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Particle acceleration in explosive reconnection

CHARM@ROB
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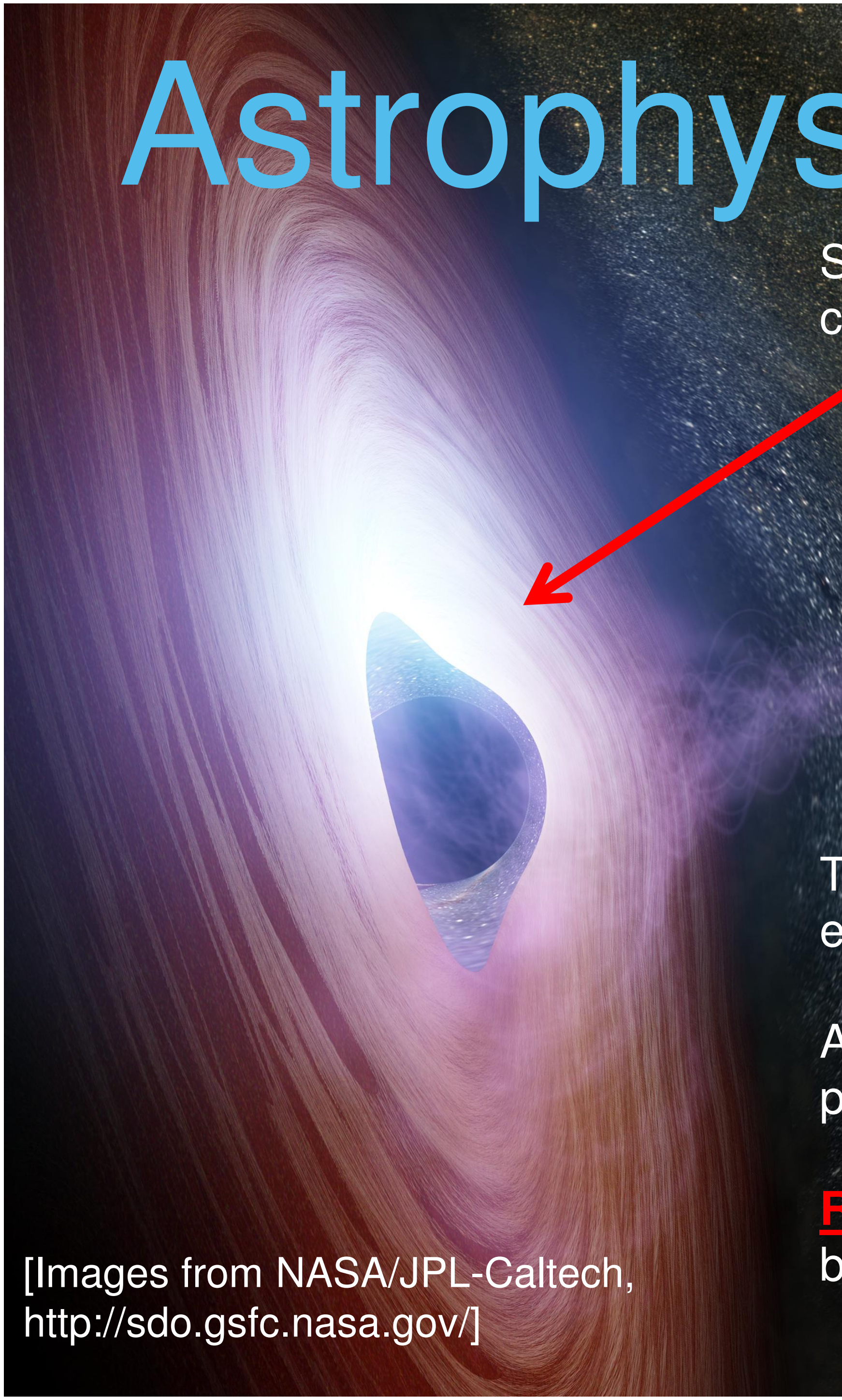
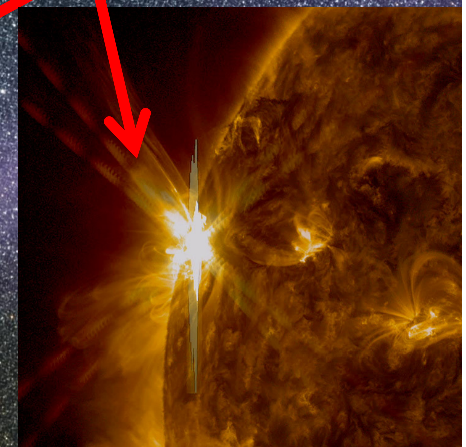
Astrophysical outflows

Stars and black holes can launch flares from their corona





These outflows are a source of extremely energetic particles guided by magnetic fields

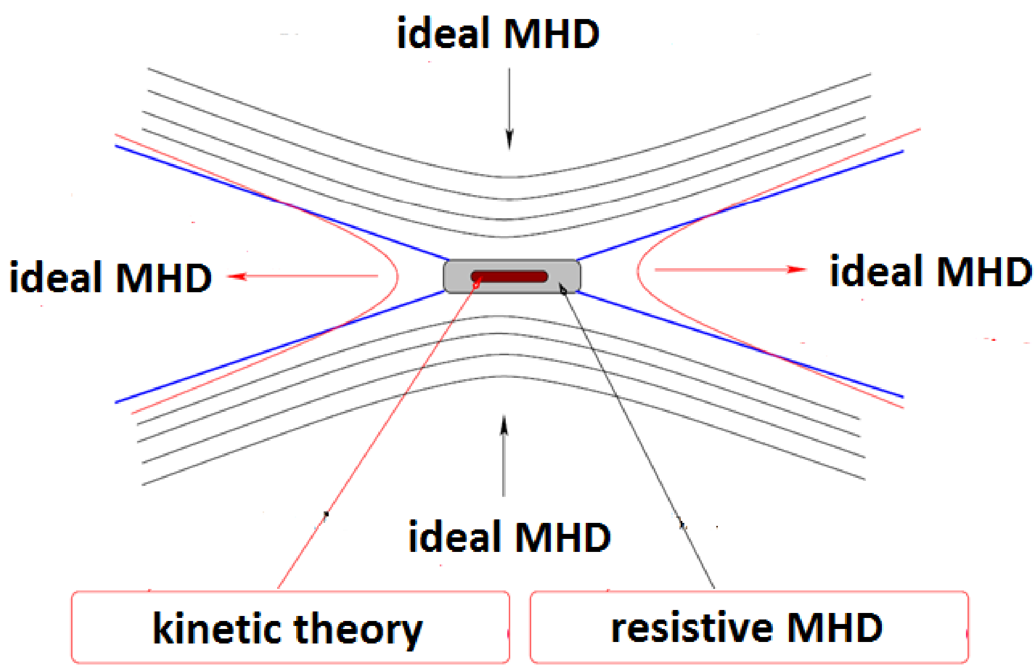
Accelerated, charged particles (electrons, positrons, protons) emit observable radiation

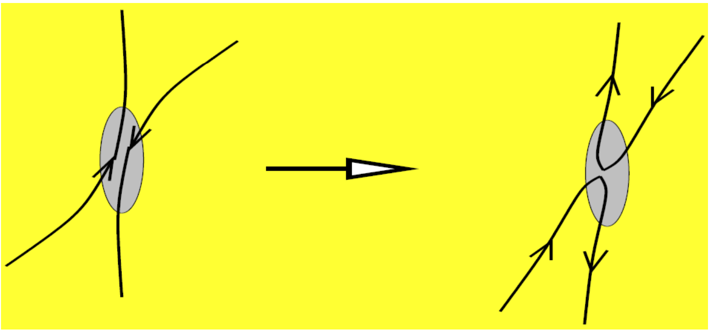
Reconnection is a possible generic mechanism behind flares and **particle acceleration**

[Images from NASA/JPL-Caltech, http://sdo.gsfc.nasa.gov/]

Magnetic reconnection

- Current dissipation through resistivity → Magnetic field reconnection
- Multi-scale character: fluid theory (MHD) → kinetic theory (particles)
- Excess magnetic energy → Particle acceleration in jets and flares

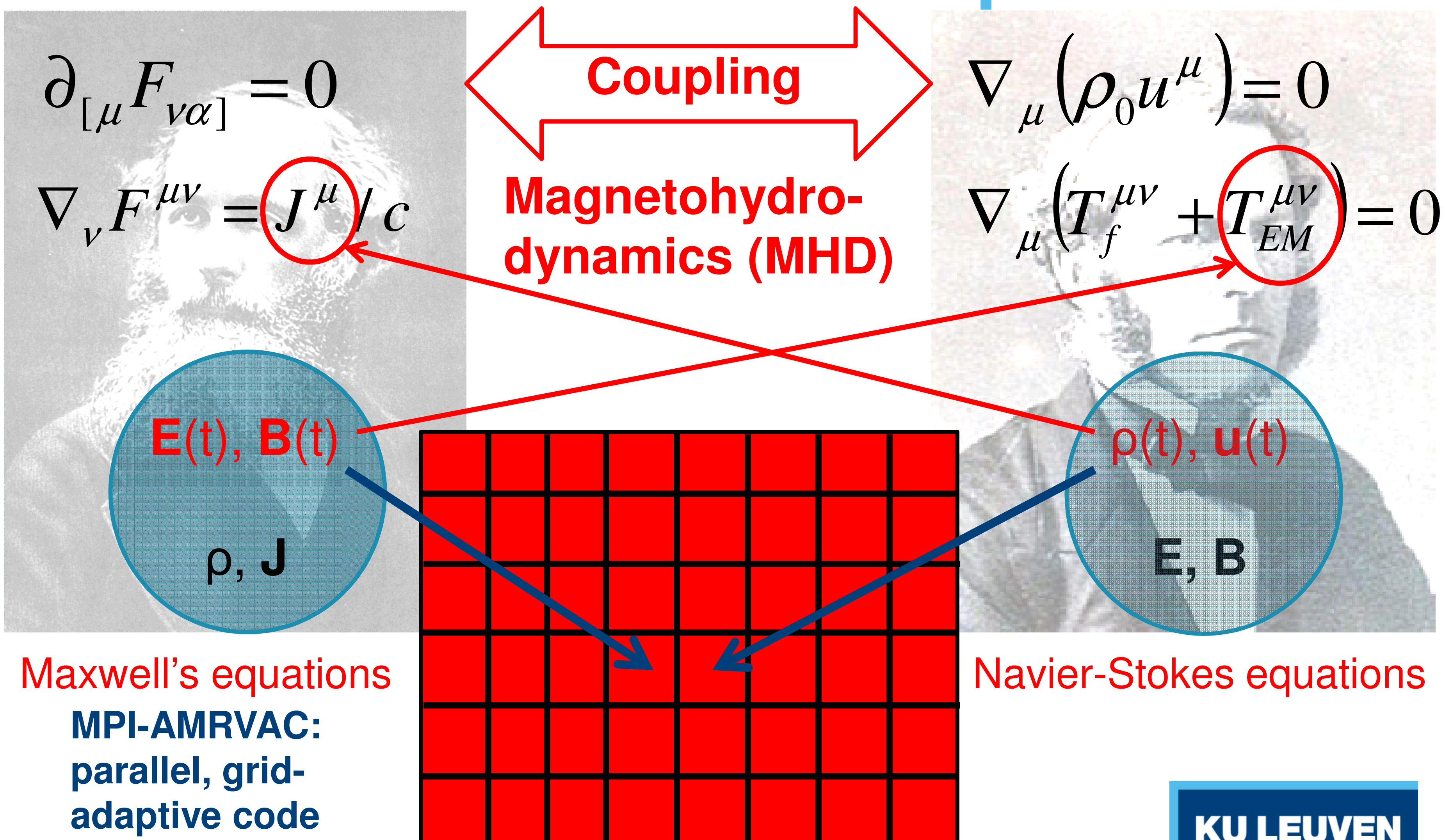




[Images obtained from Keppens, Coupling Multiple Scales, NBIA school 2013]

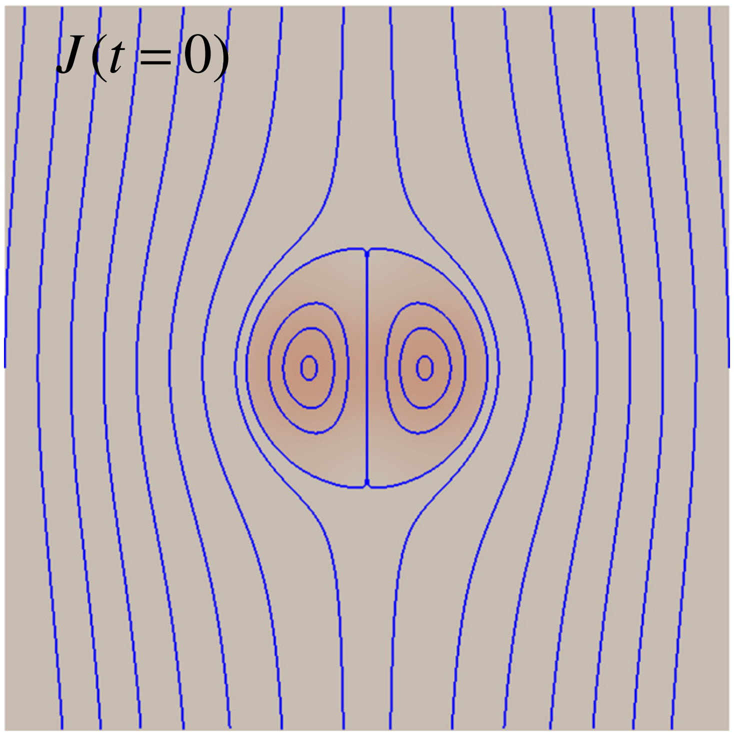
How do we model phenomena at such different scales?

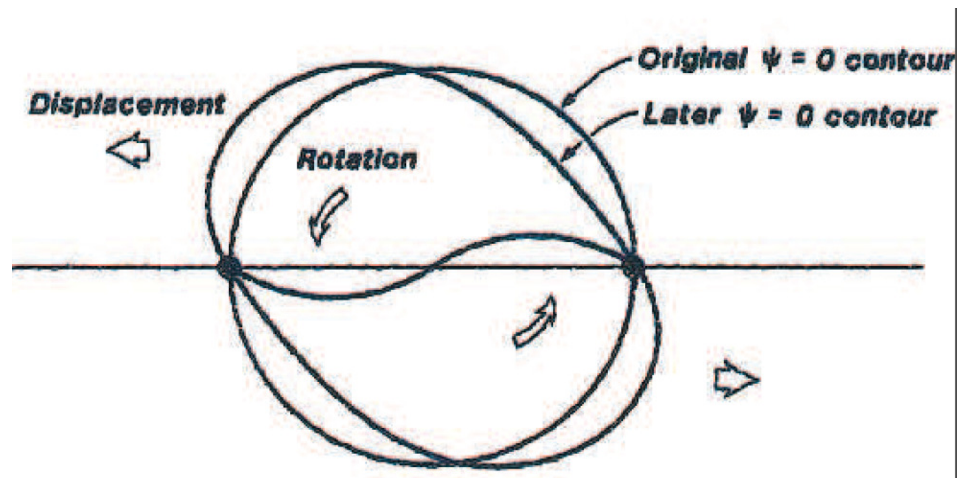
The continuum picture



Initiating reconnection in MHD

- 2D force-free ideal MHD equilibrium: two repelling currents
- → Tilt instability and resistivity → Reconnection → Particle acceleration





Sketch taken from Lankalapalli et al, JCP 225 (2007)

