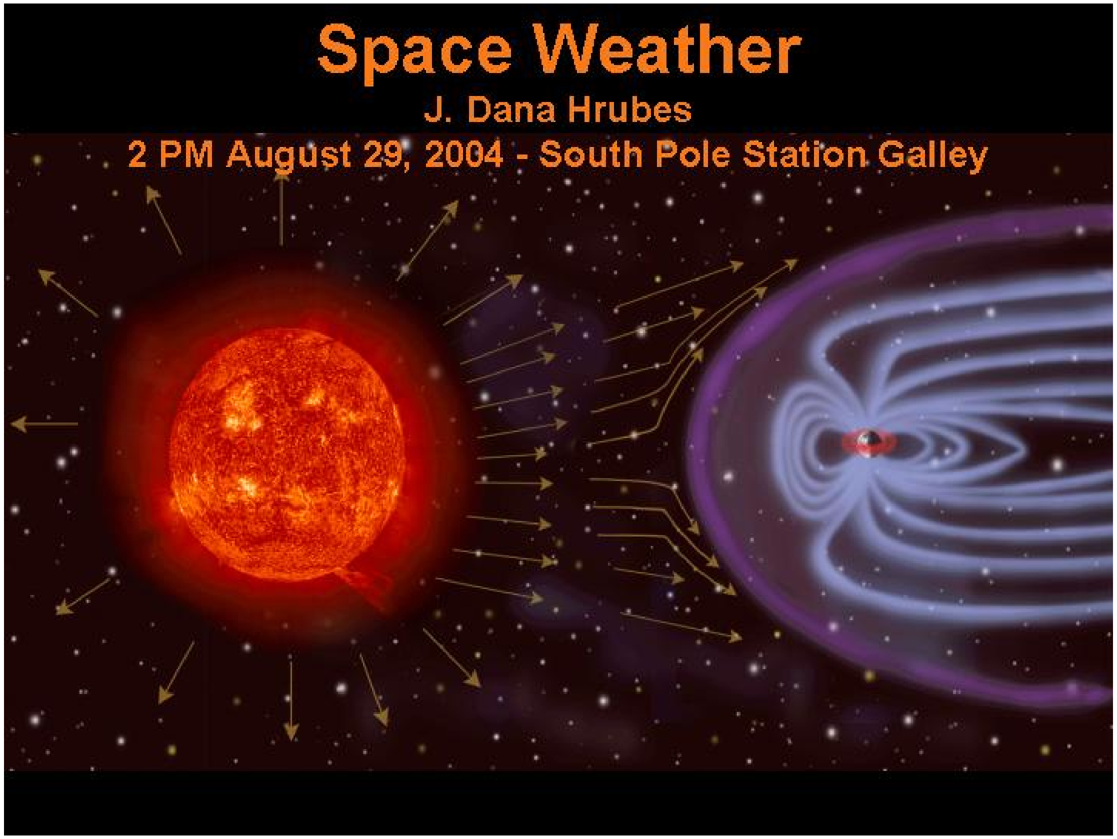
Collisionless Plasma Simulation for Space Weather

E. Alec Johnson
Department of Mathematics, UW-Madison
Presented on August 14, 2008
at the Wisconsin Space Conference
UW–Fox Valley

Problem: Space weather

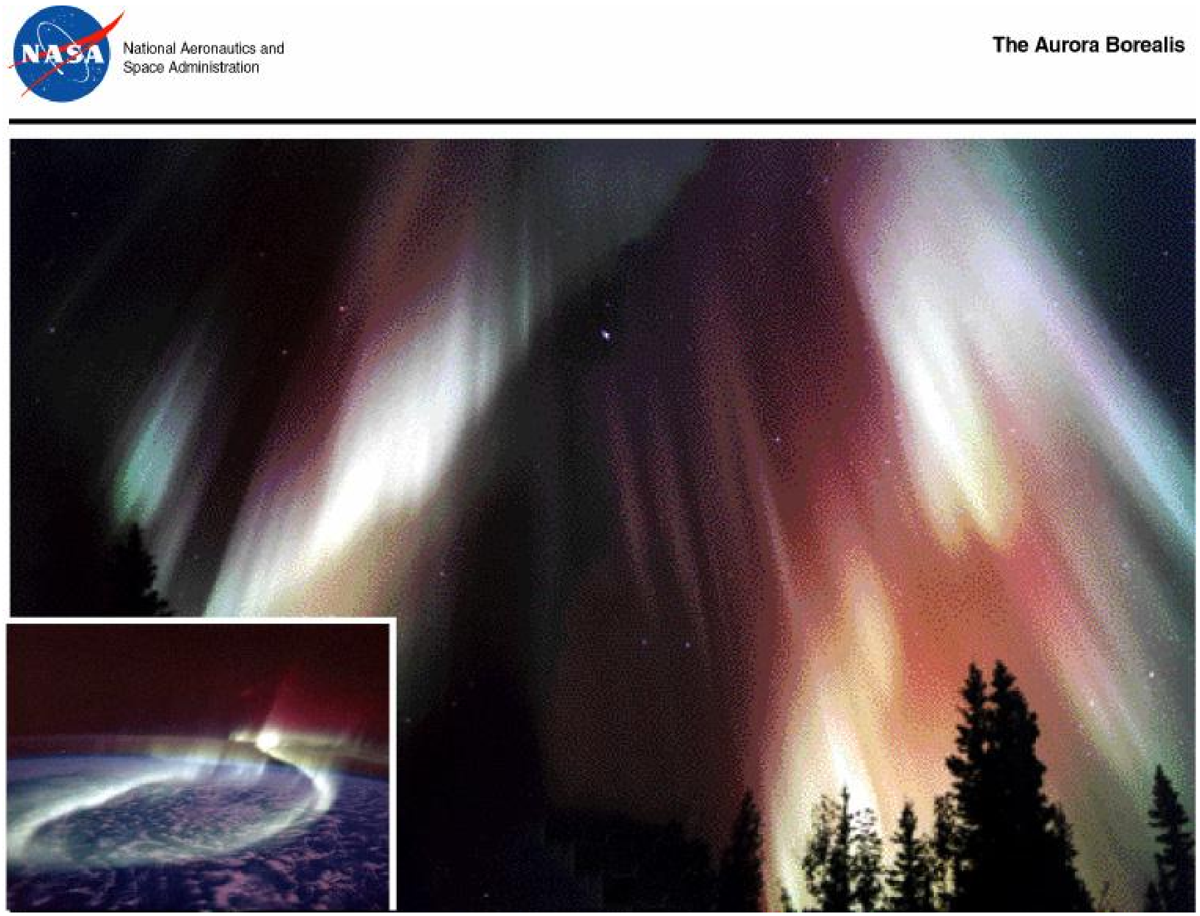
Solar wind interacts with Earth's magnetic field to produce space weather.



http://polar3.home.att.net/sept-04-pics/space-weather-announcement.jpg

Effects of Space Weather

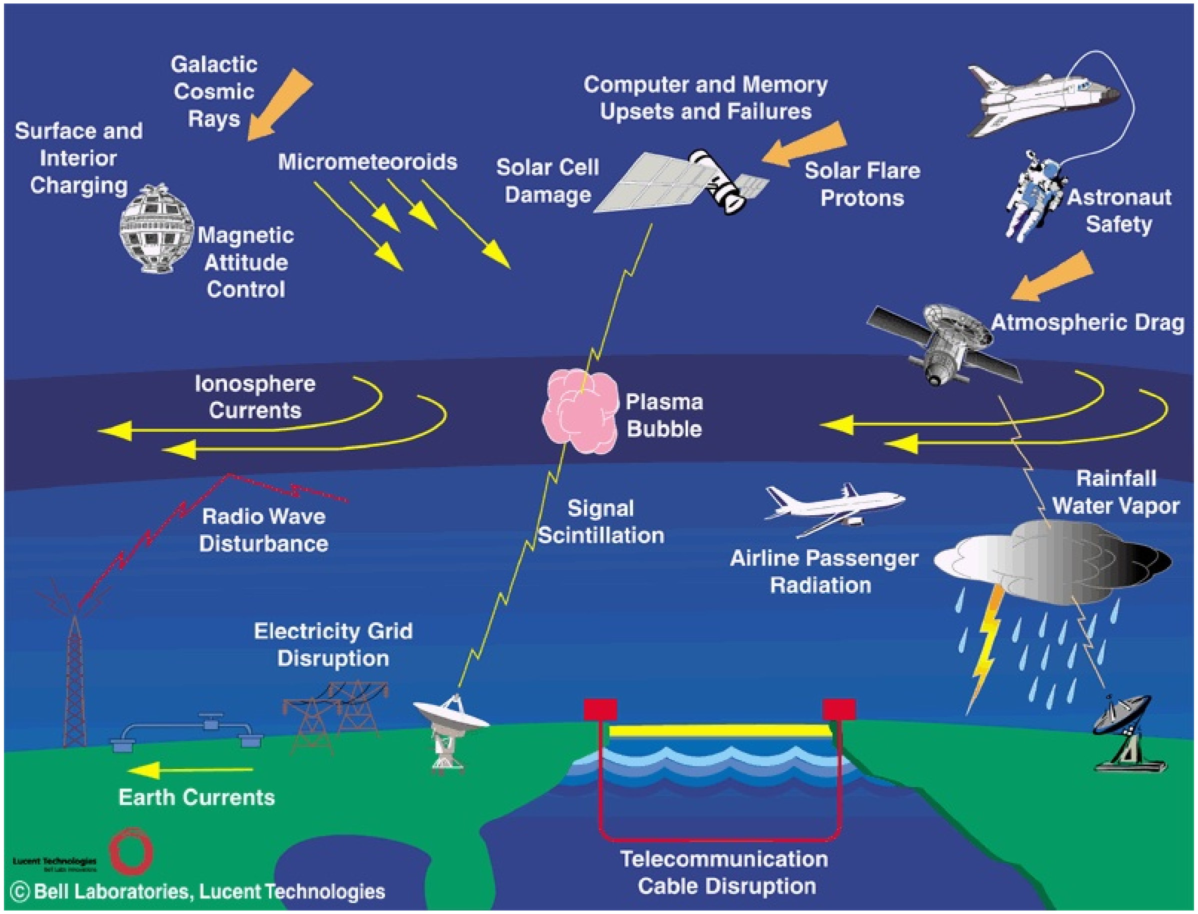
How do geomagnetic storms affect us? Auroras. . .



http://sunearth.gsfc.nasa.gov/sechtml/big10.jpg

Effects of Space Weather

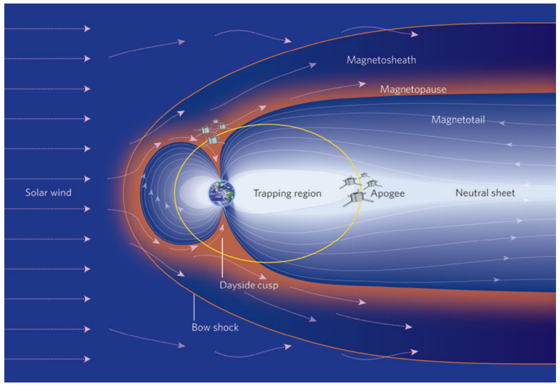
. . . Disruption



http://solarb.msfc.nasa.gov/images/science/effects.gif

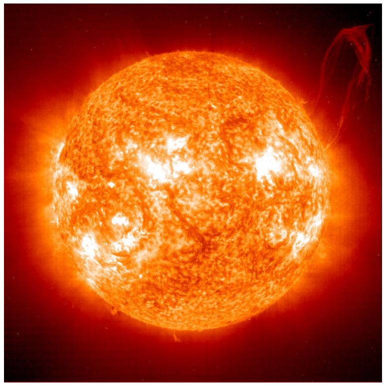
Plasma

Solar wind is a form of **plasma**.



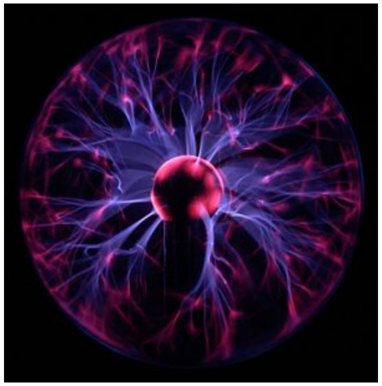
Earth's magnetosphere

(*Nature*)

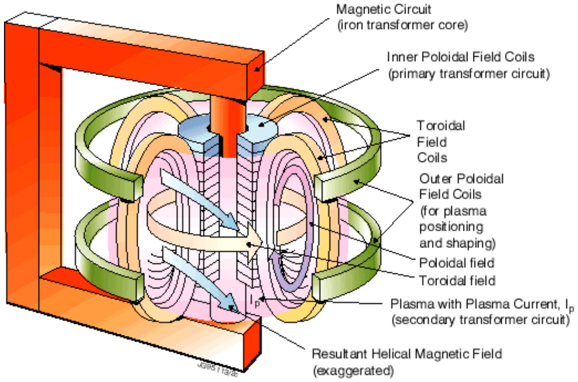


Sun

lightning



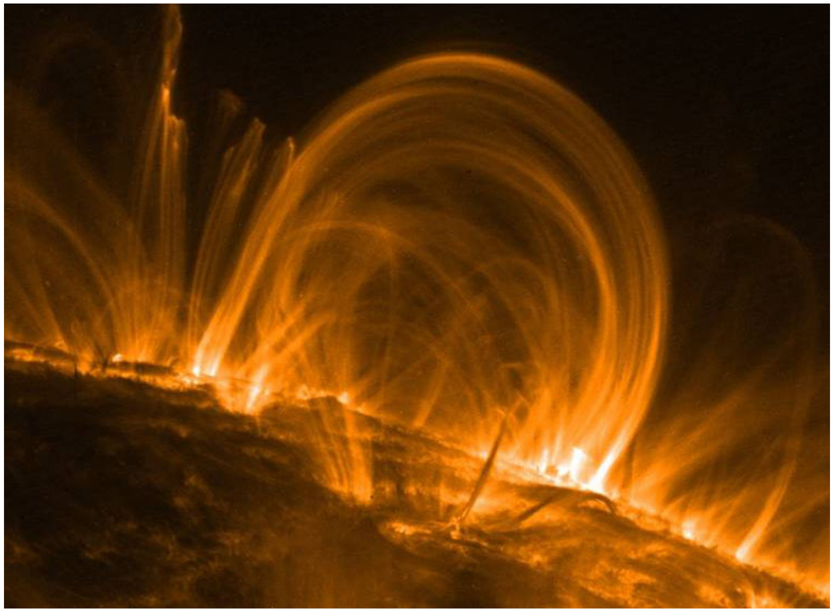
plasma lamp



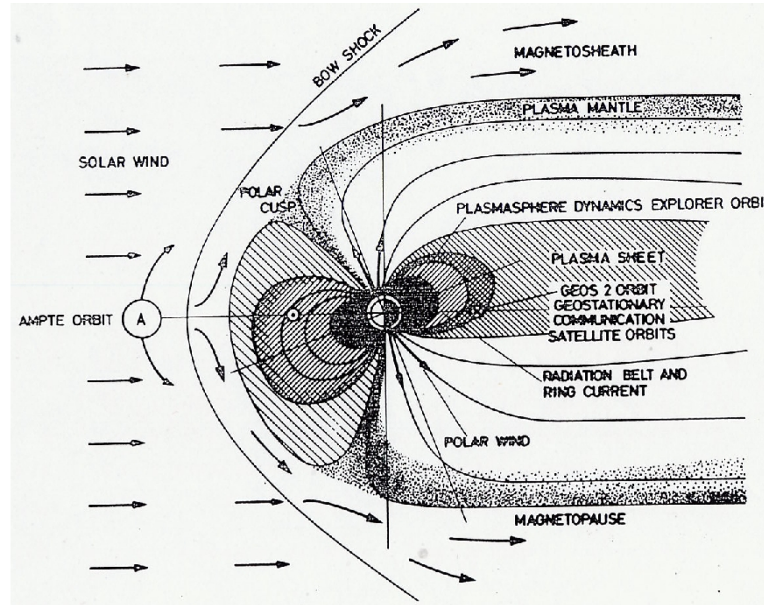
tokamak

Magnetic field lines

Plasmas carry magnetic field lines that are (almost) frozen in the plasma.



