Magnetic Null Points in 3D Kinetic Simulations of Space Plasmas

Vyacheslav Olshevsky[1,2]

sya@mao.kiev.ua

Jan Deca, Maria Elena Innocenti, Emanuele Cazzola, Ivy Bo Peng,

Andrey Divin, Elin Eriksson, Stefano Markidis, Giovanni Lapenta

Center for mathematical Plasma Astrophysics, KU Leuven, Belgium

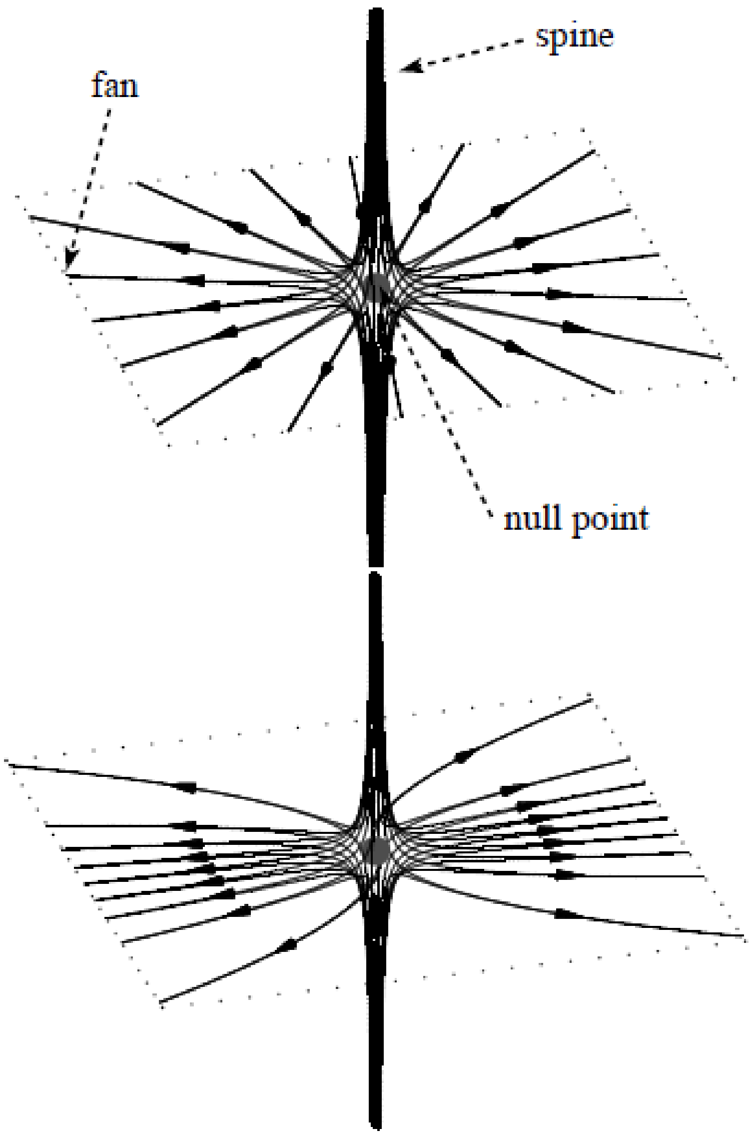
Main Astronomical Observatory, Kyiv, Ukraine

KTH Royal Institute of Technology, Stockholm, Sweden

Swedish Institute of Space Physics, Uppsala, Sweden

St. Petersburg State University, Russia

Null-point classification



$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{r}} \cdot \boldsymbol{r}$$

$$\frac{\partial \boldsymbol{B}}{\partial \boldsymbol{r}} = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix}$$

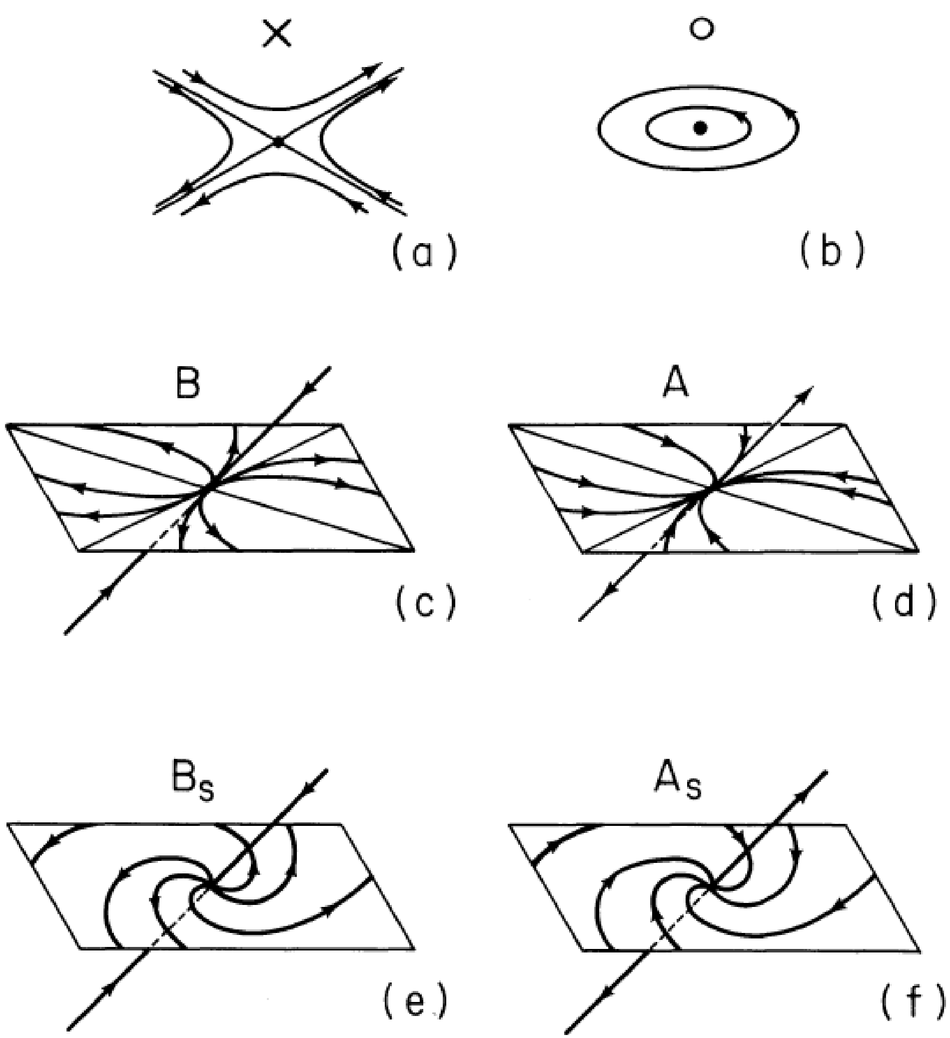
$$\boldsymbol{\nabla B} = 0 \ \rightarrow tr\left(\frac{\partial \boldsymbol{B}}{\partial \boldsymbol{r}}\right) = 0$$

3 eigenvalues:

$$\lambda + \mu + \nu = 0$$

Cowley (1973), Lau & Finn (1989), Parnell et al. (1996)

Radial and spiral null points



Nulls classification by Lau & Finn (1989)

Radial nulls
A (negative), B (positive) -> X

Spiral nulls
As (negative), Bs (positive) -> O

Configurations under study

- Harris current sheet in 3D
- 'Asymmetric reconnection'
- Lunar Magnetic Anomalies (mini-magnetospheres)
- "Multiple null points" (Olshevsky et al., *Phys Rev. Lett.* **111**, 2013)

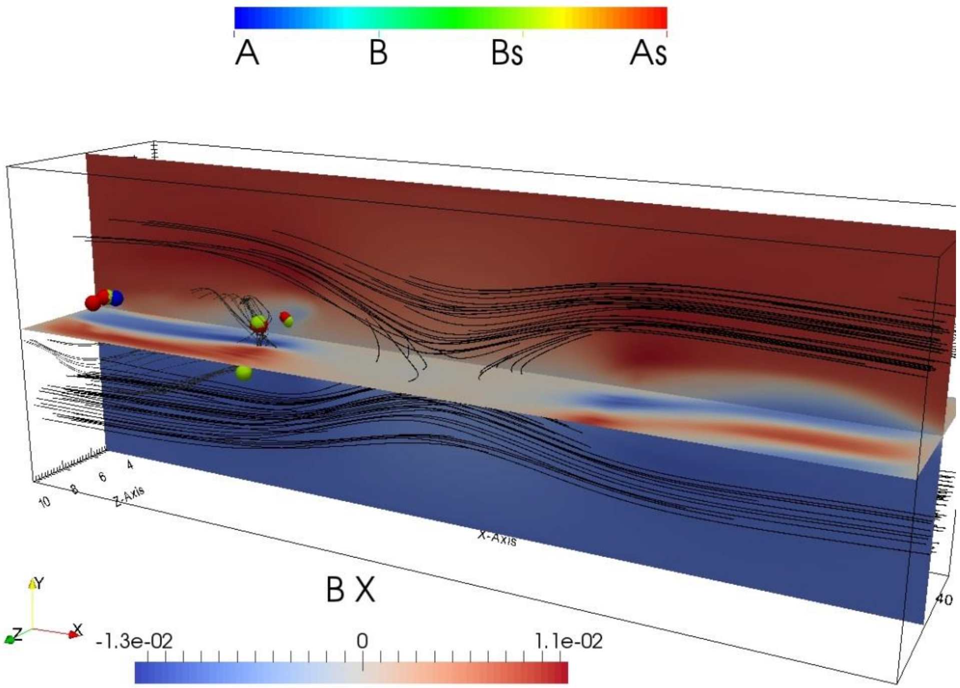
$$B_x = -B_0 \cos\frac{2\pi x}{L_x} \sin\frac{2\pi y}{L_y},$$

