Faculty of Physics and Astronomy
Theoretical Physics IV

Kinetic instabilities and fluctuations in collisionless plasmas

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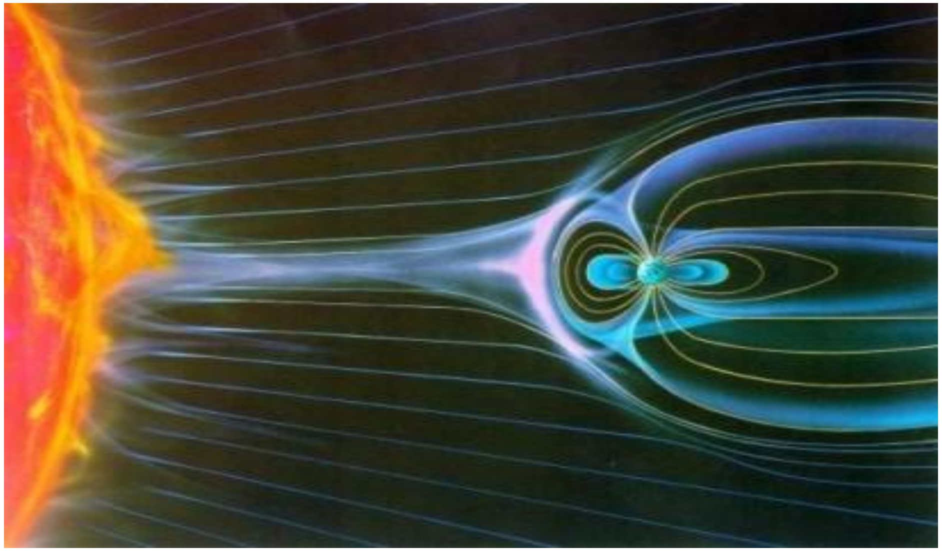
In collaboration with: R. Schlickeiser, P. H. Yoon, and M. Lazar

Future perspectives of space science and space exploration: Berlin 1-4 June 2016

Solar wind at 1 AU



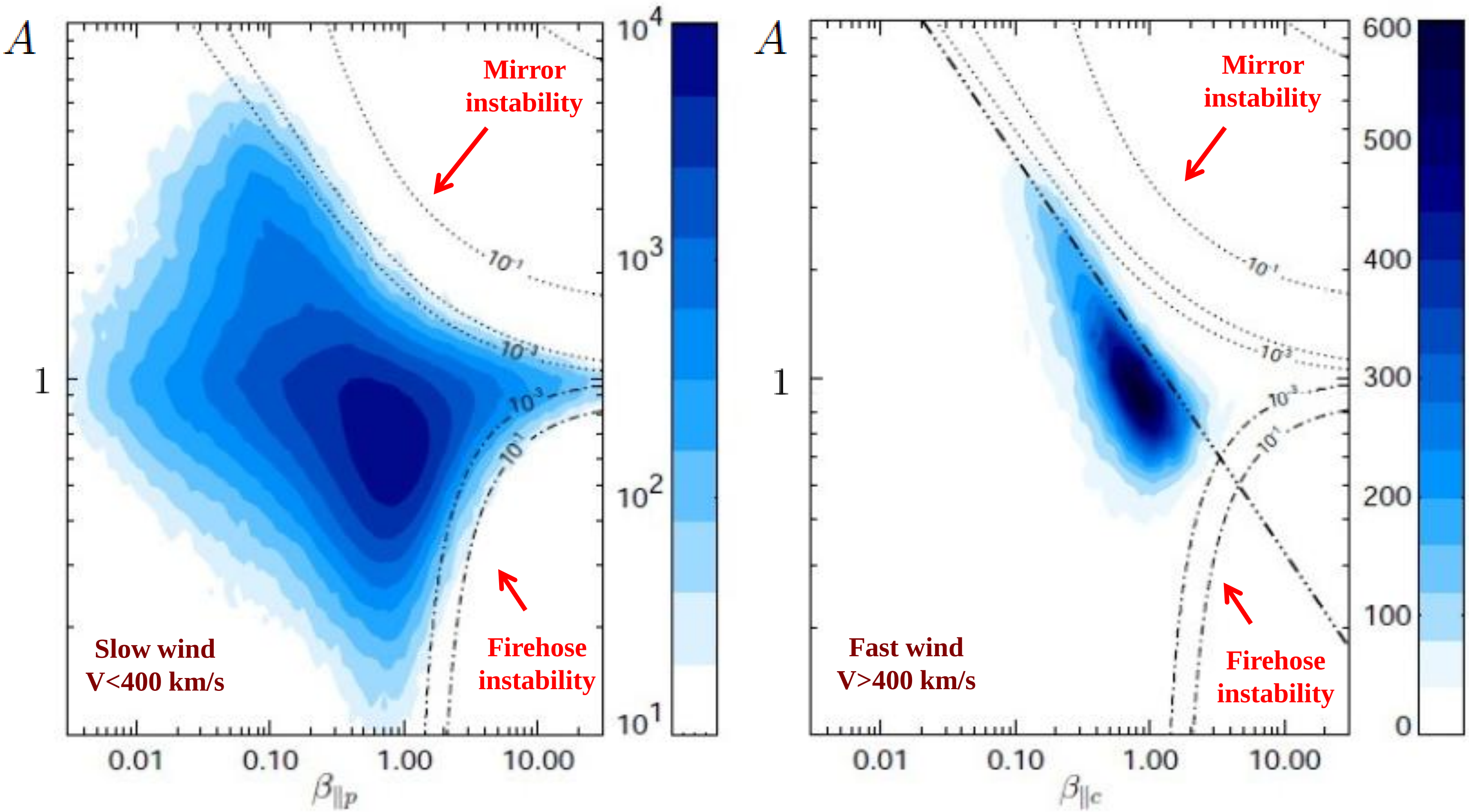
Parameter	Corona	≈ 0.1 AU	1 AU
n, cm^{-3}	10^9	10^7	10
T, K	3×10^6	10^6	10^5
B_0, G	10	0.1	5×10^{-5}
ρ_e, cm	5	3×10^2	1.8×10^5
$\lambda_{D,e}$, cm	0.37	2.1	6.9×10^2
ν_{ee}, s^{-1}	2.6	0.15	4.8×10^{-6}
λ_{ee}, AU	1.3×10^{-6}	2×10^{-5}	0.6
$\omega_{p,e}$, s^{-1}	2×10^9	2×10^8	2×10^5
Ω_e, s^{-1}	2×10^8	2×10^6	10^3

Solar wind temperature anisotropy at 1 AU

Temperature anisotropy of plasma component "a": $$A_a = \frac{T_{\perp,a}}{T_{\parallel,a}}$$

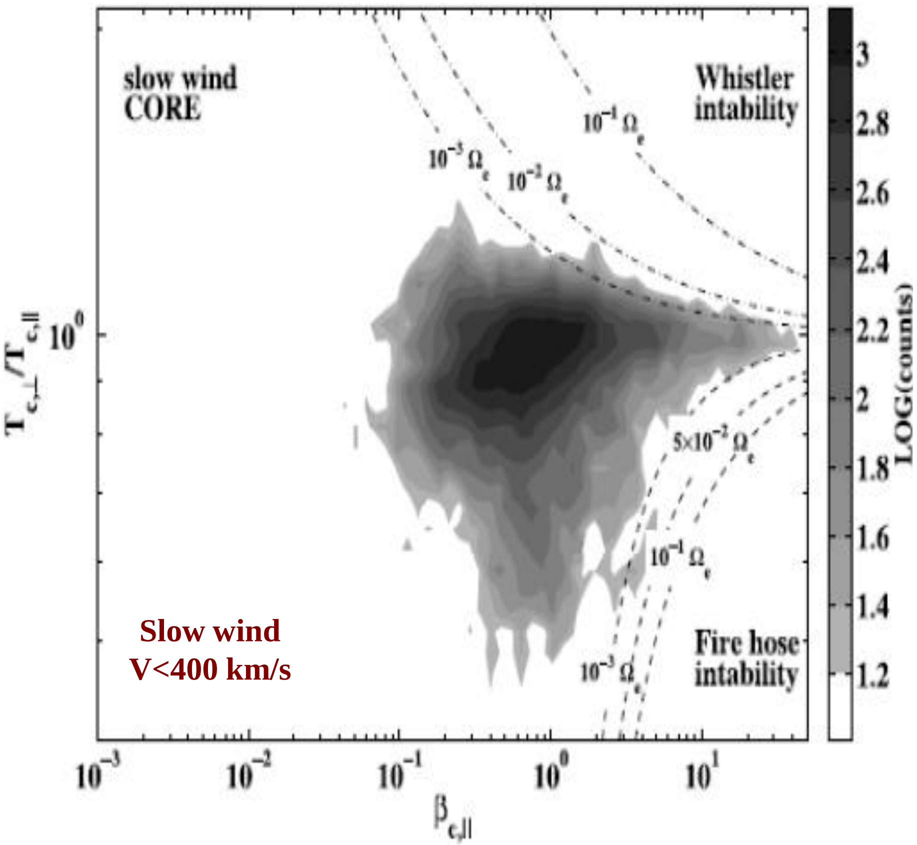
Parallel plasma beta of plasma component "a": $$\beta_{\parallel,a} = \frac{p_a}{p_M} = \frac{n_a T_{\parallel,a}}{B^2/4\pi}$$

