A Statistical Comparison Between Proton Microinstabilities and Nonlinear Effects in Space Plasmas

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UD

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$$R_j \equiv T_{\perp j} \,/\, T_{\parallel j}$$

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	Parallel ($\mathbf{k} \parallel \mathbf{B}$) & Propagating ($\omega_\mathrm{r} > 0$)	Oblique ($\mathbf{k} \nparallel \mathbf{B}$) & Non-Propagating ($\omega_\mathrm{r} = 0$)
$T_{\perp j} > T_{\parallel j}$ ($R_j > 1$)	Ion-cyclotron (Alfven mode)	Mirror (kinetic slow mode)
$T_{\perp j} < T_{\parallel j}$ ($R_j < 1$)	Parallel firehose (fast/whistler mode)	Oblique firehose (Alfven mode)

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$$\beta_{\parallel j} \equiv \frac{n_j \, k_\mathrm{B} \, T_{\parallel j}}{B^2 \,/\, (2\,\mu_0)}$$

Ion Temperature-Anisotropy Instabilities

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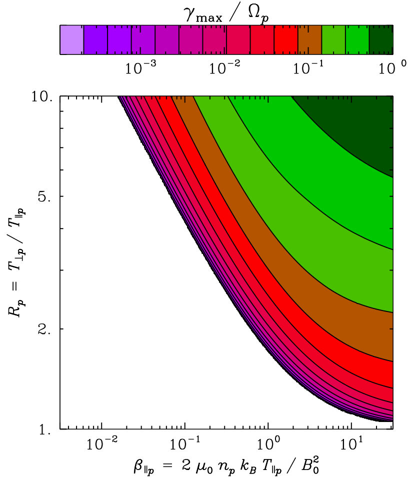
- Instabilities driven by $R_j \neq 1$
- Separate modes for $R_j > 1$ and < 1
- Separate modes for **k** parallel and oblique to **B**
- Value of γ strongly dependent on R_j and plasma beta:

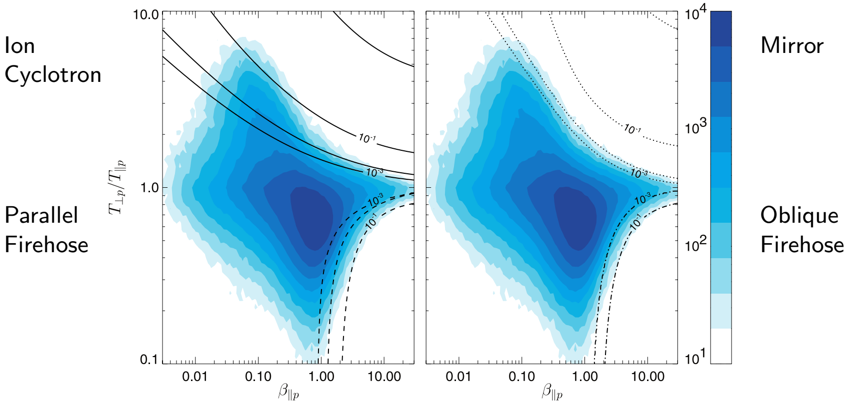
$$\beta_{\parallel j} \equiv \frac{n_j \, k_\mathrm{B} \, T_{\parallel j}}{B^2 \, / \, (2 \, \mu_0)}$$

- Example: $\gamma_\mathrm{max}(\beta_{\parallel p}, R_p)$ for mirror instability



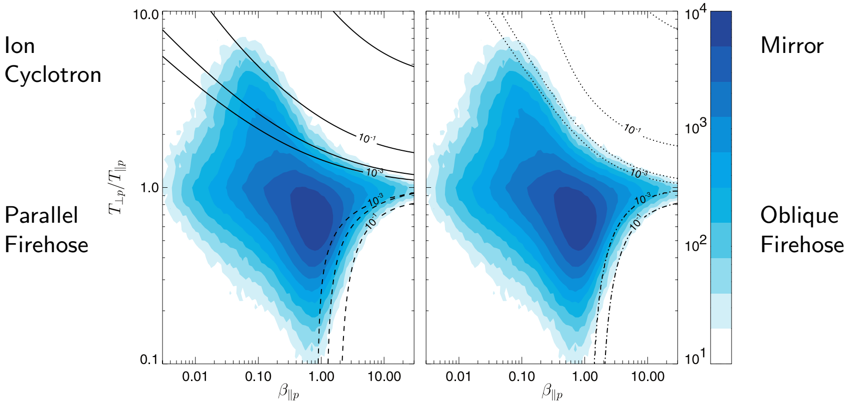
Maruca (PhD thesis, 2012)

