Nonthermal electron energization from magnetic reconnection in laser-driven plasmas

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Samuel Totorica, Tom Abel, Frederico Fiuza

U.S. DEPARTMENT OF ENERGY
Office of Science

Stanford University

KIPAC

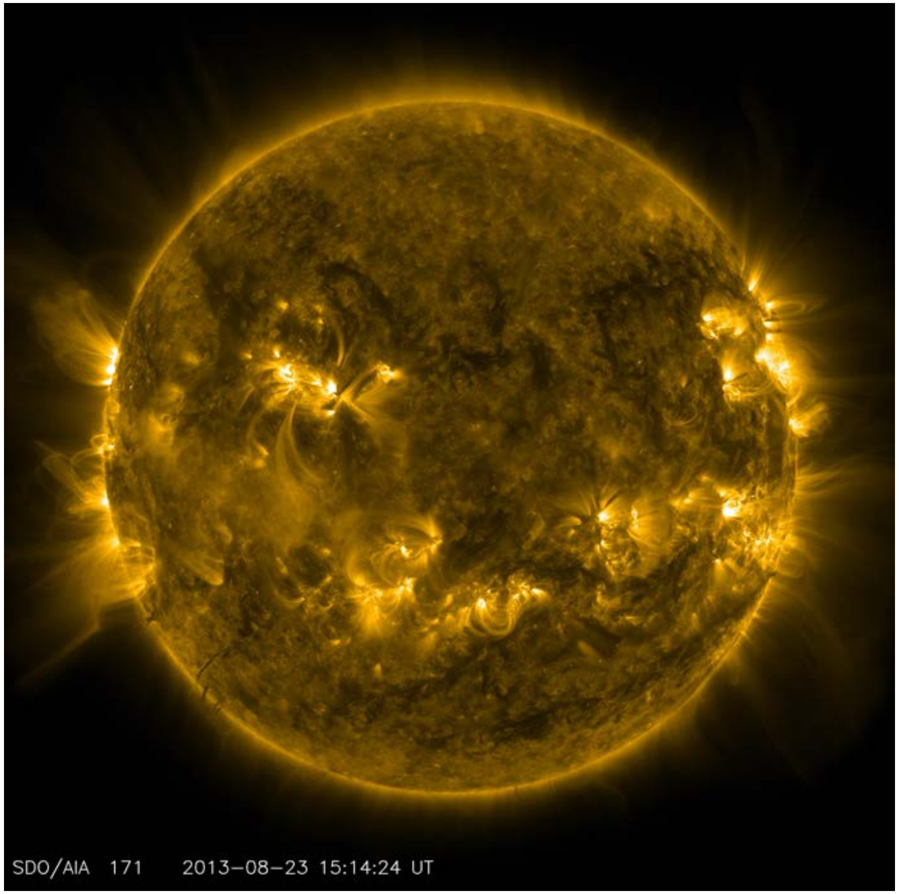
SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Background
  - Magnetic reconnection and astrophysical particle acceleration
  - Studying astrophysics using high-energy lasers
- Particle acceleration from reconnection in laser-driven plasmas
- New method for plasma simulation

Plasma is the fourth state of matter

Plasma reveals magnetic activity on sun



- Plasma:
  - A highly ionized, quasi-neutral gas
  - Abundant in the universe
  - Important for fusion energy
  - Exhibits complex collective behavior

Magnetic reconnection is a ubiquitous plasma process

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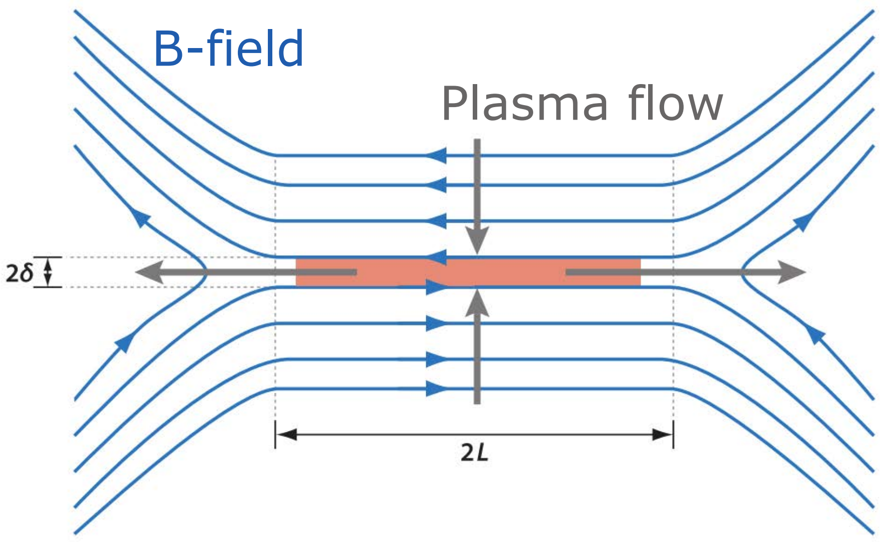
Reconnection Geometry



Zweibel, E. & Yamada, Annu. Rev. Astron. Astrophys. (2009).

- Magnetic reconnection converts magnetic field energy into plasma flows, plasma heating, and energetic particles
- Reconnection is important for magnetized plasmas from astrophysics to the laboratory

Reconnection may explain astrophysical nonthermal emissions

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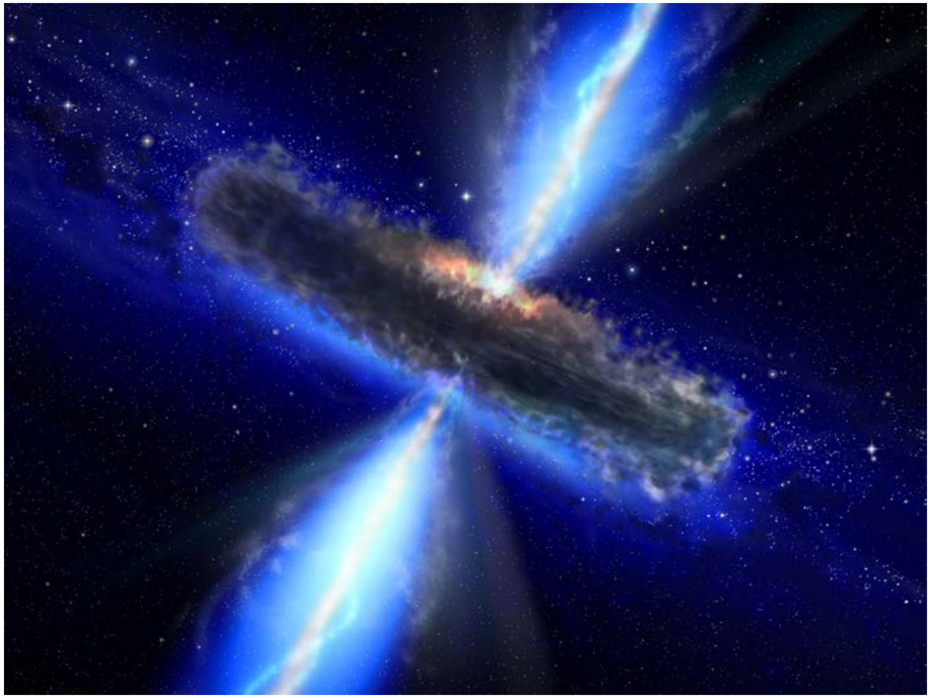
Active galactic nuclei



