Plasma Dynamo At Last?

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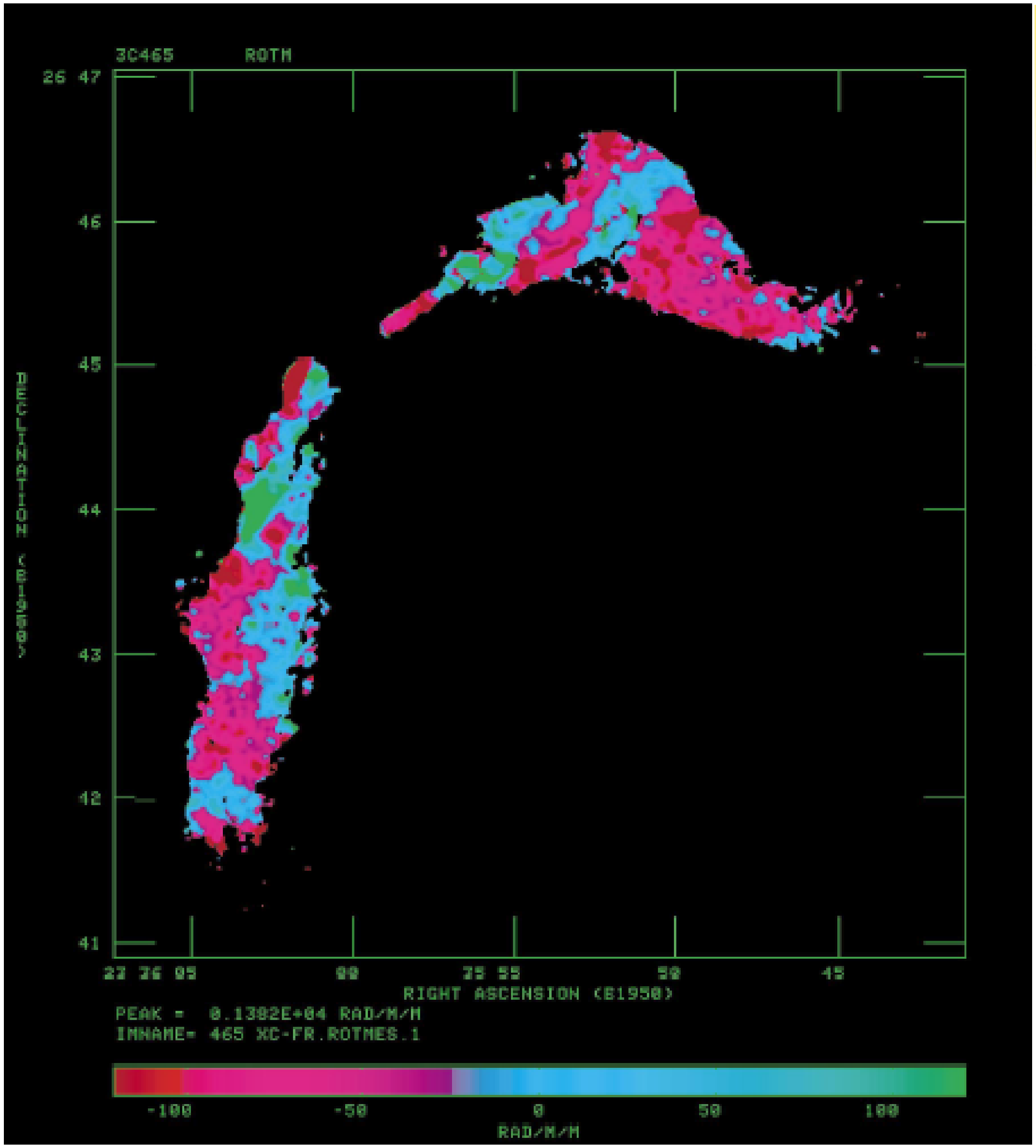
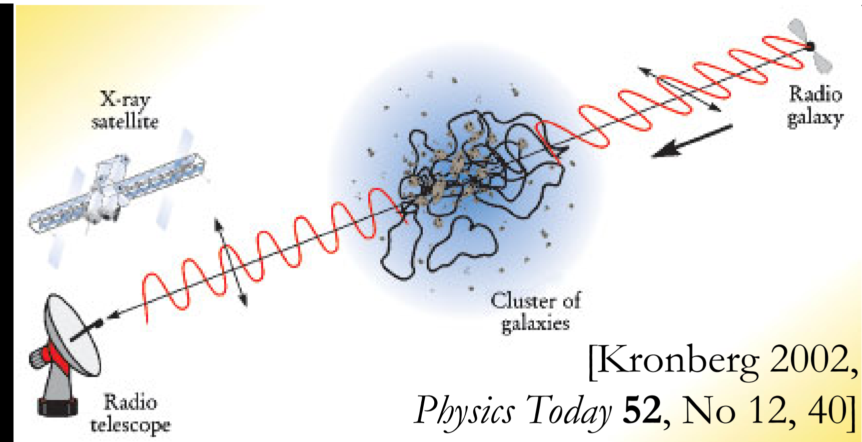
F. Rincon (Toulouse), F. Califano (Pisa), F. Valentini (Calabria),
M. Kunz, J. Stone (Princeton), S. Melville (Harvard),
P. Helander (Greifswald), M. Strumik (Oxford)

Rincon, Califano, AAS, Valentini, *PNAS* in press (2016) [arXiv:1512.06455]
Melville, AAS, Kunz, *MNRAS* in press (2016) [arXiv:1512.08131]
Rincon, AAS, Cowley, *MNRAS* **447**, L45 (2015)
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)
AAS et al., *PRL* **100**, 184501 (2008); Rosin et al., *MNRAS* **413**, 7 (2011)
Tzeferacos et al., in preparation (2016); Meinecke et al., *PNAS* **112**, 8211 (2015)
AAS et al., *NJP* **9**, 300 (2007); AAS et al., *ApJ* **612**, 276 (2004)

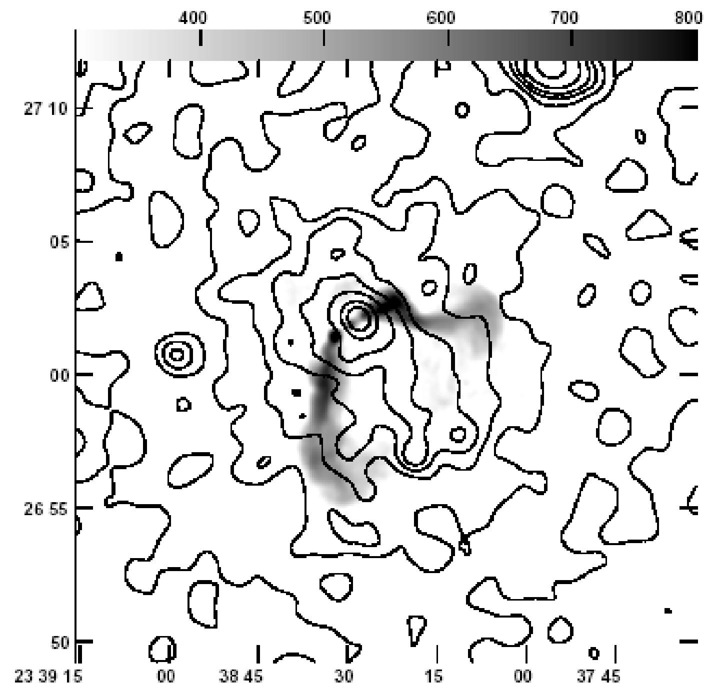
Cosmic Magnetism



[**Abell 2634 cluster**, Eilek & Owen 2002, *ApJ* **5267**, 202]

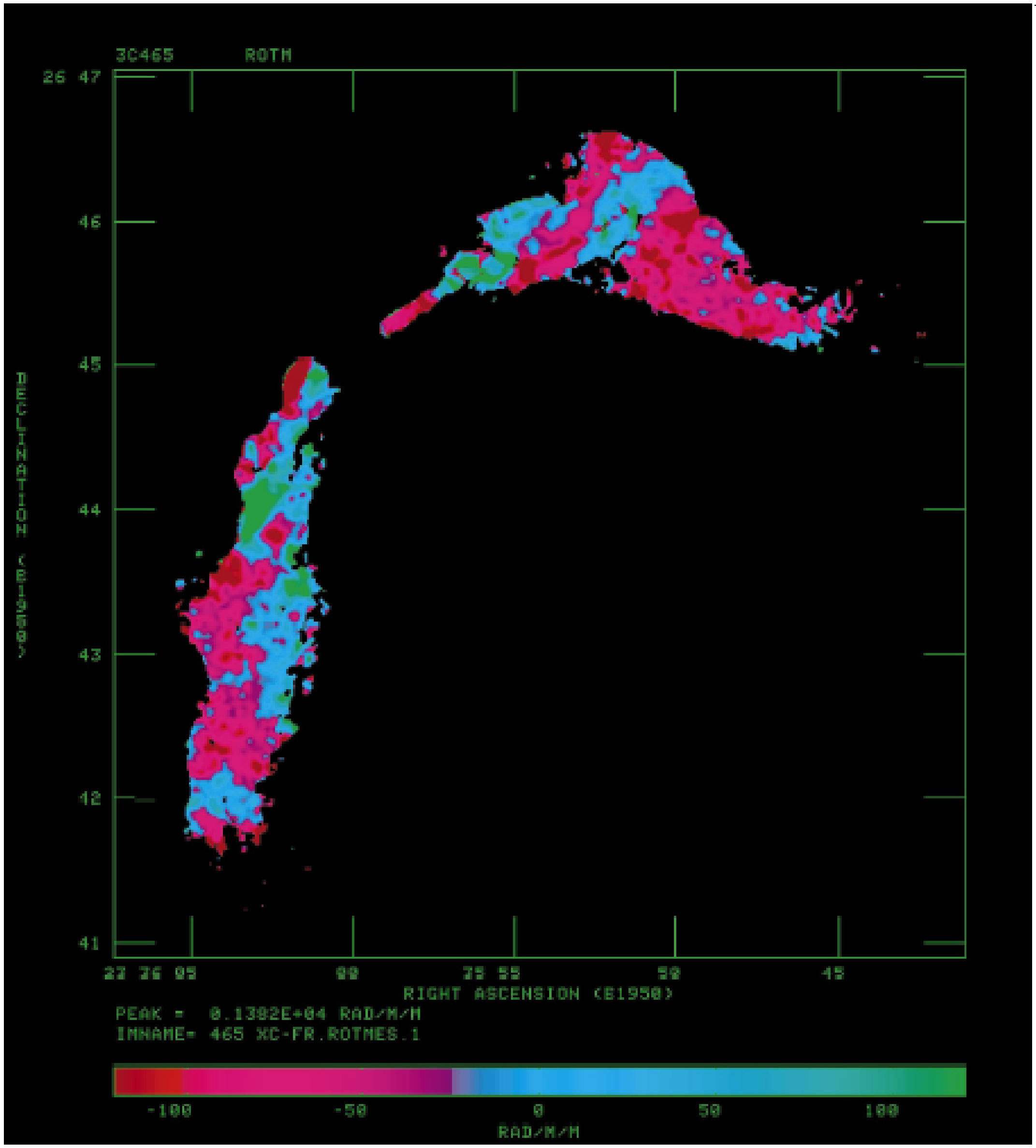


[Kronberg 2002,
Physics Today **52**, No 12, 40]



900 kpc

Cosmic Magnetism



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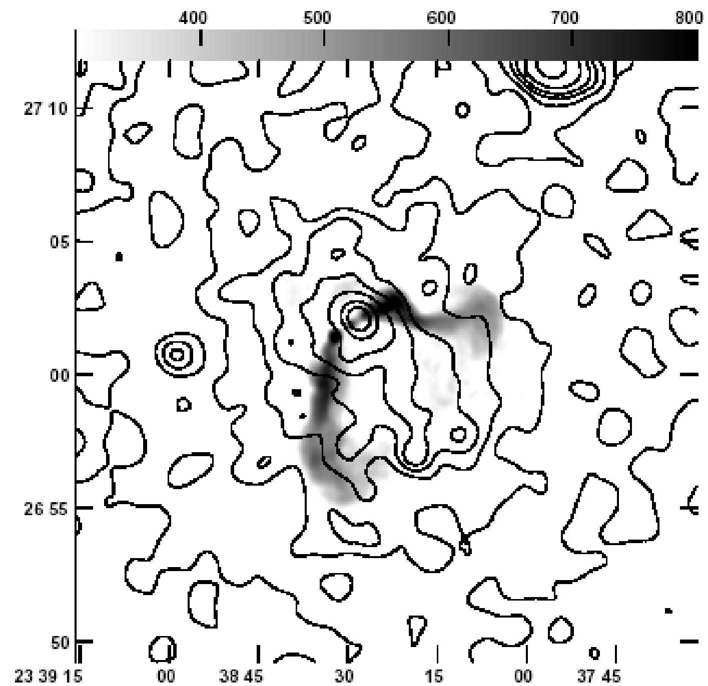
Typically,

$$B \sim 10^{-6}\ \mathrm{G}, \quad \beta \sim 10^2$$

Crucially (imho),

$$\frac{B^2}{8\pi} \sim \frac{\rho u^2}{2}$$



900 kpc

Turbulence Makes the Field

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

This equation is linear in **B**, so field will either decay to zero or grow to dynamical strength. Probably the latter.

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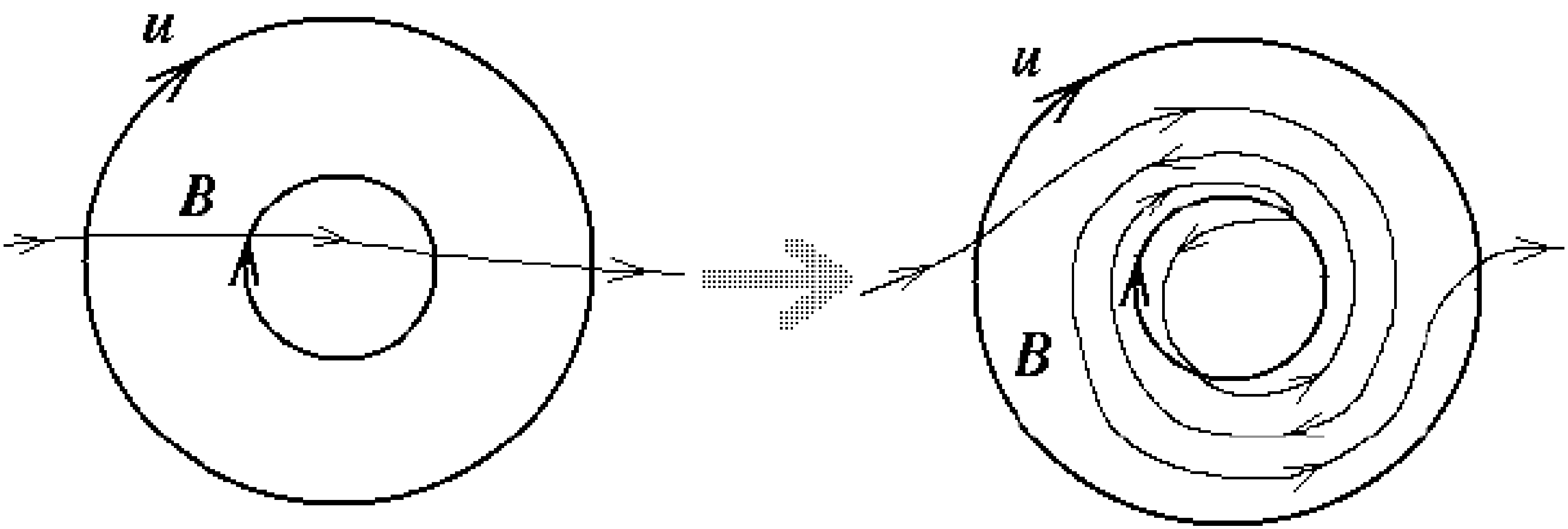


Straight field

Folded field

Turbulent Dynamo: Theory

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \cancel{\eta \nabla^2 \mathbf{B}}$$

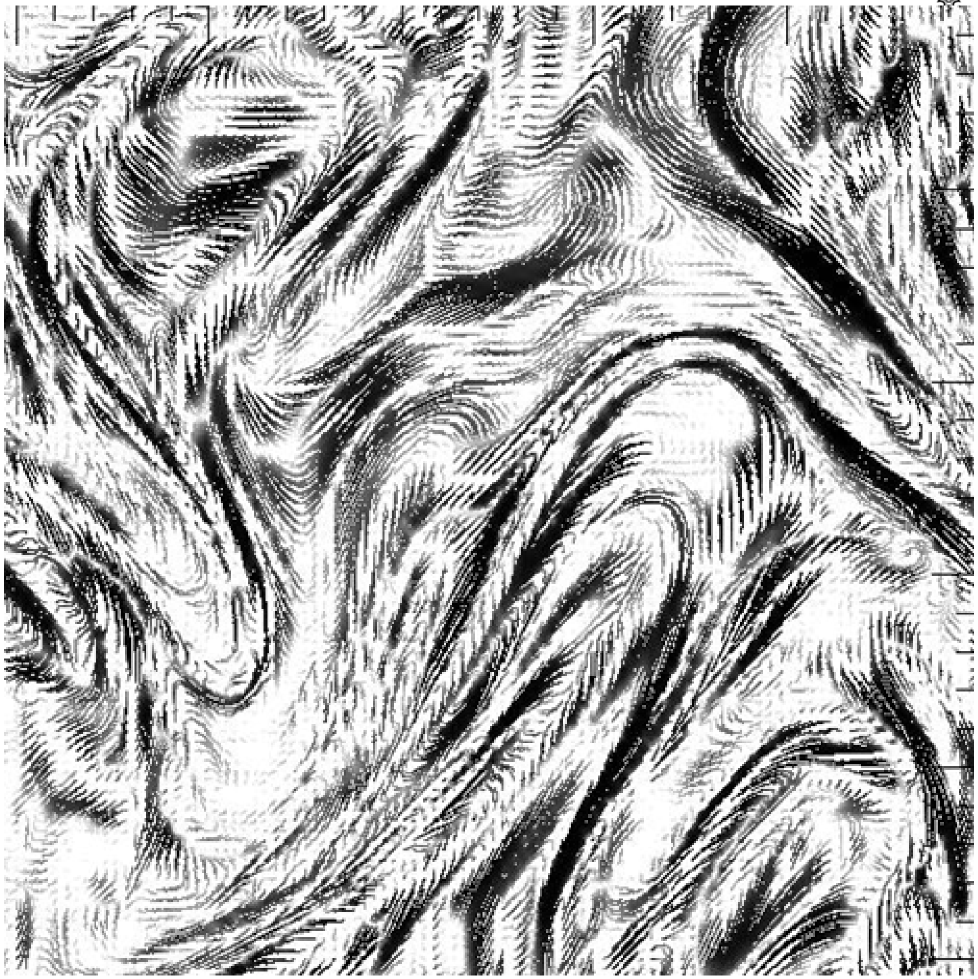
All you need is a chaotic flow

Basic idea:

$$\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t} \equiv \frac{\partial \mathbf{B}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{B} = \mathbf{B} \cdot \nabla \mathbf{u}$$

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla \mathbf{u}) B \equiv \gamma B$$

$$\ln B \sim \int^t \mathrm{d}t' \, (\mathbf{bb} : \nabla \mathbf{u})(t')$$



So, roughly, field in Lagrangian frame accumulates as random walk

AAS et al., *ApJ* **612**, 276 (2004)

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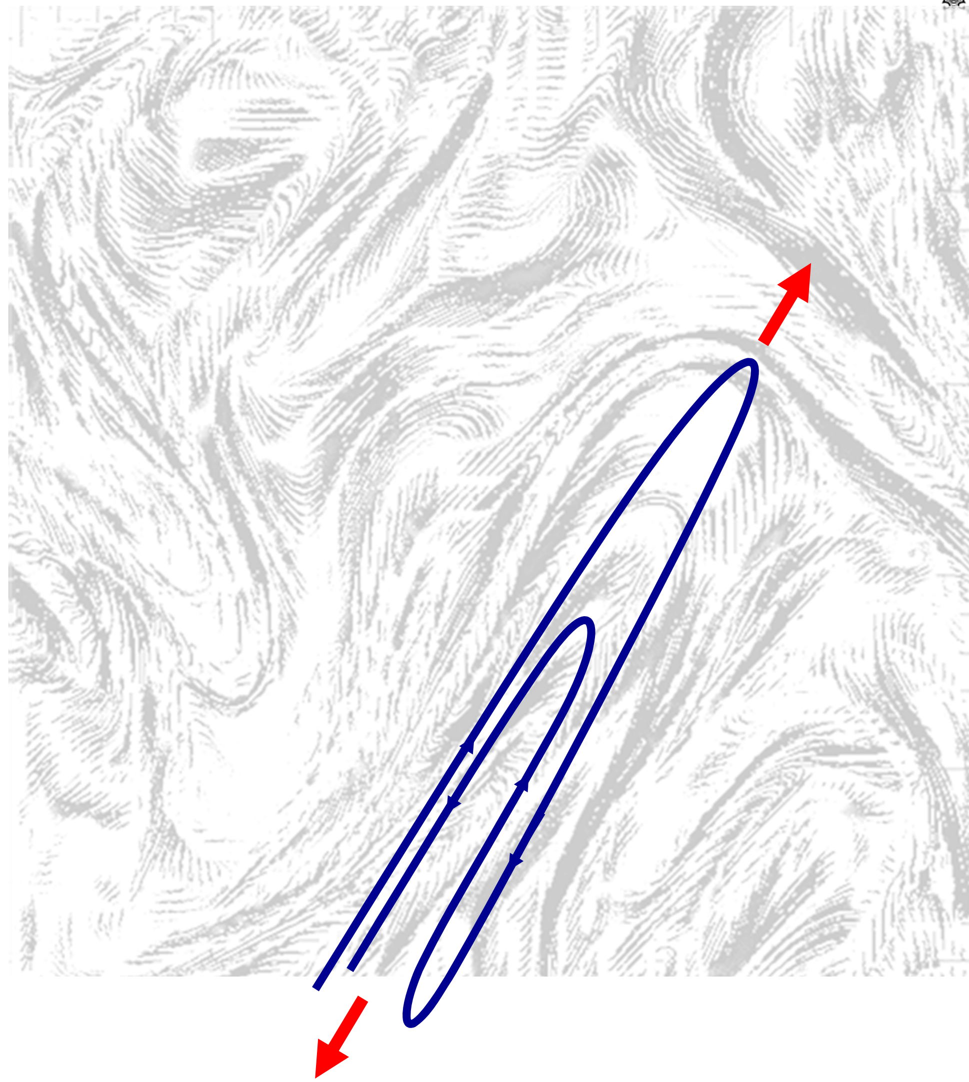

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Key effect: a succession of random stretchings (and un-stretchings)

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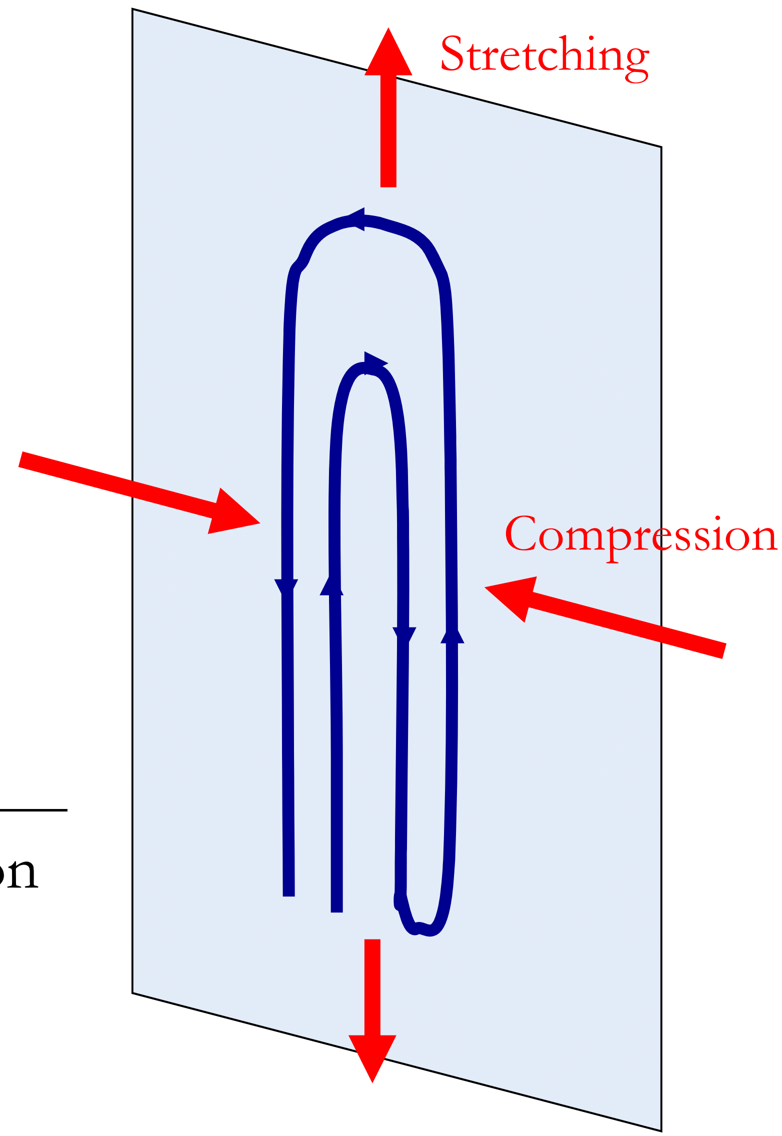

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla \mathbf{u}) B \equiv \gamma B$$

Nuance: naïve stretching-compression scenario would lead to destruction of the field (and does, in 2D)

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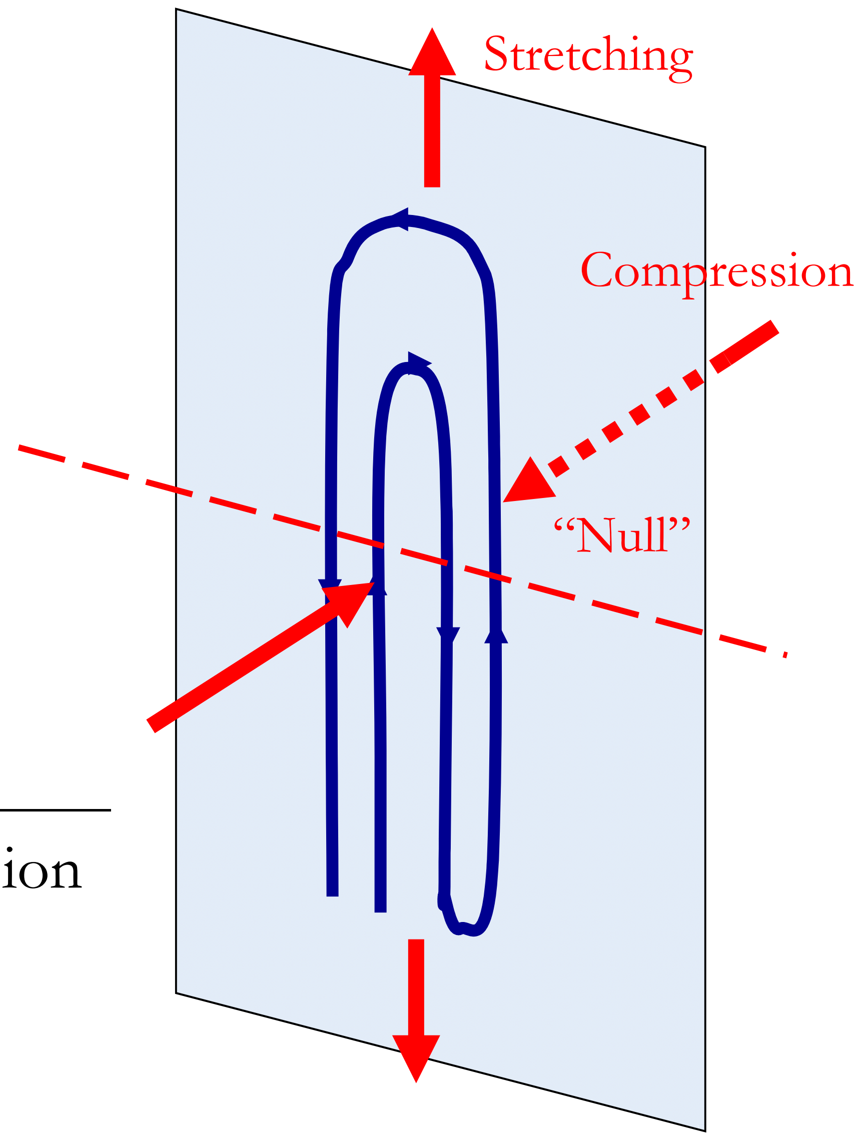
In 3D, surviving folds are in the stretching-null plane



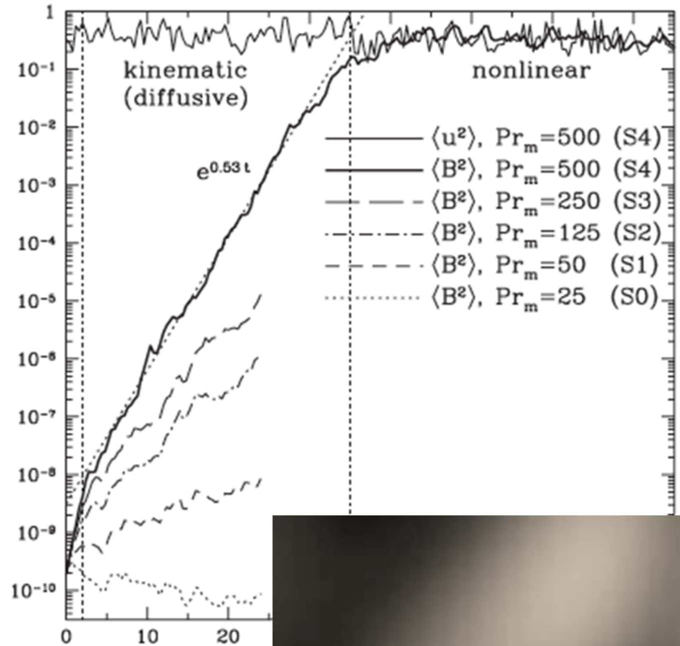
[Zeldovich et al. 1984, *JFM* **144**, 1]

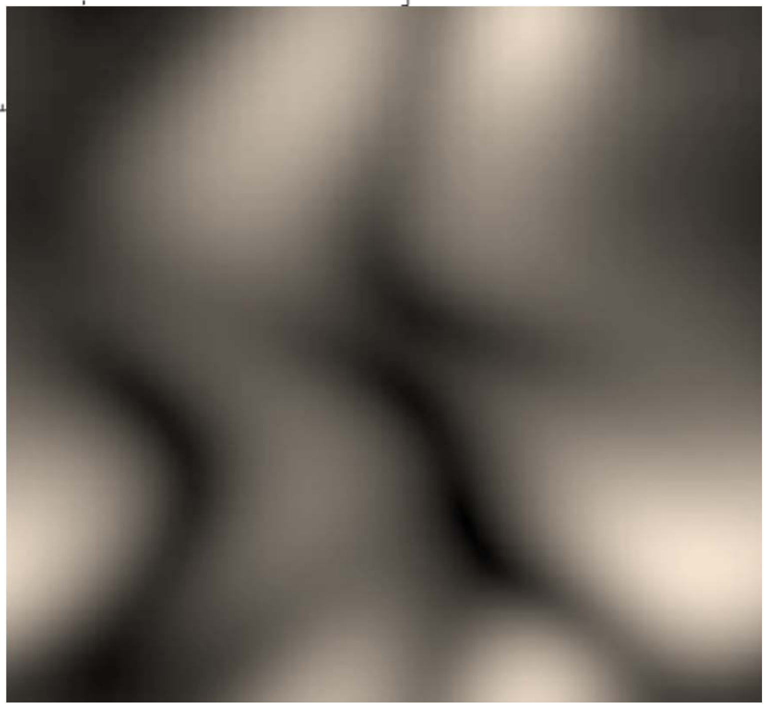
AAS et al., *ApJ* **612**, 276 (2004)

Turbulent Dynamo: Numerical Experiment

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

All you need is a
chaotic flow
(and large enough Rm)





$$\frac{dB}{dt} = (\mathbf{bb} : \nabla \mathbf{u}) B \equiv \gamma B$$

The bottom line is that
turbulent dynamo works if
Rm > Rm_c ~ 50 to 200
(depending on Re)

AAS et al., *NJP* **9**, 300 (2007)

AAS et al., *ApJ* **612**, 276 (2004)

Turbulent Dynamo: Numerical Experiment

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First evidence was in 1981:

VOLUME 47, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1981

Helical and Nonhelical Turbulent Dynamos

M. Meneguzzi
Centre National de la Recherche Scientifique and Section d'Astrophysique, Division de la Physique, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-Sur-Yvette, France

and

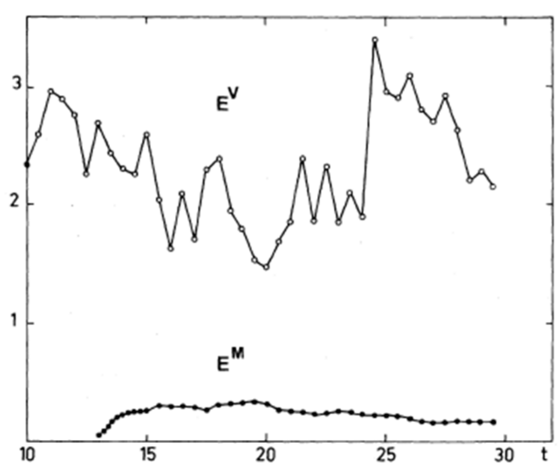
U. Frisch
Centre National de la Recherche Scientifique, Observatoire de Nice, F-06007 Nice, France

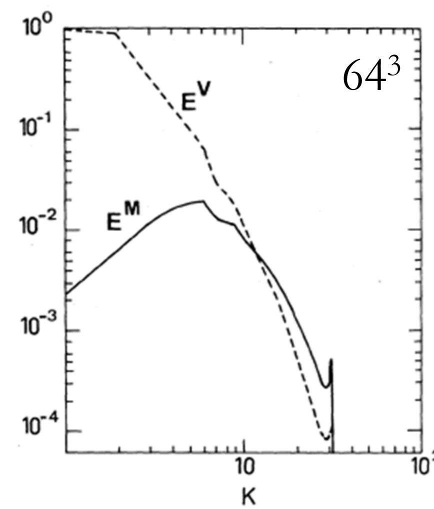
and

A. Pouquet[(a)]
Centre National de la Recherche Scientifique, Observatoire de Meudon, F-92190 Meudon, France
(Received 13 April 1981)

Direct numerical simulations of three-dimensional magnetohydrodynamic turbulence with kinetic and magnetic Reynolds numbers up to 100 are presented. Spatially intermittent magnetic fields are observed in a flow with nonhelical driving. Small-scale helical driving produces strong large-scale nearly force-free magnetic fields.

