# Global 3D Hybrid simulations of the Super-Critical Bow-Shock behavior upon a Quasi-Perpendicular interaction with the Interplanetary Magnetic Field


Laboratoire de Physique des Plasmas


## Emanuele Cazzola, Dominique Fontaine, Philippe Savoini

Laboratoire de Physique des Plasmas (LPP), CNRS, Observatoire de Paris, Sorbonne Université, Université Paris-Saclay, École Polytechnique, Institut Polytechnique de Paris



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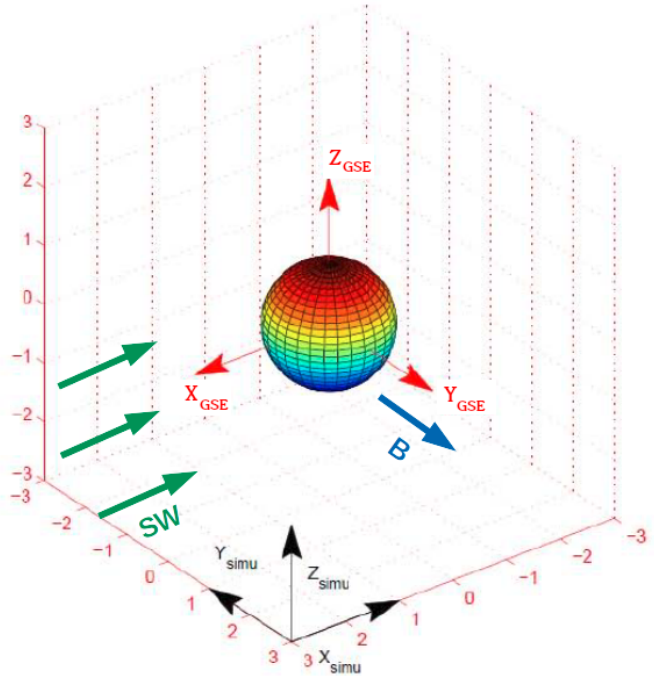
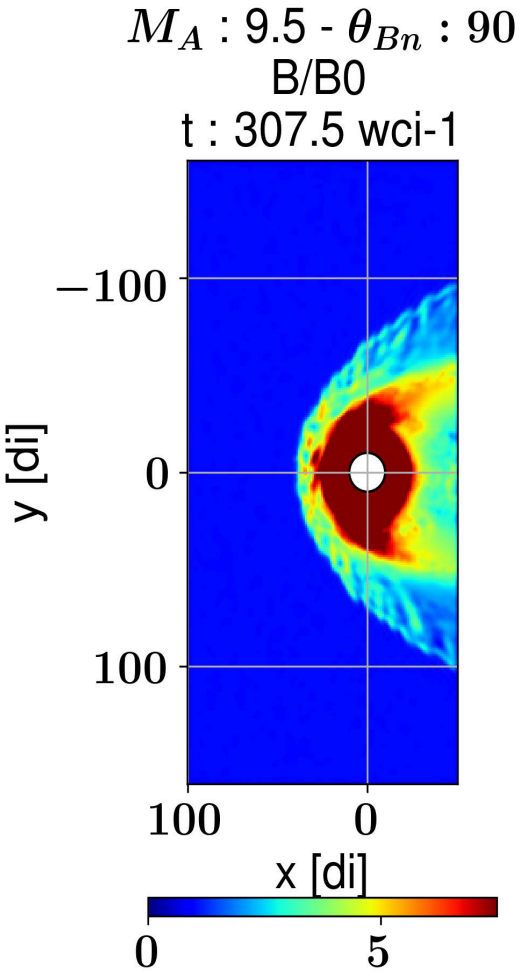
# Bow-Shock Dynamics in a Quasi-Perpendicular Configuration

## What happens at (relatively) high Alfvénic Mach number ?

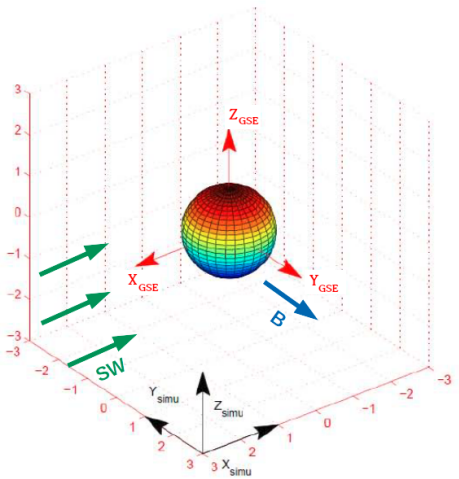


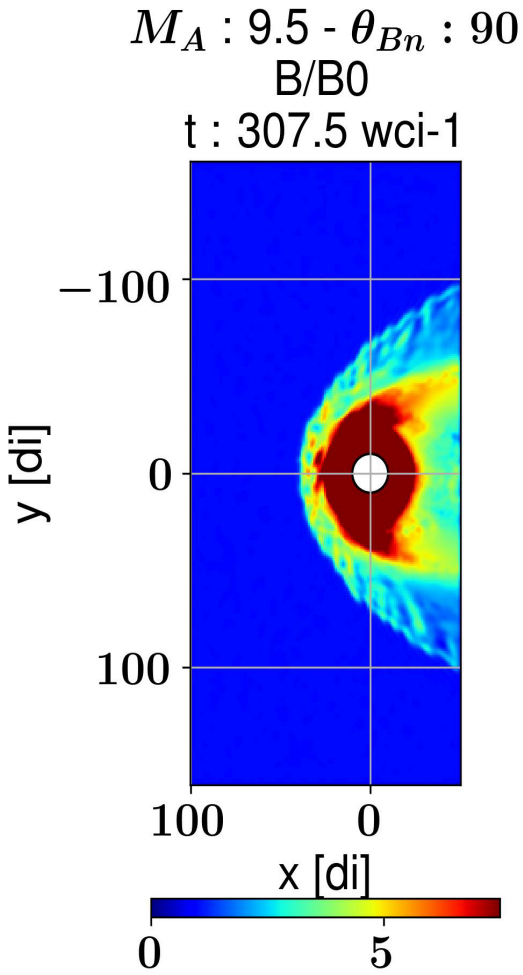

*Movie: 3D BS cross-section thru the ecliptic plane – $\theta_{Bn}$ being the angle between B and normal direction to the Bow-Shock surface at the nose*




**Apparition of waves propagating along the curved Bow-Shock**

# Bow-Shock Surface Rippling




## Rippled structures :

- Under what conditions do they appear ?
- What direction do they propagate to ?
- How fast do they propagate ?
- Where are they originated from ?
- What is wavelength and frequency ?
- How does their global view look like ?

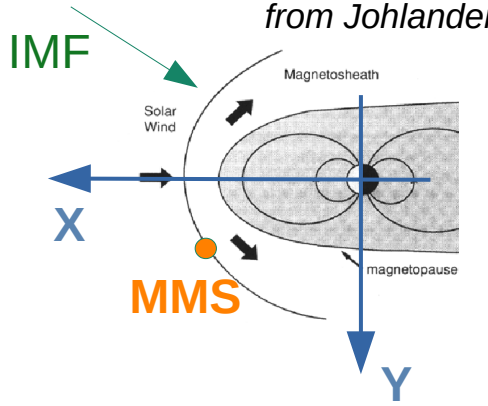
# Bow-Shock Surface Rippling

## Have they been observed in simulations and with satellites ?

### Observed with satellites crossing

- **With MMS and CLUSTER :**
  - Johlander+ 2016 (*cf.* $M_A \sim 6.2$)
  - Madanian+ 2021 (*cf.* $M_A \sim 27$)
  - Moullard+ 2006 (*cf.* $M_A \sim 11$)
  - Lobzin+ 2007 (*cf.* $M_A \sim 5$)

*from Johlander+ 2016*

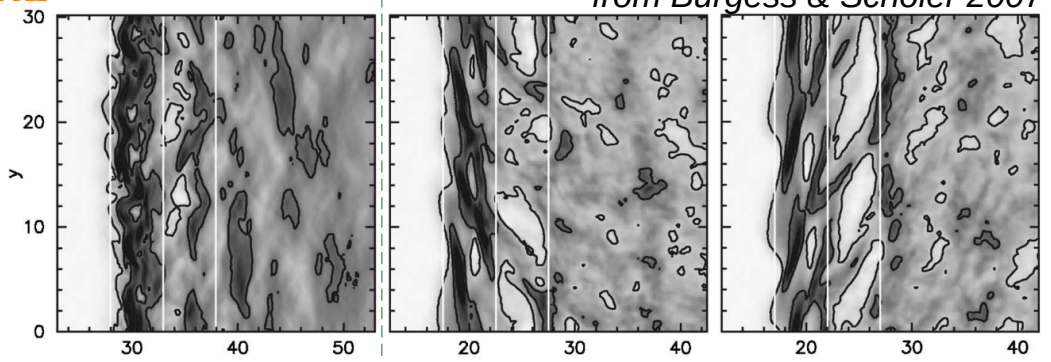



**Limited to local view**

### Planar shocks simulations and possible origins explanations

- **Normal-aligned processes :**
  - Lembege & Savoini 1992
- **Surface-aligned processes :**
  - Hellinger+ 1996
  - Hellinger & Mangeney 1997
  - Krasnoselskikh+ 2002
  - Lembège+ 2009
- **Alfvenic Ion Cyclotron Instability or Mirror Instability**
  - Tanaka+1983
  - Winske & Quest 1988
- **Reflected ions gyrating dynamics instability**
  - Burgess & Scholer 2007
- **Kinetic-based MHD surface wave**
  - Lowe & Burgess 2003

