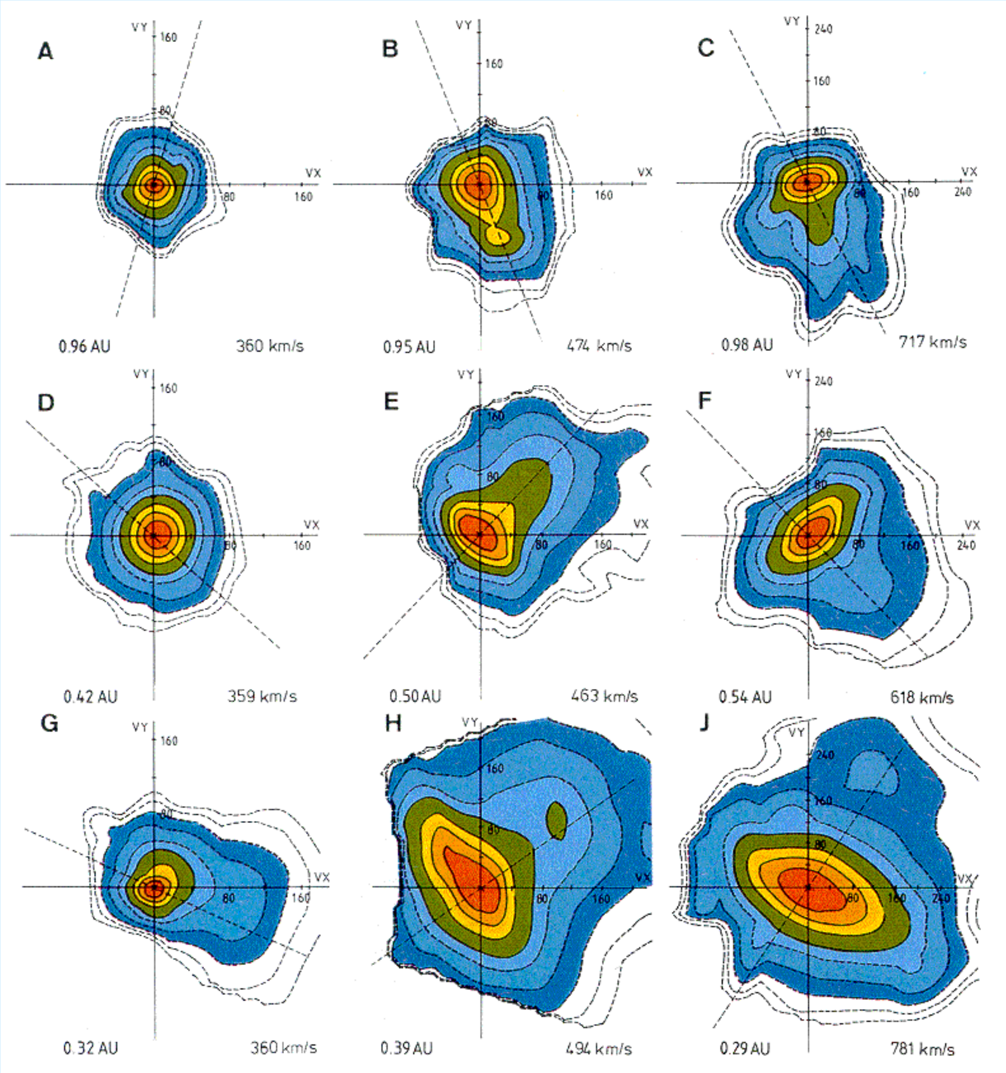
Local thermodynamic equilibrium:

$$f_j^M(\mathbf{x},\mathbf{v},t) = n_j(2\pi v_j)^{-3/2} \exp[-(\mathbf{v}-\mathbf{U}_j)^2/(2v_j)^2],$$

with number density, n_j, thermal speed, $v_j=(k_B T_i/m_i)^{1/2}$, temperature T_i, and bulk velocity, $\mathbf{U}_j$, of species j.

Dynamics in phase space: Vlasov/Boltzmann kinetic equation

Proton velocity distributions



- **Temperature anisotropies**
- **Ion beams**
- **Plasma instabilities**
- **Interplanetary heating**

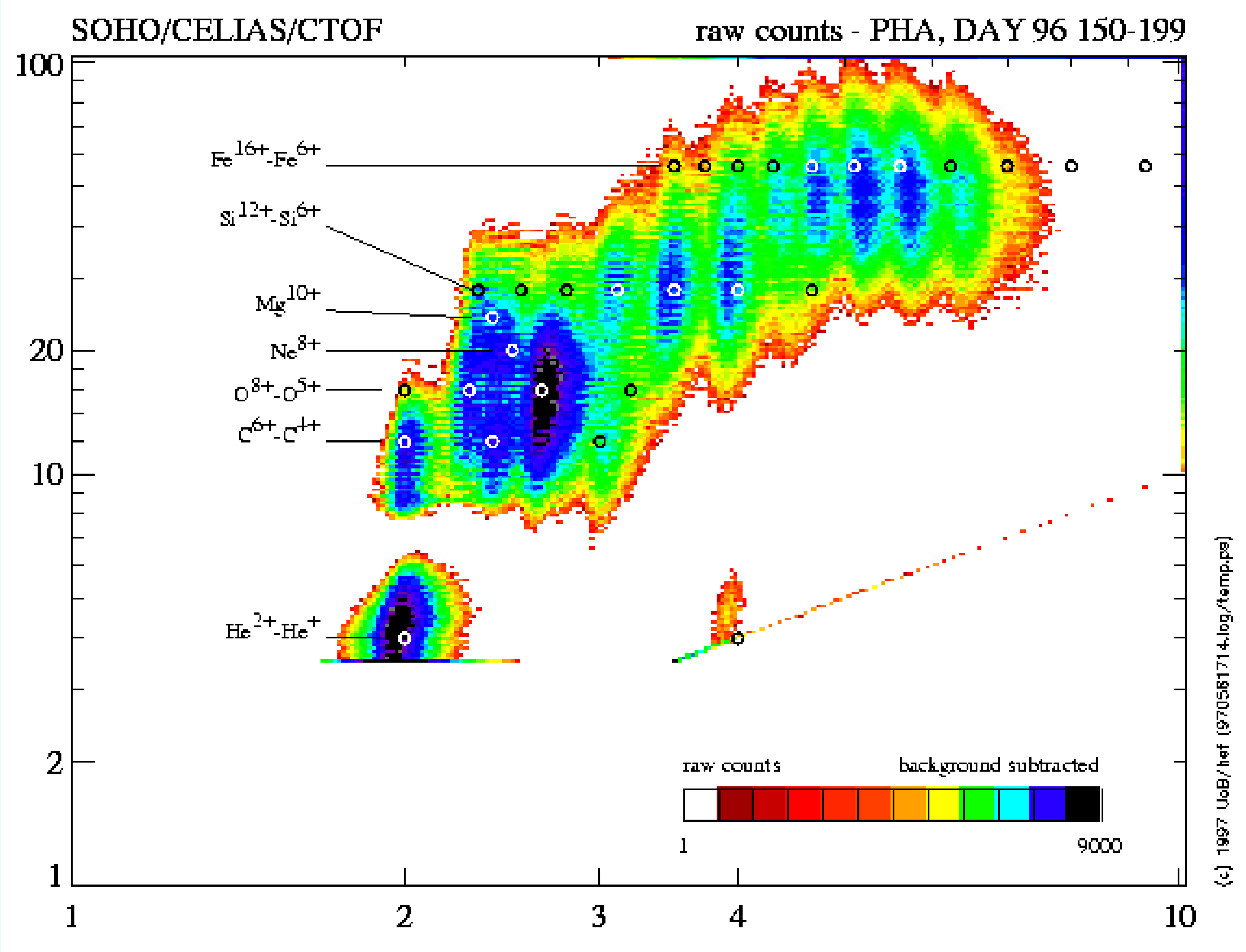
Plasma measurements made at 10 s resolution (> 0.29 AU from the Sun)

Helios

Marsch et al., JGR, **87**, 52, 1982

Ion composition of the solar wind

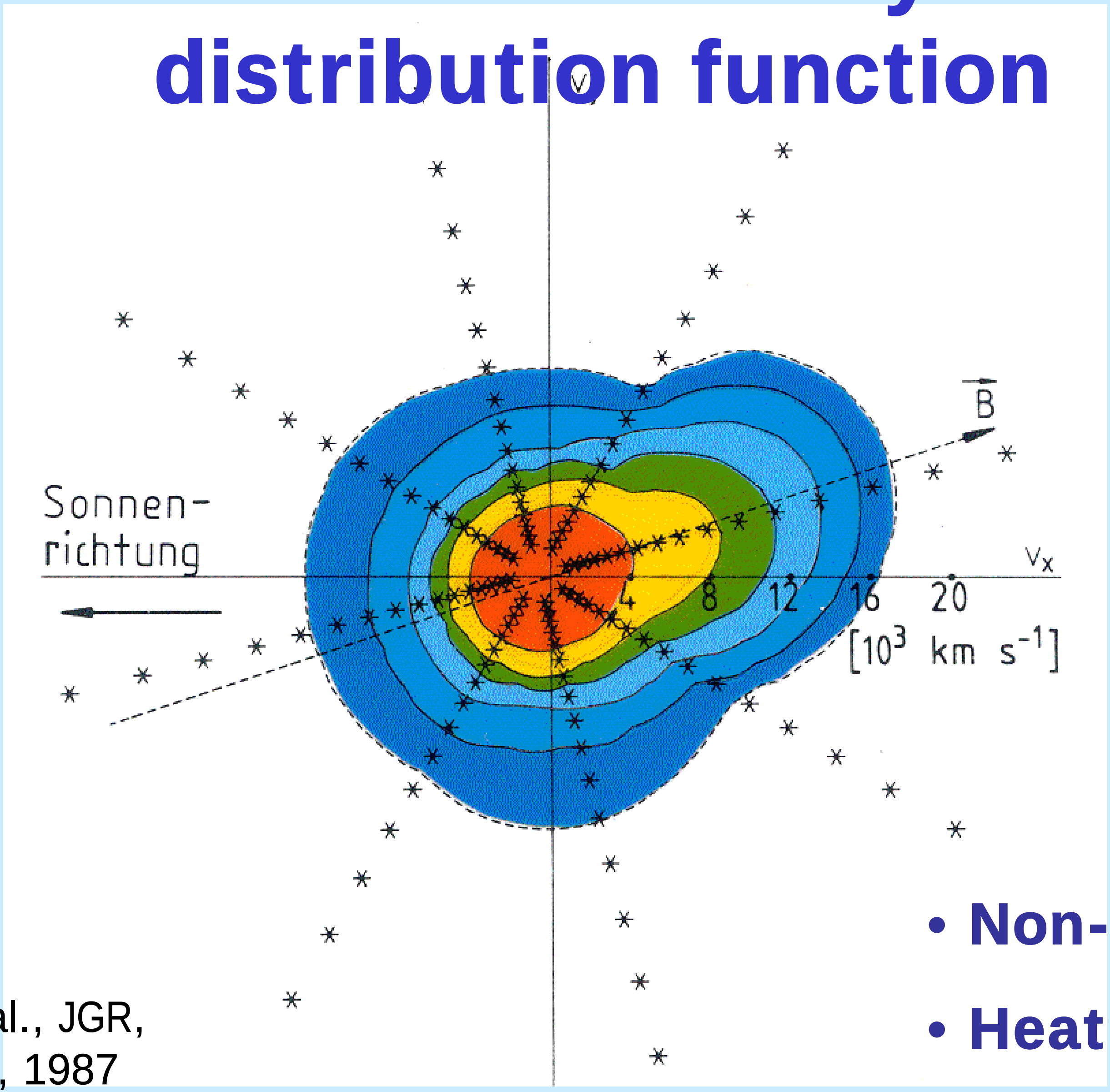
Ion mass



Mass/charge

Grünwaldt et al. (CELIAS on SOHO)

