SOLAR WIND ION AND ELECTRON DISTRIBUTION FUNCTIONS AND THE TRANSITION FROM FLUID TO KINETIC BEHAVIOR

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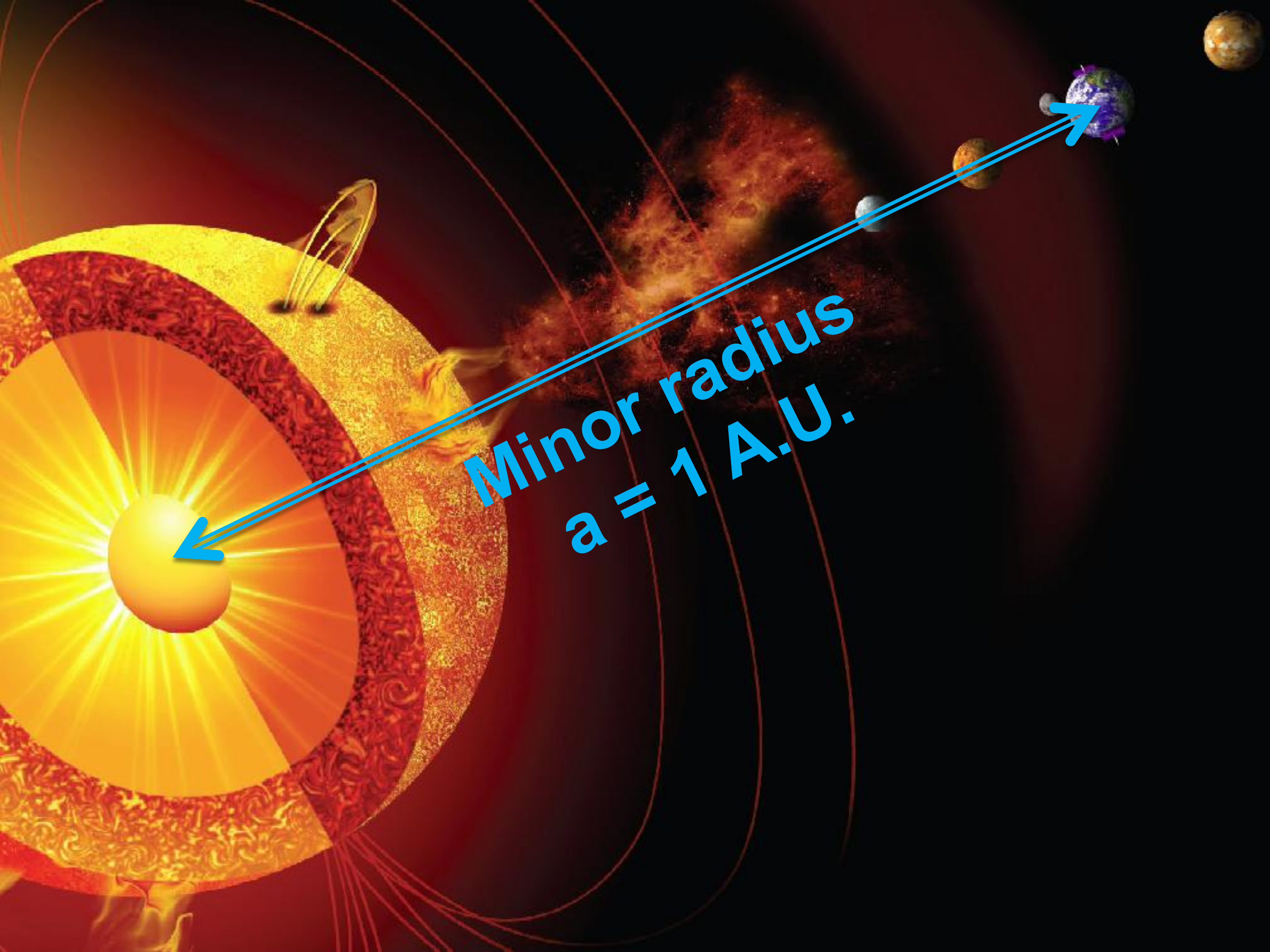
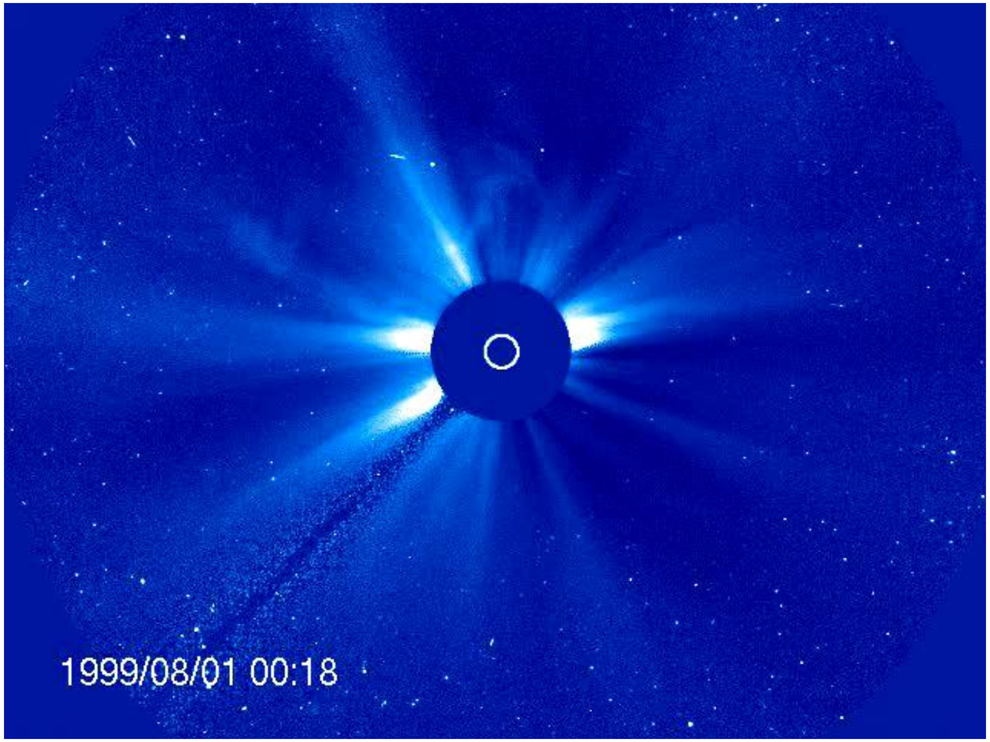
Overview

- The solar wind as a laboratory to understand plasma dynamics
  - As a function of beta
  - As a function of collision/dynamic timescales
- When can we describe these plasmas with
  - Fluid MHD (equal temperatures, velocities, …)
  - Kinetic equations (non-Maxwellian VDFs, wave-particle coupling, …)
- Example of current research
  - Instabilities
  - Ion Heating
  - Ion – Electron Interactions


Minor radius
a = 1 A.U.

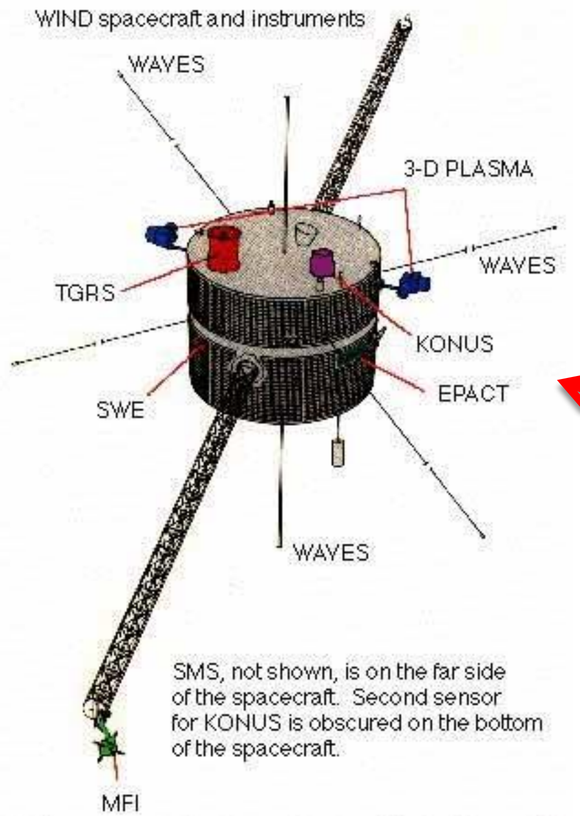
Plasma physics in the heliosphere

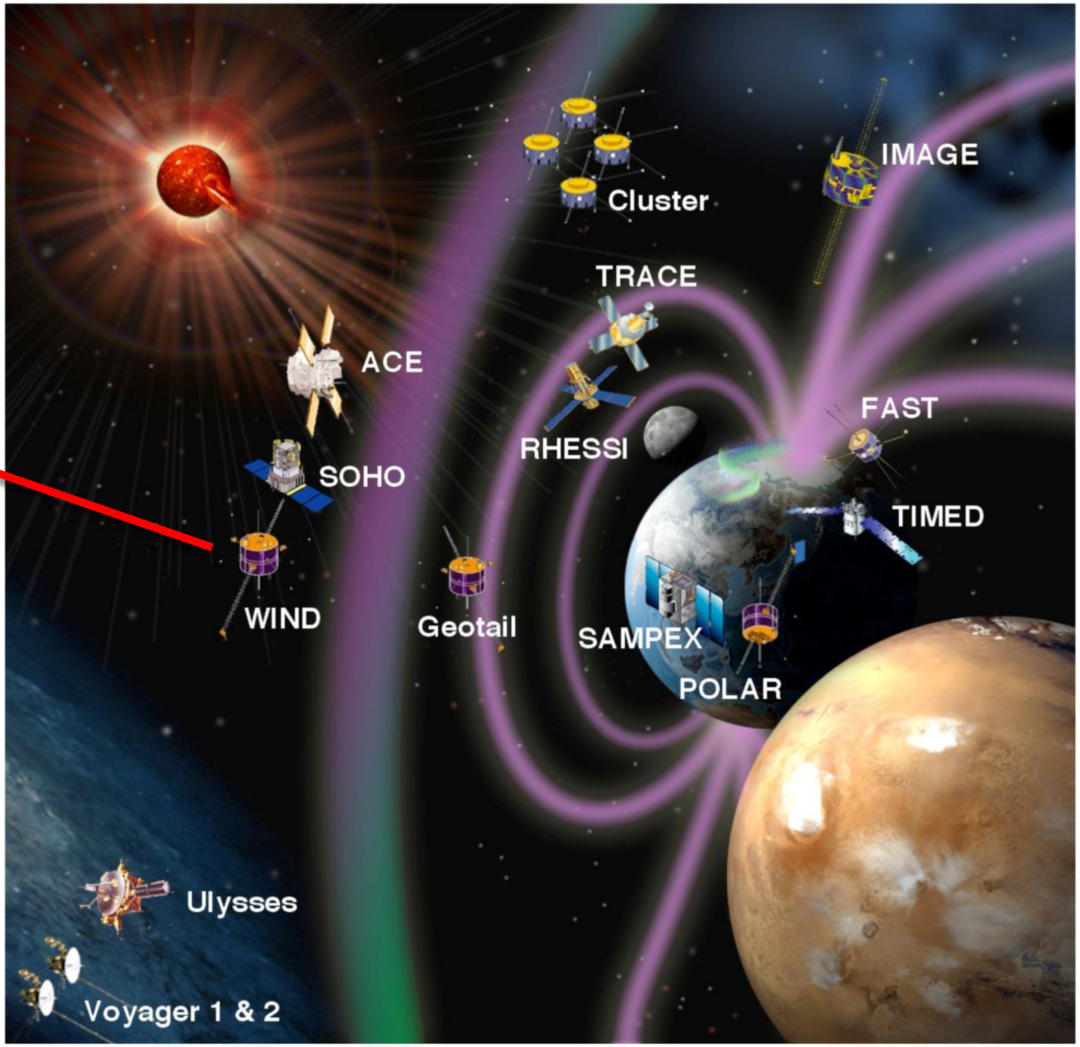


Credit: SOHO (ESA/NASA)

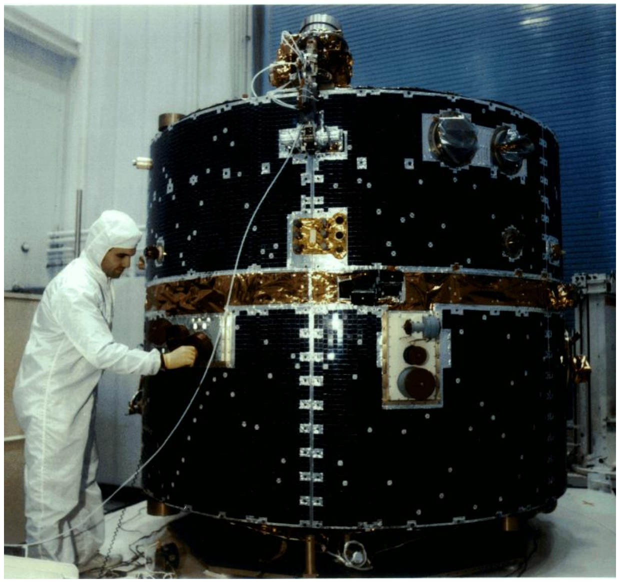
- The corona is not in hydrostatic equilibrium and a supersonic solar wind is generated. The solar wind is highly structured, with streams and shocks
- In interplanetary space, our spacecraft are much smaller than the Debye length, so we can measure the VDFs of ions and e-'s.
- We cannot prepare "shots", but we can treat the solar wind as an ergodic system that explores a wide range of states. Our starting point is a massive database of accessible plasma conditions

A fleet of spacecraft explore the heliosphere





The Wind spacecraft

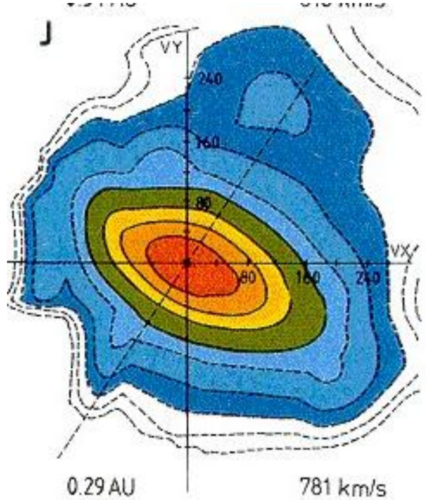


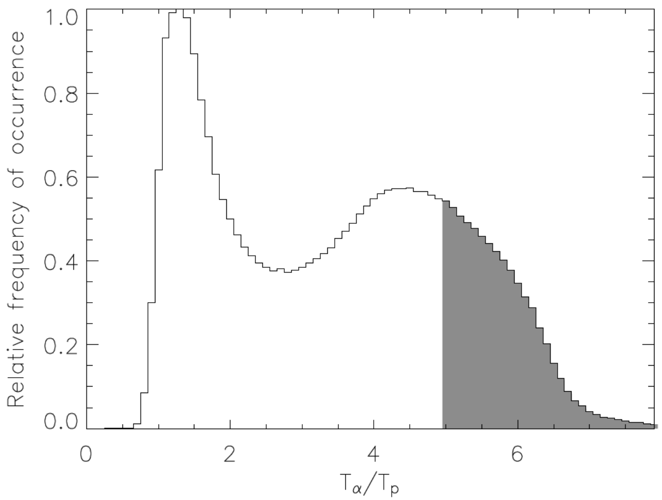
- Launched in fall 1994 and still operating
- Understand solar wind upstream of Earth
- Lots of extra fuel – new locations (L1, L2, distant prograde orbits, double lunar swing-by, …)
- Spins out of ecliptic plane at 3 seconds
- Excellent complement of stable, accurate, well-understood in situ instruments
  - Ions and Electrons (>5.3M 3D VDFs)
  - Electromagnetic fluctuations

Kinetic physics of the solar wind

- Earliest solar wind measurements showed that ion and electron velocity distribution functions (phase space density) are almost, but not quite, Maxwellian
- What keeps them from being Maxwellian?
  - Very low densities and high temperatures – at 1 AU a typical proton experiences a weak Coulomb interaction once per AU
  - Interactions between electromagnetic fields and particles of a particular speed, not as a fluid
- OK, then why are they even close to Maxwellian?
- Kinetic physics of the solar wind
  - When is MHD valid and when do we need to include details of the velocity distribution?
  - What are VDF signatures of wave-particle coupling, heating, dissipation, acceleration?
  - Testing and pushing theory with large and accurate samples of the solar wind (millions of individual spectral measurements)

