

# PRESENTATION FOR THE UNIPI SEMINAR 2=>3

ROBERTO MANUZZO, PHD STUDENT

“MAGNETOPAUSE STUDY WITH A MULTI-FLUID NUMERICAL CODE SIMULATION”





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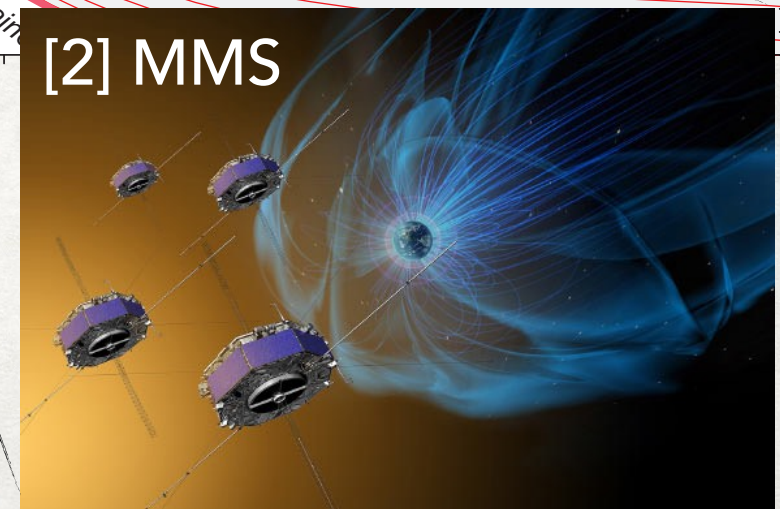
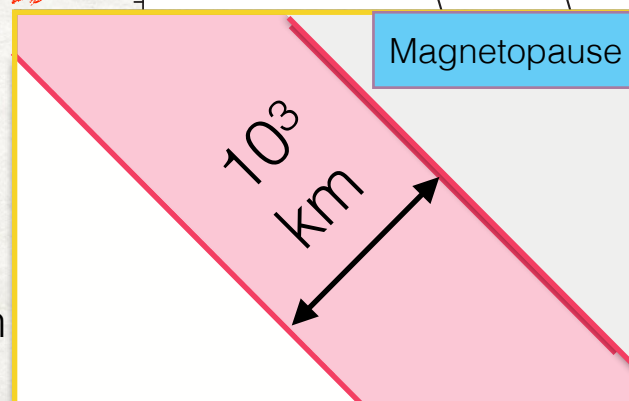
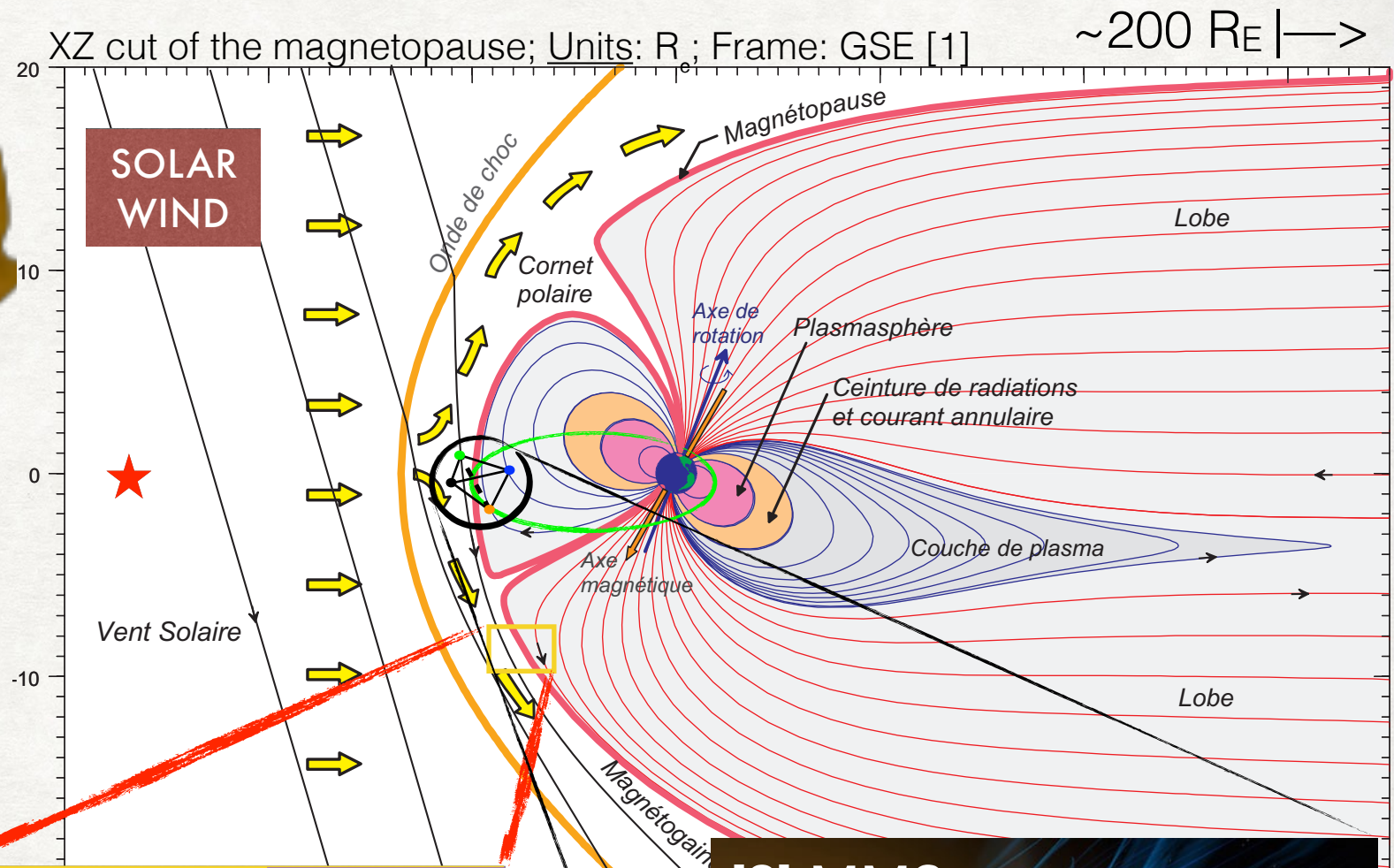
## SUMMARY

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- The plan
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- Formations

“**MAGNETOPAUSE STUDY** WITH A MULTI-FLUID NUMERICAL CODE SIMULATION”



Sun not in scale





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## "MAGNETOPAUSE STUDY WITH A MULTI-FLUID NUMERICAL CODE SIMULATION"

why? => study the energy exchanges in SW-MSph interaction

Requirements:

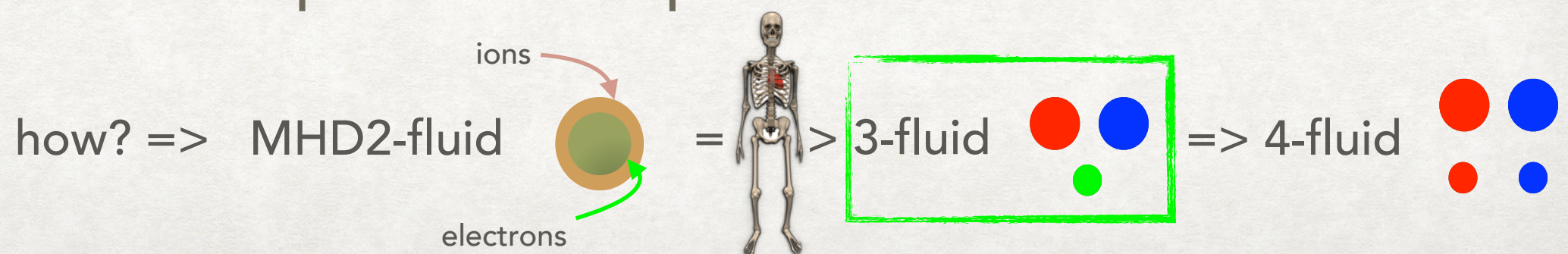
no polytropic closures

large scale structures interaction

Allows to different temperature plasma mixing

Suitable to large scale systems studies

			no polytropic closures	large scale structures interaction
Existing codes	Mono T, MHD		✗	✓
	Hybrid-Kinetic-Vlasov		✓	✗
Multi Fluid	High T, MHD Low T, MHD		✓	✓





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R. Denton



L. Rezeau



G. Belmont



F. Califano



## time line

Begin Nov2016





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- ◆ mixing of different plasmas at same place and time
  - data location along the s/c path and so across the MP structure
  - determination of a coordinate along the depth of the MP
  - determination of the MP orientation
- plasma decomposition into its temperature-labeled components
- ◆ initialisation methods for simulations