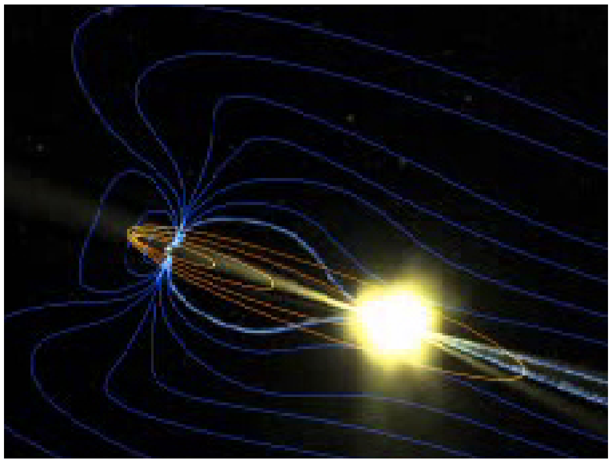
Sun's magnetic field:
coronal loops
(NASA)



Earth's magnetic field:
deflection of solar wind

Fast Magnetic Reconnection

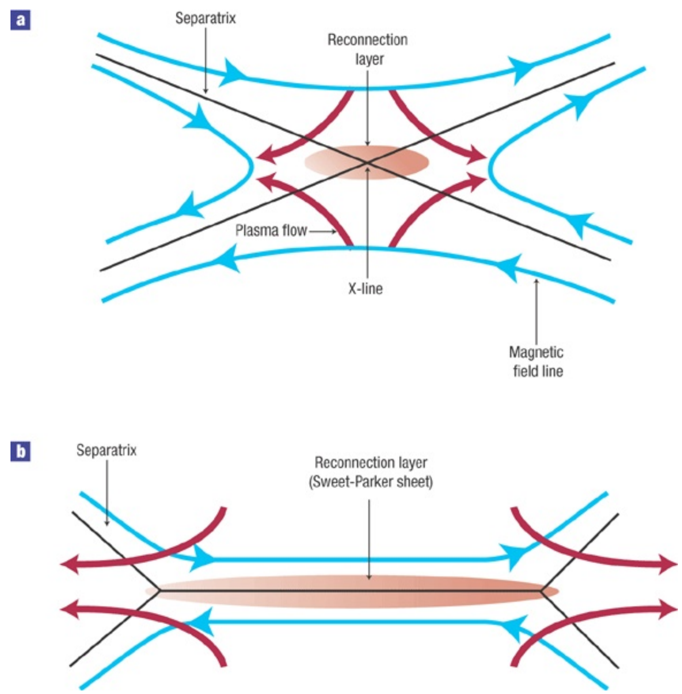
Steeply varying magnetic fields can cause field lines to “snap” and reconnect.



(artist’s concept)

Credit: NASA/Goddard Space Flight Center

Conceptual Image Lab



reconnecting field lines

Simulation

How do we model space plasma?

- Resolving fast reconnection requires more computationally expensive models.
- Fast reconnection occurs only in isolated regions.

Use domain decomposition (*multiscale* strategy):

1. *macroscale*: Use coarse model in most of the domain.
2. *microscale*: Use fine model in reconnection regions.

Models

Models that we have implemented:

1. **Macroscale model: magnetohydrodynamics (MHD)**: does not admit fast reconnection

2. **Microscale models**

   (a) **five-moment two-fluid**: admits fast reconnection, but structure of reconnection region is poor

   (b) **ten-moment two-fluid**: admits fast reconnection and resolves structure of reconnection region fairly well

   (c) **particle-in-cell (PIC)**: potentially most accurate, but noisy unless many particles are used (expensive)

Benchmark Problems

We are testing our algorithms on well-studied problems.

1. Brio-Wu shock problem

2. Linear waves (Alfven)

3. GEM magnetic reconnection challenge

1-dimensional studies.

Fast reconnection is inherently a multidimensional phenomenon.

So why study 1-dimensional problems?

Because 1D simulation helps verify agreement between models:

- We need the microscale model to agree with the macroscale model where the macroscale model is used.
- We need to verify that waves are transmitted properly across model boundaries.

Brio-Wu shock problem.

The Brio-Wu shock problem begins with constant state values to the left and right of zero.

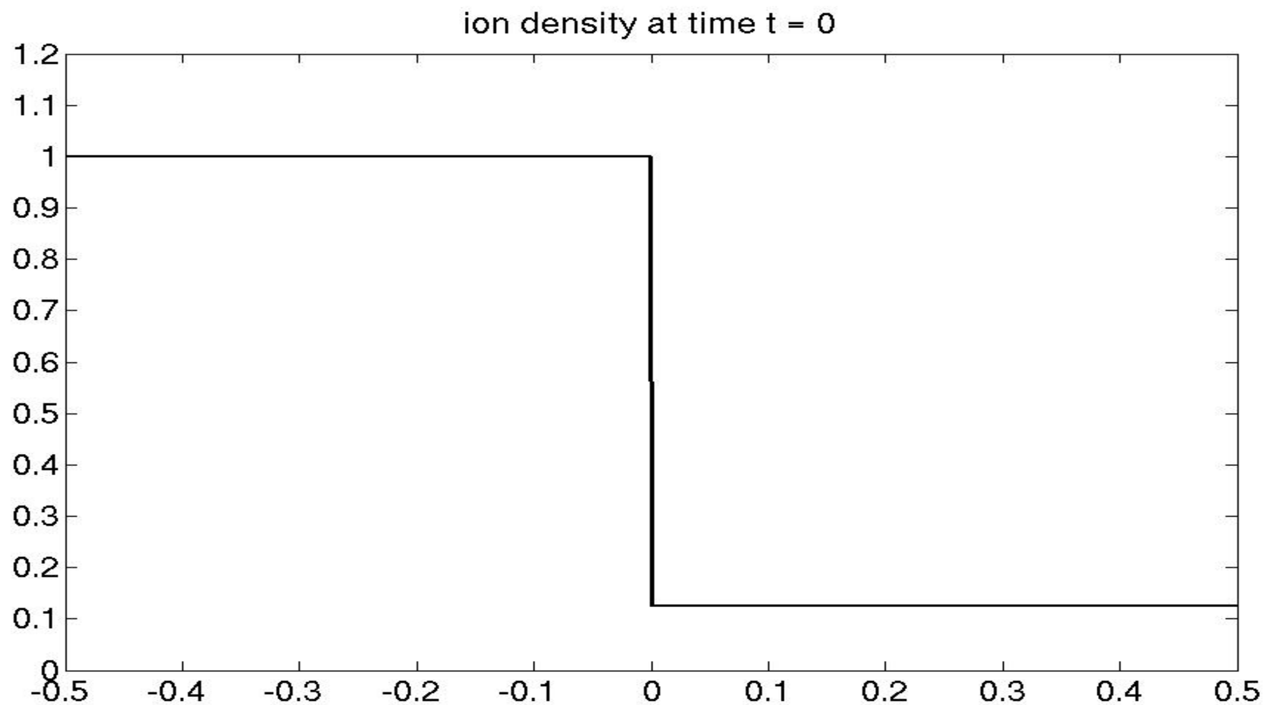
For MHD the initial conditions to the left and right of zero were:

$$\begin{bmatrix} \rho \\ v^1 \\ v^2 \\ v^3 \\ p \\ B^1 \\ B^2 \\ B^3 \end{bmatrix}_{\text{left}} = \begin{bmatrix} 1.0 \\ 0 \\ 0 \\ 0 \\ 1.0 \\ 0.75 \\ 1.0 \\ 0 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \rho \\ v^1 \\ v^2 \\ v^3 \\ p \\ B^1 \\ B^2 \\ B^3 \end{bmatrix}_{\text{right}} = \begin{bmatrix} 0.125 \\ 0 \\ 0 \\ 0 \\ 0.1 \\ 0.75 \\ -1.0 \\ 0 \end{bmatrix}$$

The equivalent initial conditions for the two-fluid model are:

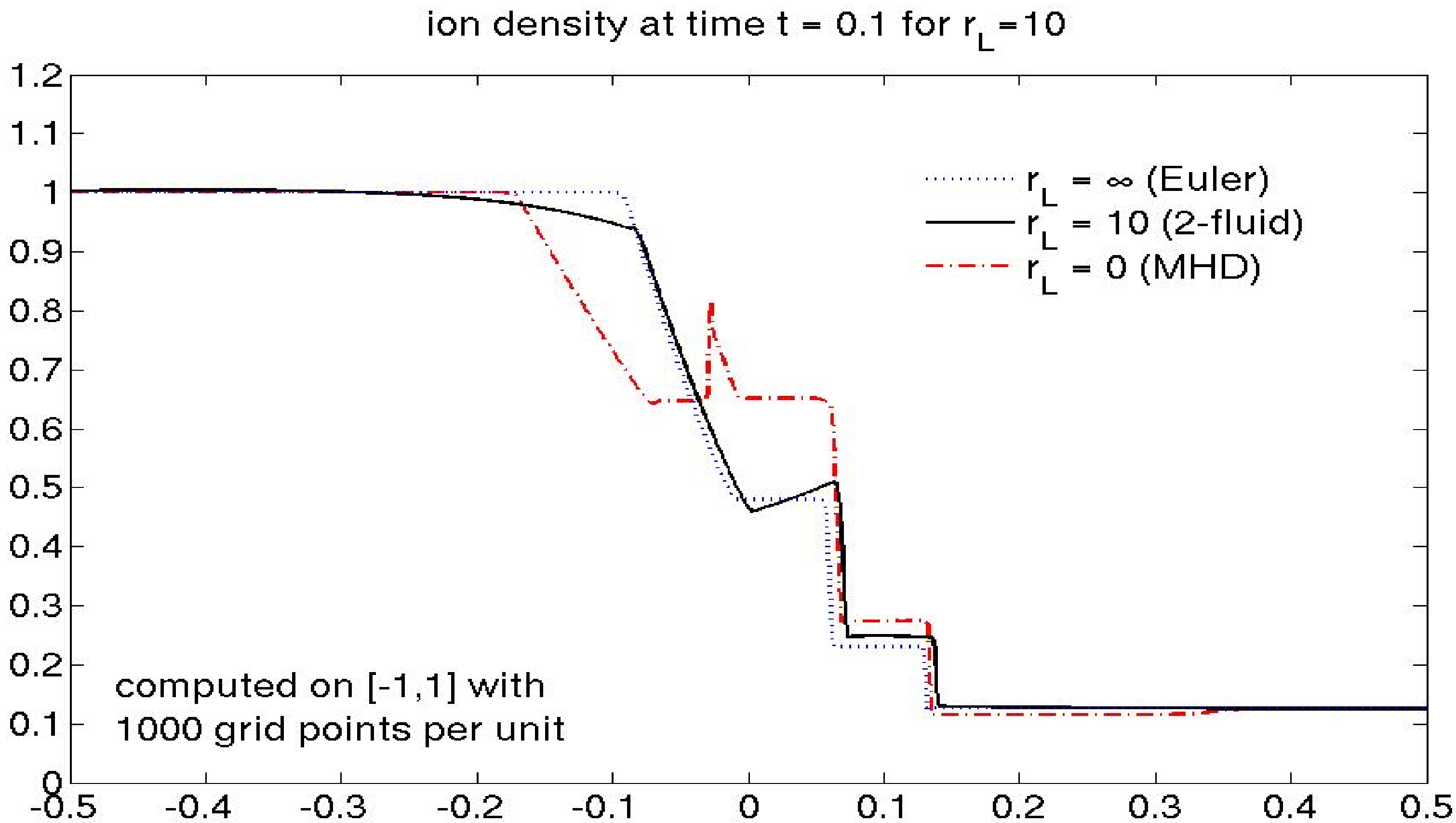
$$\begin{bmatrix} \rho_i \\ v_i^1 \\ v_i^2 \\ v_i^3 \\ p_i \\ \rho_e \\ v_e^1 \\ v_e^2 \\ v_e^3 \\ p_e \\ B^1 \\ B^2 \\ B^3 \\ E^1 \\ E^2 \\ E^3 \end{bmatrix}_{\text{left}} = \begin{bmatrix} 1.0 \\ 0 \\ 0 \\ 0 \\ 0.5 \\ 1.0\frac{m_e}{m_i} \\ 0 \\ 0 \\ 0 \\ 0.5 \\ 0.75 \\ 1.0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \rho_i \\ v_i^1 \\ v_i^2 \\ v_i^3 \\ p_i \\ \rho_e \\ v_e^1 \\ v_e^2 \\ v_e^3 \\ p_e \\ B^1 \\ B^2 \\ B^3 \\ E^1 \\ E^2 \\ E^3 \end{bmatrix}_{\text{right}} = \begin{bmatrix} 0.125 \\ 0 \\ 0 \\ 0 \\ 0.05 \\ 0.125\frac{m_e}{m_i} \\ 0 \\ 0 \\ 0 \\ 0.05 \\ 0.75 \\ -1.0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Brio-Wu initial conditions: ion density



