

PIC and MHD Simulations of Magnetic Field Amplification

Weiqun Zhang (NYU)

w/ MacFadyen, Zrake & Gruzinov (NYU)

Outline

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- **Gamma-Ray Bursts**

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- Collisionless Shocks

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- PIC Simulations
- MHD Simulations
- Discussions

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 - Some are probably the mergers of compact objects (black holes and neutron stars)

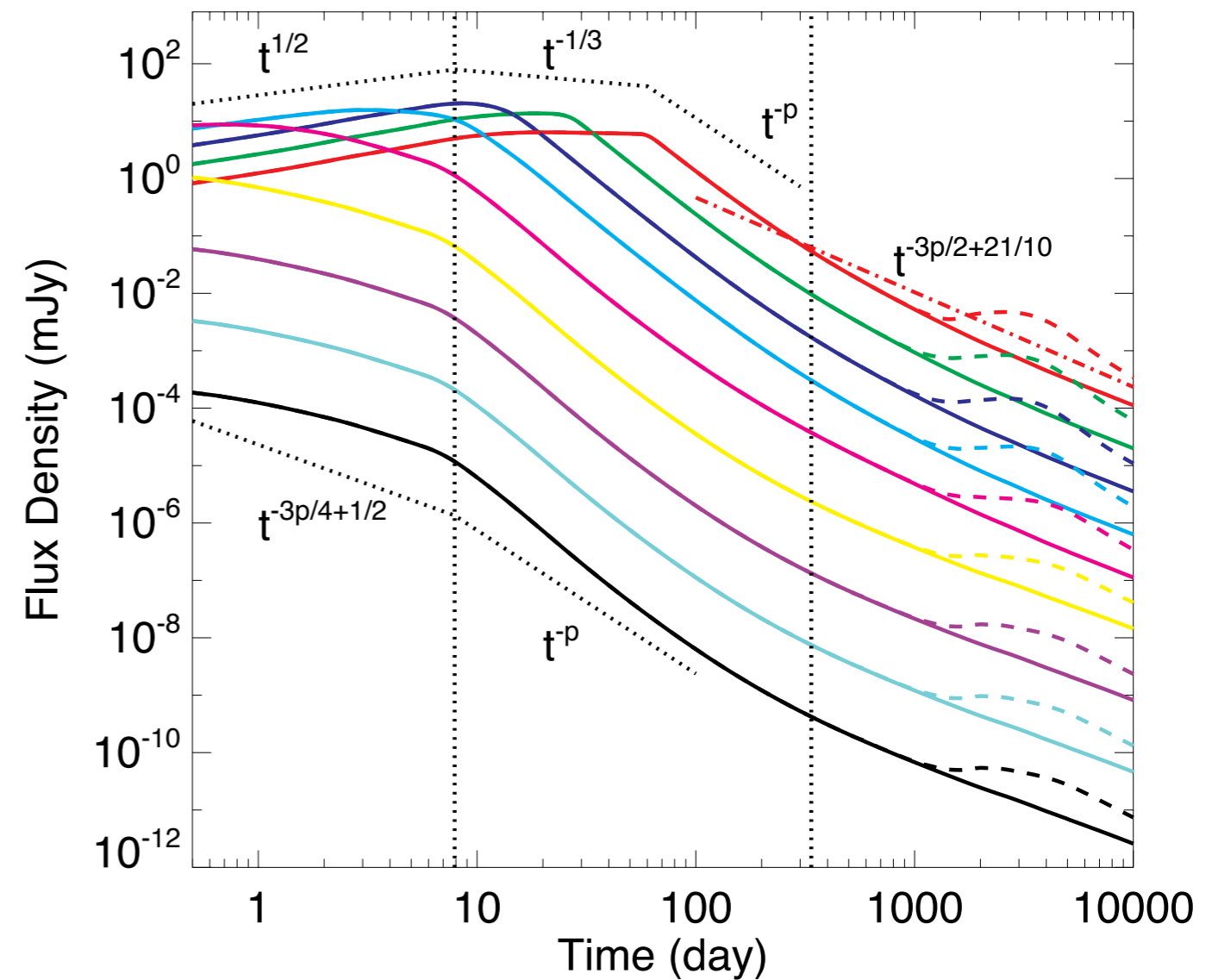
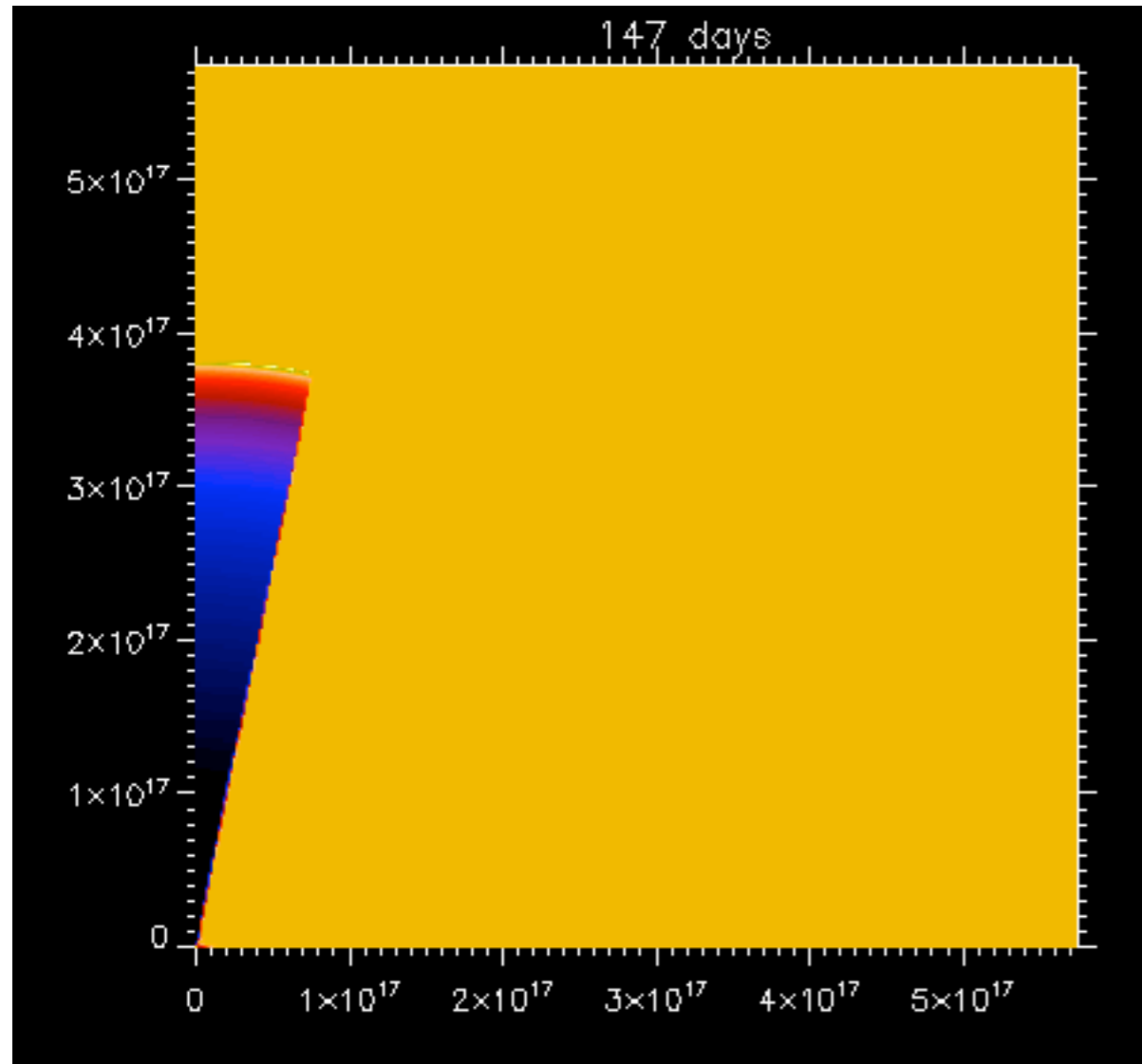
Artist's Conception of Collapsar



Credit: NASA / SkyWorks Digital

AMR Simulations of GRB Outflows

Afterglow Lightcurves



Zhang & MacFadyen (2009)

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Synchrotron radiation

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- **Magnetic field:** $\epsilon_B \sim 10^{-3} - 10^{-1}$
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Collisionless Shock!

Relativistic Collisionless Shocks

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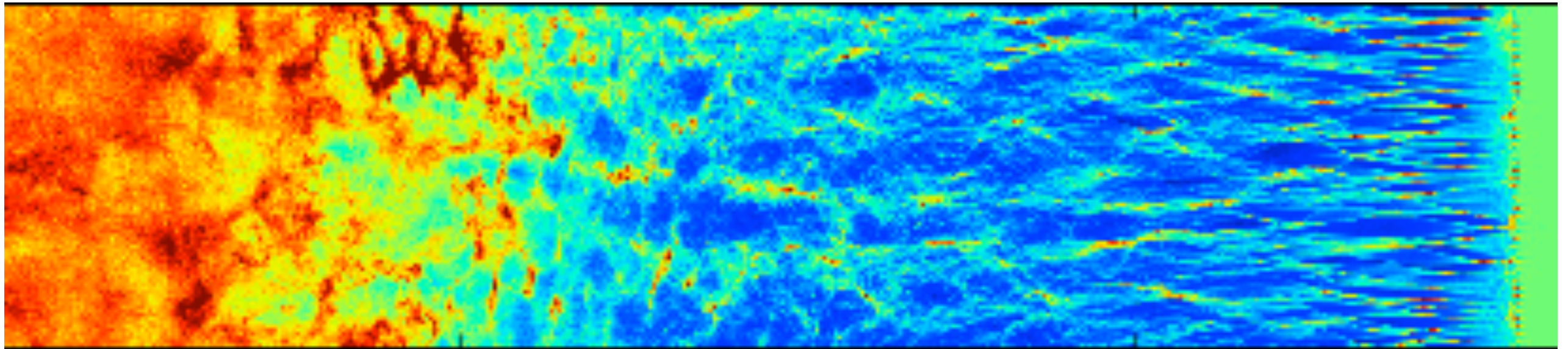
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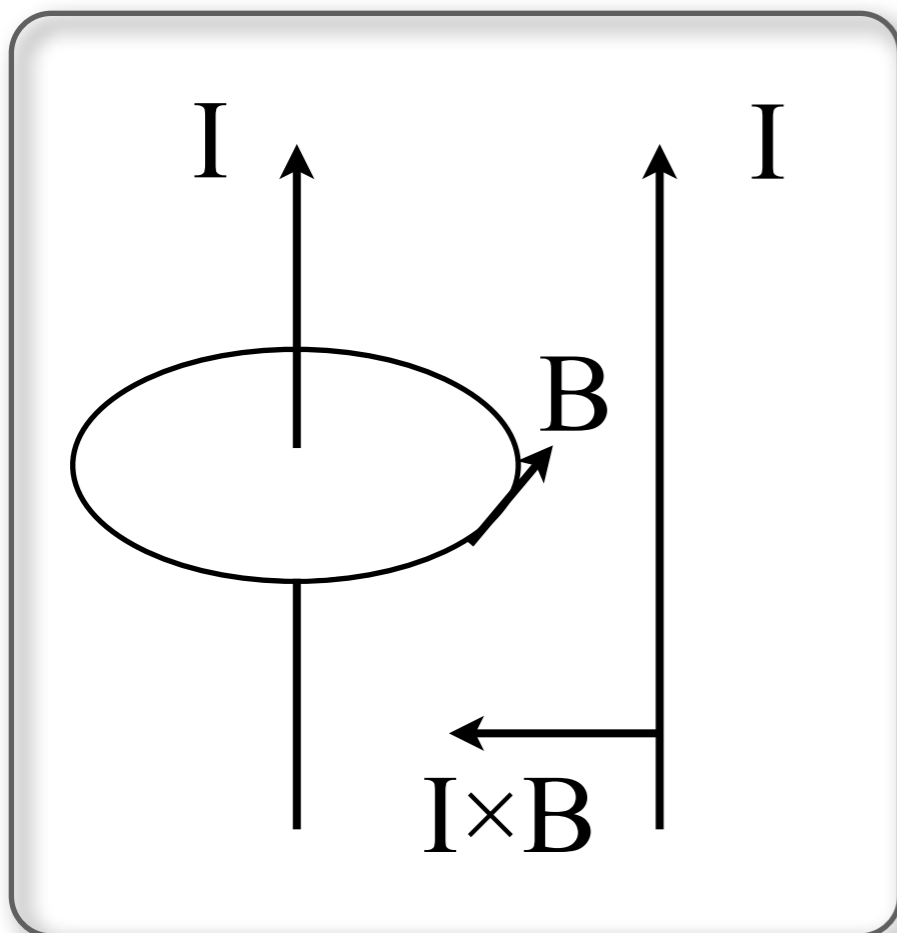


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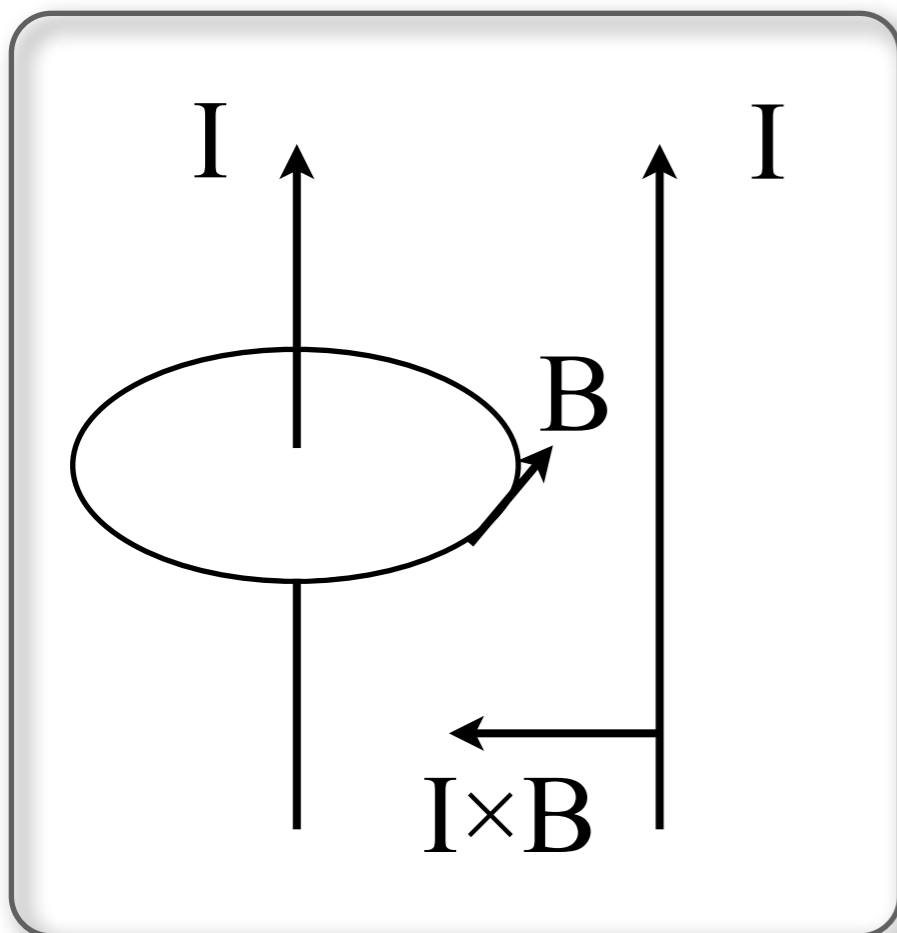
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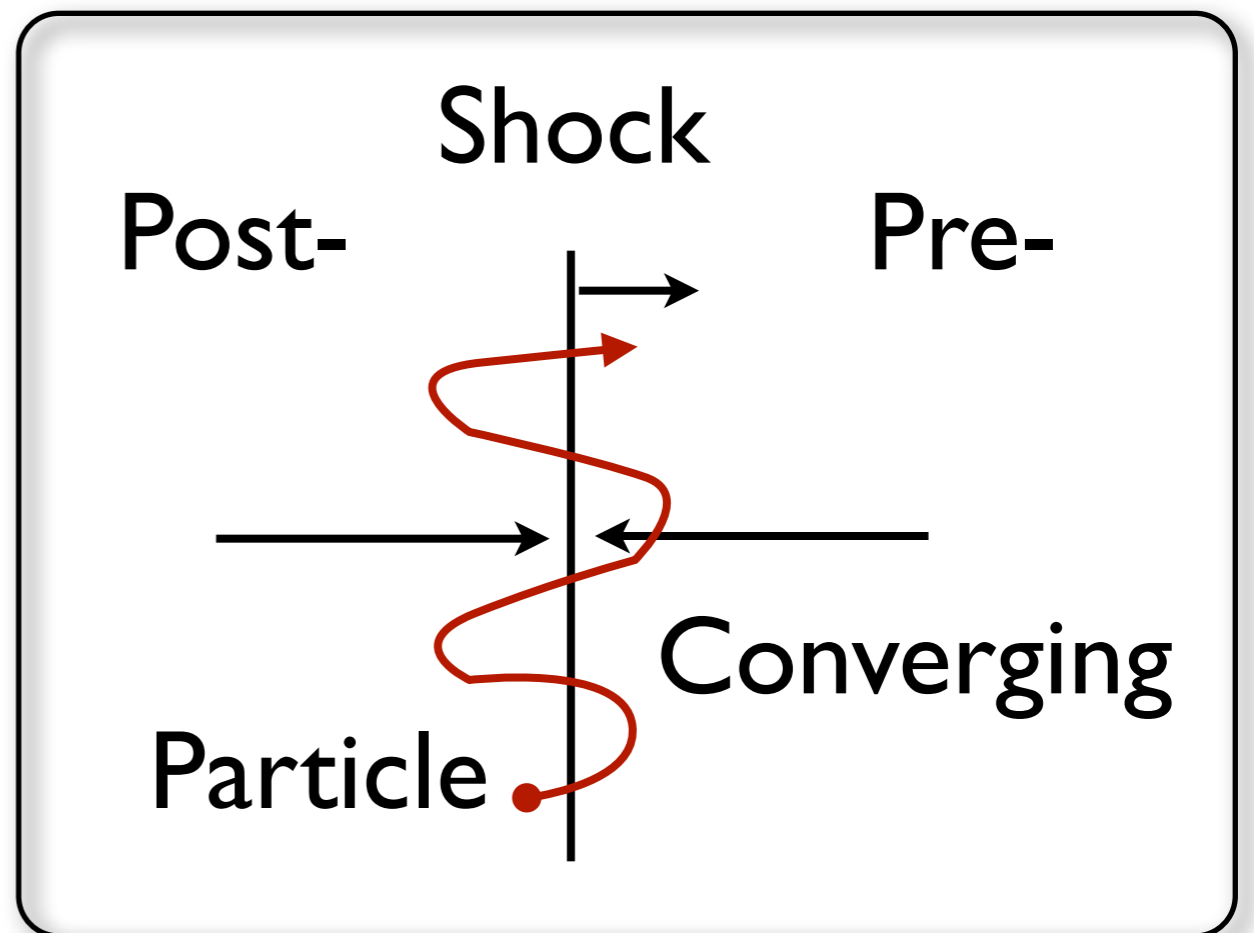
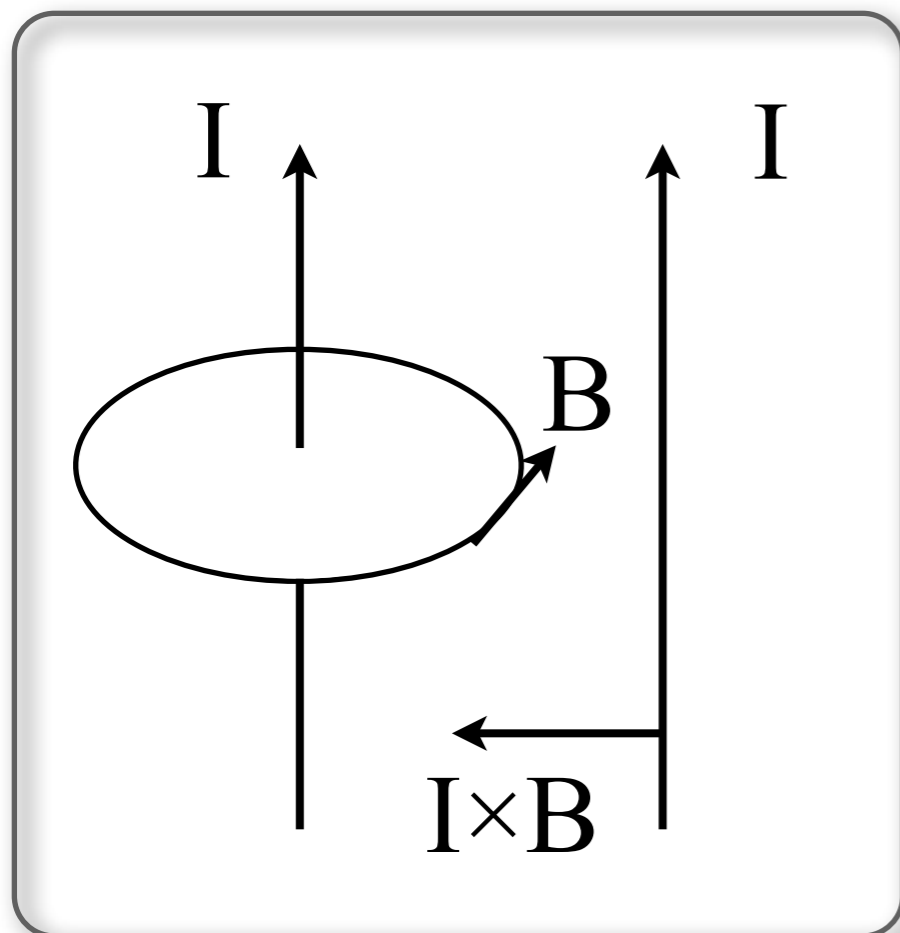
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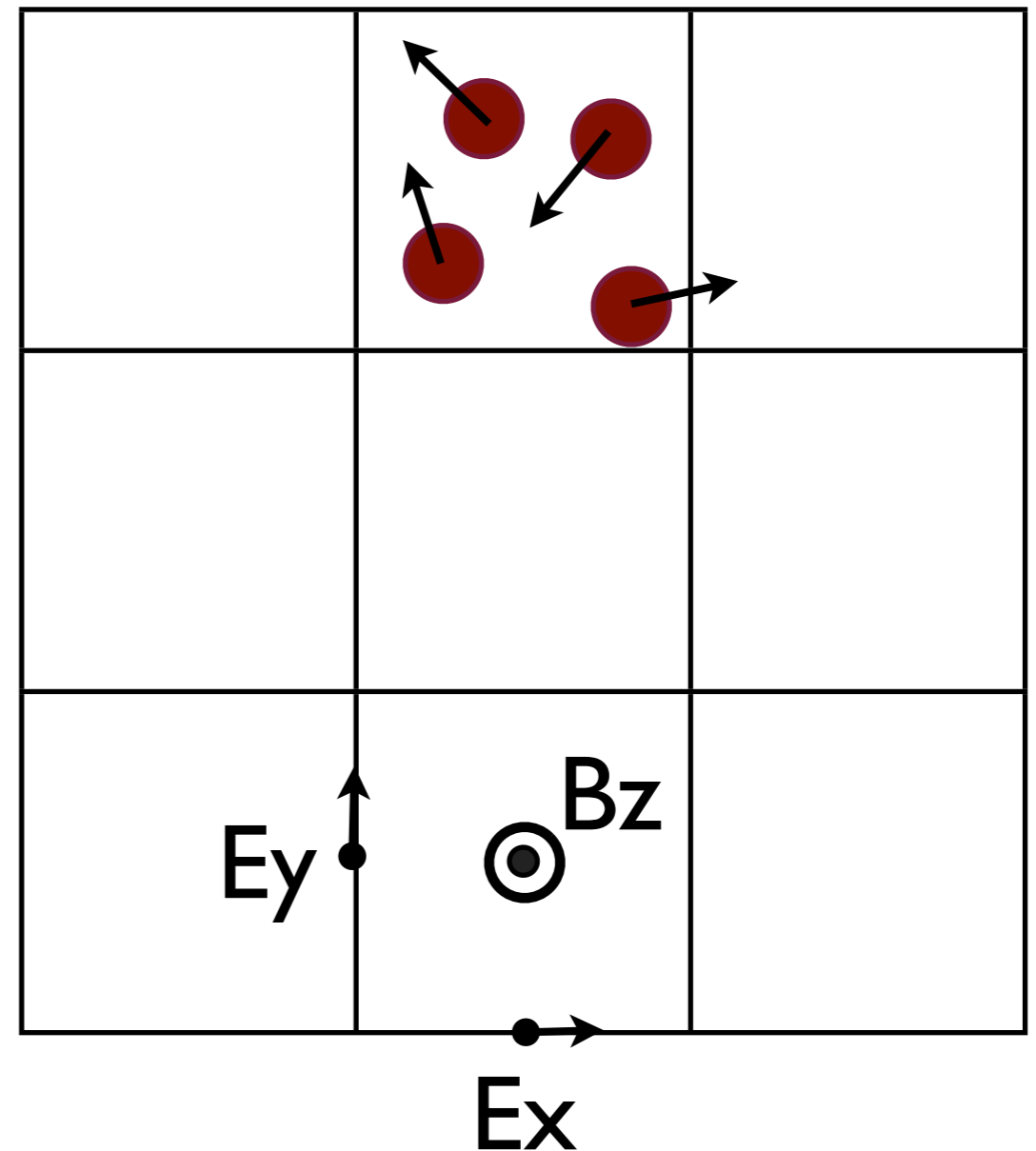
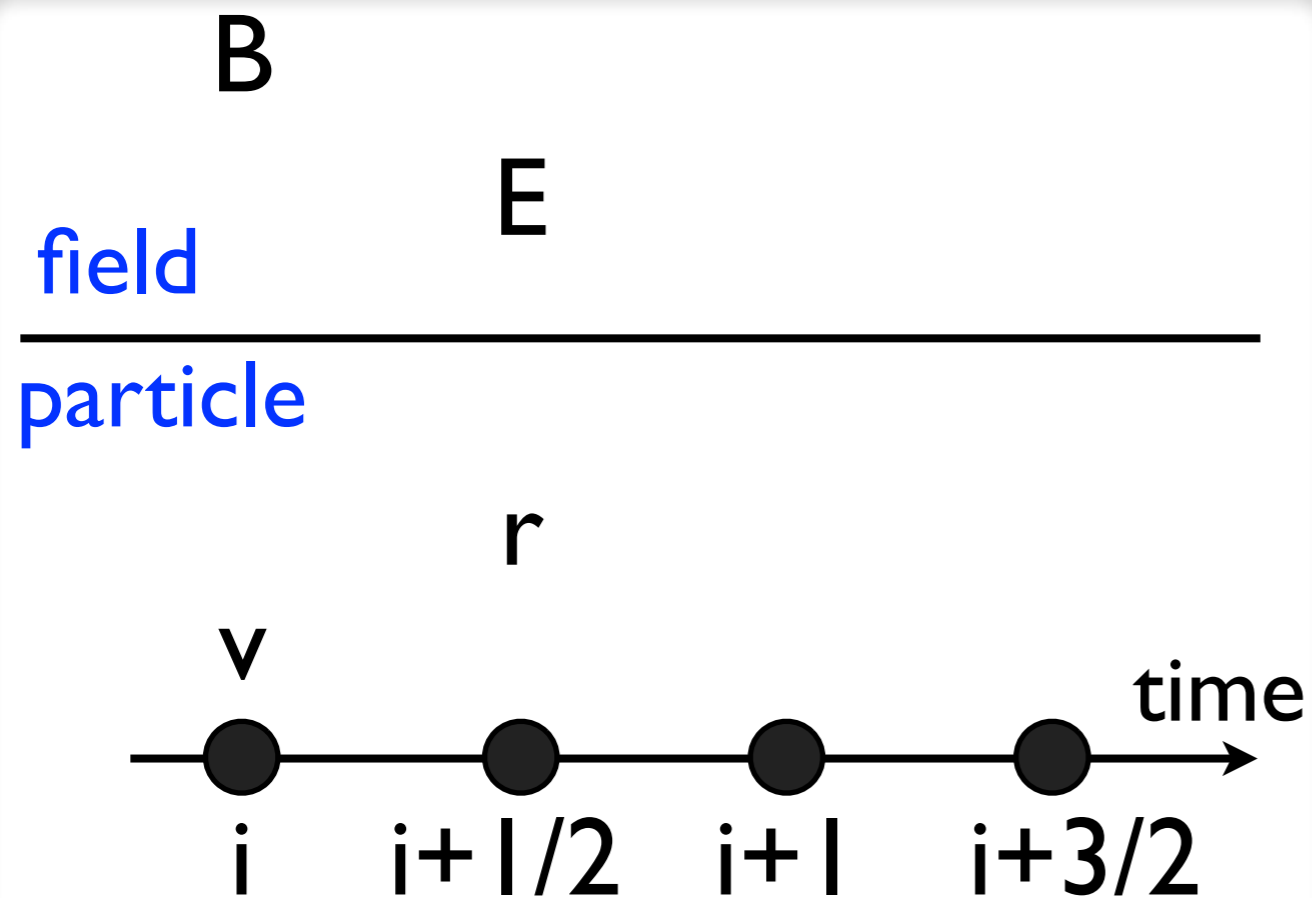


