Kinetic processes and wave-particle interactions in the solar wind

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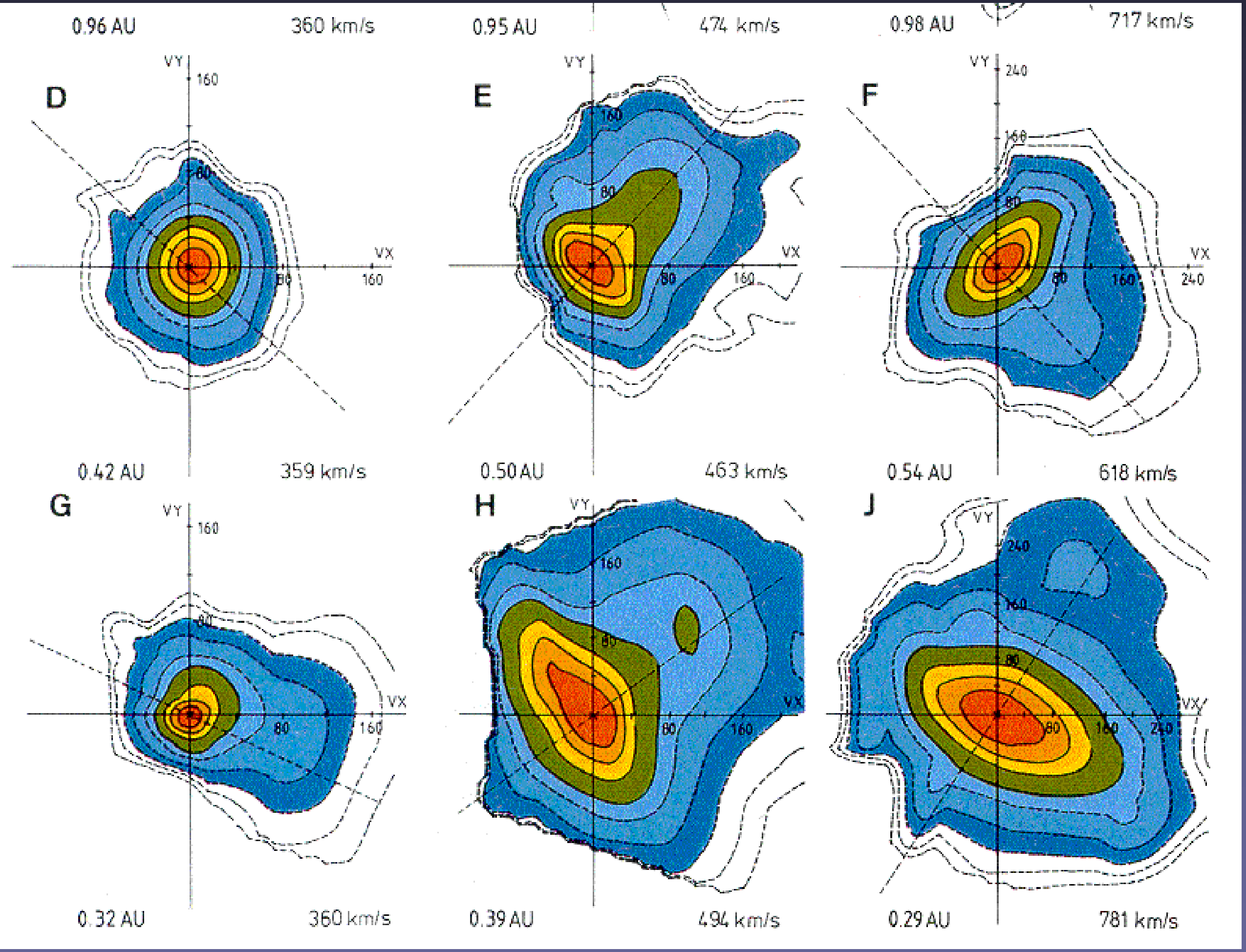
Seminar Talk at Uppsala University, Uppsala, Sweden, November 2013

Ion kinetics in the solar wind

- Prominent kinetic features observed by Helios are the proton beam and the core temperature anisotropy, $T_{c\perp} > T_{c||}$.

- Evidence for pitch-angle scattering and quasilinear diffusion, microinstablities and Coulomb collisions

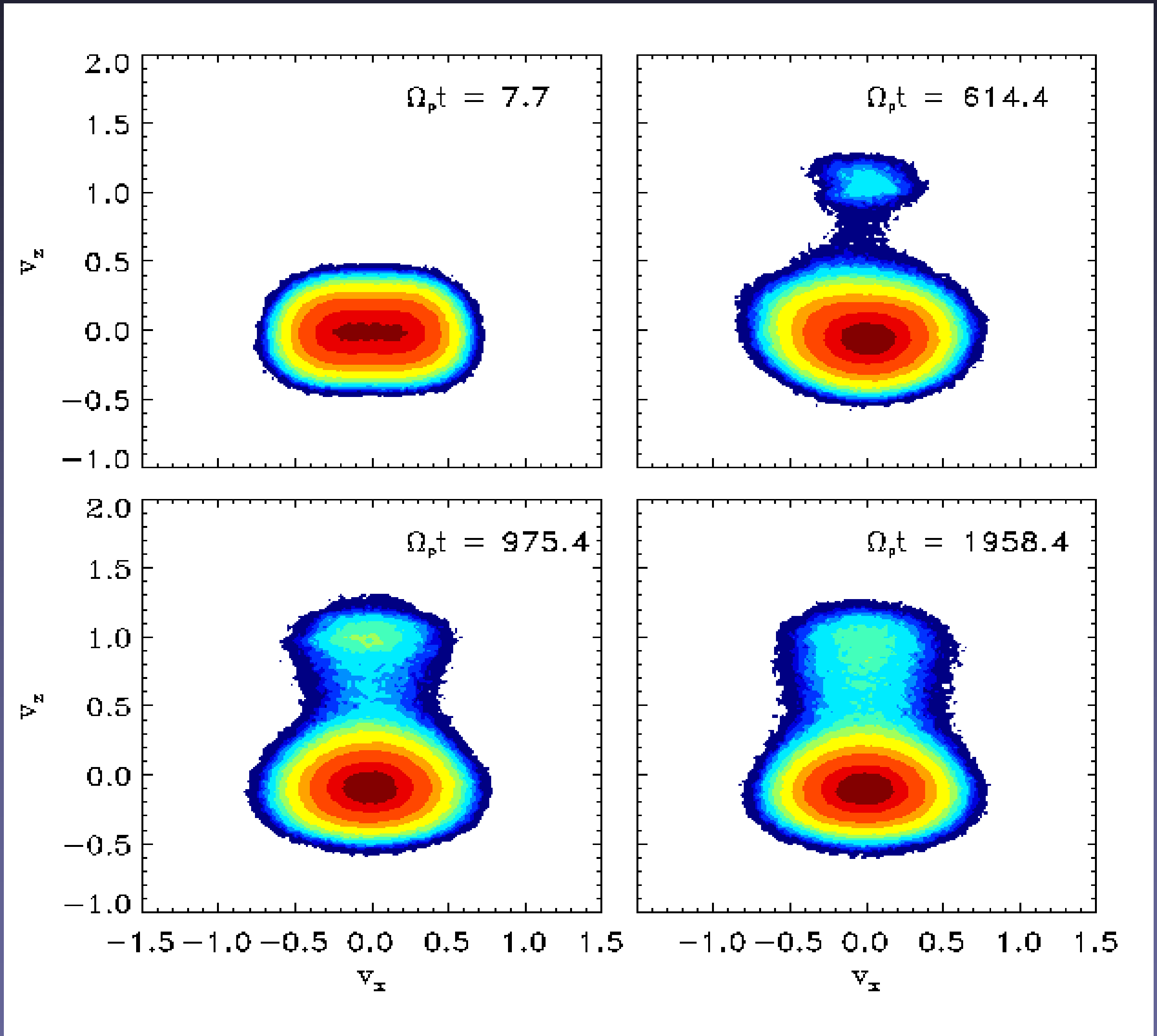


Marsch et al., JGR 1982

Wave-ion kinetic interactions

- Beams and temperature anisotropies usually occur in solar wind proton velocity distributions.
- They indicate ubiquitous kinetic wave-particle interactions, which involve cyclotron and Landau resonances with plasma waves.
- Kinetic instabilities and ion diffusion play key roles in the dissipation of MHD turbulence.

Proton core heating and beam formation



Numerical hybrid simulation show:

Beam forms through Landau resonance and anisotropy by resonant pitch-angle diffusion.

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

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

Kinetic properties of corona and wind

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

$\rightarrow$ multiple scales and complexity

- **Plasma is tenuous and turbulent**

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

Problem: Thermodynamics and transport….

Collisions and plasma turbulence

Coulomb collisions and wave-particle interactions can be represented by a second-order differential operator, including the acceleration vector A(v) and diffusion tensor *D*(v), in velocity space:

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

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

Collisional kinetics of solar wind electrons:

- Pierrard et al.
- Lie-Svendsen et al.