*from Burgess & Scholer 2007*




In-plane B ($B_{//}$ instabilities)

out-plane B ($B_{\neg}$ instabilities)

$M_A = 7.1 \quad \omega \sim 3\ \omega_{ci}$

$\lambda \sim 4 - 8\ d_i \quad V_r \sim V_{A,o}$

$M_A = 7.6 \quad \omega \sim 6 - 7\ \omega_{ci}$

$\lambda \sim 6\ d_i \quad V_r \sim 6.5 - 7.5\ V_A$

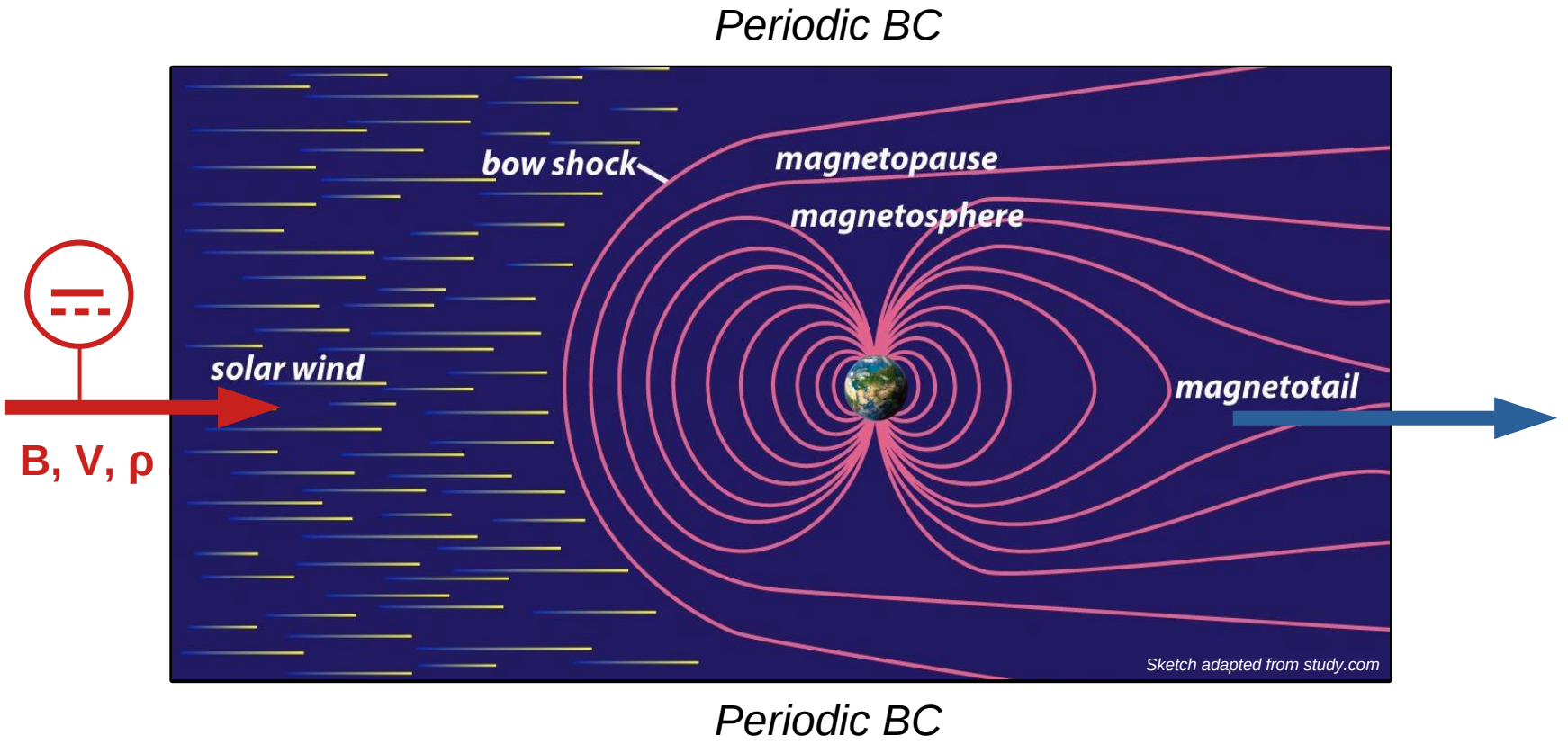
**Limited to planar shocks front (shock curvature excluded)**

# Characterizing the Bow-Shock Surface Rippling in a 3D curved scenario with hybrid simulations

**Unfortunately, observations are *local* and past simulations were *approximated to* 2D planar shocks (local point of view) … we are missing the 3D macroscopic global view of the phenomenon on a curved shock surface !**

**3D multi-species dynamic-BC ready hybrid code LatHyS *(Modolo+, 2005)*:**

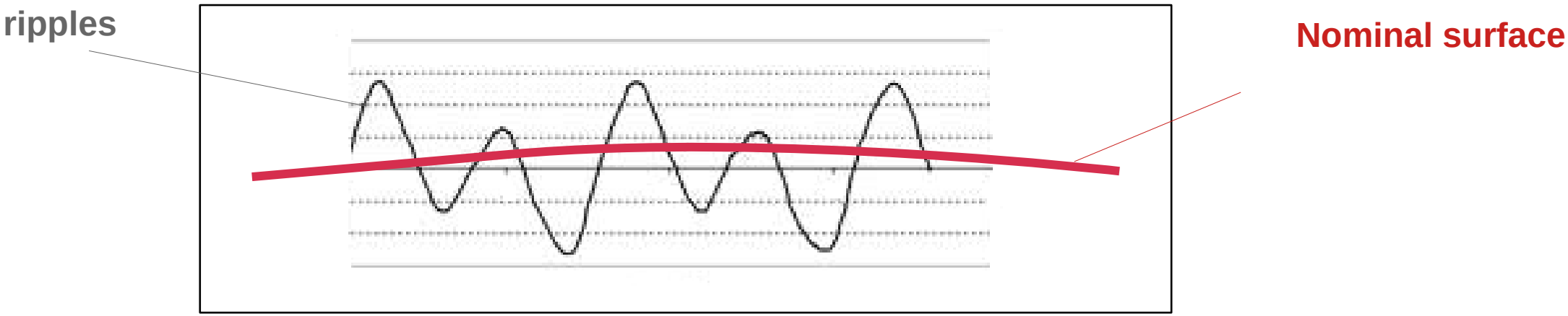
- ✗ **Rescaled problem**
  - ✗ Technique validated in Omidi+, 2004
- ✗ **Bow-Shock / Magnetosheath / Magnetopauste system self-consistently generated**
  - ✗ Qualitatively validated with models (e.g. Jerab+, 2005)
- ✗ **Solar Wind values steadily injected from left boundary**
- ✗ **Periodic BC elsewhere**



# Characterizing the Bow-Shock Surface Rippling in a 3D curved scenario with hybrid simulations

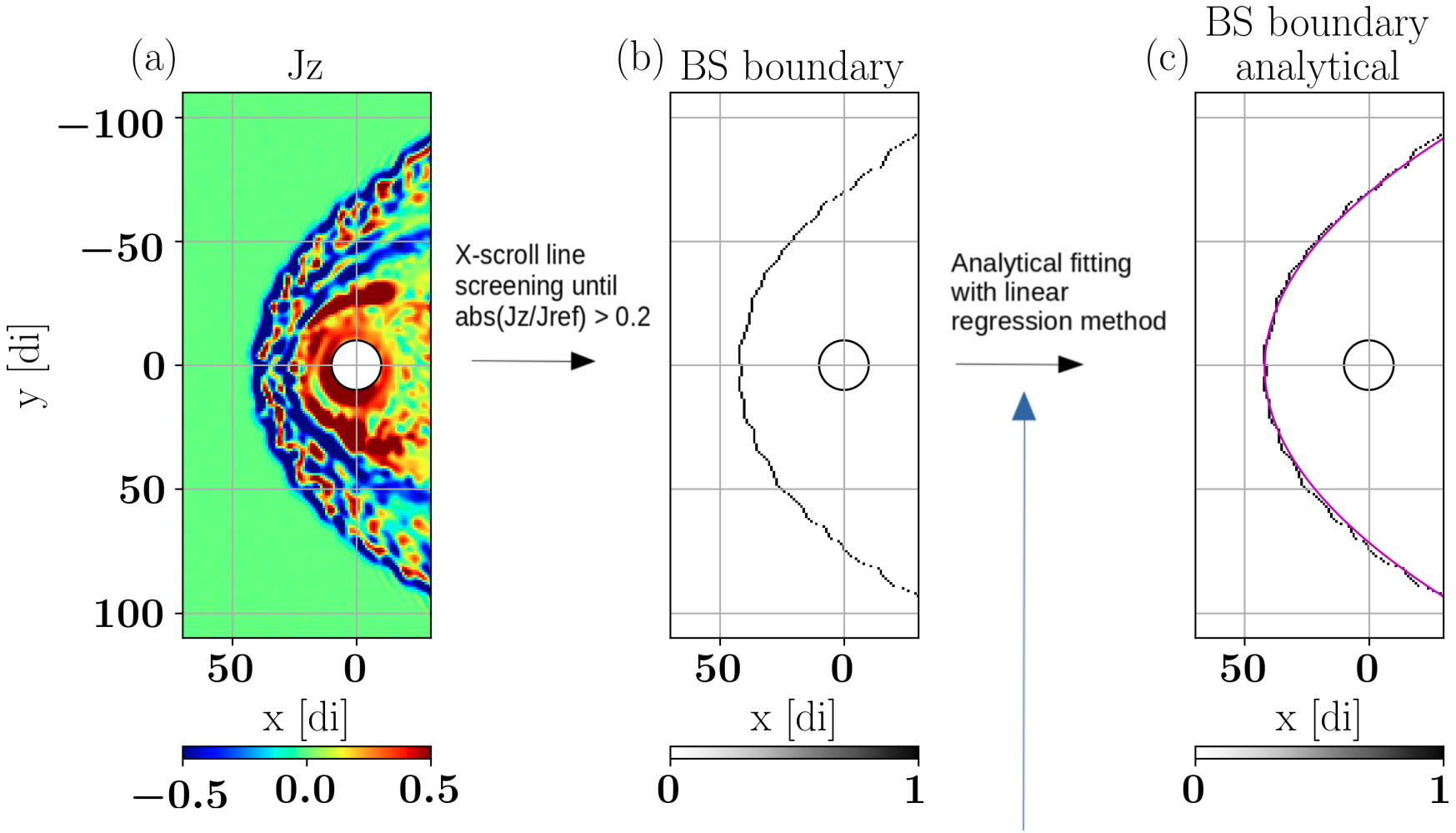
**To infer the ripples dynamics we can identify a nominal surface intercepting the ripples at all times :**

- **Models from the literature (from observations and MHD simulations)**
  - **Too inaccurate to catch the dynamics everywhere / all the time !**
  - **We can do something more … ad-hoc**



# Detecting, Identifying and Fitting a BS Nominal Surface

By exploiting the potential of structured-arrays data outputs from simulations ...