Particle-in-Cell (PIC)

$$\partial \mathbf{E} / \partial t = \nabla \times \mathbf{B} - \mathbf{j}$$

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

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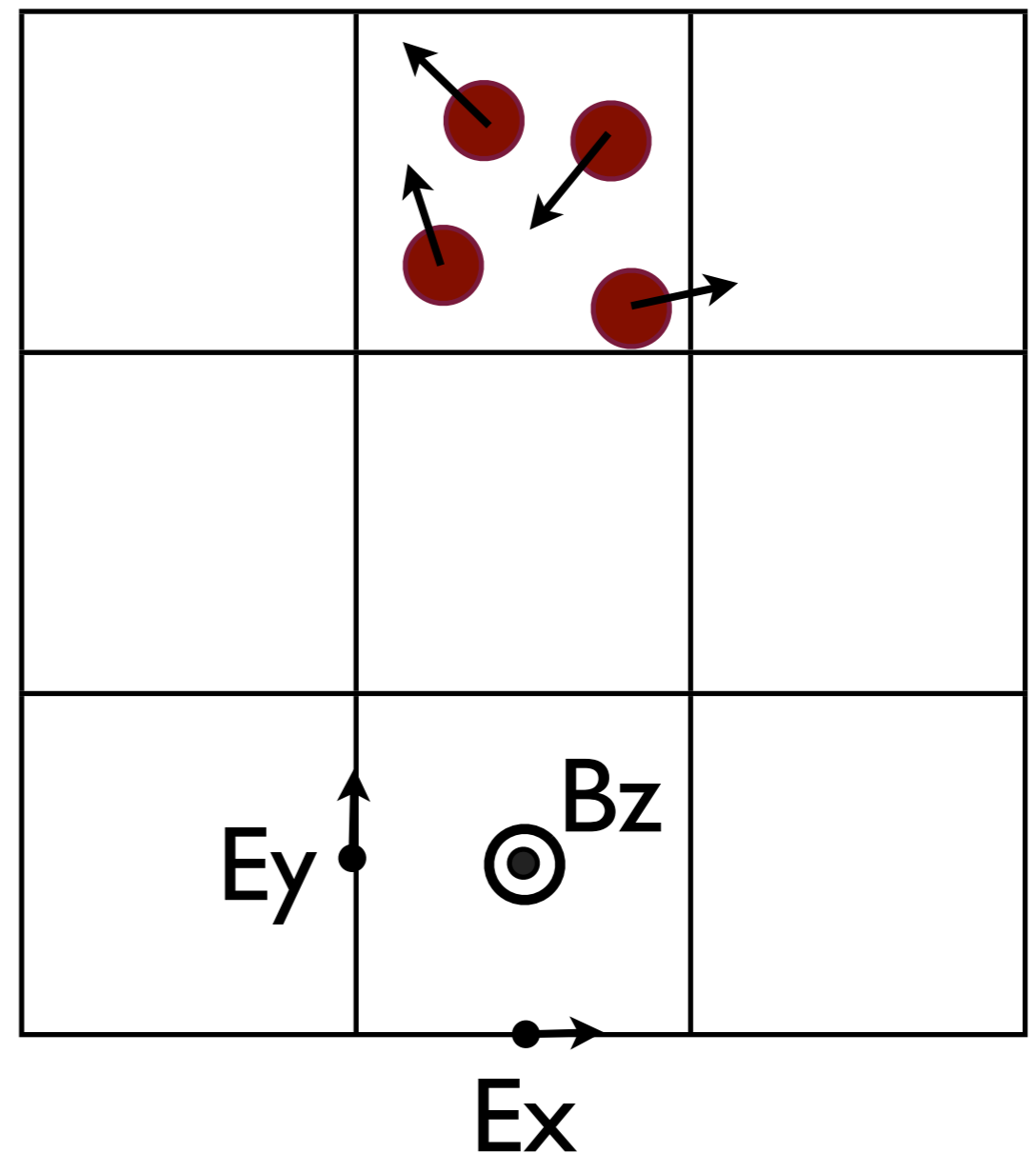
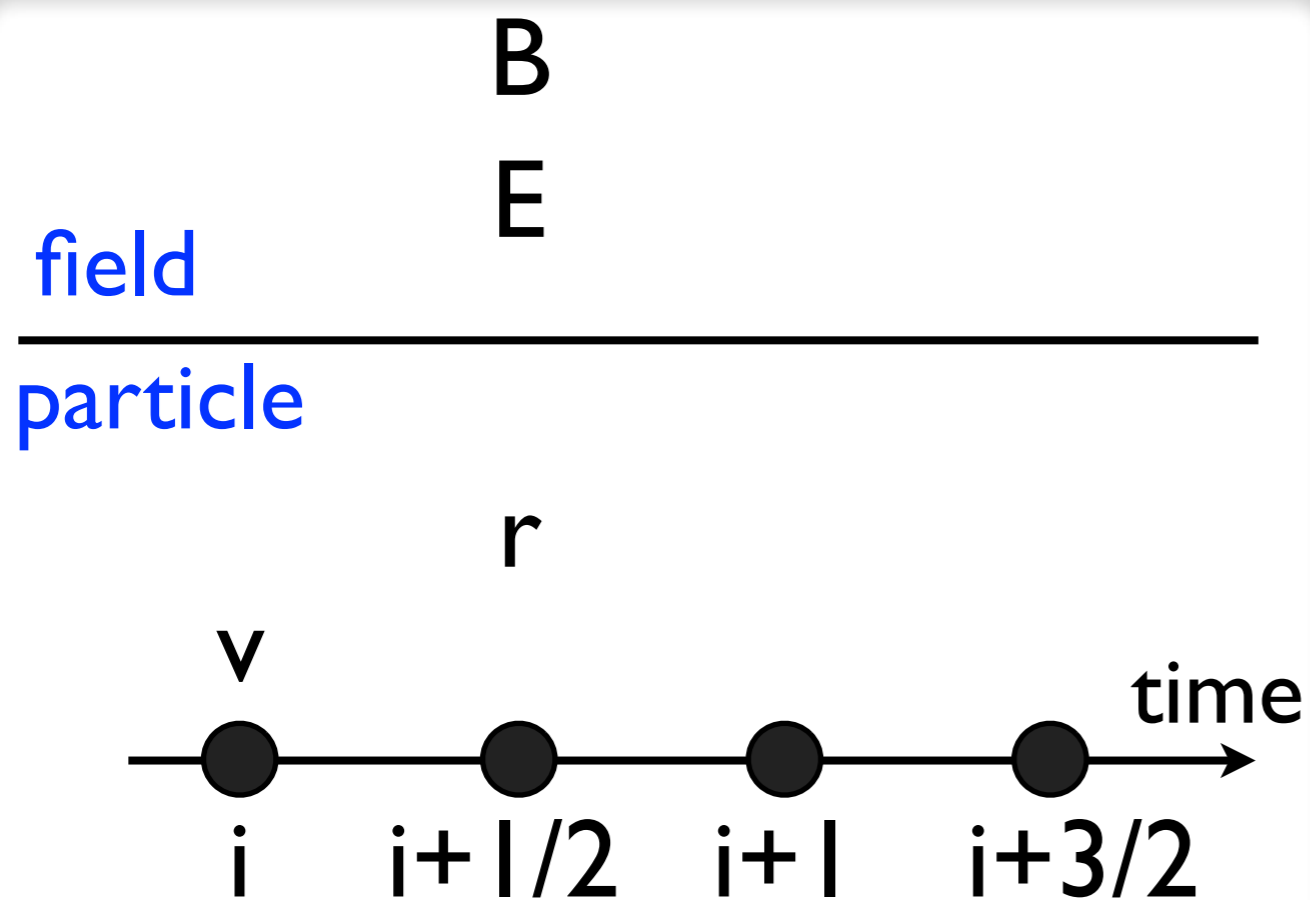
TRISTAN (Buneman)