Schwen and Marsch

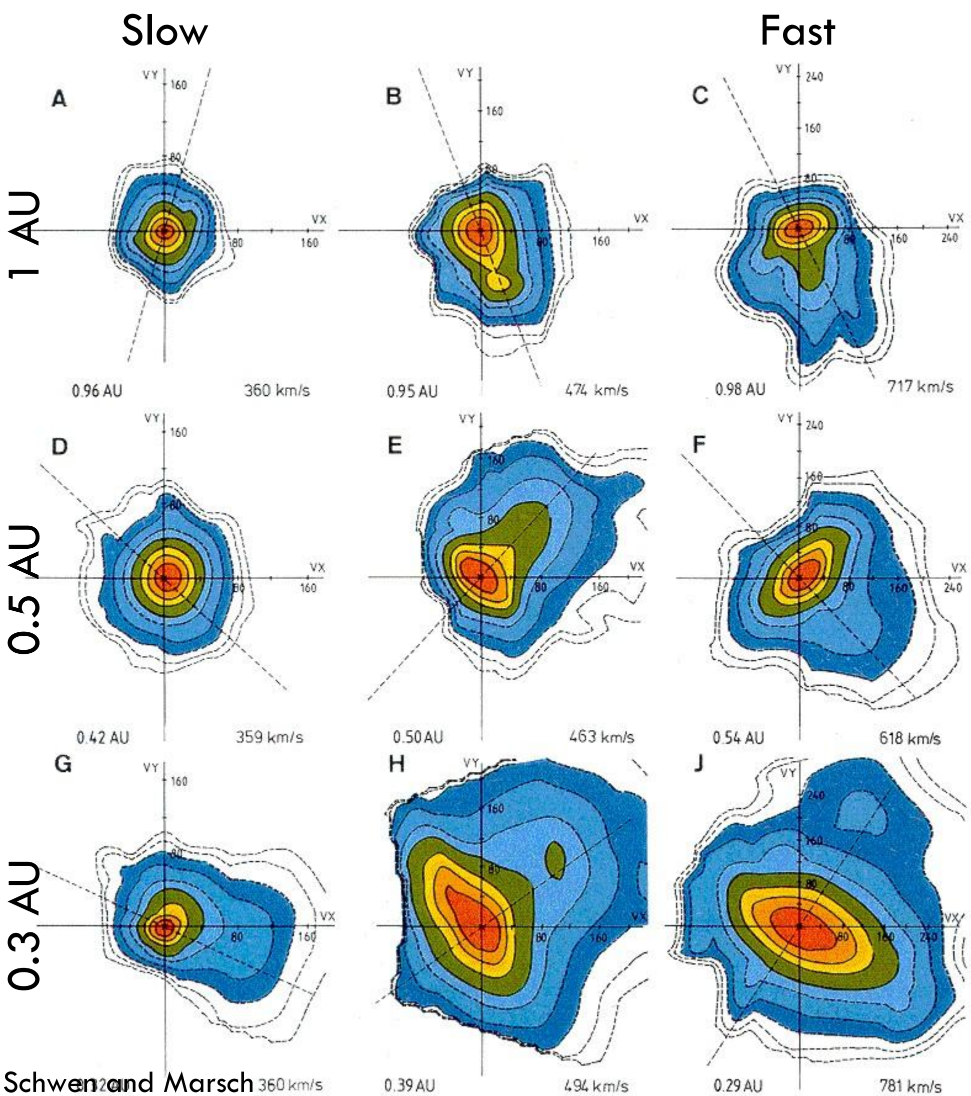




Kasper et al., 2008

Collisional relaxation in the solar wind

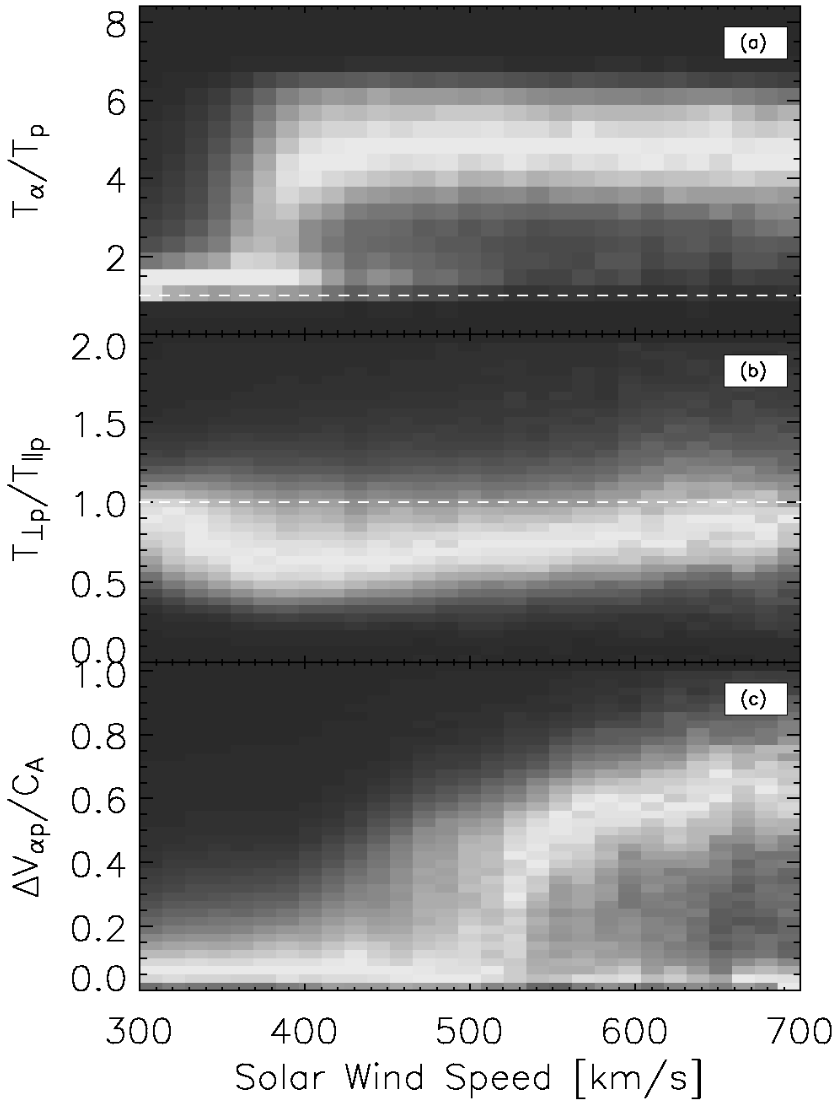
Kinetic properties of the solar wind



Schwenn and Marsch

- Kinetic or non-thermal features
  - Field-aligned anisotropies
  - Beams
  - Different temperatures
- Evolution
  - Stronger closer to Sun
  - Stronger in fast wind
- Paradigm
  - Slow wind is Maxwellian and behaves as single fluid
  - Fast wind has strong non-thermal aspects
  - Slow/fluid, Fast/kinetic

Kinetic properties ordered by speed



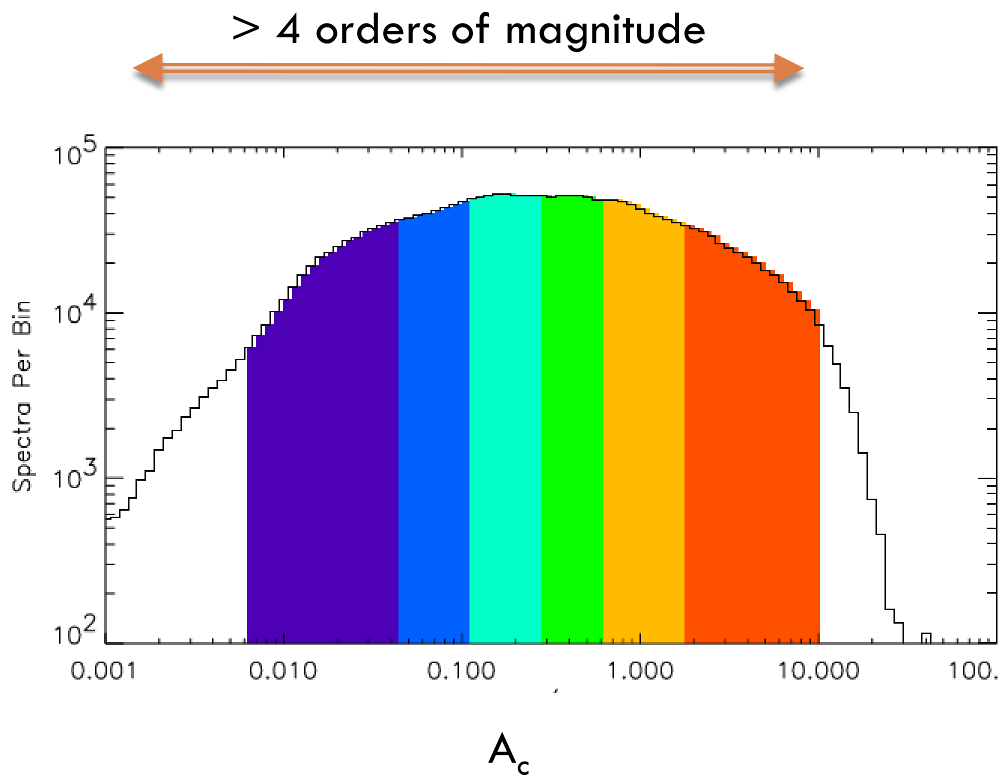
- Consider three non-thermal effects:
  - Alpha/proton temperature ratio
  - Proton temperature anisotropy
  - Differential flow
- 2D histograms of these parameters as a function of solar wind speed
- Clearly some dependence on speed
- But why sort by speed? Consider a thermalization timescale instead.

Coulomb collisional age

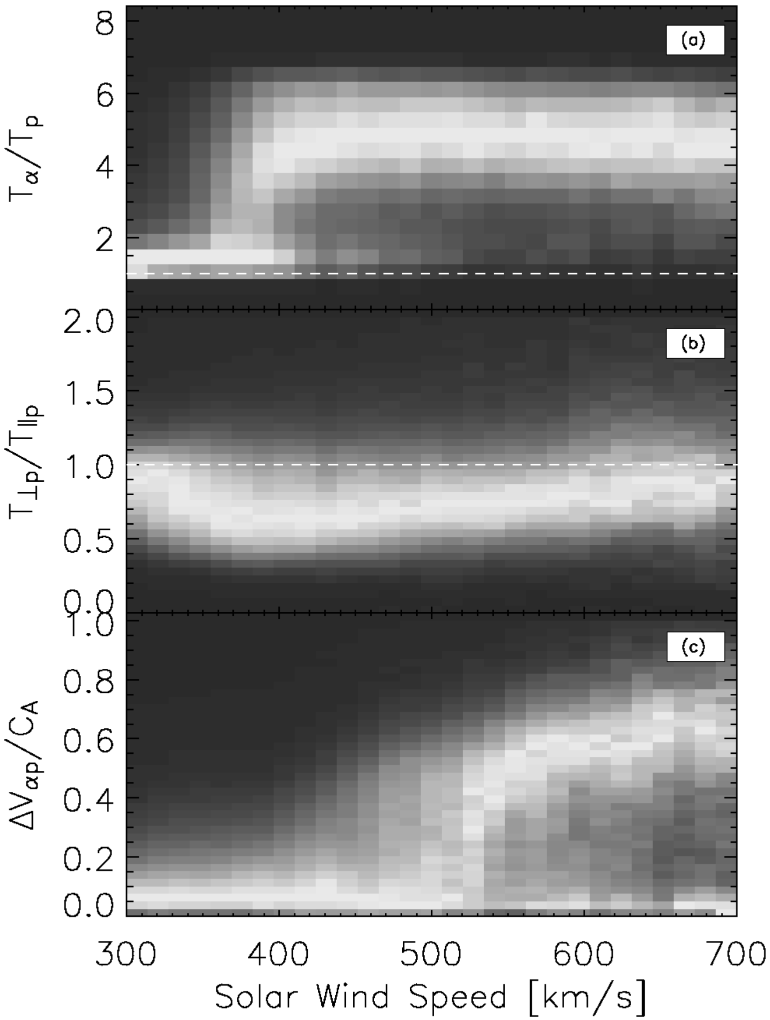
- Coulomb collisional age A_c is the number of Coulomb collisions experienced by typical particle over propagation from Sun

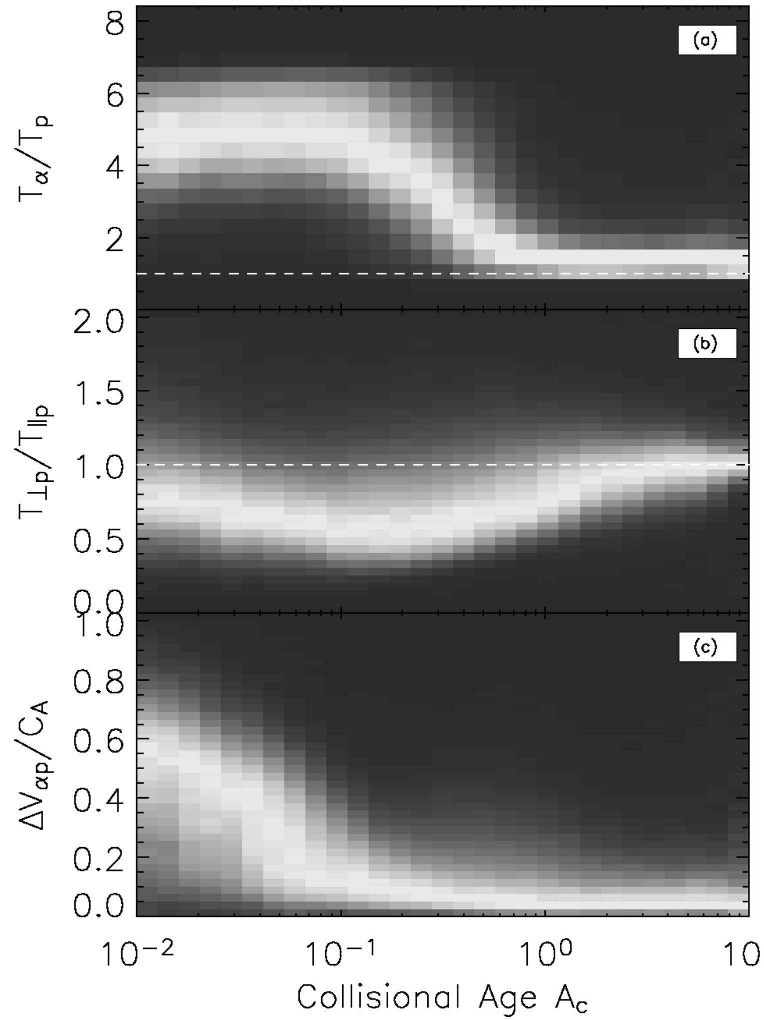
$$A_c \propto \frac{R}{U} \frac{n}{T^{3/2}}$$

  - Fast wind is hotter and less dense
- Previous work has shown that large A_c leads to smaller differential flow and $T_p \sim T_\alpha$ (Mckenzie 1987, Marsch 1983, Neugebauer 1976)



Wind speed or collisional age?