Electron velocity distribution function



Helios

Sun

- **Non-Maxwellian**
- **Heat flux tail**

Pilipp et al., JGR, **92**, 1075, 1987

Kinetic processes in the solar corona and solar wind I

- Plasma is multi-component and nonuniform

→ **complexity**

- Plasma has low density

→ **deviations from local thermal equilibrium**

→ **suprathermal particles (electron strahl)**

→ **global boundaries are reflected locally**

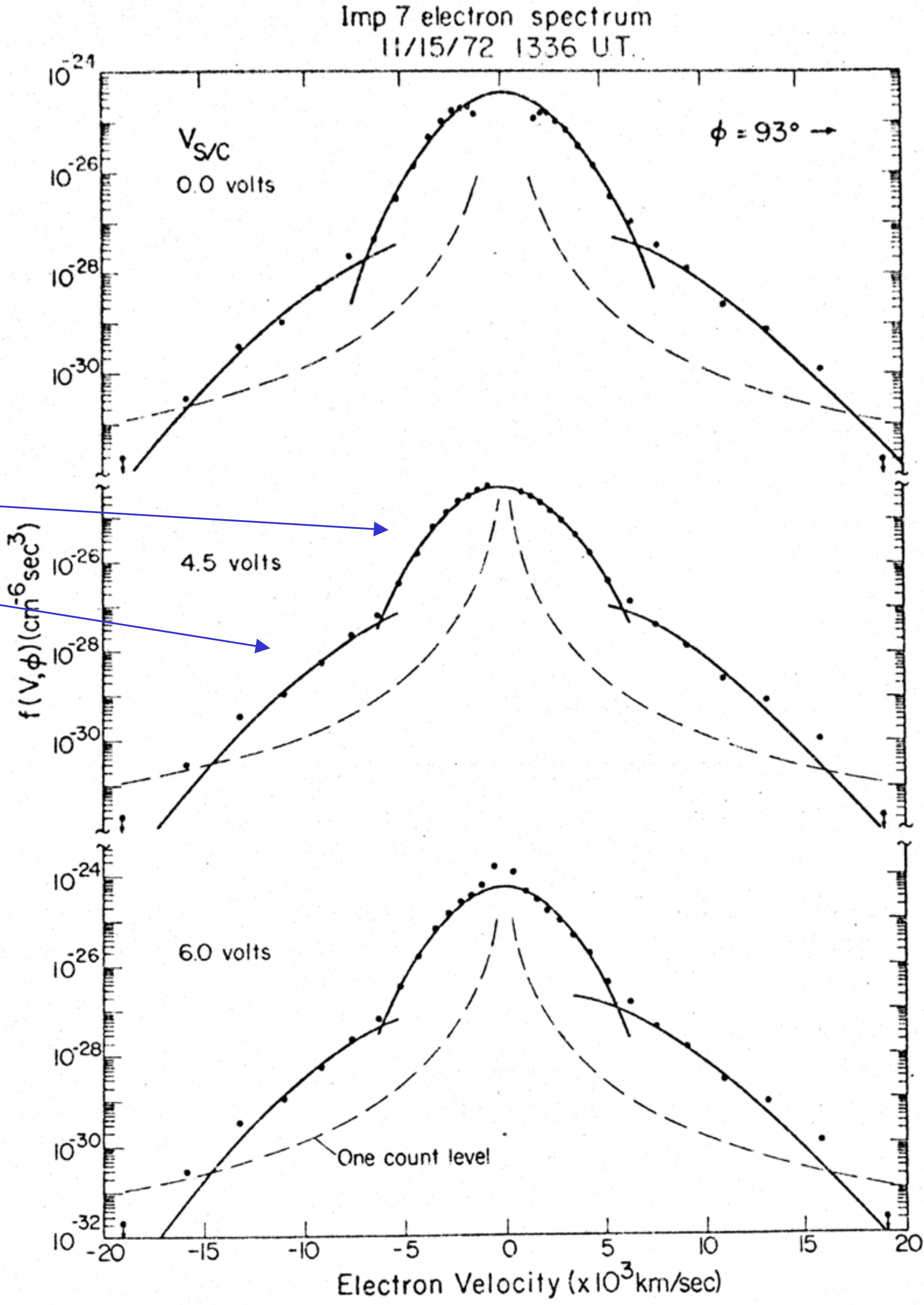
Problem: Thermodynamics of the plasma, which is far from equilibrium.....

Electron energy spectrum

IMP spacecraft

Two solar wind populations:

- Core (96%)
- Halo (4%)

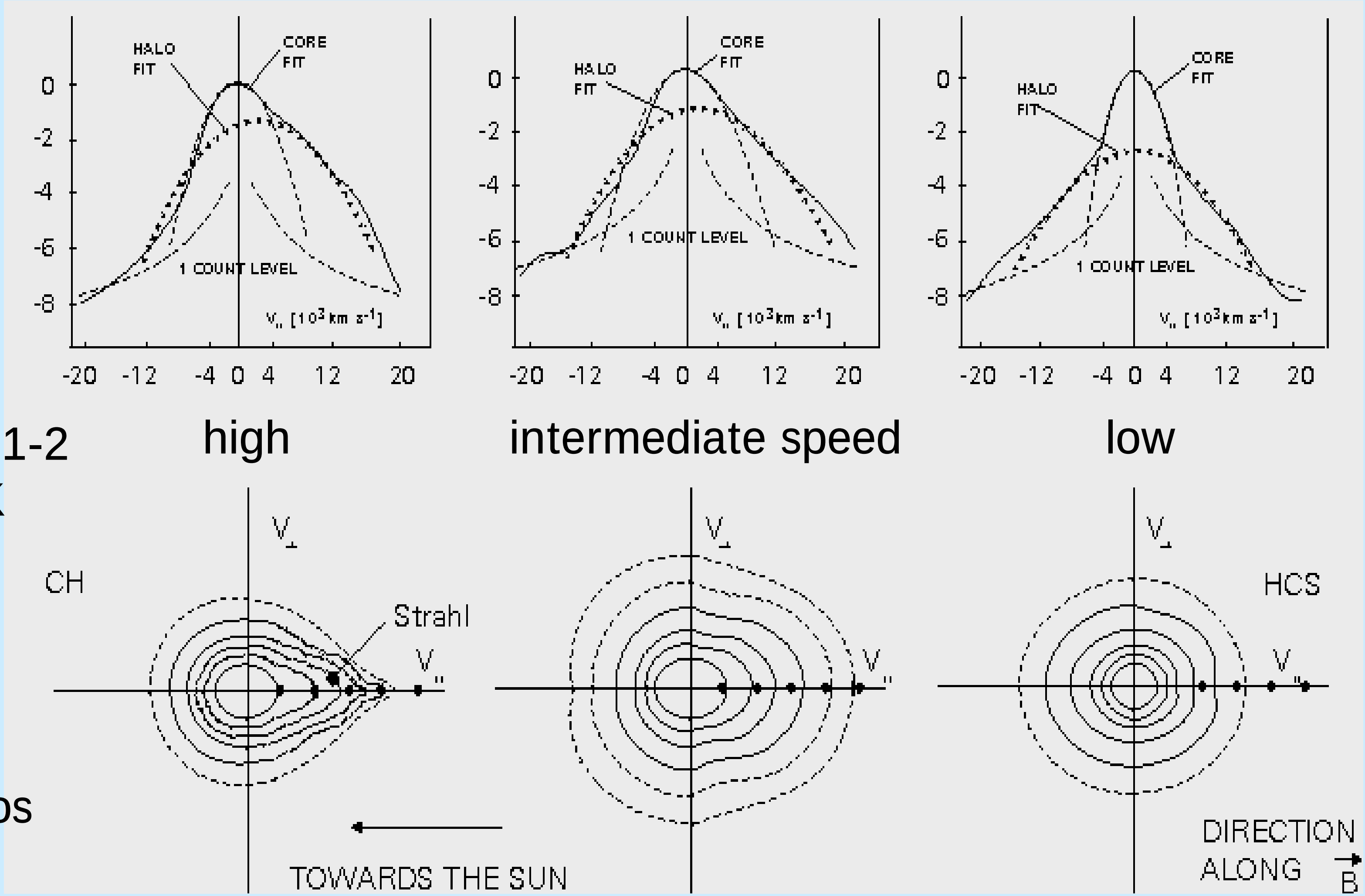


Core: local, collisional, **bound** by electrostatic potential

Halo: global, collisionless, **free** to escape (exopsheric)

