

Three-dimensional nature of magnetic reconnection X-line in asymmetric current sheets

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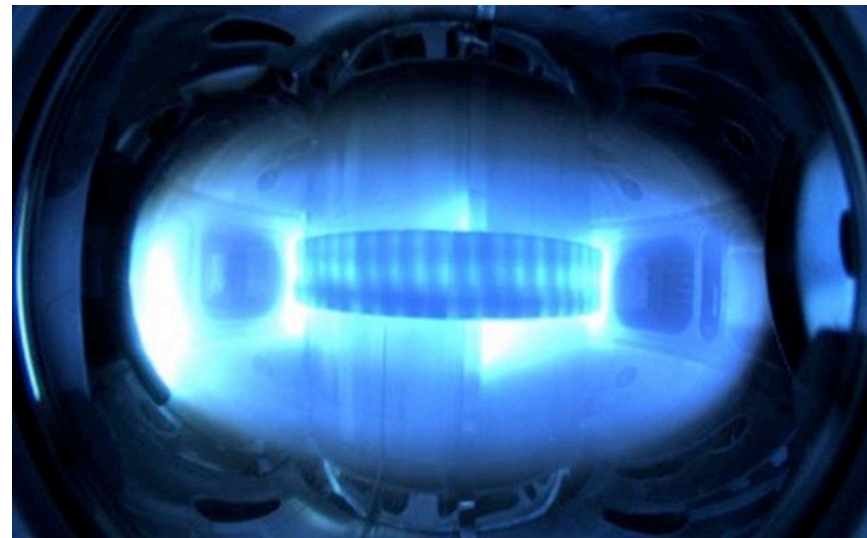
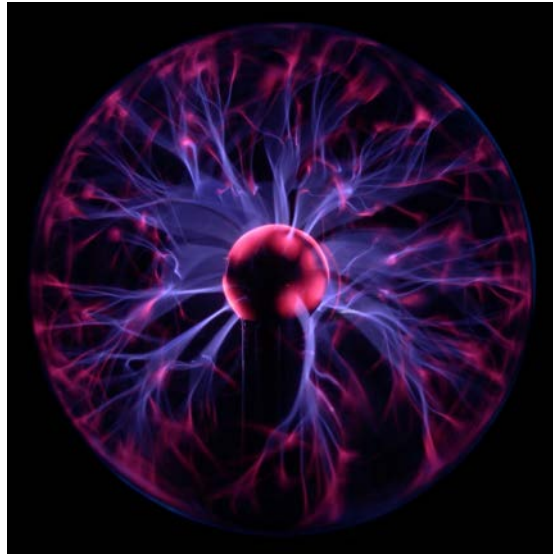
Key Challenge & Why it matters?

