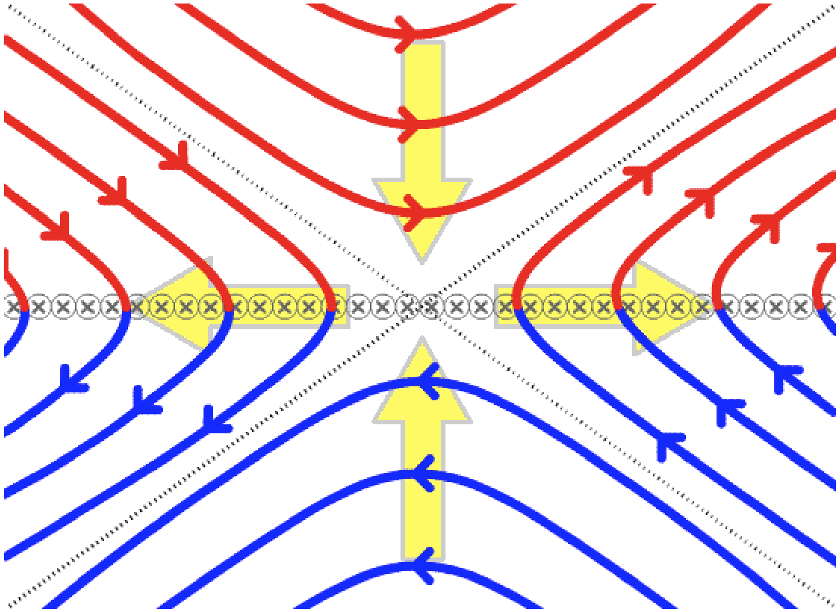
Large-scale 3D Hall-MHD reconnection

Andrey Beresnyak

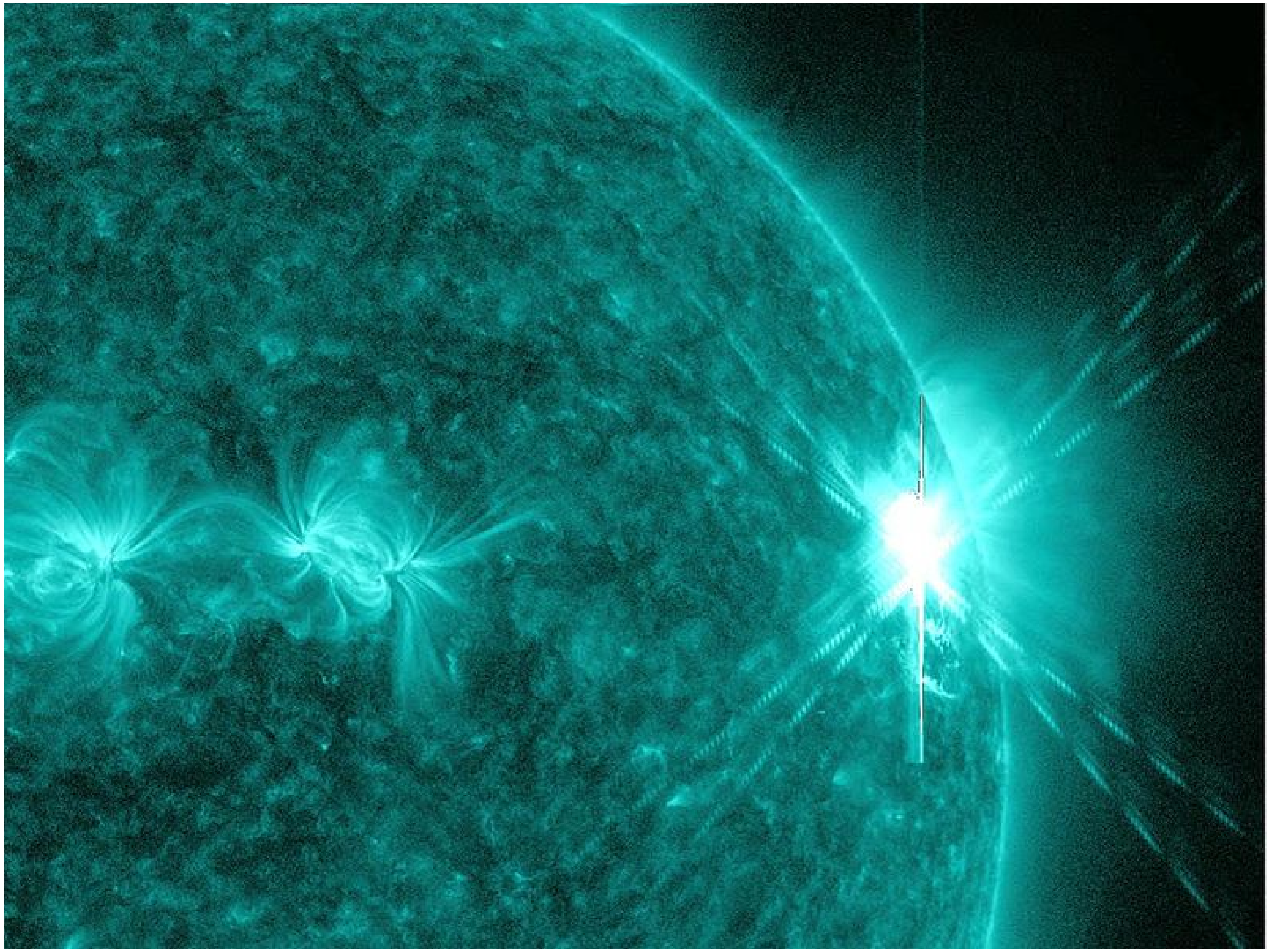
Plasma Physics Division
Naval Research Laboratory, Washington, DC

Multiscale Plasma Workshop, KITP, 2019

Magnetic Reconnection



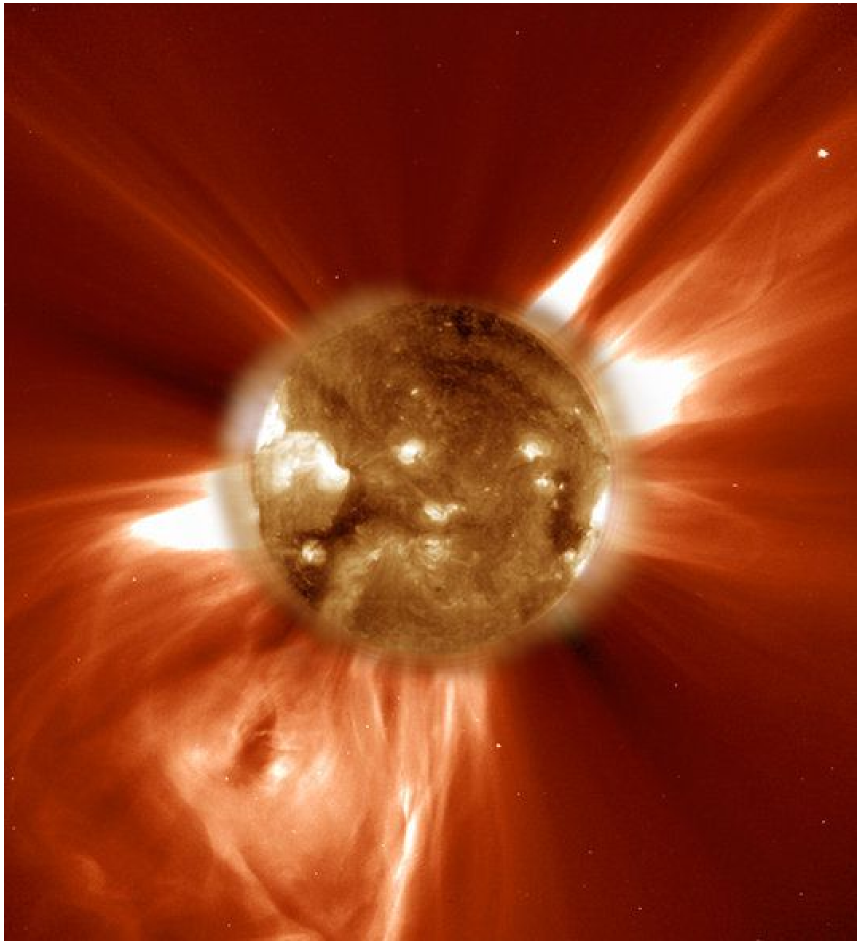
Solar X-ray flares



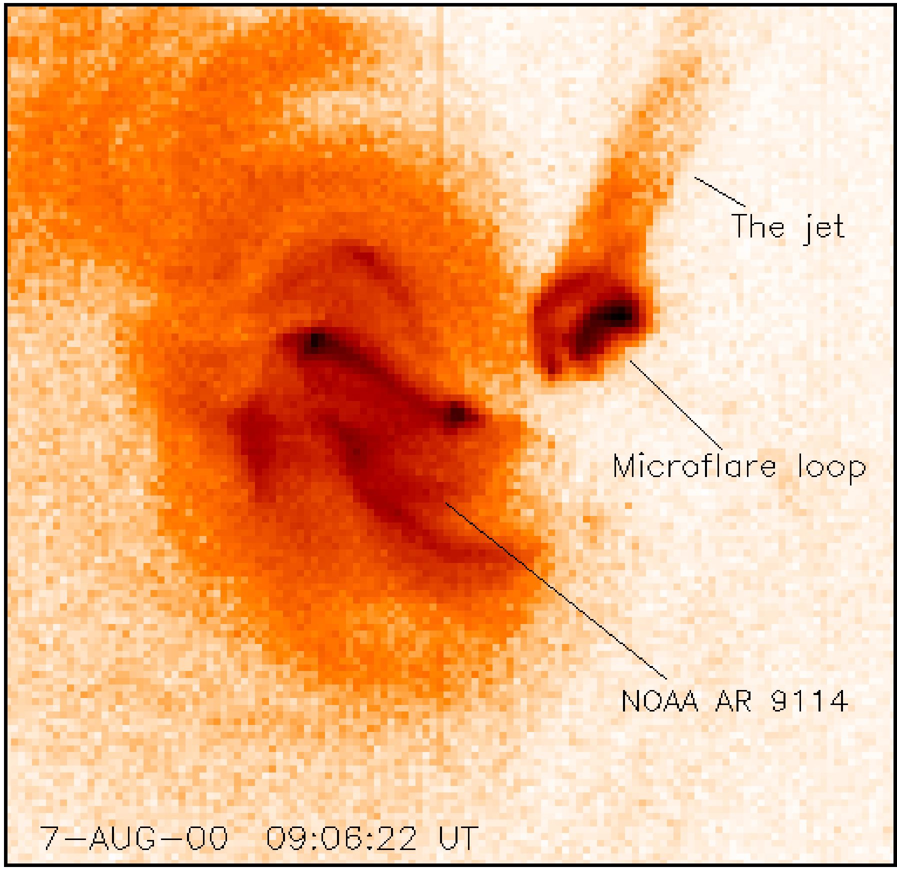
X-class flare: $6 \times 10^{32}\mathrm{erg} \approx 10^{10}\mathrm{MT}$ of energy released

