Major Advances in Understanding of Collisionless Plasmas Enabled through Petascale Kinetic Simulations

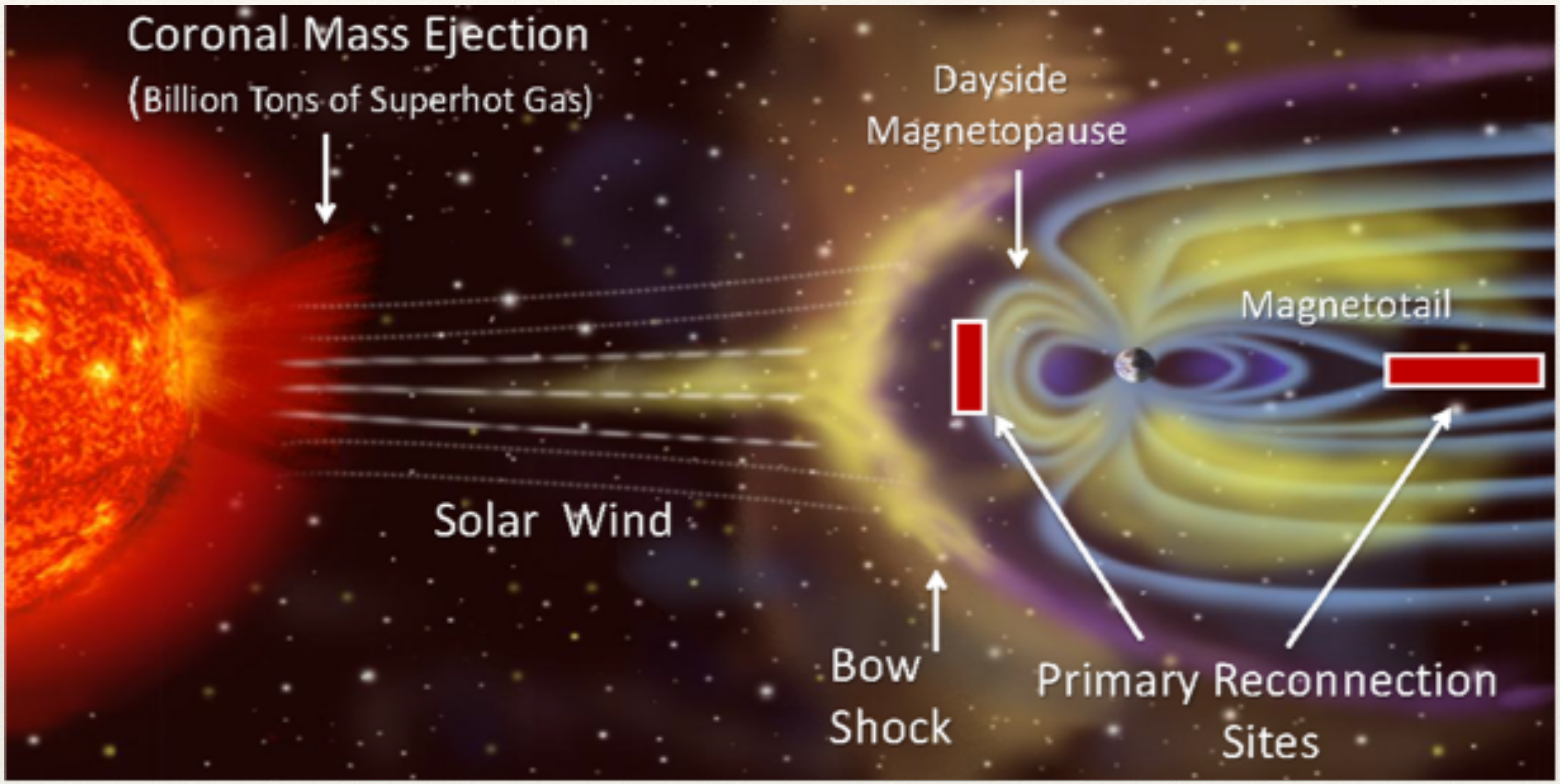
Project PI: Homayoun Karimabadi, UCSD & SciberQuest, Inc

Presented by: Vadim Roytershteyn, SciberQuest, Inc

+ many great collaborators

Presented at the 2014 Blue Waters Symposium, May 12-15 2014

Key challenge: understanding of the Sun-Earth connection (aka Space Weather)



90 million miles or ~ 100 Suns

Why it Matters: Space Weather has tangible socio-economic impacts

Potential Impact of Large-Scale Event according to “Report on Space Weather Observing Systems: Current Capabilities and Requirements For The Next Decade”

- **Electric Power Grid:** Large-scale blackouts and permanent damage to transformers, with lengthy restoration periods.
- **Global Satellite Communications:** Widespread service disruptions t financial, telemedicine, government, and Internet services
- **Global Positioning System (GPS) Positioning and Timing:** Degradations of military weapons accuracy, air traffic management, transportation, precision survey/construction, agriculture, energy exploration, ship navigation/commerce, financial transactions, and cell phone/broadband.
- **Satellites & Spacecraft:** Loss of satellites and capabilities, of space situational awareness (including detection of hostile actions), and increased risk to astronaut safety, etc

Estimated cost of a severe geomagnetic storm (such as the 1859 “super storm”) on the satellite industry alone could be approximately **$50 - $100 billion**.

The potential consequences on the Nation’s power grid are even higher, with **potential costs of $1 - 2 trillion** that could take **up to a decade to completely repair**.

