Identification of Kelvin-Helmholtz vortices at the Earth's magnetosphere

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ASI Agenzia Spaziale Italiana

GSSI GRAN SASSO SCIENCE INSTITUTE SCHOOL OF ADVANCED STUDIES Scuola Universitaria Superiore

IRF

MMS Magnetospheric Multiscale NASA Goddard Space Flight Center SwRI

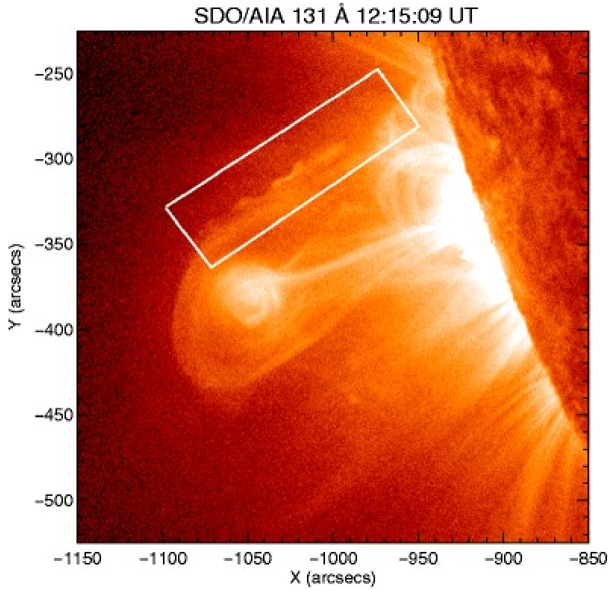
Outline

- Brief overview of the Kelvin-Helmholtz (KH) instability;
- Kinetic features to identify KH vortices
  - Hybrid Kelvin-Helmholtz simulation;
  - MMS observation of KH event at the Earth's magnetopause;
  - comparison between Kelvin-Helmholtz simulation and *in-situ* measurements;
- Large scale features to identify KH vortices
  - Mixing parameter to identify vortex boundary and phase;
  - Statistical analysis of the identified vortices.
- Summary

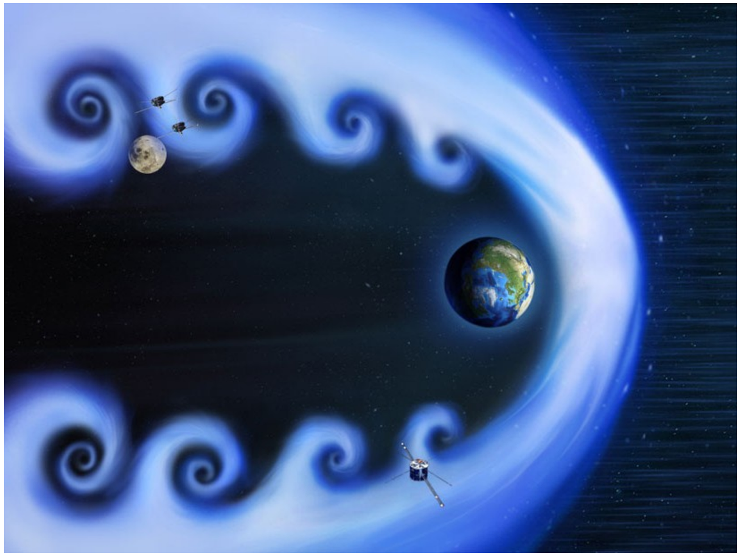
Overview

KH instability can be generated in correspondence of velocity shears.
Such systems can be observed in many natural environments

Observation of the *"Jupiter eye"* in the visible wavelength



KHI during a coronal mass ejection event



KHI at the Earth Magnetopause

We are interested in studying:

- Non-collisional, magnetized plasmas;
- Shear width $\Delta x \simeq d_p$

A kinetic approach is necessary

Hybrid Vlasov Maxwell System

- Hybrid approximation: only protons kinetic dynamics is retained and electrons are treated as a massless fluid;
- Low frequencies approximation: displacement current is discarded;
- Quasi-neutrality condition: $n_p \simeq n_e = n$

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right) \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

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

$$\nabla \times \mathbf{B} = \mathbf{J}$$

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{1}{n} \mathbf{J} \times \mathbf{B} - \frac{1}{n} \nabla p_e$$

