INSTITUTO SUPERIOR TÉCNICO

IPFN, IST, Lisbon 12 September 2014

Toward a Theory of Plasma Dynamo

Magnetic Fields and Microinstabilities in a Weakly Collisional Plasma

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Steve Cowley (UKAEA)
Matt Kunz (Princeton)
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Francois Rincon (Toulouse)
Jim Stone (Princeton)

Rincon, AAS & Cowley, arXiv:1407.4707 (2014)
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]
Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]
Kunz, AAS et al., *MNRAS* **410**, 2446 (2011) [arXiv:1003.2719]

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best astro theorist on the job market → Matt Kunz (Princeton)

Scott Melville (Oxford) ← clever undergraduate

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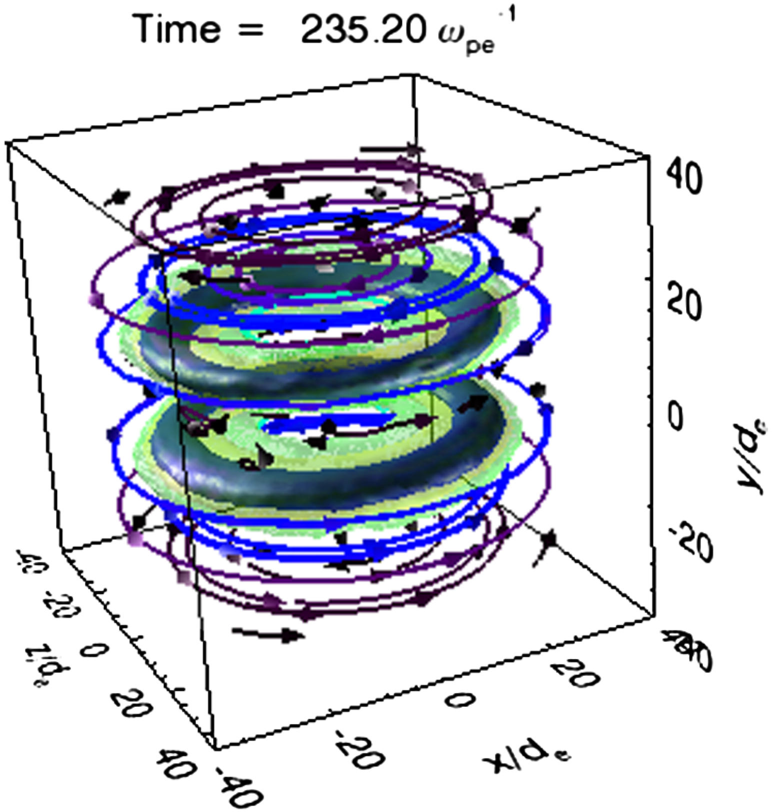
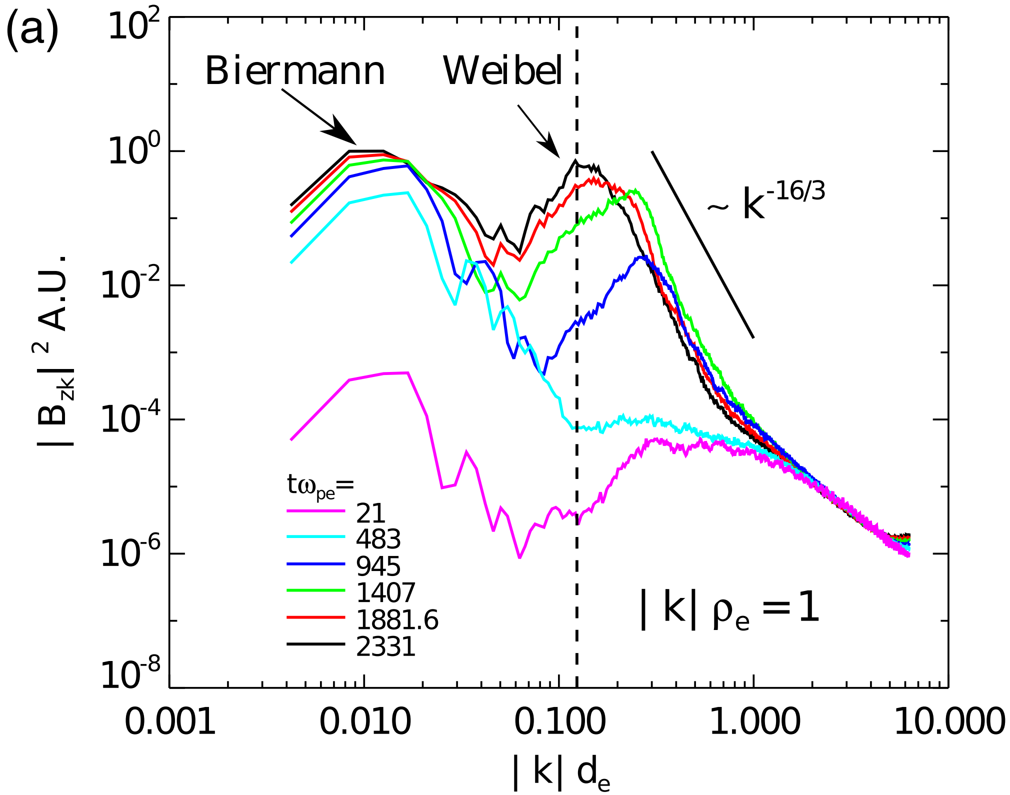
What I Will Not Talk About





[Schoeffler, Loureiro, Fonseca & Silva 2014, PRL 112, 175001]

Standard Turbulent MHD Dynamo

AAS et al., *ApJ* **612**, 276 (2004) [astro-ph/0312046]

Standard Turbulent MHD Dynamo

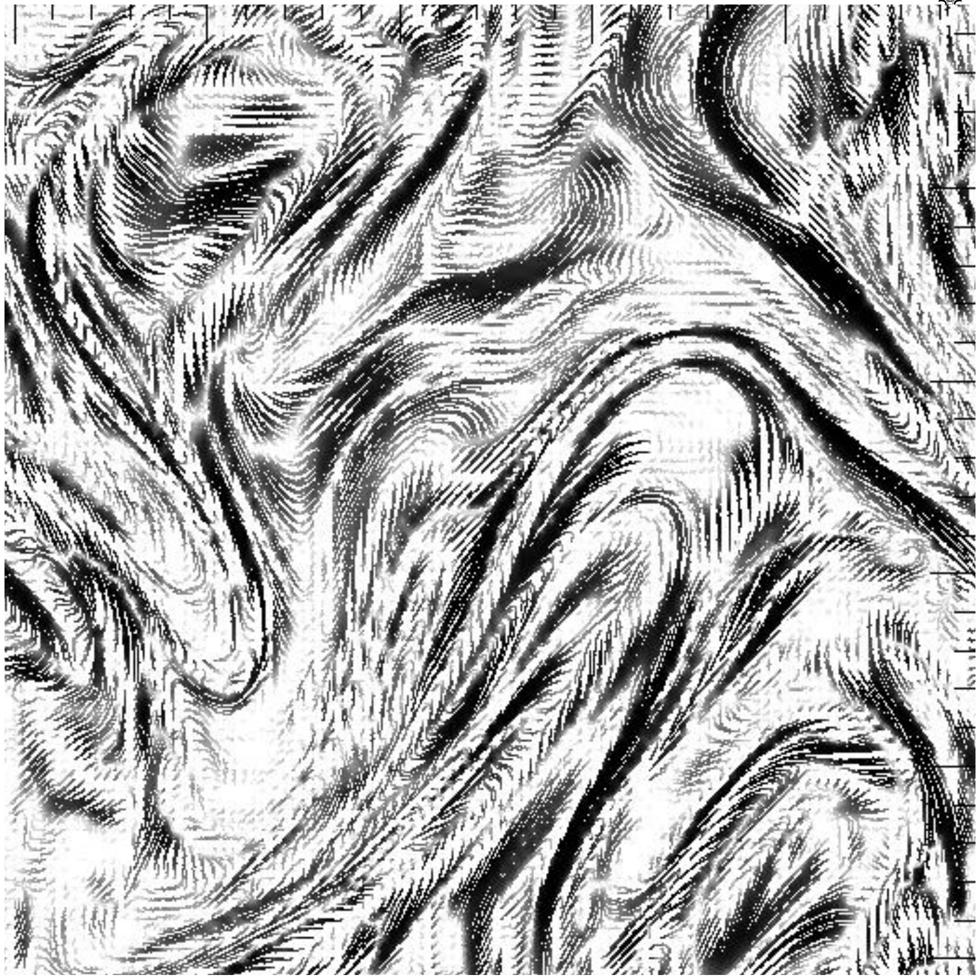
This was the solution of

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

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

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

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



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

(in fact, situation more complex because of need to combat resistivity)

AAS et al., *ApJ* **612**, 276 (2004) [astro-ph/0312046]

Standard Turbulent MHD Dynamo

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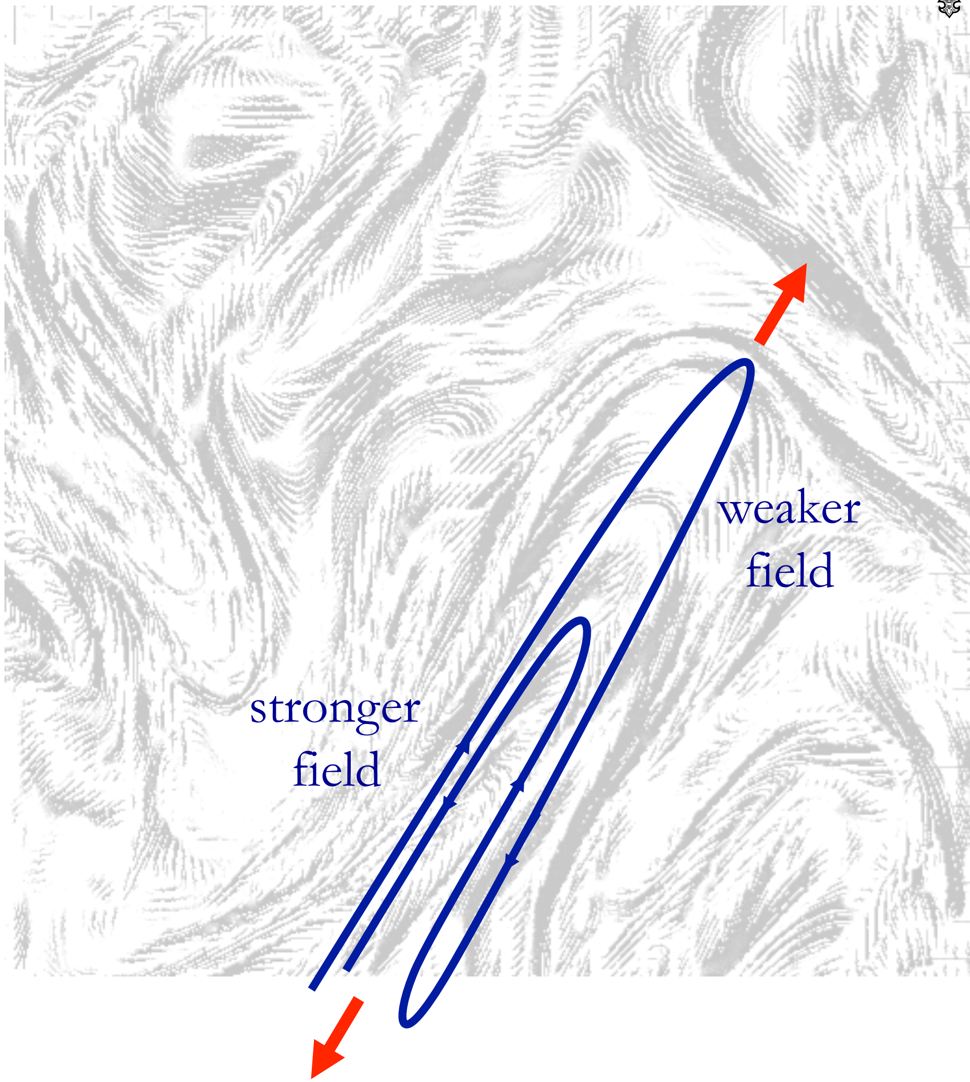

Key effect: a succession of random stretchings (and un-stretchings)

AAS et al., *ApJ* **612**, 276 (2004) [astro-ph/0312046]

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

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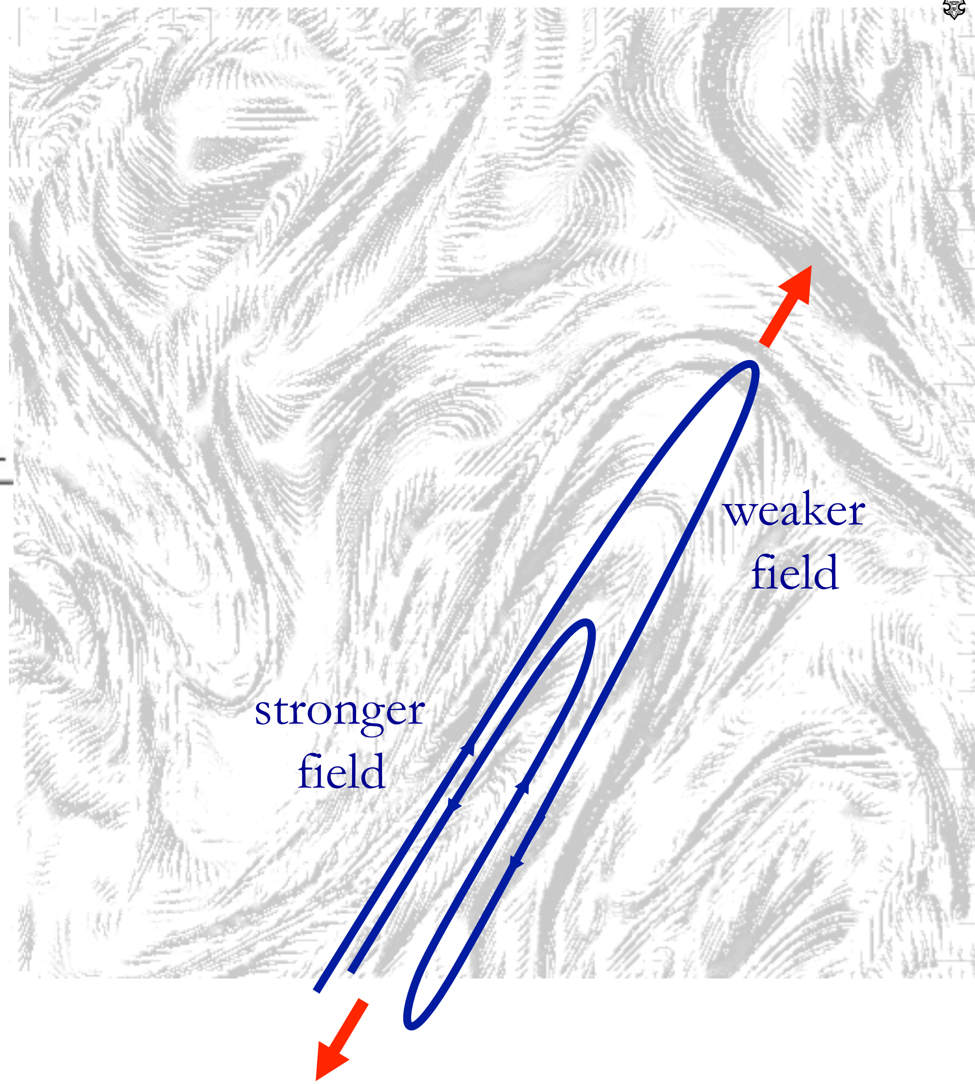

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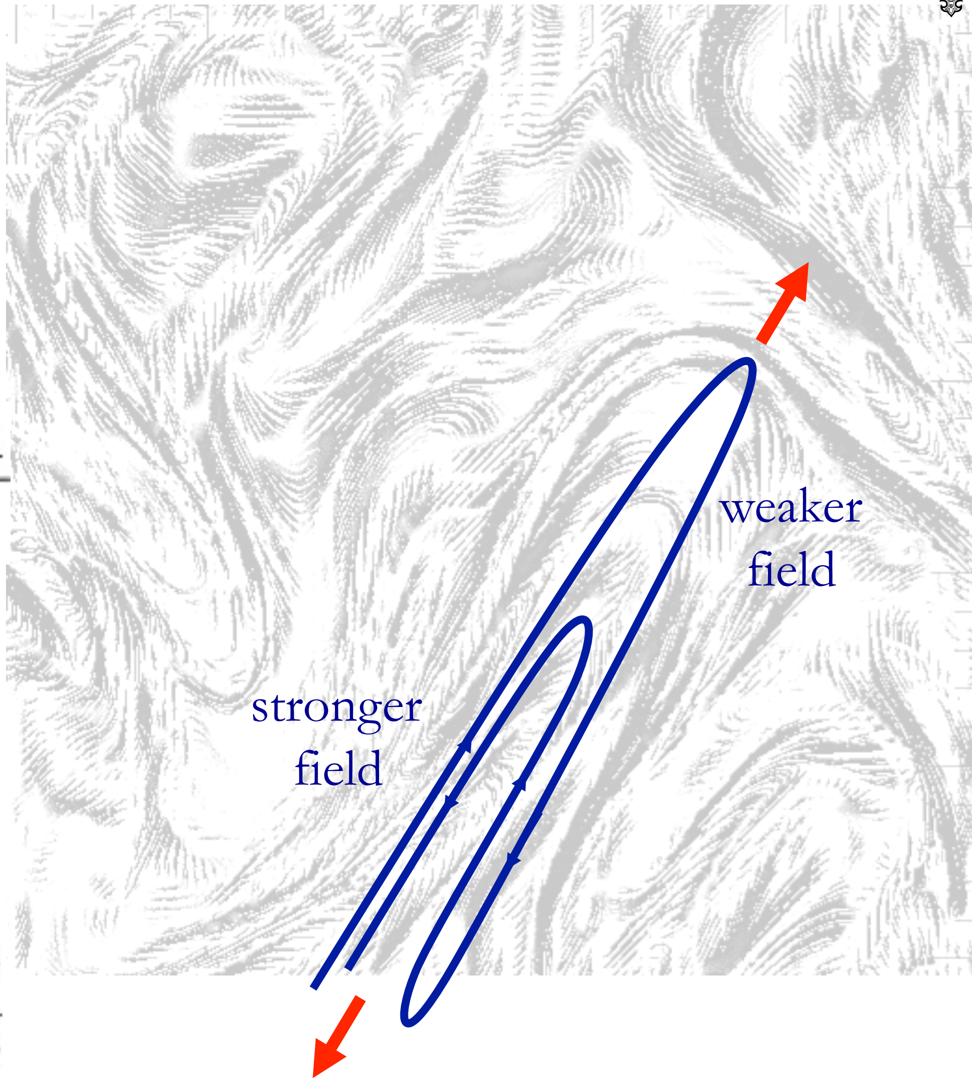
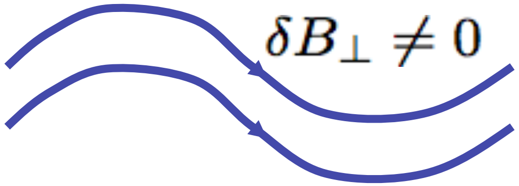
Typical pressure anisotropy:

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



Pressure Anisotropy ➔ Microinstabilities

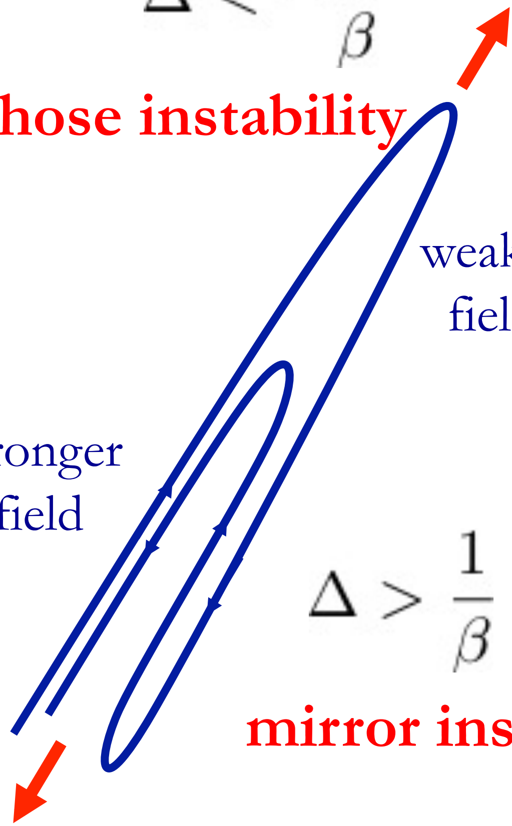
Instabilities are fast, small scale.
They are instantaneous compared
to “fluid” dynamics.



