Waves and fluctuations associated with local instabilities in the solar wind

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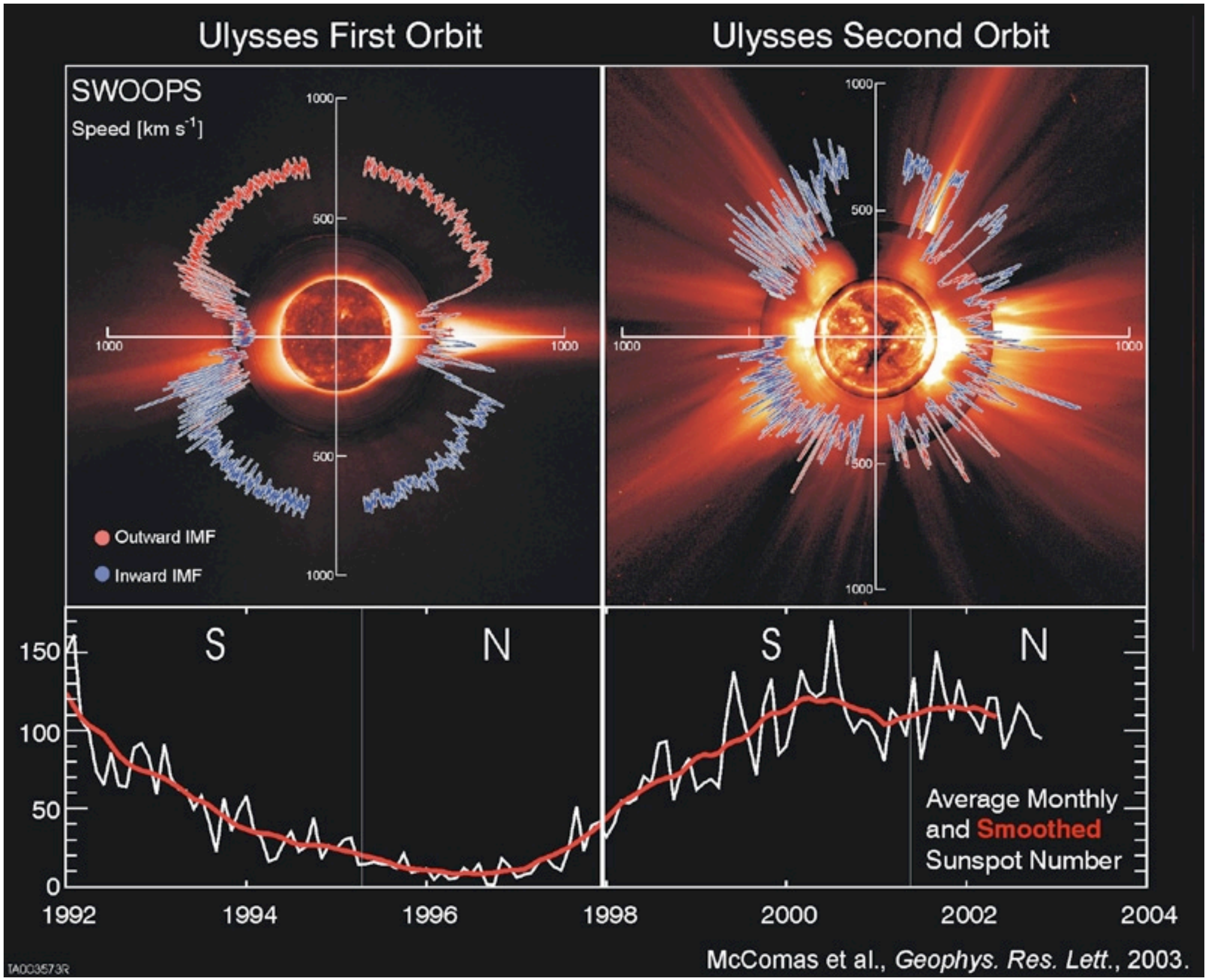
GYP01 - Kinetic-scale turbulence in laboratory and space plasmas - July 21, 2010

plan

- Solar wind properties and turbulence
- Plasma physics measurements in the solar wind
- Instabilities (as opposed to ‘turbulence’)
- For the future...

Thesis: there is finite power at and above $k\rho \sim 1$ that is unrelated to the turbulent cascade

Solar wind properties (at, say, 1 AU)



Fast wind (1 AU)

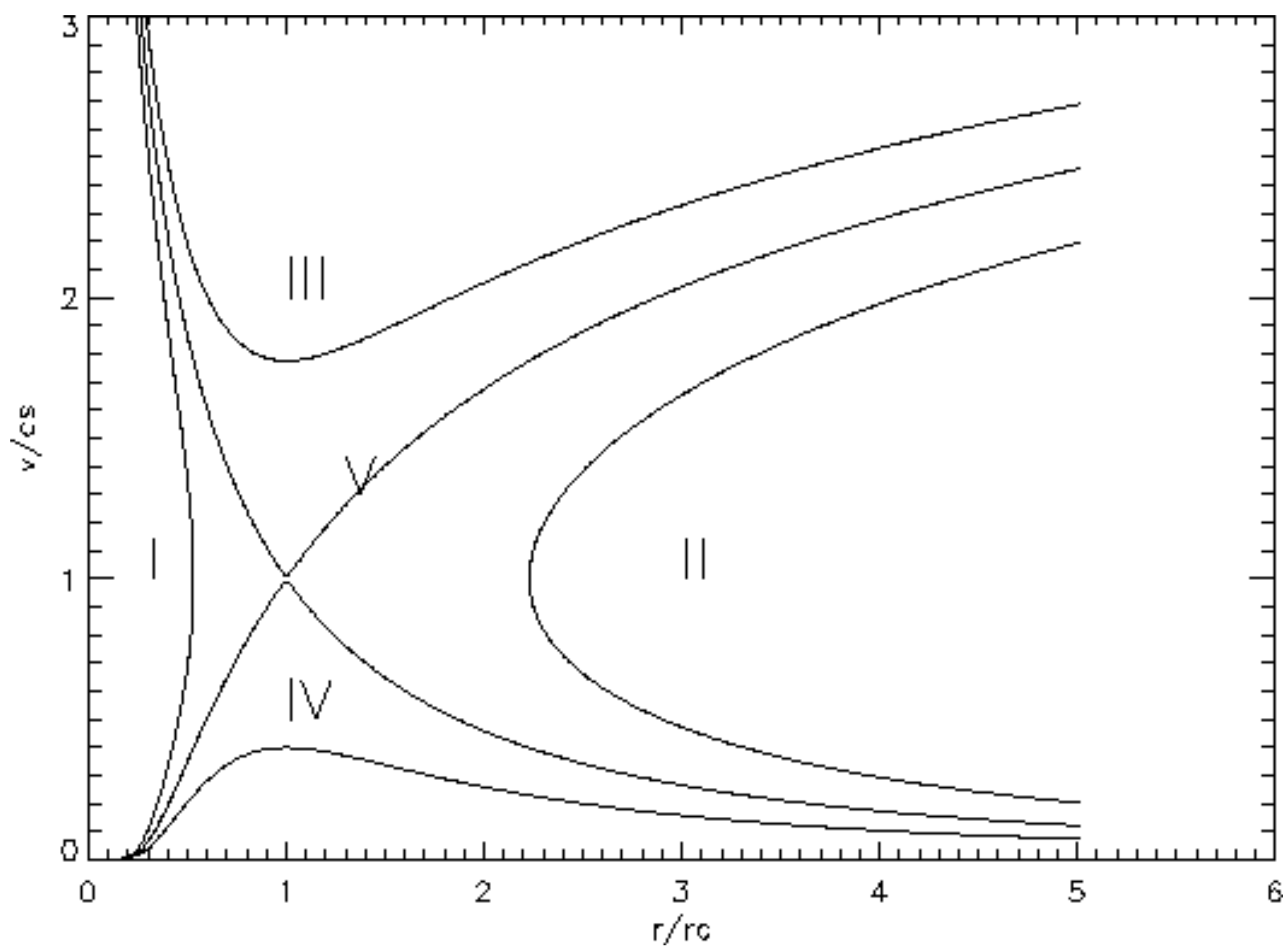
v_{sw} ~ 500-1000 km/s
T_p ~10-20 eV
T_e ~ 5-20 eV
n ~ 1-10 cm-3
B ~ 5 nT, δB is larger
β ~ 1

Slow wind (1 AU)

v_{sw} ~ 250-500 km/s
T_p ~5-20 eV
T_e ~ 5-20 eV
n ~ 5-25 cm-3
B ~ 5 nT
β ~ 1

‘Heating’ is required to accelerate the solar wind

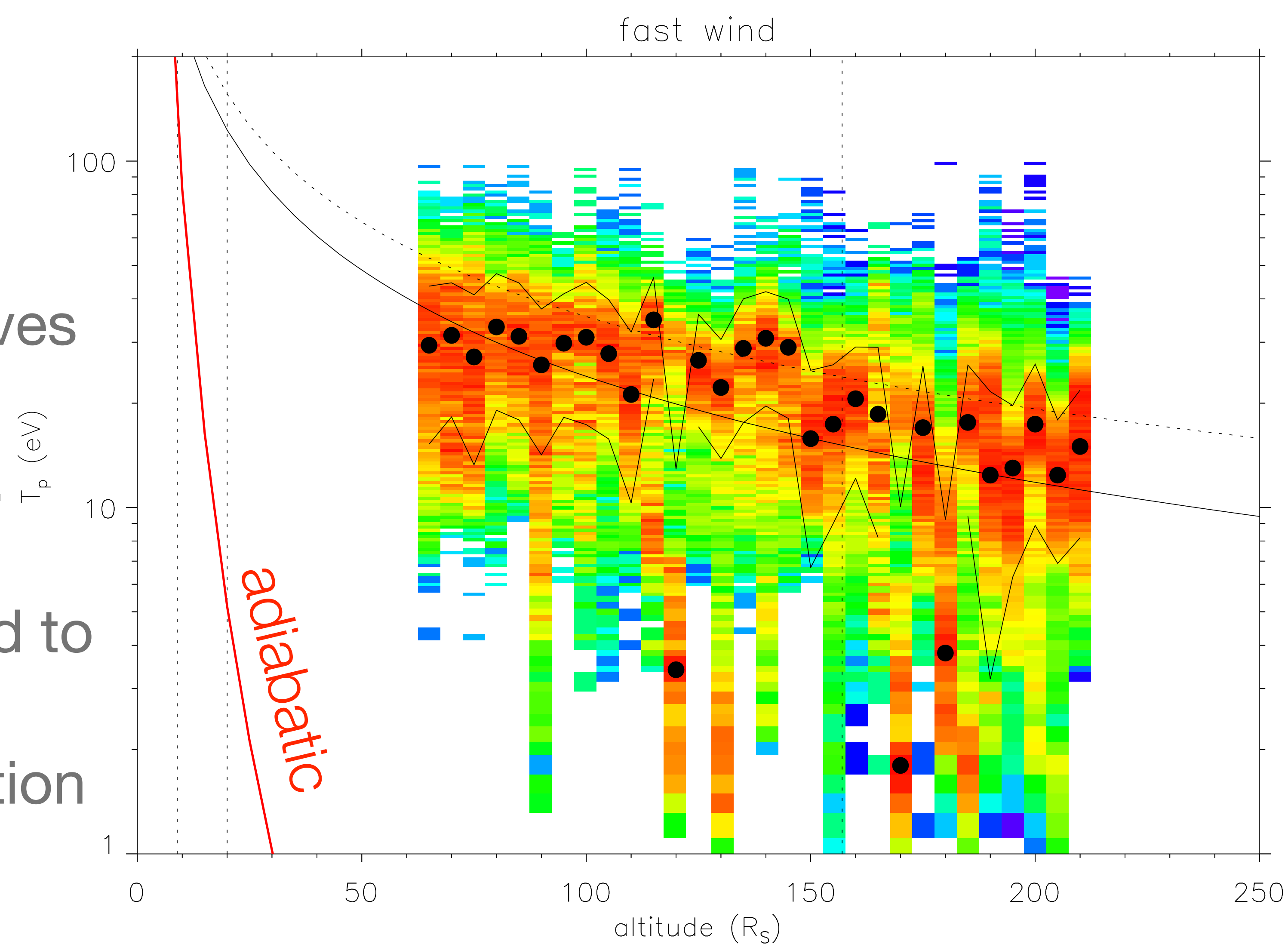
- Parker solar wind model (unmagnetized, zero angular momentum, critical points, etc.)
- Requires energy input at exobase *beyond* available photospheric thermal energy
- Plenty of magnetic energy density available
  - waves
  - reconnection
  - ambipolar electric field (exosphere)



(Parker, 1958)

‘Heating’ is required to sustain the solar wind

- Local (Rs) and extended (AU) heating are required
- Extended heating implies waves
- Alfven waves -
  - observed and copious (i.e. Belcher & Davis, 1971)
  - weakly damped (compared to fast- and slow-mode)
  - excited by large-scale motion near the Sun, n-i coupling, etc.



Helios proton temperature in the fast wind

Hence, turbulence...

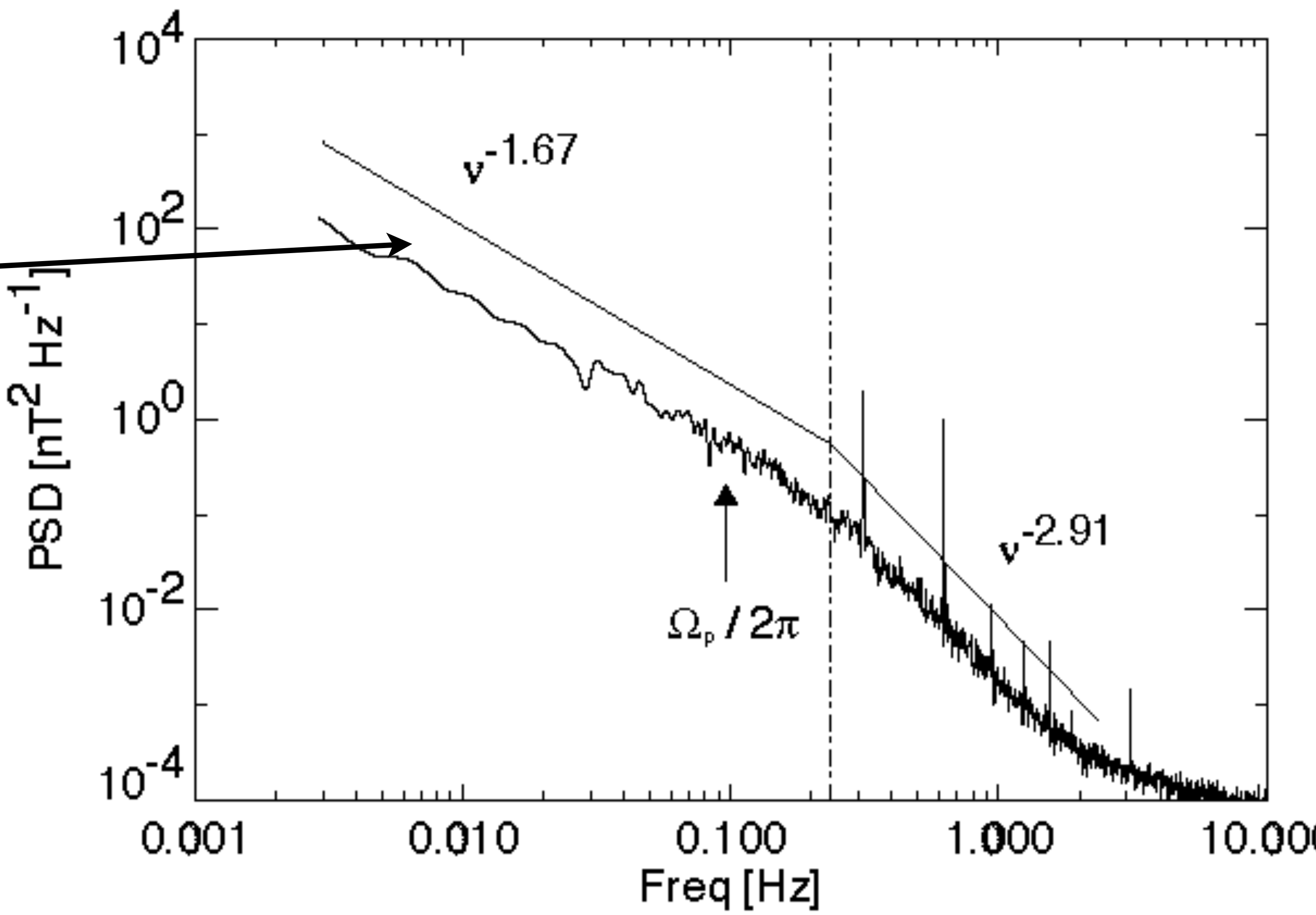
Alfvenic turbulence and heating

- Kolmogorov (isotropic, hydro) turbulence - scale free inertial range

$$\epsilon \sim \frac{u^2}{\tau} = const \qquad \tau \sim \lambda/u$$

$$\epsilon \sim u^3/\lambda \qquad u \sim (\epsilon\lambda)^{1/3}$$

$$P \sim \lambda u^2 \sim \epsilon^{2/3}\lambda^{5/3}$$



(Leamon et al., 1998)

The total field |B|, field components, density, temperature, and velocity *all* show evidence of $k^{-5/3}$ behavior (sometimes)

Alfvenic turbulence and heating

- Goldreich-Sridhar (anisotropic) turbulence - also scale free, 'strong'

perpendicular cascade $k_{||} \ll k_\perp$

critical balance $\omega \sim k_{||} v_A \sim k_\perp v_\perp$

$$\epsilon \sim \frac{v_\perp^2}{\tau} = const$$

$$\tau \sim \lambda / v_\perp \sim l_{||} / v_A$$

$$\epsilon \sim v_\perp^3 / \lambda$$

$$v_\perp \sim (\epsilon \lambda)^{1/3}$$

$$P \sim \lambda u_\perp^2 \sim \epsilon^{2/3} \lambda^{5/3}$$

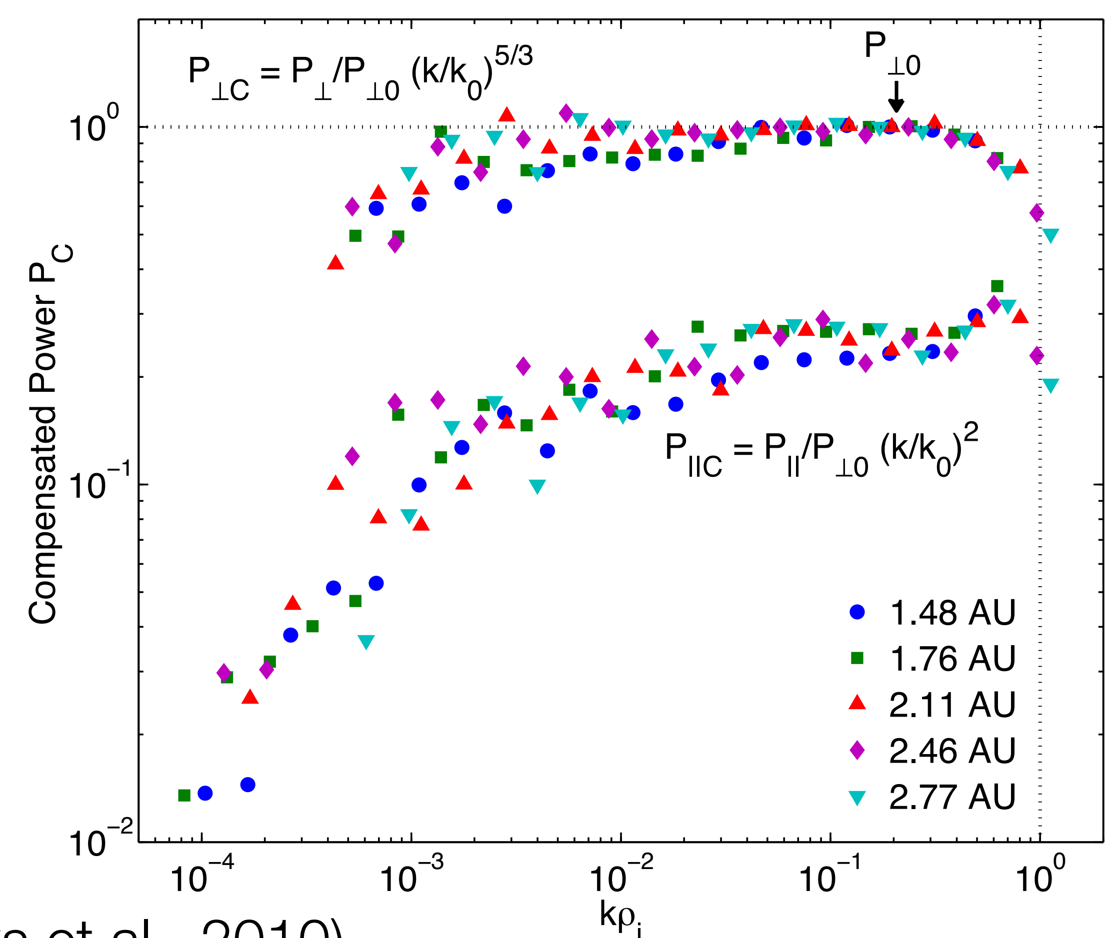
$$P_{||} \sim l^2$$

$$k_{||} \sim k_\perp^{2/3}$$

evolution is primarily in perpendicular wavenumber

Evidence for a perpendicular cascade

- Magnetic field fluctuation power shows $k^{-5/3}$ spectrum in the perp direction only
- Parallel power << perpendicular power
- Indices at high frequencies consistent with evolution to KAW



(Wicks et al., 2010)

Figure 4. Perpendicular and parallel power for each of the five periods in Table 1, compensated to remove a spectral gradient of −5/3 from the perpendicular power and −2 from the parallel.

