Numerical Simulations of Magnetic Reconnection in Solar Wind
Collisional vs Collisionless Regimes

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Solar Wind Characteristics

From Bruno & Carbone (2013):

Length	Slow wind	Fast wind
Debye	~ 4 m	~ 15 m
proton gyroradius	~ 130 km	~ 260 km
electron gyroradius	~ 2 km	~ 1.3 km
distance between 2 proton collisions	~ 1.2 AU	~ 40 AU

$R_L < \lambda_{mfp}$ - collisionless plasma

Speed	Slow wind	Fast wind
Alfvén	~ 30 km s^{-1}	~ 60 km s^{-1}
ion sound	~ 60 km s^{-1}	~ 60 km s^{-1}
proton thermal	~ 35 km s^{-1}	~ 70 km s^{-1}
electron thermal	~ 3000 km s^{-1}	~ 2000 km s^{-1}

→ $\beta \sim 1$

Fluid Description of Collisionless Plasma

Chew-Goldberger-Law (1956) – one fluid hydromagnetic equations in the absence of particle collisions

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \qquad \frac{\partial \vec{B}}{\partial t} - \nabla \times \left(\vec{u} \times \vec{B} \right) = 0$$

$$\rho \frac{\partial \vec{u}}{\partial t} + \nabla \left(p_\perp + \frac{B^2}{2\mu_0} \right) - \nabla \cdot \left[(1-\alpha) \frac{\vec{B}\vec{B}}{\mu_0} \right] = 0$$

$$\alpha = \left(p_\parallel - p_\perp \right) \mu_0 / B^2$$

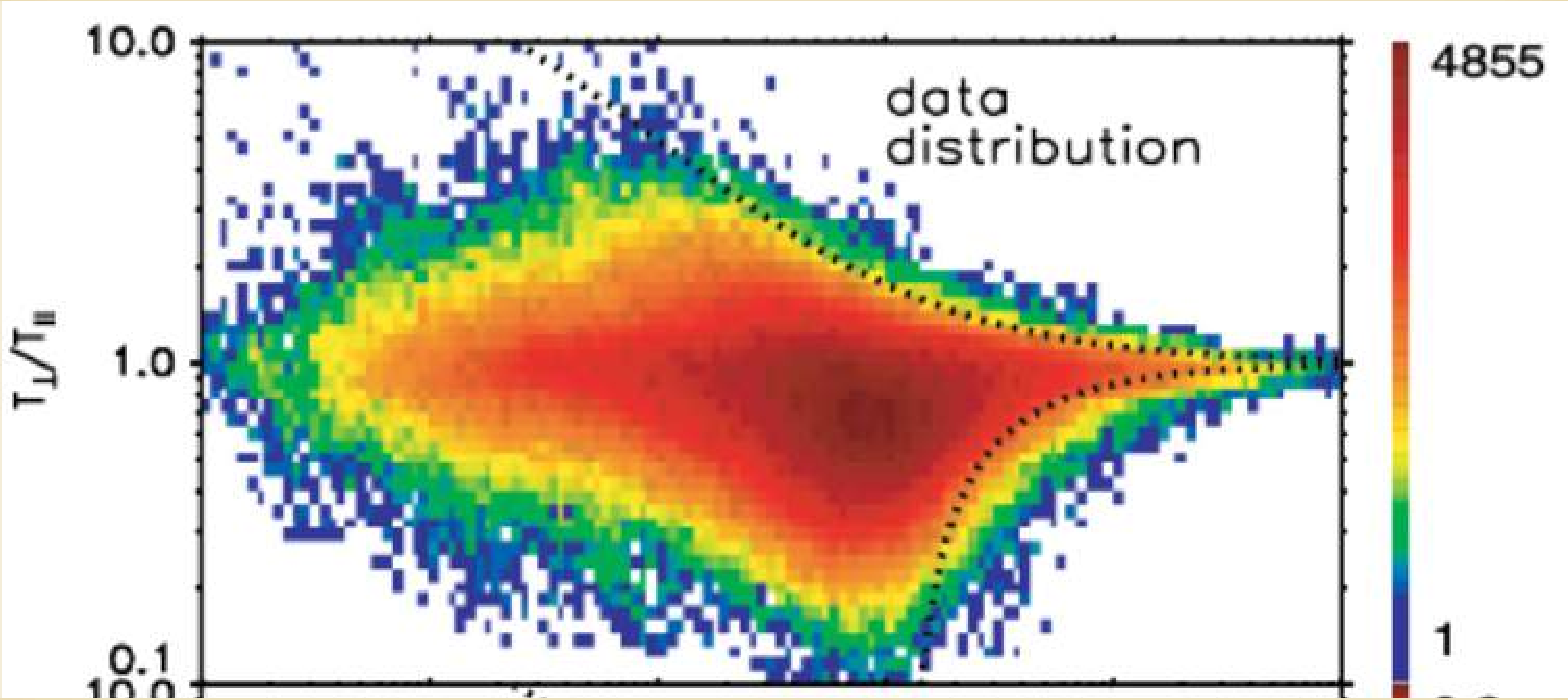
$$\frac{d}{dt} \left(\frac{p_\parallel B^{\gamma_\parallel - 1}}{\rho^{\gamma_\parallel}} \right) = 0$$

$$\frac{d}{dt} \left(\frac{p_\perp}{\rho B^{\gamma_\perp - 1}} \right) = 0$$

Pressure component evolution

Solar Wind Temperature Anisotropies

Observations of Temperature Anisotropy by Bale et al. (2009)