Our focus is on several fundamental physics issues
I. Magnetic Reconnection

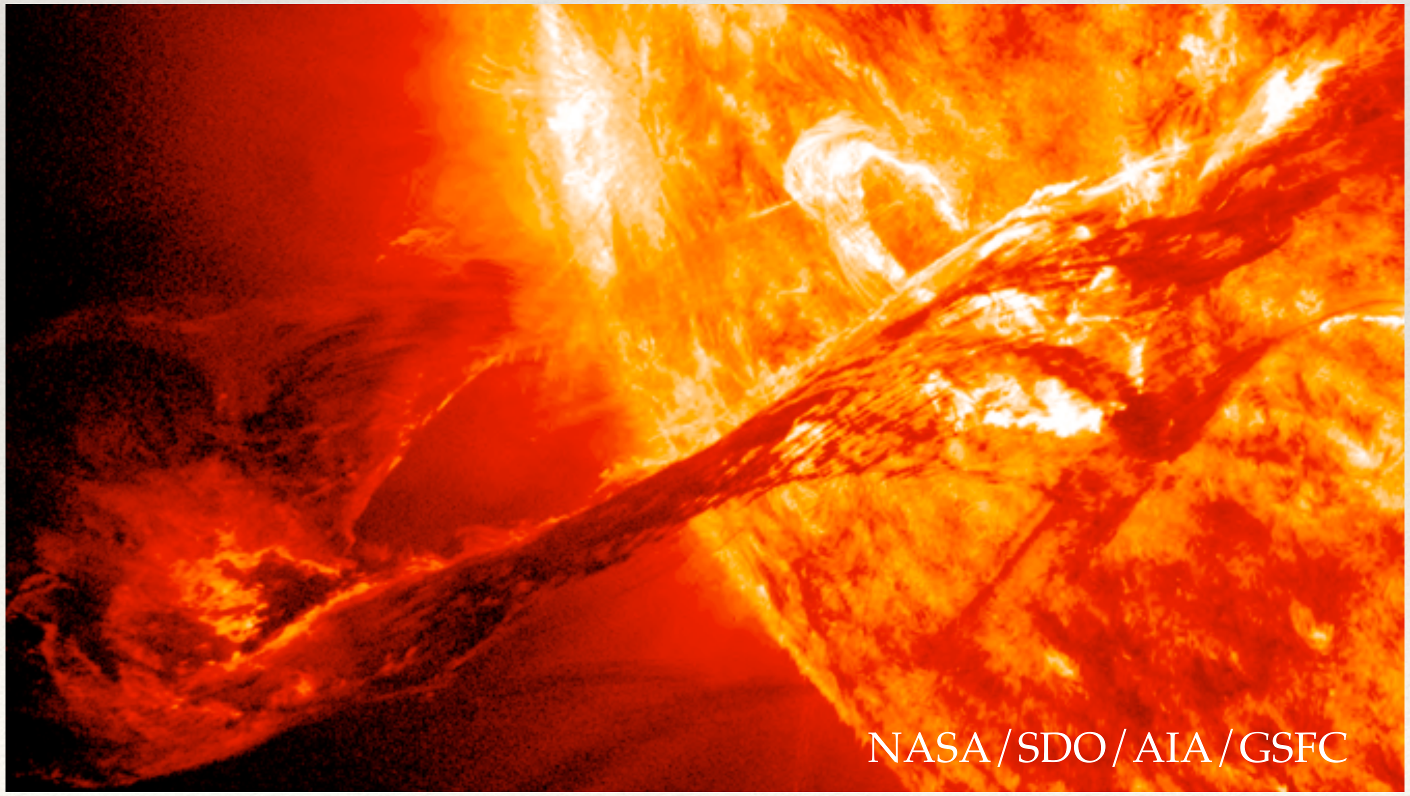
Global evolution

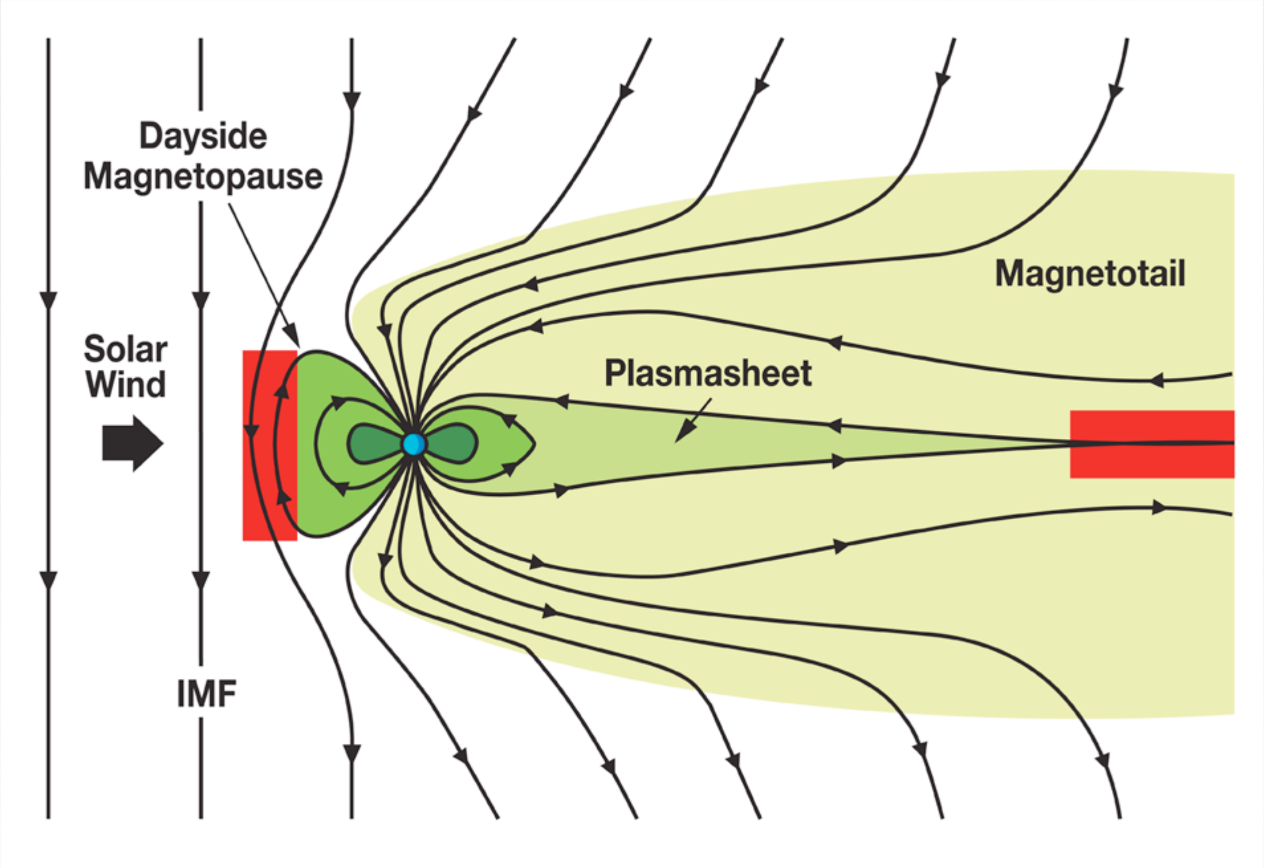
Narrow boundary layers with highly stressed magnetic field