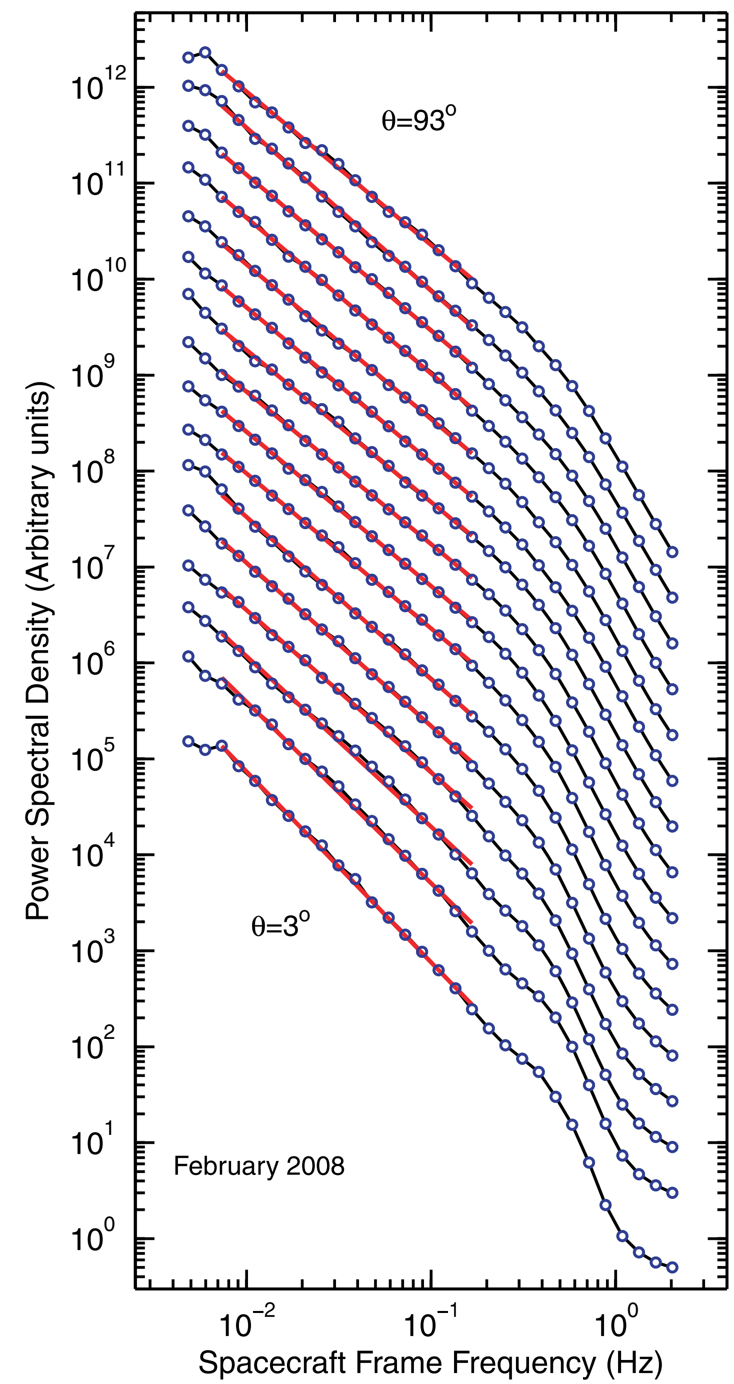


Figure 5. Power spectral density vs. frequency for angle bins centered at $\theta = 3$ (bottom), 9, 15, 21,. . . , 93 deg (top) computed using the 2008 February data in Table 1 by means of Equation (27). The different curves have been offset vertically for easier viewing.

(A color version of this figure is available in the online journal.)

(Podesta, 2009)

Alfvenic turbulence and heating

- Goldreich-Sridhar (anisotropic) turbulence - also scale free

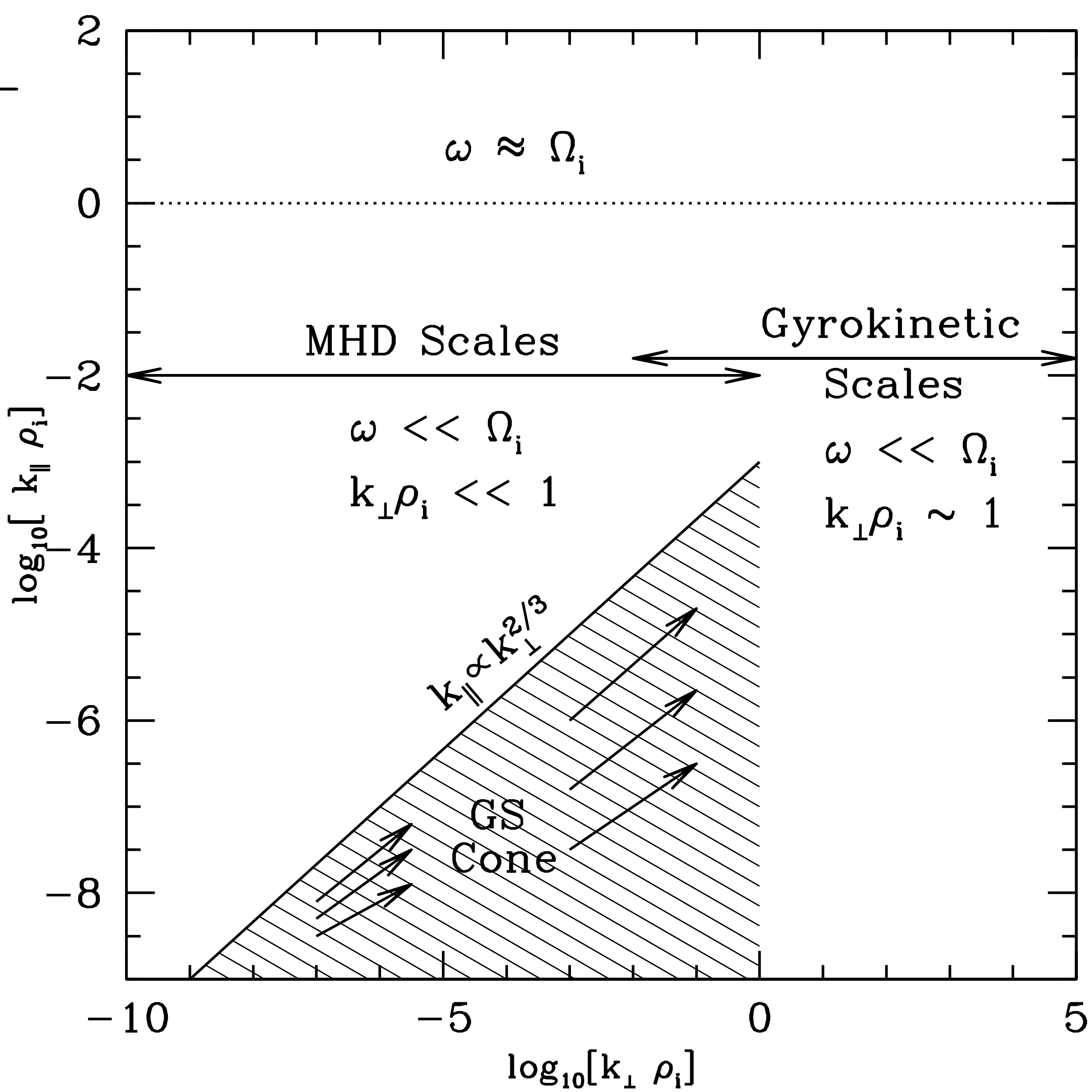
perpendicular cascade $k_{||} \ll k_{\perp}$

critical balance $\omega \sim k_{||} v_A \sim k_{\perp} v_{\perp}$

At $k_{\perp}\rho_i \approx 1$

$$\omega/\Omega_i \approx (\rho_i/L)^{1/3}\beta_i^{-1/2}$$

is very small. Far from cyclotron resonance! So we think that ω = k v_{sw} is pretty good.

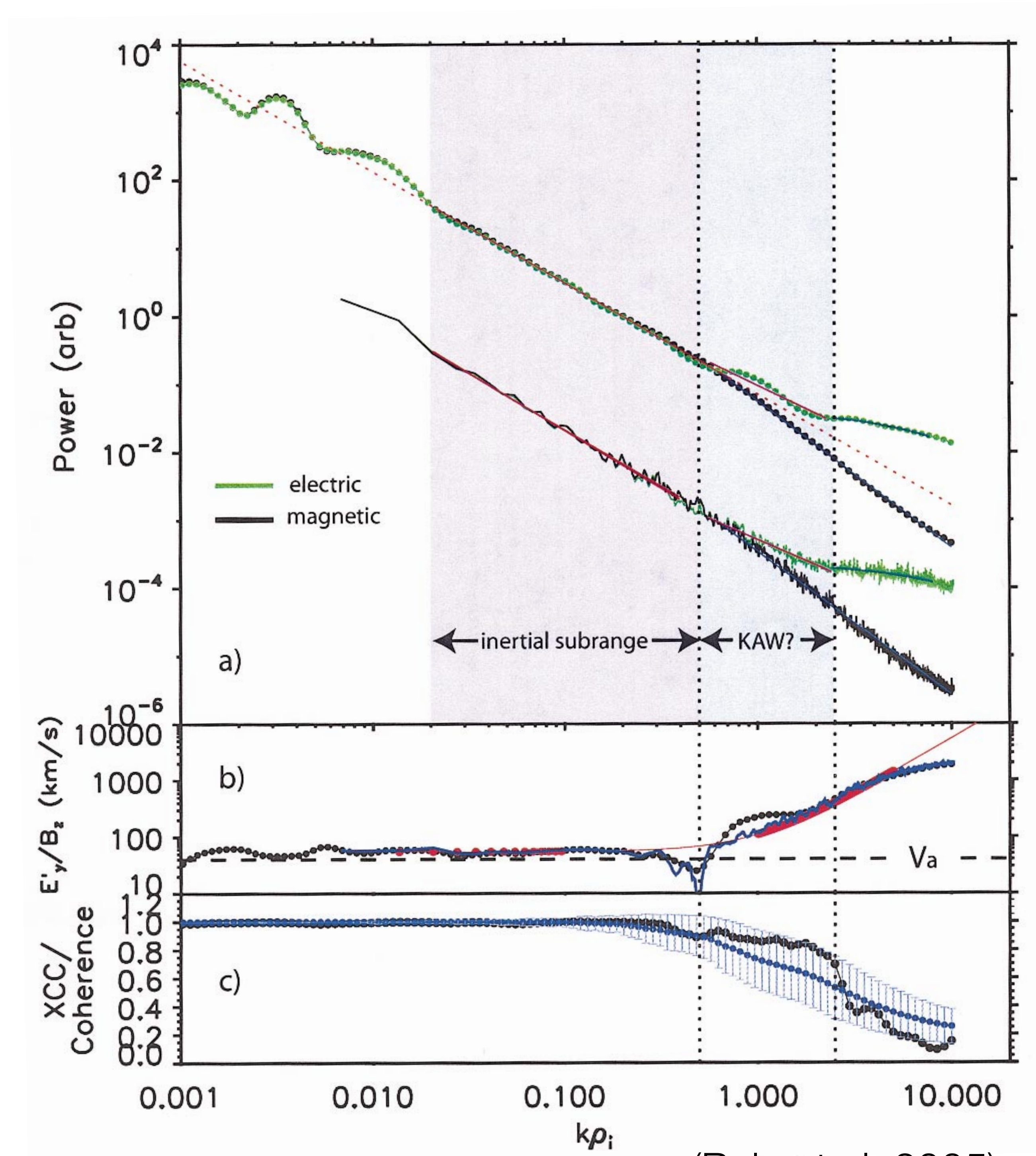


Heating is by Landau damping or transit-time damping

Evidence for a KAW/perpendicular cascade

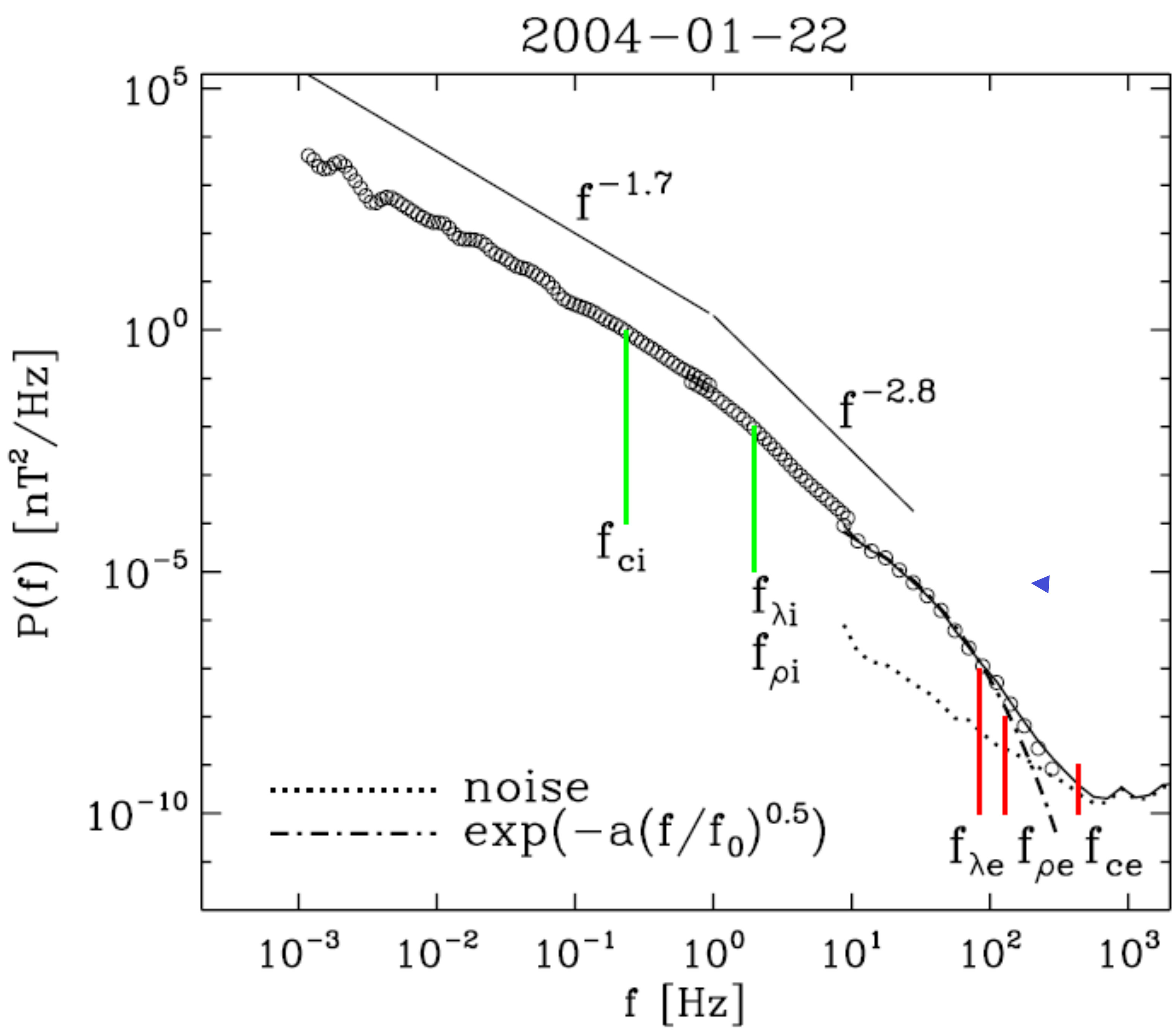
- Cluster measurements of the electric field of solar wind turbulence show that:
  1. the cascade is Alfvenic - E and B are strongly correlated
  2. the short wavelength electric field power is enhanced
  3. the E/B ratio is consistent with Alfvenic inertial range and evolution to kinetic Alfven waves at short wavelengths
  4. density spectrum is $k^{-5/3}$

Caveats:
1. Cluster is only in the solar wind for short intervals
2. Spin tones (more later...)
3. EFW noise levels and sampling rates



(Bale et al, 2005)

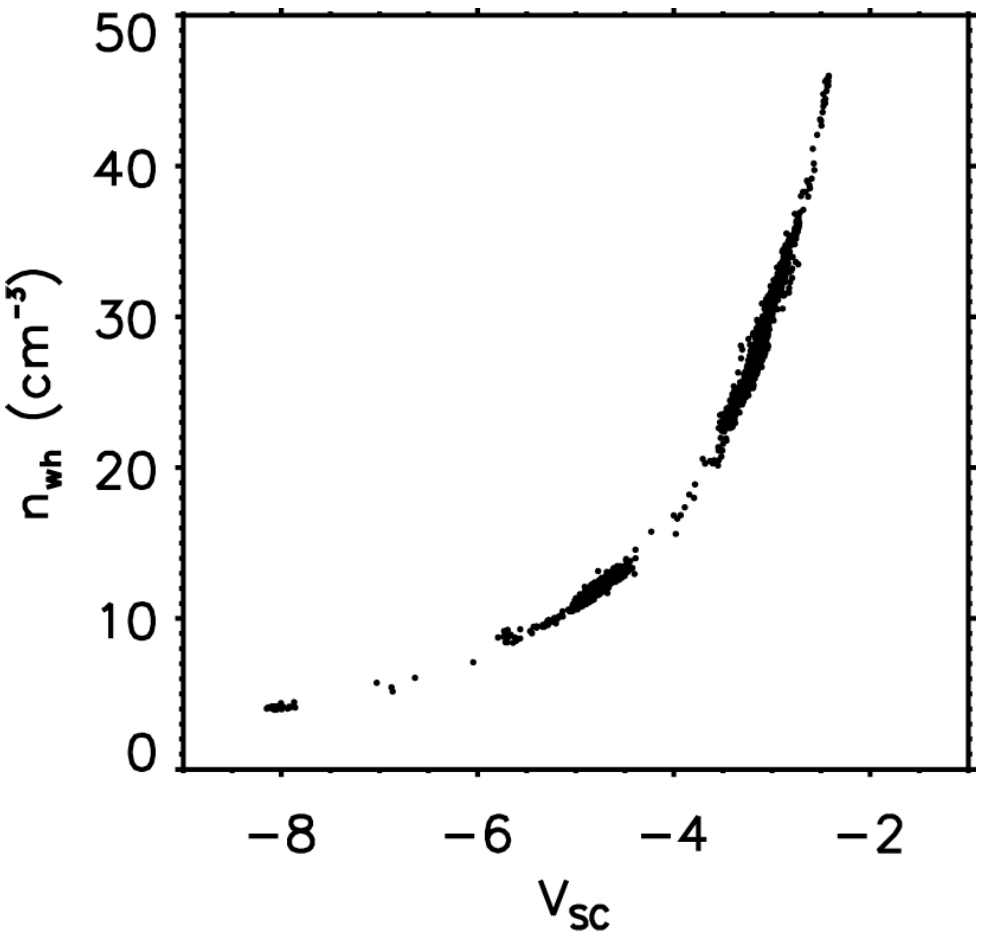
Magnetic turbulence in the Solar Wind : Evidence for slope break in the electron range

