ON THE INTERPLAY BETWEEN MICROKINETICS AND TURBULENCE IN SPACE PLASMAS

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21 June, 2021

In this talk

- Plasma and why it is important to study.
- Different kinds of plasmas
- How we study them
- Instabilities in a plasma
- Intermittency in plasmas
  - Origin
  - Measuring it
  - Consequence
- Interplay between linear and nonlinear process
- Magnetic field topology reconstruction
- Conclusion

https://slides.com/qudsi/thesis/

Plasma

- It is the fourth state of matter.
- Consists of charged particles and is generally neutral.

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Space Plasmas

- Ionosphere
- Terrestrial Magnetosheath
- Solar wind
  - At 1 au
  - Inner Heliosphere (0.2 au)
  - Outer Heliosphere
- Interstellar Medium (ISM)
- Intergalactic Medium (IGM)

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- PIC
- MHD
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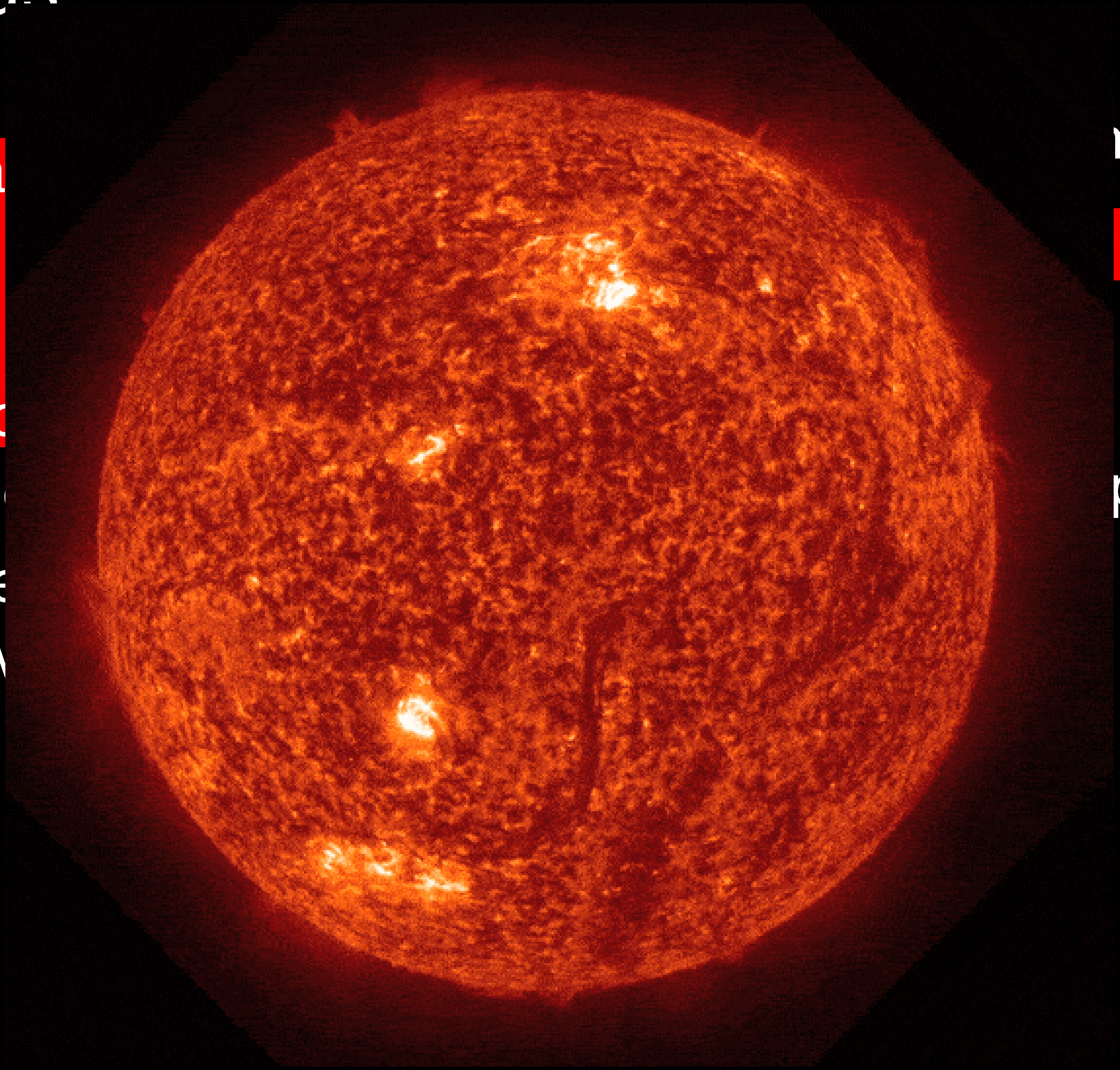

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https://news.engin.umich.edu/2018/08/the-end-of-the-mission/

Interaction between Solar Wind and Earth's Magnetic Field

1) Bow shock.

2) Magnetosheath.

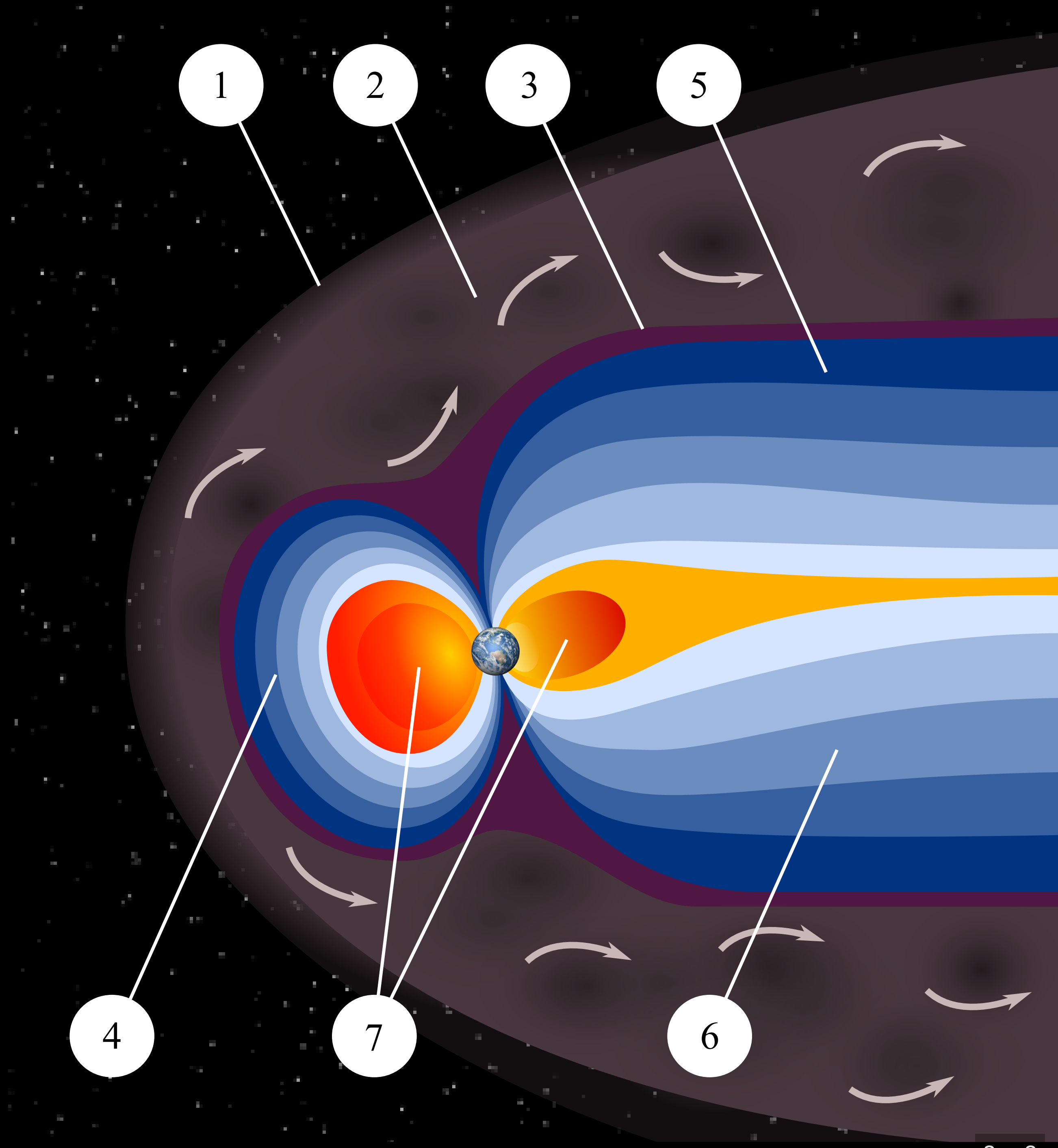
3) Magnetopause.

4) Magnetosphere.

5) Northern tail lobe.

6) Southern tail lobe.

7) Plasmasphere.



https://en.wikipedia.org/wiki/Magnetosphere

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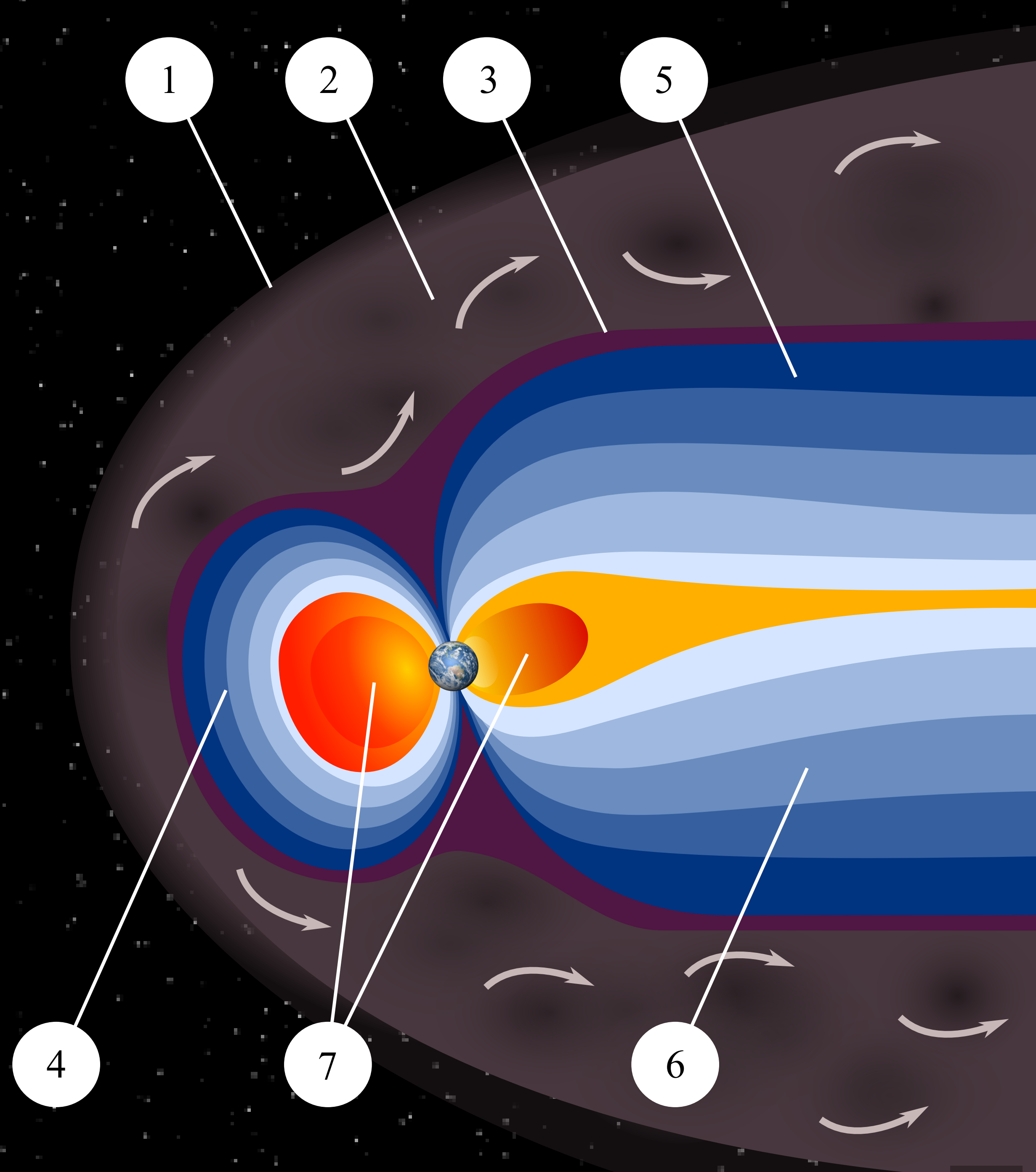

https://en.wikipedia.org/wiki/Magnetosphere

Typical Values

	0.2 au	**1 au**	**Magnetosheath**
Magnetic Field (nT)	70	5	20
Ion-density (cm^{-3})	150	5	30
Ion-speed $(\mathrm{km/s})$	400	450	250
Ion-temperature$(10^6\mathrm{K})$	1	3	2.5

Studying Plasma

Equation of Motion

$$-\frac{d\vec{P}}{dt} = m\frac{d^2\vec{x}}{dt^2}$$

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Maxwell's Equation

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

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Vlasov Equation

$$\frac{\partial f_j}{\partial t} + \vec{v} \cdot \nabla_{\vec{x}} f_j + \frac{q}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right) \cdot \nabla_{\vec{v}} f_j = 0$$

f_j is the distribution function of plasma for species j

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Dispersion Relation

$$\det(\mathbf{D}(\mathbf{k}, \omega)) = 0$$

Vlasov Equation

Vlasov Equation

↓

Linear Dispersion Equation

Vlasov Equation

Linear Dispersion Equation

Linearization

$$f_j(\vec{x},\vec{v},t) = f_j^0(\vec{x},\vec{v}) + f_j^1(\vec{x},\vec{v},t)$$
$$= f_j^0(\vec{x},\vec{v}) + f_j^1(\vec{k},\omega,\vec{v})\, e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

