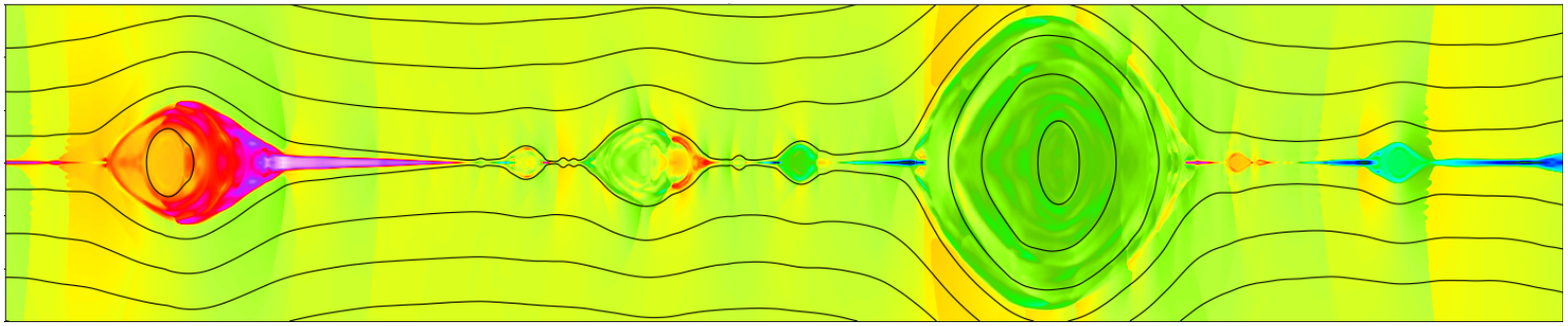
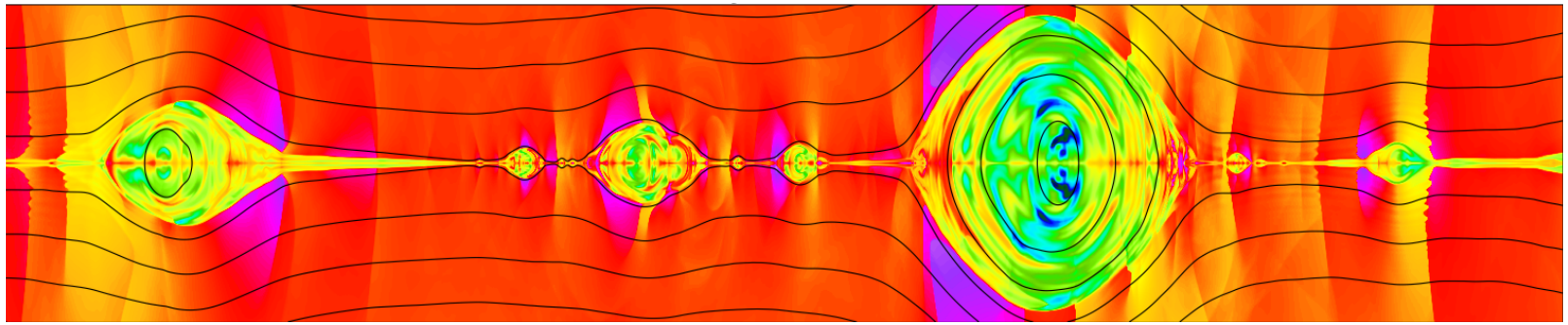
EGU22-1485



Plasmoid-dominated turbulent reconnection in symmetric and asymmetric systems

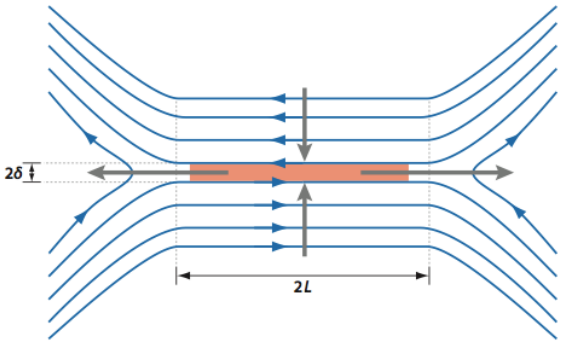
Seiji Zenitani (Kobe U)

M. Yamamoto (Kobe U), T. Miyoshi (Hiroshima U)



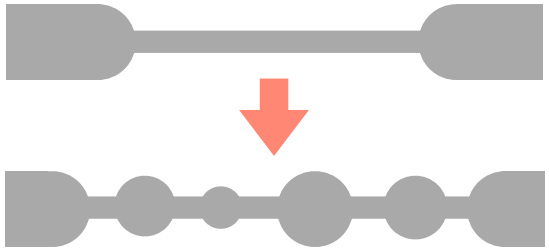
MHD models of magnetic reconnection

Sweet-Parker



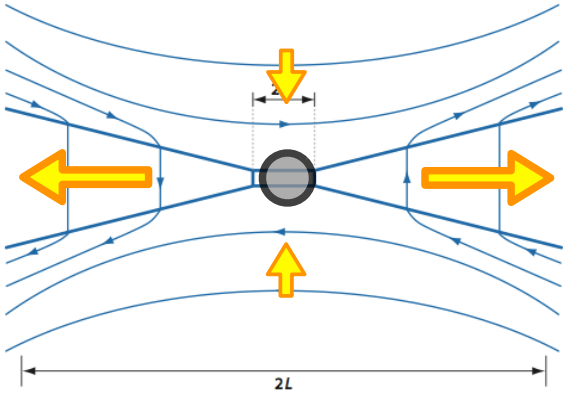
Sweet 1958, Parker 1957

plasmoid-dominated



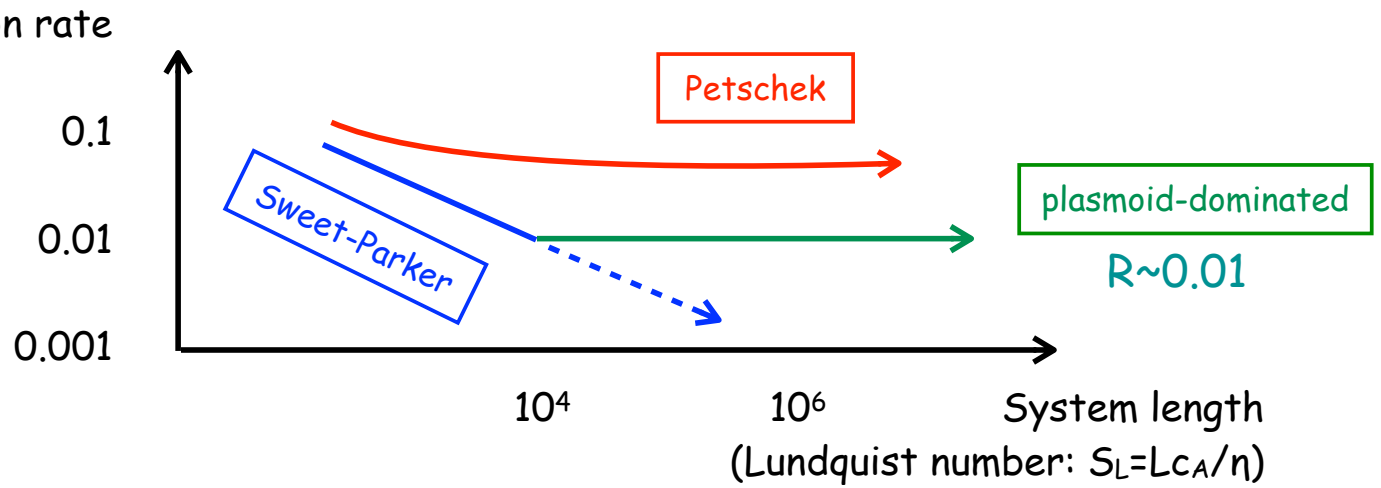
Loureiro 2007, Bhattacharjee+ 2009
Uzdensky+ 2010, Pucci+ 2014

