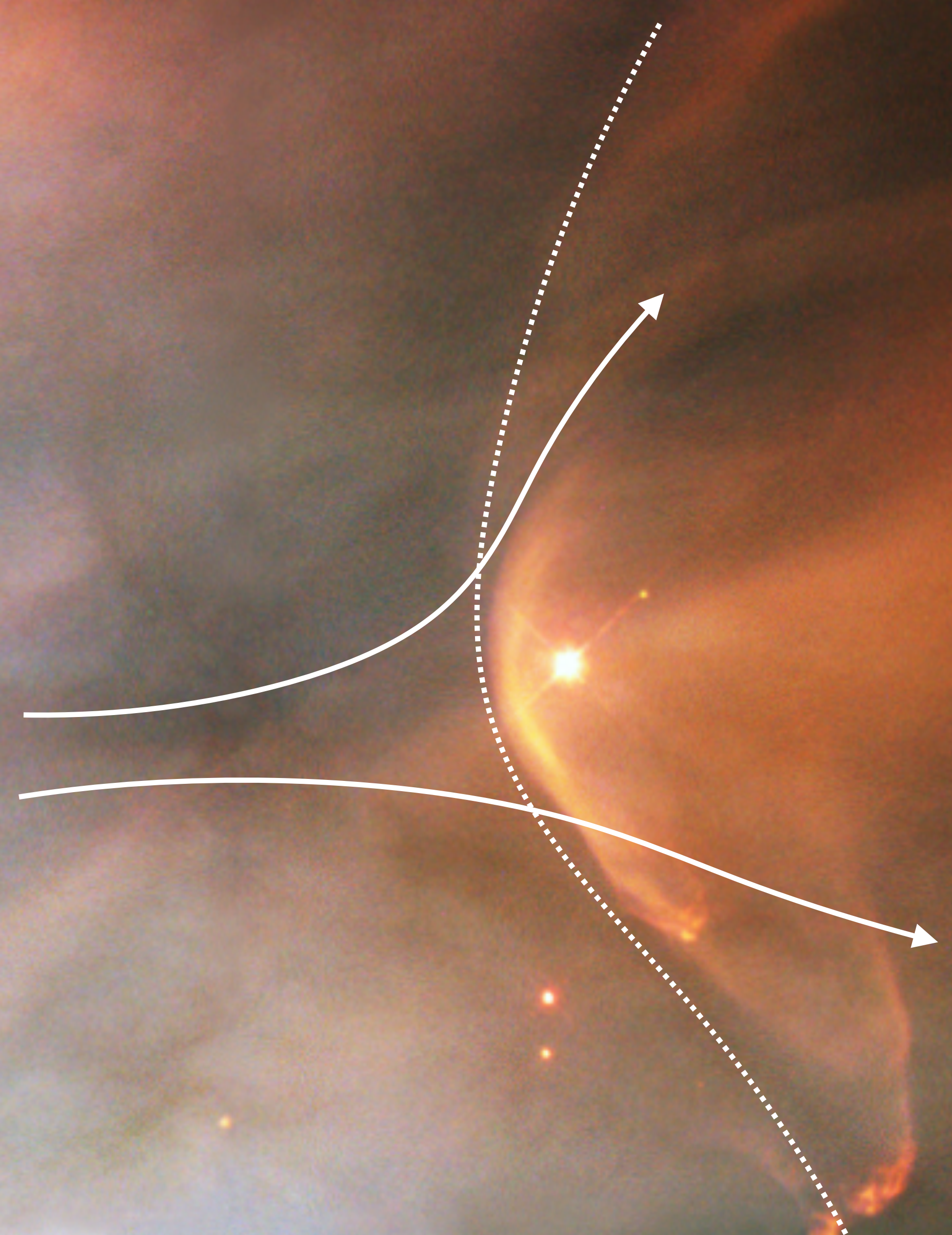
Kinetic Simulations of Magnetic Reconnection

towards multi-scale simulation…



SF2A

Lyon
17/06/2016

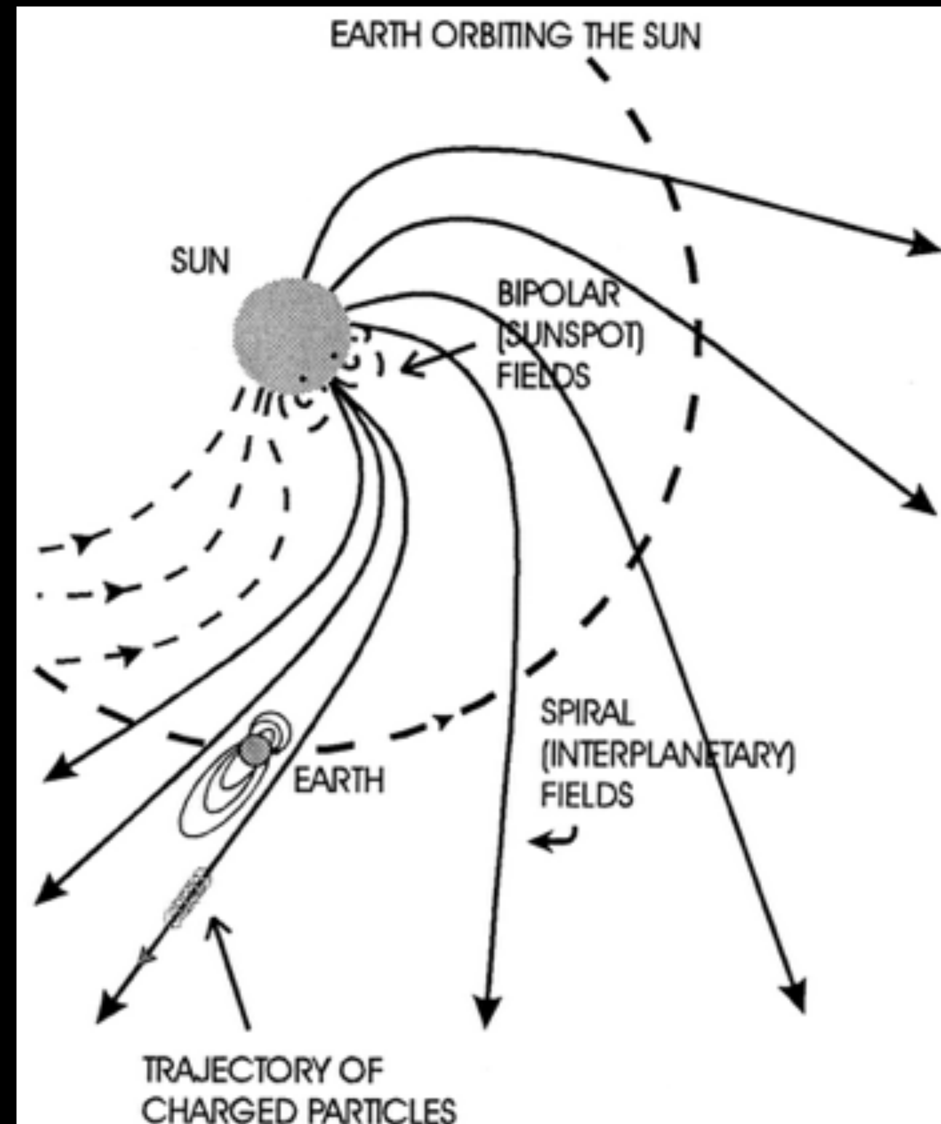
Nicolas Aunai
Andrea Ciardi
Roch Smets
Mathieu Drouin
J. Dargent
M. Hesse
B. Lavraud
M. Grech
J. Derouillat
F. Perrez
T. Vinci
A. Beck

LERMA — LPP — PLAS@PAR Plasmas à Paris — irap — NASA

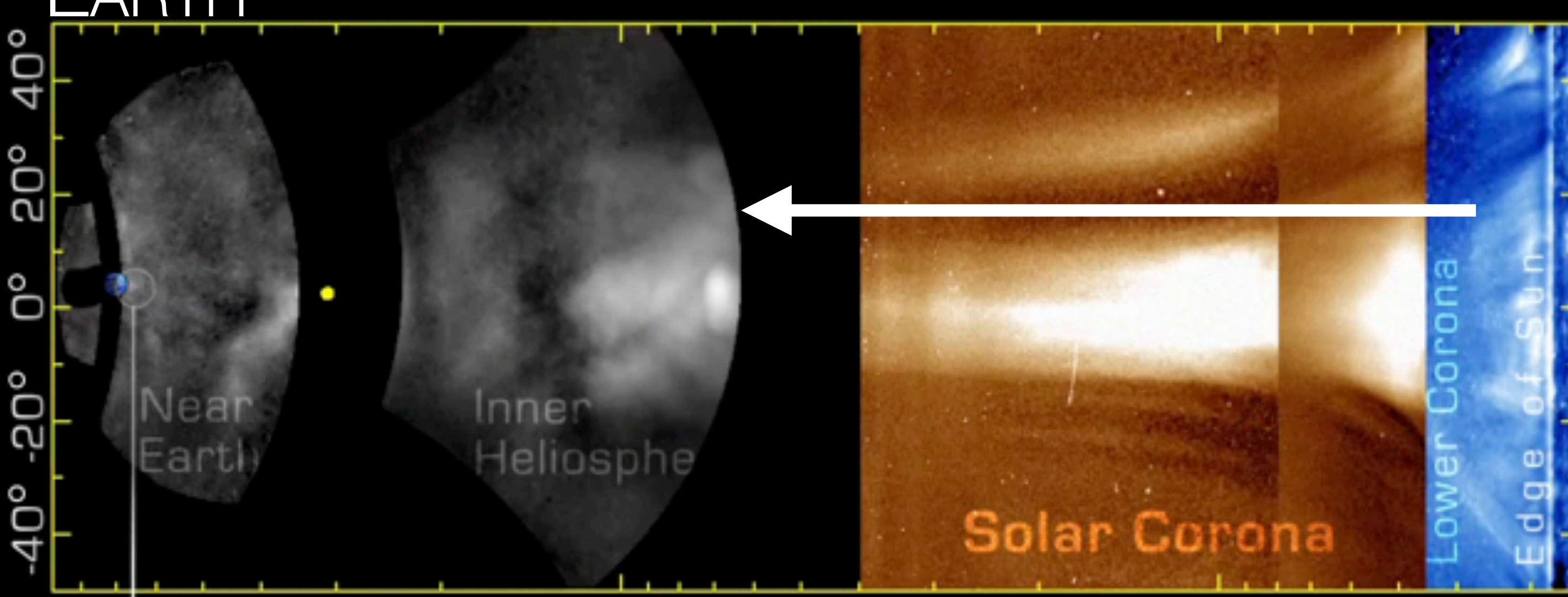
Interplanetary space

Solar Wind

Predicted by Parker 1958, confirmed Explorer 12 in 1962

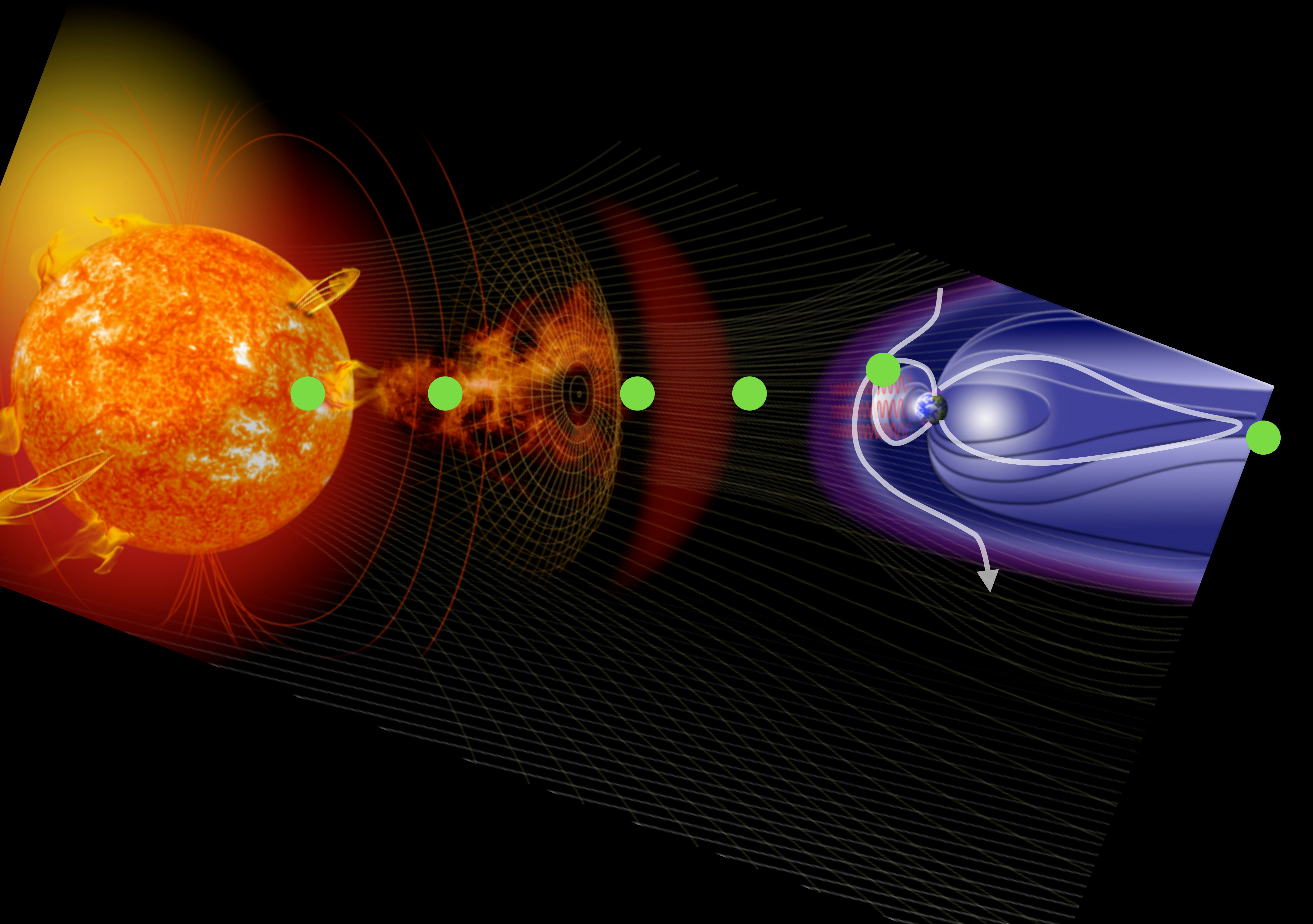


Earth



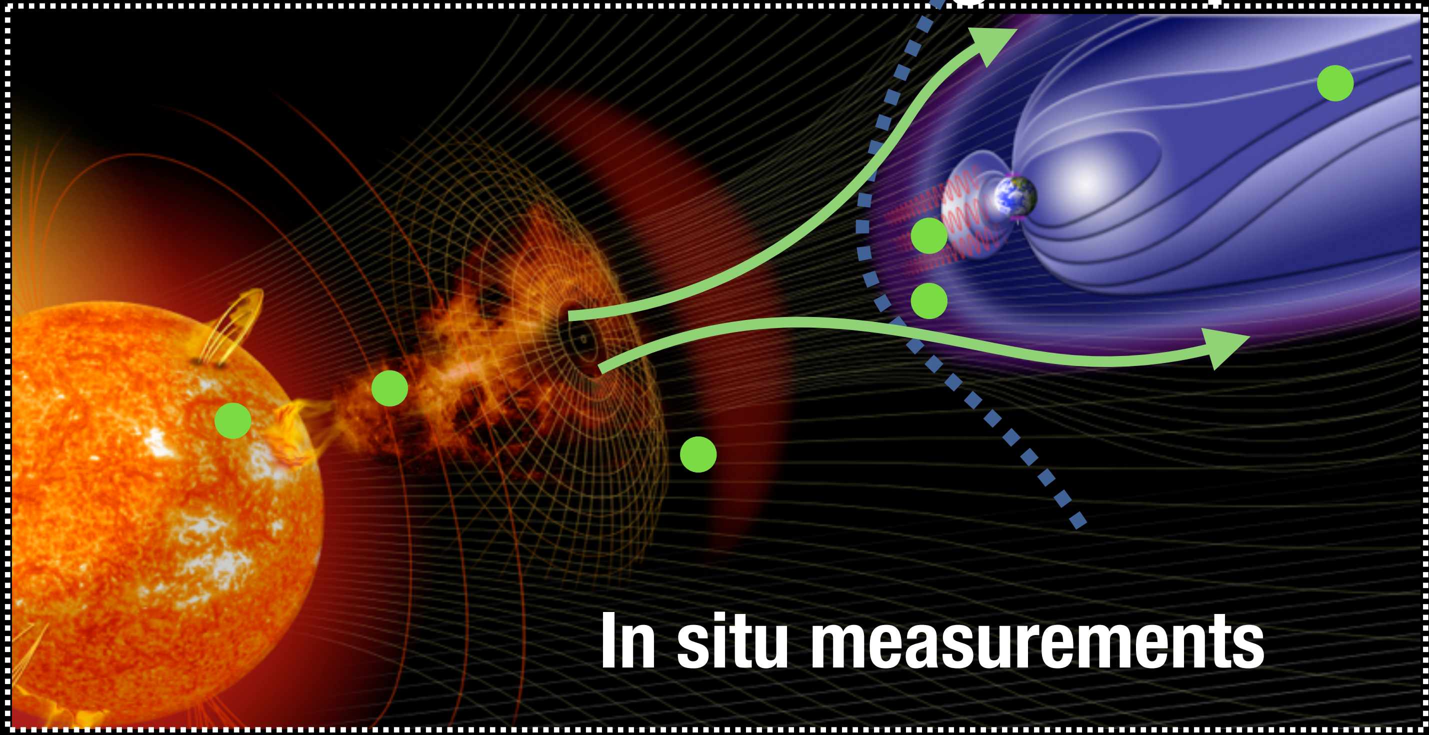
SUN

Magnetic Reconnection… key process in sun-earth coupling

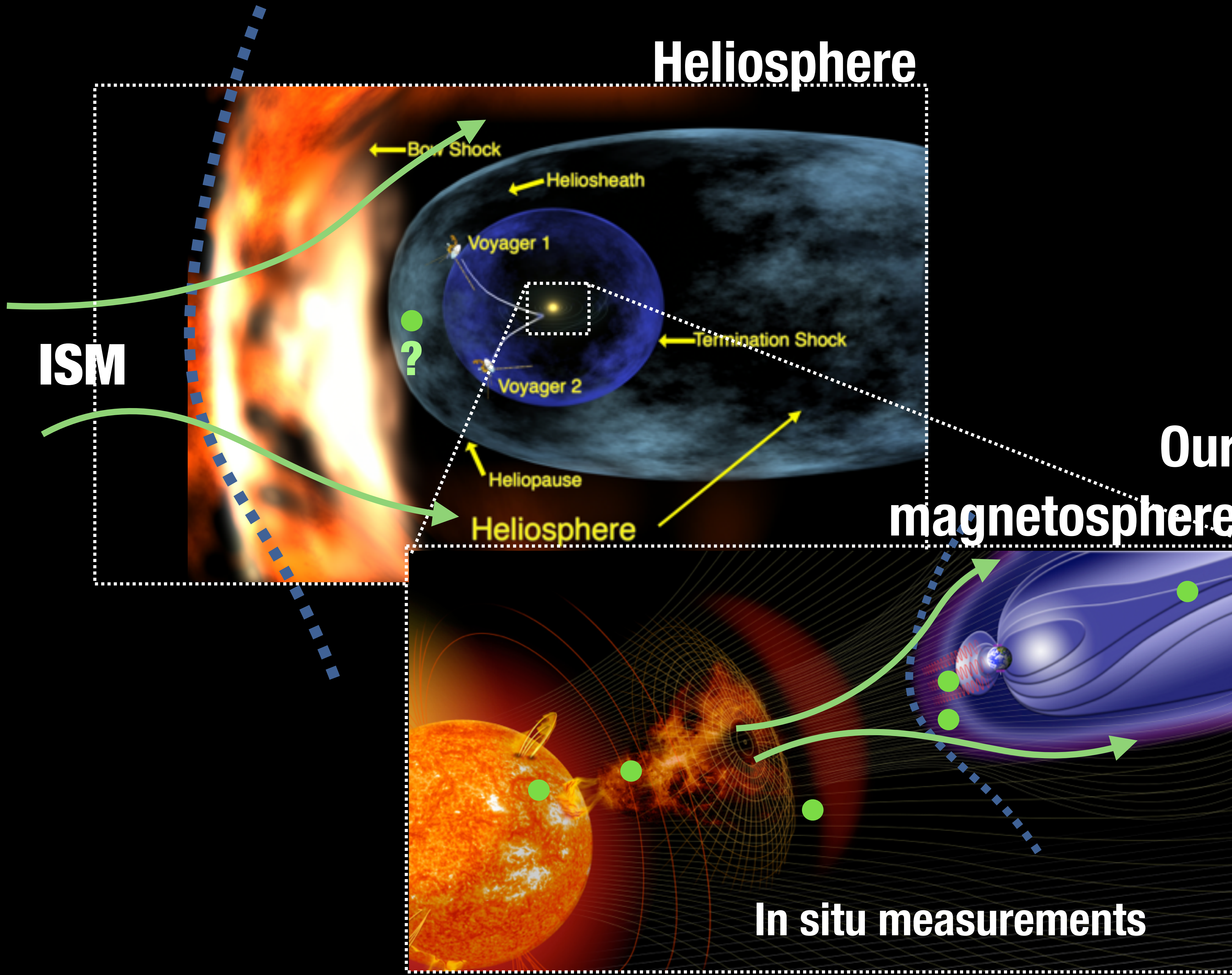


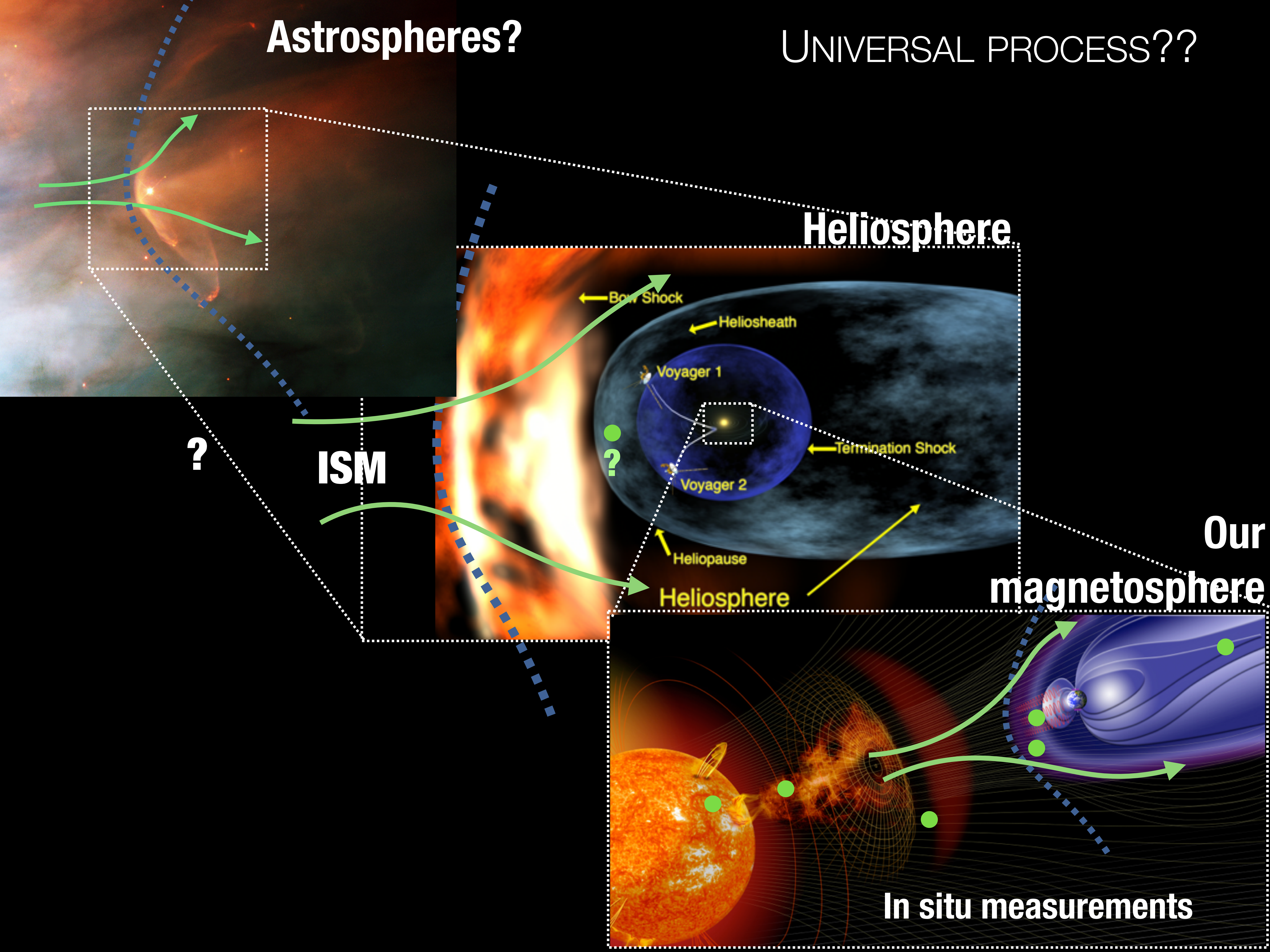
ZOOMING OUT...

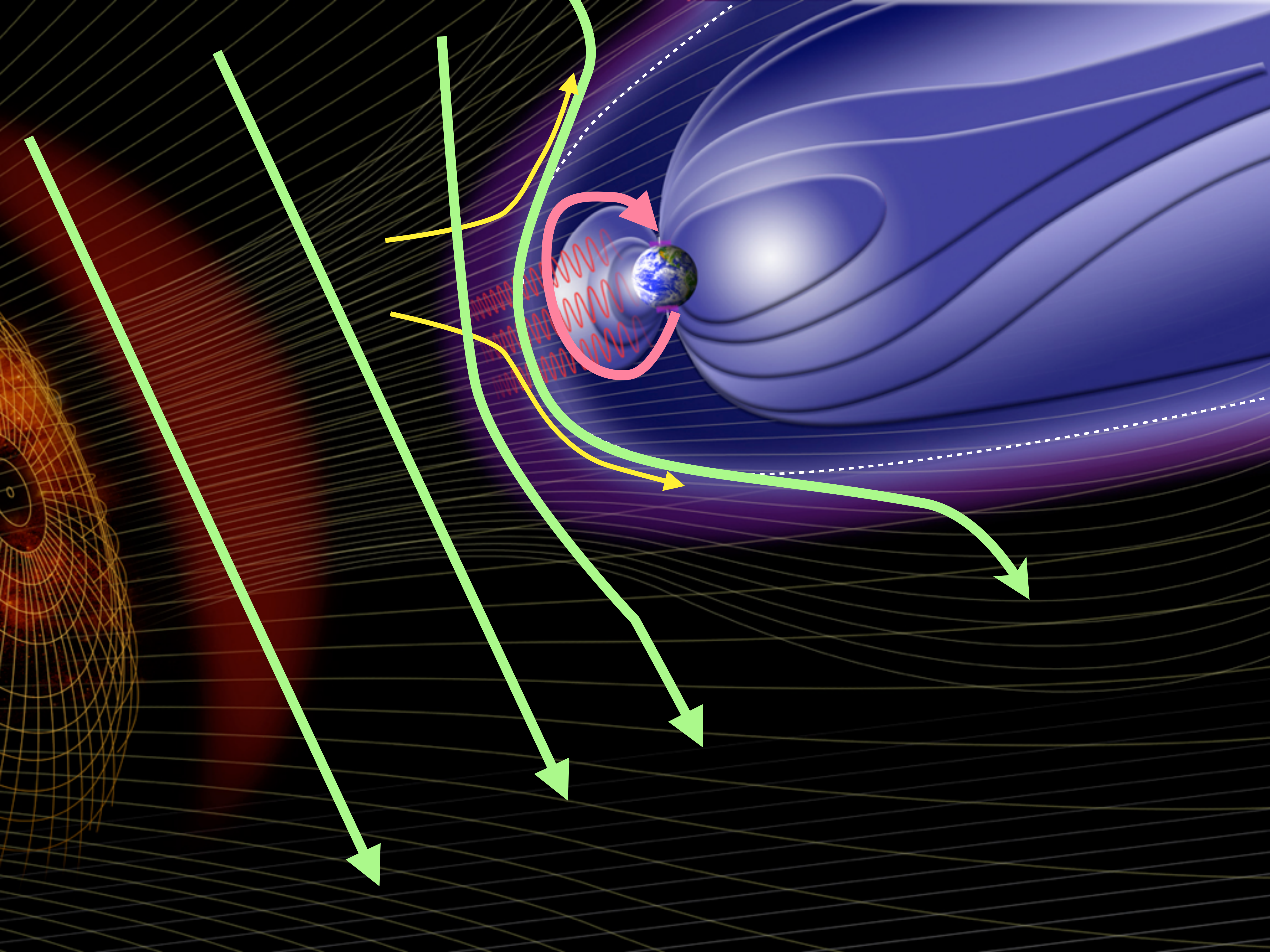
Our magnetosphere

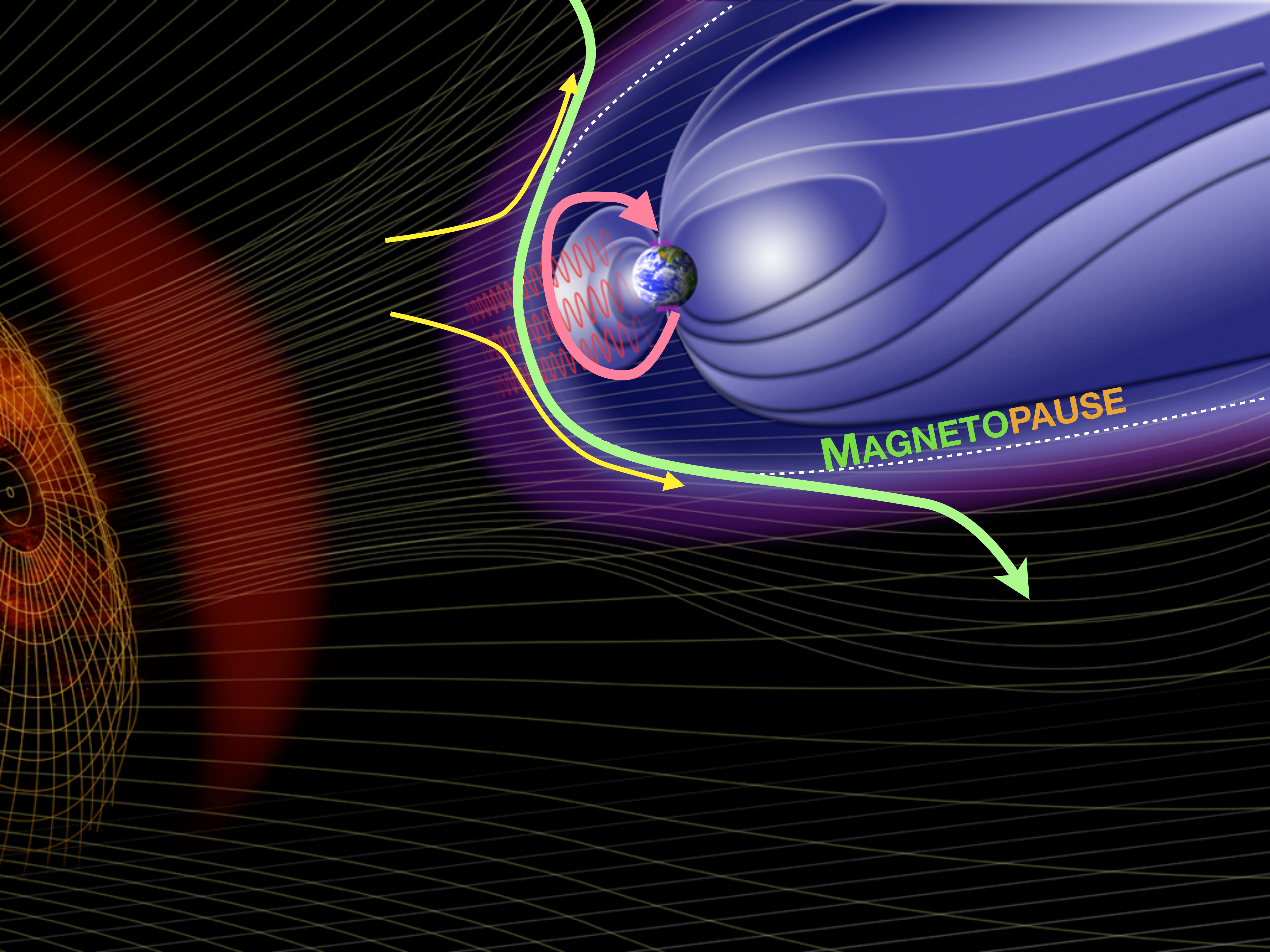


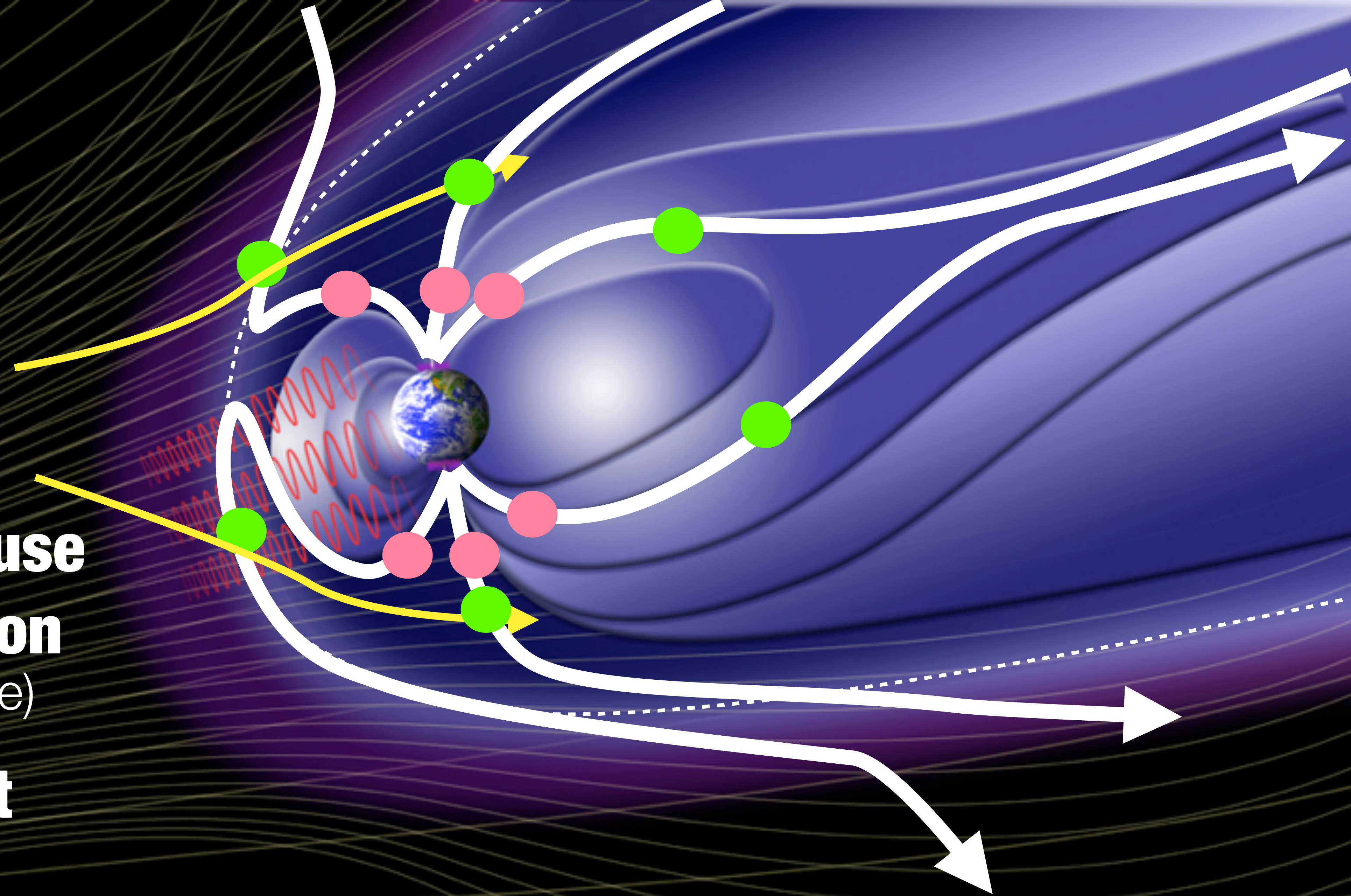
Actually also occurs **throughout the heliosphere**