Feldman et al., JGR, **80**, 4181, 1975

Electron velocity distributions



high

intermediate speed

low

T_e = 1-2 10^5 K

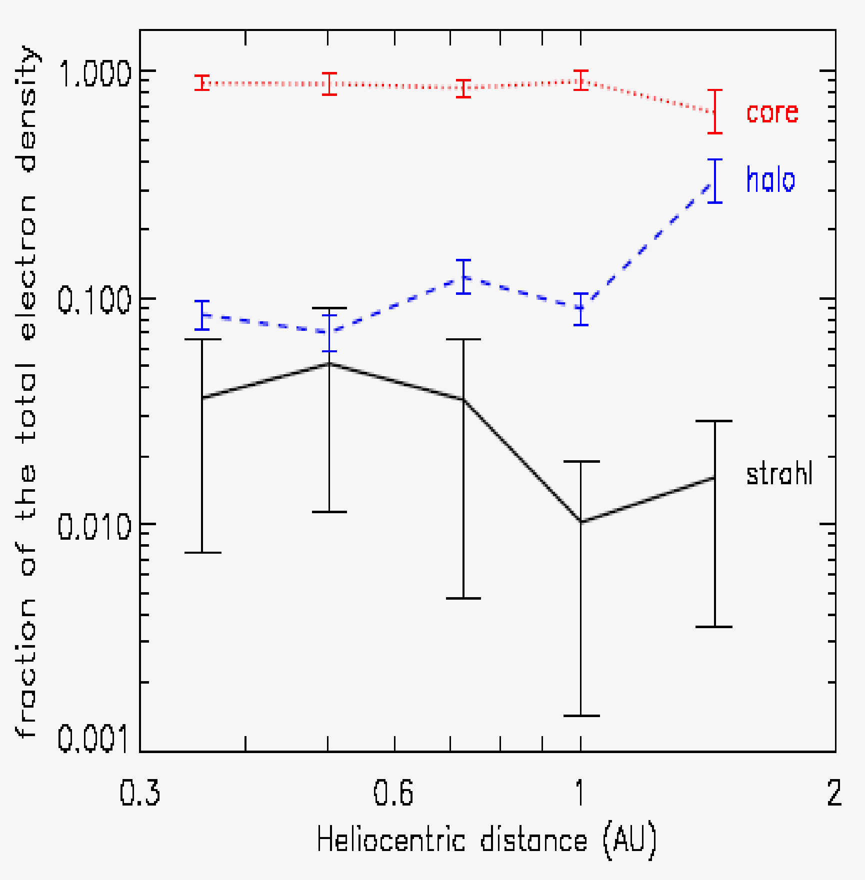
Helios

Pilipp et al., JGR, **92**, 1075, 1987

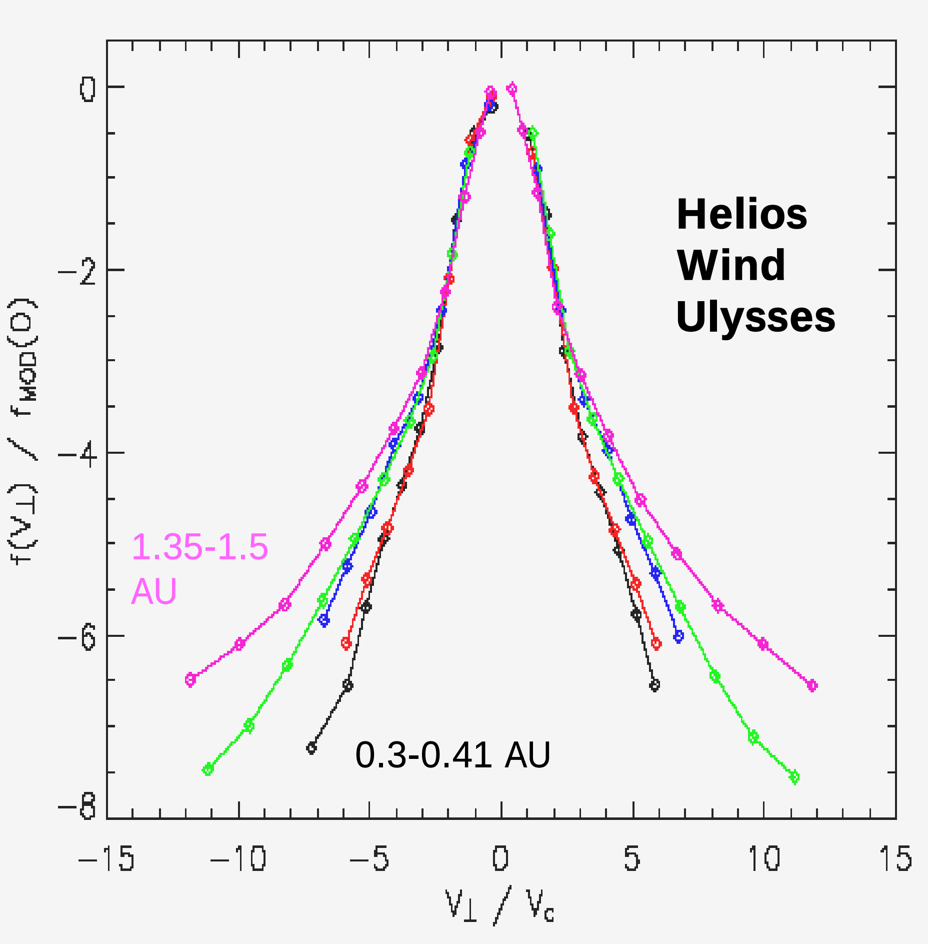
Core (96%), halo (4%) electrons, and „strahl“

Solar wind electrons: Core-halo evolution

Halo is relatively increasing while strahl is diminishing.



Normalized core remains constant while halo is relatively increasing.



Maksimovic et al., JGR 2005

Scattering by meso-scale magnetic structures

Fluid description

Moments of the Vlasov/Boltzmann equation:

Density: $n_j = \int d^3v\, f_j(\mathbf{x},\mathbf{v},t)$

Flow velocity: $\mathbf{U}_j = 1/n_j \int d^3v\, f_j(\mathbf{x},\mathbf{v},t)\, \mathbf{v}$

Thermal speed: $v_j^2 = 1/(3n_j) \int d^3v\, f_j(\mathbf{x},\mathbf{v},t)\, (\mathbf{v}-\mathbf{U}_j)^2$

Temperature: $T_j = m_j v_j^2/k_B$

Heat flux: $Q_j = 1/2m_j \int d^3v\, f_j(\mathbf{x},\mathbf{v},t)\, (\mathbf{v}-\mathbf{U}_j)\, (\mathbf{v}-\mathbf{U}_j)^2$

Electron heat conduction

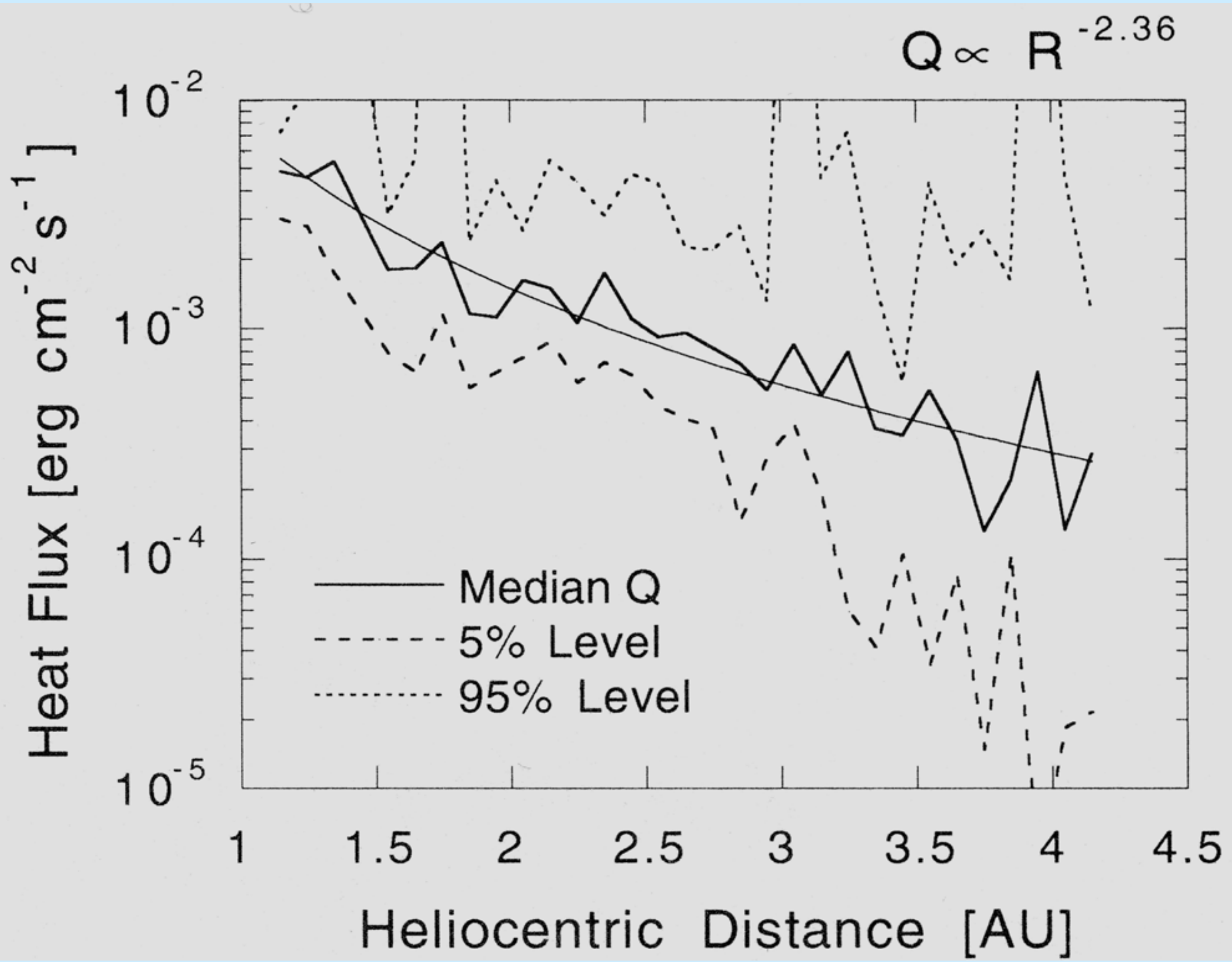
Heat carried by halo electrons!

$T_H = 7\, T_C$

Interplanetary potential:

$\Phi = 50\text{-}100$ eV

$\underline{E} = -1/n_e\, \underline{\nabla}\, p_e$



McComas et al., GRL, **19**, 1291, 1992

$\underline{Q}_{\underline{e}} \neq -\kappa \underline{\nabla}\, T_e$

Theoretical description

Boltzmann-Vlasov kinetic equations for protons, alpha-particles (4%), minor ions and electrons

Distribution functions

Kinetic equations

- \+ Coulomb collisions (Landau)
- \+ Wave-particle interactions
- \+ Micro-instabilities (Quasilinear)
- \+ Boundary conditions

→ Particle velocity distributions and field power spectra

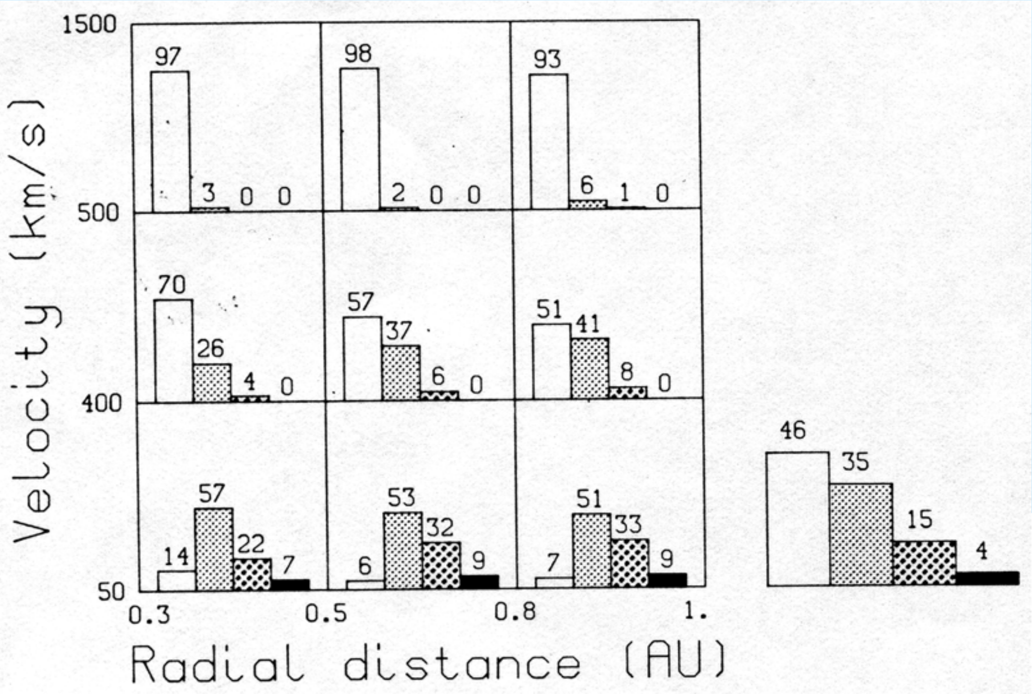
Moments

Multi-Fluid (MHD) equations

- \+ Collision terms
- \+ Wave (bulk) forces
- \+ Energy addition
- \+ Boundary conditions