Microscopic kinetic physics

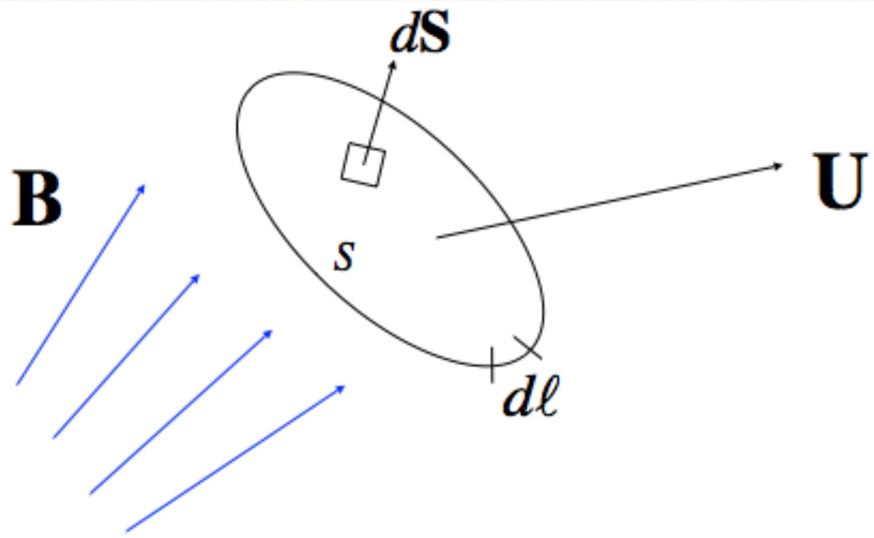
The sun

The Earth's magnetosphere





Magnetic Reconnection



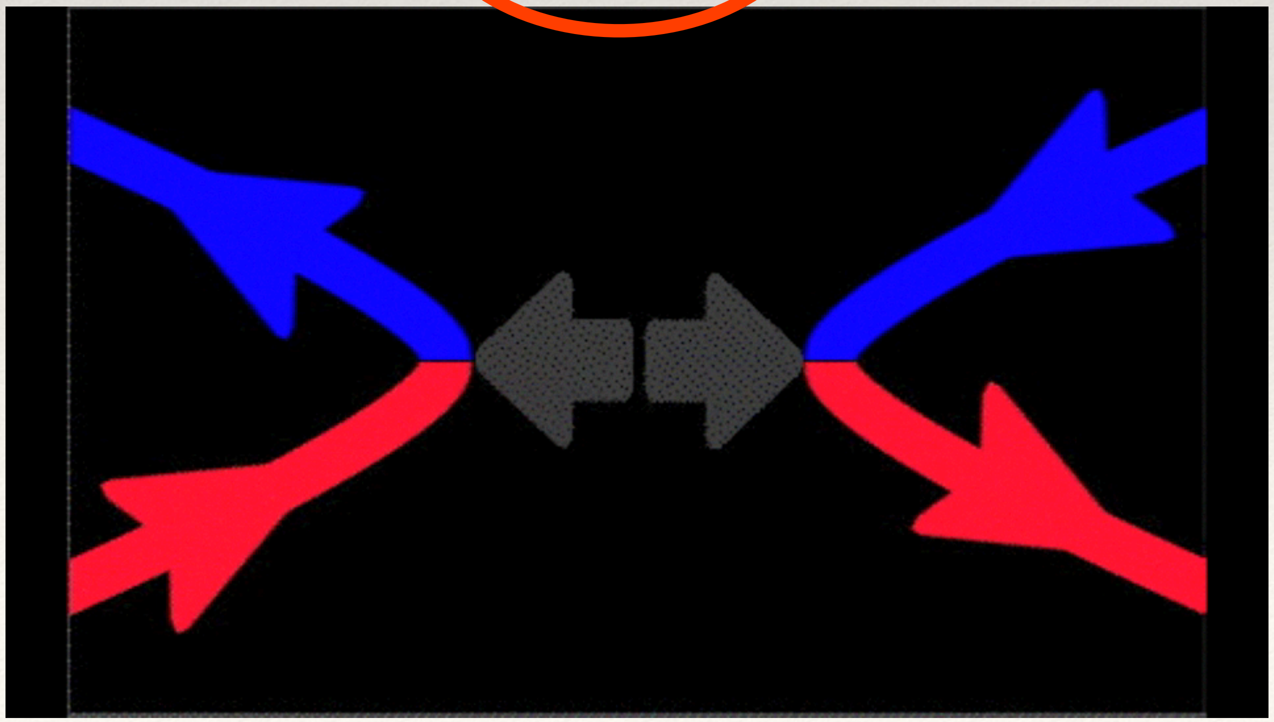
Magnetic Flux

$$\psi = \int_s \mathbf{B} \bullet d\mathbf{S}$$

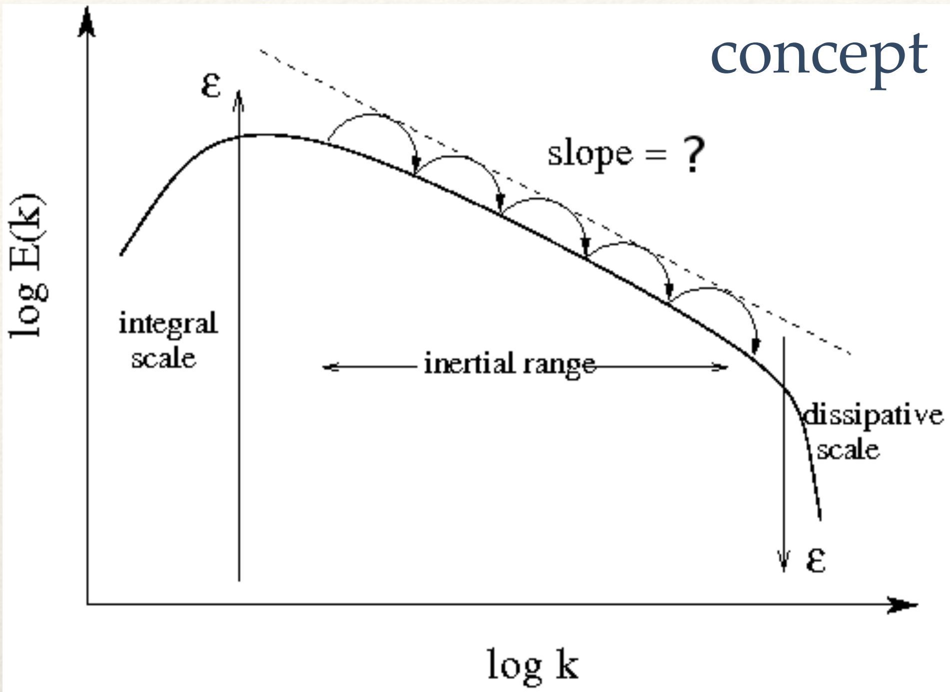
$$\frac{d\psi}{dt} = \int_s \frac{\partial \mathbf{B}}{\partial t} \bullet d\mathbf{S} - \oint (\mathbf{U} \times \mathbf{B}) \bullet d\ell$$

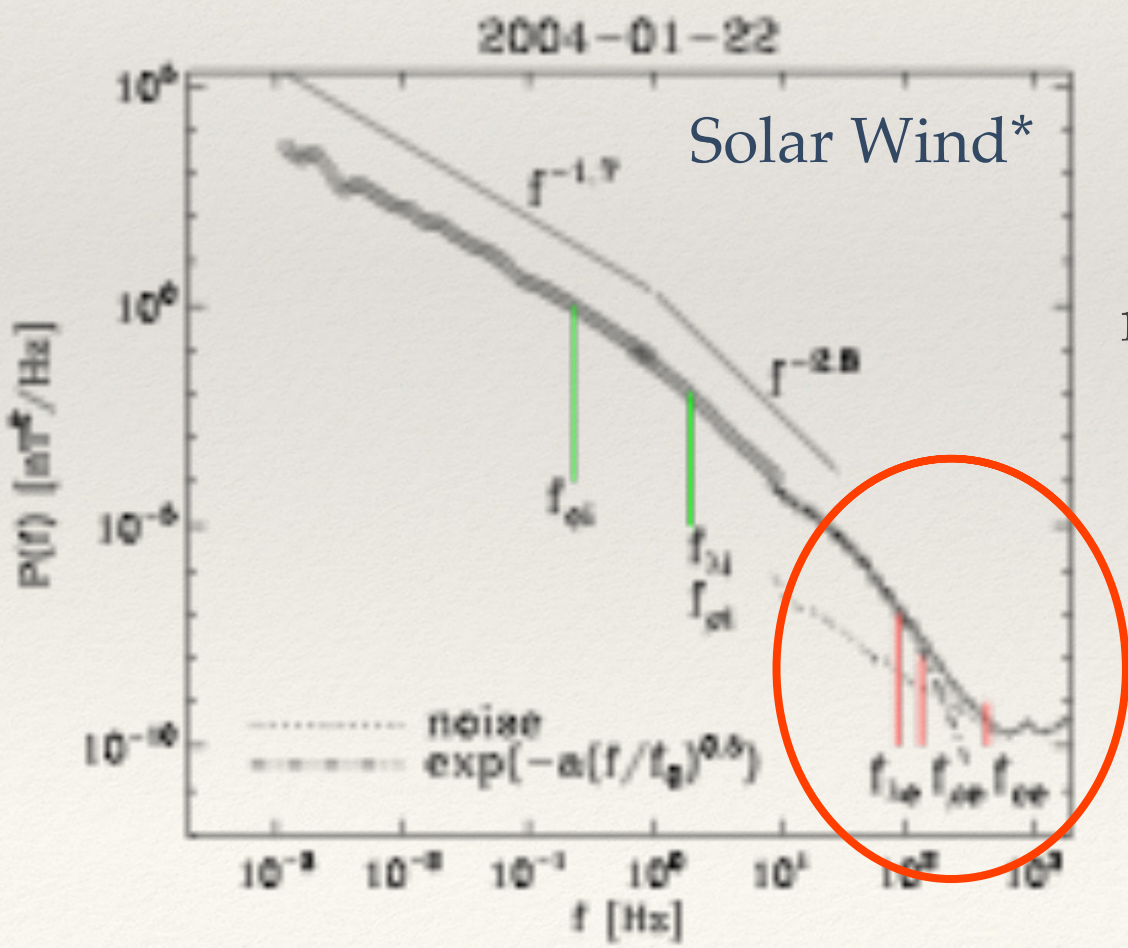
=0

$$\frac{d\psi}{dt} = -c \oint \left(\mathbf{E} + \frac{\mathbf{U} \times \mathbf{B}}{c} \right) \bullet d\ell$$



Our focus is on fundamental physics issues
II. Turbulence in Collisionless Plasma





What is the dissipation mechanism in <u>collisionless</u> plasmas?

2D fully kinetic simulation of flow-driven turbulence

*Alexandrova, *et al.*, 2009

BW is one of the largest resources available today

Both turbulence and reconnection are characterized by **large separation of scales** and require highly expensive simulations

Fully kinetic simulation

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v}\cdot\nabla f_s + \frac{q_s}{m_s}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}\right)\cdot\nabla_{\boldsymbol{v}} f_s = \sum_{s'} \mathcal{C}\{f_s, f_{s'}\}$$

+ Maxwell's equations

(all species kinetic; code: VPIC)

~up to 10^{10} cells

~up to $4\text{x}10^{12}$ particles

~120 TB of memory

~10^7 CPU-HRS

~up to 500,000 cores

Large scale hybrid kinetic simulation:

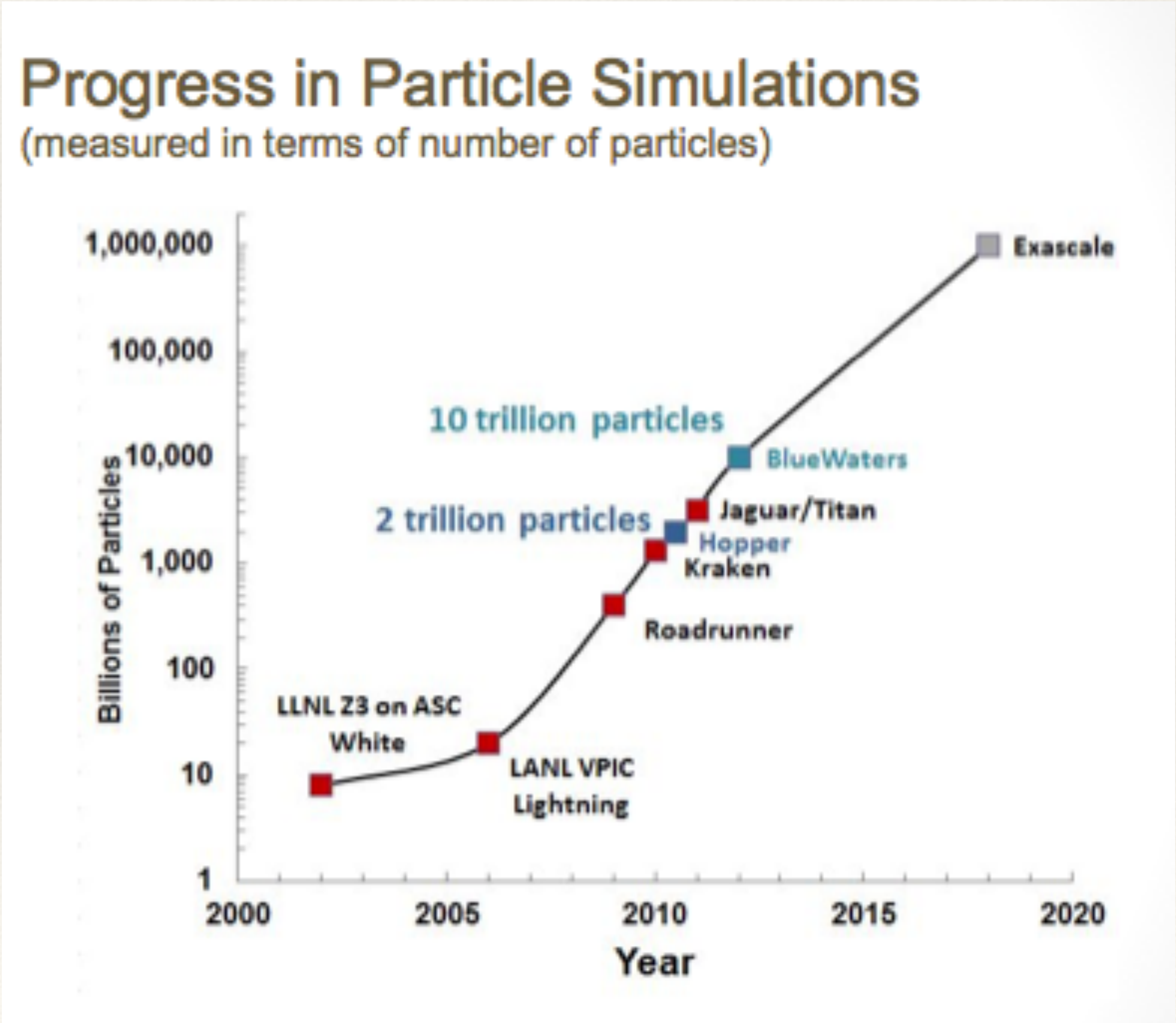
(kinetic ions + fluid electrons;

codes: H3D, HYPERES)

