Large Scale Kinetic Plasma Simulations: Bridging the Gap Between "Global" and "Local"

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

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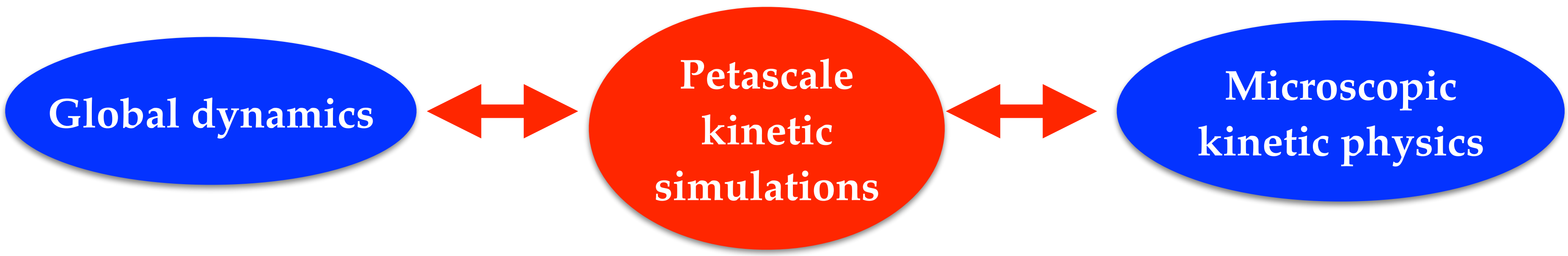
+ many collaborators

Presented at the 2015 Blue Waters Symposium, May 10-13 2015

Link Between Magnetic Reconnection, Kinetic Turbulence, and Global Dynamics (e.g. of the Earth's Magnetosphere)

Underlying theme: cross-scale coupling in collisionless plasmas.

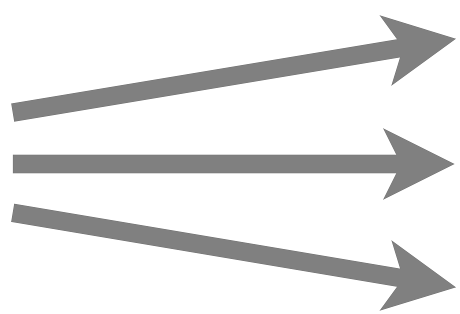


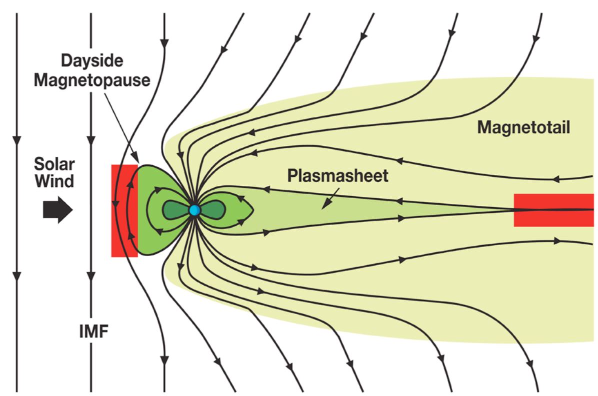
Motivation: the understanding of the Sun-Earth connection

Sun: turbulence, reconnection

Solar wind: turbulence, reconnection

Magnetosphere: global effects, reconnection, turbulence





Why it Matters: Space Weather

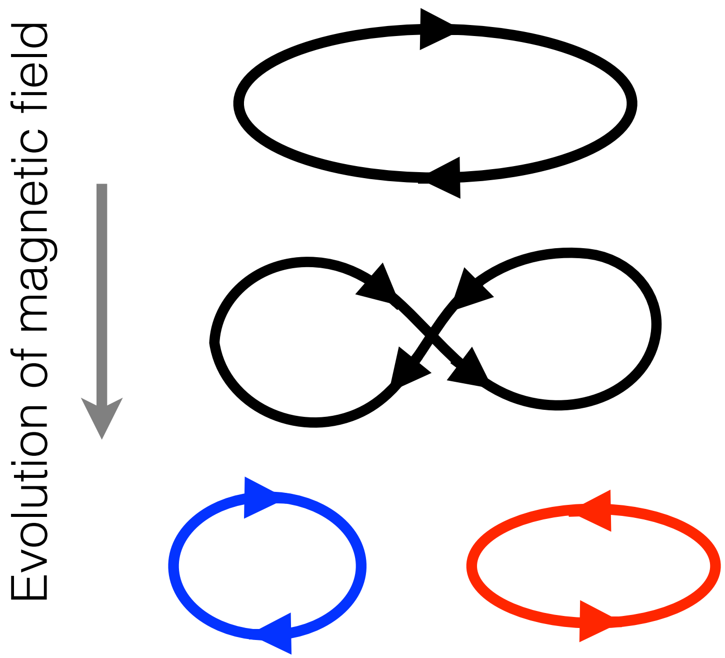
Potential Impact of Large-Scale Event according to "Report on Space Weather Observing Systems: Current Capabilities and Requirements For The Next Decade"

- **Electric Power Grid:** Large-scale blackouts and permanent damage to transformers, with lengthy restoration periods.
- **Global Satellite Communications:** Widespread service disruptions to 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

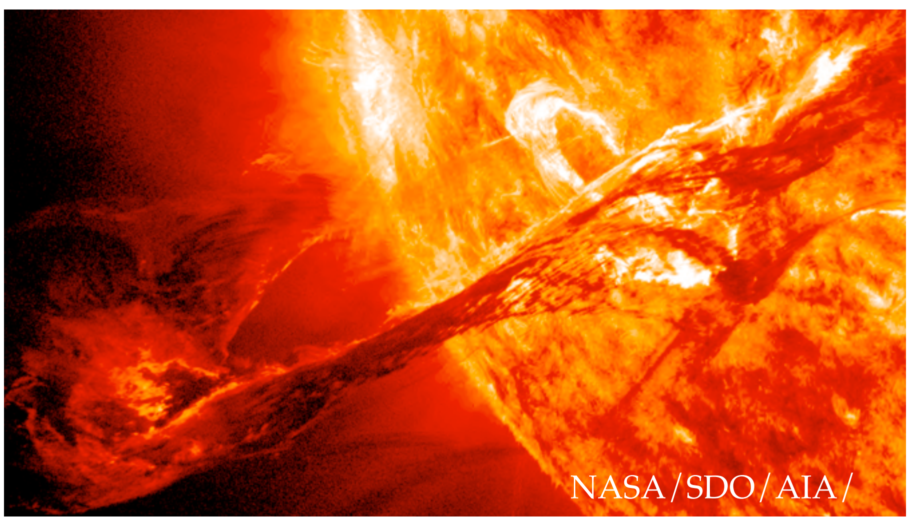
Estimated cost of a severe geomagnetic storm (such as the 1859 "super storm") on the satellite industry alone could be approximately **$50 - $100 billion**.

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**.