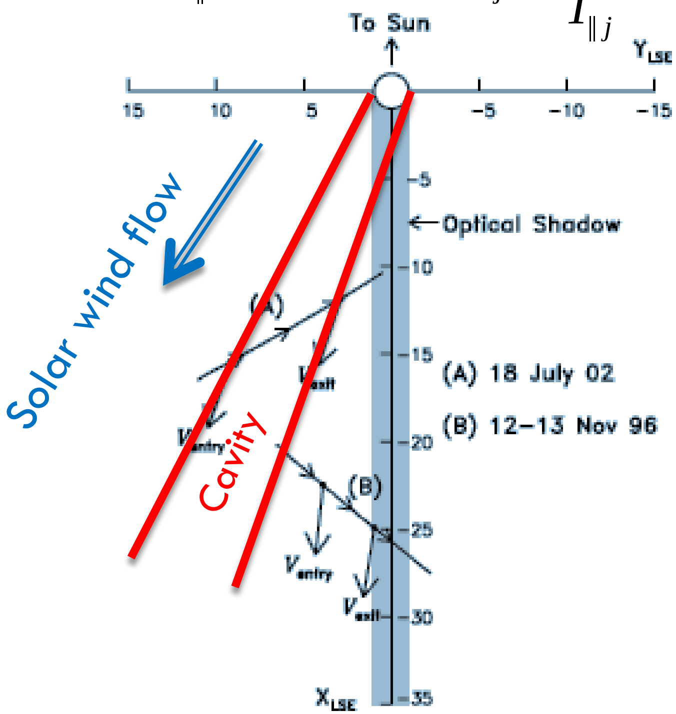


Proton temperature anisotropy

What regulates temperature anisotropy?

- Double adiabatic expansion
  (Chew, Goldberger & Low, 1965)

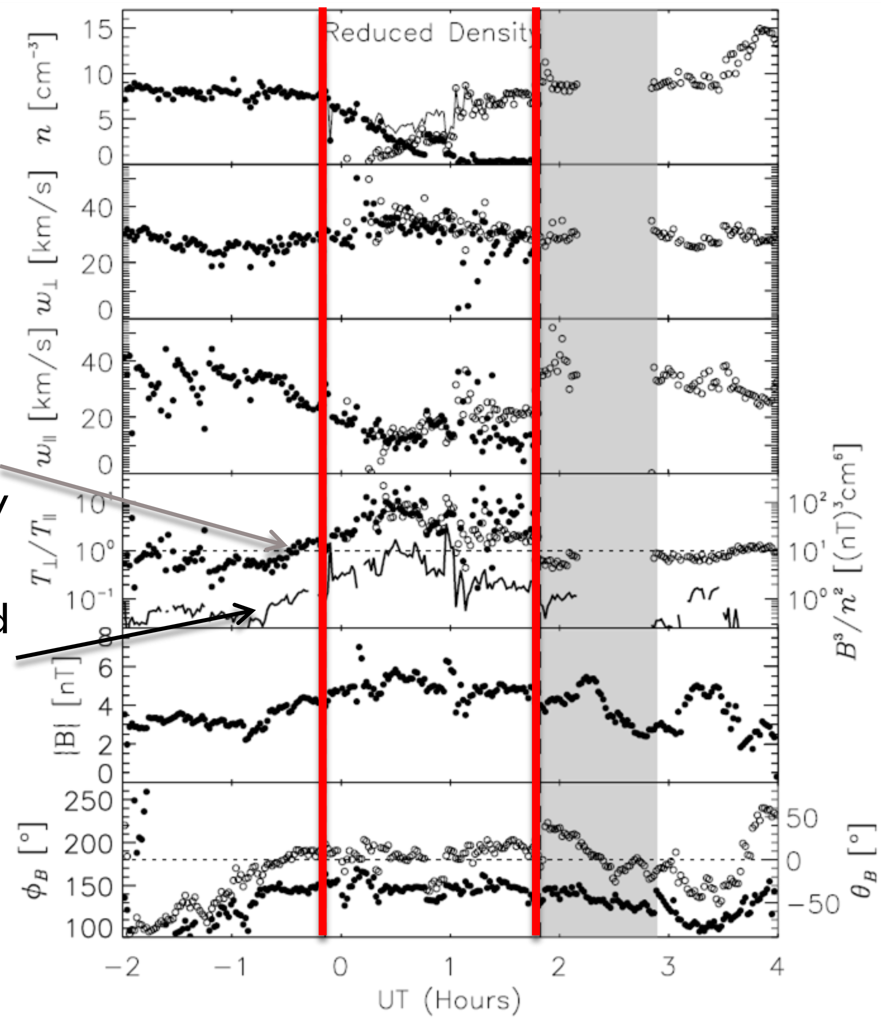
$$T_\perp \propto B, T_\parallel \propto n^2/B^2 \rightarrow R_j \equiv \frac{T_{\perp j}}{T_{\parallel j}} \propto \frac{B^3}{n^2}$$



Clack et al., 2003

Measured anisotropy

Predicted variation



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- Coulomb relaxation

$$A_c \propto \frac{n}{T^{3/2}}$$

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- Instabilities (Gary, Vinas, Hellinger, Marsch)
  - Firehose

$$R_p > 1 - \frac{S_p}{\beta_{\parallel p}{}^{\alpha_p}}$$

  - Cyclotron, Mirror

$$R_p < 1 + \frac{S_p}{\beta_{\parallel p}{}^{\alpha_p}}$$

If R_p exceeds threshold, instability begins to grow, generating waves that make the velocity distribution function more isotropic

The larger the anisotropy, the stronger the wave growth and scattering

"Instability Limit" is curve for a predefined growth rate of the instability

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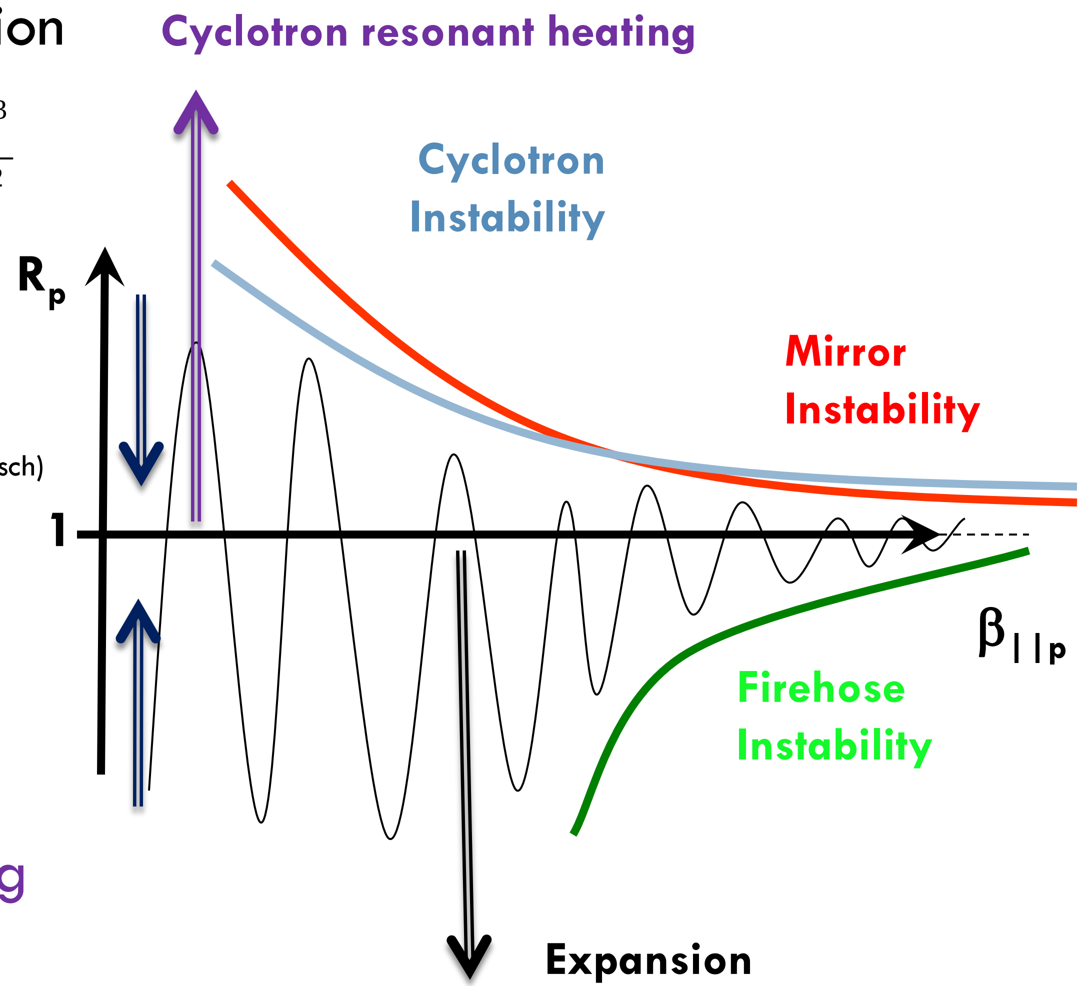
  - Mirror, Cyclotron

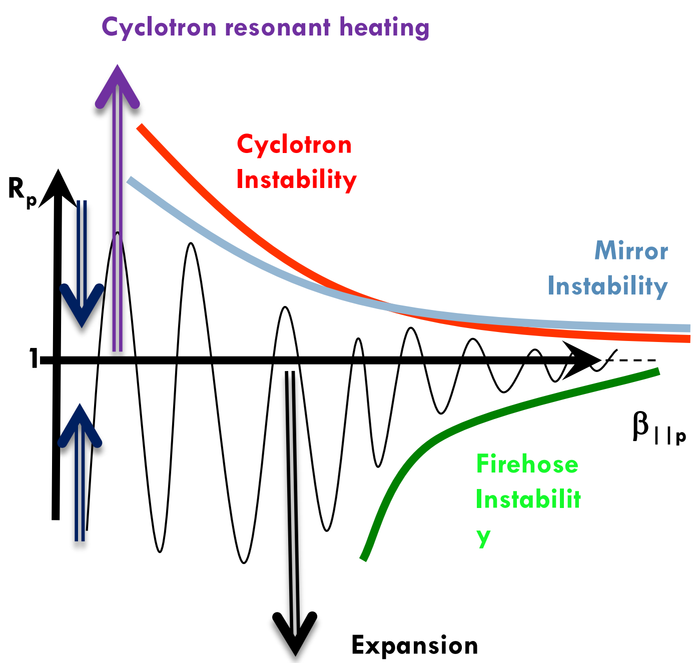
$$R_p < 1 + \frac{S_p}{\beta_{\parallel p}^{\alpha_p}}$$

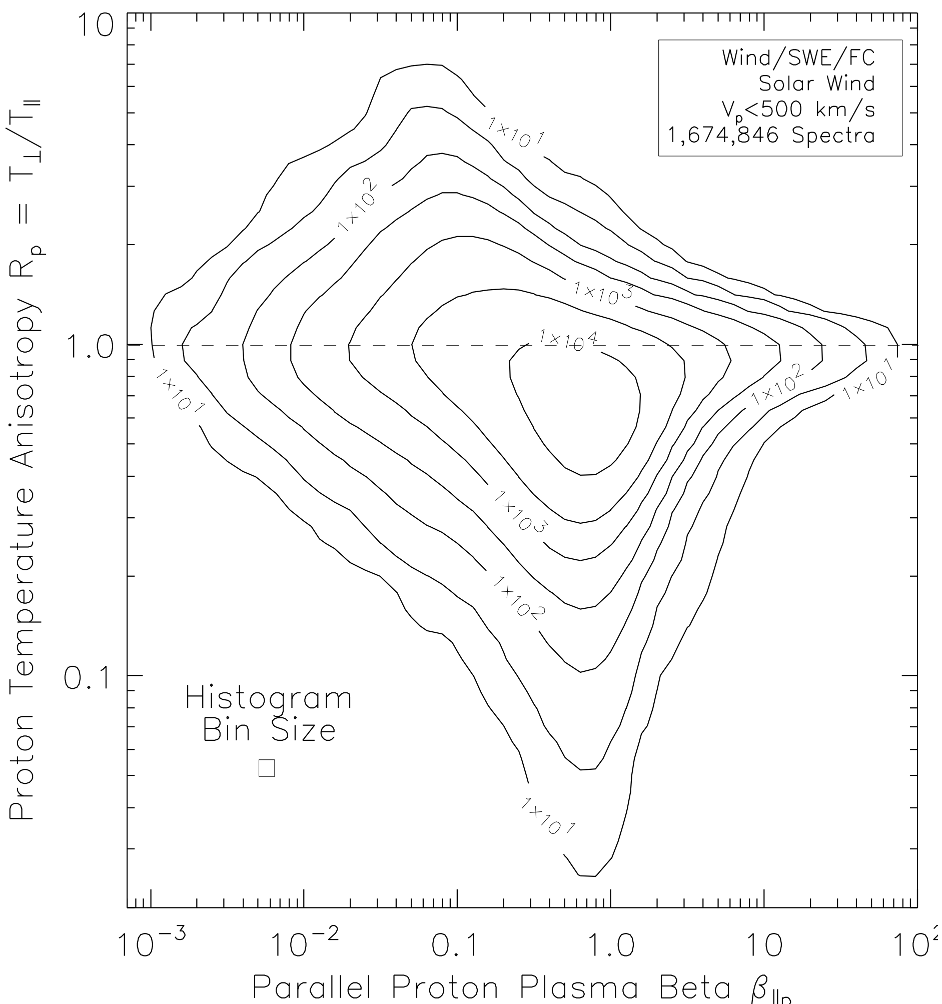
- Cyclotron-resonant heating

$$R_p > 1$$



Distribution of observed anisotropy at 1 AU





Kasper et al., 2003

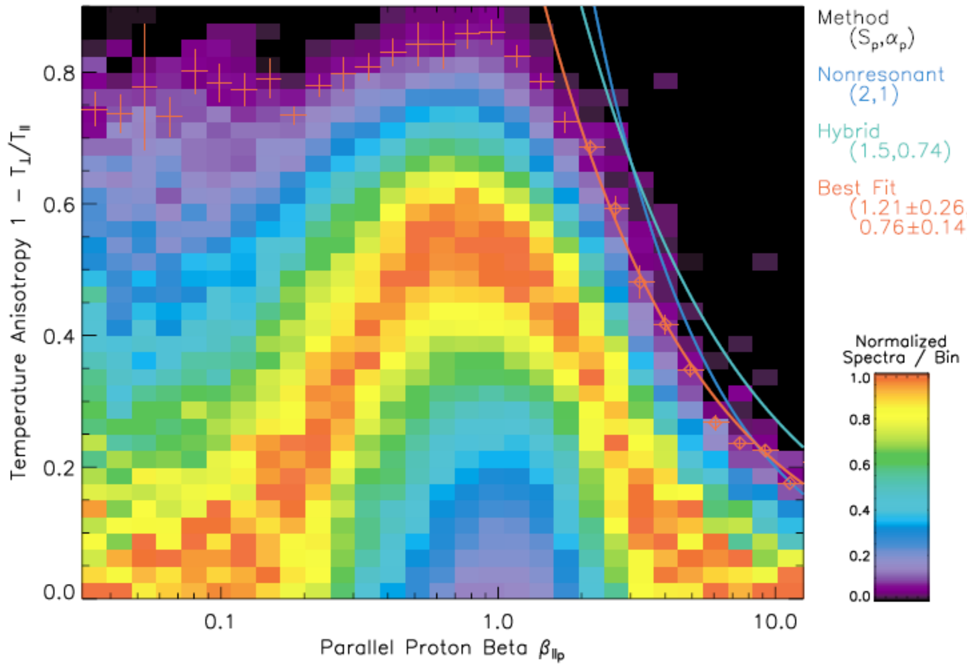
Range of anisotropy limited by instabilities

