PIC Simulations of Collisionless Shocks

Weiqun Zhang (NYU)

w/ MacFadyen, & Gruzinov (NYU)

How does a GRB Emit Radiation?

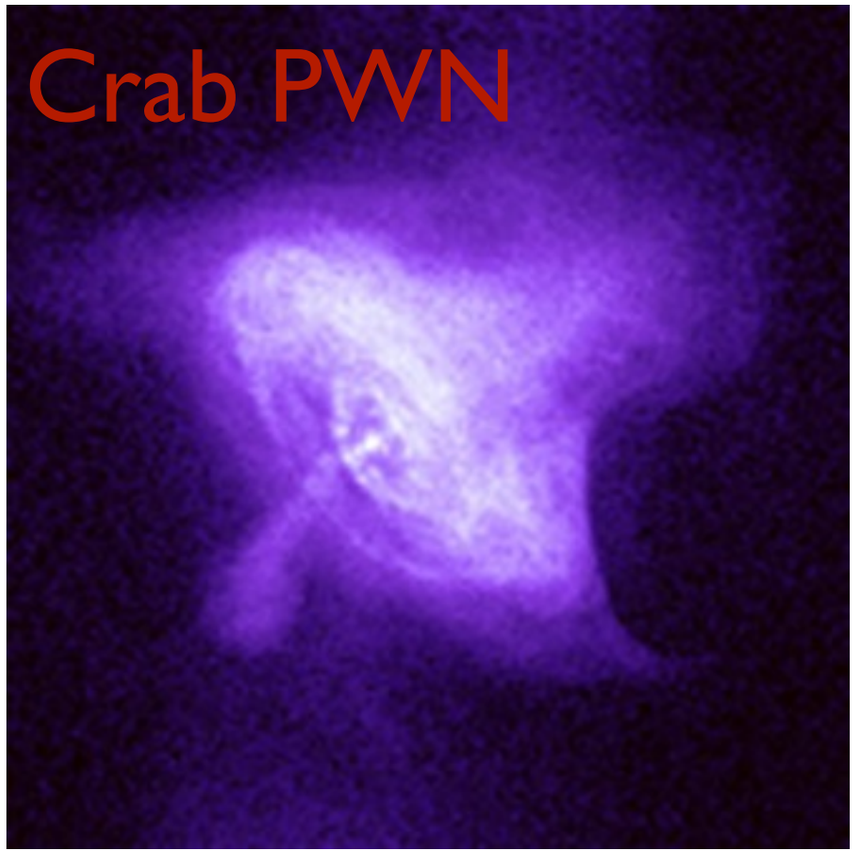
Synchrotron radiation

- Magnetic field: $\varepsilon_B \sim 10^{-3} - 10^{-1}$
  Simple compression by shocks will not work.
  Fields carried over from progenitors are too weak at large radii.

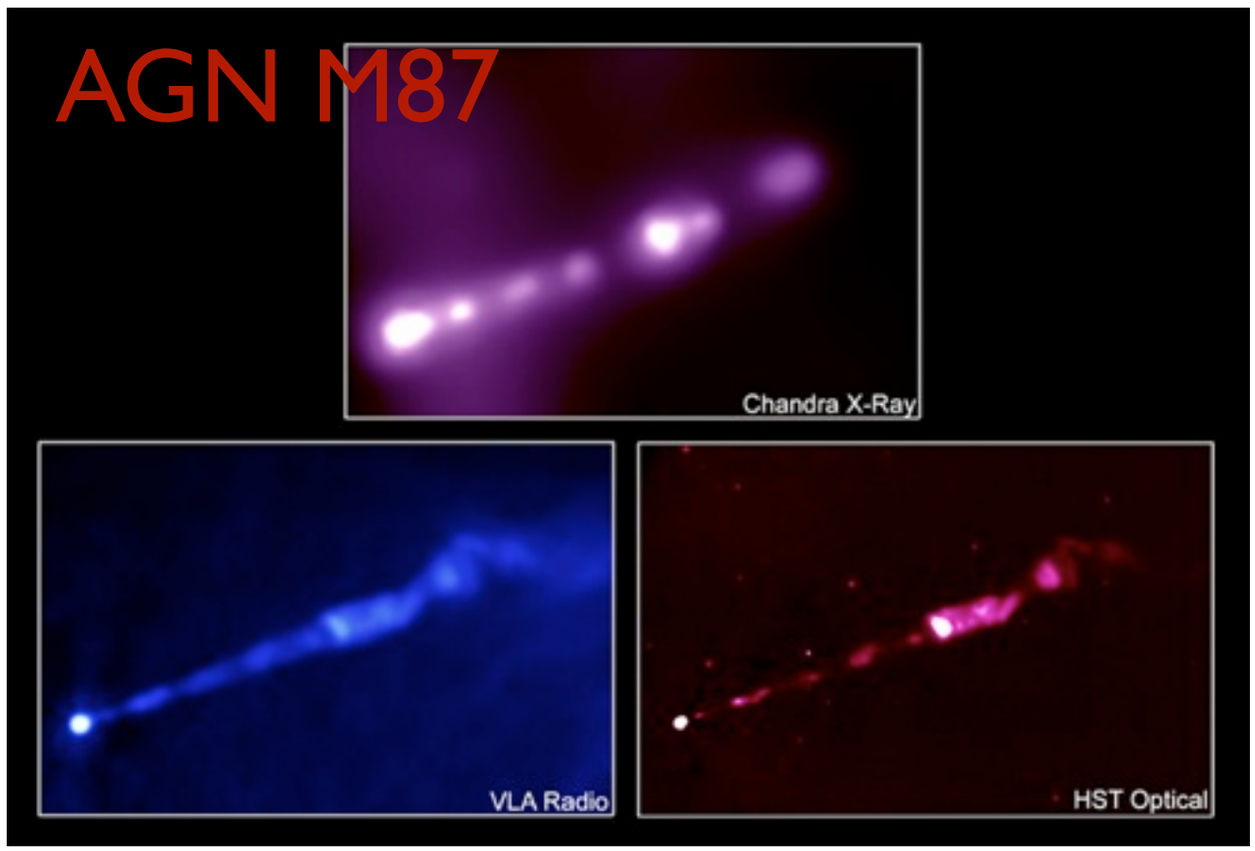
- Nonthermal electrons: $\varepsilon_e \sim 10^{-3} - 10^{-1}$
  Particle acceleration

Collisionless Shock!