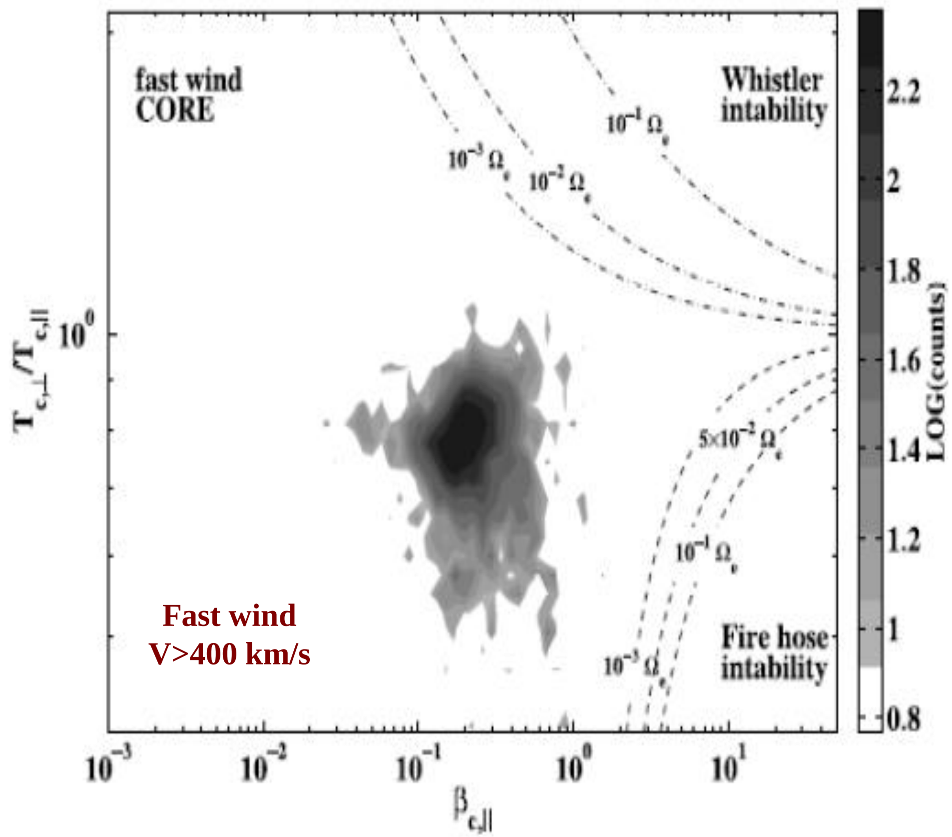
Observed temperature anisotropy of solar wind protons at 1 AU



P. Hellinger, P. Travnicek, J. C. Kasper, and A. J. Lazarus. *J. Geophys. Res.*, 33:L09101, 2006.

Observed temperature anisotropy of solar wind **electrons** at 1 AU





S. Stverak, P. Travnicek, and M. Maksimovic et. al. *J. Geophys. Res.*, 113:A03103, 2008.

Bi-Maxwellian velocity distribution function

$$f_a(v_\perp, v_z) = \frac{1}{\pi^{3/2} u_{\|,a} u_{\perp,a}^2} \exp\left(-\frac{v_\perp^2}{u_{\perp,a}^2}\right) \exp\left(-\frac{v_z^2}{u_{\|,a}^2}\right)$$

$$u_{\perp,a} = \sqrt{2T_{\perp,a}/m_a}$$

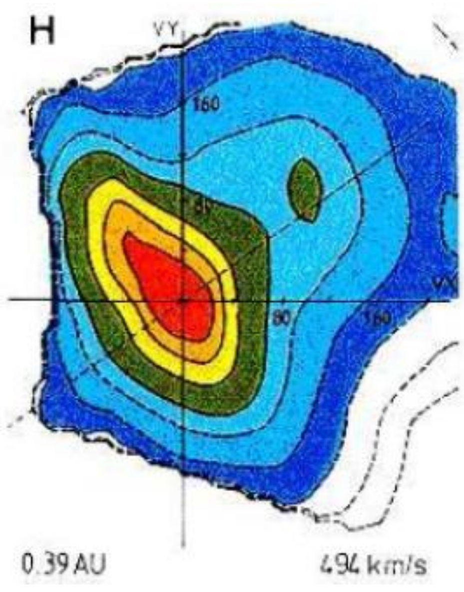
$$u_{\|,a} = \sqrt{2T_{\|,a}/m_a}$$

Counterstreaming bi-Maxwellian velocity distribution function

$$F_a(v_\perp, v_z) = F_{a,\perp}(v_\perp) \sum_s \epsilon_{a,s} F_{a,z}(v_z)$$

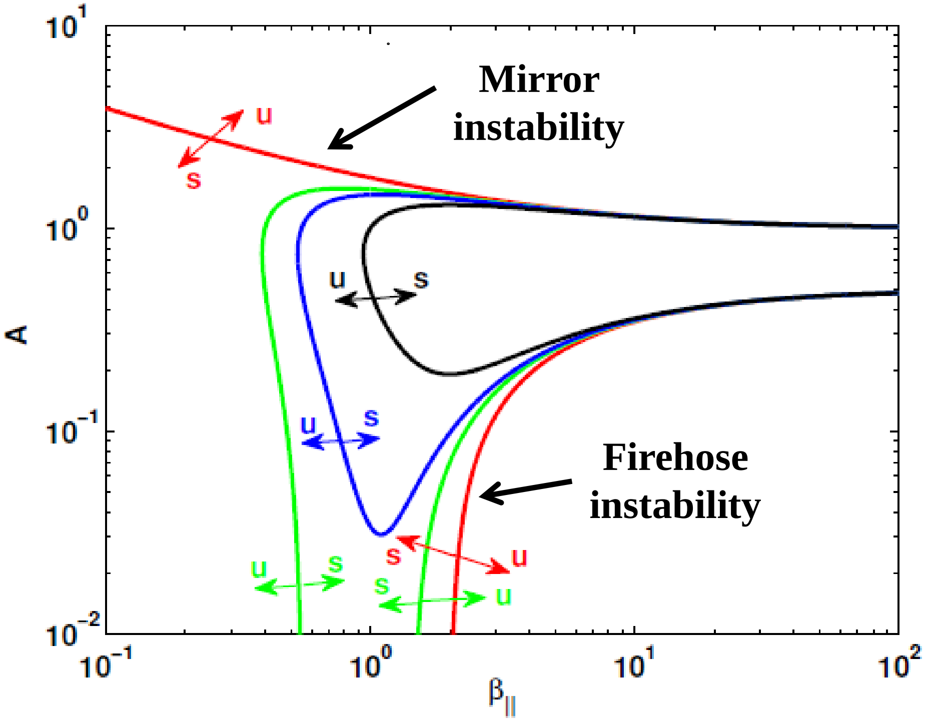
$$F_{a,\perp}(v_\perp) = \frac{1}{\pi u_{\perp,a,s}^2} \exp\left(-\frac{v_\perp^2}{u_{\perp,a,s}^2}\right)$$