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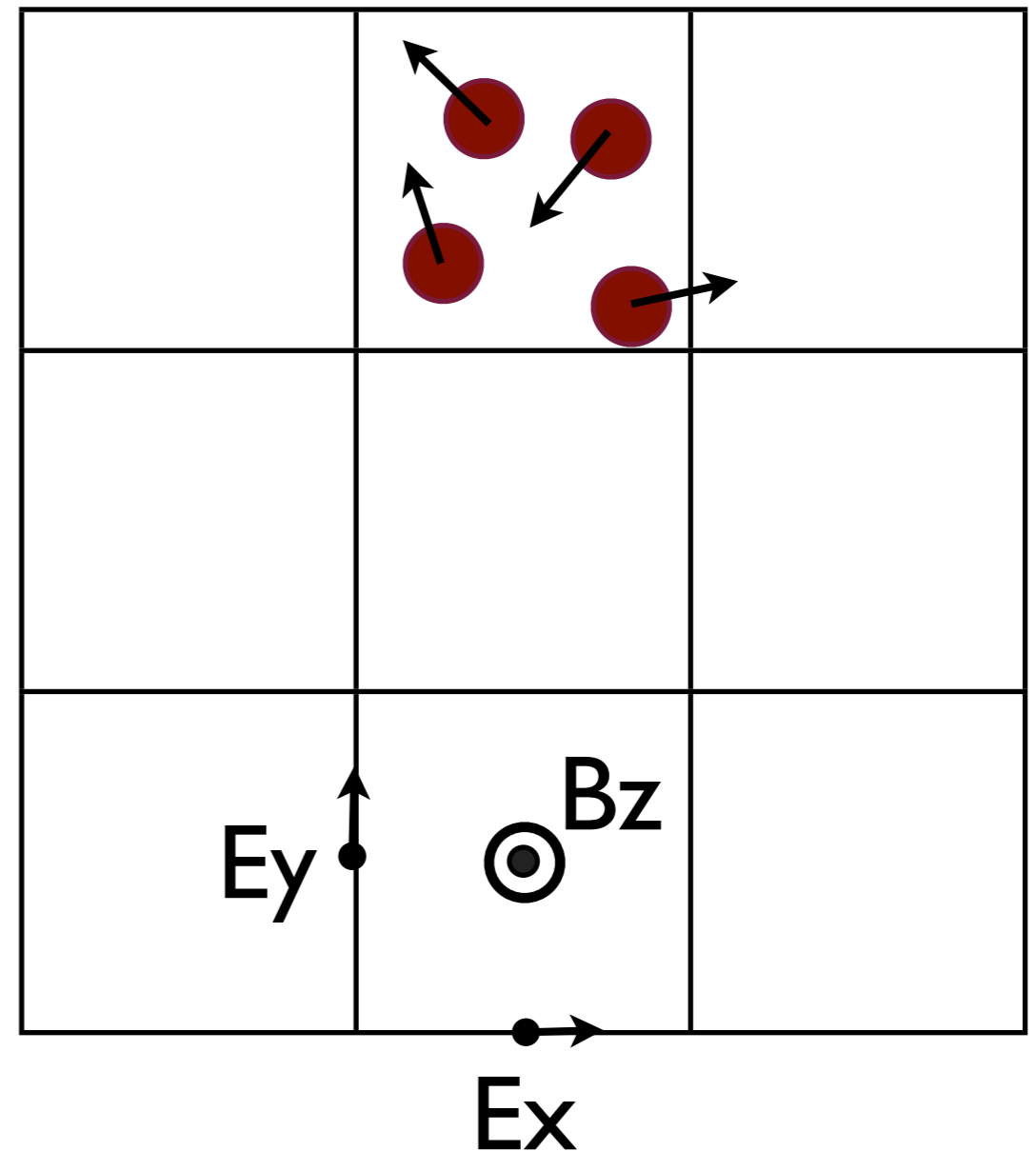
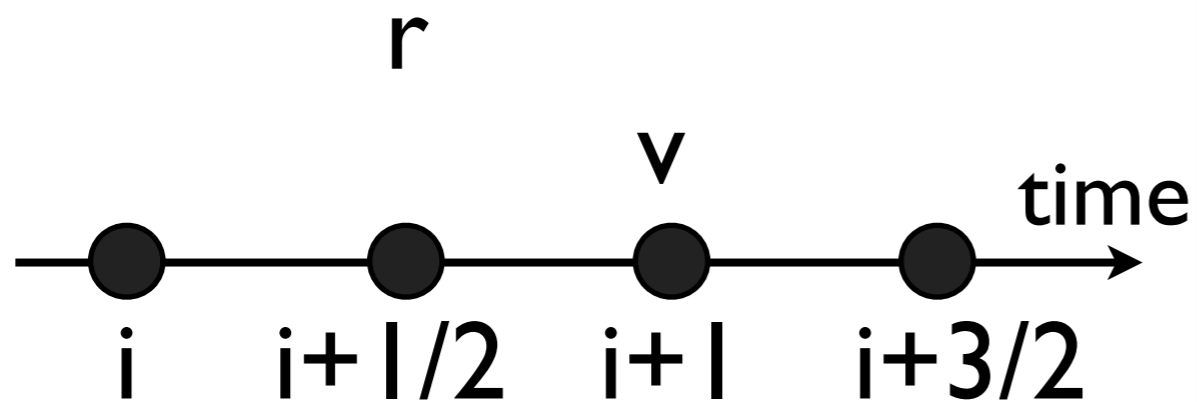
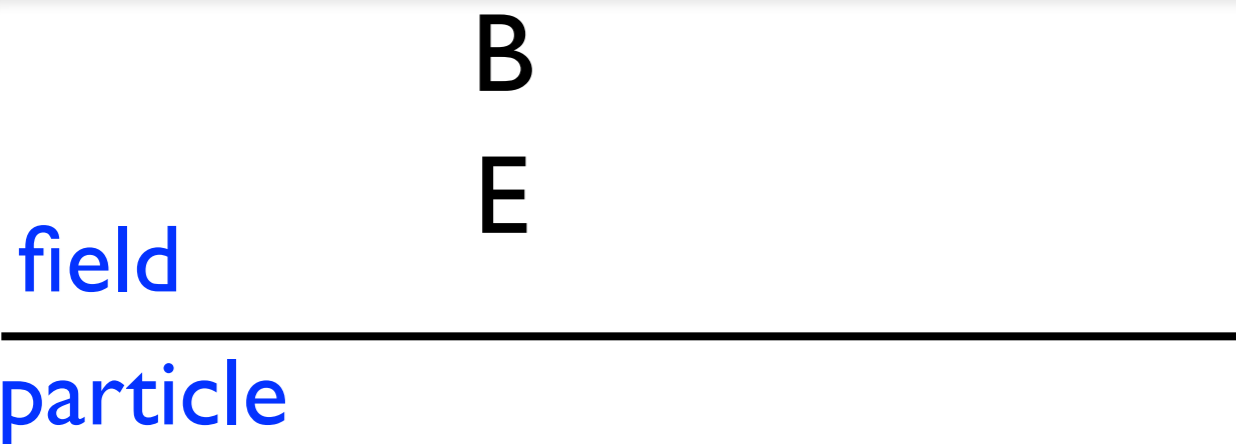
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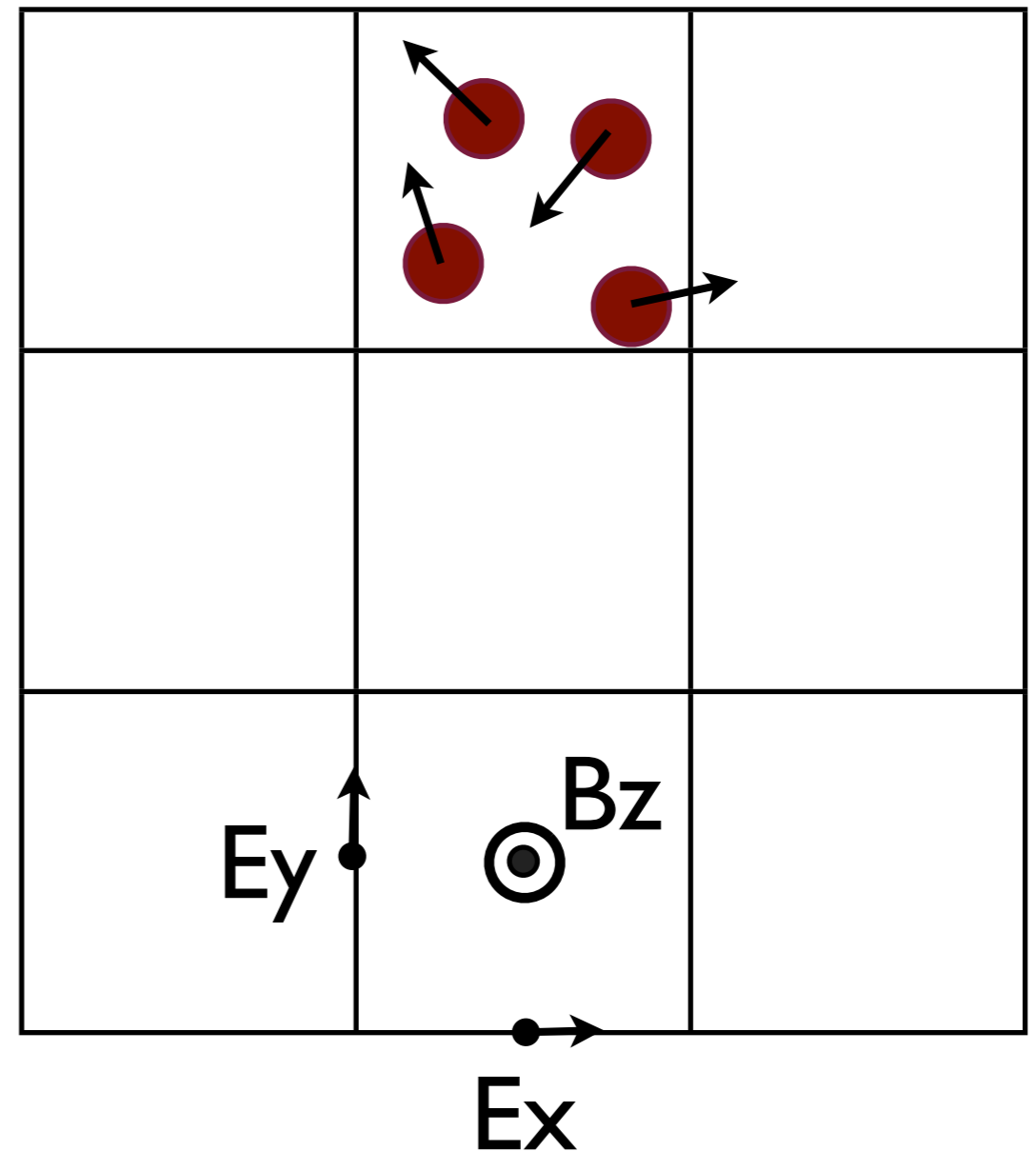
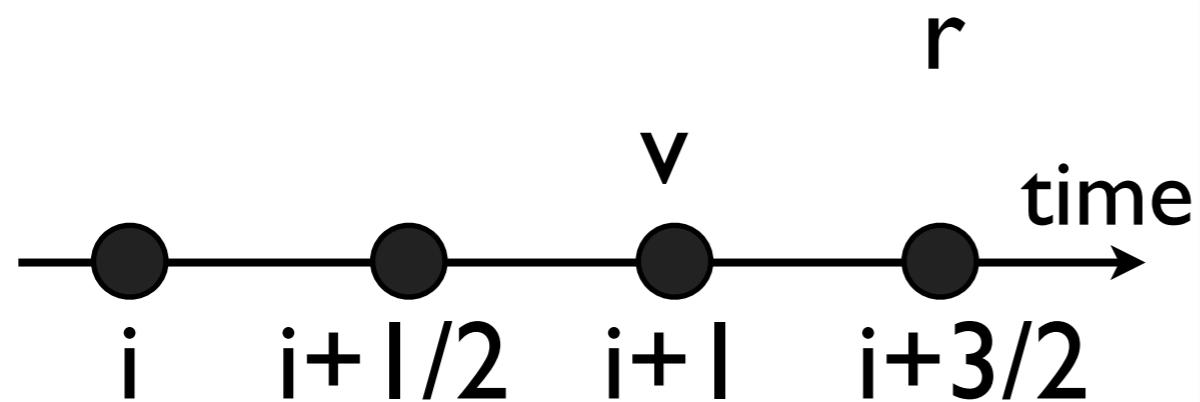
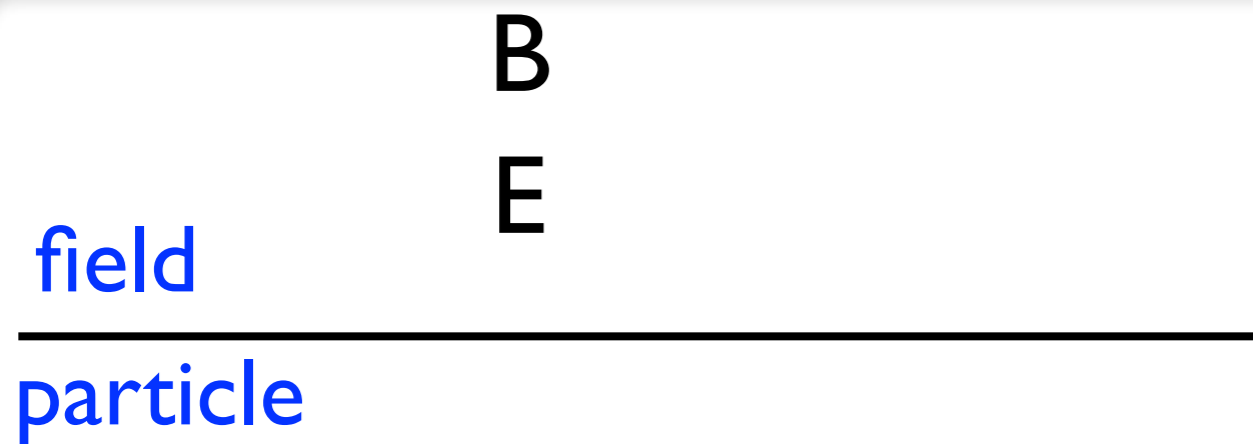
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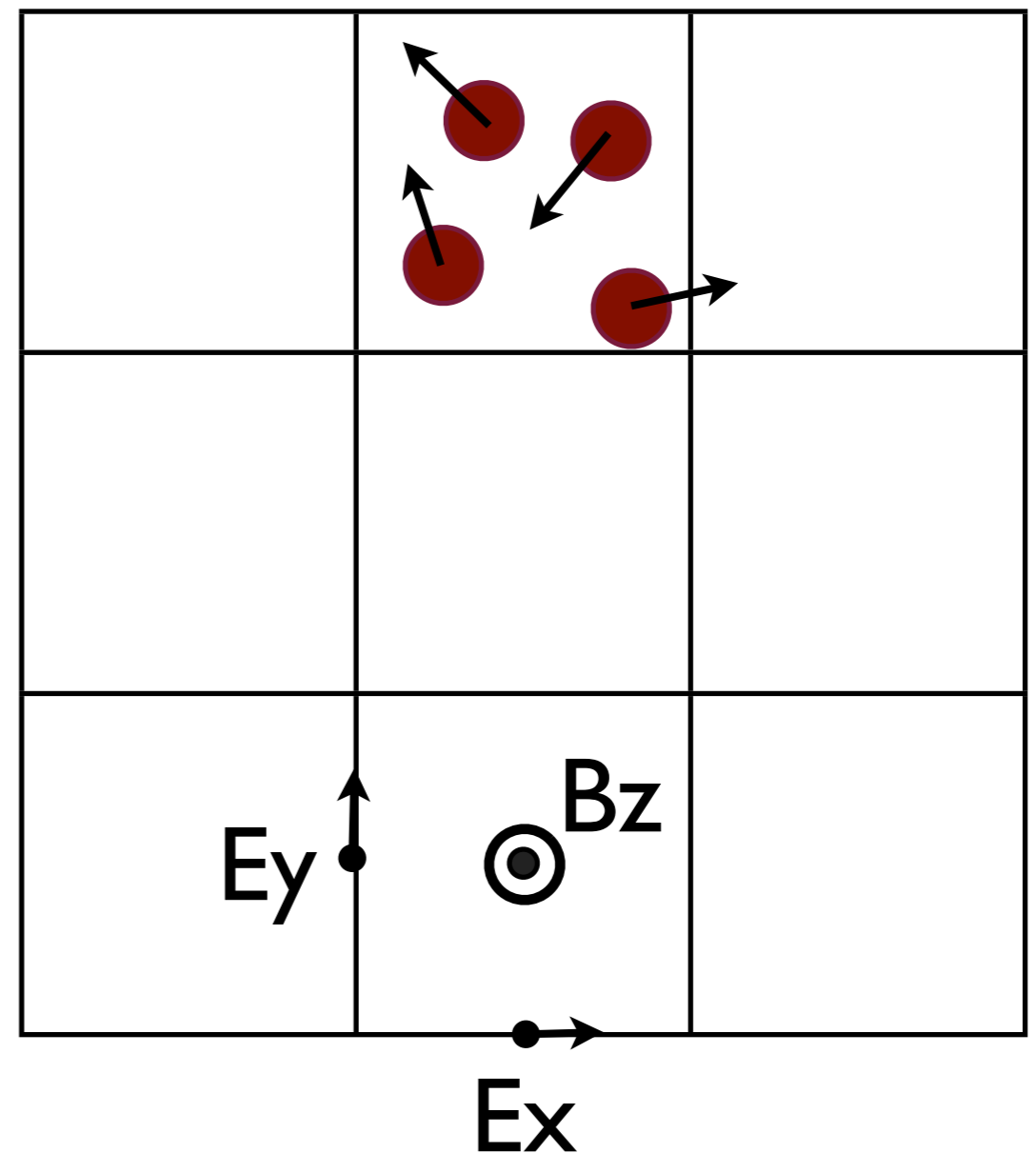
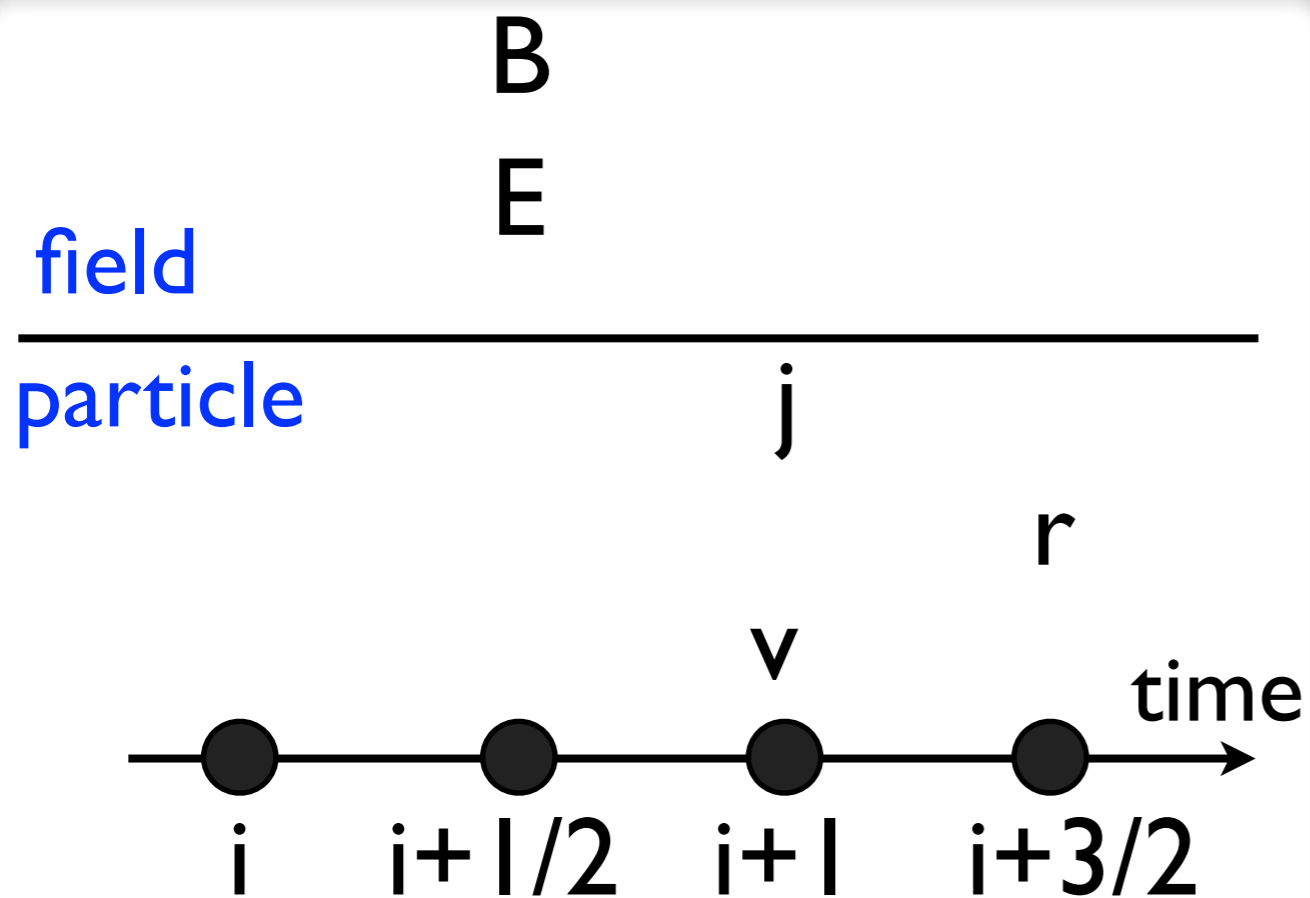
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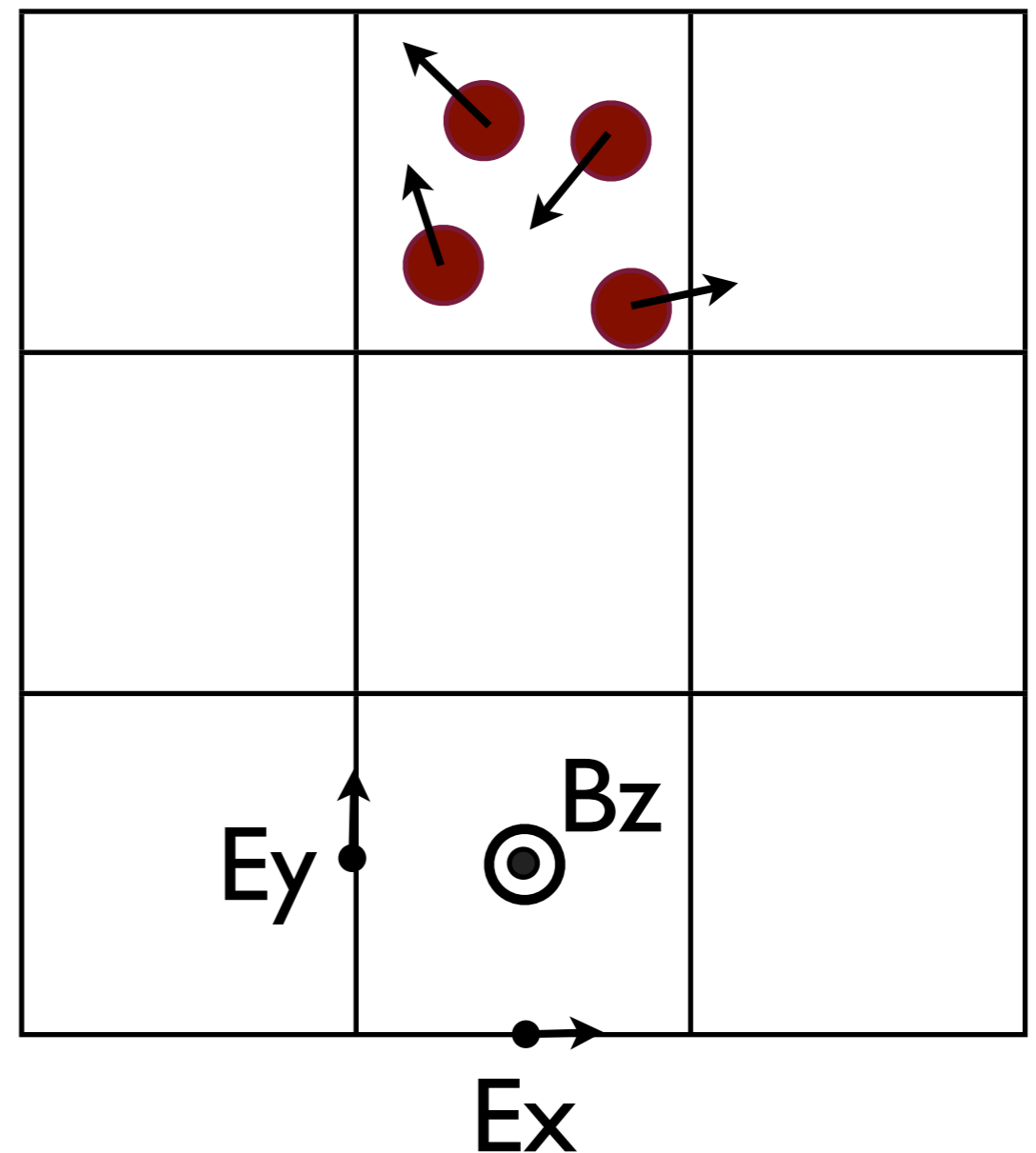
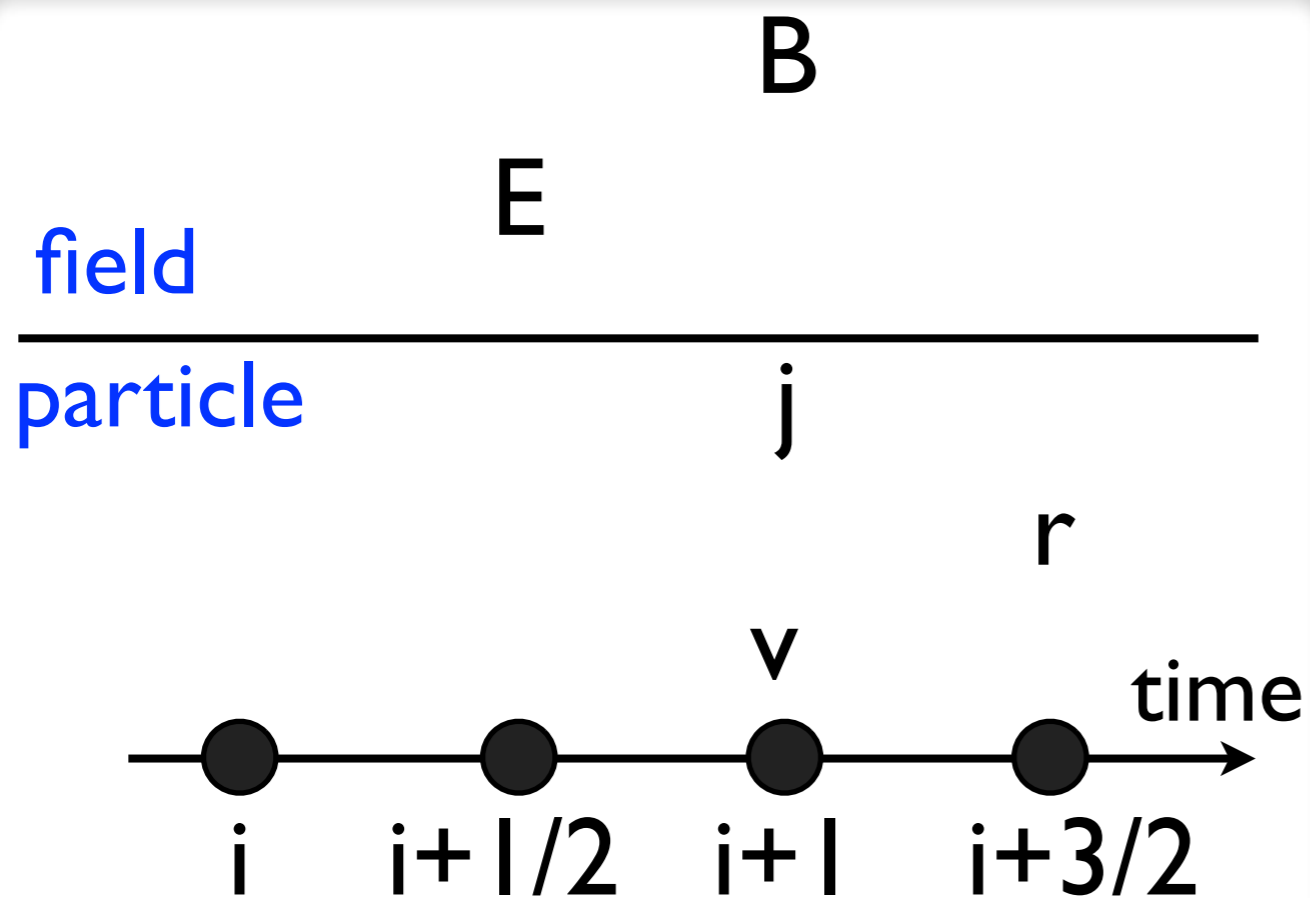
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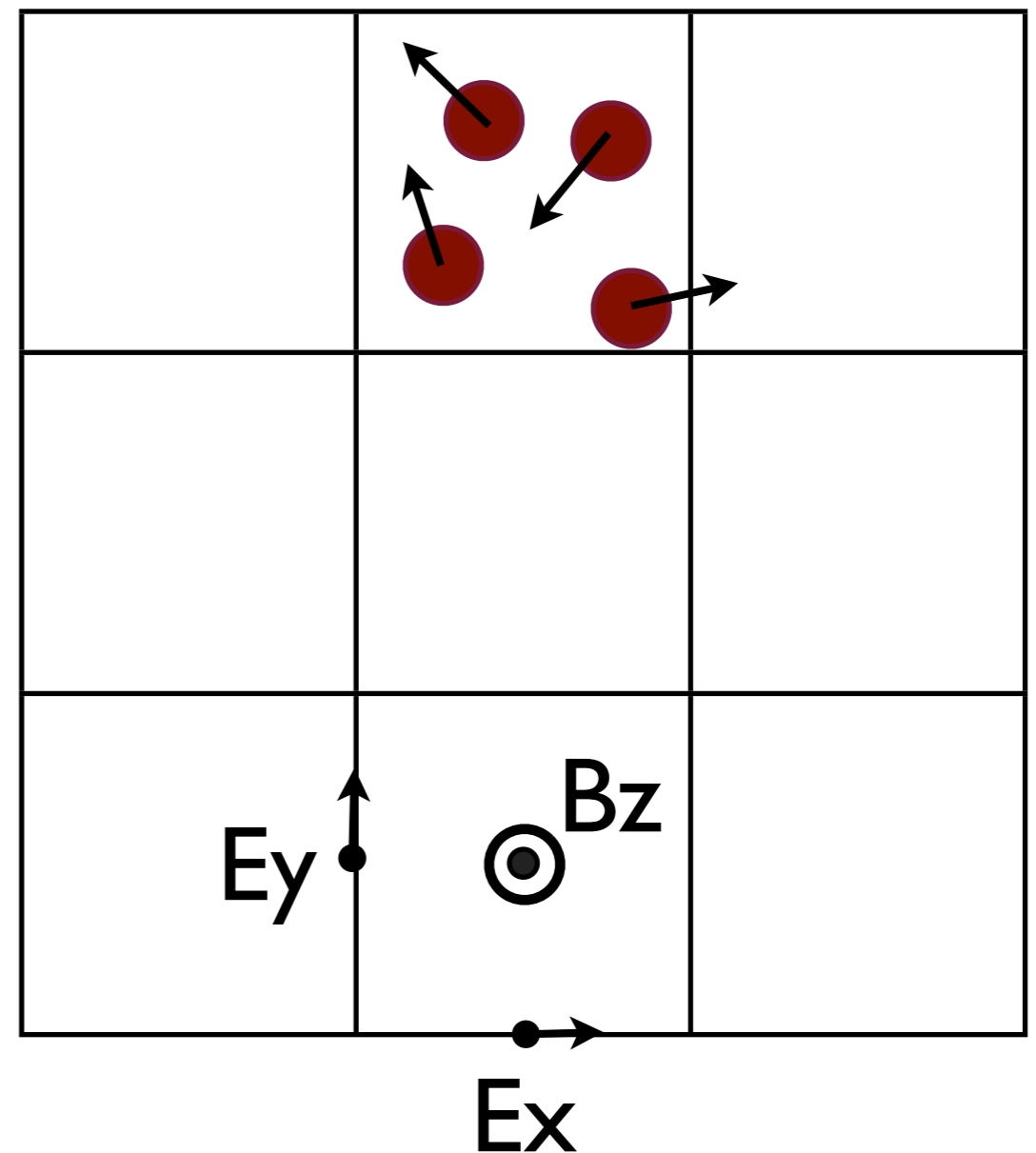
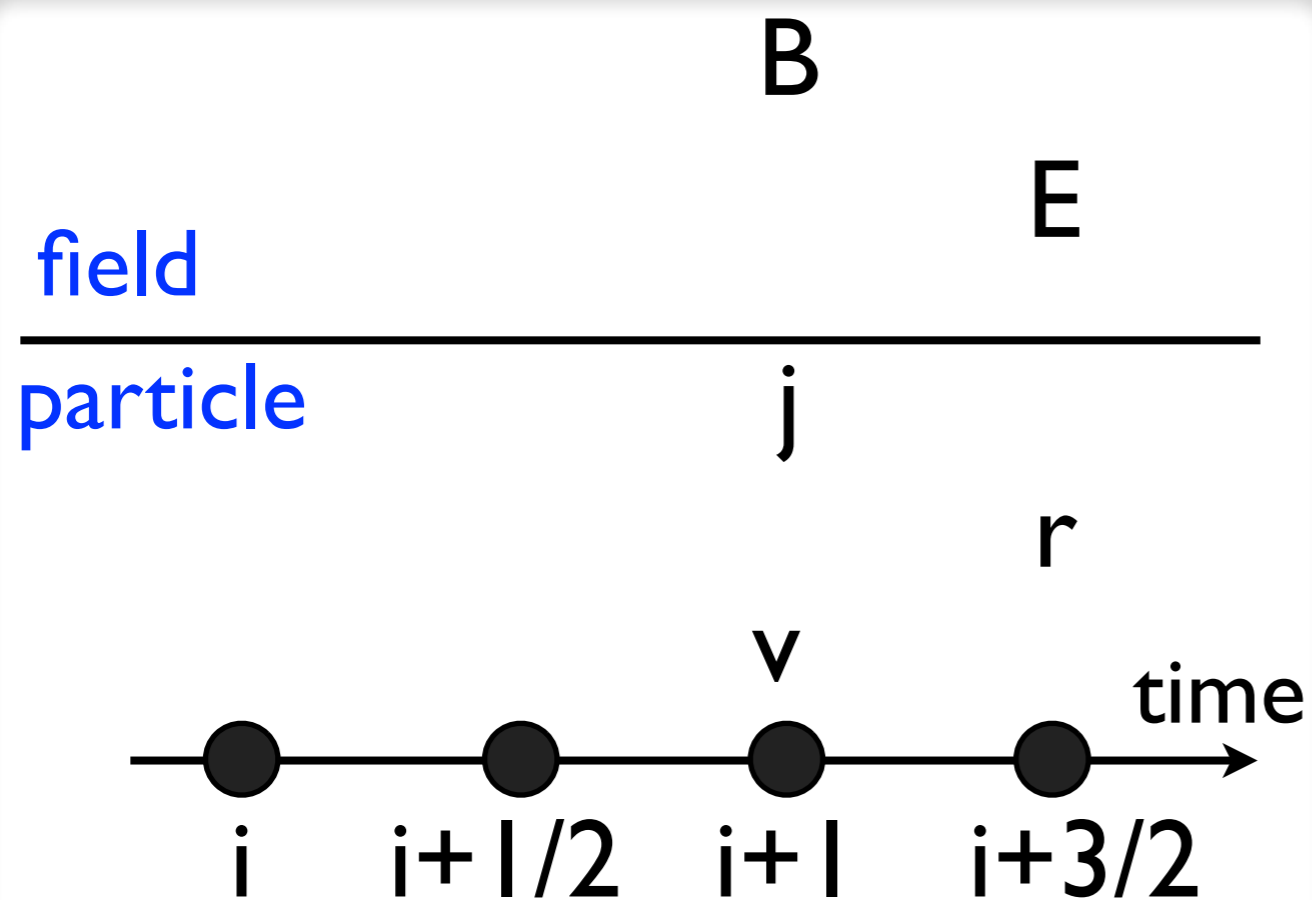
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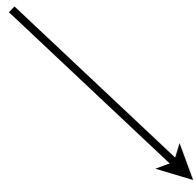
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A PIC Simulation of a Collisionless Shock

