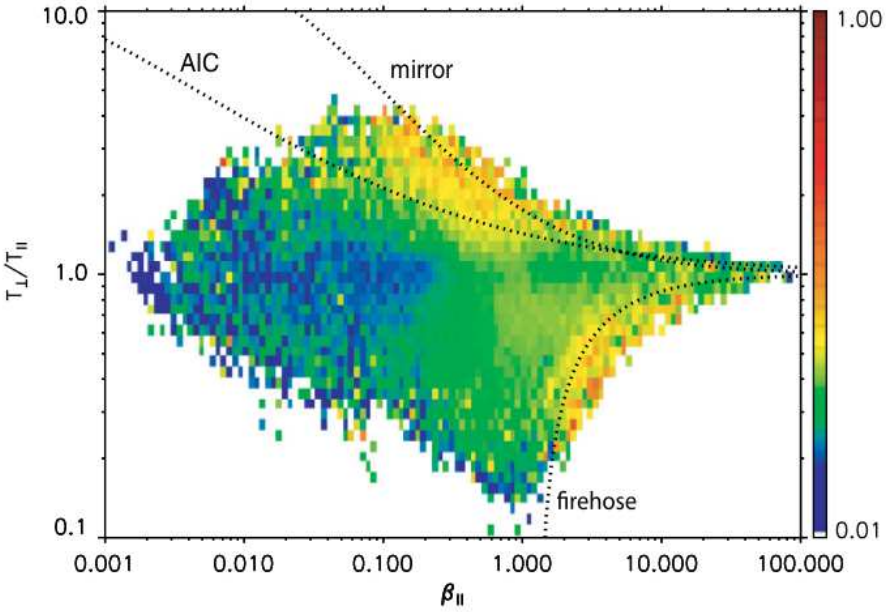
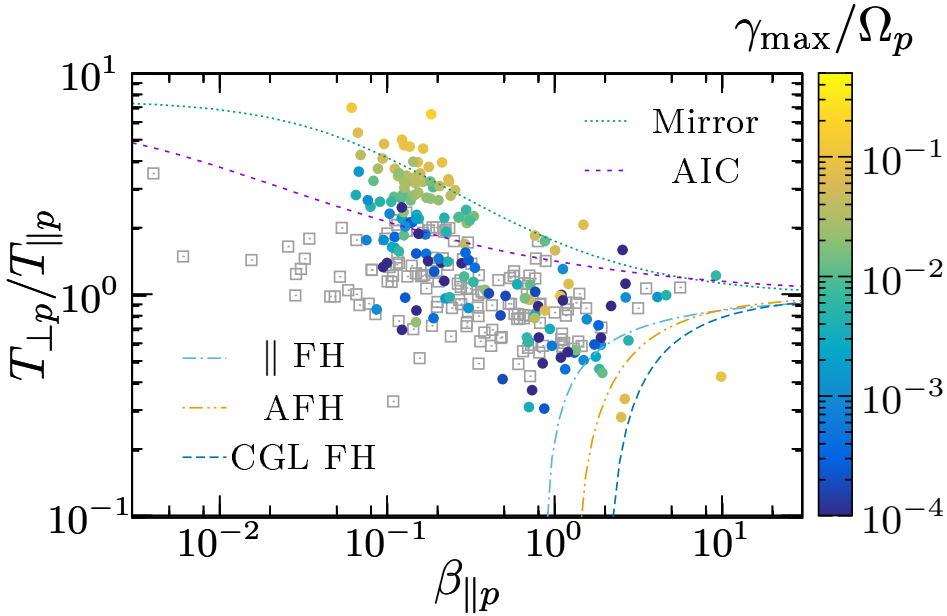
Kinetic Instabilities in Magnetized, Collisionless Plasmas



Bale et al 2009 Wind



Klein et al 2018 Wind

Kristopher G. Klein (U. Arizona)

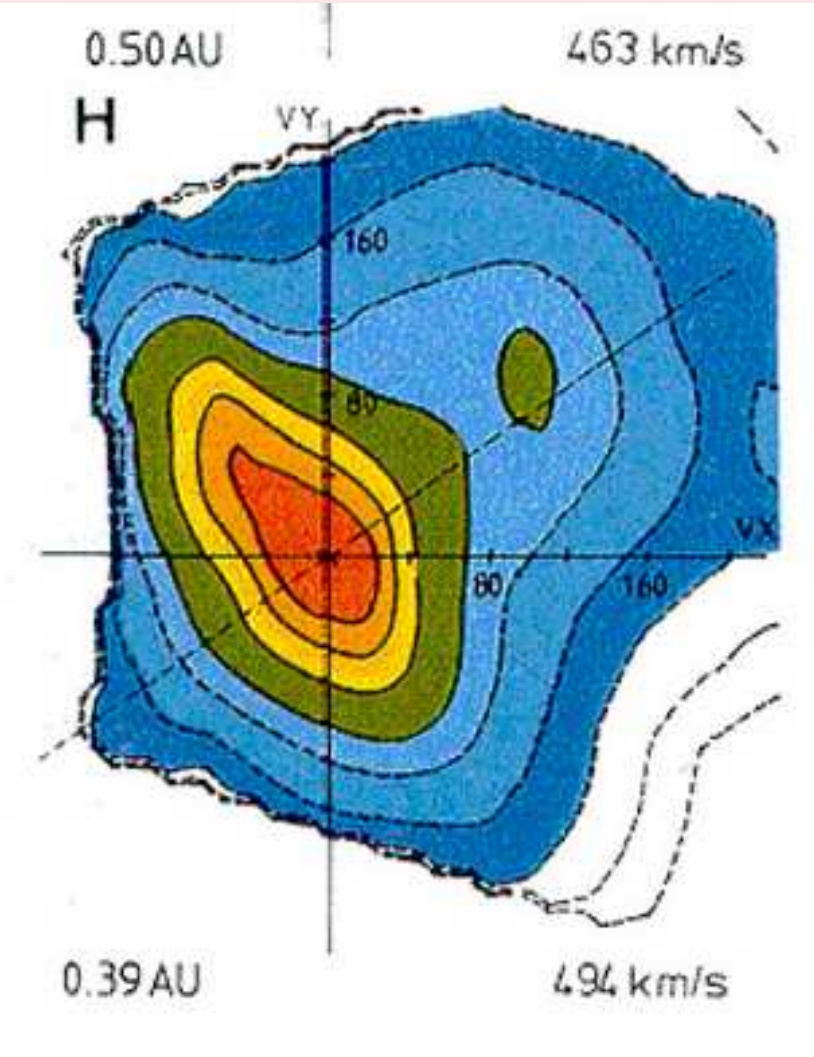
WPI Kinetic Plasma Workshop 2019

THE UNIVERSITY OF ARIZONA
COLLEGE OF SCIENCE
LUNAR & PLANETARY LABORATORY

w/ J. Kasper, D. Vech (U. Michigan) M. Stevens, K. Korreck (Harvard Smithsonian) D. Verscharen (University College London) and funding support from grants NASA HSR NNX16AM23G and NNX16AG81G.

The Solar Wind Frequently Departures from LTE

Particle Velocity Distributions $f_s(\mathbf{v})$



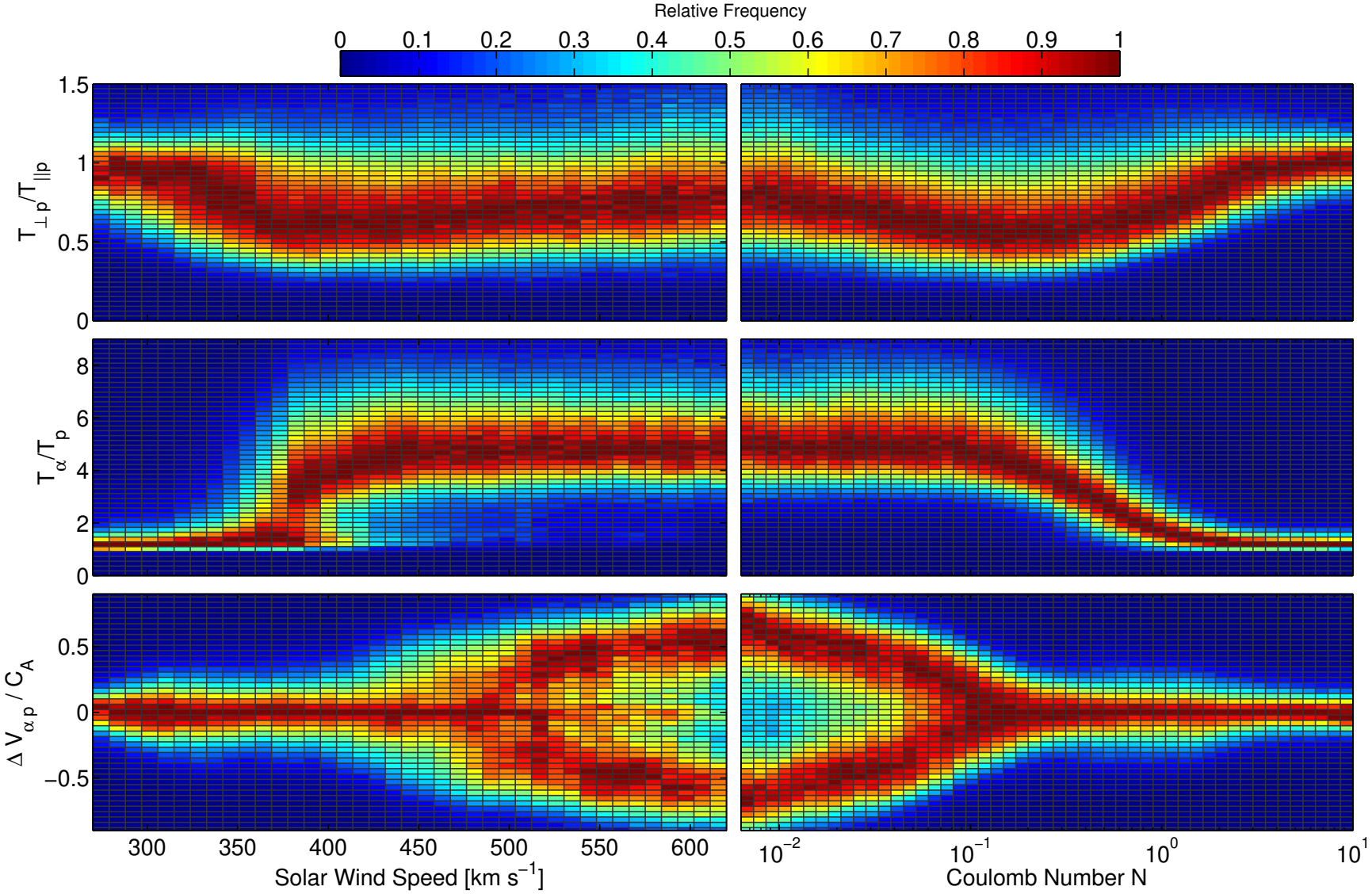
Marsch et al, 2012: Helios

Due to its hot, diffuse nature, collisions are unable to enforce a Maxwellian distribution in the solar wind:

$$\nu_{a,b} \approx 4\pi \frac{q_a^2 q_b^2 n_b \ln \Lambda}{m_a^2 w_b^3} \propto nT^{-3/2}$$