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

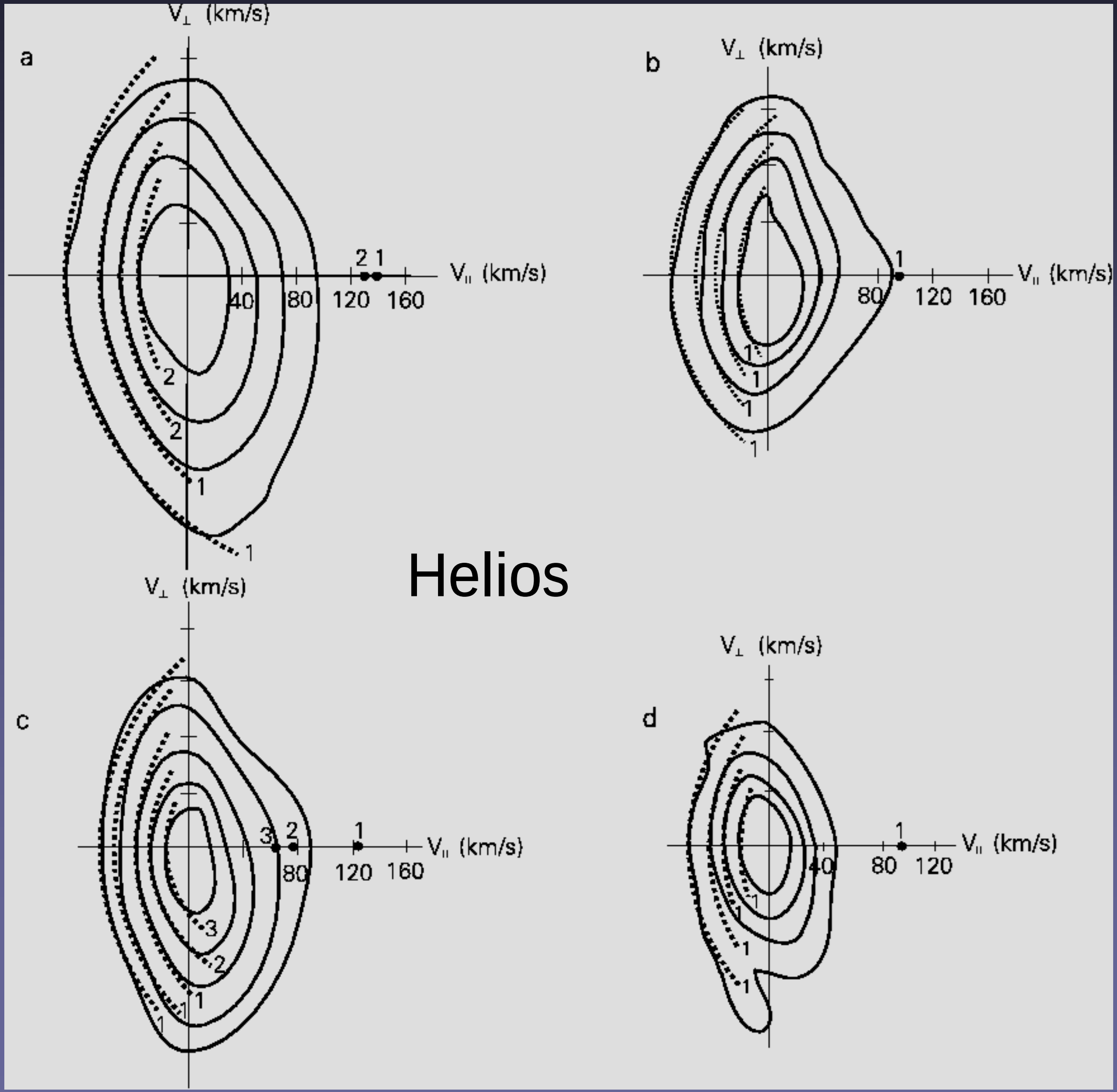
$$\frac{\partial}{\partial \alpha} = v_\perp \frac{\partial}{\partial v_{||}} - \left(v_{||} - \frac{\omega_M(\mathbf{k})}{k_{||}} \right) \frac{\partial}{\partial v_\perp}$$

