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Breakthrough Kinetic Simulations of the Earth's Magnetosphere

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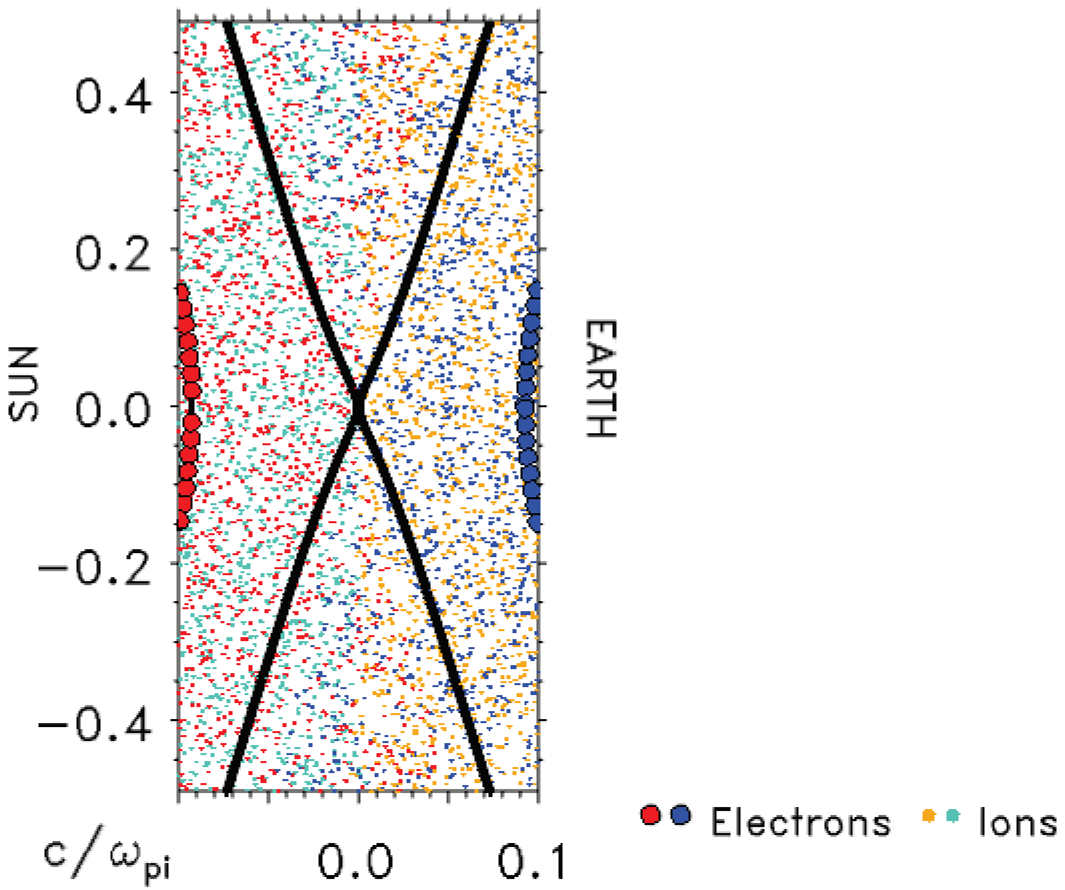
Goal: Develop accurate forecasts of space weather

- Earth is embedded in the Sun's atmosphere
- Earth's dipole field shields us for the most part from the effects of the Sun, but the shield has "cracks"
- A process called magnetic reconnection enables the solar wind to penetrate the magnetosphere
- Space weather affects the Earth and its technological systems
  - Over $4 billion in satellite losses
  - Damage sensitive electronics on orbiting spacecraft
  - Cause colorful auroras, often seen in the higher latitudes
  - Create blackouts on Earth when they cause surges in power grids

What is magnetic reconnection?