Vlasov Equation

↓

Linear Dispersion Equation

↓

$$\omega_{\mathrm{r}} + i\gamma$$

real imaginary

Linearization

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real

instability growth rate $(\gamma > 0)$

Vlasov Equation

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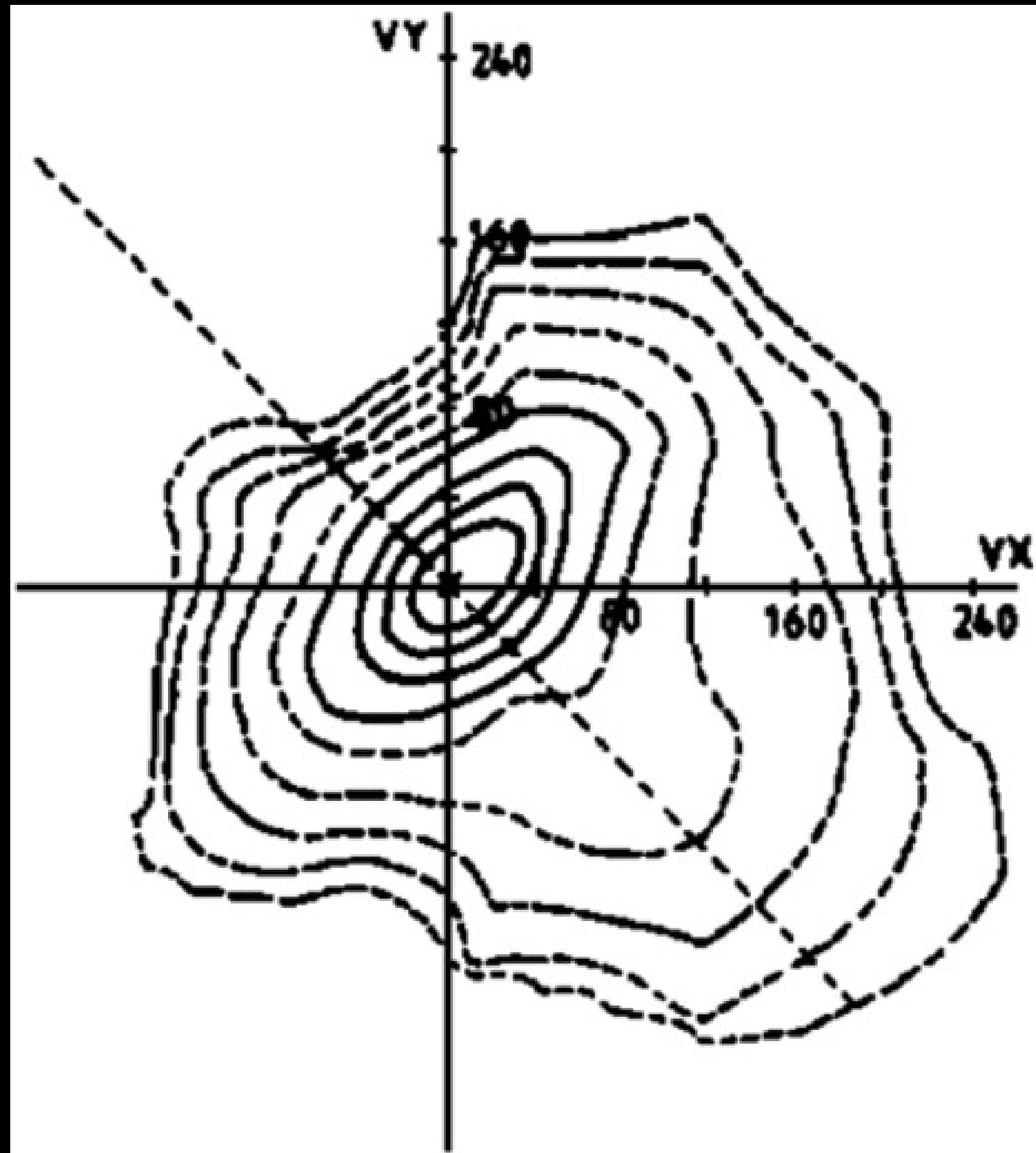
$$\omega_{\mathrm{r}} + i\gamma$$

`real` `instability growth rate` $(\gamma > 0)$

$\gamma_{\max}$ → Maximum value of growth rate of a given mode for all **k** and directions

VDF: Probability distribution function of phase space density



(Marsch, JGRL-1982)

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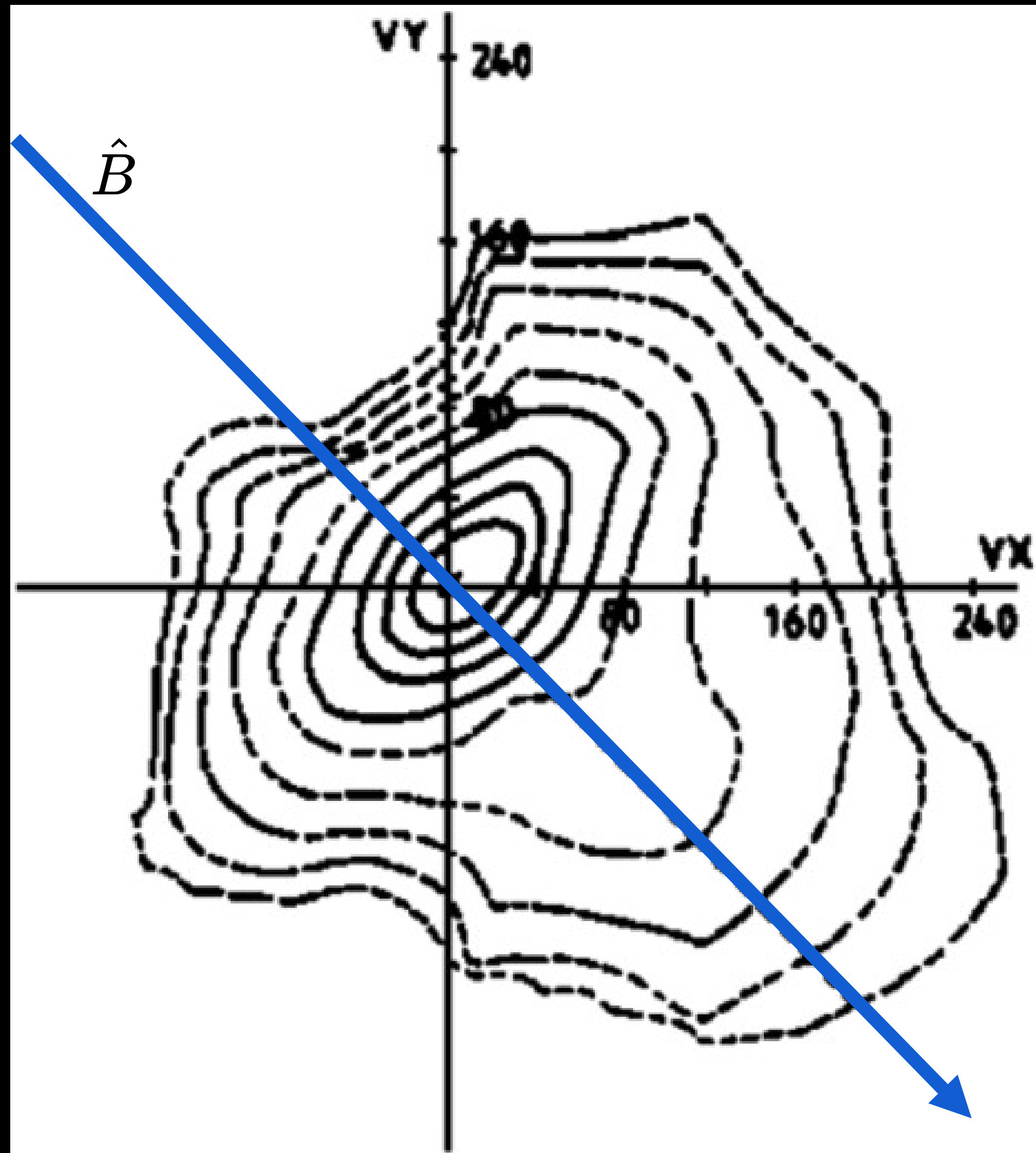

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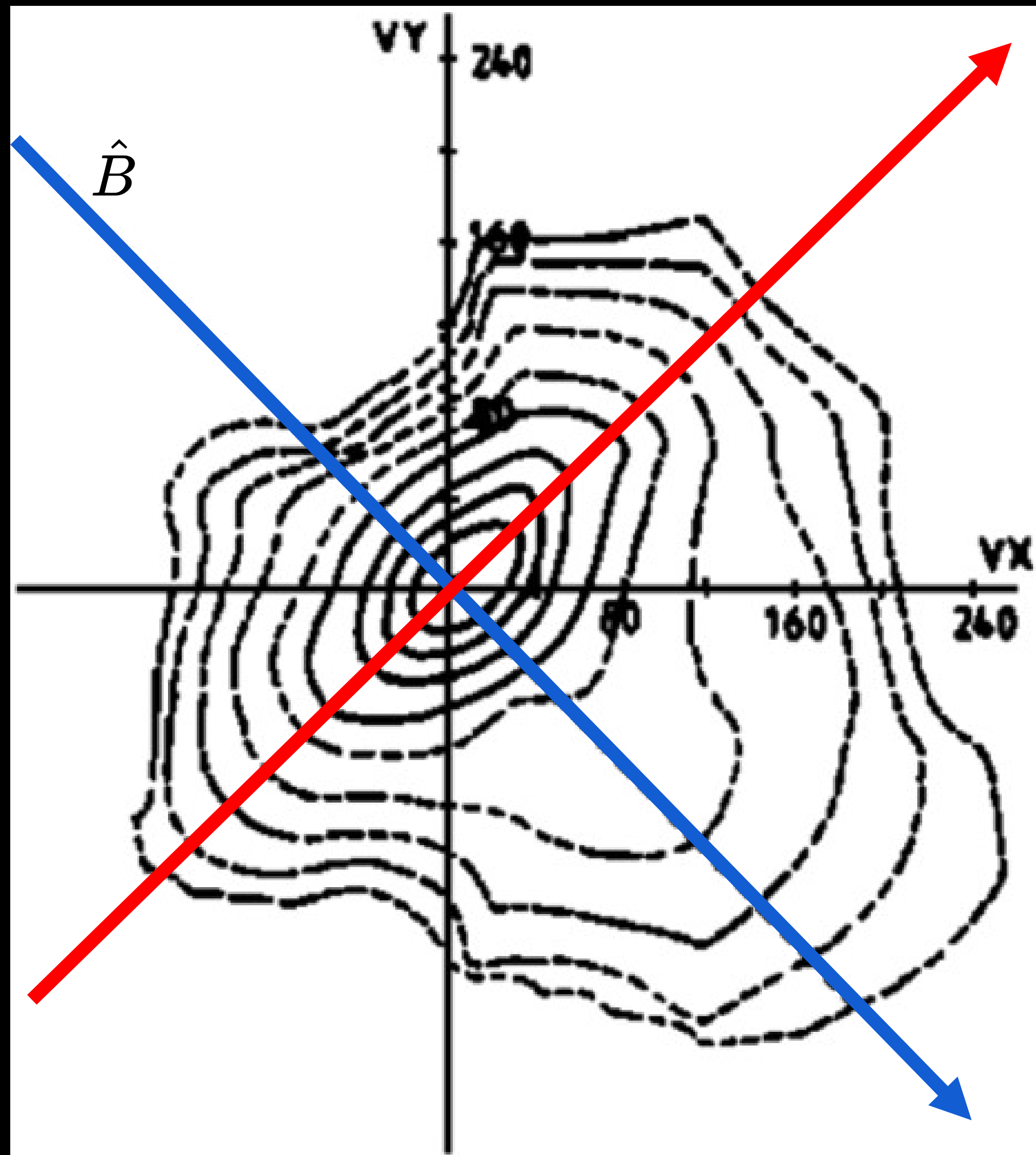

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Temperature Anisotropy:

Ratio of perpendicular and parallel temperatures

$$R_j = \frac{T_{\perp j}}{T_{\| j}}$$

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Table 2.1: List of four temperature-anisotropy induced instabilities in plasma

Anisotropy Range	Parallel ($\omega_r > 0$)	Oblique ($\omega_r = 0$)
$R_{\mathrm{p}} > 1$	Ion cyclotron	Mirror
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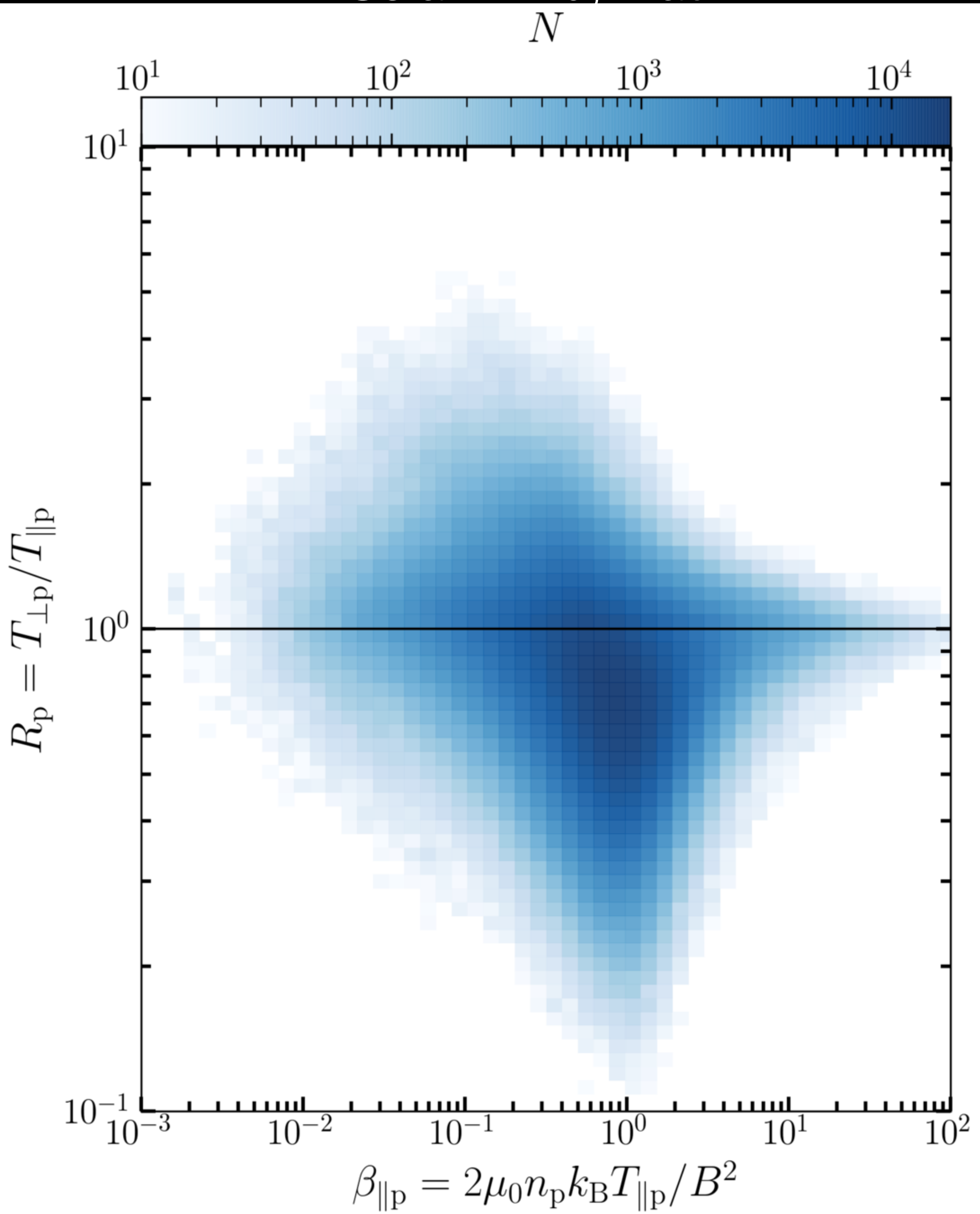
Beta:

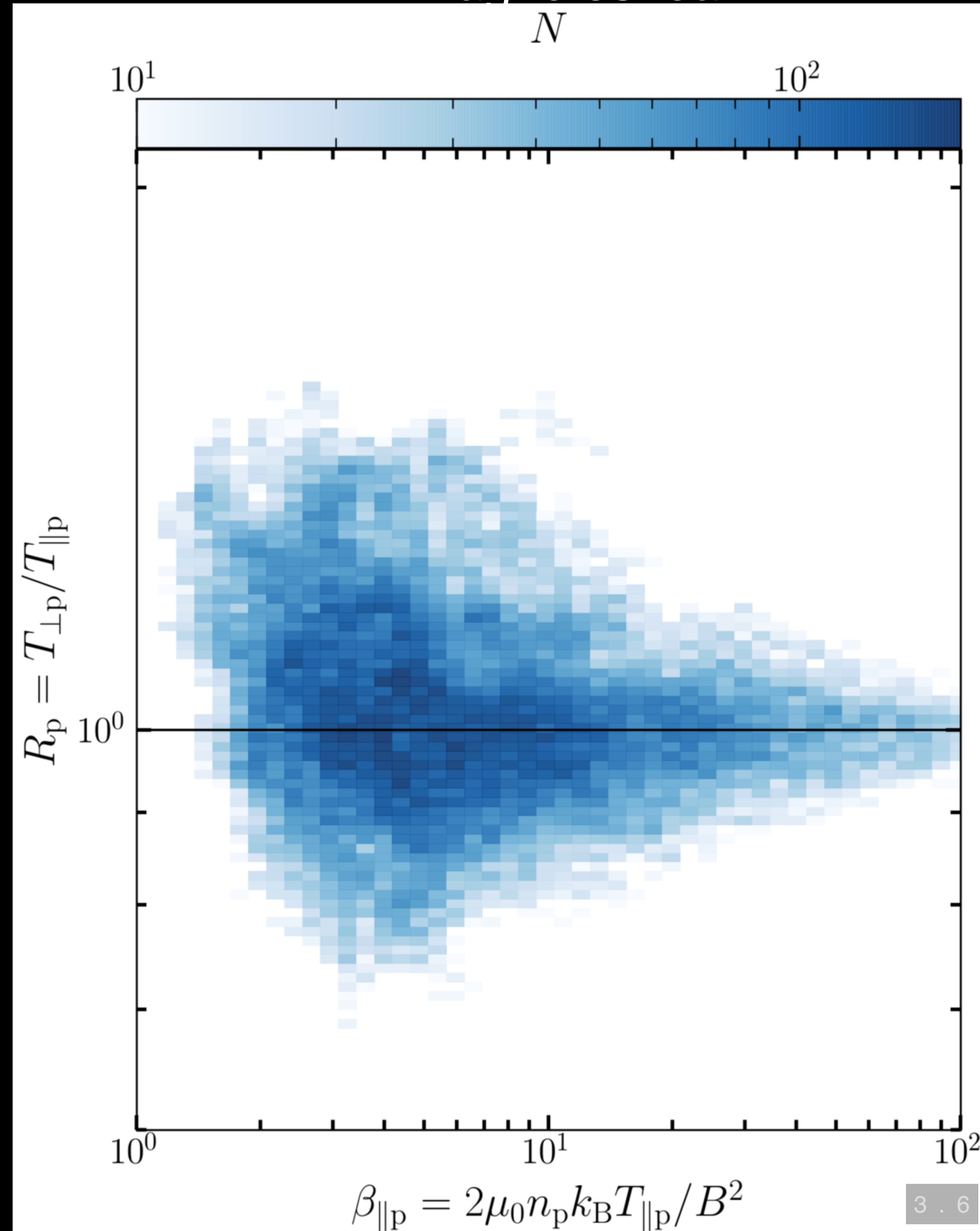
Ratio of thermal and magnetic pressure

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

Solar Wind, 1 au



Magnetosheath



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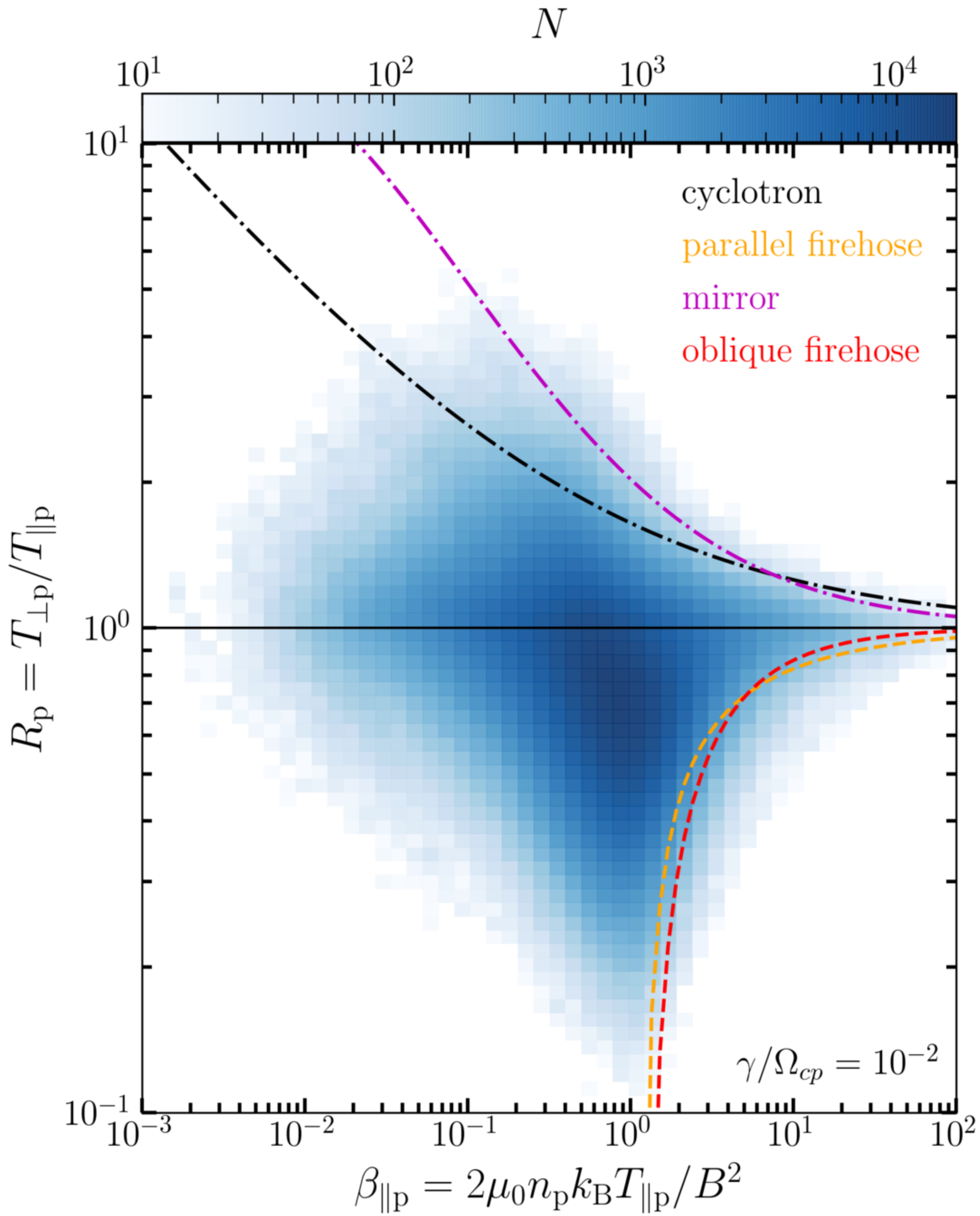

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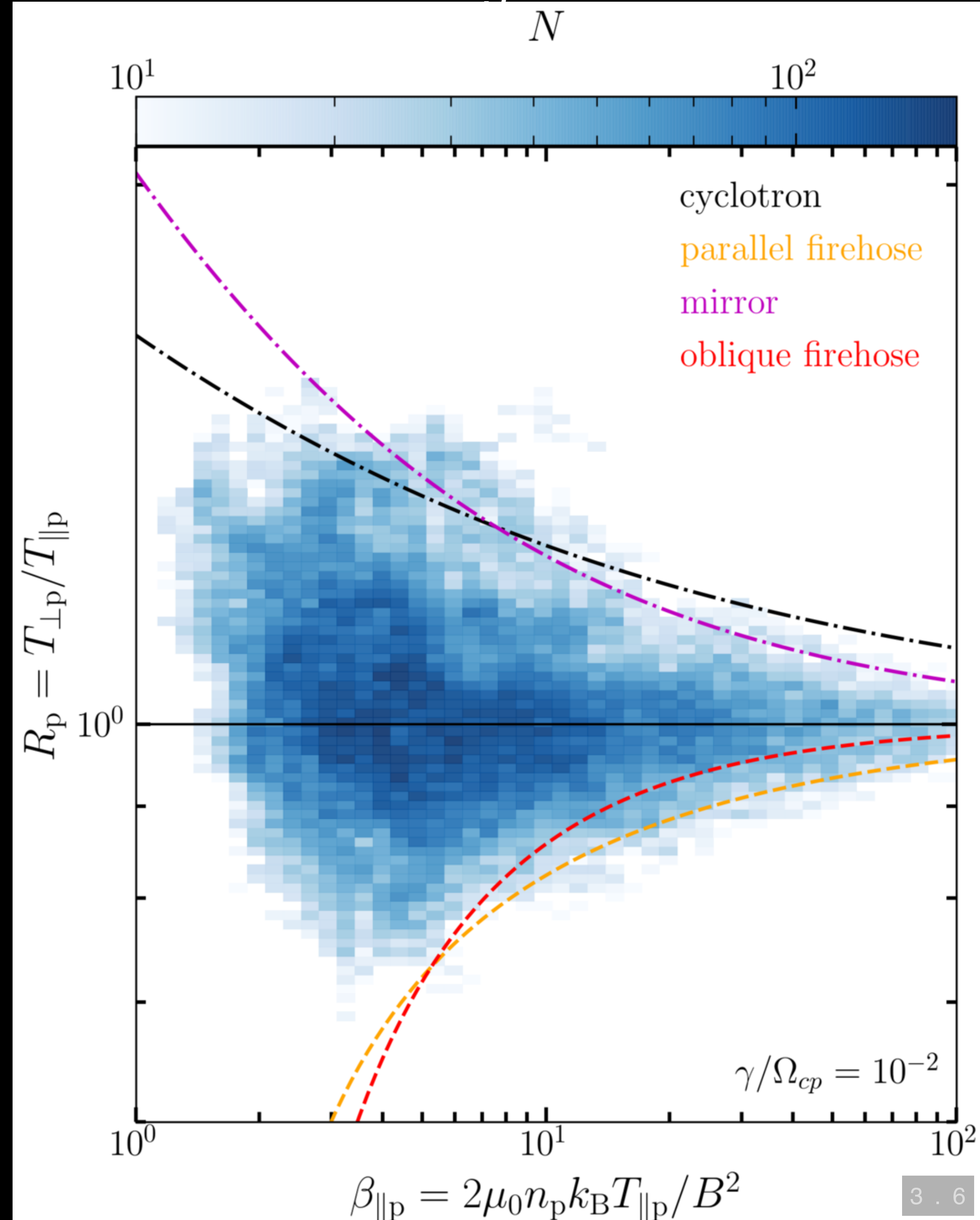
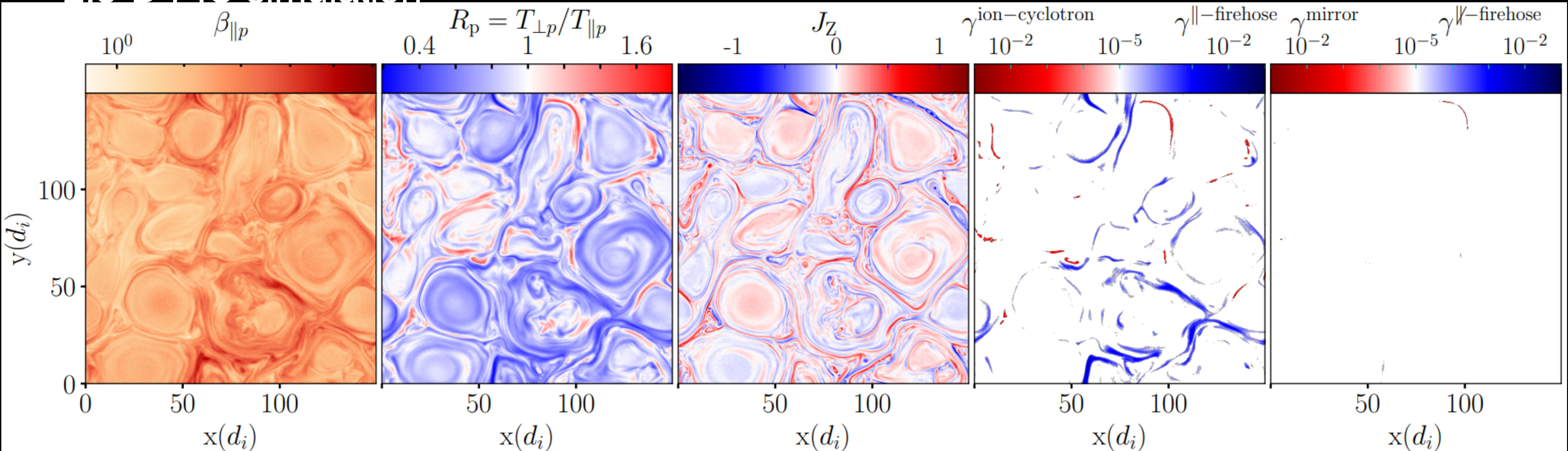


2.5-D PIC simulation



(Qudsi, ApJ-2020)