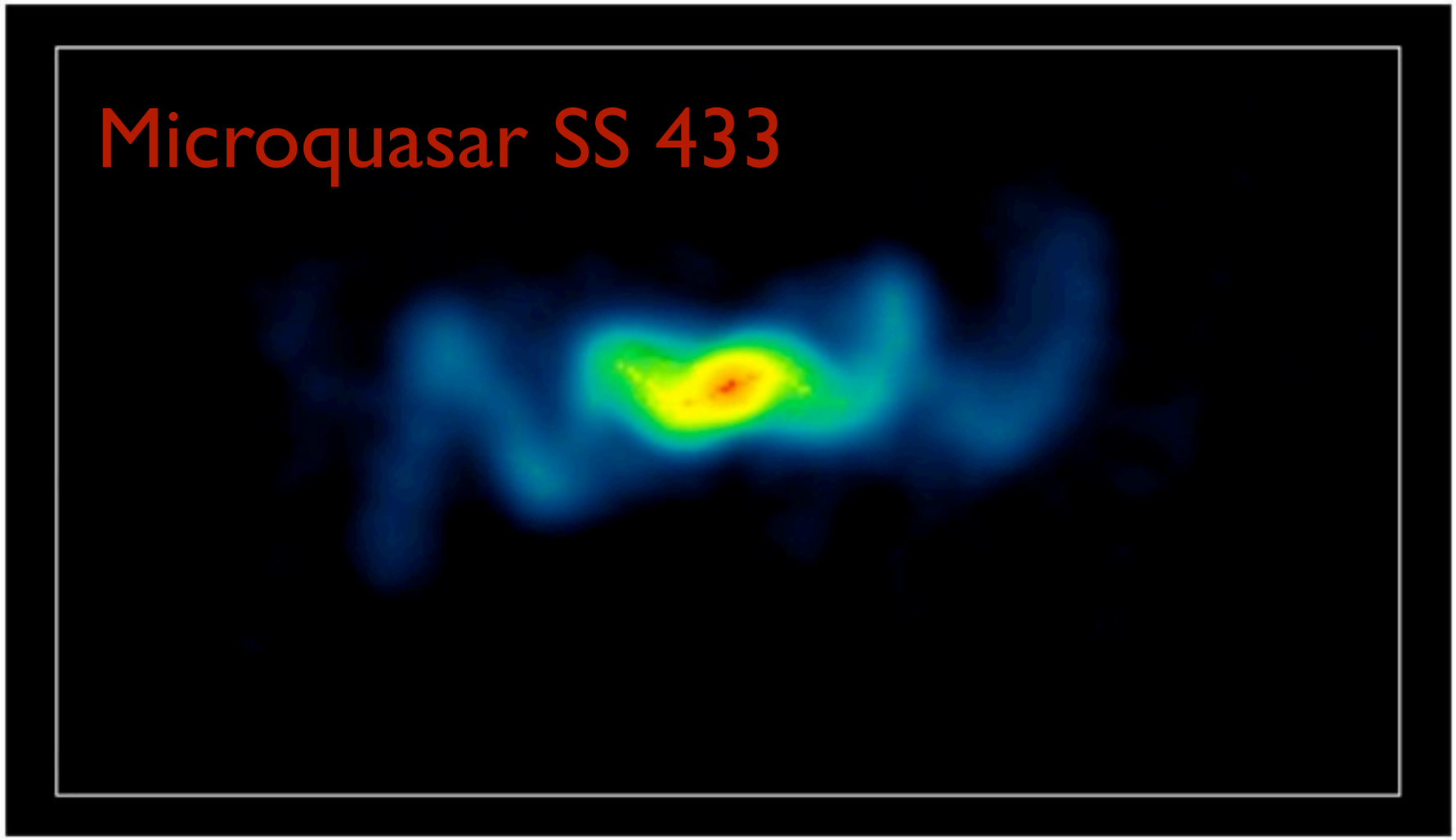
Crab PWN



AGN M87



Microquasar SS 433

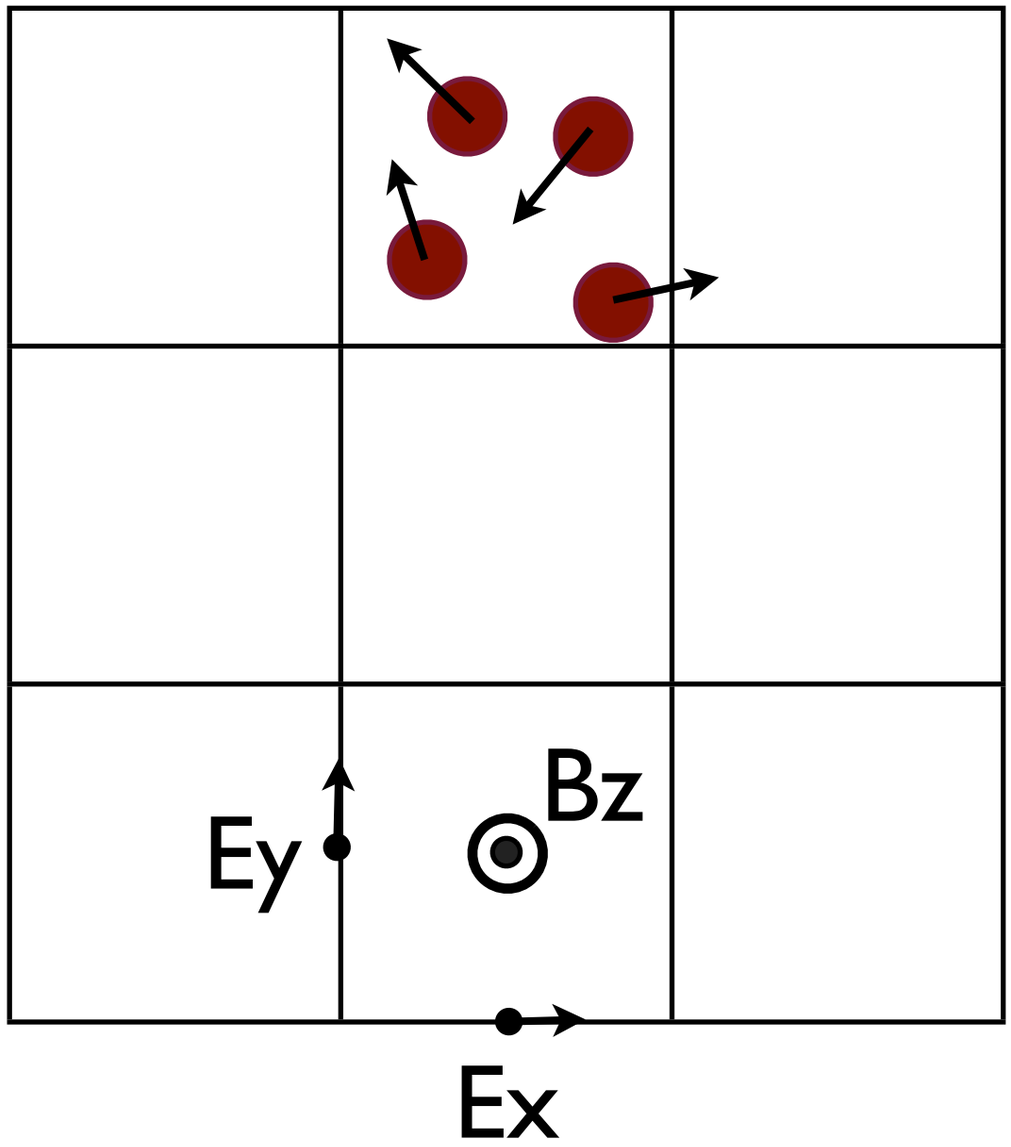


Relativistic Collisionless Shocks

- GRB outflows are collisionless.
  (mean free path >> size of the outflow)
- Shock exists because of plasma instabilities (e.g., Weibel instability). No preexisting fields required!!
- Fermi acceleration.

Particle-in-Cell (PIC, aka PM)