Instability Regulation of Temperature Anisotropy



- Joint distributions of $(\beta_{\parallel j}, R_j)$-data
  - Essentially, 2-D histograms
  - "Brazil plots"
- Popularized by Hellinger et al. (*GRL*, 2006)
  - Proton measurements *Wind*/SWE
  - Data bins smoothed into curves
  - Overlaid: contours of constant γ (theory)

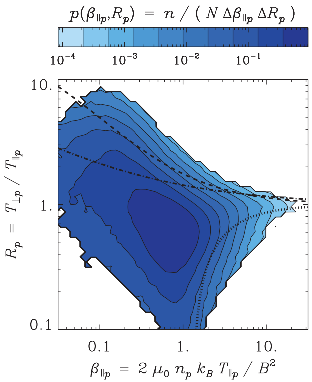
Instability Regulation of Temperature Anisotropy

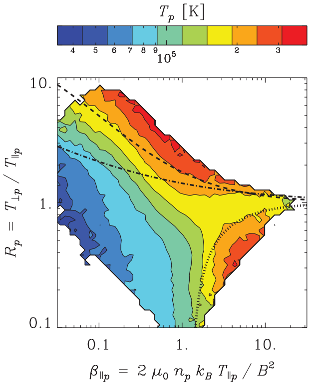


- Alignment of data with γ contours
  - Excellent for oblique modes (right)
  - Worse for parallel modes (left) – despite theoretically stricter limits (especially at low-$\beta_{\parallel p}$)
  - Cause unknown; possibly due to the shape of VDFs and the way IC resonates

Instabilities and Heating

- Probability density of $(\beta_{\parallel p}, R_p)$
  - Counts normalized by bin size
  - Bins smoothed into contours
- Temperature T_p over $(\beta_{\parallel p}, R_p)$-plane
  - Temperature enhancement in marginally unstable plasma
  - Heating (versus cooling) produces temperature anisotropy that drives instabilities
- Temperature components $T_{\perp p}$ and $T_{\parallel p}$
  - Enhancements in both at respective instability thresholds
  - Strongly preferential heating
  - No indications of cooling driving instabilities





Maruca et al. (*PRL*, 2011)

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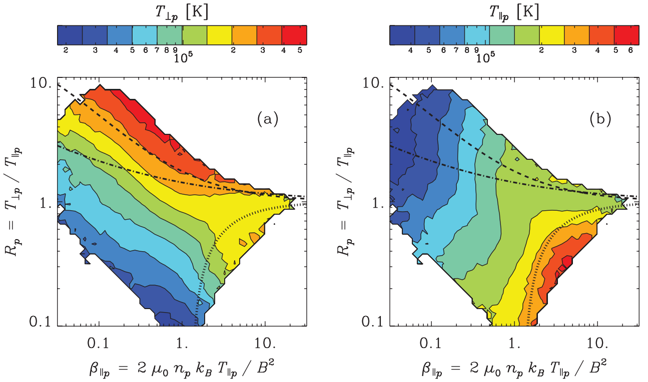
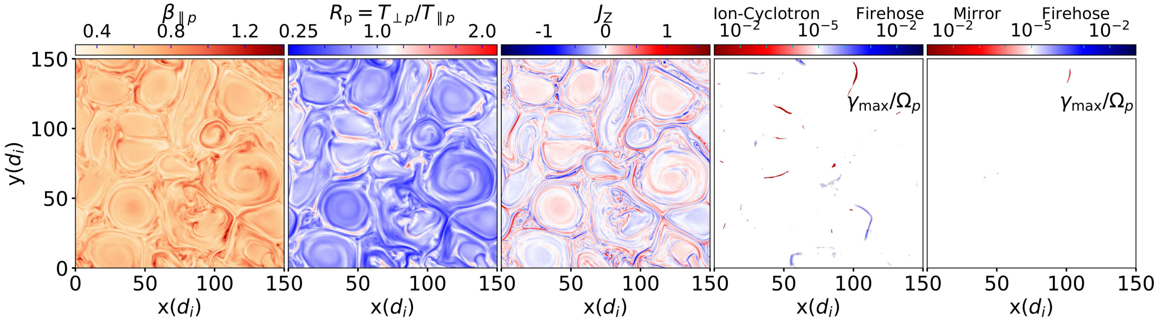


