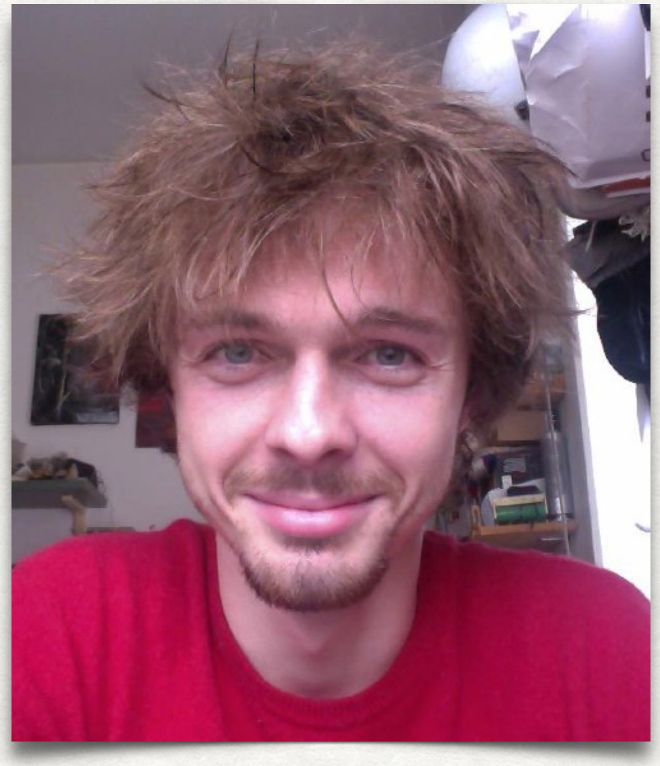
PRESENTATION FOR THE UNIPI SEMINAR 2=>3

ROBERTO MANUZZO, PHD STUDENT

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



PRESENTATION FOR THE UNIPI SEMINAR 2=>3

SUMMARY

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

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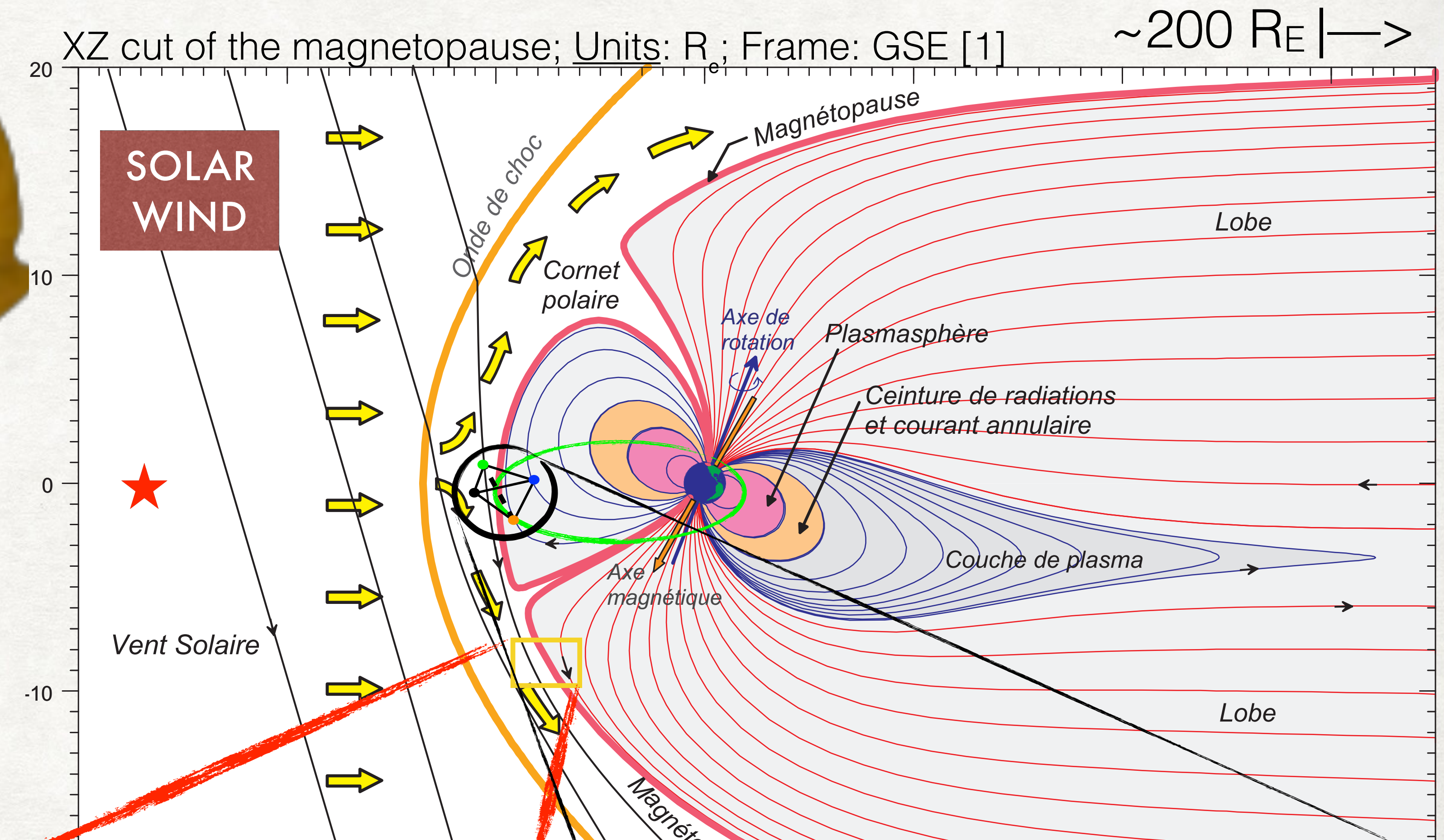

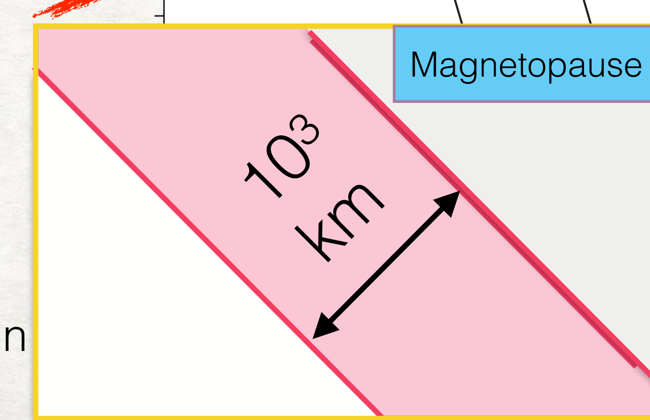

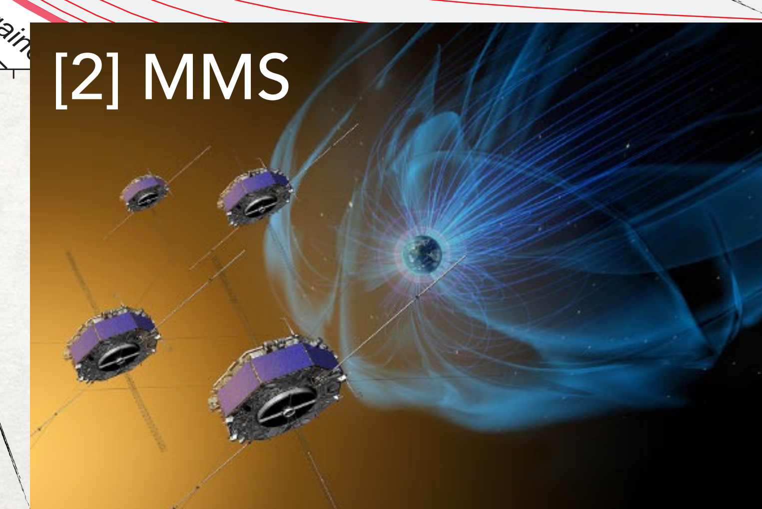

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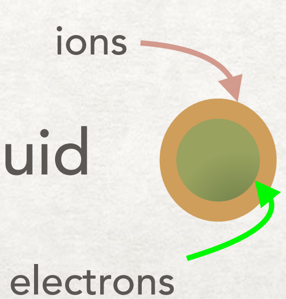
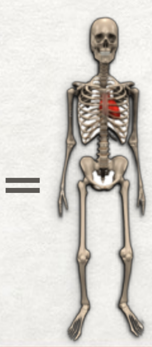
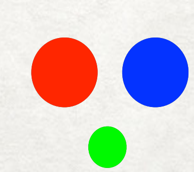
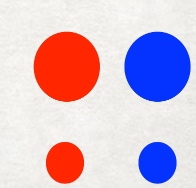
"MAGNETOPAUSE STUDY WITH A MULTI-FLUID NUMERICAL CODE SIMULATION"