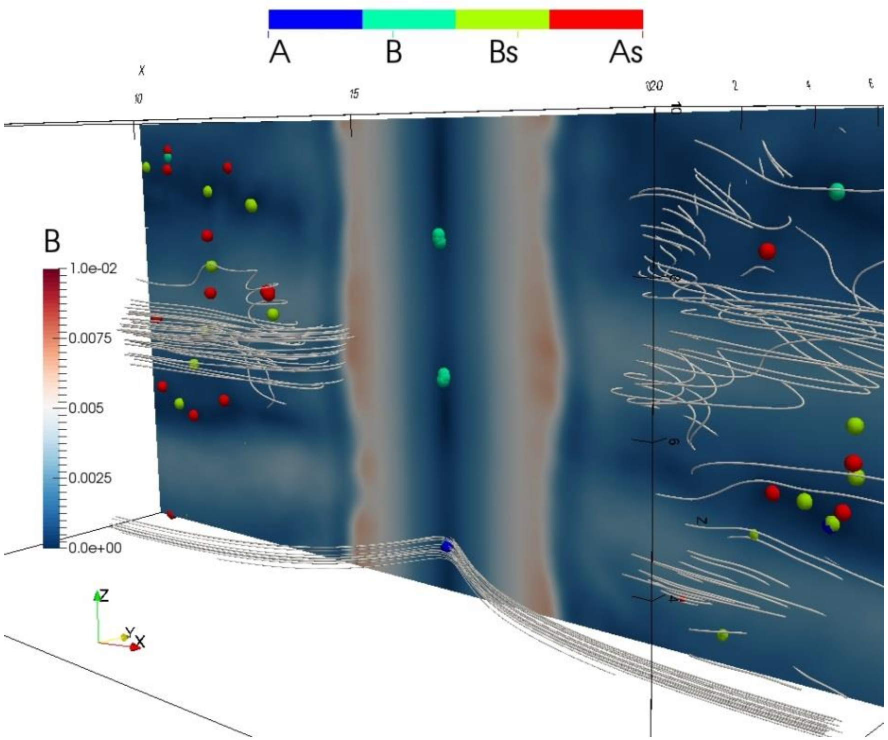
$$B_y = B_0 \cos\frac{2\pi y}{L_y}\left(\sin\frac{2\pi x}{L_x} - 2\sin\frac{2\pi z}{L_z}\right),$$

$$B_z = 2B_0 \sin\frac{2\pi y}{L_y} \cos\frac{2\pi z}{L_z}.$$

We use Poincare index method to locate and classify nulls in our simulations.

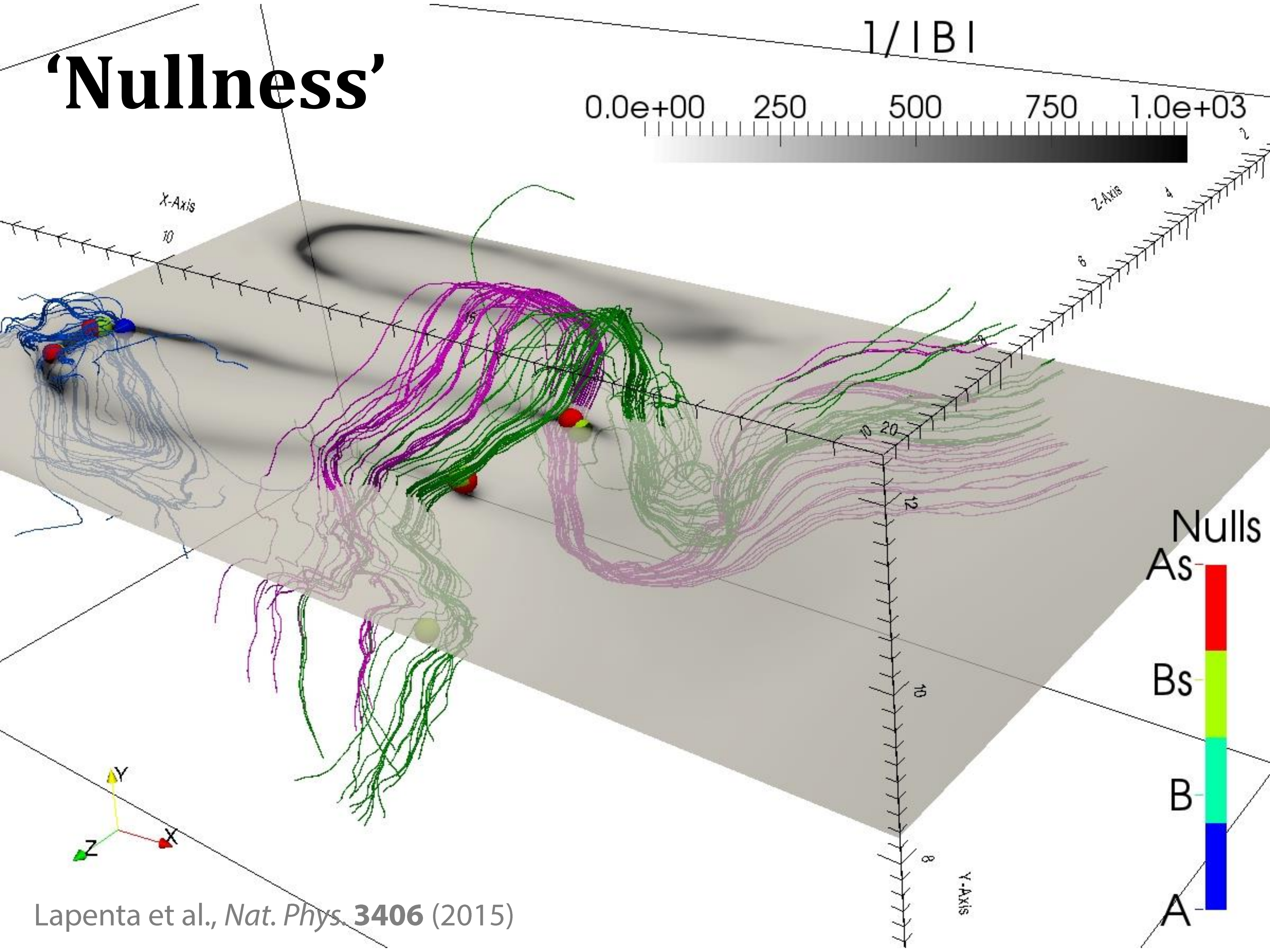
3D Harris sheet





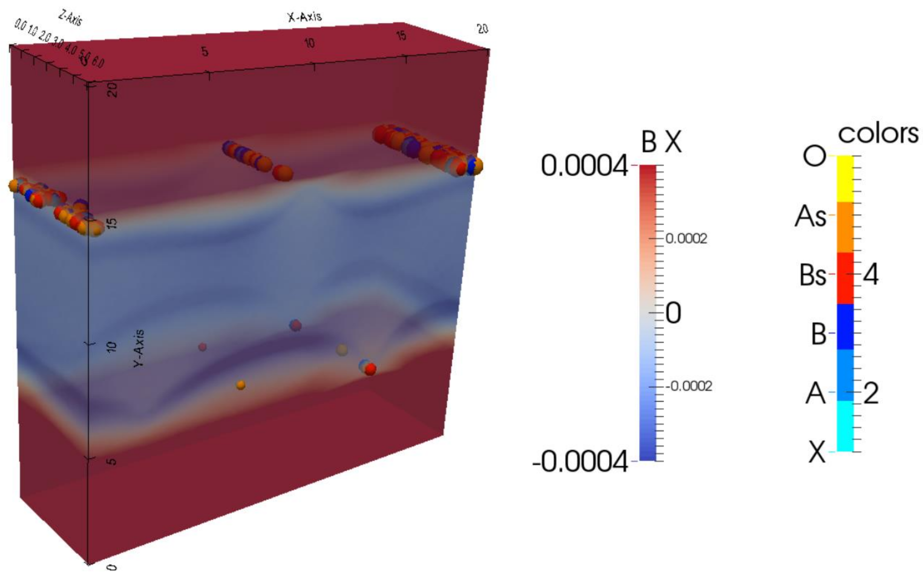
Kinetic PIC simulations by Giovanni Lapenta. Harris current sheet in 3D, with a very small guide field. The null points are identified using Poincare index method.

‘Nullness’



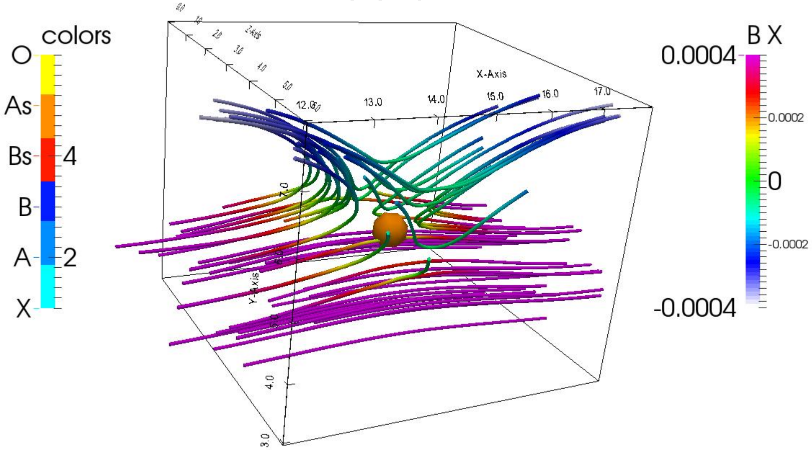
Lapenta et al., *Nat. Phys.* **3406** (2015)

‘Asymmetric reconnection’

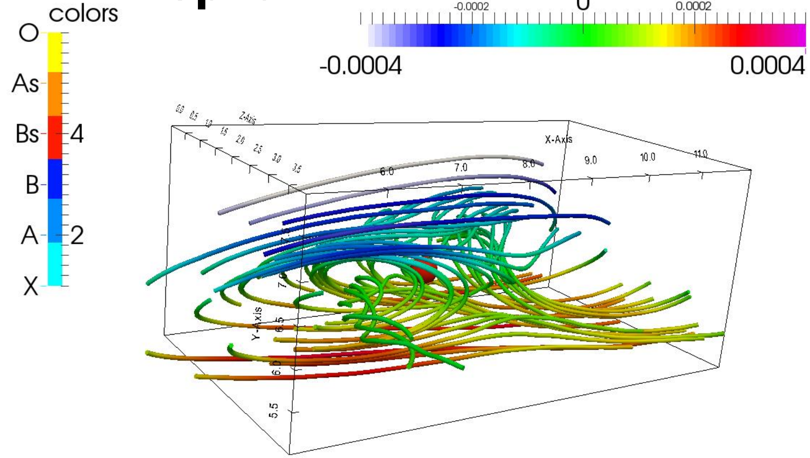


Reconnection was driven in the upper current layer, and spontaneous in the bottom one.