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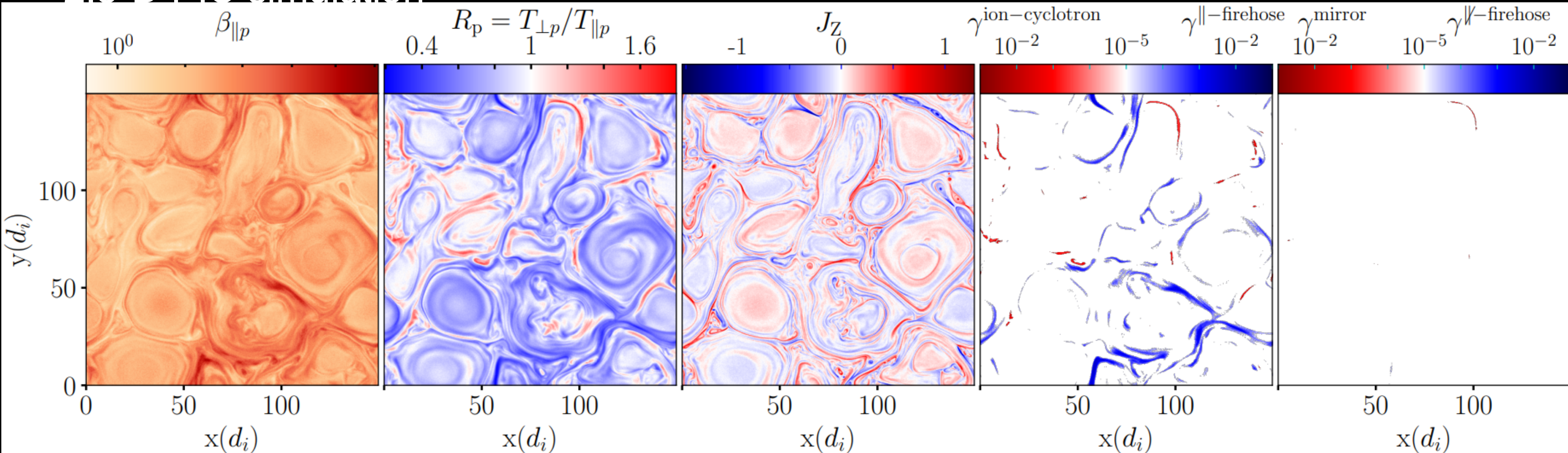
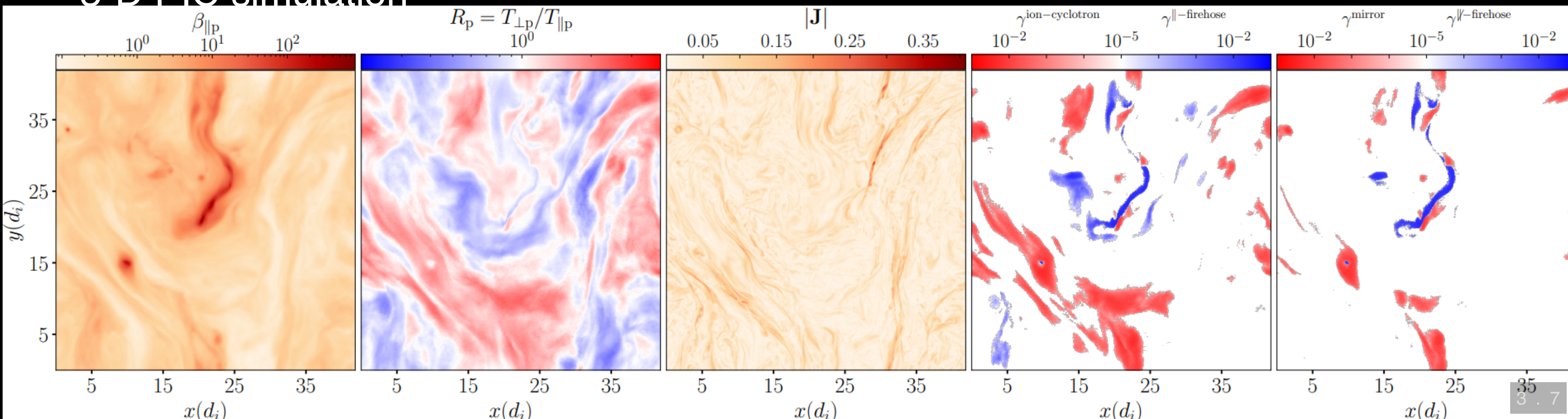
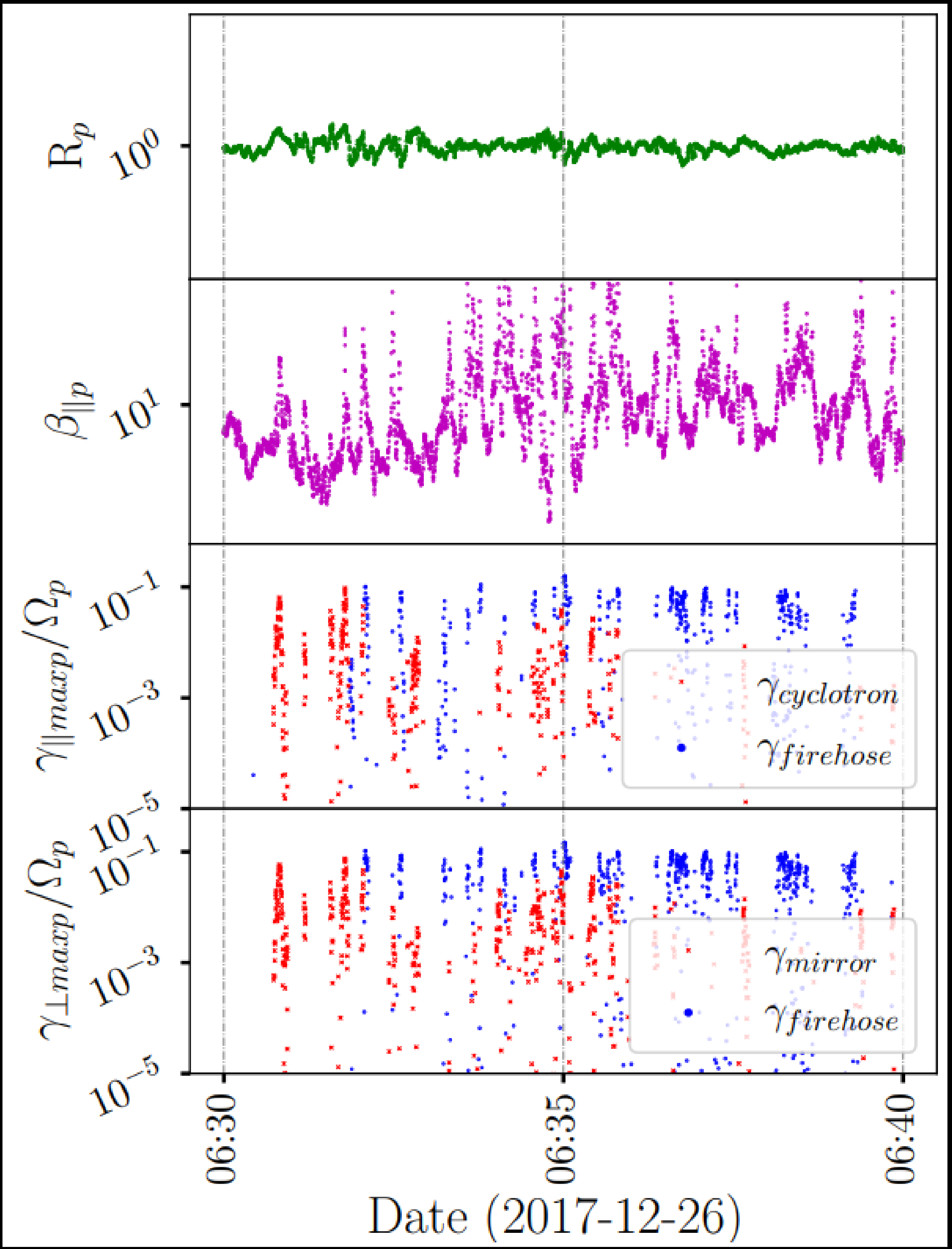


(Qudsi, ApJ-2020)

3-D PIC simulation

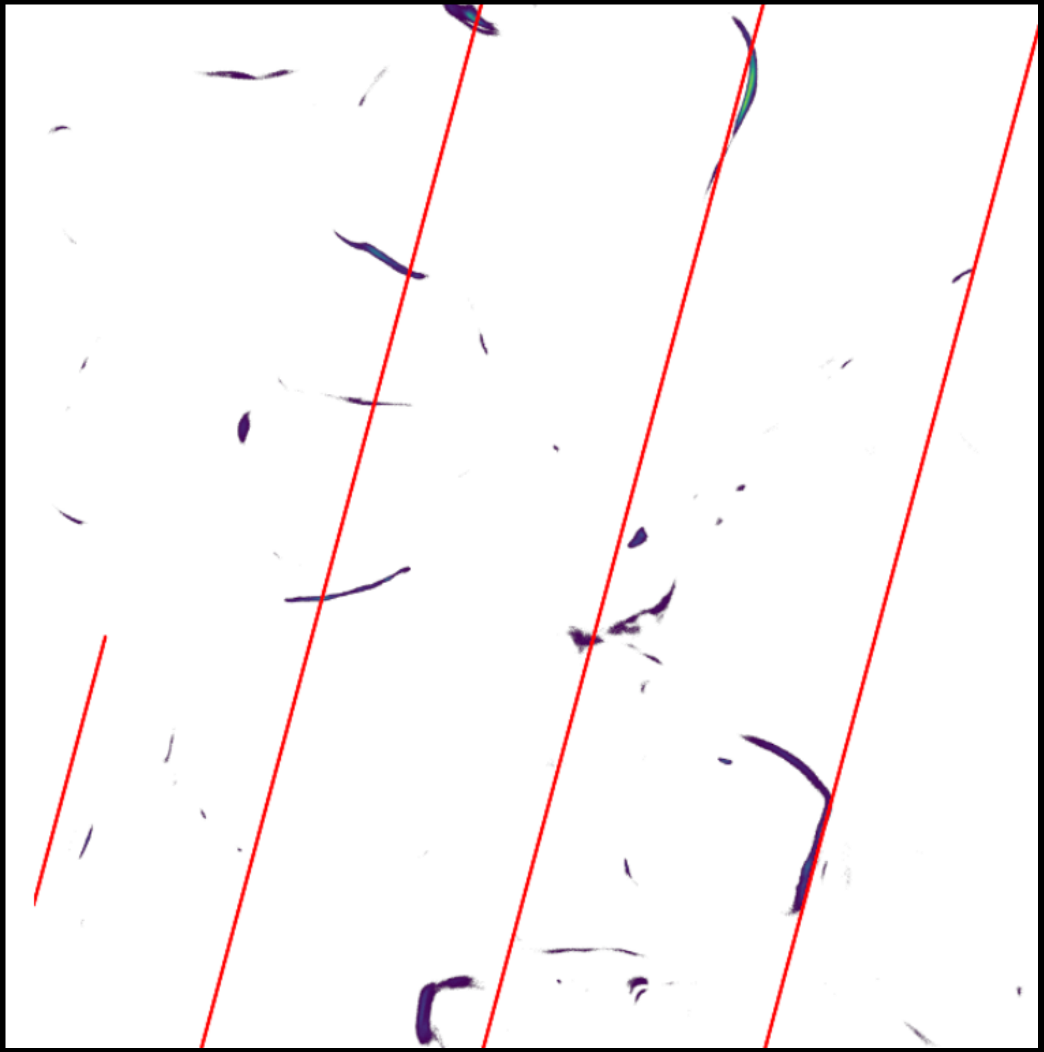


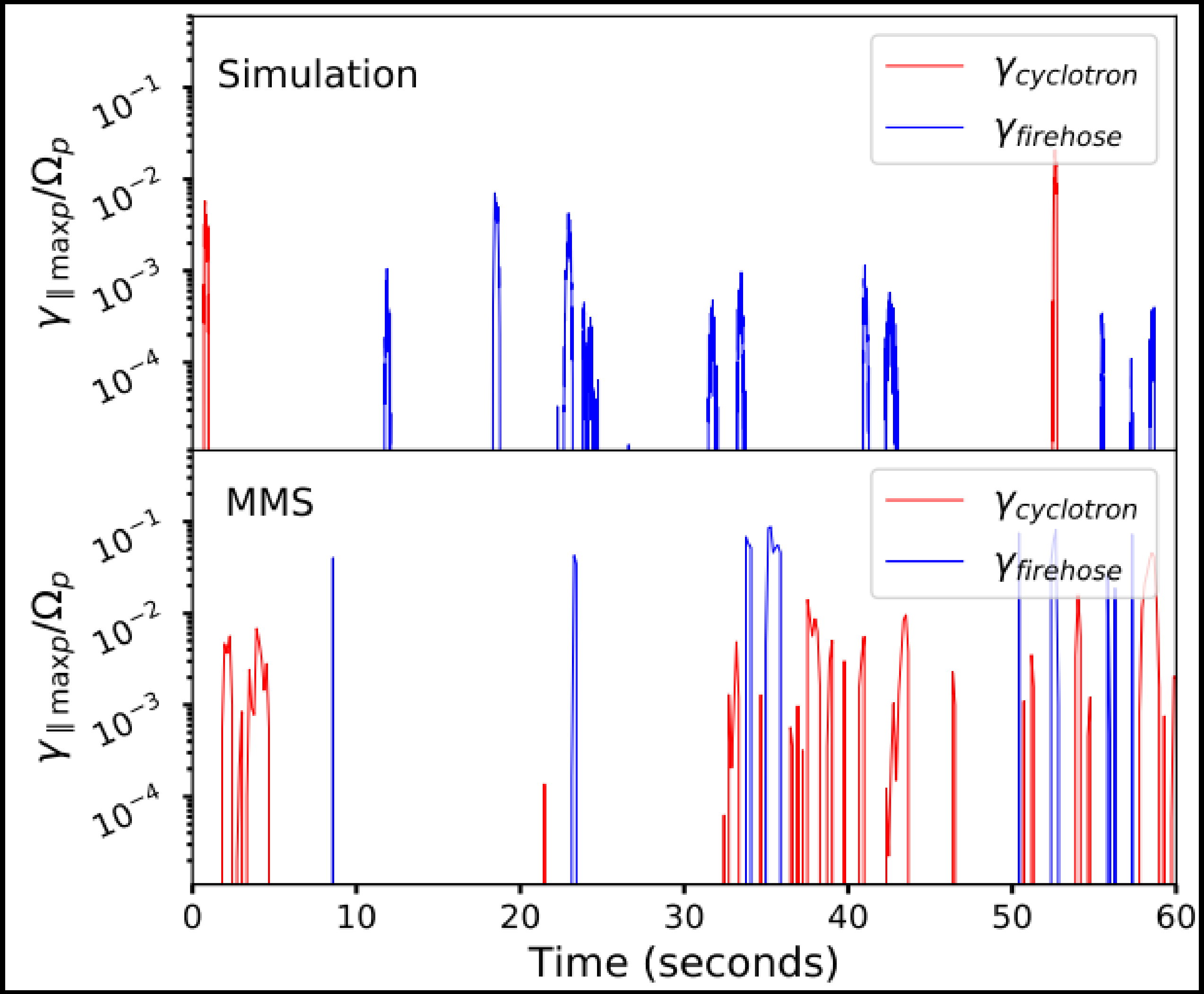
MMS Observation



(Qudsi, ApJ-2020)