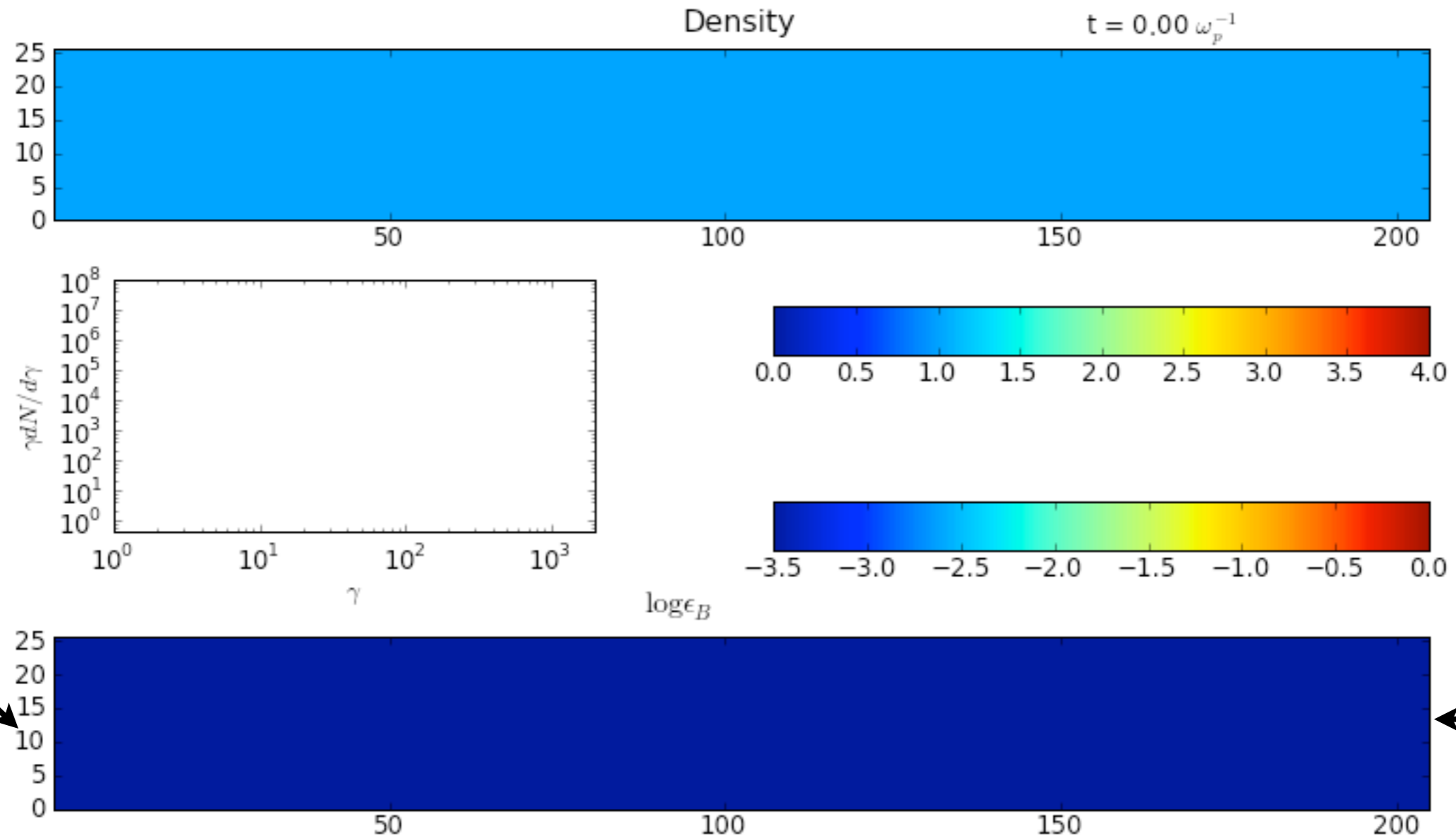
Wall



$$\overleftarrow{\frac{e^+, e^-}{\gamma = 2}}$$

- 2D w/ 20480 x 256 cells
- $\Delta x = 0.1$ skin depth
- 128 particles per cell initially, $> 10^9$ particles in the end
- Similar to Spitkovsky (2008) except for γ and resolution

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- More relevant for GRB afterglows
- Numerically easier