Superposition of linear waves with random phases

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

Kennel and Engelmann, 1966; Stix, 1992

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 ion-cyclotron-wave field

Marsch and Tu, JGR 2001

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*

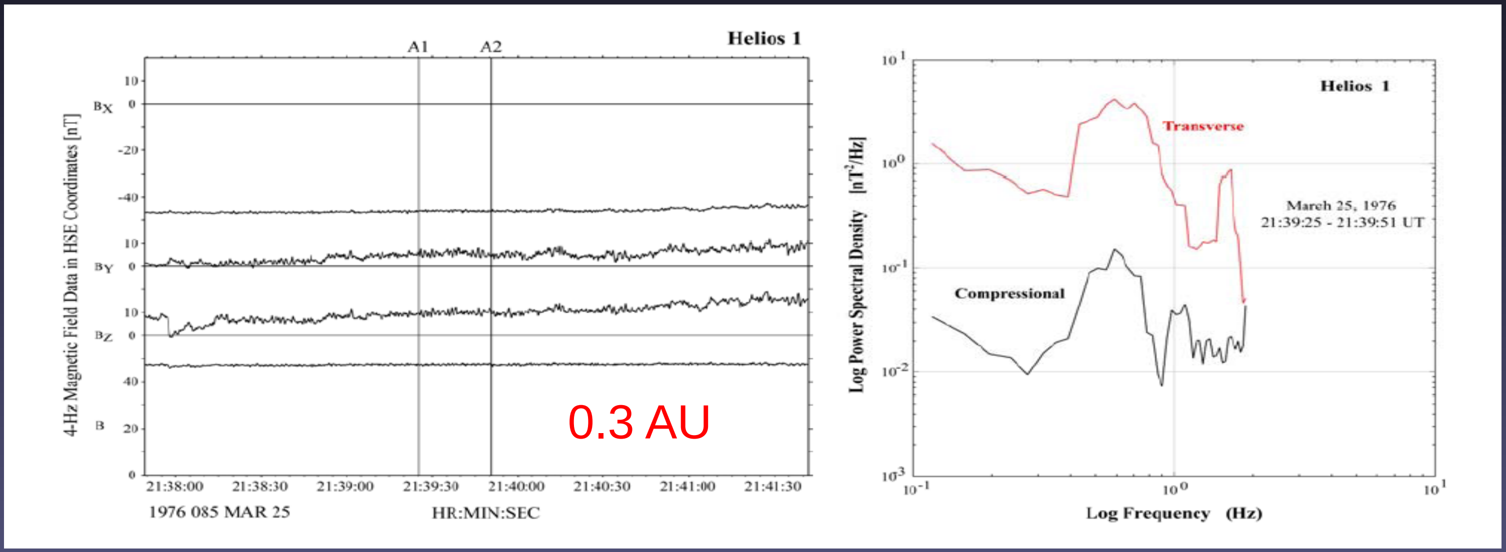
Resonant wave-particle relaxation rate

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

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

Marsch, Nonlin. Proc. Geophys. 2002

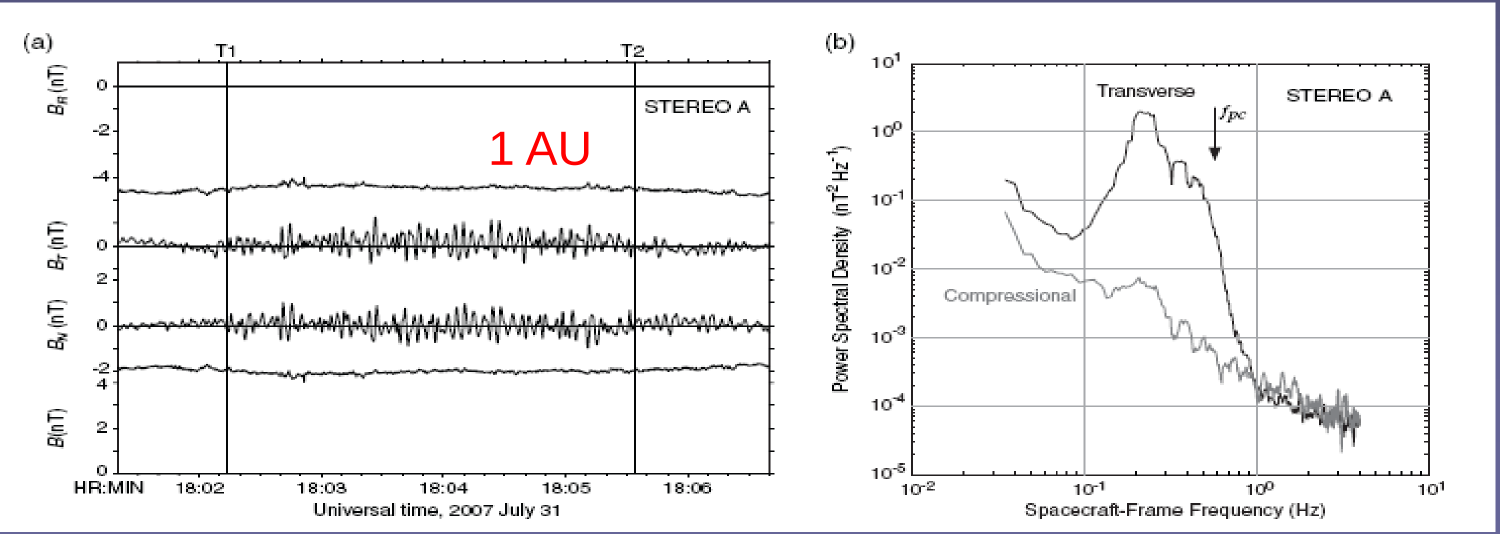
Ion cyclotron waves



Helios

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

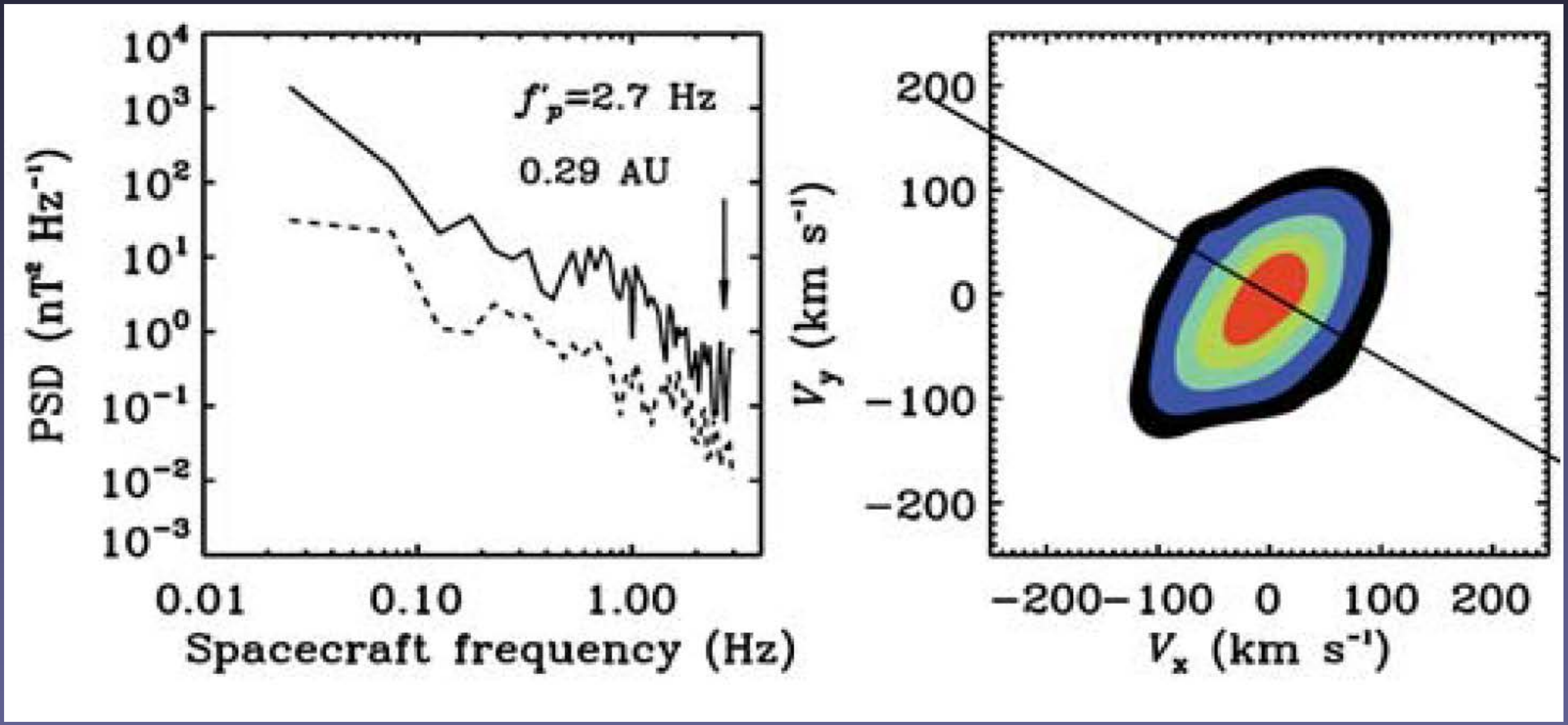
Parallel in- and outward propagation



STEREO

Jian et al., Ap.J. 2009

Transverse Alfvén/cyclotron waves

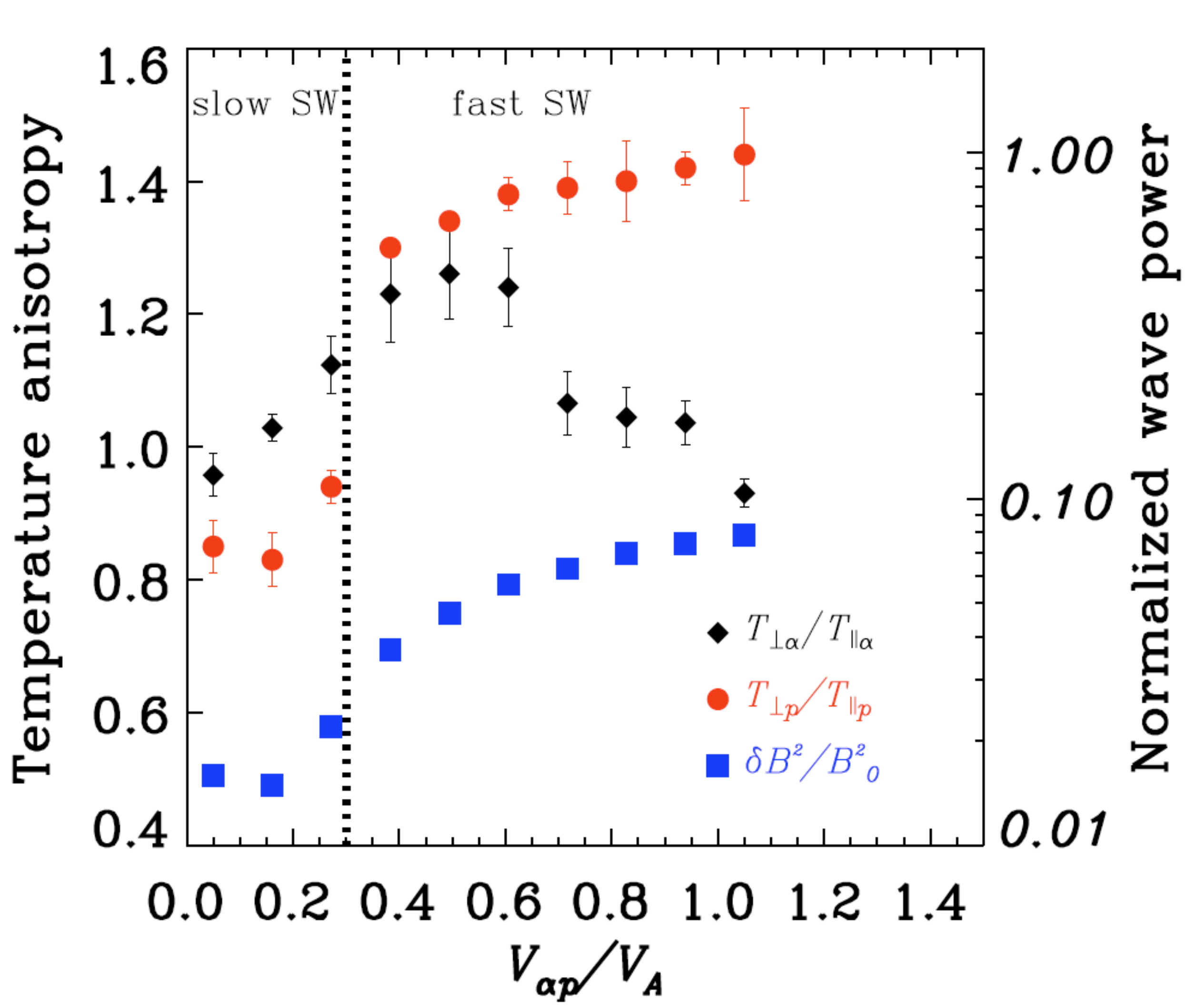


Alfvén-ion-cyclotron waves, 0.02 Hz - 2 Hz from Helios at 0.3 AU

Proton anisotropy ($T_{\perp}/T_{\parallel}>1$) is strongly correlated with wave power.

Bourouaine et al., GRL 2010

Ion differential motion



Bourouaine et al., ApJ 2011

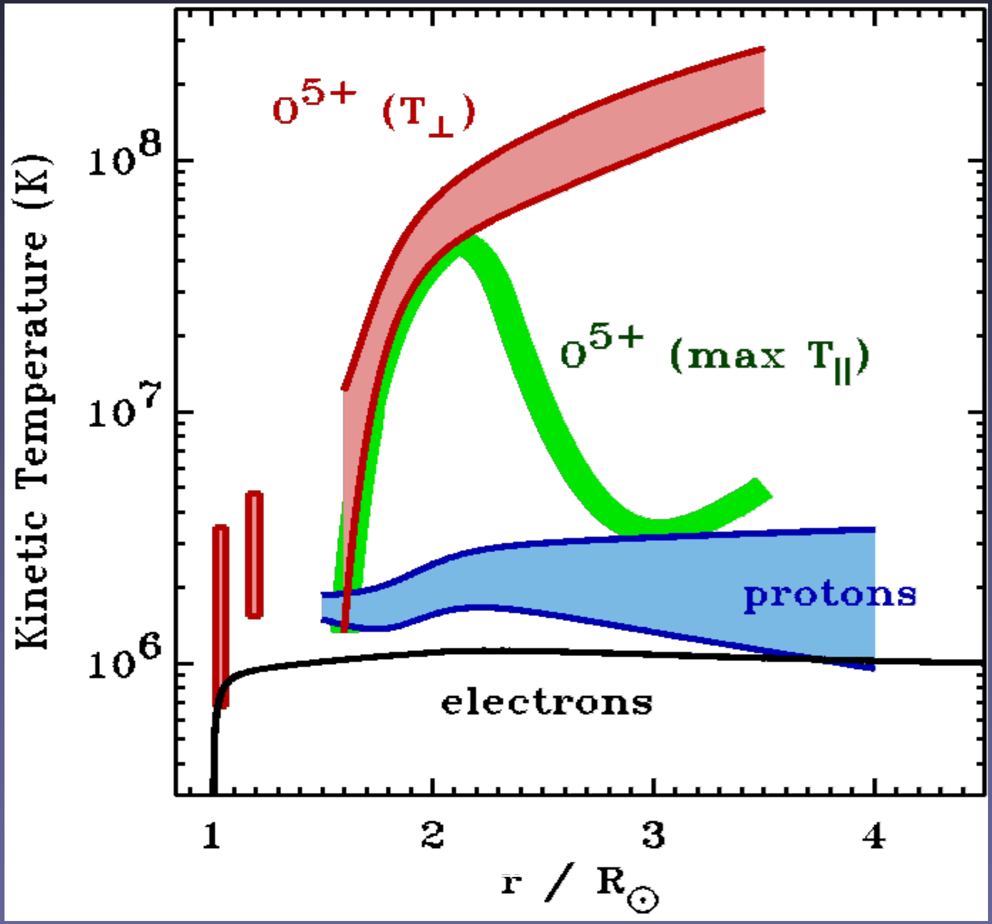
The alpha-particle temperature ratio can be explained by the kinetic theory of ion-cyclotron wave dissipation.

Alpha particles are heated by ion-wave interaction as long as they can stay in resonance with the Alfvén/ion-cyclotron waves, a process that occurs when the normalized ion differential speed is small. Resonant interaction with waves becomes less efficient if the differential speed increases, or if the wave energy input is smaller.

Spectroscopy of heavy-ion kinetics

- Plasma diagnostics of corona on disk and off limb provides composition and the ion temperature anisotropy.

- Spectroscopy of the solar wind acceleration region by observation of line broadenings (tempera-tures versus height) of ions with different charge/mass ratios.



Kohl et al., Ap. J. , 1999;
Cranmer, 2009.