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla \mathbf{u}) B \equiv \gamma B$$





The bottom line is that turbulent dynamo works if $\mathrm{Rm} > \mathrm{Rm}_c \sim 50$ to 200 (depending on Re)

AAS et al., *NJP* **9**, 300 (2007)

Turbulent Dynamo in Laser Lab (G. Gregori)

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

All you need is a
chaotic flow
(and large enough Rm)

Experiment on Omega laser:
two jet flows pass through grids,
collide, give turbulent cloud
with Re ~ 5000

The bottom line is that
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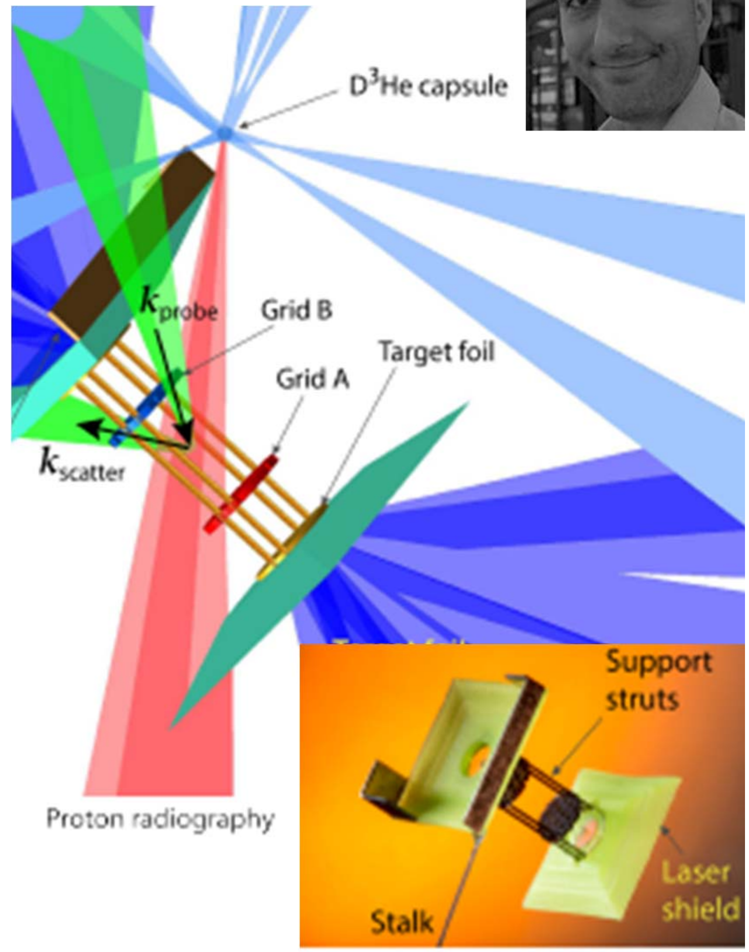
(depending on Re)

AAS et al., *NJP* **9**, 300 (2007)



Tzeferacos et al., in preparation (2016)
Meinecke et al., *PNAS* **112**, 8211 (2015)

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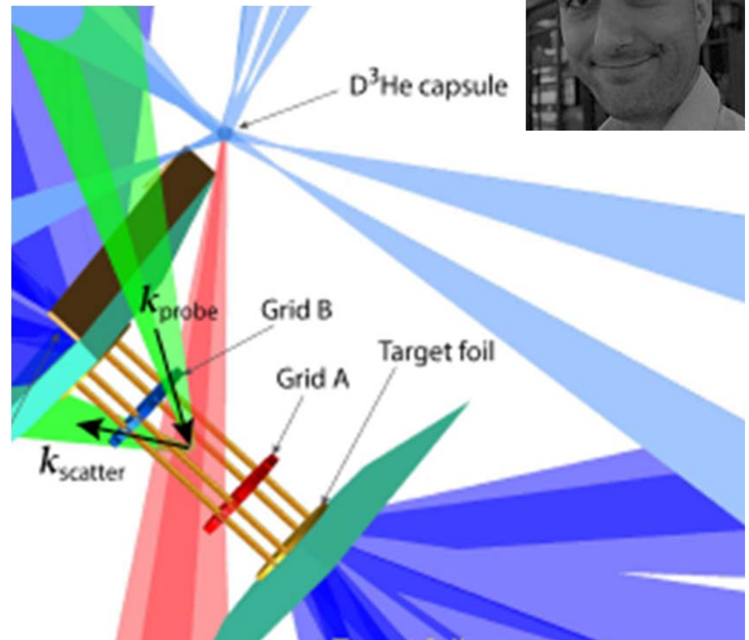
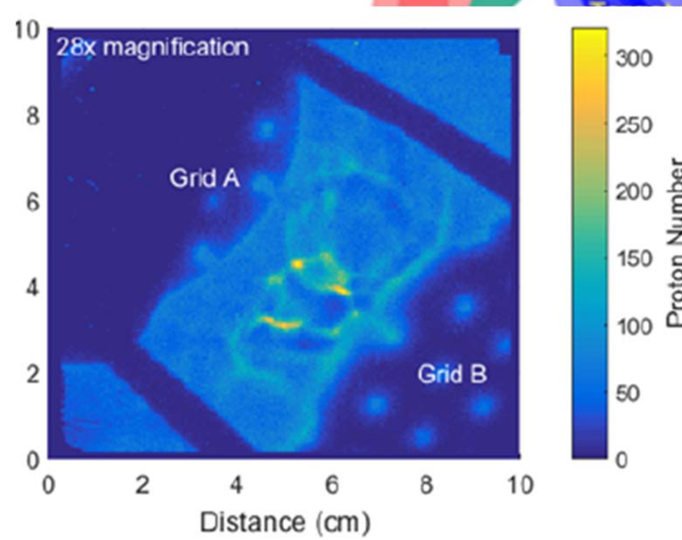


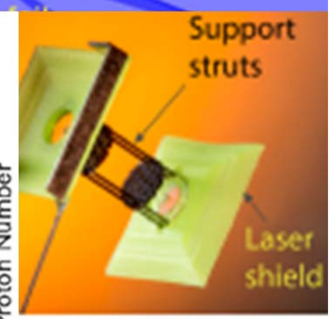
Experiment on Omega laser:

Rm~1000 > Rm_c

field amplified to B ~ 300kG

Details: come to HEDLA-2016!





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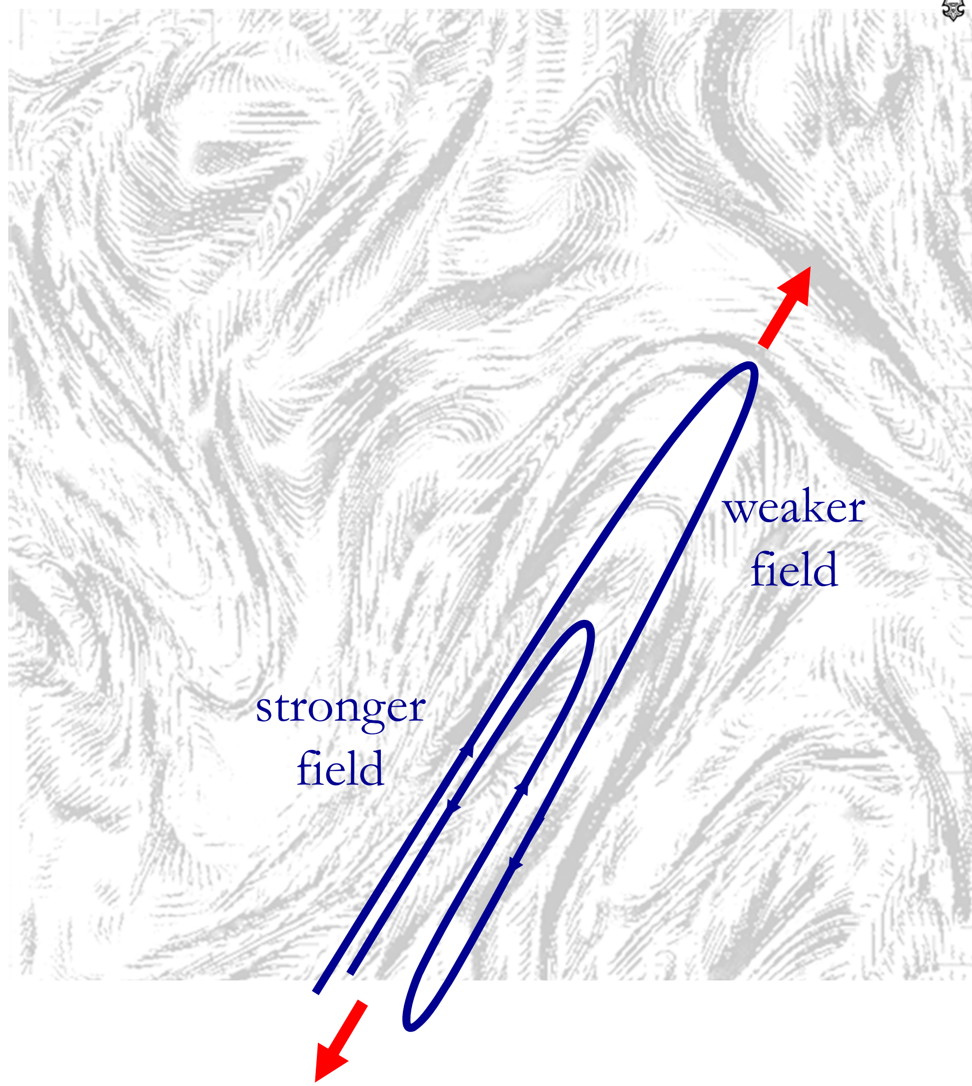
Tzeferacos et al., in preparation (2016)
Meinecke et al., *PNAS* **112**, 8211 (2015)

In Fact, This Is All Irrelevant to Astro…

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla\mathbf{u})B \equiv \gamma B$$



Key effect: a succession of random stretchings (and un-stretchings)

AAS et al., *ApJ* **612**, 276 (2004)

Collisionless Plasma: Adiabatic Constraints

Changing magnetic field causes local pressure anisotropies:

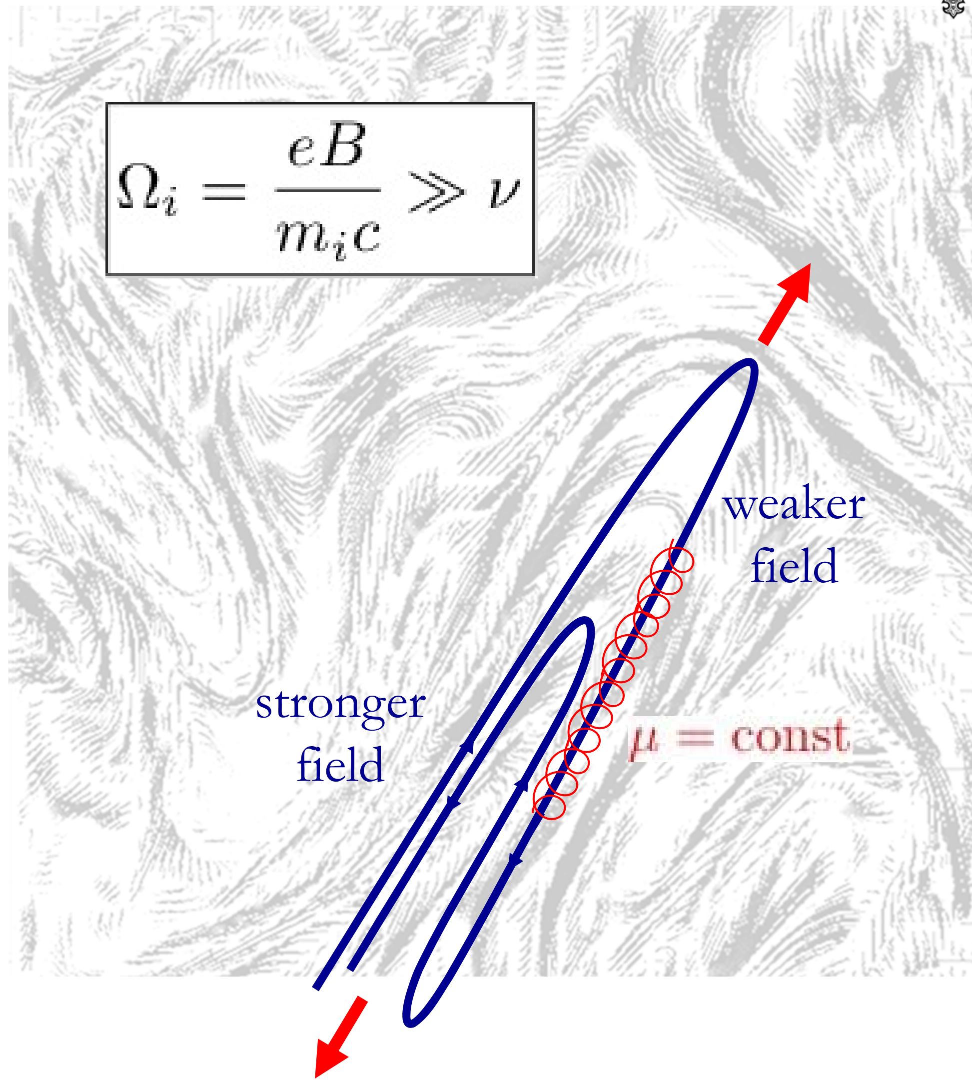
$$\frac{1}{p_\perp}\frac{\mathrm{d}p_\perp}{\mathrm{d}t} = \frac{1}{B}\frac{\mathrm{dB}}{\mathrm{d}t}$$

conservation of $\mu = v_\perp^2/B$

$$\frac{1}{2p_\parallel}\frac{\mathrm{d}p_\parallel}{\mathrm{d}t} = -\frac{1}{B}\frac{\mathrm{dB}}{\mathrm{d}t}$$

conservation of $J = \oint \mathrm{d}\ell\, v_\parallel$

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla\mathbf{u})B \equiv \gamma B$$



It is very hard to change B in the face of these constraints!

[*CGL supports no dynamo action:*
Santos-Lima et al. 2011, Proc. IAU No 274, 482]

Helander, Strumik & AAS, in preparation (2016)

Weak Collisions ➔ Pressure Anisotropy

Changing magnetic field causes local pressure anisotropies:

$$\frac{1}{p_\perp}\frac{\mathrm{d}p_\perp}{\mathrm{d}t} = \frac{1}{B}\frac{\mathrm{dB}}{\mathrm{d}t} - \nu\,\frac{p_\perp - p_\parallel}{p_\perp}$$

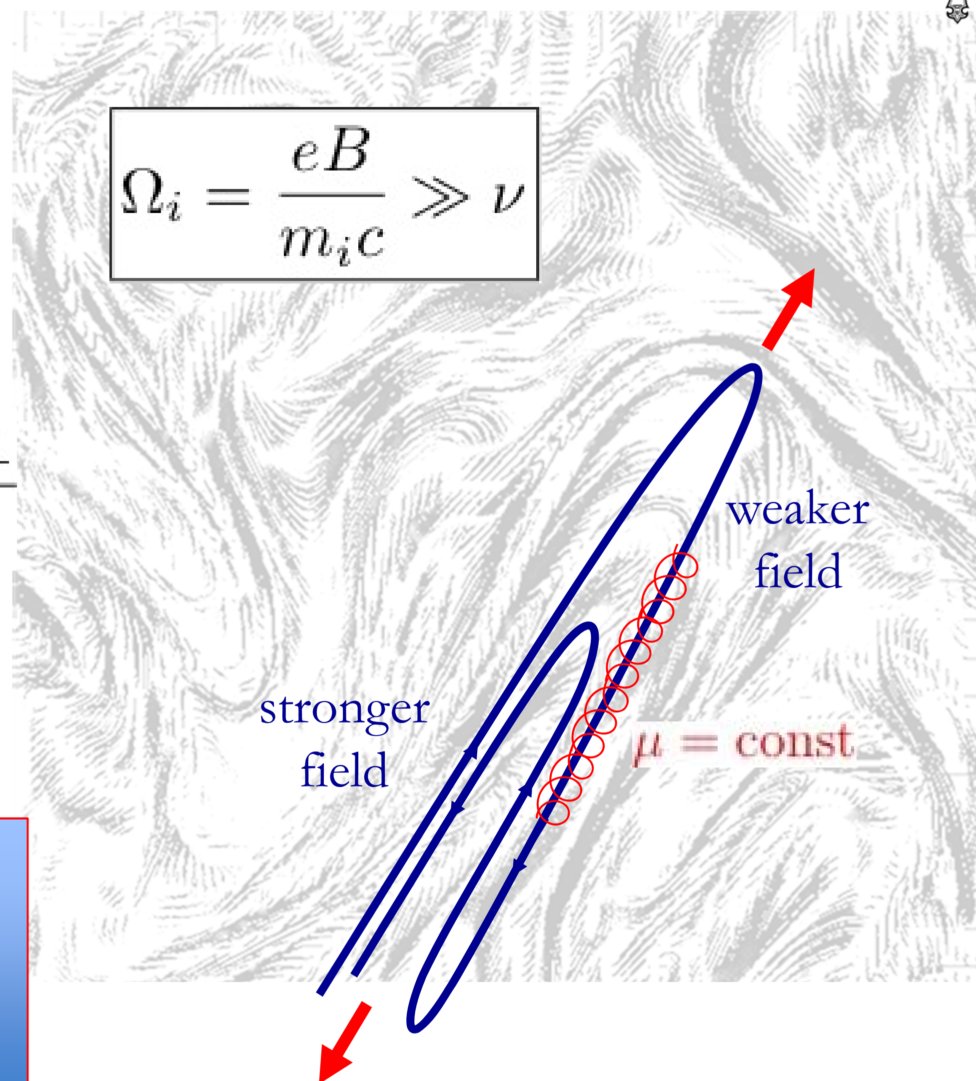
conservation of $\mu = v_\perp^2/B$

$$\frac{1}{2p_\parallel}\frac{\mathrm{d}p_\parallel}{\mathrm{d}t} = -\frac{1}{B}\frac{\mathrm{dB}}{\mathrm{d}t} - \nu\,\frac{p_\parallel - p_\perp}{p_\parallel}$$

conservation of $J = \oint \mathrm{d}\ell\, v_\parallel$

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla\mathbf{u})B \equiv \gamma B$$

$$\boxed{\Omega_i = \frac{eB}{m_i c} \gg \nu}$$

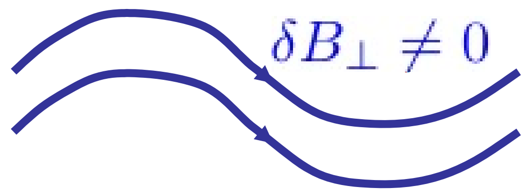


(compressions/rarefactions & heat fluxes are also sources of local pressure anisotropy)

AAS et al., *ApJ* **629**, 139 (2005); *MNRAS* **405**, 291 (2010)

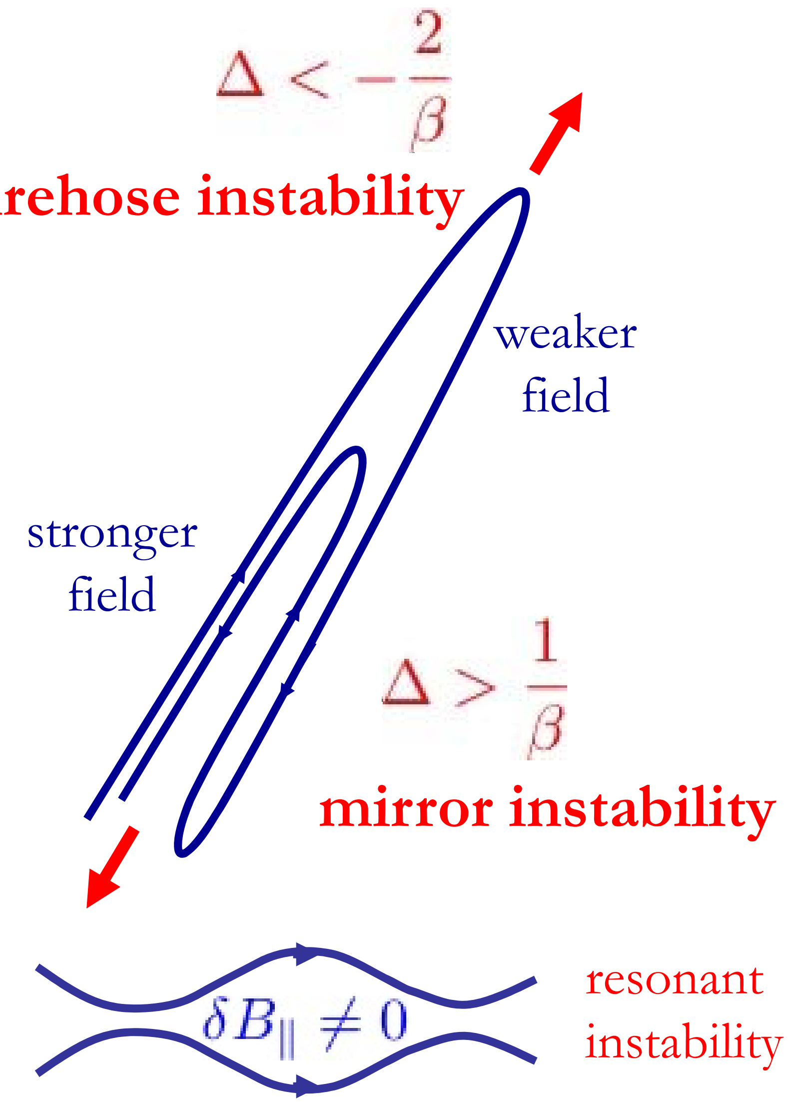
Pressure Anisotropy ➔ Microinstabilities

Instabilities are fast, small scale (~Larmor).
They are instantaneous compared
to "fluid" dynamics.



destabilised Alfvén wave

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla\mathbf{u})B \equiv \gamma B$$



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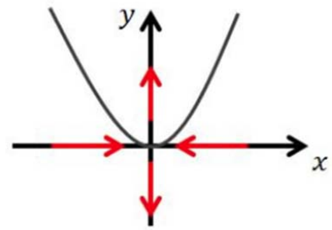
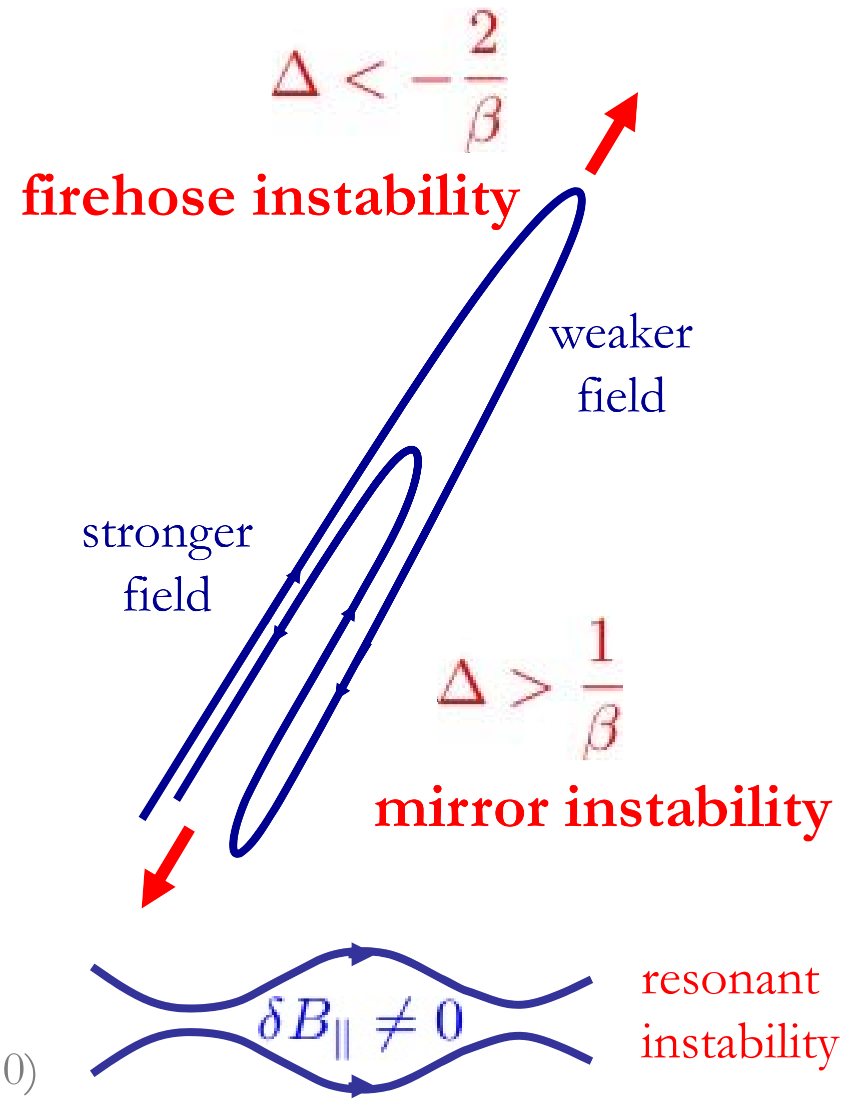
Pressure Anisotropy ➔ Microinstabilities

Scott Melville:
folding field goes firehose-unstable
(in a 1D Braginskii model)



Note the square shape of the unstable fold…



$$\Delta \equiv \frac{p_\perp - p_\parallel}{p} \sim \frac{1}{\nu}\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{\gamma}{\nu}$$

AAS et al., *ApJ* **629**, 139 (2005); *MNRAS* **405**, 291 (2010)

Instabilities in a Box (M. Kunz)

Hybrid kinetic system solved by PEGASUS code (PIC):

$$\left(\frac{\partial}{\partial t} - Sx\frac{\partial}{\partial y}\right) f_{\mathrm{i}} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f_{\mathrm{i}} + \left[\frac{Ze}{m_{\mathrm{i}}}\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right) + Sv_x\hat{\boldsymbol{y}}\right]\cdot\frac{\partial f_{\mathrm{i}}}{\partial \boldsymbol{v}} = 0$$

$$\left(\frac{\partial}{\partial t} - Sx\frac{\partial}{\partial y}\right)\boldsymbol{B} = -c\boldsymbol{\nabla}\times\boldsymbol{E} - SB_x\hat{\boldsymbol{y}}$$

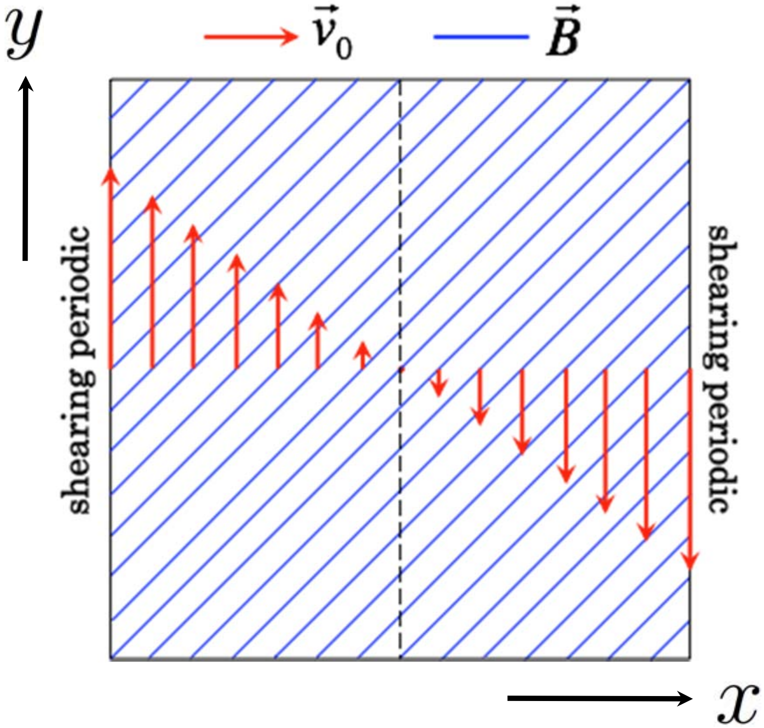
$$\boldsymbol{E} = -\frac{\boldsymbol{u}_{\mathrm{i}}\times\boldsymbol{B}}{c} + \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi Zen_{\mathrm{i}}} - \frac{T_{\mathrm{e}}\boldsymbol{\nabla} n_{\mathrm{i}}}{en_{\mathrm{i}}}$$

…in a shearing sheet $\mathbf{u} = -Sx\hat{\mathbf{y}}$

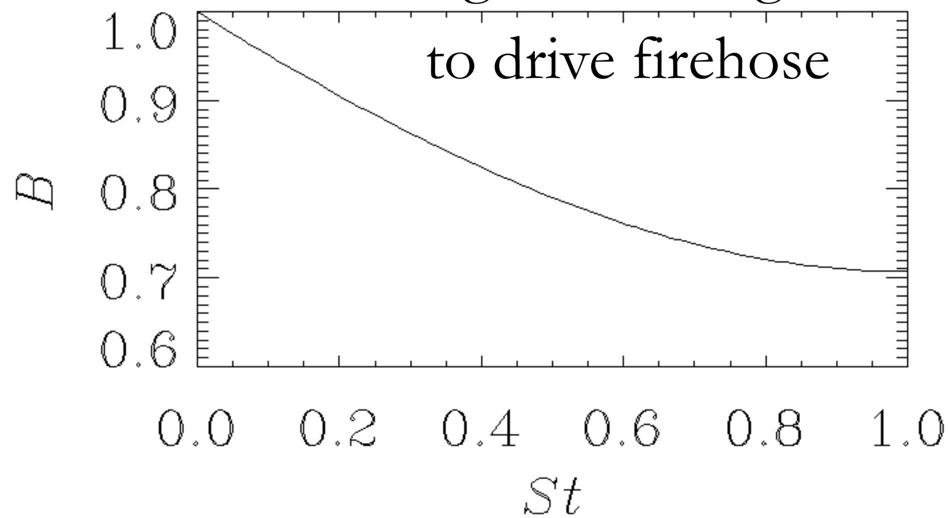
Kunz, Stone & Bai, *JCP* **259**, 154 (2014)

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

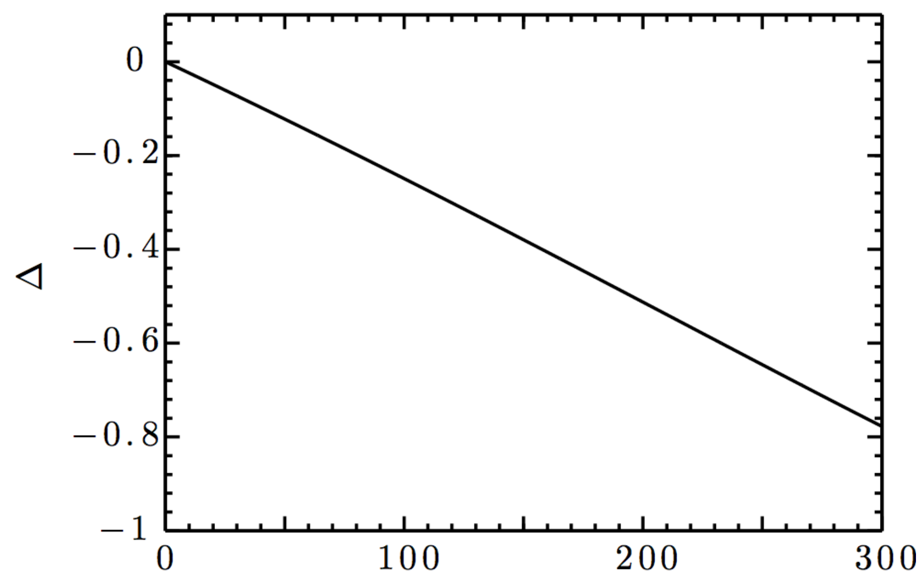
Firehose Instability (M. Kunz)



decreasing field strength
to drive firehose



$$\frac{\mathrm{d}B}{\mathrm{d}t} < 0 \quad \Rightarrow \quad \Delta = \frac{p_\perp - p_\parallel}{p} < 0$$