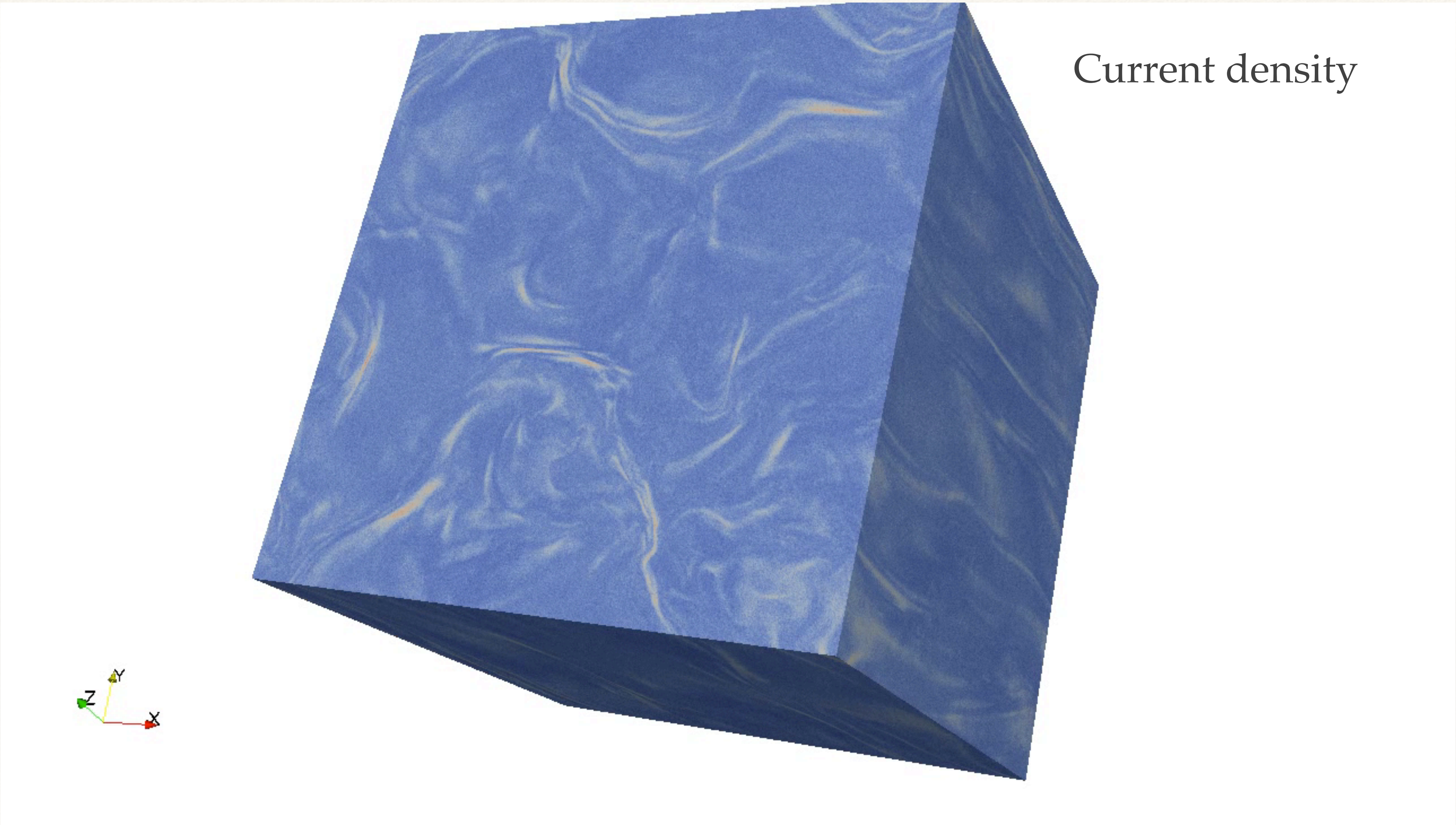
~up to $1.7\text{x}10^{10}$ cells

~up to $2\text{x}10^{12}$ particles

~130 TB of memory

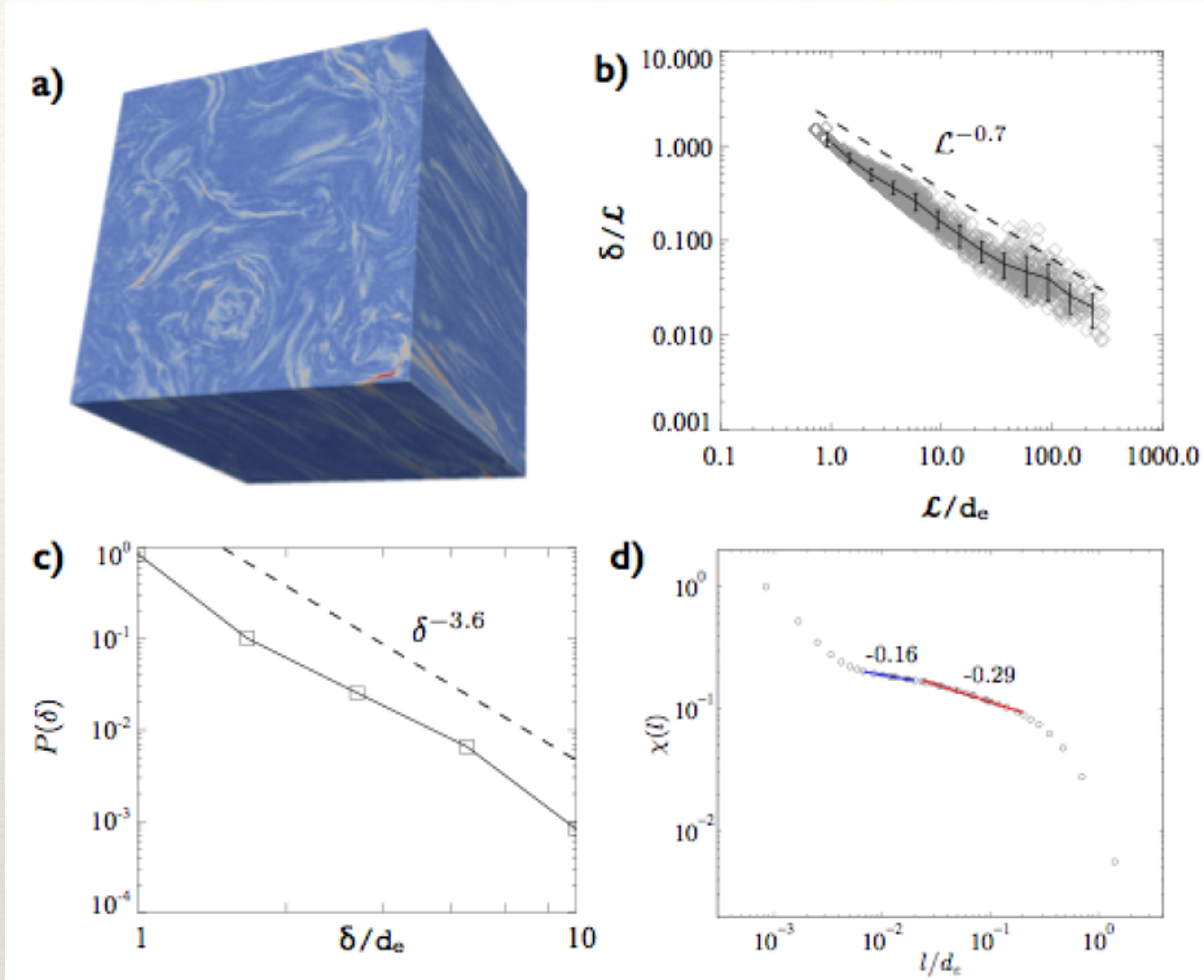


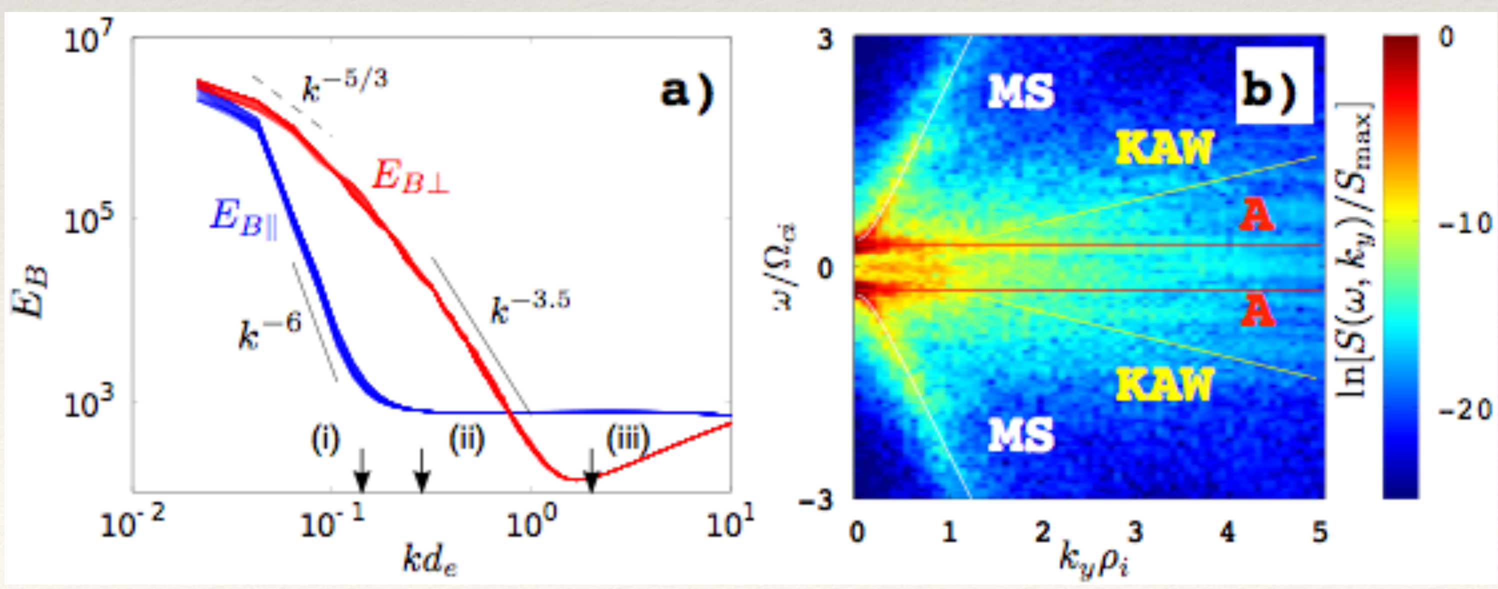
Results: the first 3D simulations of collisionless plasma turbulence that simultaneously resolve kinetic physics and large scale dynamics.



Science target: dissipation of cascading energy in collisionless plasmas: **coherent structures** vs resonant wave-particle