$T_\perp/T_{||}$ > 10

UVCS/SOHO

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

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

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

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

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

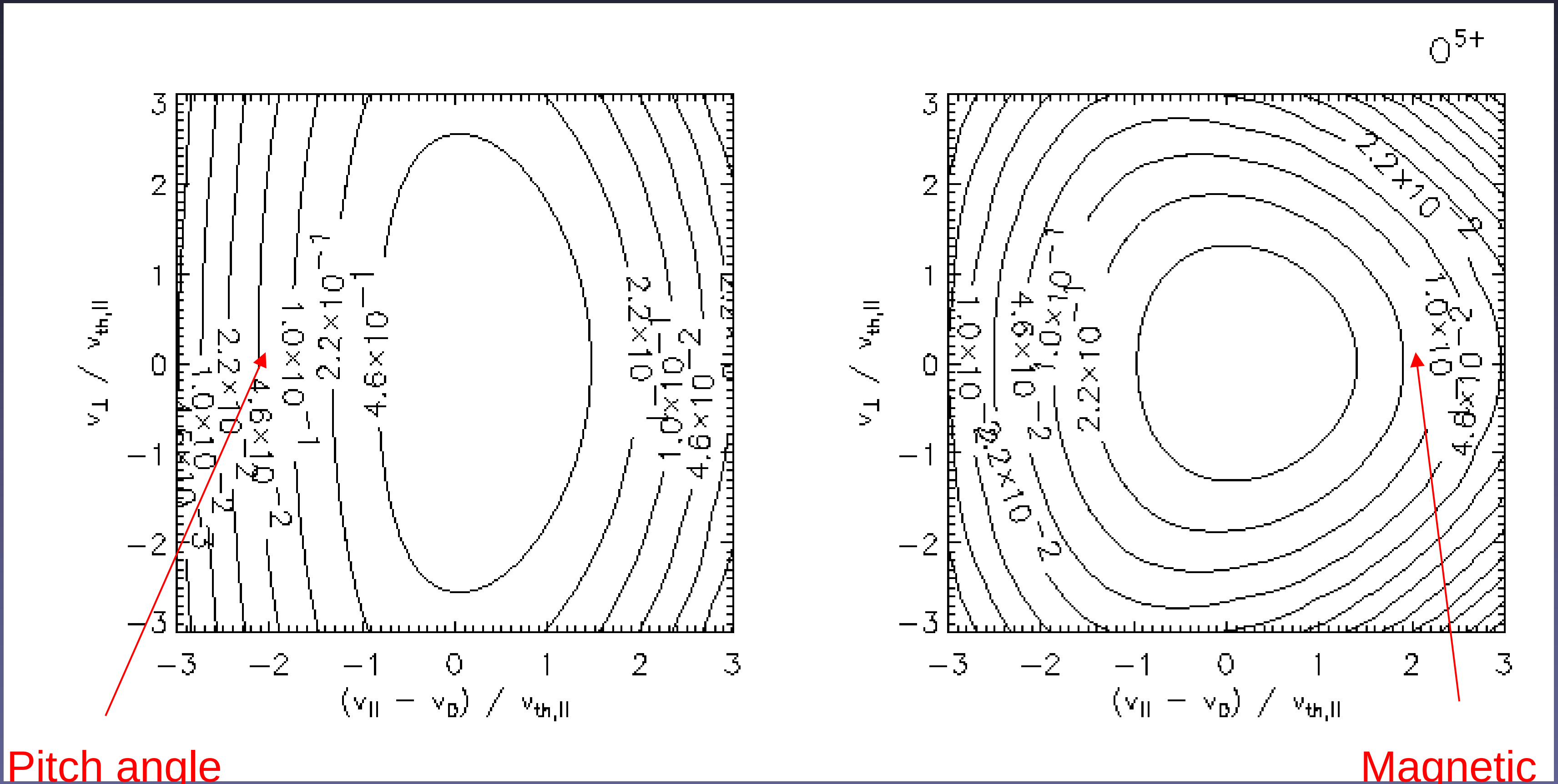
Reduced Velocity distributions

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

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

Marsch, Nonlinear Proc. Geophys., **5,** 111, 1998 Vocks and Marsch, GRL, **28**, 1917, 2001

Velocity distributions of oxygen ions



Pitch angle scattering, plateau

r= 1.44 R_s

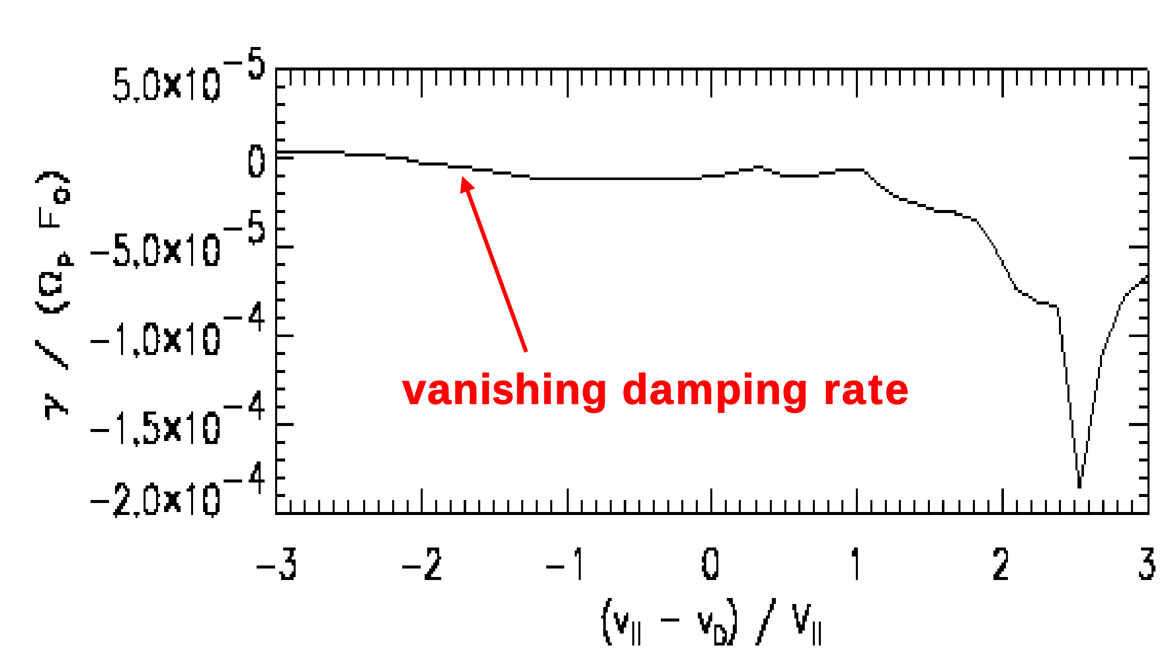
r= 1.73 R_s

Magnetic mirror force, runaway

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

Marginal stability of coronal oxygen ions

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



Model velocity distribution function

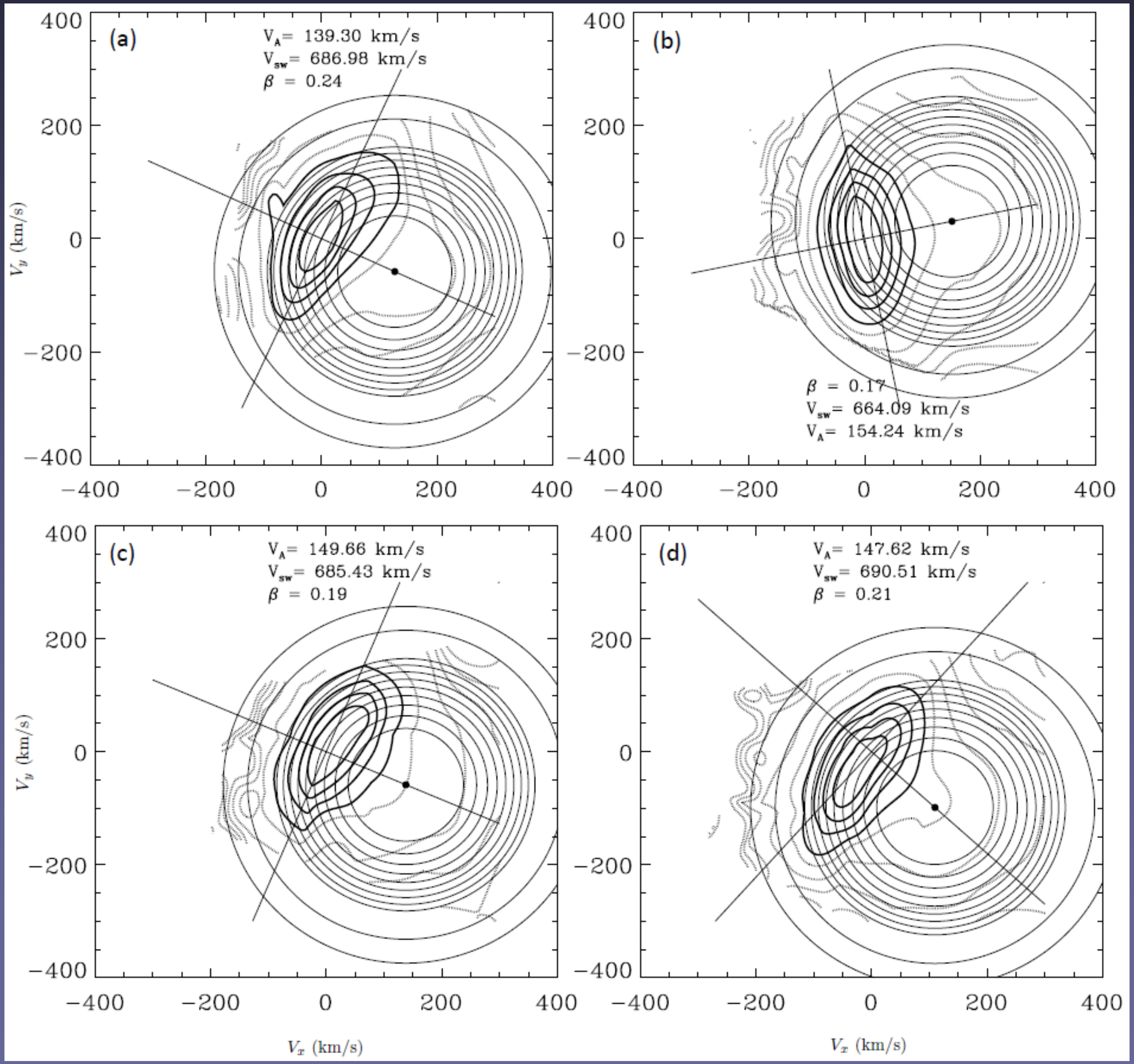
$$f_j(w_\parallel, w_\perp) = \frac{F_{j\parallel}(w_\parallel)}{2\pi W_{j\perp}^2(w_\parallel)} \exp\left(-\frac{w_\perp^2}{2W_{j\perp}^2(w_\parallel)}\right)$$

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

Effective perpendicular thermal speed

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

Proton diffusion in oblique Alfvén/cyclotron and fast-magnetoacoustic waves I



Diffusion circles centered at the local Alfvén speed (dots)

Contour lines:

80, 60, 40, 20, 10. 03, 01, 003, 001 % of the maximum.

Isocontours in plane defined by **V** and **B**

Marsch and Bouroauine, 2011

Resonance and diffusion plateaus

Cyclotron resonance

$$V_{\|} = C(y_{\|}, y_{\perp}) - \frac{s}{y_{\|}} V_{\mathrm{A}}$$

$$C(\mathbf{k}) = \omega(\mathbf{k}) / k_{\|}$$

Phase speed

$$y_{\|} = k_{\|} V_{\mathrm{A}} / \Omega_j$$

$$y_{\perp} = k_{\perp} V_{\mathrm{A}} / \Omega_j$$

Normalized wave vector

$$\int_0^{V_{\|}} dV'_{\|} C(V'_{\|}) = V_{\mathrm{A}}^2 \int_{y_0}^{y_{\|}} dy'_{\|} g(y'_{\|}, y_{\perp}) \left(\frac{s}{y'^2_{\|}} + \frac{dg}{dy'_{\|}} \right)$$

$$C(\mathbf{y}) = g(y_{\|}, y_{\perp}) V_{\mathrm{A}}$$

$$\boxed{E(V_{\|}, V_{\perp}) = \frac{1}{2}\left(V_{\perp}^2 + V_{\|}^2\right) - \int_0^{V_{\|}} dV'_{\|} C(V'_{\|})}$$

$$V_{\|}(y_{\|}) = C_{\mathrm{F,S}}(\theta(y_{\|})) - V_{\mathrm{A}} \frac{s}{y_{\|}} = \frac{V_{\mathrm{A}}}{y_{\|}} \left(\frac{\omega_{\mathrm{F,S}}}{\Omega_j} - s \right)$$