$$p_e = n T_e$$

Values used for normalization

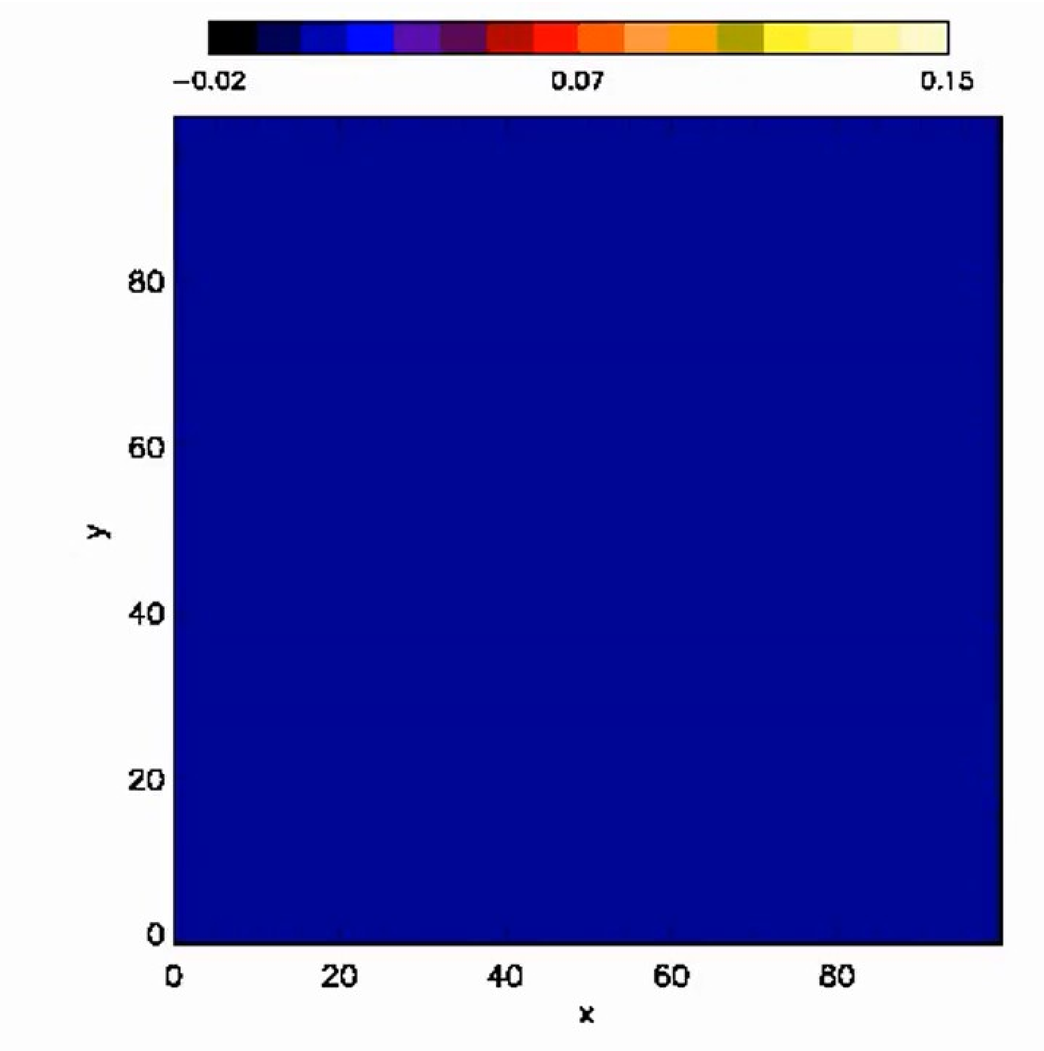
$$\tilde{u} = v_A \quad \tilde{\omega} = \Omega_{cp} \quad \tilde{p}_e = \tilde{n} m_p v_A^2$$

$$\tilde{l} = v_A / \Omega_{cp} = c / \omega_{pp} = d_p$$

$$\tilde{E} = m_p v_A \Omega_{cp} / e$$

Hybrid simulation of KH instability

isocontour of total current density along the whole simulation time



2D-3V simulation
with the HVM code;

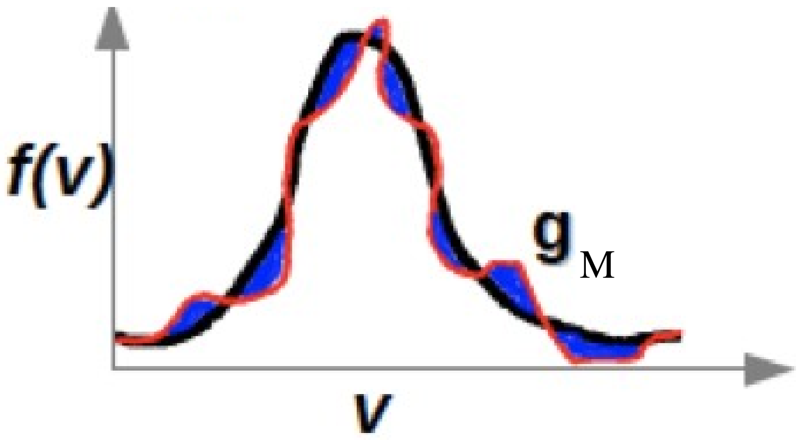
We start from an exact equilibrium configuration
(*Malara et al.* PRE, 2018)

Generation of large scale structures that collapse in two vortices and form thin current sheets.

[Settino et al., **ApJ**, 2020]

