Orientation and Stability of Magnetic Reconnection X-line at Earth's Magnetopause

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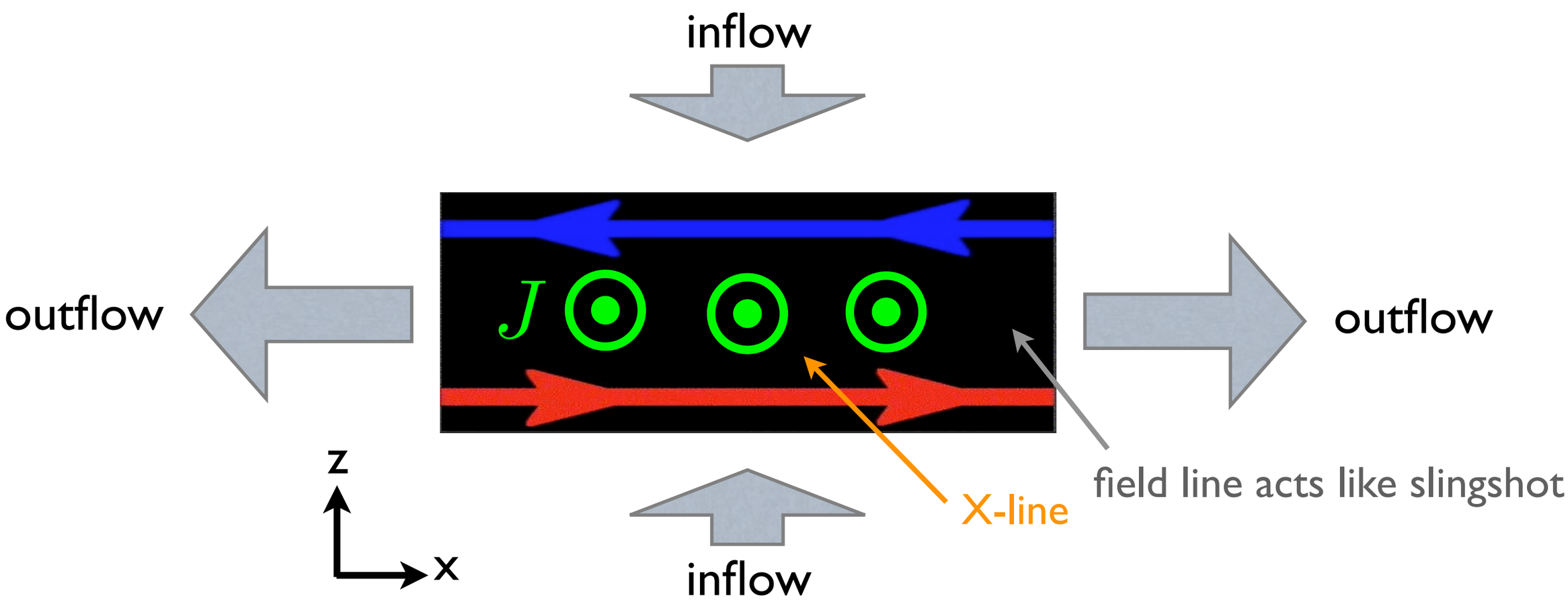
Why it matters?

Magnetic Reconnection.?

— an efficient mechanism that converts magnetic energy to plasmas kinetic energy

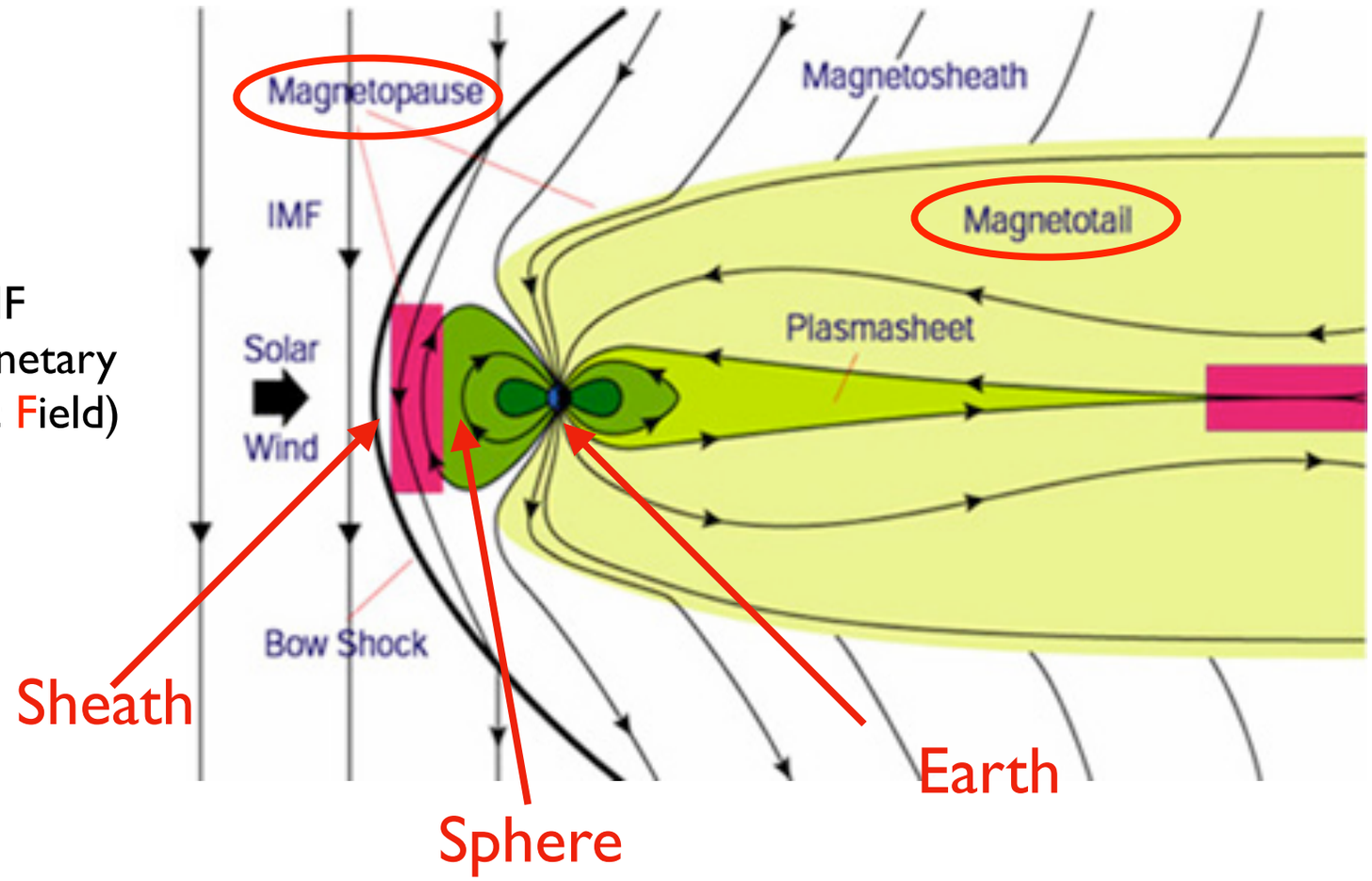


1. Inflow brings in magnetic flux
2. Field lines break & reconnect
3. Reconnected field line shoots out plasma
4. Pressure drop sucks in plasma inflow
1. Inflow brings in magnetic flux
2. .....
3. ...

A self-driven process!!!

Earth's magnetosphere

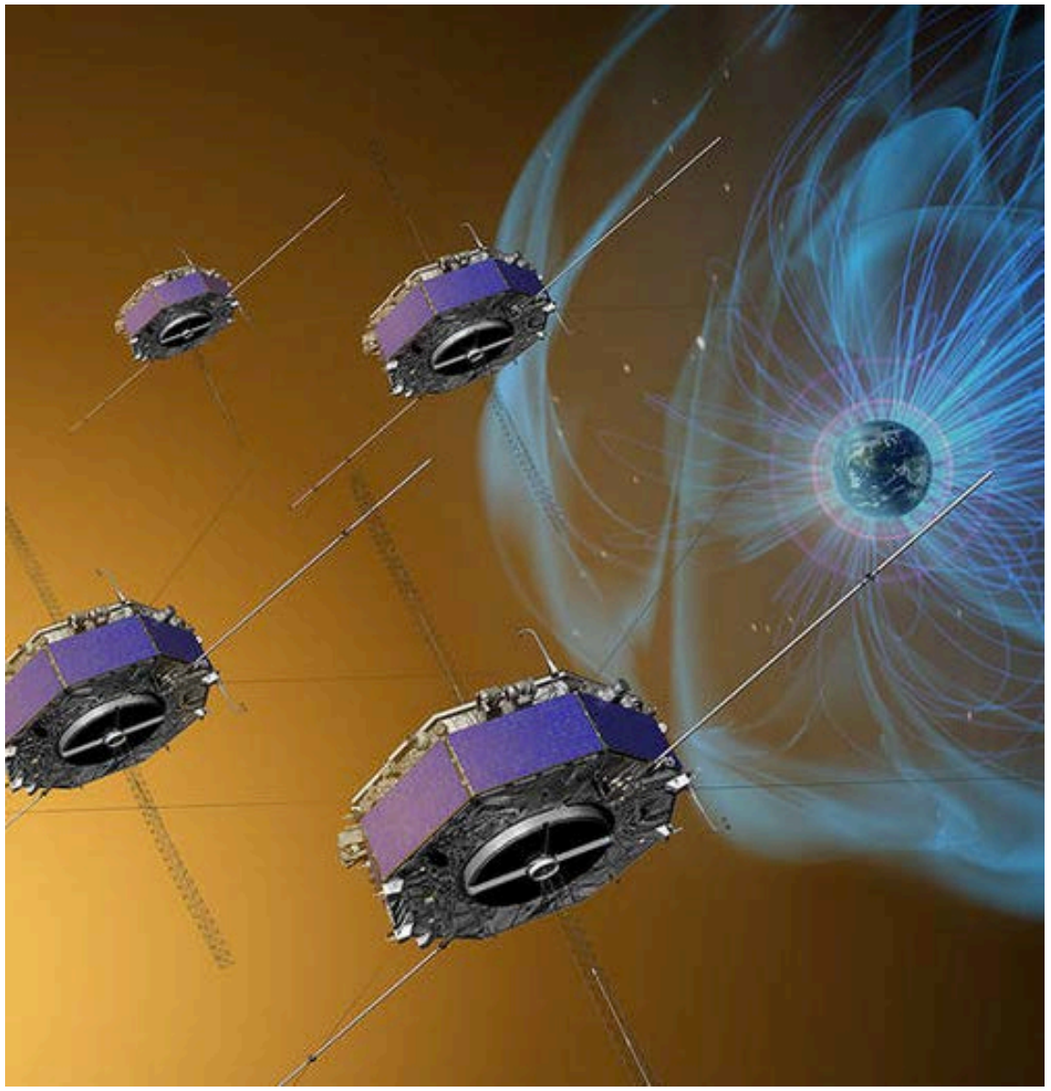
IMF
(Interplanetary
Magnetic Field)