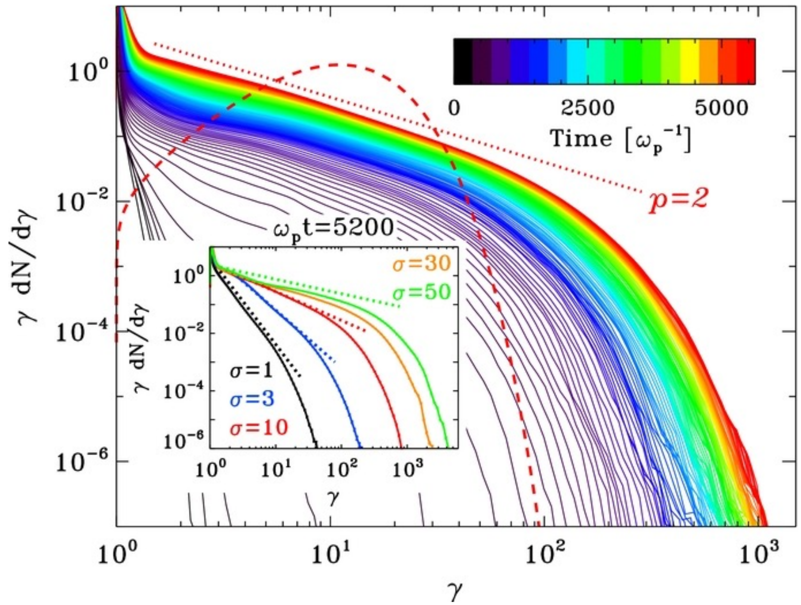
ESA / NASA

- Reconnection is often invoked to explain the non-thermal signatures observed in magnetized astrophysical outflows
- Reconnection is an efficient and fast mechanism for dissipating magnetic energy
- The efficiency of reconnection in accelerating nonthermal particles remains poorly understood

The particle acceleration properties of reconnection are an active area of research

Hard power-laws result from relativistic reconnection

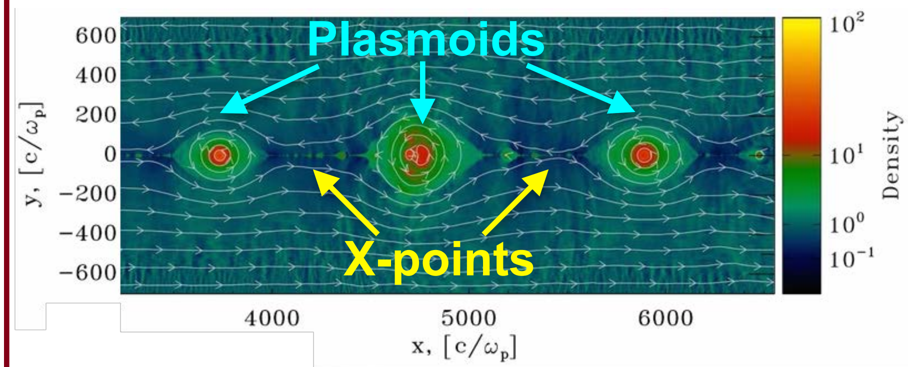
$$\sigma = B^2/(4\pi nmc^2) > 1$$



Sironi, L., & Spitkovsky, A. 2014, ApJL, 783, L21

Guo, F., et al., PRL (2014)
Cerutti, B., et al., ApJ (2014)
K. Nalewajko, et al., ApJ (2015).

Particles are accelerated by X-points and plasmoids



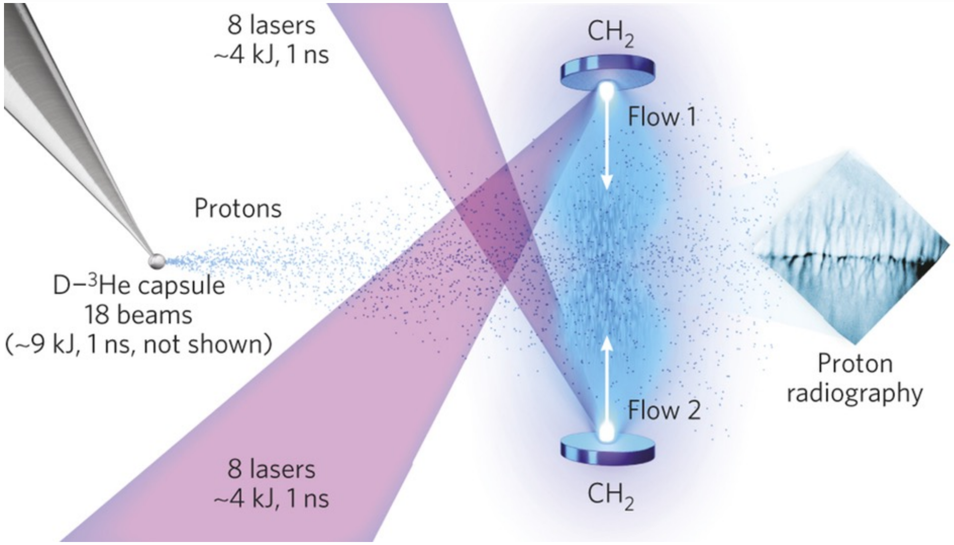
Sironi, L., & Spitkovsky, A. 2014, ApJL, 783, L21

- A variety of acceleration mechanisms have been identified
  - X-point
  - Plasmoid mergers
  - Contracting plasmoids

High-energy-density facilities allow access to extreme densities, temperatures, and velocities

- High energy laser facilities have been developed as part of the national inertial confinement fusion program
  - OMEGA: 60 beams, 30 kJ
  - NIF: 192 beams, 1.8 MJ
- ~keV plasmas can be ablated from solid targets
- Additional lasers can drive diagnostics such as proton radiography

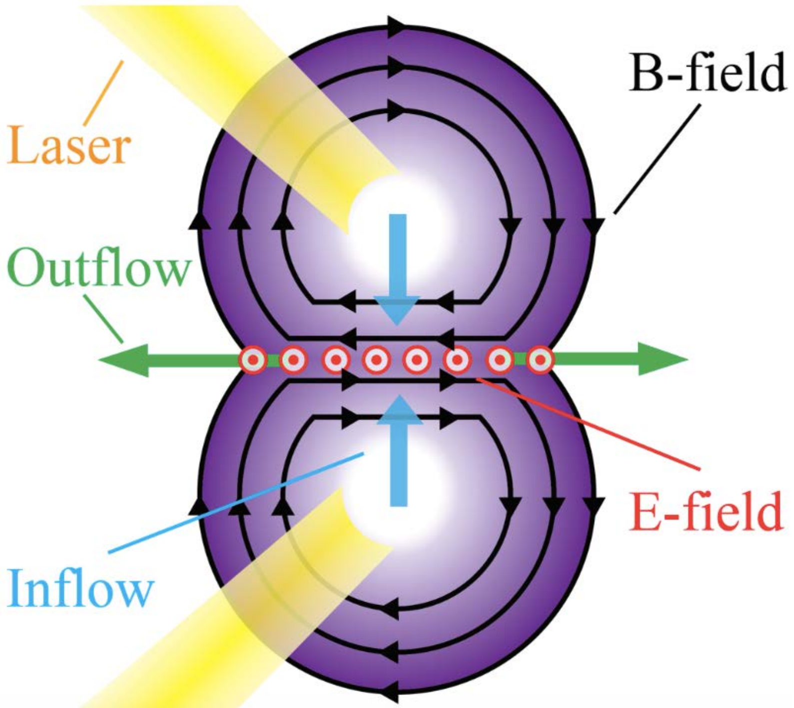
Proton radiography reveals magnetic field structure



Huntington et al., Nature Physics (2015).