→ Single / multi fluid parameters

Proton Coulomb collision statistics



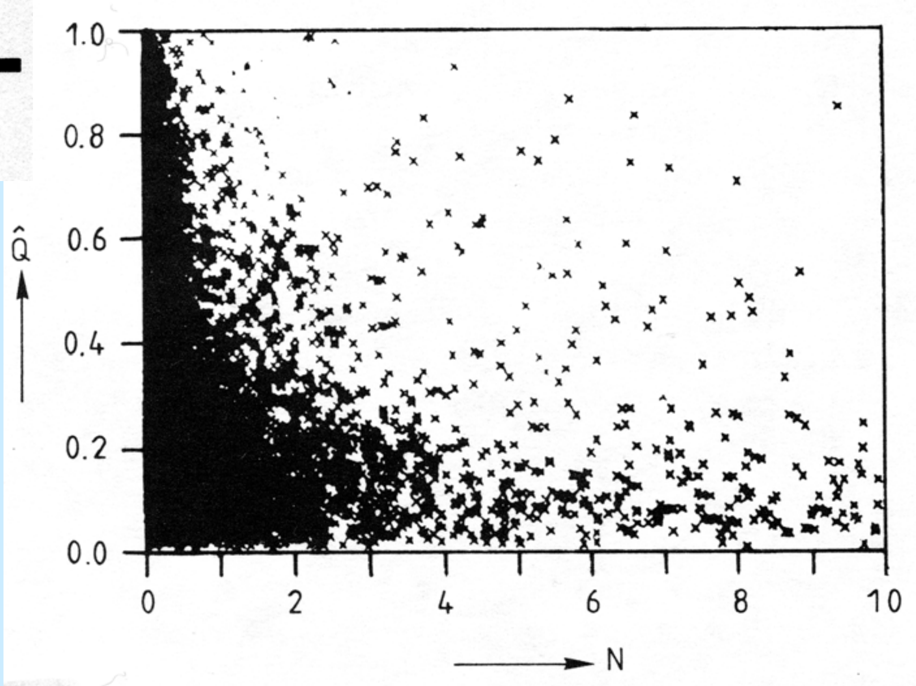
N: <0.1; [0.1, 1]; [1, 5]; >5

$$N = \tau_{exp}\nu_c \sim n_p V^{-1} T_p^{-3/2}$$

Livi et al., JGR, **91**, 8045, 1986

- **Fast protons are collisionless!**
- **Slow protons show collision effects!**

Proton heat flux regulation



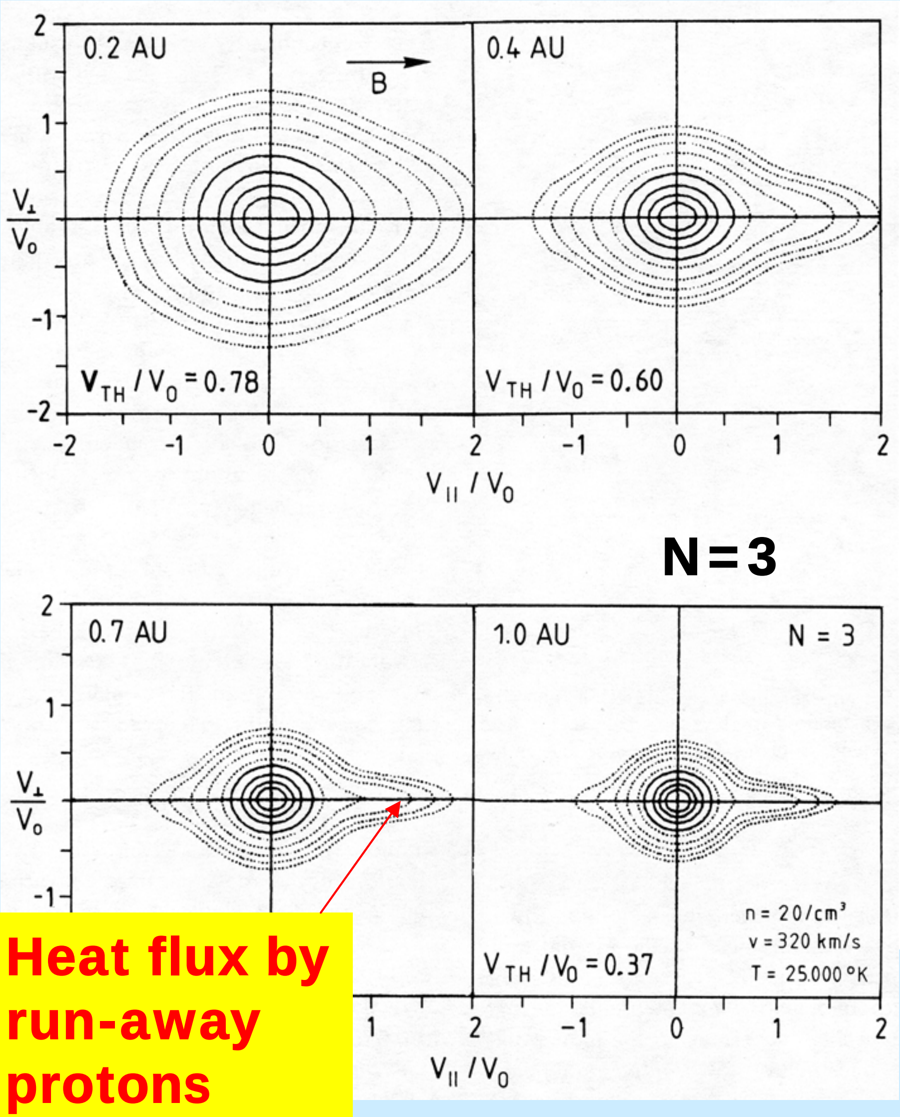
Coulomb collisions and quasilinear wave-particle interactions

$$\frac{\delta f}{\delta t} = \frac{\partial}{\partial \mathbf{v}} \cdot \left(-\mathbf{A} + \mathcal{D} \cdot \frac{\partial}{\partial \mathbf{v}}\right) f$$

Coulomb collisions and/or **wave-particle interactions** are represented by a second-order differential operator, including the acceleration vector **A**(**v**) and diffusion tensor *D*(**v**):

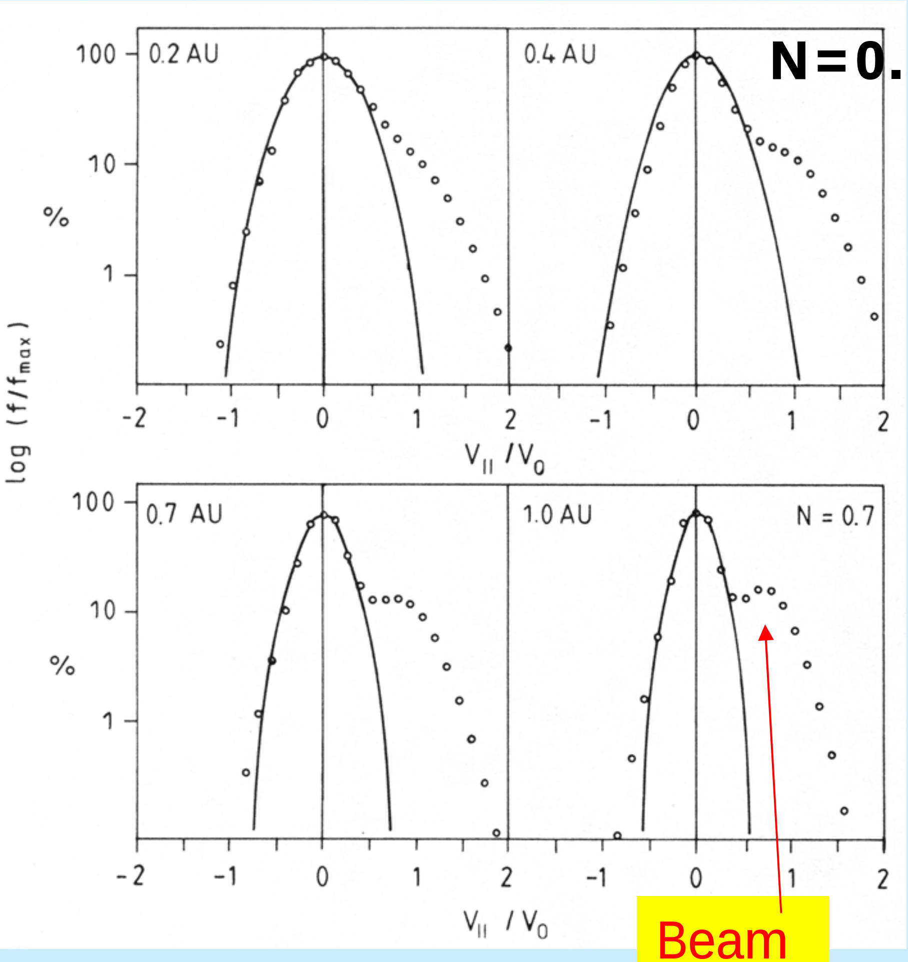
Parameter	Chromo-sphere	Corona $(1R_S)$	Solar wind (1AU)
n_e (cm^{-3})	10^{10}	10^7	10
T_e (K)	6-10 10^3	1-2 10^6	10^5
λ_e (km)	10	1000	10^7

Coulomb collisions in slow wind



N=3

Heat flux by run-away protons



N=0.7

Beam

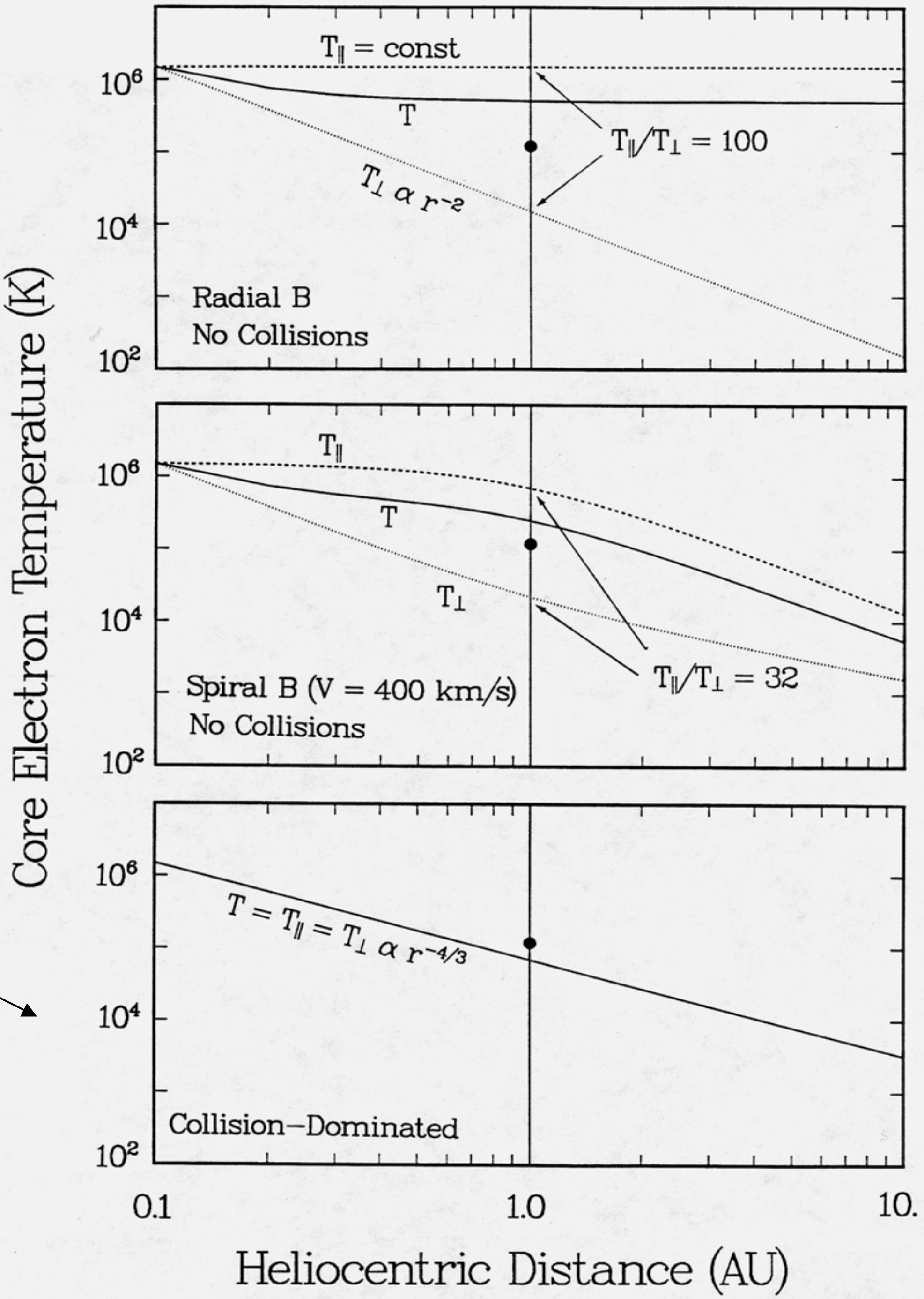
Marsch and Livi, JGR, **92**, 7255, 1987

Collisions and geometry

Double adiabatic invariance, → extreme anisotropy not observed!

