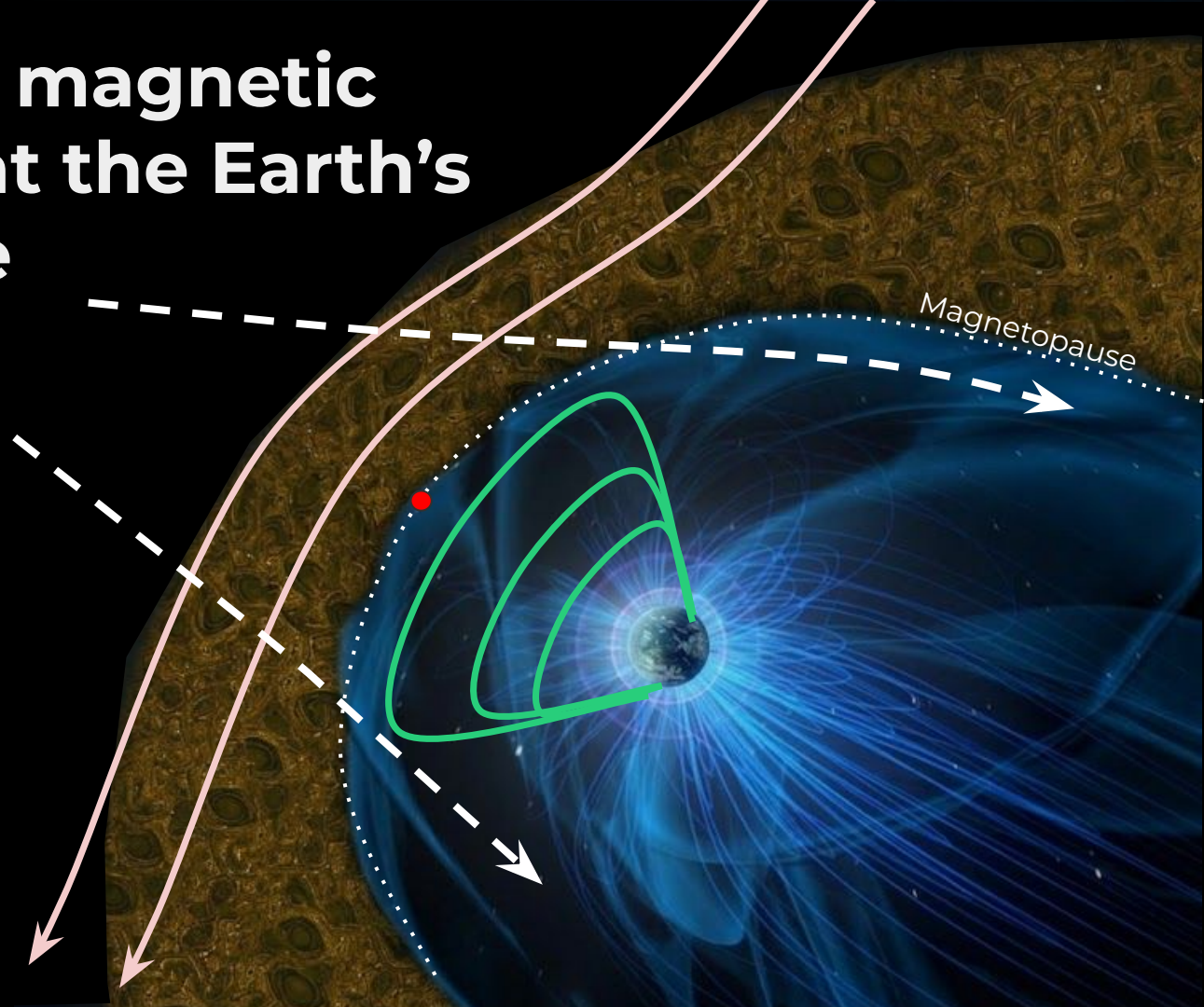


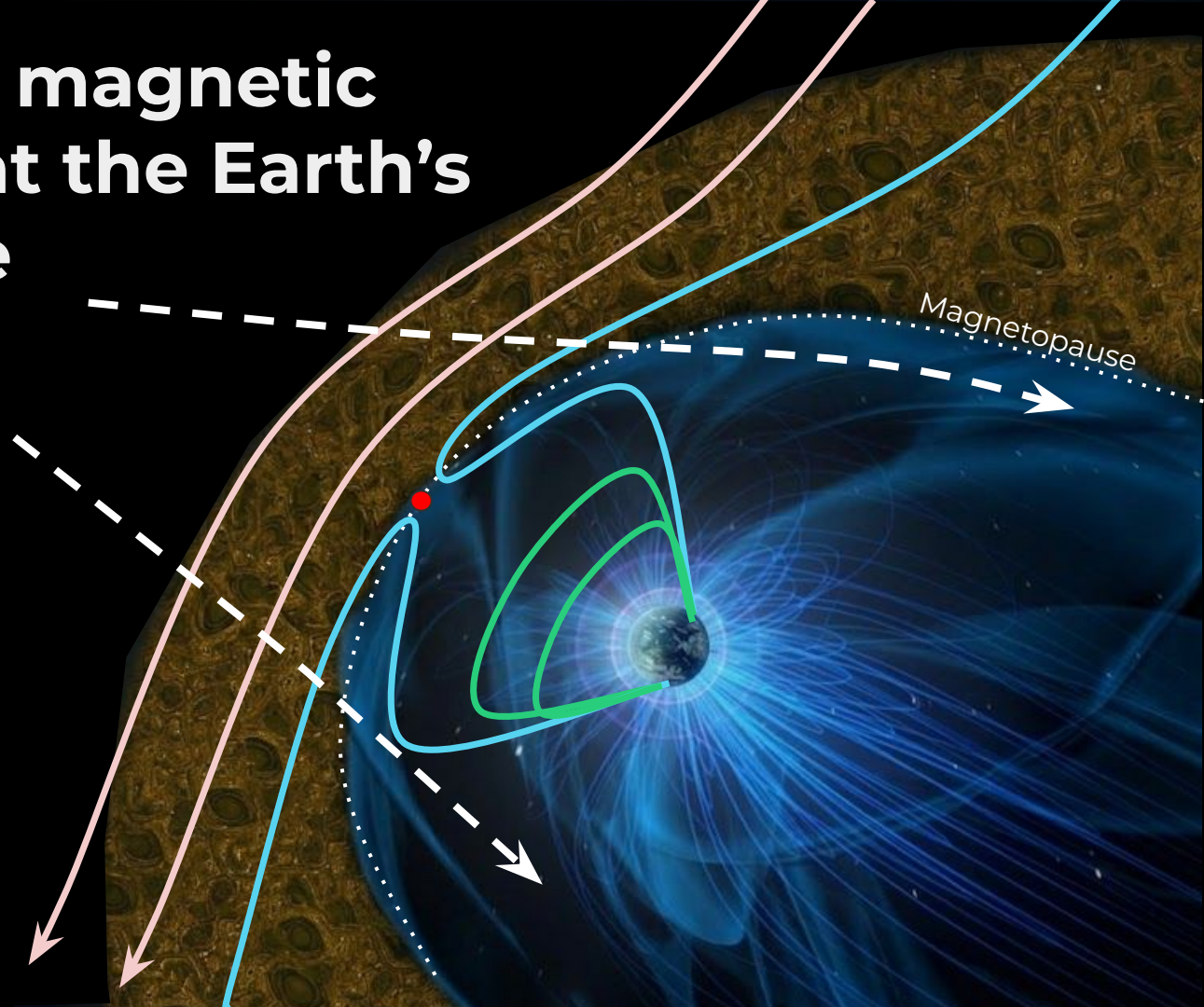
A new view on magnetic reconnection at the Earth's magnetopause

Nicolas Aunai



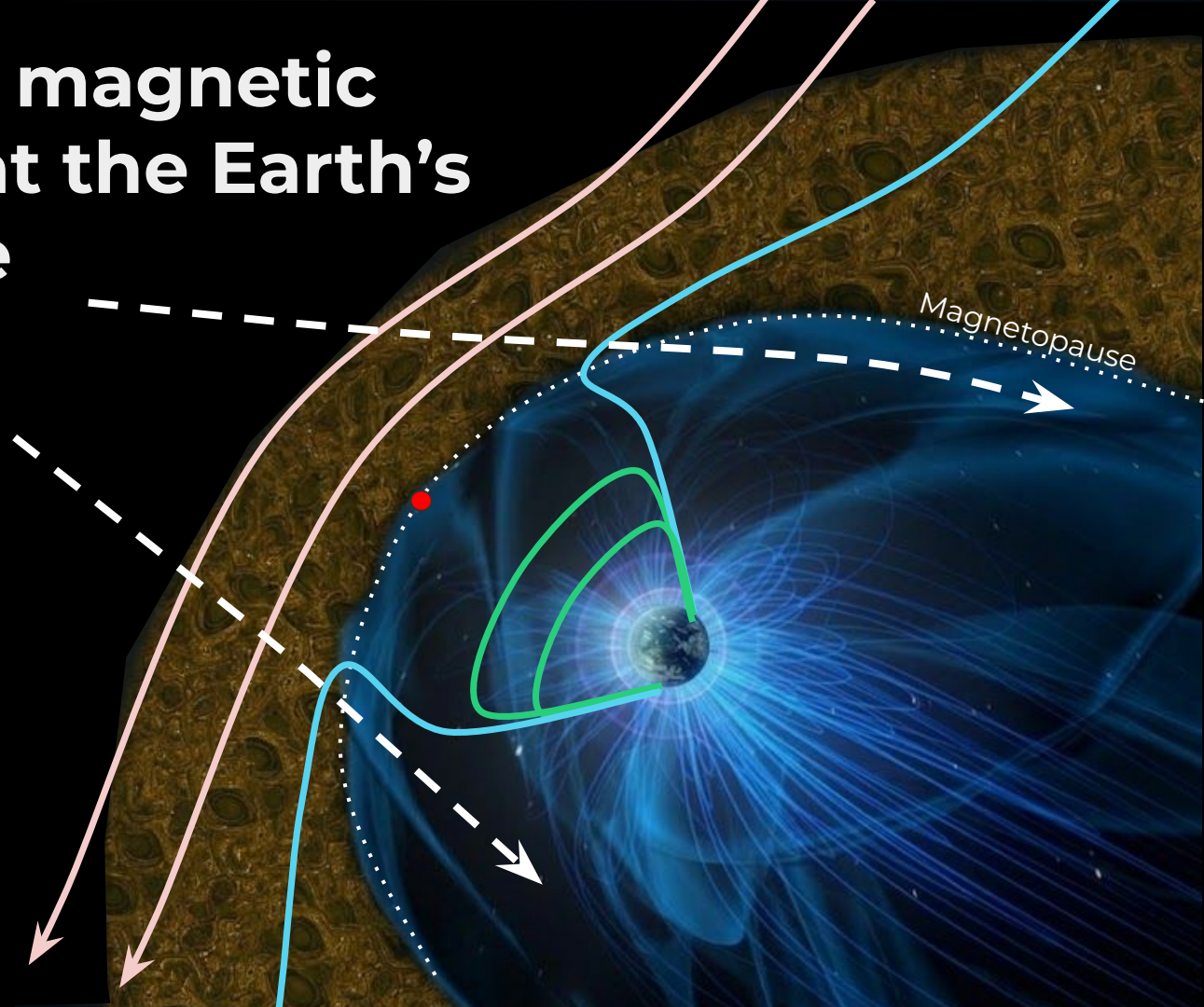
A new view on magnetic reconnection at the Earth's magnetopause

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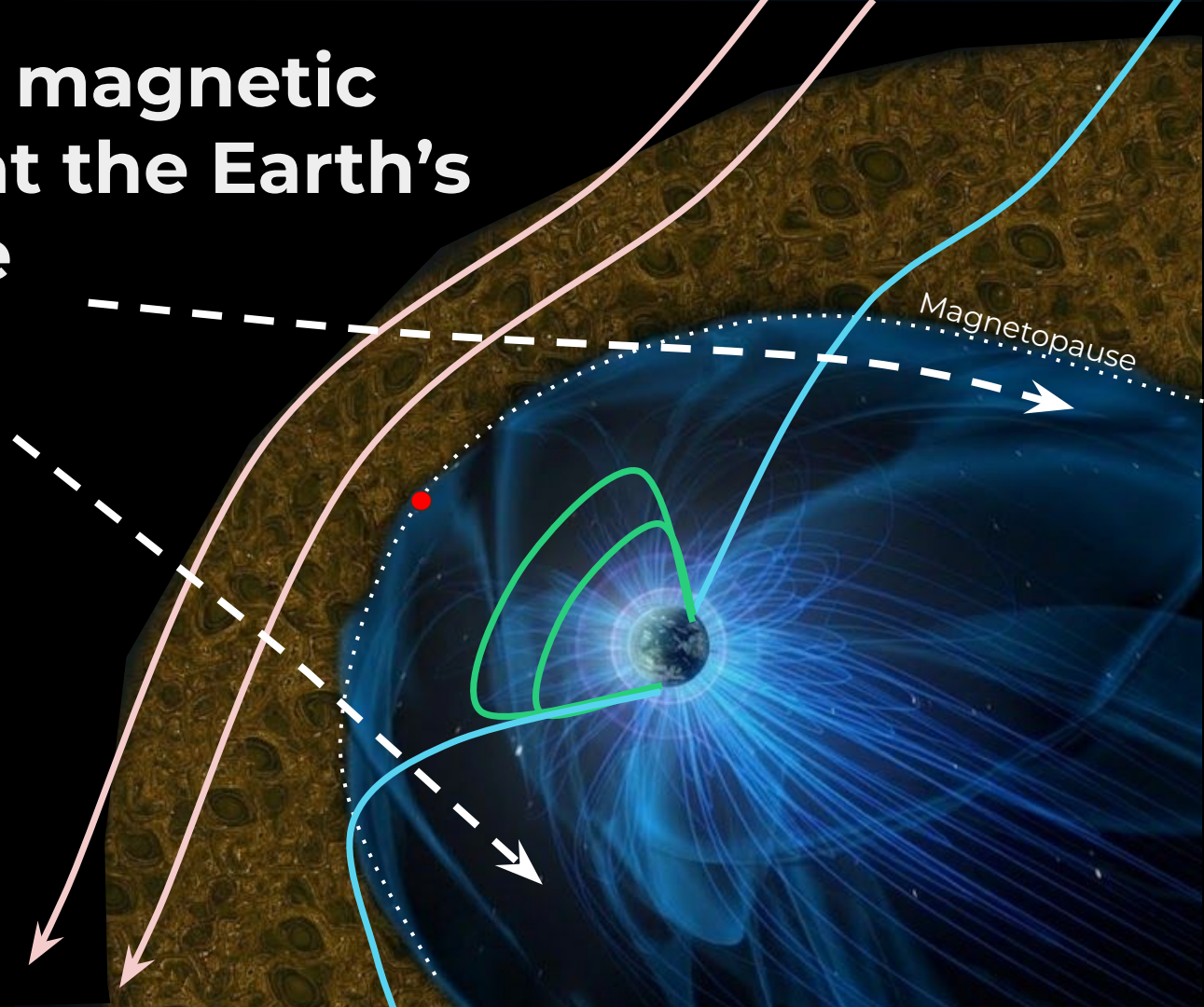
A new view on magnetic reconnection at the Earth's magnetopause