Plasmas

4th state of matter
> 99% of visible universe

Fusion device

Plasma Lamp



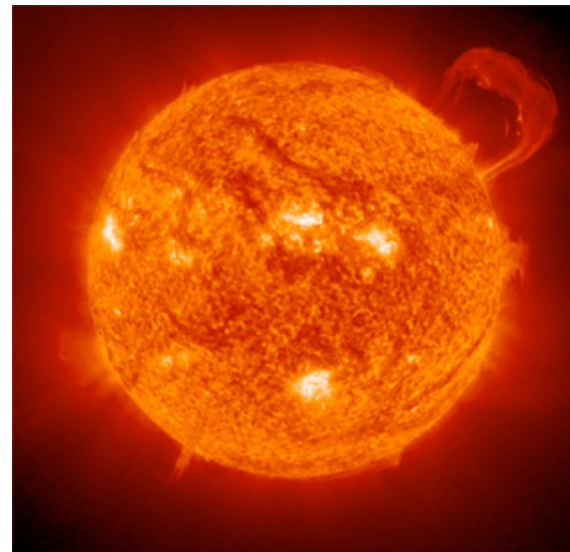
Lightning



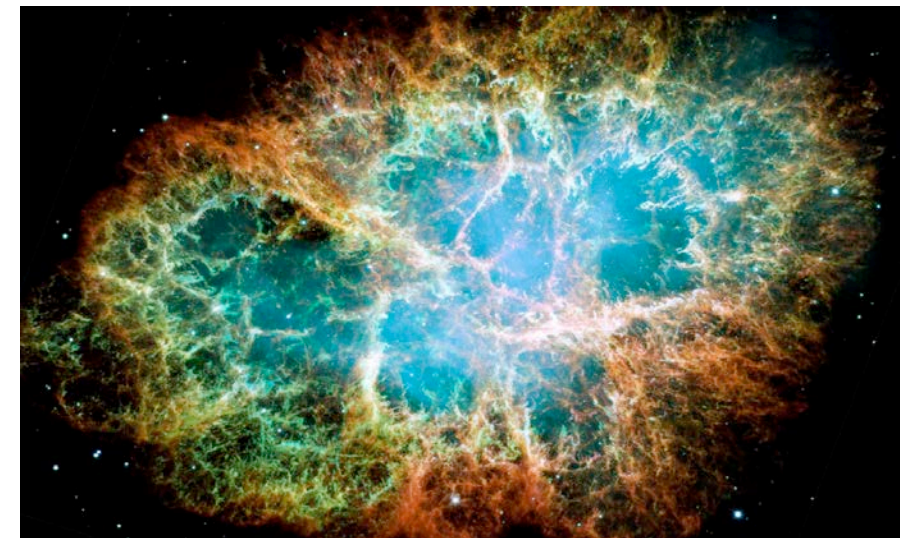
Aurora Borealis



Solar Eruption



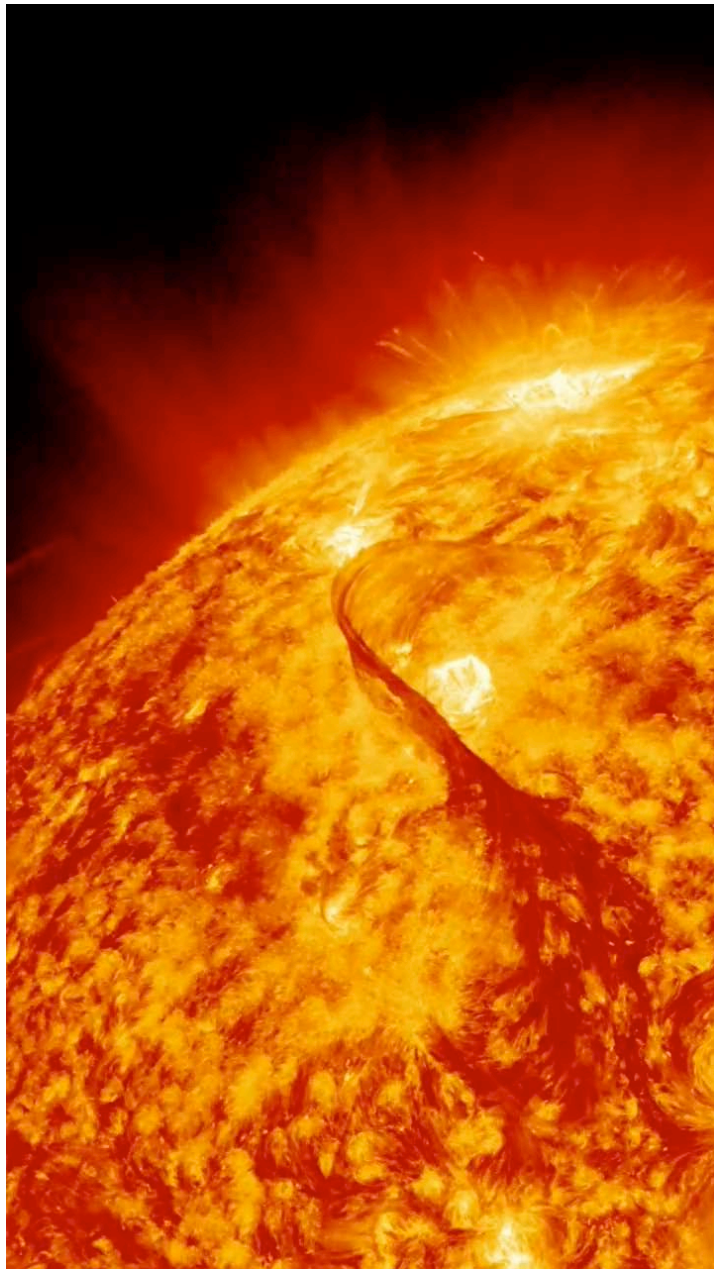
Nebula



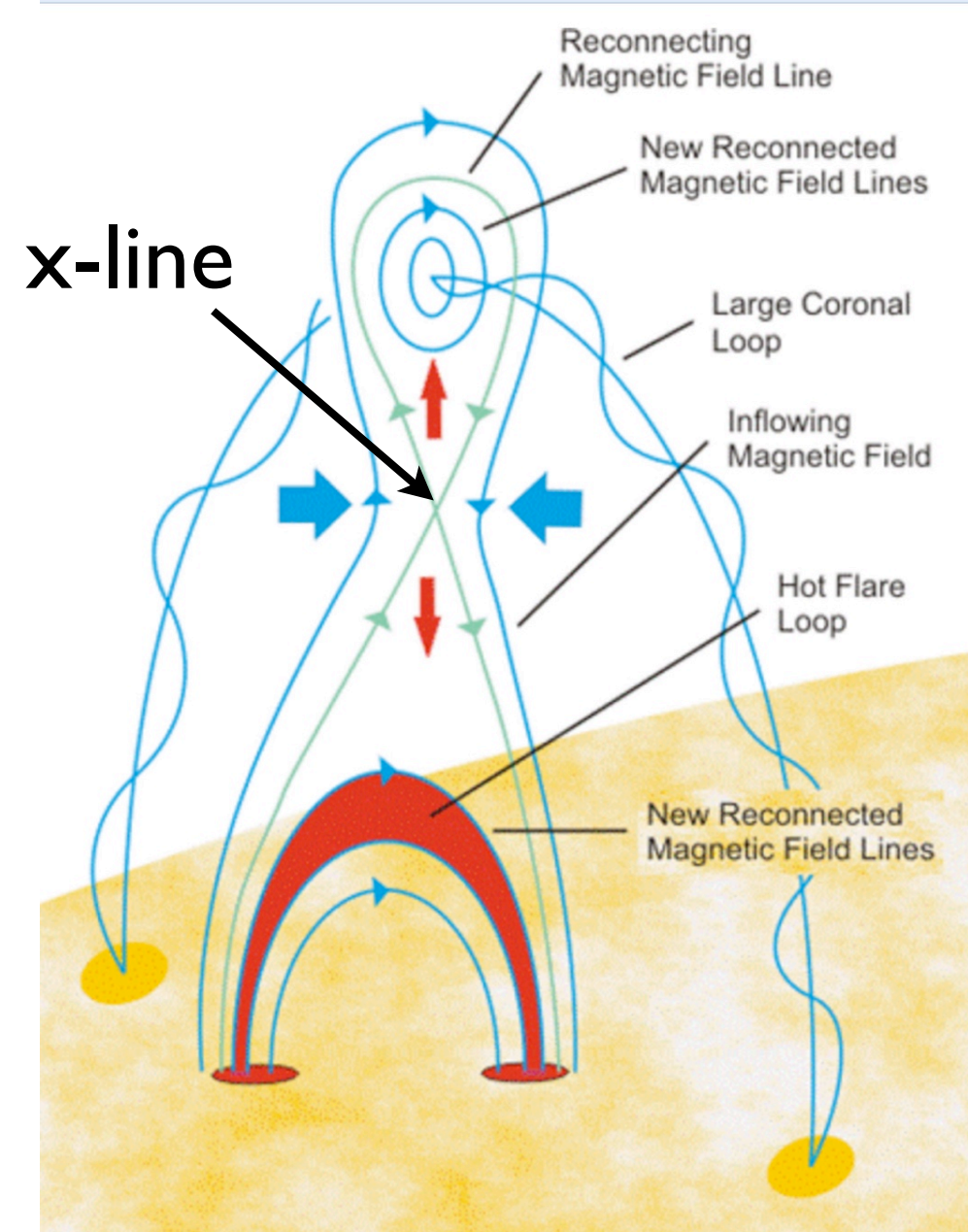
- Interaction between lotsⁿ of charge particles + electromagnetic fields
 - complicated & nonlinear!!
- Long range electromagnetic interaction!!
 - the evolution CANNOT be described by thermodynamics.

Introduction to magnetic reconnection

-- Solar Eruption



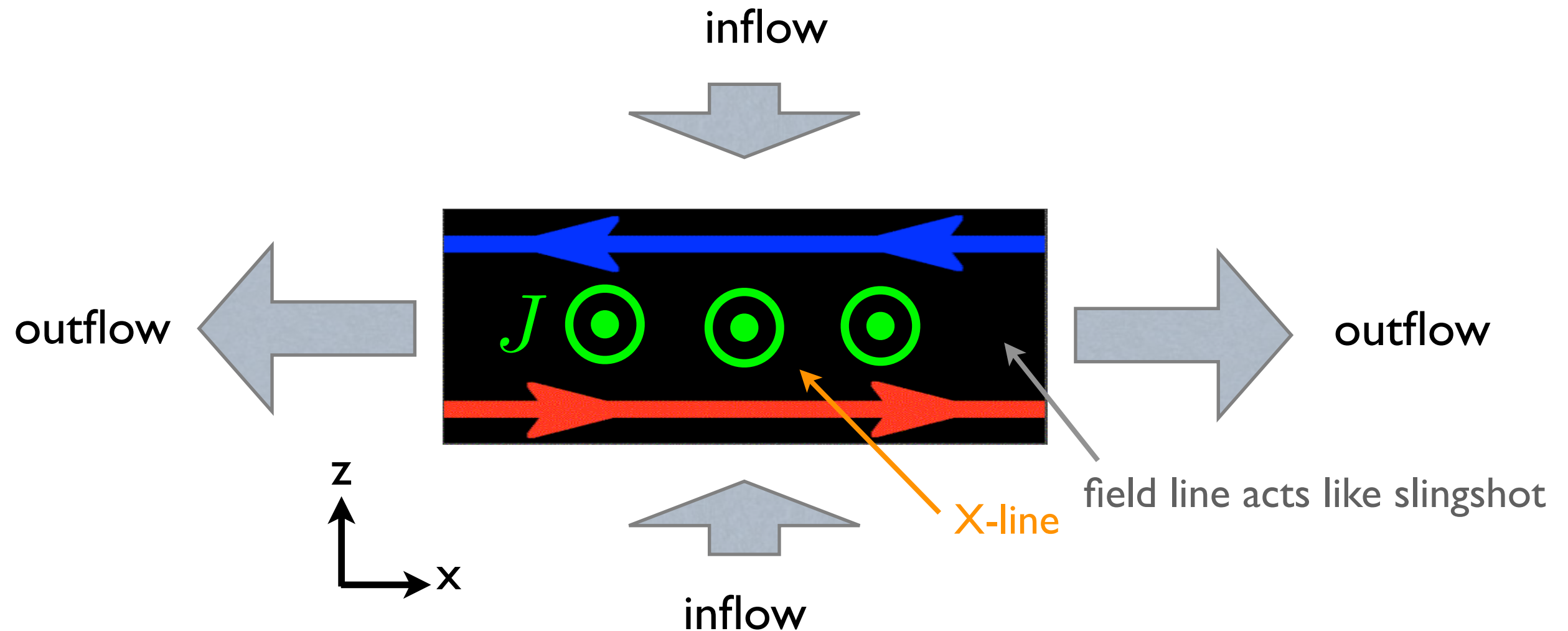
(Observation of SDO mission) $B \sim 200$ Gauss
 $T \sim 3,000,000$ K



(Courtesy of NASA)

- Energy up to 10^{32} ergs is released in ~ 20 mins
-- 40 billion atomic bombs!
- Matter up to 10^{10} tons is erupted.

Magnetic Reconnection?