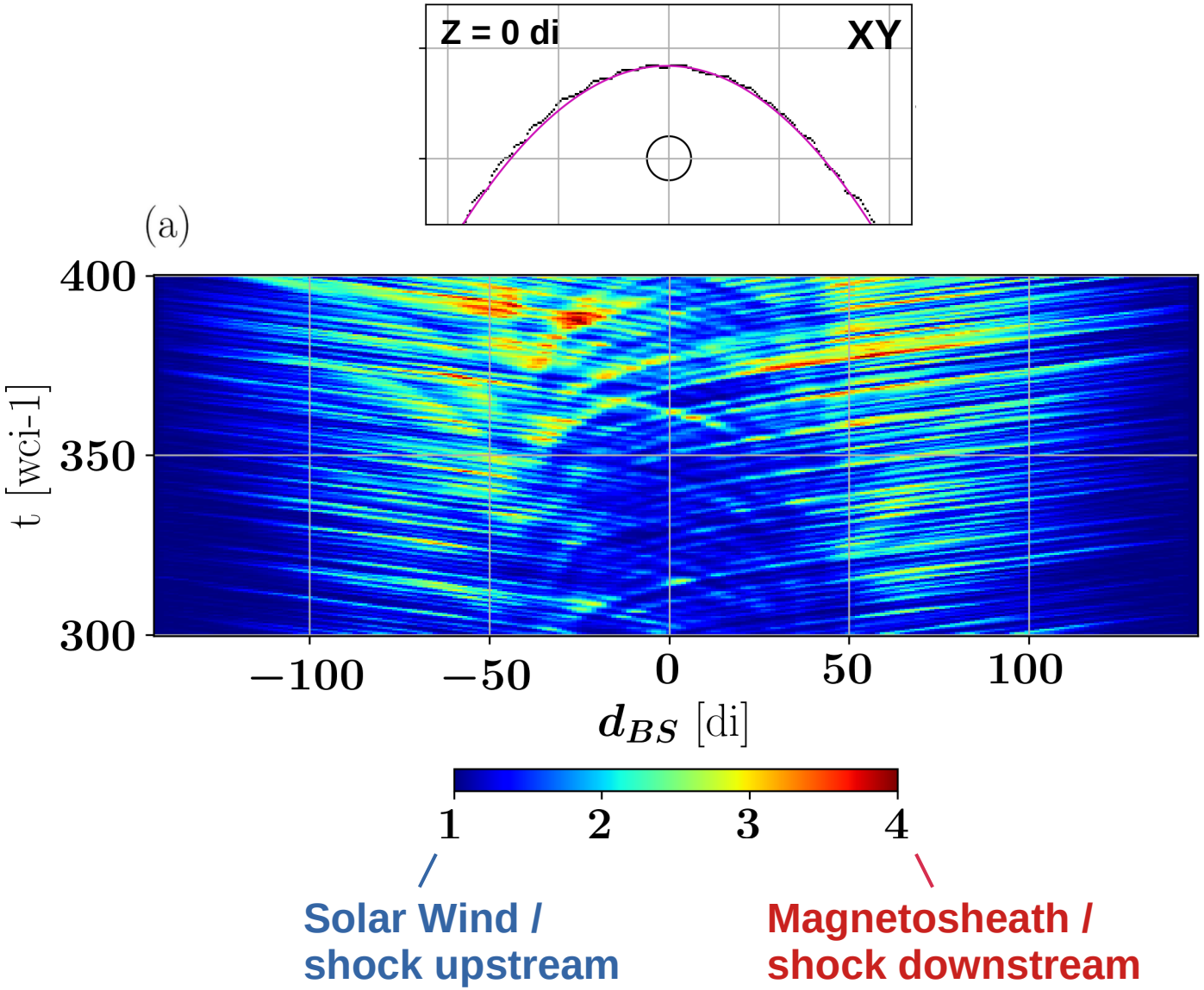



$$x\,(y,z) = a_{2,0}y^2 + a_{1,1}yz + a_{0,2}z^2 + a_{1,0}y + a_{0,1}z + a_{0,0}$$

*Figure: 2D cross-section of 3D outputs*

# Characterizing the Ripples Properties

## 2D Cross-Section Analysis



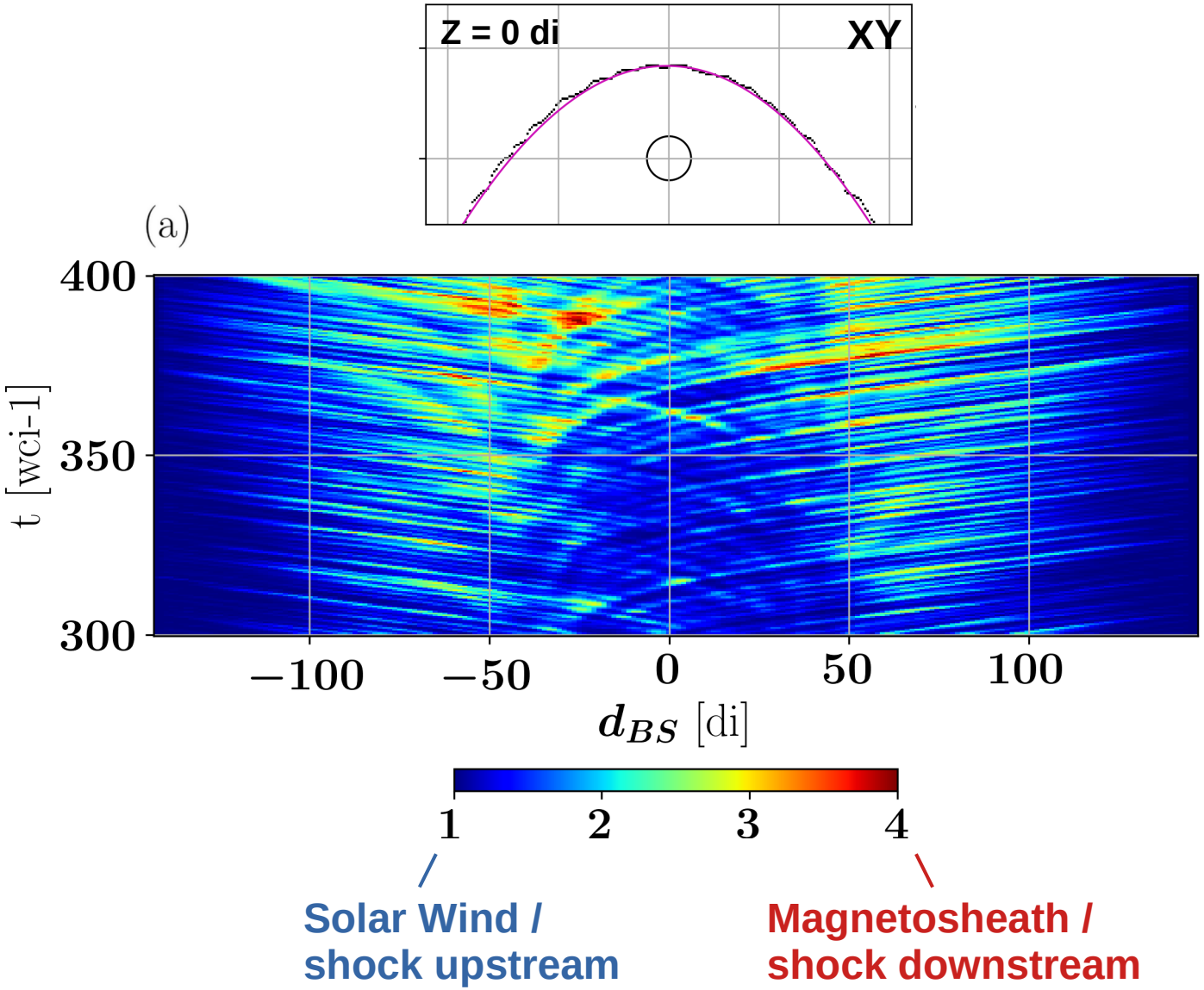

Ripples propagates from central region outward with a nearly constant velocity

This velocity does not change in time

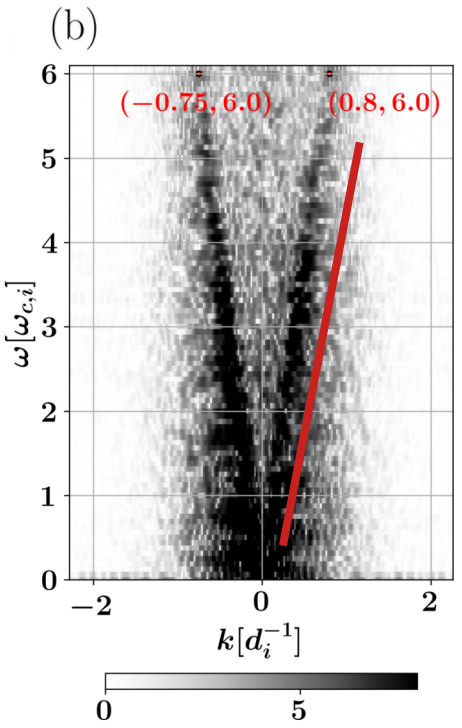
Nearly symmetric propagation over the two wings