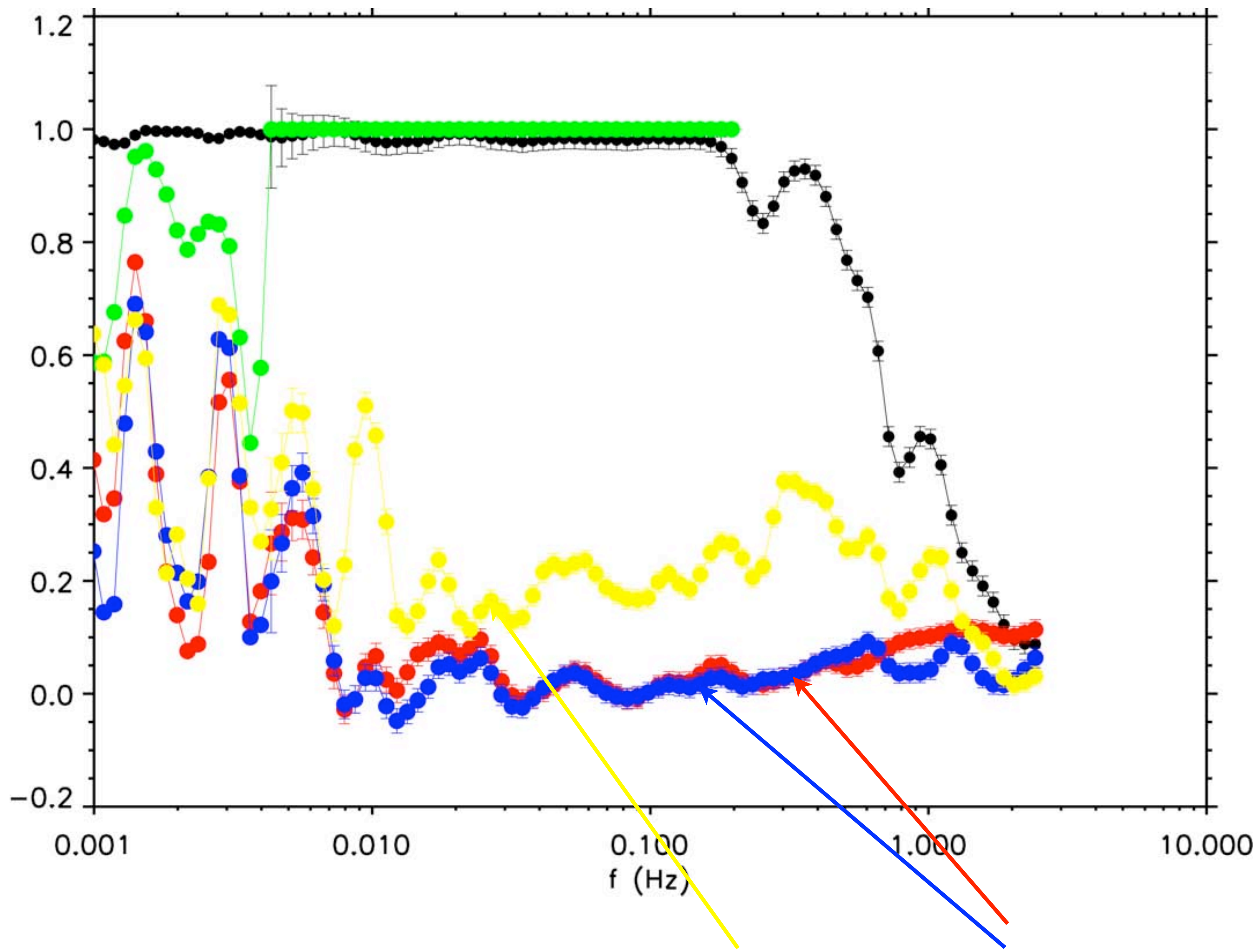


Alexandrova et al., PRL, 2009

Evidence for a perpendicular cascade

Measurements of spacecraft potential can be calibrated to give density (locally)



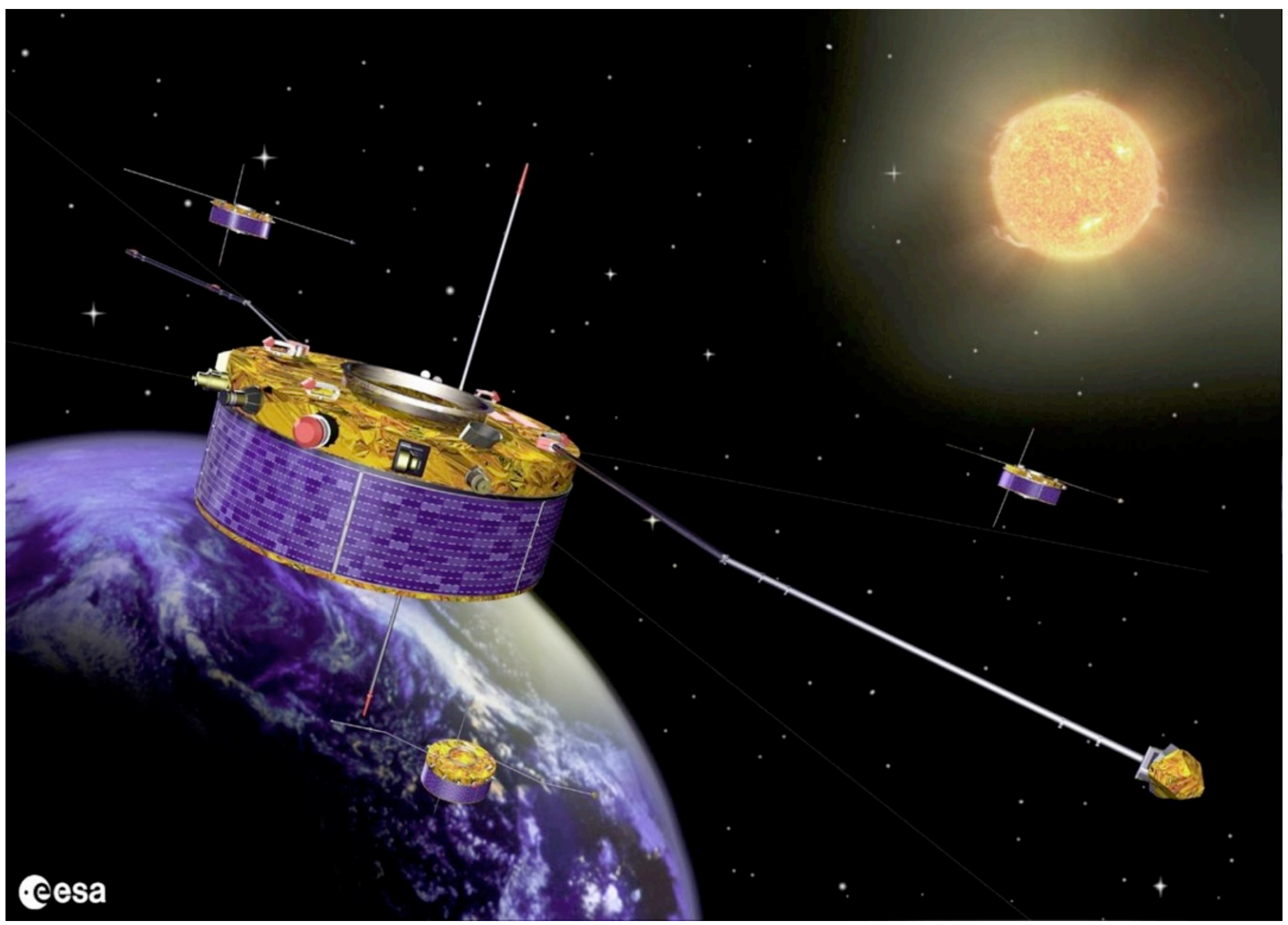


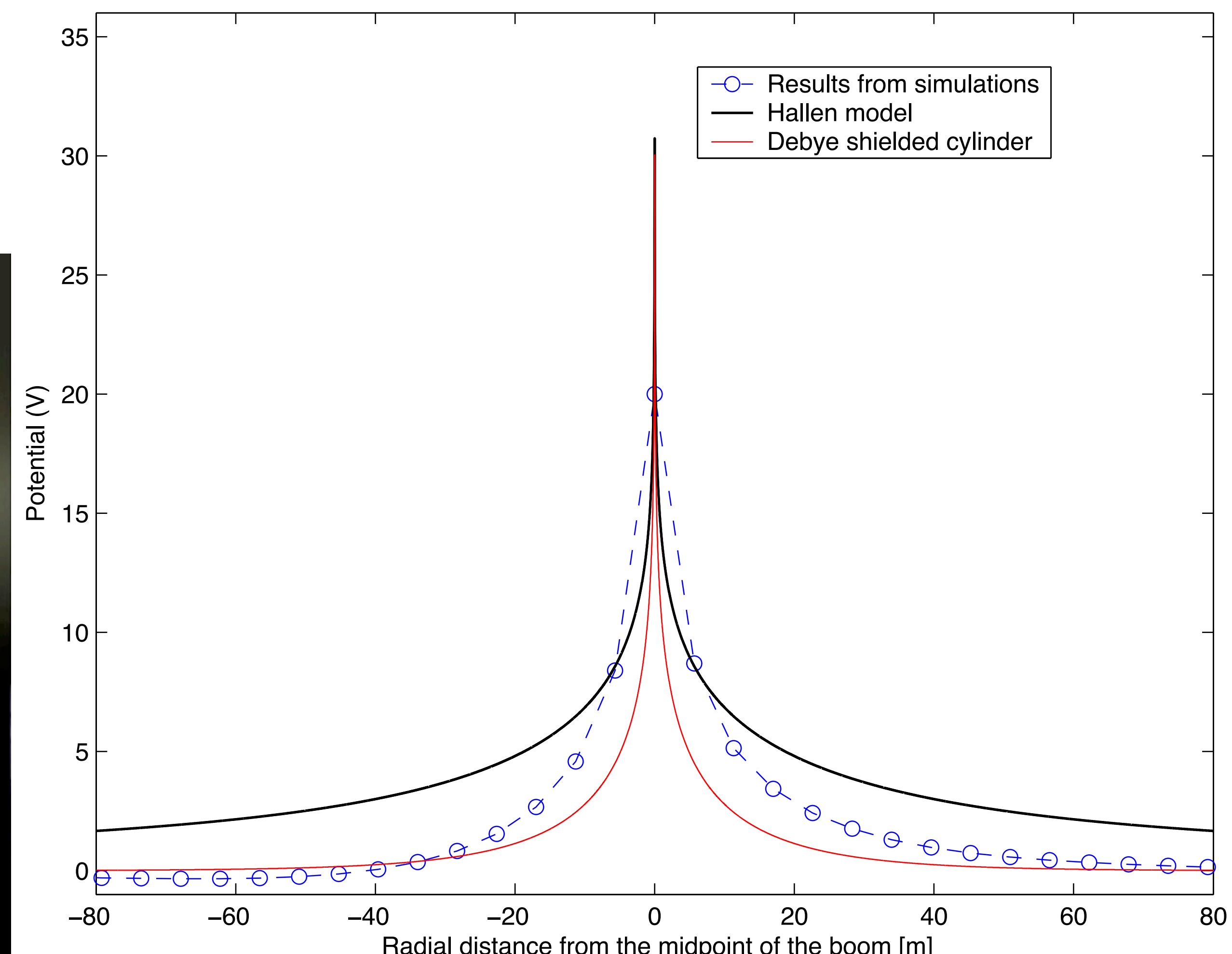
cross-correlation of density and fields

Density and fields are poorly correlated - not much compressive power!

Electric field measurements

- Voltage probes (and spacecraft) are Langmuir probes
- Current balance (thermal, photoelectron, secondaries) determines floating voltage





Cluster (and THEMIS) satellites have double-probe measurements, but ecliptic plane wire booms spin through the plasma wake (and have large photoelectron variations)

Electric field measurements

- Voltage probes (and spacecraft) are Langmuir probes
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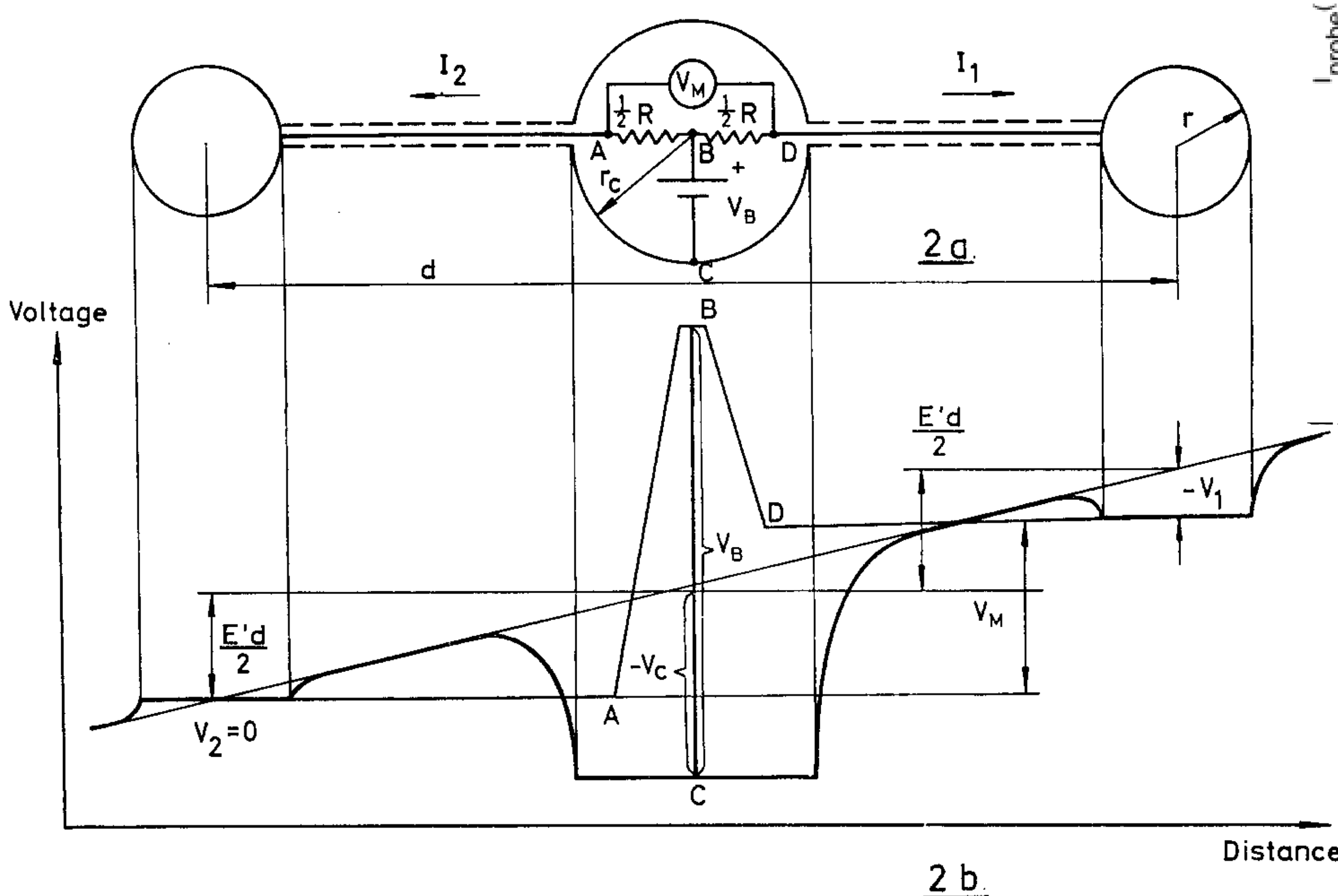
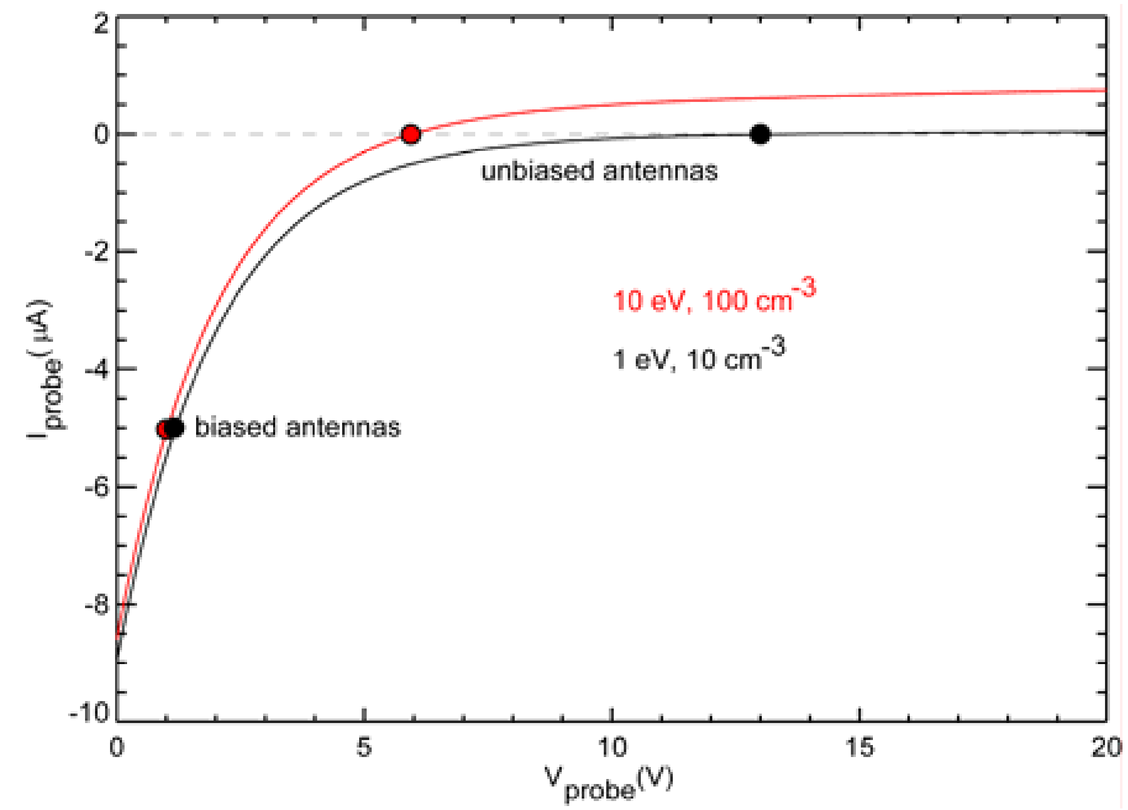


Fig. 2. Three-electrode probe system. Potential along a line in the plasma through the probes and along a line through the lead *ABD*.