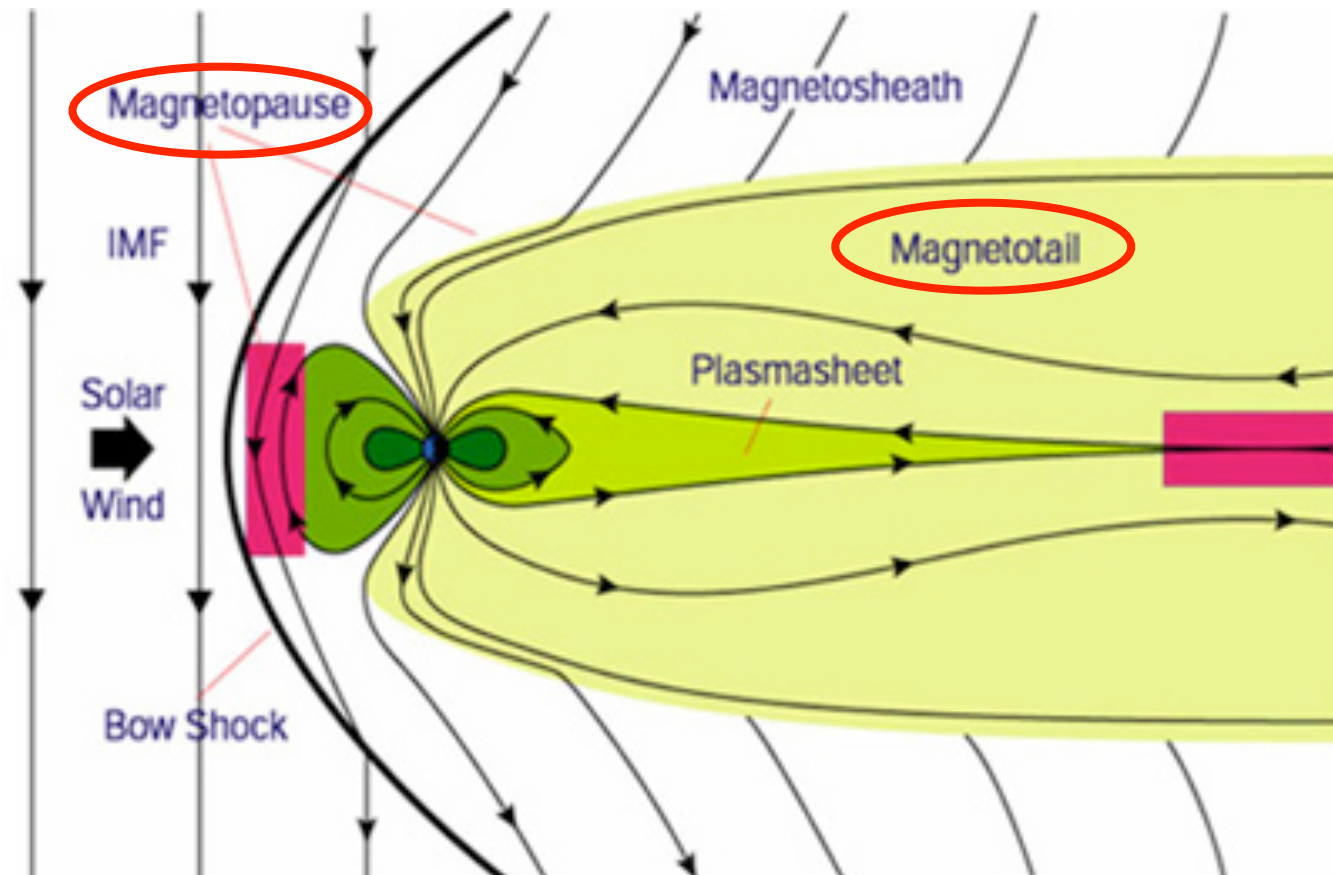
1. Inflow brings in magnetic flux
 2. Field lines break & reconnect
 3. Reconnected field line shoots out plasma
 4. Pressure drop sucks in plasma inflow
1. Inflow brings in magnetic flux
 2.
 3. ...

A self-driven process!!!

Earth's magnetosphere



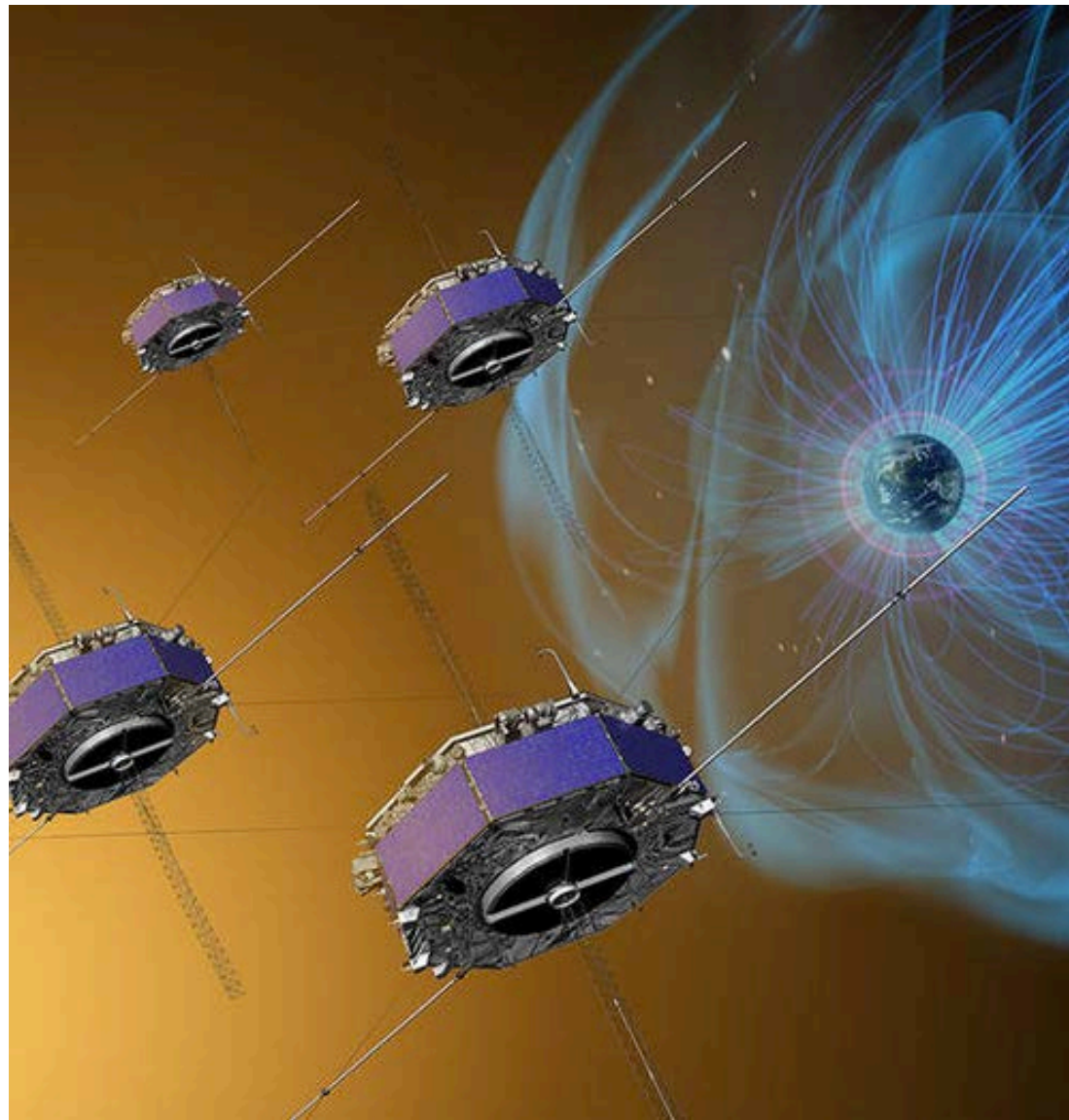
IMF
(Interplanetary
Magnetic Field)



- Reconnection occurs at both the magnetopause & magnetotail.
- Reconnection at the magnetotail drives magnetospheric substorm & causes aurora.
- **Space Weather**: a strong geomagnetic storm could do damage to **satellites, astronauts, GPS system, power grids on Earth**,....etc (e.g., 1859, 1989 Quebec blackout)

A billion \$ NASA mission designed to study magnetic reconnection

Magnetospheric Multiscale Mission (MMS)



<http://mms.gsfc.nasa.gov>

tight tetrahedron formation: separation down to 7 km!
100x faster for electrons measurement (30 ms)
30x faster for ions measurement (150 ms)

- MMS leads us into a stage where the **3D electron-scale structure** of magnetic reconnection, in nature, can be measured in an unprecedented manner.