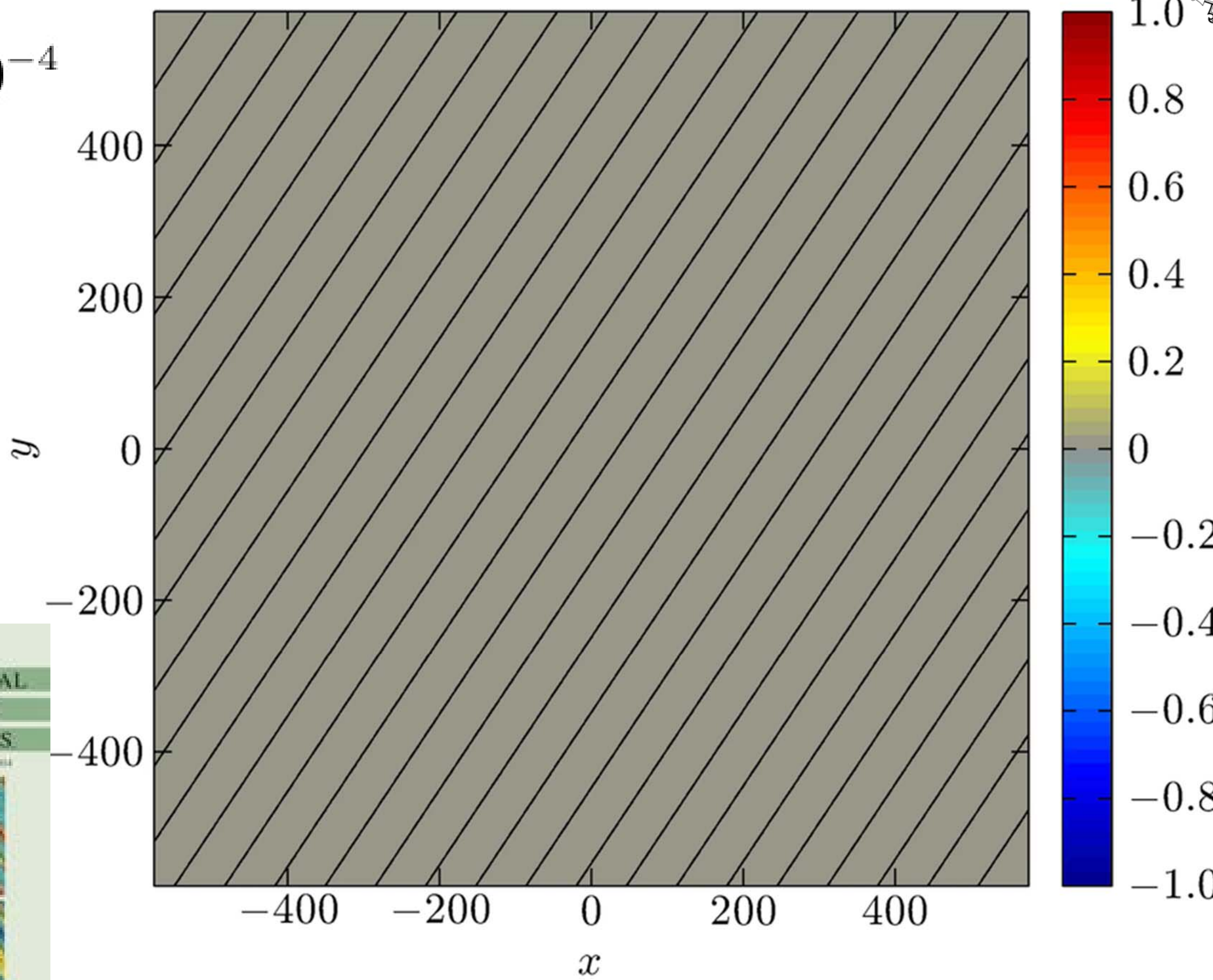


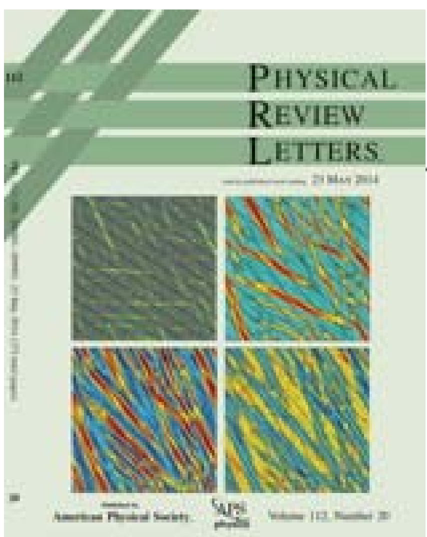
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Firehose Instability (M. Kunz)

$$\frac{S}{\Omega_i} = 3 \times 10^{-4}$$

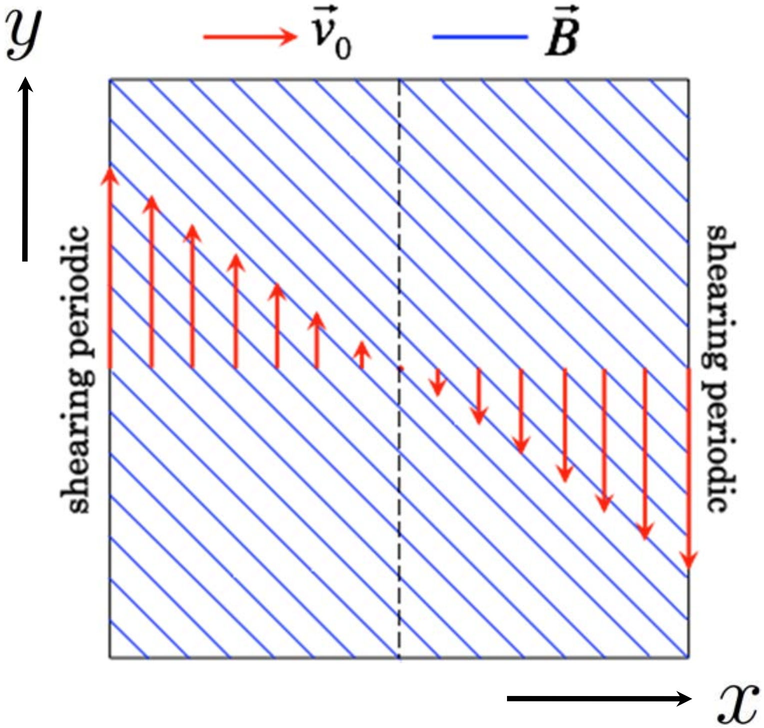
$$\beta_i = 200$$



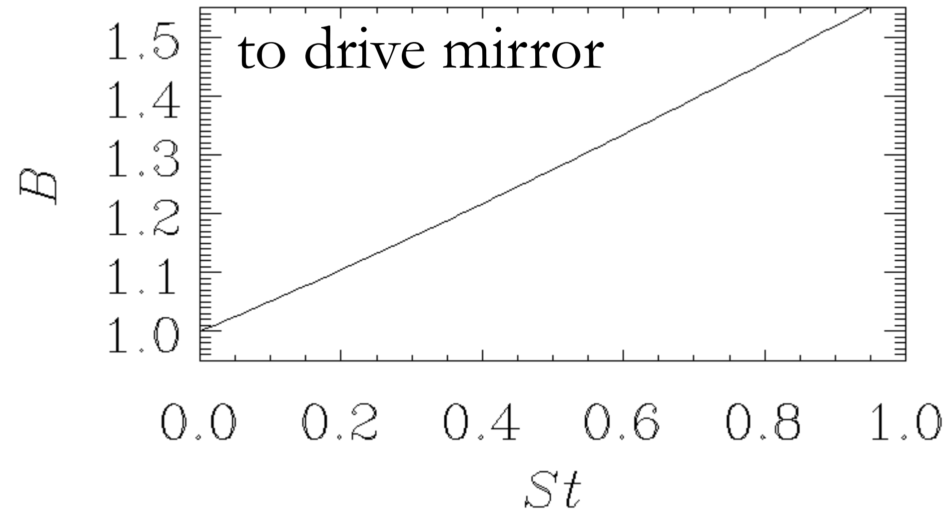


Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

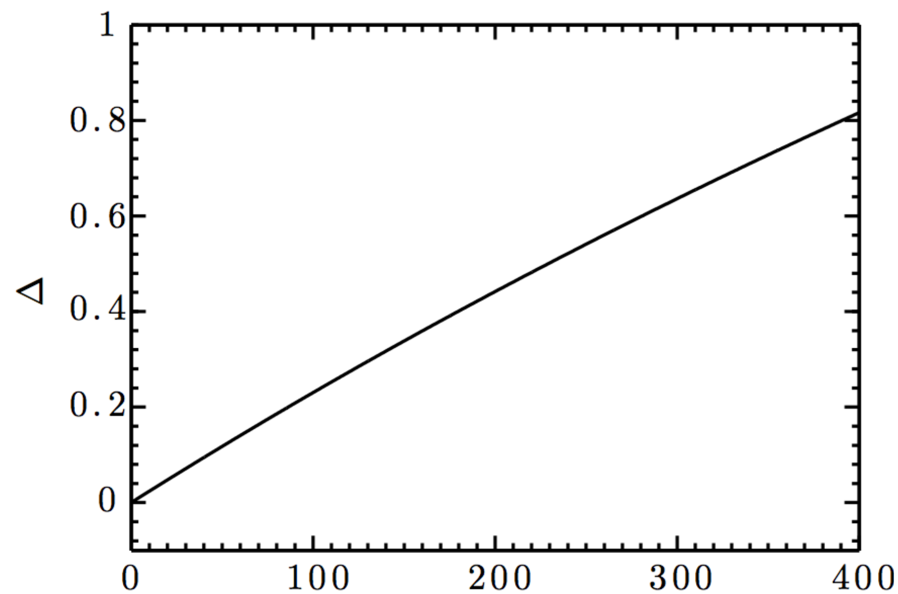
Mirror Instability (M. Kunz)



increasing field strength
to drive mirror



$$\frac{\mathrm{d}B}{\mathrm{d}t} > 0 \quad \Rightarrow \quad \Delta = \frac{p_\perp - p_\parallel}{p} > 0$$



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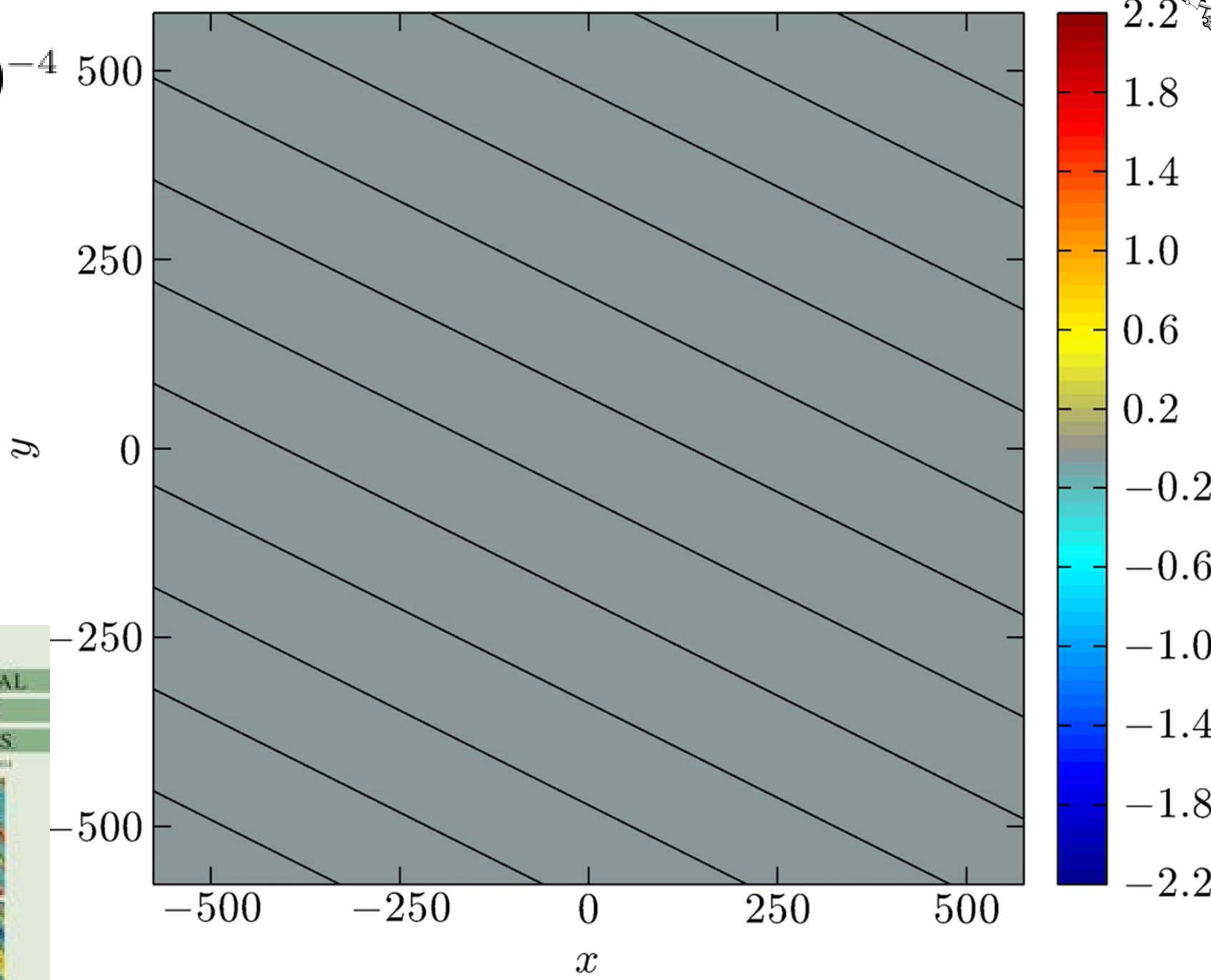
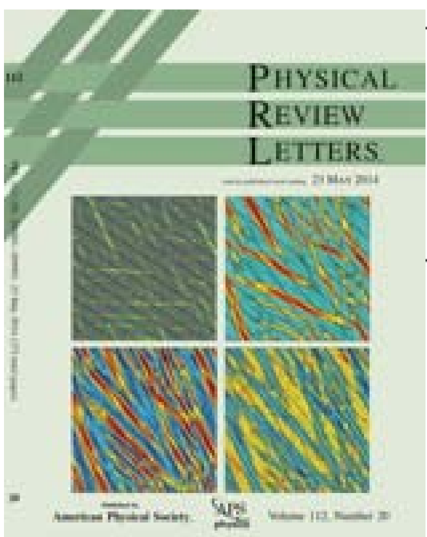


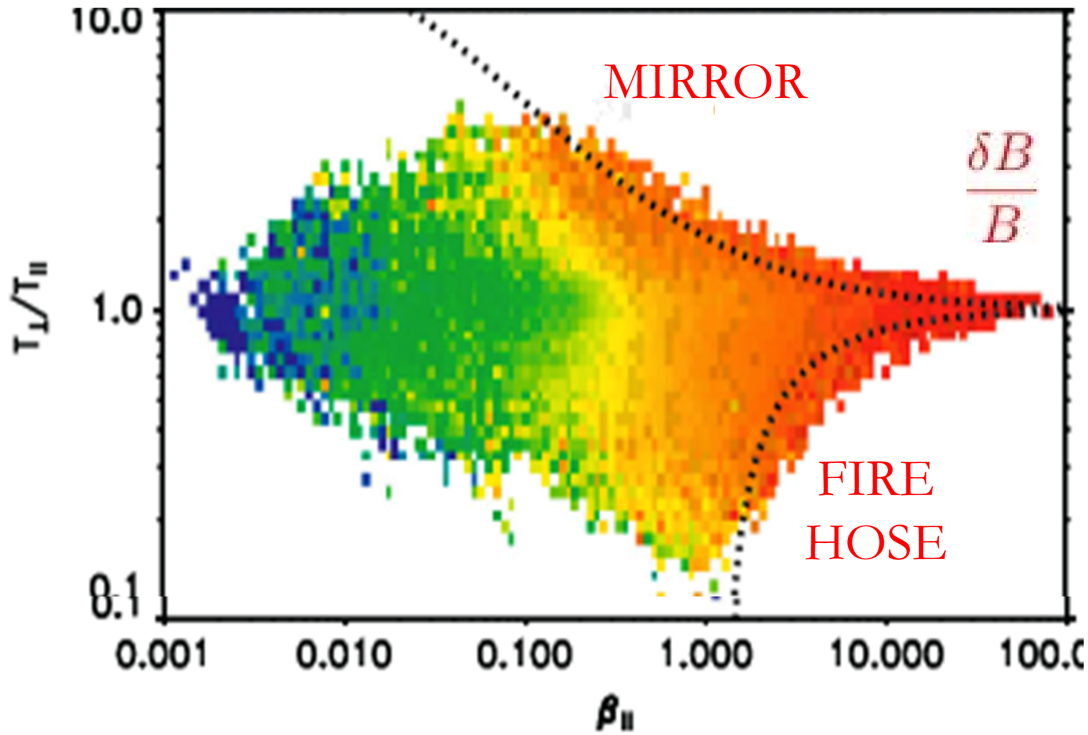


Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Marginal State At All Times?

In the **solar wind**:

[Bale et al. 2009, *PRL* **103**, 211101]



$$\Delta \equiv \frac{p_\perp - p_\parallel}{p} \sim \frac{1}{\nu}\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{\gamma}{\nu} \in \left[-\frac{2}{\beta}, \frac{1}{\beta}\right]$$

Marginal State At All Times?

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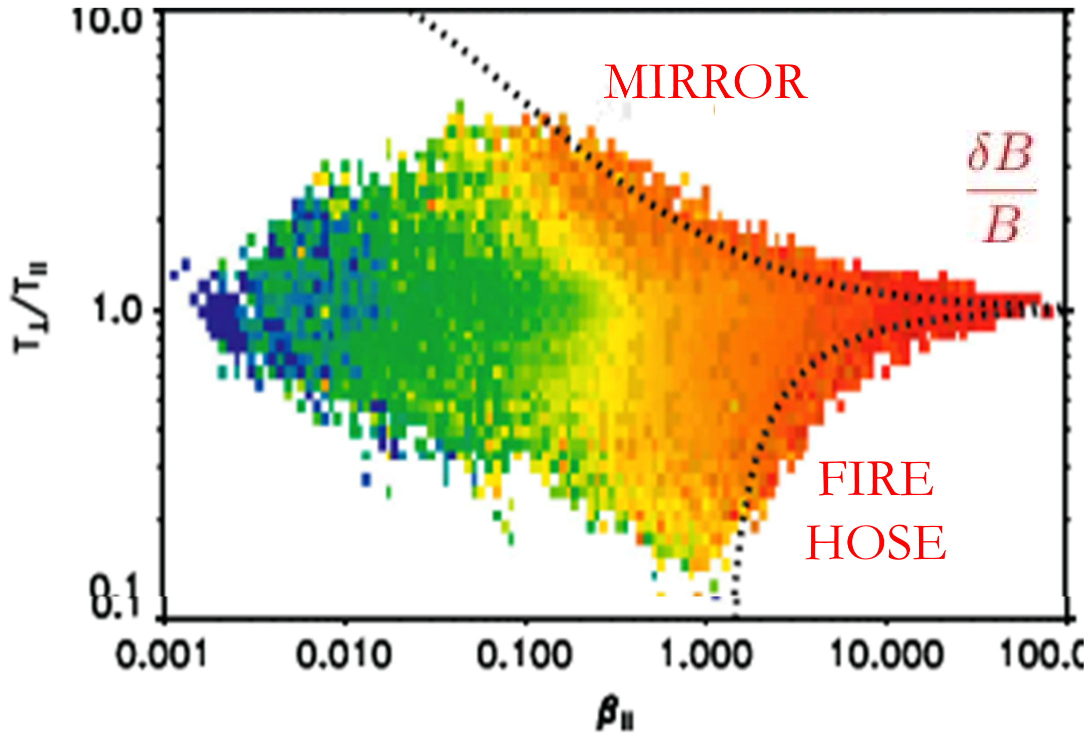
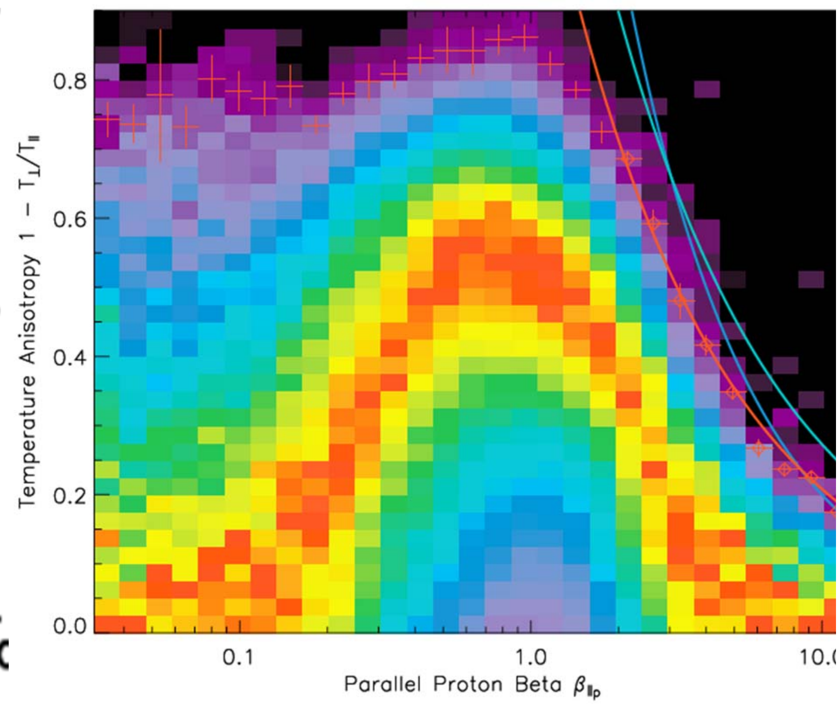


[Kasper et al. 2002, *GRL* **29**, 1839]

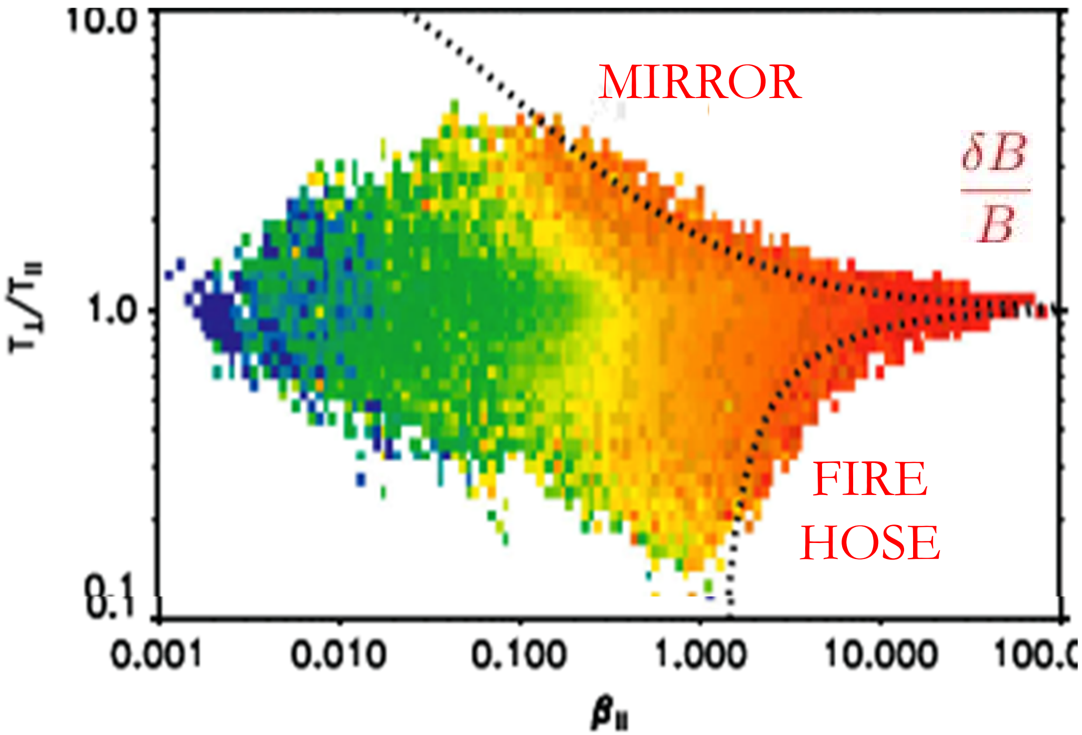


$$\Delta \equiv \frac{p_\perp - p_\parallel}{p} \sim \frac{1}{\nu}\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{\gamma}{\nu} \in \left[-\frac{2}{\beta}, \frac{1}{\beta}\right]$$

Marginal State At All Times?

In the **solar wind**:

[Bale et al. 2009, *PRL* **103**, 211101]

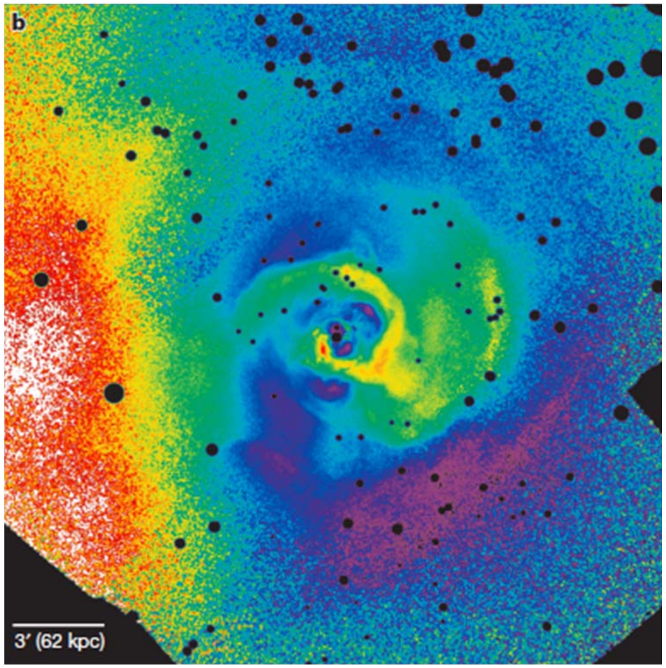


In **galaxy clusters**:

$$\beta \sim 100$$

$$\frac{\gamma}{\nu} \sim 0.01$$

[Image:
Zhuravleva et al. 2014, *Nature* **515**, 85]



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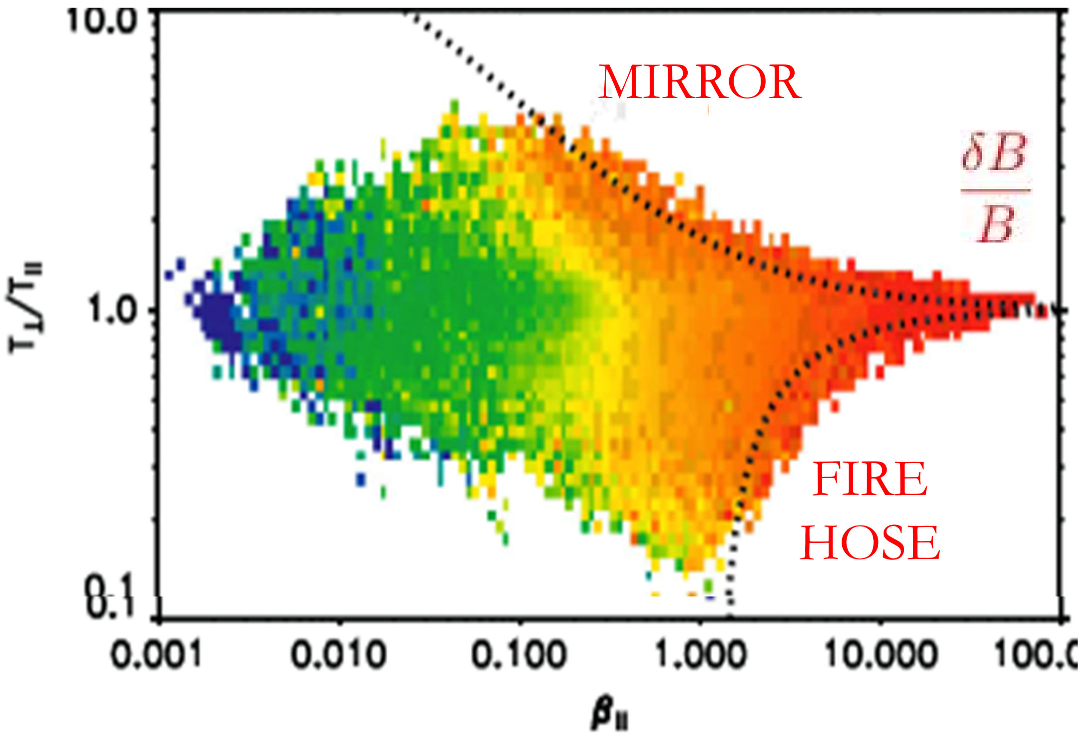
Marginal State At All Times?

How do you evolve the field from small to large while keeping everywhere within marginal stability boundaries?



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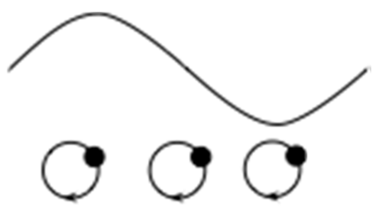
Mogavero & AAS,
MNRAS **440**, 3226 (2014)

Effective Closure Options

How do you evolve the field from small to large while keeping everywhere within marginal stability boundaries?

Way to keep const rms B needed for this

Option I: Suppress stretching



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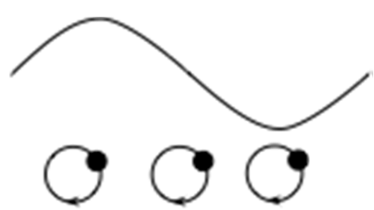

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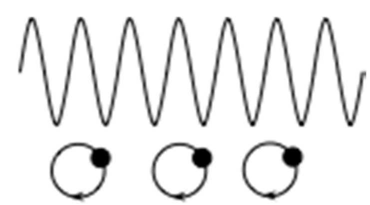
Option II: Enhance collisionality



Anomalous scattering of particles by Larmor scale fluctuations needed for this

Mogavero & AAS, *MNRAS* **440**, 3226 (2014)

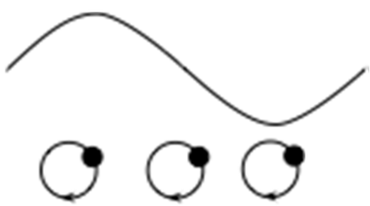
PLASMA DYNAMO?

How do you evolve the field from small to large while keeping everywhere within marginal stability boundaries?

In view of these complications, **does dynamo work in a weakly collisional plasma?**

Way to keep const rms B needed for this

Option I: Suppress stretching



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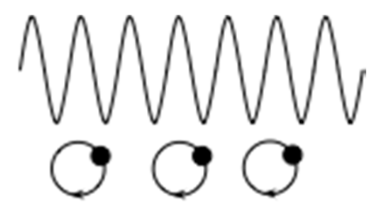


Anomalous scattering of particles by Larmor scale fluctuations needed for this

Mogavero & AAS, *MNRAS* **440**, 3226 (2014)

Plasma Dynamo Simulations by F. Rincon

Hybrid kinetic system solved by a Vlasov code (grid):

$$\frac{\partial f_i}{\partial t} + \mathbf{v}\cdot\nabla f_i + \left[\frac{e}{m_i}\left(\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right) + \frac{\mathbf{F}}{m_i}\right]\cdot\frac{\partial f_i}{\partial \mathbf{v}} = 0$$

$$\mathbf{E} = -\frac{T_e\nabla n_e}{en_e} - \frac{\mathbf{u}_e\times\mathbf{B}}{c} + \frac{4\pi\eta}{c^2}\mathbf{j}$$

isothermal, massless electron fluid

Valentini et al. *JCP* **225**, 753 (2007)

$$\mathbf{u}_e = \mathbf{u}_i - \frac{\mathbf{j}}{en_e}$$

$$\mathbf{j} = \frac{c}{4\pi}\nabla\times\mathbf{B}$$

Force randomly

Increase $\mathrm{Rm} = \frac{u_{\mathrm{rms}}L}{\eta}$

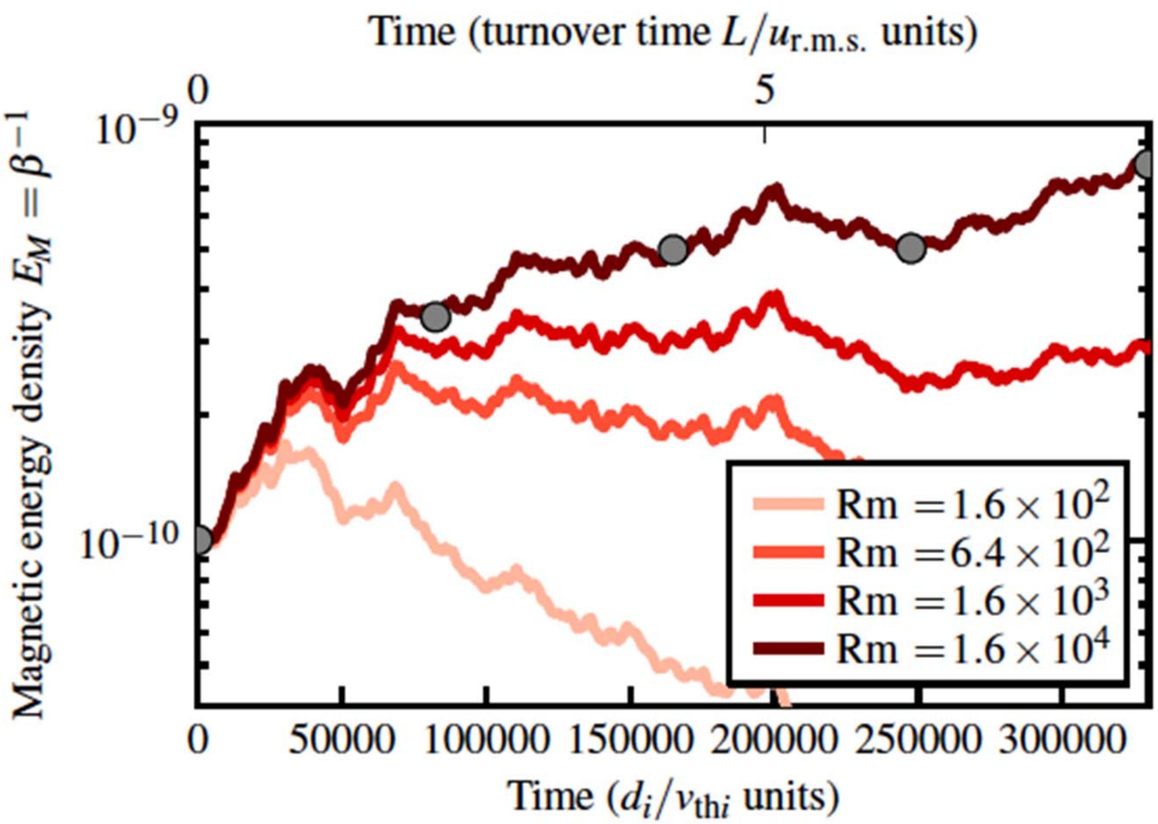
$$n_e = n_i$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla\times\mathbf{E}$$

Will magnetic energy grow?

Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

Plasma Dynamo Simulations by F. Rincon



UNMAGNETISED

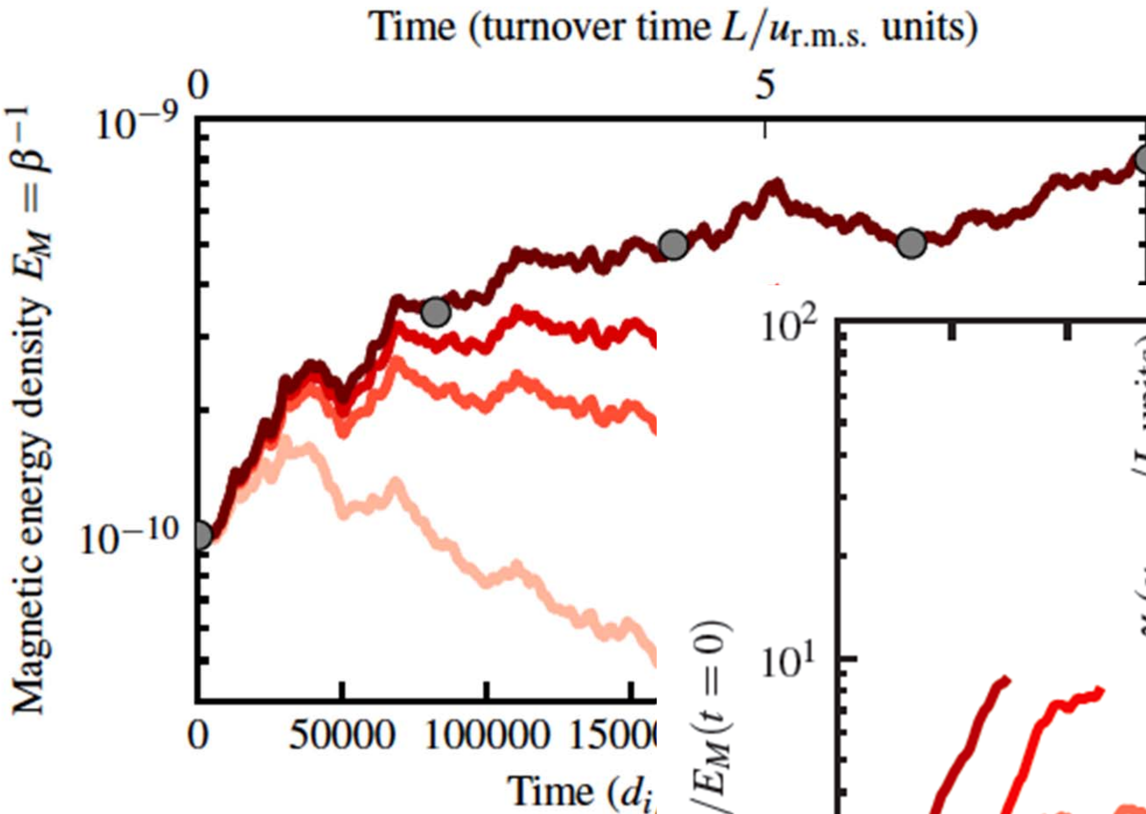
$$\beta = 10^{10} \quad \frac{\rho_i}{L} \simeq 16$$

Dynamo works!

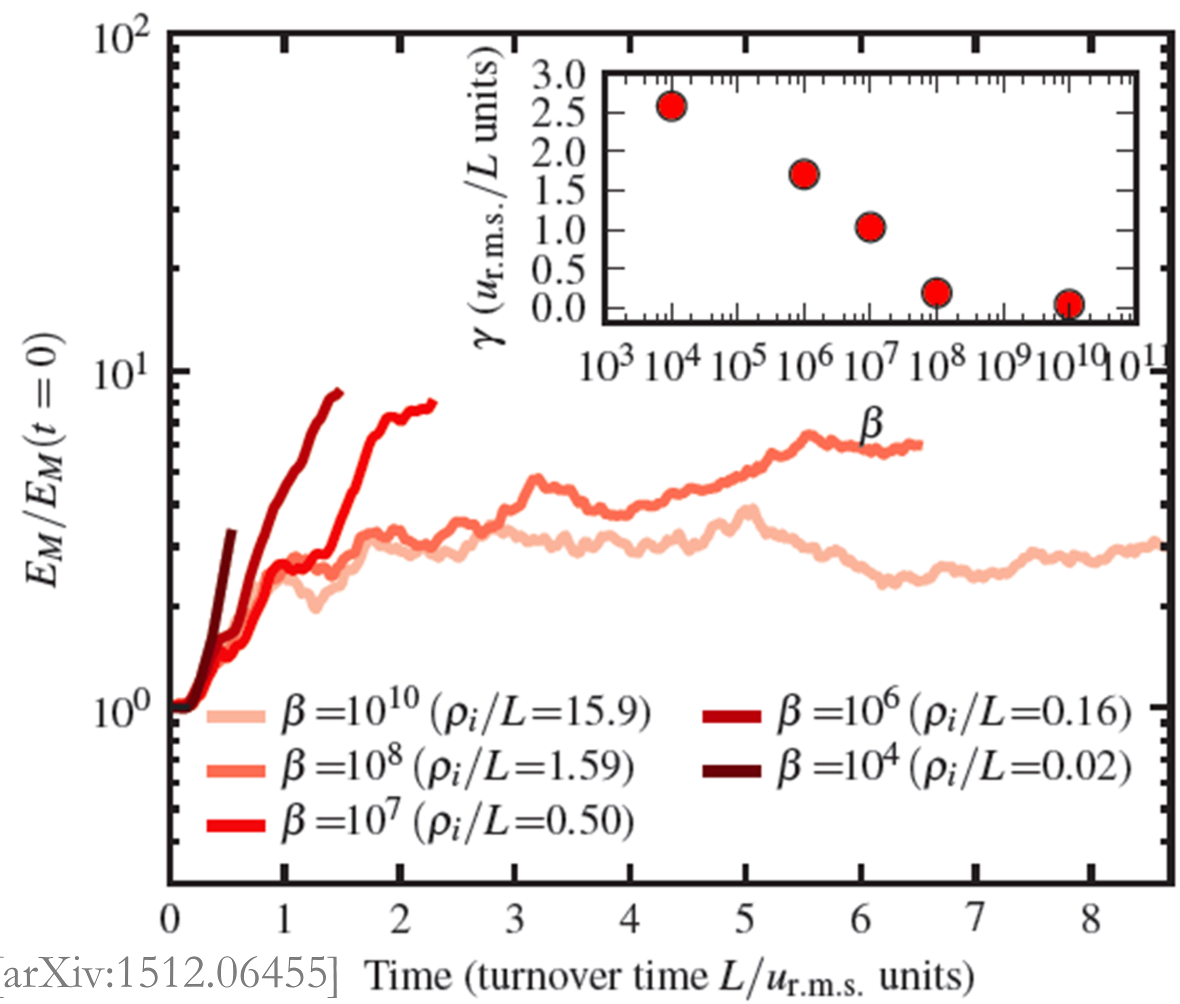
$$\mathrm{Rm}_c \sim 10^3$$

Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

Plasma Dynamo Simulations by F. Rincon



Dynamo self-accelerates!



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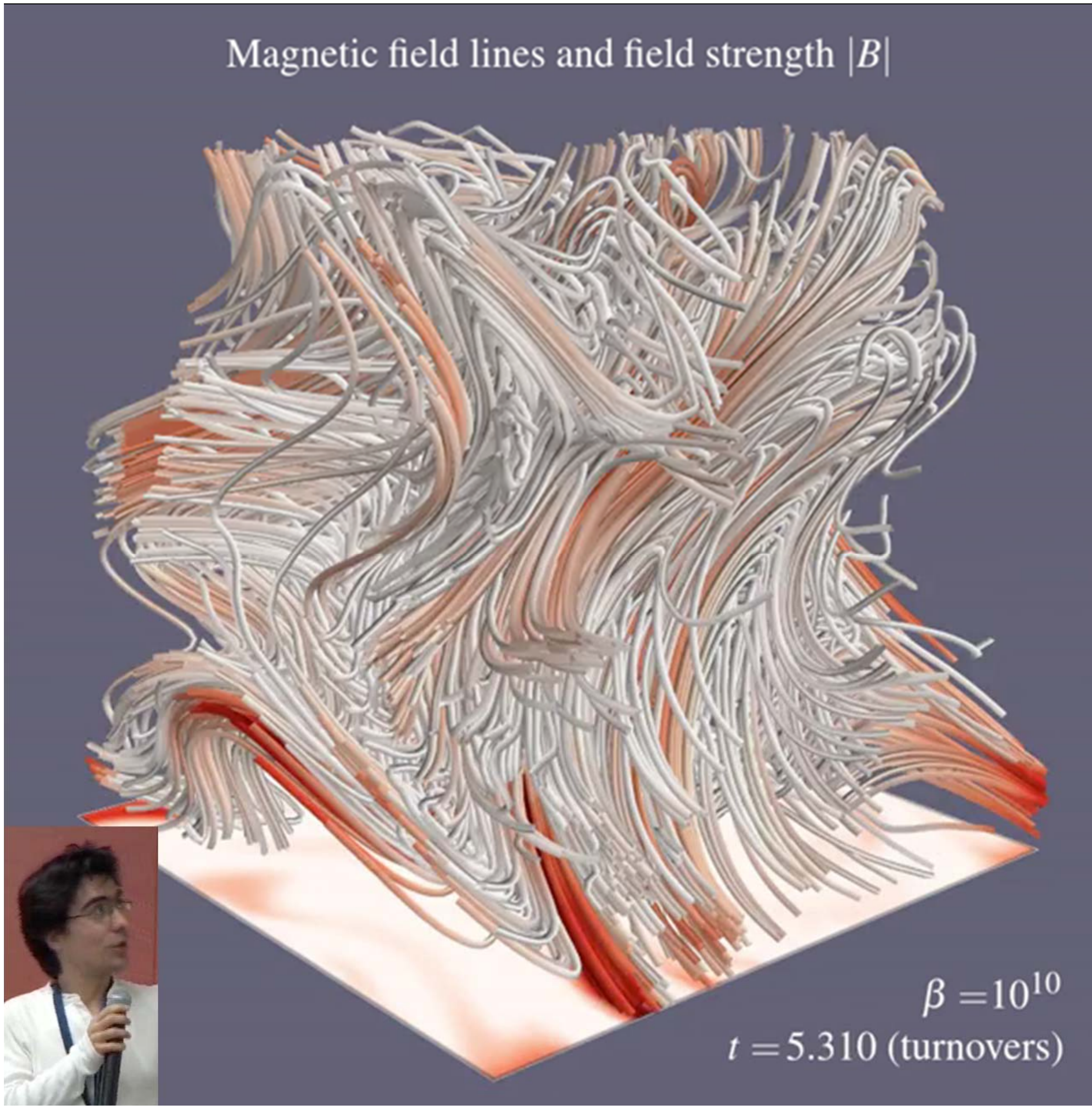

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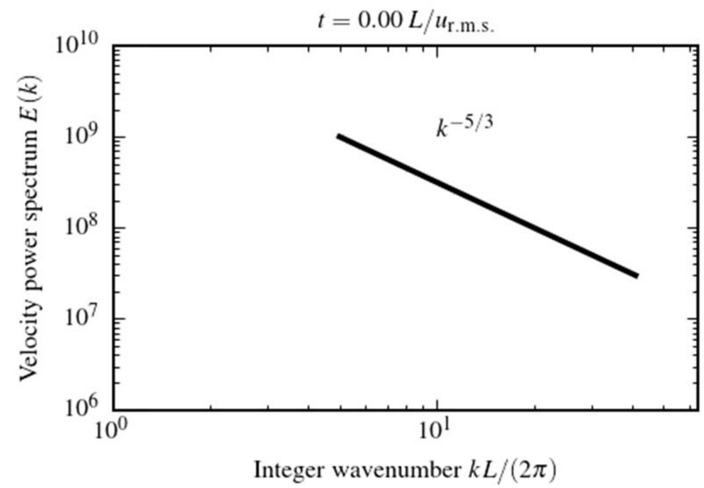
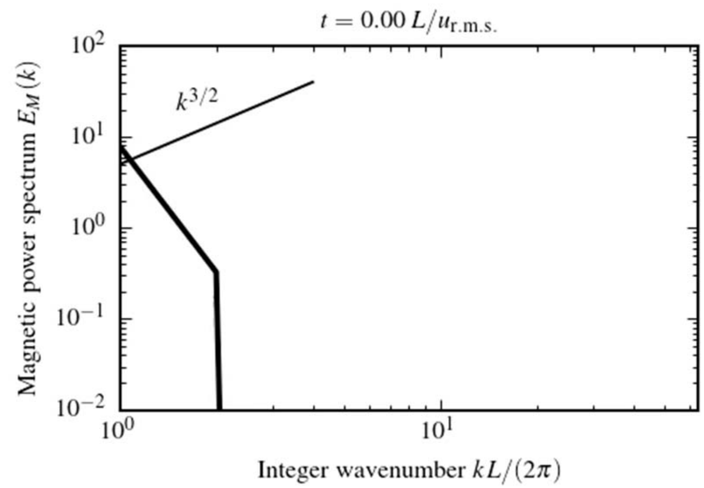
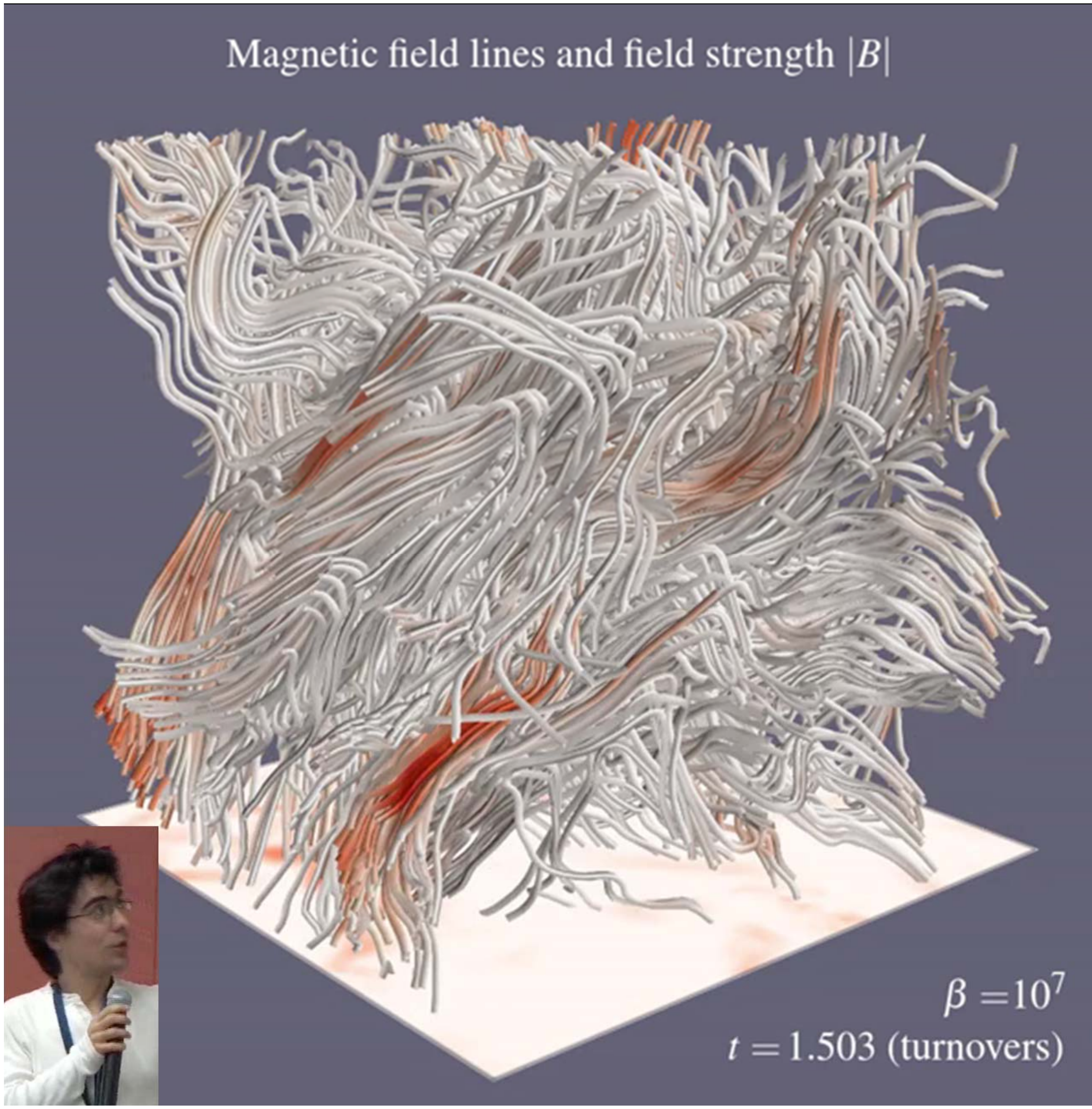




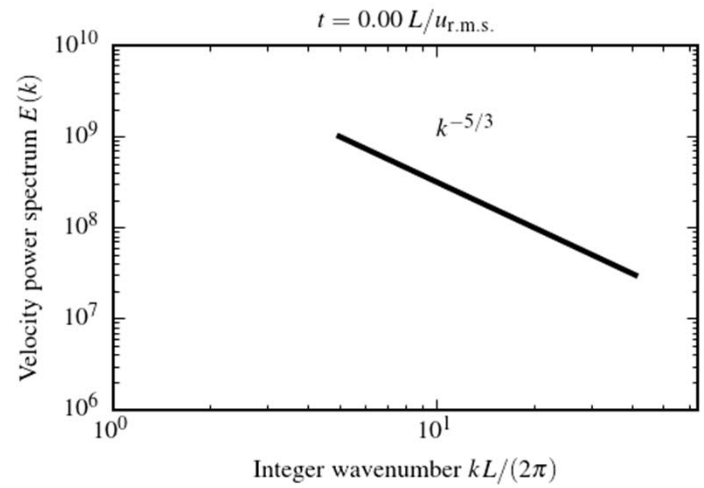
Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

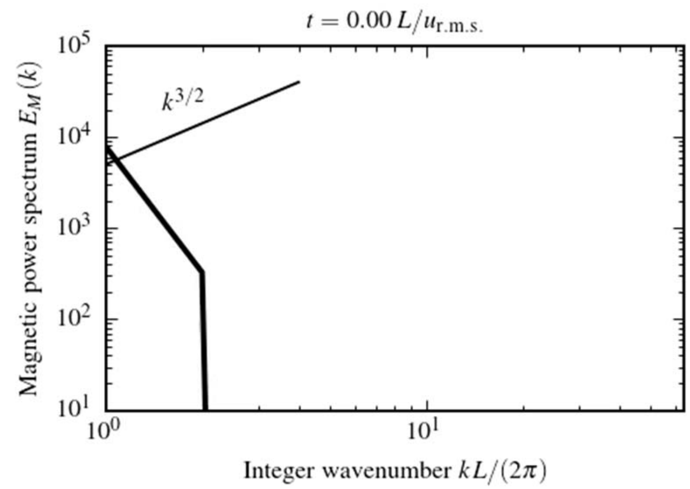
Plasma Dynamo Simulations by F. Rincon



NEARLY MAGNETISED

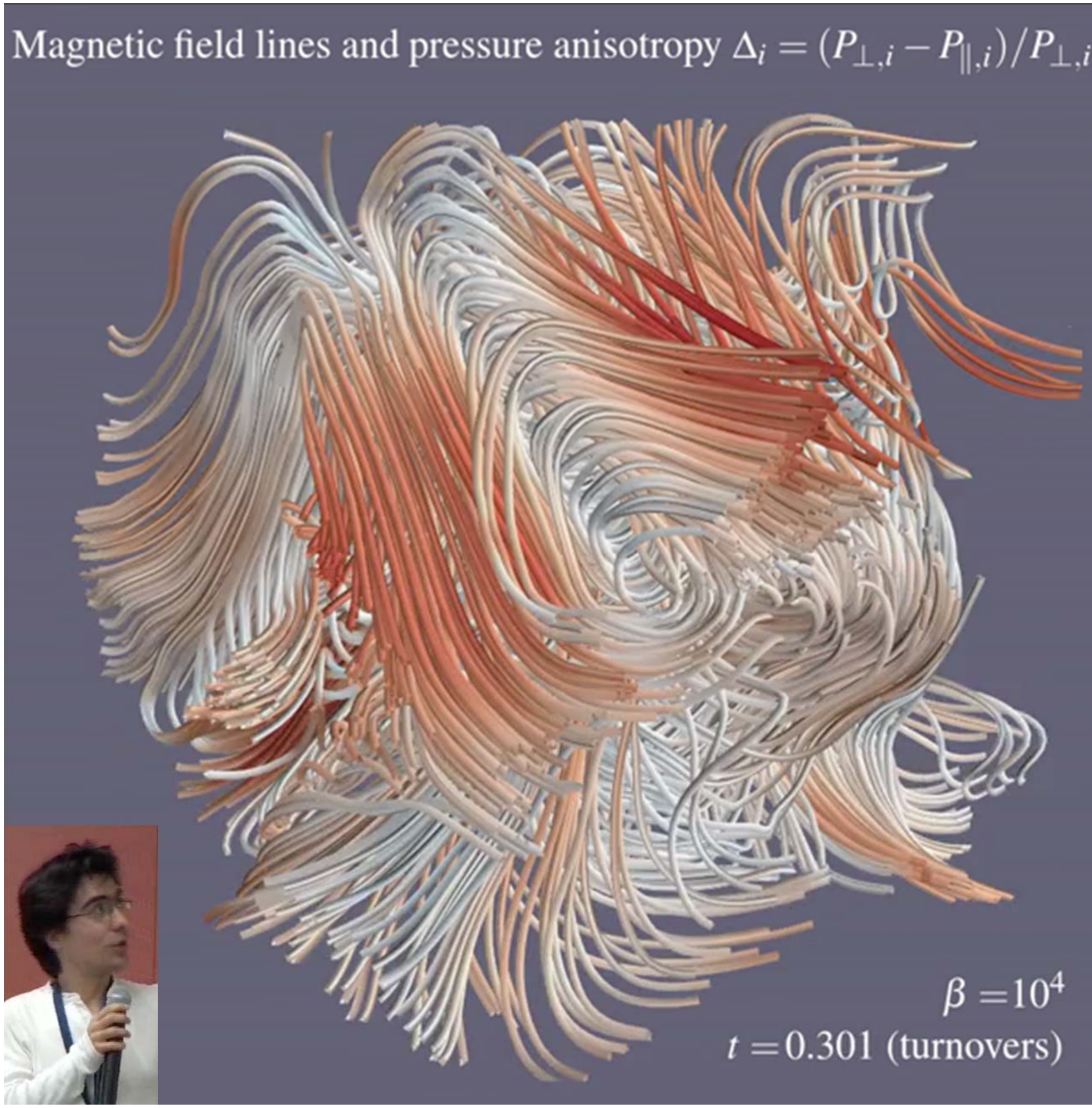
$$\beta = 10^7 \quad \frac{\rho_i}{L} \simeq 0.5$$





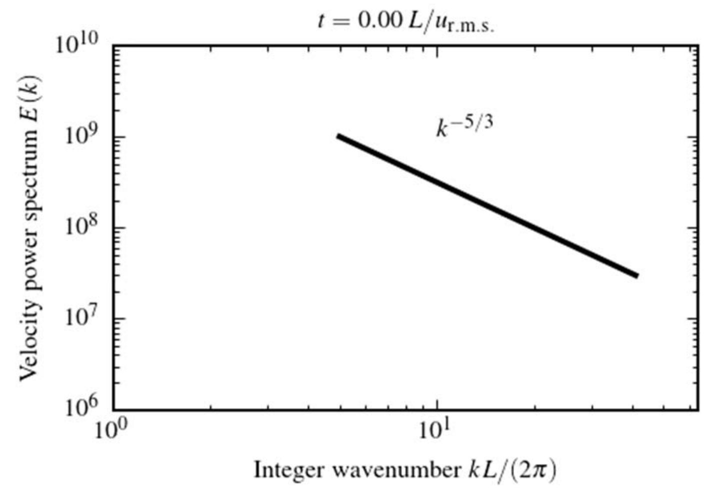
Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

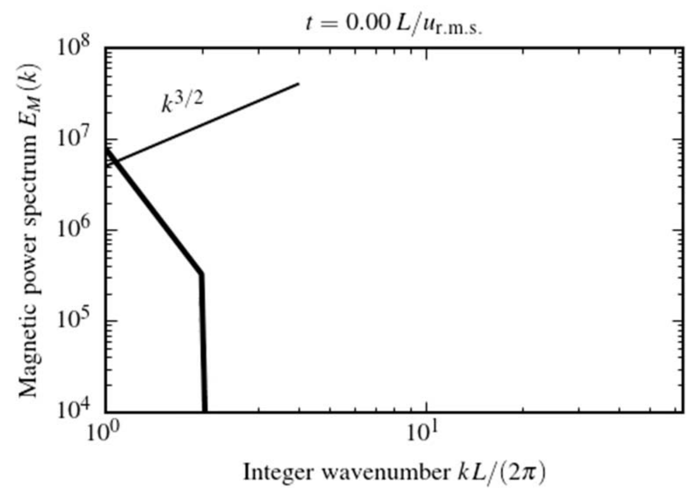
Plasma Dynamo Simulations by F. Rincon



FULLY
MAGNETISED

$$\beta = 10^4 \quad \frac{\rho_i}{L} \simeq 0.02$$



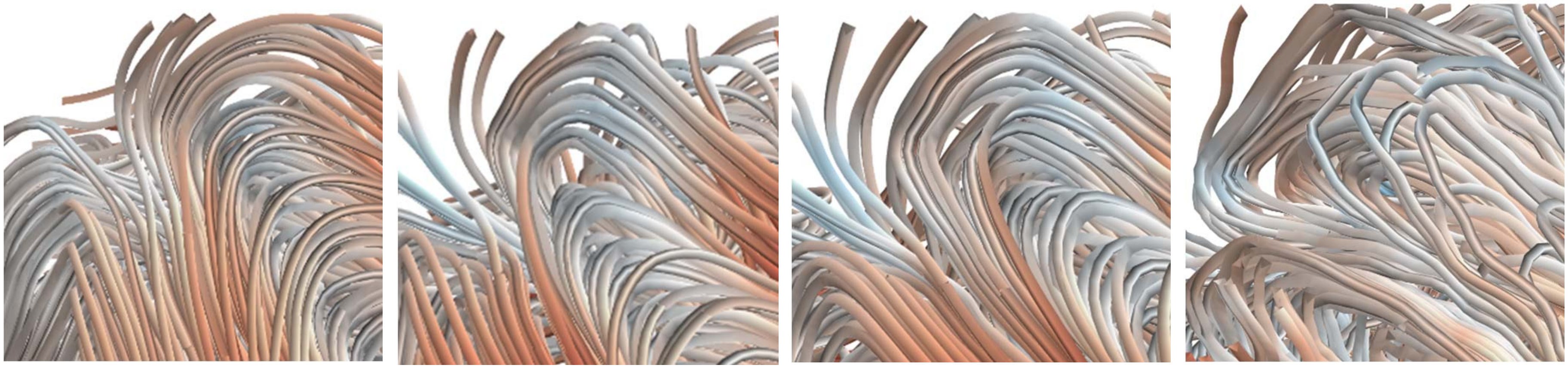


Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

Plasma Dynamo Simulations by F. Rincon

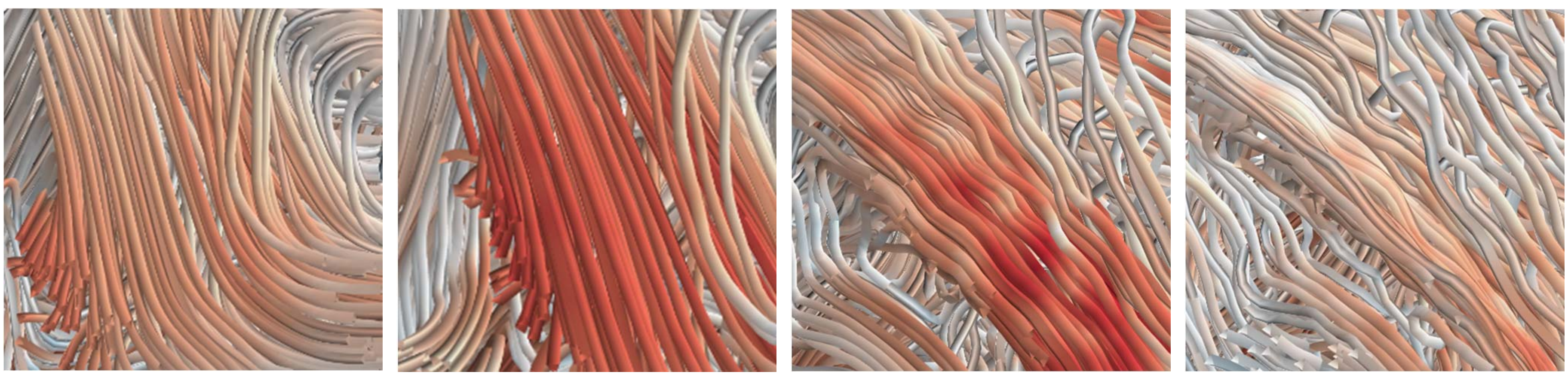
Firehoses in bends: *note square bends*

[cf. Melville & AAS 2016, in prep.]



