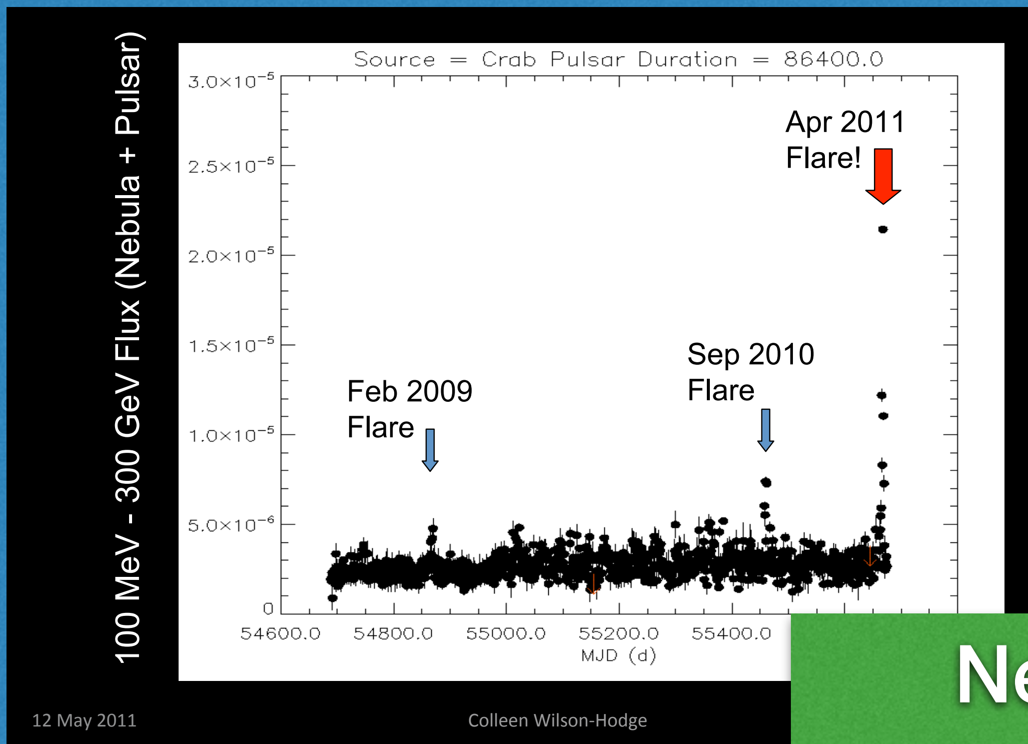
Relativistic magnetic turbulence and "magneto-luminescence"

Jonathan Zrake (Stanford / KIPAC)
Krakow Jet Meeting
22 April, 2015

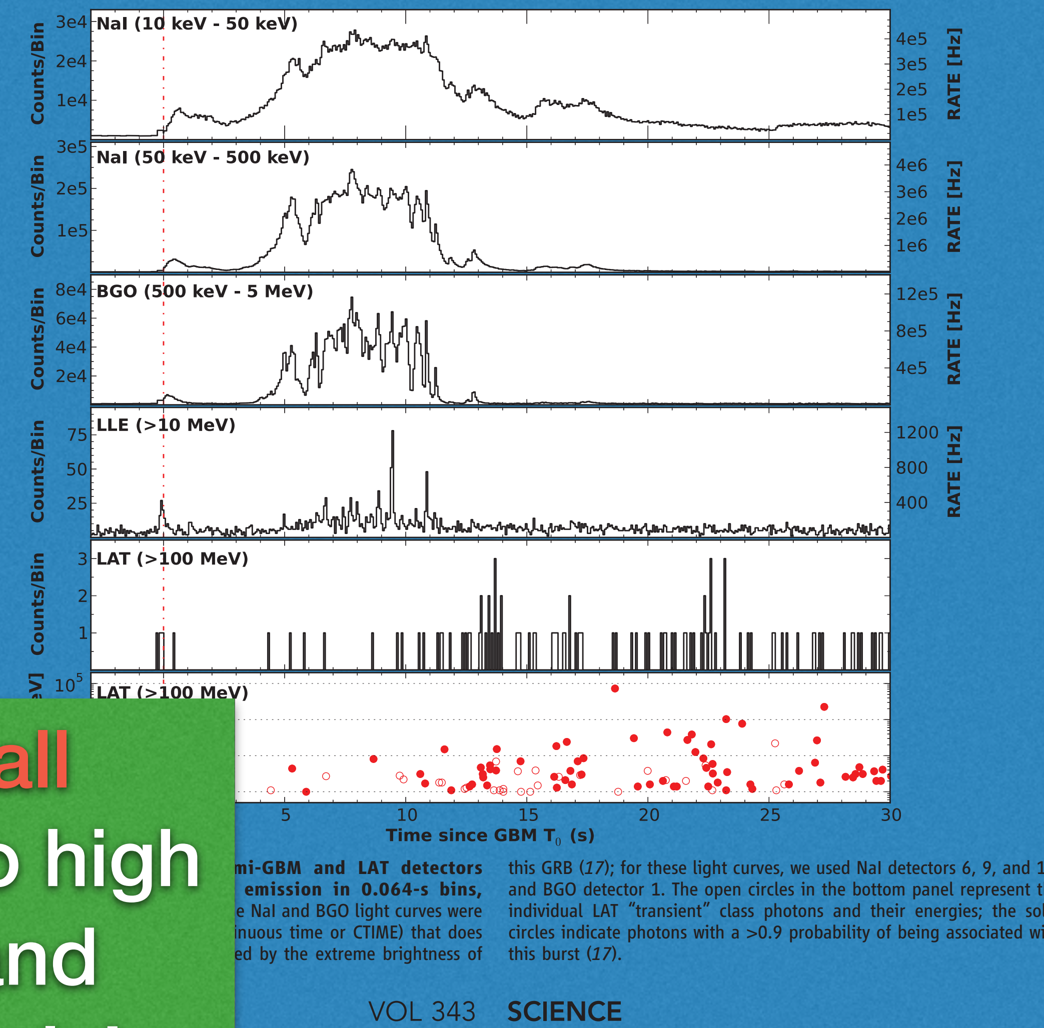
Who?

Roger Blandford
William East
Yajie Yuan
Krzysztof Nalewajko
Jonathan Zrake

Crab nebula



Gamma-ray bursts



Need to convert all magnetic energy into high energy particles and radiation, impulsively!

G. Bhatt

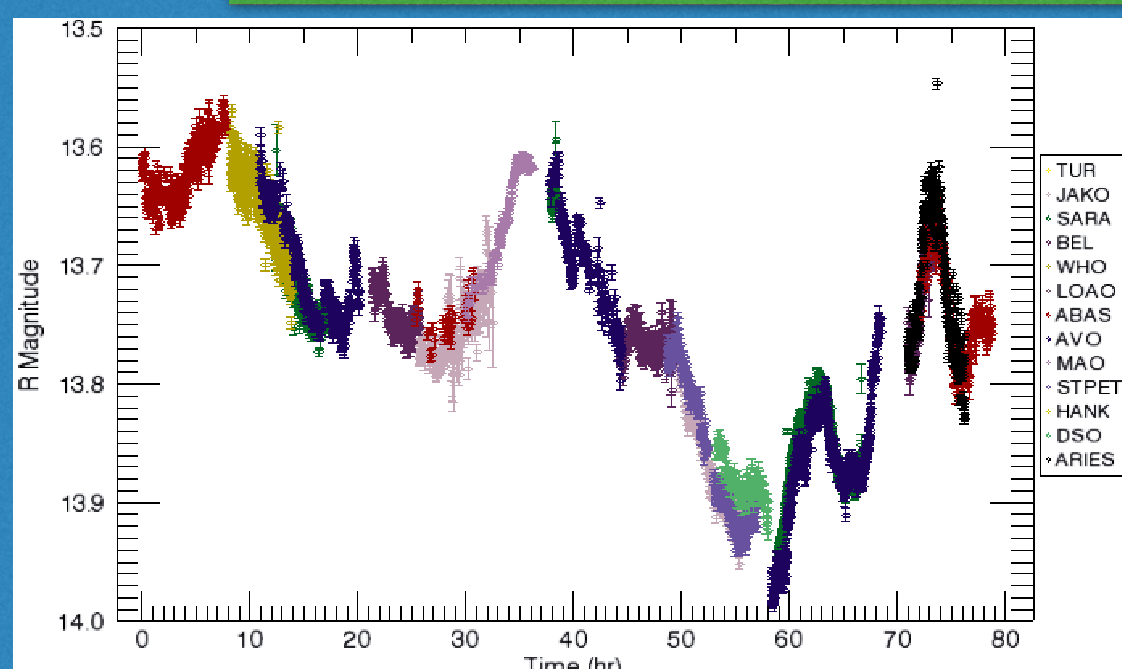


Fig. 1. Raw light curve of S5 0716+714 obtained by the compilation of some of the high quality data by major contributors. The light curves contributed from each observatory is plotted together with different symbols indentifying the observatory according to the codes given in Table 1.

- Critical magnetic reconfiguration
- that triggers volumetric magnetic energy conversion
- and energizes particles impulsively (E ~ B)

What?

Magneto-luminescence:

Rapid conversion of magnetic energy into radiation

In this talk, I’ll focus on the hydro-magnetic (RMHD), and magneto-dynamic (FFE) aspects.