Spiral reduces anisotropy!

Adiabatic collision-dominated → isotropy, is not observed!

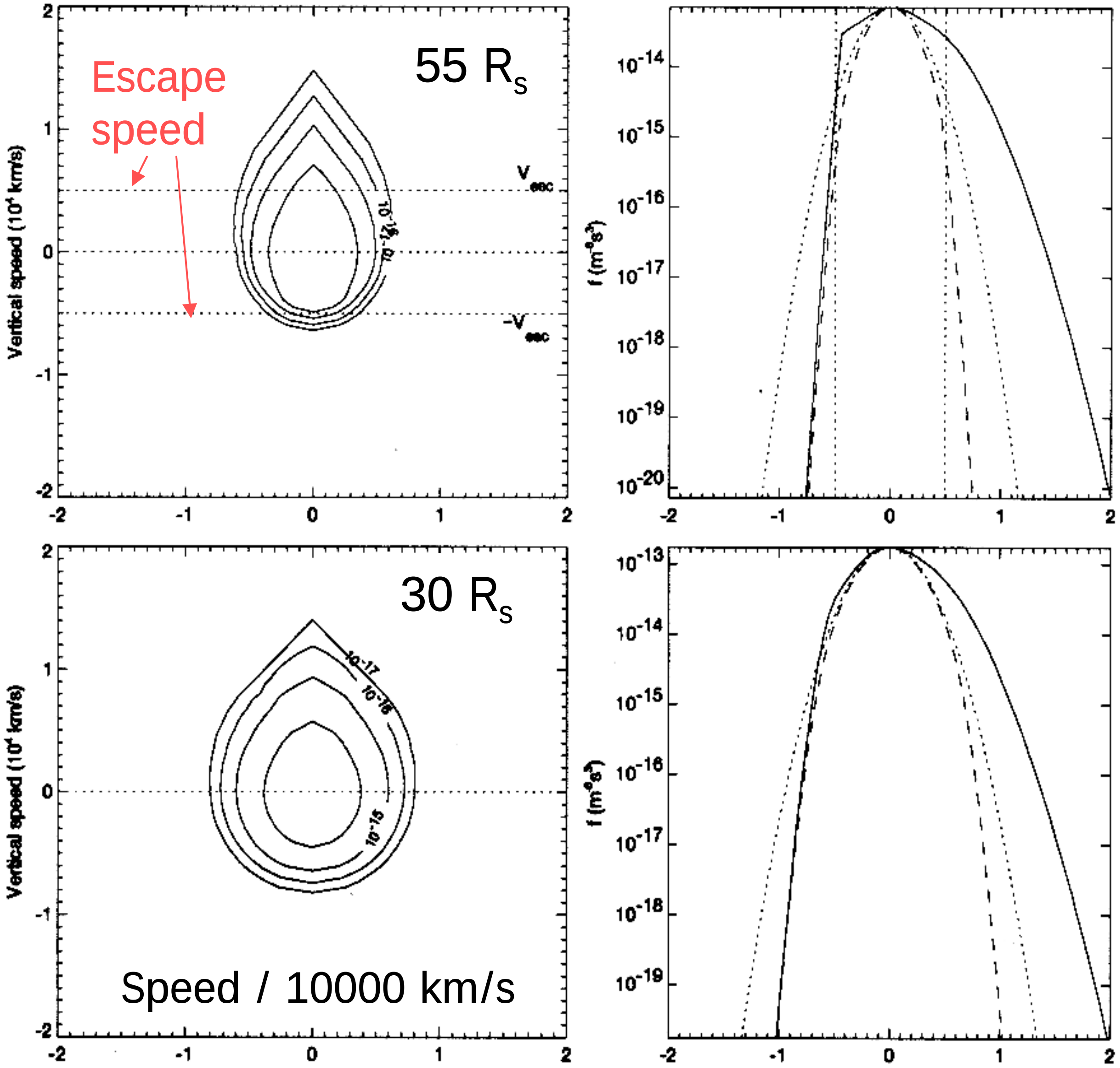


Philipps and Gosling, JGR, 1989

Coulomb collisions and electrons

Integration of Fokker-Planck equation

- **Velocity filtration is weak!**
- **Strahl formation by escape electrons**
- **Core bound by electric field**



Escape speed

55 R_S

30 R_S

Speed / 10000 km/s

Lie-Svendson et al., JGR, **102**, 4701, 1997

Wave-particle interactions

Dispersion relation using measured or model distribution functions $f(\underline{v})$, e.g. for electrostatic waves:

$$\varepsilon_L(\underline{k},\omega) = 0 \;\rightarrow\; \omega(\underline{k}) = \omega_r(\underline{k}) + i\gamma(\underline{k})$$

Dielectric constant is functional of $f(\underline{v})$, which may when being non-Maxwellian contain free energy for wave excitation.

$\gamma(\underline{k}) > 0 \rightarrow$ micro-instability......

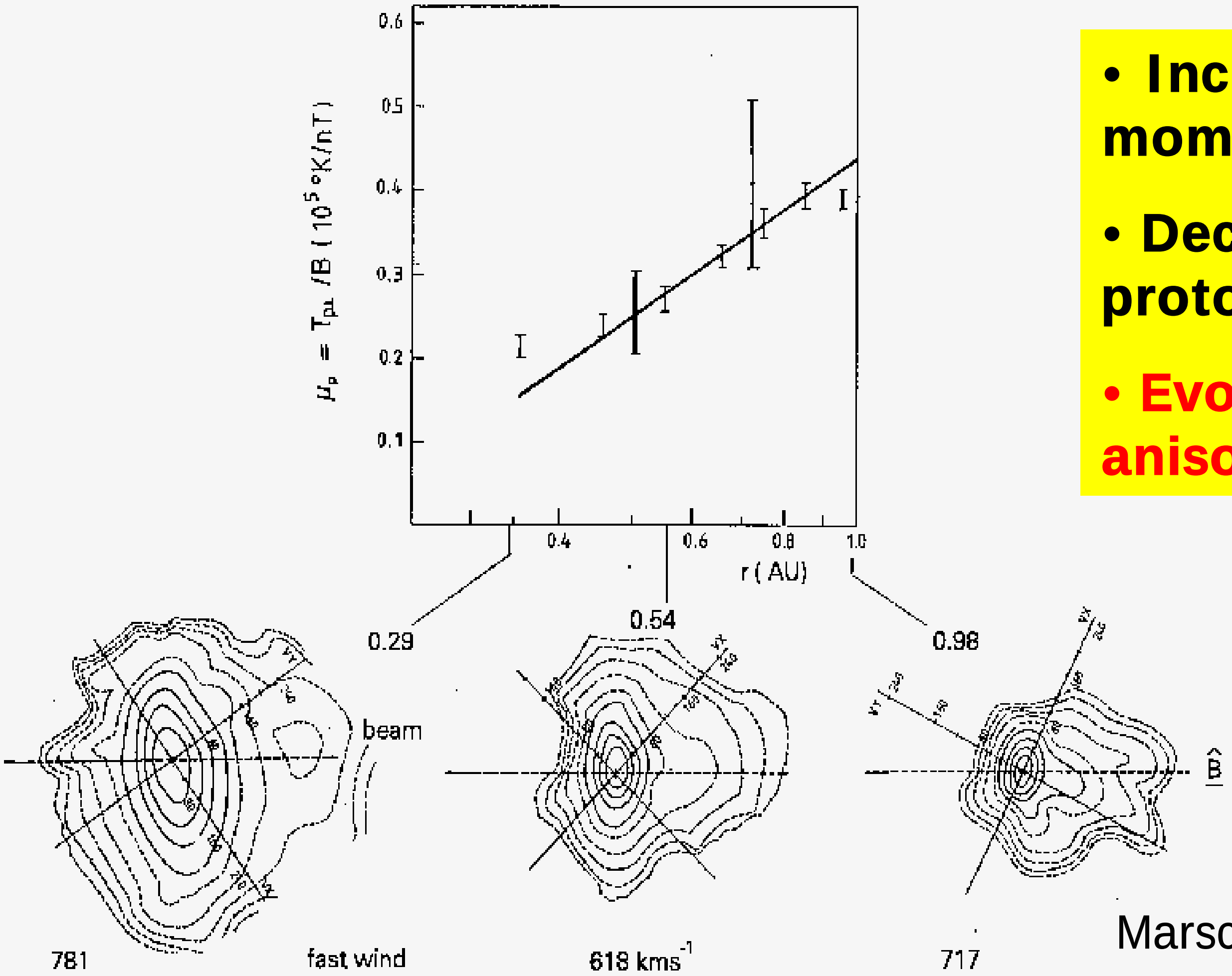
Resonant particles:

$\omega(\underline{k}) - \underline{k}\cdot\underline{v} = 0$ (Landau resonance)

$\omega(\underline{k}) - \underline{k}\cdot\underline{v} = \pm\,\Omega_j$ (cyclotron resonance)

→ Energy and momentum exchange between waves and particles. Quasi-linear or non-linear relaxation.....