Shock Structure

ISM

$$n \sim 1 \text{ cm}^{-3}$$

$$\omega_p \sim 10^4 \text{ Hz}$$

$$\delta \sim 10^6 \text{ cm}$$

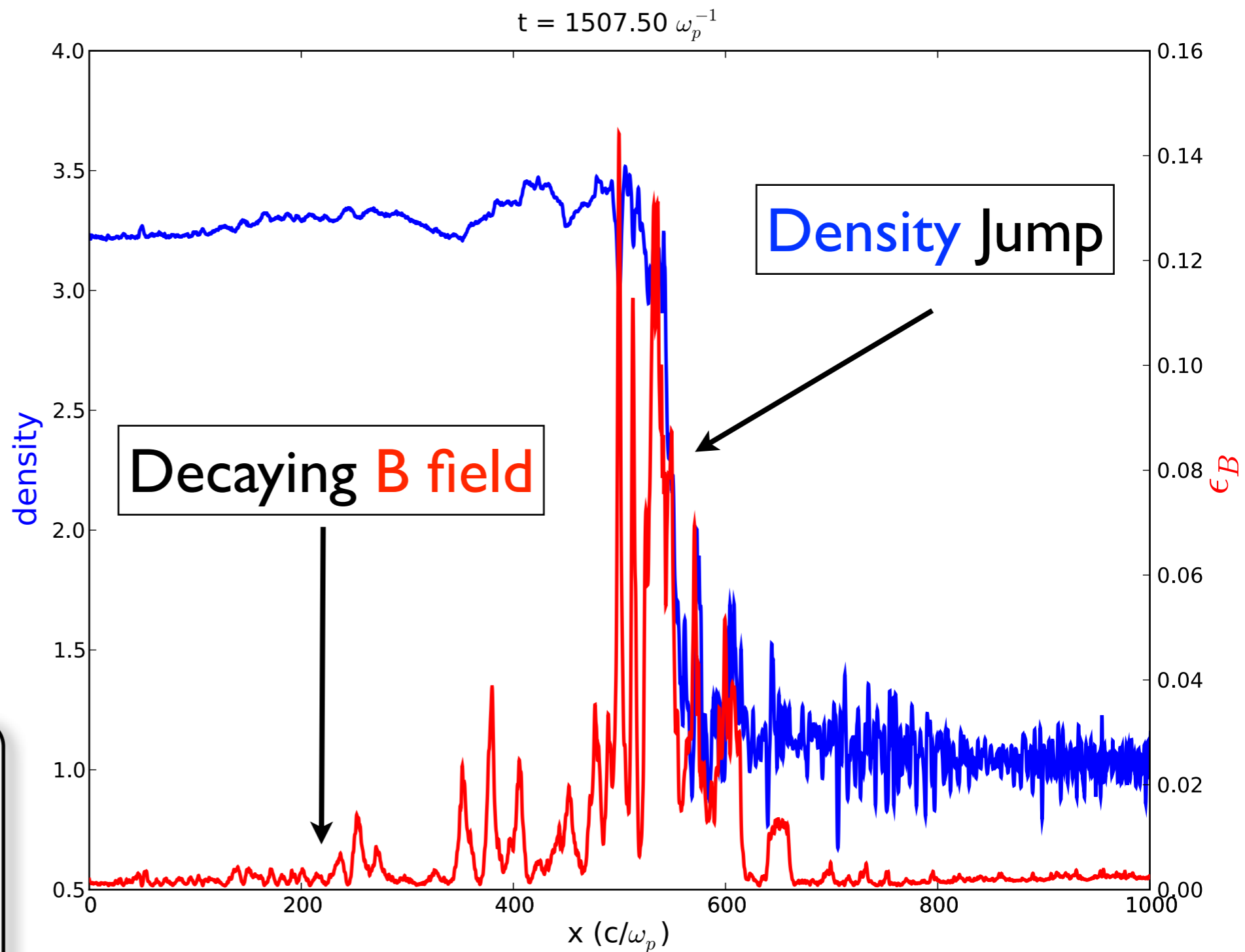
GRB at $\gamma \sim 2$

$$\sim 10^{18} \text{ cm}$$

Shock

$$\text{Width} \sim 50 \delta$$

$$\text{Speed} \sim 0.94 c$$

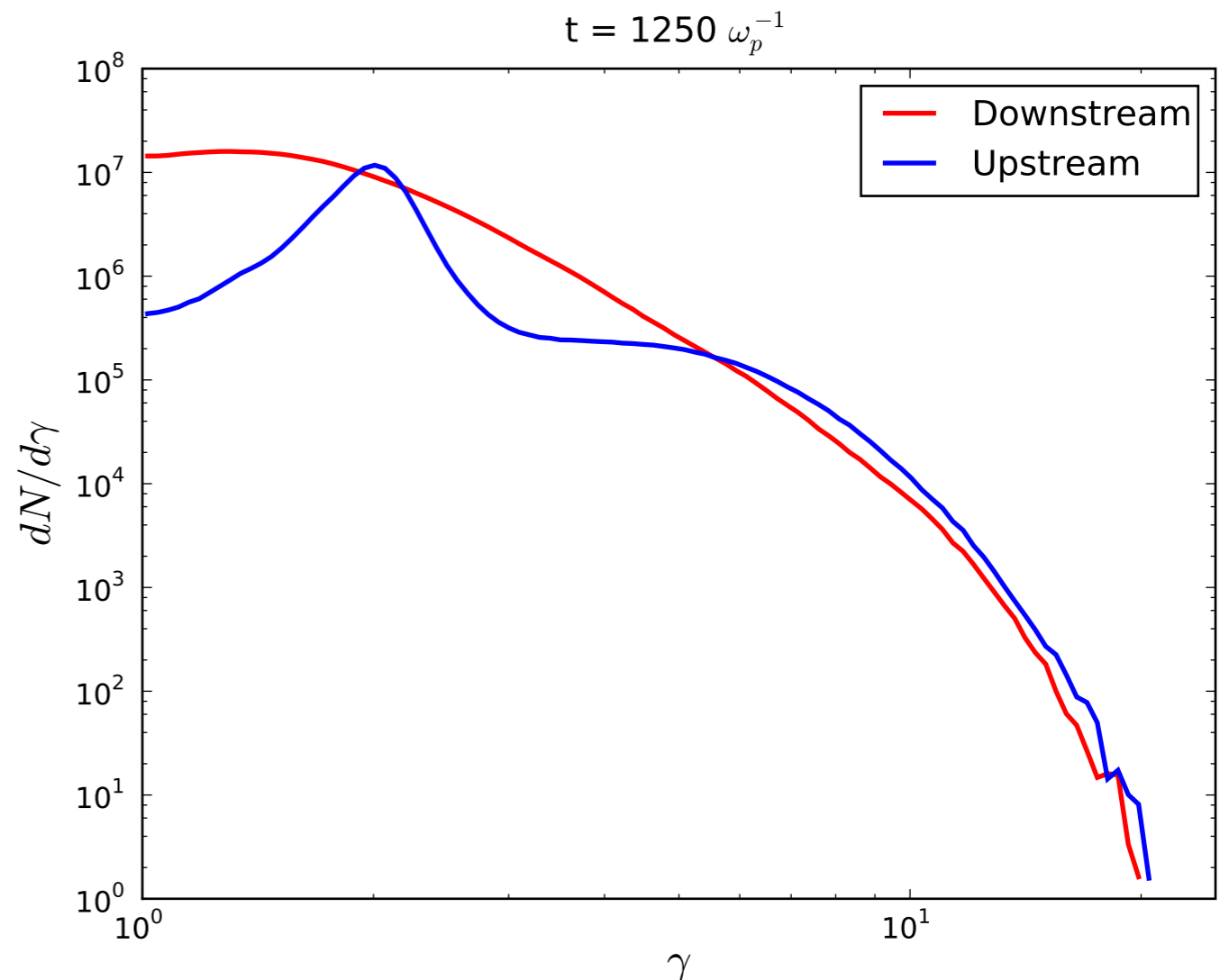


Particle Acceleration

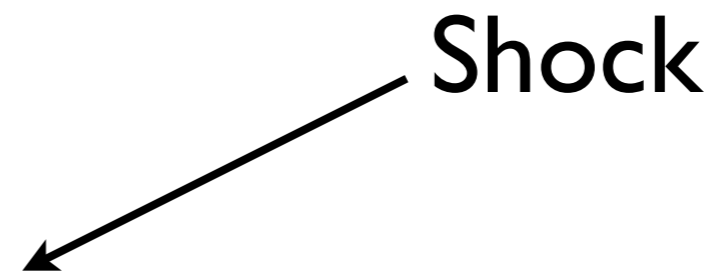
Two Slices

- **Downstream:** -50 ± 10
- **Upstream:** $+50 \pm 10$

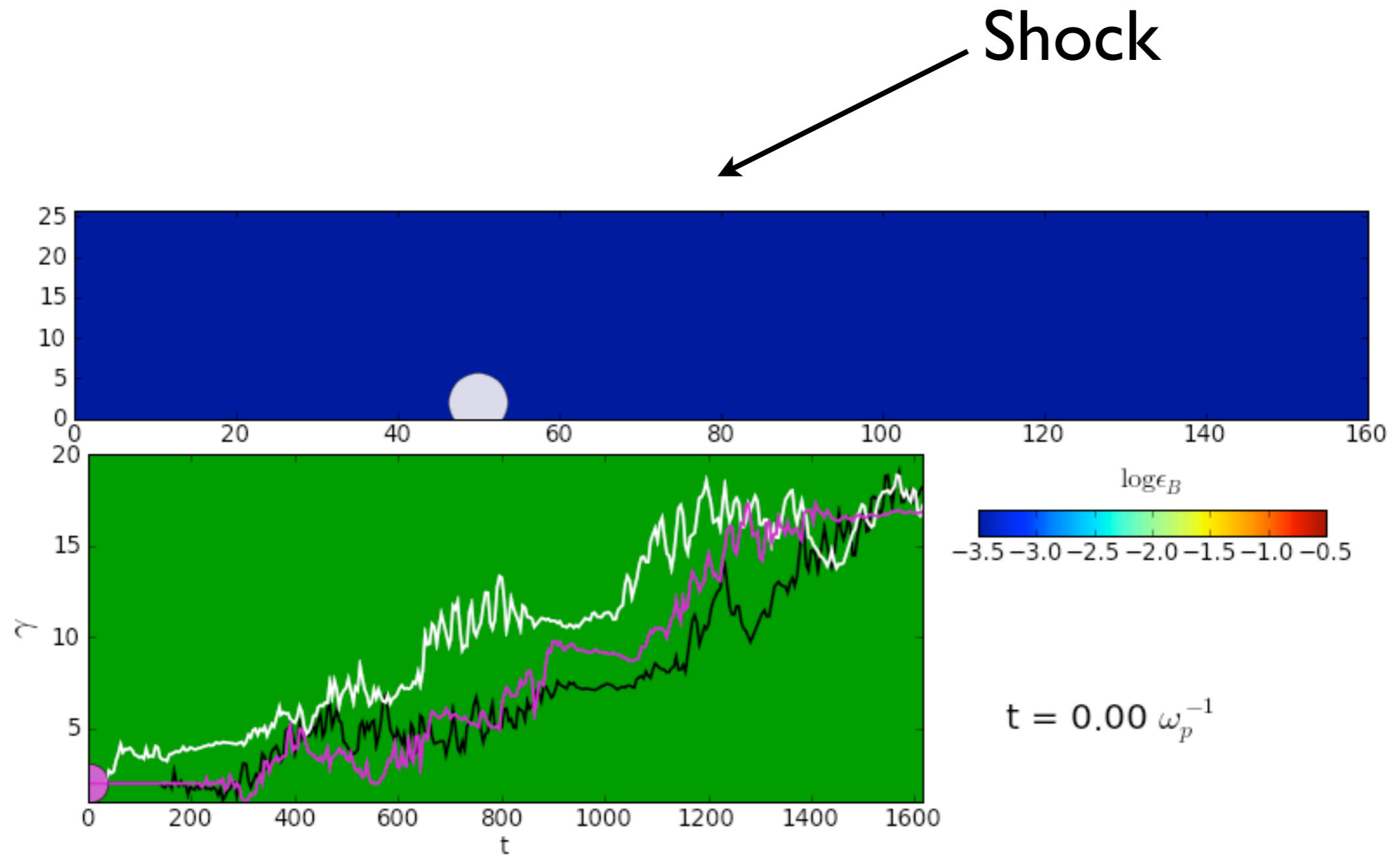
- Initial: $\gamma = 2$
- Now: up to ~ 20
- Fermi Acceleration
- Power-law?



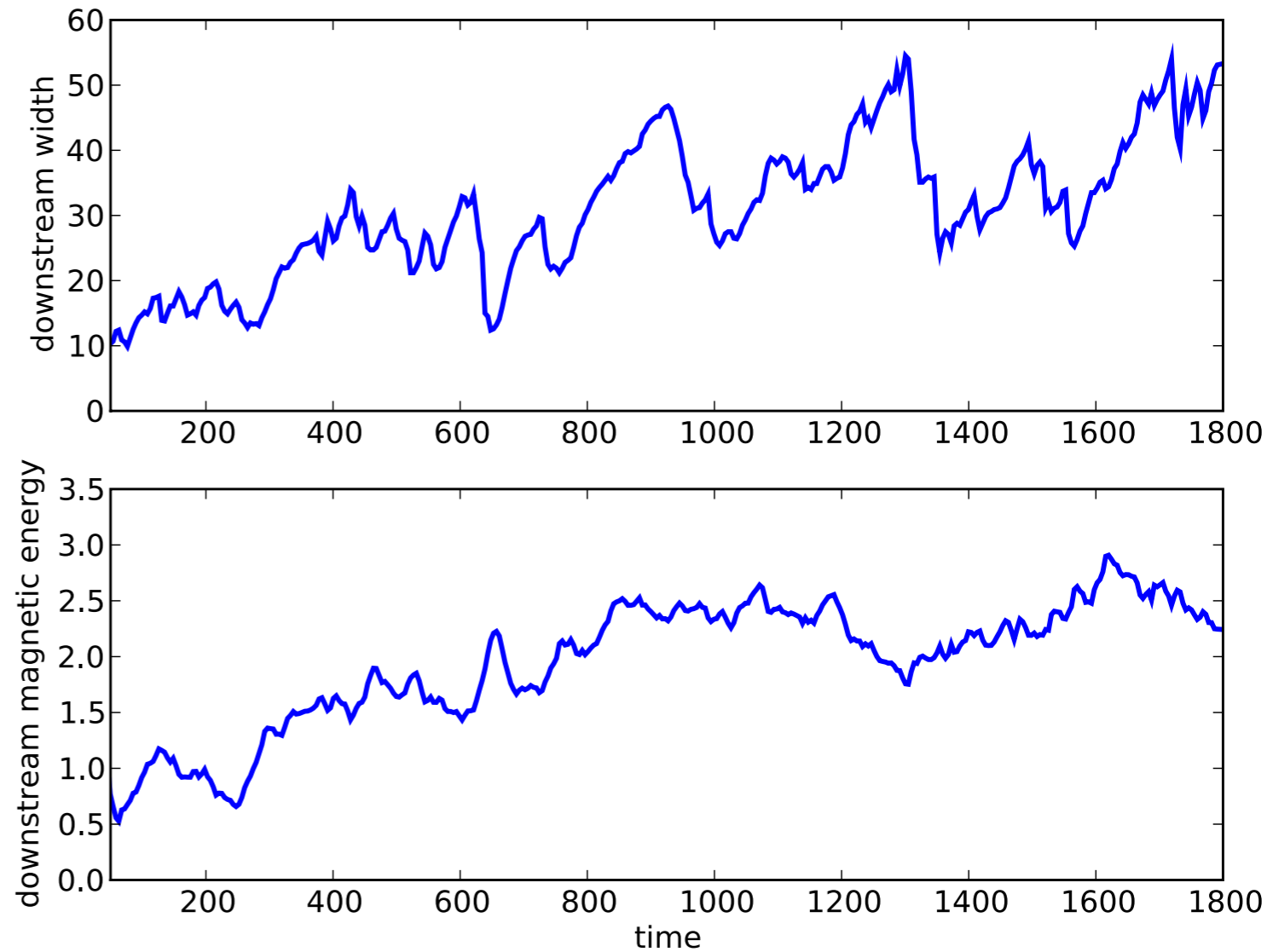
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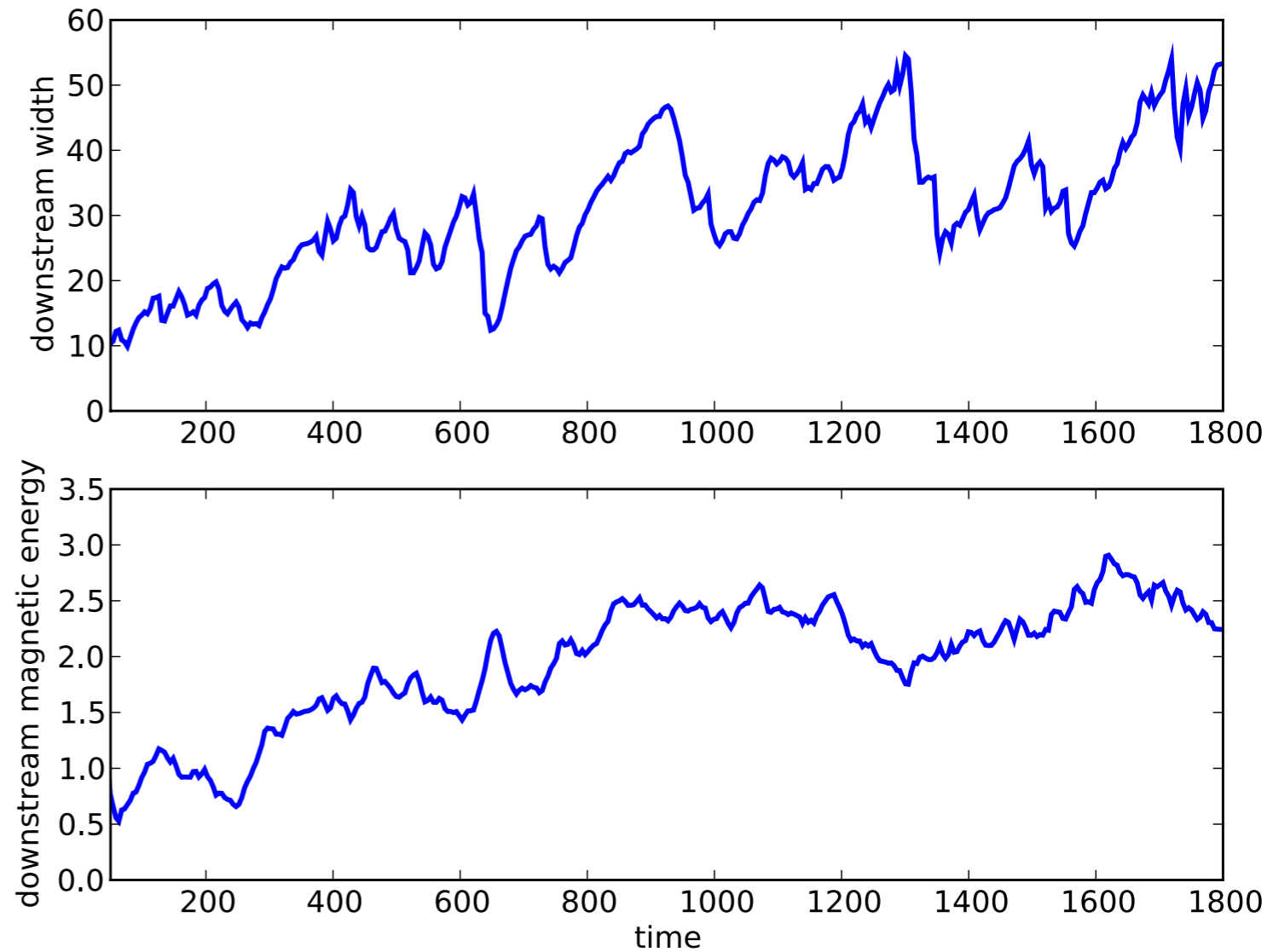
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Definition of Downstream Width
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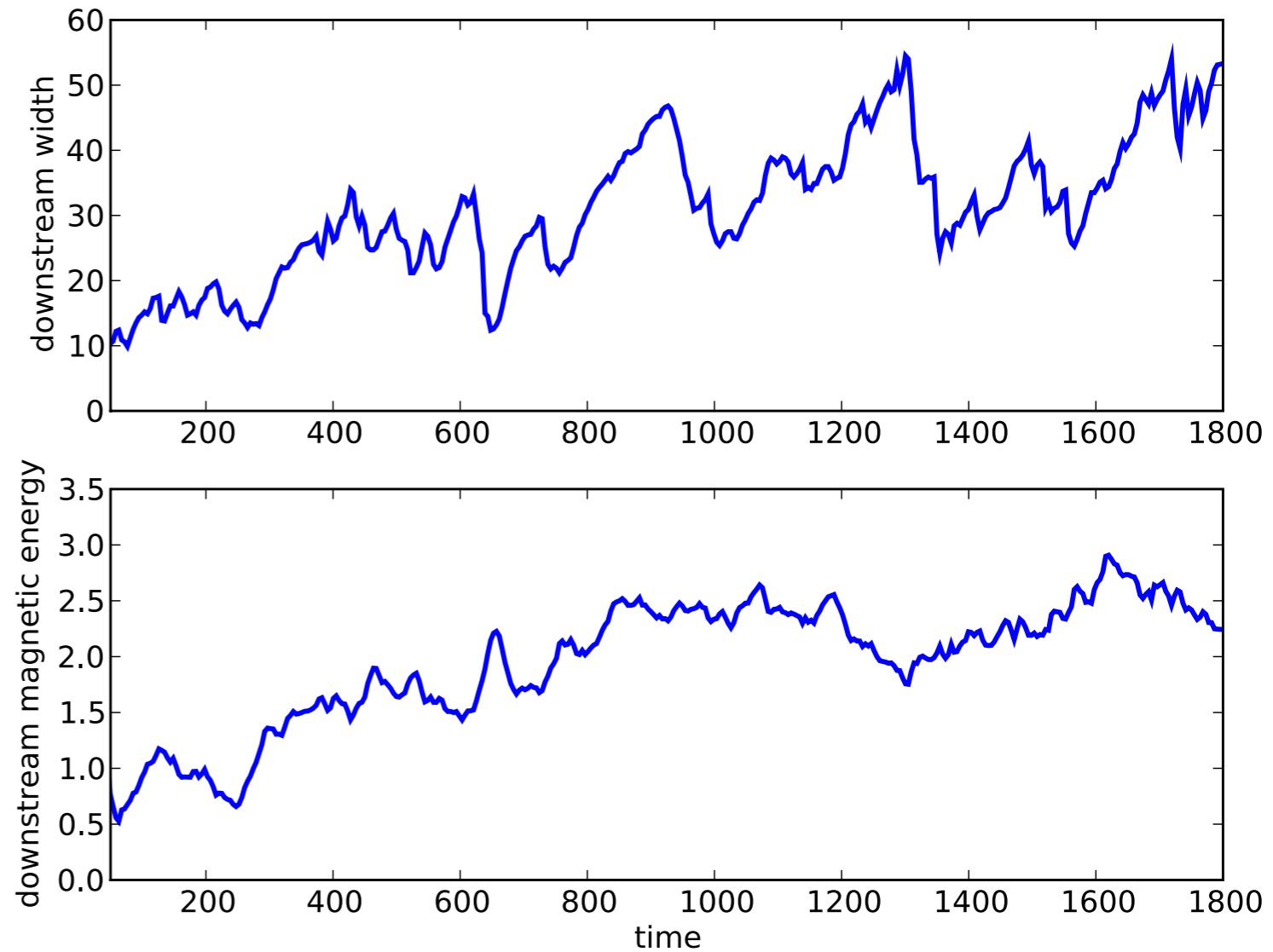
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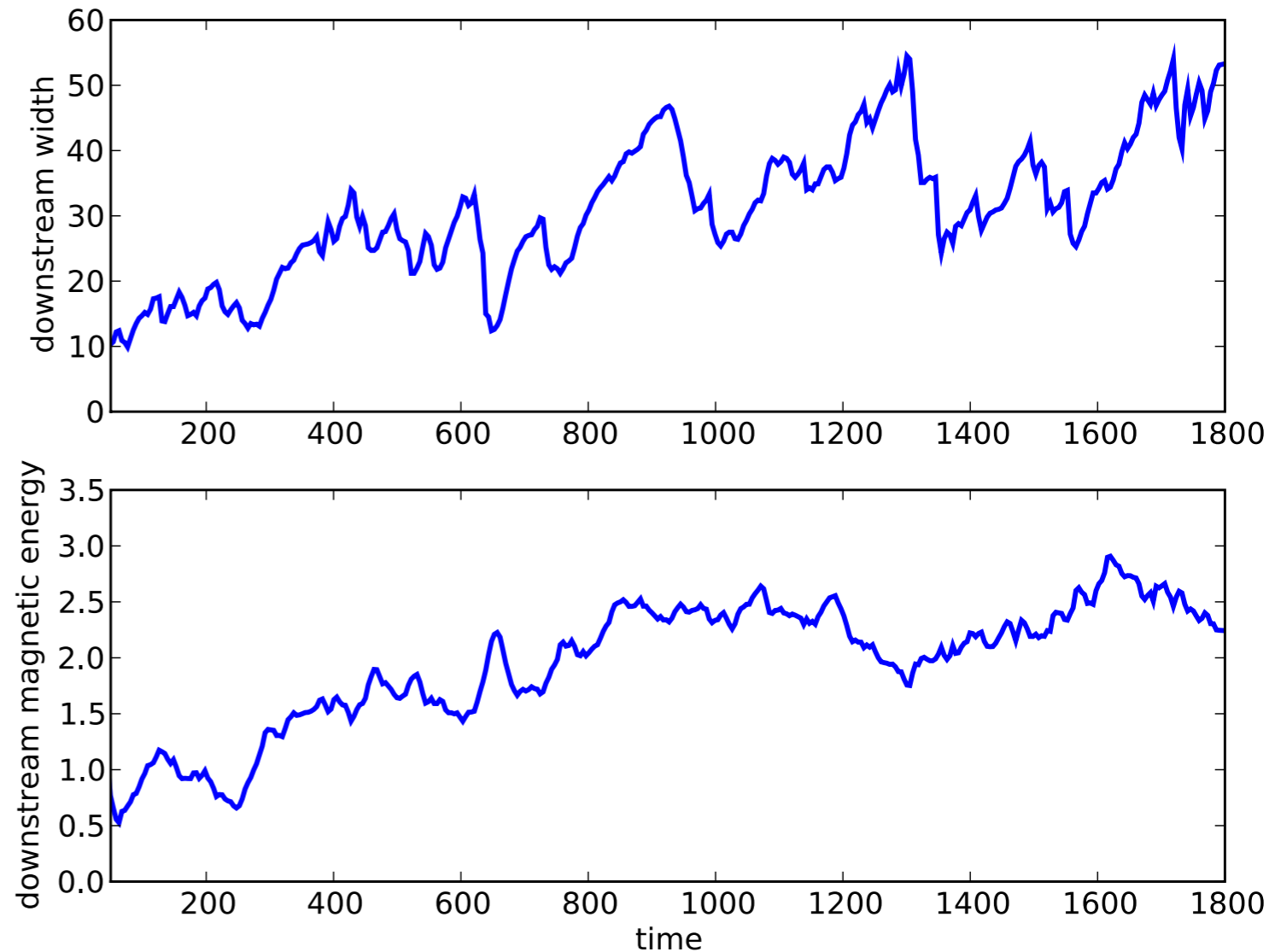
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The Problem

Magnetized region is too small!