Vocabulary

$$H = \int \mathbf{A} \cdot \mathbf{B} dV \quad = 2U/k \text{ if equilibrium}$$

$$\dot{H} = -2 \int \mathbf{E} \cdot \mathbf{B} dV \quad = 0 \text{ if ideal}$$

Magnetic helicity

M. A. Berger and G. B. Field

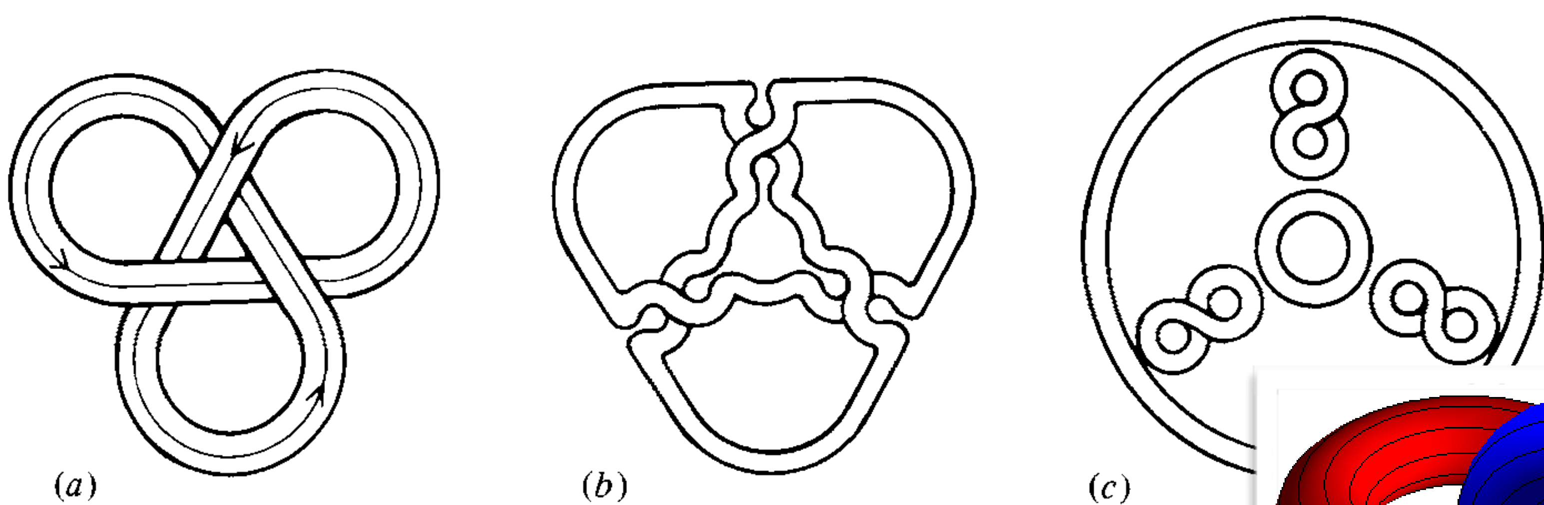
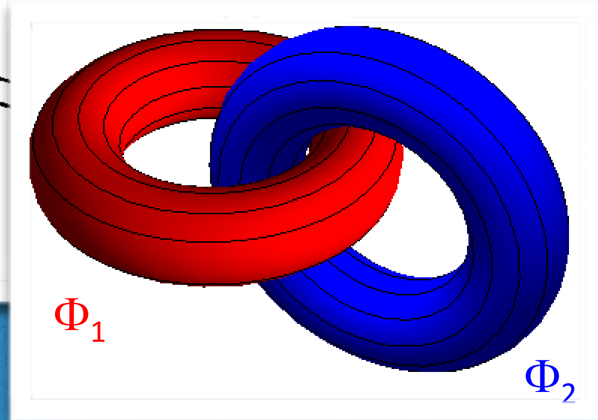


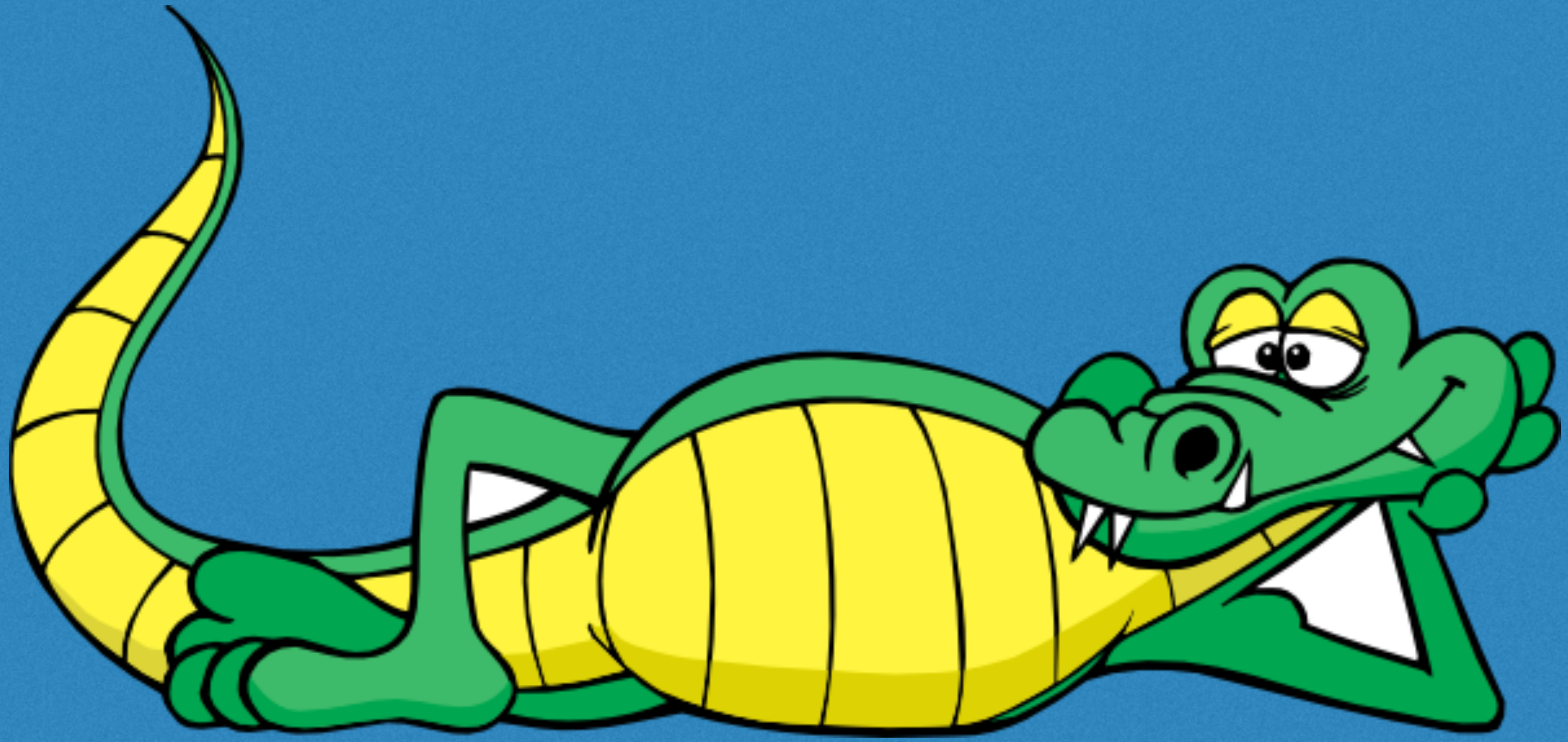
FIGURE 2. A trefoil knot with $H_K = -3\Phi^2$.



See poster by Yajie Yuan

- What characterizes the ground state?
- How long to attain it?
- Are magneto-static equilibria stable?

Magnetic relaxation



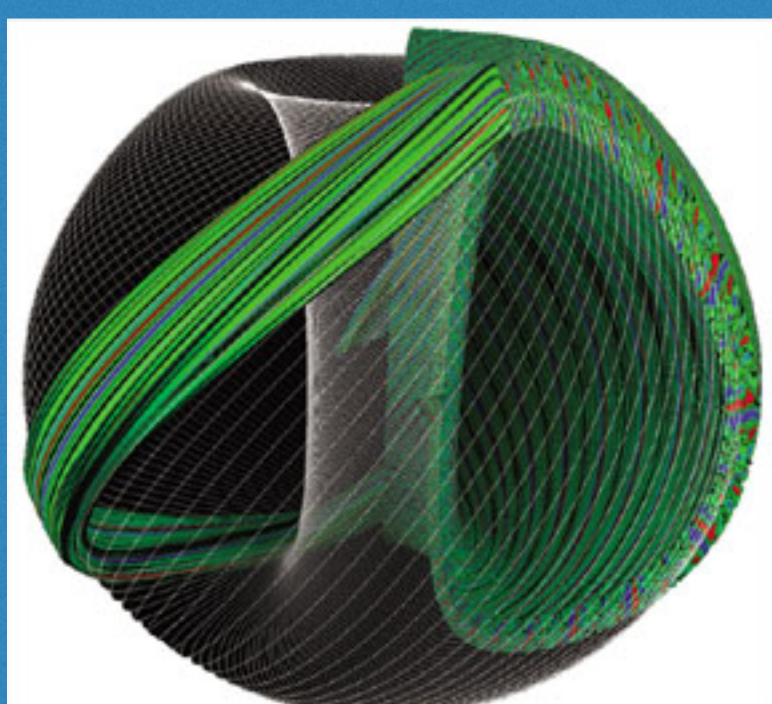
"Ground state": lowest energy allowed by topology

Electrical current is everywhere parallel to magnetic field.

