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Kinetic plasma processes in the solar corona

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- **Basic assumptions of collisional transport theory**
- **Kinetics of coronal (solar wind) heating through Landau/cyclotron damping of plasma waves**
- **Solutions of the Vlasov-Boltzmann equation**
- **Model velocity distributions in the corona**
- **Kinetic plasma instabilities in the solar wind**

Kinetic processes in the solar corona

• **Plasma is multi-component and non-uniform**

→ multiple scales and complexity

• **Plasma is tenuous and turbulent**

→ free energy for microinstabilities
→ wave-particle interactions (quasilinear diffusion)
→ weak collisions (Fokker-Planck operator)
→ strong deviations from local thermal equilibrium
→ global boundaries are reflected locally
→ suprathermal particle populations

Problem: Thermodynamics and transport...

Kinetic Vlasov-Boltzmann theory

Description of particle velocity distribution function in phase space:

$$\frac{df}{dt} + \mathbf{w} \cdot \frac{\partial f}{\partial \mathbf{x}} + (\mathbf{w} \times \mathbf{\Omega}) \cdot \frac{\partial f}{\partial \mathbf{w}} + (-\frac{d}{dt}\mathbf{u} + \frac{q}{m}\mathbf{E}') \cdot \frac{\partial f}{\partial \mathbf{w}} - \frac{\partial \mathbf{u}}{\partial \mathbf{x}} : \mathbf{w}\frac{\partial f}{\partial \mathbf{w}} = \frac{\delta f}{\delta t}$$

Convective derivative:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{u} \cdot \frac{\partial}{\partial \mathbf{x}}$$

Relative velocity **w**, mean velocity **u**(**x**,t), gyrofrequency Ω**,** electric field **E'** in moving frame:

$$\mathbf{w} = \mathbf{v} - \mathbf{u}(\mathbf{x}, t), \ \mathbf{\Omega} = \frac{q\mathbf{B}}{mc}, \ \mathbf{E}' = \mathbf{E} + \frac{1}{c}\mathbf{u} \times \mathbf{B}$$

Moments: Drift velocity, pressure (stress) tensor, heat flux vector

$$< \mathbf{w} >= 0, \mathcal{P} = nm < \mathbf{ww} >, \mathbf{Q} = nm < \mathbf{w}\frac{1}{2}w^2 >$$

$$\mathbf{\Pi} = \mathcal{P} - \mathcal{I}p \quad p = nk_BT = \frac{1}{3}Tr\mathcal{P}$$

Dum, 1990

Coulomb collisions and quasilinear wave-particle interactions

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**):

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

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

Quasi-linear pitch-angle diffusion

Diffusion equation

$$\frac{\delta}{\delta t} f_j(v_{||}, v_\perp, t) = \int_{-\infty}^{+\infty} \frac{d^3k}{(2\pi)^3} \sum_M \hat{\mathcal{B}}_M(\mathbf{k}) \frac{1}{v_\perp} \frac{\partial}{\partial \alpha} \left(\hat{\nu}_{j,M}\, v_\perp \frac{\partial}{\partial \alpha} f_j(v_{||}, v_\perp, t) \right)$$

Pitch-angle gradient in wave frame

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

Superposition of linear waves with random phases!

→ Energy and momentum exchange between waves and particles. Quasi-linear evolution.....

Kennel and Engelmann, 1966; Stix, 1992

Ingredients in diffusion equation

$$\hat{\mathcal{B}}_M(\mathbf{k}) = \left(\frac{|\,\mathbf{B}_M(\mathbf{k})\,|}{B_0}\right)^2 \left(\frac{k_{||}}{k}\right)^2 \frac{1}{1-\,|\,\hat{\mathbf{k}}\cdot\mathbf{e}_M(\mathbf{k})\,|^2}$$

Normalized wave spectrum (Fourier amplitude)

$$V_j(\mathbf{k},s) = \frac{\omega_M(\mathbf{k}) - s\Omega_j}{k_{||}}, \quad J_s = J_s\left(\frac{k_\perp v_\perp}{\Omega_j}\right)$$

Resonant speed, Bessel function of order *s*

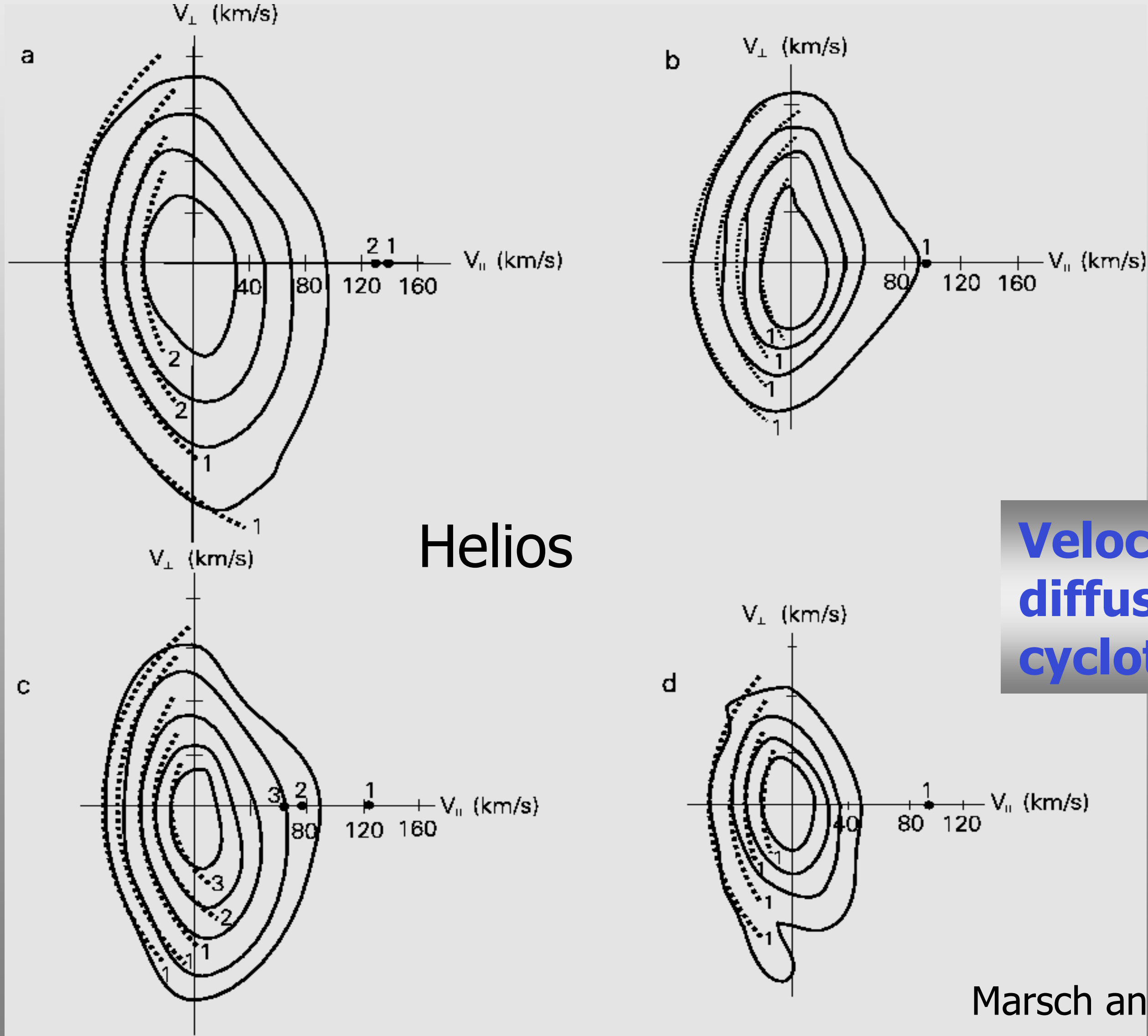
Resonant wave-particle relaxation rate

$$\hat{\nu}_{j,M}(\mathbf{k},v_{||},v_\perp) = \pi\frac{\Omega_j^2}{k_{||}}\sum_{s=-\infty}^{+\infty}\delta(V_j(\mathbf{k},s)-v_{||})\,\left|\,\frac{1}{2}(J_{s-1}e_M^{+}+J_{s+1}e_M^{-})+\frac{v_{||}}{v_\perp}J_s e_{Mz}\,\right|^2$$

Corona is weakly collisional, $\Omega_{i,e} >> \nu_{i,e}$, and strongly magnetized, $r_{i,e} << \lambda_{i,e}$

Marsch, Nonlin. Proc. Geophys. **9**, 1, 2002

Observation of pitch-angle diffusion



Solar wind proton VDF contours are segments of circles centered in the wave frame ($\omega/k \leq V_A$)