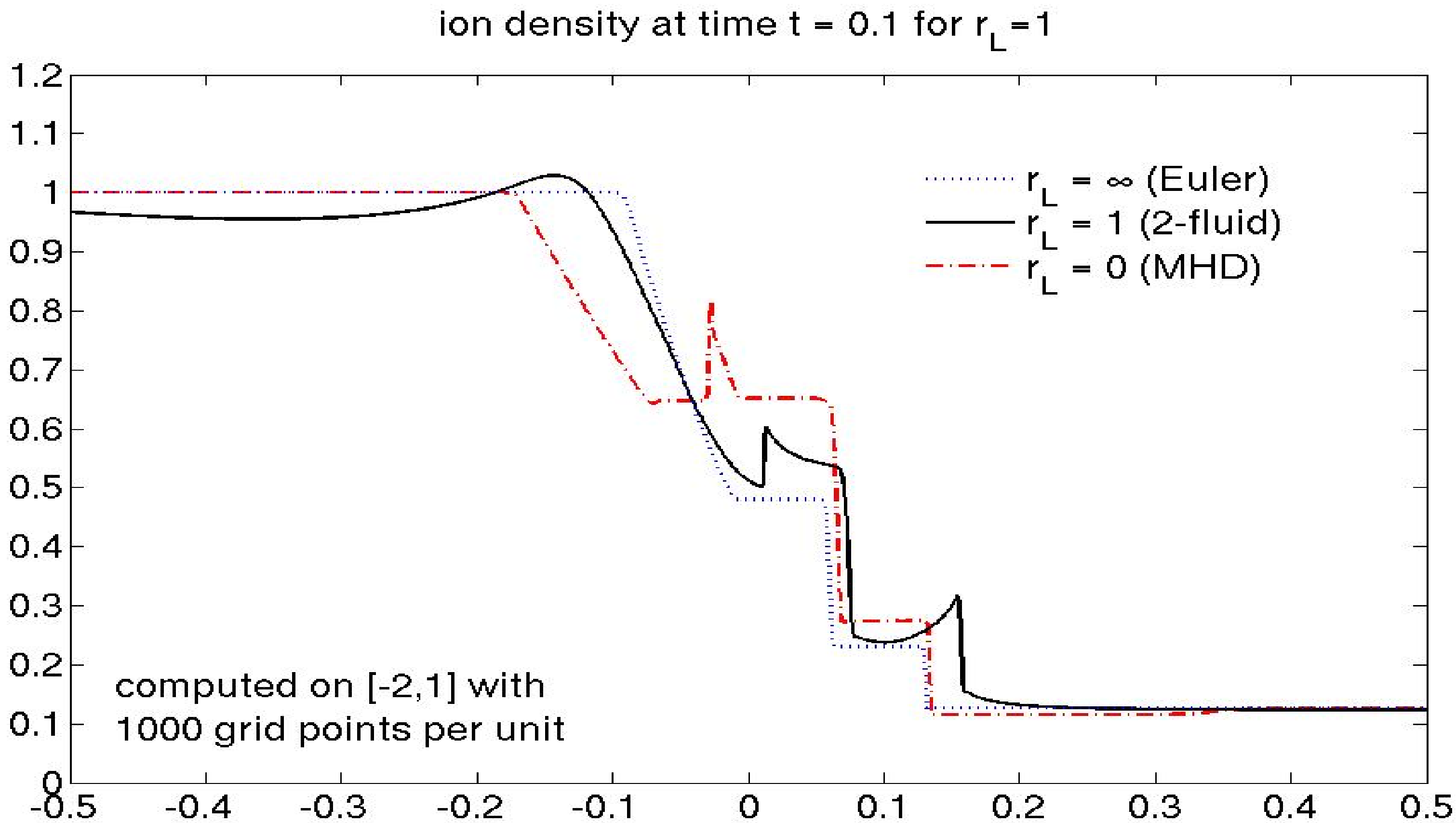
Initial conditions for ion density:
discontinuity at zero, elsewhere constant.

Brio-Wu, $r_L = 10$



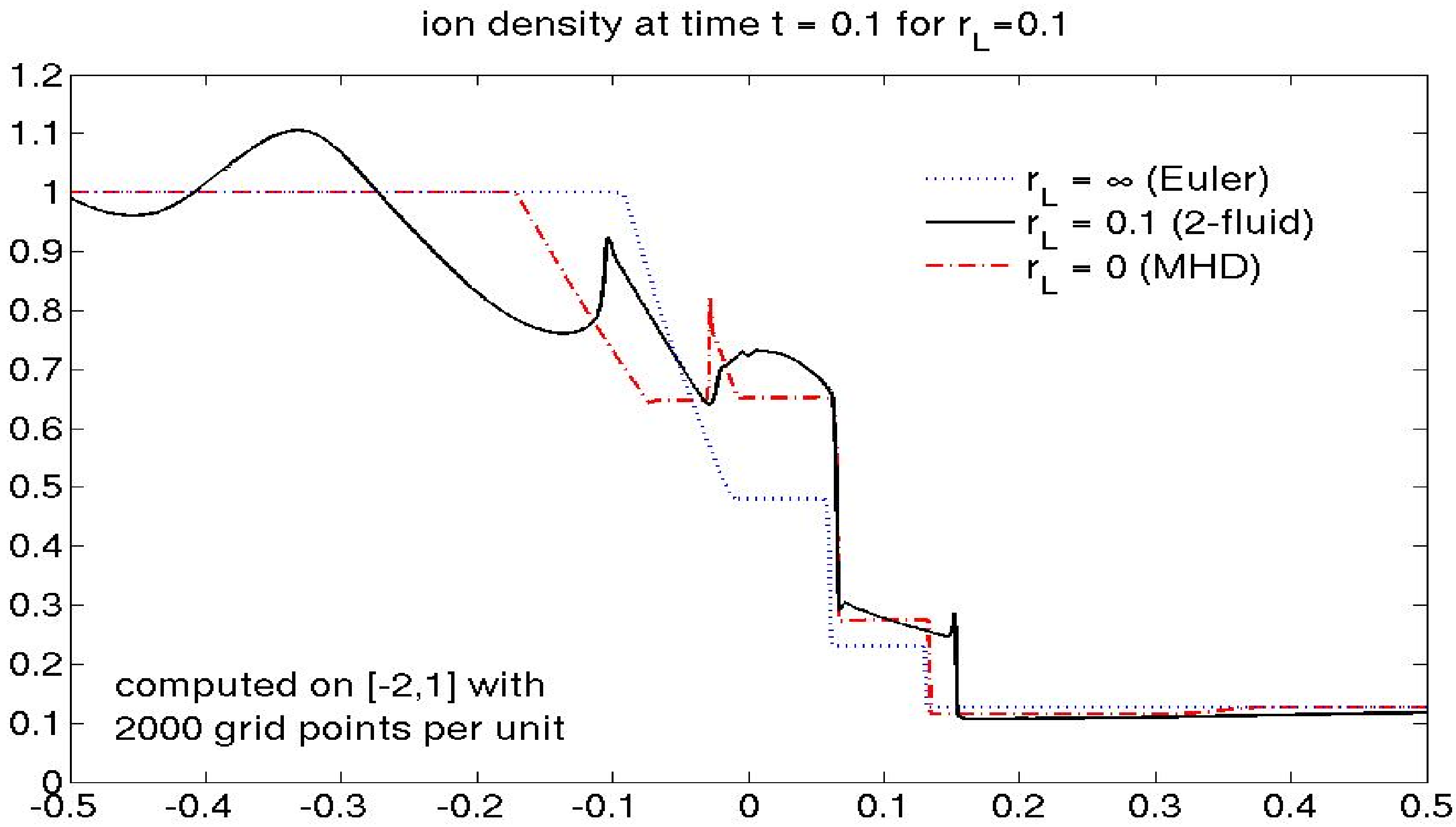
When the Larmor radius is large ($r_L = 10$), the electromagnetic effects are weak and the ions behave like an ideal gas. (At $r_L = 100$, 2-fluid is indistinguishable from Euler.)

Brio-Wu, $r_L = 1$



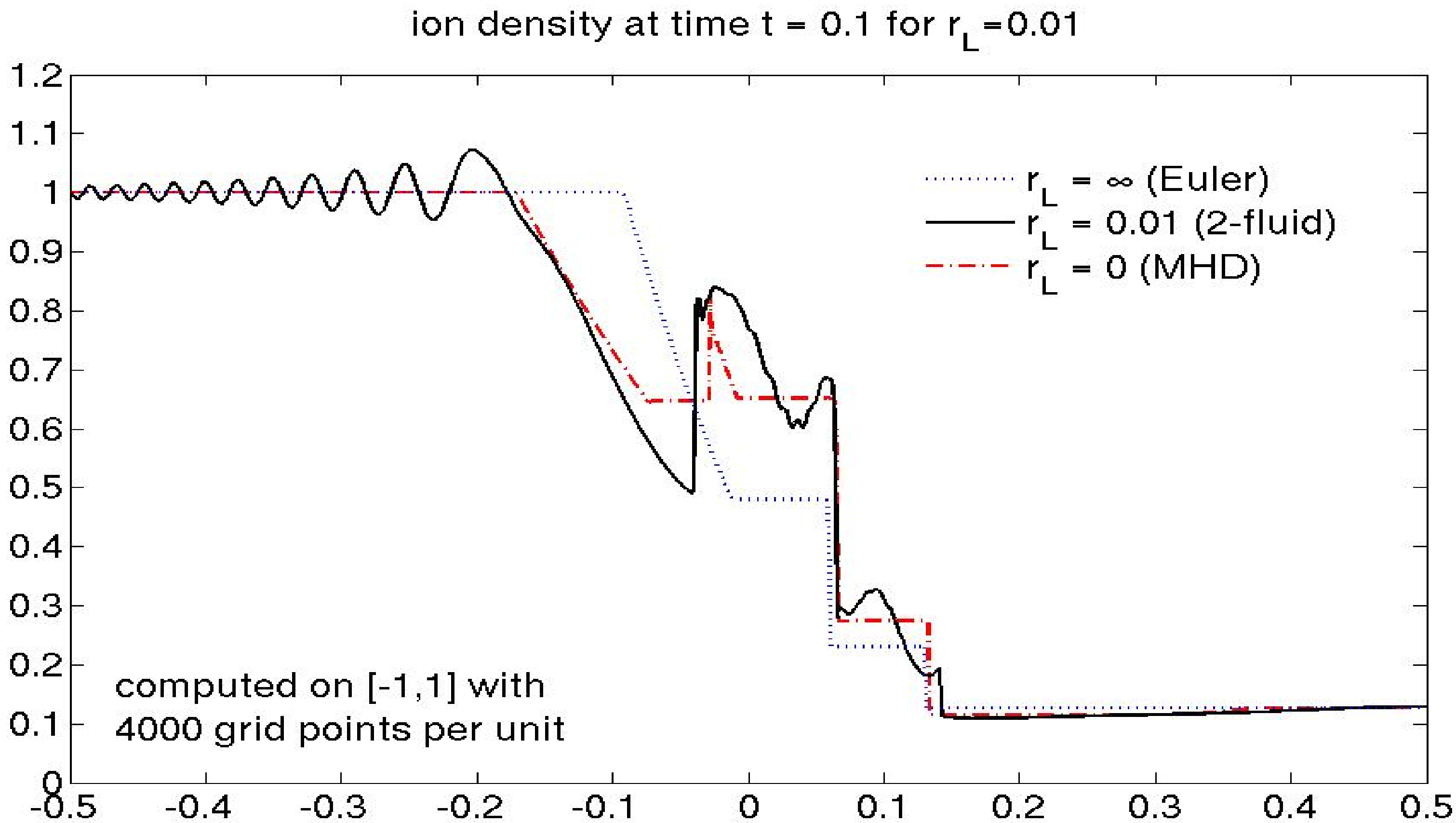
As we decrease the Larmor radius, the solution begins to transition away from gas dynamics (and eventually toward MHD).

Brio-Wu, $r_L = 0.1$



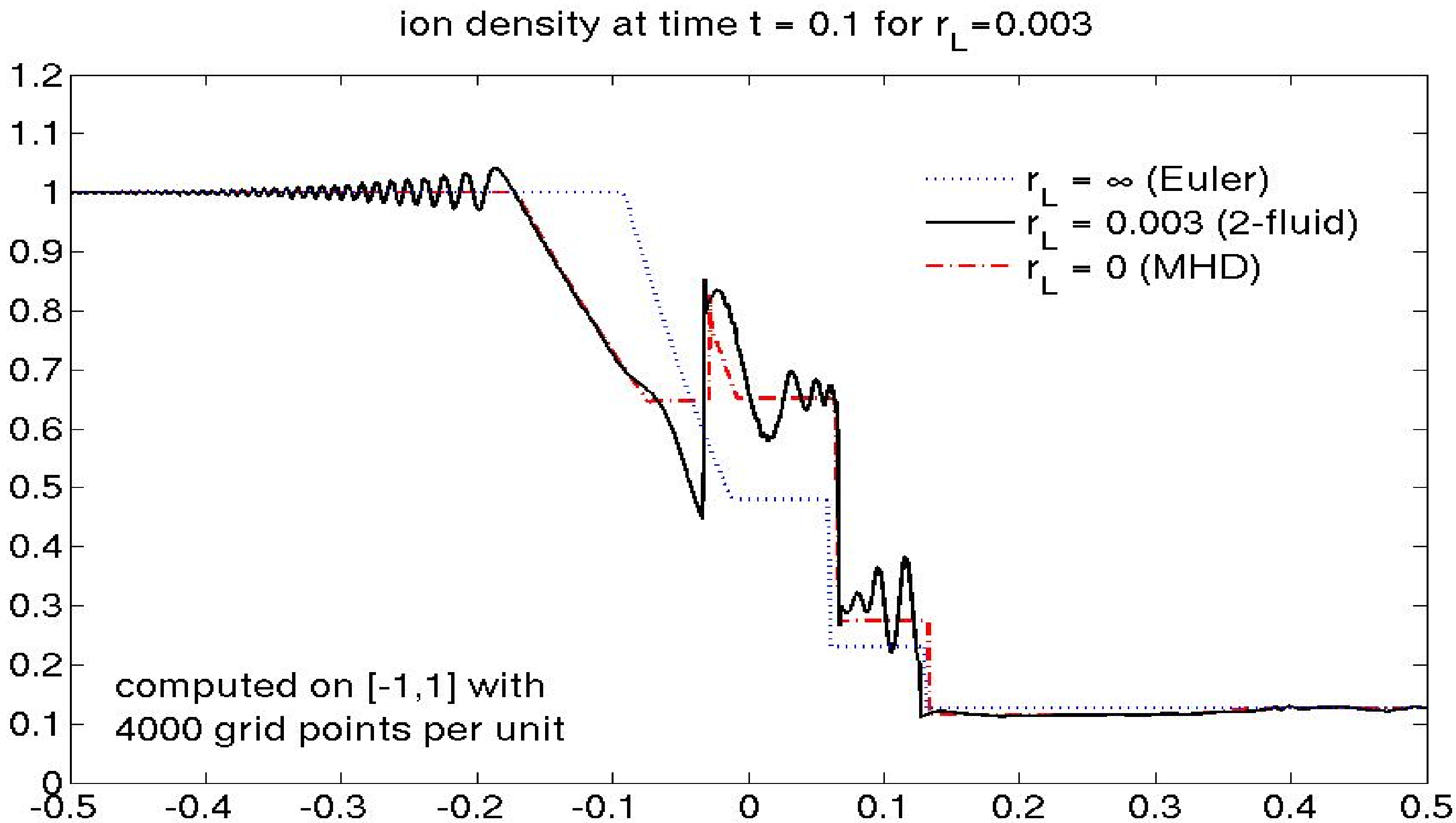
When $t \approx r_L$, the solution is roughly intermediate between Euler and MHD.