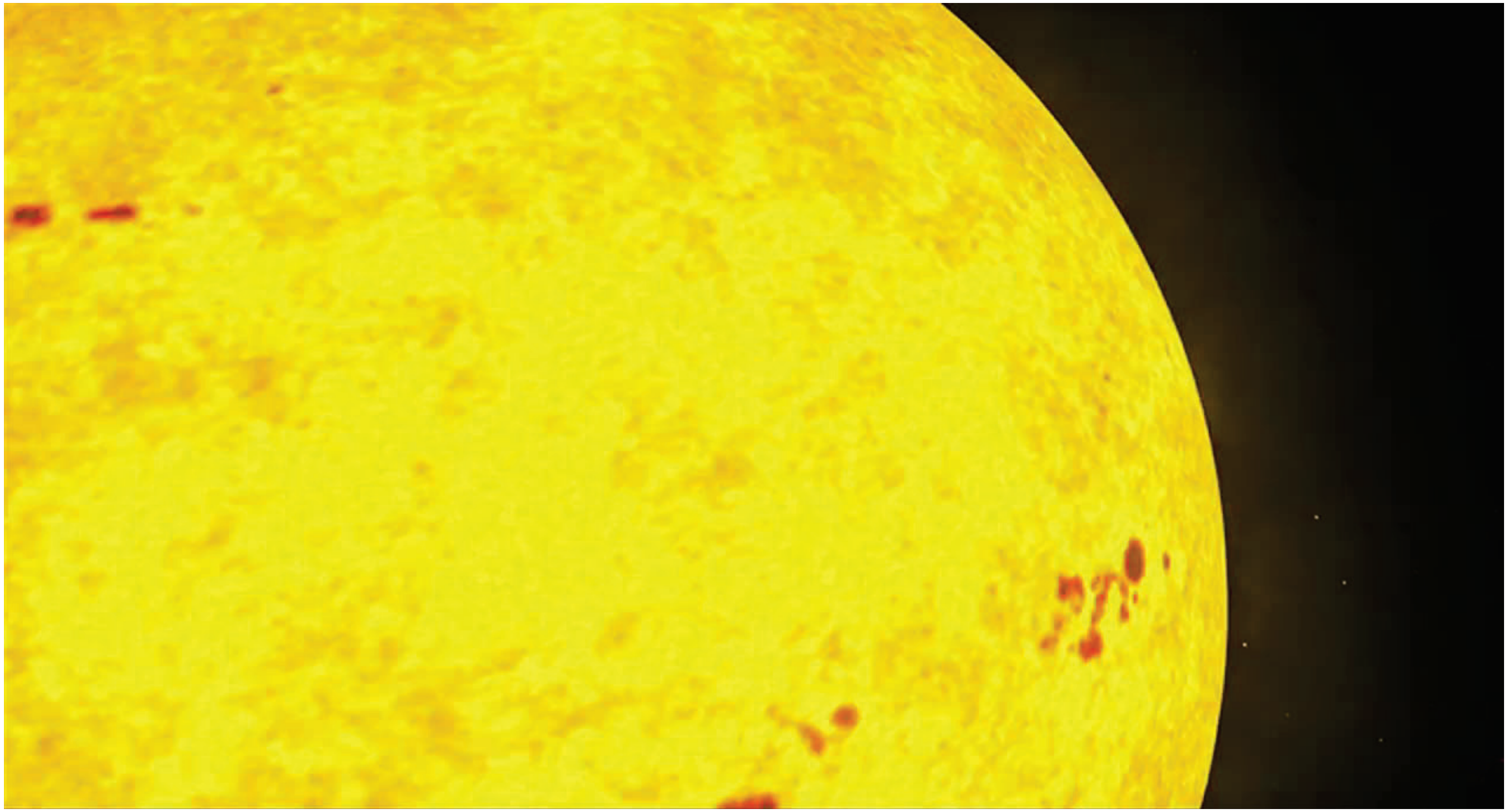


Magnetic field lines in a plasma act similar to rubber bands, which can snap and release energy while forming new structures such as magnetic islands or extended flux ropes.

Through this process, the solar wind can enter the magnetosphere

Credit:
University of Iowa/HYDRA Science Team

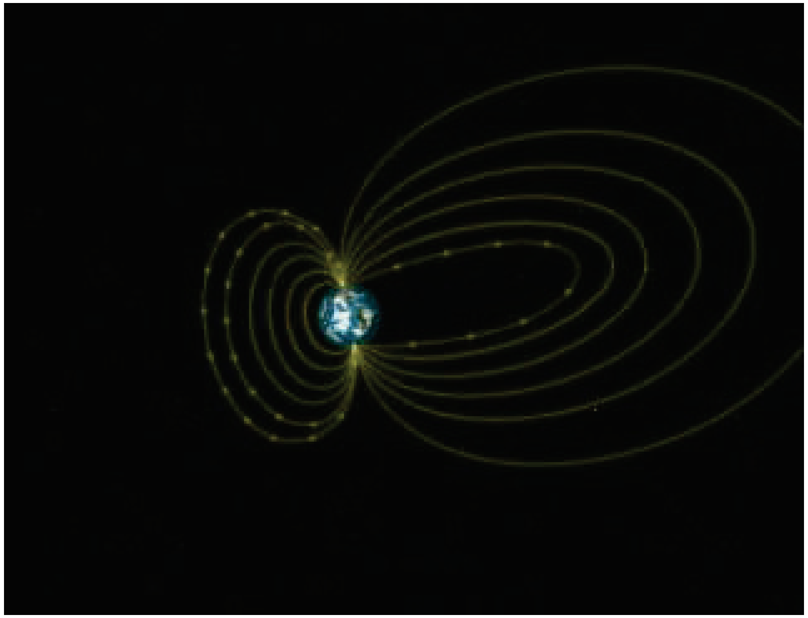
Animation of coronal mass ejection (CME)



Credit: *NASA/Goddard Space Flight Center Conceptual Image Lab*

A burst of fast material from the sun generates magnetic reconnection events in Earth's magnetic field. This eventually sends high-speed electrons and protons into Earth's upper atmosphere to form aurorae

The “crack” in the magnetosphere depends on the orientation of the magnetic field