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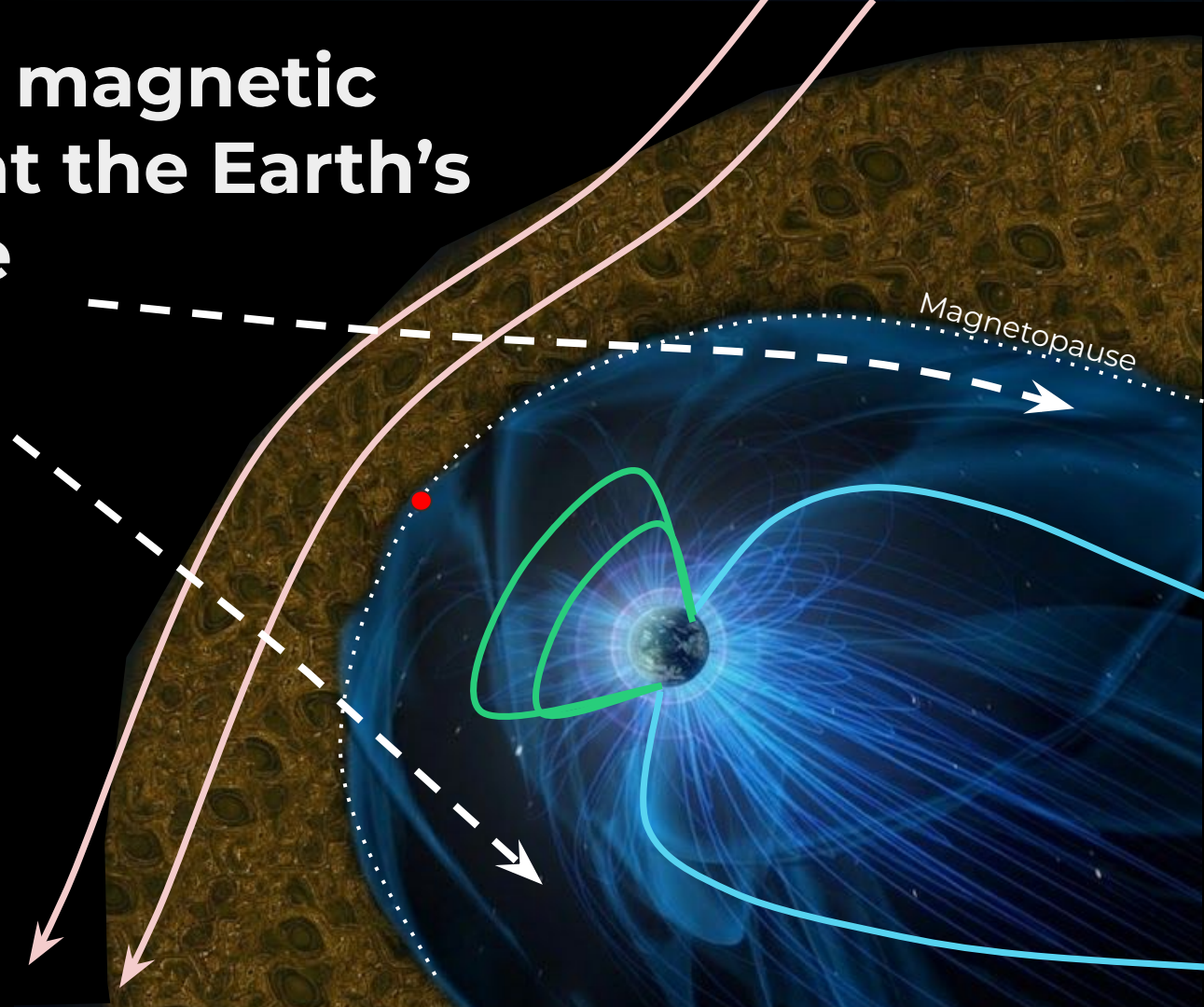
A new view on magnetic reconnection at the Earth's magnetopause

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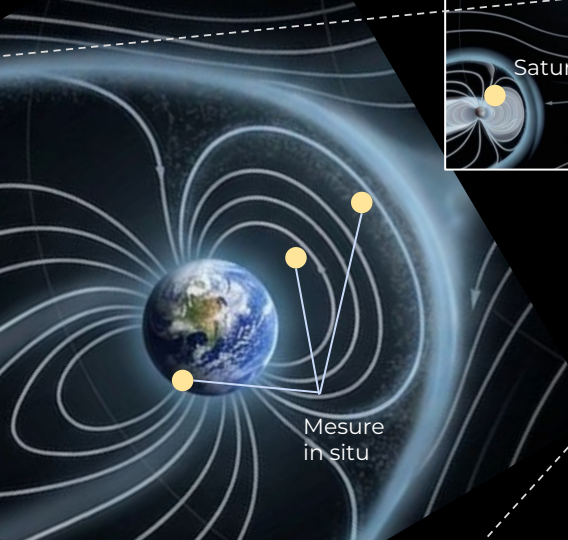
A new view on magnetic reconnection at the Earth's magnetopause

Nicolas Aunai

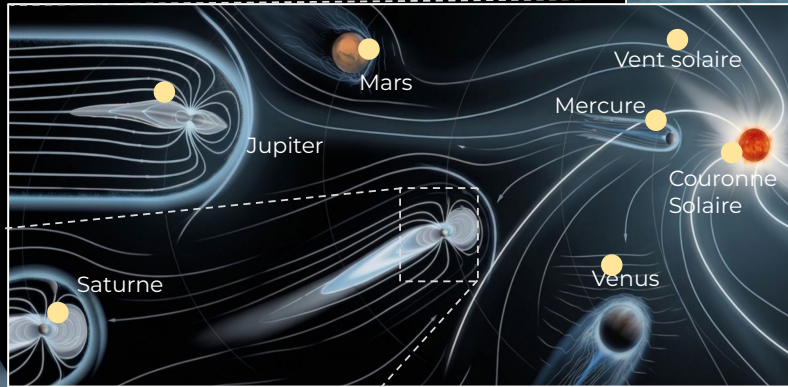


Universal process...

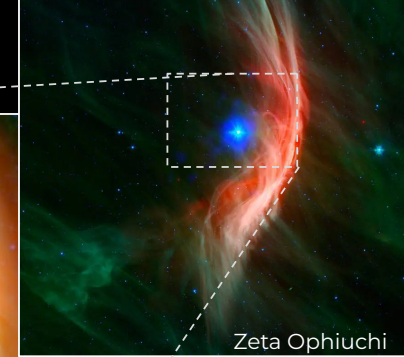
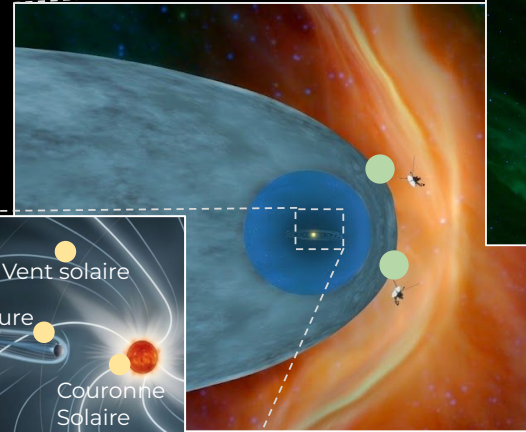
Earth's magnetosphere



Solar wind and planetary magnetospheres

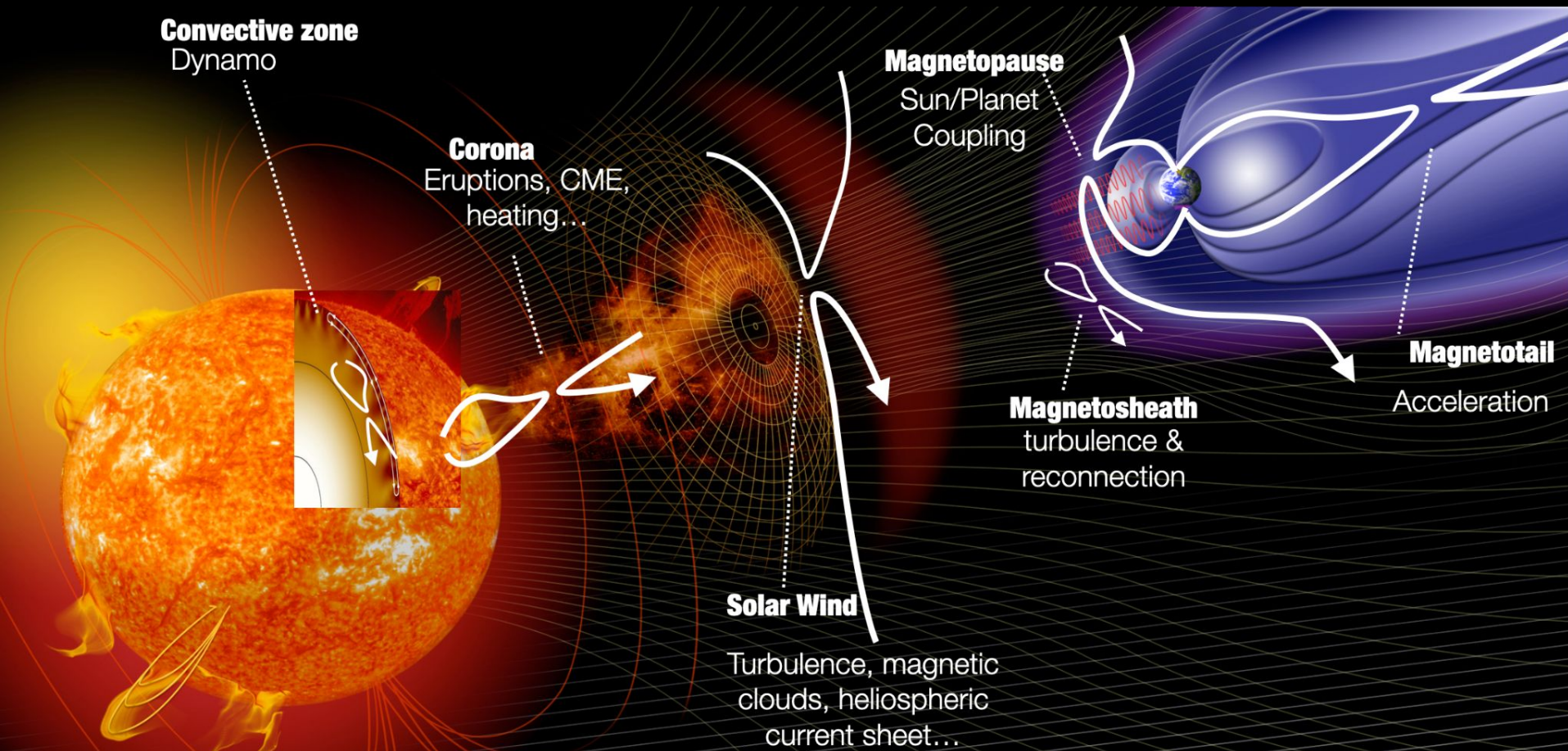


Heliosphere



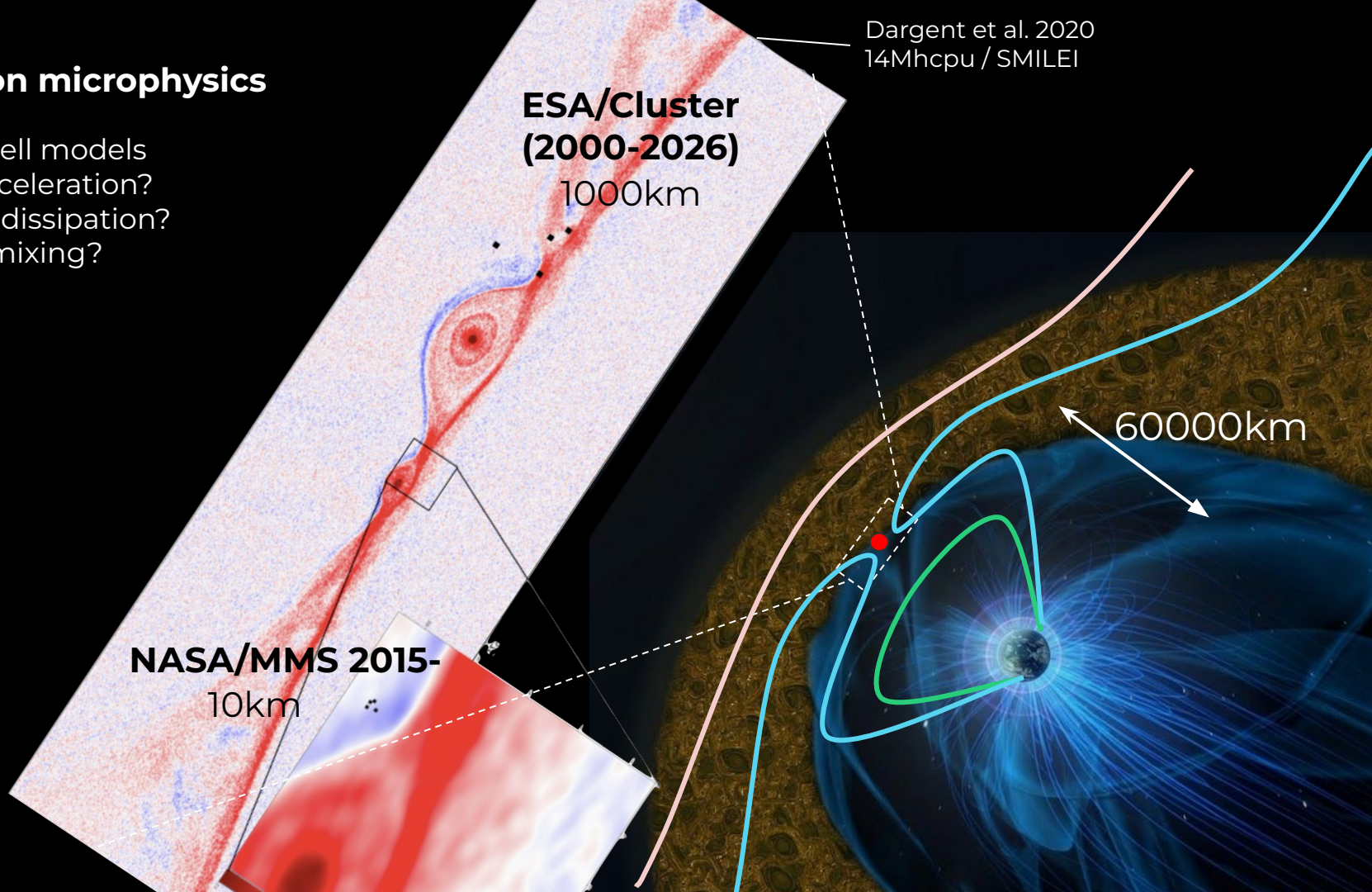
- **Societal impact** : space weather
- **Fundamental plasmas physics** : microphysics of reconnection
- **heliosphere/planetology** : wind/magnetosphere interaction
- **Astrophysics** : heating, acceleration of plasmas and particles....