Cyclotron resonance

$$V_{\|}(y_{\|}) = V_{\mathrm{A}} \left(1 - \frac{s}{y_{\|}}\right) = \frac{V_{\mathrm{A}}}{y_{\|}} \left(\frac{\omega_{\mathrm{A}}}{\Omega_j} - s \right)$$

Fast magnetoacoustic wave

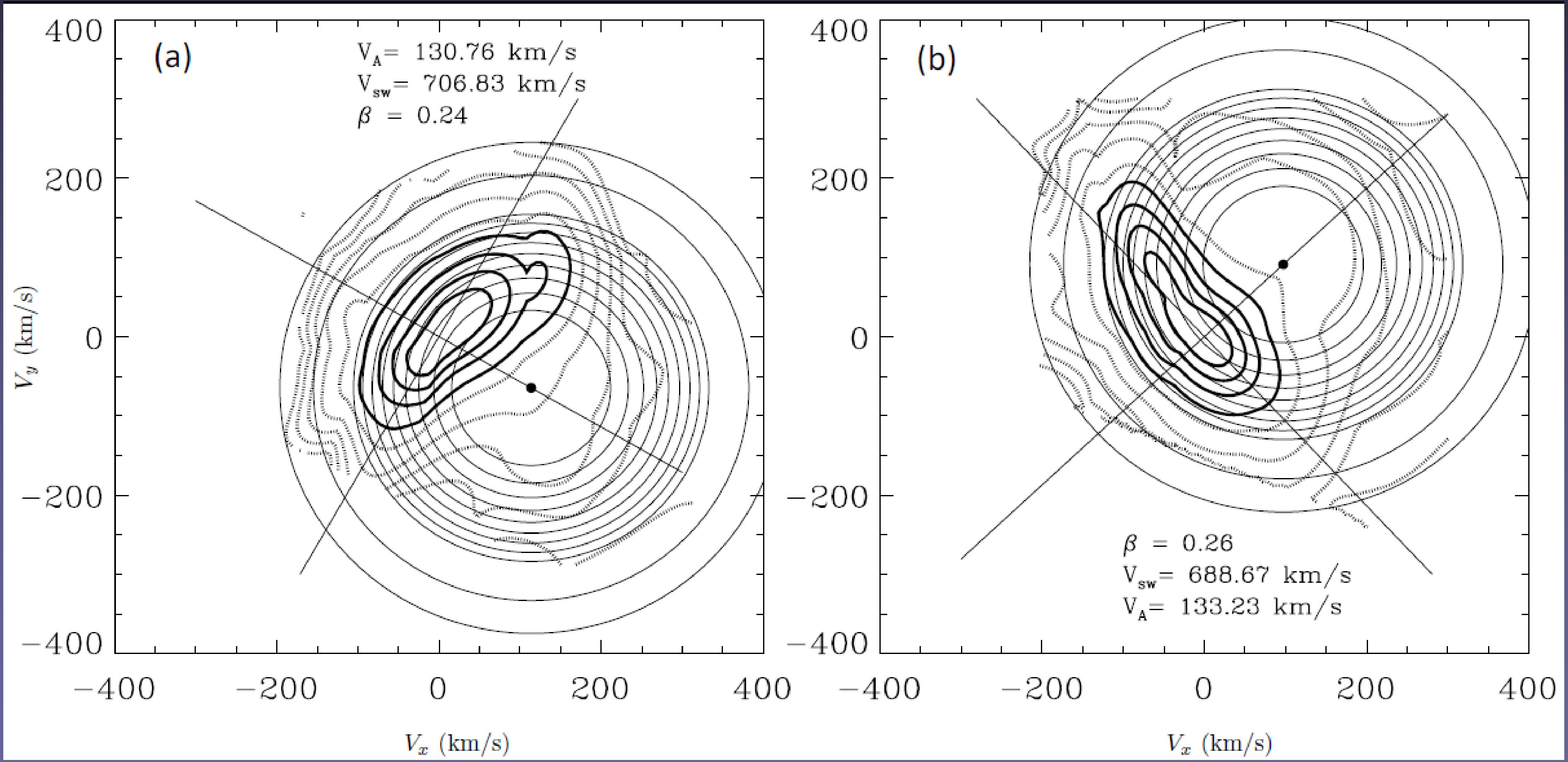
Alfven-ion-cyclotron wave

$$E_{\mathrm{F,S}}(V_{\|}, V_{\perp}, \theta) = \frac{1}{2}\left(V_{\perp}^2 + (V_{\|} - C_{\mathrm{F,S}}(\theta))^2\right)$$

$$E_{\mathrm{A}}(V_{\|}, V_{\perp}) = \frac{1}{2}\left(V_{\perp}^2 + (V_{\|} - V_{\mathrm{A}})^2\right)$$

