CLIMATE & SPACE

AMR PIC

Adaptive Mesh Refinement - Particle In Cell

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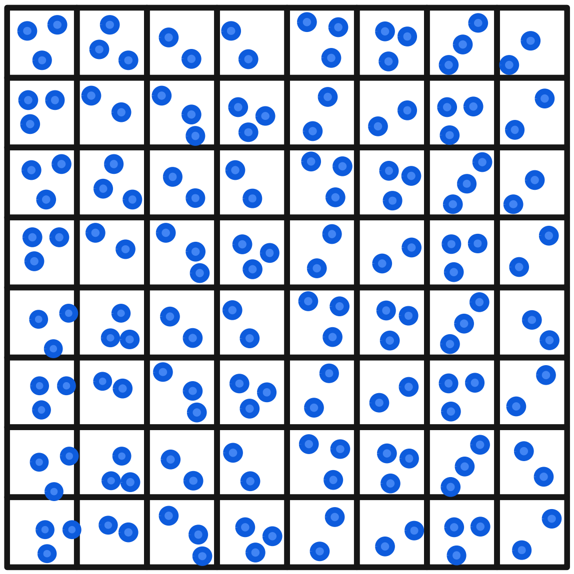
Particle in Cell Method (PIC)

- Simulate plasma as particles (ion and electrons)



- Can capture non-Maxwellian distributions
- Particles interact through electromagnetic fields
- Collisionless plasma

Electromagnetic fields move particles

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Particles are used to calculate current

$$\mathbf{J} = \sum_s q_s n_s \mathbf{v}_s$$

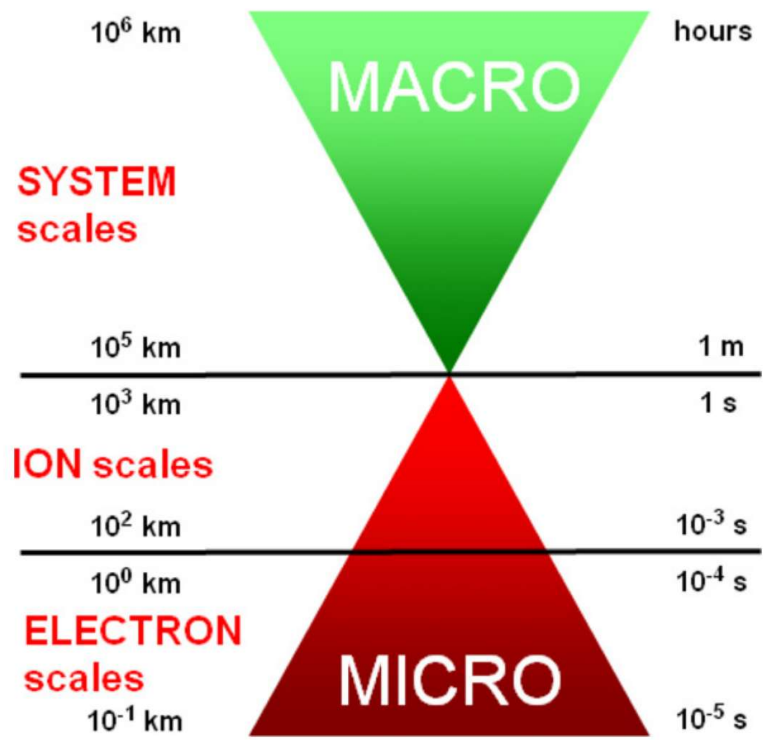
Current is used to solve Electromagnetic fields

