Gamma-ray production by turbulent plasma

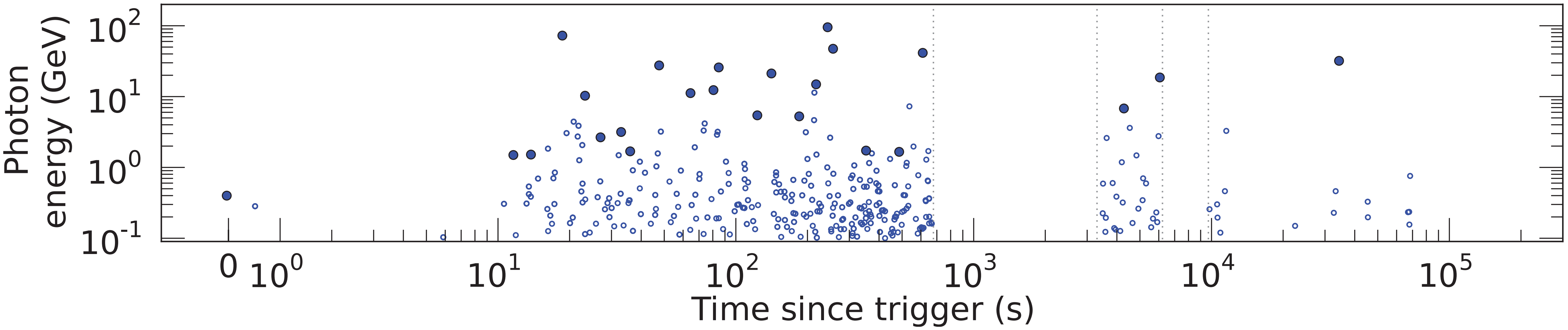
Jonathan Zrake
KIAA (Peking University) Sept. 28, 2015

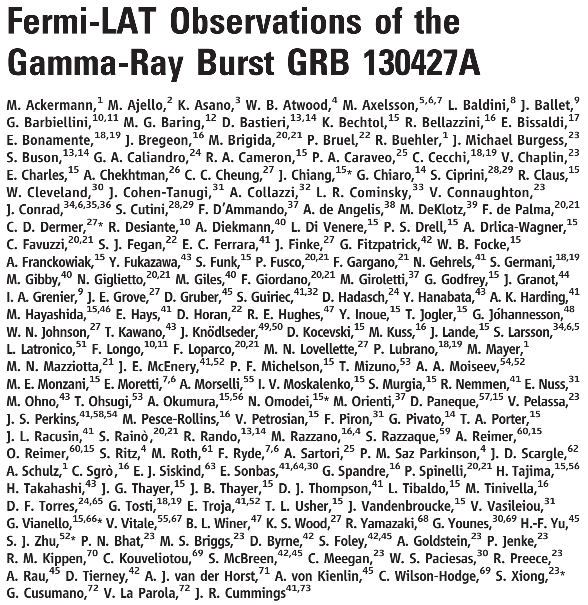
With Krzysztof Nalewajko, William East, Yajie Yuan, Roger Blandford

Context

- **Basic physics of turbulent plasma** involved in (leptonic) gamma-ray production by GRB’s, AGN, and the Crab Nebula
- **Use gamma-rays** to constrain GRB progenitor environment
- Questions about astrophysical conditions necessary for **rapid variability**

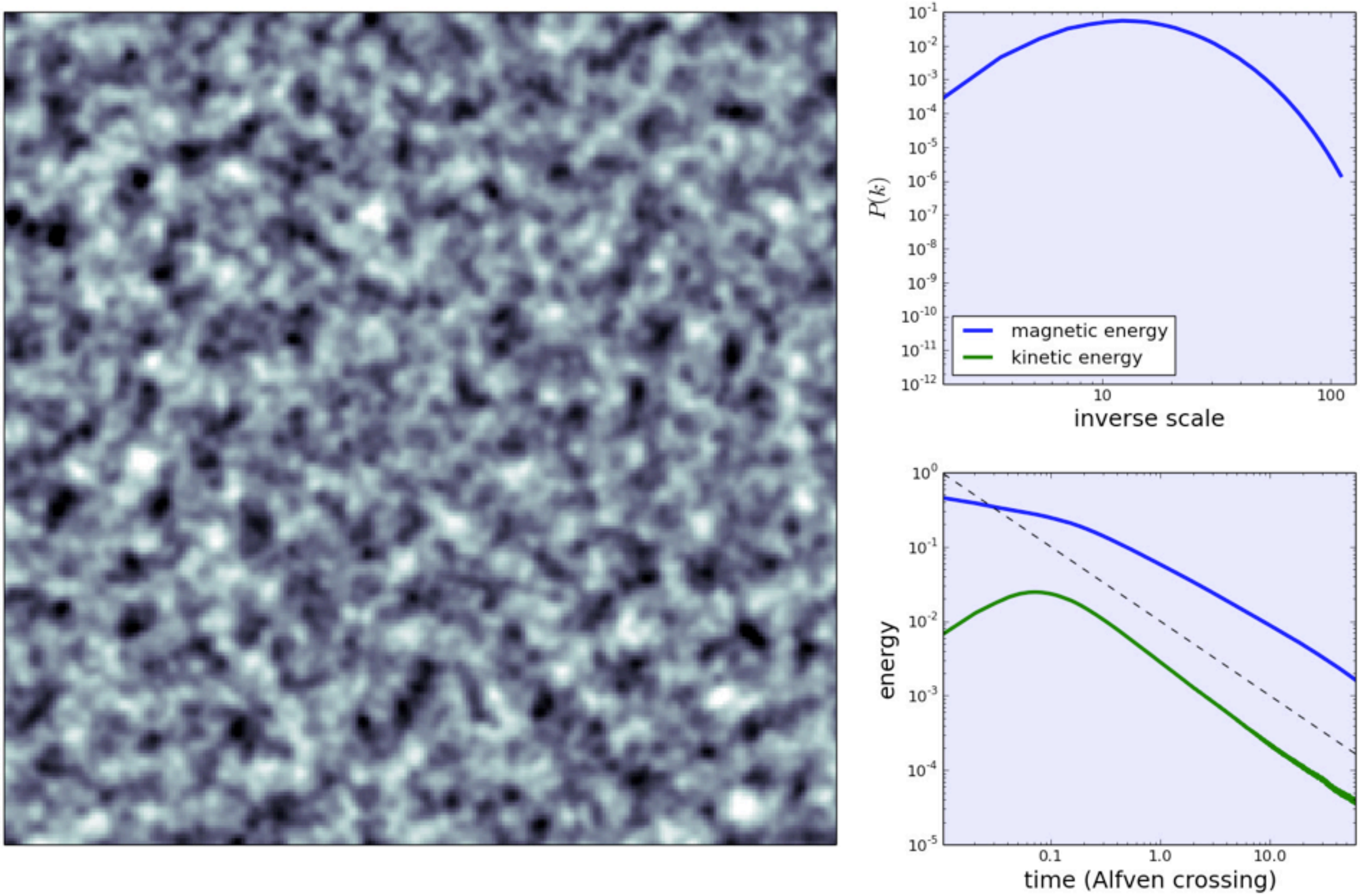
GRB Afterglow





Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A

M. Ackermann,[1] M. Ajello,[2] K. Asano,[3] W. B. Atwood,[4] M. Axelsson,[5,6,7] L. Baldini,[8] J. Ballet,[9]
G. Barbiellini,[10,11] M. G. Baring,[12] D. Bastieri,[13,14] K. Bechtol,[15] R. Bellazzini,[16] E. Bissaldi,[17]
E. Bonamente,[18,19] J. Bregeon,[16] M. Brigida,[20,21] P. Bruel,[22] R. Buehler,[1] J. Michael Burgess,[23]
S. Buson,[13,14] G. A. Caliandro,[24] R. A. Cameron,[15] P. A. Caraveo,[25] C. Cecchi,[18,19] V. Chaplin,[23]
E. Charles,[15] A. Chekhtman,[26] C. C. Cheung,[27] J. Chiang,[15]* G. Chiaro,[14] S. Ciprini,[28,29] R. Claus,[15]
W. Cleveland,[30] J. Cohen-Tanugi,[31] A. Collazzi,[32] L. R. Cominsky,[33] V. Connaughton,[23]
J. Conrad,[34,6,35,36] S. Cutini,[28,29] F. D'Ammando,[37] A. de Angelis,[38] M. DeKlotz,[39] F. de Palma,[20,21]
C. D. Dermer,[27]* R. Desiante,[10] A. Diekmann,[40] L. Di Venere,[15] P. S. Drell,[15] A. Drlica-Wagner,[15]
C. Favuzzi,[20,21] S. J. Fegan,[22] E. C. Ferrara,[41] J. Finke,[27] G. Fitzpatrick,[42] W. B. Focke,[15]
A. Franckowiak,[15] Y. Fukazawa,[43] S. Funk,[15] P. Fusco,[20,21] F. Gargano,[21] N. Gehrels,[41] S. Germani,[18,19]
M. Gibby,[40] N. Giglietto,[20,21] M. Giles,[40] F. Giordano,[20,21] M. Giroletti,[37] G. Godfrey,[15] J. Granot,[44]
I. A. Grenier,[9] J. E. Grove,[27] D. Gruber,[45] S. Guiriec,[41,32] D. Hadasch,[24] Y. Hanabata,[43] A. K. Harding,[41]
M. Hayashida,[15,46] E. Hays,[41] D. Horan,[22] R. E. Hughes,[47] Y. Inoue,[15] T. Jogler,[15] G. Jóhannesson,[48]
W. N. Johnson,[27] T. Kawano,[43] J. Knödlseder,[49,50] D. Kocevski,[15] M. Kuss,[16] J. Lande,[15] S. Larsson,[34,6,5]
L. Latronico,[51] F. Longo,[10,11] F. Loparco,[20,21] M. N. Lovellette,[27] P. Lubrano,[18,19] M. Mayer,[1]
M. N. Mazziotta,[21] J. E. McEnery,[41,52] P. F. Michelson,[15] T. Mizuno,[53] A. A. Moiseev,[54,52]
M. E. Monzani,[15] E. Moretti,[7,6] A. Morselli,[55] I. V. Moskalenko,[15] S. Murgia,[15] R. Nemmen,[41] E. Nuss,[31]
M. Ohno,[43] T. Ohsugi,[53] A. Okumura,[15,56] N. Omodei,[15]* M. Orienti,[37] D. Paneque,[57,15] V. Pelassa,[23]
J. S. Perkins,[41,58,54] M. Pesce-Rollins,[16] V. Petrosian,[15] F. Piron,[31] G. Pivato,[14] T. A. Porter,[15]
J. L. Racusin,[41] S. Rainò,[20,21] R. Rando,[13,14] M. Razzano,[16,4] S. Razzaque,[59] A. Reimer,[60,15]
O. Reimer,[60,15] S. Ritz,[4] M. Roth,[61] F. Ryde,[7,6] A. Sartori,[25] P. M. Saz Parkinson,[4] J. D. Scargle,[62]
A. Schulz,[1] C. Sgrò,[16] E. J. Siskind,[63] E. Sonbas,[41,64,30] G. Spandre,[16] P. Spinelli,[20,21] H. Tajima,[15,56]
H. Takahashi,[43] J. G. Thayer,[15] J. B. Thayer,[15] D. J. Thompson,[41] L. Tibaldo,[15] M. Tinivella,[16]
D. F. Torres,[24,65] G. Tosti,[18,19] E. Troja,[41,52] T. L. Usher,[15] J. Vandenbroucke,[15] V. Vasileiou,[31]
G. Vianello,[15,66]* V. Vitale,[55,67] B. L. Winer,[47] K. S. Wood,[27] R. Yamazaki,[68] G. Younes,[30,69] H.-F. Yu,[45]
S. J. Zhu,[52]* P. N. Bhat,[23] M. S. Briggs,[23] D. Byrne,[42] S. Foley,[42,45] A. Goldstein,[23] P. Jenke,[23]
R. M. Kippen,[70] C. Kouveliotou,[69] S. McBreen,[42,45] C. Meegan,[23] W. S. Paciesas,[30] R. Preece,[23]
A. Rau,[45] D. Tierney,[42] A. J. van der Horst,[71] A. von Kienlin,[45] C. Wilson-Hodge,[69] S. Xiong,[23]*
G. Cusumano,[72] V. La Parola,[72] J. R. Cummings[41,73]


$P(k)$
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
magnetic energy
kinetic energy
10
100
inverse scale
energy
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0.1
1.0
10.0
time (Alfven crossing)

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INVERSE CASCADE OF NONHELICAL MAGNETIC TURBULENCE IN A RELATIVISTIC FLUID