Brio-Wu, $r_L = 0.01$



As the Larmor radius becomes even smaller, the frequency of the oscillations increases and the solution begins to weakly approach the MHD solution.

Brio-Wu, $r_L = 0.003$

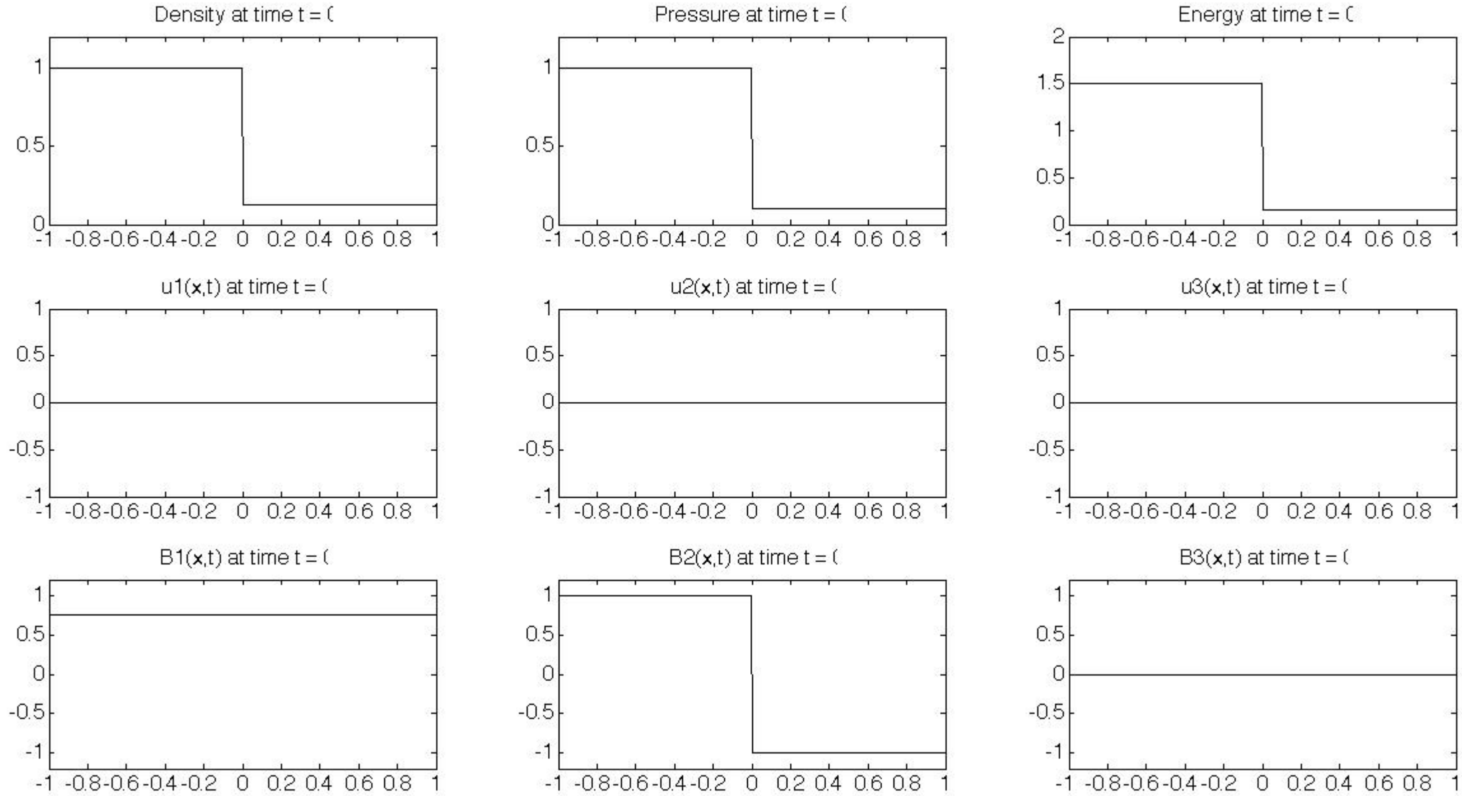


Convergence to MHD is suggested but far from confirmed. Unfortunately, computational expense increases with decreasing Larmor radius.

Brio-Wu: PIC

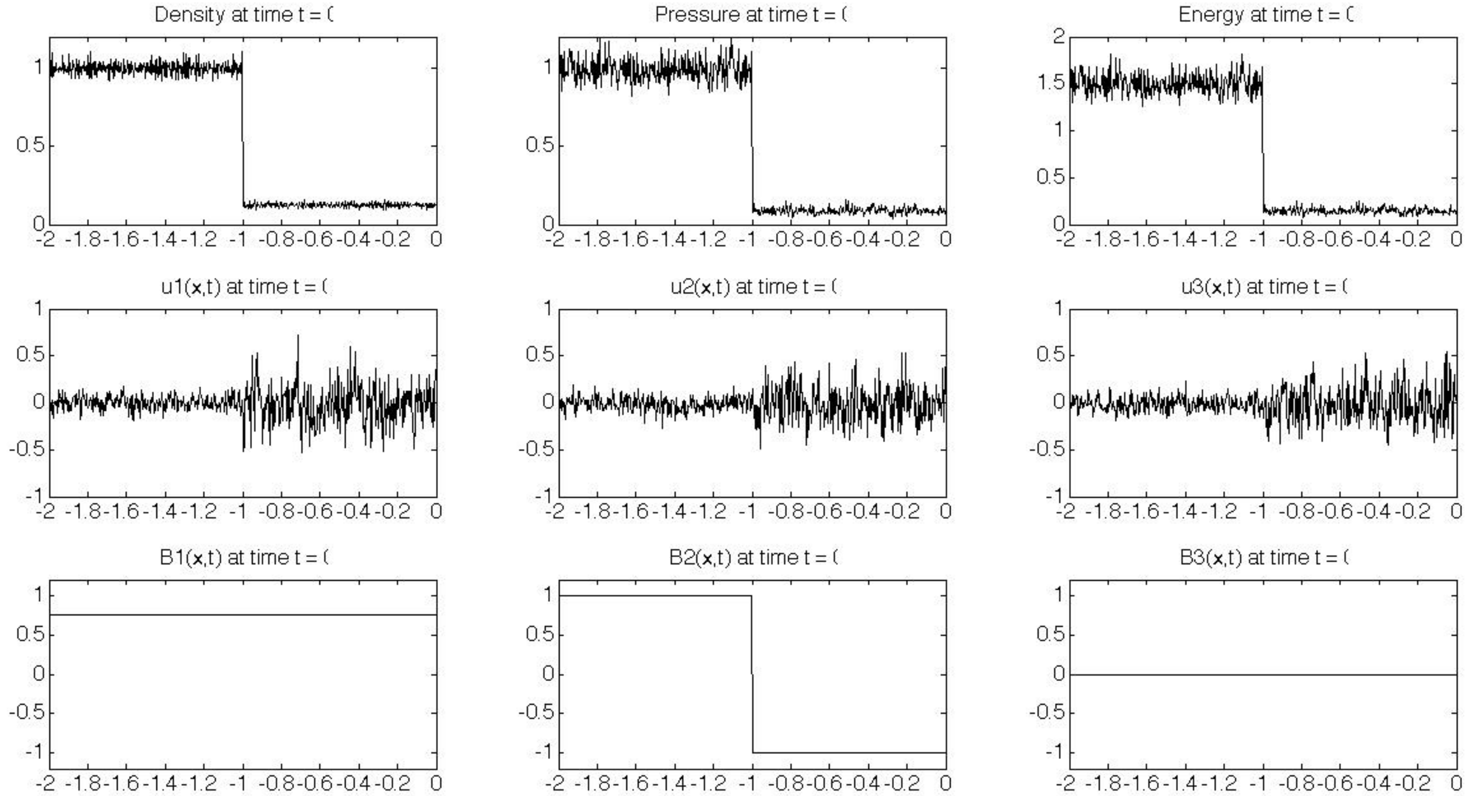
I also implemented a PIC code solver and tried it on the Brio-Wu problem. I encountered serious energy conservation issues.

Brio-Wu initial conditions $(t = 0)$



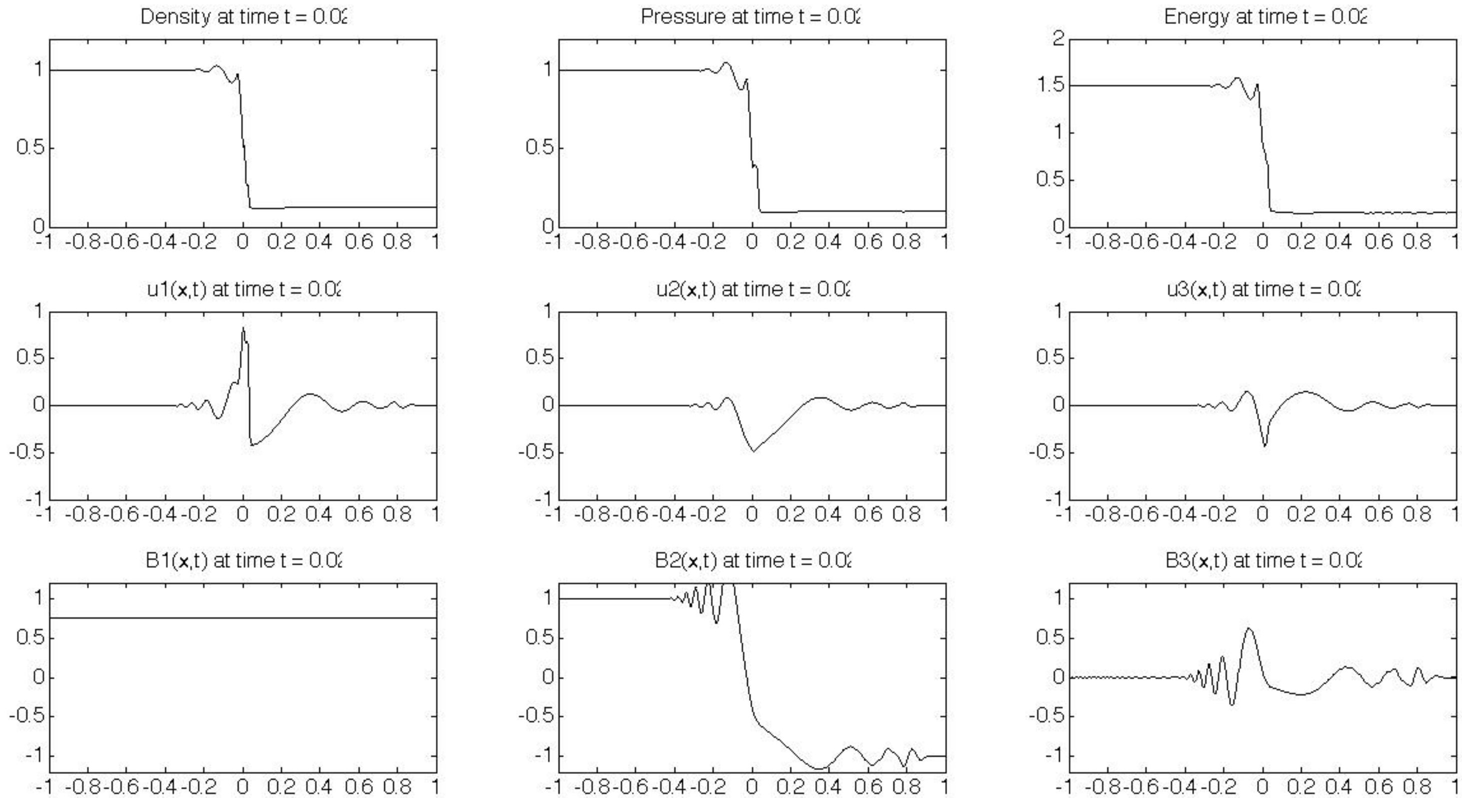
The initial conditions for the Brio-Wu problem.

Brio-Wu PIC initial conditions $(t = 0)$



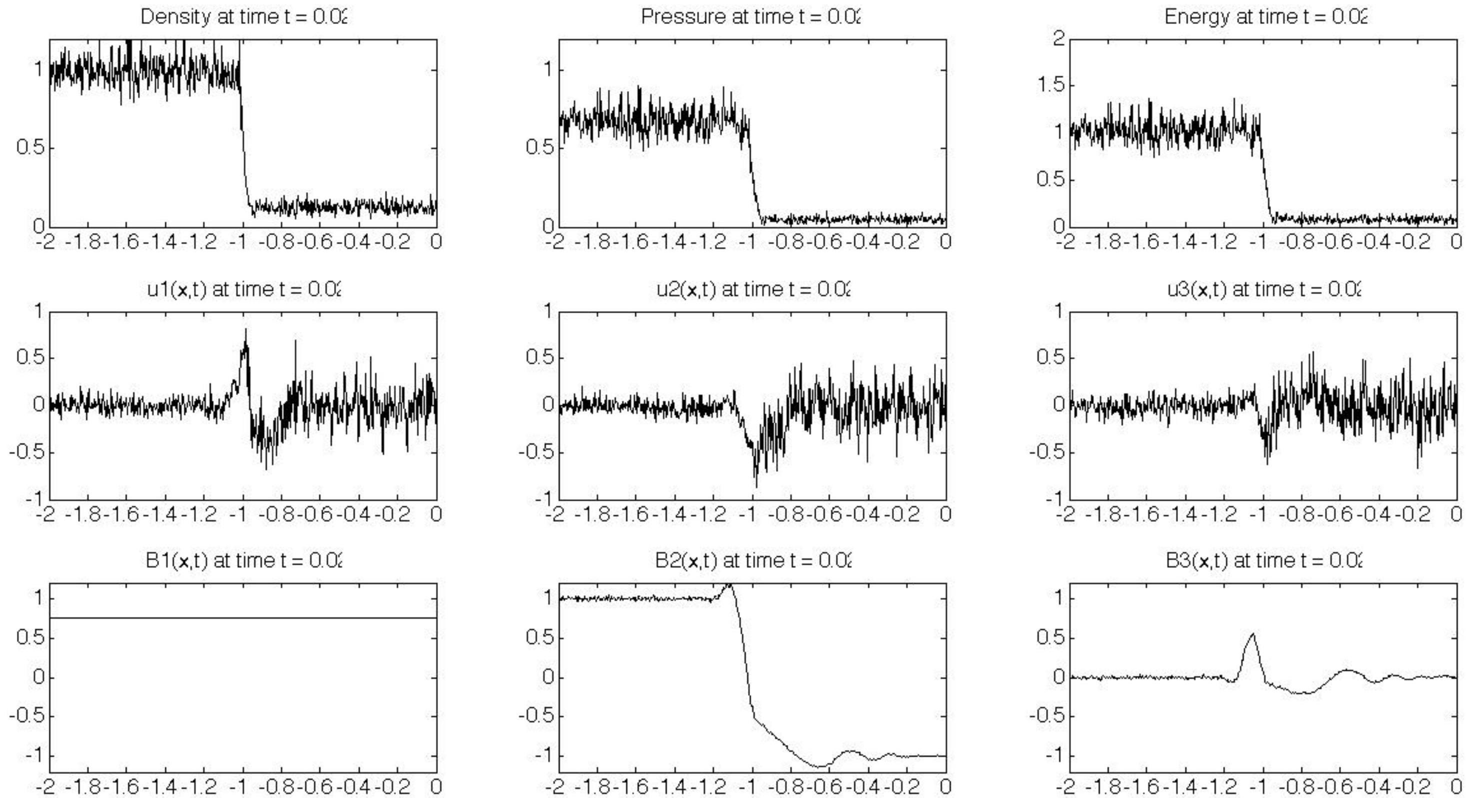
The initial conditions for a kinetic run of the Brio-Wu problem.