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

A billion $ NASA mission designed to study magnetic reconnection

Magnetospheric Multiscale Mission (MMS)

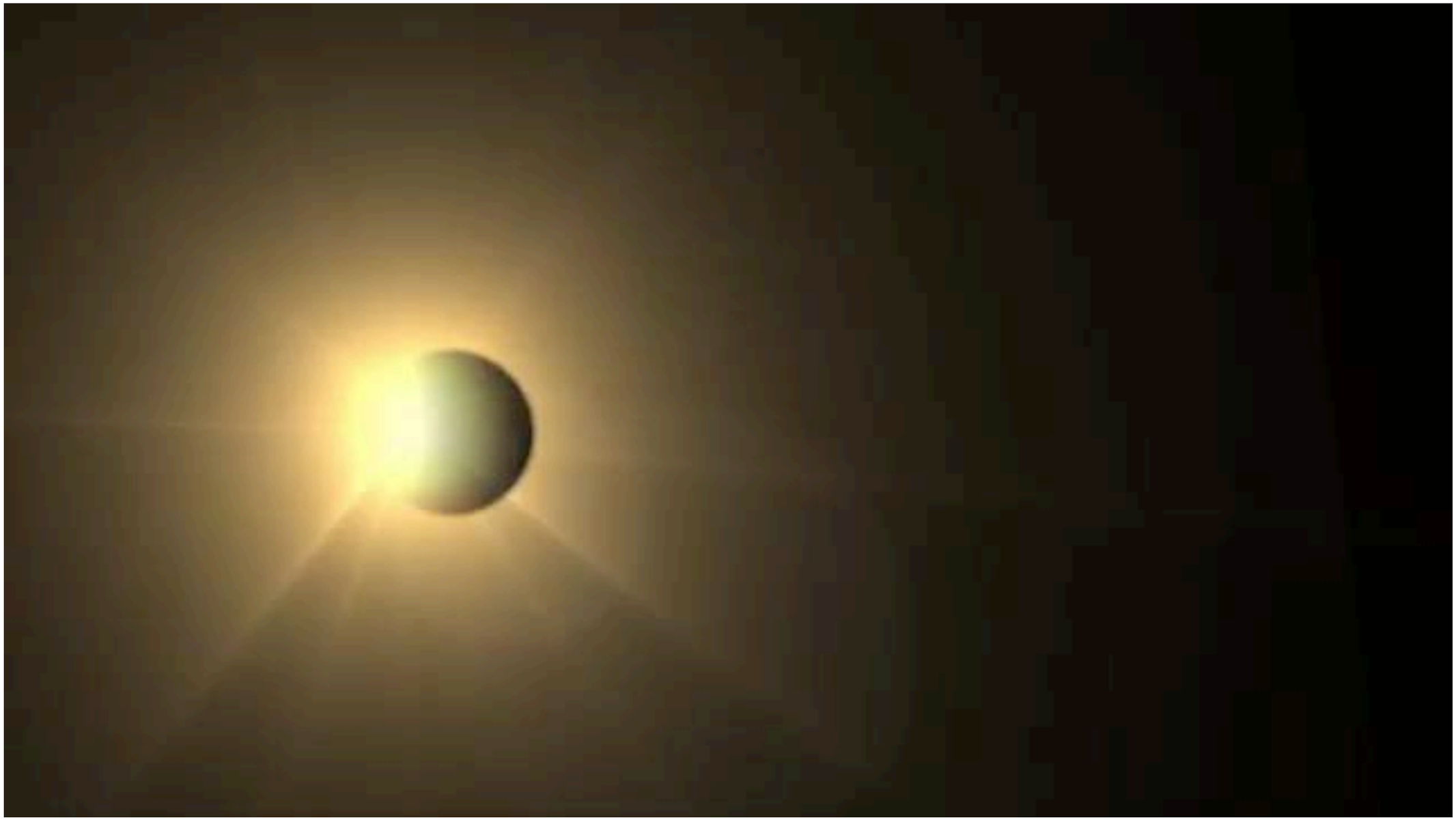


http://mms.gsfc.nasa.gov

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.

The trailer of MMS ...



Key Challenge, Why Blue Waters?
& Our accomplishments to date

Particle-in-cell Simulations

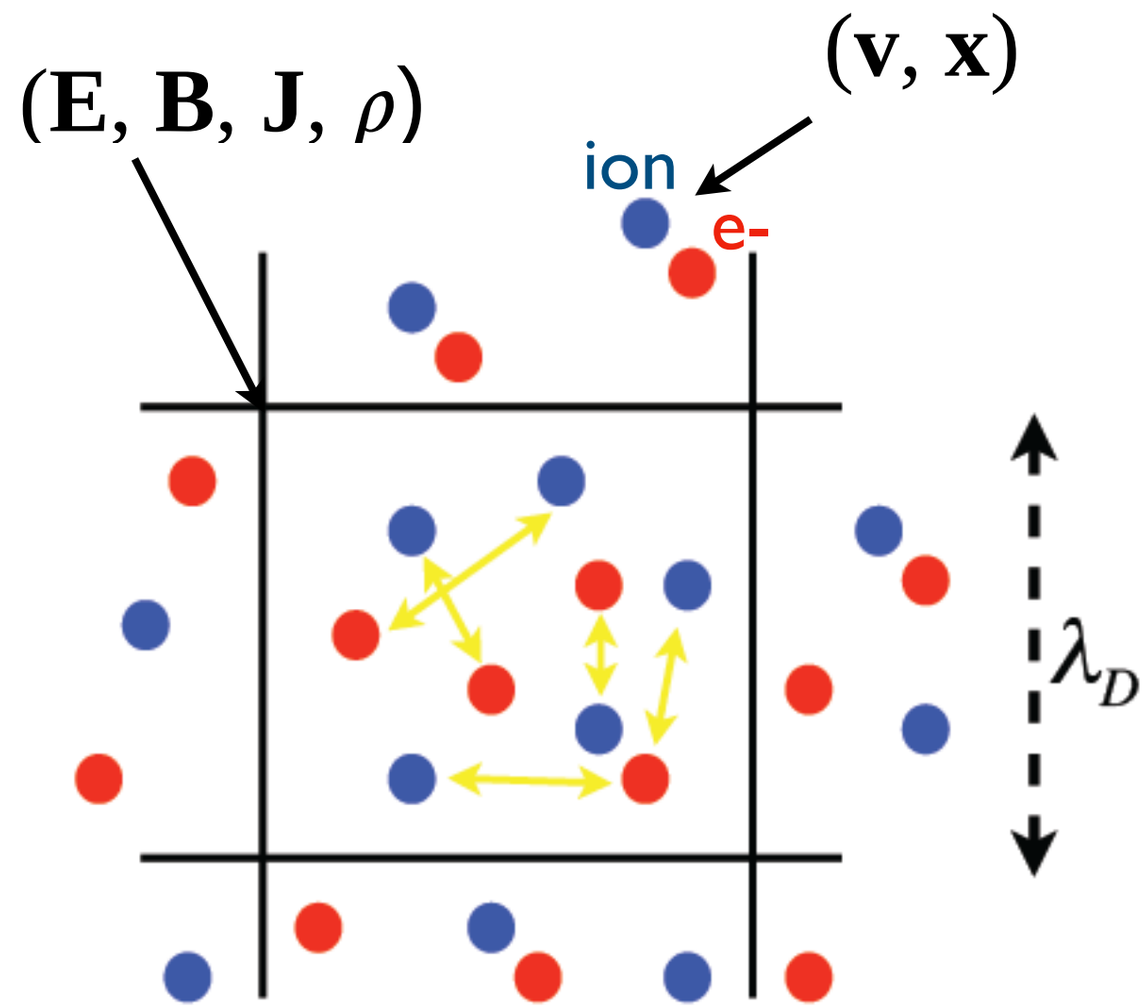
Lorentz Force

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

Maxwell Equation

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

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



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

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

The 3D nature of magnetic reconnection
-- how it differs from the conventional 2D picture?