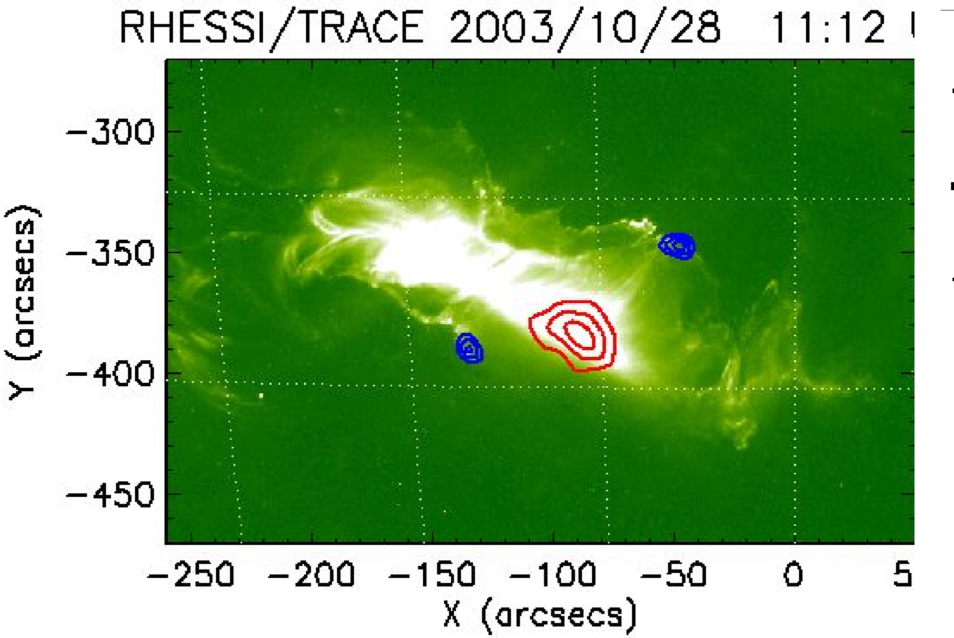
Magnetic fields anchored in the Sun move around and release energy

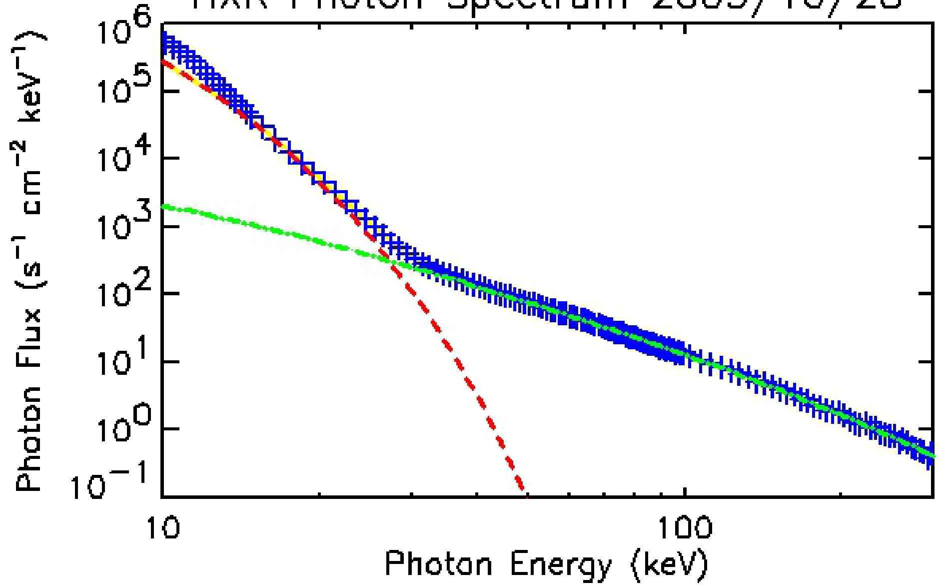
CME

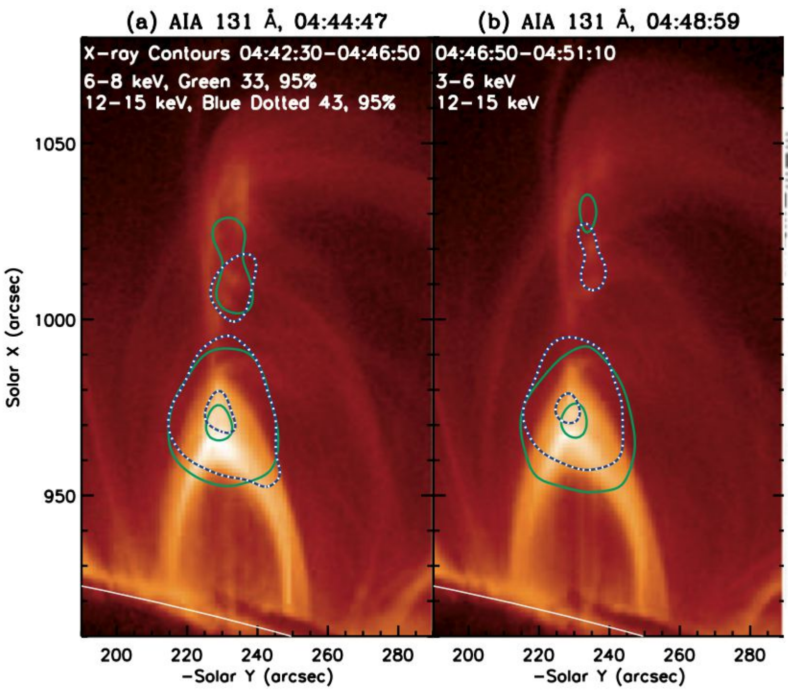


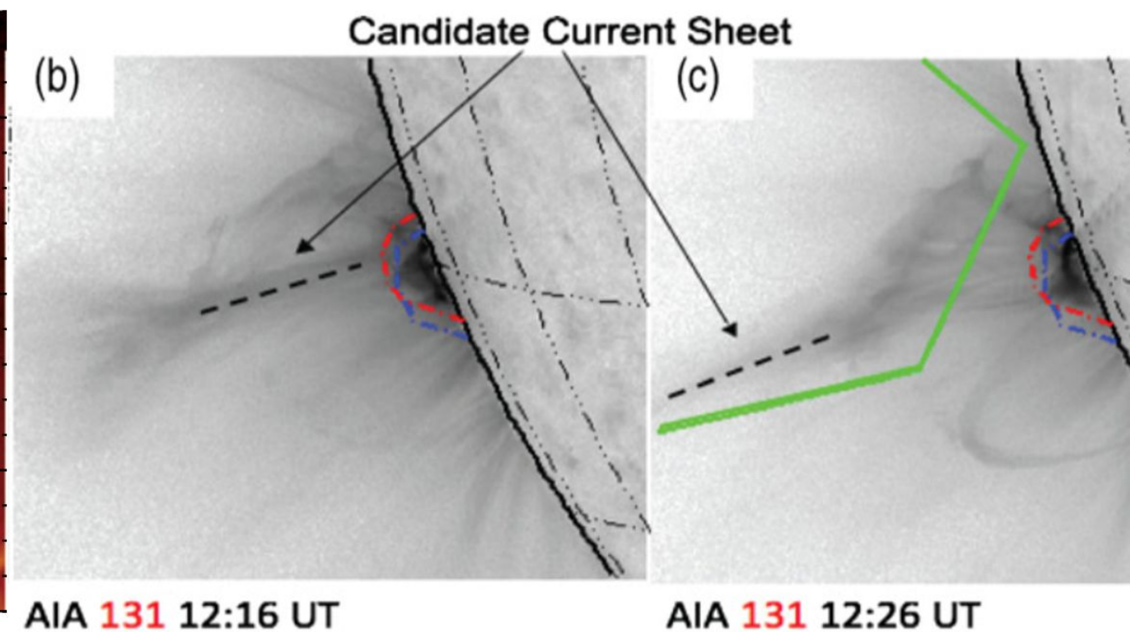
micro-jet




RHESSI/TRACE 2003/10/28 11:12
Y (arcsecs)
X (arcsecs)
-300
-350
-400
-450
-250 -200 -150 -100 -50 0 5


HXR Photon Spectrum 2003/10/28
Photon Flux (s^{-1} cm^{-2} keV^{-1})
Photon Energy (keV)
10
100