Brio-Wu 2-fluid, $r_L = 0.1, t = .02$



Two-fluid Brio-Wu solution

Brio-Wu kinetic, $r_L = 0.1, t = .02$

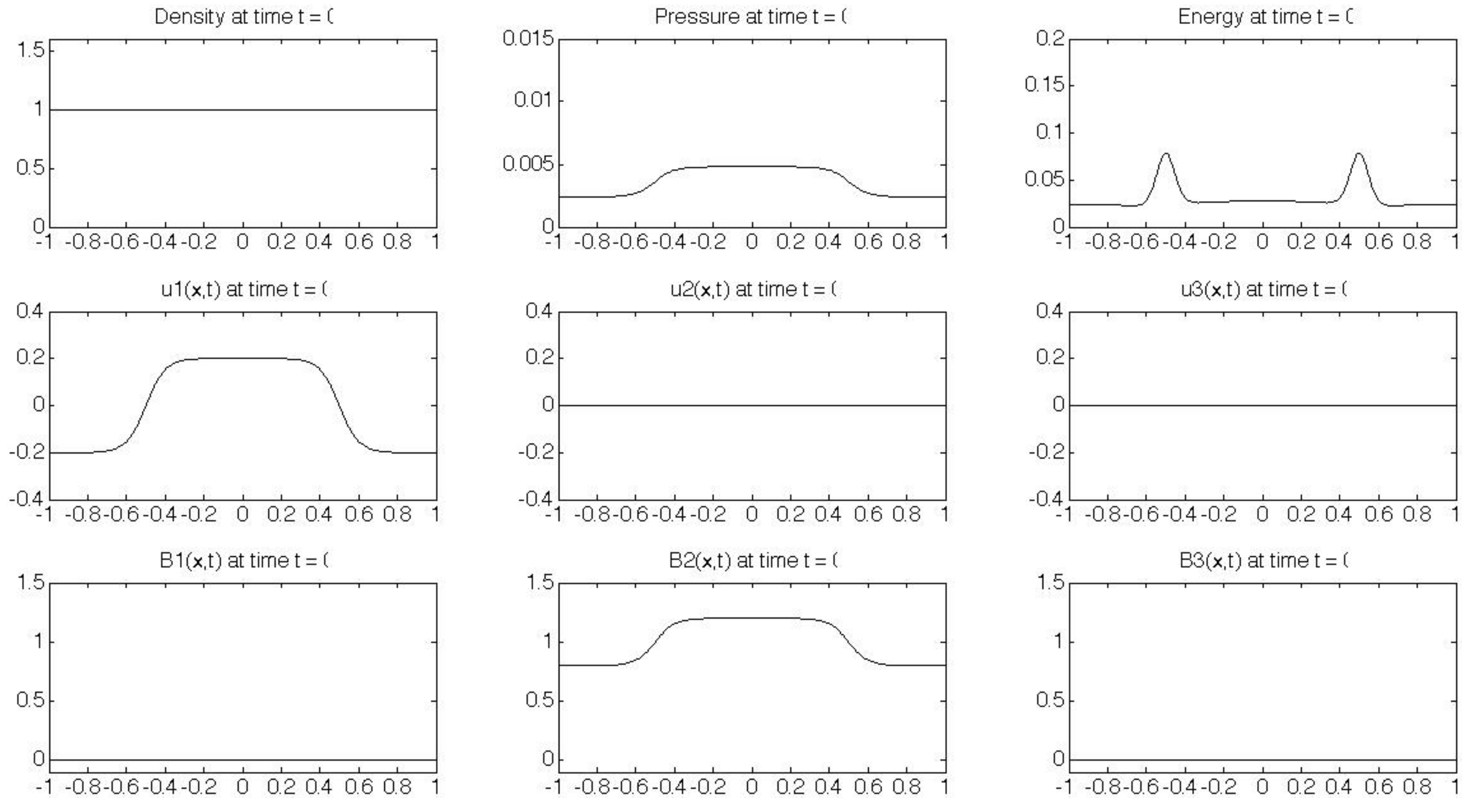


Kinetic Brio-Wu solution

Magnetosonic Wave

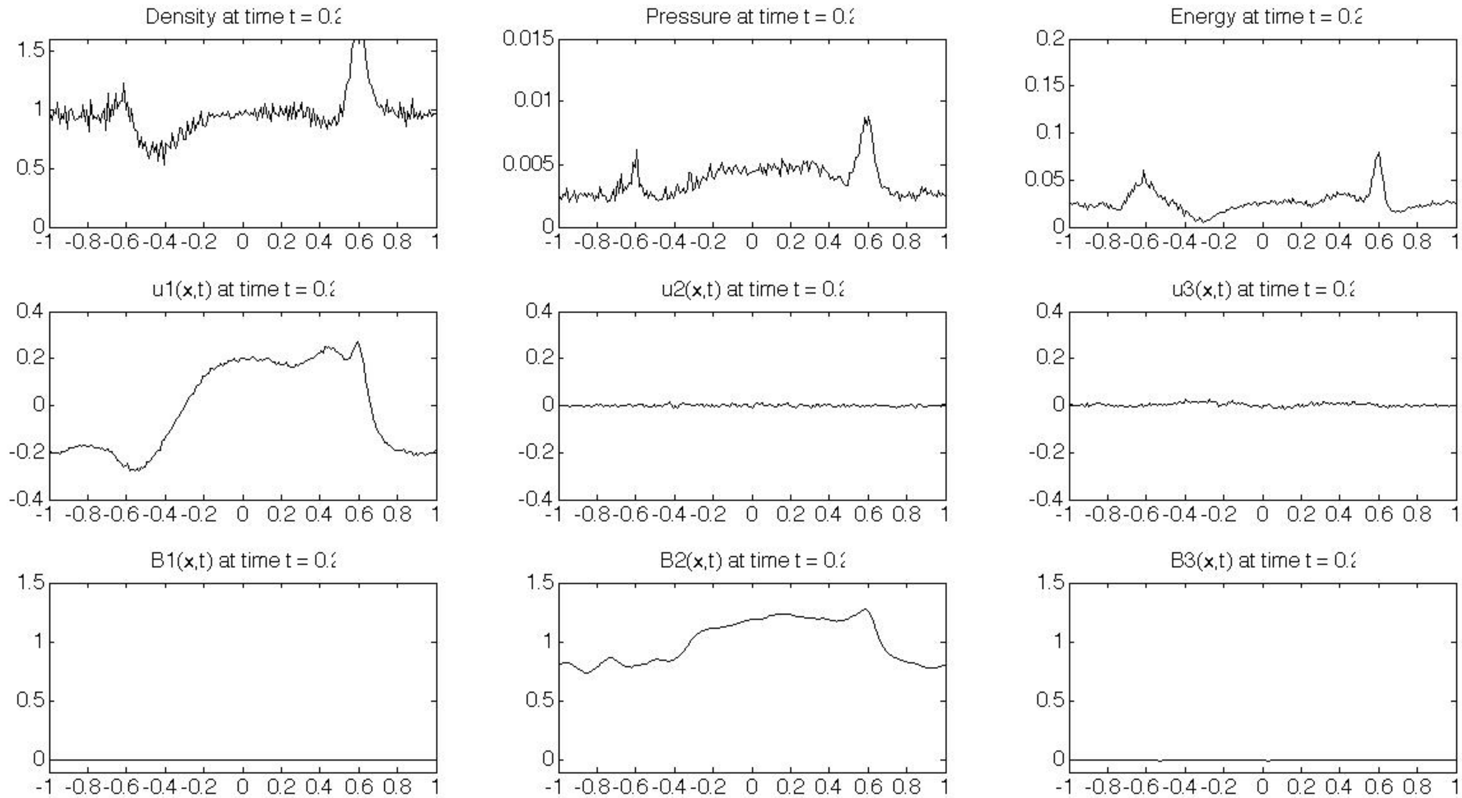
I also compared the MHD, two-fluid, and kinetic models for an MHD wave called the magnetosonic wave.