### 2. Simulations side:

- ◆ 3-Fluids code
- ◆ 4-Fluid code

### 3. Merging data analysis and simulations



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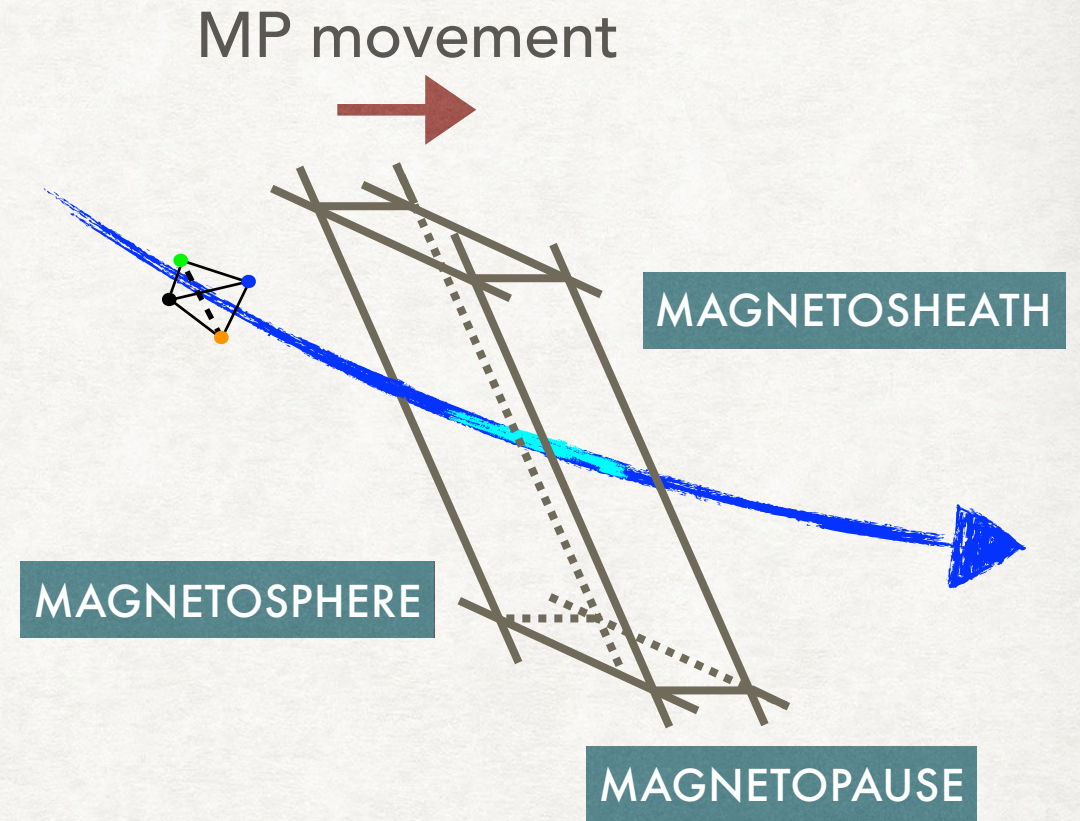
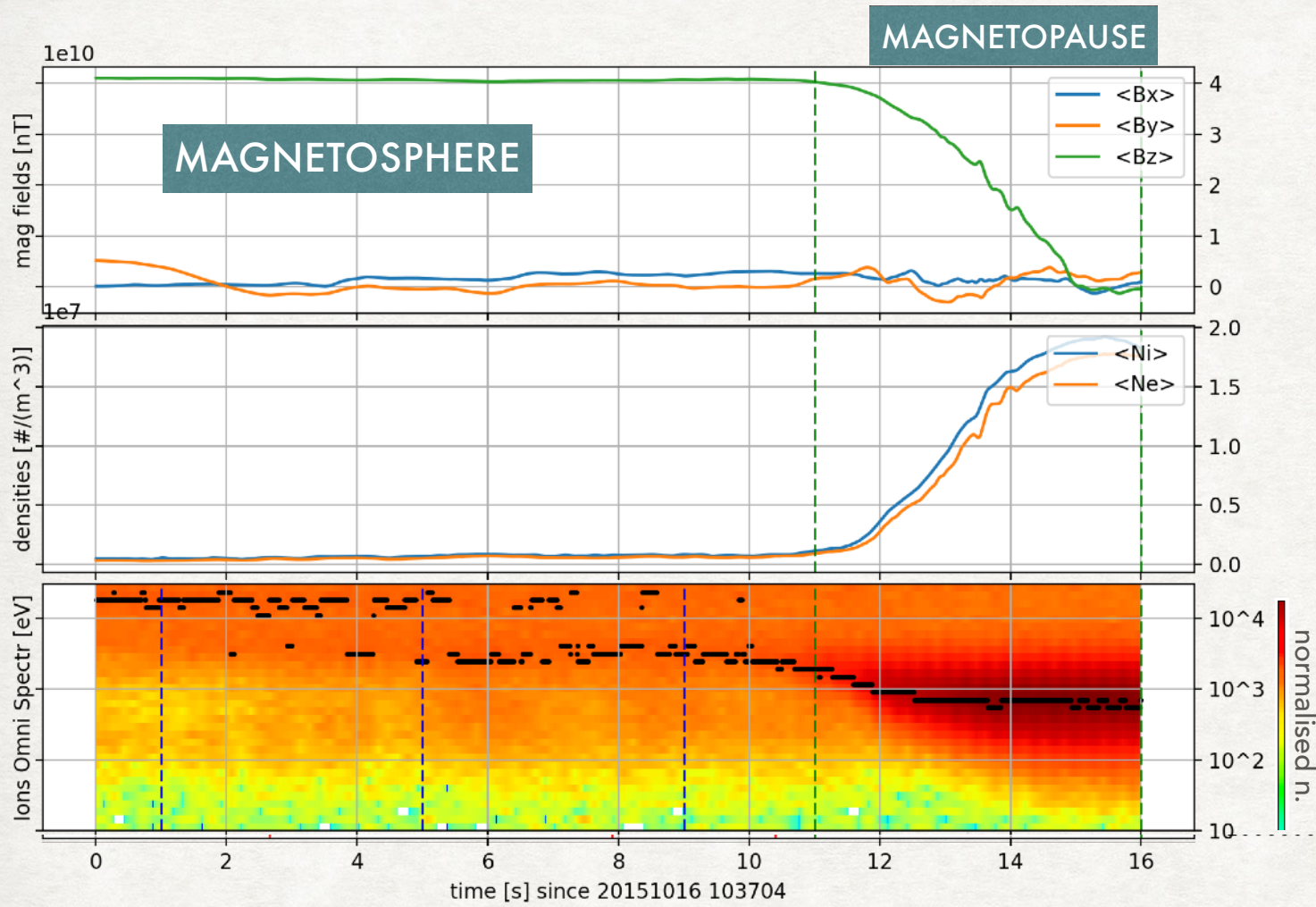
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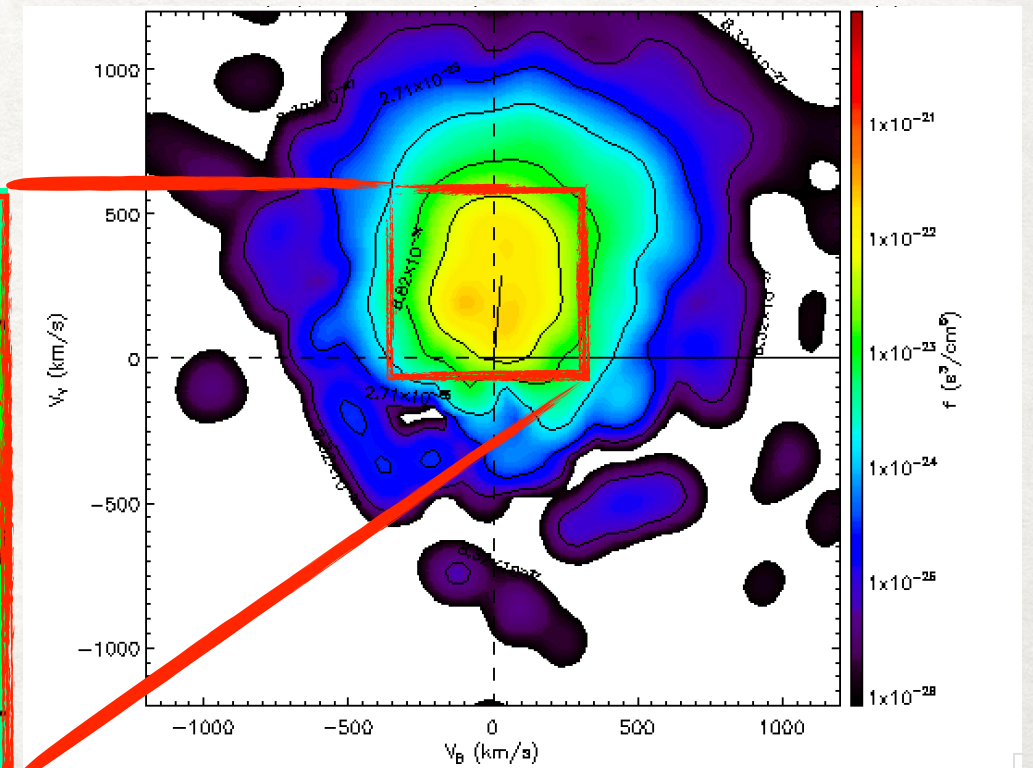
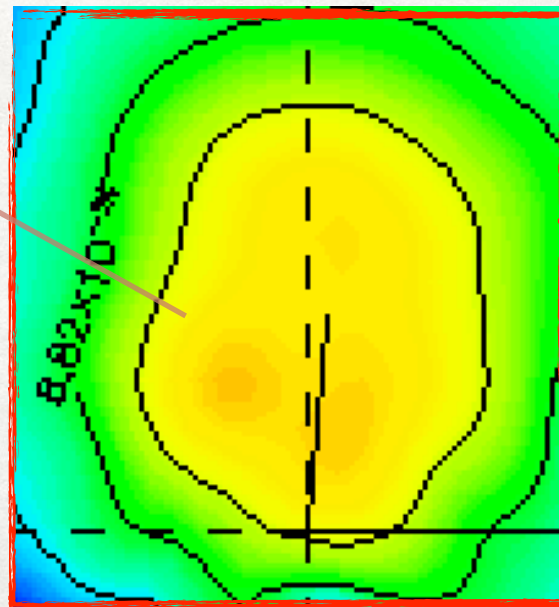
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# MIXING OF DIFFERENT PLASMAS AT SAME PLACE AND TIME



mixing!





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# DETERMINATION OF A COORDINATE ALONG THE DEPTH OF THE MP

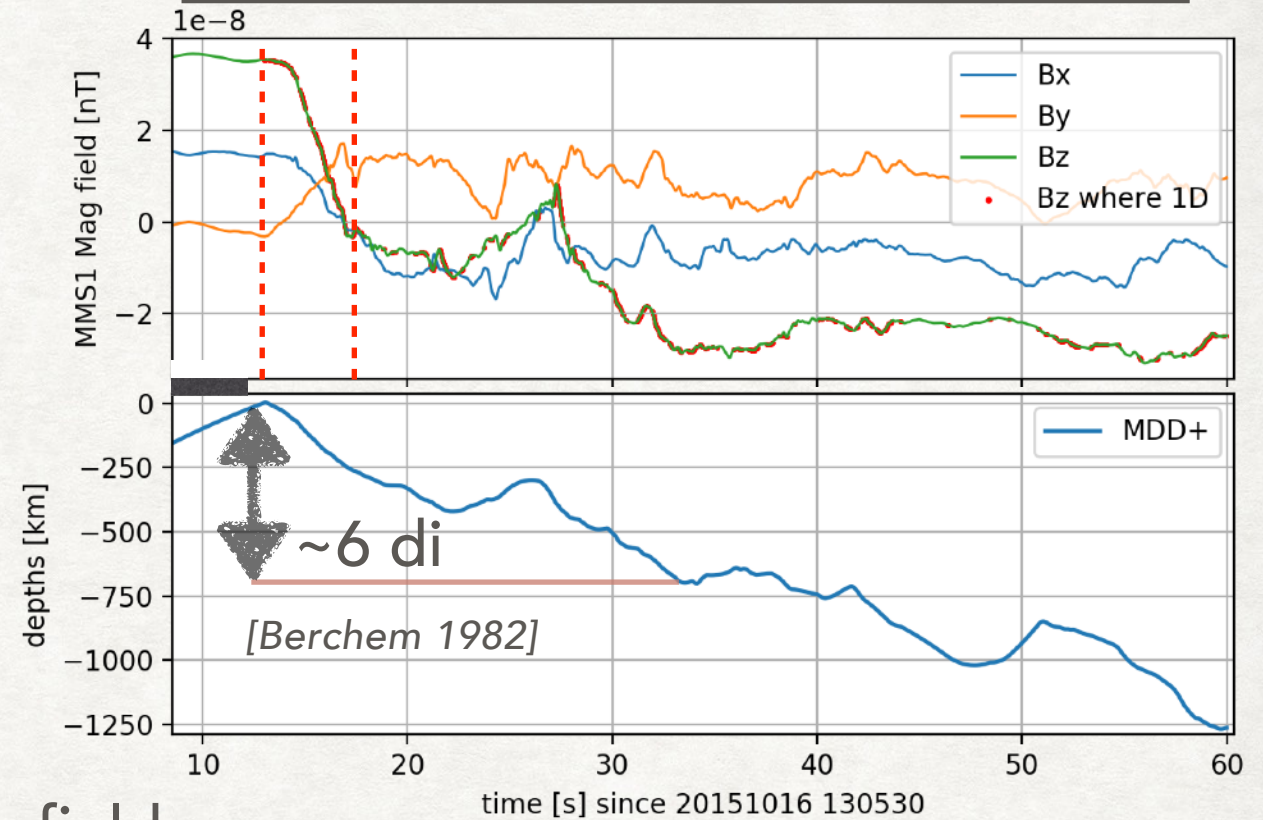
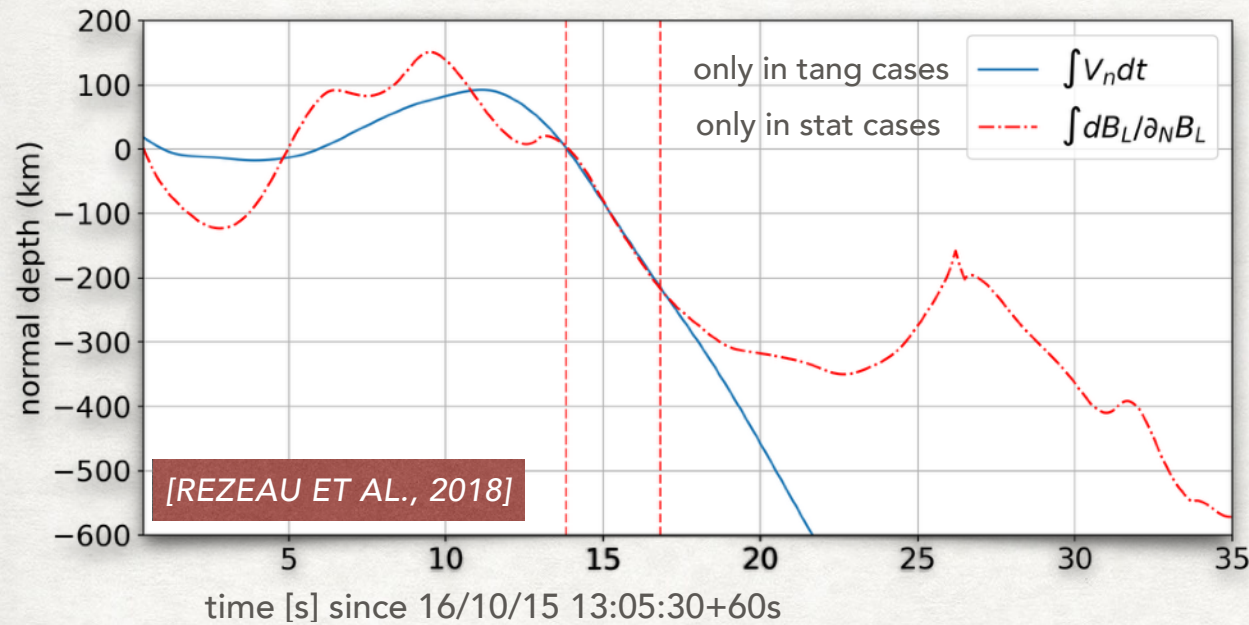
[Shi et al., 2006]

