Star burst: a solar flare as seen by NASA's Solar Dynamics Observatory. (Courtesy: NASA/SDO)

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Jet Propulsion Laboratory, California Institute of Tech

Magnetic Reconnection

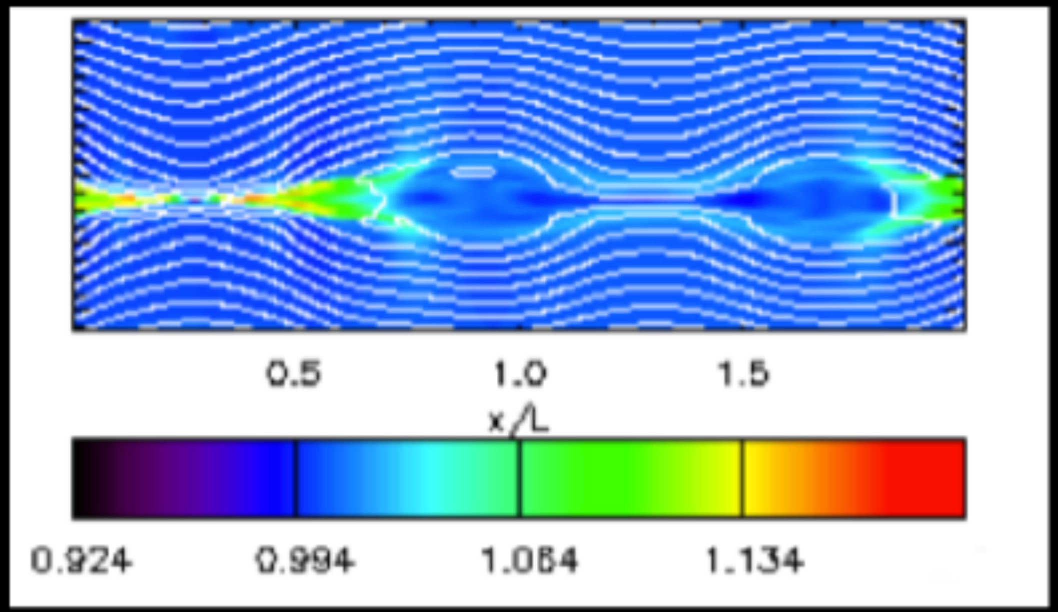
2021 Introduction to Fusion Energy and Plasma Physics Course

17th June 2021

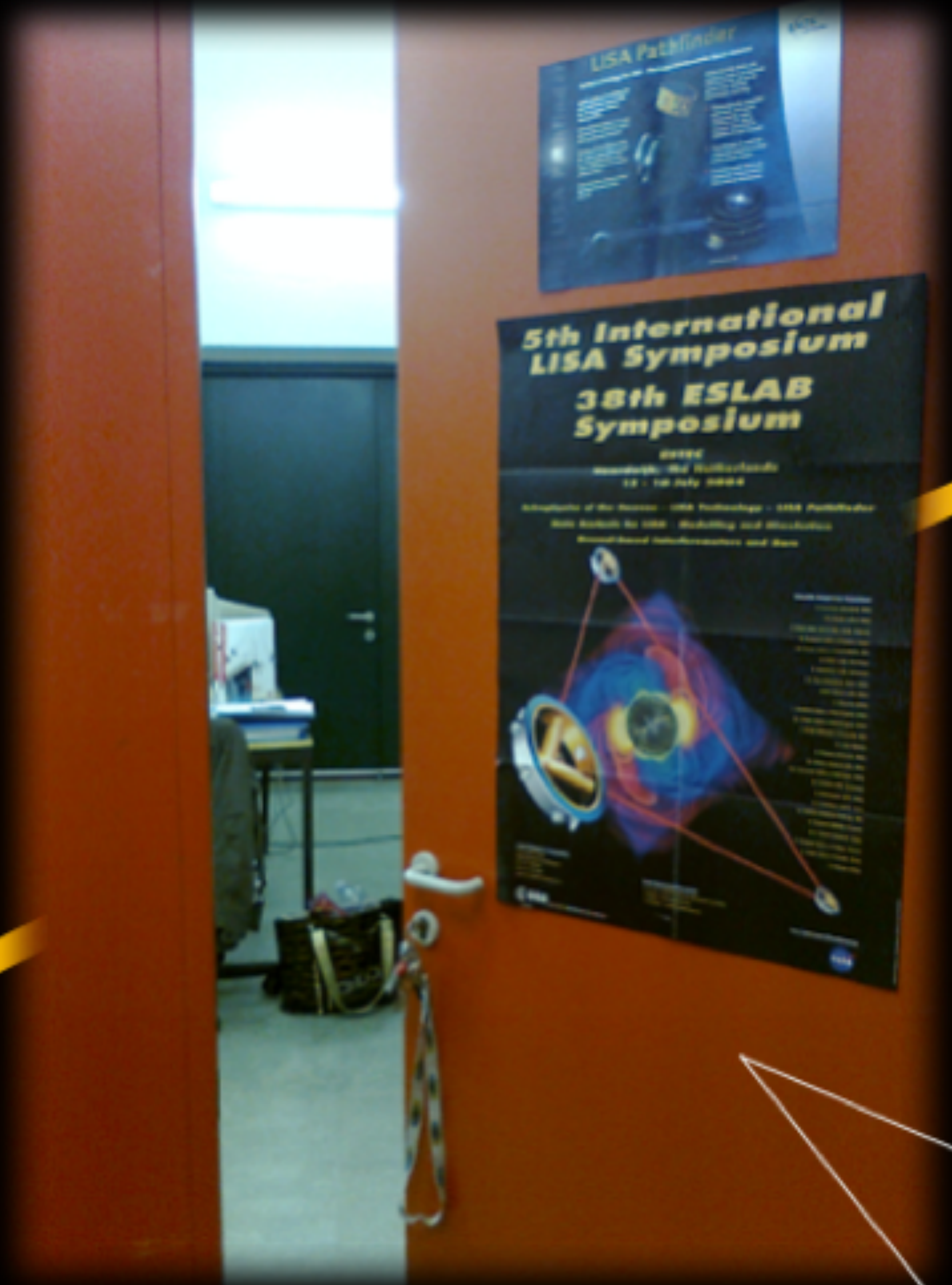
Outline

- Introduction: who is the speaker?
- What is magnetic reconnection?
- Where does magnetic reconnection occur?
- Why do we care about magnetic reconnection?
- Does reconnection actually occur? Observations and *in situ* measuraments
- Modeling magnetic reconnection
- Exciting questions about reconnection **YOU** might solve in the future!
- Some references and contacts.

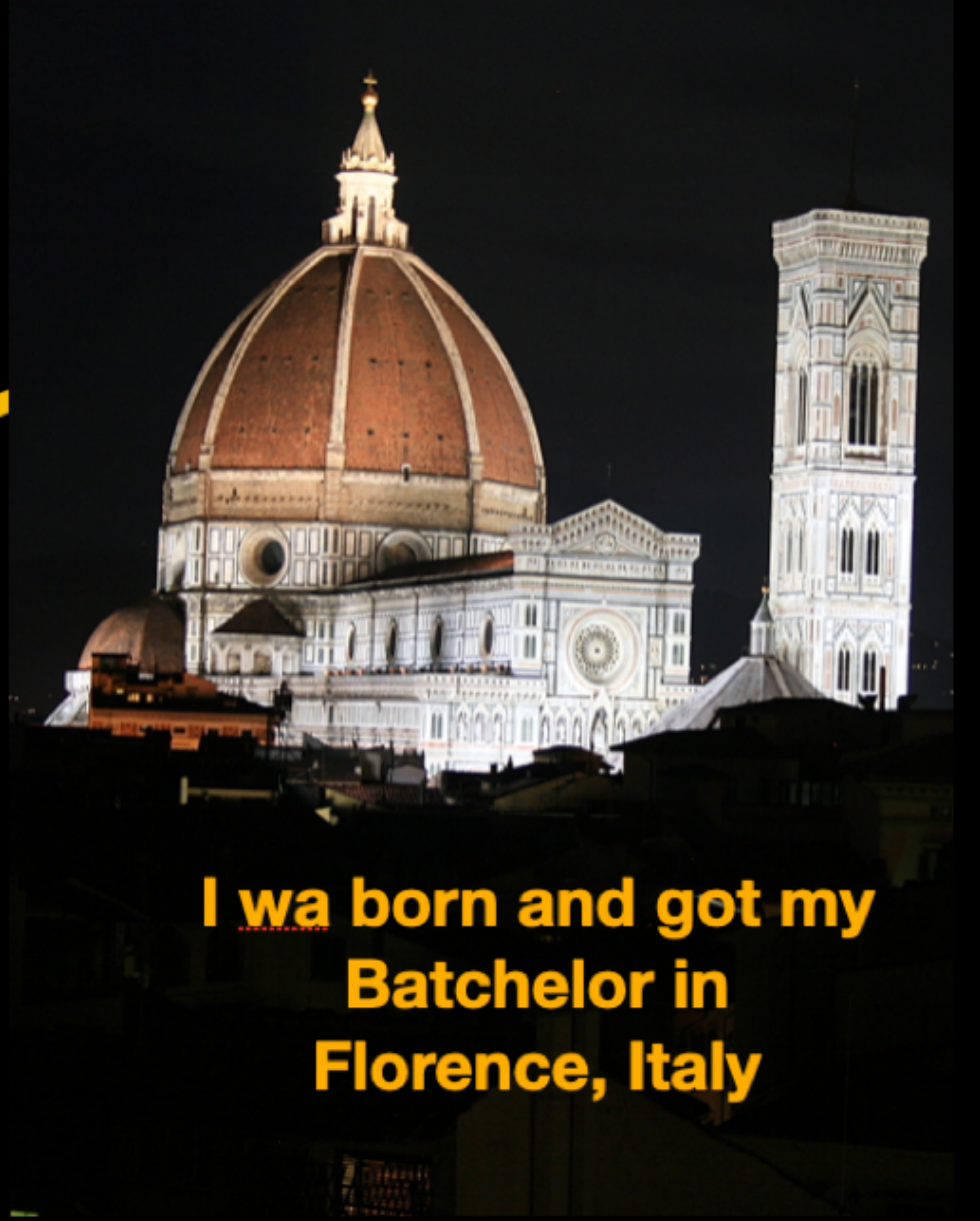
Master 2013 in
Magnetic
Reconnection
Prof. Velli



Batchelor 2011
Lisa Pathfinder



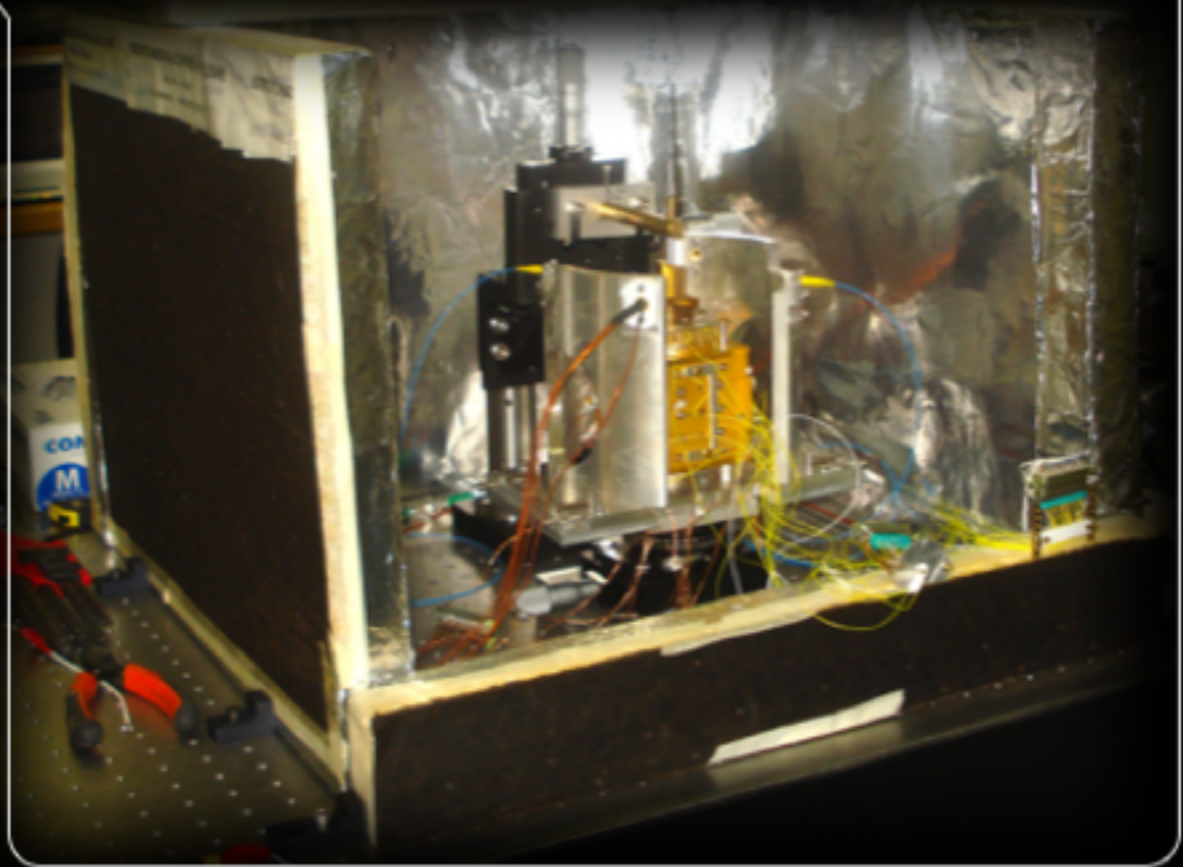
Passion for astrophysics



I wa born and got my
Batchelor in
Florence, Italy

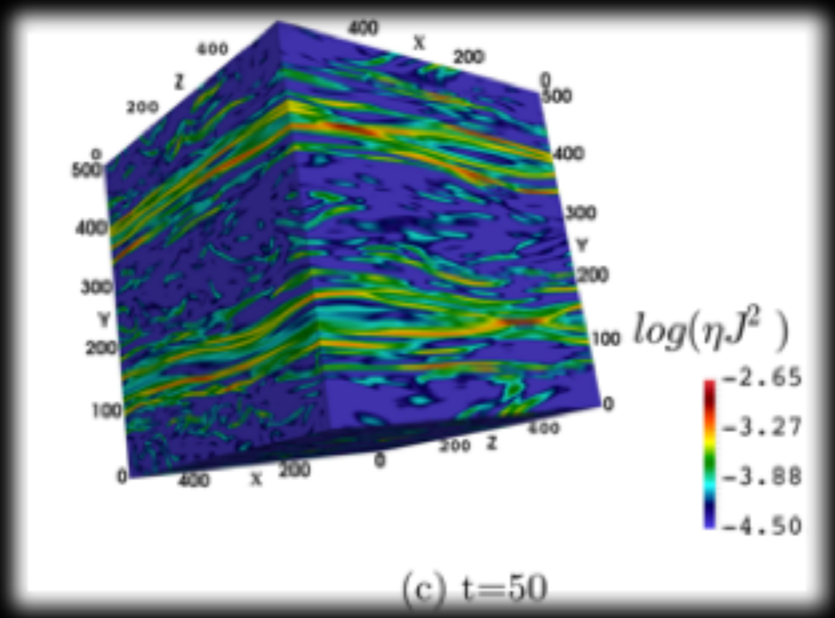
Pr. Tenerani, UT
Austin, TX
Pr. Del Sarto, Nancy
France