Radial

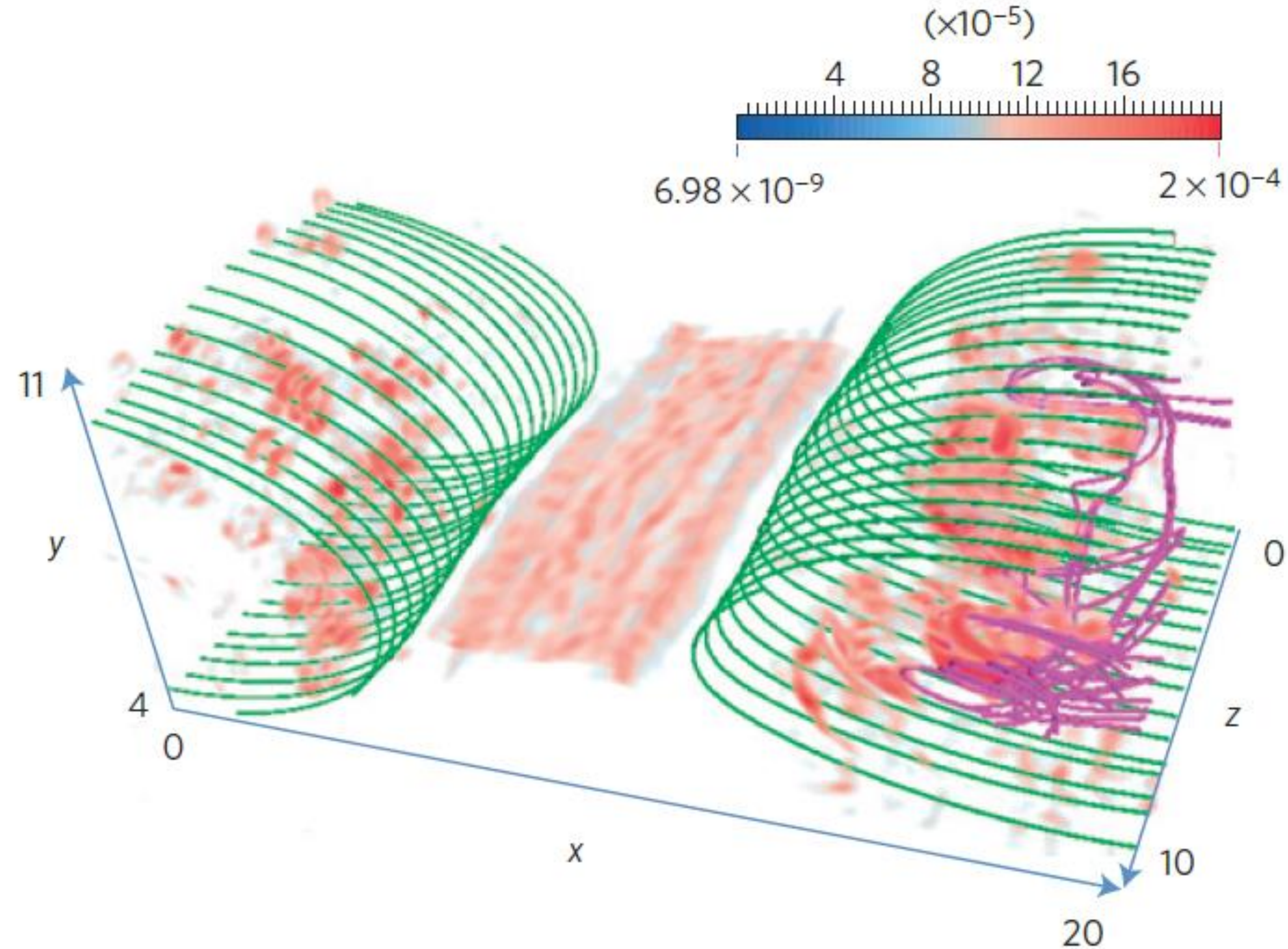


Spiral



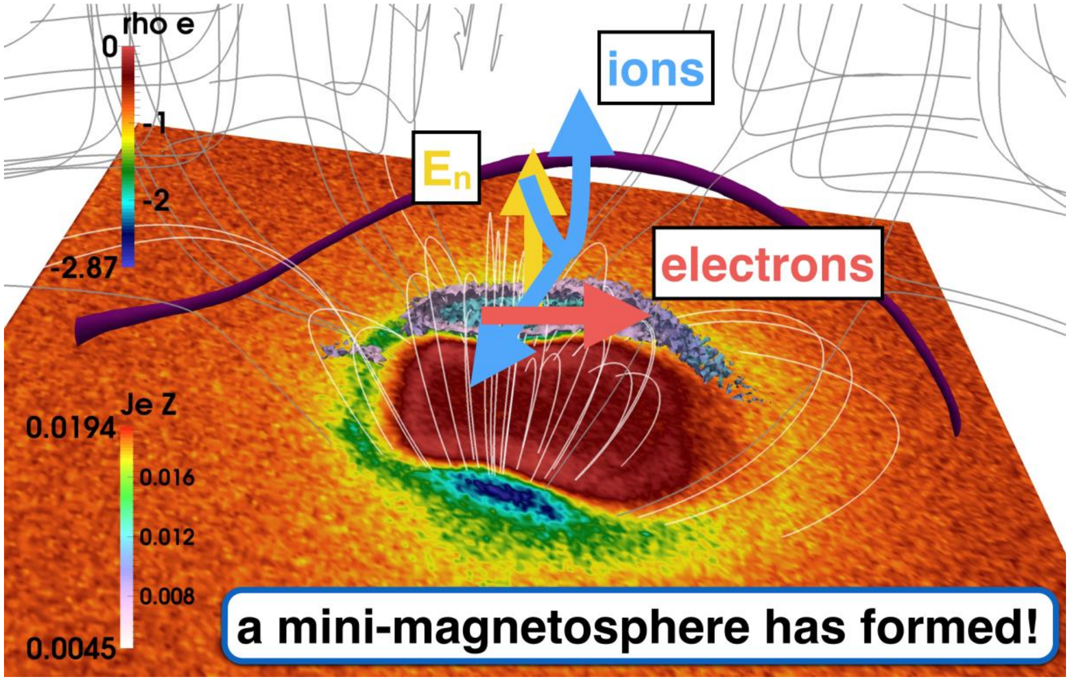
Cazzola et al., in preparation

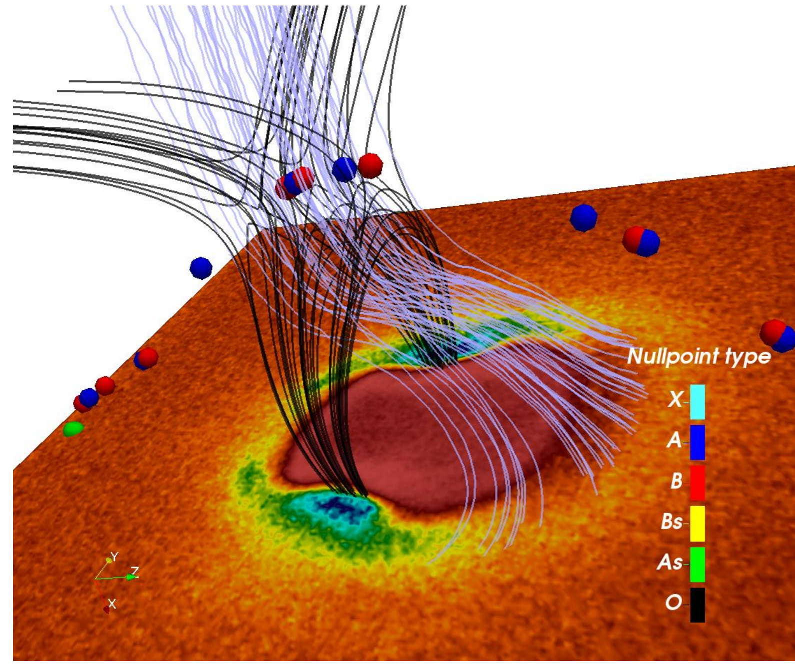
Magnetic nulls == magnetic reconnection?



Lapenta et al., *Nat. Phys.* **3406** (2015)

Radial nulls in Lunar Magnetic Anomalies





A steady-state model of the strongest dipole component of the Reiner Gamma anomaly under average solar wind conditions and the formation of a mini-magnetosphere above the lunar surface by Jan Deca.

Deca et al., *Phys. Rev. Lett.* **112** (2014)

Previous talks: nulls are ubiquitous in space.

This talk: nulls are ubiquitous in PIC simulations!

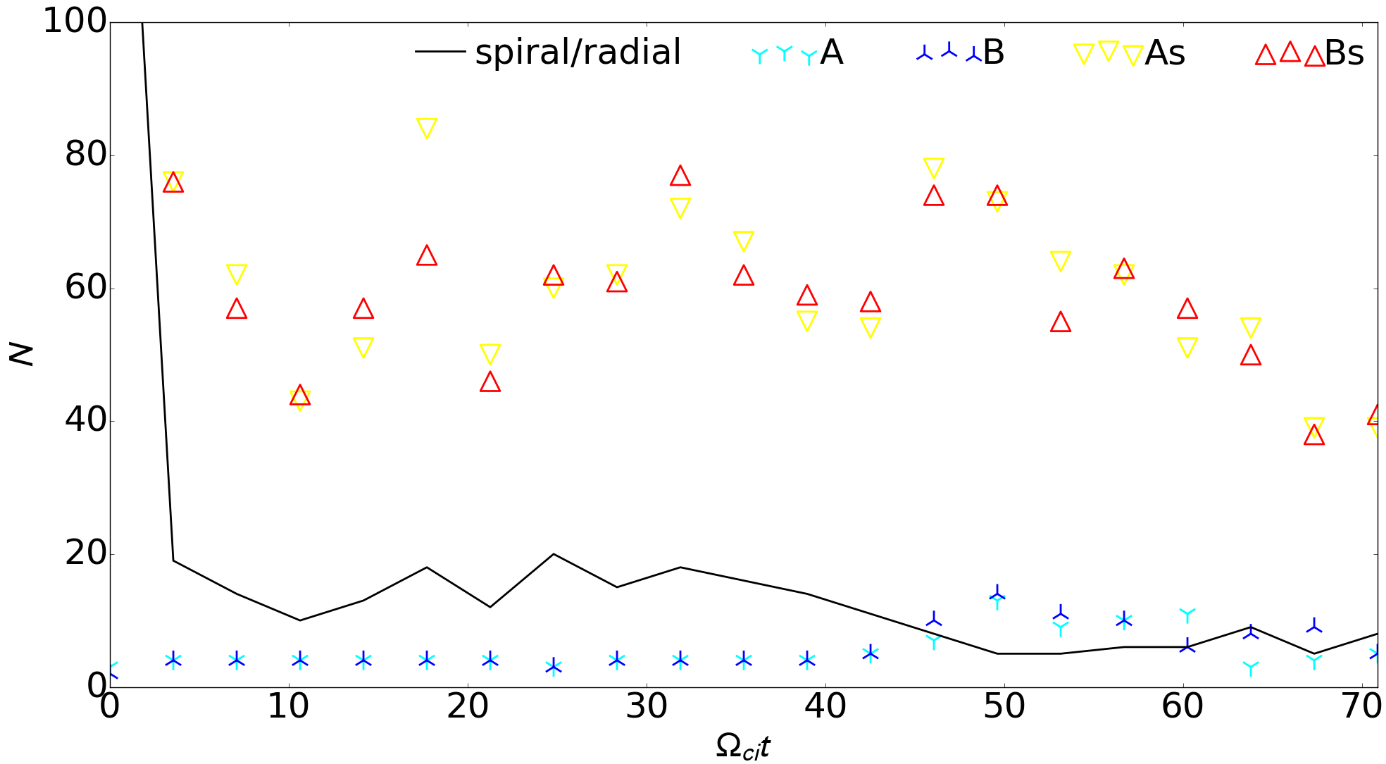
Not all nulls are important for reconnection?