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

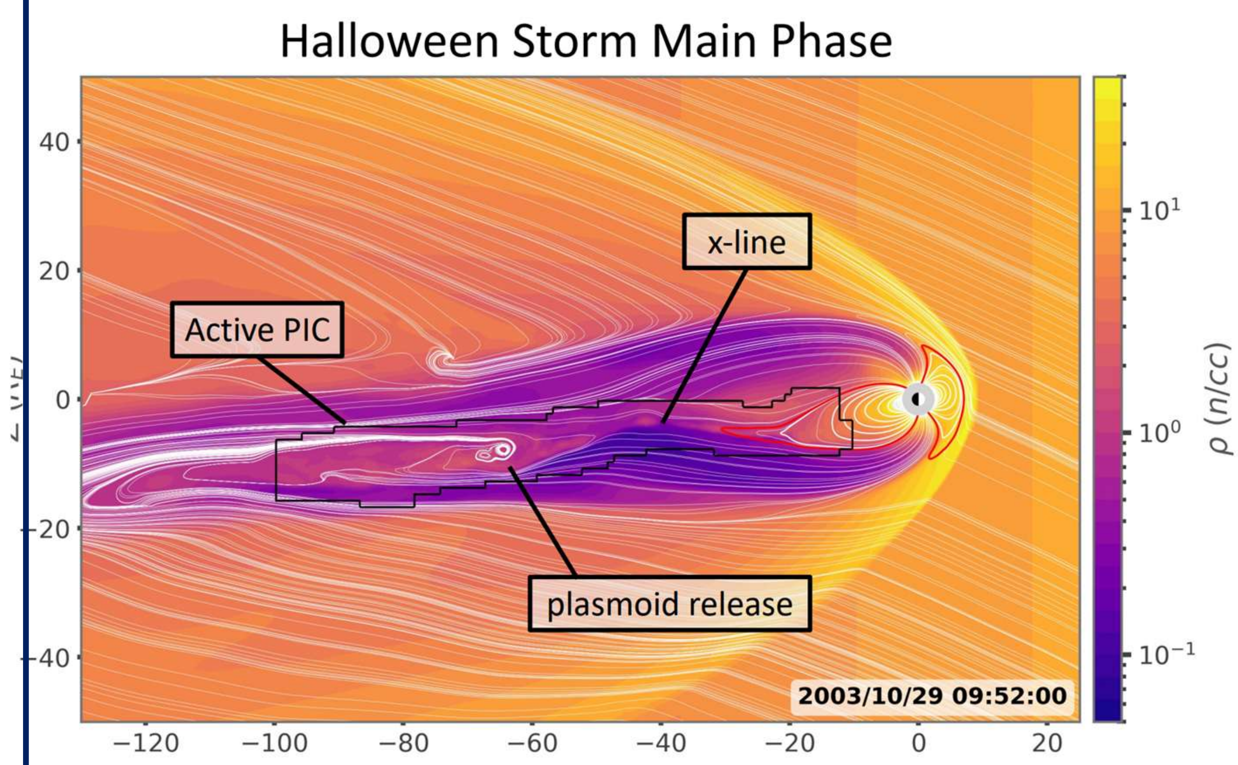
Scale Problem in Plasma Physics

- Plasma physics in space and laboratory involves processes at disparate temporal and spatial scales.
- Global scales (or system scales) include structures like the magnetosphere.
  - Spatial scale: Several million kilometes
  - Temporal scale : Several hours to days
- Ion scales:
  - Spatial scale: Few hundred kilomeres
  - Temporal scale: Milliseconds
- Electron scales:
  - Spatial scale: few hundred meters
  - Temporal scale: 10s of microseconds



MHD with Adaptively Embedded PIC (MHD-AEPIC)

- Uses ideal MHD or advanced models like Hall-MHD for the bulk of the plasma
- Kinetic simulations are used in localized regions
  - Particle in cell method (PIC)
- Very helpful if kinetic effects are important only in locallized regions
- Grid resolution of the PIC box is still fixed



Electron vs Ion scales

$$\text{ion inertial length} = c\left(\frac{\varepsilon_0 m_i}{n_i e^2}\right)^{\frac{1}{2}}$$

$$\text{electron skin depth} = c\left(\frac{\varepsilon_0 m_e}{n_e e^2}\right)^{\frac{1}{2}}$$

$$\frac{m_i}{m_e} = 1836$$

$$\frac{\text{ion inertial length}}{\text{electron skin depth}} \propto \left(\frac{m_i}{m_e}\right)^{\frac{1}{2}} = 43$$

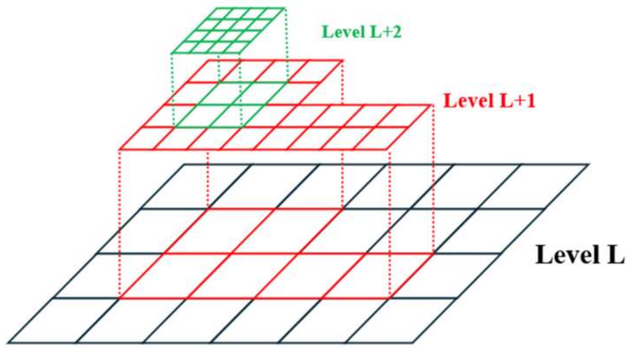
We use: $\frac{m_i}{m_e} = 100$

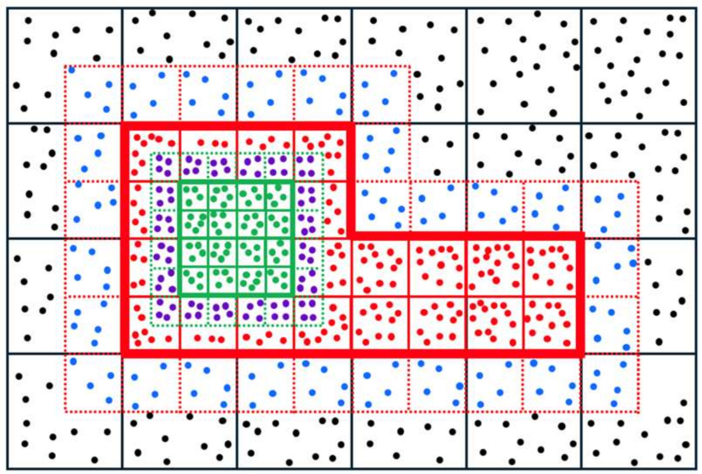
So: $\frac{\text{ion inertial length}}{\text{electron skin depth}} = 10$