$$d_t \bar{B} = \partial_t \bar{X} \cdot \nabla \bar{B}$$

=>

[Manuzzo et al., in preparation]

$$d_t \bar{B} = \partial_t \bar{X} \cdot \nabla \bar{B} + \partial_t \bar{B}$$

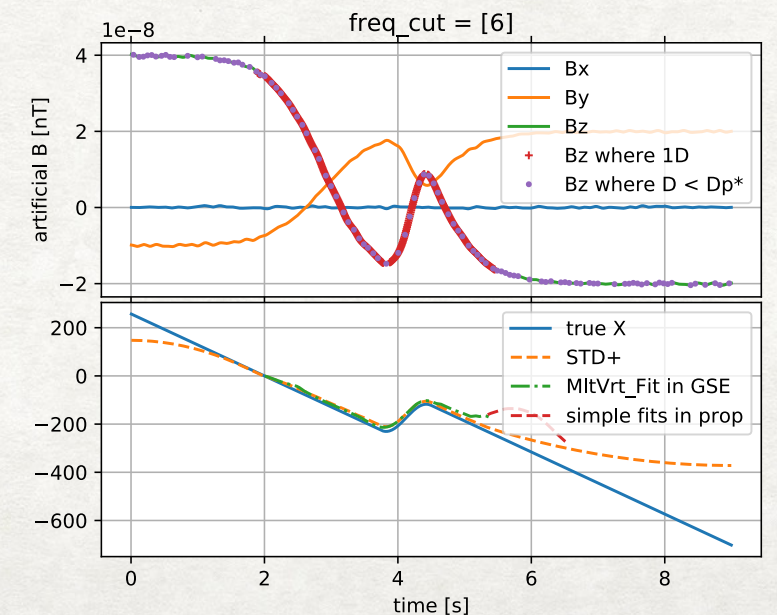
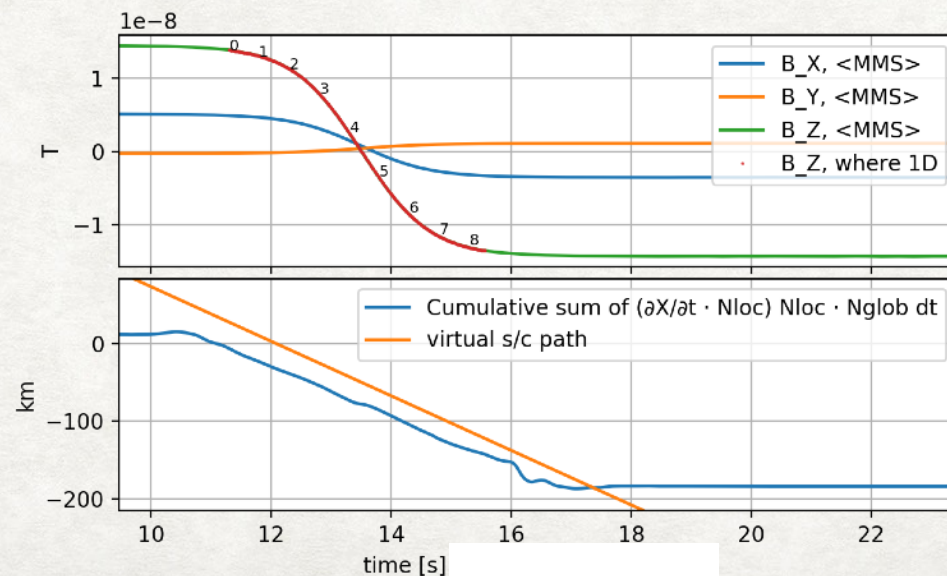


## Tests on artificial magnetic fields:

G. Kremer 1512-1594

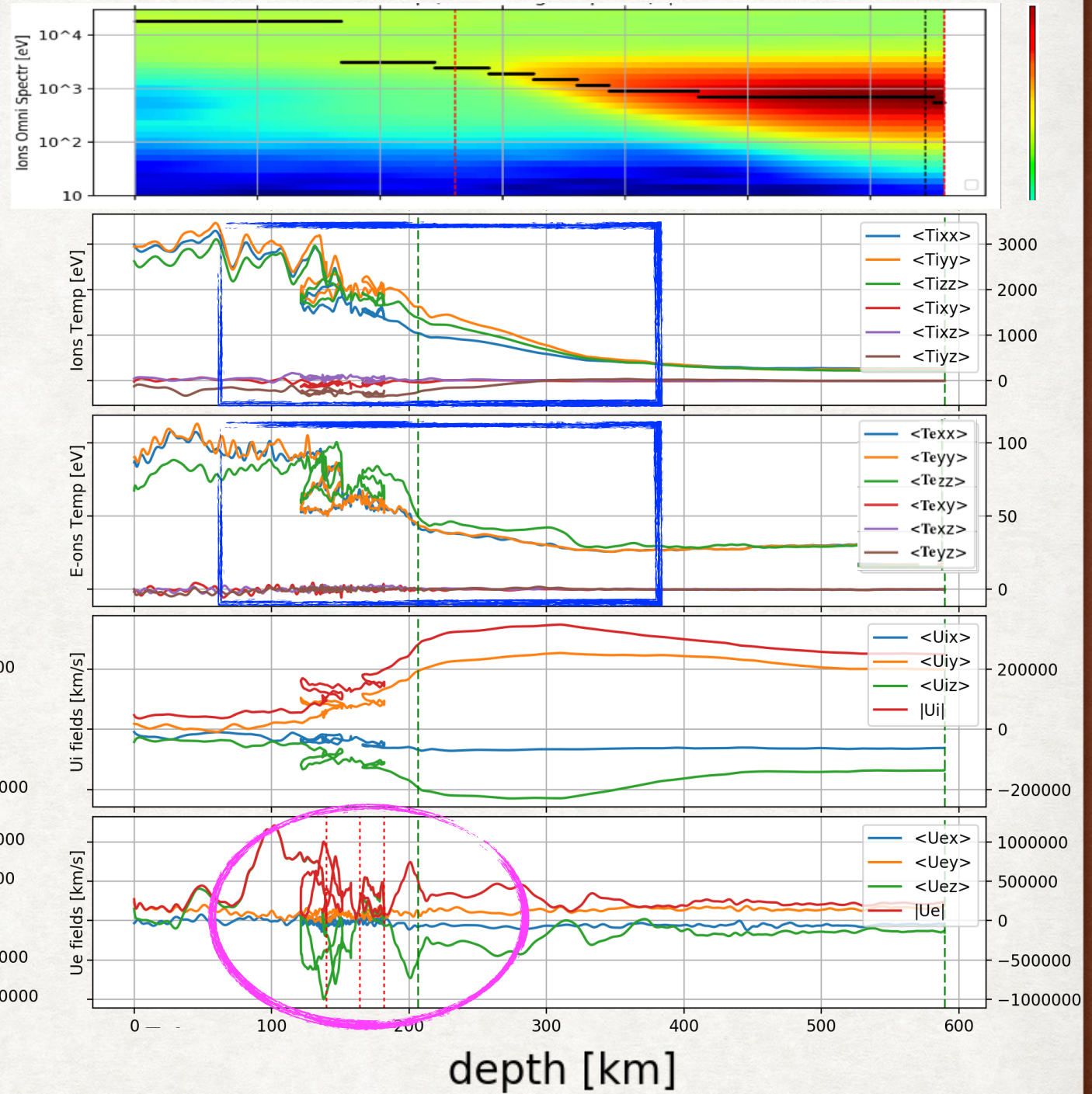
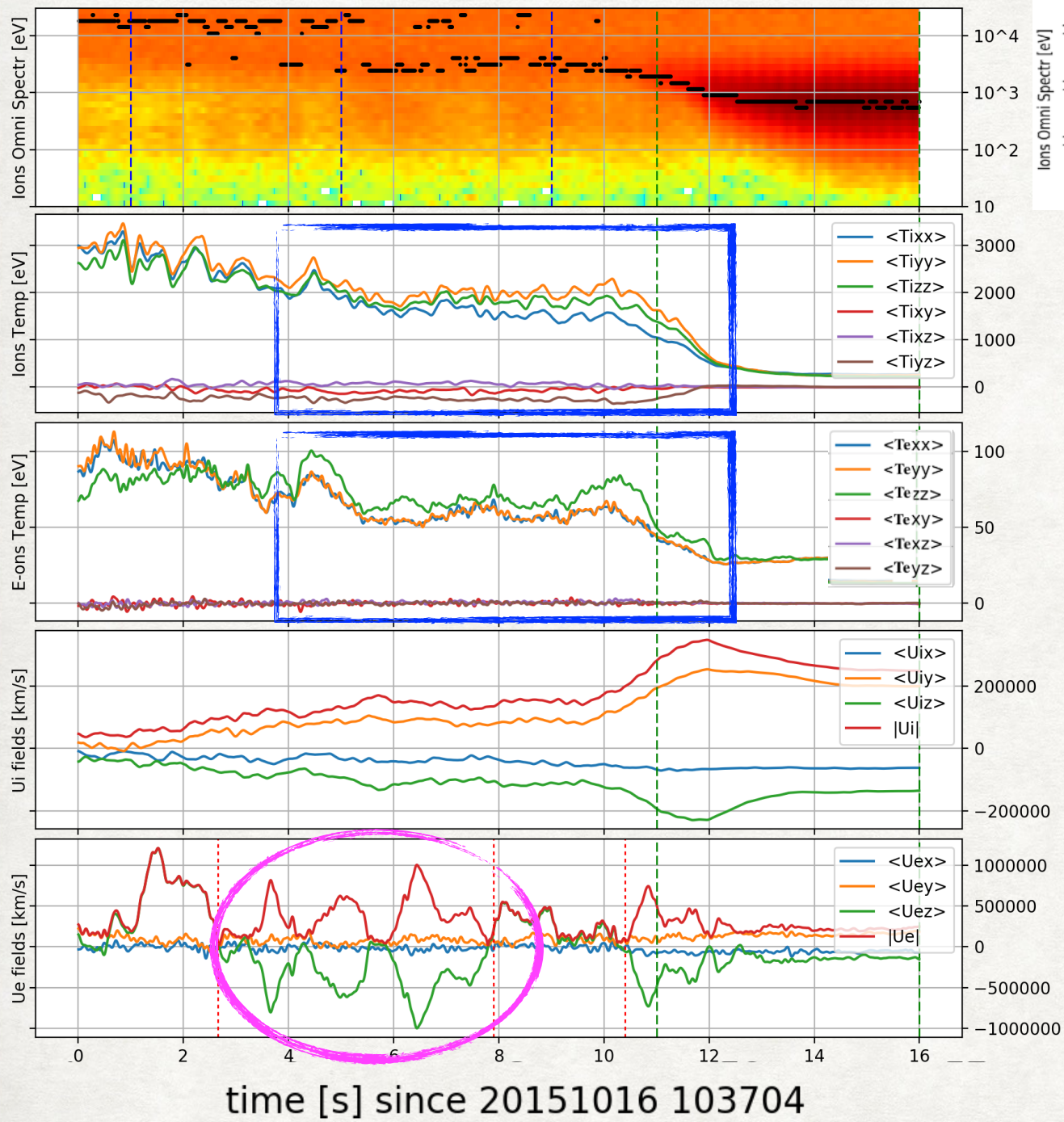