(Fahleson)

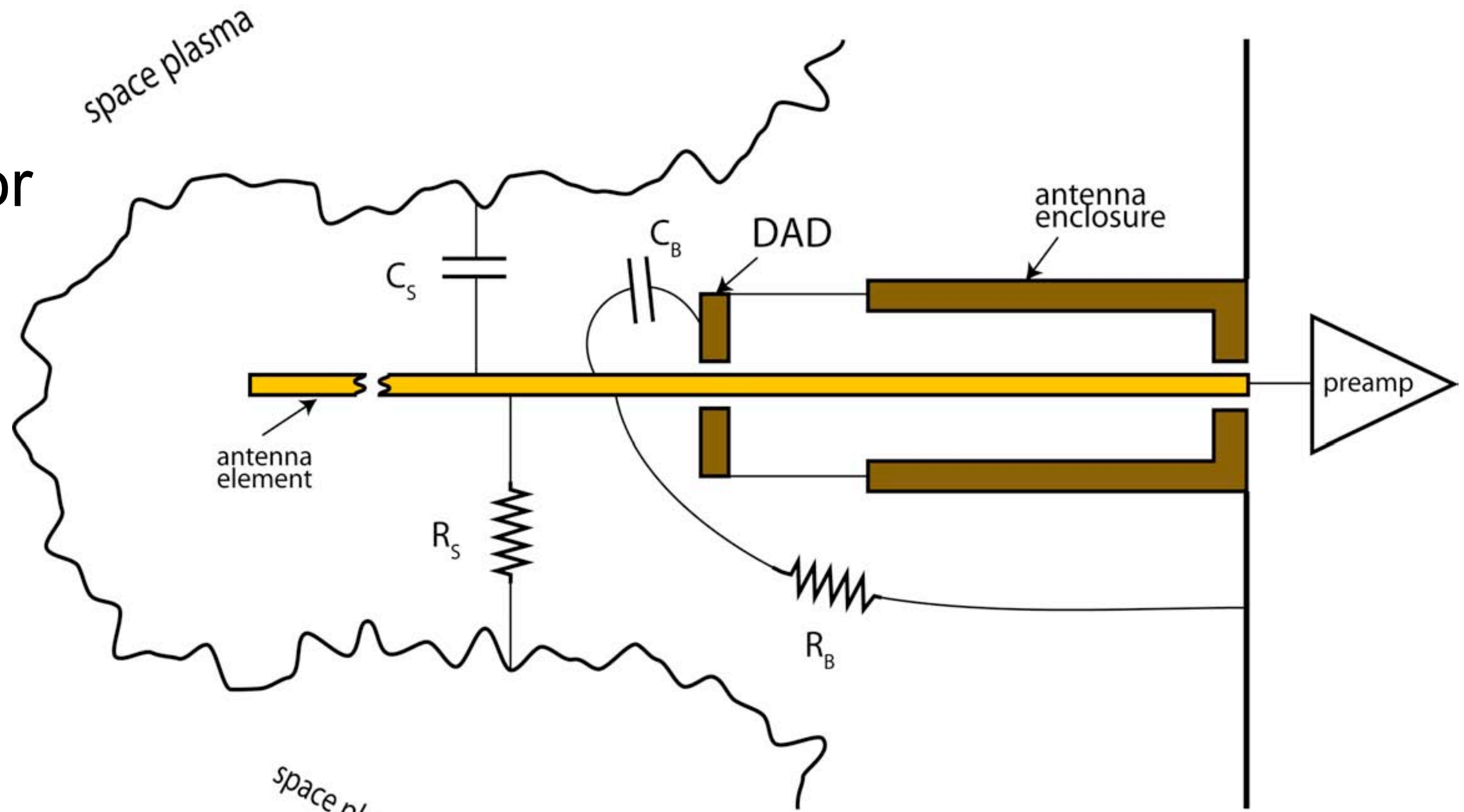


- Bias current minimizes voltage variations due to natural currents
- Unbiased probes measure primarily current variations - this is historically the case for SW experiments

LF/DC electric field measurements

Good LF gain requires that we maximize the base resistance R_B or minimize or control R_s

$$G_{LF} \approx \frac{R_B}{R_S + R_B}$$



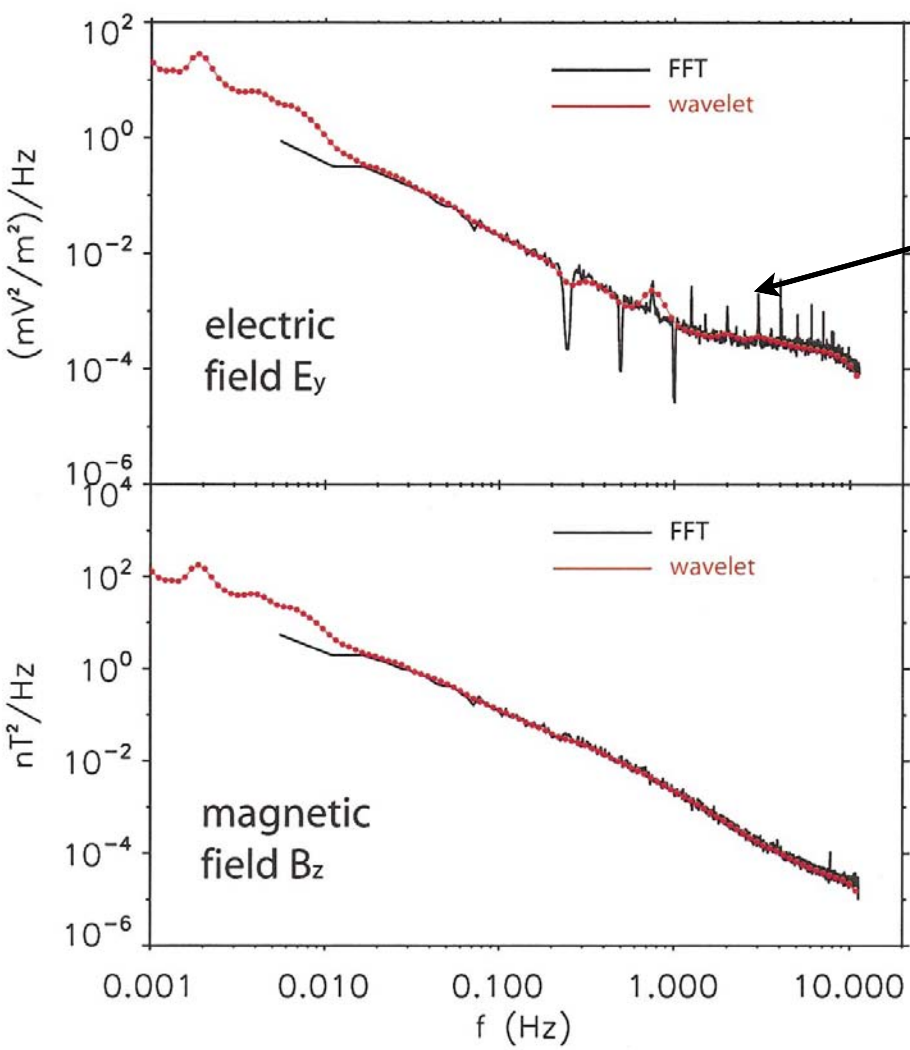
in shadow $R_s \sim T_e/j_p$ which is highly variable
in sunlight $R_s \sim V_p/(j_e + j_{bias})$ which is smaller, less variable, and easier to control

to make R_b large, minimize electron exchange between the spacecraft and sensors
- put sensors far from spacecraft (ie. sensors at the end of booms)
- put up a voltage barrier (voltage ‘guard’ surfaces)

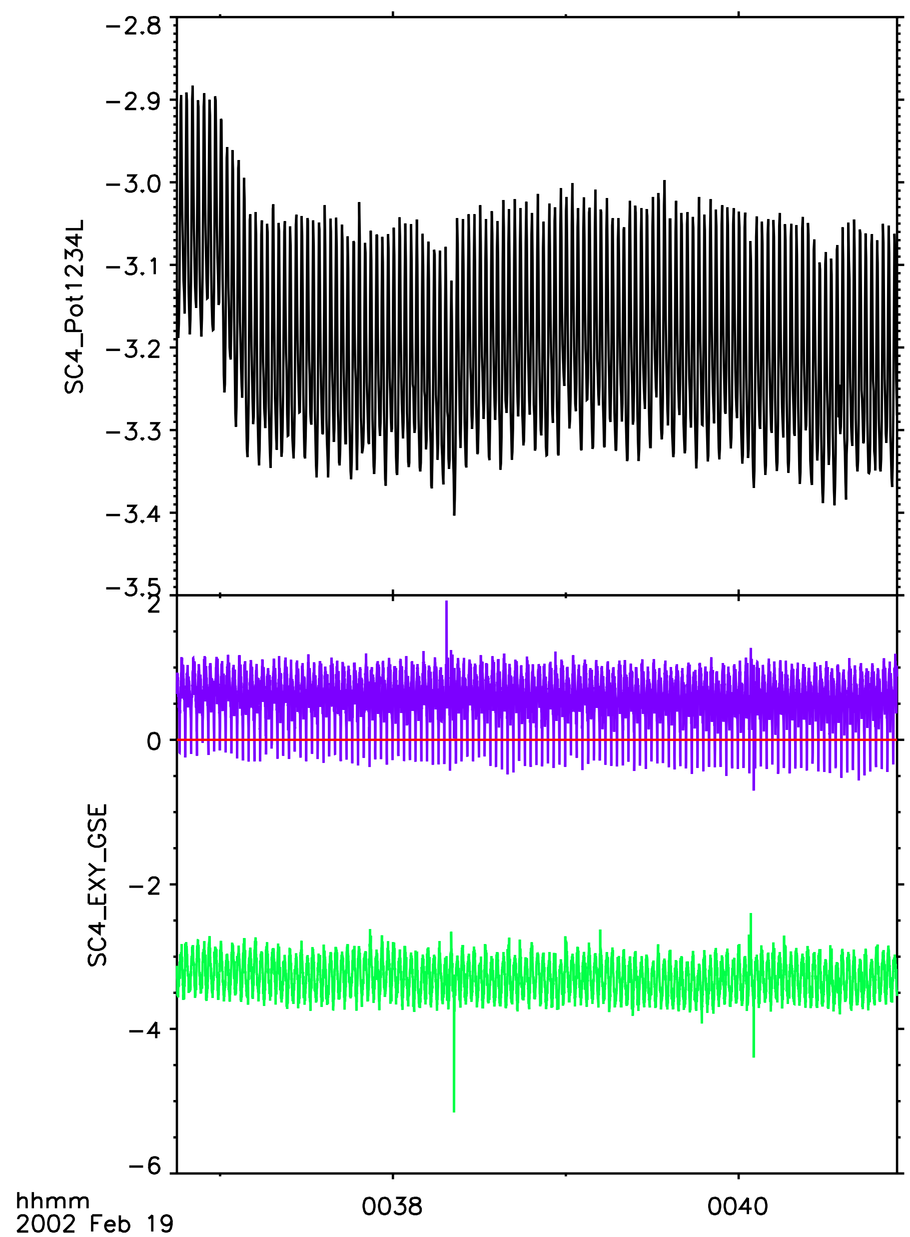
sensors are acting as Langmuir probes - put them as CLOSE as possible to each other on the I-V curve
- R_s and R_b should be same for each antenna - symmetry w.r.t the Sun is critical!

summary: antennas *in sunlight* with *good symmetry* and *away from the wake* and shorter λ_D allows the measurement of DC/LF electric field

Electric field measurements in the solar wind

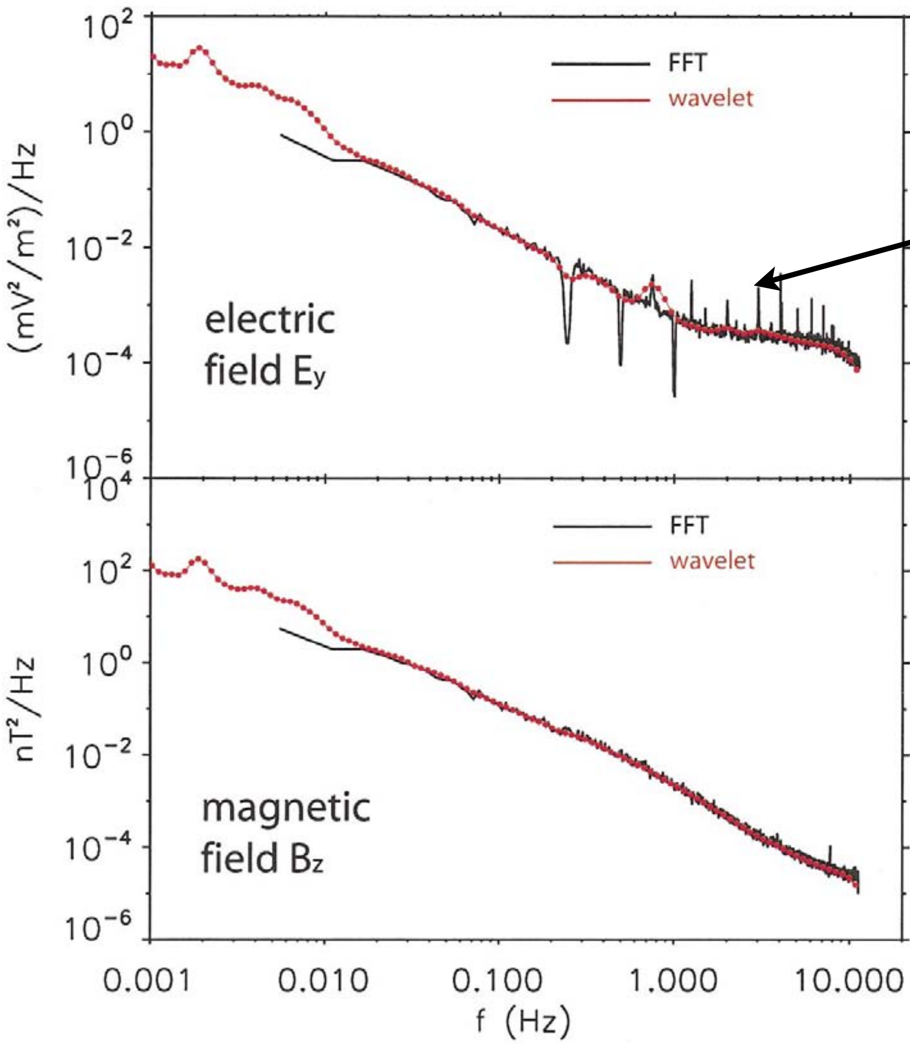


- Longer booms are better (for SNR), however spin-tones occur in the most interesting frequency range!
- Minimize variations in solar illumination



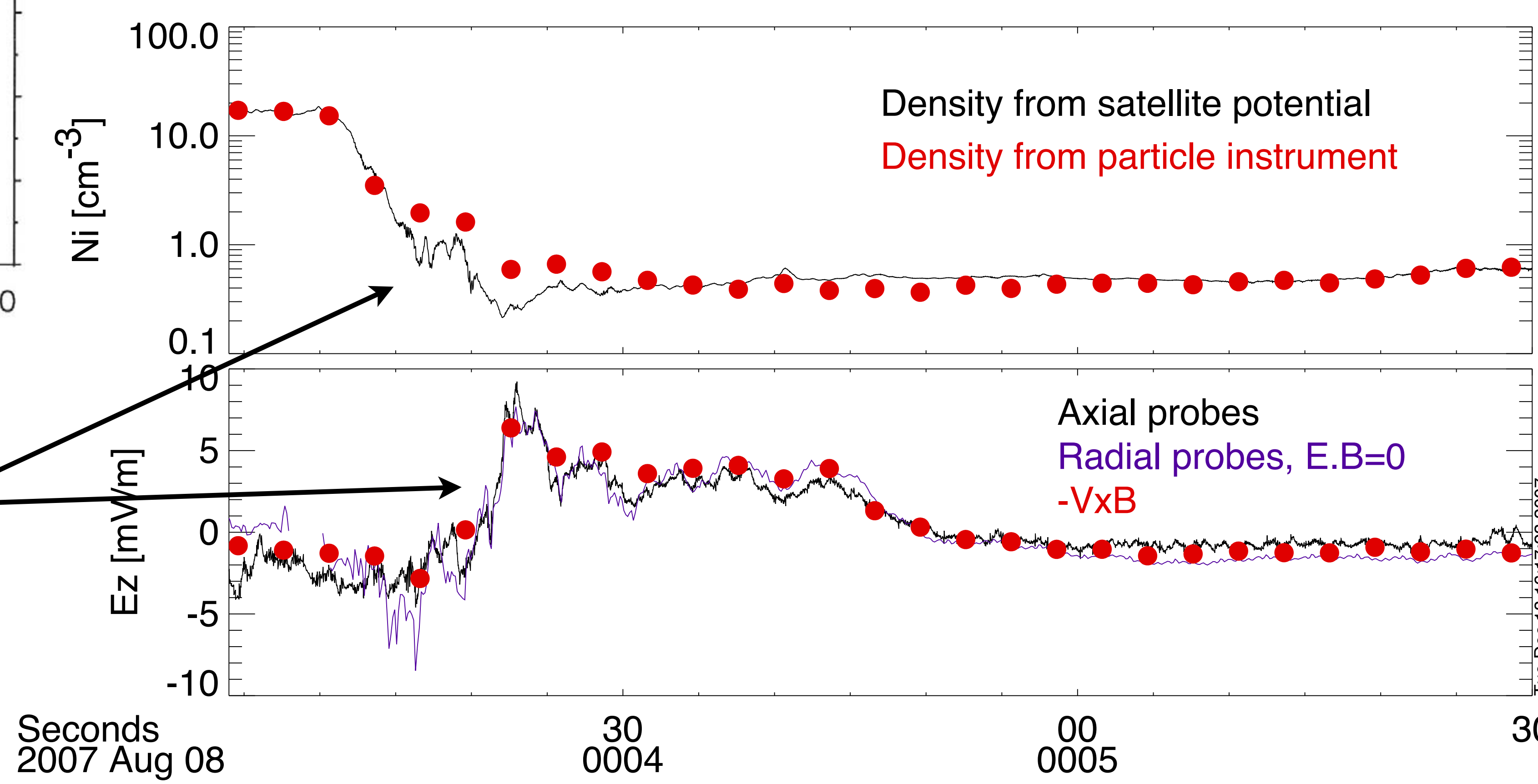
raw voltage data with spin tone

Electric field measurements in the solar wind



- Longer booms are better (for SNR), however spin-tones occur in the most interesting frequency range!
- Minimize variations in solar illumination

- Short axial booms can do pretty well, especially when λ_D is small



Magnetic field measurements

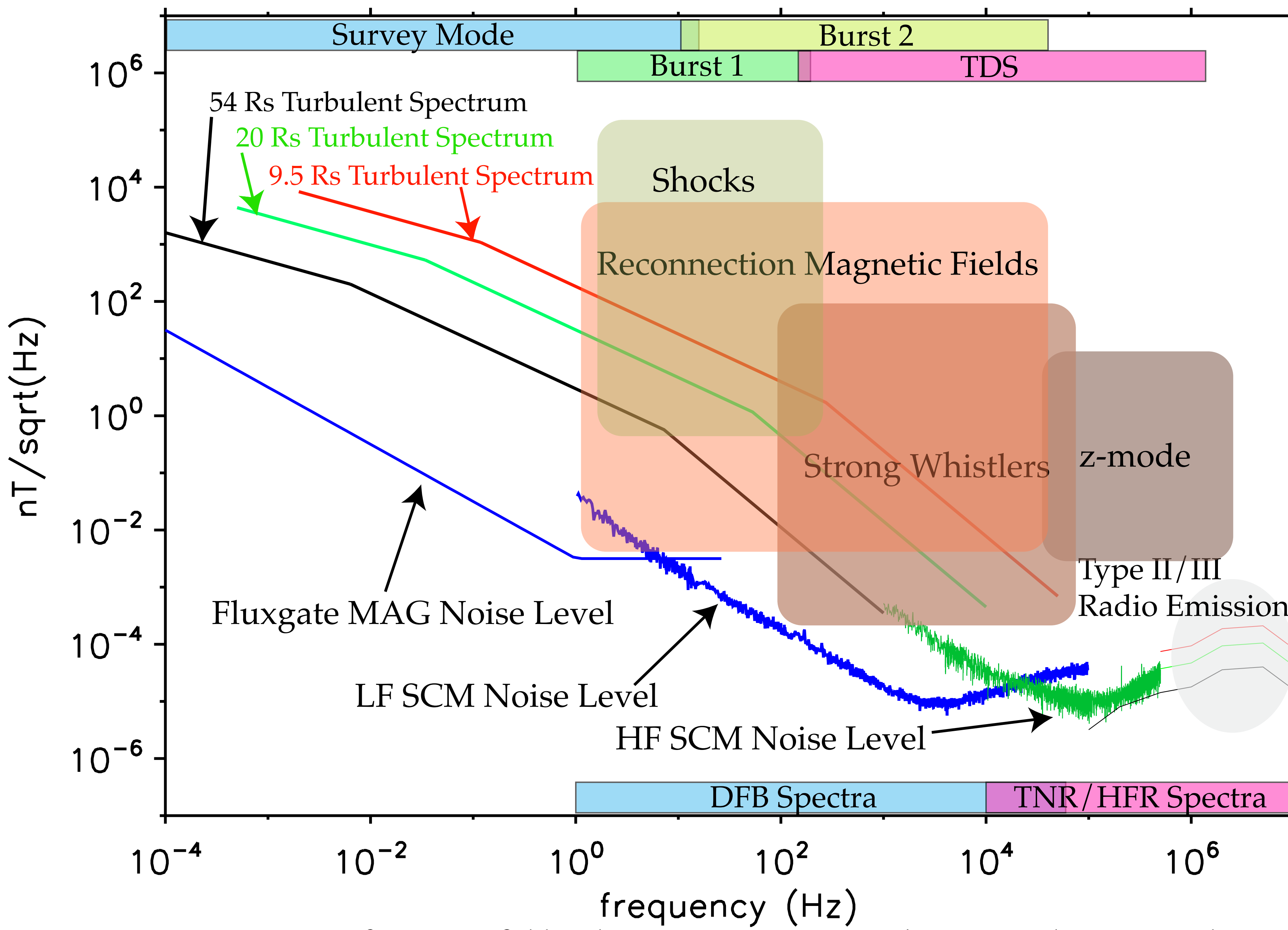
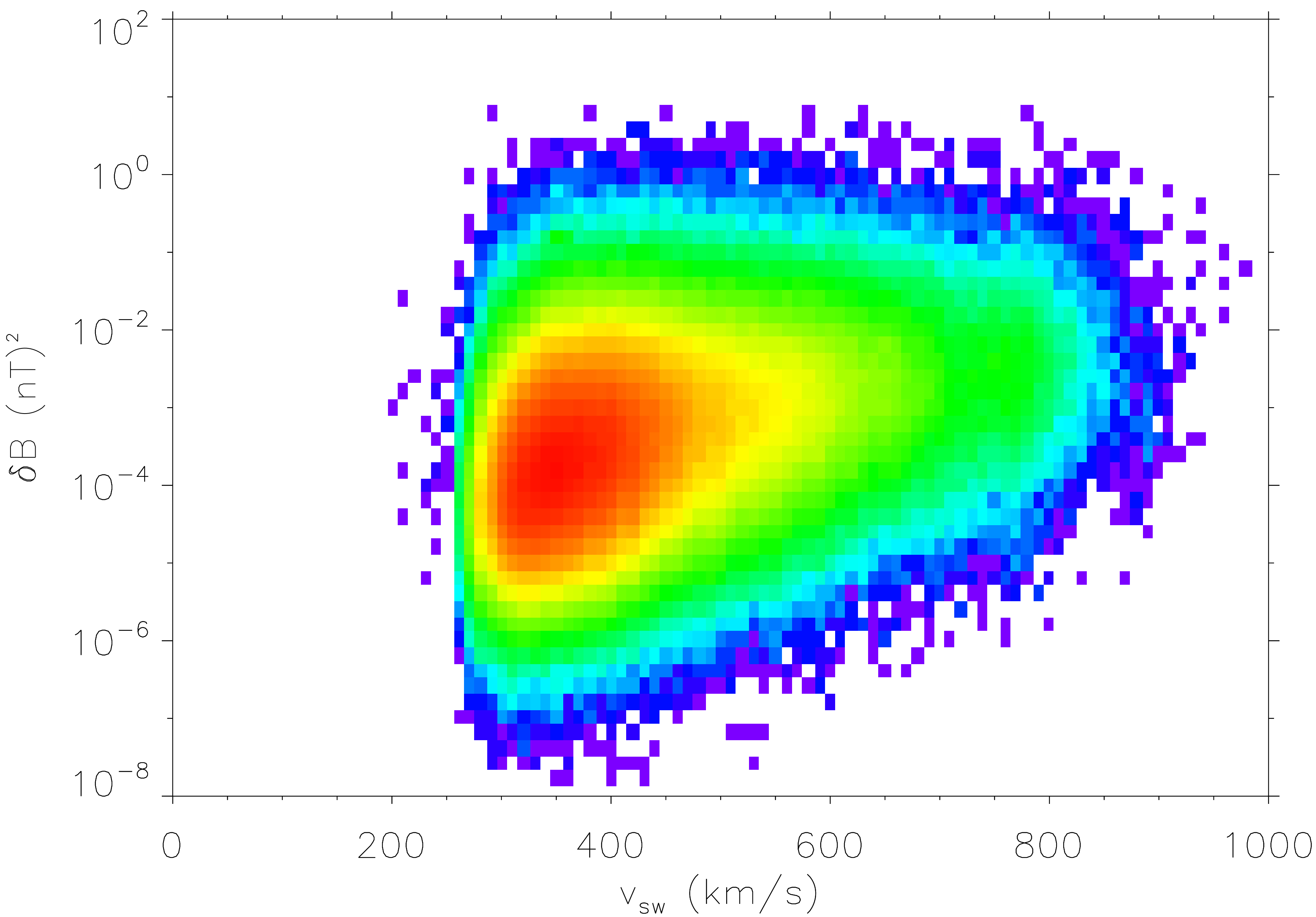