destabilised Alfvén wave

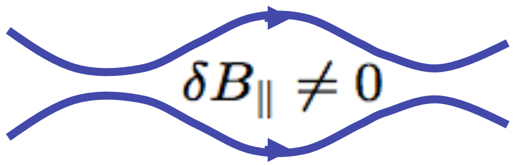
$$\Delta < -\frac{2}{\beta}$$

firehose instability



$$\Delta > \frac{1}{\beta}$$

mirror instability



resonant
instability

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

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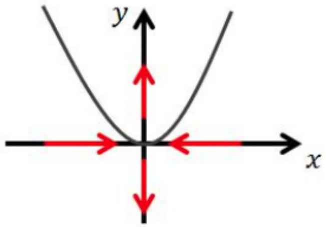
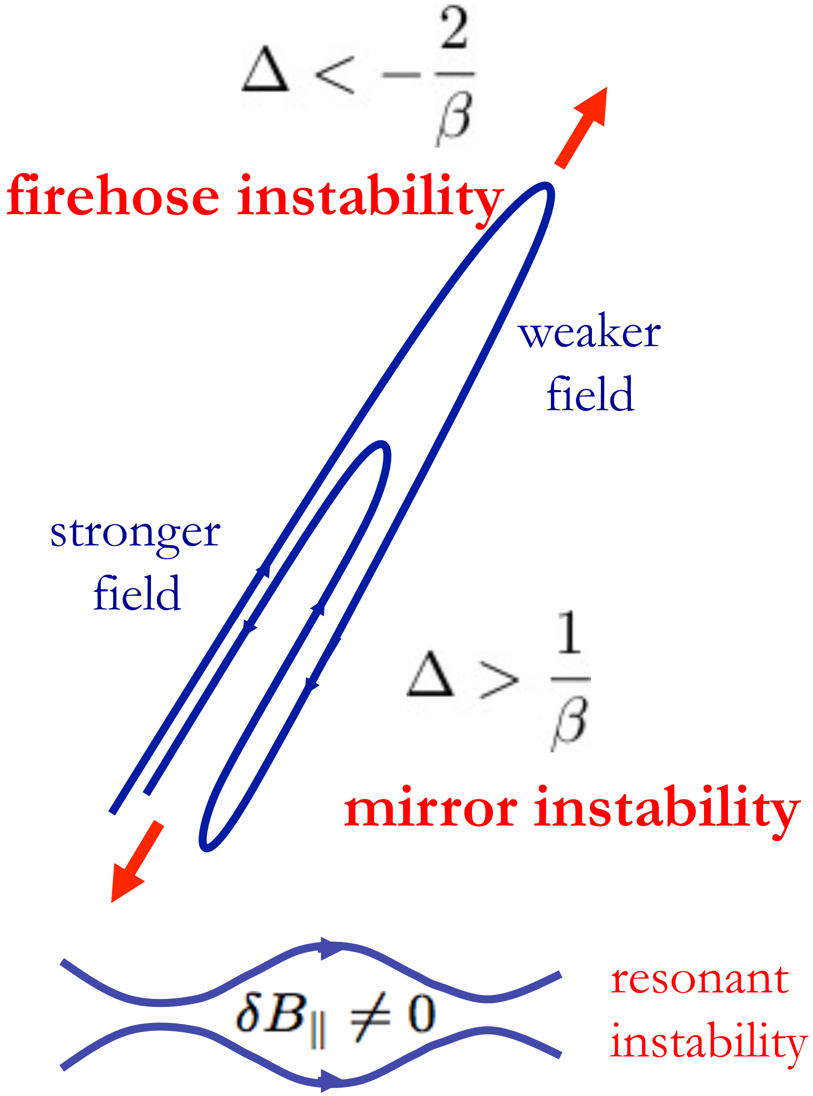
Pressure Anisotropy ➔ Microinstabilities

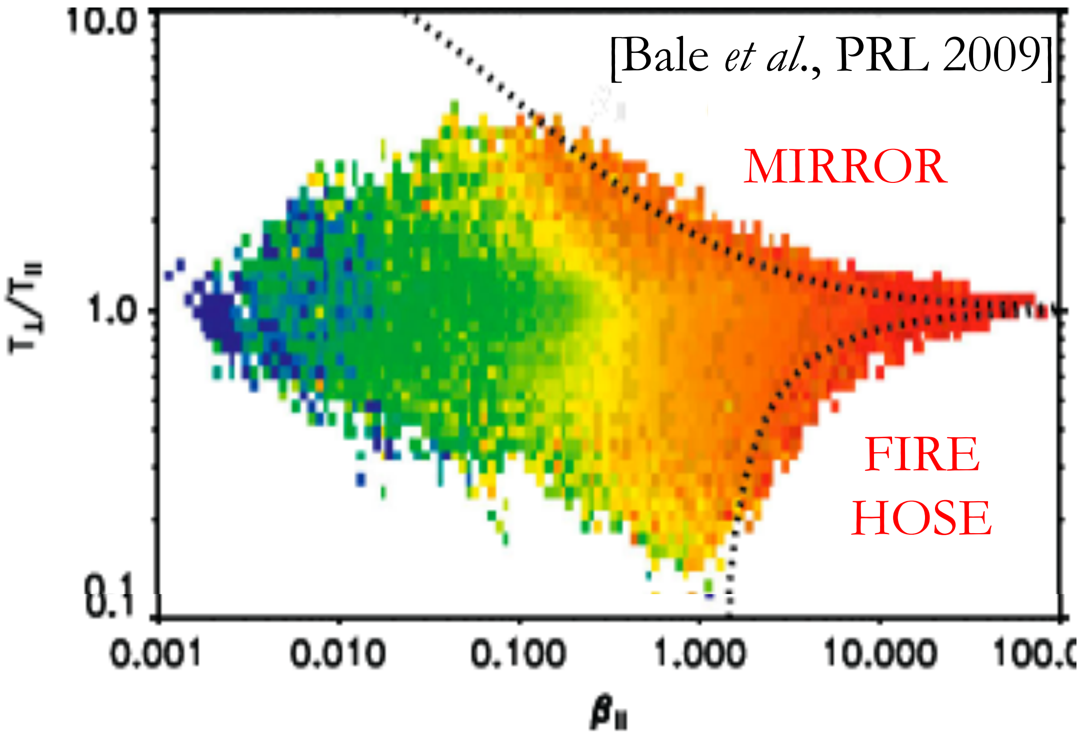
Scott Melville:
folding field goes **firehose-unstable**
(in a 1D Braginskii model)





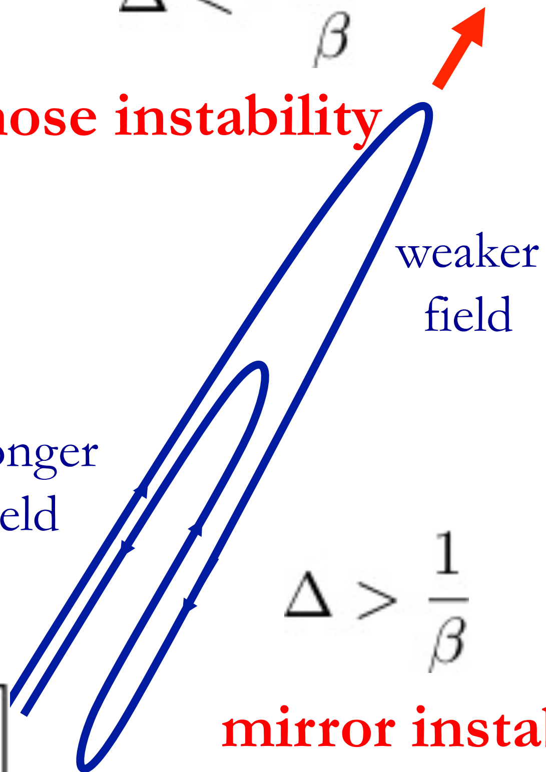
Marginal State At All Times?

In the **solar wind**:



$$\Delta < -\frac{2}{\beta}$$

firehose instability



$$\Delta > \frac{1}{\beta}$$

mirror instability

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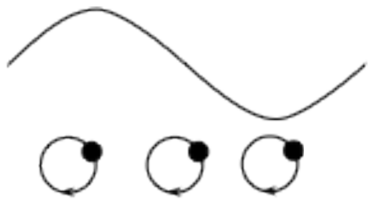
How do you evolve the field from small to large while keeping everywhere within marginal stability boundaries?

Effective Closure Dilemma

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

Model I: Suppress stretching



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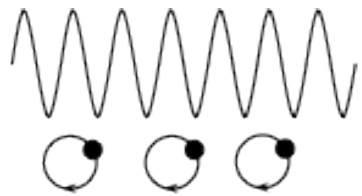
Model II: Enhance collisionality



Anomalous scattering of particles by Larmor scale fluctuations needed for this

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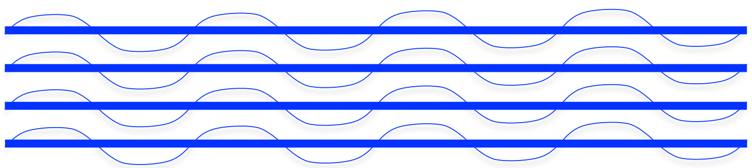
How do you evolve the field from small to large while keeping everywhere within marginal stability boundaries?

Example of mechanism to keep rate of change of B marginal when parallel-firehose unstable [Rosin et al., MNRAS 413, 7 (2011)]:



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$$= \frac{1}{B_0}\frac{\mathrm{d}B_0}{\mathrm{d}t} + \frac{1}{2}\frac{\partial}{\partial t}\frac{\overline{|\delta B_\perp|^2}}{B_0^2} \approx -\frac{2\nu_{ii}}{\beta}$$

AAS et al., *PRL* **100**, 081301 (2008)
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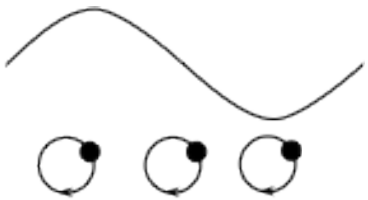

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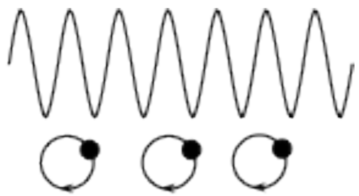

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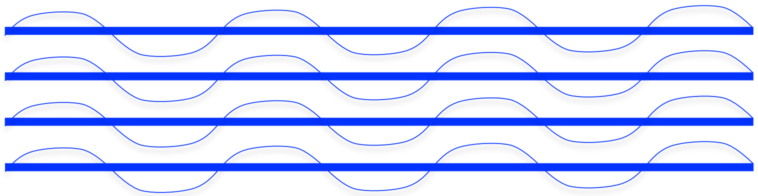

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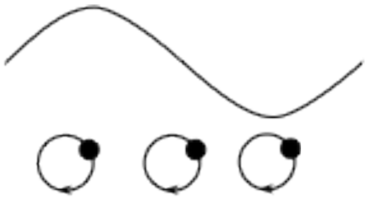

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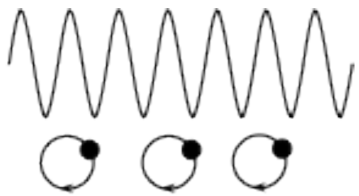

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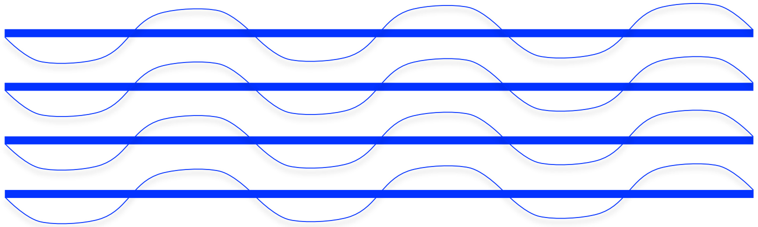

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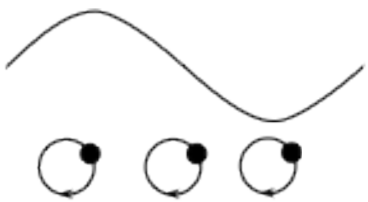

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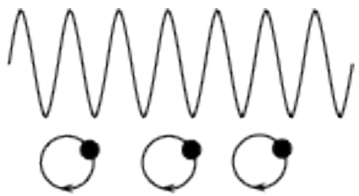

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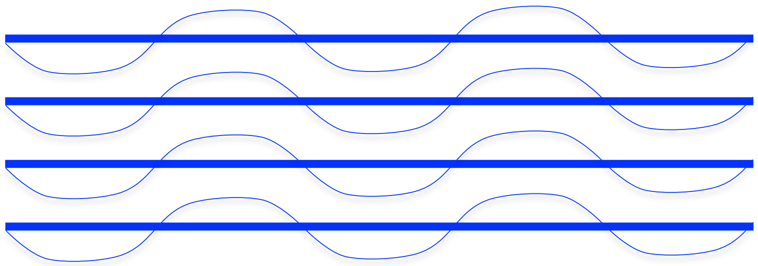

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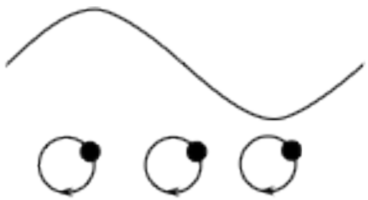

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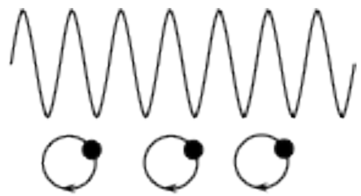

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Model II: Enhance collisionality

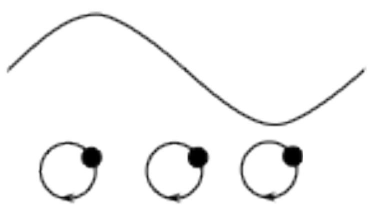
Dynamo under Model I (suppression of γ)

$$\frac{\mathrm{d}B}{\mathrm{d}t} = (\mathbf{bb} : \nabla\mathbf{u})B \equiv \gamma B \in \nu\left[-\frac{2}{\beta}, \frac{1}{\beta}\right] B$$

Suppose there is enough stirring to keep Δ at the threshold:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{\nu}{\beta} B = \frac{\nu}{8\pi p} B^3$$

Model I: Suppress stretching



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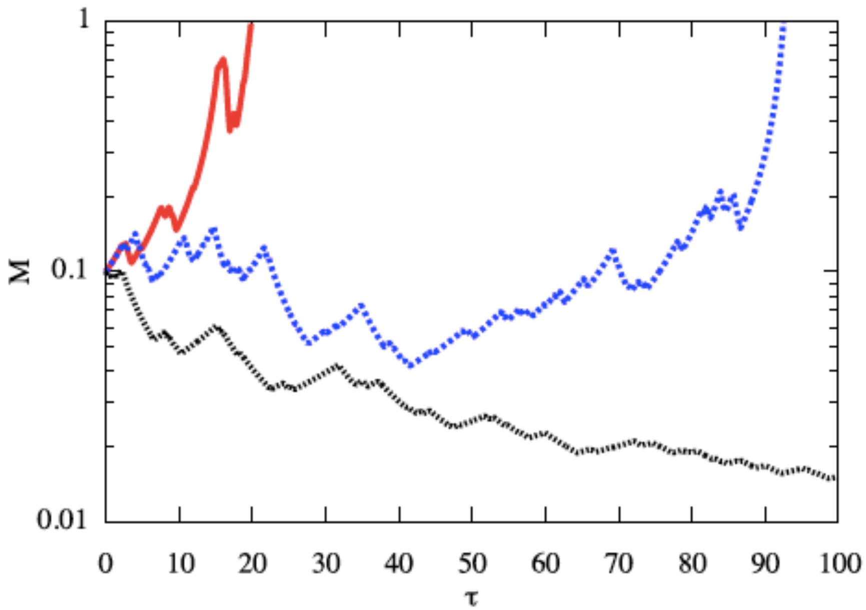
$$\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{\nu}{\beta}B = \frac{\nu}{8\pi p}B^3 \quad\Rightarrow\quad B(t) = \frac{B_0}{\sqrt{1-t/t_c}}$$

Thus, explosive growth, but takes a long time to explode: $t_c = \frac{\beta_0}{2\nu}$



for modeling details, caveats, complications, validity constraints, see

Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]

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For typical ICM parameters,

$$t_{\mathrm{growth}} \sim \frac{\beta_0}{\nu} \sim \beta_0 \times 10 \left(\frac{n_e}{0.1\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T}{2\,\mathrm{keV}}\right)^{3/2} \mathrm{yrs}$$

So this can efficiently restore fields from $B \gtrsim 10^{-8}\mathrm{G}$
to current values $B \sim 10^{-5}\mathrm{G}$,
but for growth from a tiny seed, need a different mechanism

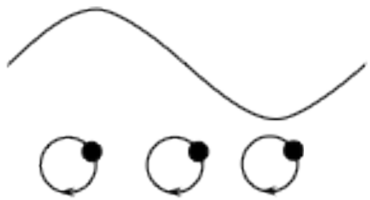
Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]

ICM heating under Model I

Viscous heating rate ($= Q_{\rm turb}$ if we ignore energy cascade below $\ell_{\rm visc}$)

$$Q_{\rm visc} = \underbrace{(p_\perp - p_\parallel)}_{p\Delta}\underbrace{\mathbf{bb} : \nabla\mathbf{u}}_{\gamma\sim\nu\Delta} \sim p\Delta\gamma \sim p\nu\Delta^2 \sim \frac{p\nu}{\beta^2}$$

Model I: Suppress stretching



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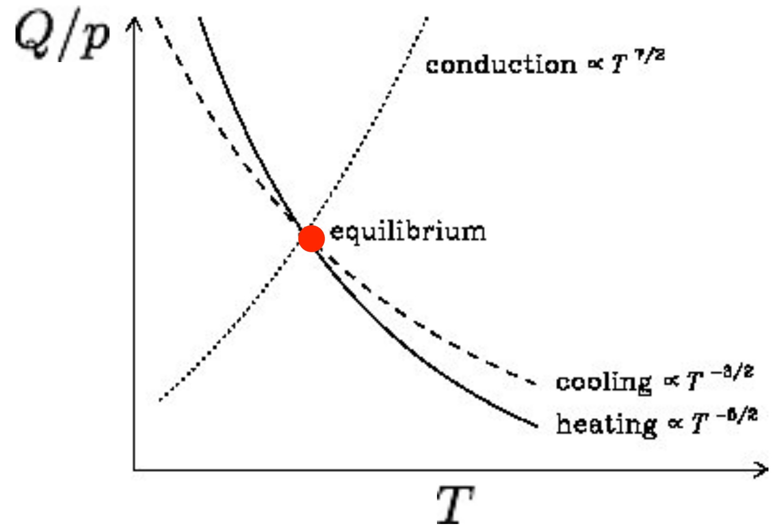
$$Q_{\rm visc} = (p_\perp - p_\|)\,\mathbf{bb} : \nabla\mathbf{u} \sim p\Delta\gamma \sim p\nu\Delta^2 \sim \frac{p\nu}{\beta^2}$$

$$\sim 10^{-25}\left(\frac{B}{10\,\mu{\rm G}}\right)^4\left(\frac{T}{2\,{\rm keV}}\right)^{-5/2}\frac{\rm erg}{\rm s\,cm^3}$$

$$Q_{\rm cool} \sim 10^{-25}\left(\frac{n_e}{0.1\,{\rm cm}^{-3}}\right)^2\left(\frac{T}{2\,{\rm keV}}\right)^{1/2}\frac{\rm erg}{\rm s\,cm^3}$$

- Thermally **stable** ICM



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ICM heating under Model I

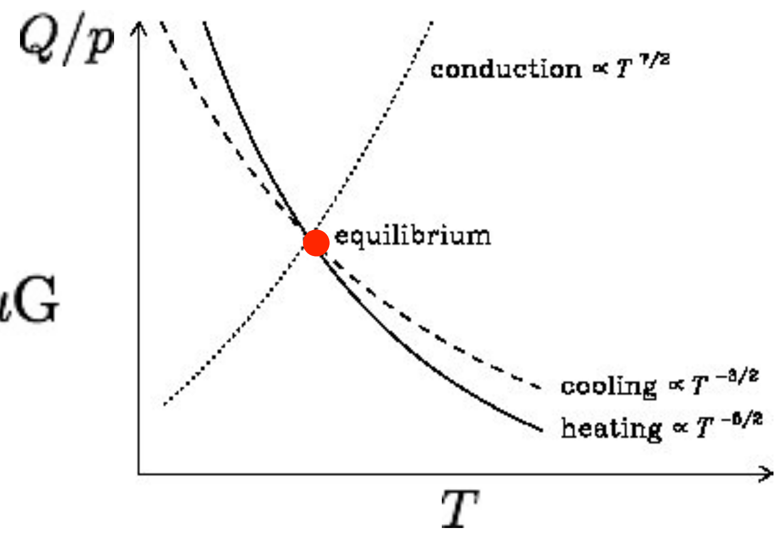
Viscous heating rate ($= Q_{\rm turb}$ if we ignore energy cascade below $\ell_{\rm visc}$)

$$Q_{\rm visc} = (p_\perp - p_\parallel)\,\mathbf{bb} : \nabla\mathbf{u} \sim p\Delta\gamma \sim p\nu\Delta^2 \sim \frac{p\nu}{\beta^2}$$

$$\sim 10^{-25}\left(\frac{B}{10\,\mu{\rm G}}\right)^4\left(\frac{T}{2\,{\rm keV}}\right)^{-5/2}\frac{\rm erg}{\rm s\,cm^3}$$

$$Q_{\rm cool} \sim 10^{-25}\left(\frac{n_e}{0.1\,{\rm cm^{-3}}}\right)^2\left(\frac{T}{2\,{\rm keV}}\right)^{1/2}\frac{\rm erg}{\rm s\,cm^3}$$

- Thermally **stable** ICM



- If $Q_{\rm visc} \sim Q_{\rm cool}$,

$$B \sim 10\left(\frac{n_e}{0.1\,{\rm cm^{-3}}}\right)^{1/2}\left(\frac{T}{2\,{\rm keV}}\right)^{3/4}\mu{\rm G}$$

- If $\rho u^2/2 \sim B^2/8\pi$,

$$u \sim 10^2\left(\frac{T}{2\,{\rm keV}}\right)^{3/4}\frac{\rm km}{\rm s}$$

Kunz, AAS et al., *MNRAS* **410**, 2446 (2011) [arXiv:1003.2719]

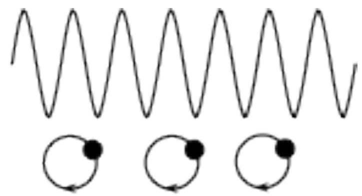
Dynamo under Model II (enhancement of ν)

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

To stay at threshold, need effective collisionality $\nu \sim \gamma\beta$

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

Model II: Enhance collisionality



Anomalous scattering of particles by Larmor scale fluctuations needed for this

Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]

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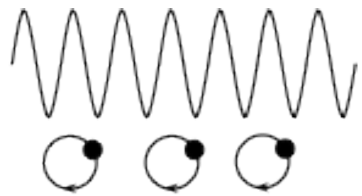

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And viscosity determines maximal rate of strain:

$$\gamma \sim \left(\frac{\varepsilon}{\mu}\right)^{1/2} \sim \left(\frac{\varepsilon\nu}{p}\right)^{1/2} \sim \left(\frac{\varepsilon\gamma\beta}{p}\right)^{1/2} \quad \Rightarrow \quad \gamma \sim \frac{\varepsilon\beta}{p} \sim \frac{\varepsilon}{B^2}$$

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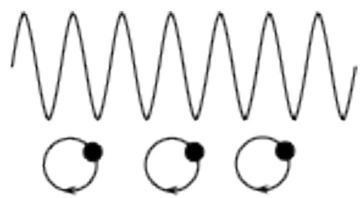

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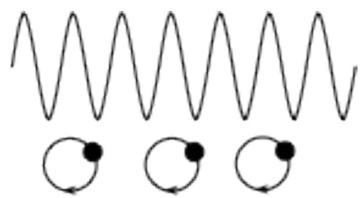

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$$\frac{\mathrm{d}B^2}{\mathrm{d}t} = 2\gamma B^2 \sim \varepsilon \quad \Rightarrow \quad B^2 \sim \varepsilon t$$

Thus, secular growth, but gets to dynamical strength very quickly:

$$t \sim \frac{B_{\mathrm{sat}}^2}{\varepsilon} \sim \frac{u^2}{\varepsilon} \sim \frac{l}{u}$$ one large-scale turnover rate

Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]

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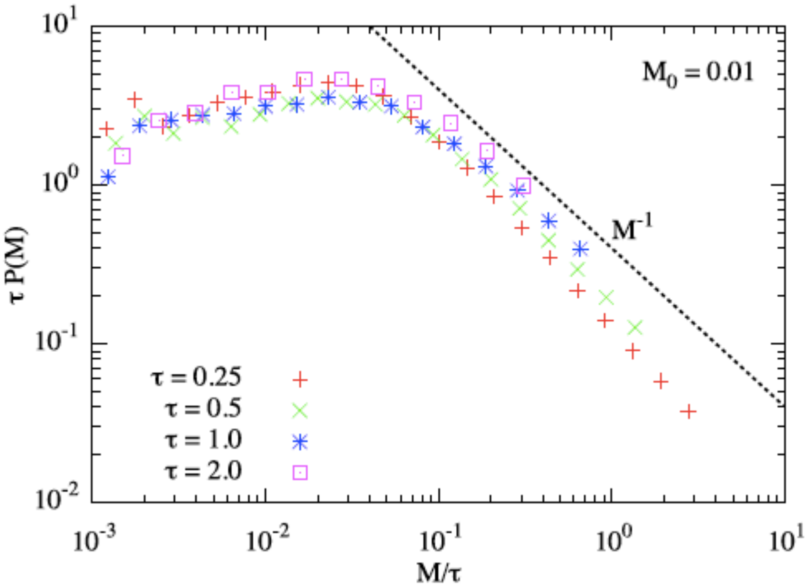

$$M = B^2$$

$$\gamma \sim \frac{\varepsilon\beta}{p} \sim \frac{\varepsilon}{B^2}$$

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Thus, secular growth, but gets to dynamical strength very quickly:

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Modeling gives extremely intermittent, self-similar field distribution; see

(➔ intermittent viscosity, intermittent rate of strain,

very hard to do right in "real" simulations with this effective closure!)

Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]

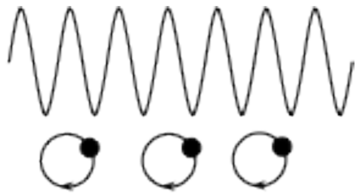
ICM heating under Model II

$$Q_{\rm visc} = \underbrace{(p_\perp - p_\|)}_{p\Delta}\,\underbrace{\mathbf{bb}:\nabla\mathbf{u}}_{\gamma} \sim p\Delta\gamma \sim \varepsilon$$

$$\gamma \sim \frac{\varepsilon\beta}{p}$$

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

Model II: Enhance collisionality



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ICM heating under Model II

$$Q_{\rm visc} = \underbrace{(p_\perp - p_\|)}_{p\Delta}\underbrace{\mathbf{bb}:\nabla\mathbf{u}}_{\gamma} \sim p\Delta\gamma \sim \varepsilon$$

So we learn nothing new: all the turbulent power input, whatever it is, gets viscously dissipated

(in Model I, $Q_{\rm visc} \sim \varepsilon$ as well, but it allows one to fix the temperature profile in terms of other parameters, while in Model II it is hard-wired)

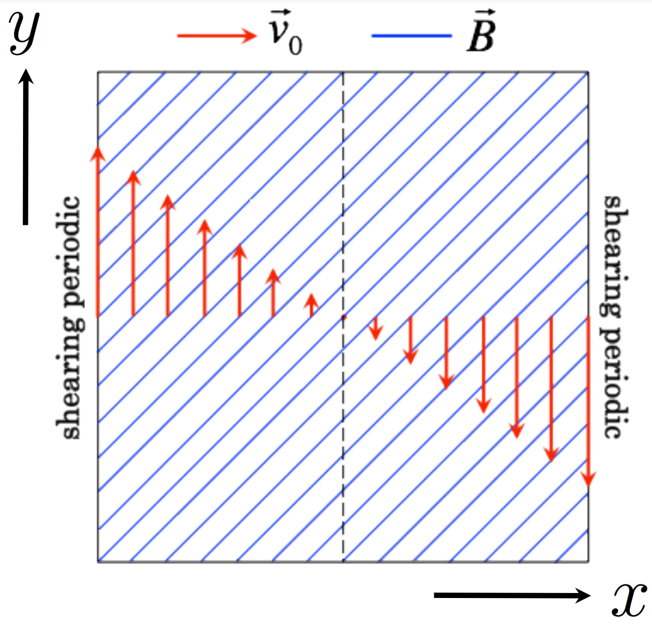
This would mean that whatever determines the thermal stability of the ICM has, under Model II, to do with large-scale energy deposition processes, not with microphysics:

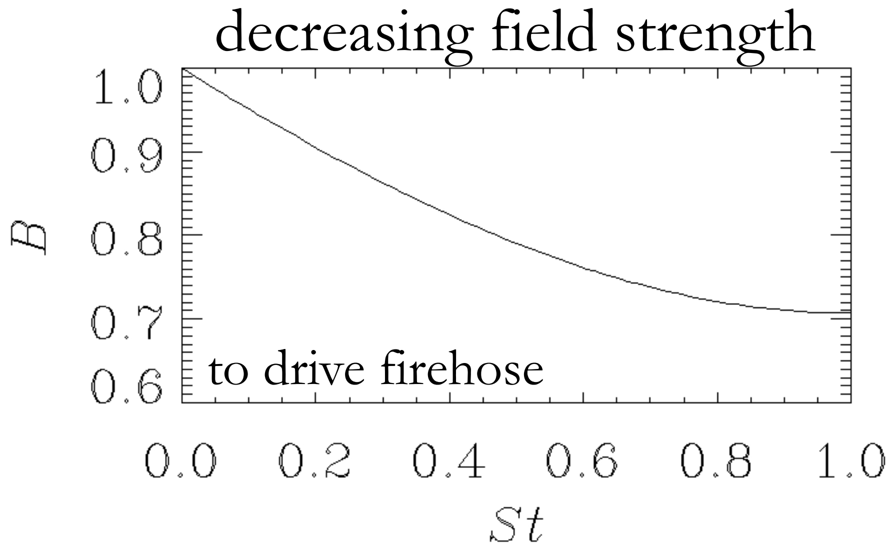
Rejoice all ye believers that microphysics should never matter!

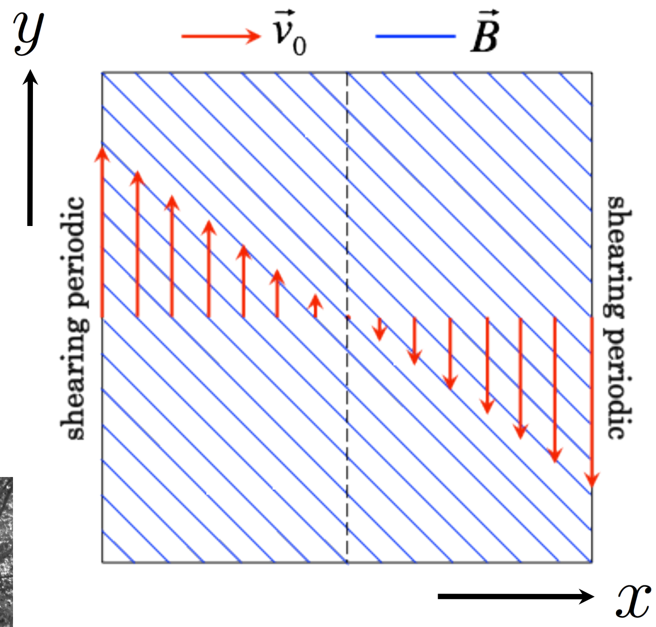
(although you need microphysics to know whether Model II is right)

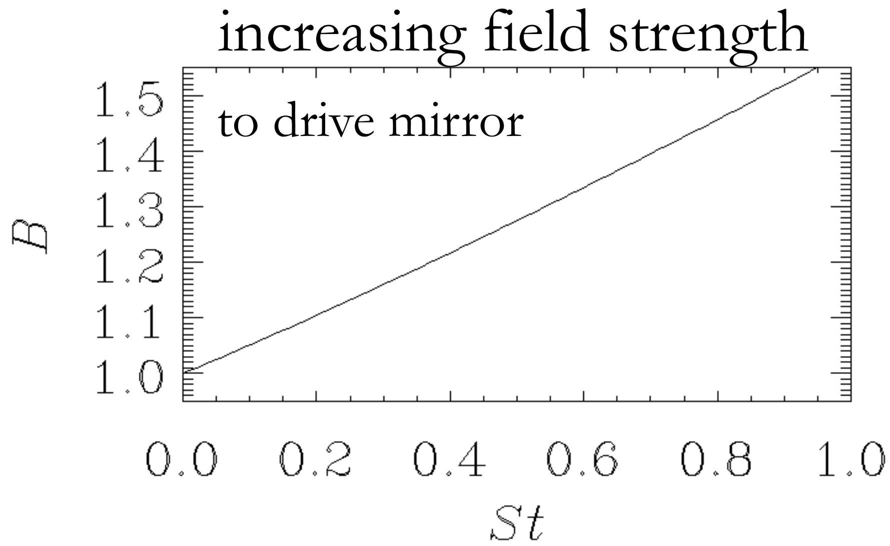
Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]

Instabilities in a Box (M. Kunz)









Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Instabilities in a Box (M. Kunz)

Hybrid kinetic system solved by PEGASUS code:

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

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

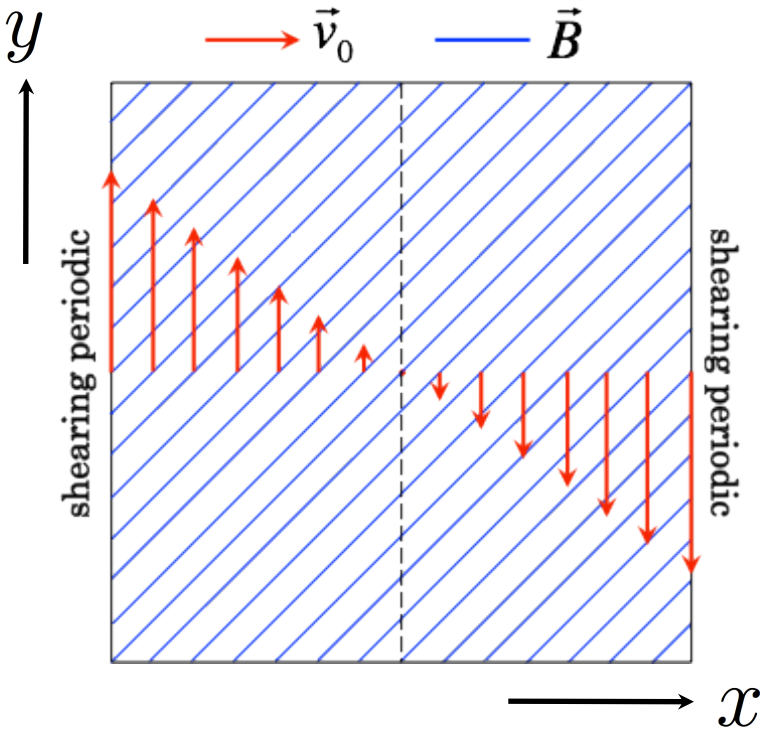
$$\boldsymbol{E} = -\frac{\boldsymbol{u}_{\rm i}\times\boldsymbol{B}}{c} + \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi Zen_{\rm i}} - \frac{T_{\rm e}\boldsymbol{\nabla}n_{\rm i}}{en_{\rm i}}$$

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

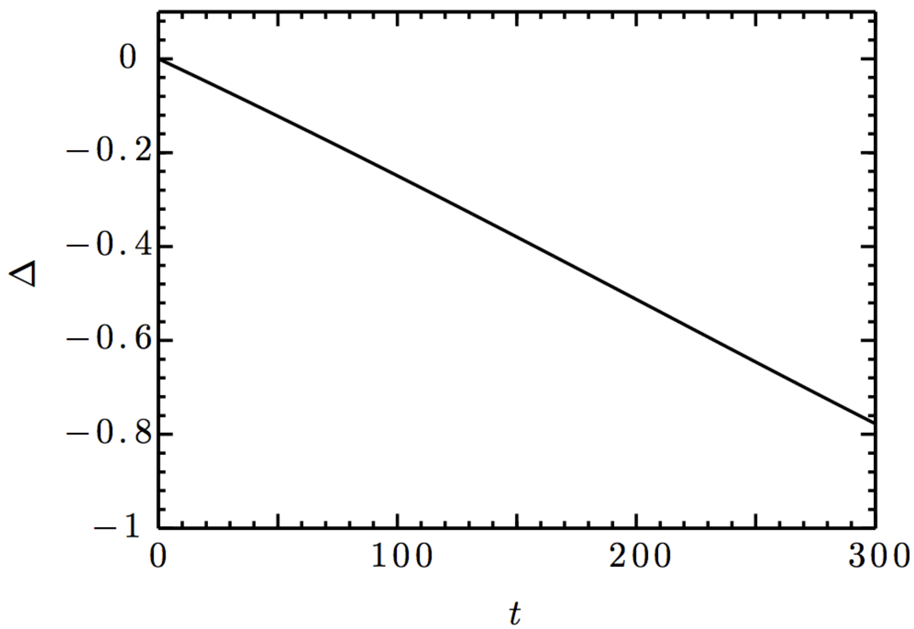
…in a shearing sheet $\mathbf{u} = -Sx\hat{\mathbf{y}}$

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Firehose Instability (M. Kunz)



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

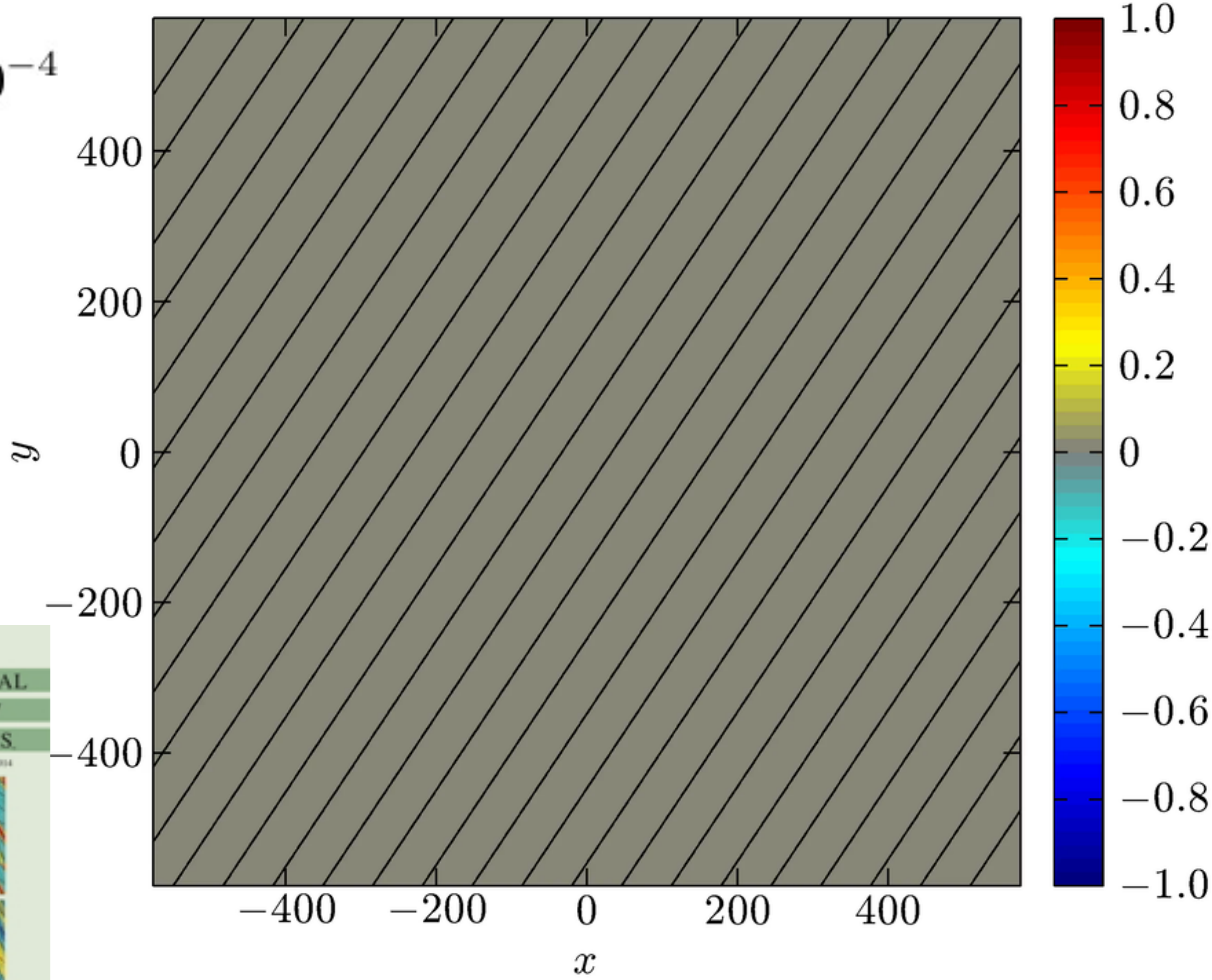


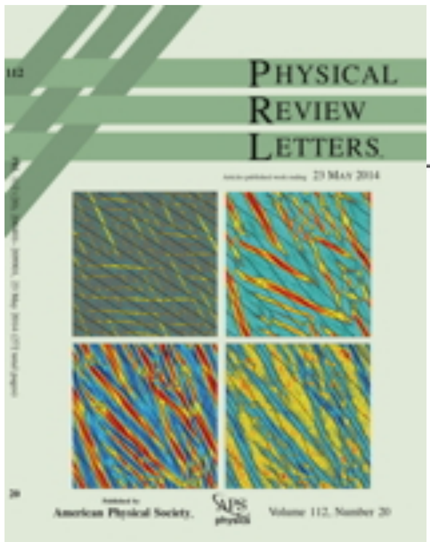
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Firehose Instability (M. Kunz)

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

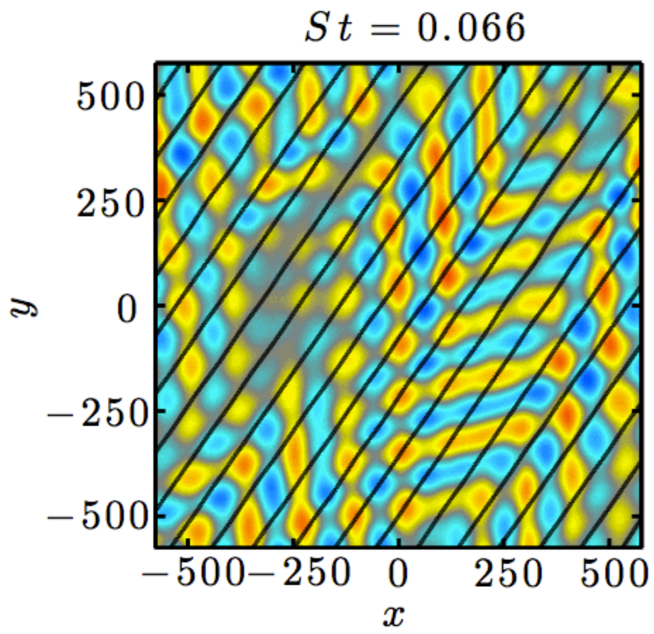
$$\beta_i = 200$$





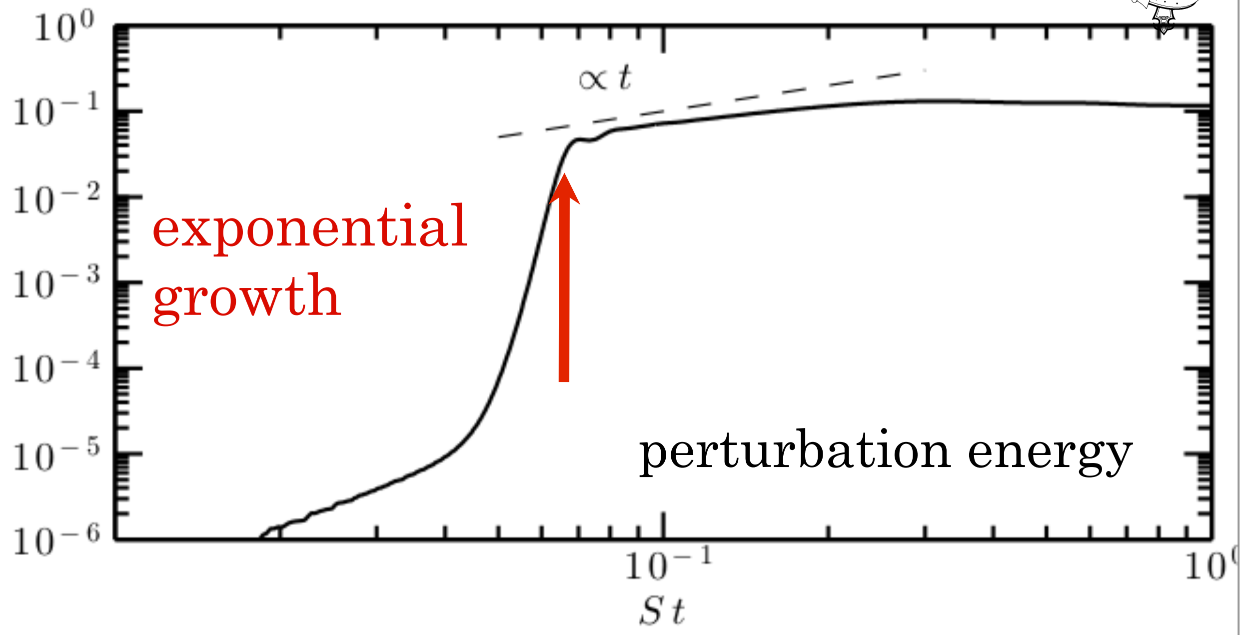
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