- 3D effects → Kink (in)stability

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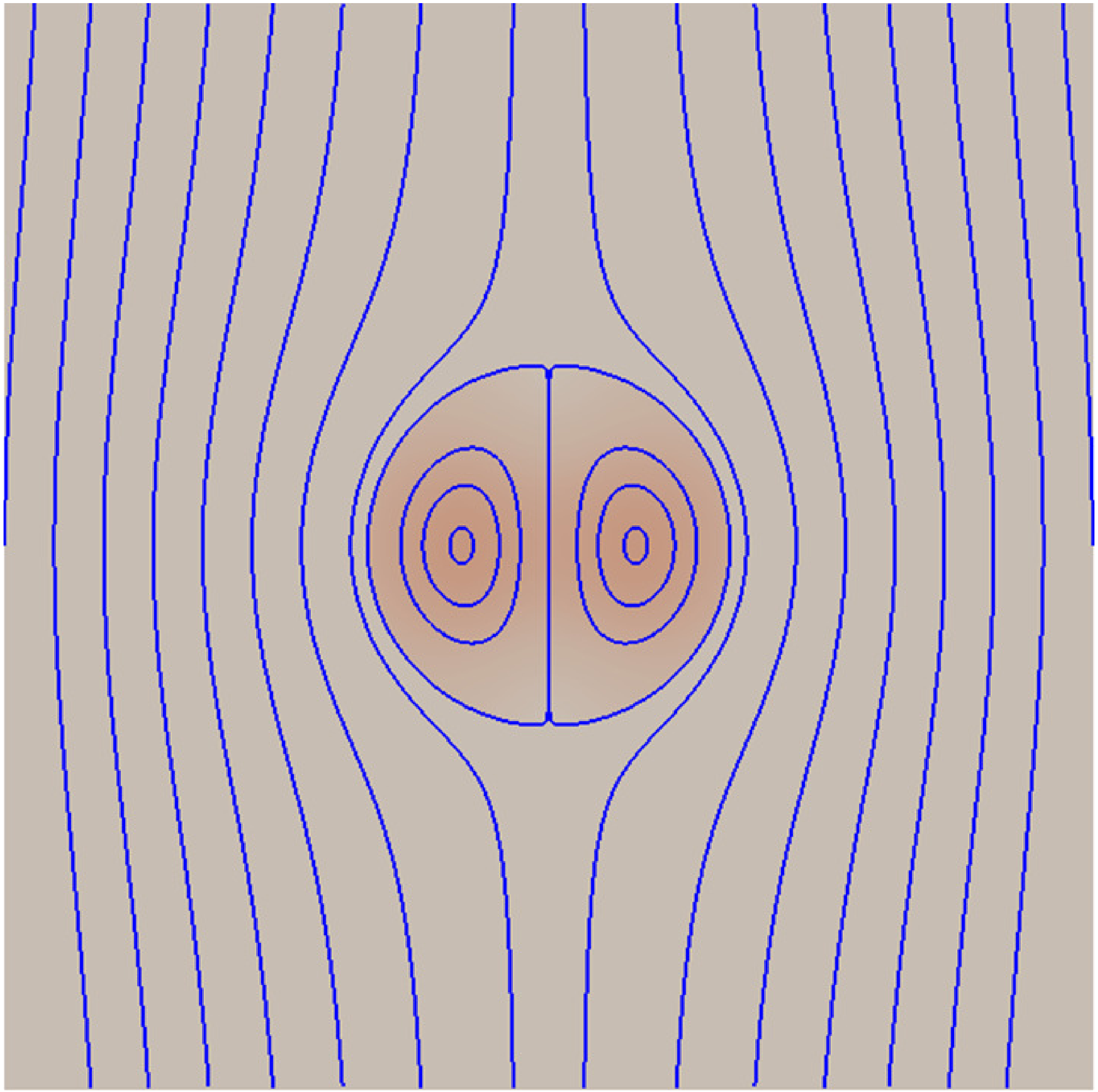
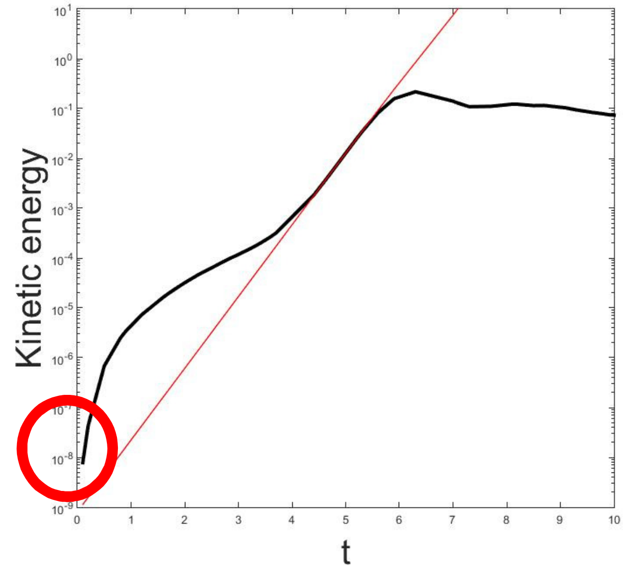
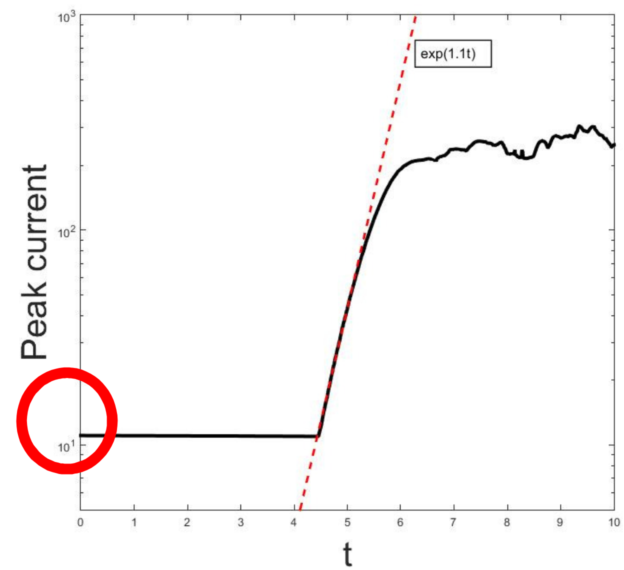
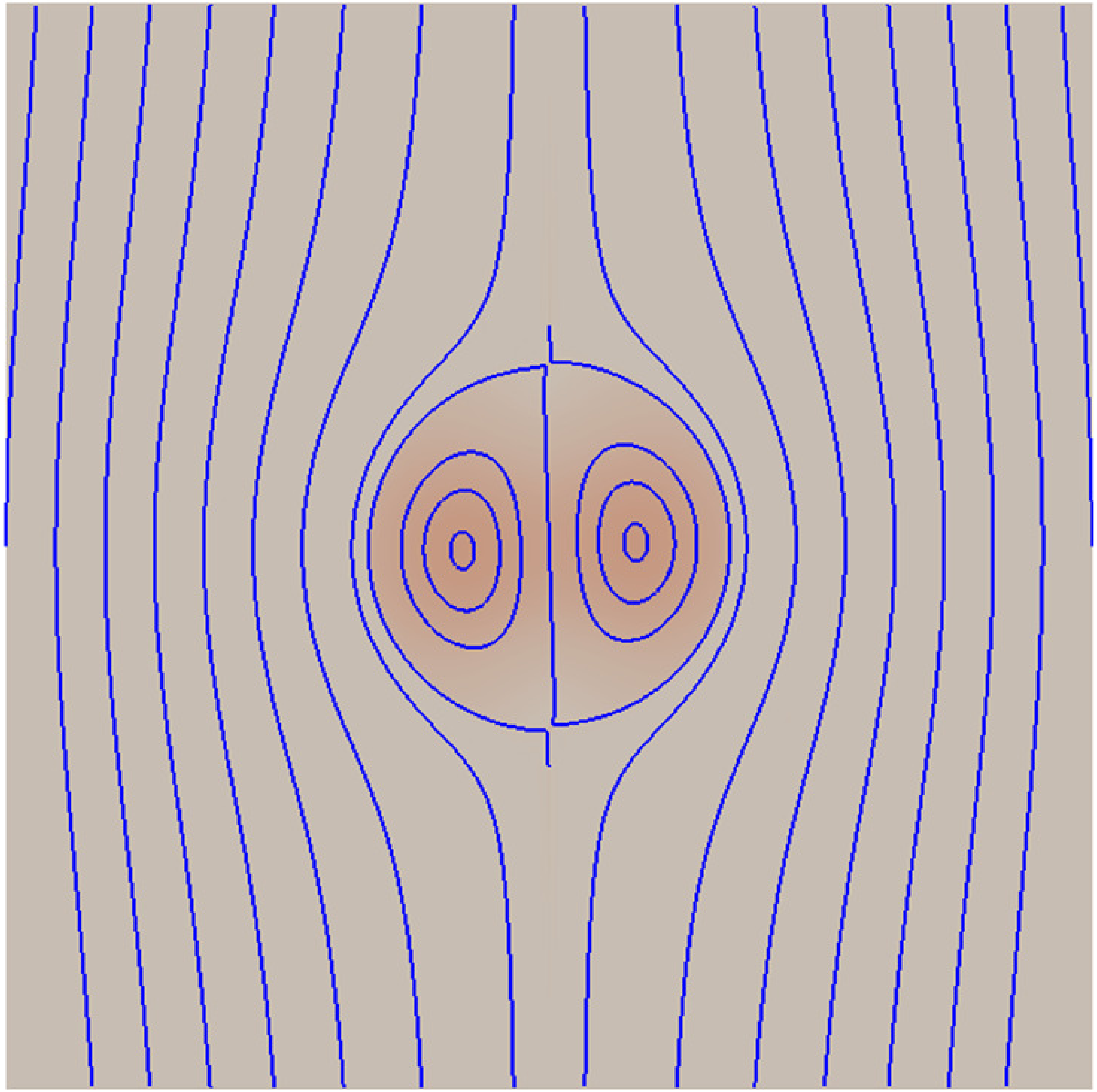
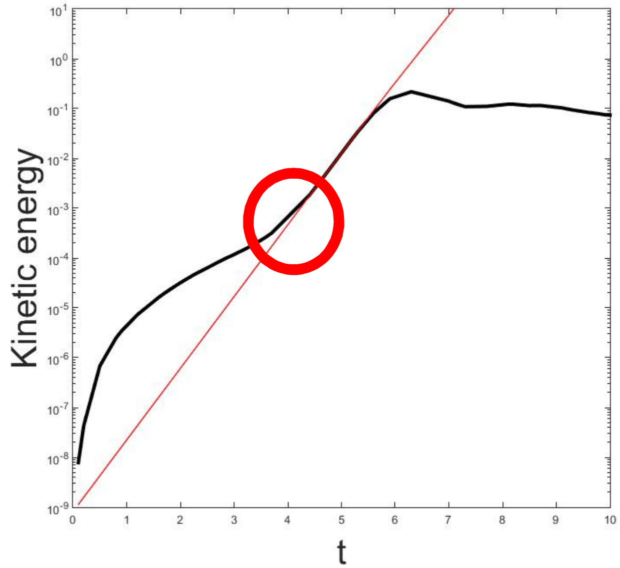


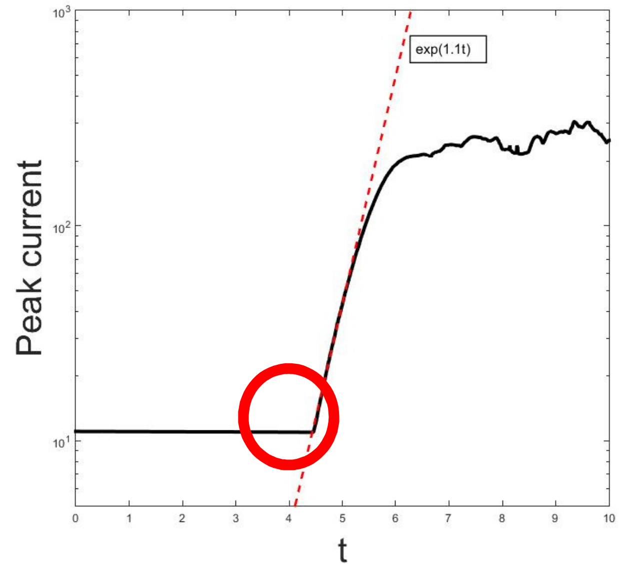




J(t=0)







J(t=4)

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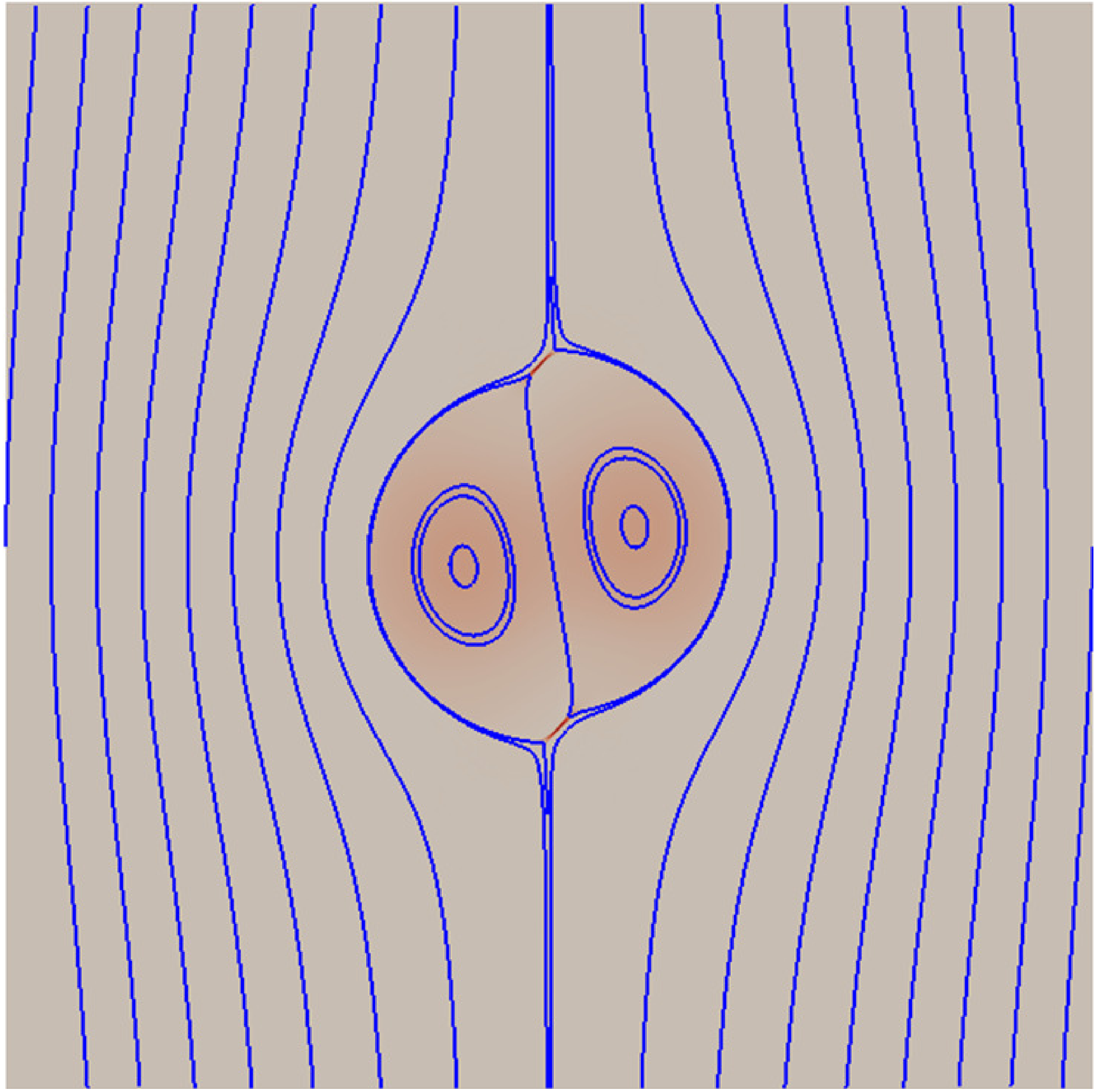