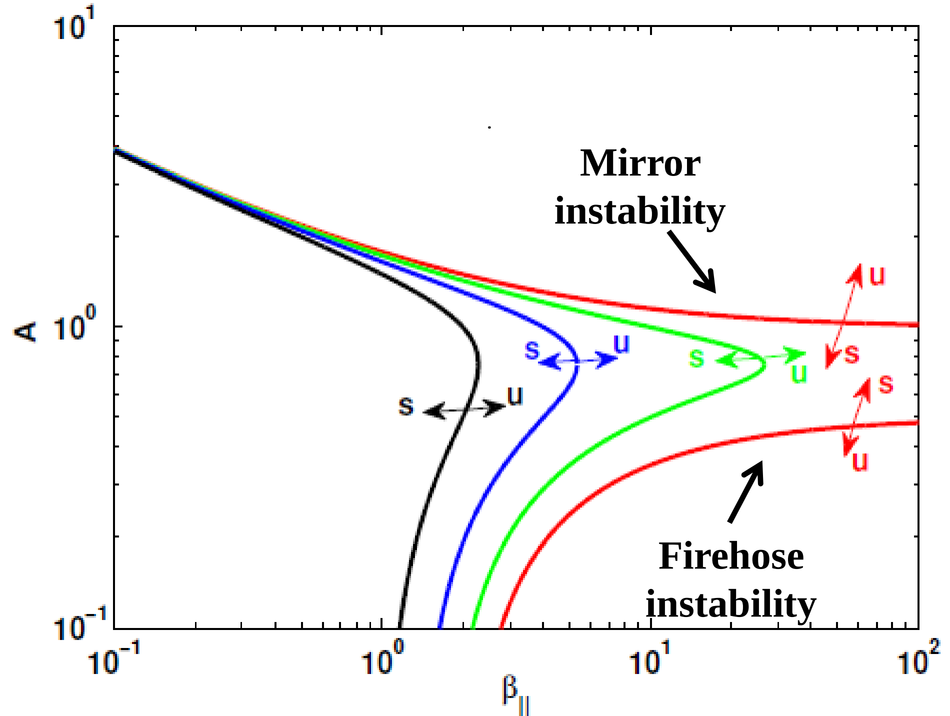
$$F_{a,z}(v_z) = \frac{1}{\pi^{1/2} u_{\|,a,s}} \exp\left(-\frac{(v_z - V_{a,s})^2}{u_{\|,a,s}^2}\right)$$



E. Marsch. *Living Rev. Solar Phys.*, 3:1, 2006.

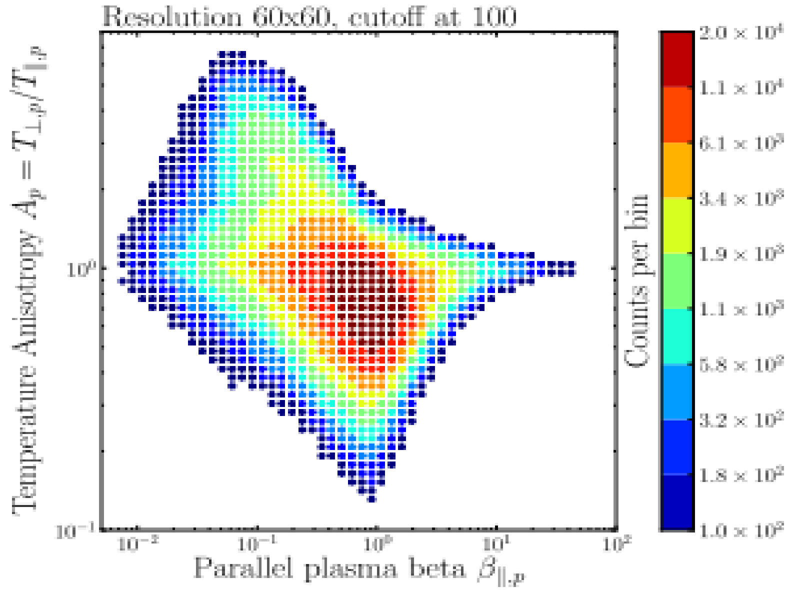
Firehose and mirror instabilities





$B = const$ and $T_{\parallel} = const$

$$P = P_1 = \frac{P_{0,1}}{\beta_{\parallel}}$$

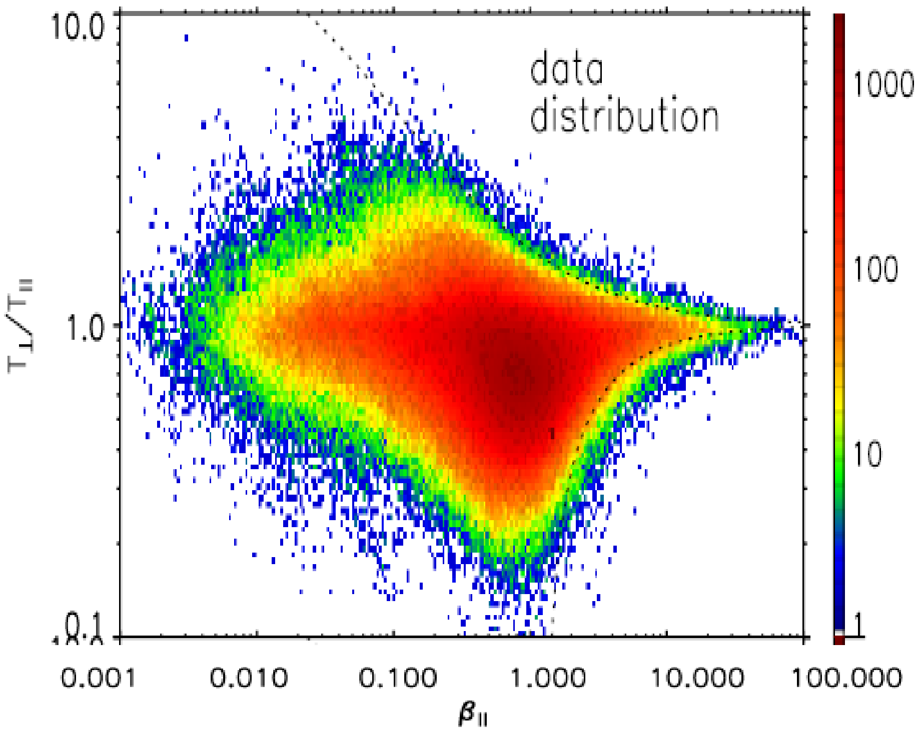


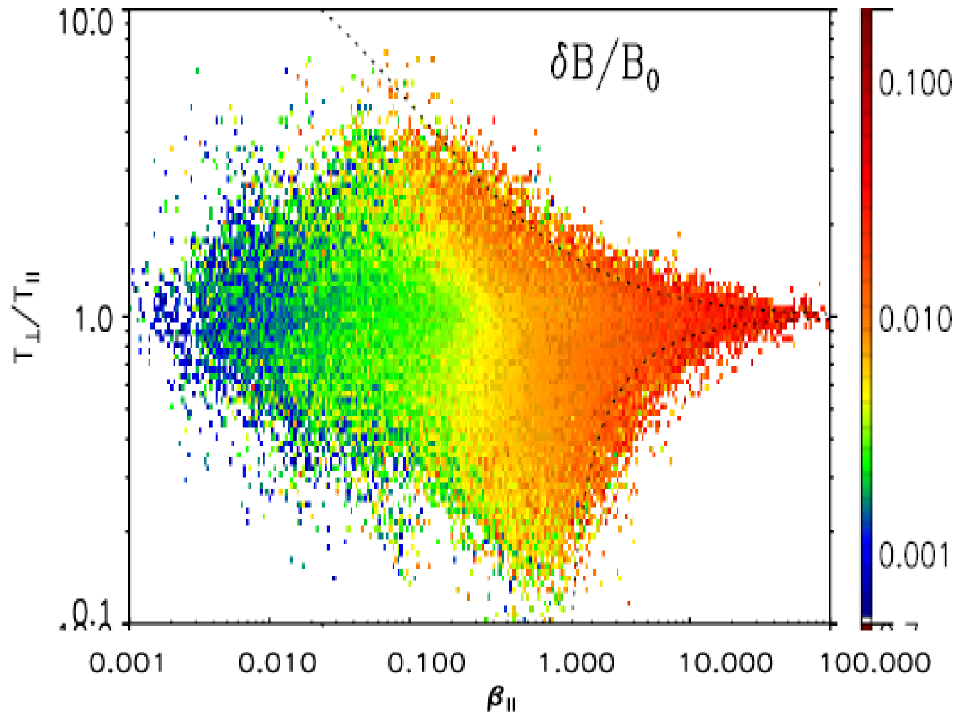
$n = const$ and $T_{\parallel} = const$

$$P = P_2 = P_{0,2}\beta_{\parallel}$$

Phys. Plasmas, 22:092131, 2015.