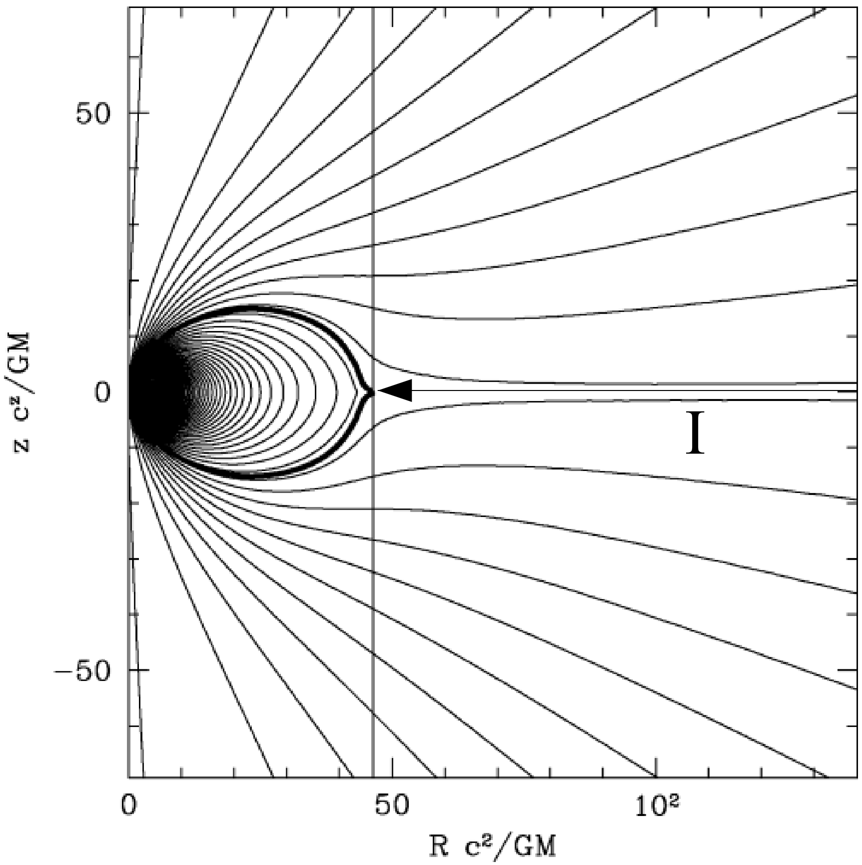

(a) AIA 131 Å, 04:44:47
(b) AIA 131 Å, 04:48:59
X-ray Contours 04:42:30-04:46:50
6-8 keV, Green 33, 95%
12-15 keV, Blue Dotted 43, 95%
04:46:50-04:51:10
3-6 keV
12-15 keV
Solar X (arcsec)
-Solar Y (arcsec)
1050
1000
950
200 220 240 260 280


Candidate Current Sheet
(b)
(c)
AIA 131 12:16 UT
AIA 131 12:26 UT

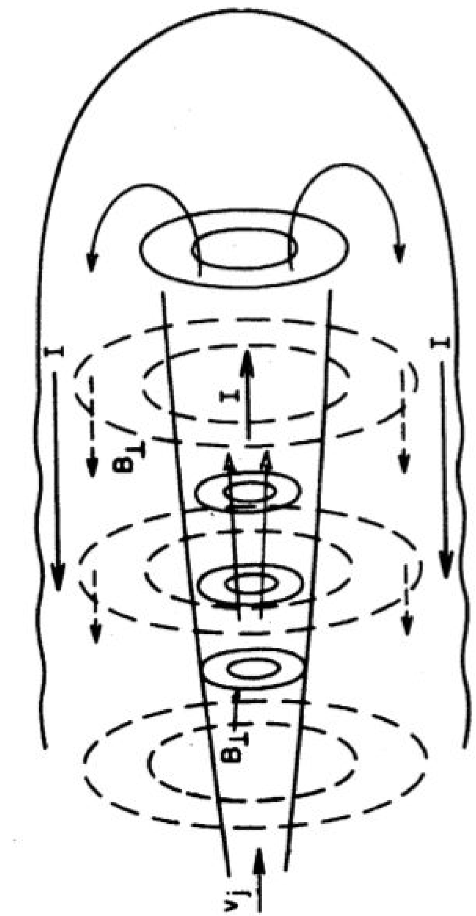
Reconnection in astrophysics

(not directly observed)

Pulsar magnetosphere



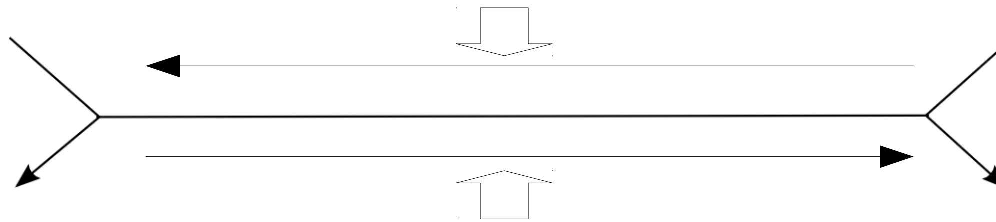
Jets



Reconnection in MHD

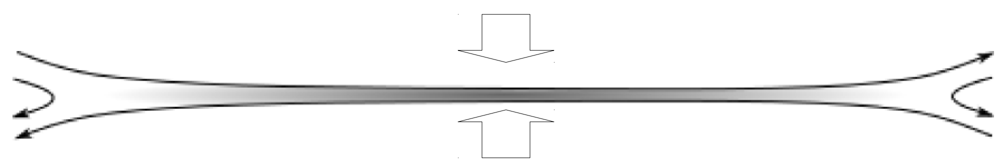
Lundquist number, dimensionless conductivity: $S = v_A L/\eta$

Syrovatski (1971)



Ideal fluid; reconnection and dissipation rates are arbitrary

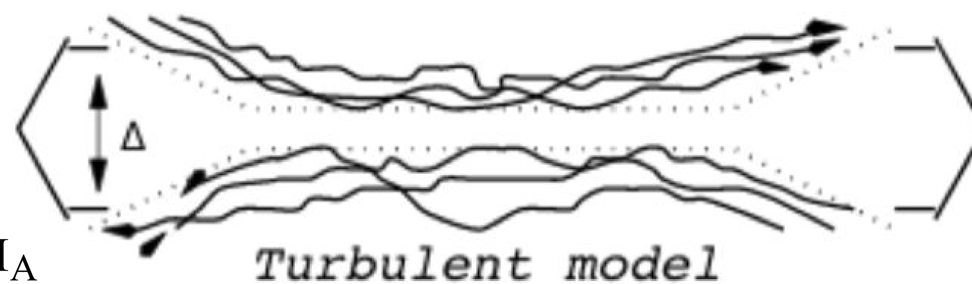
Sweet-Parker (1957)



Δ

Resistive/viscous, reconnection and dissipation rates go to zero as S goes to infinity ($1/S^{1/2}$)

Lazarian-Vishniac (1999)



Rate does not depend on S, depends on M_A

How small the resistivity is?

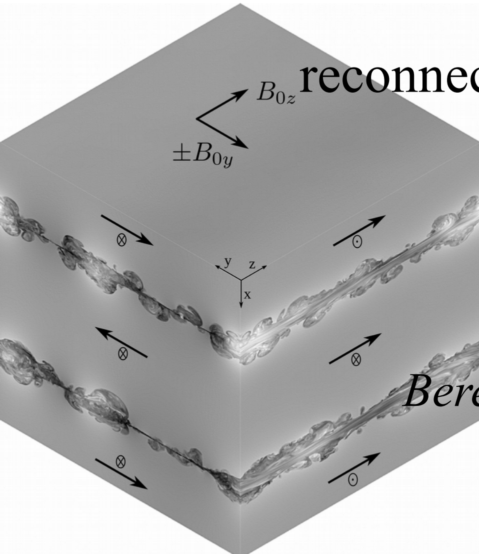
Lundquist number: $S = v_A L/\eta \approx 10^{14}$ in the solar corona

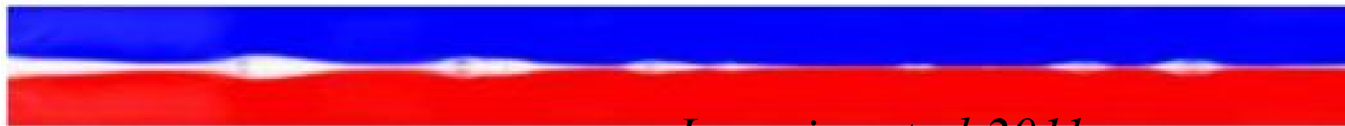
Sweet-Parker: $$\tau_{\mathrm{SP}} = \sqrt{S}\frac{L}{v_A} = 10^7\frac{L}{v_A}$$

Observed: $$\tau \approx 10 - 100\frac{L}{v_A}$$

Plasma and MHD simulations do not agree.