In 3D, resolving electrons scale physics is $10\text{x}10^3 = 10000$ times more expensive than resolving ion scale physics

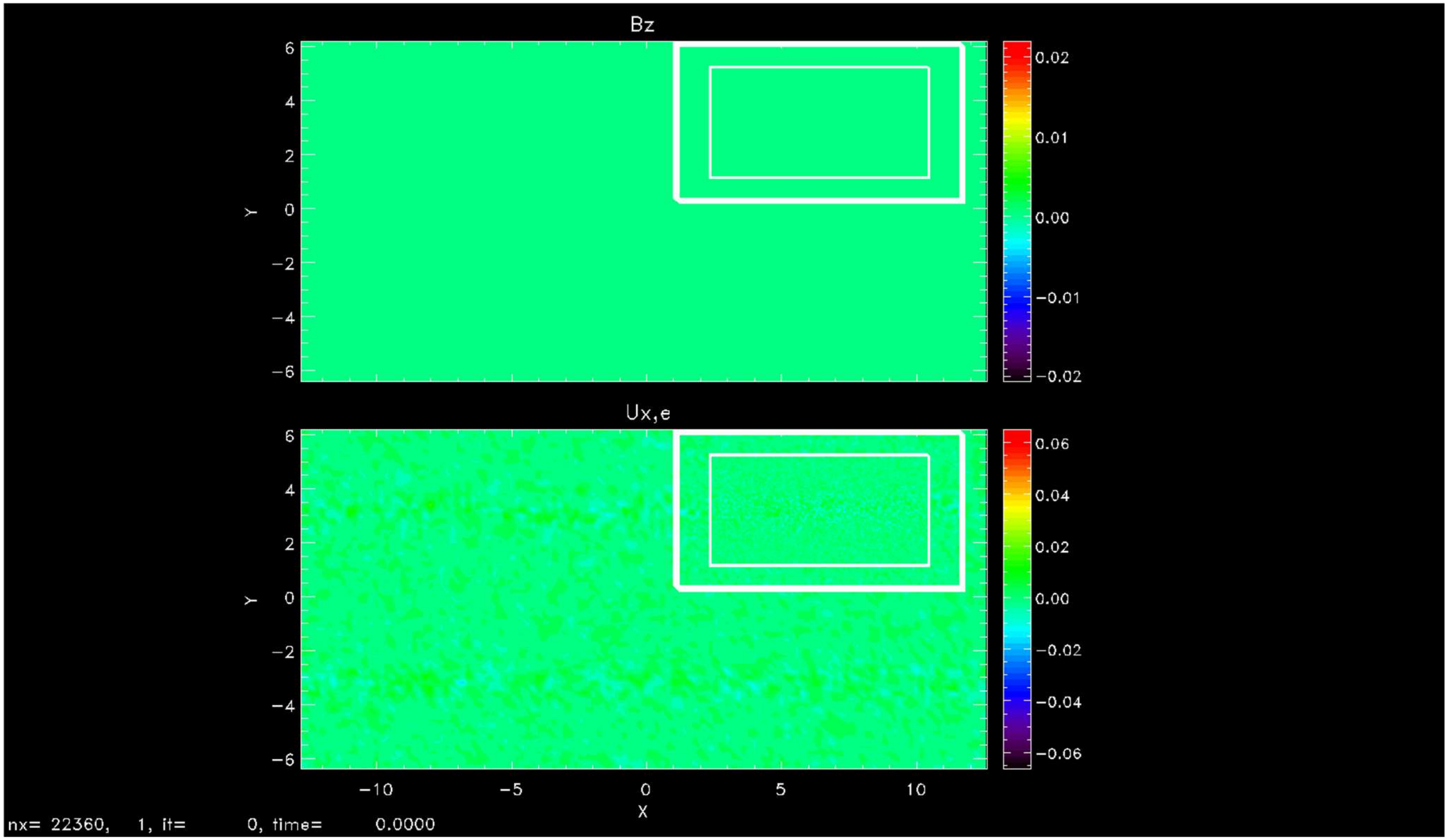
AMR PIC

- The PIC region has a refined region to resolve electron scales very close to the reconnection sites
- Ion scales are resolved on the coarse grid
- Electron scales are resolved on the fine grid
- Refined region can be any shape but cannot exist without a coarse region underneath
- Multi-level AMR PIC
- Different refinement ratios