interactions vs stochastic mechanism; Findings: current sheets and their properties; Applications: solar wind, solar corona, astrophysics, etc

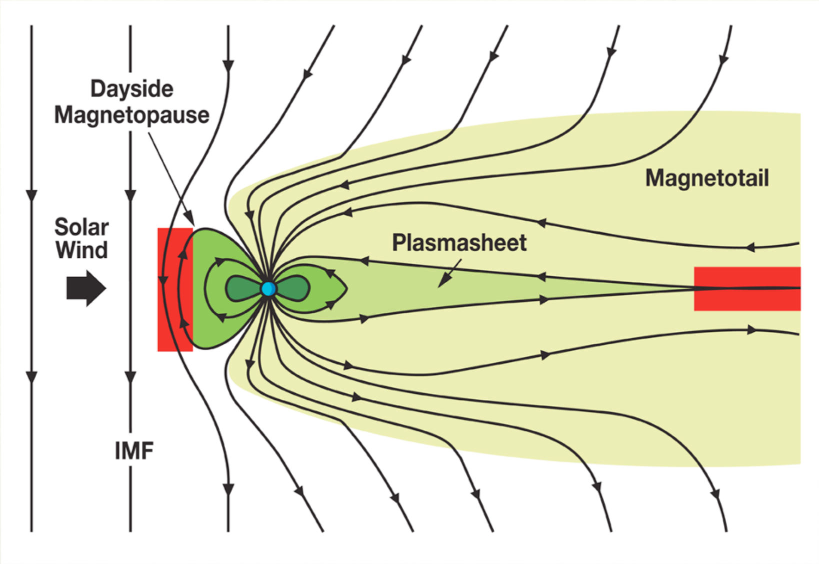
Results: properties of the fluctuations



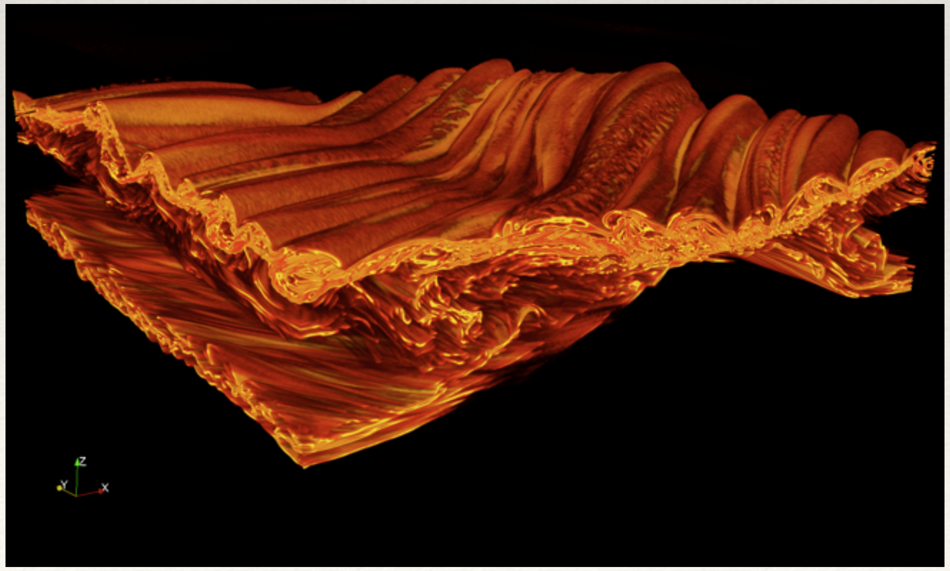


Results: 2D Global Fully Kinetic Simulations

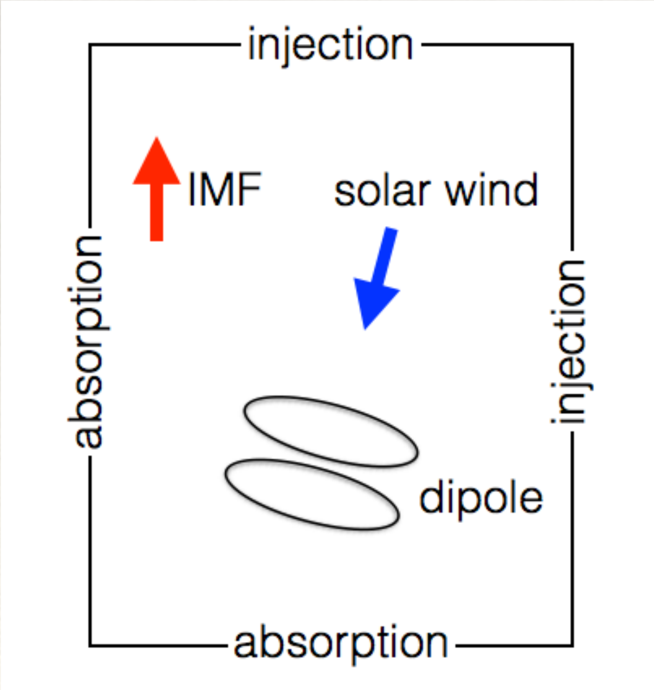
Magnetosphere



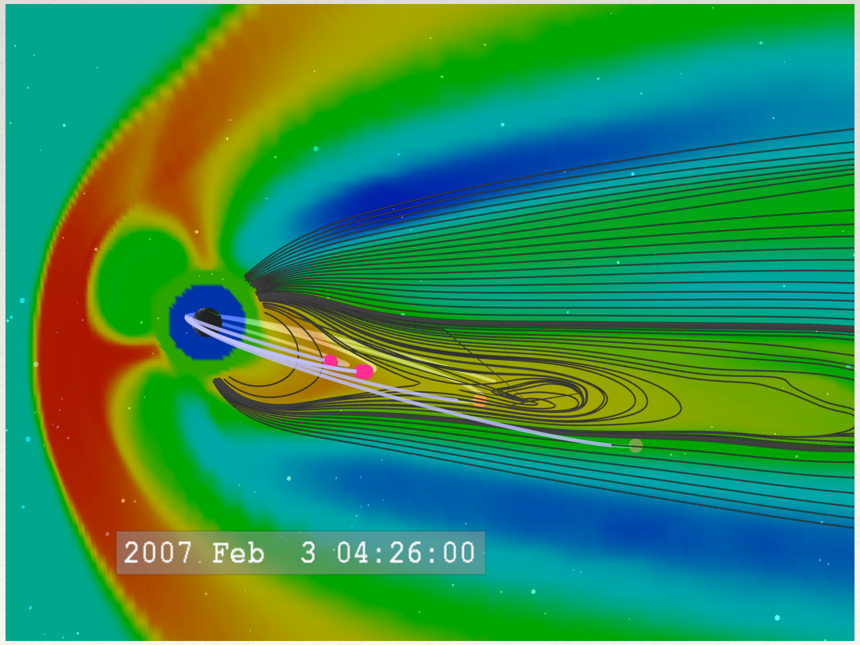
Local model: physics of reconnection, but no global geometry or drive