"Linear Beltrami fields"

Magnetic equilibrium

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}$$



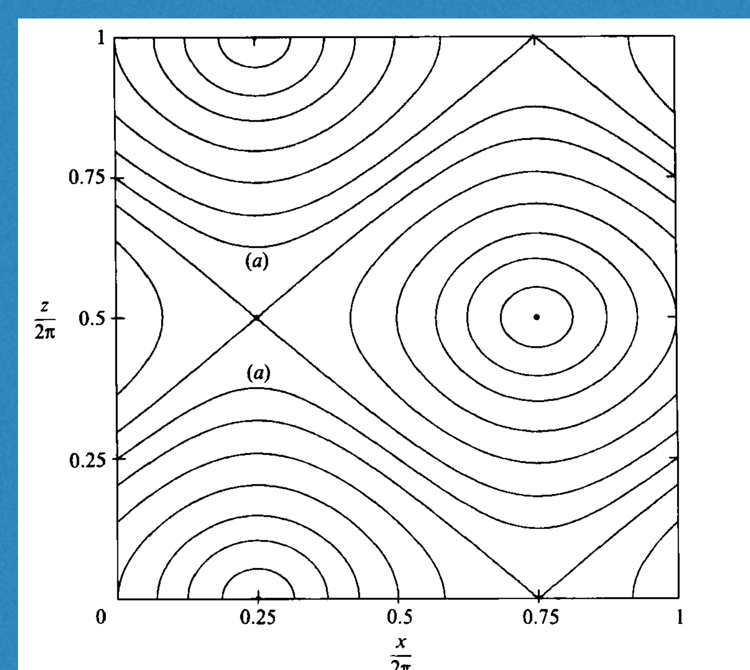


FIGURE 3. The integrable case: projection of streamlines on (x, z)-plane.

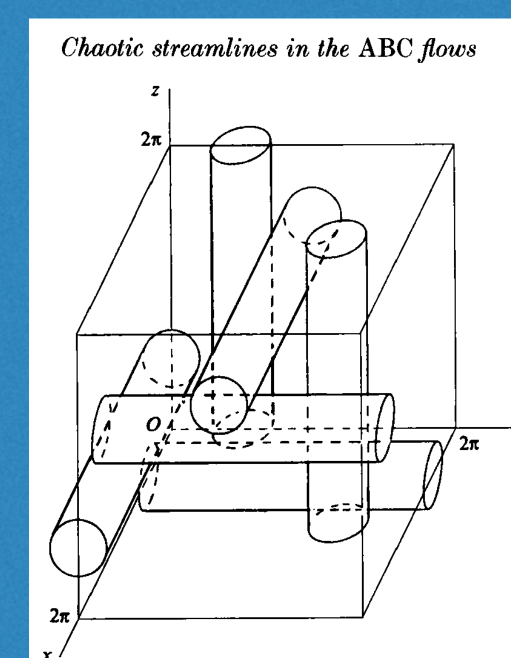


FIGURE 4. Sketch of the six principal vortices.

Spontaneous decay of periodic magnetostatic equilibria

William E. East, Jonathan Zrake, Yajie Yuan, and Roger D. Blandford
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SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

Magneto-static equilibrium

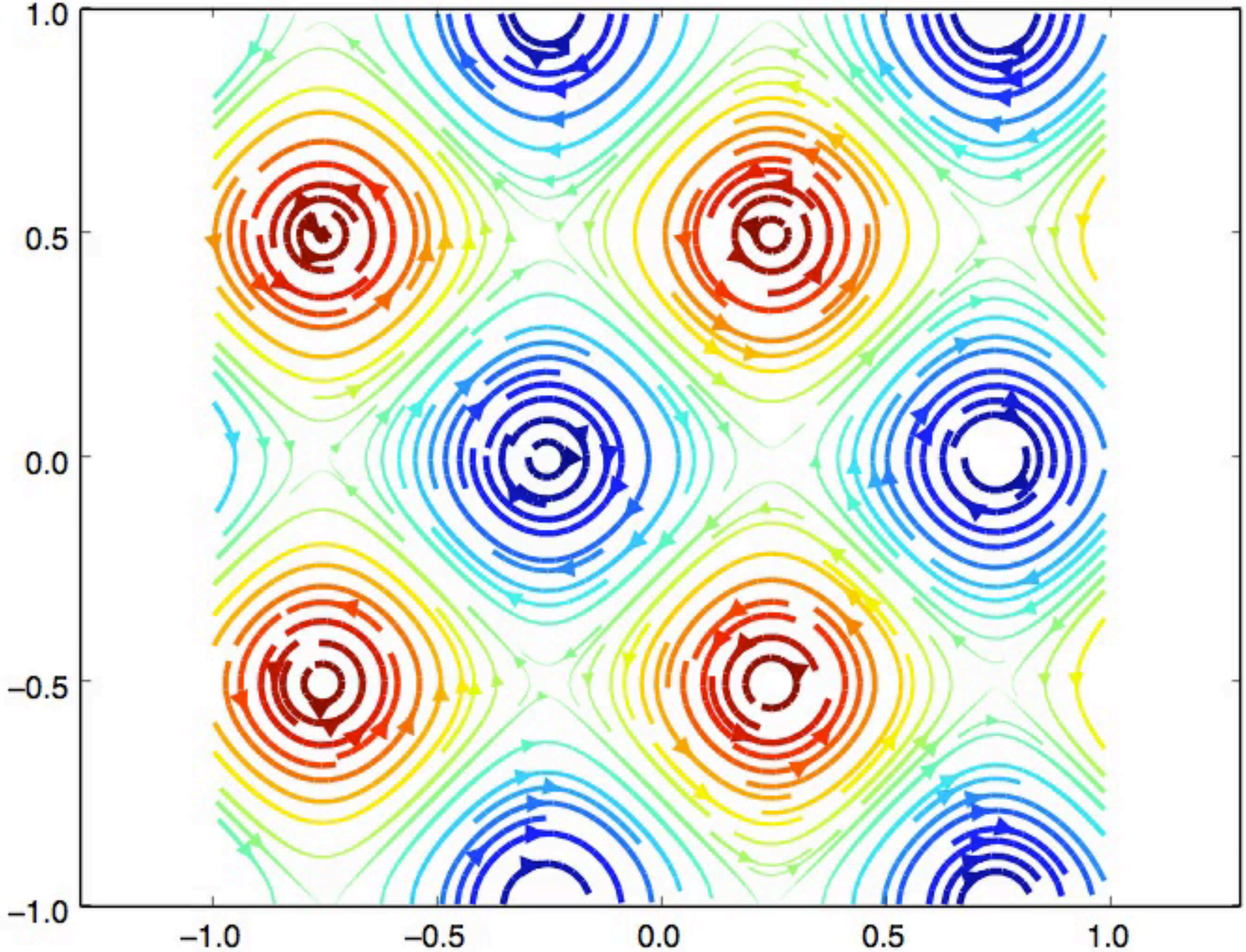
Submitted to PRL

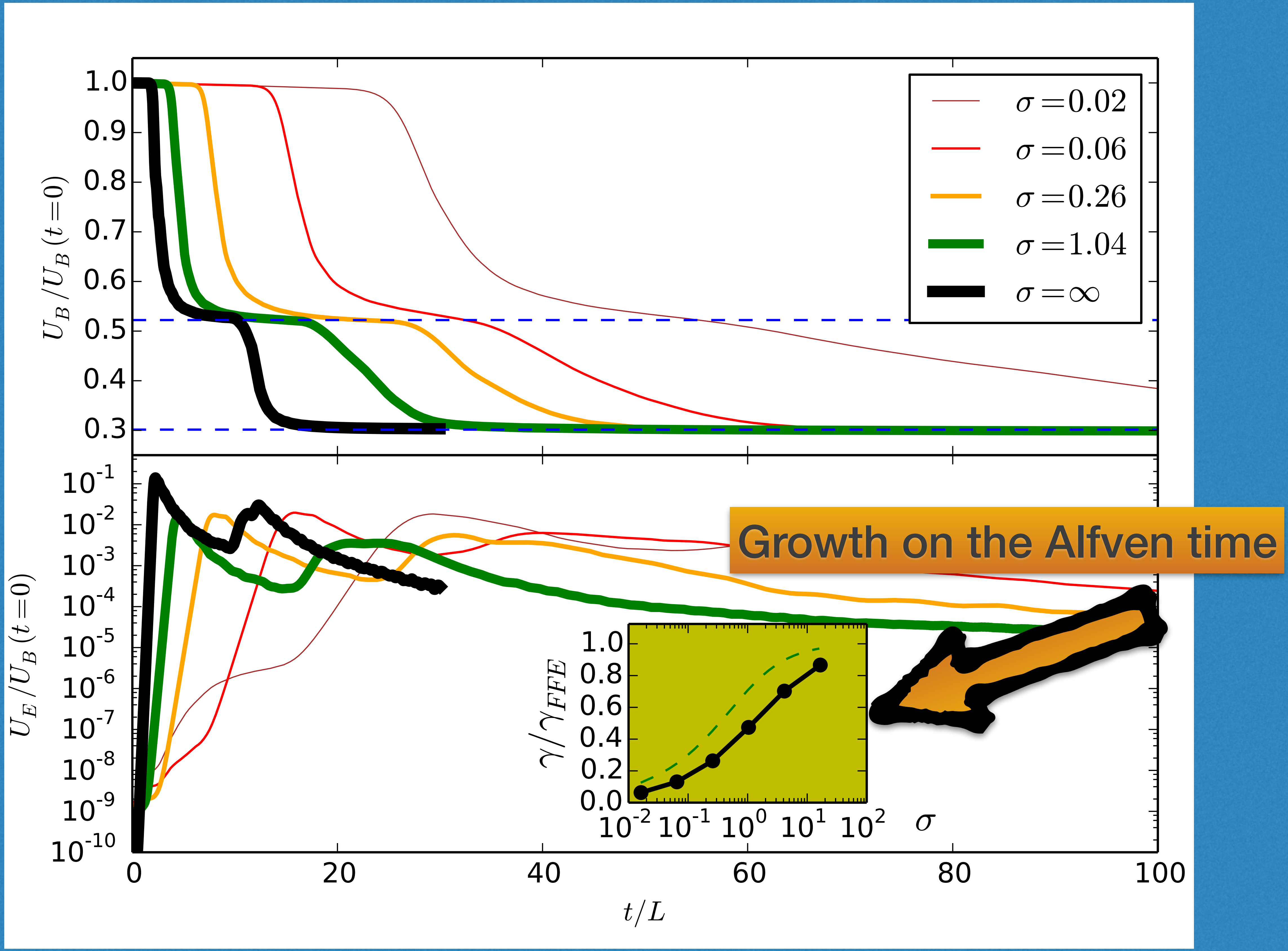
arXiv:1503.04793v2 [astro-ph.HE] 23 Mar 2015