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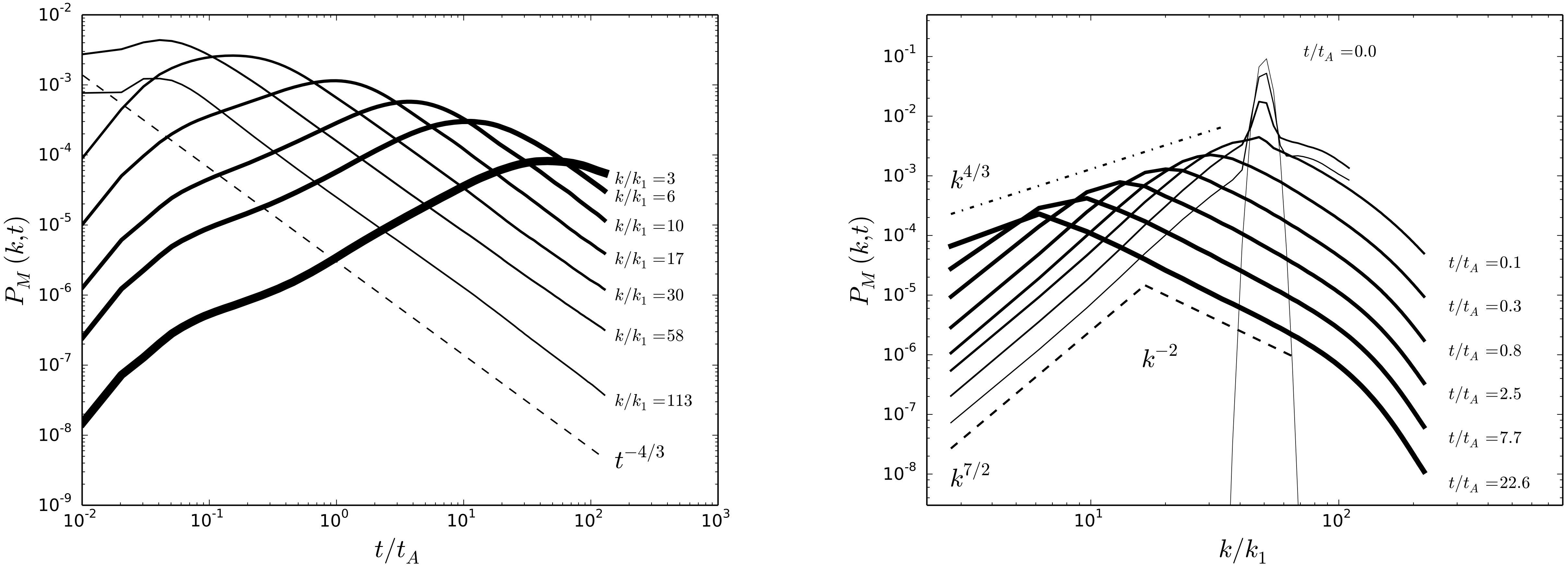
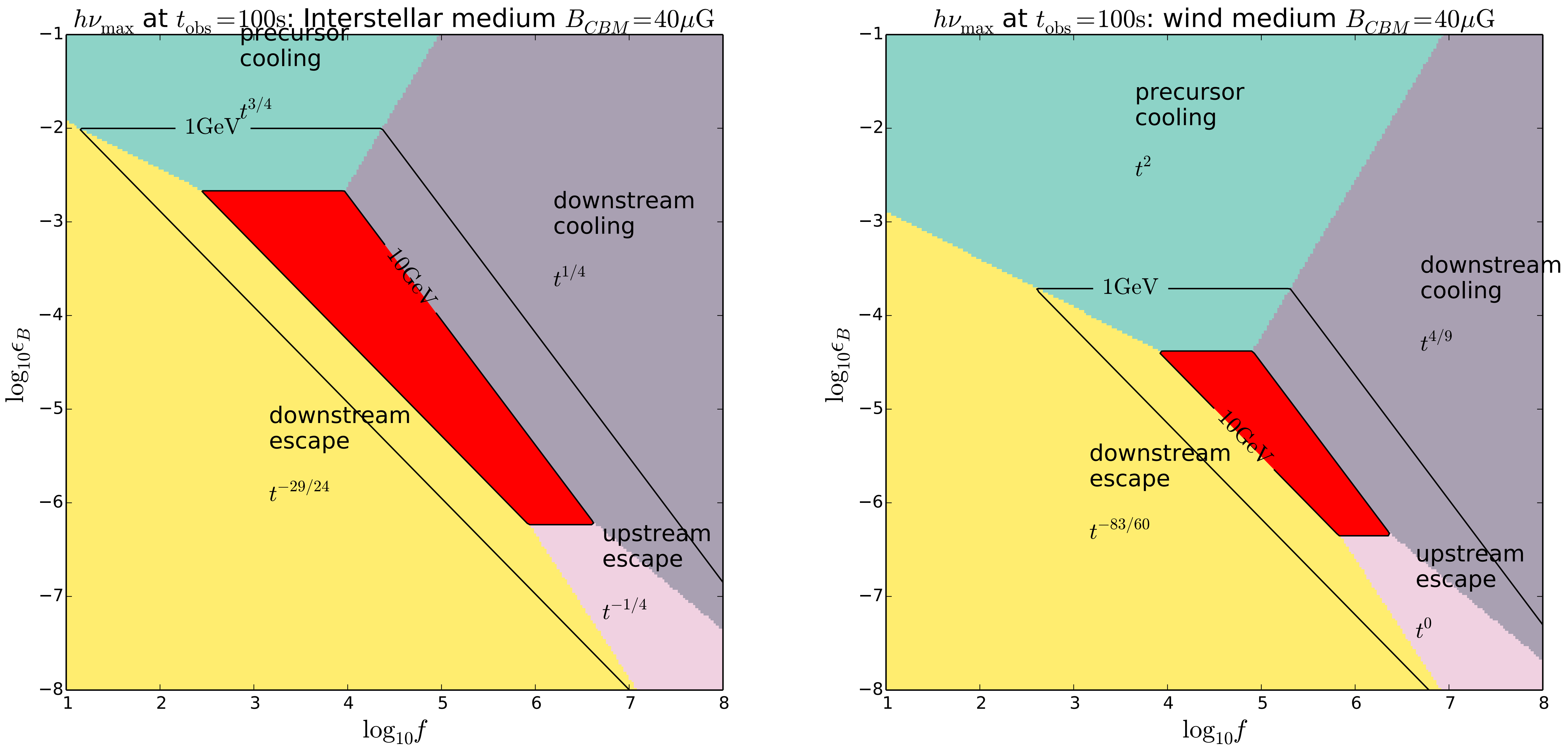
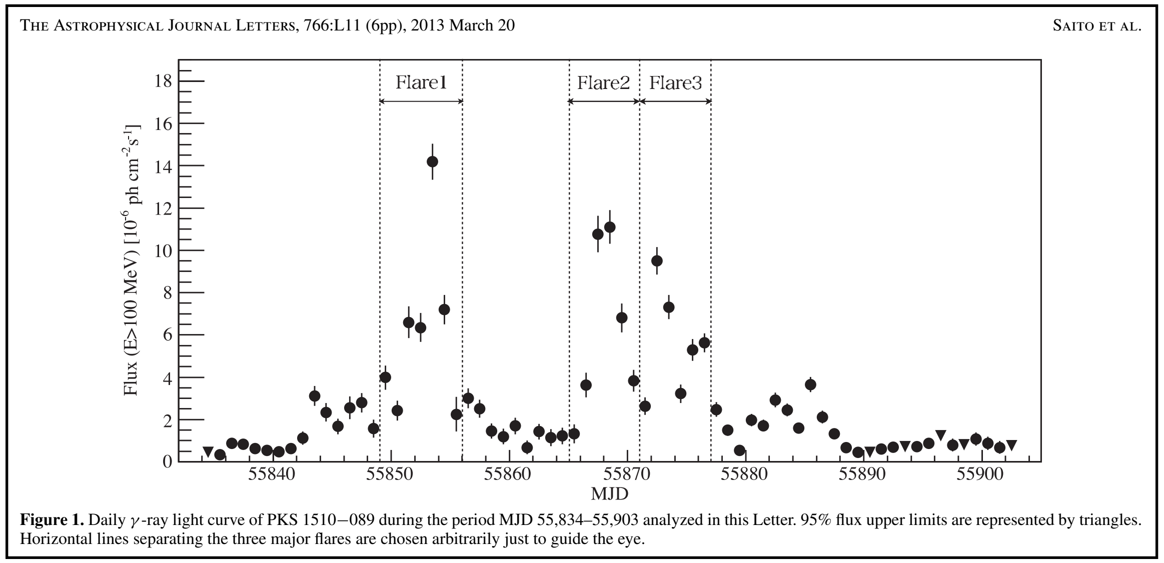


$$P_M(k,t) = s^{\gamma\beta+\delta} P_M(ks^{-\gamma}, t_A)$$

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

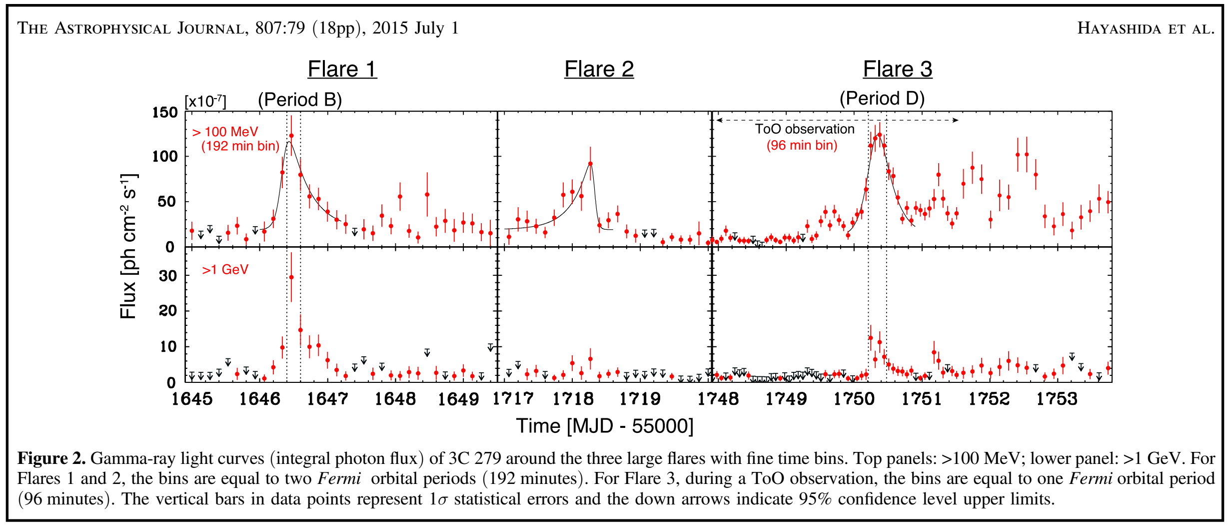


Zrake & Granot (in prep.)



THE ASTROPHYSICAL JOURNAL LETTERS, 766:L11 (6pp), 2013 March 20 SAITO ET AL.

Figure 1. Daily γ-ray light curve of PKS 1510−089 during the period MJD 55,834–55,903 analyzed in this Letter. 95% flux upper limits are represented by triangles. Horizontal lines separating the three major flares are chosen arbitrarily just to guide the eye.



THE ASTROPHYSICAL JOURNAL, 807:79 (18pp), 2015 July 1 HAYASHIDA ET AL.

Figure 2. Gamma-ray light curves (integral photon flux) of 3C 279 around the three large flares with fine time bins. Top panels: >100 MeV; lower panel: >1 GeV. For Flares 1 and 2, the bins are equal to two *Fermi* orbital periods (192 minutes). For Flare 3, during a ToO observation, the bins are equal to one *Fermi* orbital period (96 minutes). The vertical bars in data points represent 1σ statistical errors and the down arrows indicate 95% confidence level upper limits.

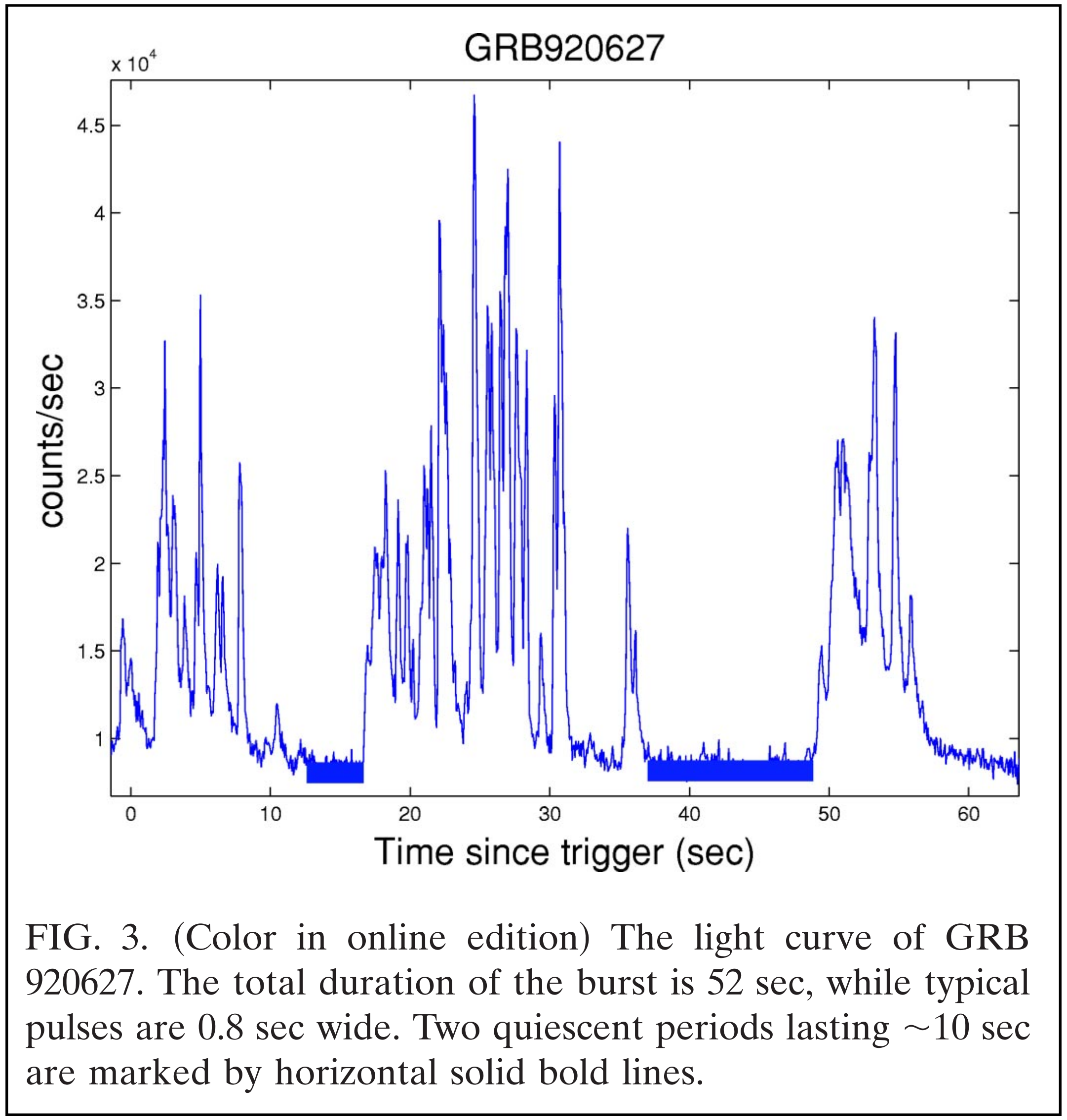


FIG. 3. (Color in online edition) The light curve of GRB 920627. The total duration of the burst is 52 sec, while typical pulses are 0.8 sec wide. Two quiescent periods lasting ~10 sec are marked by horizontal solid bold lines.