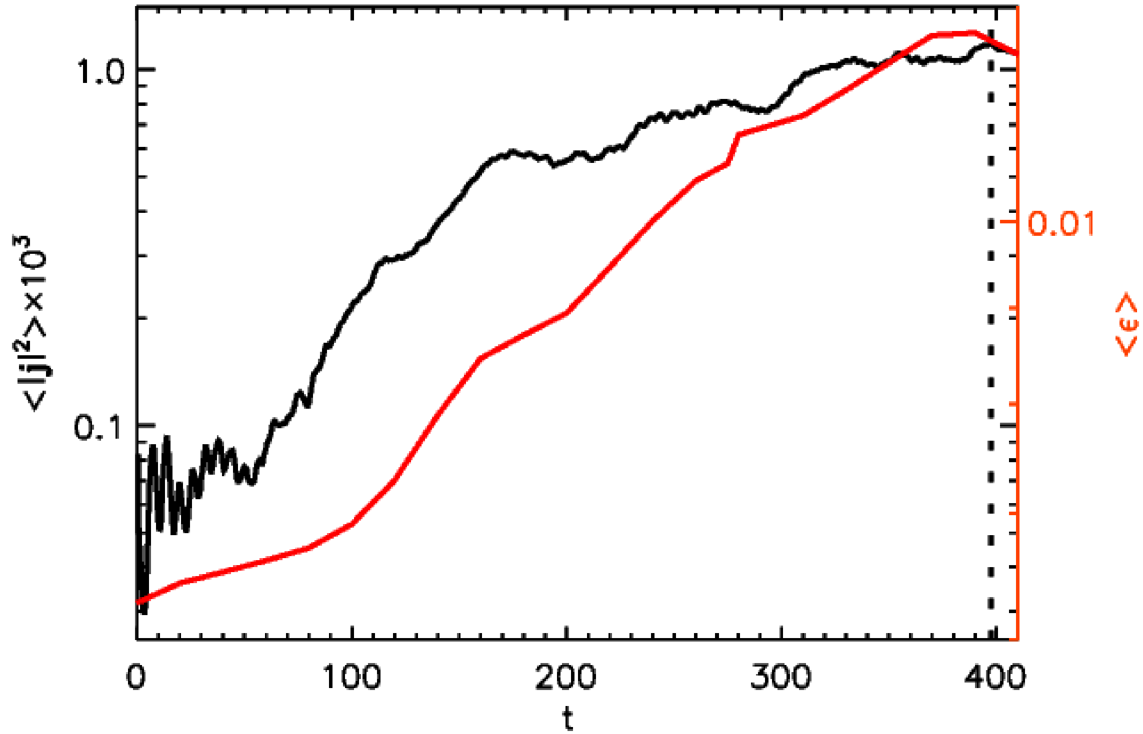
Temporal correlation

Ion non-Maxwellianity



$$\epsilon_M = \frac{1}{n_i}\sqrt{\int [f_i - g_M]^2\, d^3v}$$

Greco et al. 2012

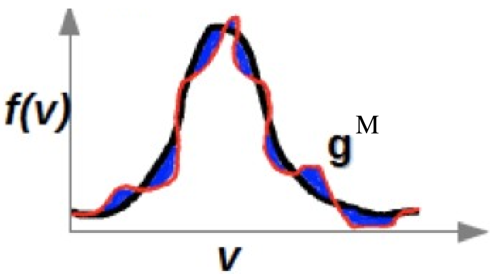


Total current density and Ion non-Maxwellianity are highly correlated in time

[Settino et al., **ApJ**, 2020]

Kinetic features

Ion non-Maxwellianity



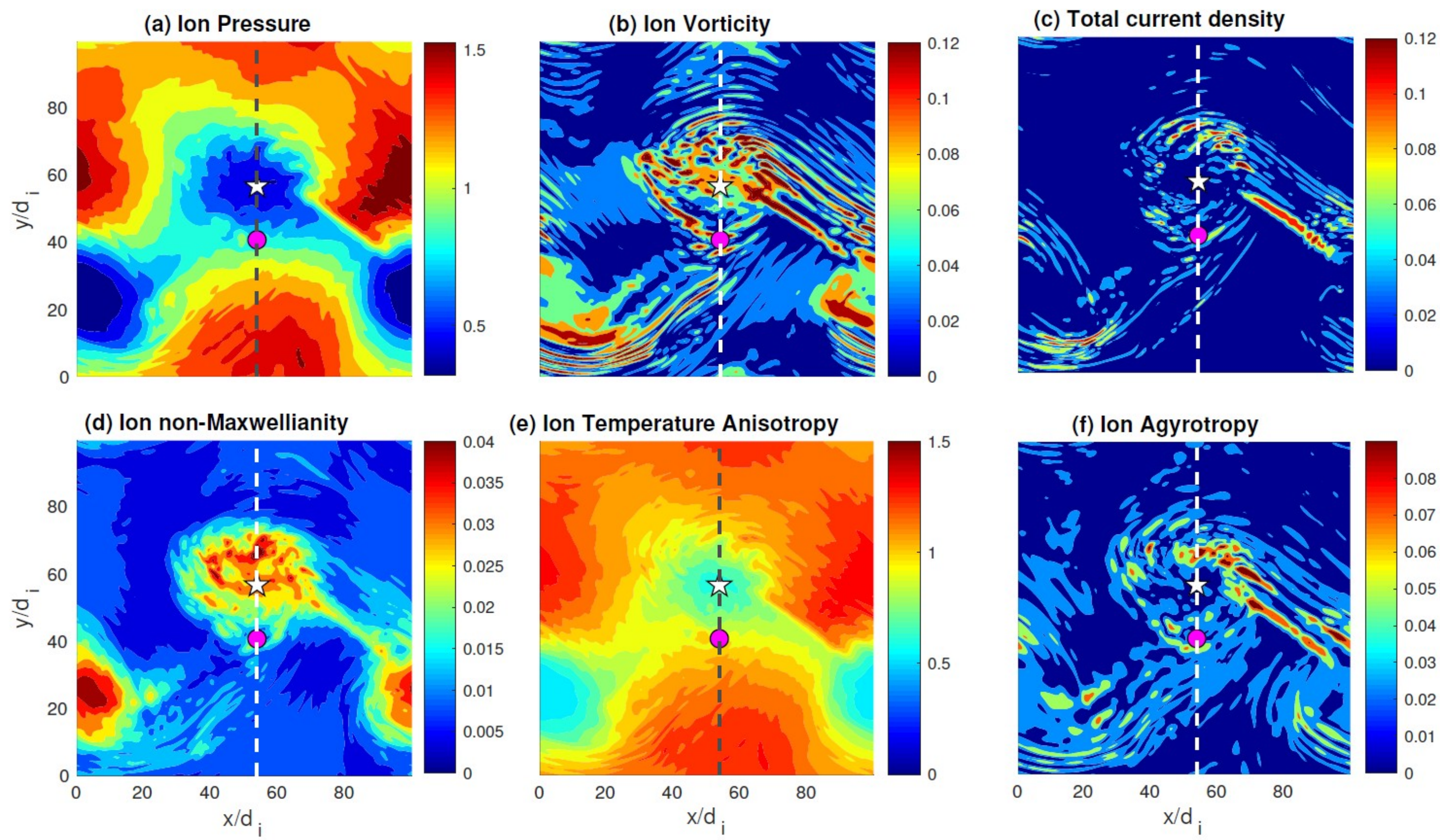
$$\epsilon_M = \frac{1}{n_i}\sqrt{\int [f_i - g_M]^2 \, d^3v}$$