Mirrors in stretched folds: *"bubbles" filled with trapped particles*

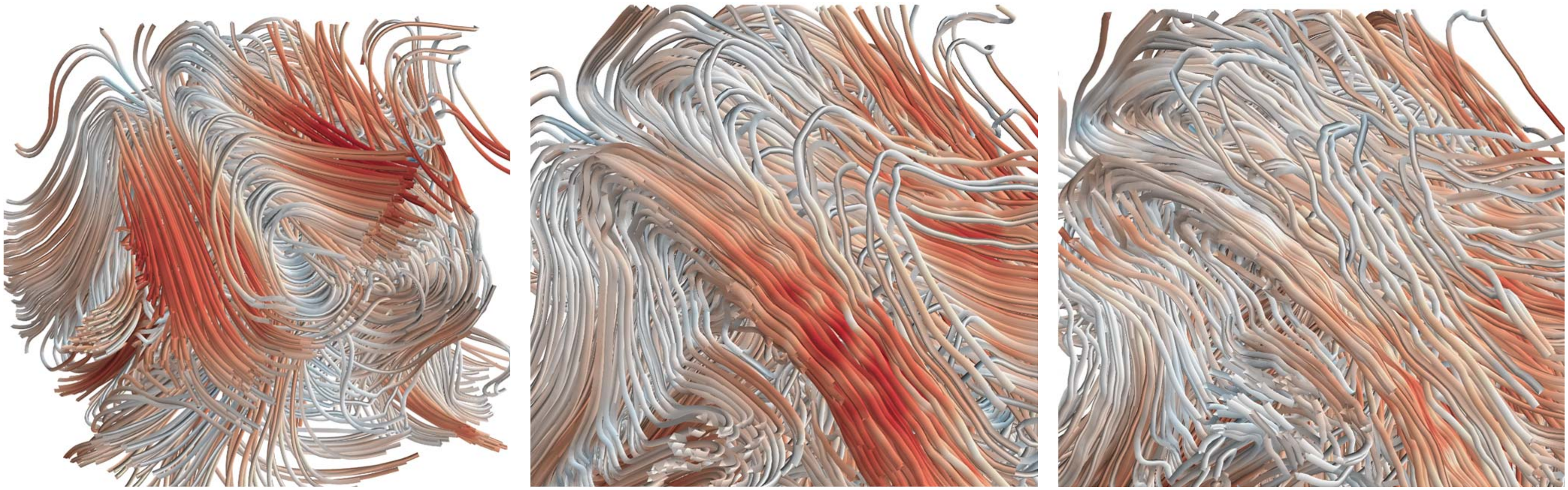
[cf. Rincon, AAS & Cowley 2015, MNRAS 447, L45]



Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

Plasma Dynamo Simulations by F. Rincon

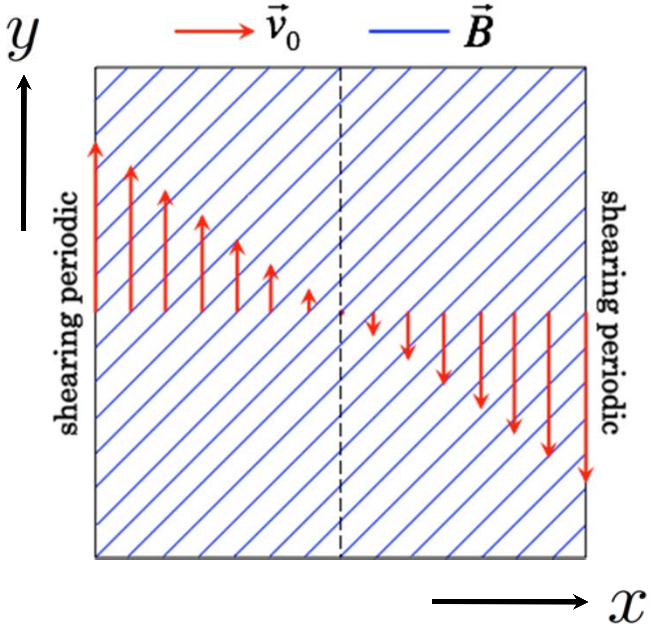
Pressure anisotropy relaxes in some self-consistent way:

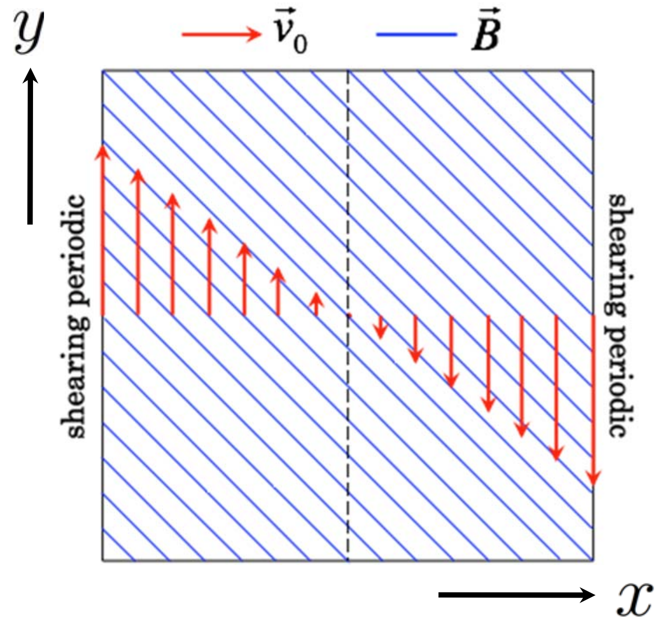


It would be fascinating to follow this dynamo for a long time and see how the macro-micro scale interaction works, how anisotropy adjusts, etc. But this is currently unaffordable in 3D3V.

Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

Back to Instabilities in a Box (M. Kunz)



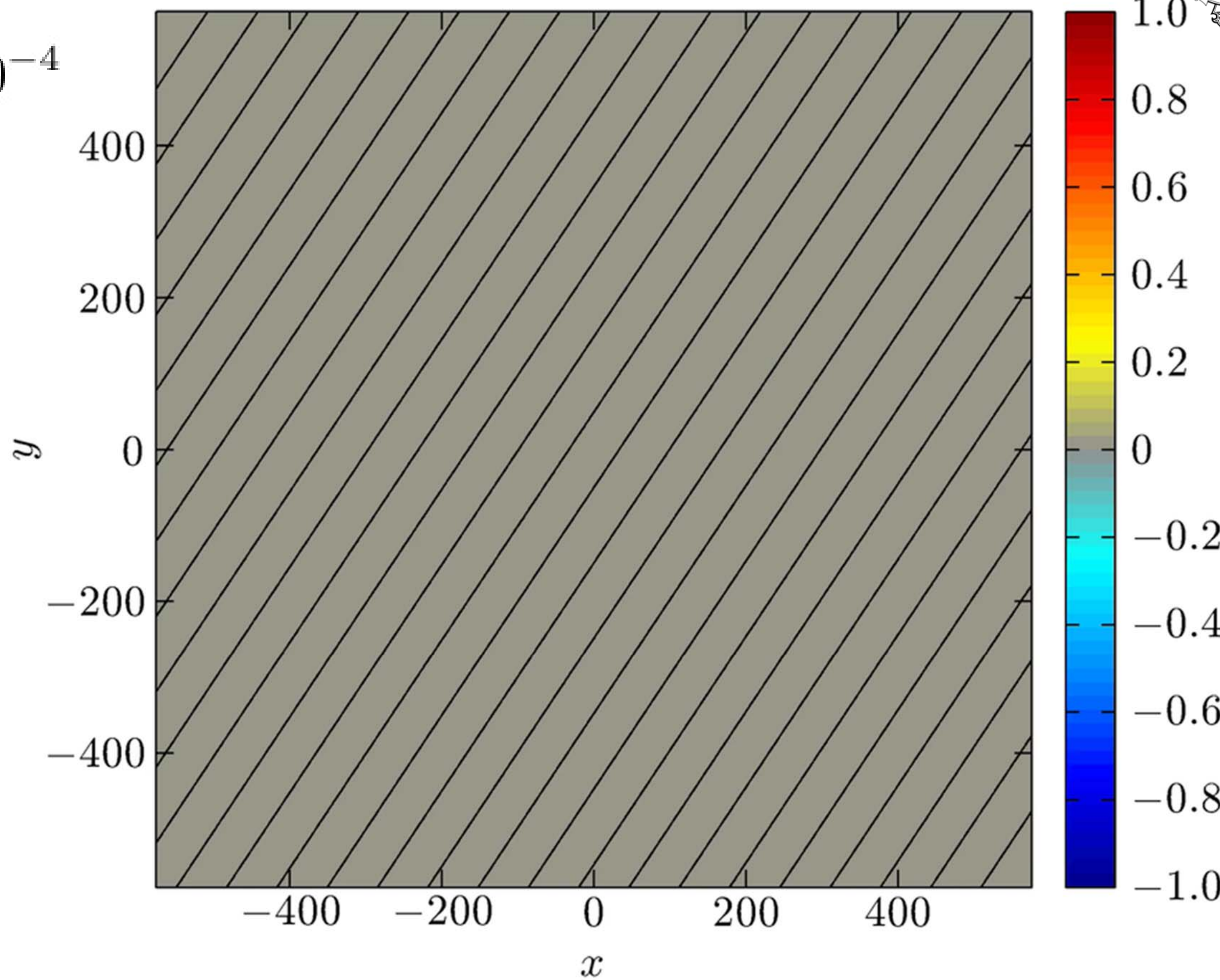


Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Firehose Instability (M. Kunz)

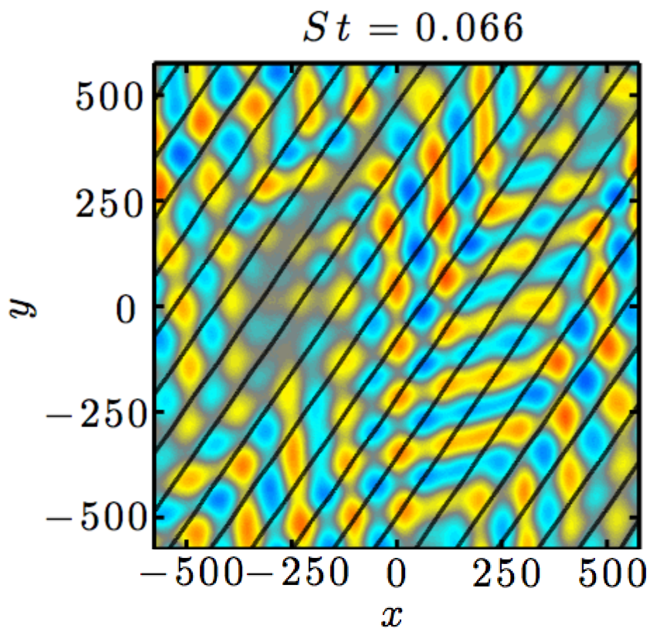
$$\frac{S}{\Omega_i} = 3 \times 10^{-4}$$

$$\beta_i = 200$$



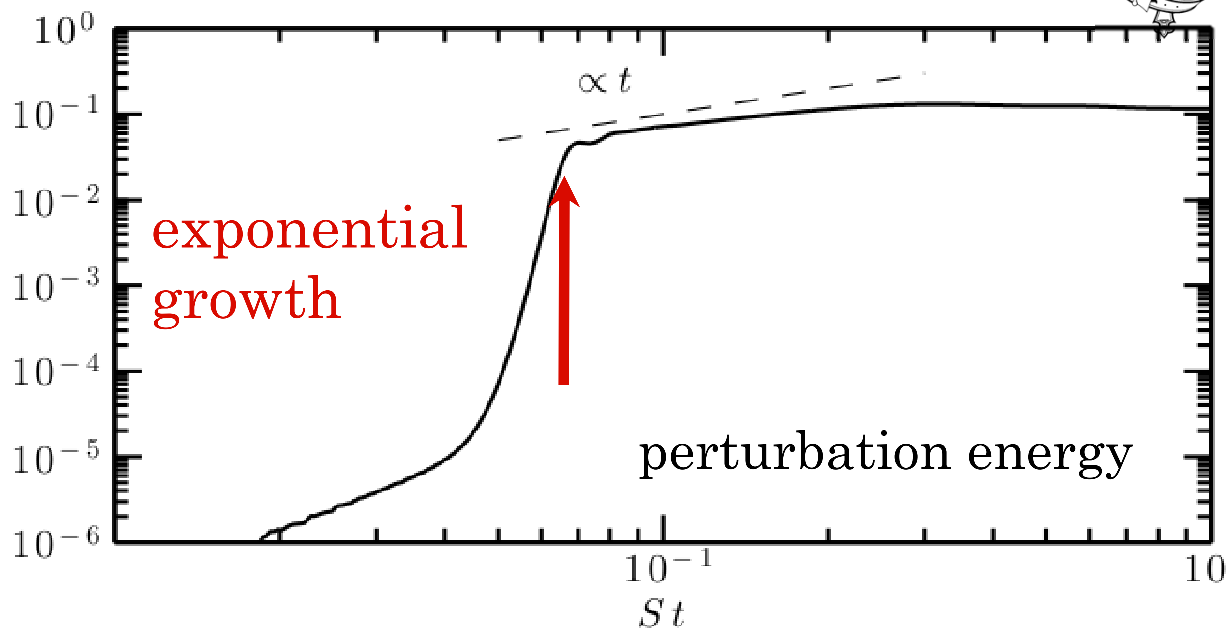
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

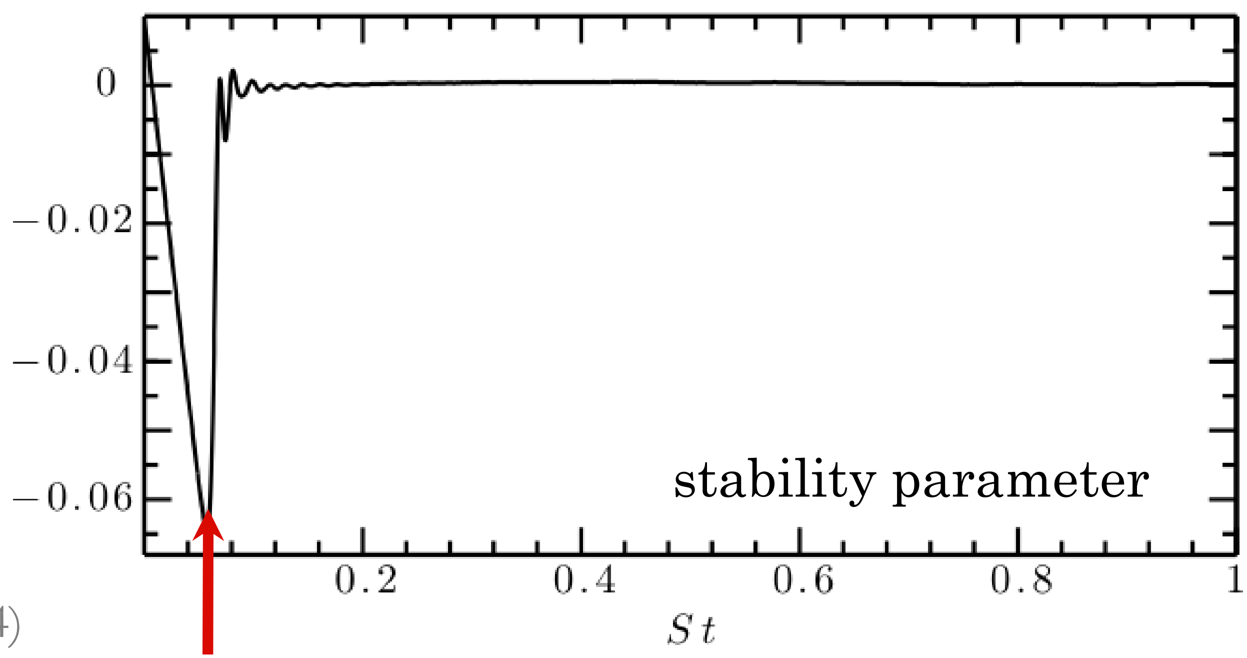
Firehose Instability: Linear



oblique modes

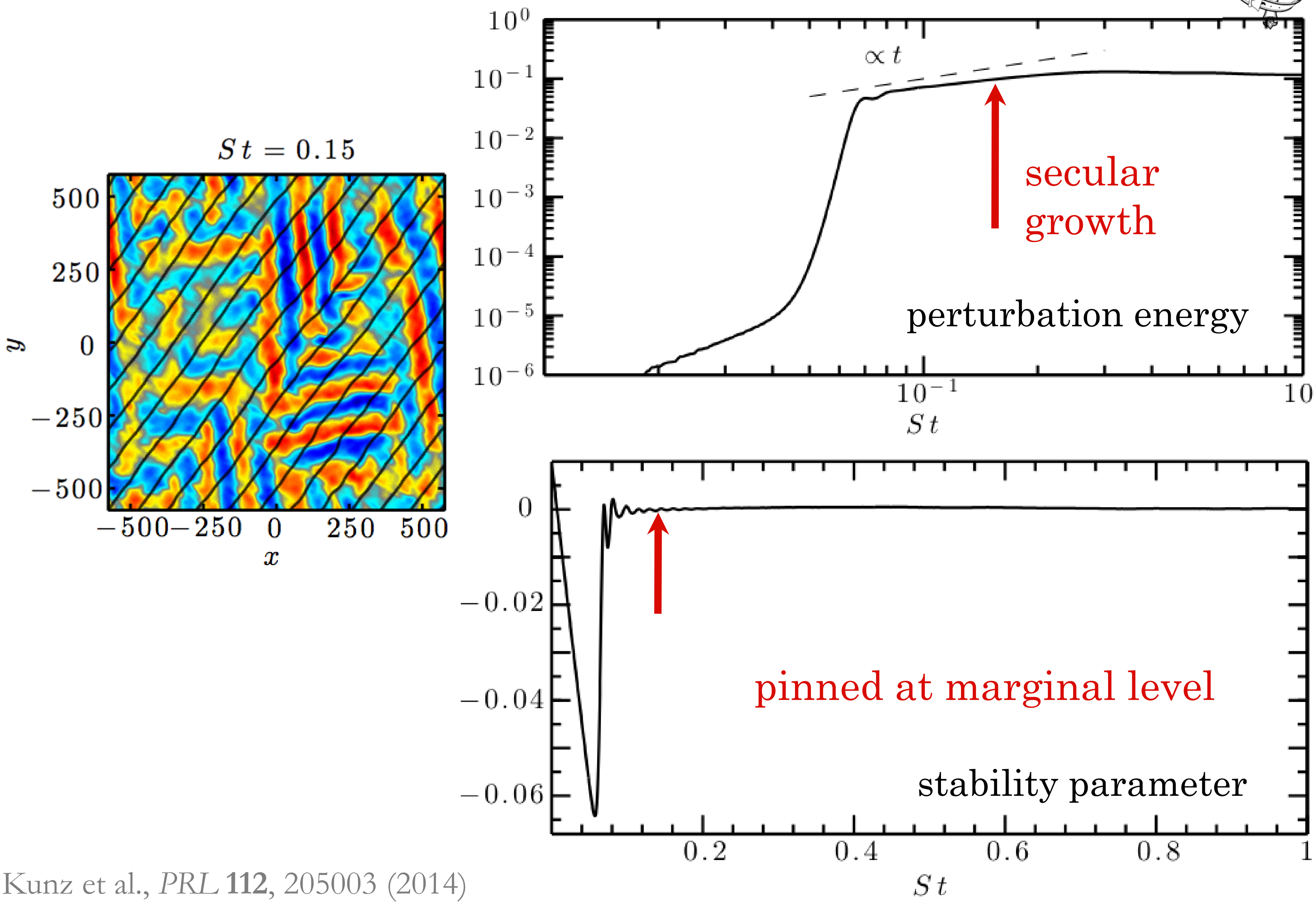
$$k_{||}\rho_i \approx k_\perp \rho_i \approx 0.4$$





Kunz et al., *PRL* **112**, 205003 (2014)

Firehose Instability: Secular

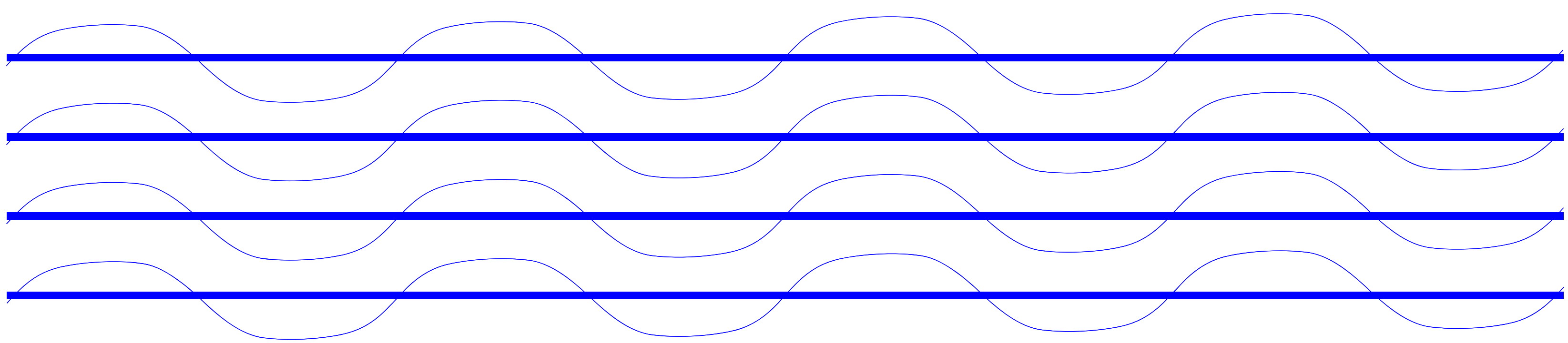


Kunz et al., *PRL* **112**, 205003 (2014)

Firehose Instability: Secular

$$\overline{B^2} = \overline{|\mathbf{B}_0 + \delta\mathbf{B}_\perp|^2} = B_0^2 + \overline{|\delta\mathbf{B}_\perp|^2}$$

$$\Delta = 3\int^t \mathrm{d}t' \, \overline{\frac{\mathrm{d}\ln B}{\mathrm{d}t}} = \int^t \mathrm{d}t' \left(\underbrace{-3\left|\frac{\mathrm{d}\ln B_0}{\mathrm{d}t}\right|}_{\text{pressure anisotropy driven by shear}} + \underbrace{\frac{3}{2}\frac{\mathrm{d}}{\mathrm{d}t}\frac{\overline{|\delta\mathbf{B}_\perp|^2}}{B_0^2}}_{\text{pressure anisotropy from firehose}} \right) \rightarrow \underbrace{-\frac{2}{\beta}}_{\text{marginal stability}}$$



AAS et al., *PRL* **100**, 081301 (2008)
Rosin et al., *MNRAS* **413**, 7 (2011)
Melville, AAS, Kunz, *MNRAS* in press (2016) [arXiv:1512.08131]

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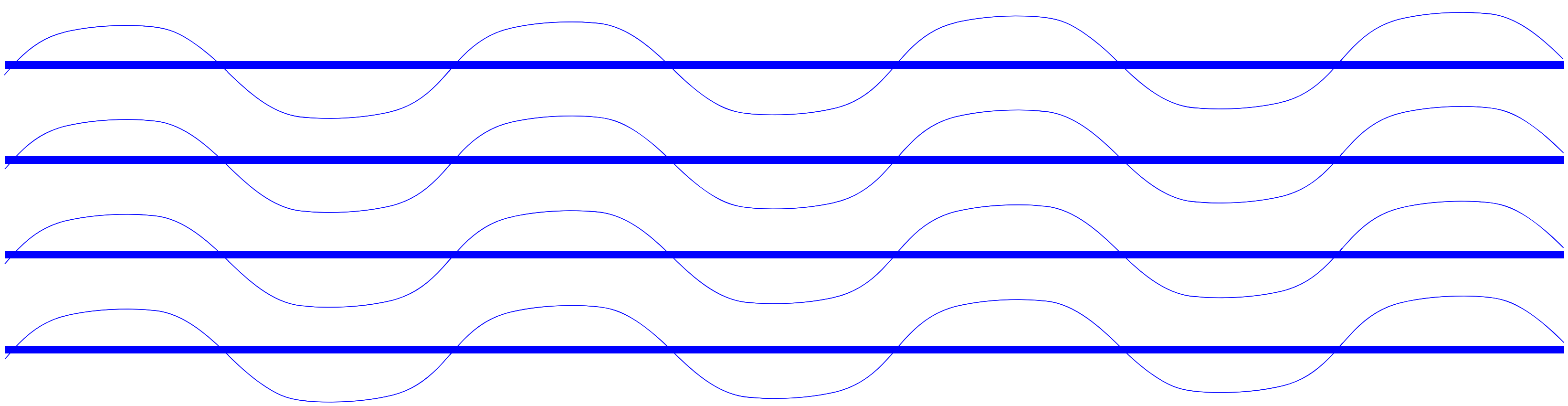

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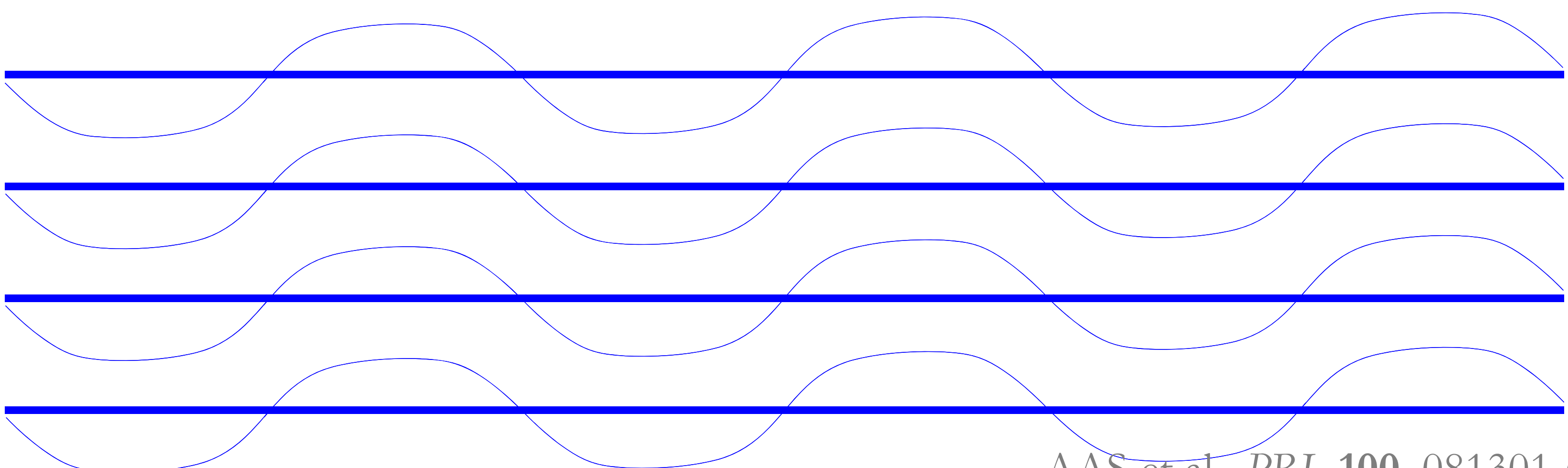

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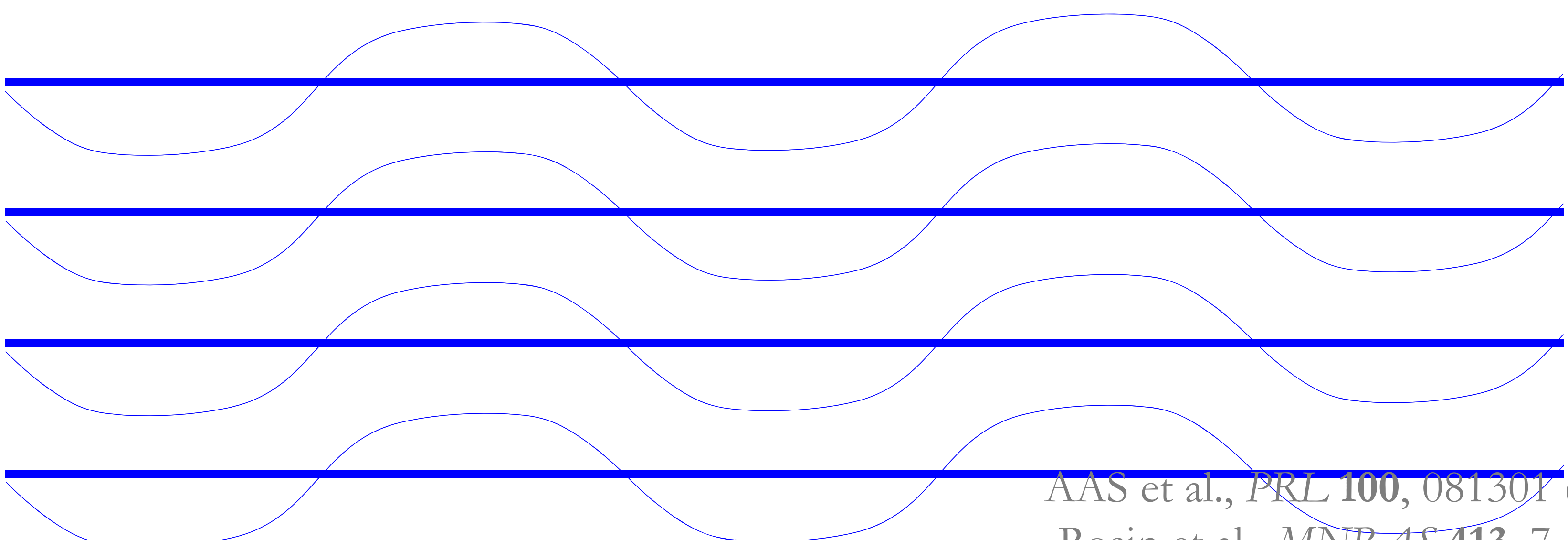

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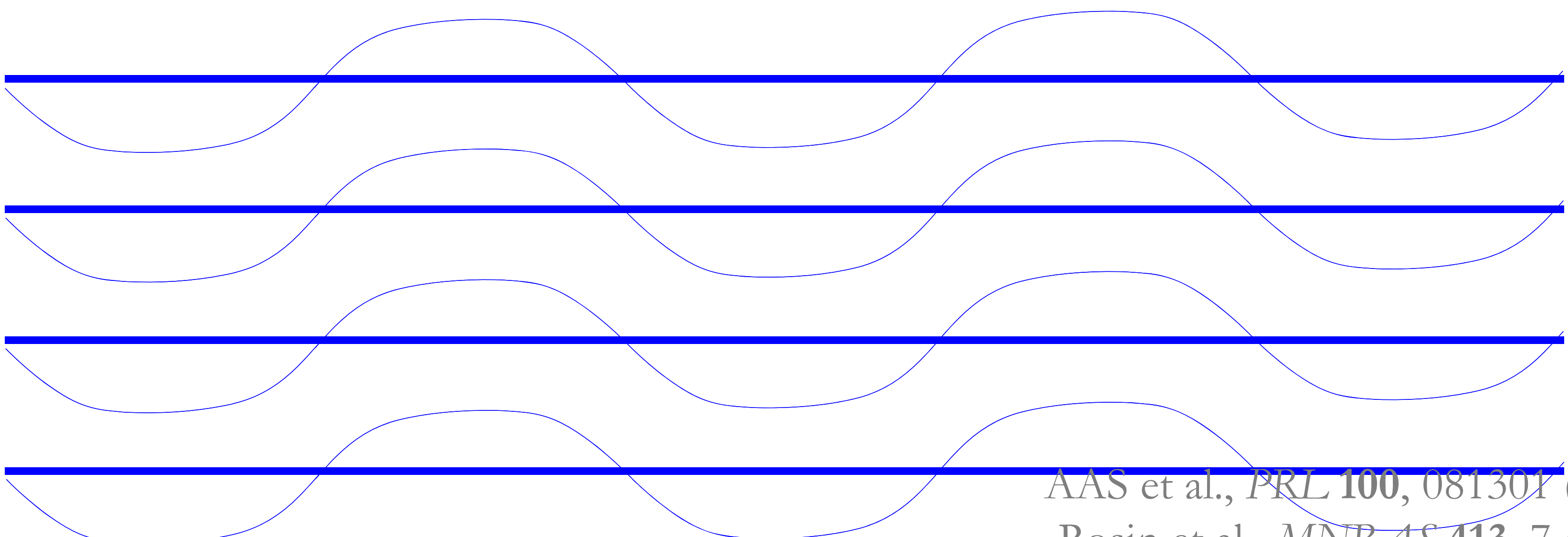
$$\frac{3}{2}\frac{\overline{|\delta\mathbf{B}_\perp|^2}}{B_0^2} = 3S\int^t \mathrm{d}t' \, \hat{b}_x(t')\hat{b}_y(t') - \frac{2}{\beta} \sim St$$

secular growth



AAS et al., *PRL* **100**, 081301 (2008)
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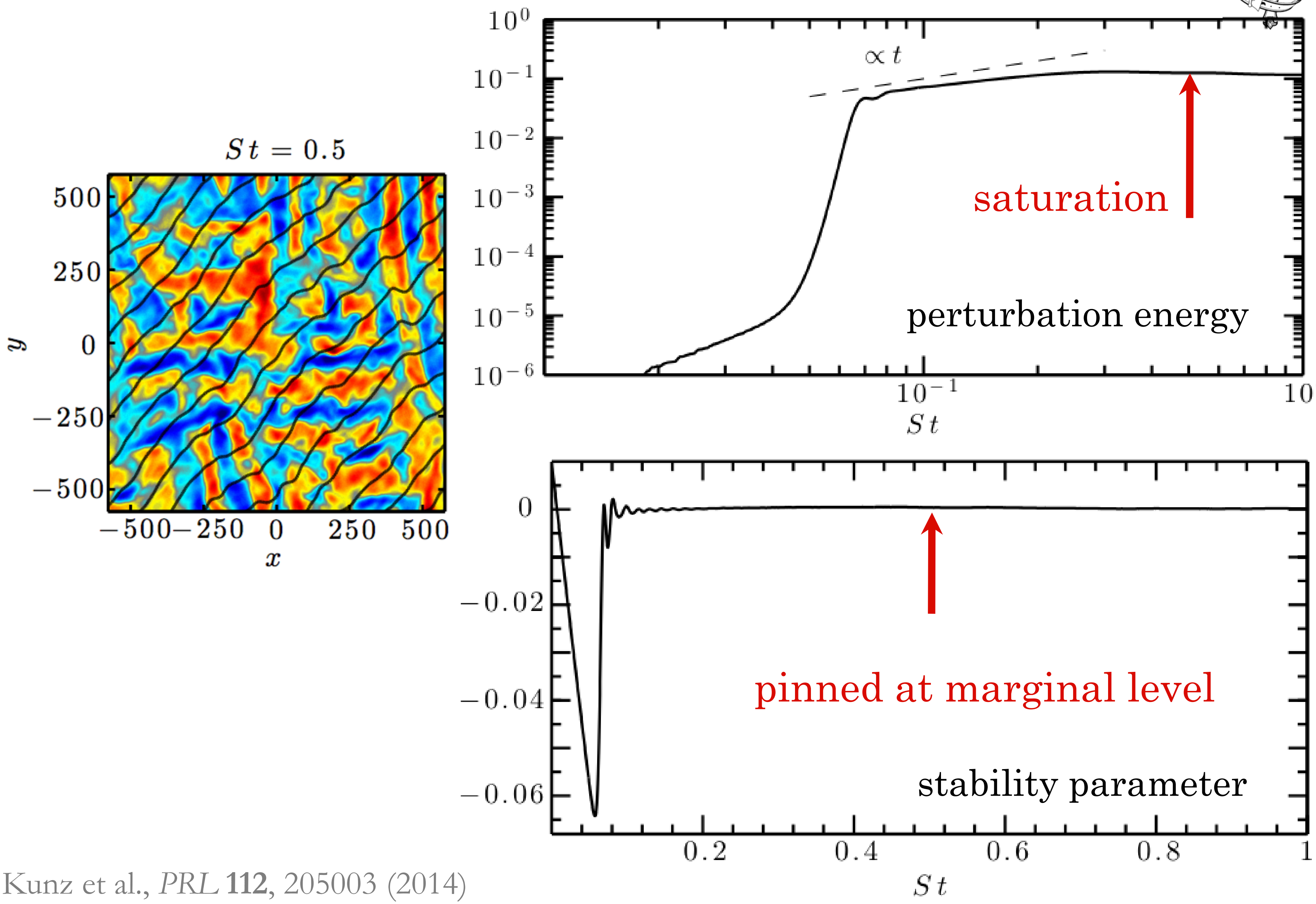
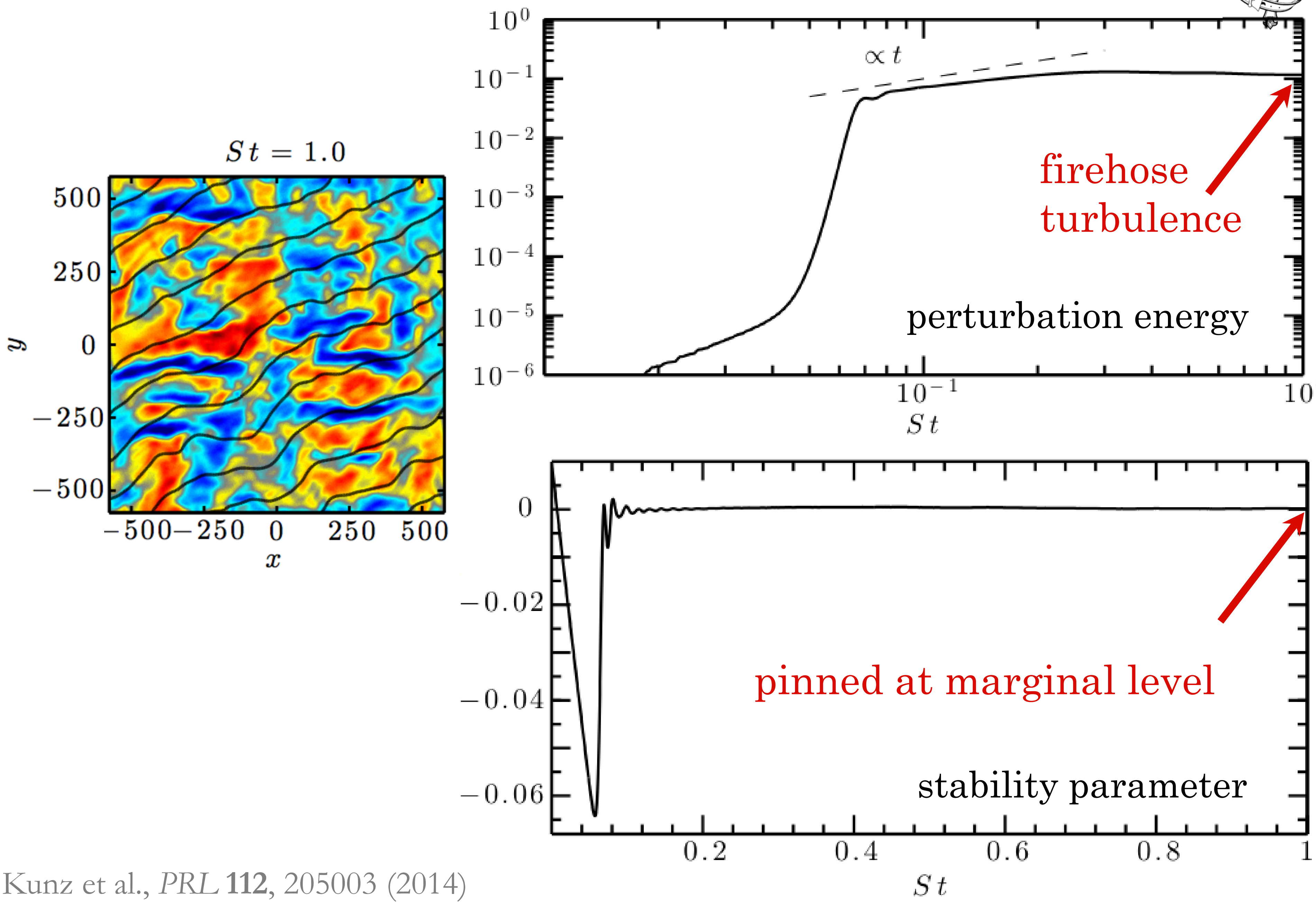
Melville, AAS, Kunz, *MNRAS* in press (2016) [arXiv:1512.08131]