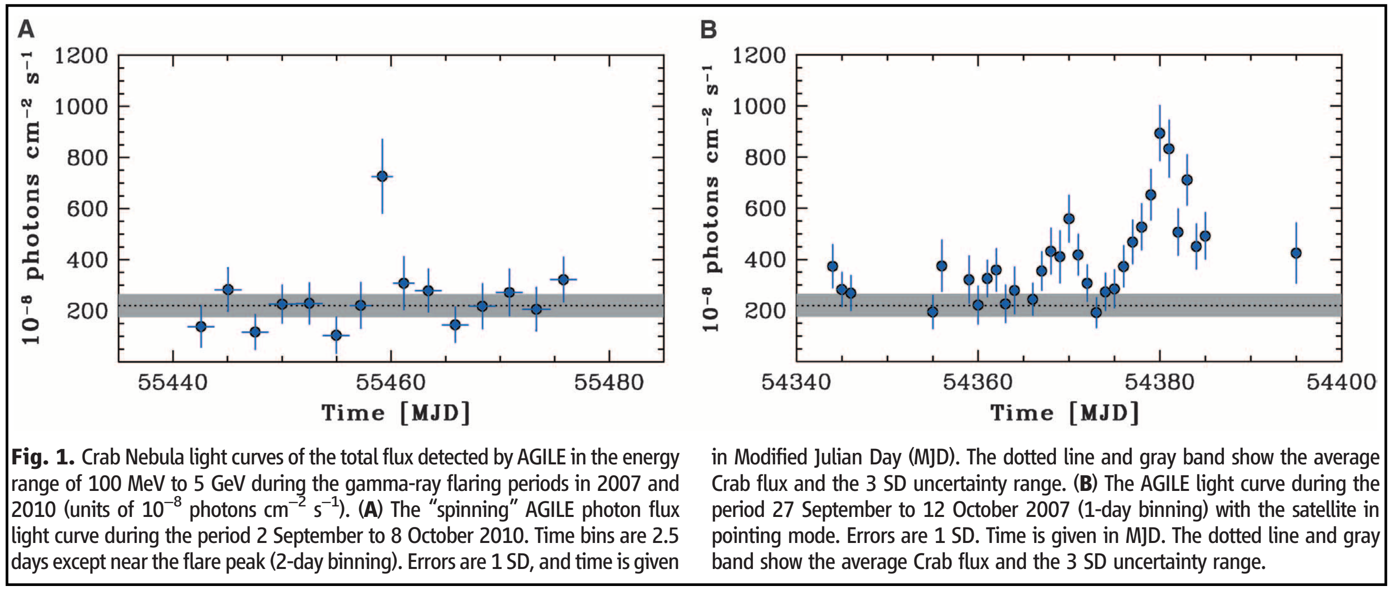
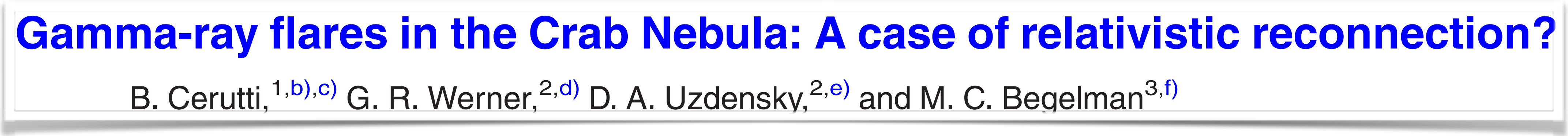


Fig. 1. Crab Nebula light curves of the total flux detected by AGILE in the energy range of 100 MeV to 5 GeV during the gamma-ray flaring periods in 2007 and 2010 (units of 10^{-8} photons cm^{-2} s^{-1}). (**A**) The "spinning" AGILE photon flux light curve during the period 2 September to 8 October 2010. Time bins are 2.5 days except near the flare peak (2-day binning). Errors are 1 SD, and time is given in Modified Julian Day (MJD). The dotted line and gray band show the average Crab flux and the 3 SD uncertainty range. (**B**) The AGILE light curve during the period 27 September to 12 October 2007 (1-day binning) with the satellite in pointing mode. Errors are 1 SD. Time is given in MJD. The dotted line and gray band show the average Crab flux and the 3 SD uncertainty range.



Gamma-ray flares in the Crab Nebula: A case of relativistic reconnection?

B. Cerutti,[1,b),c)] G. R. Werner,[2,d)] D. A. Uzdensky,[2,e)] and M. C. Begelman[3,f)]

Mon. Not. R. Astron. Soc. **426,** 1374–1384 (2012) doi:10.1111/j.1365-2966.2012.21349.x

Crab nebula gamma-ray flares as relativistic reconnection minijets

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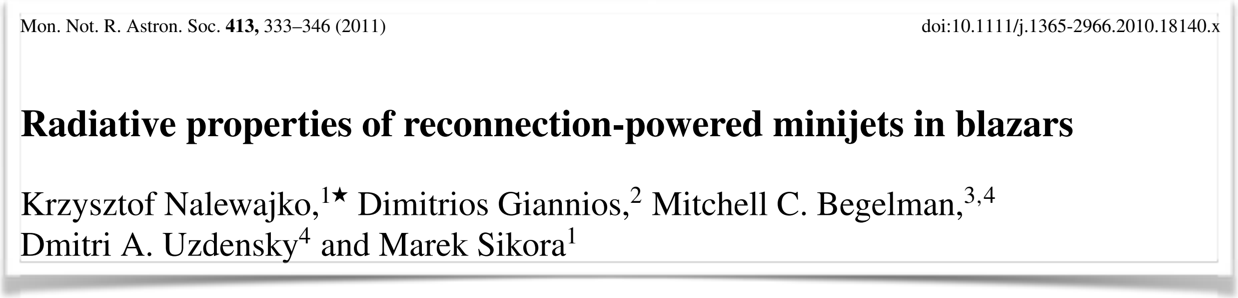
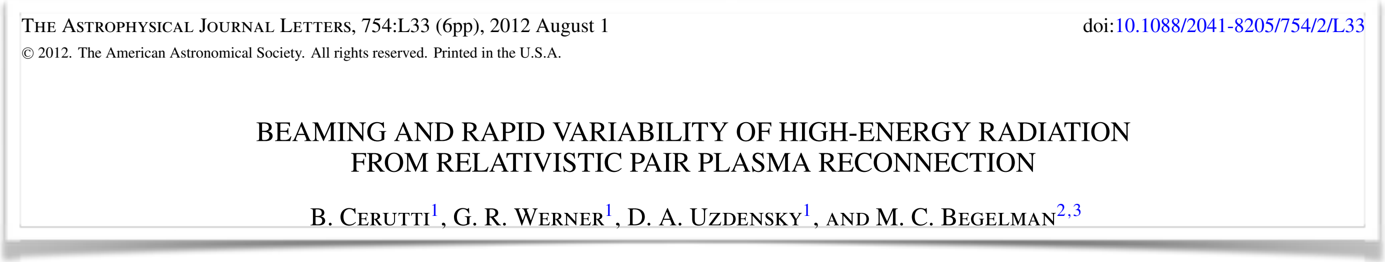


Mon. Not. R. Astron. Soc. **413,** 333–346 (2011) doi:10.1111/j.1365-2966.2010.18140.x

Radiative properties of reconnection-powered minijets in blazars

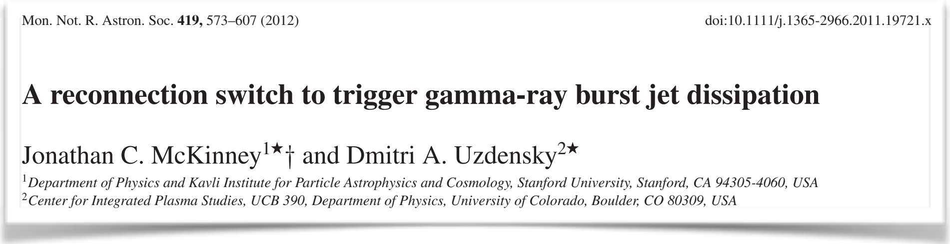
Krzysztof Nalewajko,[1]★ Dimitrios Giannios,[2] Mitchell C. Begelman,[3,4]
Dmitri A. Uzdensky[4] and Marek Sikora[1]



The Astrophysical Journal Letters, 754:L33 (6pp), 2012 August 1 doi:10.1088/2041-8205/754/2/L33

BEAMING AND RAPID VARIABILITY OF HIGH-ENERGY RADIATION FROM RELATIVISTIC PAIR PLASMA RECONNECTION

B. Cerutti[1], G. R. Werner[1], D. A. Uzdensky[1], and M. C. Begelman[2,3]



Mon. Not. R. Astron. Soc. **419,** 573–607 (2012) doi:10.1111/j.1365-2966.2011.19721.x

A reconnection switch to trigger gamma-ray burst jet dissipation

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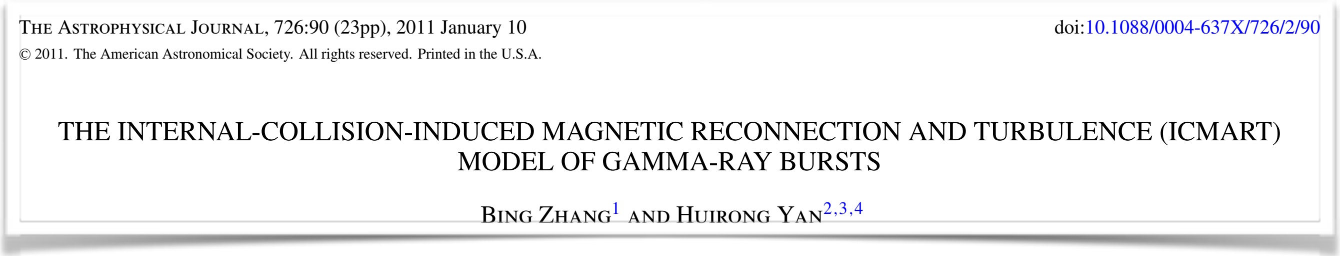
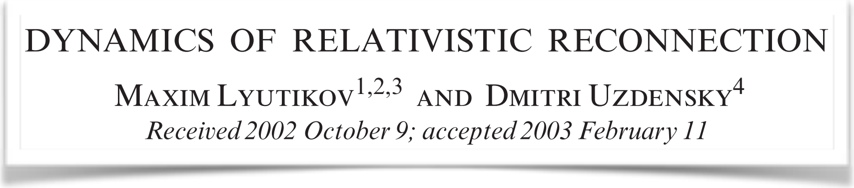


The Astrophysical Journal, 726:90 (23pp), 2011 January 10 doi:10.1088/0004-637X/726/2/90

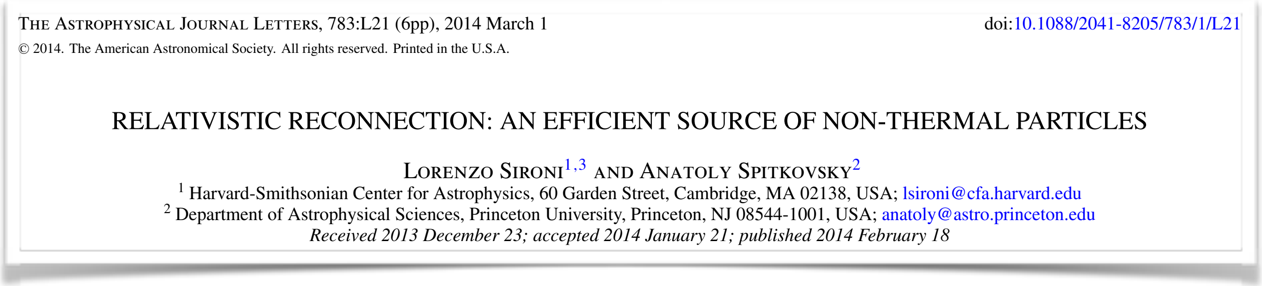
THE INTERNAL-COLLISION-INDUCED MAGNETIC RECONNECTION AND TURBULENCE (ICMART) MODEL OF GAMMA-RAY BURSTS

Bing Zhang[1] and Huirong Yan[2,3,4]



DYNAMICS OF RELATIVISTIC RECONNECTION

Maxim Lyutikov[1,2,3] and Dmitri Uzdensky[4]
Received 2002 October 9; accepted 2003 February 11



The Astrophysical Journal Letters, 783:L21 (6pp), 2014 March 1 doi:10.1088/2041-8205/783/1/L21

