Ion beams formed by Landau damping of waves

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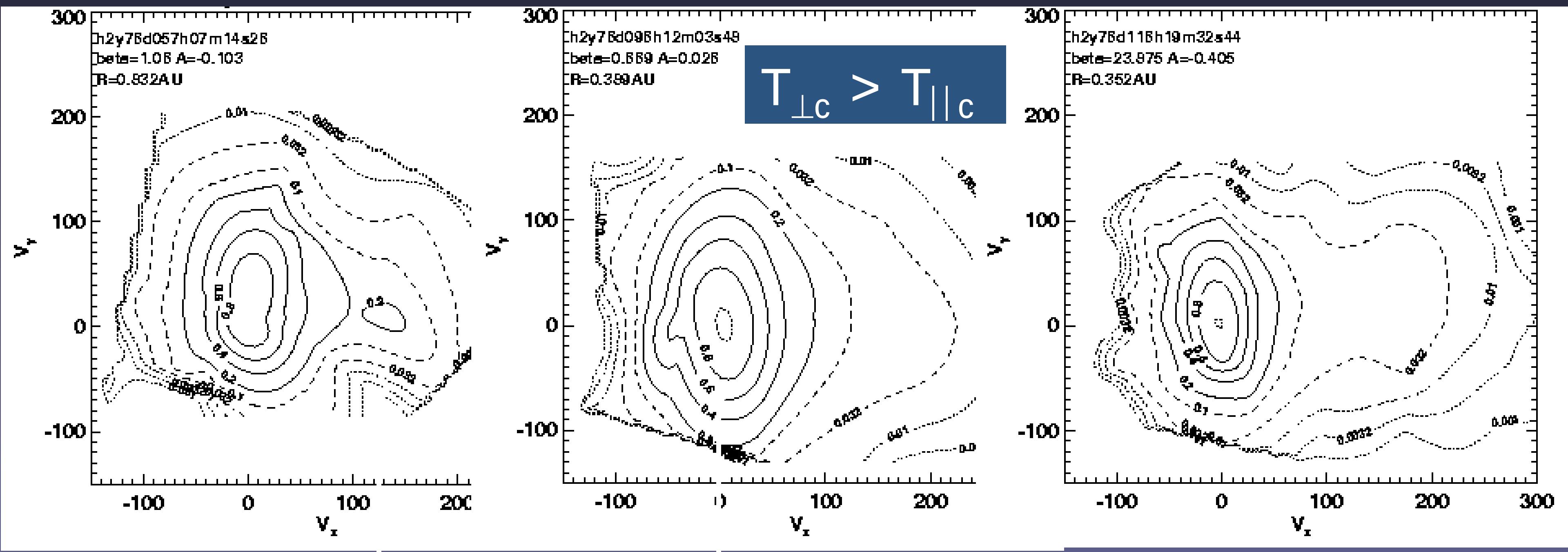
Proton beam velocity distributions



Proton beam

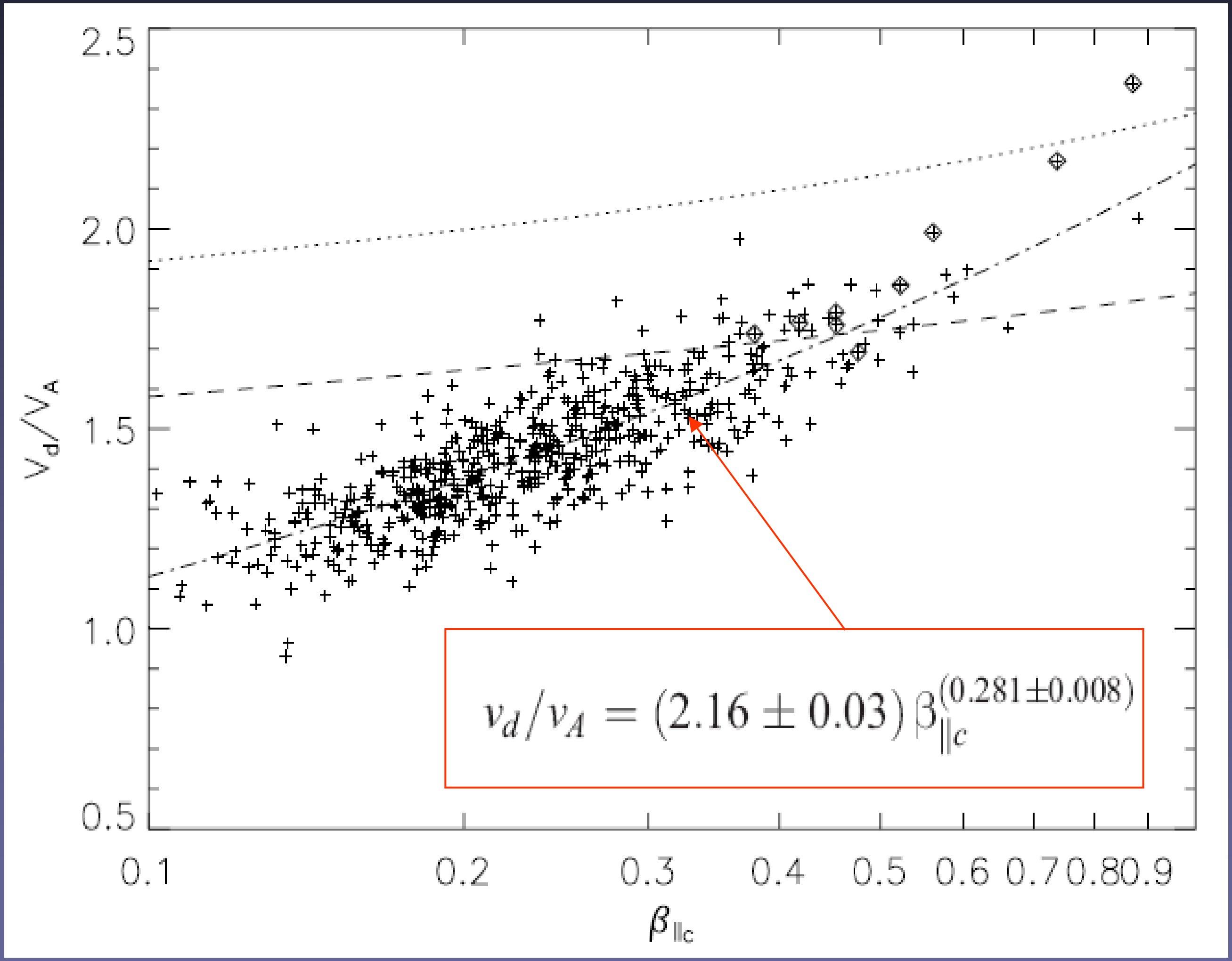
Core temperature anisotopy

Core defined to be above the 20% level of the maximum.

- Firehose instability?
- Mirror instability?

Marsch, Zhao and Tu, Annales Geophysicae 24, 2057, 2006.

Proton beam drift versus beta



The dotted and the dashed lines show the threshold of the Alfven I instability (Daughton and Gary, 1998) with a constant ratio of the proton beam density to the electron density, for the values 0.05 (top) and 0.2 (bottom line).