Spiral & Radial nulls in the 'multiple-null' setup

Cluster observations (Elin Eriksson):

	Nulls found	A (%)	B (%)	As (%)	Bs (%)
Poincaré index	64	8	1	55	36
Taylor expansion	443	14	8	42	36

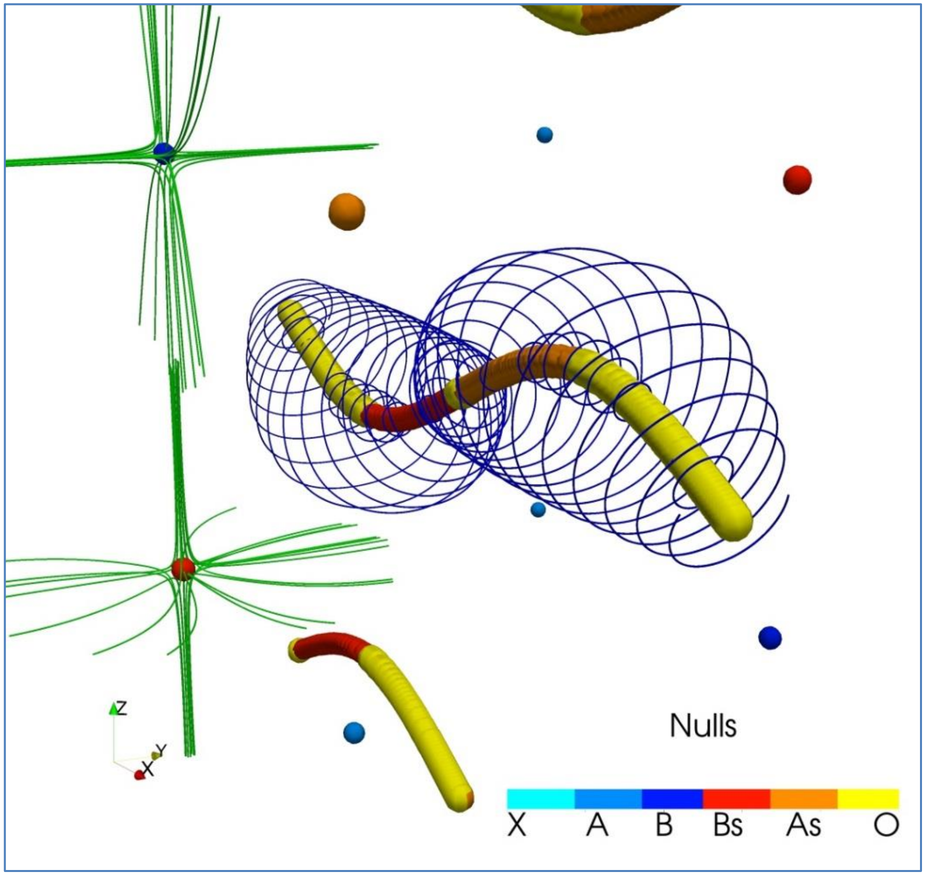
Kinetic PIC simulations:



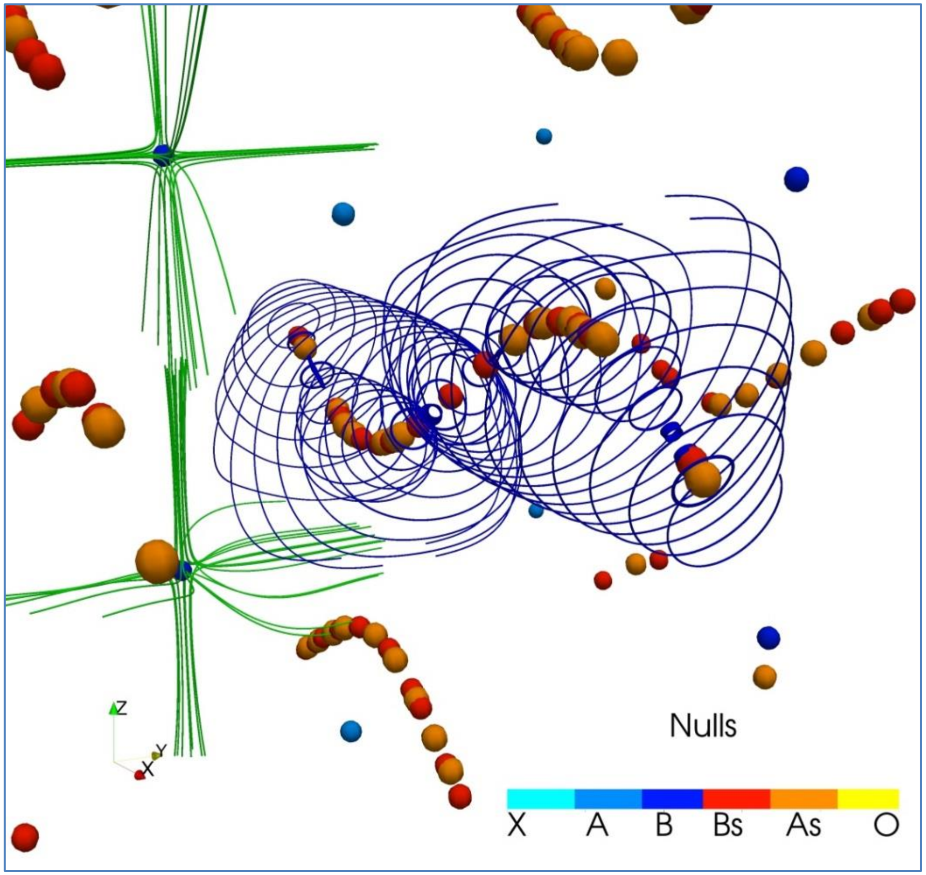
Olshevsky, Divin, Eriksson, Markidis & Lapenta, *ApJ* **807** (2015)

“Multiple nulls” scenario

O-points are structurally unstable. Topological type misdetection: A-As, B-Bs.