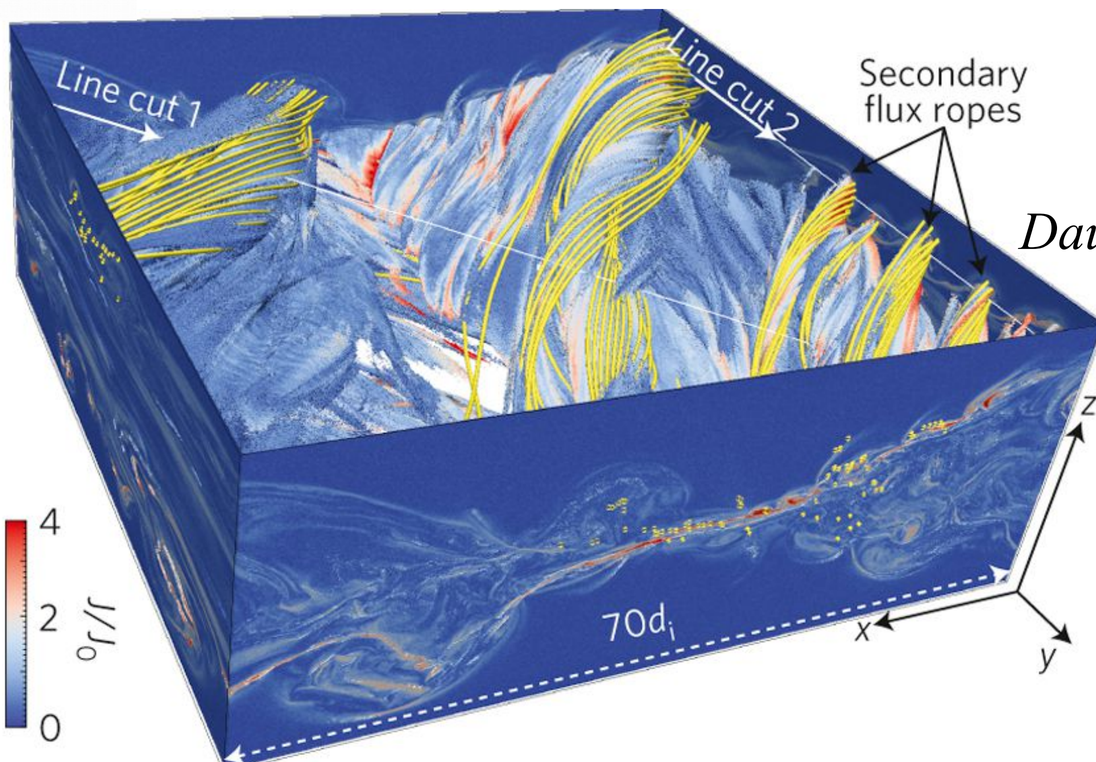
reconnection rate = 0.015 in MHD, 0.1 in Hall-MHD and plasma





Loureiro et al 2011

Beresnyak 2013



Daughton et al 2011

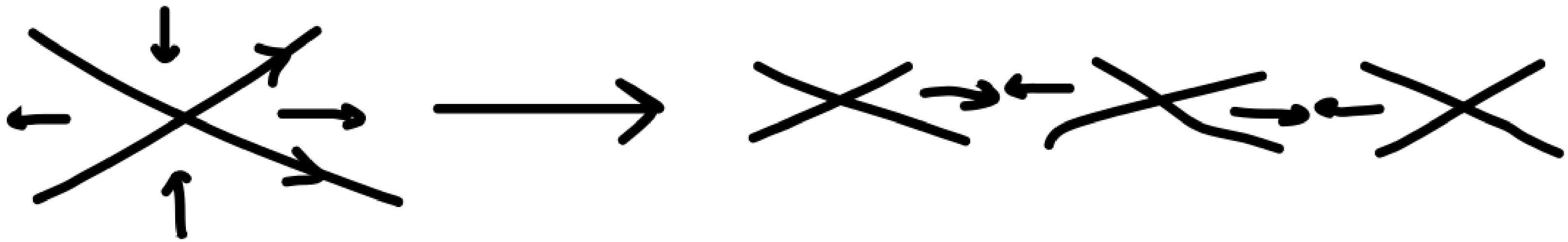
Key questions:

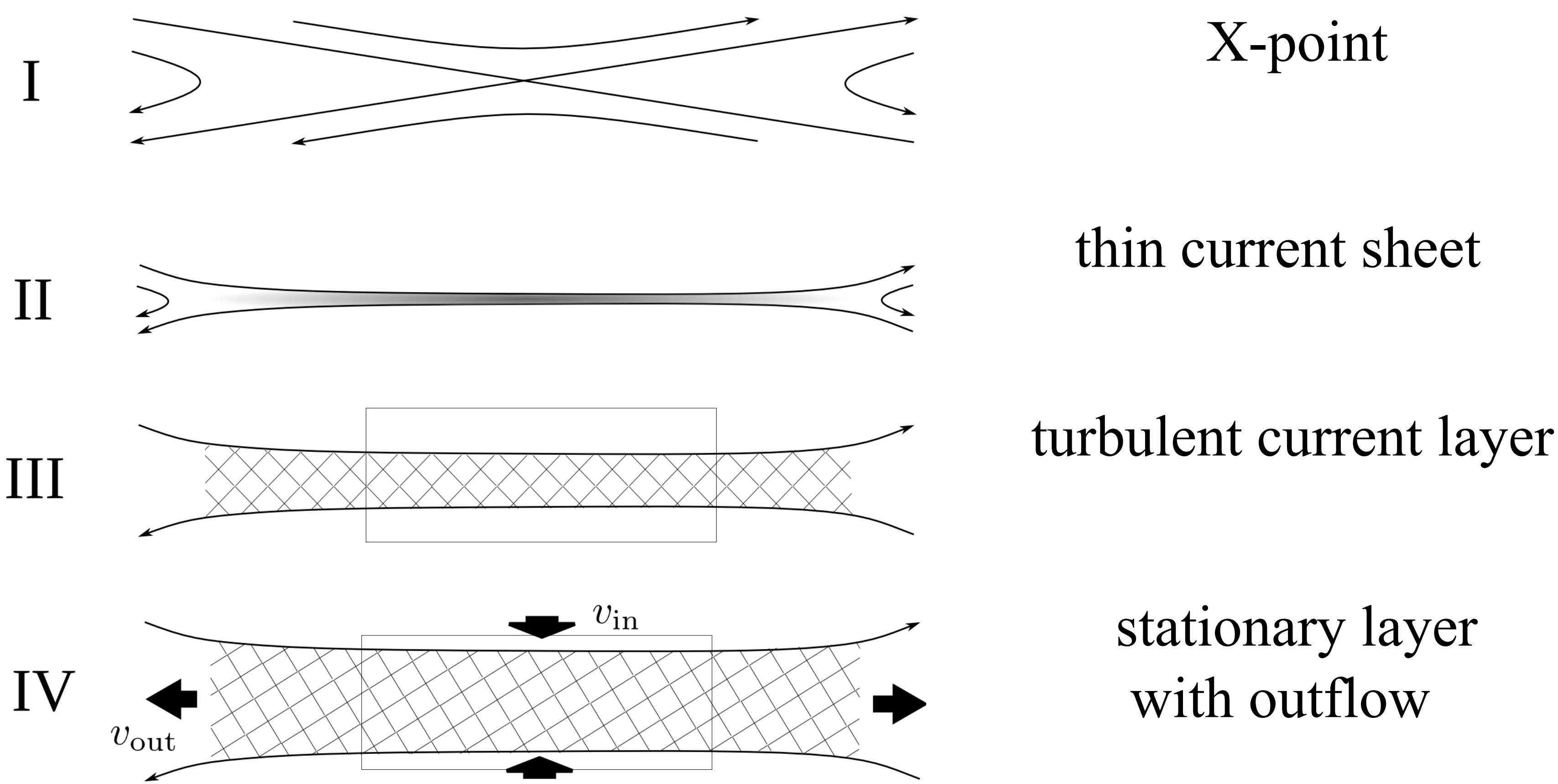
1. Is reconnection fast, e.g. the rate is independent of scale separation between large scales and micro-scales? For S=∞ Sweet-Parker model gives zero rate.

2. Is reconnection determined by plasma effects, e.g. $0.1V_A$ in e-p plasmas? That is plasma effects in the current layer makes it fast?

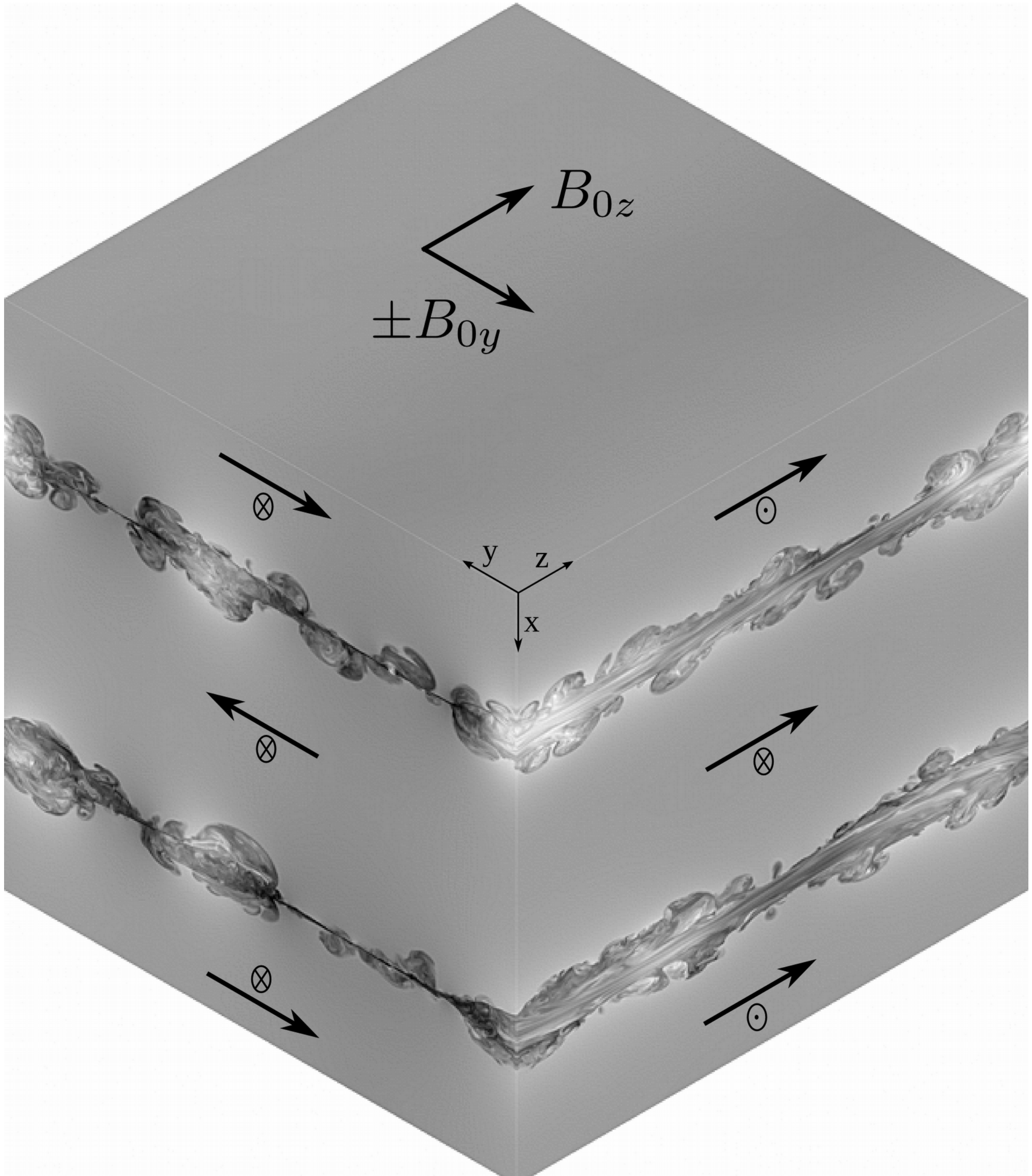
3. Do plasma effects propagates to larger scages? Rate on the Sun is 0.1-0.01 and the layer width $\sim 10^4 d_i$