Greco et al. 2012

Ion Agyrotropy

$$Q = \frac{P_{xy}^2 + P_{xz}^2 + P_{yz}^2}{P_\perp^2 + 2P_\perp P_\parallel};$$

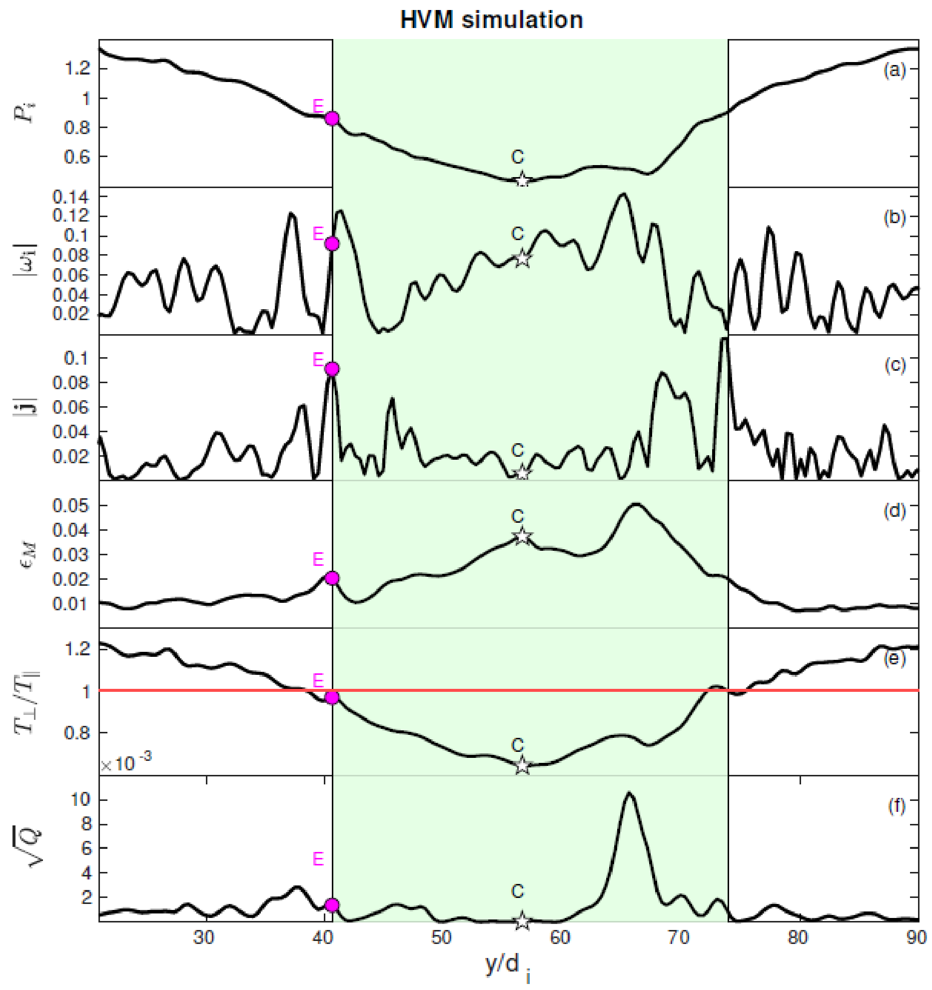
Swisdak, 2016

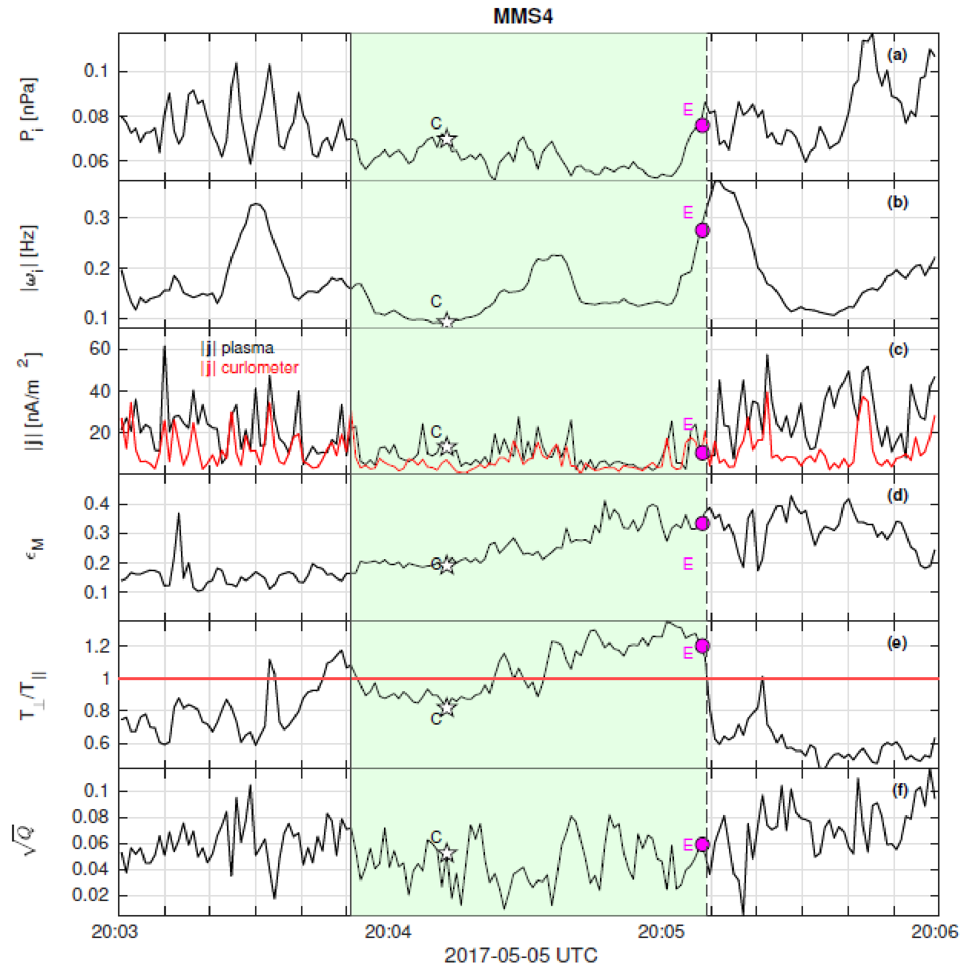


1. |**j**| peaks at the edges of the vortex;
2. ϵ_M peaks inside the vortex.