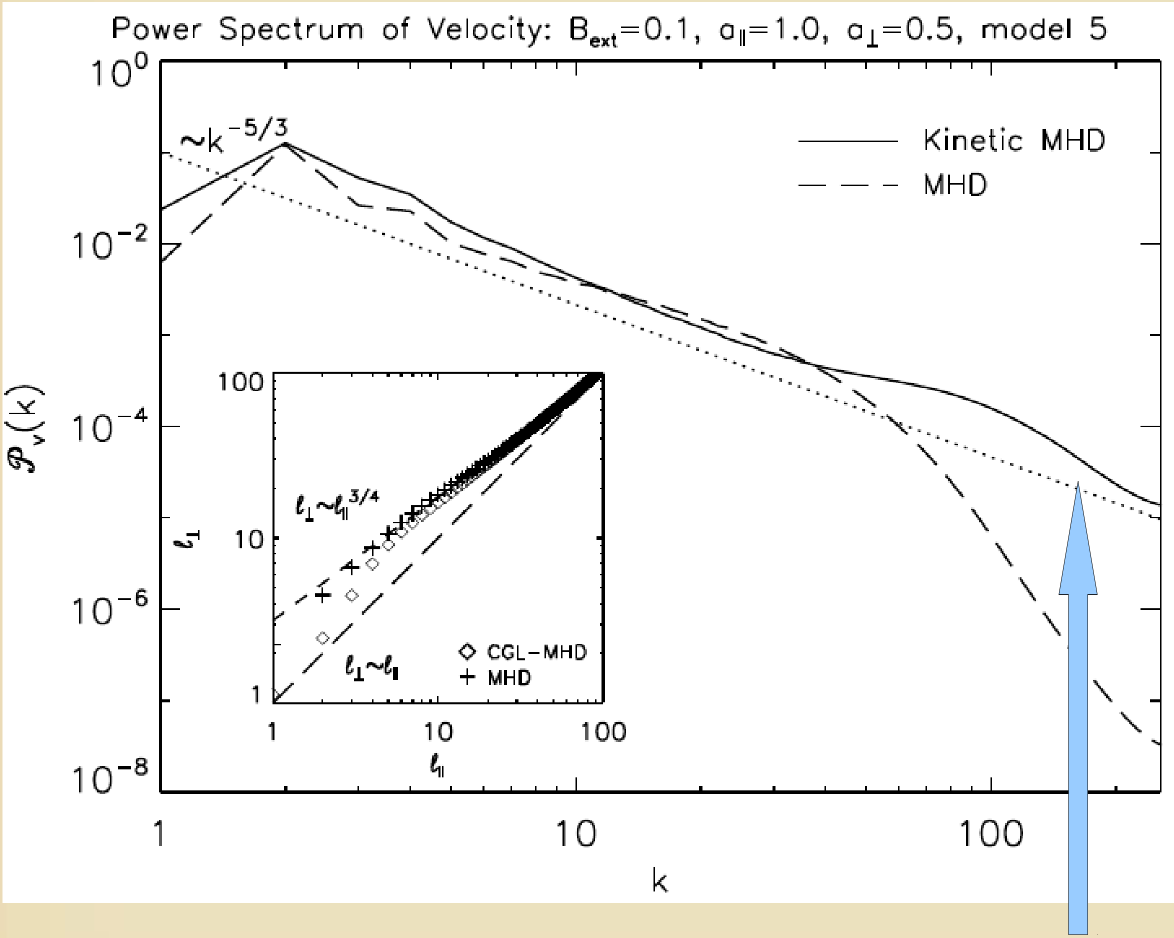
Fitting of the instability limits for protons done by Hellinger et al (2006)

$$\frac{T_{\perp p}}{T_{\parallel p}} = 1 + \frac{a}{\left(\beta_{\parallel p} - \beta_0\right)^b}$$

Instability	a	b	β_0
Proton cyclotron instability	0.43	0.42	−0.0004
Mirror instability	0.77	0.76	−0.016
Parallel fire hose	−0.47	0.53	0.59
Oblique fire hose	−1.4	1.0	−0.11

Turbulence in Collisionless Plasma

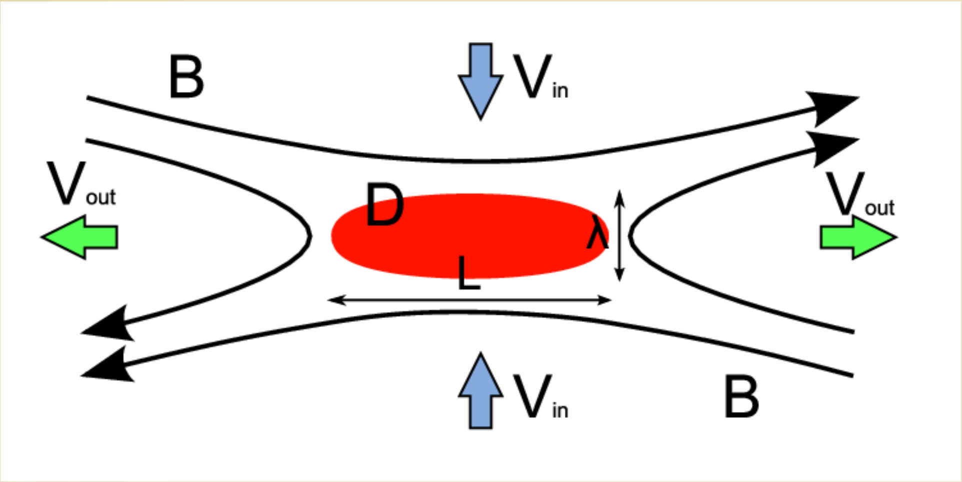
Kowal, Falceta-Gonçalves & Lazarian (2011)



Simulation of turbulence with the presence of firehose instability.

Turbulence statistics affected by kinetic instabilities

Sweet-Parker model (1957)



$$V_{inflow} = \eta / \lambda$$

Ohmic diffusion

$$V_{inflow} L = V_{outflow} \lambda$$

Mass conservation

$$V_{outflow} = V_A$$

Free outflow

Reconnection Rate:

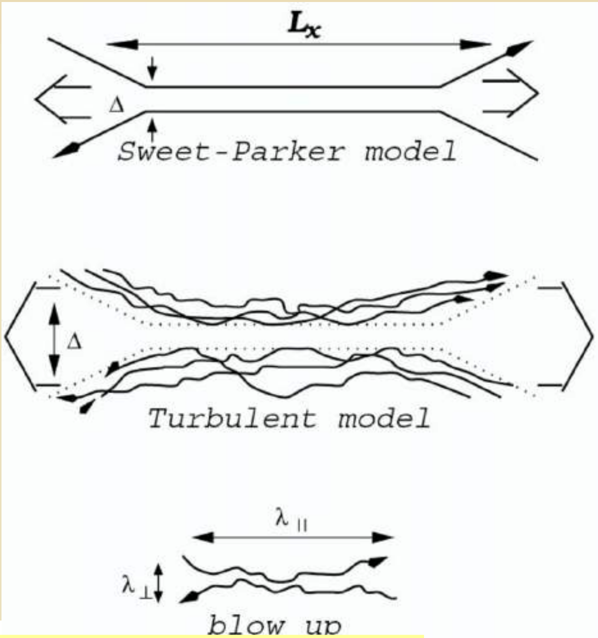
$$V_{inflow} = V_A \left(\frac{\lambda}{L} \right) = V_A \left(\frac{L V_A}{\eta} \right)^{-1/2} = V_A S_L^{-1/2}$$

Lundquist Number

PROBLEM: S_L very large for astrophysical objects!