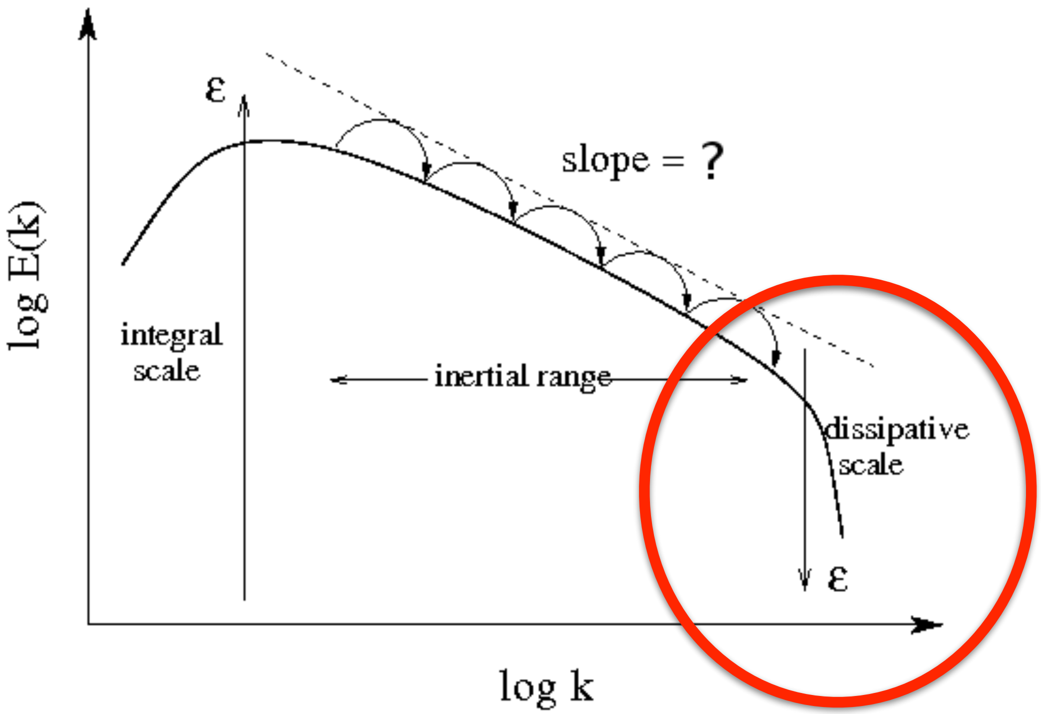
Magnetic Reconnection



- Forbidden in “ideal” MHD (superconducting fluid)
- Flux conservation is a simple, but powerful constraint that may lead to accumulation of energy
- Reconnection=breakage of the ideal constraint.
- Occurs in narrow spatial regions (current sheets)
- Leads to rapid (sometimes explosive) relaxation and energy release



Kinetic Plasma Turbulence



- Both solar wind and solar corona famously exhibit “anomalous” temperature profiles
- Local energy input due to dissipation of turbulence is a possible explanation
- Plasmas of interest are hot and rarified, i.e. “collisionless”
- Dissipation is provided by collective modes, rather that by binary Coulomb collisions
- A variety of mechanisms proposed in the literature
- Understanding of how they work together can only be provided by simulations that include all of them
- The dominant mechanism dictates partition of dissipated energy, etc

"First Principle", Large-Scale Simulations => Blue Waters

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

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

+ Maxwell's equations

<u>Fully kinetic simulation</u>

(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

<u>Large scale hybrid kinetic simulation</u>:

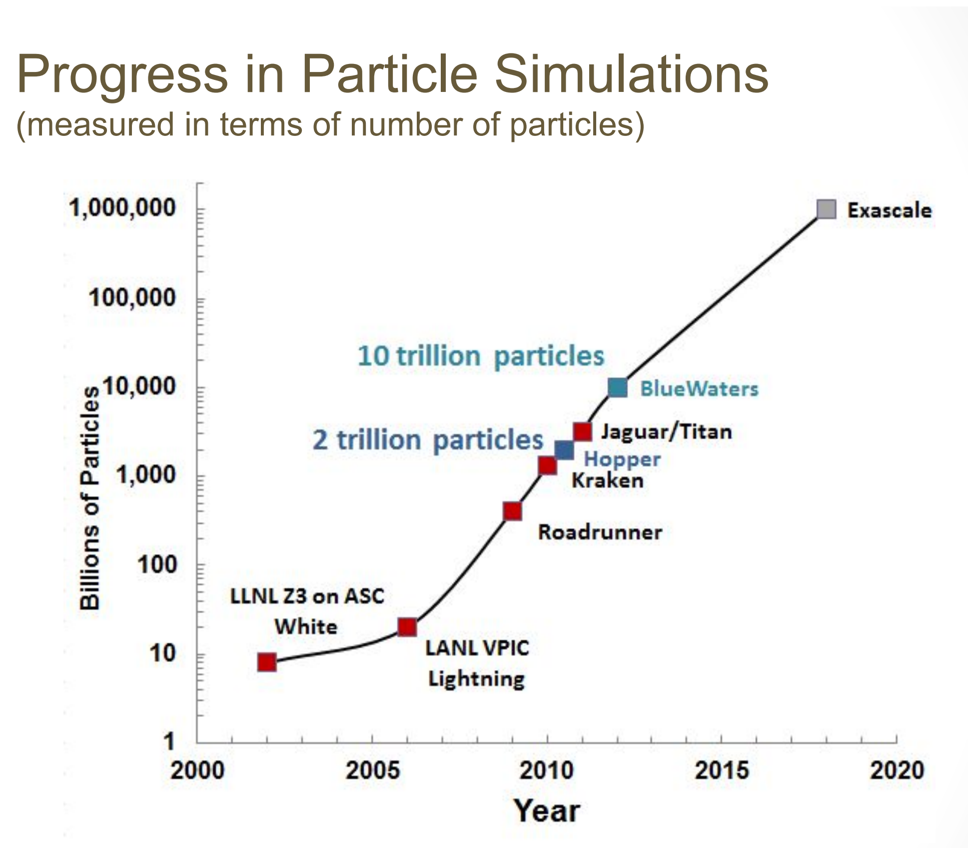
(kinetic ions + fluid electrons;

codes: H3D, HYPERES)