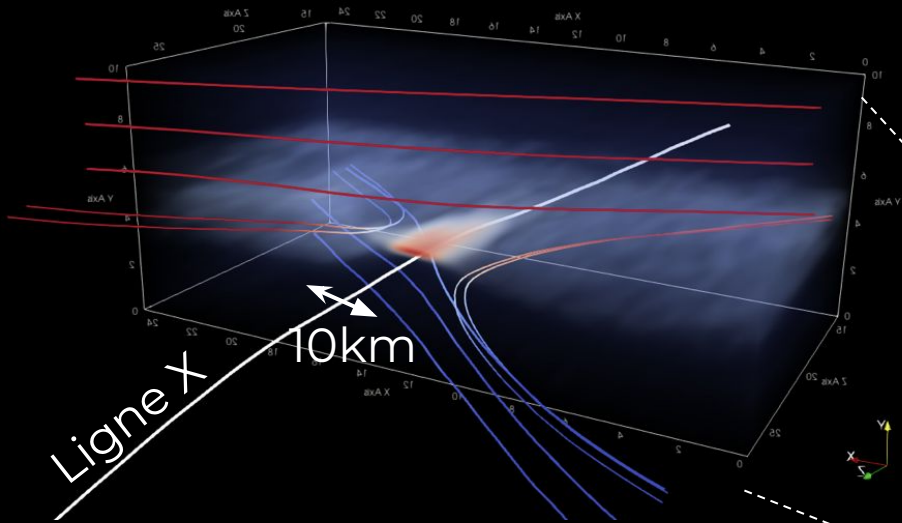
A key process in the heliosphere



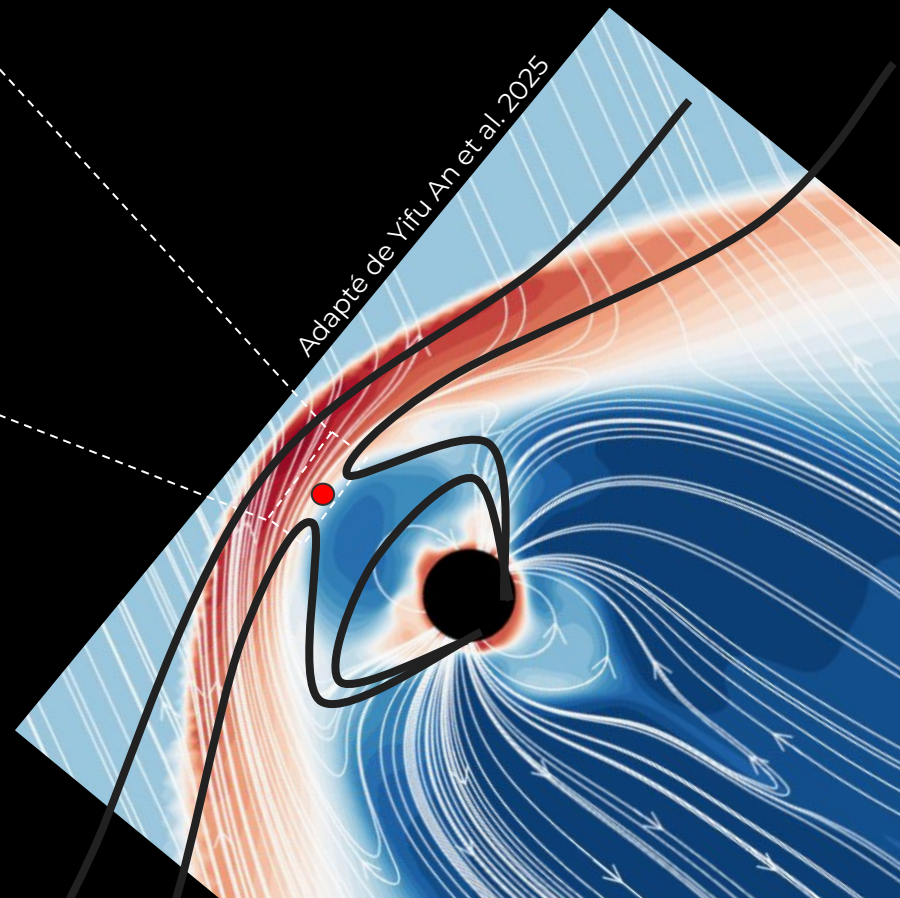
Reconnection microphysics

- Particle-In-Cell models
- Heating? Acceleration?
- Collisionless dissipation?
- Population mixing?

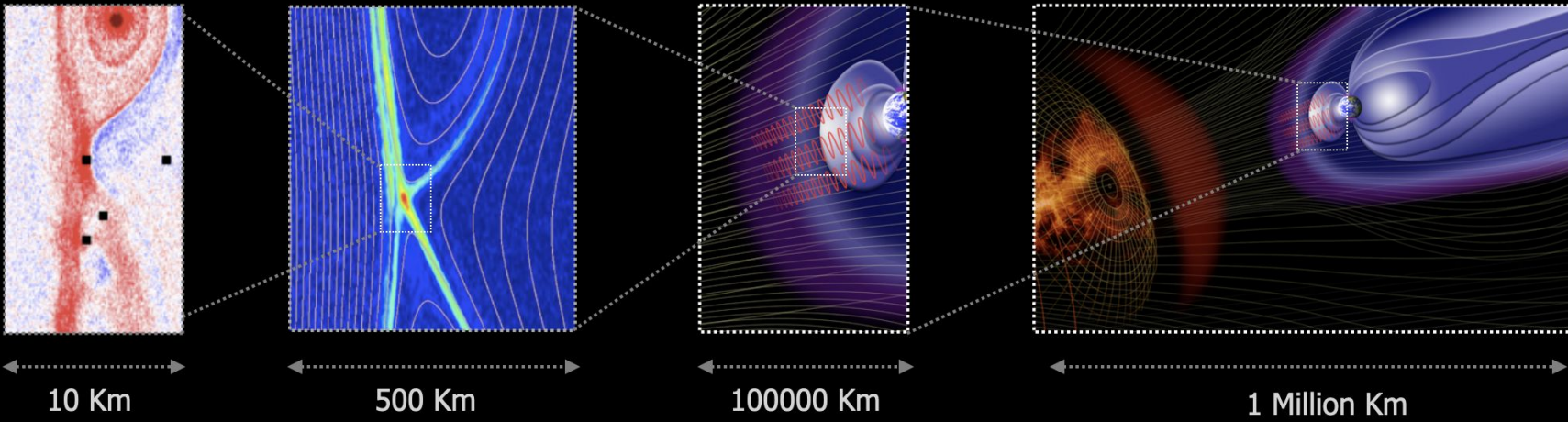




- dependency on solar wind/IMF and internal conditions?
- Where is reconnection occurring?



Multiple scales... multiple formalisms

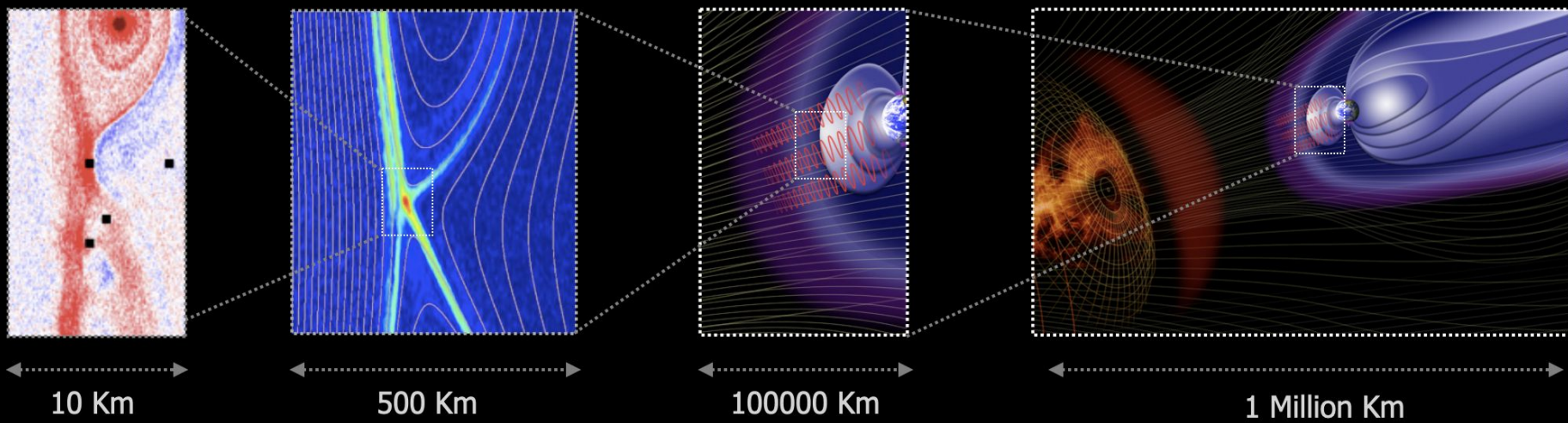


Fully Kinetic
 fully kinetic physics, but small domains, short durations

Fluid « MHD »
 Global scale system
 But no kinetic physics



Multiple scales... multiple formalisms



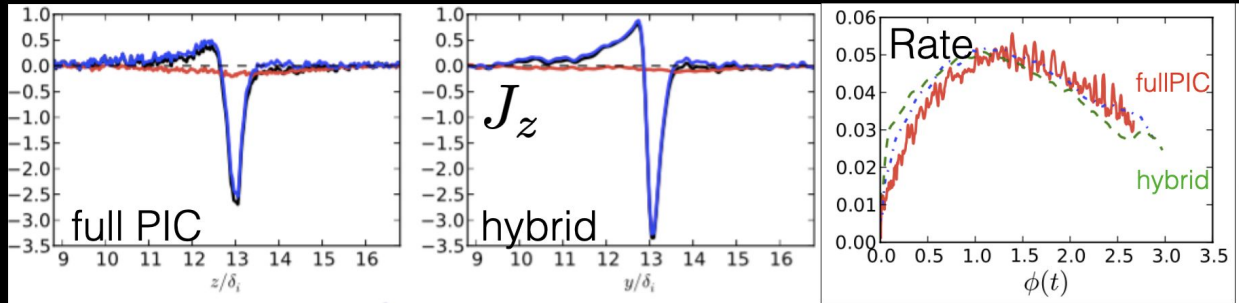
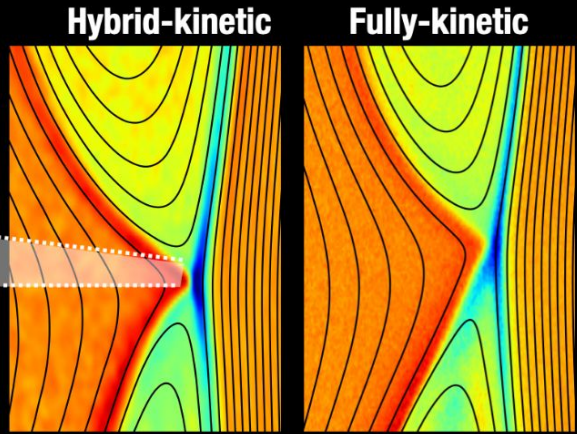
Hybrid Particle-In-Cell



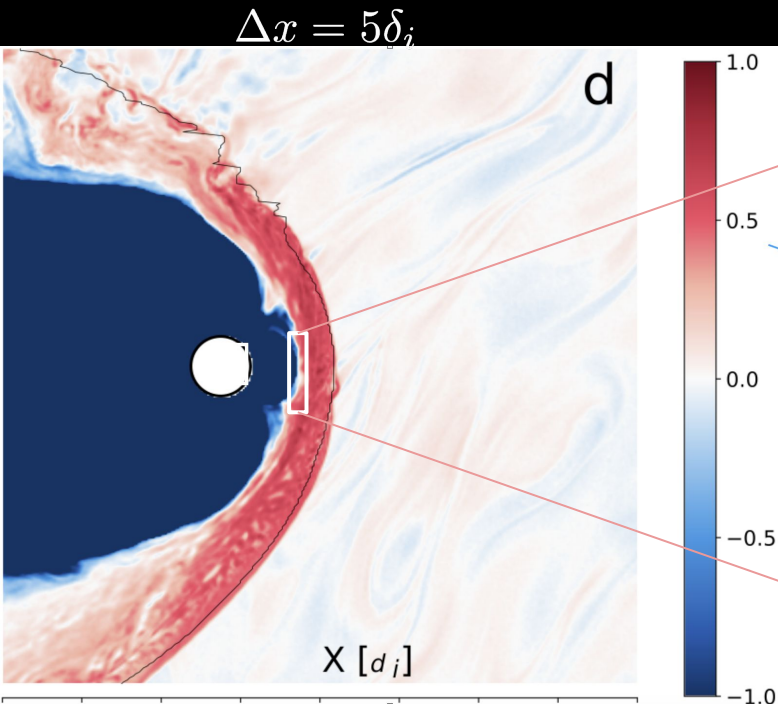
Kinetic ions is sufficient if simulations are well resolved

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left(-\mathbf{v}_i \times \mathbf{B} + \frac{\mathbf{j} \times \mathbf{B}}{ne} - \frac{\nabla P_e}{ne} - \nu \nabla^2 \mathbf{j} \right)$$

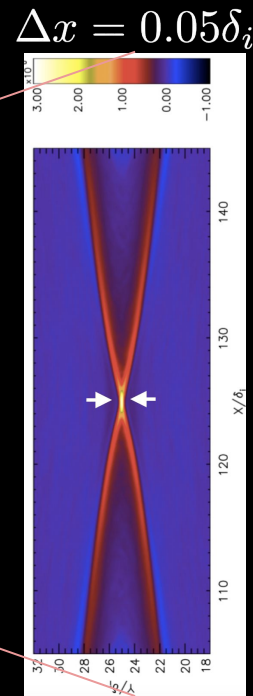
$\overleftrightarrow{\sim 100 \text{ km}}$ $\overleftrightarrow{\sim 10 \text{ km}}$



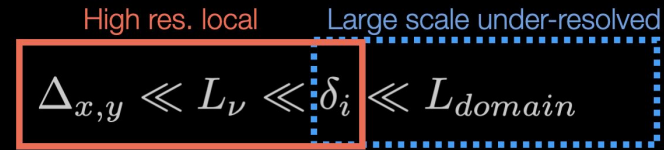
Well resolved and large scales... is very difficult...



[Behar et al. 2024]

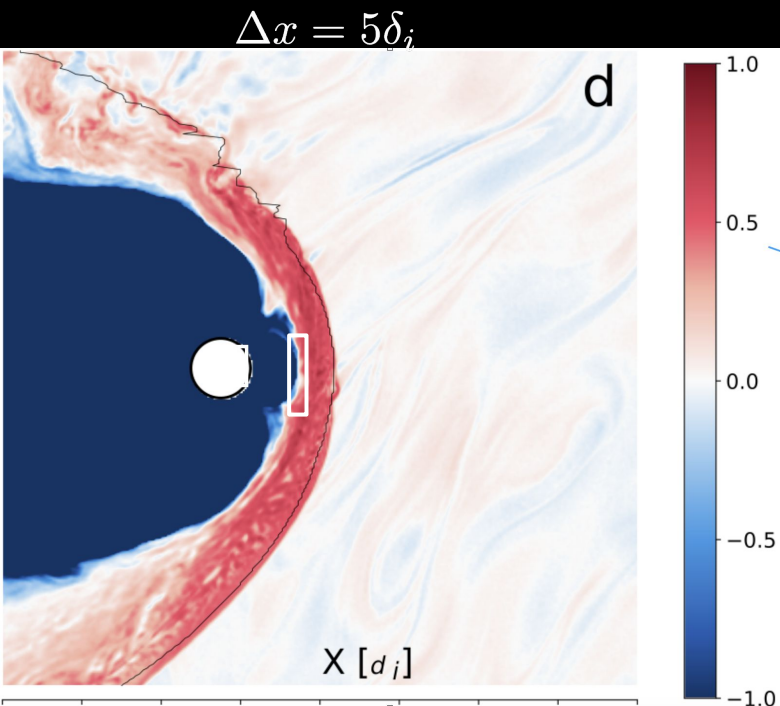


[Aunai et al. 2013]



Uniform mesh resolved (scaled down) global Earth is 100^3 times more cells and 100^2 more time steps

What is needed to go forward?