What is the mechanical stability of the following field?

$$\mathbf{B}^E = \big(B_3 \cos \alpha z - B_2 \sin \alpha y,\\ B_1 \cos \alpha x - B_3 \sin \alpha z,\\ B_2 \cos \alpha y - B_1 \sin \alpha x\big)$$

A/B=1, alpha=2





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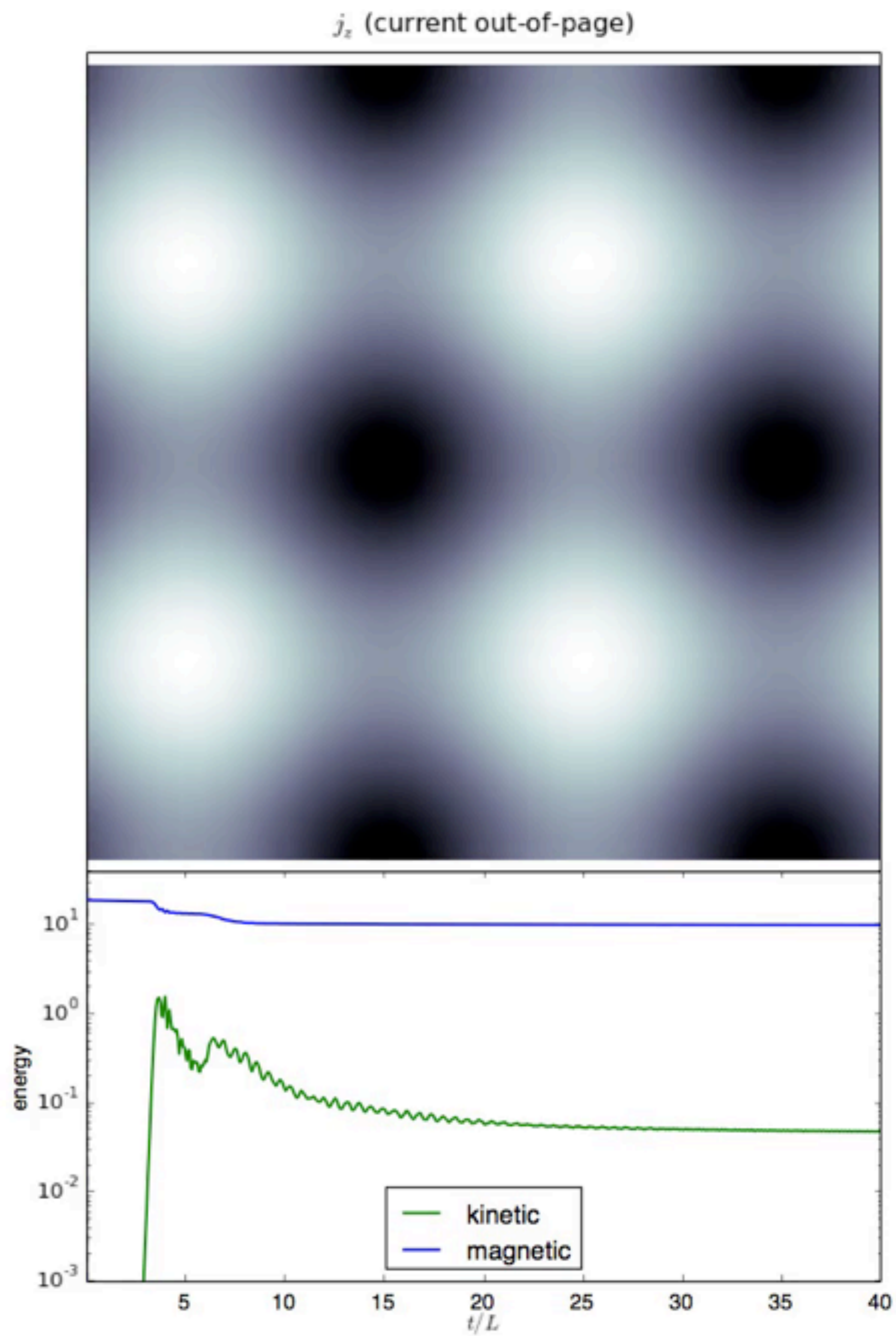
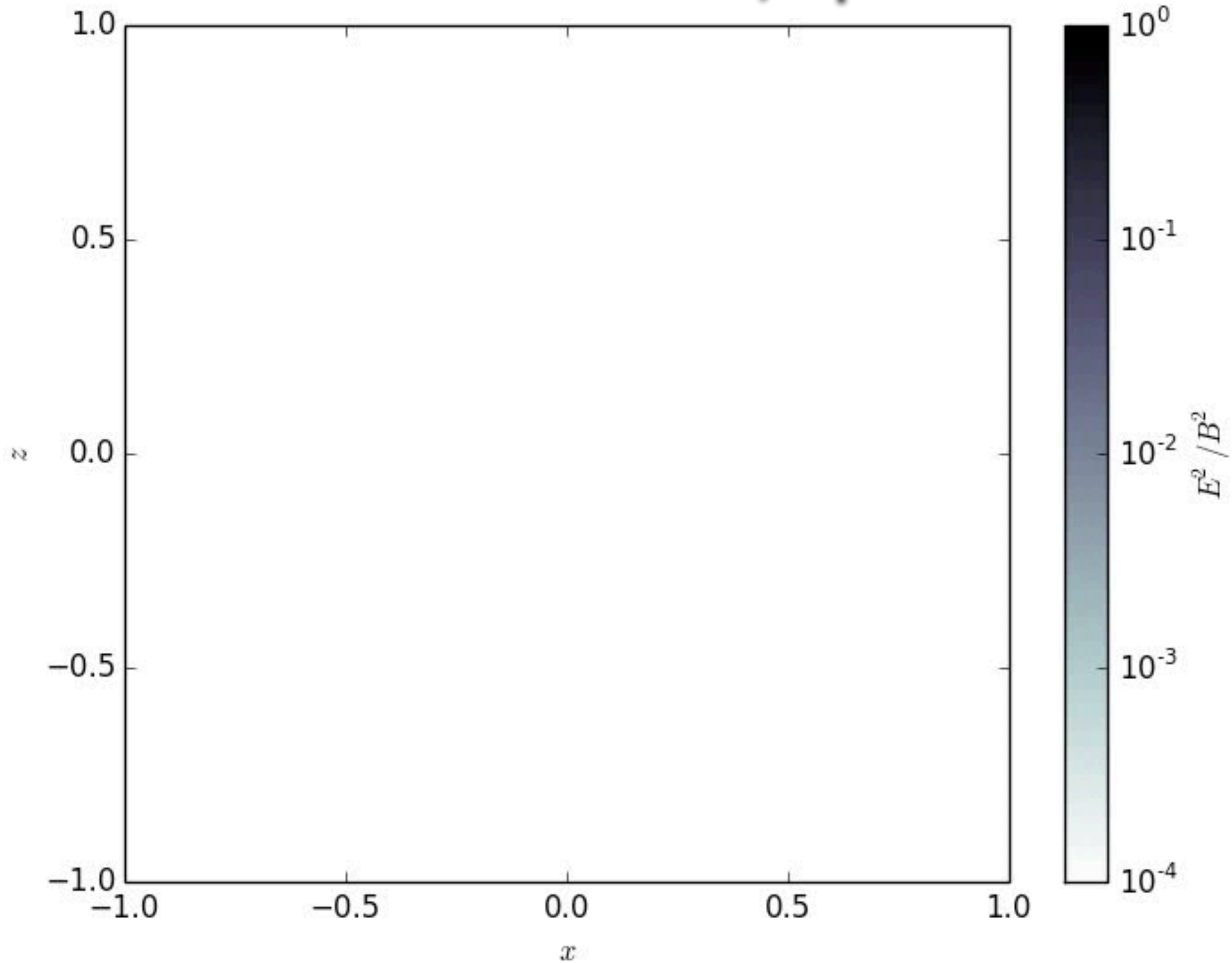
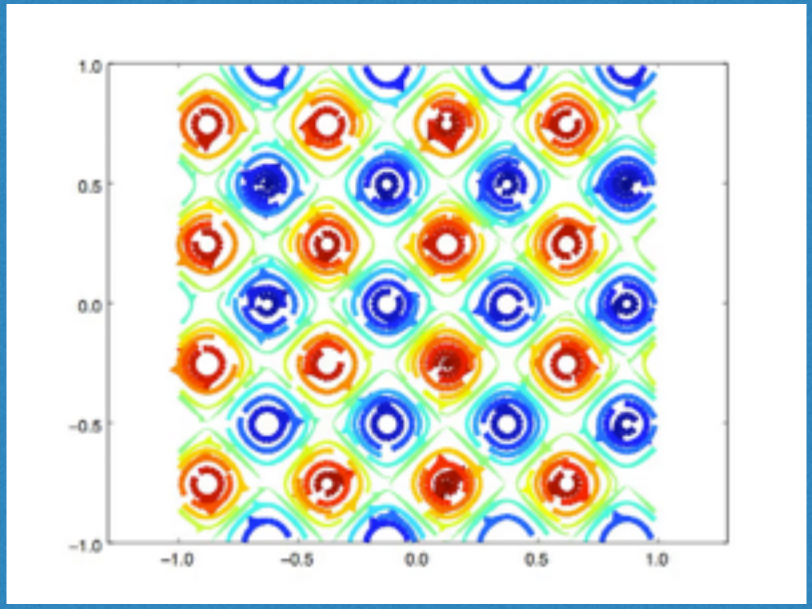