Astrospheres?
UNIVERSAL PROCESS??
Heliosphere
Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere
?
ISM
?
Our magnetosphere
In situ measurements



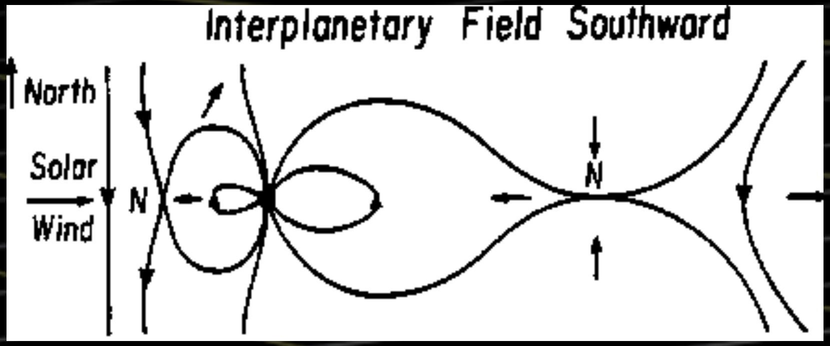

MAGNETOPAUSE

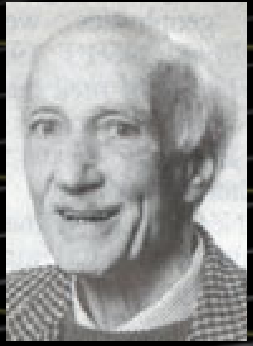


Magnetopause reconnection
(growth phase)

1 Transport

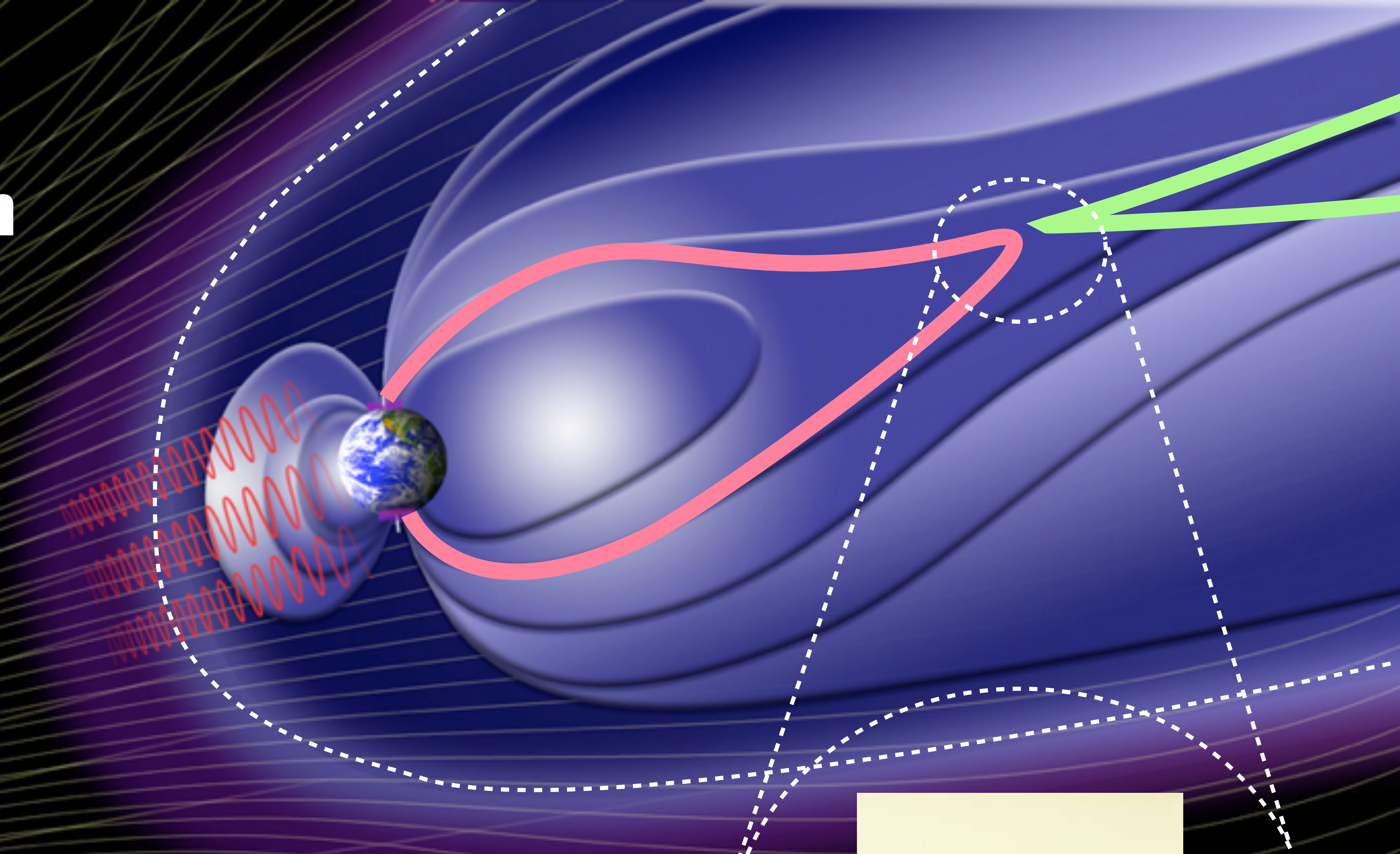
- [Dungey 1950's] (F. Hoyle student)



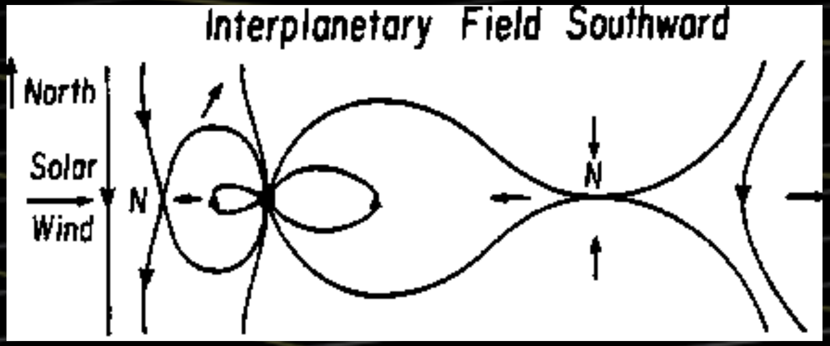


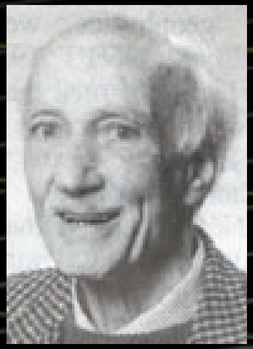
Tail reconnection
(expansion phase)

2 Accélération



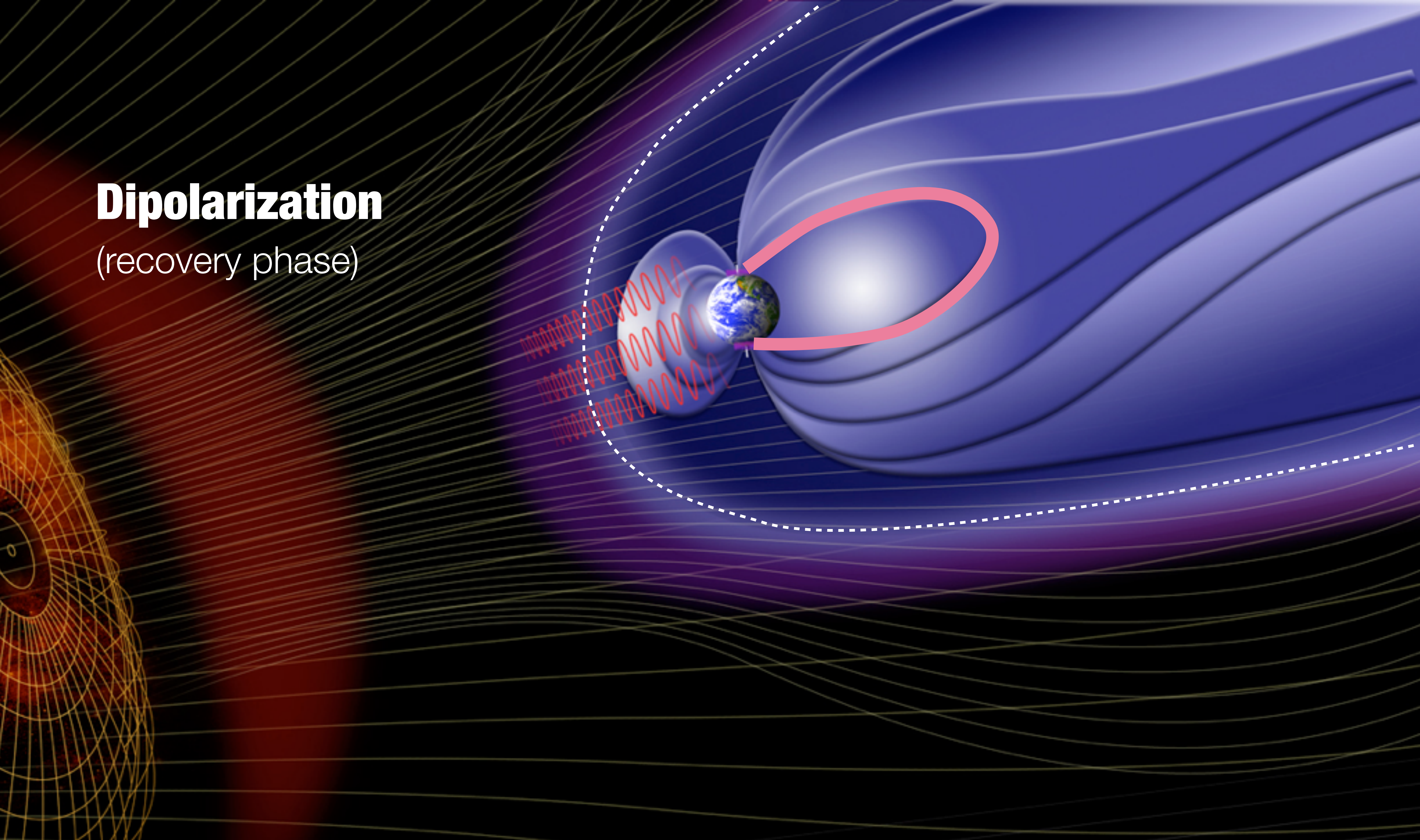
- [Dungey 1950's] (F. Hoyle student)



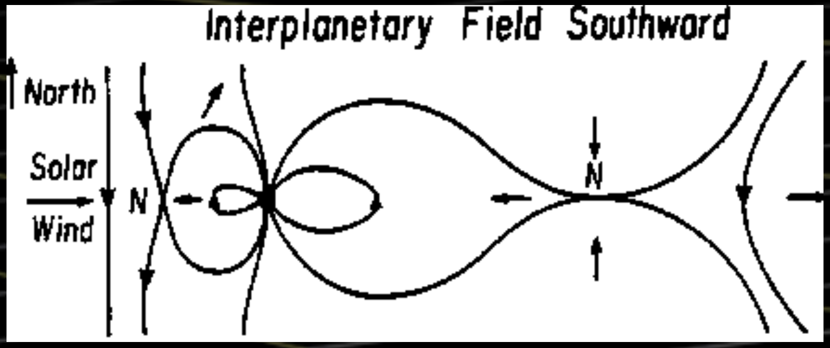


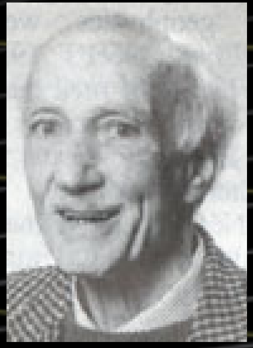
Dipolarization

(recovery phase)

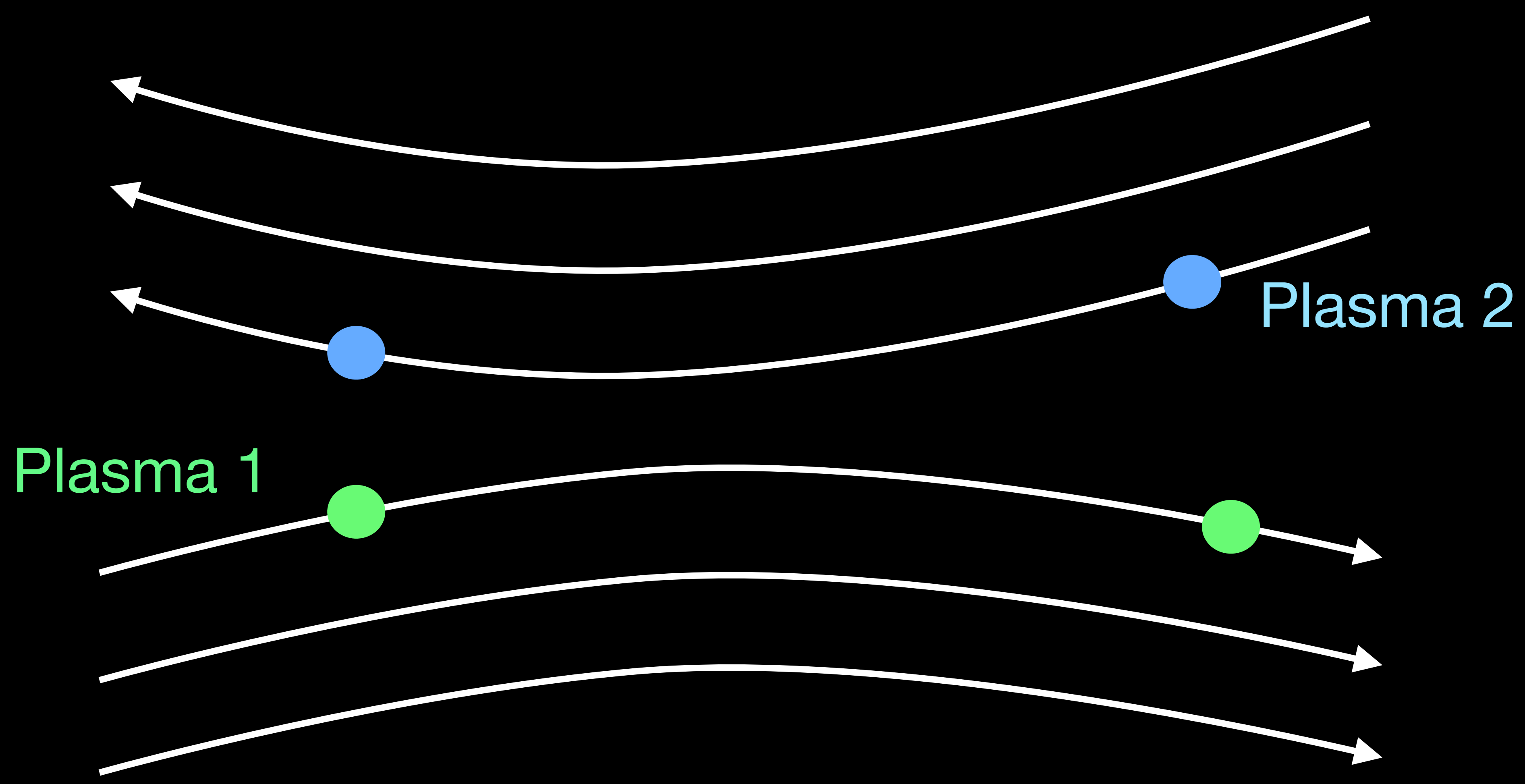


- [Dungey 1950's] (F. Hoyle student)

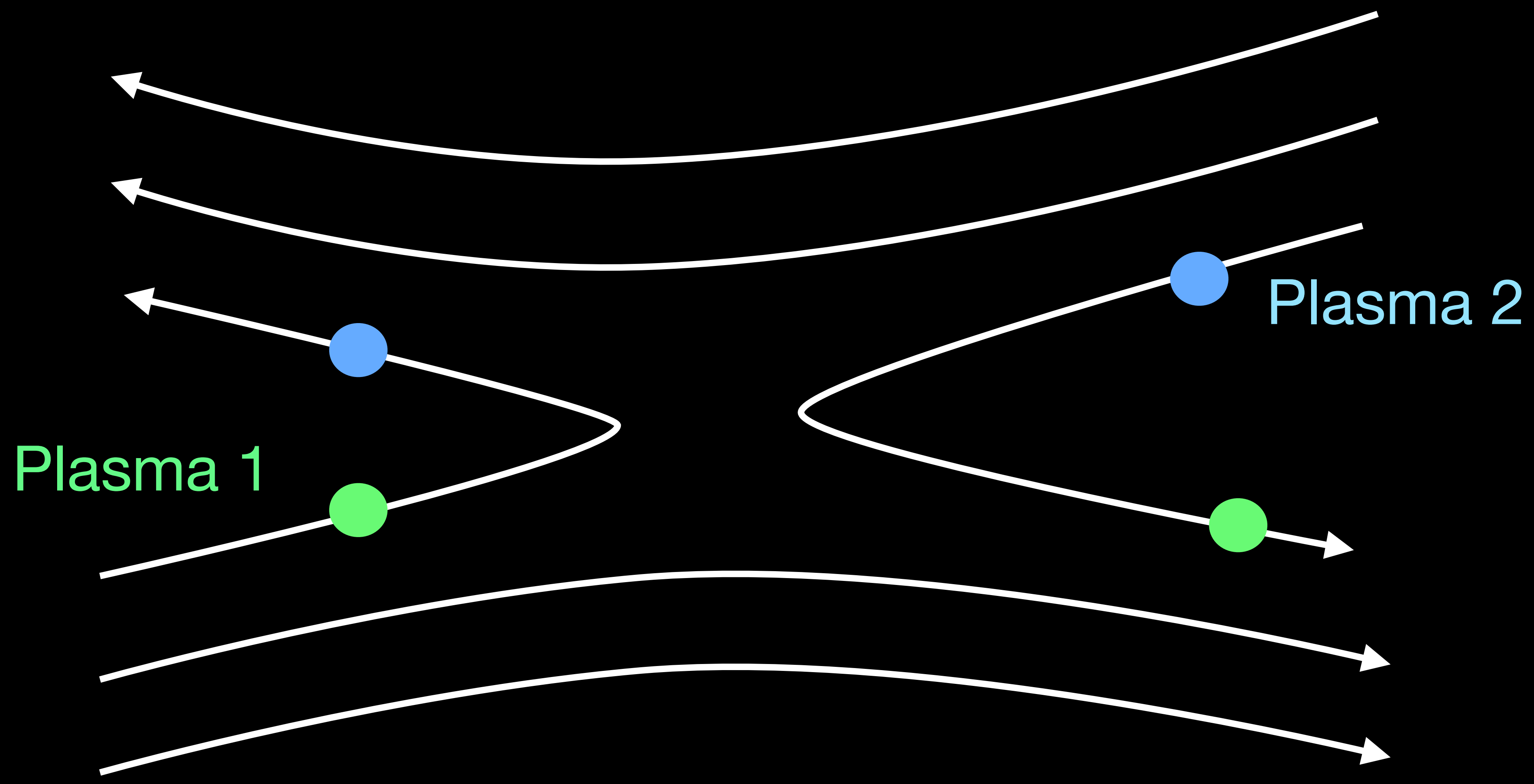




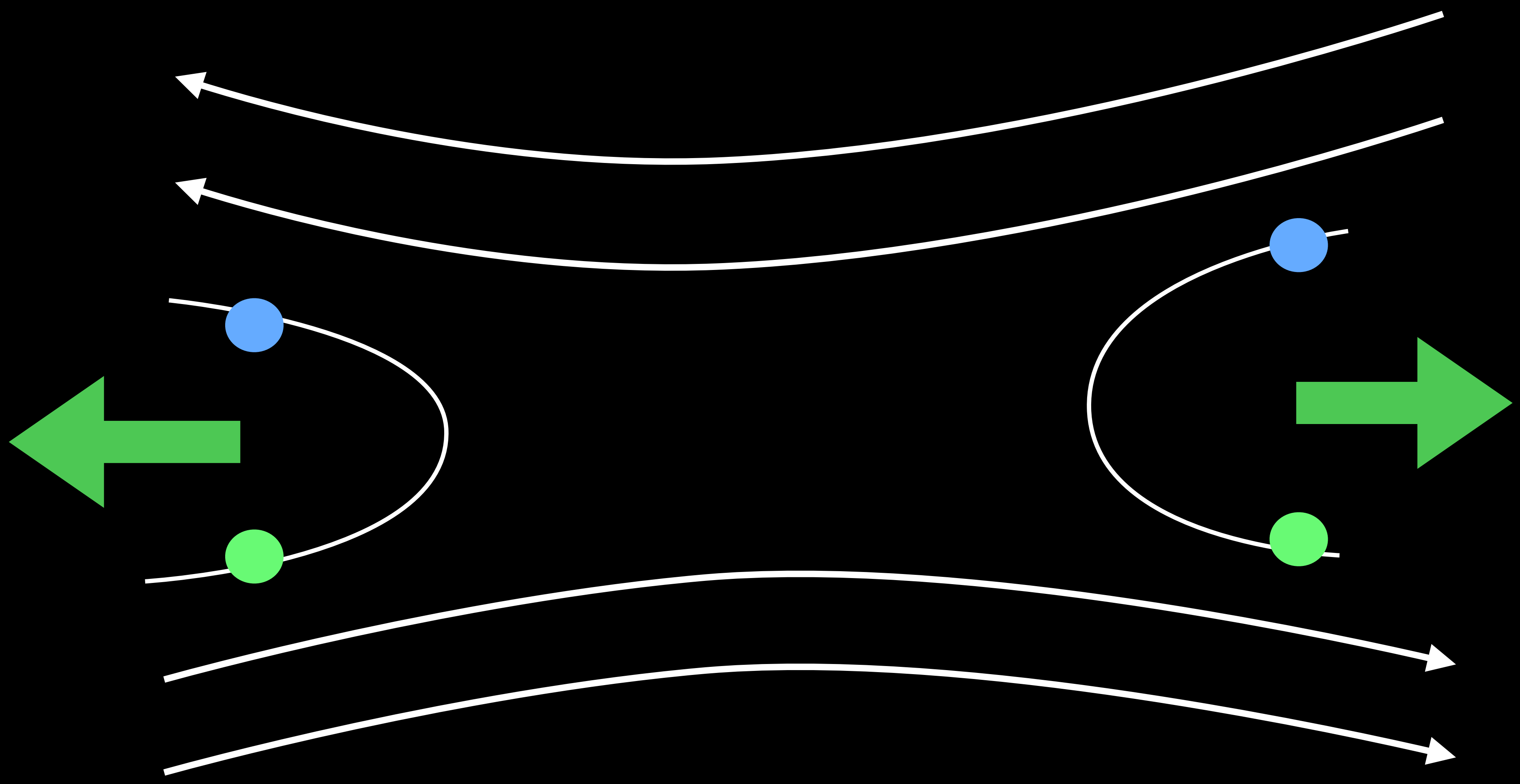
How does reconnection work?
Two magnetized plasmas in « contact »