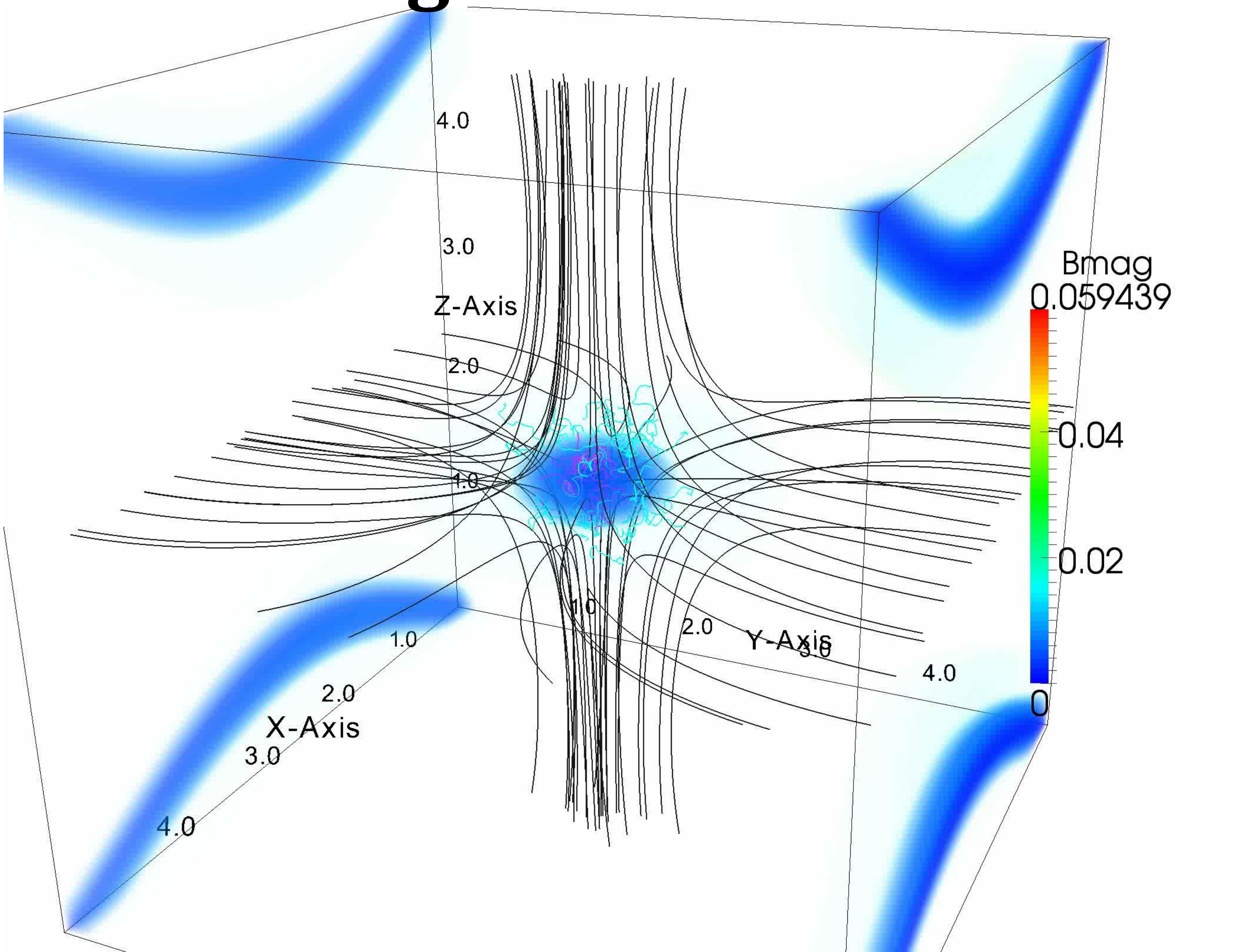


Initial condition

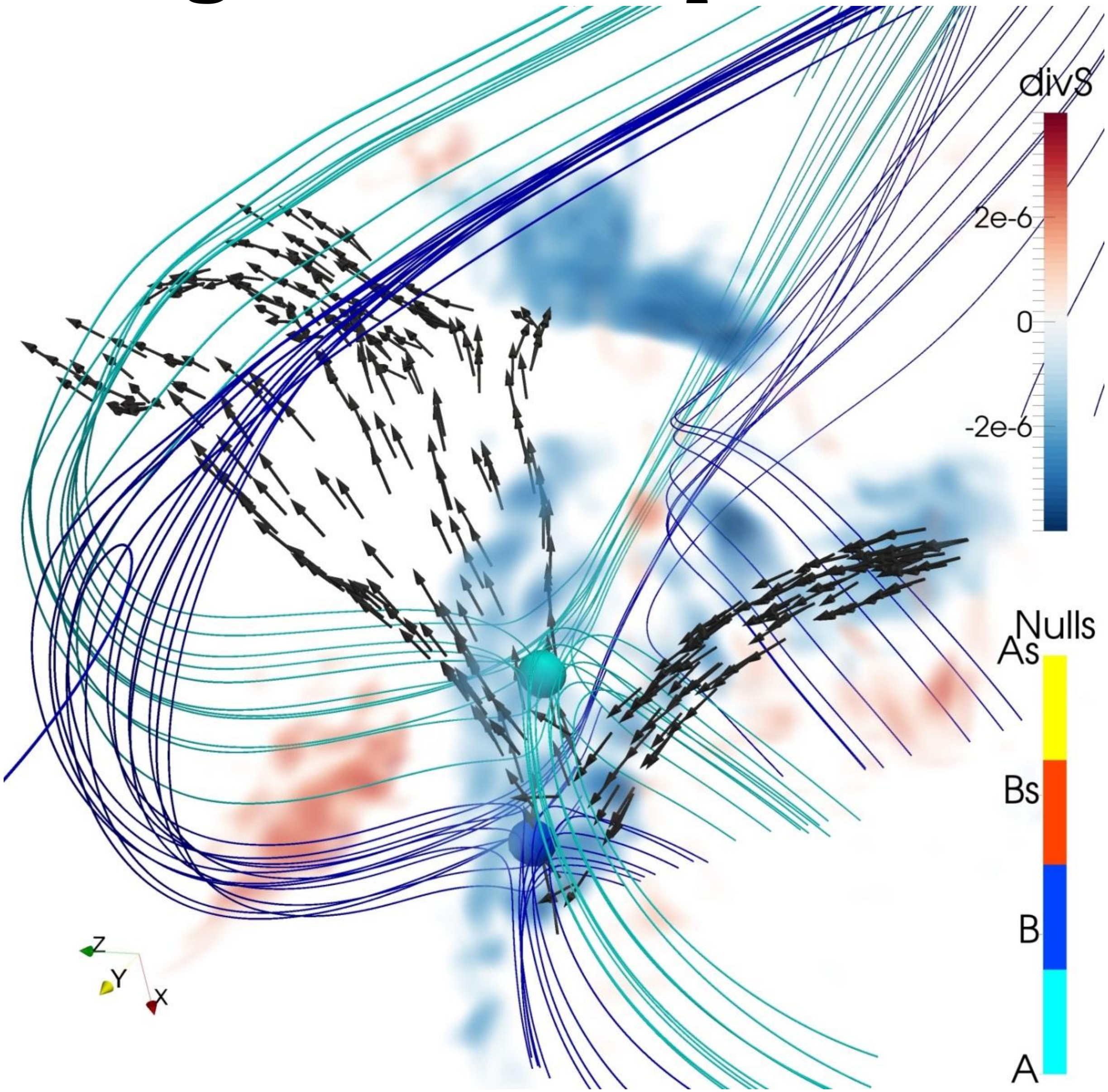


First snapshot

Reconnecting radial null



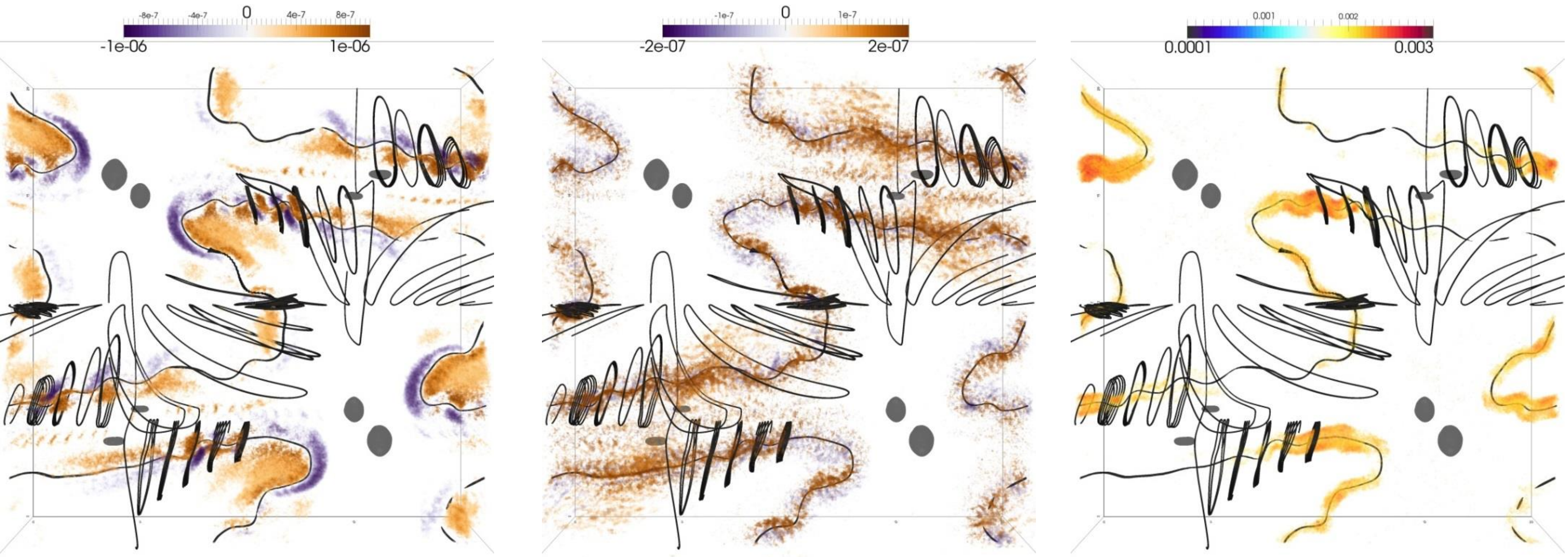
Short-living radial null pair



Reconnecting radial nulls are localized and rare.

Energy dissipation: spiral nulls!

E·J D_e T_e

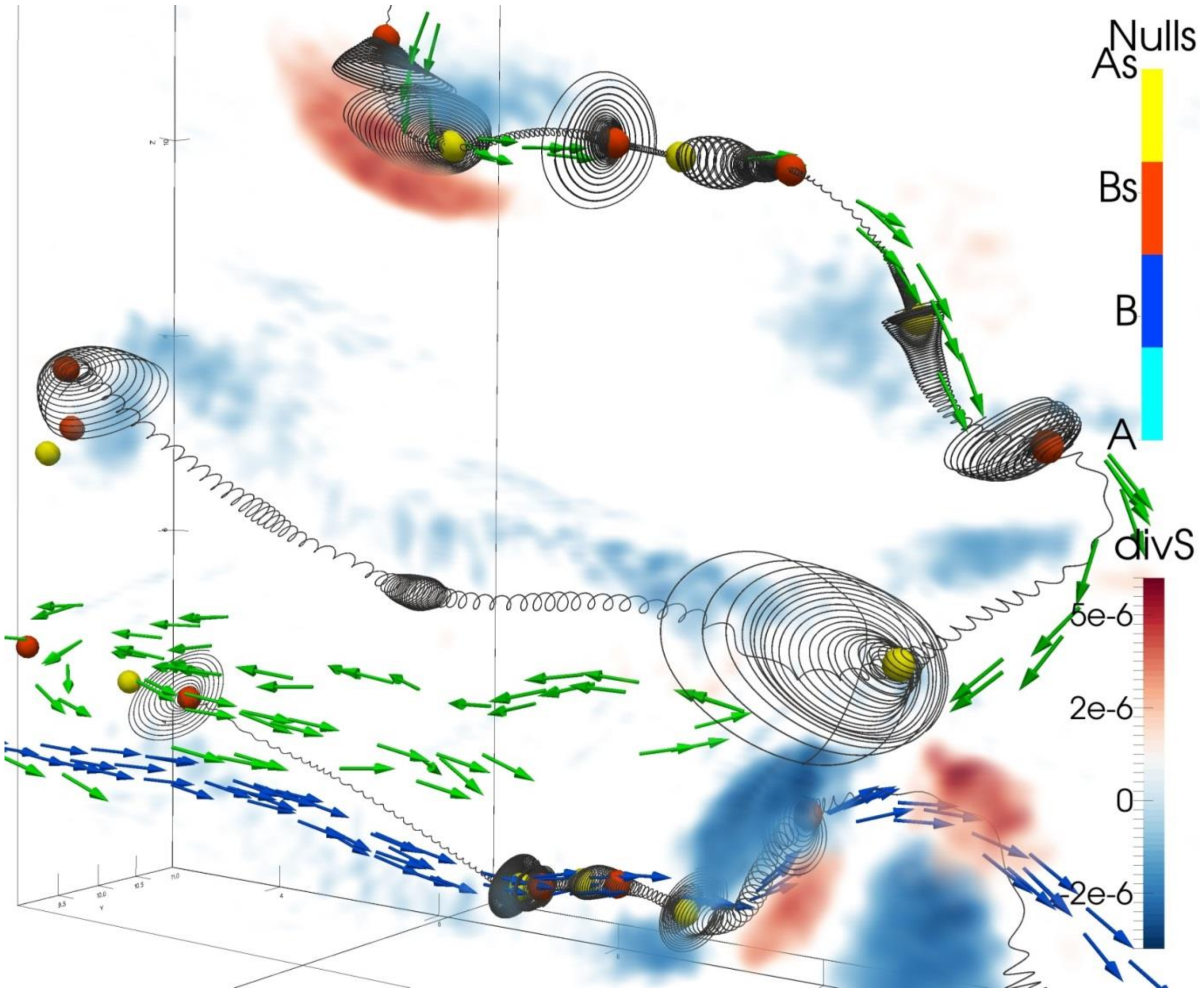


Dissipation measure D_e following Zenitani et al., Phys. Rev. Lett., 106 (2011) 359 195003