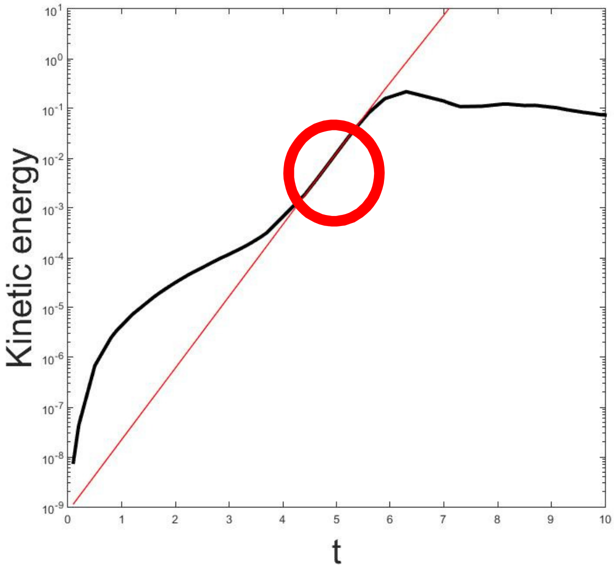

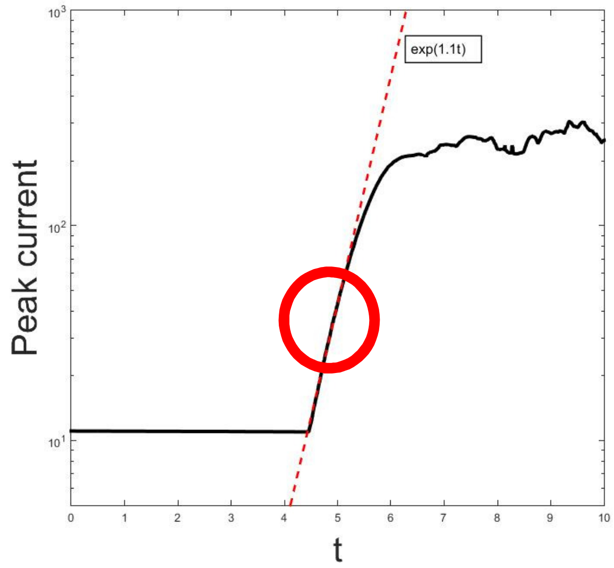

J(t=5)

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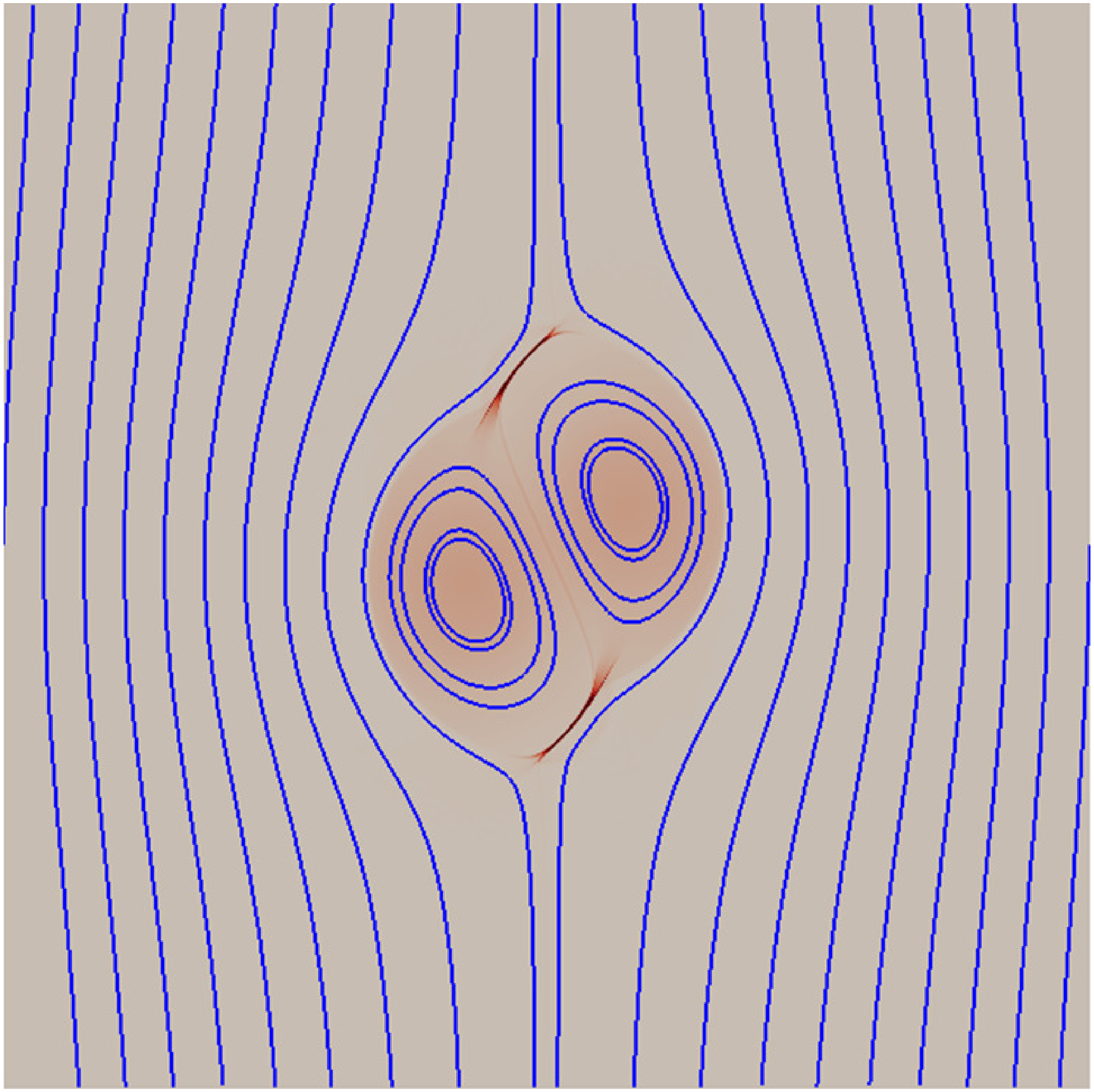
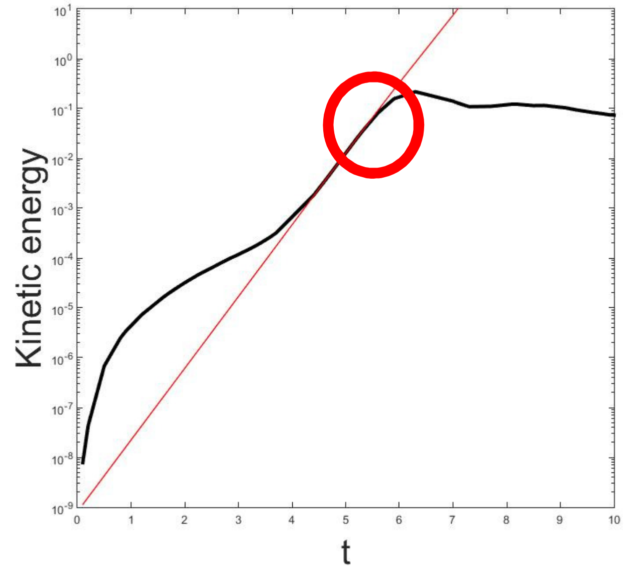
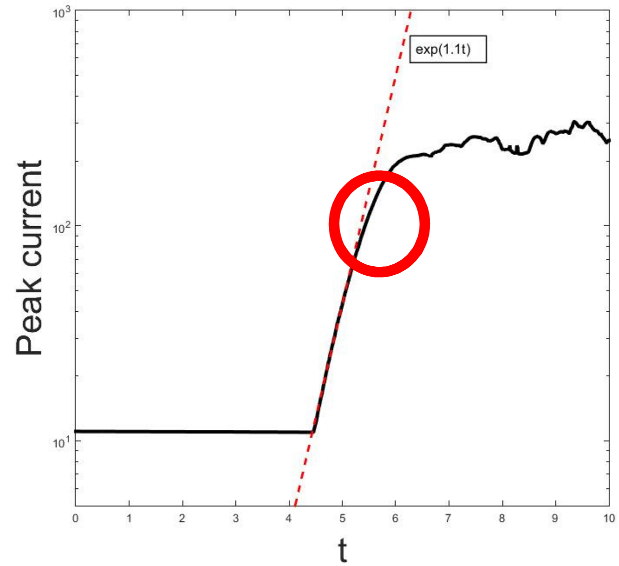
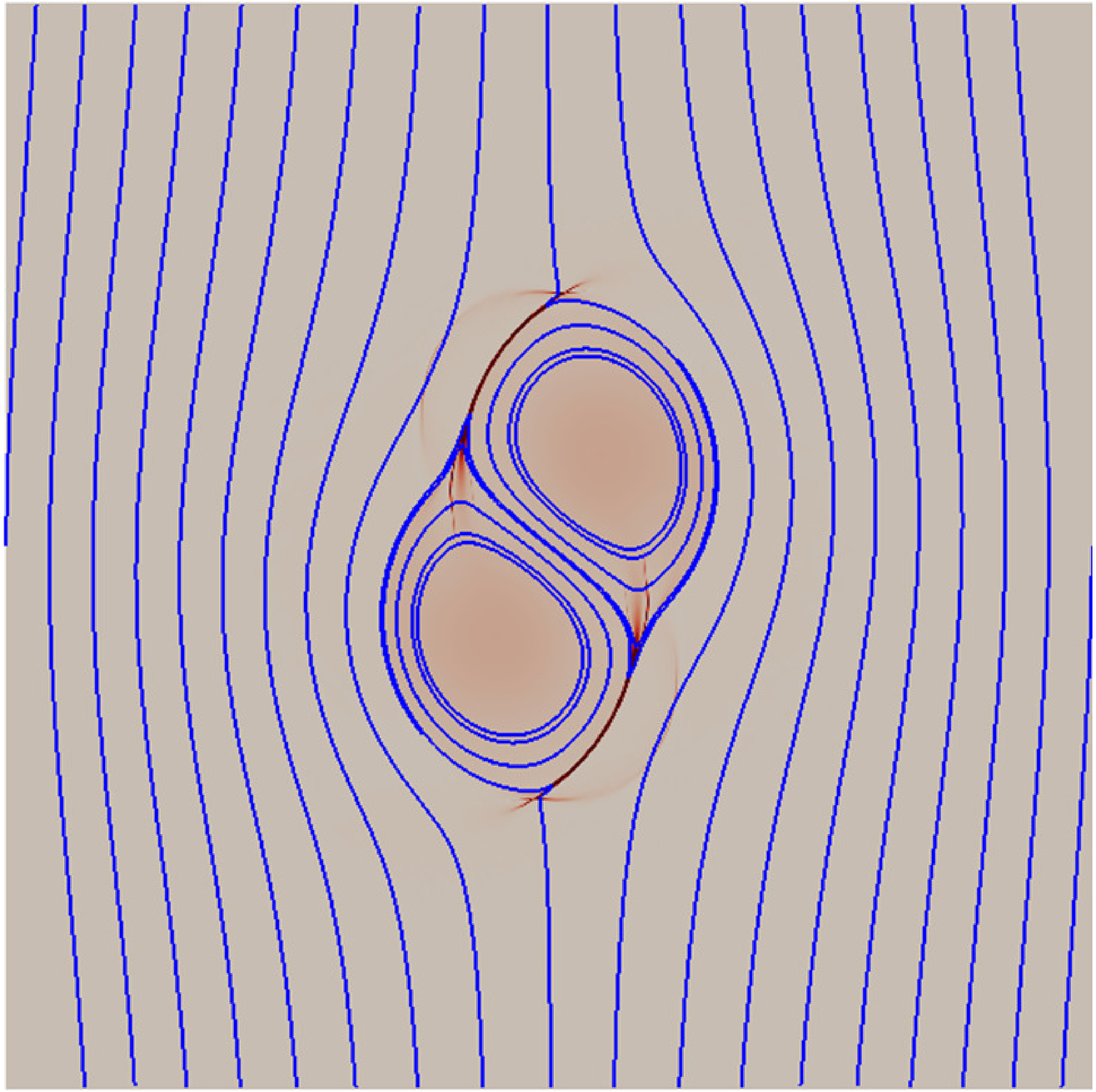
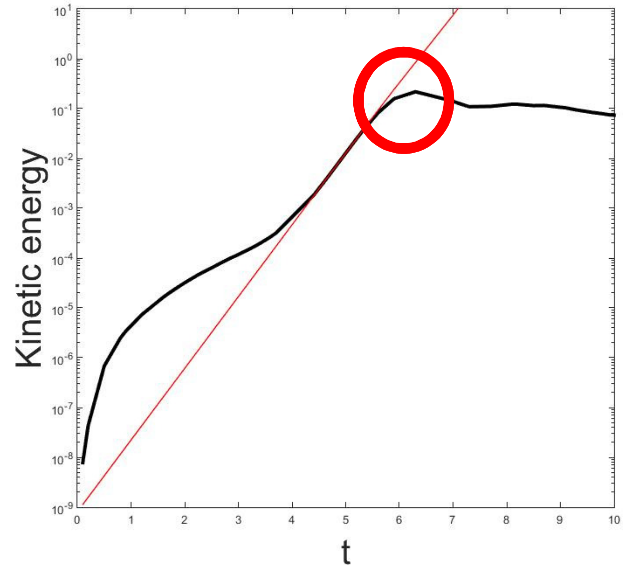


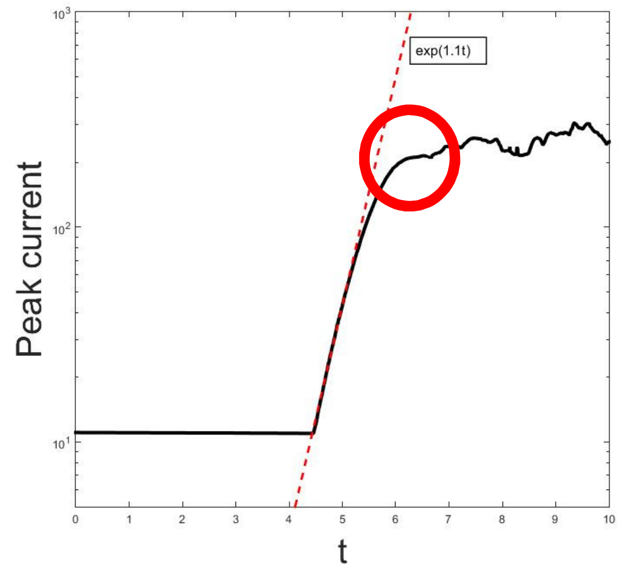




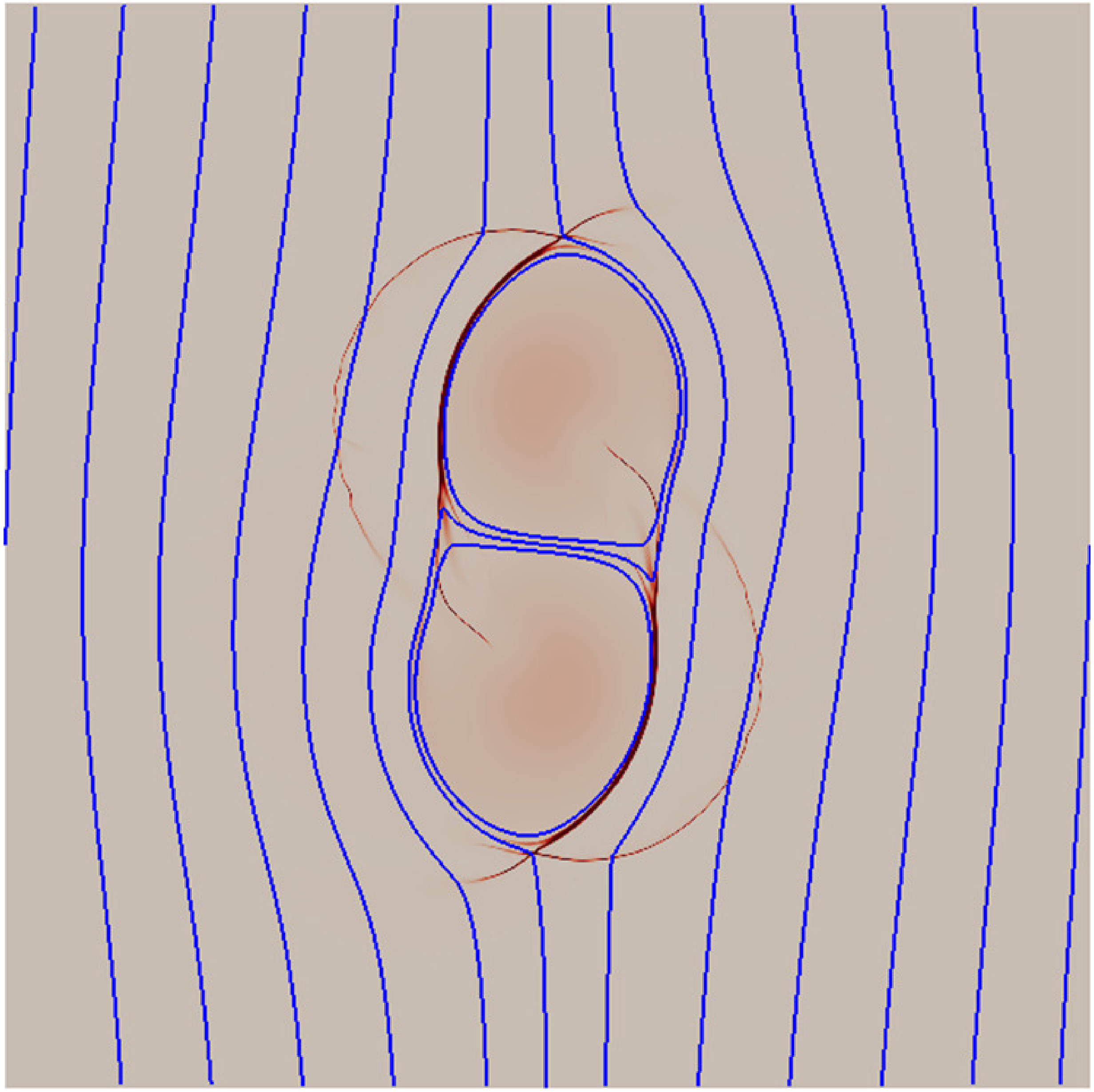
J(t=5.5)