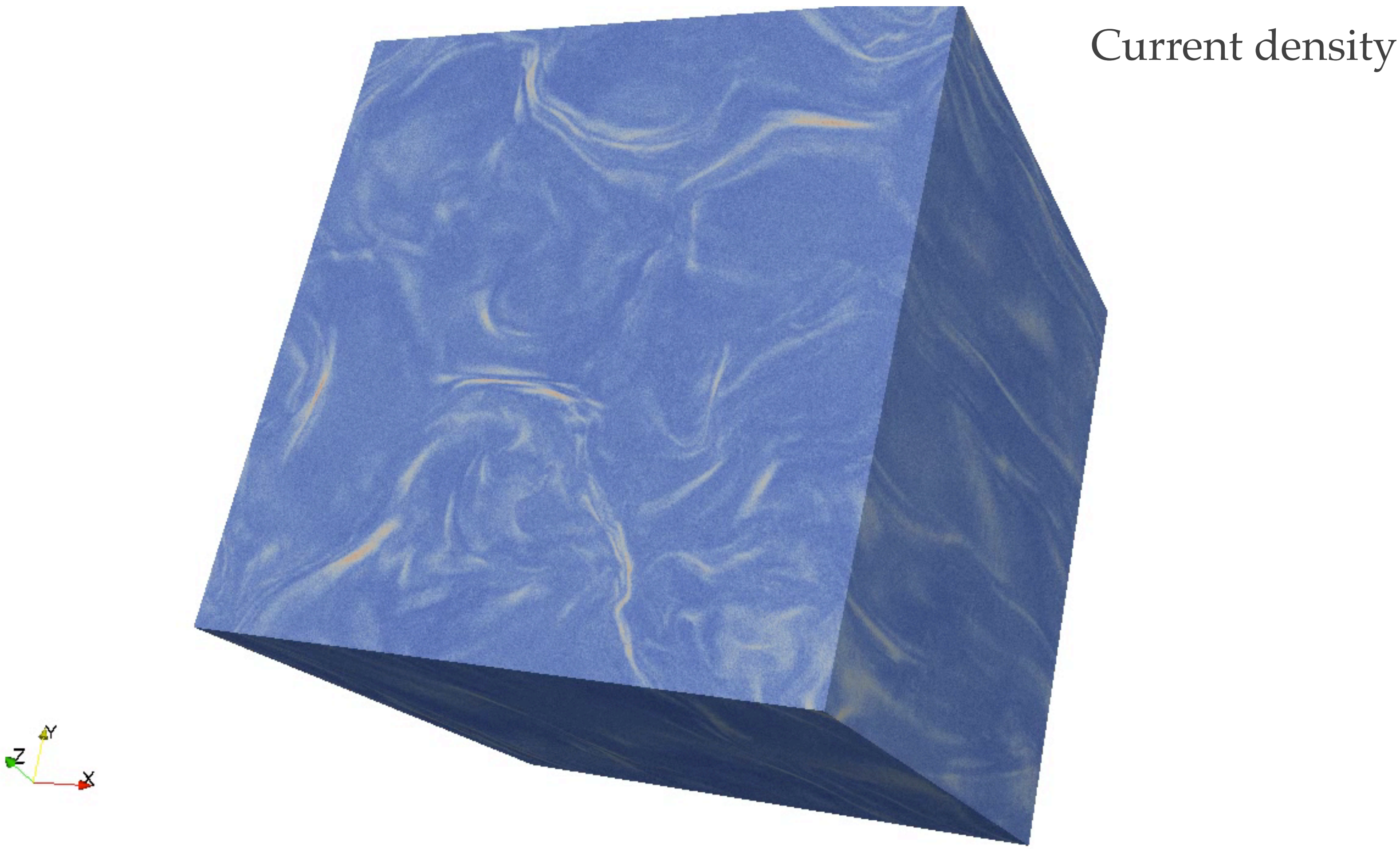
~up to $1.7\text{x}10^{10}$ cells

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

~130 TB of memory

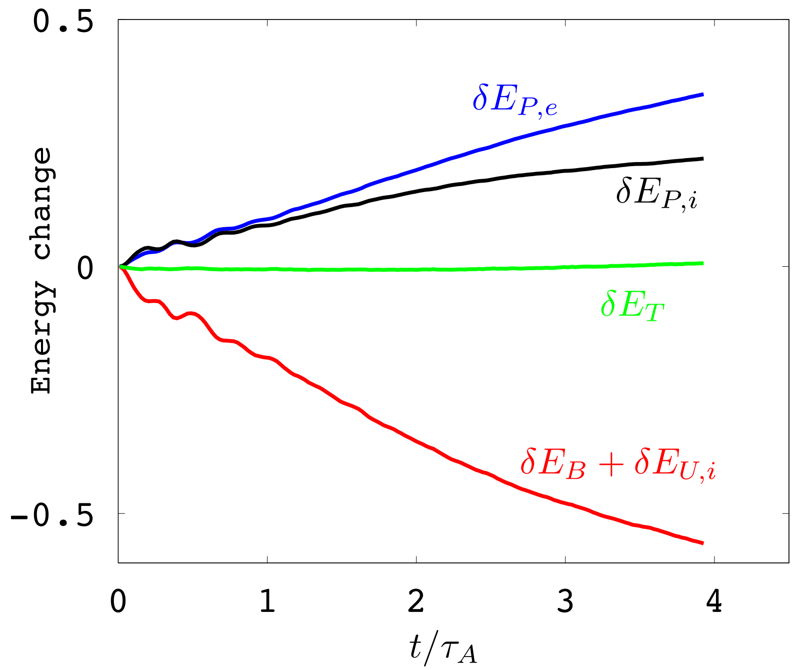


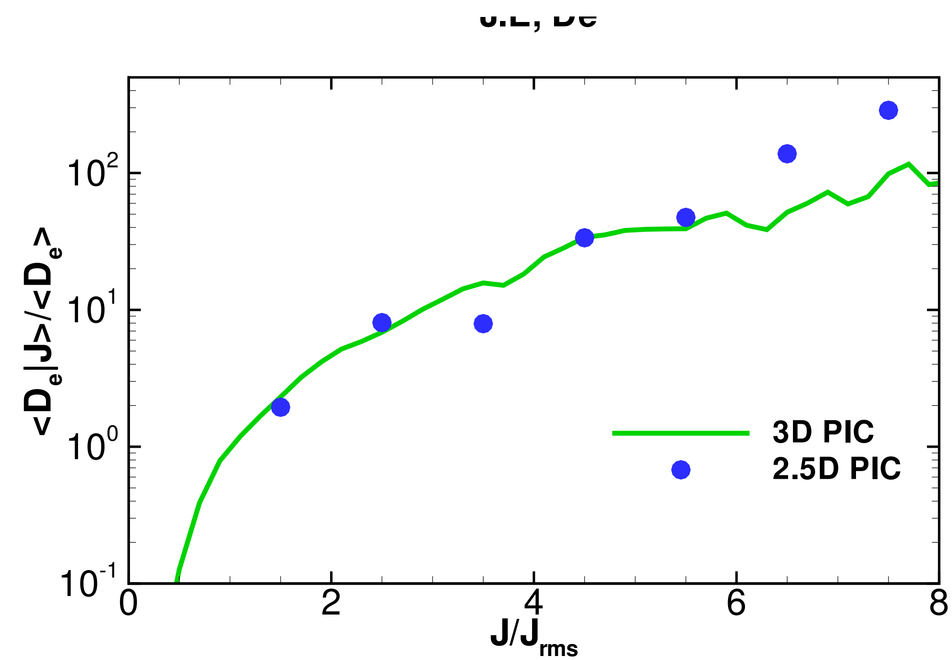
First 3D Simulations of Collisionless Plasma Turbulence that Simultaneously Resolve Kinetic Physics and Large Scale (MHD) Dynamics.



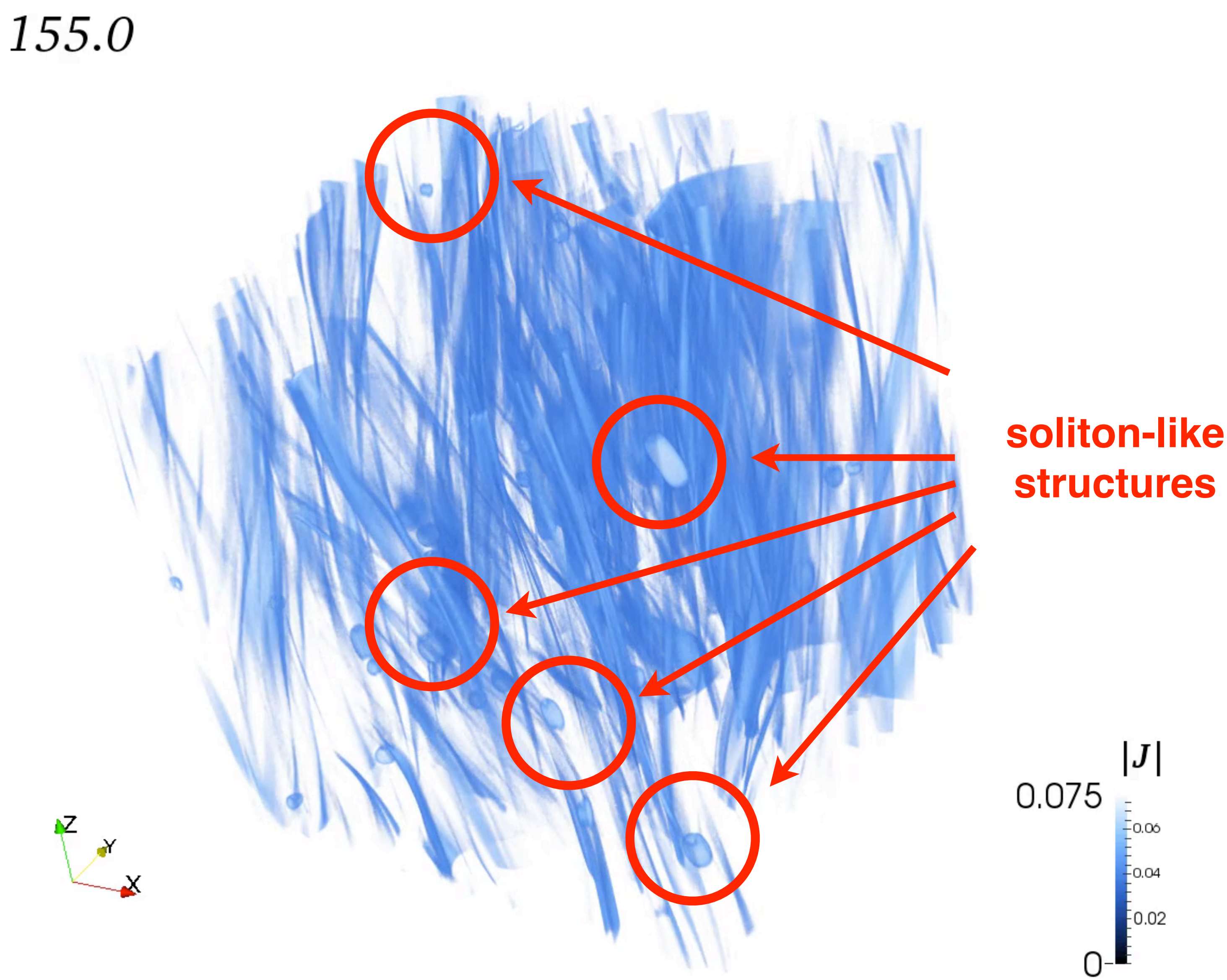
Science target: dissipation of cascading energy in collisionless plasmas: **coherent structures** vs resonant wave-particle interactions vs stochastic damping; Findings: current sheets and their properties, energy partition; Papers: Wan *et al.*, PRL 2015; Roytershteyn *et al.*, PoP , tbd