[Behar et al. 2024]

- Should we have the **same resolution everywhere?**
- Should we solve the **same equations everywhere?**

Adapt Mesh, Time step and Formalism

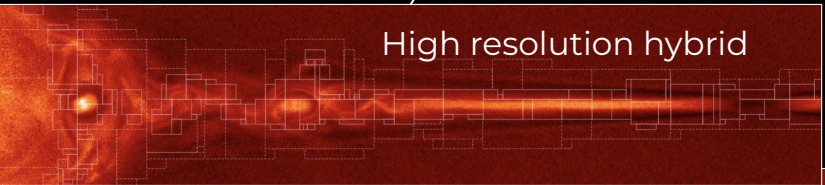
Hybride (PIC ions + fluid electrons) AMR



Hall MHD AMR



Adapt Mesh AND Model

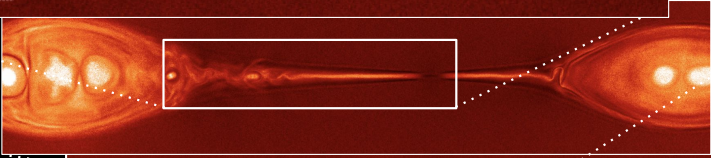


High resolution hybrid



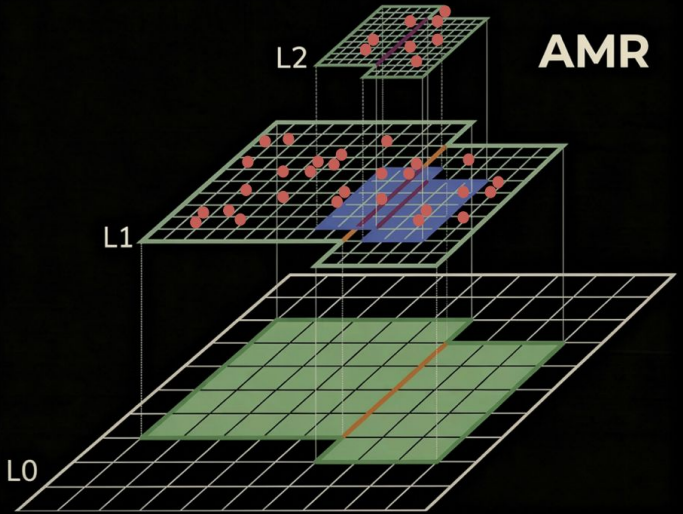
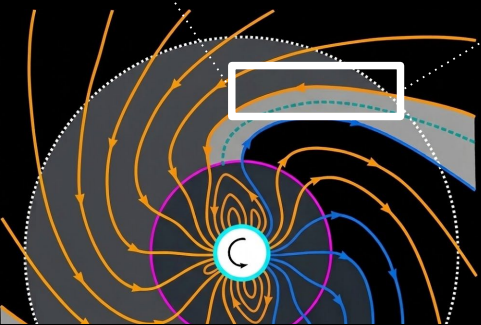
high resolution Hall MHD

[Caromel+ 2026 en prep]



Large scale low resolution

n

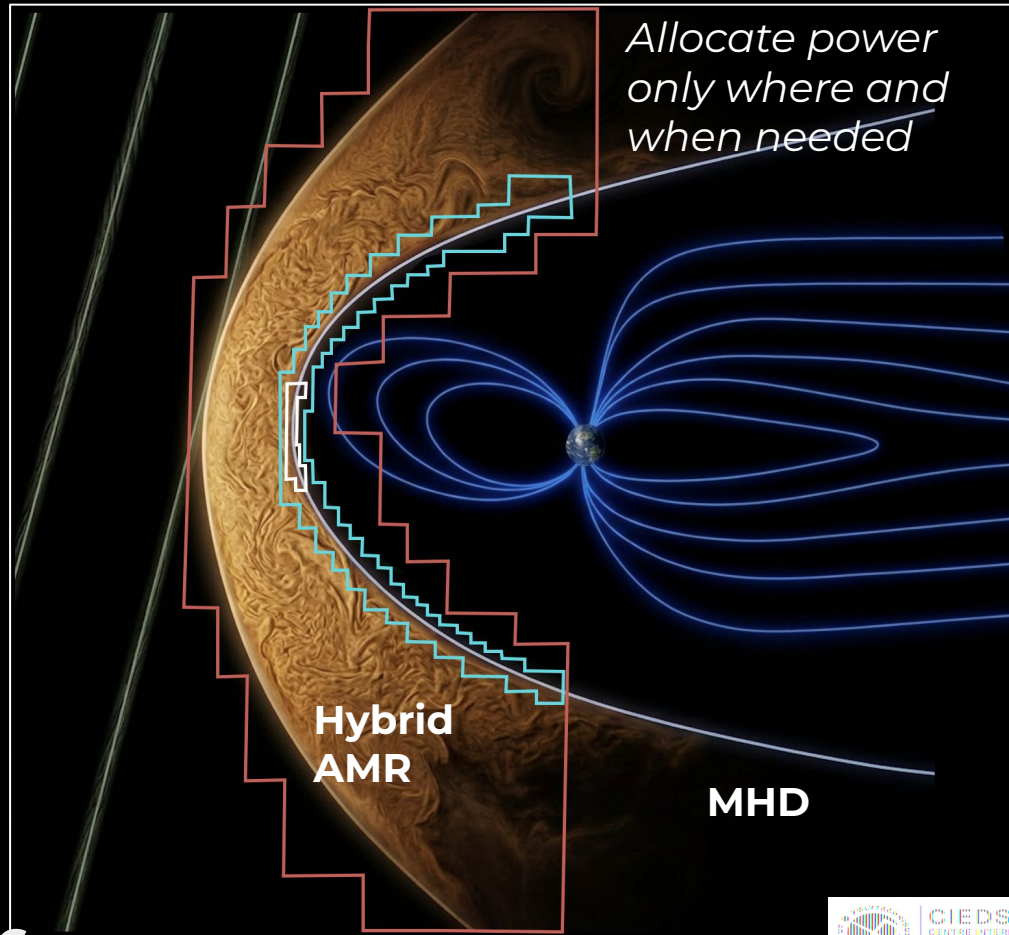


AMR

Available on GitHub – contact us

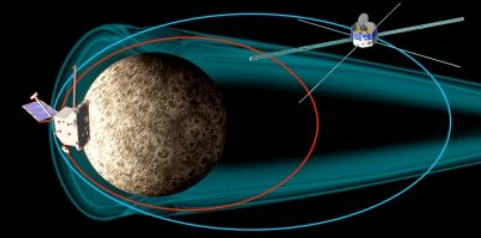


Perspectives for Earth and other planets



Mercury

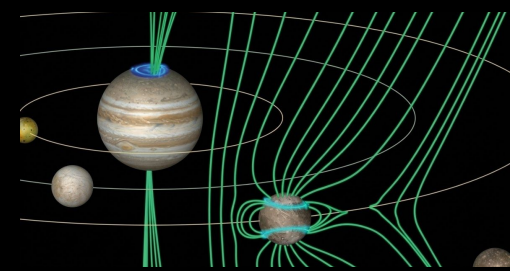
ESA/Bepi Colombo (2026)



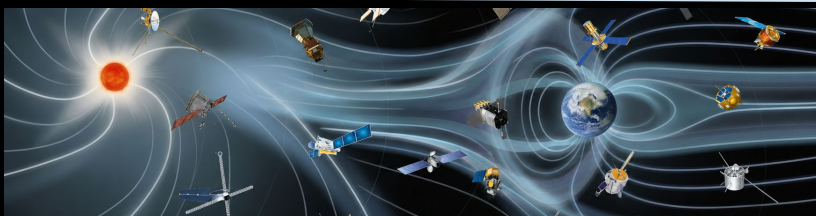
Ganymede

ESA/Juice (2034)

Hybrid magnetosphere in MHD magnetosphere



in situ data: sparse, complex and under-used data



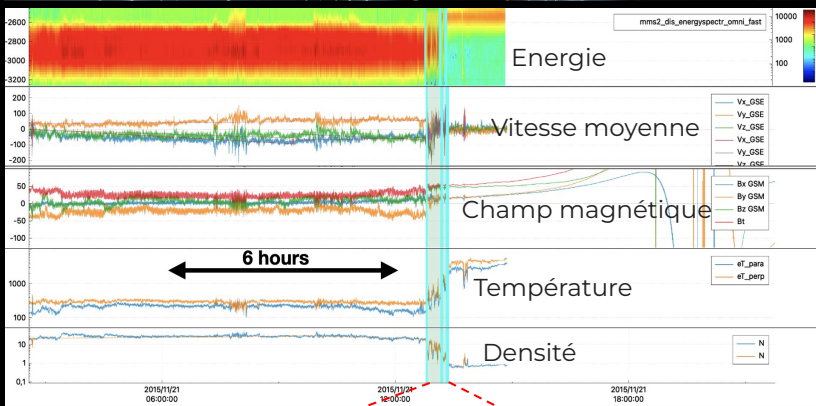
Multiple missions, decades of measurements

Natural complexity

- **complex signatures, multivariate, rare events**
- **great diversity** of the numerous causal parameters
- **local** viewpoint at the spacecraft
- “1D slice” in a 3D non-stationary systems

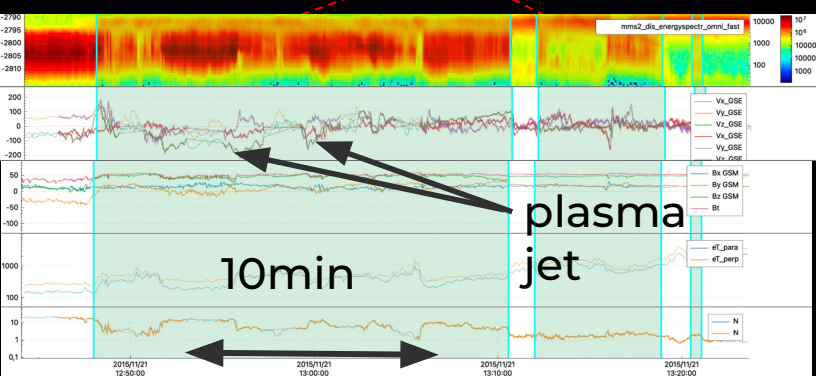
technical limitations :

- **funding is siloed** per mission
- multiple file formats, servers...
- **sparse and heterogeneous** data



very limited statistical representation of the system...

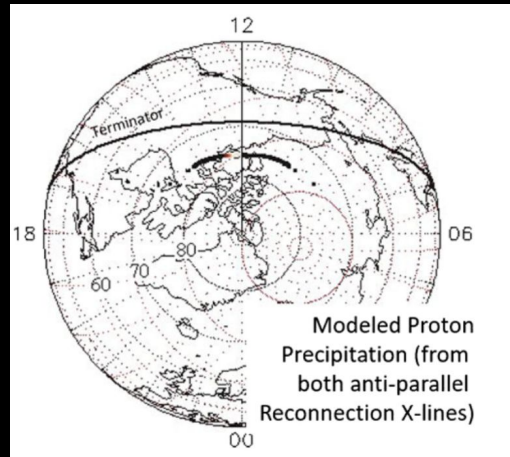
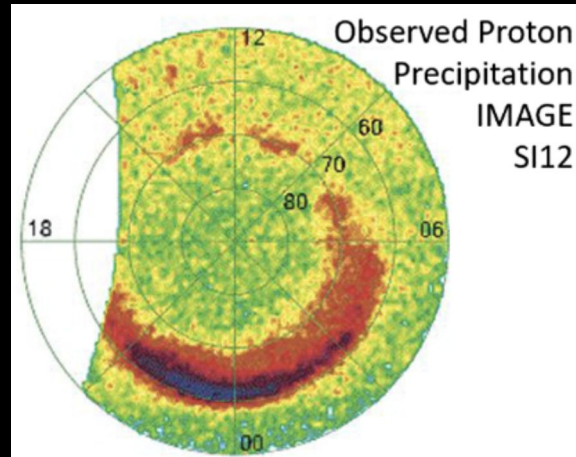
- “case studies” per mission
- generalization ?



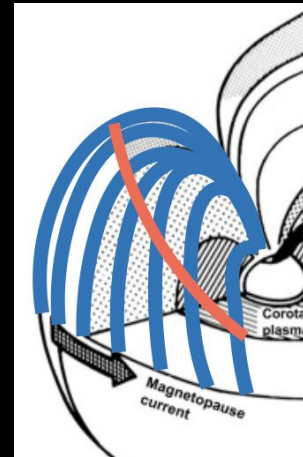
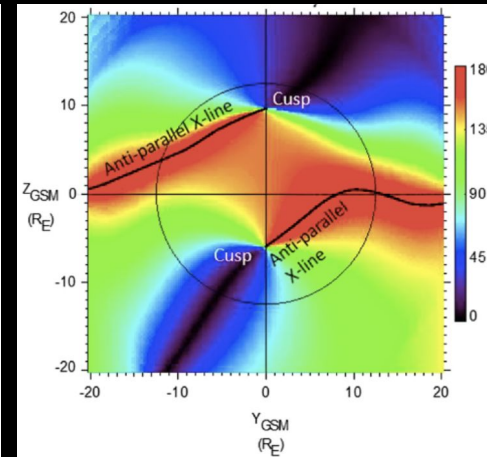
No global vision : how do processes distribute in the system ?

Global instantaneous X-line in antiparallel regions?

[Mende et al. 2000]

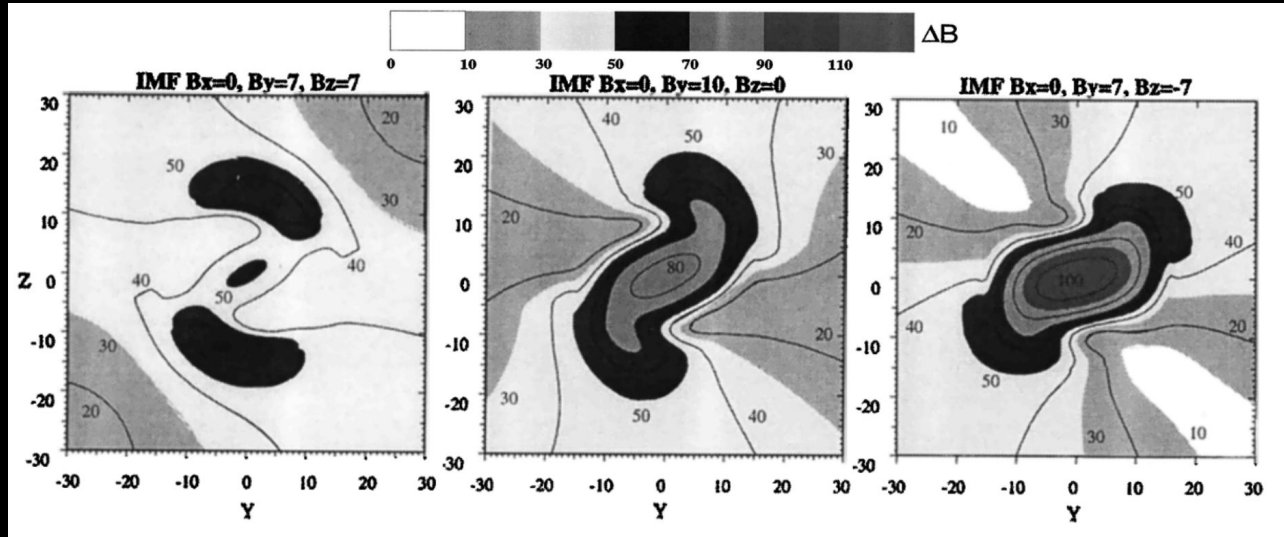
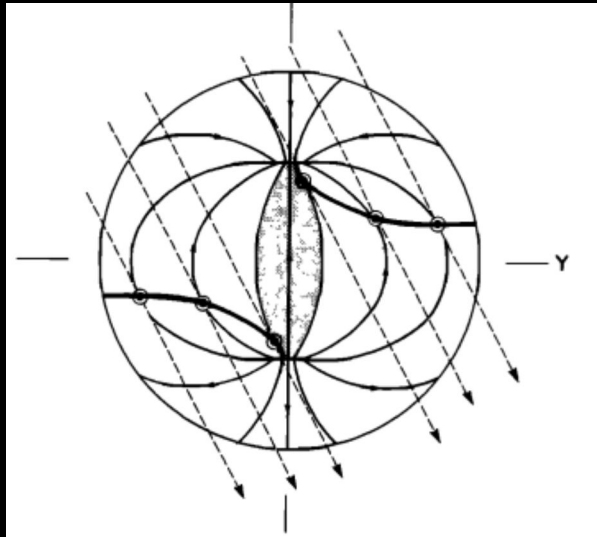


[Trattner et al. 2007]



- proton precipitation enlightens antiparallel regions
- instantaneous global X-line in antiparallel regions?
- but we see *locally* events with magnetic shears $< 180^\circ$

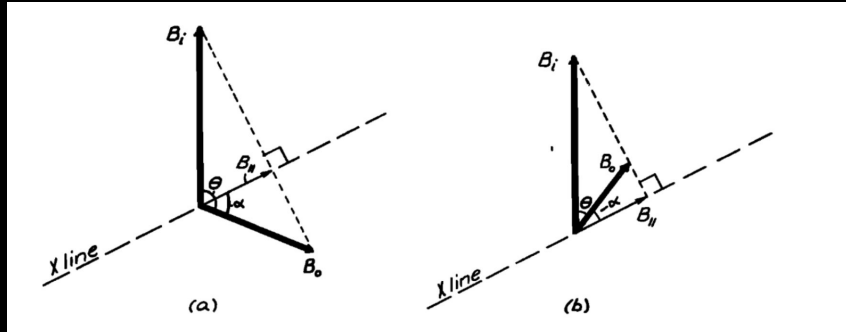
What constrains the X line to locate somewhere?