middle ground: all of physics + 2D geometry

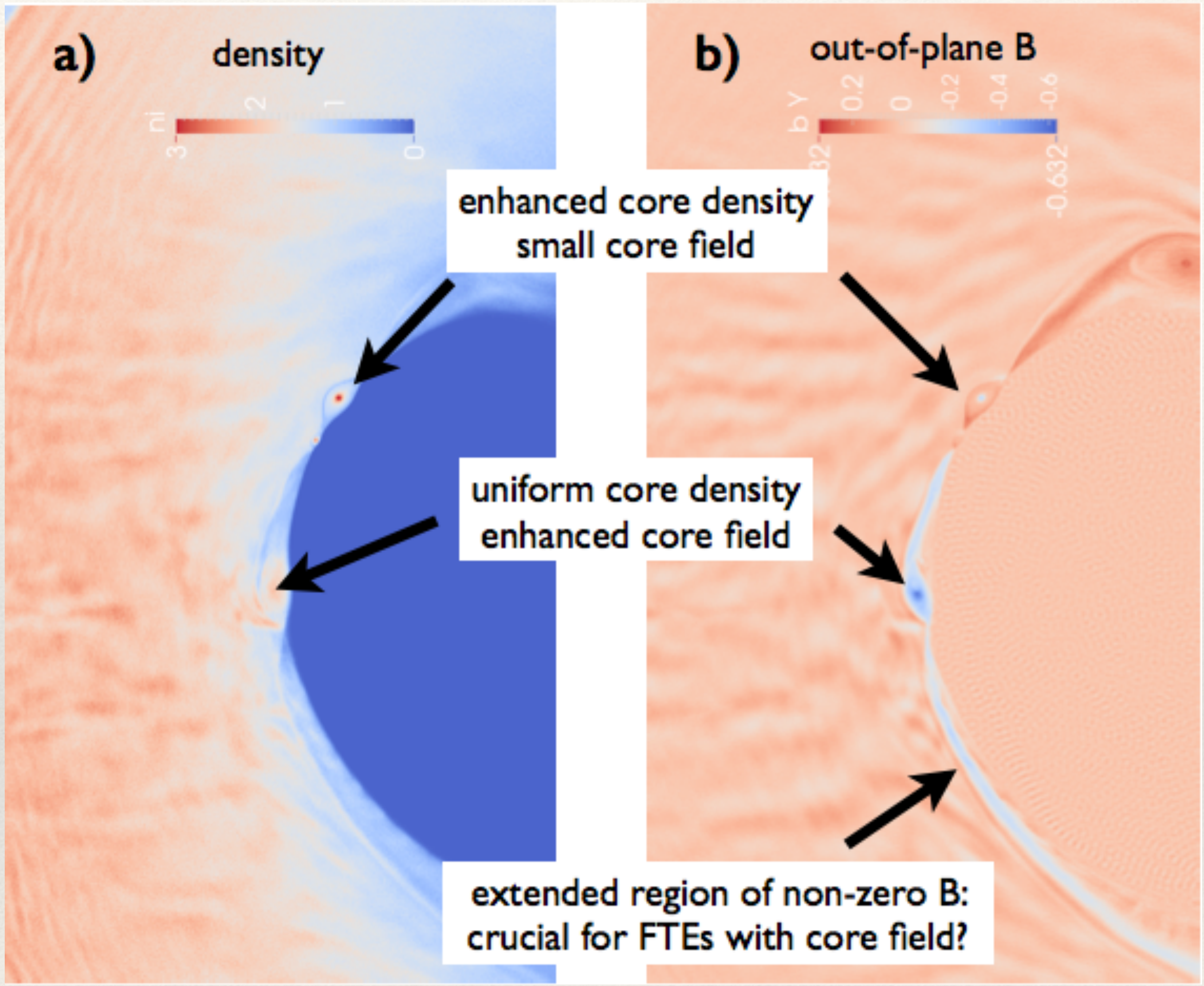


Global 3D models: reconnection is unphysical



NASA/Goddard Space Flight Center Scientific Visualization Studio

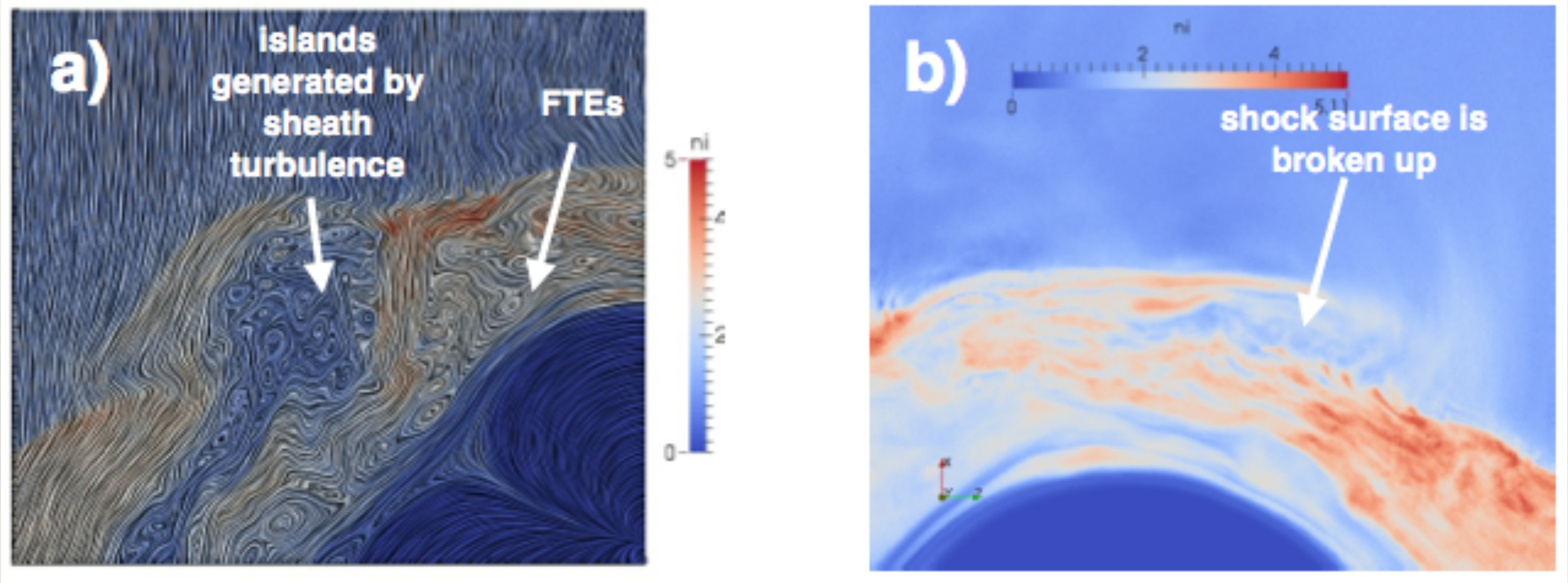
Results: 2D Global Fully Kinetic Simulations



<u>Science target</u>: coupling between magnetic reconnection and global geometry and the influence of external driving; <u>Findings</u>: unsteady, multiple X-line reconnection, structure of FTEs, etc,