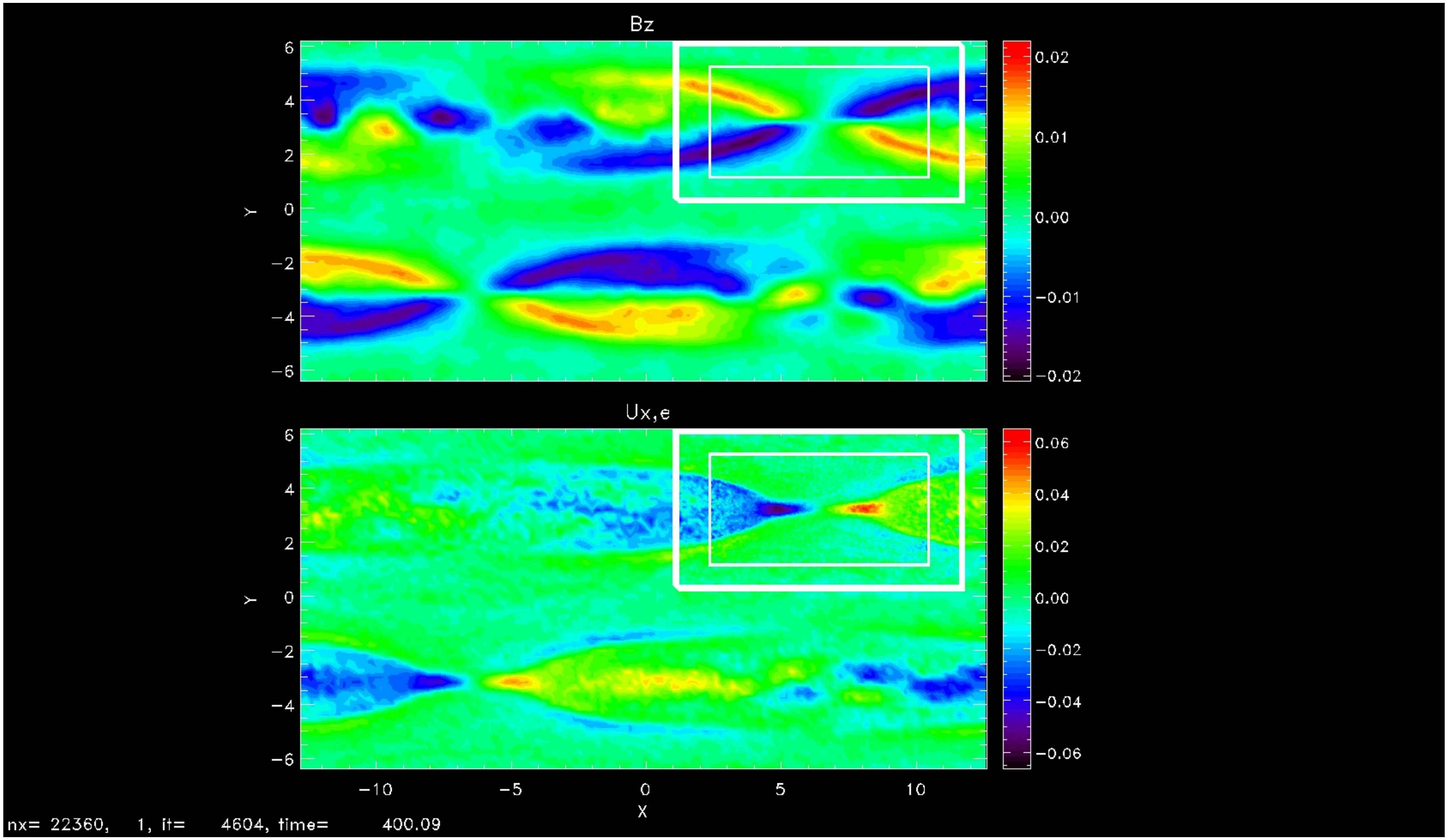




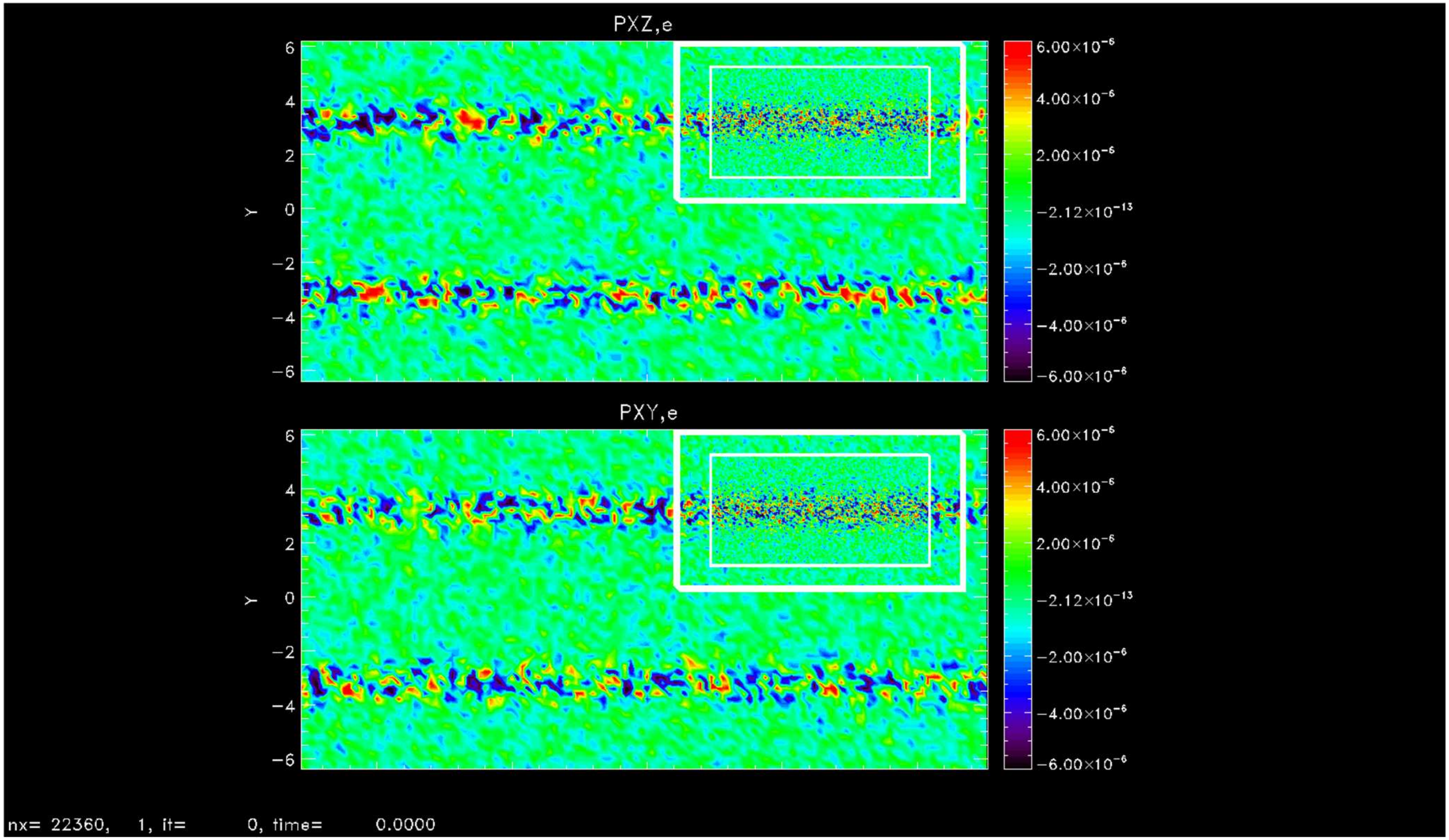
Double Current Sheet Reconnection



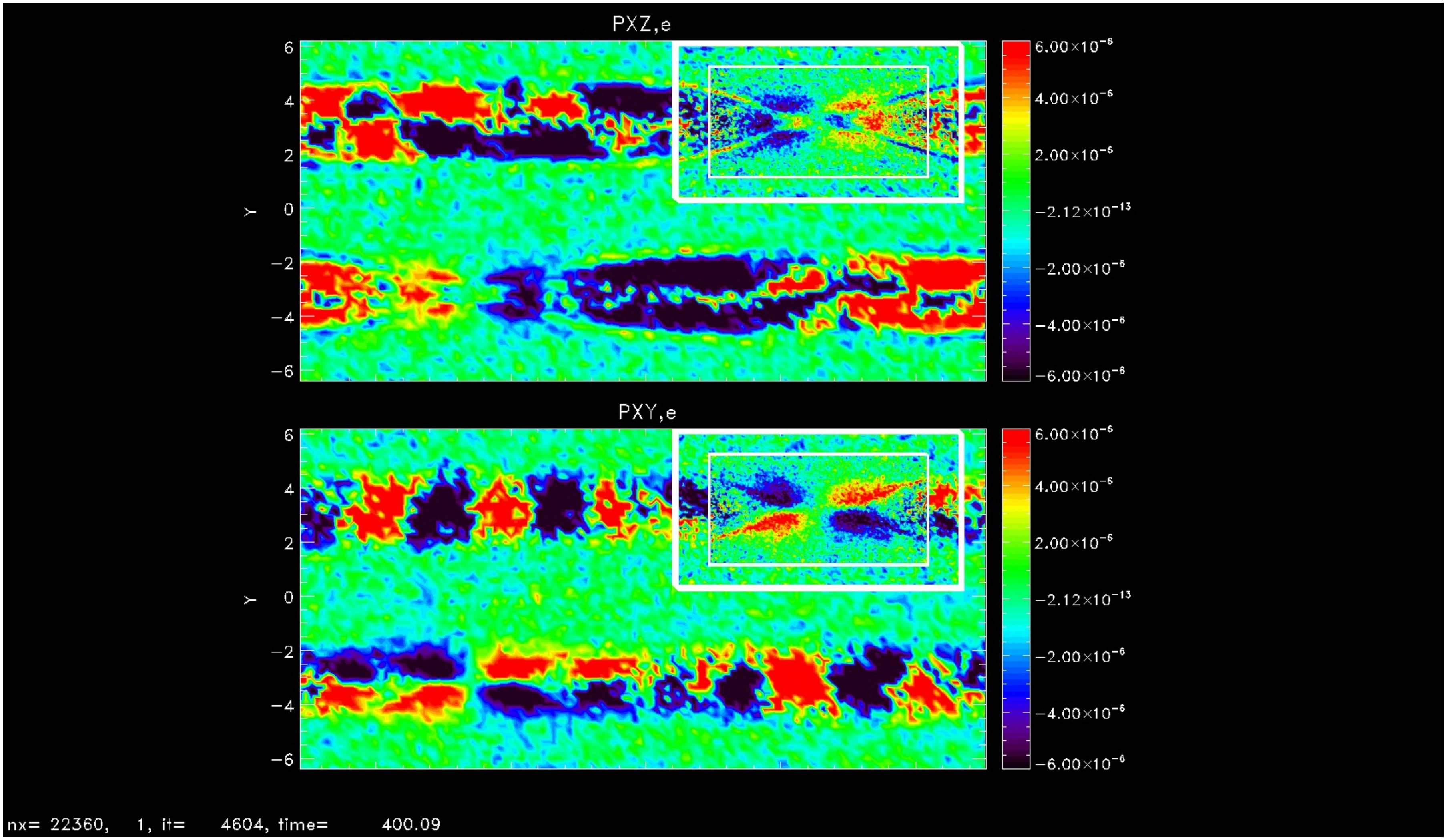
