Particle acceleration in magnetic reconnection and turbulent sites

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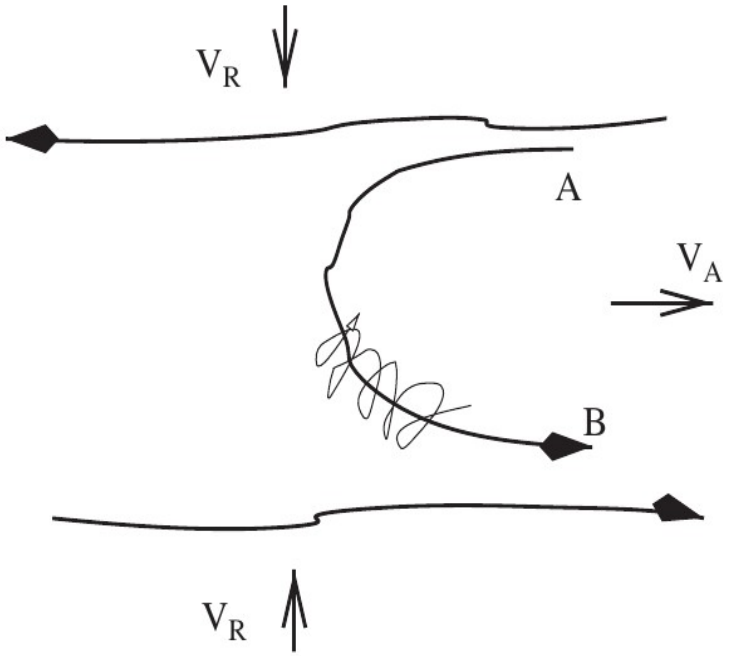
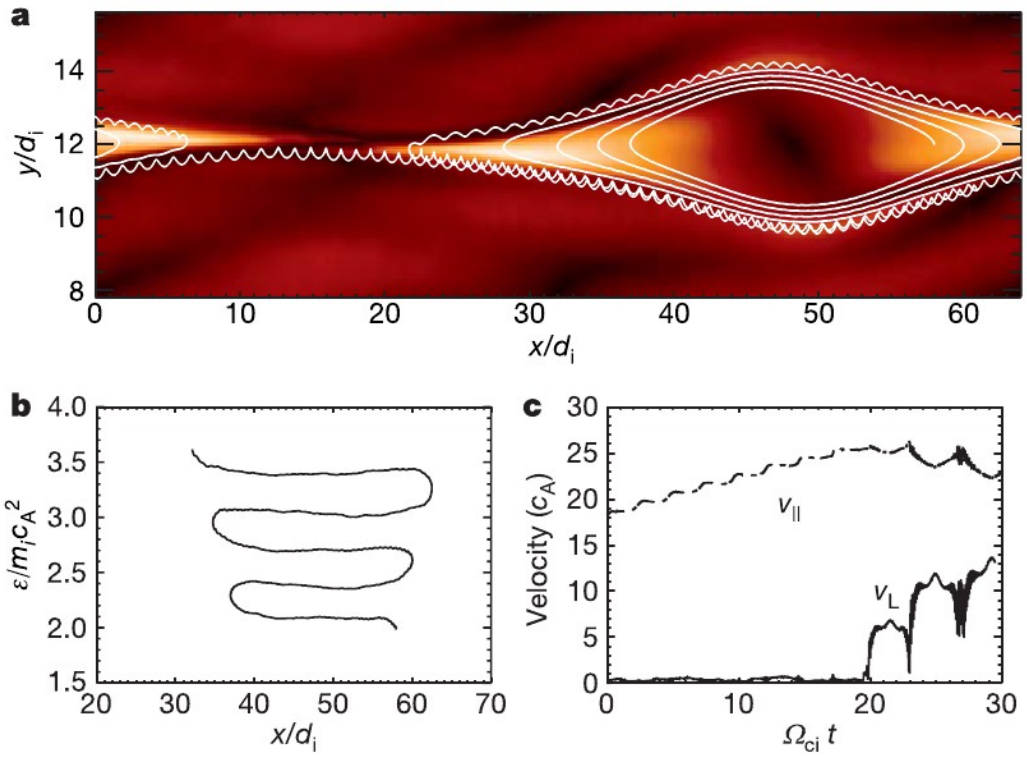
Motivation

De Gouveia Dal Pino & Lazarian (2005)



Drake et al. (2006)