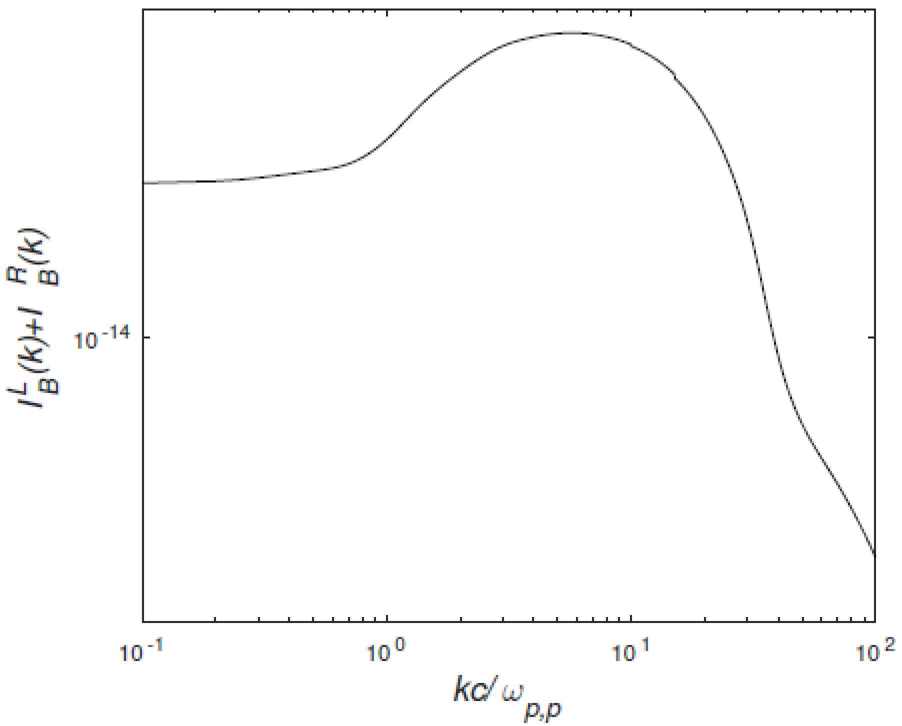
Fluctuations in the solar wind at 1 AU

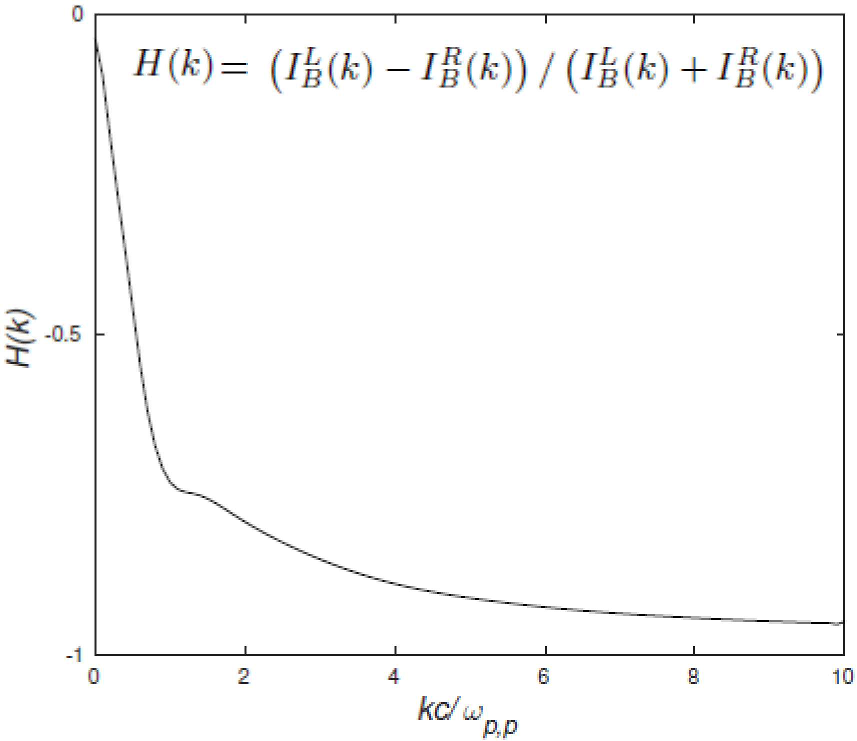




S. D. Bale, J. C. Kasper, G. G. Howes, and et. al. *Phys. Rev. Letters*, 103:211101, 2009.

Total magnetic field fluctuation spectrum and helicity for parallel wave vectors in a magnetized Maxwellian plasma





Vafin, S., Schlickeiser, R., & Yoon, P. H. 2016, Phys. Plasmas, 23, 052106

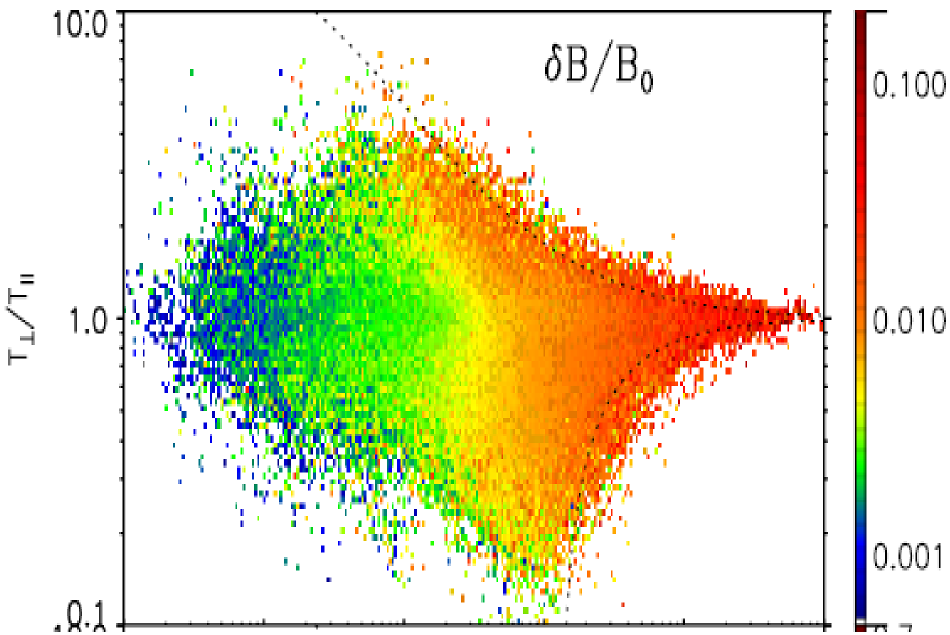
Total intensity of magnetic field fluctuations

	T=5.4×10^2 K	T=5.4×10^3 K
k_{min}	$10^{-2} k_i$	$10^{-2} k_i$
k_{max}	$10^2 k_i$	$10^2 k_i$
w_E^R, erg/cm^3	2×10^{-37}	1.8×10^{-37}
w_B^R, erg/cm^3	9.1×10^{-32}	8.8×10^{-32}