Heating of protons by cyclotron and Landau resonance

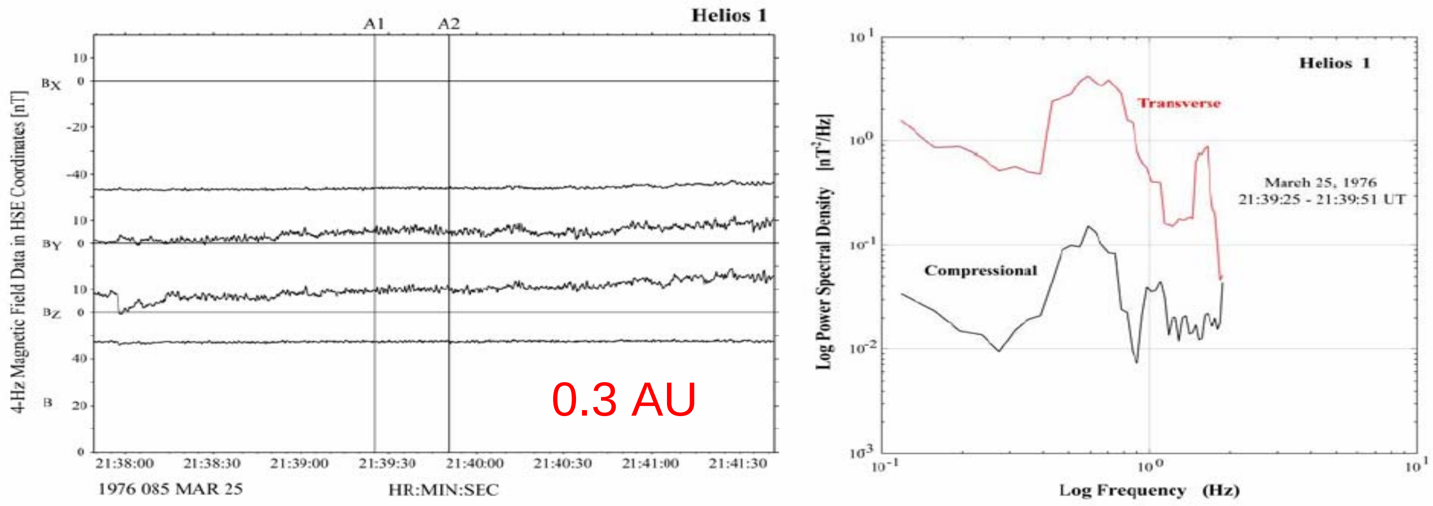


- **Increasing magnetic moment**
- **Deccelerating proton / ion beams**
- **Evolving temperature anisotropy**

Velocity distribution functions

Marsch et al., JGR, **87**, 52, 1982

Ion cyclotron waves

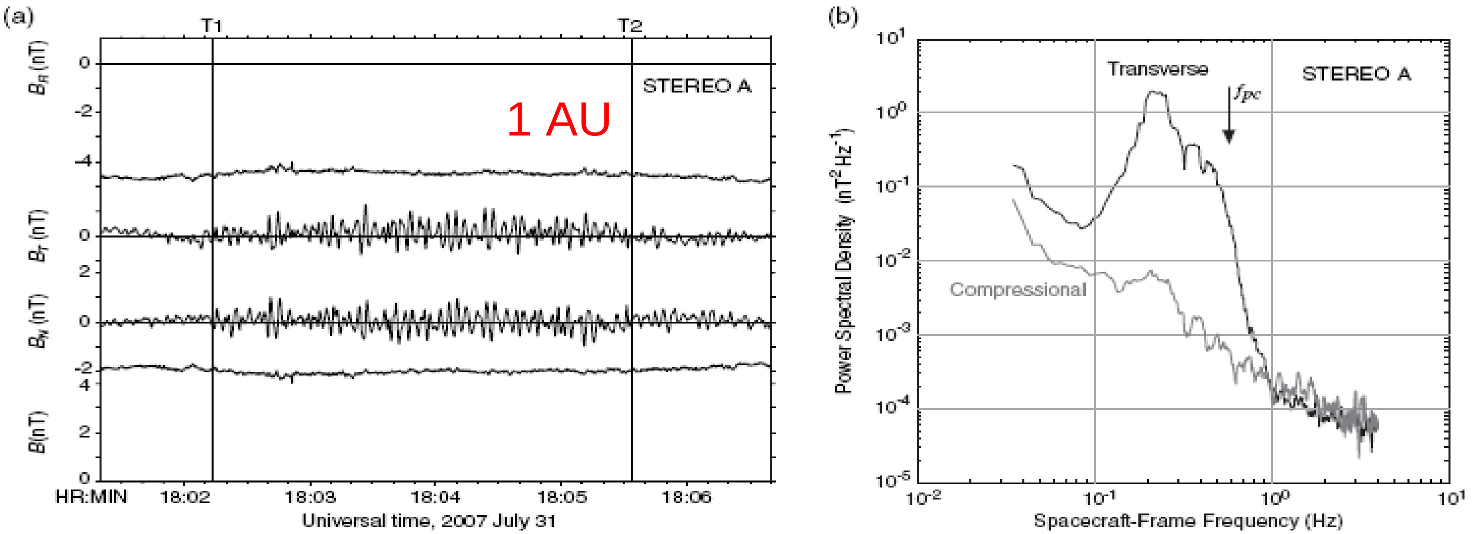


0.3 AU

Helios

Jian and Russell, The Astronomy and Astrophysics Decadal Survey, Science White Papers, no. 254, 2009

Parallel in- and outward propagation

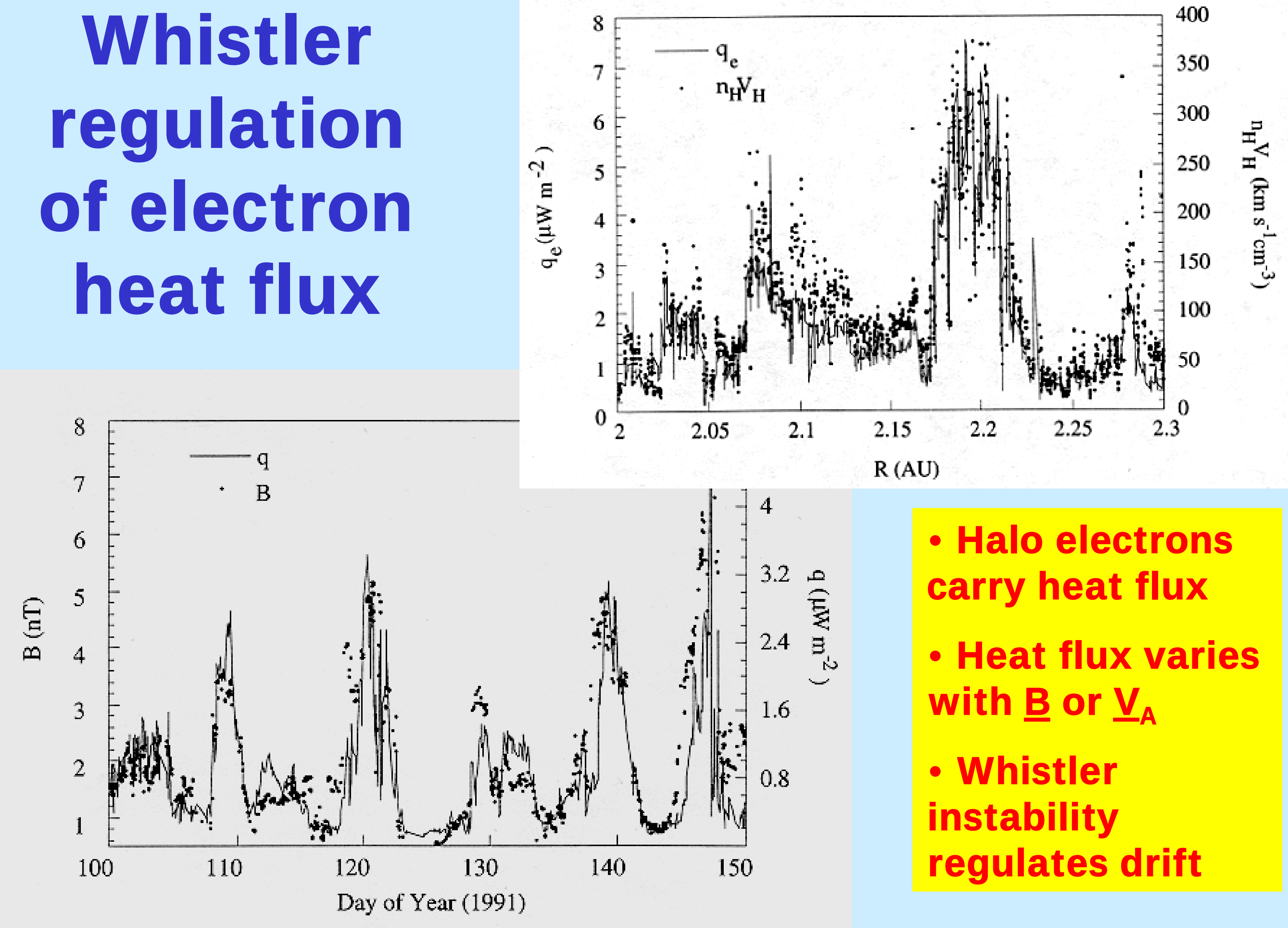


1 AU

STEREO

Jian et al. ApJ, 2009

Whistler regulation of electron heat flux



- **Halo electrons carry heat flux**
- **Heat flux varies with <u>B</u> or <u>V_A</u>**
- **Whistler instability regulates drift**

Sime et al., JGR, 1994

Kinetic processes in the solar corona and solar wind II

- Plasma is multi-component and nonuniform

→ **multi-fluid or kinetic physics is required**

- Plasma is tenuous and turbulent

→ **free energy for micro-instabilities**

→ **resonant wave-particle interactions**

→ **collisions described by Fokker-Planck operator**

Problem: Transport properties of the plasma, which involves multiple scales.....

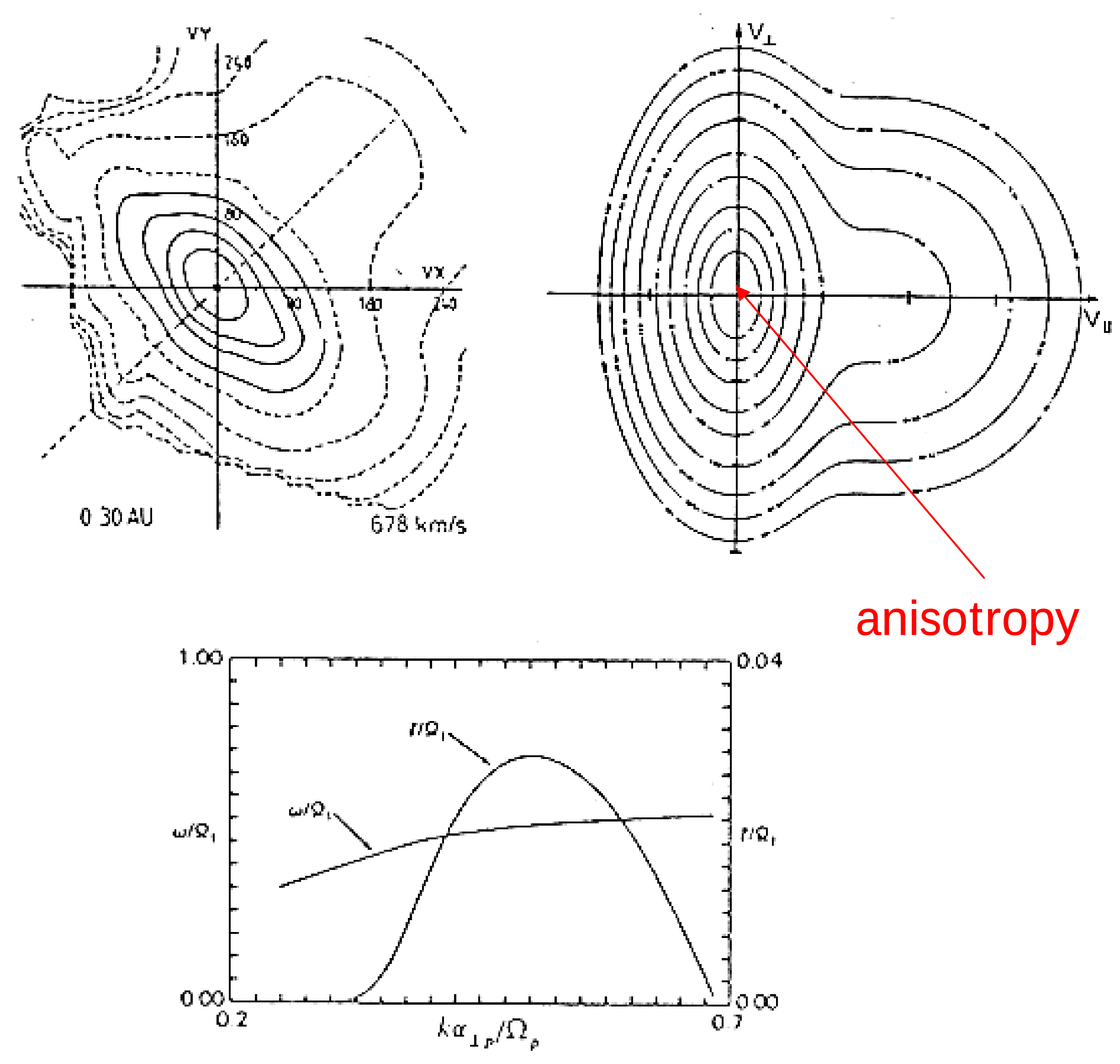
Proton temperature anisotropy

- Measured and modelled proton velocity distribution
- Growth of ion-cyclotron waves!
- Anisotropy-driven instability by large perpendicular $T_\perp$