Colisionless plasma, 2D PIC simulations

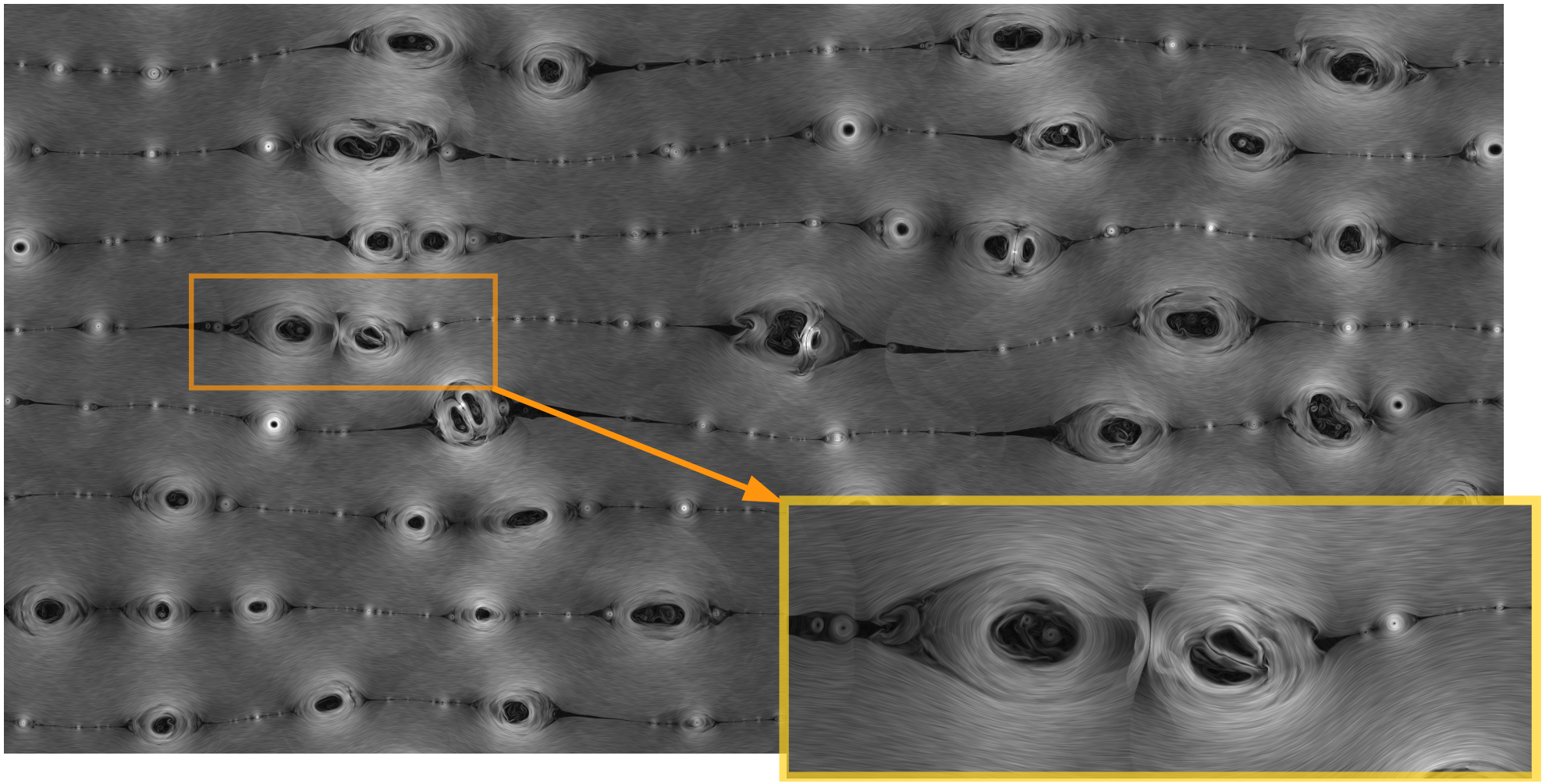


Drake et al. (2010)

- **The island contraction is controlled by firehose instability; when marginal firehose condition is violated, the contraction stops, since it is a driver of reconnection, the reconnection stops as well;**
- **The MHD model does not reliably describe magnetic reconnection and acceleration;**

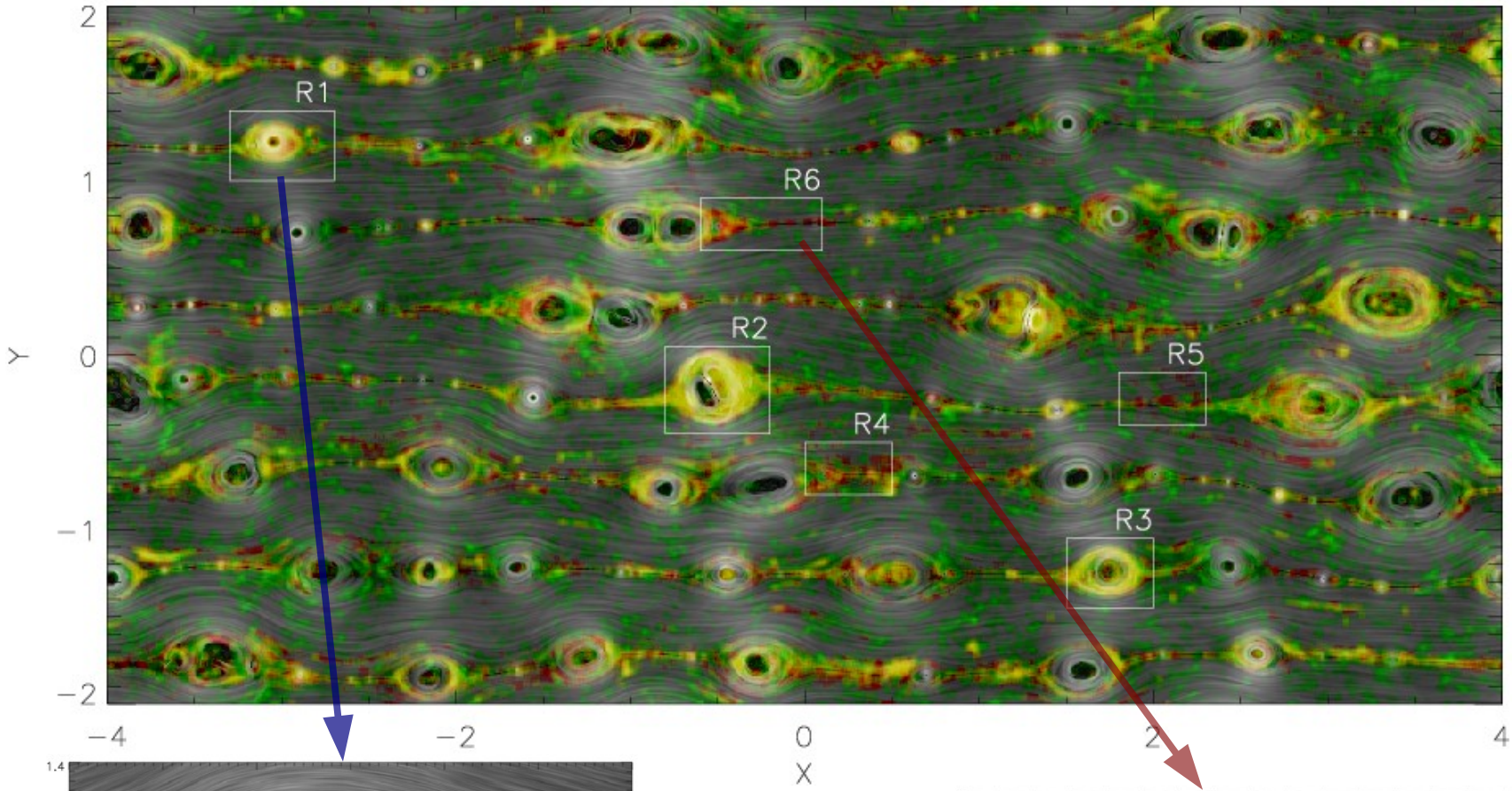
Methodology

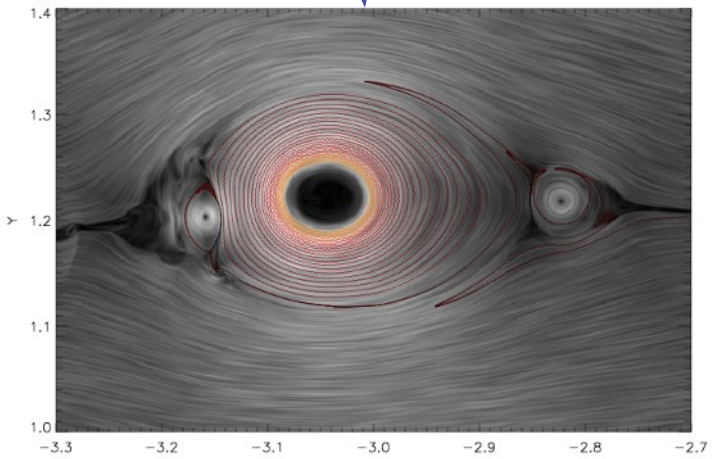
MHD Simulations: 2D and 3D periodic domains with resolution 8192x4096 (1024x512x512) in which we set up eight Harris current sheets;