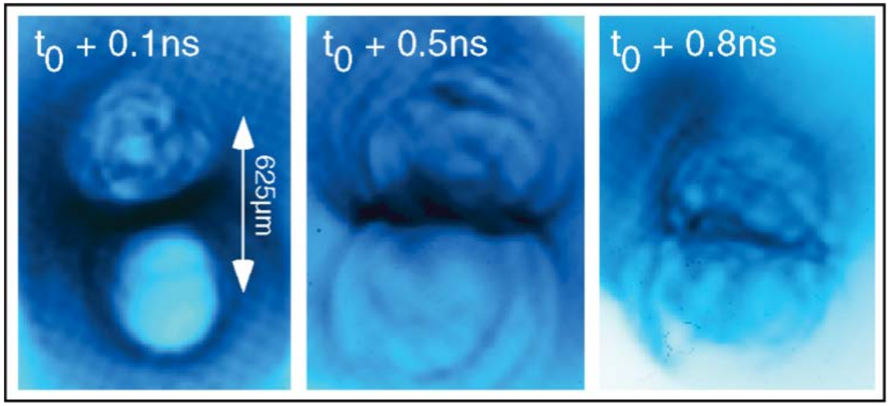
Laser-driven plasmas allow the study of reconnection in a controlled laboratory setting

Laser-Driven Reconnection Geometry



C. K. Li et al., Phys. Rev. Lett. 99, 055001 (2007).
W. Fox et al., Phys. Rev. Lett. 106, 215003 (2011).
G. Fiksel et al., Phys. Rev. Lett. 113, 105003 (2014).
M. J. Rosenberg et al., Phys. Rev. Lett. 114, 205004 (2015).

Proton Radiography Shows B-field annihilation



P. M. Nilson et al., Phys. Rev. Lett. 97, 255001 (2006).

- Several features of reconnection have been observed in laser-driven plasmas
- **Could nonthermal particle acceleration be measured?**

Particle-in-cell simulations allow us to study laser-driven plasmas from first principles

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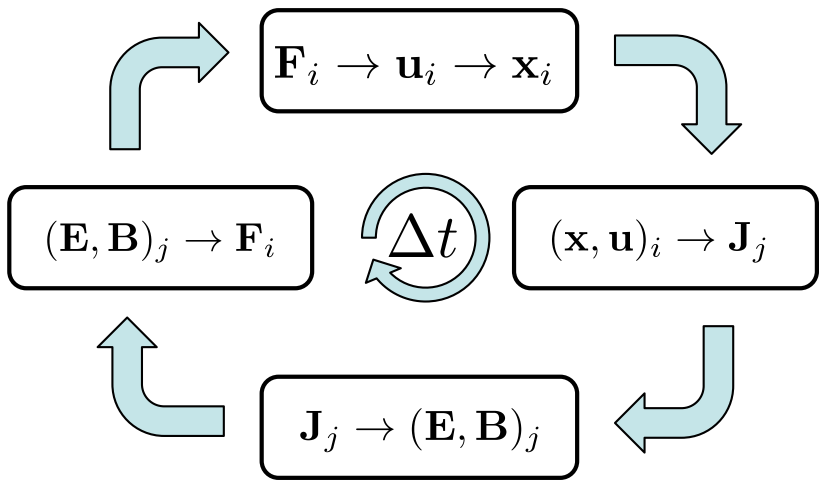
Particle-in-cell (PIC) method

- Represent the plasma by discrete simulation particles
- Calculate ρ and $\mathbf{J}$ from the particle positions and velocities
- Solve for $\mathbf{E}$ and $\mathbf{B}$ on a discrete grid using Maxwell's equations
- Update particle positions and velocities using the Lorentz force

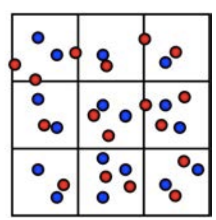
PIC Simulation Timestep

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{1}{\gamma c}\mathbf{u} \times \mathbf{B}\right)$$



$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{J}$$

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



OSIRIS: a massively parallel, fully relativistic PIC code

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osiris framework

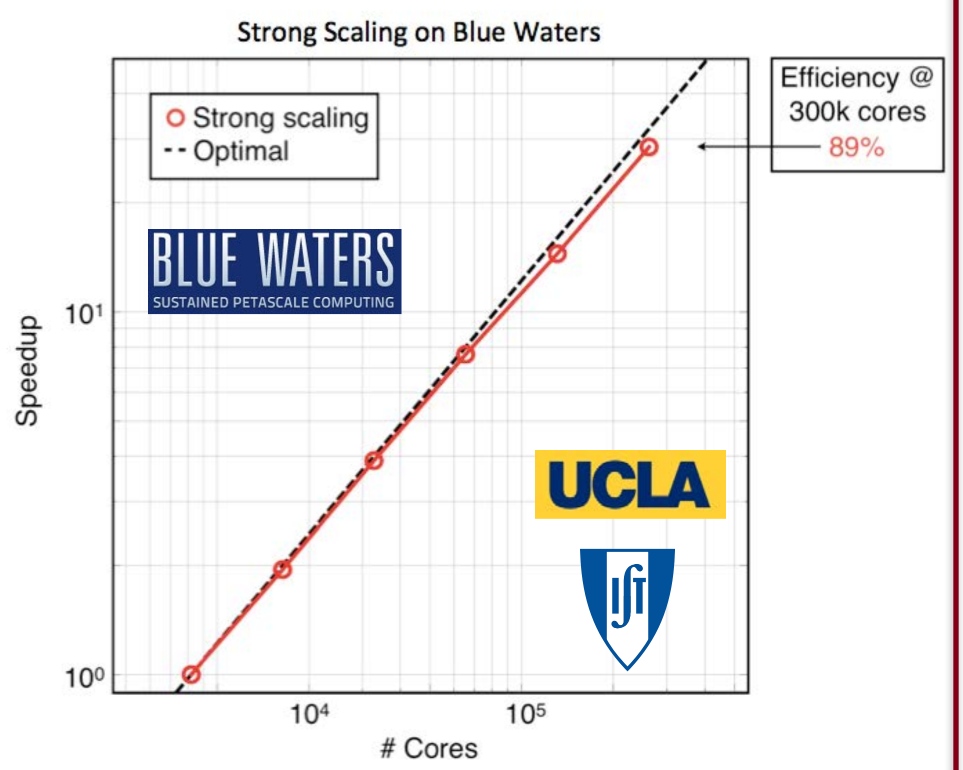
- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST

New Features in v2.0

- High-order splines
- PIC-MHD algorithm
- Binary Collision Module
- PML absorbing BC
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- Parallel I/O

Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

OSIRIS strong scaling

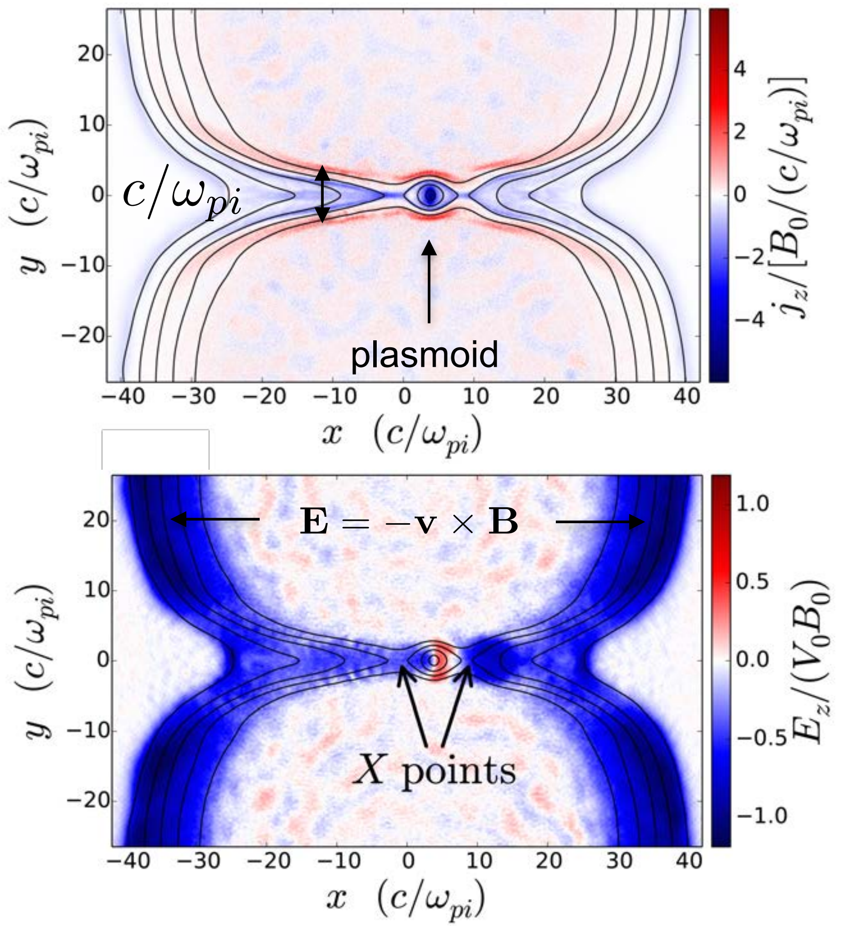


Why Blue Waters?

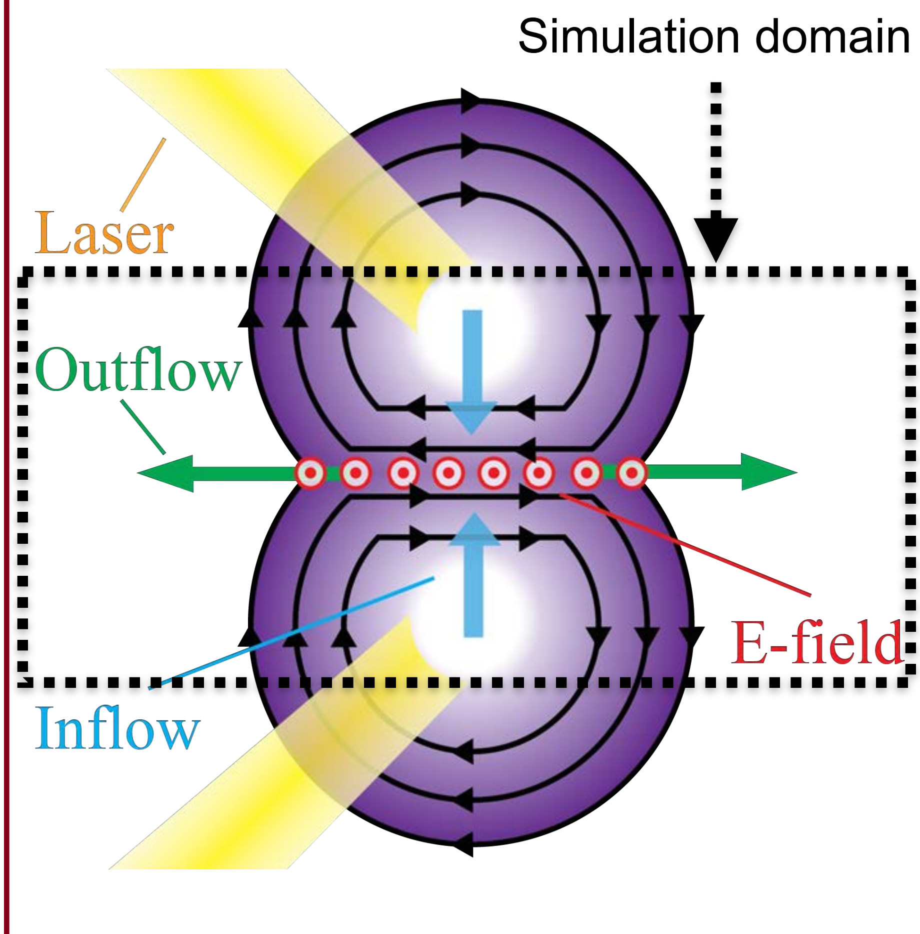
- PIC simulations require large-scale computational resources
  - Large numbers of particles are required to accurately sample the distribution function
  - Reconnection in laser-driven plasmas involves multi-scale physics
- Blue Waters Graduate Fellowship allocation of 50,000 node hours
- Fast response time of Blue Waters team minimizes downtime

We model realistic geometries and conditions for current experiments (e.g. the OMEGA Laser Facility)