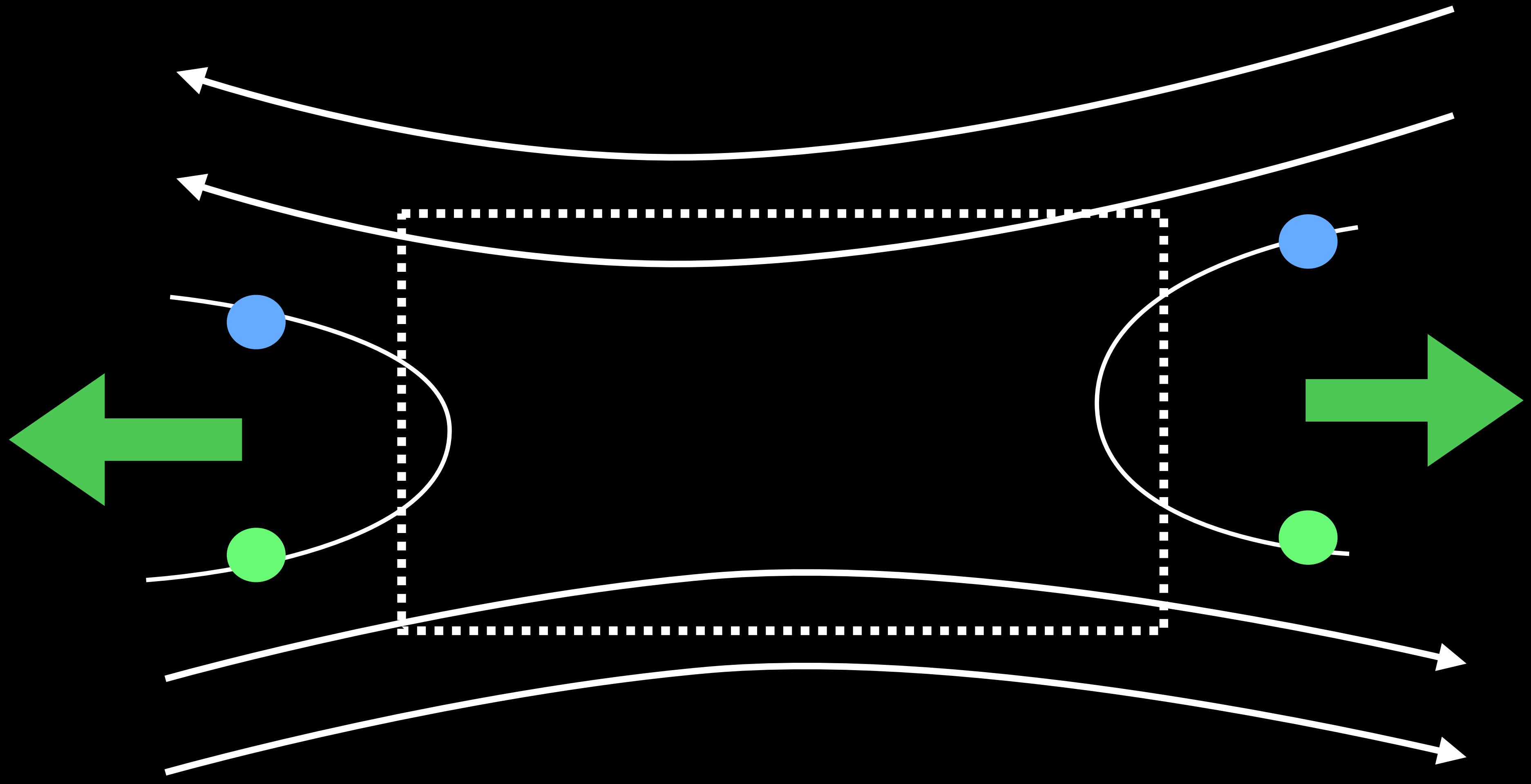
CAN BE RECONNECTED



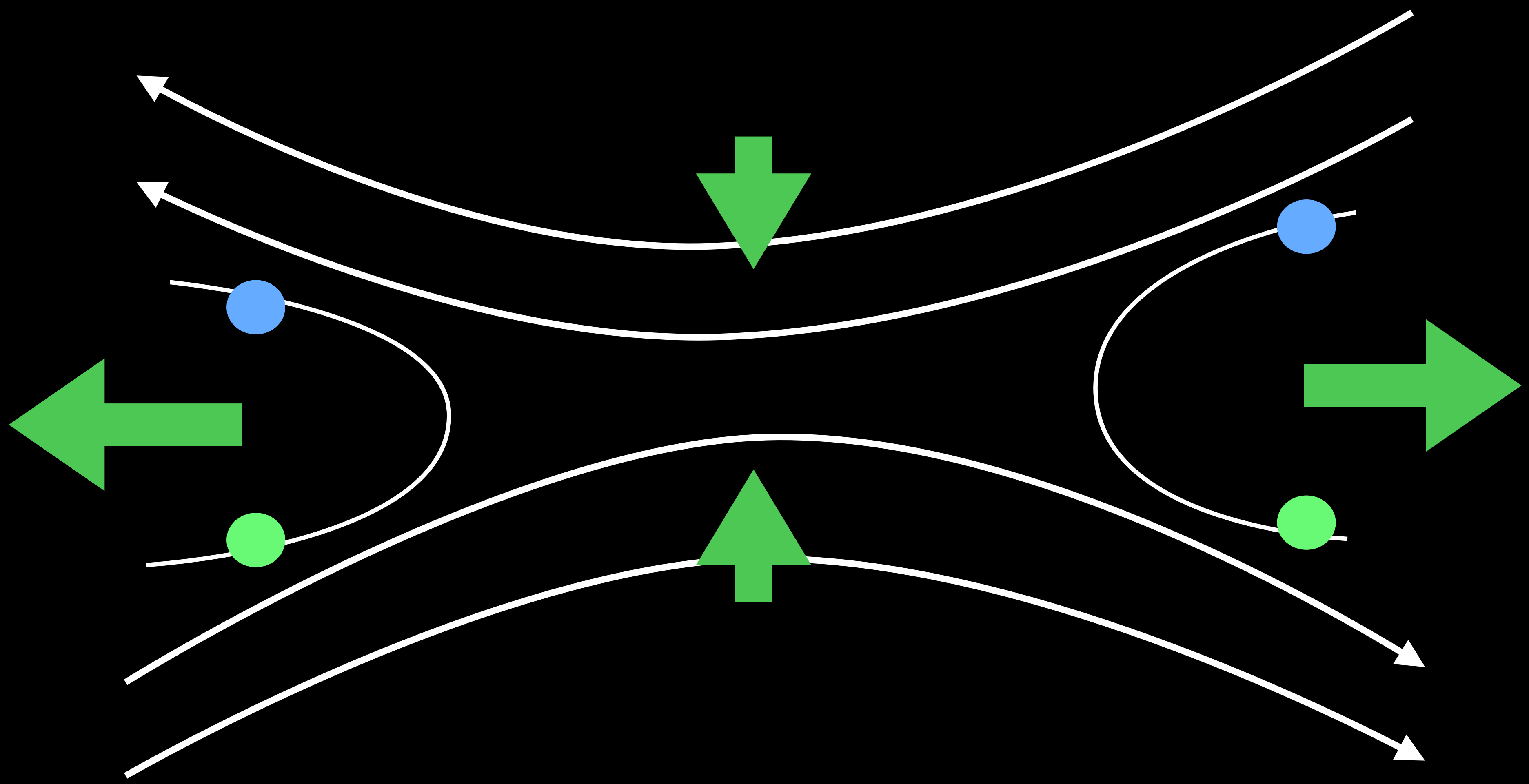
EJECTED FROM THE RECONNECTION SITE



EJECTED FROM THE RECONNECTION SITE

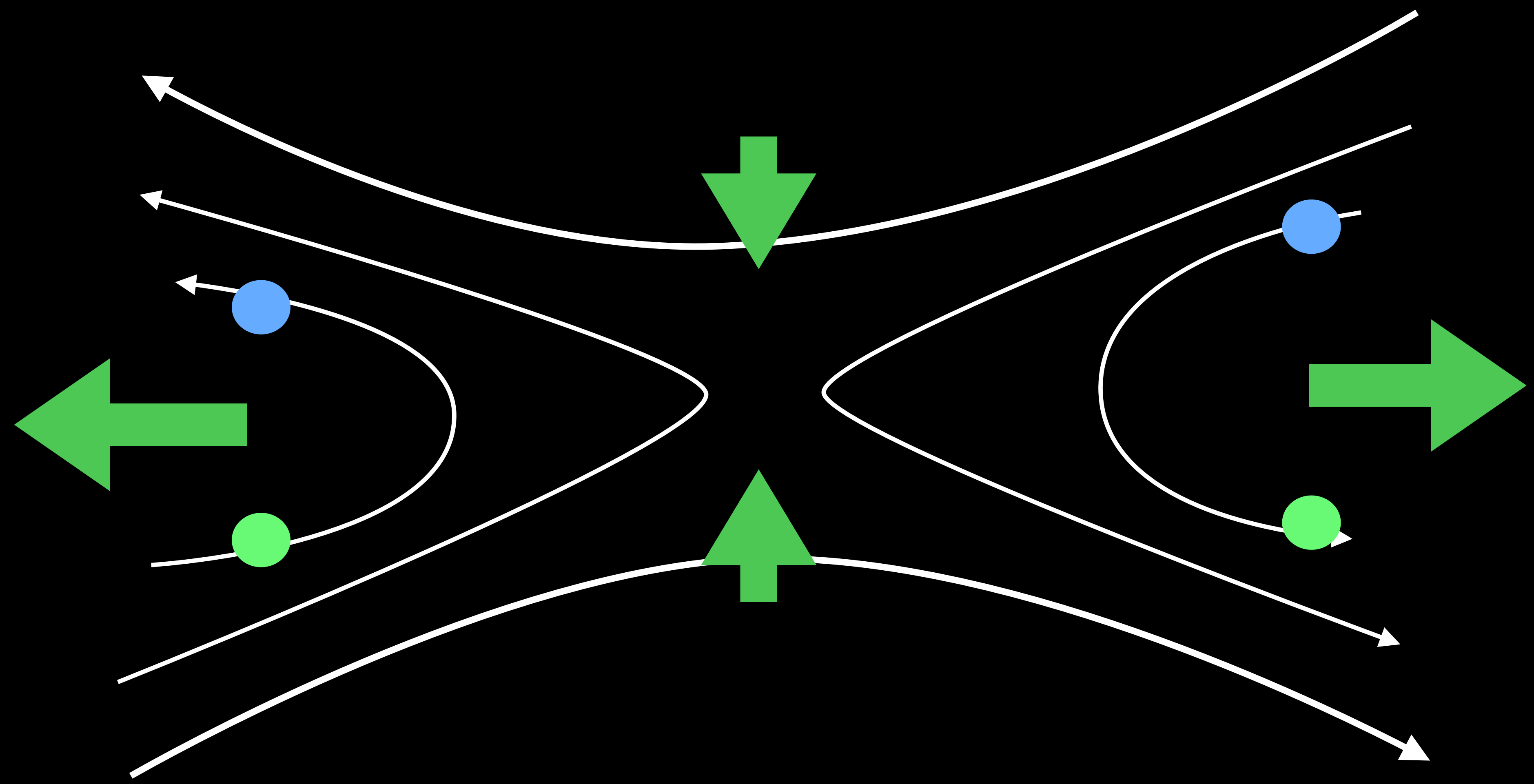


This drives the pulling of upstream flux and plasma



WHICH IS RECONNECTED AND EJECTED

ETC. ETC. AND THE PROCESS IS SELF MAINTAINED

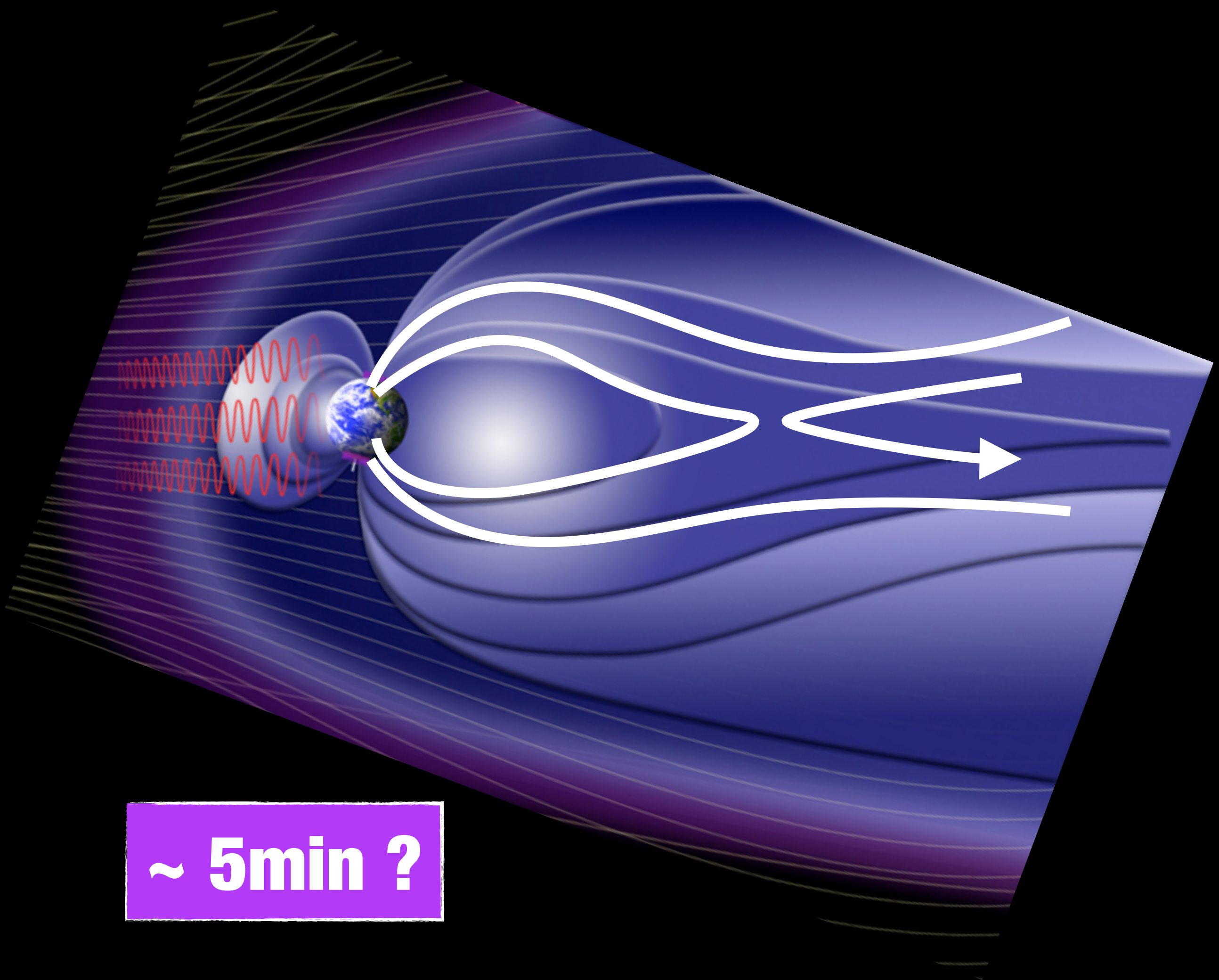


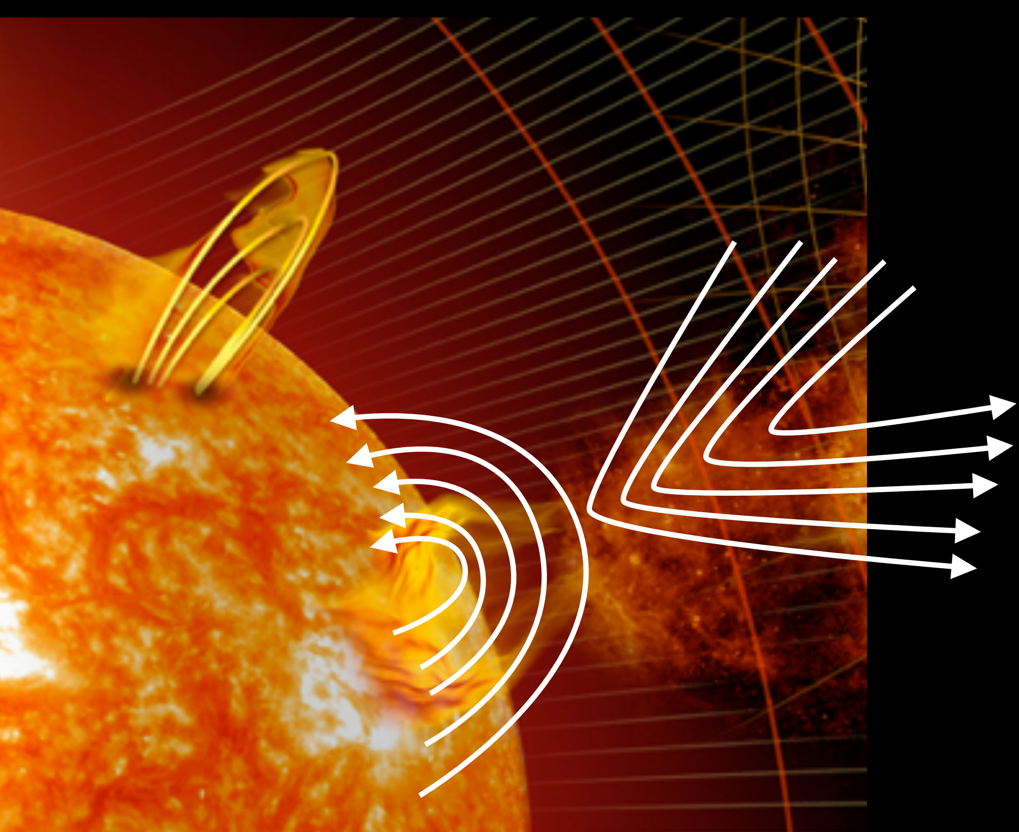
HOW MUCH FLUX DOES IT RECONNECT PER TIME UNIT?

HOW DO FIELD LINES TO CHANGE THEIR CONNECTIVITY?

WHAT MINIMAL MODEL FOR REALISTIC RECONNECTION EFFECTS?

MAGNETOHYDRODYNAMICS MODELS





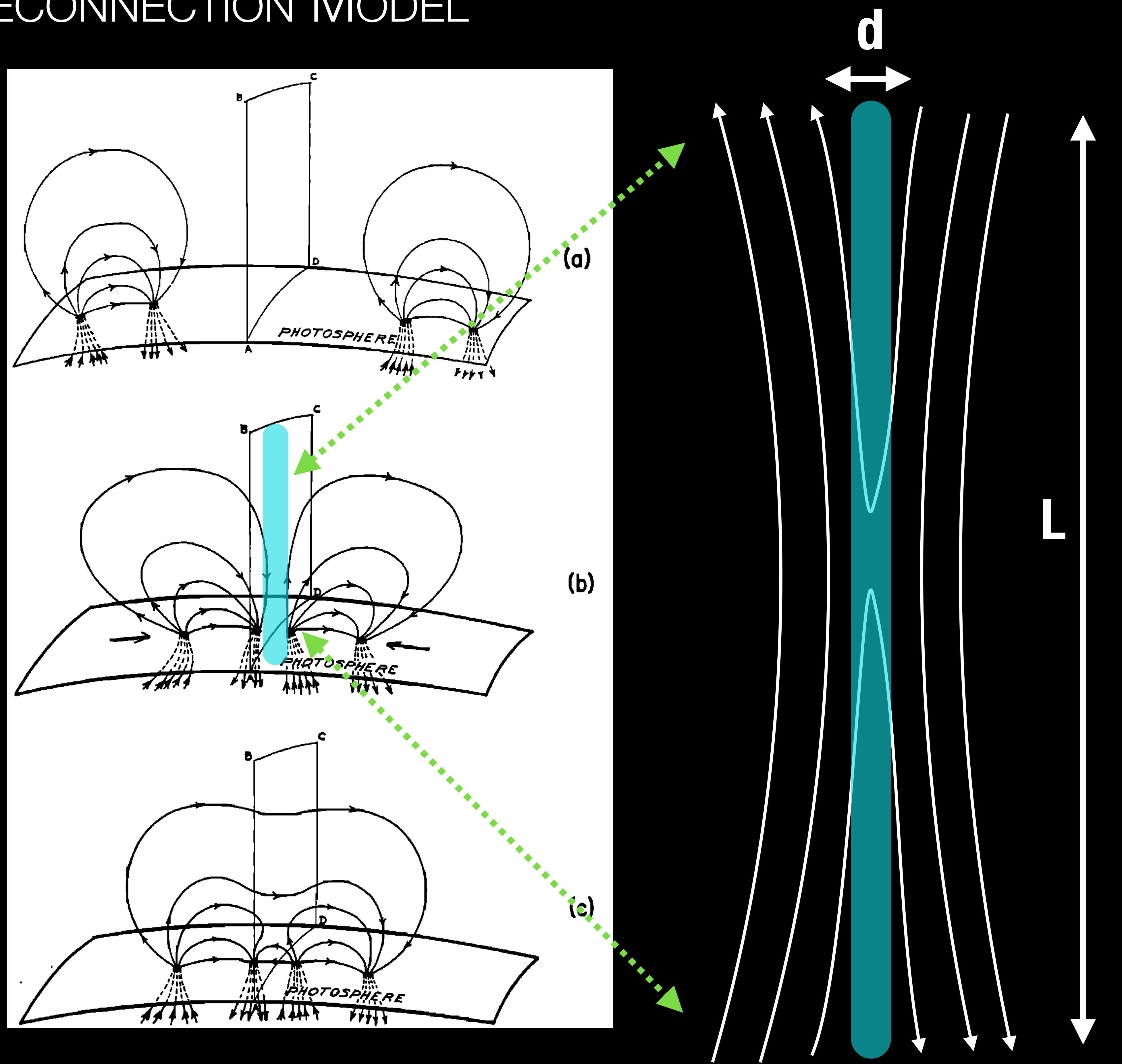
P. Sweet

E. Parker

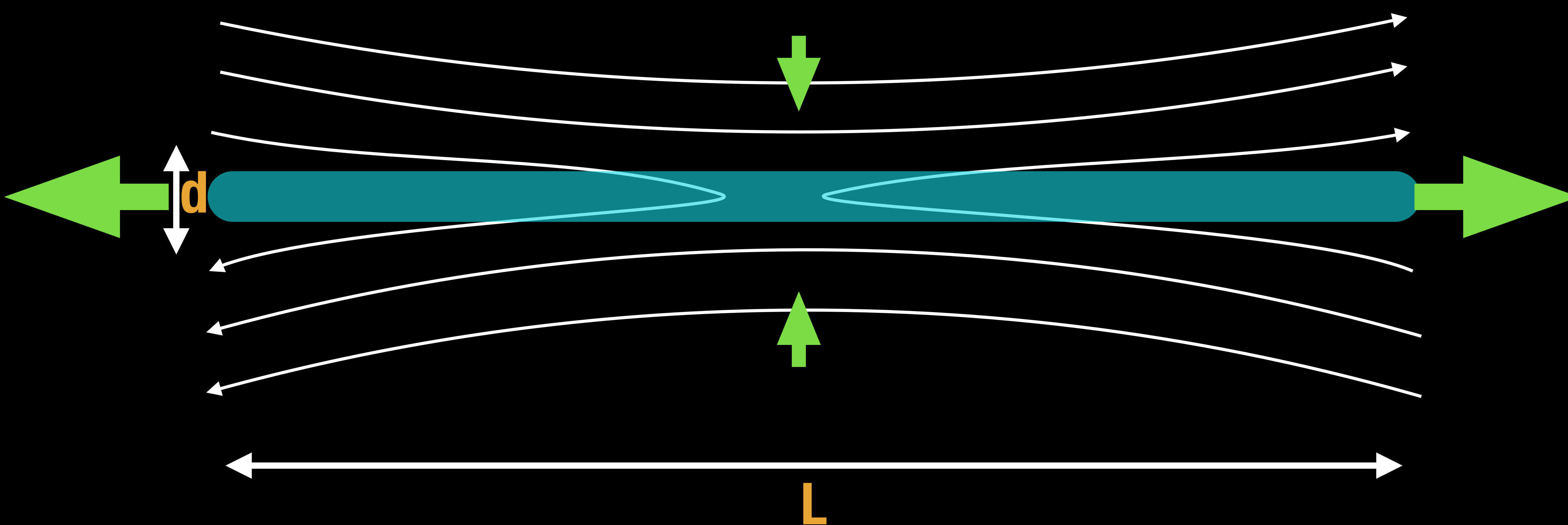
H. Petschek

Sweet-Parker Reconnection Model

1950's



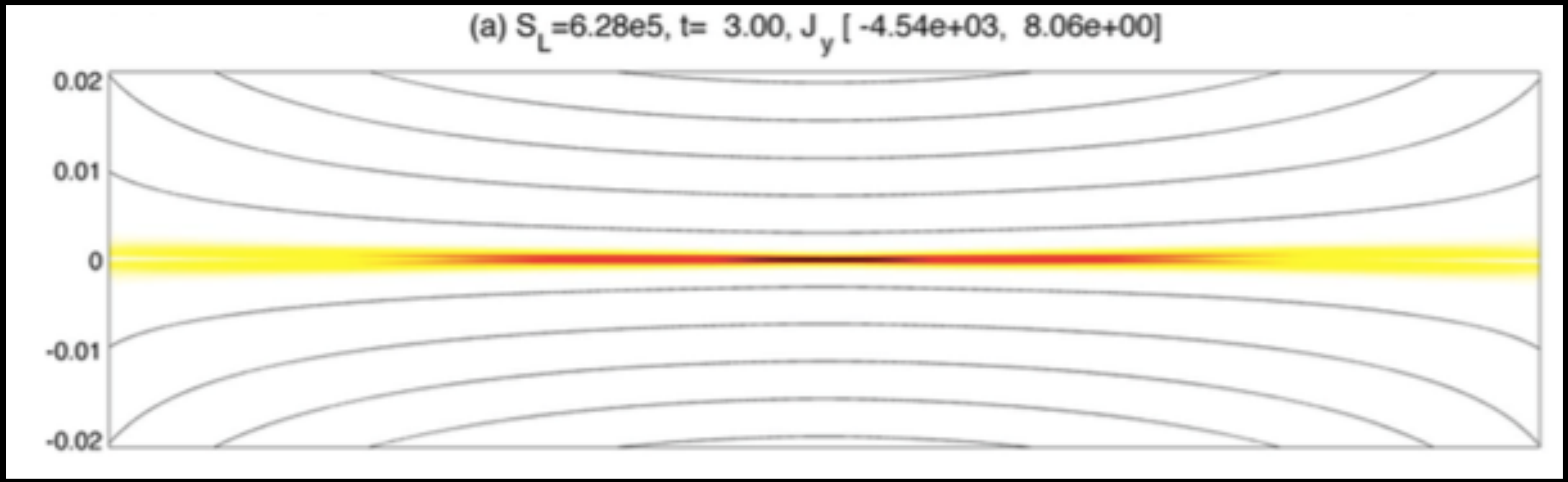
Sweet-Parker Reconnection Model
1950's



d : is the diffusion scale length : VERY small in weakly collisional plasmas

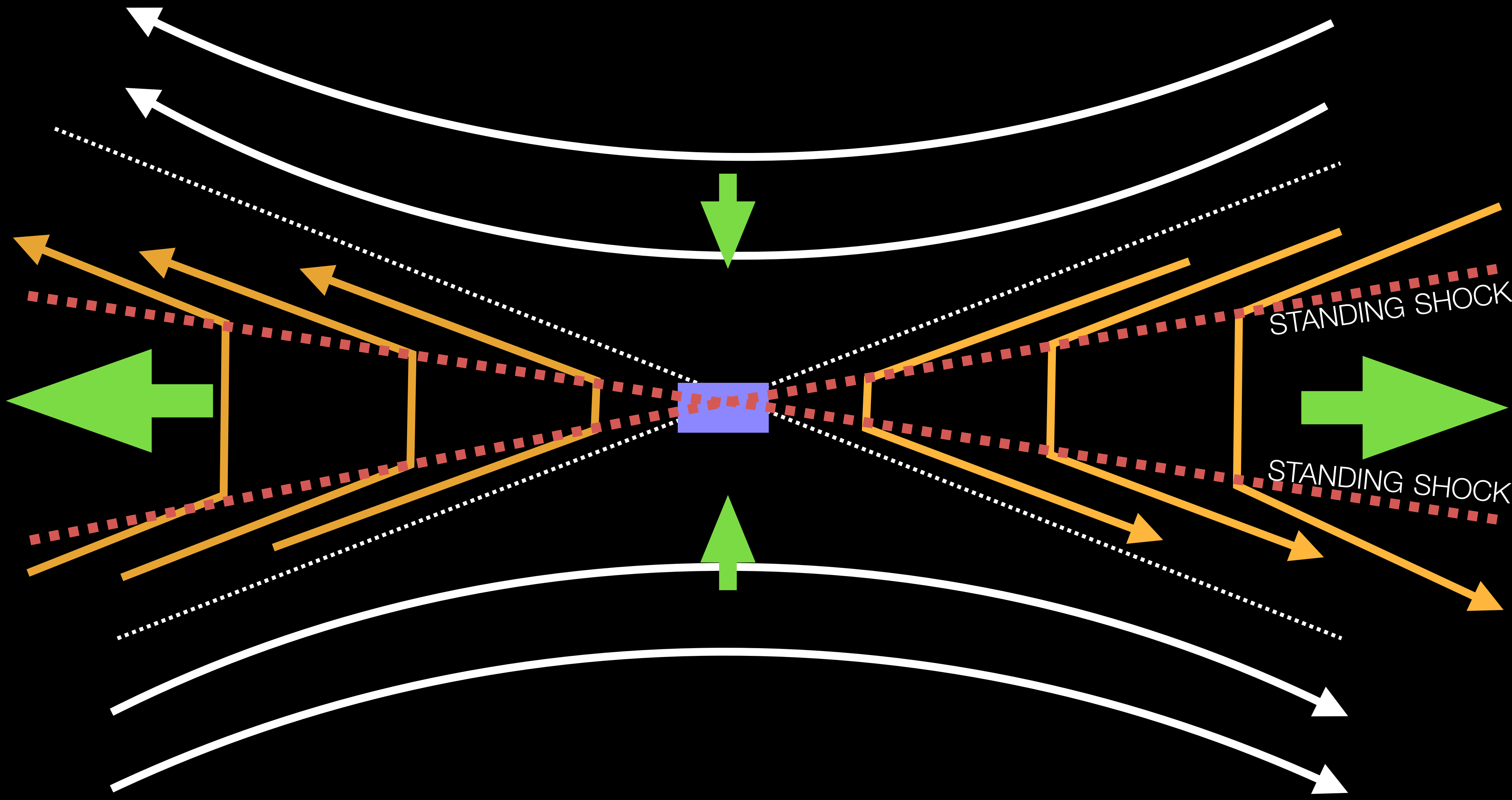
L : is comparable to the characteristic size of the reconnecting system : HUGE in astrophysics

$$v_{in} \sim \frac{d}{L} V_A$$



[Bhattacharjee et al. 2009]

Petschek Reconnection Model
1960's



Dissipation region is (chosen to be) localized in both directions

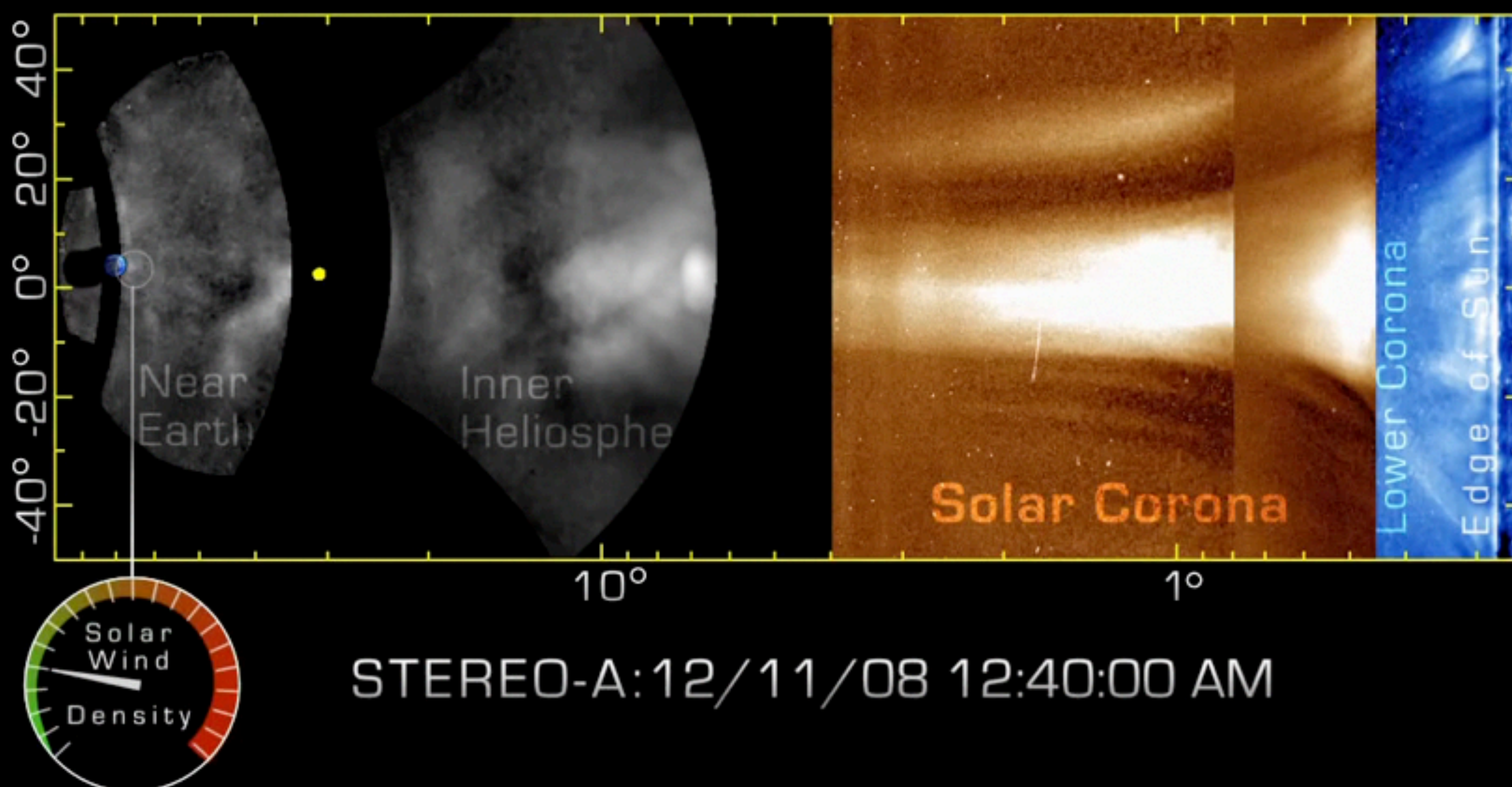
The plasma is accelerated through shocks (switch-off slow shocks)

No bottleneck, FAST RECONNECTION

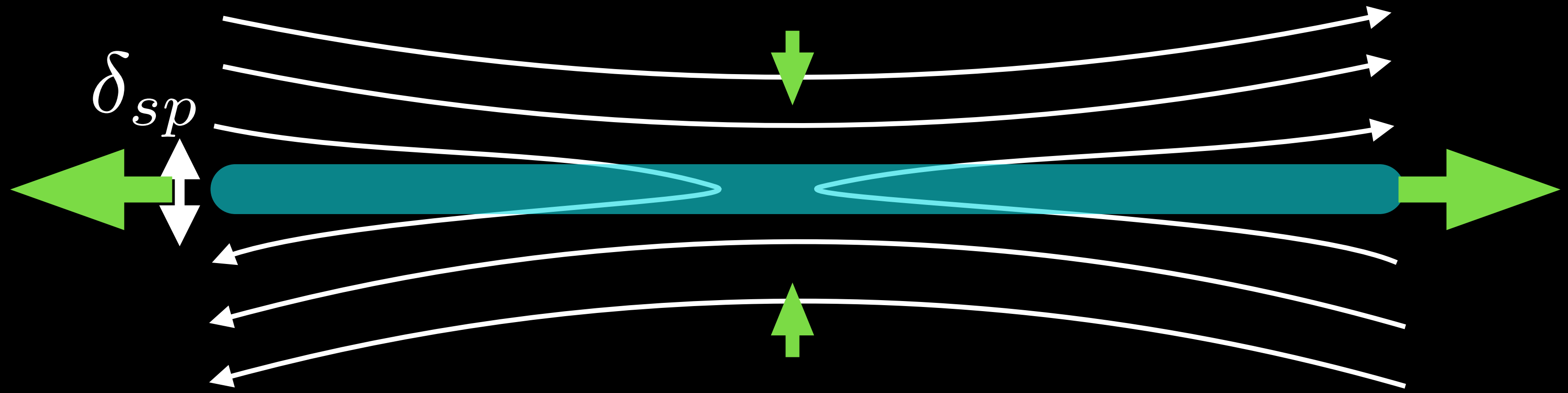
Problem : can't justify the local enhancement of resistivity

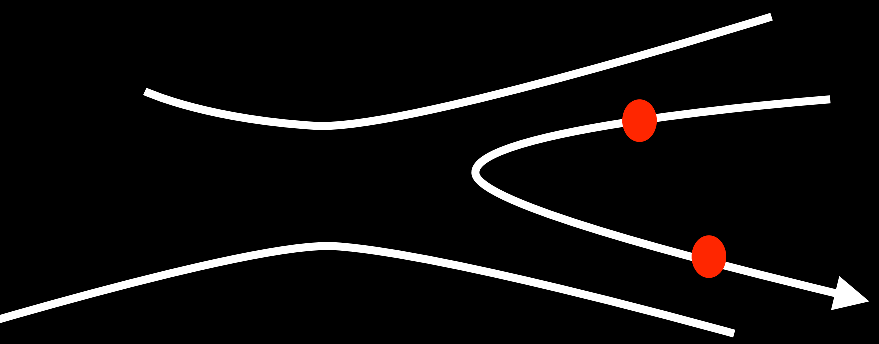
THE PLASMA IS COLLISIONLESS

MEAN FREE PATH

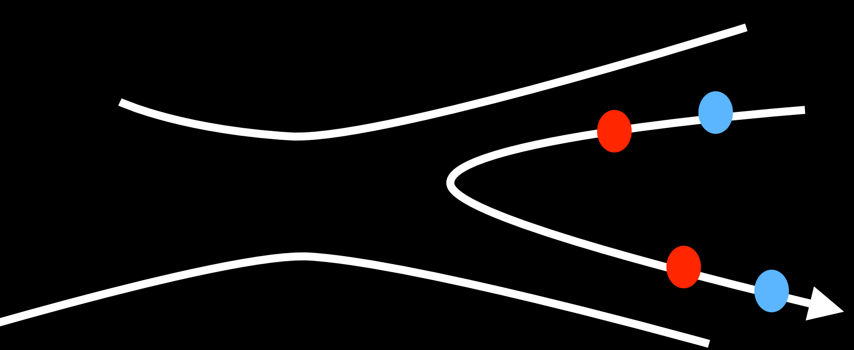


Collisionless effects

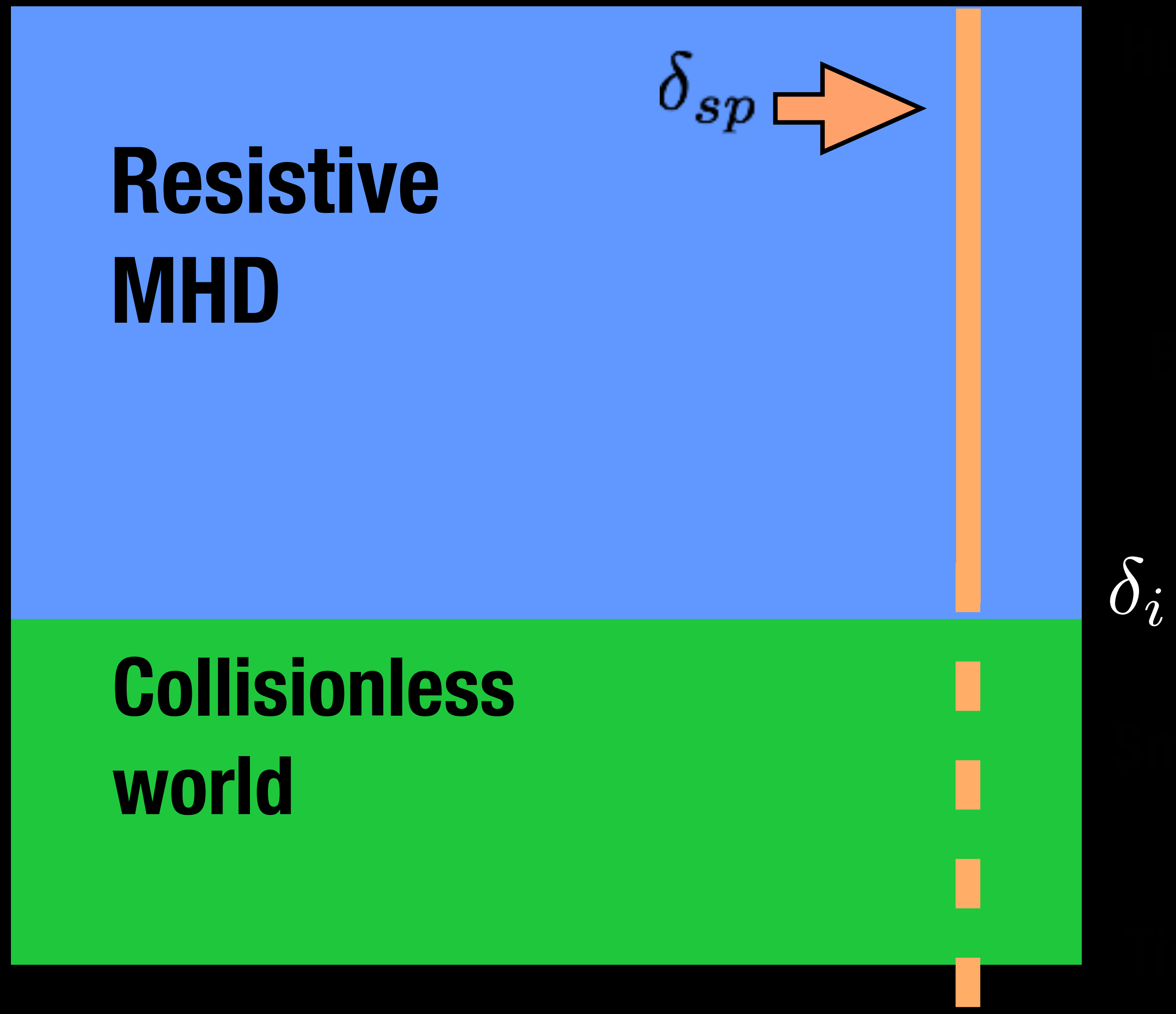




Single fluid frozen in the magnetic field



Only electrons are assumed to be frozen in B. Ion inertia allow them to detach at small scales