$$R_p > 1 - \frac{S_p}{\beta_{\parallel p}^{\ \alpha_p}}$$

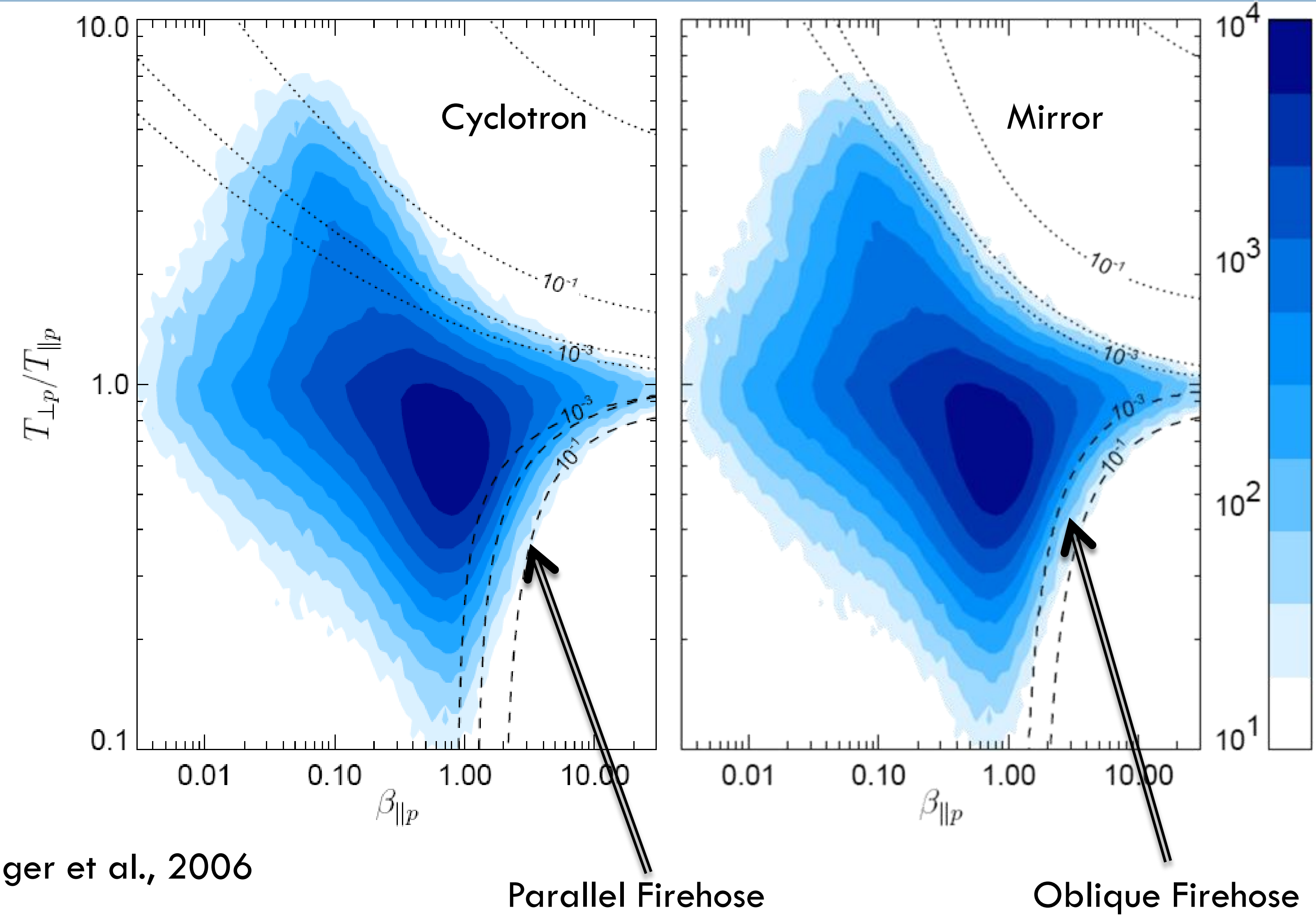
$$R_p < 1 + \frac{S_p}{\beta_{\parallel p}^{\ \alpha_p}}$$

Instability	S_p	α_p	Comments	
Mirror				
	1	1	MHD (3.13)	[(
	0.87	0.56	$\gamma_m = 0.1\Omega_p, 5 \leq \beta_{\parallel p} \leq 50$	
Cyclotron				
	0.35	0.42	$\gamma_m = 10^{-4}\Omega_p, 0.01 \leq \beta_{\parallel p} \leq 10$	
	0.43	0.42	$\gamma_m = 10^{-3}\Omega_p, 0.01 \leq \beta_{\parallel p} \leq 10$	
	0.65	0.40	$\gamma_m = 10^{-2}\Omega_p, 0.01 \leq \beta_{\parallel p} \leq 10$	
	0.55	0.51	1D Hybrid, Active ($\gamma \geq 10^{-3}$)	
	0.41	0.44	1D Hybrid, All Results	
	0.85	0.48	AMPTE/CCE Observations	[Anderson et al., 1994]
	0.58	0.53	AMPTE/IRM Observations	[Phan et al., 1994]
Firehose				
	2	1	MHD (3.14)	[Parker, 1958a]
	0.61	0.63	$\gamma_m = 10^{-3}\Omega_p, 2 \leq \beta_{\parallel p} \leq 100$	[Gary et al., 1998]
	0.90	0.72	$\gamma_m = 10^{-2}\Omega_p, 2 \leq \beta_{\parallel p} \leq 100$	" "
	1.53	0.74	$\gamma_m = 10^{-1}\Omega_p, 2 \leq \beta_{\parallel p} \leq 100$	" "
	1.53	0.74	1D, 2D Hybrid	" "

Kasper et al., 2003

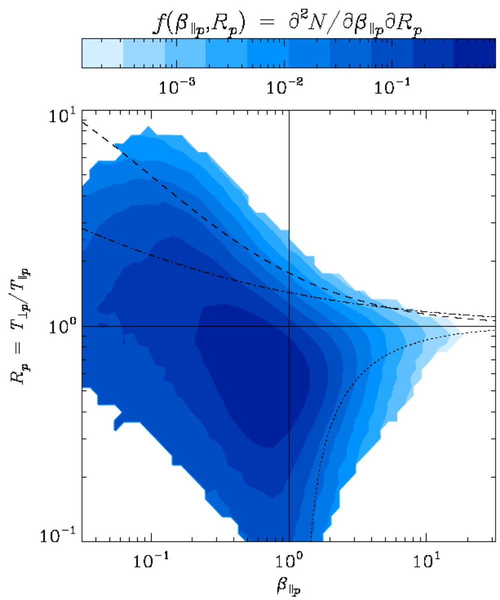


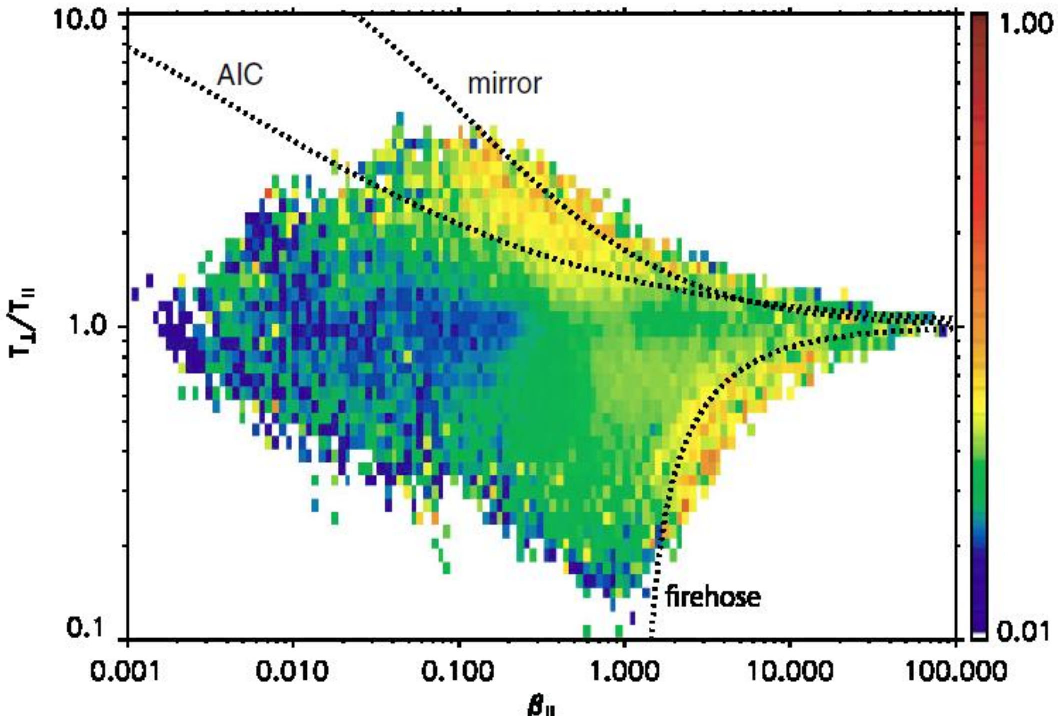
Identify the dominant instabilities using the statistical distribution of the solar wind



Hellinger et al., 2006

Power in magnetic fluctuations

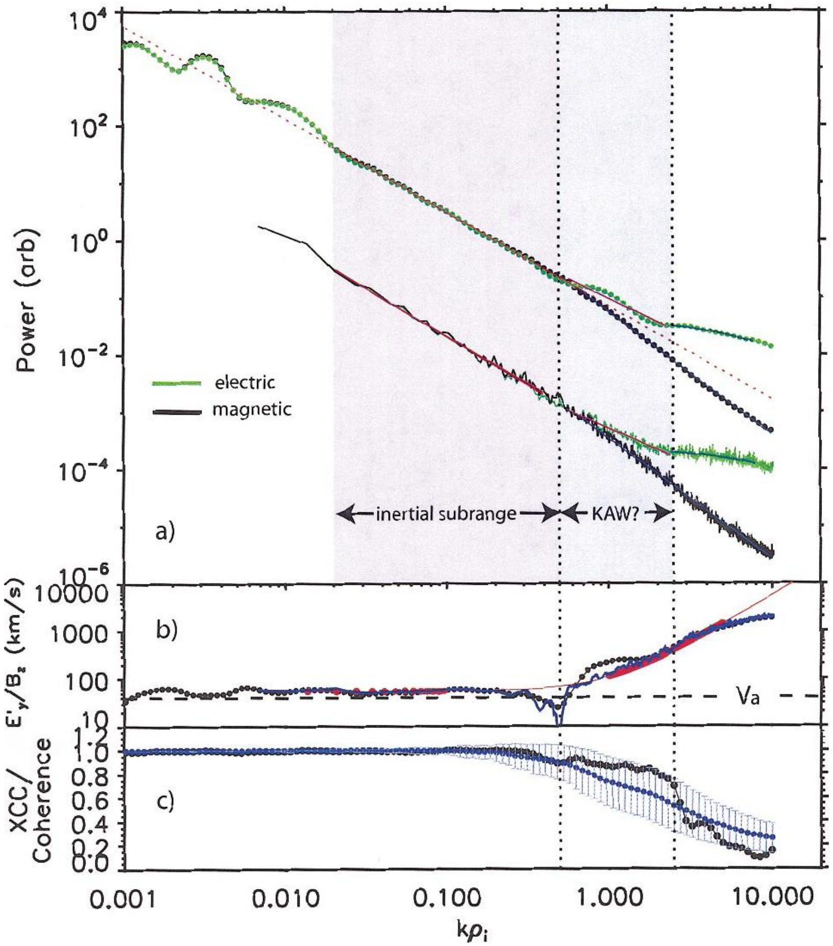




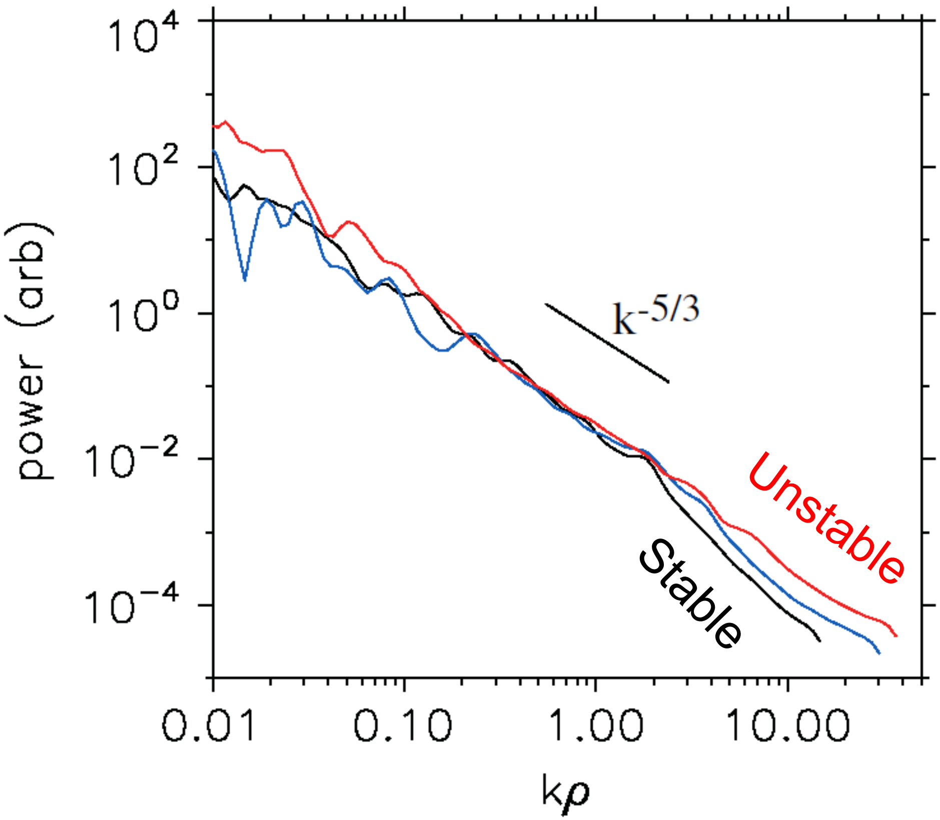
Bale et al. (2009)

- Instabilities should generate EM waves
- Look at average power of magnetic fluctuations across R_p-$\beta_{||p}$ plane

Multiple sources of power at small scales



Bale et al. (2005)

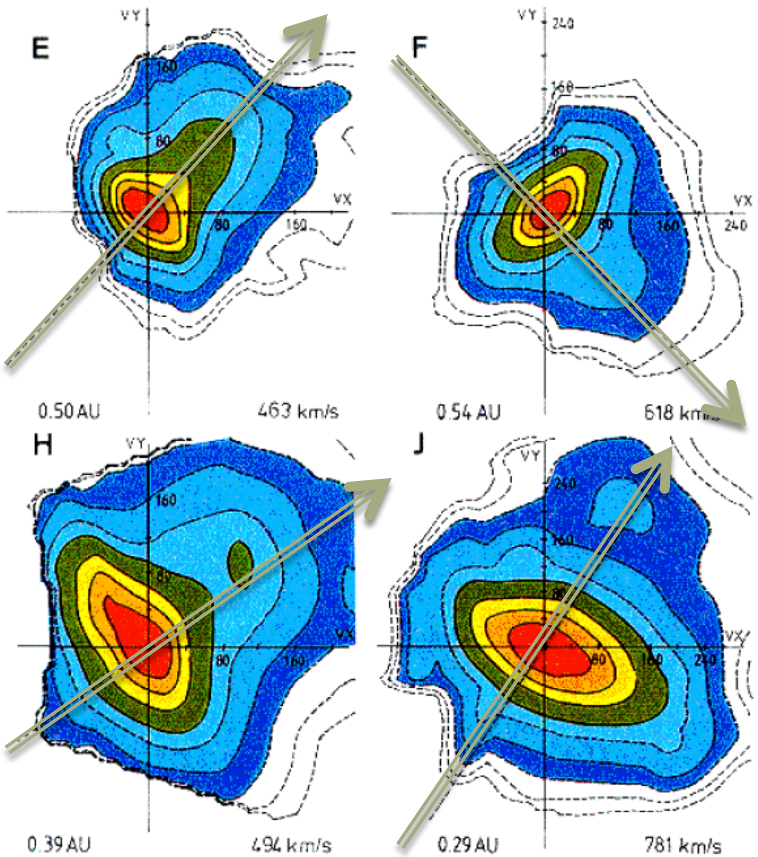


Bale et al. (2009)