$$\partial E/\partial t = \nabla \times B - j$$
$$\partial B/\partial t = -\nabla \times E$$
$$d\gamma mv/dt = q\,(E + v \times B)$$

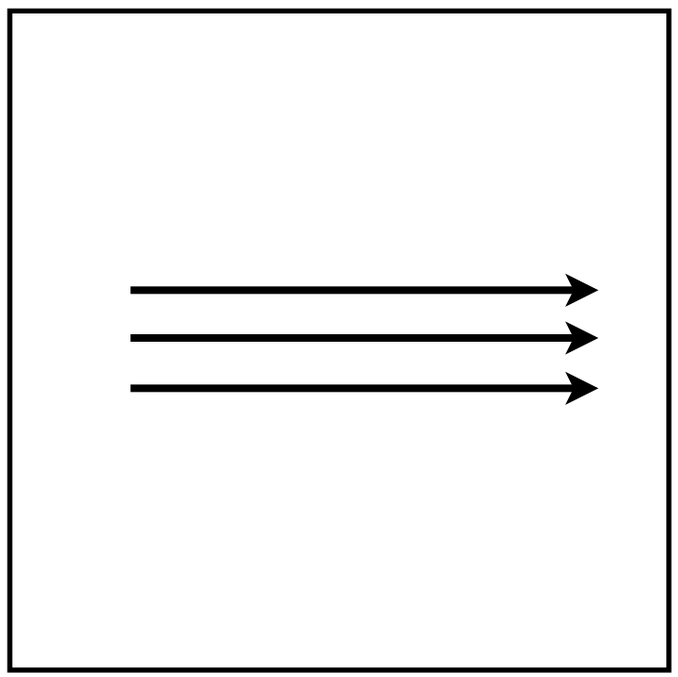


Our Simulations: Υ=2 Why γ=2, not 15?

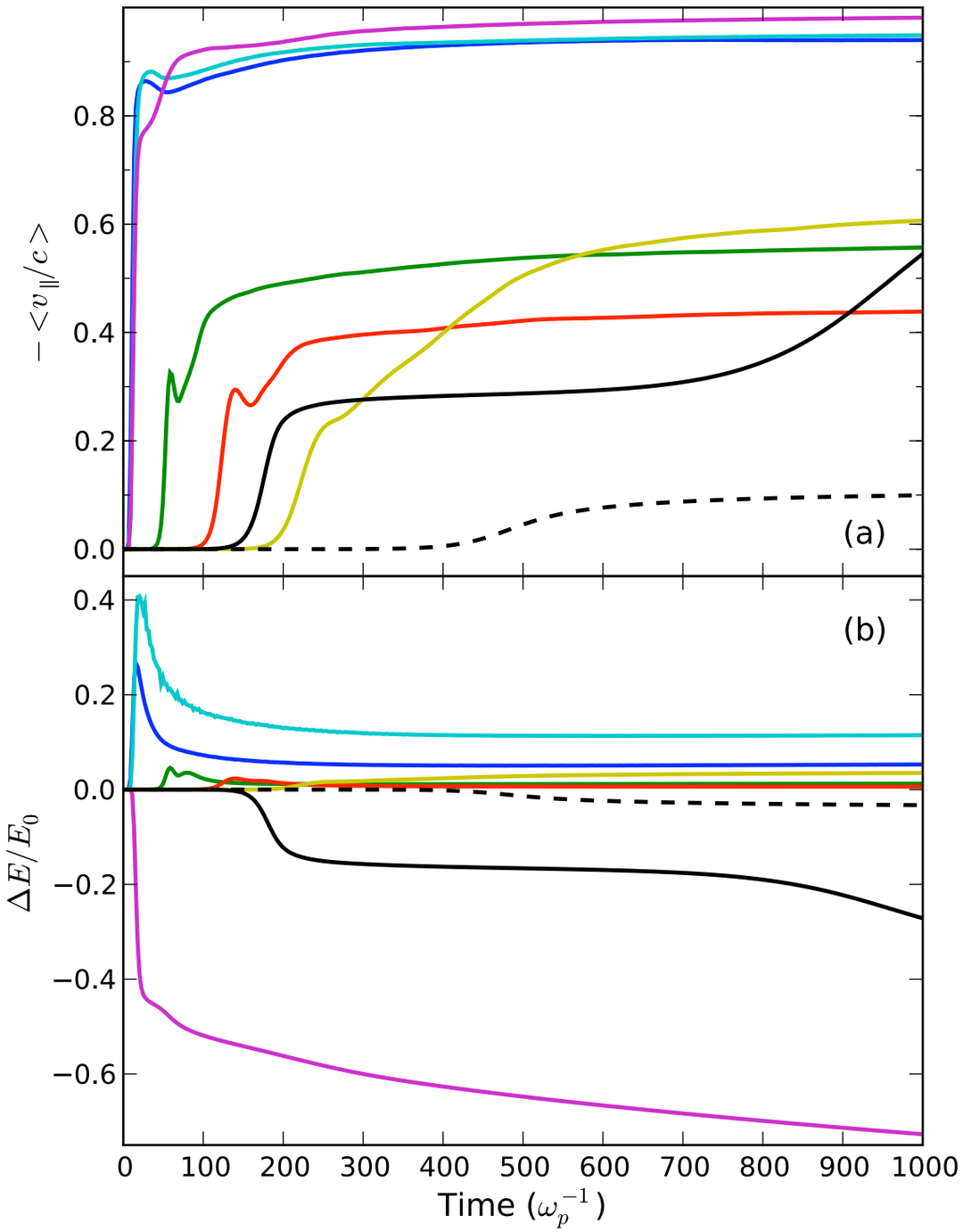
- $2 < 15$ $2^2 << 15^2$
- More relevant for GRB afterglows and prompt emissions.
- Numerically easier to control numerical Cerenkov radiation