[Alexeev et al. 1998]

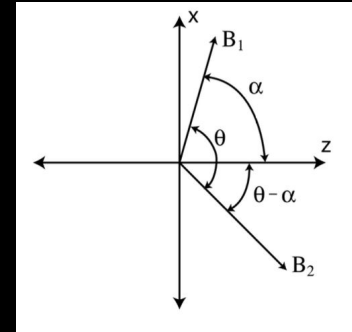
- Antiparallel magnetic shear?
- Regions of highest currents?

Simpler(?) and related : how does an X line *locally* orient?



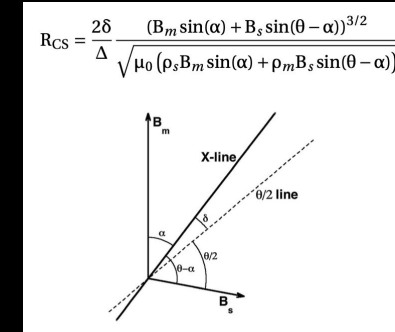
[Sonnerup et al. 1974]

X line locally aligned with current?
No! any angle... (cowley..)



[Swisdak & Drake 2007]

Maximize outflow
speed?



[Borovsky et al. 2013]

Maximize
Reconnection rate?

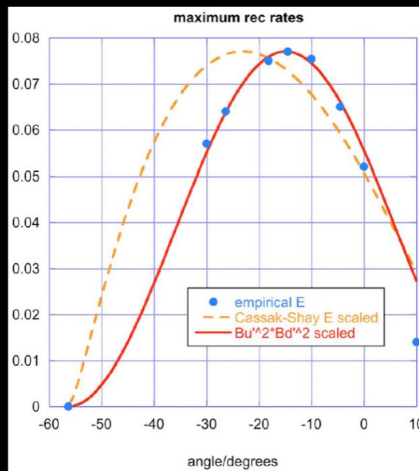
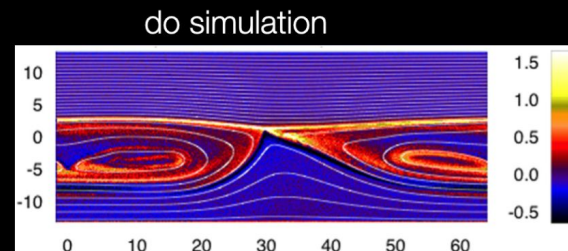
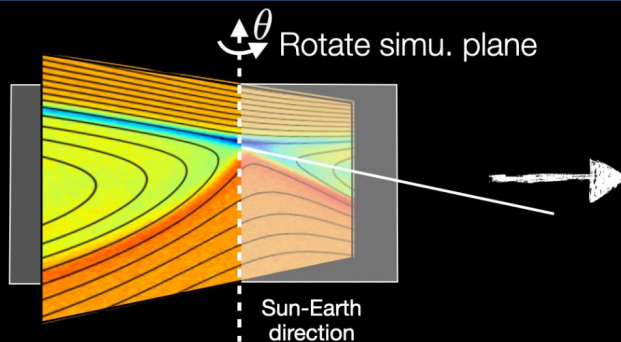
2D simulations: bisection plane reconnects the fastest

[Hesse et al. 2013, Aunai et al. 2016]

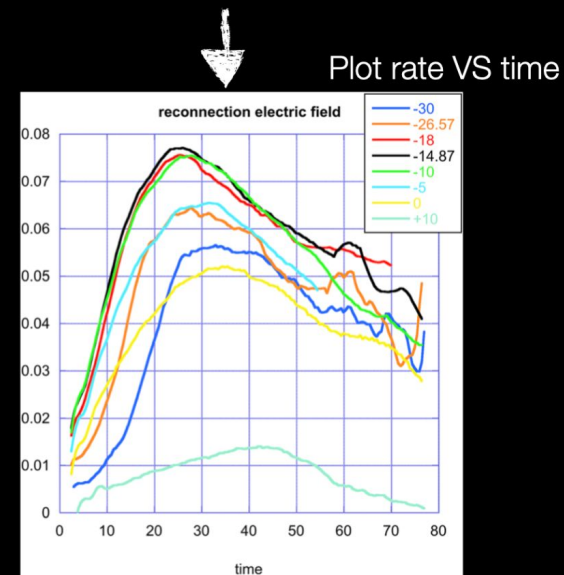
2D simulations for a given setup are ran for different simulation planes relative to the magnetic orientation

The plane perp. to the bisection of upstream field reconnects the fastest

It also is the plane maximizing the magnetic energy available to reconnection



max(Rate)
vs angle



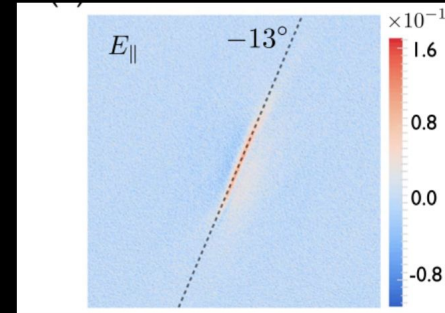
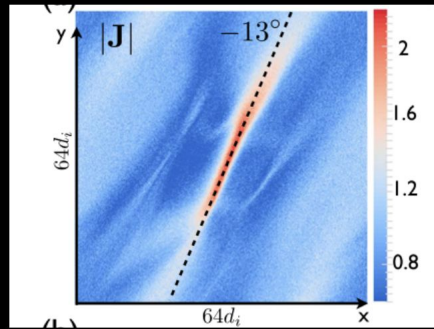
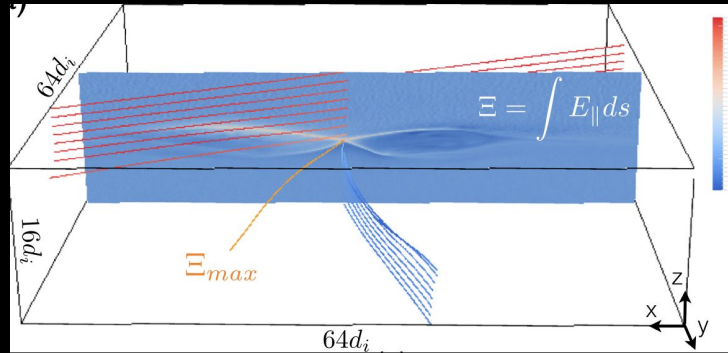
$$\max(B_{1x}(\theta)^2 B_{2x}(\theta)^2)$$

X line along bisector

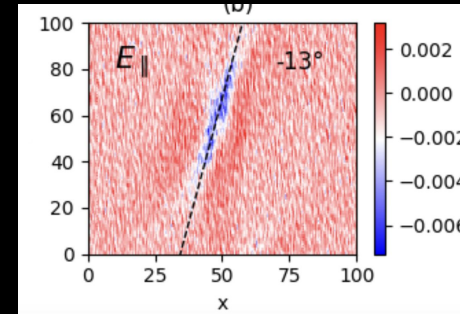
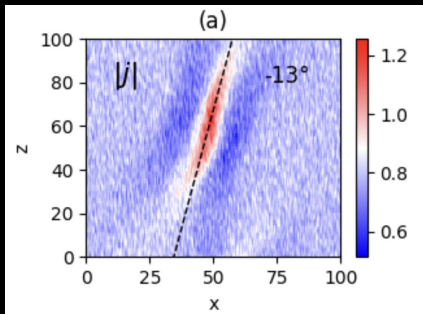
3D effects?

Confirmed with 3D local... fully and hybrid PIC models

[Liu et al. 2016]



Full PIC



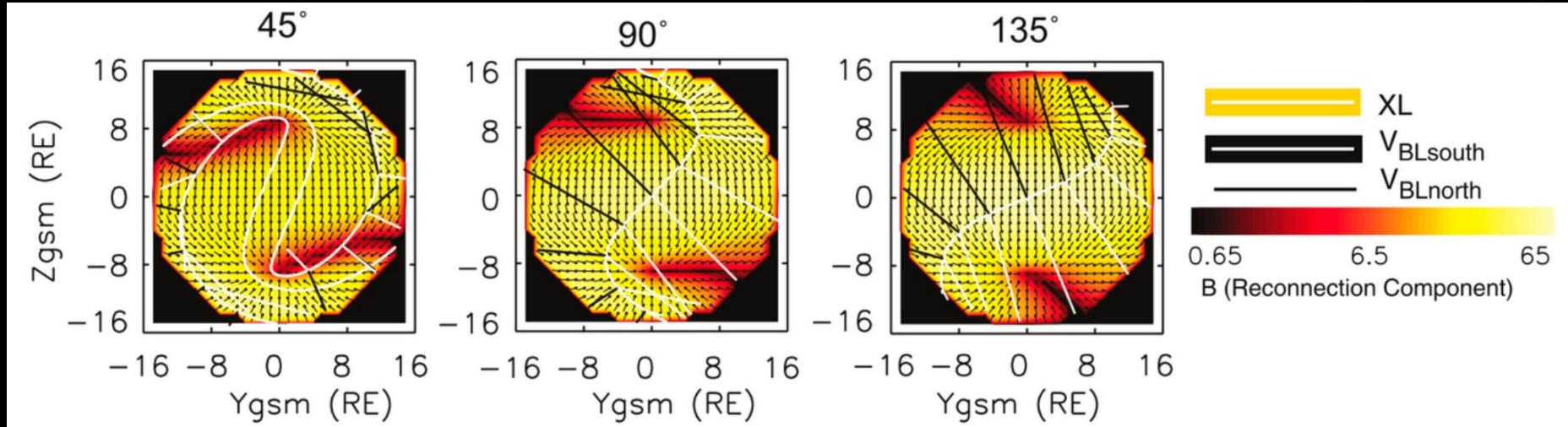
Hybrid PIC

Hall MHD with PHARE soon...

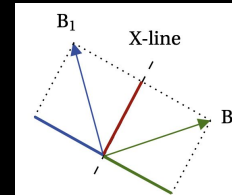
Global X line models: follow the local bisection?

Draw a line locally following the bisection of the magnetic field on each side of the magnetopause

[Moore et al 2002]

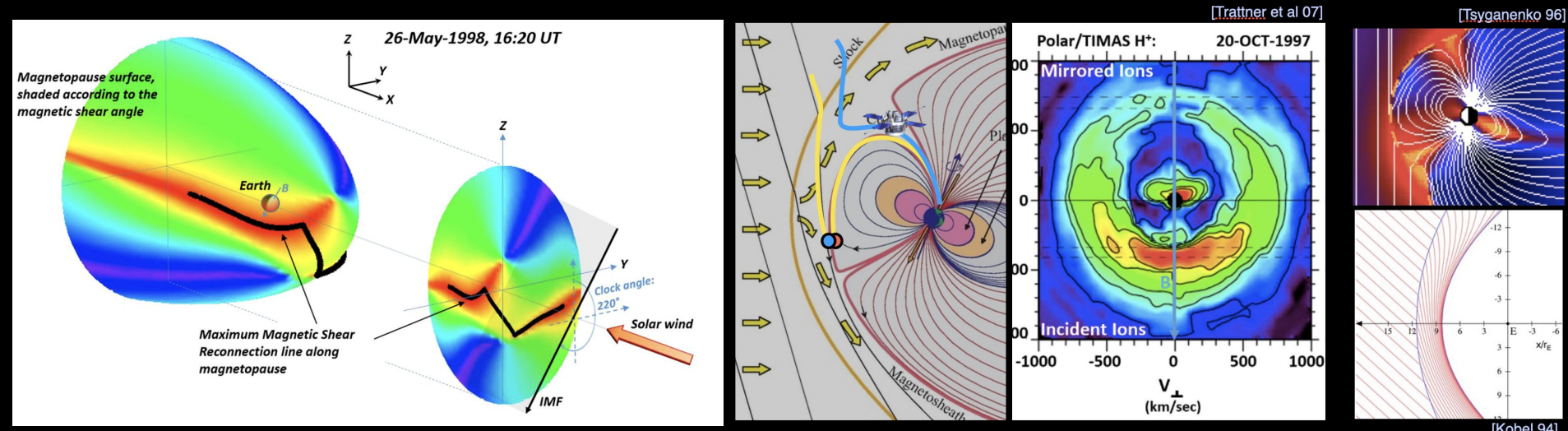


- simplified field models : symmetric amplitude (bisection = perp. bisector == Sonnerup)
- where to start the line? Arbitrarily choose where antiparallel components are the highest



Global X line models: Maximize the magnetic shear

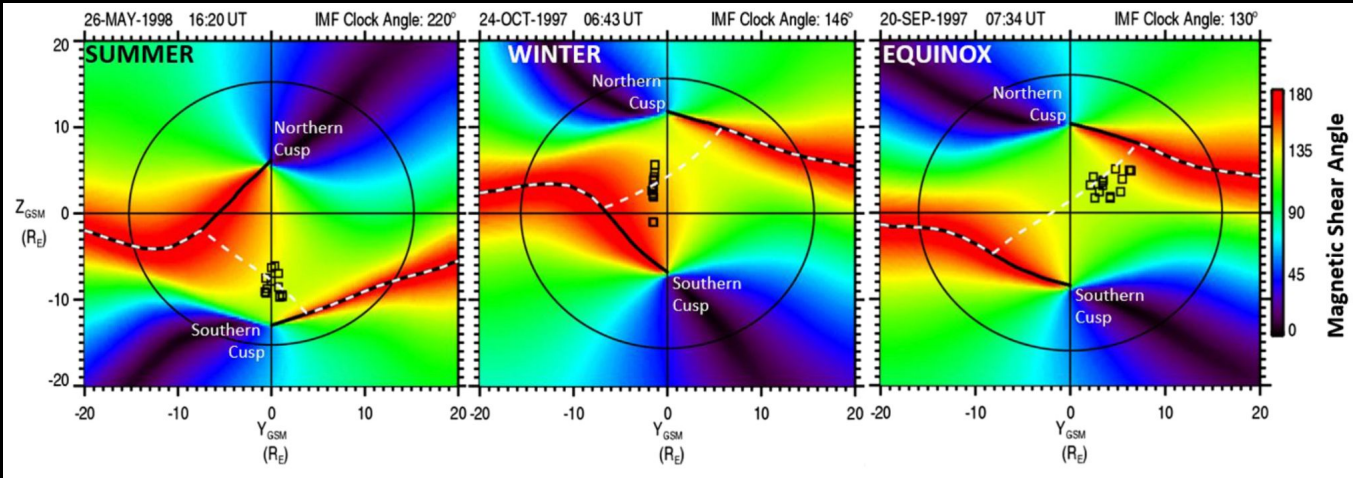
Inferring where the X line is from time of flight difference between precipitating and reflected ions



- simplified field models : symmetric amplitude (bisection = perp. bisector == Sonnerup)
- where to start the line? Arbitrarily choose where antiparallel components are the highest

Accelerated ions apparently come from highest shears

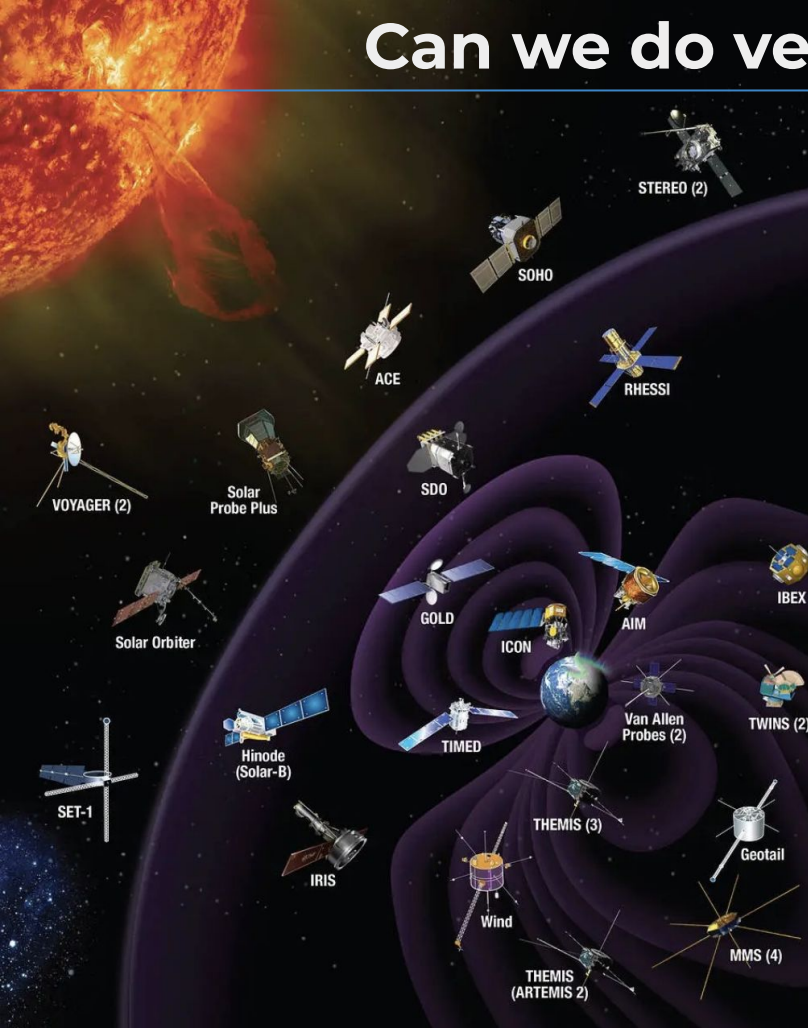
[Trattner et al. 2007]



- why is the magnetic shear so important? why no effect of the magnetic amplitude and density asymmetry?
- no role of the reconnection rate? what is the physics?
- possible bias ? highest shears = largest energies == most visible?