Tu, Marsch and Qin J.G.R,109, 2004

Numerical hybrid simulations

- 1D, non-linear, homogeneous plasma
- Quasi-neutrality and conservation of longitudinal current Isothermal massless fluid electrons contribute to electric field, but do not participate in dynamics
- Fully kinetic ions

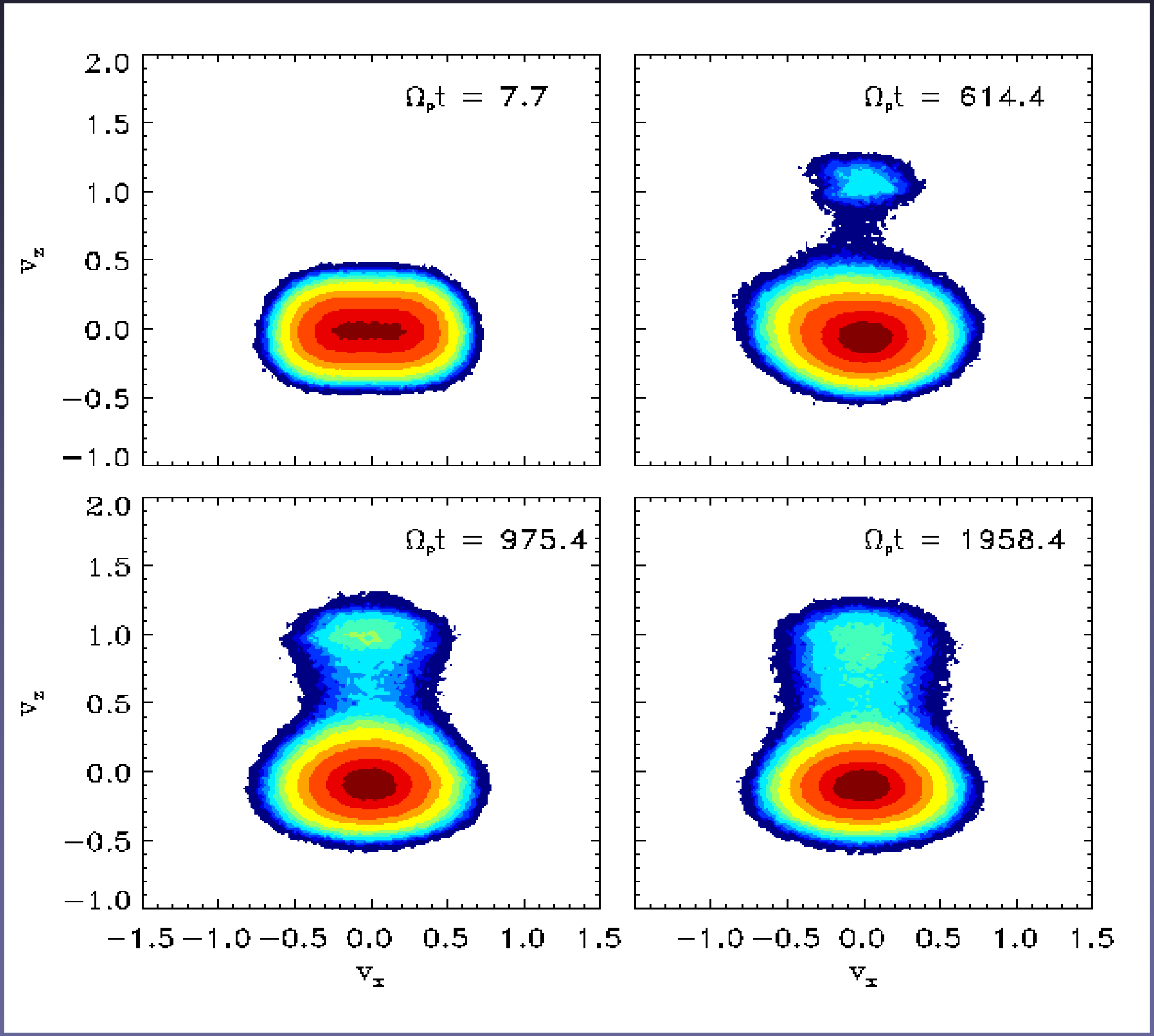
$$\mathbf{0} = -n_e e\mathbf{E} + \mathbf{J}_e \times \mathbf{B} - \nabla P_e \, .$$

$$p_e = n_e k_B T_e .$$

$$\left[\frac{\partial}{\partial t} + \vec{v} \cdot \frac{\partial}{\partial \vec{x}} + \frac{q_s}{m_s}\left(\vec{E}(\vec{x},t) + \frac{\vec{v} \times \vec{B}(\vec{x},t)}{c}\right) \cdot \frac{\partial}{\partial \vec{v}}\right] F_s(\vec{x},\vec{v},t) = 0,$$

Typical parameters: $n_\alpha/n_e = 0.05$, $n_p/n_e = 0.9$, $\beta_p = 0.1\text{-}0.2$

Proton core heating and beam formation

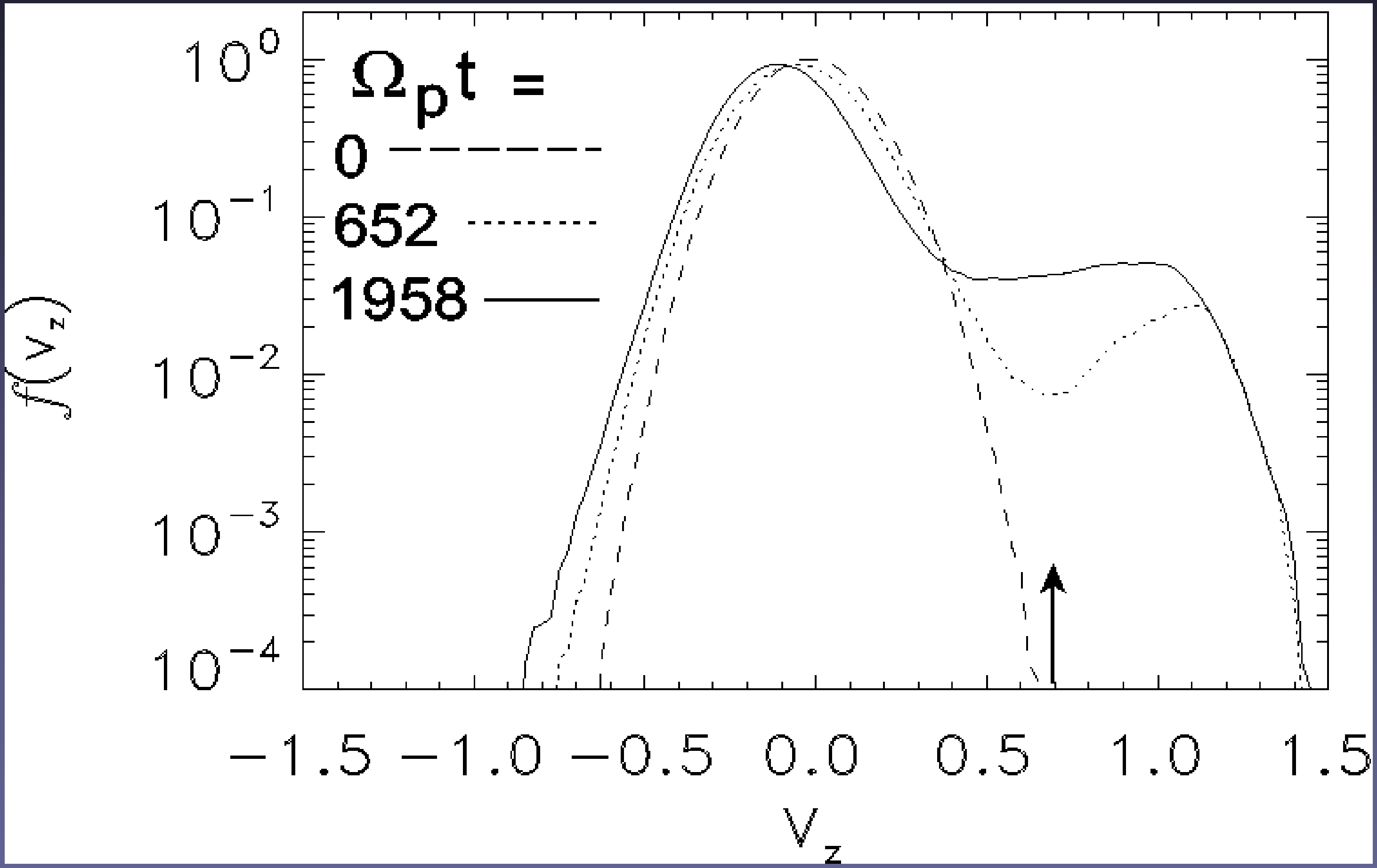


VDFs as obtained by numerical simulation of the decay of Alfvén-cyclotron waves and the related ion kinetics