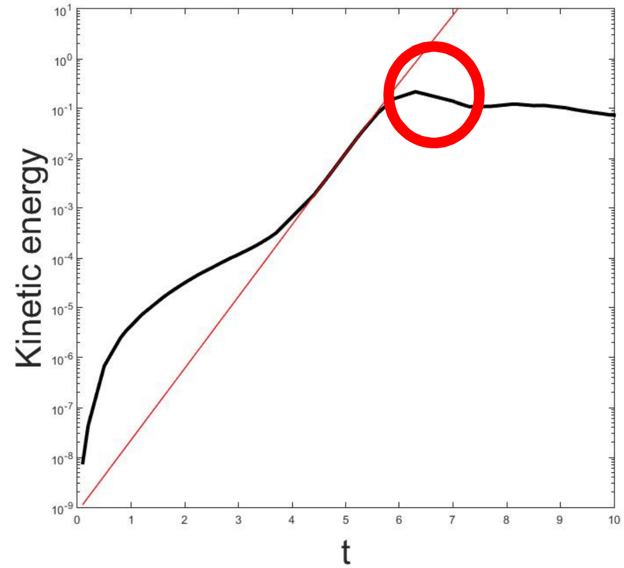


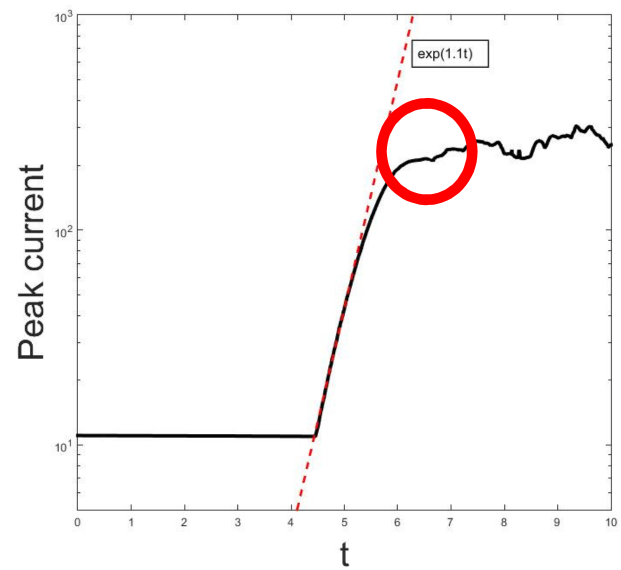

Kinetic energy
t
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
0 1 2 3 4 5 6 7 8 9 10


Peak current
t
exp(1.1t)
10^3
10^2
10^1
0 1 2 3 4 5 6 7 8 9 10

J(t=6)







J(t=6.5)

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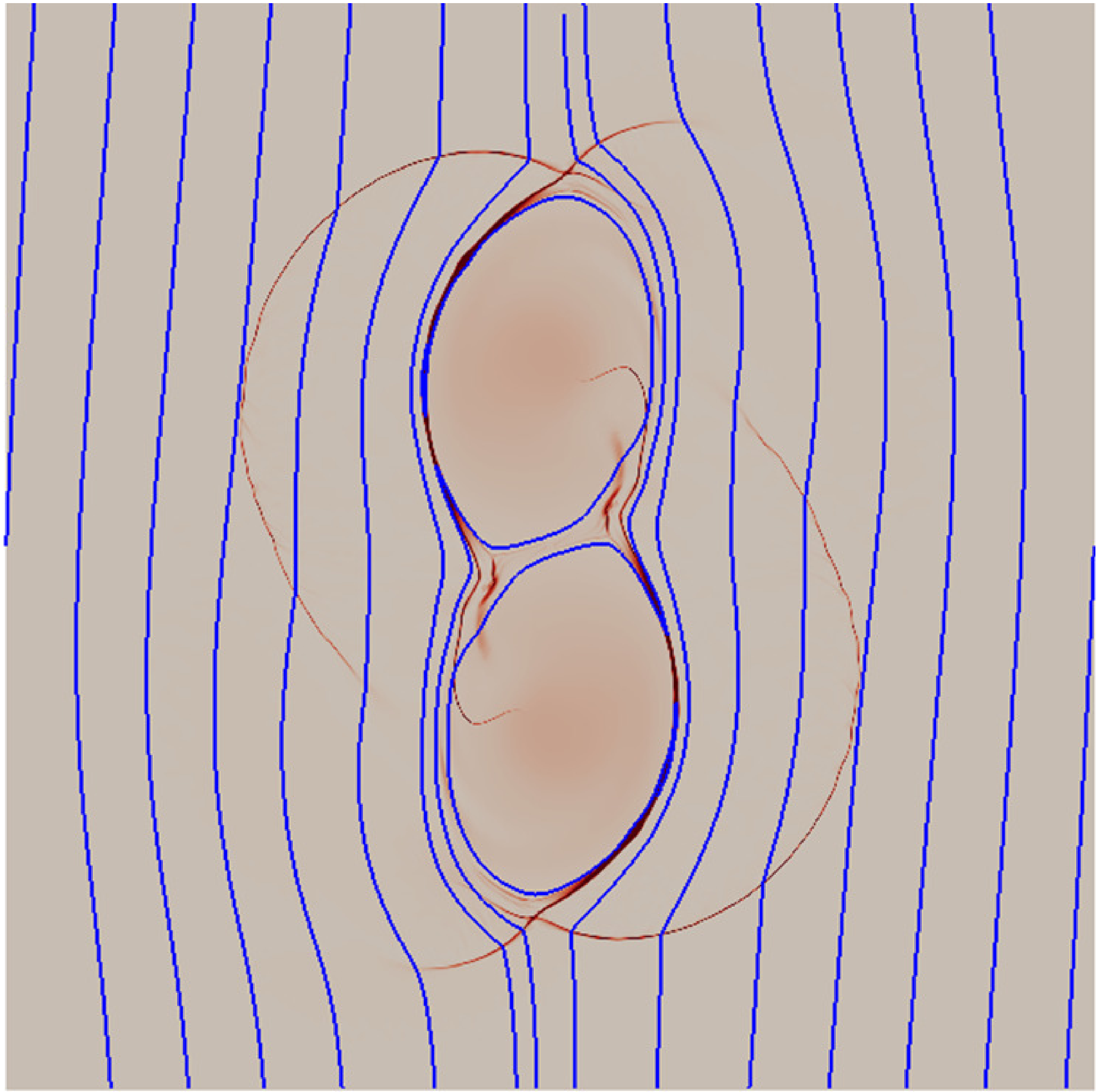

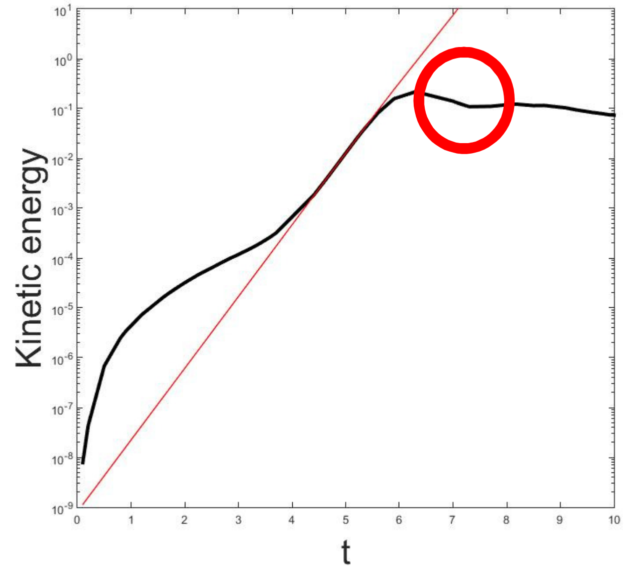

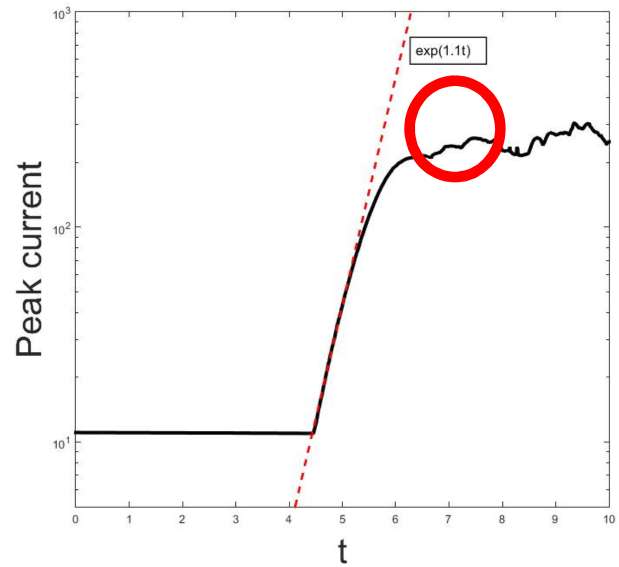

J(t=7)

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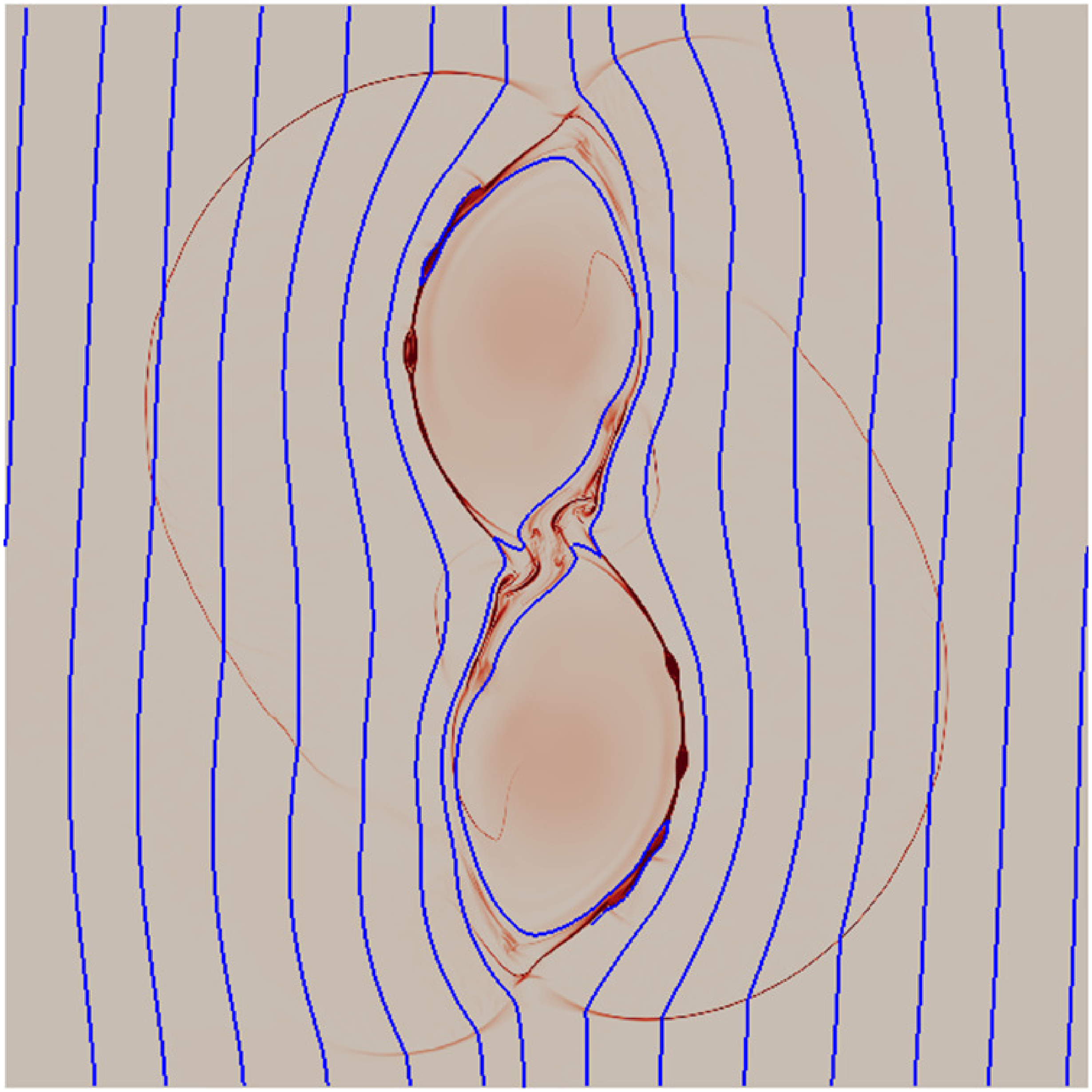
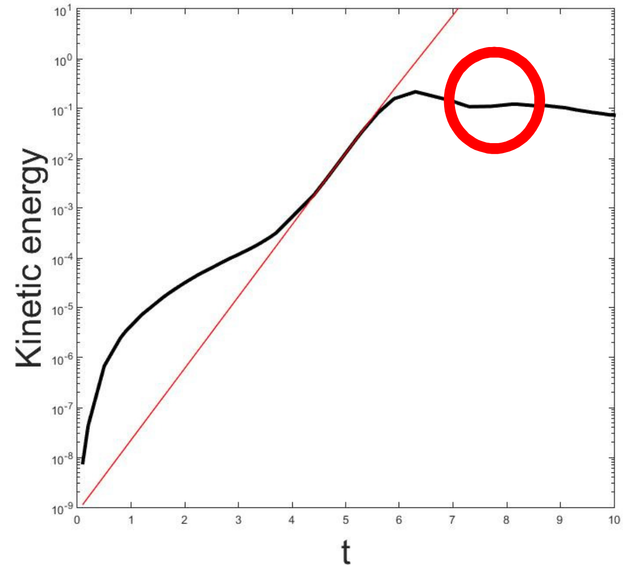
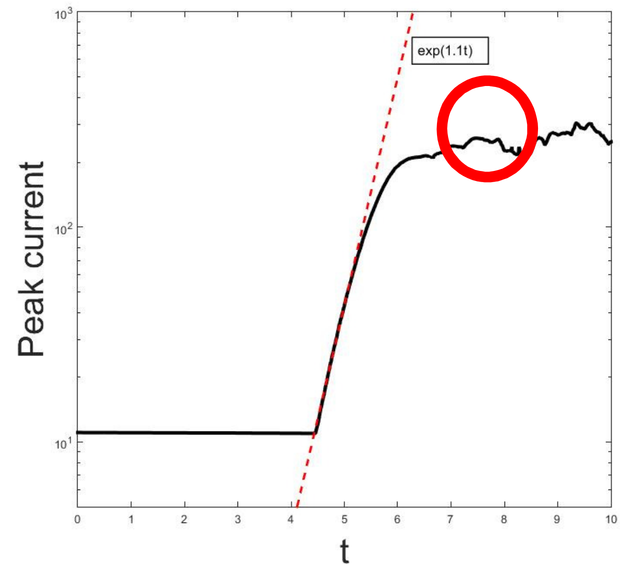
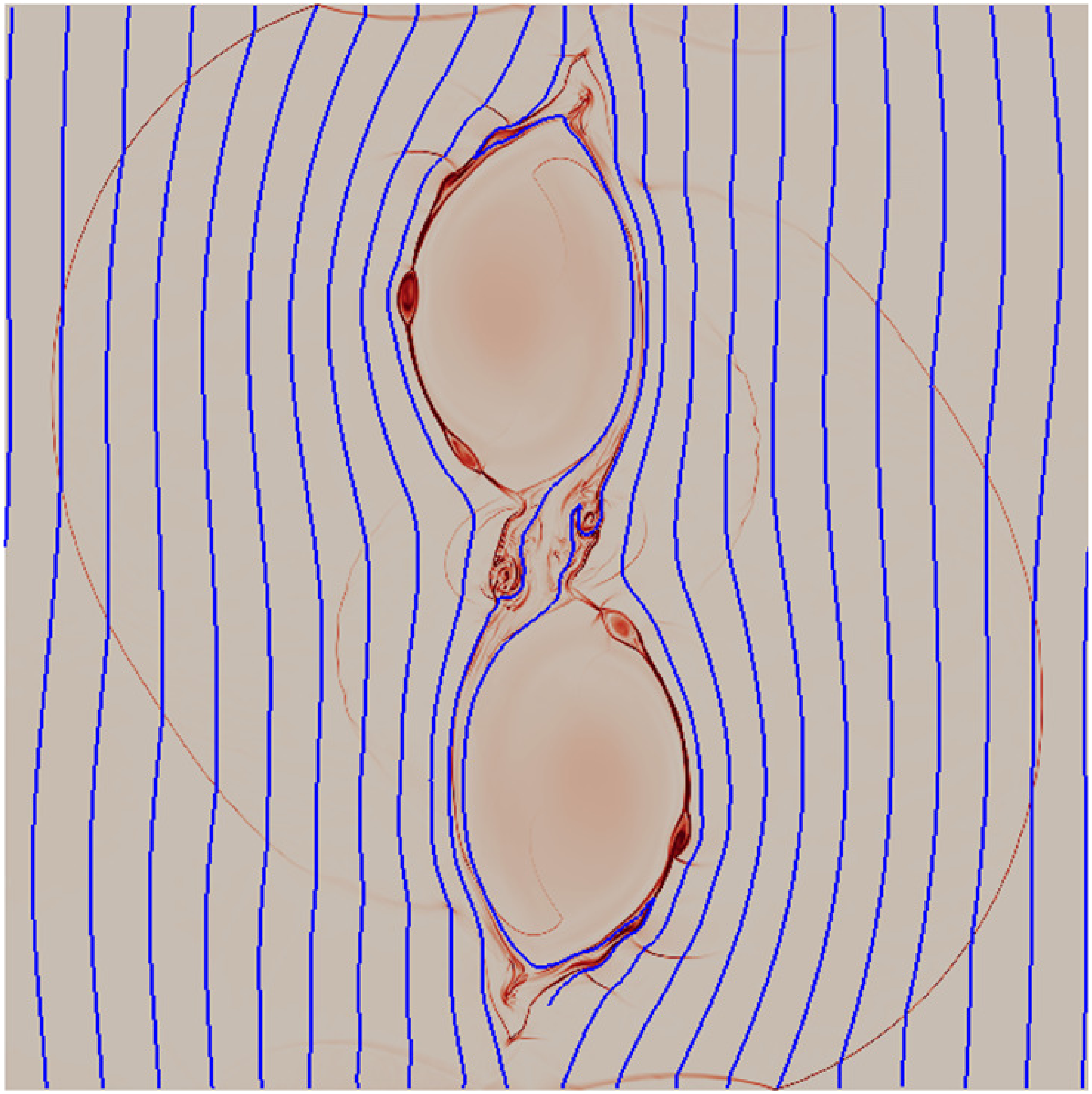