Petschek

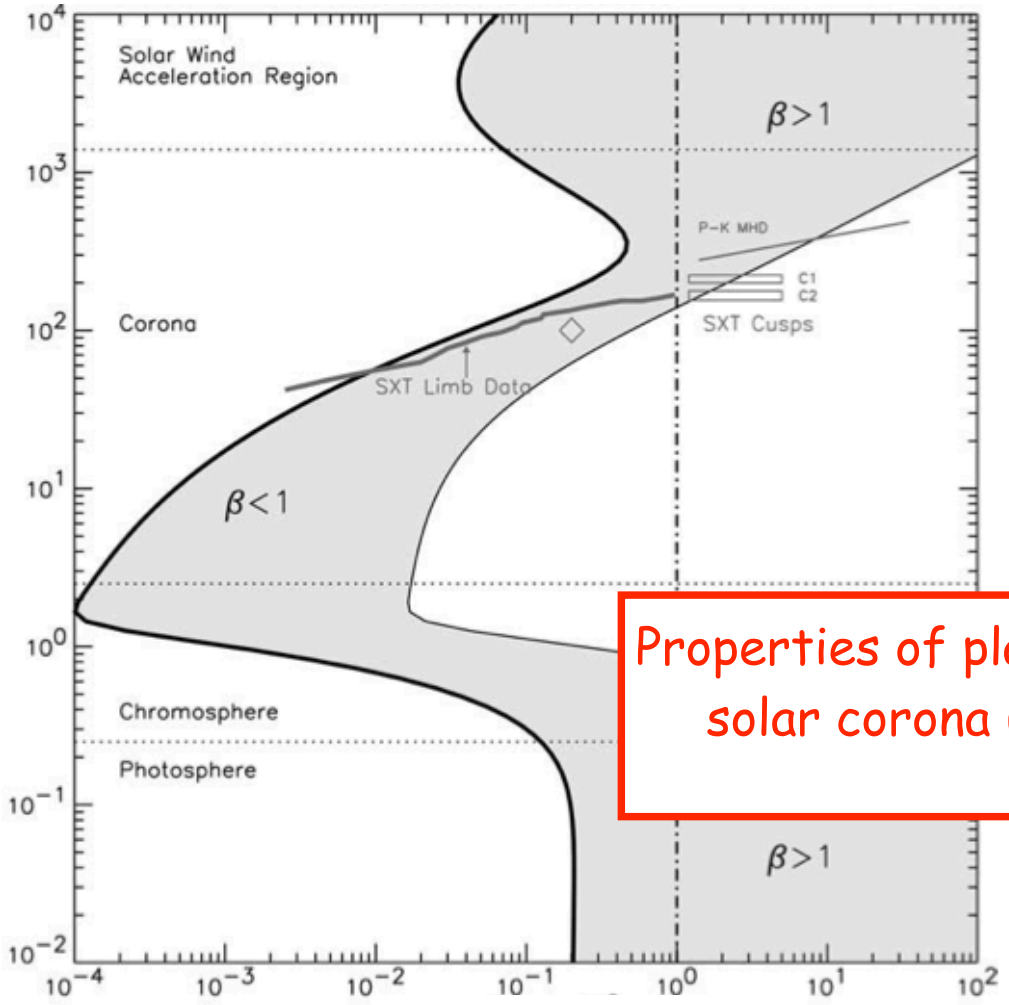


Petschek 1964

$$\mathcal{R} \equiv \frac{v_{in}}{c_A}$$



Solar corona: β<<1



Properties of plasmoid-reconnection in a solar corona (β<<1) is largely unknown.

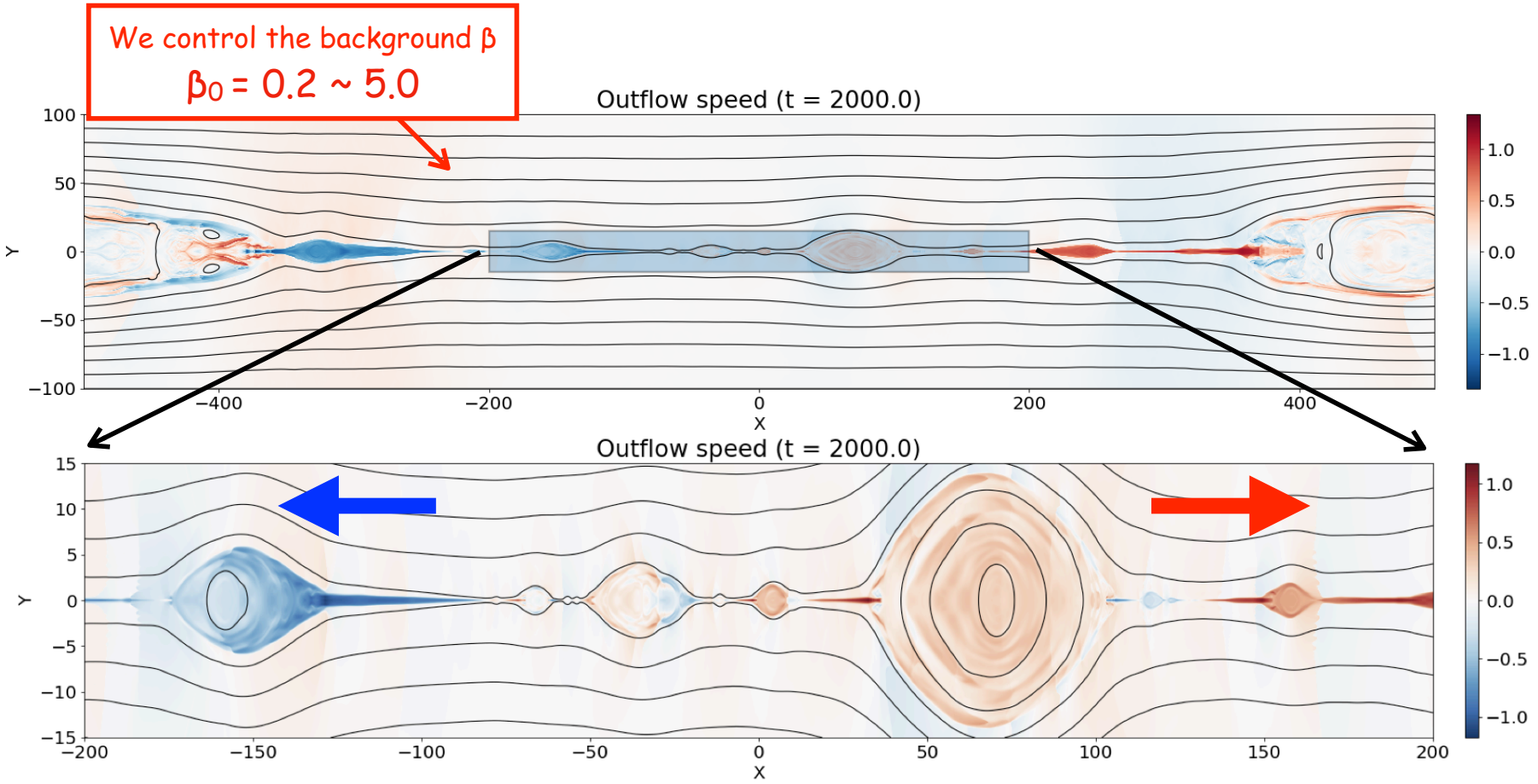
Ni+12, Baty+ 14, Peter+ 19...