Overall weak statistics... difficult to conclude... can we do better?

Can we do very large scale statistics?



- Lots of missions
- Different orbits
- Mostly same instruments

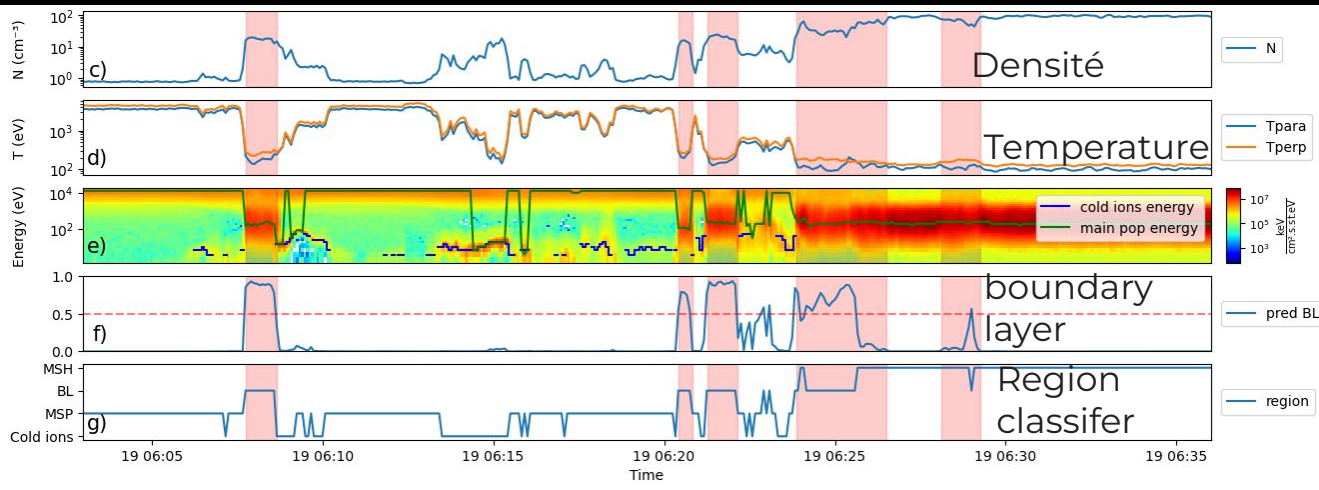
Taken alone : local and sparse view of the system

Altogether: amazing sampling in time and causal conditions

How to use all these data together?

Automatic classification and detection

- train machine learning algorithms to classify regions
- solar wind, magnetosheath, boundary layer, magnetosphere

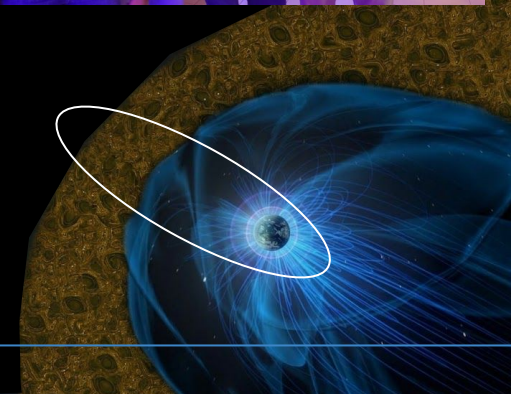


Smart student I am/was
lucky to work with

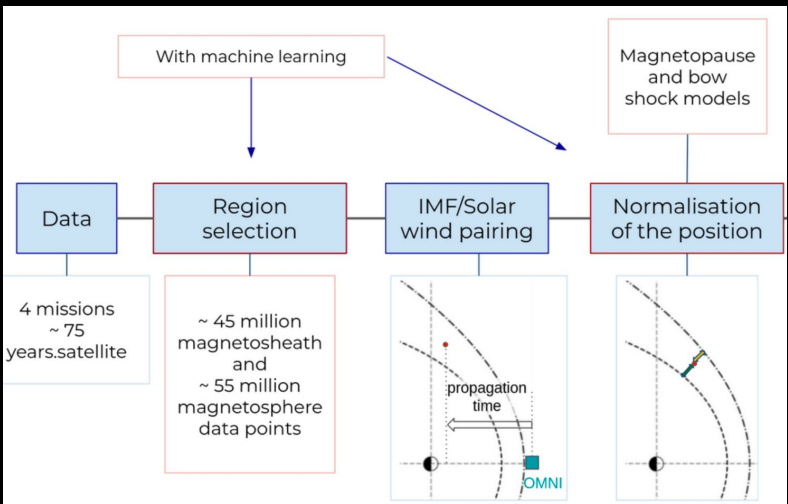
Me



Nguyen+ 2019,2022a,b,c,d / MdW+ 2022, 2025, 2026



Magnetospheric Atlas: foundation for global stats



README MIT license

MANGO: Magnetospheric Atlas from Normalized Geospace Observations

Contributors:

- jeandel Alexis Jeandel
- claude Claude
- nicolassunai Nicolas Aunai

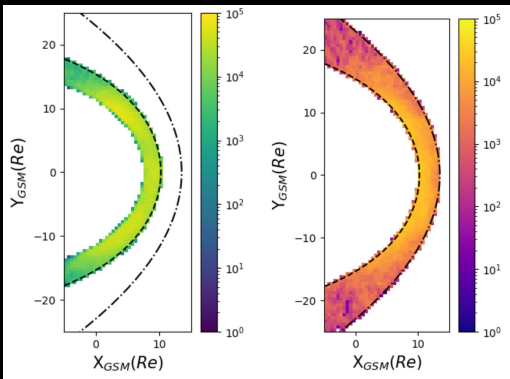
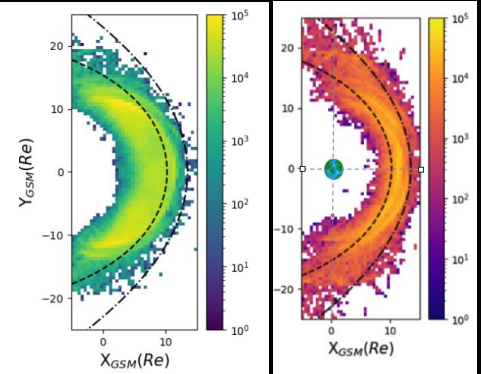
Languages:

- Python 96.6%
- Makefile 1.3%
- Dockerfile 1.3%
- Shell 0.8%

Overview

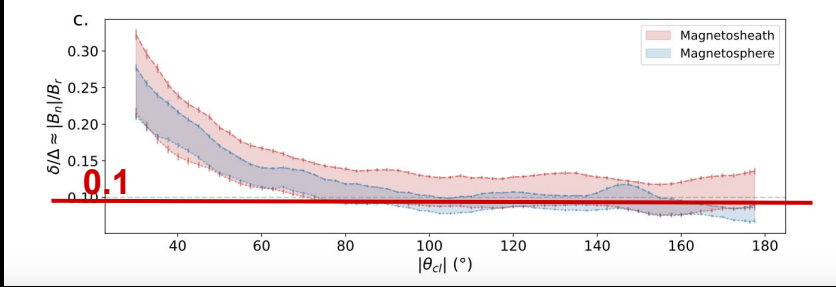
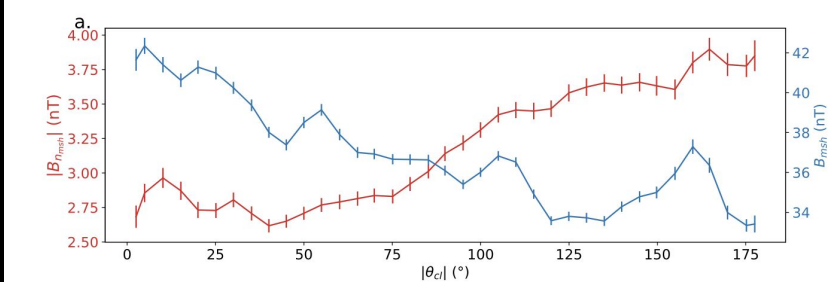
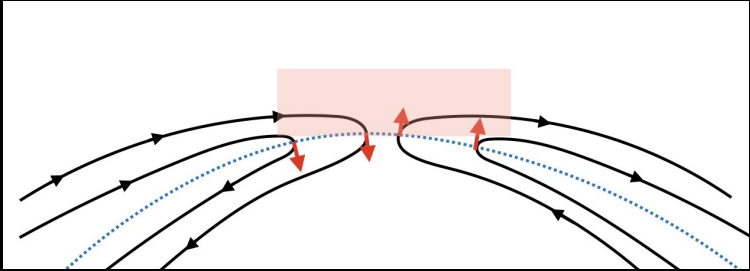
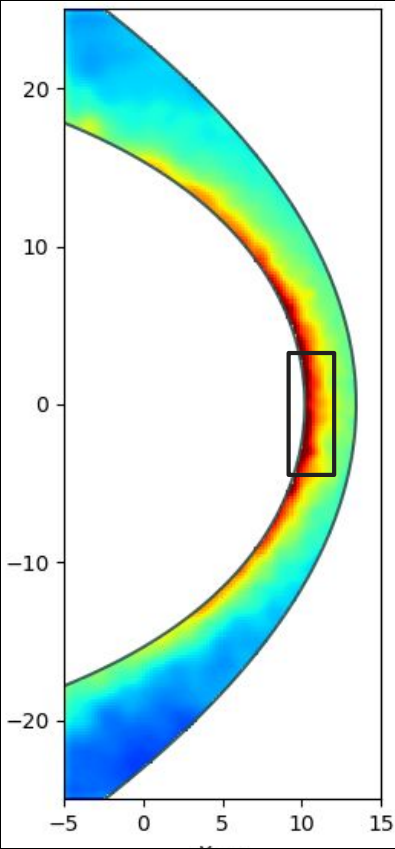
MANGO is a dataset and Python toolkit for the global analysis of Earth's magnetosphere. Unlike raw satellite observations, MANGO provides a unified, classified, and spatially normalized view of geospace, where each datapoint is contextualized by its magnetospheric region and upstream solar wind conditions and repositioned relative to dynamic boundaries like the magnetopause and bow shock.

By accounting for the dynamic nature of magnetospheric boundaries, MANGO allows researchers to treat disparate satellite observations as part of a single, coherent atlas.



Normalized reconnection rate estimate ~0.1

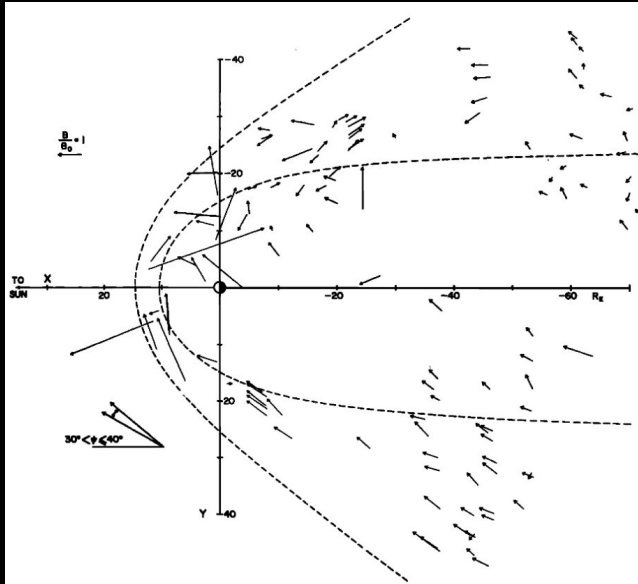
- IMF turns southward
- flux pile up less onto the obstacle
- **yet the normal component increase!!**
- Normal component usually not measurable uncertainty way too big
- signal/noise ratio favorable thanks to millions of points: surface wave cancel out on average



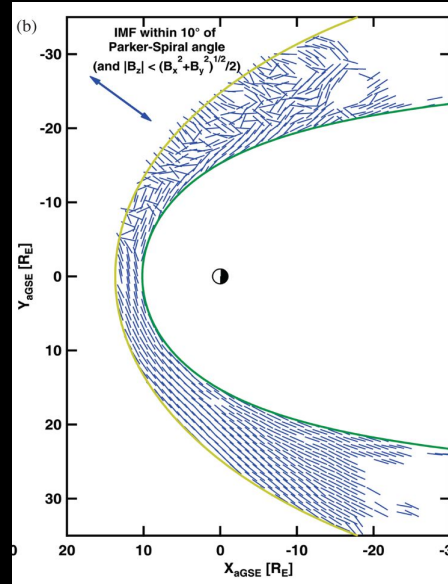
First statistical confirmation of 0.1 normalized rate and insensitive to the guide field