	T=5.4×10^2 K	T=5.4×10^3 K
$\Delta B_L/B_0$	6.8×10^{-13}	8×10^{-13}
$\Delta B_R/B_0$	6.9×10^{-12}	6.8×10^{-12}

$$B_0 = 4.3 \times 10^{-5} G$$

$$k_i = \omega_{p,p}/c = 1.38 \times 10^{-7} \text{ cm}^{-1}$$



S. D. Bale, J. C. Kasper, G. G. Howes, and et. al. *Phys. Rev. Letters*, 103:211101, 2009.

Vafin, S., Schlickeiser, R., & Yoon, P. H. 2016, Phys. Plasmas, 23, 052106

Amplification of fluctuations by plasma instabilities

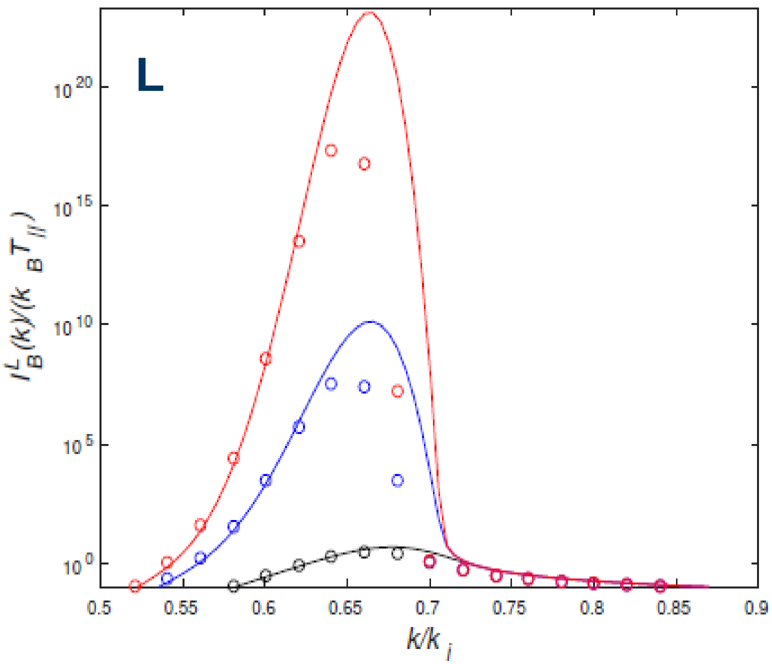


Figure 6. Same as Fig. 5, but $A = 2$. Black: $t = 1.6 \times 10^4$ s, $\Delta(10^{-3}k_i, 1.5k_i) \simeq 1.7 \times 10^{-12}$. Blue: $t = 1.6 \times 10^5$ s, $\Delta(10^{-3}k_i, 1.5k_i) \simeq 4.7 \times 10^{-8}$. Red: $t = 3.6 \times 10^5$ s, $\Delta(10^{-3}k_i, 1.5k_i) \simeq 0.1$.

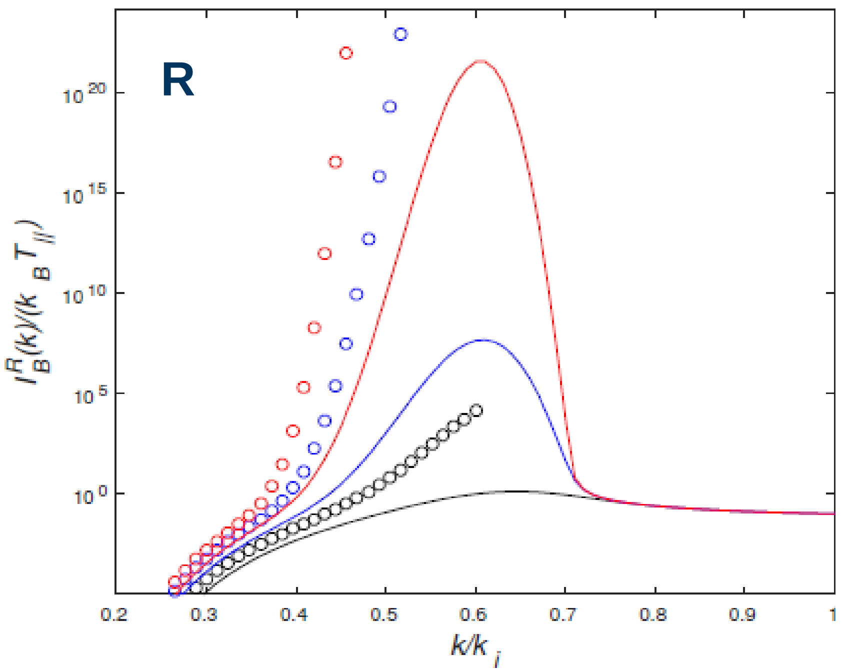


Figure 9. Same as Fig. 8, but $A = 0.5$. Black: $t = 4.3 \times 10^4$ s, $\Delta(10^{-3}k_i, 2k_i) \simeq 6.6 \times 10^{-12}$. Blue: $t = 4.3 \times 10^5$ s, $\Delta(10^{-3}k_i, 2k_i) \simeq 1.7 \times 10^{-8}$. Red: $t = 1.1 \times 10^6$ s, $\Delta(10^{-3}k_i, 2k_i) \simeq 0.1$.

$$I_B^{L,R}(k,t) = \frac{\alpha_{L,R}(k)}{2\gamma(k)}\left(e^{2\gamma(k)t} - 1\right)$$

S. Vafin, R. Schlickeiser, and P. H. Yoon, submitted to ApJ

Summary and conclusions

1. Instabilities:

1.1 Counterstreams have a dramatic effect on the instability conditions comparing to bi-Maxwellian plasmas without counterstreams.

1.2 The new results point out to a full potential explanation of the observed temperature anisotropy of the solar wind at 1 AU.

2. Fluctuations:

2.1 Electromagnetic fluctuations in an isotropic magnetized Maxwellian plasma for parallel wave vectors: the ratio $\delta B/B_0$ can be as high as 10^{-12}.

2.2 The fluctuations can be drastically amplified by plasma instabilities up to level $\delta B/B \sim 0.1$ on time scales less than the traveling time of the solar wind from the Sun to 1 AU.

Instability conditions

Bi-Maxwellian plasma without counterstreams

$$A < \left[1 - \frac{1}{\sqrt{\beta_{\|}}}\right]^2$$

$$A < 1 - \frac{1}{\beta_{\|}}$$

$$A > \frac{1}{2}\left[1 + \left(1 + \frac{2}{\beta_{\|}}\right)^{1/2}\right]$$

$$F\left(A, \beta_{\|}\right) > 0$$

Instabilities:

1. Ordinary (O-) mode
2. Alfvén, Firehose
3. Mirror

$$A = \frac{T_{\perp}}{T_{\|}}$$

$$\beta_{\|} = \frac{8\pi n T_{\|}}{B^2}$$

Bi-Maxwellian plasma with counterstreams

$$F\left(A, \beta_{\|}, P\right) > 0$$

Counterstreaming parameter:

$$P = \sum_a \sum_s \epsilon_{a,s} \left(\frac{V_{a,s}}{V_{A,a}}\right)^2$$

Alfvén velocity:

$$V_{A,a} = B/(4\pi n_a m_a)^{1/2}$$

$$F\left(A, \beta_{\|}, P\left(A, \beta_{\|}\right)\right) > 0$$

Fluctuation theory

Kinetic equation for electric field fluctuations:

$$\frac{\partial S_{ij}^{s}(\vec{k})}{\partial t} = \alpha_{ij}^{s}(\vec{k}) - \mu_{ij}^{s}(\vec{k}) S_{ij}^{s}(\vec{k})$$