Wikipedia





# DATA VISUALISATION AS A FUNCTION OF SPACE





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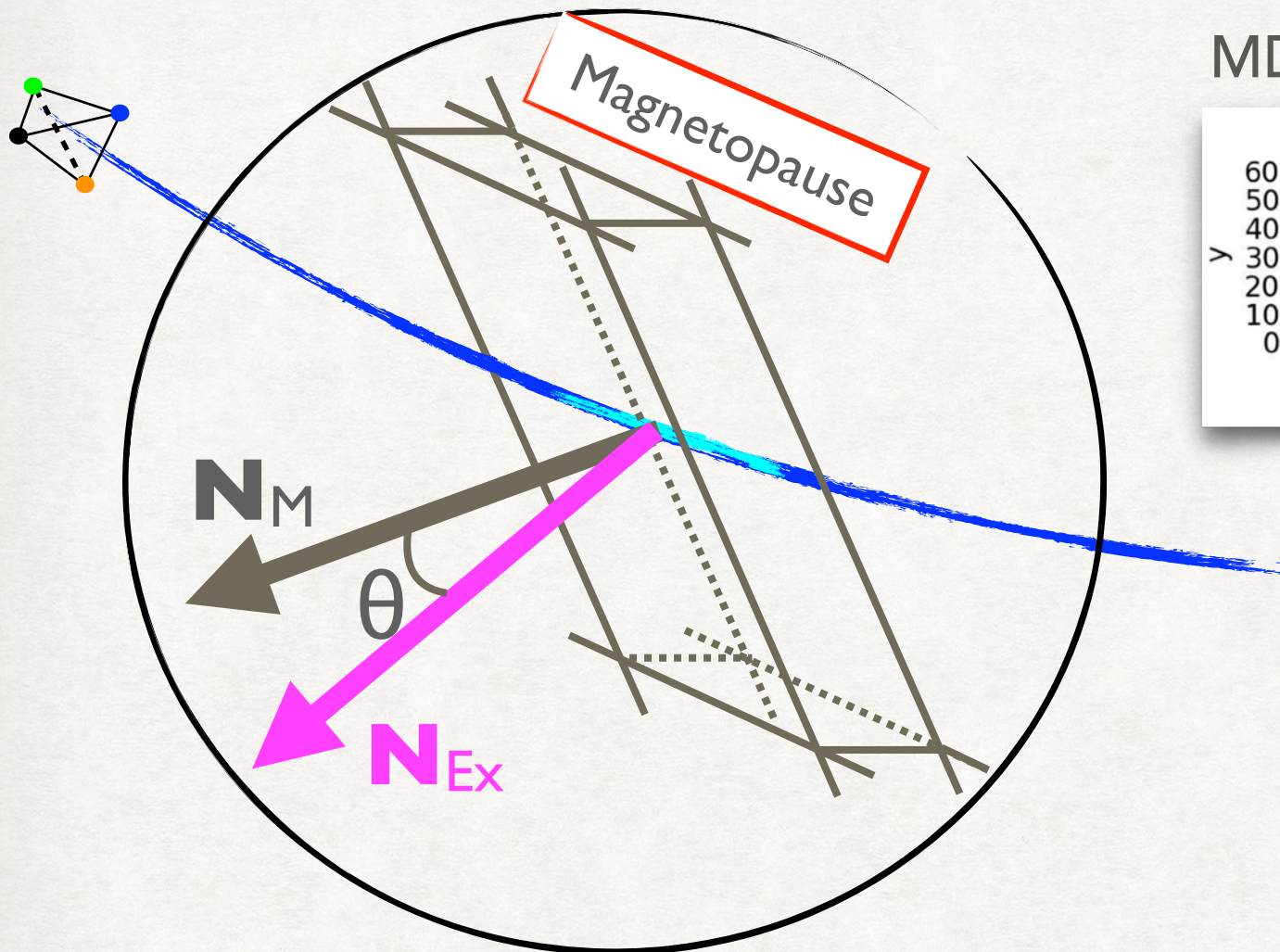
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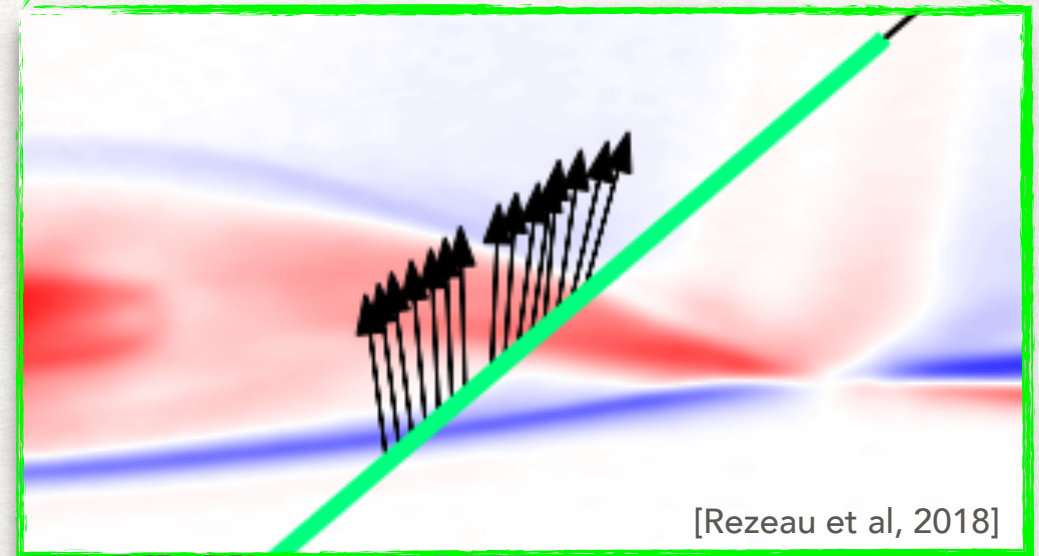
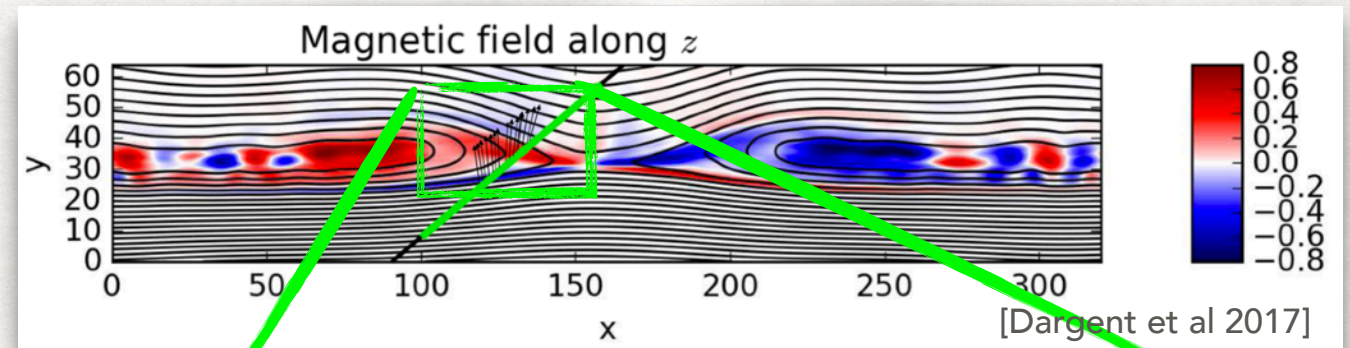
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# DETERMINATION OF THE MAGNETOPAUSE ORIENTATION



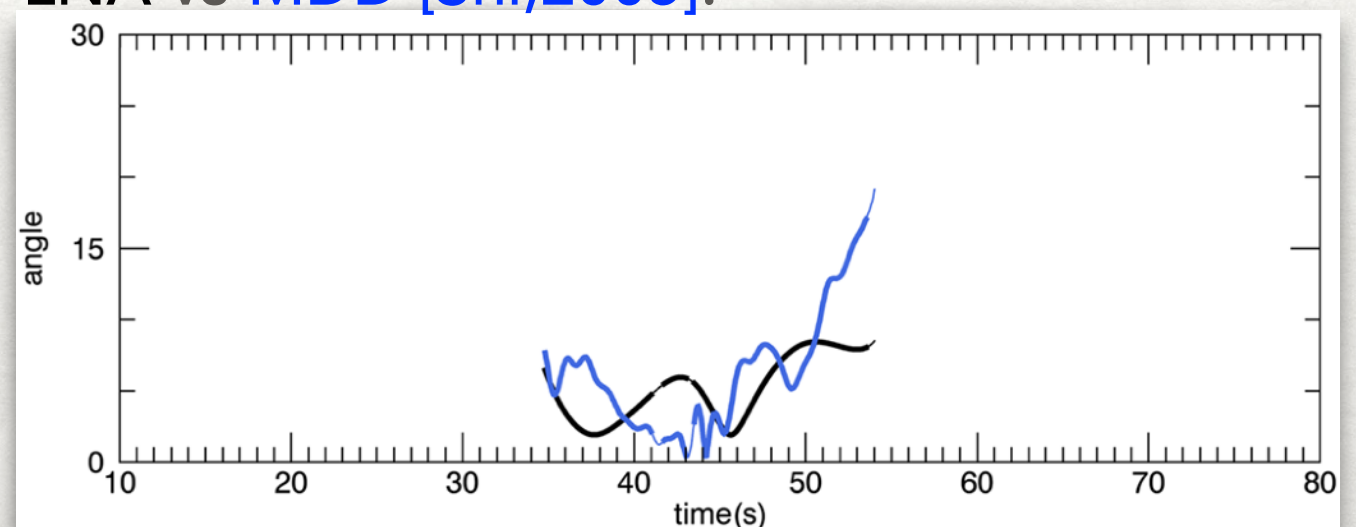
MDD:



Analysis methods	global	local
single	MVA	LNA
multi	CVA	MDD

Rezeau et al., 2018

LNA vs MDD [Shi,2005]:





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### ◆ initialisation methods for simulations

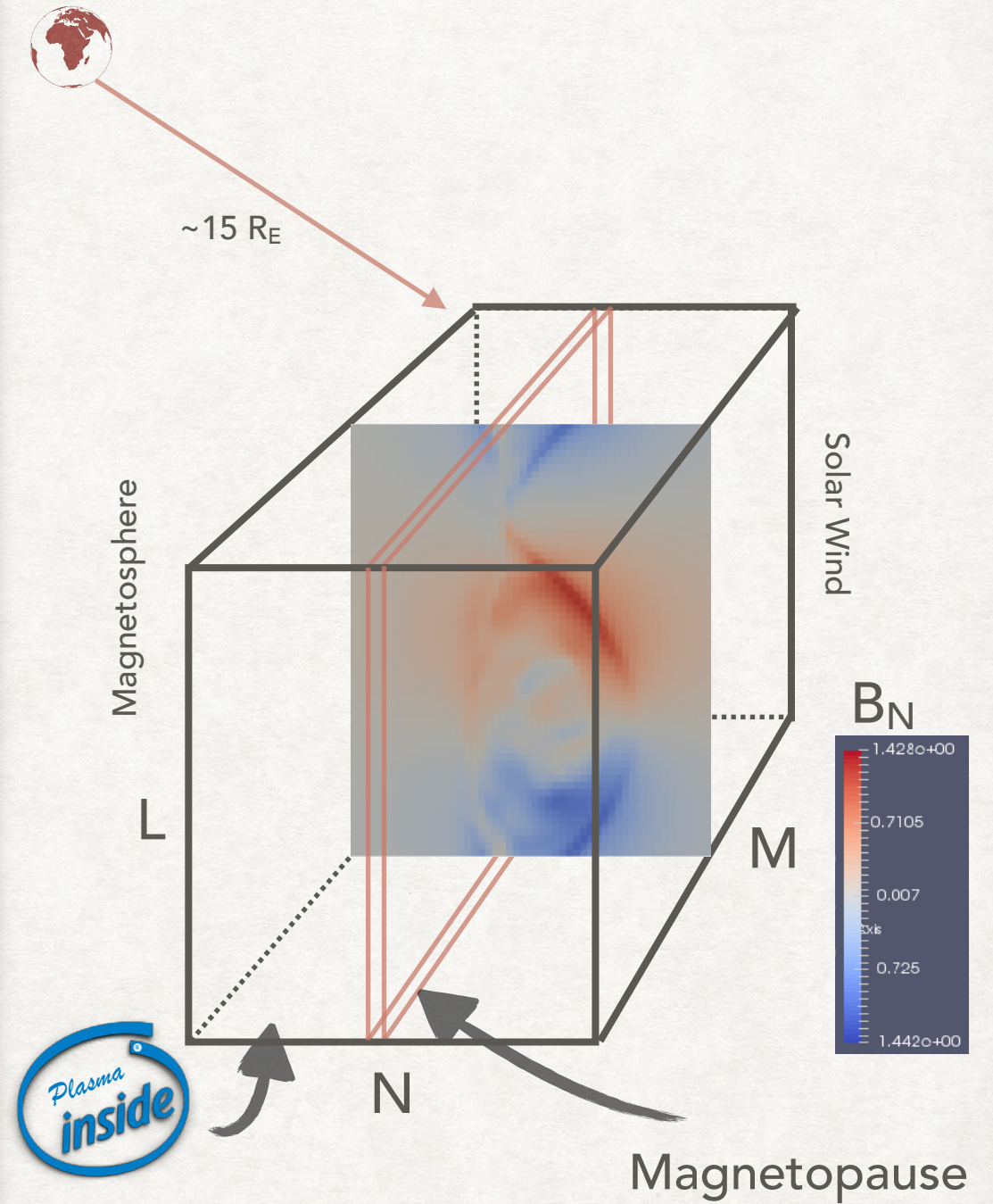
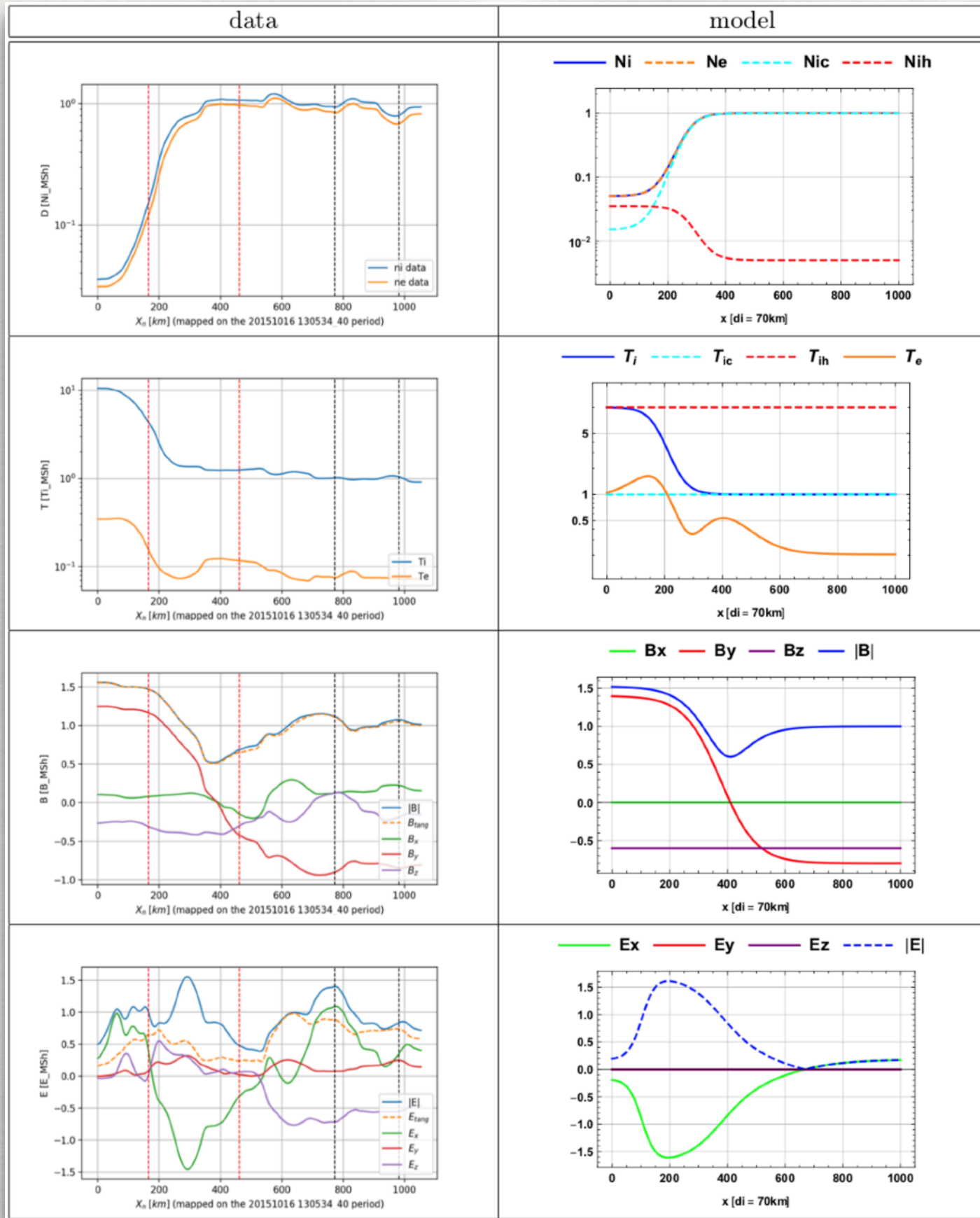
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# INITIALISATION METHODS FOR SIMULATIONS: A 3FLUID APPROACH