4. Do outflows collide and produce turbulence? Is this turbulence scale-local?

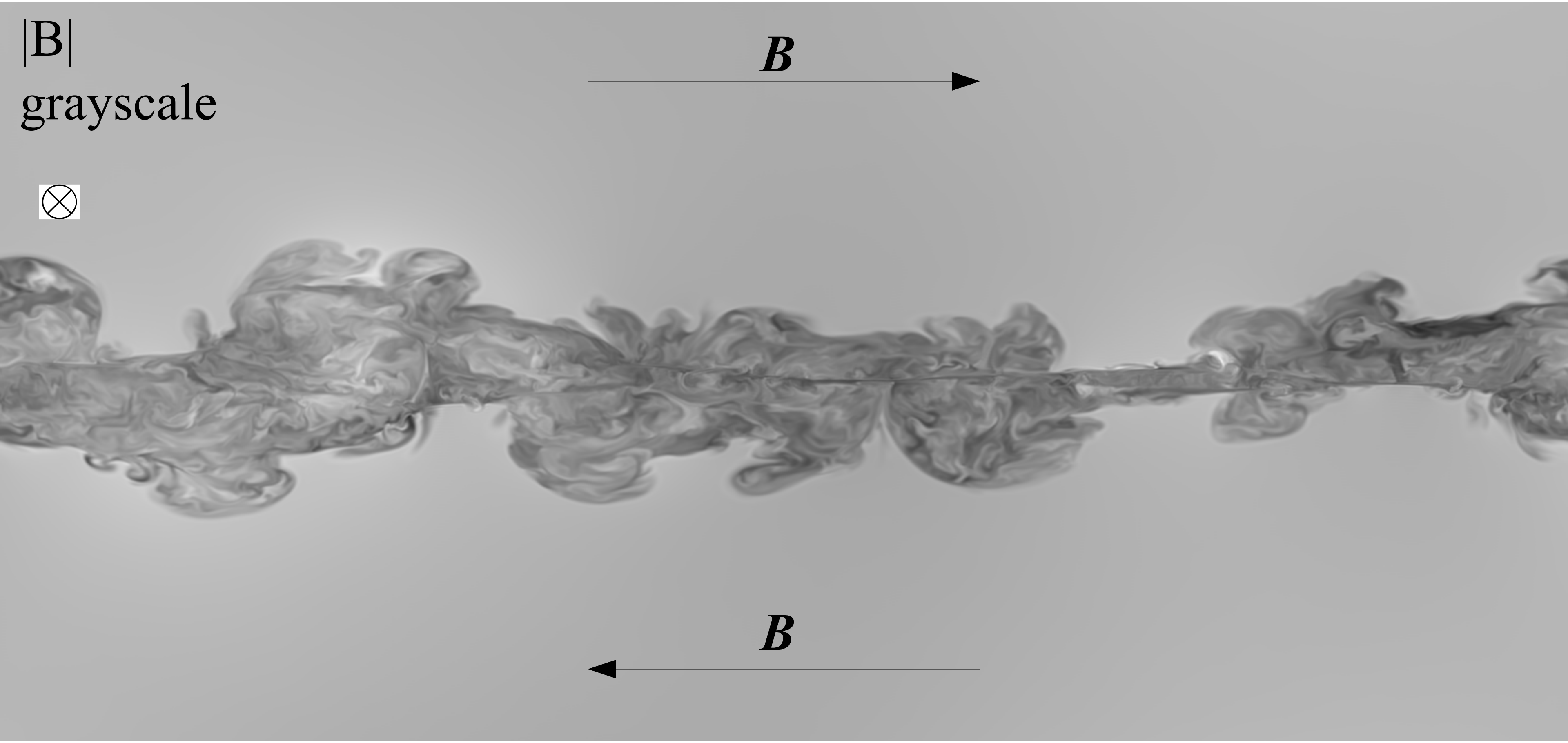



I
X-point
II
thin current sheet
III
turbulent current layer
IV
$v_{\rm in}$
$v_{\rm out}$
stationary layer
with outflow

Simplest turbulence driven by opposite B fields



Fully turbulent current layer in 3D: initial conditions are erased



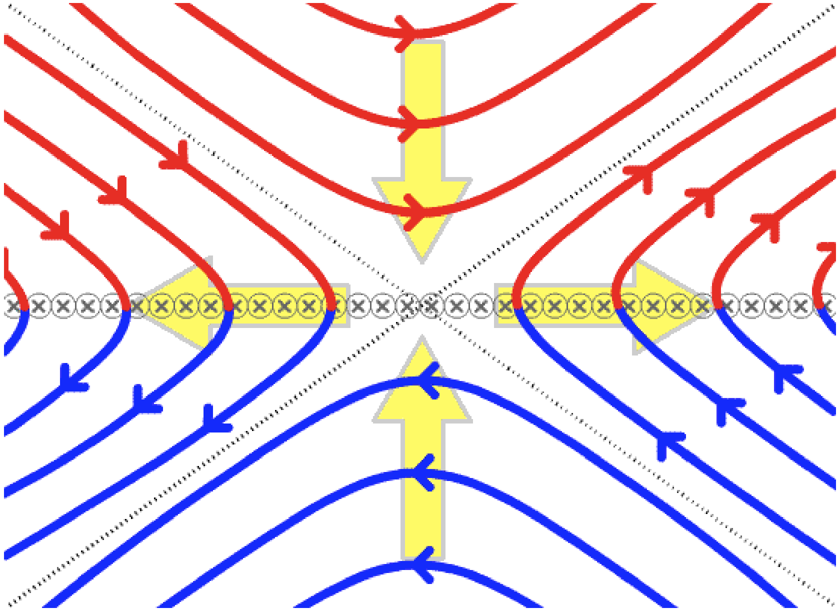
Hall-MHD equations

$$\partial_t \mathbf{v} = \hat{S}(-\omega \times \mathbf{v} + \mathbf{j} \times \mathbf{b}) + \nu_n \nabla^4 \mathbf{v},$$

$$\partial_t \mathbf{b} = \nabla \times ((\mathbf{v} - d_i \mathbf{j}) \times \mathbf{b}) + \nu_n \nabla^4 \mathbf{b},$$

$$\partial_t \phi_i + (\mathbf{v} \cdot \nabla)\phi_i = \nu_n \nabla^4 \phi_i,$$

$$\partial_t \phi_e + ((\mathbf{v} - d_i \mathbf{j}) \cdot \nabla)\phi_e = \nu_n \nabla^4 \phi_e,$$



1CARU5 is a pseudospectral C++ code, solves:
Hydrodynamic, MHD, Reduced MHD, Hall MHD and Electron MHD
goes at ~1μs/step/cell. Reached 0.3 Pflops on BG/Q Mira.