# Characterizing the Ripples Properties

## Planar Analysis




**By taking the FFT ...**

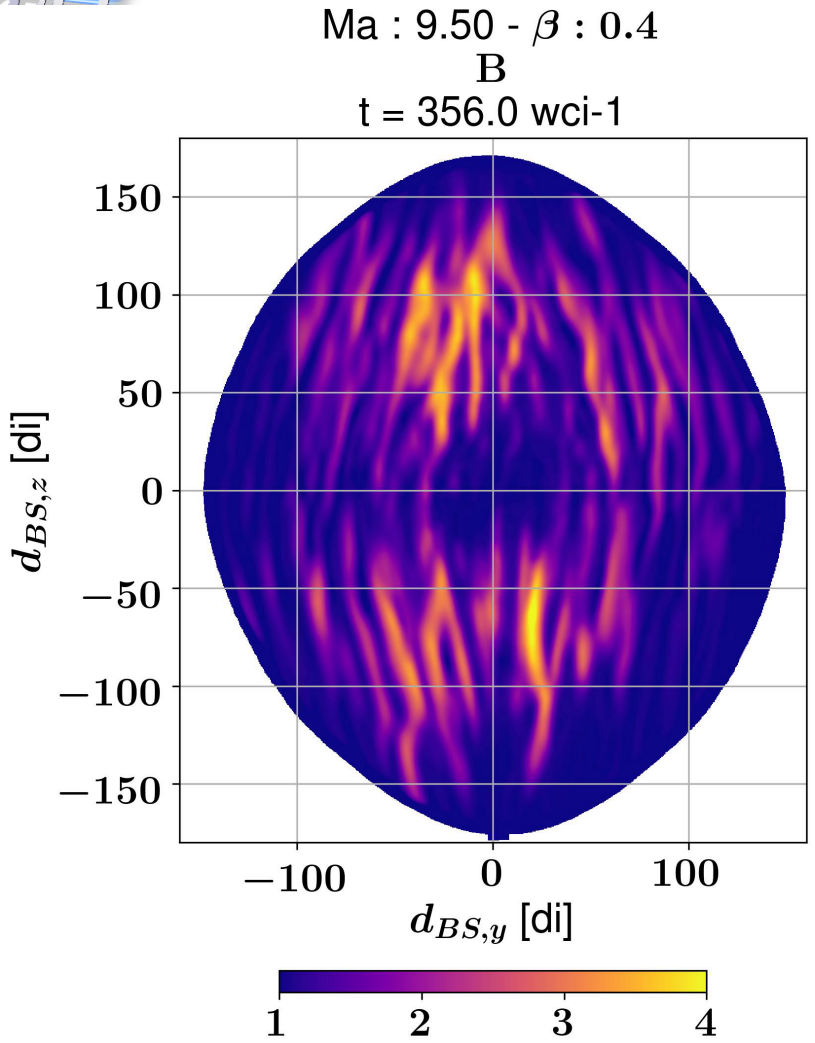


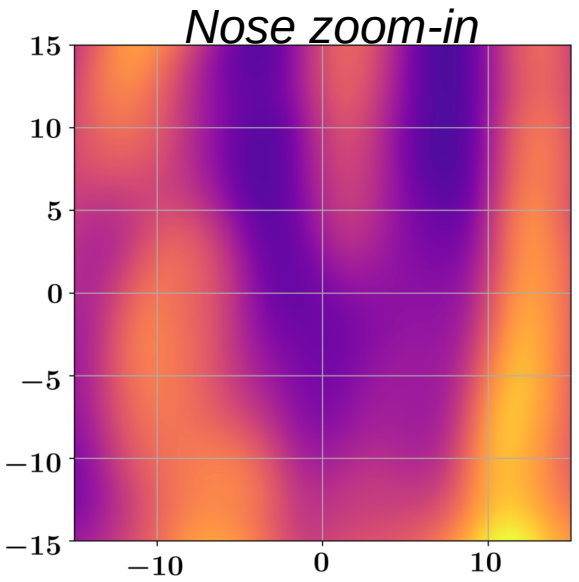

Phase speed of ~ 8 $V_A$ ~ 592 km.s-1

Broad spectrum of wavelengths (≥ 8 $d_i$ ~ 984 km) and periods (≥ 0.3 s), limited to resolution cut-off

# Characterizing the Ripples Properties

## 3D Analysis




✗ Ripples are indeed single elongated structures extending North-South and propagating from the nose outwards

✗ Quasi-Perpendicular to Quasi-Parallel transition not affecting the overall dynamics