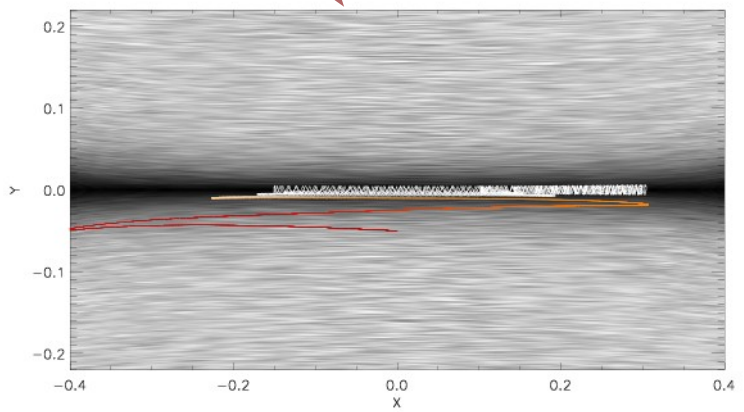
$$\frac{d}{dt}(\gamma m \boldsymbol{u}) = q(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}), \qquad \boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta \boldsymbol{j}, \qquad \gamma \equiv (1 - u^2/c^2)^{-1/2}$$

Sites of Particle Acceleration



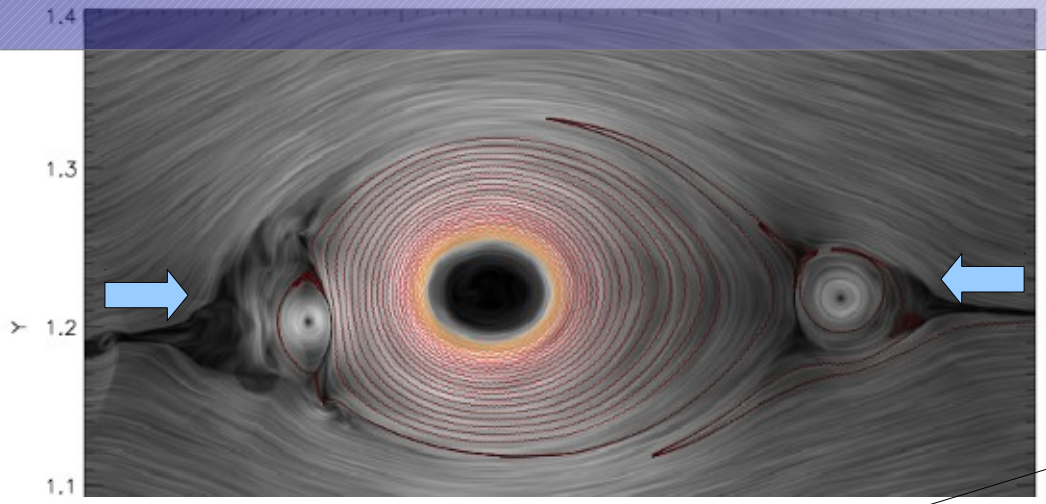