https://sites.google.com/site/andreyberesnyak/1caru5

Examples of MHD simulations:
Two 4096^3 simulations, 14 dynamical times

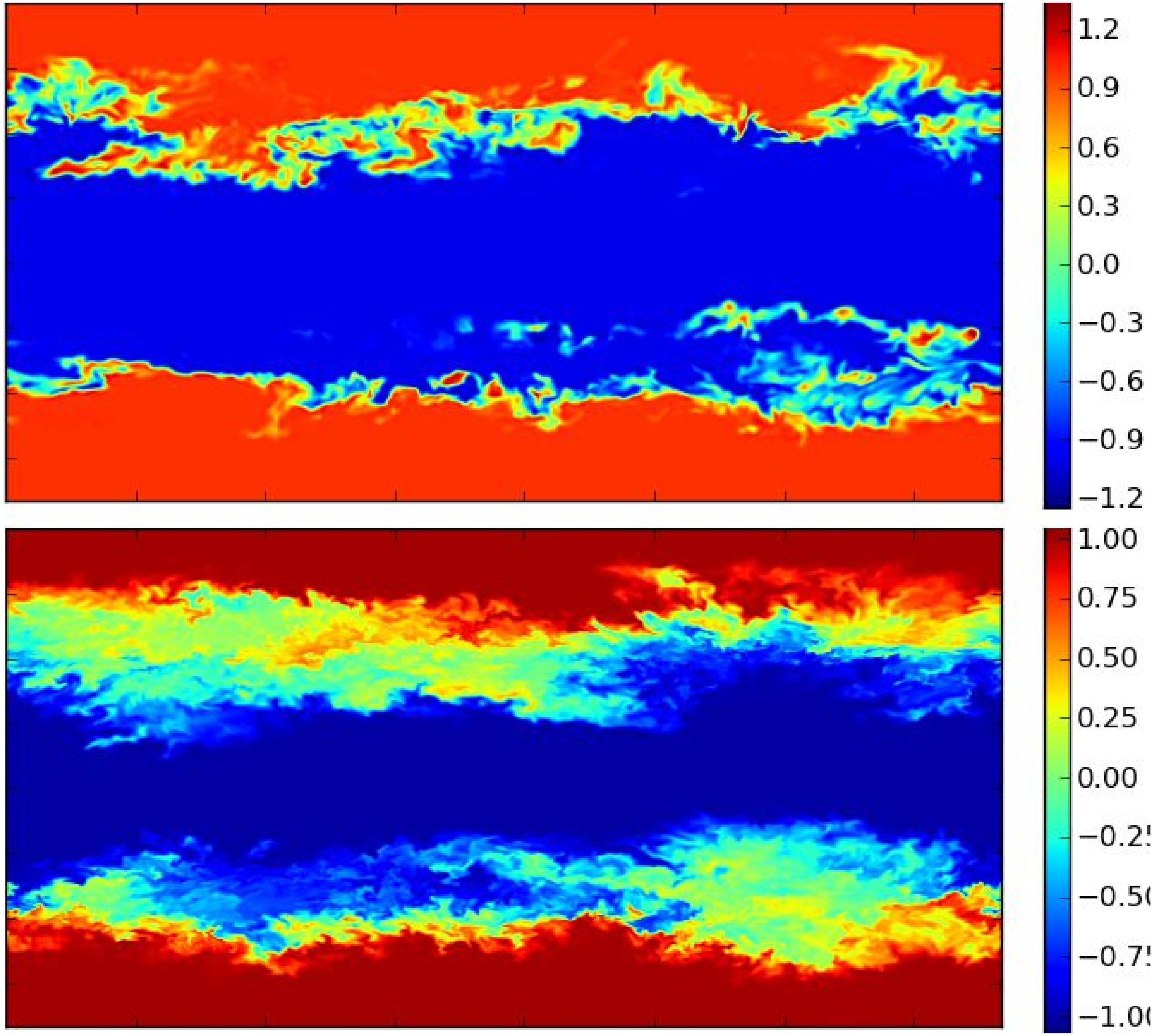
Spectra, SFs and Python scripts are public:
https://sites.google.com/site/andreyberesnyak/simulations/big3

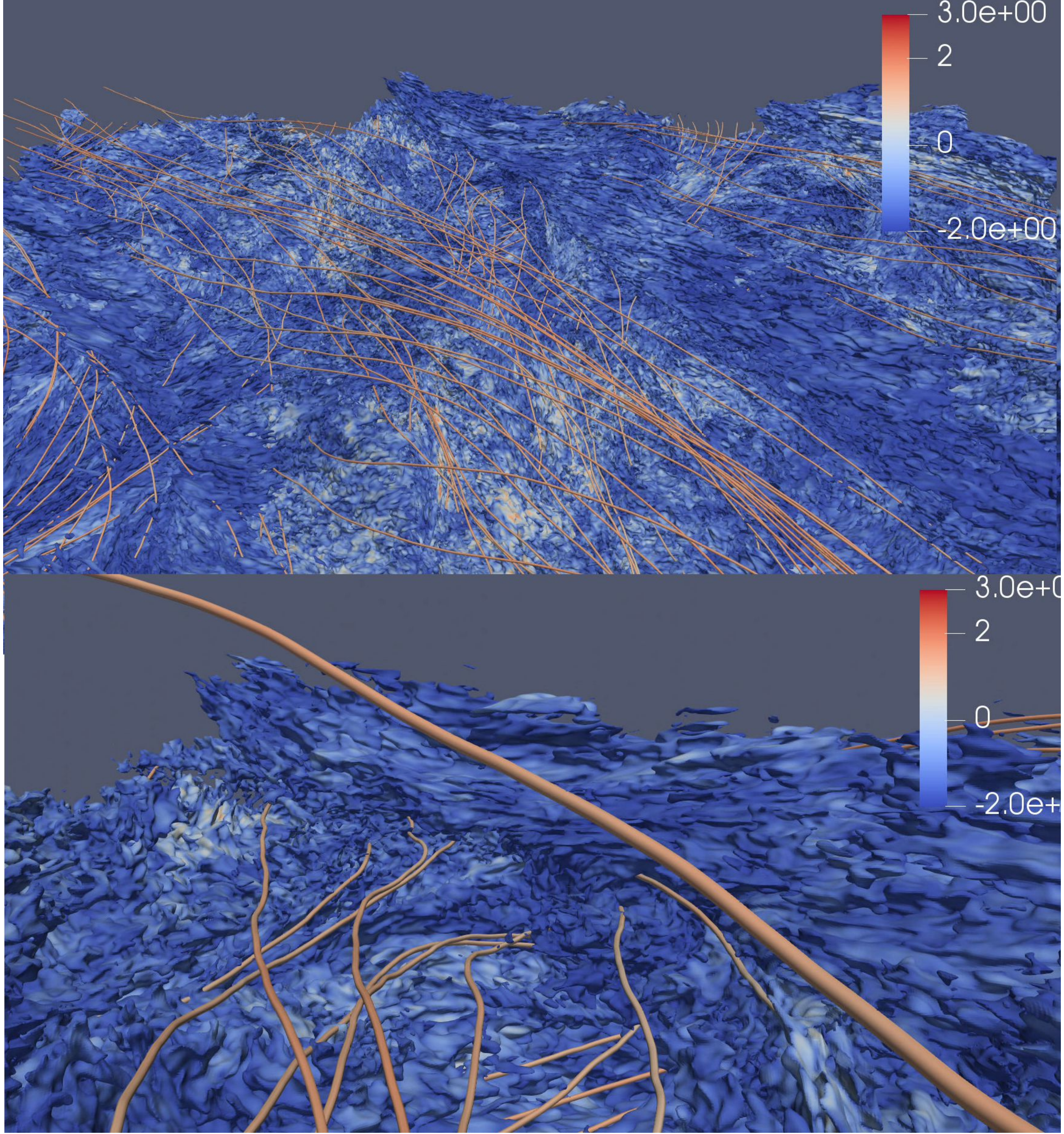
DOE INCITE 52 million hours (2017)
Hall-MHD 2304x4608^2 and 1536x3072^2 making ~10^6 steps
Total steps*nodes=3.3e16 (petascale?)
Going to box sizes of ~ 500d_i