Energy Partition



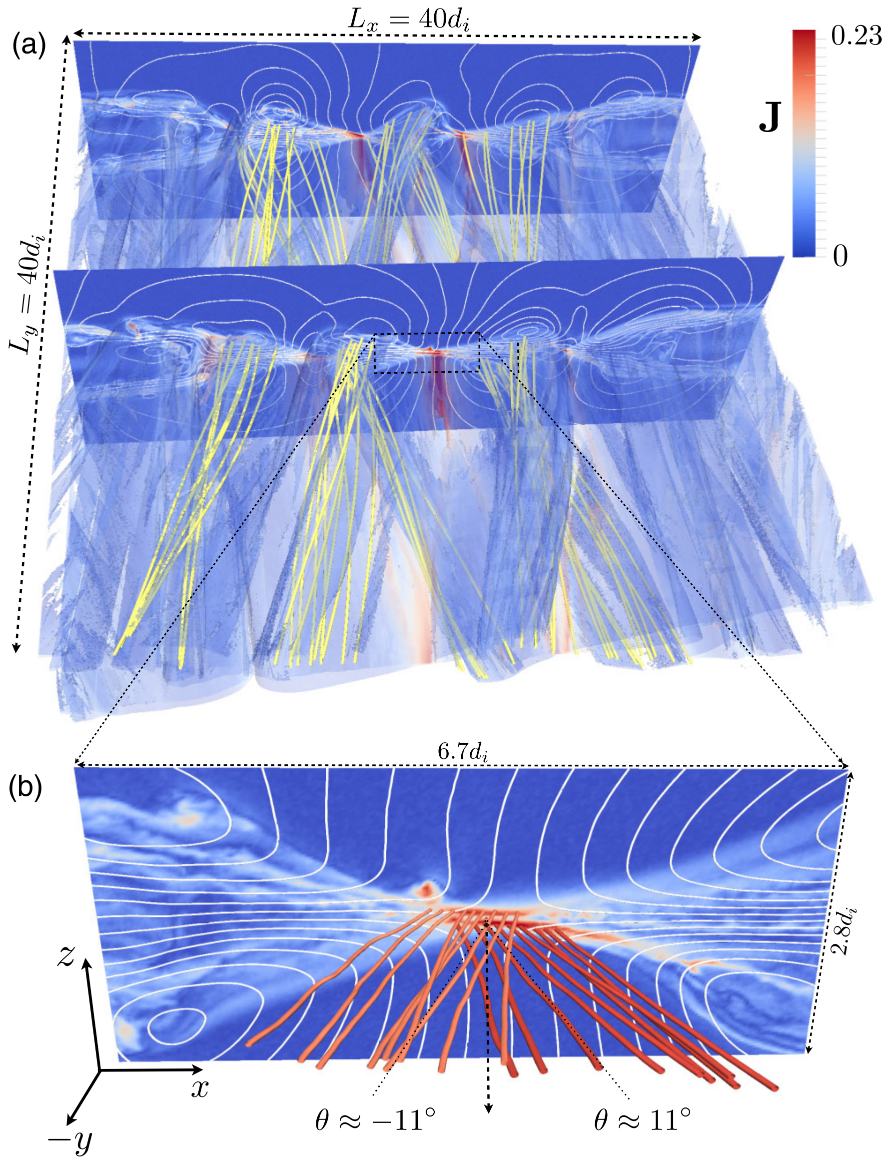


Generation of Small-Scale Magnetic Holes in Turbulence

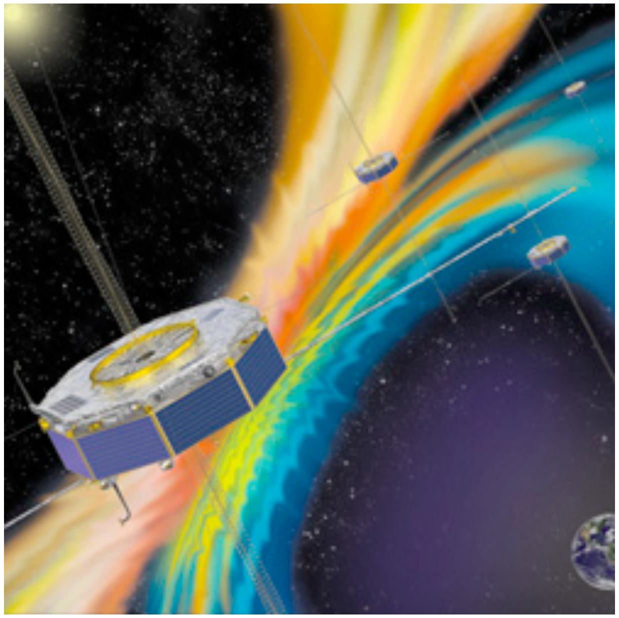


Science target: coherent structures in collisionless plasmas; Findings: electron-scale magnetic holes; Papers: Roytershteyn *et al.*, Phil. Trans. R. Soc. A 2015

3D Local Fully Kinetic Simulation of Magnetic Reconnection



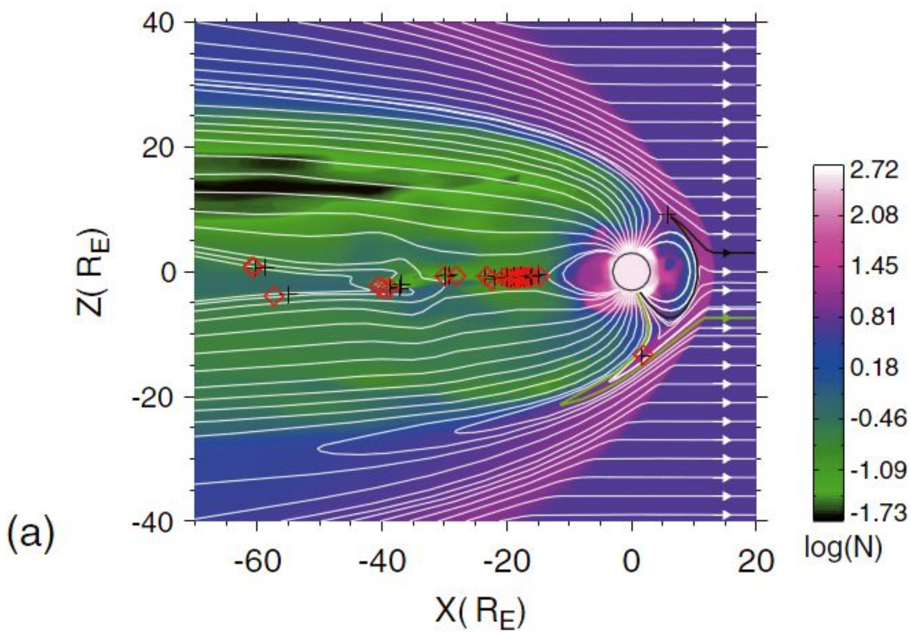
NASA Magnetospheric Multiscale (MMS) Mission