Credit:
NASA/Goddard Space Flight Center Conceptual Image Lab

This animation depicts how the magnetic field of the Sun—carried by the solar wind—can be deflected by or attached to Earth's magnetosphere (yellow lines). The earth’s magnetic field flows out of the south pole and into the north. When the solar wind is oriented to the north (red line, with arrows also pointing up), the solar wind and magnetosphere fields cannot connect, essentially repelling each other. The solar wind flows around the magnetosphere. But when the solar wind is oriented with a southward magnetic field (red line, with arrows also pointing down), it connects to the Earth's northward field (making orange field lines). This magnetic reconnection pulls field lines from the day side of Earth around to the night side, and allows electrified gas (plasma) to pour into the tail of the magnetosphere. As the field lines pile up on the night side, the system becomes unstable. Reconnection happens again—this time in the middle of the tail. Particles and energy are shot down toward Earth's poles to make auroras

But many details remain poorly understood

Challenges in global simulations

- **Multiscale coupled system**
  - Spatial scales vary from **centimeters to 200 RE**
  - Temporal scales vary from less than **milliseconds to days**
  - Kinetic effects have global consequences
- **Multiphysics**
  - Electron physics: e.g., controls reconnection rate
  - Ion physics: e.g., dominates formation of boundaries and transport
  - Global features and dynamics: e.g., magnetotail/energetic particles
  - Coupling to the ionosphere

Three approaches to global simulations

- MHD (single fluid)
  - Used extensively
  - Does not resolve important ion physics
  - Does not correctly capture the physics of reconnection
  - Not suitable for studies of boundaries and discontinuities

Petascale computing has enabled:

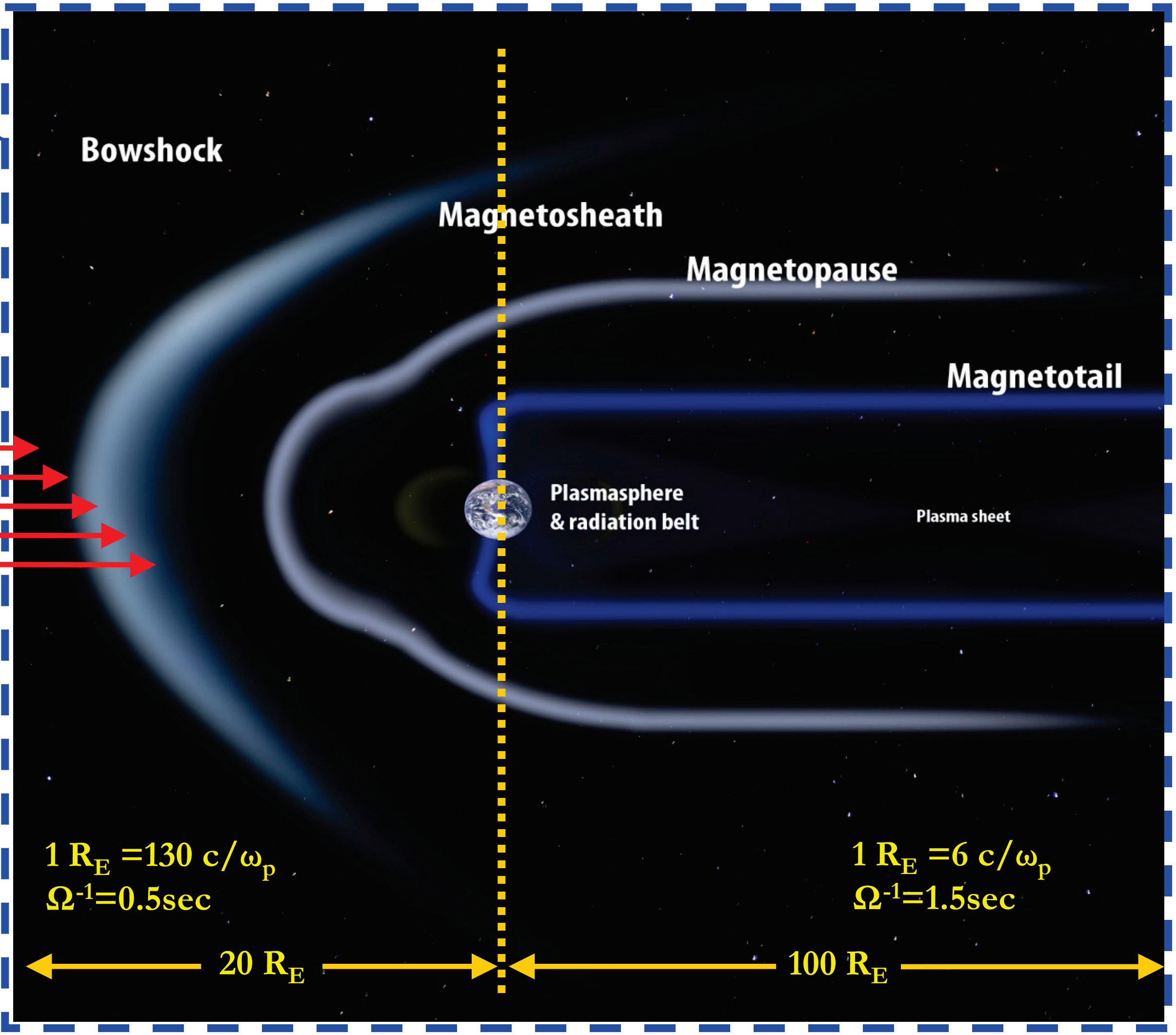
- Hybrid (fluid electrons, kinetic ions)
  - Fluid electrons, kinetic ions
  - It is the next stage of advance in 3D global simulations
  - Resolves ion spatial scales (ion inertial length) and ion temporal scales (gyroperiod)
- Full particle (kinetic electrons, kinetic ions)
  - It is the most complete description
  - Only 2D is possible