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- (Ultra-)high energy cosmic rays

From 10^6 cm to 10^{16} cm

Skin Depth



Emission Region

10 orders of magnitude

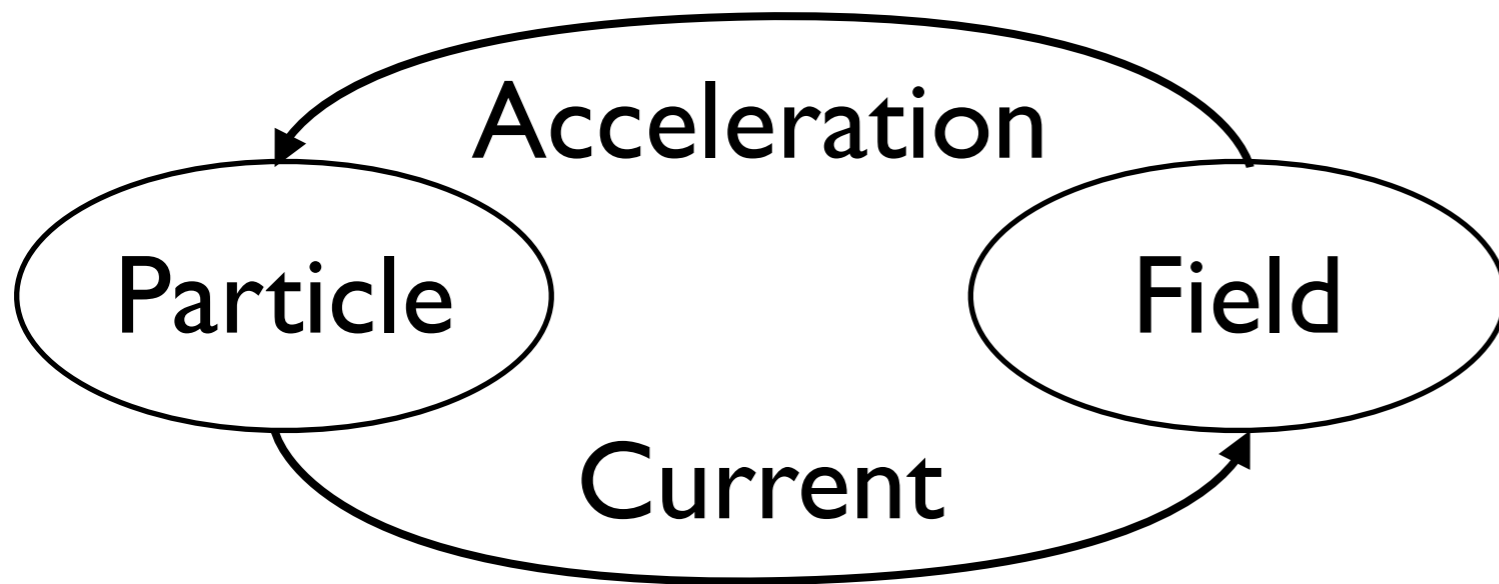
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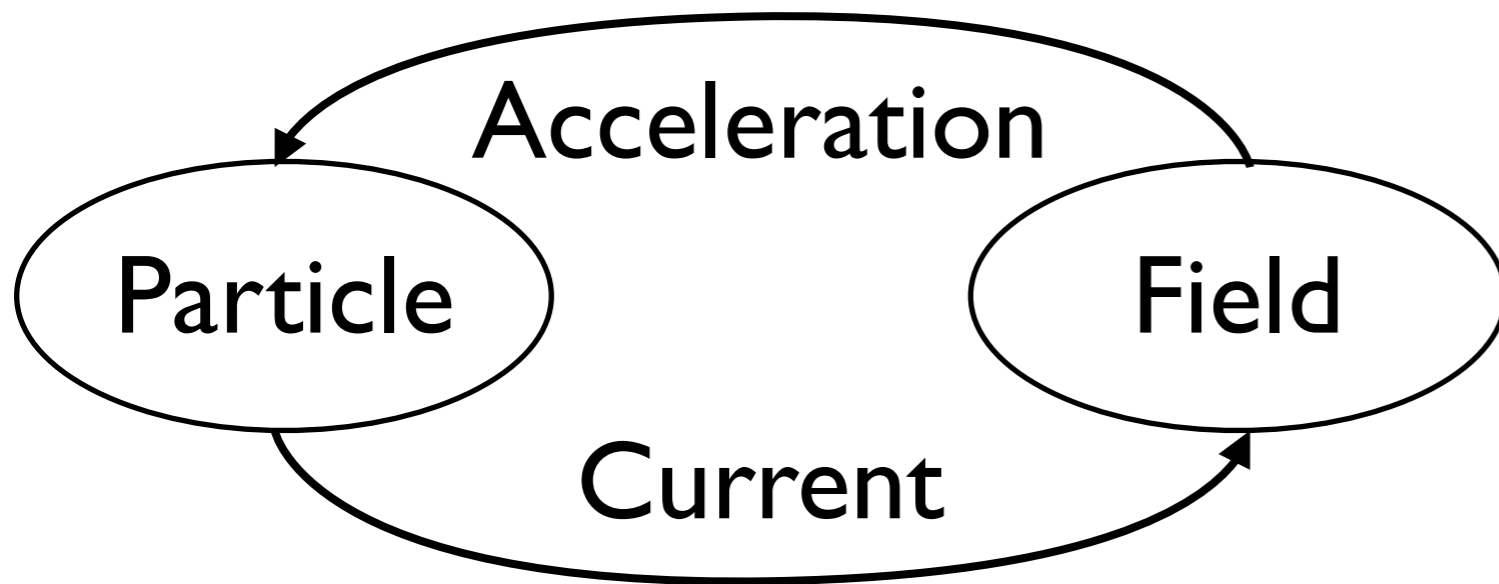
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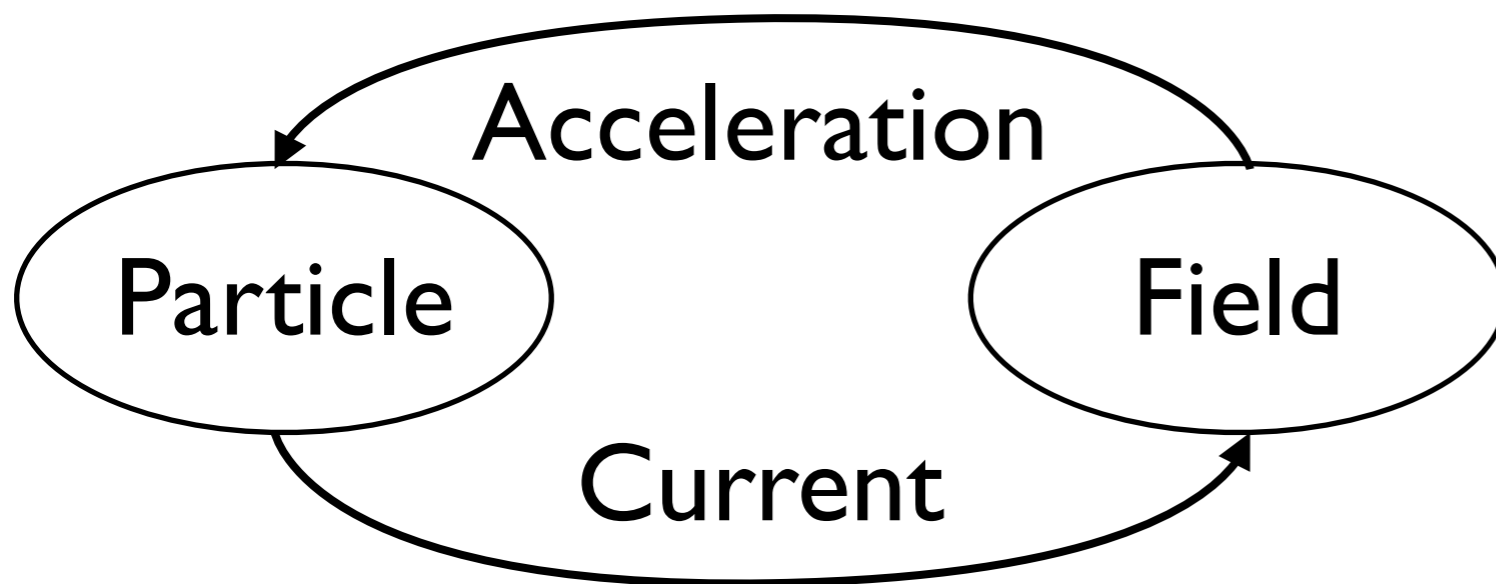
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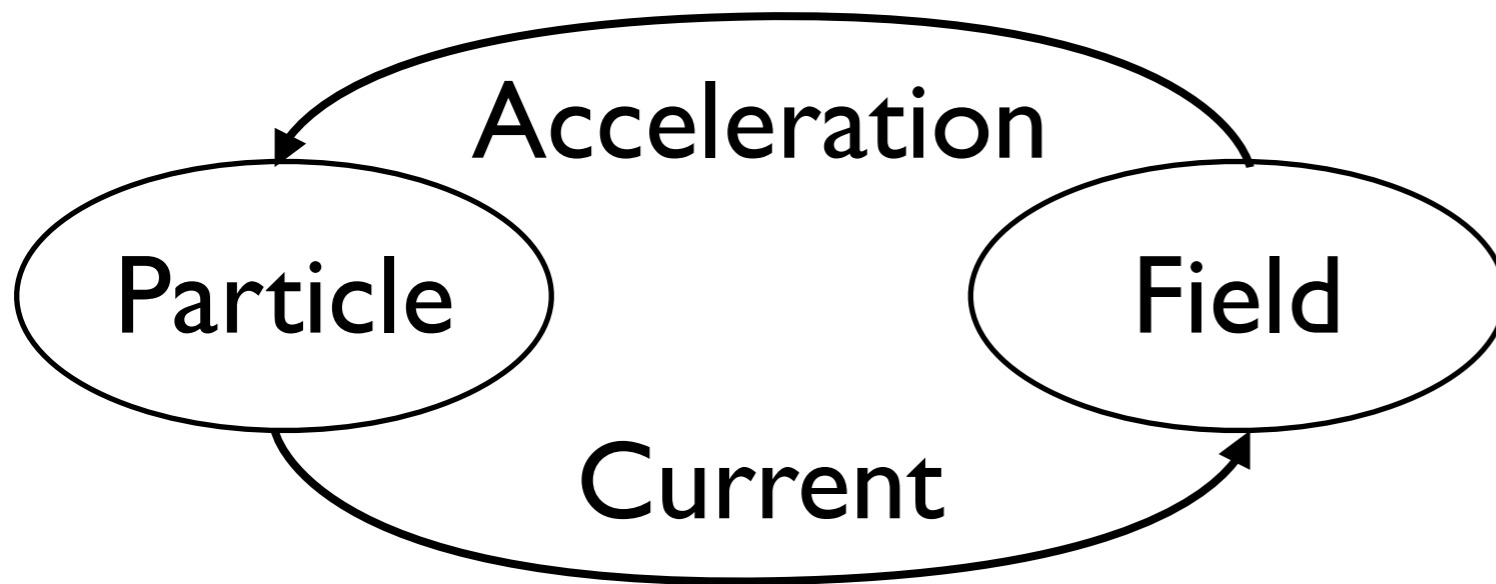
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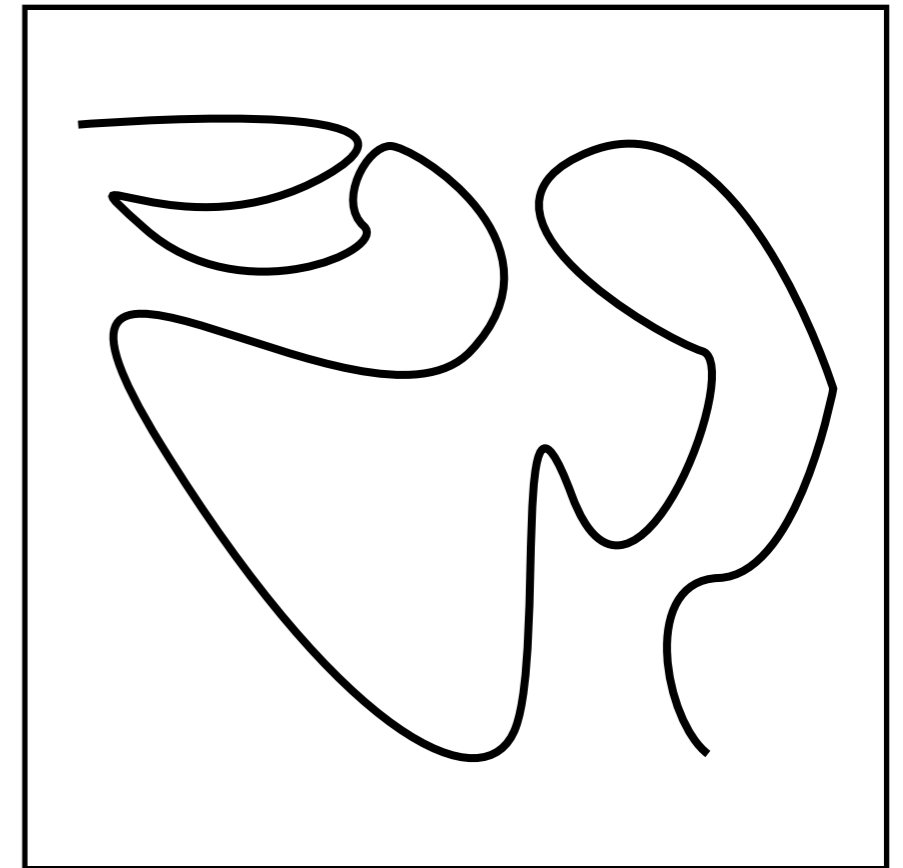
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MHD
Turbulence

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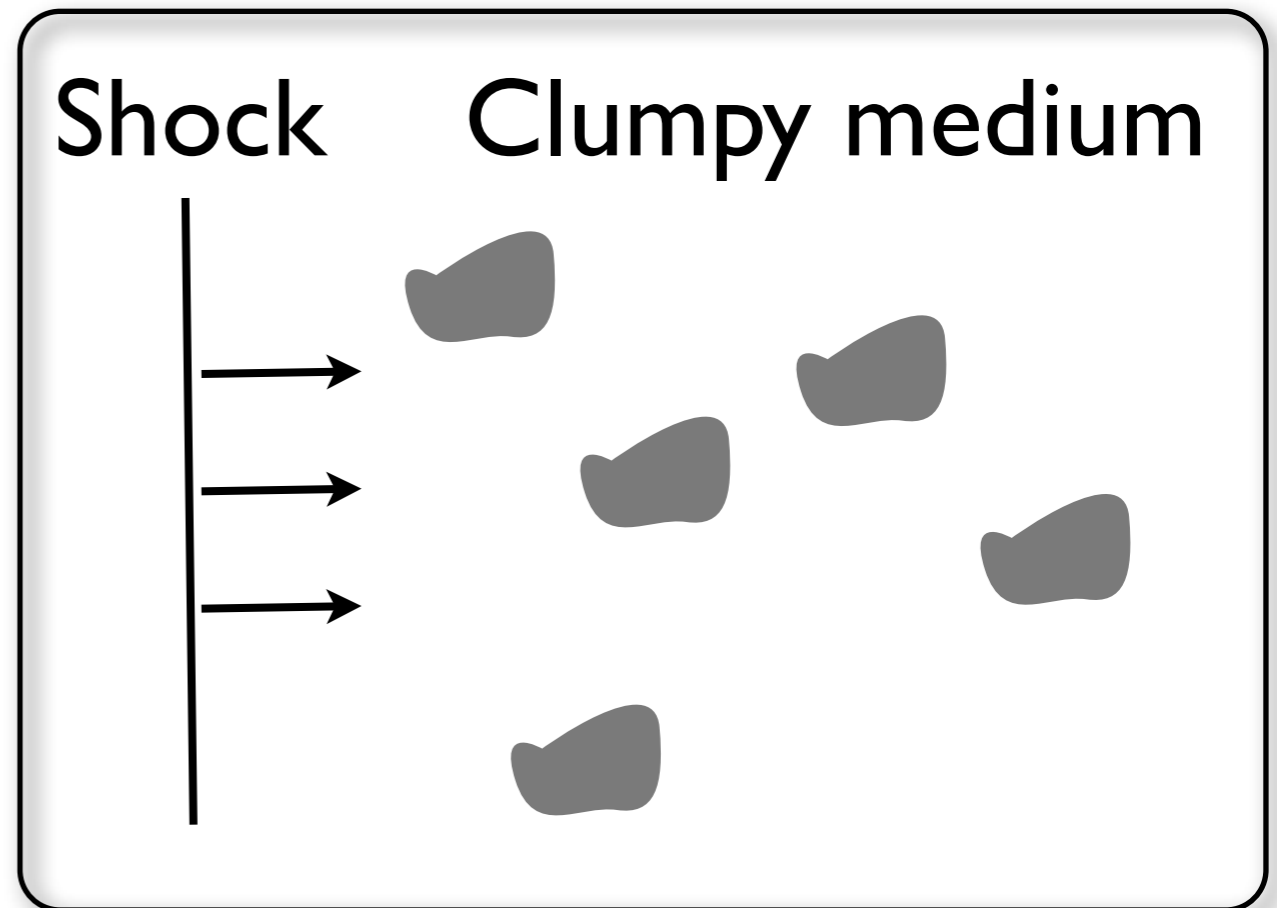
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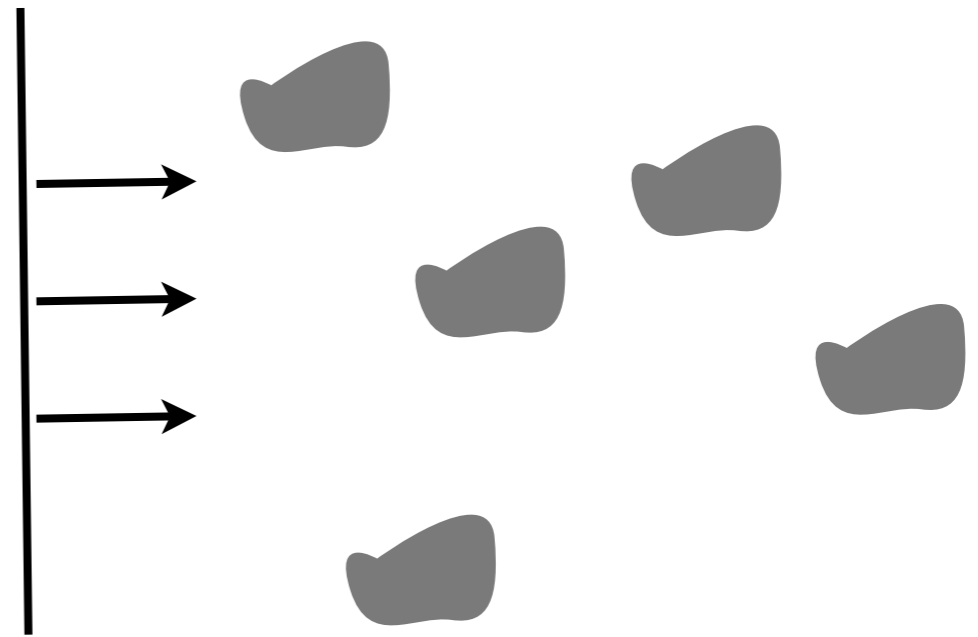
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Shock Clumpy medium