Why Blue Waters?
& Our accomplishments to date

Particle-in-cell Simulations

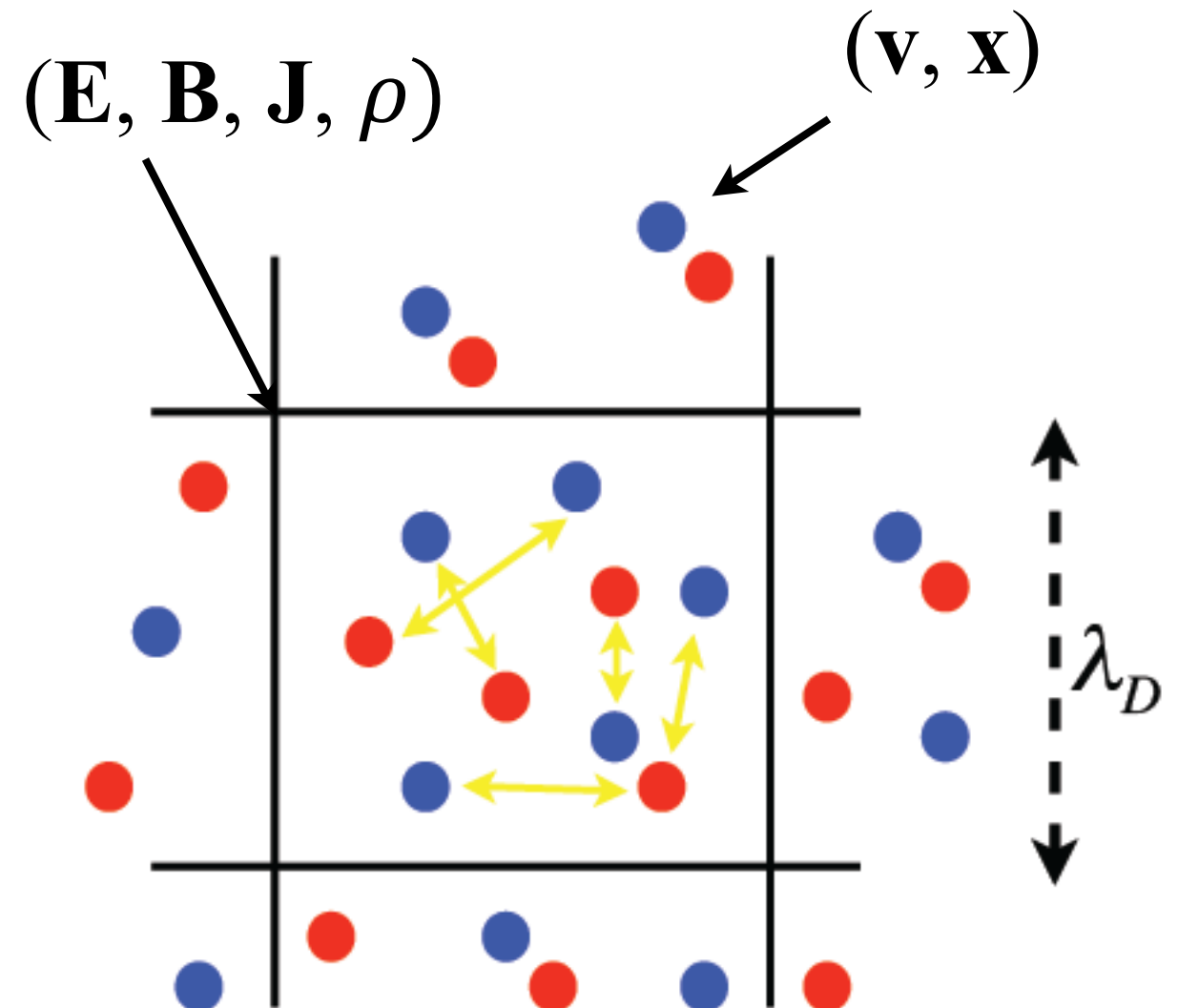
Lorentz Force

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Maxwell Equation

$$\nabla \cdot \mathbf{B} = 0 \quad \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}$$

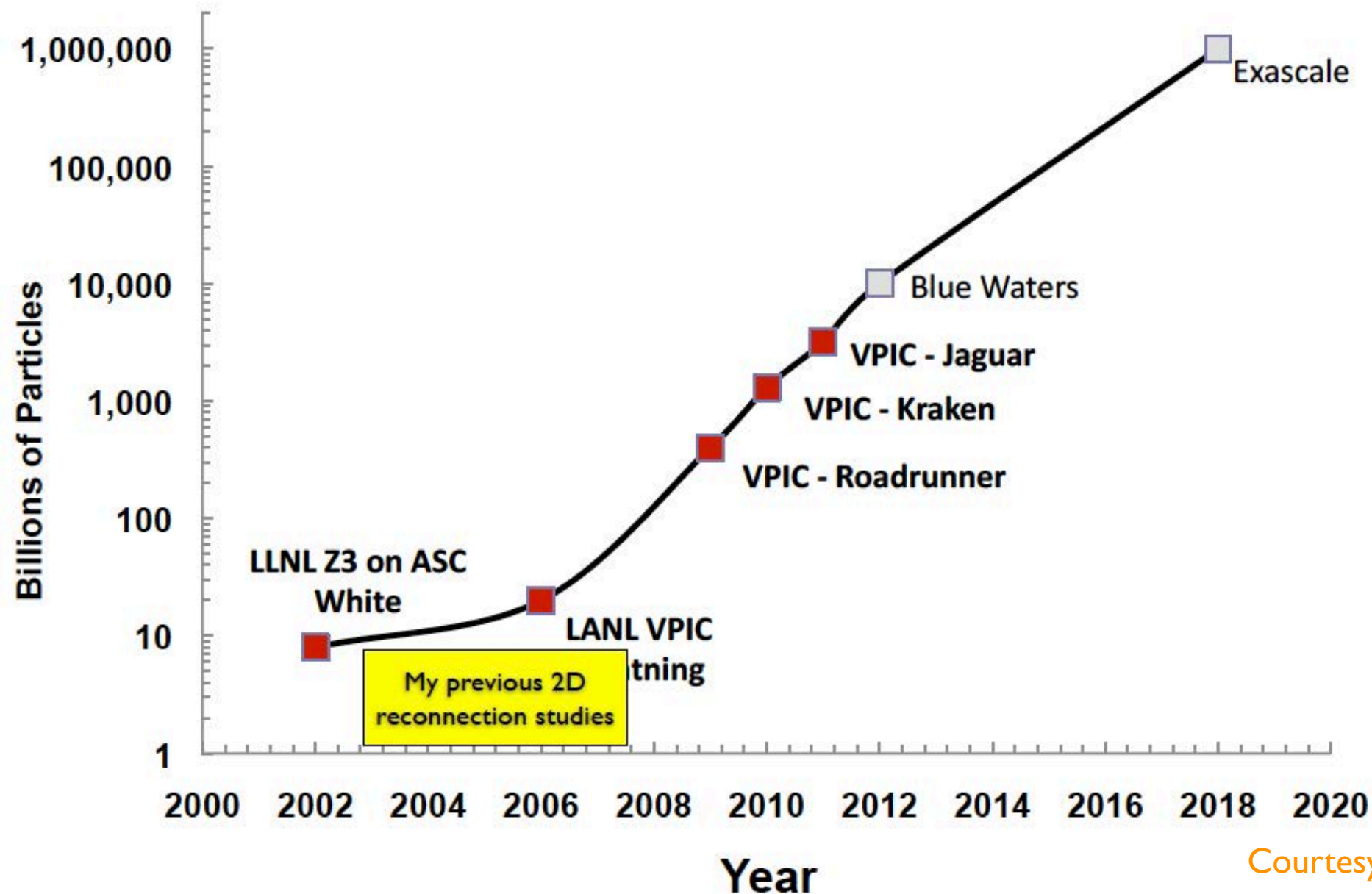
$$\nabla \cdot \mathbf{E} = 4\pi\rho \quad \nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$



Pro: A first-principle description with rich kinetic physics being captured ✓

Con: It demands considerable computational resource
, especially for 3D systems (**Challenge!**)