Firehose Instability: Saturated



Kunz et al., *PRL* **112**, 205003 (2014)

Firehose Instability: Saturated

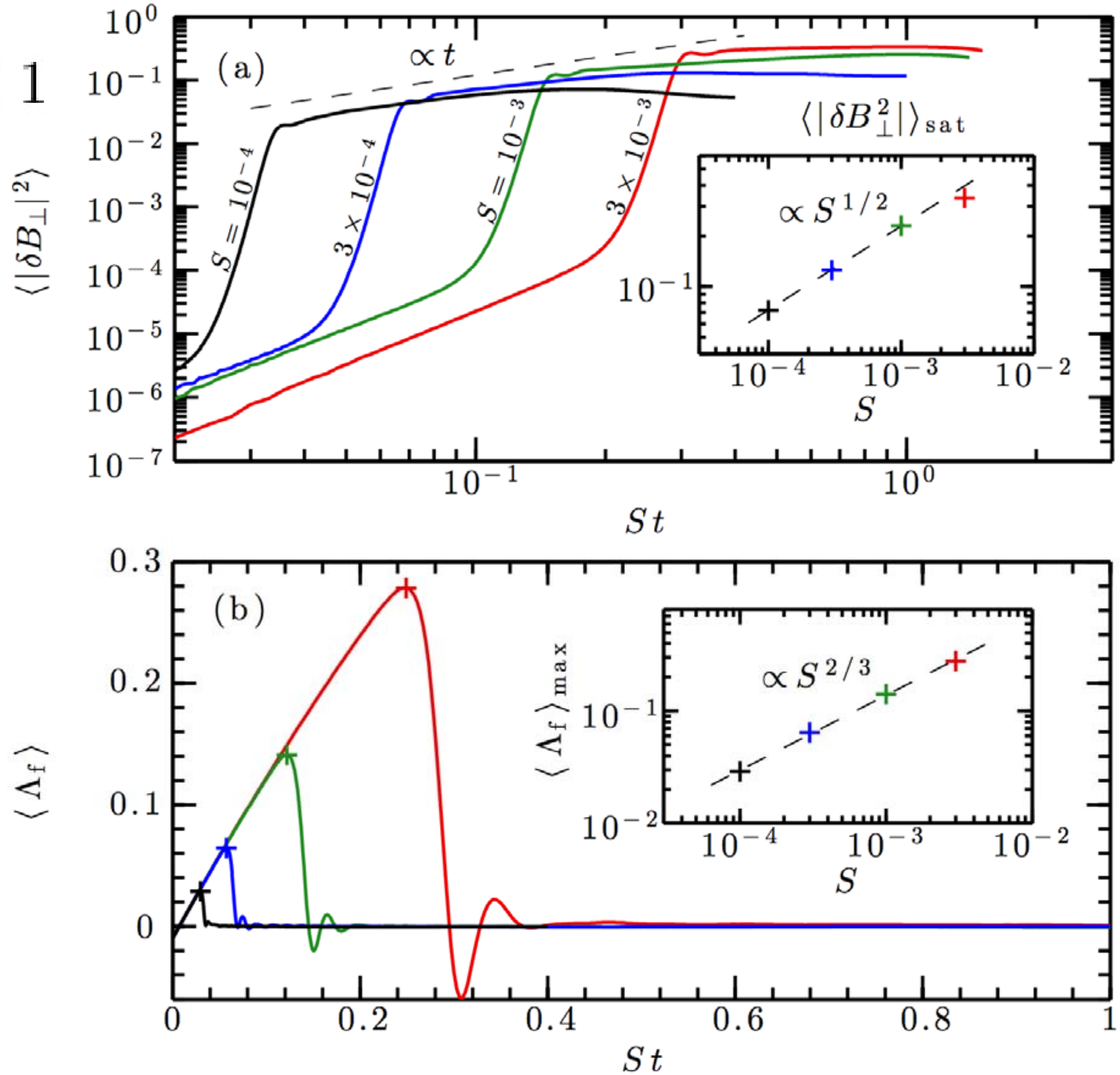


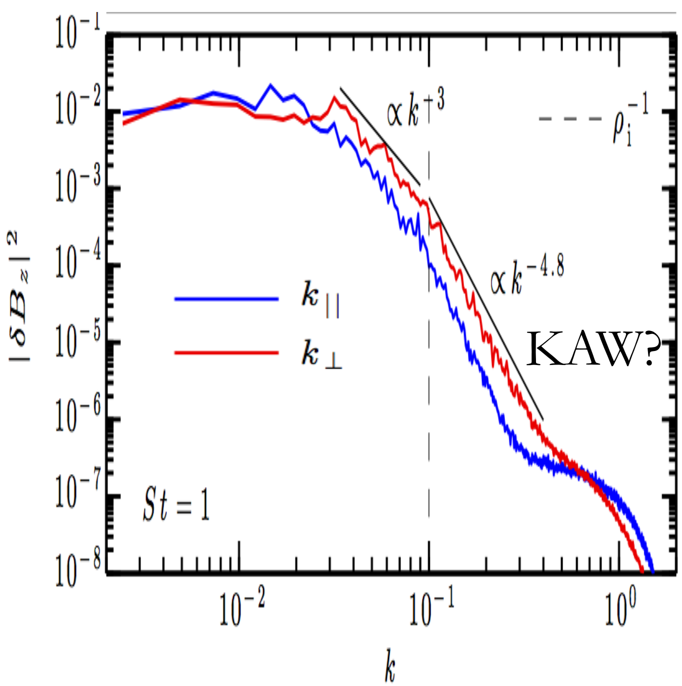
Kunz et al., *PRL* **112**, 205003 (2014)

Firehose Saturates at Small Amplitudes

$$\frac{\langle|\delta\mathbf{B}_\perp|^2\rangle}{B_0^2} \propto \left(\frac{S}{\Omega_i}\right)^{1/2} \ll 1$$

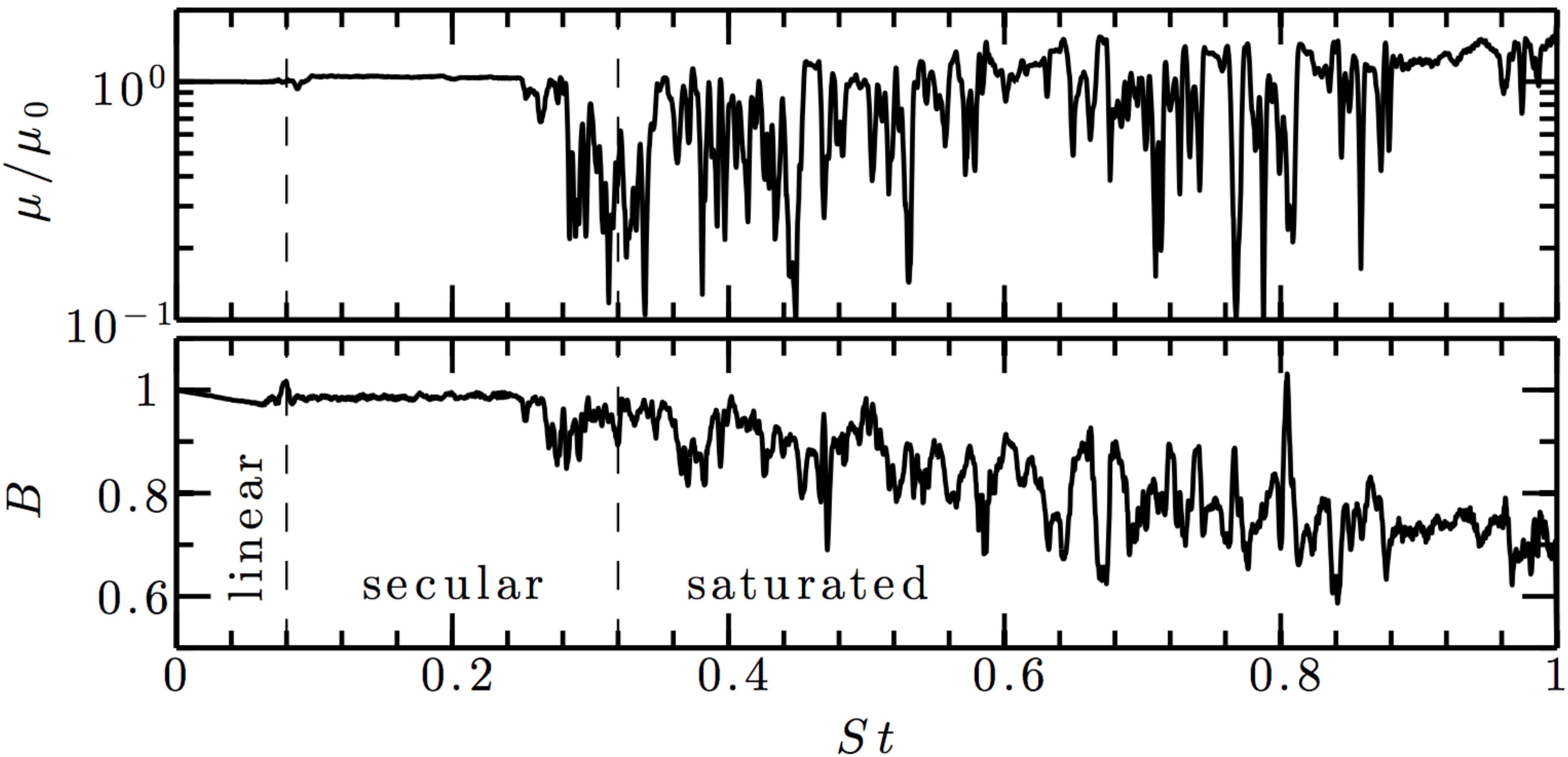
small-amplitude
Larmor-scale
firehose turbulence





Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Saturated Firehose Scatters Particles



μconservation is broken at long times, firehose fluctuations scatter particles to maintain pressure anisotropy at marginal level

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Saturated Firehose Scatters Particles

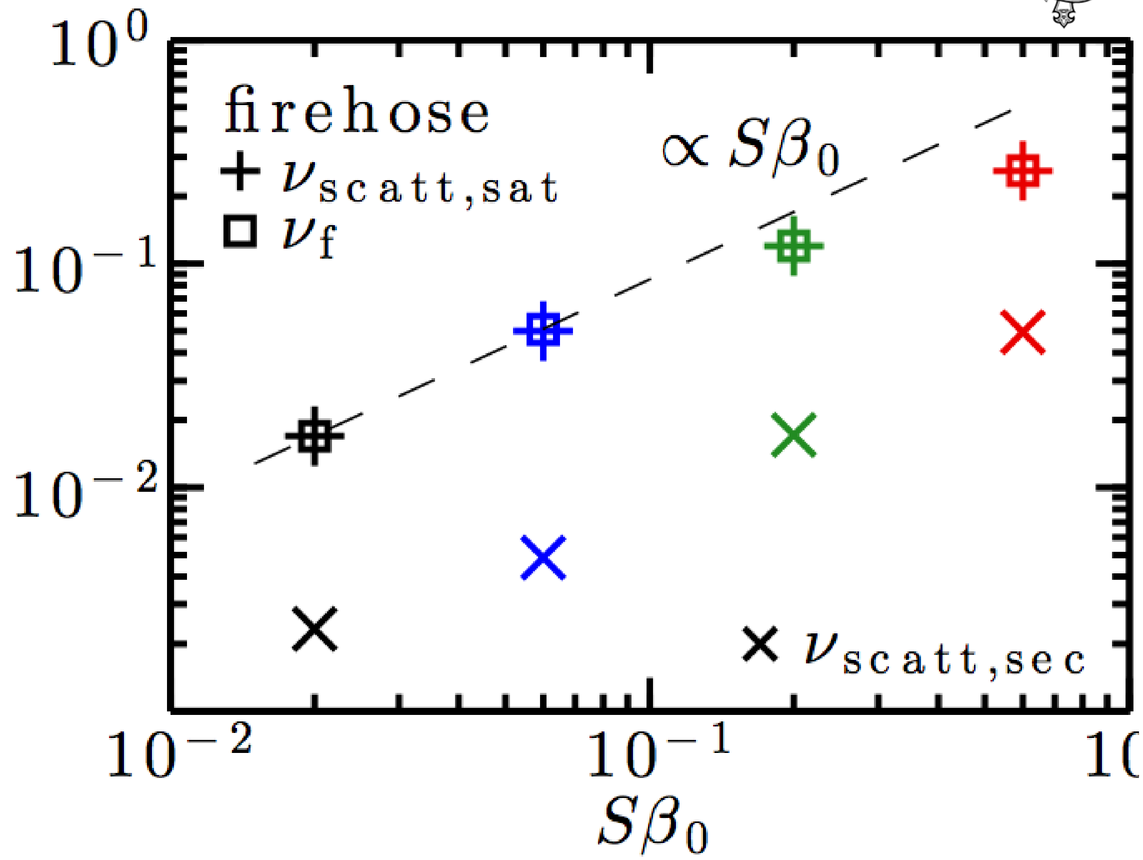
$$\frac{d\Delta}{dt} = 3\frac{d\ln|\langle \mathbf{B}\rangle|}{dt} - \nu_f \Delta$$

$$= 0$$

$$\nu_f = \frac{3}{\Delta}\frac{d\ln|\langle \mathbf{B}\rangle|}{dt}$$

$$= -\frac{3\beta}{2}\frac{d\ln|\langle \mathbf{B}\rangle|}{dt}$$

$$\sim S\beta$$



□ effective collisionality required to maintain marginal stability

+ measured scattering rate during the saturated phase

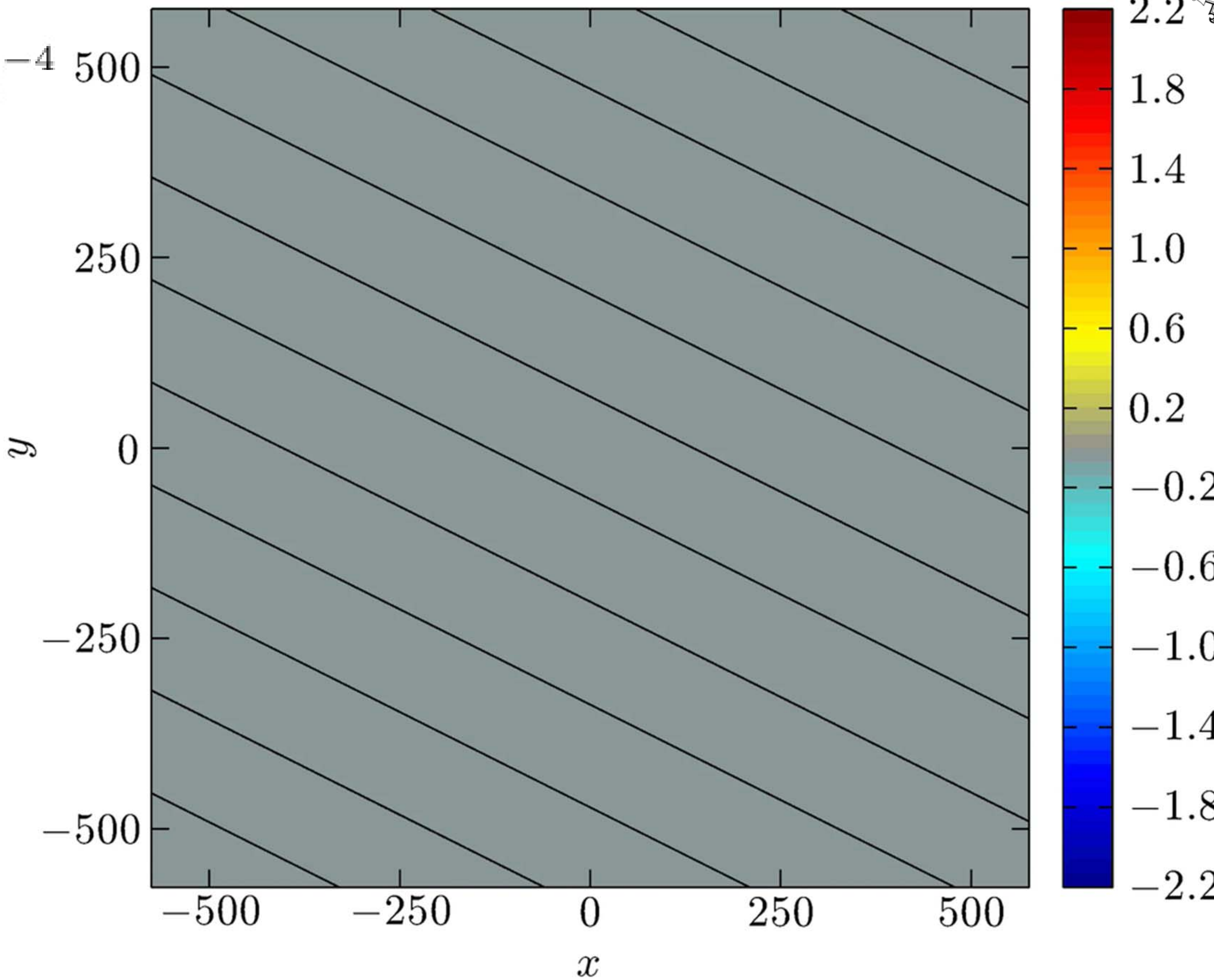
× measured scattering rate during the secular phase

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Mirror Instability (M. Kunz)

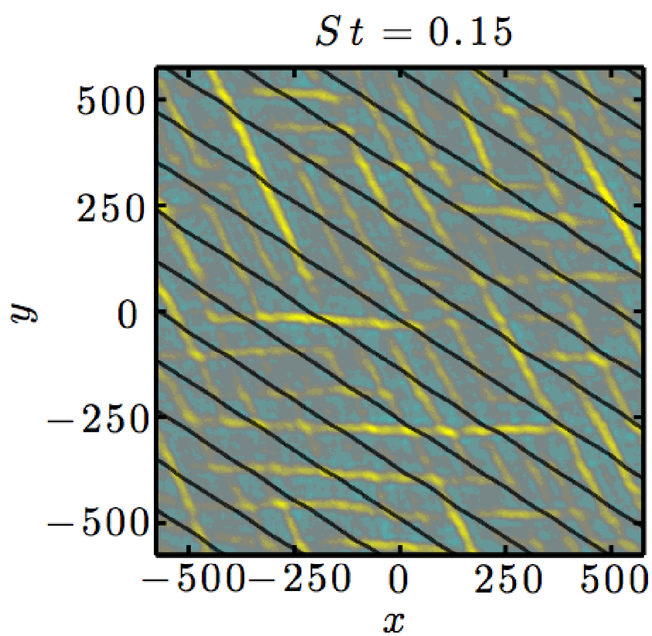
$$\frac{S}{\Omega_i} = 3 \times 10^{-4}$$

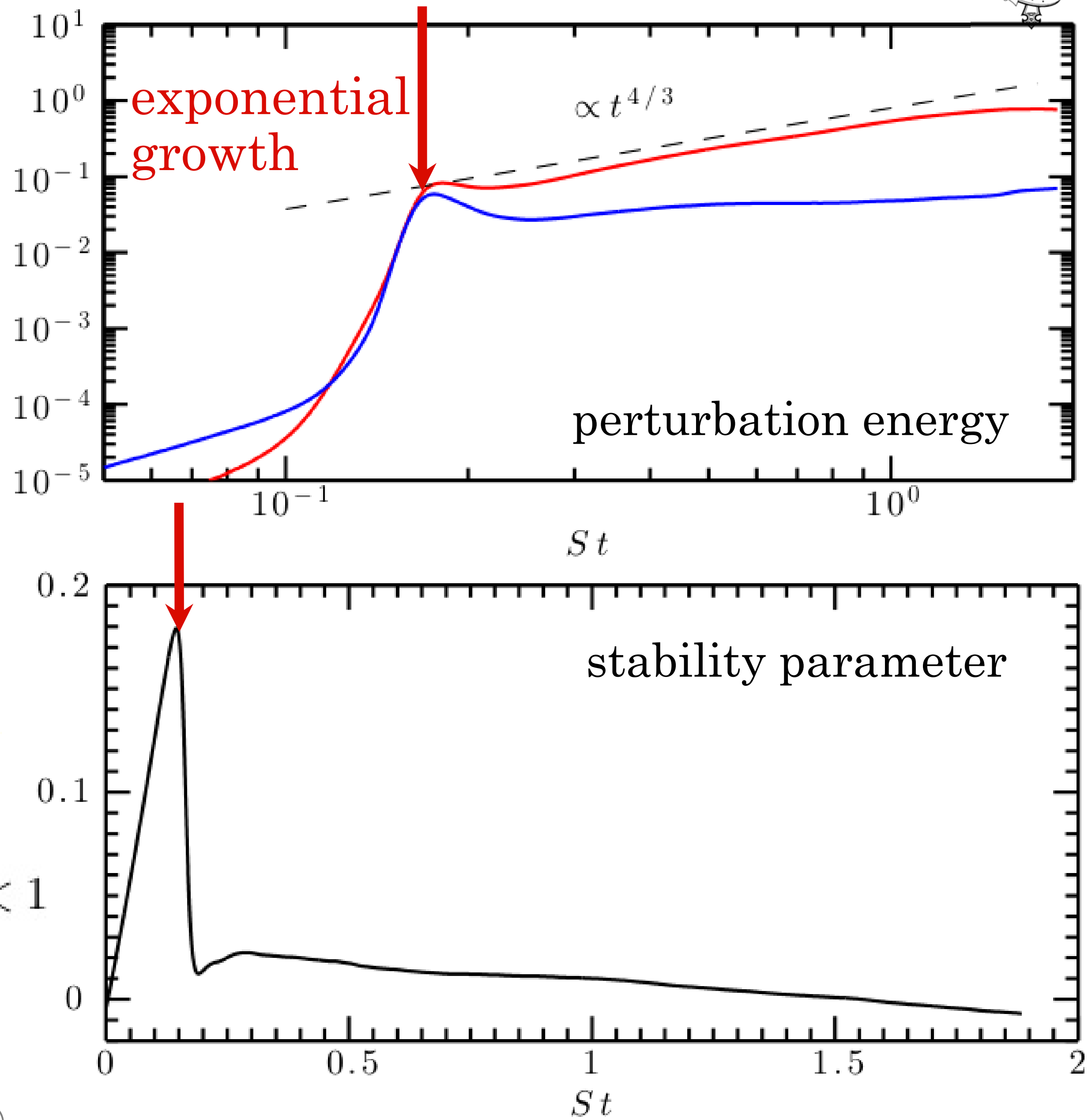
$$\beta_i = 200$$



Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Mirror Instability: Linear



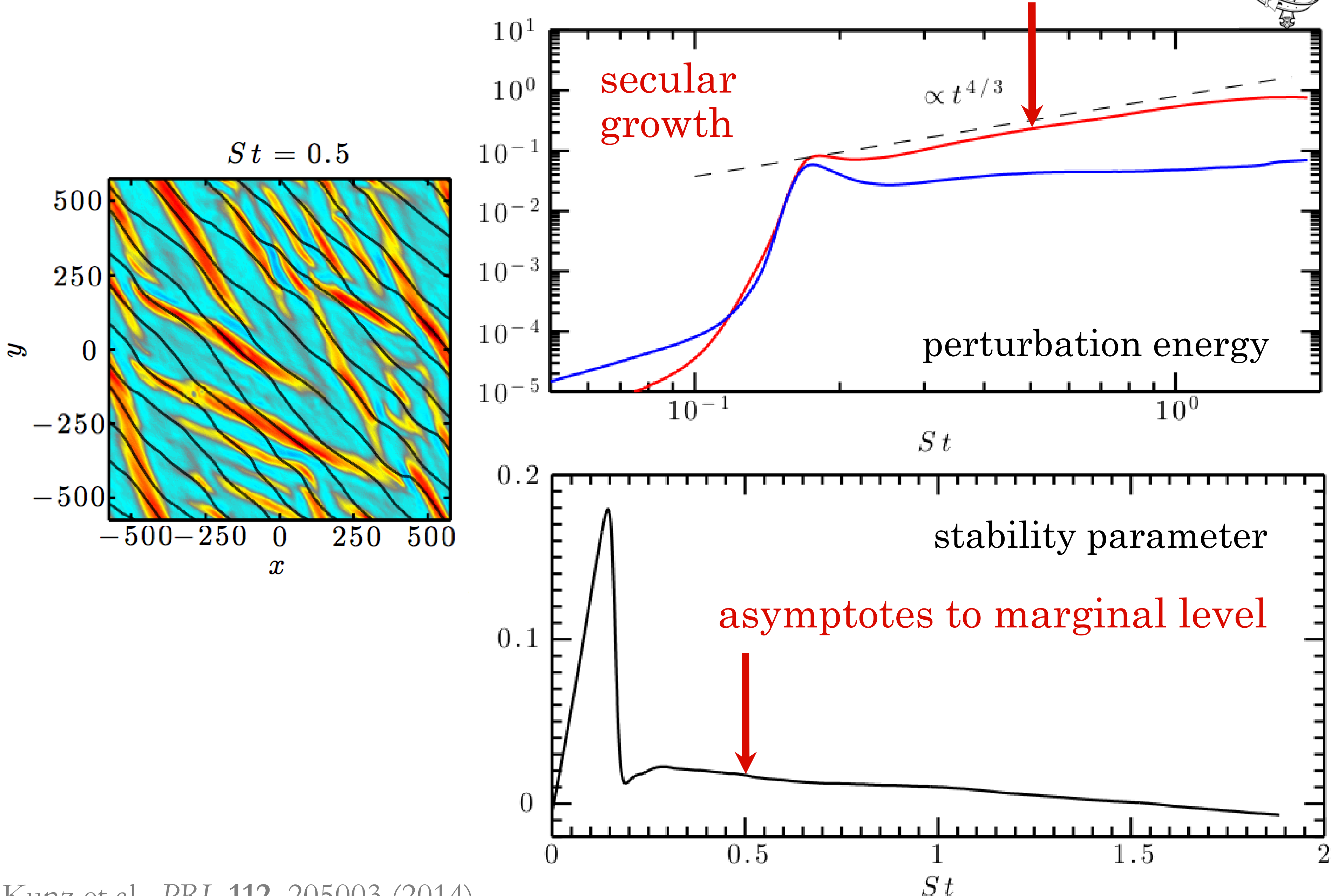


long, oblique modes

$$k_{\|}\rho_i \sim \left(\Delta - \frac{1}{\beta}\right)^{1/2} k_{\perp}\rho_i \ll 1$$

Kunz et al., *PRL* **112**, 205003 (2014)

Mirror Instability: Secular



Kunz et al., *PRL* **112**, 205003 (2014)

Mirror Instability: Secular

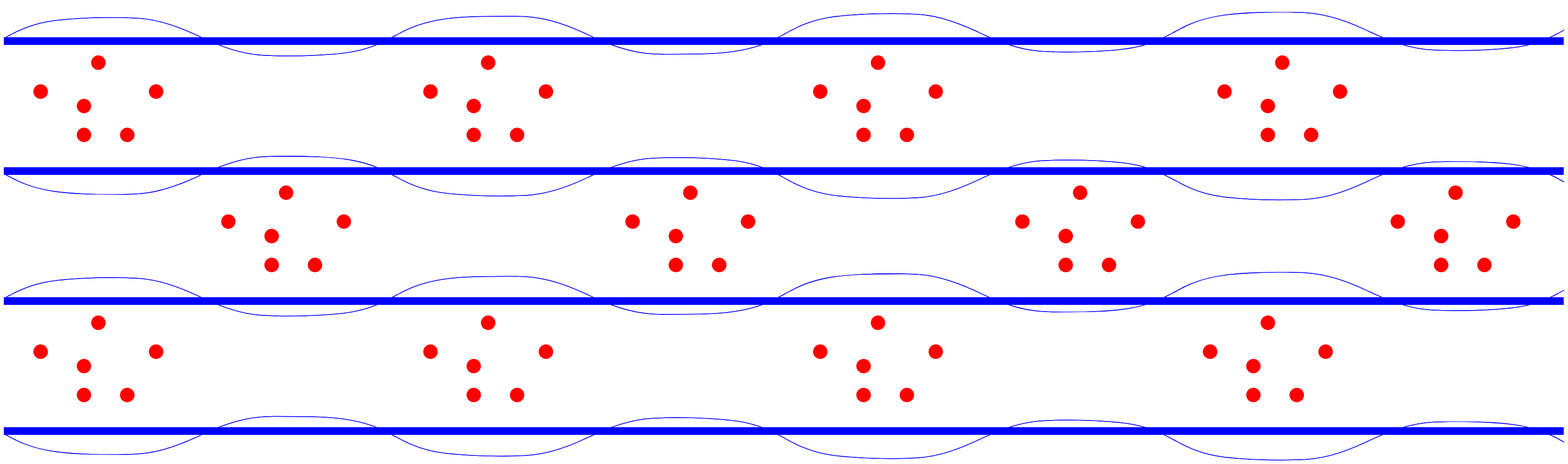
$$\overline{B} = B_0 + \overline{\delta B_\parallel}$$

$$\Delta = 3\int^t \mathrm{d}t' \, \overline{\frac{\mathrm{d}\ln B}{\mathrm{d}t}} = 3\int^t \mathrm{d}t' \left(\frac{\mathrm{d}\ln B_0}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}t}\frac{\overline{\delta B_\parallel}}{B_0} \right) \to \frac{1}{\beta}$$

pressure anisotropy driven by shear

pressure anisotropy from mirror-trapped particles in holes (fraction $\sim |\delta B_\parallel / B_0|^{1/2}$)

marginal stability



Rincon, AAS & Cowley, *MNRAS* **447**, L45 (2015)
Melville, AAS, Kunz, *MNRAS* in press (2016) [arXiv:1512.08131]