Acceleration in Contracting Islands



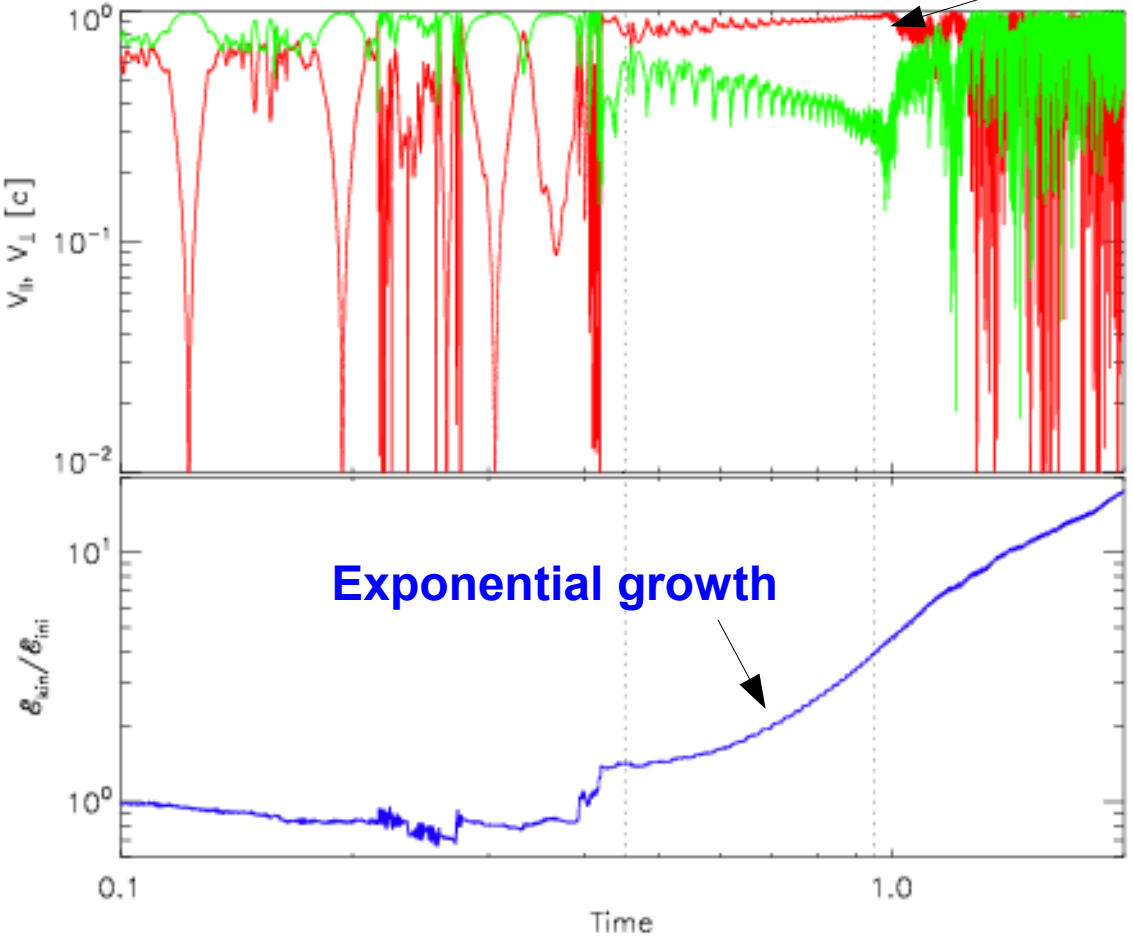
Acceleration in Current Sheets

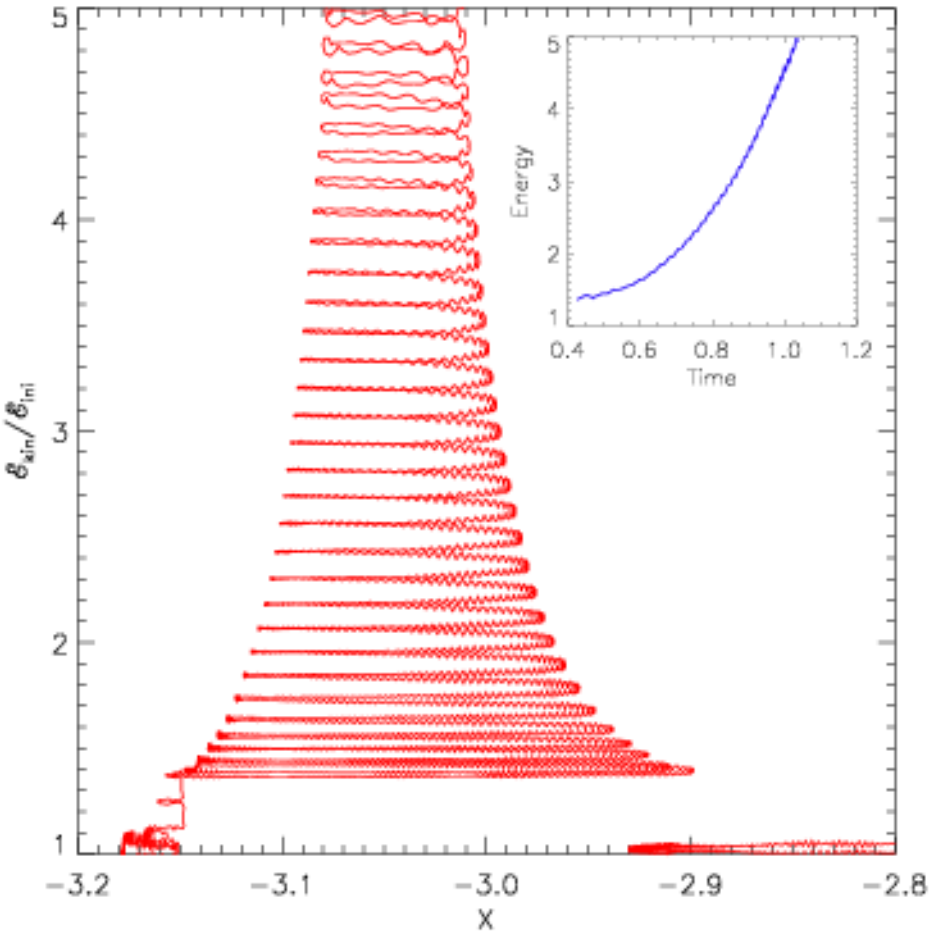
Acceleration in Magnetic Islands



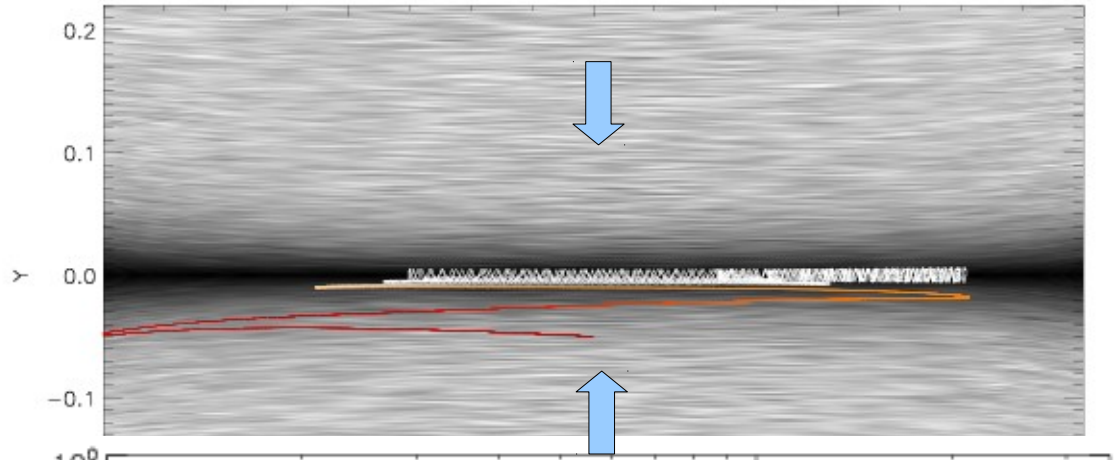
Interactions between merging islands cause their contractions!

Parallel acceleration!