RELATIVISTIC RECONNECTION: AN EFFICIENT SOURCE OF NON-THERMAL PARTICLES

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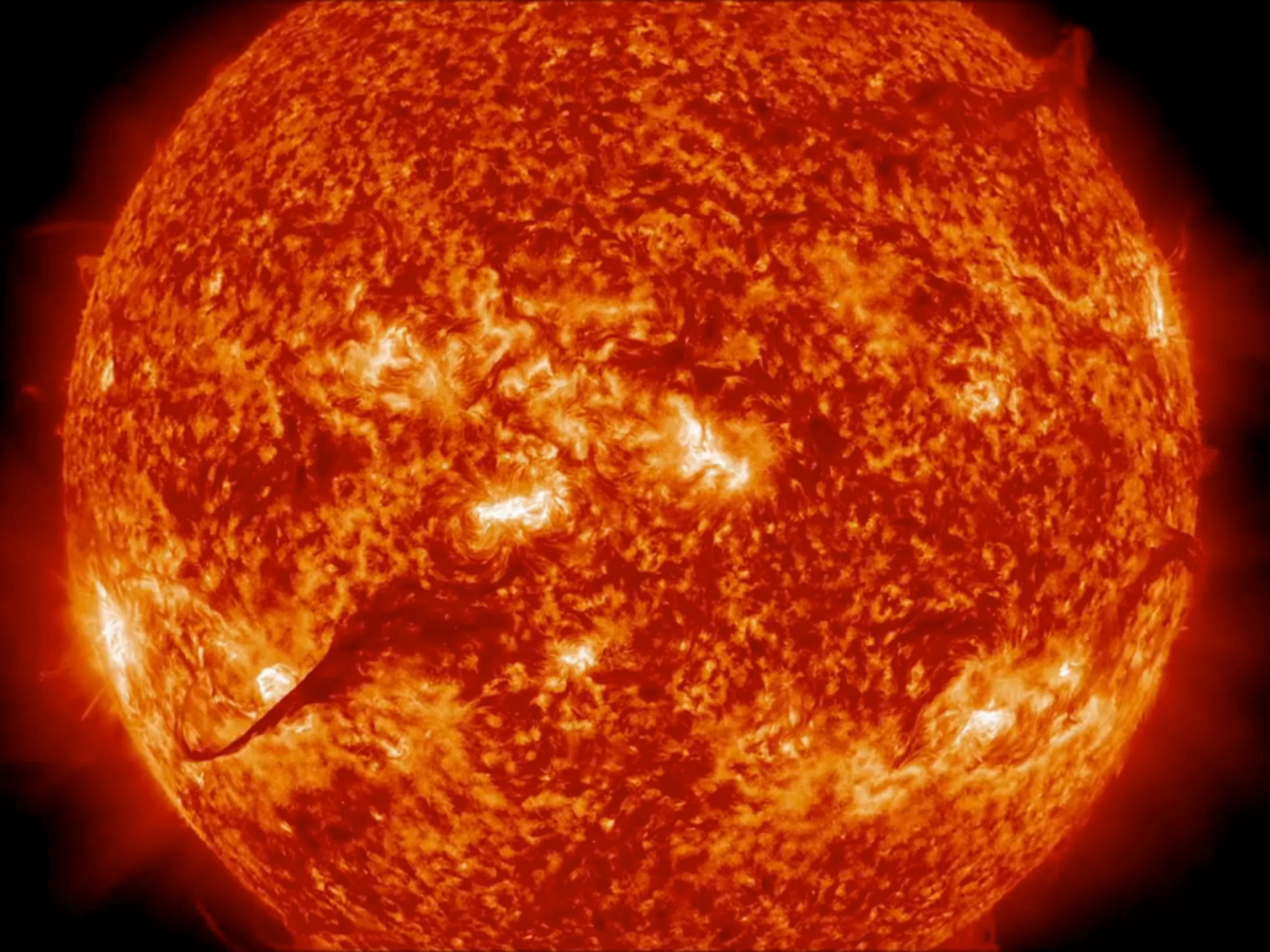
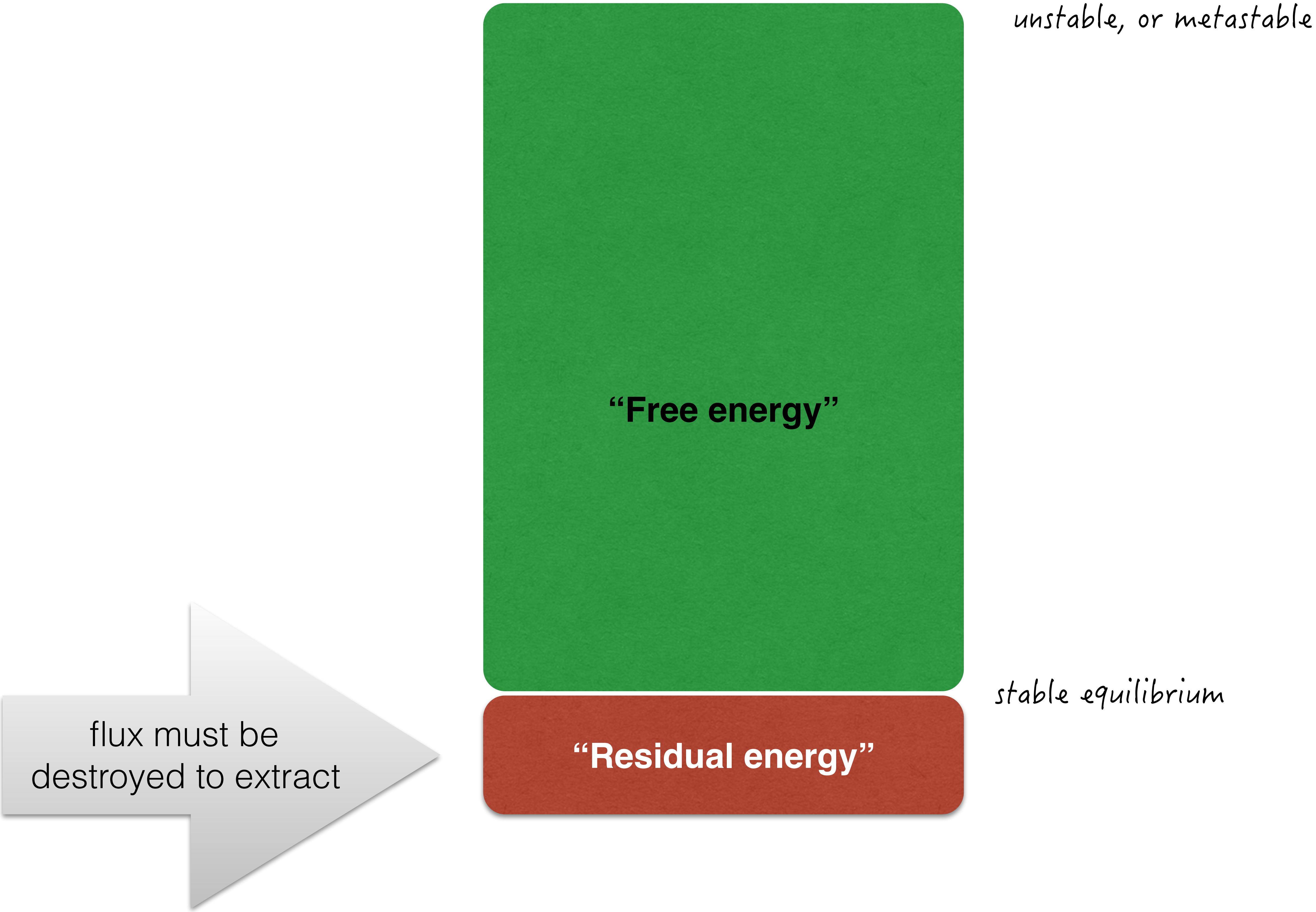


- Critical phenomena (sudden discharge) occurs in near-equilibrium plasma systems (magnetospheres)

- Problem: EM outflows strongly out of equilibrium

Is rapidly variable gamma-ray emission evidence of reconnection / MFrED?

(Note: gamma-ray flares occur within an electromagnetic outflow, far from the central engine.)



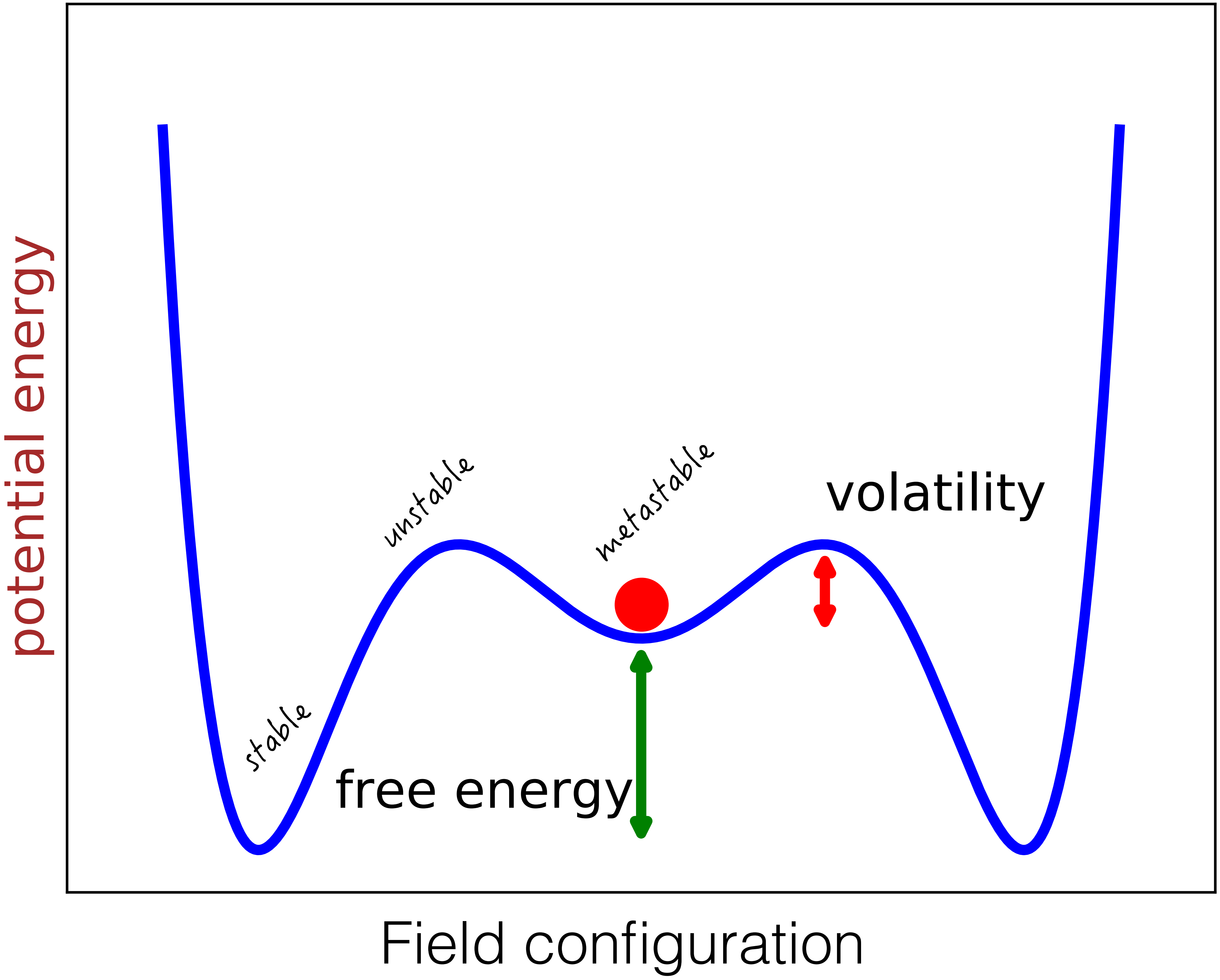
unstable, or metastable

“Free energy”

stable equilibrium

“Residual energy”

flux must be destroyed to extract


potential energy
unstable
metastable
volatility
stable
free energy
Field configuration

$$H = \int \mathbf{A} \cdot \mathbf{B} d^3x$$

$H_m=0$ $H_m=T\Phi^2$ $H_m=\pm 2\Phi_1\Phi_2$

$$\dot{H} = -2\int \mathbf{E}\cdot\mathbf{B}dV$$

Total helicity still *nearly* conserved when non-ideal volumes are *small*.

HOW MUCH ENERGY CAN BE STORED IN A THREE-DIMENSIONAL FORCE-FREE MAGNETIC FIELD?

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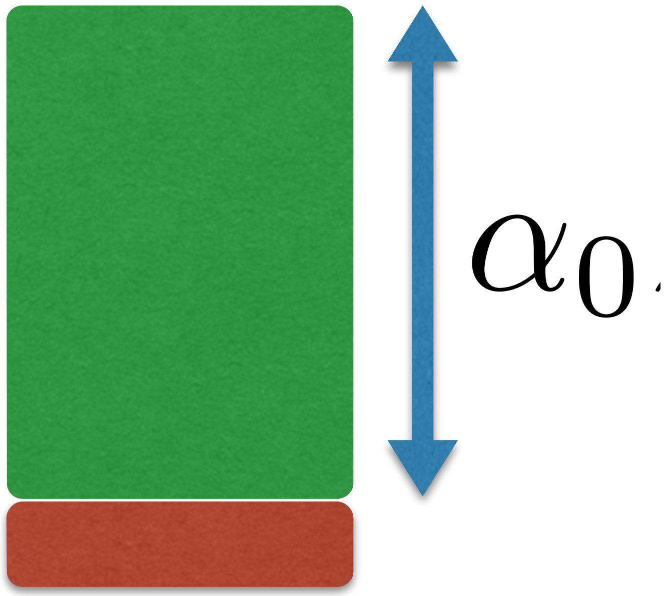
Received 1991 February 28; accepted 1991 April 24

$$\mathbf{B}^{\mathrm{ABC}}(\mathbf{x}) = \begin{pmatrix} B_3 \cos \alpha_0 z - B_2 \sin \alpha_0 y \\ B_1 \cos \alpha_0 x - B_3 \sin \alpha_0 z \\ B_2 \cos \alpha_0 y - B_1 \sin \alpha_0 x \end{pmatrix}$$



Chaotic streamlines in the ABC *flows*

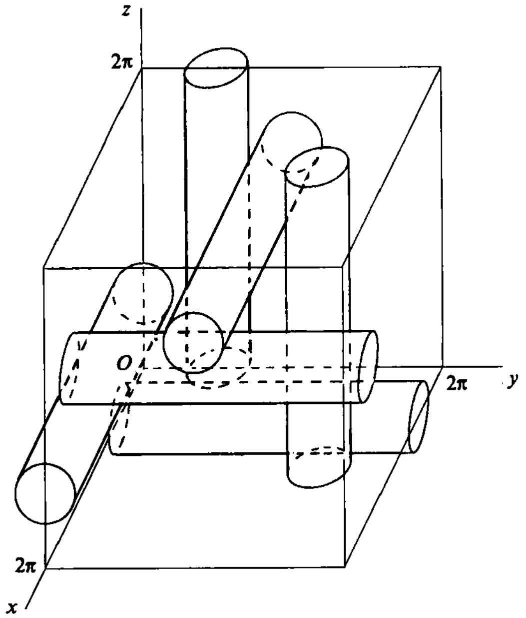


FIGURE 4. Sketch of the six principal vortices.