Computations: fast magnetosonic kinetic, $r_L = 0$



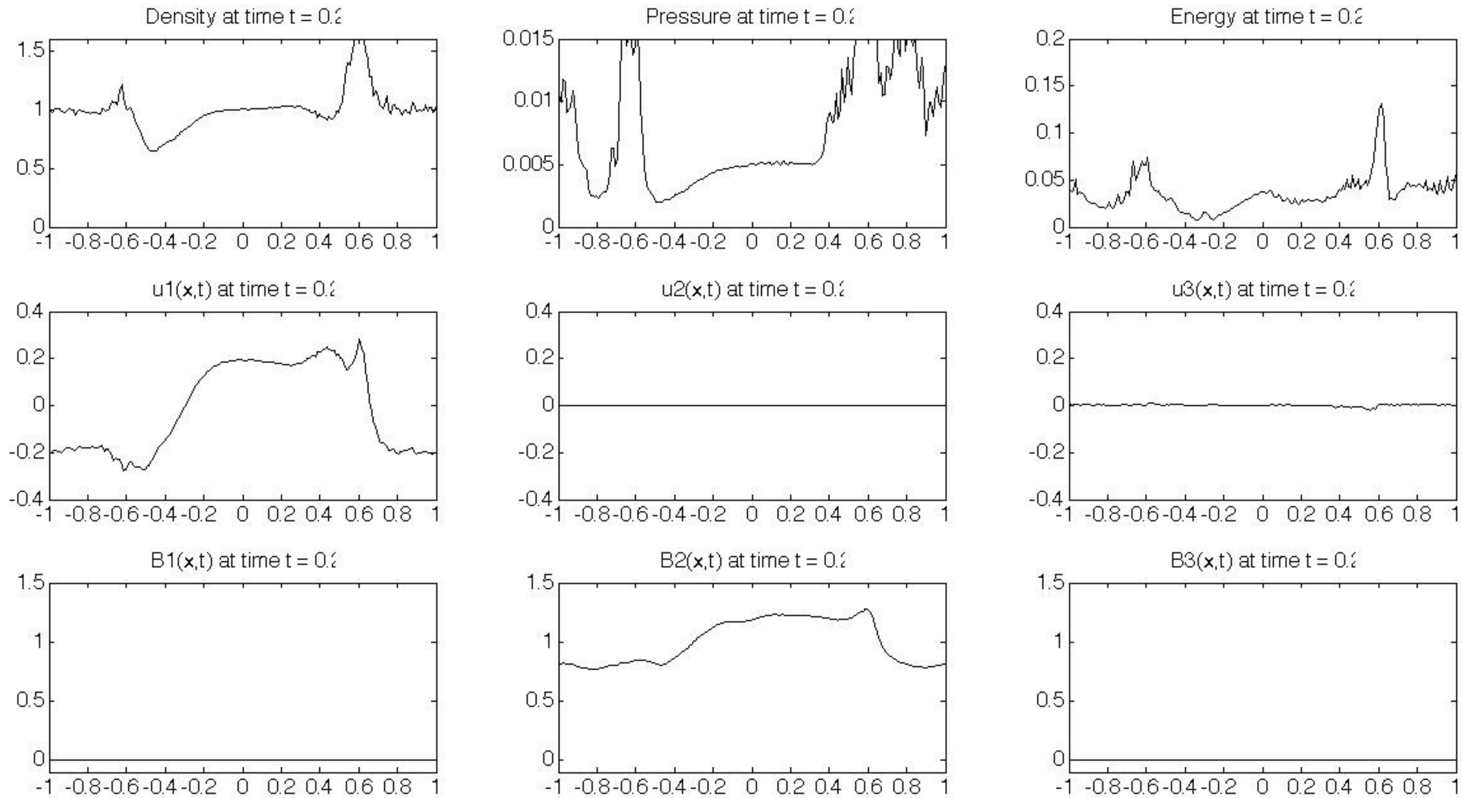
Fast magnetosonic initial conditions

Computations: fast magnetosonic kinetic, $r_L = 0.2, t = .2$



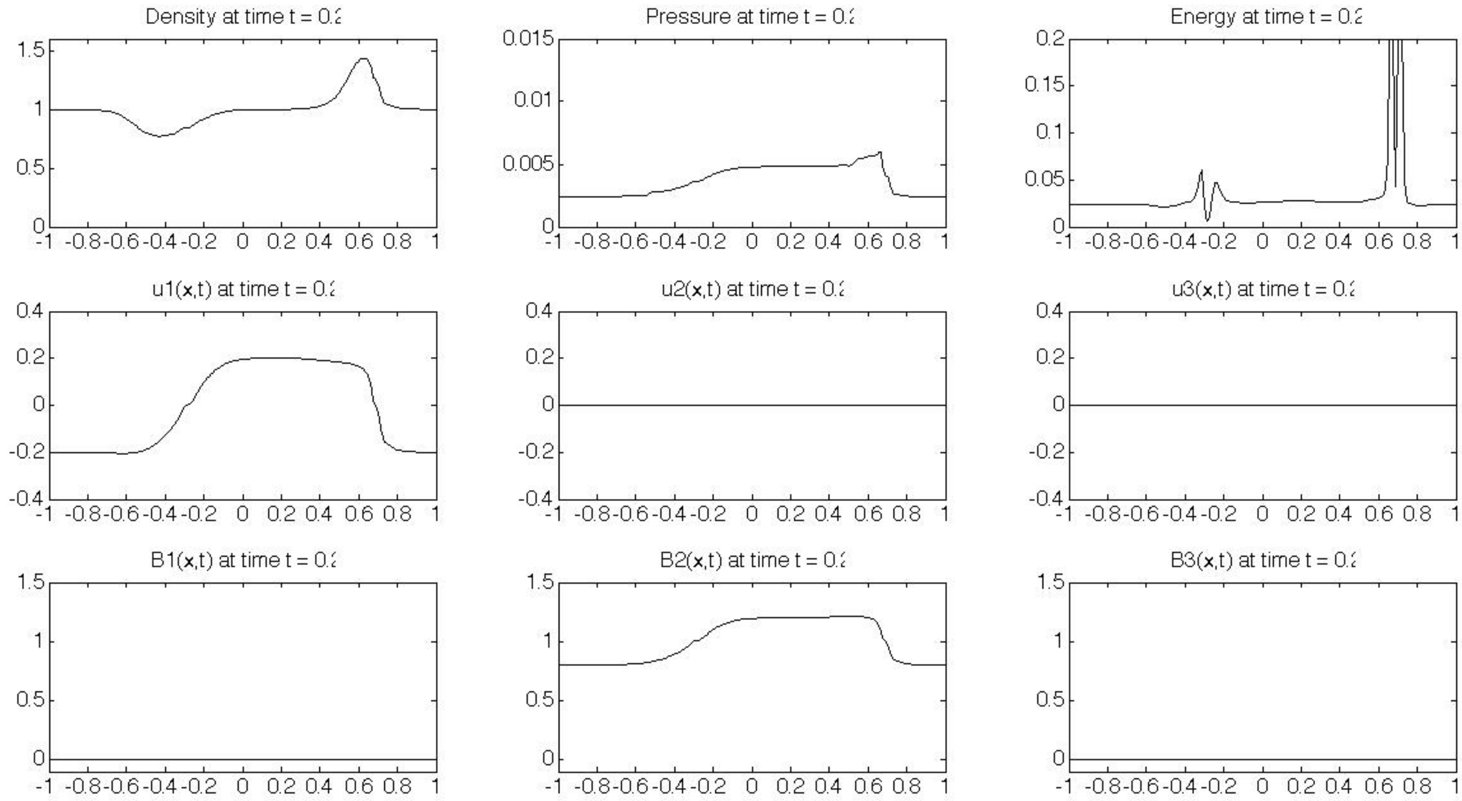
Kinetic fast magnetosonic solution

Computations: fast magnetosonic 2-fluid, $r_L = 0.2, t = .2$



2-fluid fast magnetosonic solution

Computations: fast magnetosonic MHD, $r_L = 0.2, t = .2$



MHD fast magnetosonic solution

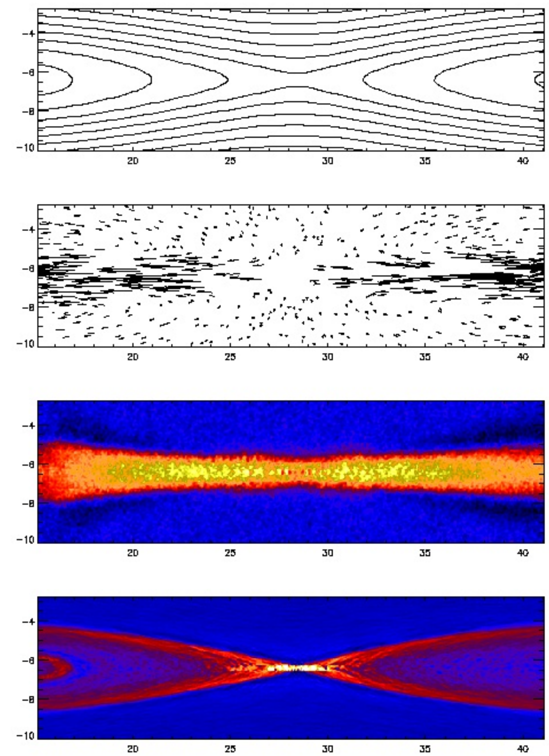
GEM reconnection challenge

The Geospace Environmental Modeling magnetic reconnection challenge problem:

- initial conditions: perturbed Harris sheet equilibrium (adjacent oppositely directed field lines)

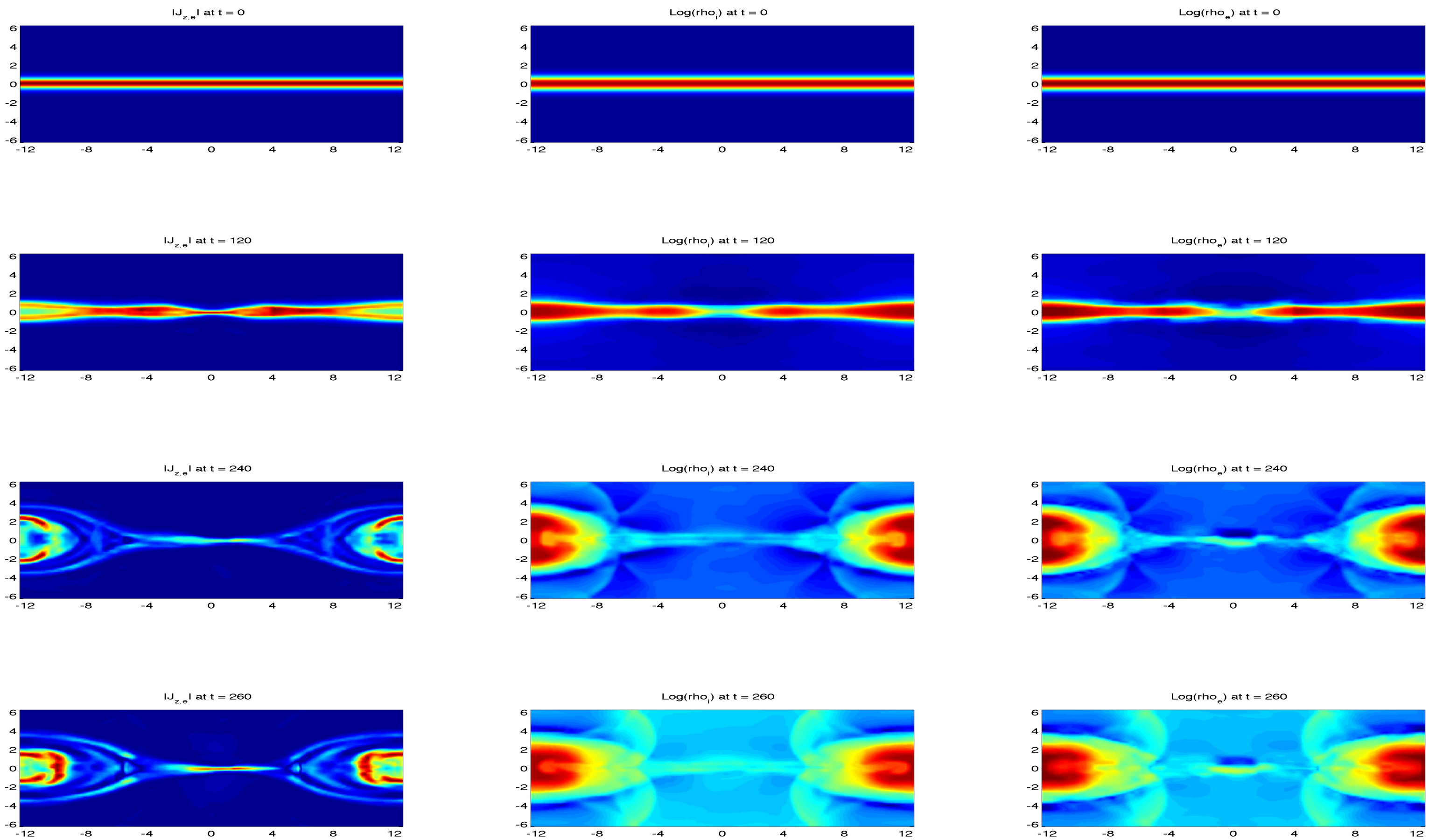
- fast reconnection ensues: field lines develop into an X-point.

http://www.glue.umd.edu/∼drake/

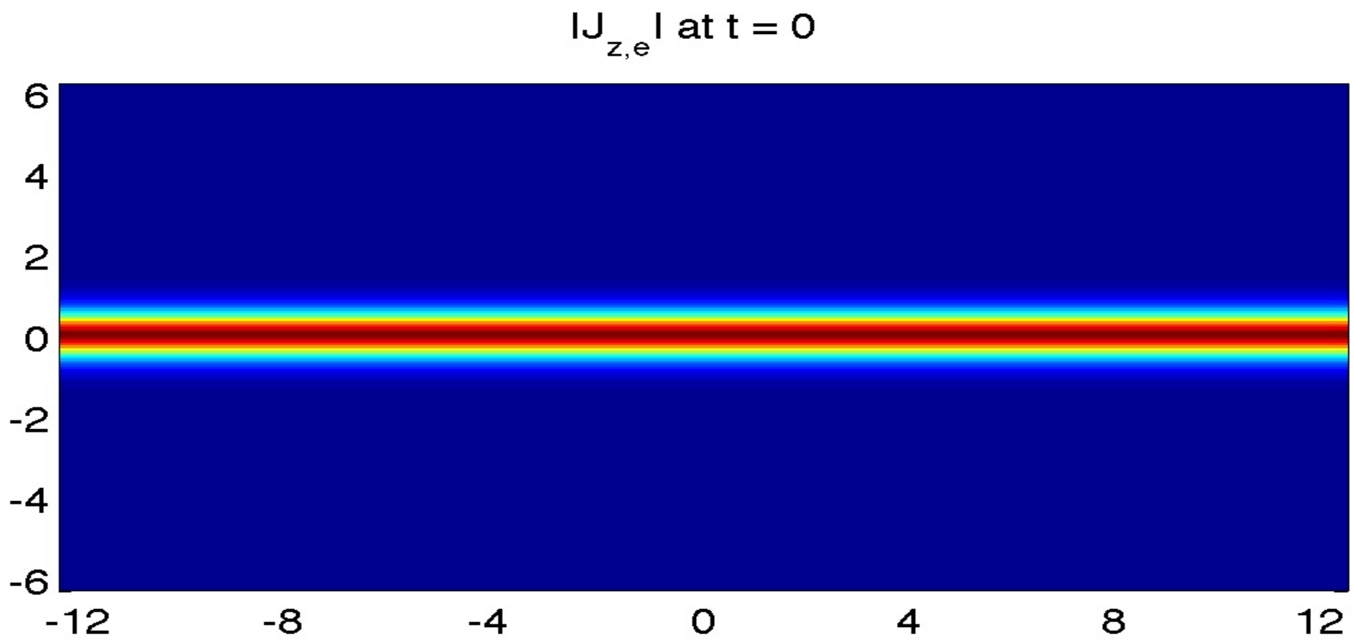


2

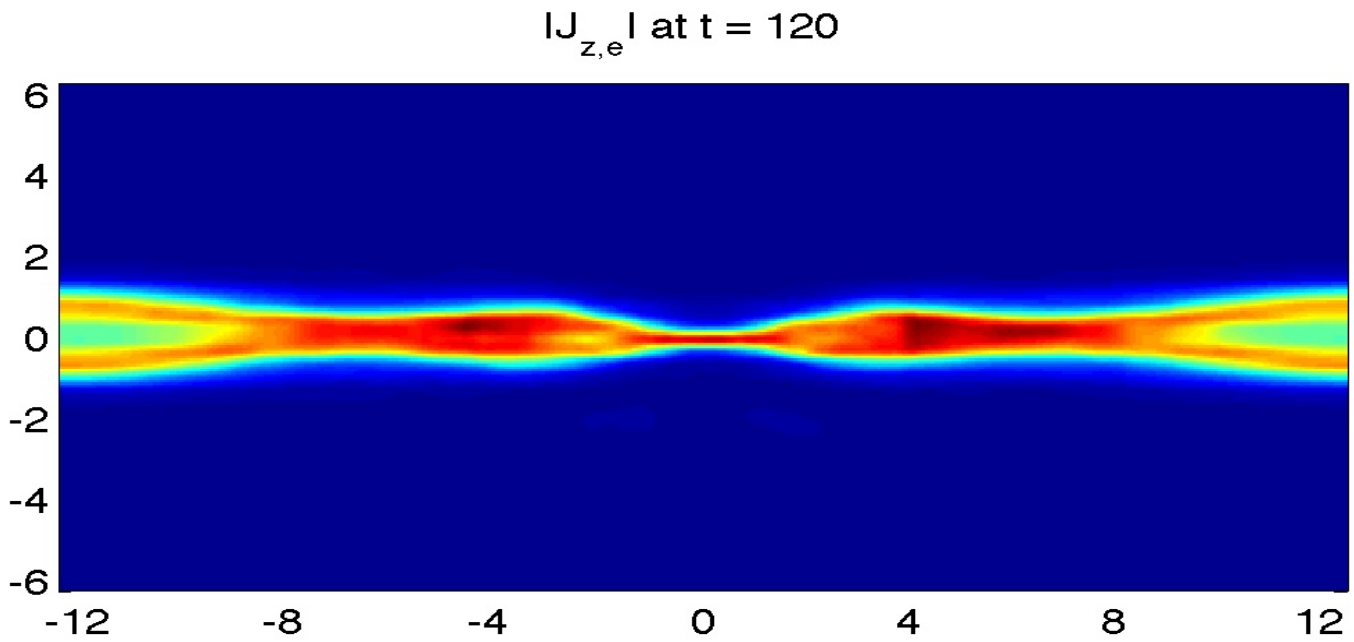
GEM reconnection challenge 2-fluid solution using DG



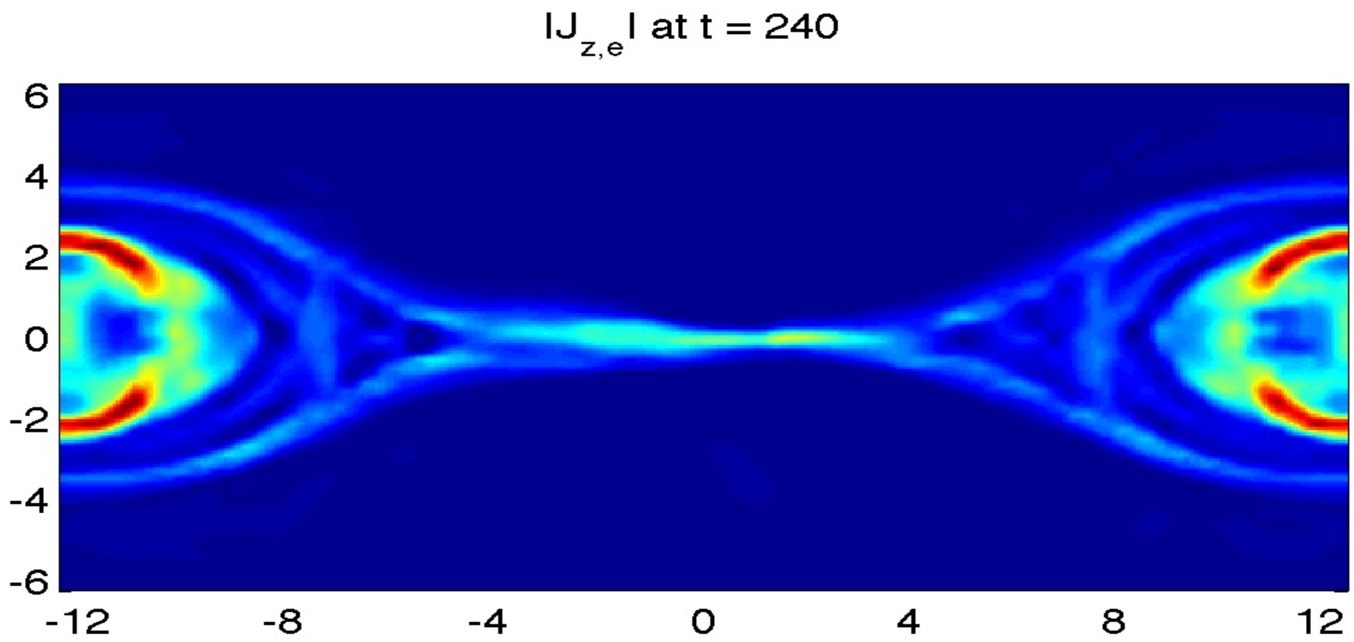
GEM reconnection challenge 2-fluid solution using DG: $|J_{z,e}|$