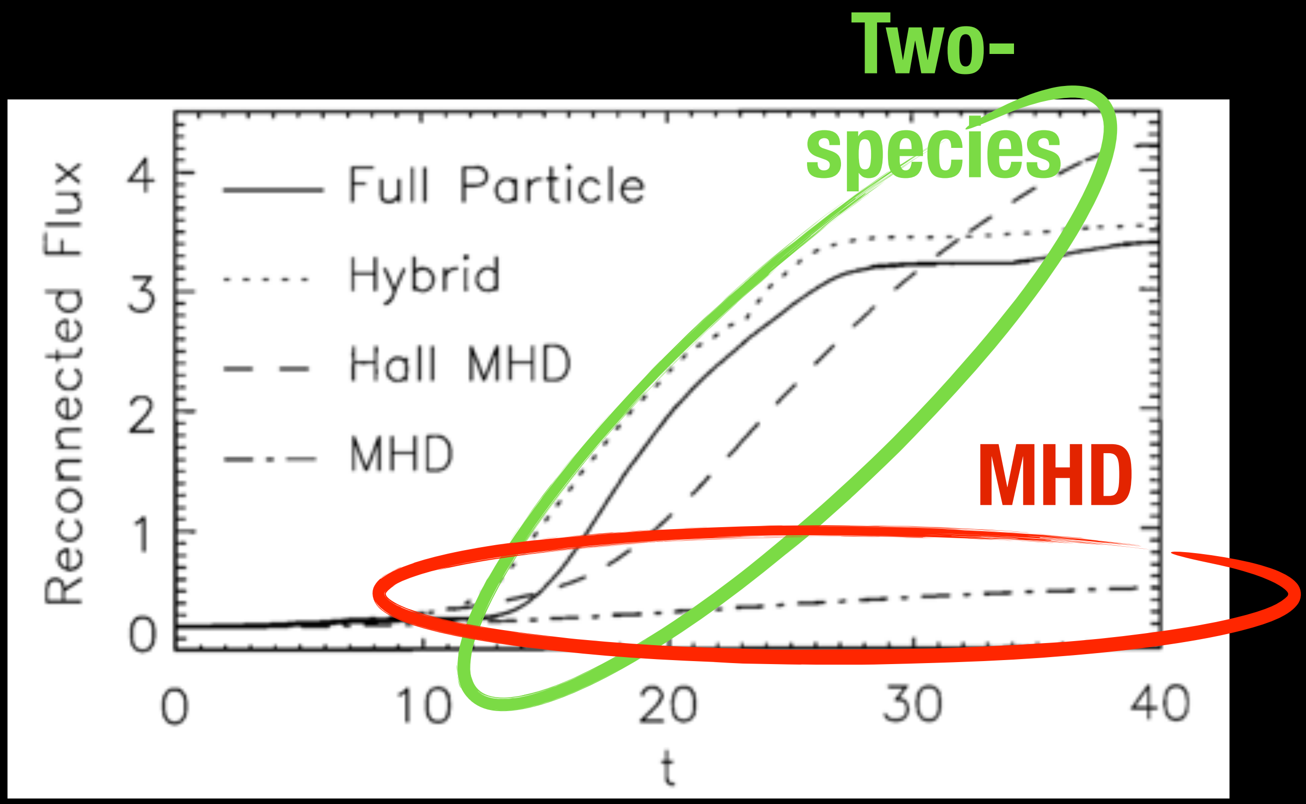
« STANDARD » COLLISIONLESS RECONNECTION MODEL

MHD　　　　Two-fluid

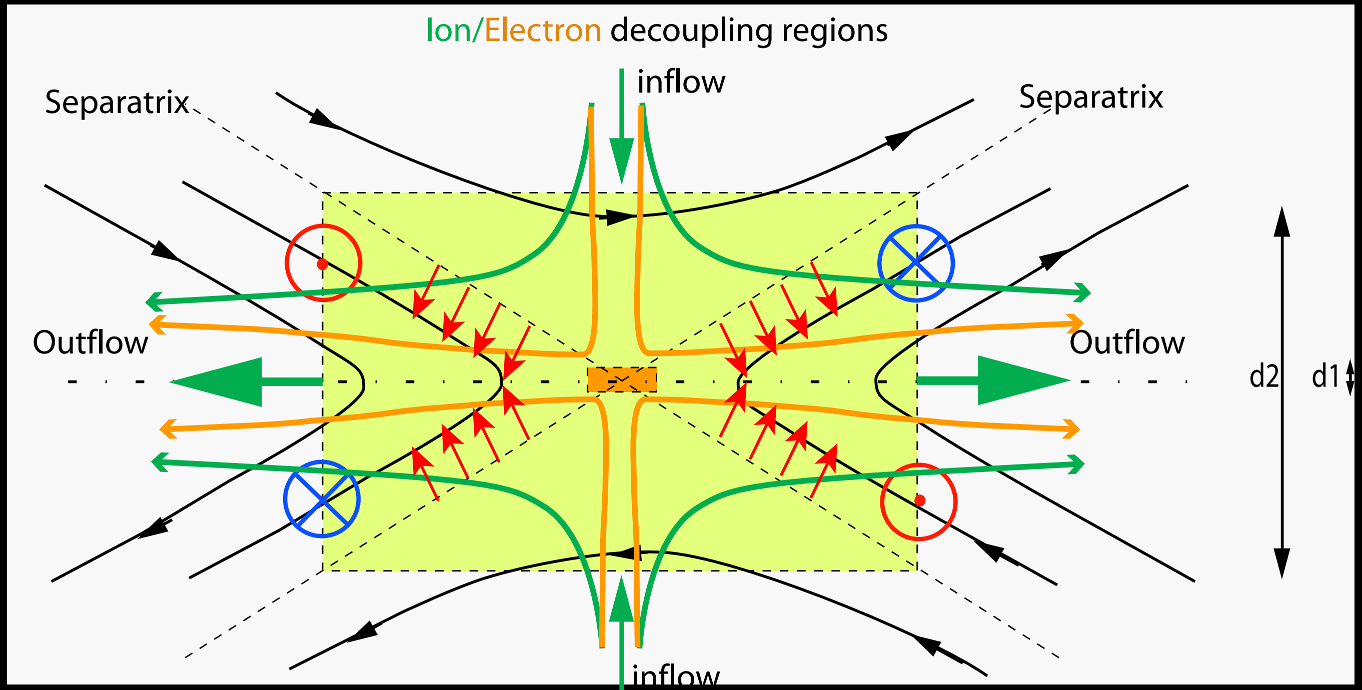
$$\mathbf{E} = \underbrace{-\mathbf{v}_i \times \mathbf{B}}_{\text{MHD}} + \underbrace{\frac{1}{ne}(\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{P}_e)}_{\text{Two-fluid}}$$

Just electron momentum eq.
Electrons are frozen in B

$$\mathbf{E} = -\mathbf{v}_e \times \mathbf{B} - \frac{1}{ne}\nabla \times \mathbf{P}_e$$

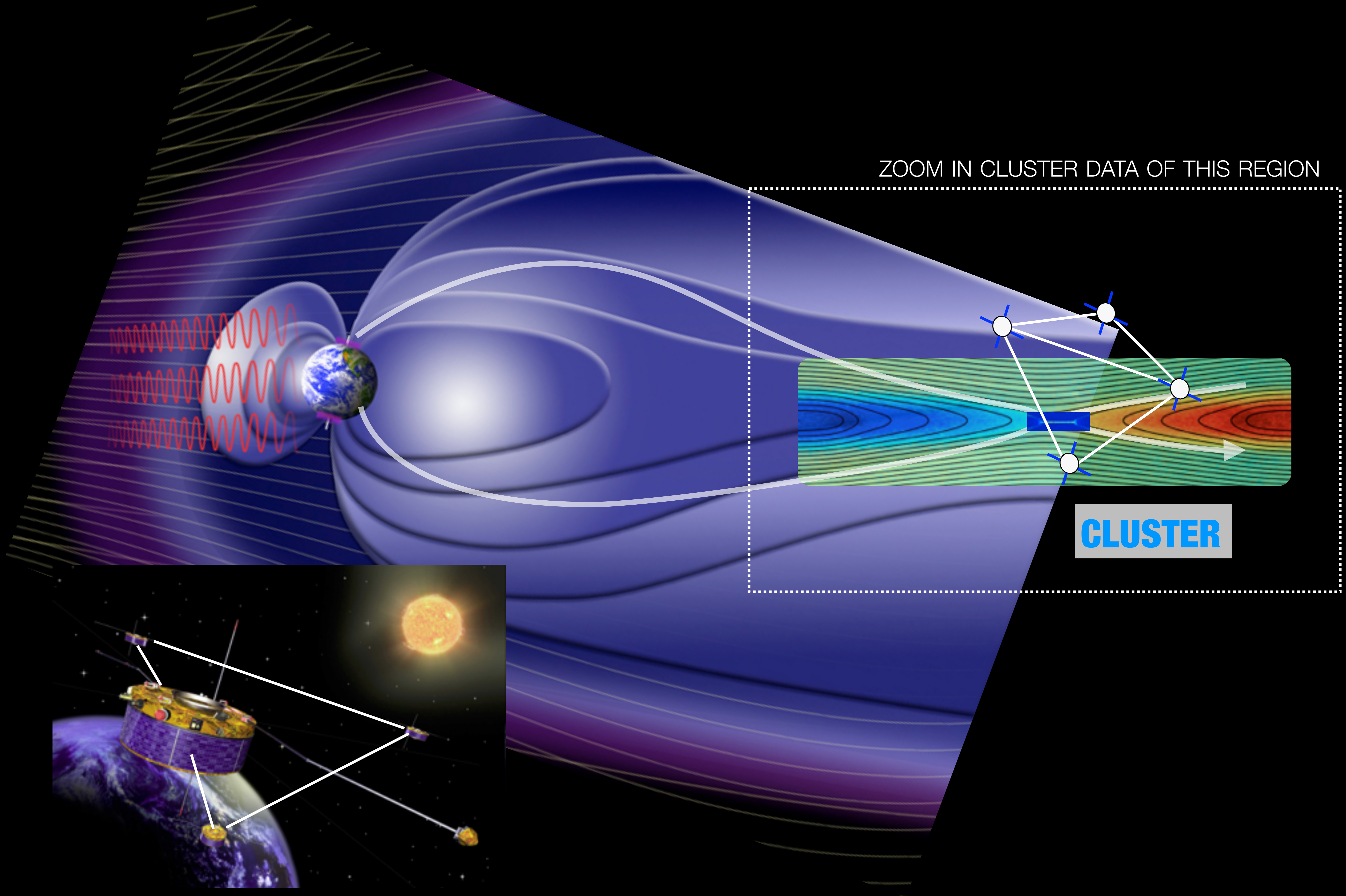


[Birn et al. JGR 2001]

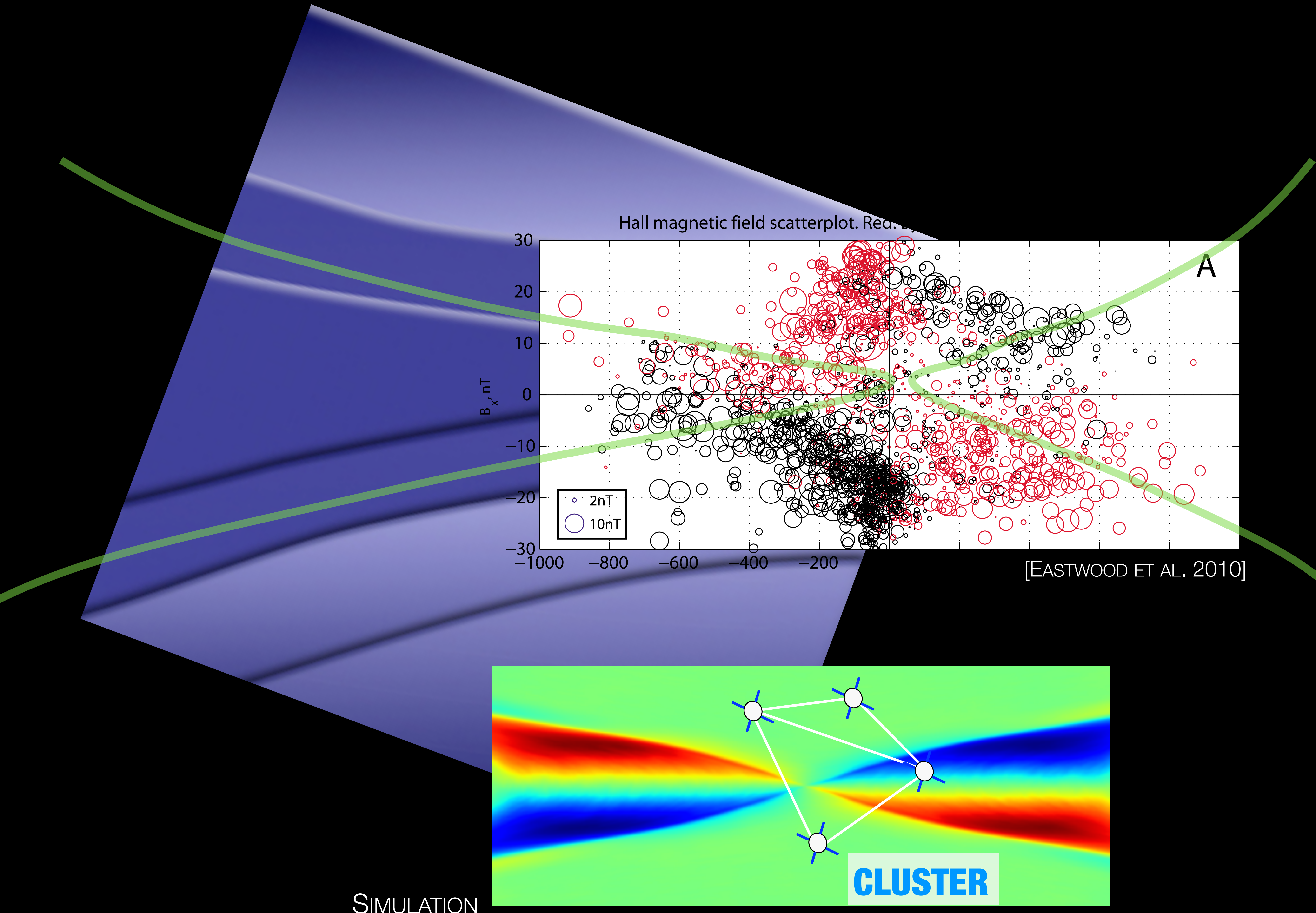


[Aunai et al. JGR 2011]

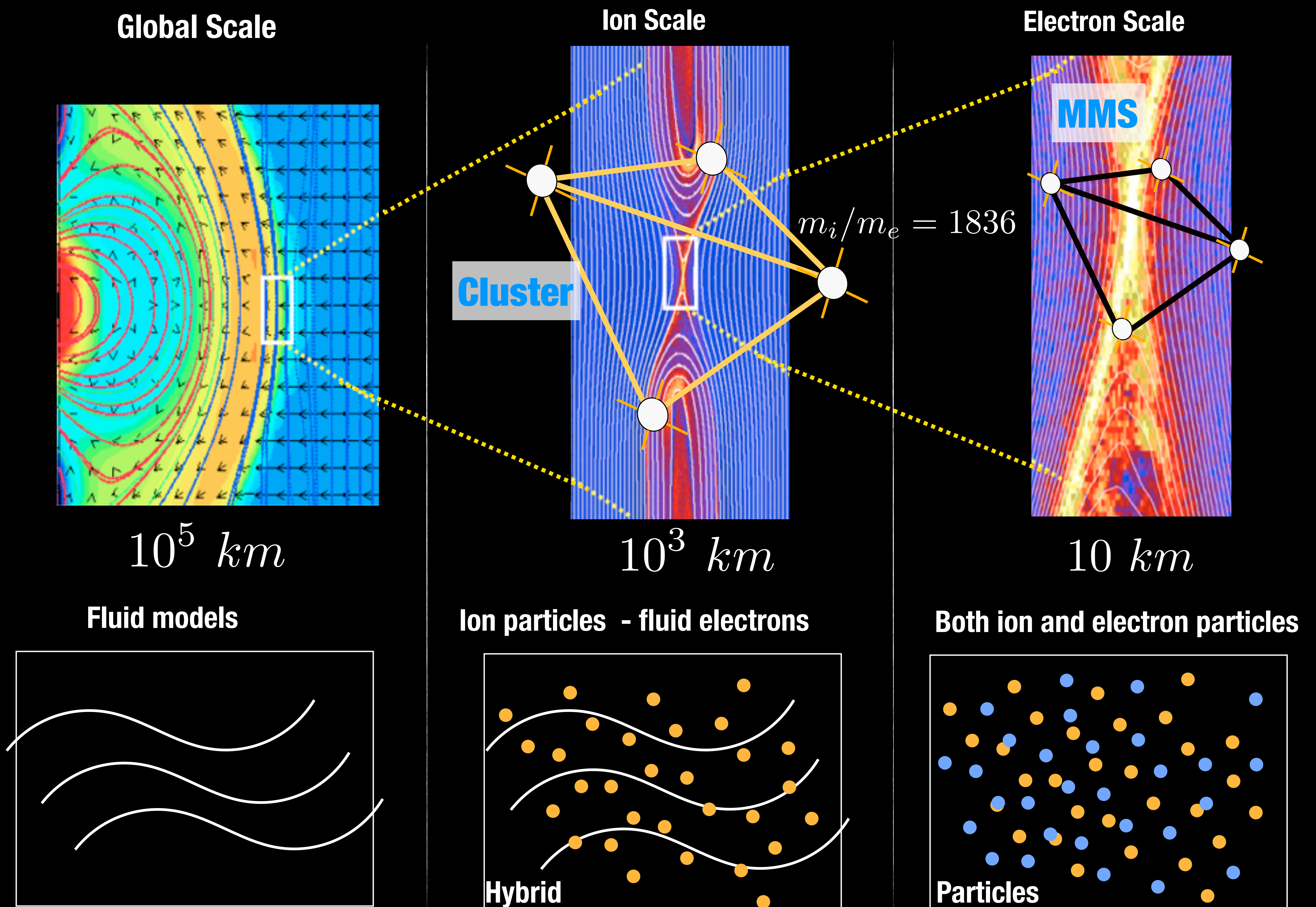
SUCCESS OF ION SCALE MULTI-SPACECRAFT MEASUREMENTS

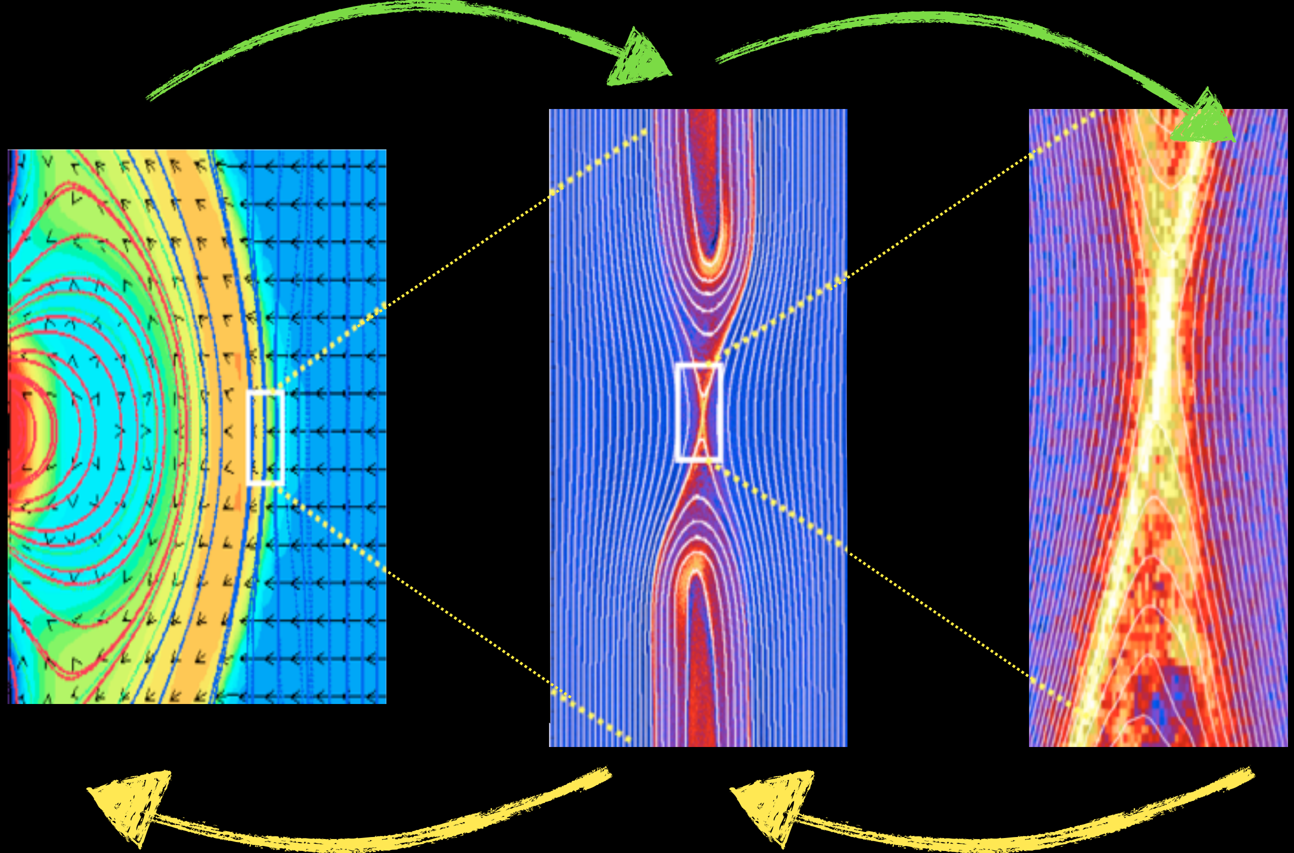


SUCCESS OF ION SCALE MULTI-SPACECRAFT MEASUREMENTS



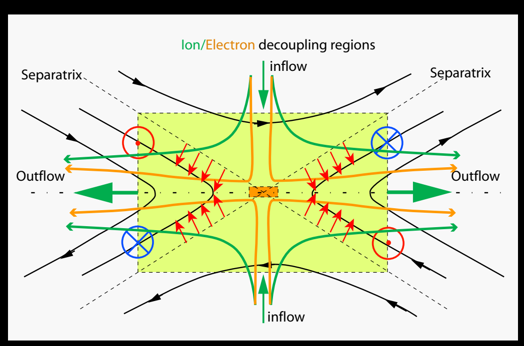
MULTI-SCALES - MULTI-PHYSICS - KEY INGREDIENTS?





2005's -> ...

Multi-Scale



1990-2005

HALL RECONNECTION

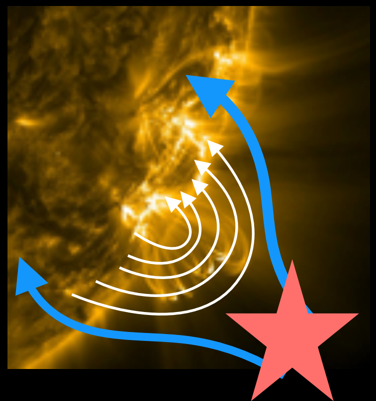

P. Sweet

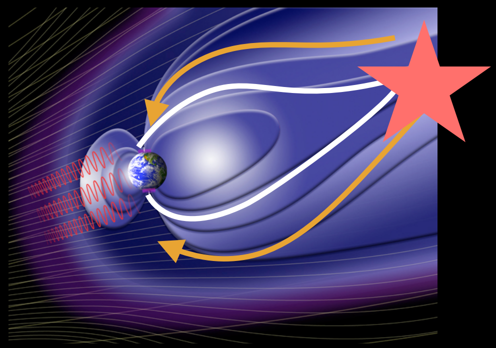

E. Parker


H. Petschek

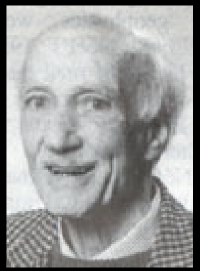
1950's 60's

FIRST MHD MODELS






Giovanelli


Dungey

1940's

BIRTH OF RECONNECTION

KINETIC MODELING — Particle-In-Cell

Particle-Mesh code

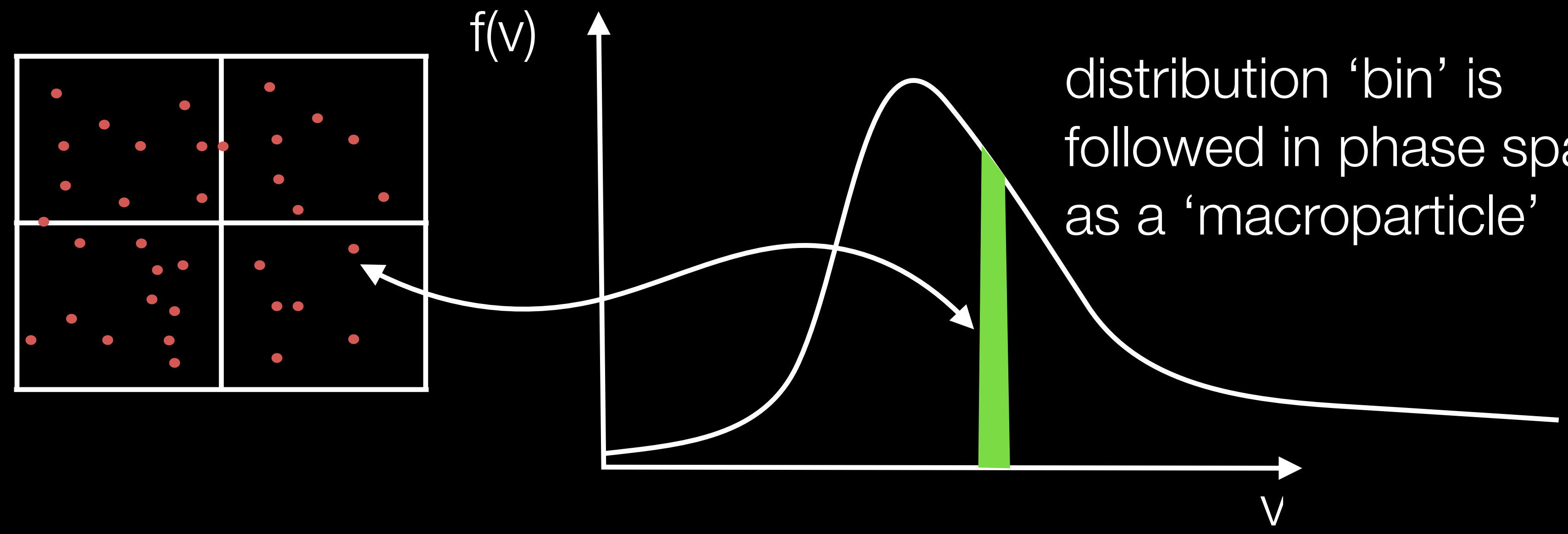
- Lagrangian version of Vlasov-Maxwell (eulerian codes are insanely expensive)

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{E} + q\mathbf{v}\times\mathbf{B}$$

$$\mathbf{v} = \frac{d\mathbf{r}}{dt}$$

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

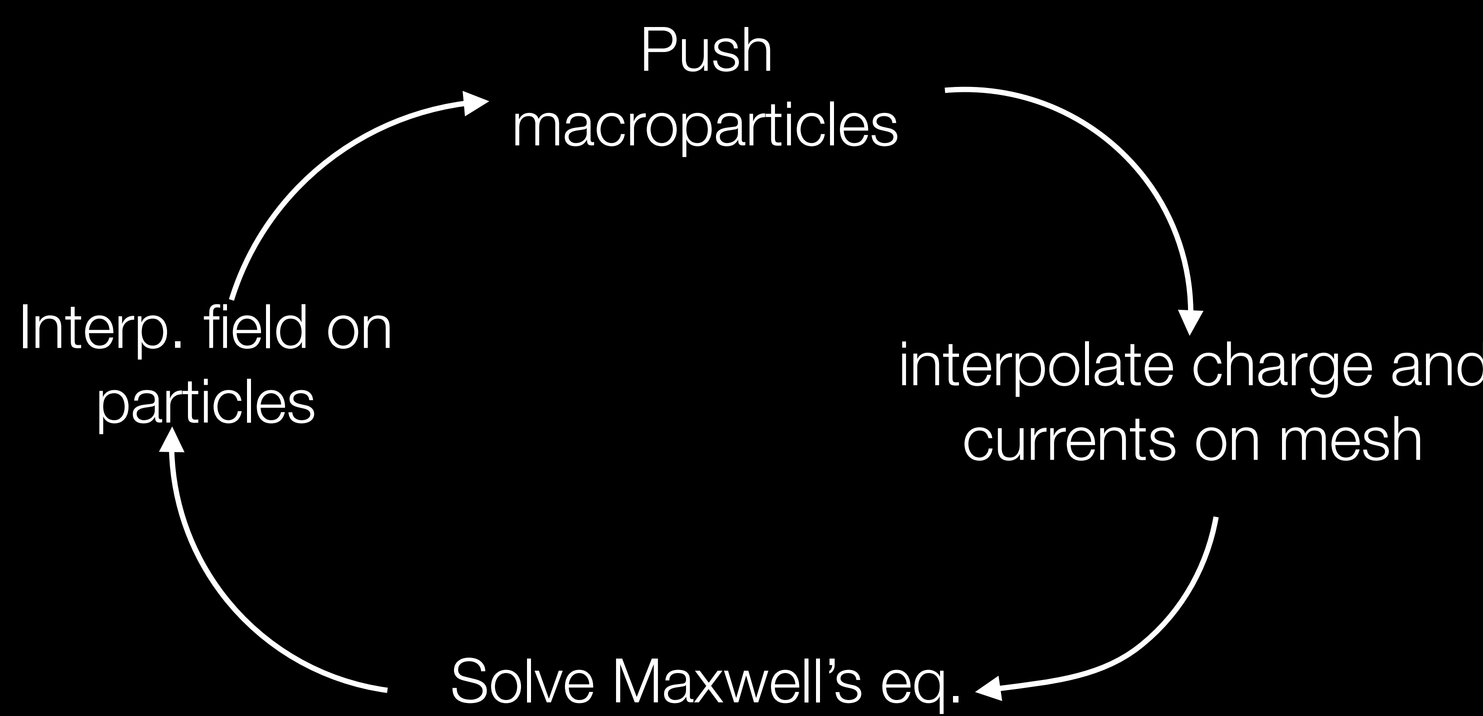
$$\frac{\partial\mathbf{E}}{\partial t} - c^2\nabla\times\mathbf{B} + c^2\mu_0\mathbf{j} = 0$$



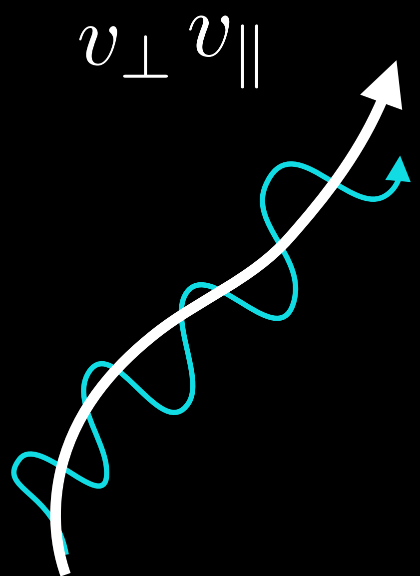
Include all relevant physics but:

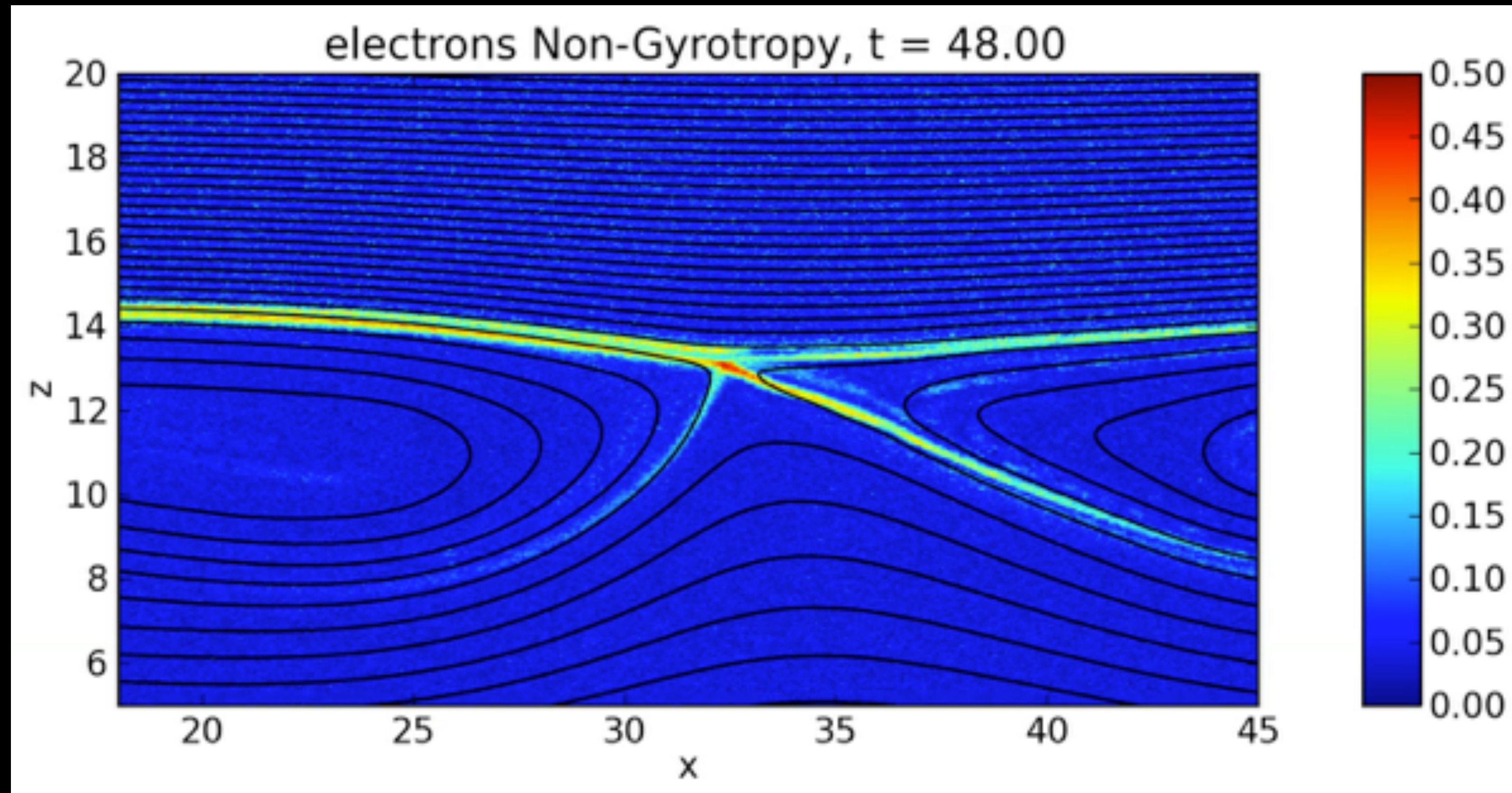
- statistical noise
- still have to cheat with m_e/m_i

$$c/V_A$$

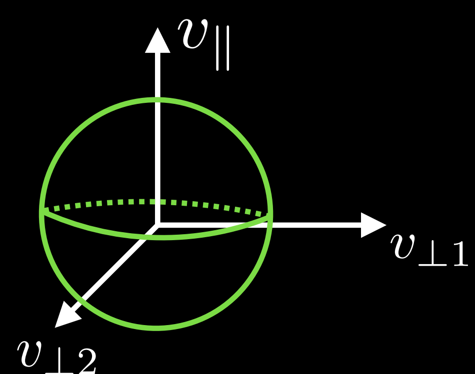


Electron scale mechanisms - Non-gyrotropy



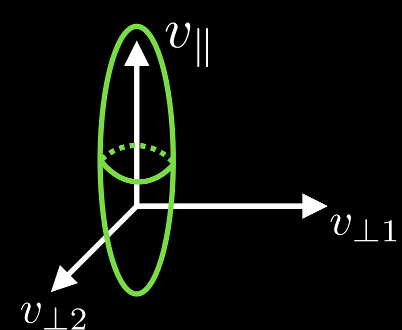


[Aunai et al. 2013]



isotropic distribution

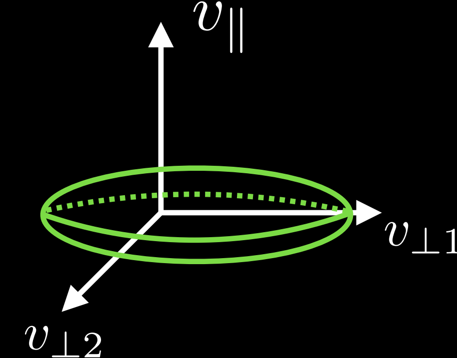
$$\begin{pmatrix} P & 0 & 0 \\ 0 & P & 0 \\ 0 & 0 & P \end{pmatrix}$$



anisotropic distribution

$T_\| > T_\perp$

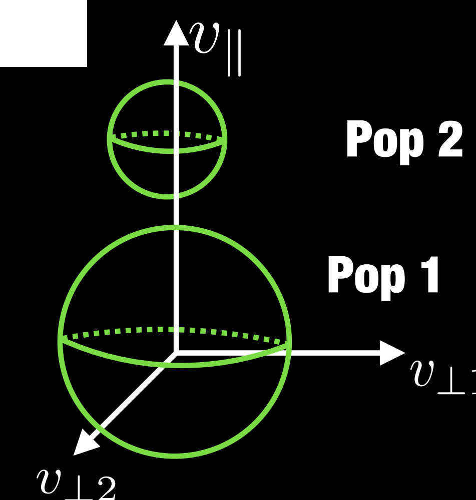
$$\begin{pmatrix} P_\| & 0 & 0 \\ 0 & P_\perp & 0 \\ 0 & 0 & P_\perp \end{pmatrix}$$



anisotropic distribution

$T_\| < T_\perp$

$$\begin{pmatrix} P_\| & 0 & 0 \\ 0 & P_\perp & 0 \\ 0 & 0 & P_\perp \end{pmatrix}$$