PIC simulations model expanding magnetized plasma bubbles



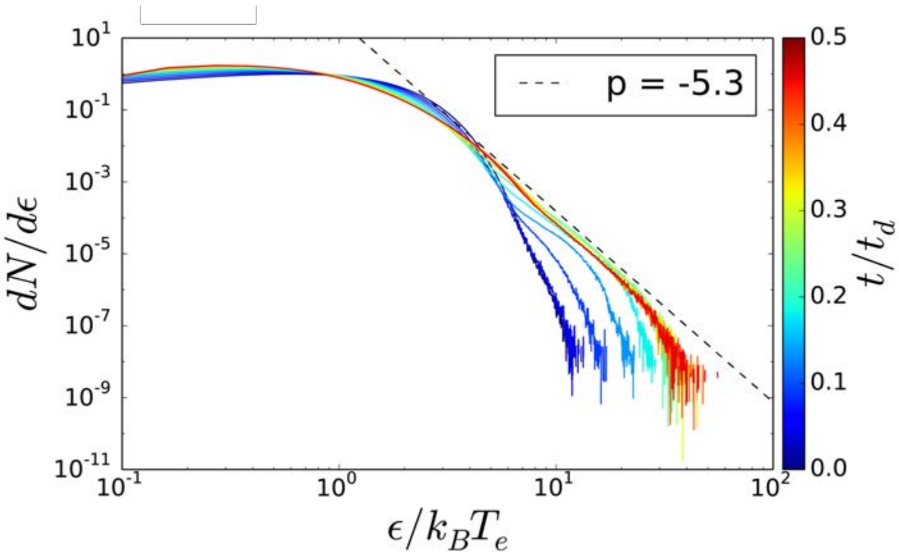
Laser-Driven Reconnection Geometry



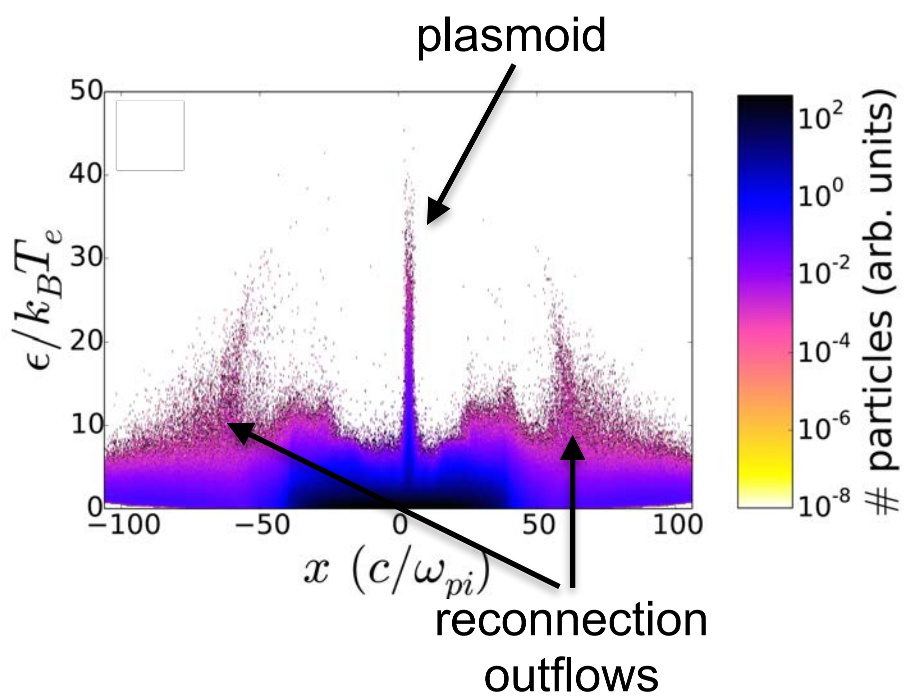
Similar setup to W. Fox et al., PRL 2011.

Electron energy spectrum develops a high energy tail

Temporal evolution of electron energy distribution



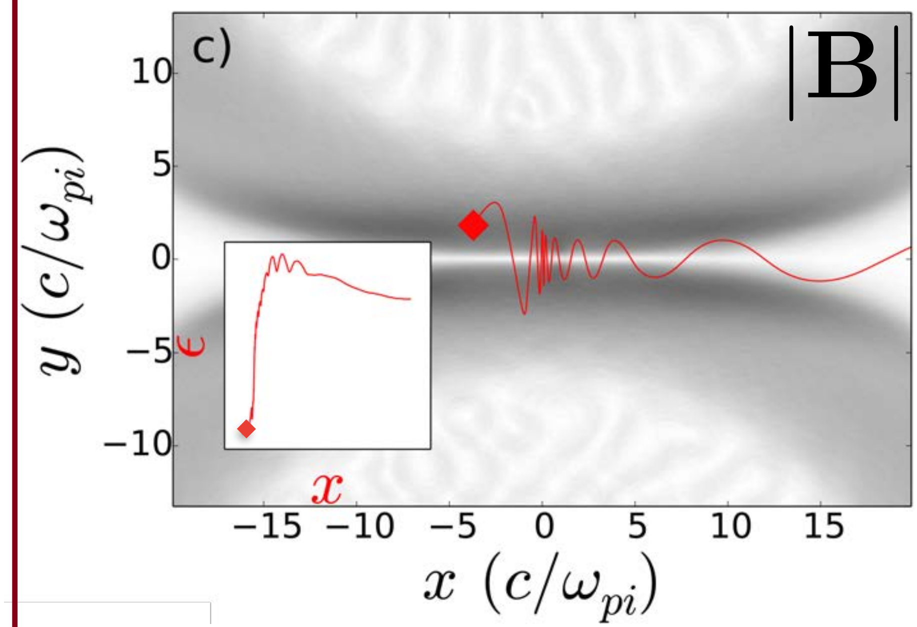
Distribution of electron energies along outflow direction