Figure D.2-6. Sensitivity of magnetic field and waves measurements. The SCM and MAG together cover the full range of required measurements. SCM becomes more sensitive than MAG at ~10 Hz. The HF SCM measures z-mode, very intense radio bursts, and very fast solitary waves.

δB^2 vs solar wind speed

high speed wind has larger magnetic fluctuation levels δB - this is well known

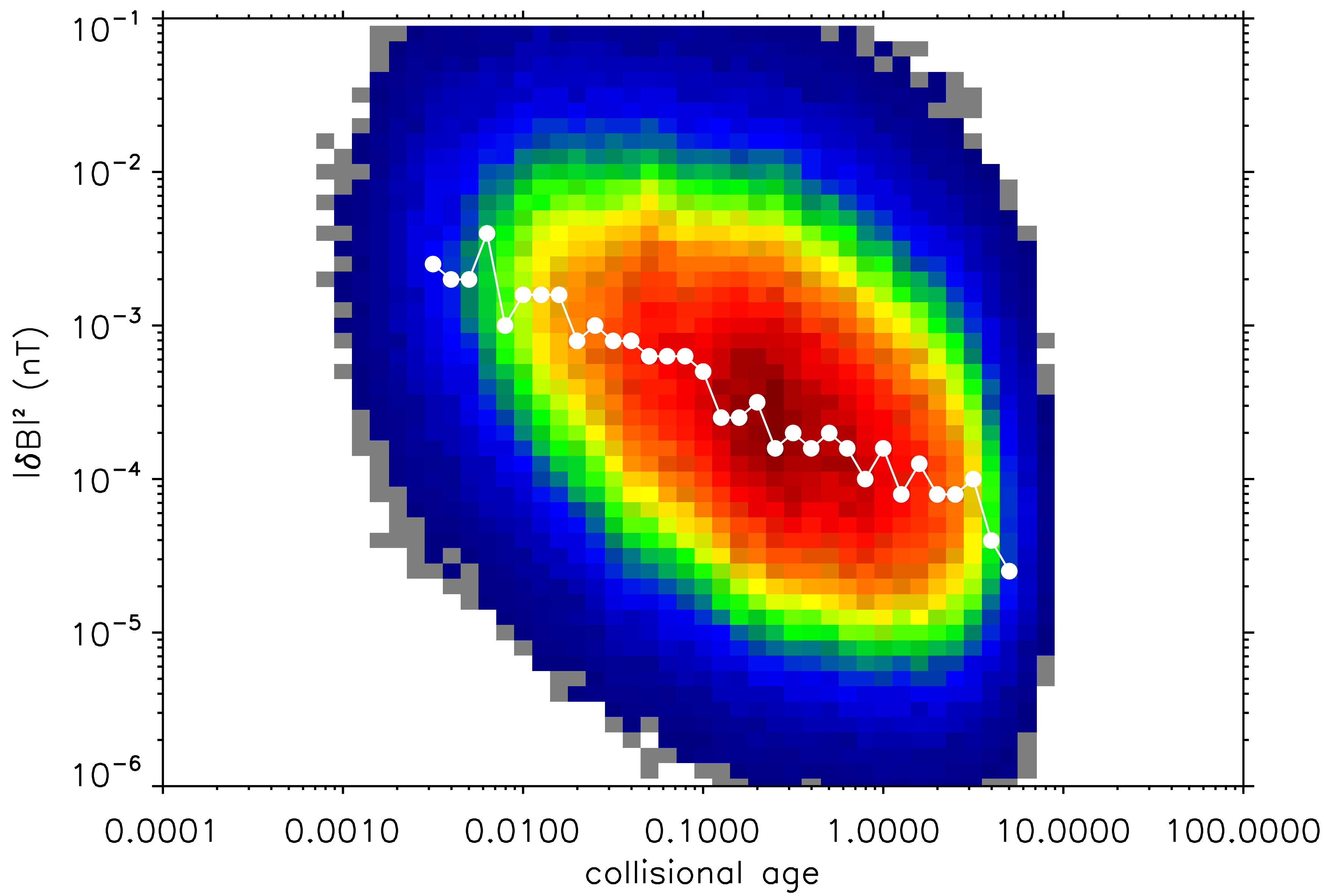
- is there something special about the source?



δB^2 vs collisional age

on the other hand, 'age' = ν R/v_{sw} is a measure of the number of Coulomb collisions since leaving the Sun. So maybe it's not the source (alone) but rather the local evolution

More 'active' plasma is more collisionless

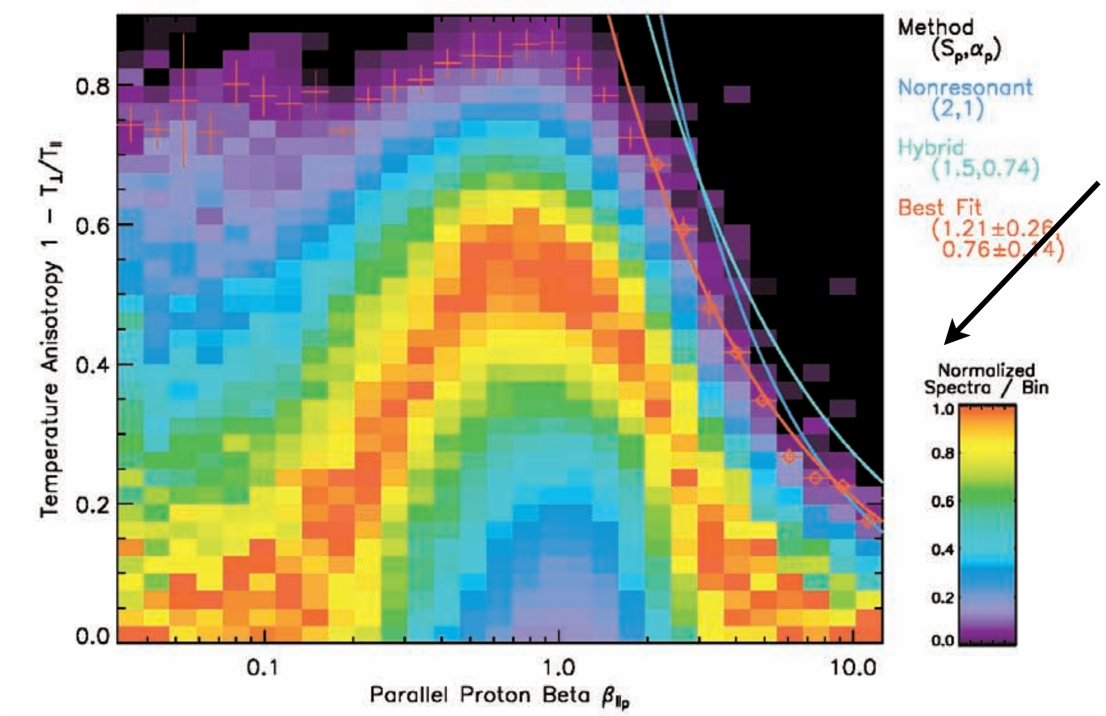


Local instabilities inject power directly at small scales

- Ion pressure anisotropy instabilities
    - Mirror and/or AIC for $T/T > 1$
    - Firehose for $T/T < 1$
- Electron pressure anisotropy instabilities
- Streaming instabilities
    - proton-proton
    - proton-alpha
- Heat flux instabilities
- Electron beam instabilities
    - Langmuir/beam mode generation at near f_{pe}

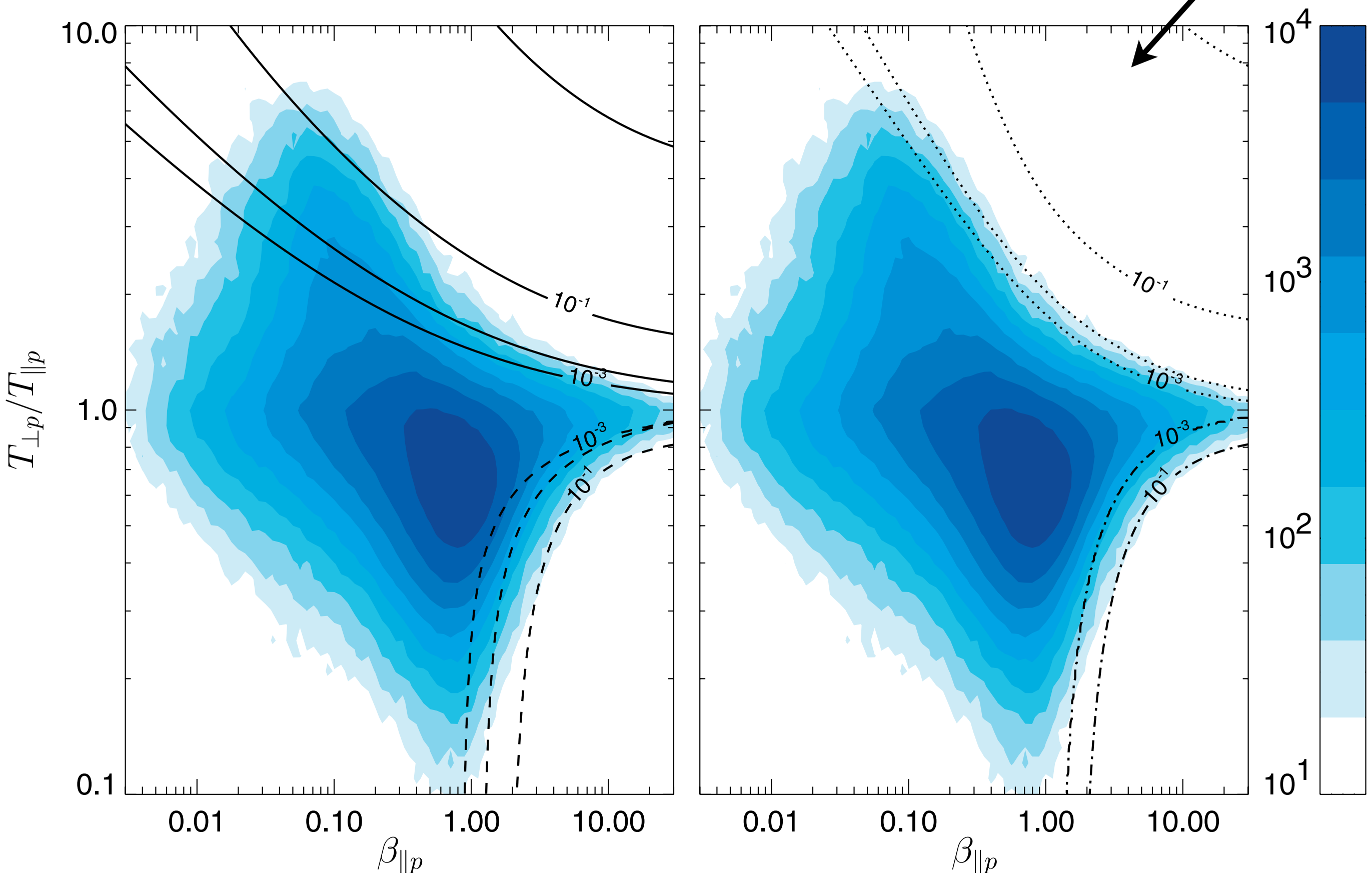
These instabilities will generate power at $k\rho_i$ ~1 or shorter

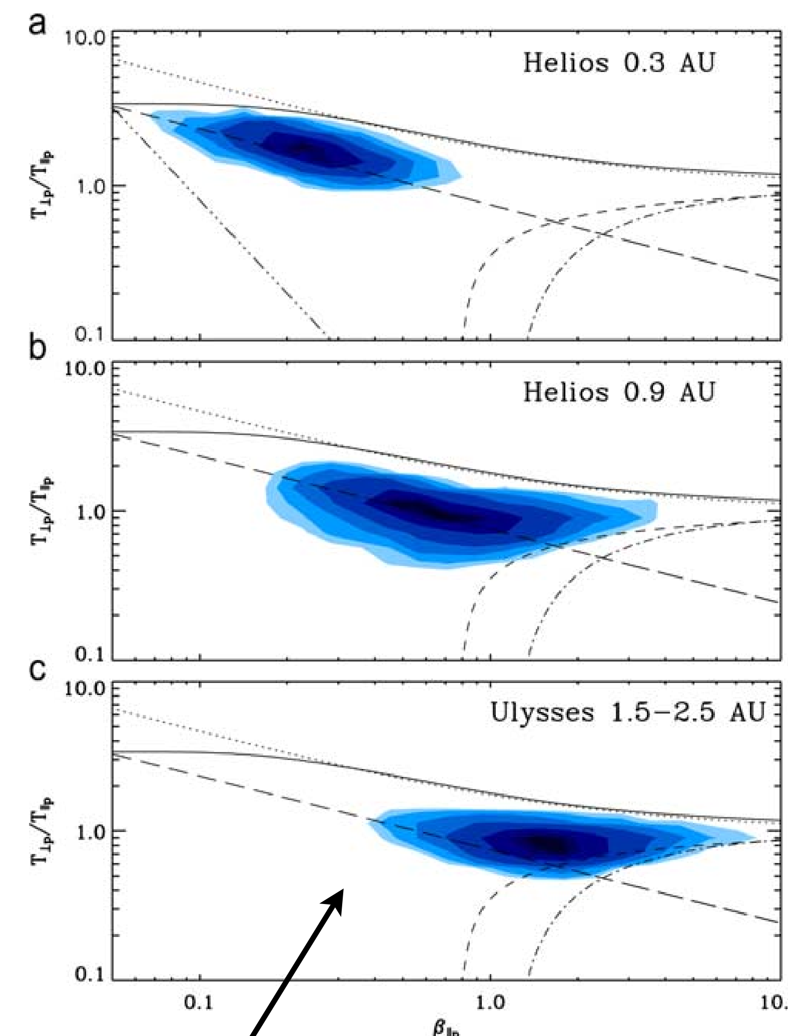
Proton pressure anisotropy



Firehose limits
(Kasper et al, 2002)

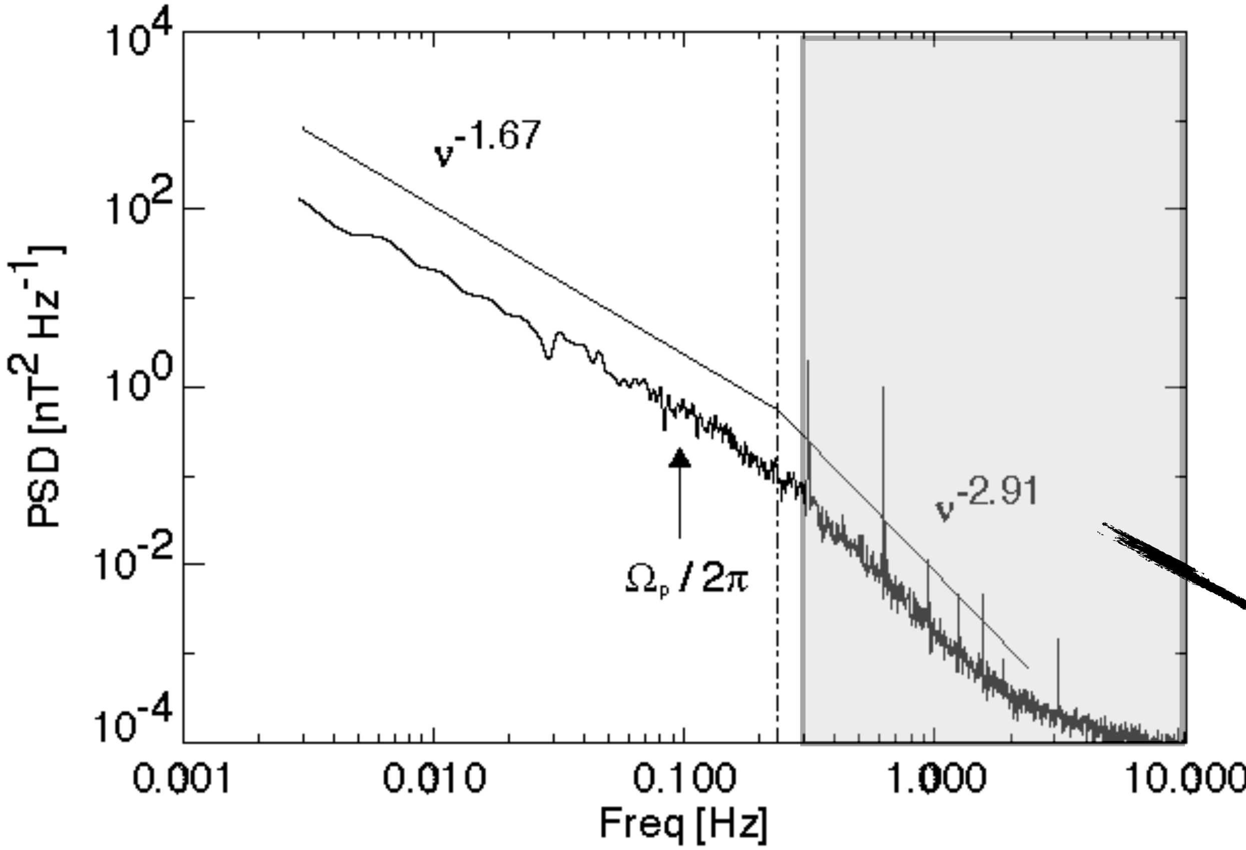
Mirror, AIC, and
oblique firehose
(Hellinger et al, 2006)