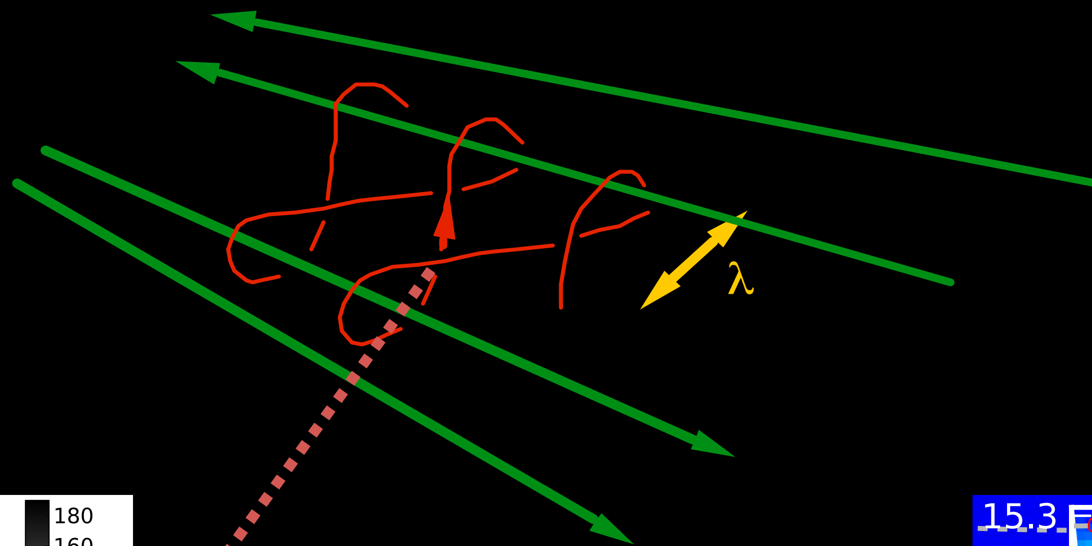
complicated anisotropic

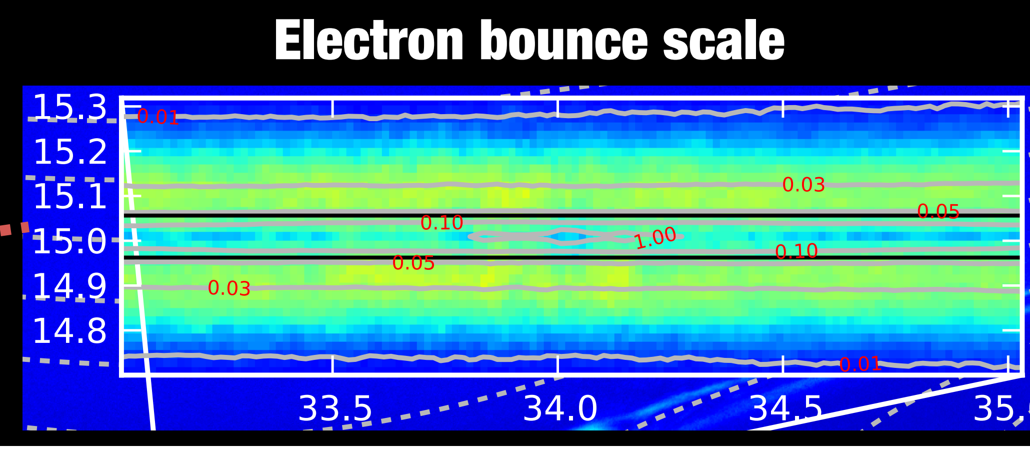
$T_\| > T_\perp$

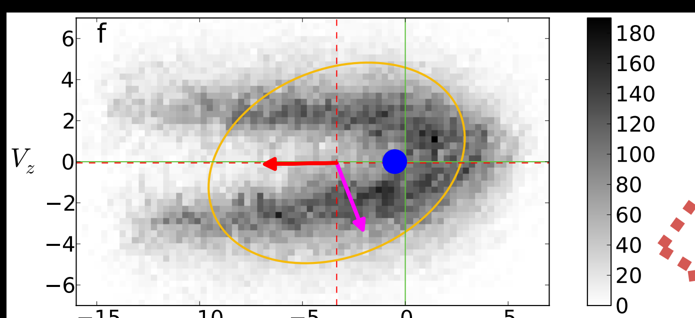
$$\begin{pmatrix} P_\| & 0 & 0 \\ 0 & P_\perp & 0 \\ 0 & 0 & P_\perp \end{pmatrix}$$

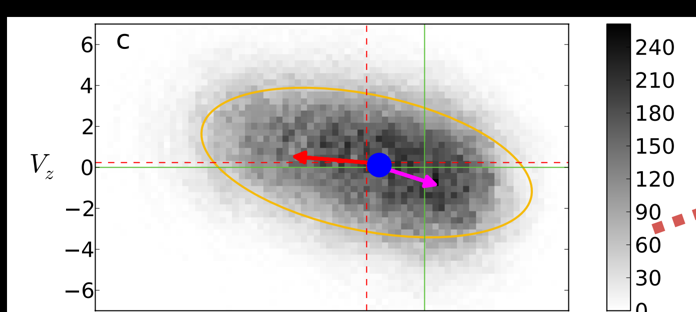
Generally true as long as $\lambda \gg \rho_L$ **and** $\omega \ll \omega_c$

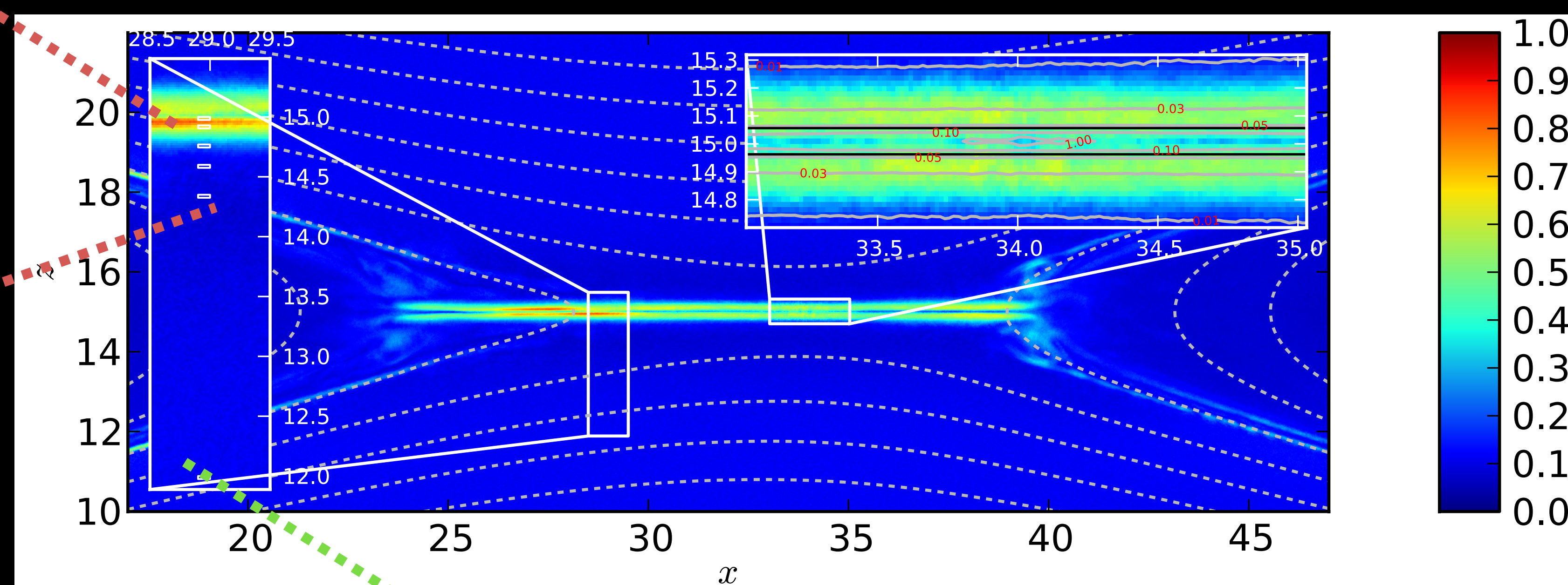
ELECTRON NONGYROTROPY [HESSE ET AL. 2010, AUNAI ET AL. 2013]





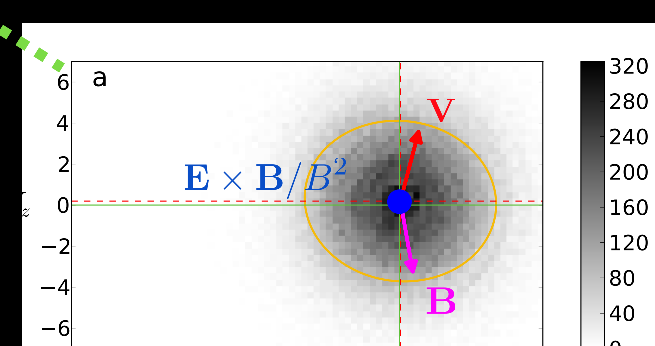






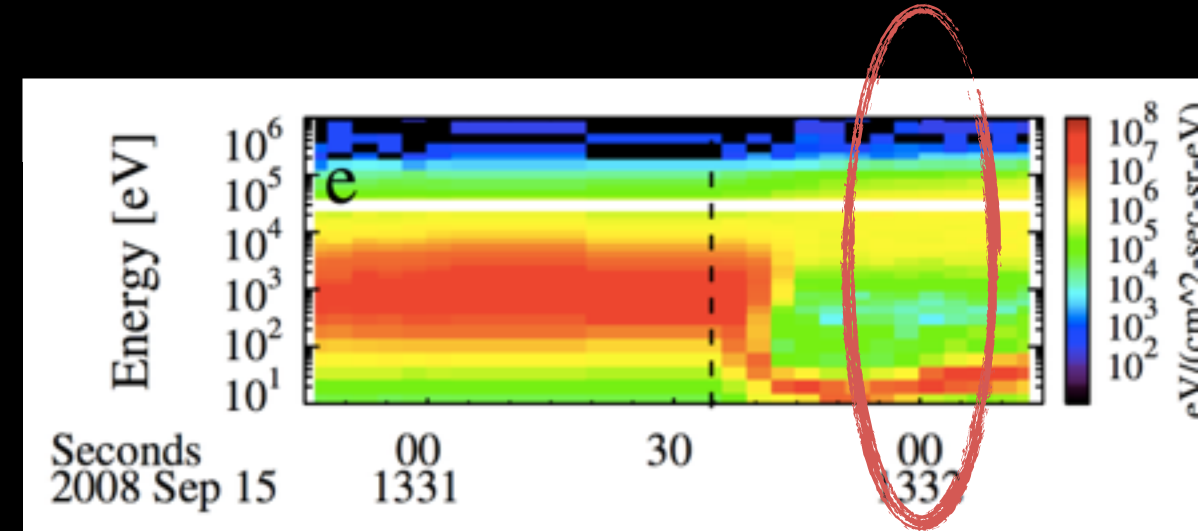
$$E = -\frac{1}{n_e e}\nabla \cdot \mathbf{P}_e$$

$$E = \frac{1}{2en_e}L^2\frac{\partial v_{ex}}{\partial x}\nabla^2\left(m_e n_e v_{ey}\right)$$

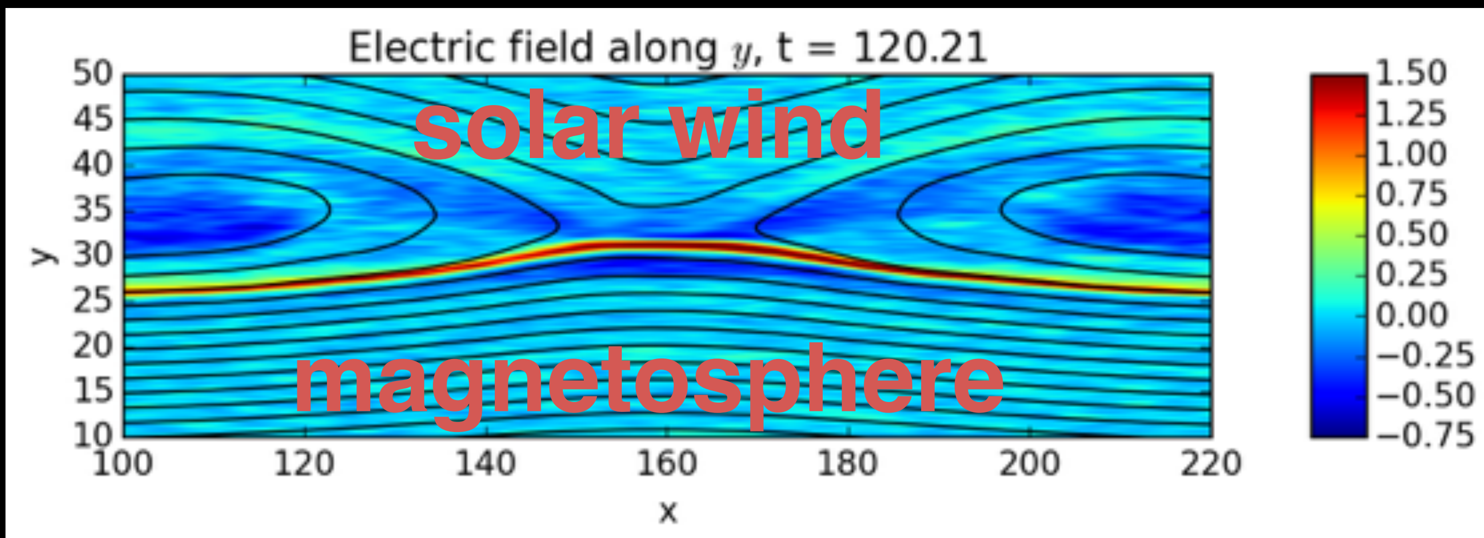


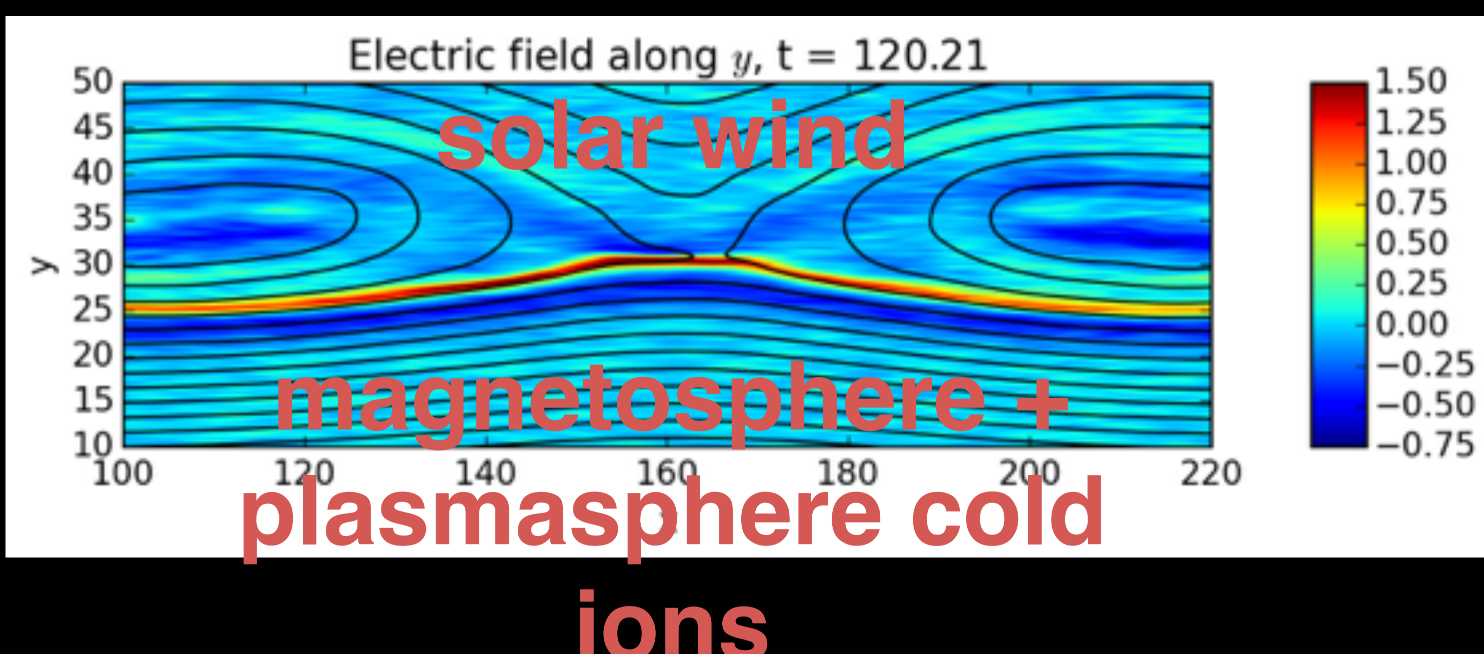
MAGNETOSPHERIC DARK MATTER [DARGENT+ IN PREP]

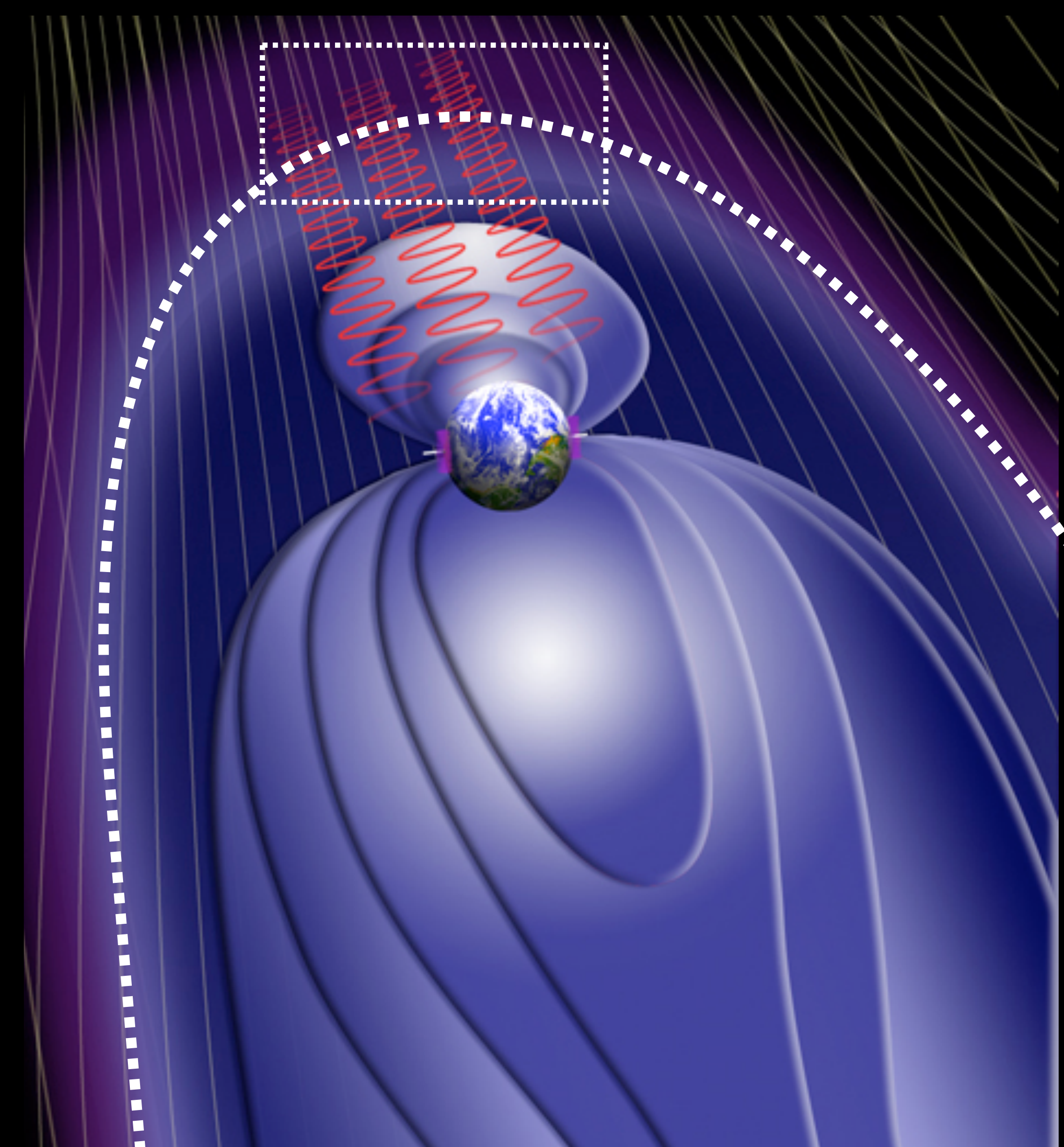
Impact of cold ions on reconnection



[Walsh+ GRL 2014]



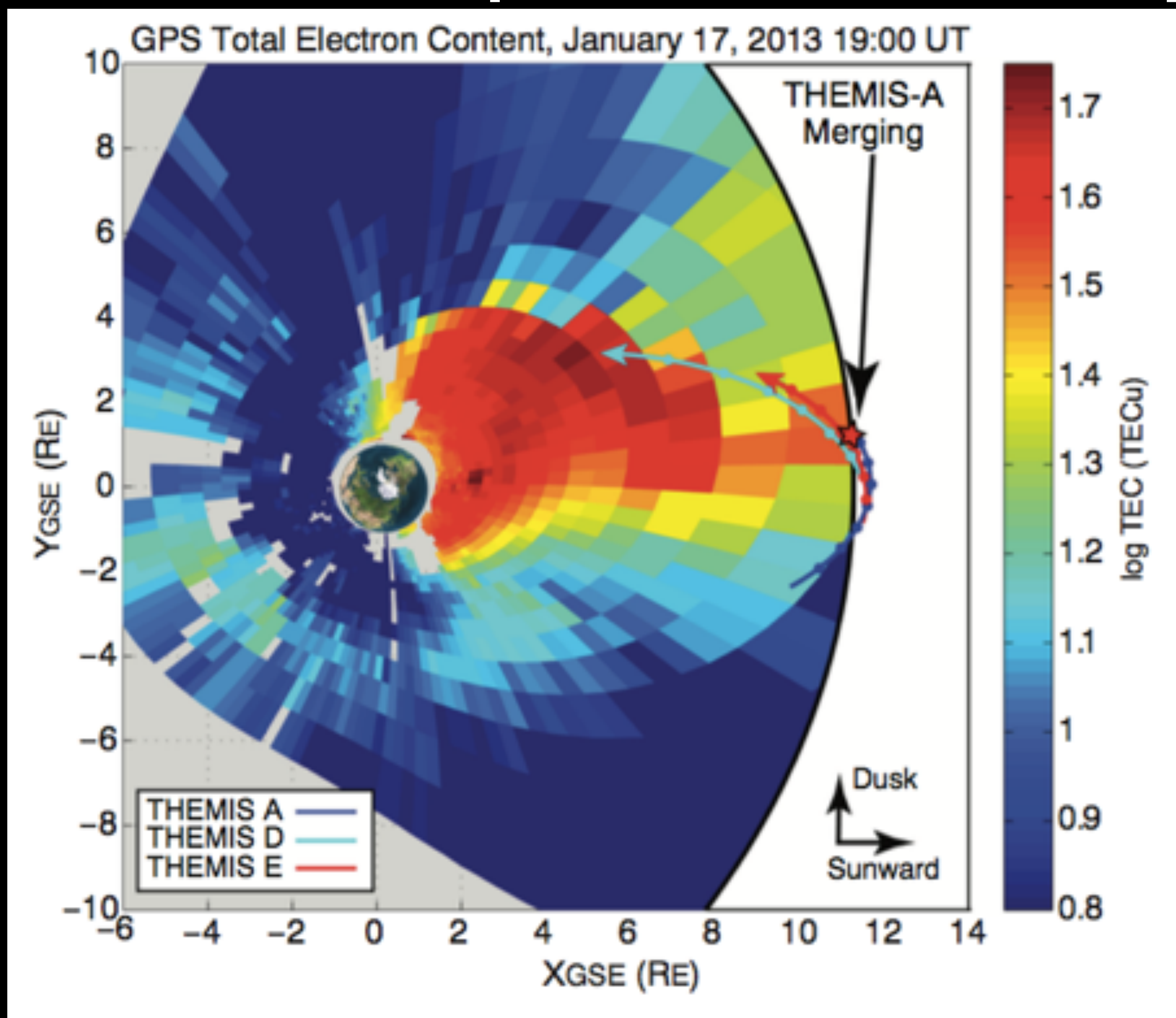




Magnetospheric Dark Matter

Plasmaspheric plume

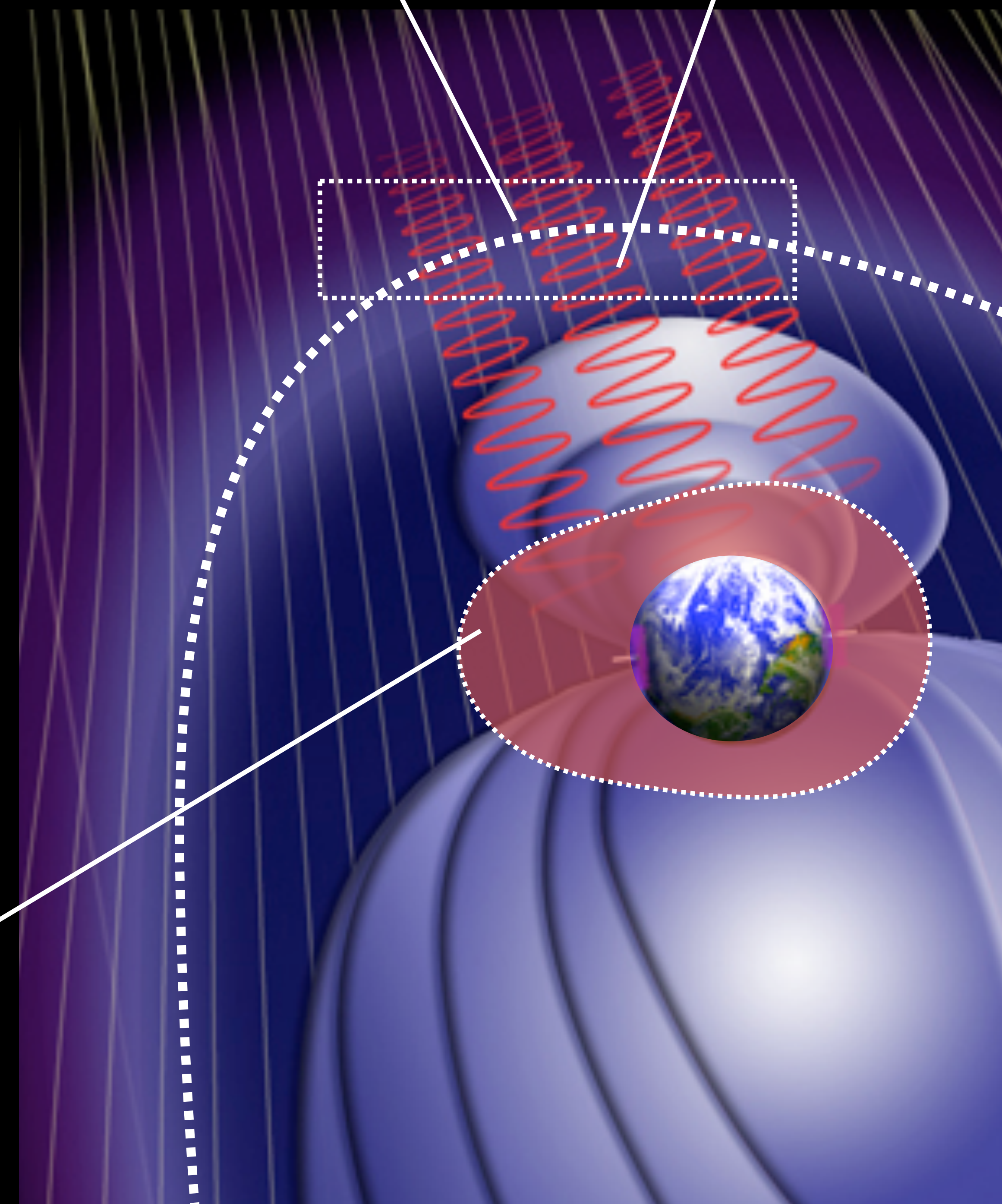
[Walsh et al. Science 2014]



Plasmaspheric plume touching the magnetopause in storm times

Magnetospheric plasma (<1 part/cm^3, 1keV)

Solar Wind (5 part/cm^3)

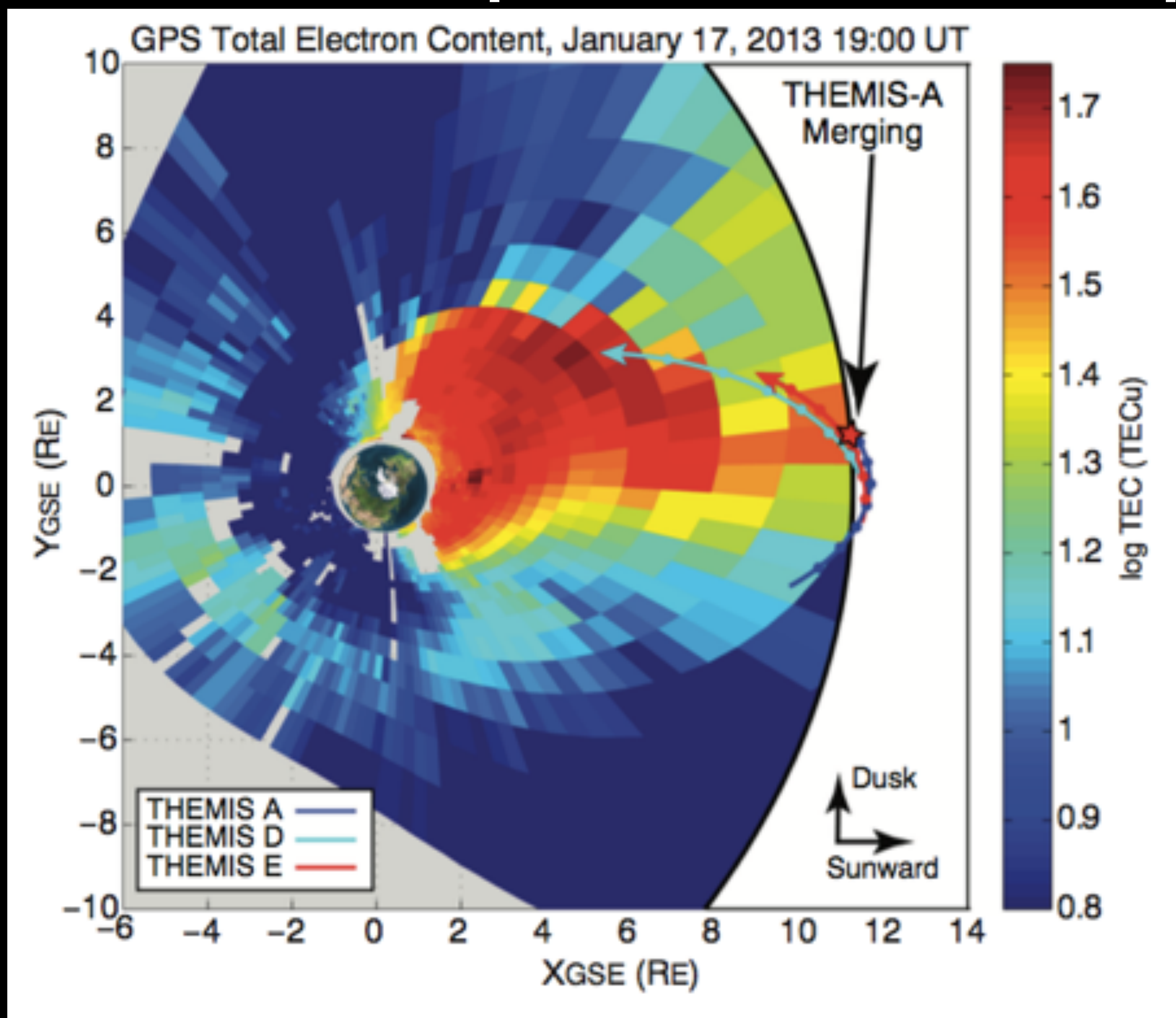


Plasmaphere plasma (>10 part/cm^3, 5eV)