Stable, or unstable?

Dombre, U. Frisch, J. M. Greene, M. Hénon, A. Mehr and A. M. Soward

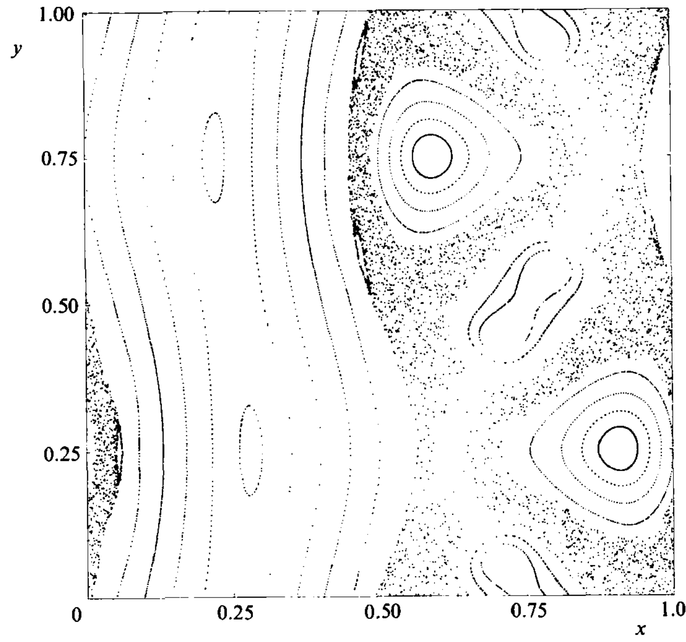
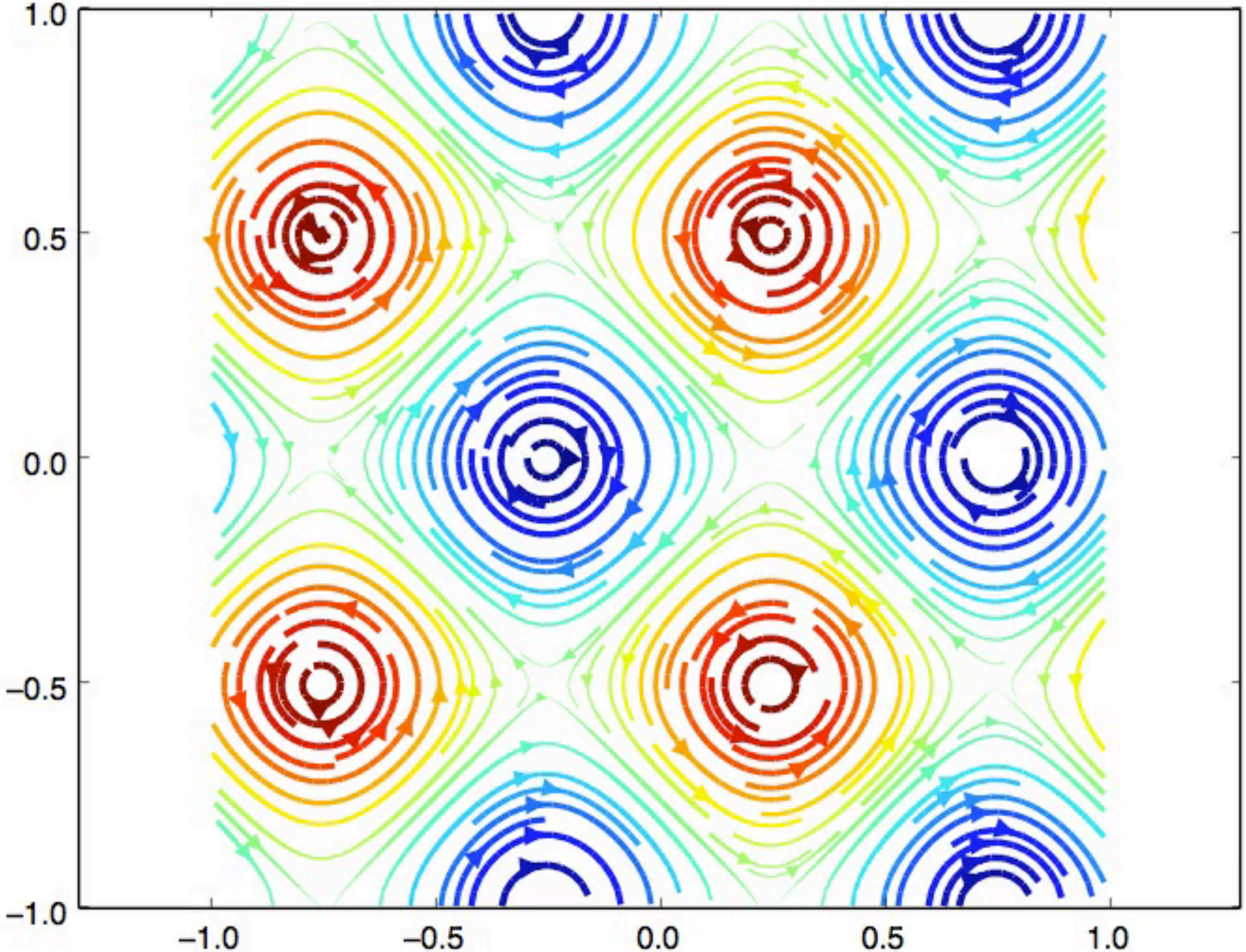


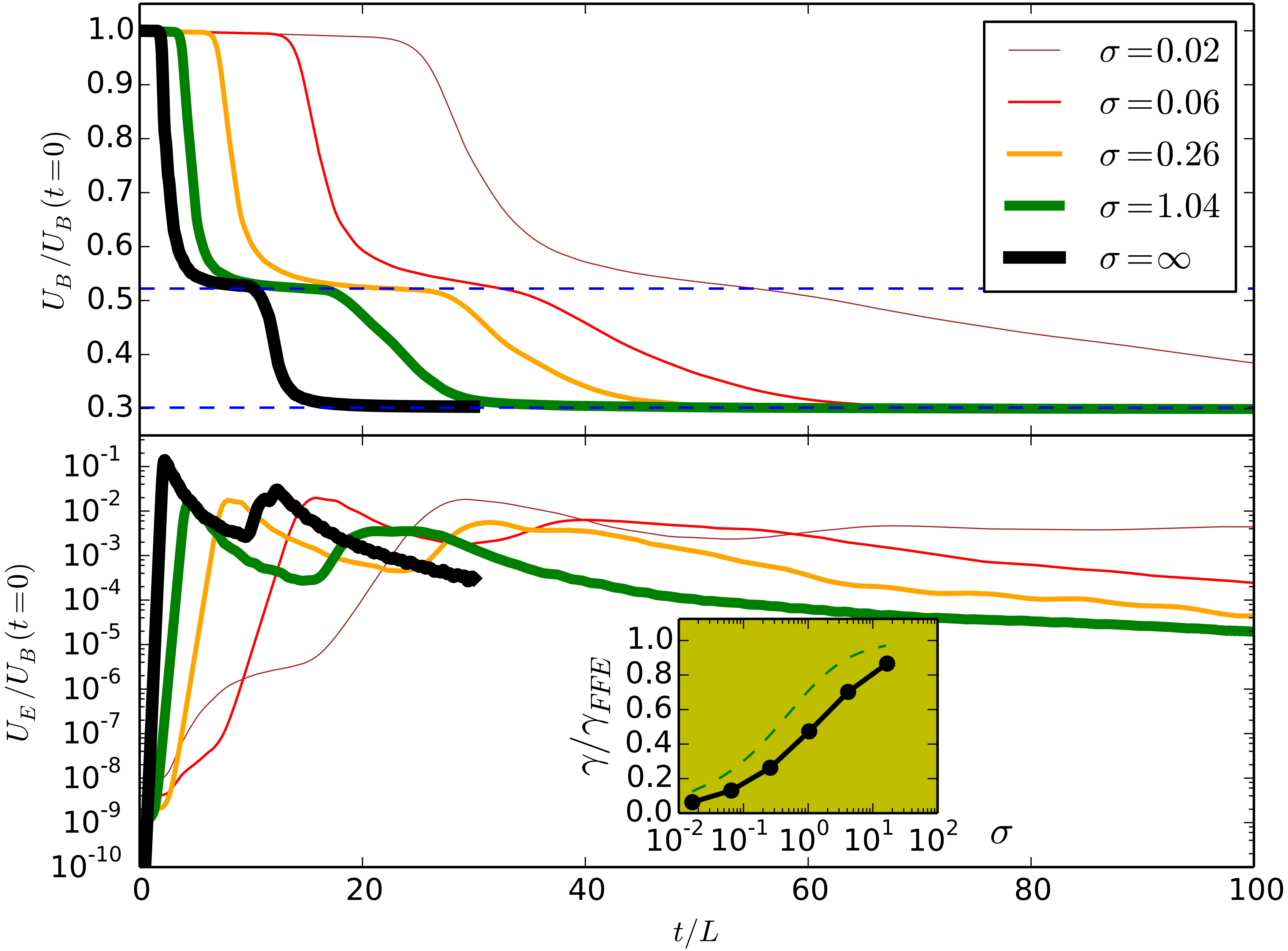
FIGURE 5. A typical Poincaré section, for the case $A^2 = 1$, $B^2 = \frac{2}{3}$, $C^2 = \frac{1}{3}$.

Note: simulations are

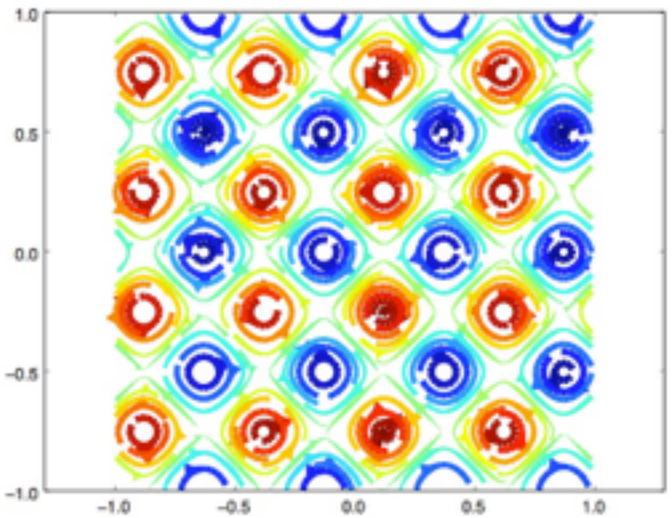
- Relativistic MHD, or
- Force-free electrodynamics (high-sigma)

A/B=1, alpha=2

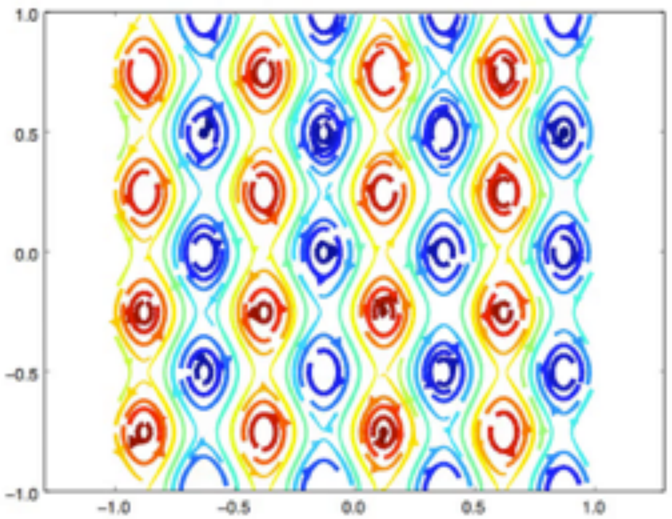



$U_B/U_B(t=0)$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
$\sigma = 0.02$
$\sigma = 0.06$
$\sigma = 0.26$
$\sigma = 1.04$
$\sigma = \infty$
$U_E/U_B(t=0)$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
γ/γ_{FFE}
1.0
0.8
0.6
0.4
0.2
0.0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
σ
0
20
40
60
80
100
t/L