Science target: structure of magnetic reconnection region; Findings: details electron diffusion region and force balance in 3D system. Paper: Liu *et al.* PRL, 2013

Global Simulations of Magnetosphere Reconnection+Turbulence+Global Dynamics

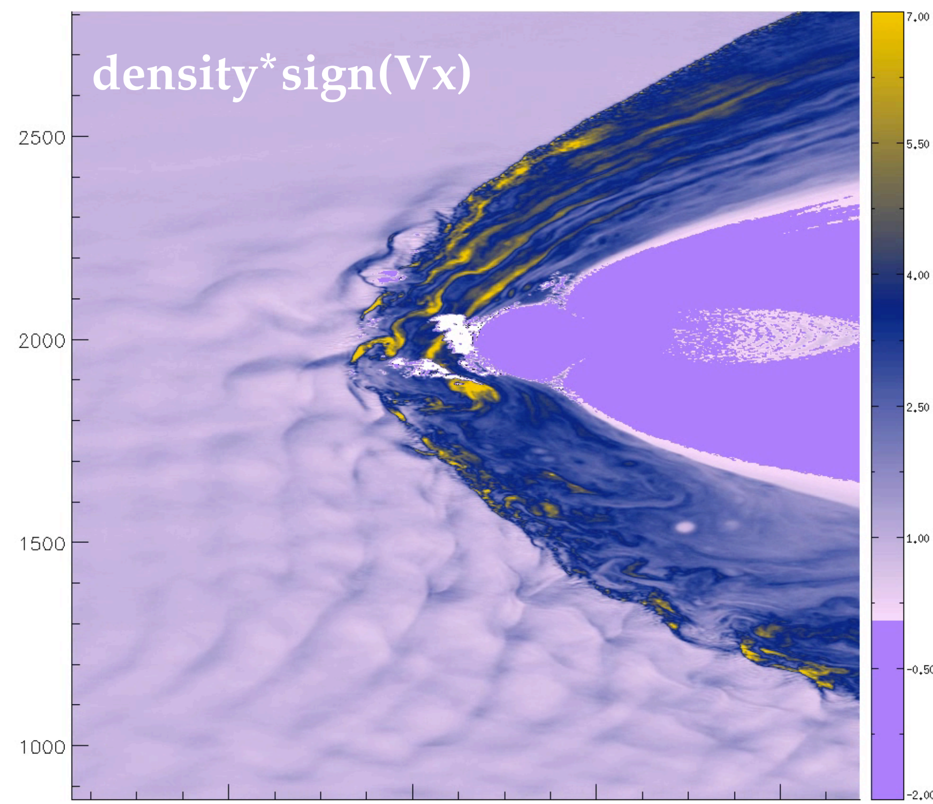
MHD: smooth
(Tang et al., JGR, 118, 2013)



Nearly radial IMF

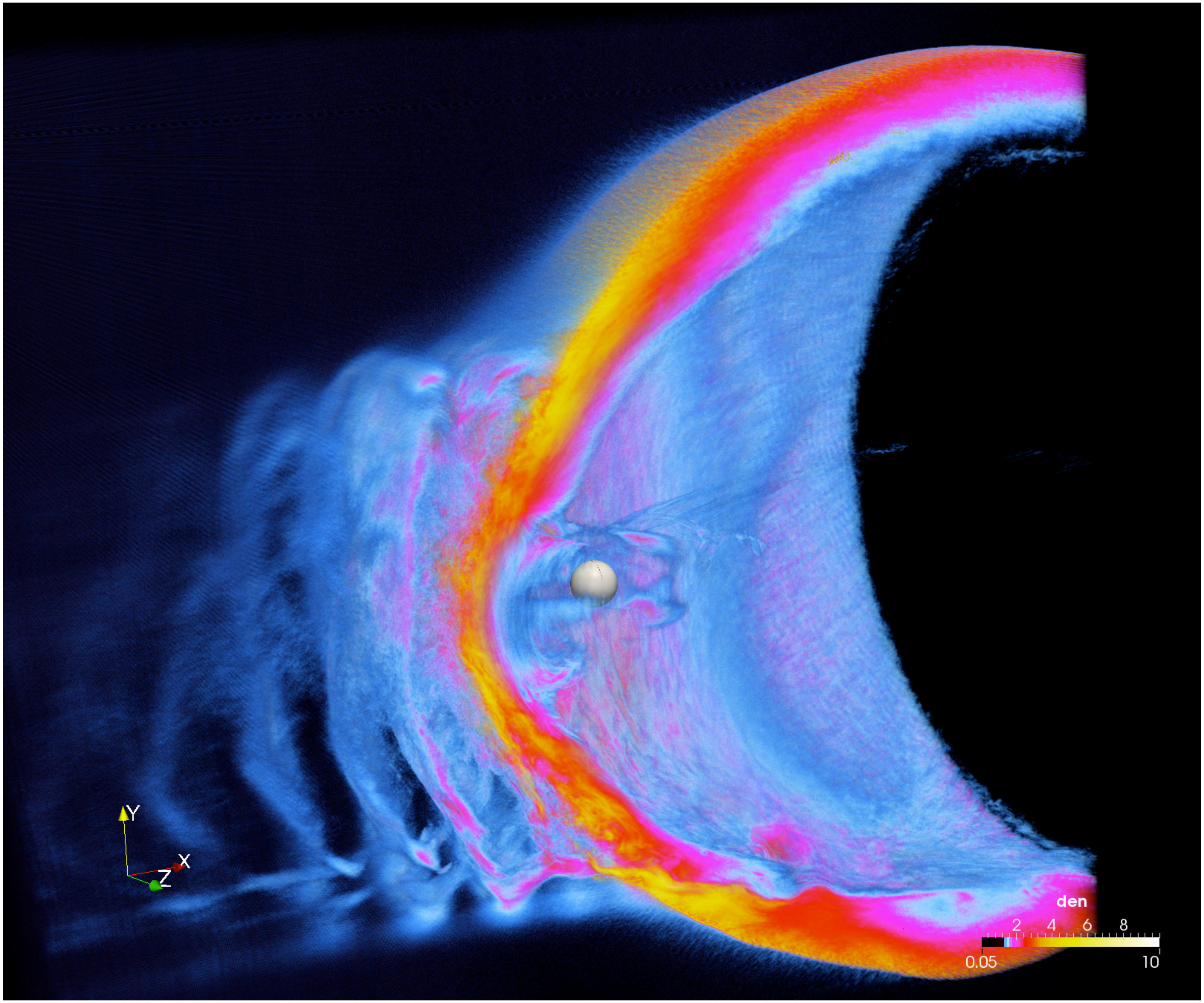
Kinetic: turbulence & large-scale perturbations (Karimabadi, *et al*. PoP, 2014)

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



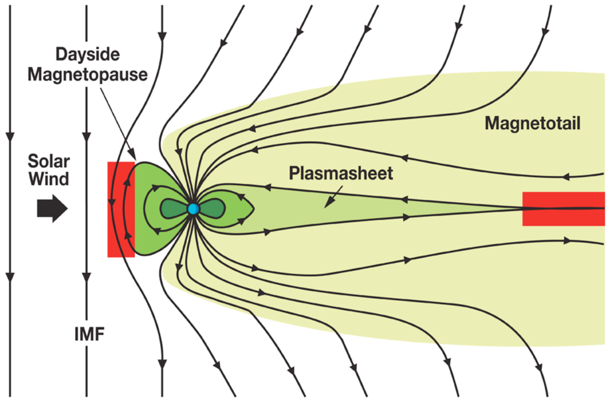
Reflected ions drive foreshock turbulence that interacts with the shock & drives magnetosheath turbulence