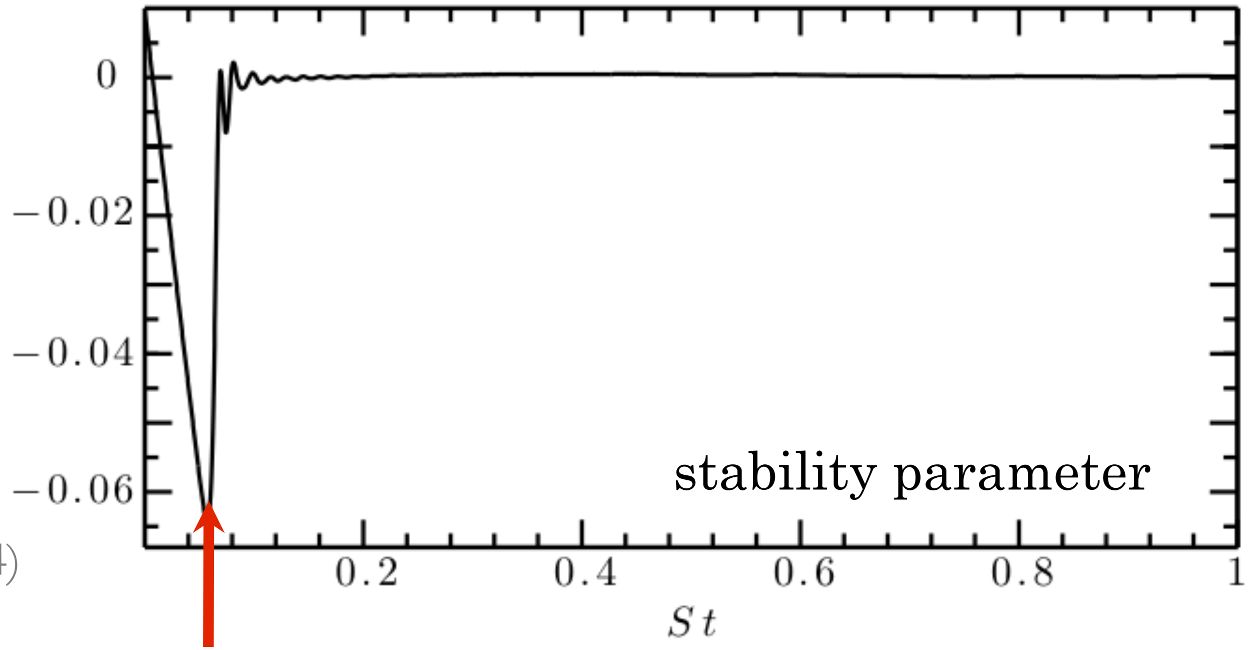
Firehose Instability: Linear



oblique modes

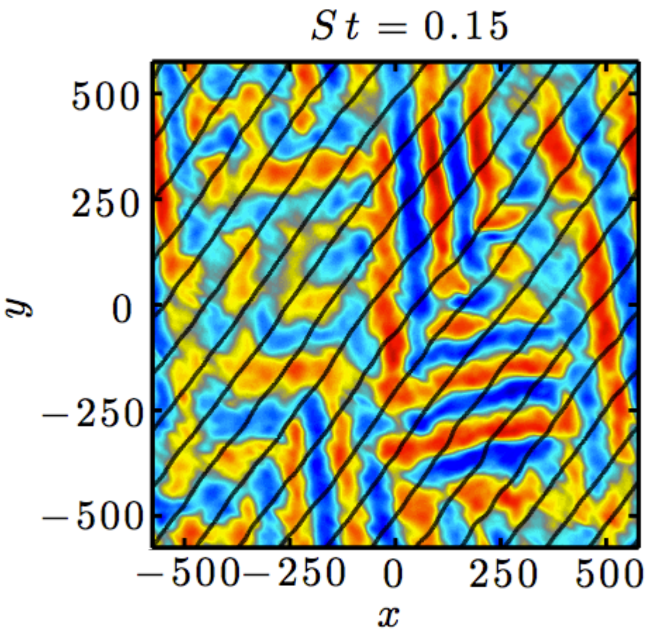
$$k_{\|}\rho_i \approx k_{\perp}\rho_i \approx 0.4$$

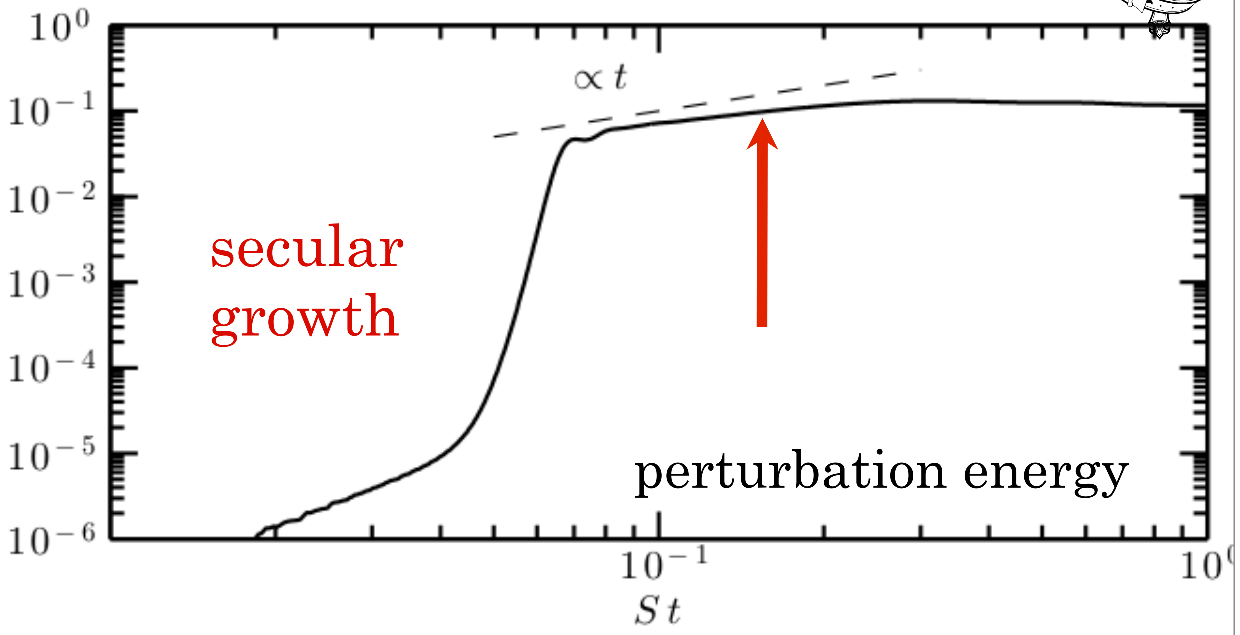


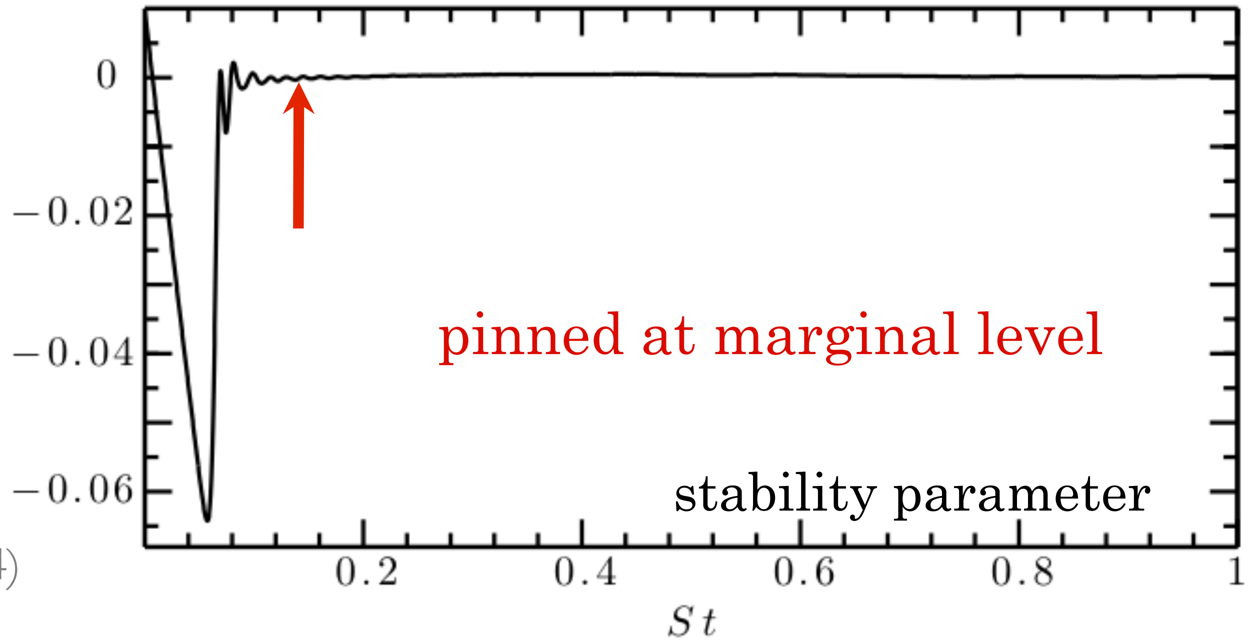


Kunz et al., *PRL* **112**, 205003 (2014)
[arXiv:1402.0010]

Firehose Instability: Secular







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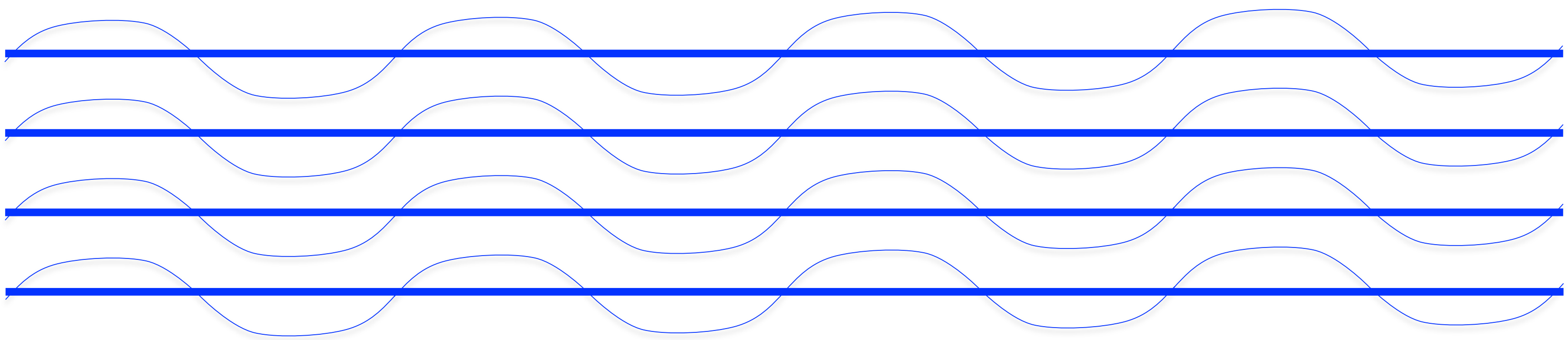
$$\overline{B^2} = \overline{|\mathbf{B}_0 + \delta\mathbf{B}_\perp|^2} = B_0^2 + \overline{|\delta\mathbf{B}_\perp|^2}$$

$$\Delta = 3\int^t \mathrm{d}t' \, \overline{\frac{\mathrm{d}\ln B}{\mathrm{d}t}} = \int^t \mathrm{d}t' \left(-3\left|\frac{\mathrm{d}\ln B_0}{\mathrm{d}t}\right| + \frac{3}{2}\frac{\mathrm{d}}{\mathrm{d}t}\frac{\overline{|\delta\mathbf{B}_\perp|^2}}{B_0^2} \right) \to -\frac{2}{\beta}$$

pressure anisotropy driven by shear

pressure anisotropy from firehose

marginal stability



AAS et al., *PRL* **100**, 081301 (2008) [arXiv:0709.3828]

Rosin et al., *MNRAS* **413**, 7 (2011) [arXiv:1002.4017]

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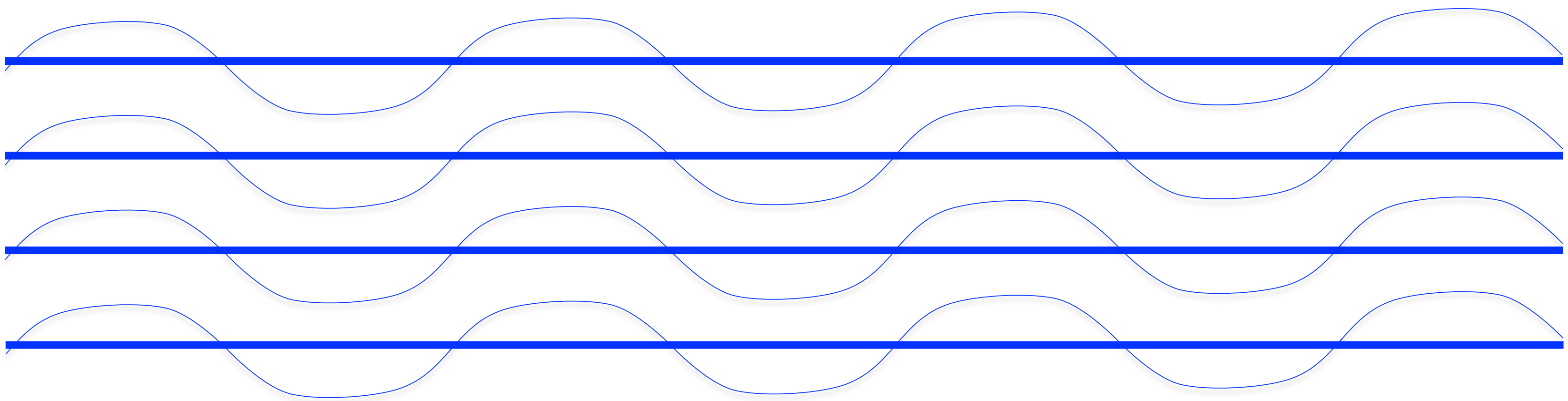

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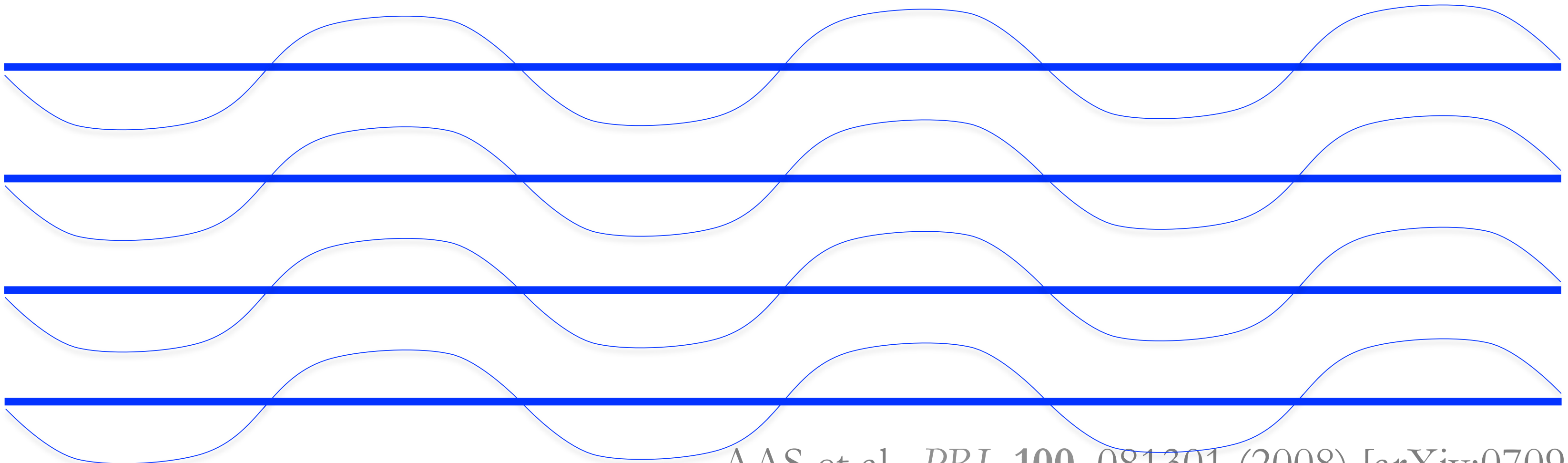

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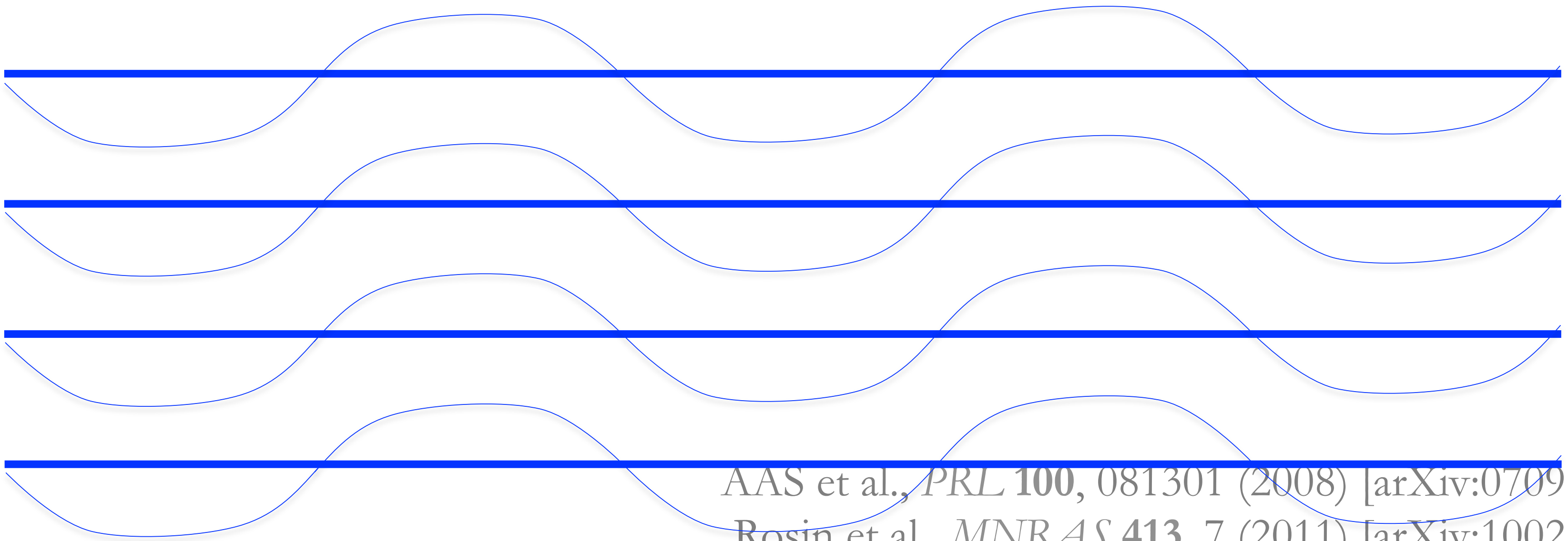

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pressure anisotropy driven by shear

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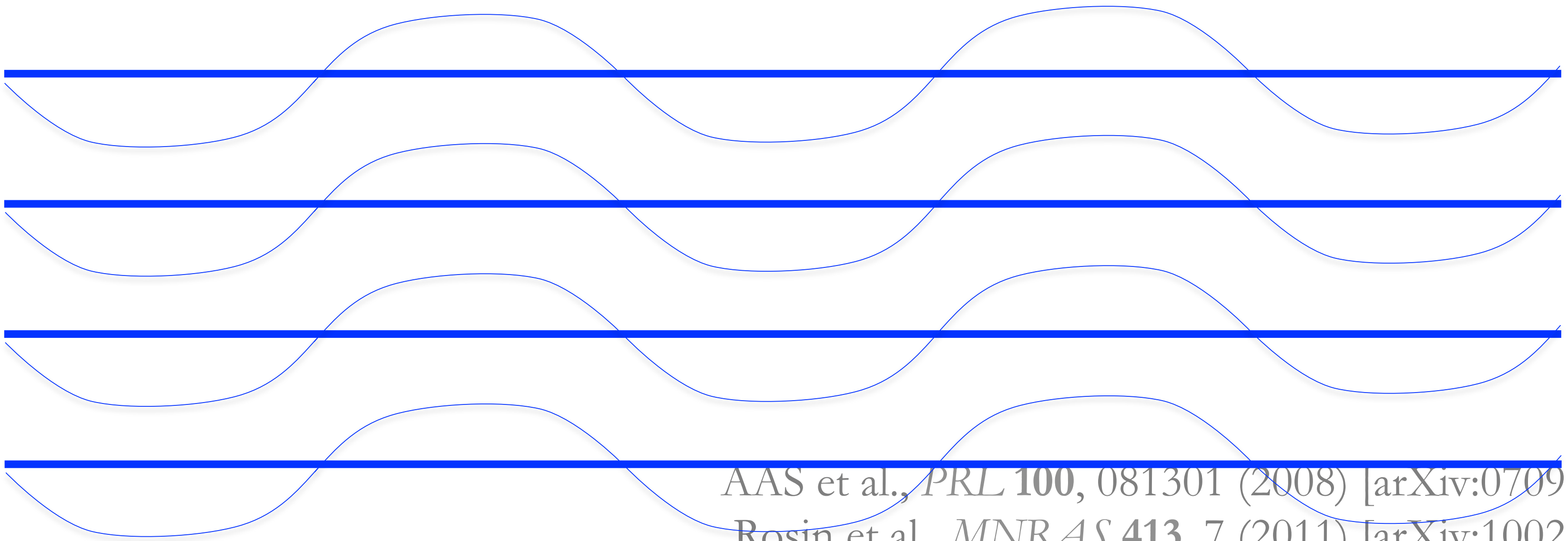
marginal stability