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
Existing codes	Mono T, MHD	✗	✓
	Hybrid-Kinetic-Vlasov	✓	✗
Multi Fluid	High T, MHD Low T, MHD	✓	✓

how? => MHD2-fluid 

=  > 3-fluid  => 4-fluid 

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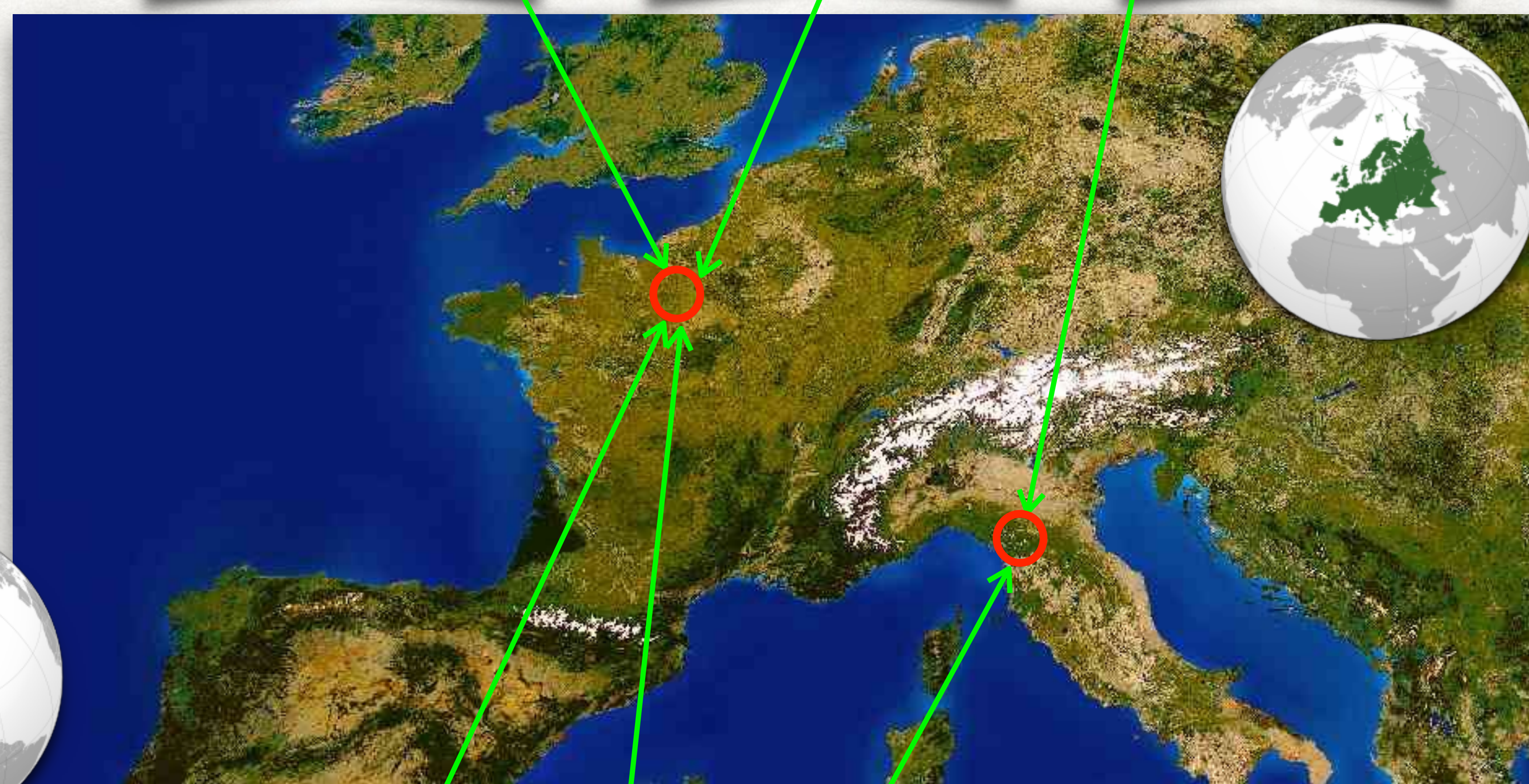
L. Rezeau

G. Belmont

F. Califano



R. Denton

SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

l'X ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

IN SUPREMÆ DIGNITATIS 1343

UNIVERSITÉ FRANCO ITALIENNE
UNIVERSITÀ ITALO FRANCESE

time line

Begin Nov2016

- data analysis — Paris
- I y
- simulations — Pise
- Today →
- II y
- merging — Paris

End 2019

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Legend

- work done
- work to be done

THE PLAN

1. **Observations** side:
   - 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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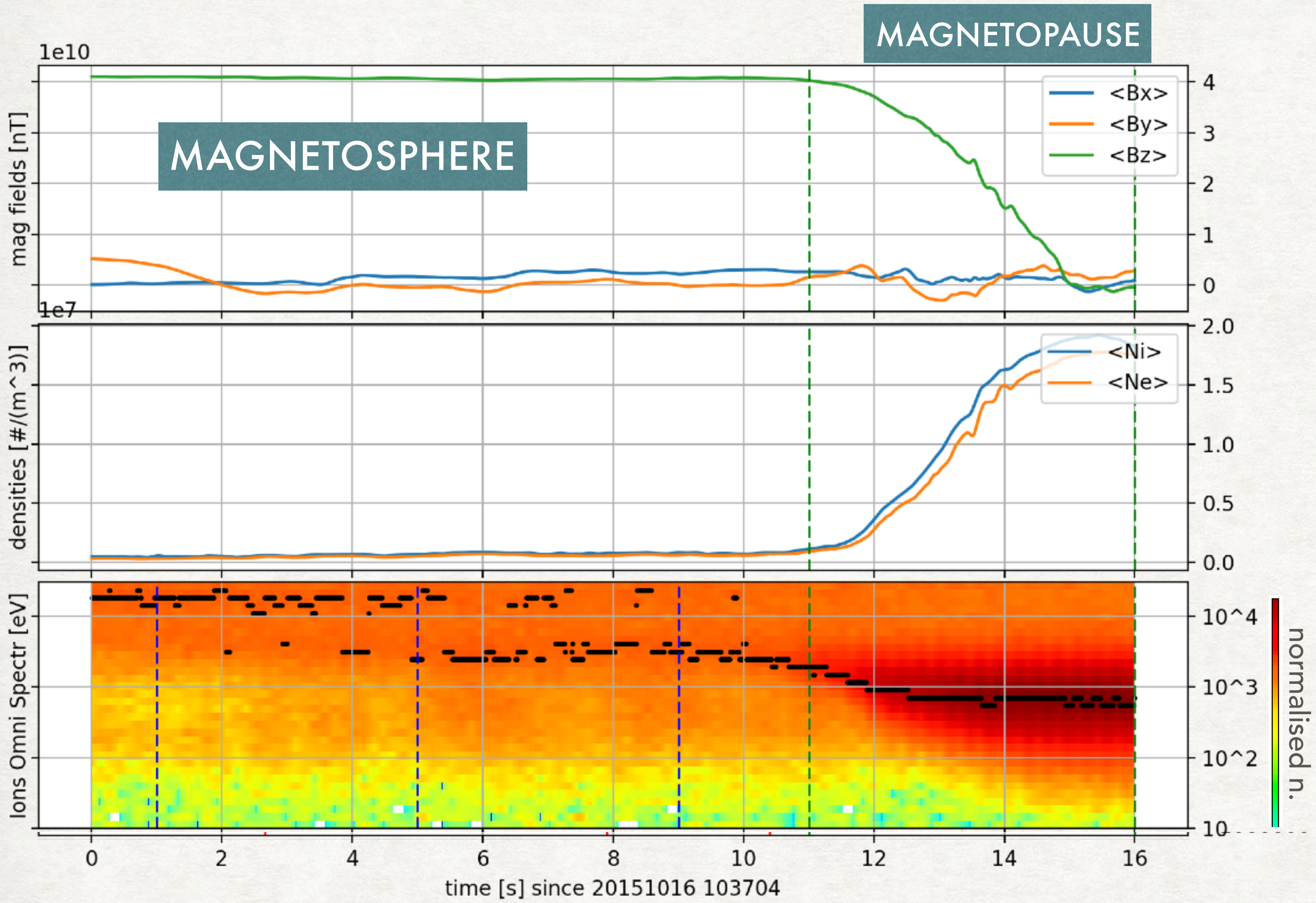
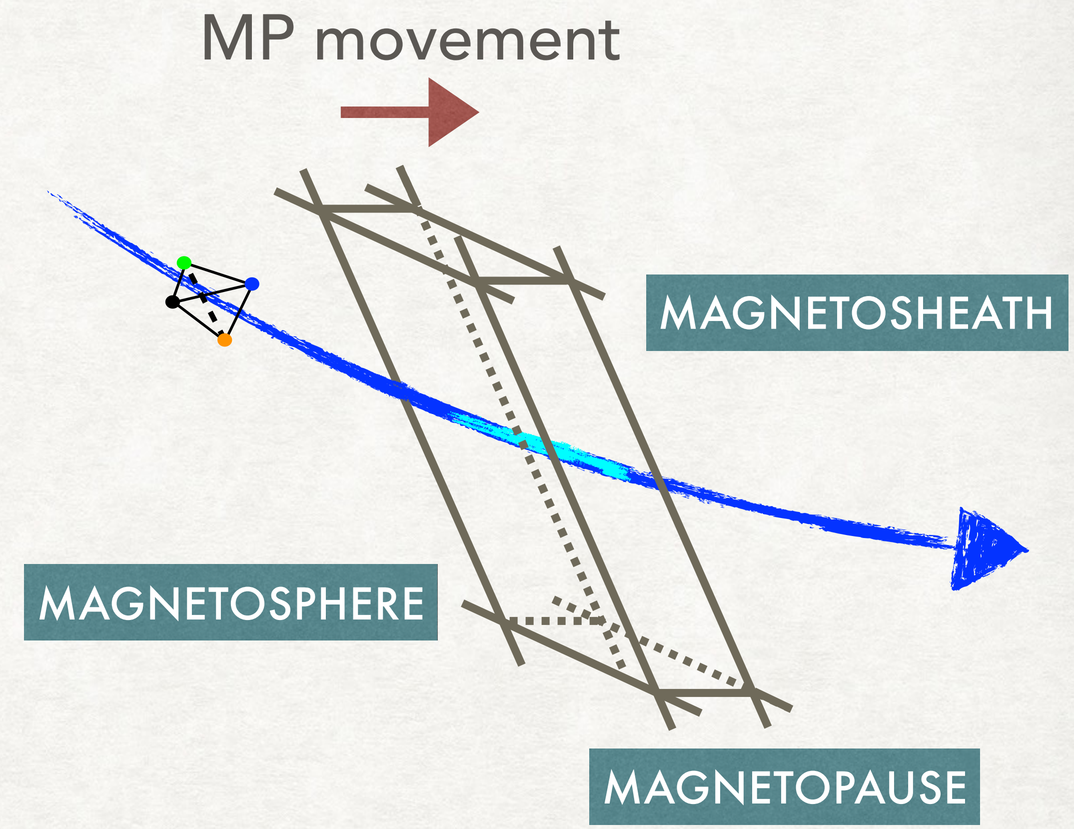
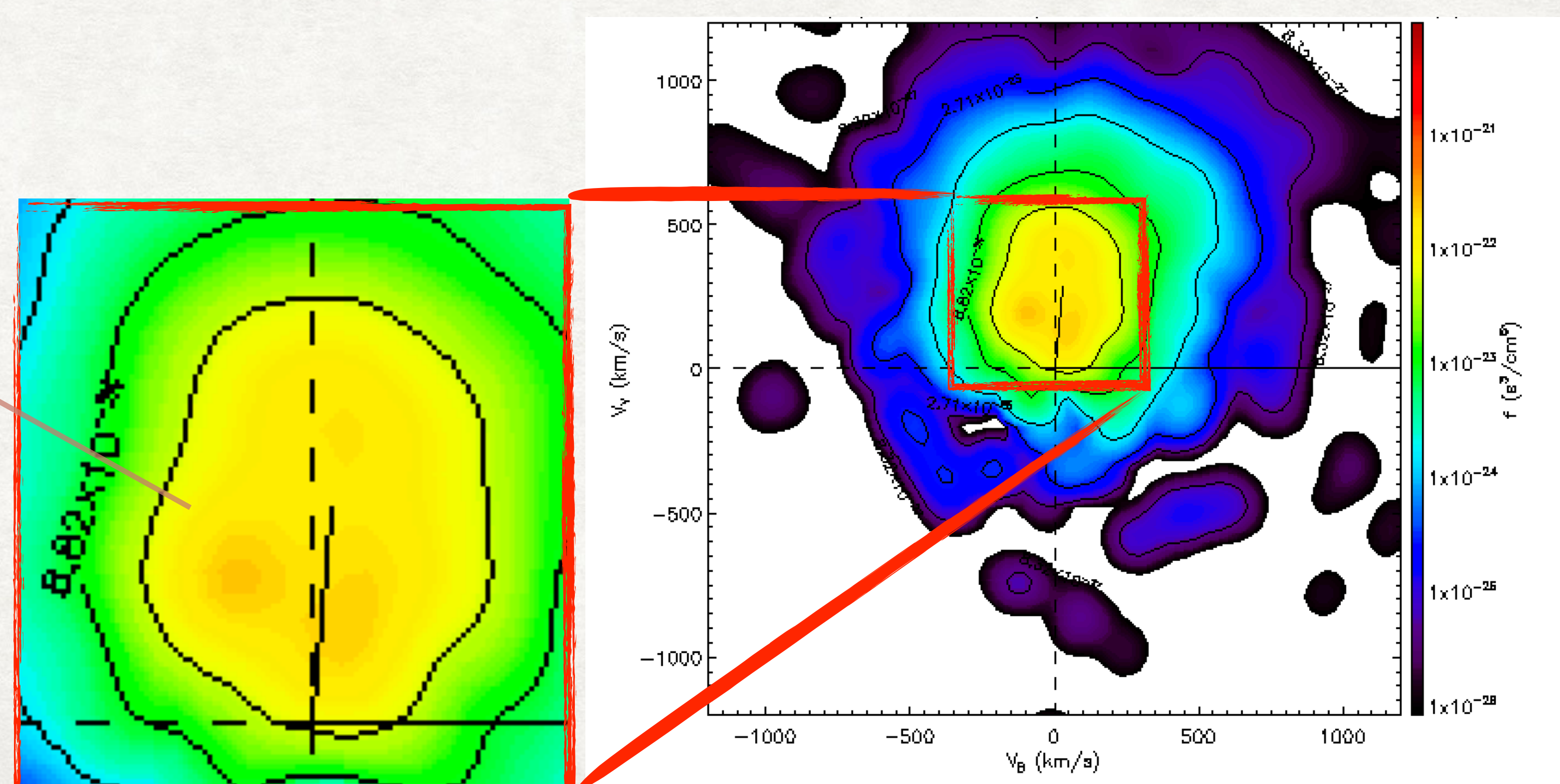
MIXING OF DIFFERENT PLASMAS AT SAME PLACE AND TIME