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# THE 3-FLUID CODE

## THE ALGORITHM

1. Transport of the density of ions and electrons entropies ( $nS \equiv Pn^{1-\gamma}$ ),  $\alpha = \{ic, ih, e\}$ :

$$\frac{\partial (n_\alpha S_\alpha)}{\partial t} + \bar{\nabla} \cdot [\mathbf{U}_\alpha (n_\alpha S_\alpha)] = 0 \quad (1)$$

2. Ions densities,  $\alpha = \{ic, ih\}$ :

$$\frac{\partial n_\alpha}{\partial t} + \bar{\nabla} \cdot (n_\alpha \mathbf{U}_\alpha) = 0 \quad (2)$$

3. Electron density from updated ions densities<sup>1</sup>,  $\alpha = \{ic, ih\}$ :

$$n_e^* = \sum_\alpha n_\alpha^* \quad (3)$$

4. Ions momenta,  $\alpha = \{ic, ih\}$ :

$$\frac{\partial (n_\alpha \mathbf{U}_\alpha)}{\partial t} + \frac{1}{m_\alpha} \bar{\nabla} P_\alpha + \bar{\nabla} \cdot (n_\alpha \mathbf{U}_\alpha \mathbf{U}_\alpha) - \frac{q_\alpha n_\alpha}{m_\alpha} (\mathbf{E} + \mathbf{U}_\alpha \times \mathbf{B}) = 0 \quad (4)$$

5. Ions and electrons pressures,  $\alpha = \{ic, ih, e\}$ :

$$P_\alpha^* = [n_\alpha S_\alpha]^* (n_\alpha^*)^{\gamma-1} \quad (5)$$

6. Ions velocities,  $\alpha = \{ic, ih\}$ :

$$\mathbf{U}_\alpha^* = (n_\alpha \mathbf{U}_\alpha)^* / n_\alpha^* \quad (6)$$

7. Magnetic field

$$\frac{\partial \mathbf{B}}{\partial t} + \bar{\nabla} \times \mathbf{E} = 0 \quad (7)$$

8. Electronic velocities,  $\alpha = \{ic, ih\}$ :

$$\mathbf{U}_e^* = \left[ \sum_\alpha (n_\alpha^* \mathbf{U}_\alpha^*) + \frac{1}{q_e \mu_0} \bar{\nabla} \times \mathbf{B}^* \right] / n_e^* \quad (8)$$

9. Electric field

$$\mathbf{E}^* = -\mathbf{U}_e^* \times \mathbf{B}^* + \frac{1}{q_e n_e^*} \bar{\nabla} P_e^* + \frac{\eta}{\mu_0} \bar{\nabla} \times \mathbf{B}^* \quad (9)$$

## THE VALIDATION TESTS

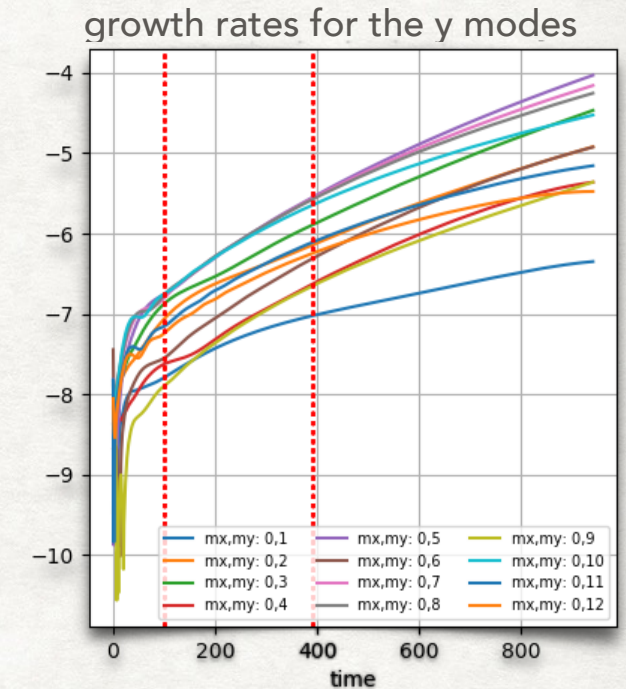
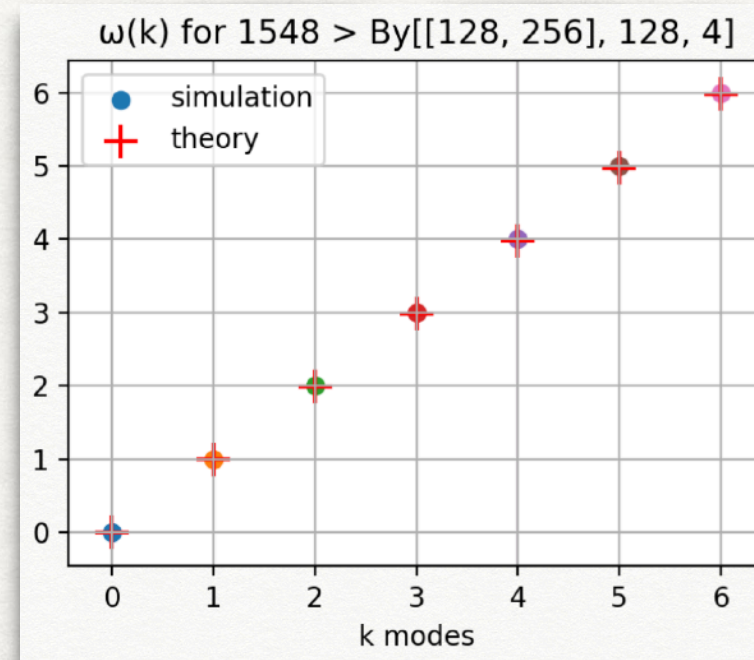
-) TIME INDEPENDENCE OF EQUILIBRIUM STATES 🍷

-) MONOCHROMATIC WAVE PROPAGATIONS:

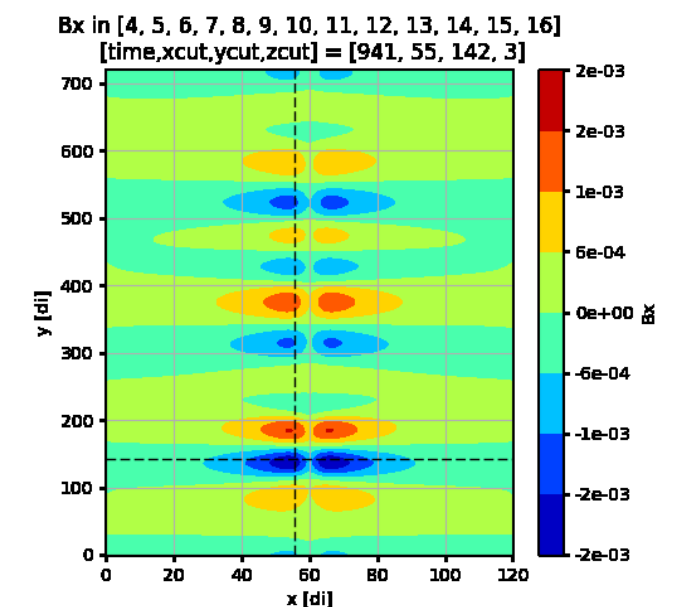
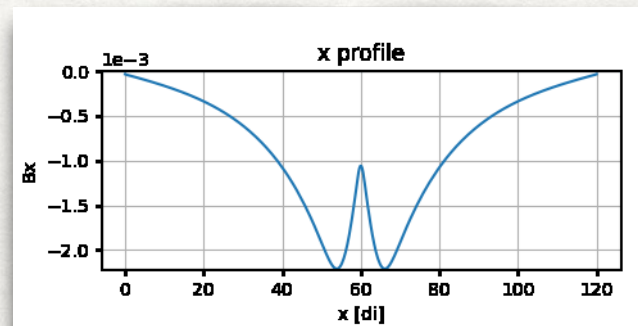
-) THE ALFVÉN WAVES 🍷

-) THE MAGNETO-SONIC WAVES 🍷

-) THE TEARING MODE INSTABILITY [FURTH ET AL., 1963] 🍷



## THE RESULTS =>





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# THE 4-FLUID CODE

... some algorithms are under study:

0. Electric field

$$\mathbf{E} = -\frac{(n_{e,h}\mathbf{U}_{e,h} + n_{e,c}\mathbf{U}_{e,c})}{n_{e,h} + n_{e,c}} \times \mathbf{B} - \frac{1}{e(n_{e,h} + n_{e,c})} \nabla \cdot (P_{e,h} + P_{e,c}) \bar{\mathbf{I}} \quad (1)$$

1. Ions densities

$$\frac{\partial n_{i,\alpha}}{\partial t} + \nabla \cdot (n_{i,\alpha} \mathbf{U}_{i,\alpha}) = 0 \quad (2)$$