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

secular growth



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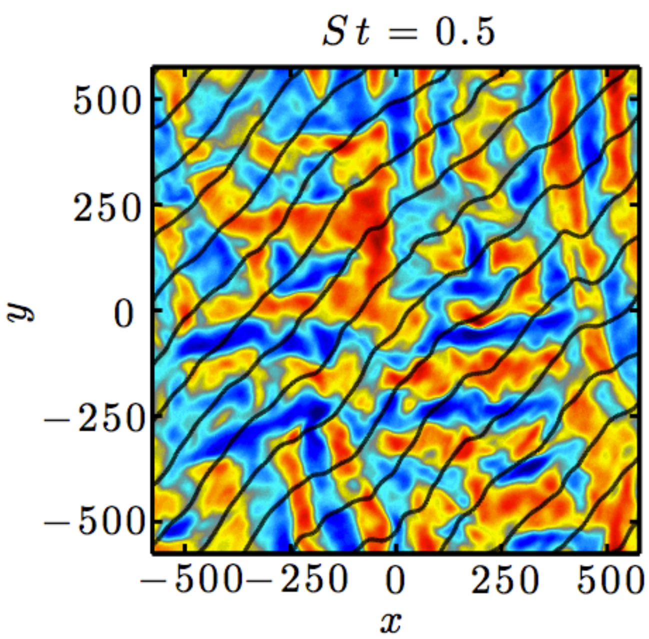
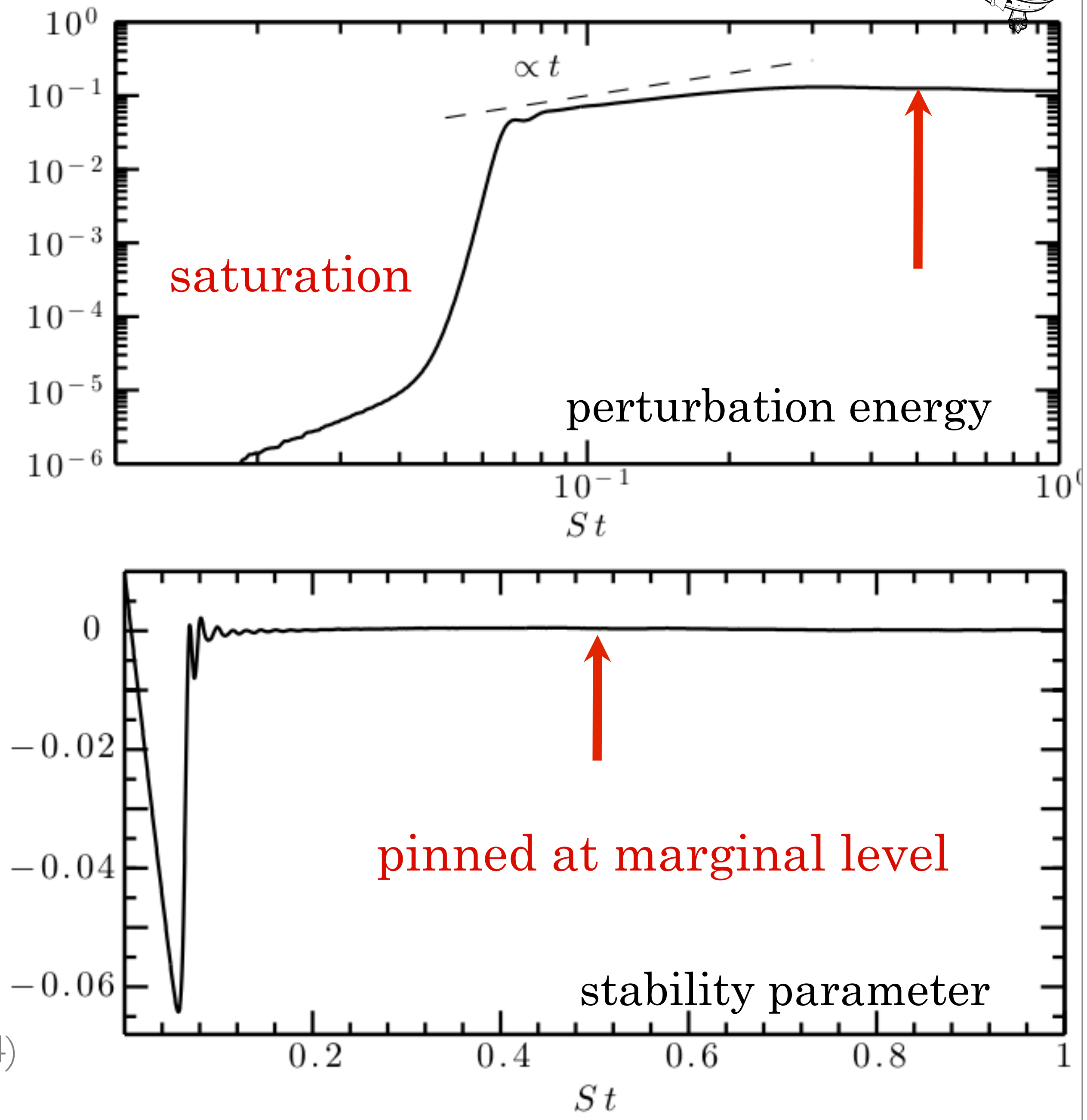
Firehose Instability: Saturated





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[arXiv:1402.0010]

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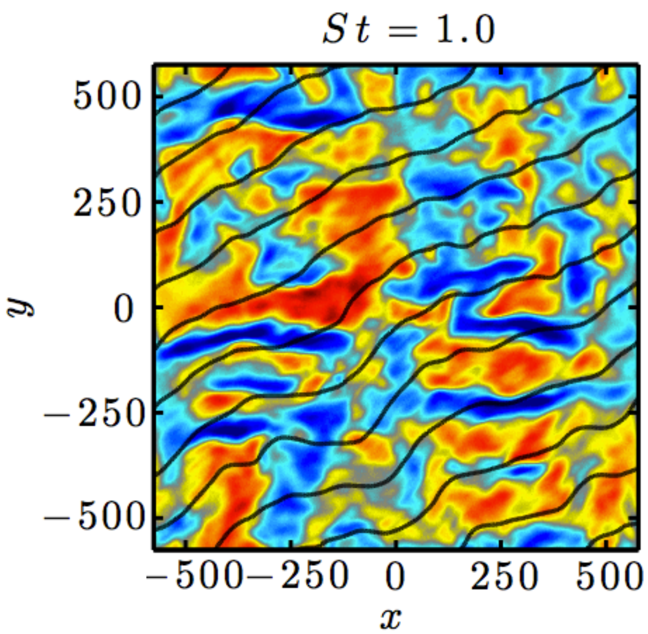
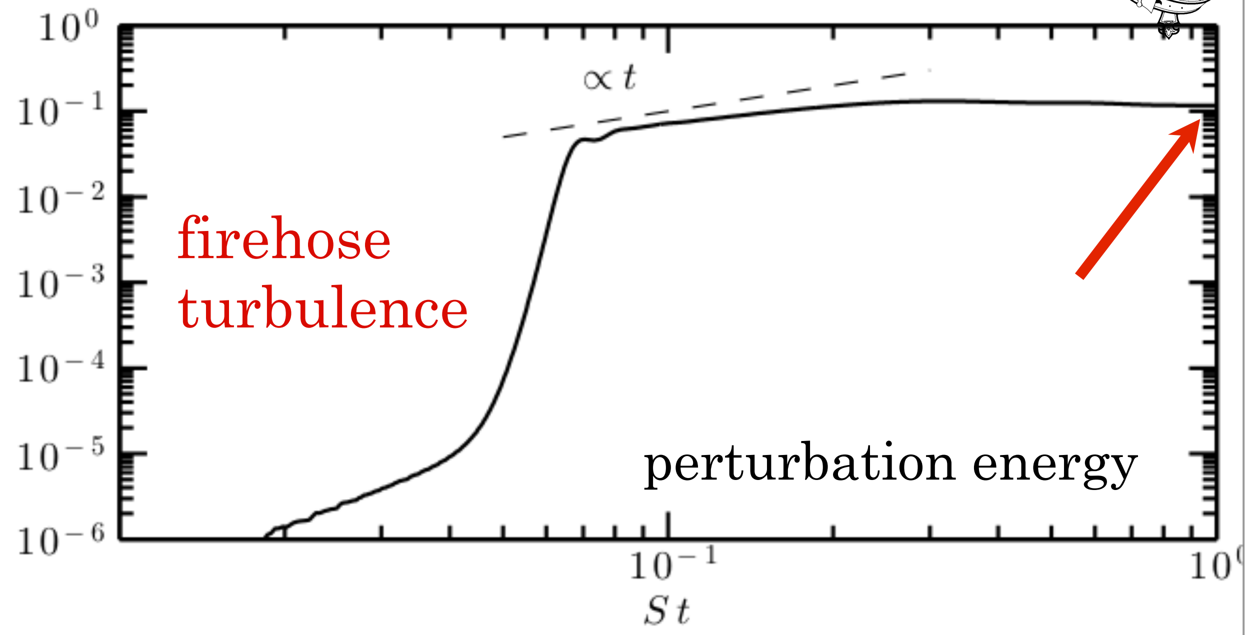
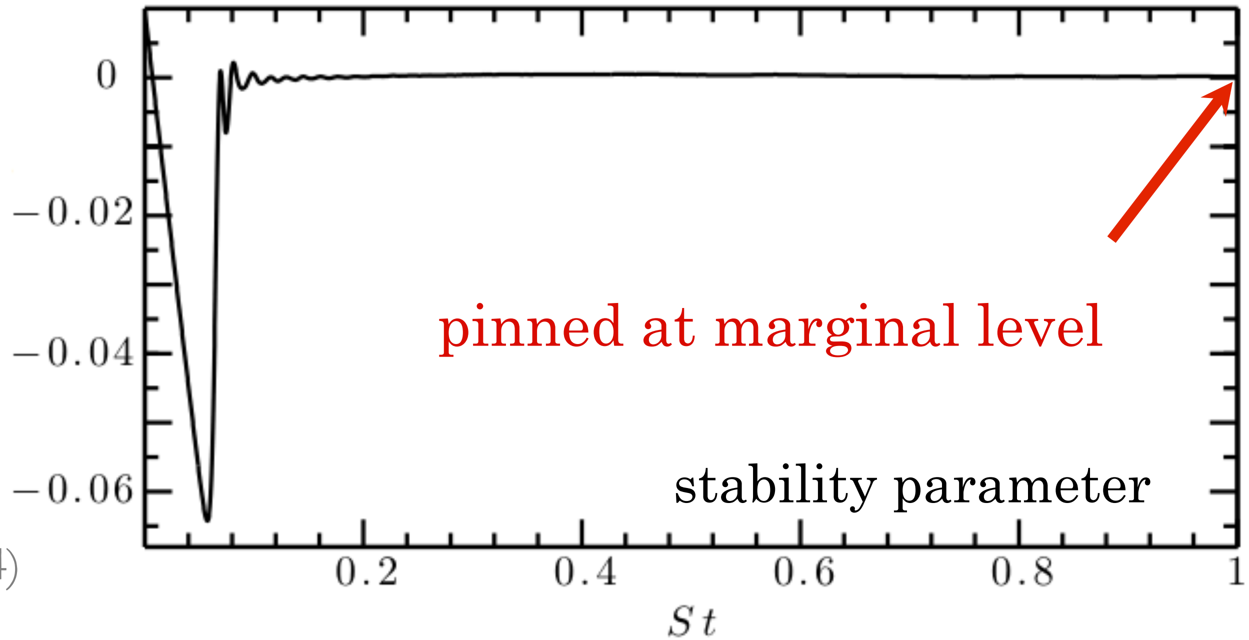




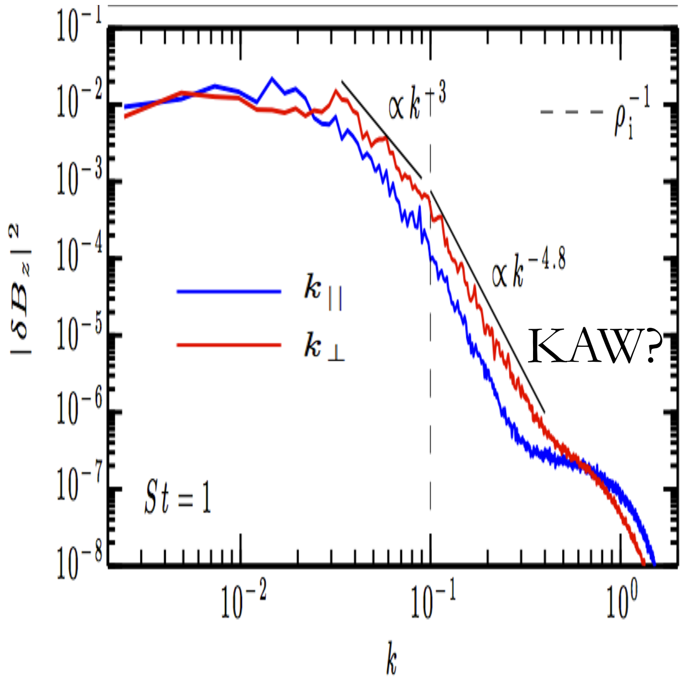


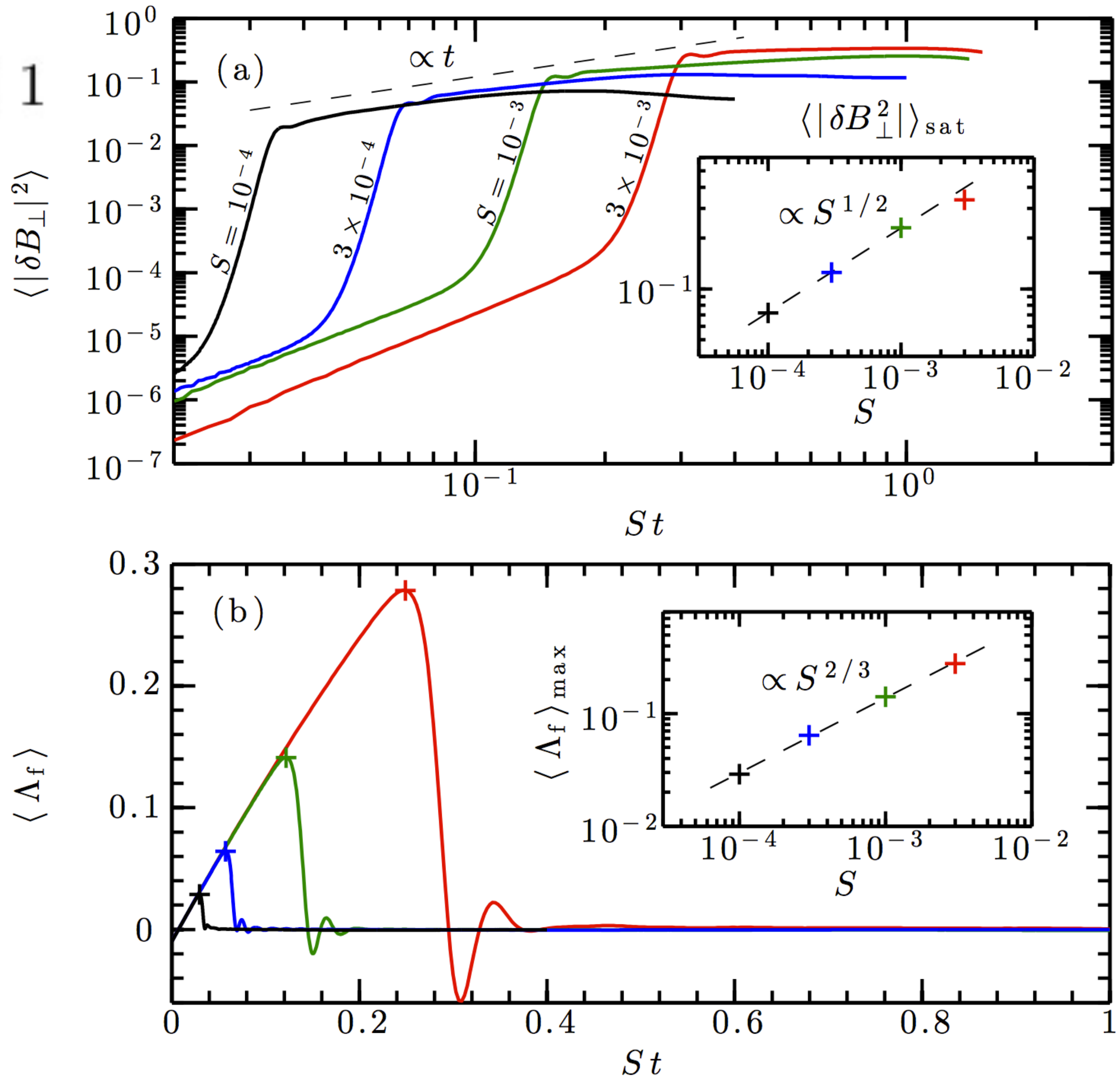
Kunz et al., *PRL* **112**, 205003 (2014)
[arXiv:1402.0010]

Firehose Saturates at Small Amplitudes

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

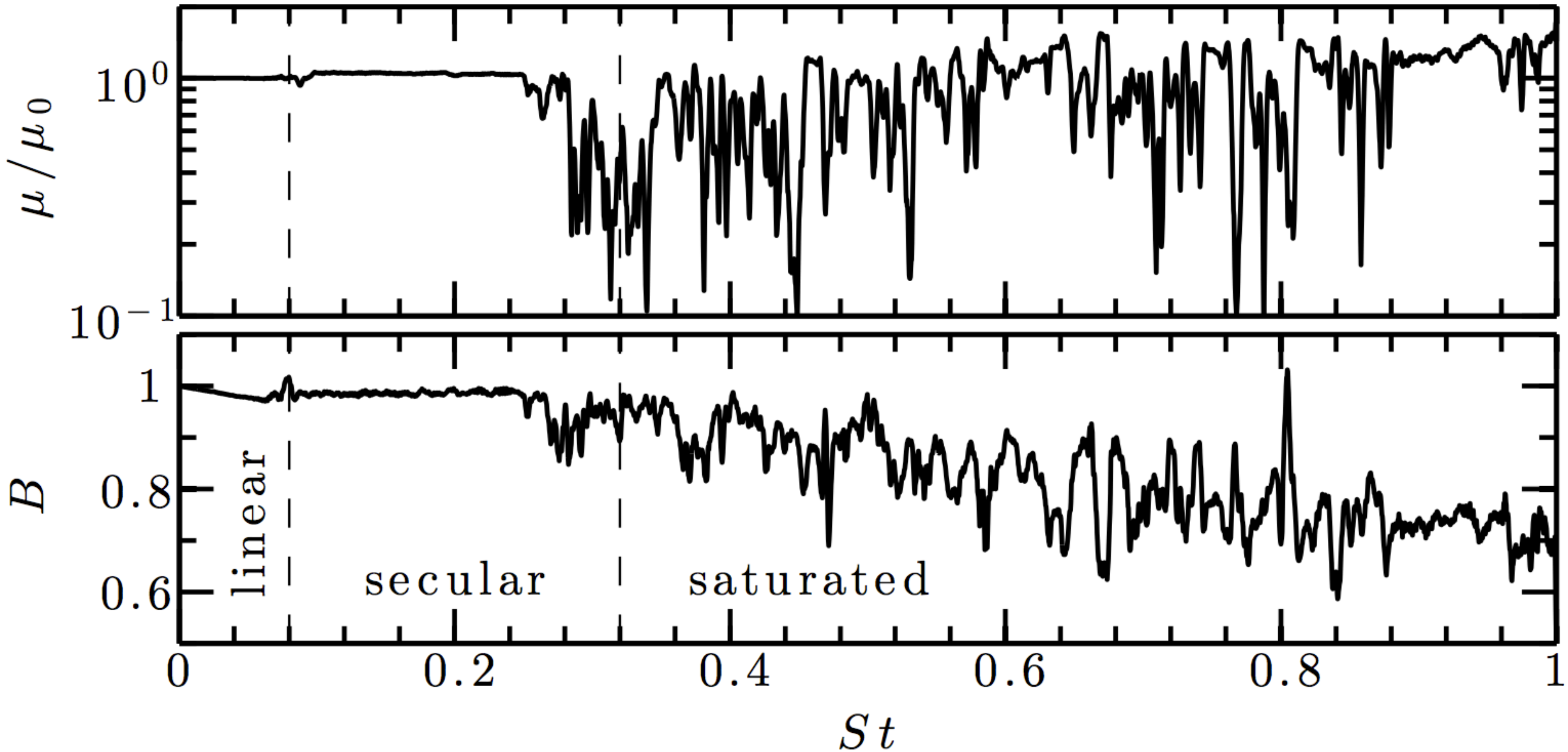
small-amplitude
Larmor-scale
firehose turbulence





Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Saturated Firehose Scatters Particles



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

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Saturated Firehose Scatters Particles