Solar Corona $S_L \sim 10^{12}$-10^{14}, ISM $S_L \sim 10^{15}$-10^{20}

Reconnection with Turbulence (LV99)

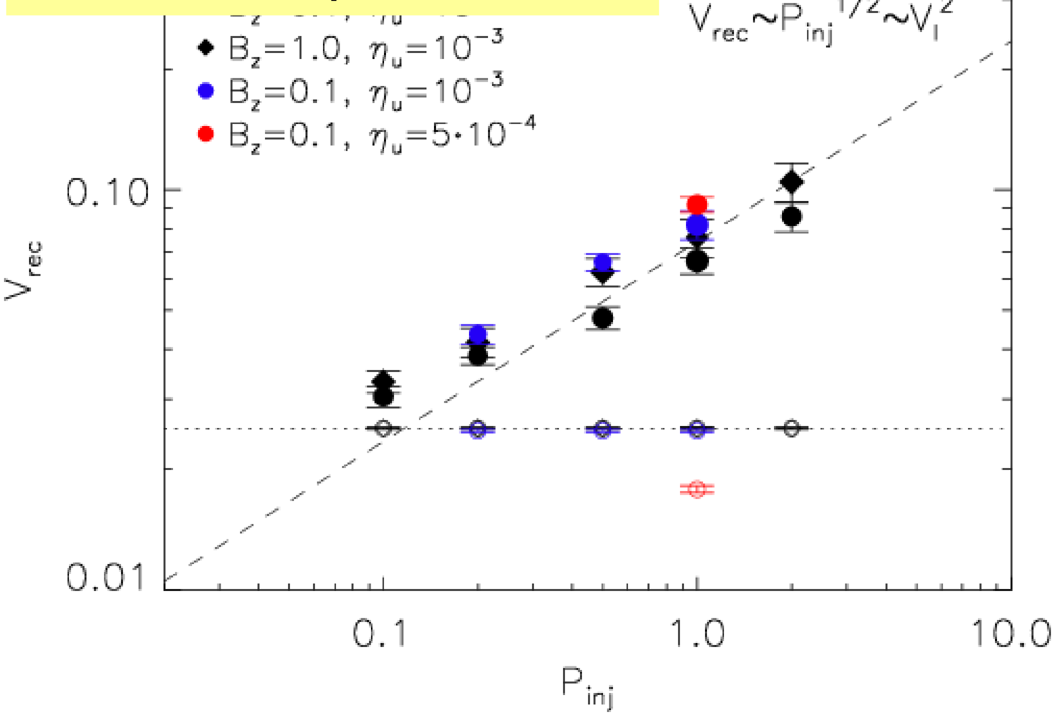


Upper limit imposed by the large-scale field line diffusion

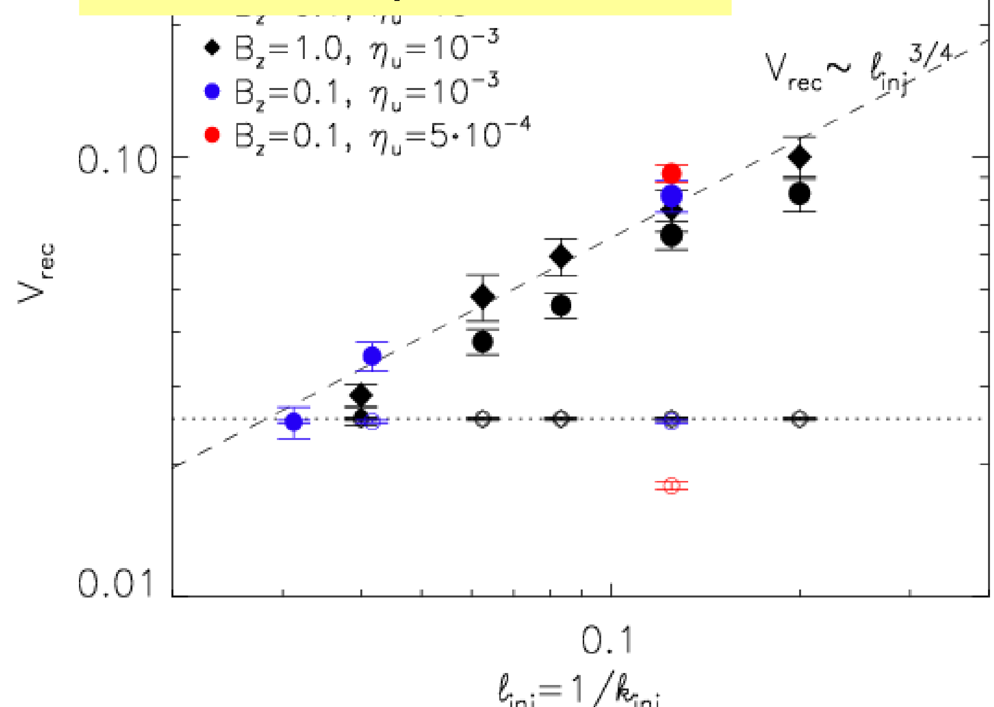
$$V_{rec} < V_A \min\left[\left(\frac{L_x}{L}\right)^{1/2}, \left(\frac{L}{L_x}\right)^{1/2}\right]\left(\frac{v_L}{V_A}\right)^2$$

Lazarian & Vishniac (1999)
Kowal et al. (2009, 2012)