2. Ions Momenta

$$\frac{\partial (n_{i,\alpha} \mathbf{U}_{i,\alpha})}{\partial t} + \nabla \cdot \left( \frac{1}{m_i} P_{i,\alpha} \mathbf{I} + n_{i,\alpha} \mathbf{U}_{i,\alpha} \mathbf{U}_{i,\alpha} \right) - \frac{en_{i,\alpha}}{m_i} (\mathbf{E} + \mathbf{U}_{i,\alpha} \times \mathbf{B}) = 0 \quad (3)$$

3. Ions pressures (through the conservation of  $S_{i,\alpha} \equiv P_{i,\alpha} n_{i,\alpha}^{1-\gamma}$ )

$$\begin{cases} 4.1 : \text{compute} & \frac{\partial S_{i,\alpha}}{\partial t} + \mathbf{U}_{i,\alpha} \cdot \nabla S_{i,\alpha} = 0 \\ 4.2 : \text{finding} & S_{i,\alpha}^* \\ 4.3 : \text{obtain} & P_{i,\alpha}^* = S_{i,\alpha}^* (n_{i,\alpha}^*)^{\gamma-1} \end{cases} \quad (4)$$

4. Magnetic field

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0 \quad (5)$$

5. Electrons densities

$$\begin{cases} 6.1 : \text{define} & n_{e,+}^* = n_{i,h}^* + n_{i,c}^* \\ 6.2 : \text{define} & n_{e,-}^* = n_{e,h} - n_{e,c} \\ 6.3 : \text{compute} & \frac{\partial n_{e,-}^*}{\partial t} + \nabla \cdot (n_{e,h} \mathbf{U}_{e,h} - n_{e,c} \mathbf{U}_{e,c}) = 0 \\ 6.4 : \text{finding} & n_{e,-}^* = n_{e,h}^* - n_{e,c}^* \\ 6.5 : \text{obtain} & n_{e,h}^* = \frac{n_{e,+}^* + n_{e,-}^*}{2} \\ 6.6 : \text{obtain} & n_{e,c}^* = \frac{n_{e,+}^* - n_{e,-}^*}{2} \end{cases} \quad (6)$$

6. Electron pressures (through the conservation of  $S_{e,\alpha} \equiv P_{e,\alpha} n_{e,\alpha}^{1-\gamma}$ )

$$\begin{cases} 7.1 : \text{compute} & \frac{\partial S_{e,\alpha}}{\partial t} + \mathbf{U}_{e,\alpha} \cdot \nabla S_{e,\alpha} = 0 \\ 7.2 : \text{finding} & S_{e,\alpha}^* \\ 7.3 : \text{obtain} & P_{e,\alpha}^* = S_{e,\alpha}^* (n_{e,\alpha}^*)^{\gamma-1} \end{cases} \quad (7)$$

7. Evolve  $\mathbf{E}$ :

$$\begin{cases} 8.1 : \text{with} & \mathbf{J} = e(n_{i,h} \mathbf{U}_{i,h} + n_{i,c} \mathbf{U}_{i,c} - n_{e,h} \mathbf{U}_{e,h} + n_{e,c} \mathbf{U}_{e,c}) \\ 8.1 : \text{compute} & \frac{\partial \mathbf{E}}{\partial t} - c^2 (\nabla \times \mathbf{B} - \mu_0 \mathbf{J}) = 0 \end{cases} \quad (8)$$

8. Electron moments

Problems arise here... how to find  $n_{e,h}^* \mathbf{U}_{e,h}^*$  and  $n_{e,c}^* \mathbf{U}_{e,c}^*$  ?

9. Go to point 1 and repeat the loop.

1) On avance les ions :

- continuités :  $n_{i1}^* = n_{i1} - \nabla \cdot (\boldsymbol{\varphi}_{i1}) \quad (1)$

$$n_{i2}^* = n_{i2} - \nabla \cdot (\boldsymbol{\varphi}_{i2}) \quad (2)$$

- momentums :  $m_i \boldsymbol{\varphi}_{i1}^* = m_i \boldsymbol{\varphi}_{i1} - \nabla \cdot \left( p_{i1} \mathbf{I} + m_i \frac{\boldsymbol{\varphi}_{i1} \boldsymbol{\varphi}_{i1}}{n_{i1}} \right) + q[n_{i1} \mathbf{E} + \boldsymbol{\varphi}_{i1} \times \mathbf{B}] \quad (3)$

$$m_i \boldsymbol{\varphi}_{i2}^* = m_i \boldsymbol{\varphi}_{i2} - \nabla \cdot \left( p_{i2} \mathbf{I} + m_i \frac{\boldsymbol{\varphi}_{i2} \boldsymbol{\varphi}_{i2}}{n_{i2}} \right) + q[n_{i2} \mathbf{E} + \boldsymbol{\varphi}_{i2} \times \mathbf{B}] \quad (4)$$

- fermetures :  $p_{i1}^* = K_{i1} (n_{i1}^*)^{\gamma_{i1}} \quad (5)$

$$p_{i2}^* = K_{i2} (n_{i2}^*)^{\gamma_{i2}} \quad (6)$$

2) On avance  $\mathbf{B}$  :

- Faraday :  $\mathbf{B}^* = \mathbf{B} - \nabla \times (\mathbf{E}) \quad (7)$

3) On avance les densités électroniques :

- différence des continuités :  $n_{e2}^* - n_{e1}^* = n_{e2} - n_{e1} - \nabla \cdot (\boldsymbol{\varphi}_{e2} - \boldsymbol{\varphi}_{e1}) \quad (8)$

- quasi-neutralité :  $n_{e2}^* + n_{e1}^* = n_{i2}^* + n_{i1}^* \quad (9)$

On en déduit  $n_{e1}^*$  et  $n_{e2}^*$  séparément.

- fermetures :  $p_{e1}^* = K_{e1} (n_{e1}^*)^{\gamma_{e1}} \quad (10)$

$$p_{e2}^* = K_{e2} (n_{e2}^*)^{\gamma_{e2}} \quad (11)$$

4) On avance les  $\boldsymbol{\varphi}$  électroniques et  $\mathbf{E}$  :

- Ampère (au temps  $t+1$ ) :

$$\boldsymbol{\varphi}_{e2}^* + \boldsymbol{\varphi}_{e1}^* = \boldsymbol{\varphi}_{i2}^* + \boldsymbol{\varphi}_{i1}^* - \frac{1}{q} \nabla \times \mathbf{B}^* / \mu_0 \quad (12)$$

- différence des momentums :

$$m_e (\boldsymbol{\varphi}_{e2}^* - \boldsymbol{\varphi}_{e1}^*) = m_e (\boldsymbol{\varphi}_{e2} - \boldsymbol{\varphi}_{e1}) - \nabla \cdot \left[ (p_{e2} - p_{e1}) \mathbf{I} + m_e \left( \frac{\boldsymbol{\varphi}_{e2} \boldsymbol{\varphi}_{e2}}{n_{e2}} - \frac{\boldsymbol{\varphi}_{e1} \boldsymbol{\varphi}_{e1}}{n_{e1}} \right) \right] - q[(n_{e2} - n_{e1}) \mathbf{E} + (\boldsymbol{\varphi}_{e2} - \boldsymbol{\varphi}_{e1}) \times \mathbf{B}] \quad (13)$$

De (12) et (13), on déduit  $\boldsymbol{\varphi}_{e2}^*$  et  $\boldsymbol{\varphi}_{e1}^*$  séparément

- somme des momentums (au moment  $t+1$ ):

$$m_e (\boldsymbol{\varphi}_{e2}^* + \boldsymbol{\varphi}_{e1}^*) = m_e (\boldsymbol{\varphi}_{e2} + \boldsymbol{\varphi}_{e1}) - \nabla \cdot \left[ (p_{e2}^* + p_{e1}^*) \mathbf{I} + m_e \left( \frac{\boldsymbol{\varphi}_{e2}^* \boldsymbol{\varphi}_{e2}^*}{n_{e2}^*} + \frac{\boldsymbol{\varphi}_{e1}^* \boldsymbol{\varphi}_{e1}^*}{n_{e1}^*} \right) \right] - q[(n_{e2}^* + n_{e1}^*) \mathbf{E}^* + (\boldsymbol{\varphi}_{e2}^* + \boldsymbol{\varphi}_{e1}^*) \times \mathbf{B}^*] \quad (14)$$



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## PUBLICATIONS

### 1. Already published:

1. Rezeau, Belmont, Manuzzo, Aunai, Dargent, 2018, "Analysing the magnetopause internal structure: new possibilities offered by MMS tested in a case study", J. Geophys. Res., 122.

### 2. Previewed:

1. A study about the Magnetopause kinematics and thickness and about the localisation of spacecraft/data with respect to the magnetopause itself
2. A paper on the new 3-fluid and 4-fluid codes
3. A paper as co-author in magnetopause frame determination (Denton, work in progress)



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## AGU 2017 IN NEW ORLEANS



### Determining the Thickness and the Sub-Structure Details of the Magnetopause from MMS Data R. Manuzzo<sup>1,2</sup>, G. Belmont<sup>1</sup>, L. Rezeau<sup>1</sup>, F. Califano<sup>2</sup> 1: Université Pierre et Marie Curie, Paris; 2: Università di Pisa, Italy

**I. Abstract:** The magnetopause thickness, like its mean location, is a notion that can have different meanings depending which parameters are considered (magnetic field or plasma properties). In any case, all the determinations have been done, up to now, considering the magnetopause boundary as a structure strictly stationary and 1D (or with a simple curvature). These determinations have shown to be very sensitive to the accuracy of the normal direction, because it affects the projection of the quantities of

interest in studying geometrical sensitive phenomena such as the magnetic reconnection. Furthermore, the 1D stationary assumptions are likely to be rarely verified at the real magnetopause. The high quality measurements of MMS and their high time resolution now allow investigating the magnetopause structure in its more delicate features and with an unequal spatio-temporal accuracy. We make use here of the MDD and RTD tools developed by Shi et al. (2005, 2006) and new methods implemented by us recovering the spacecraft path across the magnetopause in order to compute the dimensionality, the local normals and

the thickness of the Earth's magnetopause and its sub-structures. Applying this method to various quantities, we can draw their profiles as functions of a physical abscissa (length instead of time) along a sensible normal. This procedure allows answering quantitatively the questions concerning the locations and the thicknesses of the different sub-structures encountered inside the "global magnetopause" (Rezeau, 2017).

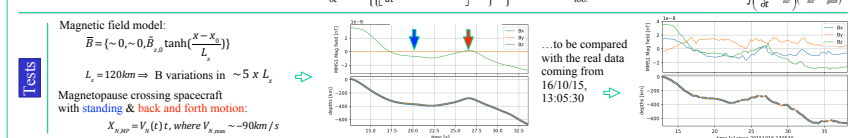
**II. The problem:** The observational studies in space plasma physics deal with time series of data measured by spacecraft crossing plasma structures. Scientists often need to deduce the geometrical features (orientations, dimensions) of these structures being key features of phenomena happening inside them. The time-to-space translation process often involves strong hypotheses never fully satisfied in real conditions. Furthermore, the help of data-initialised simulations can be sometimes misleading because the evolution of the real plasma can differ substantially from its virtual counterpart due to the over-simplified boundary conditions (kinetic and Vlasov simulations) or the over-simplified governing equations (fluid simulations) used in simulations.

**III. The solution** consists in recovering the space plasma structure geometry from the magnetic field by means of a time integration of the  $\partial\mathbf{X}/\partial t$  term contained within the Lagrangian derivative of  $\mathbf{B}=\mathbf{B}(\mathbf{x}(t),t)$ :  $d\mathbf{B}/dt = \partial\mathbf{X}/\partial t \cdot \nabla\mathbf{B} + \partial\mathbf{B}/\partial t$ . As a matter of facts, thanks to the multi-spacecraft NASA's Magnetometer MultiScale mission (MMS) (Burch et al., 2015), we have the capabilities to recover the  $\nabla\mathbf{B}$  term (Chanteur, 1998).