MHD simulation

Plasma beta $\beta \equiv \dfrac{p_{\rm gas}}{p_{\rm mag}}$

Gary 2001

MHD simulation

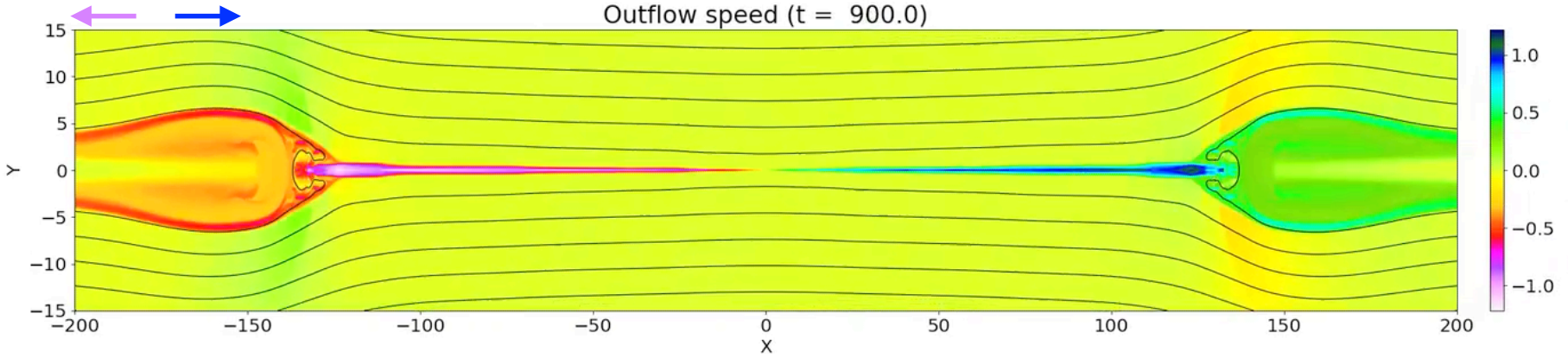


- $\eta = 1/1000$, $S_L = 2.5 \times 10^5$ for $L_{cs} = 250$
- 30,000 x 3,000 (x 2) grid points
- 500 cores on a supercomputer or 1 GPU (NVIDIA A100)

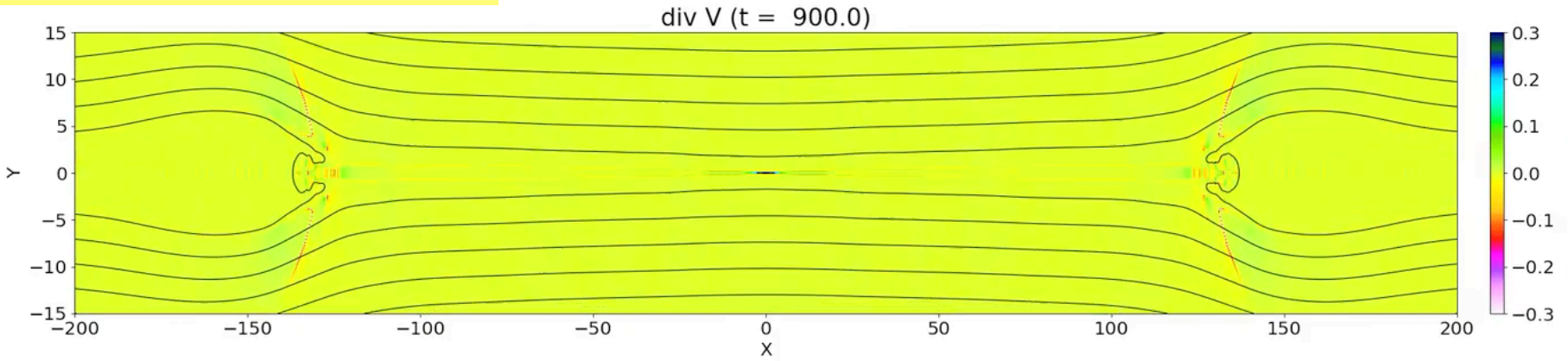
Simulation results (Movies)

- https://sci.nao.ac.jp/MEMBER/zenitani/files/b02_outflowB.mp4
- https://sci.nao.ac.jp/MEMBER/zenitani/files/b02_divvB.mp4

Outflow speed (V_x)