[*Settino et al.*, ***ApJ***, *2021* (in press)]

Comparison between simulation and in-situ data

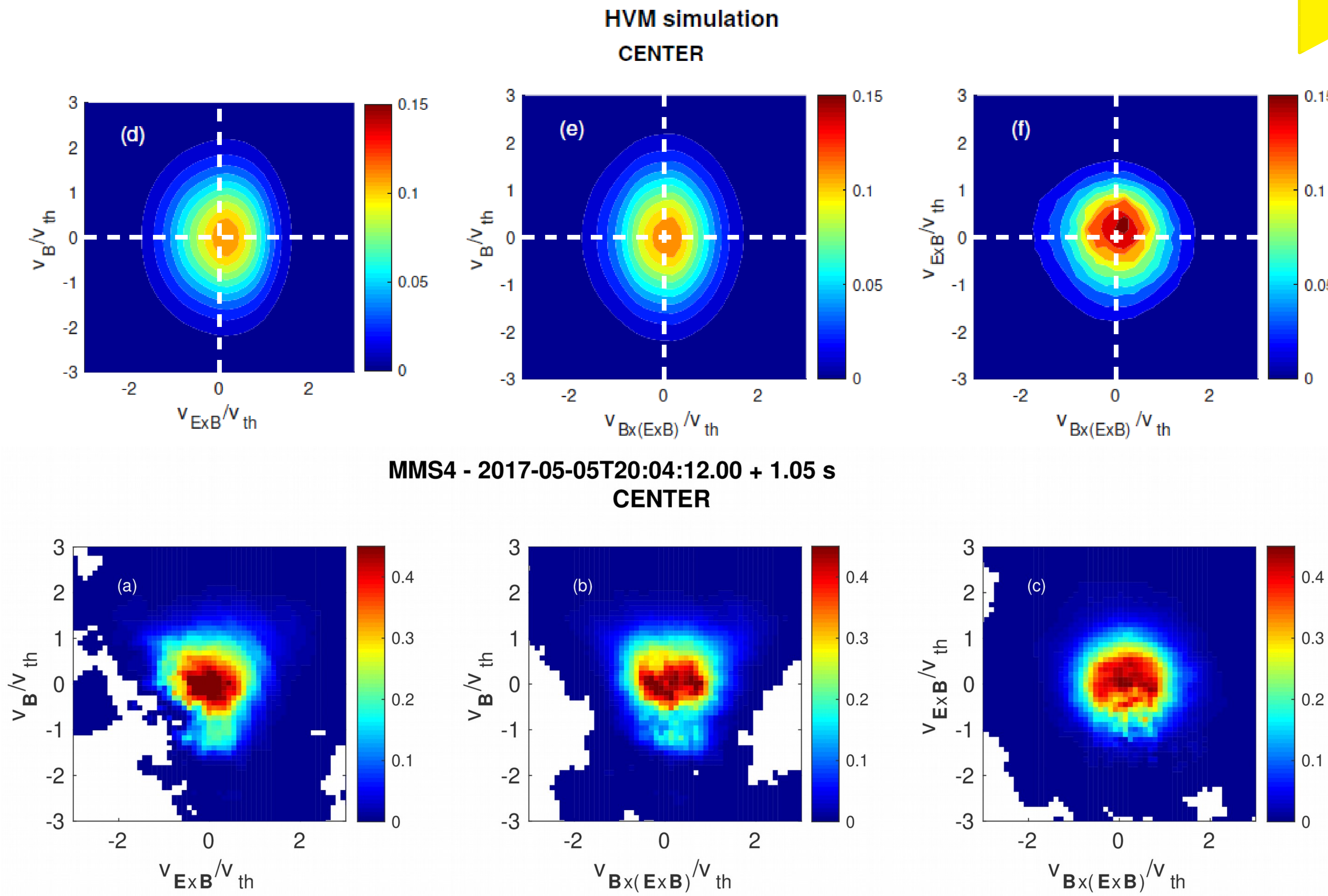




Vortex boundaries have been identified by Hwang et al. 2020

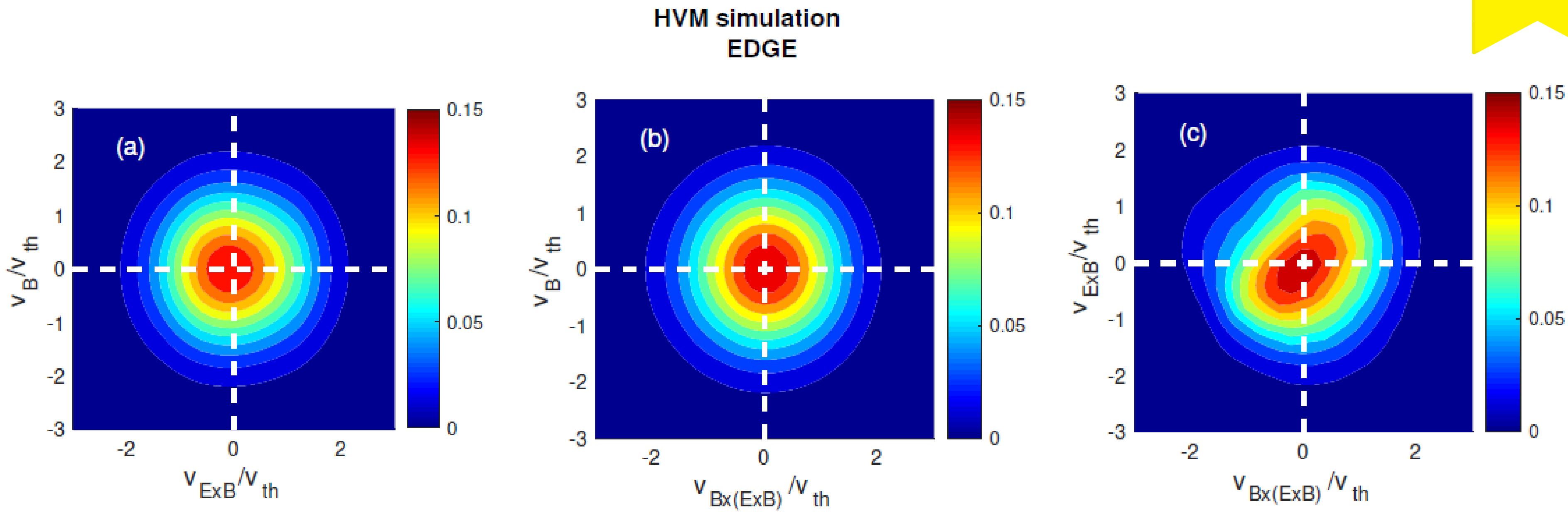
[*Settino et al.*, ***ApJ***, *2021* (in press)]