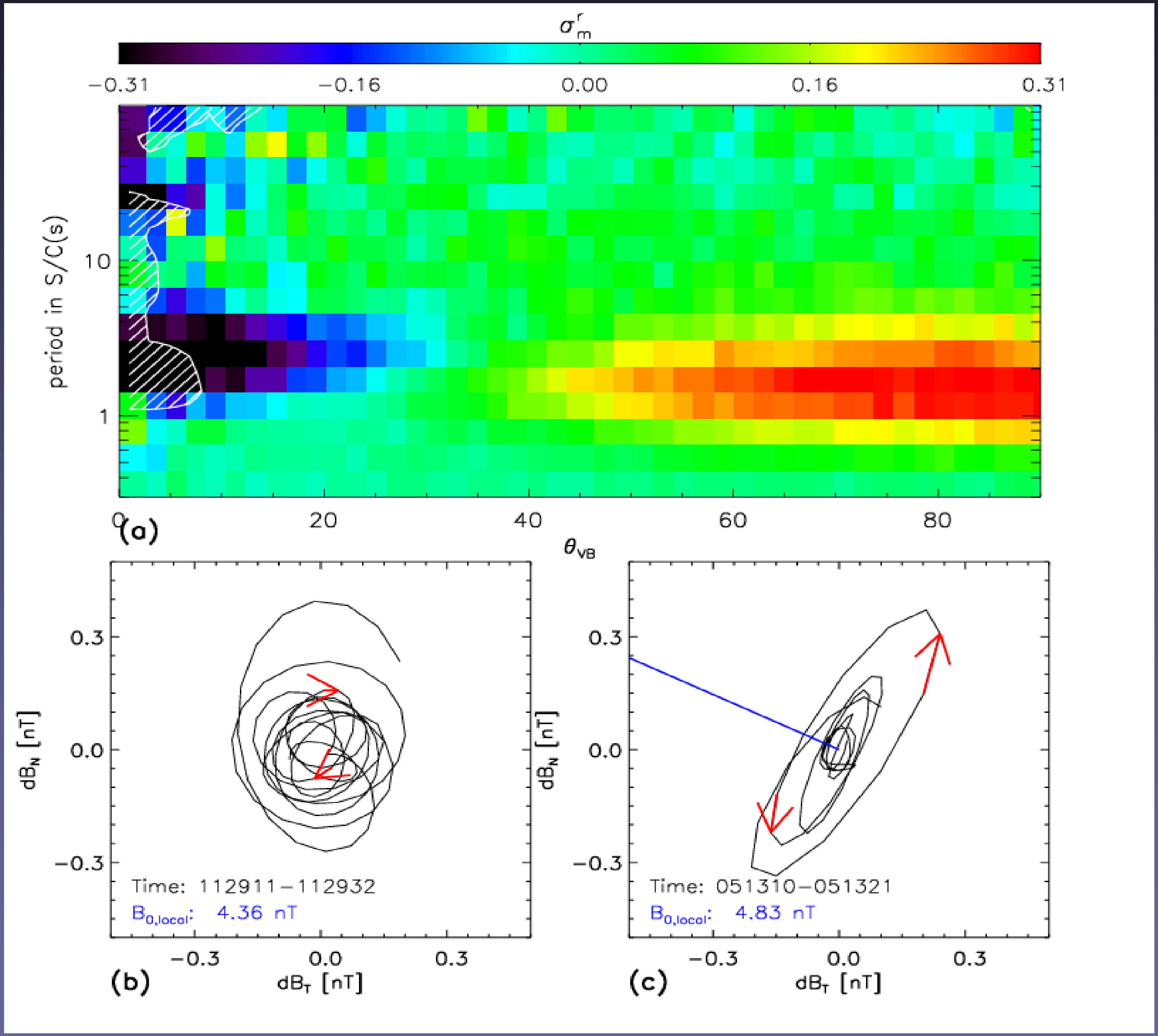
Marsch and Bouroauine, 2011

Proton diffusion in oblique Alfvén/cyclotron and fast-magnetoacoustic waves II



Marsch and Bouroauine, Ann. Geophys. 2011

Normalized magnetic helicity

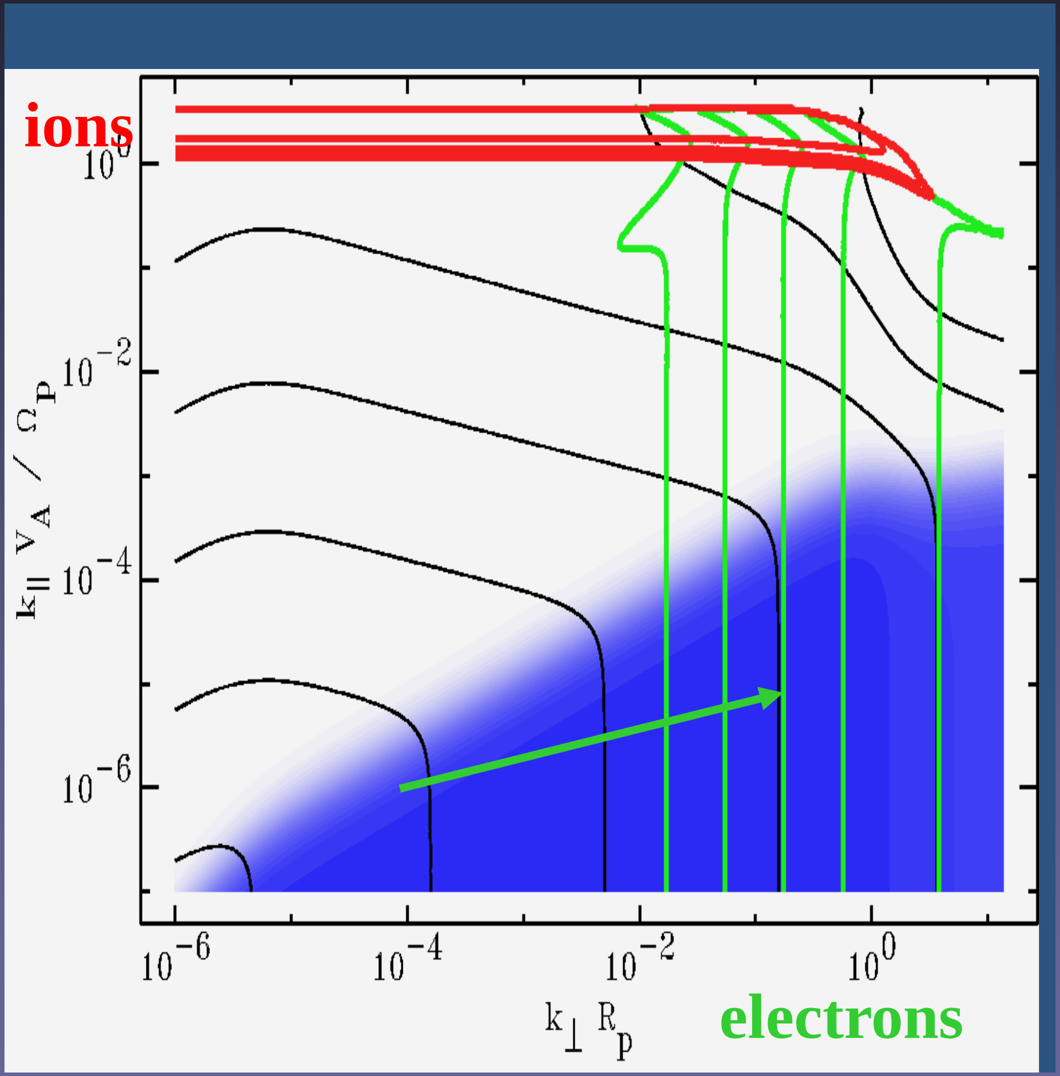


Helicity versus angle between solar wind flow and magnetic field vectors (STEREO, MAG)

Hodograph of normal and transverse magnetic field component, with (b) parallel left-handed and (c) perpendicular right-handed polarization

He, Tu, Marsch, and Yao, Astrophys.J. 2012

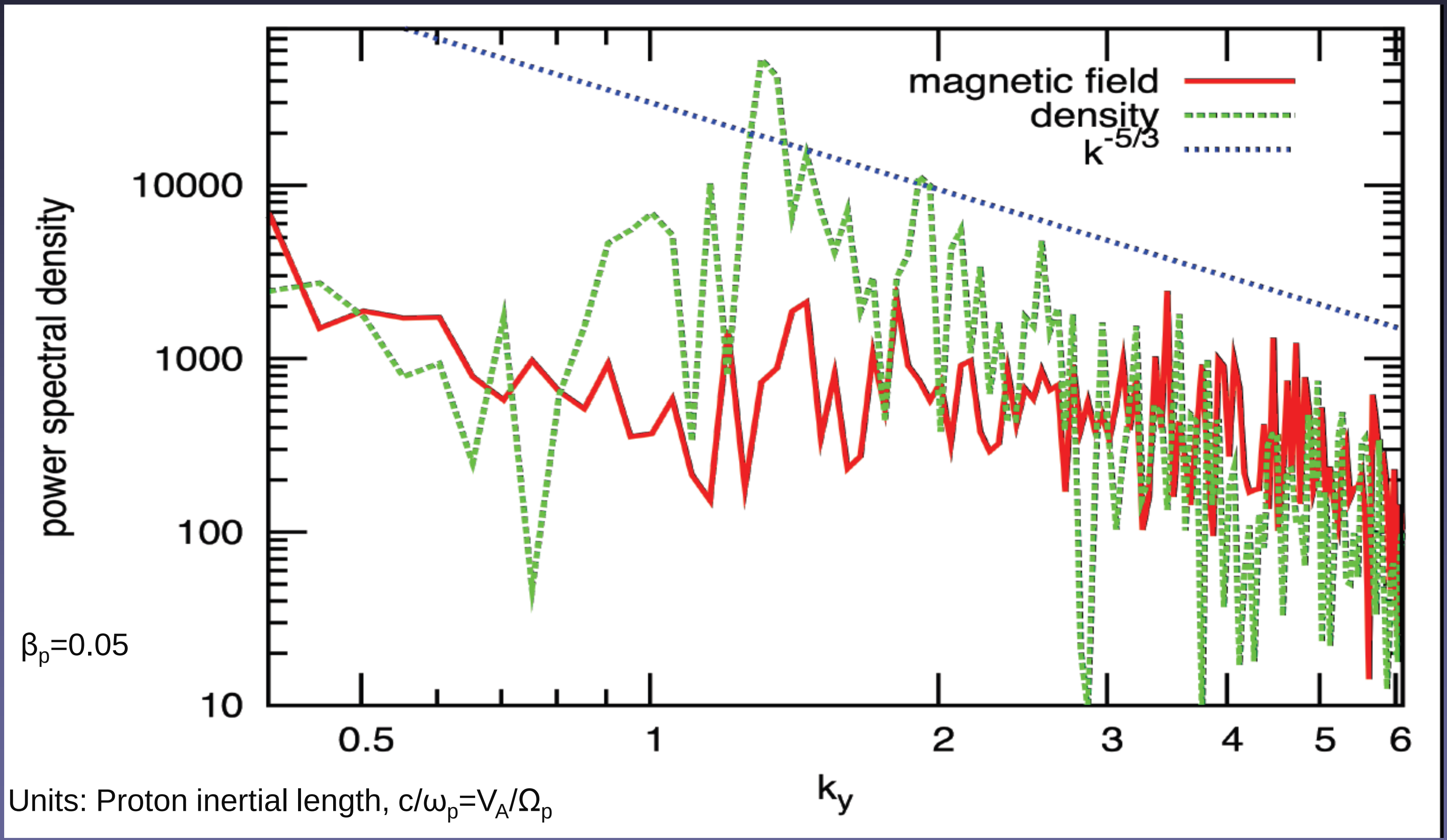
Anisotropic turbulent cascade



- MHD simulations and analytic models predict cascade from small to large $k_\perp$, leaving $k_{||}$ unchanged.
- **Critical balance** assumes $\omega_A = k_{||}V_A \cong \omega_{NL} = k_\perp \delta V$ (Goldreich and Sridar, ApJ. 1995, 1997)
- **Kinetic Alfvén wave** (KAW) with large $k_\perp$ does not necessarily have high frequency ω_A.
- In a low-beta plasma, KAWs are Landau-damped, heating **electrons** preferentially.

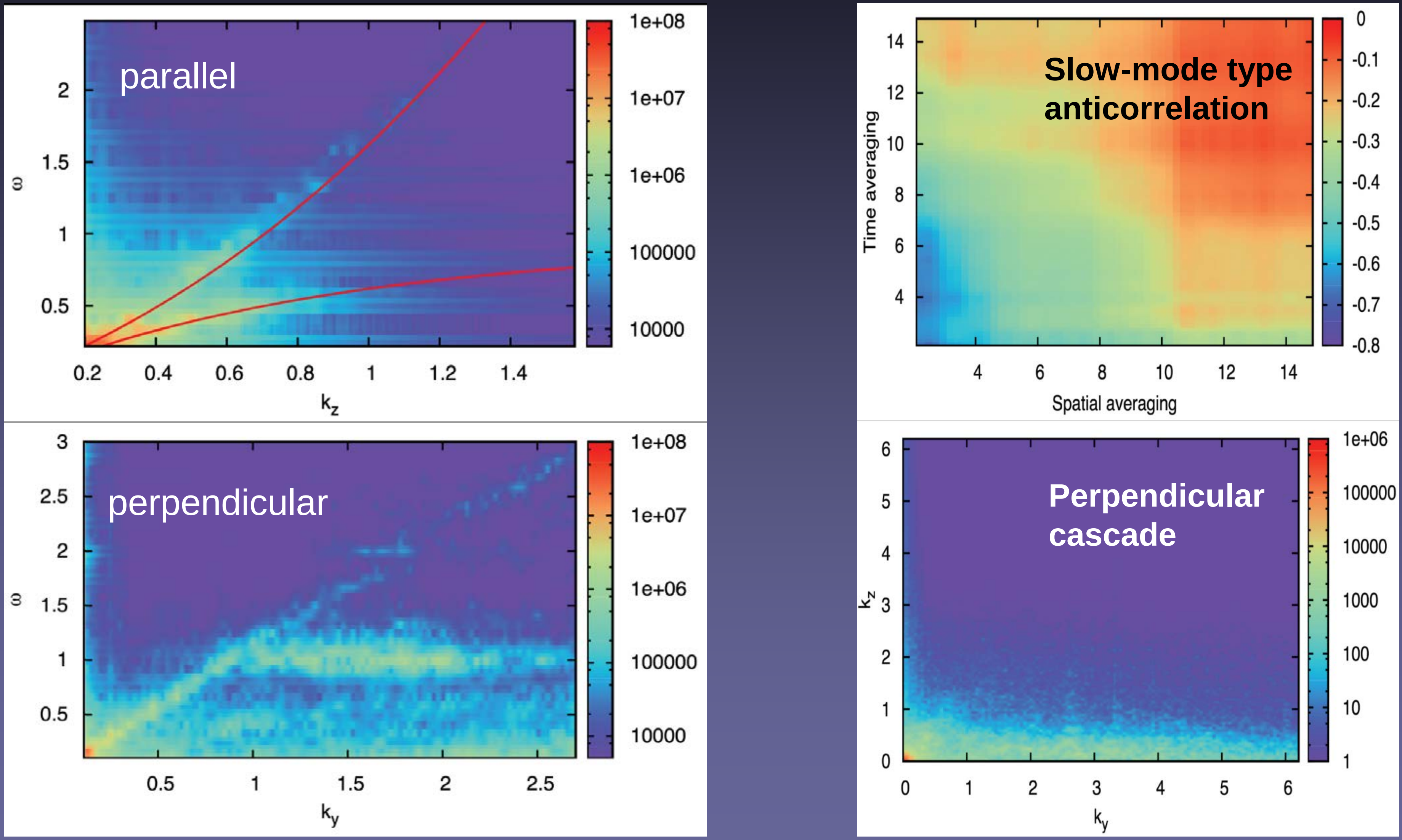
after Cranmer, 2010

Kinetic cascade beyond MHD of solar wind turbulence in two-dimensional hybrid simulations