Mixing in ion and electron fluid

ion

electron



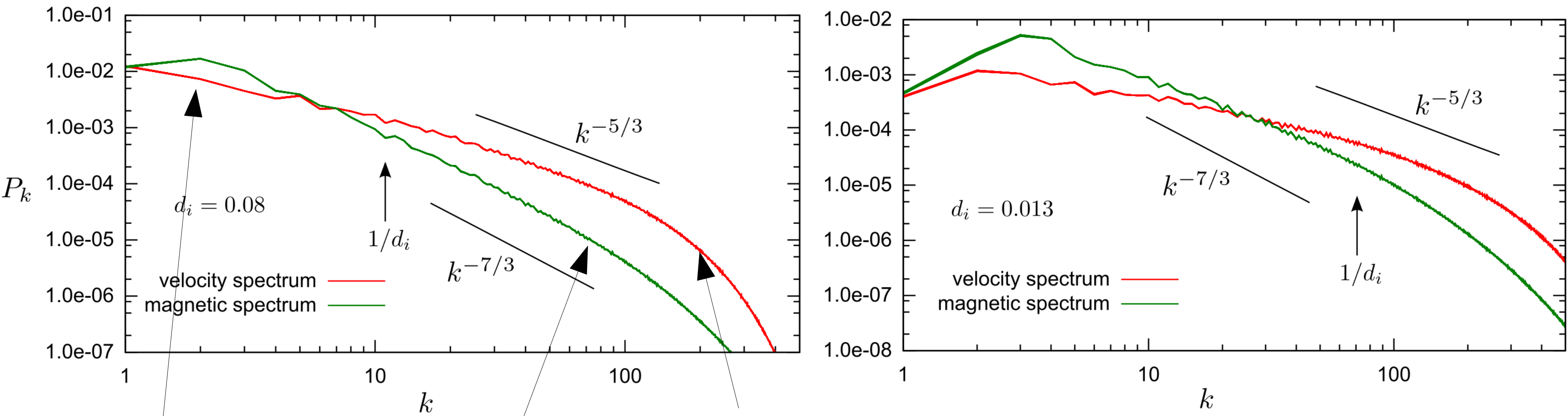

3.0e+00
2
0
-2.0e+00
3.0e+0
2
0
-2.0e+

The spectra of kinetic (red) and magnetic (green) energies

Two cases with different d_i

d_i=0.08/2π of box size

d_i=0.13/2π of box size



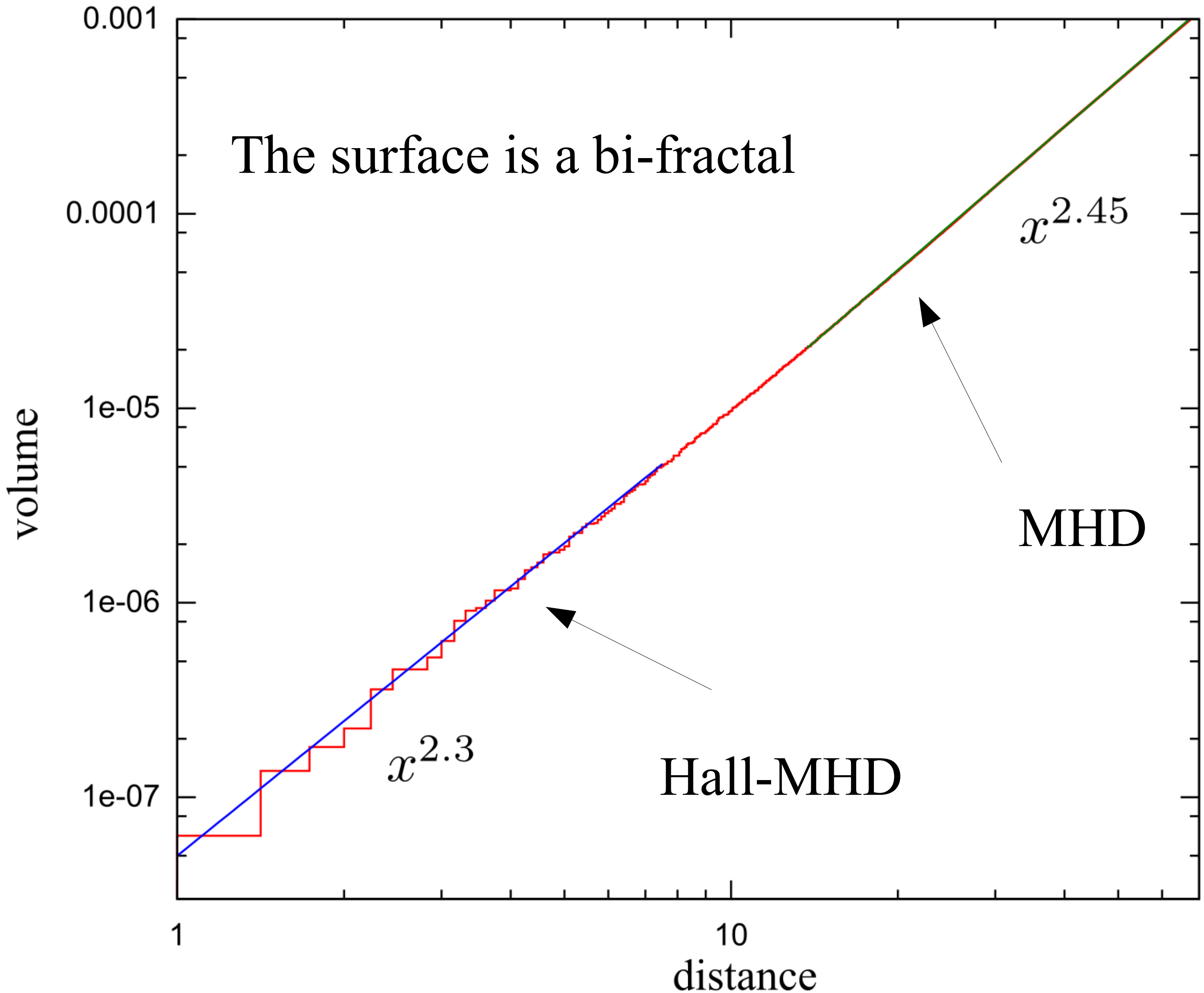
Ion cyclotron waves(left-circularly polarized)

Alfven waves

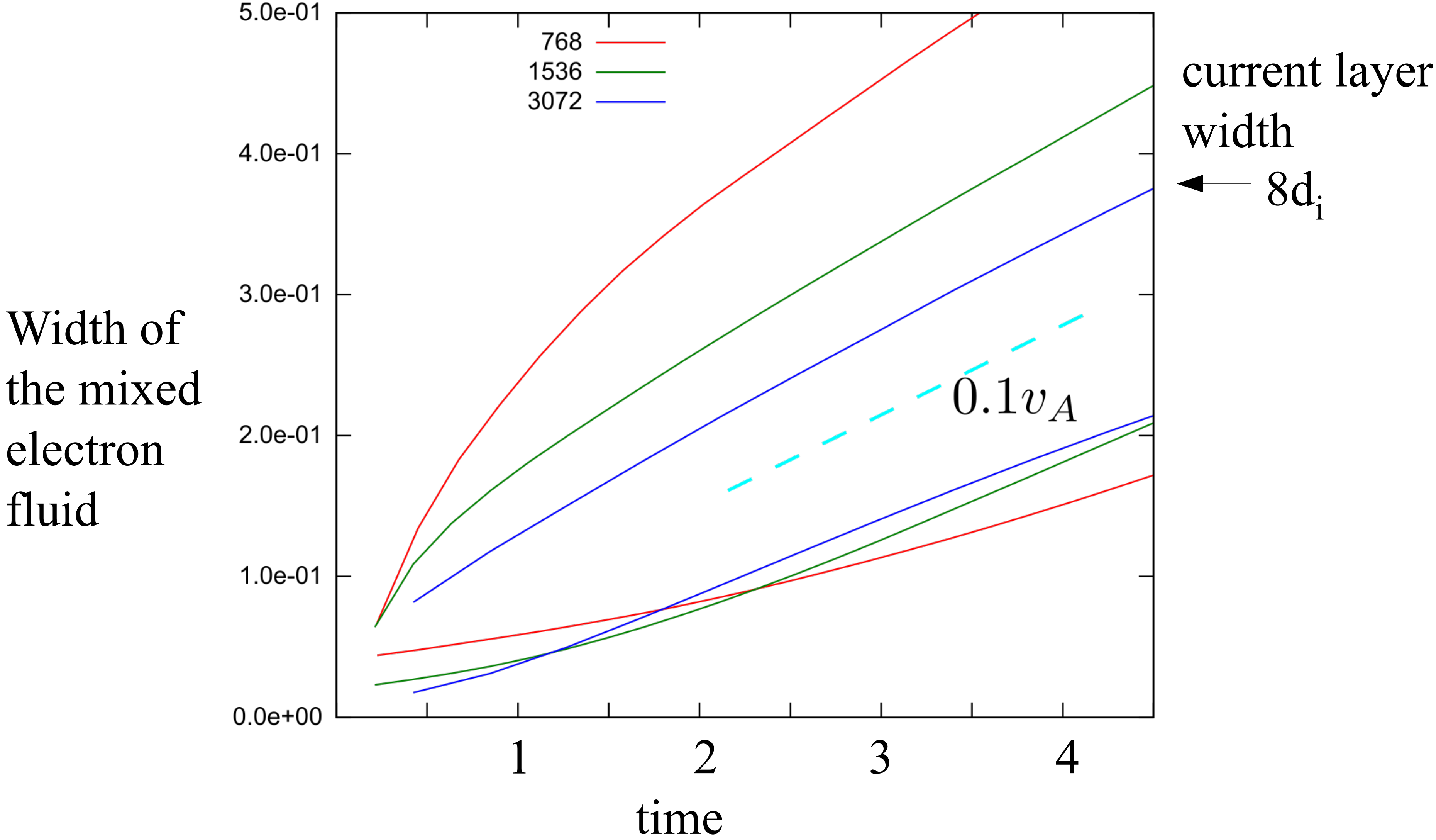
Whistlers (right-circularly polarized)

Spacial dimension of the mixing surface

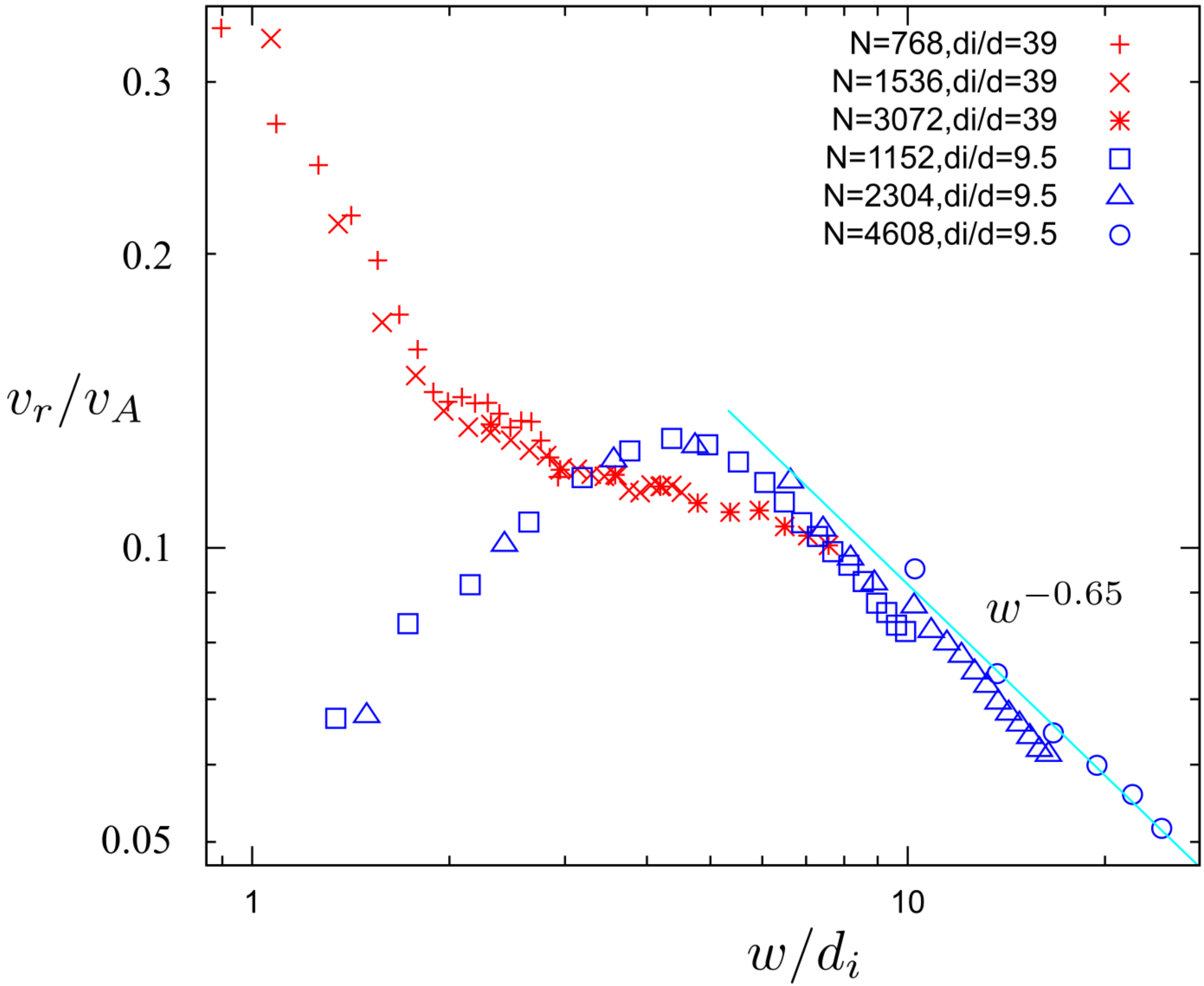
measured by counting fraction of points within specified radius