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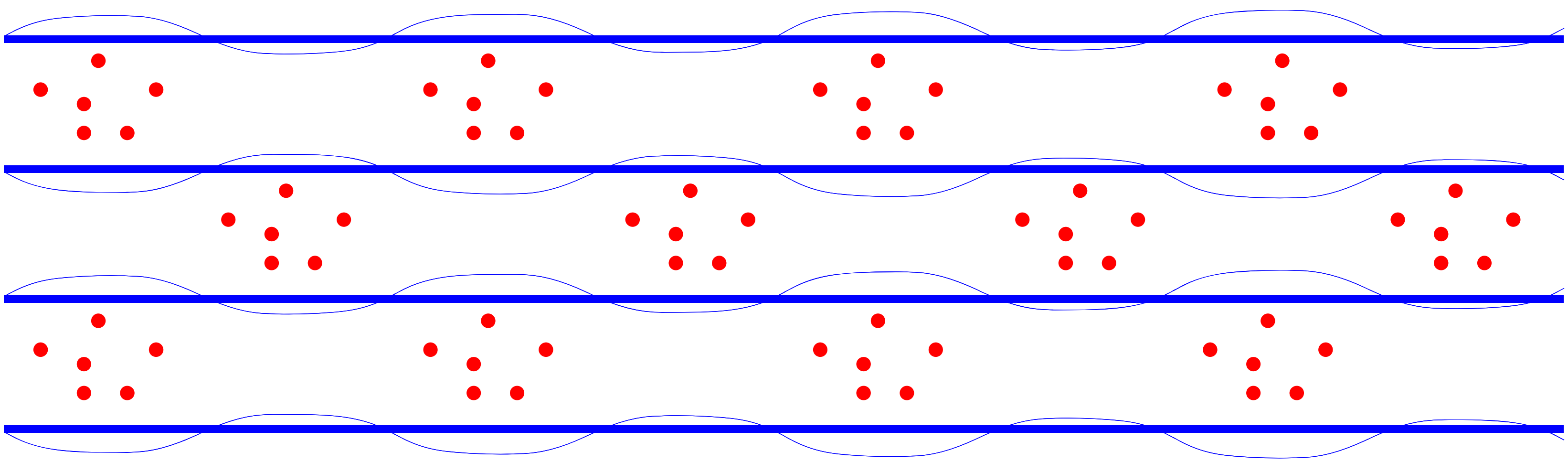

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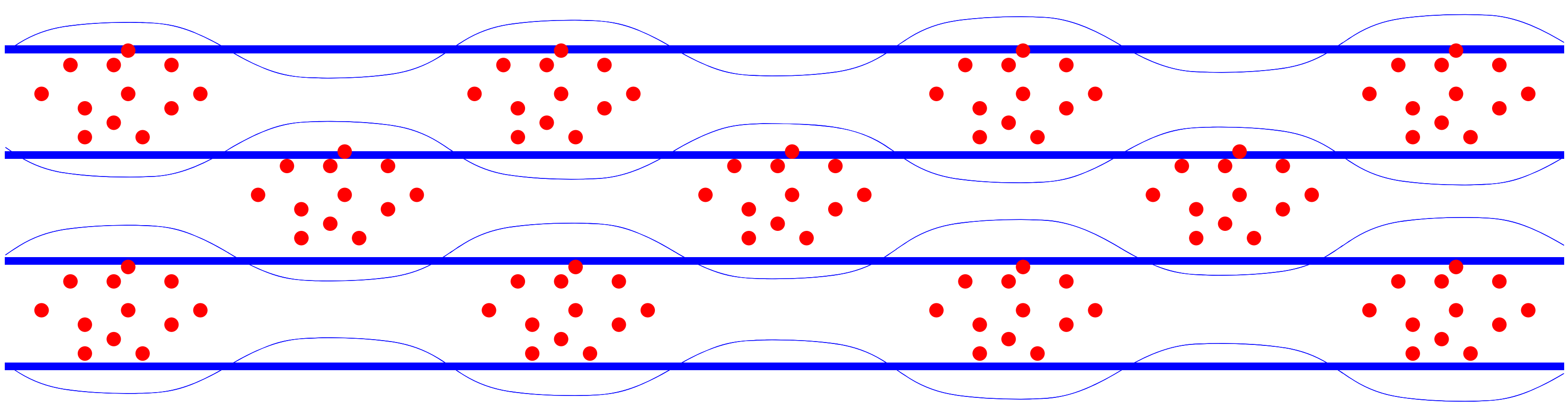

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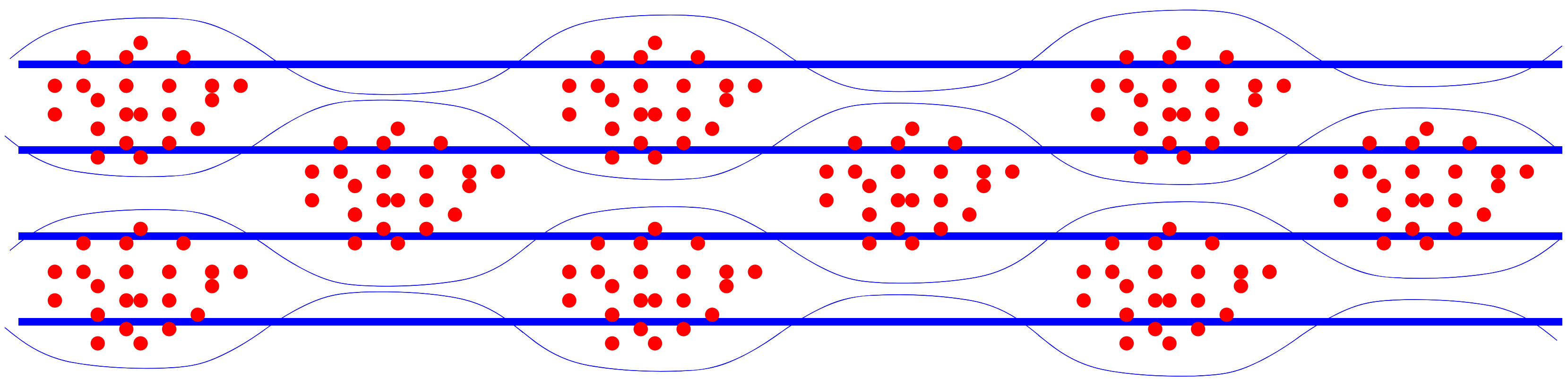

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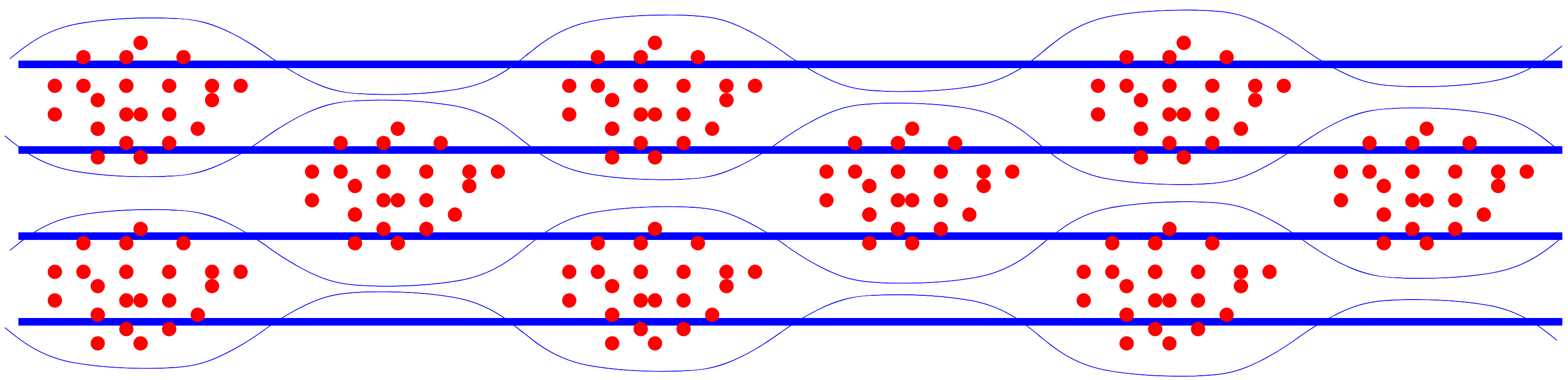
$$\overline{\left|\frac{\delta B_\parallel}{B_0}\right|^{3/2}} = S\int^t \mathrm{d}t' \, \hat{b}_x(t')\hat{b}_y(t') - \frac{1}{\beta} \quad \Rightarrow \quad \frac{\delta B_\parallel^2}{B_0^2} \sim (St)^{4/3}$$

secular growth



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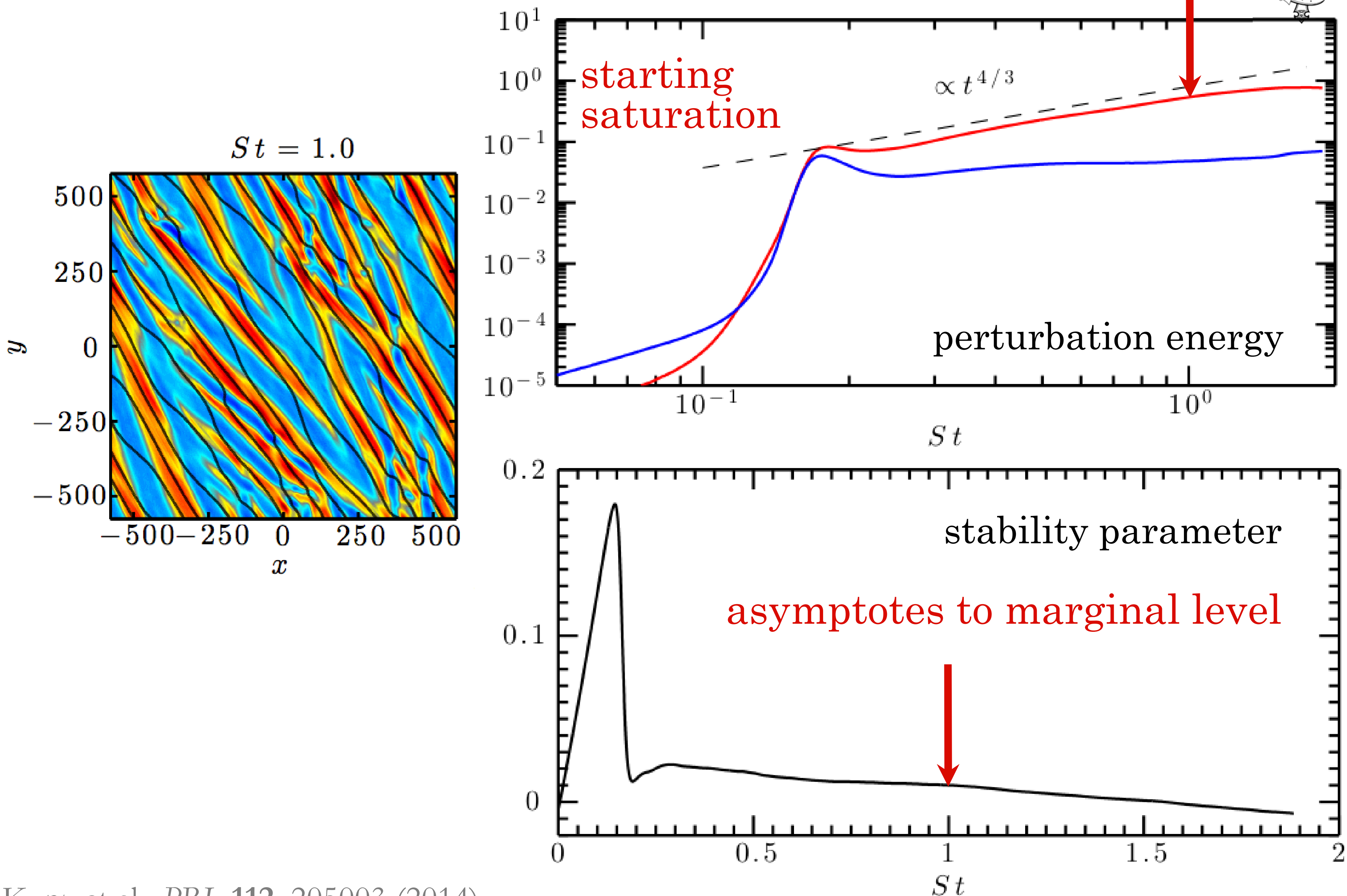
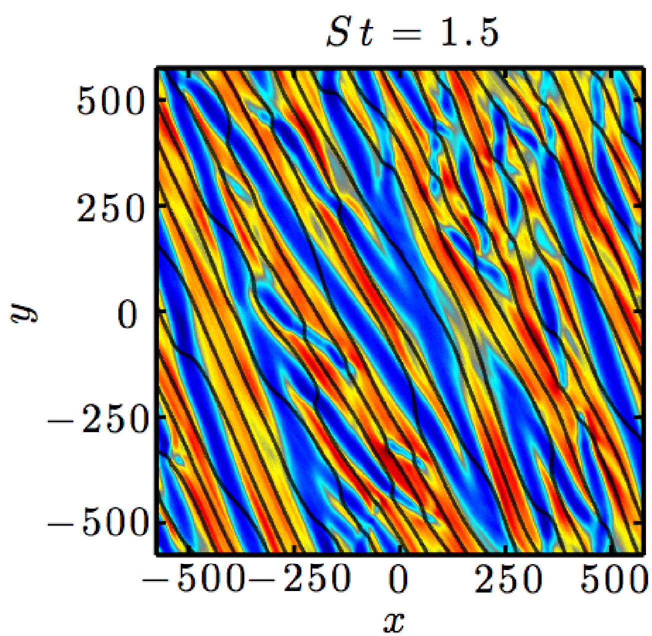
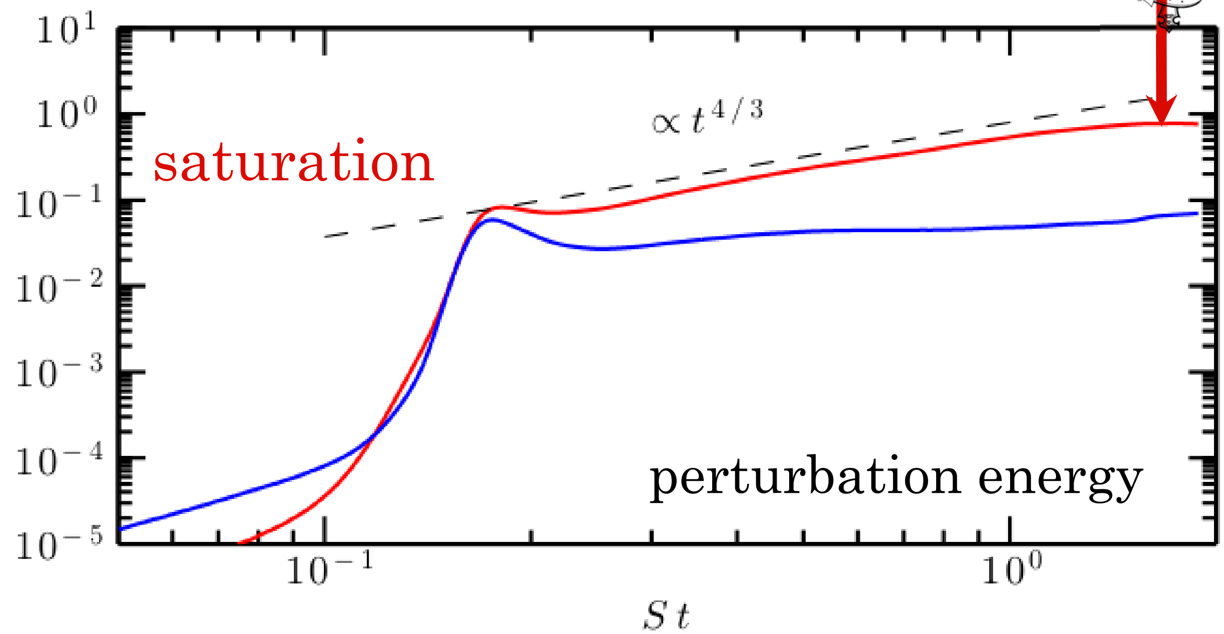
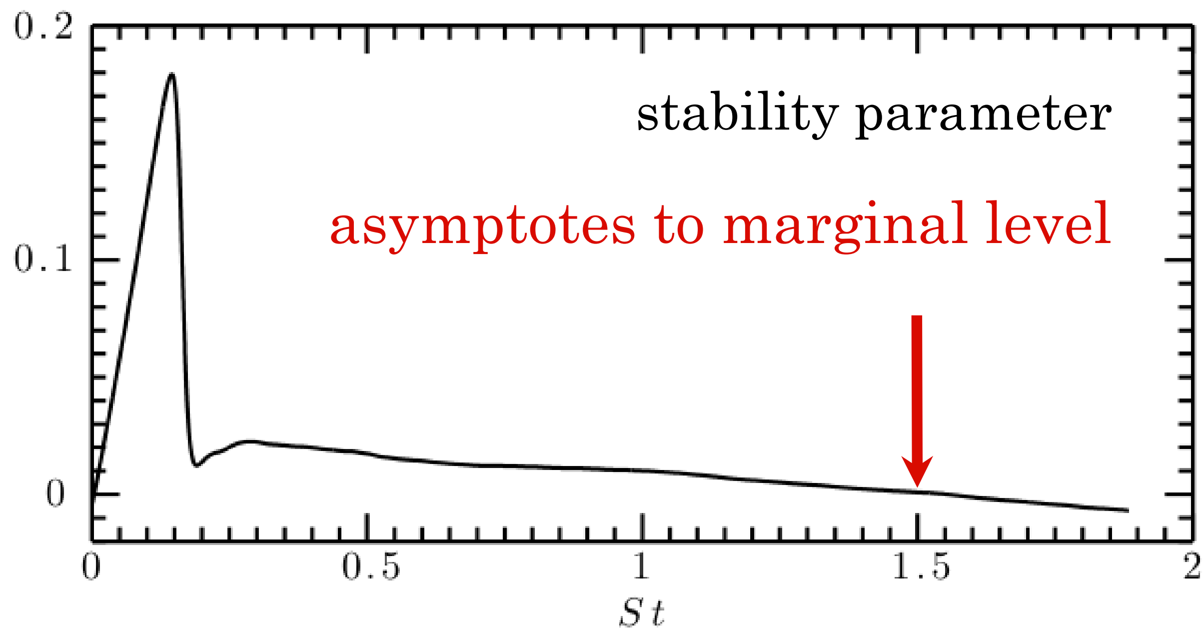


Kunz et al., *PRL* **112**, 205003 (2014)

Mirror Instability: Saturated





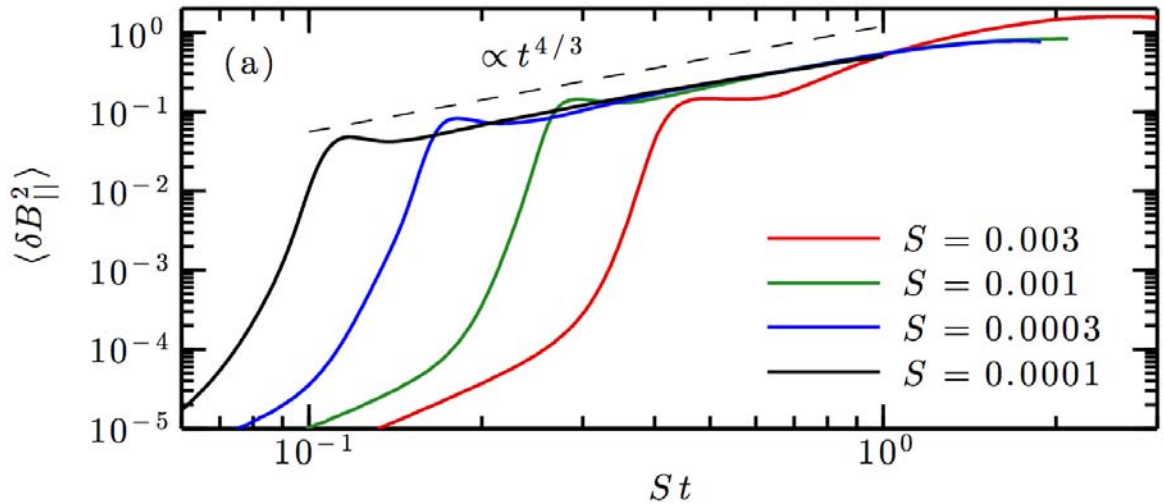


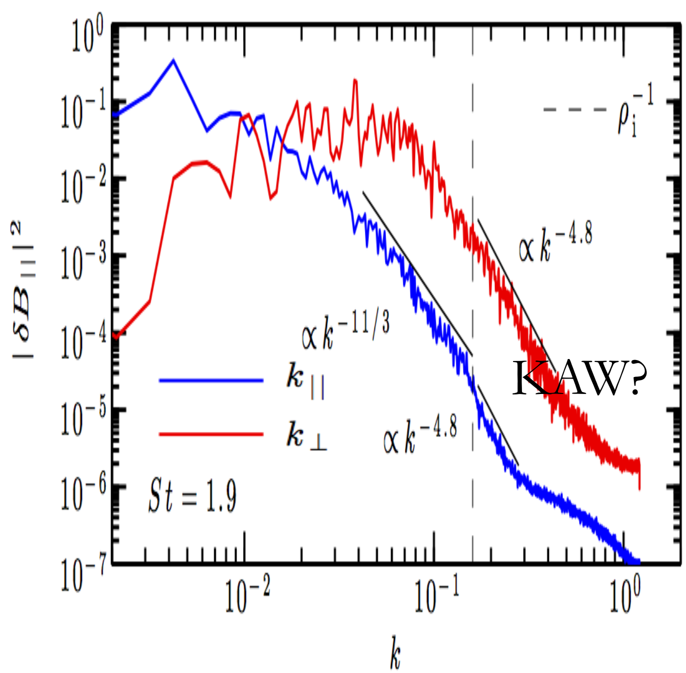
Kunz et al., *PRL* **112**, 205003 (2014)

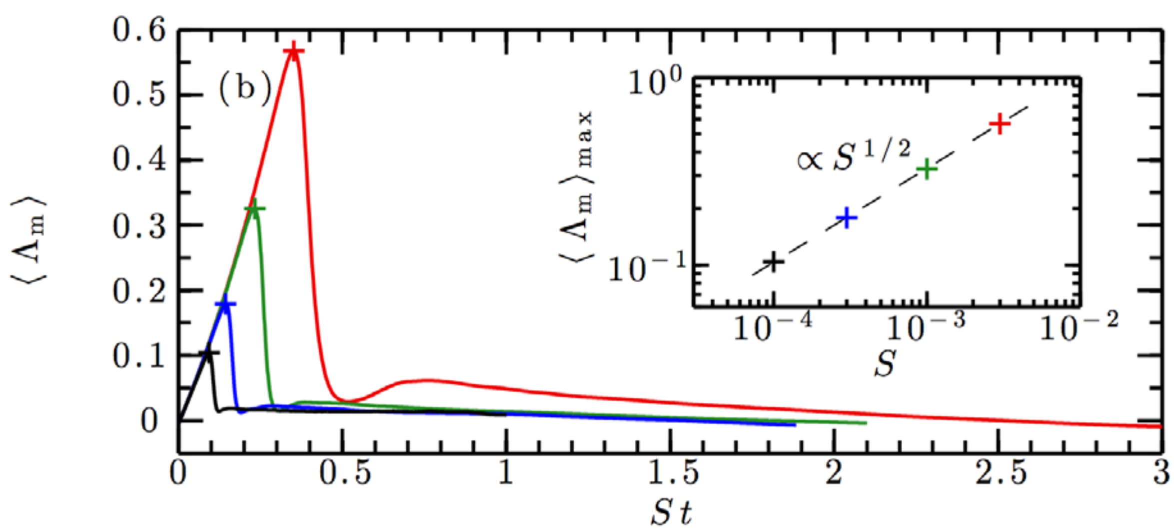
Mirror Saturates at Order-Unity Amplitudes

$$\frac{\langle \delta \mathbf{B}_{\parallel}^2 \rangle}{B_0^2} \sim 1$$

order-unity-amplitude (independent of S) long-parallel-scale mirror turbulence

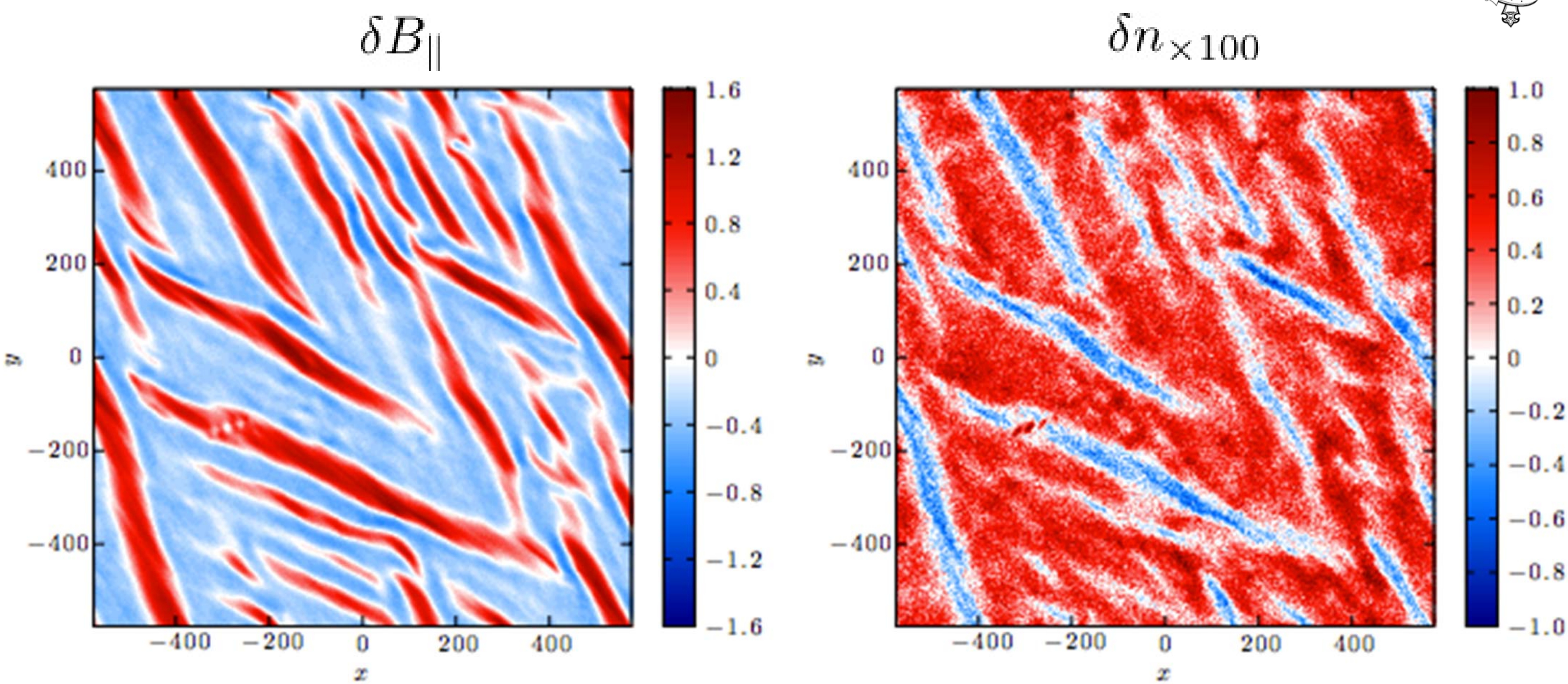






Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

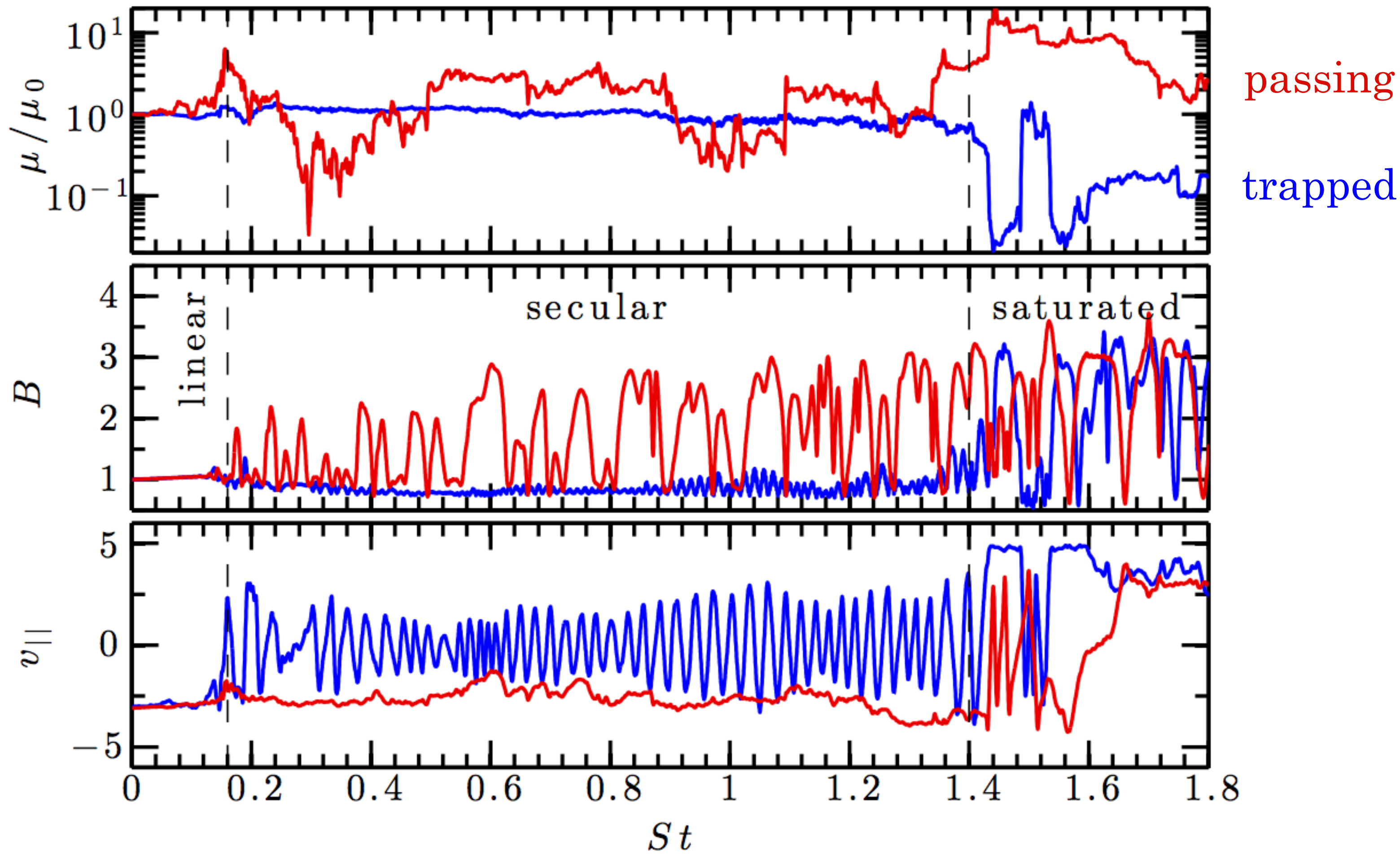
Mirror Instability: Trapped Particles



pressure anisotropy is regulated by trapped particles in magnetic mirrors, where field strength stays constant on average…

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Secular Mirror Doesn't Scatter Particles



pressure anisotropy is regulated by trapped particles in magnetic mirrors, where field strength stays constant on average…

no particle scattering until (late) saturation (then scattering off mirror edges)

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Secular Mirror Doesn't Scatter Particles