Anisotropic heating of protons

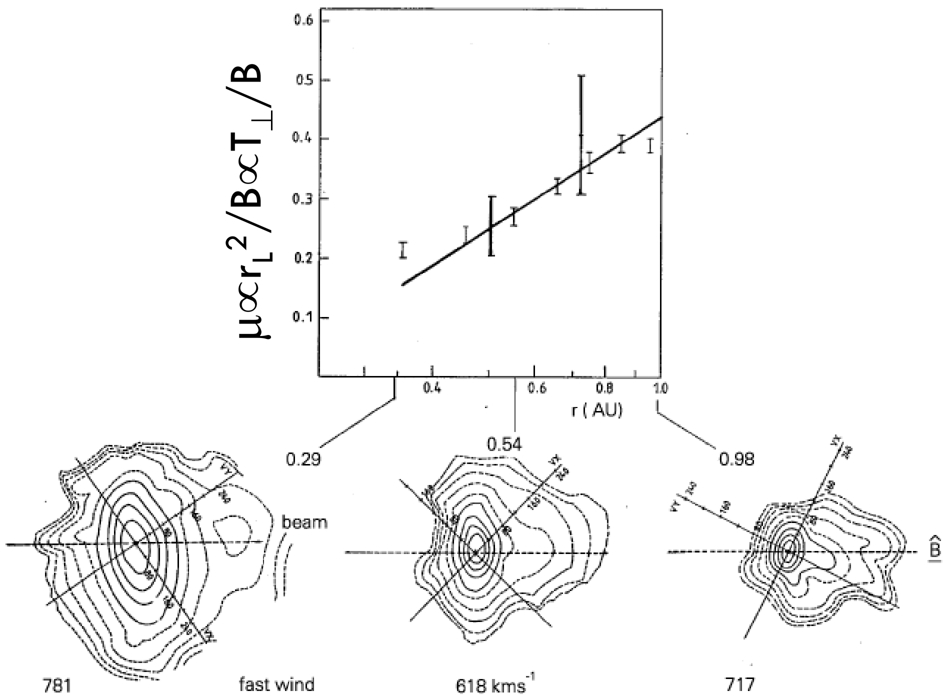
In situ signatures of heating process

Large perpendicular temperature anisotropies



Marsch et al., 1982

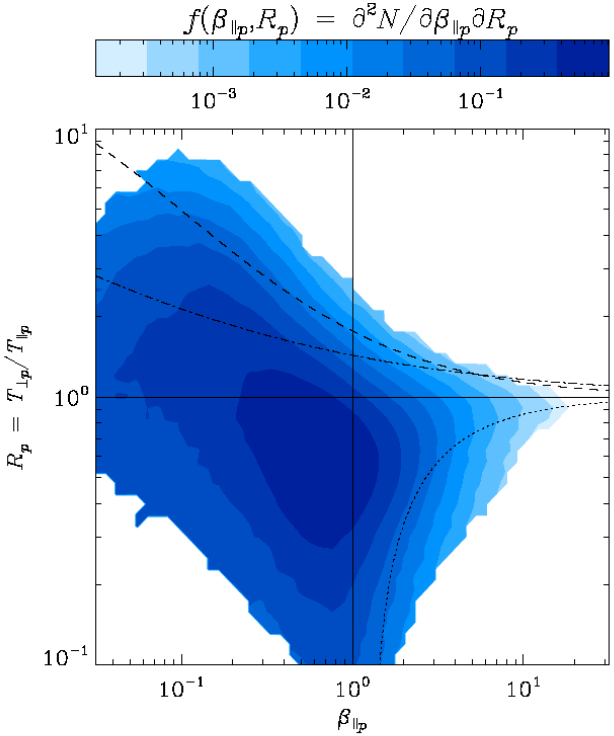
Proton magnetic moment not conserved as the solar wind expands

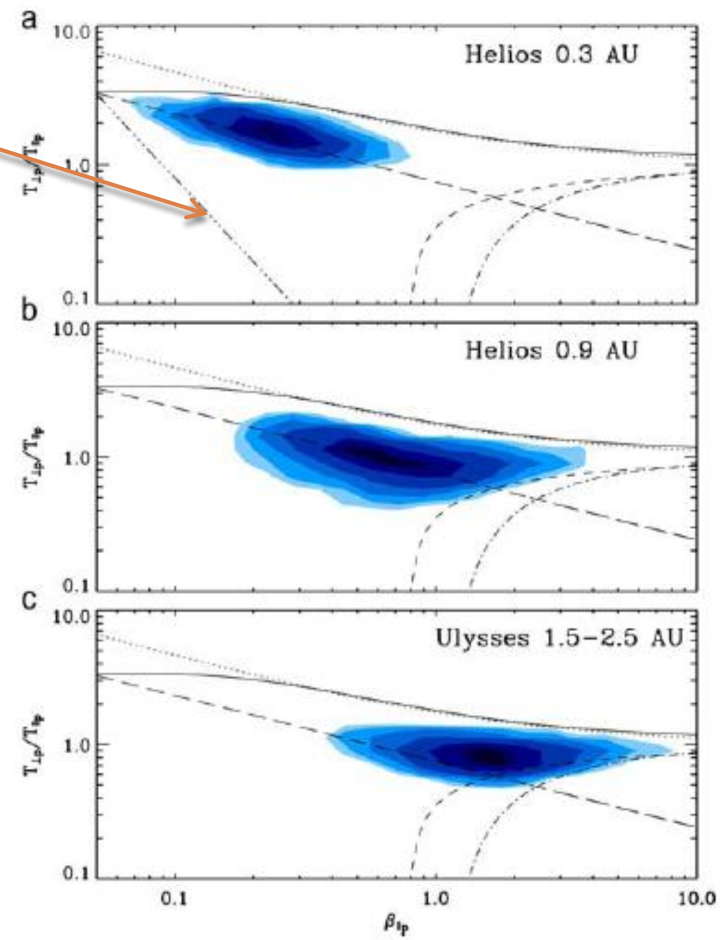


Marsch, 1991

Radial evolution and heating

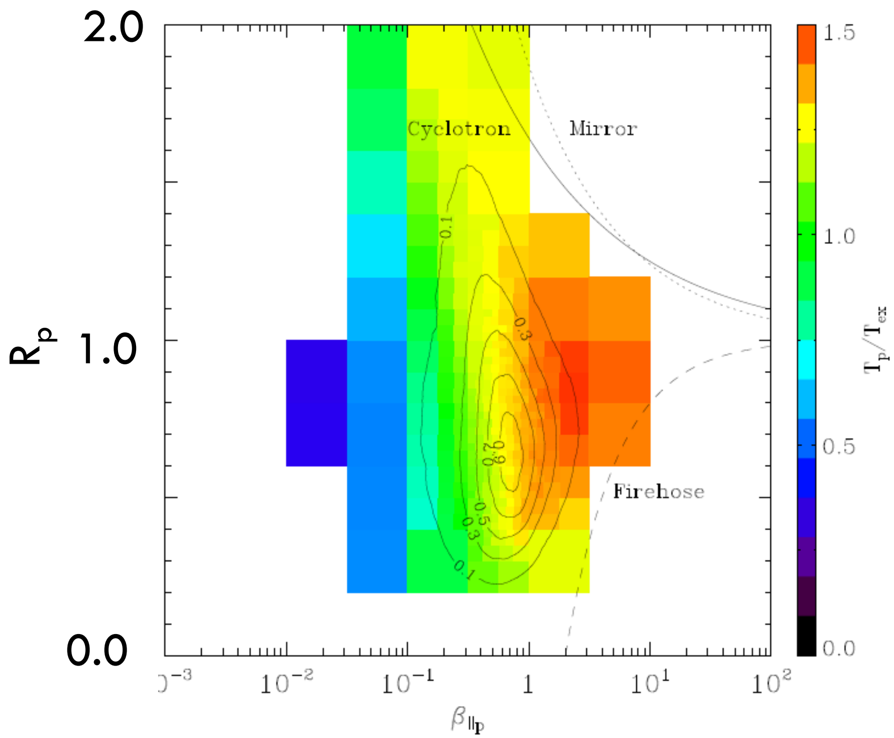
$$T_\perp \propto B, T_\parallel \propto n^2 / B^2 \rightarrow R_j \propto \frac{B^3}{n^2}$$



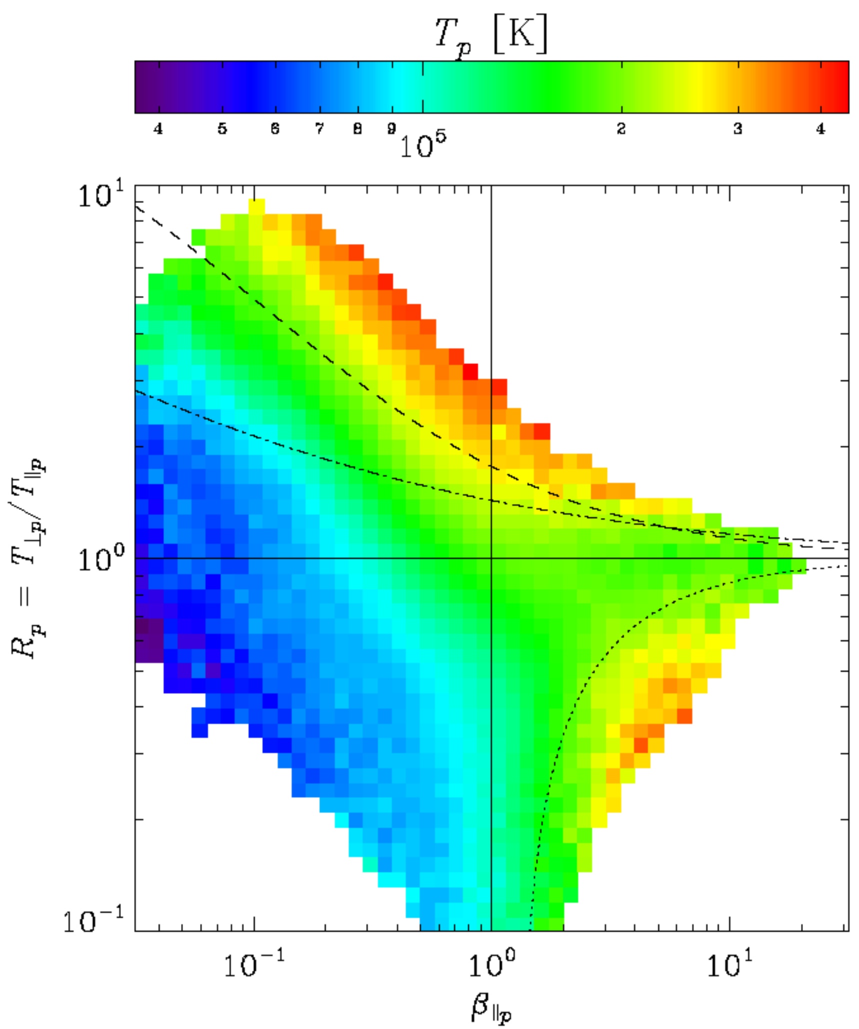


Matteini et al., 2007

Proton temperature near instability thresholds

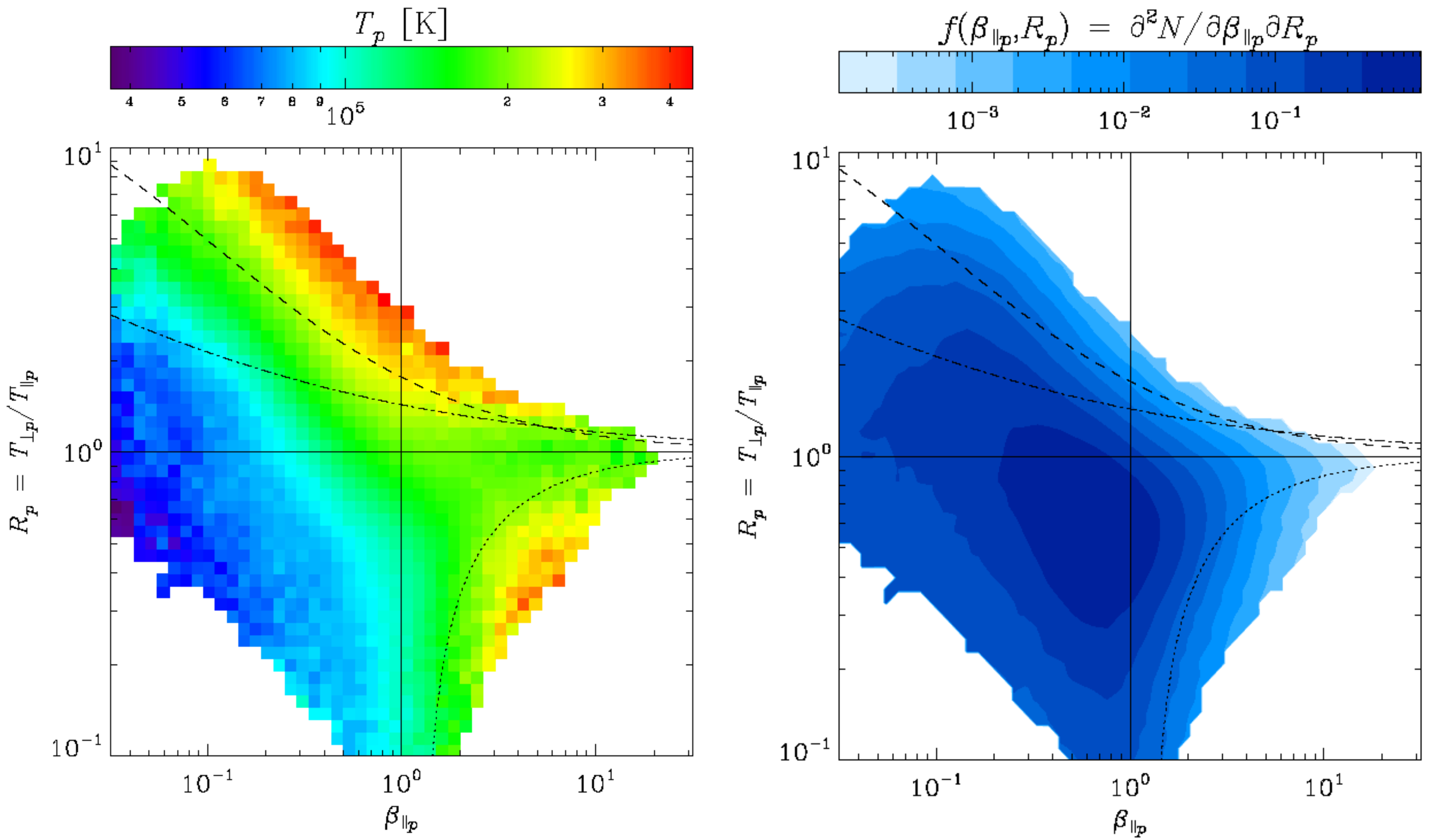


Liu et al. (2006)

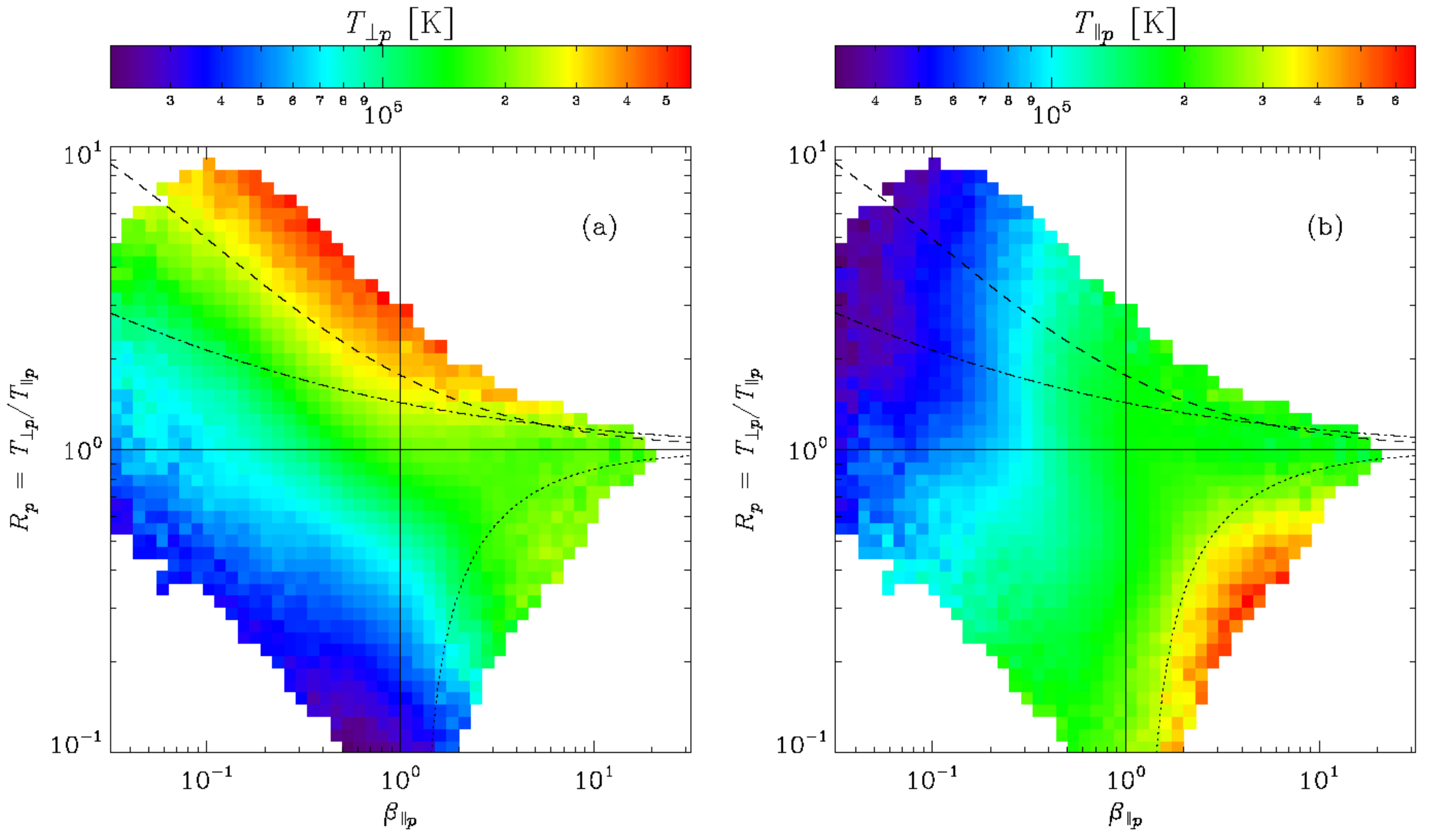


Maruca et al. (2009)