Typical structures include:

- $T_\perp \neq T_\parallel$
- $T_i \neq T_j$
- relative drifts
- agyrotropy

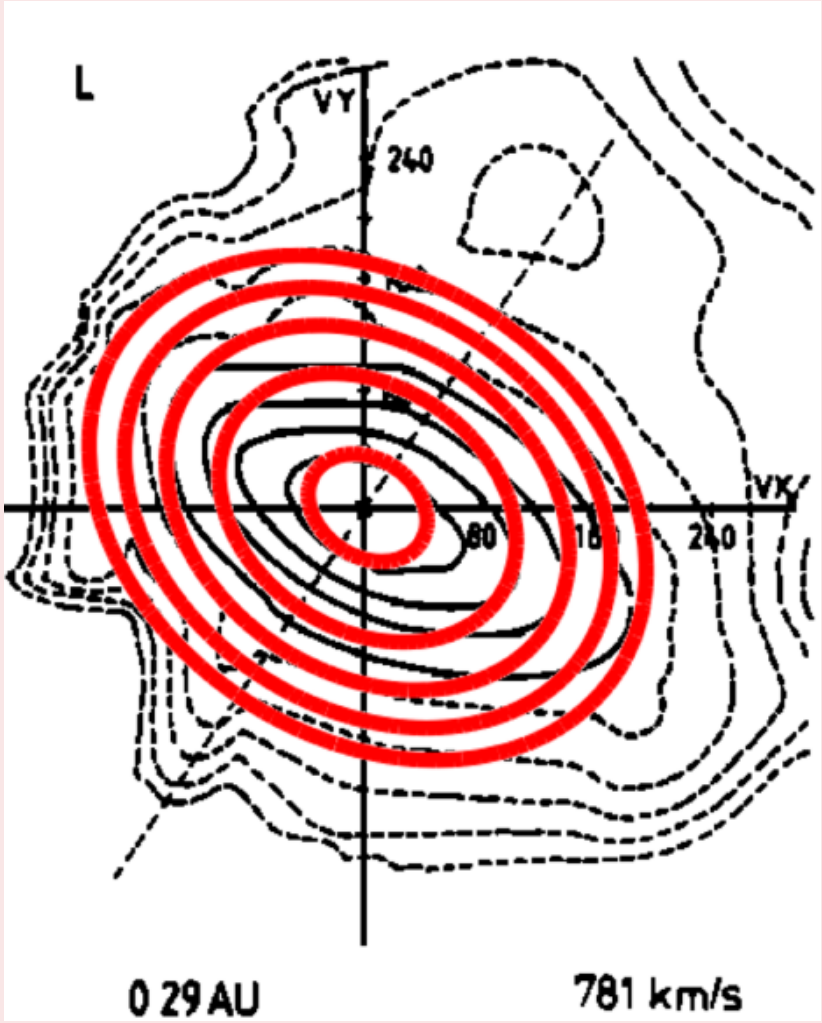


Kasper et al, 2017: Wind

'Collisionality' (e.g. $N_c = \nu_{a,b}\frac{R}{V_{sw}}$) organizes anisotropies, disequalibria, and relative drift speeds of components.

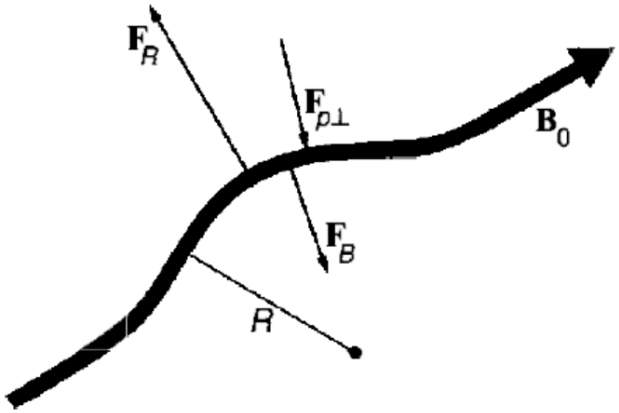
Extracting "Energy" from non-Maxwellian Distributions

Particle Velocity Distributions $f_s(\mathbf{v})$



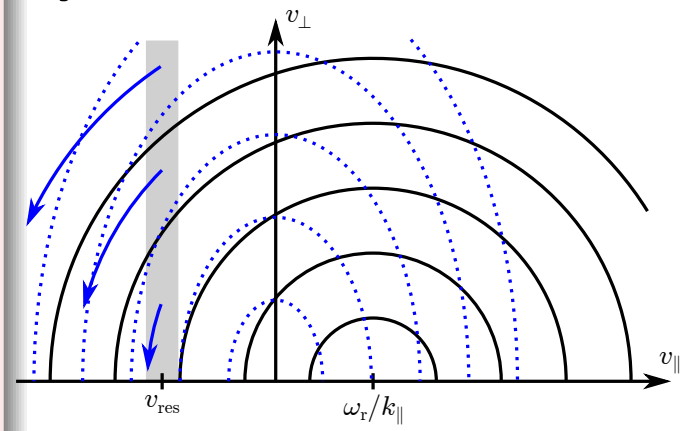
Marsch et al, 2012: Helios

Fluid Firehose Instability:



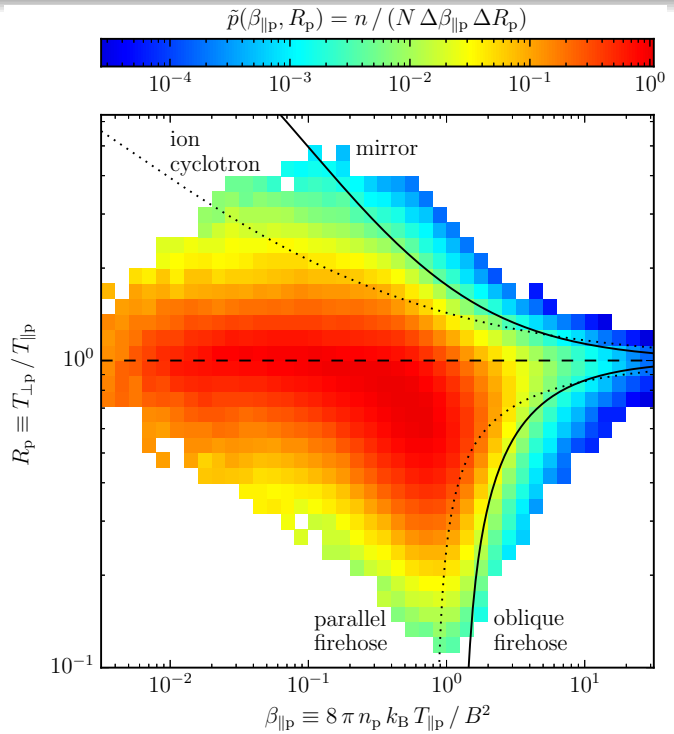
Treumann & Baumjohann, 1997

Cyclotron **Resonant** Instability:



Verscharen, Klein, & Maruca, under review

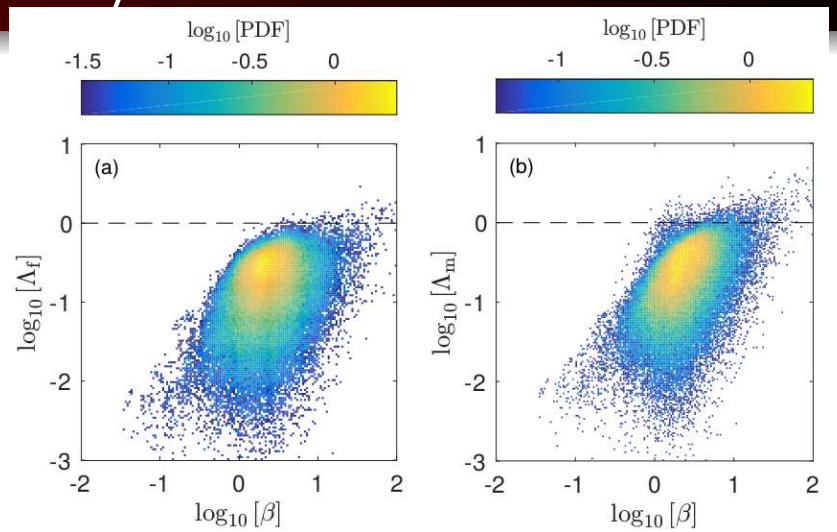
"Simple Models" for Stability Thresholds



Verscharen, Klein, & Maruca Wind

$$\frac{T_{\perp,p}}{T_{\|,p}} = 1 + \frac{a}{\left(\beta_{\|,p} - \beta_0\right)^b}$$

Hellinger et al. 2006



Chen et al 2016 Wind

$$\Lambda_{\text{firehose}} = \frac{\beta_\| - \beta_\perp}{2} + \frac{\sum_s \rho_s |\Delta \mathbf{v}_s|^2}{\rho v_A^2} > 1$$

$$\Lambda_{\text{mirror}} = \sum_s \beta_{\perp s}\left(\frac{\beta_{\perp s}}{\beta_{\| s}} - 1\right) + \frac{\left(\sum_s q_s n_s \frac{\beta_{\perp s}}{\beta_{\| s}}\right)^2}{2\sum_s \frac{(q_s n_s)^2}{\beta_{\| s}}} > 1$$

Kunz et al 2015

Such models do not account for other energy sources
(e.g. other species anisotropies, relatively drifting components)

Identifying Instabilities from Linear Dispersion Relation $|\mathcal{D}|$

Given the wave vector equation

$$\mathbf{n} \times (\mathbf{n} \times \mathbf{E}) + \underline{\underline{\epsilon}} \cdot \mathbf{E} = \underline{\underline{\mathcal{D}}} \cdot \mathbf{E} = 0$$

normal modes (ω, γ) arise for $|\mathcal{D}| = 0$.