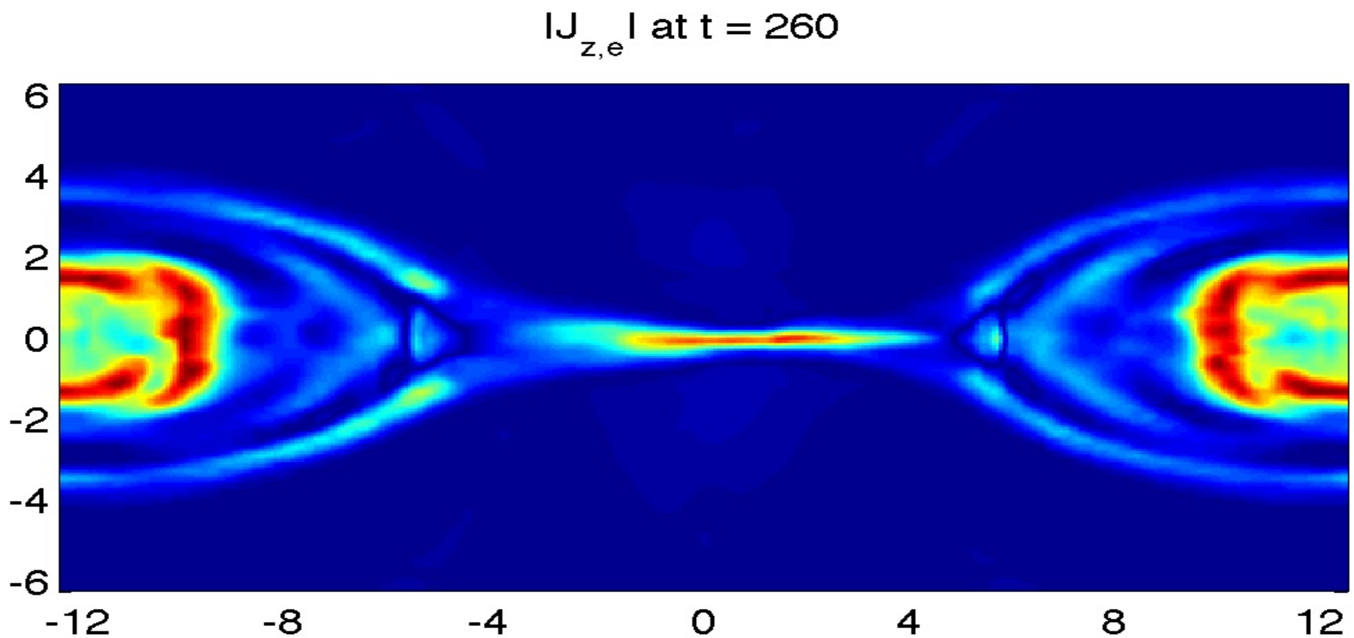
GEM reconnection challenge 2-fluid solution using DG: $|J_{z,e}|$



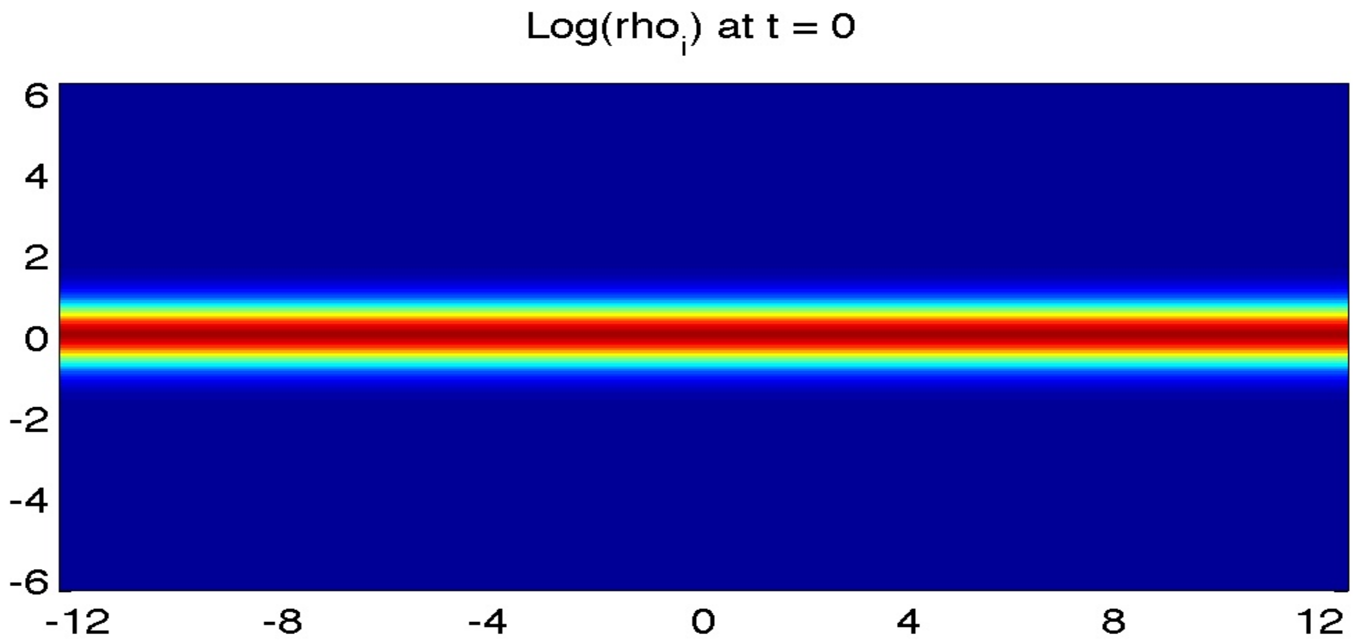
GEM reconnection challenge 2-fluid solution using DG: $|J_{z,e}|$



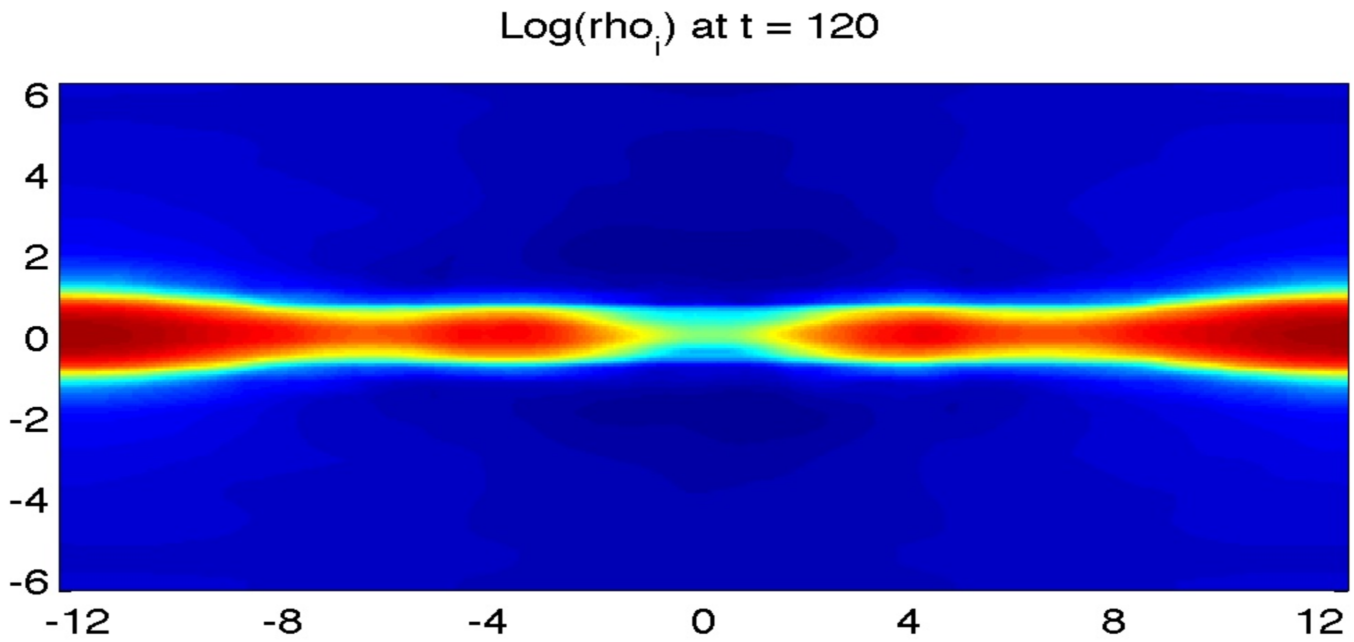
GEM reconnection challenge 2-fluid solution using DG: $|J_{z,e}|$



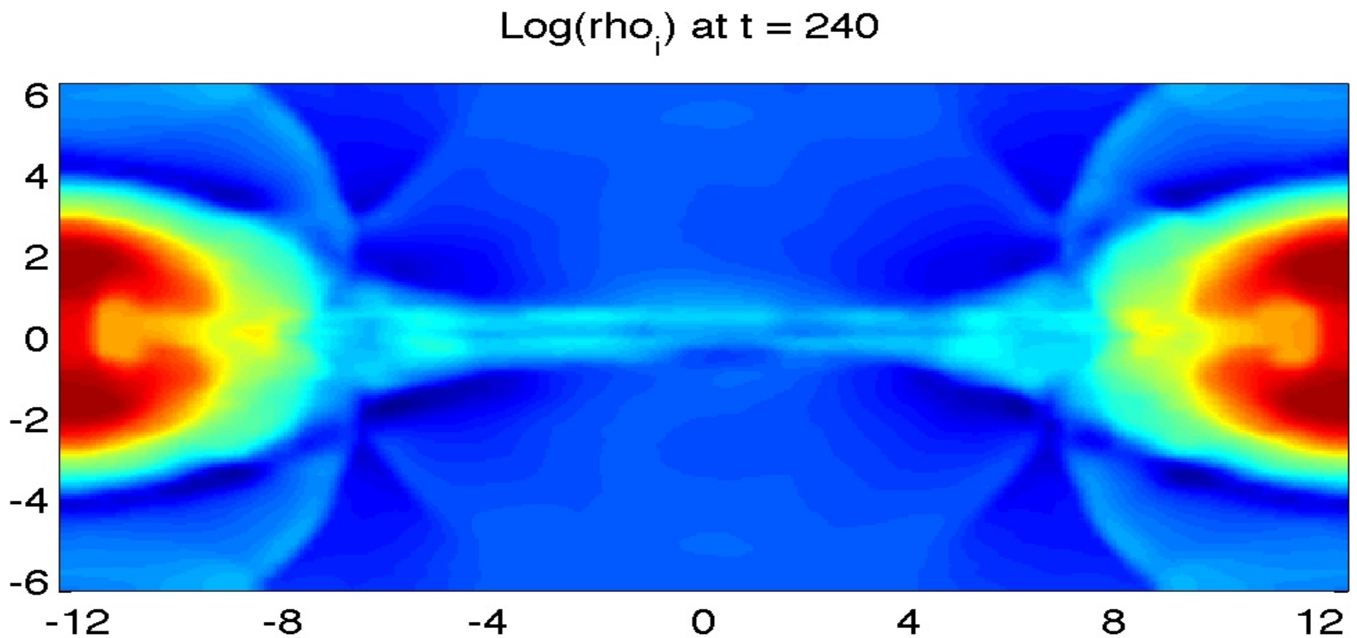
GEM reconnection challenge 2-fluid solution using DG: ρ_i



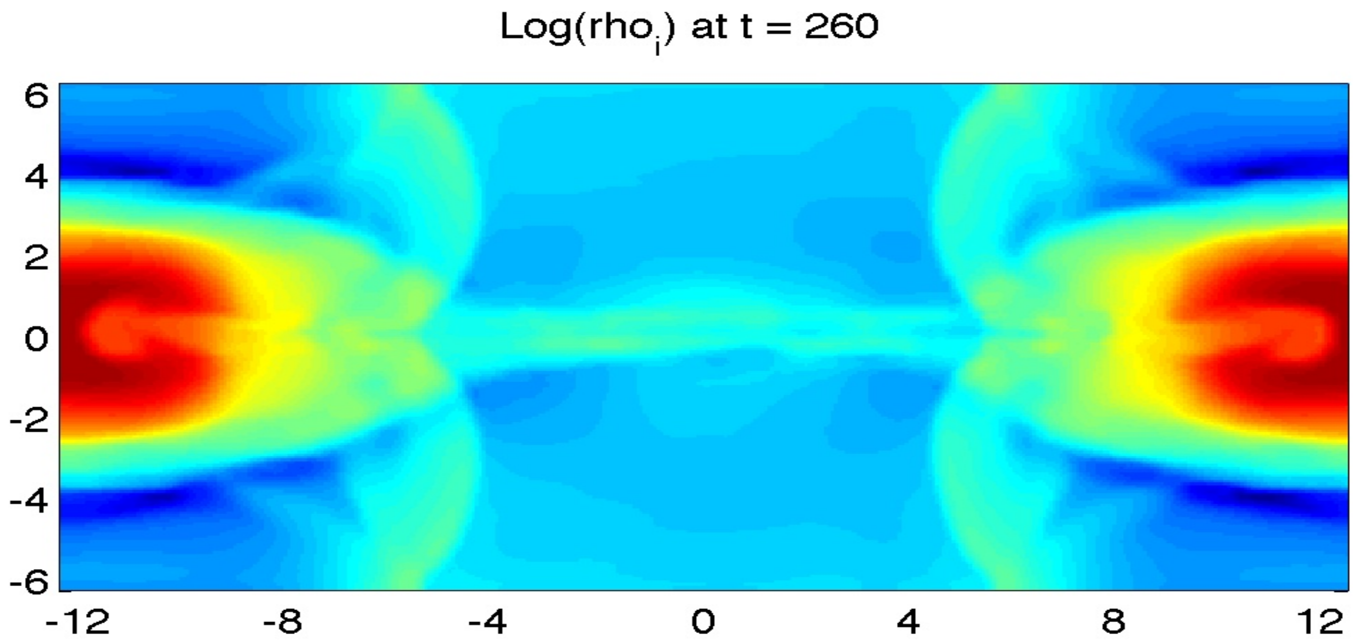
GEM reconnection challenge 2-fluid solution using DG: ρ_i