Double Current Sheet Reconnection



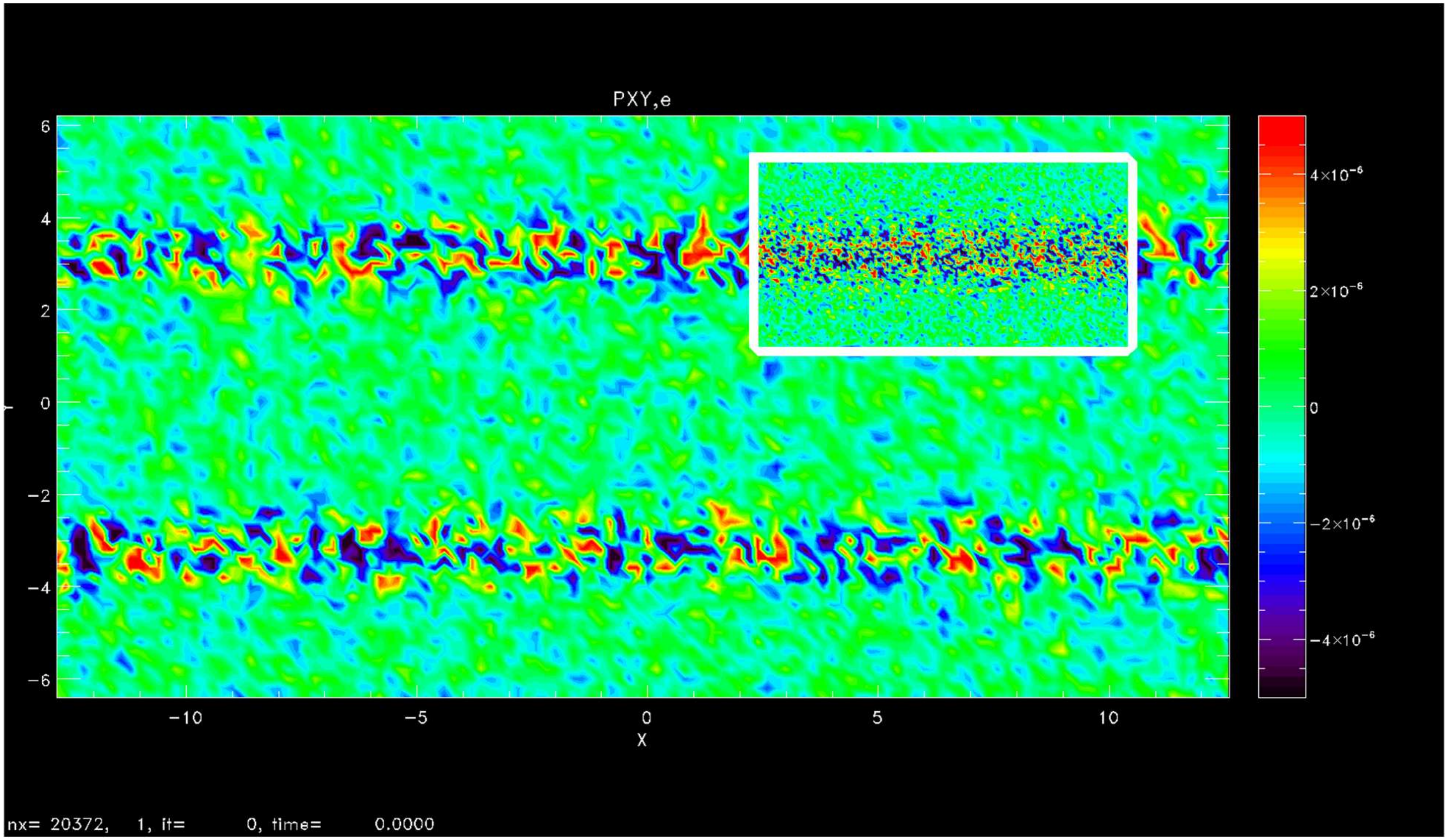
Double Current Sheet Reconnection



Double Current Sheet Reconnection



Dynamic AMR


PXY,e
6
4
2
0
−2
−4
−6
−10
−5