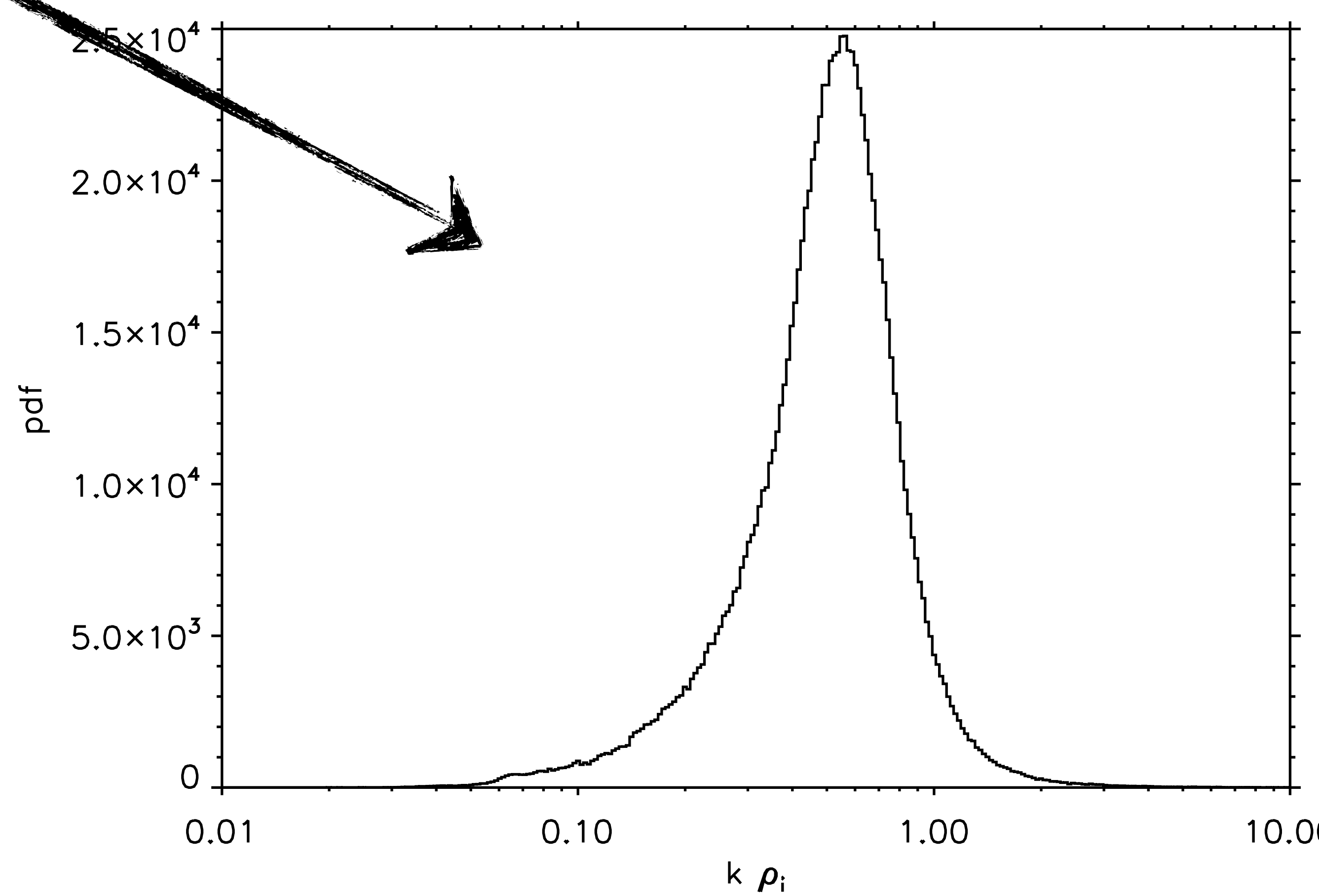
Fast wind evolution
and constraints
(Matteini et al, 2007)

WIND magnetic field data - bandwidth



(Leamon et al., 1998)

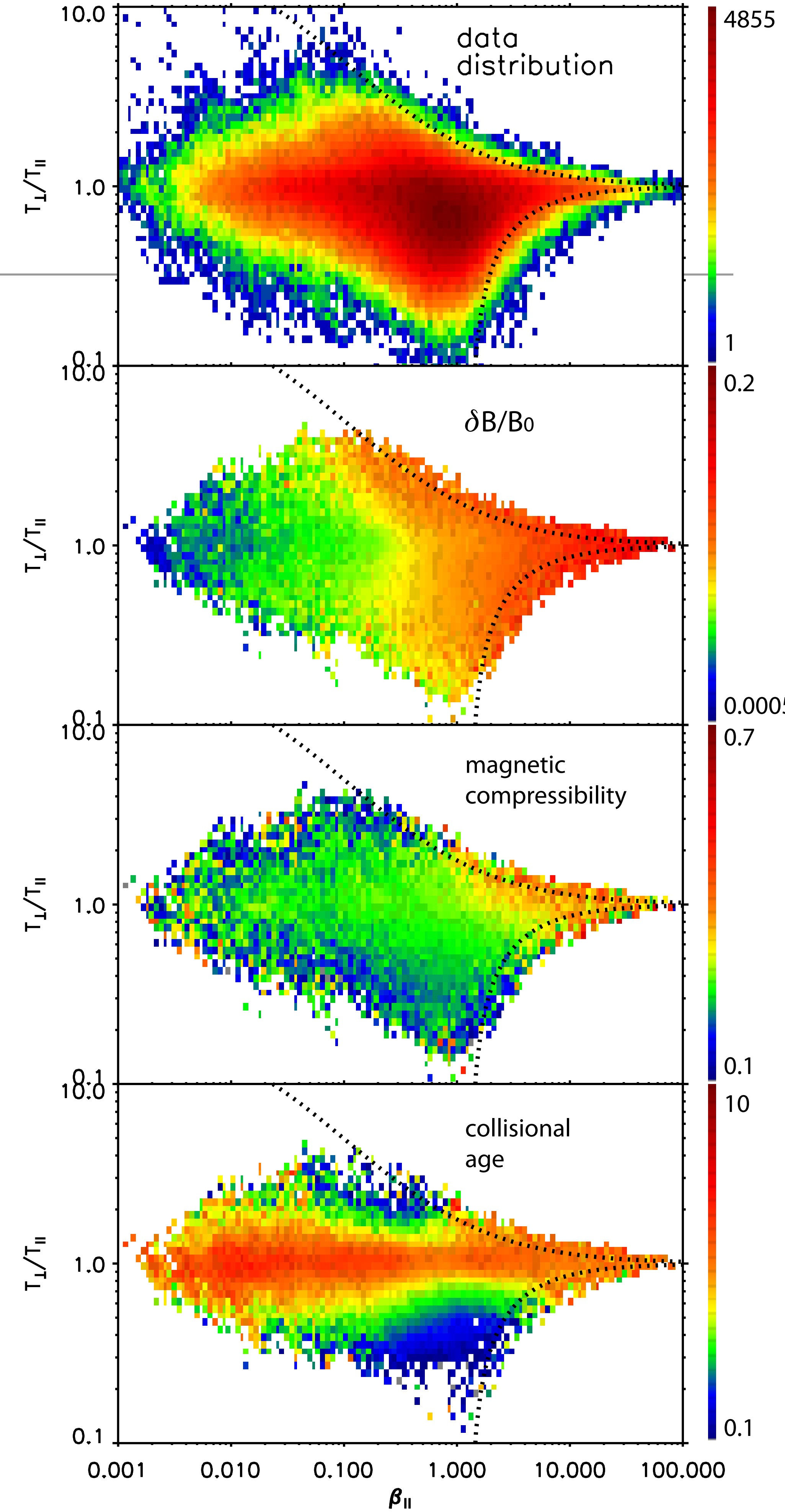
magnetic fluctuation data integrated over this band (3 sec and faster)...



...corresponds to $k\rho_i \sim 0.6$
(in part, because $T_p \sim v^2_{sw}$)

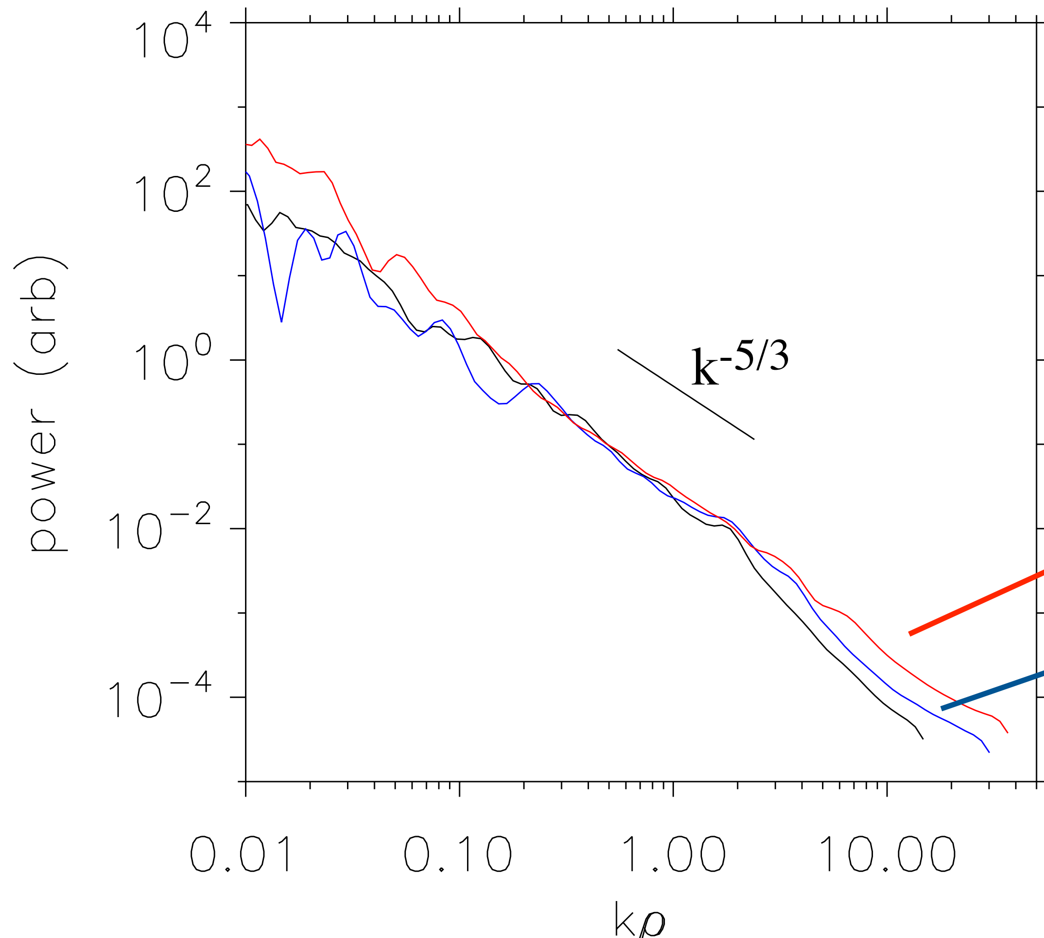
Proton anisotropy instabilities

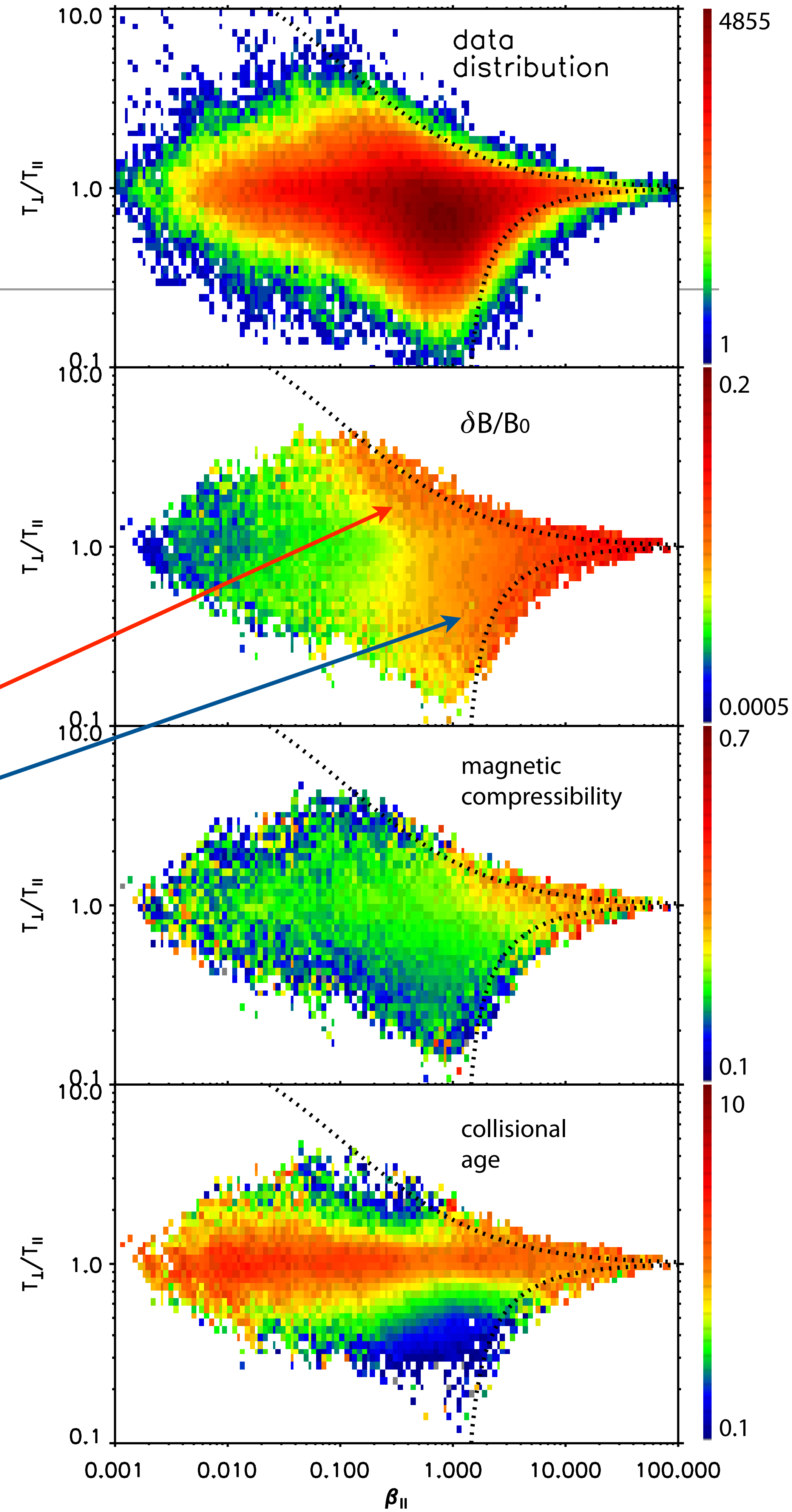
- Solar wind expansion and compression drive the proton distributions towards pressure-anisotropy instability thresholds
  1. Alfven/Ion-cyclotron
  2. Mirror mode
  3. Oblique firehose instability
- Wind measurements show δB fluctuations associated with instability thresholds, suggest mirror and oblique firehose (no δE measurements!)
- These instabilities inject fluctuation power directly at k ρ ~ 1 (in contrast to the turbulent cascade)



(Bale et al., 2009)

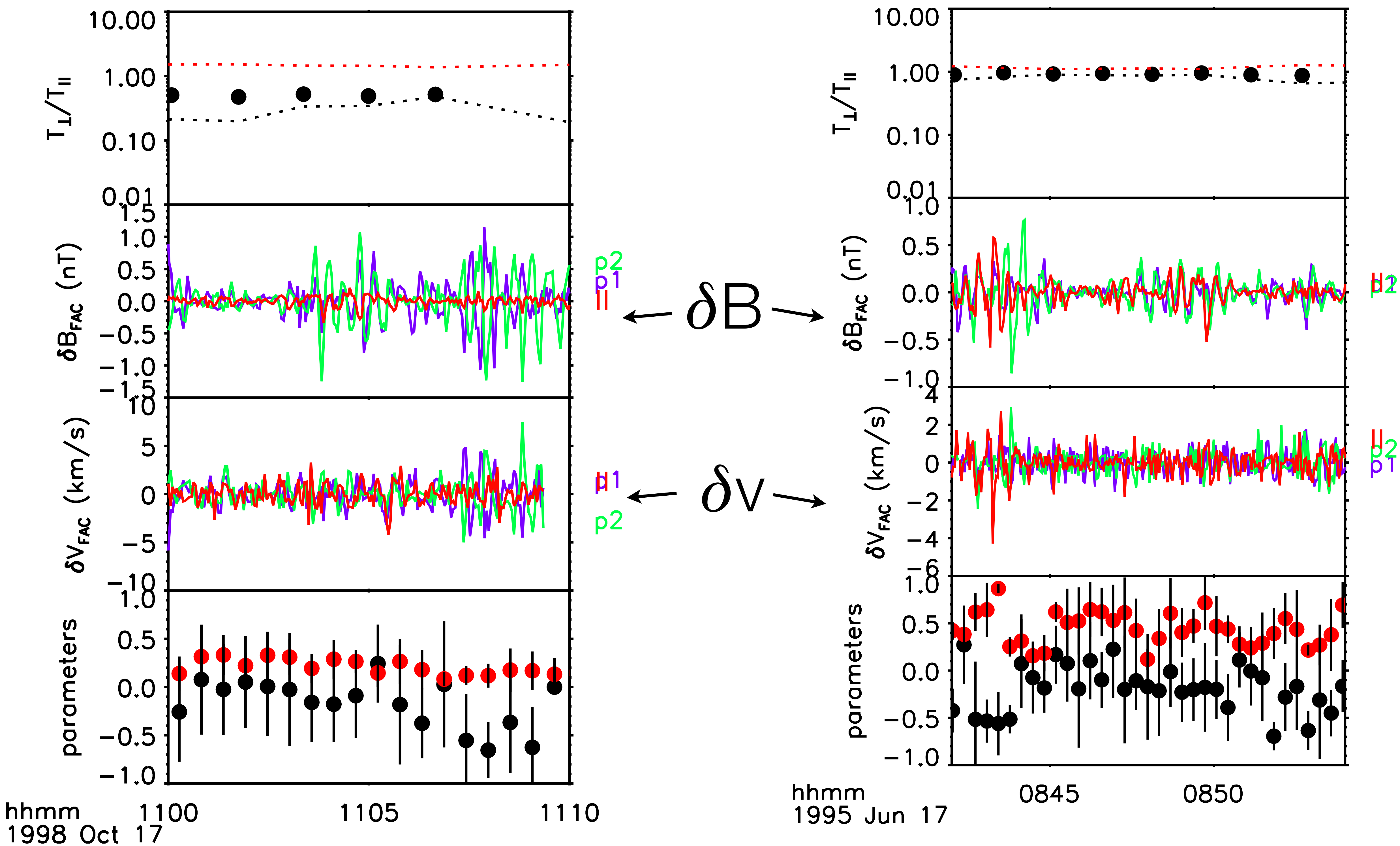
Proton anisotropy instabilities



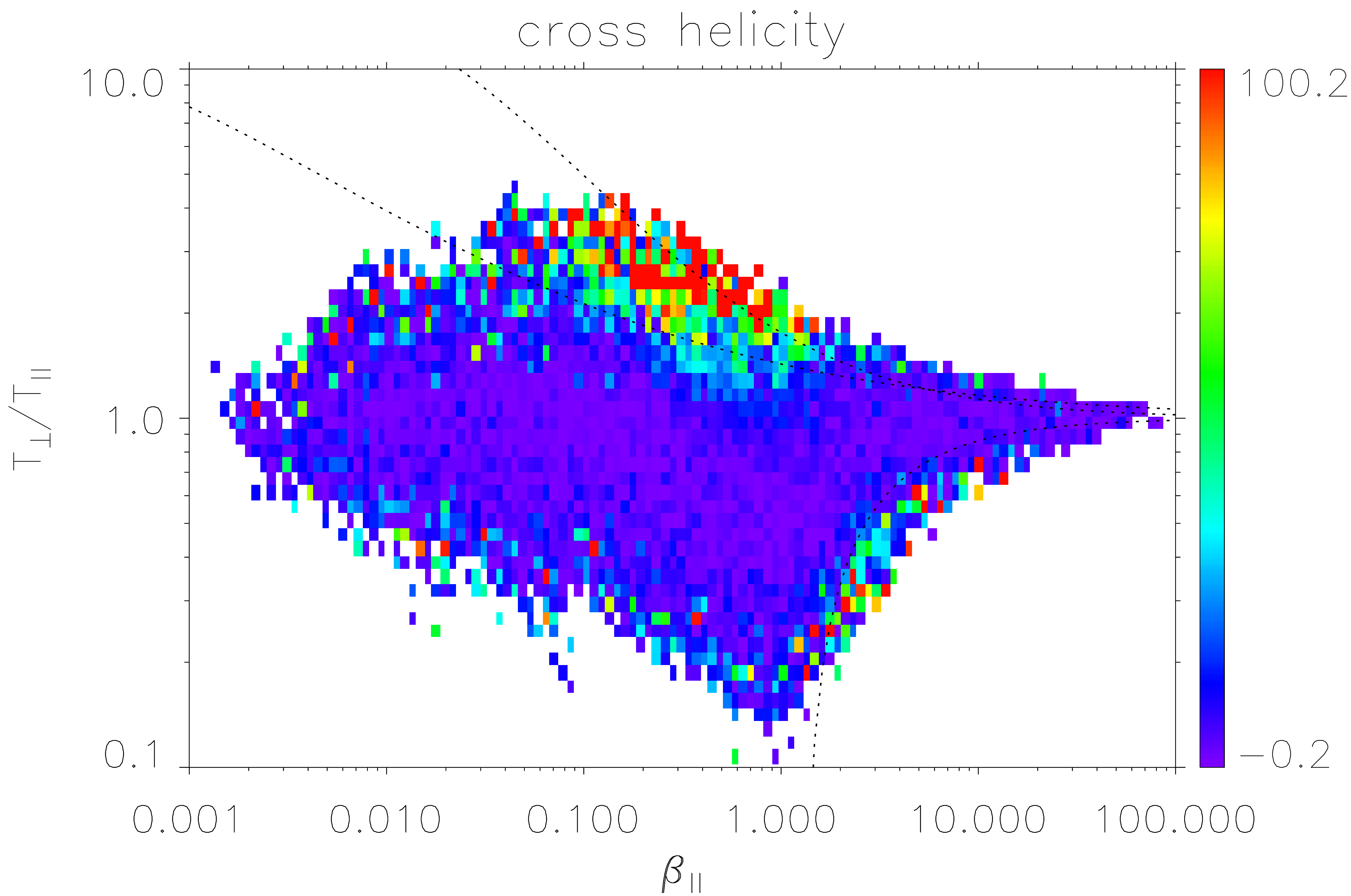


- black = isotropic, red = perp anisotropy, blue = parallel anisotropy
- white noise removed
- power at this intensity and bandwidth appears in the 'dissipation' (KAW) range
- any meaningful study of turbulent (wave-wave) dissipation must address the locally generated fluctuations