Proton temperature near instability thresholds



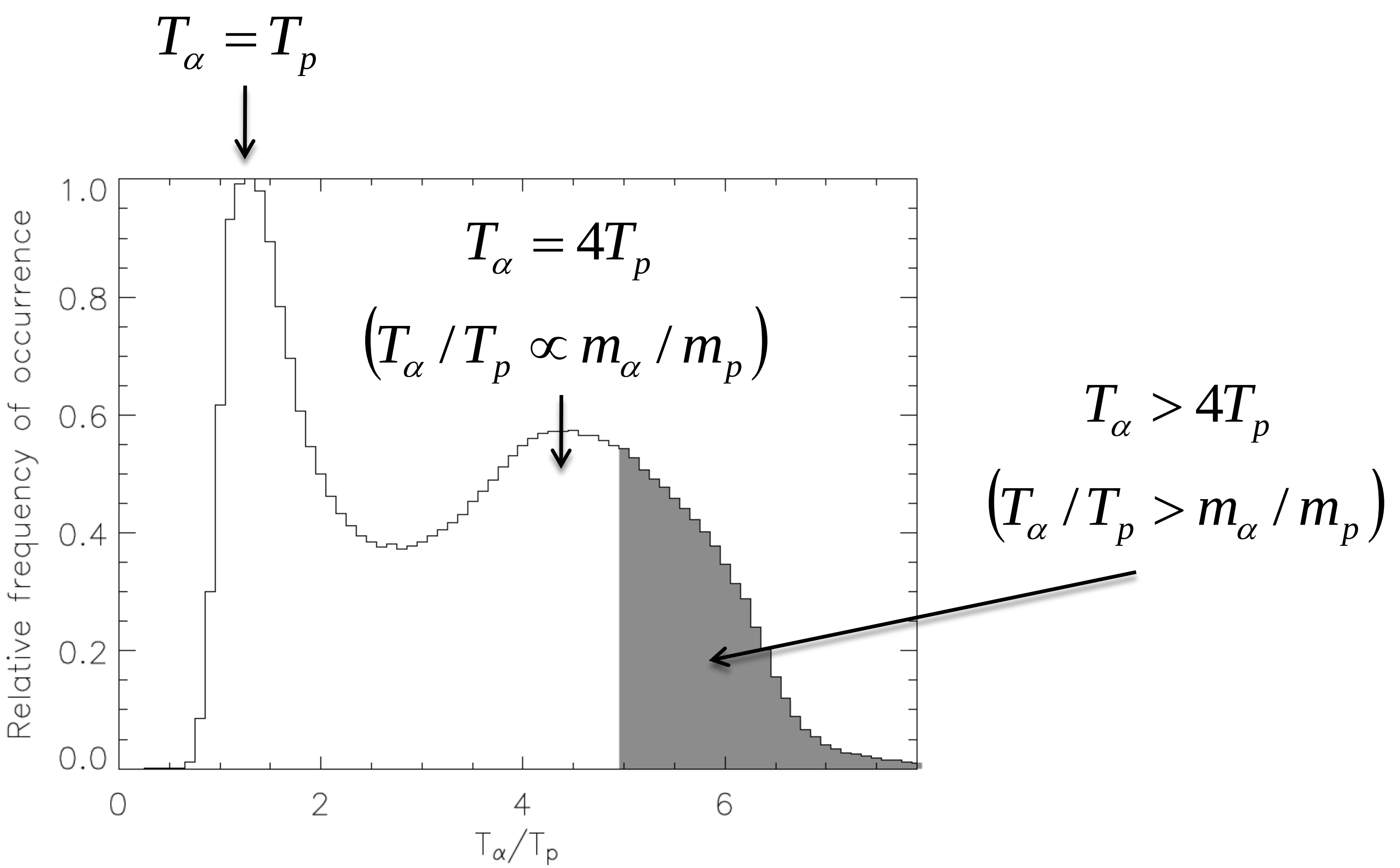
Components of proton temperature near instability thresholds



Kasper et al. (in prep)

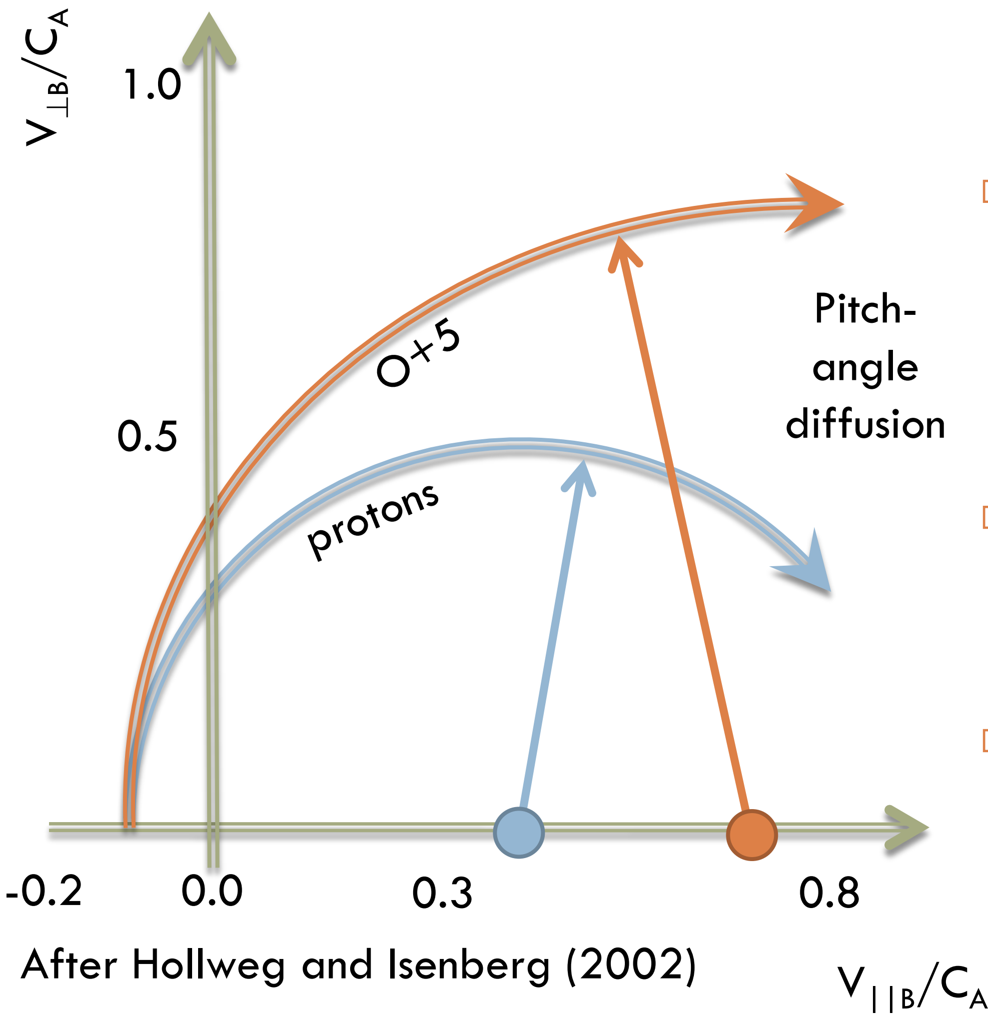
Relative heating of ions

Helium/hydrogen temperature ratio



Kasper et al. (2008)

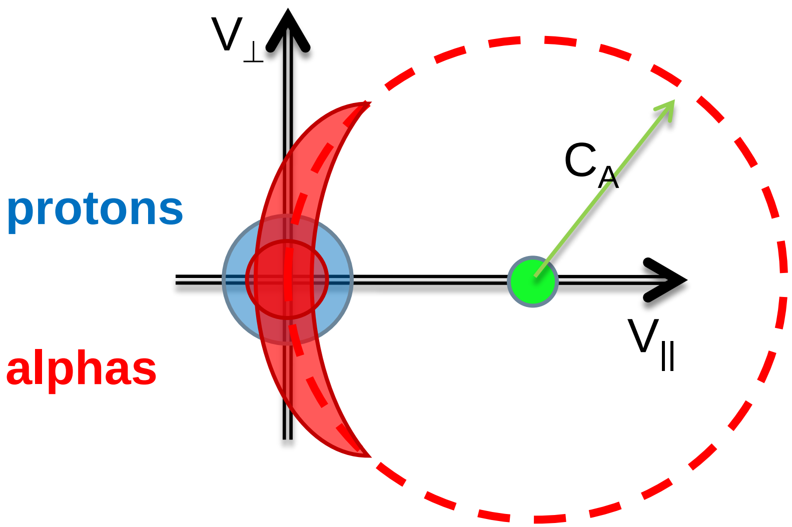
The Alfven-Cyclotron Resonant Interaction



After Hollweg and Isenberg (2002)

- Turbulence in the corona and solar wind transports power to shorter scales, creating a spectrum of Alfven waves
- Several models of dissipation have focused on the absorption of Alfven-cyclotron fluctuations in a plasma with multiple ion species (Hu 1999, Cranmer 2003, Hellinger 2005, Isenberg 2007)
- In a frame moving with the wave, particles will stochastically diffuse along the surface $v_{||B}^2 + V_{\perp B}^2 =$ const
- Heavier ions resonate with slightly faster waves so if diffusion is sufficiently fast a heavy ion can achieve $T_{\perp i}>(m_i/m_p)T_{\perp p}$

Test for Alfvén-cyclotron resonant heating in a two species plasma



- Relative heating may also be regulated by differential flow (Gary 2004, Gary 2005, Hellinger 2005)
- Significant because heavier ions often flow faster than protons. In general the differential flow $\Delta V_{\alpha p}=|V_\alpha - V_p|$ reaches but rarely exceeds the Alfven speed, C_A (Neugebauer 1976, Marsch 1982, Reisenfeld 2001)
- Prediction
  - For $\Delta V_{\alpha p}/C_A \sim 0$, helium will have a stronger cyclotron resonance than hydrogen, and thus will be heated faster and develop larger temperature anisotropies.
  - On the other hand, if $\Delta V_{\alpha p}/C_A$ is increased, the helium ions come out of resonance with the waves and the protons are heated instead.

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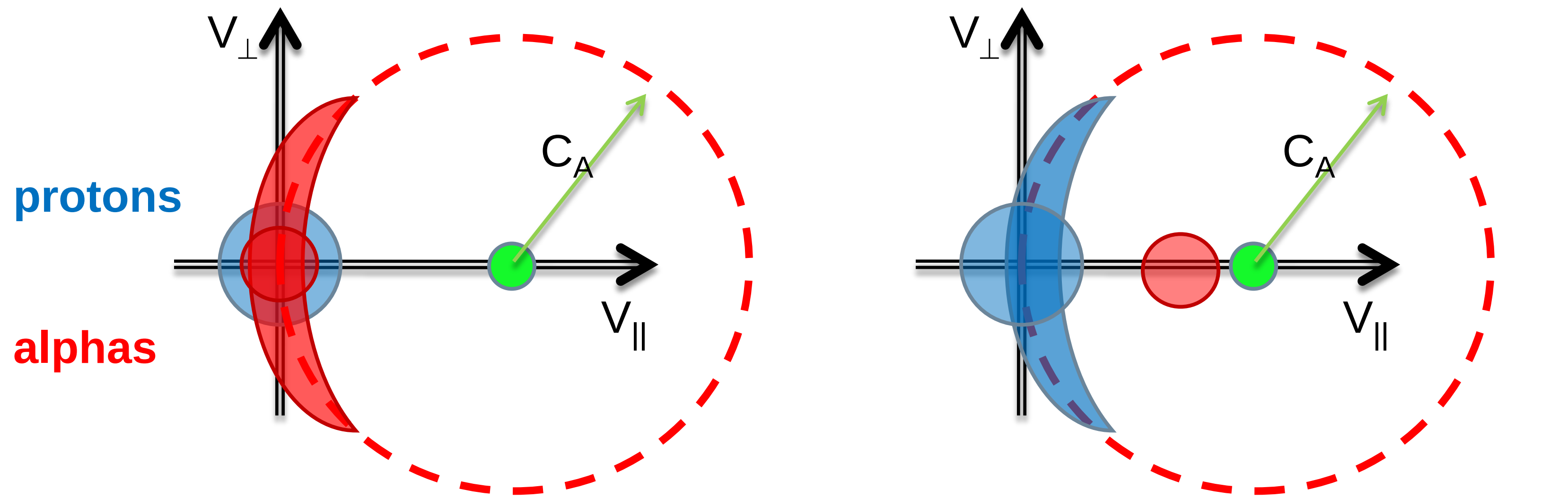