0
5
10
X
4×10⁻⁶
2×10⁻⁶
0
−2×10⁻⁶
−4×10⁻⁶
nx= 20372, 1, it= 0, time= 0.0000

Gauss Law Cleaning

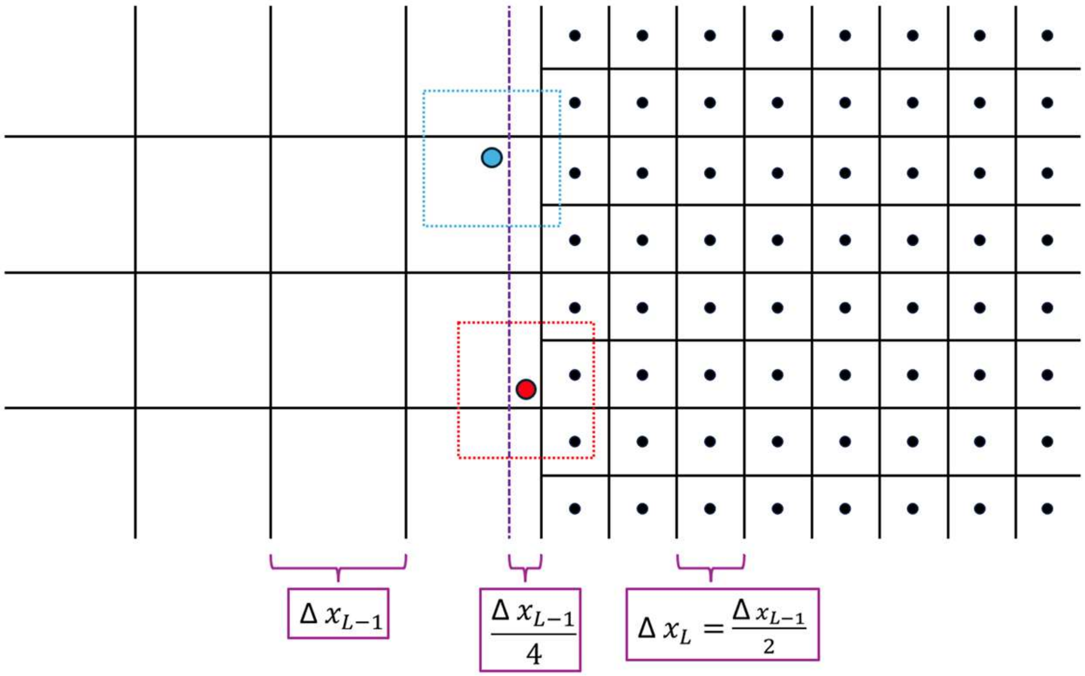
- Gauss's Law:

$$\nabla \cdot E = 4 \pi \rho_c$$