div V - Compression in red

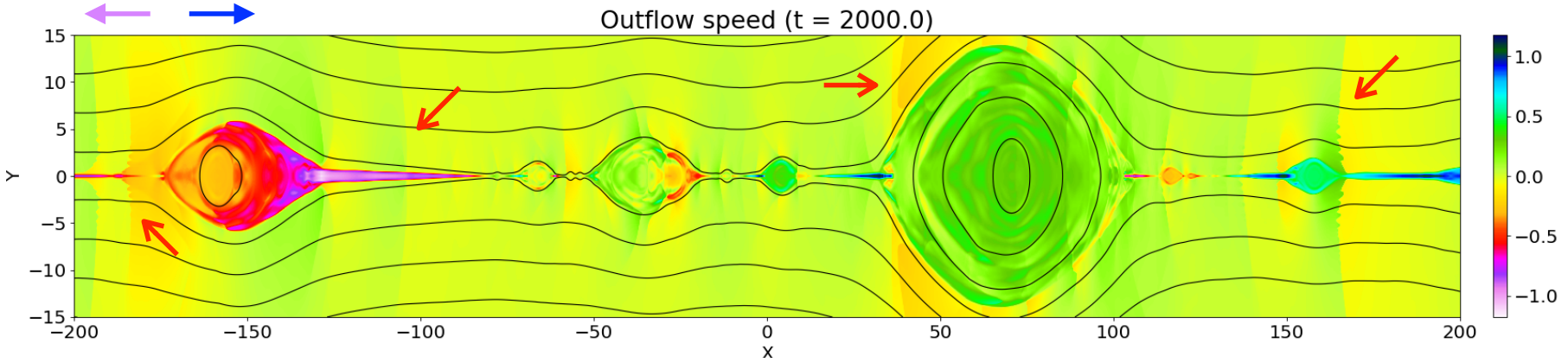


SZ & Miyoshi 2020

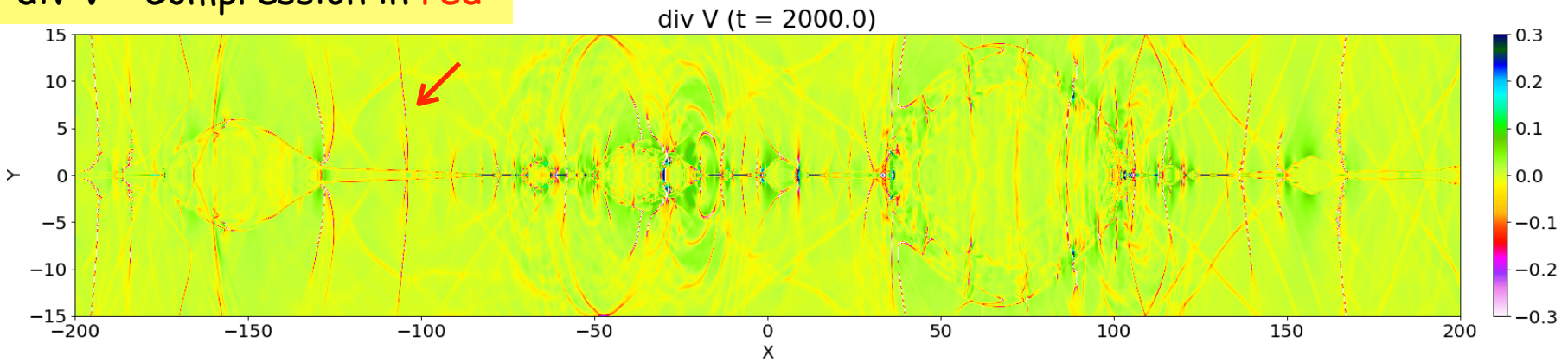
Normal slow shocks

- Normal slow shocks travel in the left and right directions, even inside the plasmoids
- Transonic/supersonic motion of plasmoids (SZ & Miyoshi 2011, SZ 2015, Arnold+ 2022)
- Plasmoid-plasmoid collision sometimes generates fast shocks

Outflow speed (V_x)

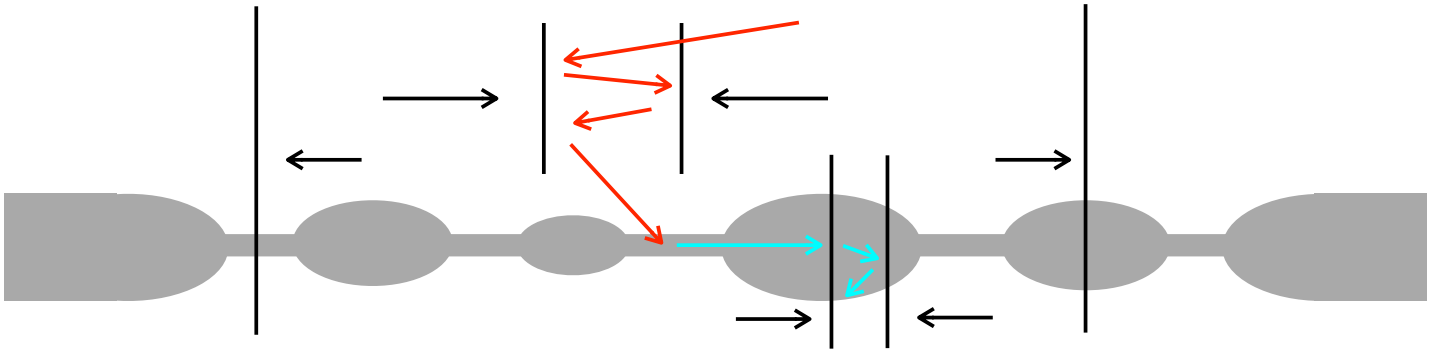


div V - Compression in red

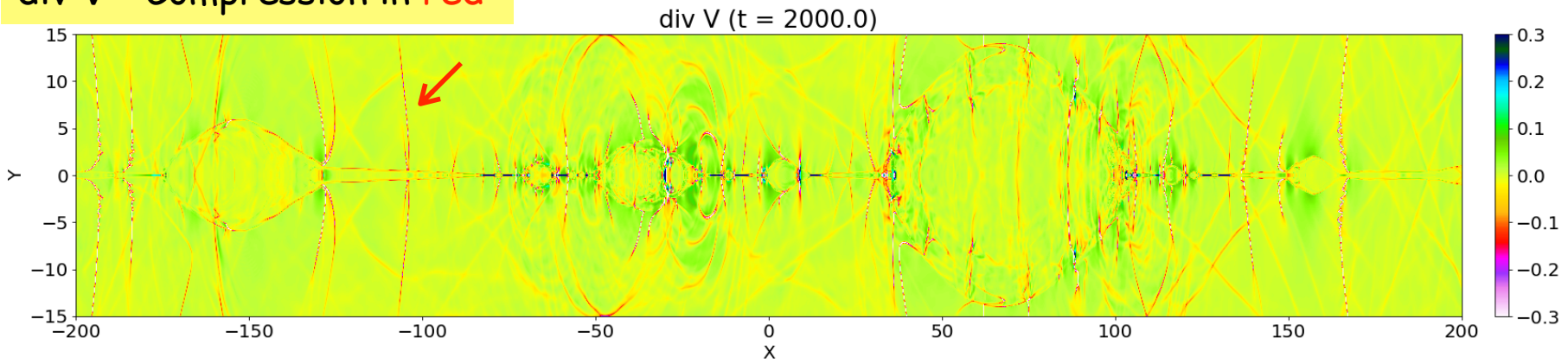


Pre-acceleration by normal shocks?