Maruca et al. (*PRL*, 2011)

Temperature Anisotropy Instabilities in PIC simulation and Earth's Magnetosheath

Instability Analysis of PIC Simulation

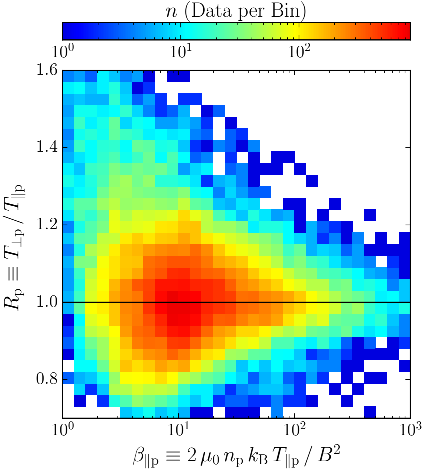


Qudsi et al. (*ApJ*, submitted)

- 2.5-D fully kinetic PIC simulation
- Departures from LTE near current sheets (Greco et al., *PRL*, 2008; *PhRvE*, 2012)
- Linear Vlasov theory: growth rates of $R_p \neq 1$ instabilities
- Distinct regions of $\gamma_{\text{max}} > 0$
  - More with parallel than oblique instabilities
  - Near (not co-local with) current sheets
- Turbulence generating anisotropic heating that drives instabilities?

MMS/FPI Measurements in the Magnetosheath

- *MMS*/FPI burst-mode measurements of protons
  - Burst-mode cadence: $150\,\mathrm{ms}$
  - 58,510 data from 6 distinct intervals
  - Intervals previously studied by Chasapis et al. (*ApJ*, 2017; *ApJL*, 2018)
  - Chosen for duration and turbulence activity
  - Four spacecraft used independently
  - For each interval, $\mathrm{median}(R_p) \approx 1$
- Synchronization of proton and magnetic-field data
- Binning of data over $(\beta_{\parallel p}, R_p)$-plane

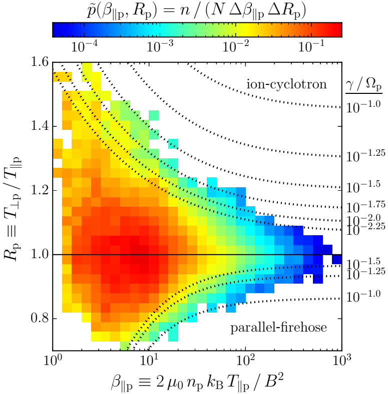


Maruca et al. (*ApJ*, 2018)

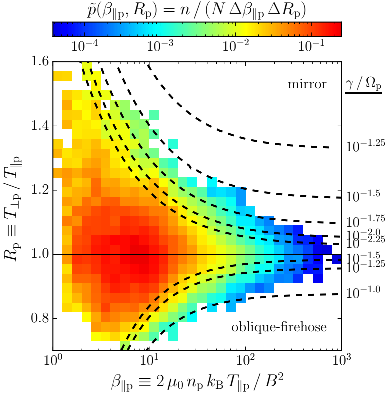
Comparison of *MMS* Data and Linear Vlasov Theory