- Error in Gauss's Law slowly builds up in PIC runs

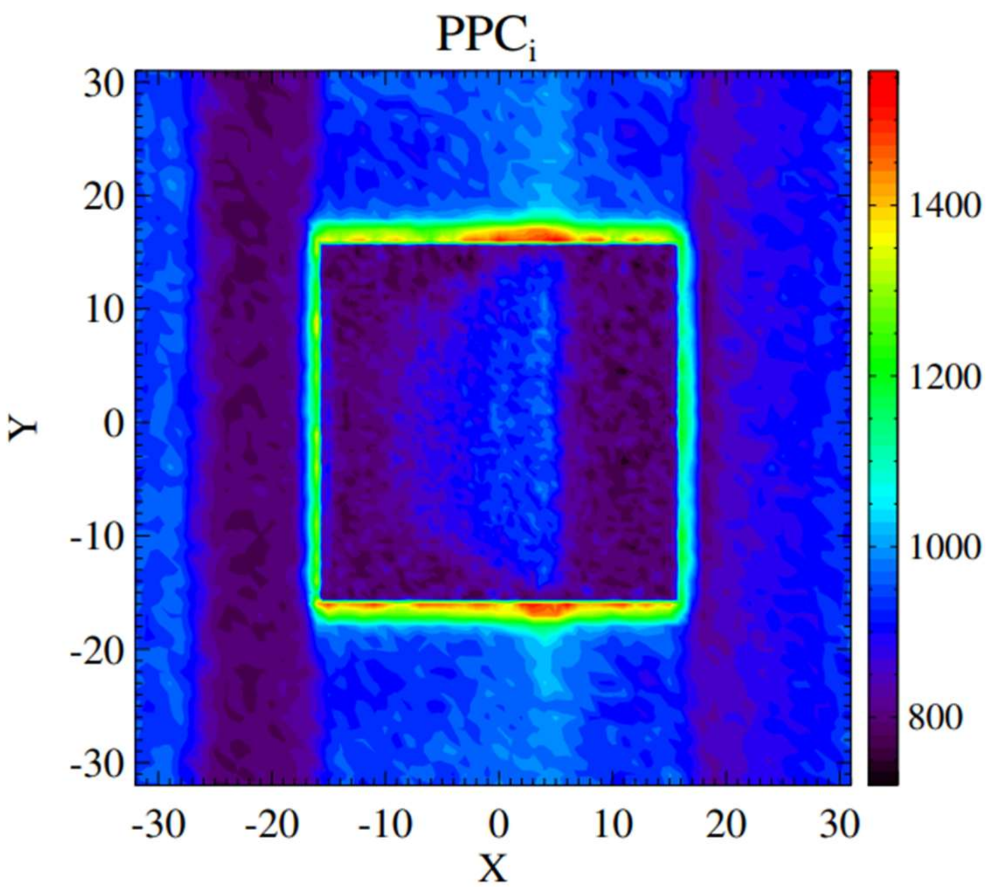
- This error is cleaned by particle displacement instead of field adjustment