j_z (current out-of-page)
energy
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
kinetic
magnetic
5
10
15
20
25
30
35
40
t/L

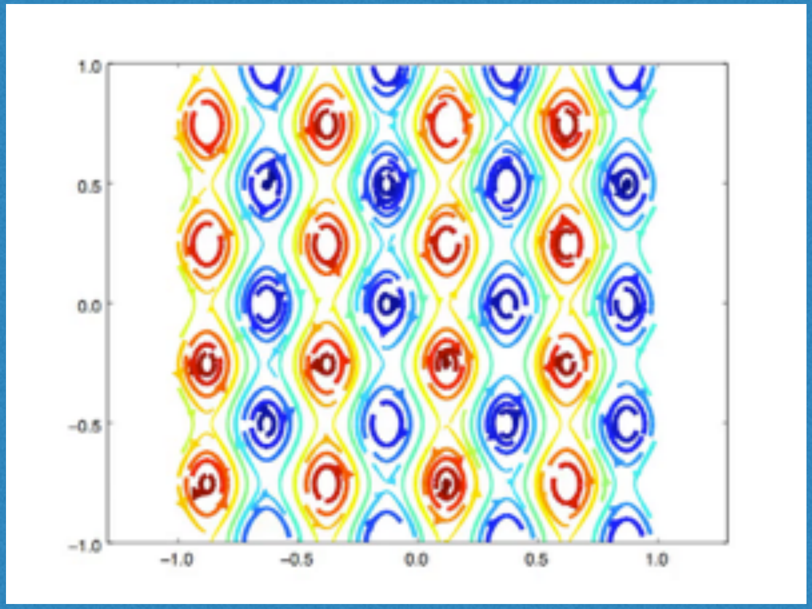
$t = 0.00$ Three-dimensional, alpha=$3^{1/2}$



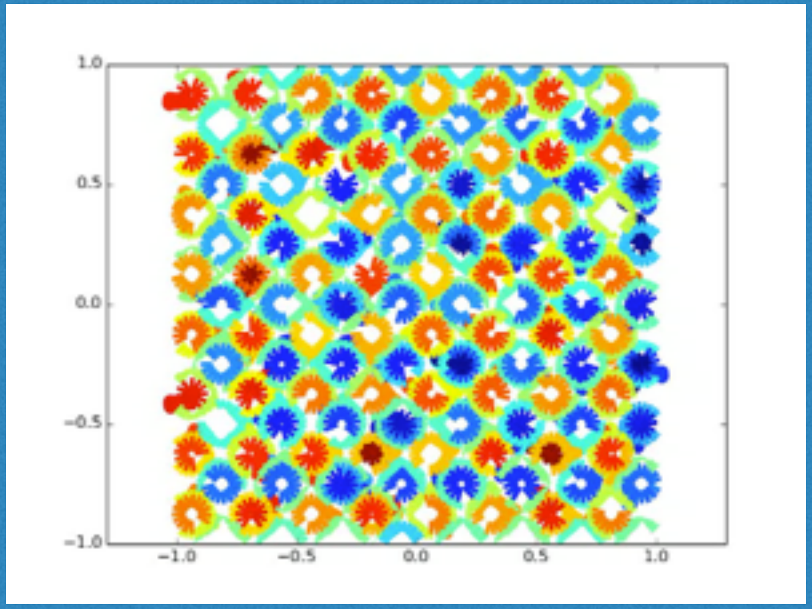
A/B=1, alpha=4

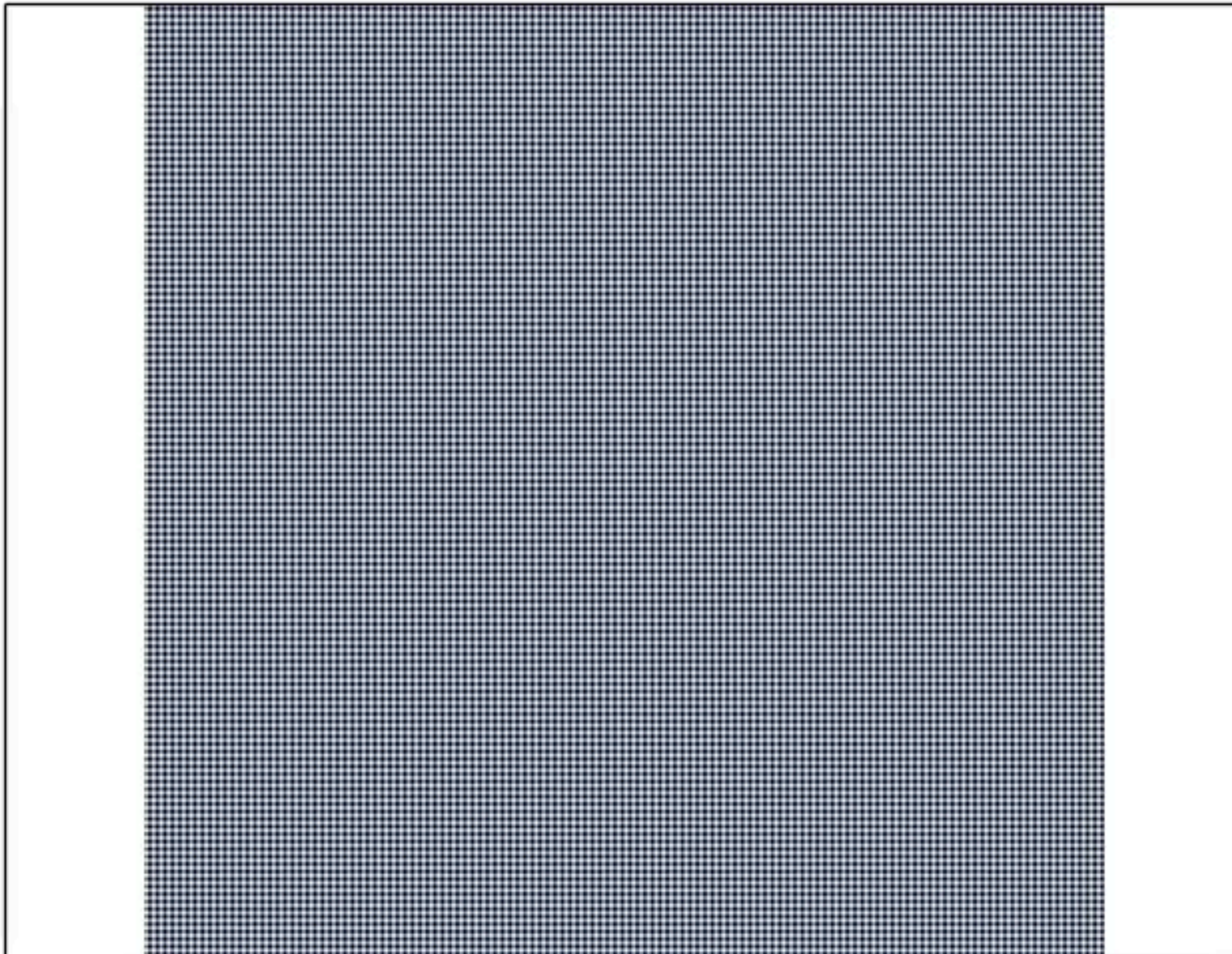


A/B=2, alpha=4



A/B=1, alpha=8





Zrake, East, Yuan, Blandford (in prep)

Equilibrium spectrum of magnetic energy strongly peaked at largest accessible scale.
(Frisch et. al. 1975)

Inverse cascade

Growing magnetic field at large wavelengths.

Typically believed to occur only when the magnetic helicity is non-zero.