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

Proton beam development



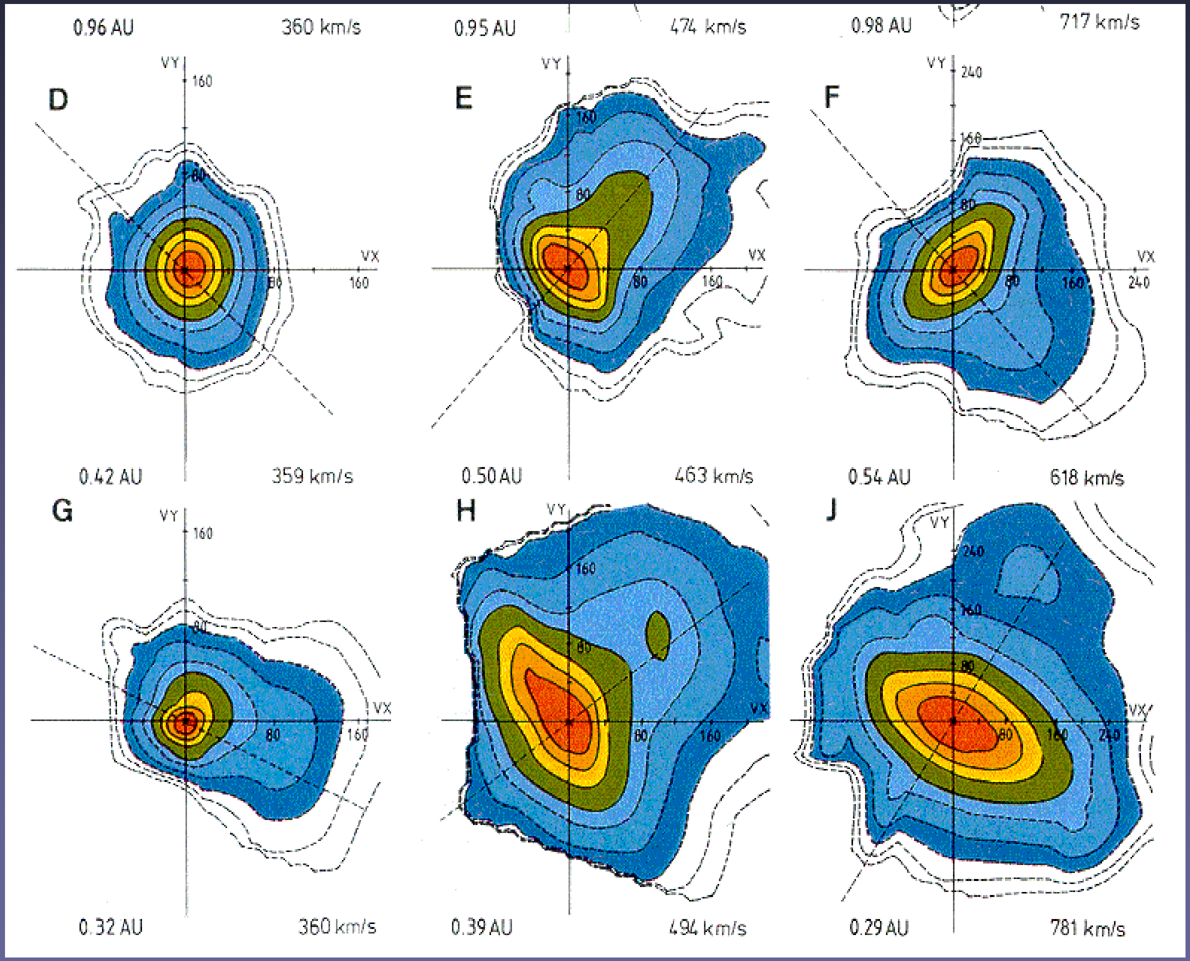
Numerical simulation results: One-dimensional cuts through the proton VDF as a function of v_z along the magnetic field direction for the dispersive-wave case at three instants of time. Note the formation of a beam with a final relative density of about 7%.

Conclusions

- Beams, diffusion plateaus and temperature anisotropies of ion velocity distributions are interpreted as evidence for ongoing wave-particle interactions in the solar wind.
- They can be either non-resonant fluid-like or more likely of plasma kinetic nature, involving cyclotron and Landau resonances with plasma waves.
- We argue that kinetic instabilities (plasma wave emission and absorption) play a key role in the dissipation of turbulence.