3D RMHD Simulation of Kelvin-Helmholtz

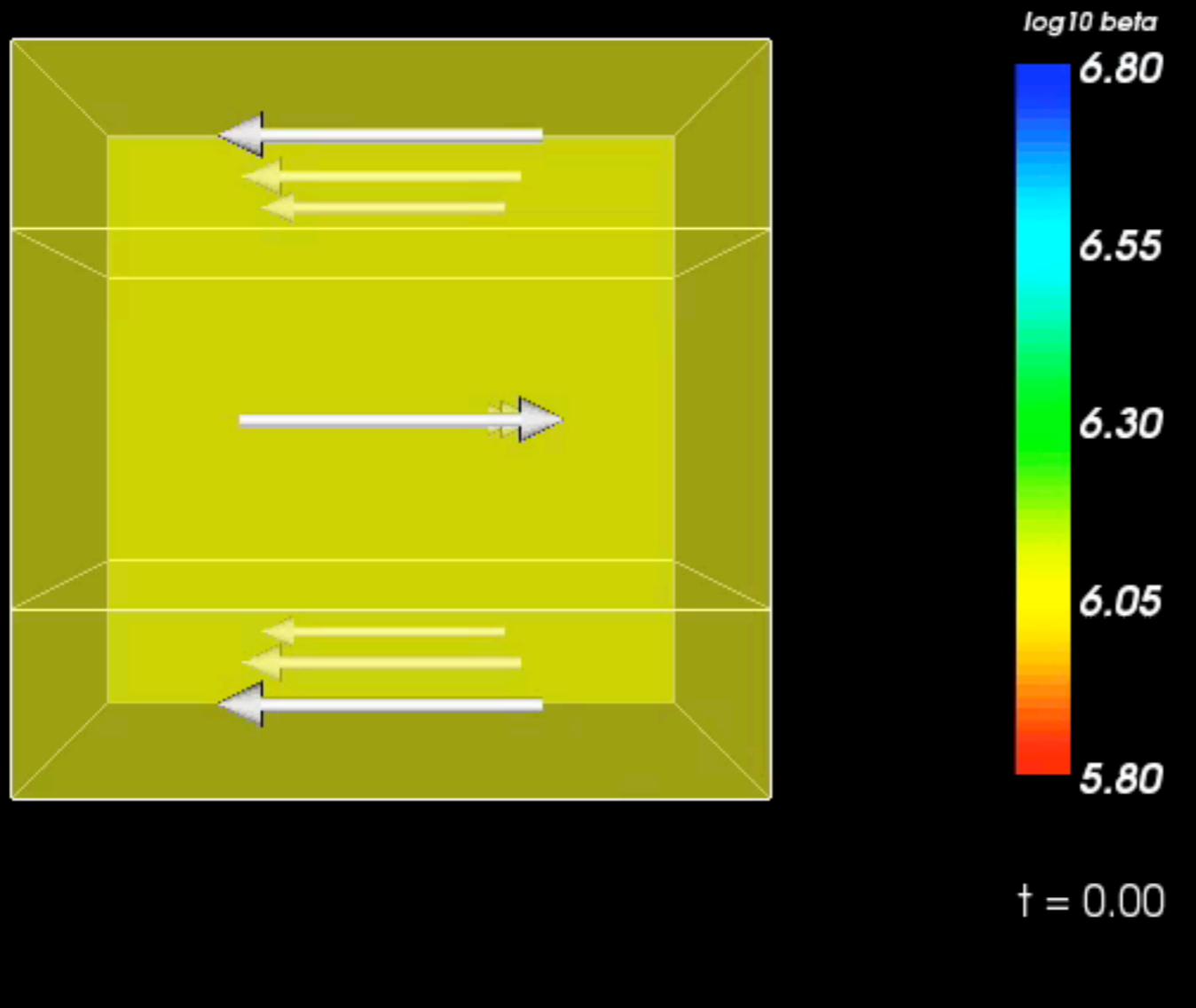
- Velocity shear
- Vortex
- Winding up field
- Instability grows
- Turbulence
- Stretching & folding
- Field amplification

Zhang, MacFadyen & Wang
(2009)

1024 x 1024 x 1024

Initial: $v = 0.5 c$, weak B

3D RMHD Simulation of Kelvin-Helmholtz



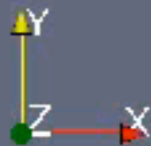
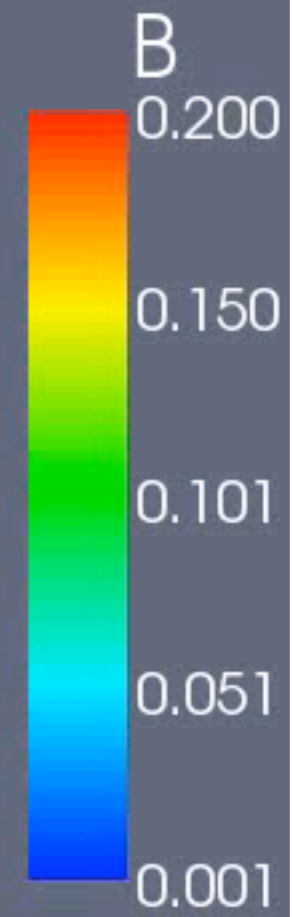
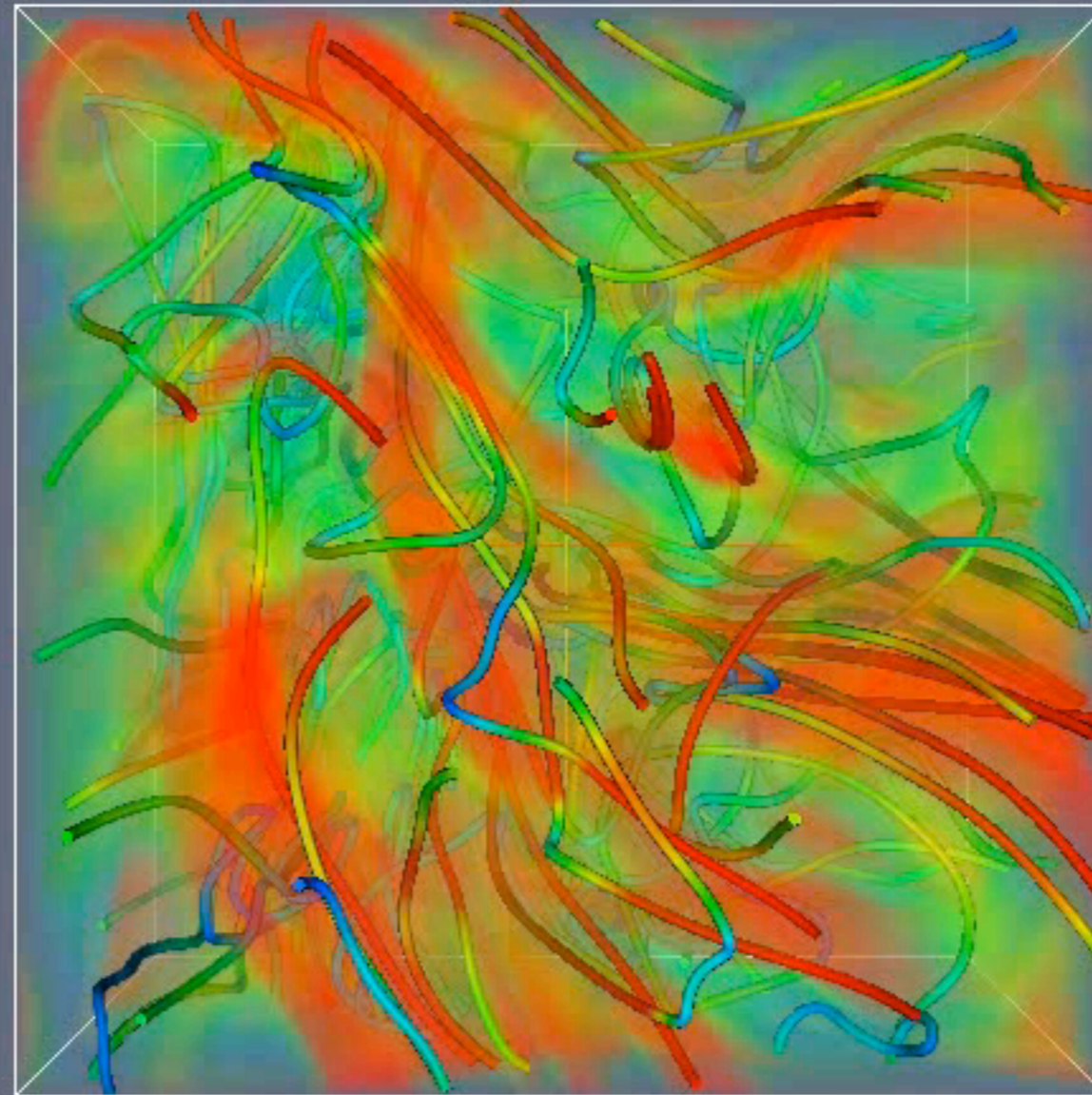
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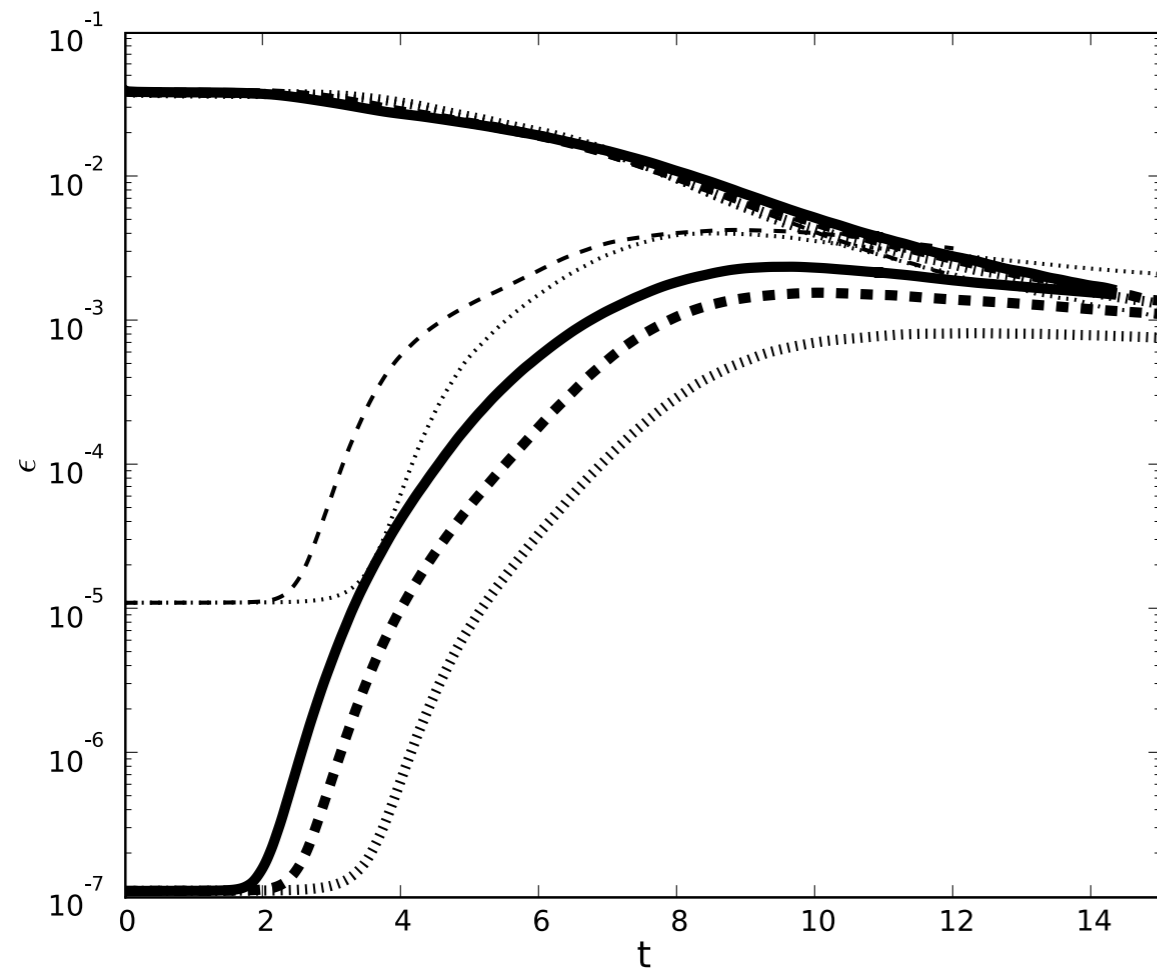
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Magnetic Field Structure