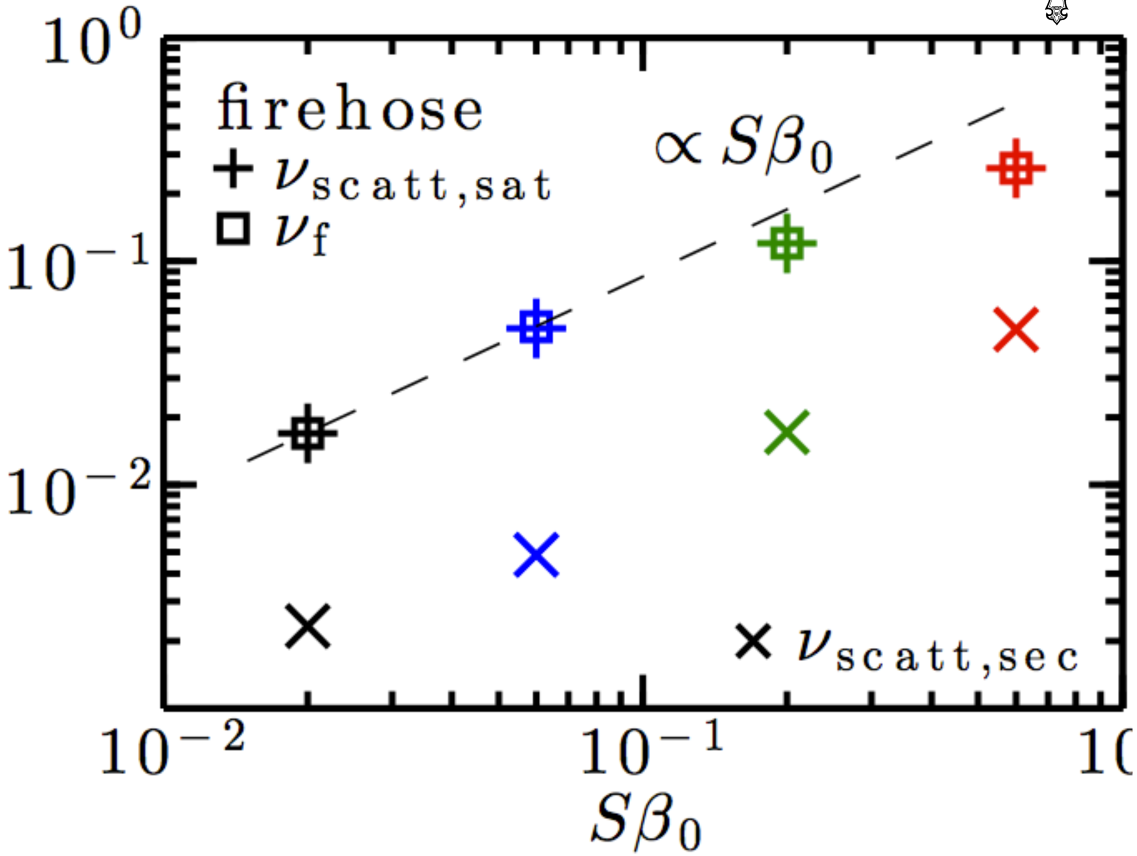
$$\frac{\mathrm{d}\Delta}{\mathrm{d}t} = 3\frac{\mathrm{d}\ln|\langle\mathbf{B}\rangle|}{\mathrm{d}t} - \nu_{\mathrm{f}}\Delta$$

$$= 0$$

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

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

$$\sim S\beta$$



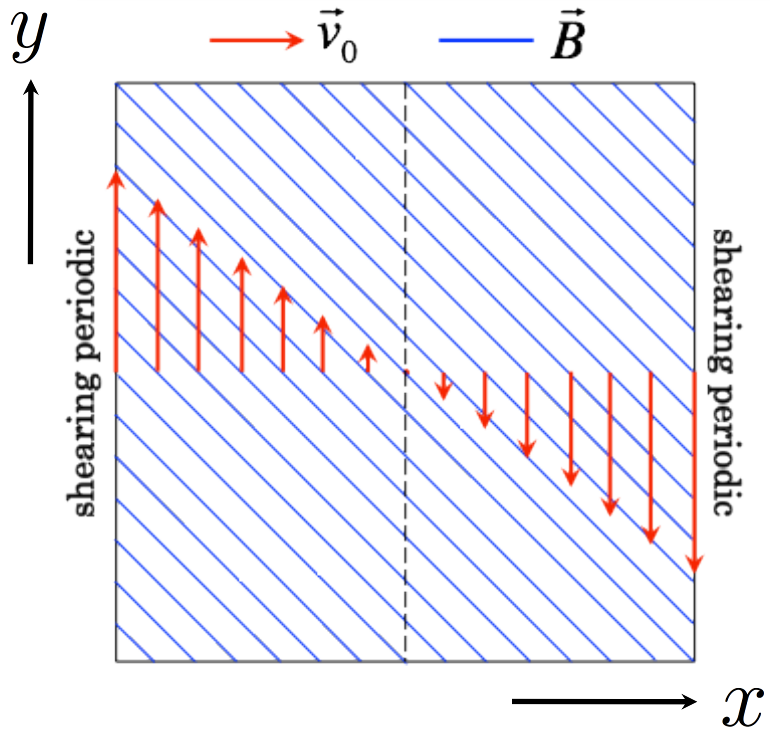
□ effective collisionality required to maintain marginal stability

+ measured scattering rate during the saturated phase

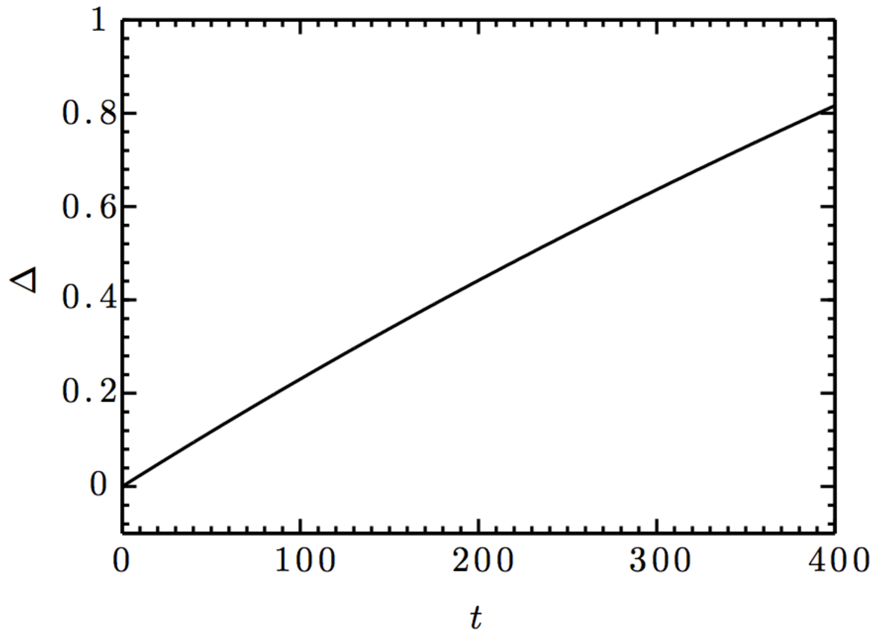
× measured scattering rate during the secular phase

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Mirror Instability (M. Kunz)



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

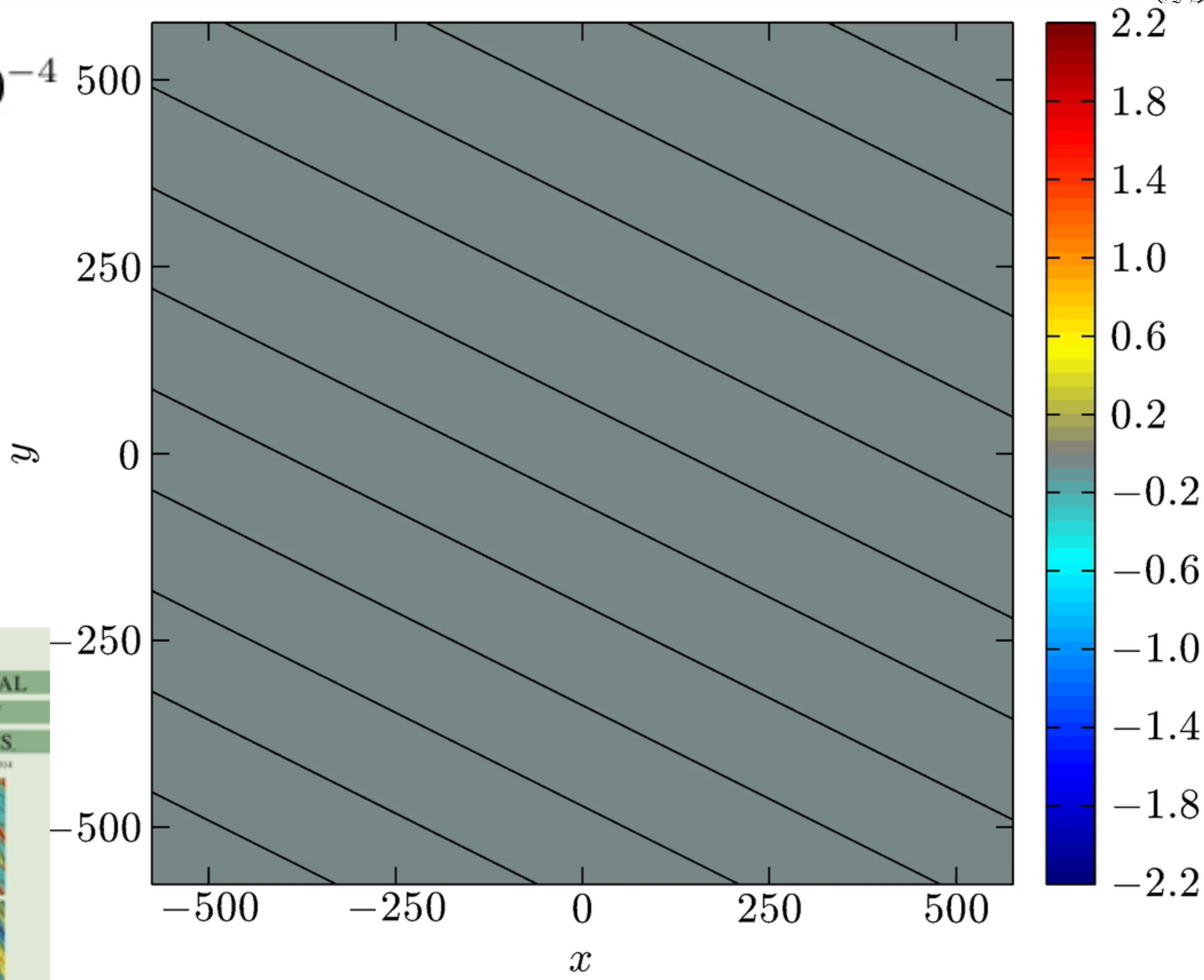


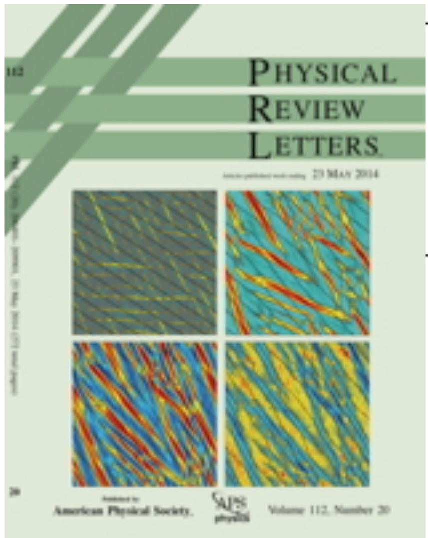
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]
Riquelme, Quataert & Verscharen, arXiv:1402.0014 (2014)

Mirror Instability (M. Kunz)

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

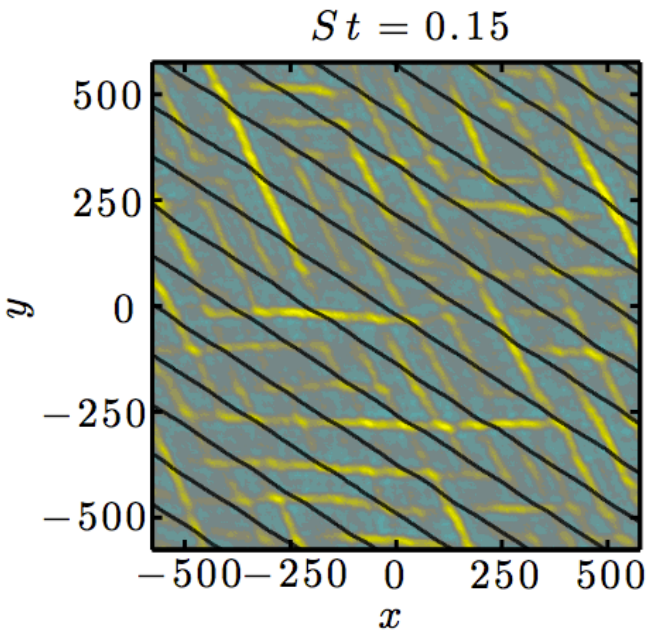
$$\beta_i = 200$$

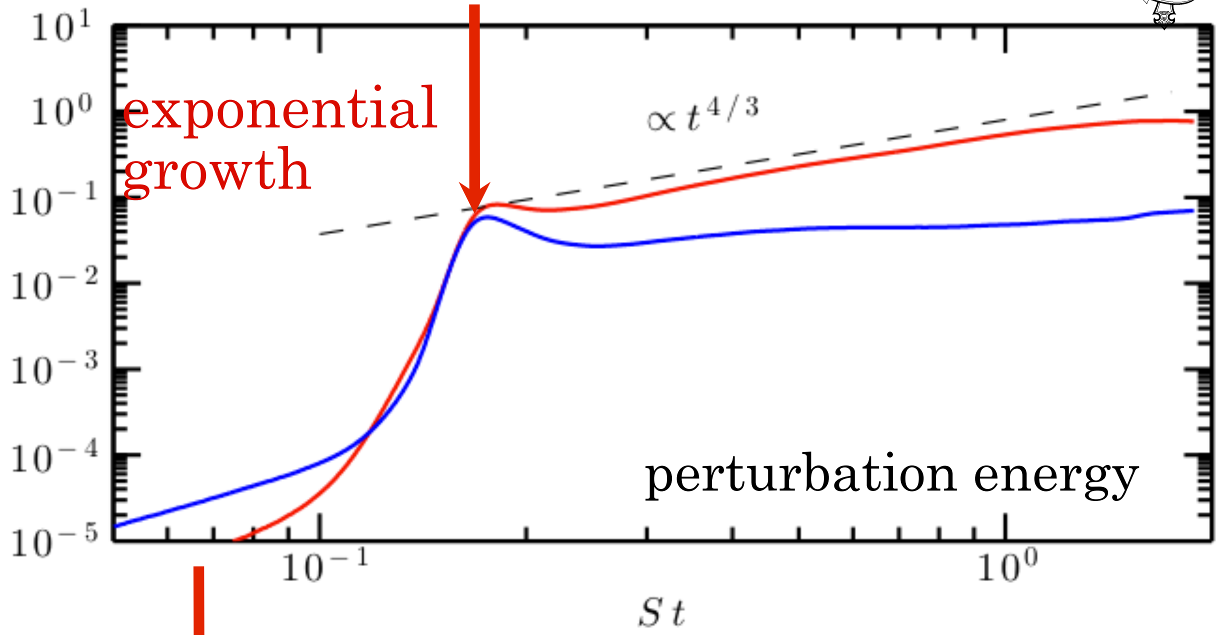


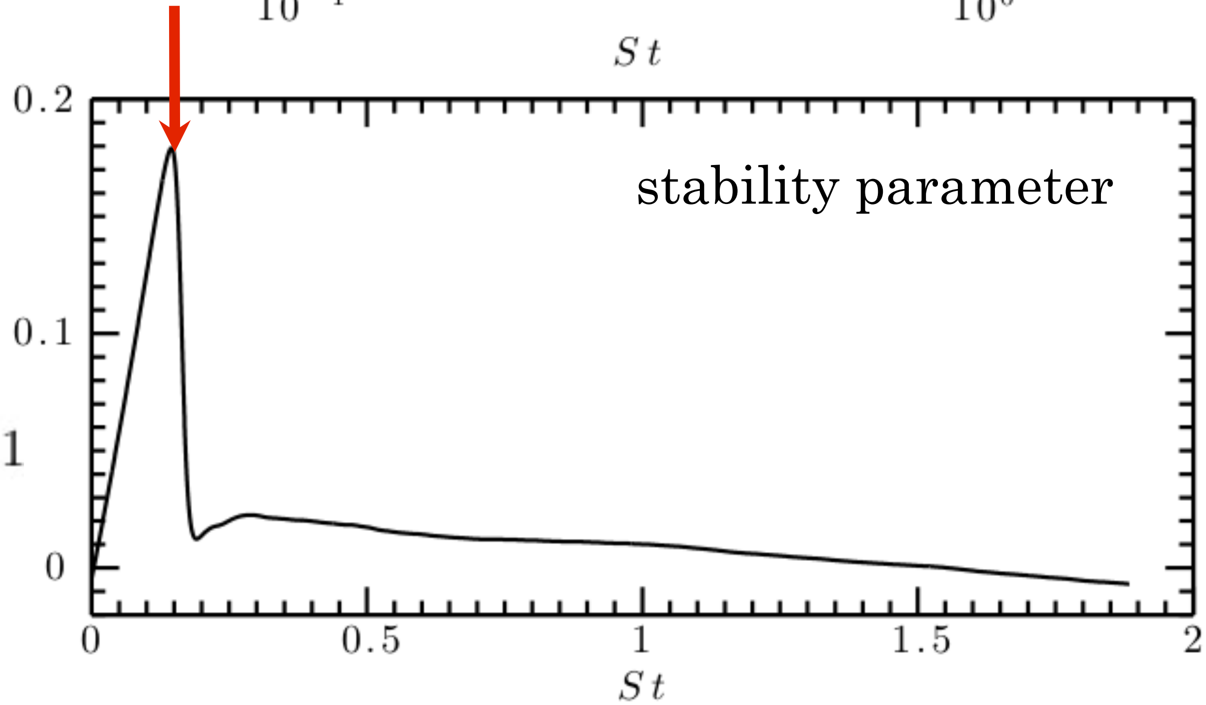


Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Mirror Instability: Linear





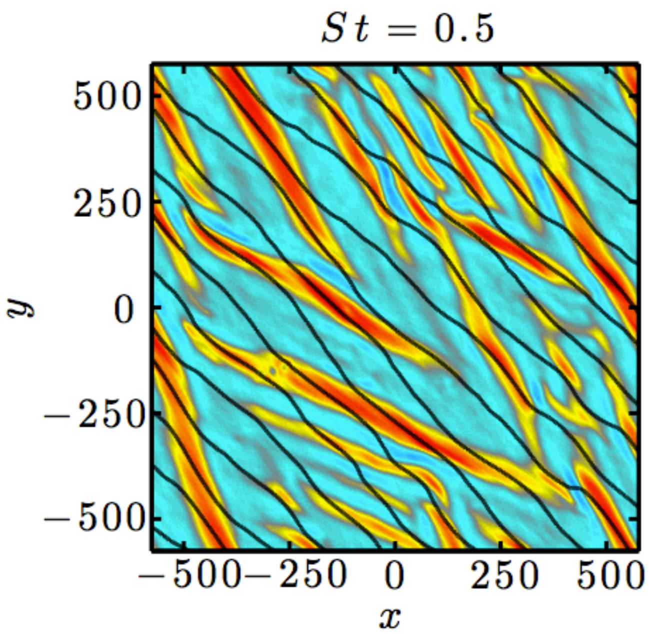


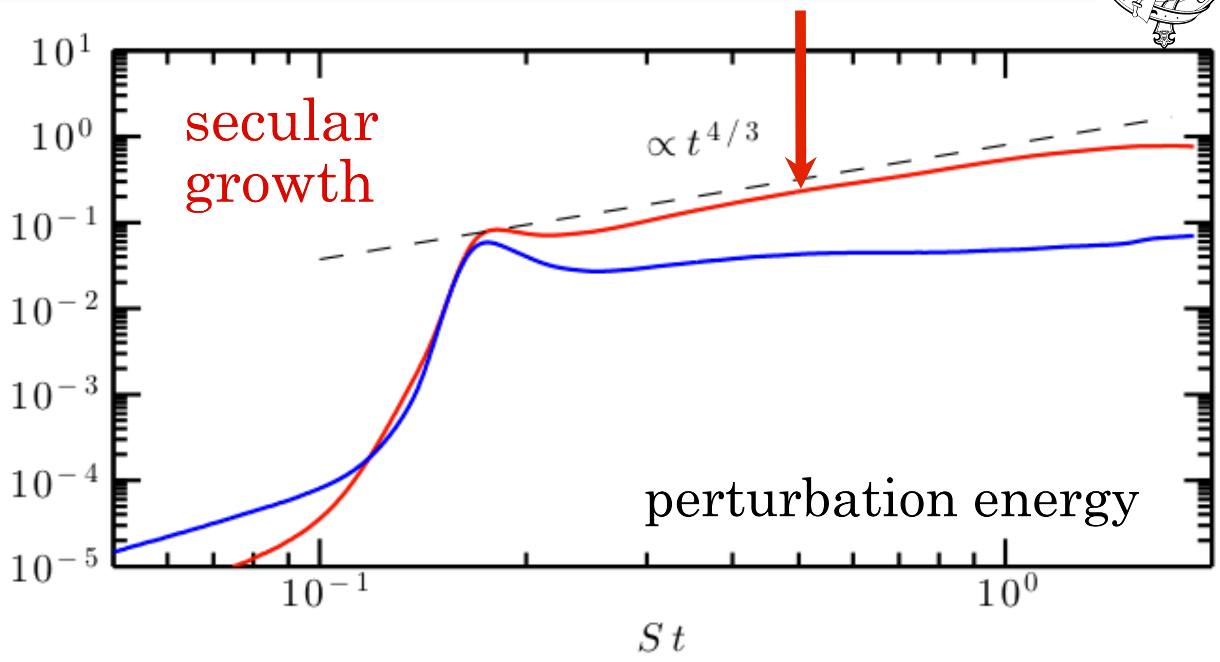
long, oblique modes

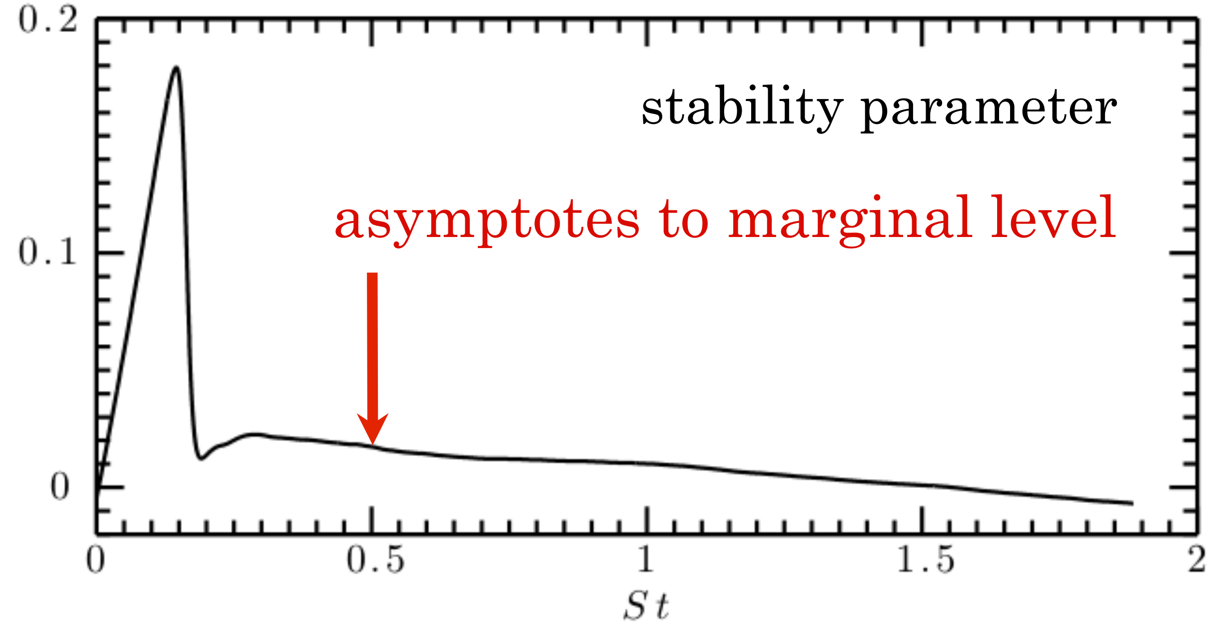
$$k_{\|}\rho_i \sim \left(\Delta - \frac{1}{\beta}\right)^{1/2} k_{\perp}\rho_i \ll 1$$