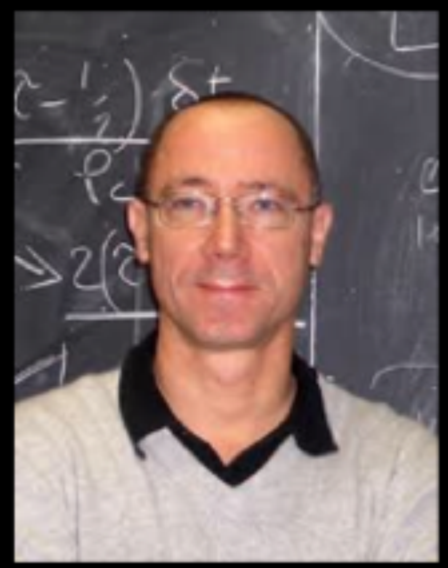
Internship
JPL Pasadena, CA 2013



Capacitive sensor
For LISA Pathfinder
For gravitational wave
detection

PHD Rome 2016

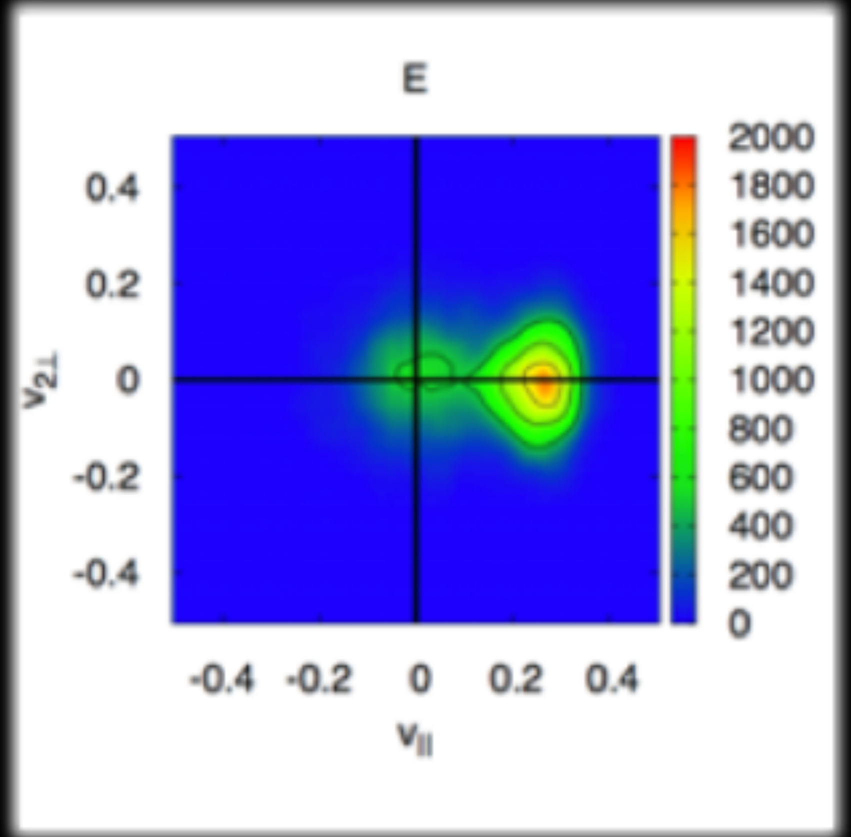


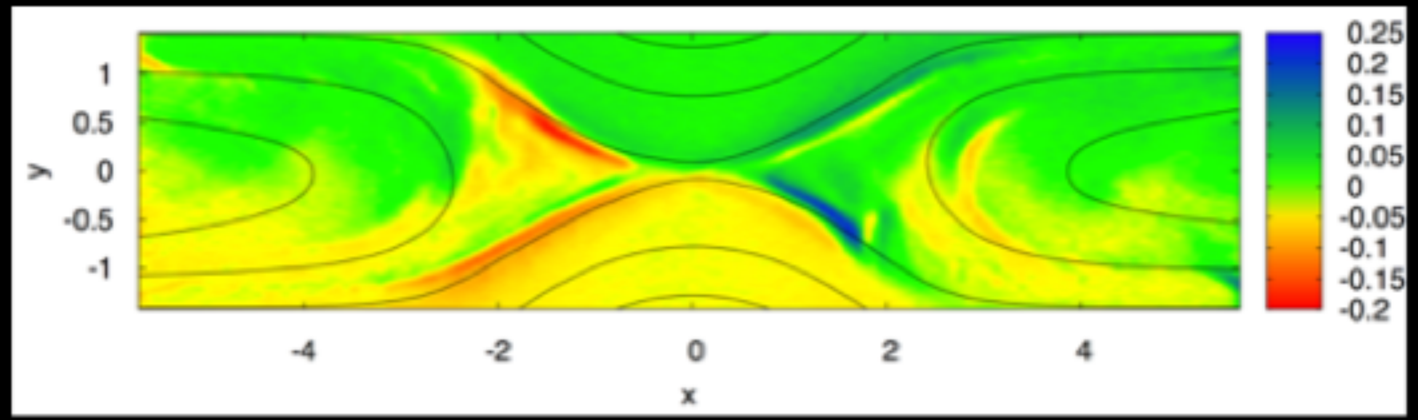


Turbulence, Prof. Biferale
MHD code Complete, ERC

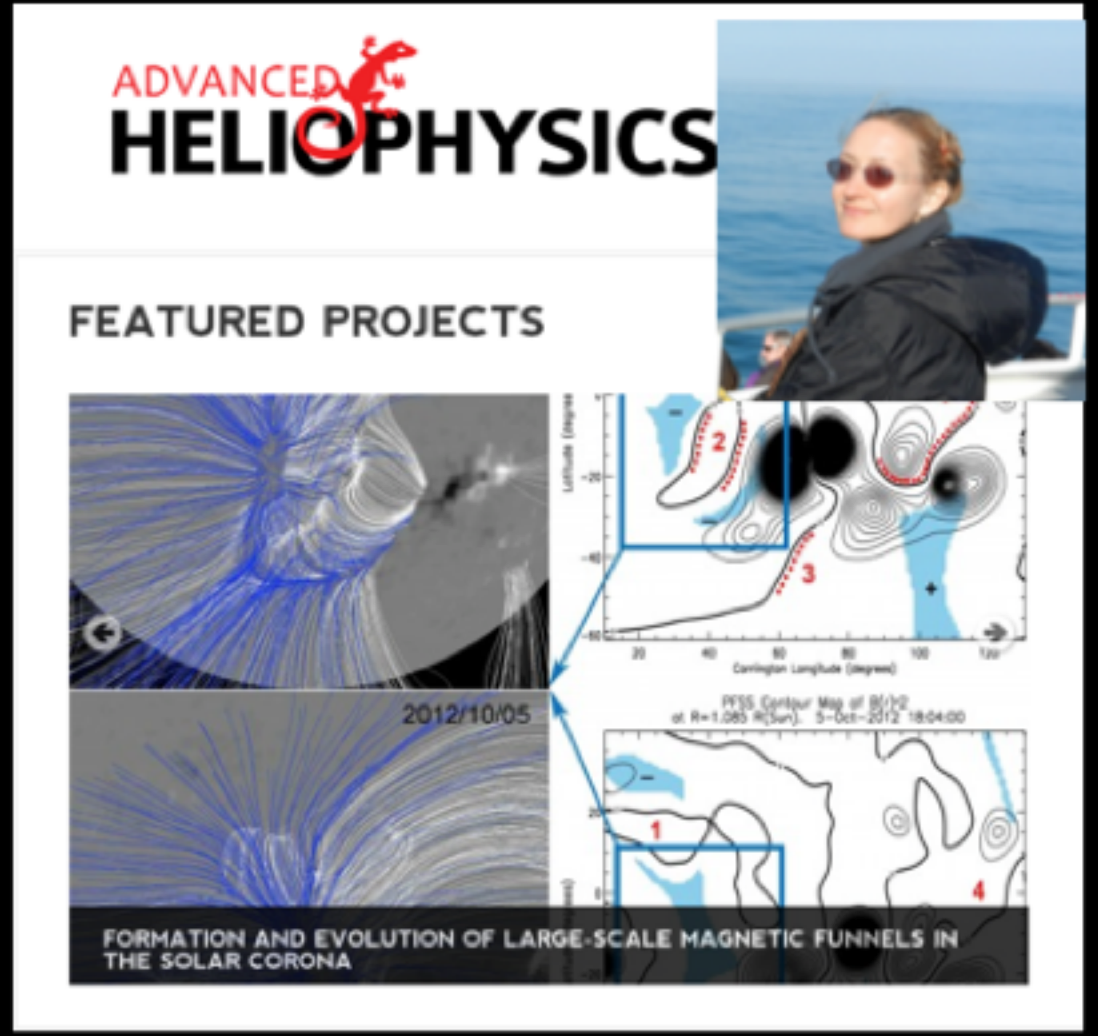
PIC Sim for Magnetic Reconnection

PASMO CODE: Prof. S. Usami, Prof. Horiuchi, Dr. Okamura

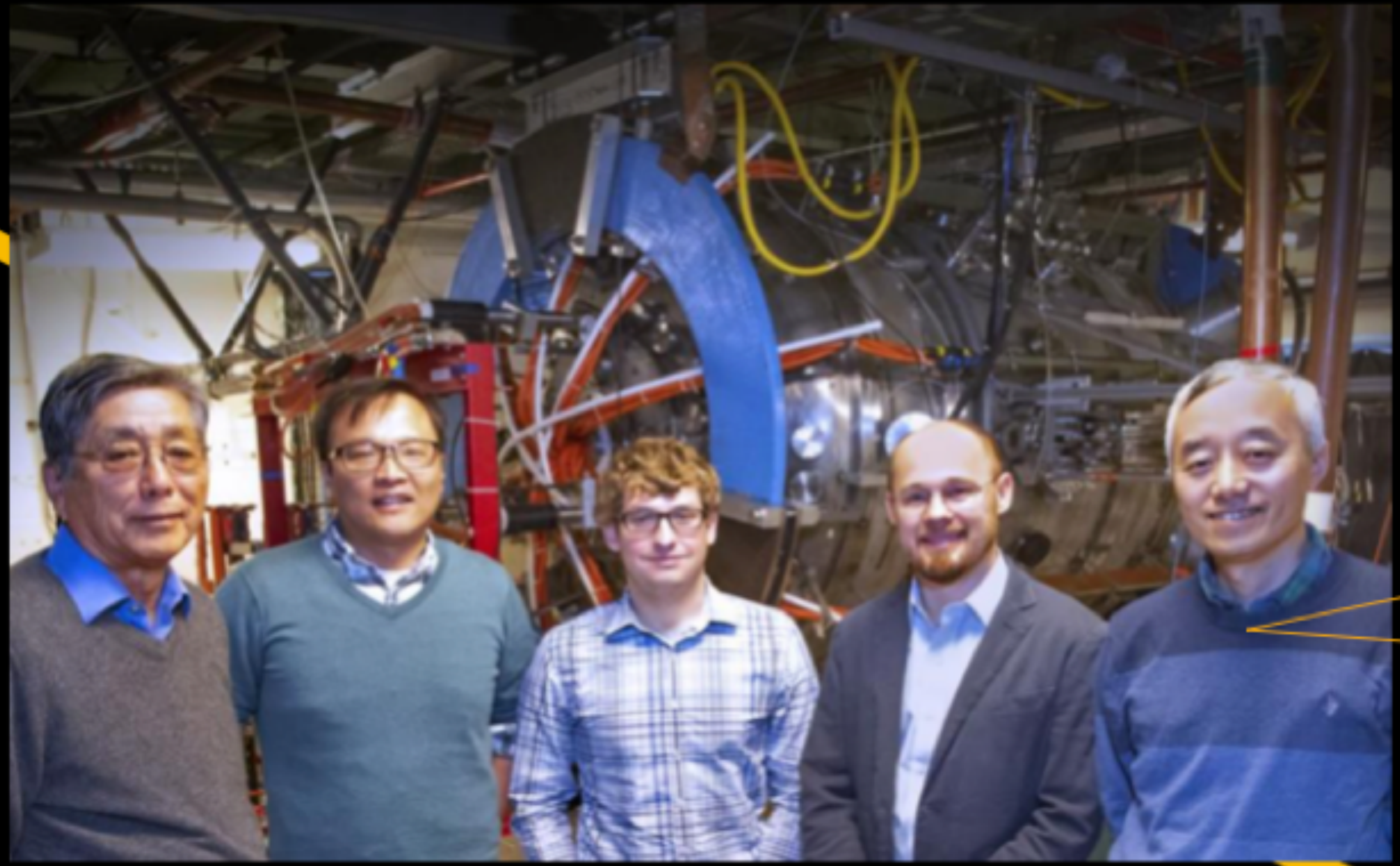




NIFS and NINS



Flare forecasting
Dr. Olga Panasenco

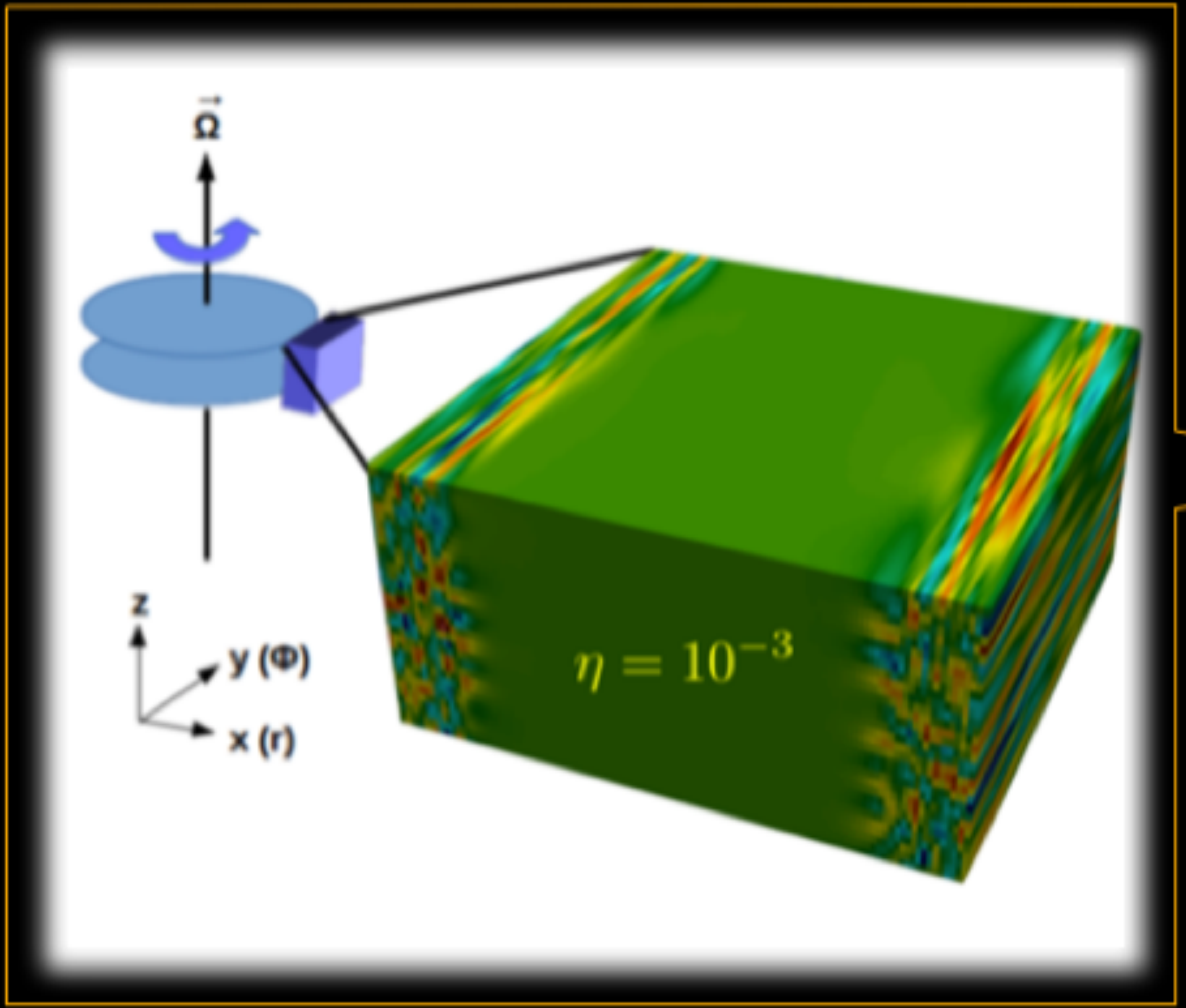


MRX: Prof. Yamada, Dr. Yoo, Dr. Jara-Almonte, Dr. Fox, Prof. H. Ji

Postdoctoral Fellow In NIFS-Princeton Collaboration

August 2018 PSP Launch, Cape Canaveral

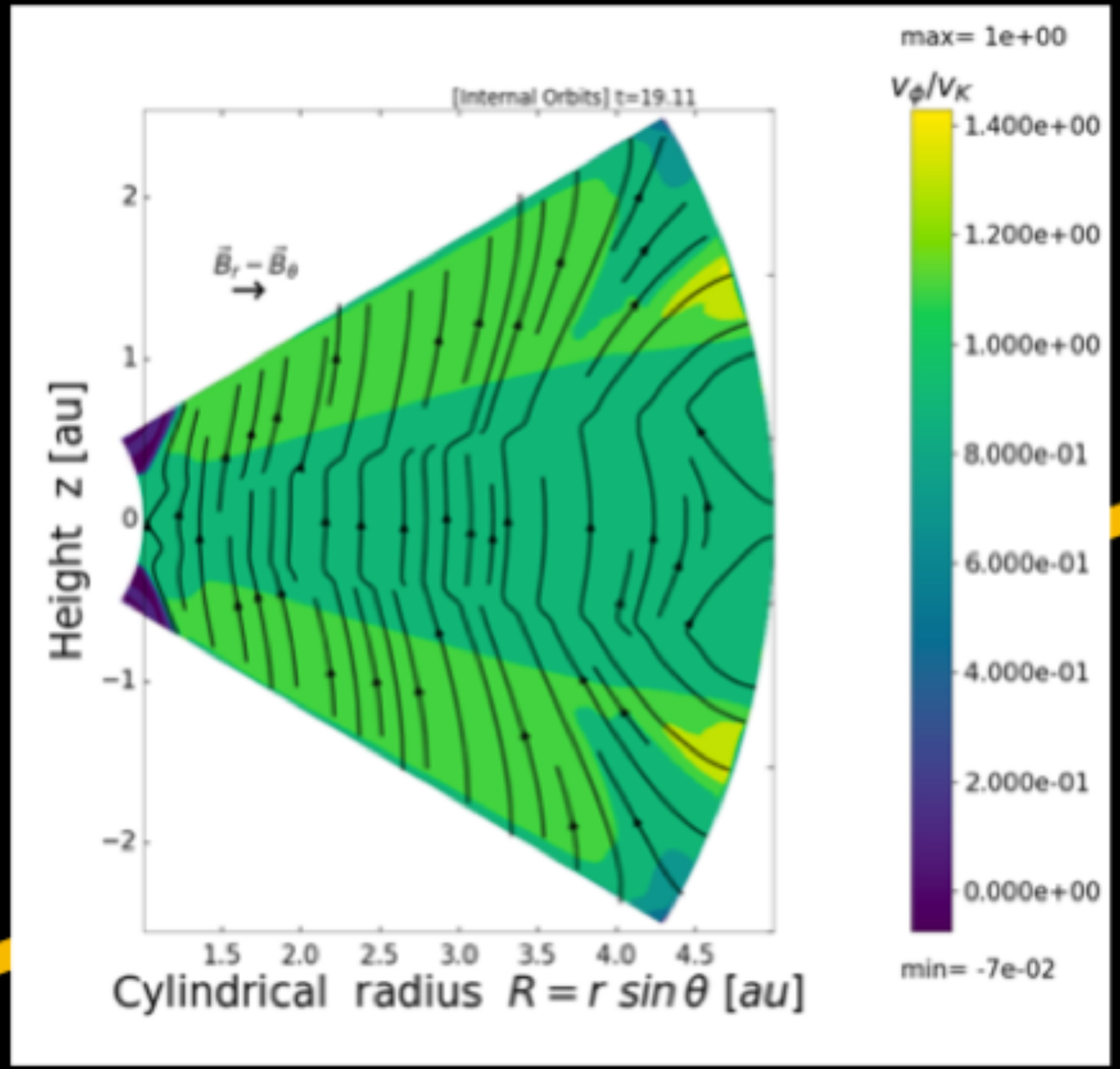
Protoplanetary disks MRI in MHD



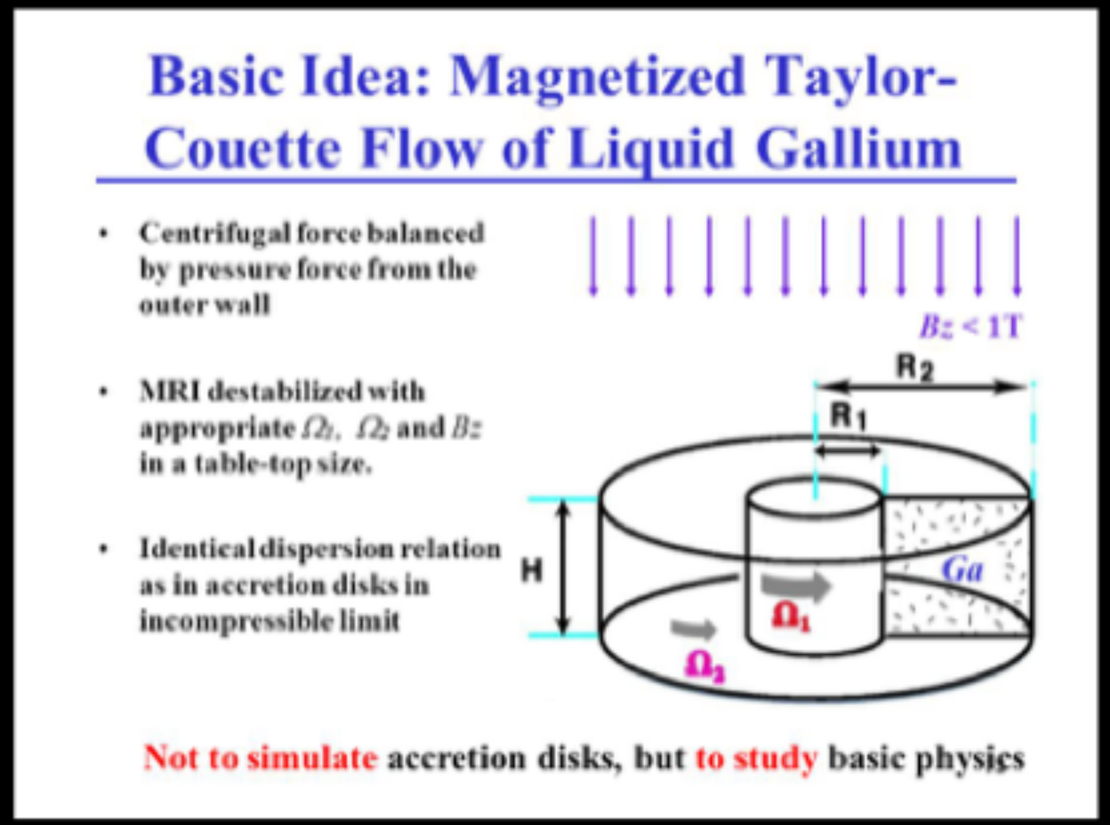
IRCC Fellow in NAOJ Japan, Princeton-MP: Dr.-Takasao (Osaka U), Prof. Tomida (Tohoku U), Prof. Stone (Princeton U), Prof. Yenko (Max Plank)

Dr. Gorti, Dr. Turner JPL

TODAY: MHD global simulations with A++

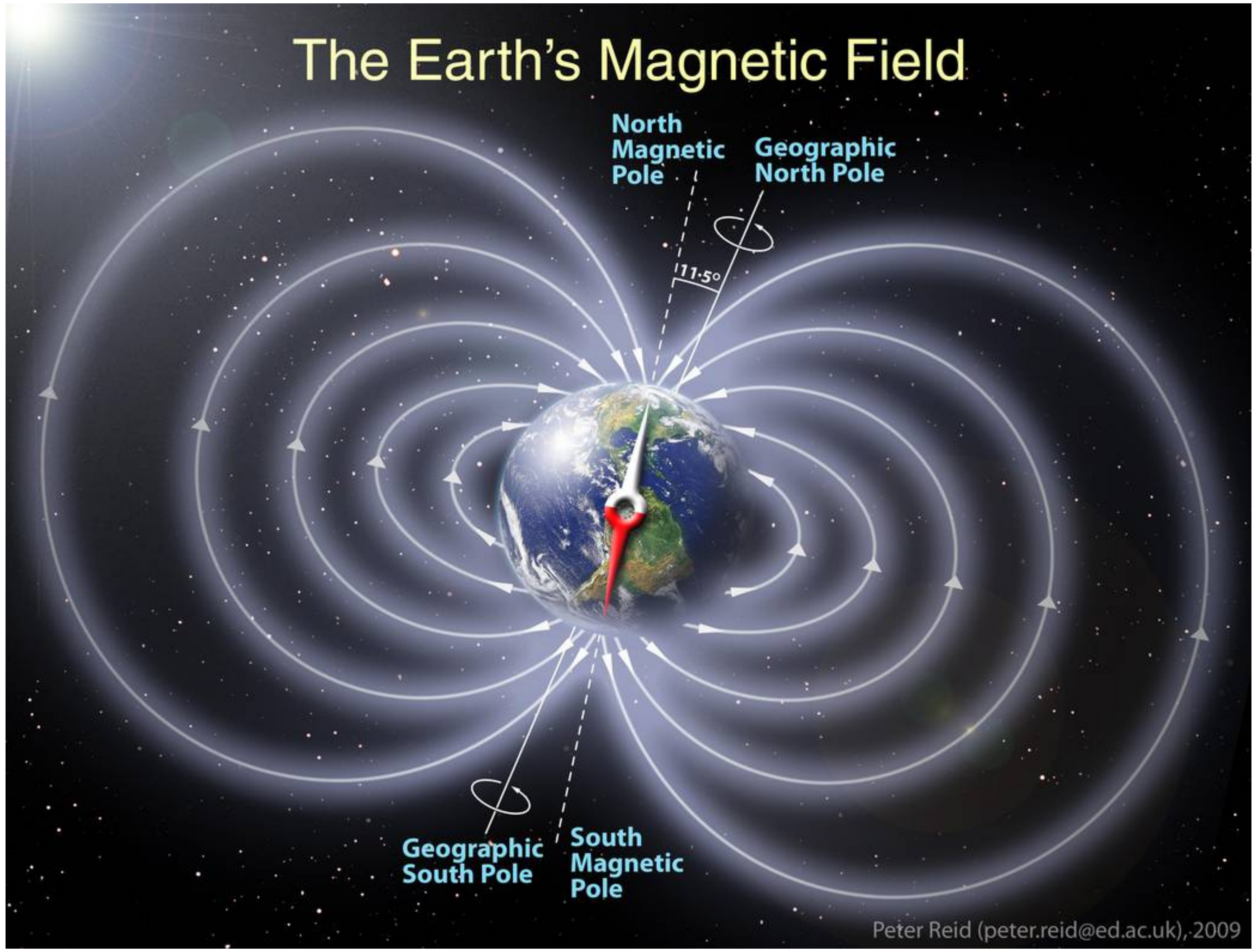


MRI Experiment PPPL Prof. H. Ji



What is magnetic reconnection?

Magnetic: it involves the (electro)magnetic field.



$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

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

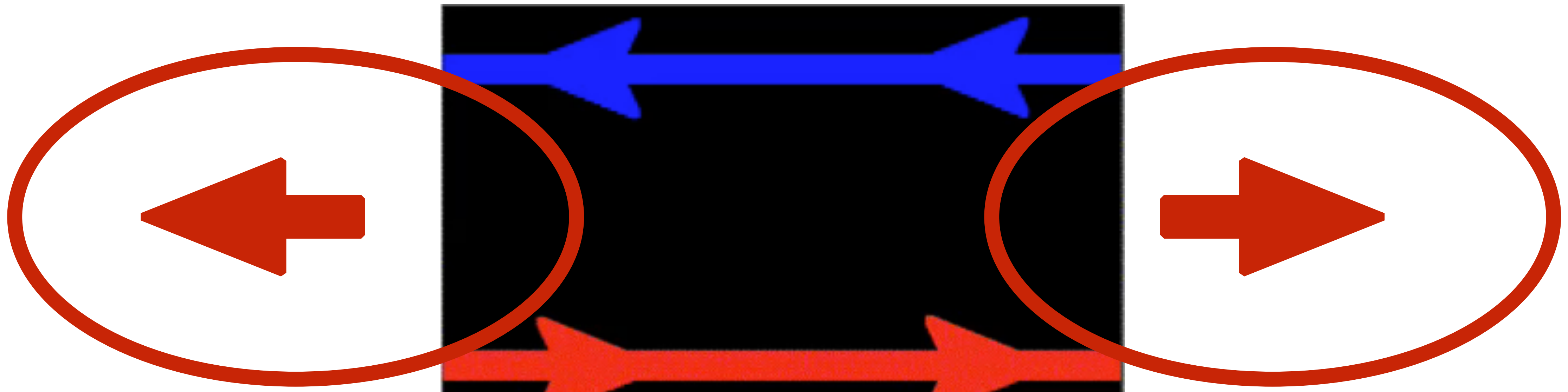
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

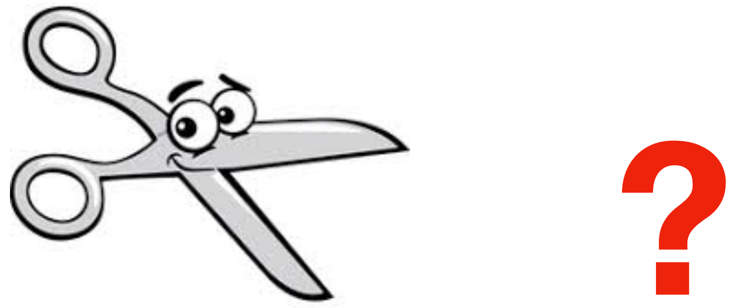
Reconnect: something gets disconnected and connects again.

Why are we interested in magnetic reconnection?

Current sheet forms in connection with the field topology change!

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$



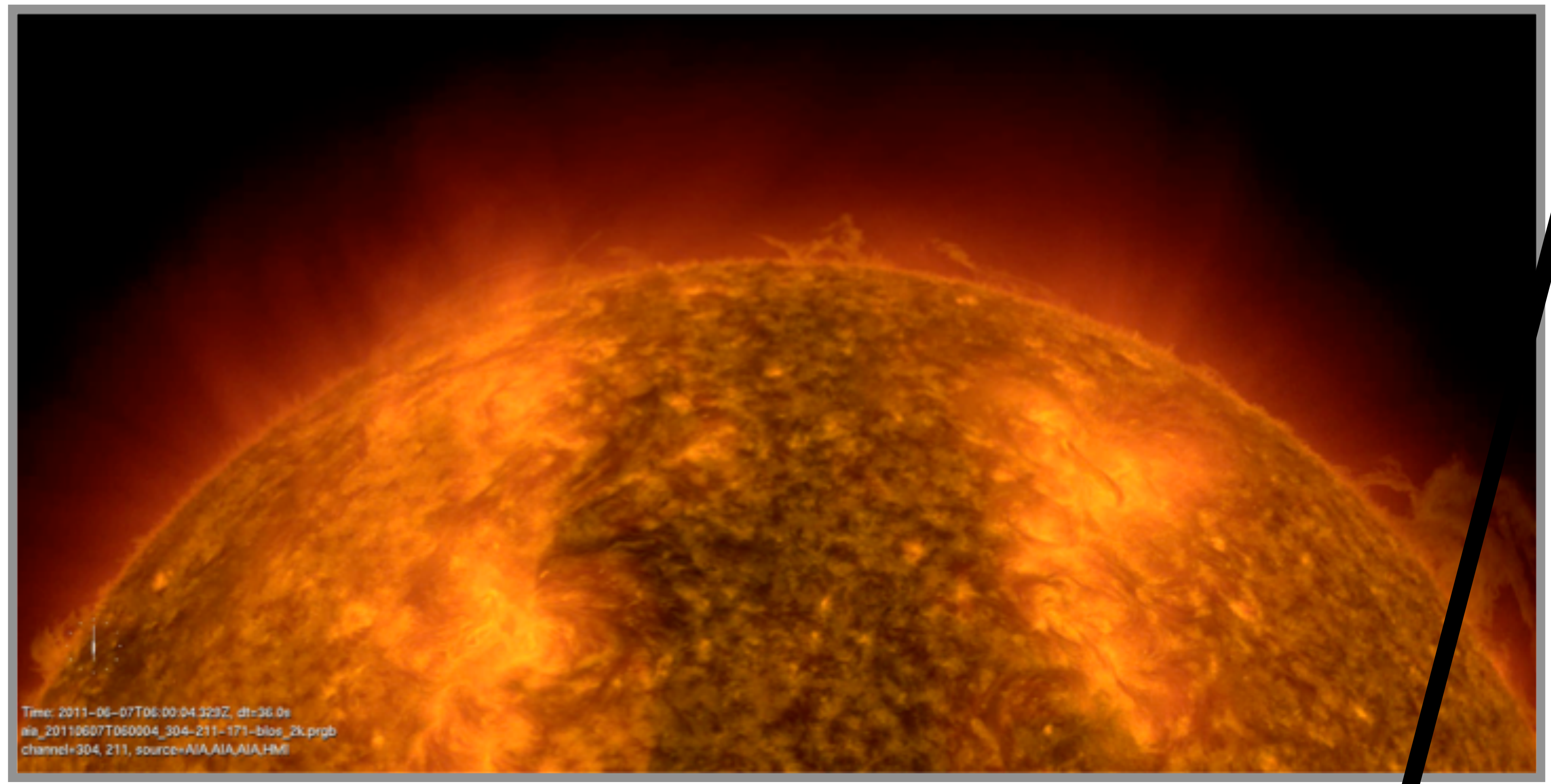


Before reconnection: Energy stored in the magnetic field

After reconnection: energy is converted to particle acceleration and then heating

Magnetic reconnection on the SUN

- Flares and CMEs: sudden energy release
- Driven/Spontaneous process (reconnection?)
- Dynamics of flare loop: magnetic field canceling and emergence.
- Nano-flare and coronal heating problem
- Solar Wind launching and acceleration.



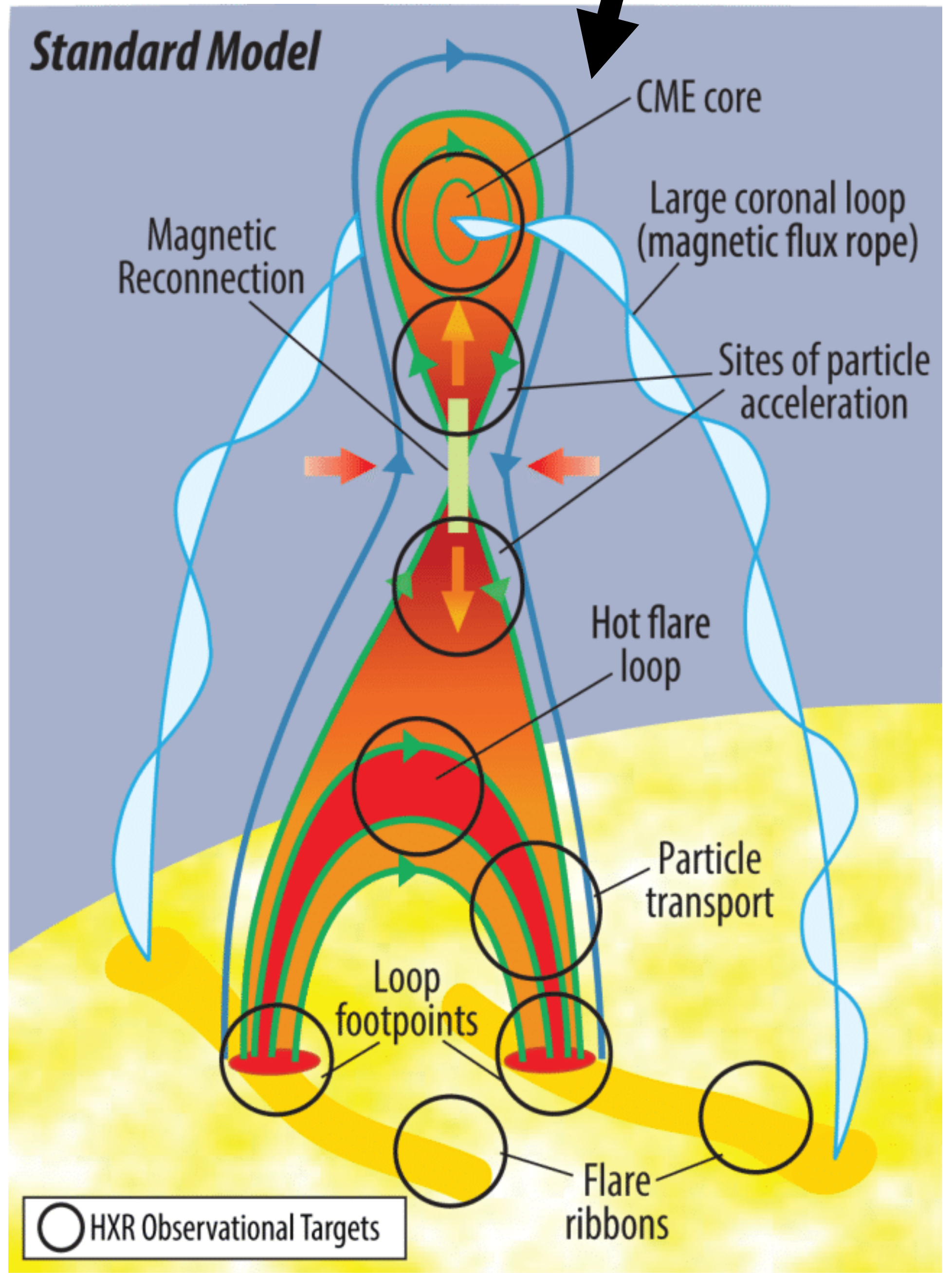
$$E \simeq 10^{32}\mathrm{erg}$$

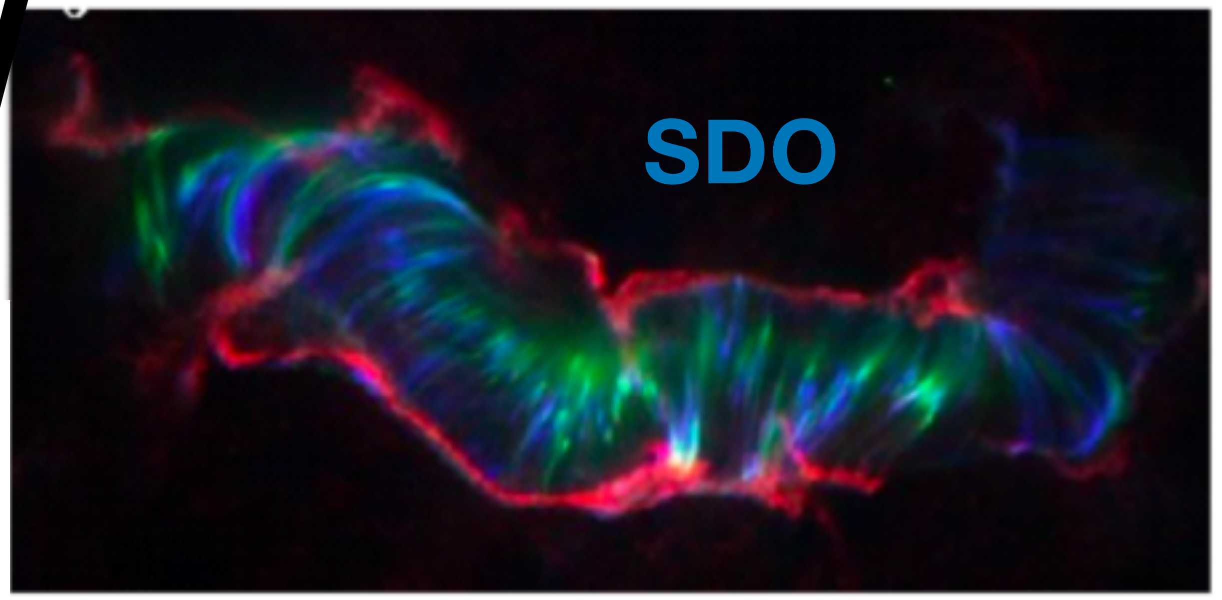
$$\mathcal{L} \sim 10^{9} - 10^{10}\ \mathrm{cm}$$