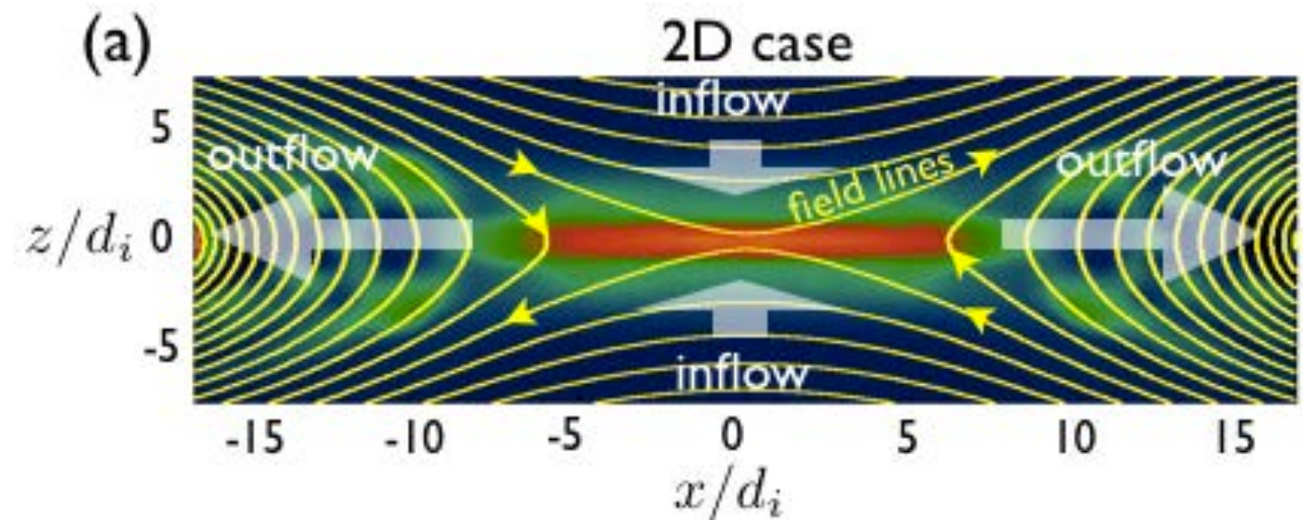
3D nature of reconnection X-line

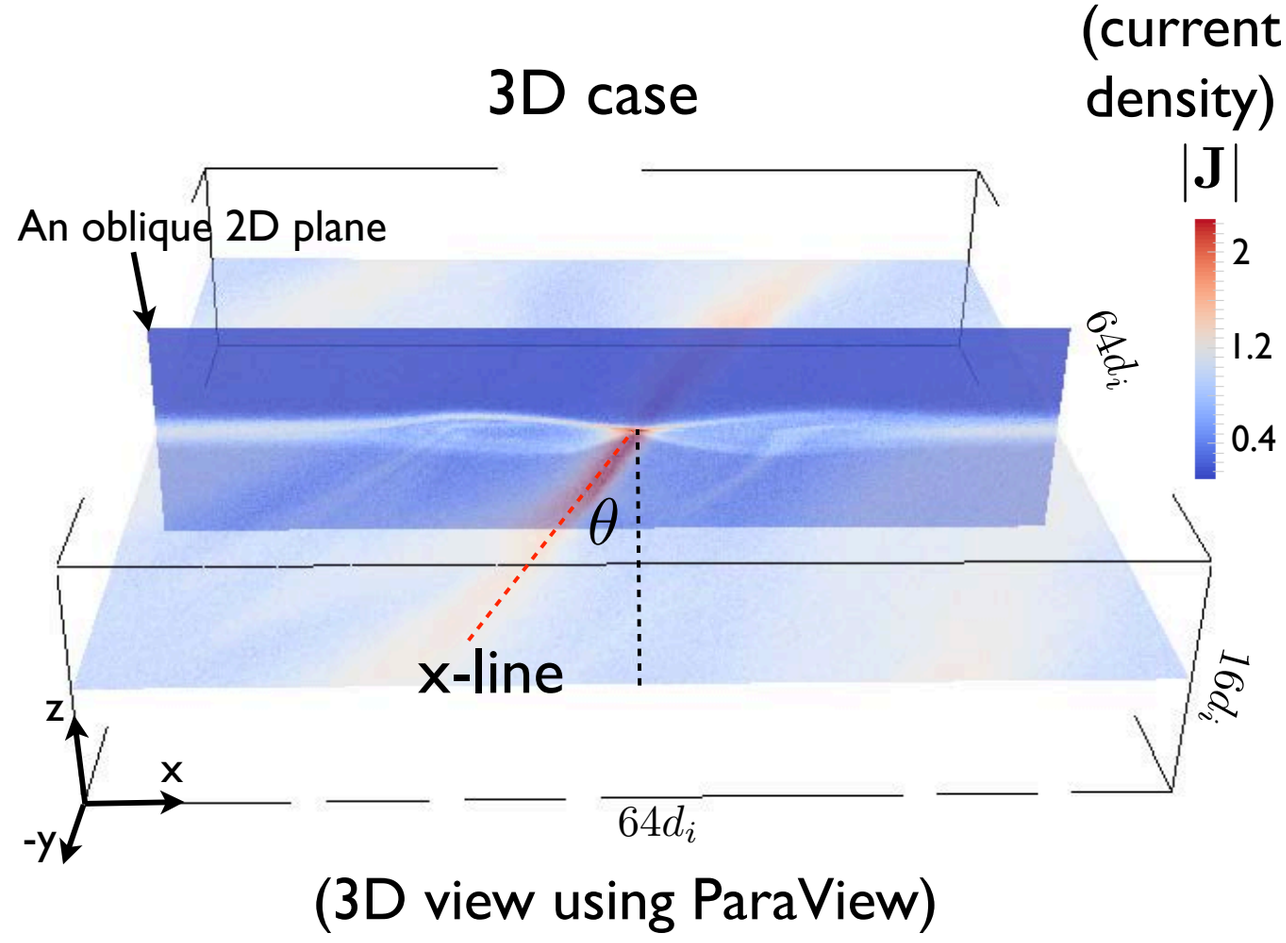
Q: What determines the orientation of the x-line??

Hypothesis: the system may tend to maximize

— the reconnection rate.?
— the outflow speed.?
— principle of maximum entropy?
— or ...??

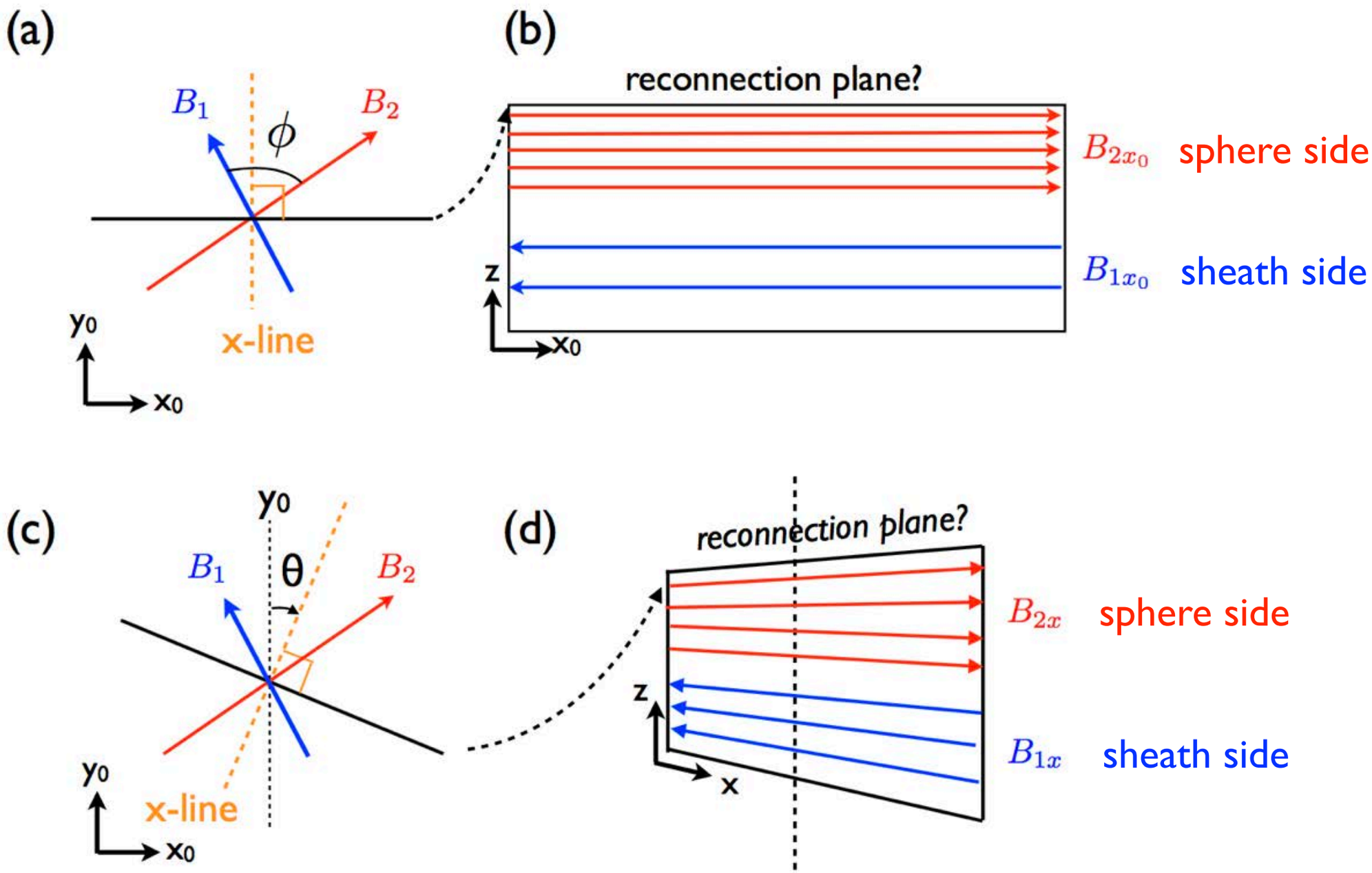
- Simulation on BW provides a first-principle test!