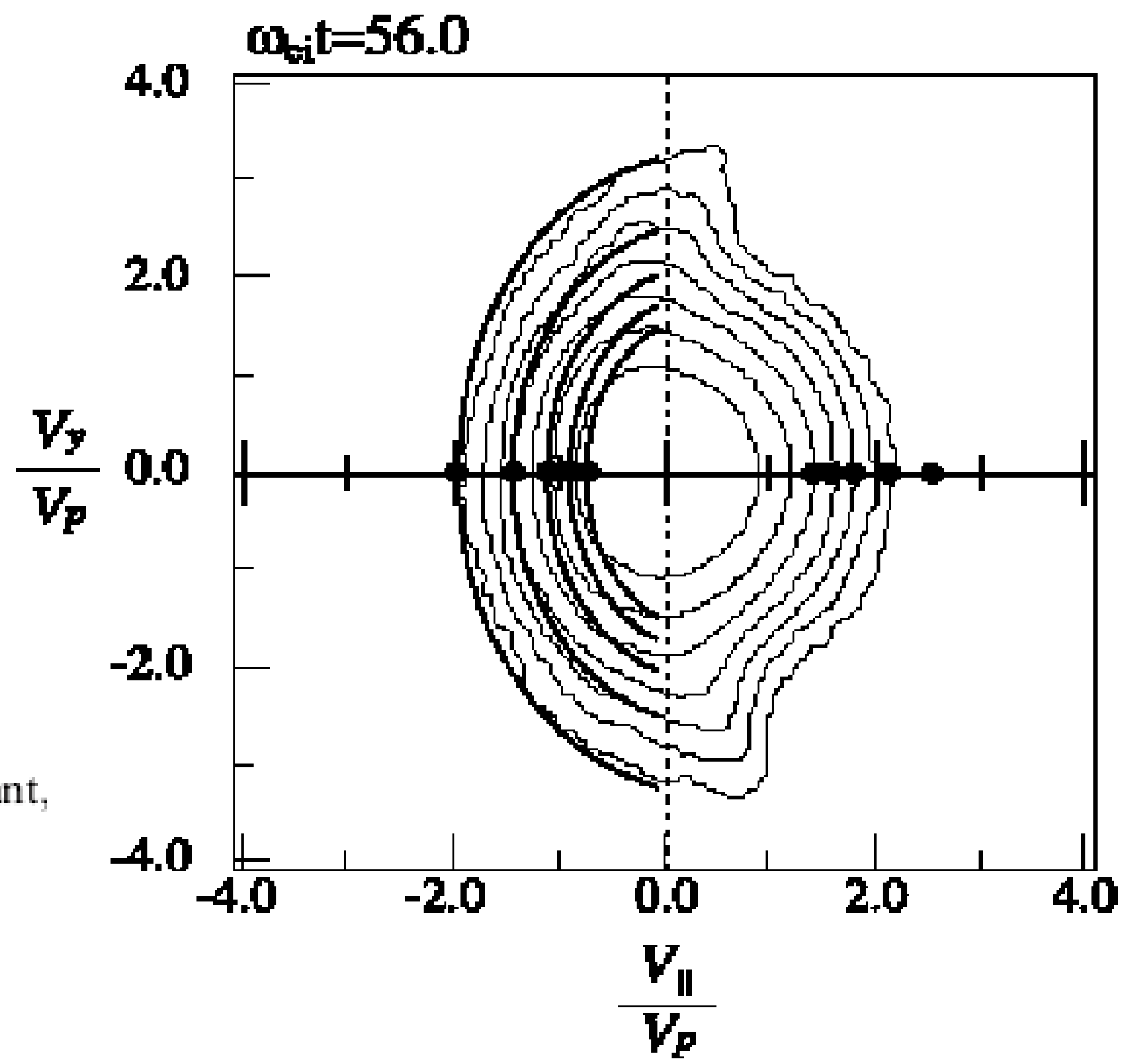
Velocity-space resonant diffusion caused by the cyclotron-wave field!

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

Numerical simulation of diffusion

Proton velocity distribution from a direct numerical simulation. The phase speeds of the left-hand polarized modes are indicated by the right dots. The five left dots represent the corresponding cyclotron resonance velocities. The corresponding ion diffusion plateaus are indicated by heavy solid lines.

$$v_{\|}^2 + v_{\perp}^2 - 2\int^{v_{\|}} \frac{\omega_r\left(v'_{\|}\right)}{k\left(v'_{\|}\right)} dv'_{\|} = \text{constant},$$



Gary and Saito, JGR, 2003

Semi-kinetic model of wave-ion interaction in the corona

$$F_{j\|}(w_\|) = 2\pi \int_0^\infty dw_\perp w_\perp f_j(w_\perp, w_\|)$$

$$F_{j\perp}(w_\|) = 2\pi \int_0^\infty dw_\perp w_\perp \frac{w_\perp^2}{2} f_j(w_\perp, w_\|)$$

$$\int_{-\infty}^{\infty} dw_\| F_{j\|}(w_\|) \begin{pmatrix} 1 \\ w_\| \\ w_\|^2 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ V_{j\|}^2 \end{pmatrix}$$

$$\int_{-\infty}^{\infty} dw_\| F_{j\perp}(w_\|) = V_{j\perp}^2$$

Reduced Velocity distributions

$$\frac{\partial F_\|}{\partial t} + v_\| \frac{\partial F_\|}{\partial s} + \left(\frac{q}{m}E_\| - g(s)\right)\frac{\partial F_\|}{\partial v_\|} + \frac{1}{2A(s)}\frac{\partial A(s)}{\partial s} \cdot 2\left(\frac{\partial F_\perp}{\partial v_\|} + v_\| F_\|\right) = \frac{\delta F_\|}{\delta t} + \frac{\delta F_\|}{\delta t}\Big|_{Coul.}$$

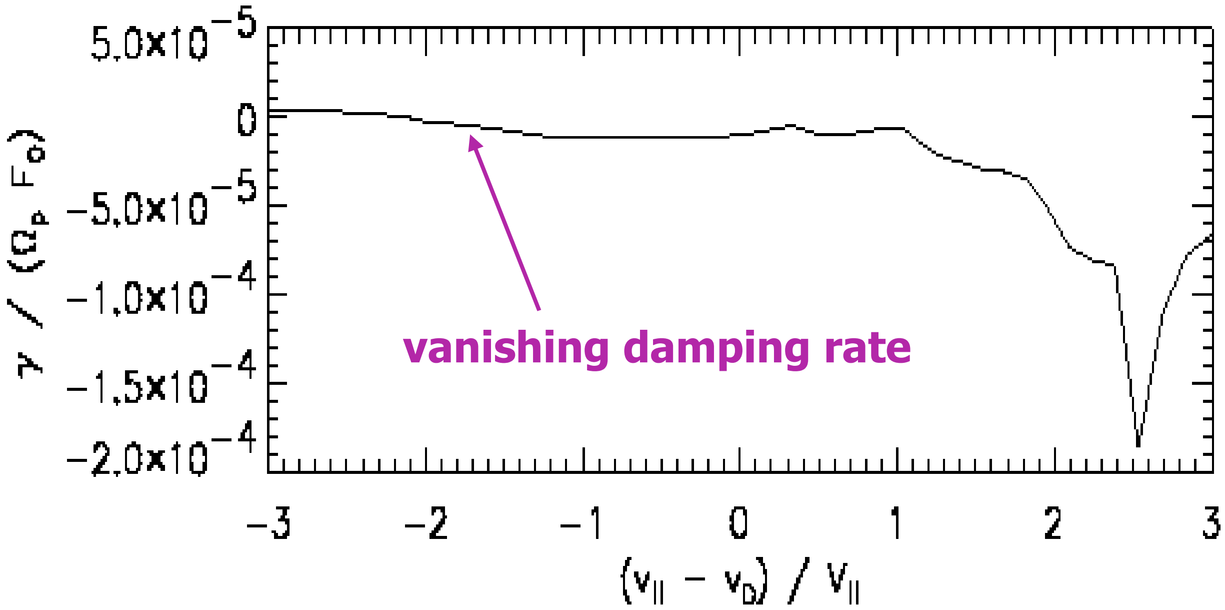
$$\frac{\partial F_\perp}{\partial t} + v_\| \frac{\partial F_\perp}{\partial s} + \left(\frac{q}{m}E_\| - g(s)\right)\frac{\partial F_\perp}{\partial v_\|} + \frac{1}{2A(s)}\frac{\partial A(s)}{\partial s} \cdot 4\left(v_{j\perp}^2 \frac{\partial F_\perp}{\partial v_\|} + v_\| F_\perp\right) = \frac{\delta F_\perp}{\delta t} + \frac{\delta F_\perp}{\delta t}\Big|_{Coul.}$$