Maxwellian in rest frame

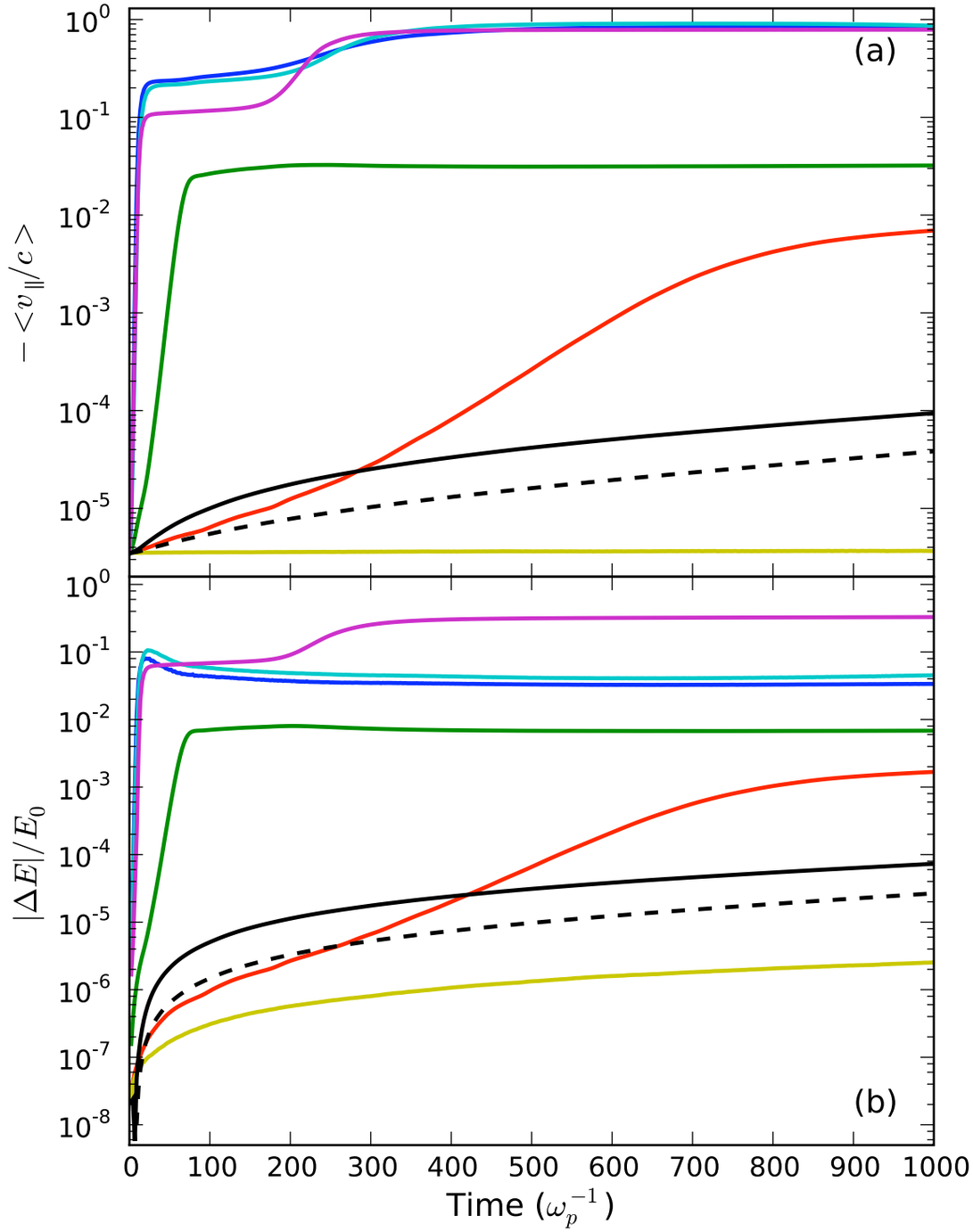
Nothing should happen!