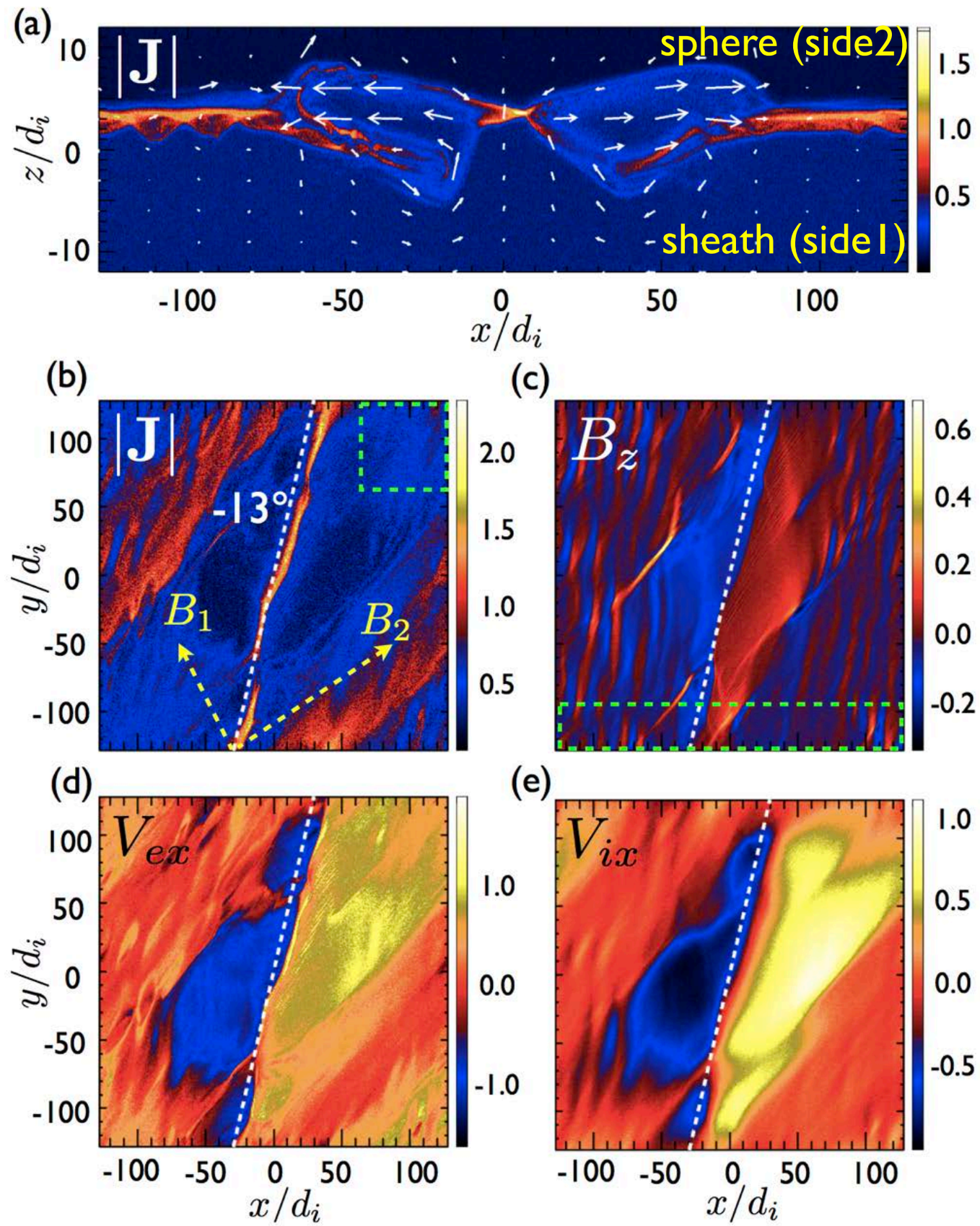
(3D view using ParaView)

The question to solve



Q: Which plane does reconnection "preferred"??

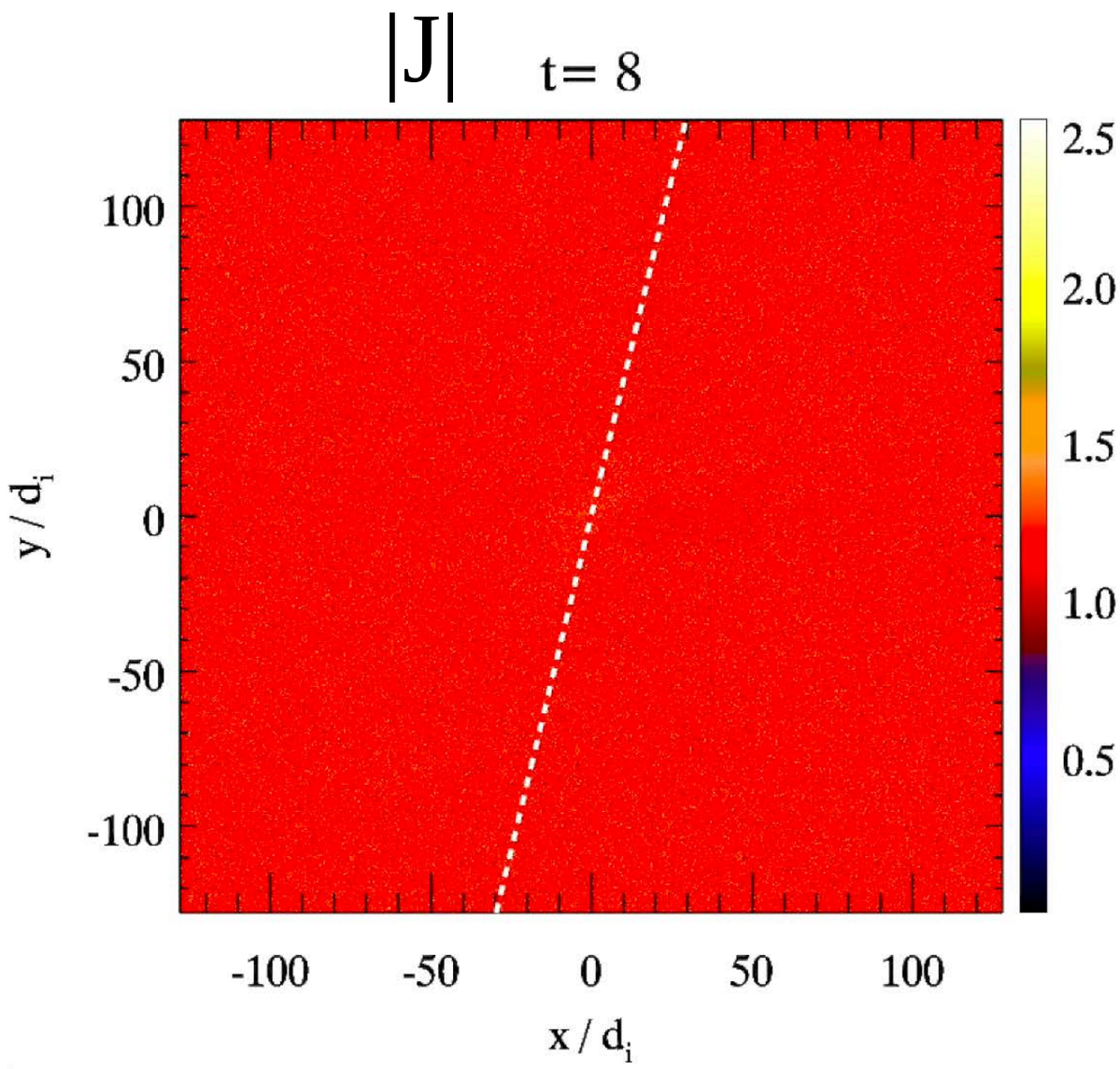
Result I: X-line Orientation



- A well-defined x-line orientation develops!!