mixing!





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DETERMINATION OF A COORDINATE ALONG THE DEPTH OF THE MP

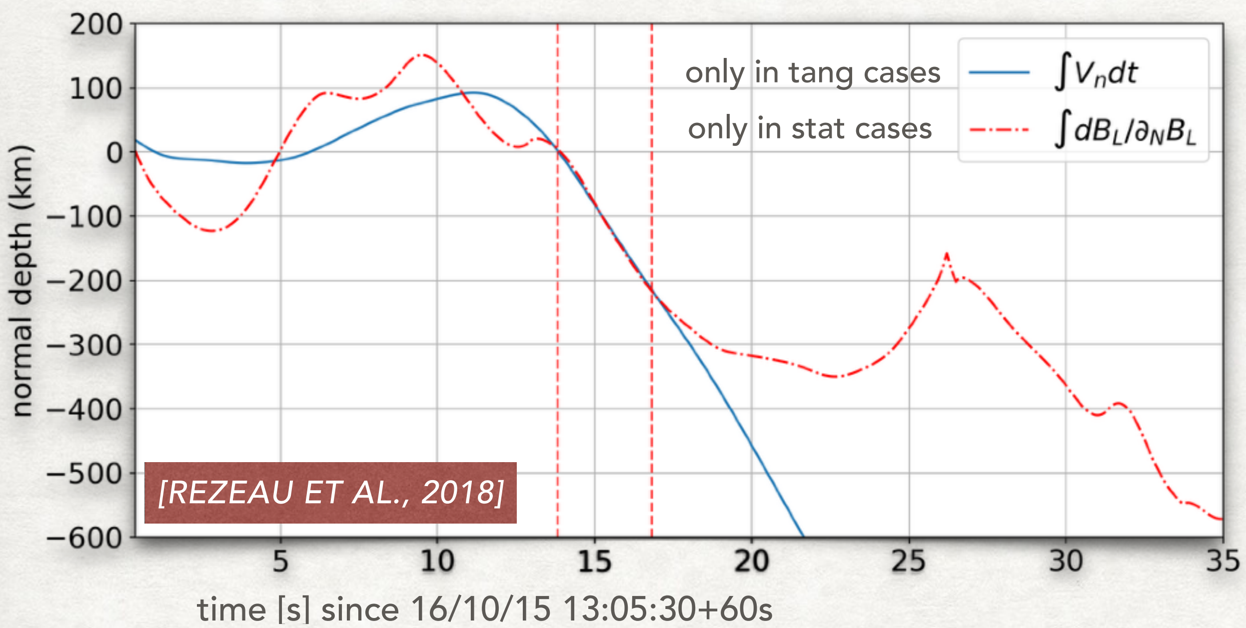
[Shi et al., 2006]

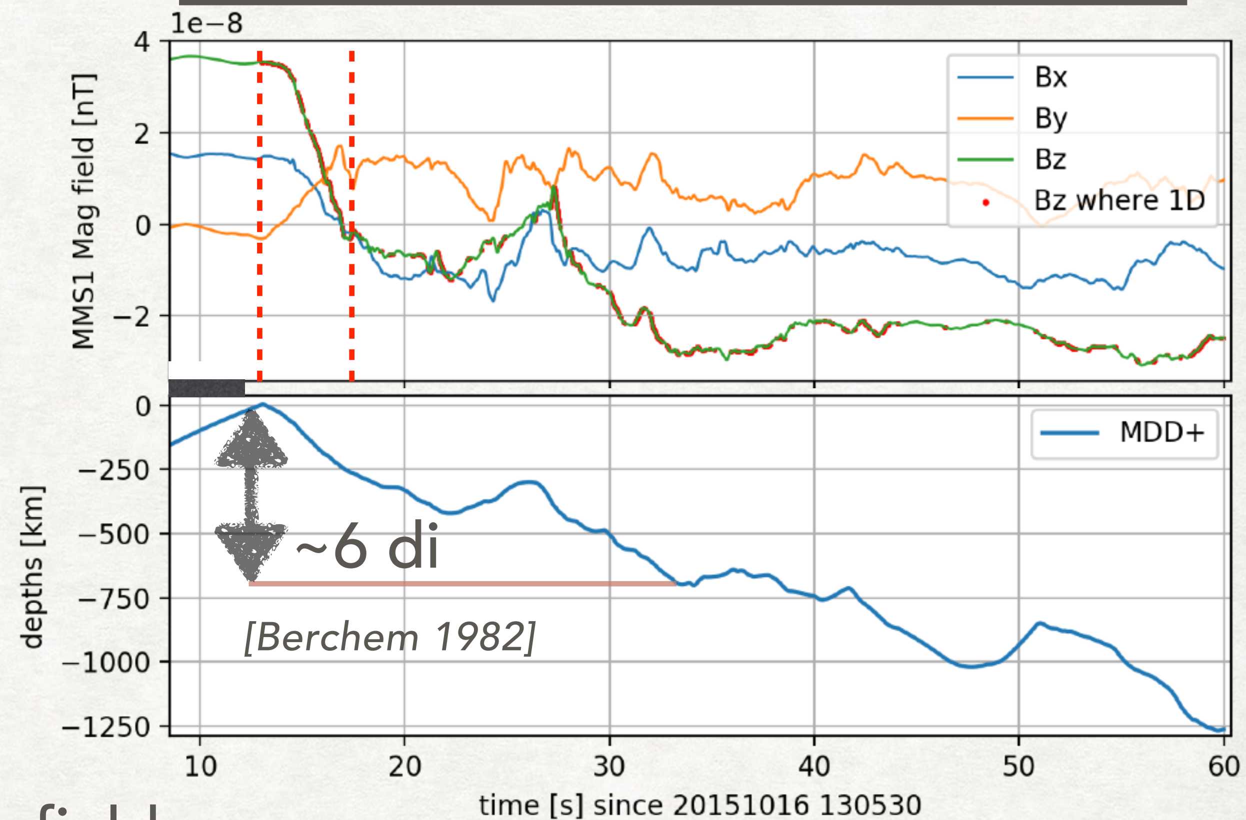
$$d_t\overline{B} = \partial_t\overline{X} \cdot \overline{\nabla}\,\overline{B}$$

=>

[Manuzzo et al., in preparation]