Numerology and the computational challenge

Simulation Domain

$120 \times 30 \times 30\ R_E^3$

Solar Wind Inflow Boundary Condition



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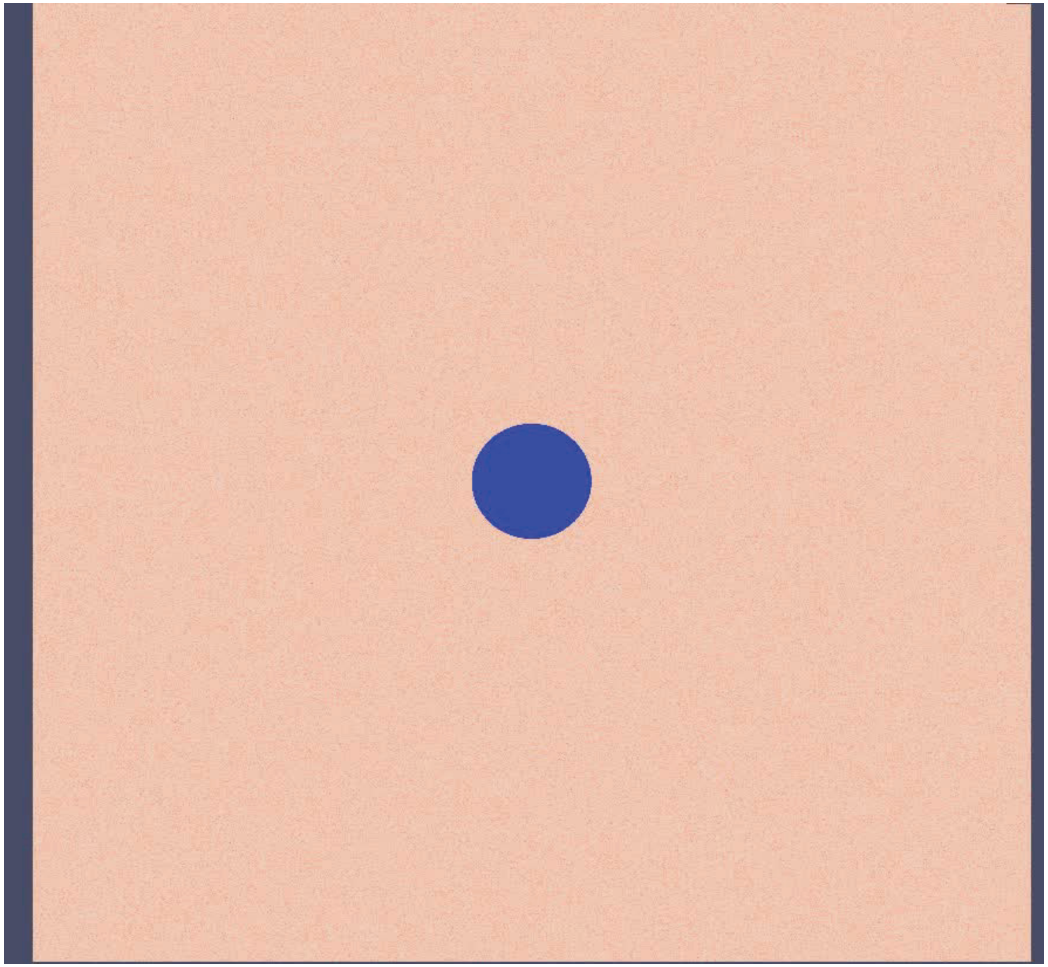
Results using 98K cores on Kraken at the National Institute for Computational Sciences

Kraken: They've got it right !