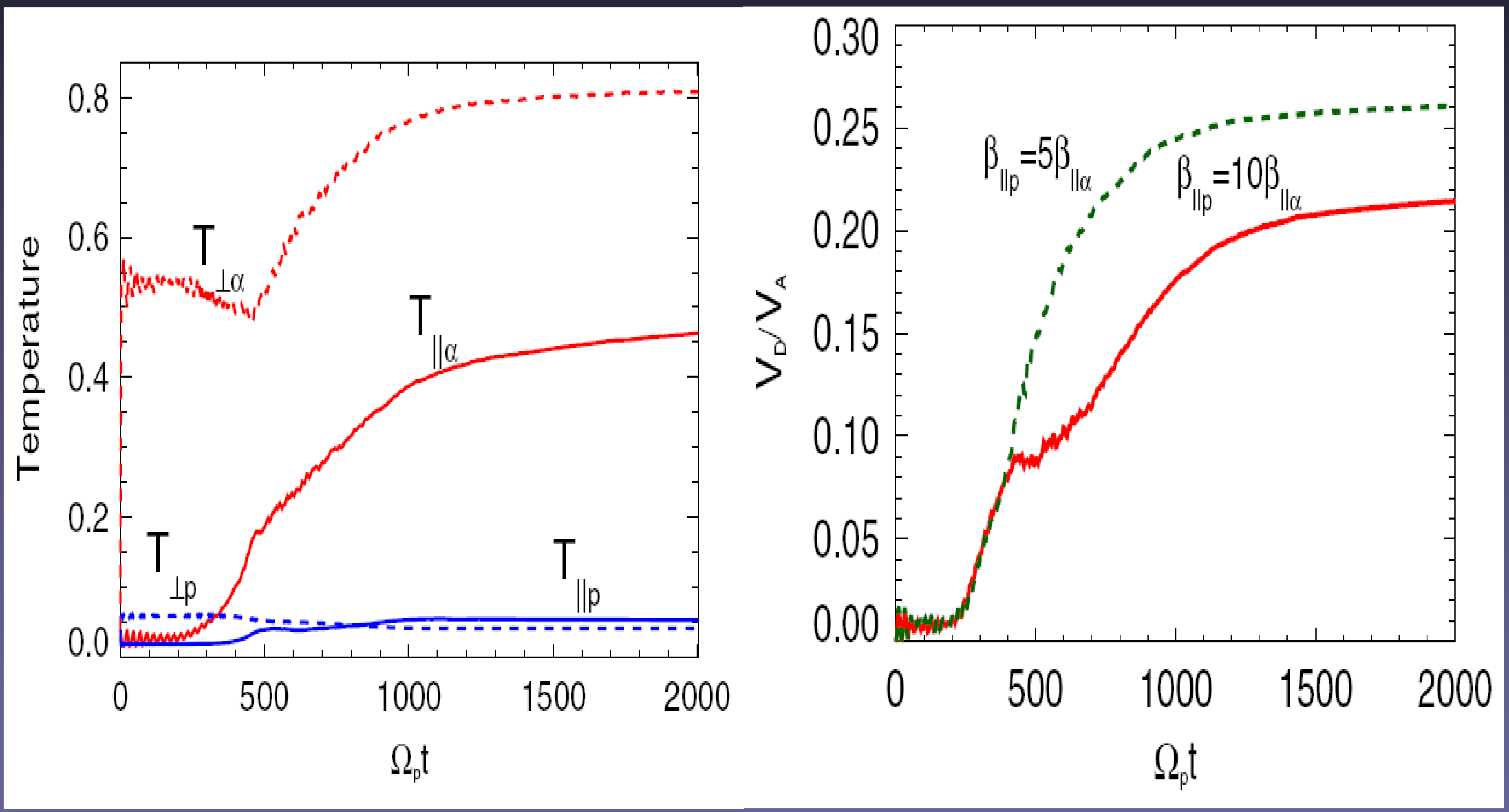
Ion kinetics in the solar wind

- **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**



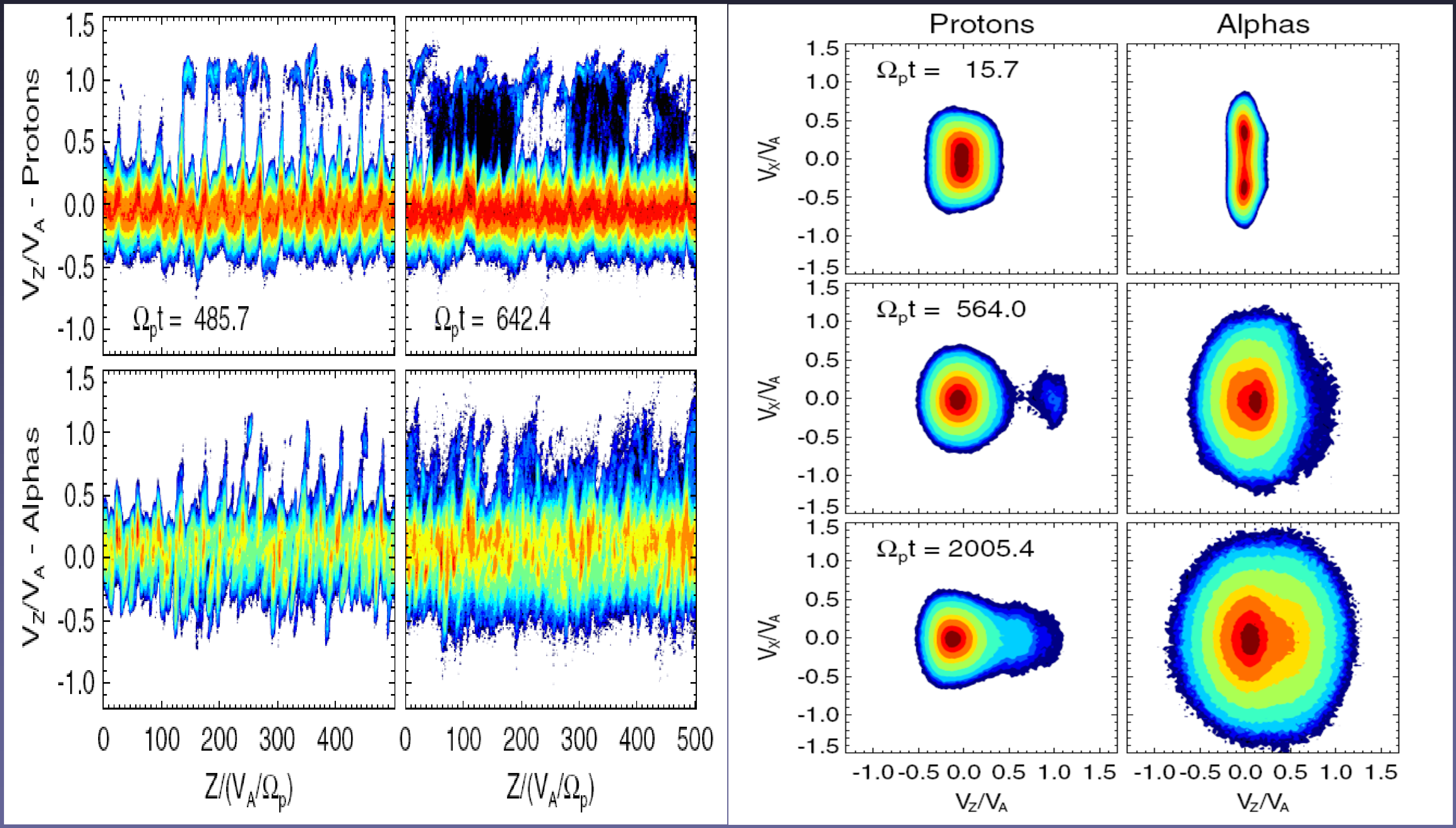
Marsch et al., JGR, 87, 52, 1982

Ion differential heating and acceleration



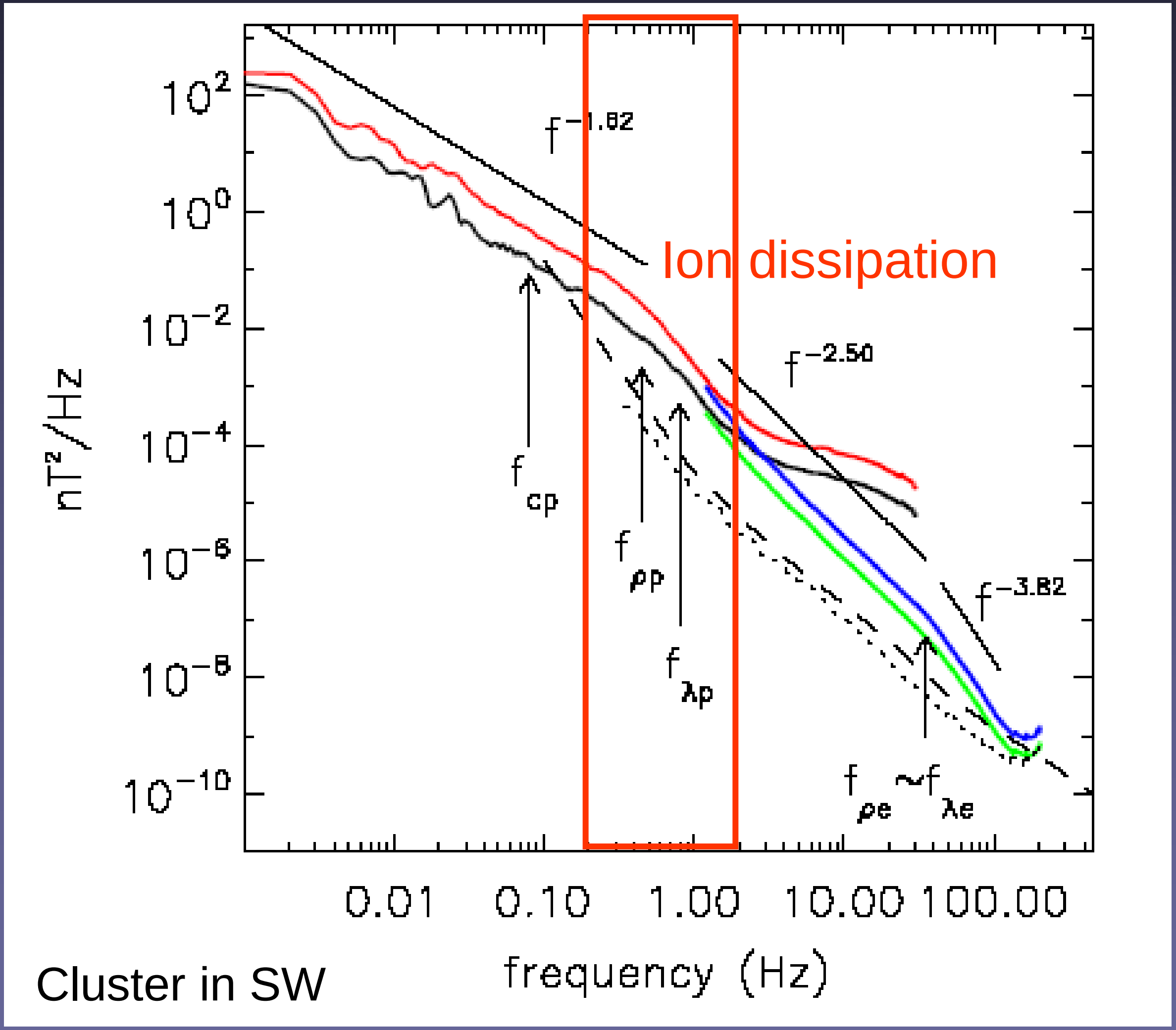
J.A. Araneda, Y. Maneva, and E. Marsch, Phys. Rev. Lett., **102**, 175001, 2009