$$\omega \approx 0.5\Omega_p$$

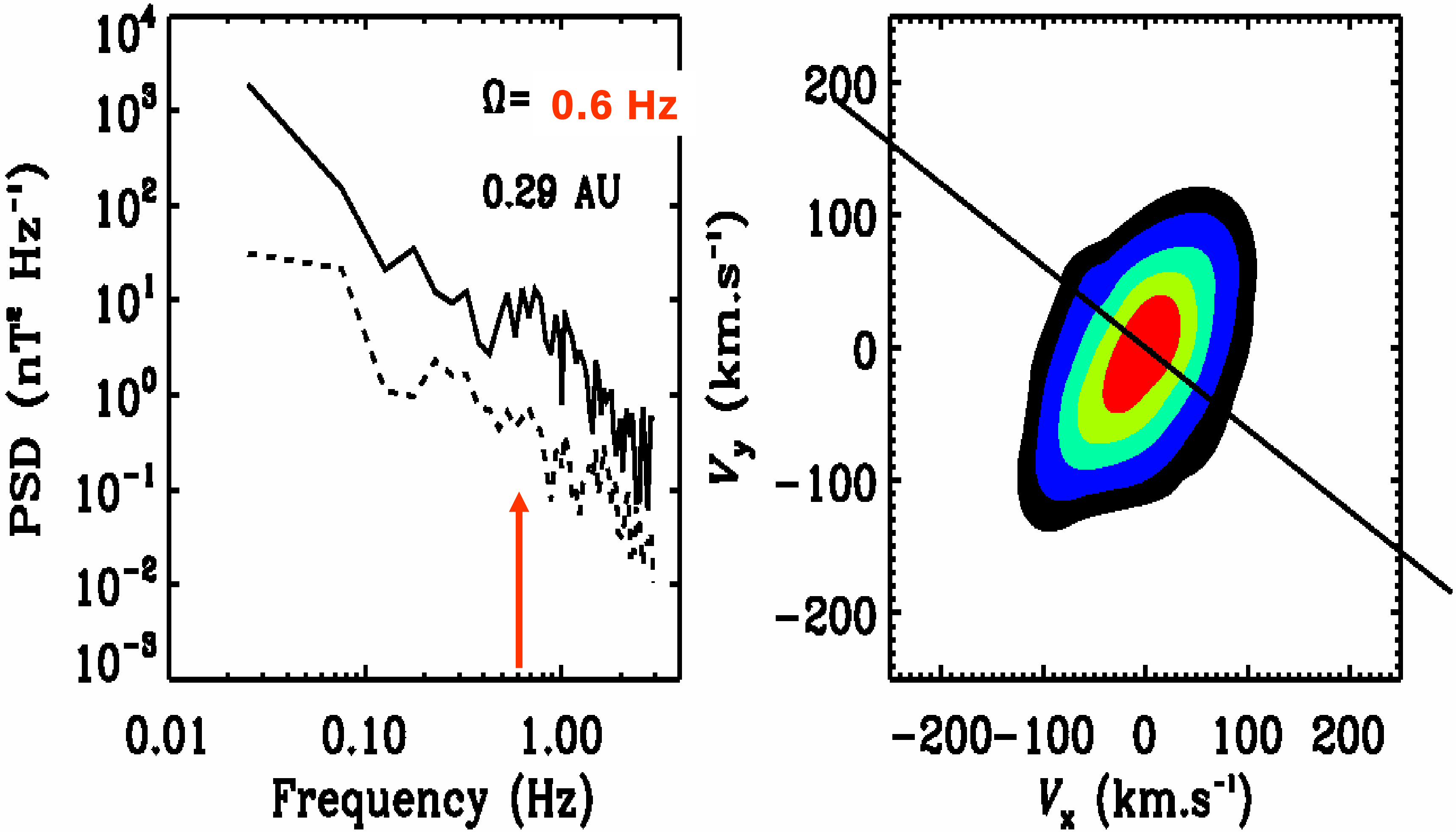
$$\gamma \approx 0.05\Omega_p$$

Marsch, 1991



anisotropy

Correlation of anisotropy with Alfvén-cyclotron wave power



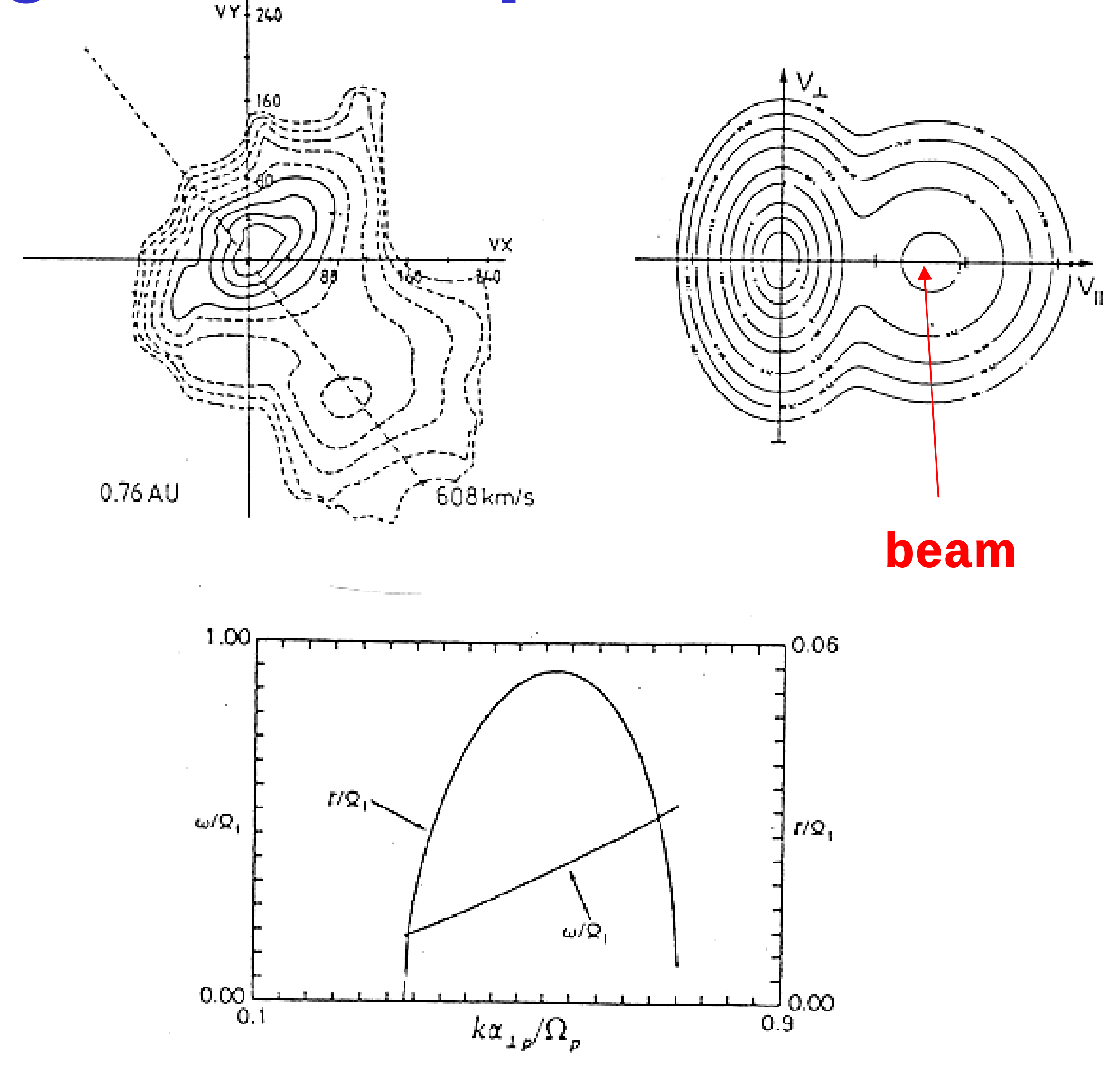
Wave regulation of proton beam

- Measured and modelled velocity distribution
- Growth of fast mode waves!
- Beam-driven instability, large drift speed

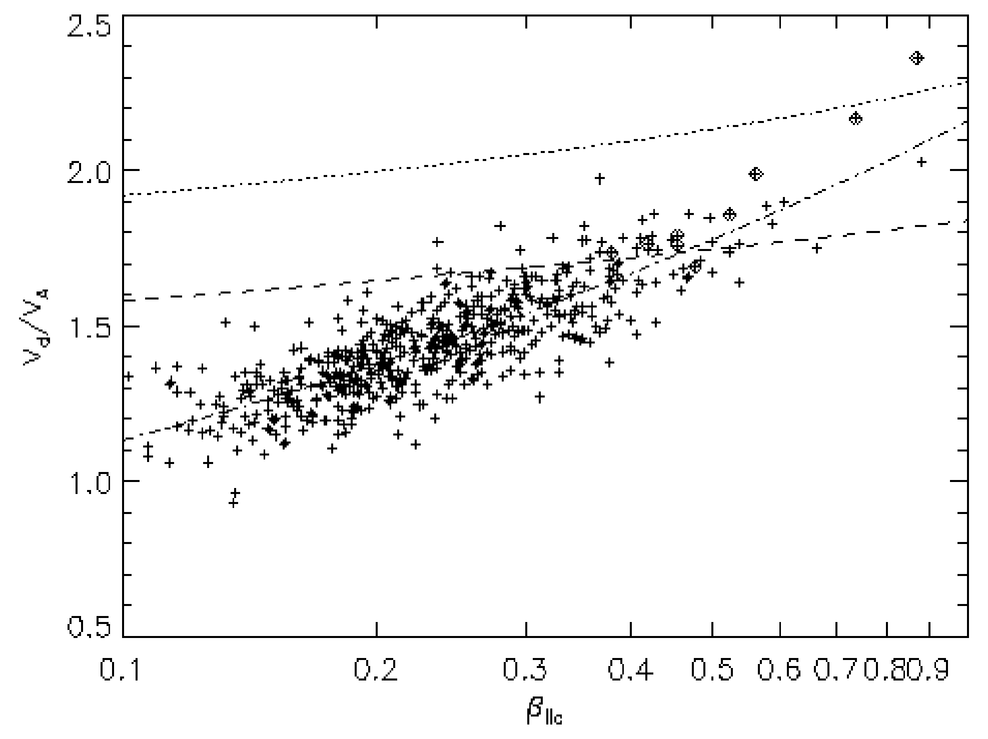
$$\omega \approx 0.4\Omega_p$$

$$\gamma \approx 0.06\Omega_p$$

Marsch, 1991



Beam drift versus core plasma beta



$$V_d / V_A = (2.16 \pm 0.03)\, \beta_{||c}^{(0.28 \pm 0.01)}$$

(empirical fit to data given by the dot-dash line)

- Origin of the beam not yet explained (mirror force in corona, Coulomb collisions)
- Quasilinear resonant pitch-angle diffusion determines the kinetics (thermodynamics) of solar wind protons.
- Proton beam drift speed is regulated by wave-particle interactions and depends on the plasma beta.