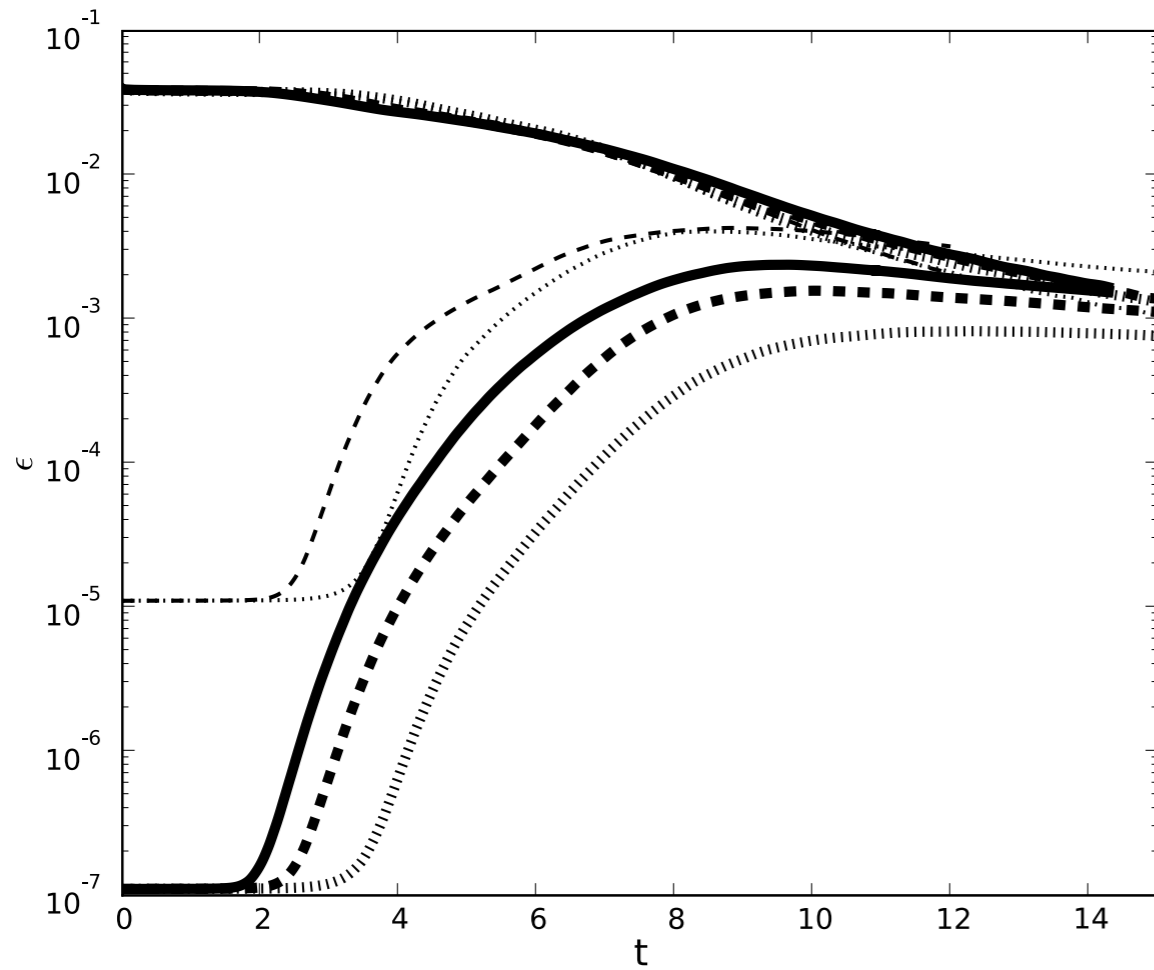


Time: 12 Length: 1/8

Amplification of Magnetic Fields

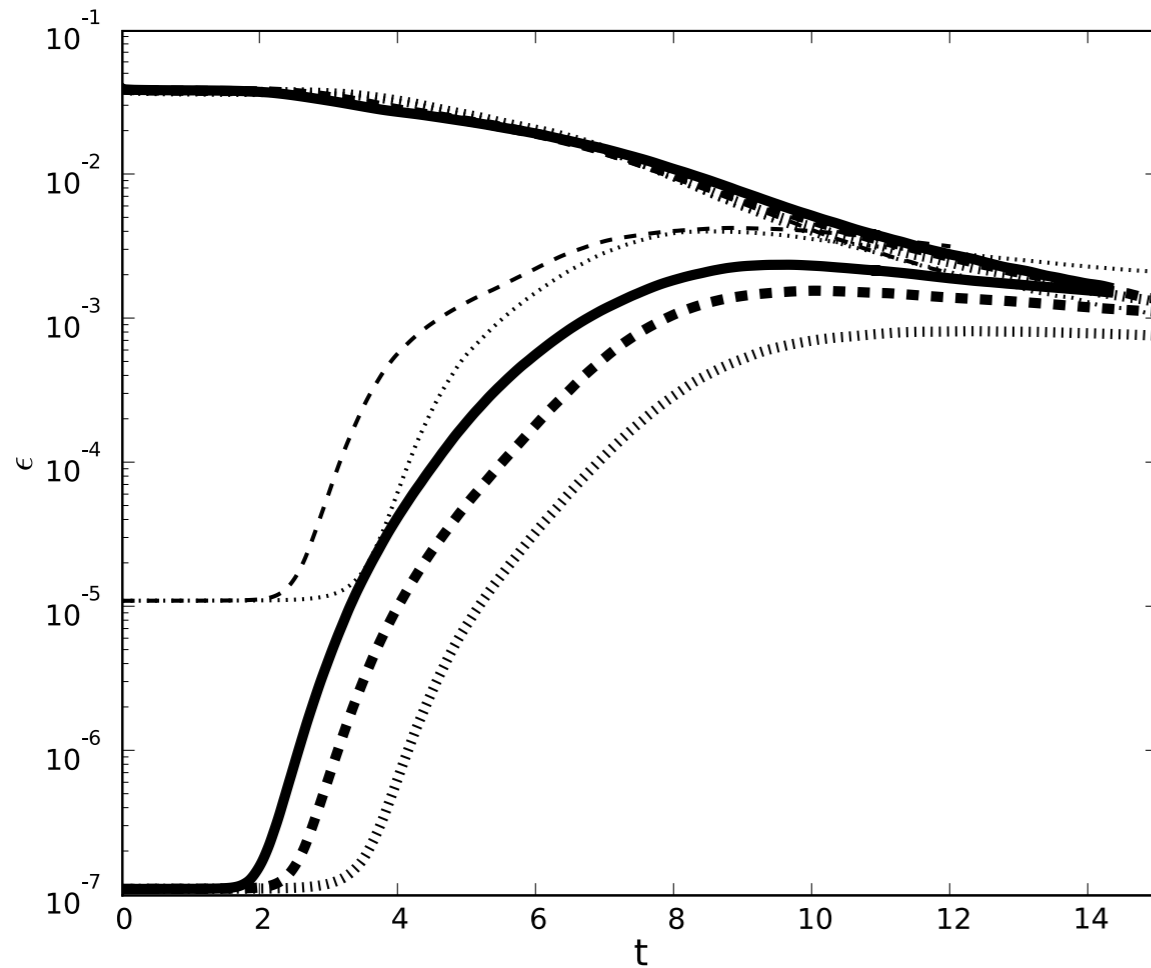


Amplification of Magnetic Fields



● $\epsilon_B \sim 5 \times 10^{-3}$

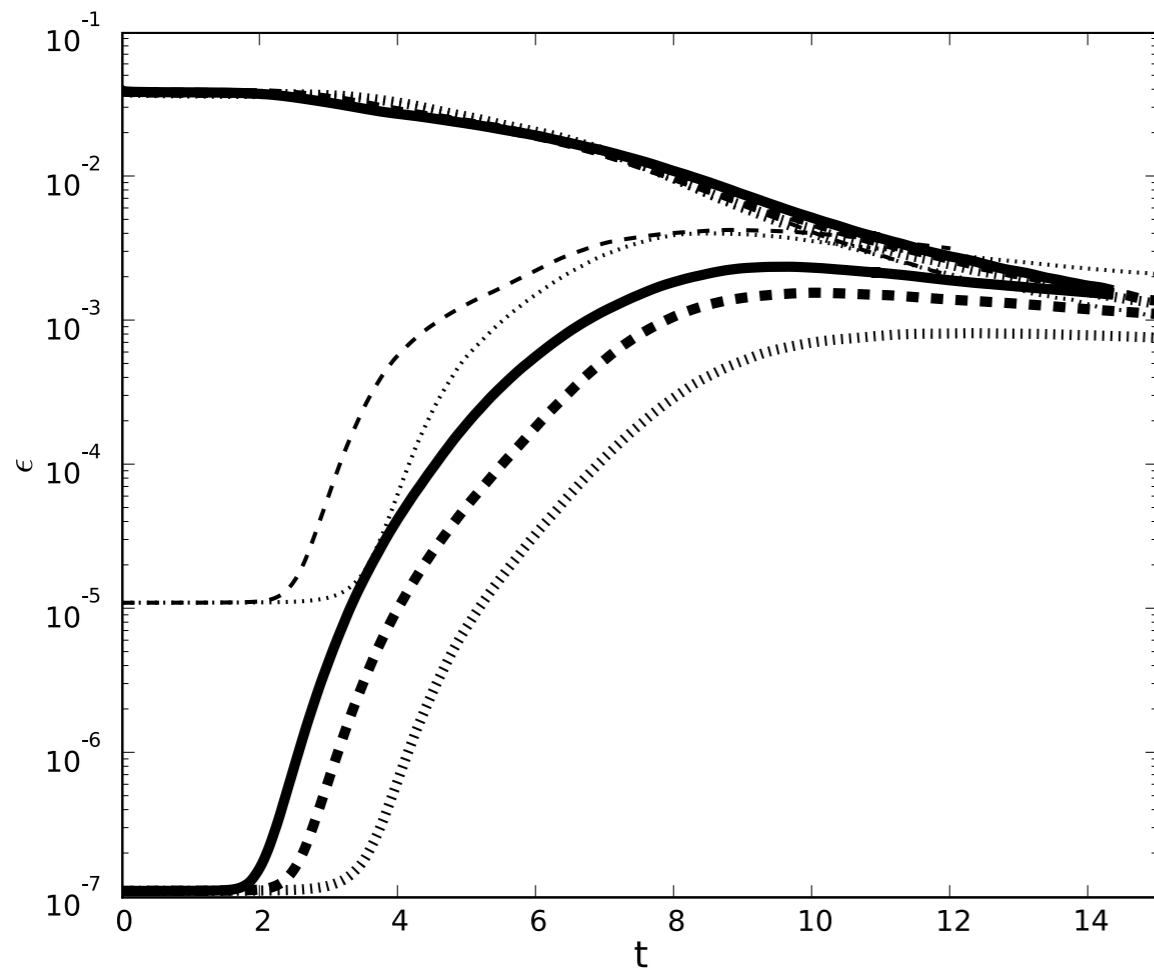
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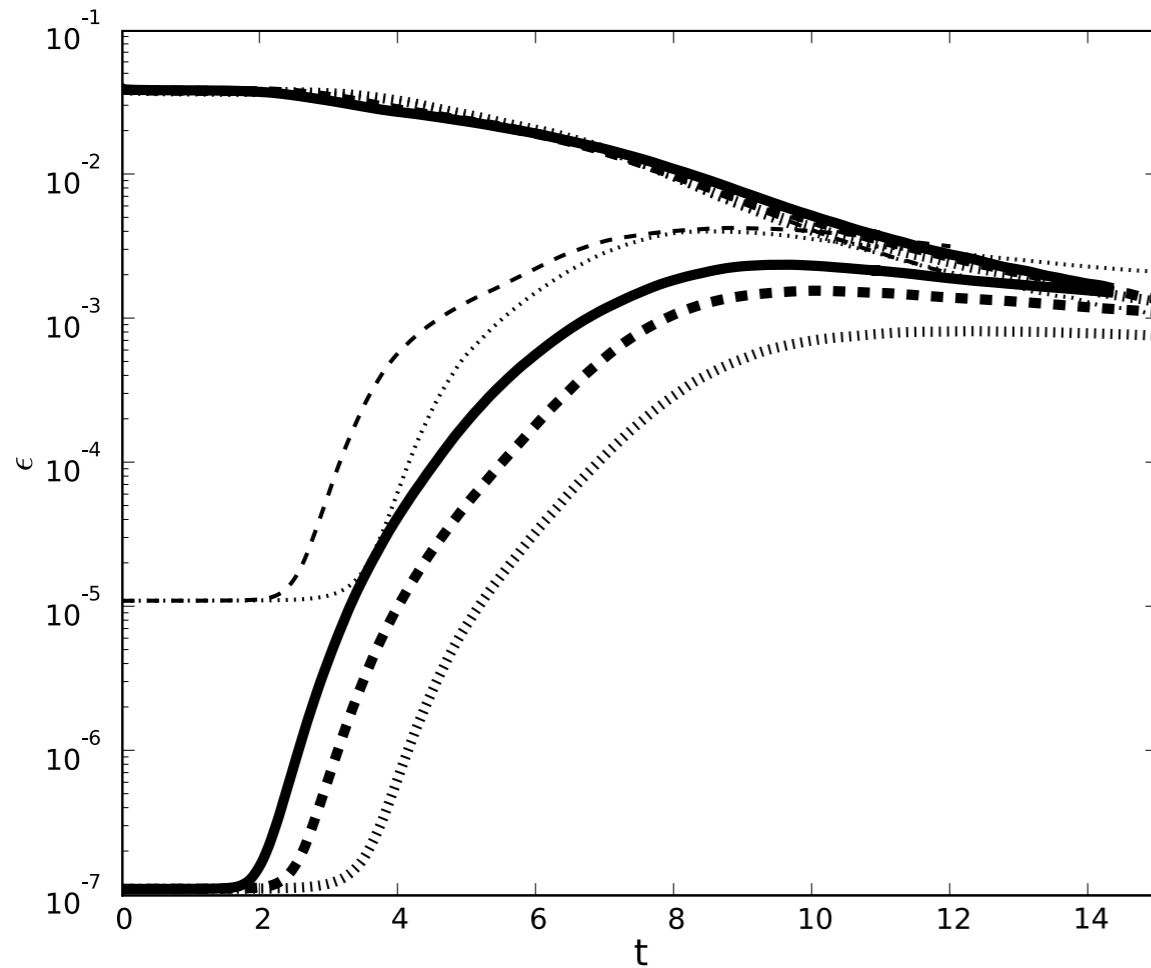
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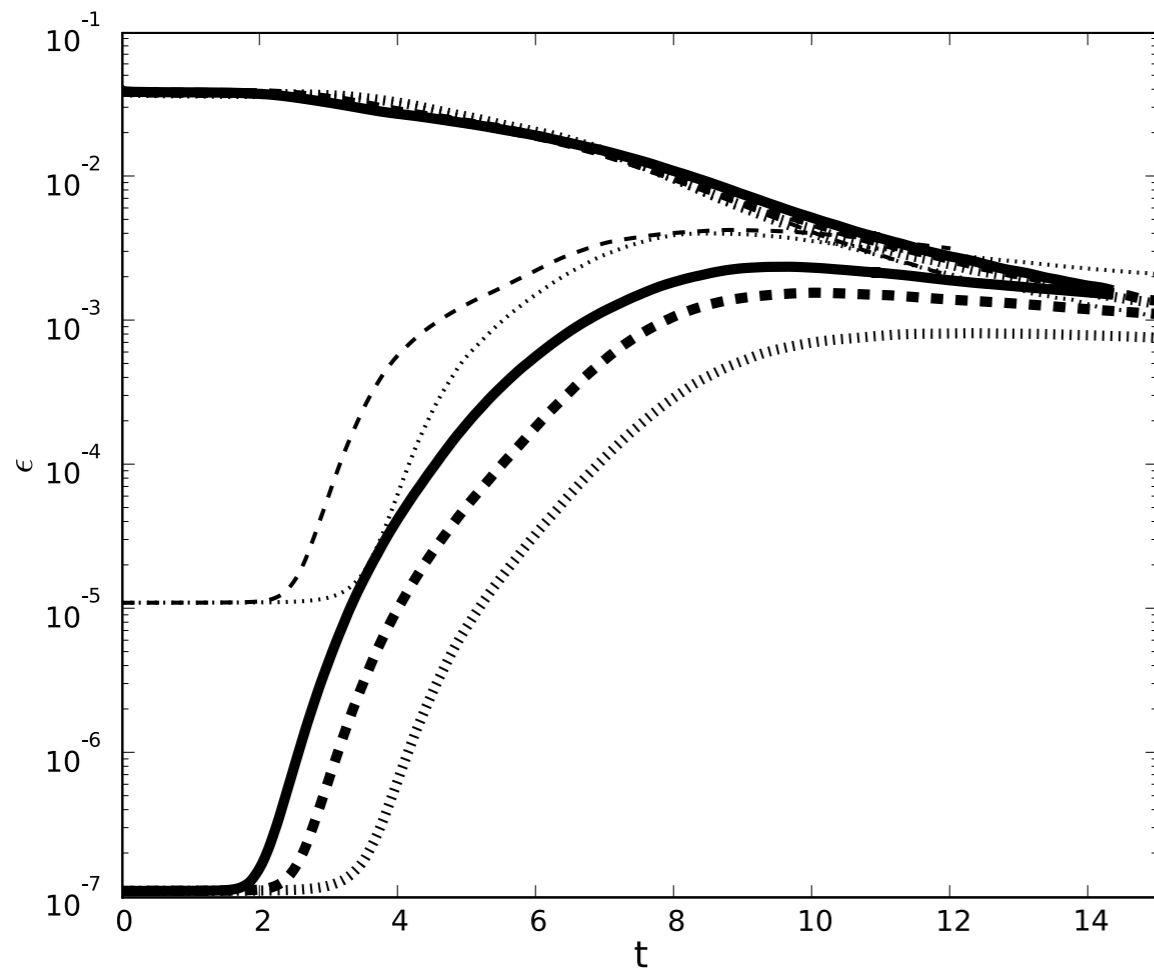
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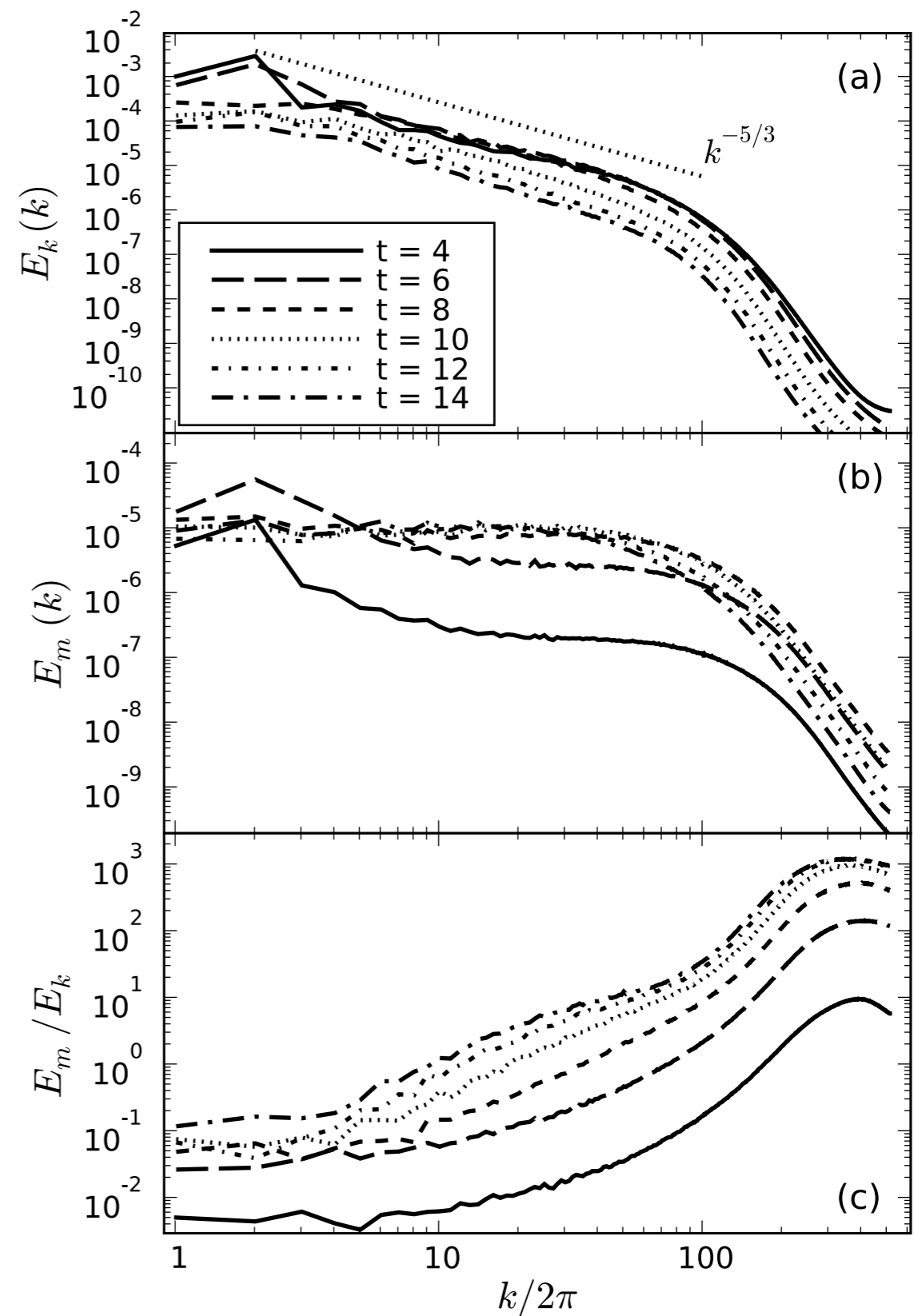


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- Grow rapidly
- Decay very slowly
- Small-scale fields

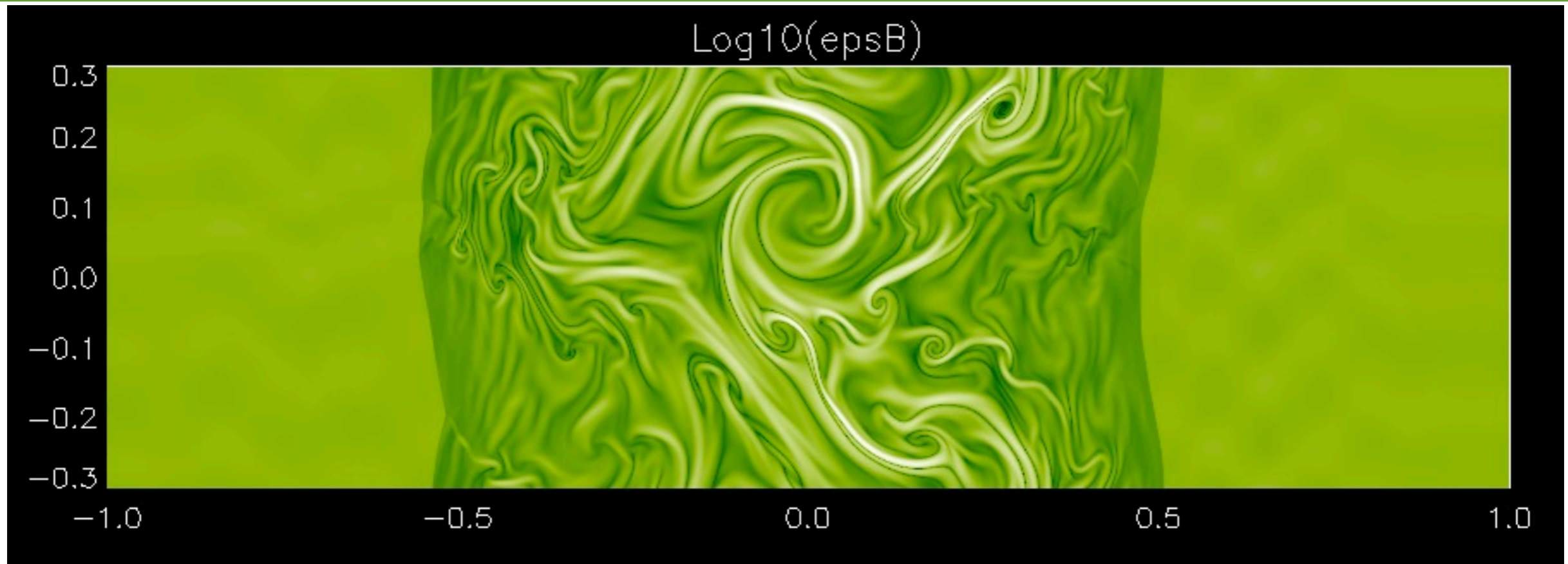
Amplification of Magnetic Fields



- $\epsilon_B \sim 5 \times 10^{-3}$
- Grow rapidly
- Decay very slowly
- Small-scale fields



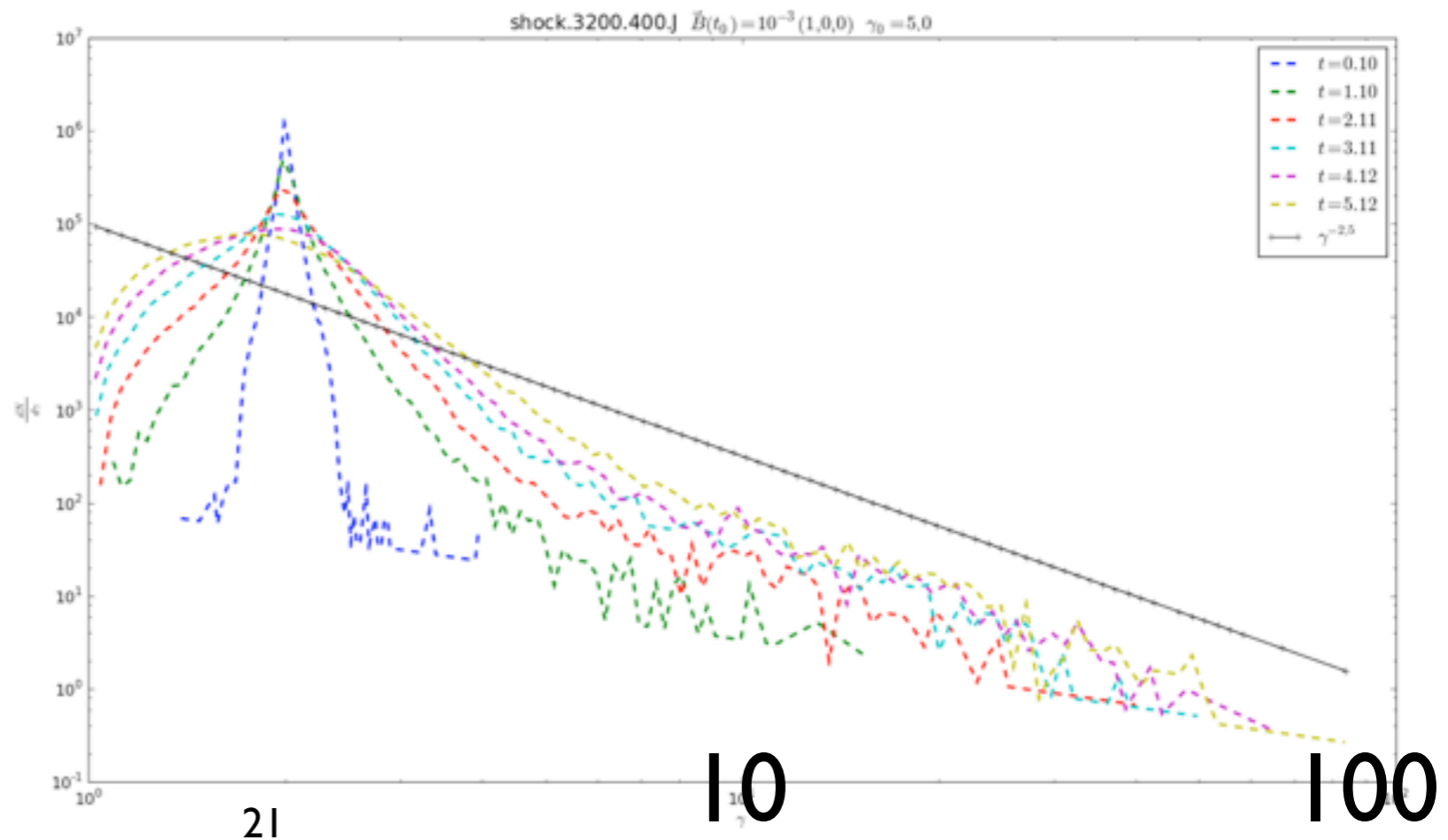
Particle + MHD



Relativistic MHD
+
tracer particles

Turbulence
due to stirring

Zrake et al.



PIC

vs.

MHD

- Kinetic effects
- “First principles”
- Back reaction from particles

- Better methods (e.g., AMR)
- Large-scale
- MHD waves

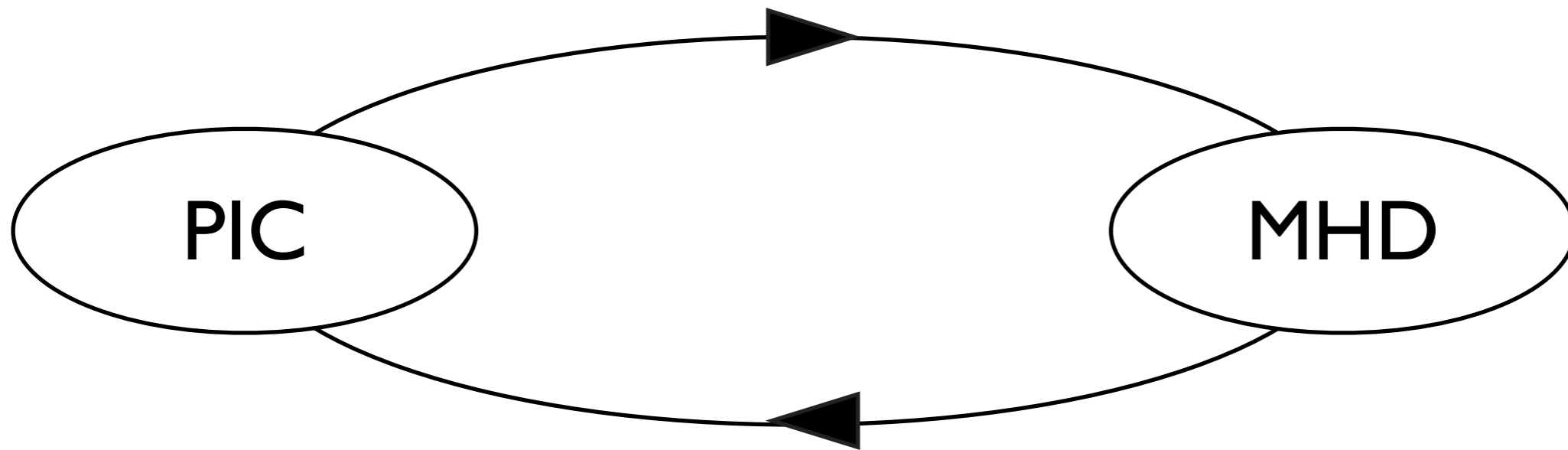
Pros

Cons

- Small-scale
- Noise from particles
- MHD waves

- Lack of Scattering by high frequency waves
- Back reaction from particles

Particle Effects



Initial Conditions