✗ The propagation speed does not change with latitude

✗ Propagation along the IMF orientation

Magnetosheath / shock downstream

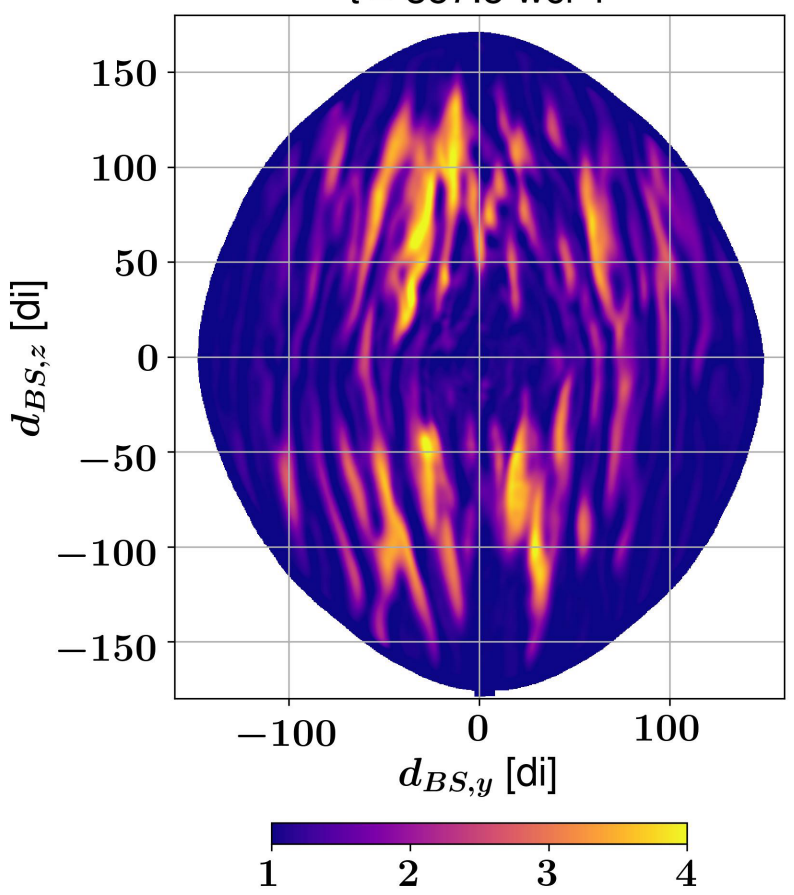
IMF

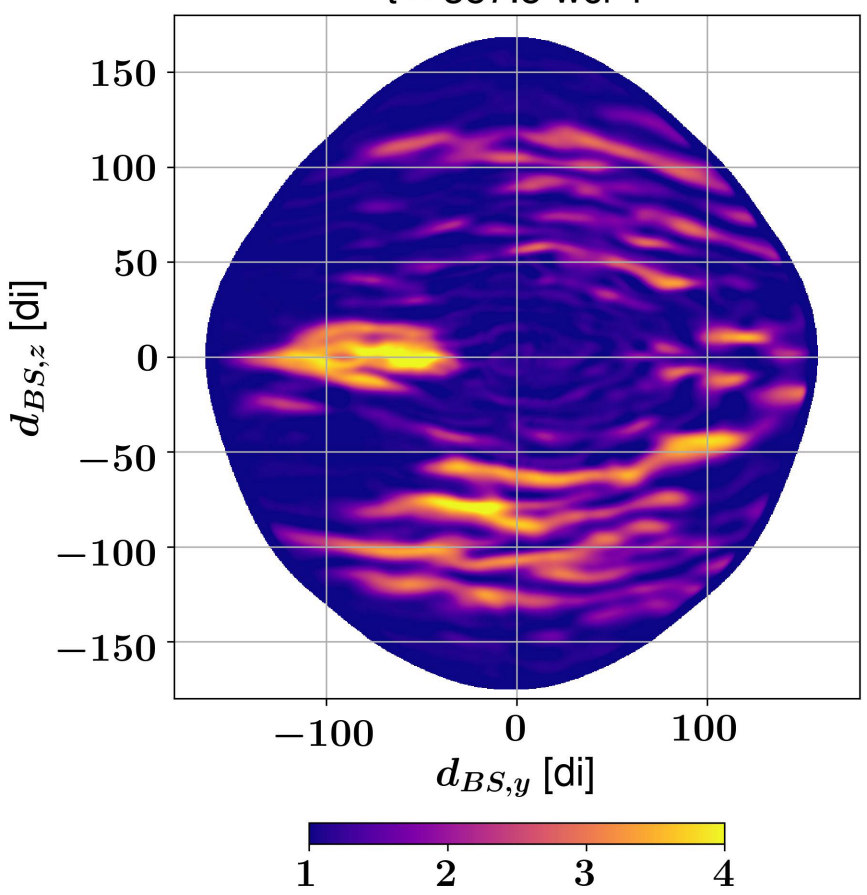
Solar Wind / shock upstream

# Characterizing the Ripples Properties

## What happens if we switch the IMF direction ?

IMF




IMF

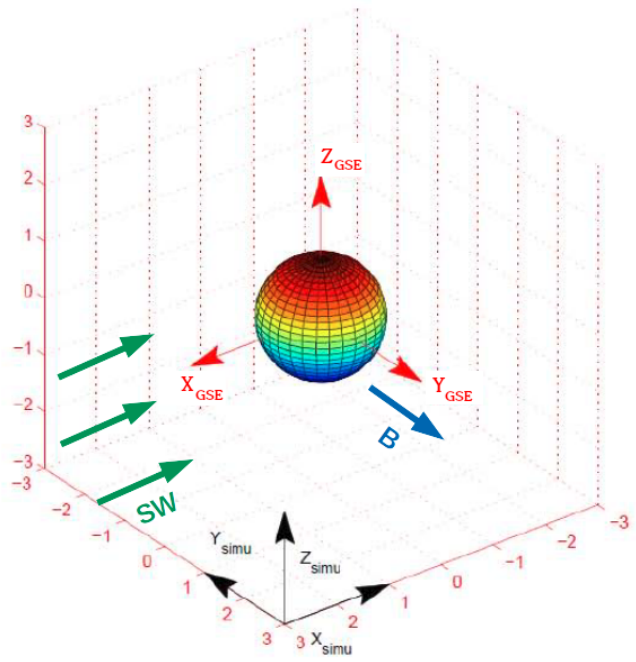
**Modulations direction of propagation is parallel to the IMF – Solar Wind direction/velocity not changed**

**So far we were in a (relatively) high $M_A$ supercritical conditions :**

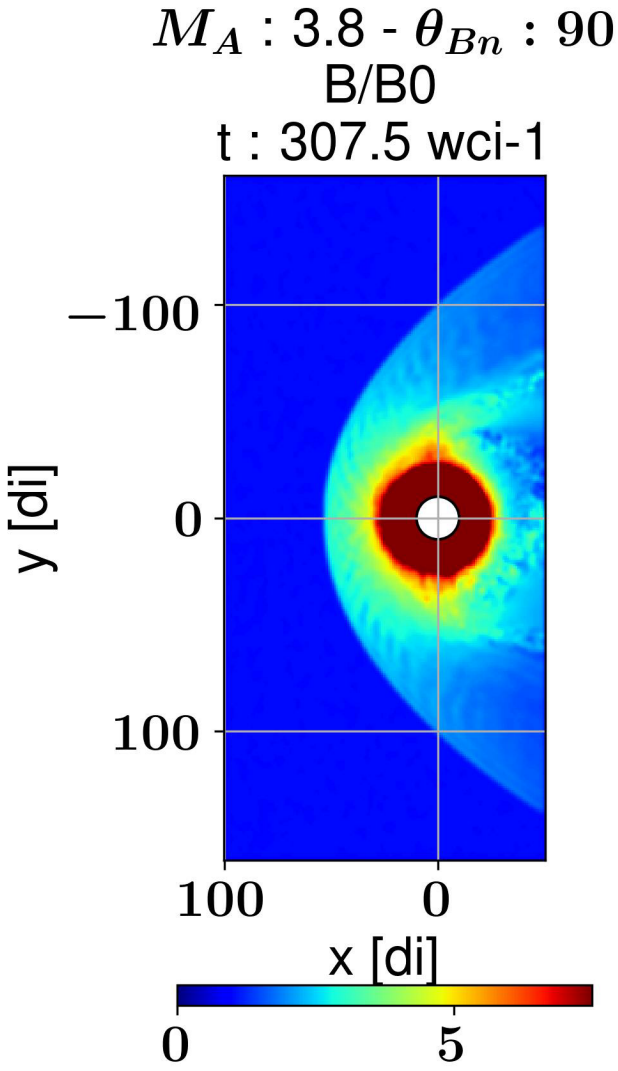
- **Kinetic effects dominant**
- ***Are ripples present for lower $M_A$ ?***

# Bow-Shock Dynamics in a Quasi-Perpendicular Configuration

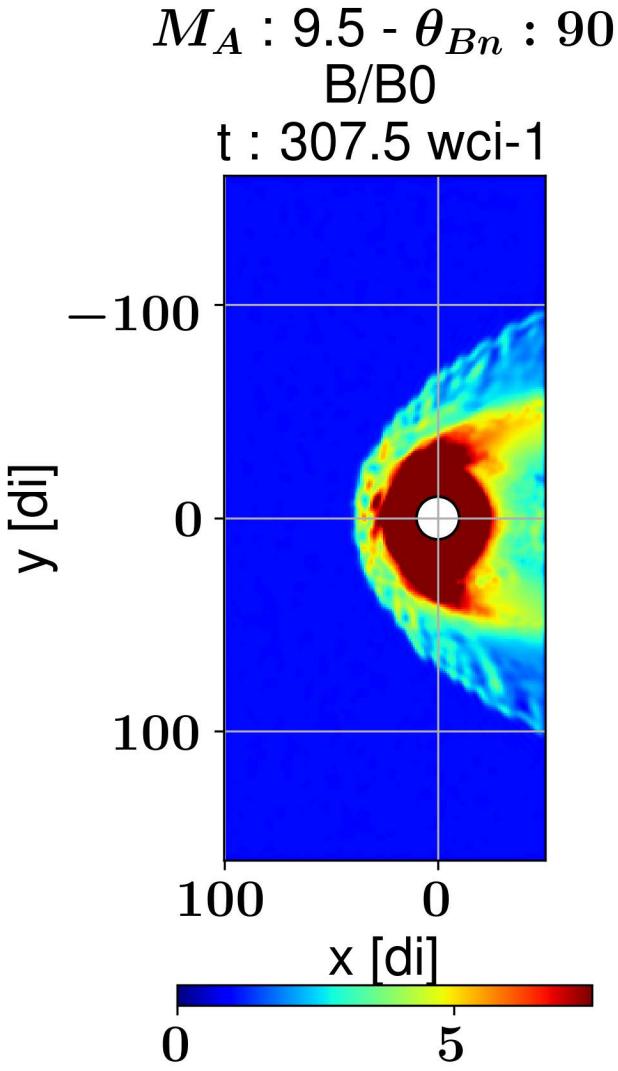
## What happens at low Alfvénic Mach number ?




*Movies: 3D BS cross-section thru the ecliptic plane – $\theta_{Bn}$ being the angle between B and local normal direction at the nose*