Marsch, Nonlinear Proc. Geophys., **5,** 111, 1998

Vocks and Marsch, GRL, **28**, 1917, 2001

Transparency of coronal oxygen ions

Plateau formation and marginal stability of the oxygen O^{5+} VDF at 1.44 R_s



Model velocity distribution function

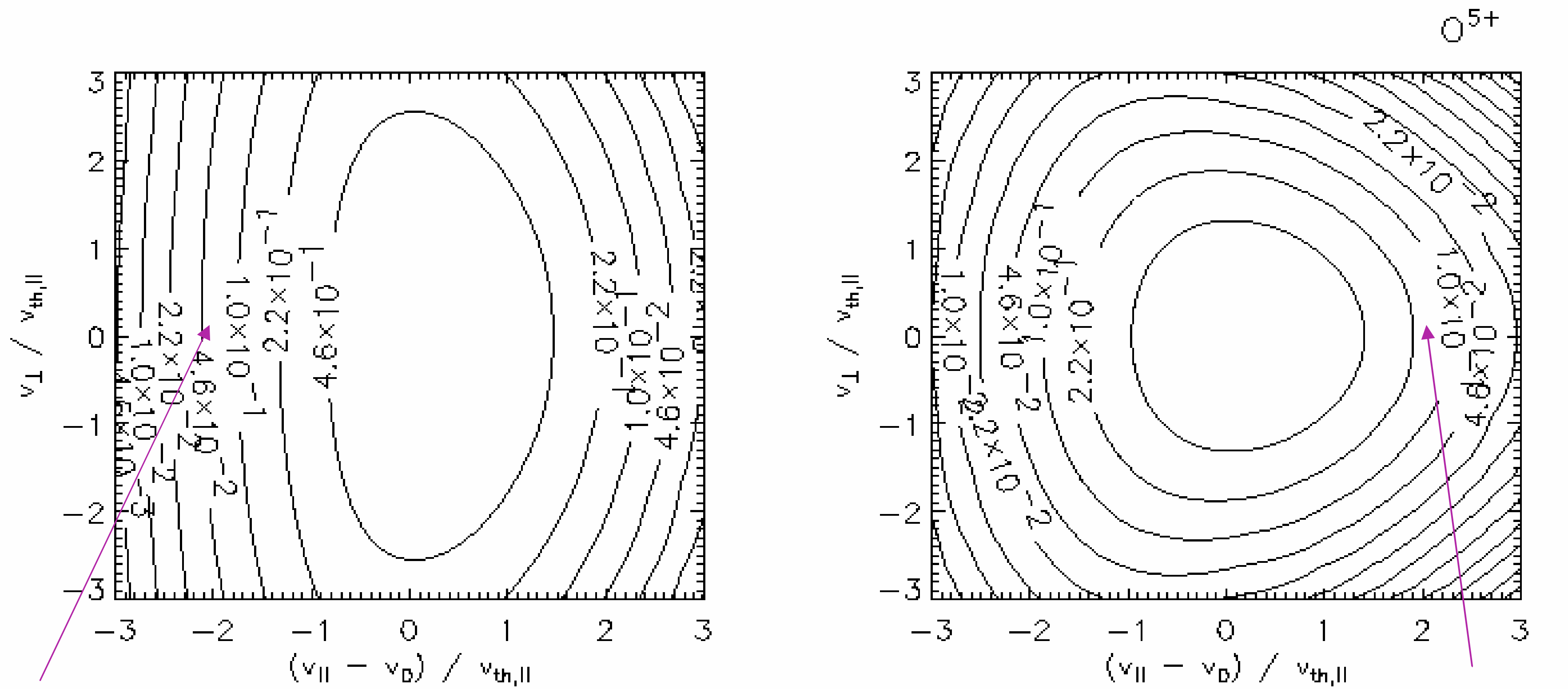
$$f_j(w_\|, w_\perp) = \frac{F_{j\|}(w_\|)}{2\pi W_{j\perp}^2(w_\|)} \exp\left(-\frac{w_\perp^2}{2W_{j\perp}^2(w_\|)}\right)$$

$$W_{j\perp}^2(w_\|) = \frac{F_{j\perp}(w_\|)}{F_{j\|}(w_\|)}$$

Effective perpendicular thermal speed

Vocks & Marsch, Ap. J. **568**, 1030 , 2002

Velocity distributions of oxygen ions



Pitch angle scattering, plateau

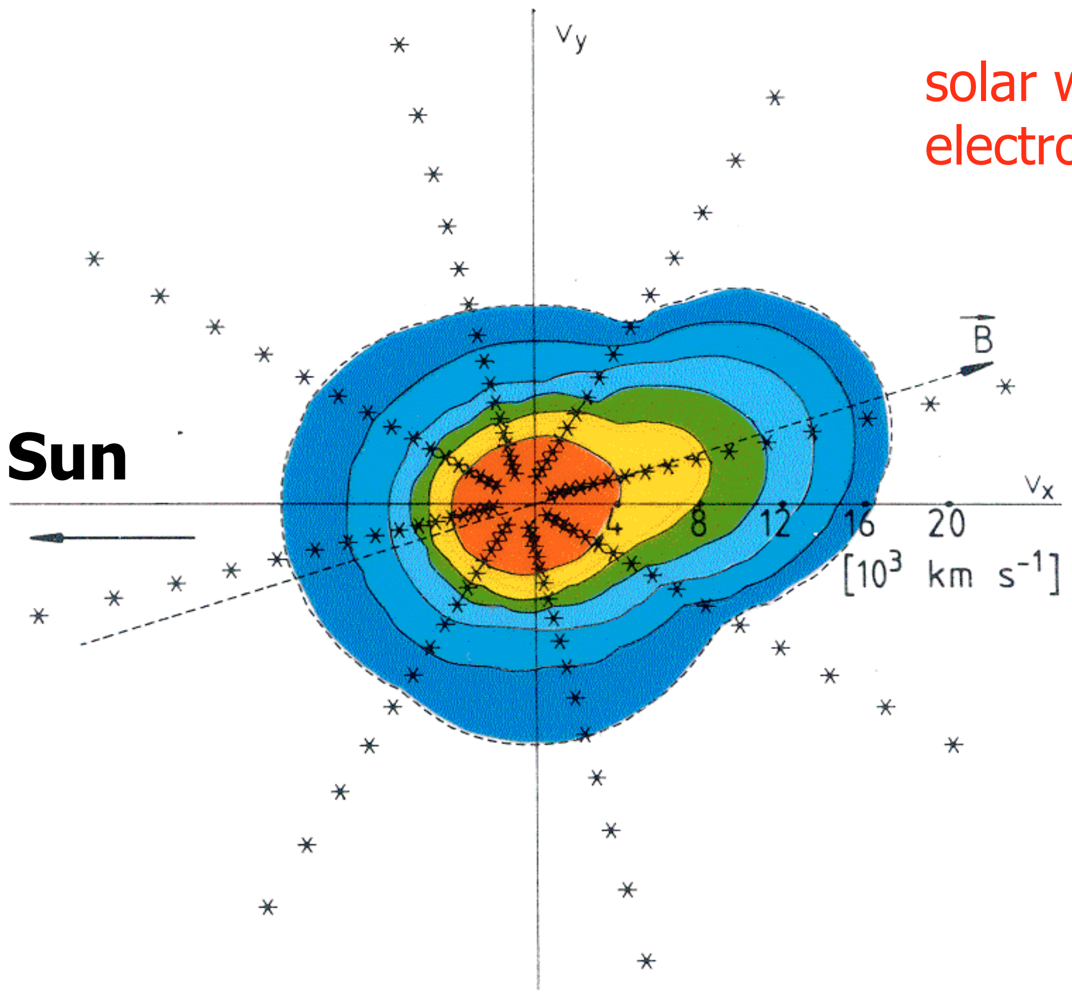
r= 1.44 R_s

r= 1.73 R_s

Magnetic mirror force, runaway

Vocks & Marsch, Ap. J. **568**, 1030 , 2002

Breakdown of classical transport theory



solar wind electrons

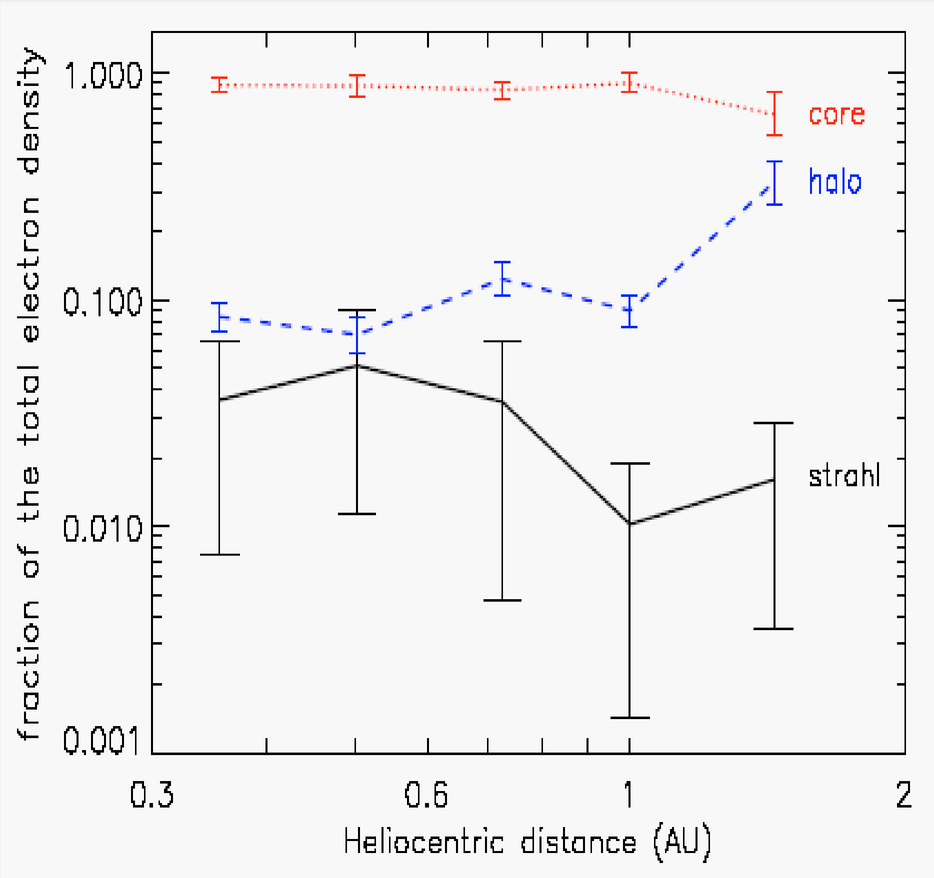
n_e = 3-10 cm^{-3} T_e = 1-2 10^5 K at 1 AU