We model $|\mathcal{D}|$ in the solar wind using:

- a collection of N_s bi-Maxwellian distributions
- drifting relative to one another
- with a background magnetic field

Normal modes are a function of $6N_s - 1$ parameters:

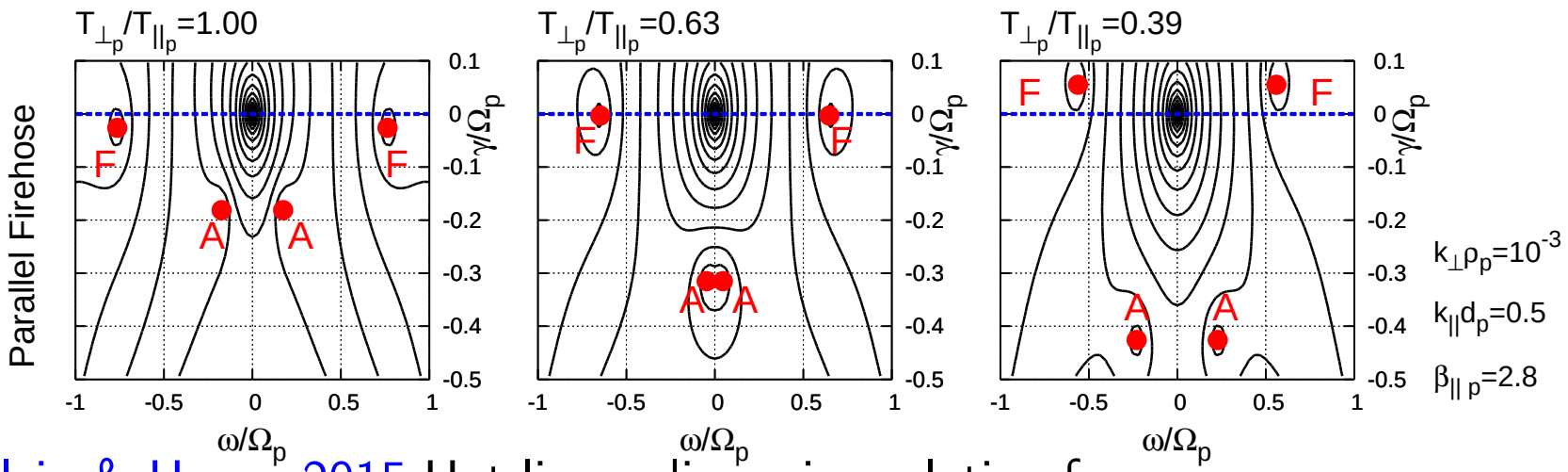
- wavevector $k_\perp \rho_R, k_\parallel \rho_R$
- 'global' plasma parameters $\beta_{\parallel,R}$ and $v_{t,\parallel,R}/c$
- the ratios $T_\perp/T_\parallel|s$, $T_{\parallel,R}/T_{\parallel,s}$, n_s/n_R, m_s/m_R, q_s/q_R, and $V_{\mathrm{drift},\parallel,s}/v_{AR}$ for each population s

Identifying Instabilities from Linear Dispersion Relation $|\mathcal{D}|$

Given the wave vector equation

$$\mathbf{n} \times (\mathbf{n} \times \mathbf{E}) + \underline{\underline{\epsilon}} \cdot \mathbf{E} = \underline{\underline{\mathcal{D}}} \cdot \mathbf{E} = 0$$

unstable modes are solutions $|\mathcal{D}| = 0$ in complex frequency space (ω, γ) that have a positive damping rate $\gamma > 0$.



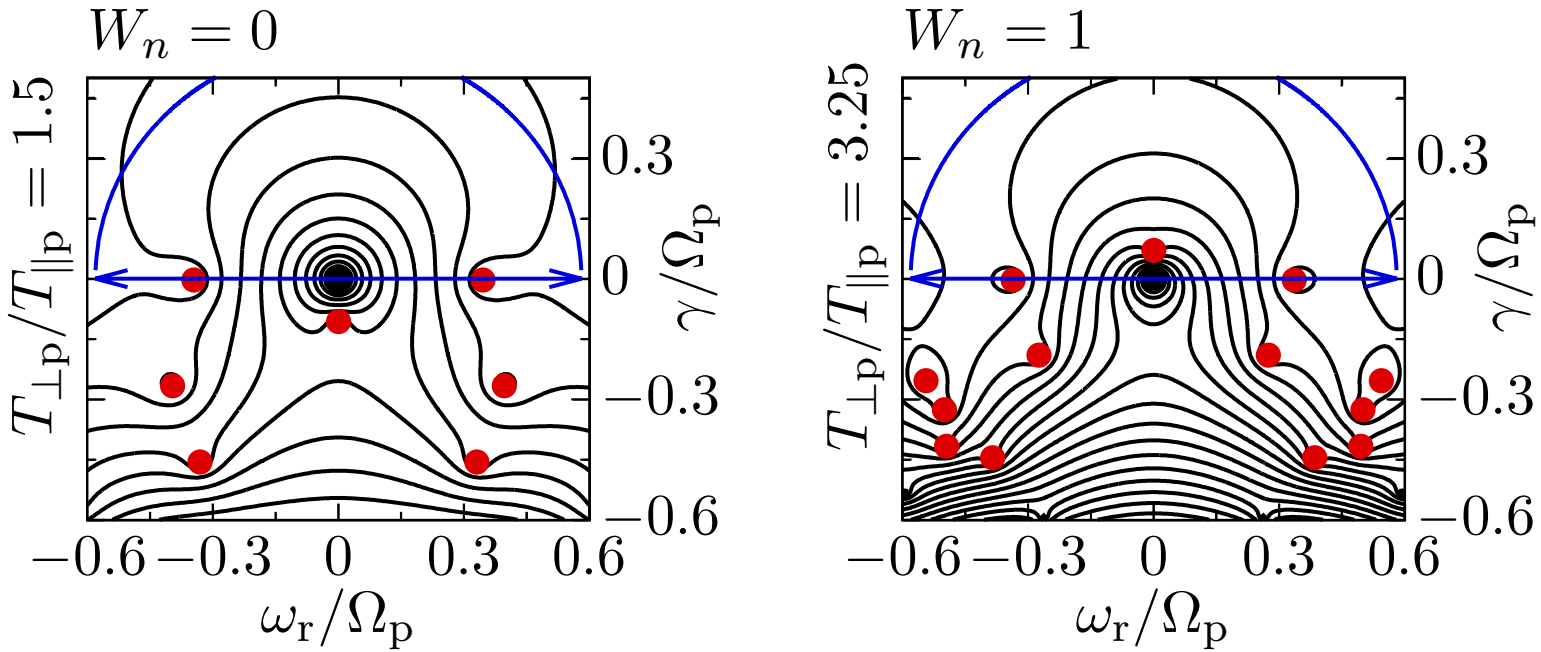
Klein & Howes 2015 Hot linear dispersion relation from **P**lasma in a **L**inear **U**niform **M**agnetized **E**nvironment (PLUME)

Stability sensitively depends on the bulk parameters of each species, which cover a wide range of values in the solar wind, making implementing a manual scan time consuming.

The Nyquist Instability Criterion (Nyquist 1932)

Instead of searching for solutions of $|D(\omega, \gamma > 0)| = 0$, we evaluate the contour integral for the number of unstable modes: (PLUMAGE; Klein et al. 2017 JGR).

$$W_n = \frac{1}{2\pi i} \oint \frac{d\omega}{|D(\omega, \gamma)|}.$$

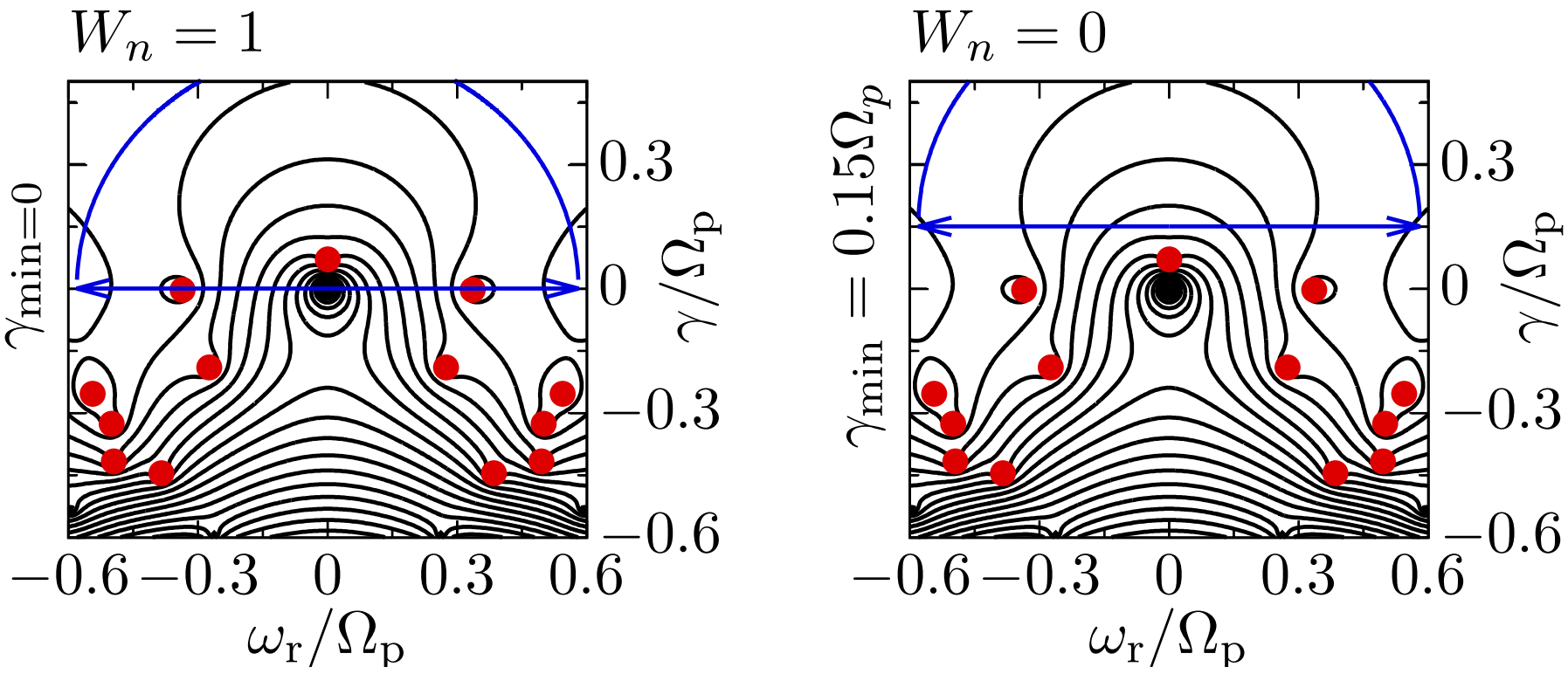


"In another hundred and twenty days the building of the Integral will be completed. The great historic hour is near, when the first Integral will rise into the limitless space of the universe."
—*We* Yevgeny Zamyatin

We can test for arbitrarily fast growing modes

Instead of using $\gamma = 0$ to define the contour,
we calculate W_n for any growth rate γ_{min}.

(This requires the insertion of a branch cut).