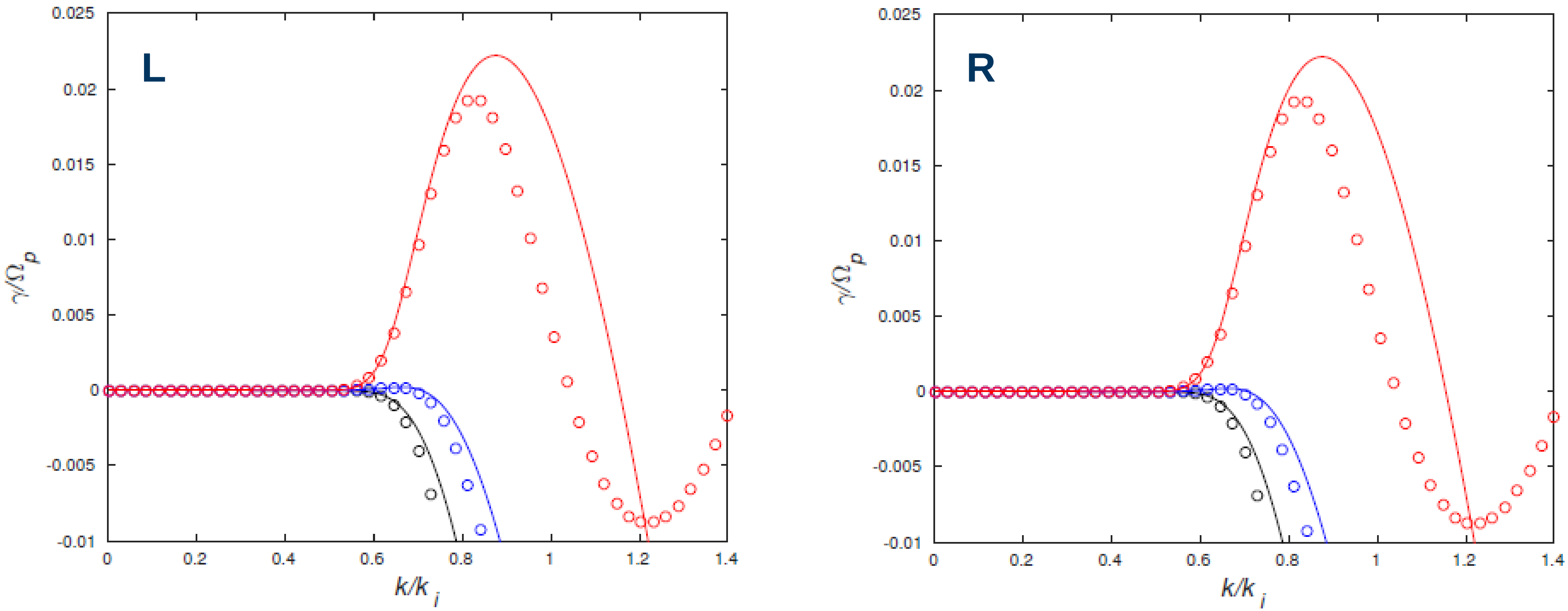
$$\alpha_{ij}^{s}(\vec{k}) = \frac{4\pi K_{ij}\left[\vec{k}, \varpi_s(\vec{k})\right]}{\left|\frac{\partial \Lambda\left[\vec{k}, \varpi_s(\vec{k})\right]}{\partial \varpi_s(\vec{k})}\right|^2}, \quad \mu_{ij}^{s}(\vec{k}) = -2\Gamma_s(\vec{k}).$$

Magnetic field fluctuations:

$$S_{ij}^{Bs}(\vec{k}) = \langle \delta B_i^{s}(\vec{k}) \delta B_j^{s*}(\vec{k}) \rangle = \frac{c^2}{|\omega|^2} \epsilon_{iab} \epsilon_{jcd} k_a k_c S_{bd}^{s}(\vec{k})$$

R. Schlickeiser and P. H. Yoon, Phys. Plasmas, **22**, 072108 (2015)

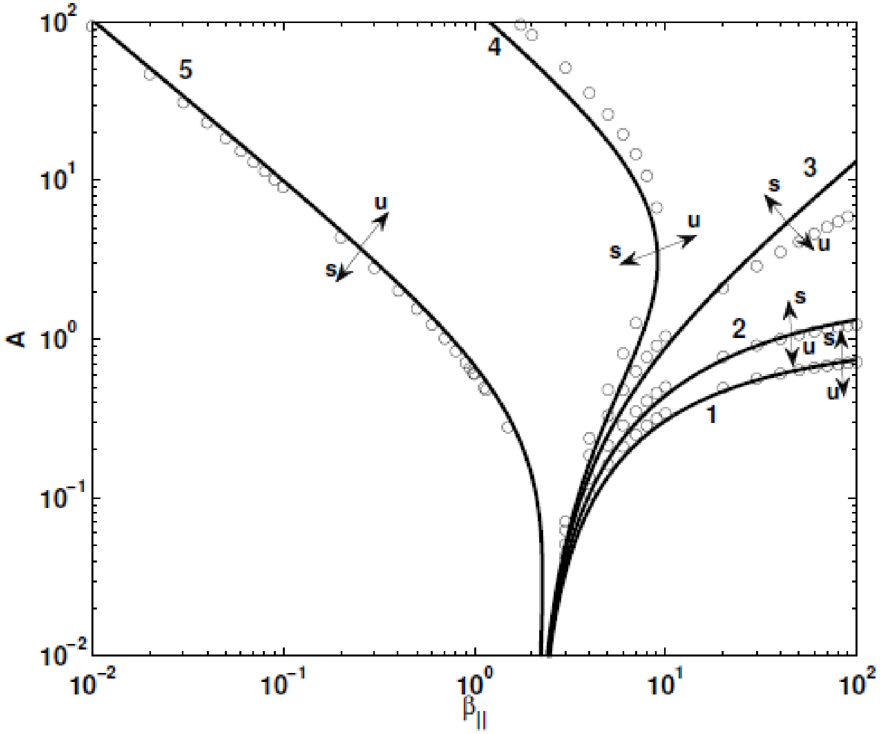
Amplification of fluctuations by plasma instabilities

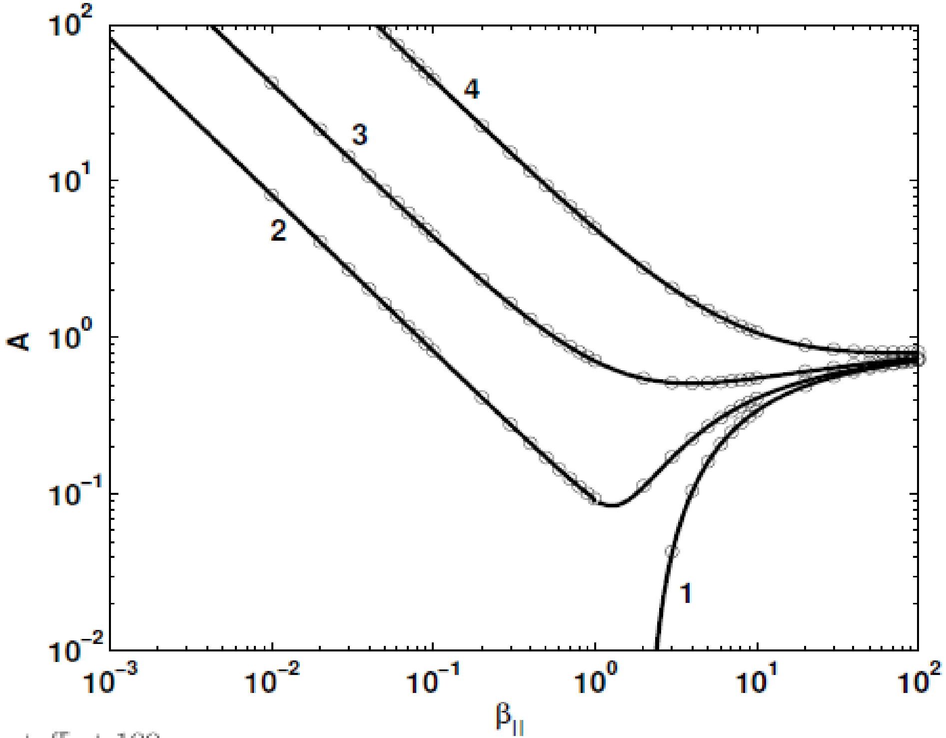


$$I_B^{L,R}(k,t) = \frac{\alpha_{L,R}(k)}{2\gamma(k)}\left(e^{2\gamma(k)t} - 1\right)$$