- Strong heat flux tail
- Collisional free path λ_c much larger than temperature-gradient scale L
- Polynomial expansion about a local Maxwellian hardly converges, as $\lambda_c >> L$

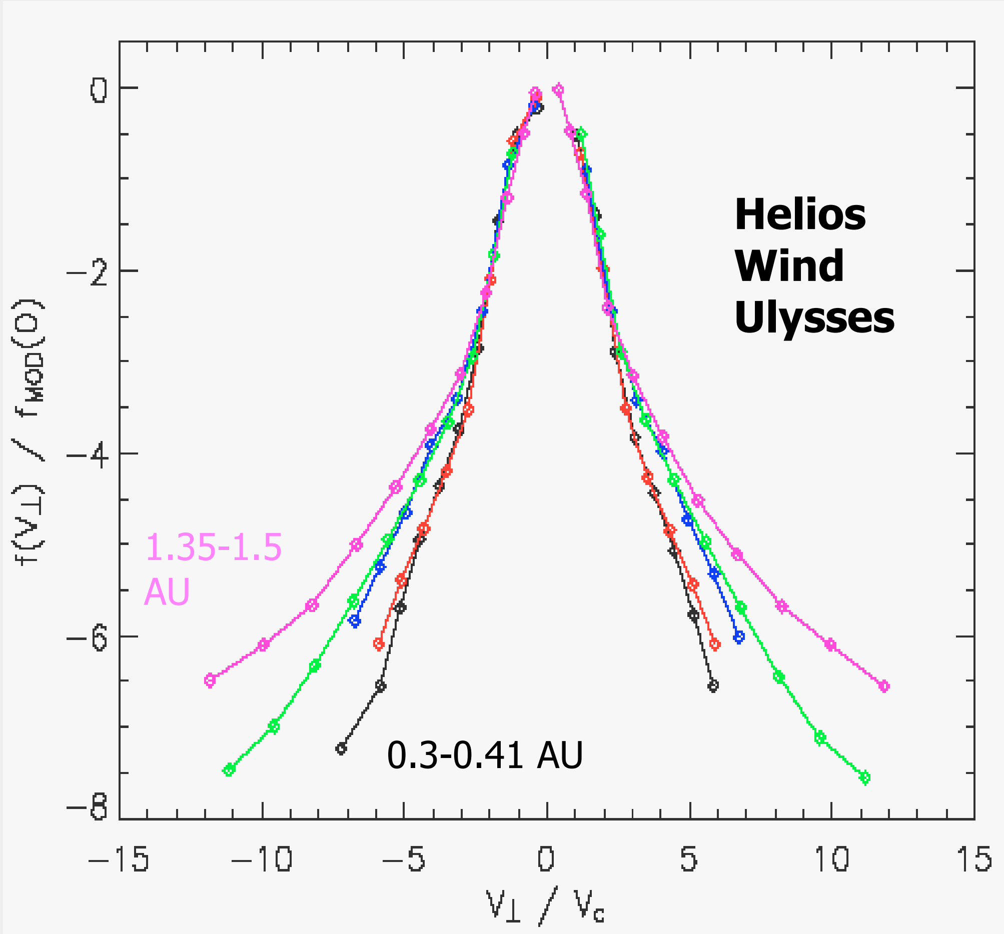
Pilipp et al., JGR, **92**, 1075, 1987

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, in press 2005

Scattering by meso-scale magnetic structures

Spitzer-Härm theory invalid

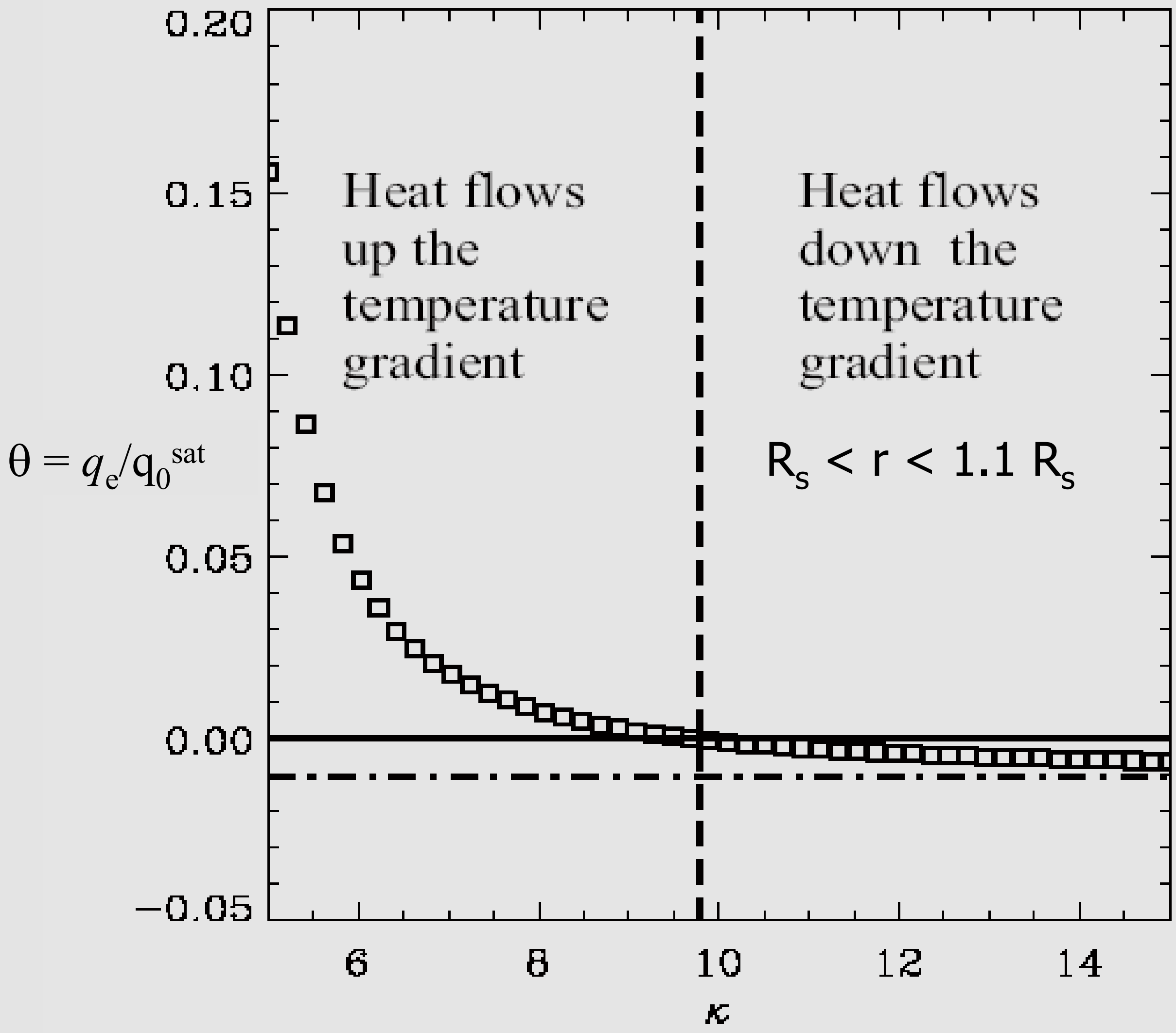
$$q_e = -\eta_e \left[F_1 \frac{1}{n}\frac{dn}{dz} + F_2 \frac{1}{T}\frac{dT}{dz} + F_3\right]$$

$$\eta_e = q_0^{sat} \sigma \lambda_0 (T/T_0)^{7/2}$$

For a κ-function (or any other VDF with moderate non-Maxwellian tails) heat (T_0=5 10^5 K) may flow up the temperature gradient!