**III.a:** We implemented the Spatio-Temporal difference method (Shi et al. 2006), by means of the inversion of  $d\mathbf{B}/dt = \partial\mathbf{X}/\partial t \cdot \nabla\mathbf{B}$  (neglecting the  $\partial\mathbf{B}/\partial t$  term due to the hypothesis of stationarity). Care is needed during the inversion procedure because the singularities of  $\nabla\mathbf{B}$  (due to 1D structures and experimental fluctuations which causes the zeros of the adjoint of  $\nabla\mathbf{B}$  to be elsewhere with respect to the zeros of  $\det(\nabla\mathbf{B})$ ).

$$\vec{B} = \vec{B}(\vec{X}(t), t) \Rightarrow \frac{d\vec{B}}{dt} = \frac{\partial\vec{B}}{\partial t} + \frac{\partial\vec{B}}{\partial\vec{X}} \cdot \frac{d\vec{X}}{dt}$$

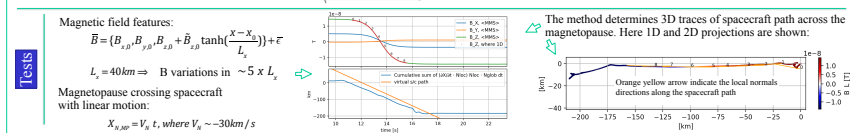
$$\frac{\partial\vec{B}}{\partial\vec{X}} = \left[ \left( \frac{d\vec{B}}{dt} - \frac{\partial\vec{B}}{\partial t} \right) \det(\nabla\vec{B}) \right] / \det(\nabla\vec{B})$$



**III.b:** Under the hypothesis of constancy of the  $\partial\mathbf{X}/\partial t$  and the  $\partial\mathbf{B}/\partial t$  terms during periods of a few data points (instead of the hypothesis of stationarity during the global crossing, which is done usually), the previous equation can be viewed as a linear system, where the 6 unknowns  $\partial\mathbf{X}/\partial t$  and  $\partial\mathbf{B}/\partial t$  can be easily estimated by a least square regression (LSR) procedure. The  $\partial\mathbf{X}/\partial t$  vectors, once projected to the corresponding local MDD normals  $\mathbf{N}_{\text{loc}}$  (where defined), represent the normal displacement needed by the magnetic field structure to have a variation  $d\mathbf{B}/dt = \partial\mathbf{B}/\partial t$  due to a gradient  $\nabla\mathbf{B}$ . Finally, the cumulative sum of  $(\partial\mathbf{X}/\partial t \cdot \mathbf{N}_{\text{loc}}) \cdot \mathbf{N}_{\text{loc}} \cdot \mathbf{N}_{\text{loc}}$  returns the normal (with respect to the MP) trace of MMS across the MP. The method clearly give access to quasi non-stationary conditions. Furthermore, the explicit measure of an error (from the LSR procedure) can return an error on the determination of the spacecraft path (work in progress).

$$\vec{B} = \vec{B}(\vec{X}(t), t) \Rightarrow \frac{d\vec{B}}{dt} = \frac{\partial\vec{B}}{\partial t} + \frac{\partial\vec{B}}{\partial\vec{X}} \cdot \frac{d\vec{X}}{dt}$$

$$\vec{y} = \vec{C} \cdot \vec{x} + \vec{q}$$



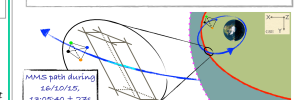
References:  
• Shi et al. (2005), "Dimensional analysis of observed structures using multi-point magnetic field measurements: Application to Cluster", *Geophys. Res. Lett.*, 32, L12205.  
• Rezeau et al. (2017), "Analyzing the magnetopause internal structure: new possibilities offered by MMS tested in a case study", submitted to *JGR Space Physics*.  
• Shi et al. (2006), "Motion of observed structures calculated from multi-point magnetic field measurements: Application to Cluster", *Geophys. Res. Lett.*, 33(8).  
• Burch et al. (2016), "Electron-scale measurements of magnetic reconnection in space", *Science*, 352, aa2939.  
• Burch et al. (2015), "Magnetospheric MultiScale Overview and Science Objectives", *Space Science Reviews*.  
• Chanteur (1998), "Spatial Interpolation for Four Spacecraft: Theory", *ISS Scientific Reports Series*, 1, 349-370.



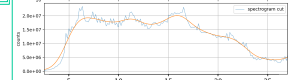
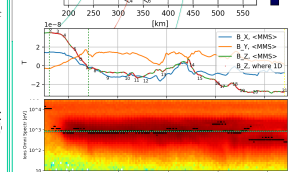
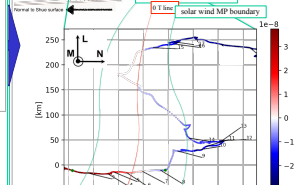
**V. Some results:** Here are collected two from the main results obtained in computing the MMS path through the Magnetopause during two crossings.

New insights onto the 16/10/15, 13:05:30 + 60s event

We concentrated on a very famous case study (the crossing used by Burch et al. (2016) to compute the LMN frame for the close reconnection event) in order to test our method. We found a more complex MP back and forth motion than expected and we got a determination of the normal(s) direction(s) along the s/c path which seems more in-line than the kinematics sketched by Burch et al. (2016) and that show how labelling an entire crossing with only one global normal can be a rough procedure in view of data projection.

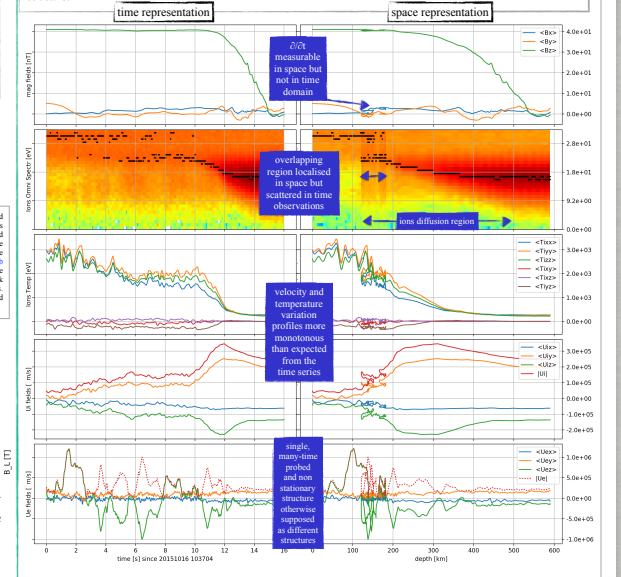


On the left, we sketched the path MMS did across the MP during this crossing. The arrows indicate the normal to the slice surface and those determined by the MDD method. The magnetic force lines are drawn by hand. On the bottom, the path is recovered by the MDD solution and projected onto the LN plane (MVAH) between green dots. The black arrows indicate the local normal directions. The s/c return inside magnetosphere is pointed out by some spectrograms (see face bottom).



New insights in the magnetopause sub-layer structure: the 16/10/15, 10:37:04 + 16s event

The space representation of data for another case study (16/10/15, 10:37:04 + 16s event) unlocked observations such as the  $\partial\mathbf{B}/\partial t$  terms measurements, the precise pinpointing of mixing sub-layers where the magnetospheric and solar wind plasmas have similar energies, a more monotonous space variation of physical quantities of interest (also for simulation initialisations) and the revealing of a many-time probed and non stationary structure otherwise simply believed as different structures.



### Conclusions and perspectives:

We presented two methods to analyse the internal structure of the magnetopause, the two differing on the hypothesis about the importance of the  $\partial\mathbf{B}/\partial t$  term and in the number of data point to be processed each step. No hypothesis has been done a priori on the dimensionality (but for 1D or 2D projections of the resulting 3D trajectories), allowing these procedures to be applied to real cases with a very few restrictions. We performed tests to validate the methods on artificial magnetic fields affected by noise and probed as if the magnetopause overcame MMS with constant velocities, sudden standings and/or back and forth motions. We applied the methods onto two real cases study during 16/10/15: for the 13:05:30+60s case we obtained a new perspective on the MP kinematics; for the 10:37:04+16s case we got new understandings about the sub-layers structures, dimensions and respective locations. We aim to ameliorate the methods, by cross-checks, error computations and applications to fluid simulation data probed by virtual spacecraft. Finally, the methods will allow to measure the plasma flux flowing across the magnetopause.

...BUT ALSO EGU 2018, AGU 2018...



# PRESENTATION FOR THE UNIPI SEMINAR 2=>3

## SUMMARY

- The target
- People & places
- The plan
- Publications
- Congresses
- Formations

## FORMATIONS

1. [30h] Python coding (online certified course)
2. [1 week] "Description fluide et cinétique des plasmas" 2017, Observatoire de Meudon, Paris
3. [2 weeks] École de Physique des Houches 2017
4. [1 week] Cineca Summer School on High Performance Computing, 2017, Bologna, Italy
5. [2.5 h] Ethique et intégrité scientifique




**ATTESTATION DE SUIVI**

**Roberto Manuzzo**  
a suivi avec succès le MOOC\*

Python : des fondamentaux à l'utilisation du langage  
proposé par Inria  
et diffusé sur la plate-forme FUN  
Le 12/12/2016

<https://www.fun-mooc.fr>

\* MOOC : cours en ligne  
La présente attestation n'est pas un diplôme et ne confère pas de crédits (ECTS). Elle n'atteste que la participation à la formation.  
L'identité du participant n'a pas été vérifiée.



Meudon, le 25 janvier 2017


Observatoire de Paris - LESIA  
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

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LESIA, bdt. 16  
Observatoire de Paris-Meudon  
5 place Jules Janssen  
92195 Meudon Cedex, France  
Tél. +33 (0)1 45 07 76 77  
E-Mail: Filippo.Pantellini@obspm.fr

Attestation de participation à une formation doctorale


J'atteste que **M Roberto MANUZZO** a participé, de façon assidue, à la formation doctorale d'une durée de **30 heures** intitulée "Description fluide et cinétique des plasmas".

La formation, proposée dans le cadre des cours pour doctorants de l'École Doctorale (Astronomie et Astrophysique d'Ile de France), s'est tenue du **lundi 16 au vendredi 20 janvier 2017** dans les locaux de l'Observatoire de Paris à Meudon.



Filippo Pantellini  
(responsable de la formation)

[www.lesia.obspm.fr](http://www.lesia.obspm.fr)



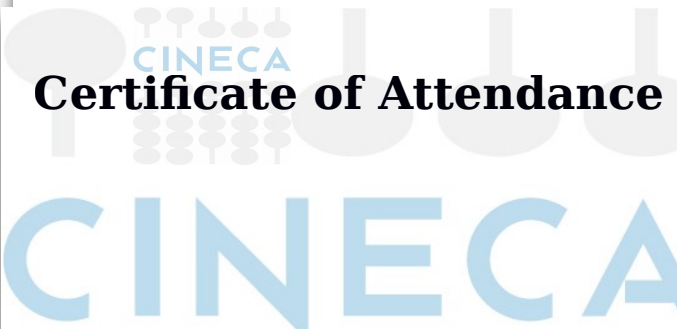



ÉCOLE DE  
PHYSIQUE  
DES HOUCHES

TO WHOM IT MAY CONCERN

This is to certify that **Roberto MANUZZO** attended the course on **astrophysics: the expanding universe of plasma physics** from May 1<sup>st</sup> until May 12<sup>th</sup>, as a full participant.