Ion trapping and scattering in wave field



J.A. Araneda, Y. Maneva, and E. Marsch, Phys. Rev. Lett., **102**, 175001, 2009

Magnetic power spectrum



Cascades:

- 5/3 MHD

Ion disspation

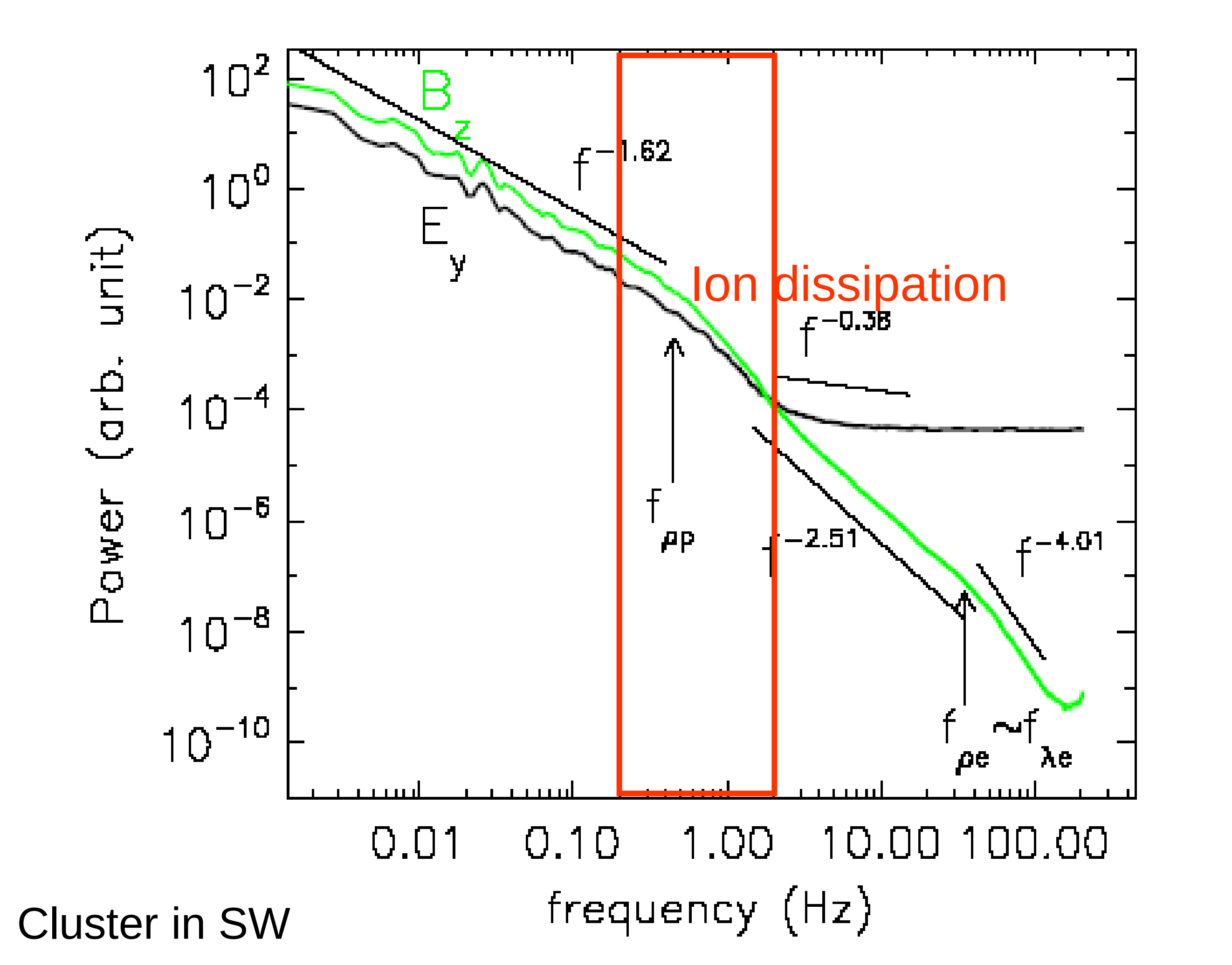
- 2.5 HMHD

-4

Electron dissipation

Sahraoui et al PRL, 2009

Electric power spectrum



Cascades:

- 5/3 MHD

Ion disspation

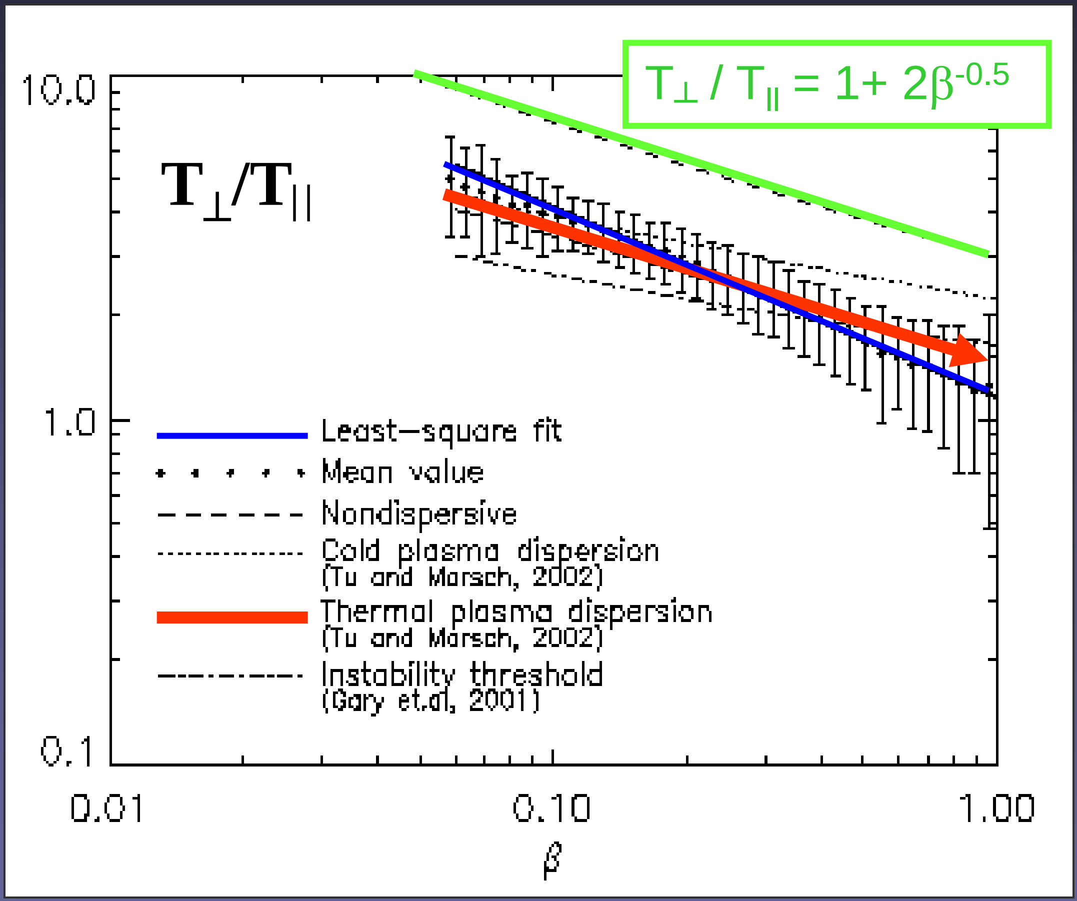
- 2.5 HMHD

-4

Electron dissipation

Sahraoui et al PRL, 2009

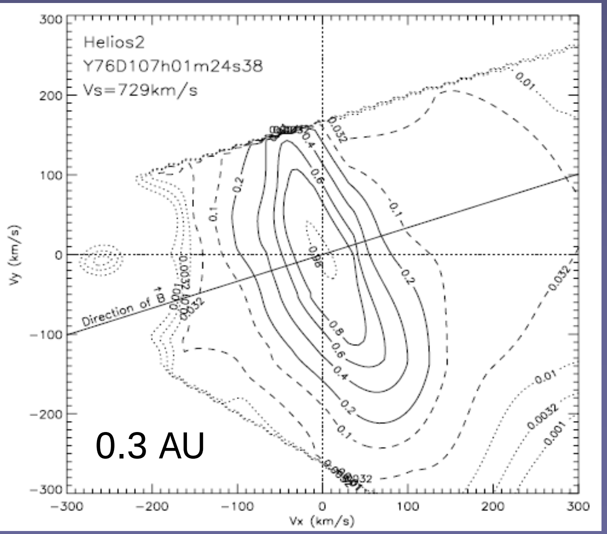
Temperature ratio versus beta



Blue line empirical fit:

$$T_\perp / T_{||} = 1.16\ \beta^{-0.55}$$

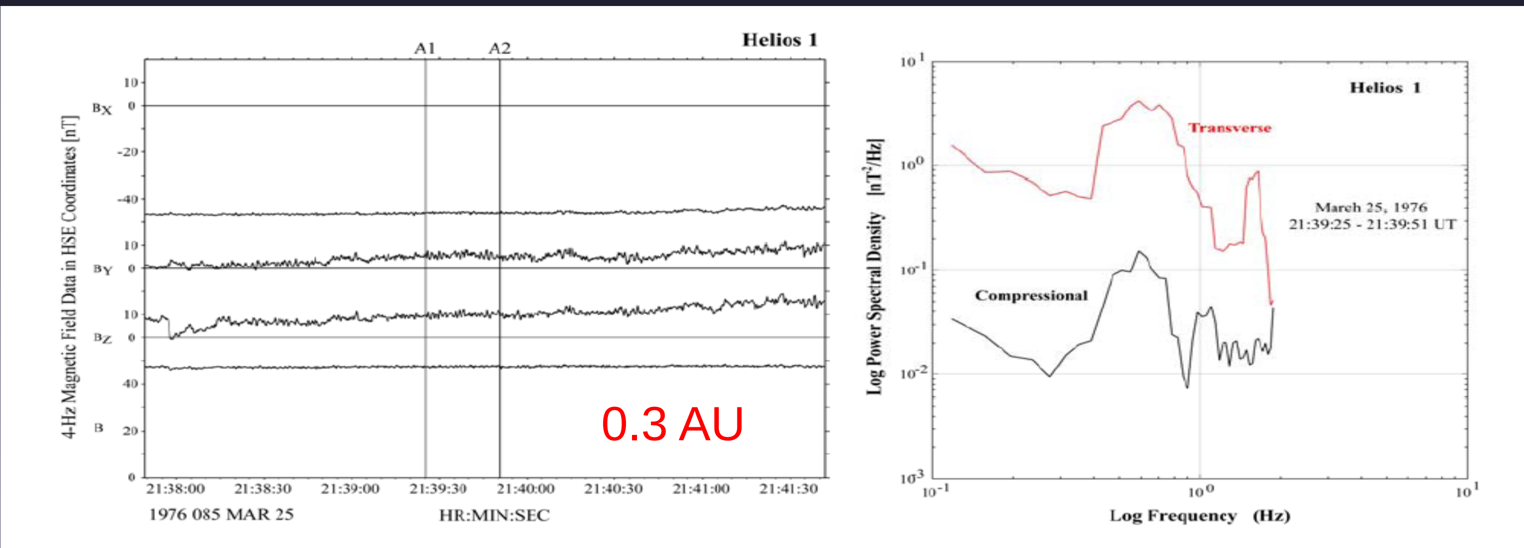
The core temperature anisotropy is regulated by quasilinear diffusion of protons in resonance with thermal cyclotron waves.