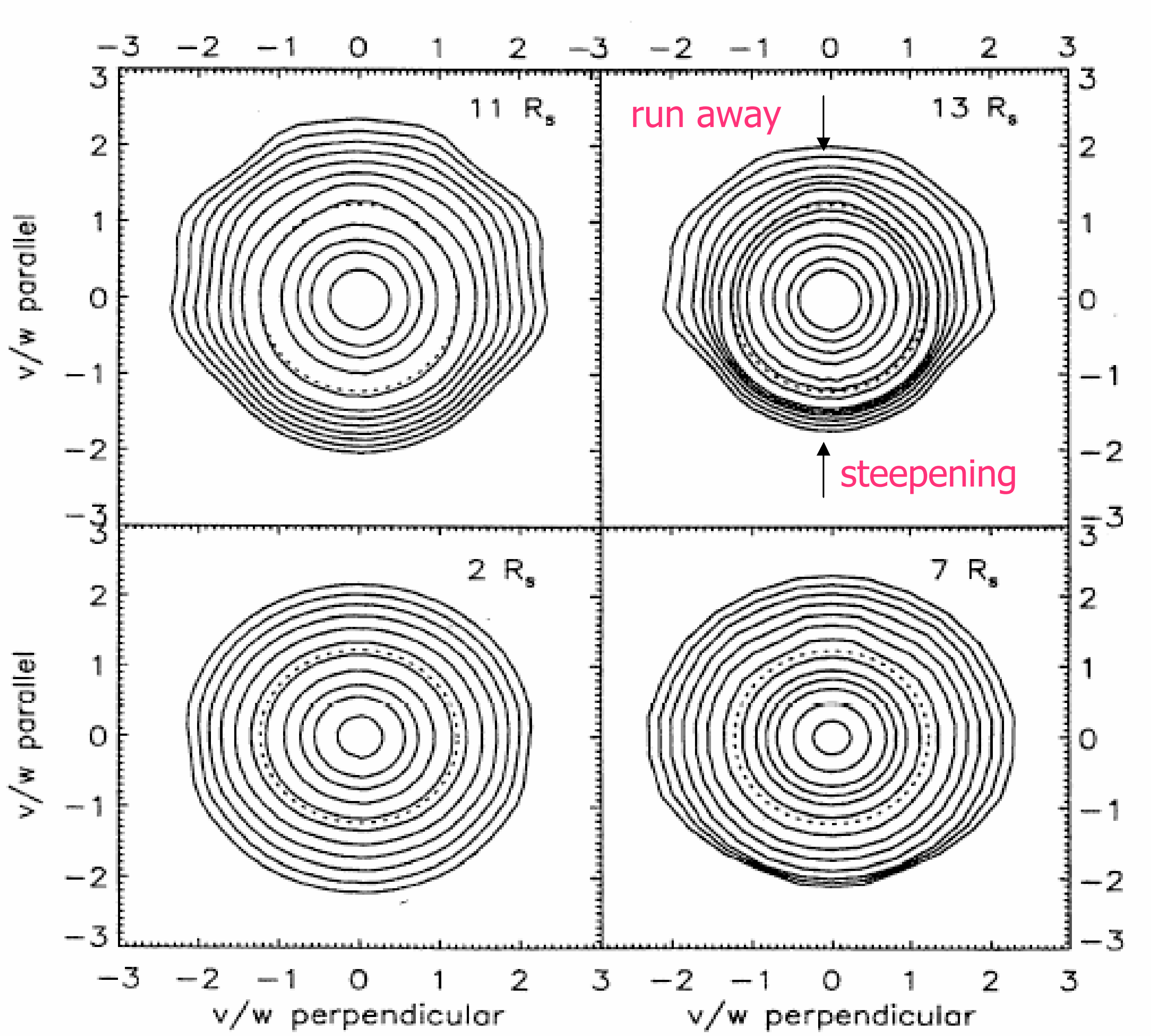
Reason: Trapping of low-energy electrons and the resulting velocity filtration.

Dorelli and Scudder, GRL, 1999



Collisional electrons in corona

- Numerical solution of Boltzmann equation with full Fokker-Planck operator
- Collisions (self- and with protons) shape pitch-angle distribution.
- Gravitational and electro-static potential matter.
- At the lower boundary Maxwellian, at $14R_s$ no sunward electrons above $V^2_{esc}=2e\Phi_E/m_e$.
- Dots: $w^2=2k_BT_0/m_e$, i.e. the thermal speed at T_0.



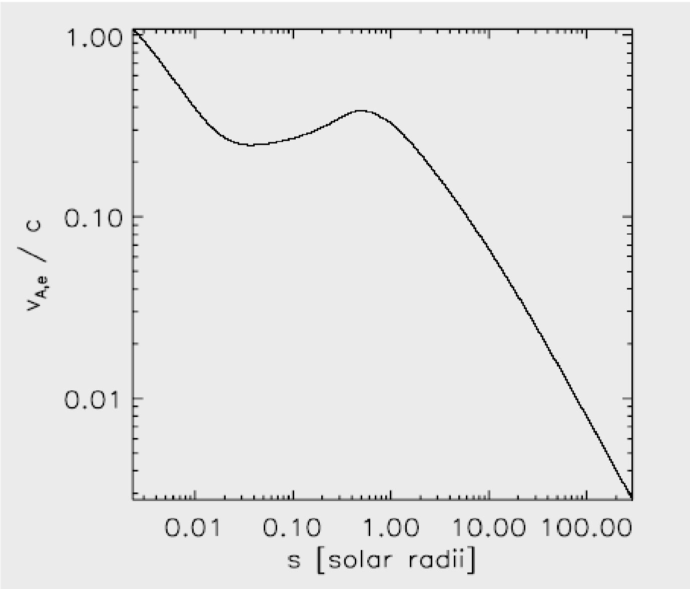
Pierrard et al., JGR, 2001

Suprathermal coronal electrons caused by wave-particle interactions I

$$\frac{\partial f}{\partial t} + v_{\parallel}\frac{\partial f}{\partial s} + \left(g_{\parallel} - \frac{e}{m_e}E_{\parallel}\right)\frac{\partial f}{\partial v_{\parallel}} + \frac{v_{\perp}}{2A}\frac{\partial A}{\partial s}\left(v_{\perp}\frac{\partial f}{\partial v_{\parallel}} - v_{\parallel}\frac{\partial f}{\partial v_{\perp}}\right) = \left(\frac{\delta f}{\delta t}\right)_{w\text{-}p} + \left(\frac{\delta f}{\delta t}\right)_{\text{Coul}}.$$