- Additional acceleration scenarios to the known acceleration mechanisms



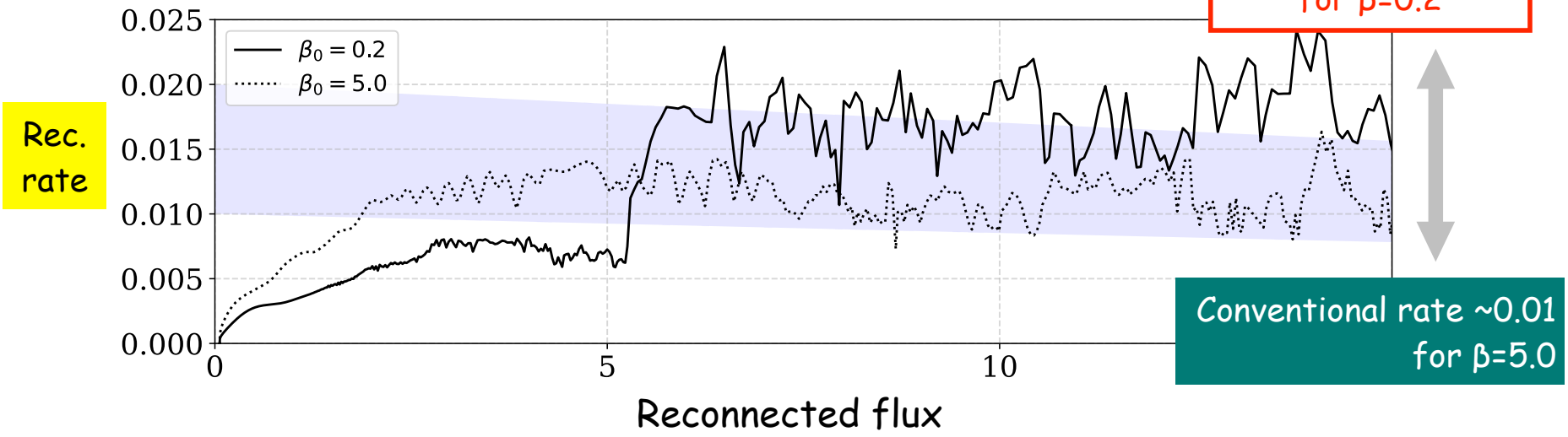
div V - Compression in red



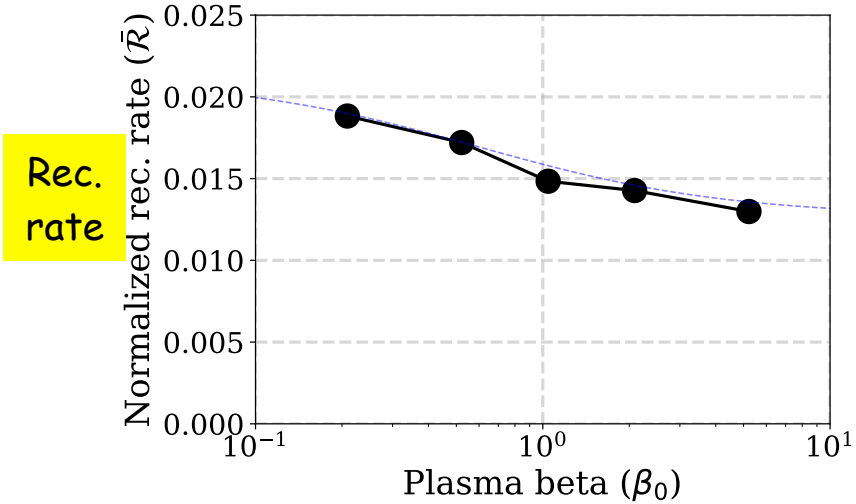
Reconnection rate

$$\mathcal{R} = -\frac{1}{c_{A0} B_{A0}} \frac{\partial \Psi}{\partial t}$$

Faster rate ~0.02 for β=0.2



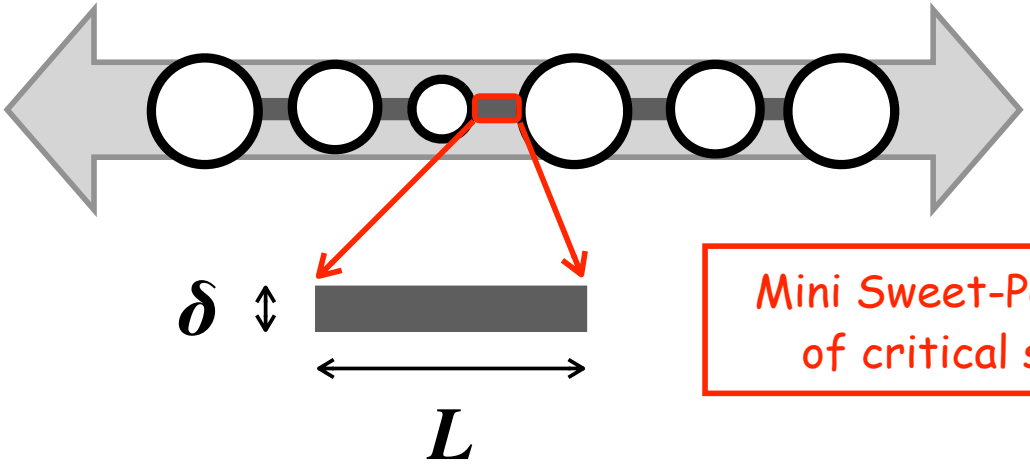
Conventional rate ~0.01 for β=5.0



- Faster for lower-β cases

- For β<<1, the rate approaches R~0.02
- For β>>1, it approaches the conventional value of R~0.01

Estimating the reconnection rate



Mini Sweet-Parker (SP) layers of critical size (S_{crit} ~10^4)

- Rate of the mini S-P layer is controlled by the compression ratio and the aspect ratio (Hesse+ 2011)
- We assume that the typical aspect ratio is similar.
- Global reconnection rate should scale like the compression ratio.

$$\mathcal{R}_{\rm sp} \equiv \frac{v_{in}}{c_A} = \frac{2\gamma(1+\beta)}{3(\gamma-1)+2\gamma\beta}\left(\frac{\delta}{L}\right)$$

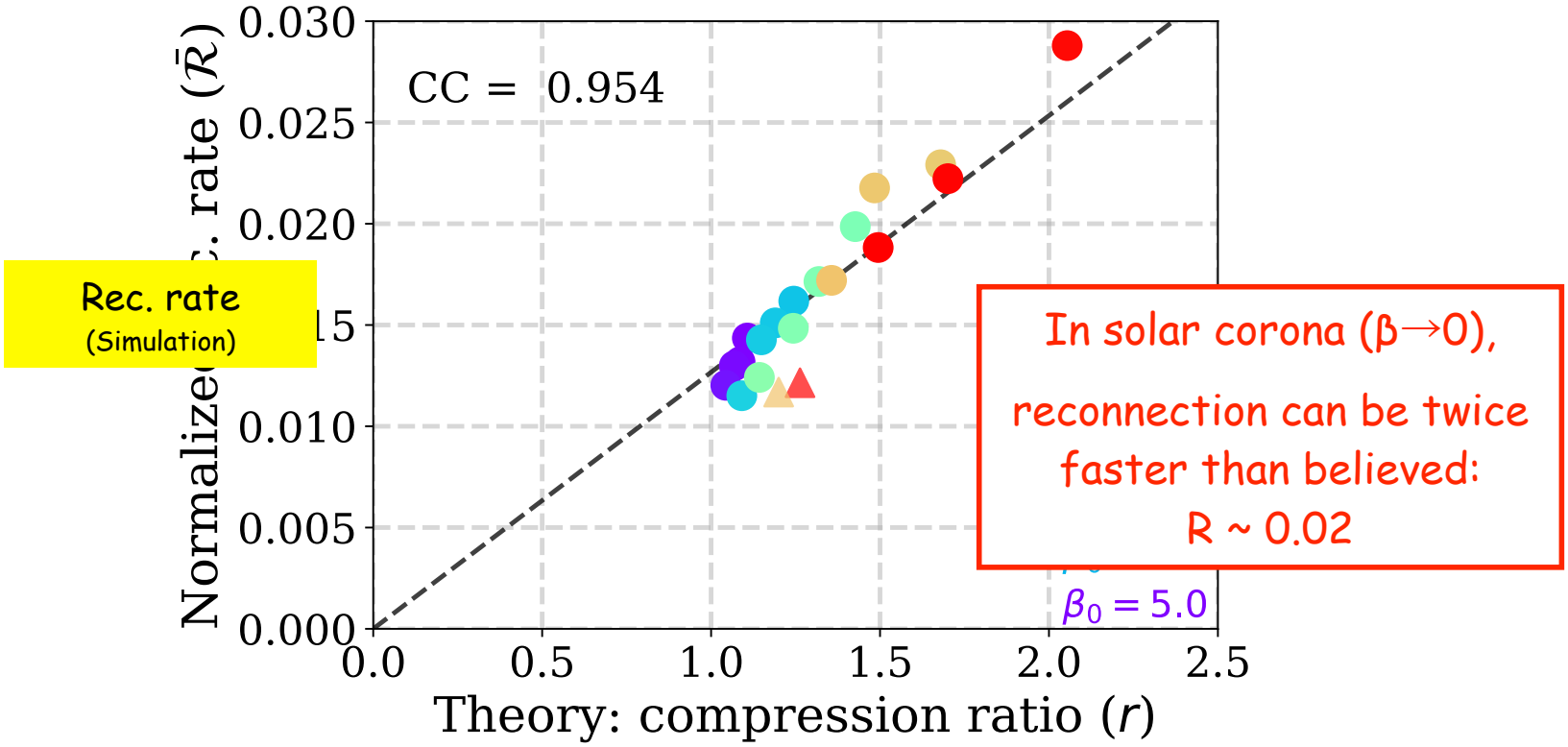
$$\left(\frac{\delta}{L}\right) \approx S_{\rm crit}^{-1/2} = \text{const.}$$

$$\langle \mathcal{R} \rangle \sim \mathcal{R}_{\rm sp} \propto \frac{2\gamma(1+\beta)}{3(\gamma-1)+2\gamma\beta}$$