Anny GLO  
Head of Ad


149 Chemin de la Côte, F-74310 Les Houches / France



**Certificate of Attendance**

This is to certify that  
**MANUZZO ROBERTO**  
has successfully attended the course  
**26<sup>th</sup> SUMMER SCHOOL ON  
PARALLEL COMPUTING**  
which has taken place on **May 15<sup>th</sup>-26<sup>th</sup> 2017**  
at Cineca - BOLOGNA

Responsible for School and  
Courses SCAI - Cineca  
**Elda Rossi**



Head office: BOLOGNA via Magnanelli, 6/3 40033 - Casalecchio di Reno (BO) - Tel. +39 051 6171411  
Other offices: MILAN - Via R. Sanzio, 4 - 20090 Segrate (MI) - Tel. +39 02 269951;  
ROME - Via del Tizii, 6 - 00185 Rome - Tel. +39 06 444861

Capitulatif de participation aux Formations  
**Roberto MANUZZO**

Physique d'Ile-de-France  
septembre 2016 (2 A en 2017)  
une simulation numérique quadri-fluide

**Formations suivies**

l'utilisation du langage Organisateur: Inria. Platform: Mooc-Fun (<https://www.fun-mooc.fr>).  
Astrophysique d'Ile-de-France.  
laboratories to astrophysics: the expanding universe of plasma physics Université Grenoble Alpes,  
Astrophysique d'Ile-de-France.  
CINECA CINECA, Italia  
Astrophysique d'Ile-de-France.  
Durées : 90 h  
le  
juillet 2017) Amphithéâtre Hubert Curien - 62 bis rue Gay Lussac 75005 Paris  
éthique et intégrité scientifique : 2.5 h  
disciplinaires proposées par une école doctorale  
as (16 janvier 2017) CIAS (Chateau de l'Observatoire de Meudon)  
Astrophysique d'Ile-de-France.  
Formations scientifiques pluridisciplinaires proposées par une école doctorale : 30 h  
dules



End

## References

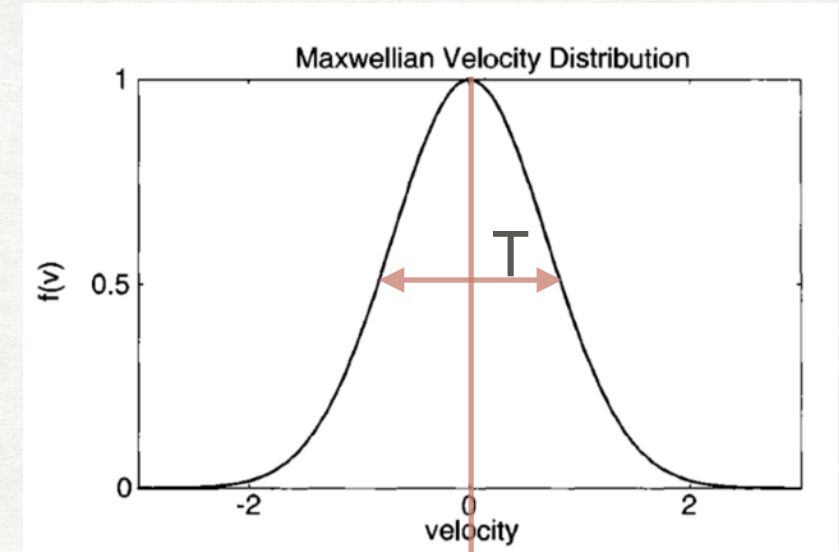
1. P. Robert, CETP/CNRS, 1996
2. Burch & al., "Magnetospheric Multiscale Overview and Science Objectives", Space Science Review, (2015)
3. Stone & al., "The Advanced Composition Explorer", Space Science Reviews 86-1, 1, (1998)
4. Rezeau et al., 2018, "Analyzing the magnetopause internal structure: new possibilities offered by MMS tested in a case study", J. Geophys. Res., 122.
5. Shi et al., "Dimensional analysis of observed structures using multipoint magnetic field measurements: Application to Cluster", GRL, vol.32, L12105, (2005)
6. Paschmann, "Analysis methods for multi-spacecraft data", ESA Publications Division Keplerlaan
7. Dargent, J., Aunai, N., Lavraud, B., Toledo-Redondo, S., Shay, M. A., Cassak, P. A., & Malakit, K.(2017). Kinetic simulation of asymmetric magnetic reconnection with cold ions. *Journal of Geophysical Research: Space Physics*, **122**, 5290–5306.
8. Furth et al, 1963, "Finite-Resistivity instabilities of a Sheet Pinch", Phys. Fluids 6, 4



# How to discover several species in one distribution function?

-) Reminder: the physical meaning of a distribution function in a 1V phase space:

$$f_{MB}(v) = n \left( \frac{m}{2\pi kT} \right)^{3/2} \text{Exp} \left( - \frac{m(v-u)^2}{2kT} \right)$$



-) 1V Hermite transform representation[\*]:

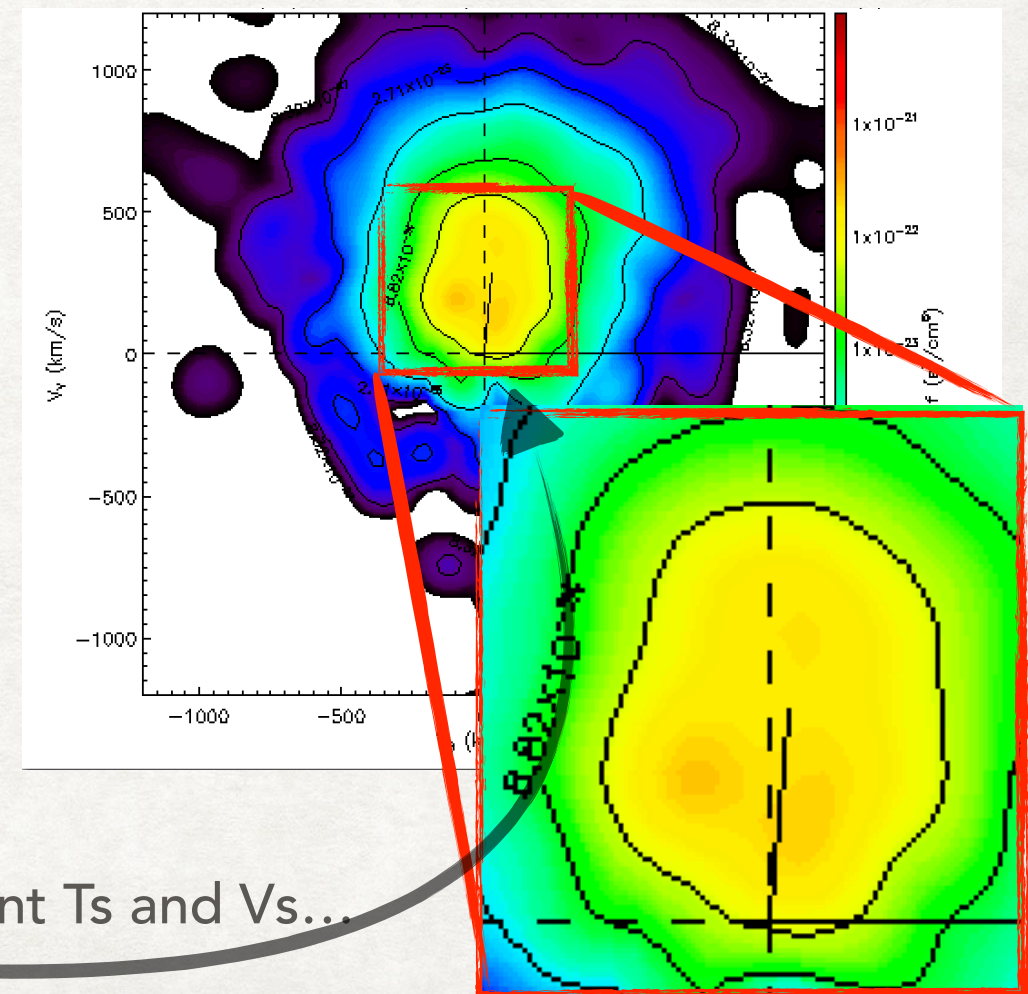
$$\begin{cases} f_v = \sum_m f_m \psi_m(v) \\ \int_{-\infty}^{\infty} \psi_m \psi_l = \delta_{ml} \\ \psi_m(v) = \frac{H\left(\frac{v-u}{v_{th}}\right)}{\sqrt{2^m m!} \sqrt{\pi} v_{th}} \exp\left(-\frac{m(v-u)^2}{2v_{th}^2}\right) \\ H_m(v) = (-1)^m e^{v^2} \frac{d^m}{dv^m} e^{-v^2} \end{cases}$$

*N.B.* :  $\psi_{m=0}(v) \propto F_{MB}$

-) idea: apply the HTR to the 3V distr. func.:

$$\psi_m(\mathbf{v}) = \psi(m_x, v_x) \psi(m_y, v_y) \psi(m_z, v_z)$$

allowing for the presence of different species having different  $T_s$  and  $V_s$ ...



[\*] Servidio et al., "Magnetospheric MultiScale (MMS) observation of plasma velocity-space cascade: Hermite representation and theory", Phys. Plasmas, arXiv:1707.08180v1 (2017)



The Minimum Directional Derivative method (MDD, Shi [2005])...



$$\bar{\bar{G}} = \nabla \bar{B} \quad \bar{n} \cdot \bar{\bar{G}} = \bar{D} = \frac{\partial \bar{B}}{\partial \bar{n}}$$

If  $\mathbf{n} = \mathbf{N}$  was the invariant direction along which all the parameters remain constant  $\Rightarrow D^2 = 0$

$$\text{diagonalization}(\bar{\bar{G}} \bar{\bar{G}}^T) \left\{ \begin{array}{lll} \lambda_1 & \bar{v}_1 & \text{maximum} \\ \lambda_2 & \bar{v}_2 & \text{intermediate} \\ \lambda_3 & \bar{v}_3 & \text{minimum} \end{array} \right\} \text{ of } \mathbf{D} \quad \begin{array}{l} \lambda_1 \gg \lambda_2 \wedge \lambda_3 \Rightarrow \text{1D str.} \\ \lambda_1 \sim \lambda_2 \gg \lambda_3 \Rightarrow \text{2D str.} \\ \lambda_1 \sim \lambda_2 \sim \lambda_3 \Rightarrow \text{3D str.} \end{array}$$

... our Local Normal Analysis method (LNA, [Rezeau, 2018])

Hp.: stationarity and 1D



$$\bar{J} = \bar{N} \times \partial_N \bar{B} \perp \partial_N \bar{B} = -V_N \cdot \partial_N \bar{B}$$

return



# Methods used to find the normal to the magnetopause

Common Hypotheses: magnetopause = 1D and stationary layer  $\Rightarrow \mathbf{B}_n \neq \mathbf{B}_n(N, t)$

Single spacecraft

Minimum Variance  
Analysis method

1) Find  $\mathbf{N}$  in order to minimize:

$$\sum_i \left\| (\mathbf{B}_i - \bar{\mathbf{B}}) \cdot \mathbf{N} \right\|^2$$

2) How to? Diagonalize

$$\begin{cases} M_{\mu\nu} = \langle B_\mu B_\nu \rangle - \langle B_\mu \rangle \langle B_\nu \rangle \\ \mu, \nu = x, y, z \end{cases}$$

3) Results:

- ) eigenvalues:  $\lambda_1, \lambda_2, \lambda_3$
- ) eigenvectors:  $\mathbf{L}, \mathbf{M}, \mathbf{N}$

Pro: simple hypotheses

Vs: bad determination if not 1D

BV  
method

1) Other hypotheses needed:

- ) no flow through the magnetopause
- )  $\mathbf{B}$  behaves like:

$$\begin{cases} B_L = B_{0L} \cos(\alpha) \\ B_N = B_{0N} \\ B_M = B_{0M} \sin(\alpha) \end{cases}$$

where:

$$\alpha = \alpha_1 + (\alpha_2 - \alpha_1) \frac{N}{y_{max}}$$

and

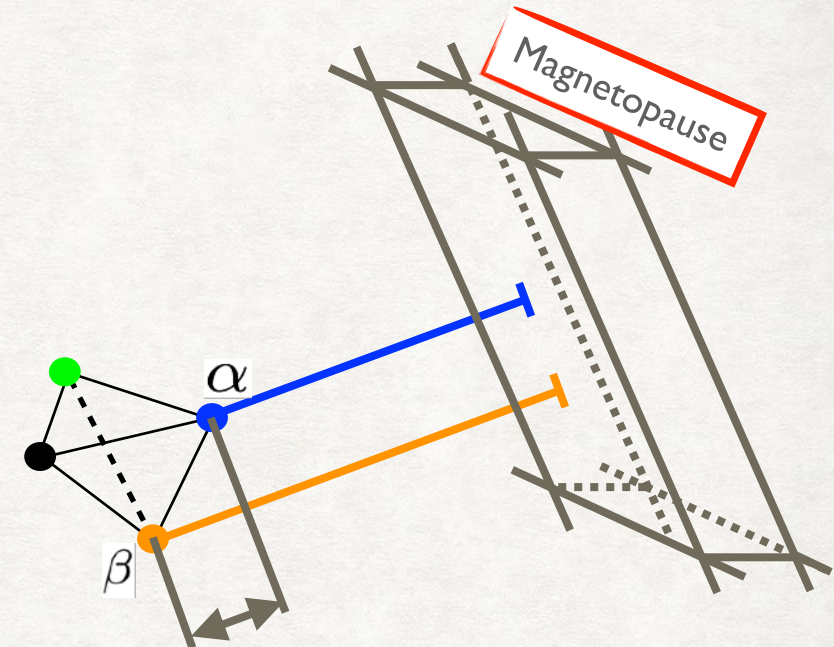
$$\mathbf{N} = \int_{crossing} \mathbf{V}_{BF}(t) \cdot \mathbf{N} dt$$

Pro: particle data involved too

Vs: Hypotheses

Multi spacecraft

Constant Velocity  
Approach method



$$\begin{matrix} \Delta t_{\alpha\beta} \\ \mathbf{r}_{\alpha\beta} \end{matrix}$$

$$(\mathbf{V} \Delta t_{\alpha\beta}) \cdot \mathbf{N} = \mathbf{r}_{\alpha\beta} \cdot \mathbf{N}$$

Pro: Less hypoth, Simple, Mean

Vs: Problem with MMS data

return