Boltzmann equation with waves and collisions

A(s) flux tube area function

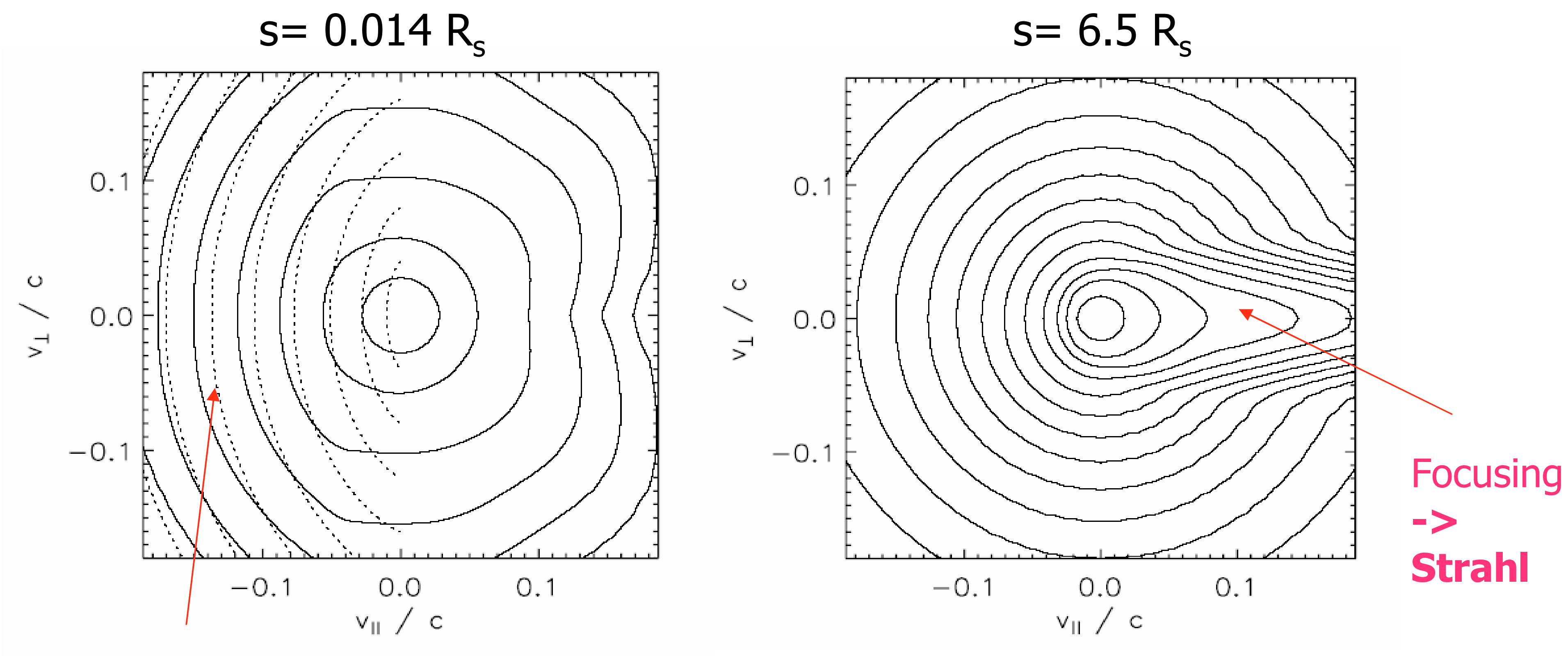


Electron pitch-angle scattering in the whistler wave field

Phase speed $v_{A,e}$ in solar corona

Vocks and Mann, Ap. J., **593**, 1134, 2003

Suprathermal coronal electrons caused by wave-particle interactions II



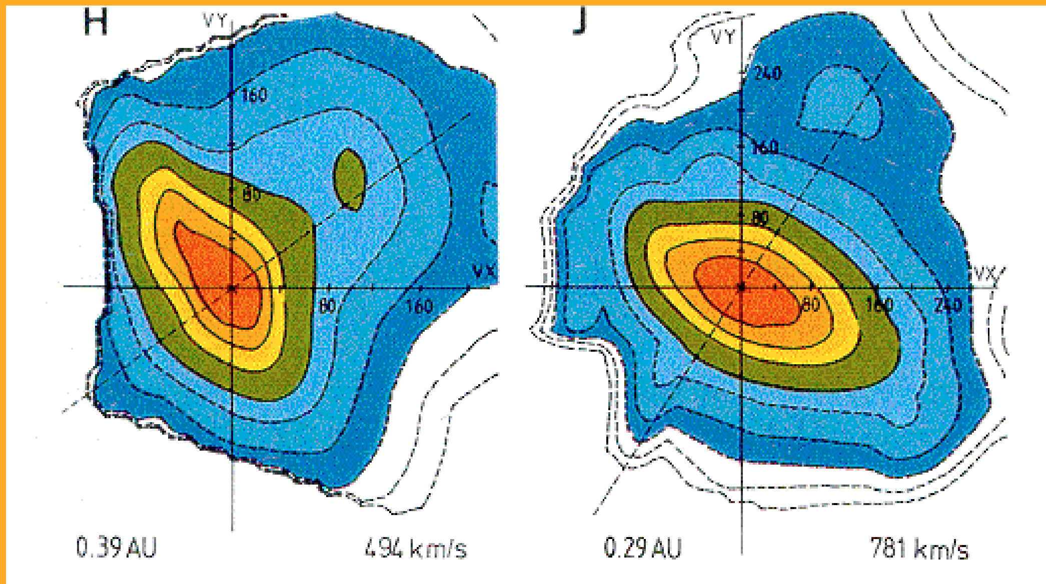
Pitch-angle scattering **->**
shell formation

Vocks and Mann, Ap. J., **593**, 1134, 2003

Protons and cyclotron waves

- Ion core temperature anisotropy (cyclotron resonance)
- Hot ion beams (coronal jets?)
- Loss-cone type distribution
- Parametric decay of large-amplitude Alfvén waves
- Sporadic electron beams may drive electrostatic ion-cyclotron waves

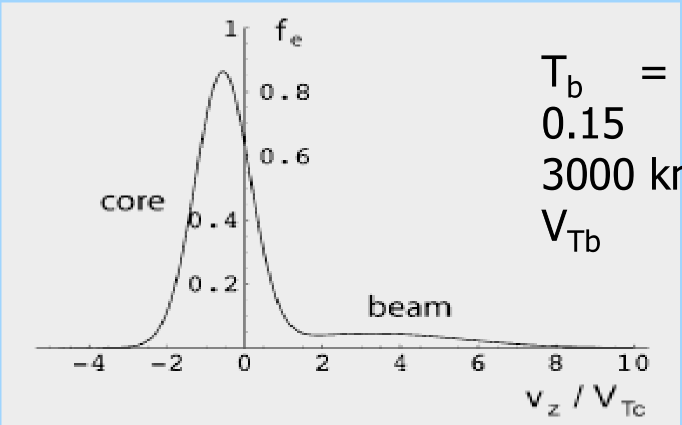
Anisotropic isocontours of proton velocity distributions in fast solar wind (Helios)



Do these kinetic processes operate in the corona?

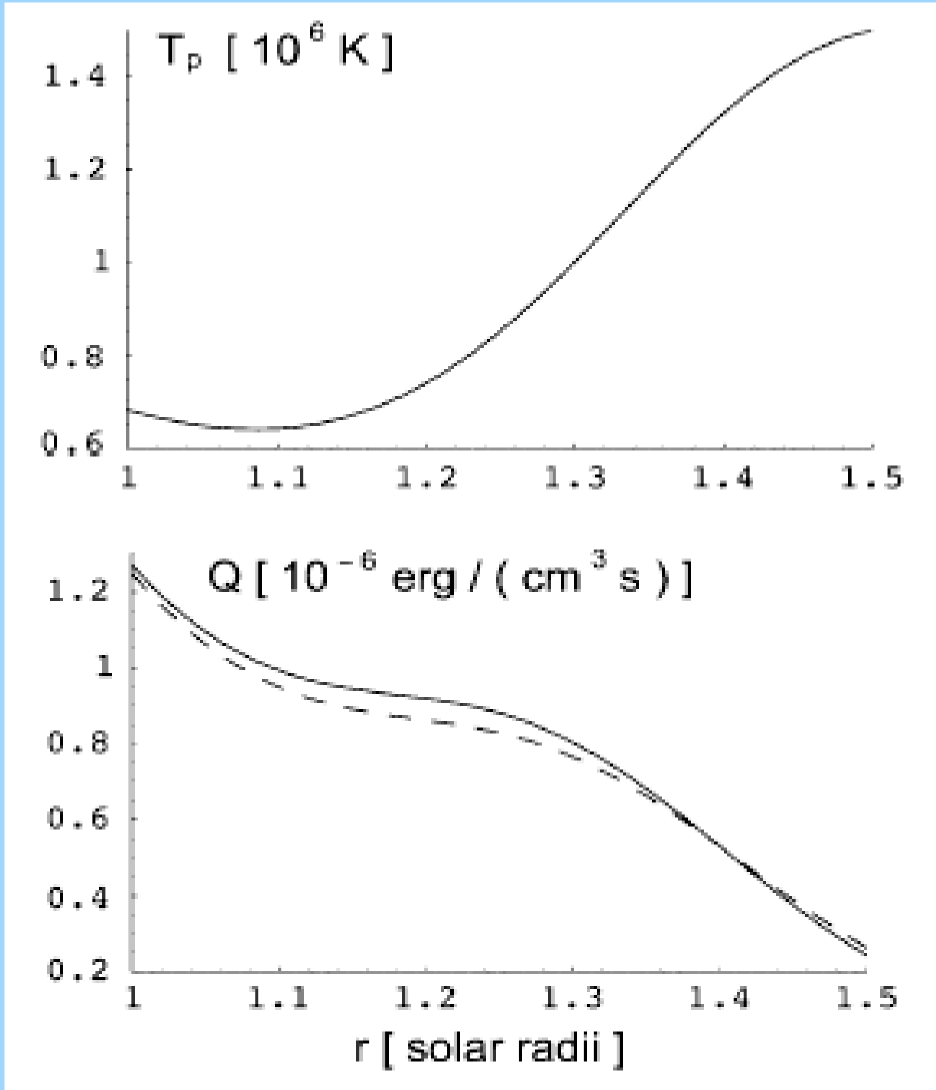
Heat flux generated cyclotron waves

Intermittent (δt = 1 s) electron heat flux caused by small-scale reconnection (microflares) at coronal base



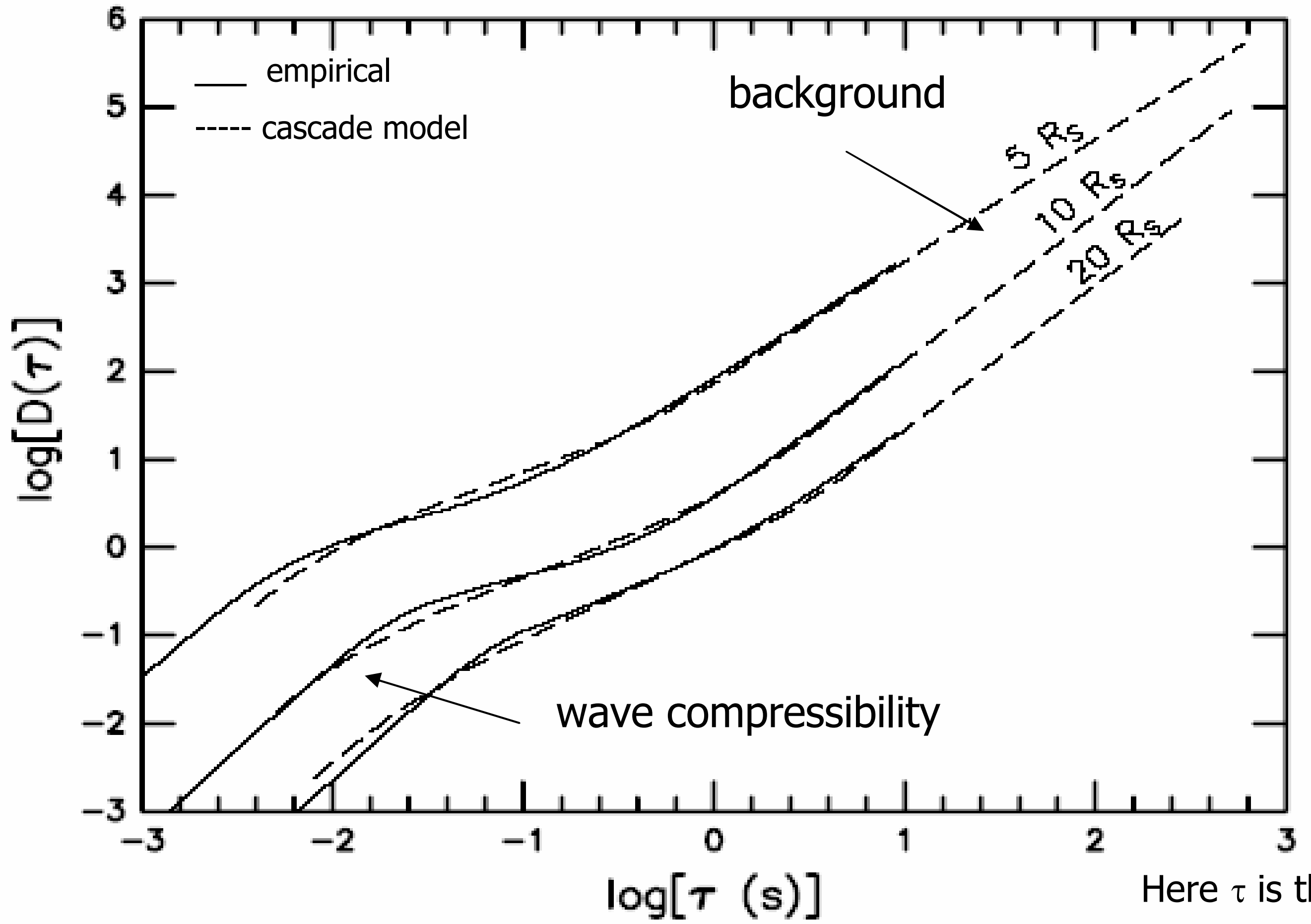
T_b = $10T_c$ n_b/n_c= 0.15 V_A = 3000 km/s u_b = V_{Tb}