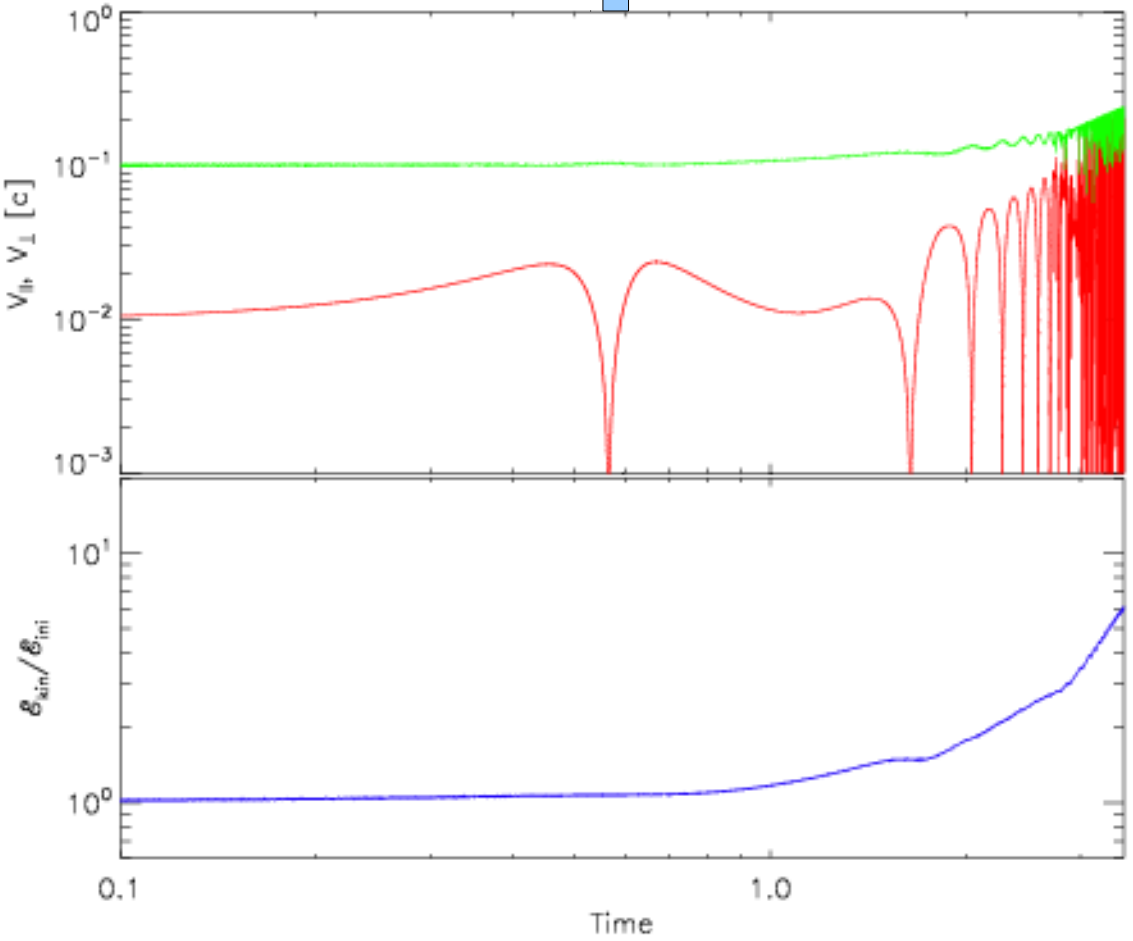


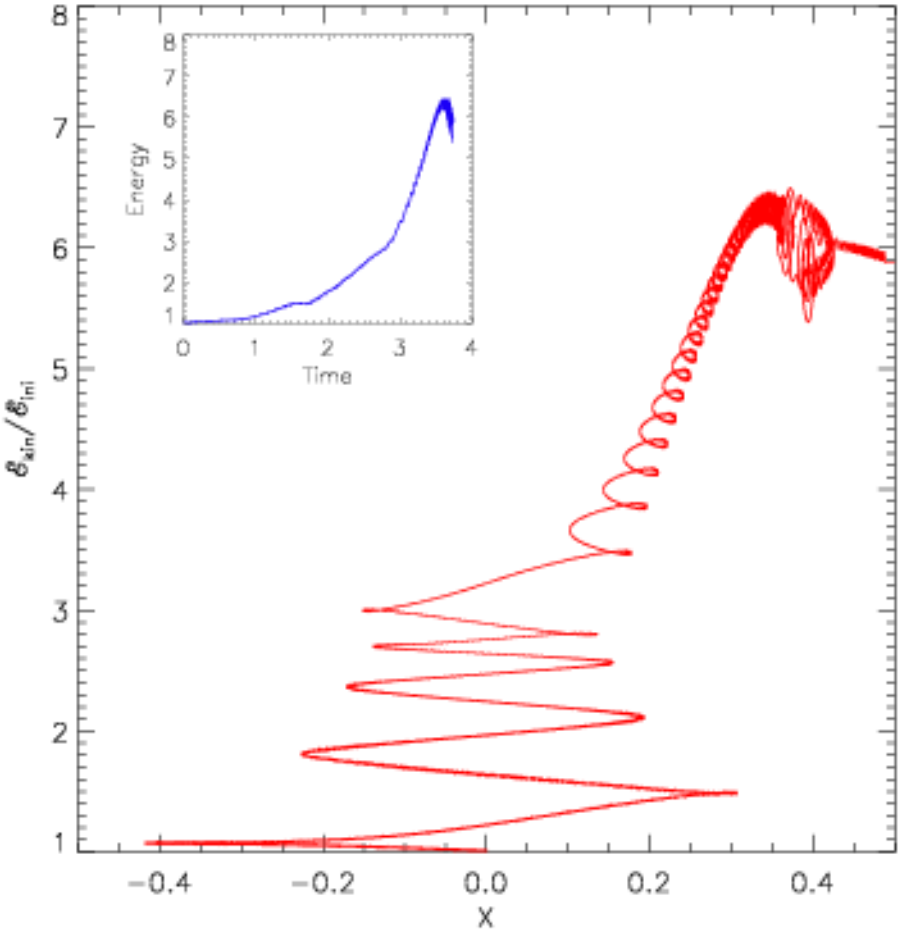


Acceleration in Current Sheets



Acceleration is possible in current sheets and it's similar to the mechanism described by De Gouveia Dal Pino & Lazarian (2005)