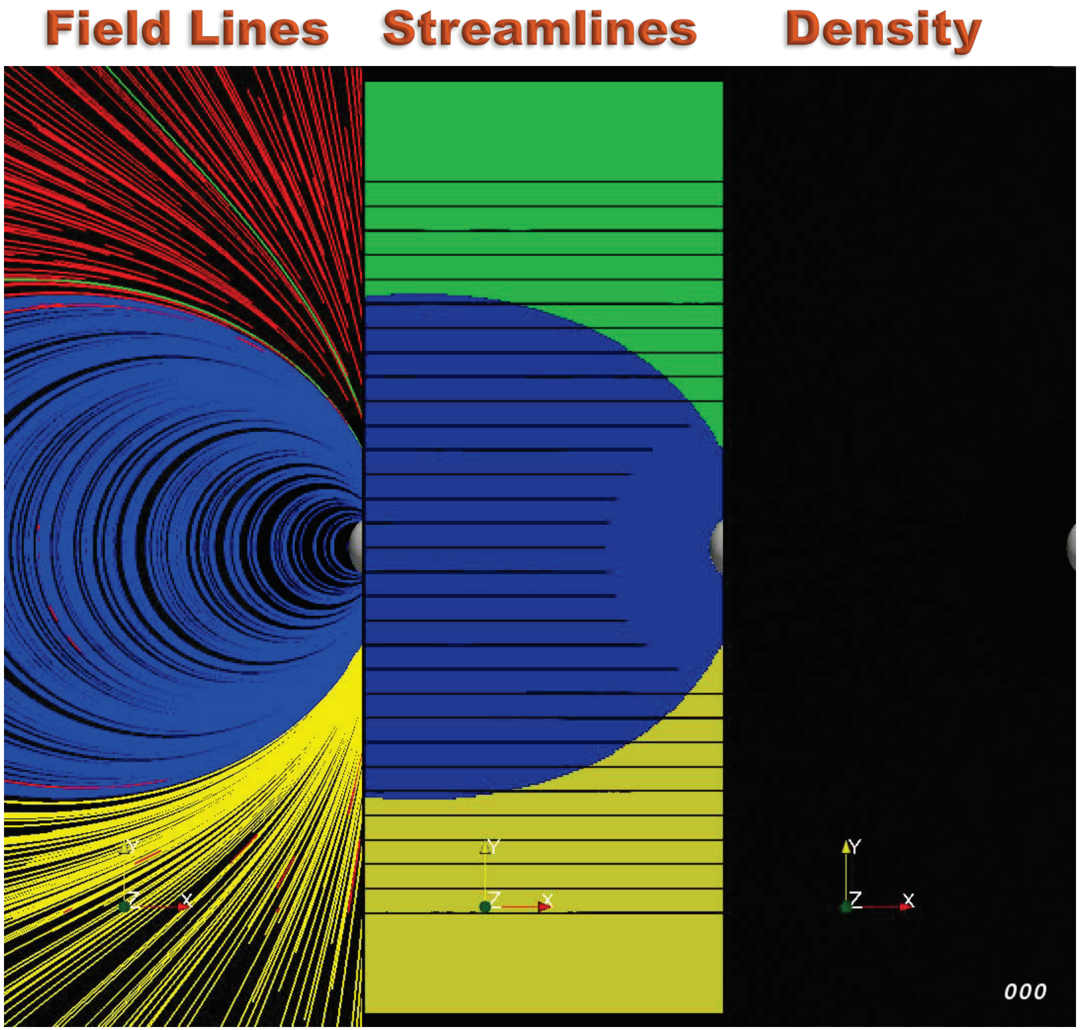
- The support and infrastructure for large users are unmatched
- They have a team of highly competent scientists and engineers that understand what it takes to run simulations that test the limitations of the hardware
- The ability to use the whole machine is critical for making our simulations possible

Fully kinetic simulation of magnetosphere



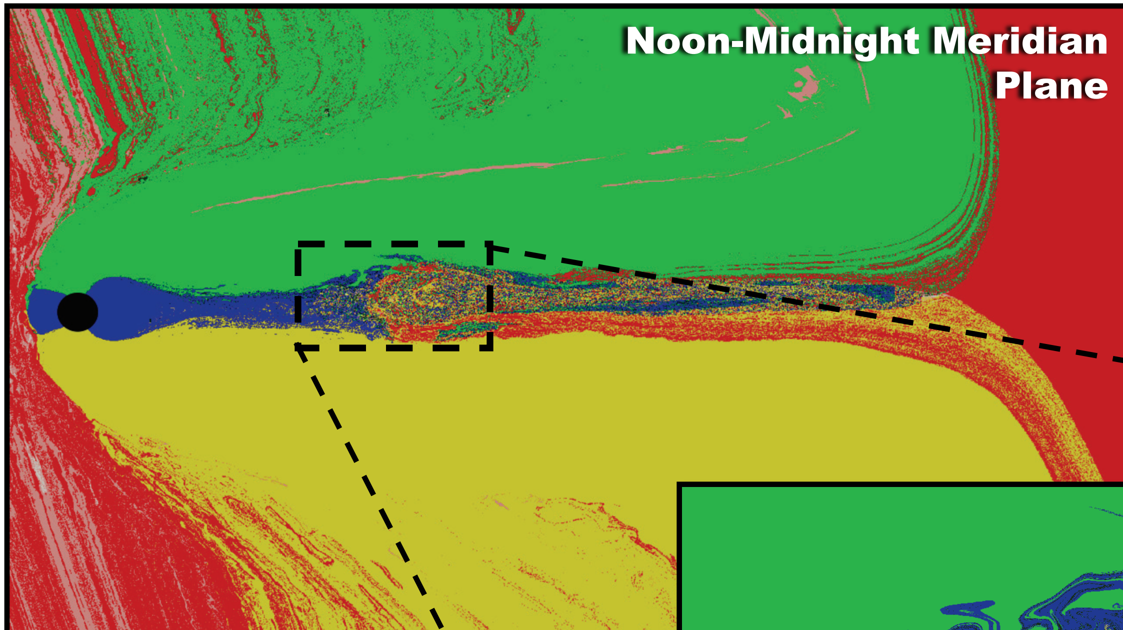
Demonstration of the formation of flux ropes that have been observed in spacecraft data