This procedure for a range of wavevectors produces $\gamma_{\mathrm{max}}(\mathbf{k})$

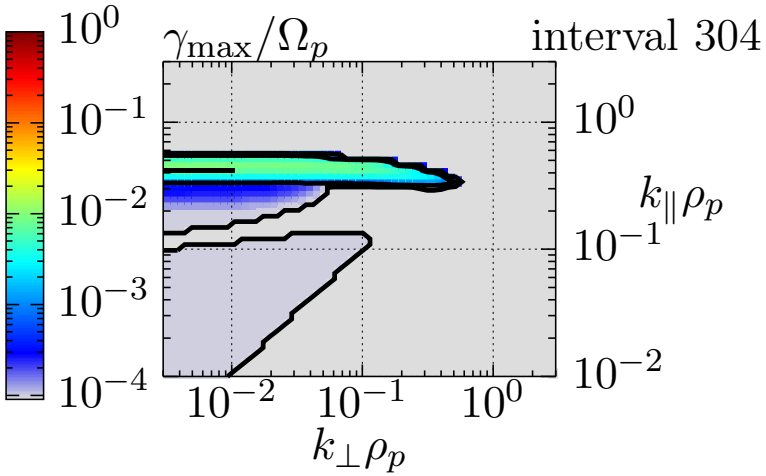
A Statistical Data Set from the Solar Wind

- We select a random set of Wind spectra, the first nominal spectra a day from 309 days in 2016 & 2017.
- For each spectrum, a nonlinear-least-squares Bi-Maxwellian fit is performed for up to three ion components;
  proton core $n_p, T_{\perp p}, T_{\| p}$,
  proton beam $n_b, T_{\perp b}, T_{\| b}, \Delta v_{pb}$,
  α **population** $n_\alpha, T_{\perp \alpha}, T_{\| \alpha}, \Delta v_{p\alpha}$,
  and combined with $|B|$ to produce the associated dimensionless parameters. (Klein et al 2018)

- For Each Spectra, we calculate $W_n(\mathbf{k}\rho_p)$ on a grid covering $(k_\perp, k_\|)\rho_p \in [10^{-2}, 10^1]$.
- The maximum growth rates of unstable spectra are found within $\gamma_{\min}/\Omega_p = [10^{-4}, 1]$.

Occurrence of Ion-Driven Instabilities

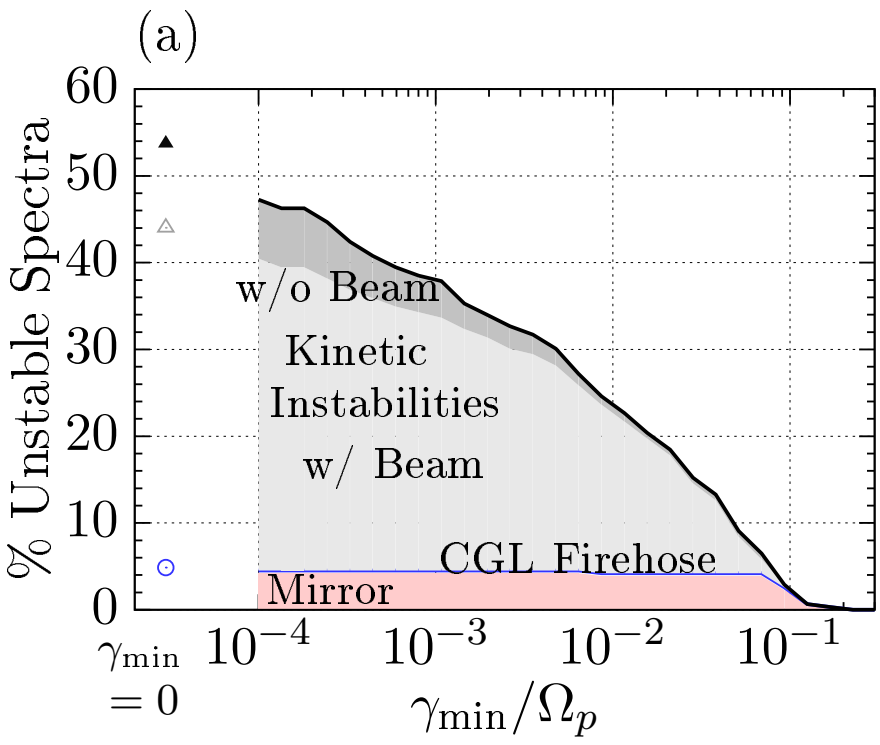
	# Spectra	# Unstable	Mirror	CGL FH	Kinetic
Total	309	166	14	1	151
p, b, & α	189	130	12	0	118
p & α	114	33	2	1	30
p & b	5	3	0	0	3
p	1	0	0	0	0

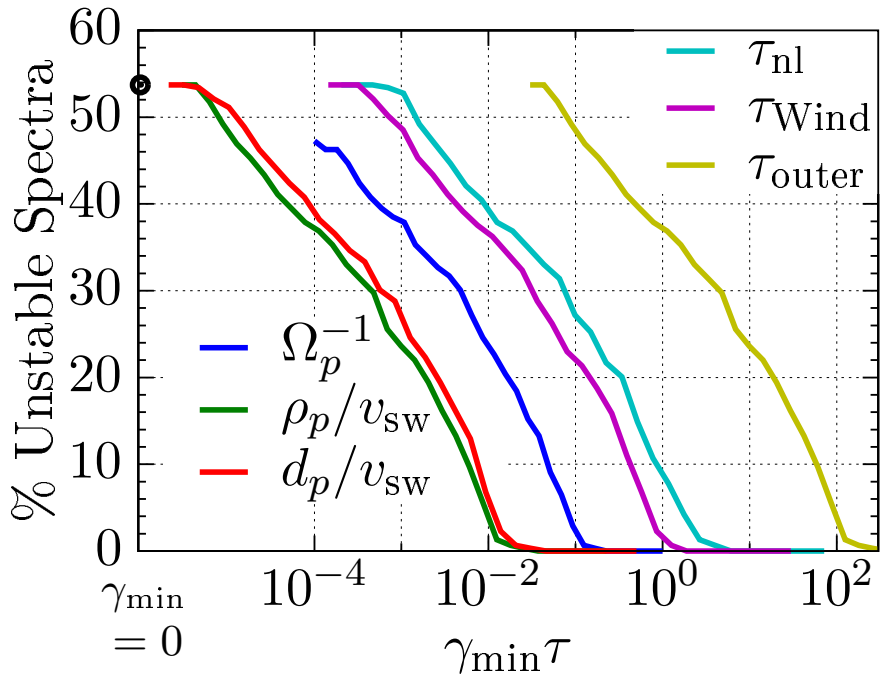


Klein et al 2018

- 54% of spectra are unstable
- The majority of the instabilities are kinetic, i.e. $k_\perp \rho_p < k_\parallel \rho_p \lesssim 1$
- Instabilities preferentially arise when a proton beam is resolved