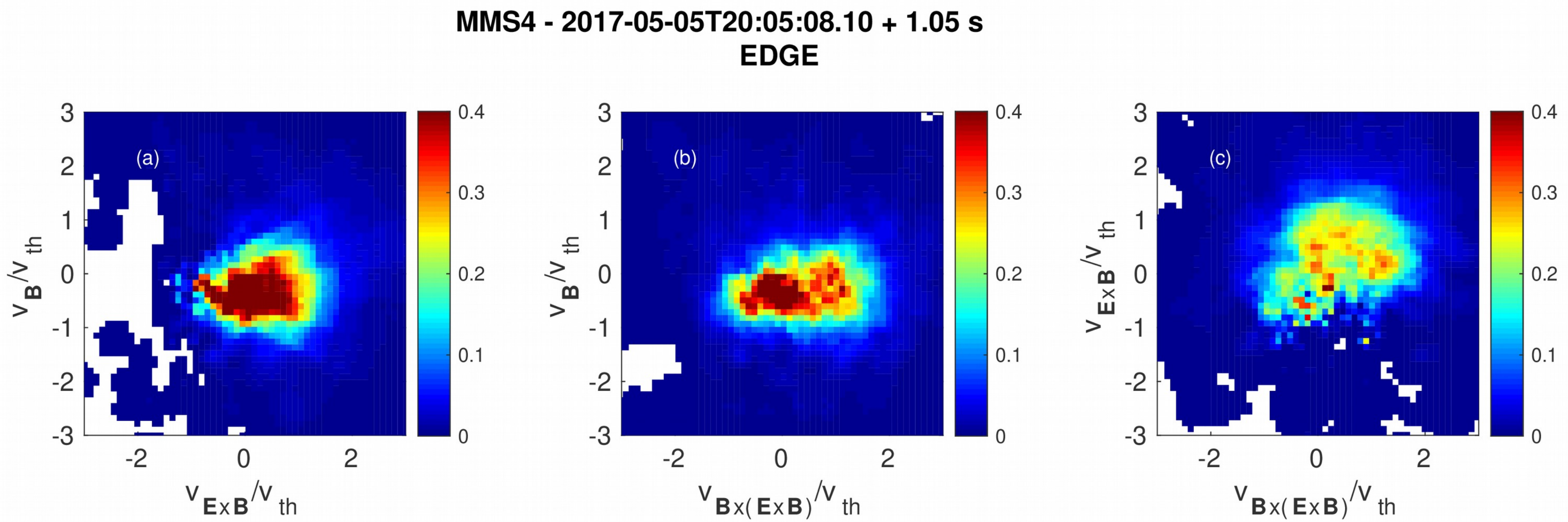
VDF at the center of the vortex



[*Settino et al.*, ***ApJ***, *2021* (in press)]