Olshevsky et al., *Journal of Plasma Physics* (2015)

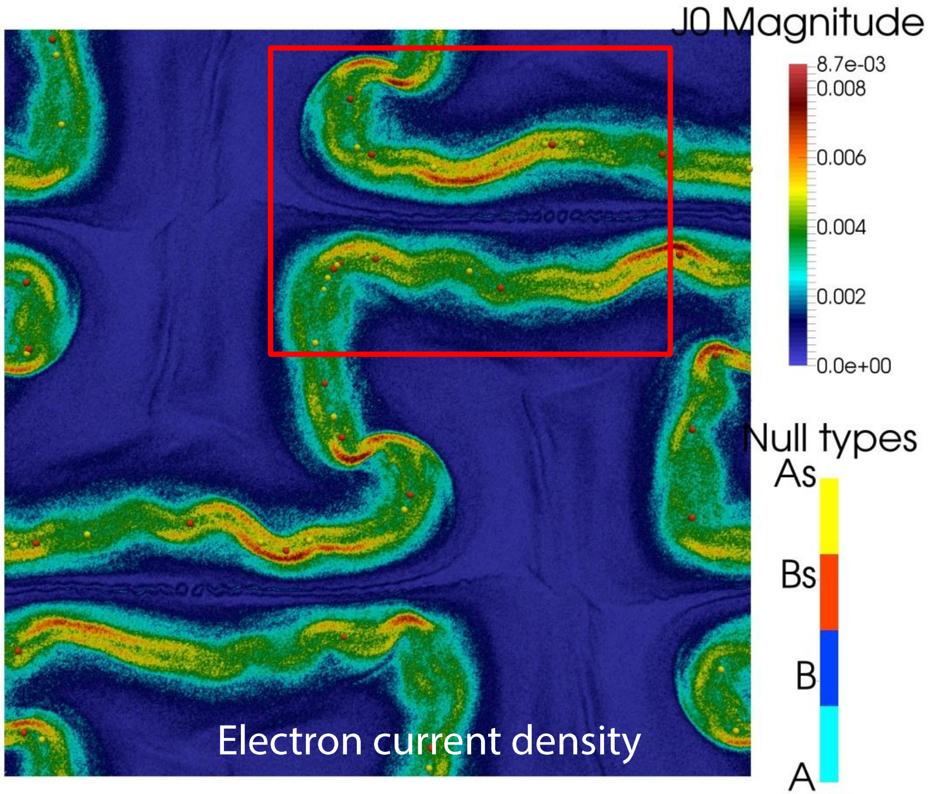
Spiral nulls inside magnetic flux ropes are more important for energy dissipation than radial nulls.

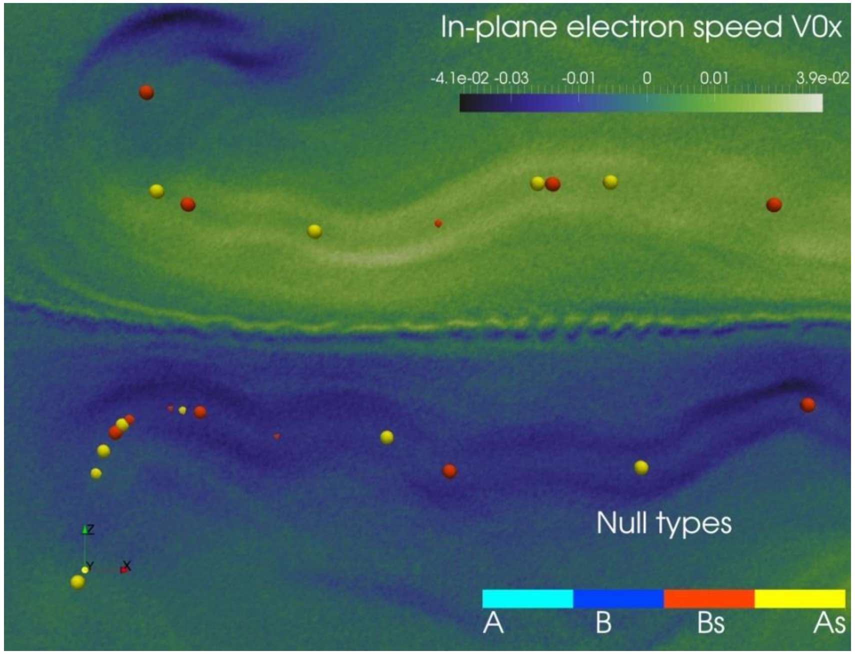
Spiral nulls inside magnetic flux ropes

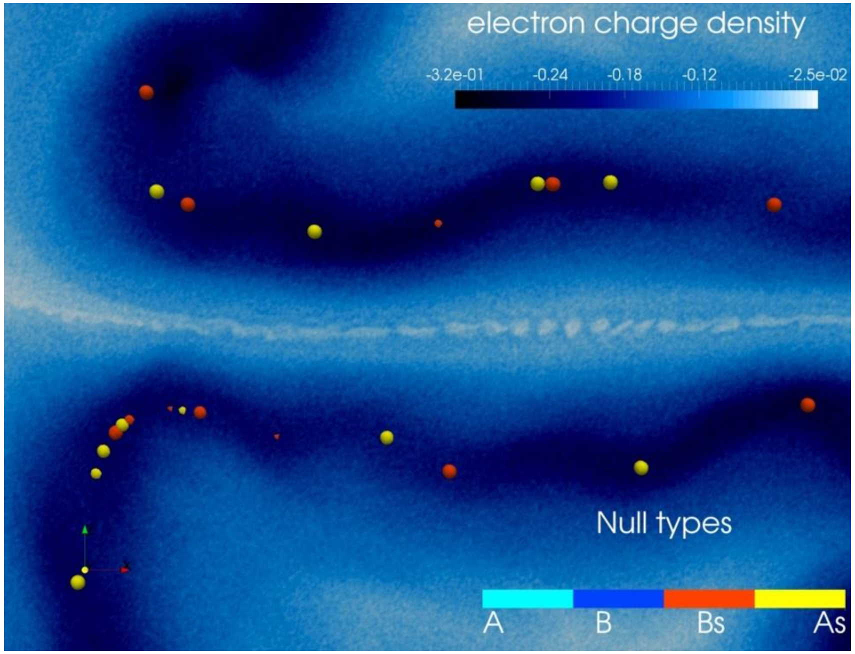


Very similar to MHD 'secondary bifurcations' described by Wyper & Pontin (2014).
Fan-fan separators and torsional spine reconnection.
Olshevsky et al., *ApJ* **807** (2015)