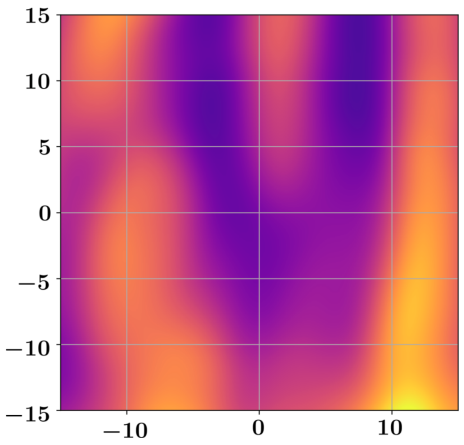

low $M_A$

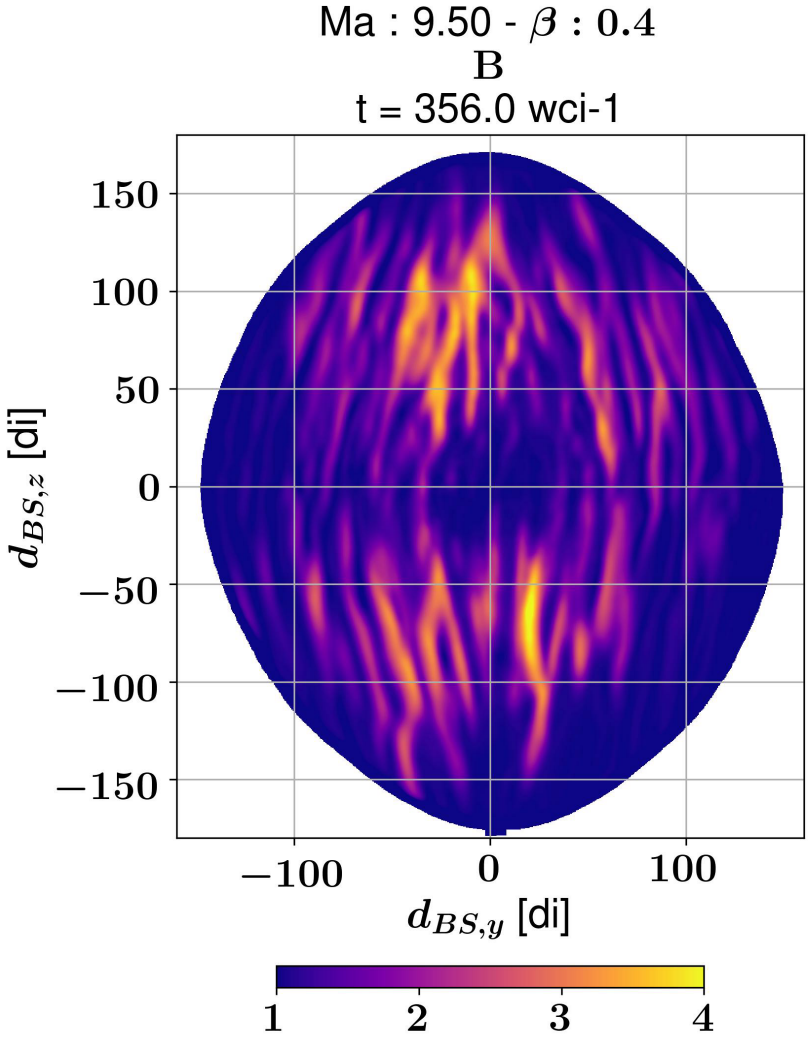


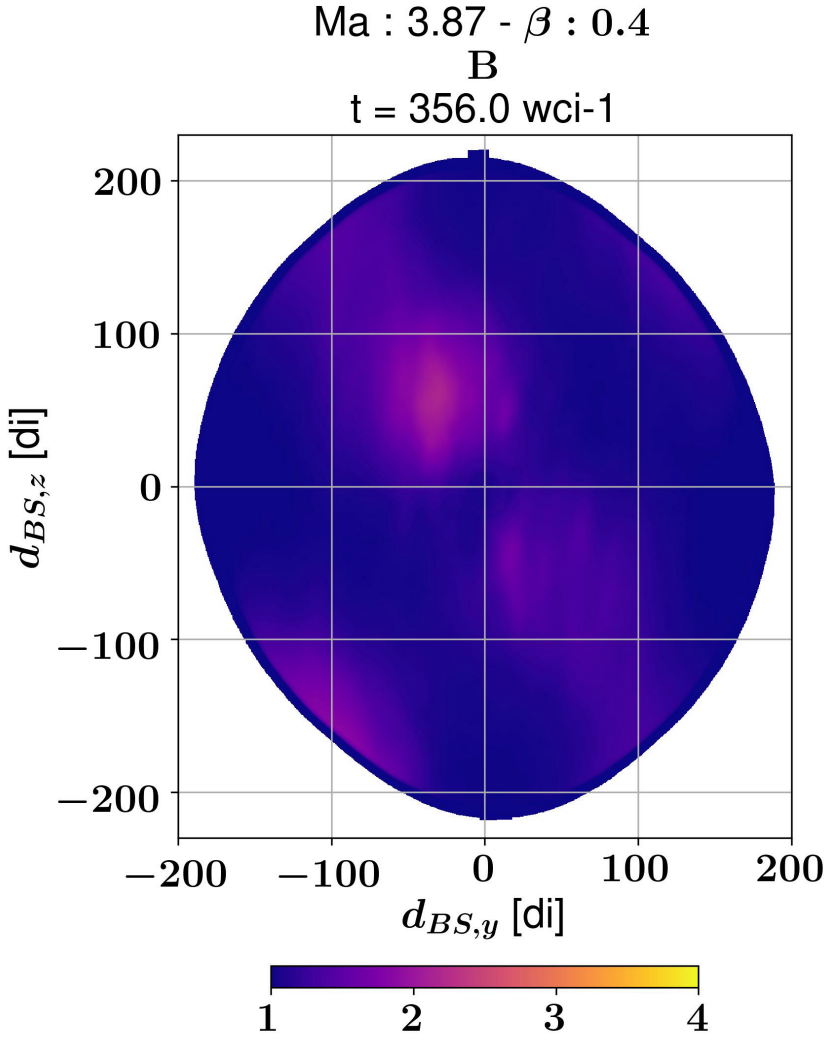

high $M_A$

# Characterizing the Ripples Properties

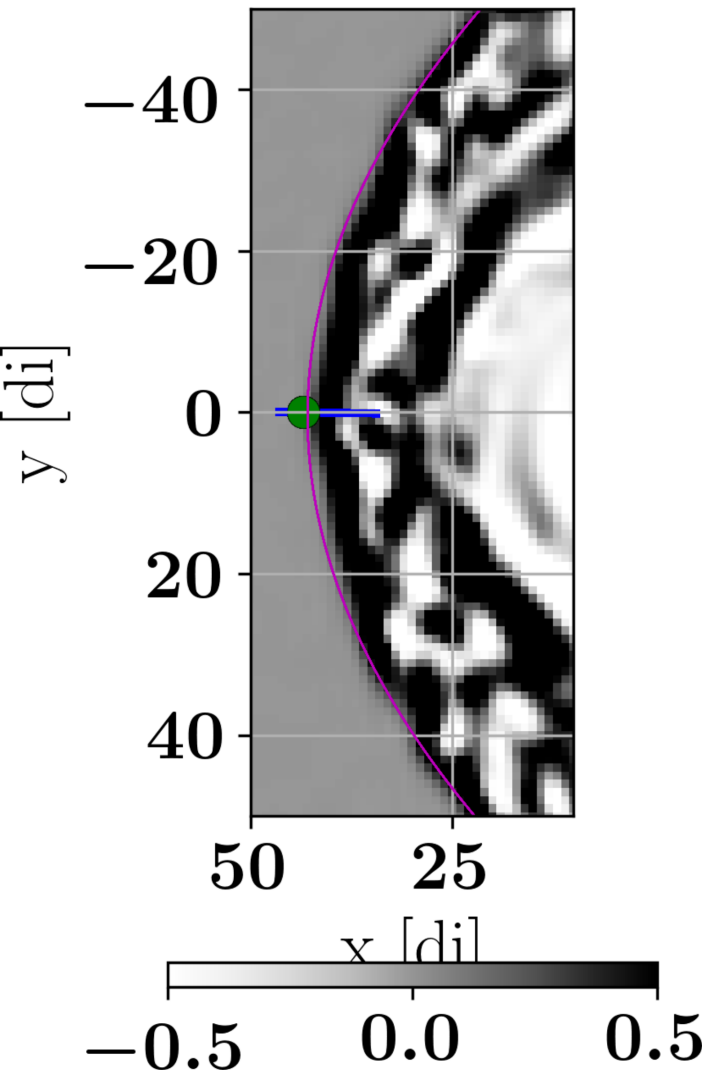
## What happens for a lower $M_A$ ?