VDF at the edge of the vortex

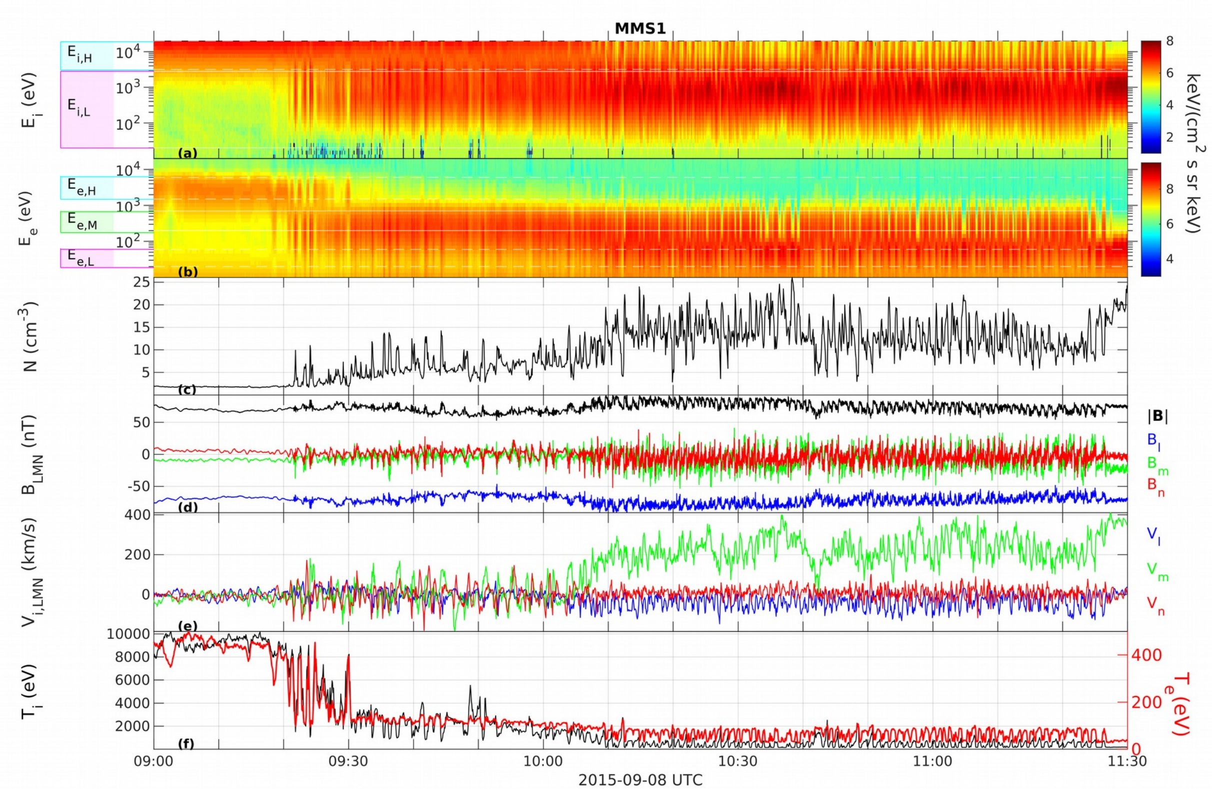


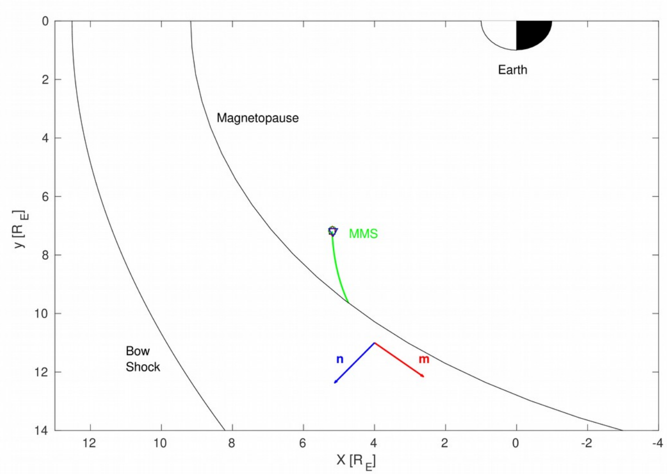


[*Settino et al.*, ***ApJ***, *2021* (in press)]

Large scale features to identify Kelvin-Helmholtz vortices and their evolutionary stage