“Seeing” the magnetic draping

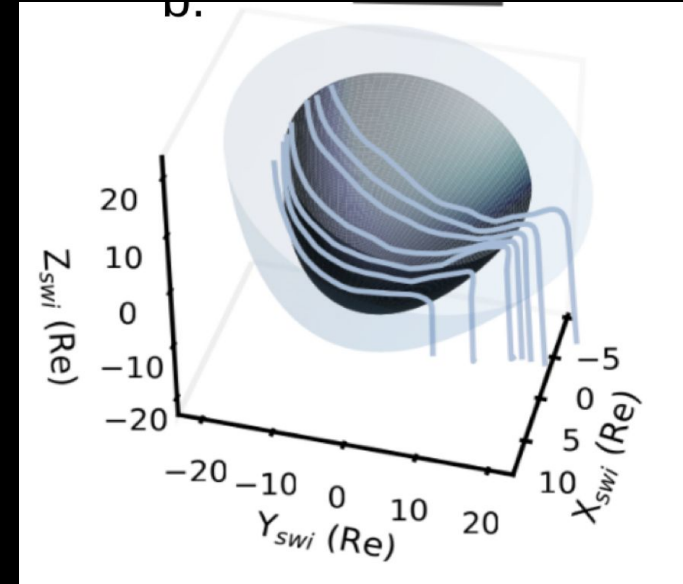
Benhanon+ 1969



Petrinec+ 2012



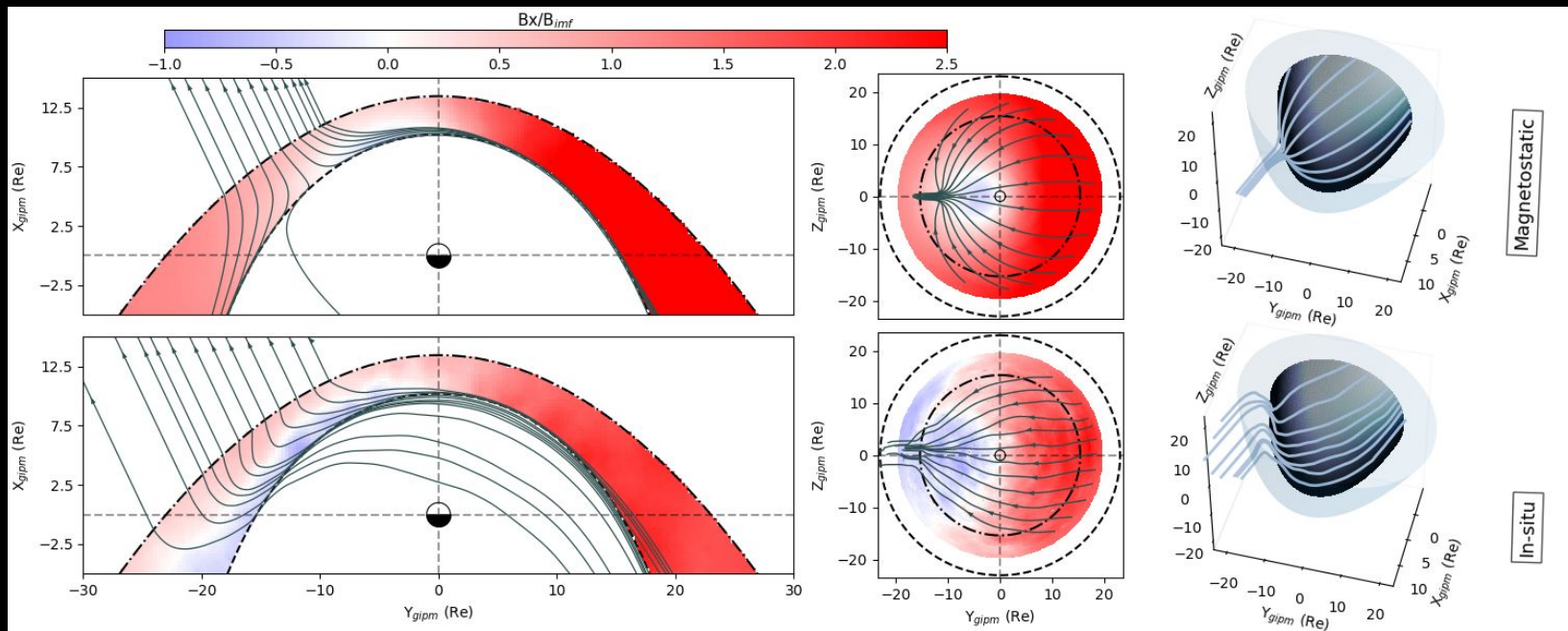
Michotte de Welle+ JGR 2012



First global dayside detailed reconstruction of the magnetic draping as a function of the interplanetary magnetic field orientation.

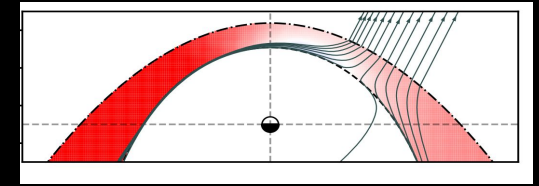
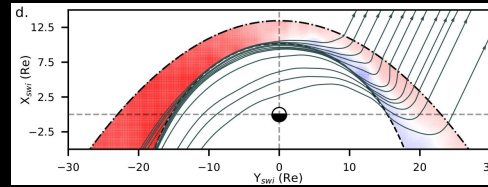
Widely used analytical models are wrong...

- current-free draping is not correct
- the magnetic draping must respect the frozen-in constraint

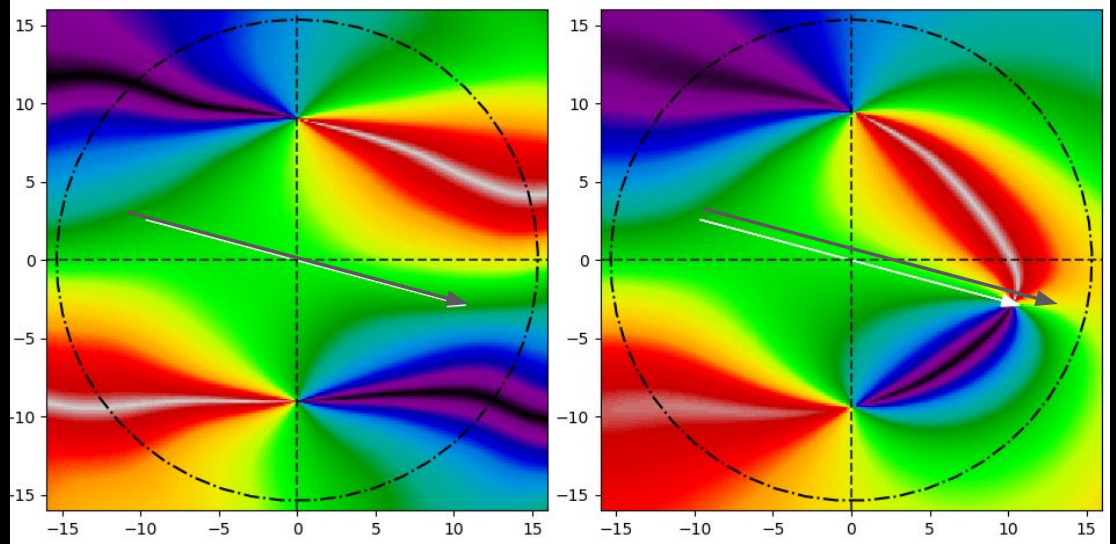


[Michotte de Welle et al. 2024]

Global magnetopause maps from local data!

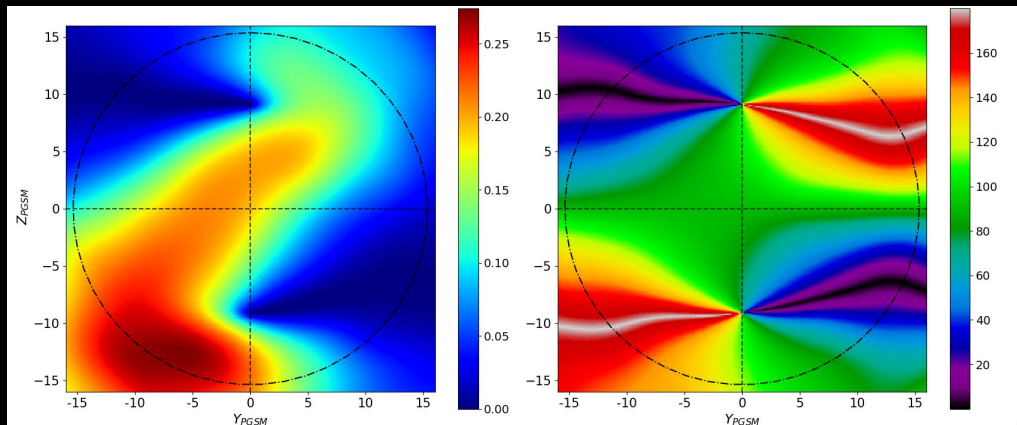
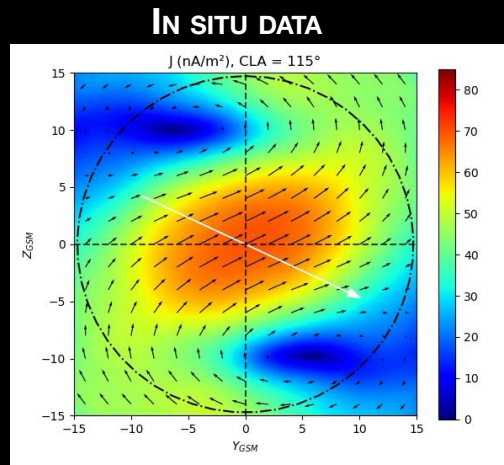
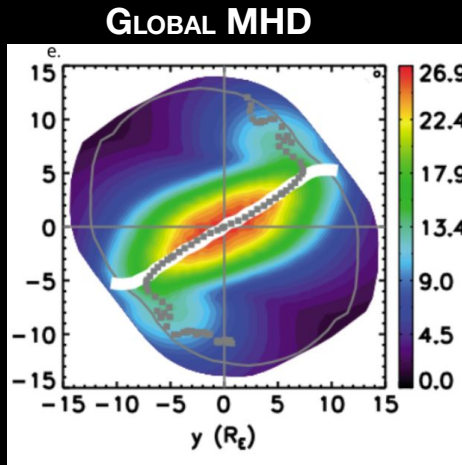


- Magnet draping being wrong...
- shear maps derived from it are... wrong!



[Michotte de Welle et al. 2025]

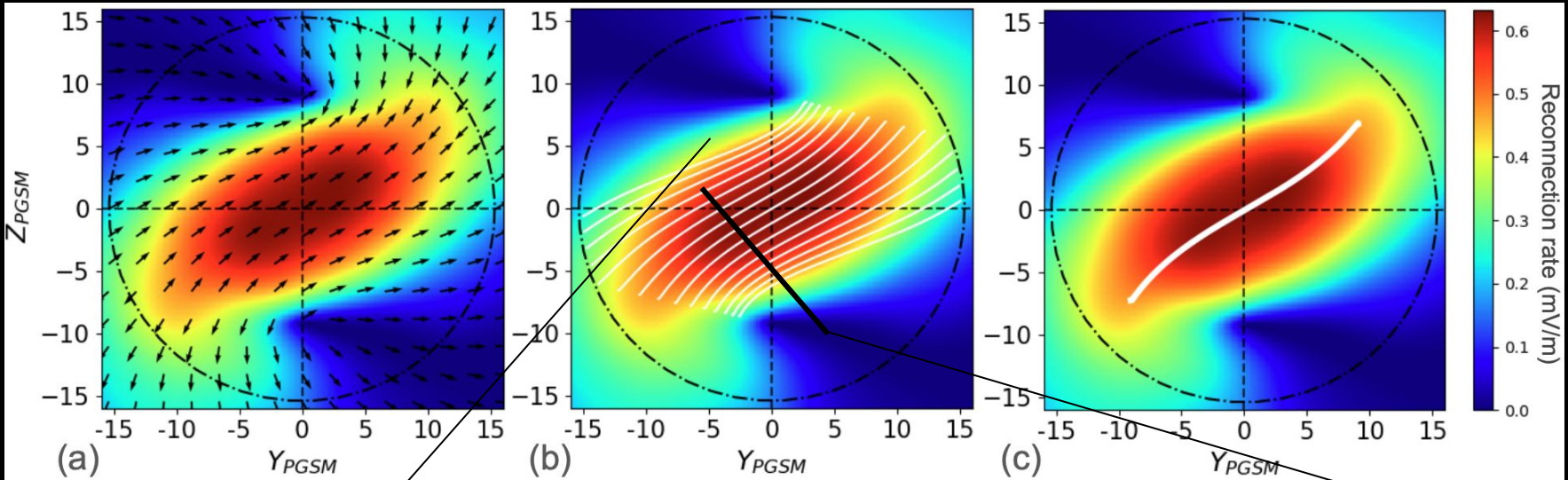
Beyond just the shear: current and rec. rate maps



[Michotte de Welle et al. 2025]

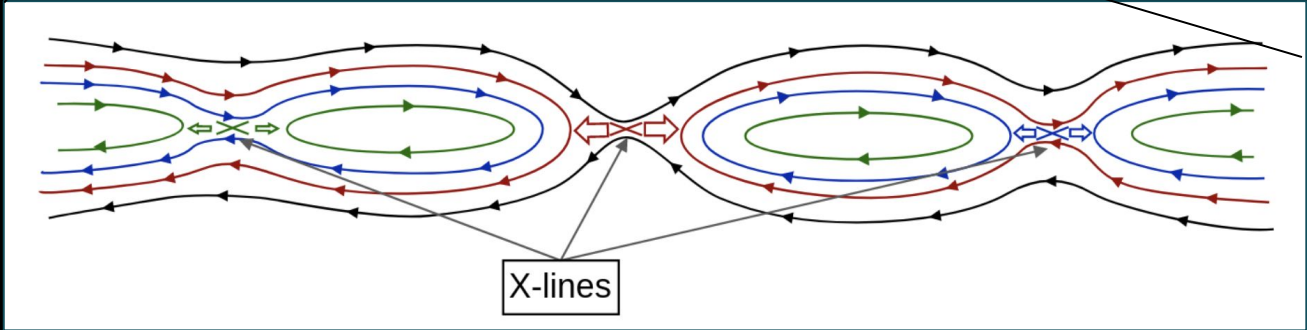
- maps consistent with MHD results
- rate maps are highly asymmetric because of the quasi-perp VS quasi-para asymmetry
- How are X line constrained by these distributions?

Dominant X line model

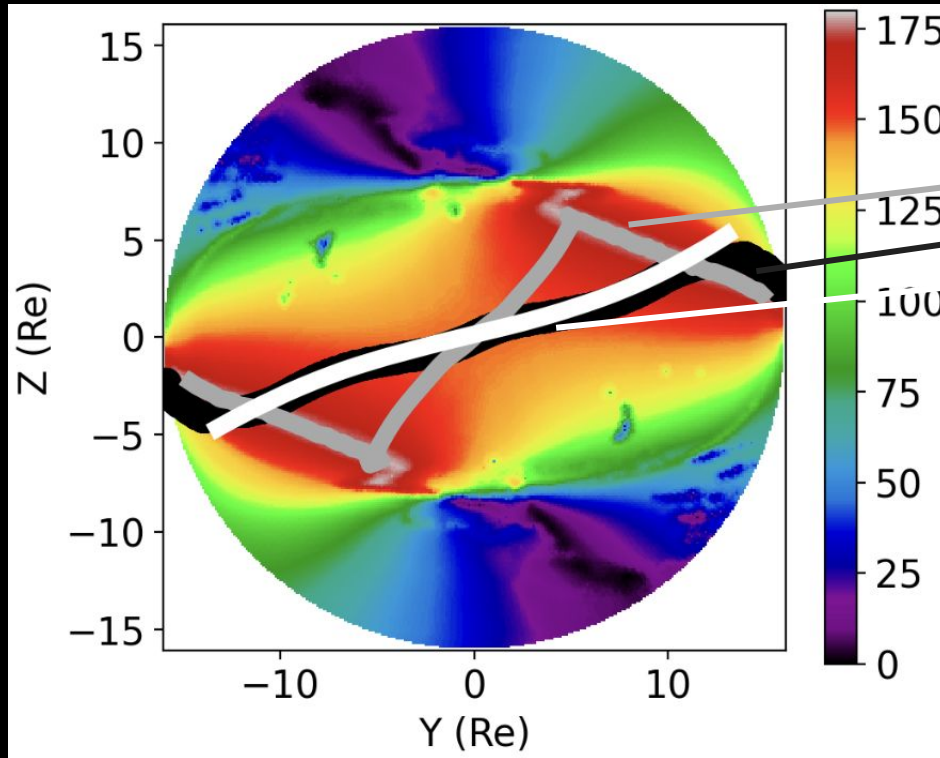


Dominant X line
expels all others

Michotte de Welle+ [2025]