The beam velocity in the original rest frame should be 0

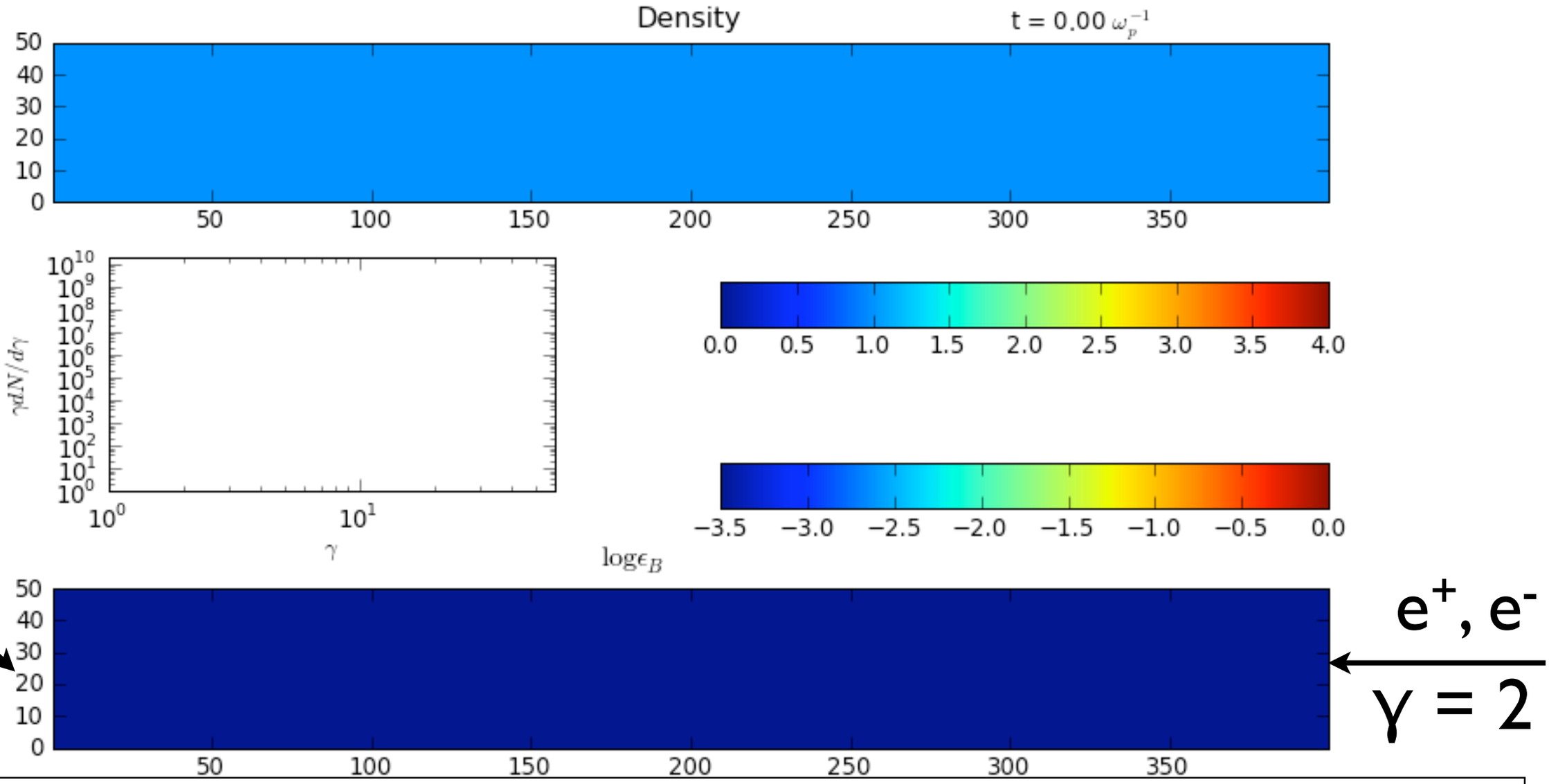


γ =15



γ = 2

PIC Simulations of Collisionless Shocks

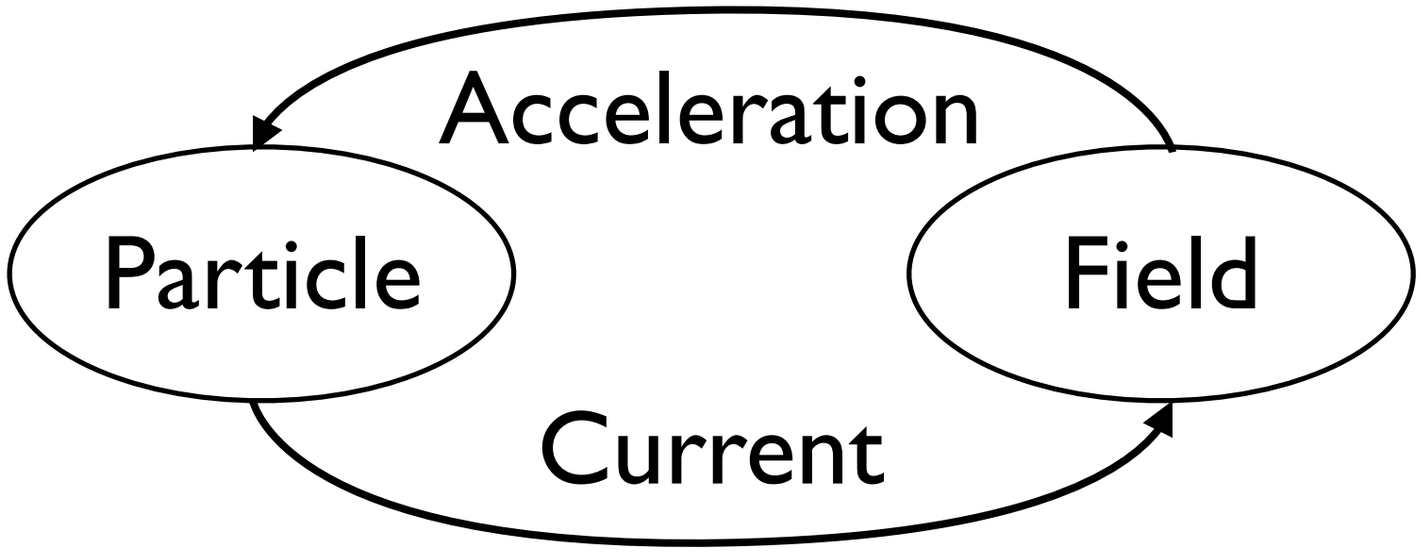


- 2D w/ 50000 x 1000 cells
- Δx = 0.05 skin depth
- 32 particles per cell initially, 4 billion particles in the end
- Similar to Spitkovsky & Arons except γ and resolution