Hybrid simulation of magnetosphere

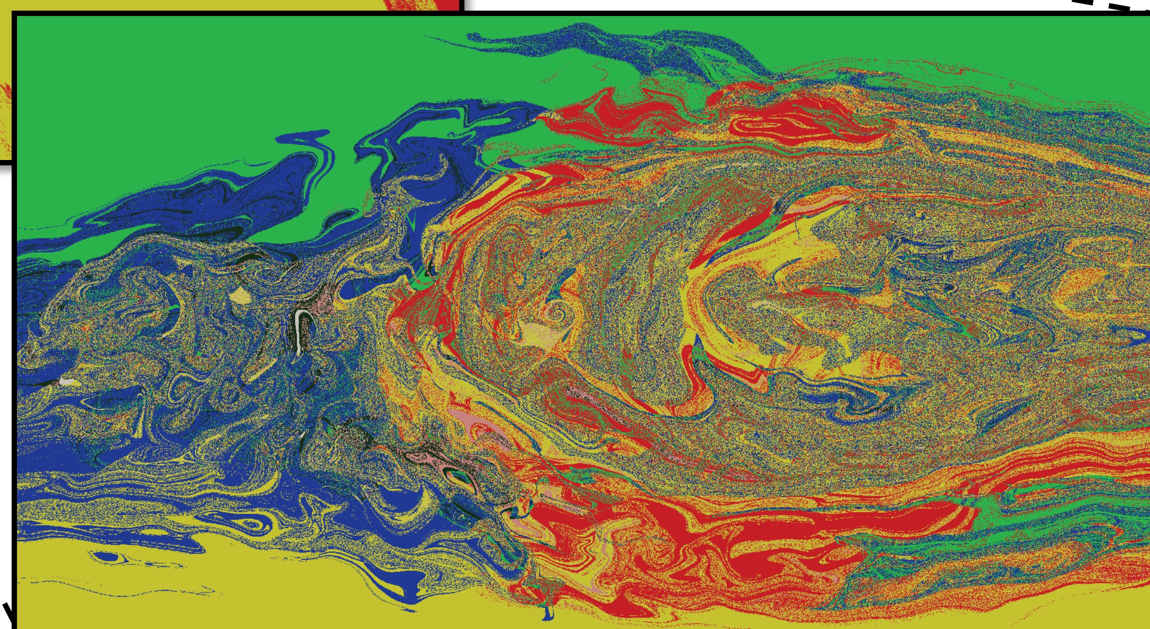


Shows the formation of flow vortices associated with flux ropes

Turbulent magnetosphere

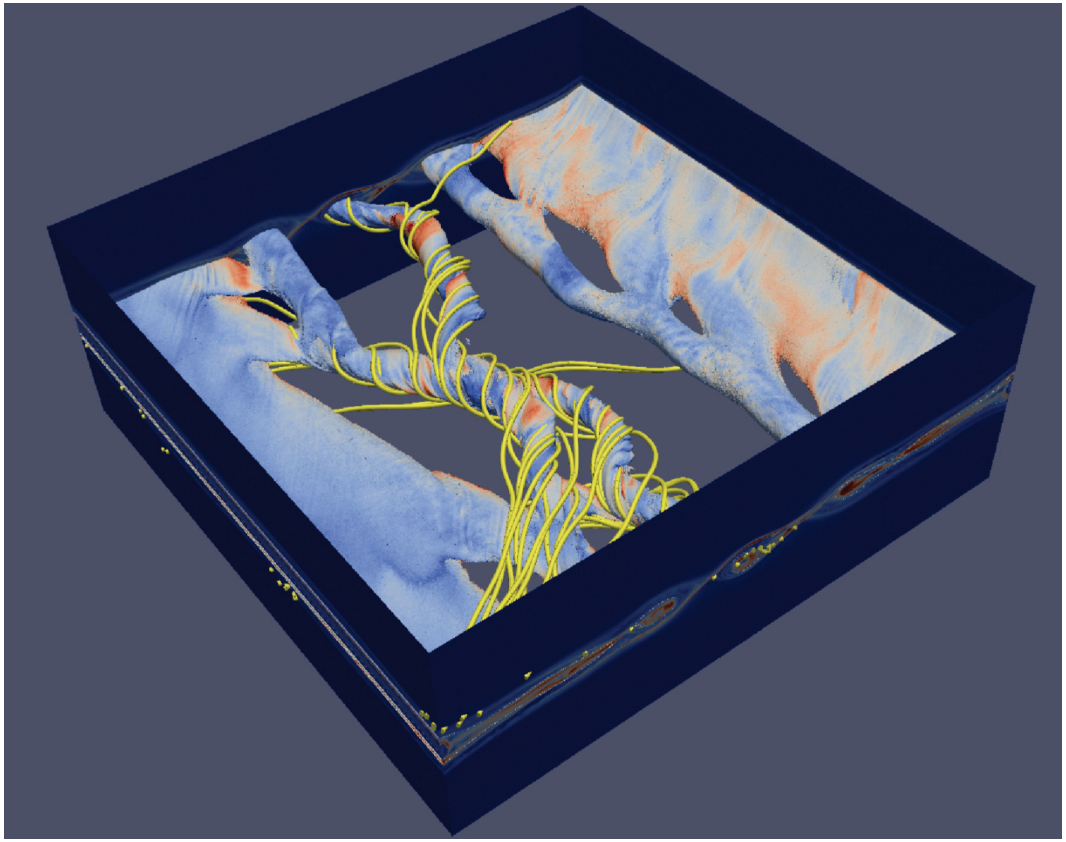


Highly complex!