Statistics of Instability Timescales

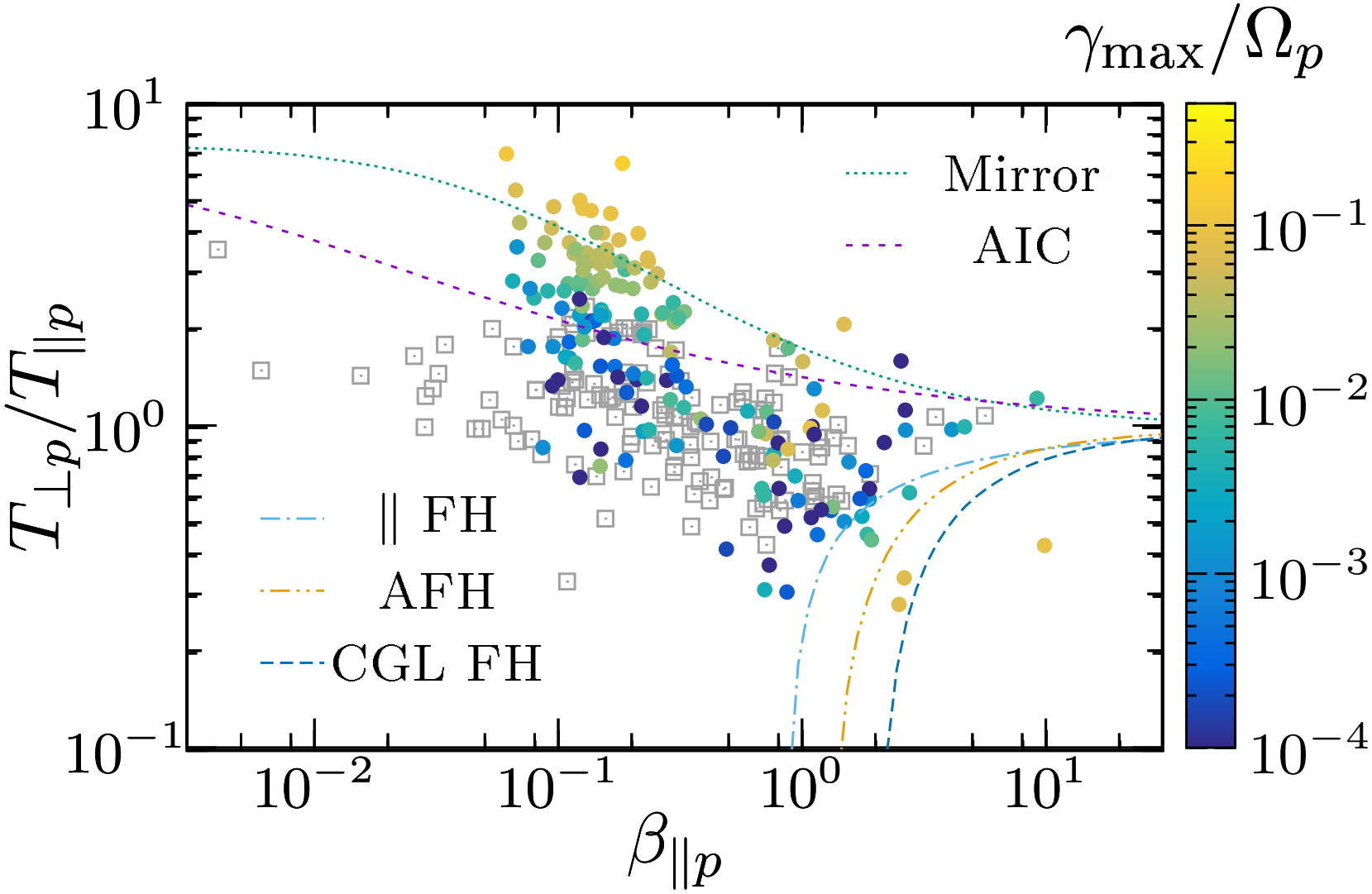




Klein et al 2018

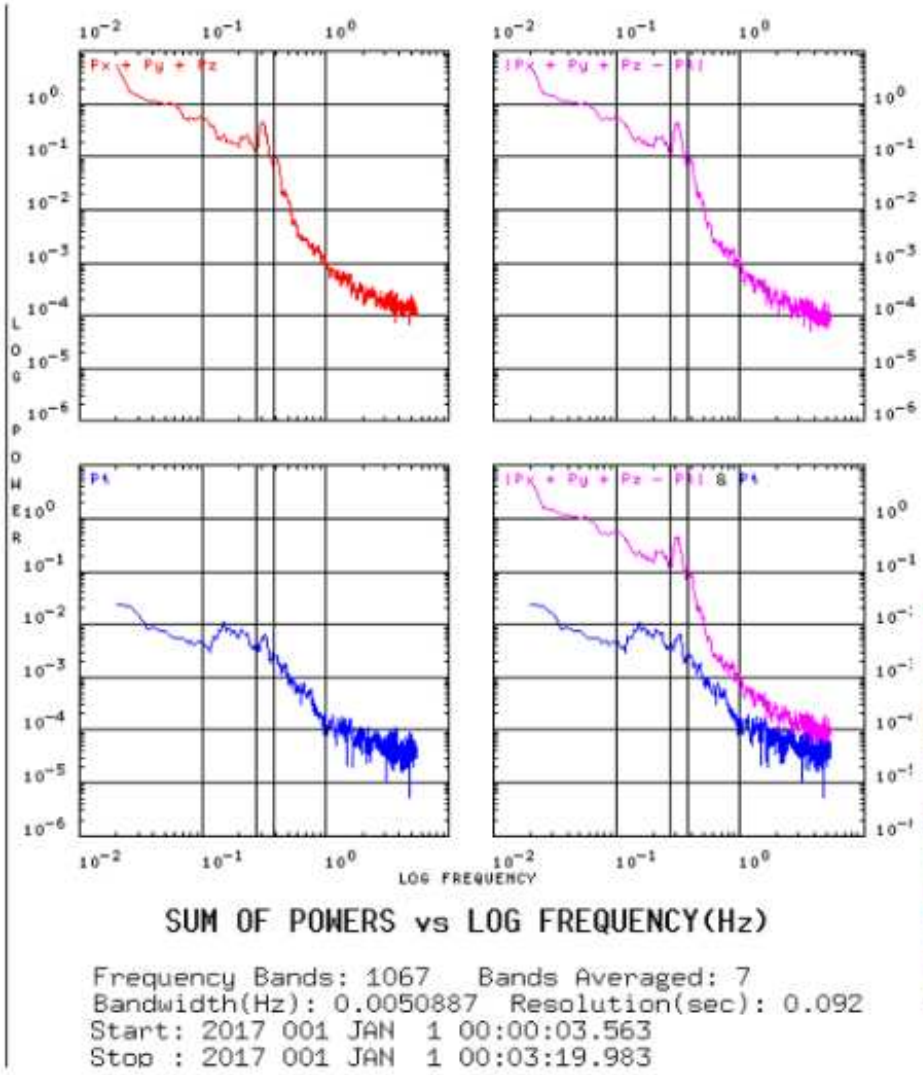
- The fluid instabilities have the largest growth rates
- Unstable intervals w/o proton beams are less virulent
- 10% of the spectra have γ comparable to the cascade time at $k_\perp \rho_p = 1$.

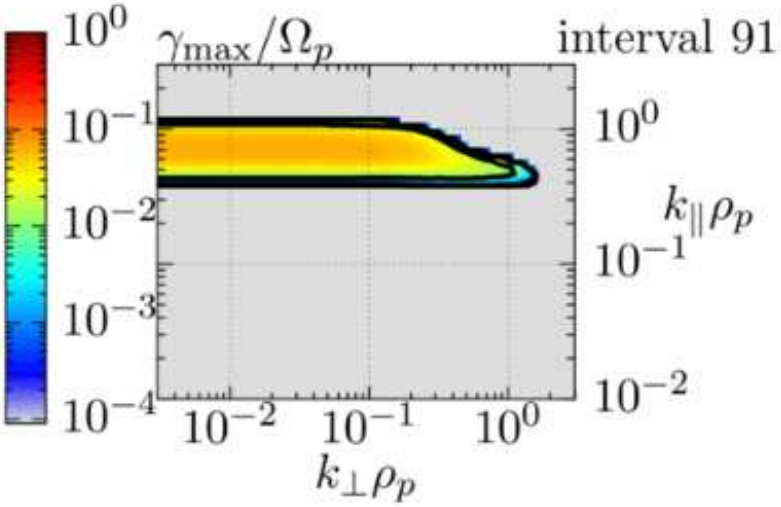
Comparing To Temperature Anisotropy Thresholds

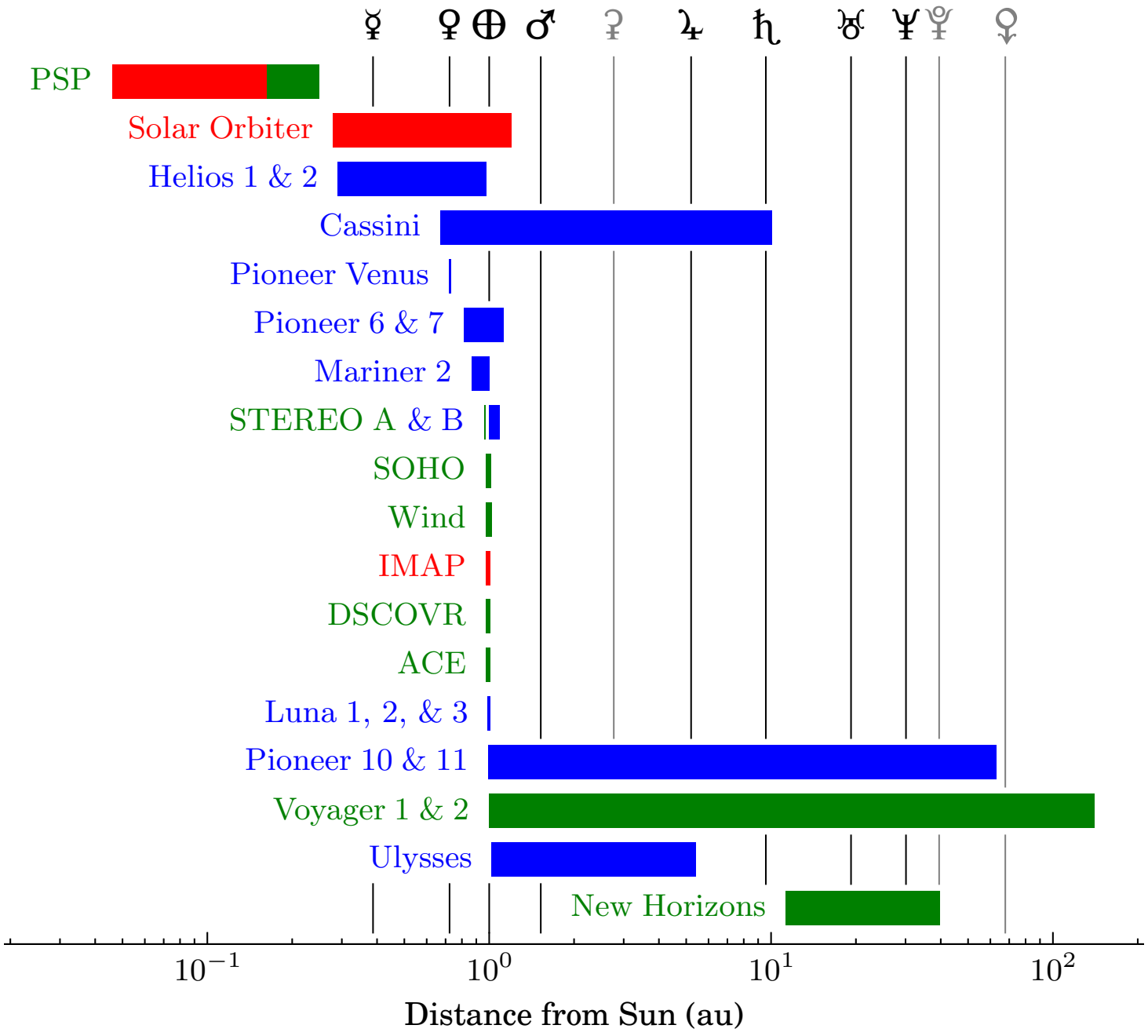


A significant fraction of spectra in the 'stable' region support growing modes. (Klein et al 2018)

Are there actually waves here?



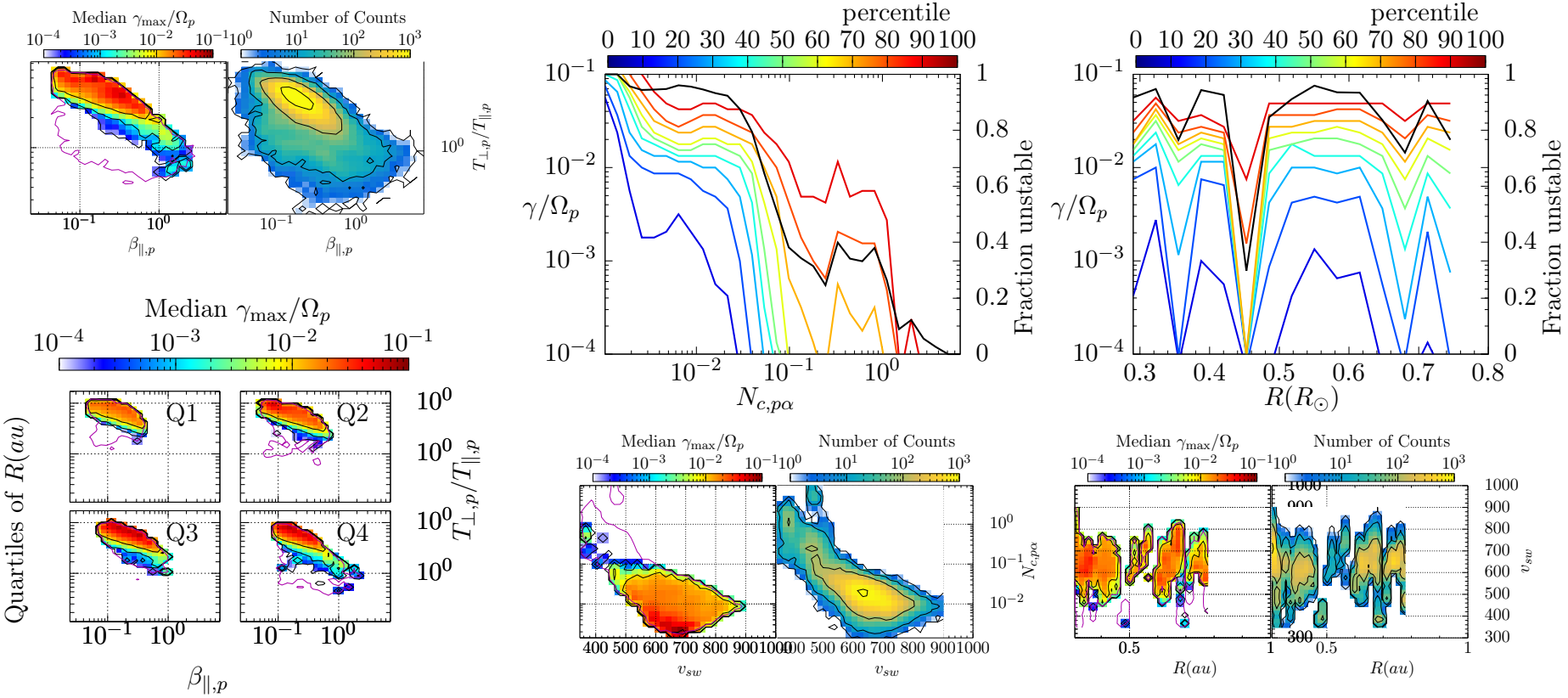


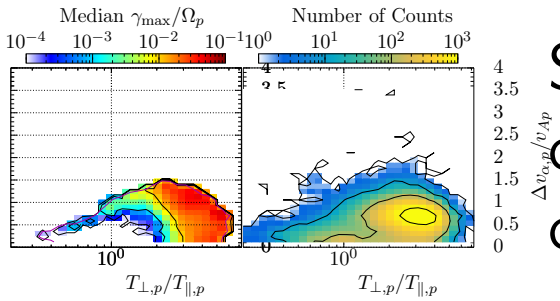


Verscharen, Klein, & Maruca, under review

Seeking Insight into Radial Variations.