3D Global Hybrid Simulations of Magnetosphere

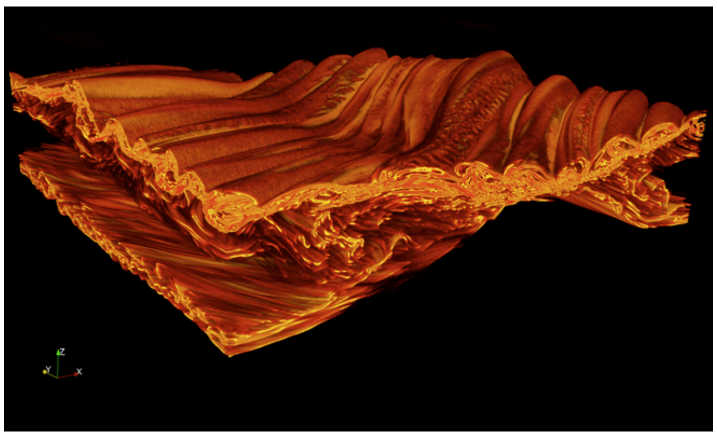


Global Fully Kinetic Simulations of Magnetosphere

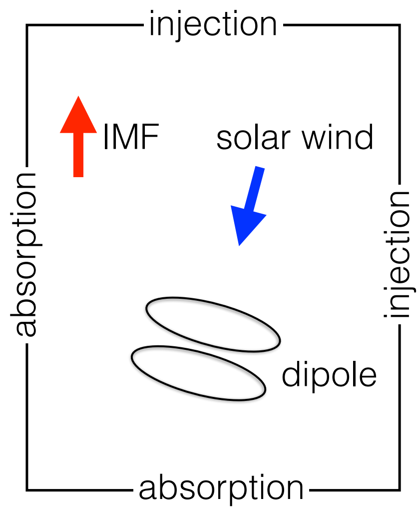
Magnetosphere



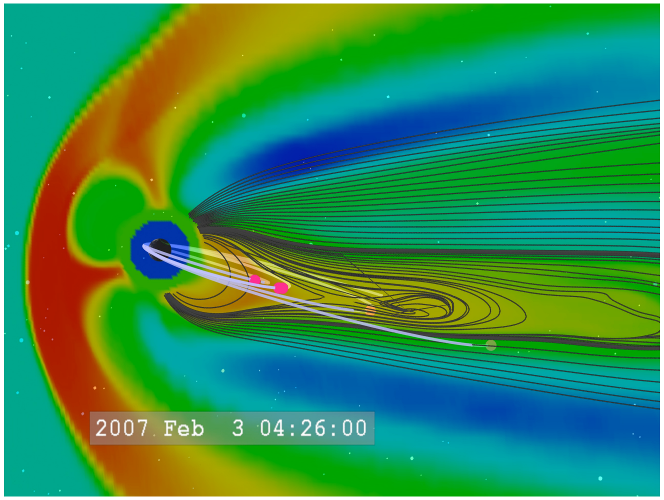
Local model: physics of reconnection, but no global geometry or drive