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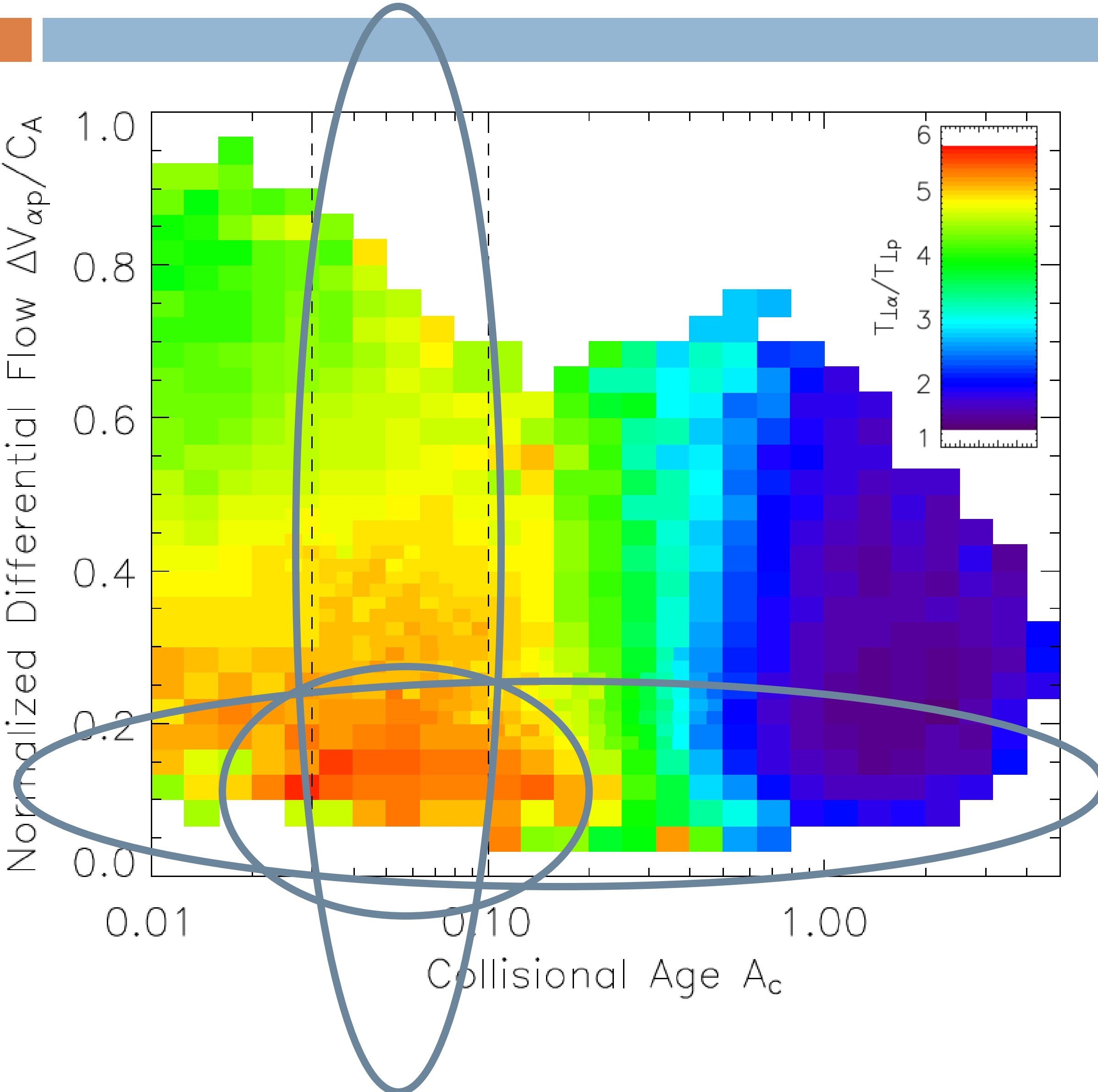
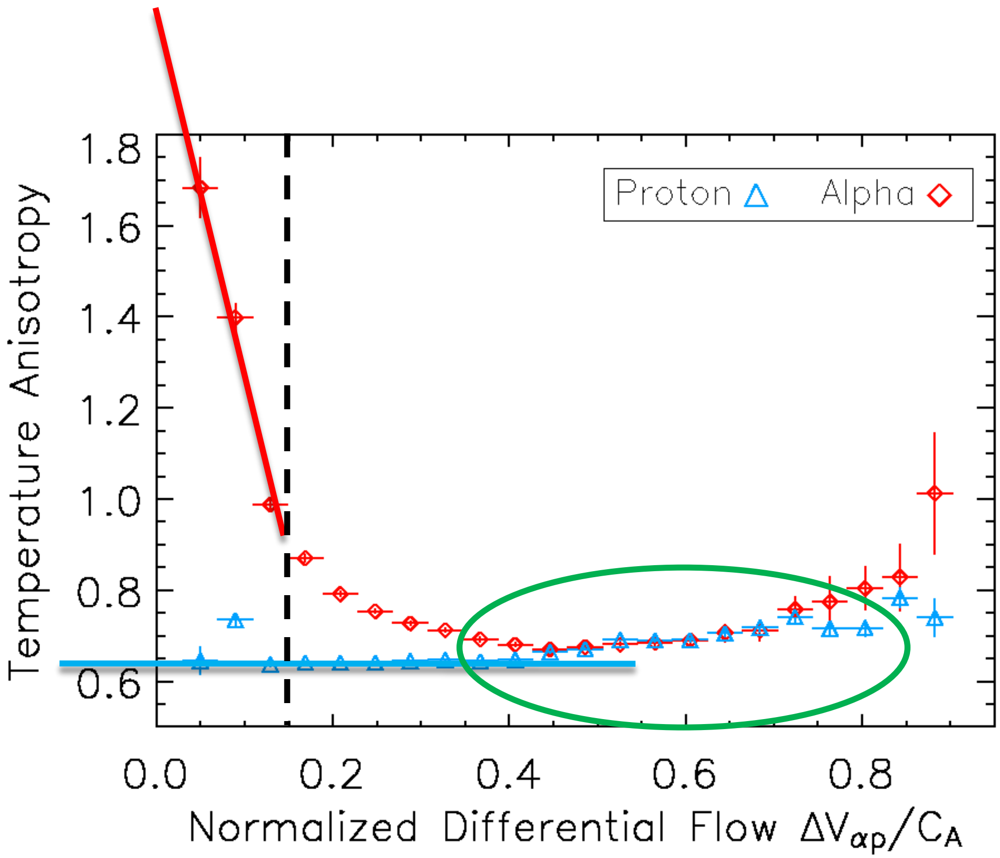
- Prediction
  - For $\Delta V_{\alpha p}/C_A < 0.15$, helium will have a stronger cyclotron resonance than hydrogen, and thus will be heated faster and develop larger temperature anisotropies.
  - On the other hand, if $\Delta V_{\alpha p}/C_A$ is increased, the helium ions come out of resonance with the waves and the protons are heated instead.

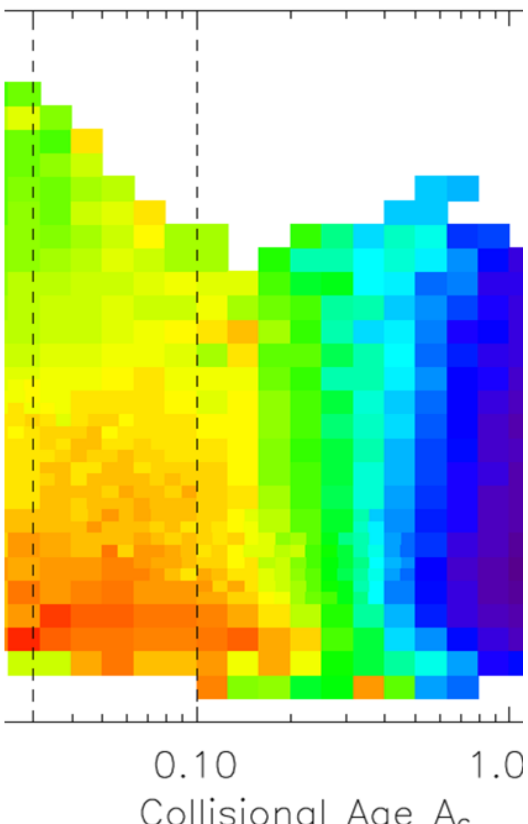
T_α/T_p as a function of A_c and $\Delta V_{\alpha p}$



- For fixed A_c, T_α/T_p increases as $\Delta V_{\alpha p}$ drops
- At small A_c and $\Delta V_{\alpha p}$, the average value of $T_\alpha/T_p \sim 6$
- In fact, higher T_α/T_p is seen even at high A_c

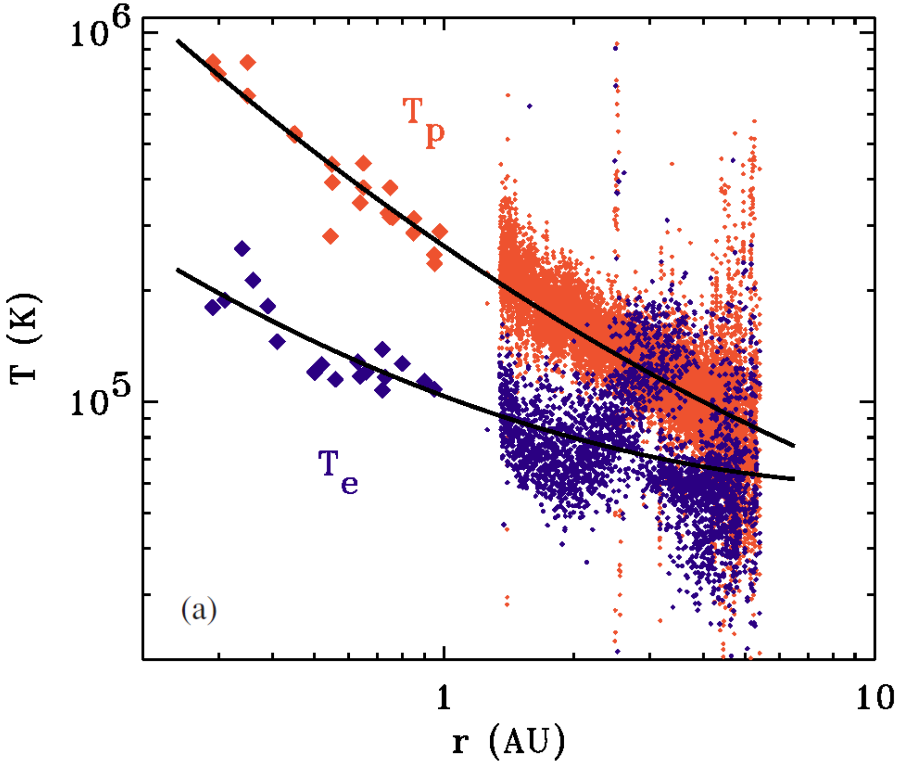
Anisotropy of heating and dependence on $\Delta V_{\alpha p}/C_A$

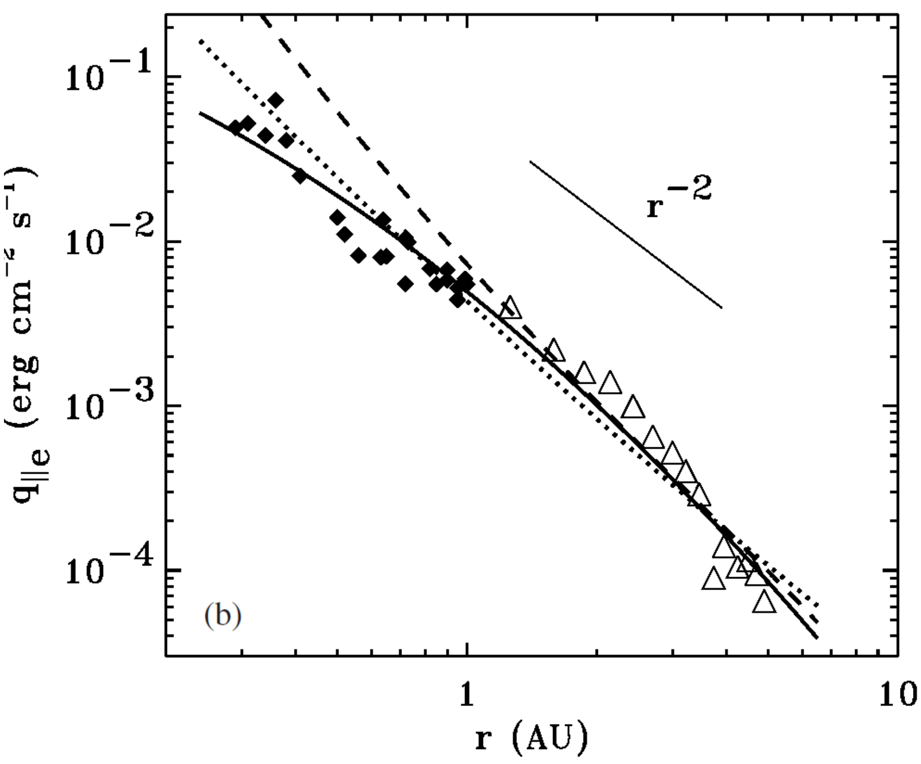




Ion-Electron Interactions

Relative heating of ions and electrons





Cranmer et al. (2008)

Prescription

Start with empirical dependence of temperature and heat flux on distance:

$$\ln\left(\frac{T_p}{10^5\,\mathrm{K}}\right) = 0.9711 - 0.7988x + 0.07062x^2,$$

$$\ln\left(\frac{T_e}{10^5\,\mathrm{K}}\right) = 0.03460 - 0.4333x + 0.08383x^2,$$

$$\ln\left(\frac{q_{\parallel,e}}{q_0}\right) = -0.7032 - 2.115x - 0.2545x^2,$$

Insert into equations for internal energy:

$$\frac{3}{2}n_p u k_\mathrm{B}\frac{\partial T_p}{\partial r} - u k_\mathrm{B} T_p \frac{\partial n_p}{\partial r} = Q_p + \frac{3}{2}n_p k_\mathrm{B}\nu_{pe}(T_e - T_p),$$

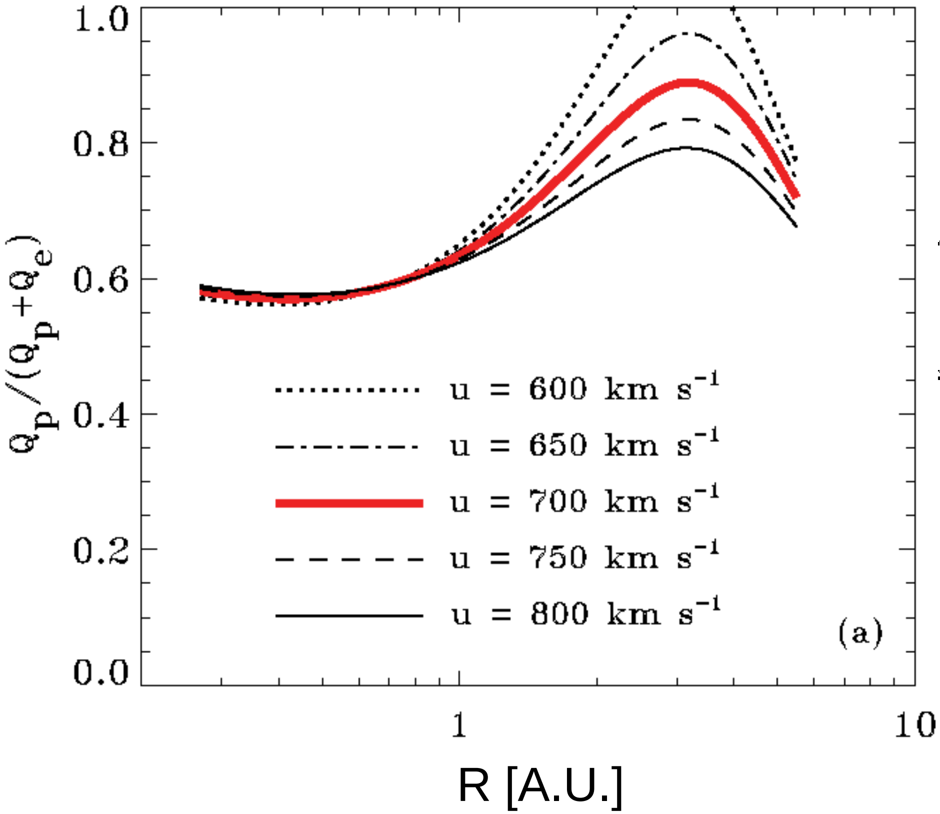
$$\frac{3}{2}n_e u k_\mathrm{B}\frac{\partial T_e}{\partial r} - u k_\mathrm{B} T_e \frac{\partial n_e}{\partial r} = Q_e + \frac{3}{2}n_e k_\mathrm{B}\nu_{ep}(T_p - T_e) - \frac{1}{r^2}\frac{\partial}{\partial r}\left(q_{\parallel,e} r^2 \cos^2\Phi\right),$$

Extract Q_p and Q_e

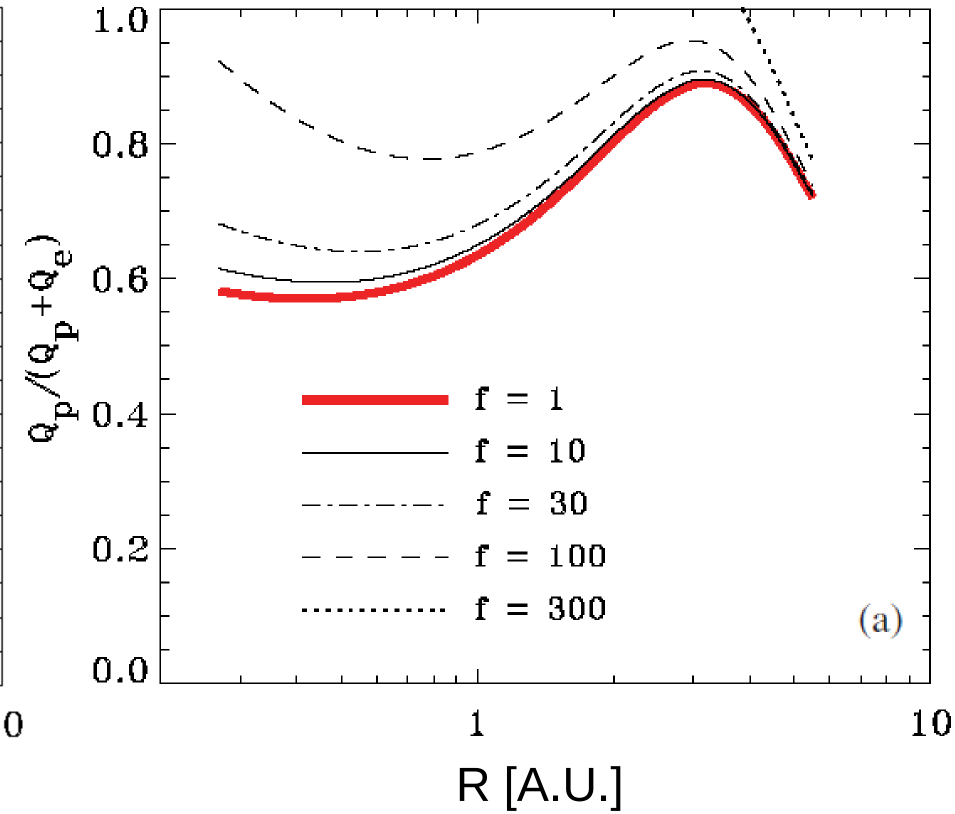
Relative heating with distance

Red curve is best-fit fraction of power dissipated into protons as a function of distance from the Sun