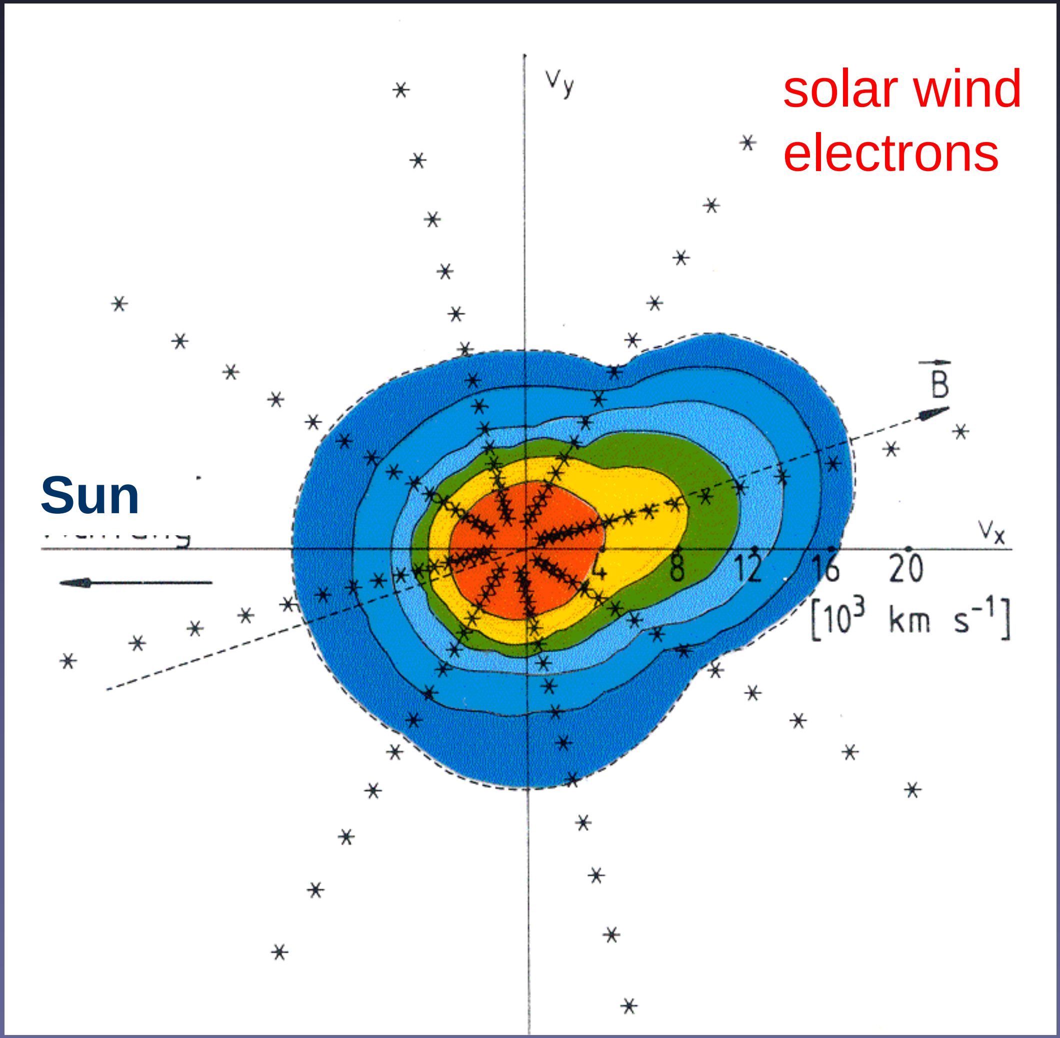
Verscharen, Marsch, Motschmann, and Müller, Phys. Plasmas 2012

Dispersion relation and wave power



Verscharen, Marsch, Motschmann, and Müller, Phys. Plasmas 2012

Invalidity of classical transport theory



n_e = 3-10 cm^{-3},

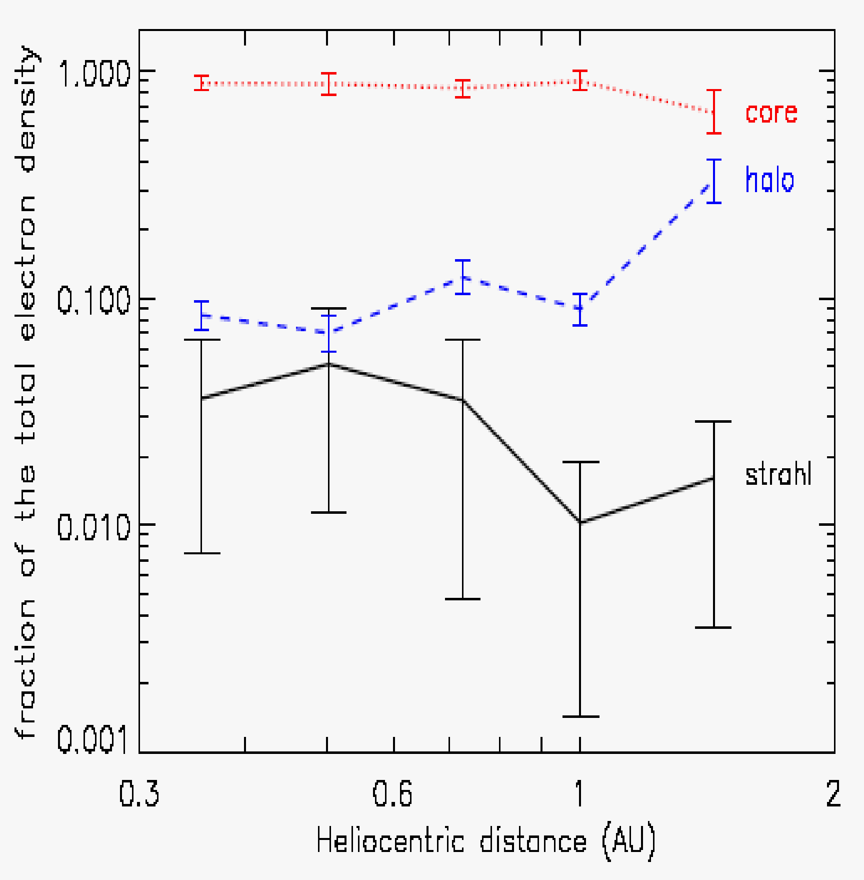
T_e = 1-2 10^5 K at 1 AU

- 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 λ_c >> L

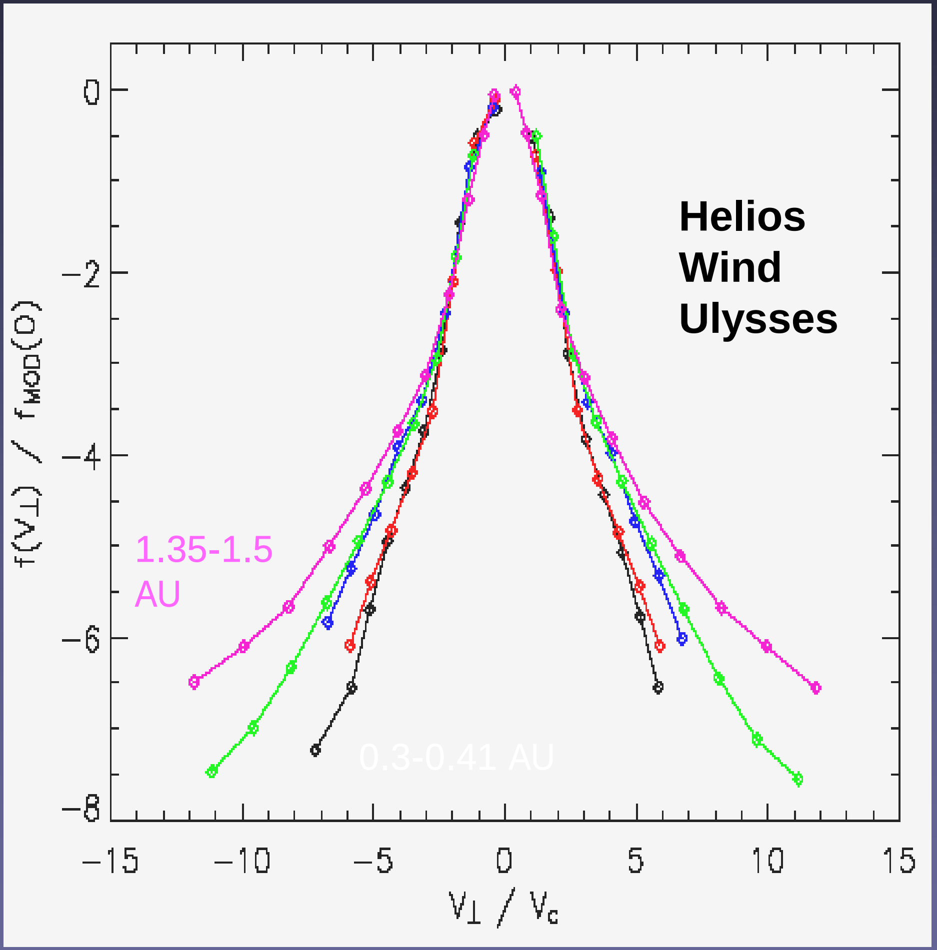
Pilipp et al., JGR, **92**, 1075, 1987

Solar wind electrons: Core-halo evolution

Halo is relatively increasing while strahl is diminishing.



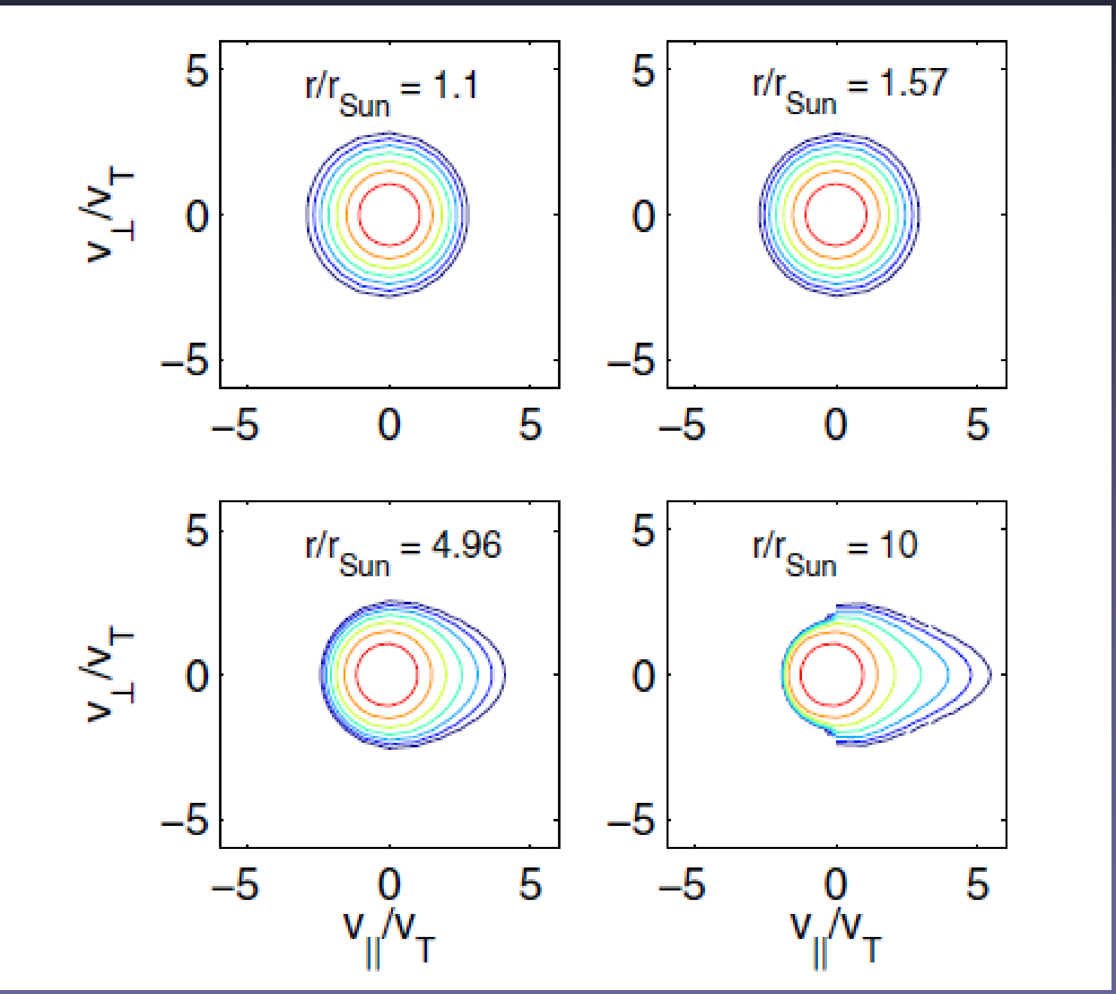
Normalized core remains constant while halo is relatively increasing.