middle ground: all of physics + 2D geometry

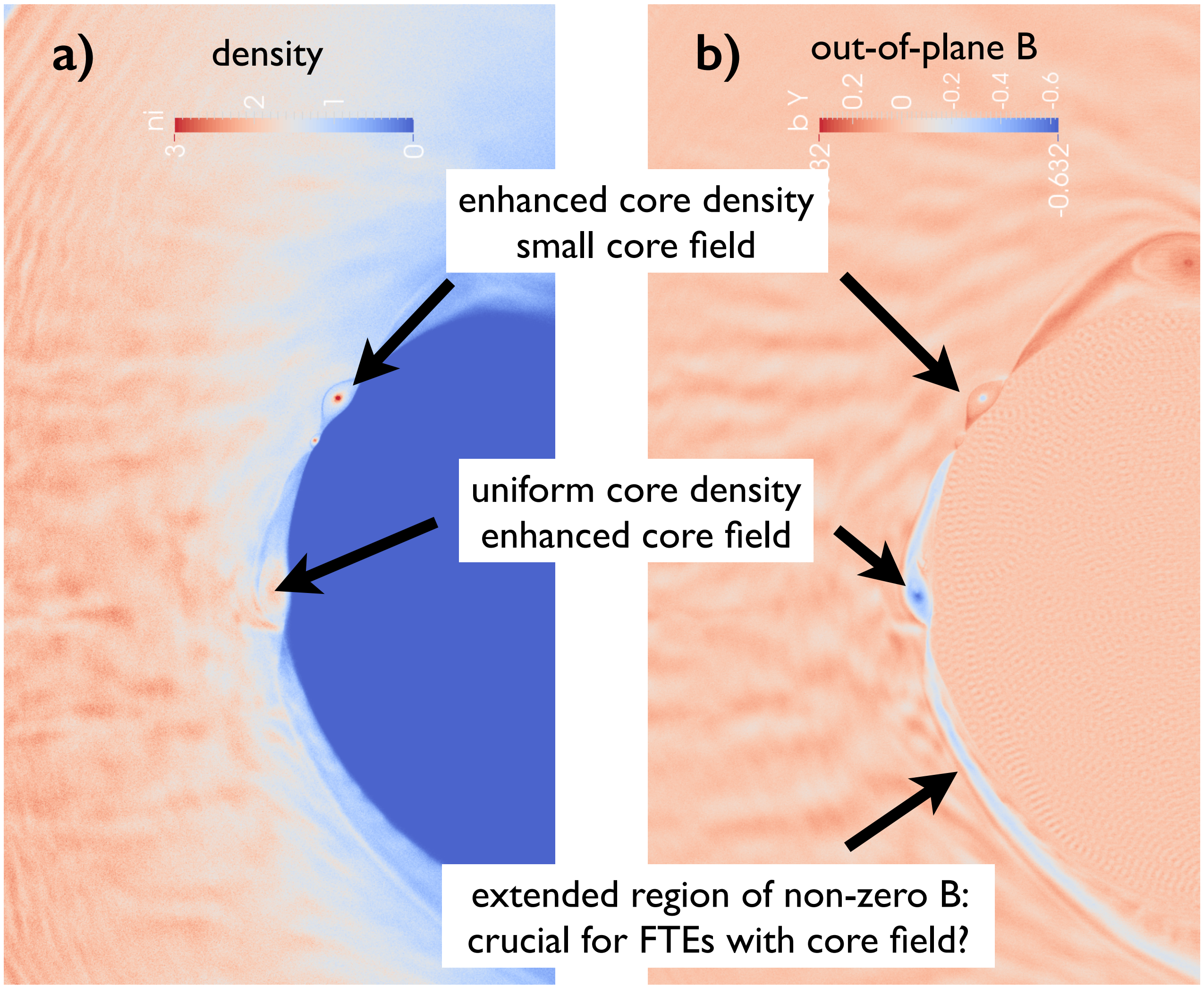


Global 3D models: reconnection is unphysical



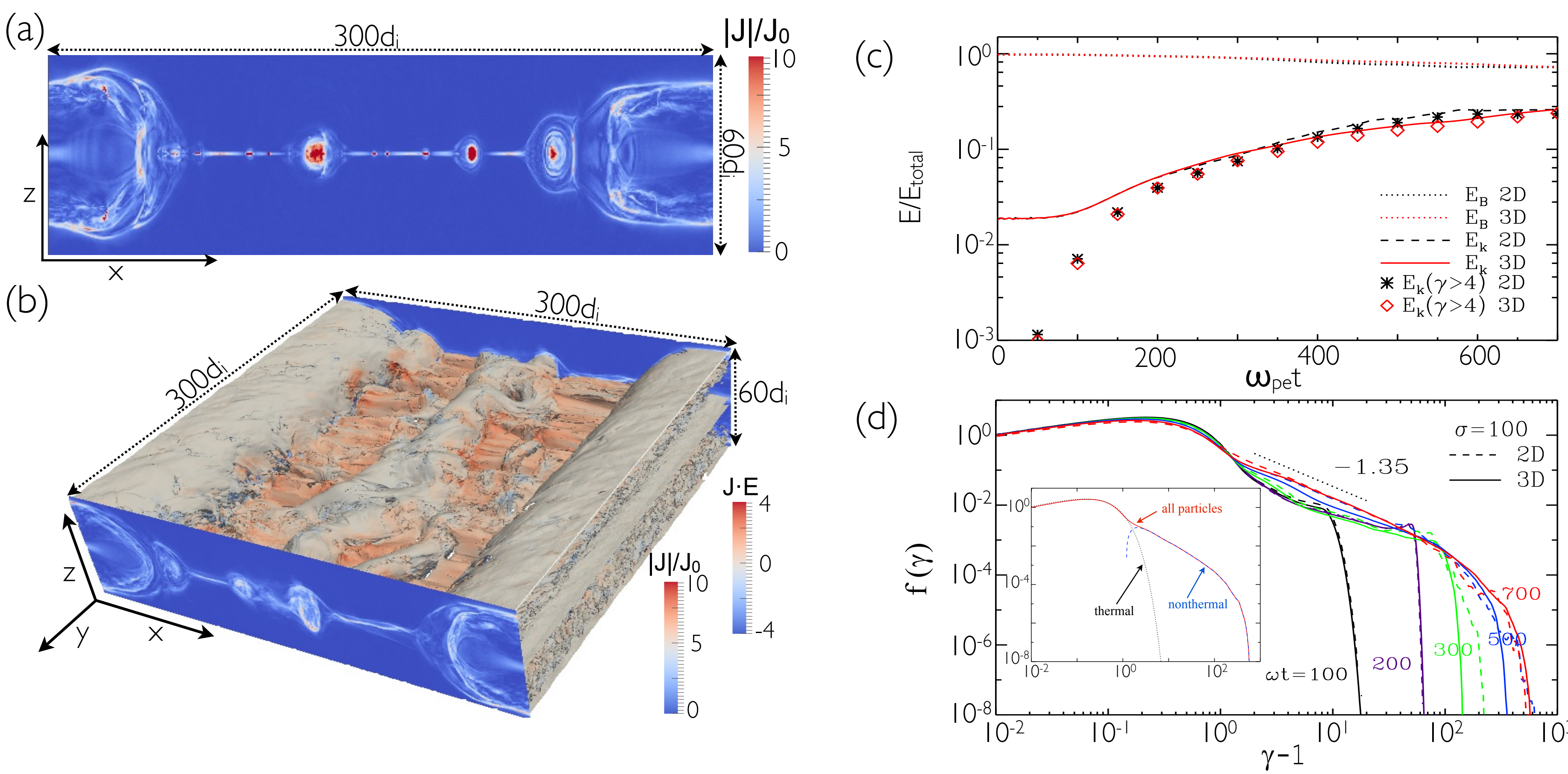
NASA/Goddard Space Flight Center Scientific Visualization Studio

2D Global Fully Kinetic Simulations



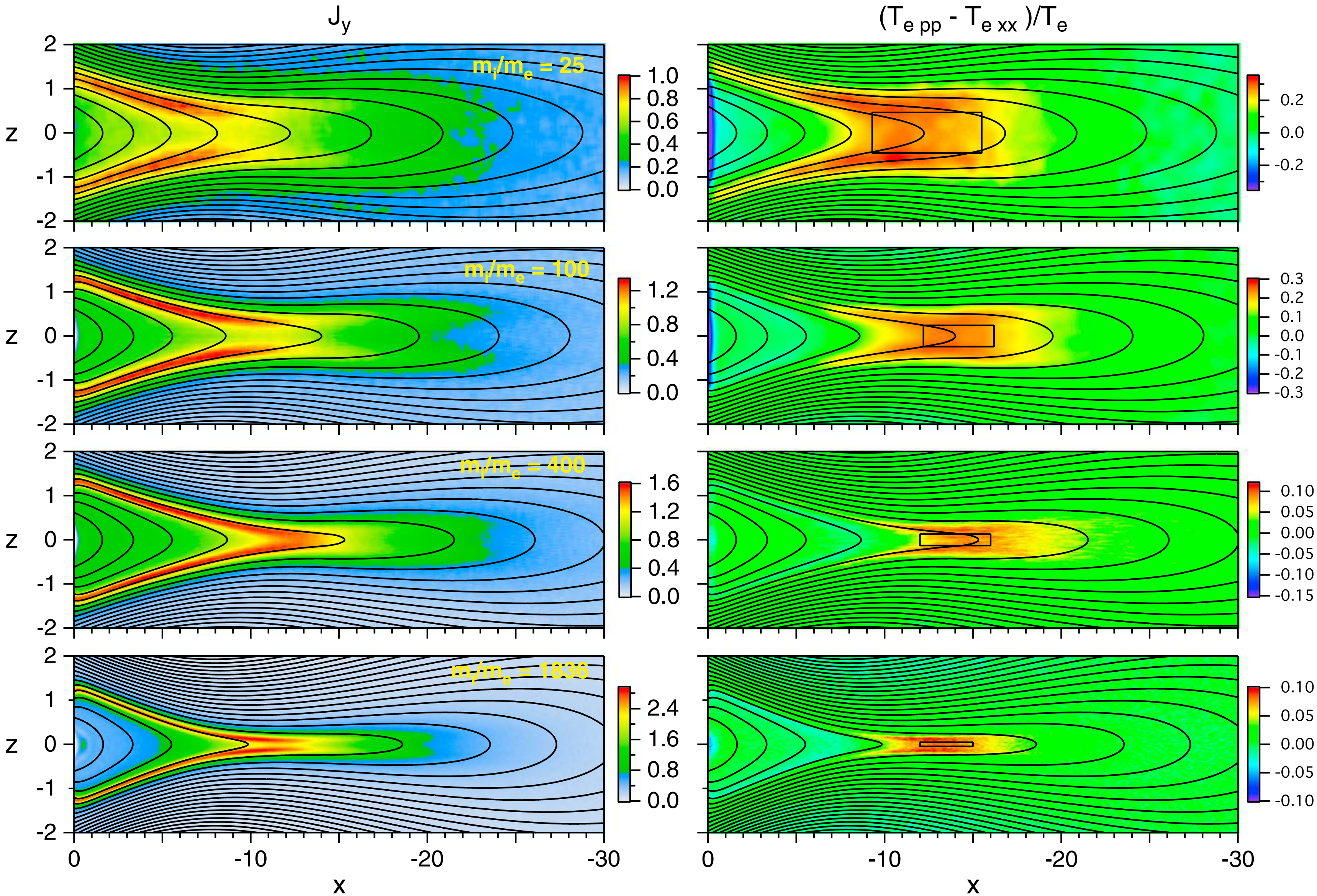
Science target: magnetic reconnection in a global environment. Coupling between microphysics of reconnection and global dynamics. Paper: Karimabadi, *et al.* PoP, 2014

Particle Acceleration by Magnetic Reconnection



Science target: particle acceleration by magnetic reconnection in relativistic regimes; Findings: acceleration mechanism. Paper: Guo *et al.* PRL, 2014

Fully Kinetic Mesoscale Simulations of Tail Dynamics



Science target: onset of magnetic reconnection in the magnetotail. Findings: onset mechanism, structure of the diffusion region. Paper: Liu *et al.* JGR, 2014