γ: adiabatic index

Simulation vs Theory

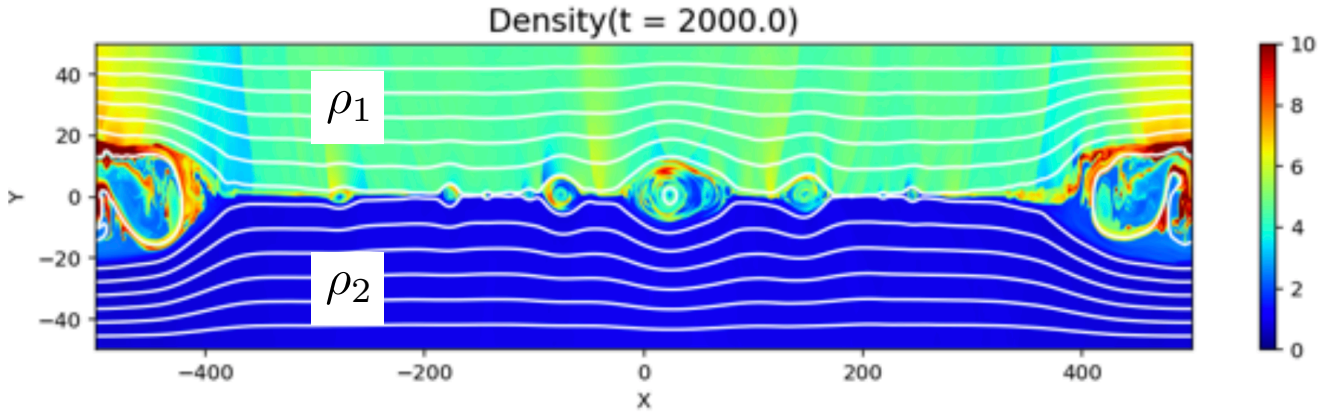
- Compression ratio (theoretical prediction) is a function of (β, γ)
- Numerical survey for β=[0.2, 0.5, 1.0, 2.0, 5.0], γ=[1.33, 1.5, 1.67, 2.0]
- Rec. rate (simulation) is proportional to the compression ratio



SZ & Miyoshi 2020

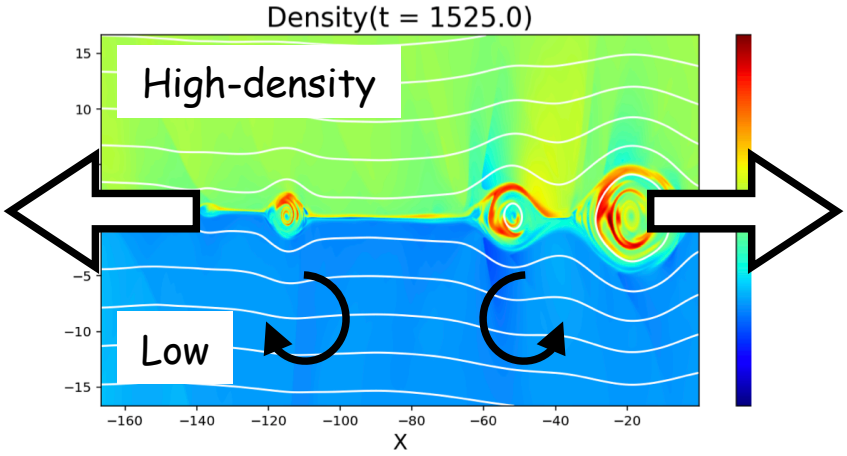
Plasmoid reconnection with density-asymmetry

by Momoka Yamamoto

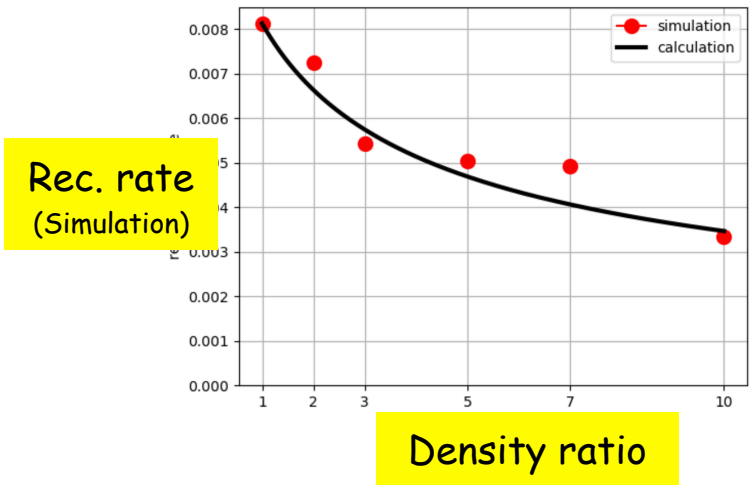


$$\rho_1 > \rho_2$$

1. Swirling plasmoids

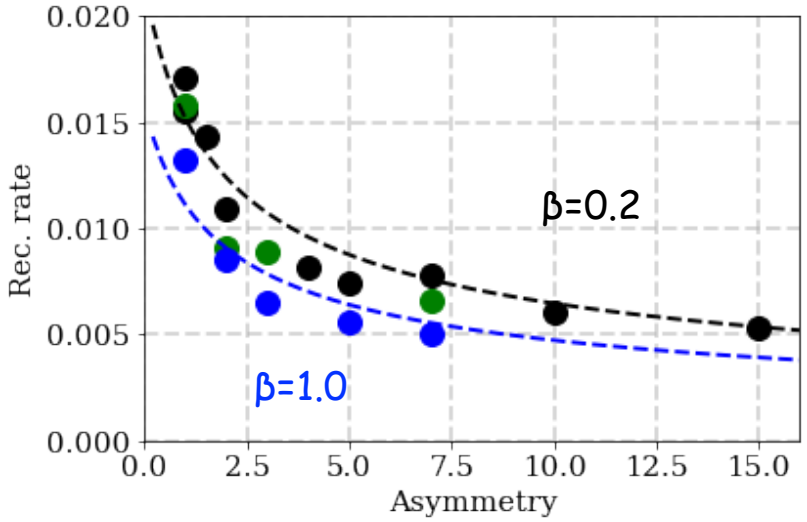


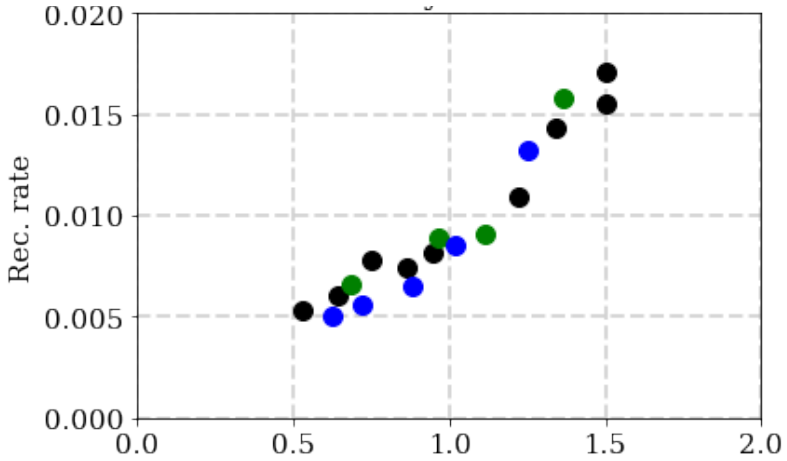
2. Reconnection rate follows Cassak=Shay relation