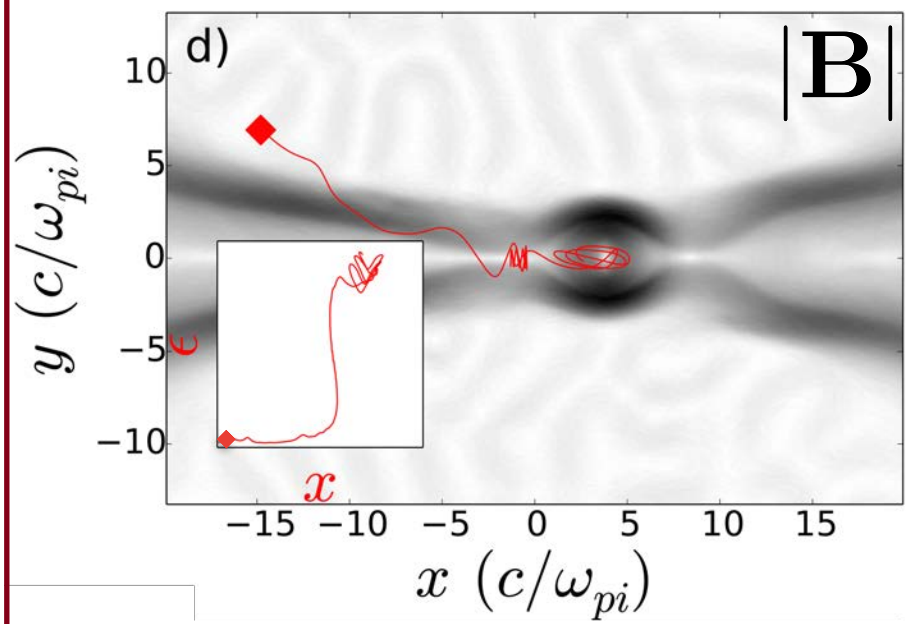
$M_S = 2$, $M_A = 4$

Energetic electrons either escape or become trapped in a plasmoid

Trajectory of escaping electron



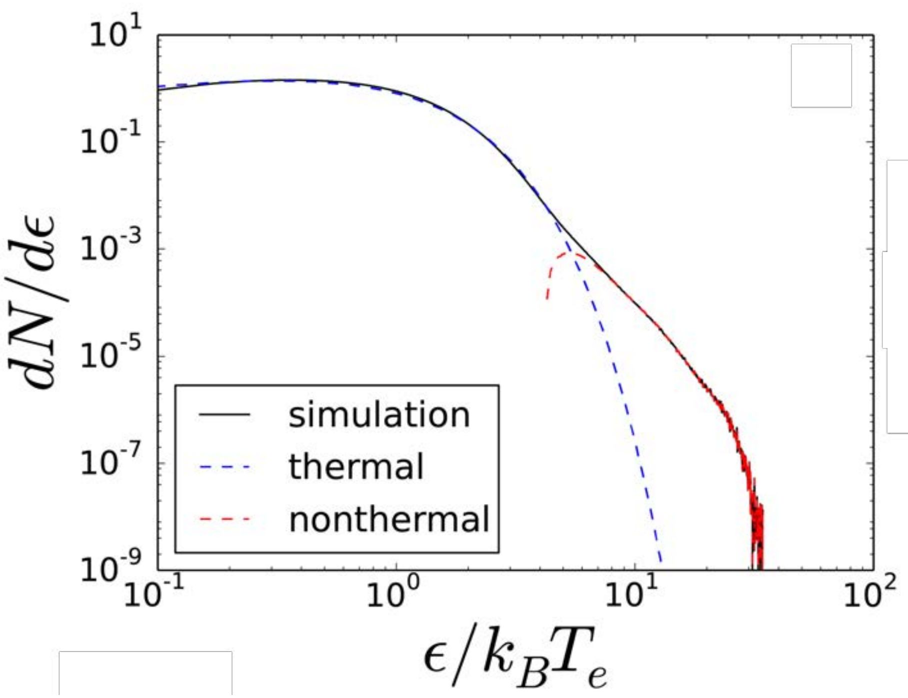
Trajectory of trapped electron



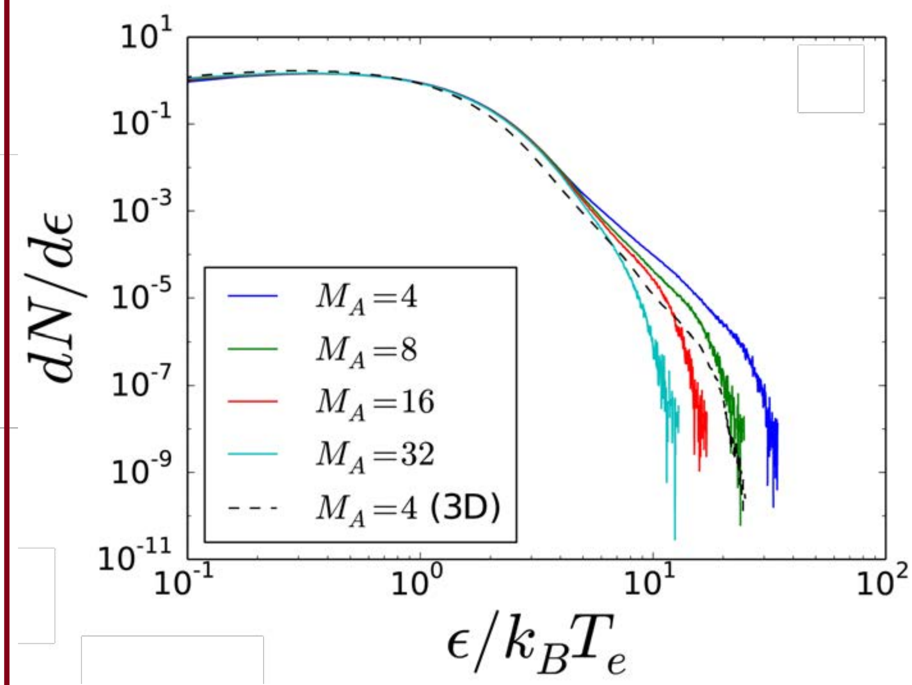
$M_S = 2$, $M_A = 4$

High energy tail is consistent over wide range of initial conditions

Nonthermal component has a power-law shape



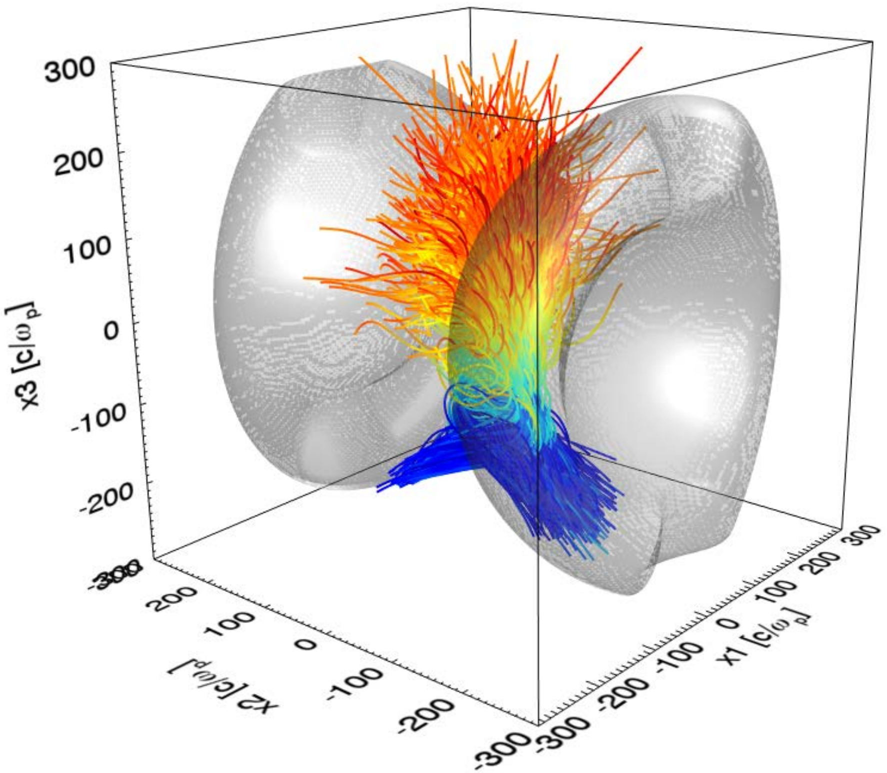
Maximum energy scales with initial magnetic field



Power-law is the result of direct acceleration at X-points

Maximum energy and spatial distribution are different in 3D

Trajectories of energetic electrons



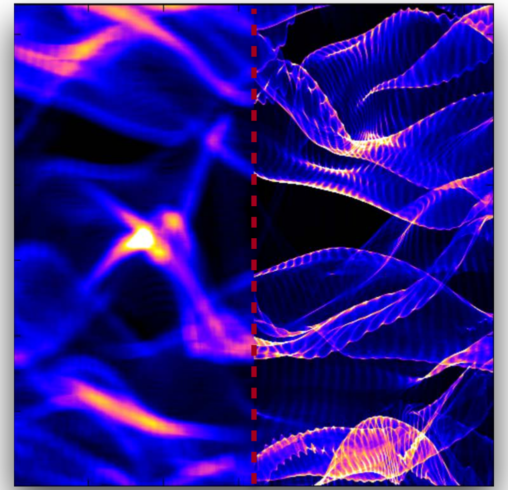
- Energetic electrons are emitted in a fan-like profile
- Maximum electron energy is limited by the finite size of the system
- $\epsilon_{max}/k_B T_e \approx \left(\frac{M_s^2}{M_A}\right)\left(\frac{R_{bubble}}{c/\omega_{pi}}\right)$

For current experiments (OMEGA conditions):

- $\epsilon_{max}/k_B T_e \approx 25 - 75$

S. Totorica, T. Abel, and F. Fiuza, "Nonthermal electron energization from magnetic reconnection in laser-driven plasmas", Physical Review Letters 116, 095003, (2016).