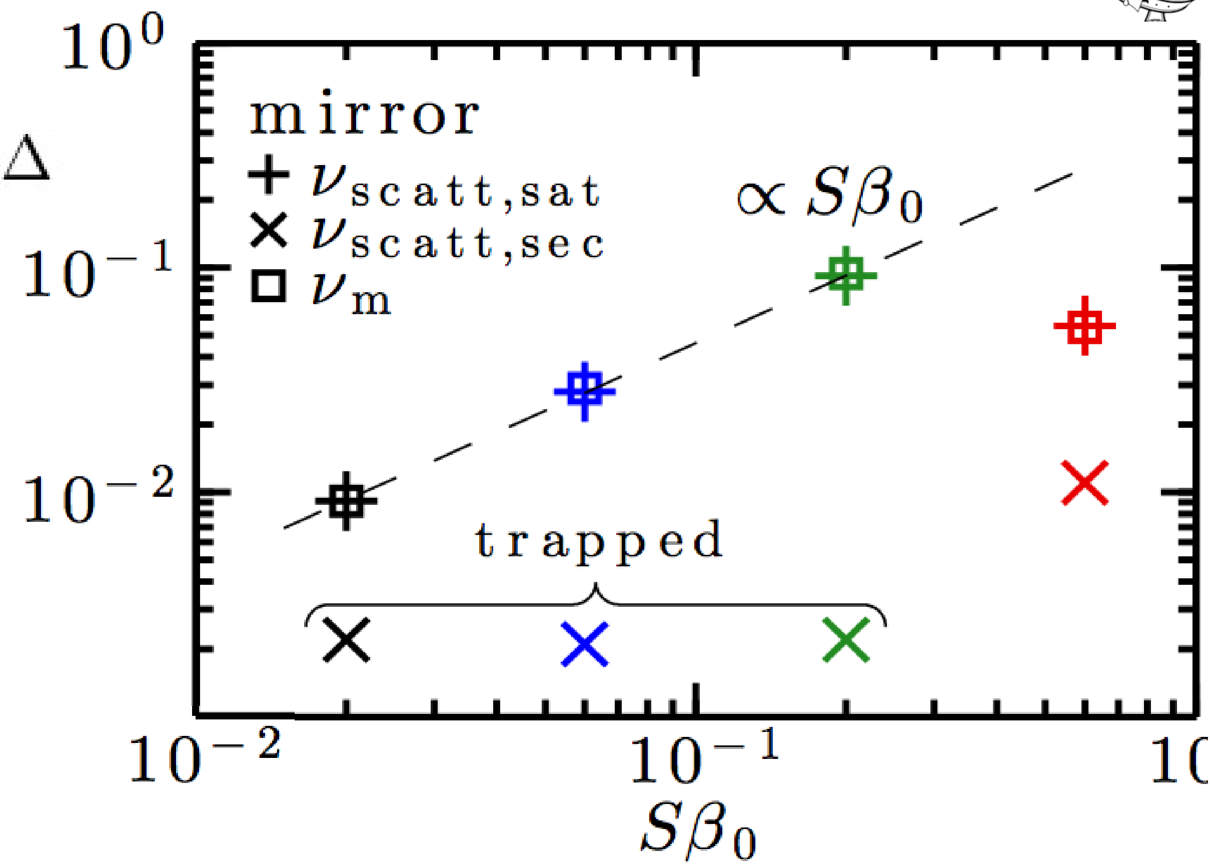
$$\frac{\mathrm{d}\Delta}{\mathrm{d}t} = 3\frac{\mathrm{d}\ln|\langle\mathbf{B}\rangle|}{\mathrm{d}t} - \nu_{\mathrm{m}}\Delta$$

$$= 0$$

$$\nu_{\mathrm{m}} = \frac{3}{\Delta}\frac{\mathrm{d}\ln|\langle\mathbf{B}\rangle|}{\mathrm{d}t}$$

$$= 3\beta\frac{\mathrm{d}\ln|\langle\mathbf{B}\rangle|}{\mathrm{d}t}$$

$$\sim S\beta$$



□ effective collisionality required to maintain marginal stability

+ measured scattering rate during the saturated phase

× measured scattering rate during the secular phase

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014)

Effective Closure Options

This in fact also happens for firehoses, at ultra-high beta $\beta > \Omega / S$

Option I: Suppress stretching

$$\Delta \equiv \frac{p_\perp - p_\parallel}{p} \sim \frac{1}{\nu}\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{\gamma}{\nu} \in \left[-\frac{2}{\beta}, \frac{1}{\beta}\right]$$

Option II: Enhance collisionality

This happens for firehoses (also mirrors in saturation & decaying)

Melville, AAS & Kunz
arXiv:1512.08131

Effective Closure Options

Option III: Skew the average towards regions of weaker field by trapping particles

This happens for secularly growing mirrors

Option I: Suppress stretching

$$\Delta \equiv \frac{p_\perp - p_\|}{p} \sim \frac{1}{\nu}\overline{\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}t}} = \frac{\gamma}{\nu} \in \left[-\frac{2}{\beta}, \frac{1}{\beta}\right]$$

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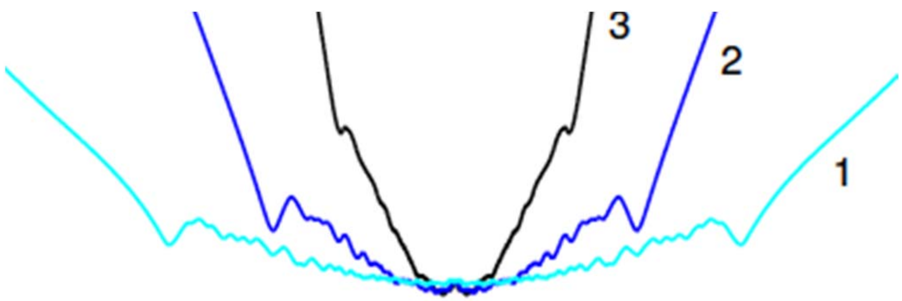
Conclusion: Implications for Plasma Dynamo

- In firehose regions, anomalous scattering will marginalise anisotropy



Melville, AAS & Kunz
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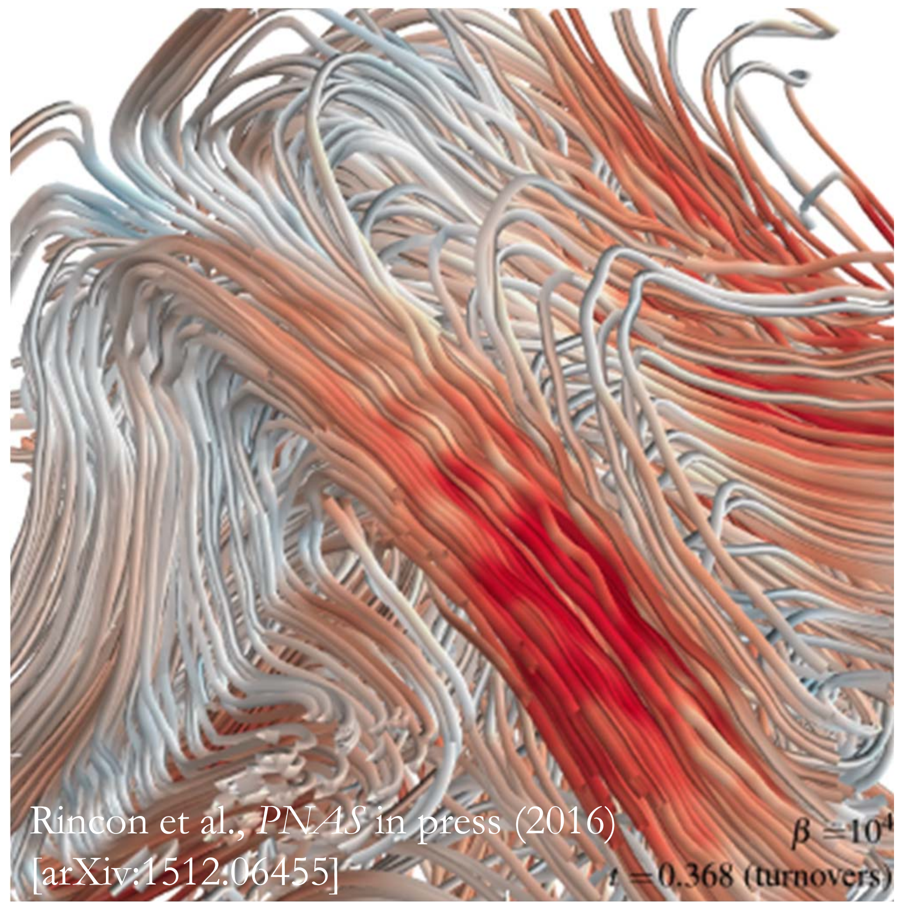
- It appears that in the stretching regions, *B* can grow, at the price of "mirror-bubble" infestation (as long as the stretching does not last longer than ~ turnover time



Conclusion: Implications for Plasma Dynamo

- In firehose regions, anomalous scattering will marginalise anisotropy

  Eff. collisionality: $\nu_{\text{eff}} \sim S\beta$

  to keep anisotropy marginal:

  $$\Delta \sim \frac{S}{\nu_{\text{eff}}} \sim \beta^{-1}$$

Melville, AAS & Kunz
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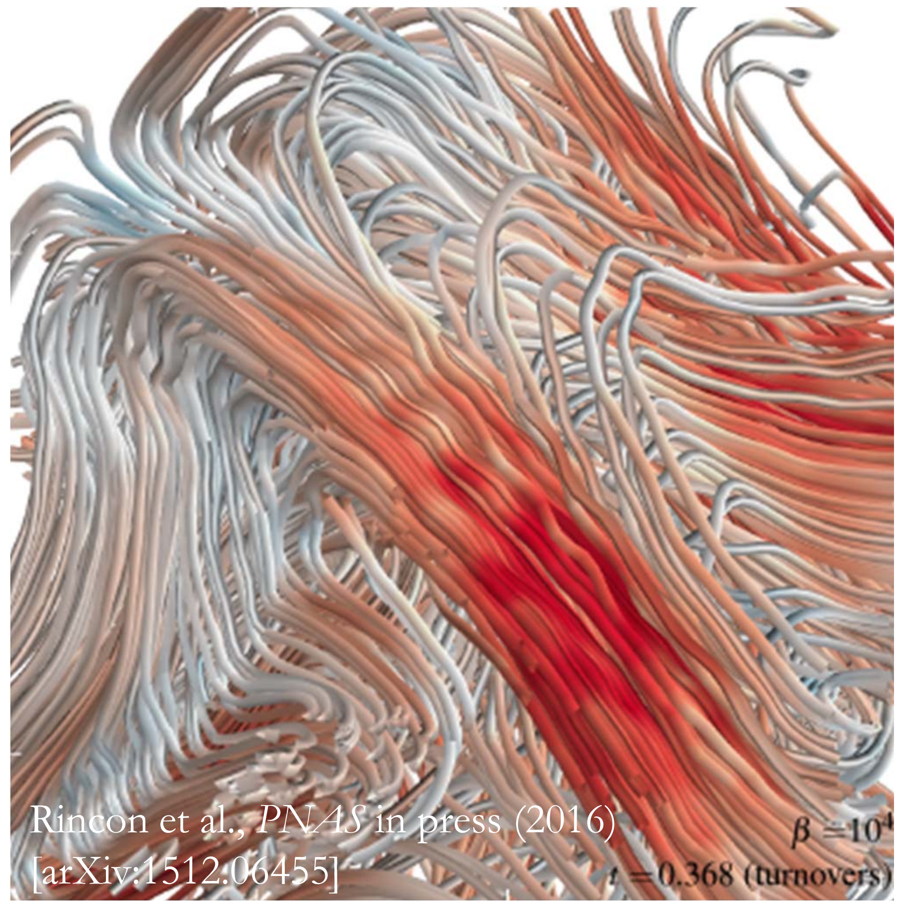

Rincon et al., *PNAS* in press (2016) [arXiv:1512.06455]

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Eff. collisionality: $\nu_{\rm eff} \sim S\beta$

Eff. viscosity: $\mu_{\rm eff} \sim \dfrac{p}{\nu_{\rm eff}} \sim \dfrac{B^2/8\pi}{S}$

NB: regions of weaker field are less viscous!

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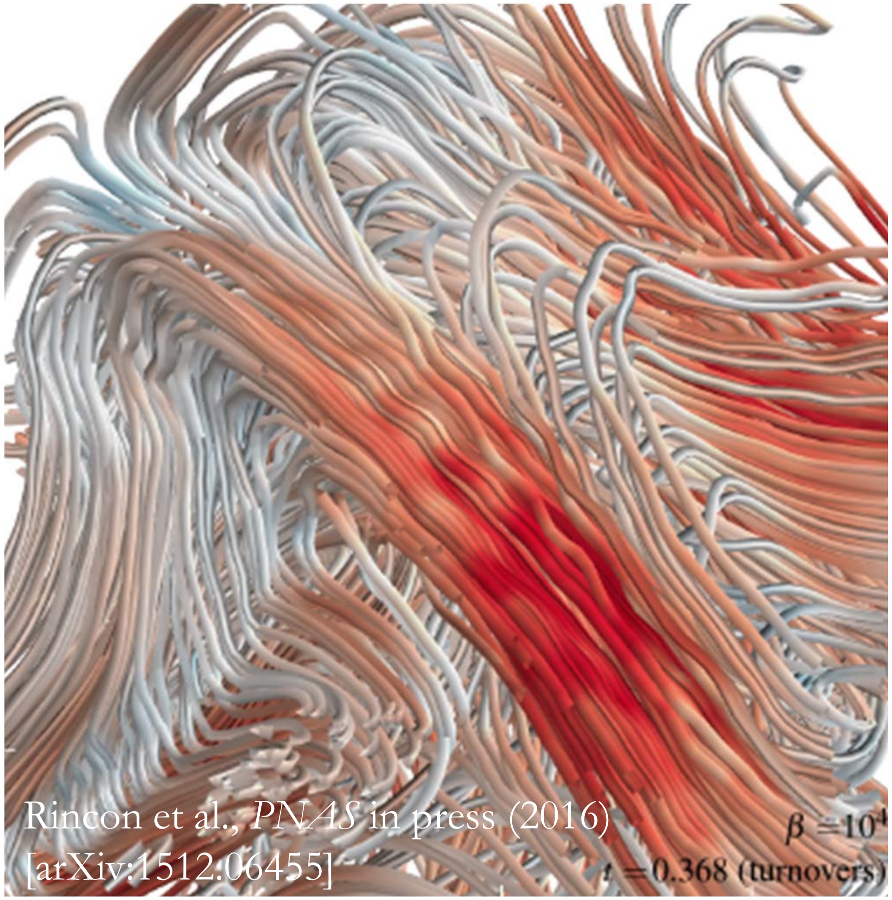

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Energy flux (Kolmogorov): $\varepsilon \sim \dfrac{\rho U^3}{L}$

Fastest turnover rate:

$$S \sim \left(\frac{\varepsilon}{\mu_{\rm eff}}\right)^{1/2} \sim \mathrm{Ma}\left(\frac{U}{L}\nu_{\rm eff}\right)^{1/2} \sim \frac{U}{L}\mathrm{Ma}^2\beta$$

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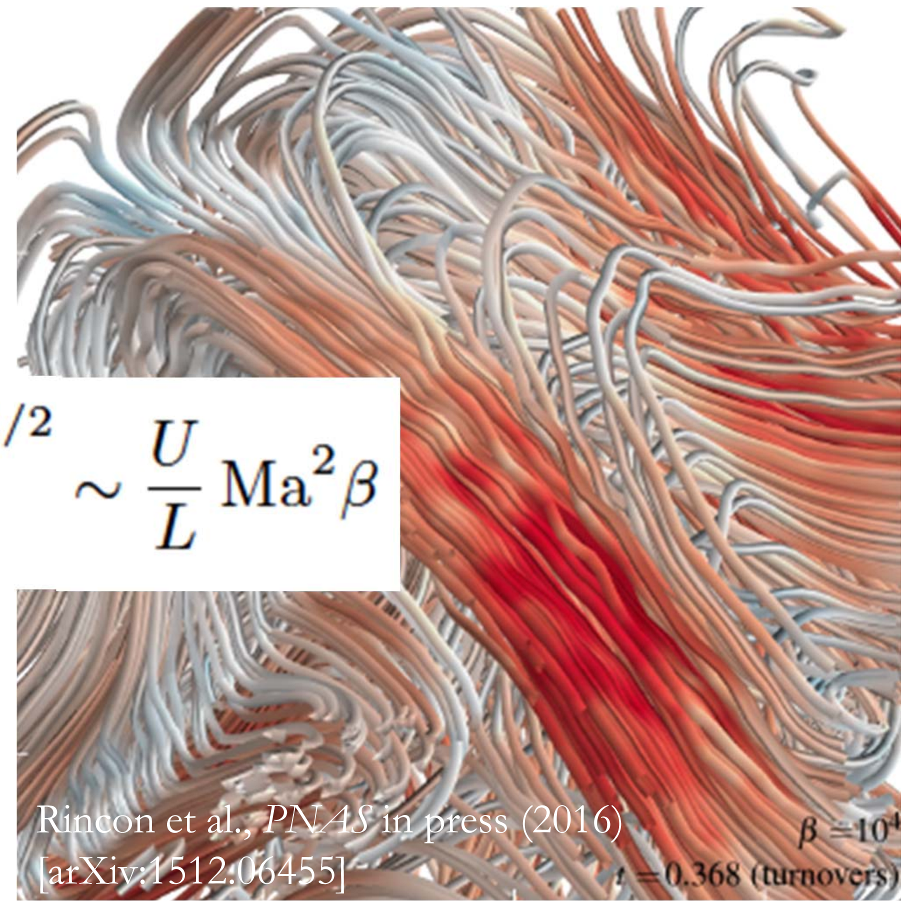

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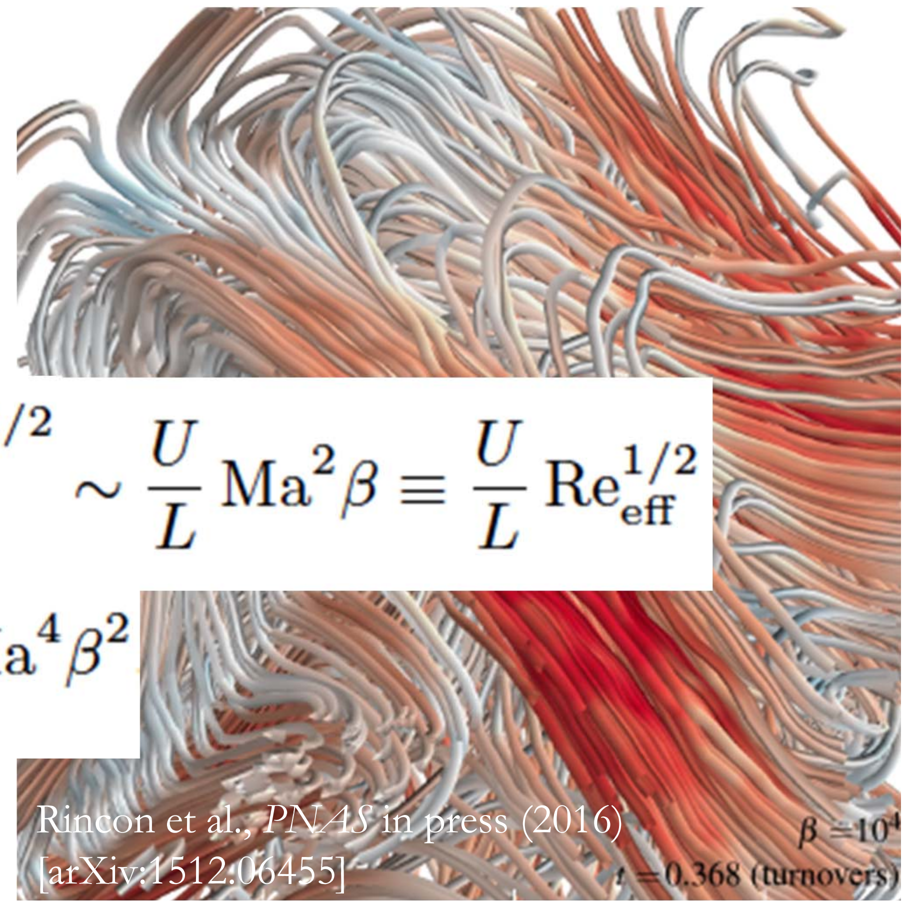
Effective Reynolds number: $\mathrm{Re}_{\rm eff} = \mathrm{Ma}^4\beta^2$

- Regions of decreasing field will quickly break up?

- It appears that in the stretching regions, B can grow, at the price of "mirror-bubble" infestation (as long as the stretching does not last longer than ~ turnover time



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Fastest turnover rate:

$$S \sim \left(\frac{\varepsilon}{\mu_{\rm eff}}\right)^{1/2} \sim \frac{\varepsilon}{B^2/8\pi}$$

NB: faster if the field is weaker

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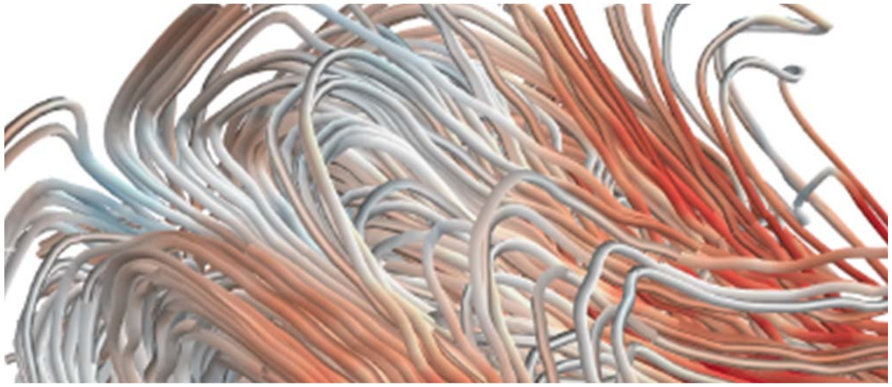

So magnetic energy grows in one turnover time from any level:

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{B^2}{8\pi} \sim S\,\frac{B^2}{8\pi} \sim \varepsilon$$

(but only if this enhanced collisionality persists)

Mogavero & AAS, *MNRAS* **440**, 3226 (2014)

Conclusion: Implications for Plasma Dynamo

- In firehose regions, anomalous scattering will marginalise anisotropy
- Regions of decreasing field will quickly break up?

Thus, it is quite difficult to decrease B in a weakly collisional plasma, while growth is OK (and maybe even faster!). Good news for fast plasma dynamo!

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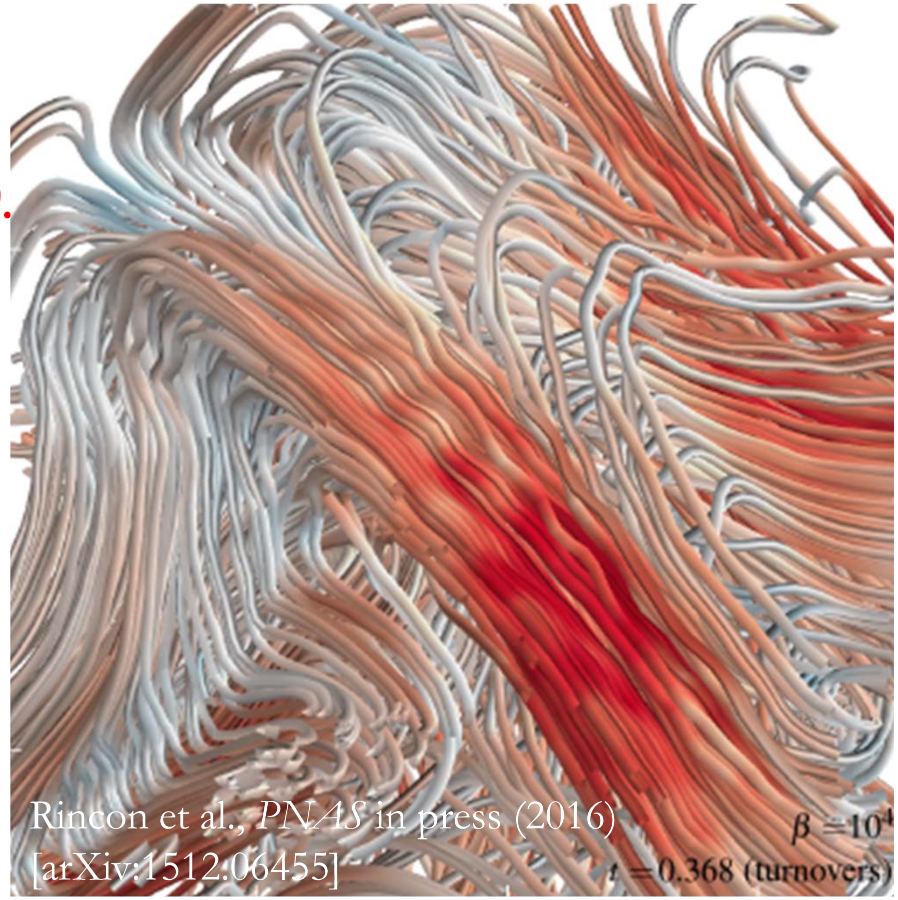

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These are speculations.
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(F. Rincon, M. Kunz …)

✧ **NIF dynamo experiment**
(G. Gregori, in ~6 months)

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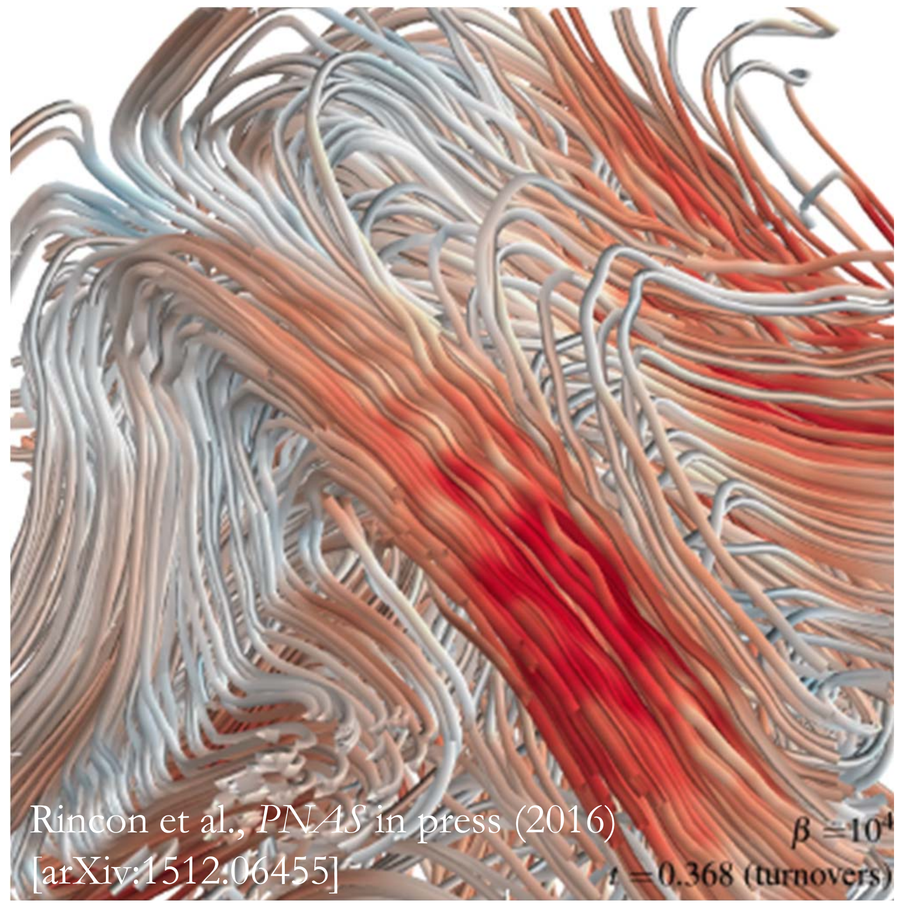

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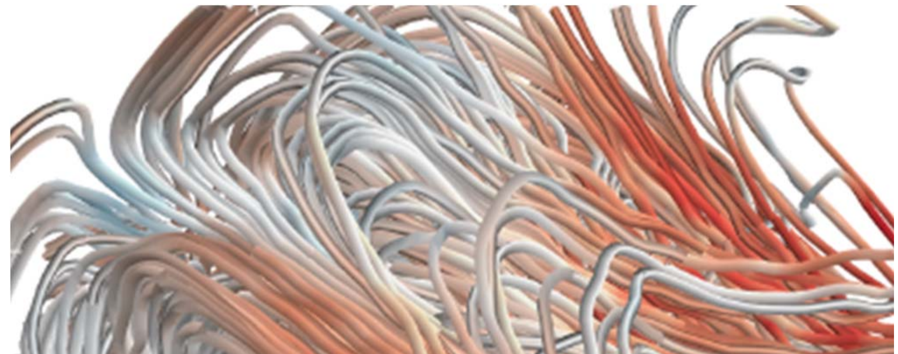

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At any rate, high-beta, weakly collisional plasma dynamics are interesting and still to be understood.

For astrophysics, paradigm change in the air?

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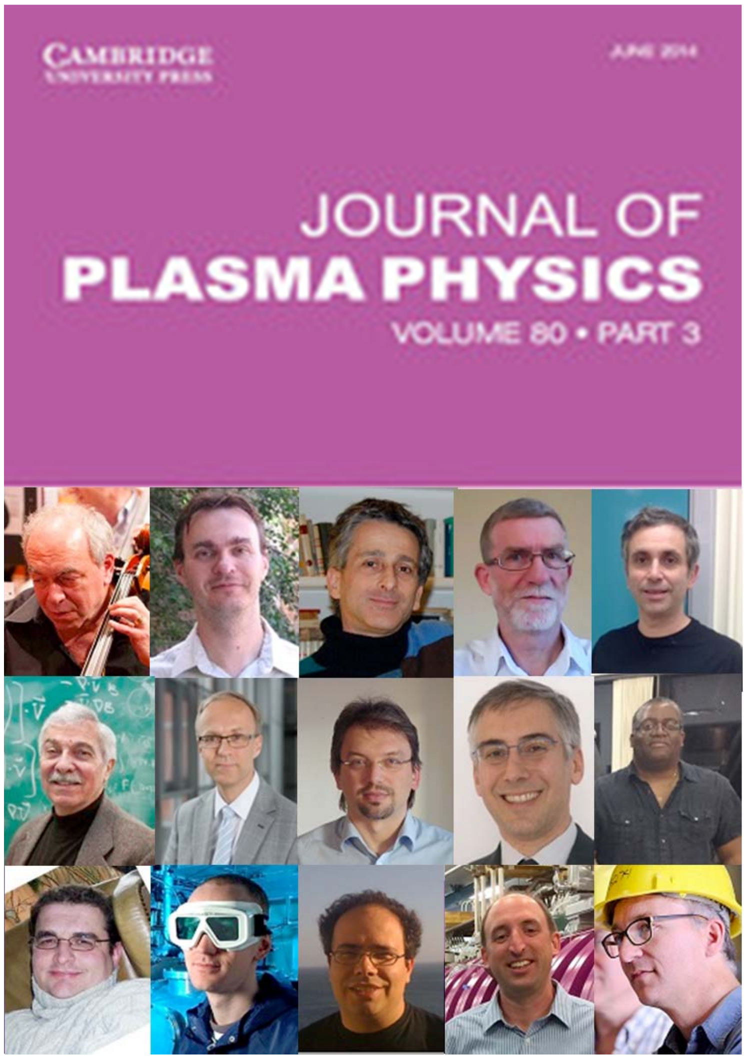

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Magnetic Fusion: Peter Catto (MIT), Per Helander (IPP Greifswald), Frank Jenko (UCLA), Piero Martin (Padua)
Dusty Plasmas: Ed Thomas Jr (Auburn)
HEDP: Antoine Bret (Castilla La Mancha), Stuart Mangles (Imperial College), Luis Silva (IST Lisbon)
Basic Lab Plasmas: Troy Carter (UCLA), Cary Forest (UW Madison)

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A 19th Century Programme…

- What is the **viscosity** of a high-beta plasma?
- What is the **thermal conductivity** of a high-beta plasma?

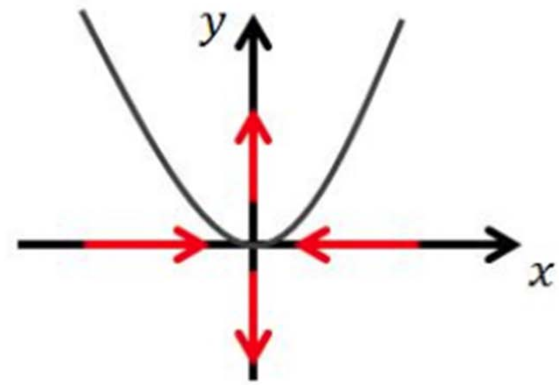
When dining, I had often observed that some particular dishes retained their Heat much longer than others; and that apple-pies, and apples and almonds mixed, - (a dish in great repute in England) - remained hot a surprising length of time. Much struck with this extraordinary quality of retaining Heat, which apples appear to possess, it frequently recurred to my recollection; and I never burnt my mouth with them, or saw others meet with the same misfortune, without endeavouring, but in vain, to find out some way of accounting, in a satisfactory manner, for this surprising matter.

Count Rumford, 1799

WE DON'T REALLY KNOW (YET) HOW MAGNETISED, HIGHβ

Effects of Magnetic Field

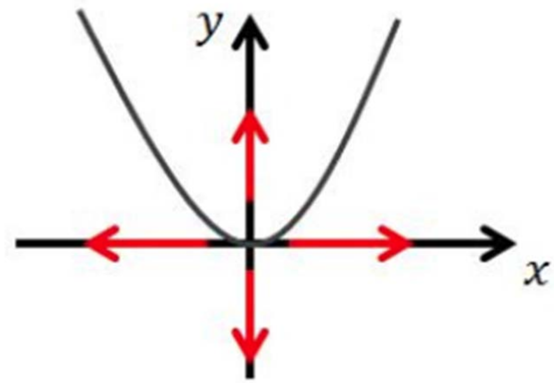
Initially parabolic magnetic field line subject to Braginskii viscosity (by Scott Melville)



WE DON’T REALLY KNOW (YET) HOW MAGNETISED, HIGHβ

Effects of **Magnetic Field**

Initially parabolic magnetic field line subject to Braginskii viscosity (by Scott Melville)



WE DON'T REALLY KNOW (YET) HOW MAGNETISED, HIGHβ