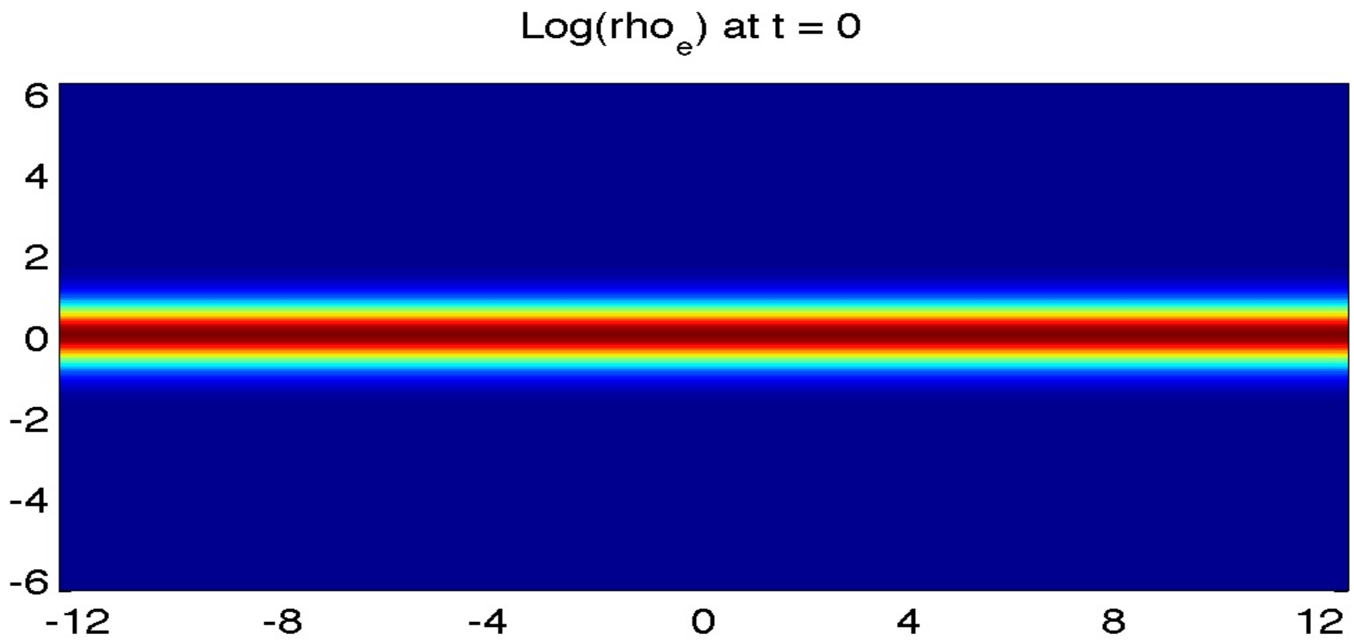
GEM reconnection challenge 2-fluid solution using DG: ρ_i



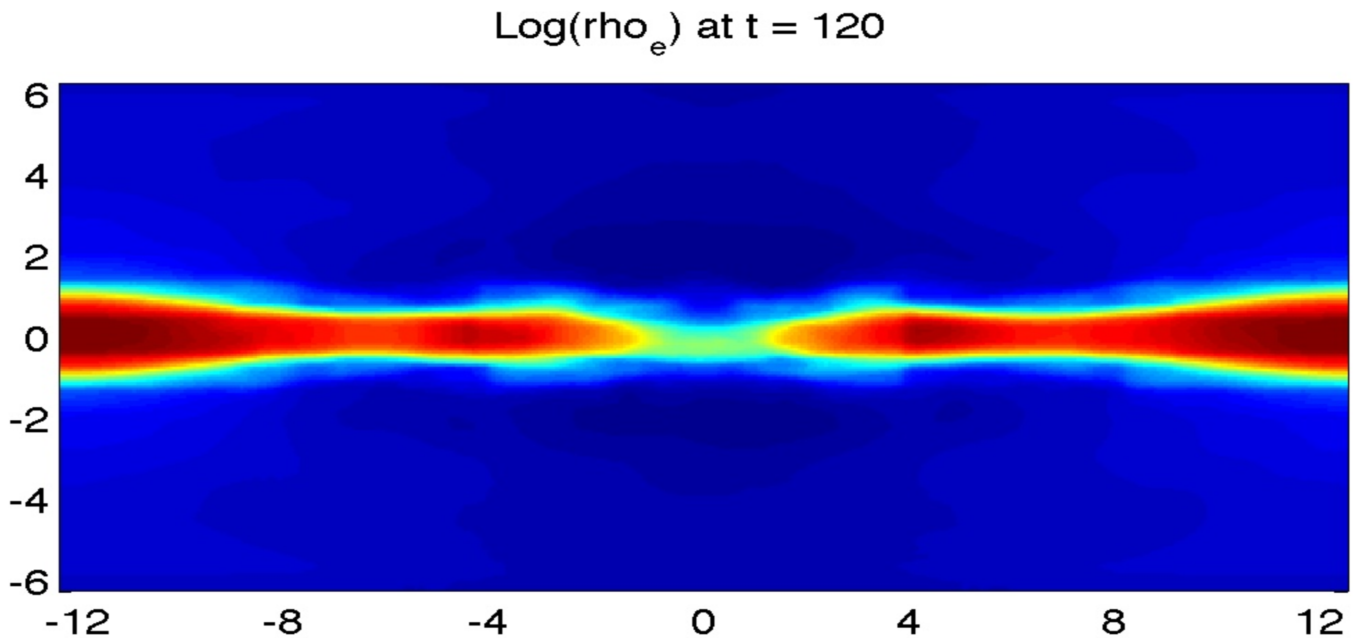
GEM reconnection challenge 2-fluid solution using DG: ρ_i



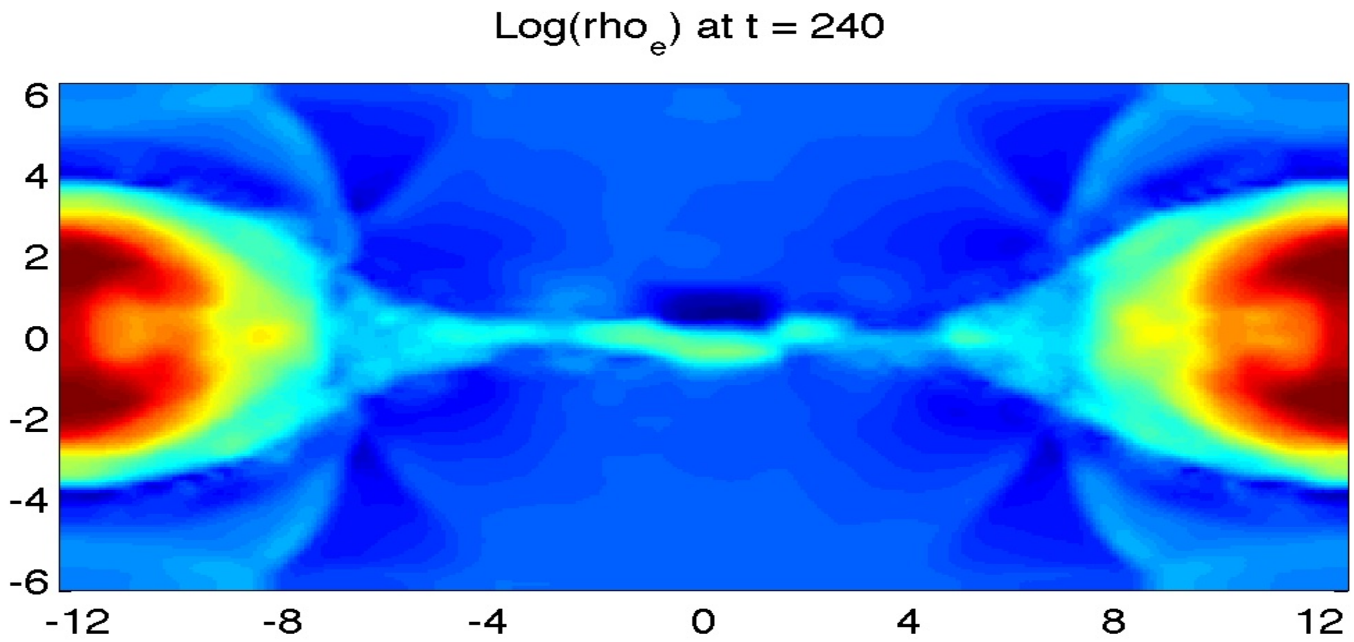
GEM reconnection challenge 2-fluid solution using DG: ρ_e



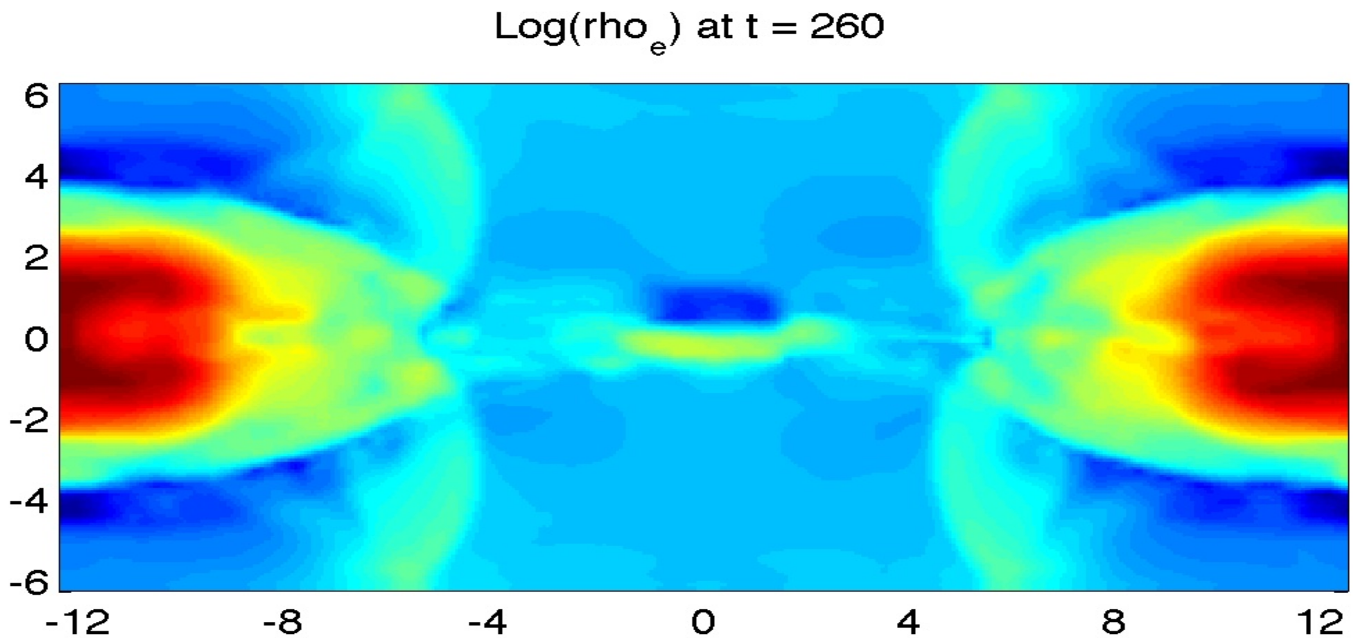
GEM reconnection challenge 2-fluid solution using DG: ρ_e



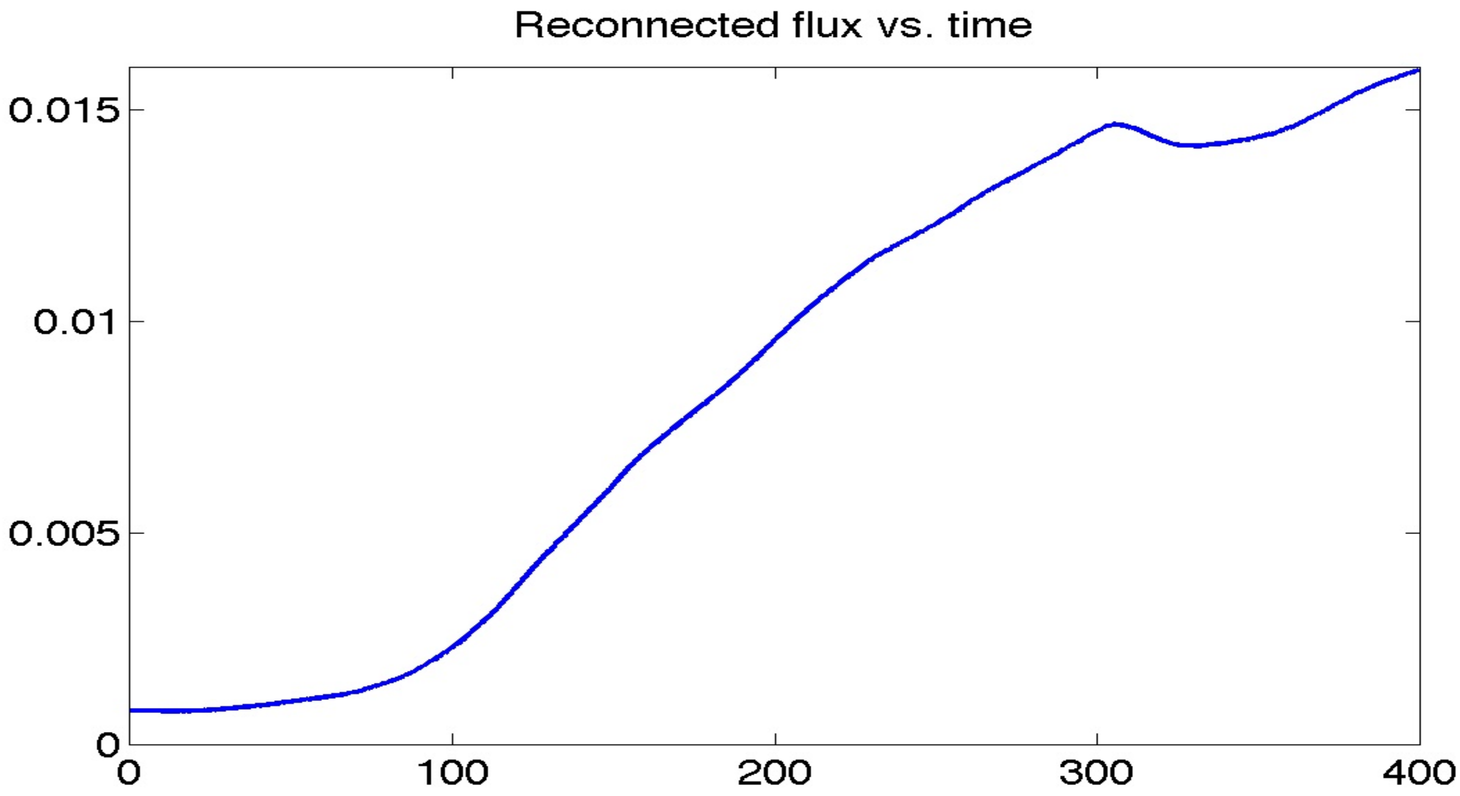
GEM reconnection challenge 2-fluid solution using DG: ρ_e



GEM reconnection challenge 2-fluid solution using DG: ρ_e



GEM 2-fluid DG solution: reconnected flux



Acknowledgements

- Wisconsin Space Grant Consortium
- My advisor, James Rossmanith
- Helpful conversations with Nick Murphy, Ping Zhu, Ammar Hakim, Uri Shumlak, James Drake, Nick Hitchon, and Andrew Christlieb.