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

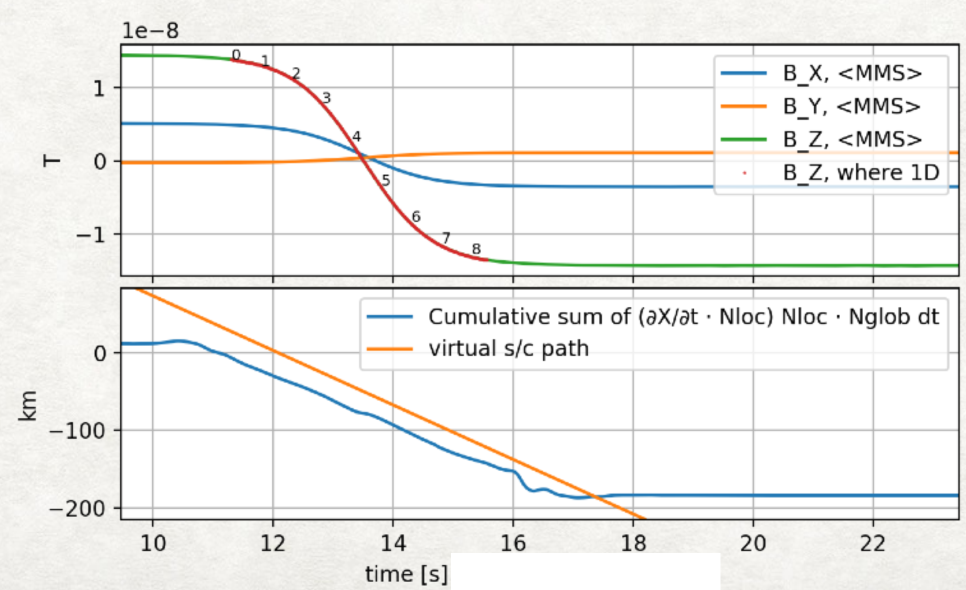


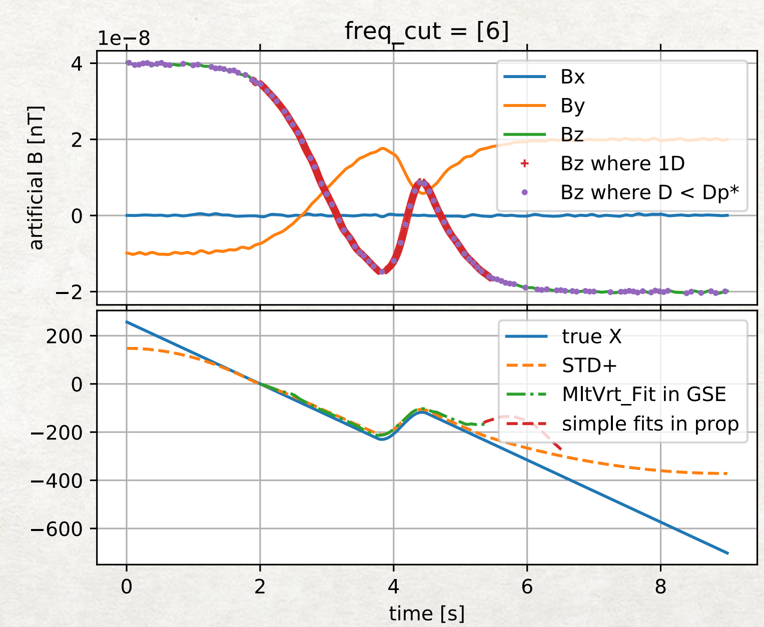


Tests on artificial magnetic fields:

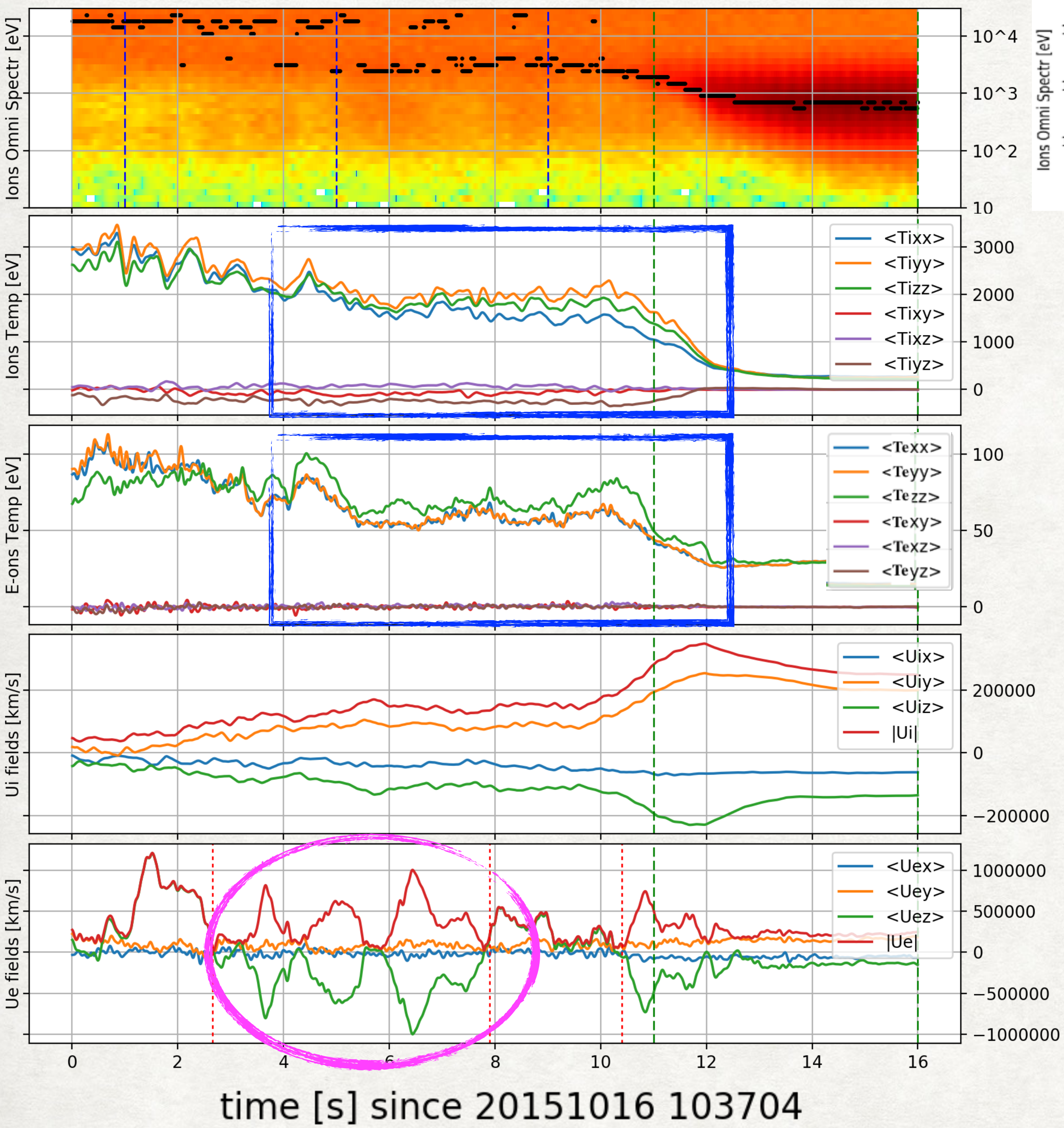
G. Kremer 1512-1594

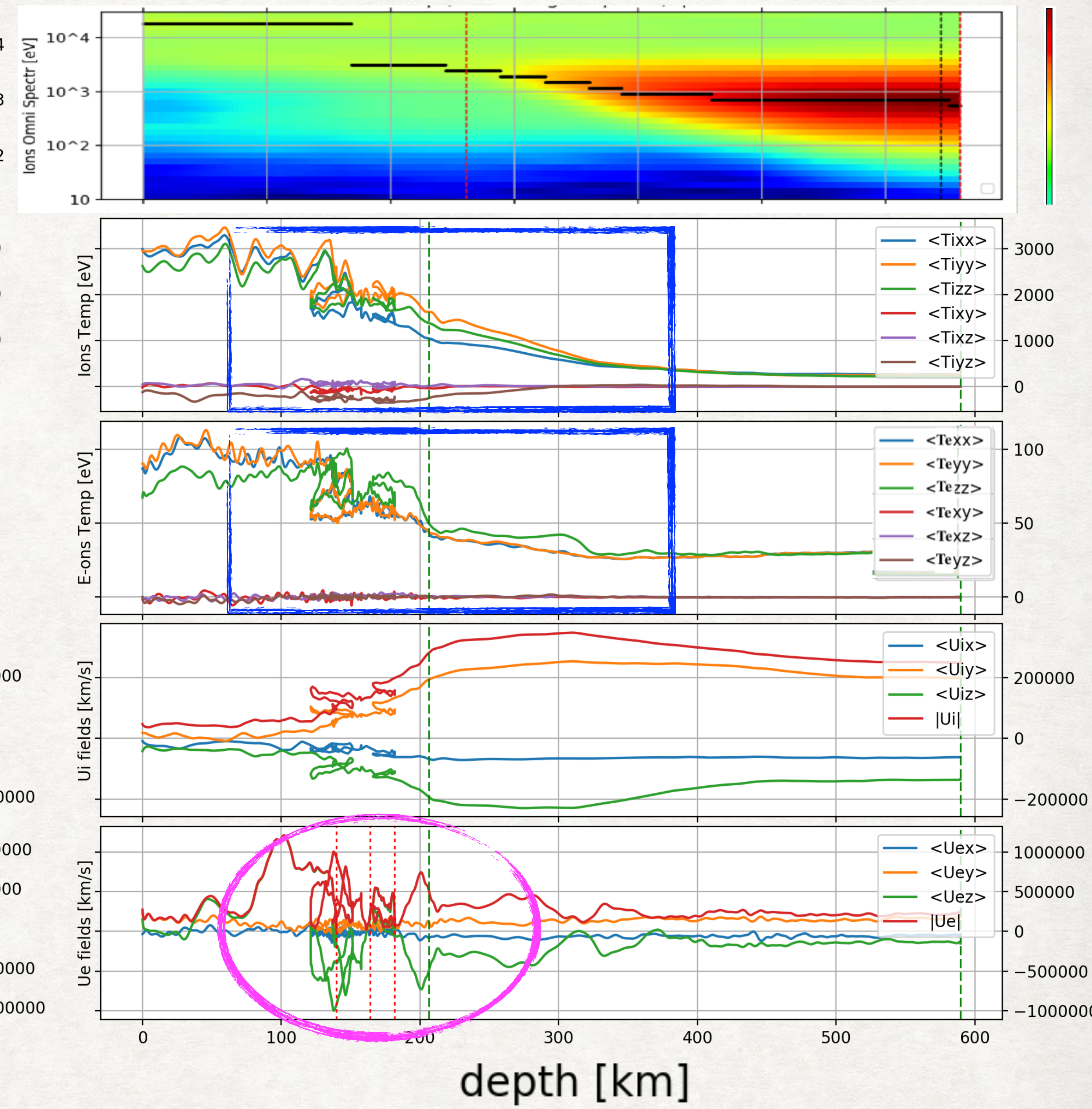
Wikipedia





DATA VISUALISATION AS A FUNCTION OF SPACE





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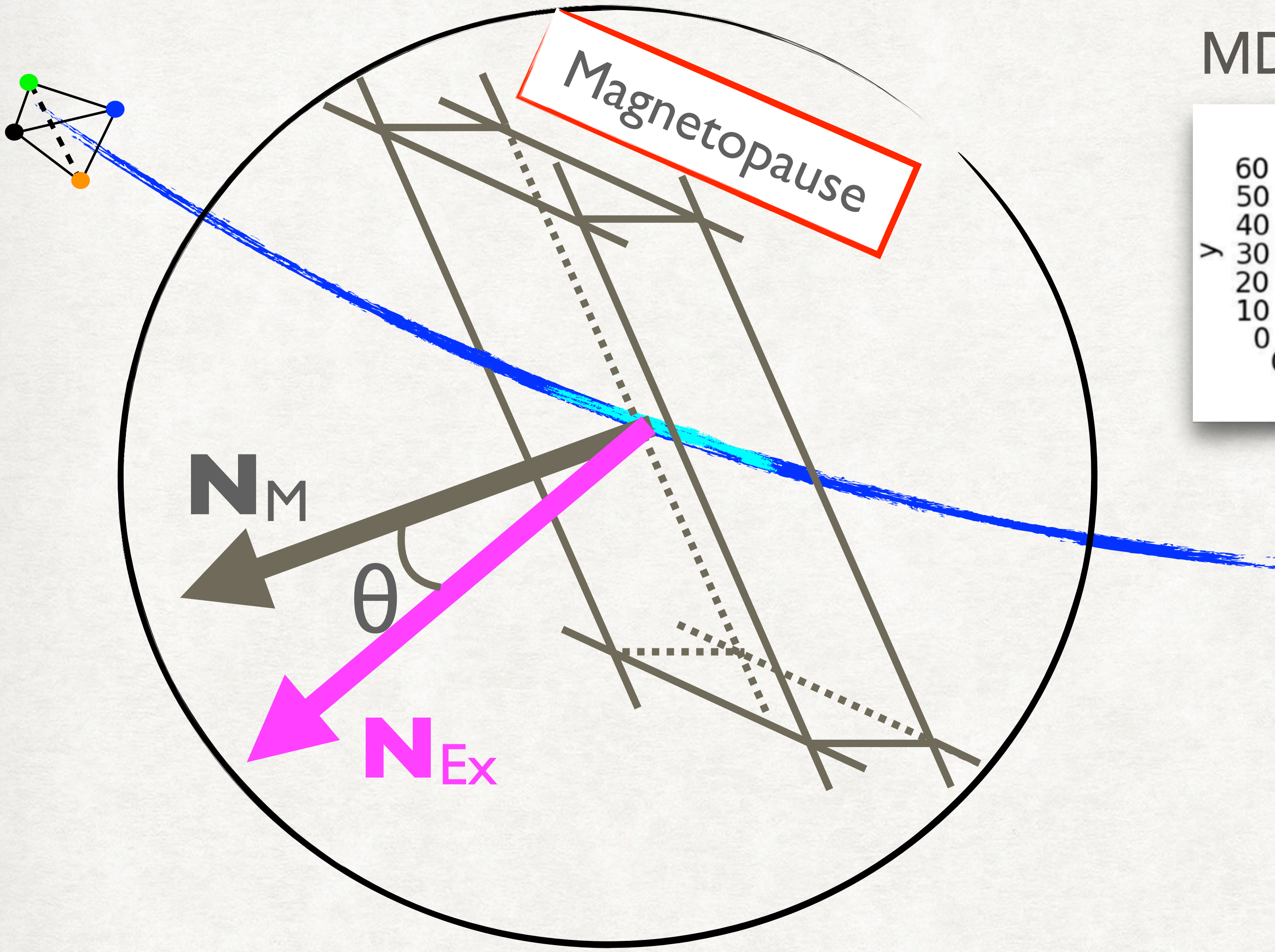
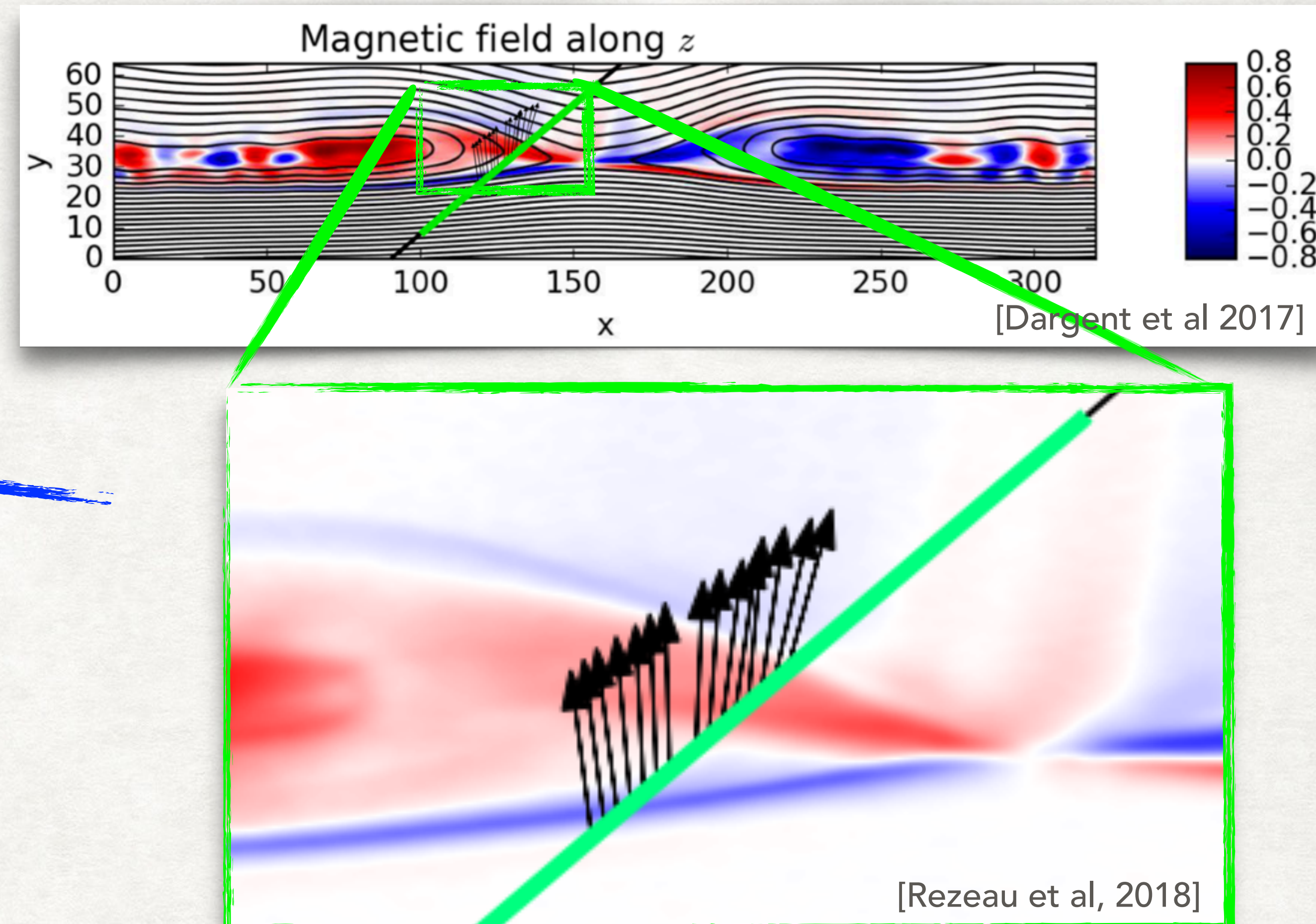
DETERMINATION OF THE MAGNETOPAUSE ORIENTATION



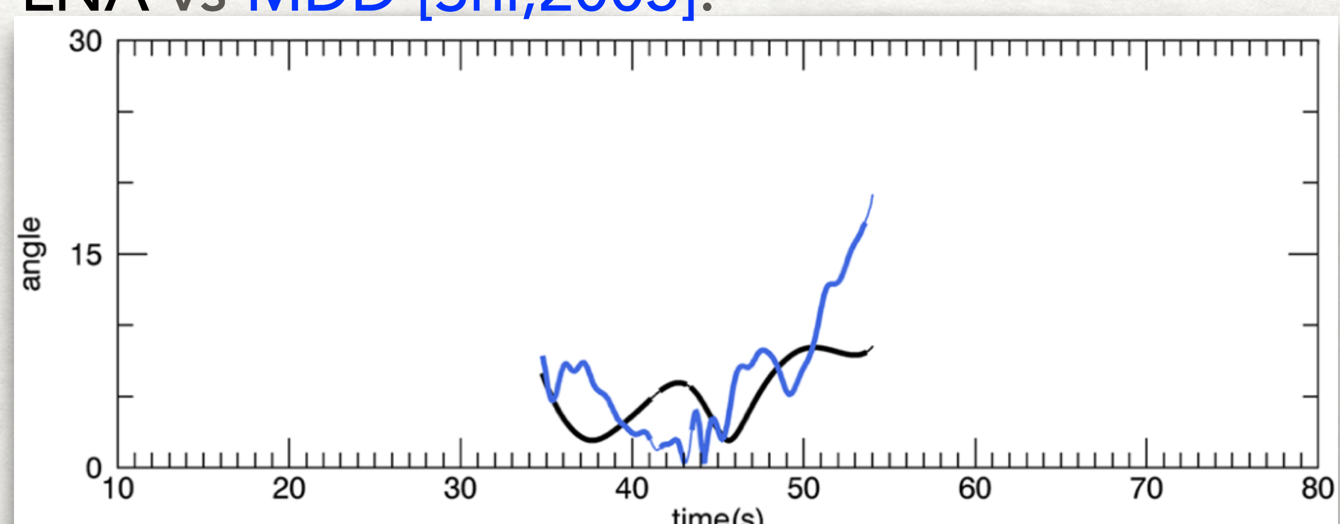
MDD:



Analysis methods	global	local
single	MVA	LNA
multi	CVA	MDD

Rezeau et al., 2018

LNA vs MDD [Shi,2005]:



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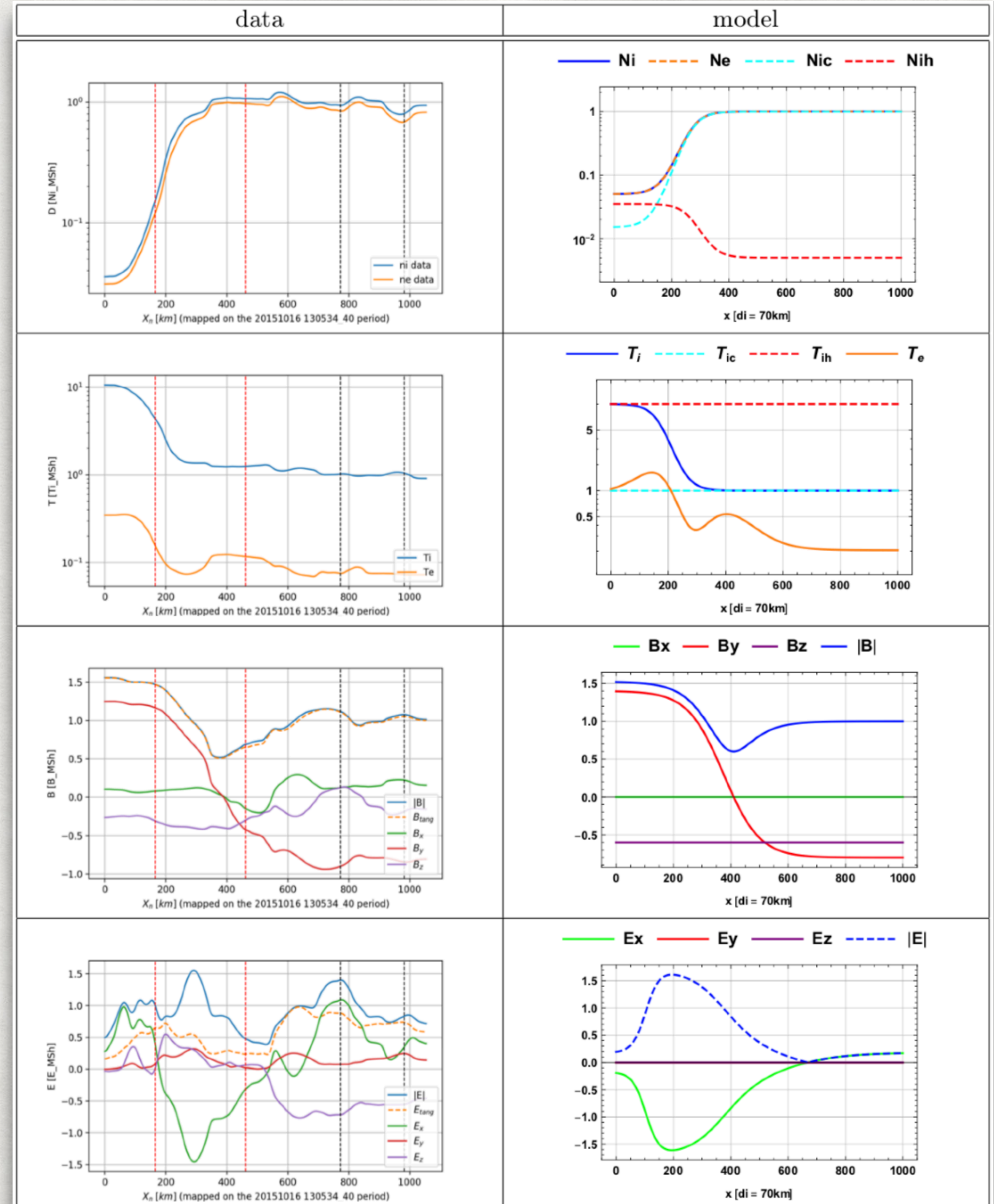
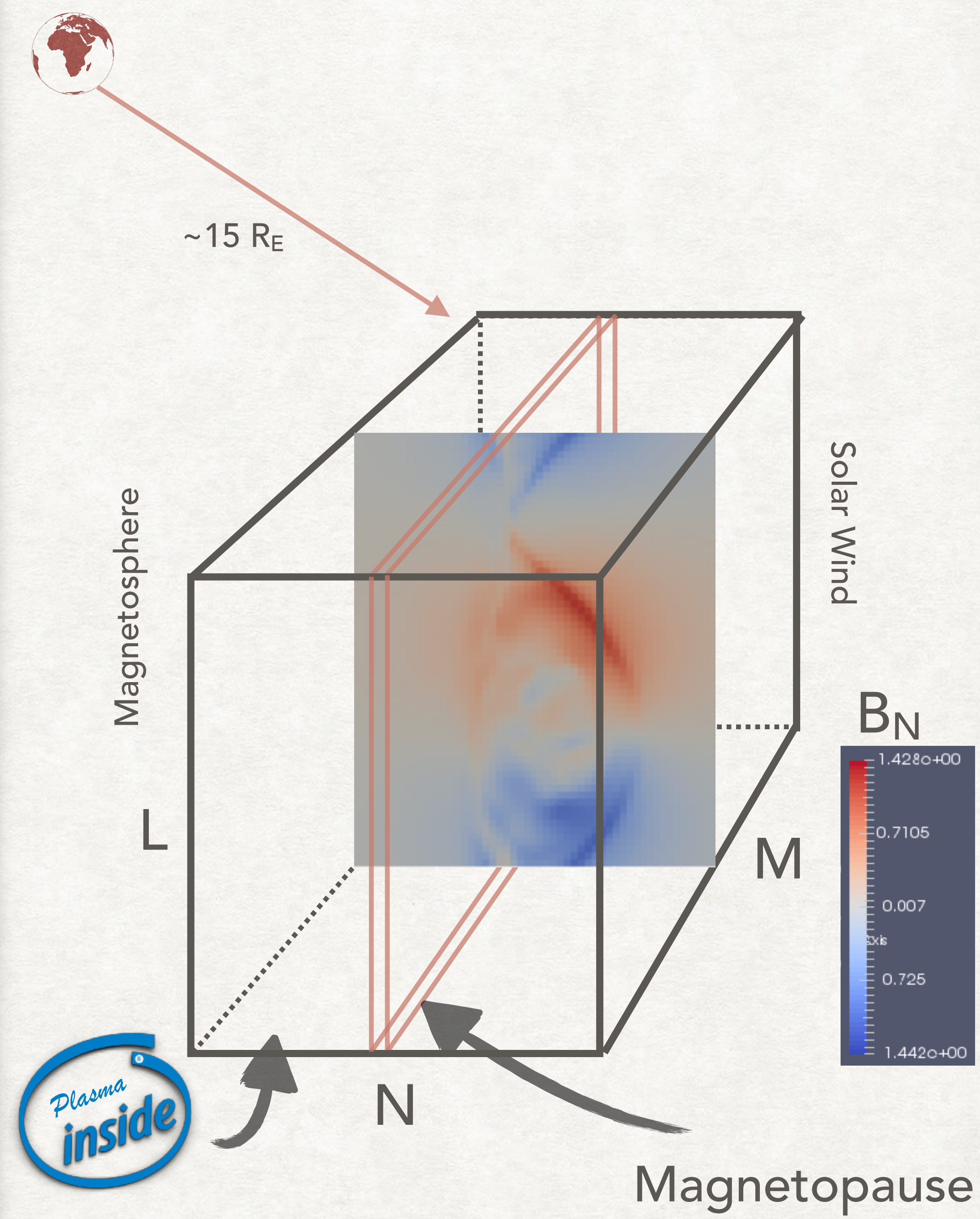
INITIALISATION METHODS FOR SIMULATIONS: A 3FLUID APPROACH





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THE 3-FLUID CODE

THE ALGORITHM

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

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

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

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

3. Electron density from updated ions densities[1], $\alpha = \{ic, ih\}$:

$$n_e^* = \sum_\alpha n_\alpha^* \tag{3}$$

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

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

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

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

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

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

7. Magnetic field

$$\frac{\partial \mathbf{B}}{\partial t} + \overline{\nabla} \times \mathbf{E} = 0 \tag{7}$$

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

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

9. Electric field

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

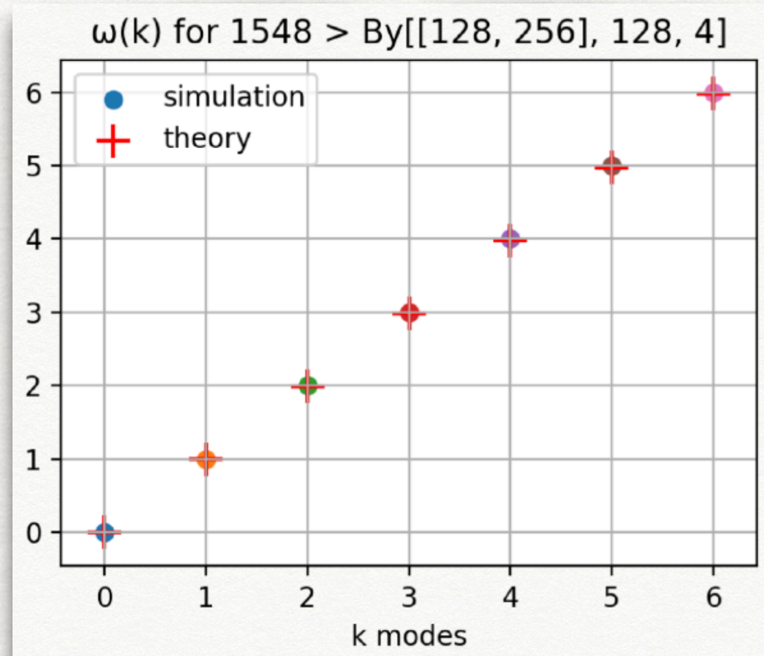
THE VALIDATION TESTS

-) TIME INDEPENDENCE OF EQUILIBRIUM STATES

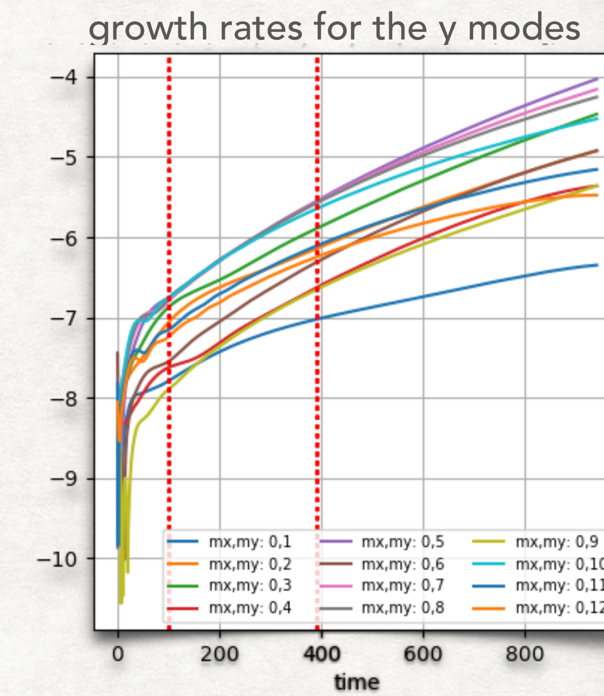
-) MONOCHROMATIC WAVE PROPAGATIONS:

-) THE ALFVÉN WAVES

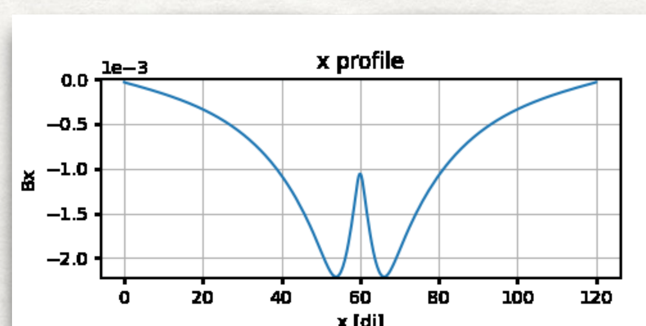
-) THE MAGNETO-SONIC WAVES

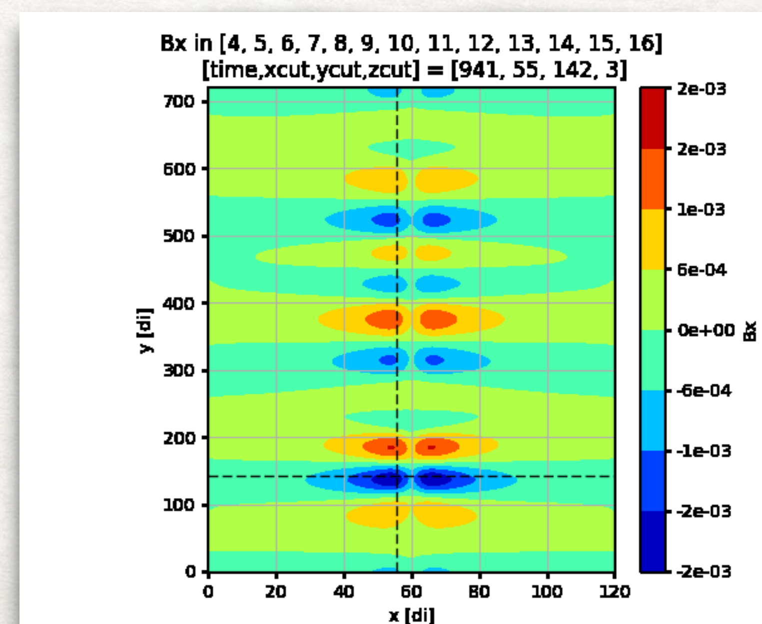


-) THE TEARING MODE INSTABILITY [FURTH ET AL.,1963]



THE RESULTS =>





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THE 4-FLUID CODE

… some algorithms are under study:

0. Electric field

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

1. Ions densities

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

2. Ions Momenta

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

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

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

4. Magnetic field

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

5. Electrons densities

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

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

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

7. Evolve $\mathbf{E}$:

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

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 :

$$n^*_{i1} = n_{i1} - \nabla.(\boldsymbol{\varphi}_{i1}) \quad (1)$$

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

- momentums :

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

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

- fermetures :

$$p^*_{i1} = K_{i1}(n^*_{i1})^{\gamma_{i1}} \quad (5)$$

$$p^*_{i2} = K_{i2}(n^*_{i2})^{\gamma_{i2}} \quad (6)$$

2) On avance B :

- Faraday :

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

3) On avance les densités électroniques :

- différence des continuités :

$$n^*_{e2} - n^*_{e1} = n_{e2} - n_{e1} - \nabla.(\boldsymbol{\varphi}_{e2} - \boldsymbol{\varphi}_{e1}) \quad (8)$$

- 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 φ électroniques et E :

- Ampère (au temps t+1) :

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

- différence des momentums :

$$m_e(\boldsymbol{\varphi}^*_{e2} - \boldsymbol{\varphi}^*_{e1}) = m_e(\boldsymbol{\varphi}_{e2} - \boldsymbol{\varphi}_{e1}) - \nabla.\left[(p_{e2} - p_{e1})\mathbf{I} + m_e\left(\frac{\boldsymbol{\varphi}_{e2}\boldsymbol{\varphi}_{e2}}{n_{e2}} - \frac{\boldsymbol{\varphi}_{e1}\boldsymbol{\varphi}_{e1}}{n_{e1}}\right)\right]$$

$$-q[(n_{e2} - n_{e1})\mathbf{E} + (\boldsymbol{\varphi}_{e2} - \boldsymbol{\varphi}_{e1}) \times \mathbf{B}] \quad (13)$$

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

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

$$m_e(\boldsymbol{\varphi}^{**}_{e2} + \boldsymbol{\varphi}^{**}_{e1}) = m_e(\boldsymbol{\varphi}^*_{e2} + \boldsymbol{\varphi}^*_{e1}) - \nabla.\left[(p^*_{e2} + p^*_{e1})\mathbf{I} + m_e\left(\frac{\boldsymbol{\varphi}^*_{e2}\boldsymbol{\varphi}^*_{e2}}{n^*_{e2}} + \frac{\boldsymbol{\varphi}^*_{e1}\boldsymbol{\varphi}^*_{e1}}{n^*_{e1}}\right)\right]$$

$$-q[(n^*_{e2} + n^*_{e1})\mathbf{E}^* + (\boldsymbol{\varphi}^*_{e2} + \boldsymbol{\varphi}^*_{e1}) \times \mathbf{B}^*] \quad (14)$$

work in progress…

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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

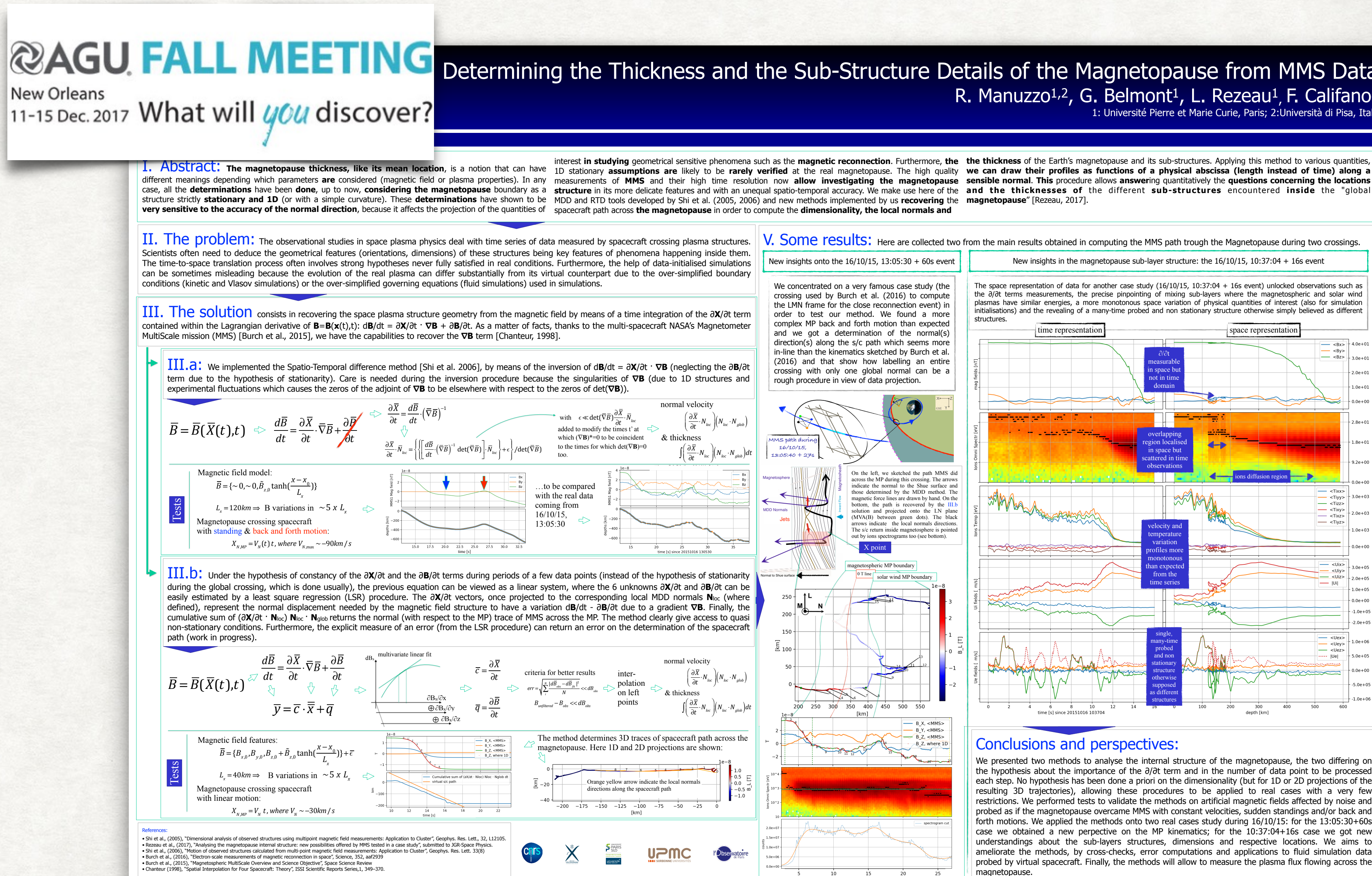
   3. A paper as co-author in magnetopause frame determination (Denton, work in progress)