MAGNETOSPHERIC DARK MATTER

Plasmaspheric plume

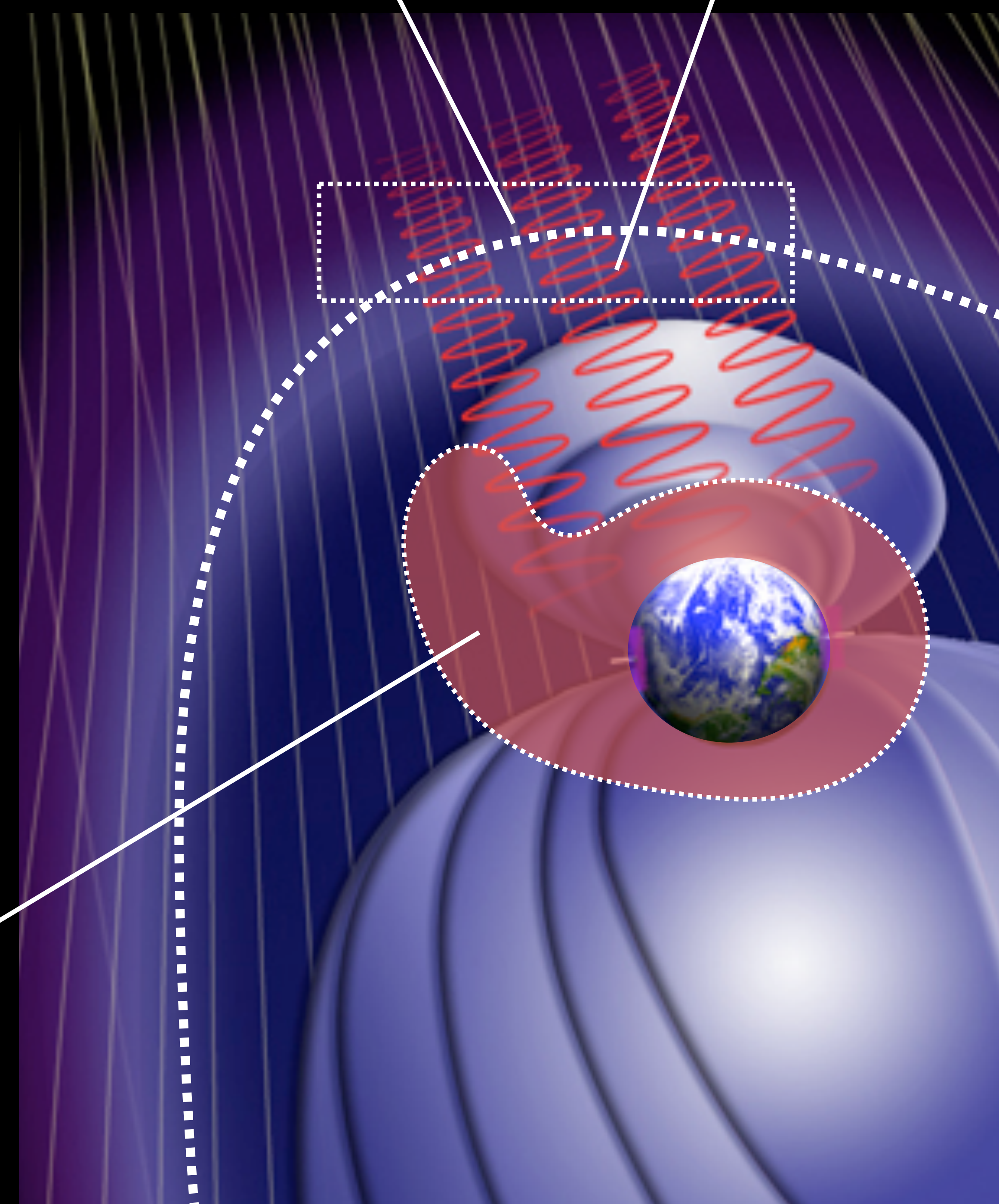
[Walsh et al. Science 2014]



Plasmaspheric plume touching the magnetopause in storm times

Magnetospheric plasma
(<1 part/cm^3, 1keV)

Solar Wind
(5 part/cm^3)

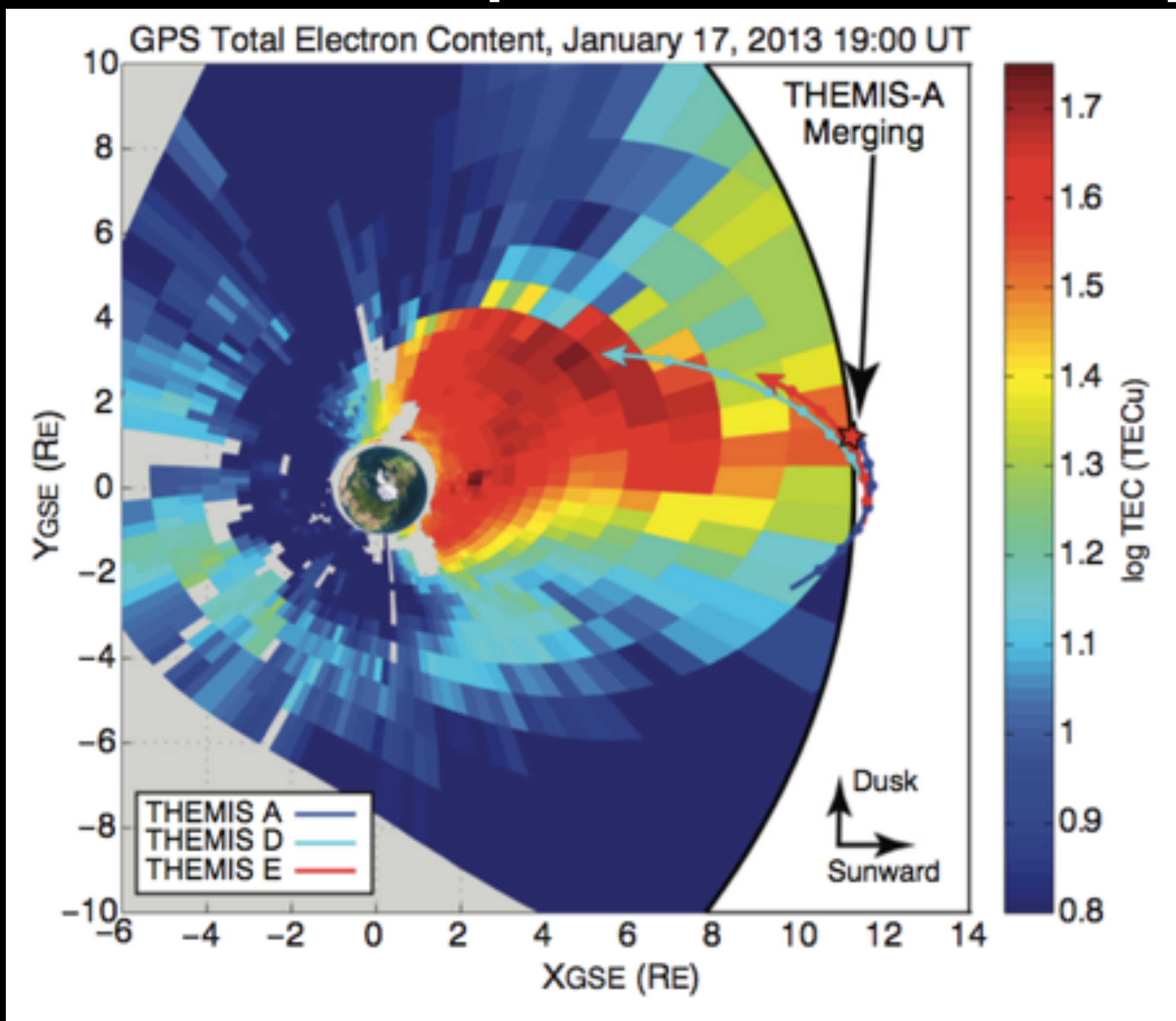


Plasmaphere plasma
(>10 part/cm^3, 5eV)

MAGNETOSPHERIC DARK MATTER

Plasmaspheric plume

[Walsh et al. Science 2014]



Plasmaspheric plume touching the magnetopause in storm times

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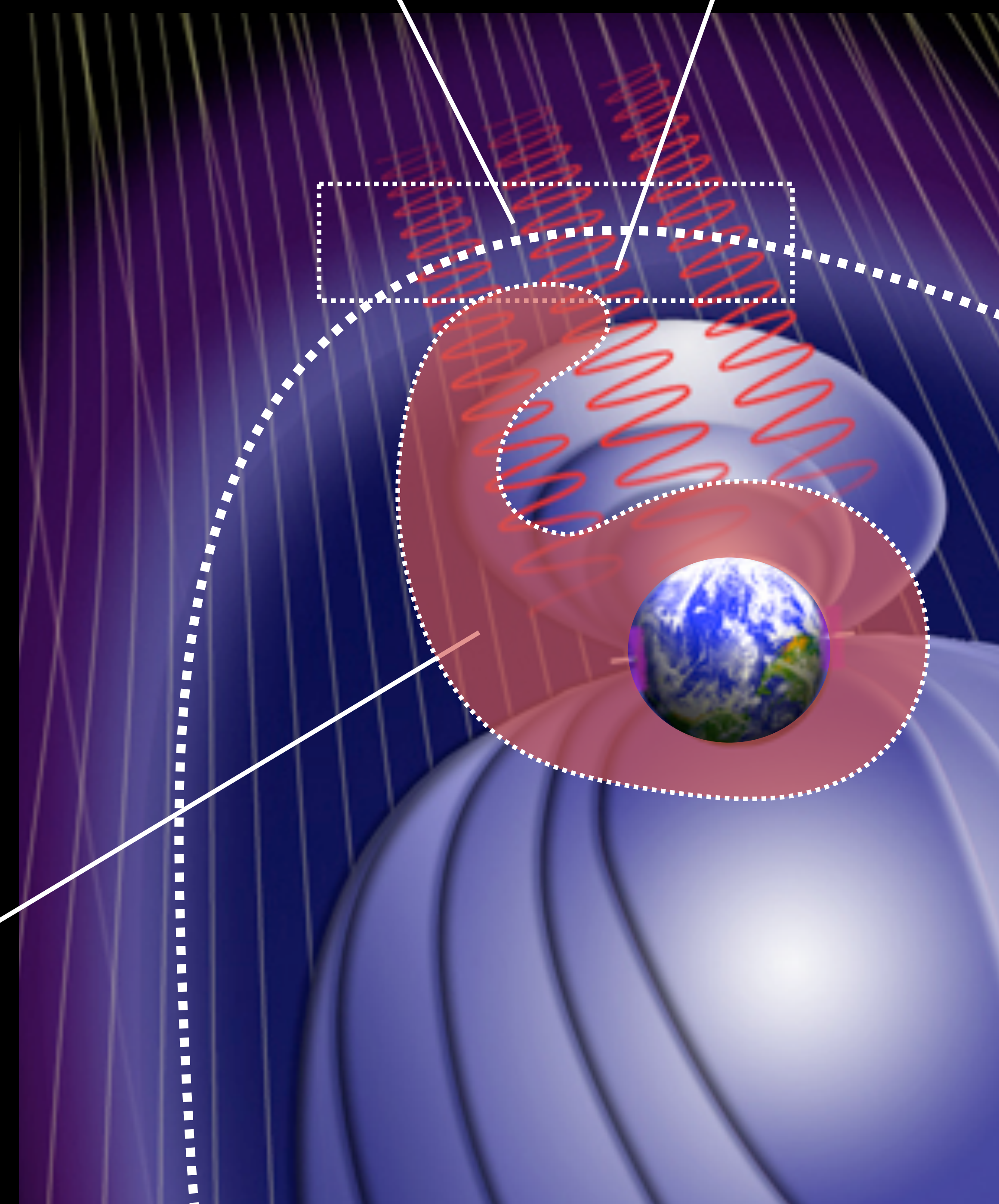
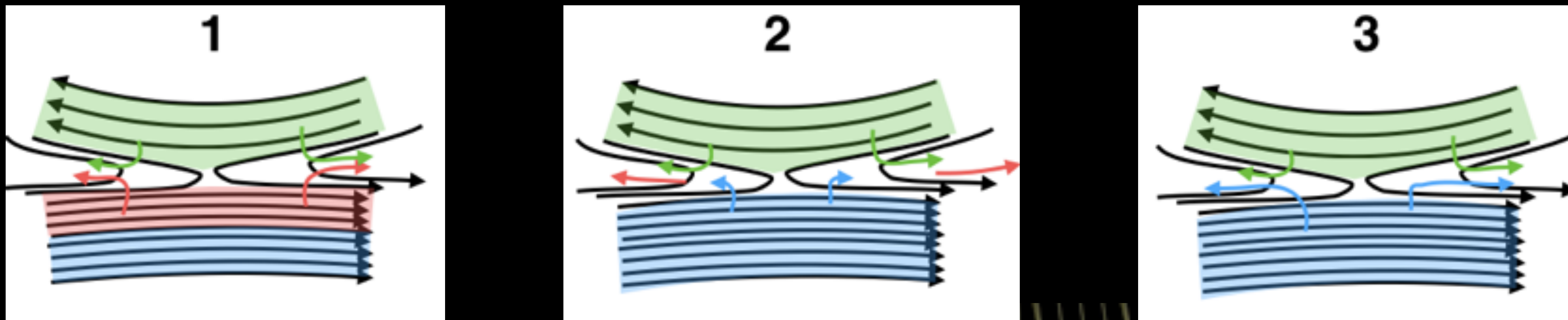
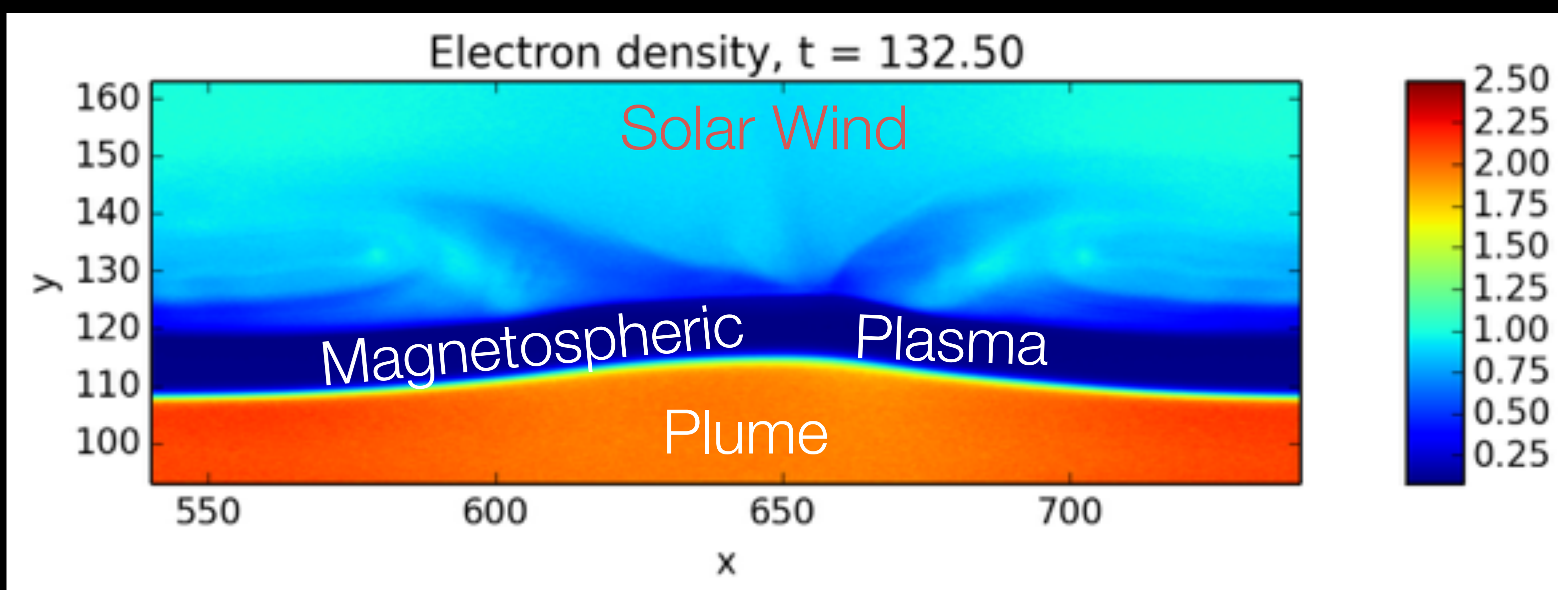


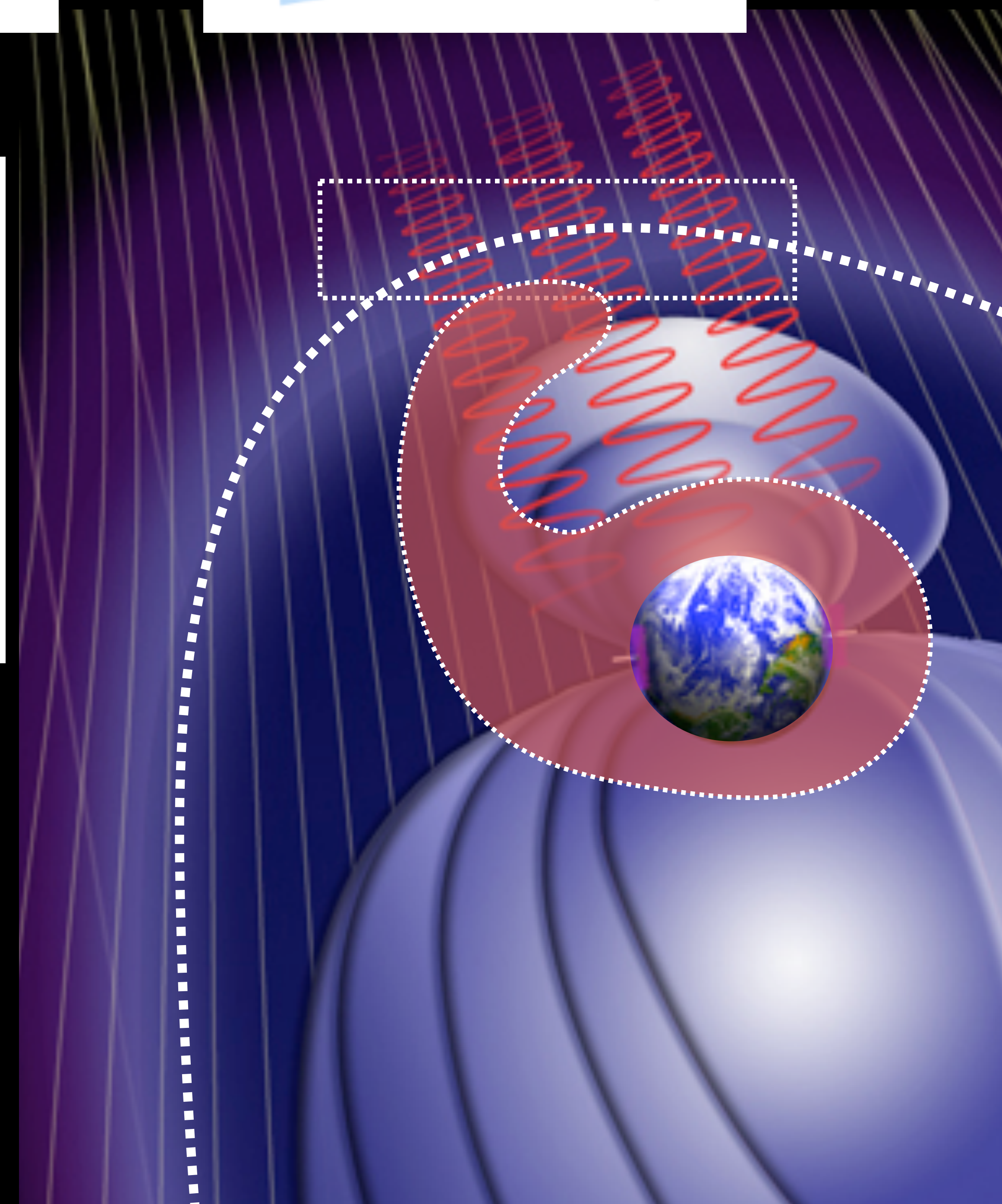
Plasmaphere plasma (>10 part/cm^3, 5eV)

MAGNETOSPHERIC DARK MATTER

Plasmaspheric plume





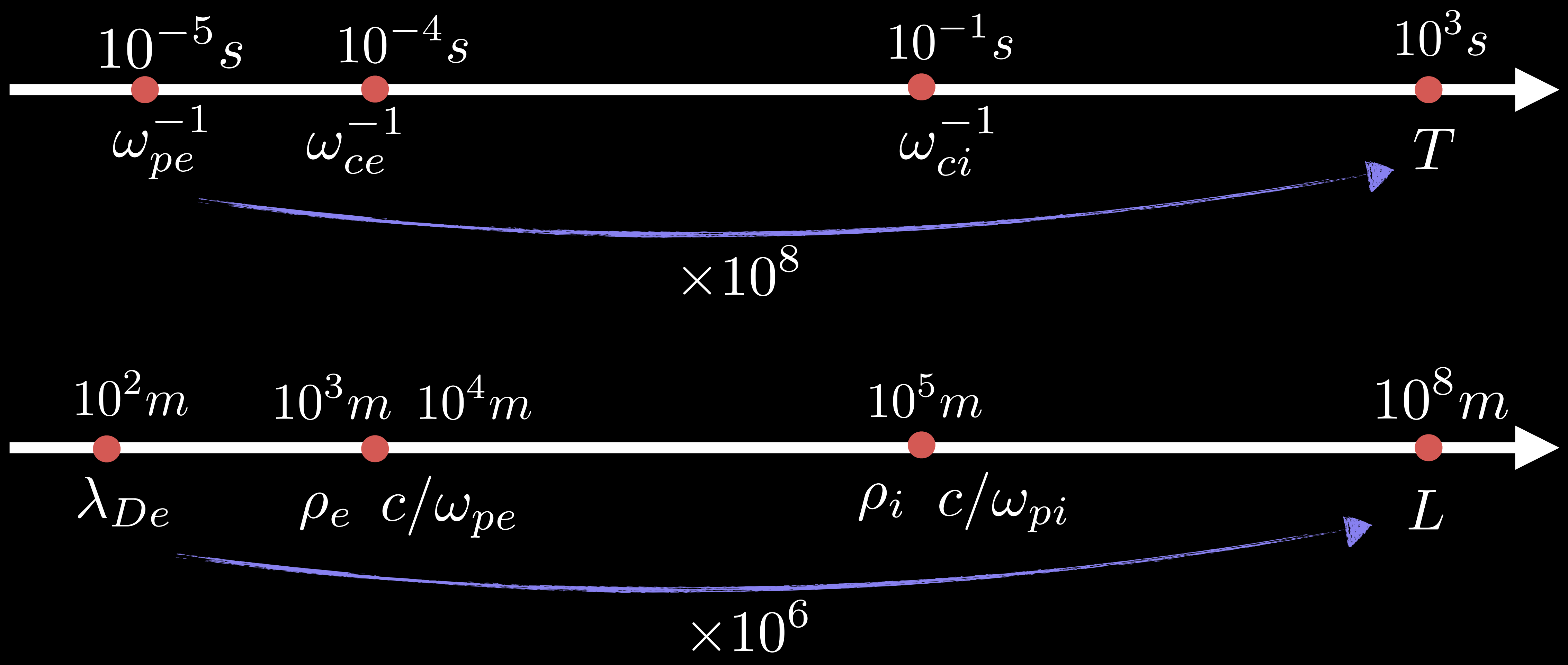


25600x10240 cells
3.3e10 macroparticles

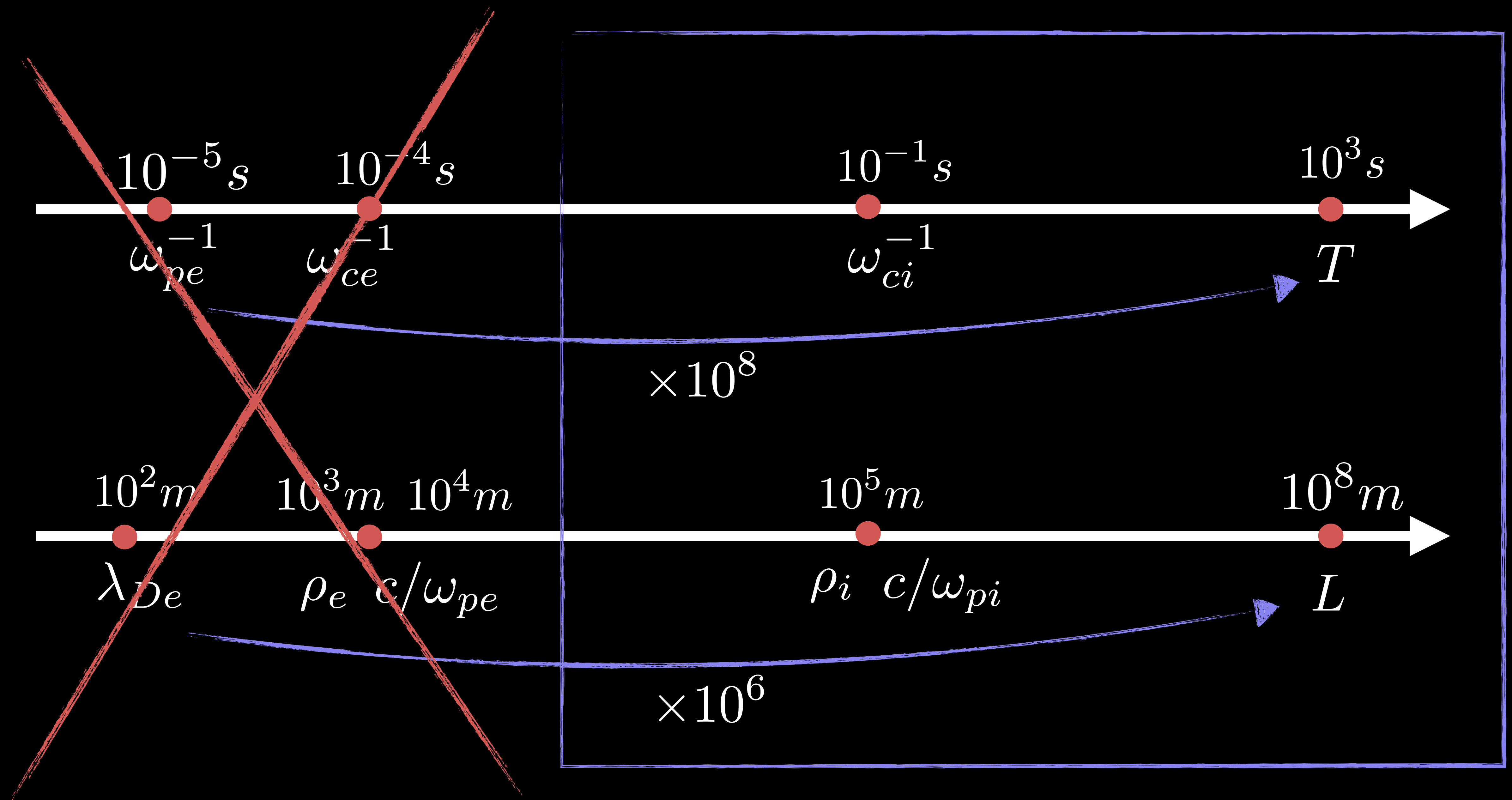
10e6 CPU hours on Curie NF
with 16384 cores

350To field only data

Kinetic modeling



KINETIC MODELING

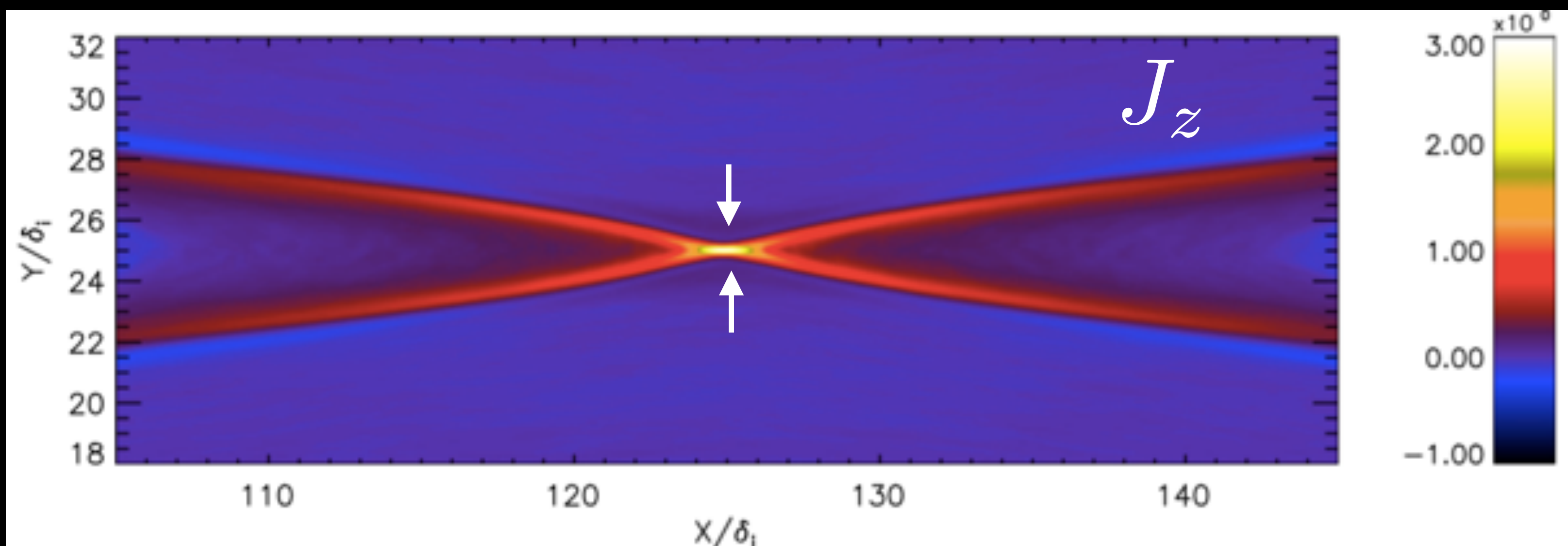


Can we use transport coef. and forget about electron kinetic physics?