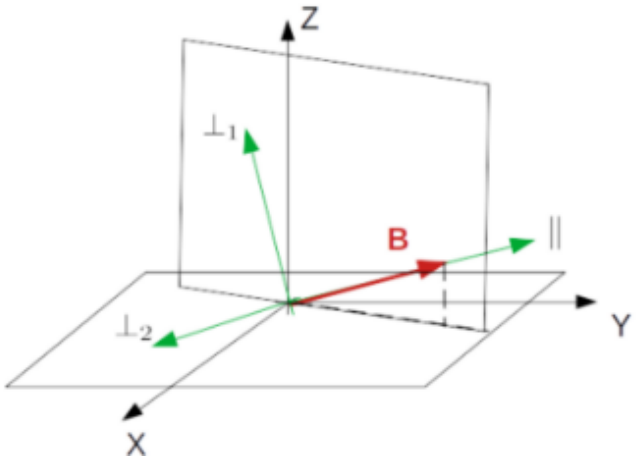



# Possible Kinetic Ripples Origins

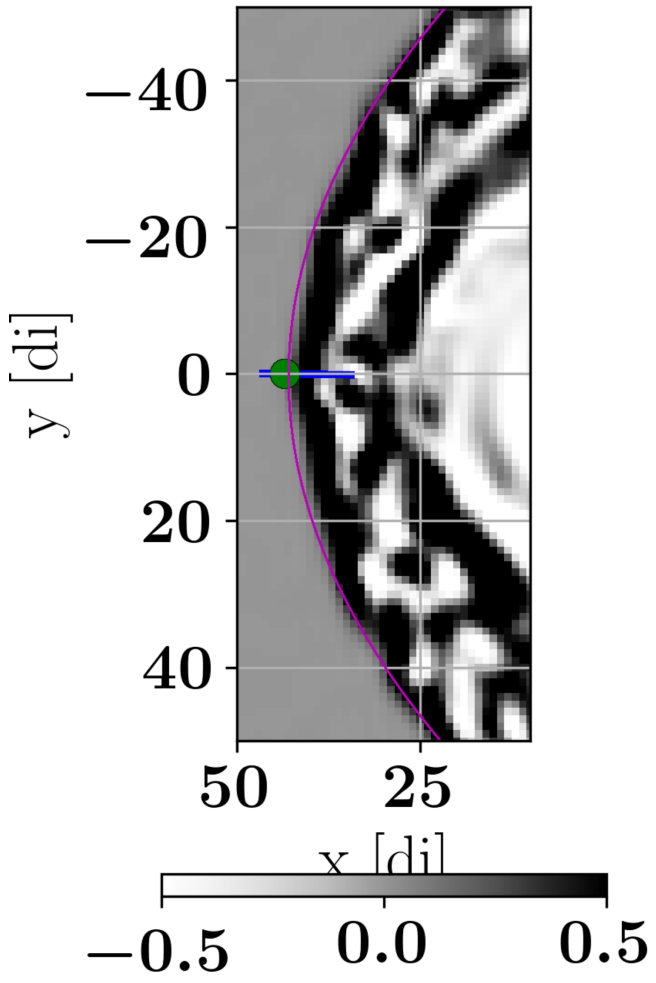


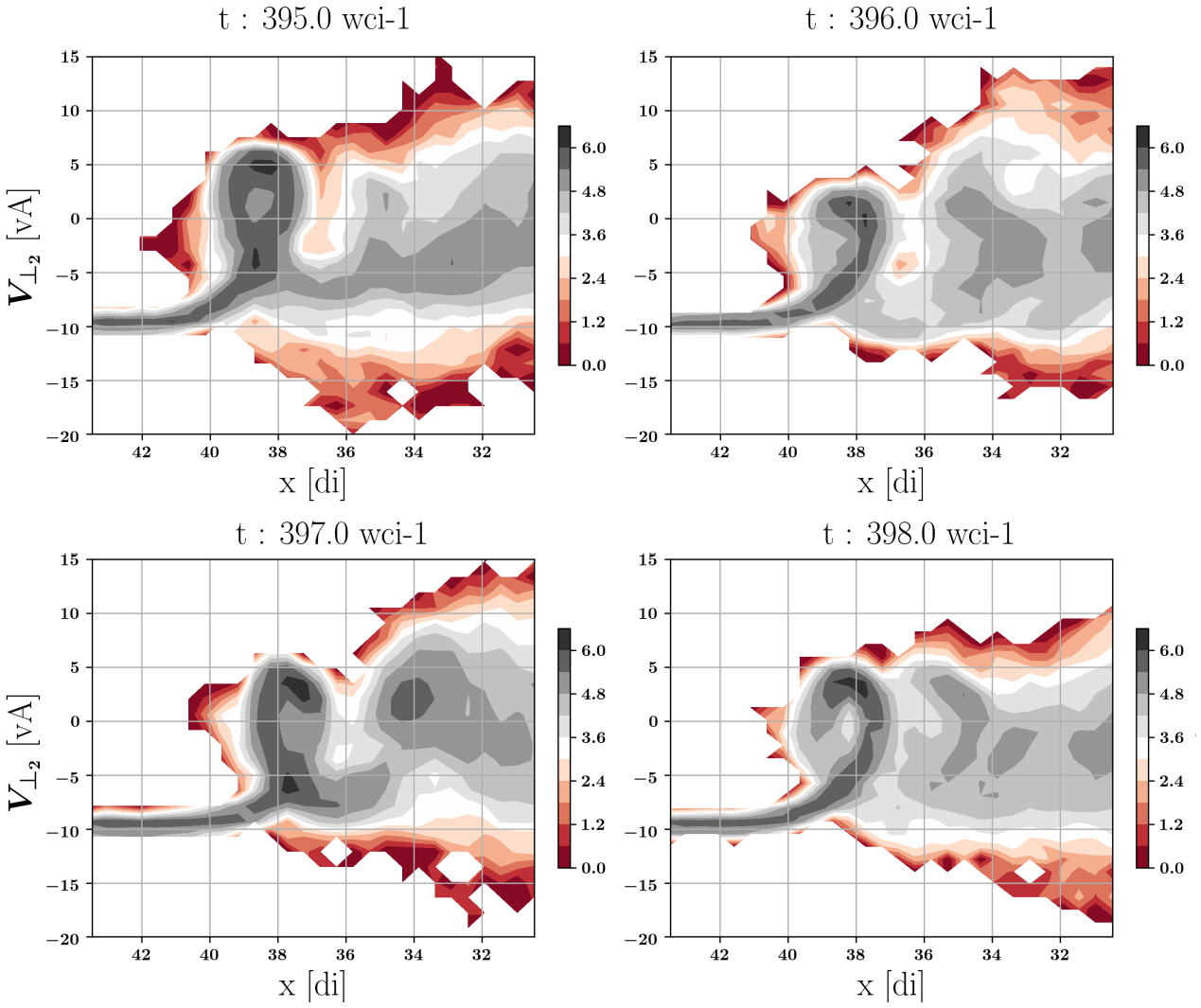

As the Bow-Shock nose is the first impact point and the ripples appear to be propagating from this region …

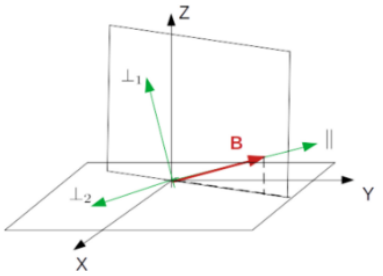
… let's check the ions velocity distribution in the local-B frame across this point !