In-plane view

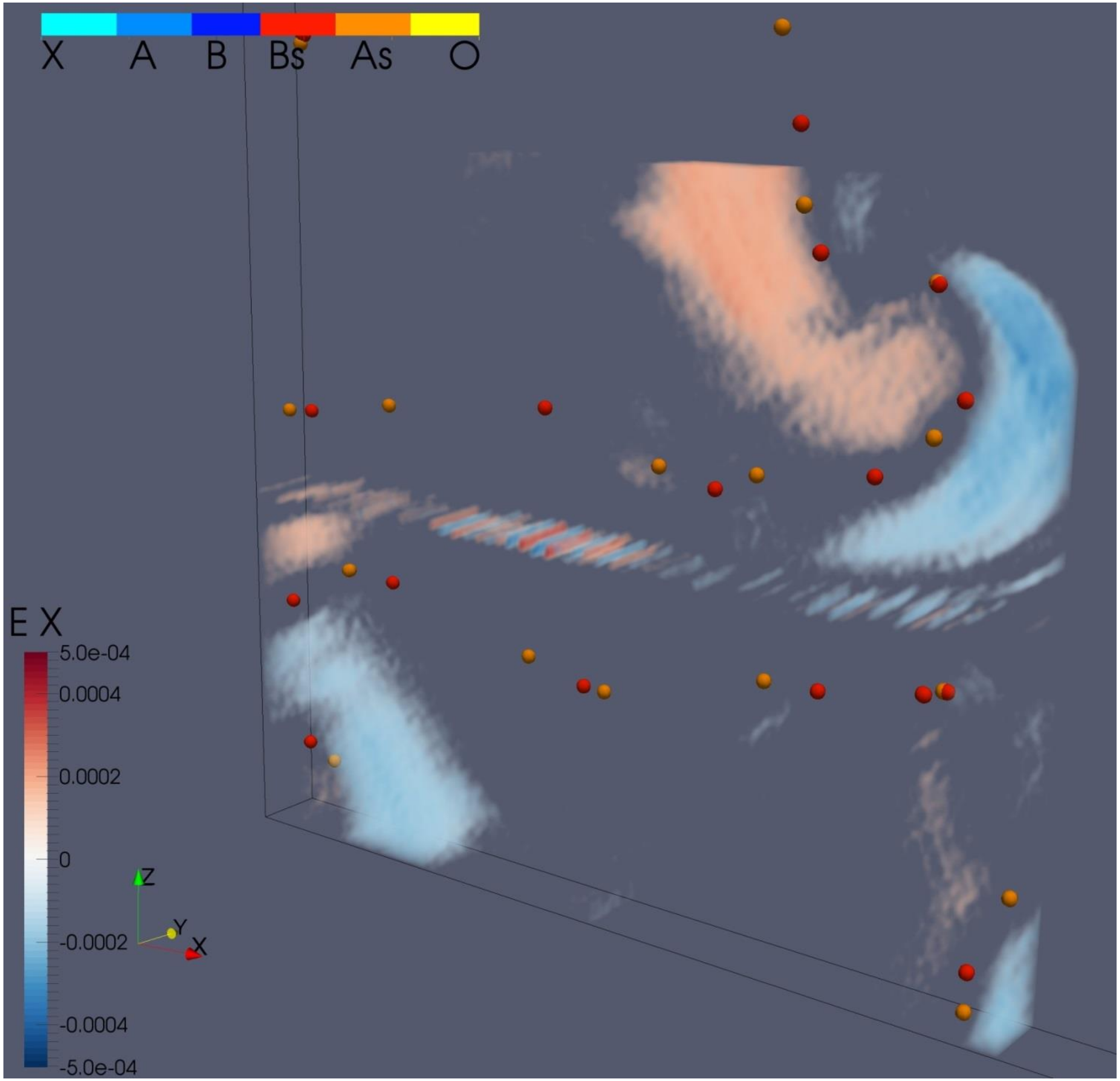




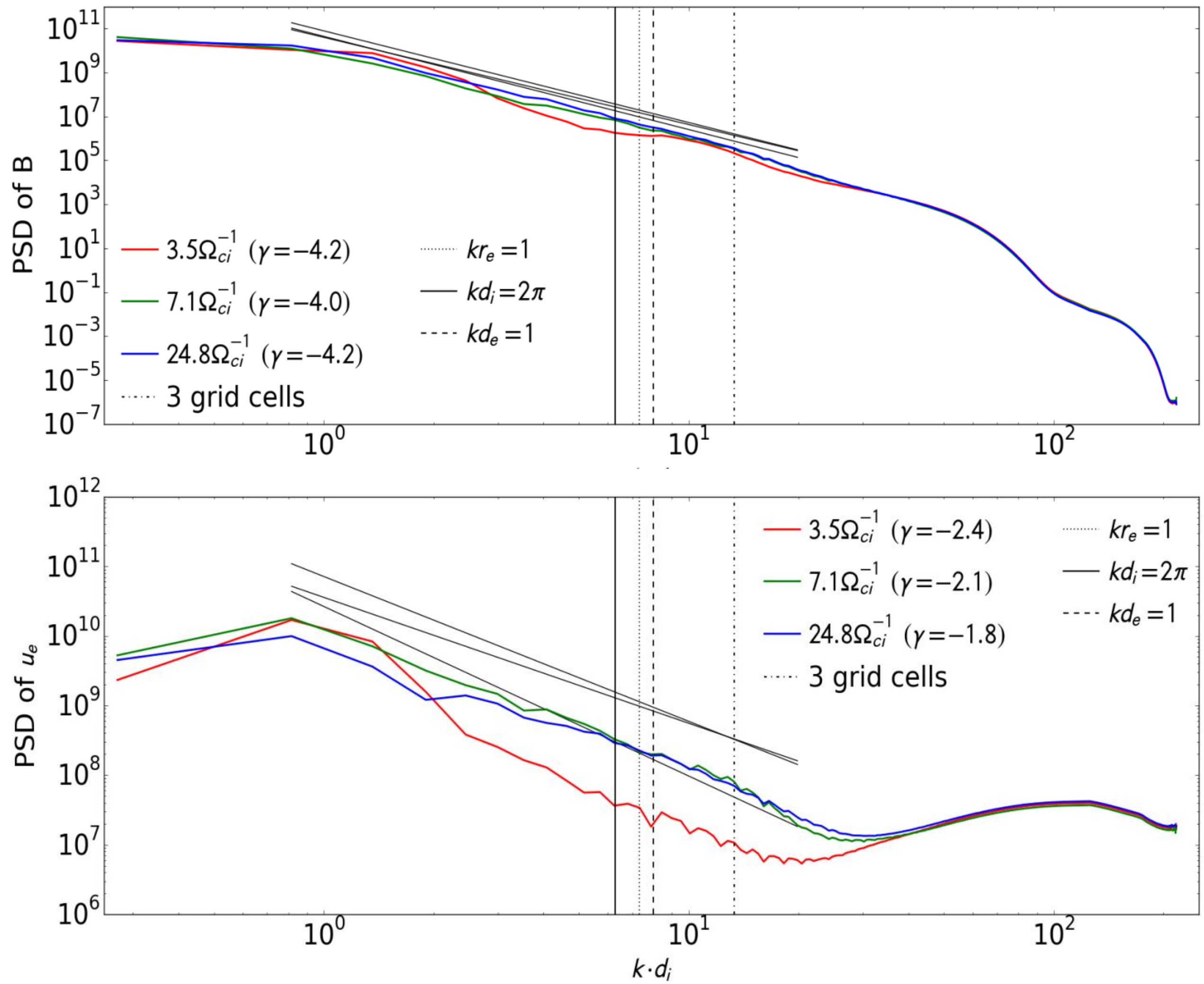


High-resolution (0.025 d_i) simulations reveal small-scale instabilities on the interface of two magnetic flux ropes.

Electron holes on the interface of two streams



Link to THOR?



Kinetic-scale reconnection events and instabilities associated with null points can create energy cascade at small scales?

Conclusions & Questions

1. Null points are ubiquitous in space plasmas, but not always they indicate magnetic reconnection!
2. Spiral nulls + magnetic flux ropes are more important for energetics? An extensive survey with Cluster and MMS is needed.
3. Nulls and instabilities associated with interacting magnetic flux ropes may be the intermittent structures in the kinetic-scale turbulence?

Acknowledgments

- Thanks to Yu. Khotyaintsev, A. Vaivads & H. Fu for useful discussions.
- This material is based upon work supported by the Air Force Office of Scientific Research, Air Force Materiel Command, USAF under Award No. FA9550-14-1-0375.
- The simulations were conducted on the computational resources provided by the PRACE Tier-0 project 2013091928 (SuperMUC)

Equations of PIC

Maxwell's equations

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

$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{j}$$

$$\epsilon_0 \nabla \cdot \mathbf{E} = \rho$$

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

Equations of motion
(moments of Vlasov)

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p$$

$$\frac{d\mathbf{v}_p}{dt} = \frac{q_s}{m_s}(\mathbf{E}_p + \mathbf{v}_p \times \mathbf{B}_p)$$

Coupling of fields and particles in the implicit code iPic3D:

$$(\mathbf{I} + \chi^n) \cdot \mathbf{E}^{n+1} - (c\Delta t)^2(\nabla^2 \mathbf{E}^{n+1} + \nabla\nabla \cdot (\chi^n \cdot \mathbf{E}^{n+1})) = \mathbf{E}^n + c\Delta t \left(\nabla \times \mathbf{B}^n - \frac{4\pi}{c} \hat{\mathbf{J}}^n \right) - (c\Delta t)^2 \nabla 4\pi \hat{\rho}^n$$

Lapenta (2012), Markidis, Lapenta & Rizwan-uddin (2010)

Simulation 1: mi/me=25

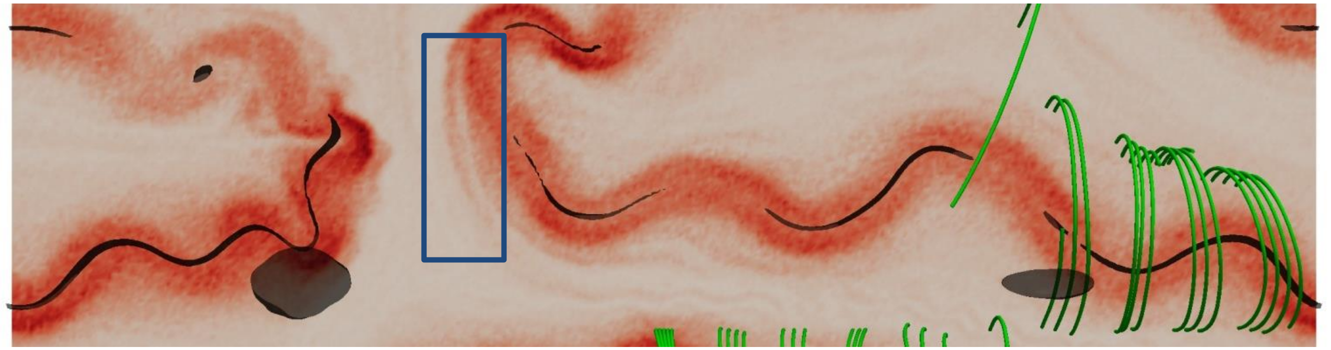
- 400^3 cells, $20^3\, d_i$
- 128 particles/cell: ions and electrons
- $\frac{T_i}{T_e} = 5, \frac{m_i}{m_e} = 25$
- $u_{the}/c = 0.04$
- $\Delta t = 0.15/\omega_{pi}$
- Duration: $100/\Omega_{ci}$
- 4000 cores

Simulation 2: mi/me=64

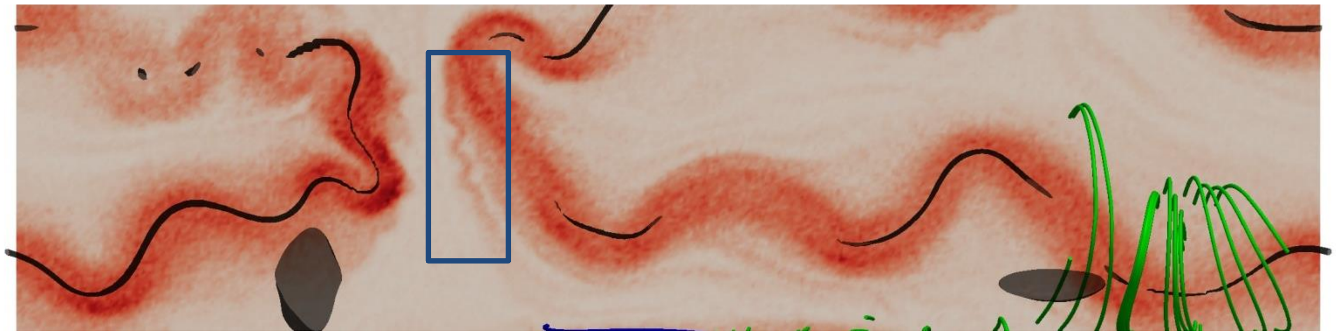
- 800^3 cells, 20^3 d_i
- 128 particles/cell: ions and electrons
- $\frac{T_i}{T_e} = 5, \frac{m_i}{m_e} = 100$
- $u_{the}/c = 0.032$
- $\Delta t = 0.075/\omega_{pi}$
- Duration: $25/\Omega_{ci}$
- 32768 cores
- ~5 Mil CPU hours