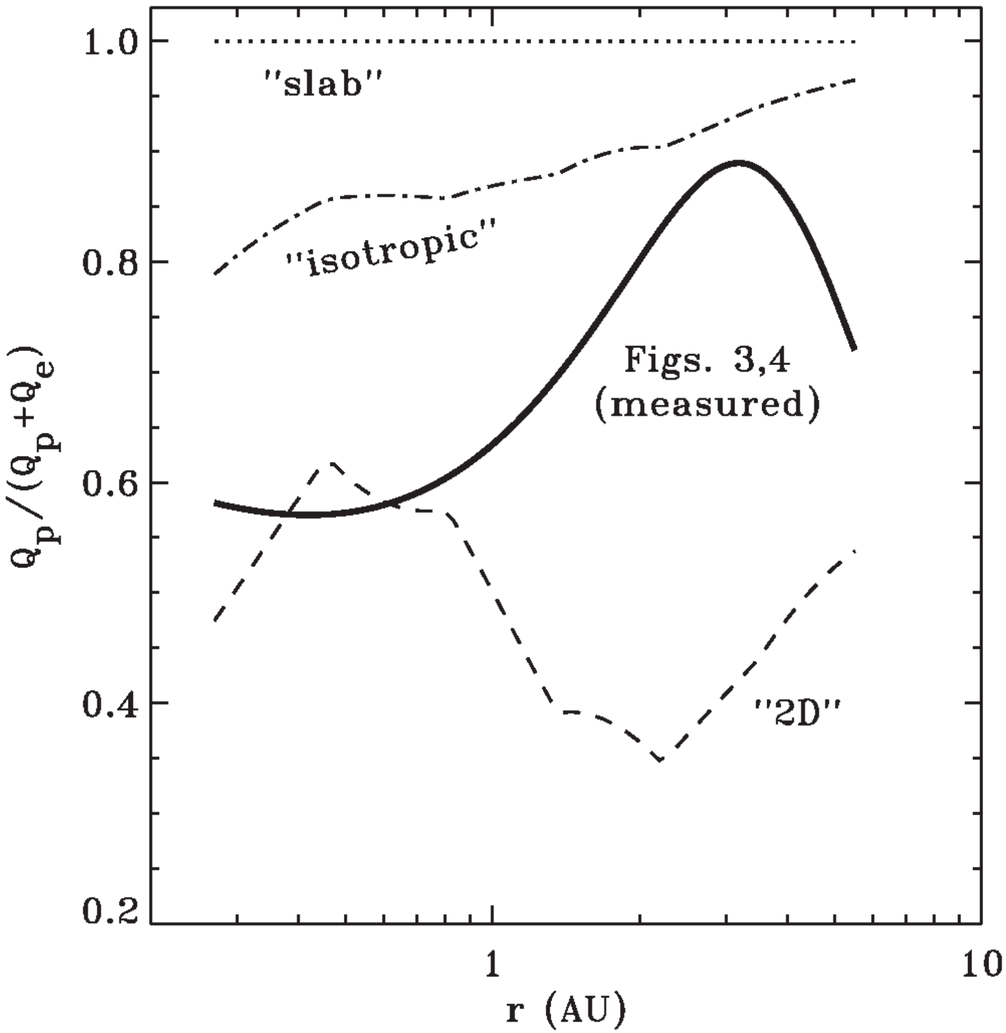
Change assumed mean speed



Raise Coulomb collision frequency



What explains this partition?



Next Steps

Models

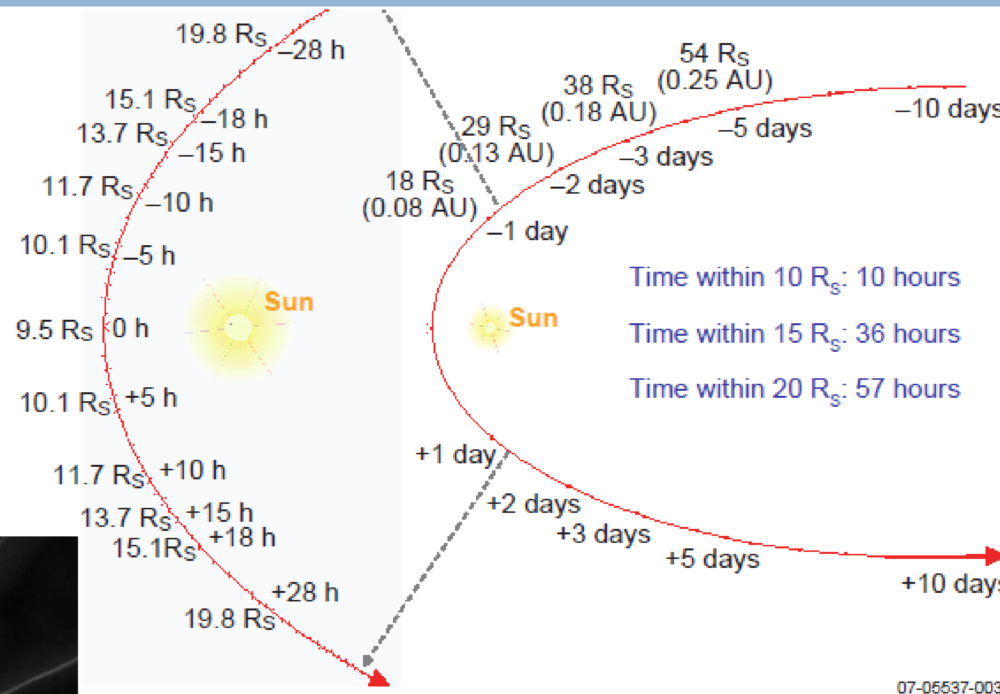
Data

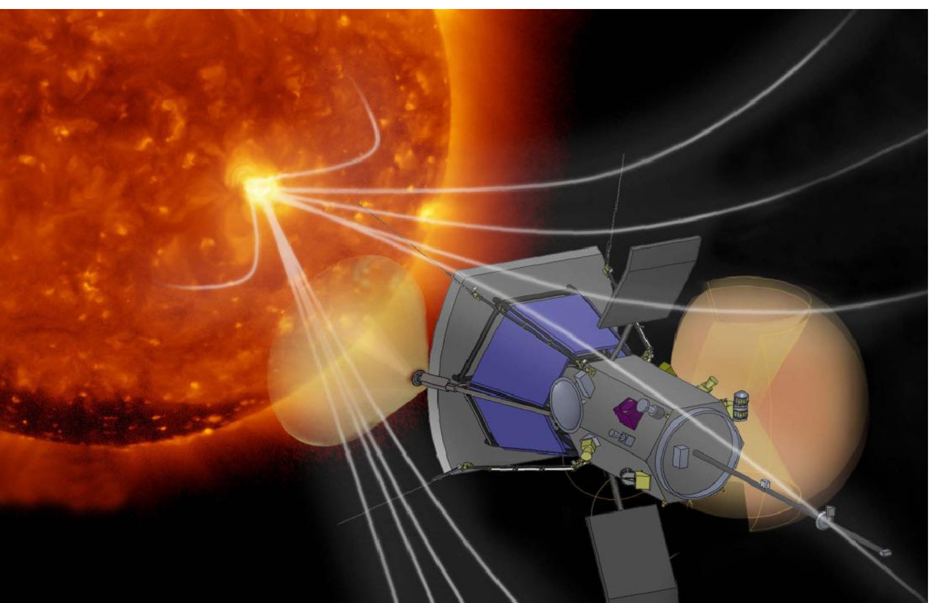
Spacecraft

Theoretical models and data analysis

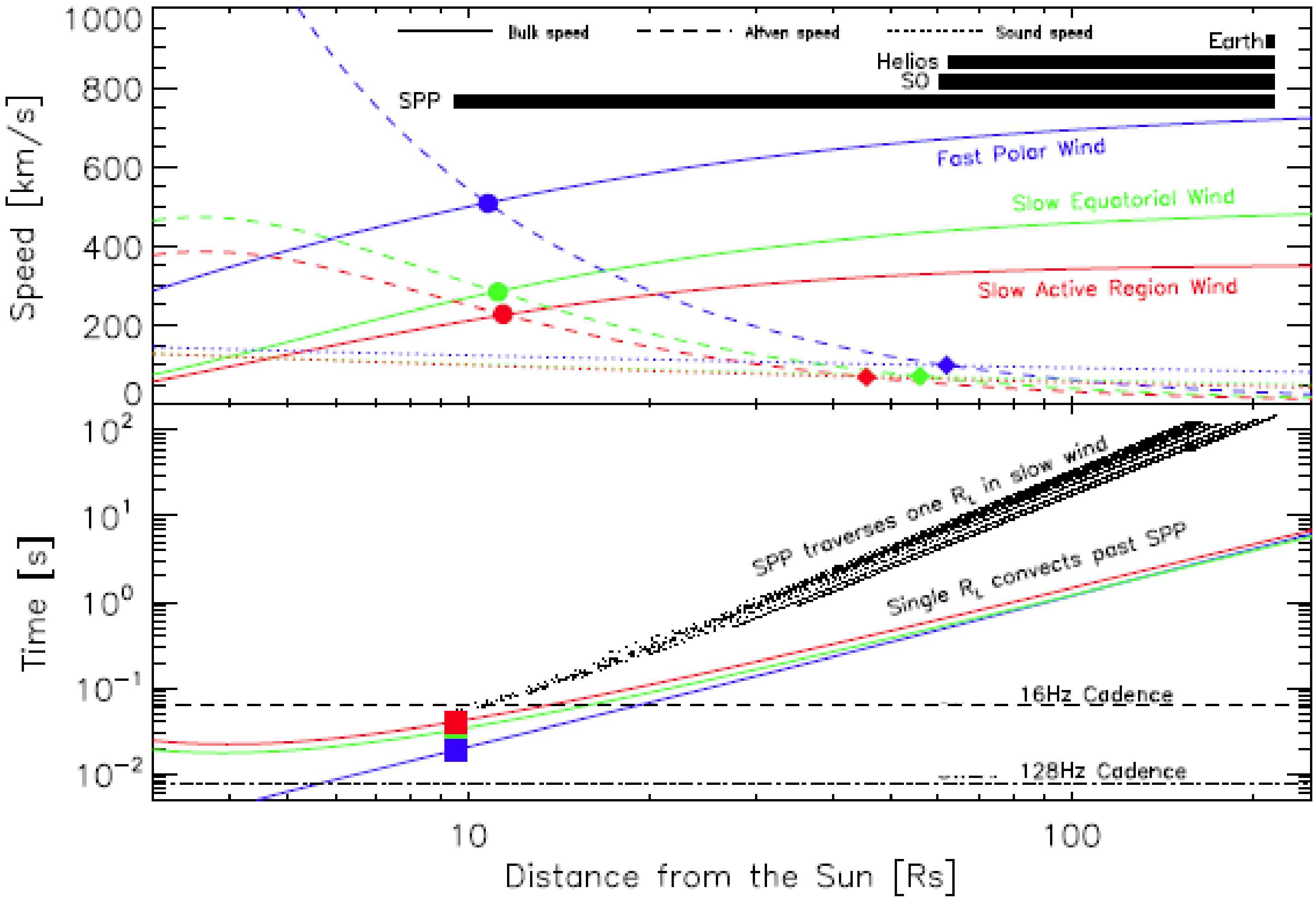
- Models
  - Is the mirror instability really more important than the cyclotron instability at regulating temperature anisotropy?
  - Predictions of wave power
- Data analysis
  - Ion-electron interactions
  - Plasma at higher cadence
  - Combine electromagnetic fields with plasma

Solar Probe Plus (SP+)

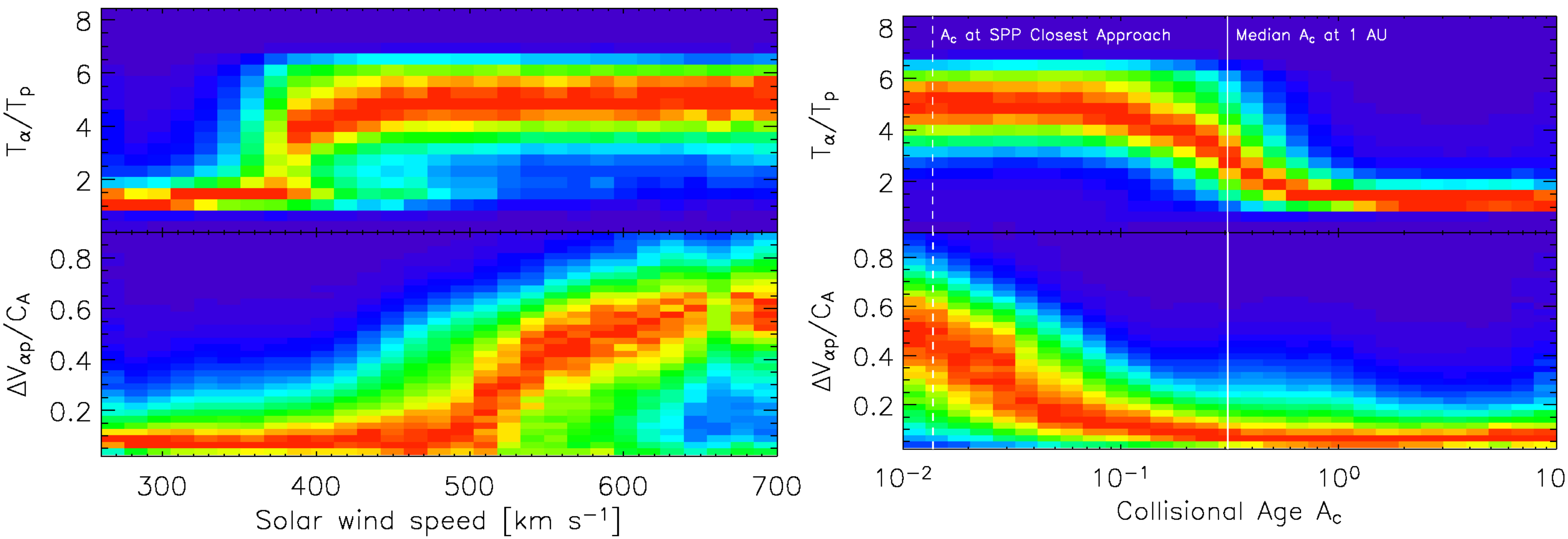




Advantages of SPP orbit



Rich kinetic dataset



Conclusions

- We can use large sets of precise solar wind measurements to conduct sensitive and quantitative kinetic physics experiments
- Microphysics is important at all solar wind speeds
- Instabilities
  - Experienced by protons, electrons (alphas, minor ions?)
  - Limit anisotropy, generate waves, heat plasma
- Heating mechanisms
  - Alfven-ion cyclotron heating is occurring in solar wind
- Upcoming missions to the inner heliosphere such as Solar Orbiter and Solar Probe can conduct groundbreaking kinetic physics experiments
  - Kinetic physics will be important at all solar wind speeds once we get close in
  - Need to be able to make fast and accurate measurements of bulk properties of solar wind ions and electrons, electric and magnetic field
  - Radial gradients important – operate these missions beyond encounters