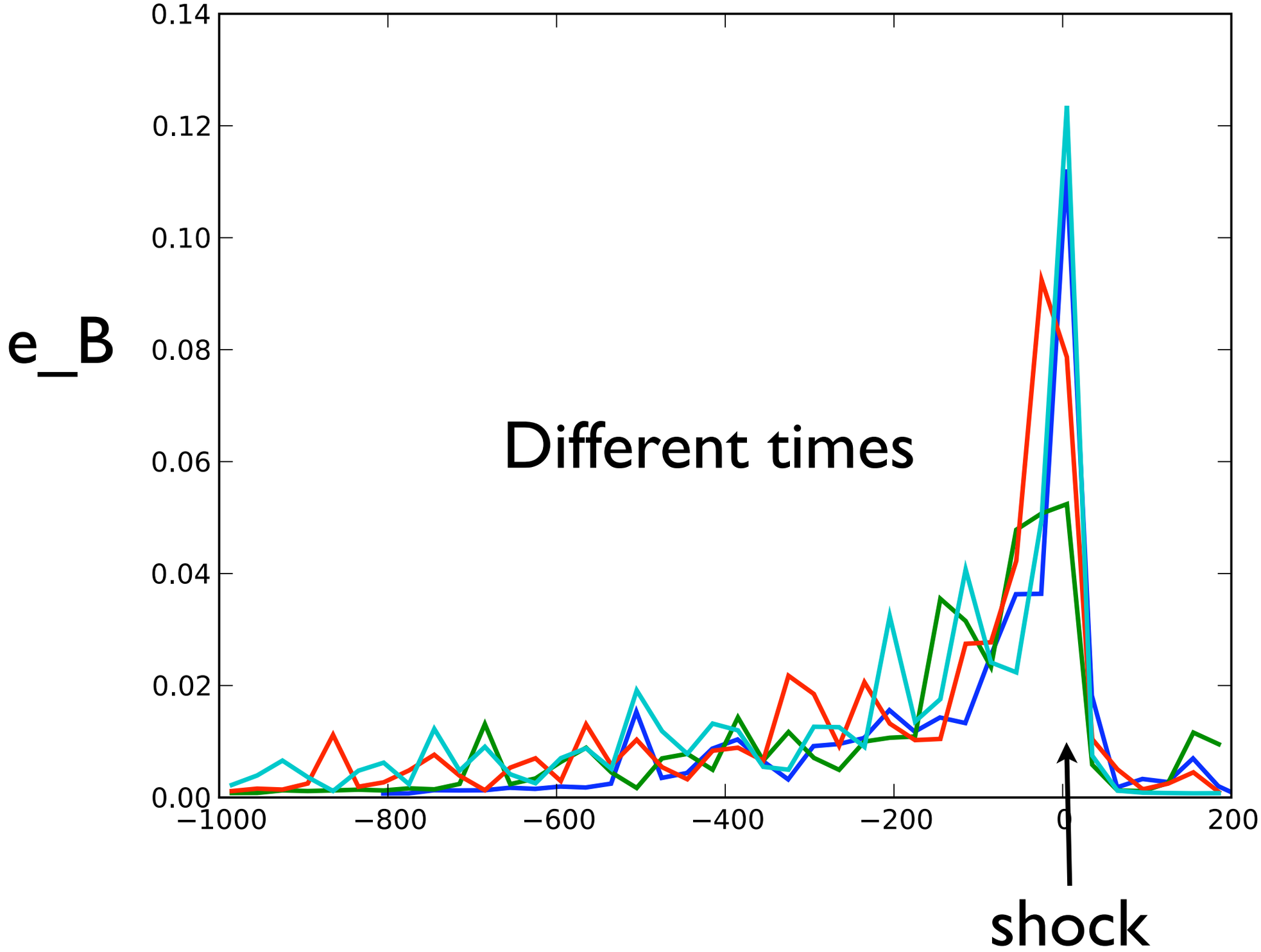
From 10^6 cm to 10^{16} cm

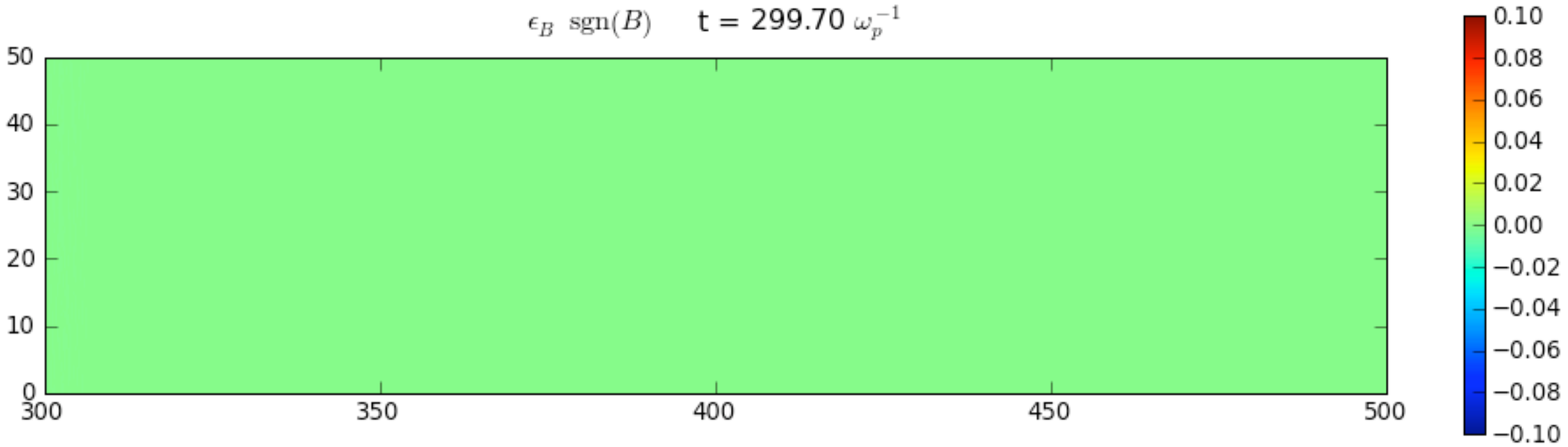
Skin Depth ⟶ Emission Region

10 orders of magnitude

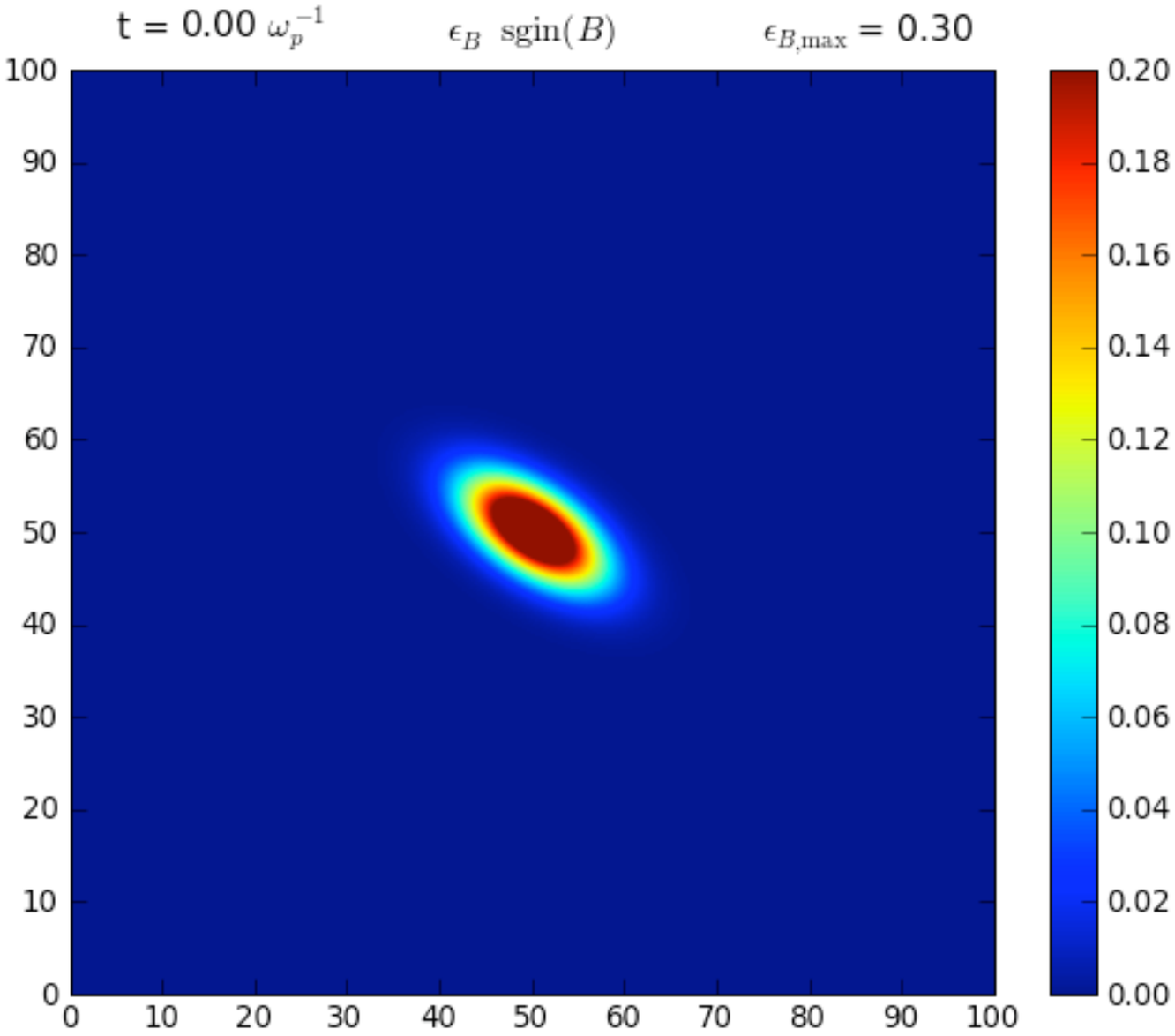


- 10-100 skin of $\varepsilon_B \sim 0.1$ is all a shock needs.
- Magnetic fields dissipate.
- Most particles are stopped by the shock.


e_B
Different times
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−1000
−800
−600
−400
−200
0
200
shock