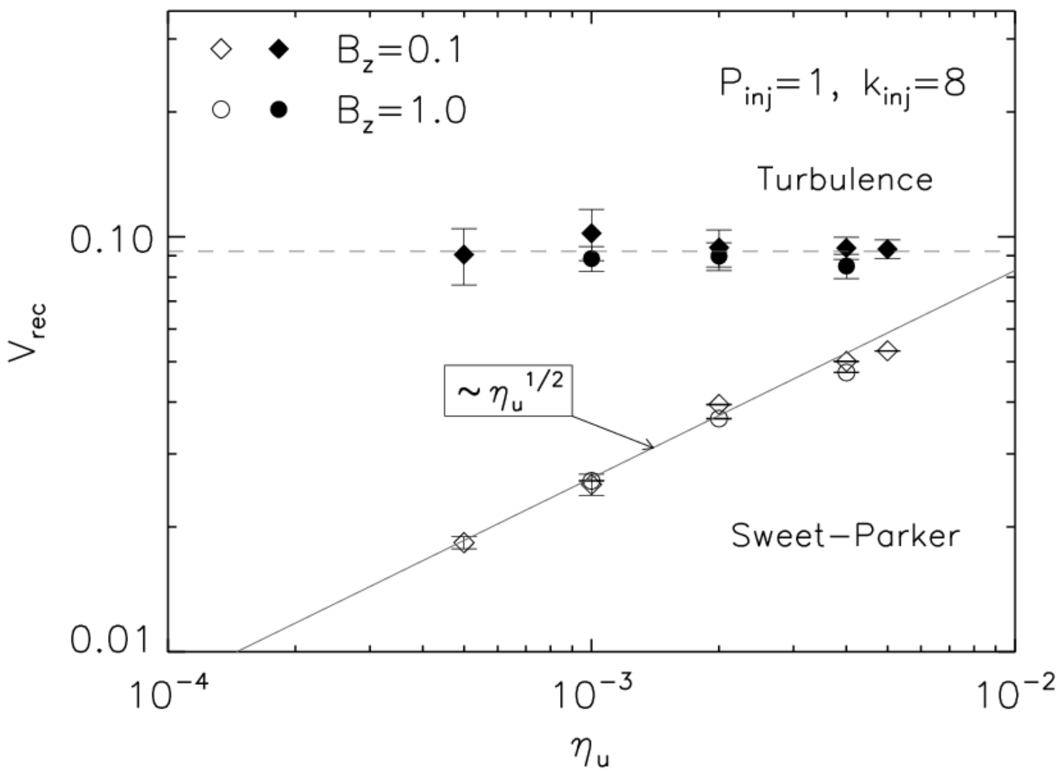
Power dependence



Scale dependence

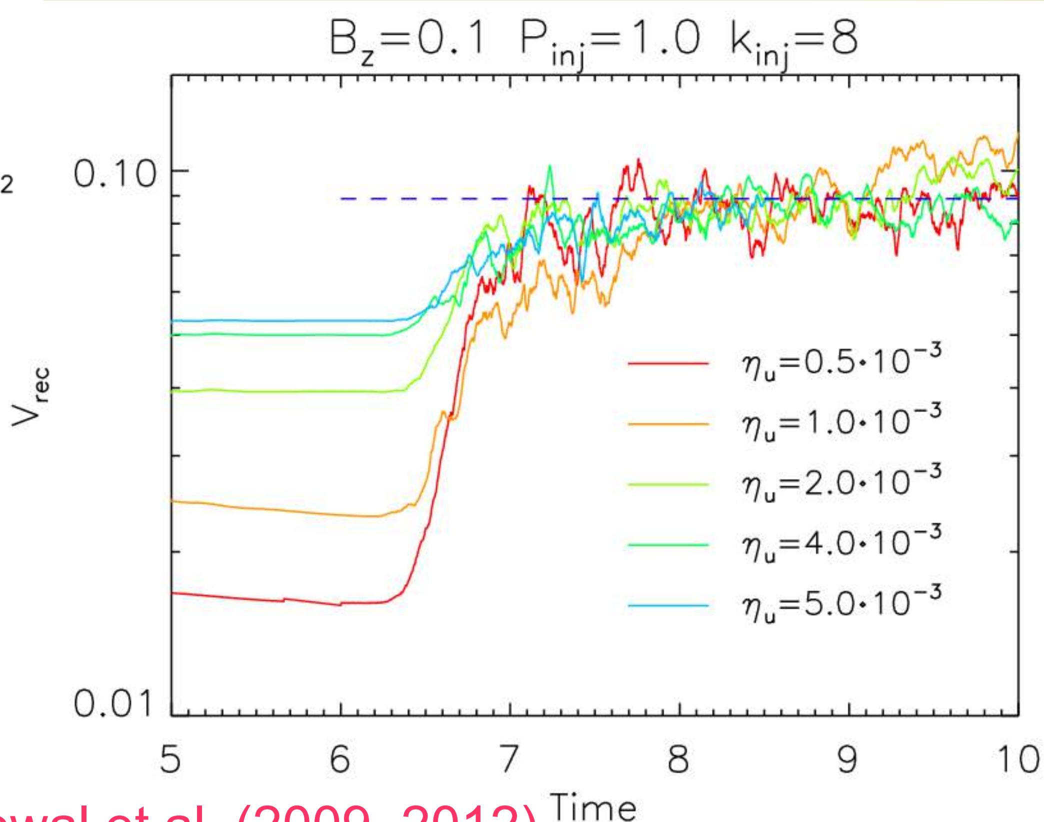


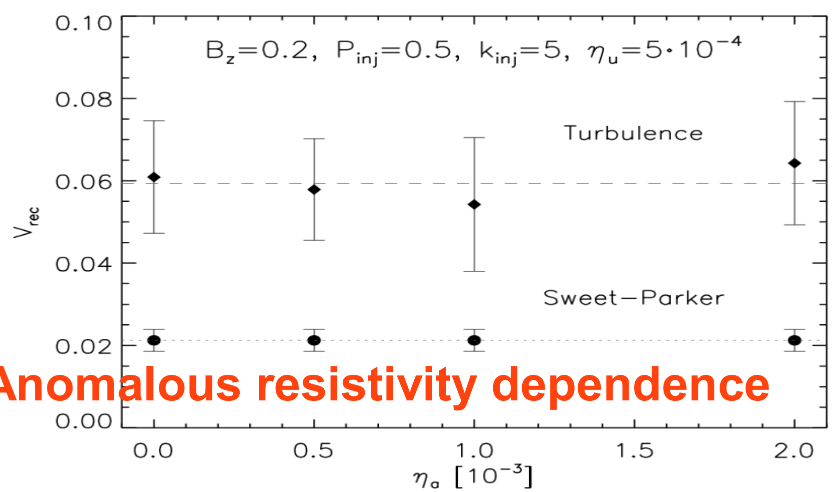
Dependence on Resistivity



The reconnection rate does not depend on the Ohmic resistivity, thus the reconnection is FAST!