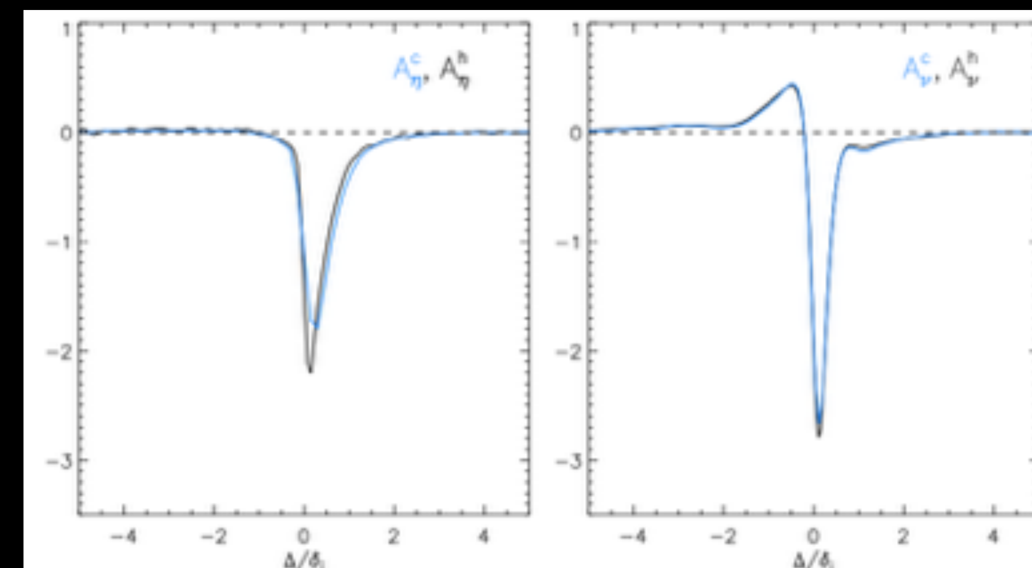
« Hybrid » codes

SCALES IN HYBRID CODES

$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{1}{ne}\left(\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{P}_e\right) + \mathbf{D}$$

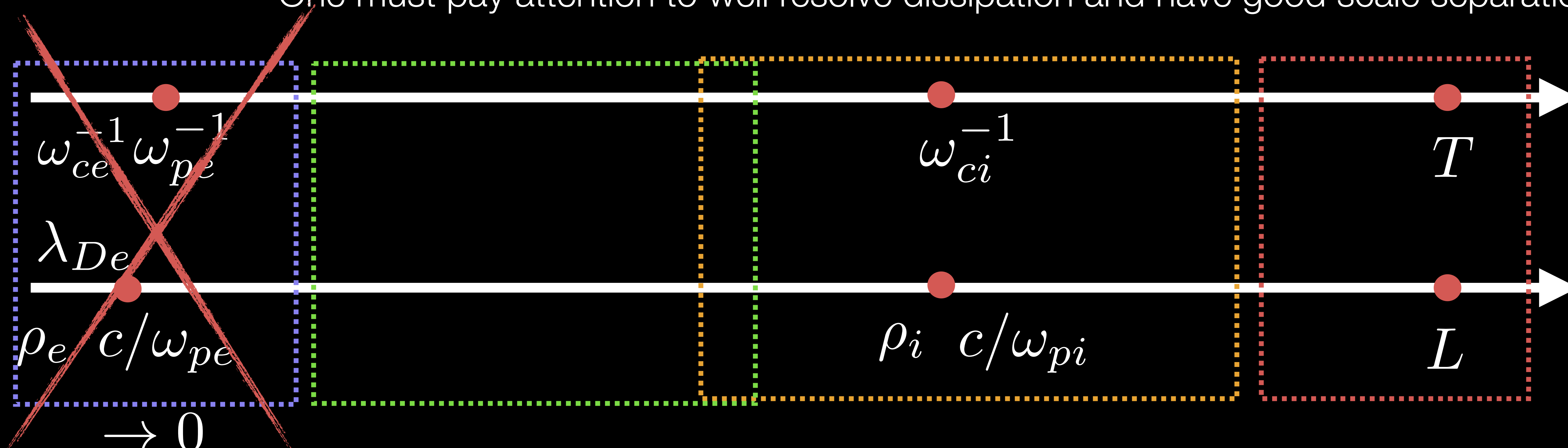


[AUNAI ET AL. 2013A]



$\mathbf{D} = \eta \mathbf{j}$ $\mathbf{D} = -\nu \nabla^2 \mathbf{j}$

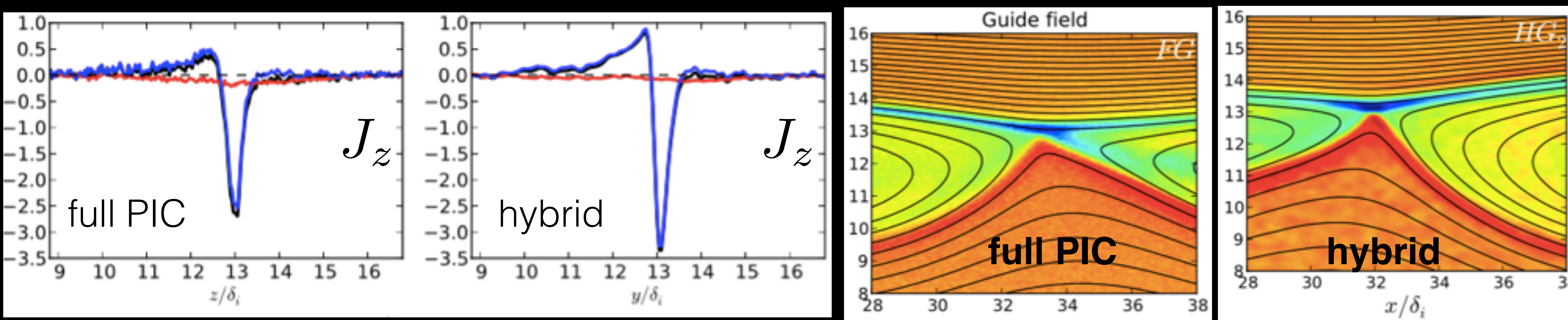
One must pay attention to well resolve dissipation and have good scale separation



Hybrid runs VS full PIC runs

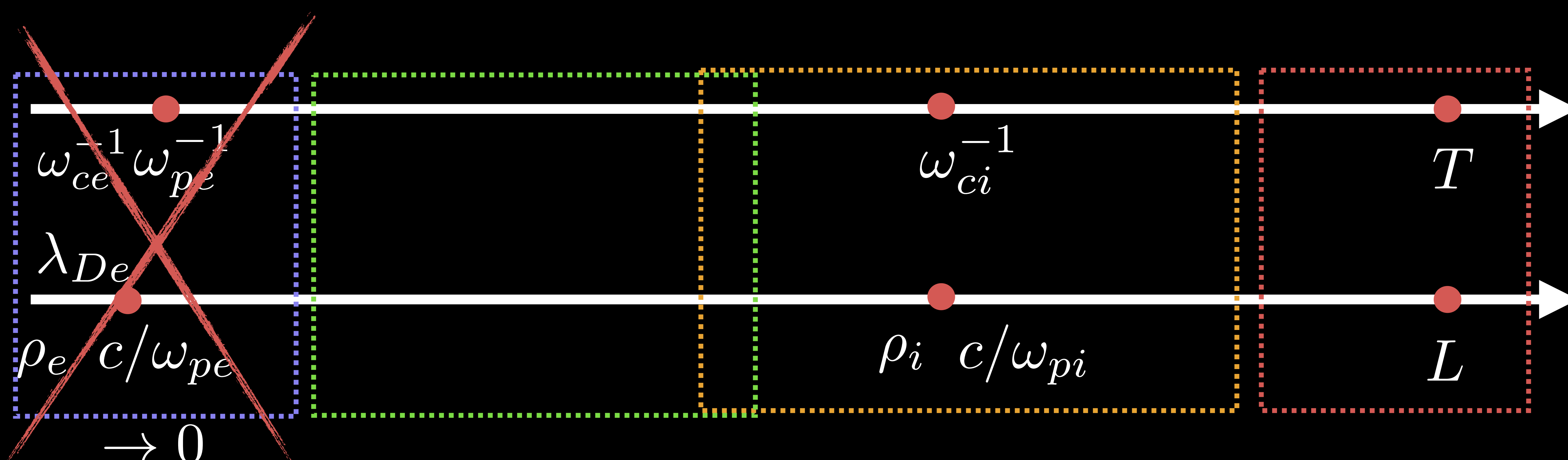
$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{1}{ne}\left(\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{P}_e\right) + \mathbf{D}$$

isothermal, polytropic, electron FLR..?



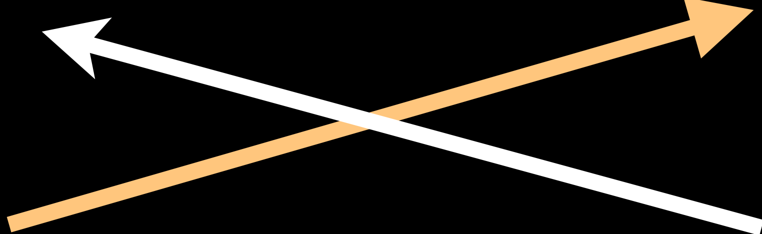
[Aunai et al. 2013b]

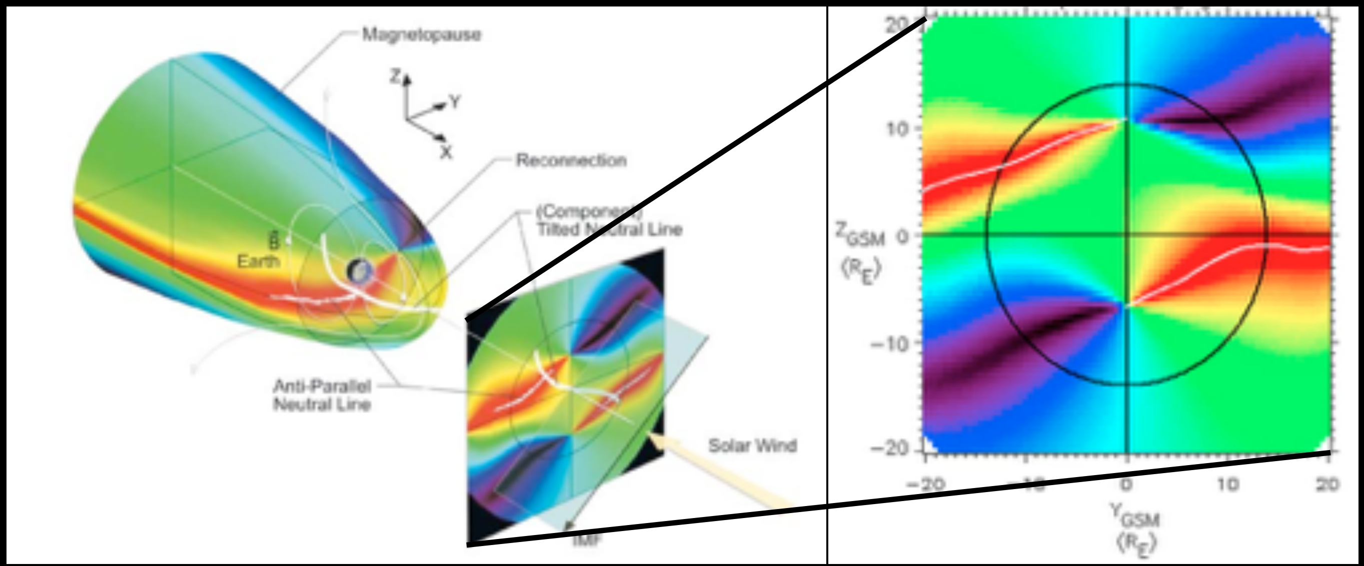
full PIC and hybrid PIC lead to a very similar evolution of asymmetric reconnection



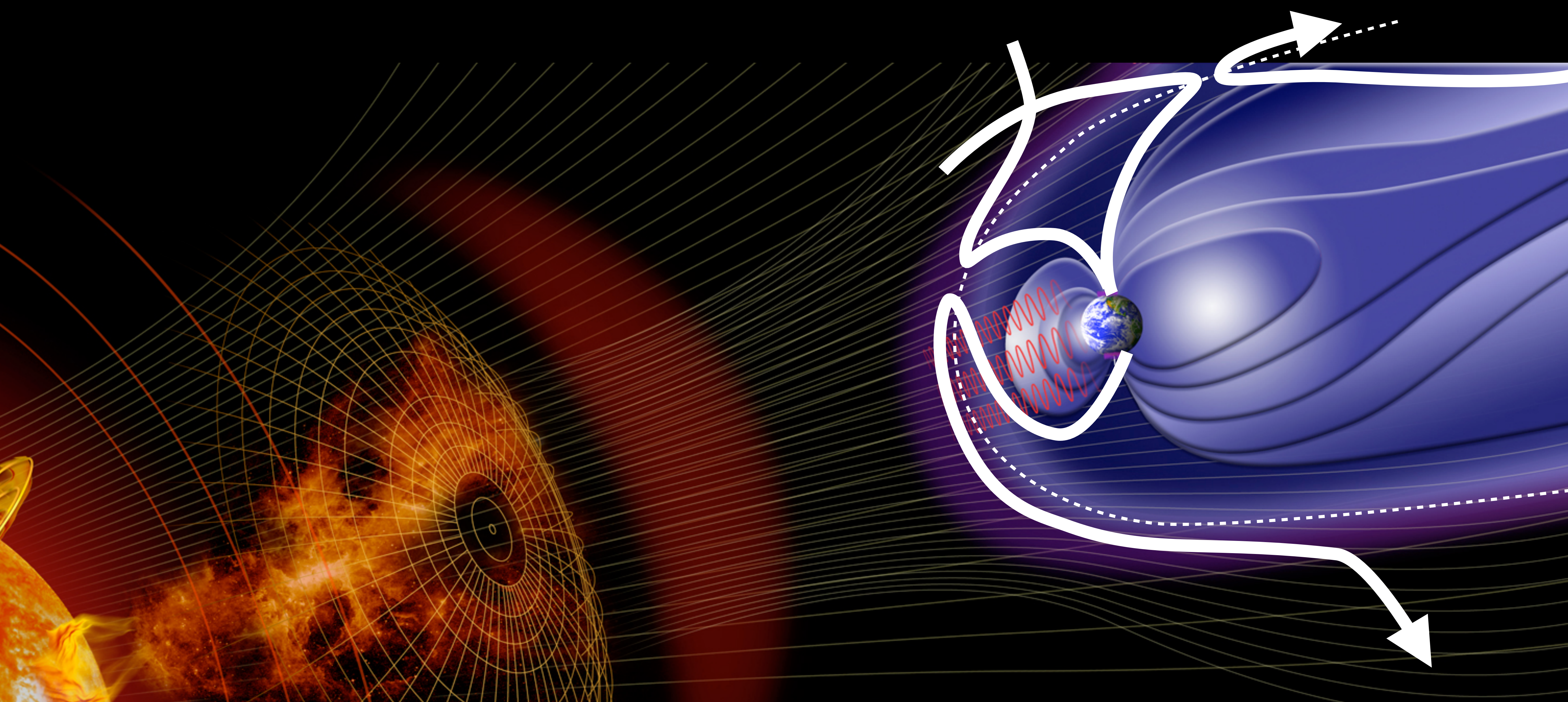
Role of the IMF orientation

IMF -> local magnetic shear

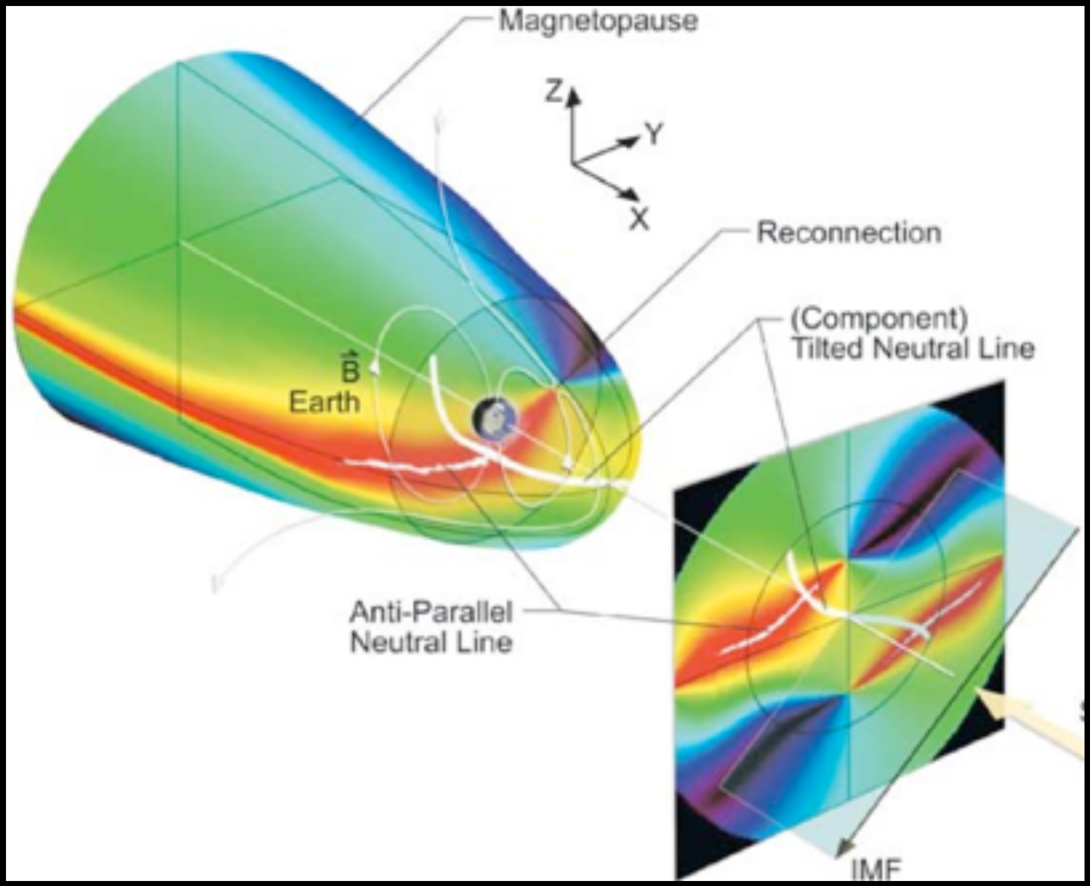




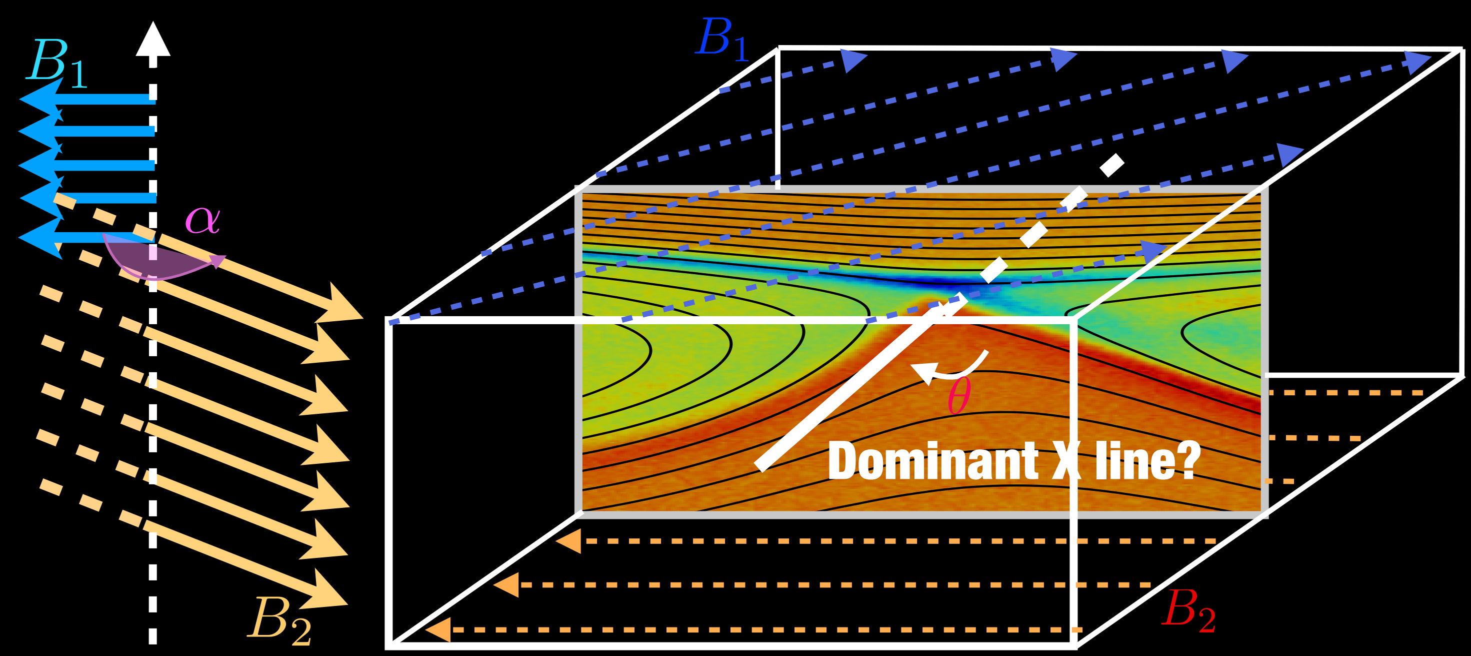
[Trattner et al. JGR (2010)]



Reconnection at the Magnetopause

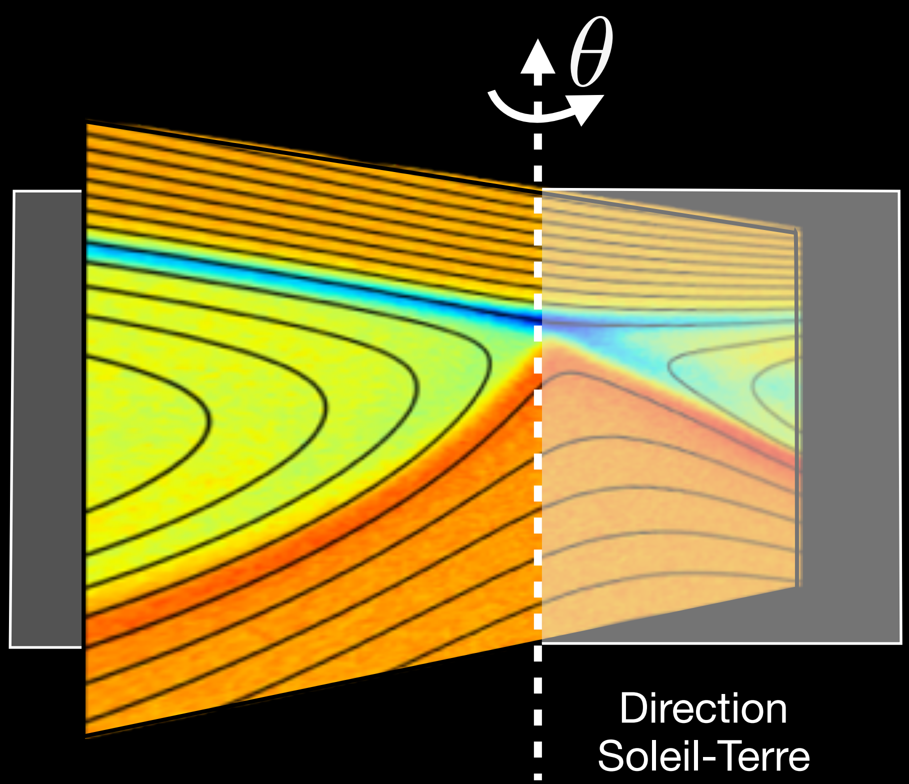


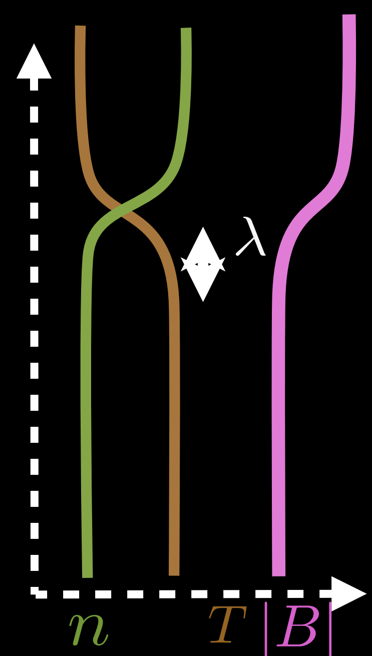
- Where does it start ? and why ?
- How does it spread?
- How does it evolve?
- How does it affect transport?
- etc.
- How does it couples to solar wind?
- etc.

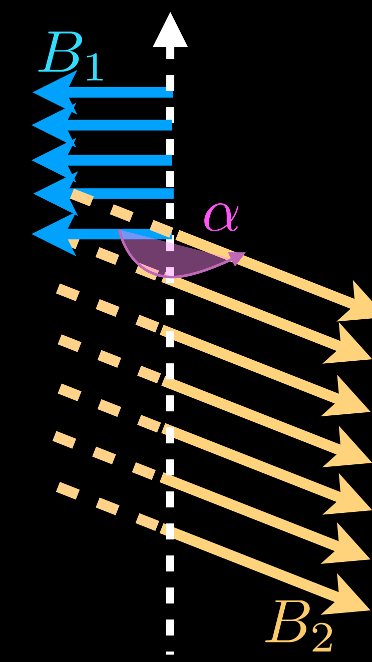


How does reconnection orient itself?

IF 2D… WHAT'S THE RECONNECTION PLANE ORIENTATION?

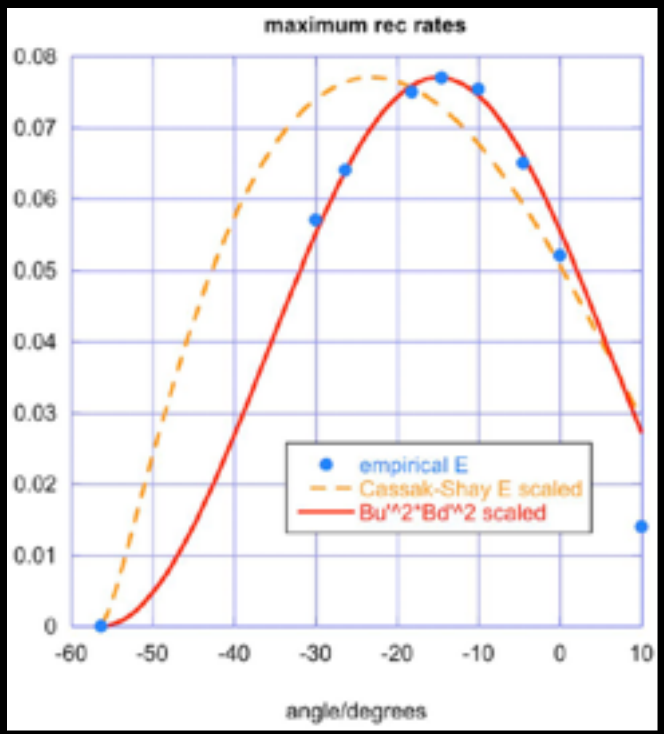




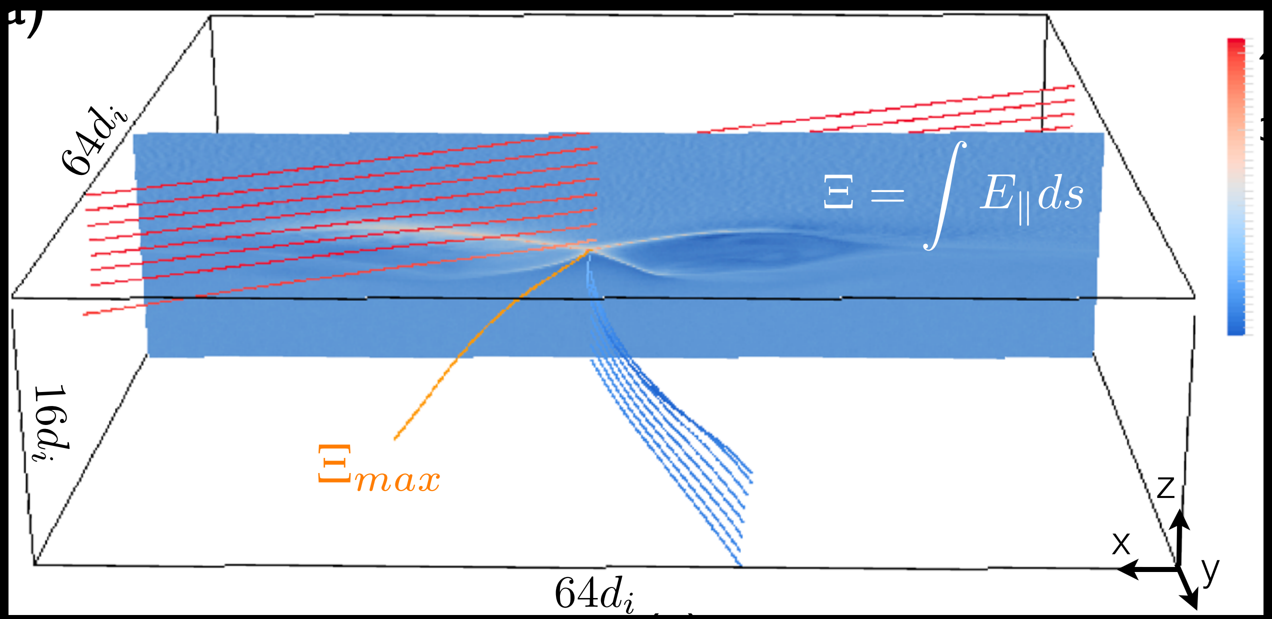


FIND THE « FASTEST PLANE »

[LIU+ PHYS. PLAS. 2015]



[HESSE+ PHYS. PLAS. 2013]

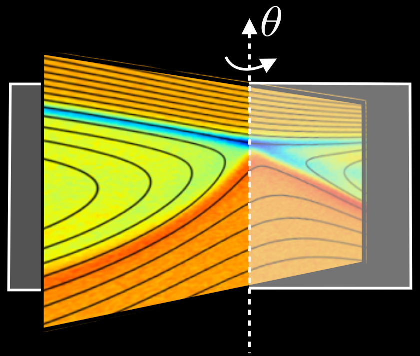


$$max(B_{1x}(\theta)^2\, B_{2x}(\theta)^2)$$

X line along bisector

X LINE ORIENTATION Hybrid runs varying shear angles and asymmetry

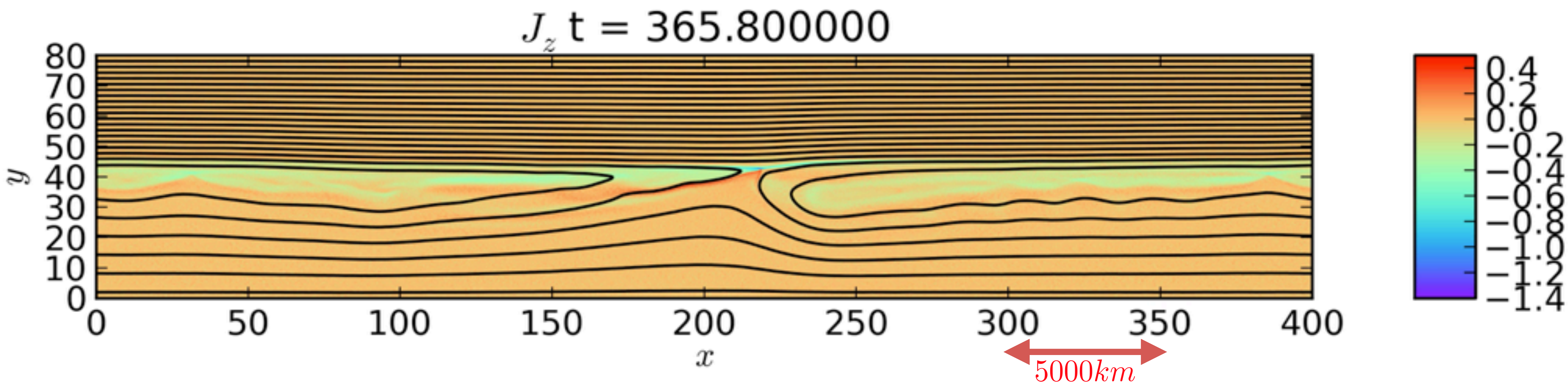
[AUNAI+ JPP 2016]

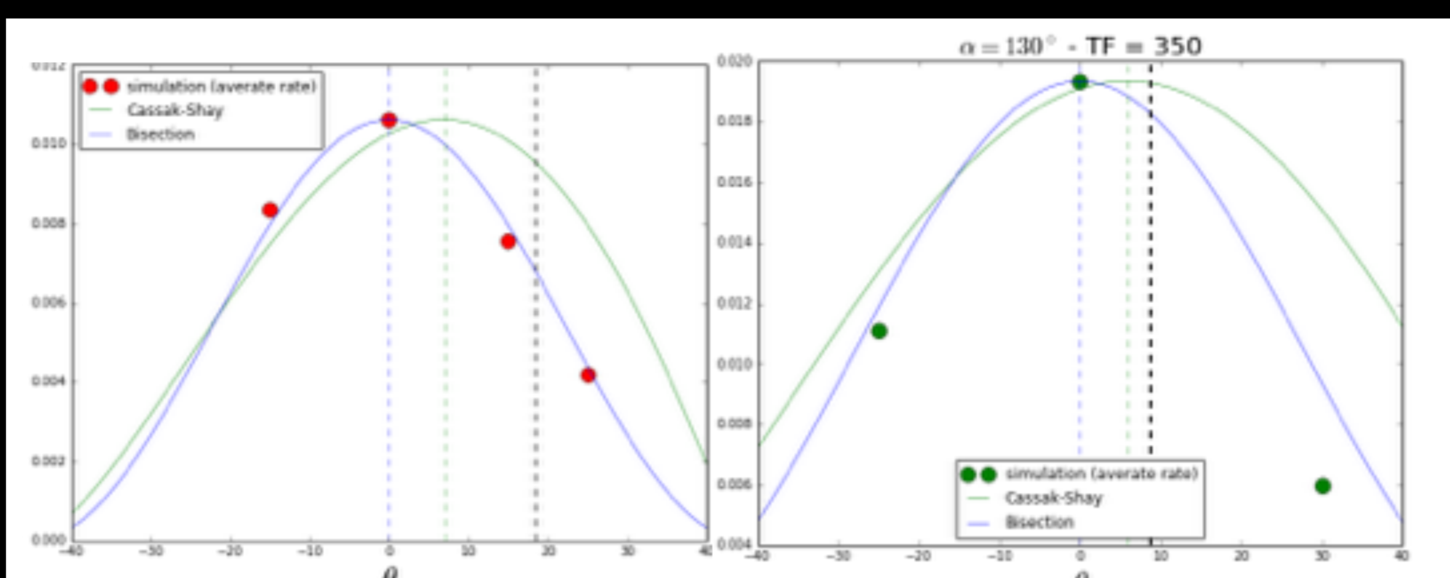


simulation plane rotation

B shears, 90° and 130°
different asymmetry

$\Delta x = 0.1\delta_i$
0.5e9 macroparticles
7x 80000hcpu





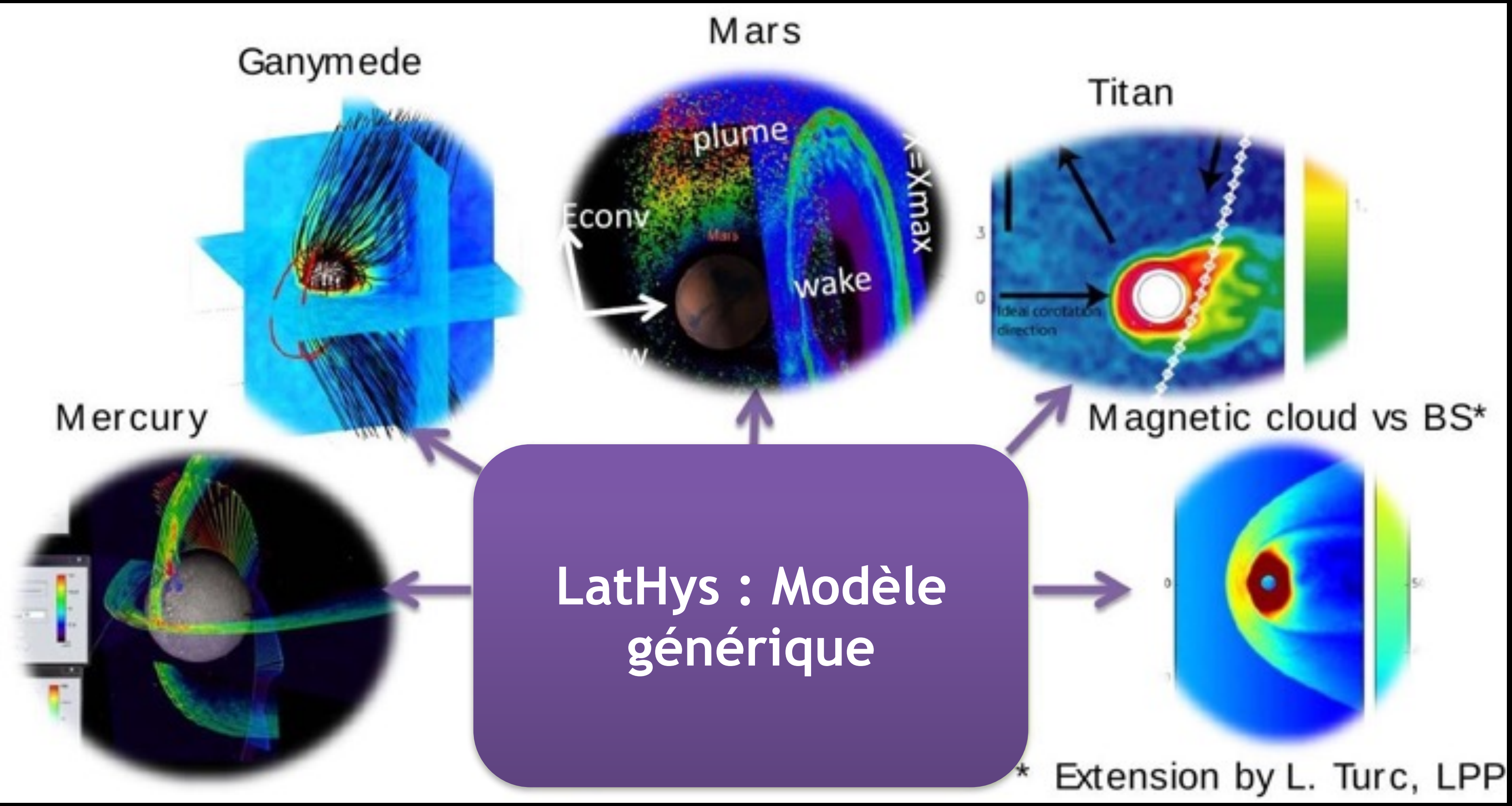
Reconnection rate as a function of the plane orientation