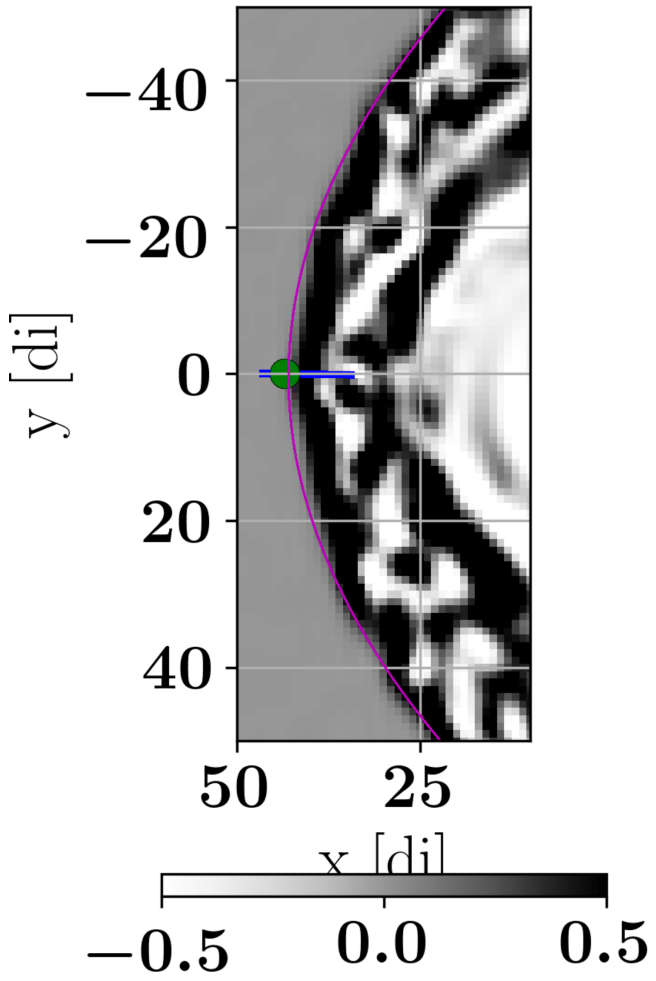
# Possible Kinetic Ripples Origins

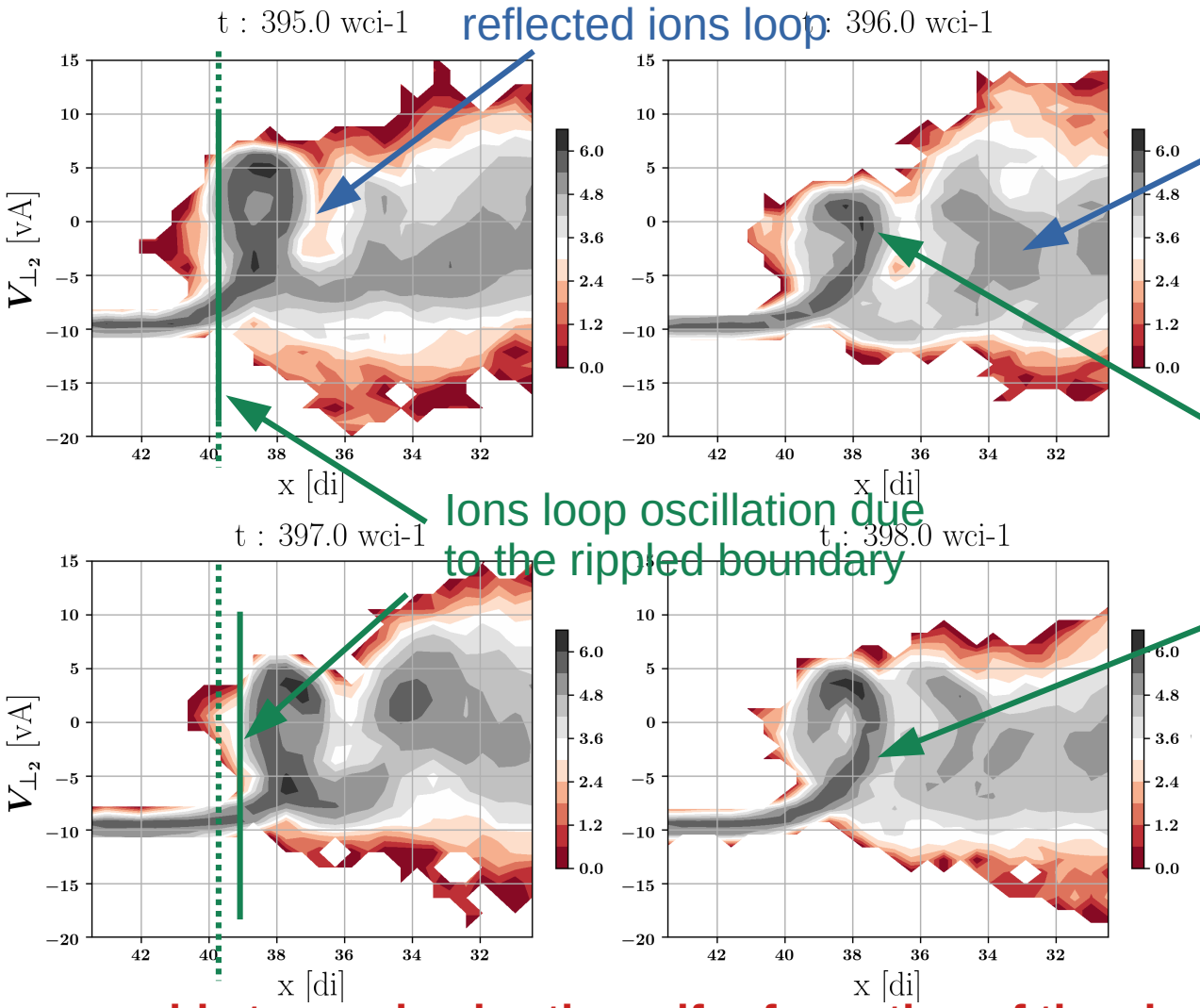


# Possible Kinetic Ripples Origins



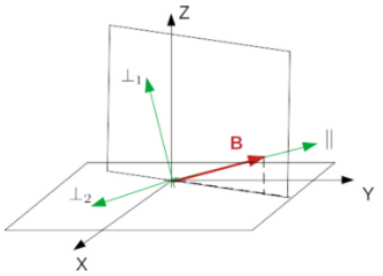




Typical shock-reflected ions loop

Heated Transmitted ions

Density gyro-variation as sign of shock-reformation

Ions loop oscillation due to the rippled boundary

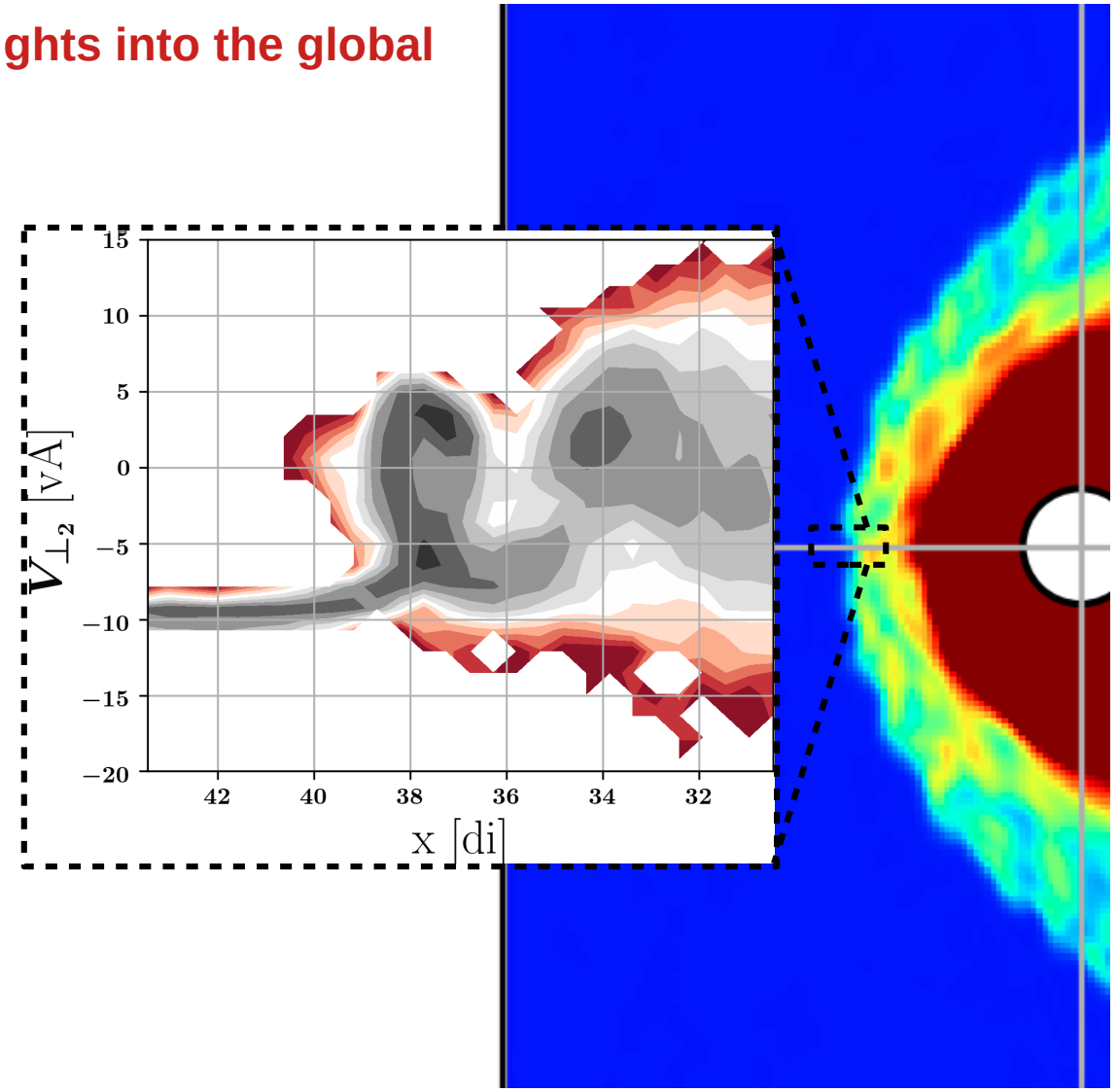



**With 3D hybrid simulations we are able to emphasize the self-reformation of the shock wave thru the ion phase space (as already observed by Hellinger & Travnicek 2002)**

# Summary

**We need realistic 3D hybrid simulations to gain better insights into the global ripples dynamics, finding that :**

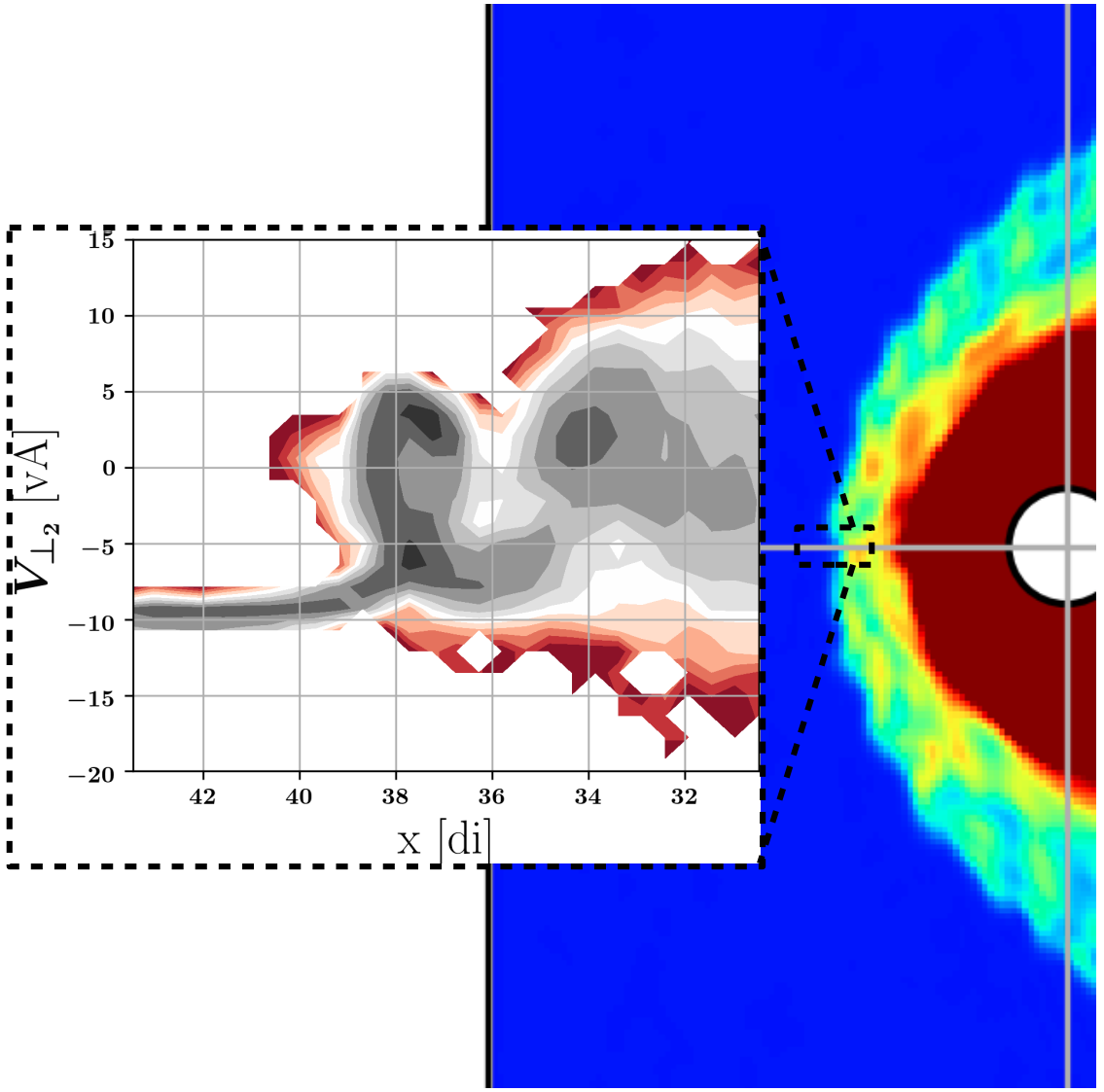
- Ripples are :
  - elongated structures extending perpendicular to the IMF orientation
  - propagate from the nose region outwards along the flanks with a constant – in space and time - speed along the IMF orientation
  - feature a broad band of wavelengths and periods ($\lambda \geq 950$ km, $T \geq 0.3$ s)
- Shock-front reformation occurring at the nose
  - causing a localized inward-outward Bow-Shock oscillation
  - Acting as a local perturbation that later propagates as a surface wave



# Outlook

## Remaining questions to address :

- Based on what mechanism do ripples propagate ?
- We have also noticed that ripples propagate ~ 15-18 % faster than the local Solar Wind tangential velocity … What can explain such discrepancy ?
- What are other possible kinetic mechanisms to explain their origins and their behavior ?



# Thank you ... Questions ?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