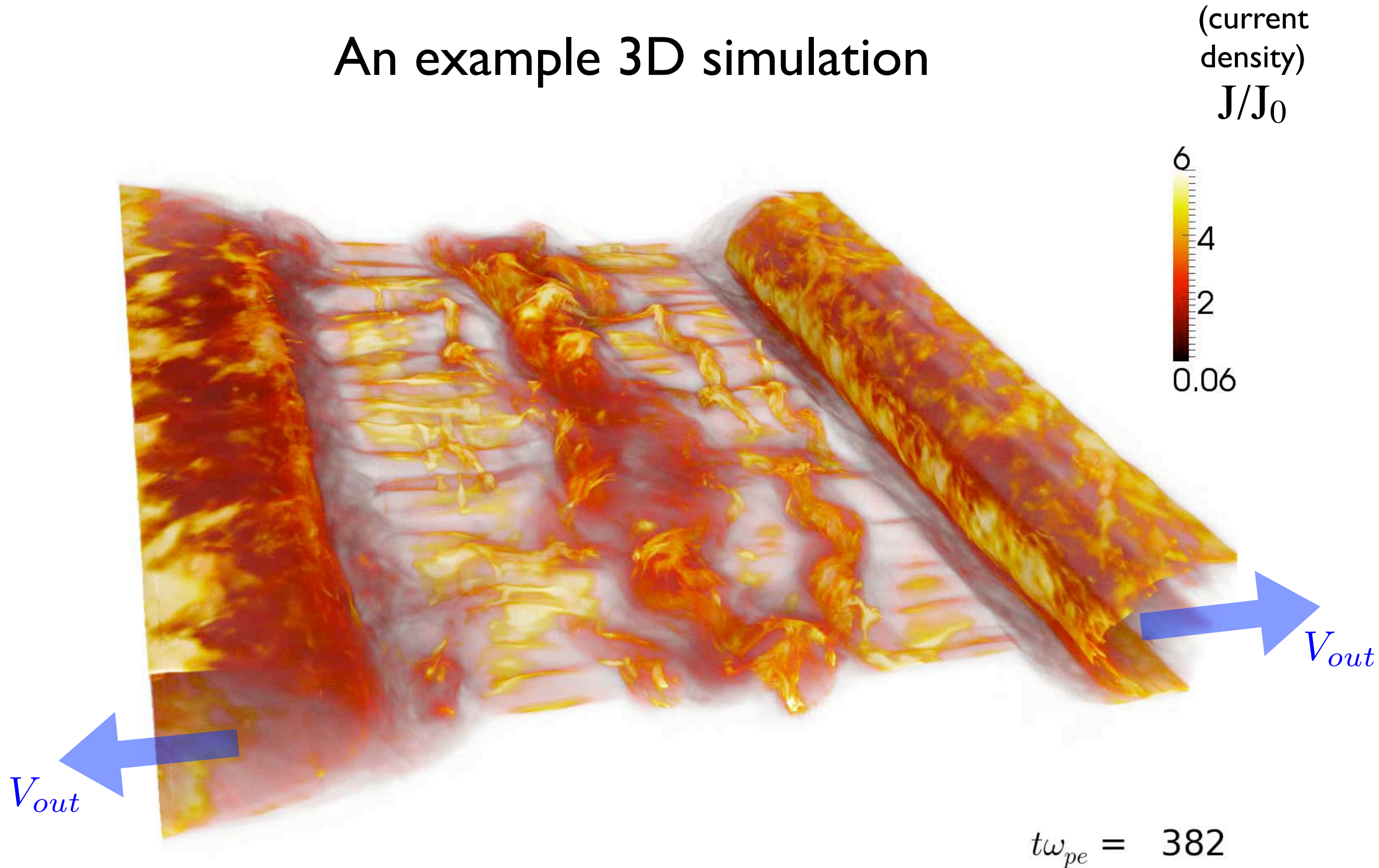
Progress of Particle-in-Cell simulations



- Resource required for a typical run in our BW project:
 - ~2 trillion particles; ~ 6 billion cells;
 - ~12 million core-hours; ~ 260 K cores;
 - ~200 TB output (including restart files)

Q: What is the 3D nature of magnetic reconnection??
-- how it differs from the conventional 2D picture

An example 3D simulation



Distinct 3D features, including

- flux ropes.
- kink instability.
- turbulence.

(Previous BW results.
Guo, Li, Daughton, Liu, PRL 2014
Guo, Liu, Daughton, Li, APJ 2015)

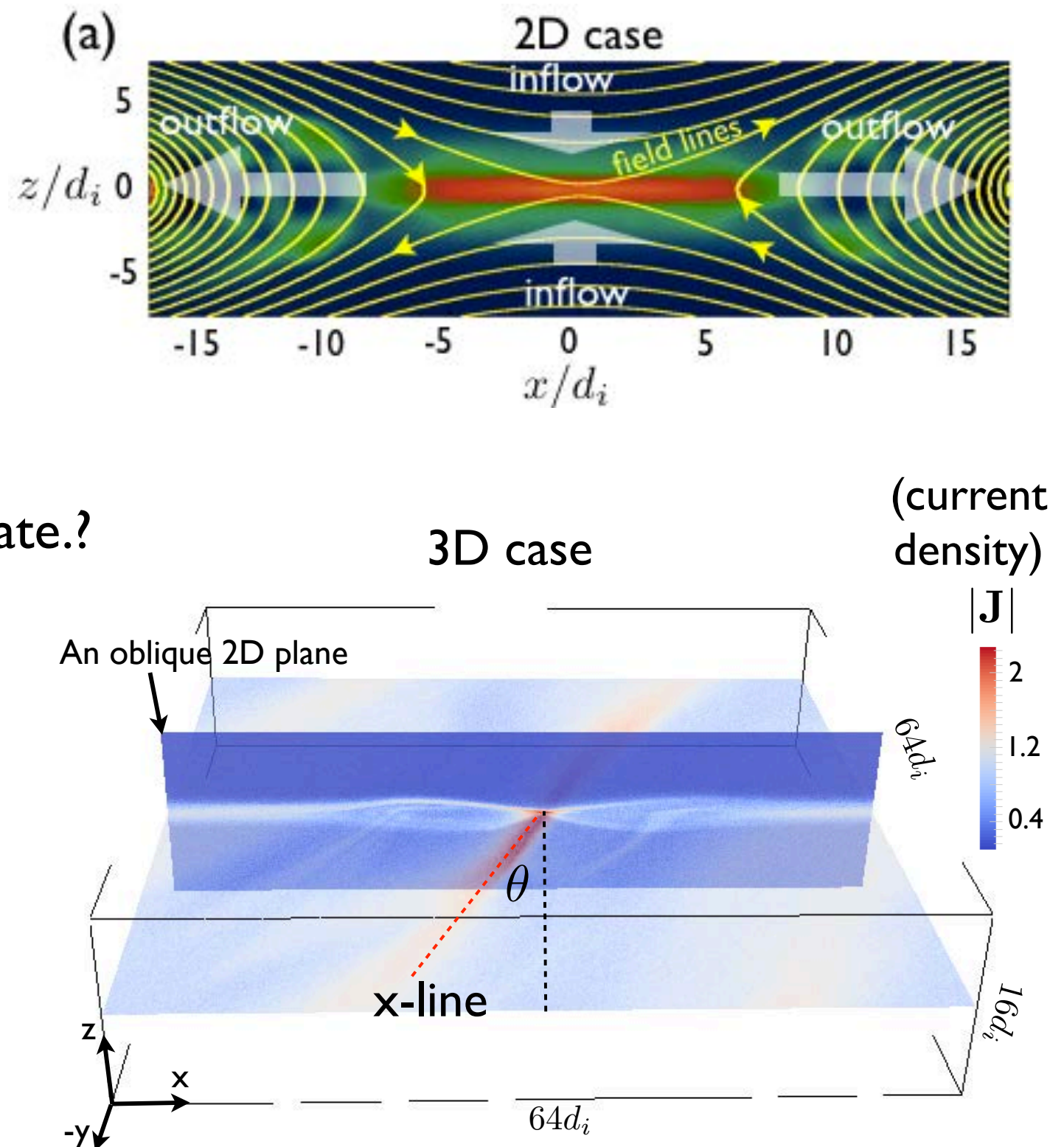
3D nature of reconnection X-line

Q: What determines the orientation of x-line??