The Astrophysical Journal Letters, 794:L26 (5pp), 2014 October 20 doi:10.1088/2041-8205/794/2/L26

INVERSE CASCADE OF NONHELICAL MAGNETIC TURBULENCE IN A RELATIVISTIC FLUID

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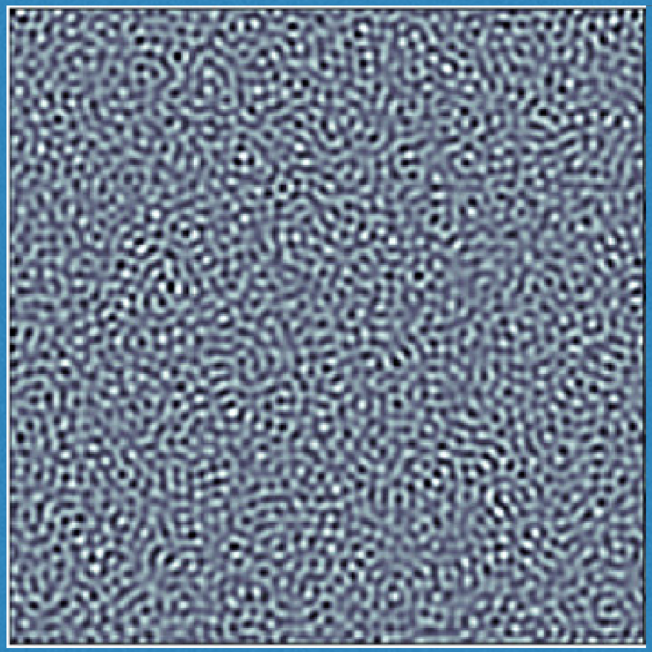
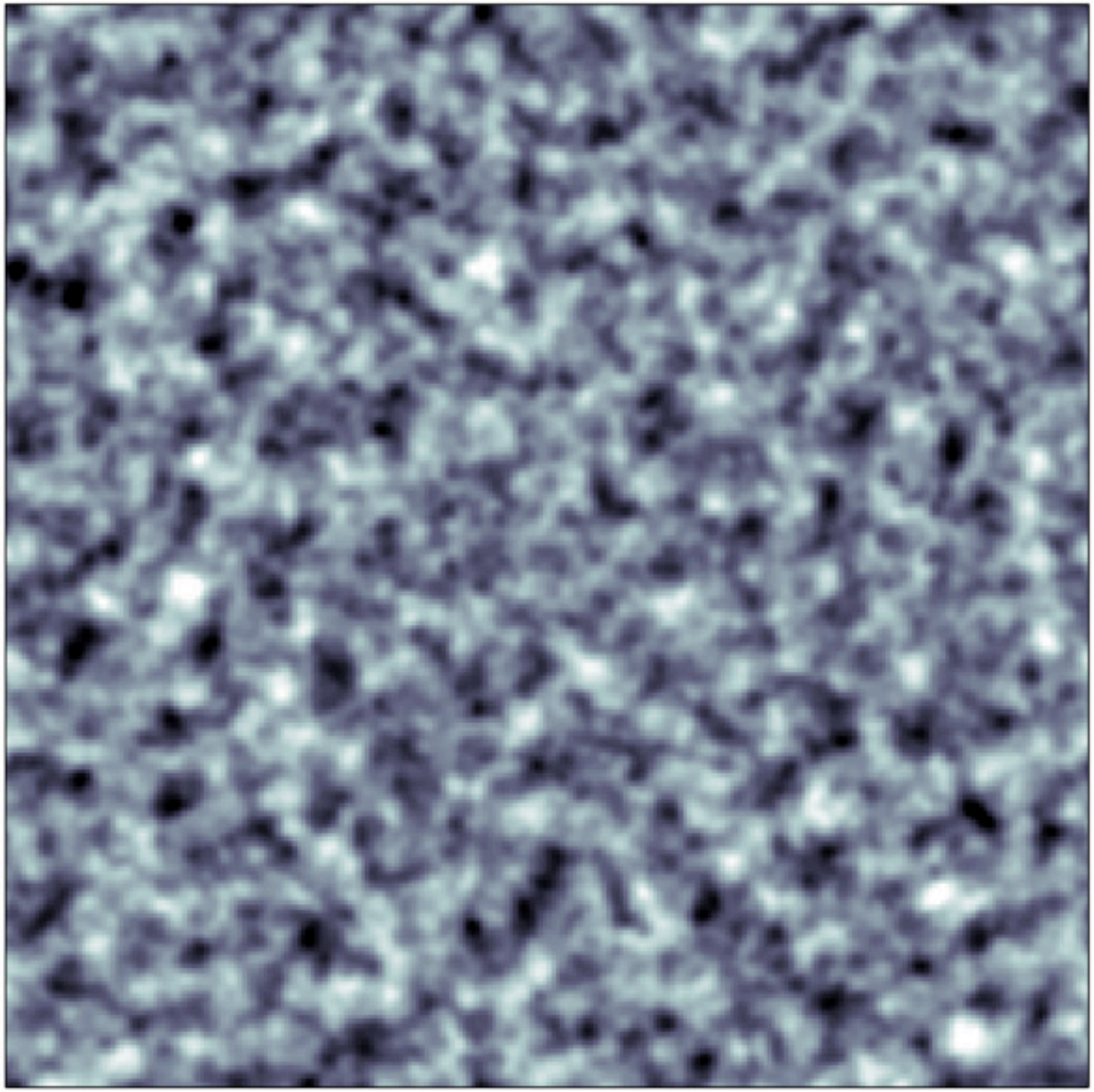
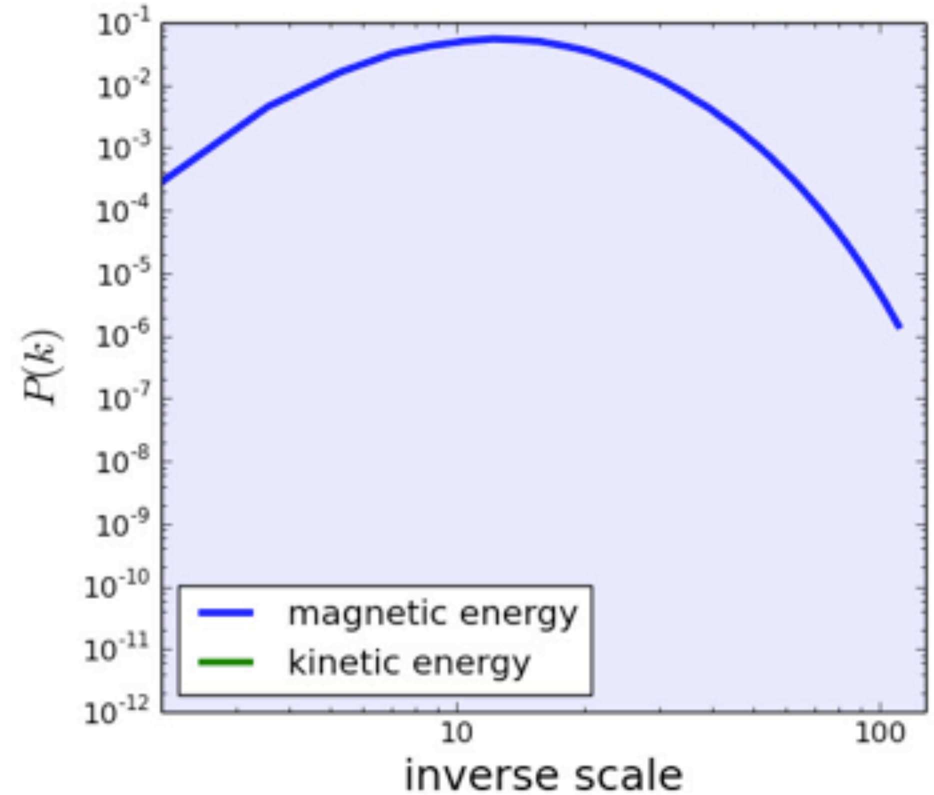
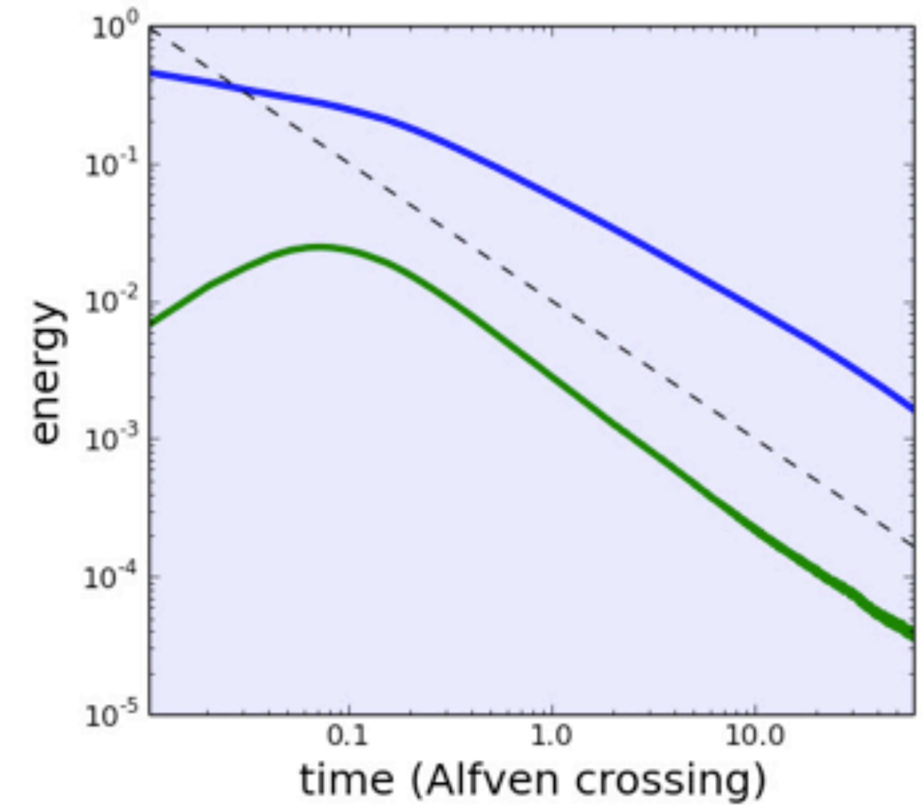
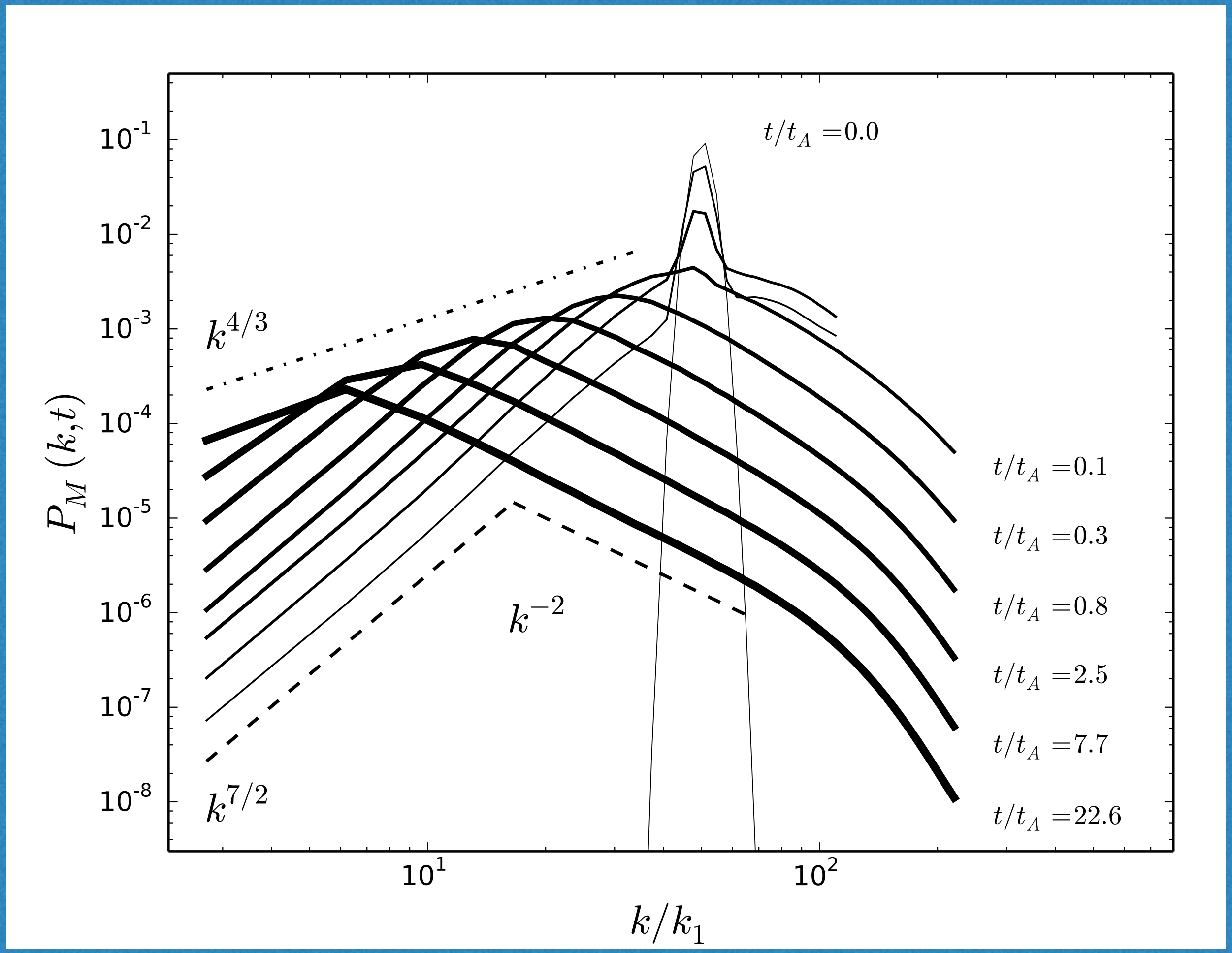