New method for plasma simulation



Novel phase-space interpolation may improve PIC simulations

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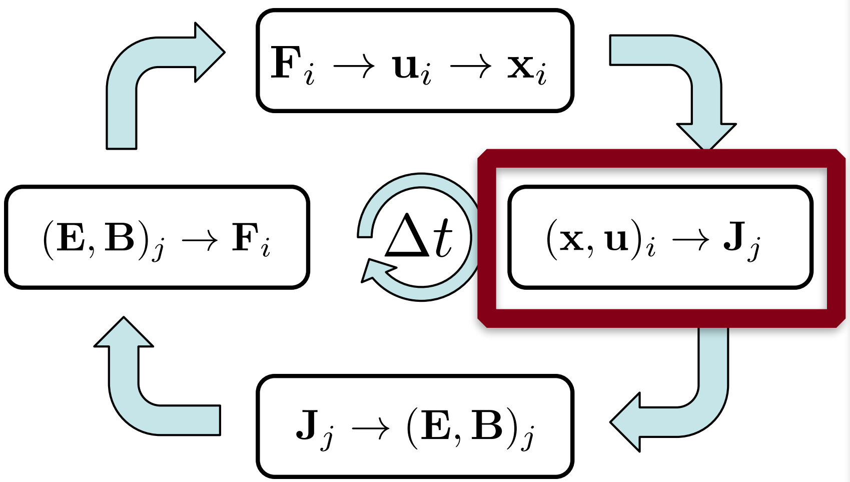
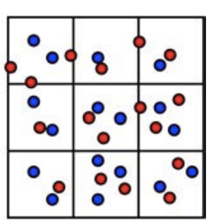
PIC Simulation Timestep

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{1}{\gamma c}\mathbf{u} \times \mathbf{B}\right)$$



$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{J}$$

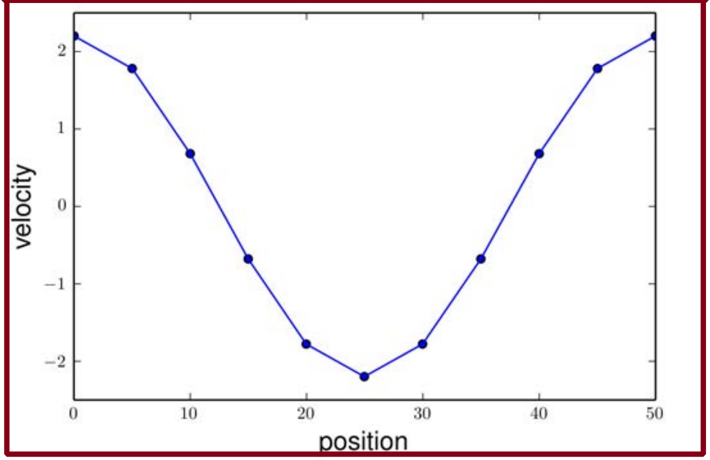
$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$



- Simulation particles can be interpreted as the vertices of a mesh that traces the distribution function in phase space
- Originally developed for cosmological dark matter simulations (Abel et al., MNRAS 2012.)
- Physical quantities are continuously defined in space, revealing fine-scale detail
- With access to the full distribution function, more accurate charge and current densities can be calculated

New method uses deformable phase-space volume elements rather than fixed shape particles