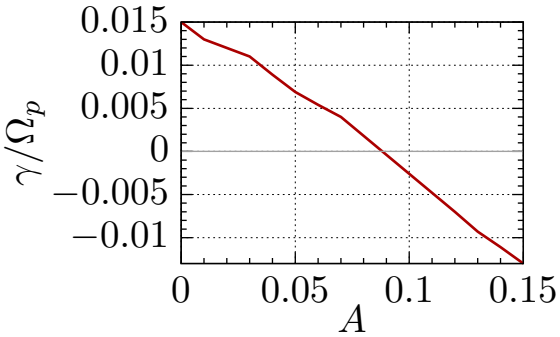
Applying *PLUMAGE* to $\sim 40,000$ measurements from Helios (Stansby et al 2018), we find $\sim 80\%$ are unstable.





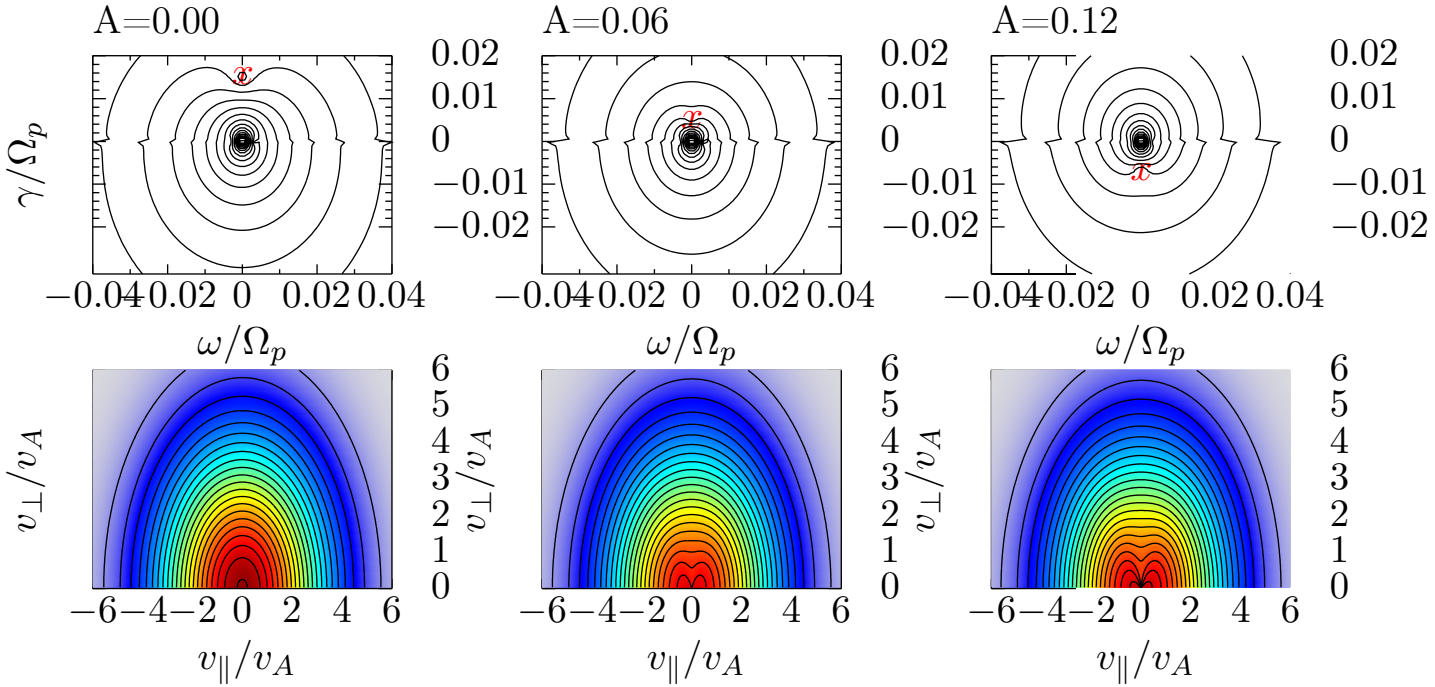
Stability does not seem to *primarily* depend on proximity to the Sun or v_{sw}, but rather on N_C, $T_\perp/T_\parallel$, and $\Delta v_{\alpha,p}$.

Arbitrary **L**inear **P**lasma **S**olver (ALPS, Verscharen et al 2018, JPP) solves the full hot-plasma dispersion relation for a set of plasma populations with **arbitrary** velocity distributions defined on a grid in momentum space.

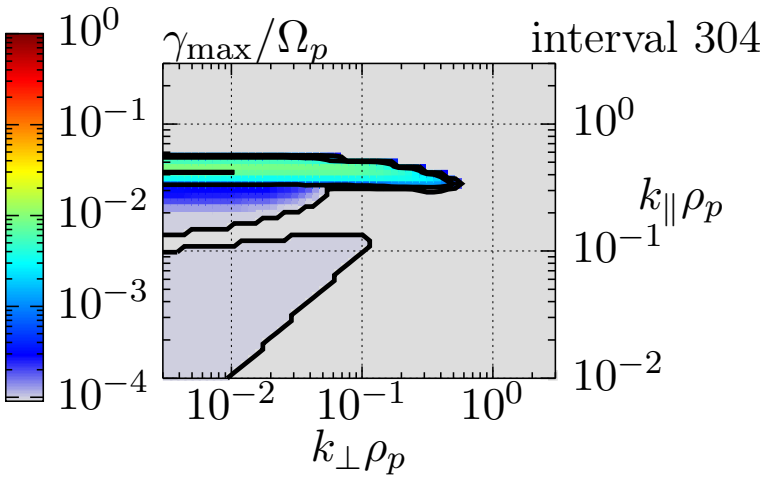


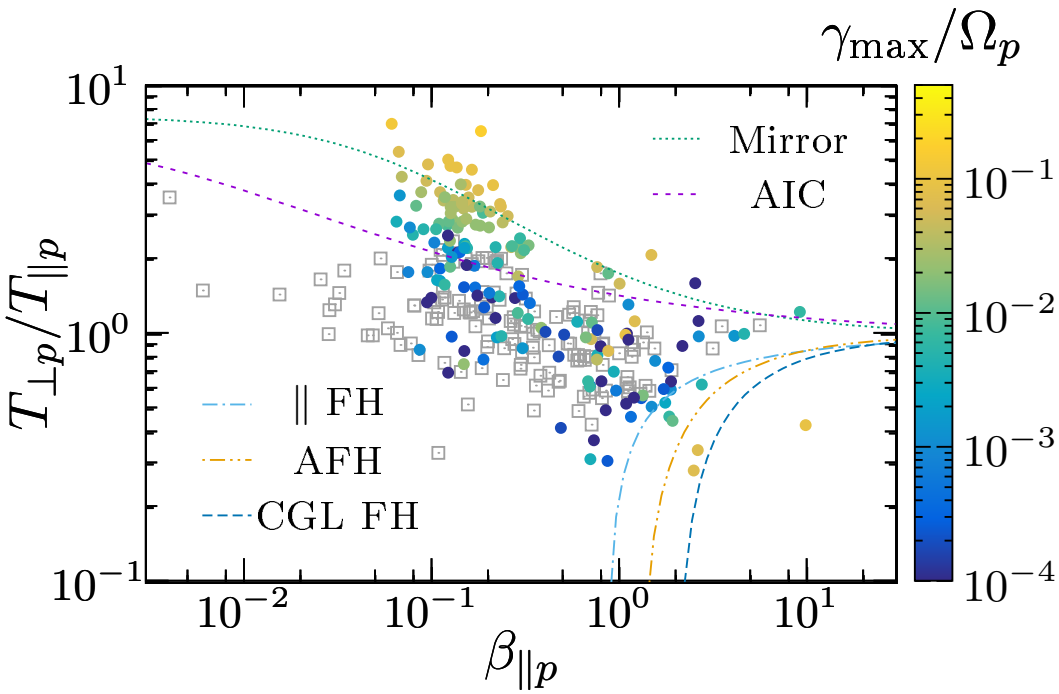
$T_\perp/T_\parallel = 1.40$
$\beta_{\parallel,p} = 10.0$
$k_\perp d_p = 0.40$
$k_\parallel d_p = 0.20$

$$f(v_\perp, v_\parallel) = f_{\mathrm{Bi}}(v_\perp, v_\parallel)\left(1 - A\exp\left[\frac{-v_\parallel^2}{(0.6v)^2}\right]\right)$$



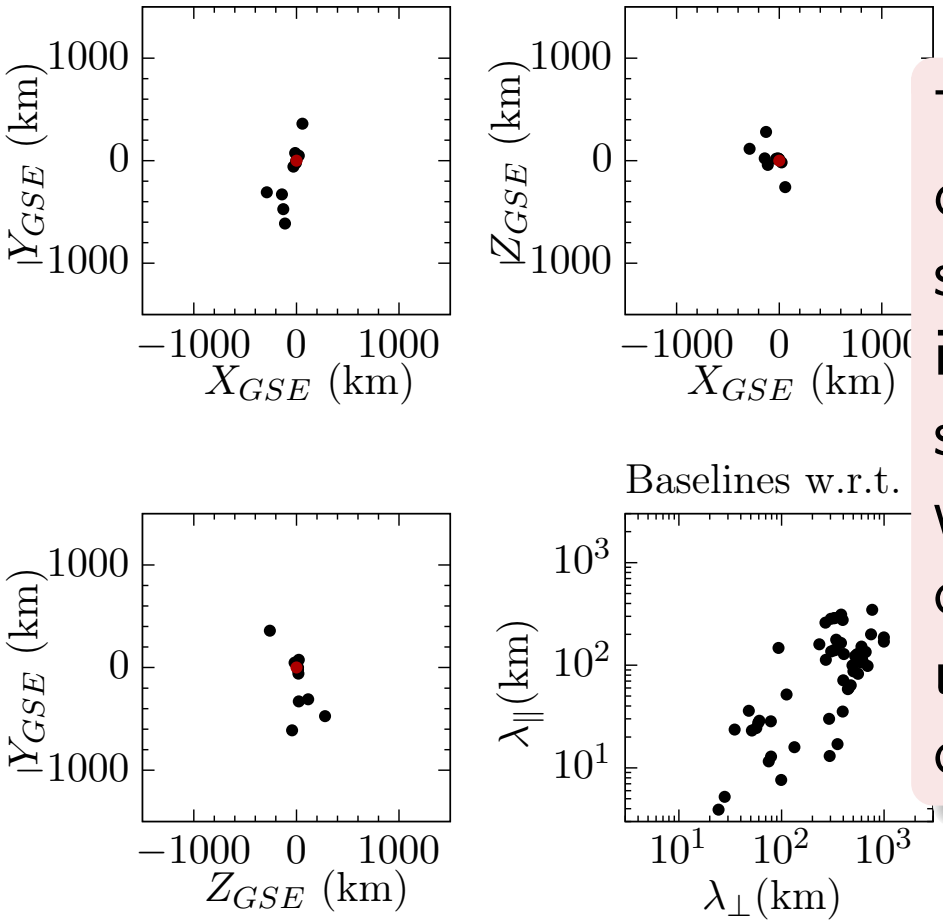
In Conclusion





Non-thermal structure is ubiquitous and provides several sources of free energy to drive instabilities.