Bisecting upstream fields lead to faster rates

GLOBAL HYBRID Solar wind - magnetosphere coupling

[Modolo+2005] [Modolo+ 2007] [Richer+2012] [Turc+ 2014] [Leclercq+ 2015]

Mars **Titan** **Mercury** **MC vs BS** **Ganymede**

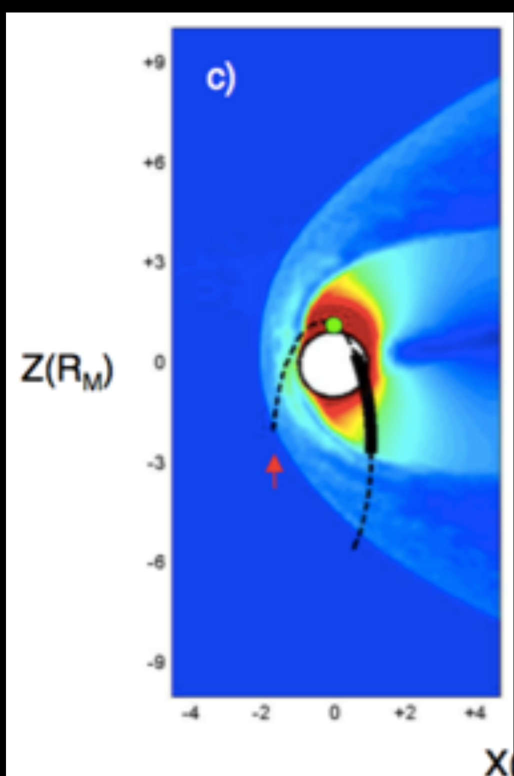


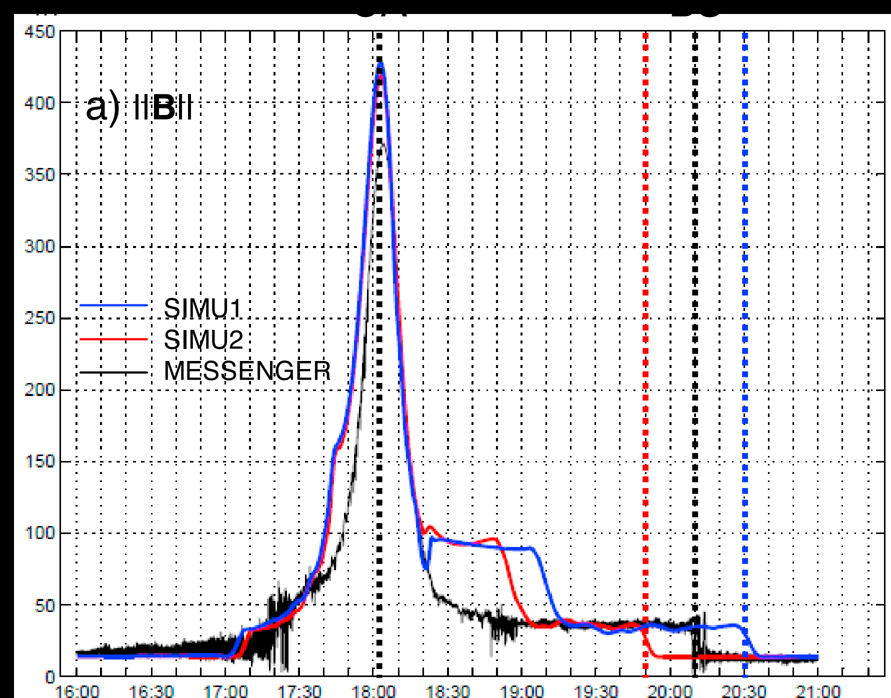
GLOBAL HYBRID Solar wind - magnetosphere coupling

Mercury's magnetosphere simulation

Solar wind interaction with different dipolar or multipolar intrinsic field

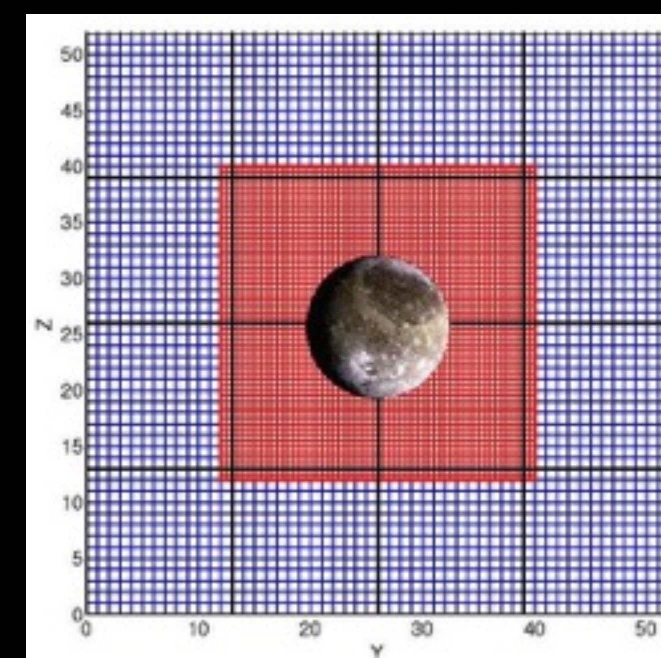
$\Delta x = \delta_i$ [RICHER ET AL. 2012]





Comparisons to Messenger data

[LECLERCQ+ 2015]

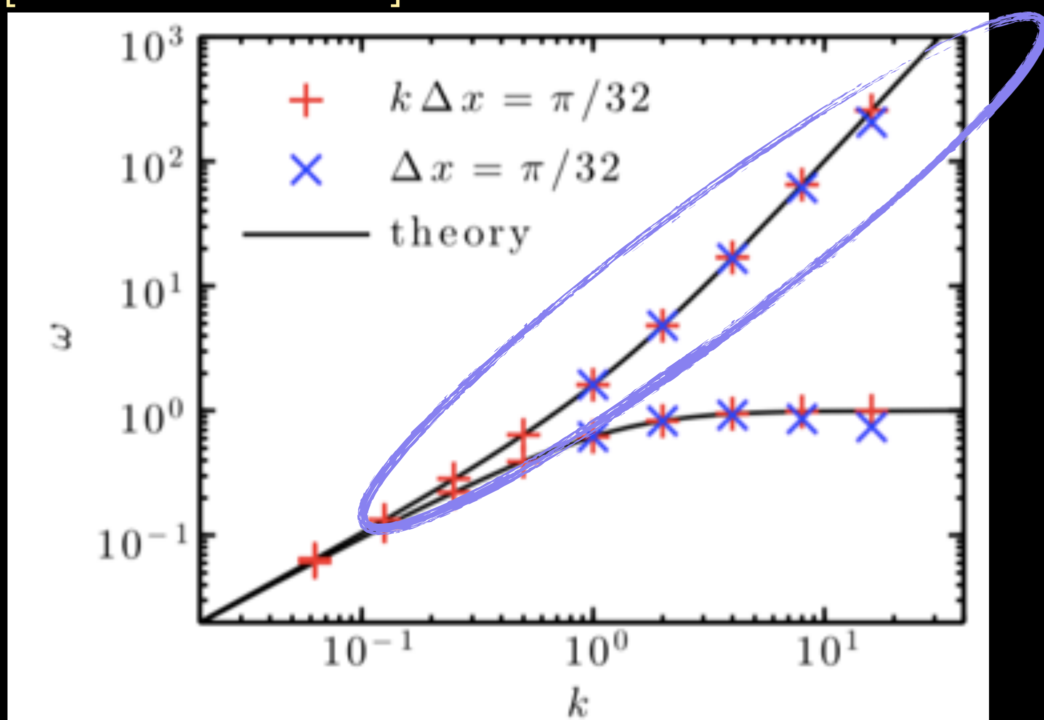


Ganymede with 2 grids

WHISTLER WAVES KILLERS

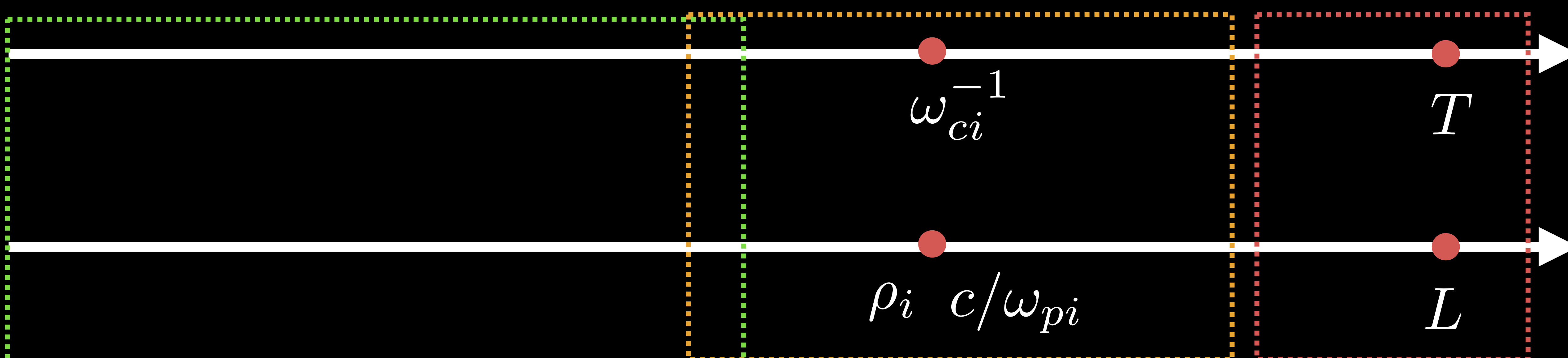
$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{1}{ne}(\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{P}_e) + \mathbf{D}$$

[Kunz et al. 2014]



$$w \propto k^2$$
$$dt \propto dx^2$$

Very strong constraint on Hybrid codes (and Hall MHD codes)

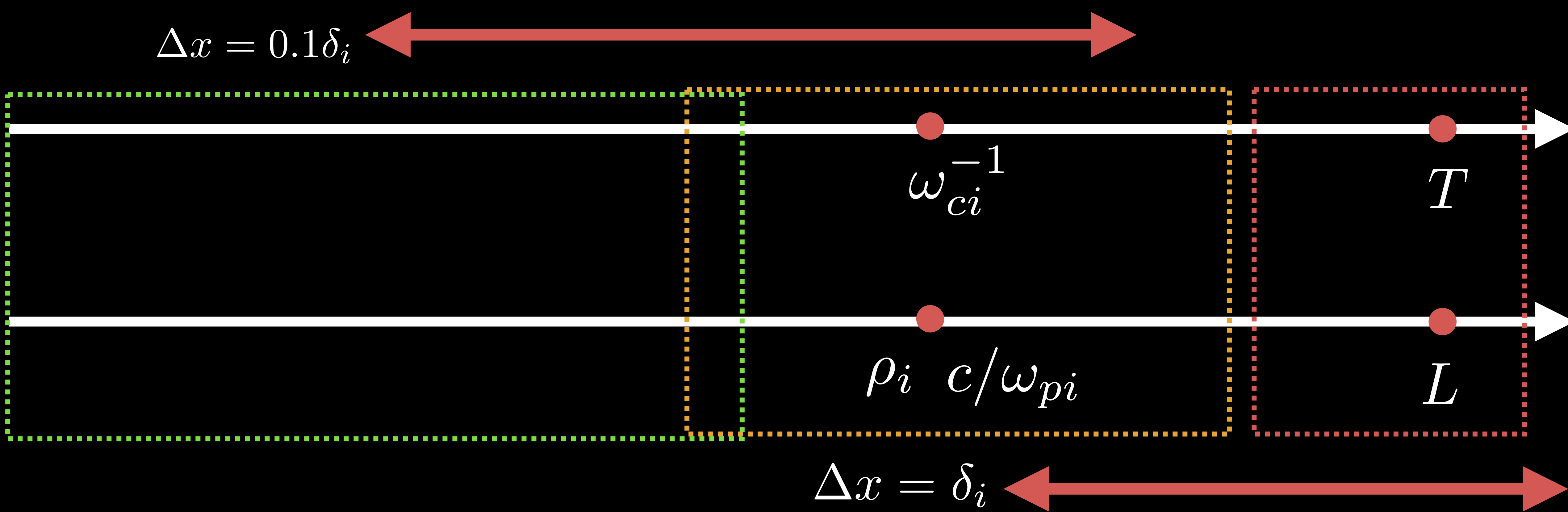


Hybrid codes

do not successfully fill the gap between small and large scales

$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{1}{ne}\left(\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{P}_e\right) + \mathbf{D}$$

Processes simulations:
- scale separation + local process scales
- struggle to have large scales

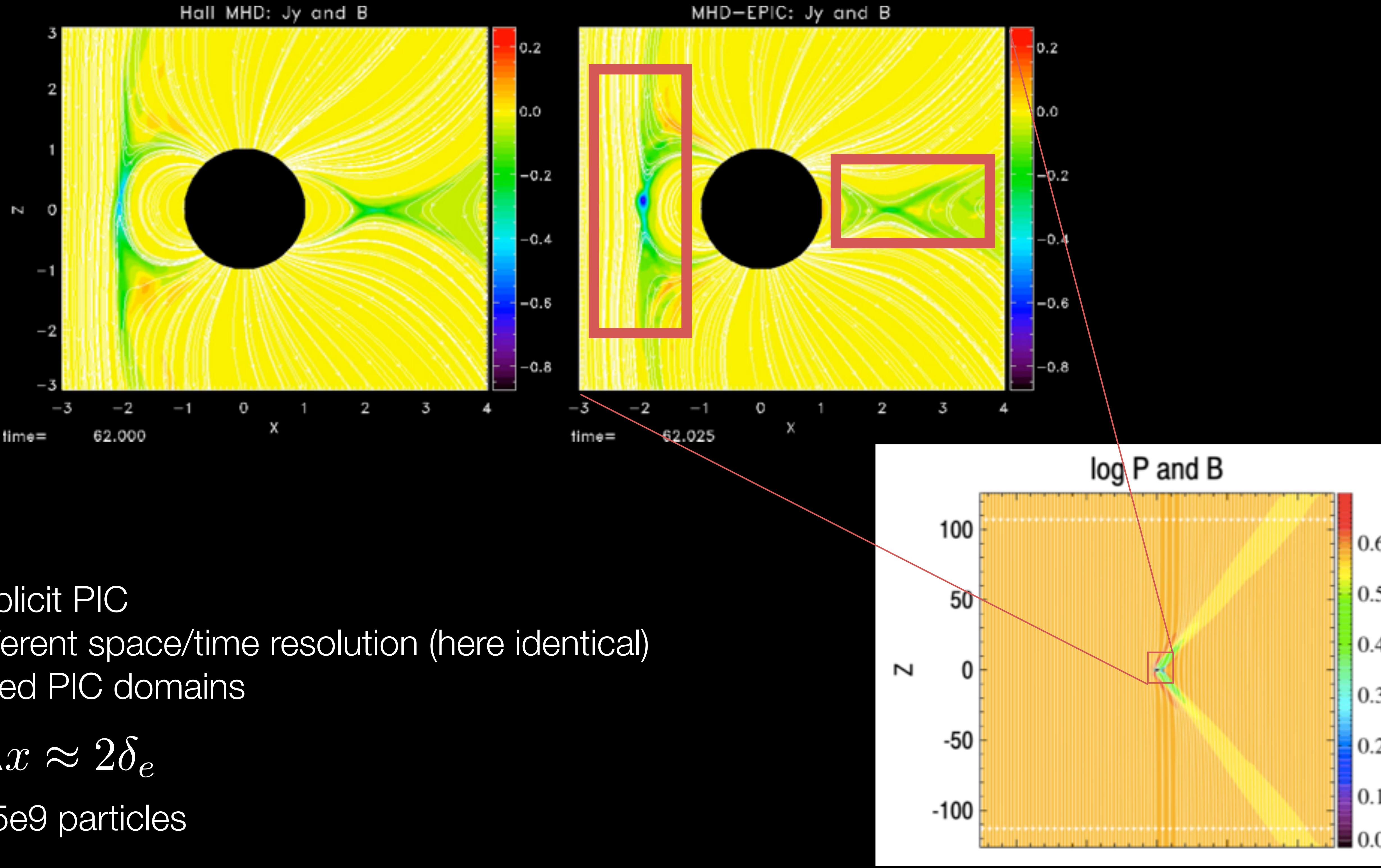


Global simulations
- Have relevant global effects
- struggle to handle processes

MHD - FULL PIC COUPLING BATSRUS+iPIC3D

[TOTH ET AL. 2015]

3D (implicit) fully kinetic embedded in a MHD domain for Ganymede simulation



- Implicit PIC
- different space/time resolution (here identical)
- Fixed PIC domains

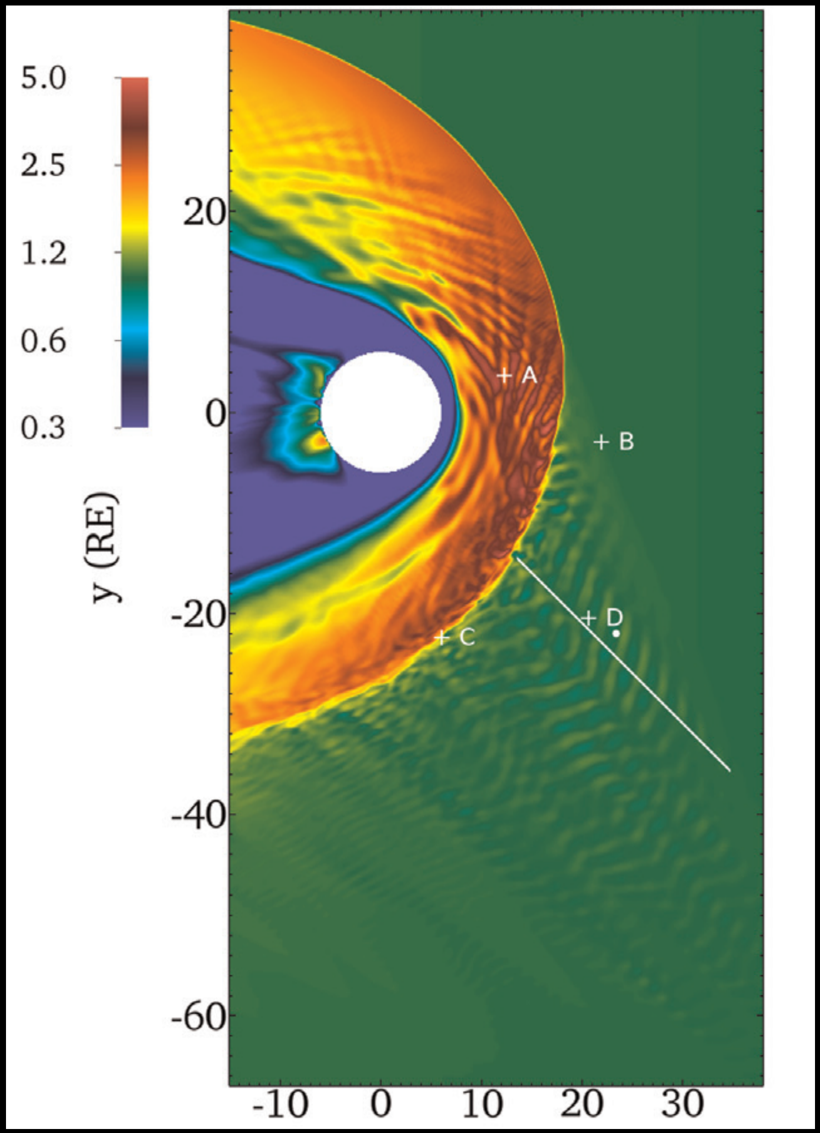
$$\Delta x \approx 2\delta_e$$

1.5e9 particles

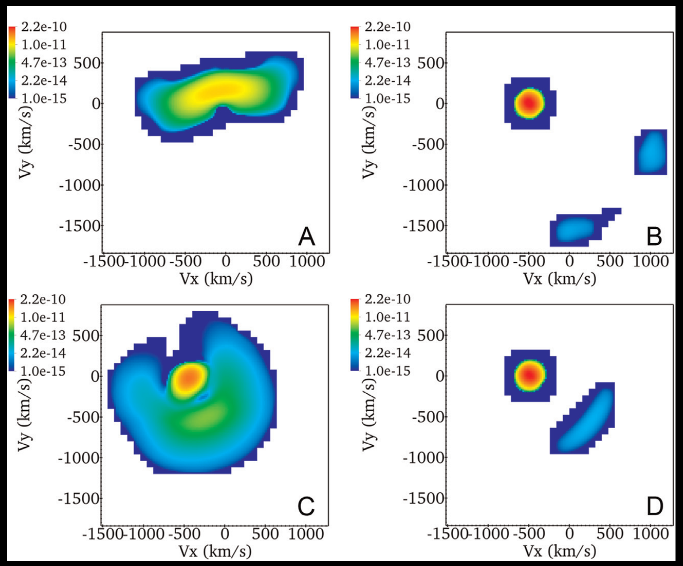
VLASIATOR Towards a global Vlasov - Hybrid magnetosphere model?

- Global simulations of Earth magnetosphere
- **Vlasov** hybrid : mesh velocity space ! Huge memory consumption

- 3D : $1000^3 * 100^3 = 10^{15}$ phase space cells!
- Only 2D3V simulations (so far) : 10^{12} cells!
- MPI/OpenMP + Dynamic load balancing (Zoltan)



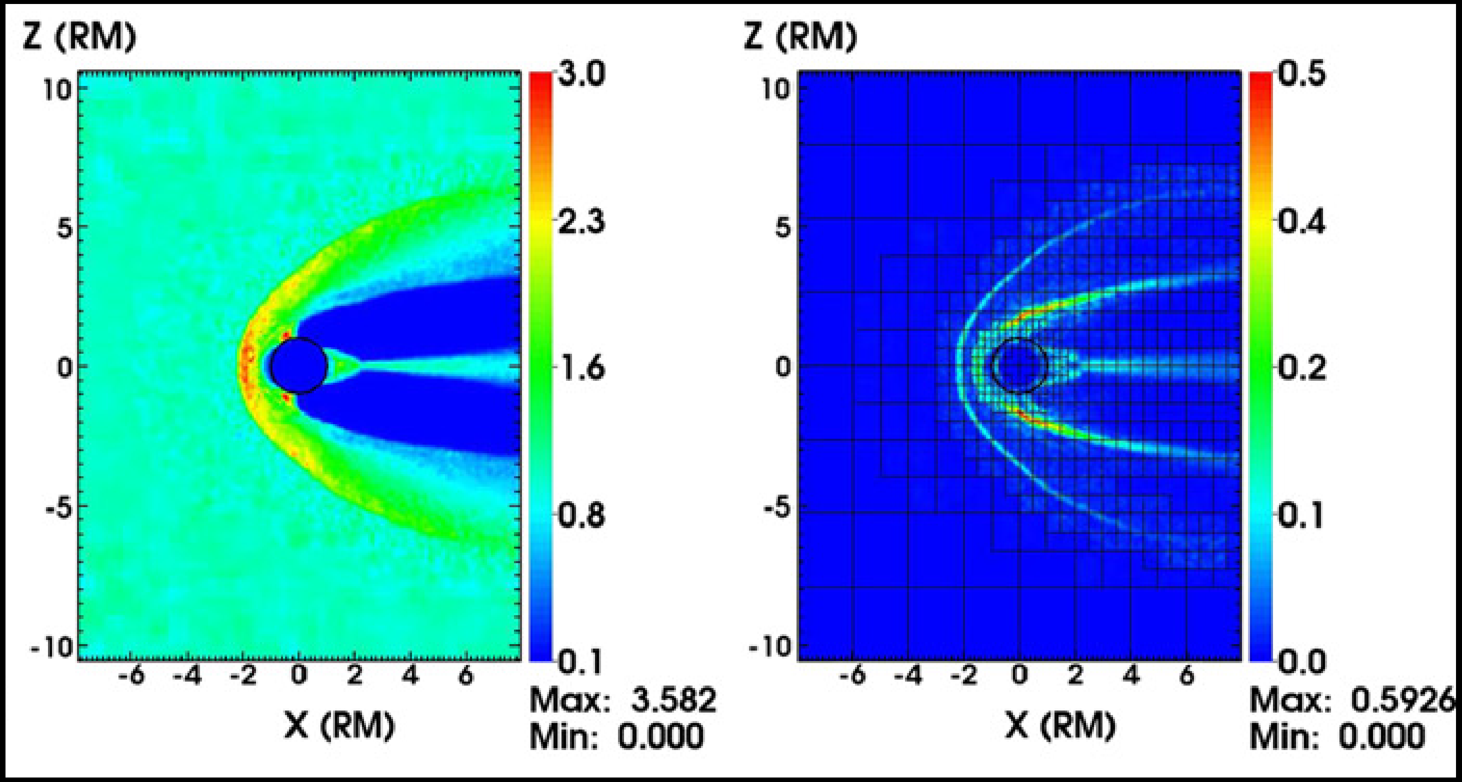
[VON ALFTHAN ET AL. 2014]



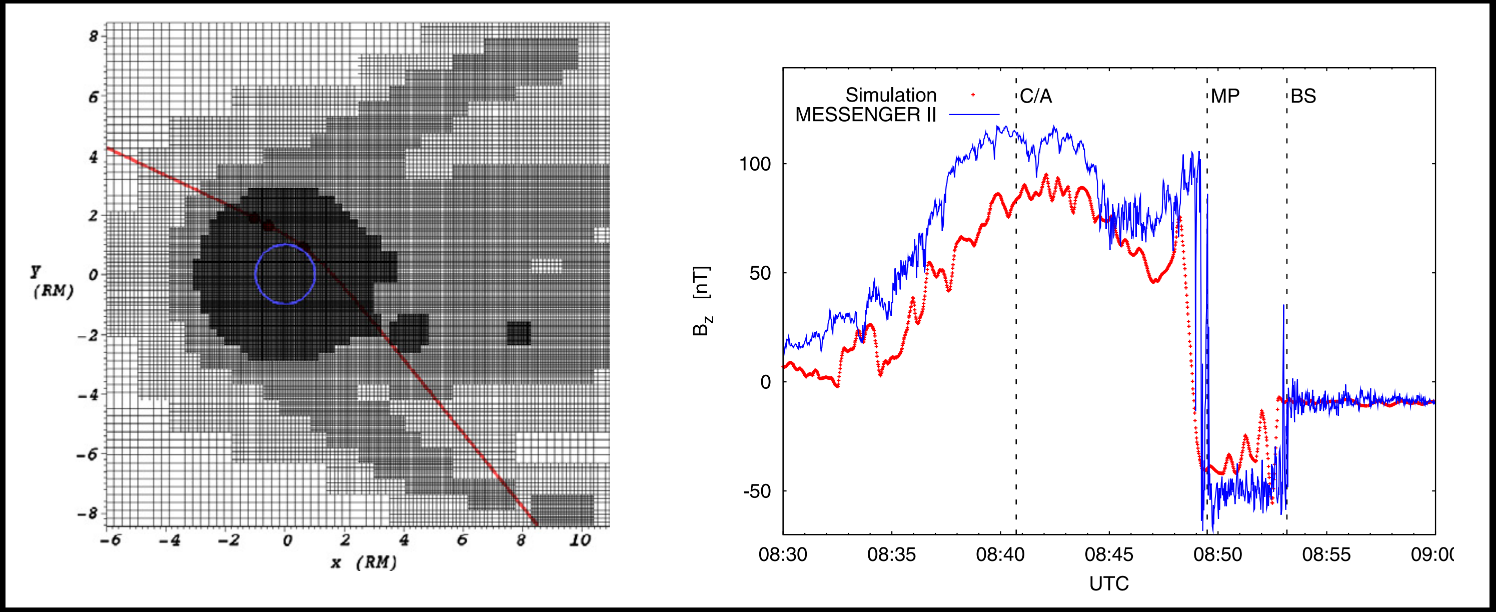
Proton distribution functions from meshed velocity space

AIKEF Adaptive (Mesh Refinement) Ion Kinetic Electron Fluide code [MULLER AL. 2011]

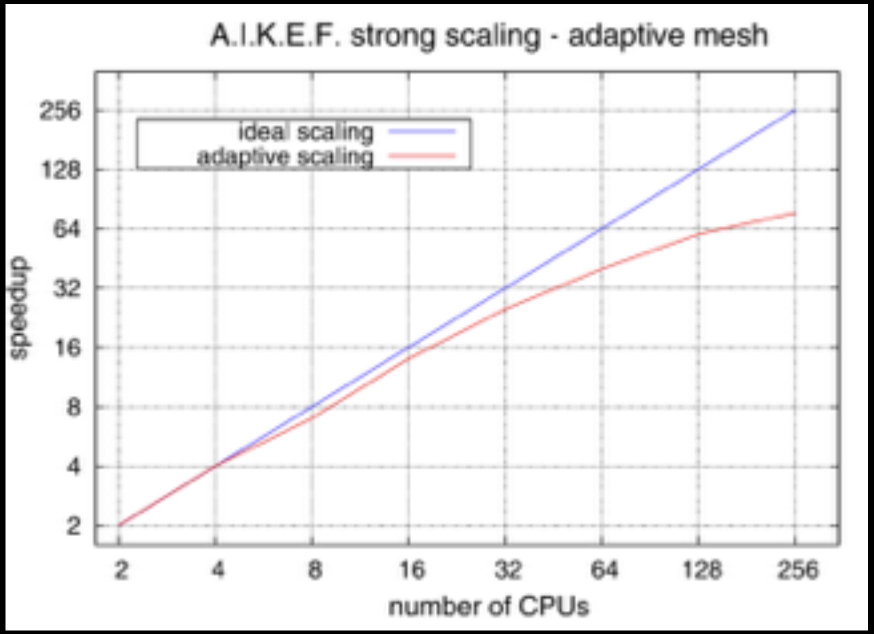
Adaptive Mesh capability
Not trivial for kinetic
- dispersive waves
- merge/split macroparticles
Complicated load balancing



Comparison to Messenger data
Sharp magnetopause and shock



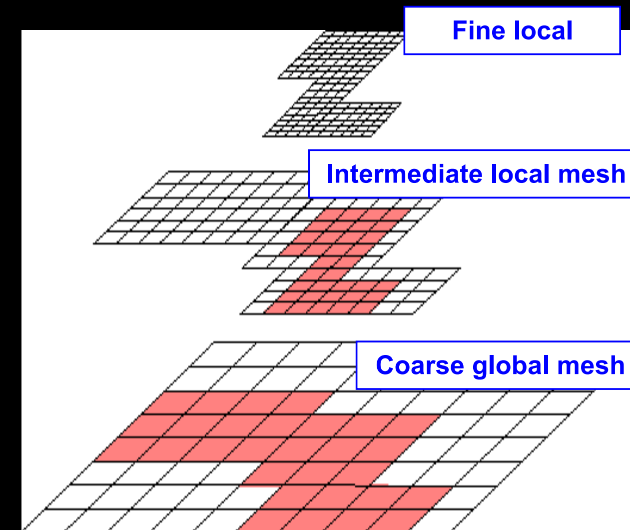
Proof of concept but no scalability for large number of cores



PHARE Parallel Hybrid code with Adaptive Mesh Refinement

PLAS@PAR Plasmas à Paris

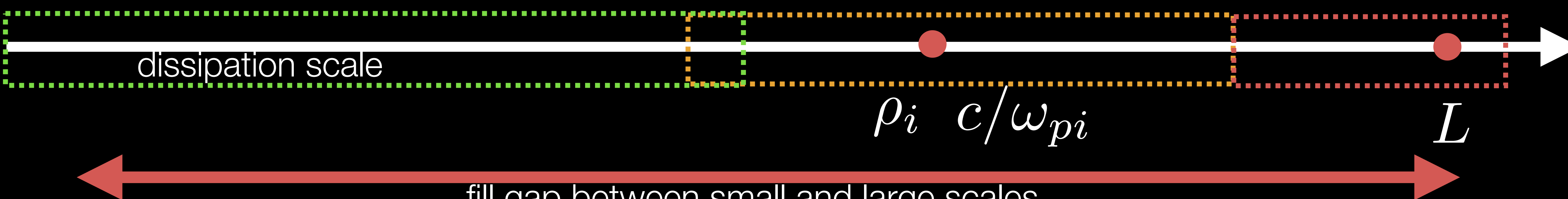
- Hybrid code for space/astro/laboratory plasmas
- 3 years project
- full time research engineer expert on PIC codes
- First release's objective: 3D hybrid code with excellent scalability up to 10^4 cores
- Open Source C++ Versatile code
- Big brother of fully kinetic code SMILEI



SAMRAI Patch AMR library

PHARE Team

Andrea Ciardi
Roch Smets
Nicolas Aunai
Mathieu Drouin
A. Bourdon
C. Briand
P-Q. Elias
C. Riconda
P. Savoini
T. Vinci



mi/long-term:

- sheath models
- electron physics (full pressure tensor, radiative cooling, code coupling…)
- vacuum regions
- thermal conduction (anisotropic)
- Laser energy deposition
- radiation transport

ONERA THE FRENCH AEROSPACE LAB — LERMA — LPP — PLAS@PAR Plasmas à Paris