No eta-dependence!





Anomalous resistivity dependence

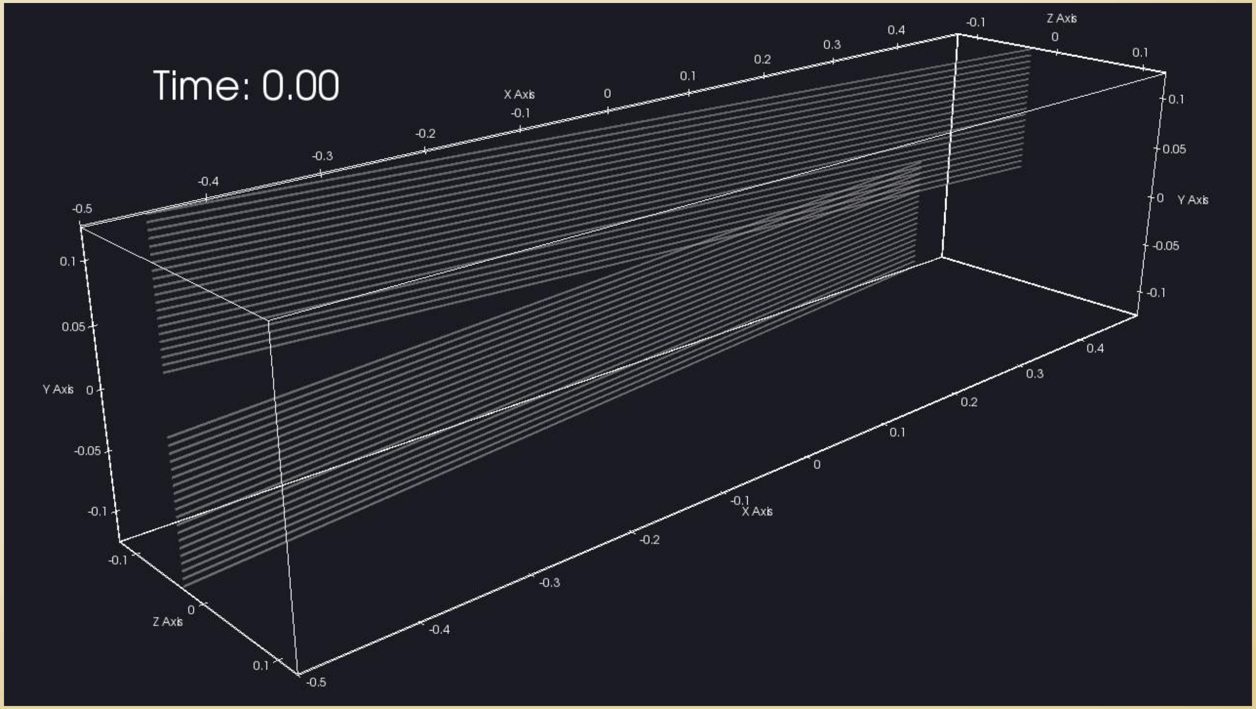
Kowal et al. (2009, 2012)

Numerical Setup

- initial Harris current sheet setup

$$B_x(x,y)=B_0\tanh(y/h), B_y(x,y)=0$$

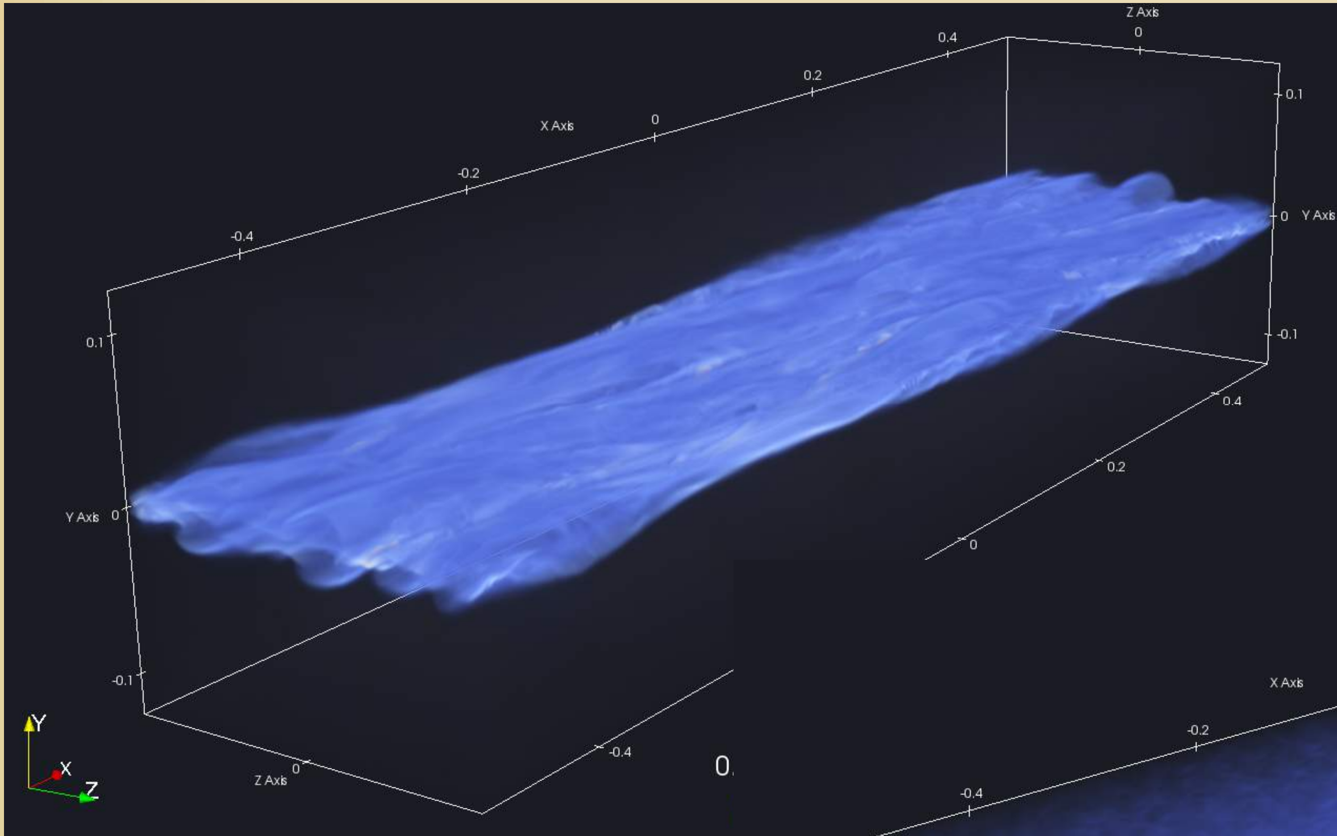
- $B_0=1$, $B_z=0.1$
- initially firehose unstable sound speeds $a_{\parallel} = 1.5$, $a_{\perp} = 1.0$
- initial random velocity perturbation with amplitude < 0.1
- periodic box