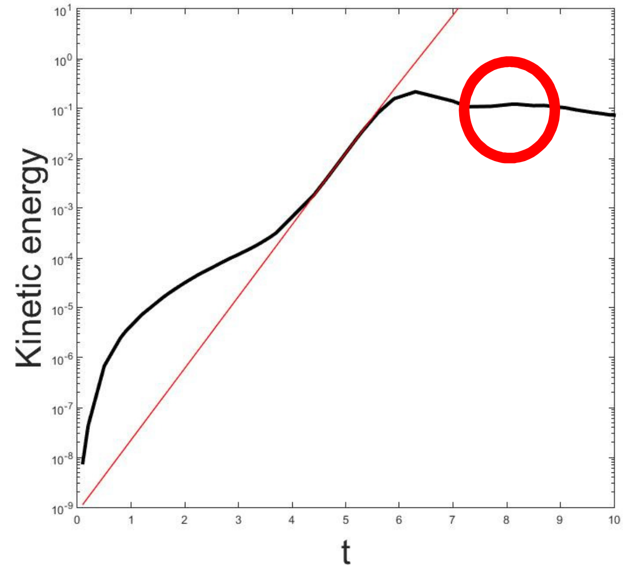


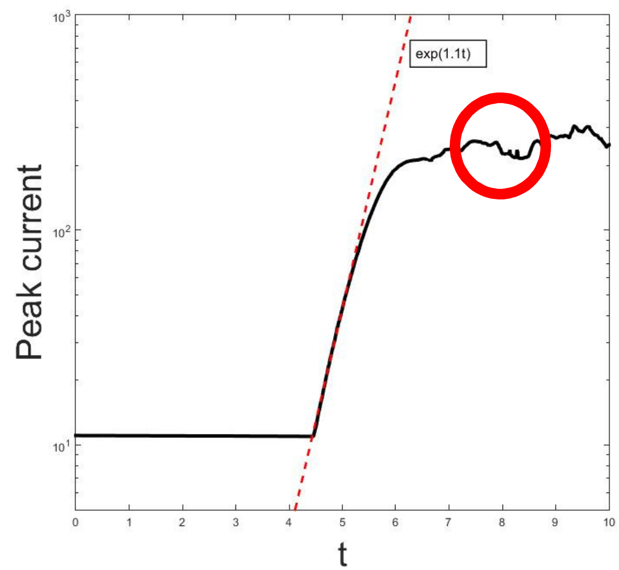


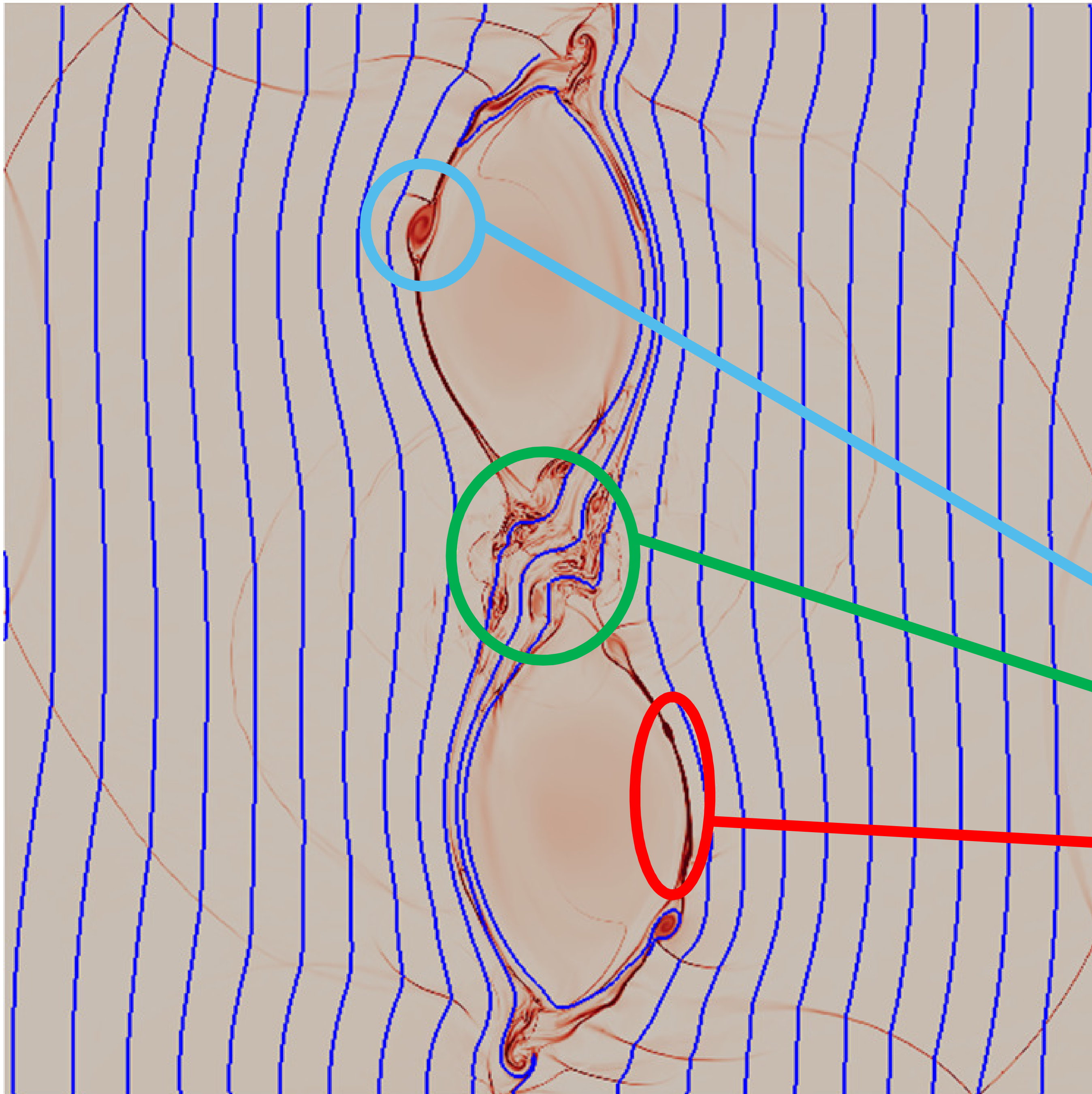
J(t=7.5)



J(t=8)







J(t=8.5)

- β = 0.04
- Similar behaviour for larger β, but delayed
- Secondary islands
- Reconnection
- Fast forming current sheets

→ Particle acceleration

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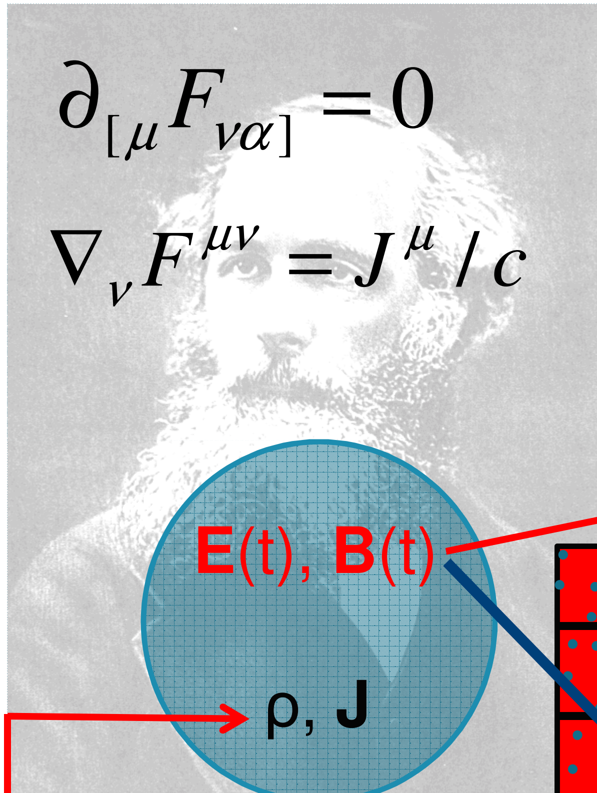
… and now with particles



$$\partial_{[\mu} F_{\nu\alpha]} = 0$$

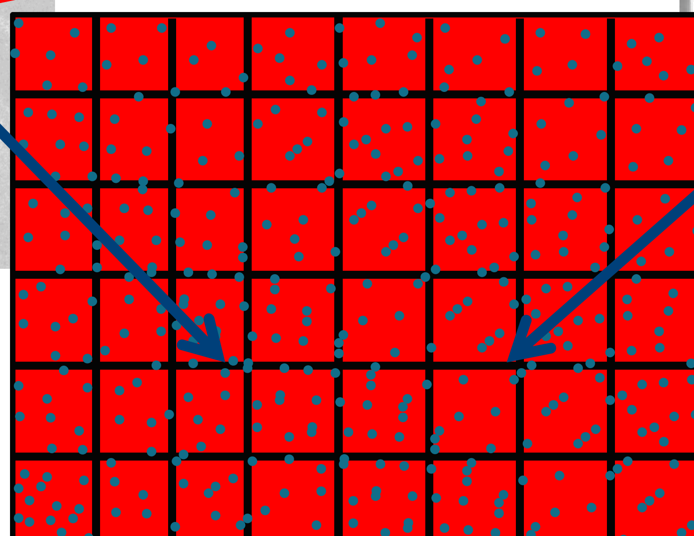
$$\nabla_\nu F^{\mu\nu} = J^\mu / c$$

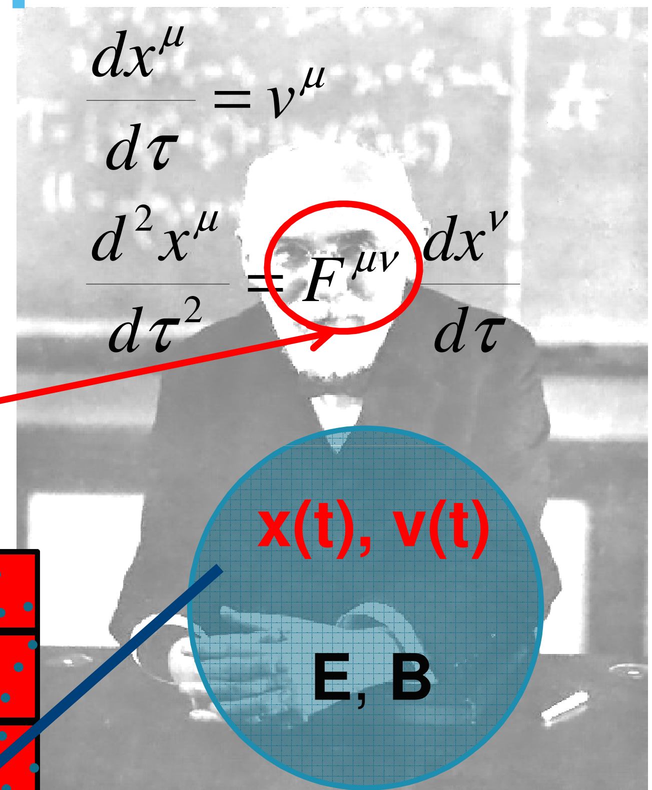
Maxwell's equations

Still obtained from fluid equations

Particles follow fields

Relativistic test particles in MHD





$$\frac{dx^\mu}{d\tau} = v^\mu$$

$$\frac{d^2 x^\mu}{d\tau^2} = F^{\mu\nu} \frac{dx^\nu}{d\tau}$$

Relativistic equations of motion

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Which particles are we interested in?

Two populations of particles are considered

- Thermal plasma described by a Maxwellian distribution.
  → MHD is a satisfactory description.
  → The largest scales of the system are studied.

- Non-thermal plasma, with highly accelerated particles and a power law distribution.
  → Relativistic particle equations of motion are required.
  → The microscopic scales of the system are studied.

So for now..

- Fluid models: Good for global dynamics and energetics
  But.. fail to tell you anything about kinetic processes
- Kinetic models: The opposite...