Kunz et al., *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Mirror Instability: Secular







Kunz et al., *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Mirror Instability: Secular

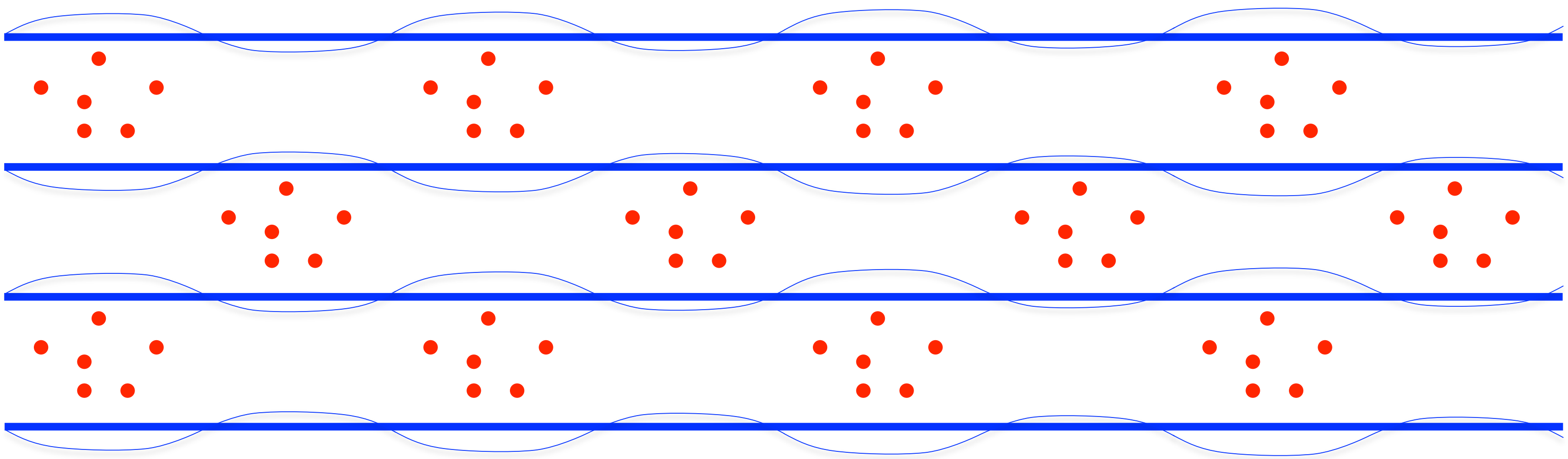
$$\overline{B} = B_0 + \overline{\delta B_\parallel}$$

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

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, arXiv:1407.4707

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

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$$\Delta = 3\int^t \mathrm{d}t' \,\overline{\frac{\mathrm{d}\ln B}{\mathrm{d}t}} \sim 3\int^t \mathrm{d}t' \left(\frac{\mathrm{d}\ln B_0}{\mathrm{d}t} - \frac{\mathrm{d}}{\mathrm{d}t}\overline{\left|\frac{\delta B_\parallel}{B_0}\right|^{3/2}} \right) \to \frac{1}{\beta}$$

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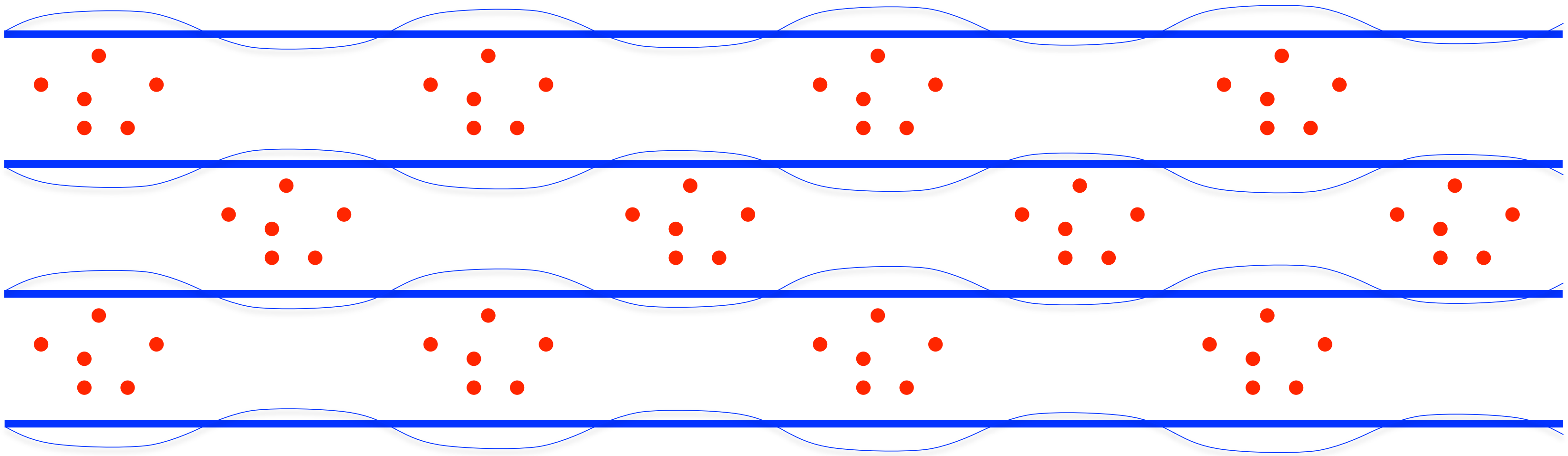

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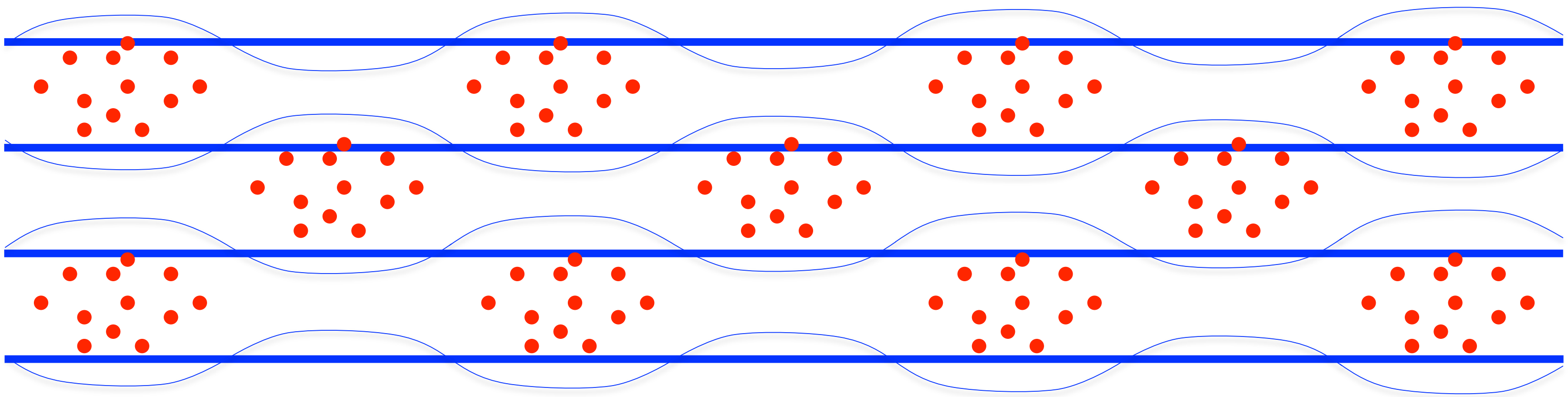

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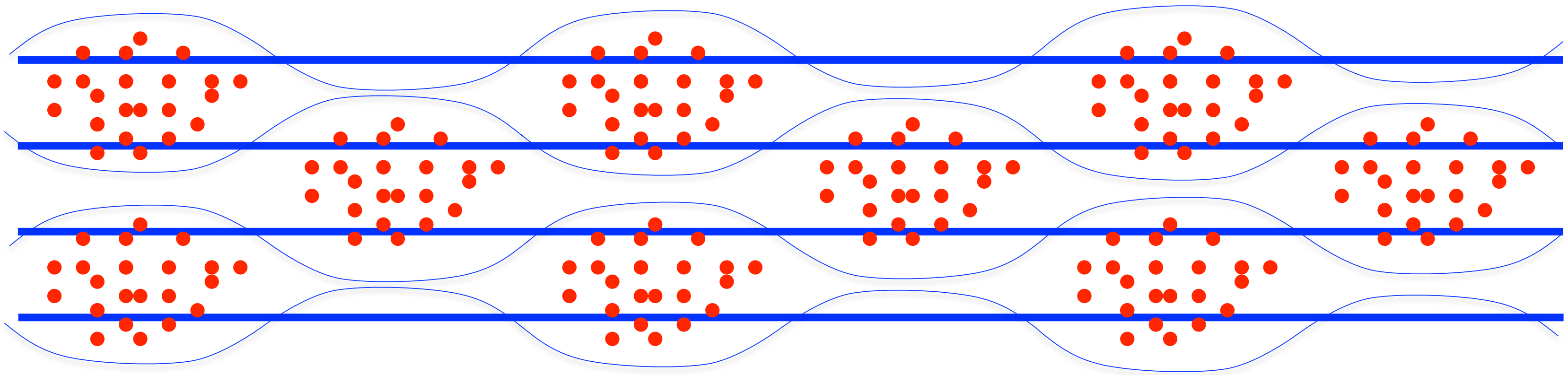

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Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

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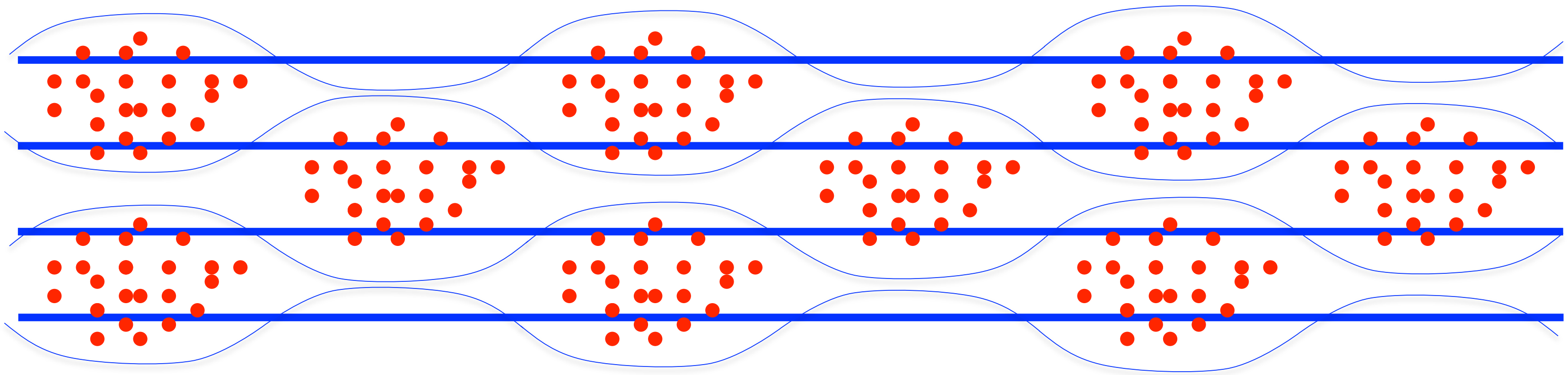
$$\overline{\left|\frac{\delta B_\parallel}{B_0}\right|^{3/2}} = S\int^t \mathrm{d}t' \, \hat{b}_x(t')\hat{b}_y(t') - \frac{1}{\beta} \quad \Rightarrow \quad \frac{\delta B_\parallel^2}{B_0^2} \sim (St)^{4/3}$$

secular growth



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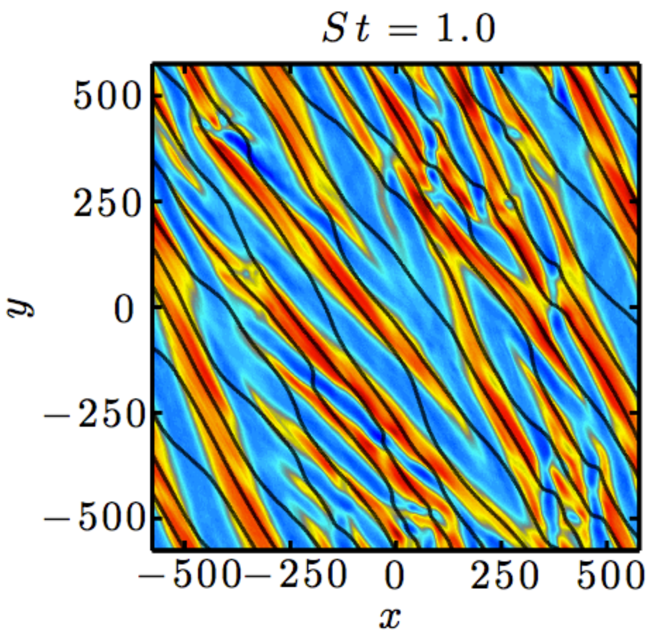
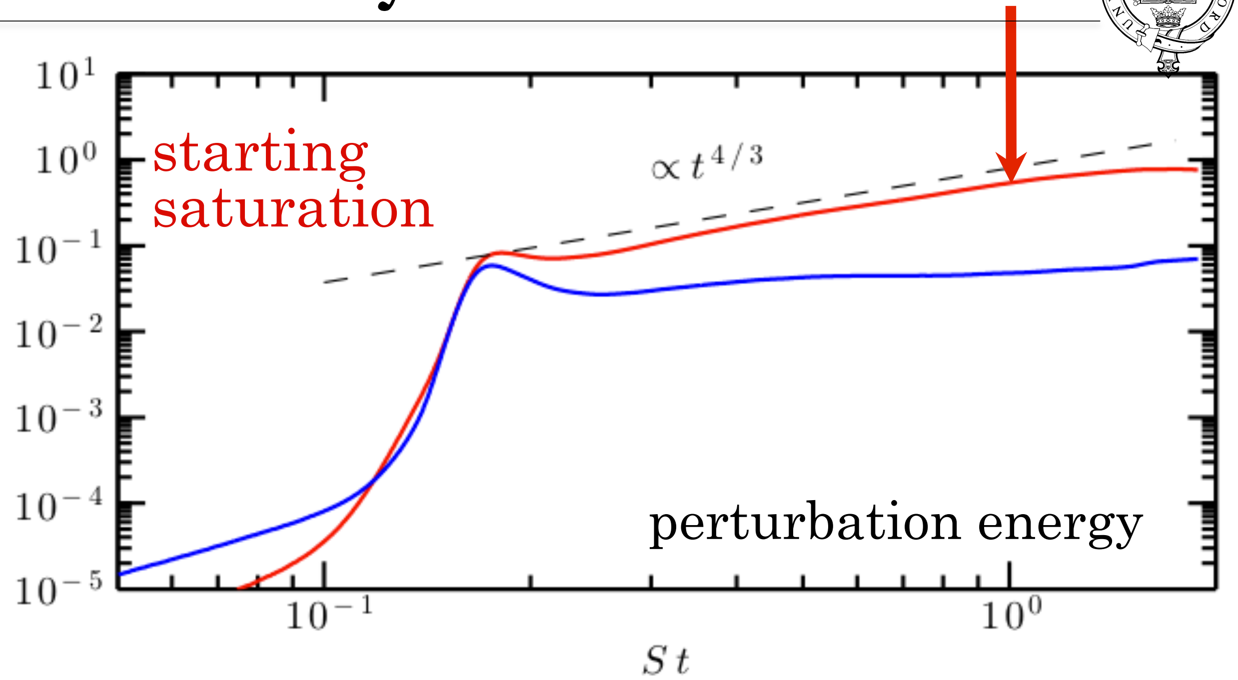
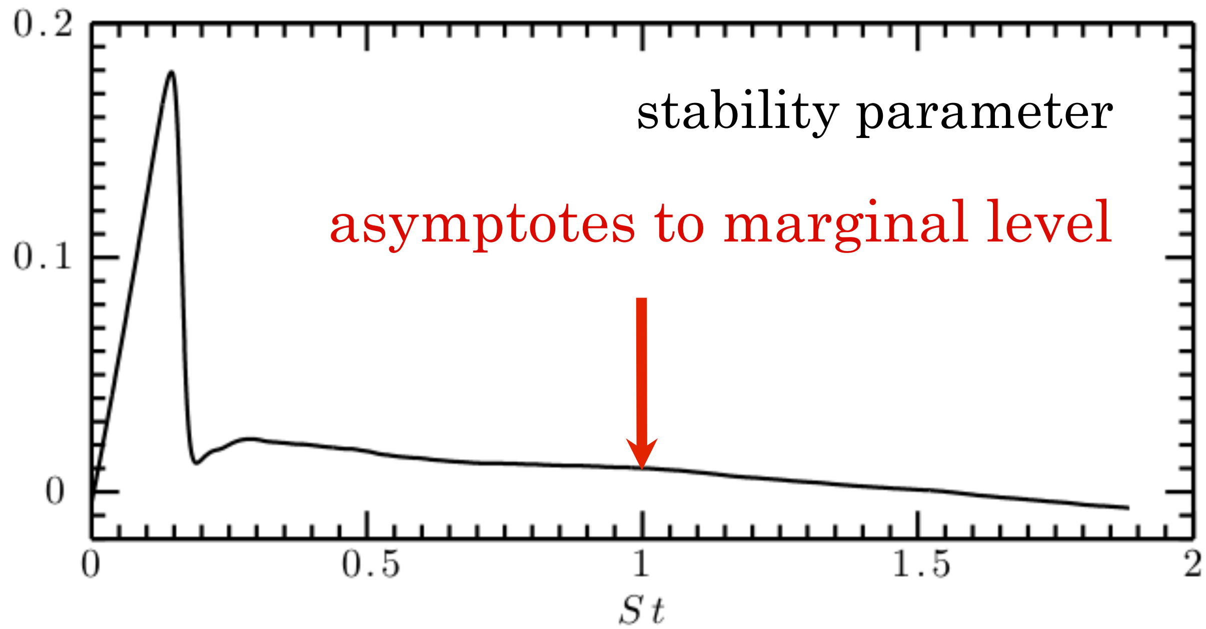
Mirror Instability: Secular