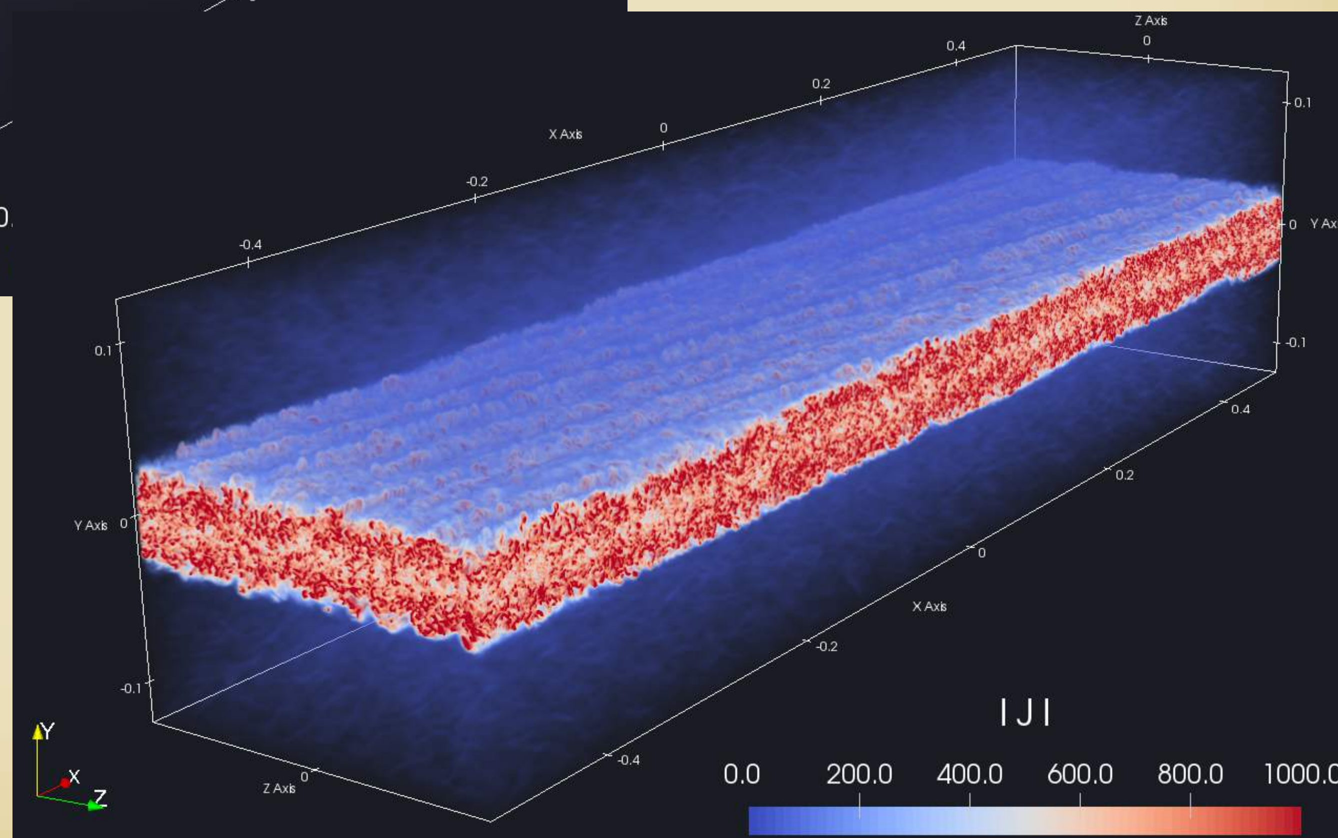
Current Density

Kowal et al. (in prep.)