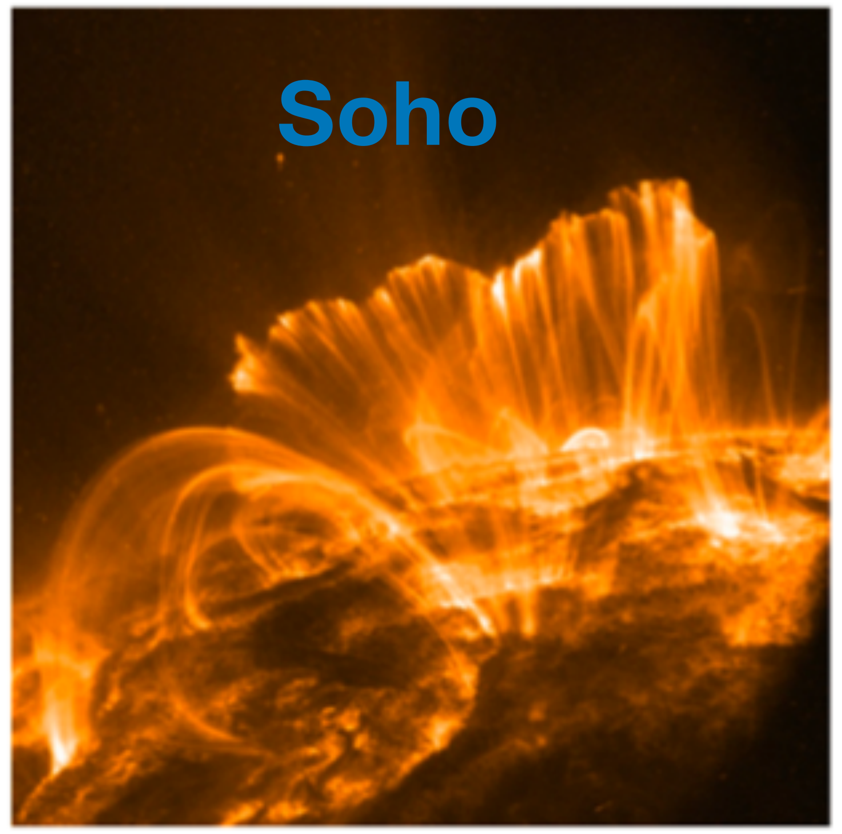
$$\tau \leq 1600s$$

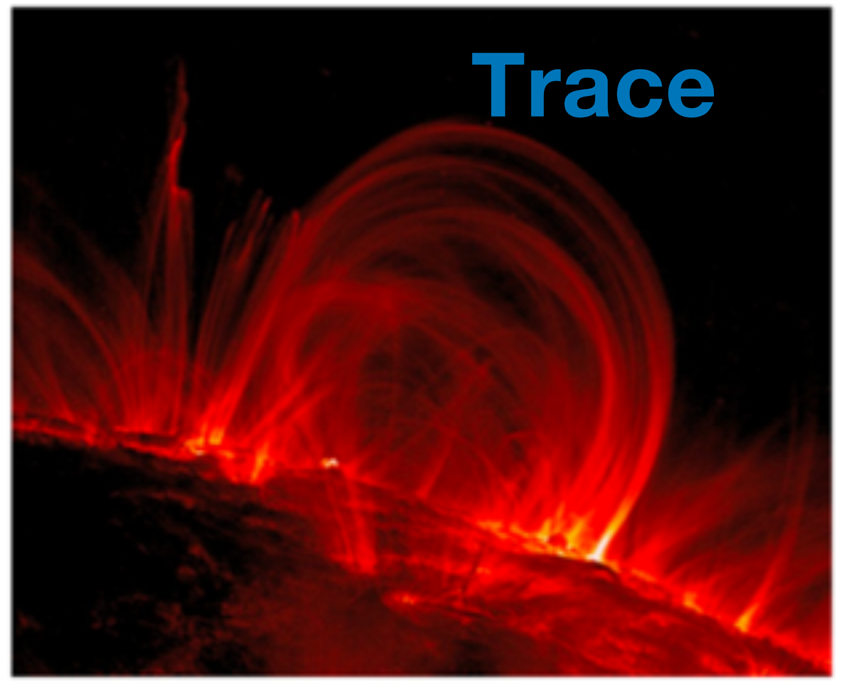
K. Shibata et al. 1995
K. Shibata, A. F. Tanuma, 2001

Plasmoid

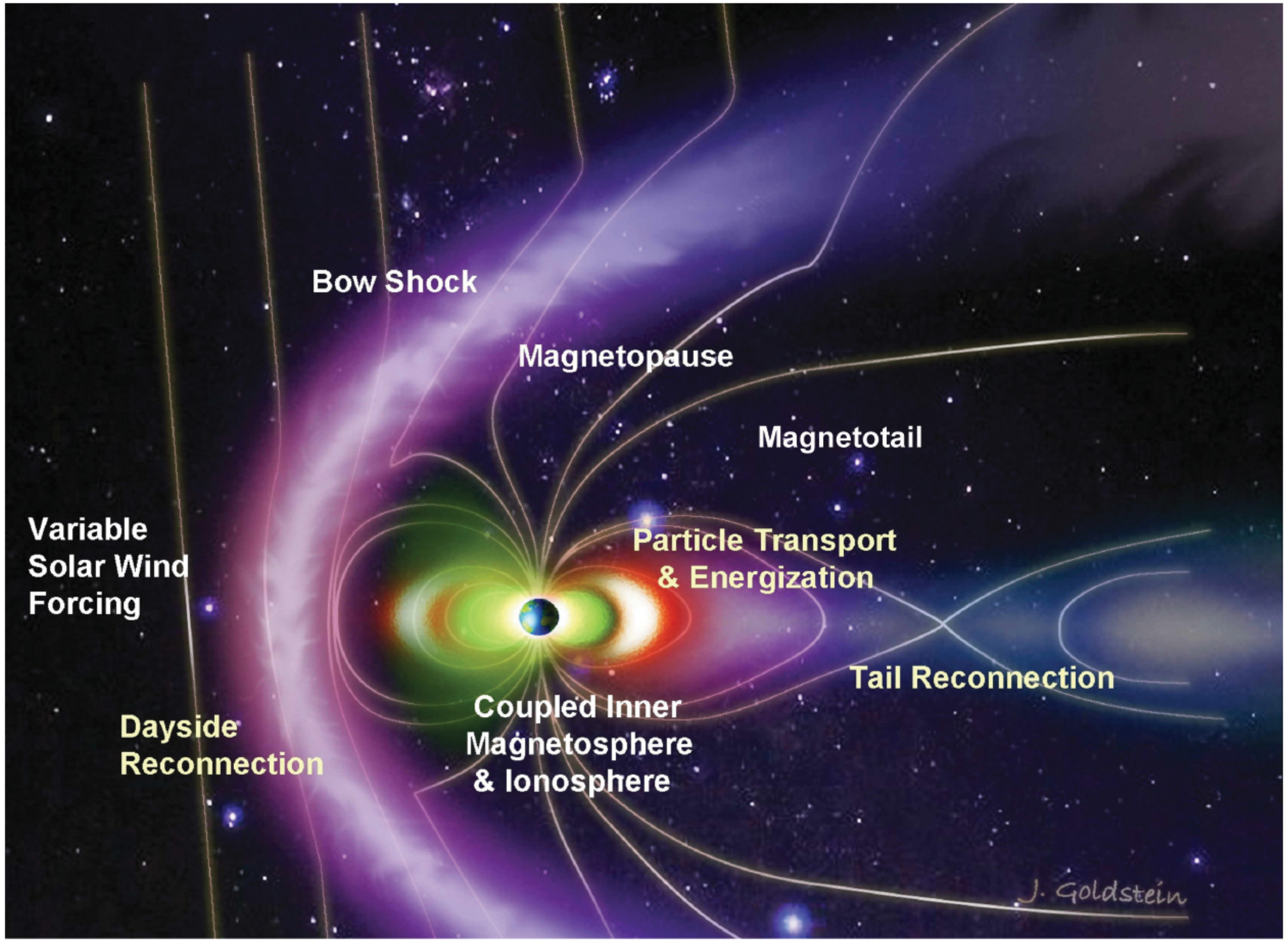






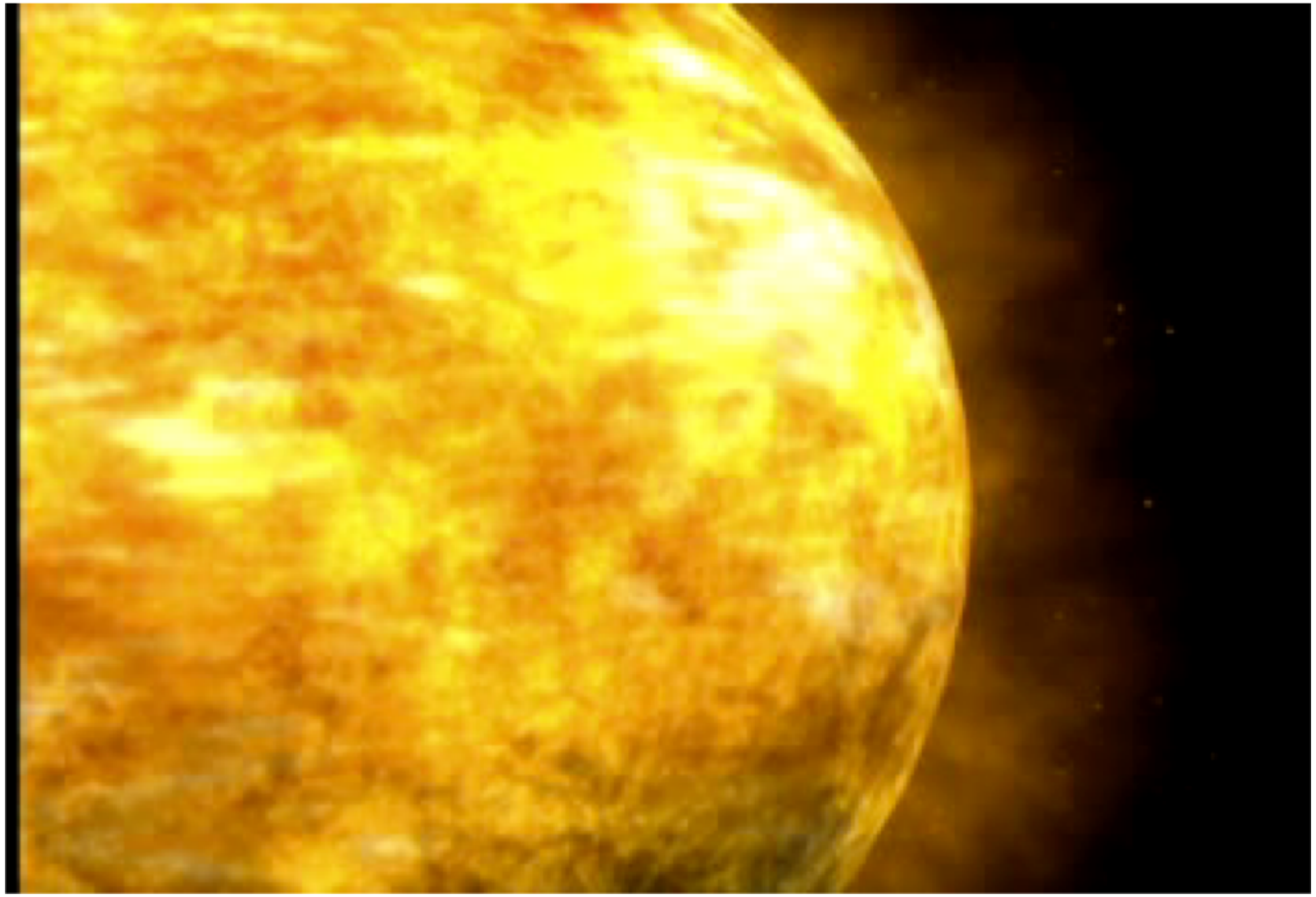


Magnetic reconnection in the Earth's Magnetosphere

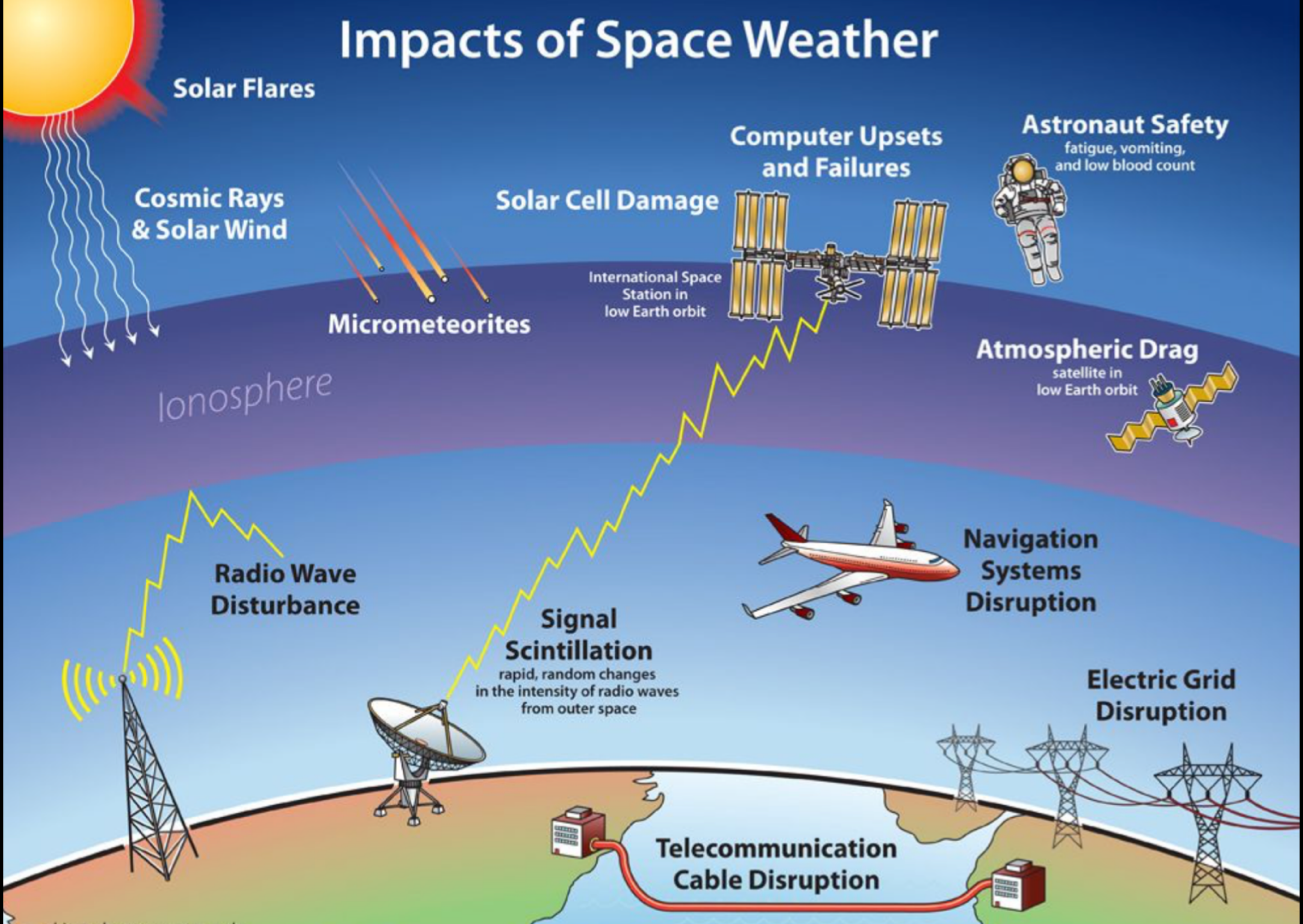


- Multiple reconnection sites
- Magneto-sheat reconnection and magnetotail reconnection
- Different topologies and dynamics
- Driven/Spontaneous reconnection
- Magnetosphere - Solar wind interaction

Why we care about magnetic reconnection?

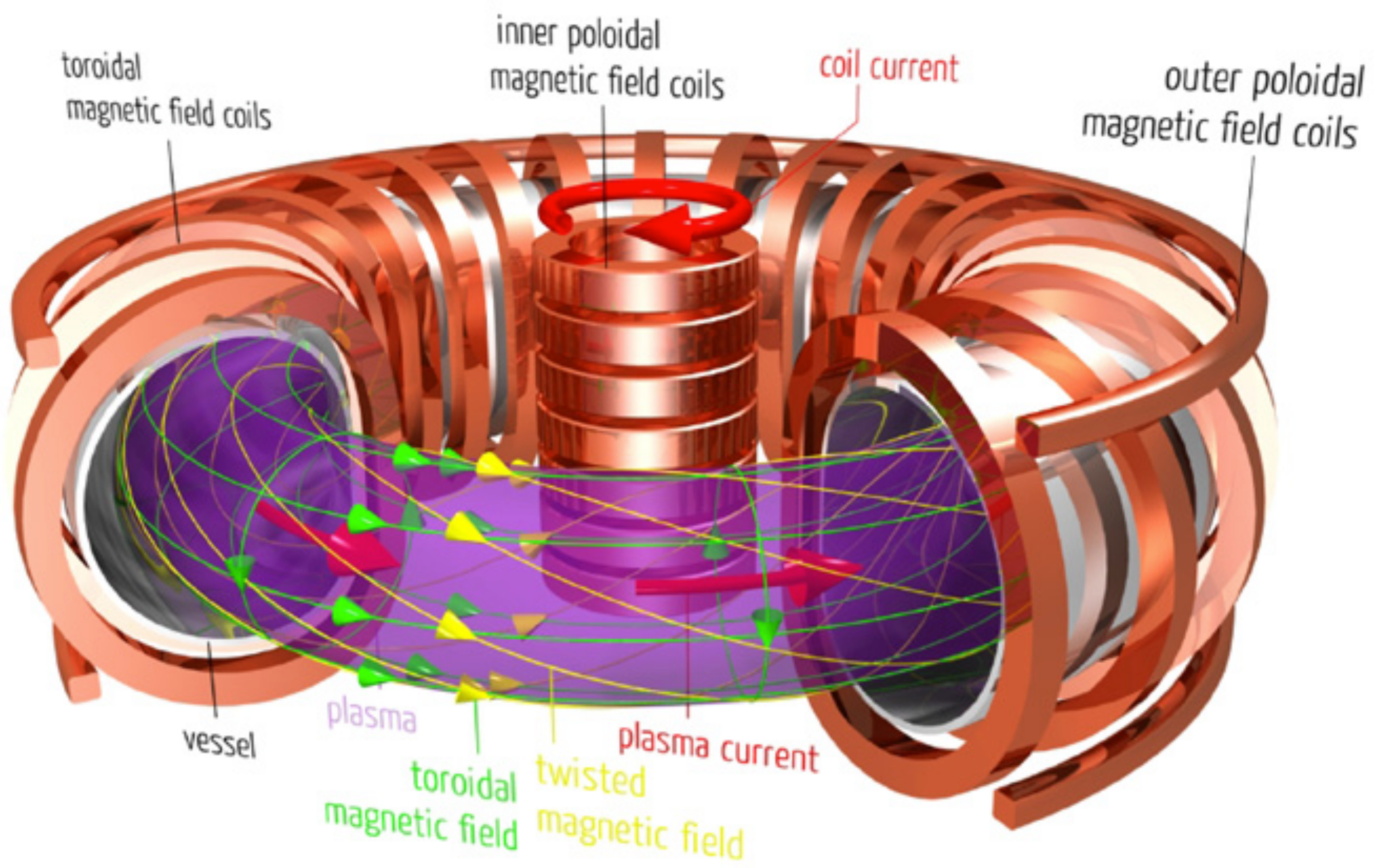


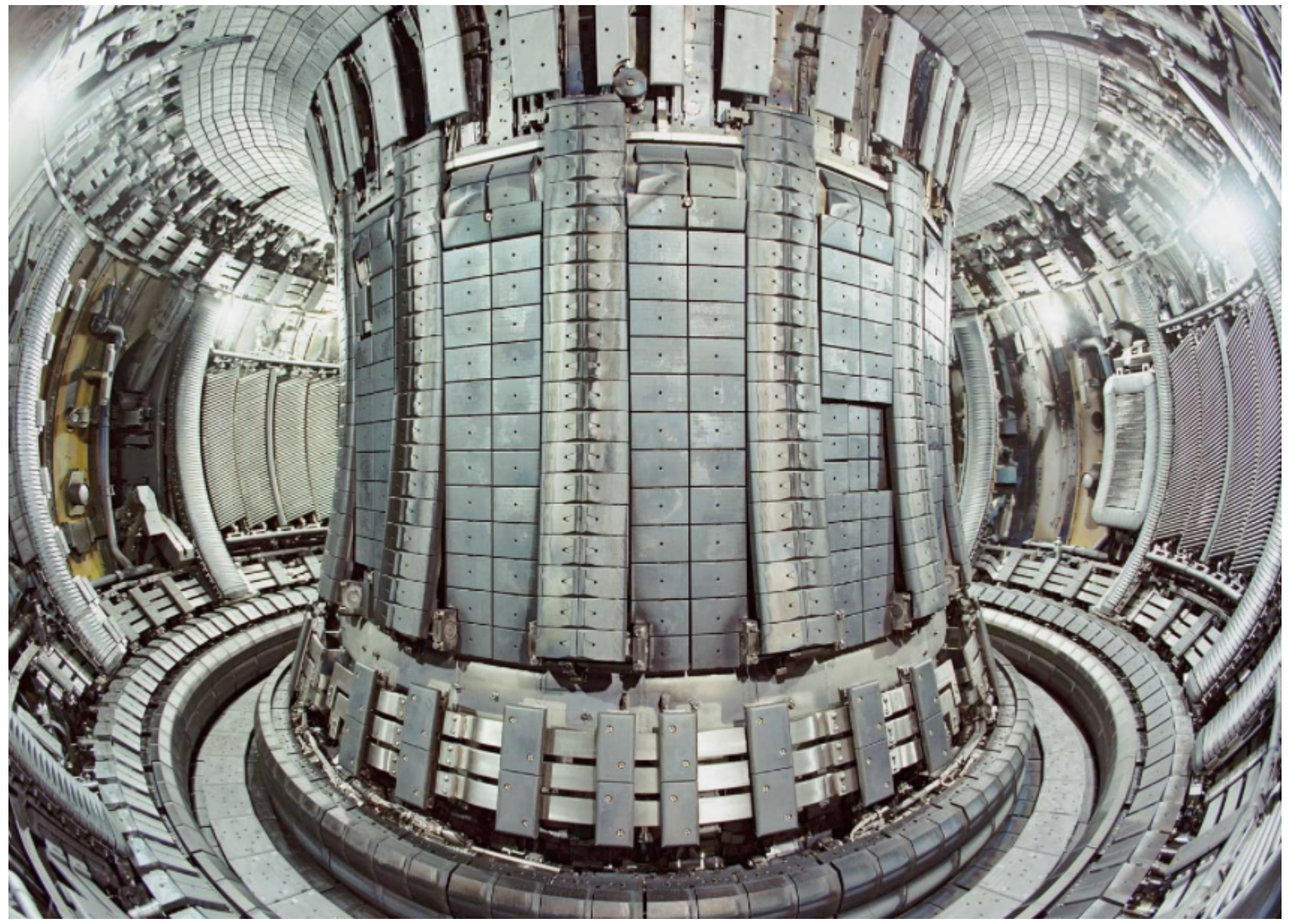
- Particles released by CMEs and solar wind impact our heliosphere and magnetosphere
- Charged particles gyrate around magnetic field lines
- How they are accelerate and reach the Earth depends on the topology and dynamics of the magnetic field.



Impacts of Space Weather
Solar Flares
Cosmic Rays
& Solar Wind
Micrometeorites
Ionosphere
Solar Cell Damage
International Space
Station in
low Earth orbit
Computer Upsets
and Failures
Astronaut Safety
fatigue, vomiting,
and low blood count
Atmospheric Drag
satellite in
low Earth orbit
Radio Wave
Disturbance
Signal
Scintillation
rapid, random changes
in the intensity of radio waves
from outer space
Navigation
Systems
Disruption
Electric Grid
Disruption
Telecommunication
Cable Disruption

Magnetic reconnection on the Earth: Fusion Devices



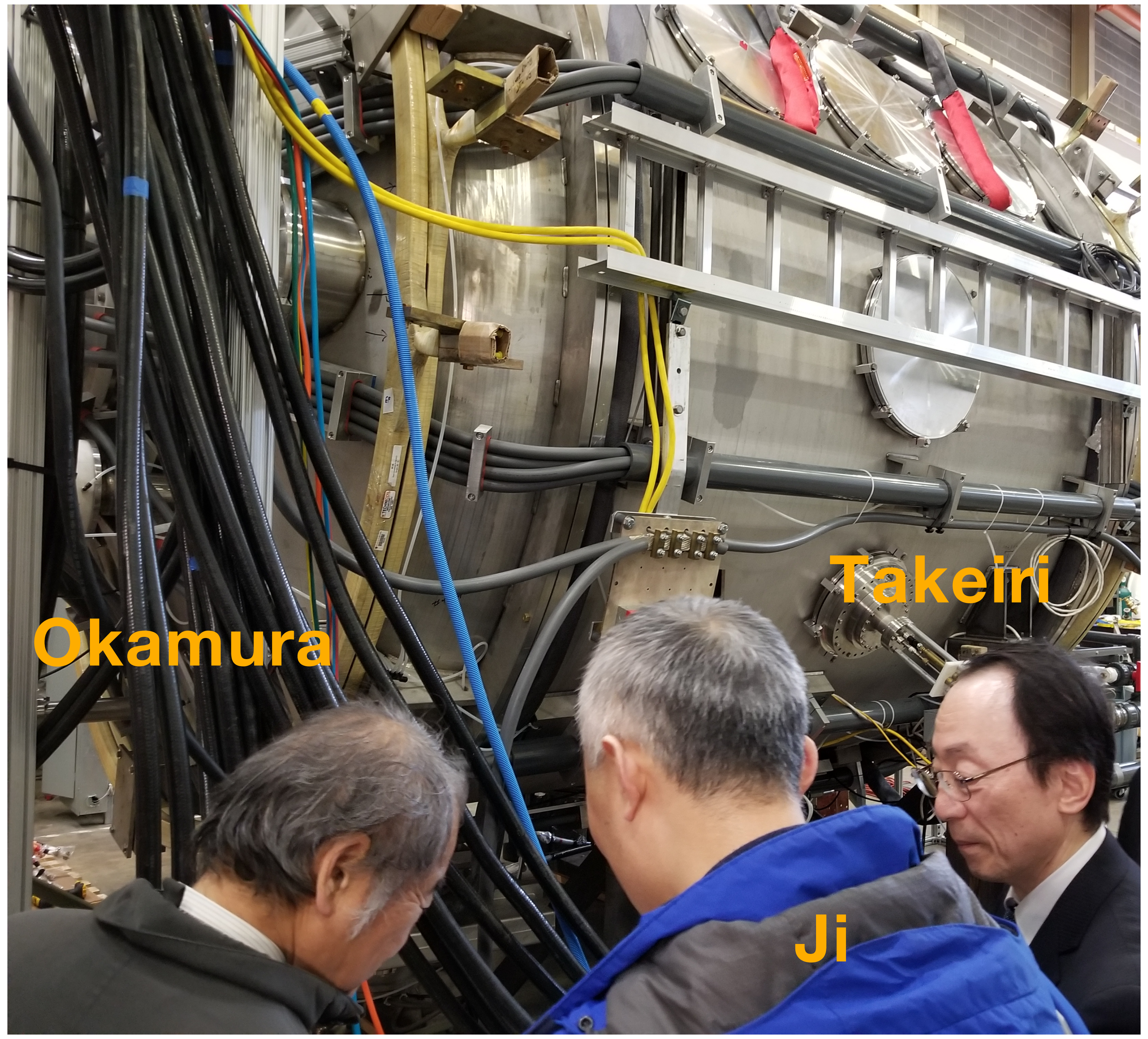


- Reconnection is an obstacle to Plasma Confinement for fusion devices

- The topology and scales and other parameters in fusion devices differ from the ones involved in astrophysical/space plasmas