- **Sporadic heat flux (resonant core electrons) drives sunward electrostatic ion-cyclotron wave (ω = 1.15 Ω_p)**
- **Intermittent ion heating by wave absorption ($\delta T/T$ = 0.07 per burst)**



Markovskii and Hollweg, Ap.J., 608, 1112, 2004

Kinetic Alfvén (compressive ion-cyclotron) waves inferred from radio scattering



Radio wave structure function (electric field coherence) relates to local density fluctuation spectrum.

Inner dissipation scale at proton inertial length:

$k_D = \omega_p/c = \Omega_p/V_A$

Electron Landau and ion cyclotron damping!

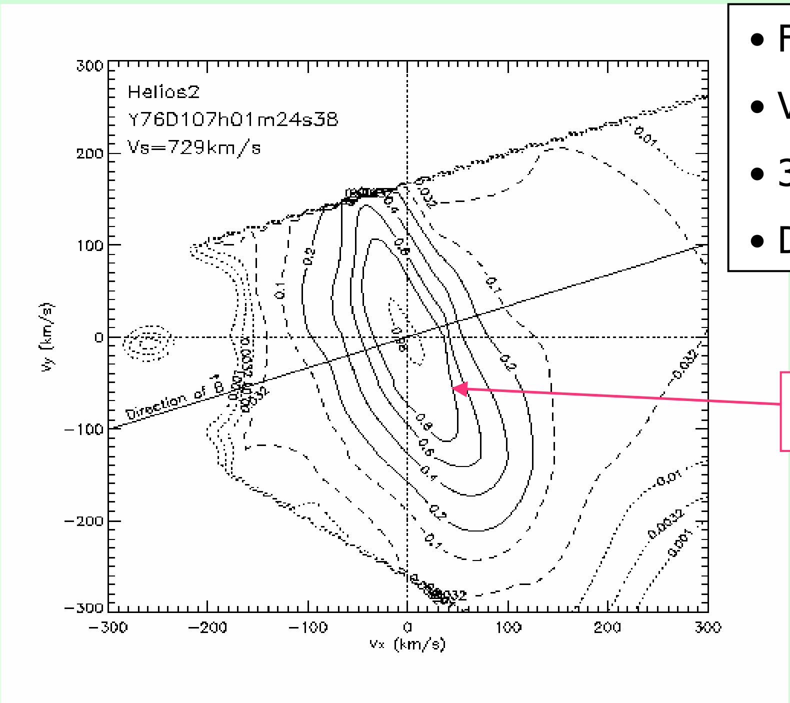
k_D^{-1} = 150 m in coronal hole

Here τ is the time lag, and $\omega = \omega_0 + \kappa \bullet \mathbf{V}$.

Harmon and Coles, JGR, 2005

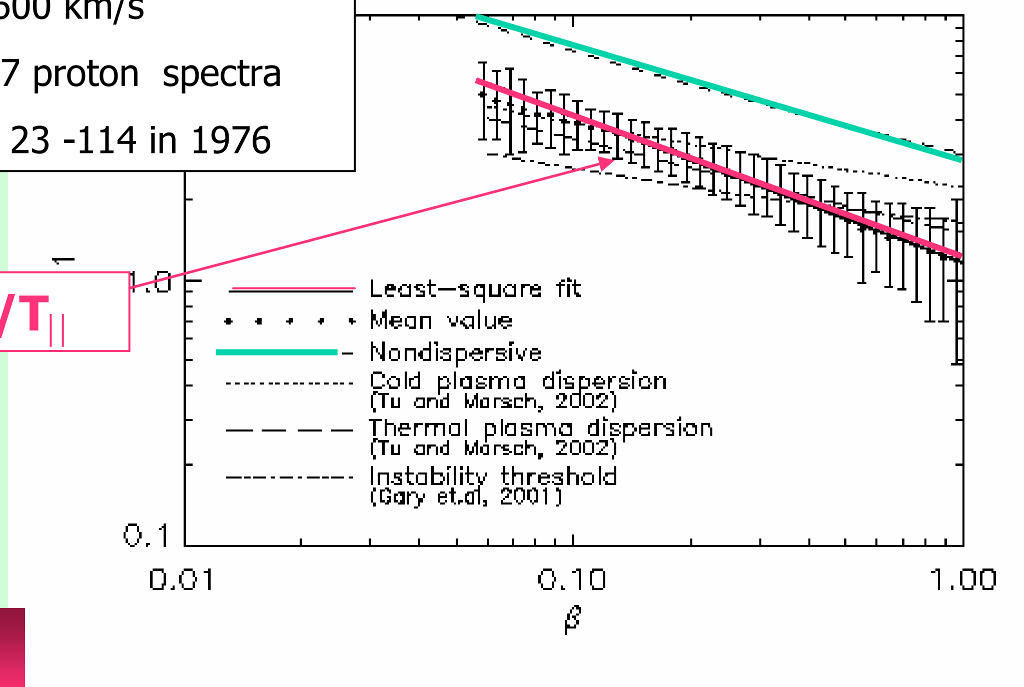
$$D(\tau) = 4\pi r_e^2 \lambda^2 \int\int\int [1 - \cos(\omega\tau)] S_N(\kappa, z; k_z = 0)\, d^2\kappa\, dz$$

Regulation of proton core anisotropy



- Fast solar wind
- V > 600 km/s
- 36297 proton spectra
- Days 23 -114 in 1976

$T_{\perp}/T_{||}$



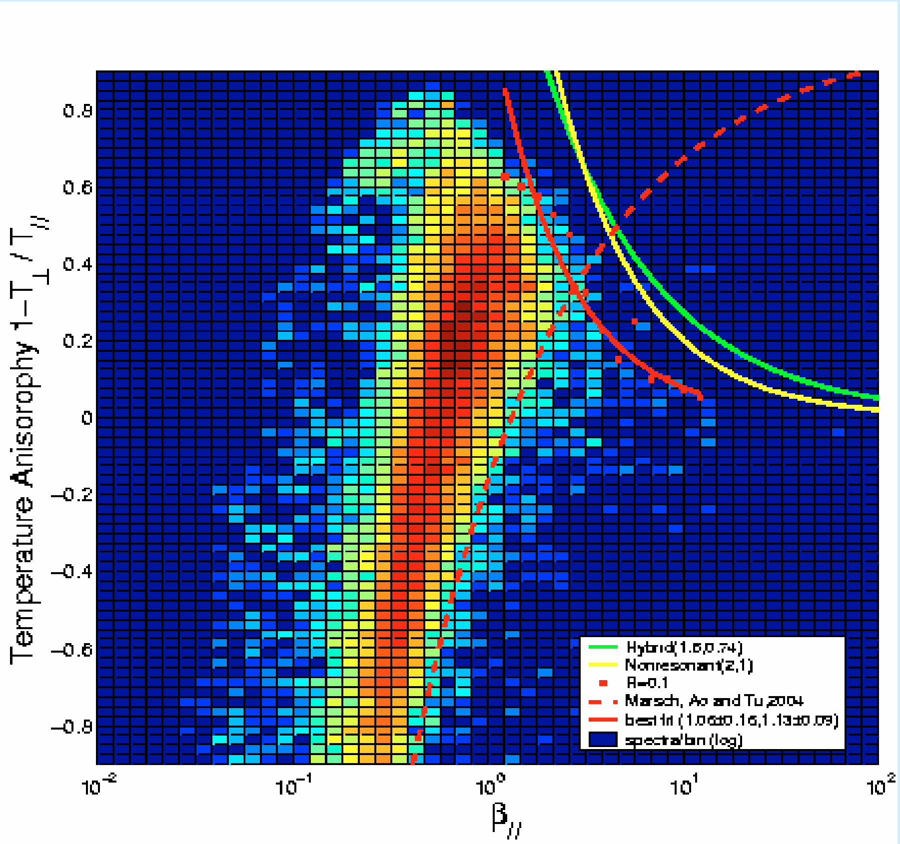
The core temperature anisotropy is regulated by quasilinear diffusion of protons in resonance with thermal dispersive cyclotron waves!