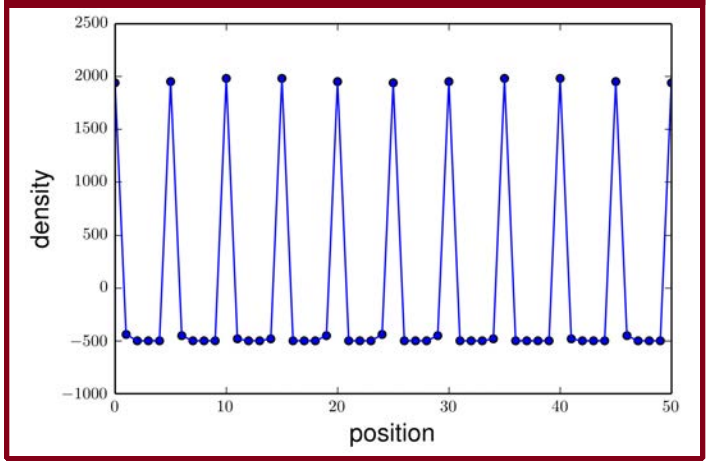
Cold plasma oscillation



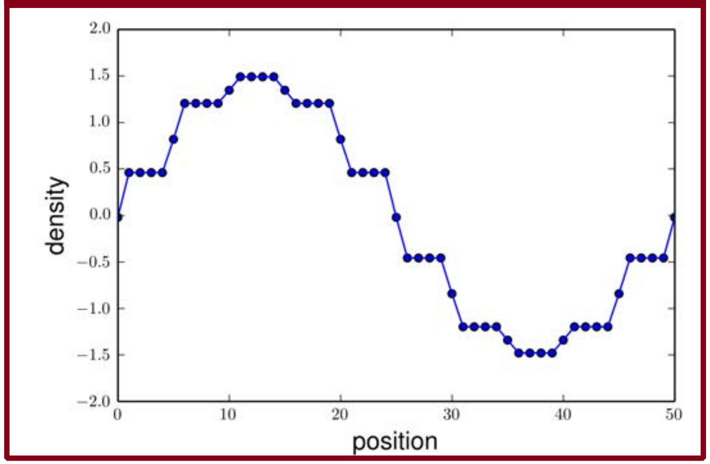
particles

line segments

Cloud-in-cell

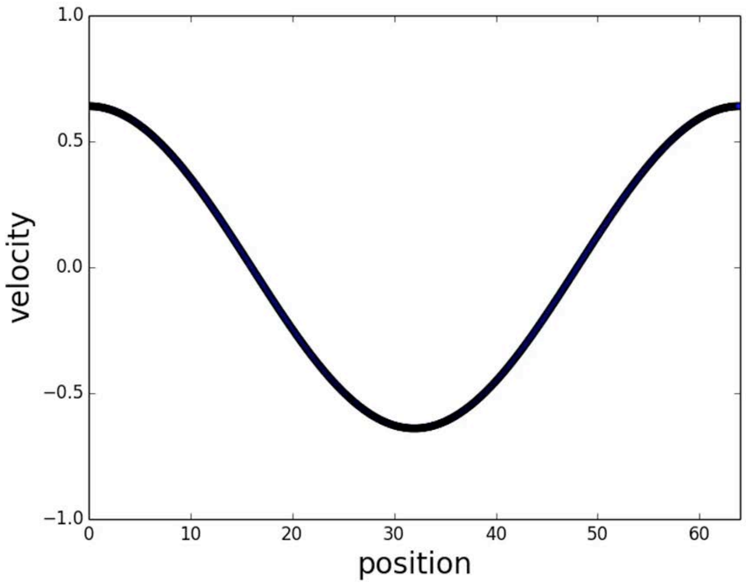


New method

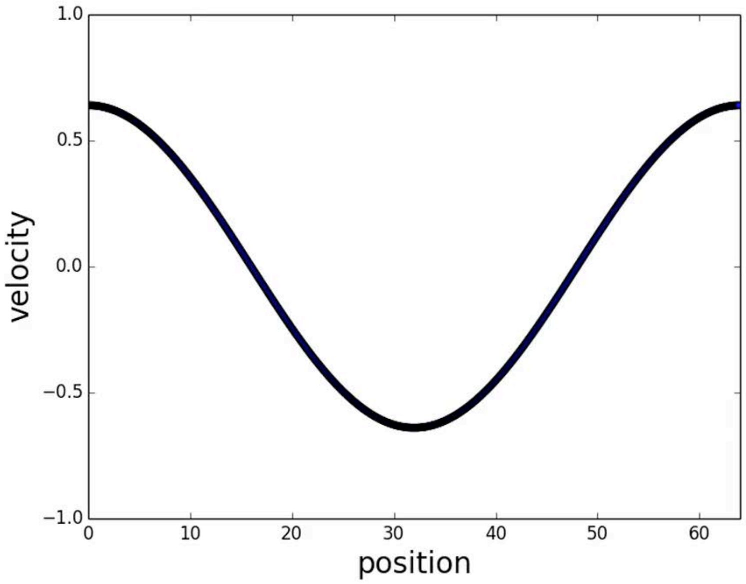


Simple test problems demonstrate the merits of the new method

Standard method



New method



New method reduces noise and accurately models 1D test problems using fewer simulation particles

J. Kates-Harbeck, S. Totorica, J. Zrake, T. Abel, "Simplex-in-cell technique for collisionless plasma simulations", Journal of Computational Physics 304 (2016).

New method reveals fine-scale structure in the charge density

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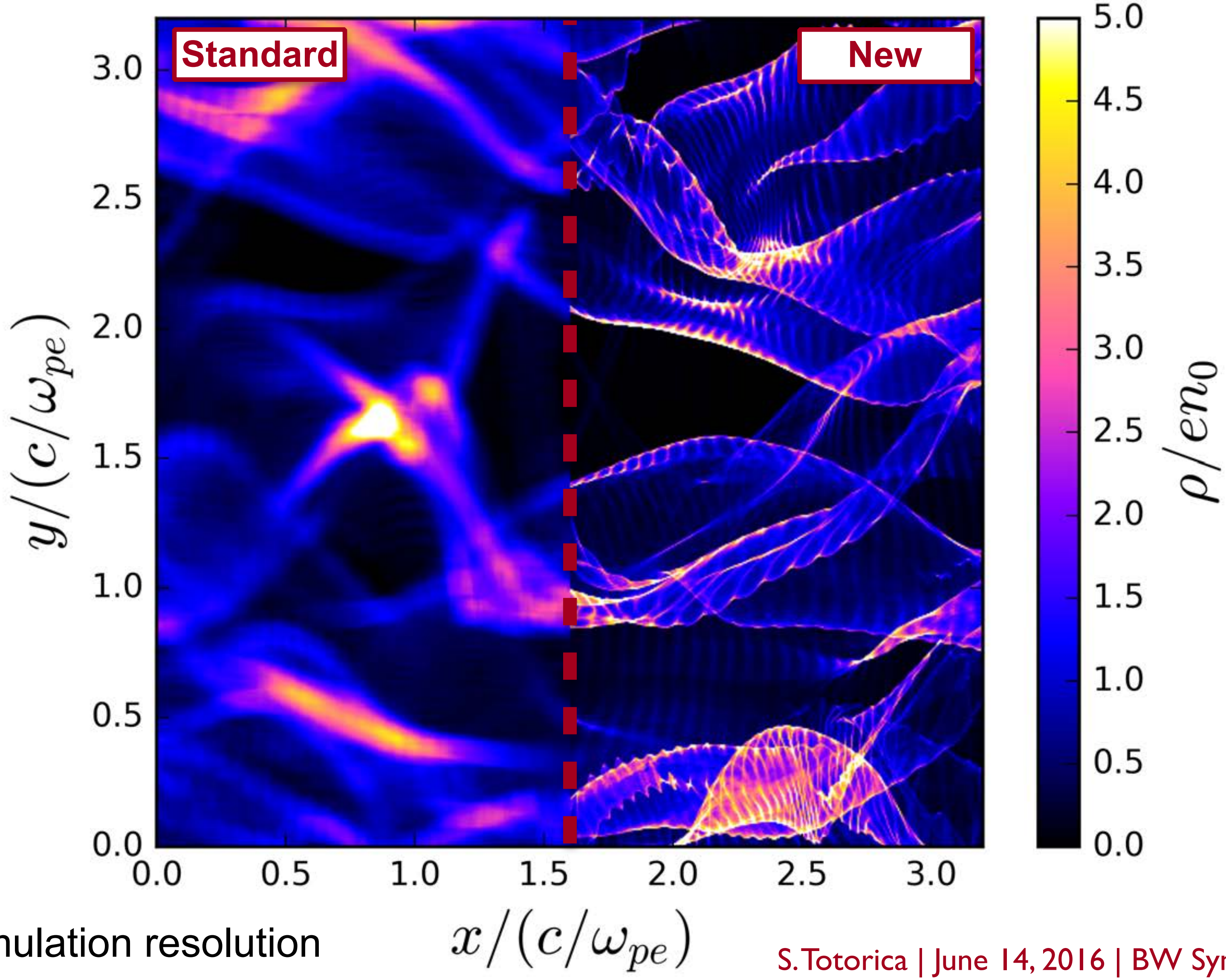

4 PPC
16x16 simulation resolution

Conclusions

- Laser-driven plasmas offer a new experimental platform for studying particle acceleration induced by magnetic reconnection
- Nonthermal electrons gain energy by direct acceleration from the reconnection electric field, and current experimental conditions can produce energies of $\approx 25 - 75\ k_B T_e$
- Novel phase-space interpolation method may reduce noise and number of simulation particles required in PIC simulations

S. Totorica, T. Abel, and F. Fiuza, "Nonthermal electron energization from magnetic reconnection in laser-driven plasmas", Physical Review Letters 116, 095003, (2016).

J. Kates-Harbeck, S. Totorica, J. Zrake, T. Abel, "Simplex-in-cell technique for collisionless plasma simulations", Journal of Computational Physics 304 (2016).

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  - OSIRIS consortium (UCLA/IST)
  - Simulations performed on Blue Waters (NCSA), Mira (ANL), and SLAC Bullet Cluster
  - Blue Waters Graduate Fellowship
  - DoD NDSEG