Figure 1. Two-dimensional slices of transverse magnetic field component showing the progression of magnetic field decay in a three-dimensional relativistic MHD turbulence. The leftmost panel shows the initial condition, and then from left to right the solution is shown at 4, 32, and 128 initial Alfvén crossing times of the simulation domain.




$P(k)$
inverse scale
magnetic energy
kinetic energy
10
100


energy
time (Alfven crossing)
0.1
1.0
10.0



Spectral evolution is self-similar:

$$P_M(k,t) = s^{\gamma\beta+\delta} P_M(ks^{-\gamma}, t_A)$$

$$\lambda_t \propto t^{2/5}$$

Zrake (2014)

Forward Alfven cascade

$$\dot{E} = -E/t_A$$

$$t_A = \lambda/v_A$$

$$v_A \propto E^{1/2}$$

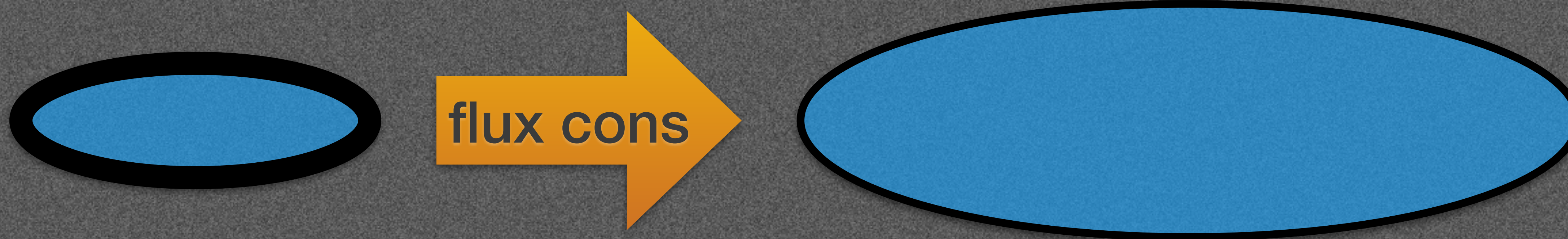
$$\lambda \propto t^{2/5}$$

→

$$E \propto t^{-6/5}$$

Too fast!

“Untangling” alone



$$B \propto \lambda^{-1}$$

$$\lambda \propto t^{2/5}$$

$$\rightarrow E \propto t^{-4/5}$$

Too slow!

For short wavelength configurations (large alpha),

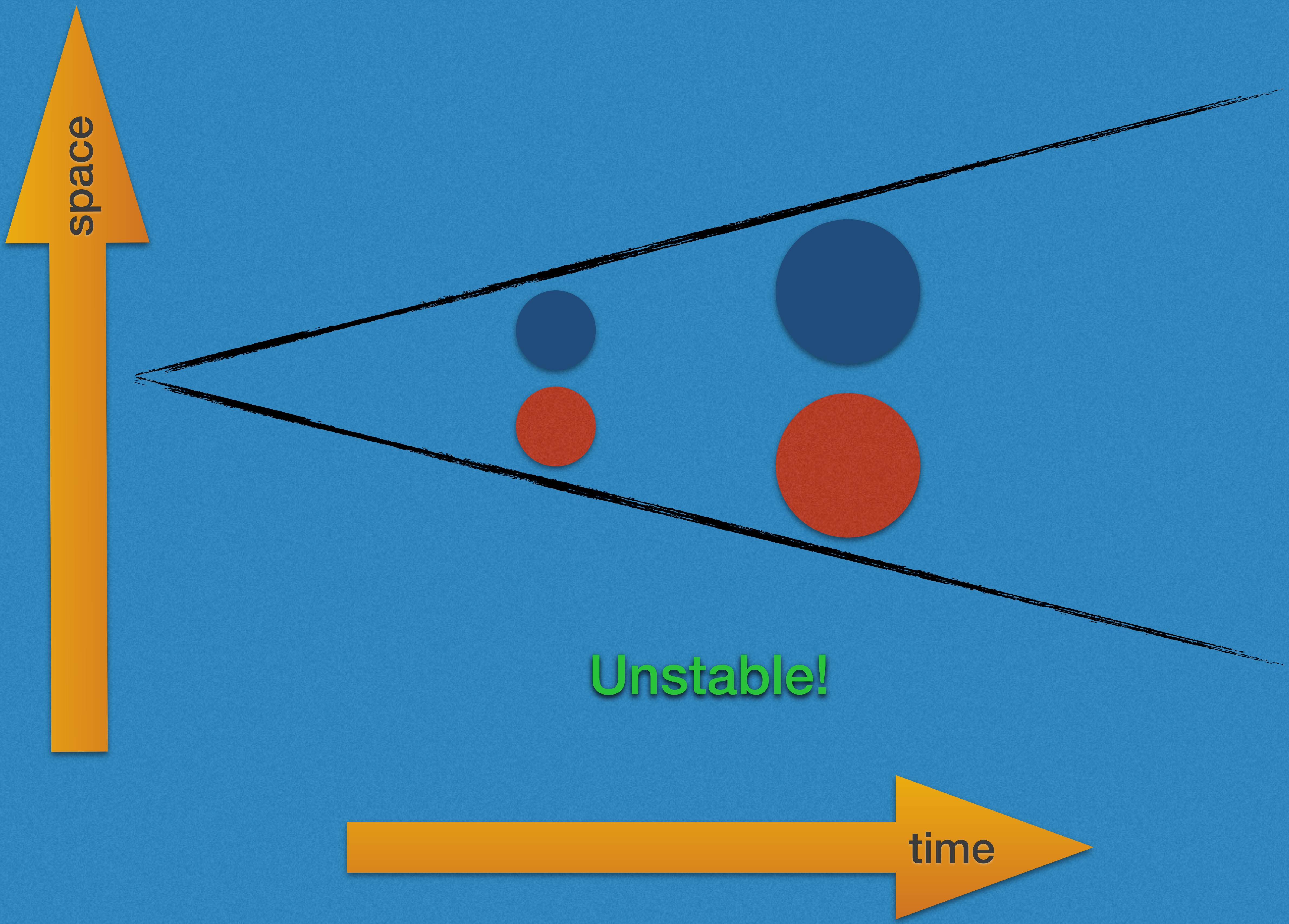
2D is very different from 3D!