Legend		
Class	Color	Description
d ⇔ d		solar wind
ø ⇔ d		
i ⇔ d		
n ⇔ s		closed magnetosphere
n ⇔ d		northern hemisphere connected
n ⇔ ø		
n ⇔ i		
n ⇔ n		
s ⇔ d		southern hemisphere connected
s ⇔ ø		
s ⇔ i		
s ⇔ s		
ø ⇔ ø		field null
i ⇔ ø		
i ⇔ i		

Largest full PIC simulation of reconnection



Using VPIC on 98K cores on Kraken

Fully kinetic 3D simulation of magnetic reconnection of a Harris sheet with finite guide field ($B_y = 0.5B_o$), mass ratio $m_i/m_e = 64$, and open boundary conditions. Simulation parameters are 2048 x 2048 x 768 cells and 1.1 trillion particles. Shown is an isosurface of particle density colored by the current density, along with some sample magnetic field lines (yellow) to illustrate the interaction of the flux ropes in this simulation

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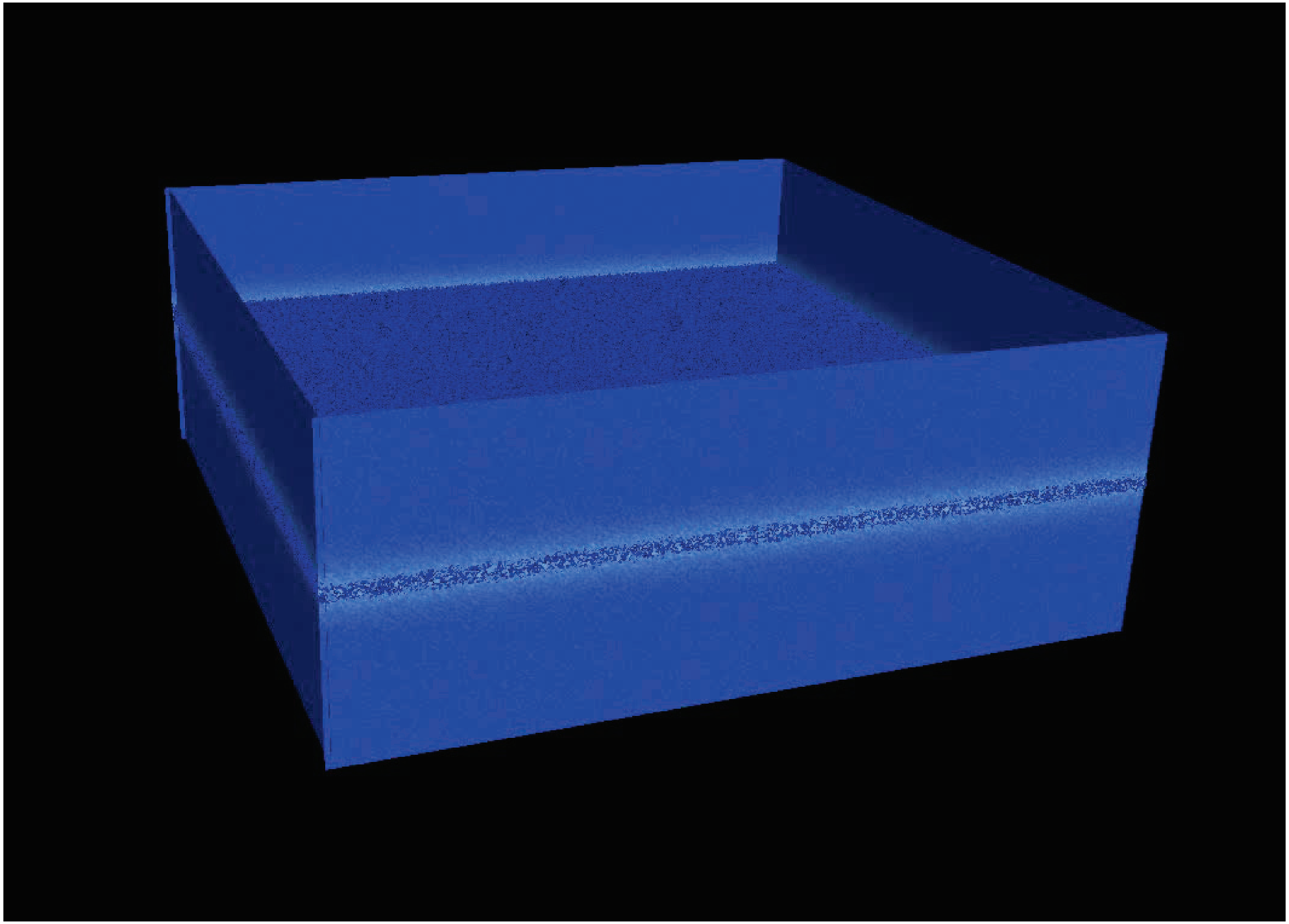
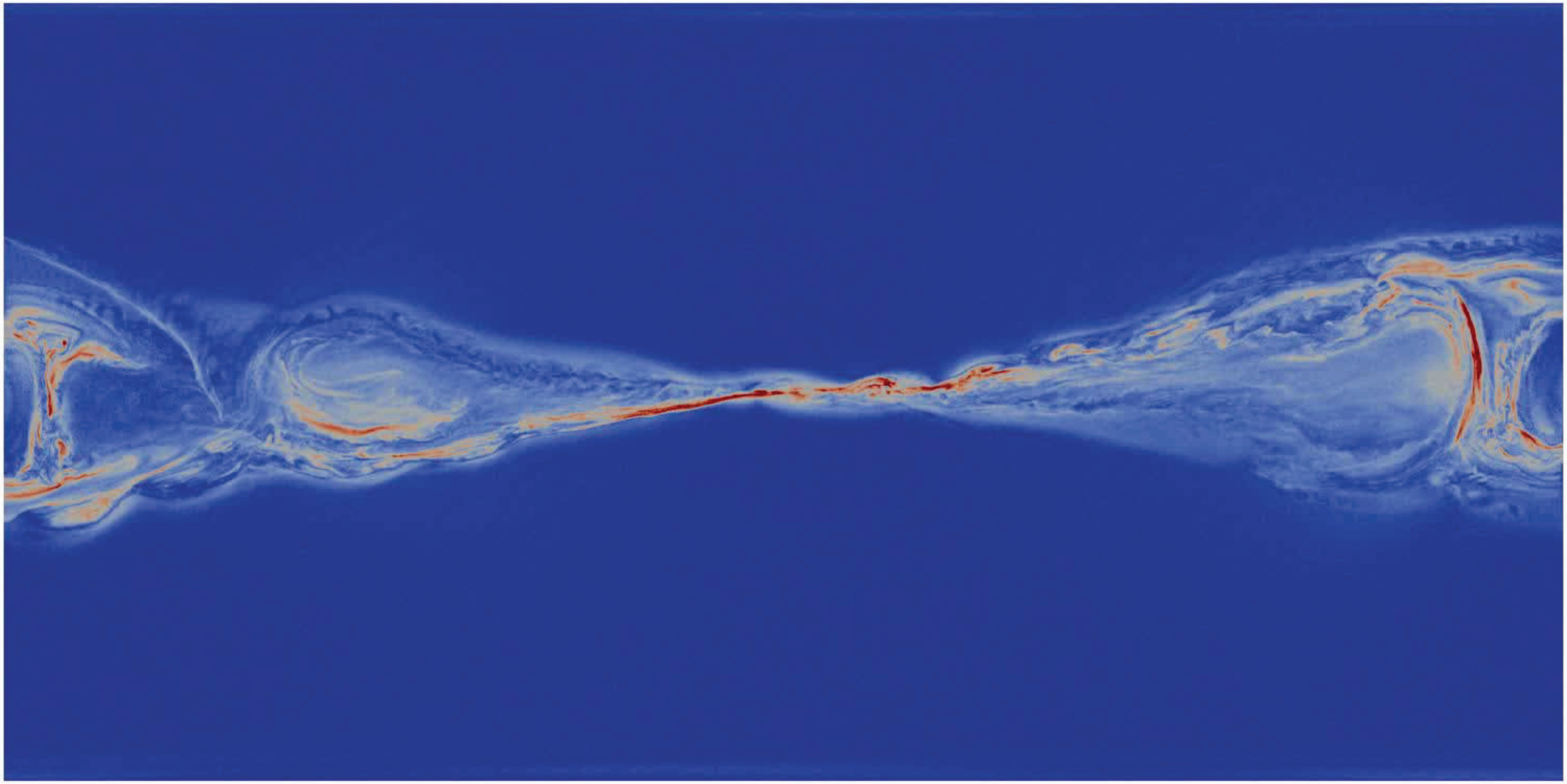
Self-generation of flux ropes



Magnetic reconnection gives rise to turbulence



Summary

- Global kinetic simulations of the magnetosphere are now possible
- These simulations are providing first ever glimpse at complex dynamics of solar wind interaction with the magnetosphere
- New understanding of magnetic reconnection has been achieved

Acknowledgments

Hybrid Code

H. X. Vu[1,2], Y. A. Omelchenko[1,2] , B. Loring[6], M. Tatineni[3], A. Majumdar[3], U. Catalyurek[4]

Fully Kinetic Simulations of Reconnection

W. Daughton[5], V. Roytershteyn[1,2]

Scientific Visualization

B. Loring[6]

MHD Simulations

J. Dorelli[7], J. Raeder[8]

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This research is supported by the NSF PETA-APP grant at UCSD, several NASA grants, and an allocation of advanced computing resources at the National Institute for Computational Sciences provided by the National Science Foundation.

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