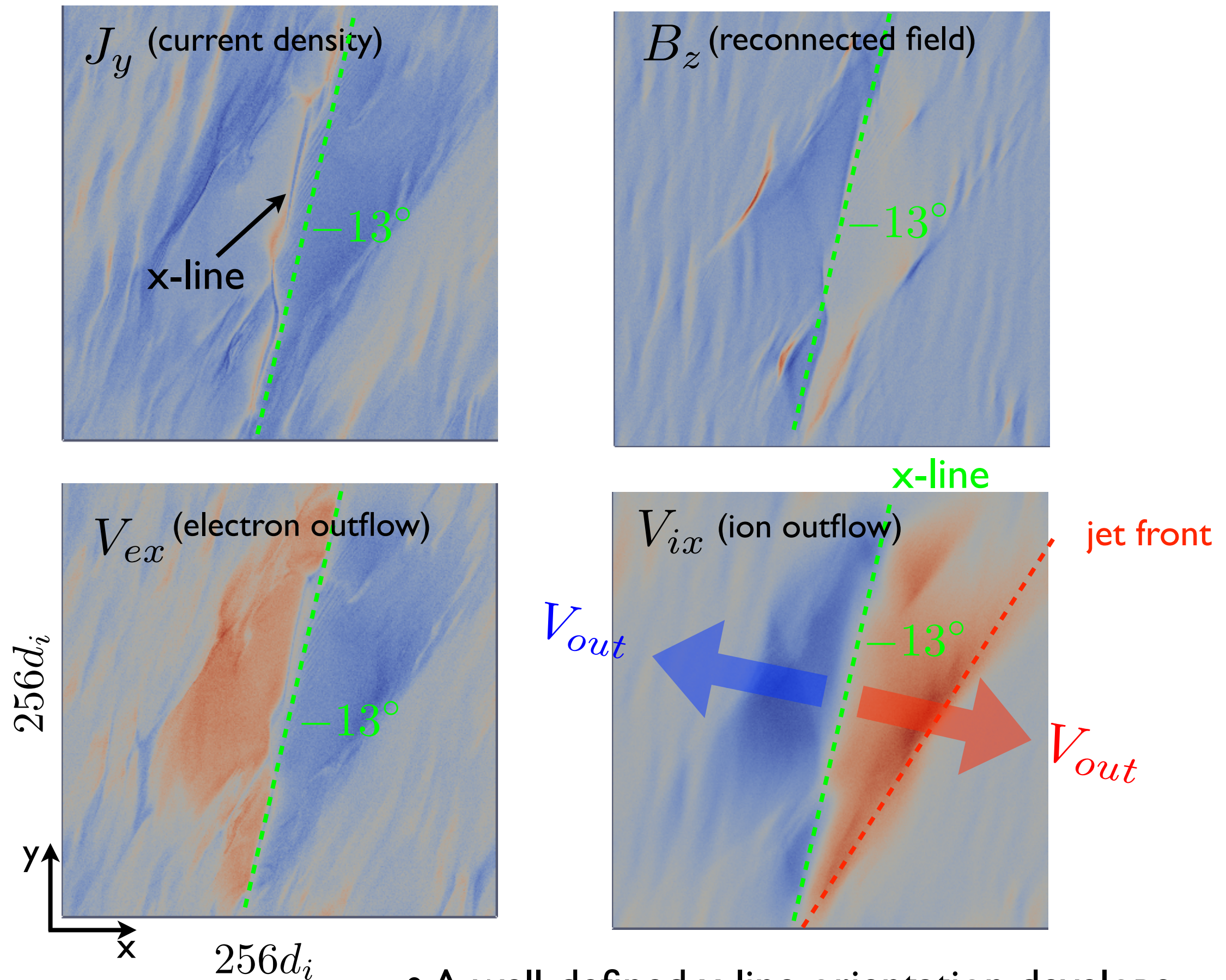
Hypothesis: the system may tend to maximize

- the magnetic energy conversion rate.?
- the outflow speed.?
- or ??

- Simulation on BW provides a first-principle test!

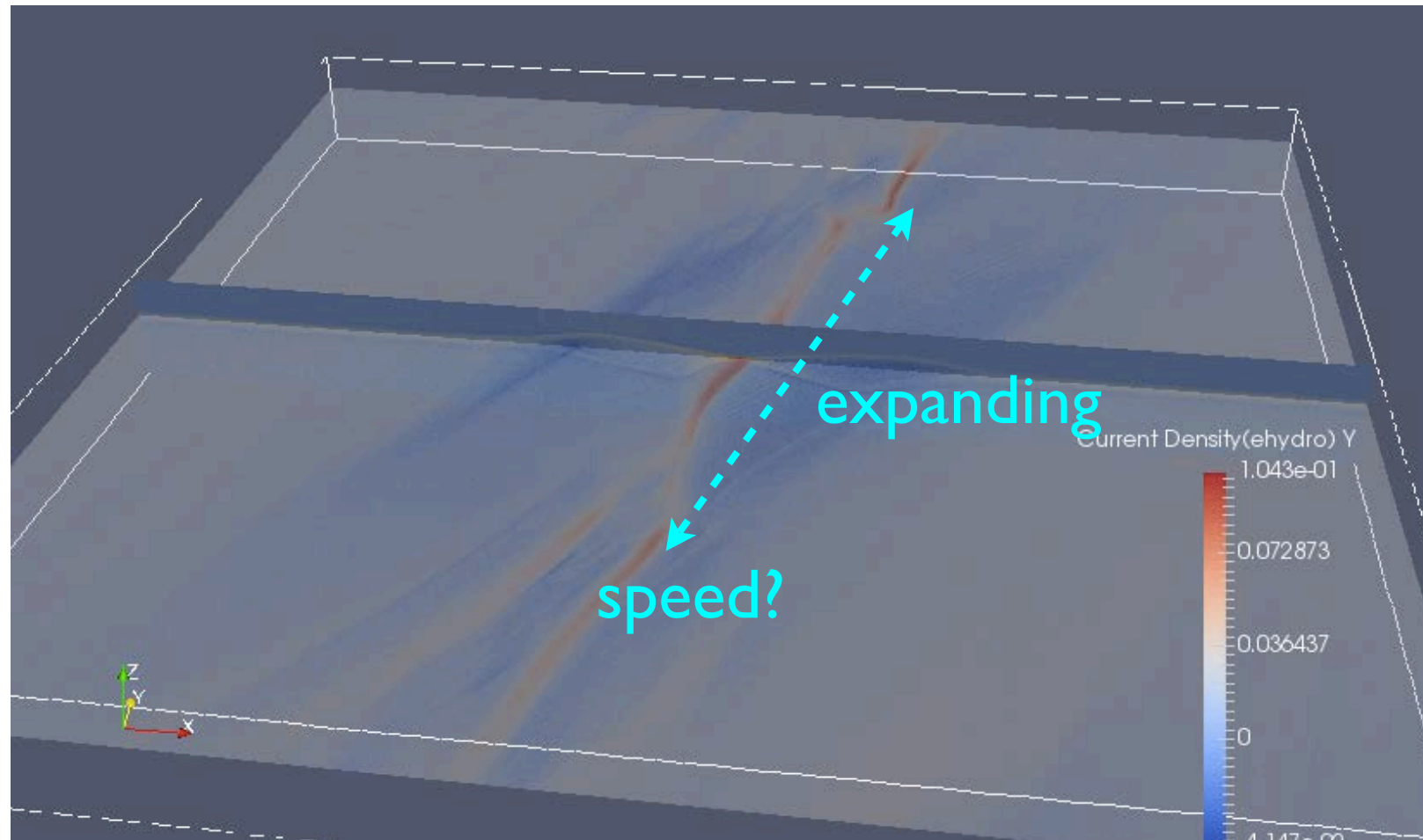


Result I: X-line Orientation



Result II: Extent and expansion of reconnection x-line in the magnetopause geometry