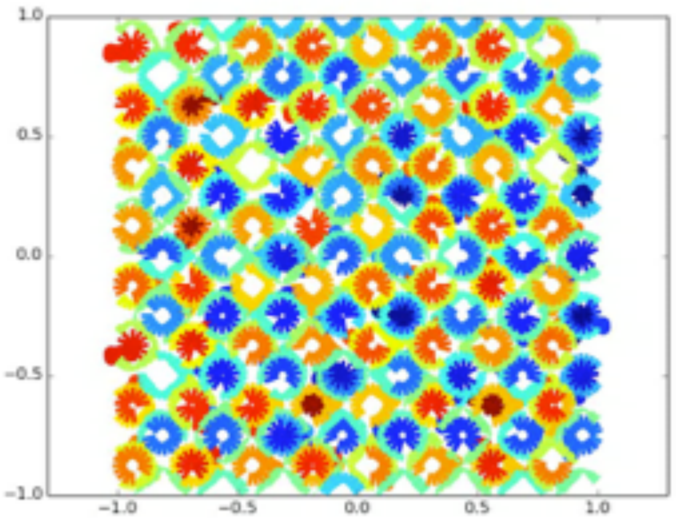
A/B=1, alpha=4



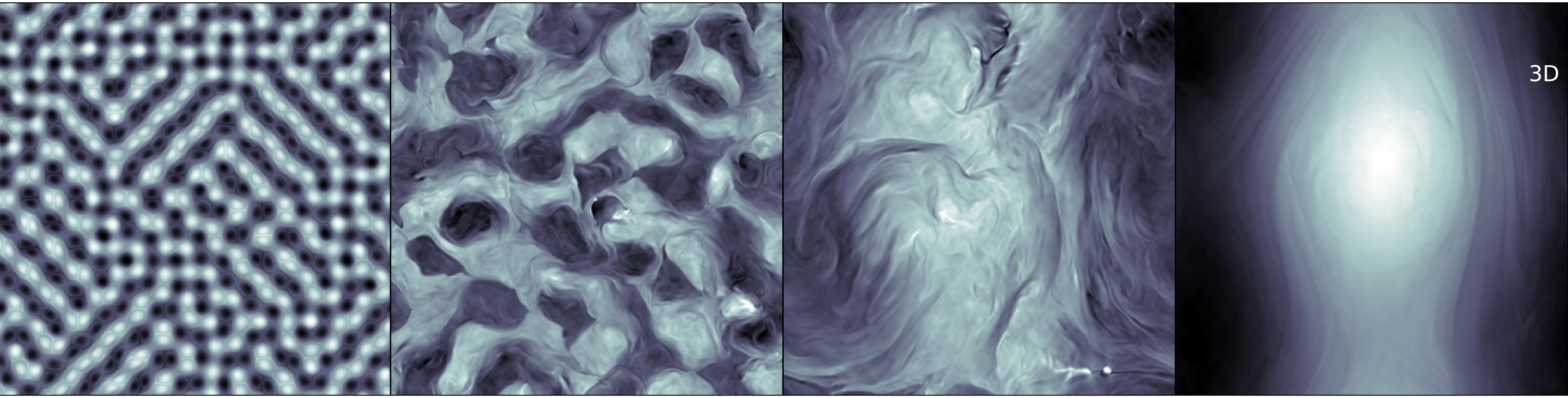
A/B=2, alpha=4



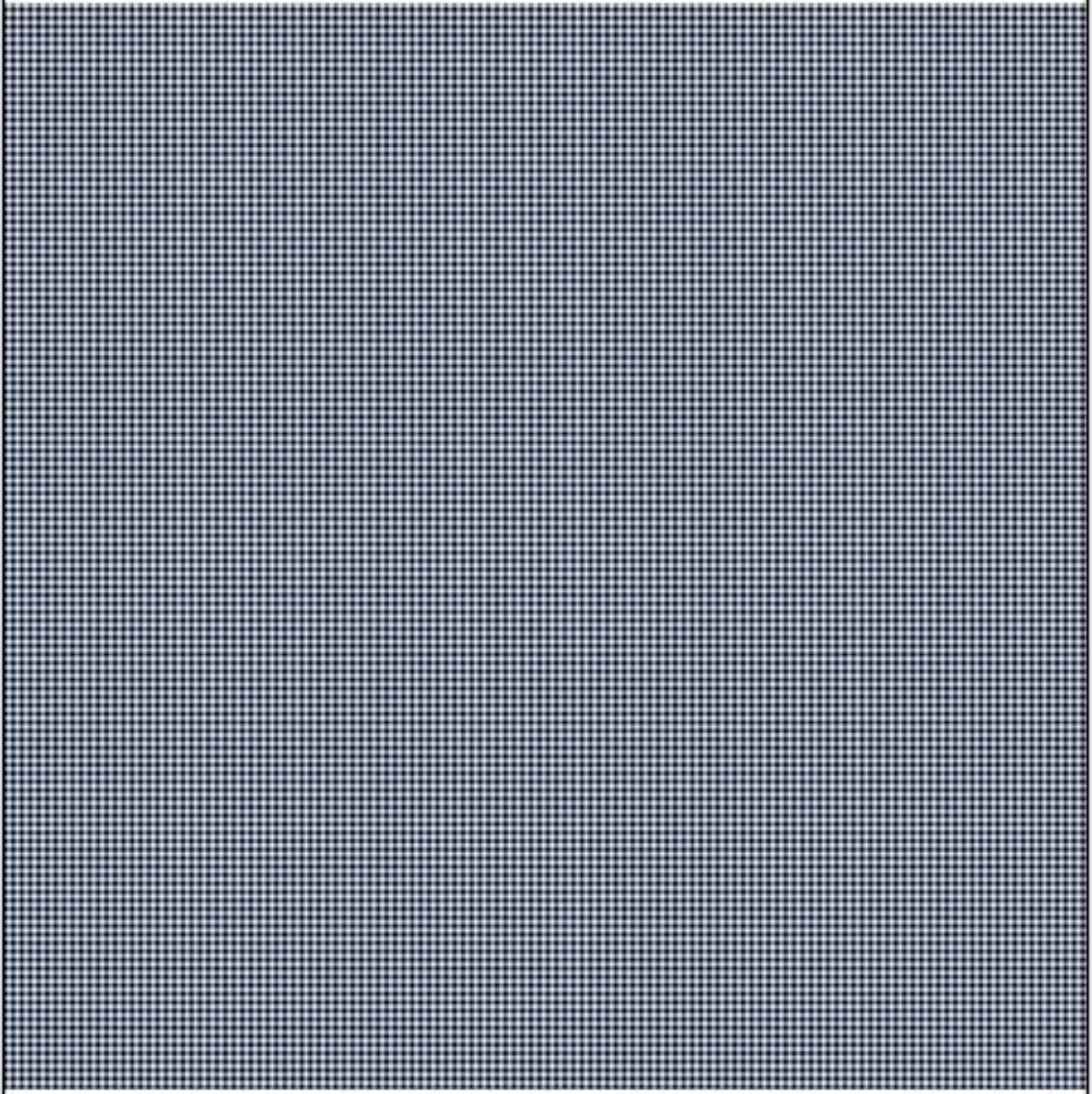
A/B=1, alpha=8



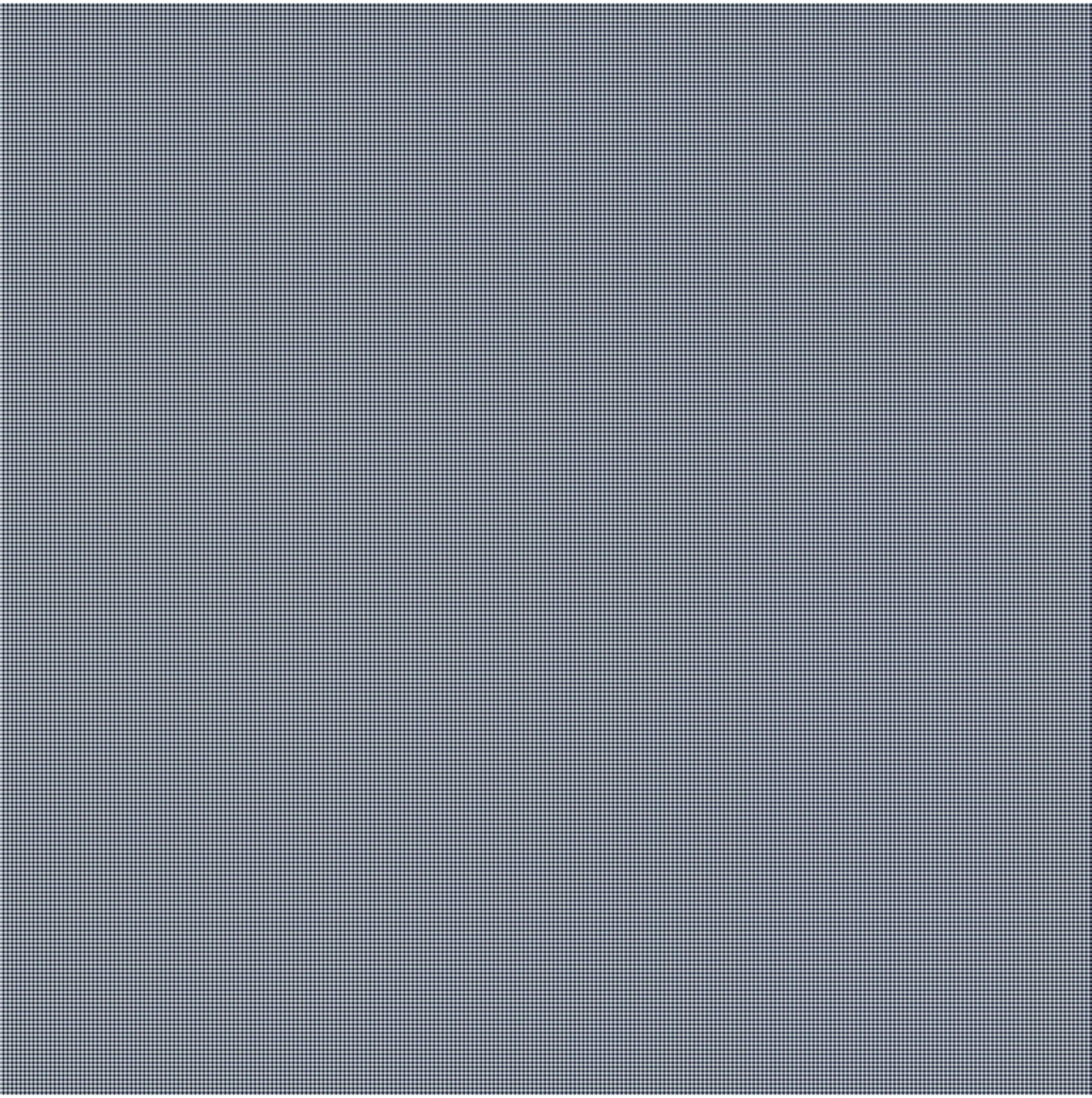
> “Plasma relaxes to the lowest energy state allowed by the total helicity invariant.”
>
> –Taylor (1974)


3D

A/B=1, alpha=128 (RMHD)



A/B=1, alpha=256 (FFE)



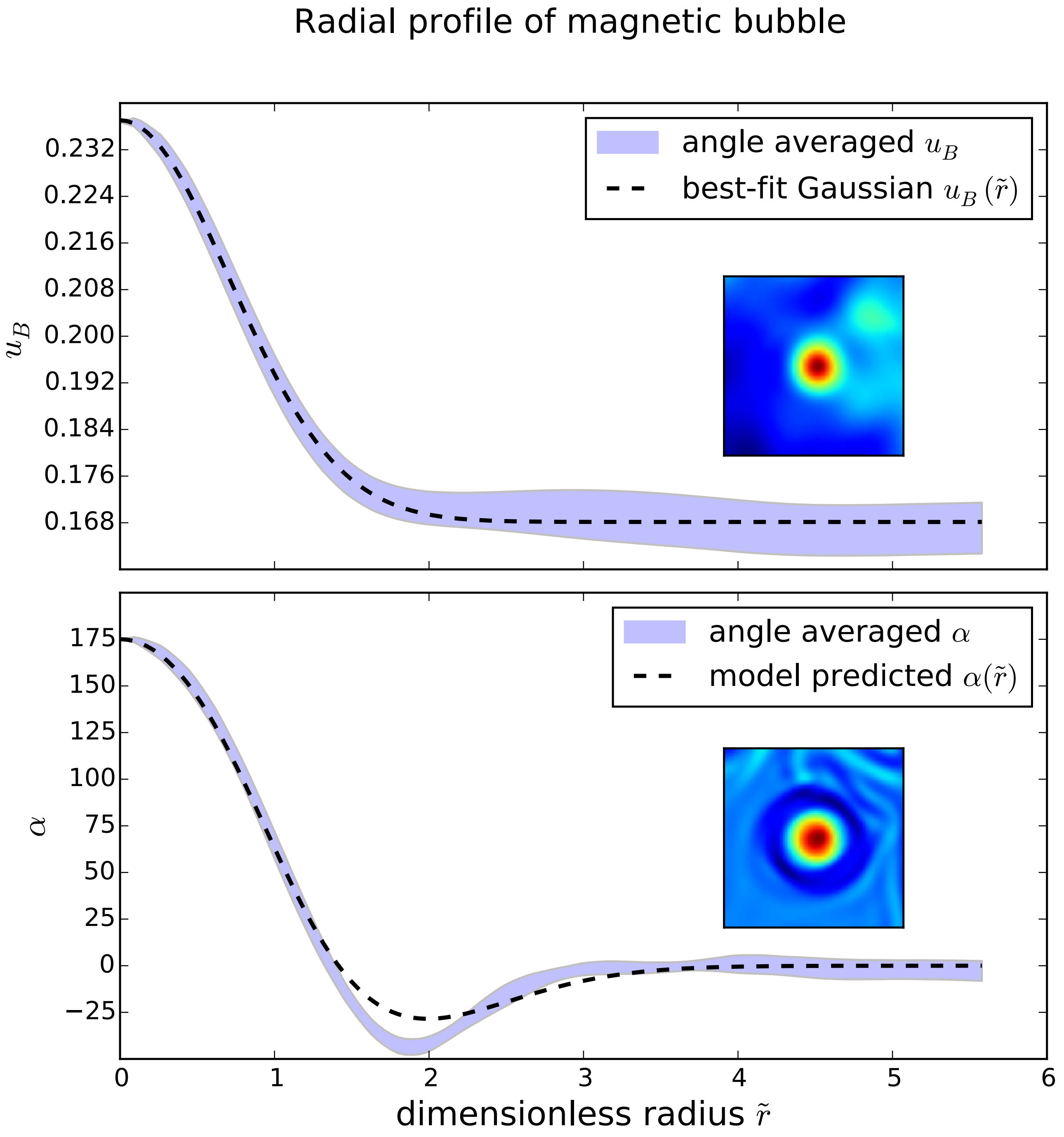


Fig. 7.— **Top** — The magnetic pressure profile of a magnetic bubble in the dimensionless cylindrical radius $\tilde{r} = \alpha_b r$. The blue shaded region indicates the azimuthal standard deviation at each radius from the center, and the dashed line shows the best-fit model parameters for the Gaussian mangetic pressure enhancement given by Equation 15. **Bottom** — The azimuthally averaged value of α along with its predicted value (dashed line) given by Equation 16. The top and bottom insets show two-dimensional relief plots of u_B and α, respectively.