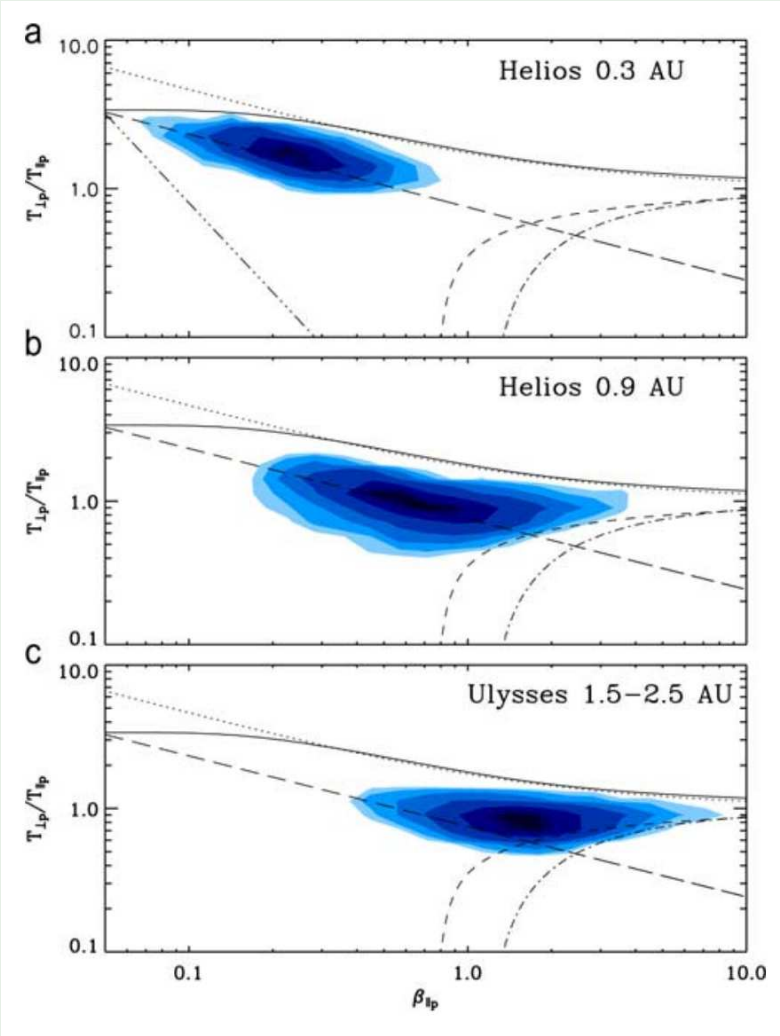
Future Concepts to Explore Space Plasma Processes



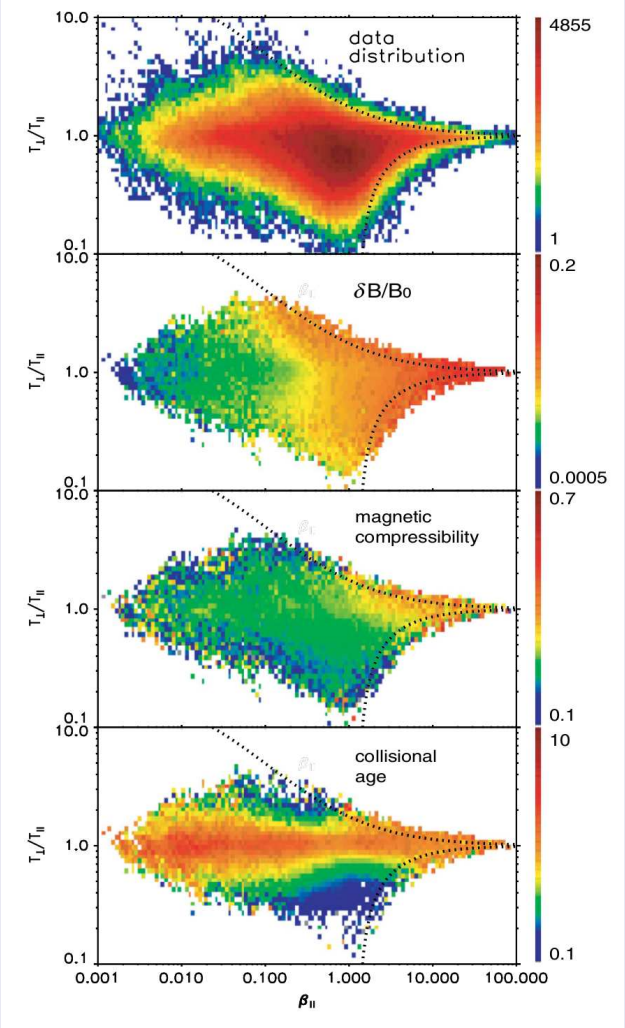
To-be-proposed missions comprised of many spacecraft, such as **HelioSwarm** with inter-spacecraft separations spanning large and small scales, will enable more detailed studies of energy transport, including unstable growth and its effect on the background turbulence.

Instabilities Limit the Solar Wind's Evolution

Matteini et al 2007



Bale et al 2009



These correlations may mask underlying dependencies.

(Hellinger & Travnicek 2014)

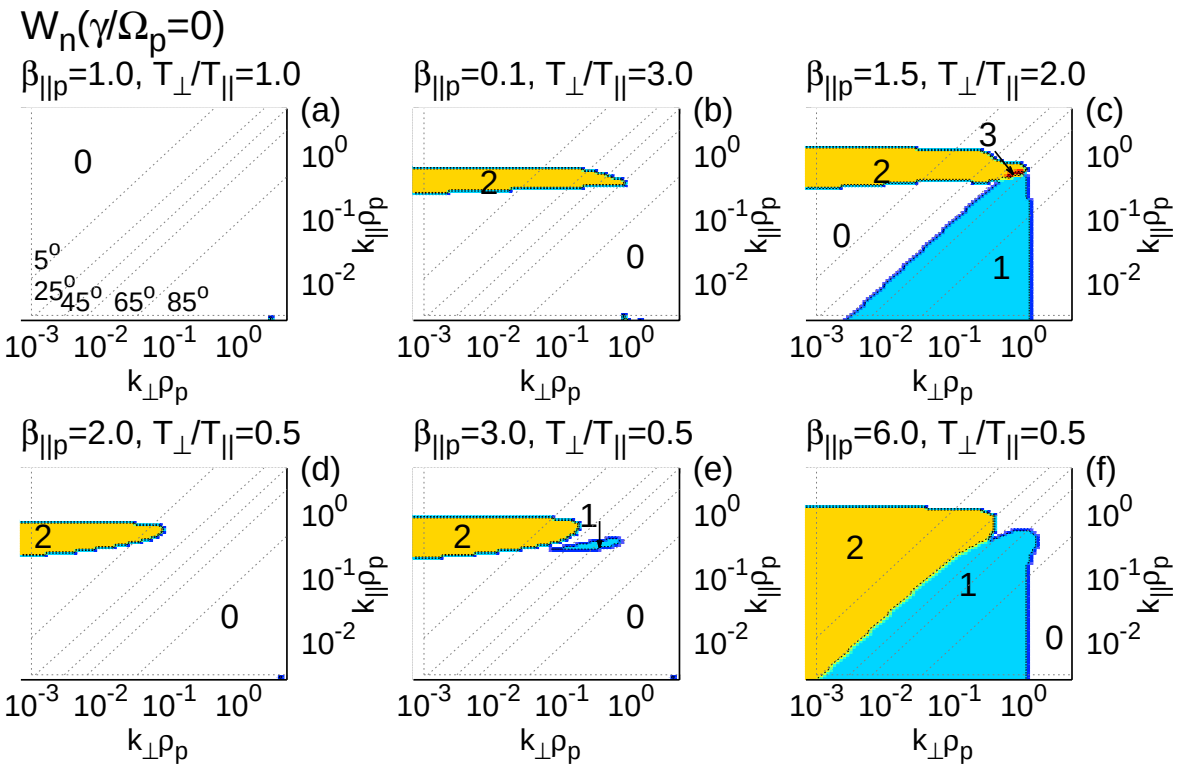
Parametric Dependence of Ion-Driven Instabilities

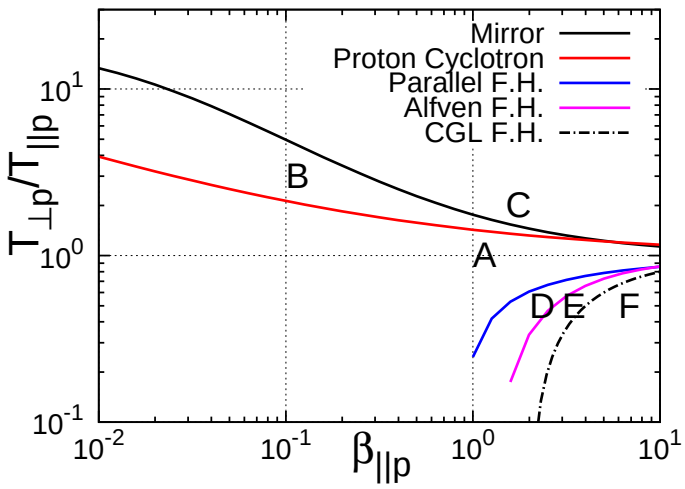
$$\Delta X \equiv \frac{\bar{X}_{\text{unstable}} - \bar{X}_{\text{stable}}}{\bar{X}}.$$

	$\beta_{\parallel p}$	$10^4 v_{tp}/c$	$T_{\perp p}/T_{\parallel p}$	$T_{\perp \alpha}/T_{\parallel \alpha}$	$T_{\perp b}/T_{\parallel b}$
Total	0.60	1.07	1.57	0.96	1.48
Stable	0.50	0.91	1.12	1.03	1.39
Unstable	0.68	1.21	1.96	0.90	1.52
$\Delta X_{p,\alpha,b}(\%)$	19.12	13.46	50.59	-21.06	8.45
$\Delta X_{p,\alpha}(\%)$	132.53	57.59	-26.77	14.16	—

	$T_{\parallel \alpha}/T_{\parallel p}$	$T_{\parallel b}/T_{\parallel p}$	n_α/n_p	n_b/n_p	$\lvert v_\alpha\rvert/v_A$	$\lvert v_b\rvert/v_A$
Total	10.89	2.72	0.04	0.43	0.31	0.84
Stable	5.24	2.35	0.04	0.41	0.16	0.73
Unstable	15.74	2.88	0.05	0.44	0.44	0.89
$\Delta X_{p,\alpha,b}(\%)$	64.27	20.83	2.61	2.90	61.57	21.84
$\Delta X_{p,\alpha}(\%)$	26.46	—	18.10	—	77.44	—