Intermittency comparison between spacecraft observation and simulation





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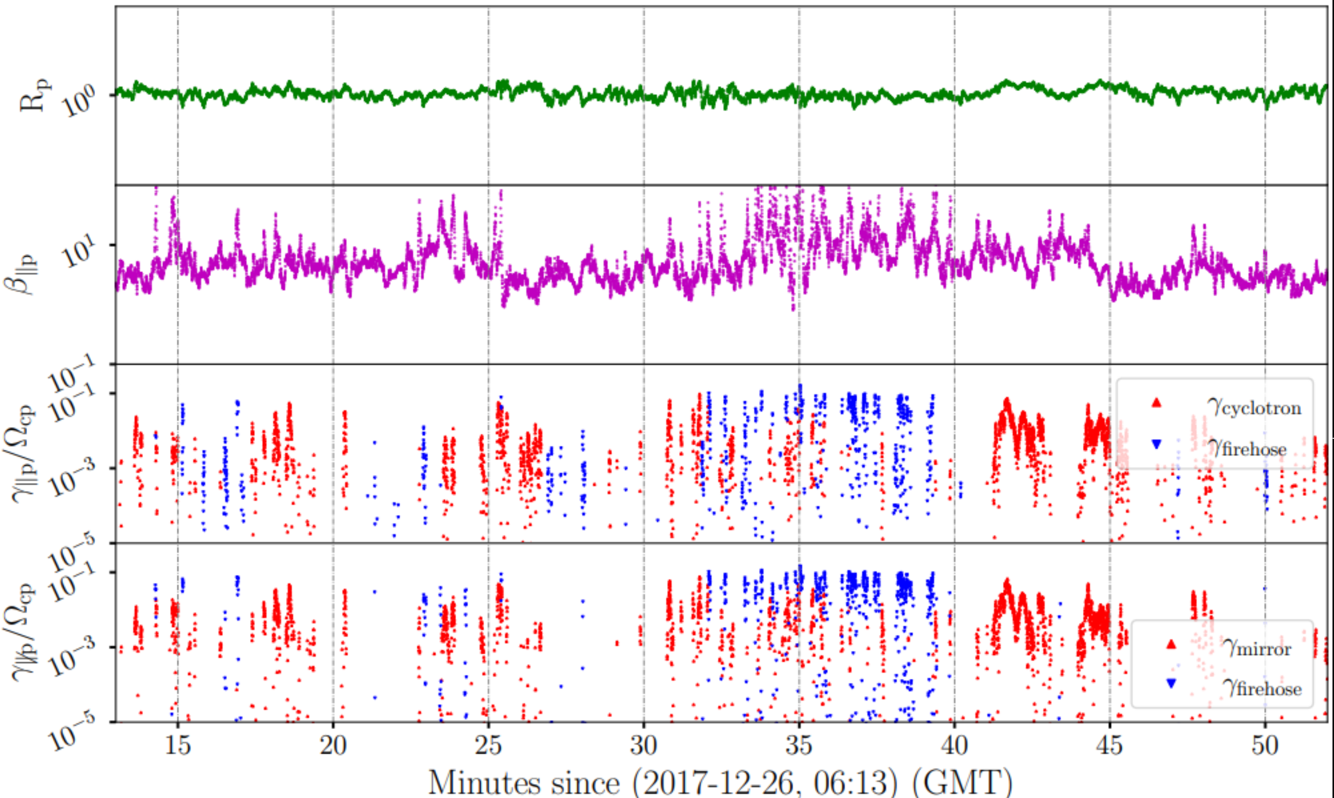
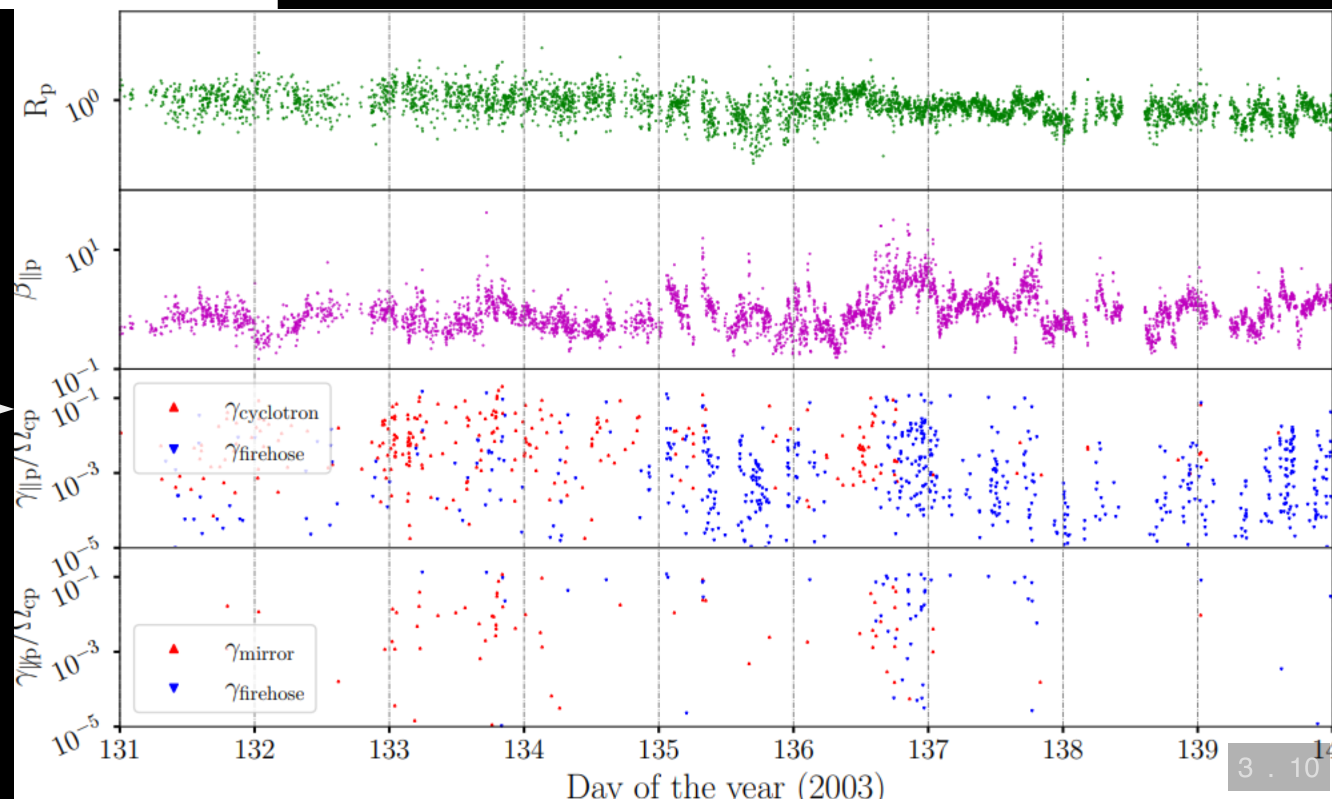


R_p
$\beta_{\parallel p}$
$\gamma_{\parallel p}/\Omega_{cp}$
$\gamma_{cyclotron}$
$\gamma_{firehose}$
γ_{mirror}
$\gamma_{firehose}$
Minutes since (2017-12-26, 06:13) (GMT)

MMS

Wind



R_p
$\beta_{\parallel p}$
$\gamma_{\parallel p}/\Omega_{cp}$
$\gamma_{cyclotron}$
$\gamma_{firehose}$
γ_{mirror}
$\gamma_{firehose}$
Day of the year (2003)

Measuring Intermittency

Intermittency: Burstiness

Distribution is not uniform and has localized structures

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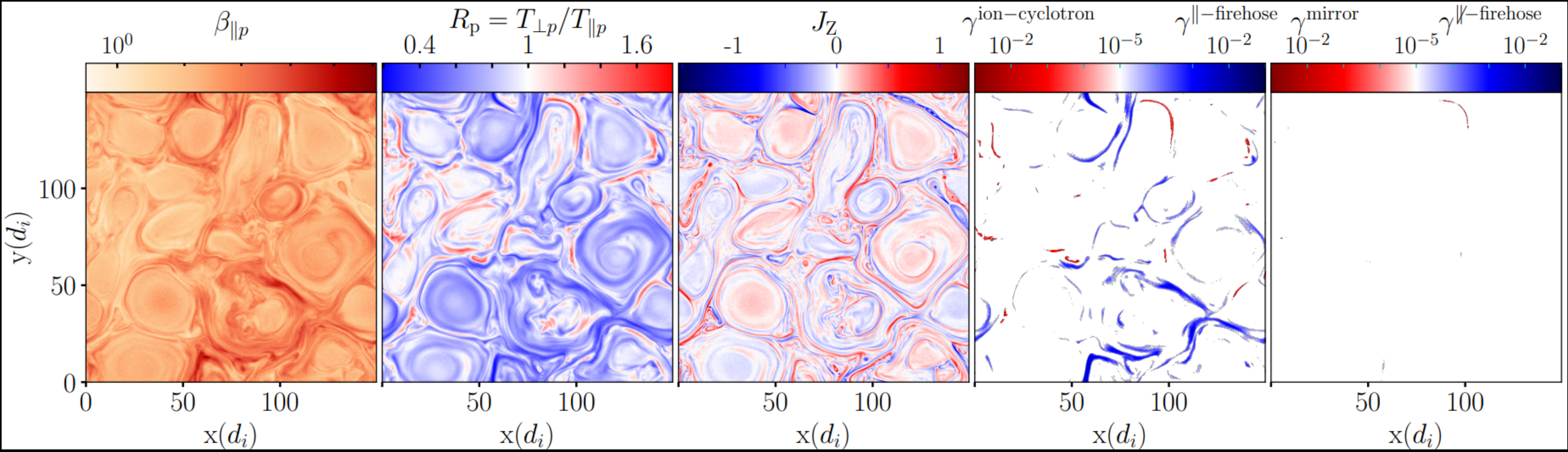

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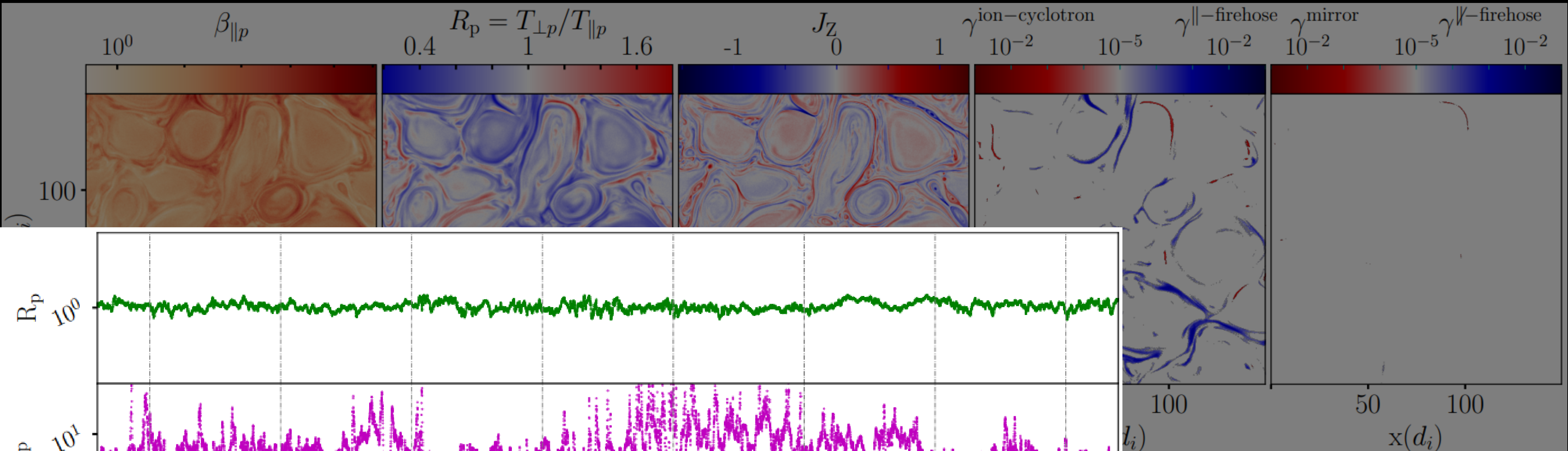