Asymmetric reconnection rate in low-β regimes

3. Reconnection rate also depends on plasma β





Cassak-Shay-Birn theory

Reconnection rate is best scaled by

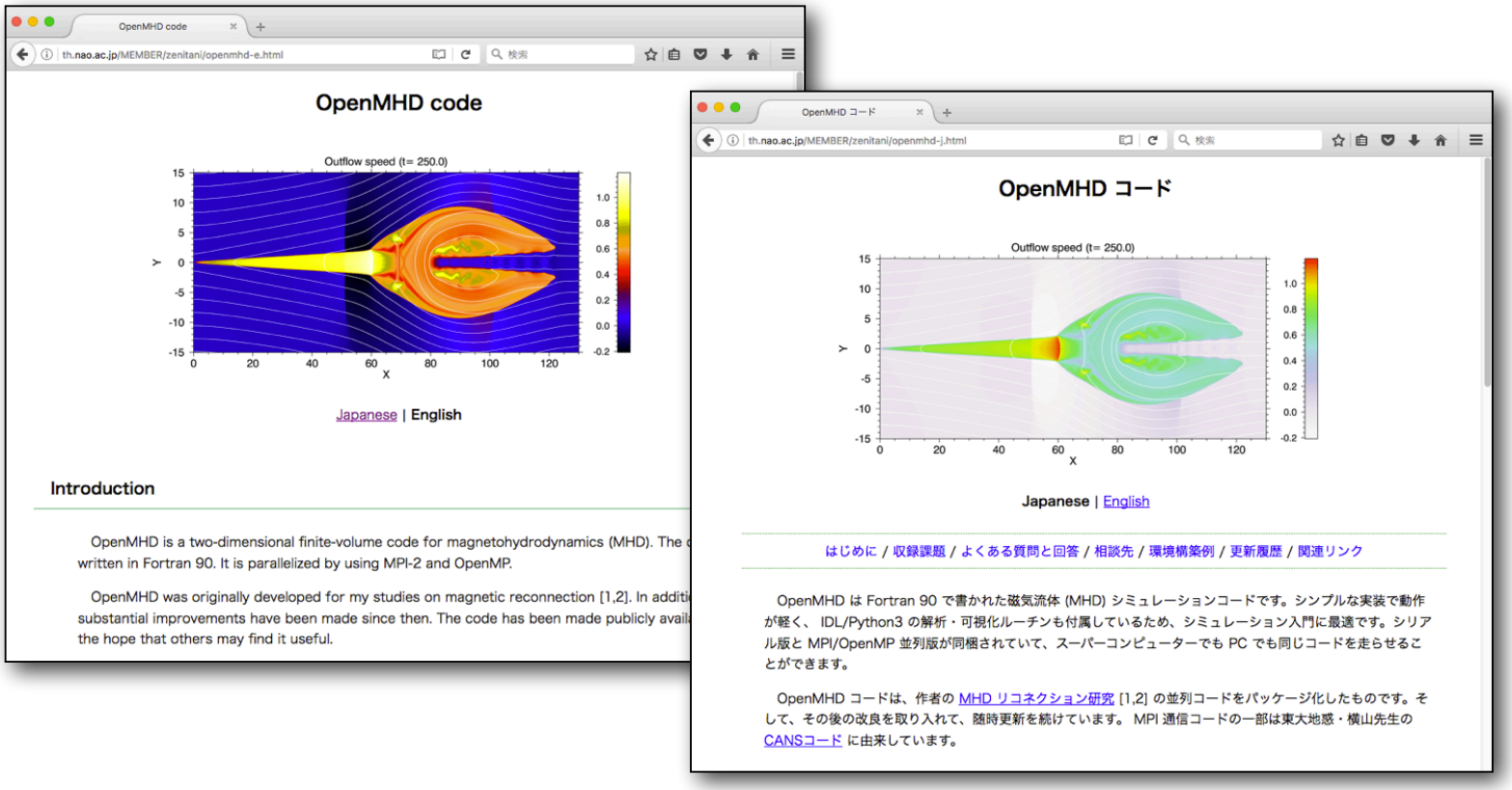
$$-\frac{\partial}{\partial t}\Psi_{\rm rec} \sim \mathcal{R}_0 \left(\frac{B_1 B_2 (B_1+B_2)}{\rho_1 B_2 + \rho_2 B_1}\right)^{1/2} \left(\frac{2B_1 B_2}{B_1+B_2}\right) \times \frac{\Gamma(B_1+B_2)}{\lambda_2 B_1 + \lambda_1 B_2}$$

Cassak-Shay (2007)

Birn+ (2010)'s compression factor

Our code: OpenMHD

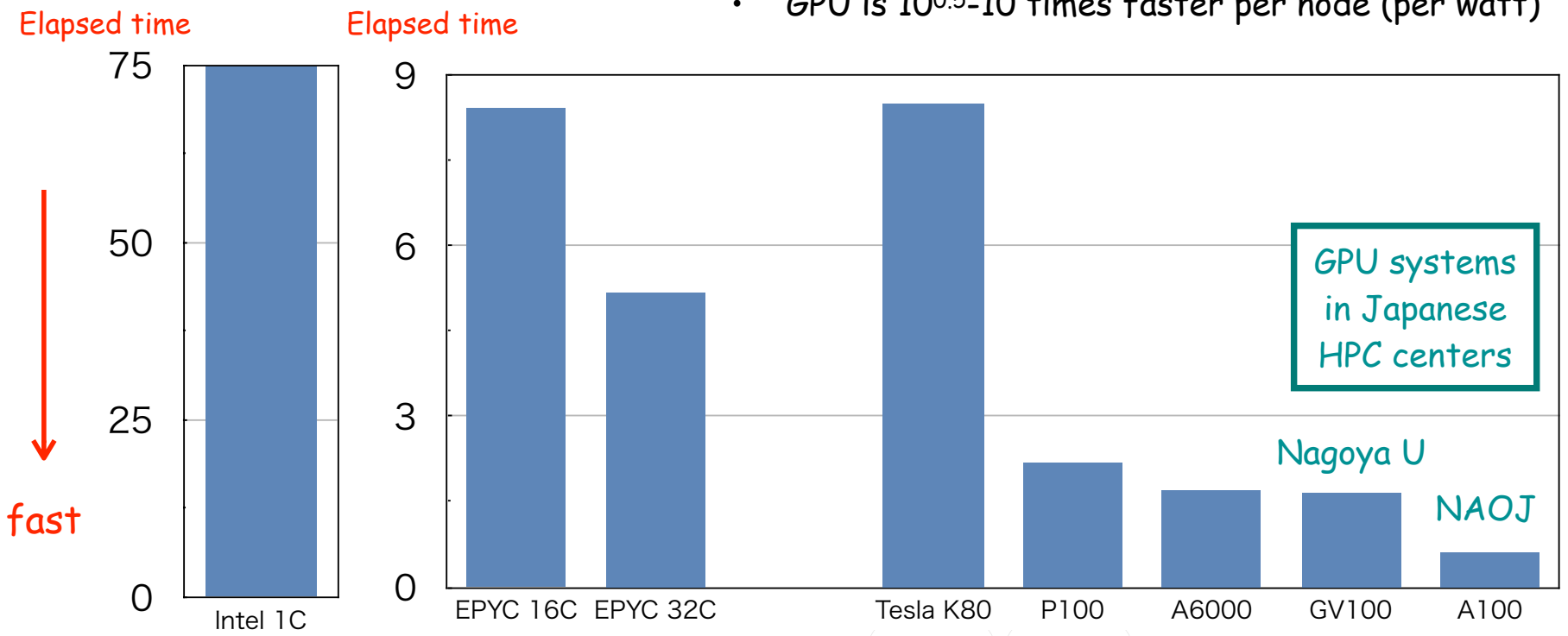
- Parallelized by MPI, OpenMP
- Also ported to NVIDIA GPUs with CUDA Fortran