- Speed V > 600 km/s
- 36297 proton spectra

Marsch, Ao, Tu, JGR, **109**, 2004

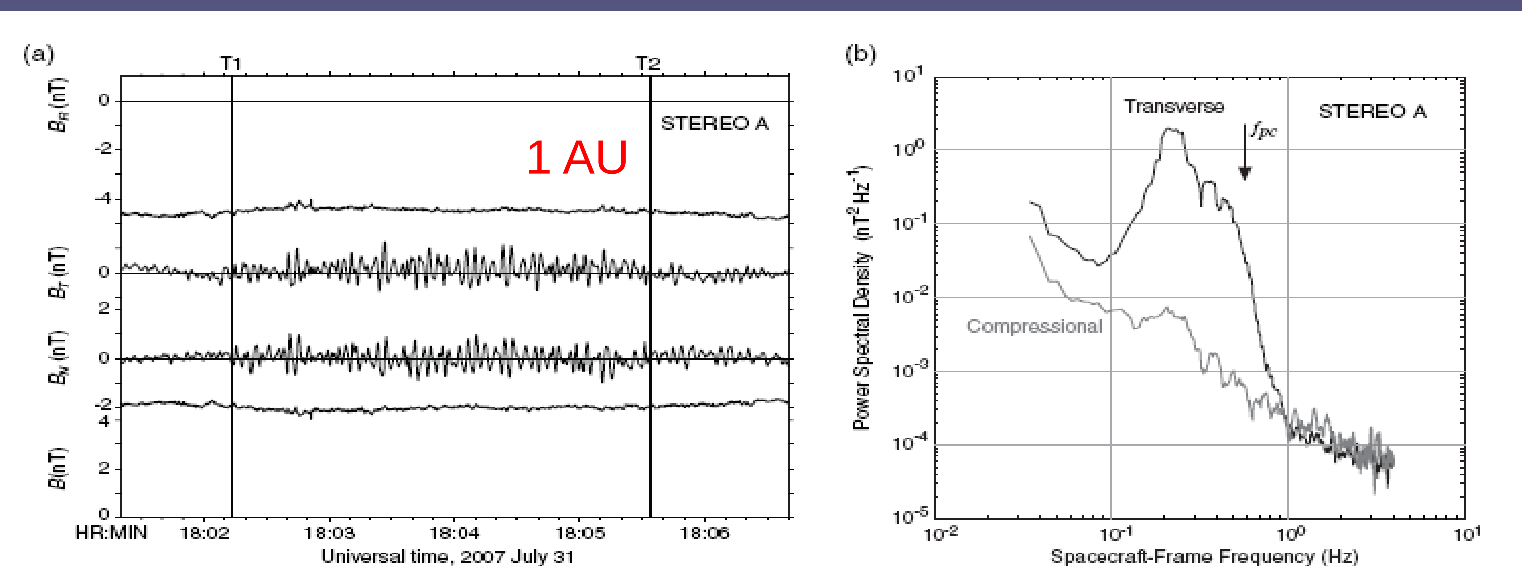
Ion cyclotron waves



Helios

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

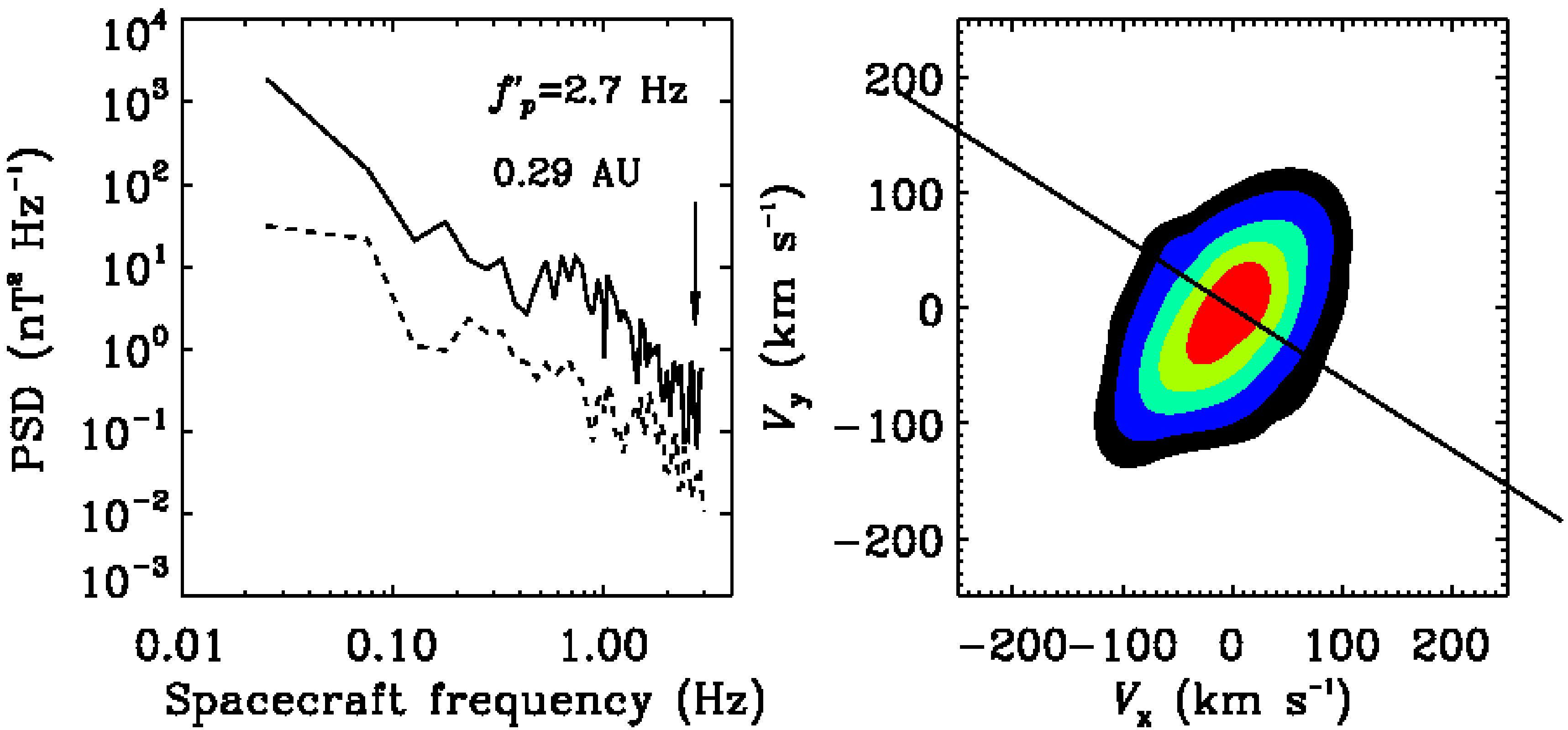
Parallel in- and outward propagation



STEREO

Jian et al. ApJ, 2009

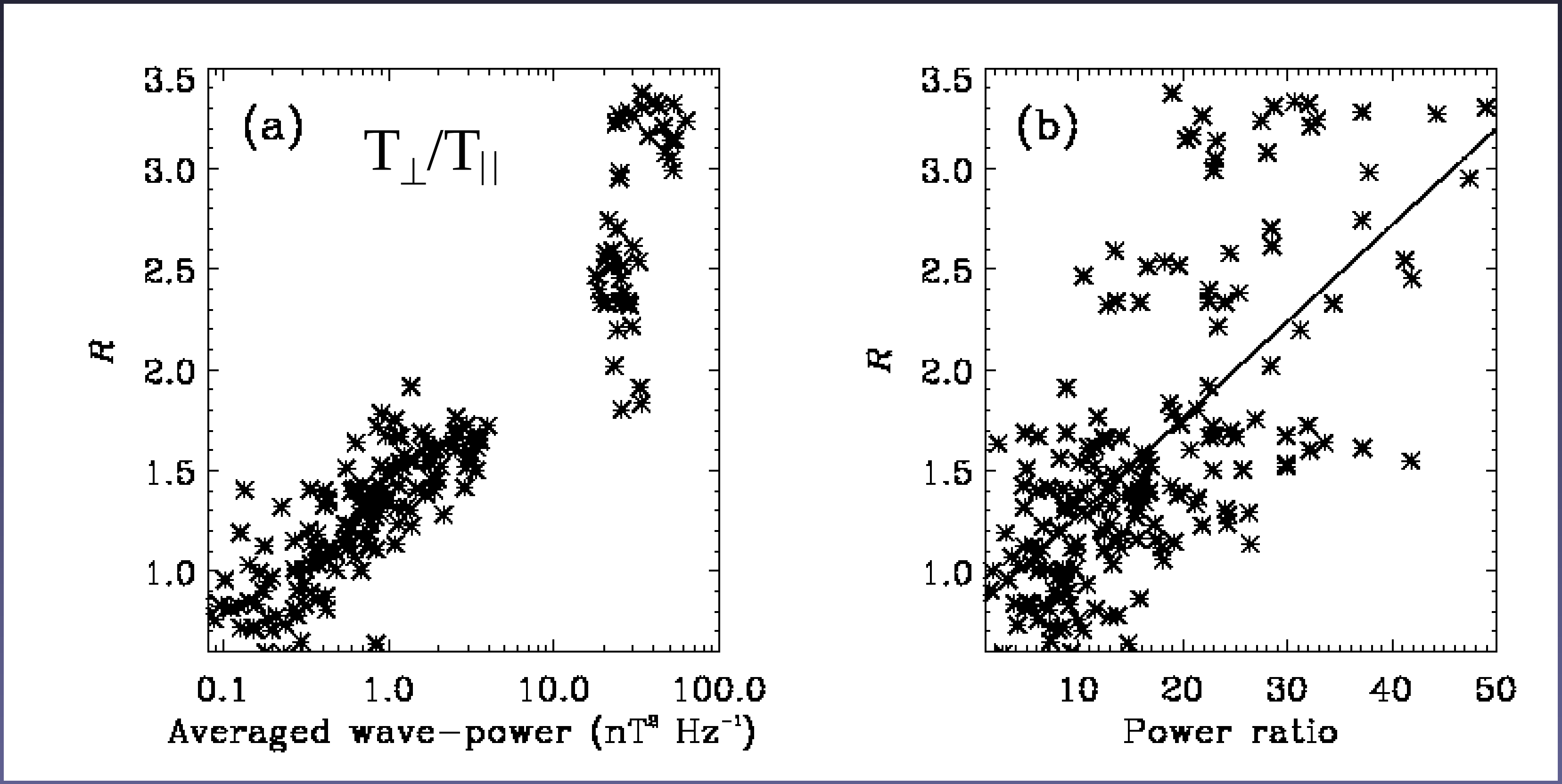
Correlation of anisotropy with transverse Alfvén wave power