- Same data in both plots
- Low-count bins suppressed
- Normalization by bin size: probability density
- Contours of constant growth rate $\gamma_{\max}$: same code as Maruca et al. (*ApJ*, 2012)
- Very close alignment of data distribution to theoretical contours

Parallel Instabilities



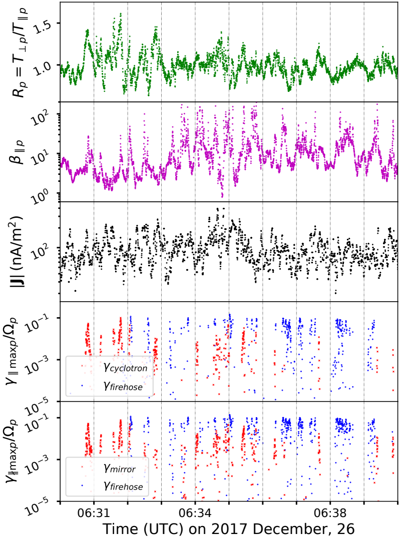
Oblique Instabilities



Maruca et al. (*ApJ*, 2018)

Instability Analysis of Time Series

- Multiple, longer periods of *MMS* data
- Growth rates of all 4 ion temperature anisotropy instabilities
- Distinct periods of $\gamma_{\max} > 0$
  - Typical duration $\approx$ few seconds
  - Similar results for parallel and oblique instabilities
  - Some alternation between $R_p < 1$ and $R_p > 1$ periods
- Frequency of $\gamma_{\max} > 0$ periods varies widely



Are these instabilities important?

Majority of solar wind is unstable ($\sim$54 %)

- statistical assessment of solar wind stability at 1 AU against ion sources of free energy using Nyquist's instability criterion
- Considered multiple sources of free energy
- Less than 10% of the spectra have growth rates faster than $\tau_{\rm nl}$

	# 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. (*PRL,2018*)

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  - $\tau_{\rm nl}$ is an estimate for the nonlinear turbulent energy transfer time at the proton gyroscale

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$$\tau_{\rm nl} = (k_0 \rho_p)^{-1/3} \rho_p / V_A$$

PIC simulation: Comparison between γ and ω

$\tau_{\rm nl}(r) = \ell/\delta b_\ell$

where $\delta b_\ell = |\hat{\boldsymbol{\ell}} \cdot [\mathbf{b}(\mathbf{r} + \boldsymbol{\ell}) - \mathbf{b}(\mathbf{r})]|$

$\omega_{\rm nl} = 2\pi/\tau_{\rm nl}$

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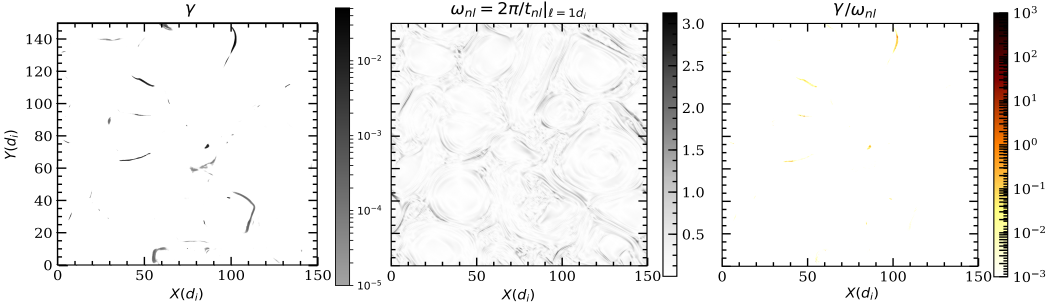
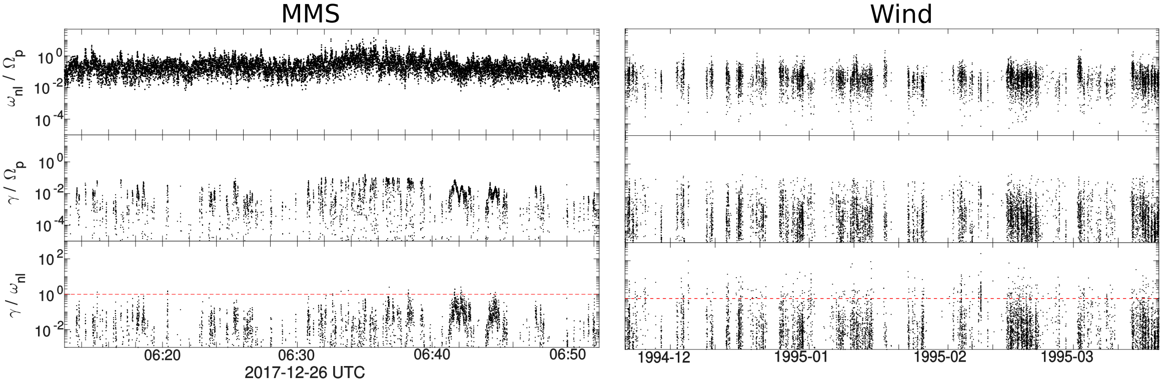