- Gauss's Law error can be cleaned perfectly around refinement changes by carefully selecting which particles to move



Particle Merging/Splitting

- Number of particles per cell (PPC) is kept close to a target number
- Near constant PPC is essential for effective load balancing
- Particles are split in regions of low PPC
- Particles are merged in regions of high PPC – mass, momentum and energy are conserved

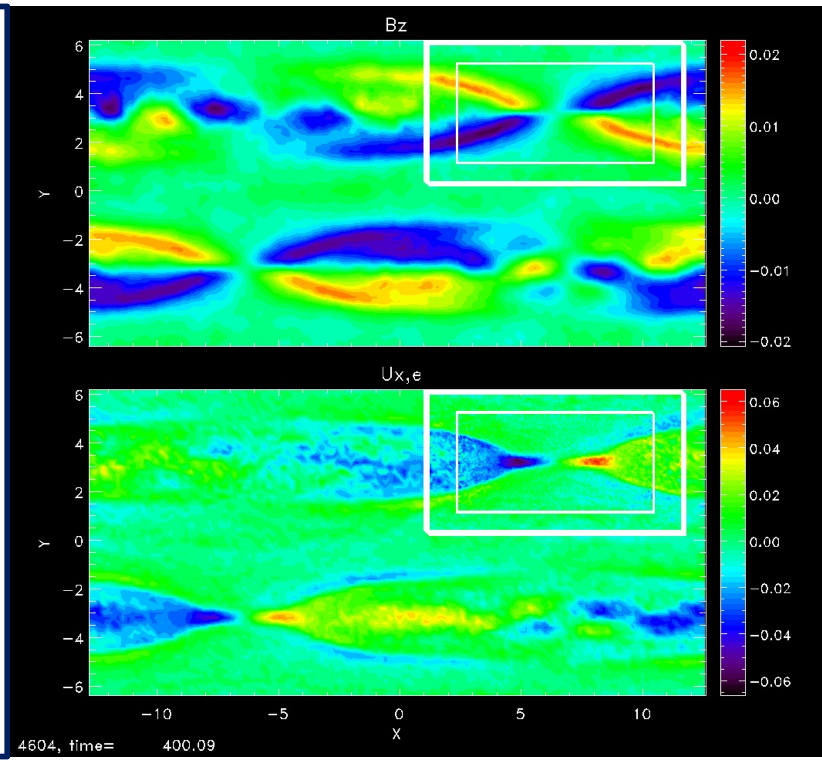


Speed Up

- Speed-up =

$$\frac{Time\ taken\ by\ uniform\ grid\ run\ with\ high\ resolution}{Time\ taken\ by\ AMR\ run}$$

- The refined region covers about 10% of the total area
- Theoretical expected speed-up is about 5.4 times
- Actual speed up is about 4.9 times



Conclusion

- This is the first true AMR implemented into a semi-implicit PIC model
- Previous multi-level multi-domain (MLMD) uses independent particles at different levels
- Explicit PIC with AMR (e.g. WARPX) is limited by stability constraints: cannot take full advantage of AMR
- The AMR PIC method has been developed and tested
- The manuscript has been submitted to “Computer Physics Communications” journal
- The AMR PIC model will be used in 3D MHD-AEPIC global magnetospheric simulations to resolve electron-scale physics close to reconnection sites while only resolving ion-scale physics further away from the reconnection sites
- MHD-AEPIC combined with AMR PIC will enable us to resolve all scales ranging from global scales to electron scales in global magnetospheric simulations.

Thank You.