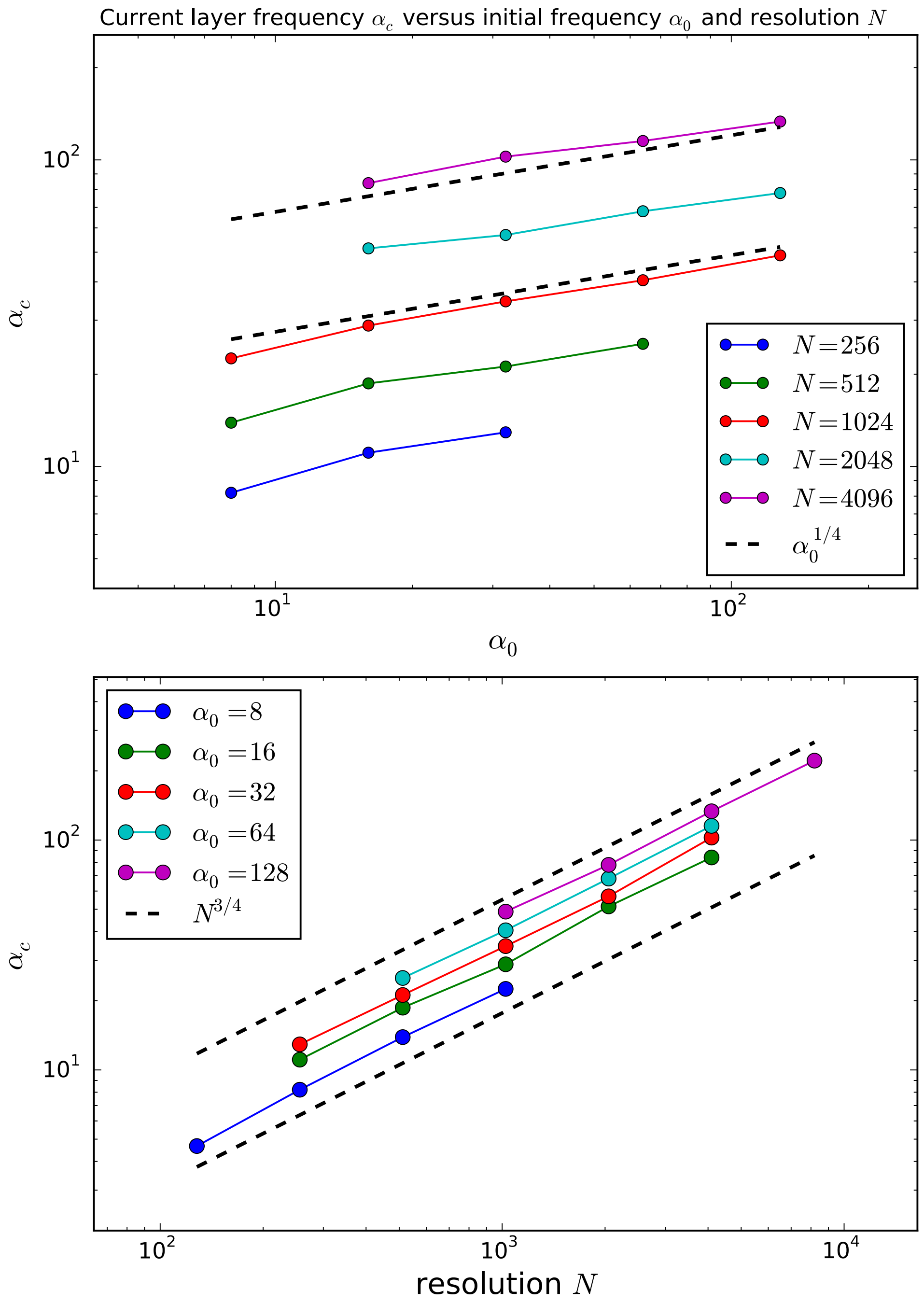


FIG. 5.— Depenency of the current layer frequency α_c on the frequency α_0 of the initial field configuration (top) and the grid resolution N (bottom). α_c is defined to be the second local maximum (other than $\alpha = 0$) in the probability density function $P(\alpha)$, where $\alpha = \mathbf{B} \cdot \nabla \times \mathbf{B}/B^2$.

$$\alpha_c = k_1^{3/4} \alpha_0^{1/4}$$

$$\mathcal{H}(\psi) = \int \Theta(A_z(\mathbf{x}) - \psi)\mathbf{A} \cdot \mathbf{B} d^3 x$$

> “Taylor conjecture is satisfied only in 3D.”

–Zrake & East (2015)

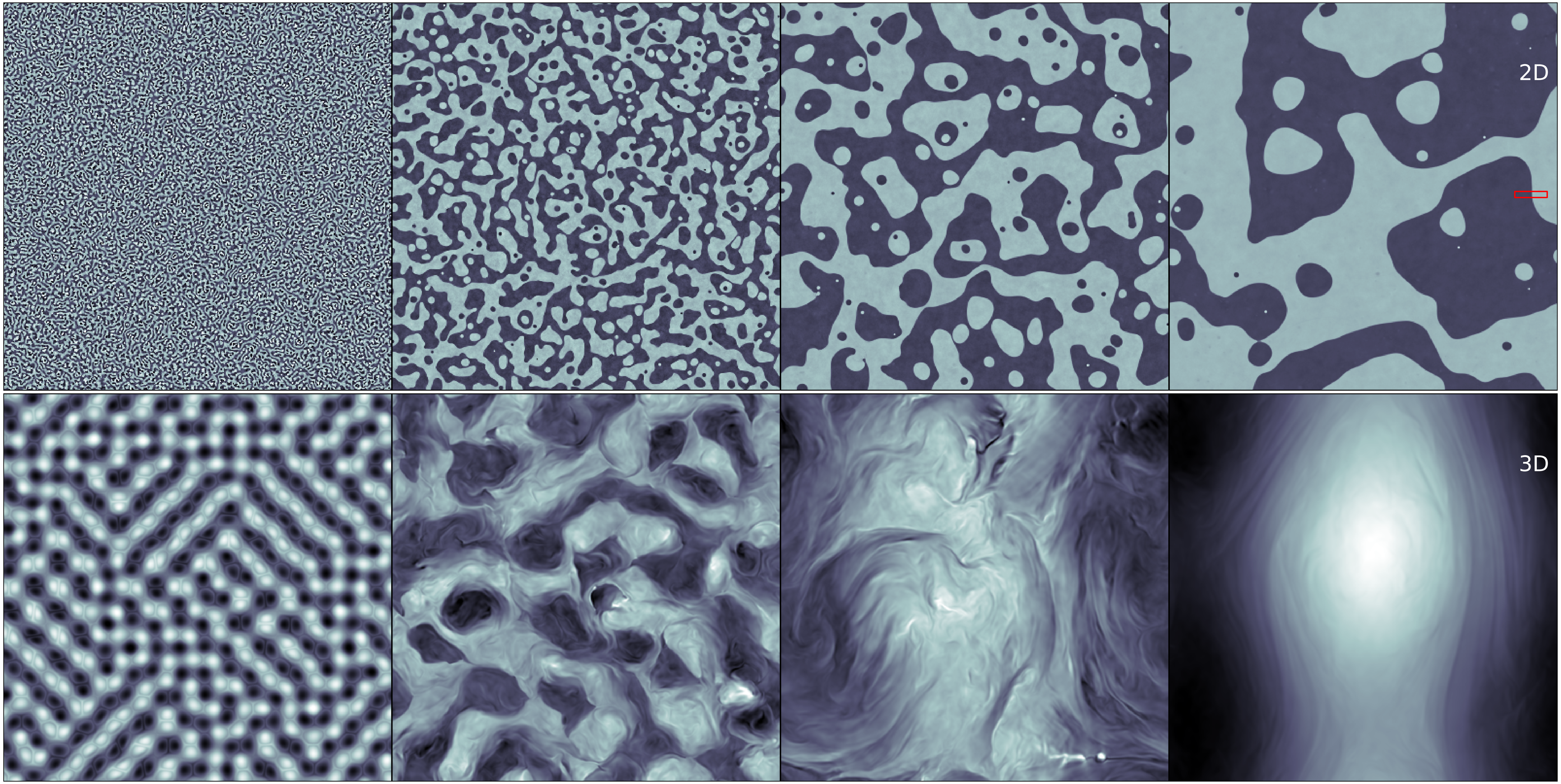
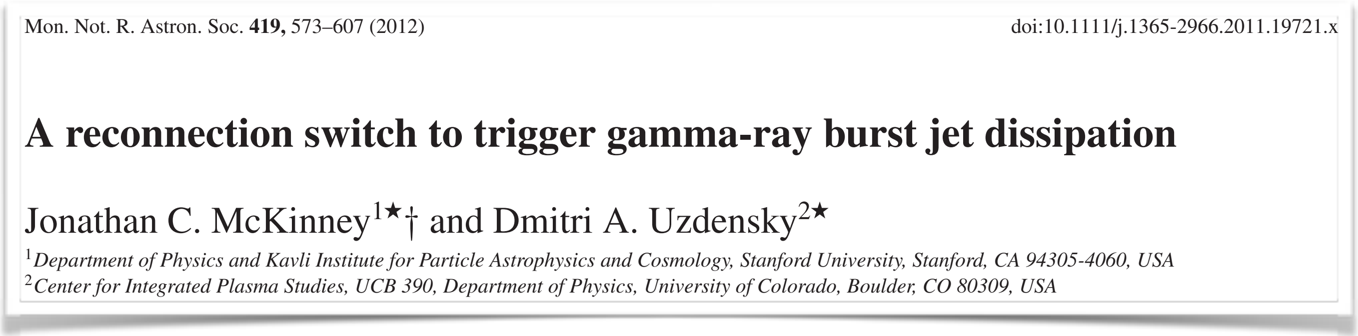


FIG. 1.— **Top**: Two-dimensional turbulent relaxation in force-free electrodynamics at logarithmically spaced times ($t = 0.08, 0.32, 1.28, 5.12$). The initial condition is the $\alpha_0 = 256$ ABC field with $B_1 = 1, B_2 = 1, B_3 = 0$ and grid resolution 3072^2. Shown is the out-of-plane magnetic field component scaled linearly between the initial minimum and maximum values. The small red rectangle overlying the right-most panel is the region shown amplified in Figure 2. The end-state is not a linear force-free equilibrium. **Bottom**: Three-dimensional turbulent relaxation under the same conditions except that $\alpha_0 = 16$, the grid resolution is 512^3, and the times $t = 0.625, 1.0, 3.0, 16.0$ are chosen to elucidate the sequence of decay epochs. The color mapping accomodates the instantaneous data range, as it decreases appreciably throughout the decay. The end-state is a linear force-free equilibrium with $\alpha = 1$.



Mon. Not. R. Astron. Soc. **419,** 573–607 (2012) doi:10.1111/j.1365-2966.2011.19721.x