<u>Applications</u>: the Earth's magnetosphere, other planetary magnetospheres

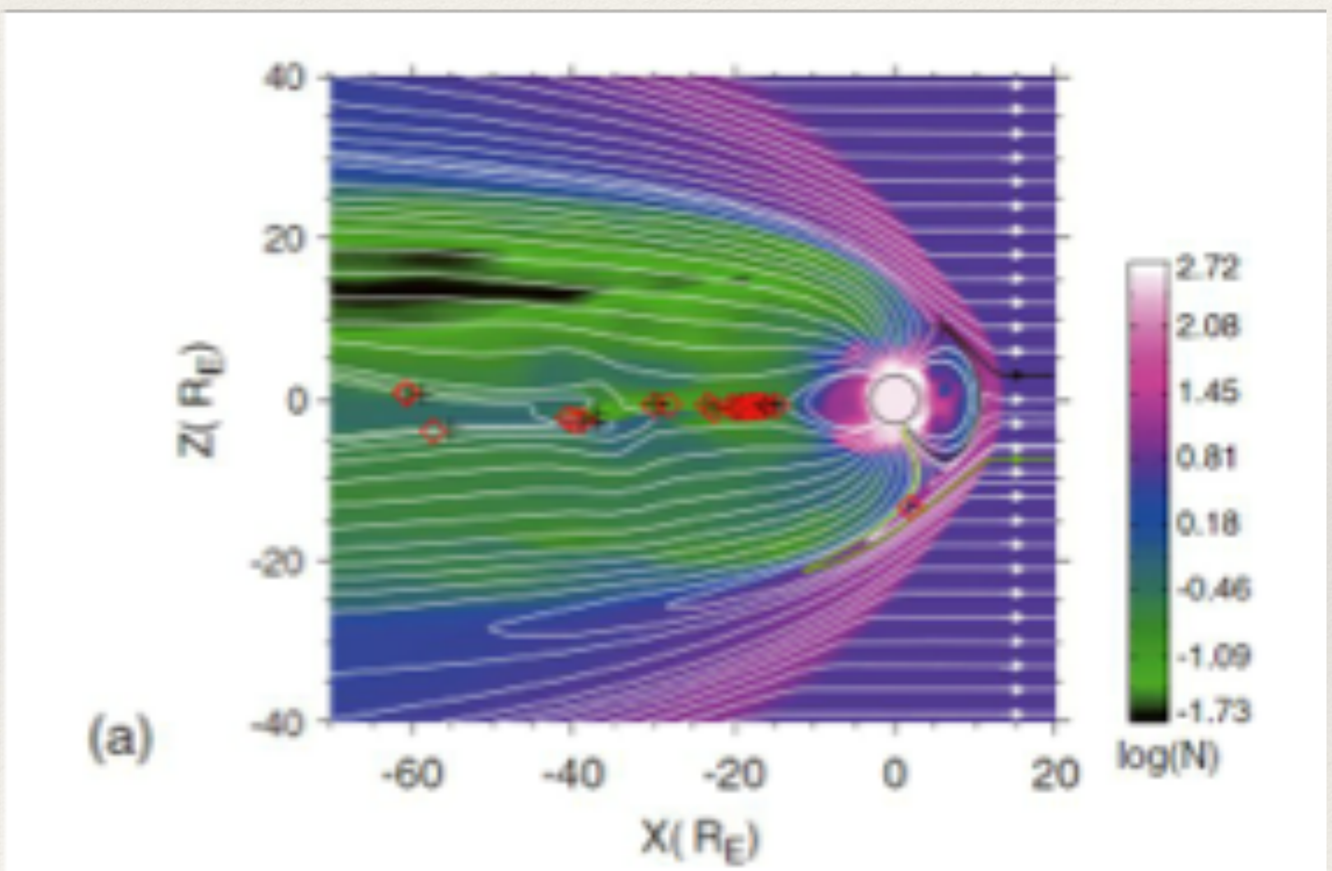
Results: Global fully kinetic simulation



Science target: coupling between shock physics, magnetosheath turbulence, and global disturbances

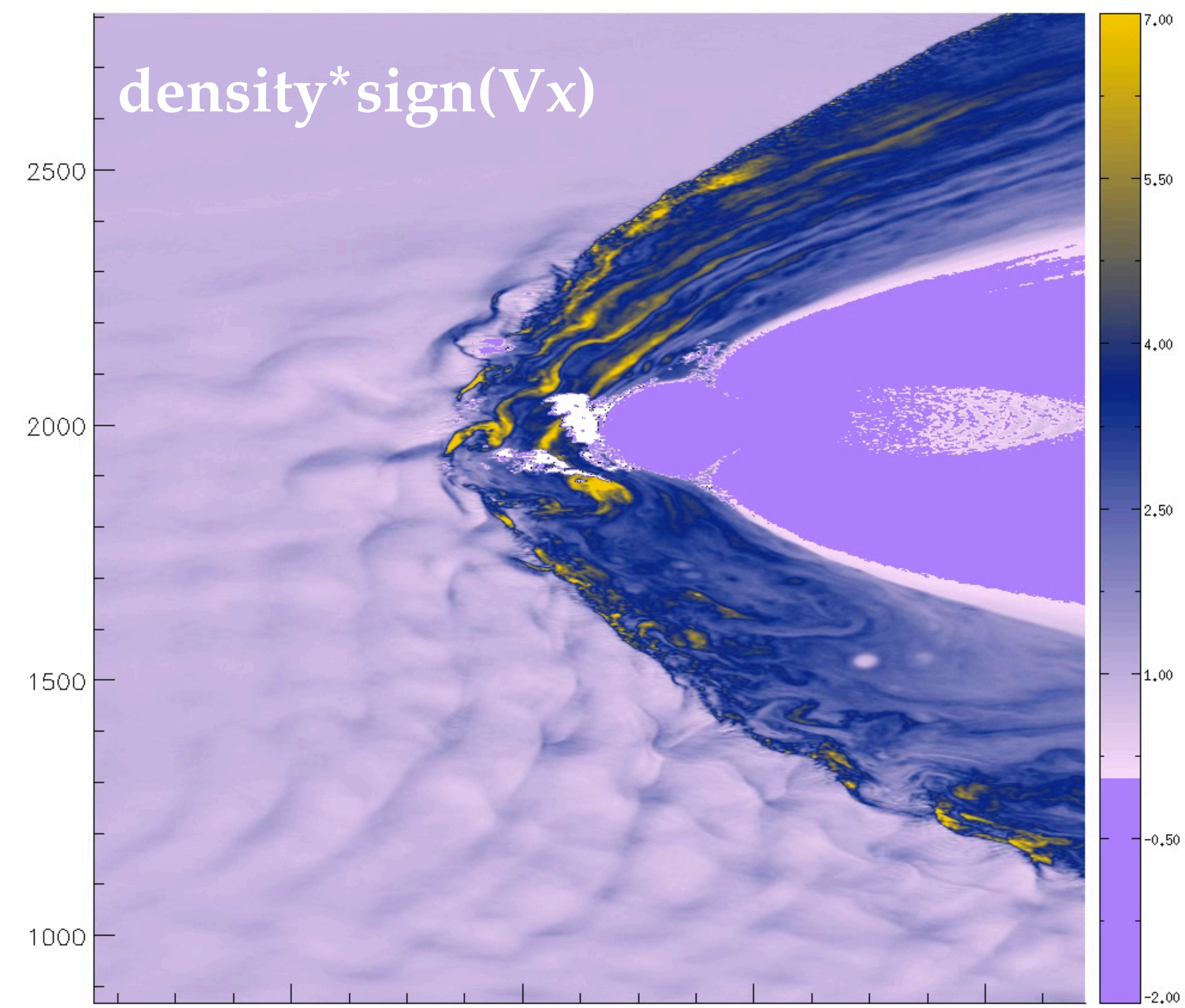
Nearly radial IMF

MHD: smooth
(Tang et al., JGR, 118, 2013)



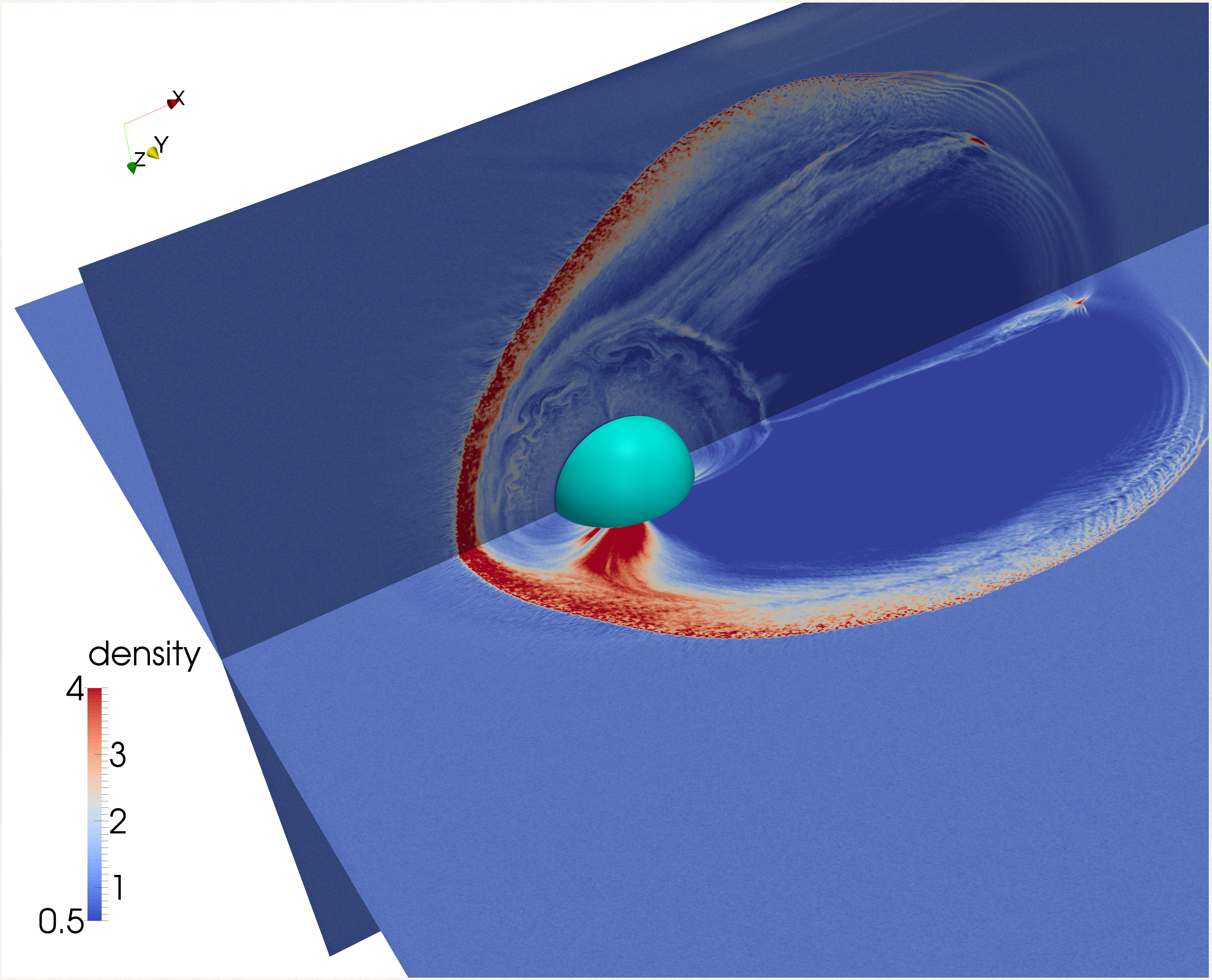
Kinetic: turbulence & large-scale perturbations