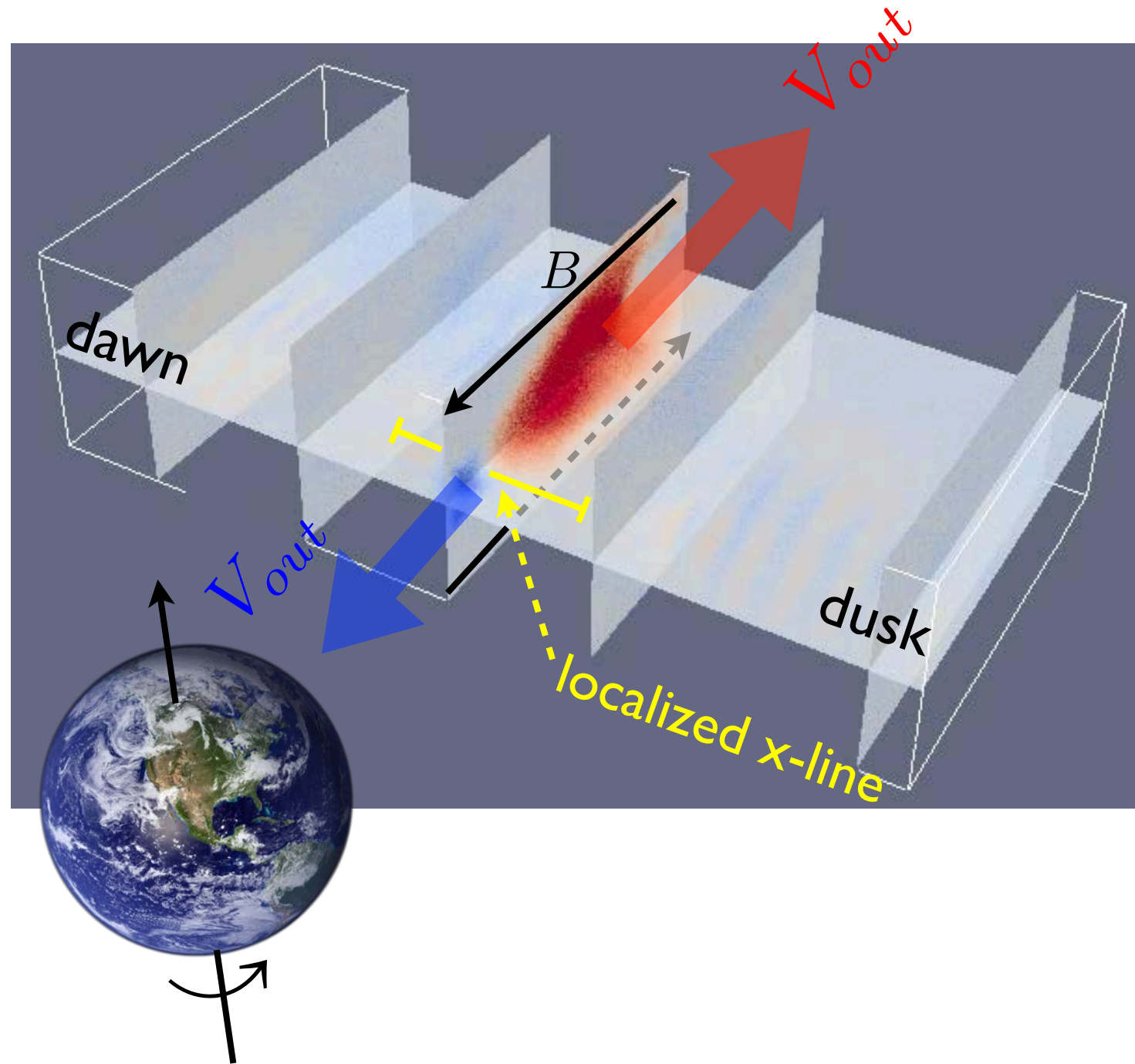
(3D view using ParaView)



Q: How does the x-line expand? what is the expanding speed?

--- Knowing the length of x-line is crucial for estimating the entry rate of solar wind plasmas into Earth's magnetosphere.

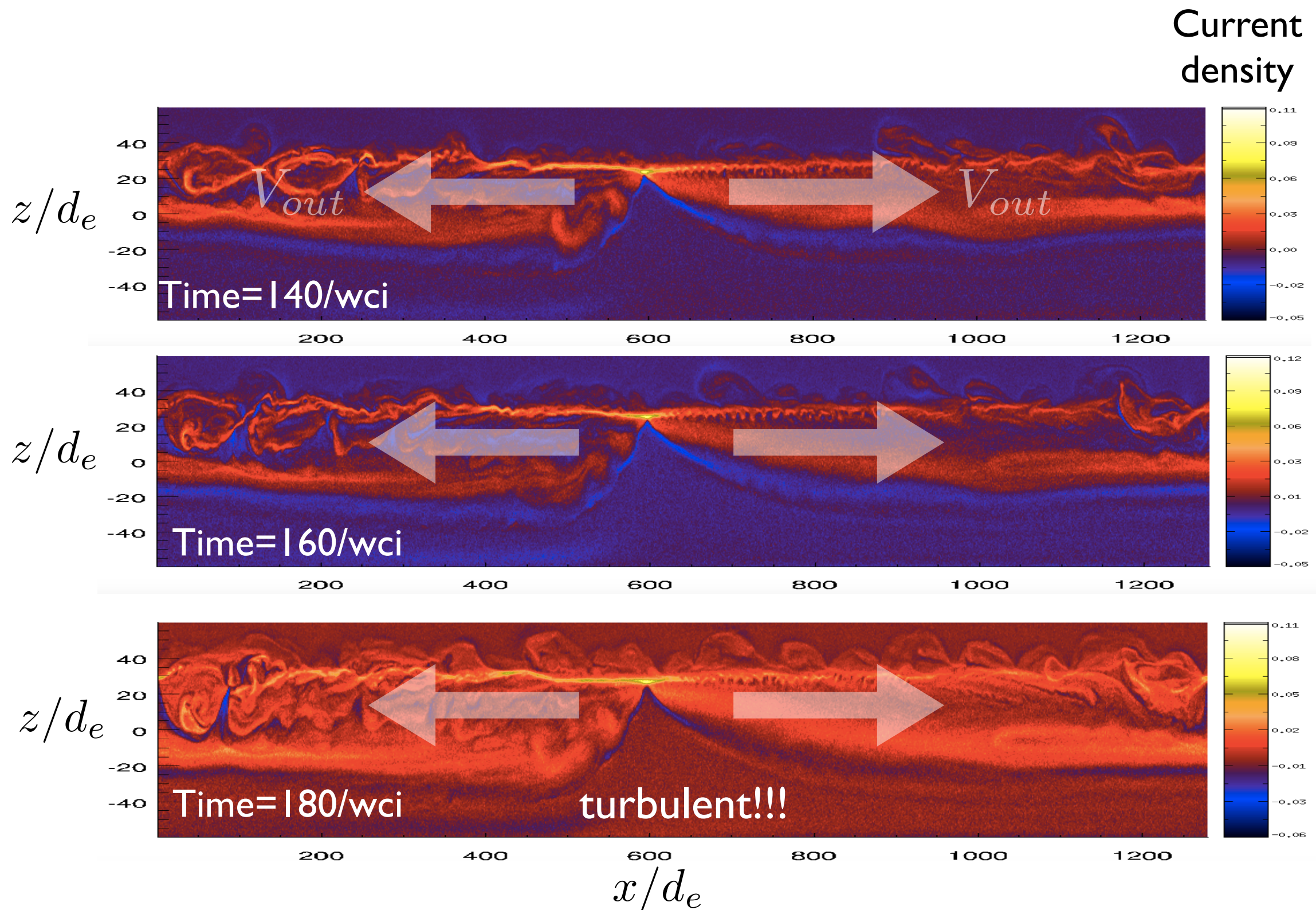
Result III: Extent and expansion of reconnection x-line in the magnetotail geometry



Q: Is there a limited x-line extent in the tail geometry?
-- Relevant to the formation of Bursty Bulk Flows (BBFs)
often observed at Earth's magnetotail.