Empirical least-squares fit of anisotropy versus plasma beta:

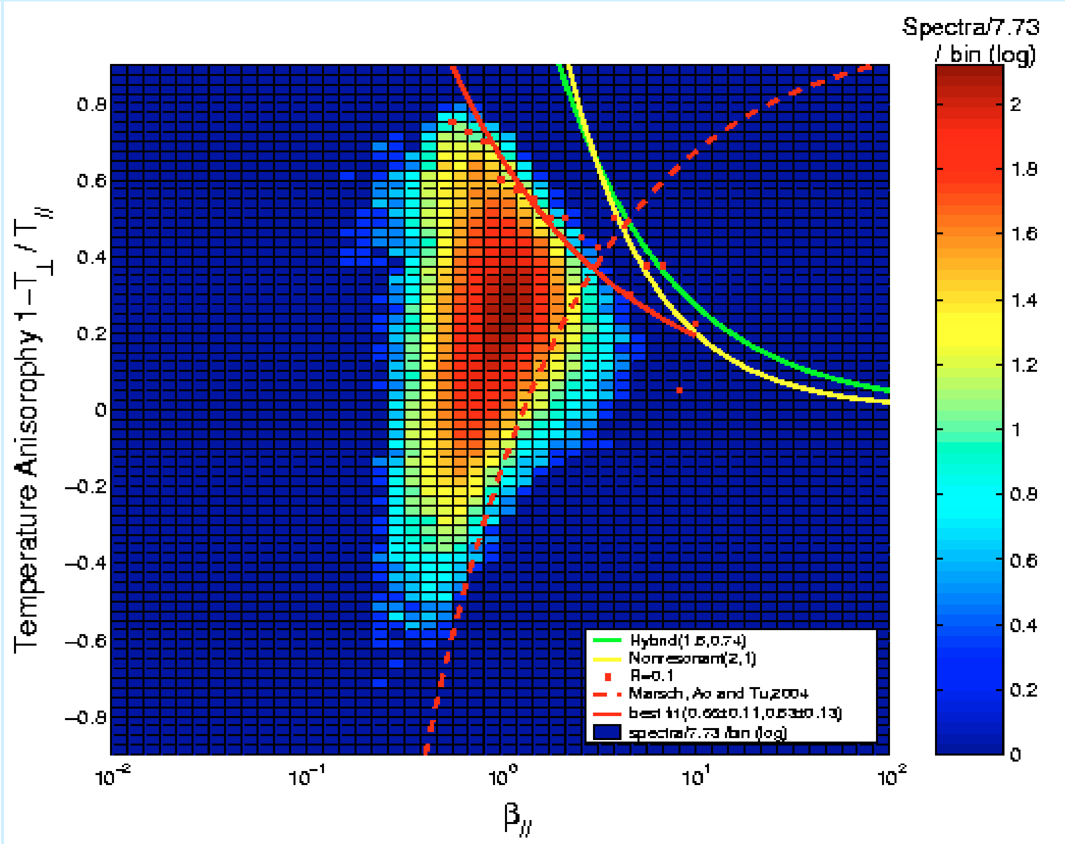
$$T_{\perp}/T_{||} = 1.16\ \beta_{||c}^{(-0.55)}$$

Marsch et al., J. Geophys. Res., **109**, 2004

Proton temperature anisotropy and firehose instability



R < 0.4 AU

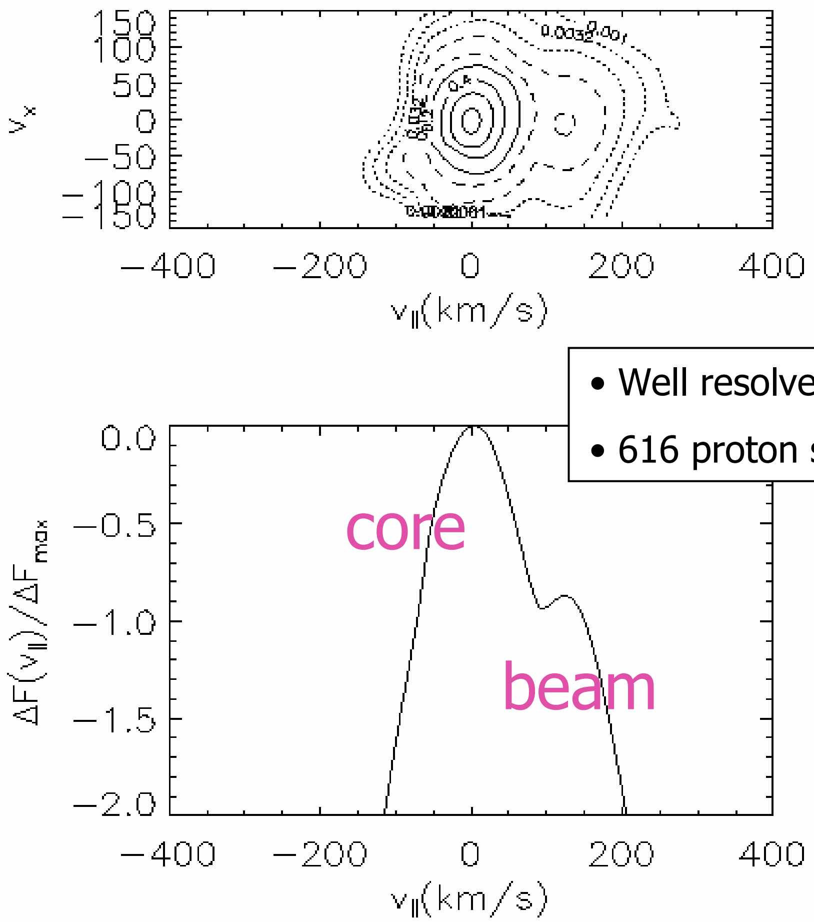


0.4 AU < R < 1 AU

Marsch, Zhao, Tu, Ann. Geophysicae, submitted, 2005

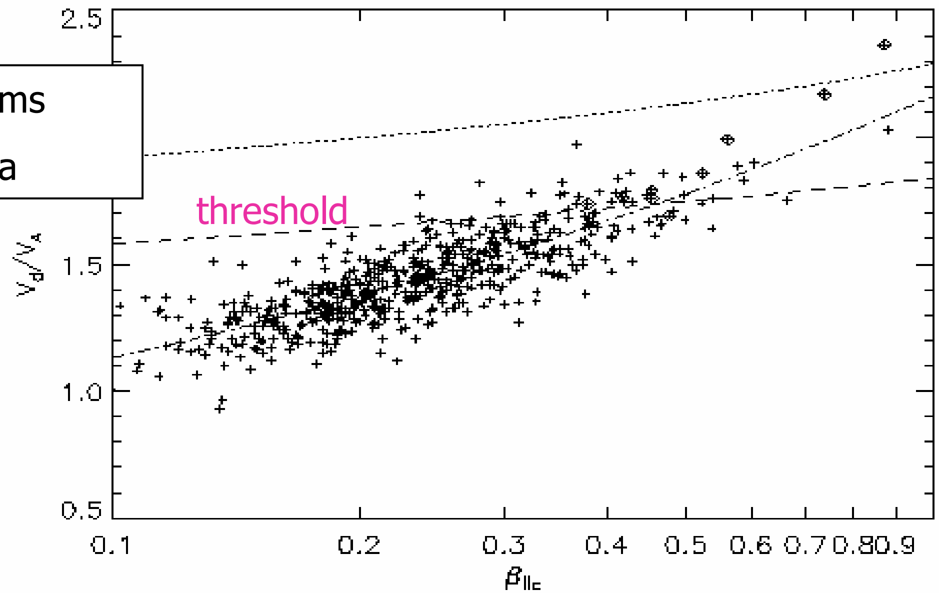
$$A = 1 - T_{\perp} / T_{||}$$

Stability of solar wind proton beams



- Origin of the proton beam not yet explained; collisions or waves?
- Proton beam speed is regulated by wave-particle interactions!

- Well resolved beams
- 616 proton spectra



Tu et al., J. Geophys. Res., **109**, 2004

Plot of drift speed versus plasma beta, $V_d/V_A = 2.16\,\beta^{0.28}$, indicates stability!

Conclusions

- Classical transport theory for ions and electrons breaks down already low in the solar corona and even more so in the solar wind.

- Electron heat conduction is not well understood in the presence of whistler turbulence, collisional run-away and electrons being trapped in or escaping from the electrostatic (gravitational) potential.

- Kinetic physics including wave-particle interactions adequately describes key non-thermal features of solar wind ions, but a turbulent wave transport theory (coefficients) for the corona does not yet exist.

- Viscous, ohmic and conductive (collisional) heating are insufficient, however a simple rescaling of transport coefficients is not meaningful.

- The thermodynamics (heating) of the solar corona will ultimately require a kinetic plasma approach to understand the dissipation.