Badyopadhyay et al. (in prep)

Observations: Comparison between γ and ω



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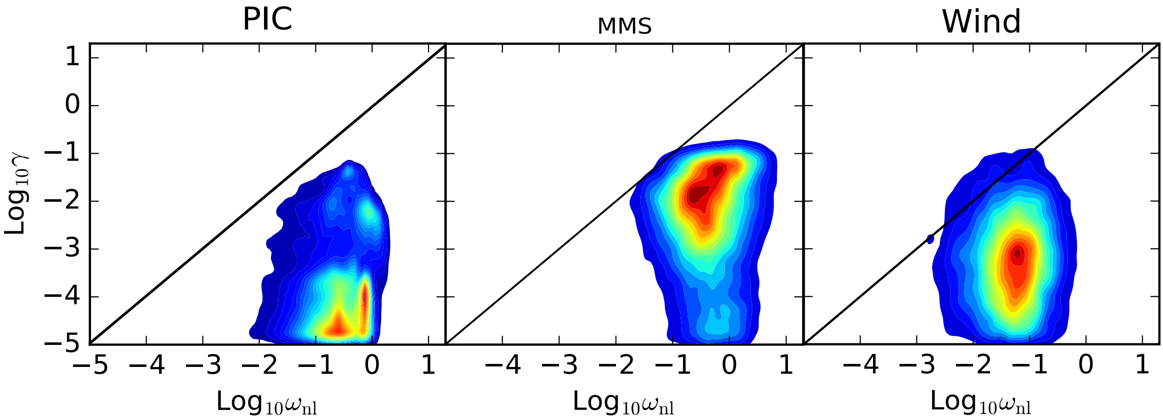

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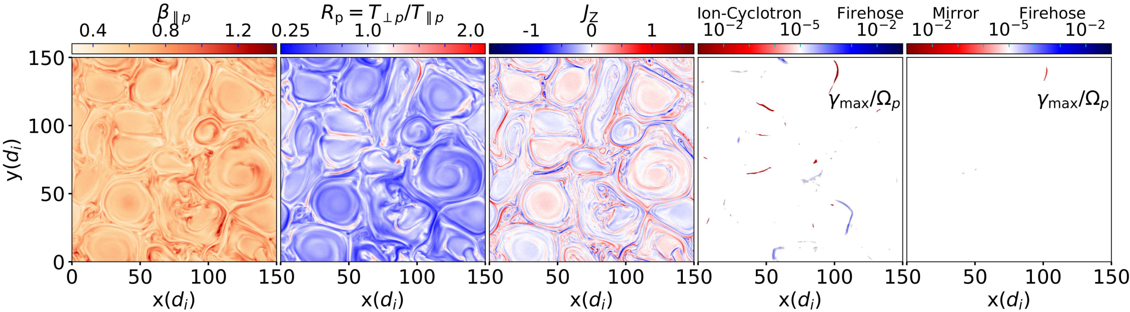
Discussion and Conclusions

- Turbulence heats the plasma anisotropically giving rise to anisotropic distribution of instabilities in space plasma