PRESENTATION FOR THE UNIPI SEMINAR 2=>3

SUMMARY

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

AGU 2017 IN NEW ORLEANS



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

PRESENTATION FOR THE UNIPI SEMINAR 2=>3

SUMMARY

- The target
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- **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

End

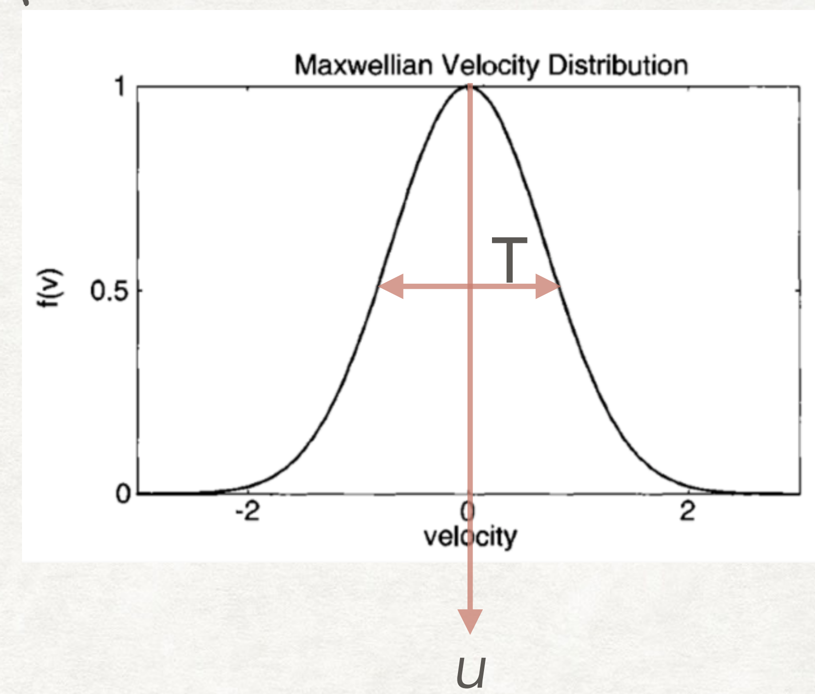
References

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:

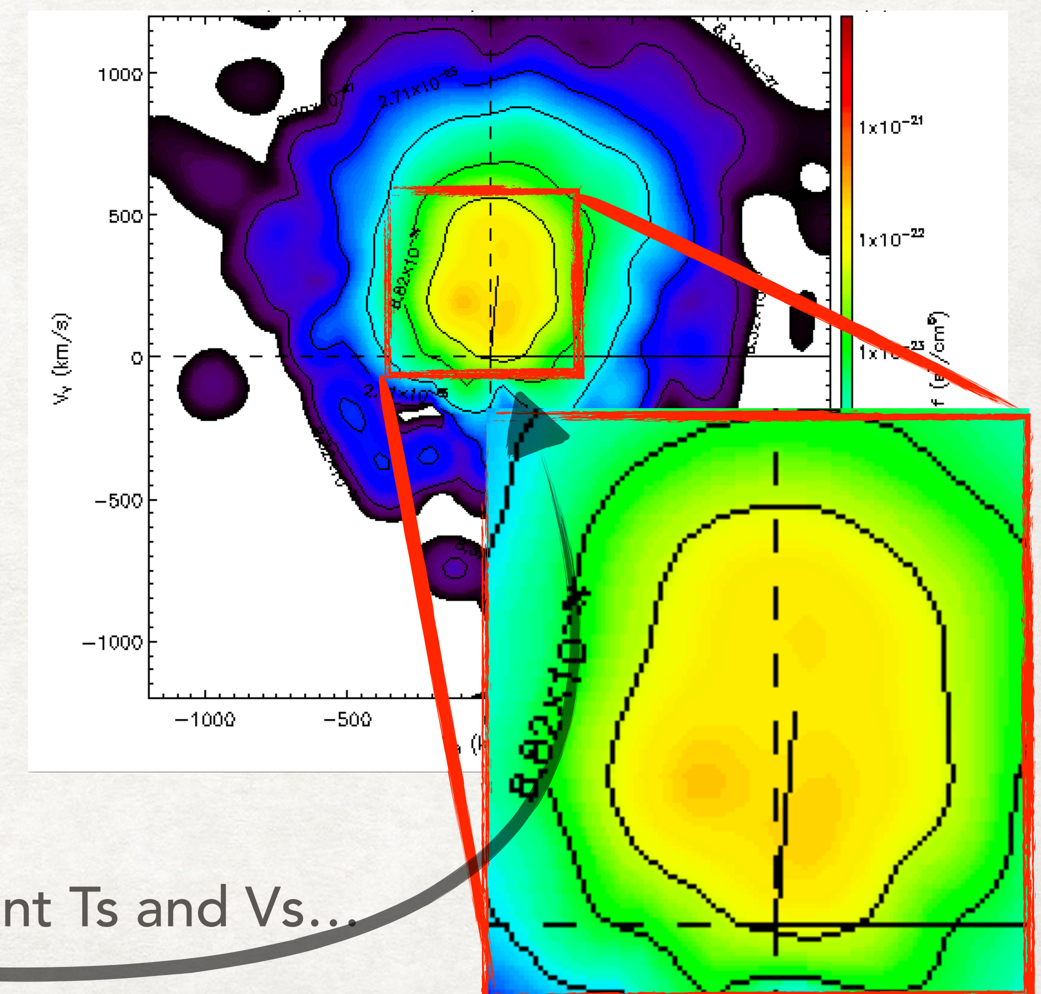
$$f_{MB}(v) = n(\frac{m}{2\pi kT})^{3/2} Exp(-\frac{m(v-u)^2}{2kT})$$



-) 1V Hermite transform representation[*]:

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

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



-) 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 Ts and Vs…

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

return

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

$$\overline{\overline{G}} = \nabla \overline{B} \qquad \overline{n} \cdot \overline{\overline{G}} = \overline{D} = \frac{\partial \overline{B}}{\partial \overline{n}}$$

If **n** = **N** was the invariant direction along which all the parameters remain constant => $D^2 = 0$

$$diagonalization(\overline{\overline{G}}\,\overline{\overline{G}}^T) \begin{cases} \lambda_1 & \overline{v}_1 & \text{maximum} \\ \lambda_2 & \overline{v}_2 & \text{intermediate} \\ \lambda_3 & \overline{v}_3 & \text{minimum} \end{cases} \Bigg\} \text{ of } \mathbf{D}$$

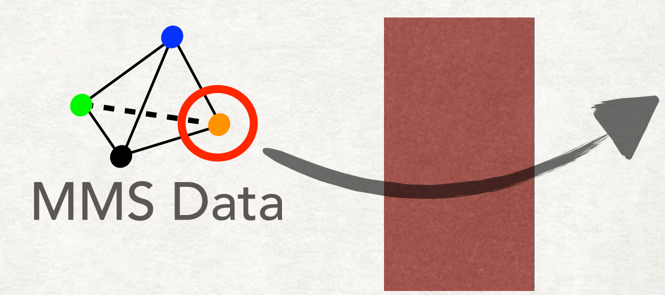
$\lambda_1 \gg \lambda_2 \wedge \lambda_3$ => 1D str.

$\lambda_1 \sim \lambda_2 \gg \lambda_3$ => 2D str.

$\lambda_1 \sim \lambda_2 \sim \lambda_3$ => 3D str.

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

Hp.: stationarity and 1D



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

return

Methods used to find the normal to the magnetopause

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

Single spacecraft

Minimum Variance Analysis method

1) Find **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: **L**, **M**, **N**

Pro: simple hypotheses
Vs: bad determination if not 1D

BV method

1) Other hypotheses needed:
- -) no flow through the magnetopause
- -) **B** behaves like:

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

where:

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

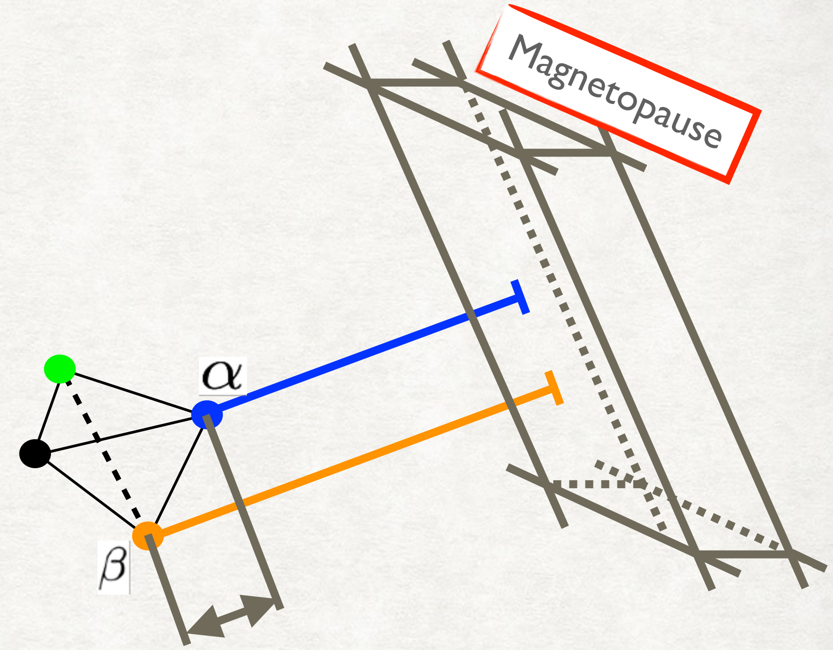
and

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

Pro: particle data involved too
Vs: Hypotheses

Multi spacecraft

Constant Velocity Approach method



→ $\triangle t_{\alpha\beta}$

→ $\mathbf{r}_{\alpha\beta}$

↓

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

Pro: Less hypoth, Simple, Mean
Vs: Problem with MMS data

return