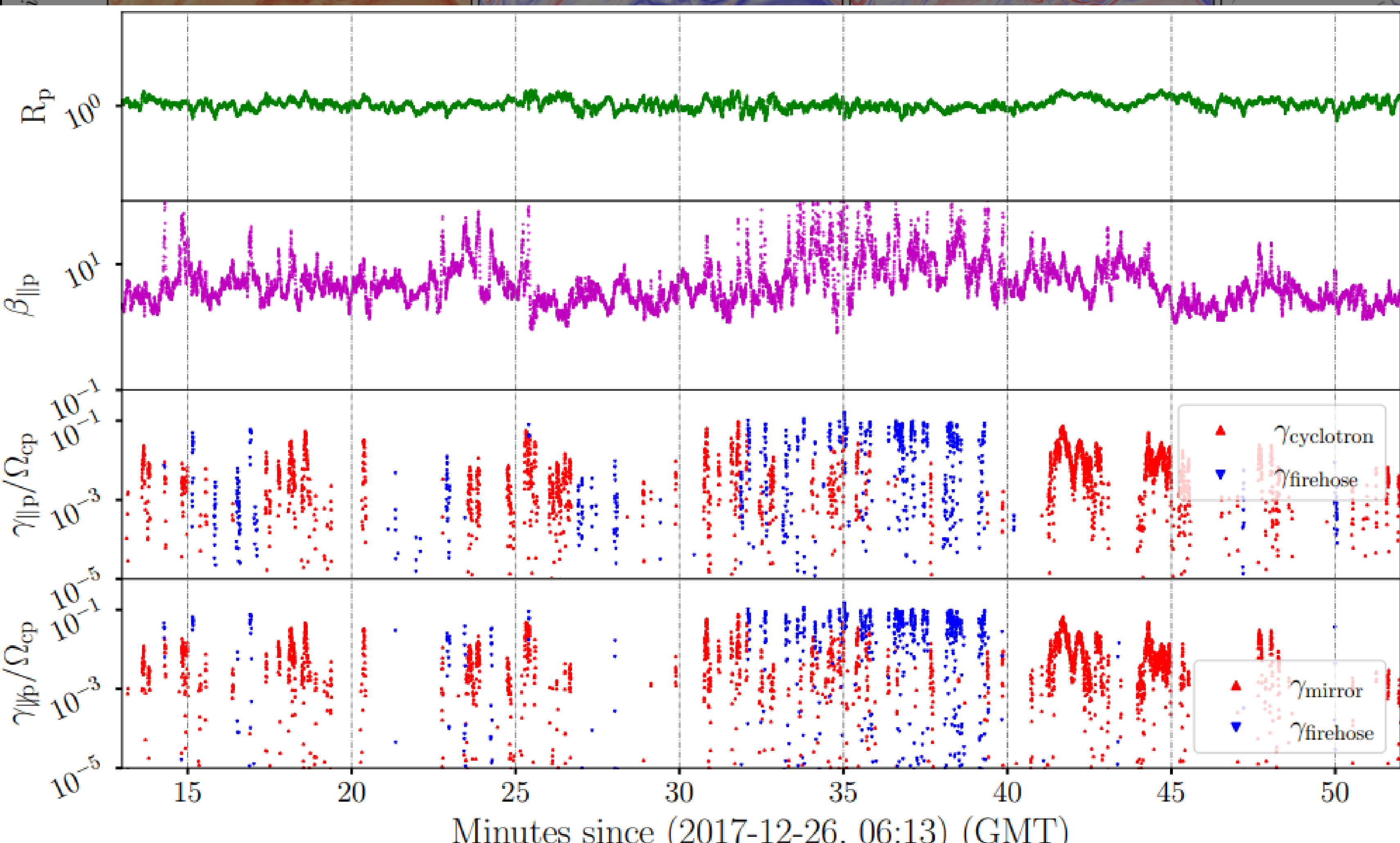

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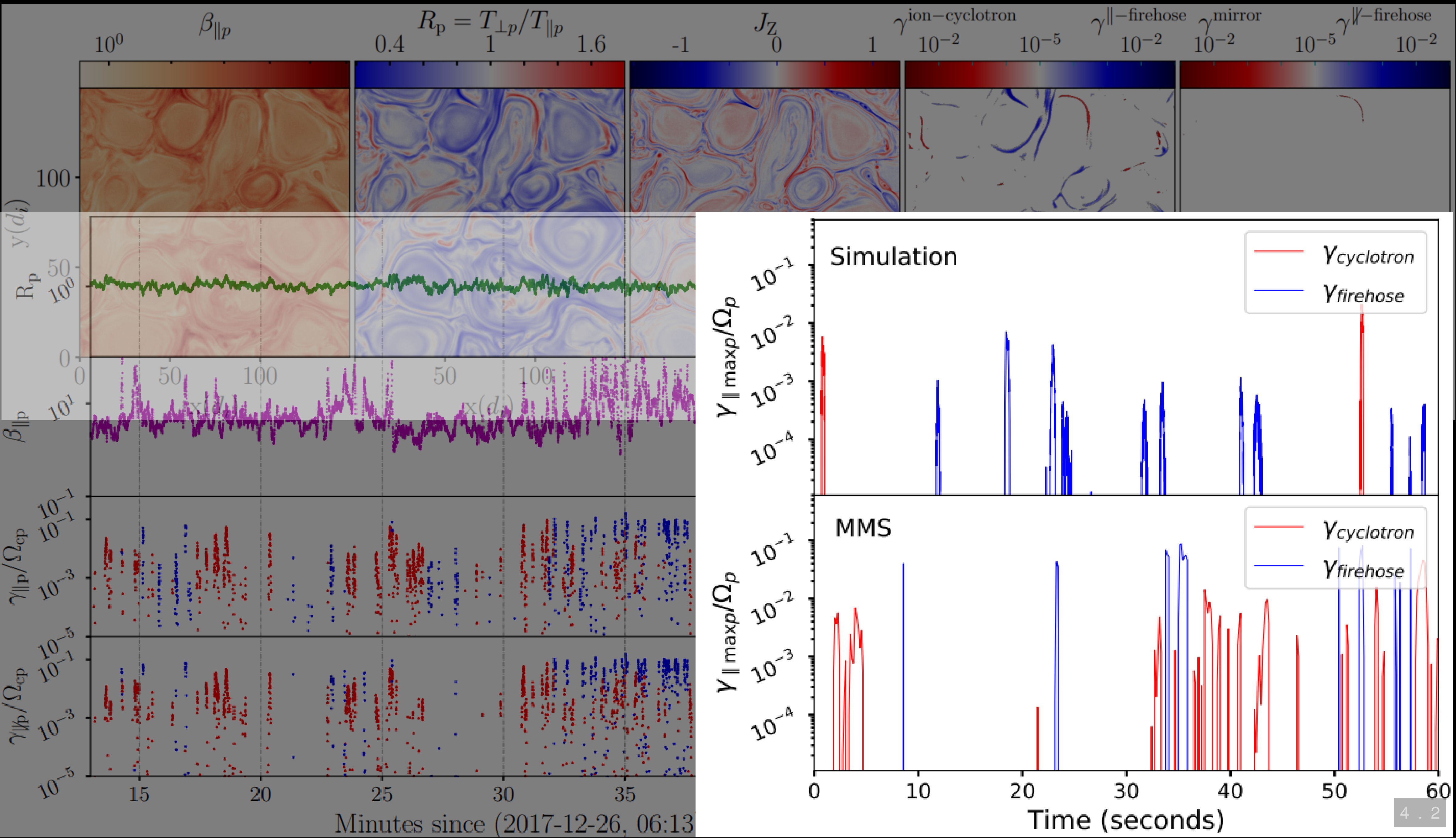

Measuring intermittency

$$\text{PVI} \longmapsto \mathcal{I}(t,\tau) = \frac{|\Delta \mathbf{B}(t,\tau)|}{\sqrt{\langle|\Delta \mathbf{B}(t,\tau)|^2\rangle_\Delta}}$$

$$\Delta \mathbf{B}(t,\tau) = \mathbf{B}(t+\tau) - \mathbf{B}(t)$$

τ : Time lag

(Greco, GRL-2008)

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$\mathcal{I} > 2.4 \implies$ Non-Gaussianity

(Osman, PRL-2012)

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Lag in distance

$$\ell = v \cdot \tau$$ (Assuming Taylor hypothesis)

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What value of τ and Δ one should choose?

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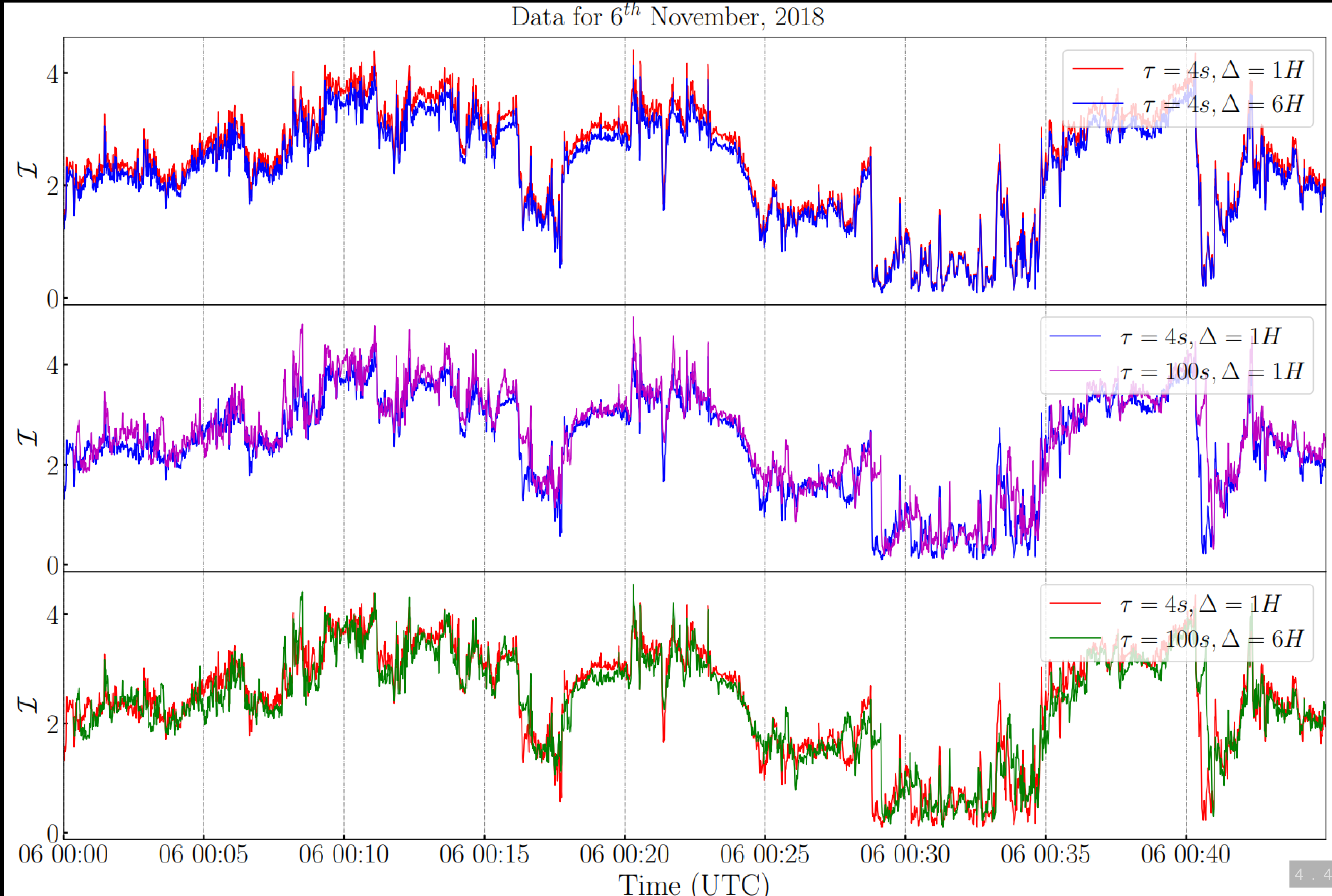
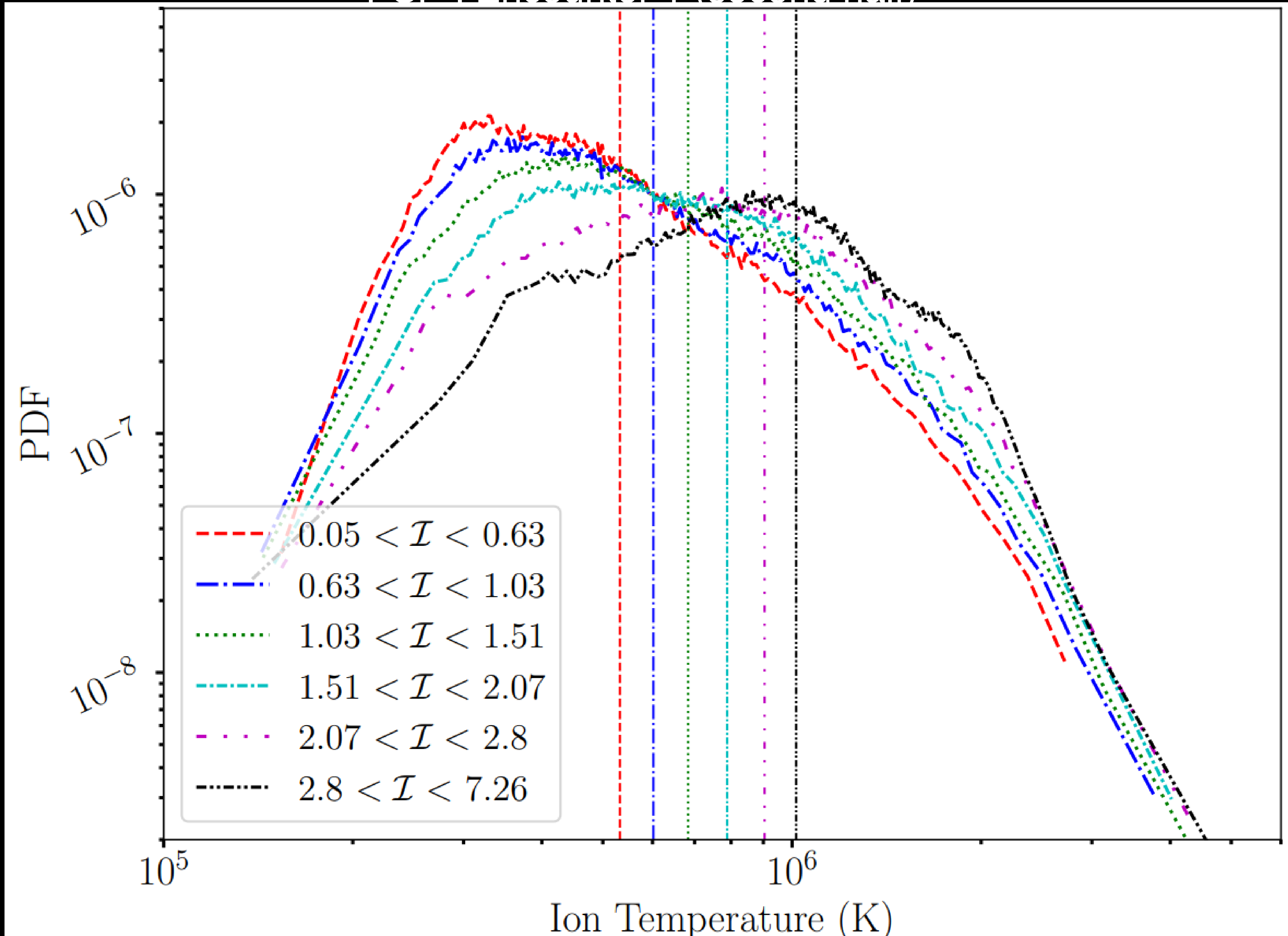
$$\tau \ll \tau_{\text{correlation}}$$

$$\Delta \gg \tau_{\text{correlation}}$$


Data for 6^{th} November, 2018
$\mathcal{I}$
$\tau = 4s, \Delta = 1H$
$\tau = 4s, \Delta = 6H$
$\tau = 4s, \Delta = 1H$
$\tau = 100s, \Delta = 1H$
$\tau = 4s, \Delta = 1H$
$\tau = 100s, \Delta = 6H$
0
2
4
06 00:00
06 00:05
06 00:10
06 00:15
06 00:20
06 00:25
06 00:30
06 00:35
06 00:40
Time (UTC)

PSP : Encounter 1 (second half)



(Qudsi, ApJS-2020)

Conditional Temperature Averages

$$\widetilde{T}_p(\delta t, \theta_1, \theta_2) = \langle T_p(t_{\mathcal{I}} + \delta t) | \theta_1 \leq \mathcal{I}(t_{\mathcal{I}}) < \theta_2 \rangle$$

Conditional Temperature
Averages

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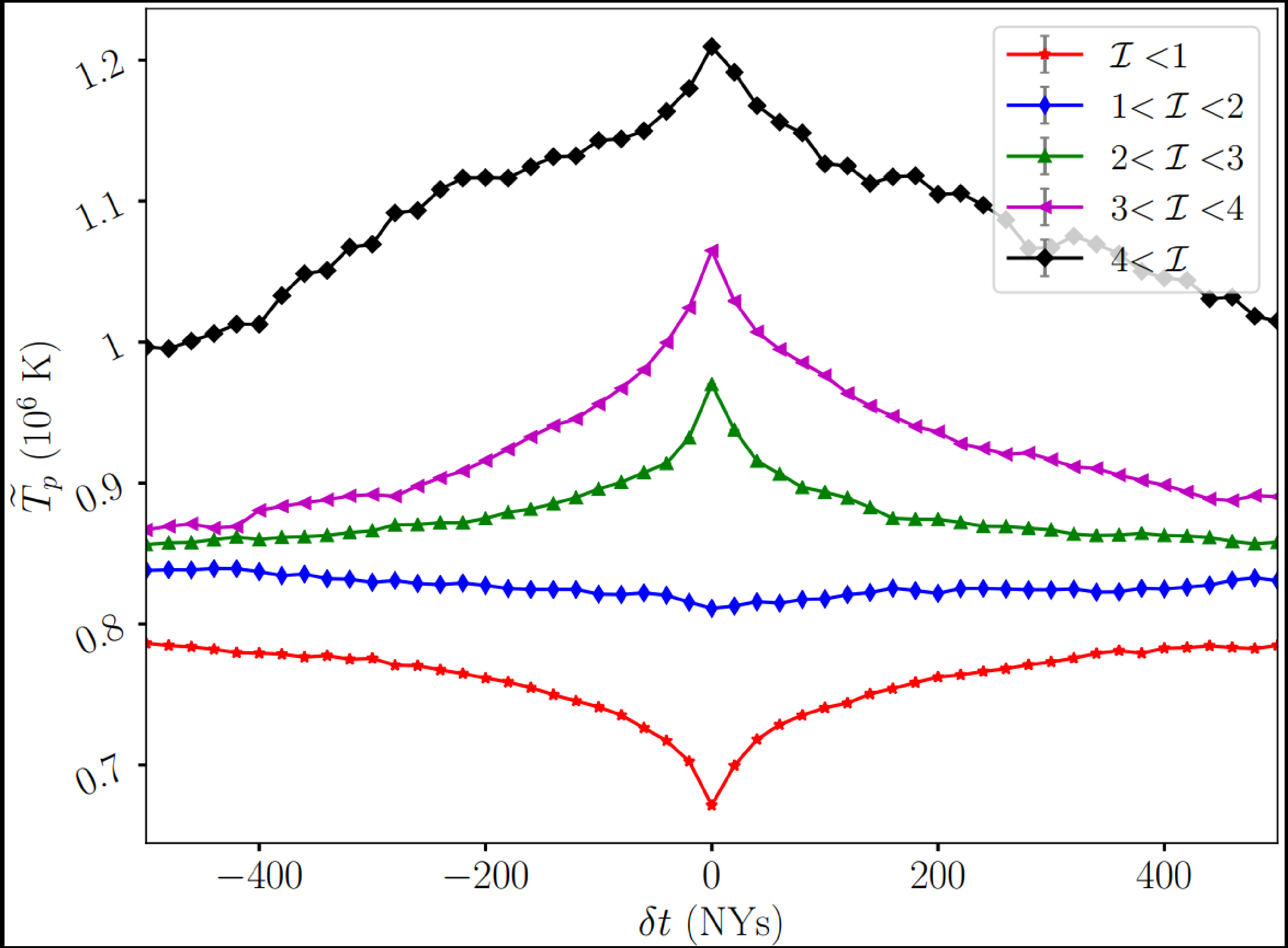