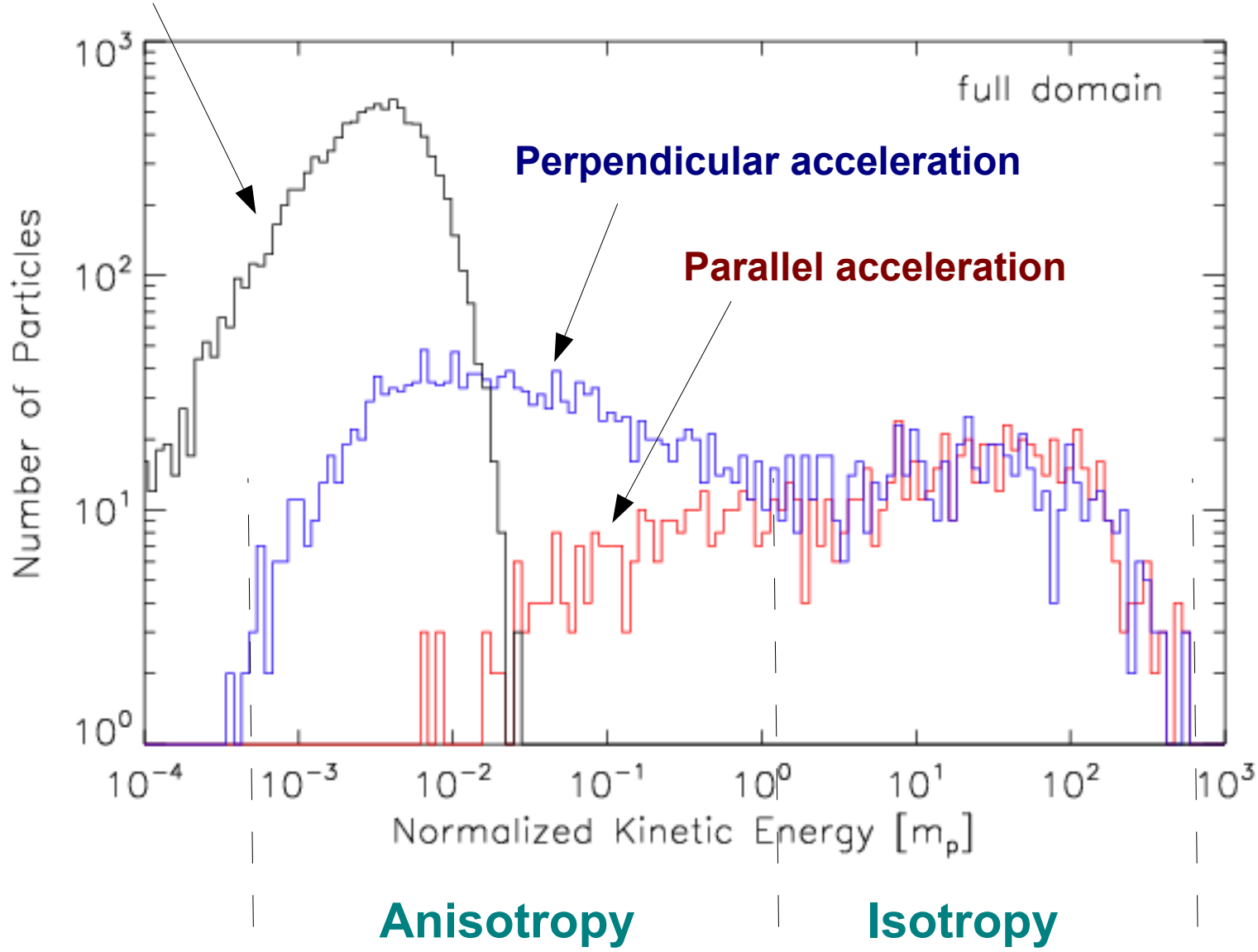




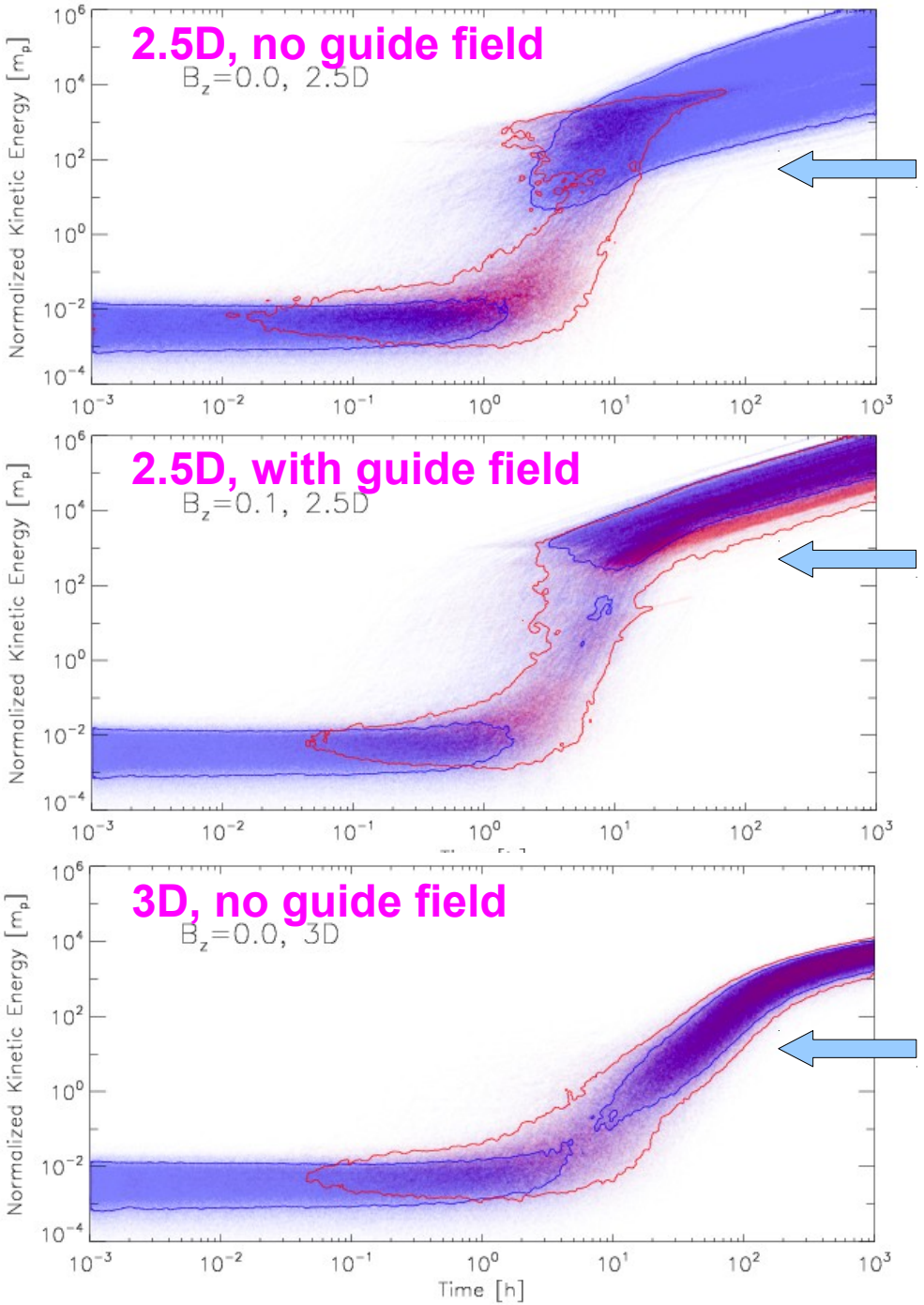
Particle Energy Distribution

Energy distribution after 1 hour from the injection.