$f'_p = f_p(1+M_A)$; $f_p = eB/(2\pi mc)$

Bourouaine et al., submitted to GRL, 2010

Temperature ratio versus wave power



Alfvén-cyclotron waves, 0.02 Hz - 2 Hz

$P_\perp/P_{||}$

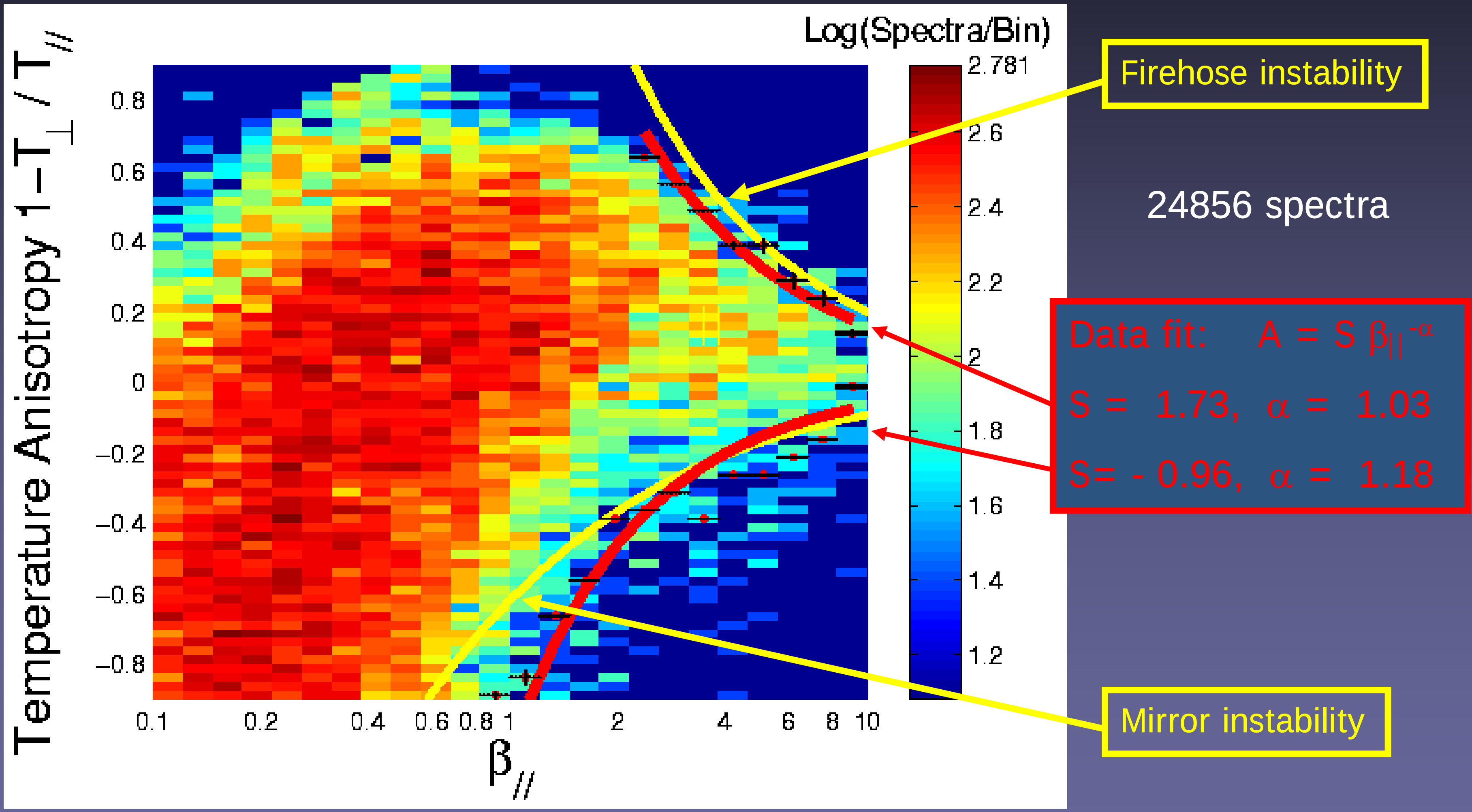
Mean **B** for 40 s; Helios distances: 0.3 - 0.9 AU

Bourouaine et al., submitted to GRL, 2010

Helios data analysis procedure

- Parameters: Core proton temperatures $T_{\perp}$ and $T_{||}$, in the directions perpendicular and parallel to the magnetic field, and parallel plasma beta, $\beta_{||}$.
- The data are separately analyzed for two distance ranges: R < 0.4 AU and R > 0.4 AU.
- Division into 24 bins for $\beta_{||}$, in the range from 0.1 to 10.
- Division into 72 bins for the core temperature anisotropy, $A = 1 - T_{\perp}/T_{||}$, in the range from −0.9 to 0.9.
- The number of spectra in each bin is determined to obtain colour-coded distributions.
- Statistical results given in two-dimensional histograms

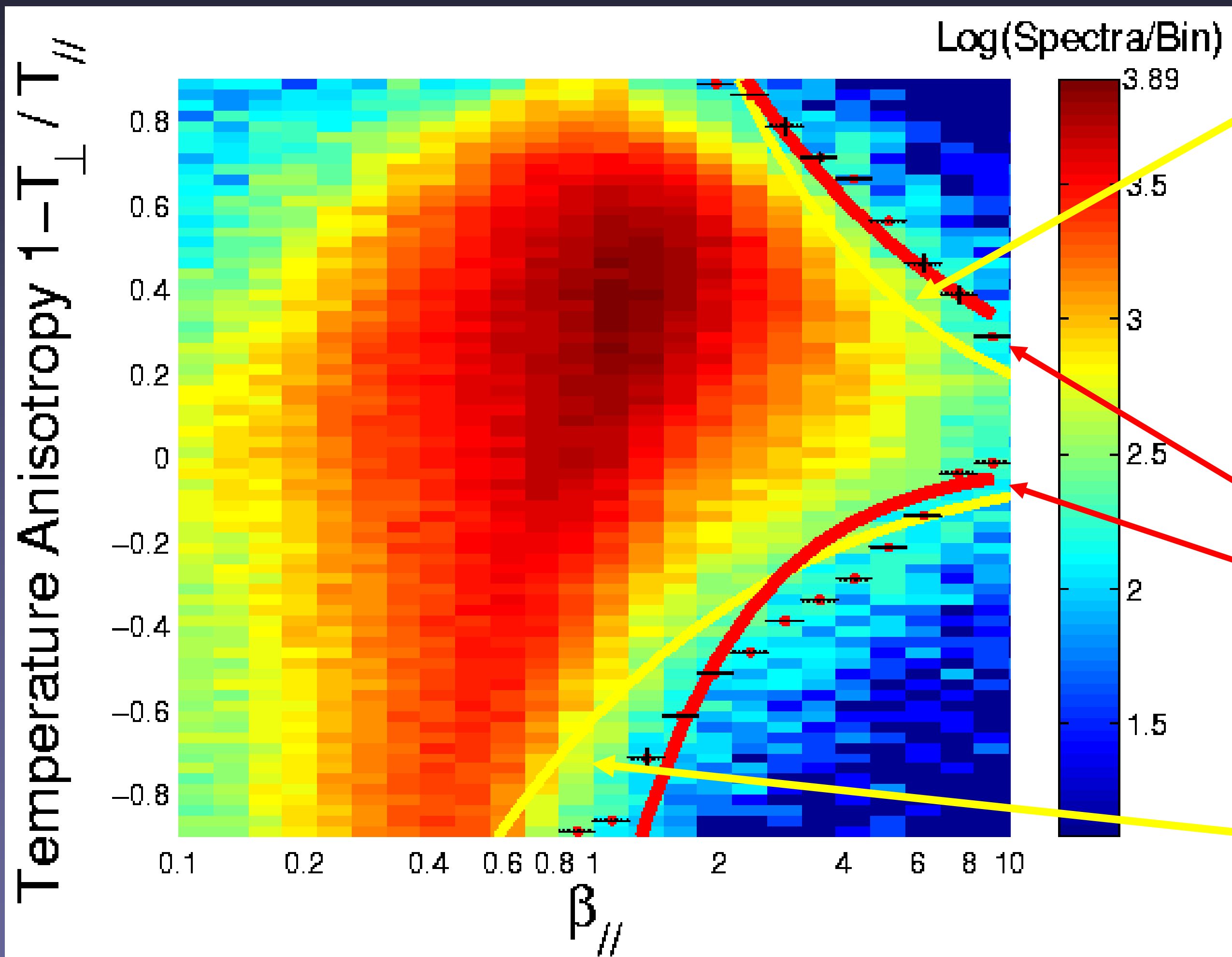
Anisotropy histogram for r < 0.4 AU



Red lines at 8% level

Marsch, Zhao and Tu, Ann. Geophysicae, 24, 2057, 2006

Anisotropy histogram for r > 0.4 AU



Firehose instability

193902 spectra

Data fit: $A = S\,\beta_{||}^{-\alpha}$

S = 1.64, α = 0.71

S = - 1.33, α = 1.50

Mirror instability

Red lines at 3% level

Marsch, Zhao and Tu, Ann. Geophysicae, 24, 2057, 2006