Dominant X line model



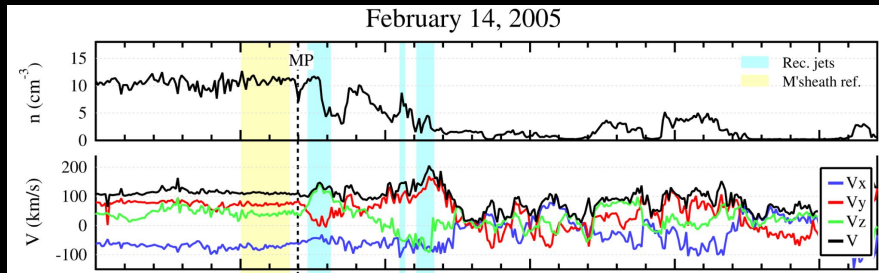
Maximum Shear
X line location in the simulation
Model prediction

Dominant X line model is the only
one matching X line locations in
simulations

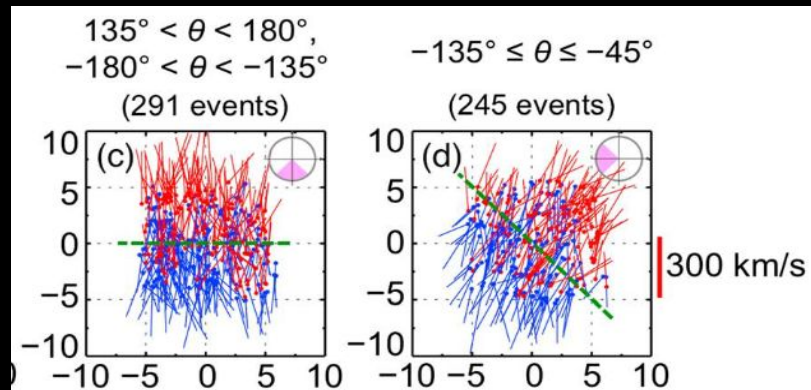
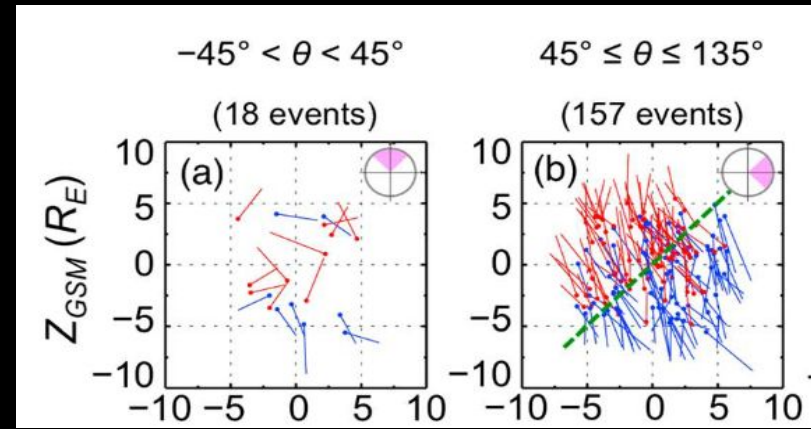
What can we say with data?

Michotte de Welle+ [2025]

Inferring the X line from plasma jets

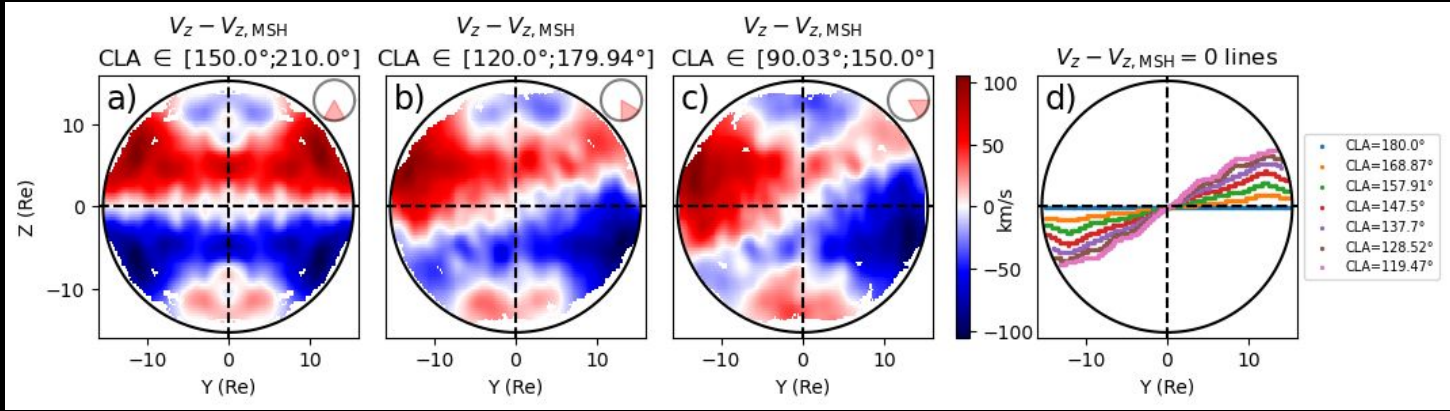
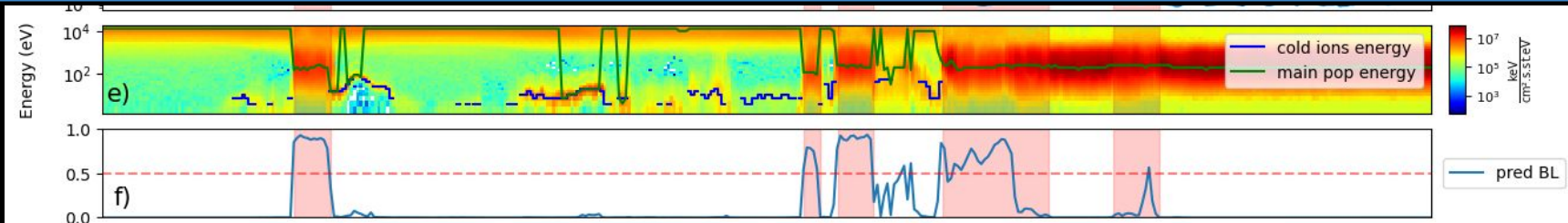


- select jets in magnetopause crossings
- report their orientation on the magnetopause
- red=northward, blue southward jets
- jet orientations seem to rotate with the interplanetary magnetic field
- only few hundreds of events, too coarse to discard models from one another



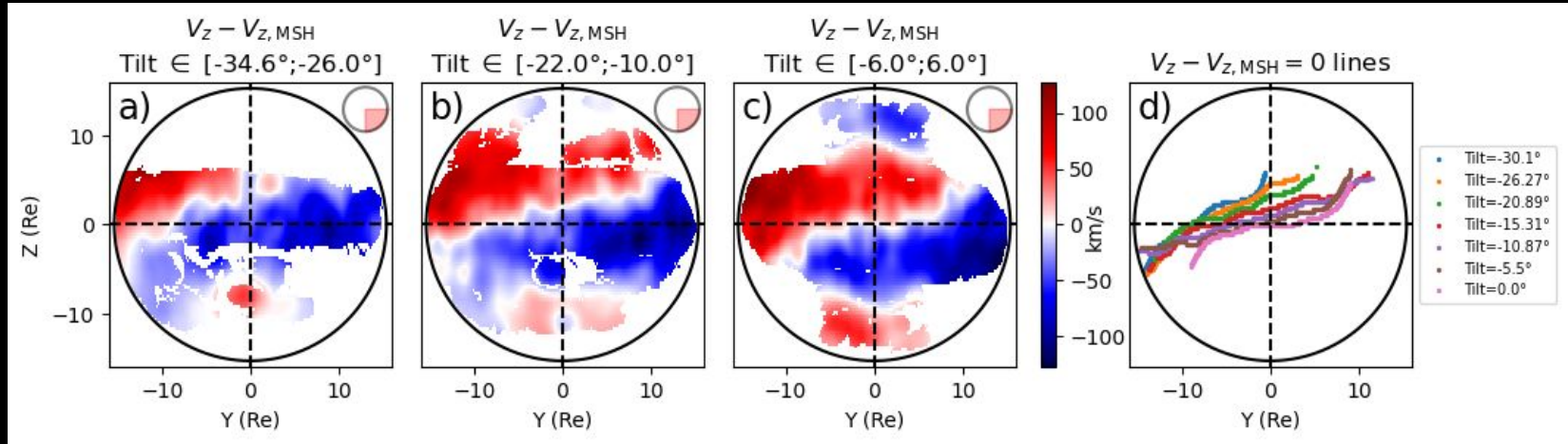
[Hoshi et al. 2018]

Reconnection structures the whole magnetopause flow

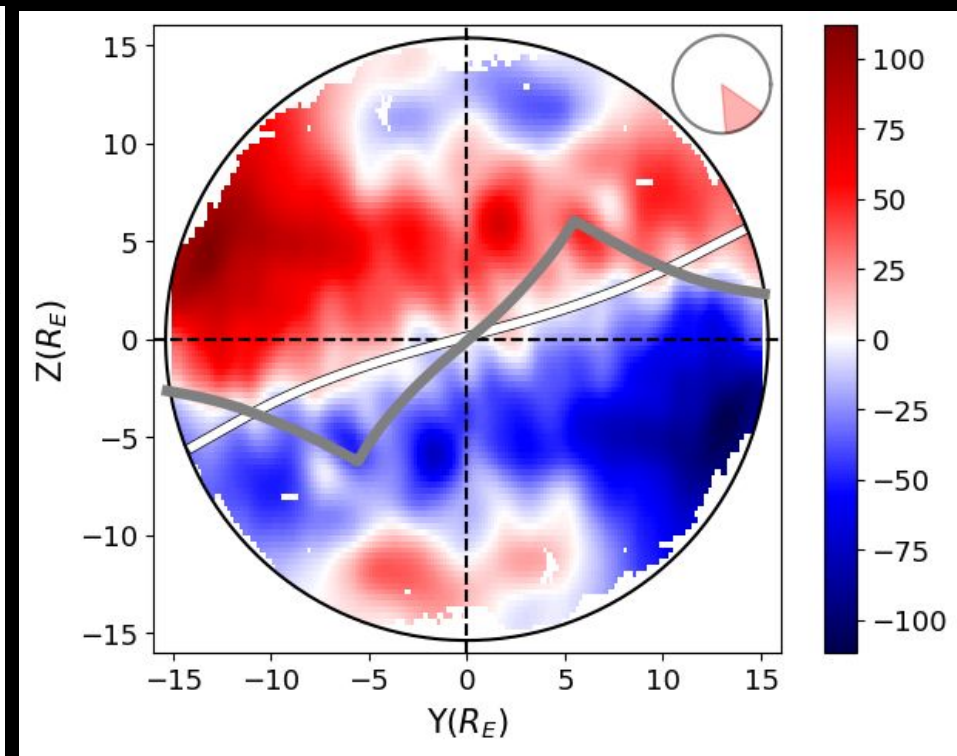
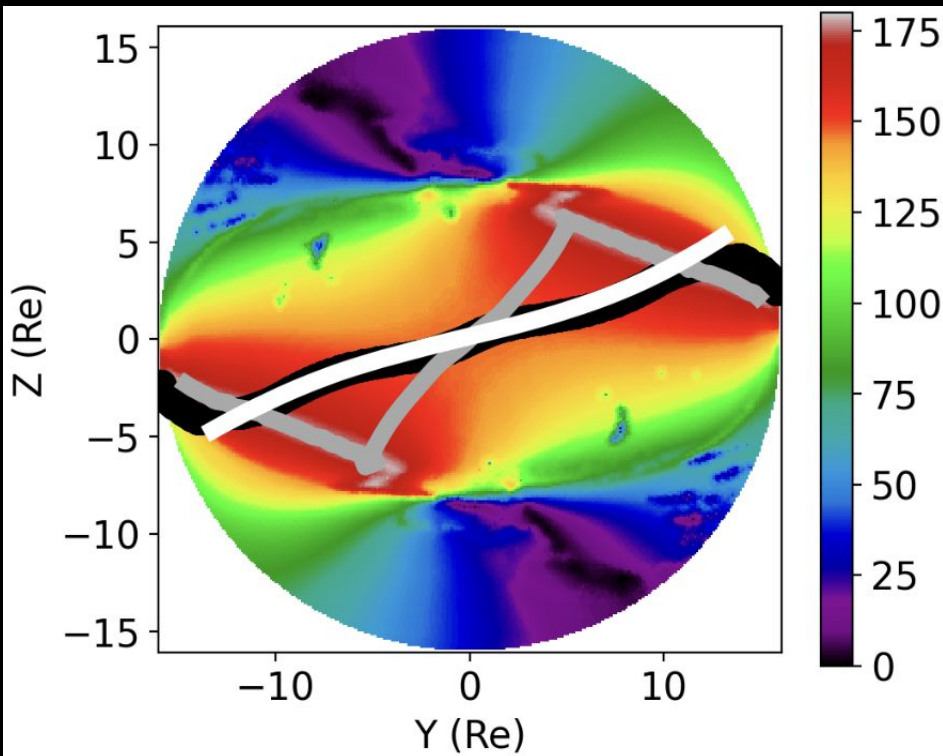


- Precise automatic detection of the whole boundary layer with machine learning
- Pairing with upstream conditions
- Mapping the magnetopause with the boundary layer flow
- The whole magnetopause flow is controlled by reconnection
- rotates with IMF

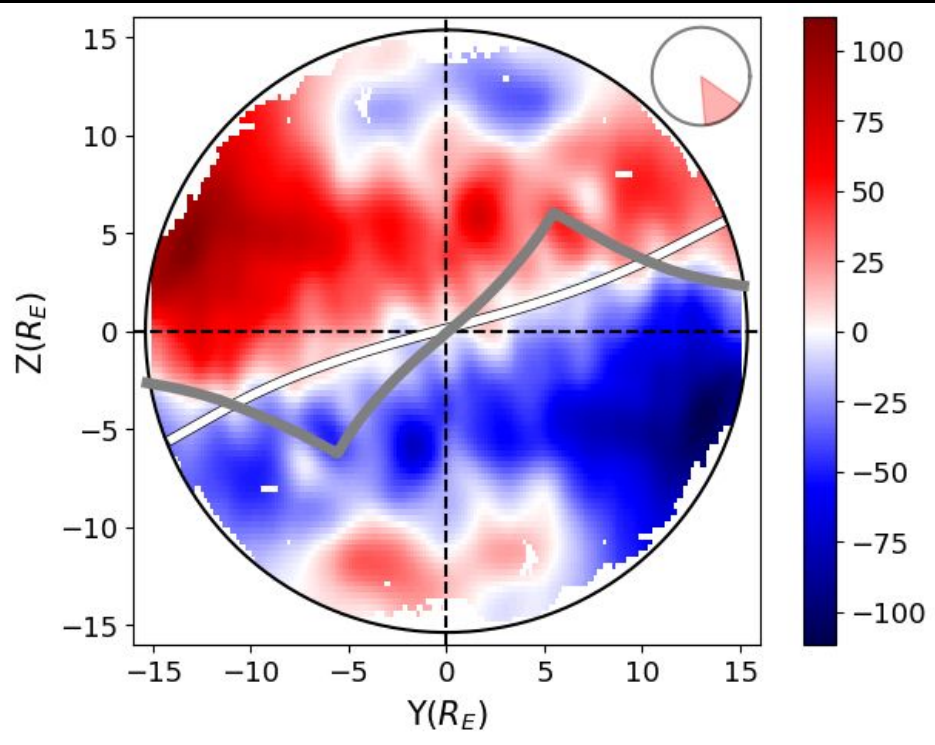
The flow origin shifts with the dipole tilt



The flow origin shifts with the dipole tilt



End of the story? No!



- This is an average view....Is it meaningful?
- Is that the X line? or a region where reconnection is occurring?
- How does the picture change with slowly varying IMF? With fastly rotating IMF?
- How is the “real X line”?
 - is it a tortuous global X line whose average location is as shown here?
 - is it a collections of X lines here and there?
 - ...?