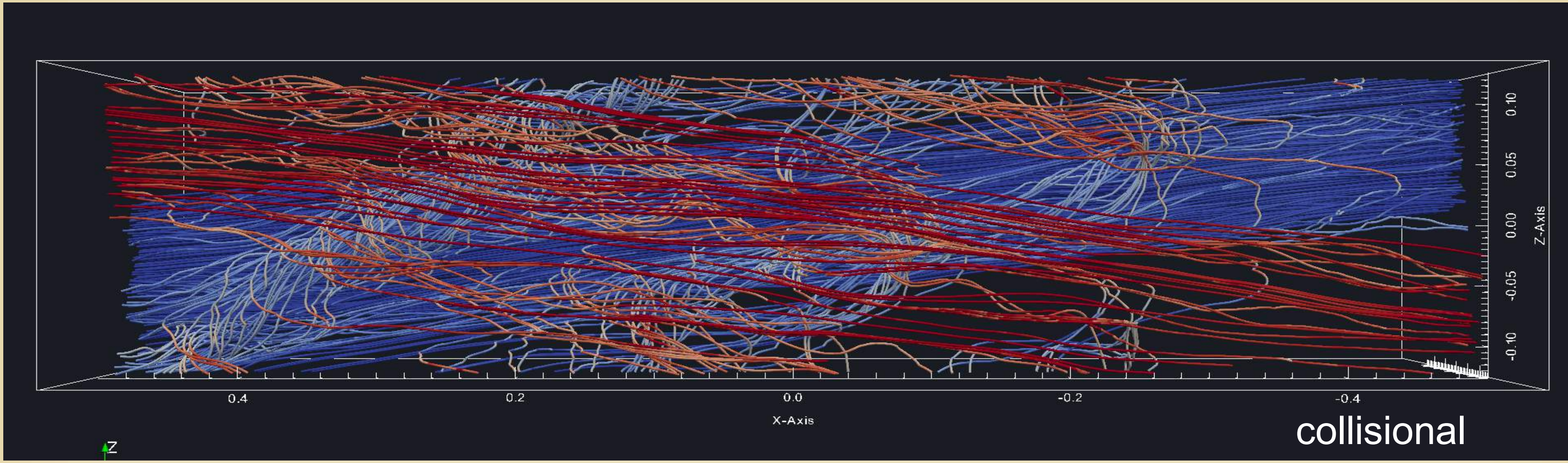
Collisional case – current sheet centered around the midplane with fluctuations due to the self-induced reconnection

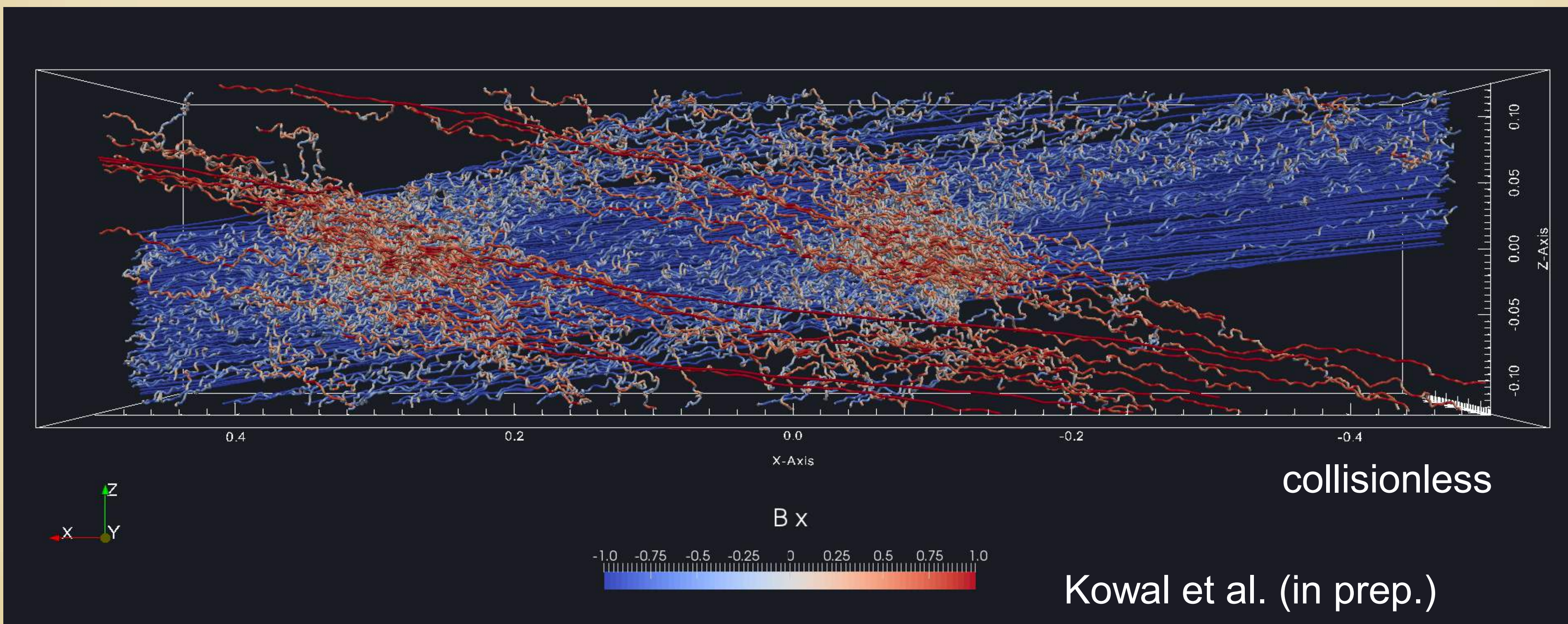


Collisionless case – initial velocity perturbations not only induce the reconnection but also bring the plasma to the firehose unstable regime causing strong field fluctuations and increase of |J|