(Qudsi, ApJS-2020)

Non-linear Processes

Non-linear time scale (ω_{nl})

Non-linear time scale (ω_{nl})

We estimate it from the spectral amplitude near the ion-inertial scale

Non-linear time scale (ω_{nl})

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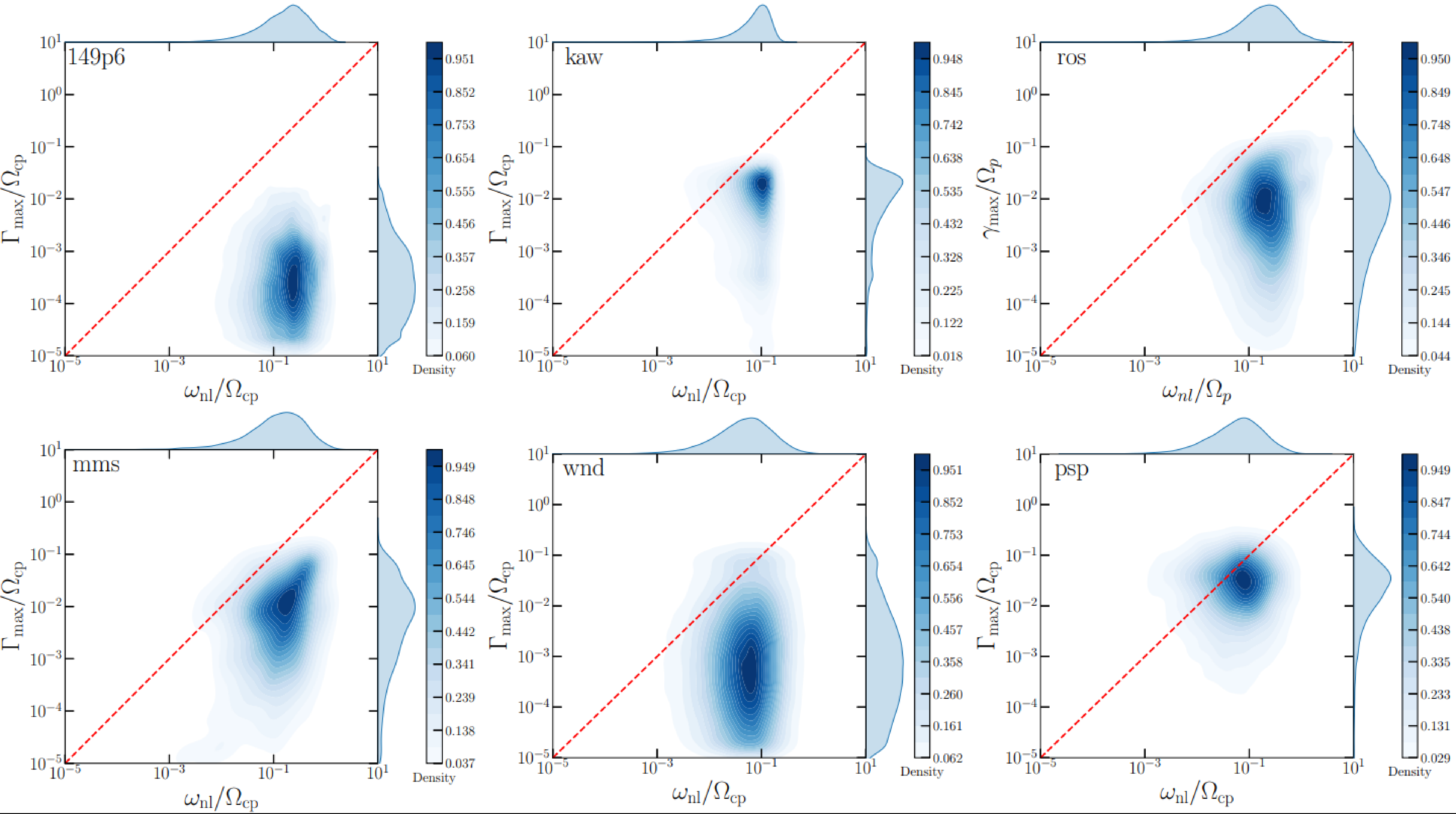
$$\Gamma_{\mathrm{max}} = \mathrm{max}(\gamma_{\mathrm{max,\ cyclotron}}, \gamma_{\mathrm{max,\ mirror}}, \gamma_{\mathrm{max,\ \|firehose}}, \gamma_{\mathrm{max,\ \nparallel firehose}})$$

Comparison between $\omega_{\rm nl}$ and $\Gamma_{\rm max}$



(Qudsi2021a, in prep)

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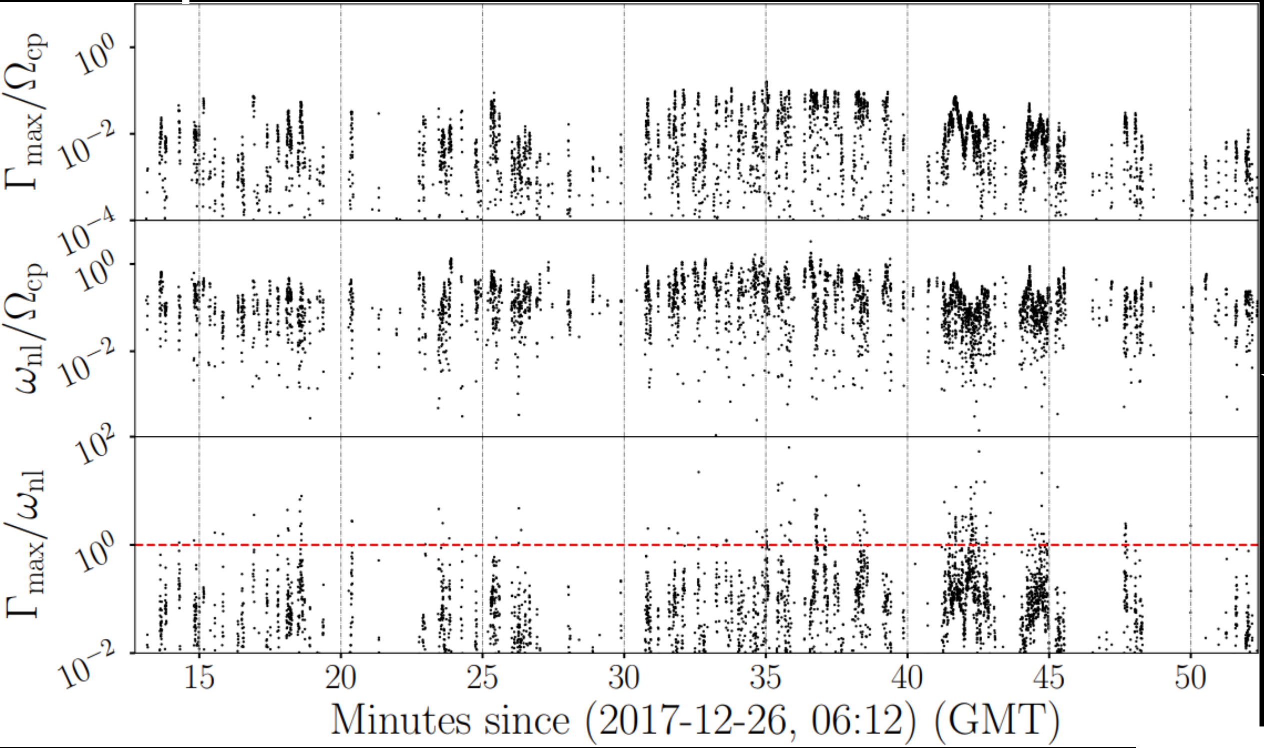
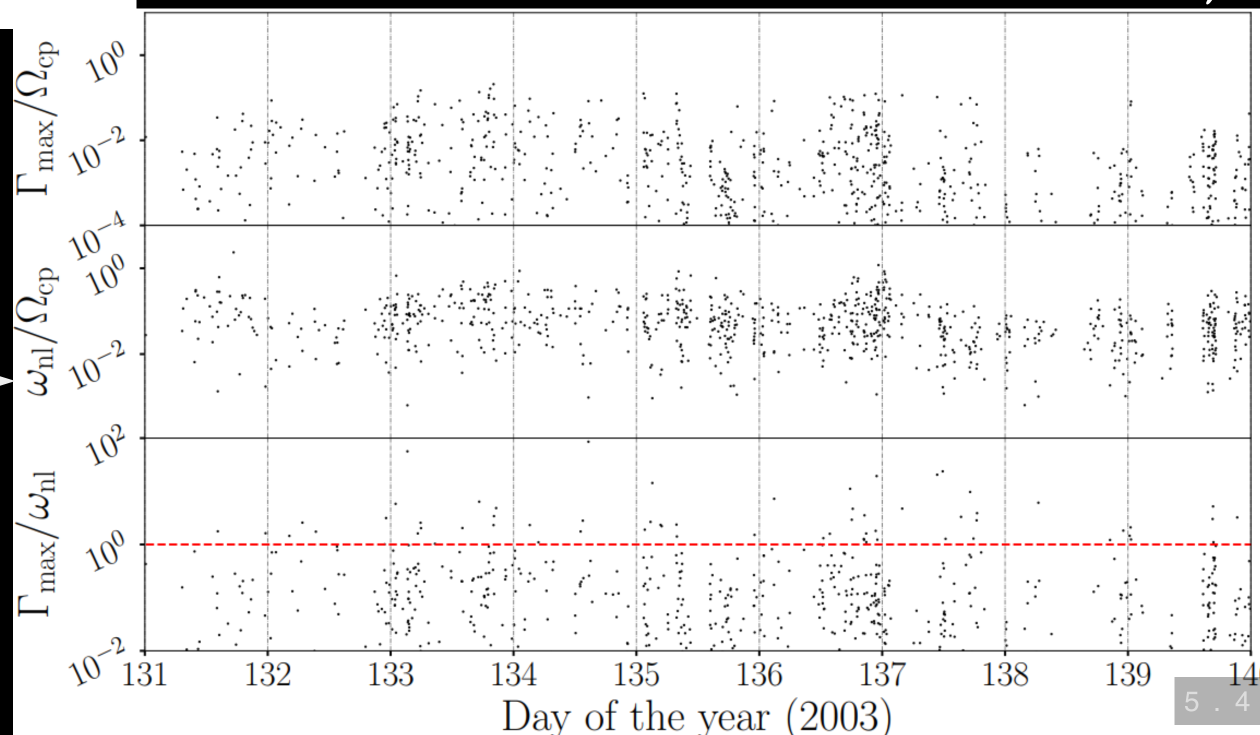


MMS

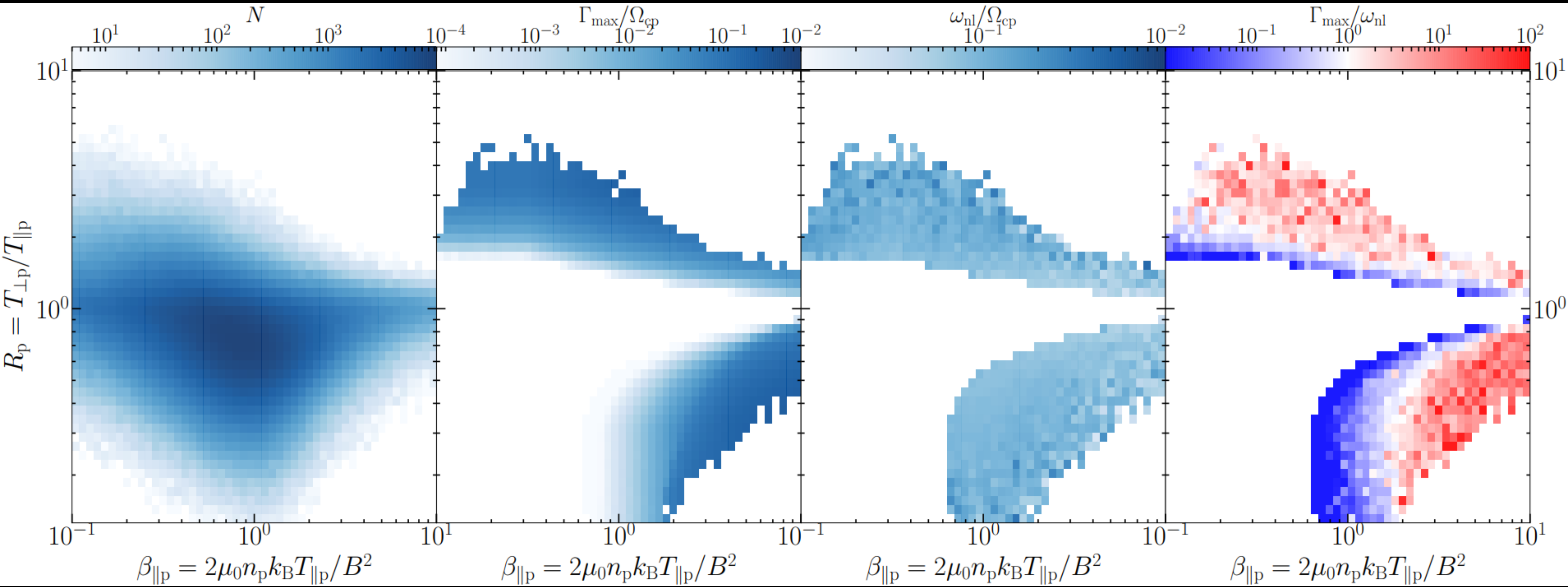
(Bandyopadhyay, PRL-2021, under review)