- Ultimately the reconnection mechanism and trigger is the same

Experiments devoted to Magnetic Reconnection Studies



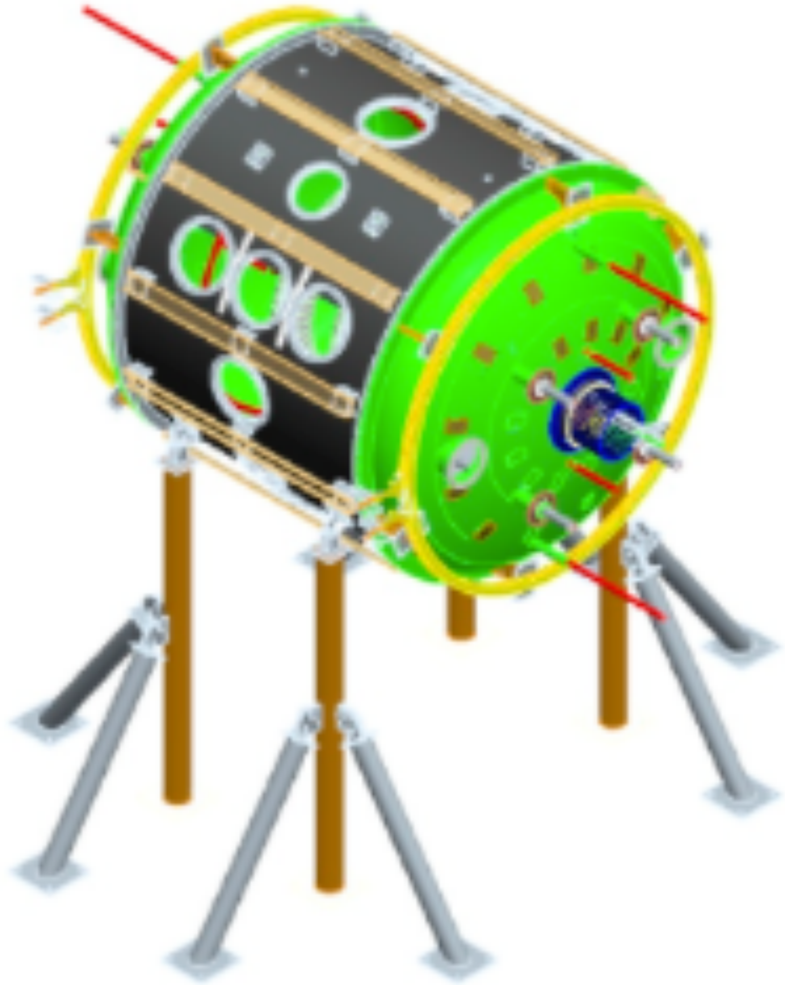
H. Ji and W. Daughton, POP, 2011

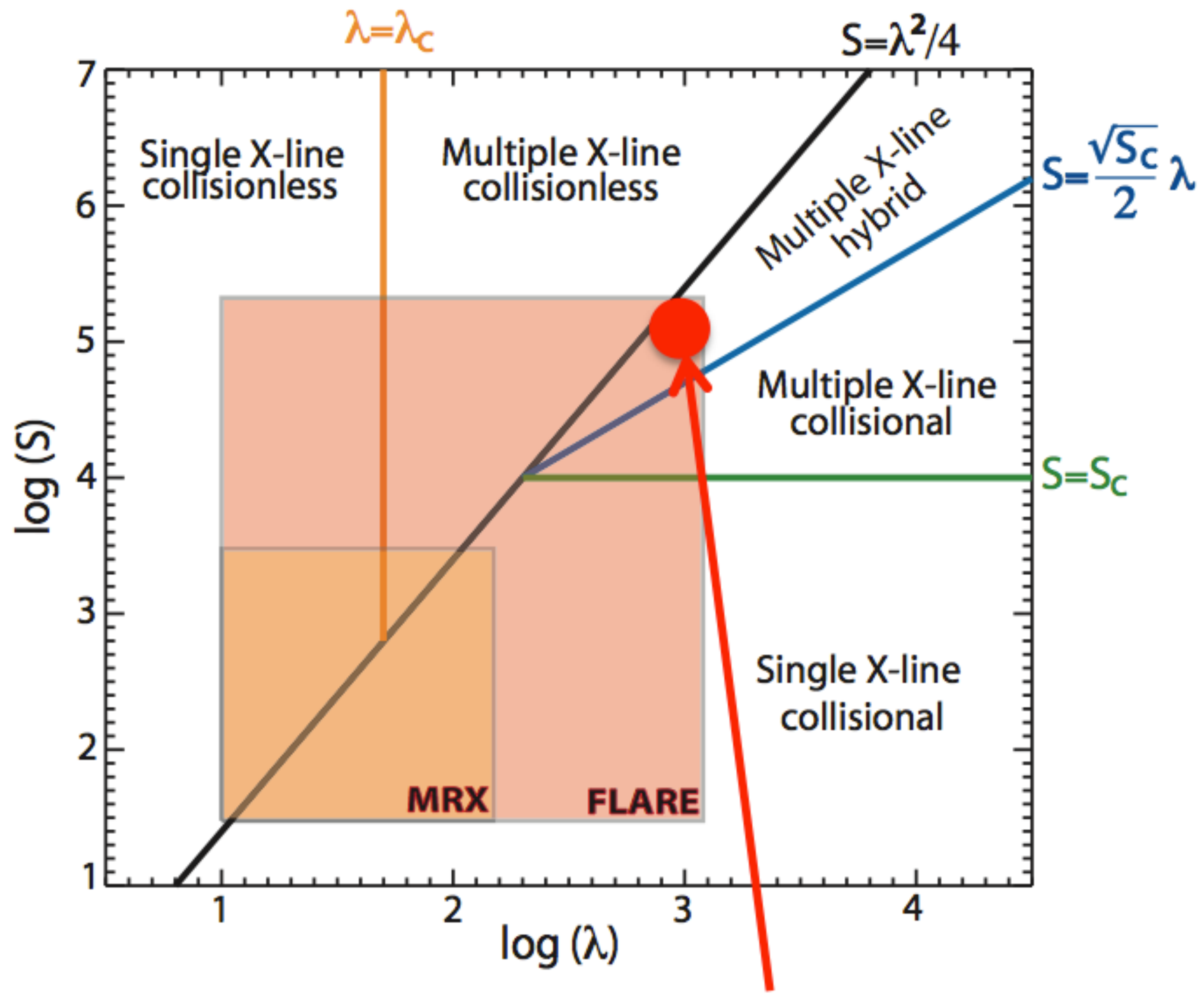
$$\lambda = d_i/L$$

$$S = L v_A/\eta$$

$$d_i = c/\omega_{pi}$$

$$d_e = c/\omega_{pe}$$

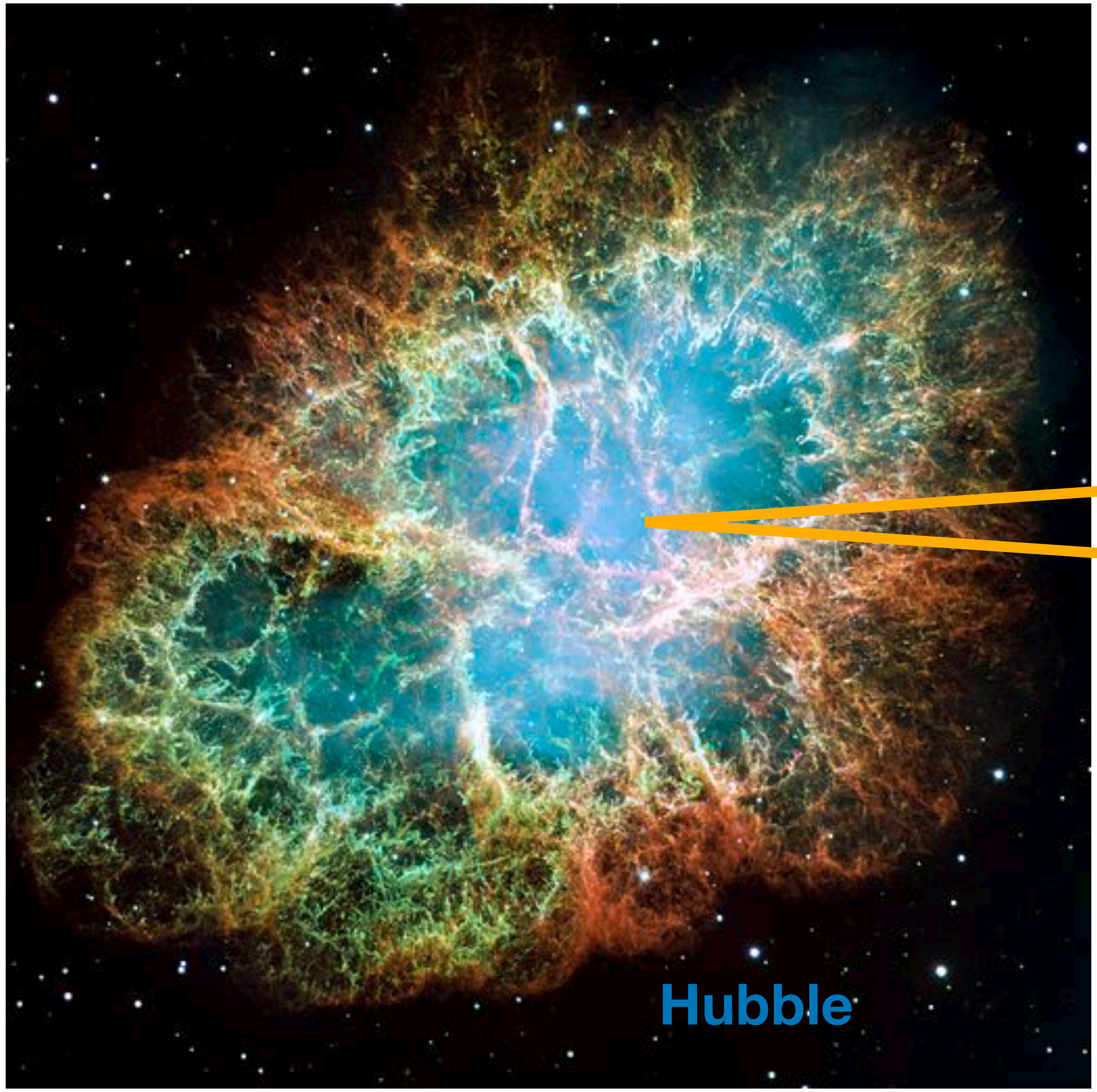


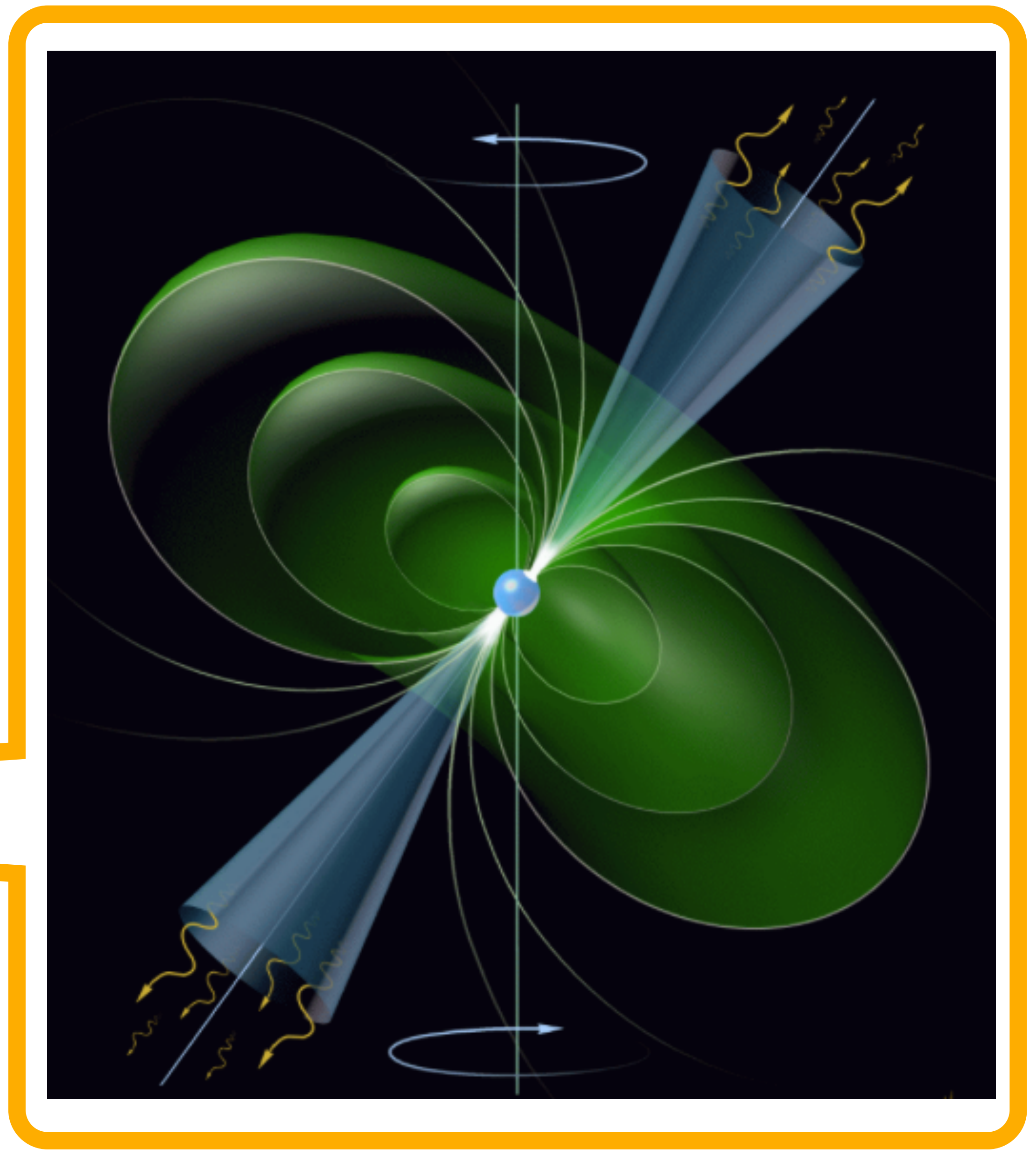


Design target for FLARE to access all reconnection phases

- Magnetic Reconnection eXperiment (MRX, Princeton)
- Flare (Princeton)
- TS Experiment at Tokyo University
- Swarthmore Spheromak Experiment (Yamada et al. 2010, 2016 for reviews)