2D hybrid simulation (~10K cores on NASA Pleiades)

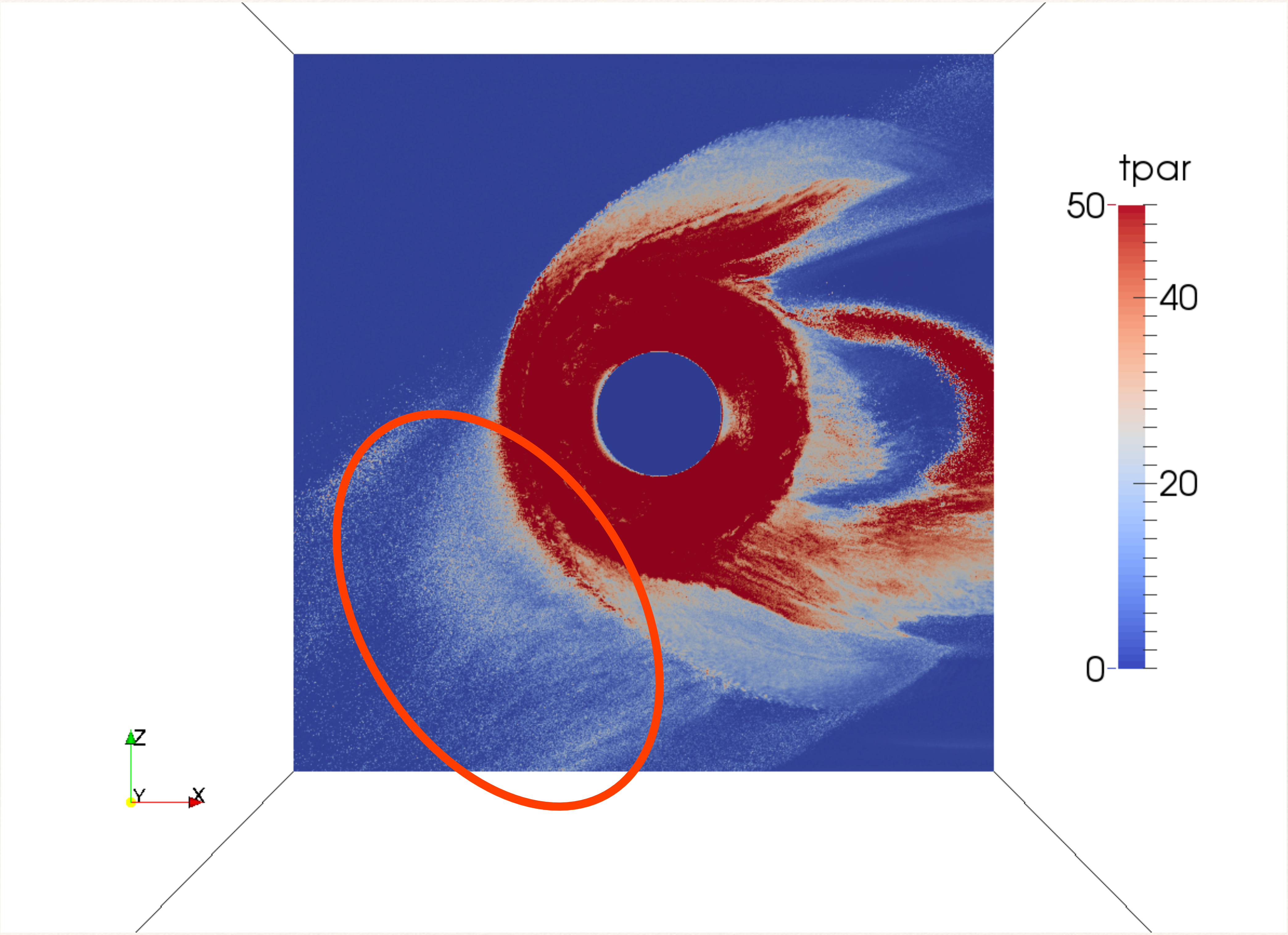


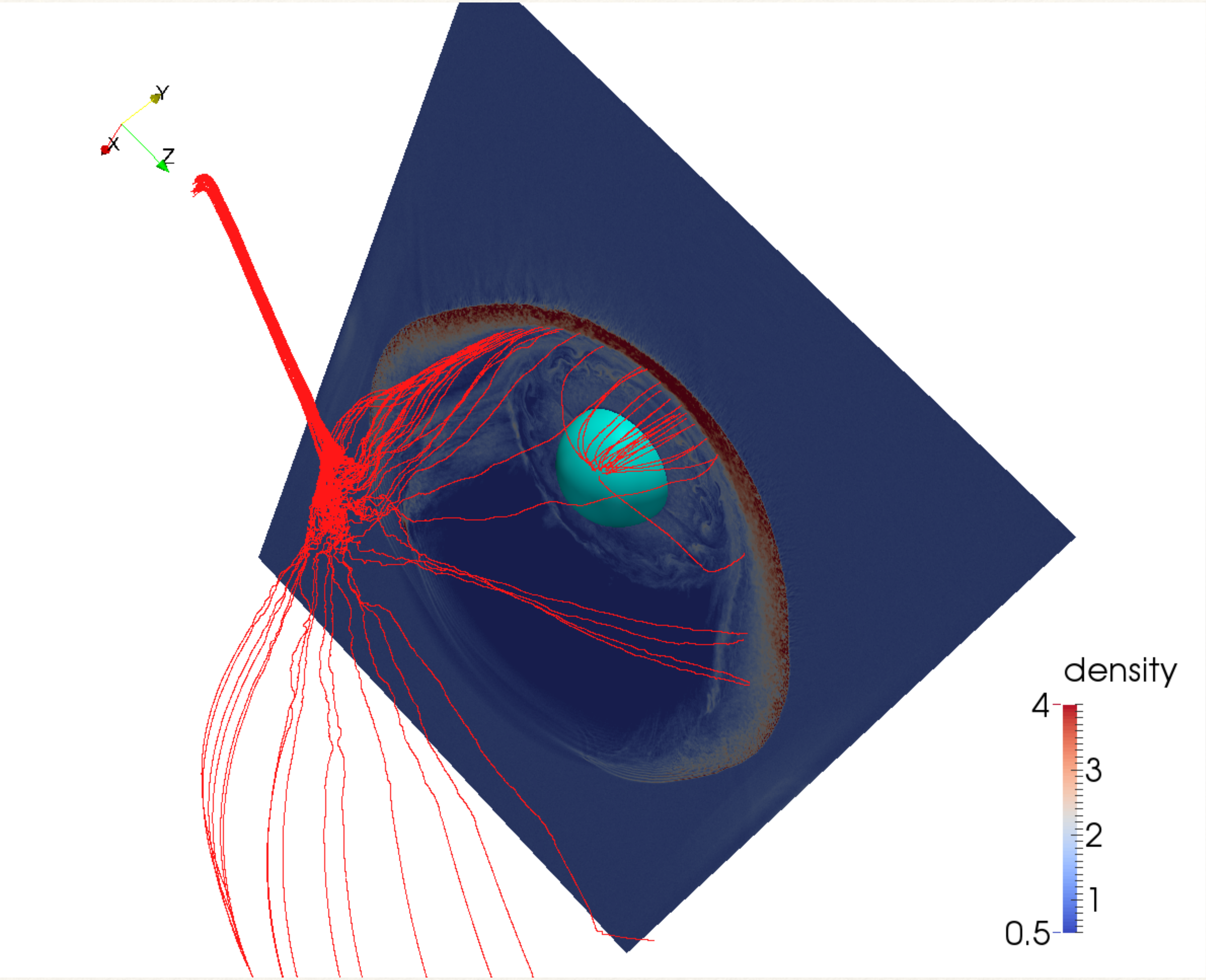
Reflected ions drive foreshock turbulence that interacts with the shock & drives magnetosheath turbulence

Results: Turbulence in 3D Global hybrid Simulations (focus on ion kinetic effects)



Results: Turbulence in 3D Global hybrid Simulations





Y
X
Z
density
4
3
2
1
0.5

Summary

- The project "Major Advances in Understanding of Collisionless Plasmas Enabled through Petascale Kinetic Simulations" attacks fundamental plasma physics issues highly relevant to space weather research
- Blue Waters provides unique capabilities for conducting the required simulations
- Major results to date:
  - Global fully kinetic simulations of magnetic reconnection
  - First large-scale 3D simulations of decaying collisionless plasma turbulence
  - 3D global hybrid simulations addressing coupling between shock physics & magnetosheath turbulence