Wind



Comparison between ω_{nl} and Γ_{max}

Solar Wind, 1 au



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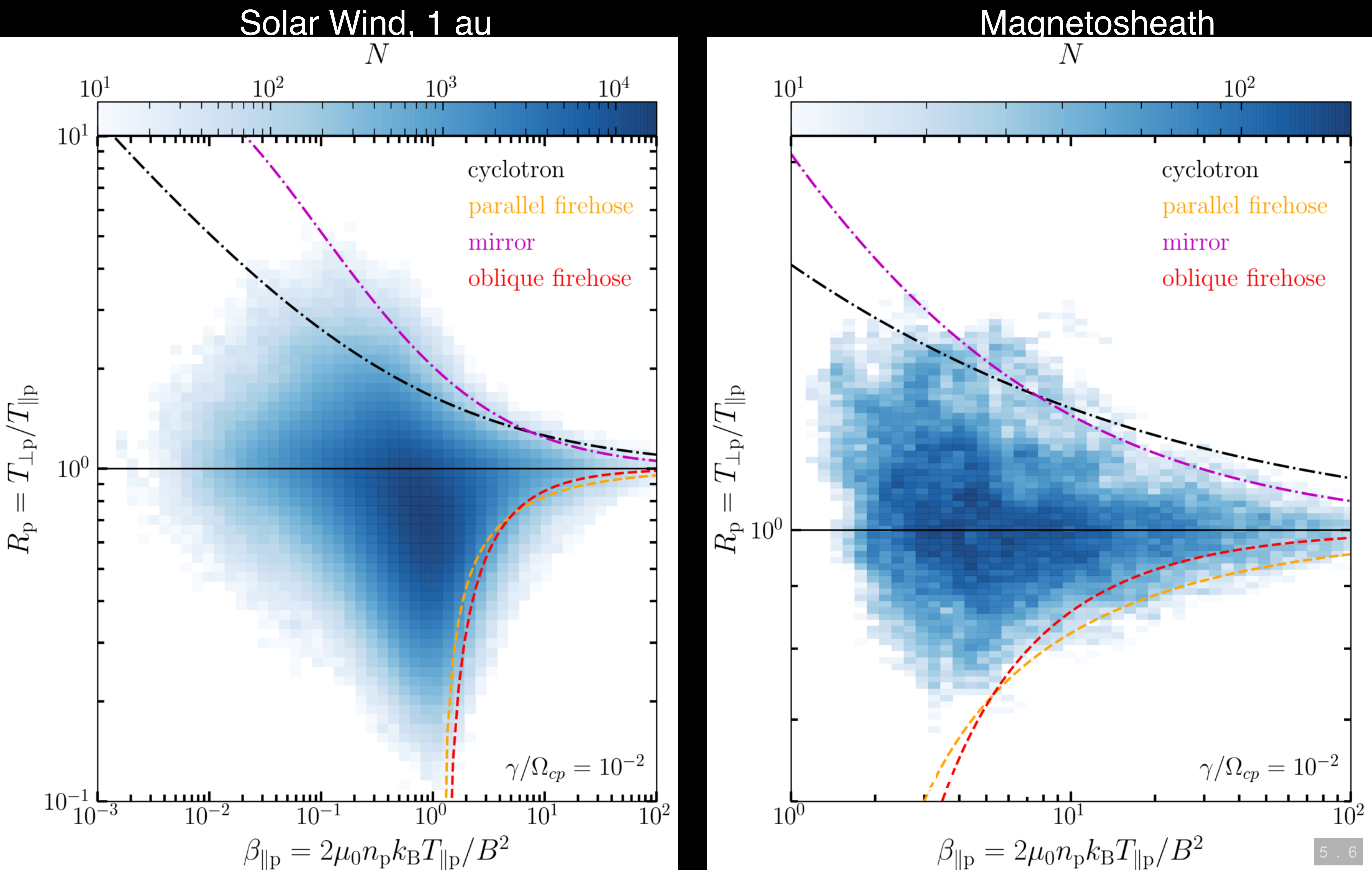

Solar Wind, 1 au
Magnetosheath
N
10^1 10^2 10^3 10^4
cyclotron
parallel firehose
mirror
oblique firehose
$\gamma/\Omega_{cp} = 10^{-2}$
$R_p = T_{\perp p}/T_{\parallel p}$
$\beta_{\parallel p} = 2\mu_0 n_p k_B T_{\parallel p}/B^2$
10^{-1} 10^0 10^1
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2

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Complete 3D structure of interplanetary magnetic field

Magnetic Field Reconstruction

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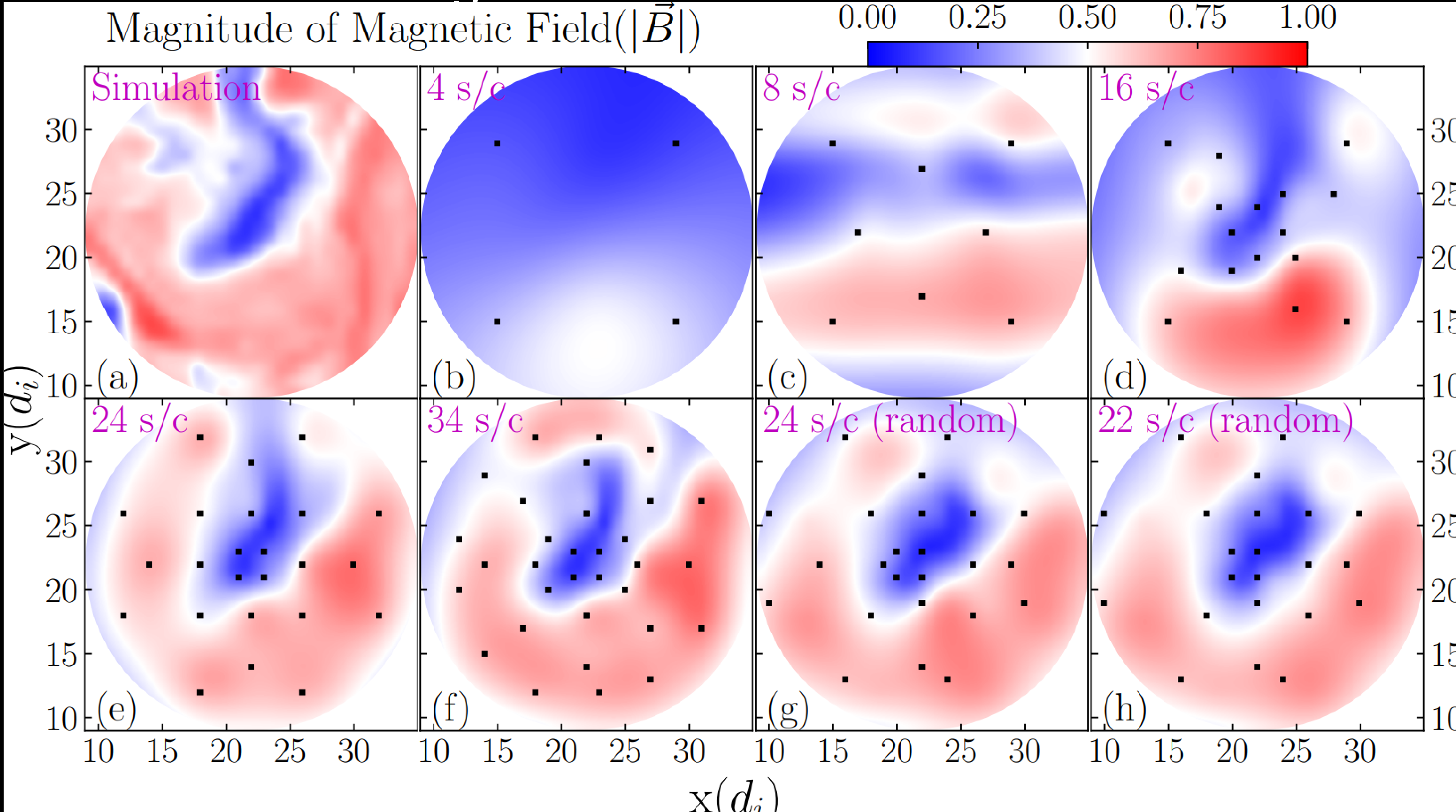
Gaussian Processes

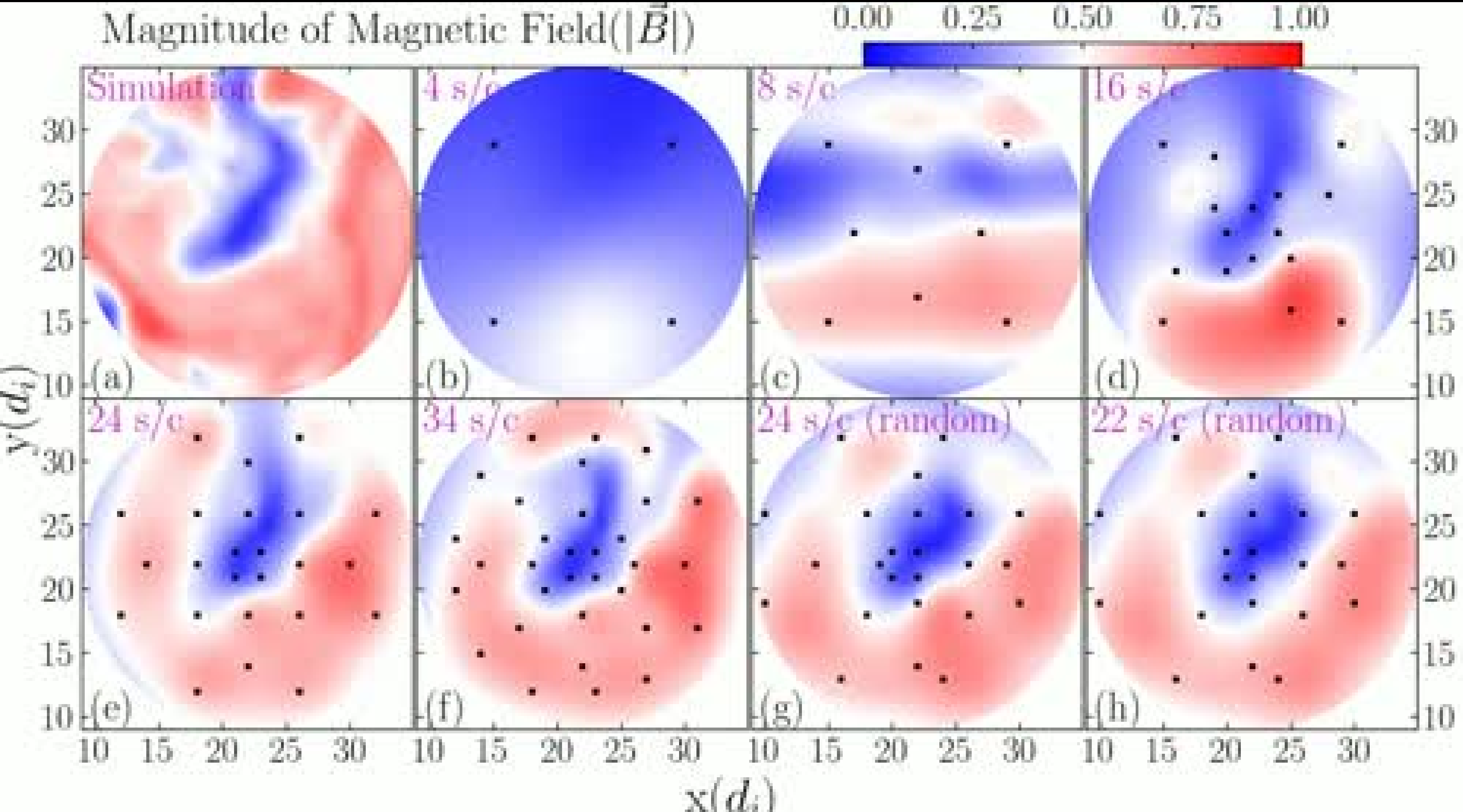
$$f(\mathbf{x}) \sim \mathcal{GP}\left(m(\mathbf{x}), k(\mathbf{x}, \mathbf{x}')\right)$$

https://scikit-learn.org/stable/modules/gaussian_process.html

Reconstructed Magnetic Field

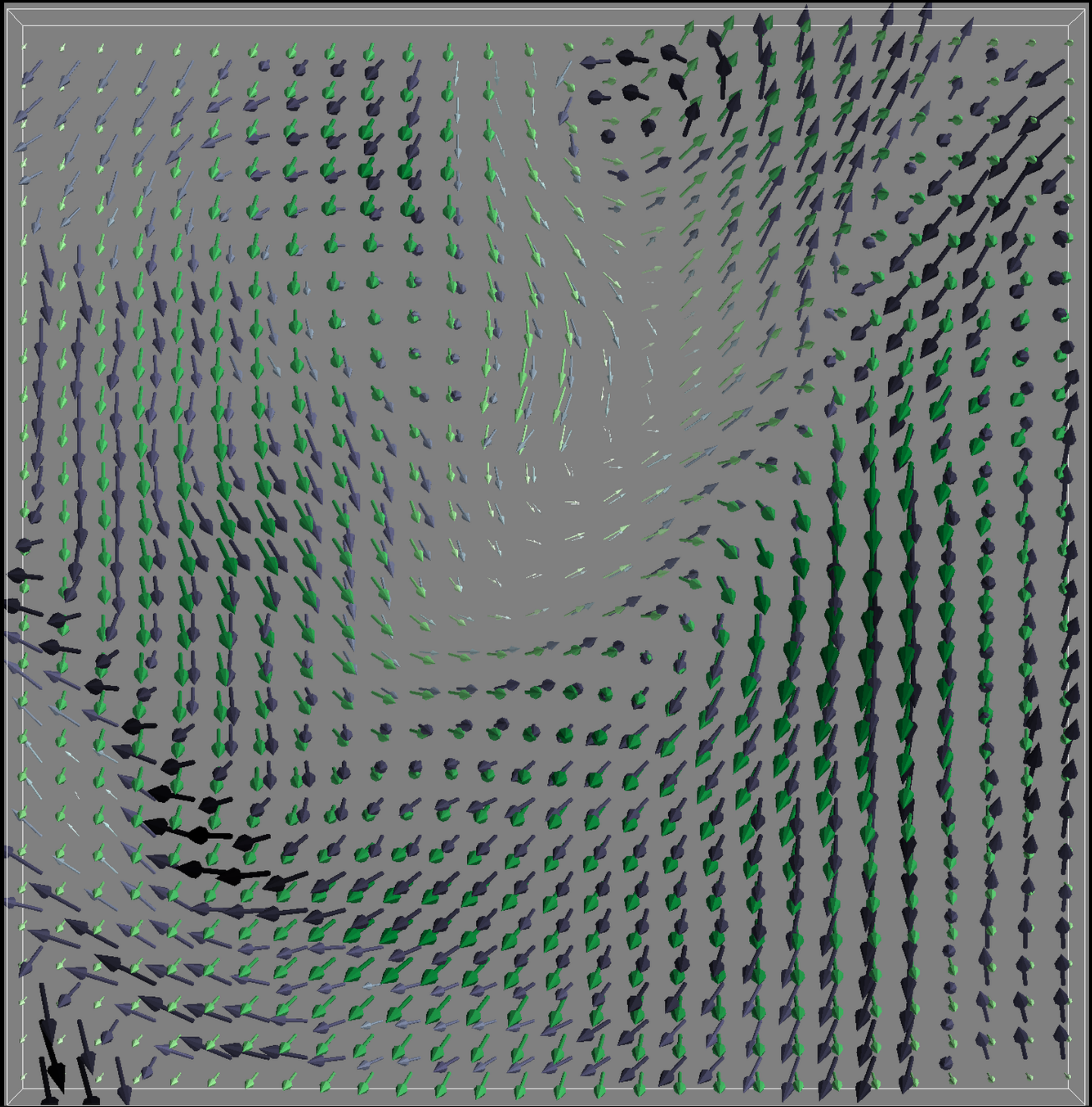


(Maruca, Frontiers-2021)



Magnitude of Magnetic Field($|\vec{B}|$)
0.00
0.25
0.50
0.75
1.00
Simulation
4 s/c
8 s/c
16 s/c
24 s/c
34 s/c
24 s/c (random)
22 s/c (random)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
$y(d_i)$
$x(d_i)$
10
15
20
25
30

Reconstructed Magnetic Field



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- Knowledge of full 3D structure of interplanetary magnetic field will help with this.
- We showed that we need at least 24 spacecraft to reconstruct magnetic field with sufficient accuracy.

Acknowledgements

Questions?

https://xkcd.com/1403/

https://slides.com/qudsi/thesis/

Thank You! :)