→ Assume fluid models are largely correct and see how test particles behave in the global flow:

- Acceleration mechanisms
- Particle orbits and drifts
- Non-thermal distributions
- (Radiation)

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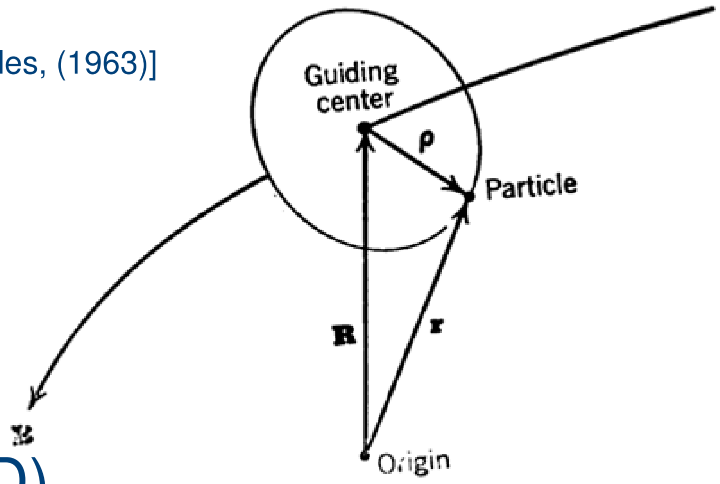
[Northrop, The Adiabatic Motion of Charged Particles, (1963)]



Assumptions

- Low $\beta = 2p / B^2$ (e.g. solar flares)
- Low $\sigma \rightarrow v_A << c$ (non-relativistic MHD)
- $\partial t_{particle} << \partial t_{MHD}$ → relativistic particles in MHD evolutions
- MHD → magnetic field, velocity and density
- Test particles → collisions and effect on fields ignored
- Gyroradius $R_c = \frac{\gamma m v_\perp}{Bq} \sim 10^{-1} m - 10^{-3} m << \text{grid cell size} \sim 10^3 m$

  → Replace particles position by its guiding centre

Particle	$B\ [T]$	$T\ [K]$	$n\ [m^{-3}]$	$v_{thermal}\ [m/s]$	$\beta\ [-]$	$R_c\ [m]$	$\gamma\ [-]$
Electron	$0.03\ T$	$10^6\ K$	$10^{16}\ m^{-3}$	$5.5 \times 10^7\ ms^{-1}$	0.0004	$10^{-3}\ m$	1.0002
Proton	$0.03\ T$	$10^6\ K$	$10^{16}\ m^{-3}$	$1.3 \times 10^6\ ms^{-1}$	0.0004	$4.4 \times 10^{-2}\ m$	1.0000

[Goedbloed & Poedts, Principles of Magnetohydrodynamics, (2004)]

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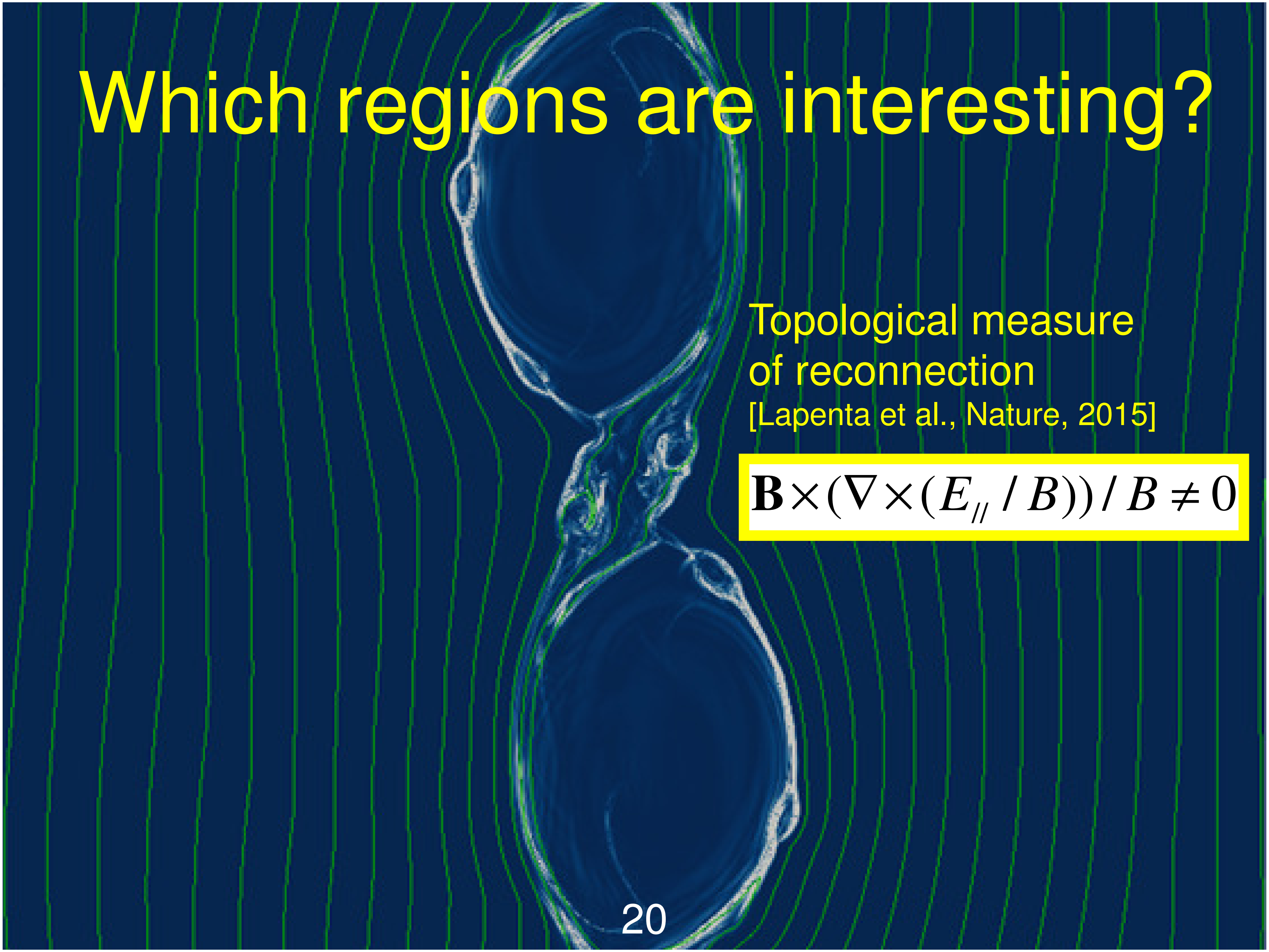
Which regions are interesting?

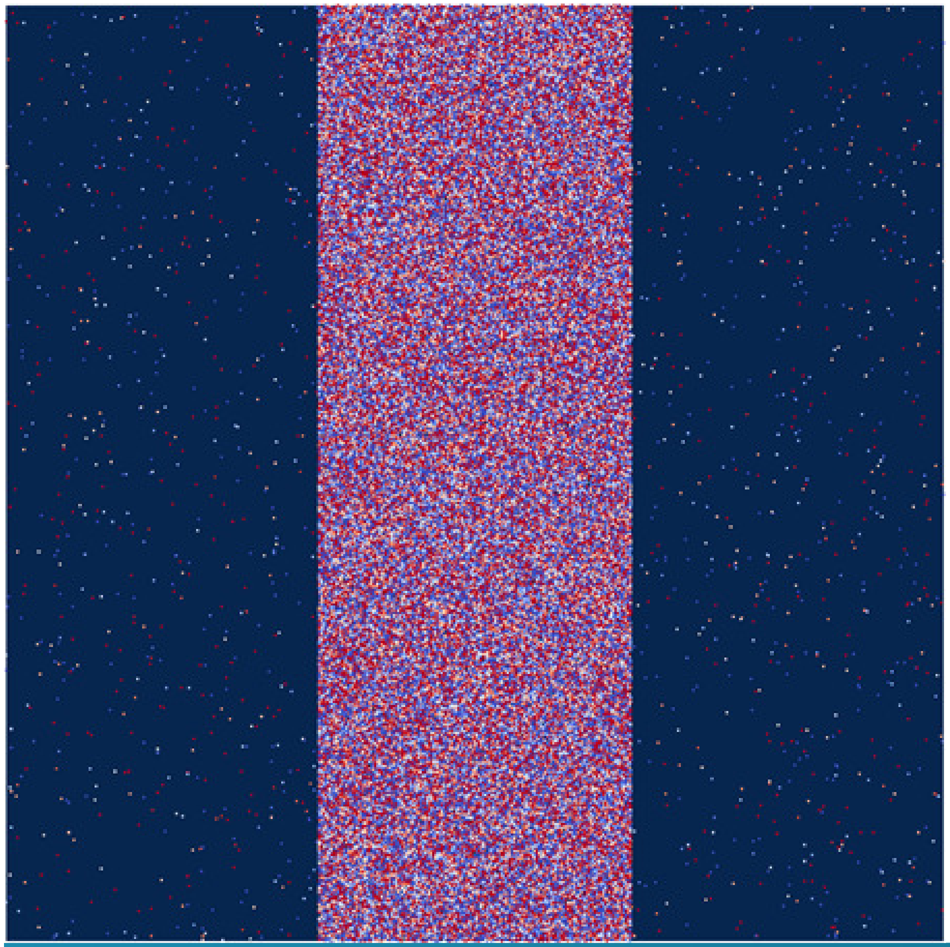


Topological measure of reconnection
[Lapenta et al., Nature, 2015]

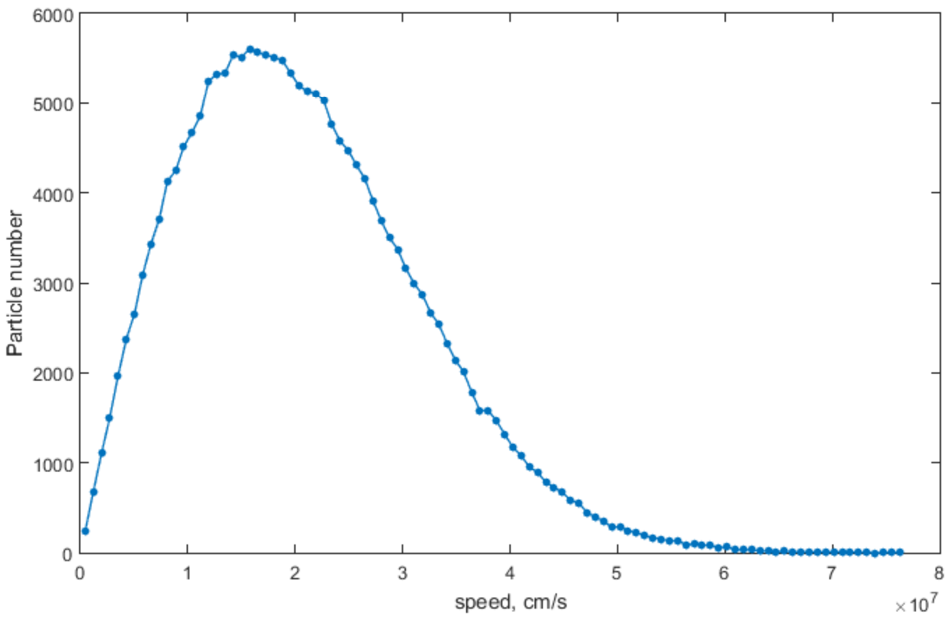
$$\mathbf{B}\times(\nabla\times(E_{//}/B))/B\neq 0$$

Test particles initialisation

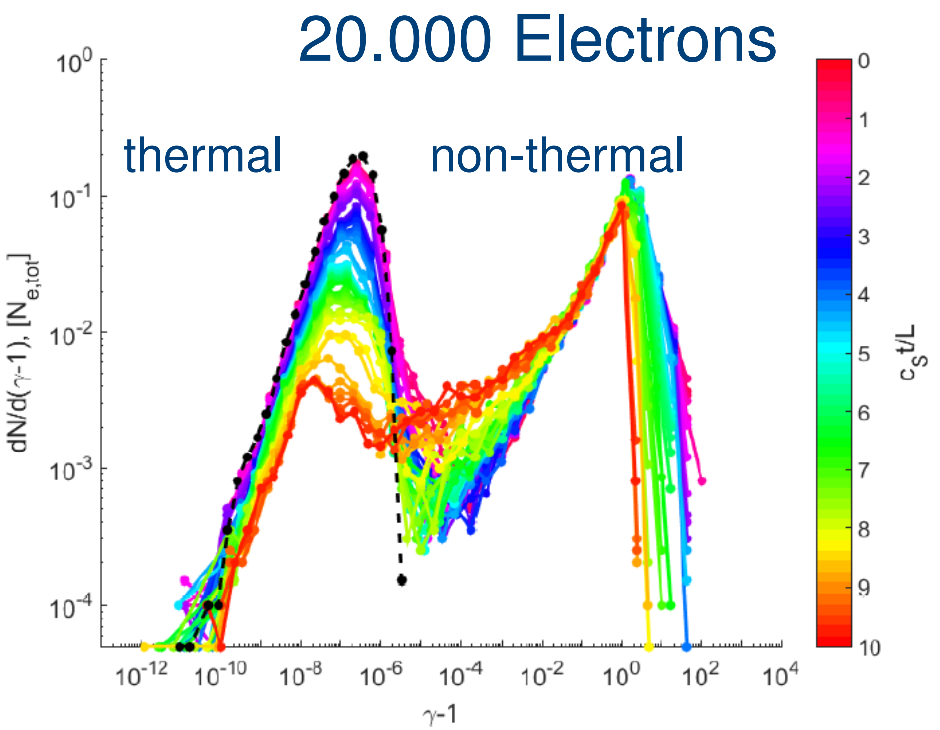
Particles coloured by parallel velocity

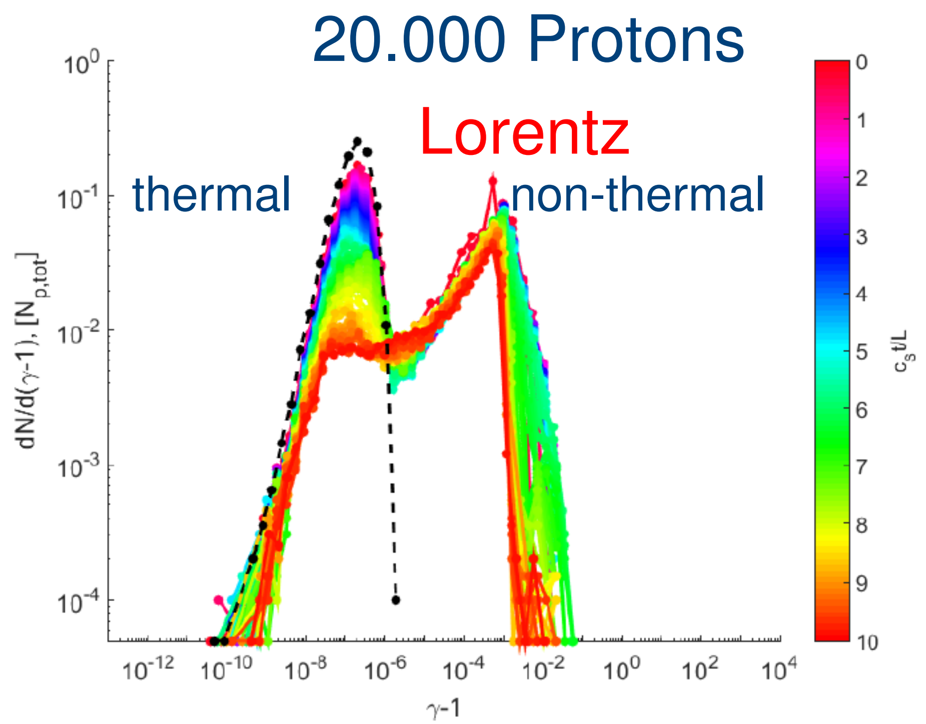


- 20.000 Maxwellian electrons/protons
- Randomly and uniformly initialised
- 99% in area current channels



2.5D results: Energy distribution





- Particle distribution develops high energy tail
- Thermal bath is applied in periodic direction
- Guiding centre approximation valid