S. Vafin, R. Schlickeiser, and P. H. Yoon, submitted to ApJ

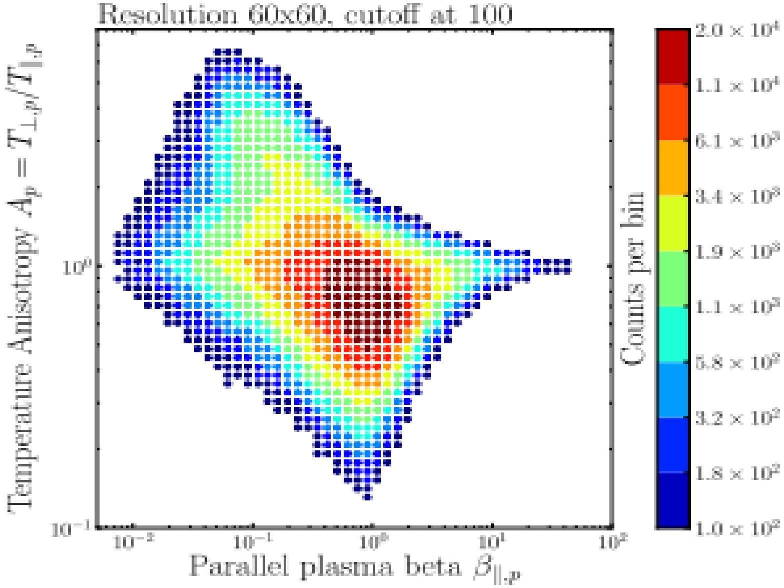
Ordinary (O-) mode instability





$$R_\perp = \frac{V_{n1}^2}{u_{\perp n}^2} = \text{const.}$$

$$P(A, \beta_\parallel) = P_0 R_\perp A \beta_\parallel$$

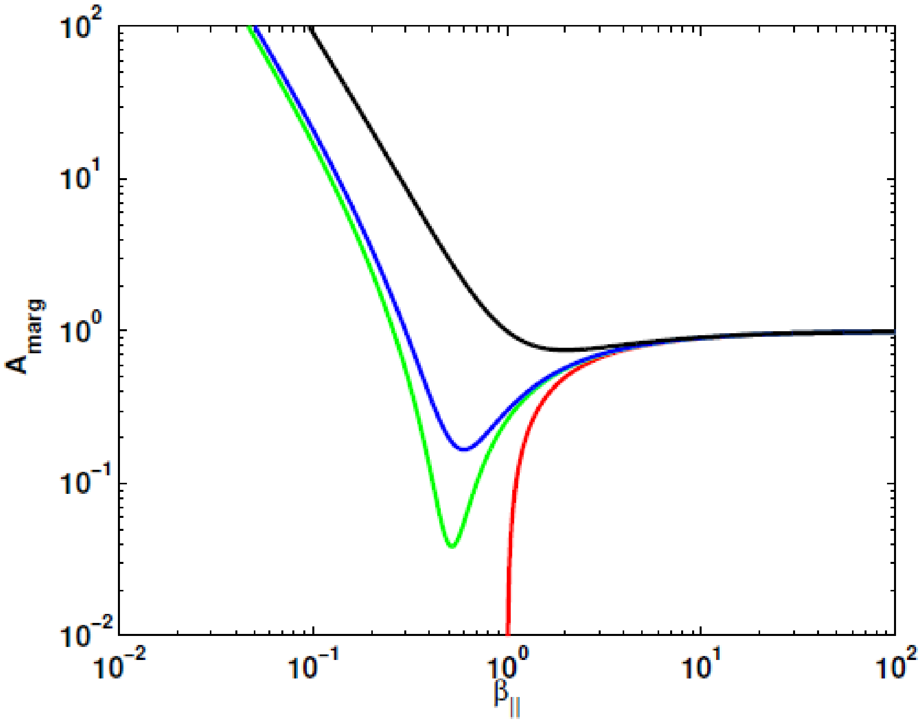


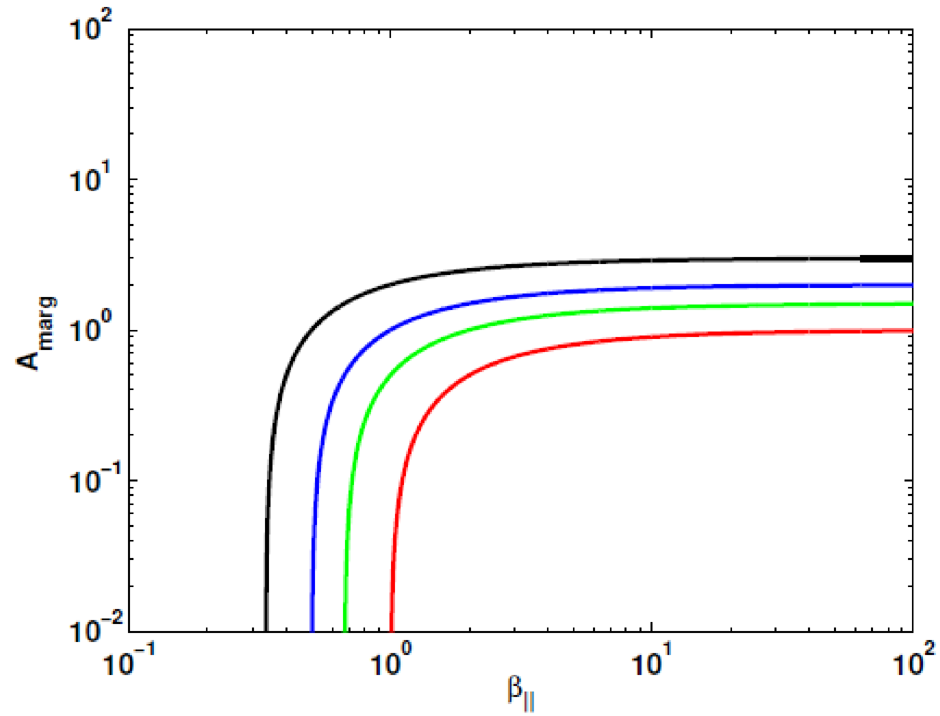
$$P = const$$

Phys. Plasmas, 22:022129, 2015.

Phys. Plasmas, 21:072119, 2014.

Alfvén instability





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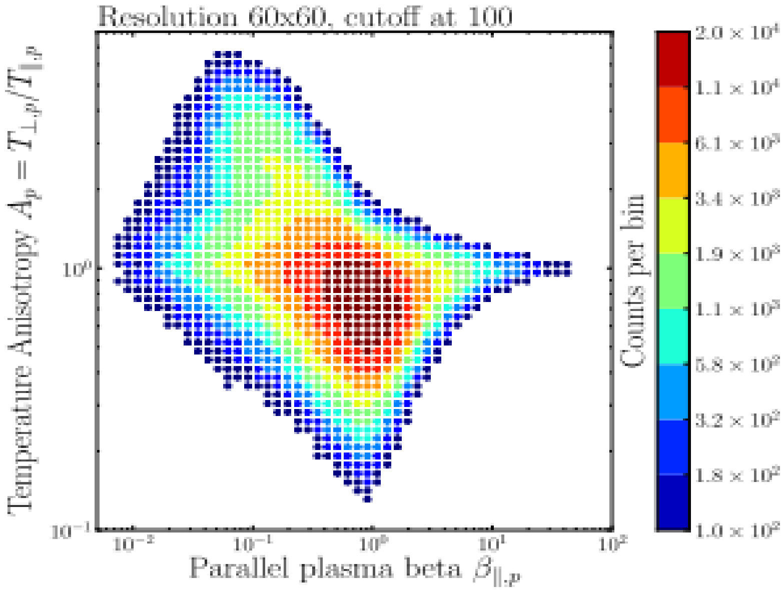
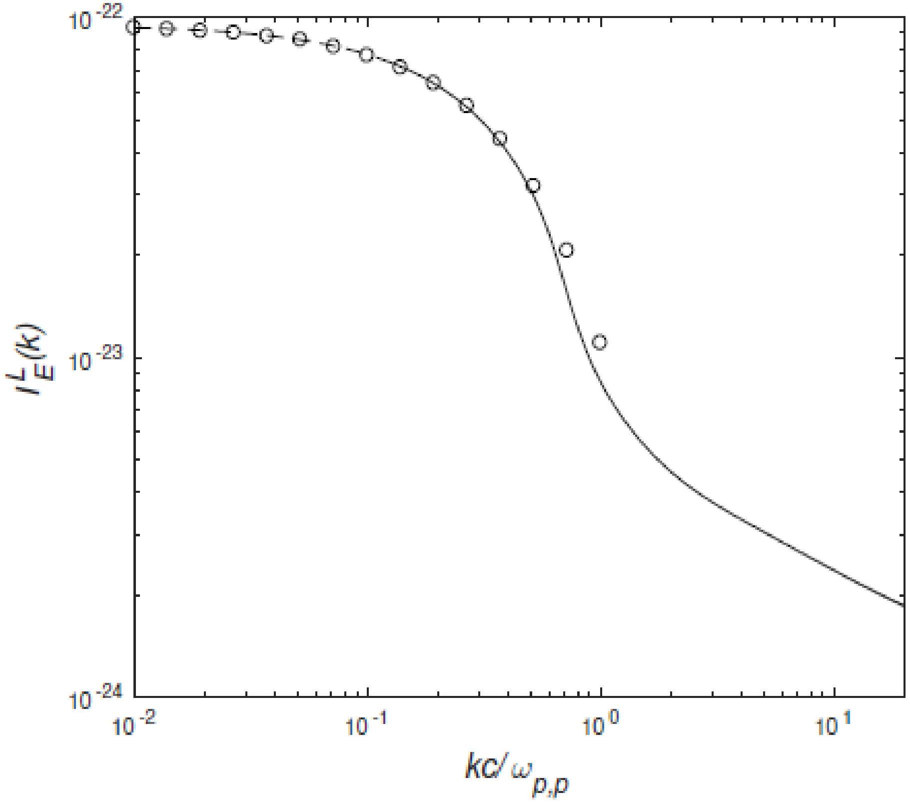