- The dotted (dashed) line corresponds to a relative beam density of 0.05 (0.2).

Tu, Marsch and Qin, JGR, **109**, 2004

Kinetic plasma instabilities

- Observed velocity distributions at margin of stability
- Selfconsistent quasi- or non-linear effects not well understood
- Wave-particle interactions are the key to understand ion kinetics in corona and solar wind!

Wave mode	Free energy source
Ion acoustic	**Ion beams, electron heat flux**
Ion cyclotron	**Temperature anisotropy**
Whistler (Lower Hybrid)	**Electron heat flux**
Magnetosonic	**Ion beams, differential streaming**

Marsch, 1991; Gary, Space Science Rev., **56**, 373, 1991

Quasi-linear (pitch-angle) diffusion

Diffusion equation

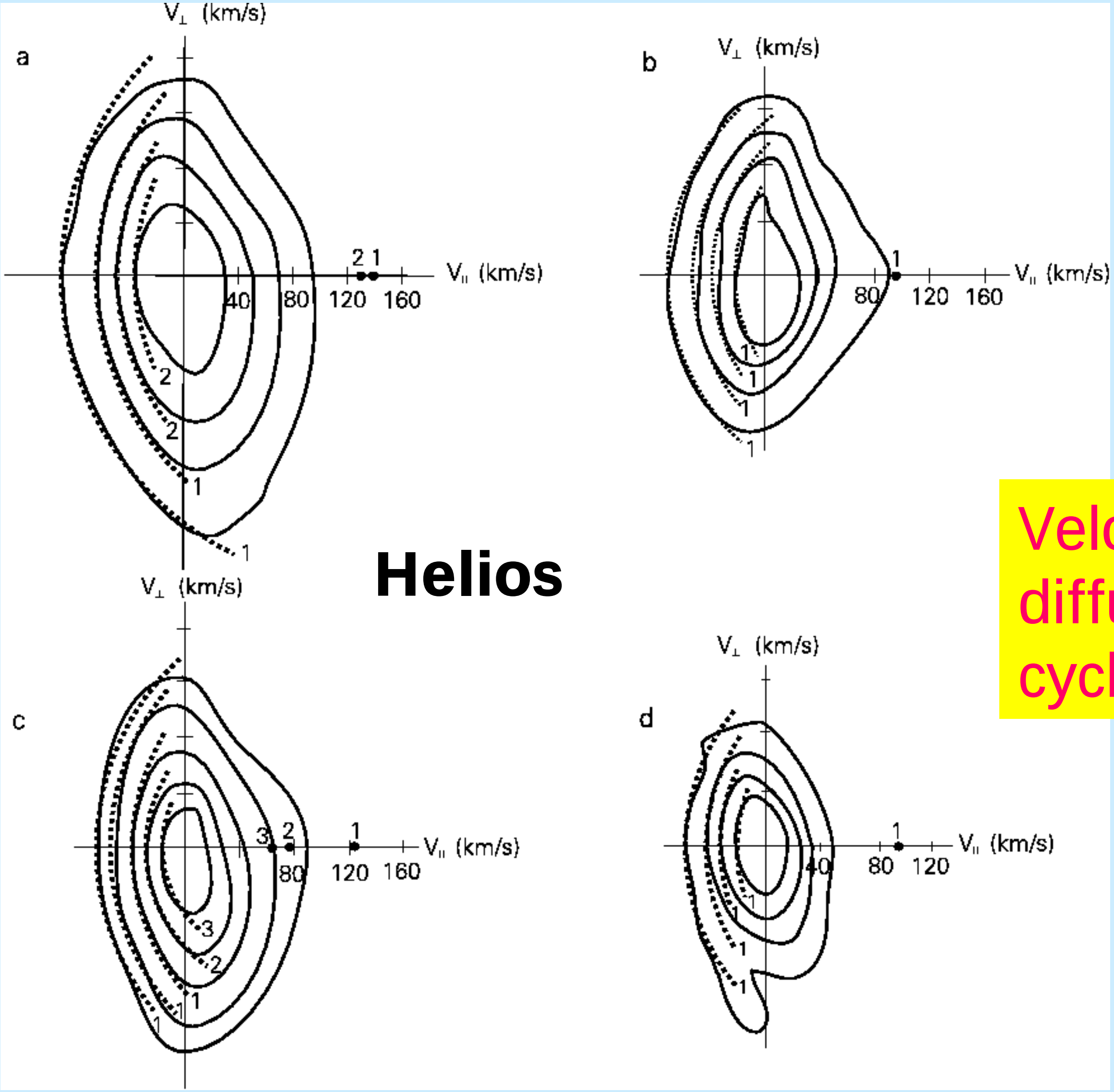
$$\frac{\partial}{\partial t} f_j(V_\perp, V_\parallel, t) = \sum_M \sum_{s=-\infty}^{+\infty} \frac{1}{(2\pi)^3} \int_{-\infty}^{+\infty} d^3k\, \hat{\mathcal{B}}_M(\mathbf{k}) \\ \times \frac{1}{V_\perp} \frac{\partial}{\partial \alpha} \left(V_\perp\, \nu_j(\mathbf{k}, s; V_\parallel, V_\perp) \frac{\partial}{\partial \alpha} f_j(V_\perp, V_\parallel, t) \right)$$

Pitch-angle gradient in wave frame

$$\frac{\partial}{\partial \alpha} = V_\perp \frac{\partial}{\partial V_\parallel} - \left(V_\parallel - \frac{\omega_M(\mathbf{k})}{k_\parallel} \right) \frac{\partial}{\partial V_\perp}$$

Kennel and Engelmann,
Phys. Fluids, **9**, 2377, 1966

Pitch-angle diffusion of protons

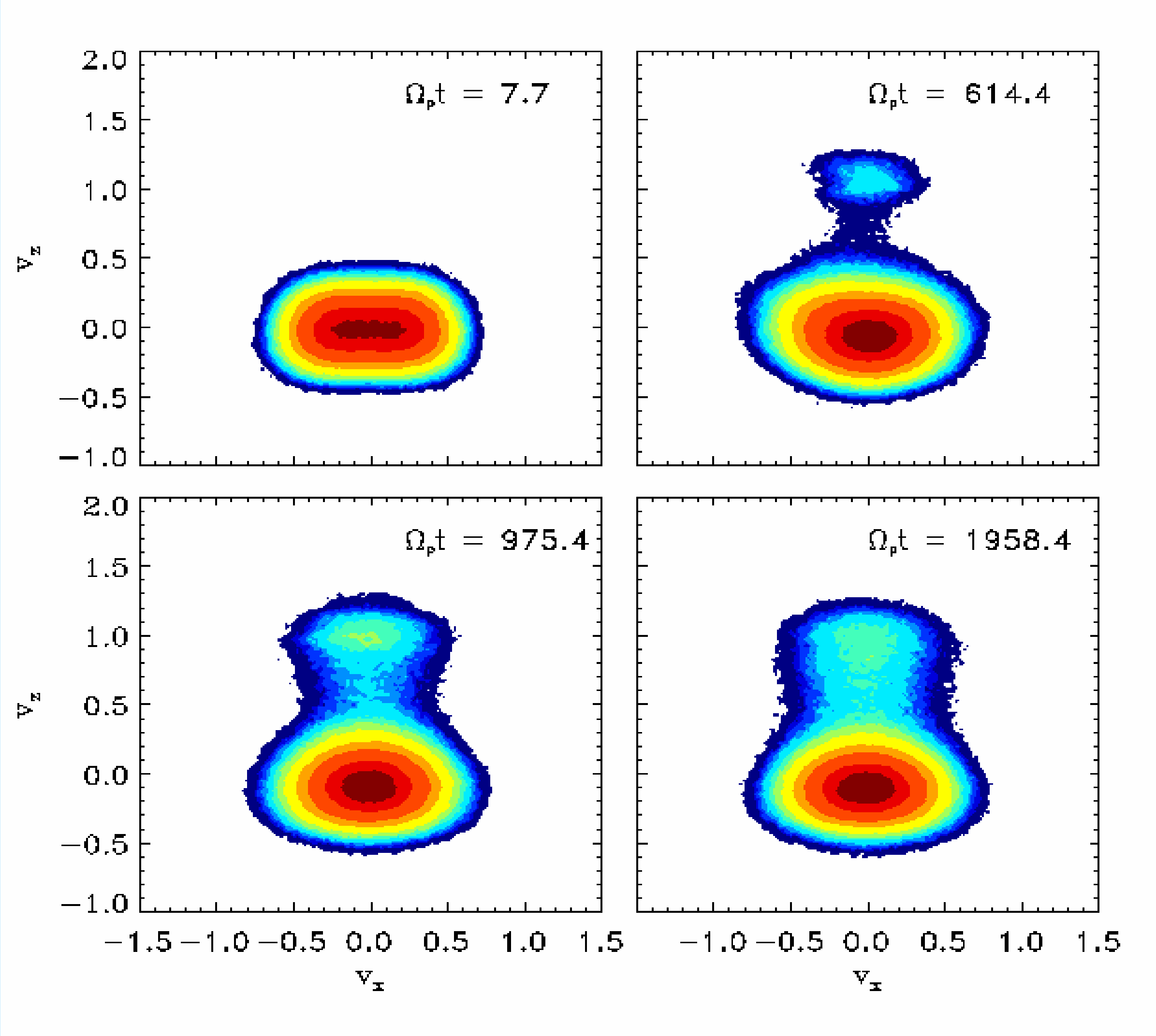


VDF contours are segments of circles centered in the wave frame (< V_A)

Velocity-space resonant diffusion caused by the cyclotron-wave field!

Marsch and Tu, JGR **106**, 8357, 2001

Proton core heating and beam formation



VDFs as obtained by numerical simulation of the decay of Alfvén-cyclotron waves and the related ion kinetics

Contour plots of the proton VDF in the v_x-v_z-plane for the dispersive-wave case at four instants of time. The color coding of the contours corresponds, respectively, to 75 (dark red), 50 (red), 10 (yellow) percent of the maximum.

J.A. Araneda, E. Marsch, and A.F. Viñas, Phys. Rev. Lett., **100**, 125003, 2008

Summary

- **In-situ ion and electron measurements indicate strong deviations from local (collisional) thermal equilibrium**

- **Wave-particle interactions and micro-instabilities regulate the kinetic features of particle velocity distributions**

- **Kinetic models are required to describe the essential features of the plasma in the solar wind**

- **The non-equilibrium thermodynamics in the tenuous solar wind involve particle interaction with micro-turbulent fields**

- **Wave energy transport as well as cascading and dissipation in the kinetic domain are still not well understood**