The next magnetic reconnection frontier: realistic, first-principles kinetic simulations of reconnection in large 3D systems with and without radiation

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Magnetic Reconnection

- Magnetic reconnection is a fundamental plasma process involving rapid rearrangement of magnetic field topology.
- It leads to violent conversion of magnetic energy to:
  - plasma thermal energy,
  - bulk kinetic energy;
  - nonthermal particle acceleration.
  - (radiation).
- Reconnection is important in:
  - magnetic fusion (sawtooth disruptions);
  - solar/space physics (solar flares, magnetospheric substorms);
  - astrophysics (high-energy flares in various systems).

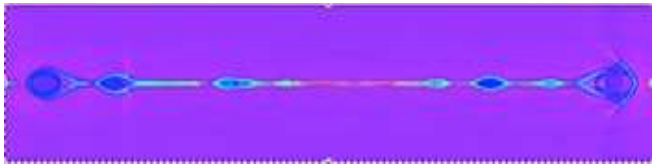
See Hantao Ji/Masaaki Yamada's presentation!

Simulations of Magnetic Reconnection

- Reconnection is studied using analytical theory, numerical simulations, laboratory experiments, and space observations.
- **Simulations** have played and will continue to play an important role in reconnection research.
- Most reconnection environments of interest are **collisionless**, requiring a **kinetic approach**.
- A popular tool of choice for numerical studies is **particle-in-cell (PIC)** simulations.

Simulations of Magnetic Reconnection: Technical Challenges

- Disparity of electron & ion scales; $\rho_i \approx 43\ \rho_e$
- Separation between plasma micro-scales (ρ_i) and real system size $L >> \rho_i$ secondary instabilities;



- 2D vs. 3D (more later!);

Classical, traditional idealized studies of recn.

- **Additional physics:** collisions, partial ionization, radiation, relativistic effects.
- **More realistic context:** current-sheet formation, interaction with turbulence.

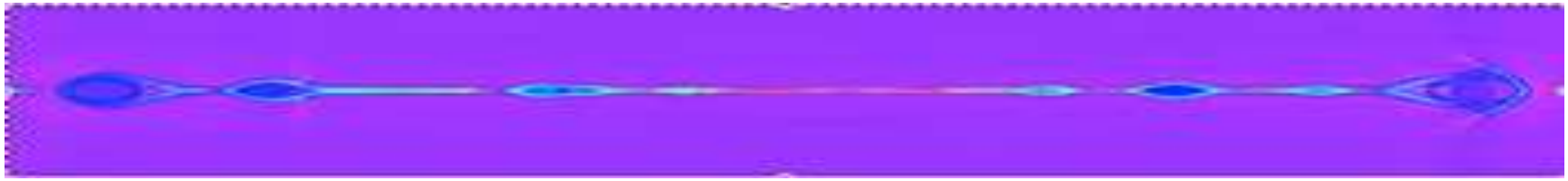
Physics frontiers: less explored; new questions, new challenges!

I. Challenges and Prospects for Classical Reconnection Problem: 2D now → 3D in 10 yrs

Where we are today:
Large 2D systems with large mass ratio.

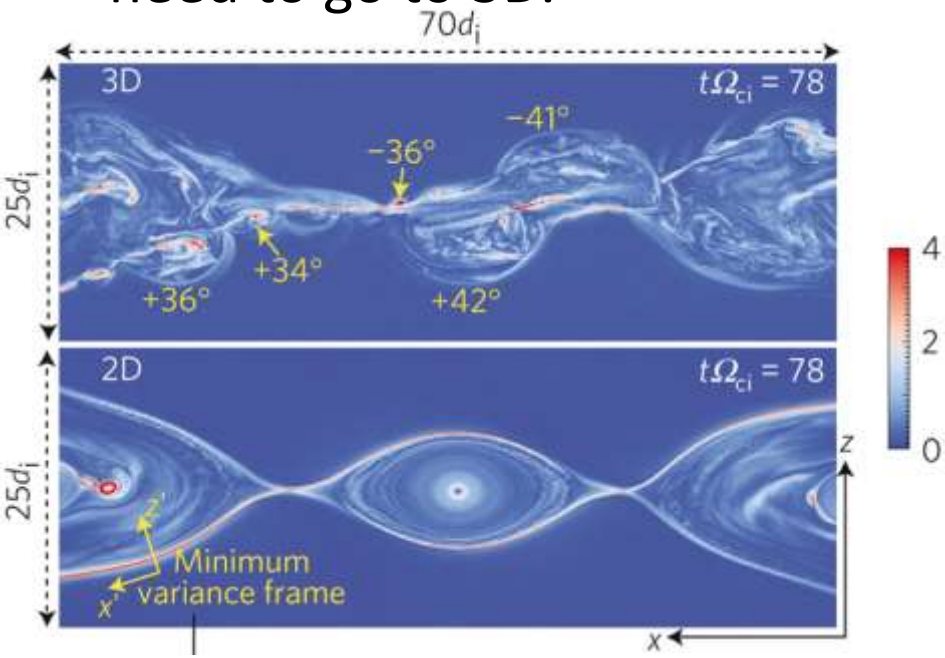
- Unlike MHD dynamo or turbulence, reconnection problem is not meaningless in 2D (a mixed blessing).
- State of the art numerical simulations today:

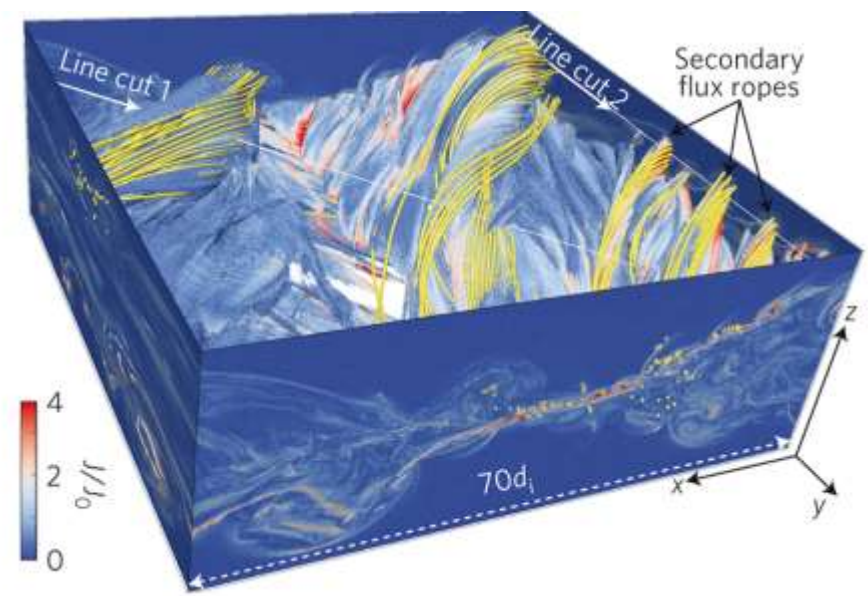
  We can now study reconnection numerically in asymptotically large (with scale separation $L/\rho_i >> 100$) plasmas (both pair e^+e^- and *ei* with high mass ratio) in **2D**.
- 2D classic reconnection problem with traditional physics will be done in a few years!
- We will have mapped out the key outputs as functions of key input parameters.



Is 2D enough?

- There are some preliminary indications that some key reconnection outcome parameters --- reconnection rate, nonthermal particle acceleration --- are similar in 2D and 3D.
- But our world is 3D and there will be always be doubt that 2D may not be provide a good description of reality and that we ultimately need to go to 3D.





PIC simulations by Bill Daughton et al. (2011)

Where we will/should be in 10 years: 3D

- 3D simulations (both PIC and fluid) of reconnection have been done for some time already, but so far these runs were in relatively small comp. boxes, and so have not yet allowed confident extrapolation to asymptotically large systems.
- With expected continuing rise in computing power, we expect to be at the same stage in 3D in about a decade.
- With Moore's law --- doubling in 18 months, increasing roughly by a factor of 100 in 10 years --- traditional reconnection problem will be solved in 3D in about 10-15 years:

  we will have a predictive, quantitatively accurate theoretical description of reconnection!

- The **Frontier** will shift elsewhere: new questions will be posed, new physics explored…
- The same is true for other basic plasma processes: shocks, turbulence, dynamo.

BOTTOM LINE:

- Magnetic Reconnection is an important basic plasma process with wide applications to laboratory, space, and astrophysical plasmas.
- Progress on understanding reconnection can be made using advanced numerical simulations.
- With continued strong investment in scientific computing infrastructure for reconnection studies, we have a reasonable expectation to essentially fully solve the classic reconnection problem in full 3D in about a decade.

II. Challenges and Prospects for new physics frontiers: Radiative Magnetic Reconnection

Radiation in Astrophysical Reconnection

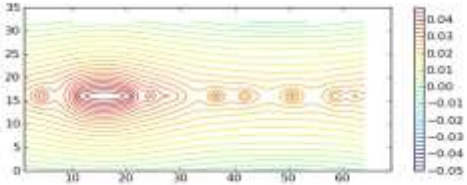
- In conventional reconnection studies (space/solar/lab), plasma consists of electrons and ions --- **no photons!**
- In contrast, in many high-energy ***astrophysical*** situations **radiation** is important --- strongly affects reconnection:

  - Radiative cooling; - Radiative drag on recn. outflow;

  - Radiation pressure; - Compton-drag resistivity.
- In addition, radiation is our only ***observational diagnostic*** into astrophysical reconnection.

  How does a reconnection layer look like, literally?

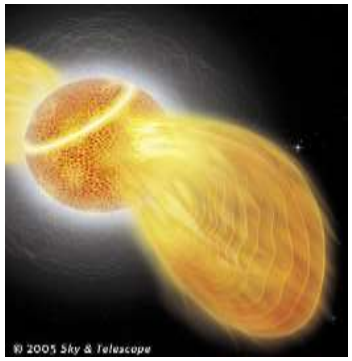
  – what are (prompt) **radiative signatures** (spectra, light curves) of reconnection seen by an outside observer?



Radiative magnetic reconnection is a new frontier in plasma astrophysics!!

Reconnection in Astrophysics

- Pulsar magnetospheres, winds, PWNe
- AGN (e.g., blazar) jets, radio-lobes
- Gamma-Ray Bursts (GRBs)
- Magnetar (SGR) flares



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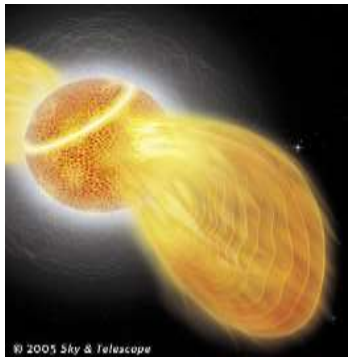

Radiative PIC reconnection simulations

- Radiative relativistic PIC code **Zeltron** (Cerutti et al.):
  - self-consistently includes radiation-reaction force on the particles due to synchrotron and inverse- Compton;
  - computes observable radiation signatures: spectra, light curves, etc.;
  - has been used to study reconnection relevant to Crab PWN;
  - does not yet include non-rel. cyclotron, collisions, bremsstrahlung,