A Solar Wind Relevant Example

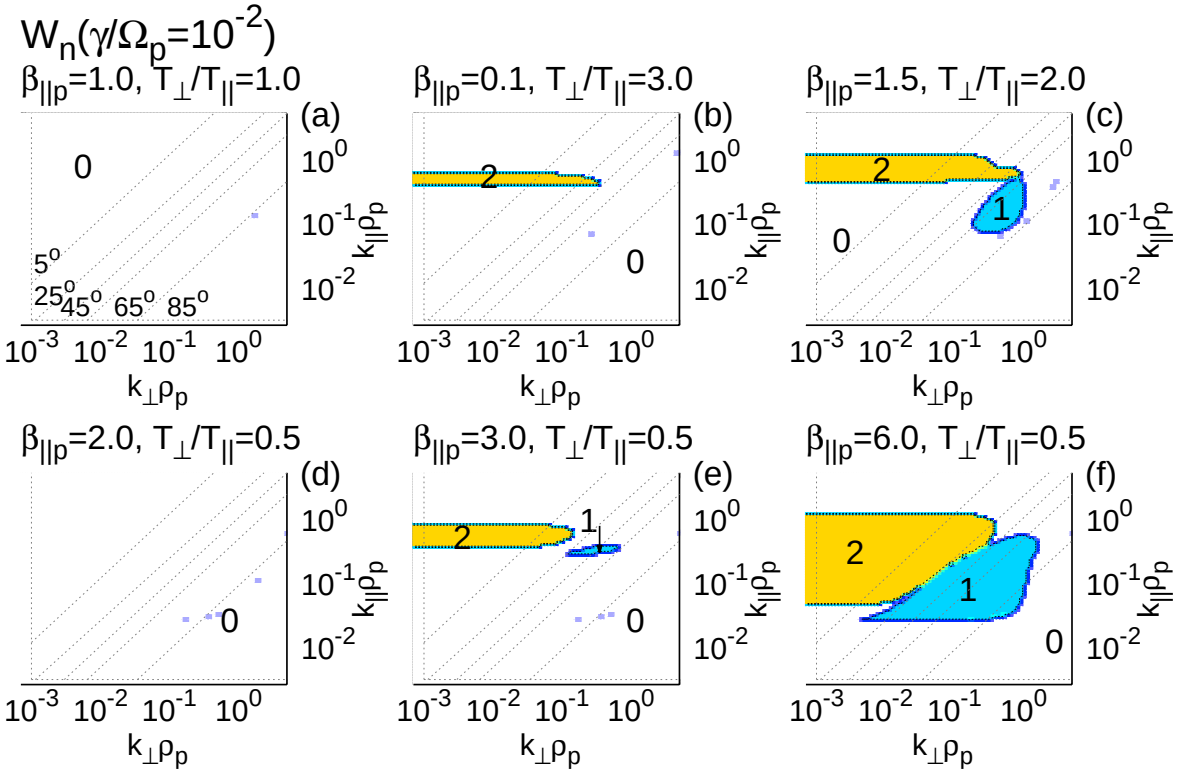


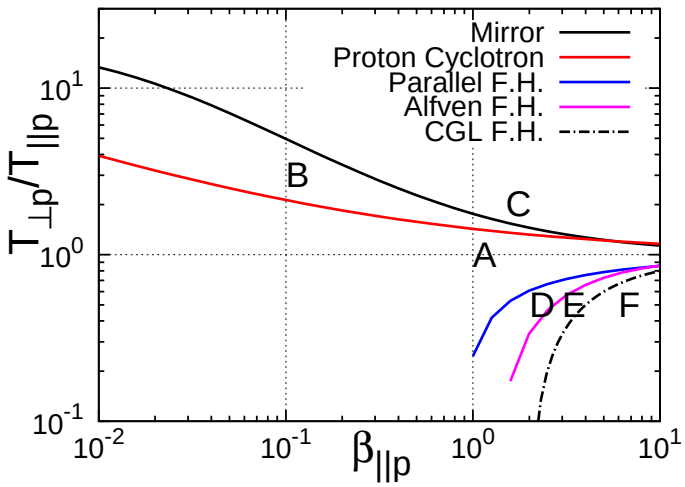


To Verify Our Algorithm

we calculate $W_n(\mathbf{k})$ for points in the $(\beta_{||p}, T_{\perp p}/T_{||p})$ plane using PLUME's hot, magnetized plasma dispersion relation.

Faster Growing Modes

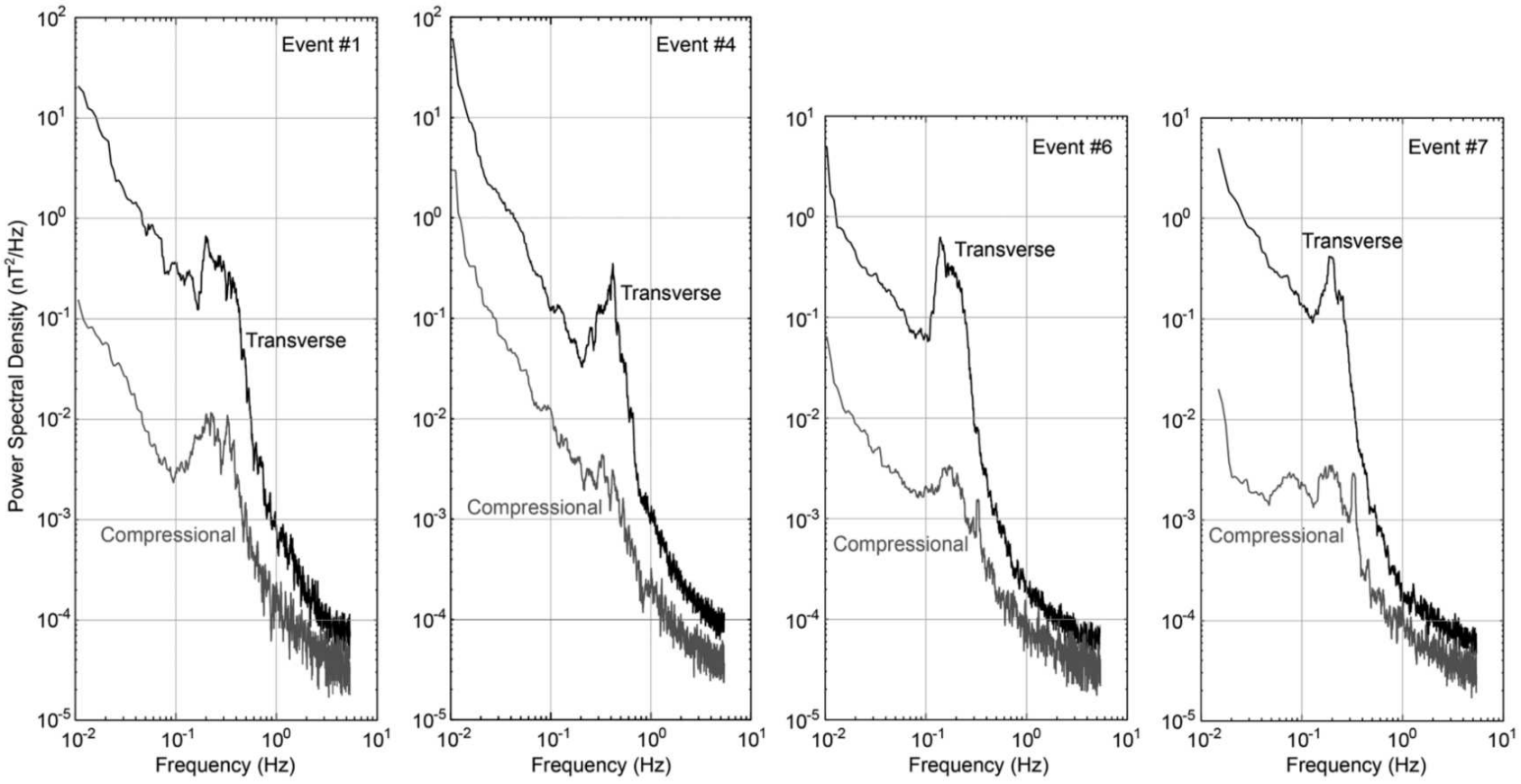




Instead of using the $\gamma = 0$ contour,
we calculate W_n for $\gamma_{\min} = 10^{-2}\Omega_p$.

Comparisons to Actual Solar Wind Measurements

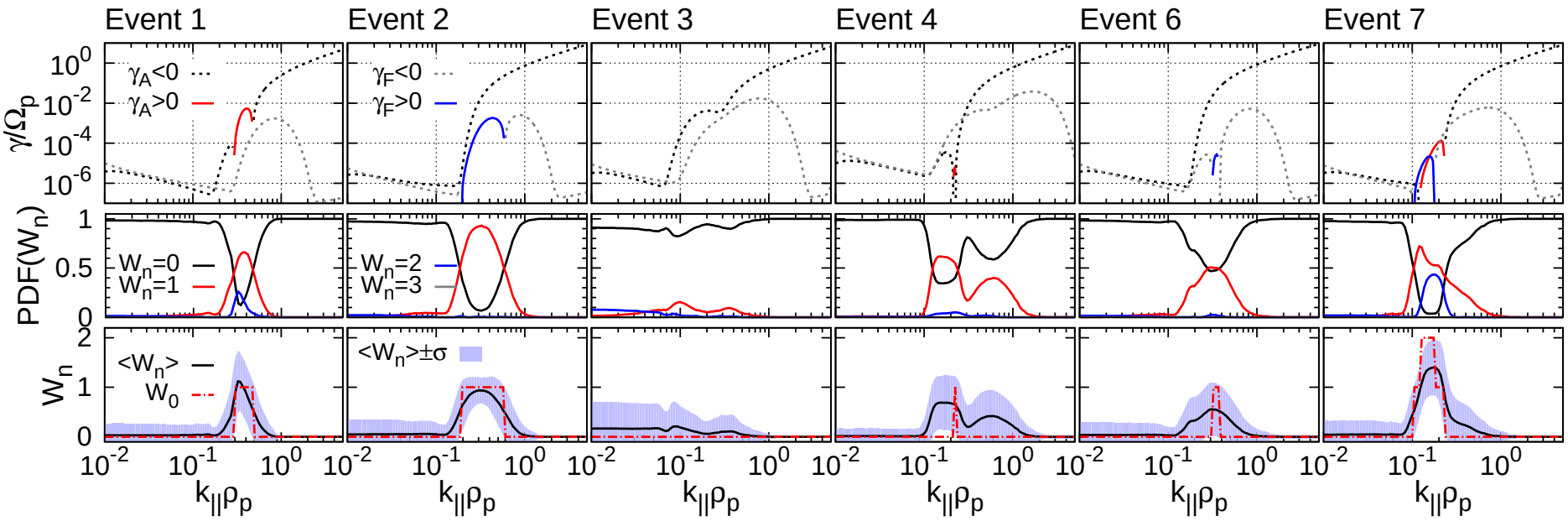
Gary et al 2016; Wind



Identified 6 intervals with observational signatures of parallel propagating instabilities in the magnetic power spectra.

How Robust are these Results?

10 % Monte Carlo variation of
proton core & beam, He^{++}, and e^{-} parameters.



Klein et al 2017

Events 4 & 6 are near unstable regions of parameter space