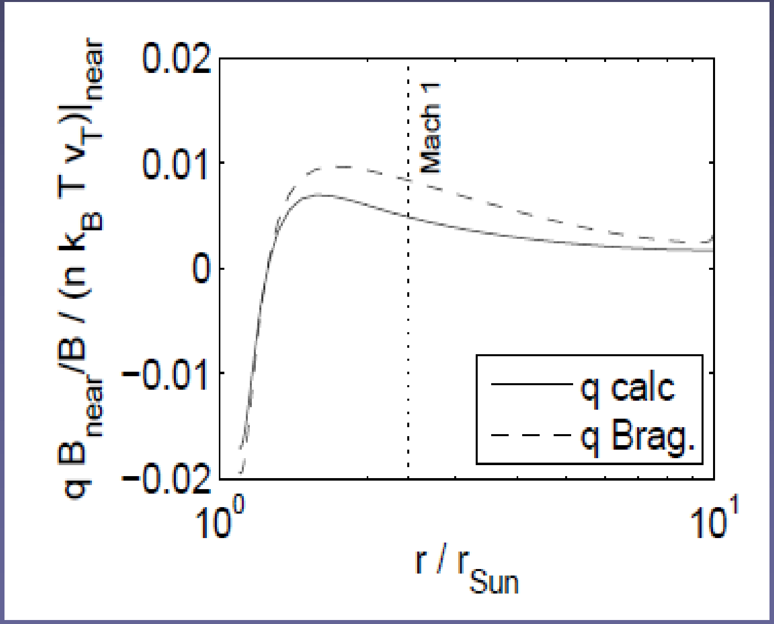
Maksimovic et al., JGR, 2005

Scattering by meso-scale magnetic structures

Collisional core – runaway strahl



Collisional transport in corona with Fokker-Planck operator in Boltzmann equation with self-consistent electric field

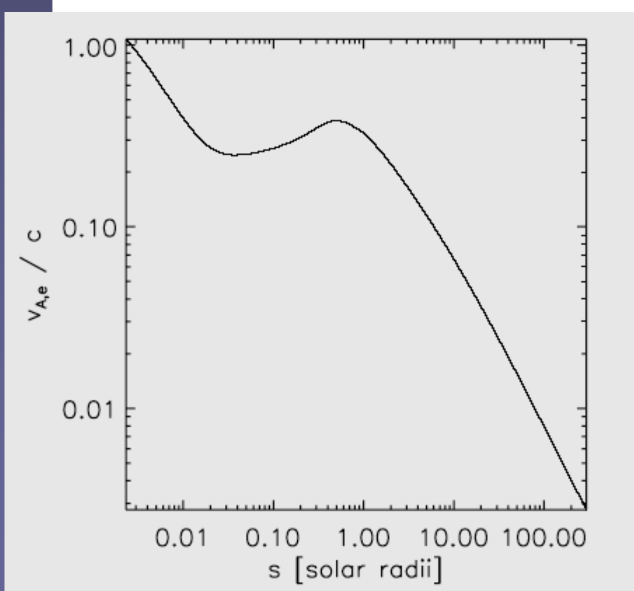


Heat flux smaller than classical

Smith, Marsch, Helander, ApJ, 751, 2012

Suprathermal coronal electrons caused by wave-particle interactions I

$$\frac{\partial f}{\partial t} + v_\parallel \frac{\partial f}{\partial s} + \left(g_\parallel - \frac{e}{m_e} E_\parallel\right) \frac{\partial f}{\partial v_\parallel} + \frac{v_\perp}{2A} \frac{\partial A}{\partial s} \left(v_\perp \frac{\partial f}{\partial v_\parallel} - v_\parallel \frac{\partial f}{\partial v_\perp}\right)$$
$$= \left(\frac{\delta f}{\delta t}\right)_{w\text{-}p} + \left(\frac{\delta f}{\delta t}\right)_{\rm Coul} . \qquad (7)$$



Boltzmann equation with waves and collisions

A(s) flux tube area function

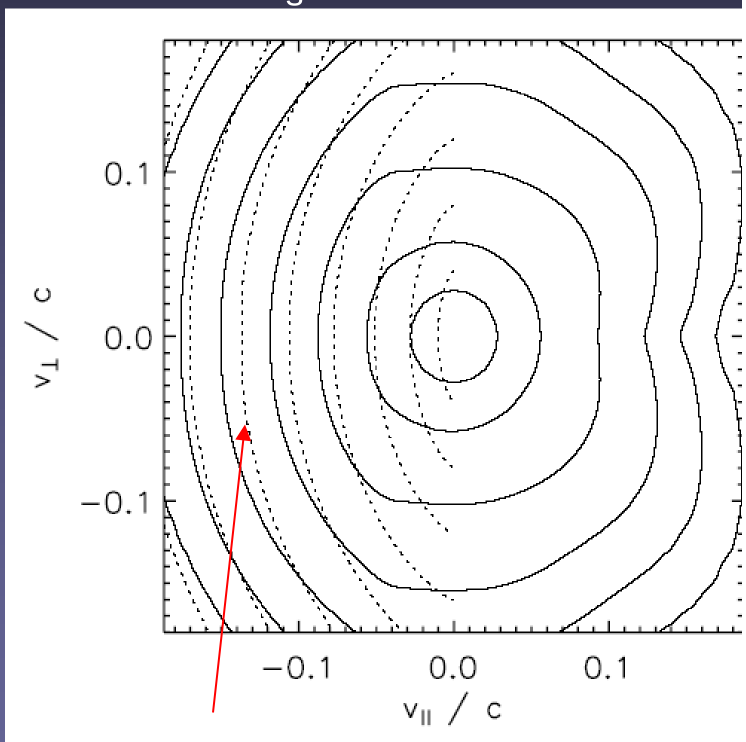
Electron pitch-angle scattering in the whistler wave field

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

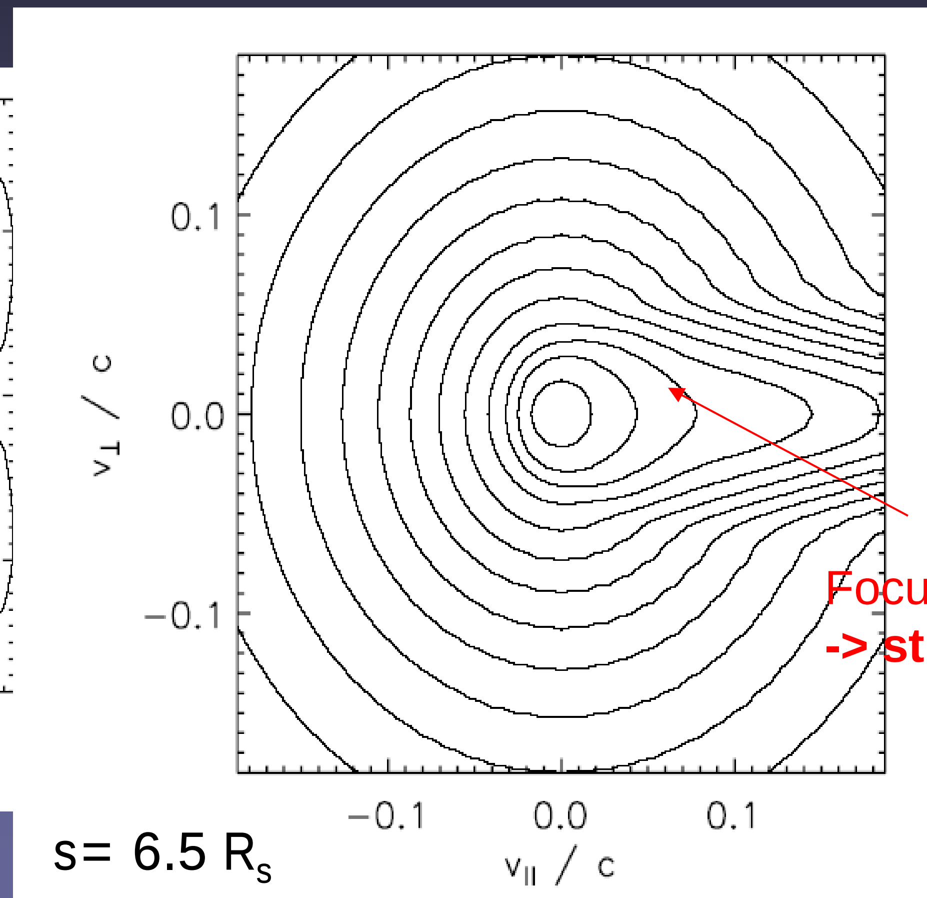
Vocks and Mann, Ap. J., **593**, 1134, 2003

Suprathermal coronal electrons caused by wave-particle interactions II

s= 0.014 R_s



Pitch-angle scattering
-> shell formation



Focusing
-> strahl

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

Conclusions

- Solar wind ion velocity distributions are shaped generally by resonant interactions with different kinds of plasma waves.
- The proton core temperature anisotropy originates from diffusion involving resonances with mostly parallel and anti-parallel uncompressive ion-cyclotron waves.
- The hot proton beam at its outer edges is shaped and confined by proton diffusion in highly oblique compressive Alfvén/ion-cyclotron waves.
- Diffusion implies inelastic scattering of protons by waves, and thus leads to turbulence dissipation.
- The electron core is shaped by Coulomb collisions and the halo and strahl are affected by whistler turbulence.