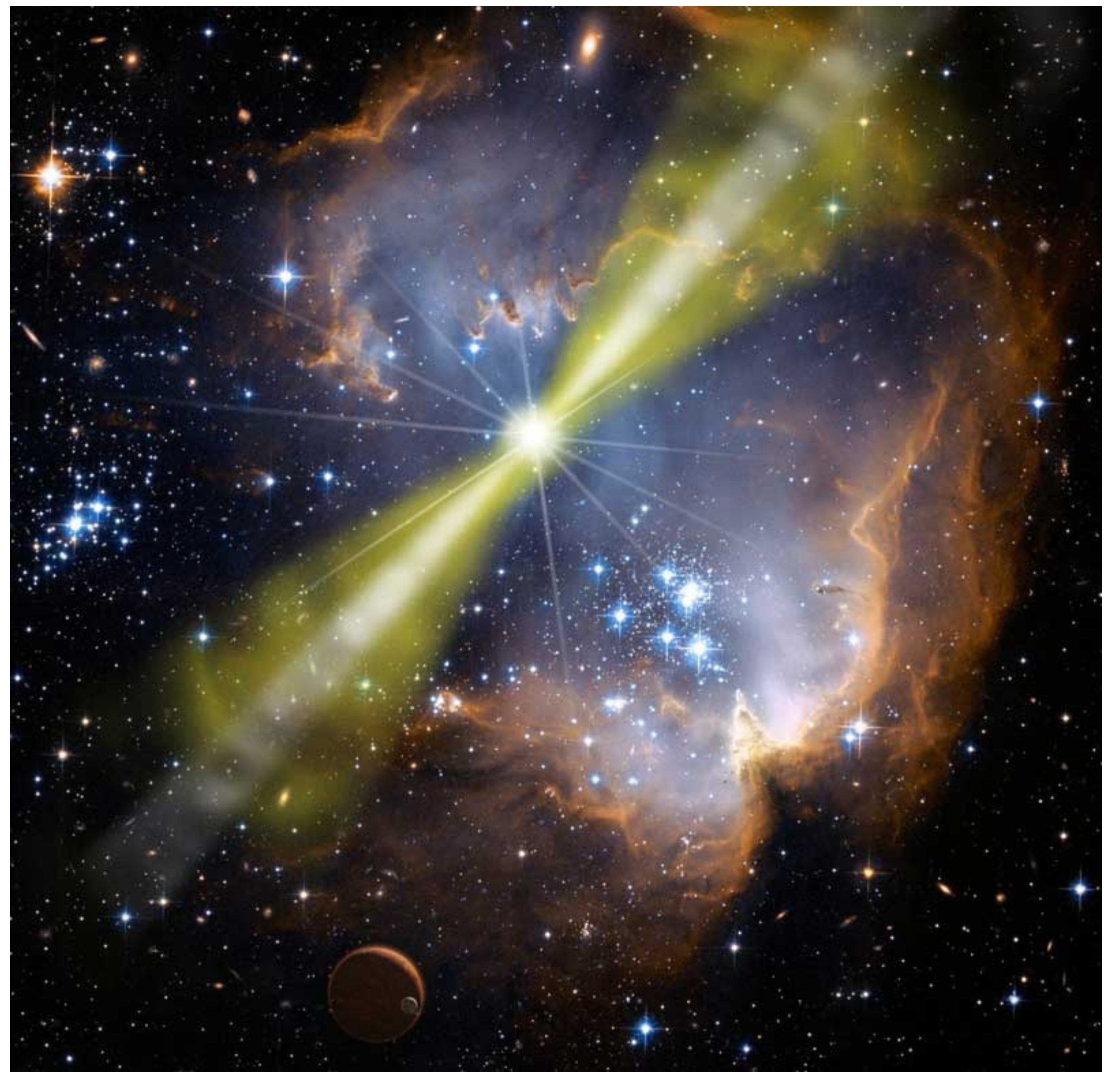
Magnetic reconnection in the Universe

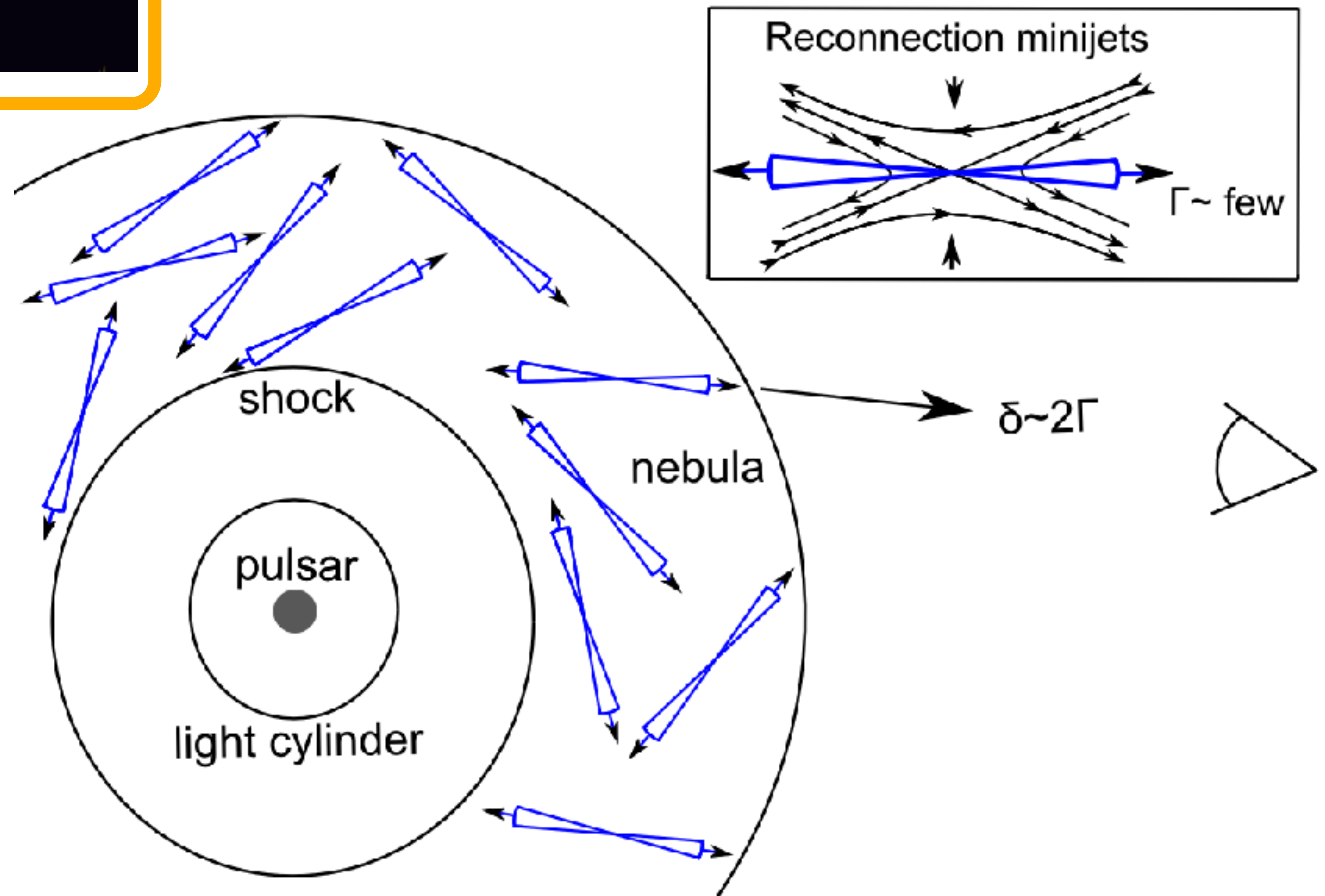




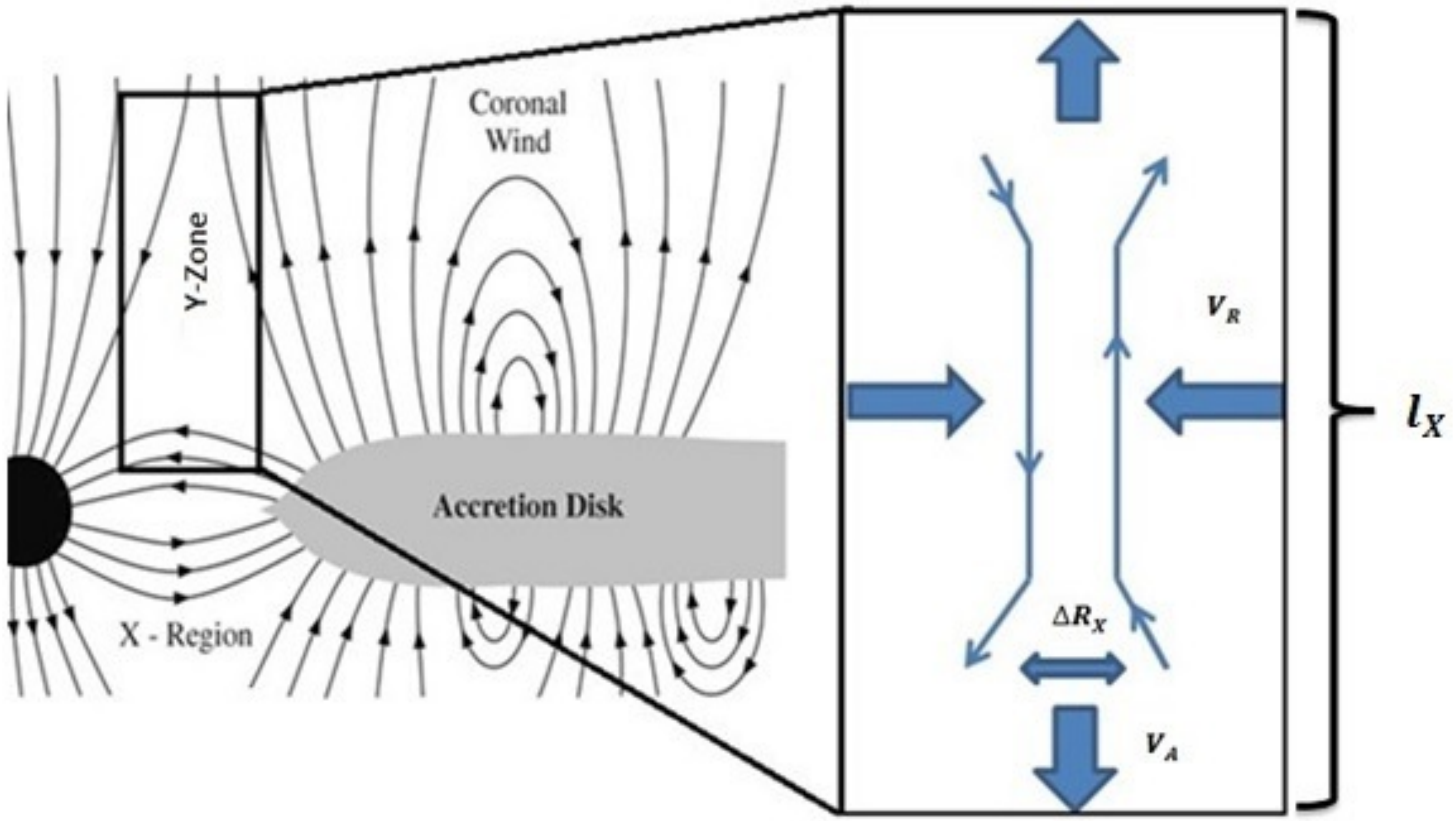
Pulsar and Pulsar Wind Nebulae

GRBs

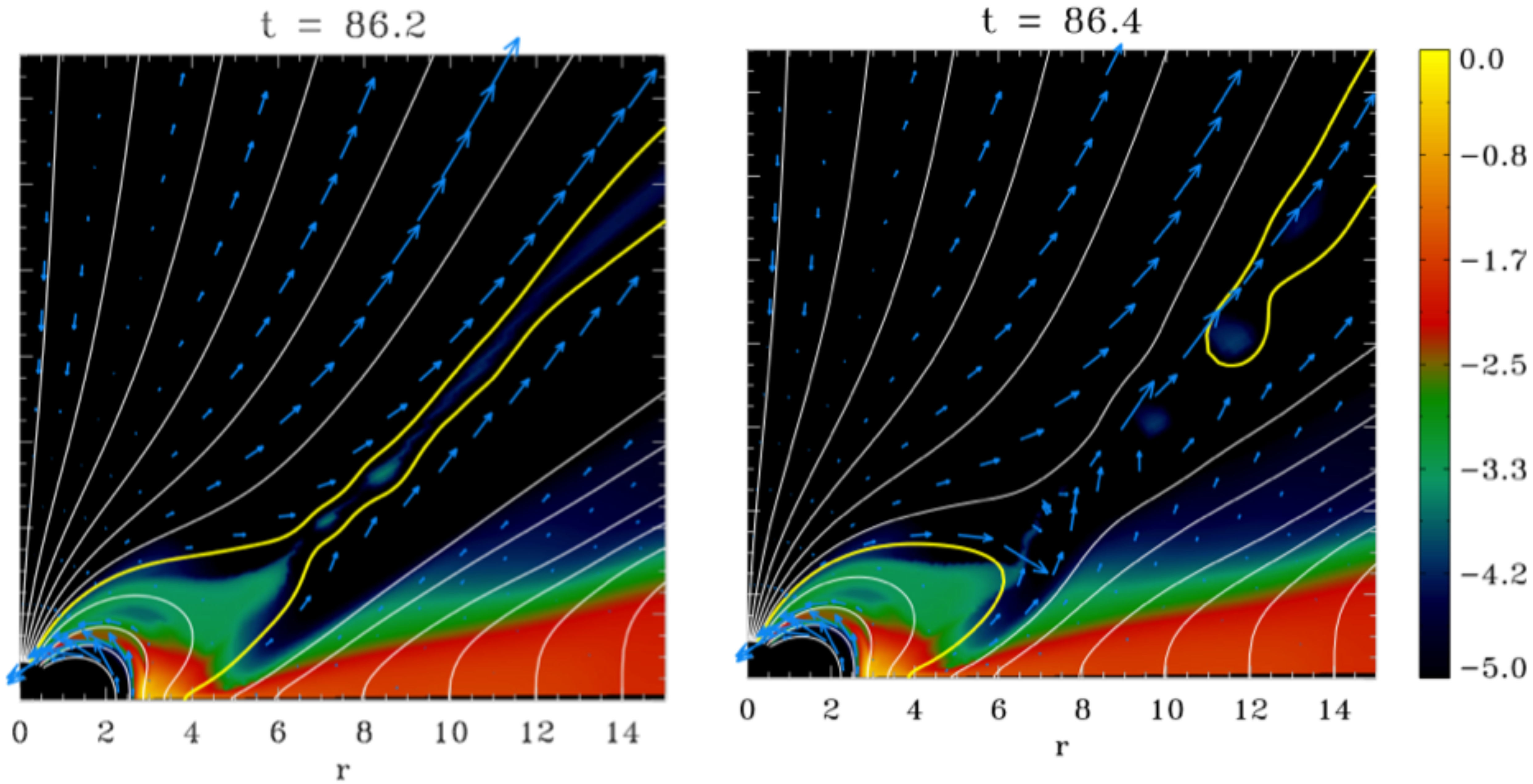




Magnetic reconnection in the Universe II

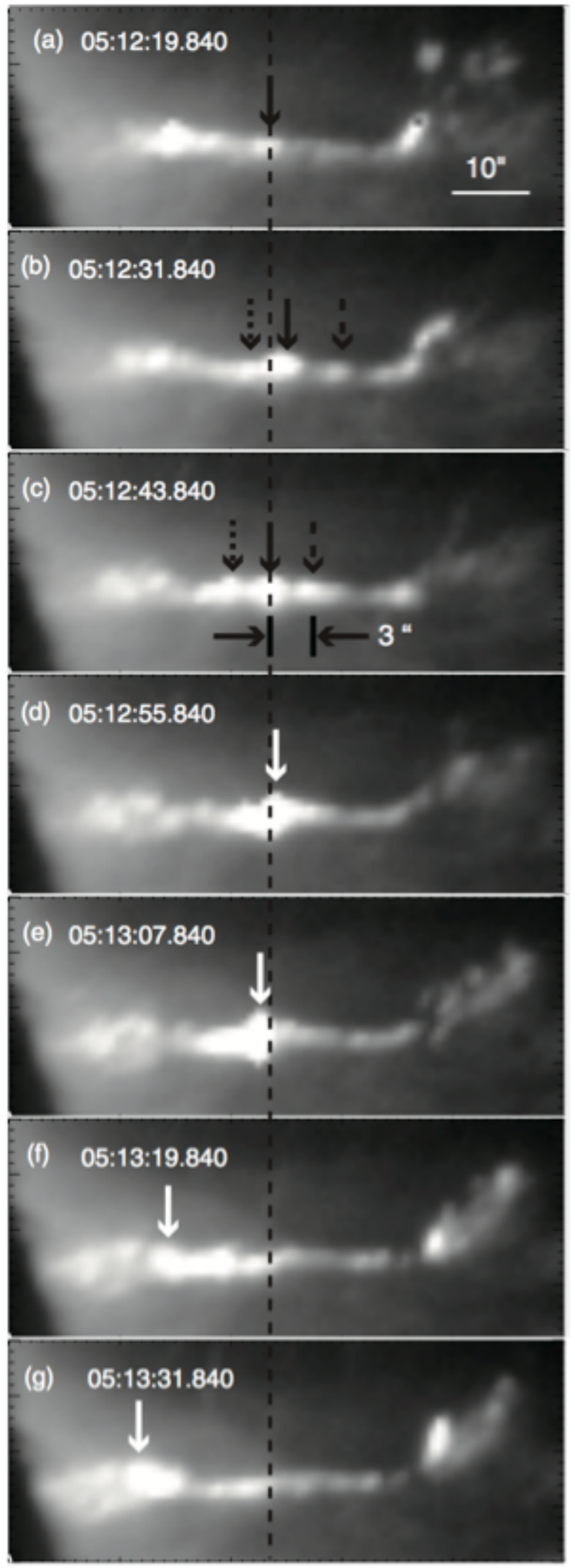


PPDs Accretion disks

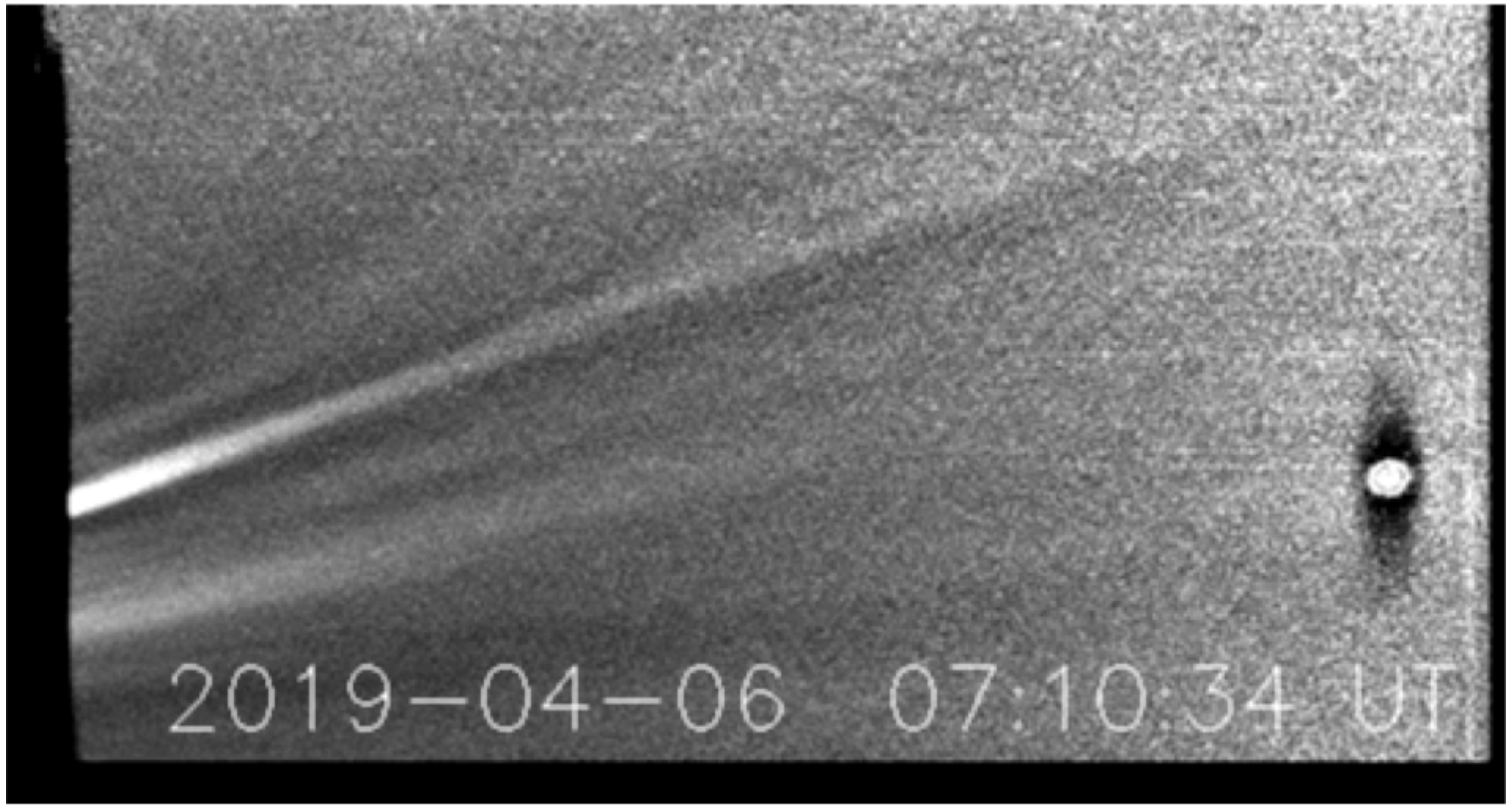


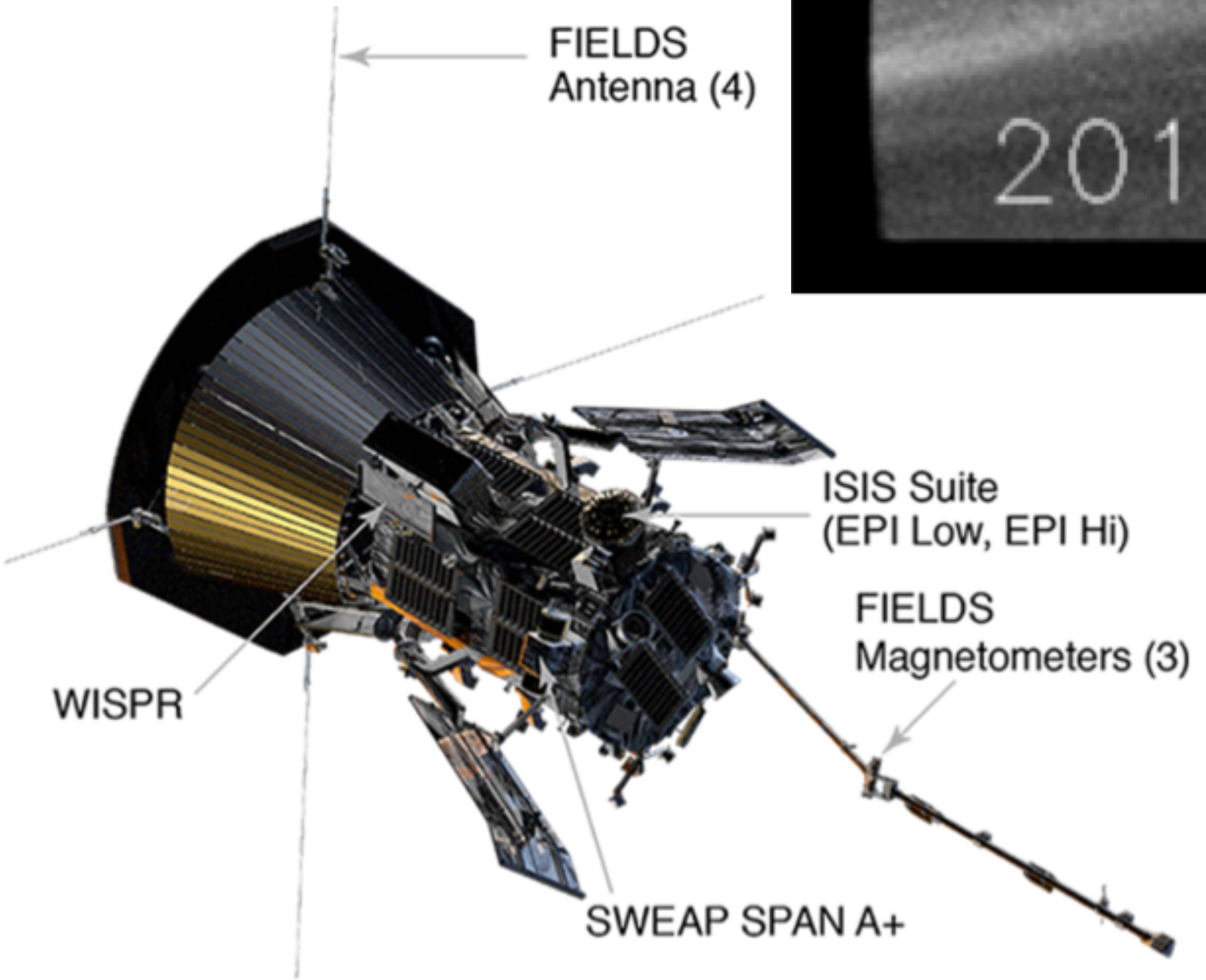
BH Accretion disks

Remote observations of magnetic reconnection



Takasao et al. ApJL, 2012 examined morphology and dynamics of the magnetic reconnection region in the limb flare on 2010 August 18