Initial thermal distribution



Guide Field and 2D vs. 3D



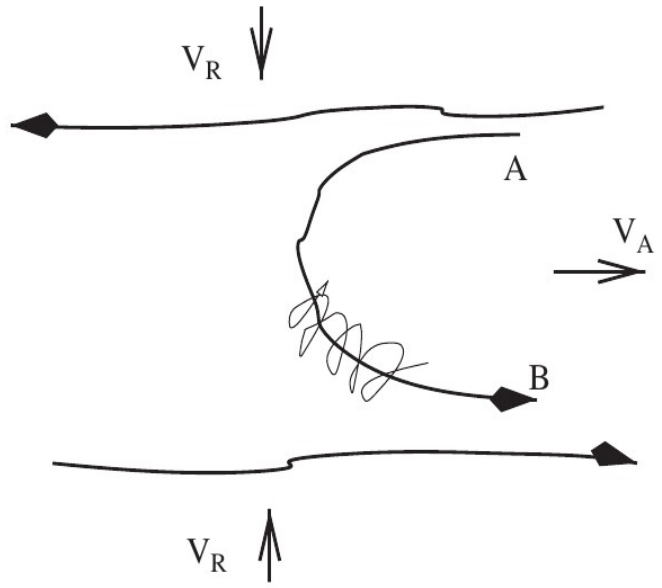
In 2D model without a guide field particles are trapped in the contracting islands. As soon as their gyro-radii reach the size of island they are trapped in, the parallel acceleration stops.

A guide field opens up the closed magnetic loops in the islands. This allows for the parallel acceleration to continue even if the gyro-radius is larger than the characteristic island dimension. The acceleration mechanism, however, is different then.

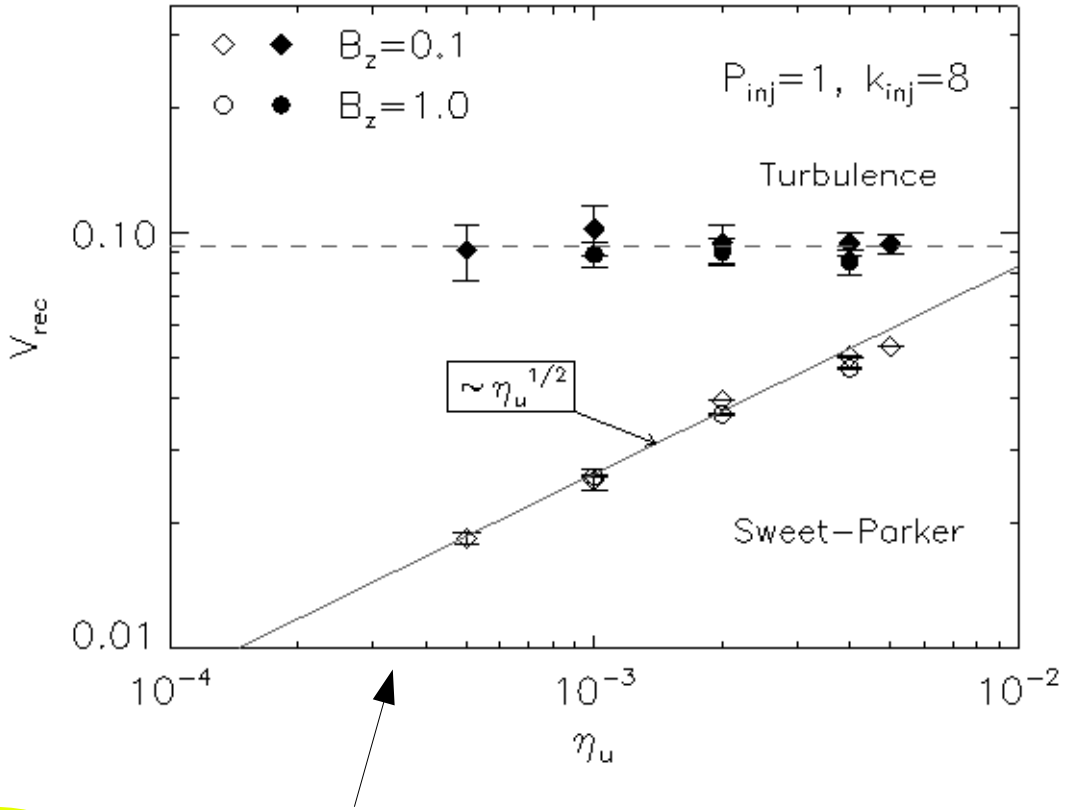
In the full 3D model, the parallel acceleration is possible, even without a guide field!

Acceleration in Turbulent Reconnection

De Gouveia Dal Pino & Lazarian (2005)



Lazarian & Vishniac (1999)
Kowal et al. (2010)