(Liu et al., JGR, 2018)

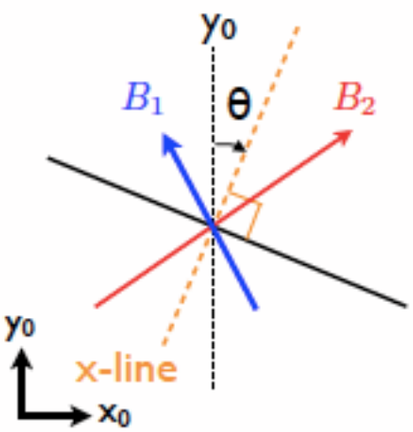
Temporal Evolution



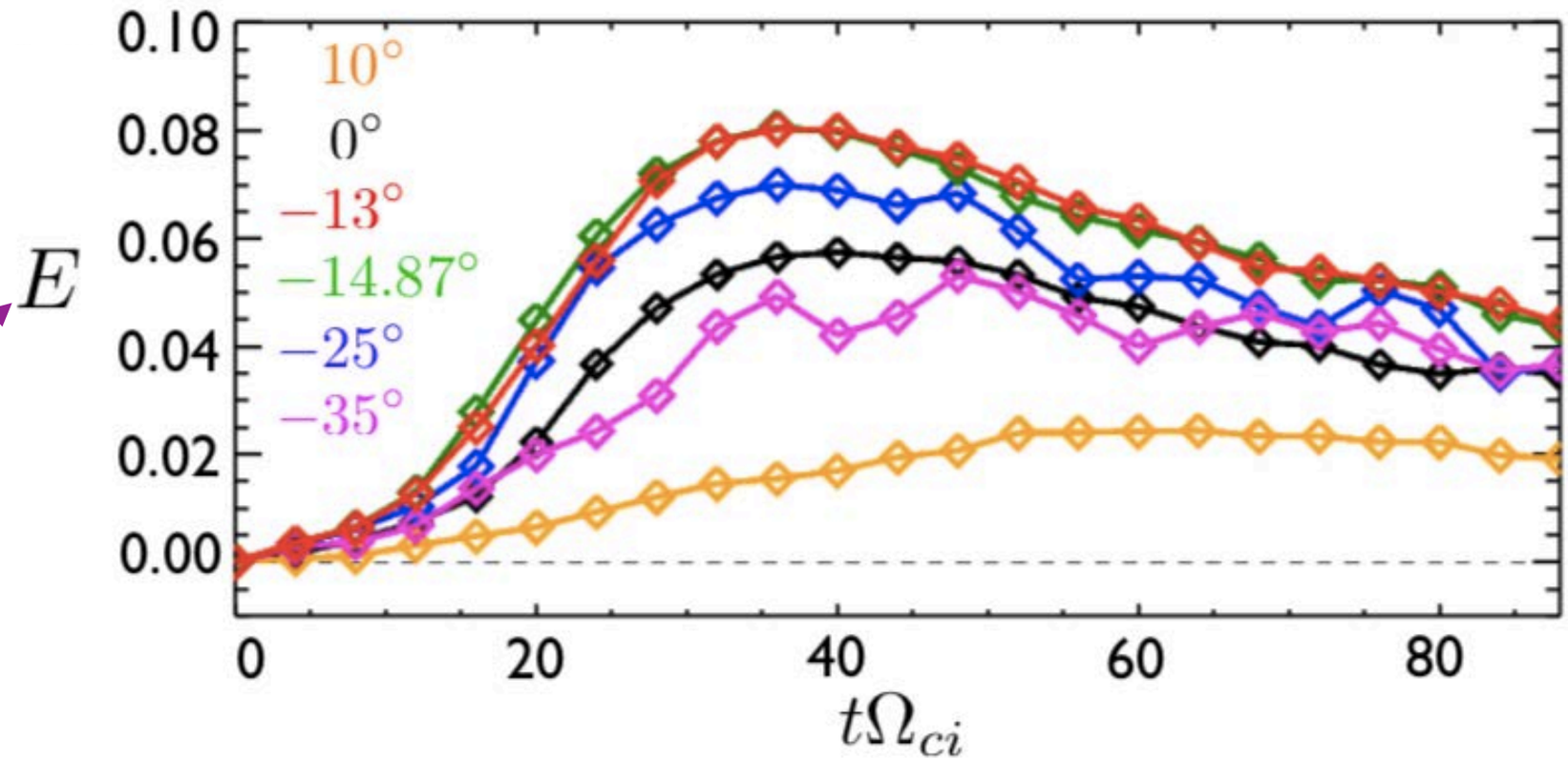
(Liu et al., JGR, 2018)

- Check out the stability of this x-line~

What can companion 2D simulations tell us?

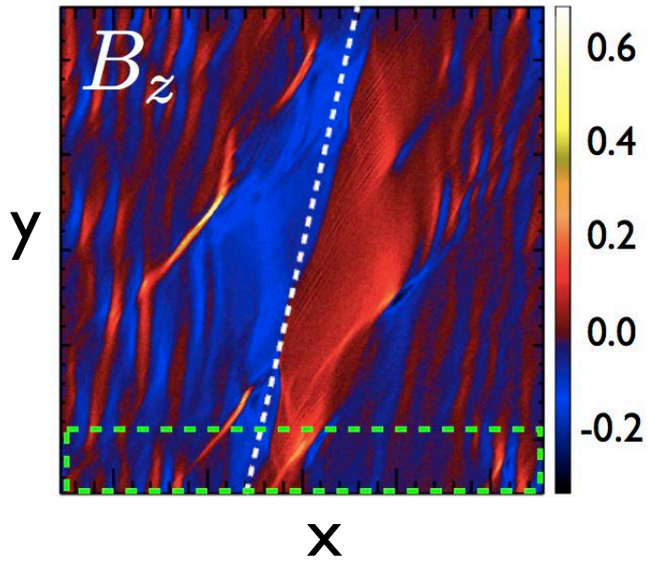


Reconnection electric field i.e., a measure of the reconnection rate



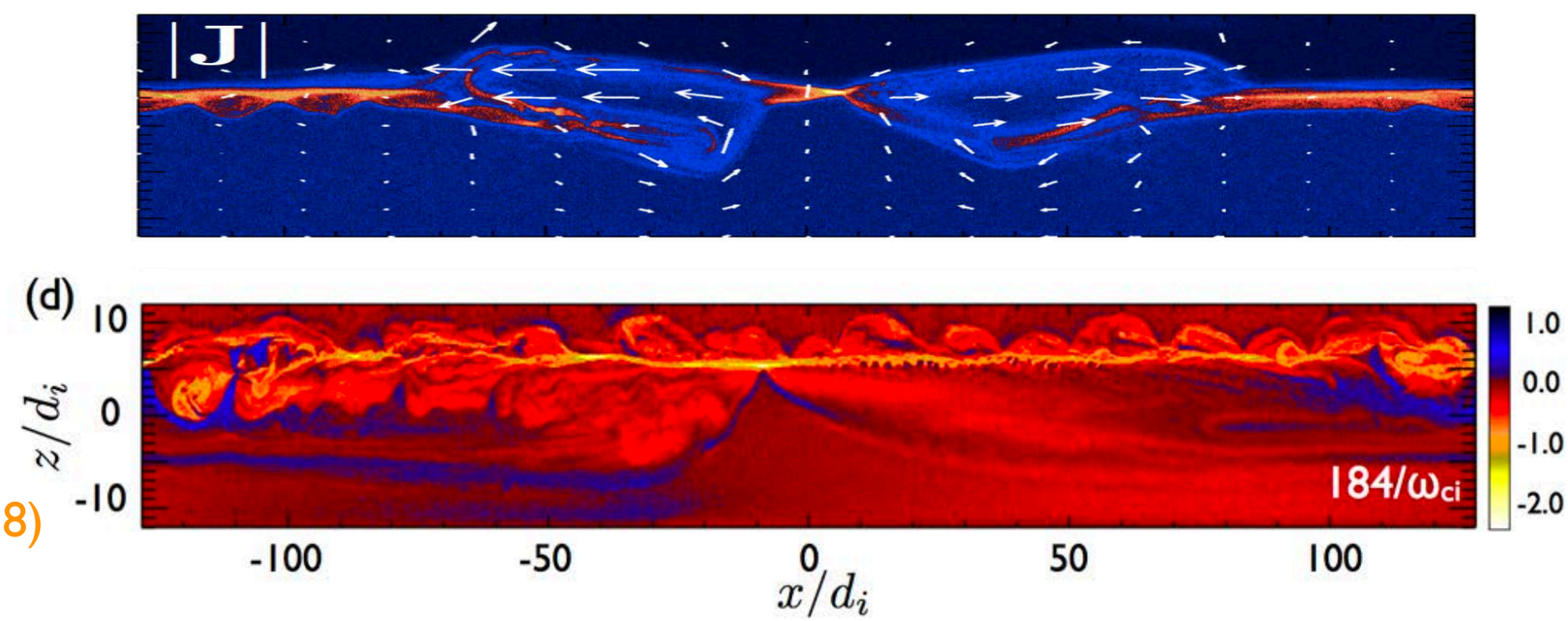
(Liu et al., JGR, 2018)

- 2D simulations suggest that the 3D system selects a state with (or at least near) the maximal reconnection rate!
  —i.e., maximizing the energy release!



Numerical experiment with Quasi-2D boxes -- laminar vs. turbulent x-line!?