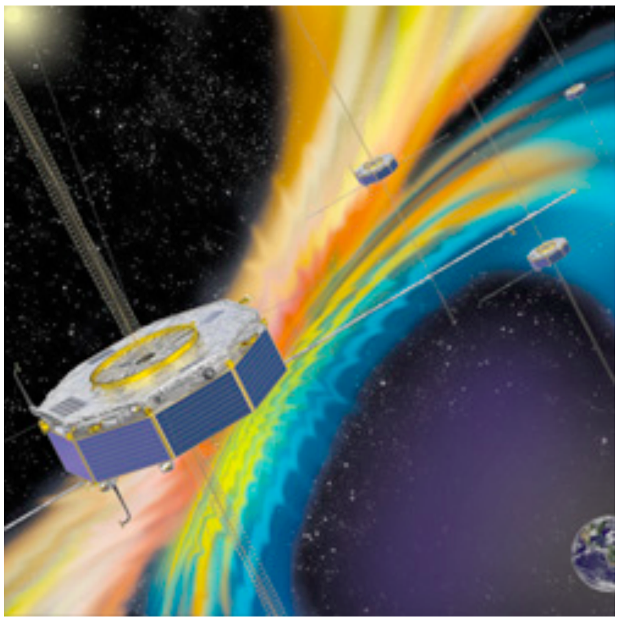
Blue Waters Team Contributions

- Code optimization (VPIC and H3D). Kalyana Chadalavada (NCSA) and Jim Kohn (Cray)
- Visualization support
- Lots of support for day-to-day issues, data management, I/O, storage, globus, etc (Many thanks to Ryan Mokos for coordinating these efforts)

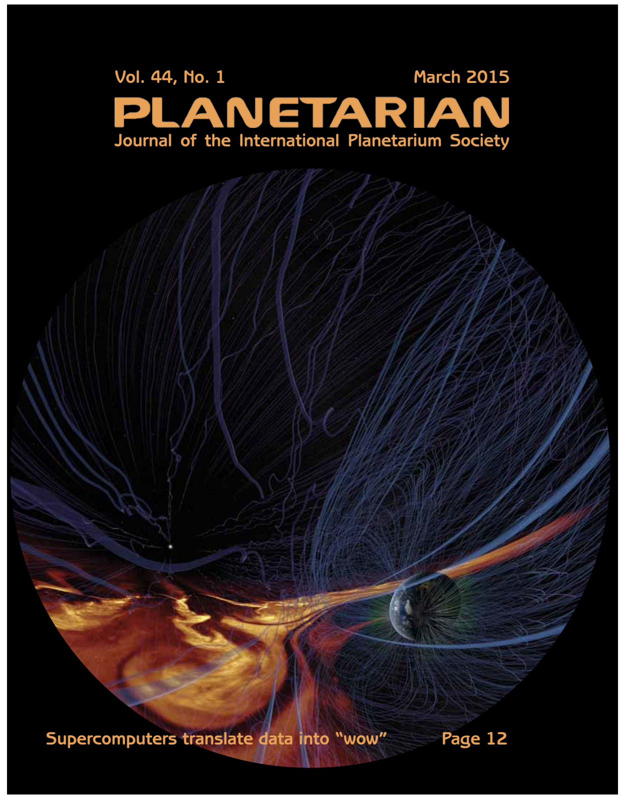
Broader Impact

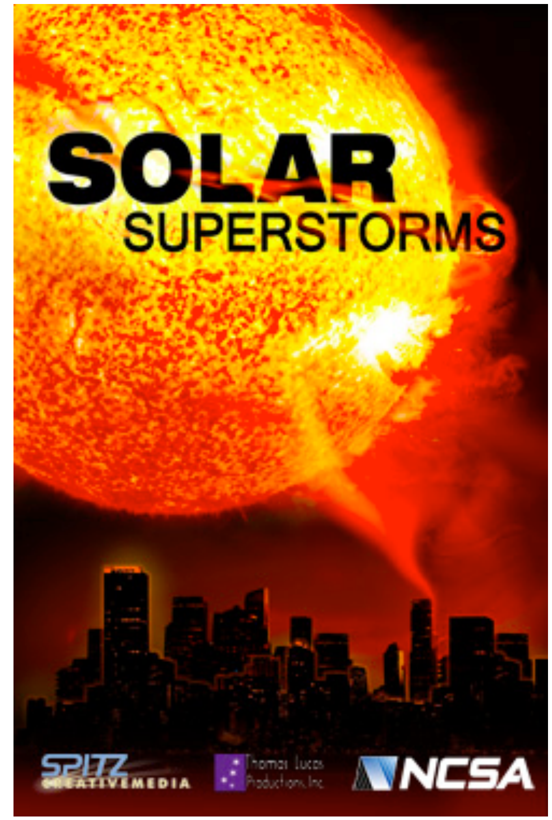
Understanding of fundamental plasma phenomena feeds into many areas: laboratory, space, astrophysics, etc. We also did our bit in popularizing the research

Spacecraft observations



NASA MMS





Advanced Visualization Lab (Donna Cox, Robert Patterson, Stuart Levy, AJ Christensen, Kalina Borkiewicz, Jeff Carpenter)

Shared Data

All of our datasets are available to researchers worldwide upon request.
Partial list of BW's data users:

Princeton University
University of Delaware
NASA Goddard
NASA Ames
Catholic University of America
University College London
LANL
UCLA

Products

- Datasets
- Papers

M. Wan, W. H. Matthaeus, V. Roytershteyn, H. Karimabadi, T. Parashar, P. Wu, and M. Shay, Intermittent Dissipation and Heating in 3D Kinetic Plasma Turbulence, Phys. Rev. Lett. 114, 175002

Roytershteyn V., Karimabadi H., Roberts A., Generation of magnetic holes in fully kinetic simulations of collisionless turbulence, Philos Trans A Math Phys Eng Sci. 2015 May 13;373(2041). pii: 20140151. doi: 10.1098/rsta.2014.0151.

Karimabadi, H.; Roytershteyn, V.; Vu, H. X.; Omelchenko, Y. A.; Scudder, J.; Daughton, W.; Dimmock, A.; Nykyri, K.; Wan, M.; Sibeck, D.; Tatineni, M.; Majumdar, A.; Loring, B.; Geveci, B., The link between shocks, turbulence, and magnetic reconnection in collisionless plasmas, Physics of Plasmas, Volume 21, Issue 6, id.062308

Yi-Hsin Liu, W. Daughton, H. Li, H. Karimabadi, V. Roytershteyn, Bifurcated structure of the electron diffusion region in three-dimensional magnetic reconnection, Phys. Rev. Lett. 110, 264004, 2013

J. Jara-Almonte, W. Daughton, and H. Ji, Debye Scale Turbulence within the Electron Diffusion Layer during Magnetic Reconnection, Phys. Plasmas 21, 032114, 2014

Fan Guo, Hui Li, W. Daughton, and Yi-Hsin Liu, Formation of Hard Power Laws in the Energetic Particle Spectra Resulting from Relativistic Magnetic Reconnection, Phys. Rev. Lett. 113, 155005, 2014

Yi-Hsin Liu, J. Birn, W. Daughton, M. Hesse and K. Schindler, Onset of reconnection in the near magnetotail: PIC simulations, J. Geophys. Res. 119, 2014, doi:10.1002/2014JA020492

K. D. Makwana, V. Zhdankin, H. Li, W. Daughton and F. Cattaneo, Energy dynamics and current sheet structure in fluid and kinetic simulations of decaying magnetohydrodynamic turbulence, Phys. Plasmas 22, 042902, 2015

Fan Guo, Yi-Hsin Liu, William Daughton and Hui Li, Particle acceleration and plasma dynamics during magnetic reconnection in the magnetically-dominated regime, Astrophysical Journal, in press, 2015

+ several more in the pipeline