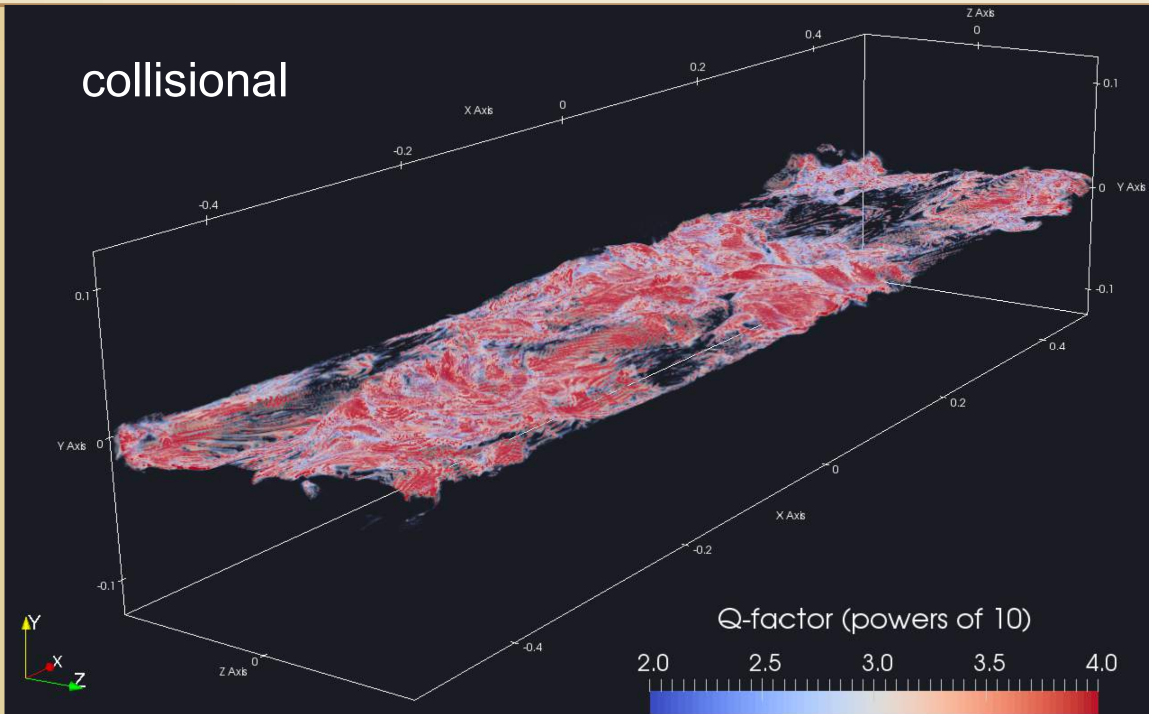


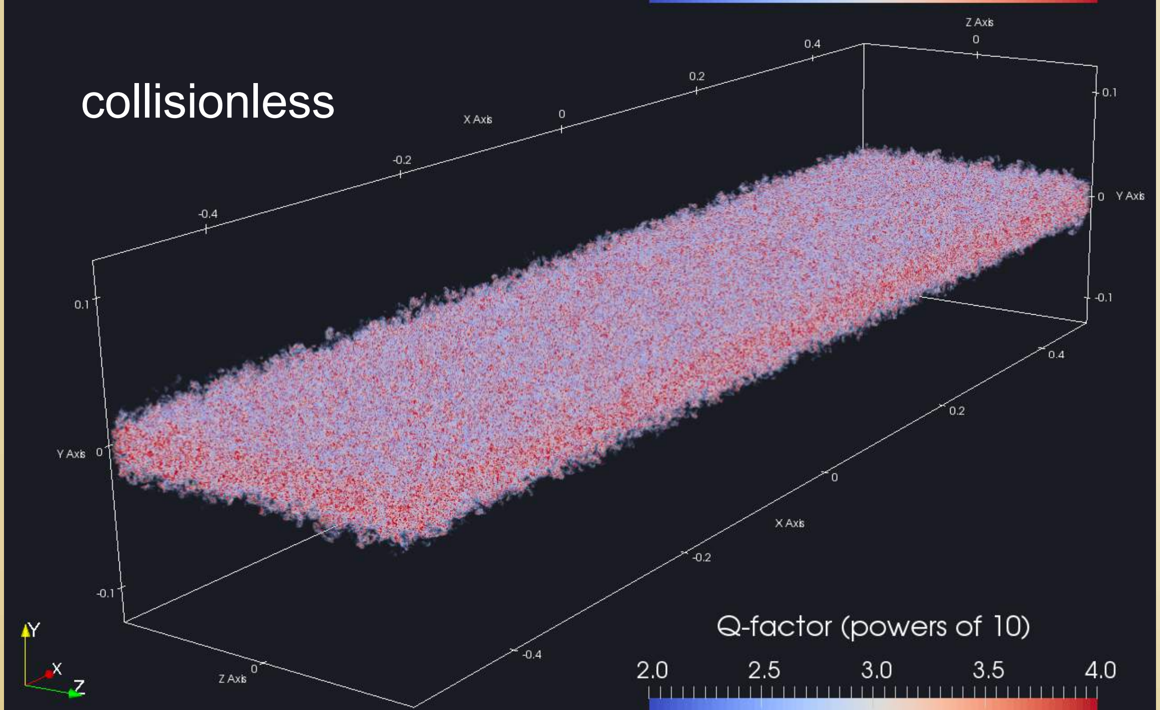
Magnetic Line Deformation

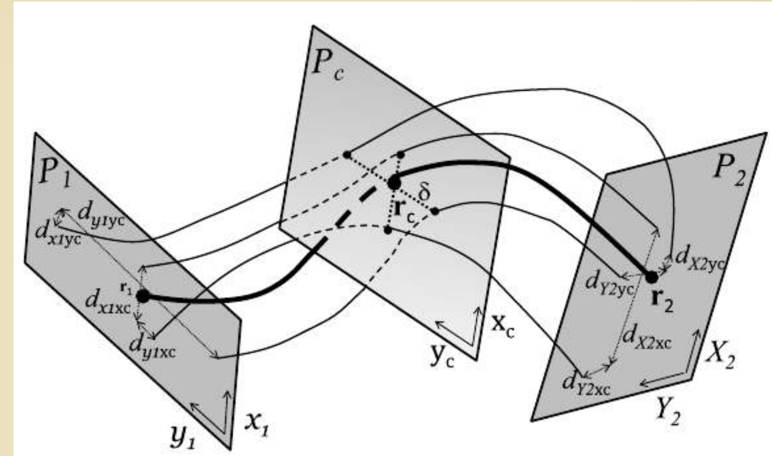




Global Reconnection Rate using Q-factor







<u>Pariat & Démoulin (2012):</u>
Squashing degree, Q - the field-line invariant quantifying the deformation of elementary flux tubes.

Collisional: $\overline{Q} = 5 \cdot 10^4$
Collisionless: $\overline{Q} = 10^6$

Kowal et al. (in prep.)

Conclusions

- In the collisionless regime the presence of pressure anisotropy allows for the development of instabilities, such as firehose
- In the current sheet we expect the drop of magnetic field strength, allowing for the firehose instability condition $\beta_{\parallel}-\beta_{\perp}>2$ to be fulfilled
- The instability directly affects the topology of magnetic field creating helical loop-like deformations in the current sheet, which effectively increase the reconnection rate, as we have shown using the Q-factor