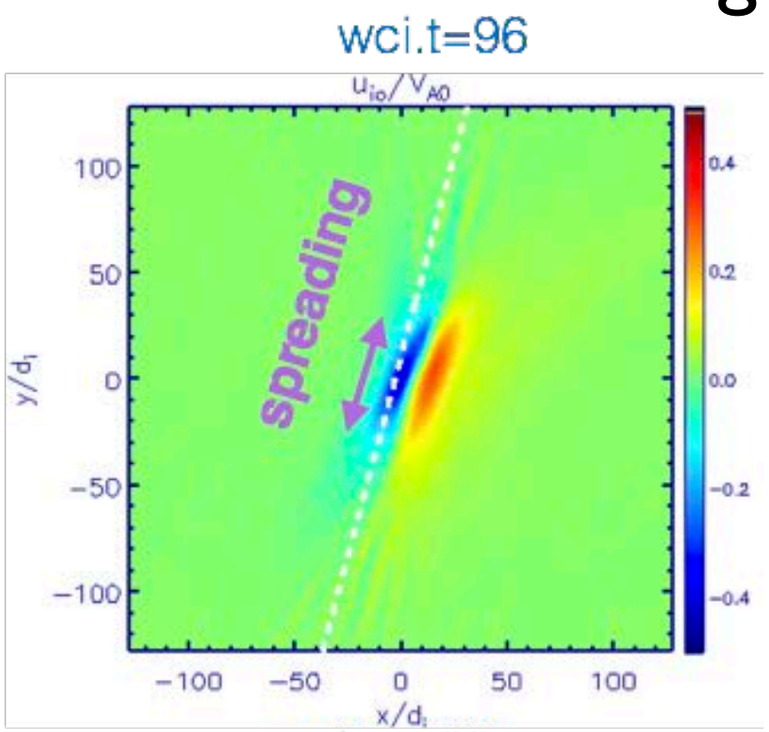
In comparison...

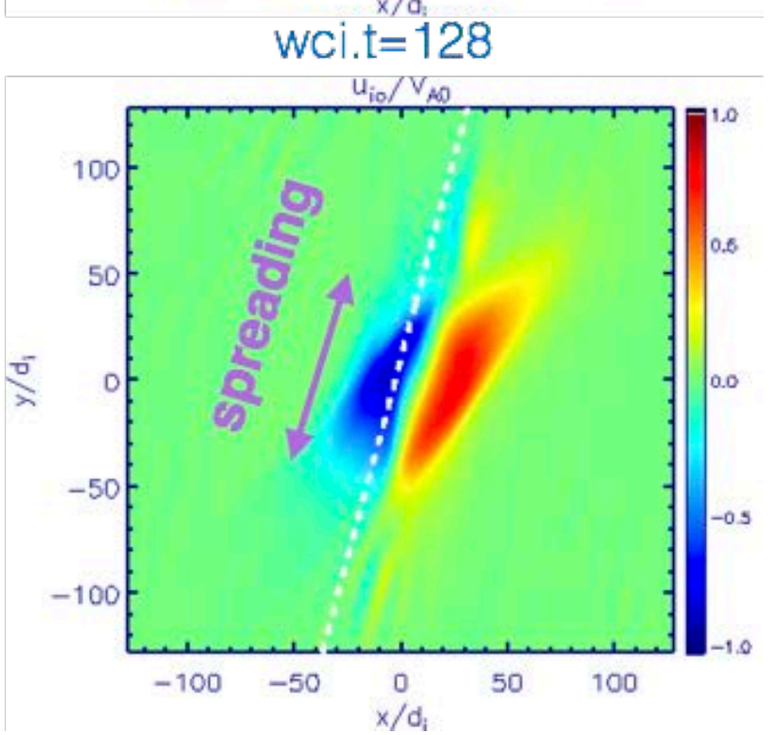


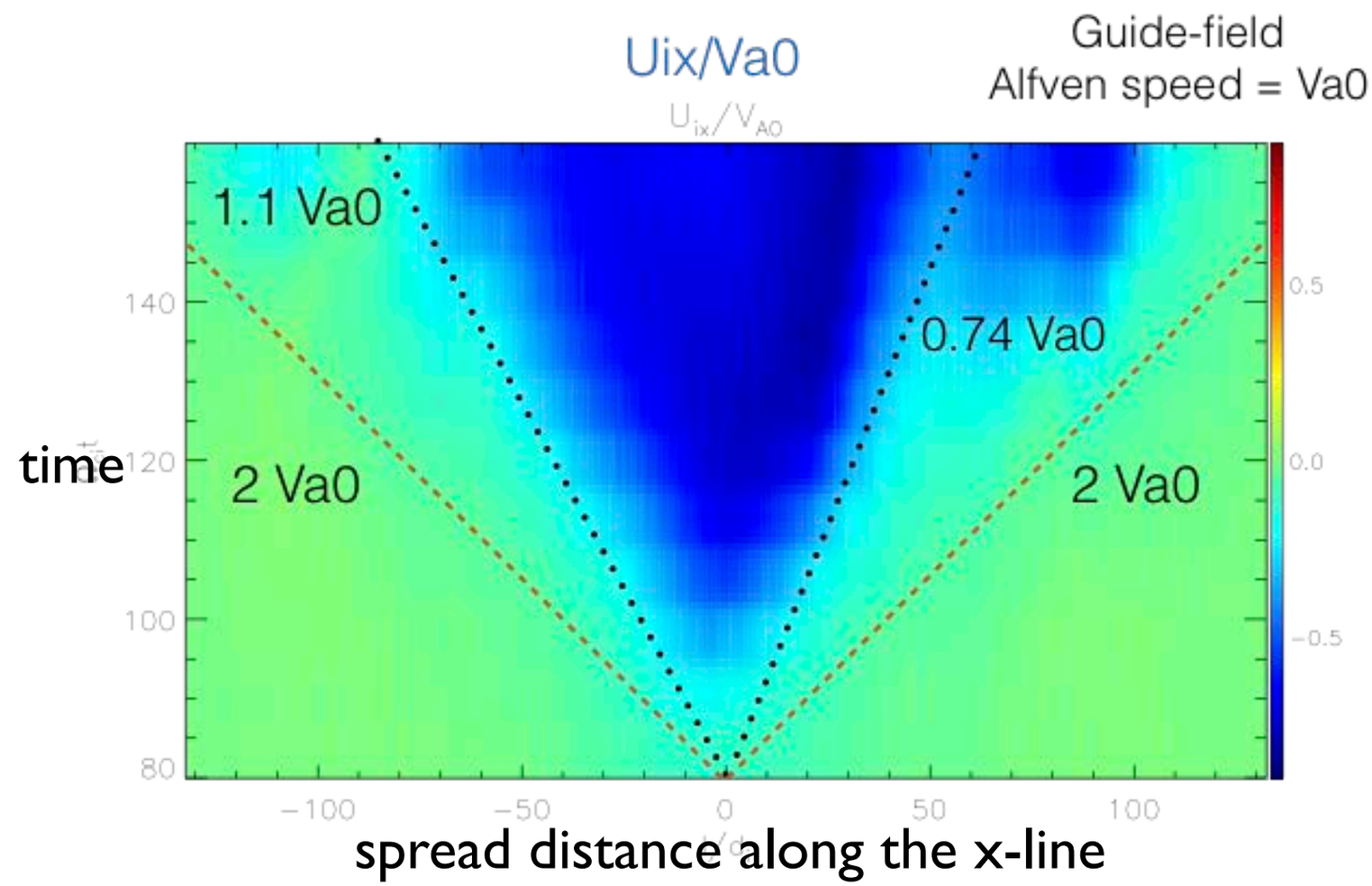
(Liu et al., JGR, 2018)

- Small periodic systems have often over-estimated the turbulence level.

Result II: Spread of reconnection x-line in Earth's magnetopause geometry







Work-in-progress:

What determines the spread speed of the x-line??

— Alfvén speed?