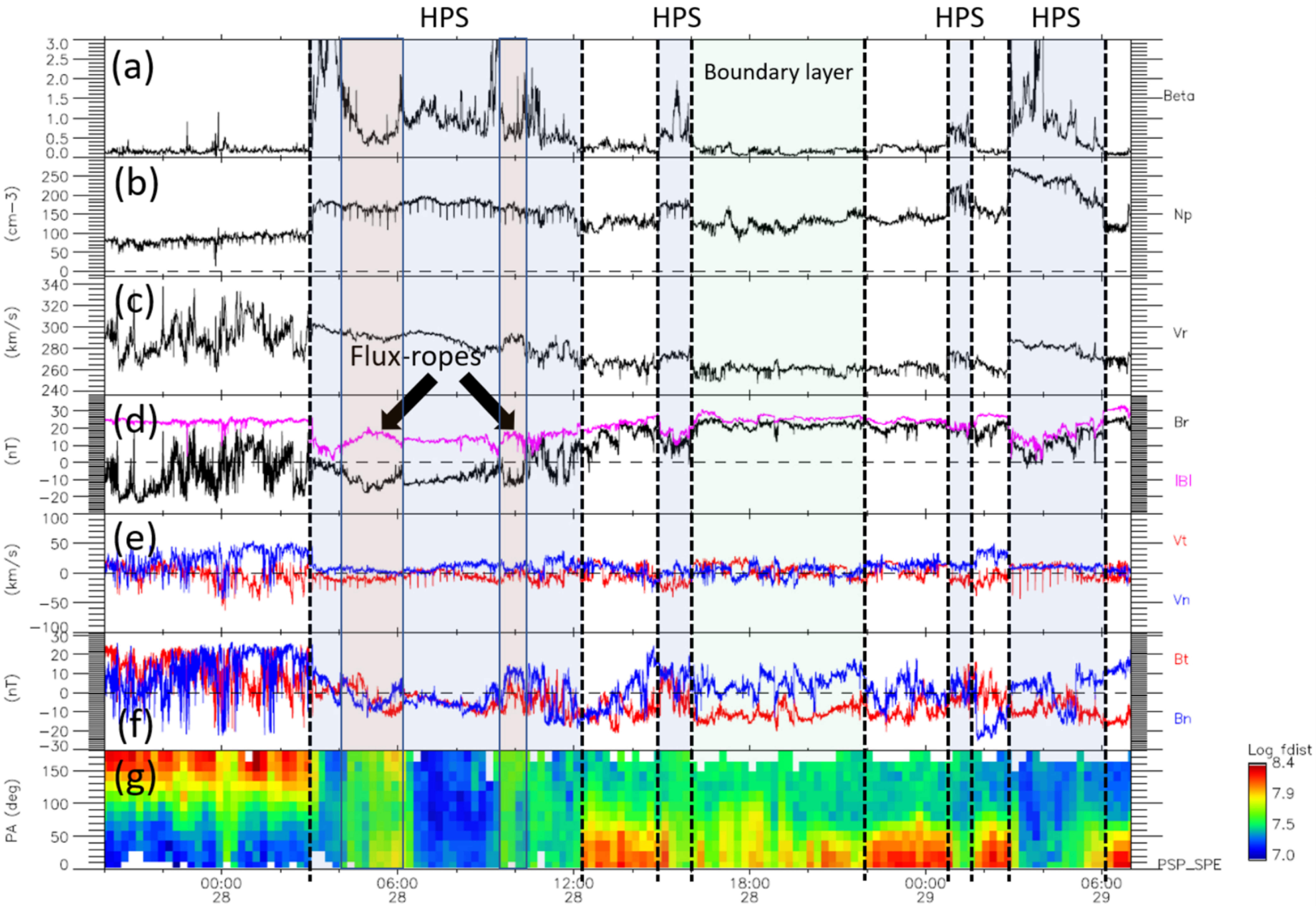


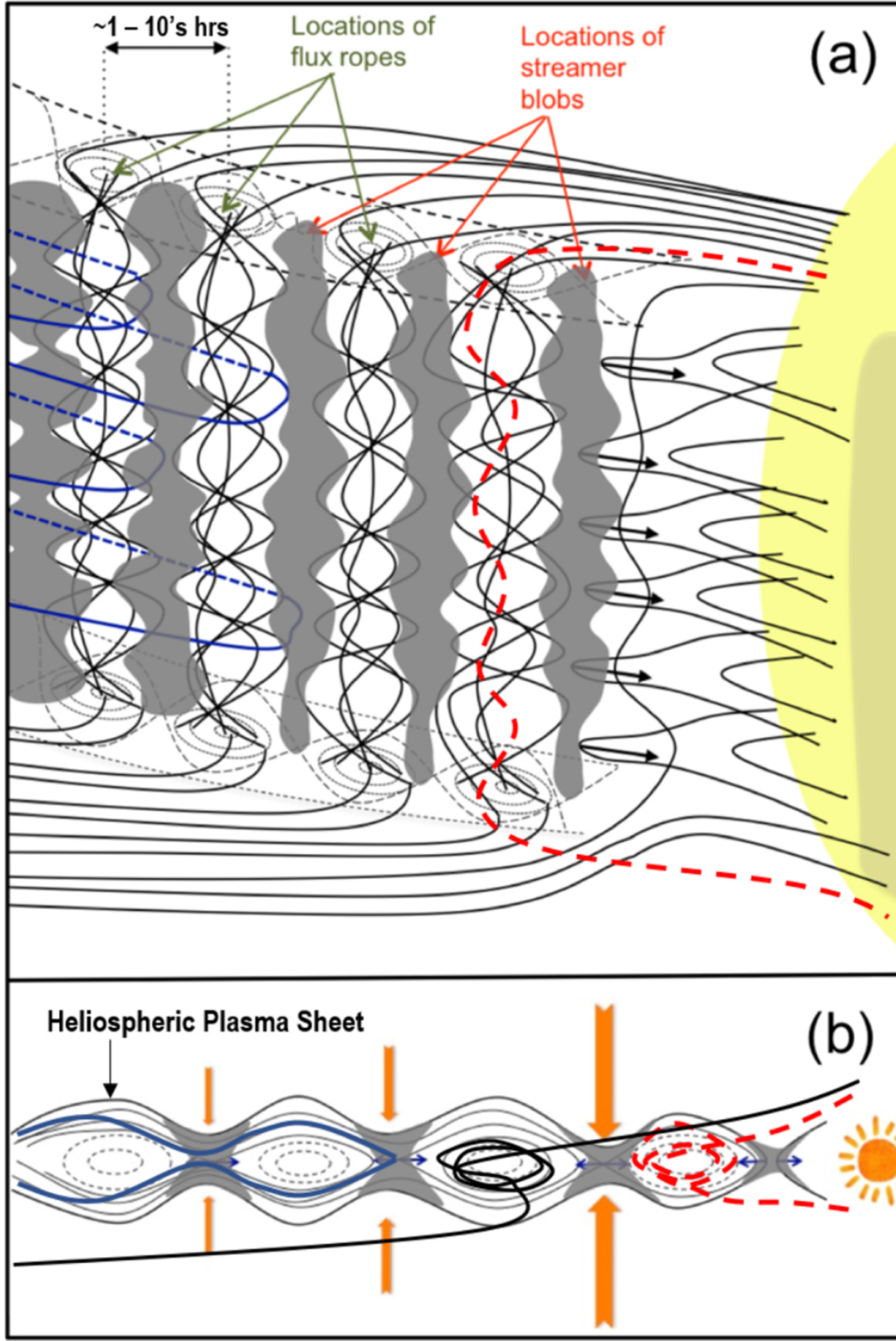


PSP: Howard et al 2019

Magnetic reconnection in situ

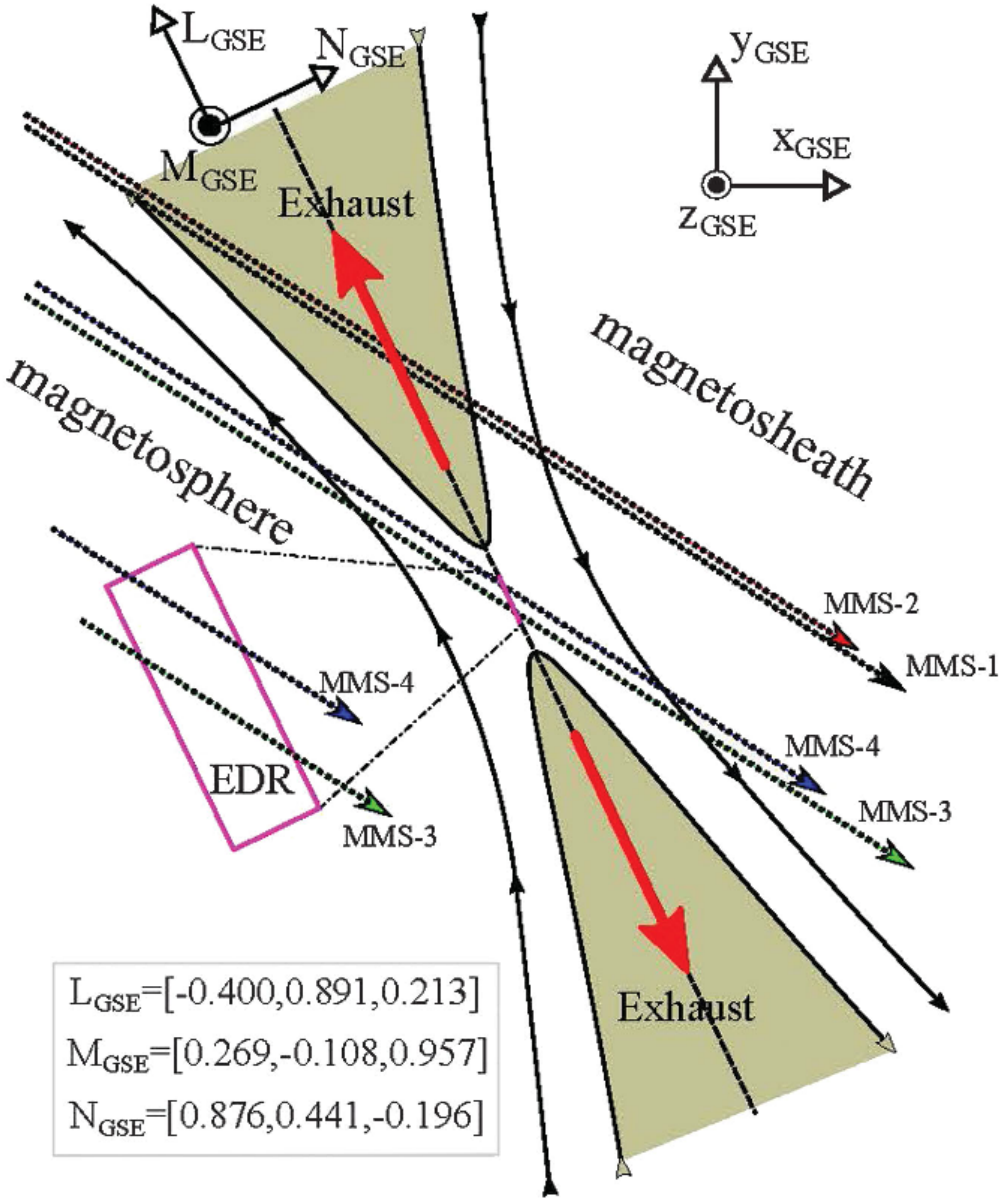
Parker Solar Probe

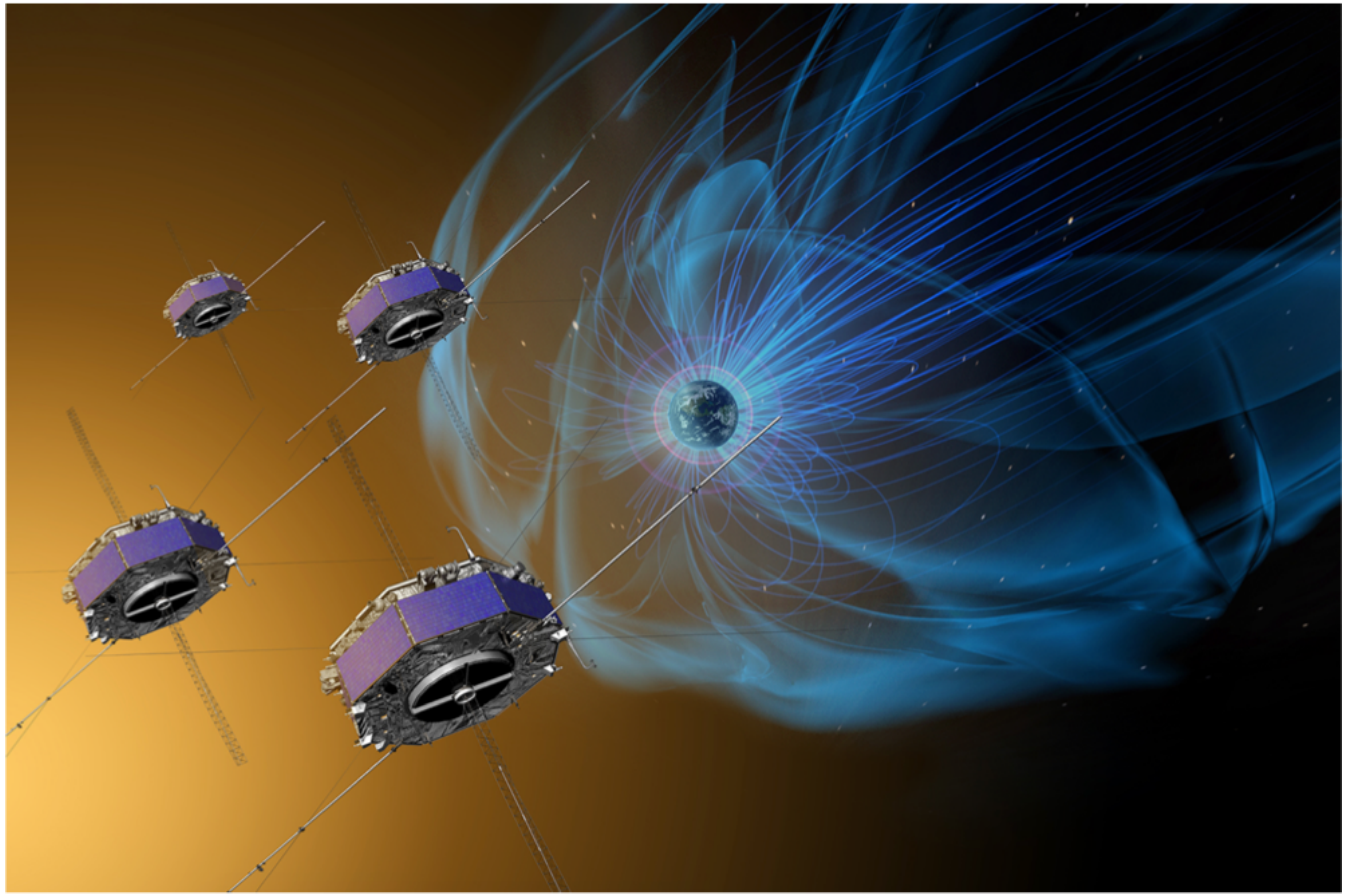




Probing magnetic reconnection in situ

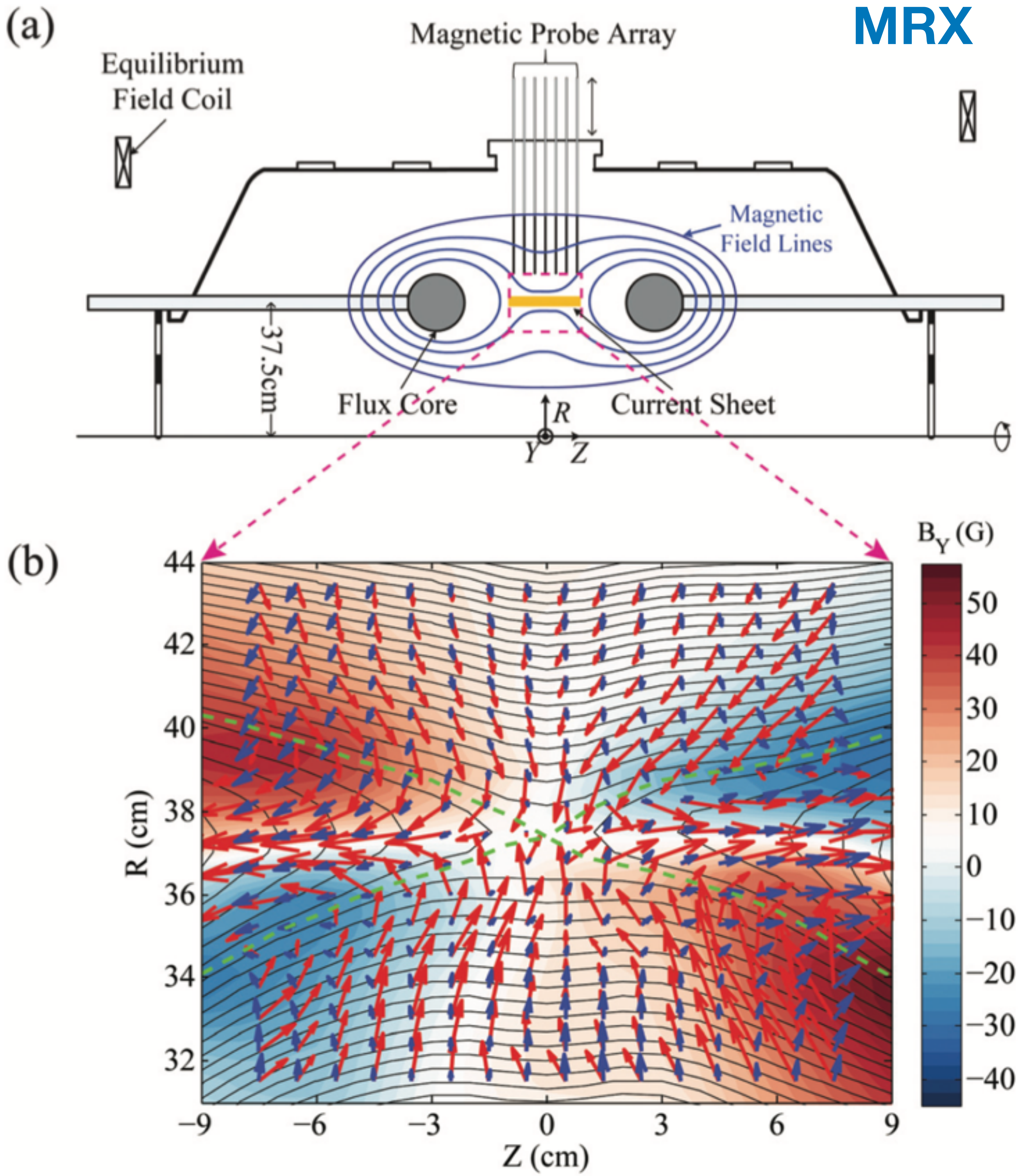
Magnetospheric Multiscale Mission





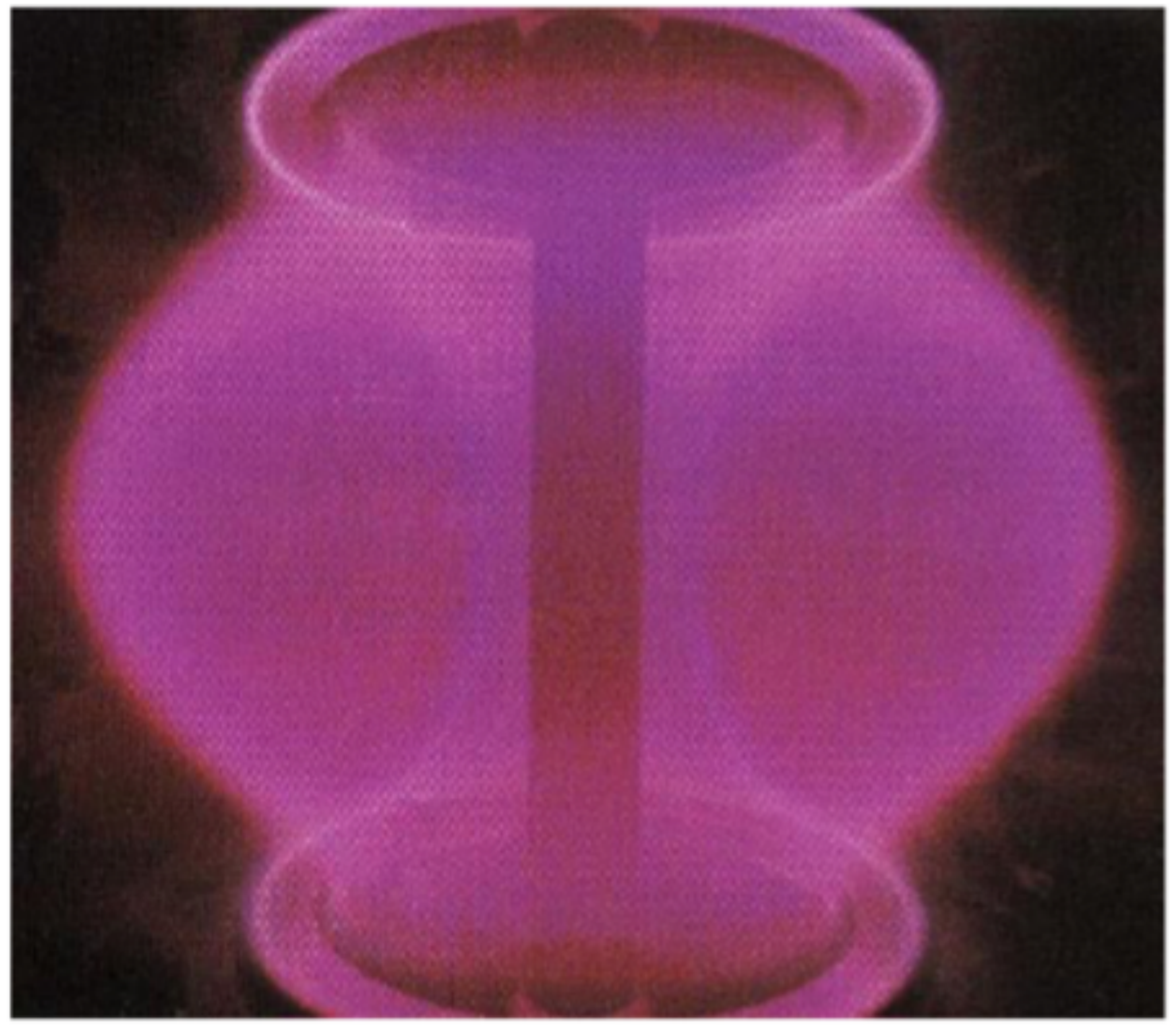
Magnetic reconnection experiments

MRX

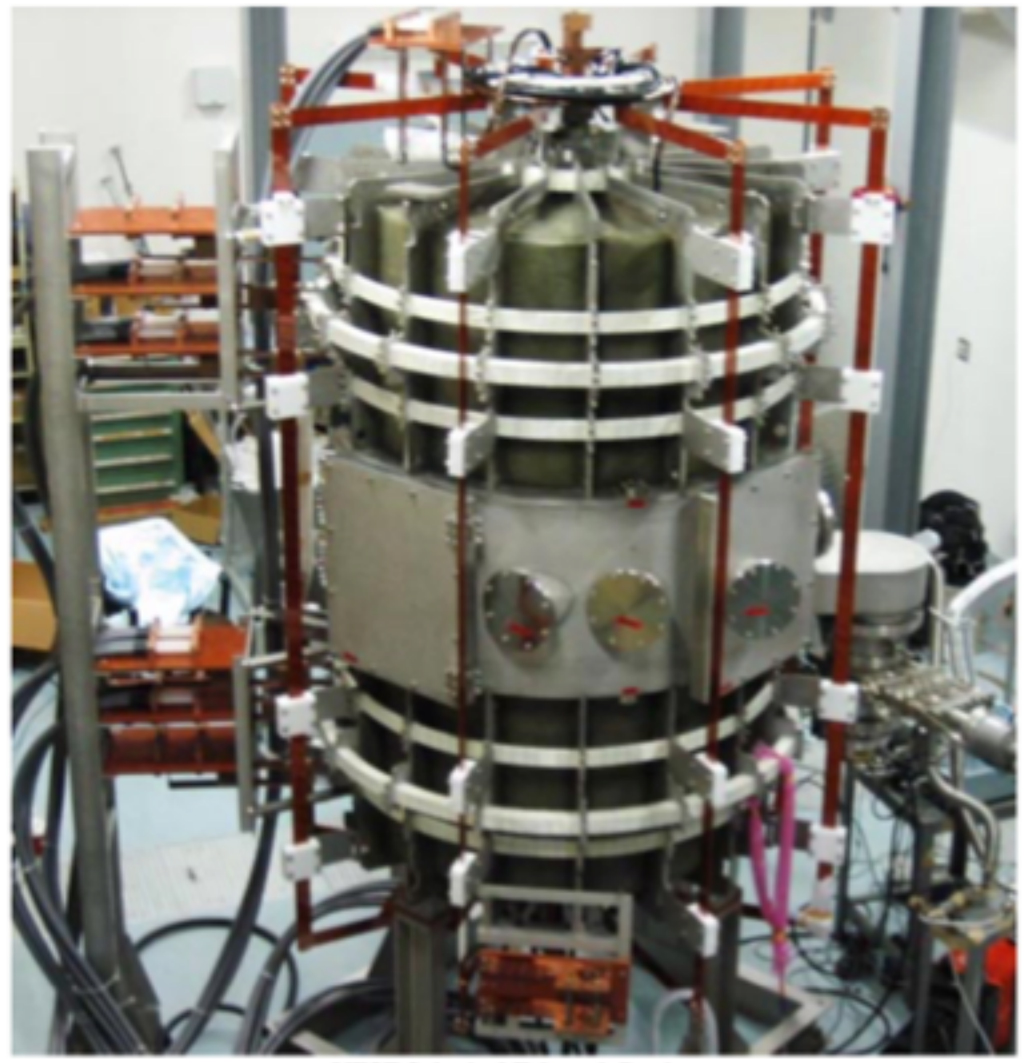


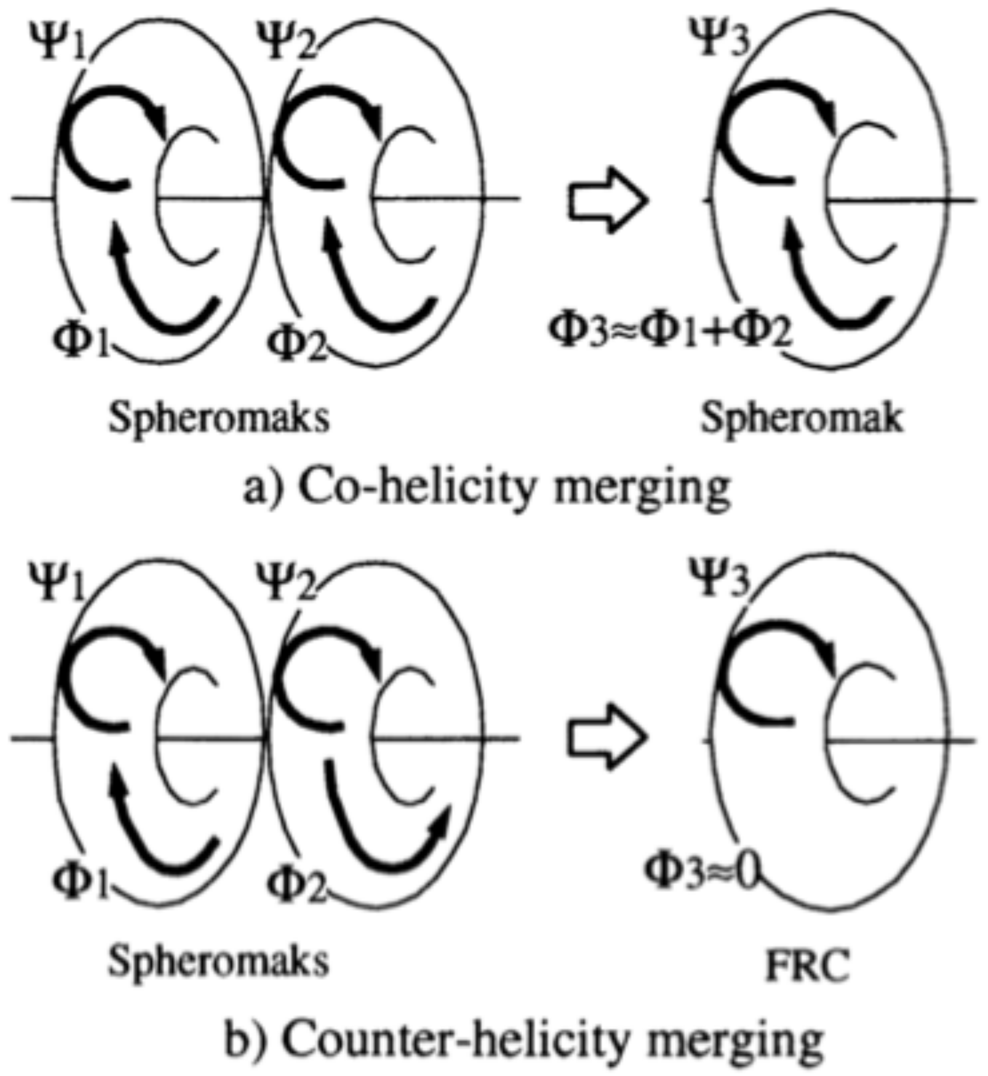
Spheromax Merging Discharge

Ultra-High Beta ST Experiment,TS-4, TS-6



Spherical Tokamak Discharge (START)

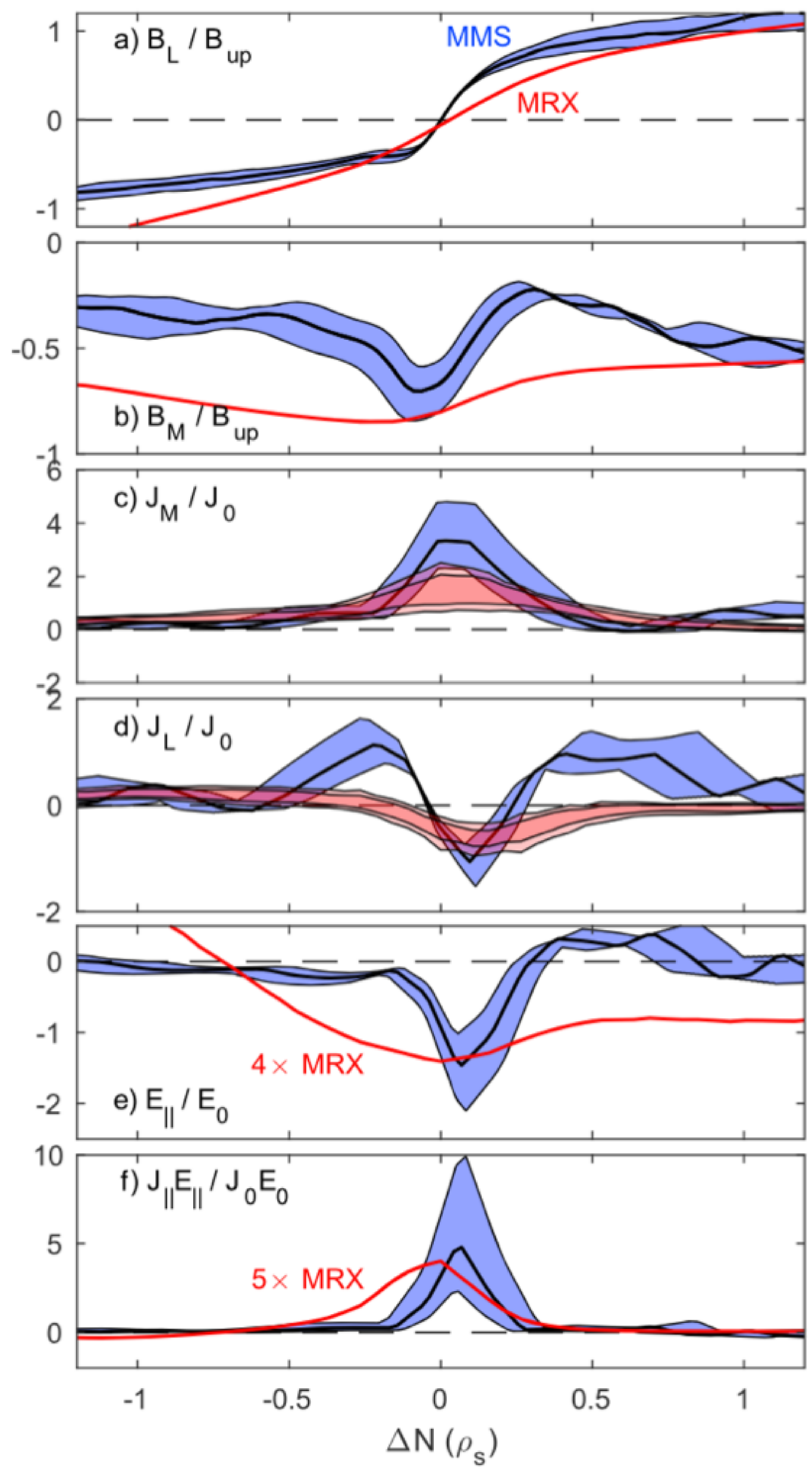




MRX vs MMS

Fox et al 2018

- Comparisons between experiments and space missions are possible
- Scales and different parameters must be taken into account
- While a satellite observation is unique the experiment can be reproduced, probes can be adjusted/added so that the experiment gives us access to quantities and particulars space mission can't provide.
- Ultimately the reconnection mechanism and trigger is the same
- It is important to understand the 'calibration' and the difference in the dynamics



Modeling magnetic reconnection in plasmas

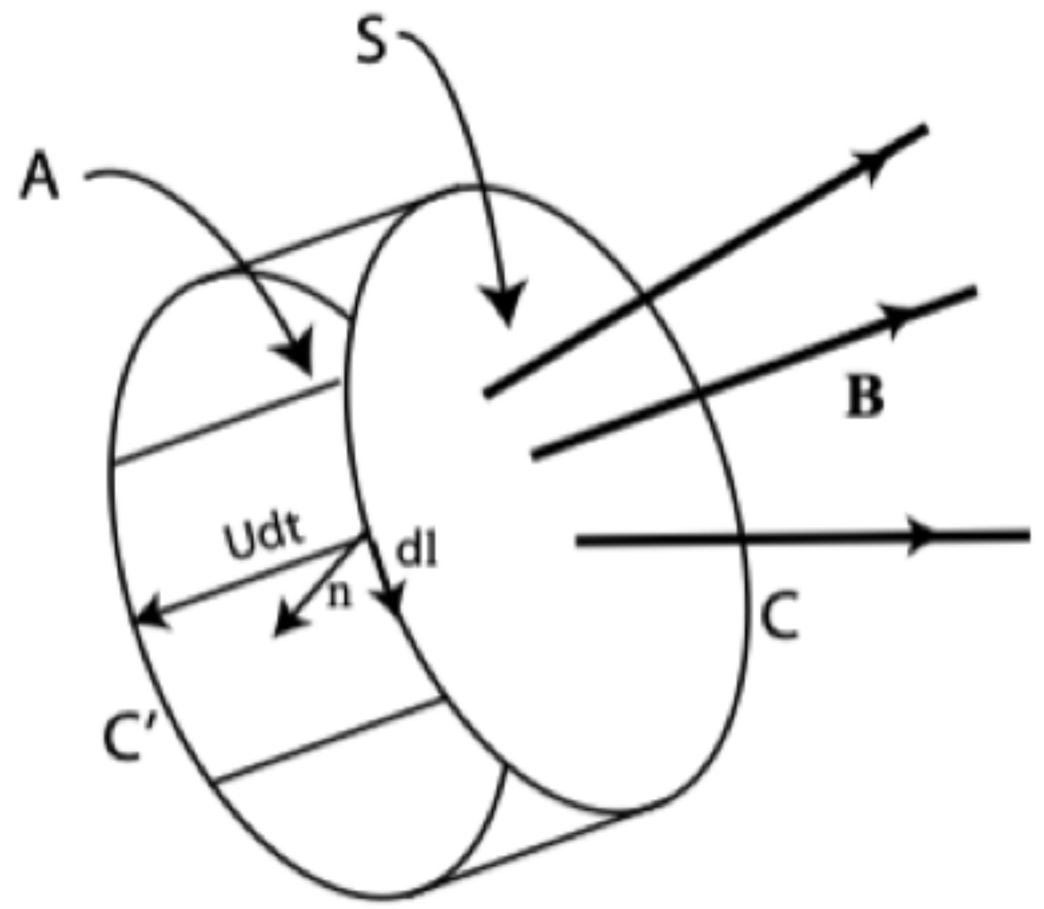
Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Diffusivity

$$\eta = \frac{c^2}{4\pi\sigma} \qquad \sigma = \frac{e^2 n_e}{m_e \nu_c}$$

$$\tau = \frac{\mathcal{L}}{\mathcal{U}} \qquad \tau_D = \frac{\mathcal{L}^2}{\eta} \qquad S = \frac{\tau_D}{\tau}$$

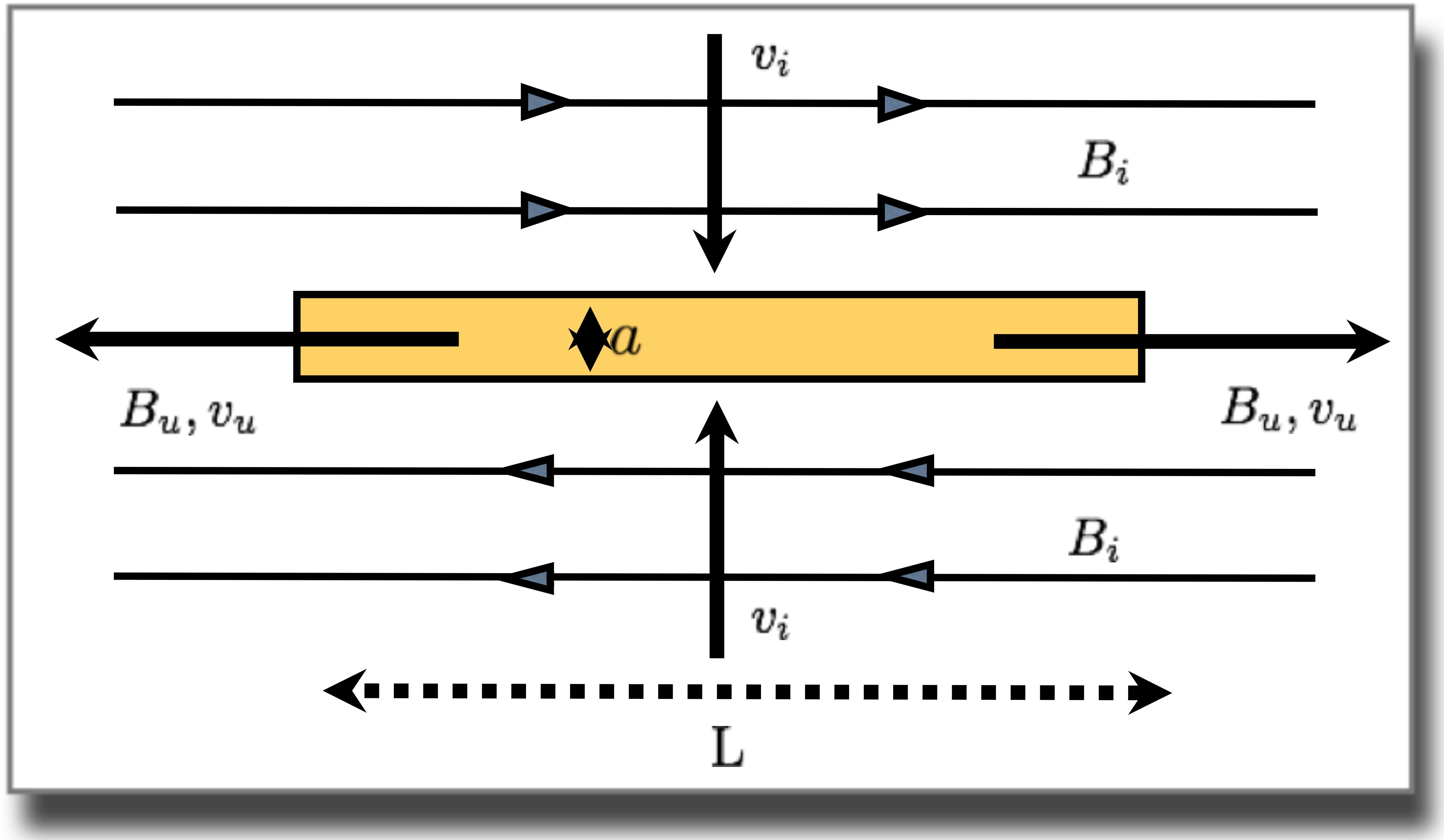


Alfvén Theorem: *magnetic flux through a closed line which moves with the fluid is constant in time.*

? What are the scissors that cut magnetic field lines?

Sweet and Parker model for magnetic reconnection

$$\frac{a}{L} \sim S^{-1/2}$$



"The observational and theoretical difficulties with the hypothesis of magnetic-field line annihilation suggest that other alternatives for the flare must be explored." E. Parker, 1963

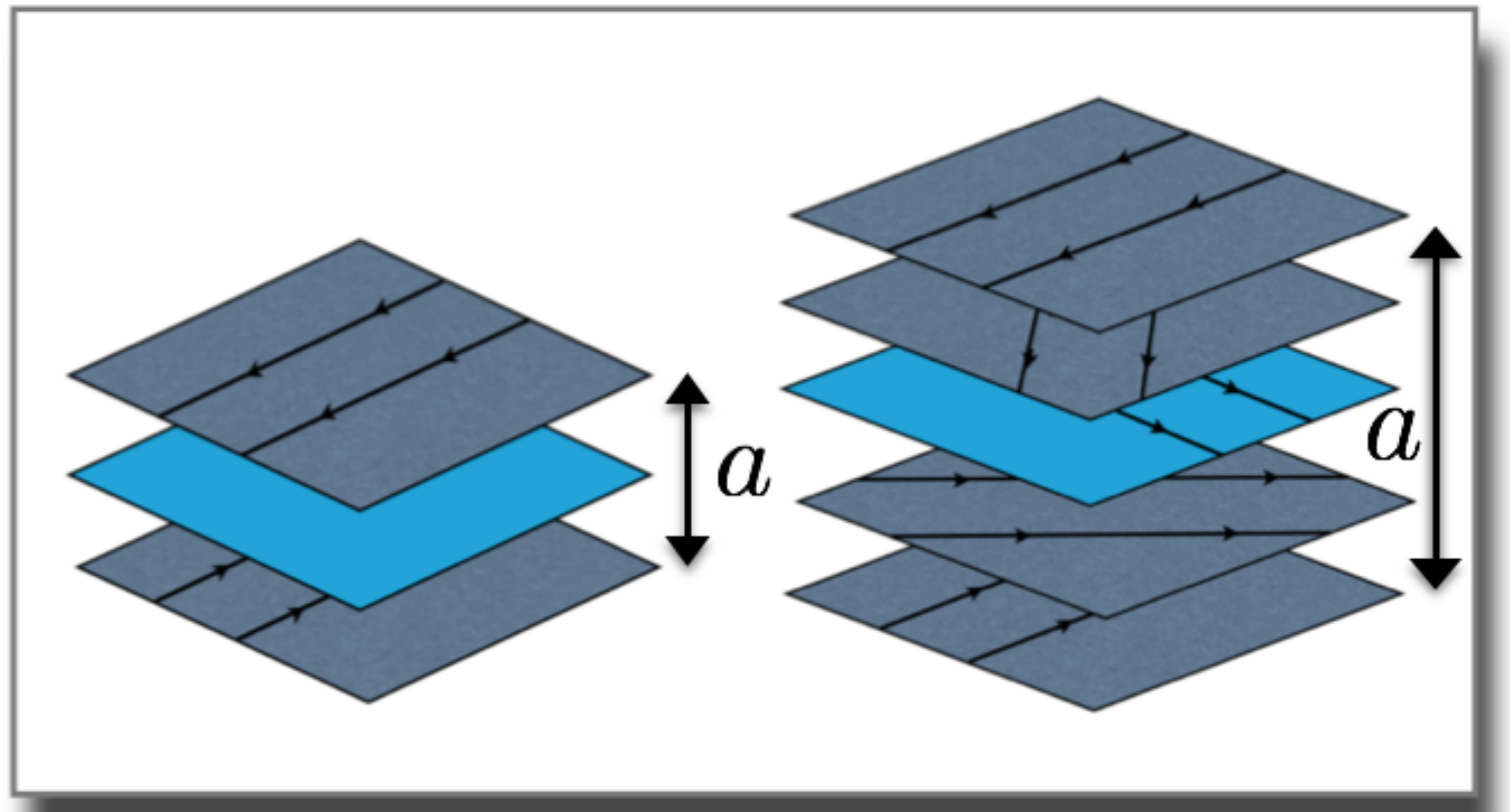
$$S := \frac{a v_A}{\eta} \qquad \tau_A := \frac{a}{v_A}$$