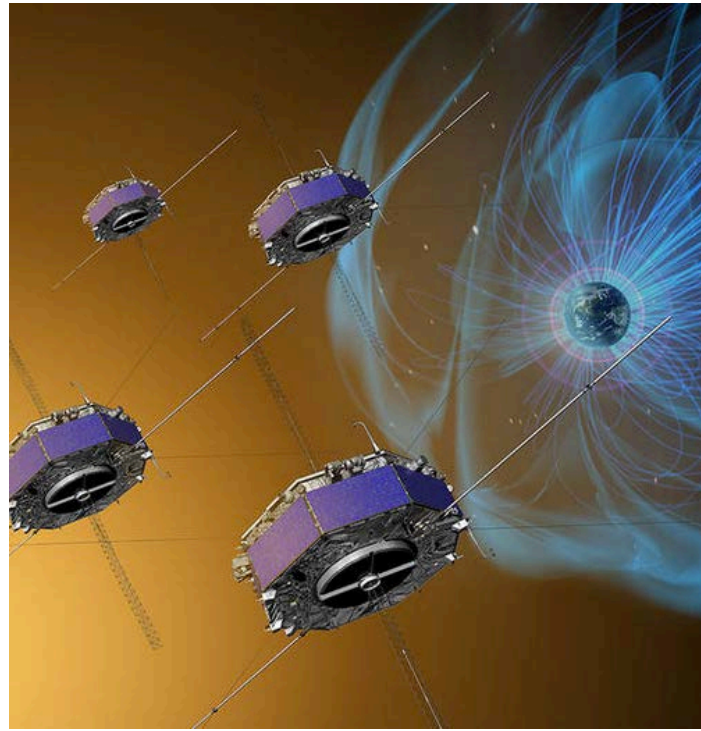
Result IV: Self-generated turbulence in Reconnection



- The reconnection current sheet & x-line can become turbulent in 3D!
-- the cause? the effect on the dissipation & energy conversion rate?

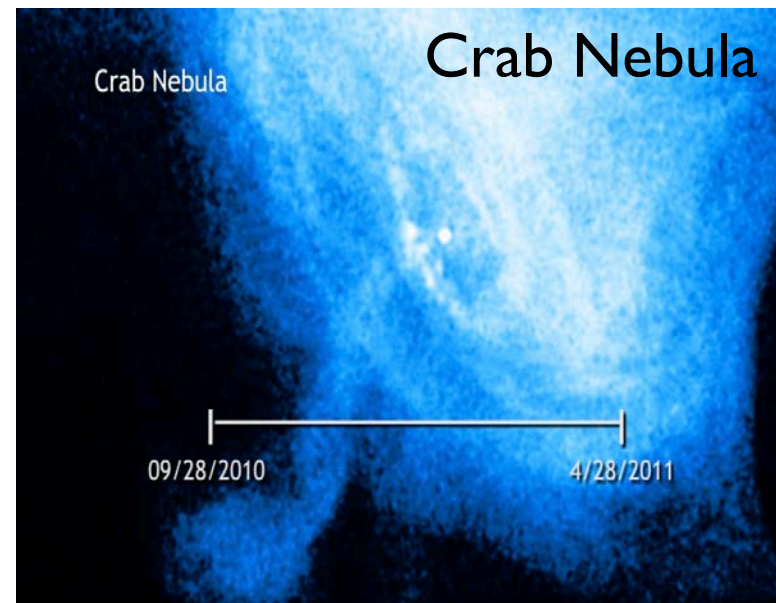
Broader Impact

Space Science



NASA's MMS mission

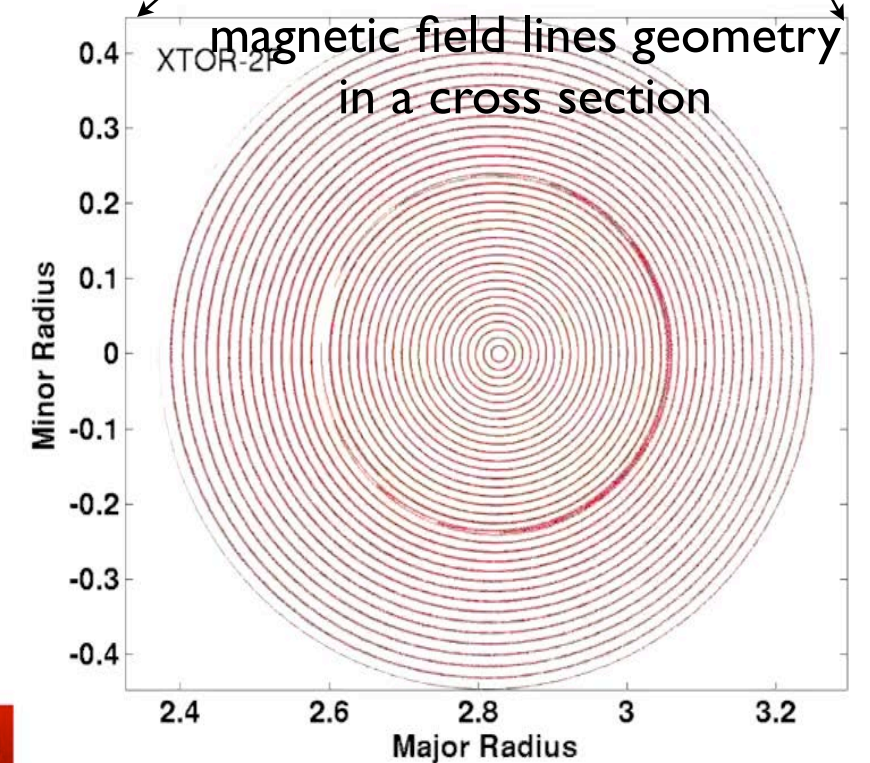
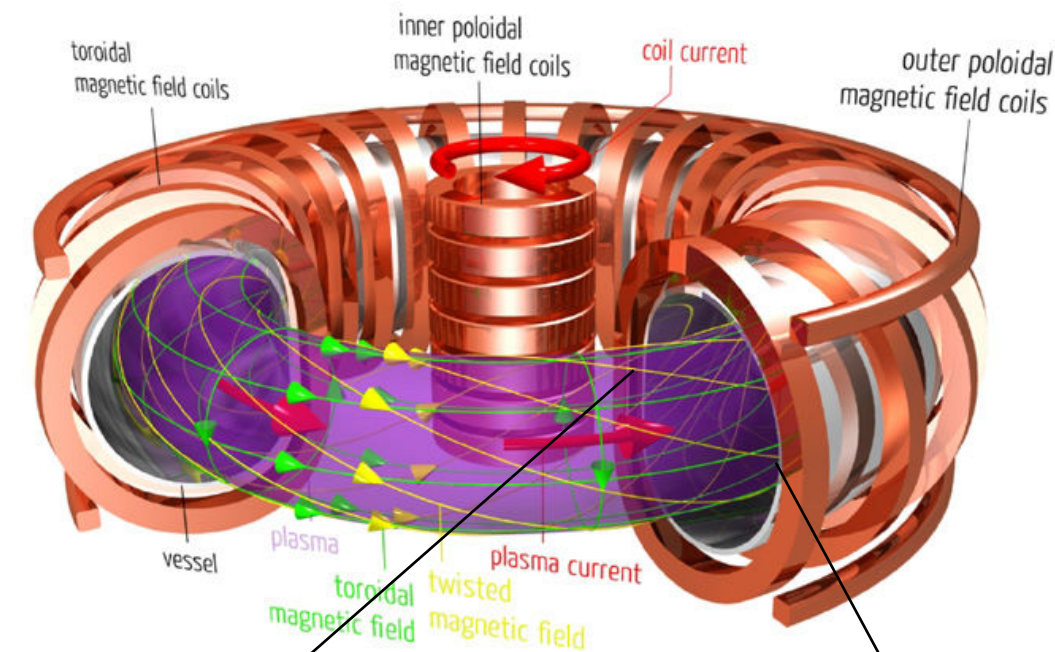
Astrophysics



Fermi Gamma Ray Space Telescope

Fusion device

e.g., ITER Tokamak @ France



Blue Waters Team Contributions

Special thanks to

Ryan Mokos for the help & advices on the data archiving.

JaeHyuk Kwack for the script that simultaneously launches tar command in multiple cores!

Craig Steffen & storage group for fixing the error in my file system at Nearline.

Roberto Sisneros & visualization group for helping setup the 3D visualization using ParaView.

Summary

Magnetic Reconnection is the key process that releases the magnetic energy stored in space, astrophysical and laboratory plasma systems.

- The 3D nature of reconnection x-line remains unclear!
- Blue Waters provides the opportunity to explore this challenging problem.

The on-going science topics run on Blue Waters include:

- The orientation of 3D x-lines.
- The extent and expansion of 3D x-lines with local geometries similar to Earth's magnetopause & magnetotail.
- The turbulent nature of 3D x-lines.