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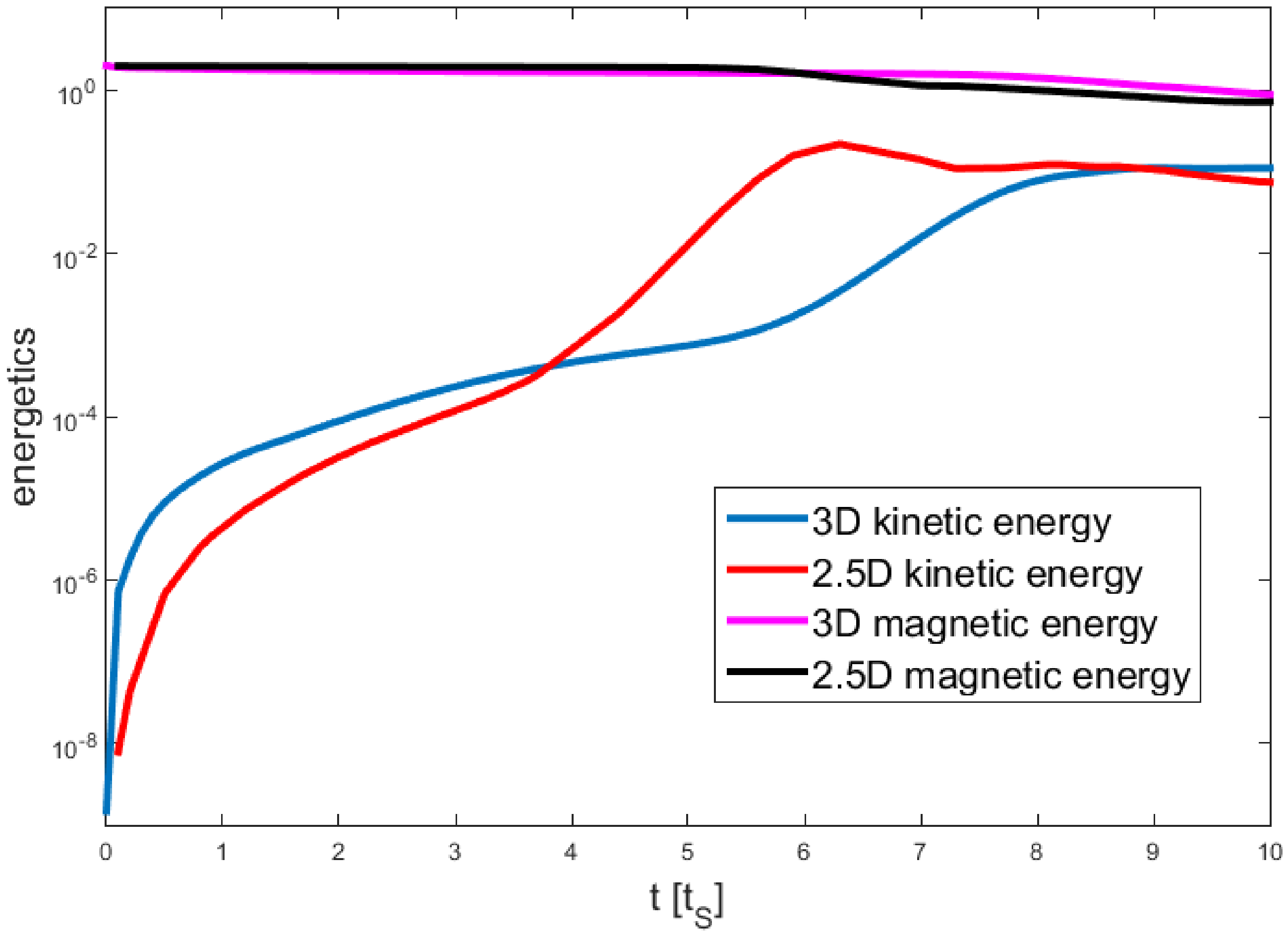
3D MHD effects

- Magnetic tension delays linear growth phase of instability



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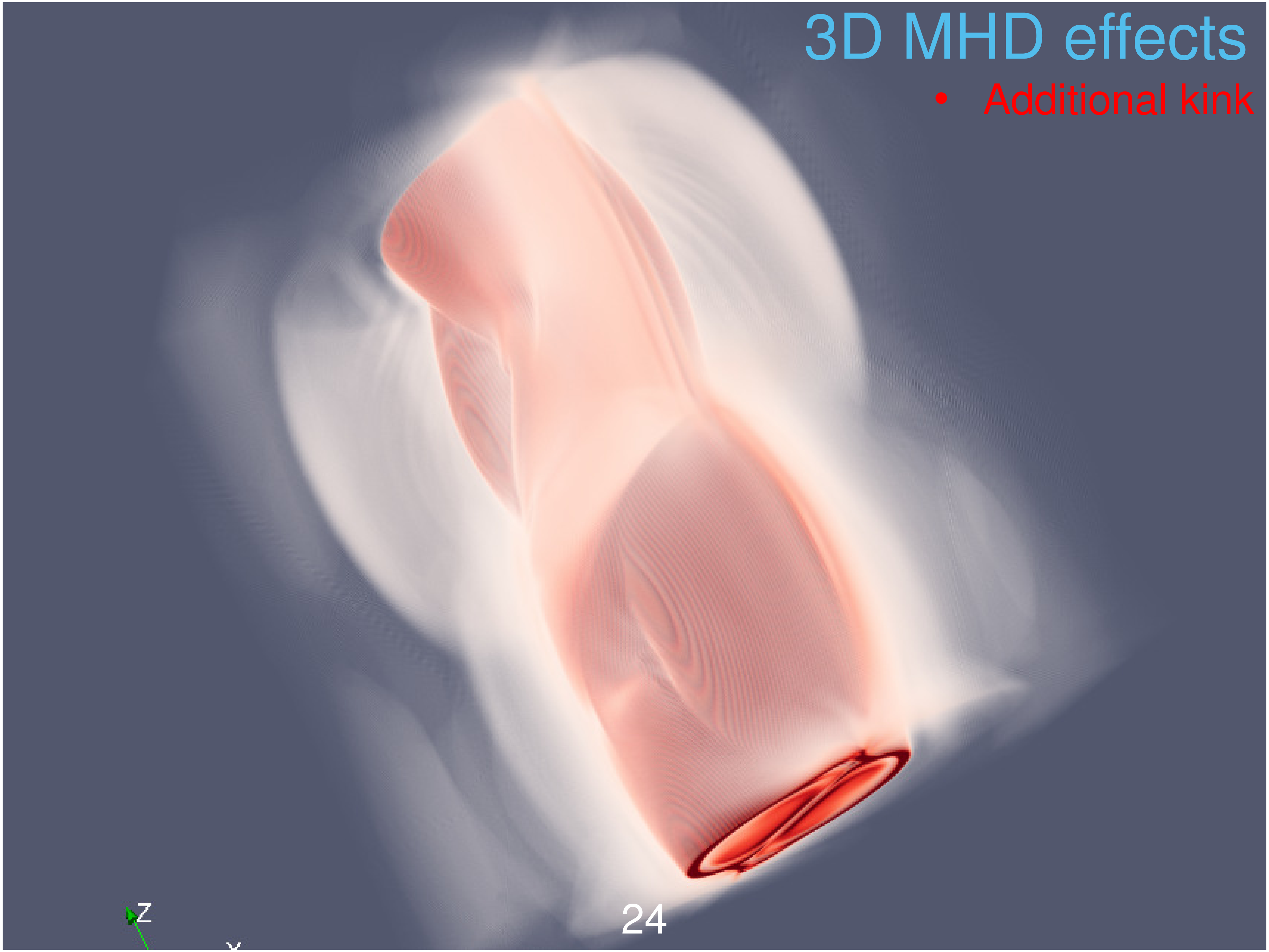
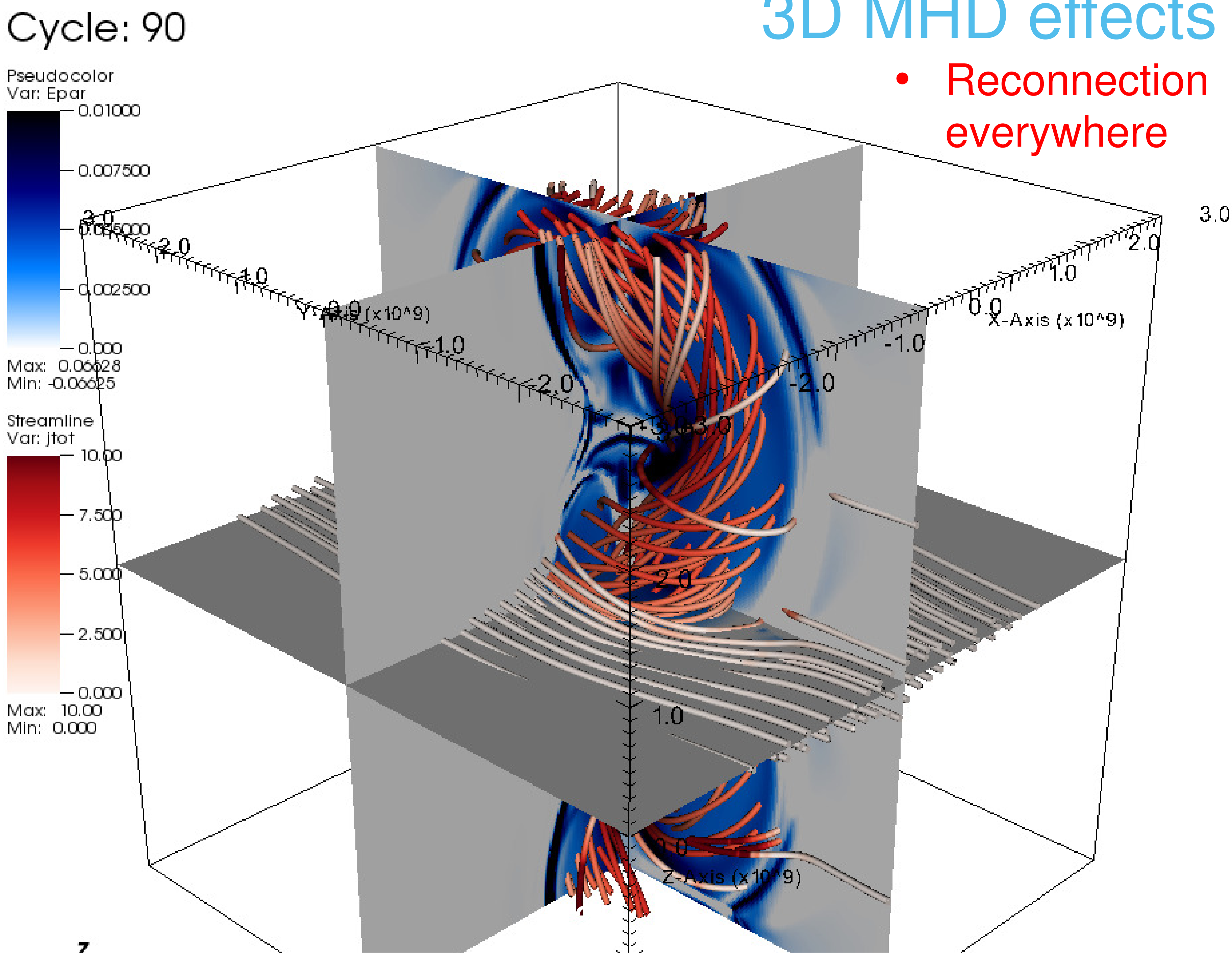
3D MHD effects

- Additional kink



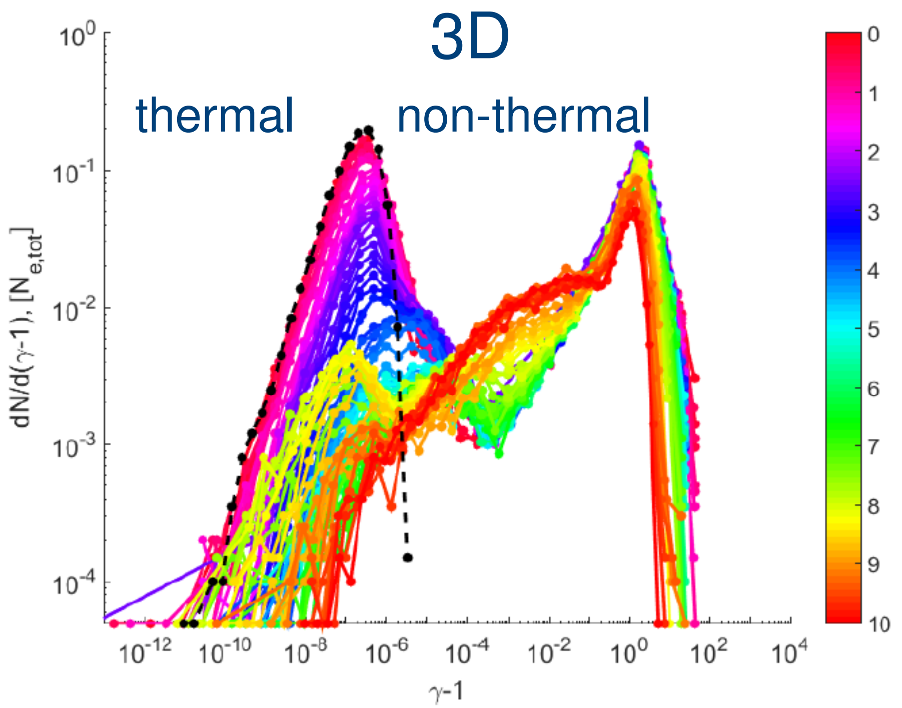
3D MHD effects

- Reconnection everywhere

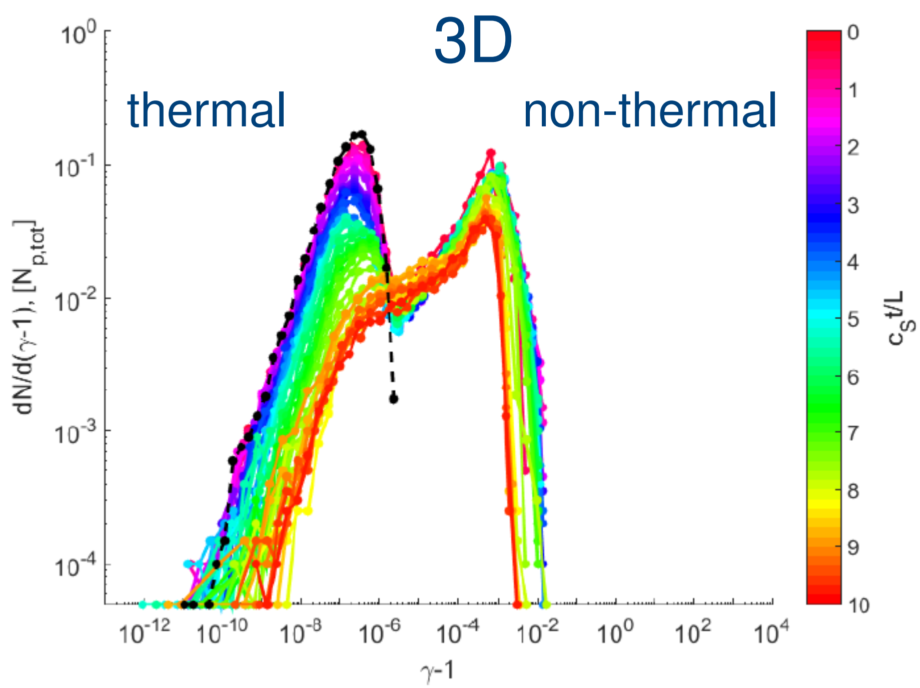


3D results: Energy distribution

20.000 Electrons



20.000 Protons



- Kink adds medium energy tail and redistributes particles in the thermal distribution
- Results confirmed for 200.000 electrons