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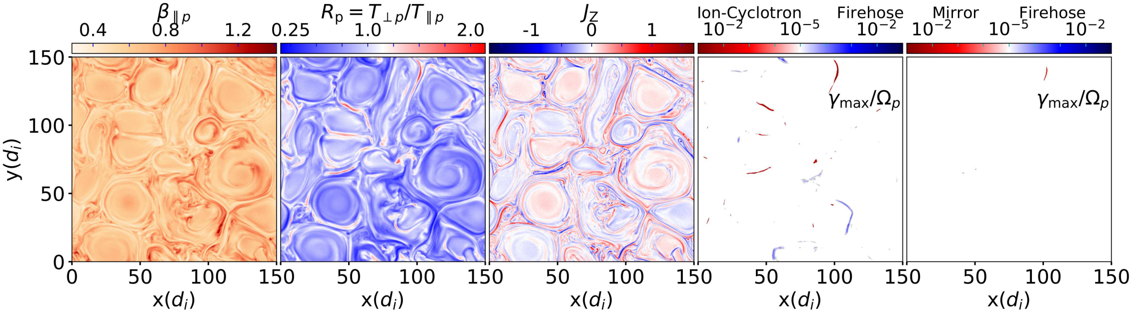
- The linear instability thresholds acts on plasma and restrict its excursion to extreme values of R_p



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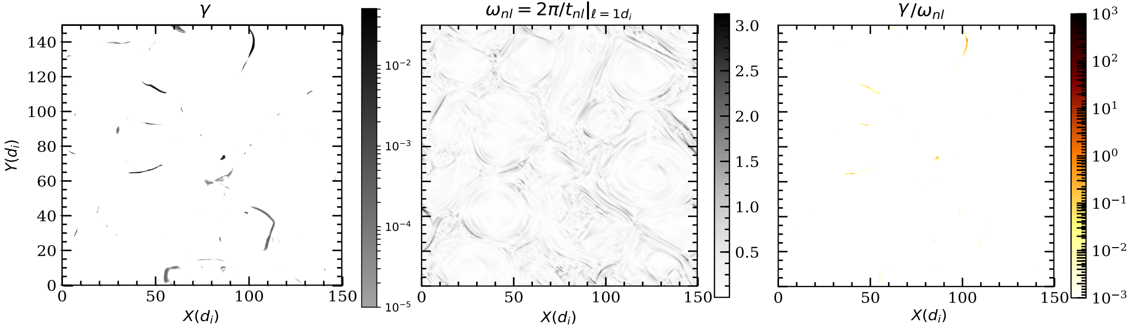

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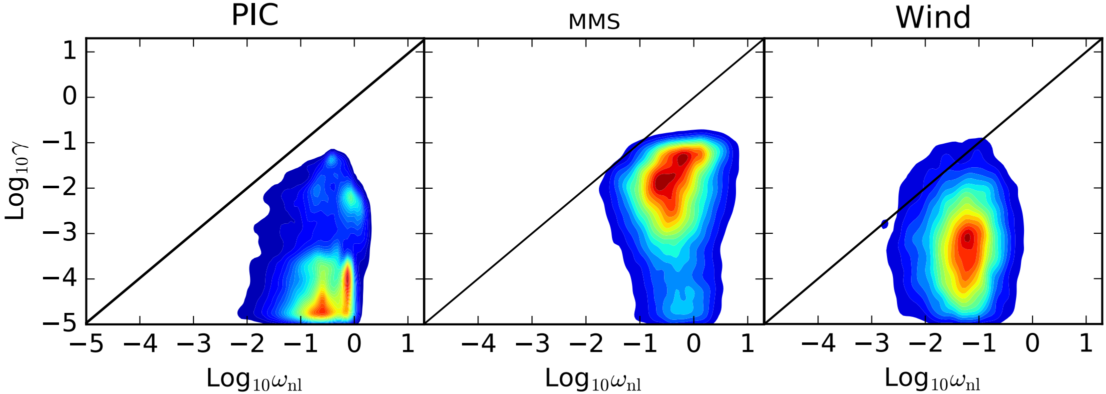

Questions?

Thank you!