Proton anisotropy instabilities - δv data

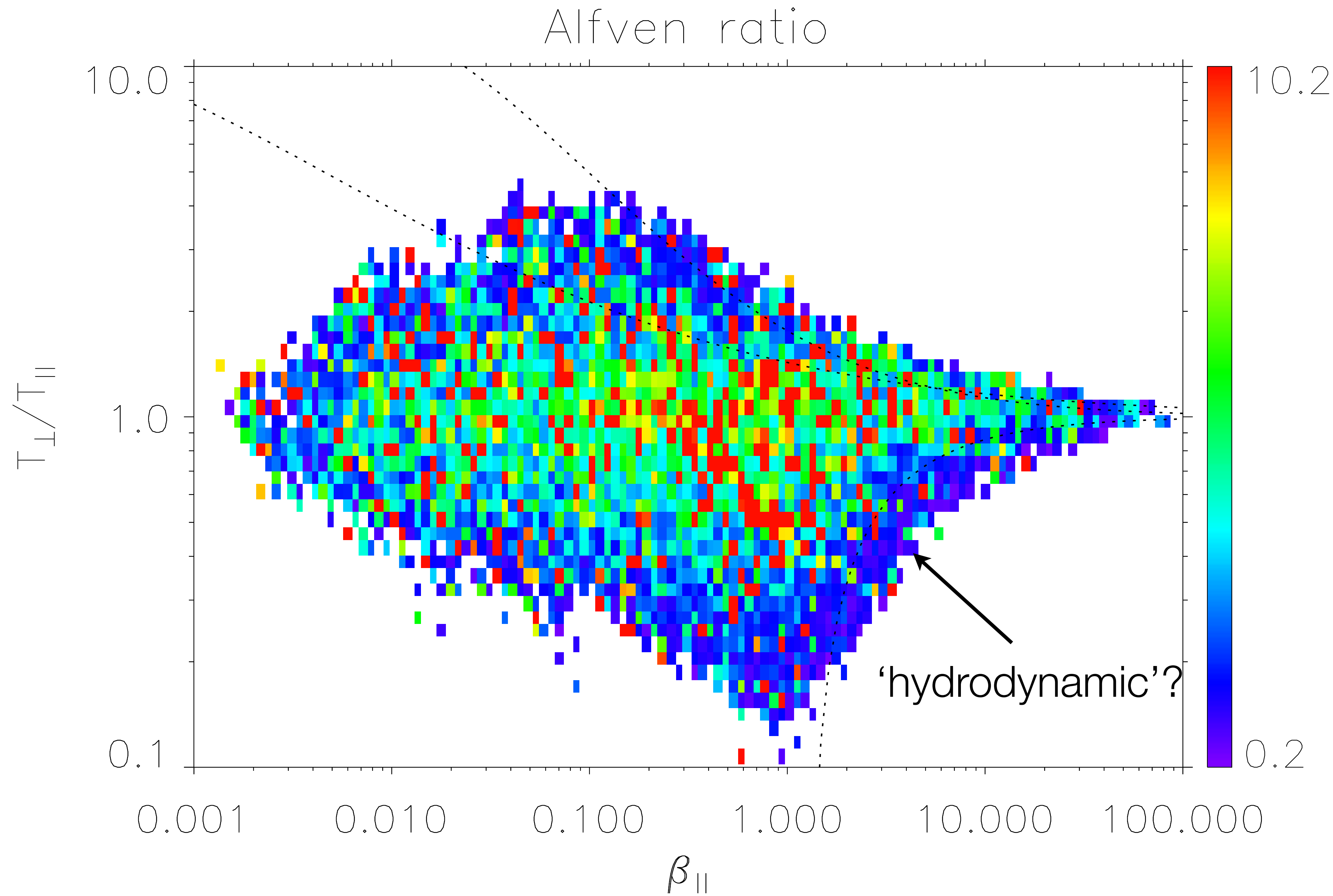


Proton anisotropy instabilities - new things



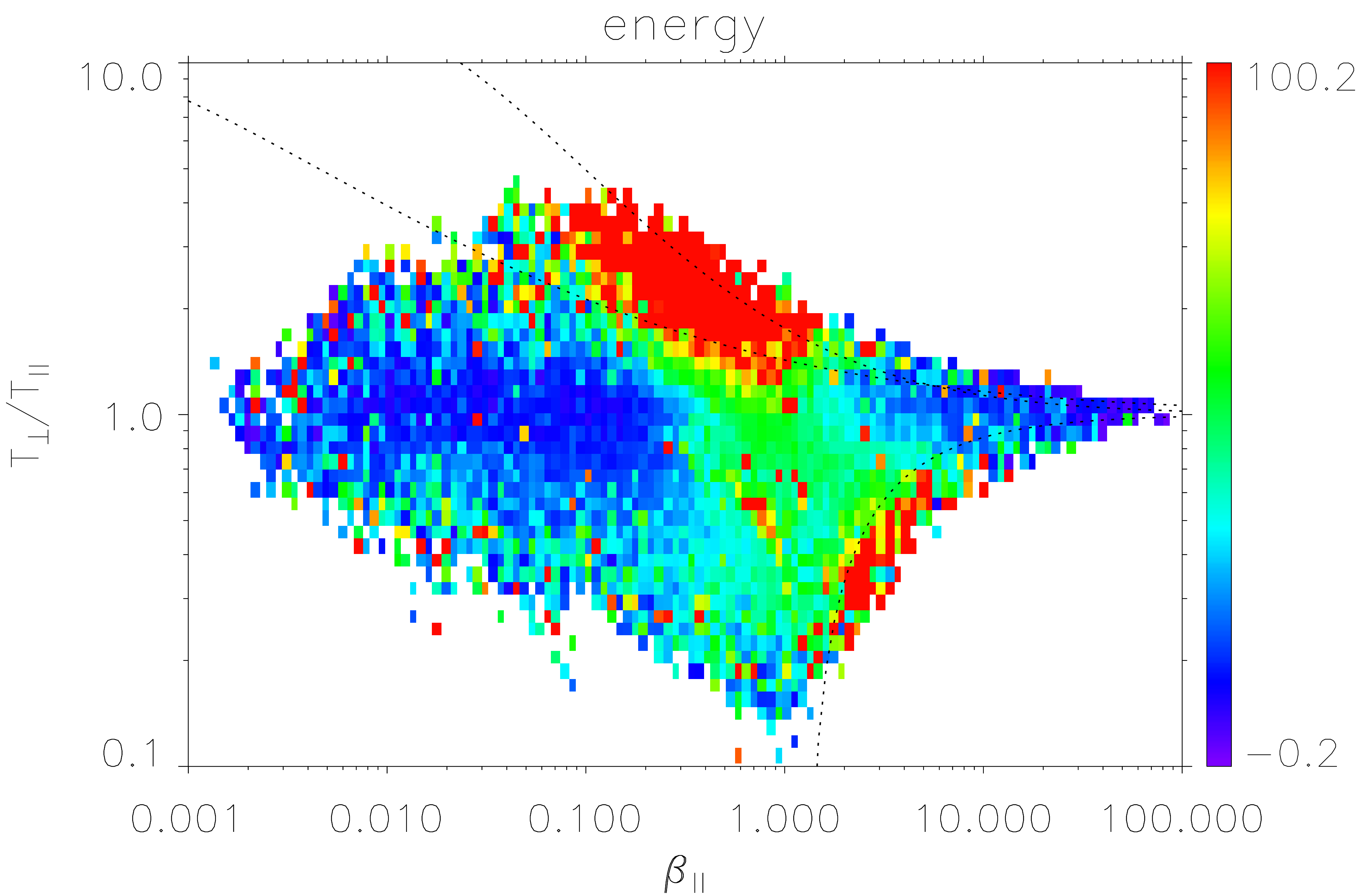
$< \delta v \cdot \delta b >$ (Δt = 3 sec, T = 15 sec)

Proton anisotropy instabilities - new things



$< (\delta v)^2/(\delta b)^2 >$ (Δt = 3 sec, T = 15 sec)

Proton anisotropy instabilities - new things



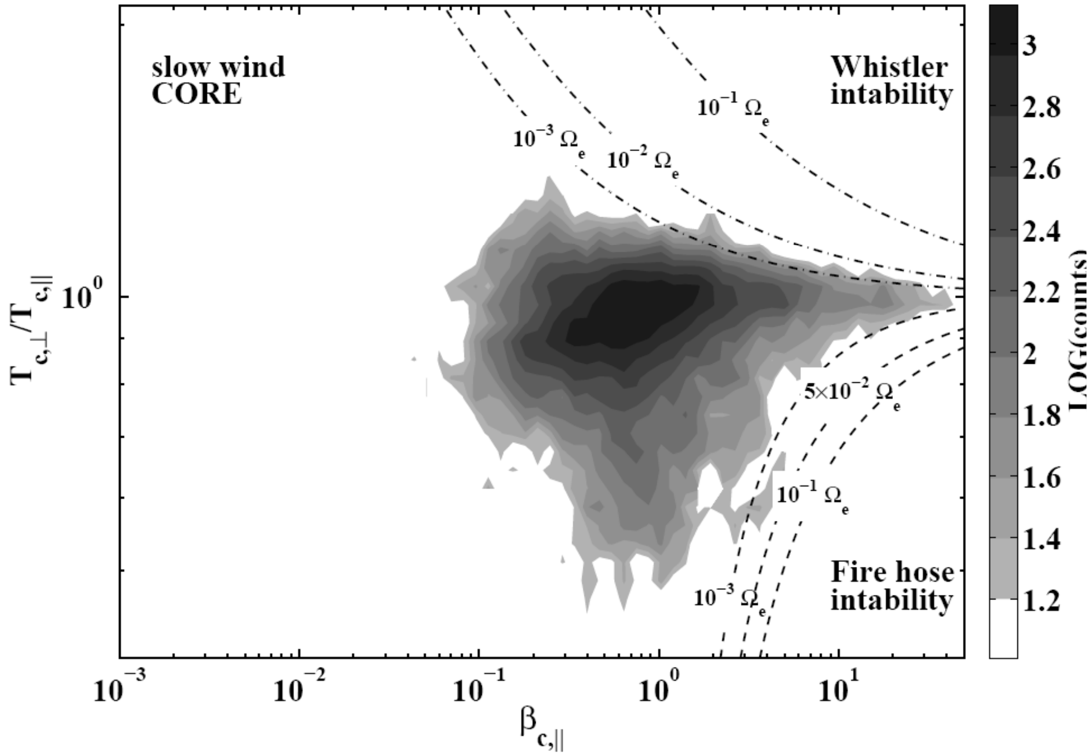
$< (\delta v)^2 + (\delta b)^2 >$ (Δt = 3 sec, T = 15 sec)

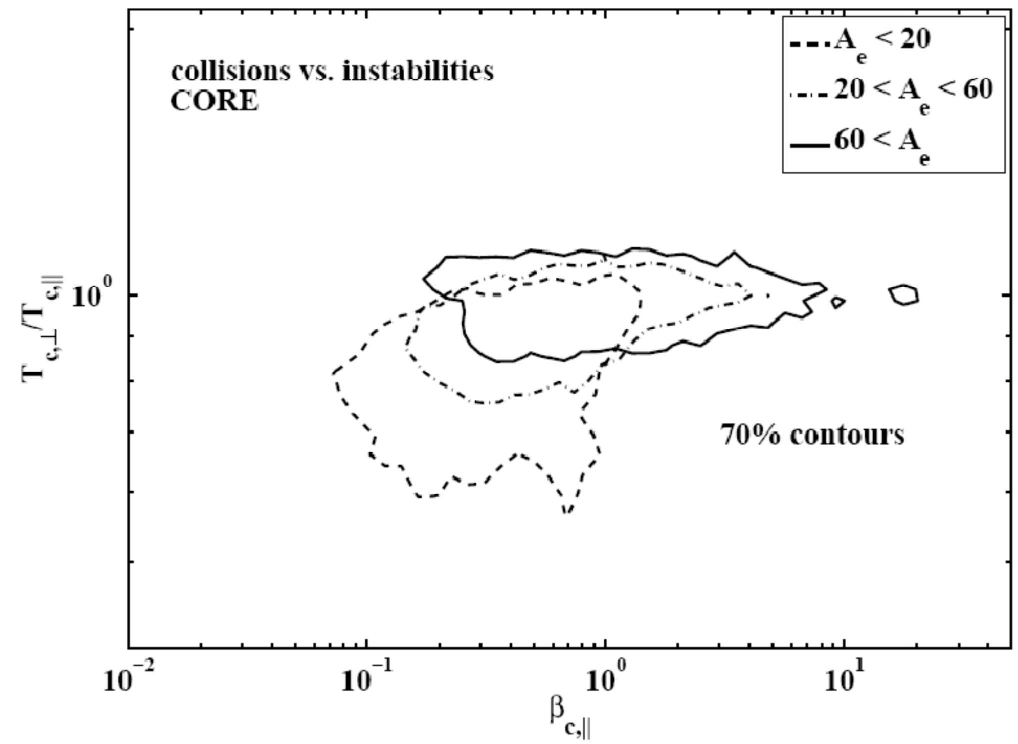
anisotropic viscous stress

$$W_{r\phi} = -\left(1 - \frac{p_{\parallel} - p_{\perp}}{B^2}\right)\frac{B_r B_\phi}{4\pi} + \rho v_r \delta v_\phi$$

- can be comparable to the Maxwell stress in astrophysical plasmas
- results in ion and electron heating
- constrained by μ invariance and instabilities

Evidences for both collisions and instabilities shaping the eVDFs





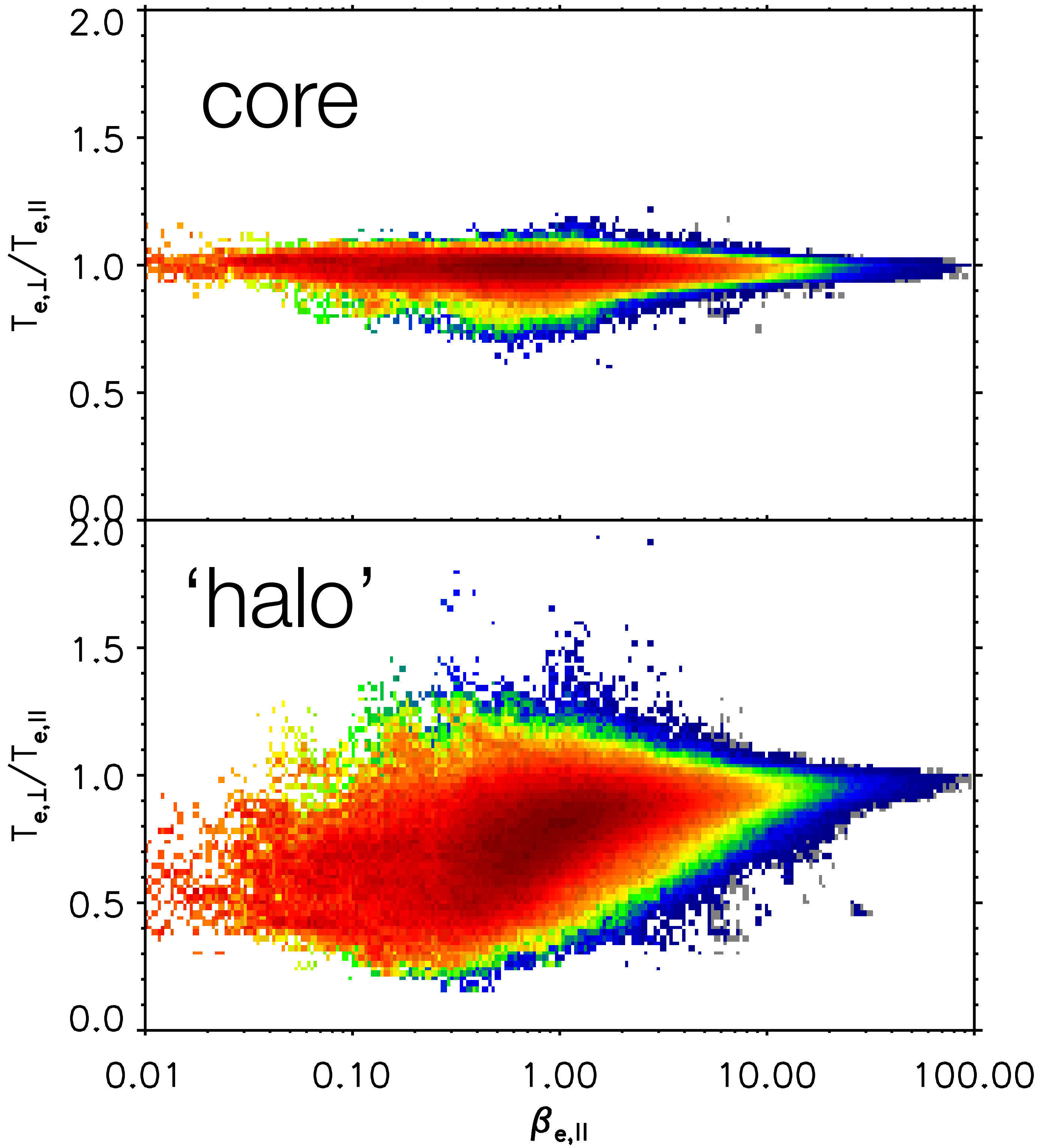
$$A_e = \upsilon_{ee} \frac{R}{V} \quad : \text{collisional age}$$

Stverak et al., JGR, 2008

Similar for protons : Kasper et al., Hellinger et al.