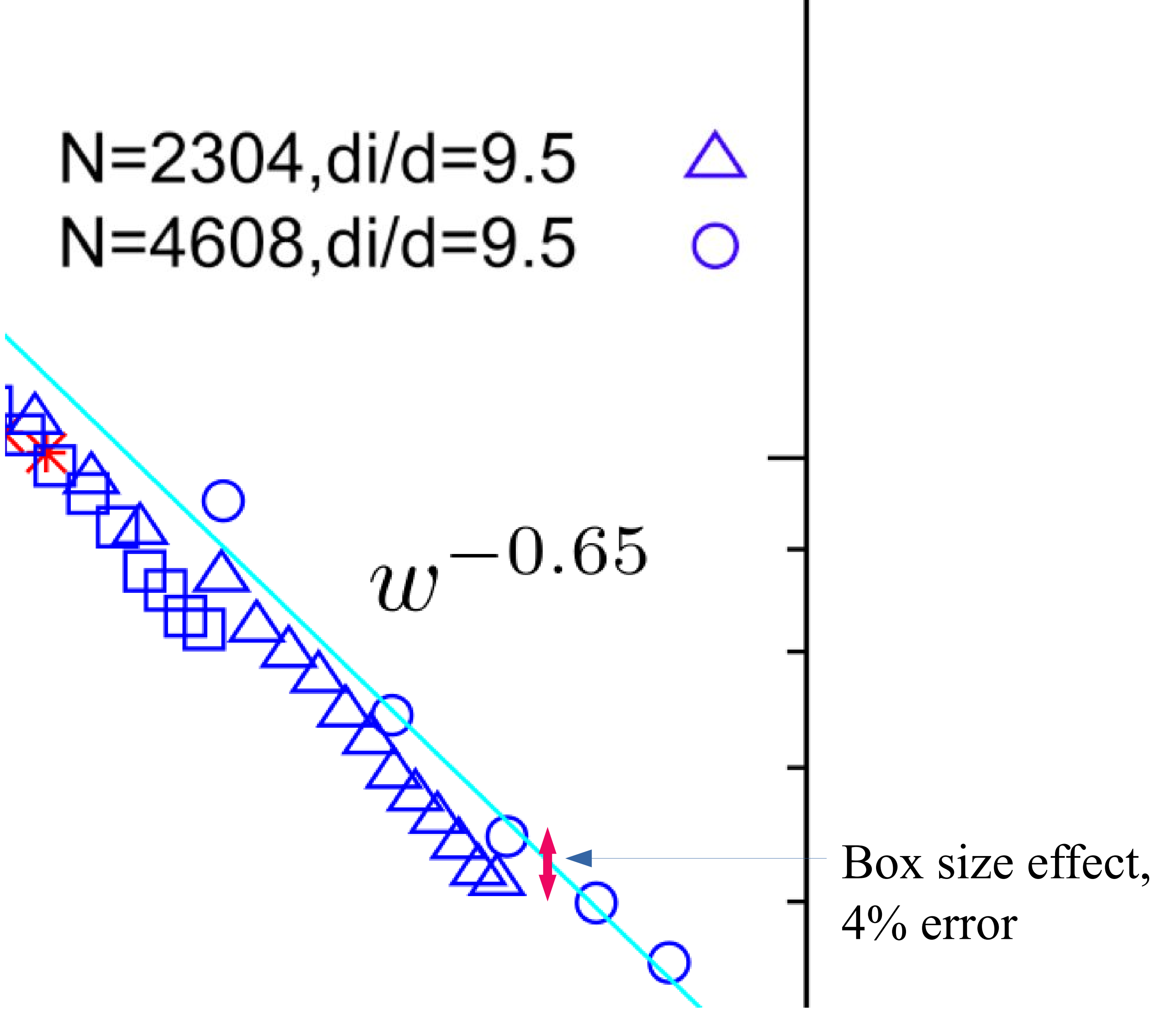


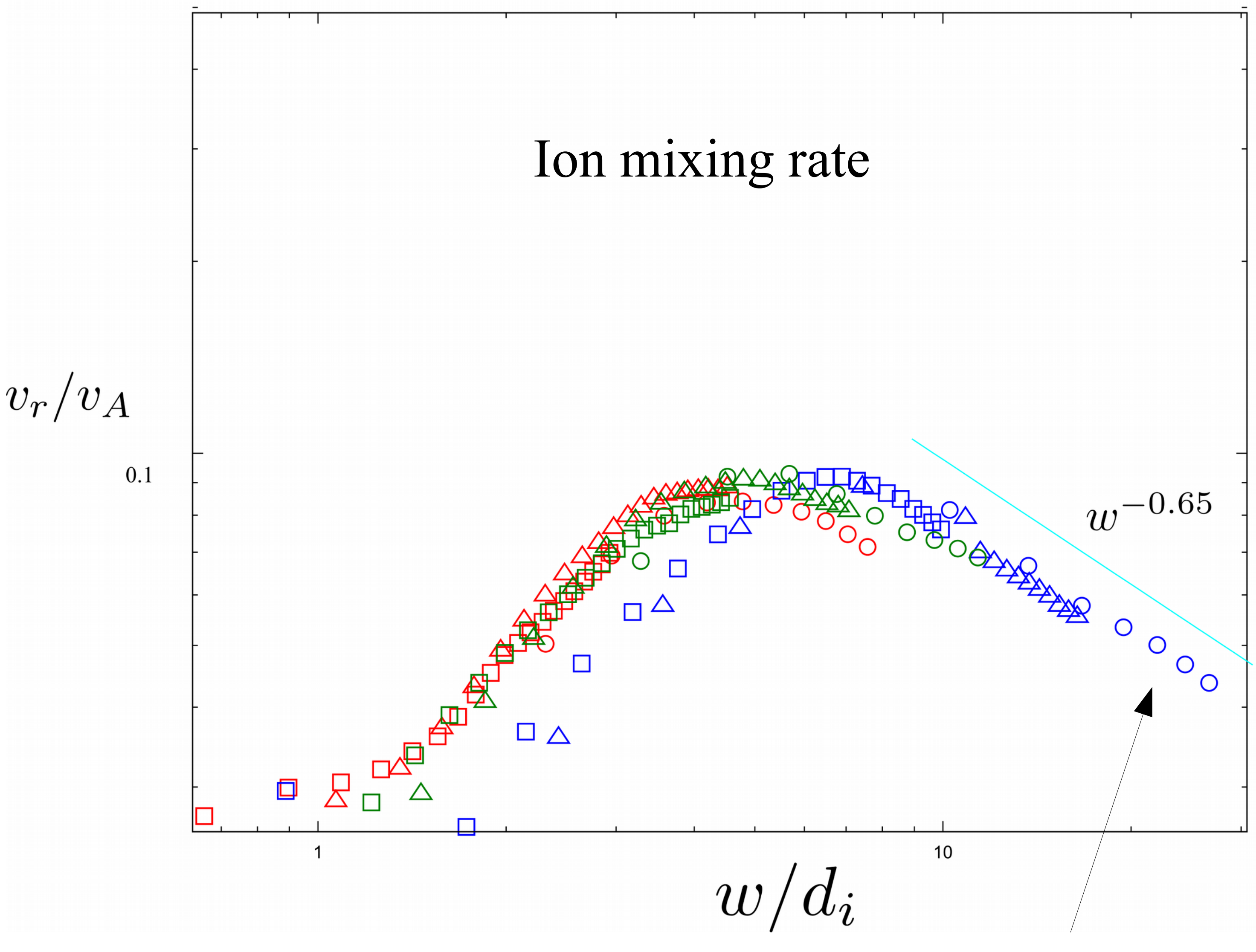
We measure reconnection rate as the mixing rate of electron fluid



Reconnection rate as a function of layer width




N=2304,di/d=9.5
N=4608,di/d=9.5
$w^{-0.65}$
Box size effect,
4% error



ion and electron mixing rates converge

Summary

• Spontaneous turbulent reconnection is a fast reconnection with a certain reconnection rate and dissipation rate per unit area. What makes it fast is a turbulence locality – separation between small and large-scale physics

• In plasmas the current layer is possibly also turbulent. So, what is the cause of fast reconnection – turbulence or small-scale effects?

• The mixing layer is bi-fractal – different physics on small and large scales – electron turbulence on small scale and MHD turbulence on large scale

• Hall-MHD results which reached current layer width of $25d_i$ show that the rate decreases from the standard value of 0.1. What is the rate at $L=10^4 d_i$? We don't know for sure, theory (turbulence locality) suggests it will approach MHD value of 0.015 and numerics hints it will happen at $w=200d_i$.

• Numerics suggests that ion and electron rates converge – good news for the single-fluid MHD models.