Mixing parameter

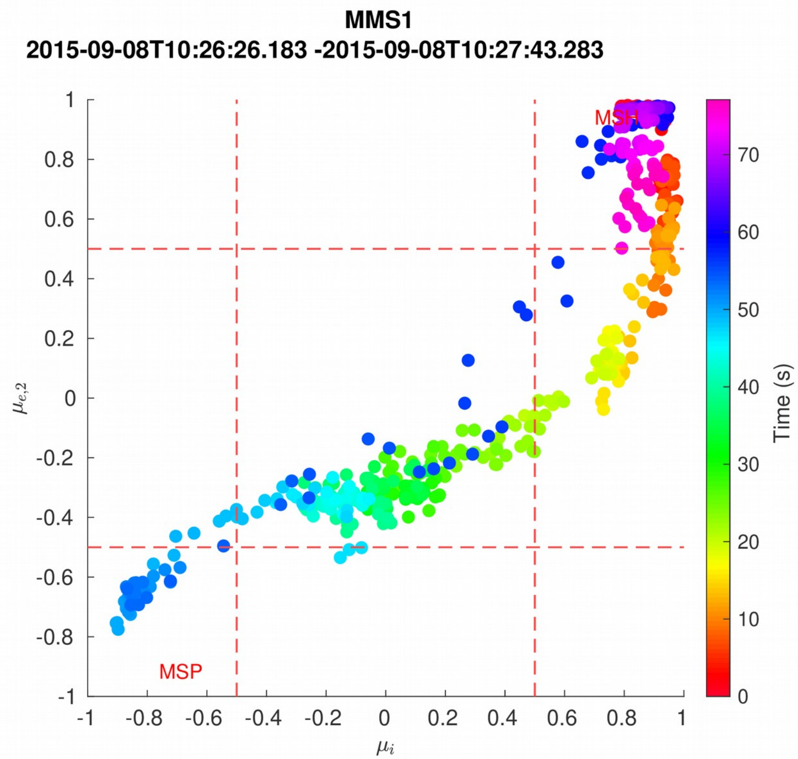




Ion and electron mixing

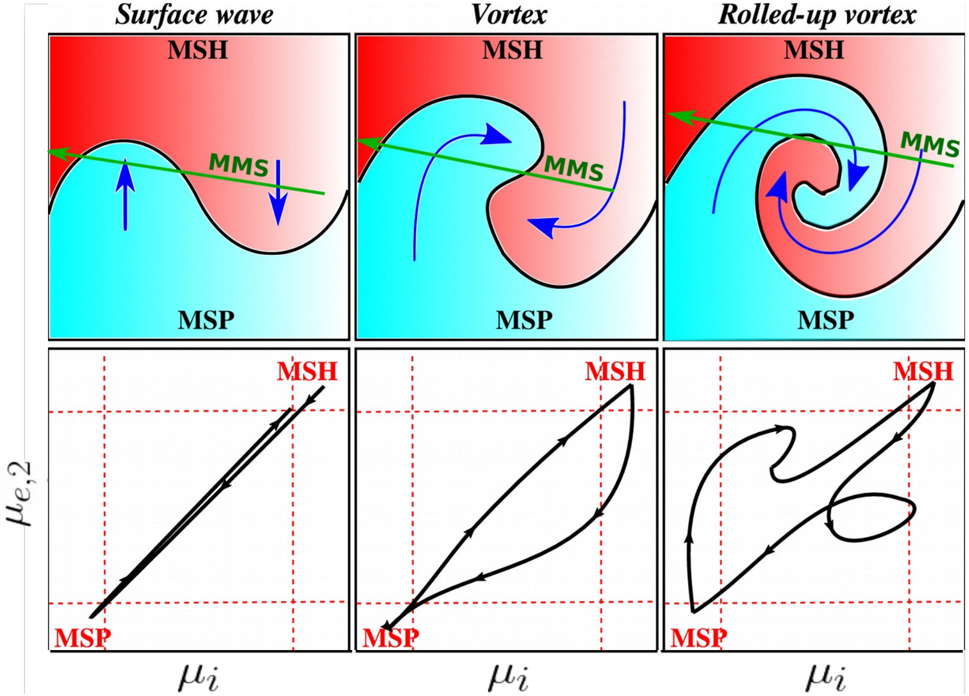
$$\mu_\alpha = \frac{\sigma_{\alpha,a} - \sigma_{\alpha,b}}{\sigma_{\alpha,a} + \sigma_{\alpha,b}}$$

where, $\sigma_{\alpha,a} = \int_{E_{\alpha,a}} f_\alpha(E,t)\ dE$



[Settino et al., to be submitted]

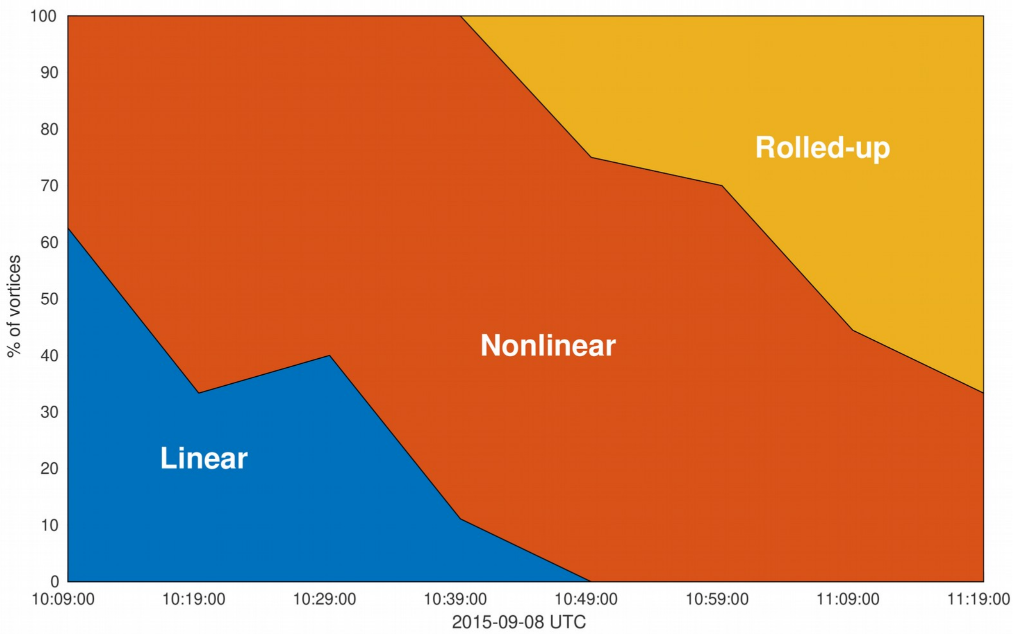
Statistical analysis



Three main shapes have been recognized in the space of the mixing parameter:

(a) same path trajectory;
(b) different path trajectory;
(c) complex trajectory with loops and twists.

- 69 crossings have been identified;
- Each crossing has been categorized according to its shape in the space of the mixing parameter;
- For each time interval the percentage of vortices has been evaluated.



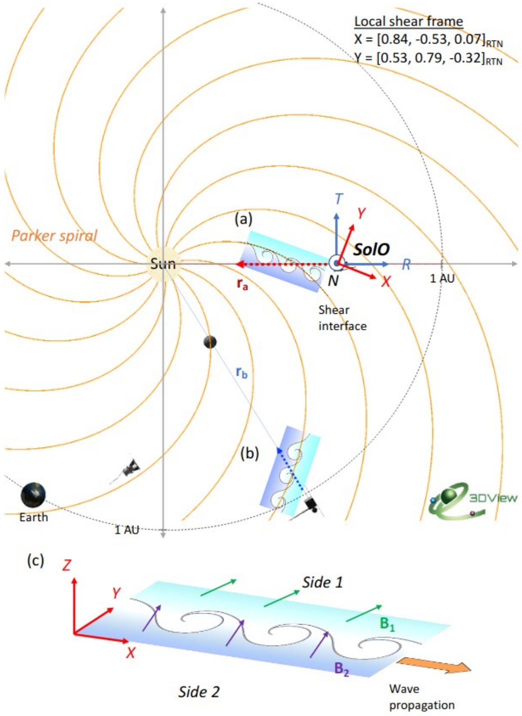
[Settino et al., in prep.]

Summary

- Comparison between KH simulation and observations has suggested new quantities that can be used for the identification of vortices:

  1. Magnitude of the total current density peaks at the edges of the vortices and has a minimum inside the vortex;
  2. The ion non-Maxwellianity is low at the edges of the vortex and increases inside the vortex;

- Single spacecraft measurements which need a good resolution for the particles instrument;
- These quantities can be used in the Solar Orbiter mission to identify KH vortices.
- Electrons and ions mixing provide information about the topology and the plasma mixing respectively;
- The mixing parameters allow the identification of the evolutionary stage of the KH instability.



[Kieokaew et al. 2021, **arxiv**]

Thank you for listening!