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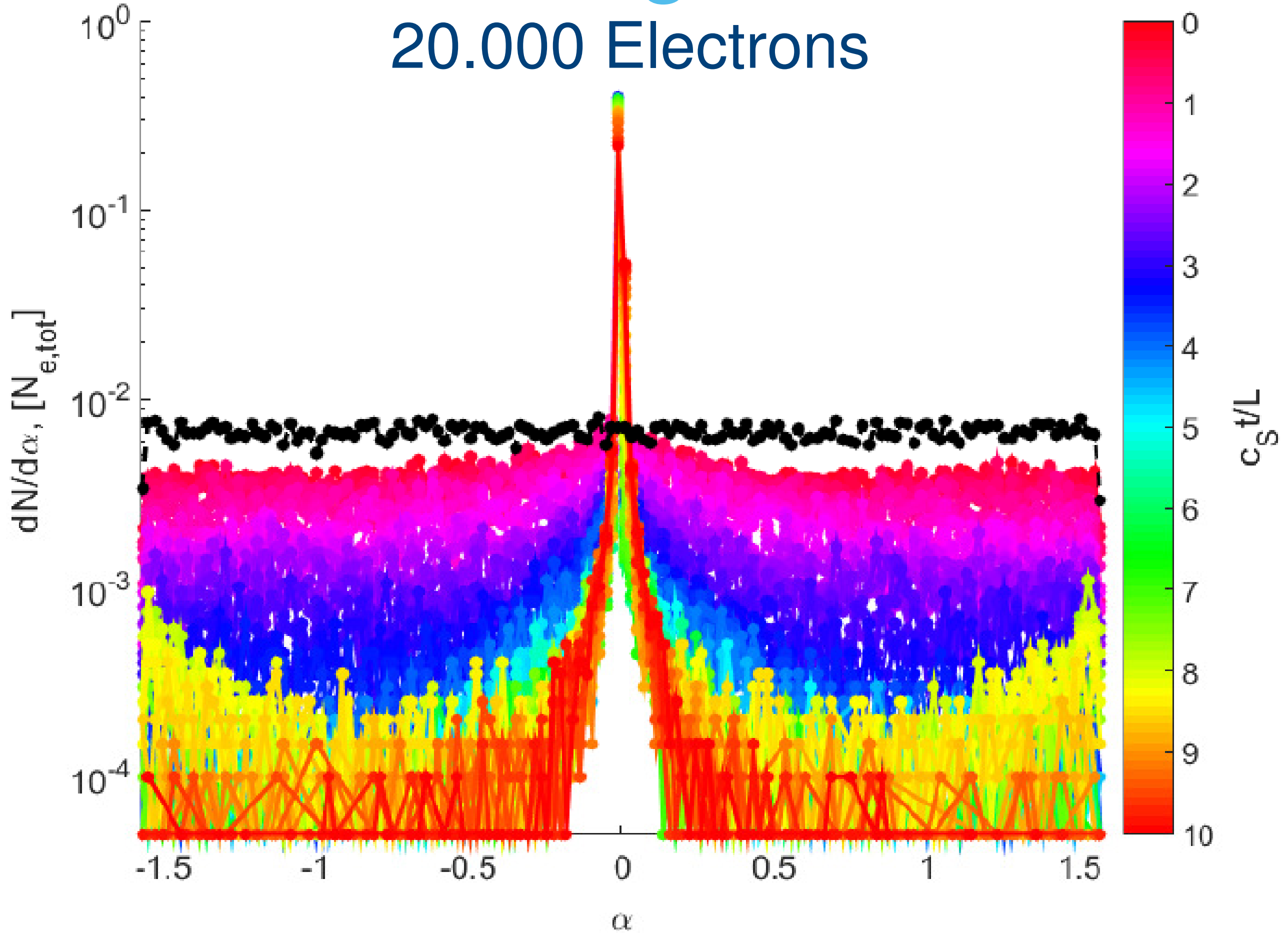
3D results: Pitch angle distribution



- Pitch angle strongly peaked around 0
- Acceleration in direction parallel to magnetic field

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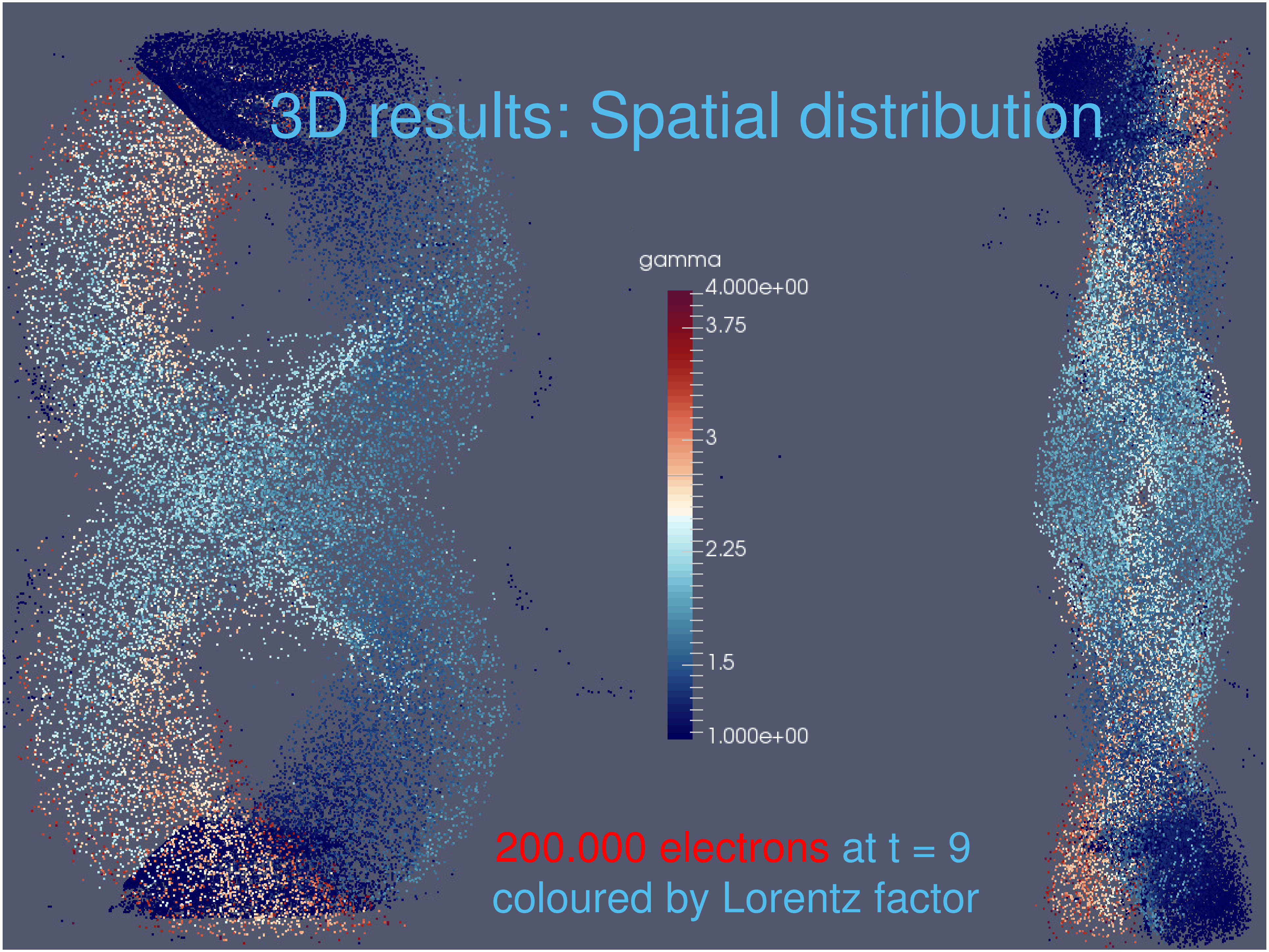
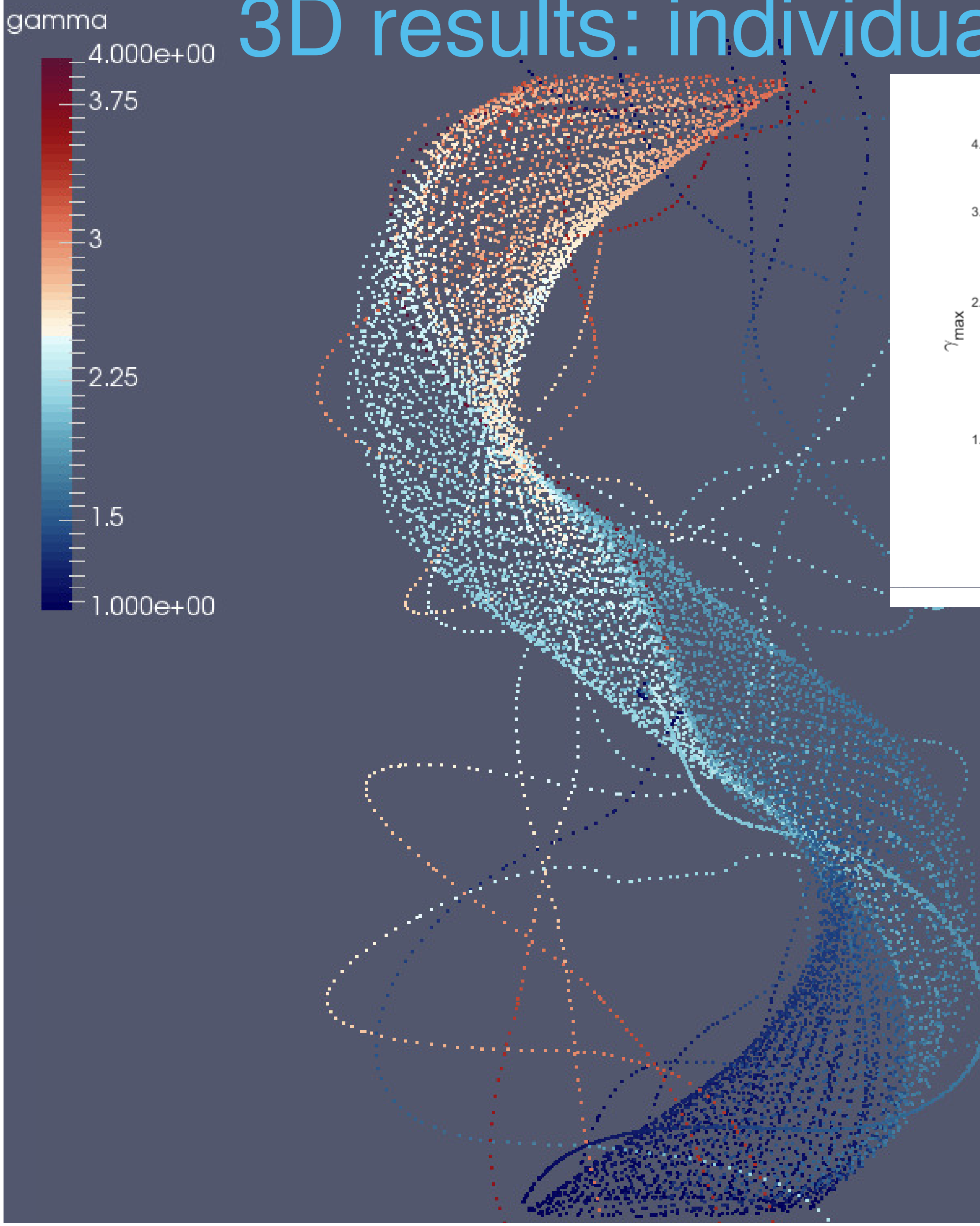
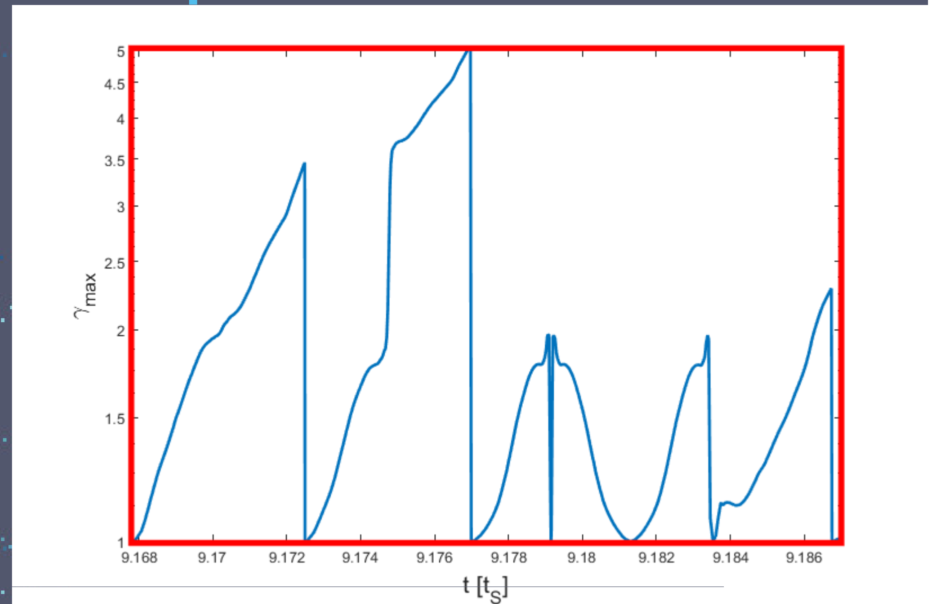
3D results: Spatial distribution



200.000 electrons at t = 9
coloured by Lorentz factor

3D results: individual particle orbit

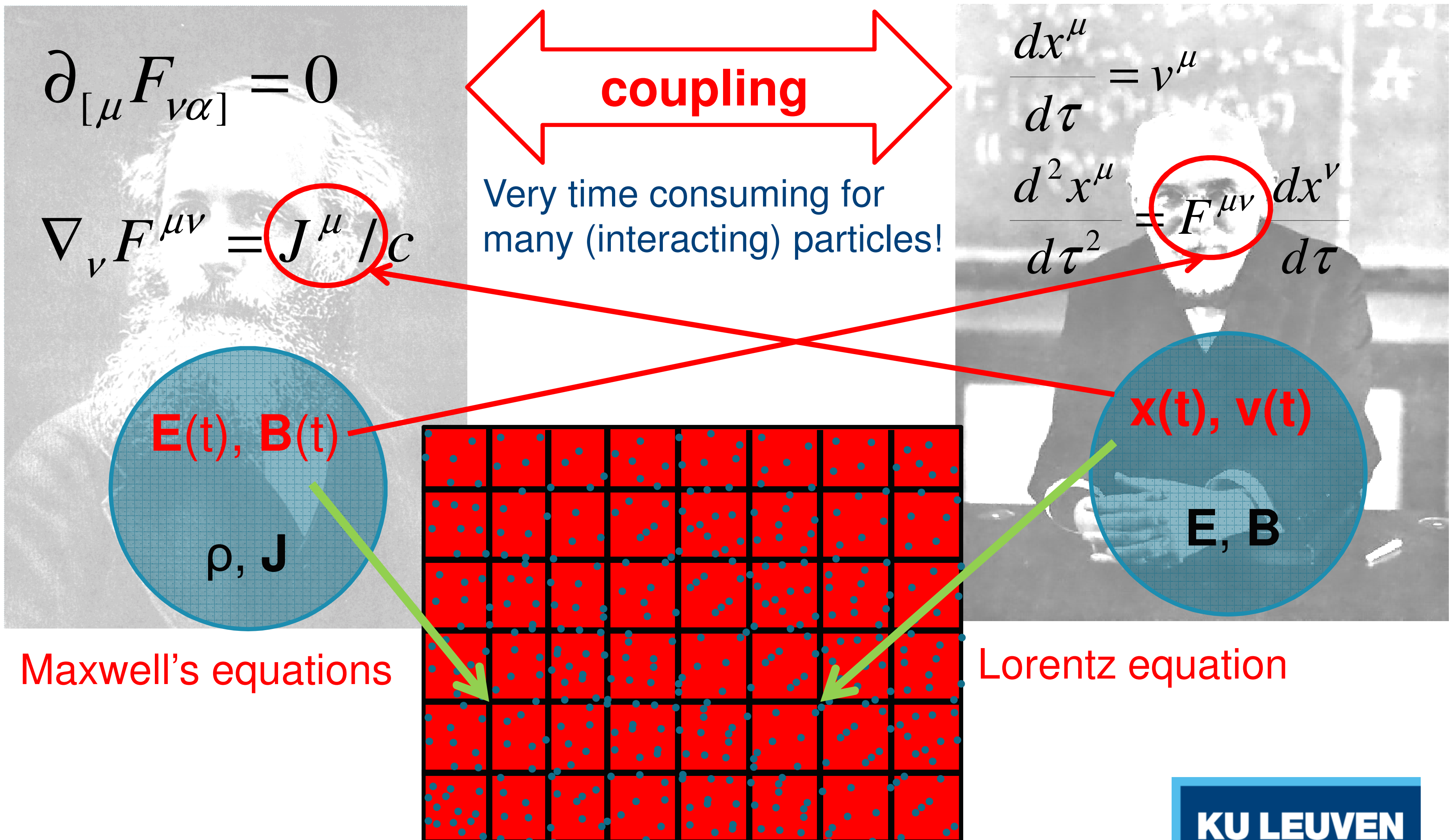




Lorentz factor evolution

- Thermalised after cycle through current channel
- Expelled from current channel by kink
- Decelerates to thermal energy and re-accelerates

... But charged particles do affect fields!



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