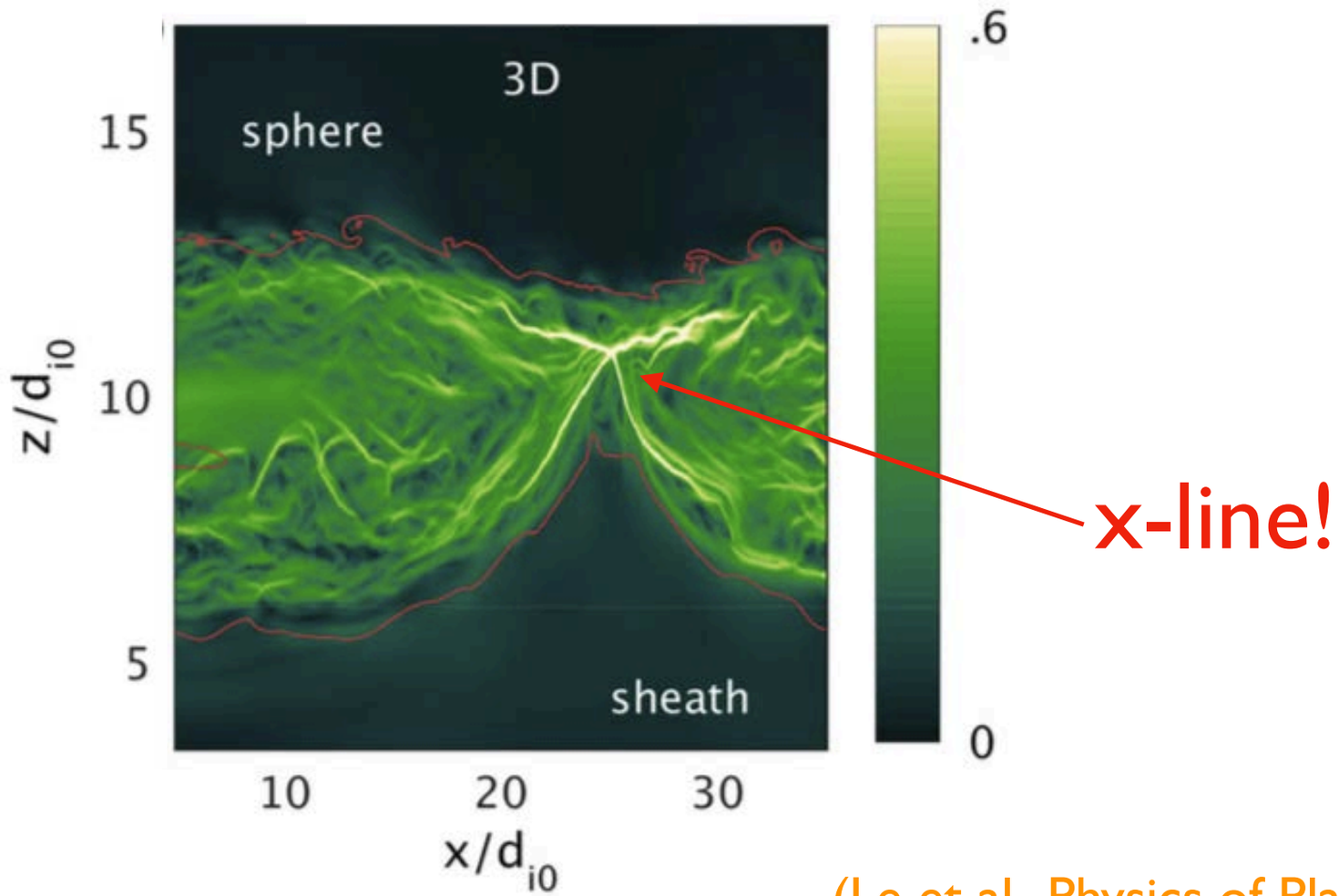
— Current carrier speed?

— Or ... something else?

Result III: Defining the x-line in the turbulent layer

(*parameters chosen to match real MMS events)

Lyapunov exponent of field lines

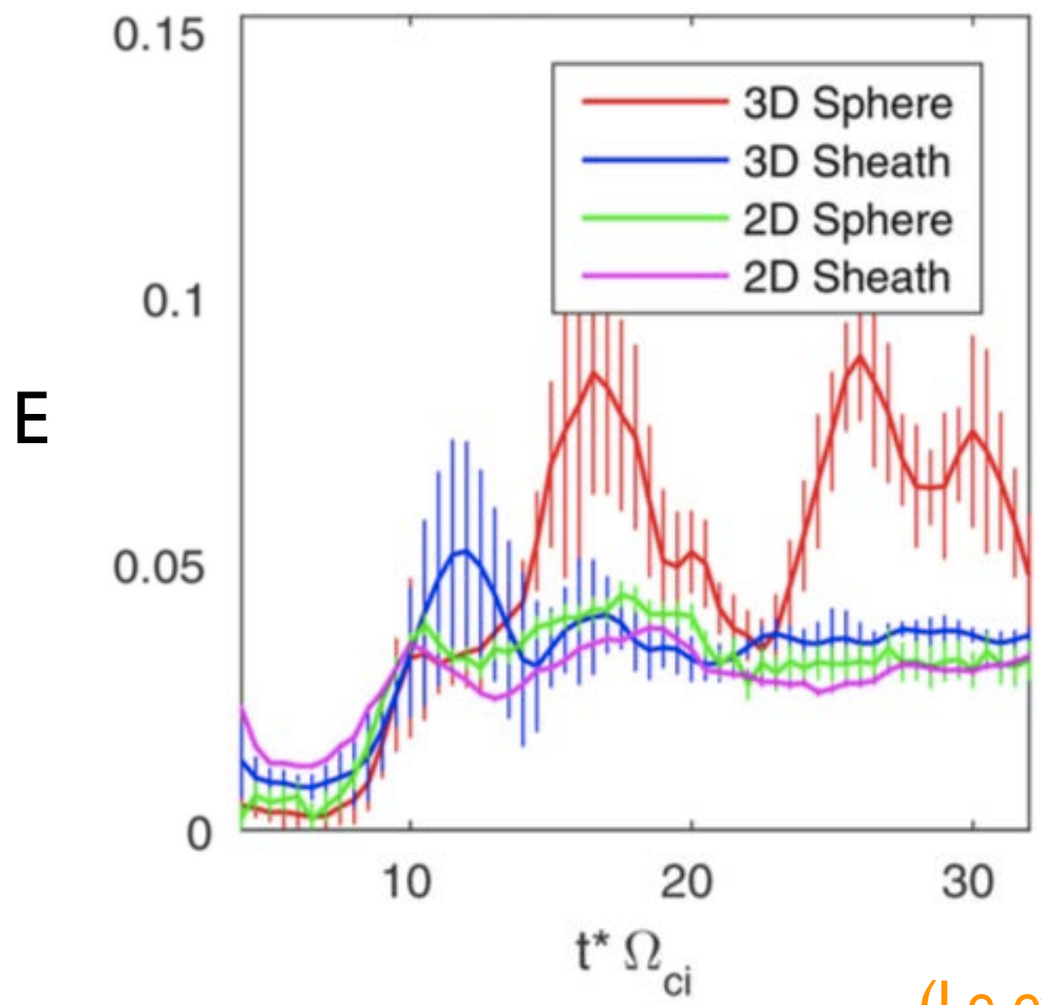


(Le et al., Physics of Plasmas, 2018)

- Turbulence caused by the lower-hybrid drift instability (LHDI).
- Using Lyapunov exponent of field lines (Quasi-separarix layer) to trace the turbulent x-line.

Result IV: Reconnection rate in laminar 2D vs. turbulent 3D x-line

(*parameters chosen to match real MMS events)



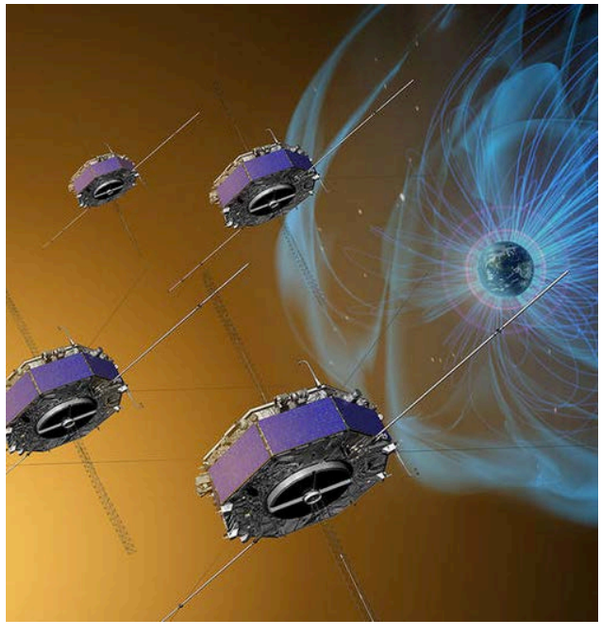
(Le et al., Physics of Plasmas, 2018)

- Surprisingly, 3D turbulence does not affect the global reconnection rate!

(ps: the rate measurement based on the electron mixing on the sphere side does not work because of the cross-field transport by the turbulence)

Broader Impact

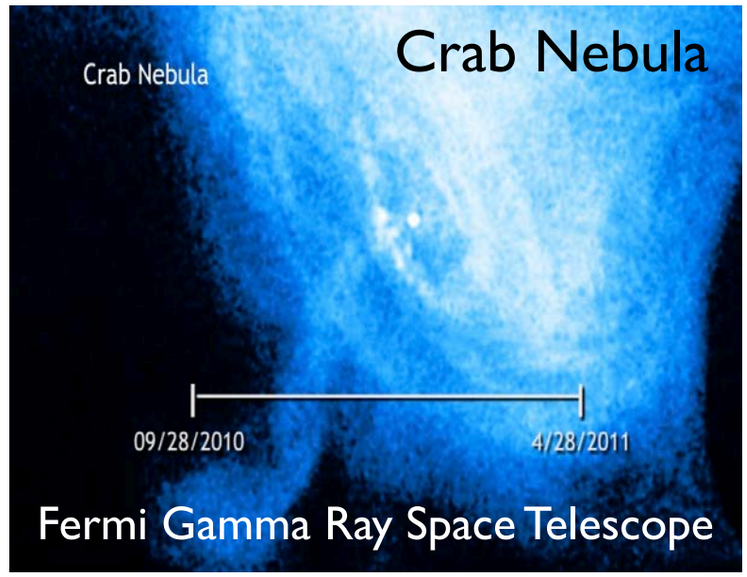
Space Science



Geomagnetic storms, substorms!

Solar flares!