Energy dissipated in an Alfvén time in the sheet is proportional to:

$$L^2 v_i \tau_A = S^{-1/2} L^2 v_{Ai} \tau_A = L^3 S^{-1/2}$$

Non-stationary reconnection: Tearing instability

H. Furth, J. Killeen, and M. N. Rosenbluth, 1963

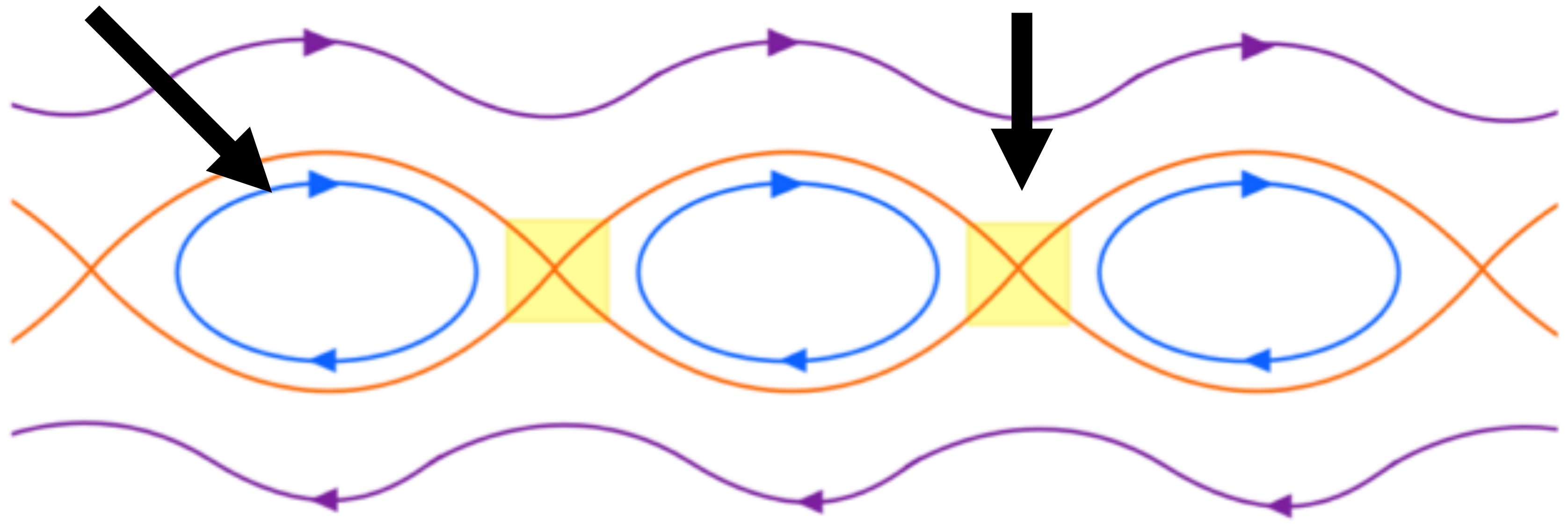


Harris Sheet **Force-free**

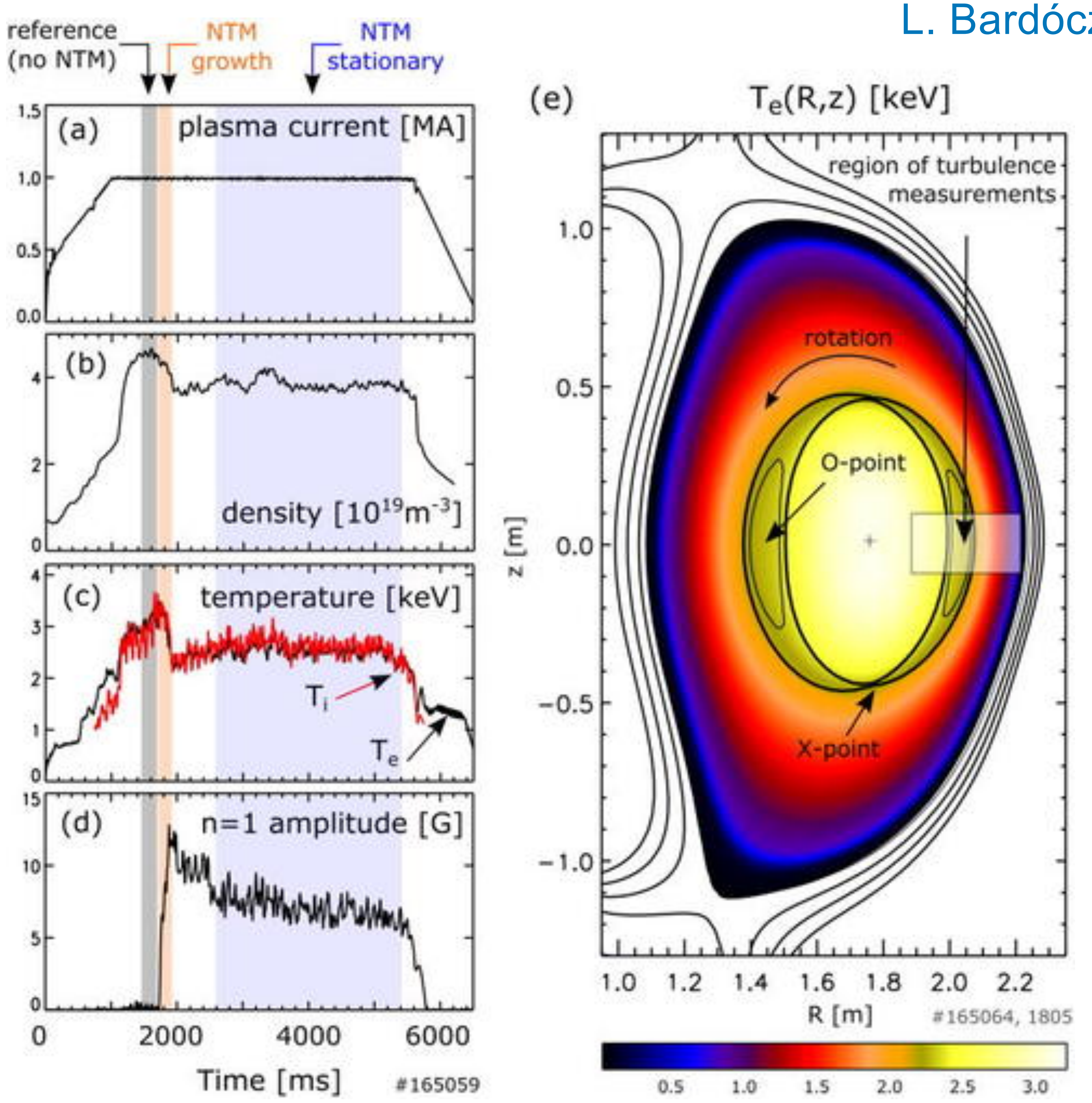
Perturbation to the initial equilibrium configuration

$$v_1 = v_x(x,y,t)\hat{i} + v_y(x,y,t)\hat{j} \qquad \vec{B}_1 = b_x(x,y,t)\hat{i} + b_y(x,y,t)\hat{j}$$

O-points X-points



L. Bardóczi et al 2018



Magnetic reconnection at kinetic scales

$$E_i + \frac{1}{c}(\vec{U} \times \vec{B})_i - \frac{J_i}{\sigma} = \frac{m_e}{e^2 n_e}\left[\frac{\partial J_i}{\partial t} + \frac{\partial}{\partial x_k}(J_i U_k + J_k U_i)\right] + \frac{1}{e n_e c}\left(\vec{J} \times \vec{B}\right)_i - \frac{1}{e n_e}\frac{\partial P_{ik}^{(e)}}{\partial x_k}$$

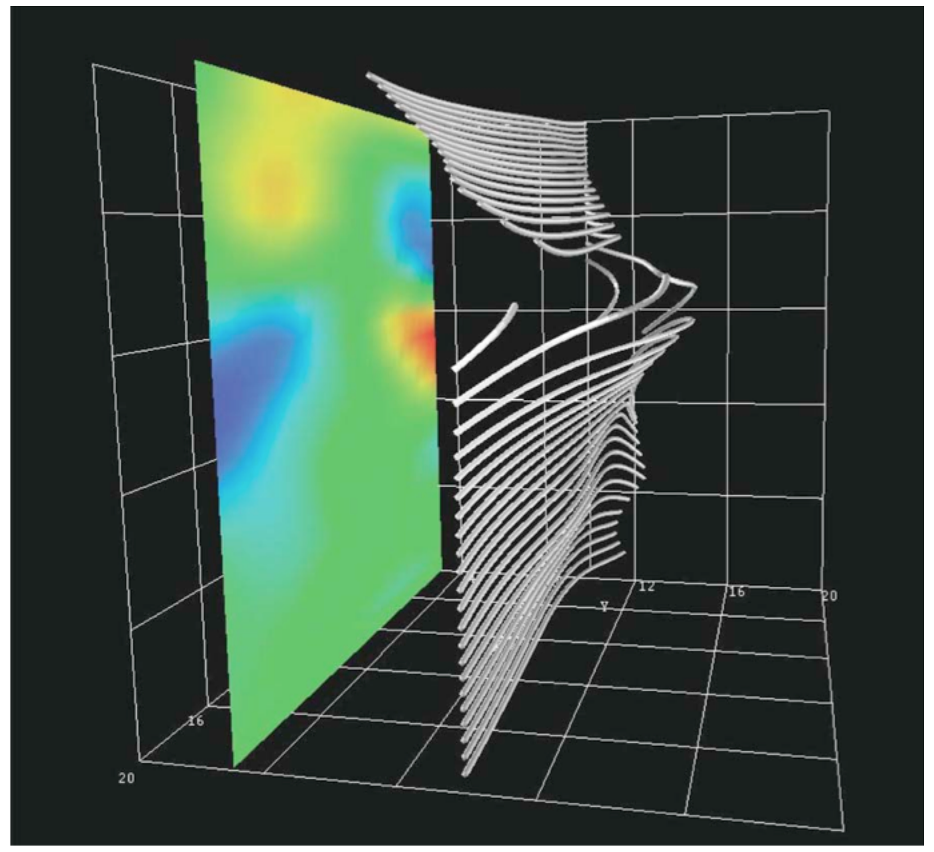
Generalized Ohm's equation

Ideal

Ion scales: Hall effect

Electron scales:

- Electron Inertia
- Electron Pressure tensor



Ren et al. 2006, PRL

Electrons are magnetized

$$L \gg \rho_e$$

Parameters

$$n_e = 2\text{–}6 \times 10^{13} cm^3$$

$$T_e = 5\text{–}15 eV$$

$$B = 0.1\text{–}0.3 kG$$

$$S > 400$$

Numerical simulations of magnetic reconnection

PIC

Example: Spitkovksy, Dorland, Drake, Sironi, Zenitani- Hesse, Horiuchi-Usami, Kumar Et al..

Implicit- PIC

Lapenta, Pucci, Marchidis, Innocenti

Gyrokinetic

Juno, Teenbarge
Jekyll Code

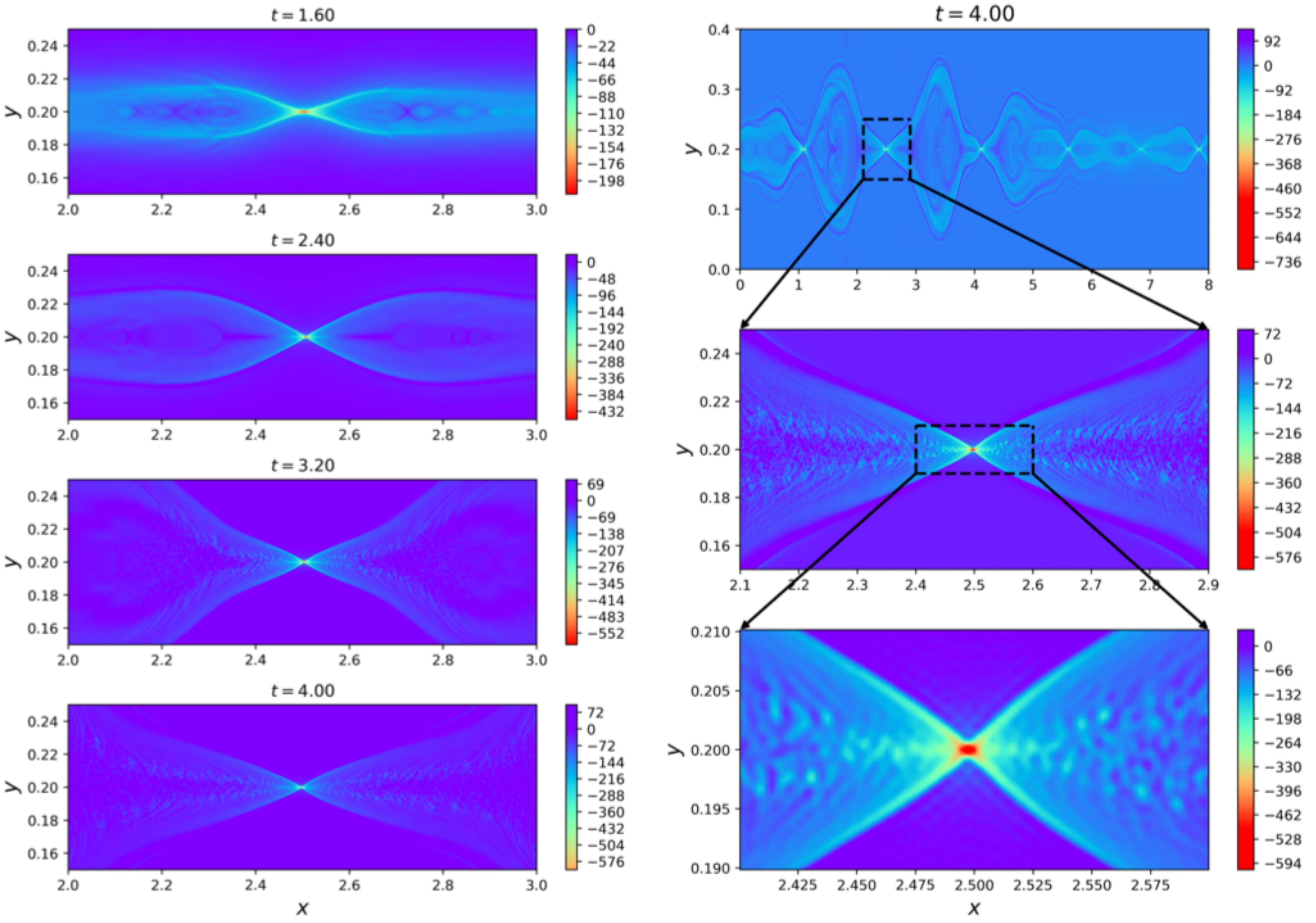
Frank Yenko
(Max Plank)

Generalized Fluid

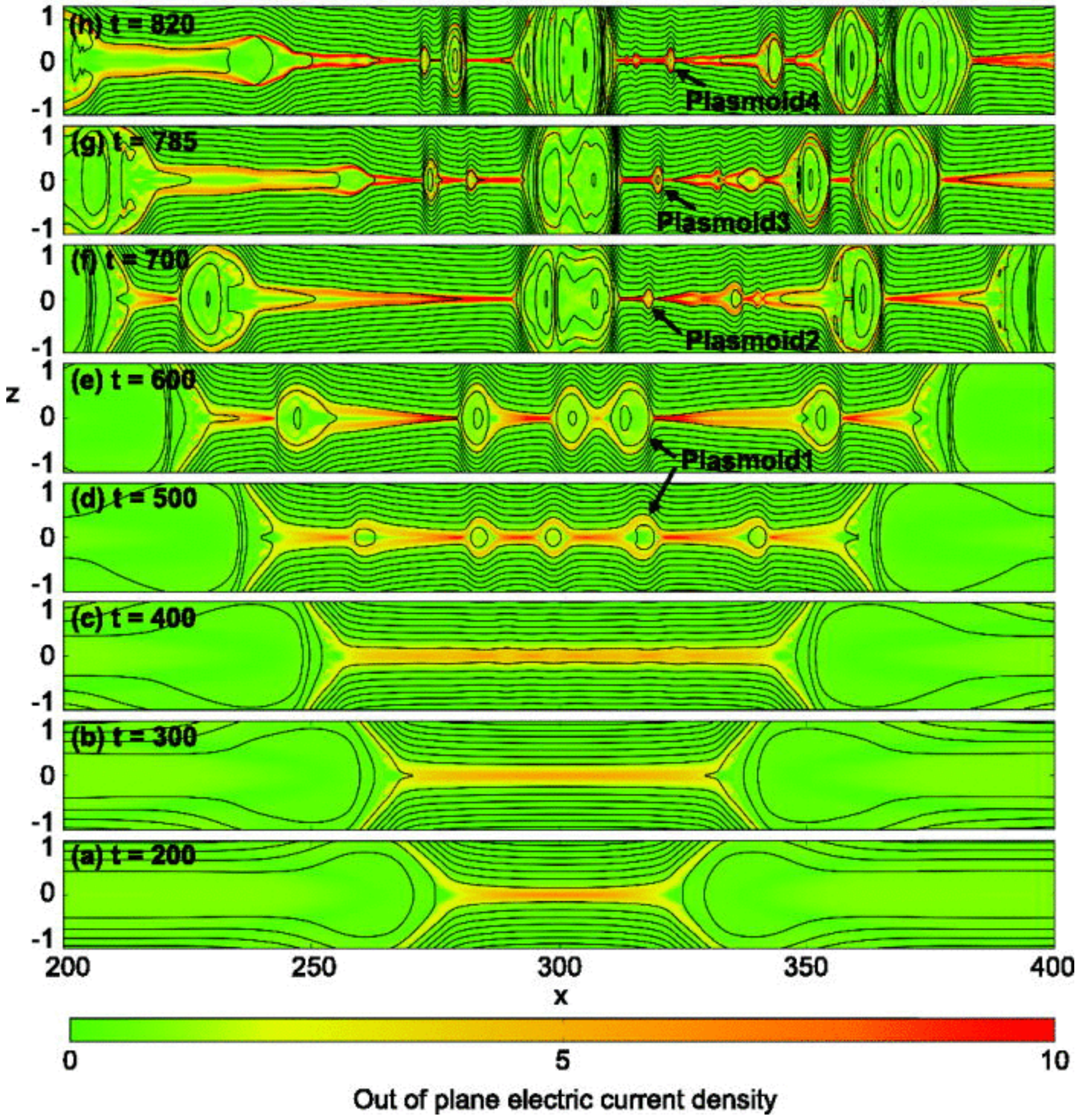
Example: Murphy, Tenerani-Velli-Shi, Rappazzo, Matthaeus

Fluid simulations of magnetic reconnection

Hall reconnection: Shi et al. 2021

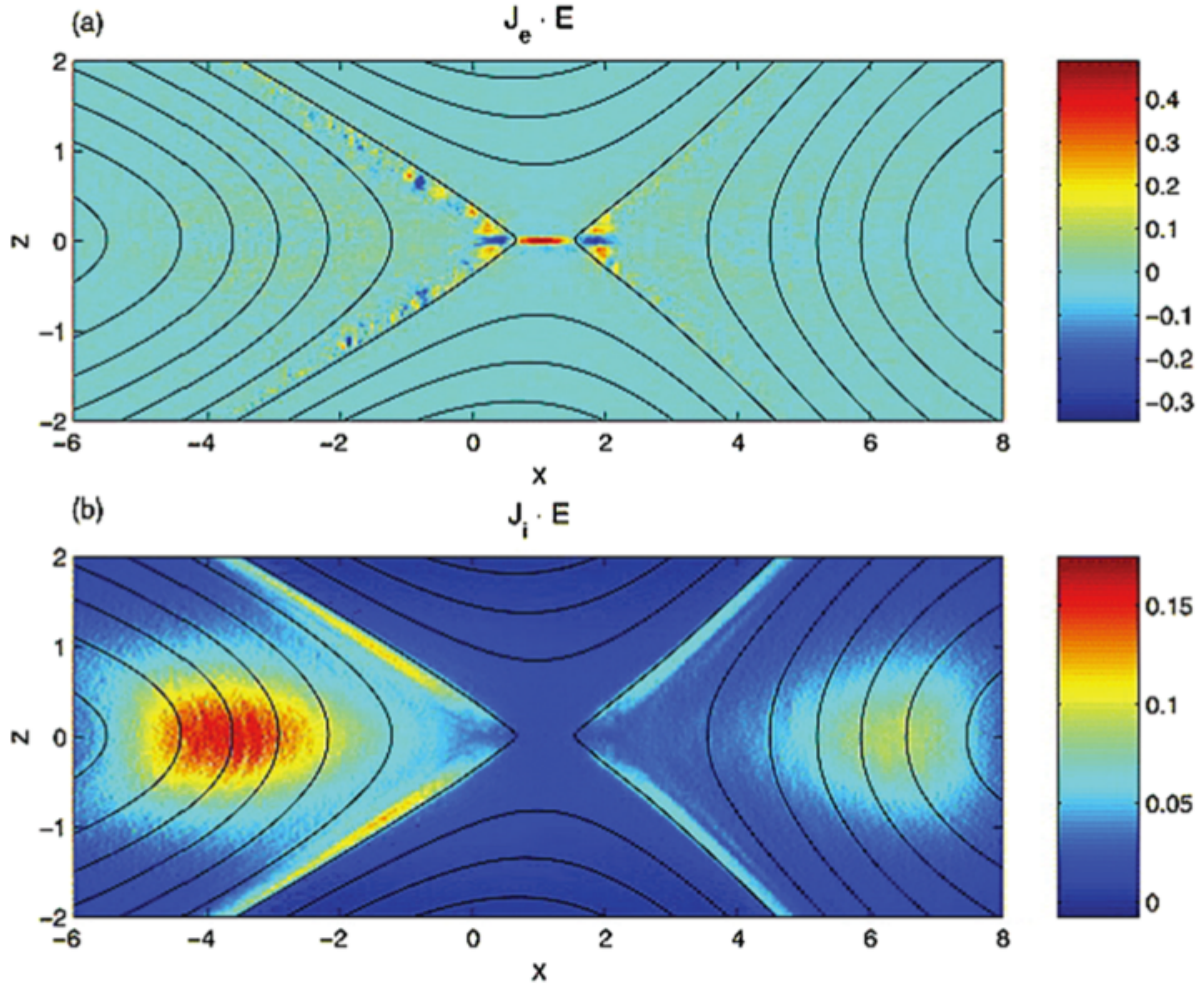


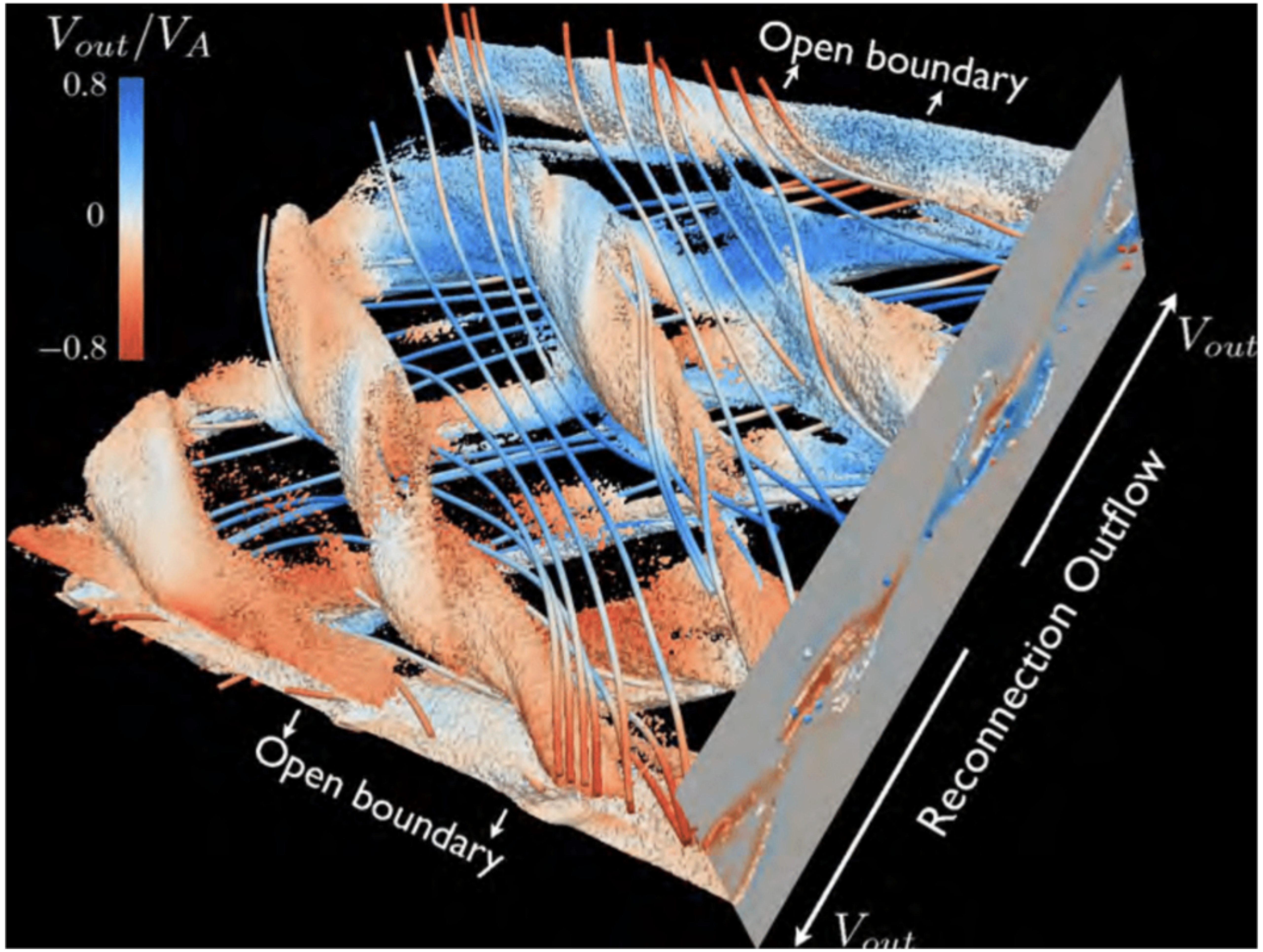
Petschek reconnection: Shibayama et al. 2015