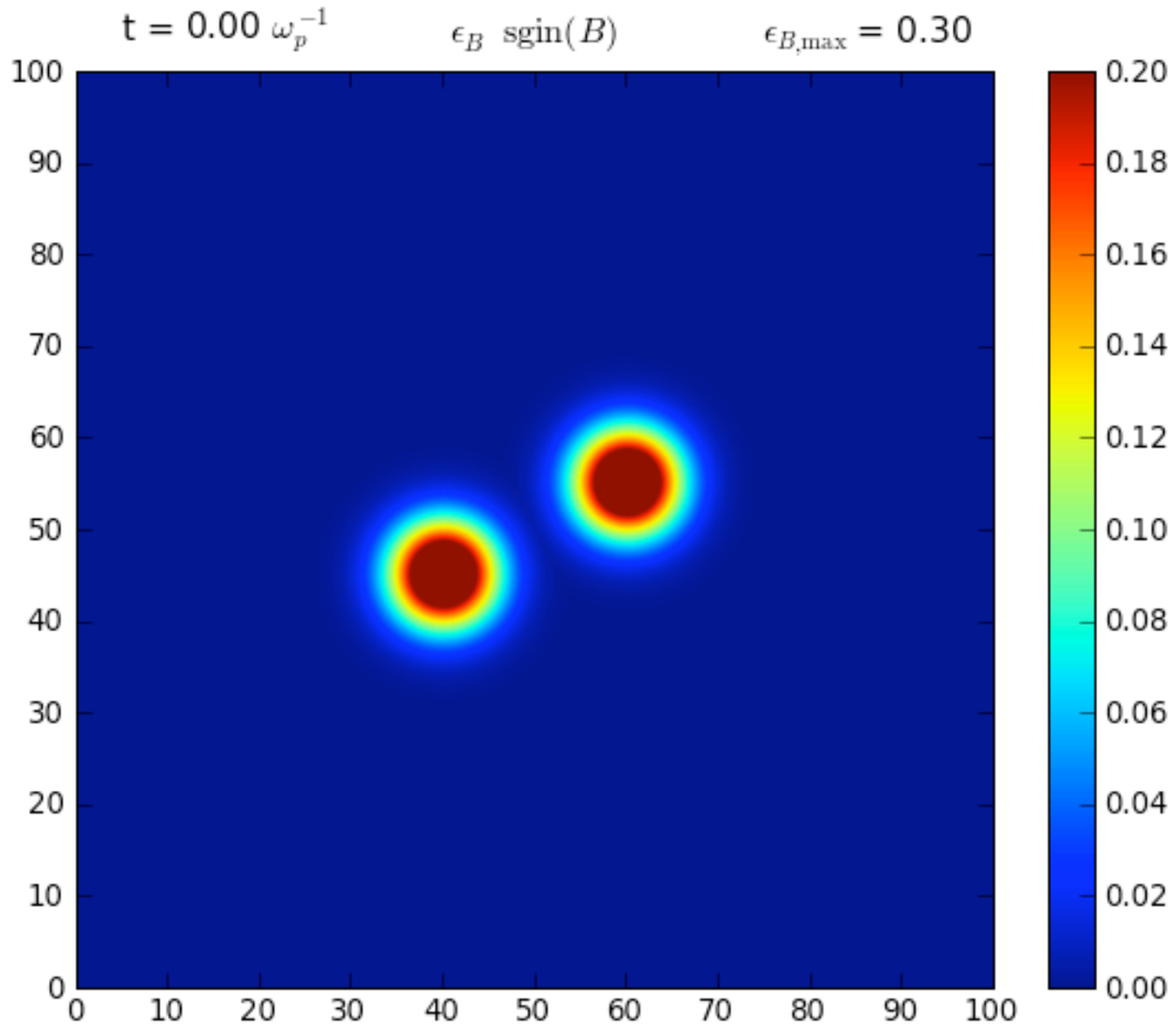


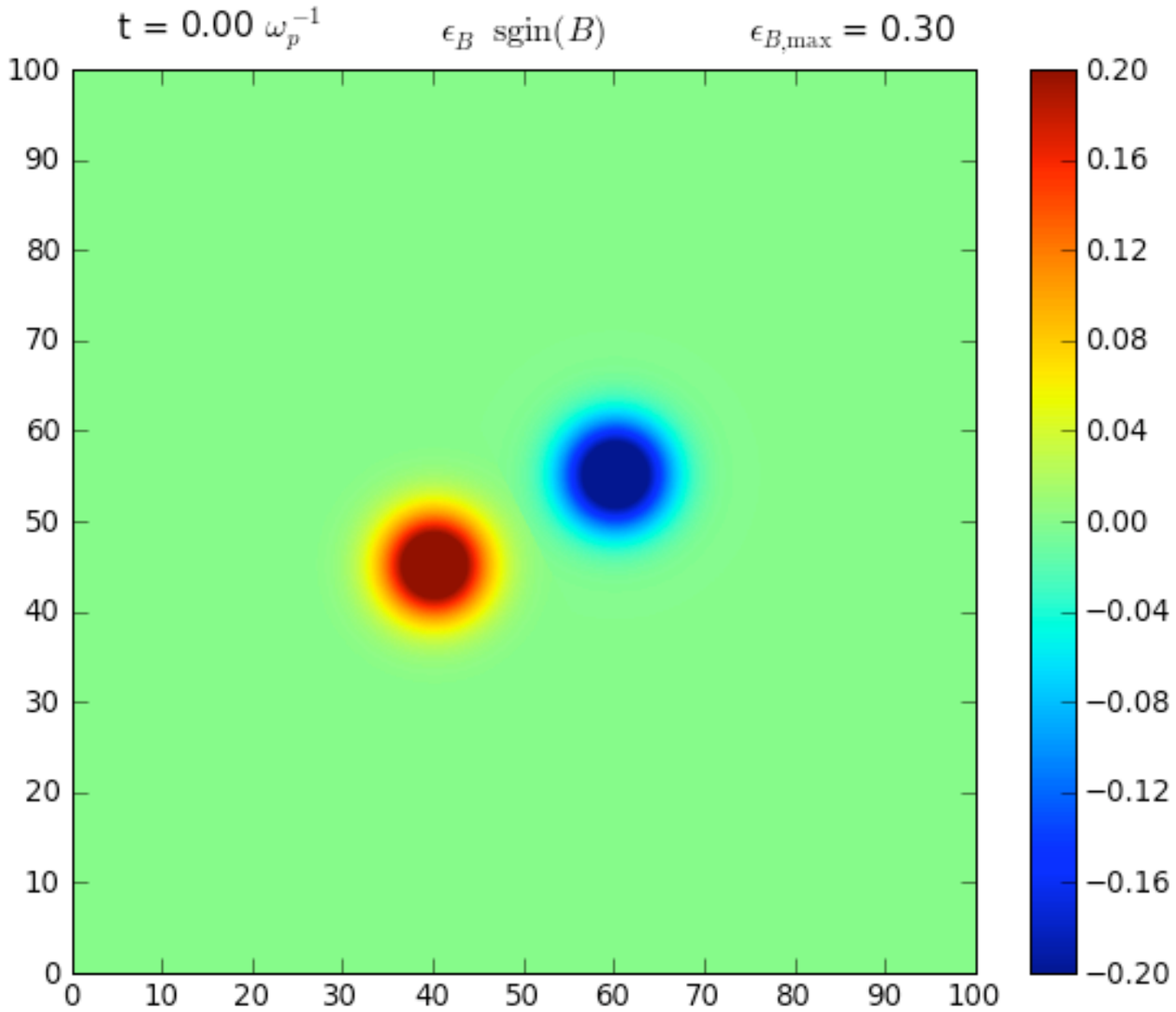
- Elongated ==> Circular
- Same signs: merge
- Opposite signs: kill each other
- e_B ~ t^-0.5 ?



- curl B ≠ 0
- E
- particles moves
- chaotic, nonintegrable, energy is the only integral of motion
- circular, integrable, second integral of motion: generalized angular momentum

Initial conditions:
Maxwellian particles + magnetic bubble


t = 0.00 ω_p^{-1}
ϵ_B sgin(B)
$\epsilon_{B,\max}$ = 0.30
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00


t = 0.00 ω_p^{-1}
ϵ_B sgin(B)
$\epsilon_{B,\max}$ = 0.30
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
0.20
0.16
0.12
0.08
0.04
0.00
−0.04
−0.08
−0.12
−0.16
−0.20

- Simple 2D models do not work!?
- 3D??? Magnetic fields in 3D probably decay faster.
- MHD???
- upsteam???