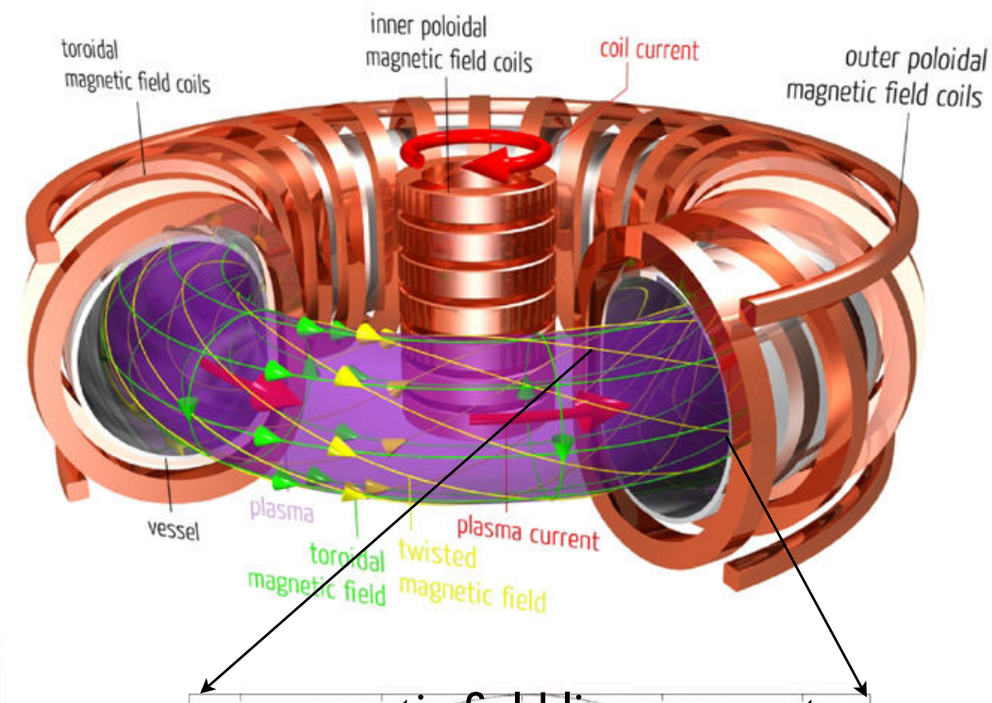
Astrophysics

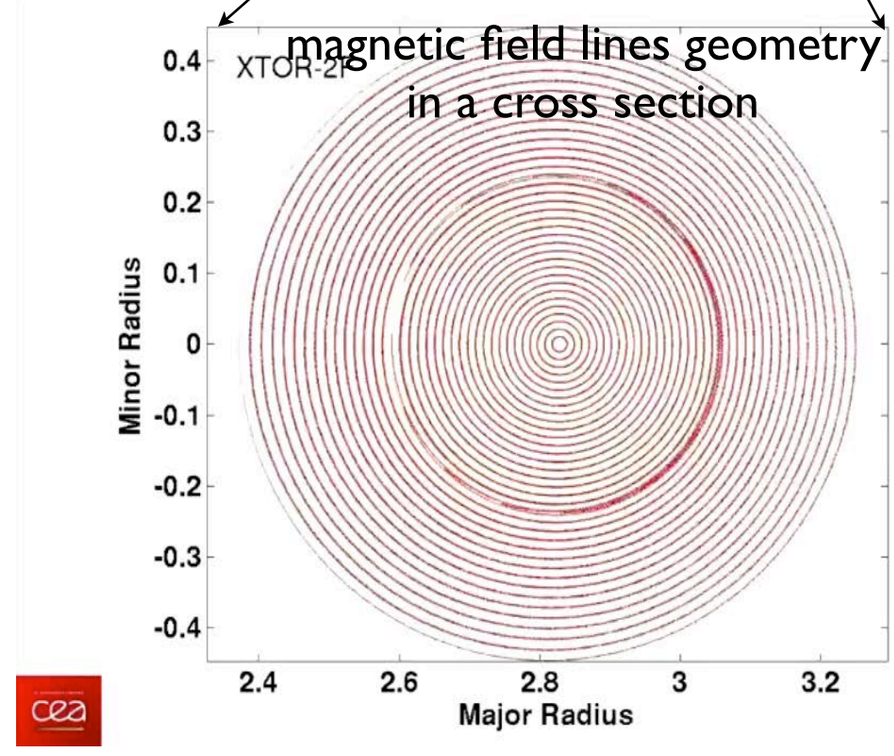


Super flares!

Fusion device

e.g,, ITER Tokamak @ France





Summary

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

— The 3D nature of magnetic reconnection remains unclear!

— Blue Waters provides the opportunity to explore this challenging problem.

Using Blue Waters, we have studied:

— The orientation of 3D x-lines.

*the 3D system tends to maximize the reconnection rate!

— The spread of 3D x-lines.

— The laminar vs. turbulent x-lines.

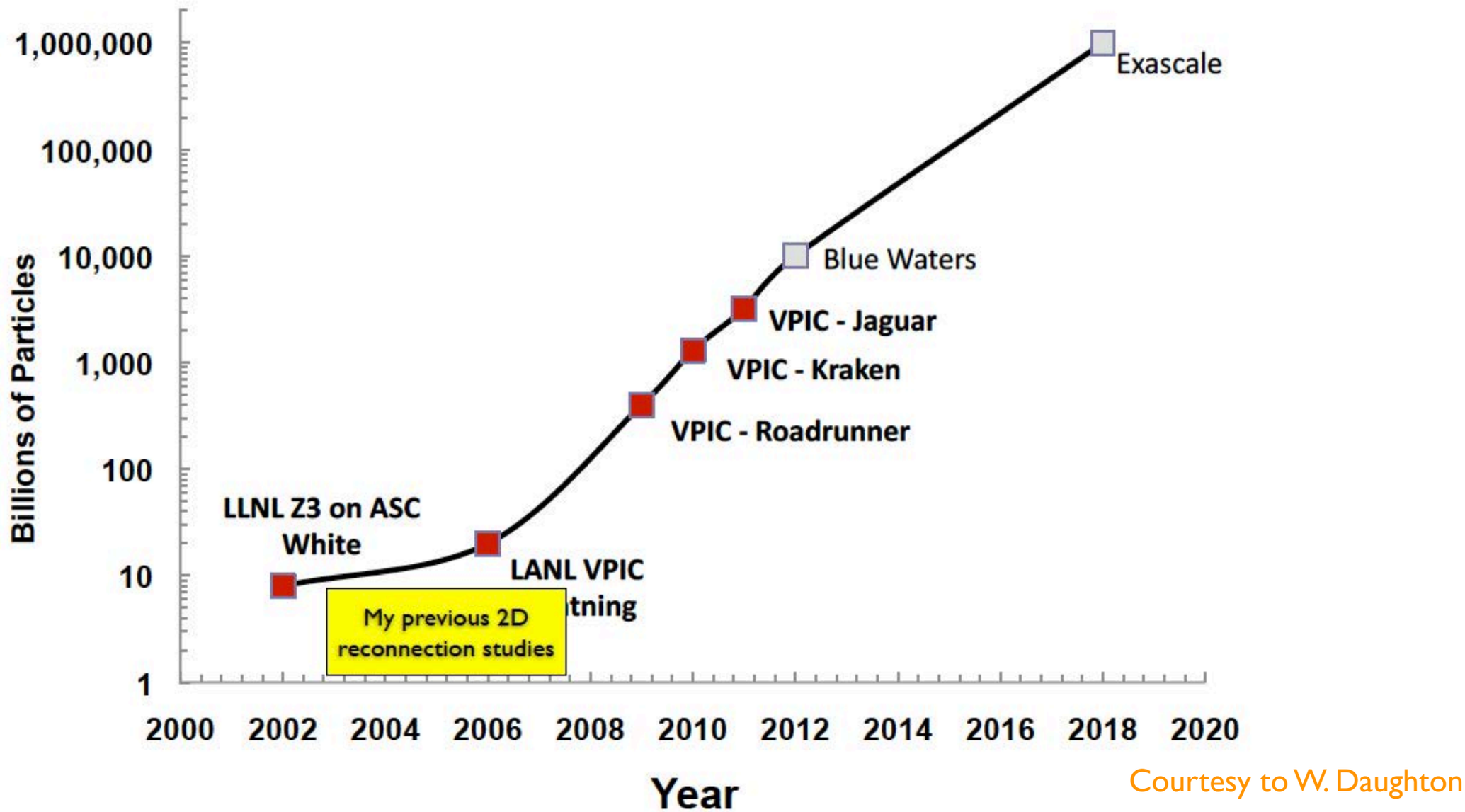
— 3D reconnection rate.

Broader Impact:

— for instance, help interpret the 3D geometry in MMS observations.

- Y.-H. Liu et al., *Orientation and stability of asymmetric magnetic reconnection x-line*, J. Geophysical Research, doi: 10. 1029/2018JA025410 (2018)
- A. Le et al., *Drift turbulence, particle transport, and anomalous dissipation at the reconnecting magnetopause*, Physics Plasmas, 25, 062103, (2018)
- T. C. Li et al., *Spread of asymmetric magnetic reconnection x-line*, work in progress (2018)

Progress of Particle-in-Cell simulations



Courtesy to W. Daughton

- VPIC: ~8 million particle pushes/sec, MPI + OpenMP hybrid architecture.

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

Blue Waters Team Contributions

Special thanks to

Creg Bauer & Michelle Butler & storage group for fixing the error in my file system at Nearline, for accommodating larger Nearline storage.
Ryan Mokos for the help & advices on the data archiving.
JaeHyuk Kwack for the script that simultaneously launches tar comment in multiple cores!
Roberto Sisneros & visualization group for helping setup the 3D visualization using ParaView.