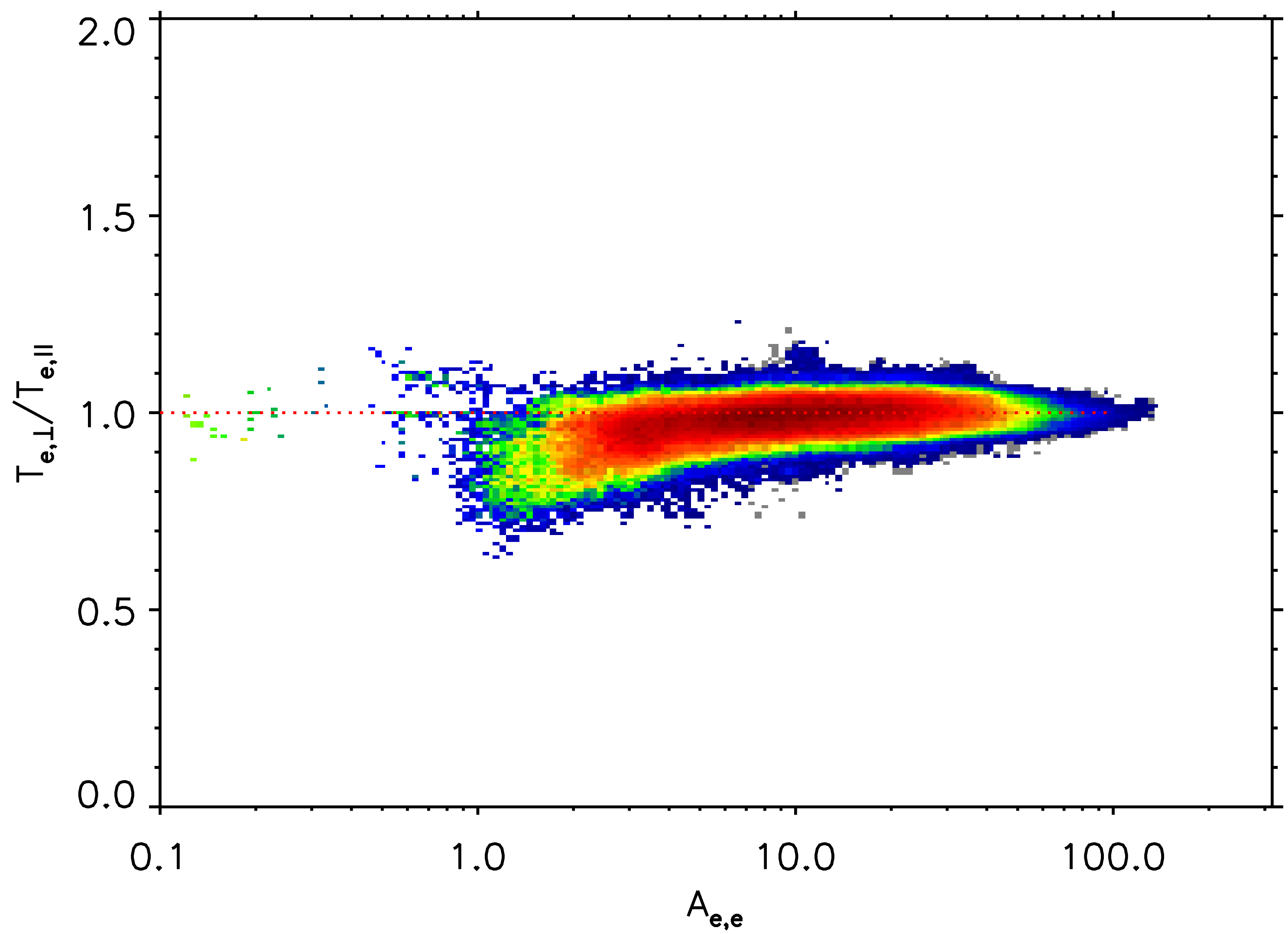
electron anisotropies

- Wind/3DP electron distributions at same time intervals as before
  ~ 1 million independent measurements
- corrected for spacecraft potential using SWE moments
- integrated into two populations:
  - core: 0 - 80 eV
  - halo: 80 - 1000 eV (anisotropy only)
- core is very isotropic - collisions
- halo is ordered by electron β



core anisotropy vs collisional age

- a ‘collisional age’ can be estimated from collision frequency and transit time (viz. Salem et al)
- core electrons appear to be well-ordered by collisions (here, at 1 AU)
- some anisotropy consistent with conservation of magnetic moment

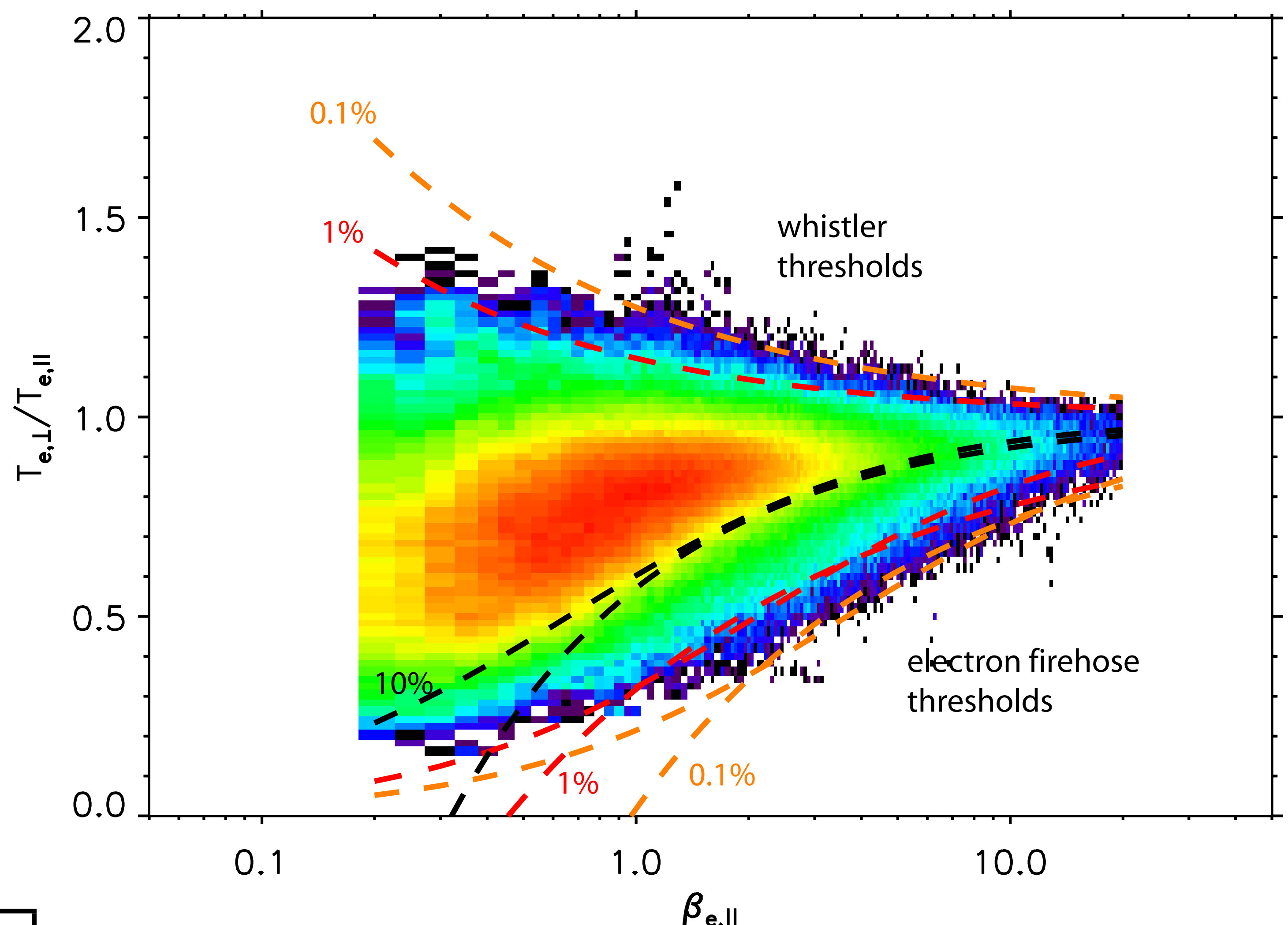


Halo anisotropies are constrained by instabilities

- halo is constrained by a whistler instability for $T_\perp / T_\| > 1$
- halo is constrained by the electron firehose instability for $T_\perp / T_\| < 1$

$$T_\perp / T_\| < 1 + S/\beta_{e,\|}^{\alpha}$$

	whistler		e- firehose	
count level	S	α	S	α
0.1%	0.275	0.577	-0.982	0.579
1%	0.147	0.647	-0.682	0.485
10%	-	-	-0.429	0.744



Halo anisotropies are constrained by instabilities

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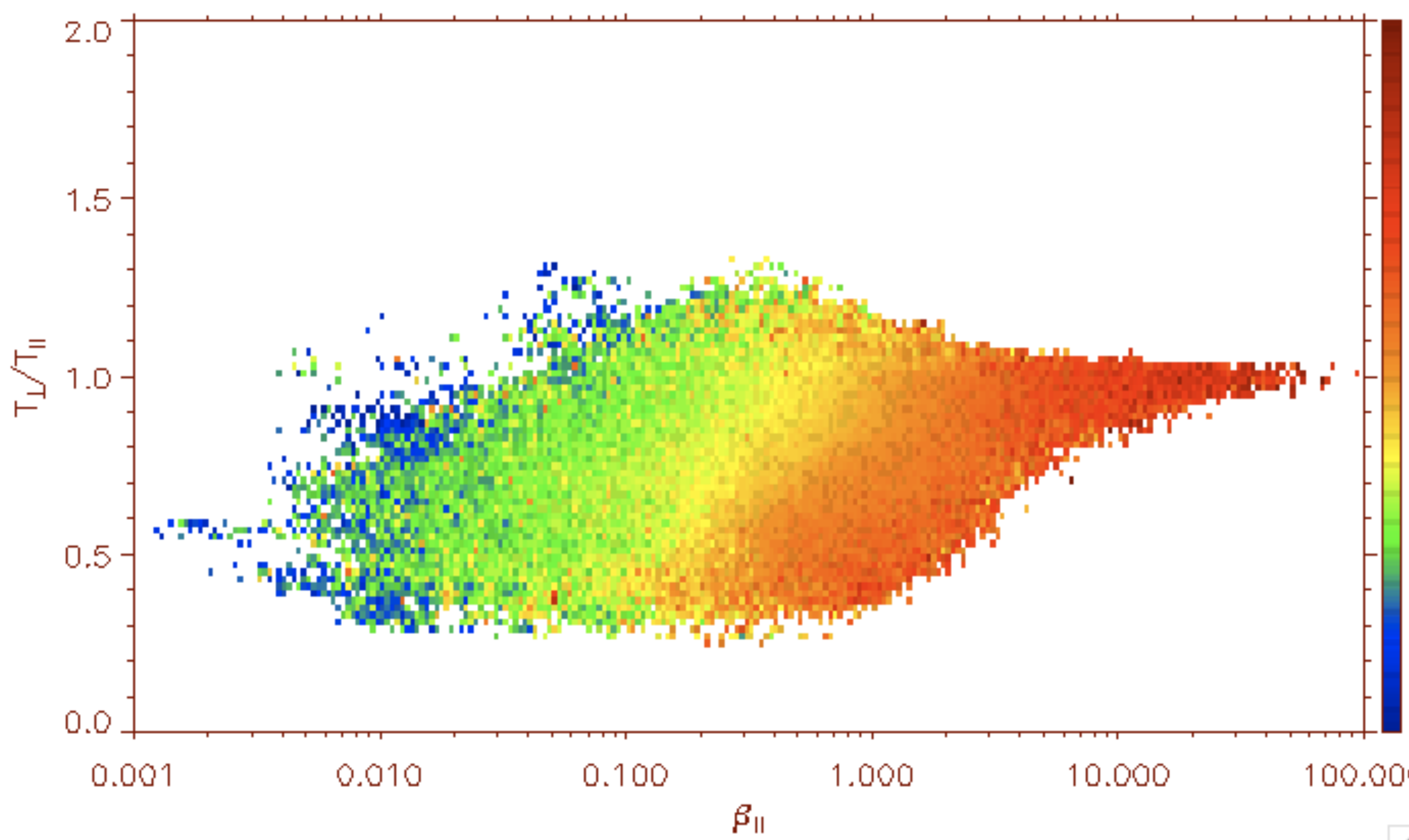
Wind SCM data - ~20 Hz



Conclusions

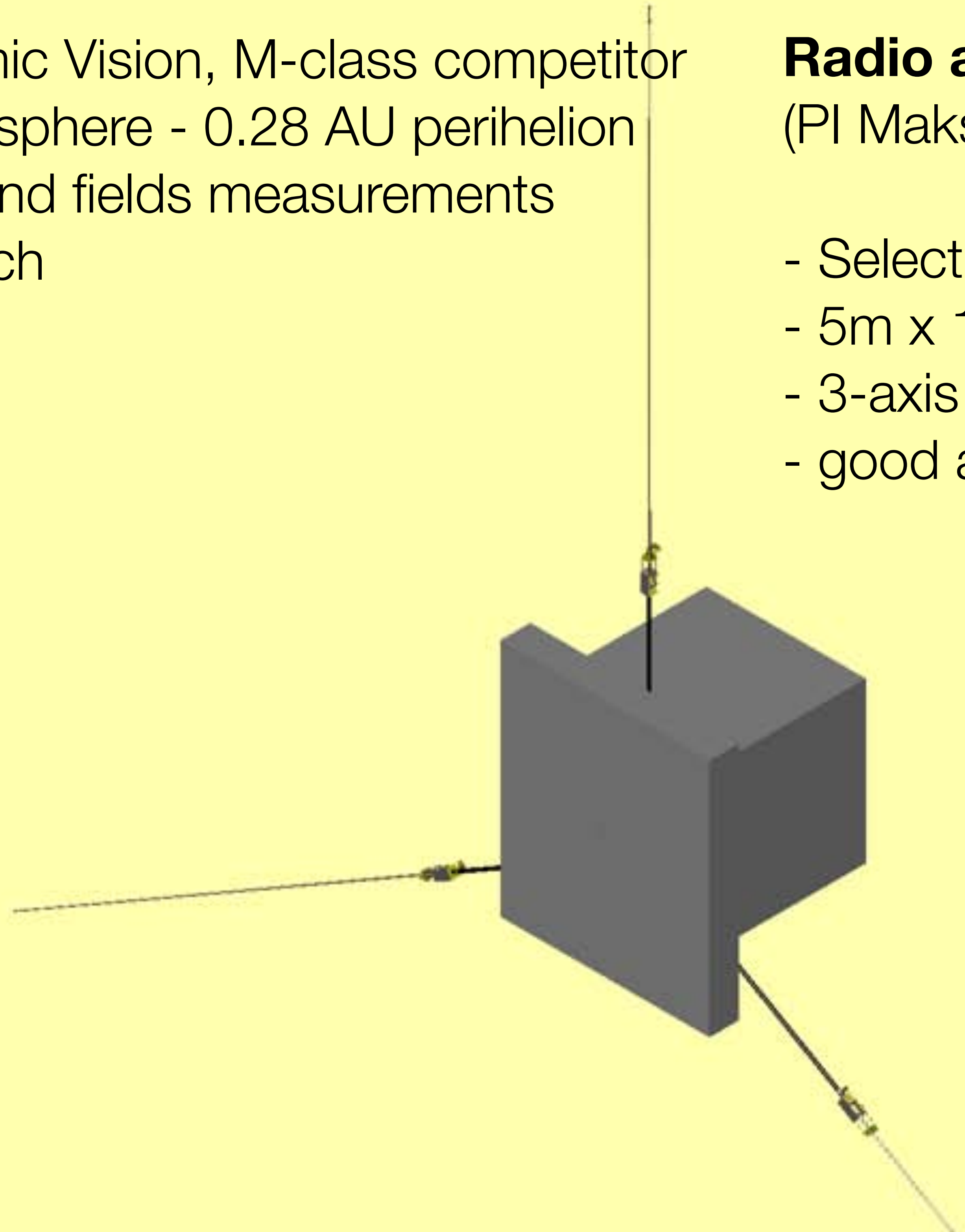
- Solar wind requires heating, both at the source and extended
- Extended, distributed heating implies turbulent dissipation
- Resistively-coupled electric field measurements provide critical diagnostics
- Local instabilities generate power in precisely the same spectral range as turbulent dissipation occurs
- Excellent opportunities for these measurements on the next generation of solar wind missions.

Solar Orbiter RPW Instrument

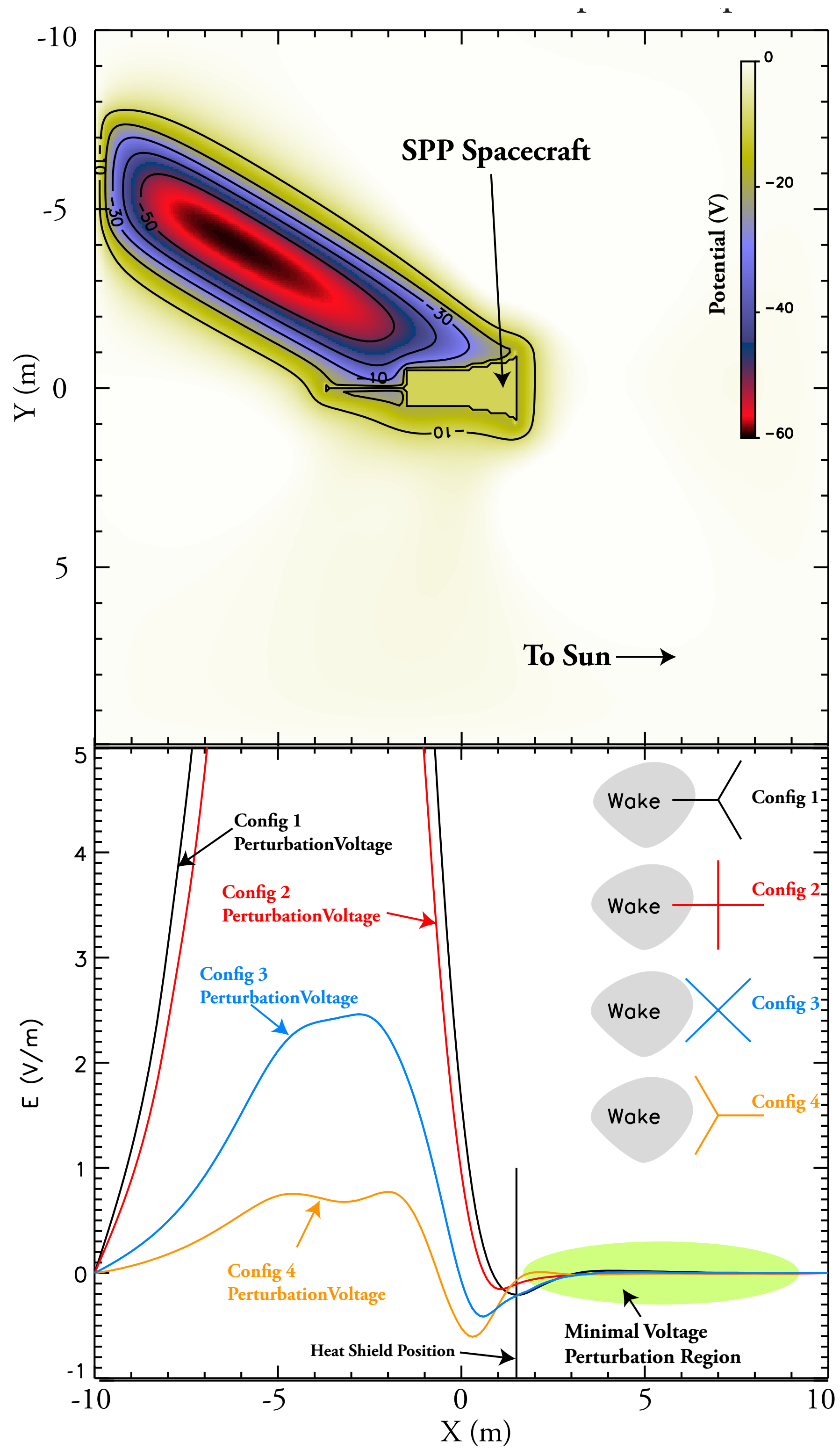
- ESA Cosmic Vision, M-class competitor
- Inner heliosphere - 0.28 AU perihelion
- Particles and fields measurements
- 2017 launch

Radio and Plasma Waves = RPW
(PI Maksimovic)

- Selected with 3 antenna booms
- 5m x 1.5 cm sensor on a 1m boom
- 3-axis stable spacecraft
- good and stable Sun symmetry



Solar Probe Plus



- NASA LWS mission
- Inner heliosphere - 9.5 R_S perihelion
- Particles and fields measurements
- 2018 launch
- nasty plasma wake