Electron current from another simulation (higher initial magnetic field, mi/me=25)

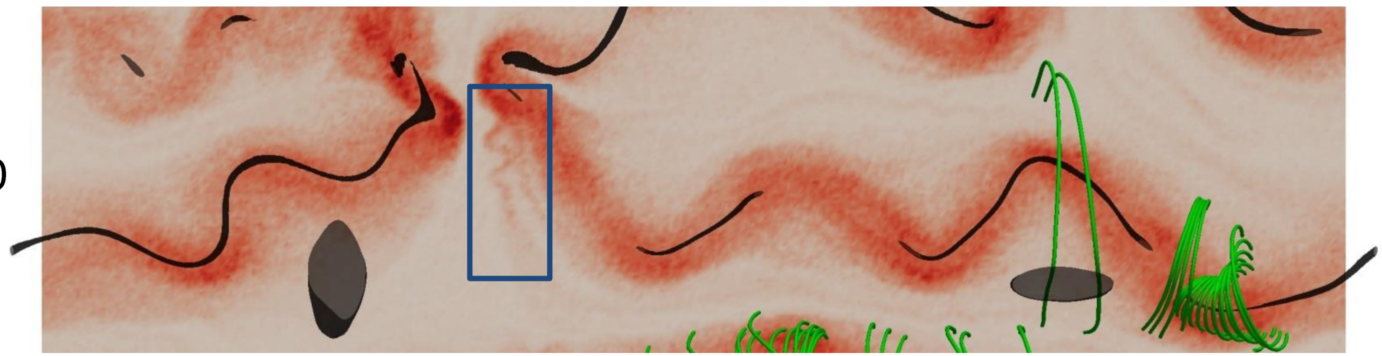
$\omega_{ci} t = 33.8$



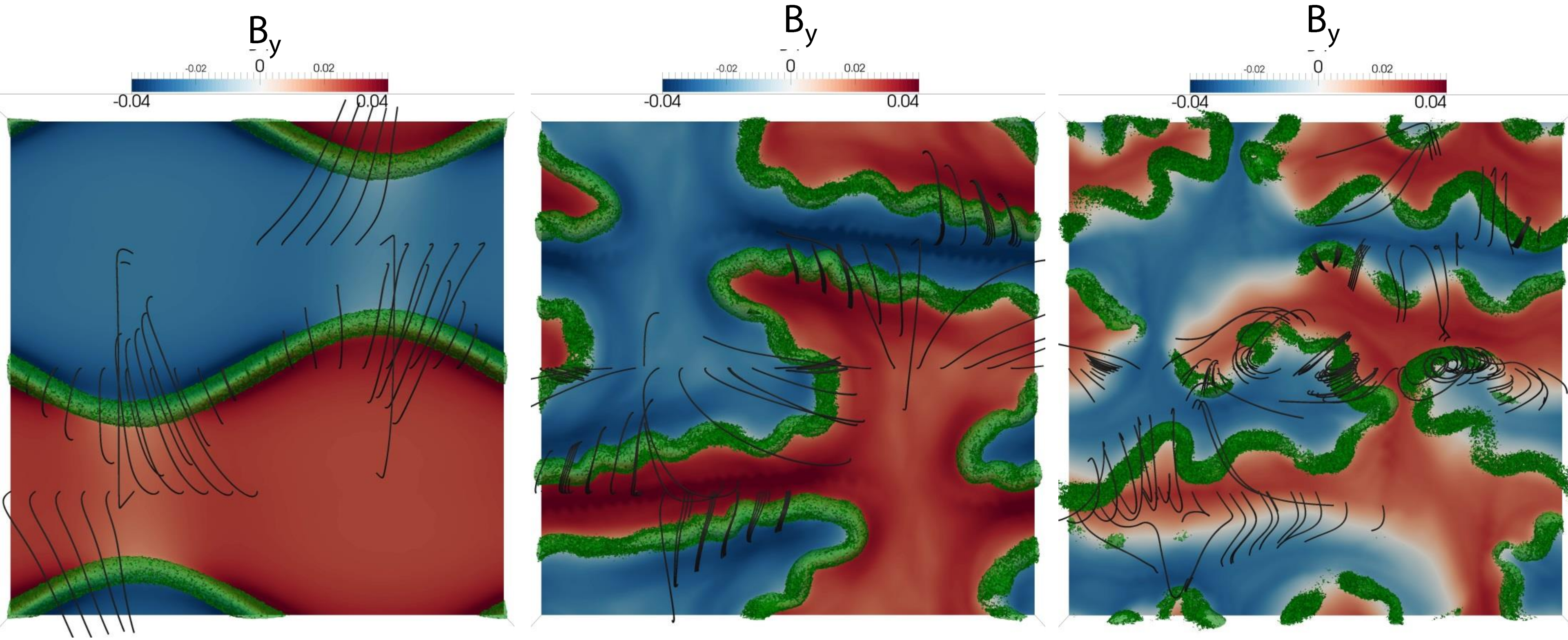
$\omega_{ci} t = 36.4$



$\omega_{ci} t = 39.0$



Spiral nulls form Z-pinches in the Y=10 plane



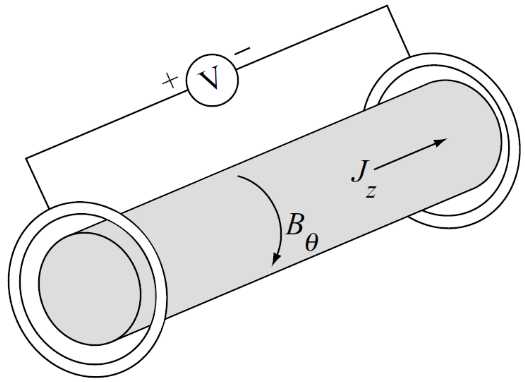
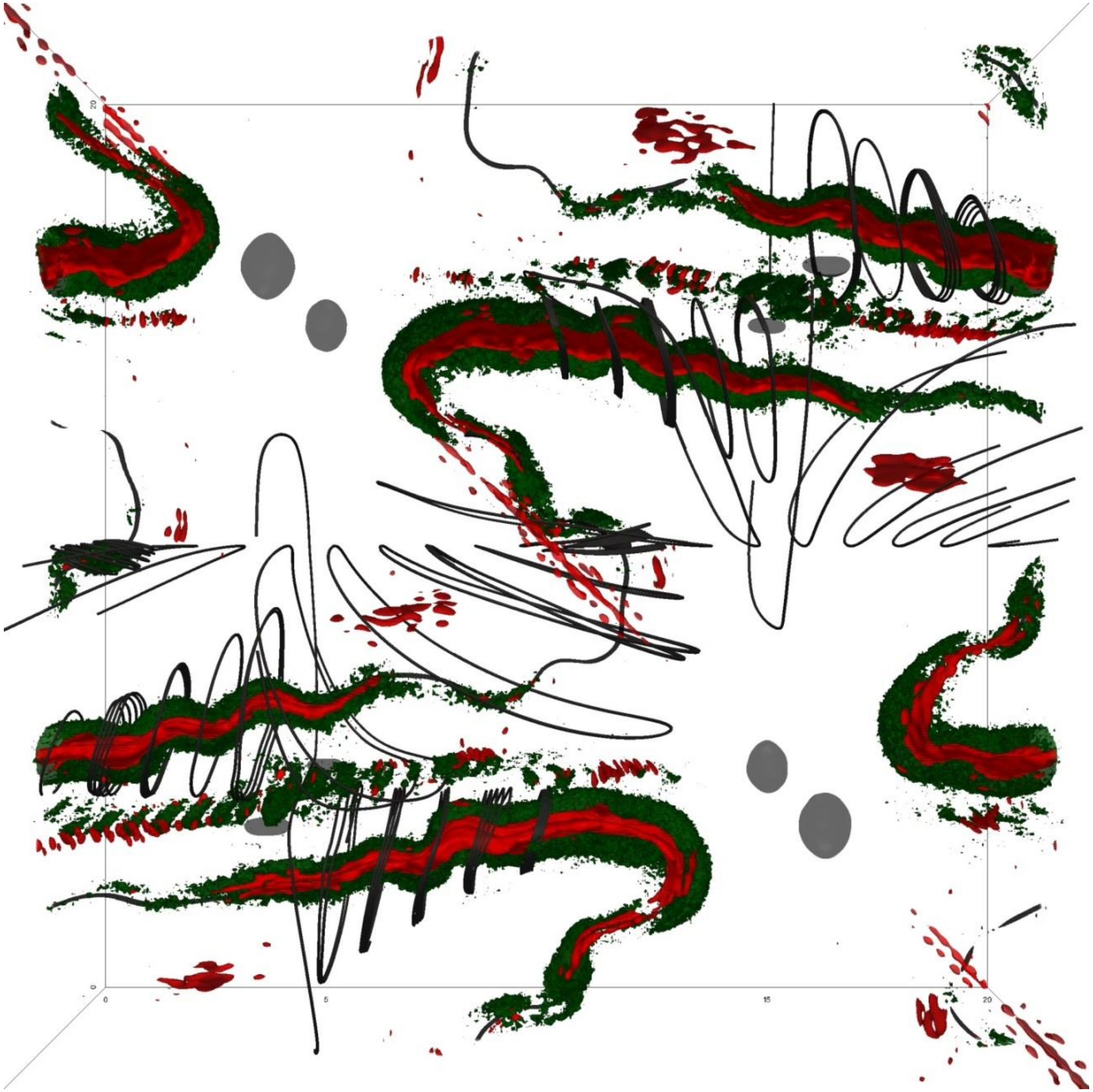


Figure 11.14 Schematic diagram of a Z-pinch.

(Freidberg, Plasma Physics and Fusion Energy, 2007)

Magnetic reconnection indicators



Green: $\left|\frac{v_{\perp,e}}{B} - \frac{[\vec{E}\times\vec{B}]}{B^2}\right|$ Red: $\left|\frac{\vec{B}}{B} \times \left[\nabla \times \left(\frac{E_{||}\vec{B}}{B}\right)\right]\right|$ (Hesse & Schindler, JGR 93, 1988)