In 3D, ground state is attained on a dynamical time-
whereas in 2D, it takes resistive time

Zrake, East, Yuan, Blandford (in prep)

This process is implosive, *not* explosive!

Instability can be triggered by deceleration of the flow.



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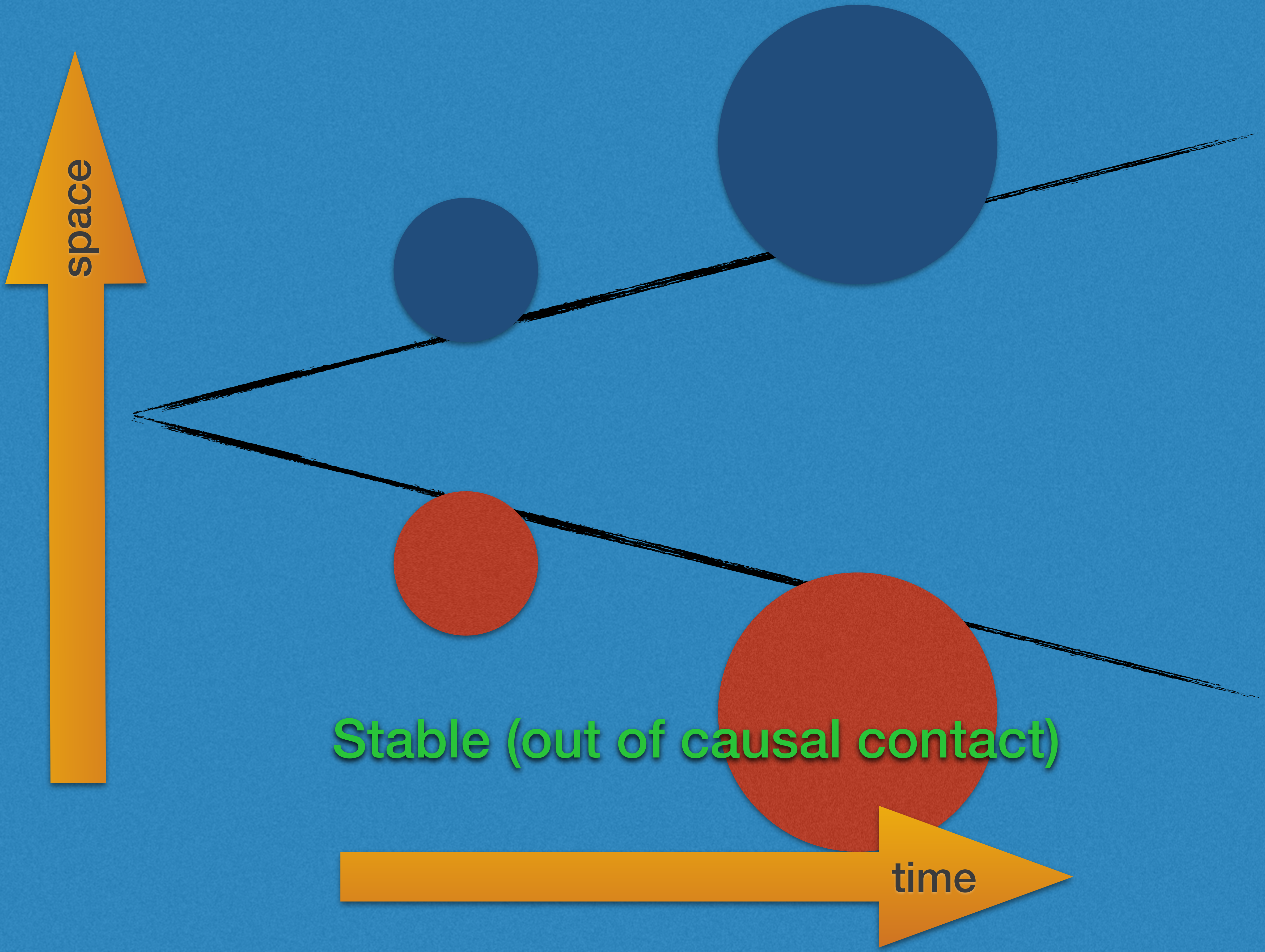

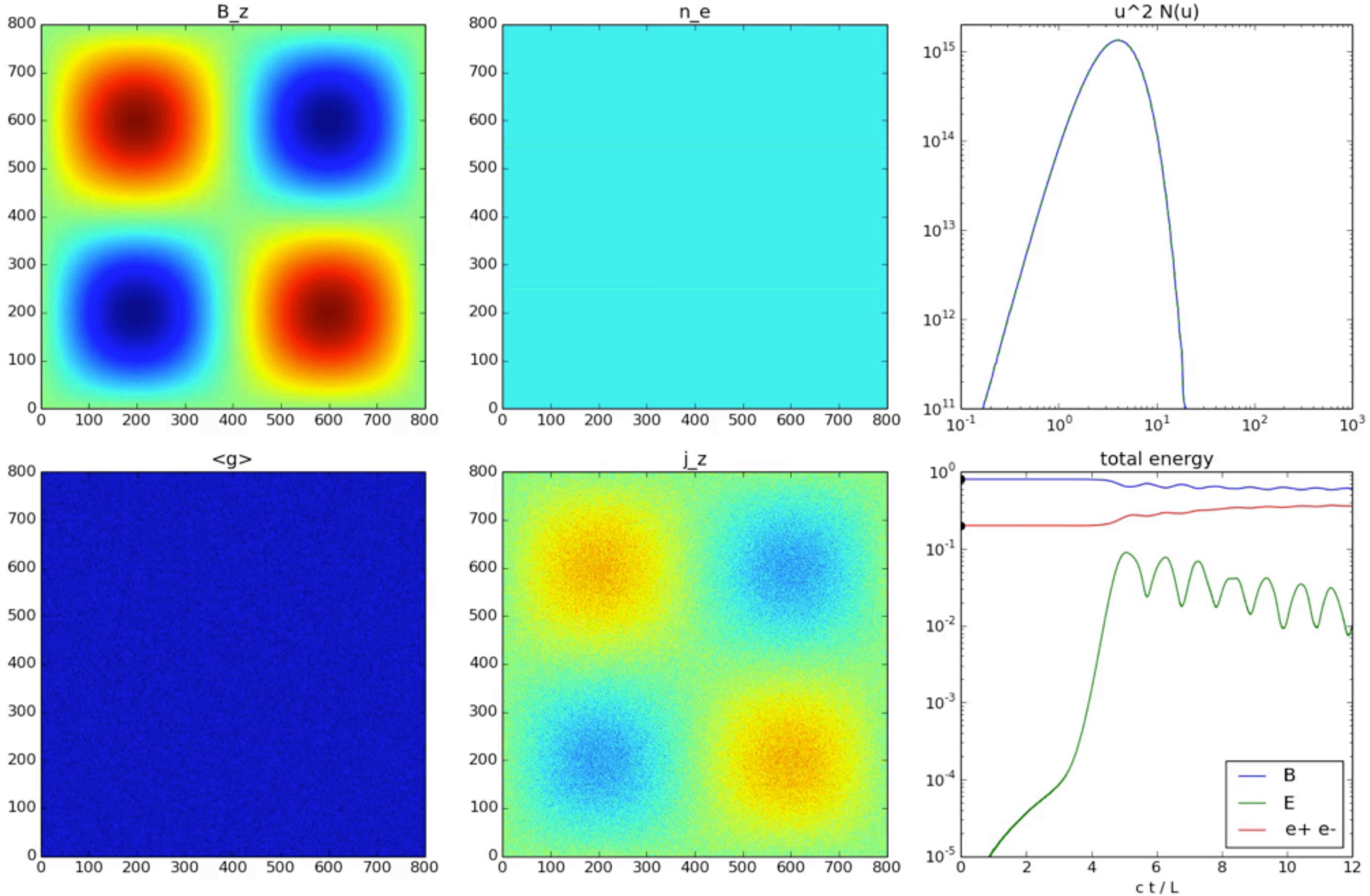

Nalewajko, Zrake, East, Yuan, Blandford (in prep)

- Only ground-state equilibria are stable
- Transition to ground state is bursty when helical
- Smooth when non-helical
- Inverse cascading both with and without helicity
- Mutual agreement among [analytic, FFE, RMHD, PIC]
- e+/e- form soft power-law tail in non-linear regime