A reconnection switch to trigger gamma-ray burst jet dissipation

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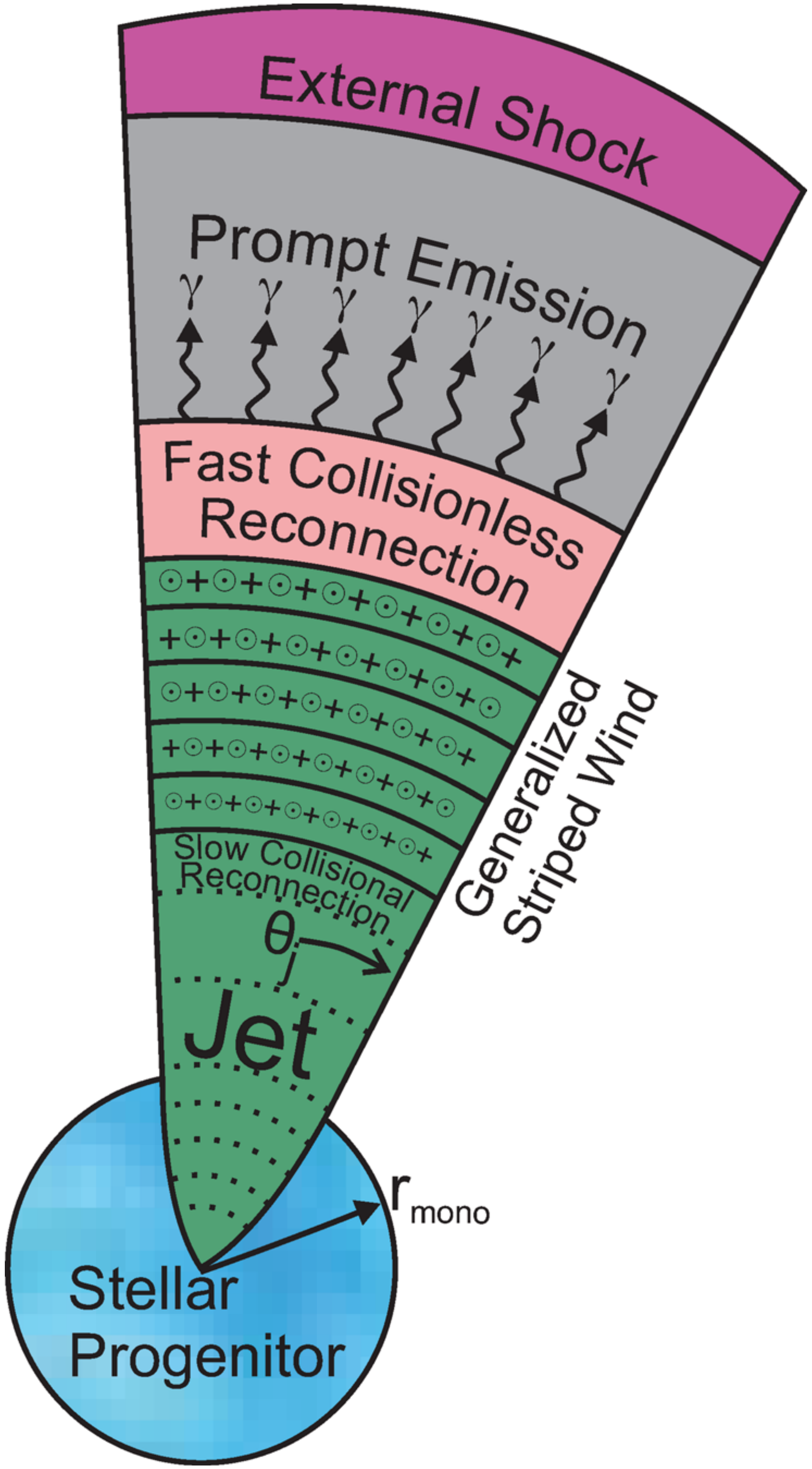
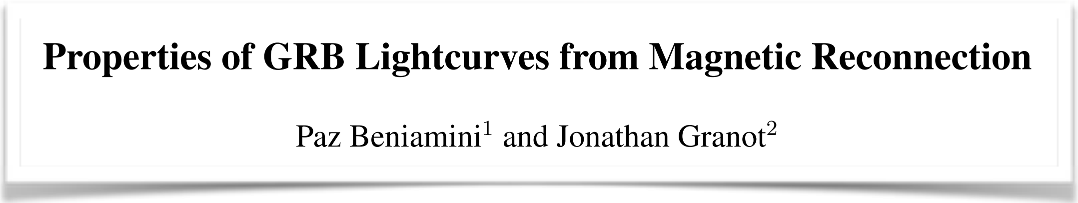
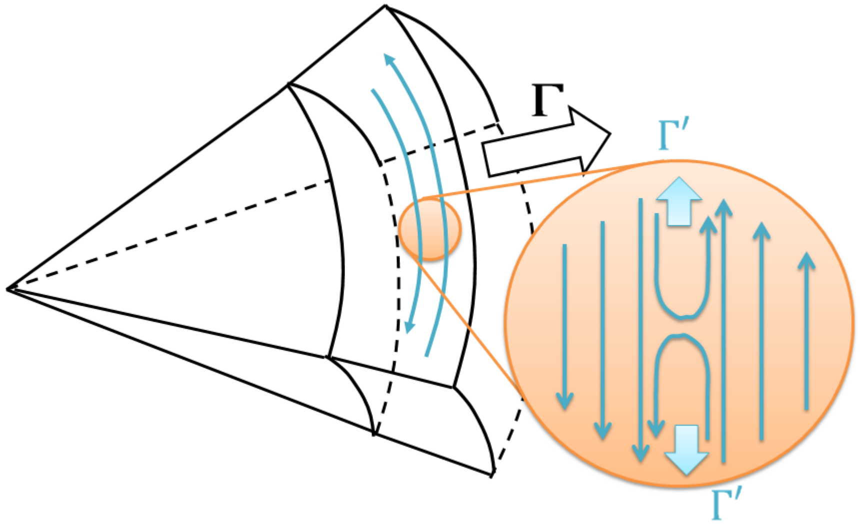




Properties of GRB Lightcurves from Magnetic Reconnection

Paz Beniamini[1] and Jonathan Granot[2]



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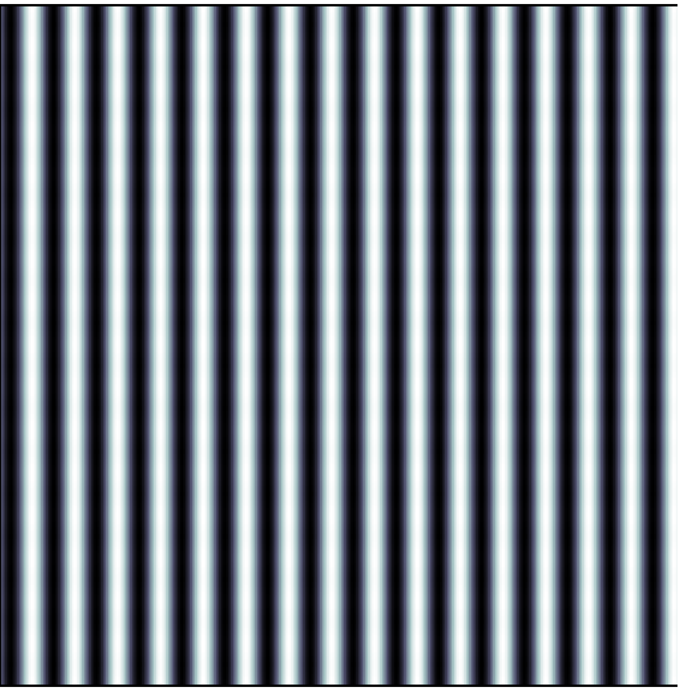


“striped wind in co-moving frame”

(really, it’s an ABC field with small B and C=0)

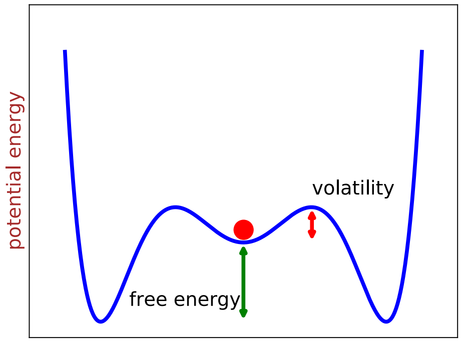
This suggests that “MFrED” could power the prompt emission, but onset is controlled by causality, not microphysics.

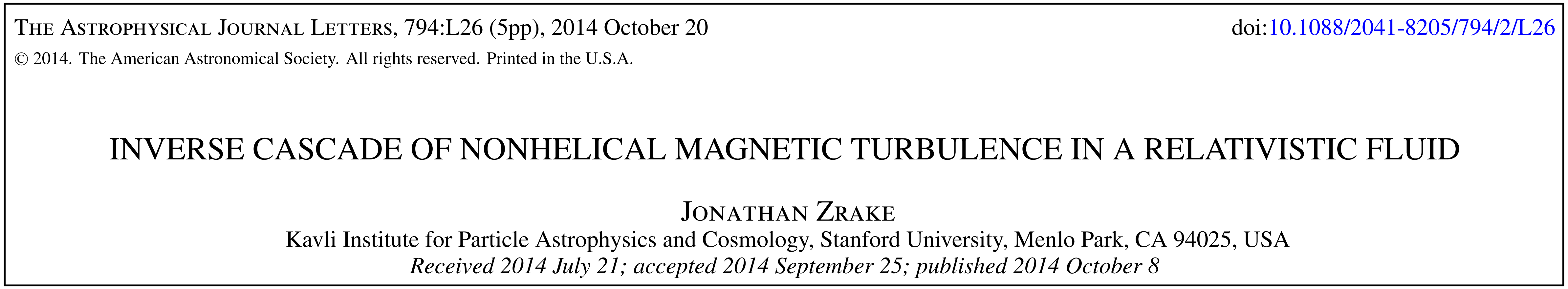
Conclusions

- “Excited” Taylor states are unstable
- Current-layers are *not* generic in highly magnetized plasma without walls (3D)
- 2D is very different (we know this)
- Magnetic *free* energy dissipation is universal; no Lundquist number dependence

More conclusions

- Strongly magnetized plasma promptly attains a minimally dissipative state, unless forced
- No metastable hydromagnetic equilibria? Is this true?





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INVERSE CASCADE OF NONHELICAL MAGNETIC TURBULENCE IN A RELATIVISTIC FLUID

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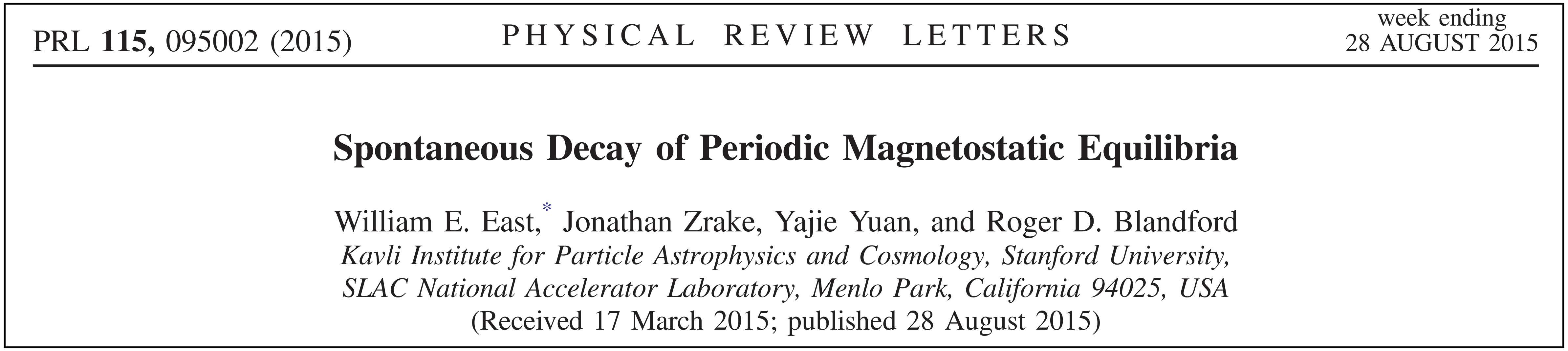

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Spontaneous Decay of Periodic Magnetostatic Equilibria

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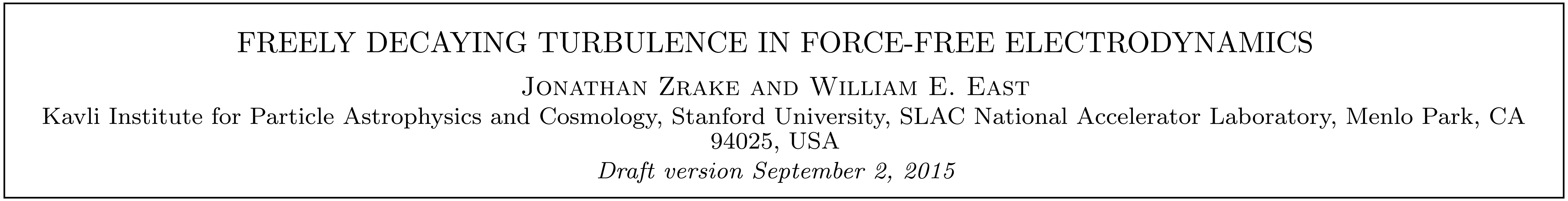

FREELY DECAYING TURBULENCE IN FORCE-FREE ELECTRODYNAMICS

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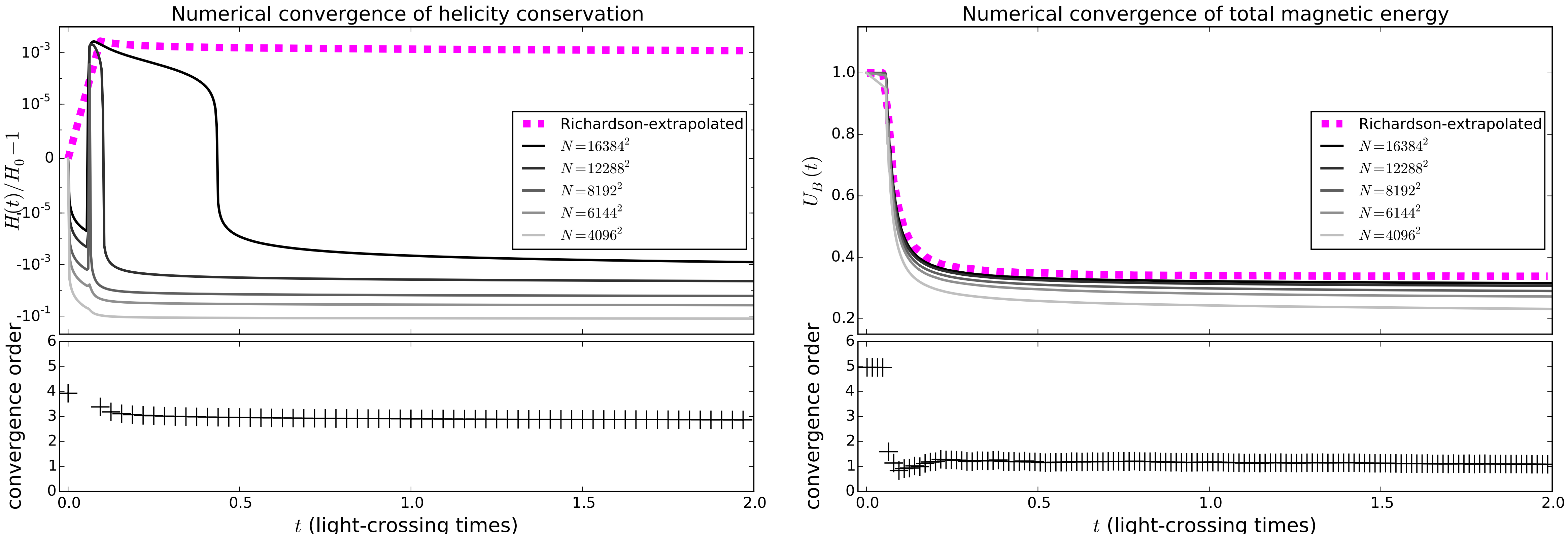

Fig. 11.— **Left** - Error in the conservation of magnetic helicity H. The upper panel shows the fractional helicity change $\Delta h(t) = H(t)/H_0 - 1$ on symmetric logarithmic axes (to account for anomolous helicity change of either sign) for six different values of the mesh spacing h. The dashed magneta line shows the Richardson-extrapolated value of $\Delta h(t)$, which remains constant at roughly 10^{-3}. The lower panel shows the convergence order of $\Delta h(t)$ at representative times. **Right** - Evolution of the total magnetic energy $U_B(t)$ for the same six values of the mesh spacing. The dashed magenta line on the upper panel shows the Richardson-extrapolated time series of $U_B(t)$, and the convergence order is shown on the lower panel.