https://sci.nao.ac.jp/MEMBER/zenitani/openmhd-e.html
https://sci.nao.ac.jp/MEMBER/zenitani/openmhd-j.html

Benchmarks: CPU vs GPU

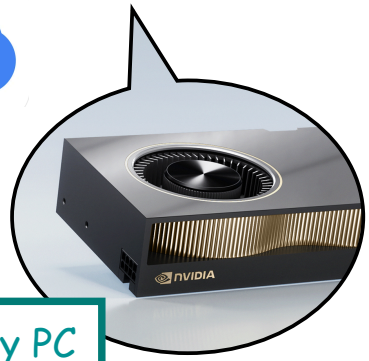
- GPU is $10^{0.5}$-10 times faster per node (per watt)



Intel i9 processor in my PC

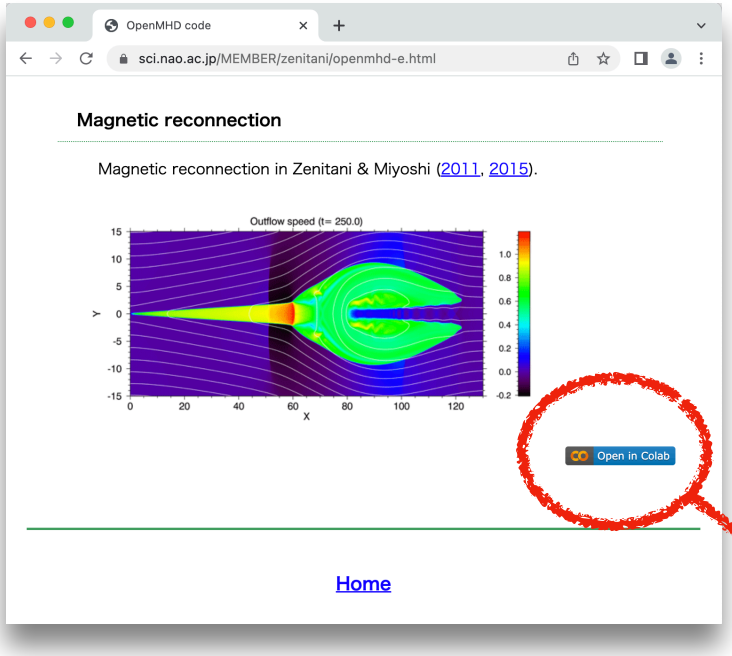
AMD EPYC processors with 16 or 32 cores (7282 or 7452)

GPUs on cloud

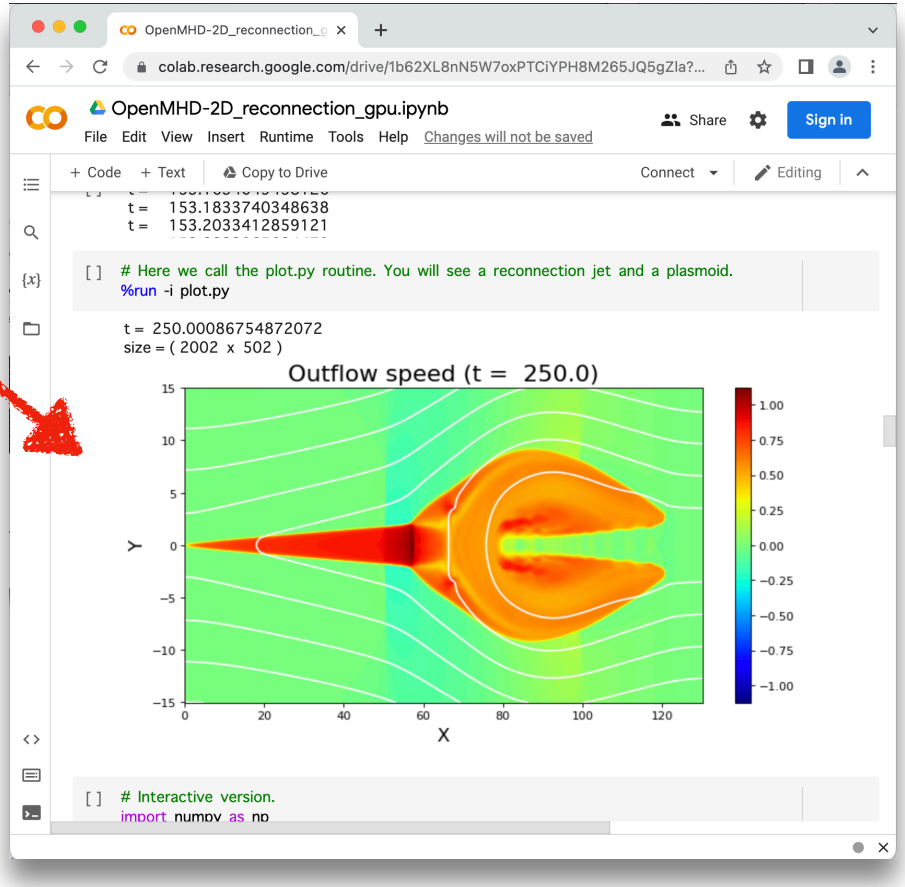


GPU in my PC

OpenMHD on a cloud



- You can run your simulations on either CPU or GPU virtual machines on Google cloud (Google Colaboratory)



- Ideal for EPO
- All we need is
  - Google Colab account
  - Web browser

Summary

- 1. Symmetric plasmoid-dominated reconnection for low-β
  - Normal shocks -- potential role in particle acceleration?
  - Compressible theory predicts R ~ 0.02
- 2. Density-asymmetric plasmoid-dominated reconnection
  - Swirling plasmoids
  - Reconnection rate is scaled by the Cassak-Shay-Birn relation
- 3. OpenMHD
  - Accelerated by GPU
  - Can be tested on cloud

- Reference
  - Zenitani & Miyoshi, ApJL, 894, L7 (2020), https://doi.org/10.3847/2041-8213/ab8b5d