Full-PIC simulations of magnetic reconnection

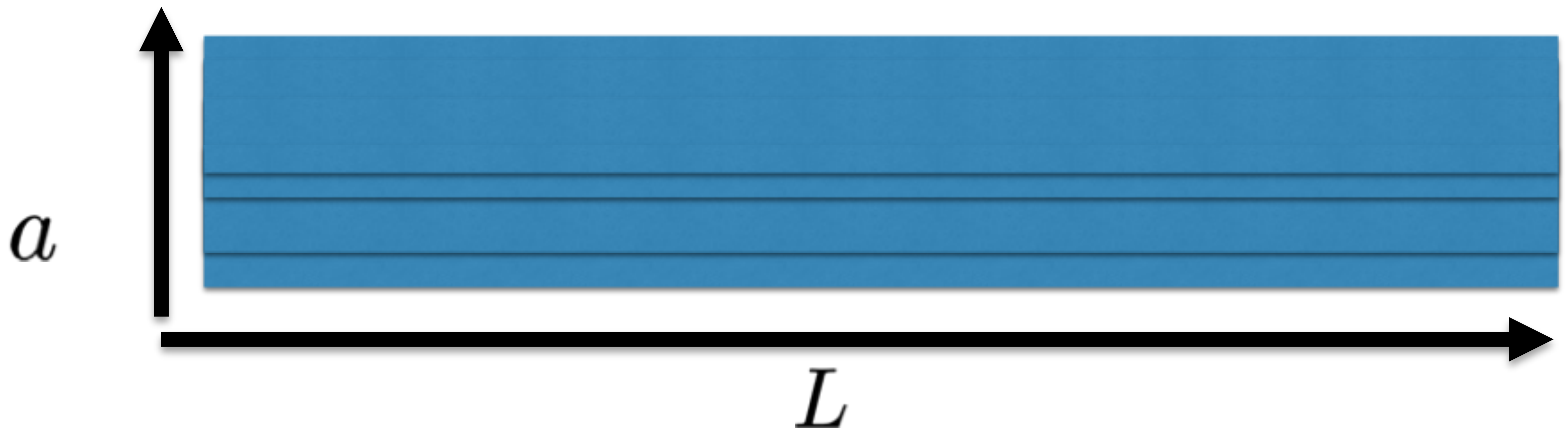
Pritchett et al 2010



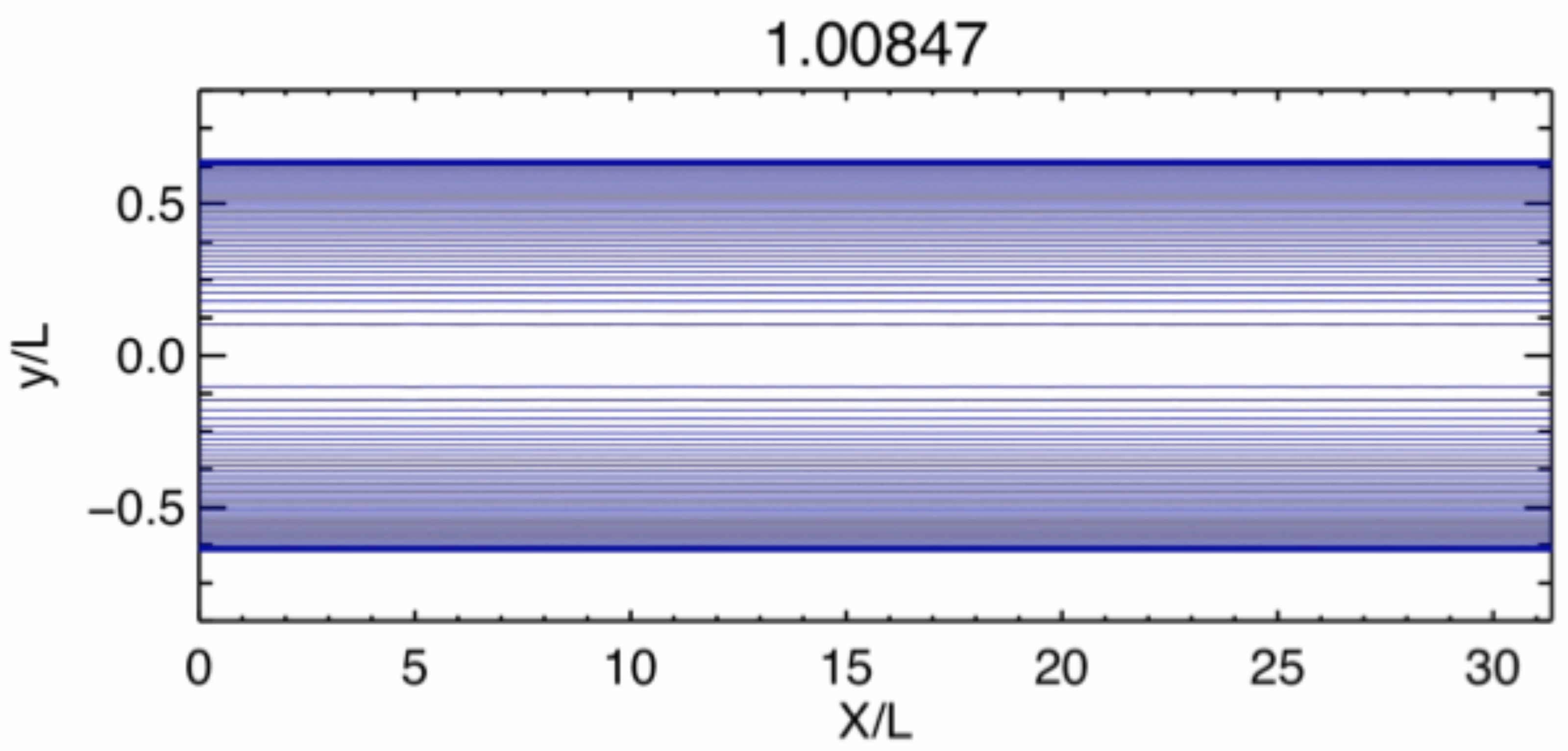


Daughton et al 2006

Onset of magnetic reconnection



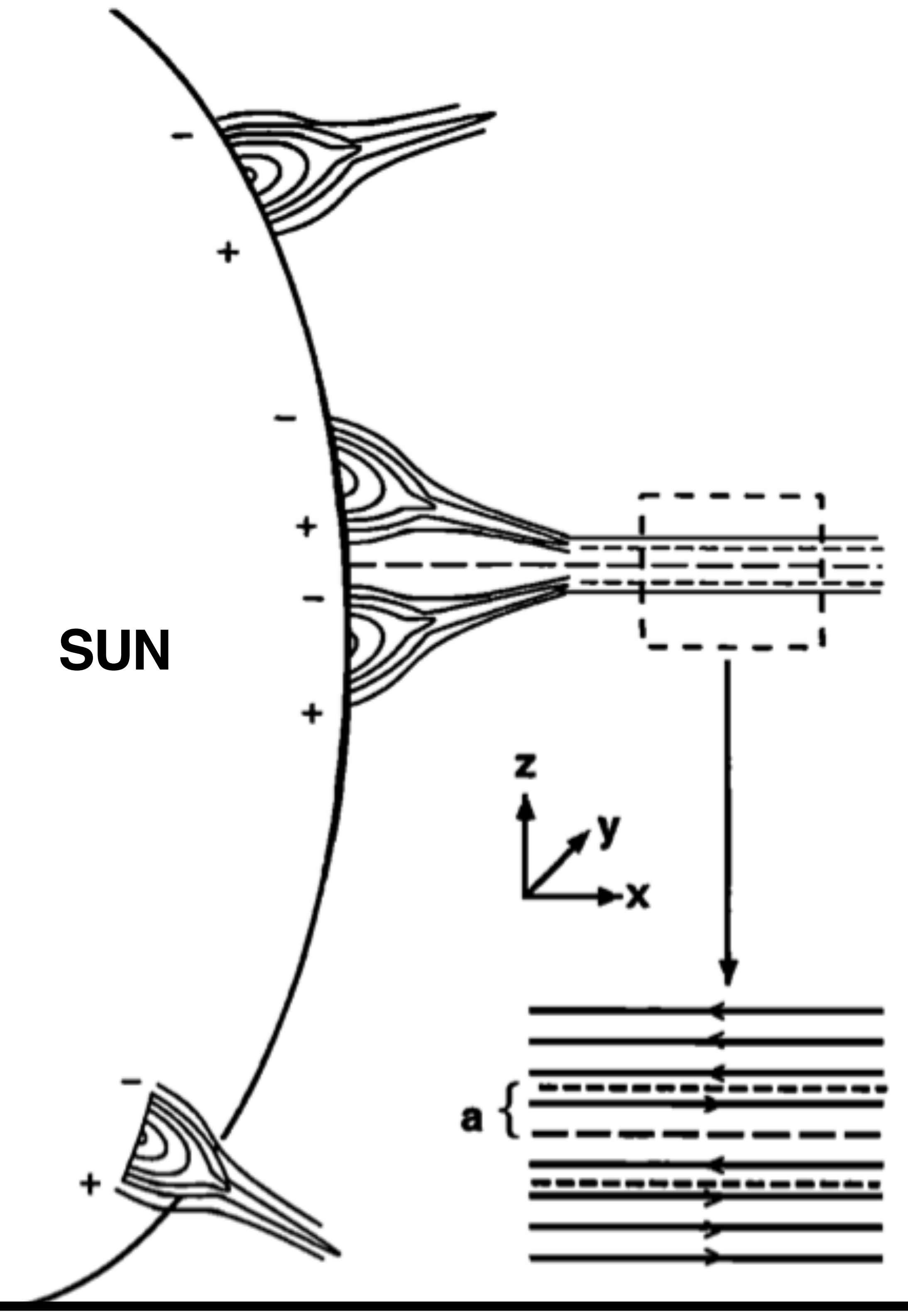
If reconnection was on at all times, how could the energy accumulate during the build up phase? There must be a trigger mechanism!



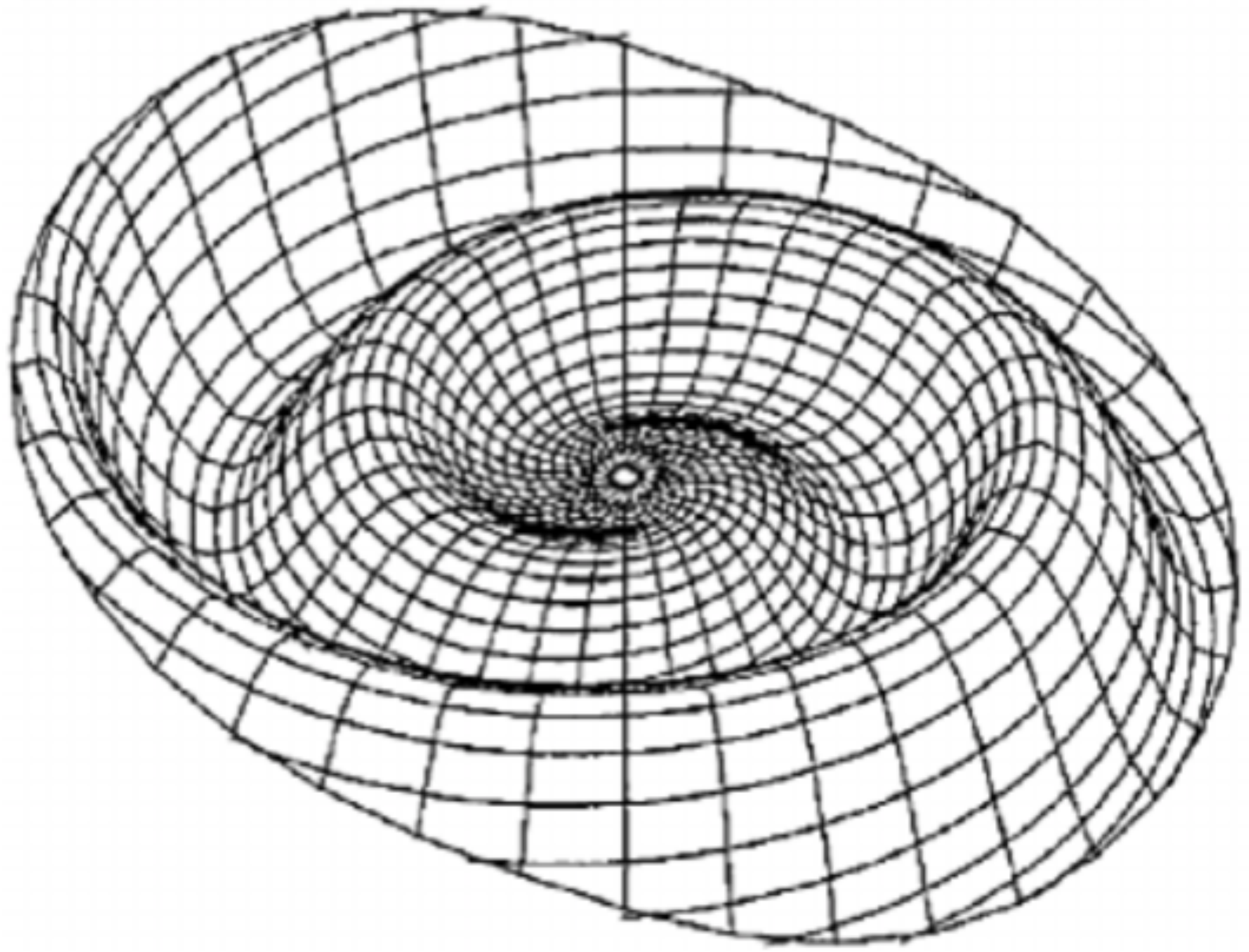
Pucci and Velli ApJL 2014

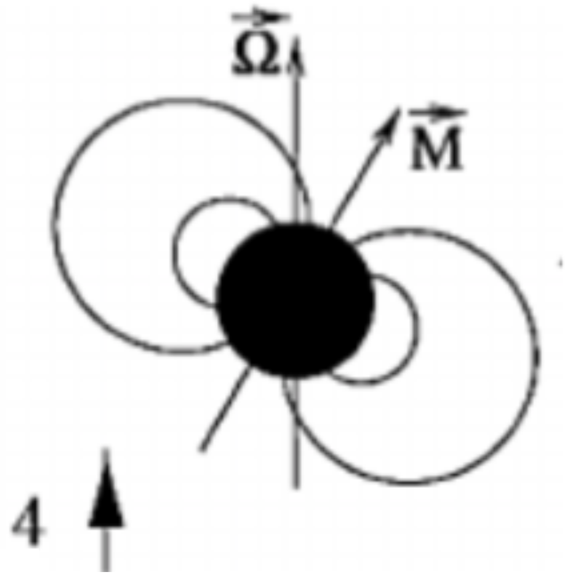
Tenerani et al. ApJ, 2015a

Reconnection in realistic setups: 3D multiple current sheets



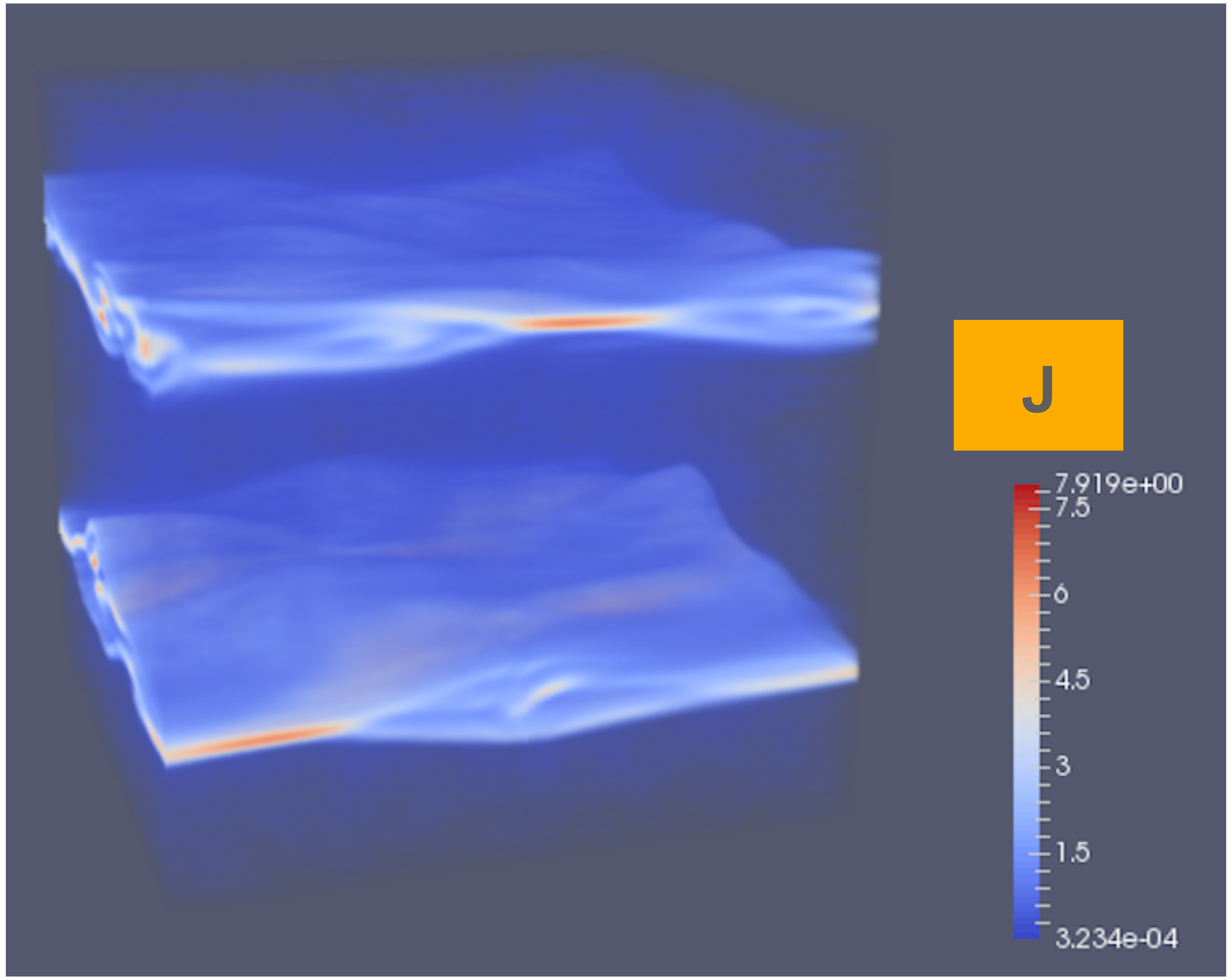
Sketch of the 'ballerina' curtain separating the polarities of the magnetic field lines of a rotating oblique split monopole.





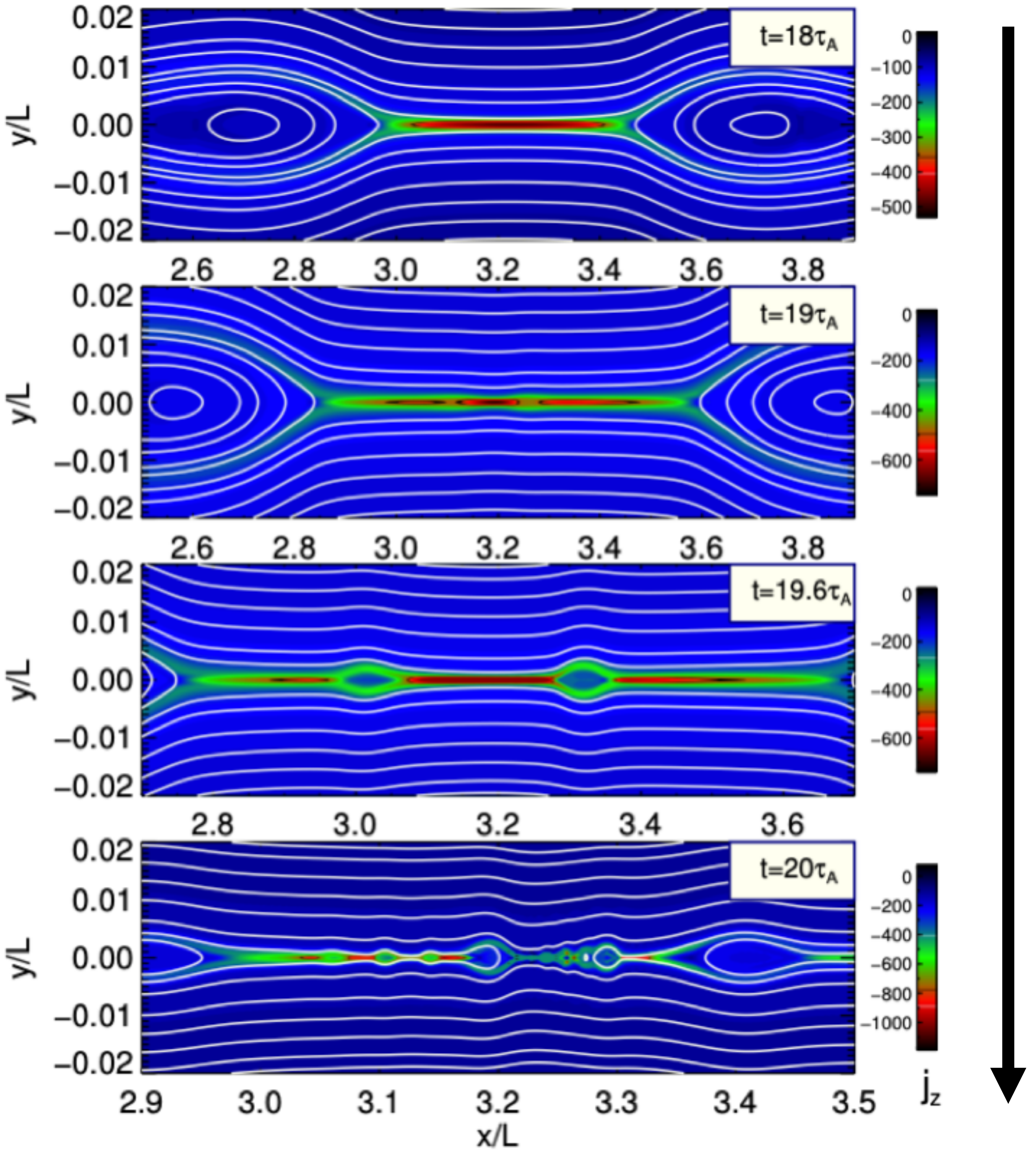
Dahlburg and Karpen 1995: model of two adjoining coronal helmet streamers and definition sketch of triple current sheet.

PERTURBATION AMPLITUDE f_v=0.01 f_b=0.01



Pucci et al 2016 PhD Thesis

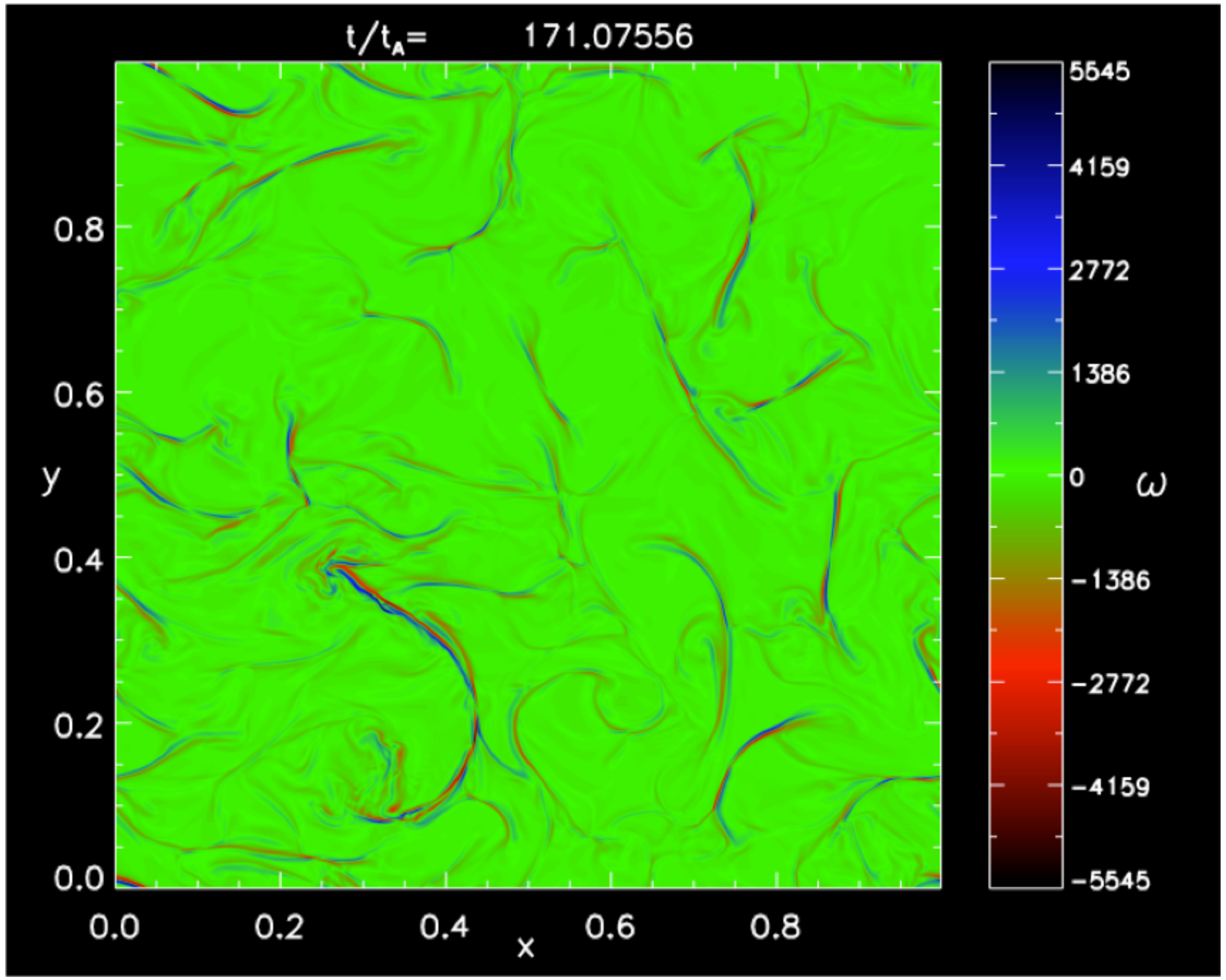
Turbulent reconnection

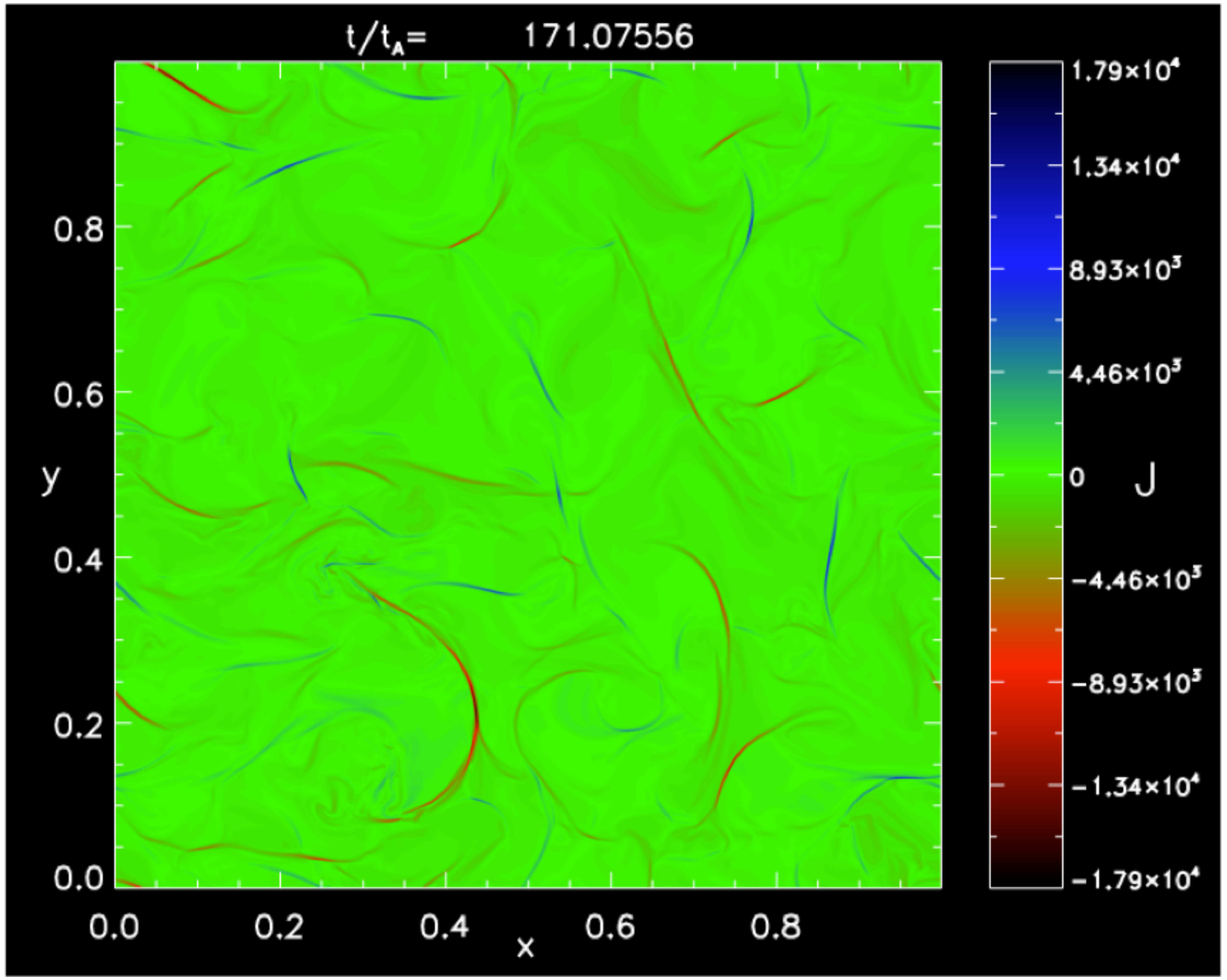


- Energy is ultimately dissipated at small scales
- We know kinetic physics of magnetic reconnection becomes important within the current sheet.
- How reconnection transfers energy from large to small scales? Plasmoid-instability (Loureiro 2007, Bhattacharjee 2009, Pucci 2013, Uzdensky et al 2016)
- Plasmoid formation and merging
- Dynamics changes at different scales.

Turbulent reconnection

Reconnection in a turbulent setup





Some Reference and Open questions

- Trigger of magnetic reconnection with a normal component: magnetospheric reconnection storms and substorms (Sitnov et al 2019, Birn 2009)
- Trigger of CMEs: ideal instability or simulations ? (Wyper et al 2017, Kliem 2006, Ishiguro and Kusano 2007)
- Does reconnection explain for coronal heating through nano-flares? (Rappazzo et al 2007-2008, Hansteen et al 2014)
- Energy transfer and dissipation from large to small scales (see. Masaaki Yamada, Russell Kulsrud, and Hantao Ji 2010)
- Do current sheet form in turbulent magnetic setups? What is the role of Intermittency? (Wan et al.2013, Osman et al 2014)
- What terms provide actual irreversible particle heating? (Yang et al 2017, Zenitani 2011)
- Exciting questions about reconnection **YOU** might solve in the future!

Additional material and contacts

Thank you for your attention!

- **BOOKs:**
- Magnetic Reconnection by Biskamp (2009)
- Magnetic Reconnection by Priest and Forbes (2000)
- “Basics of Plasma Astrophysics” by Chiuderi and Velli (2015)
- “Introduction to Magnetic Reconnection in Plasmas” by Porcelli (2012)
- “Spheromaks” by Paul Bellan (2000)
- fulvia.e.pucci@jpl.nasa.gov, fulvia.pucci87@gmail.com I am happy to set up a zoom call to answer your questions!