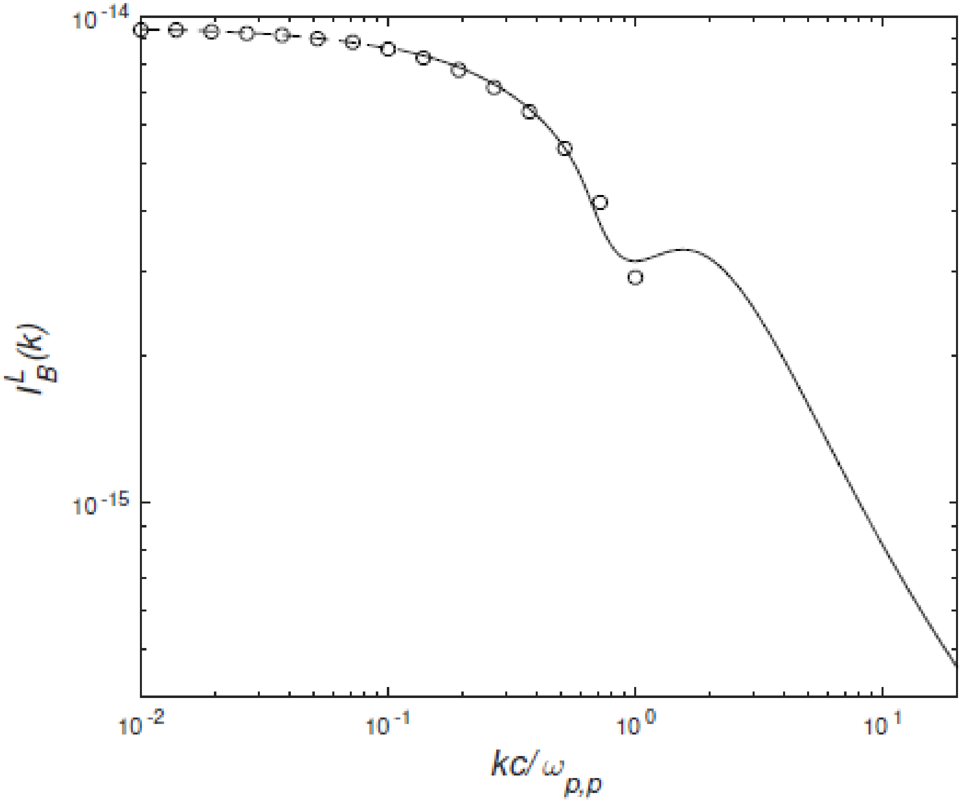
$n = const$ and $T_{\|} = const$

$$P = P_2 = P_{0,2}\beta_{\|}$$

Phys. Plasmas, 22:092131, 2015.

Fluctuation spectrum of the Left-handed polarized waves





$\beta = 0.1$

$V_A/c = 10^{-4}$

$k_i = \omega_{p,p}/c = 1.38 \times 10^{-7}\ \mathrm{cm}^{-1}$

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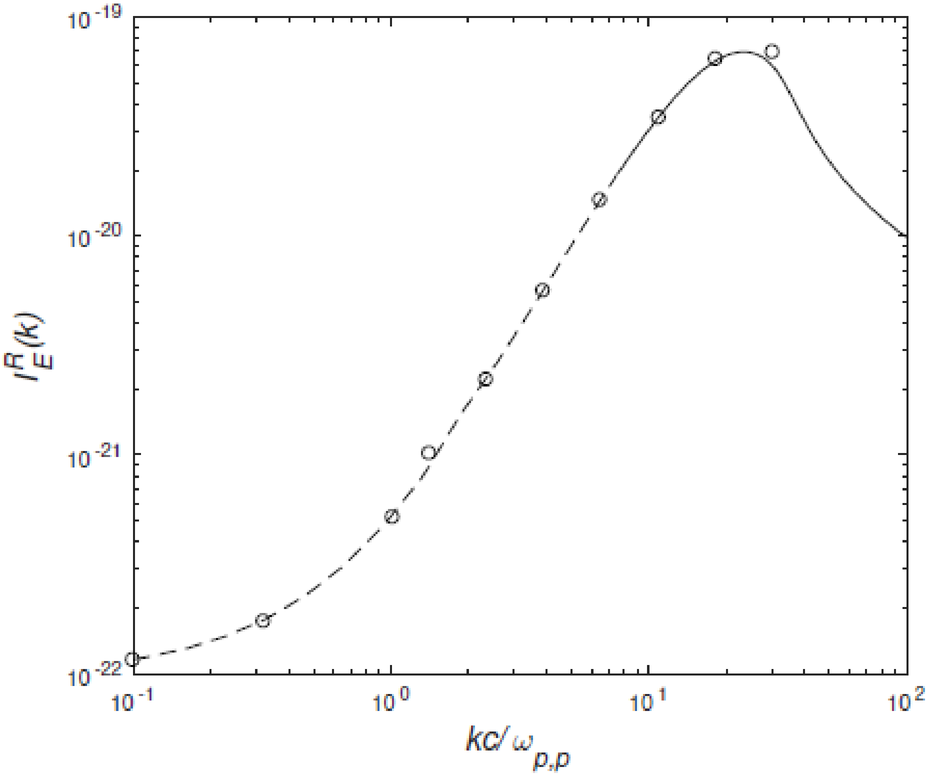
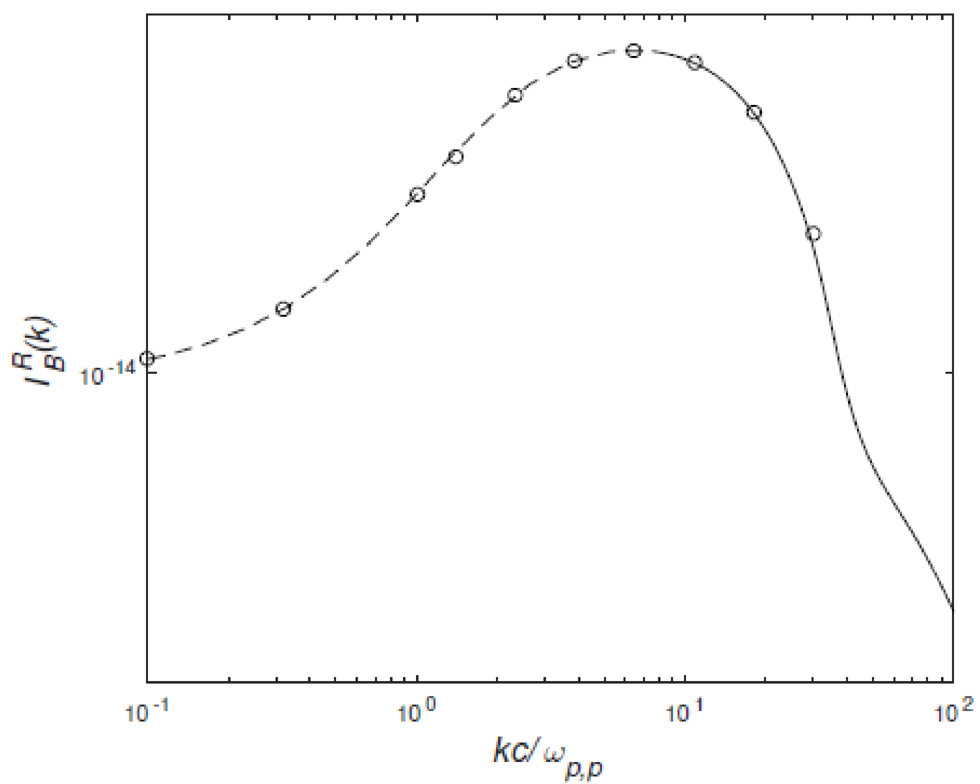
Fluctuation spectrum of the Right-handed polarized waves





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Vafin, S., Schlickeiser, R., & Yoon, P. H. 2016, Phys. Plasmas, 23, 052106