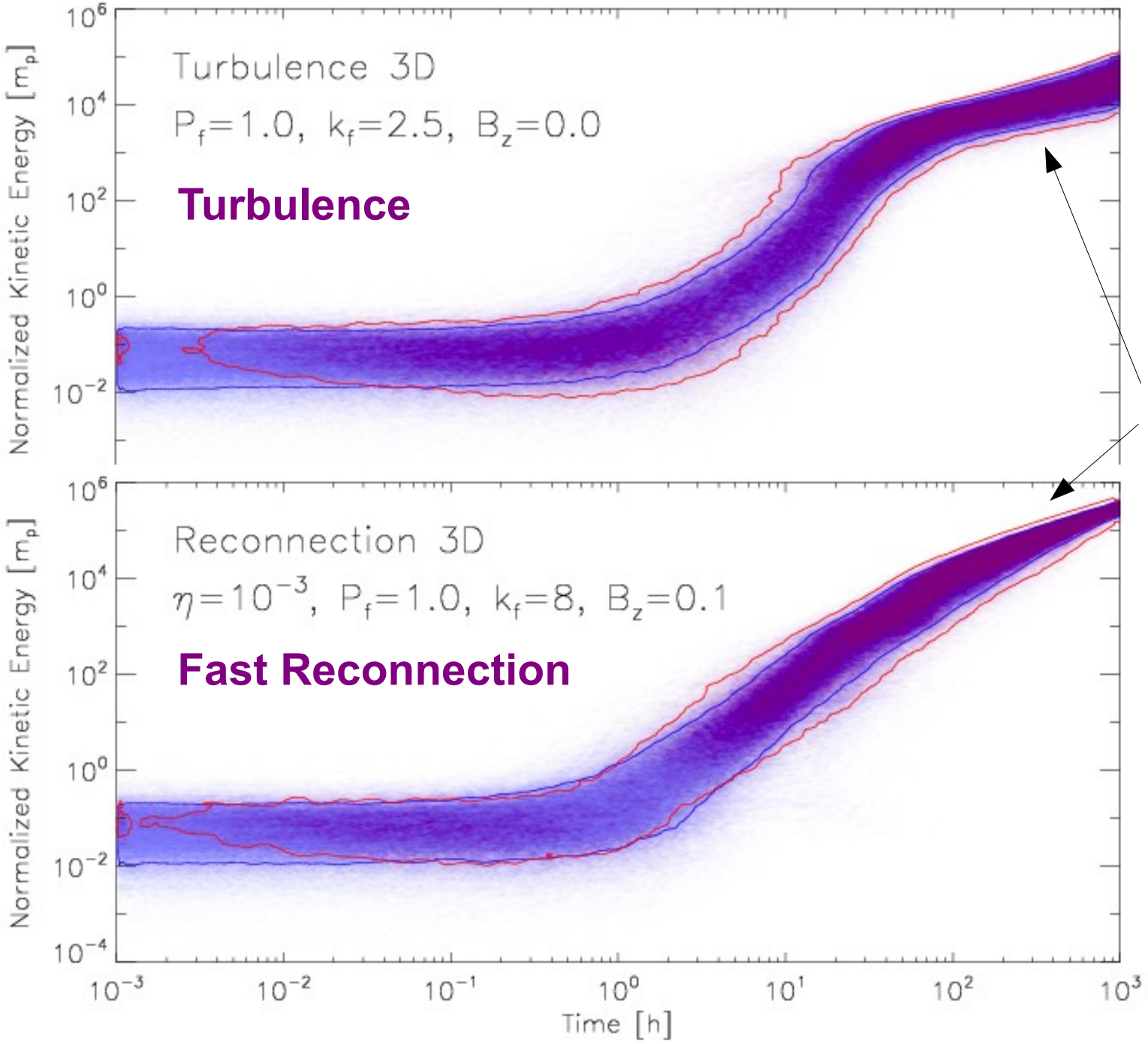


Average energy gain per crossing the reconnection region:

$$\langle \delta E/E \rangle = \frac{V_R}{c}\int_0^{\pi/2} 2\cos^2\theta\sin\theta\, d\theta = 4/3\,\frac{V_R}{c}.$$

Acceleration should be very efficient in turbulent reconnection!

Turbulence vs. Fast Reconnection



In Fast Reconnection models particles start to accelerate earlier and reach about one order of magnitude higher energies at the end.

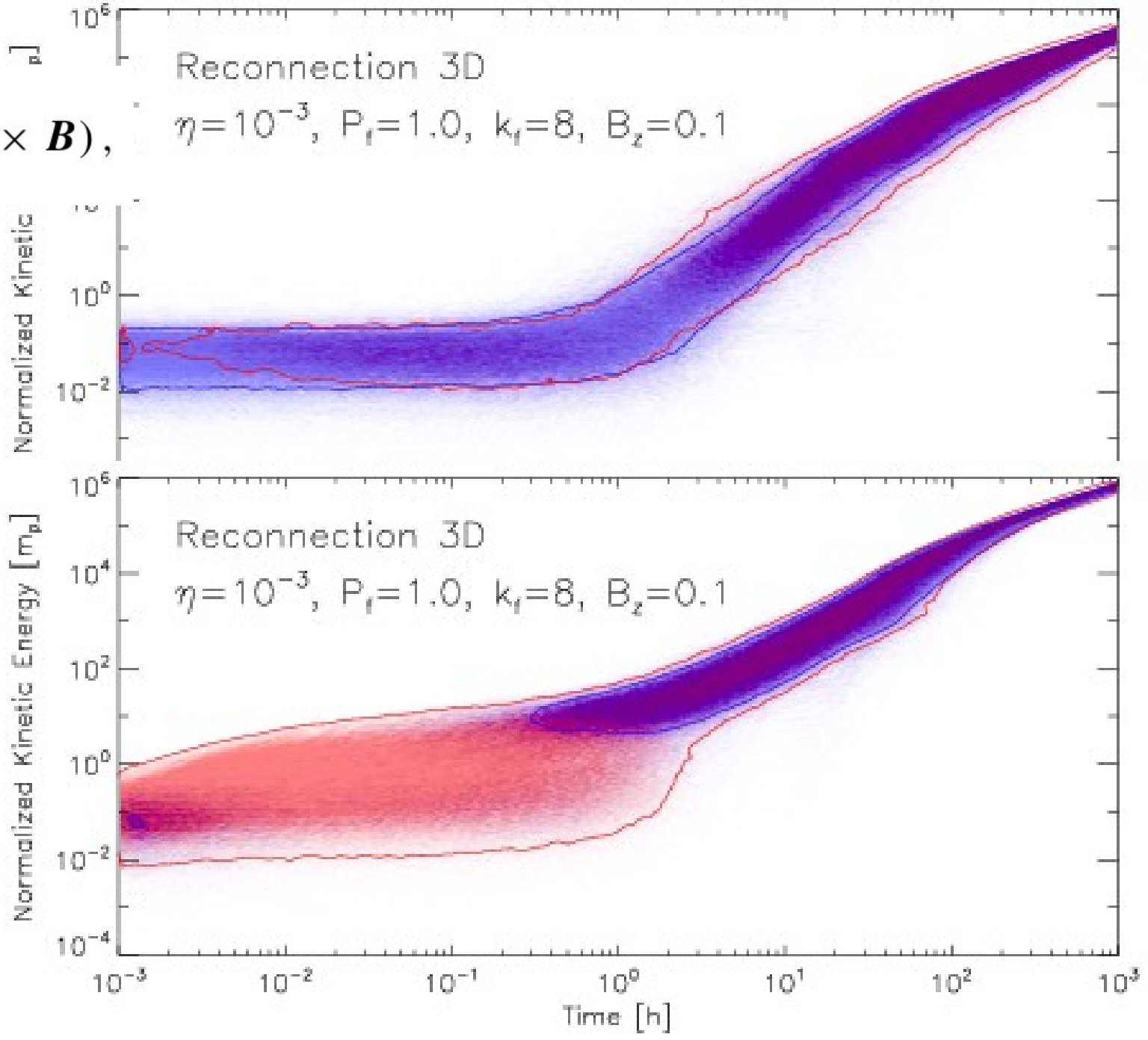
Acceleration with the Resistive Term

$$\frac{d}{dt}(\gamma m \boldsymbol{u}) = q(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}),$$

$$\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta \boldsymbol{j},$$

Resistive term is important only initially, i.e., when the particle speed is small.

If we scale resistivity to the astrophysical values, the resistive term can be neglected.



Conclusions

✔ Contracting magnetic loops in magnetic reconnection in 2D, in the MHD regime, provides the acceleration which successfully reproduces the results obtained earlier with more complicated PIC codes, which proves that the acceleration in reconnection regions is a universal process that is not determined by the details of plasma physics.

✔ Acceleration of energetic particles in 2D and 3D shows substantial differences, which call for focusing on realistic 3D geometries of reconnection. Our study also shows that apart from the first-order Fermi acceleration, additional acceleration processes interfere.

✔ Initial numerical results of the acceleration in the model of Lazarian-Vishniac (1999) look promising, signifying that the fast reconnection sites can efficiently produce cosmic rays.

✔ Resistive terms do not determine the global acceleration rate, and can be negligible in the fast reconnection zones.