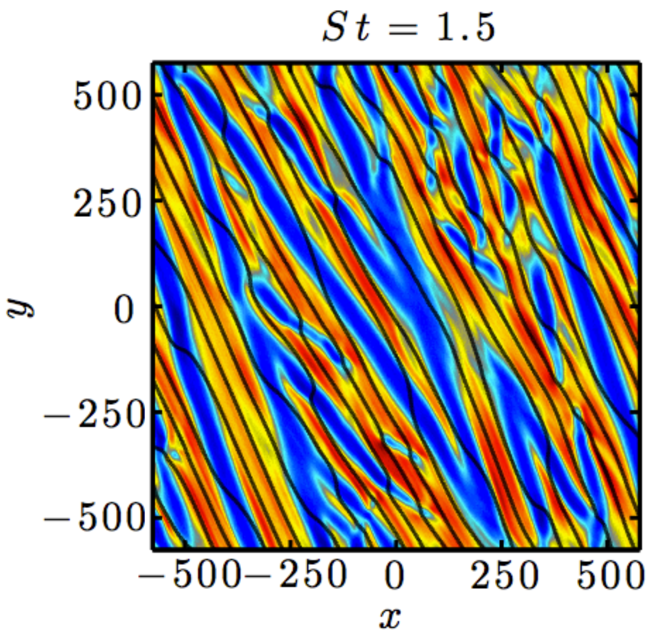


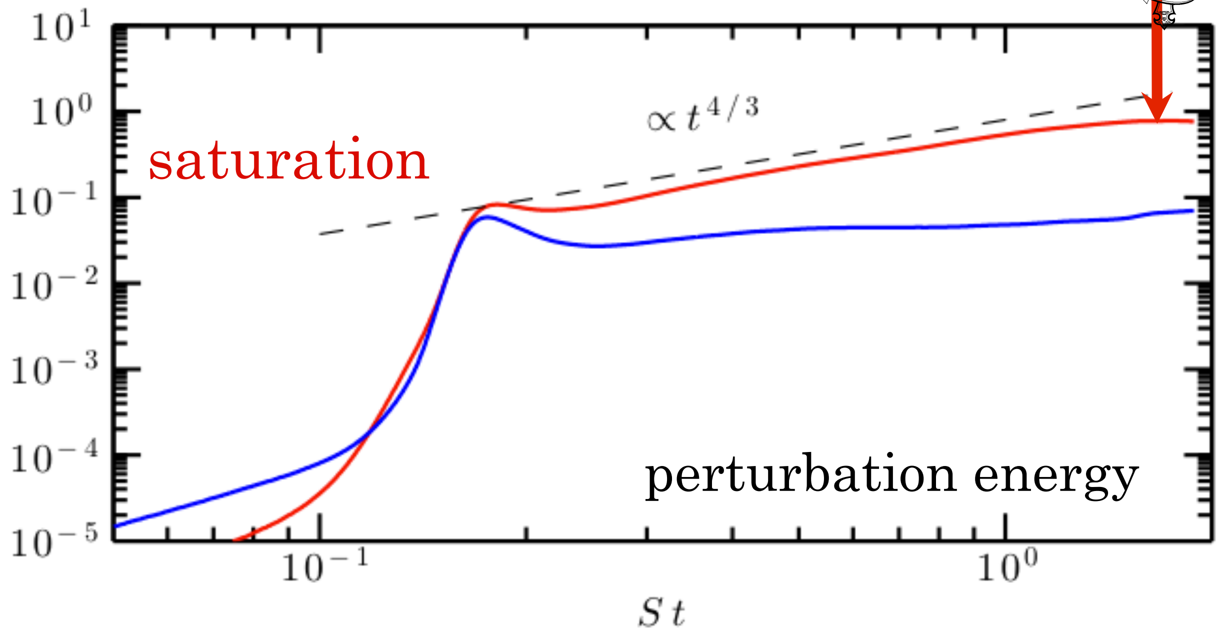


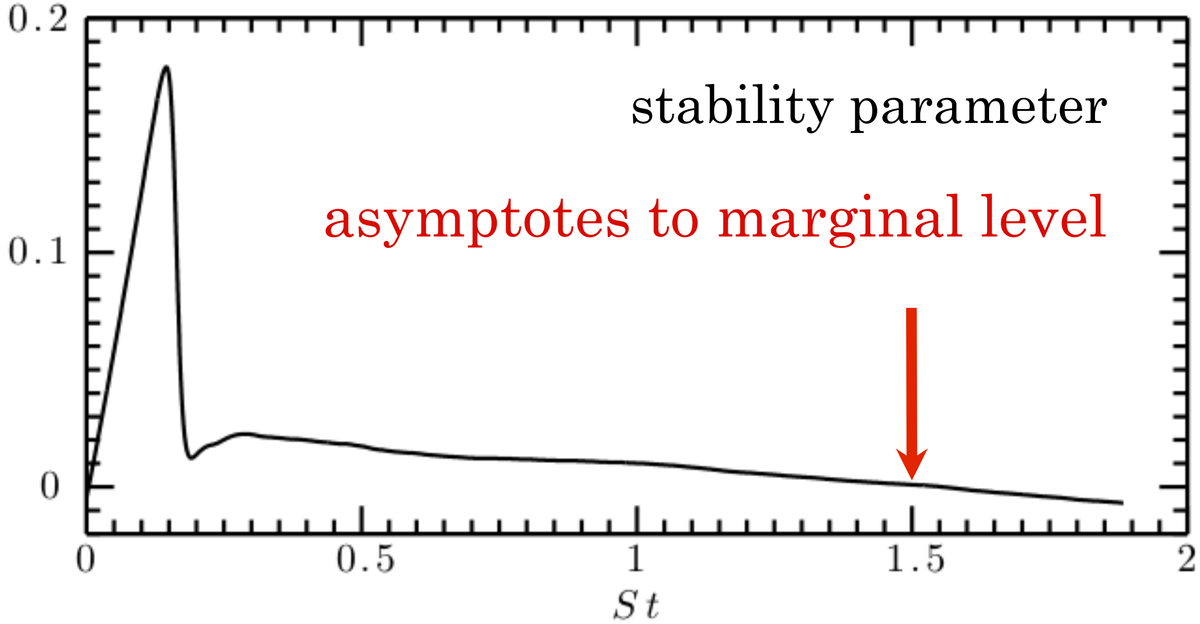


Kunz et al., *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Mirror Instability: Saturated





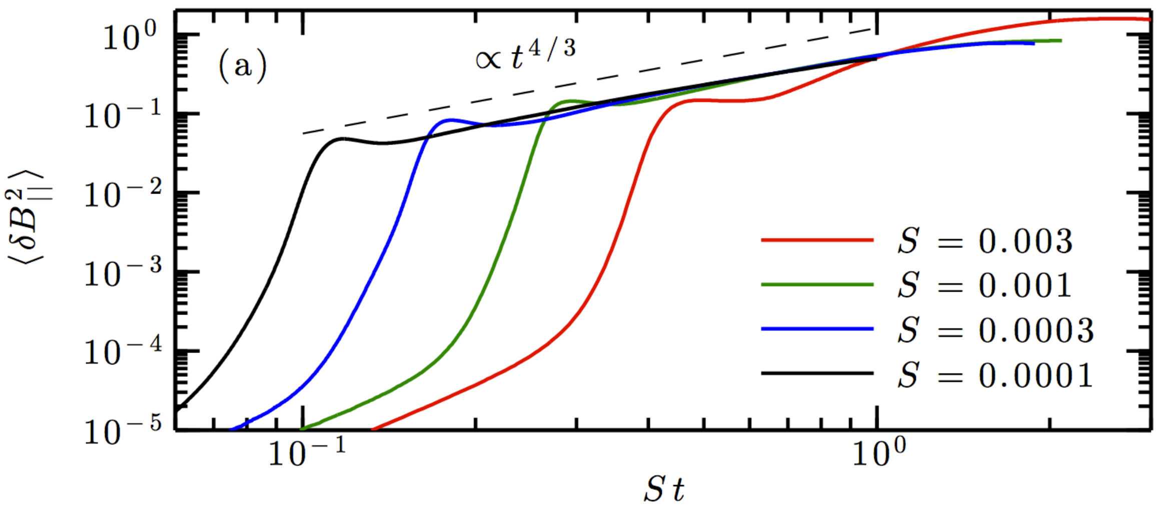


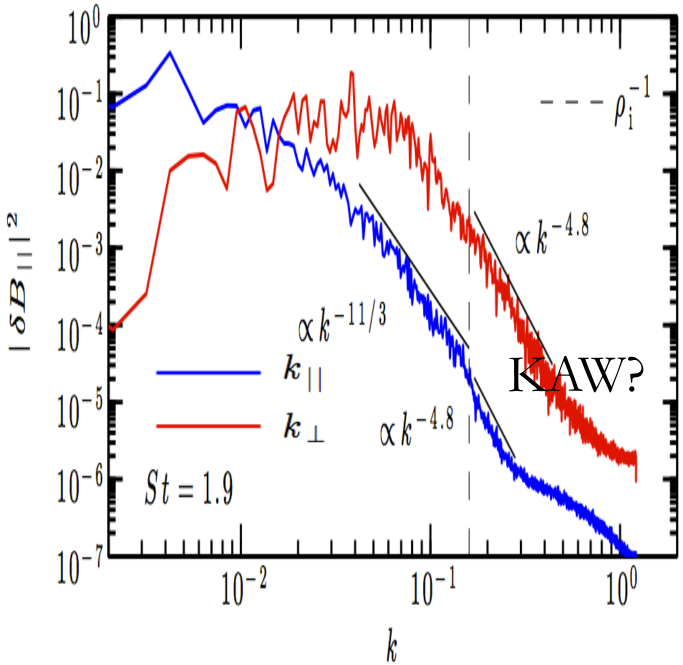
Kunz et al., *PRL* **112**, 205003 (2014)
[arXiv:1402.0010]

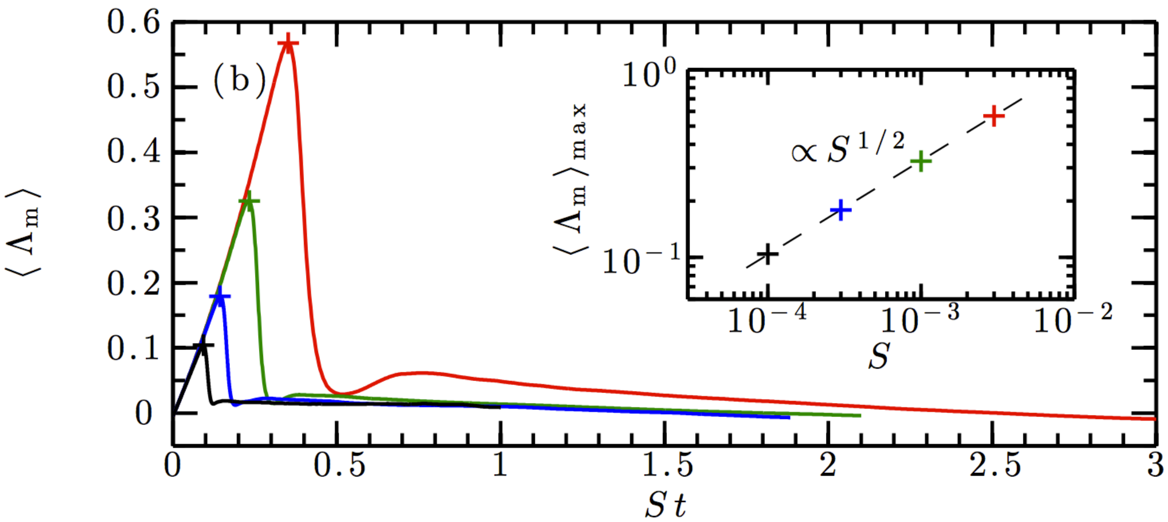
Mirror Saturates at Order-Unity Amplitudes

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

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

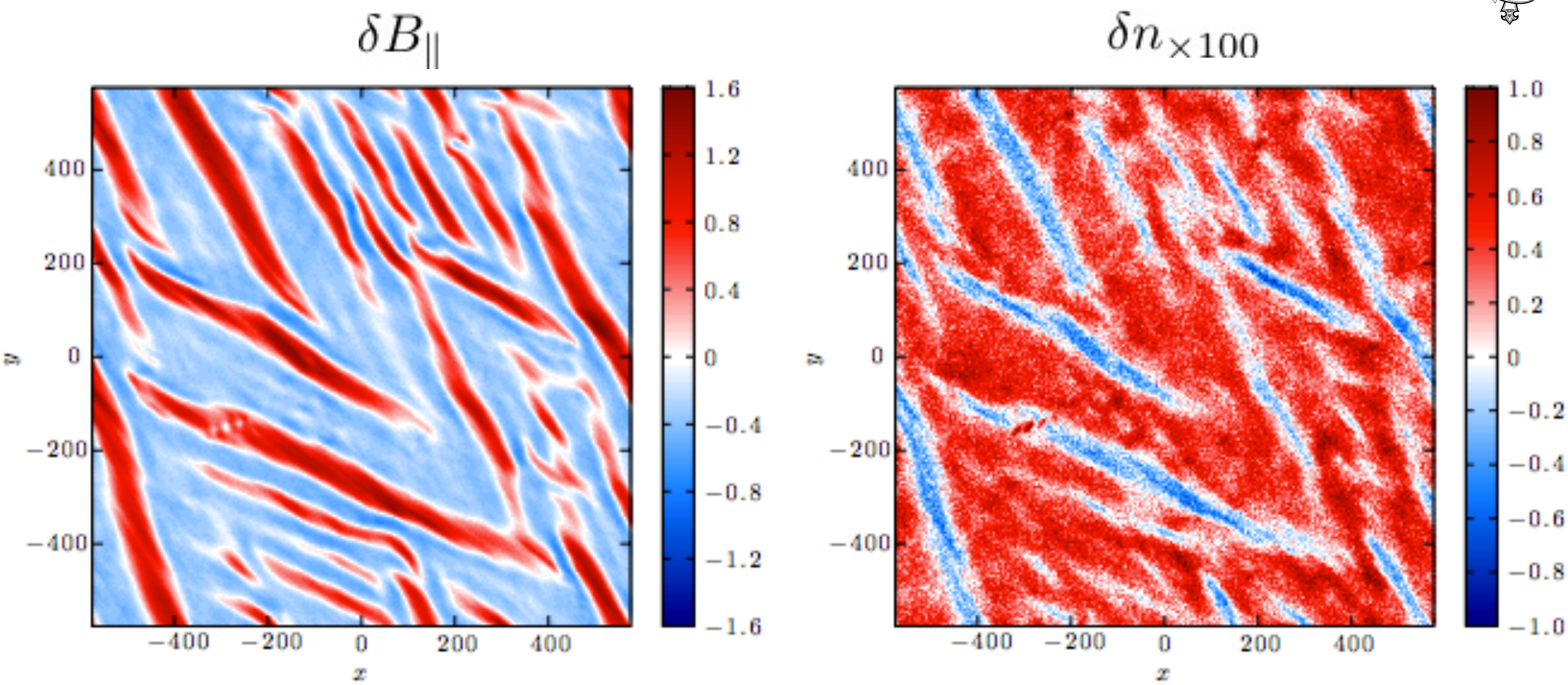






Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

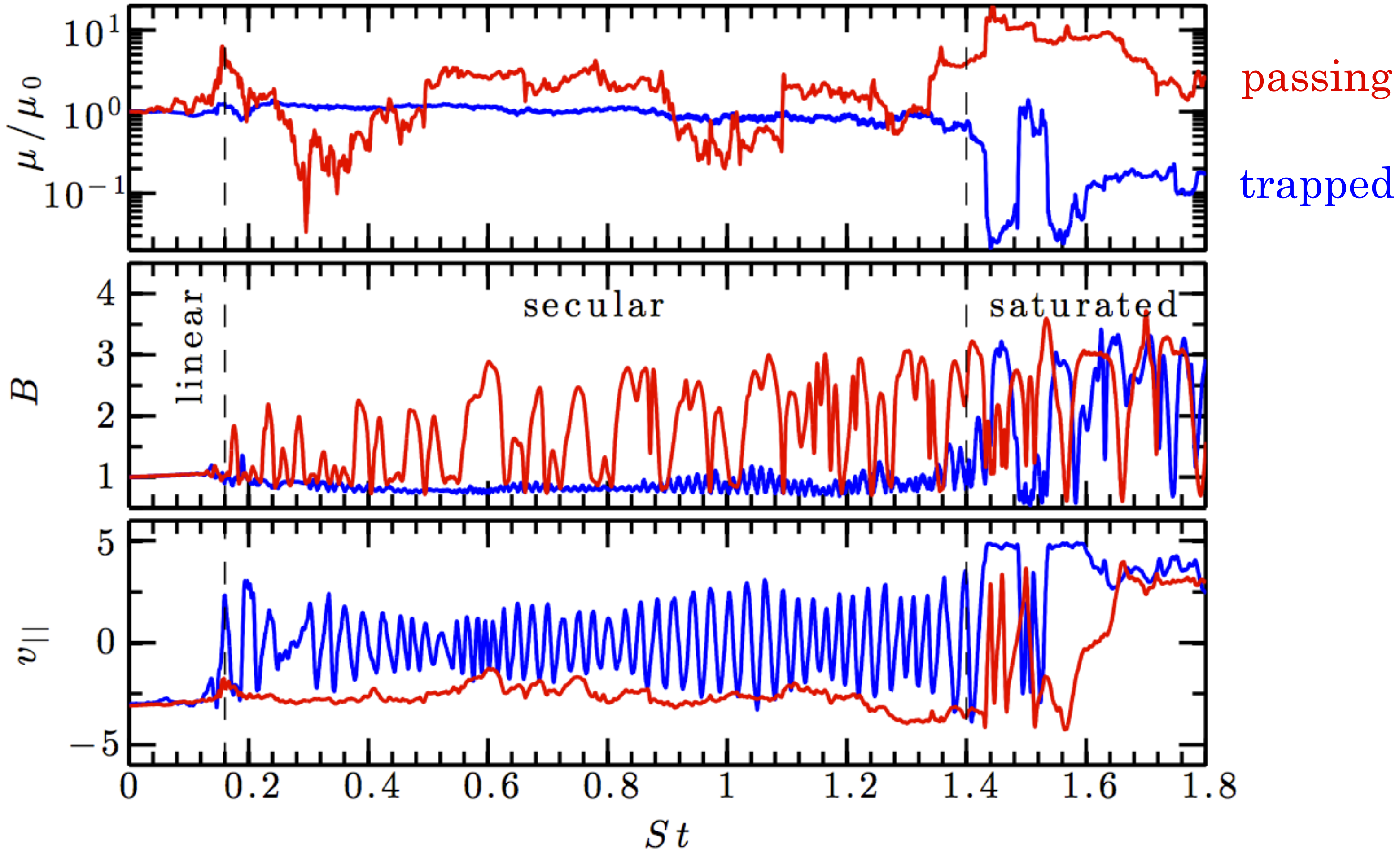
Mirror Instability: Trapped Particles



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

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

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 (off mirror edges)

Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Secular Mirror Doesn't Scatter Particles

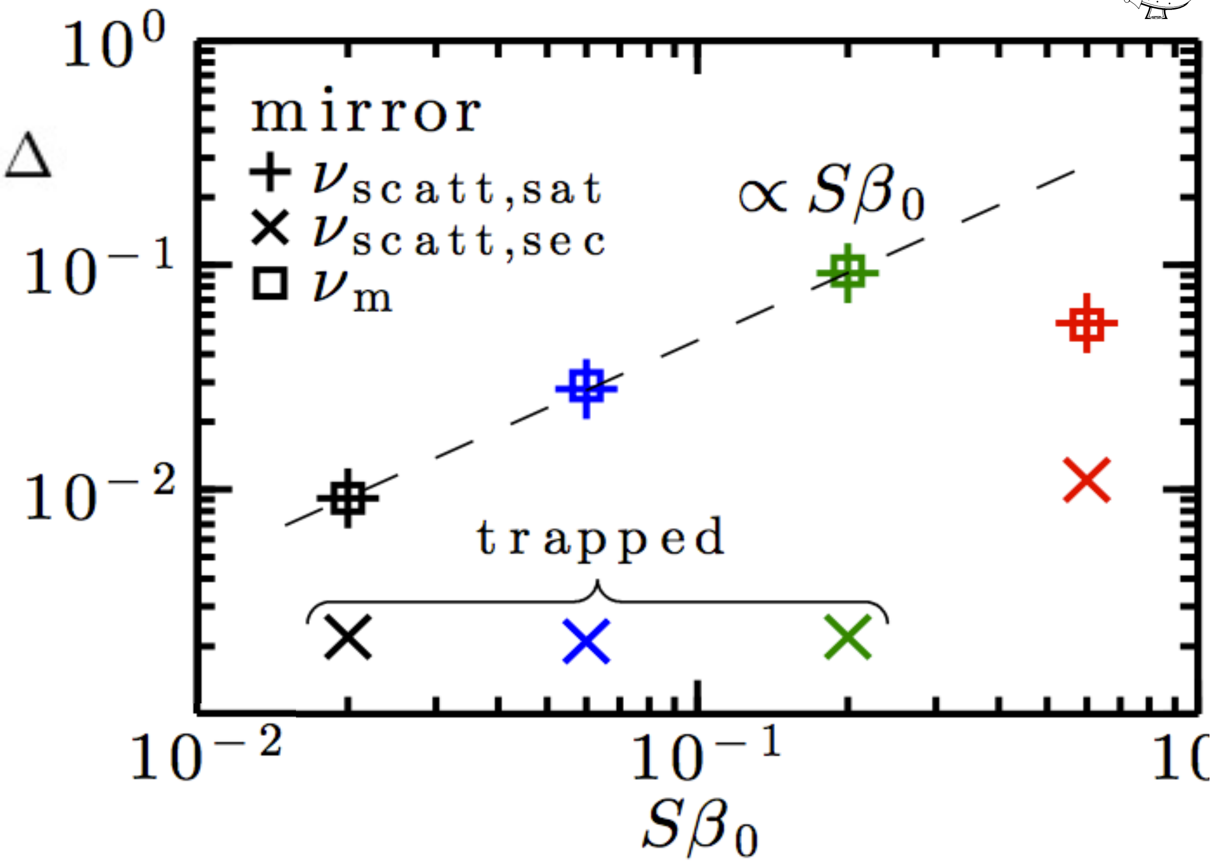
$$\frac{d\Delta}{dt} = 3\frac{d\ln|\langle \mathbf{B}\rangle|}{dt} - \nu_f \Delta$$

$$= 0$$

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

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

$$\sim S\beta$$



□ 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) [arXiv:1402.0010]

Conclusions So Far

- *Very different scenarios for plasma dynamo depending on whether nonlinear firehose and mirror fluctuations regulate pressure anisotropy by scattering particles or by adjusting rate of change of the magnetic field:*
  - **No scattering** → explosive growth, but long time to get going

    $t \sim \beta_0/2\nu$ scales with collision time and initial field
  - **Efficient scattering** → secular growth, but very fast

    $t \sim l/u$ one large-scale turnover time
- Driven **firehose** saturates at low amplitudes, scatters particles
- Driven **mirror** grows to $\delta B/B \sim 1$ without doing much scattering (marginal state achieved via trapped population in mirrors)
- [Both instabilities have a sub-Larmor tail, which appears to be KAW turbulence with the usual spectrum]
- Plasma Dynamo: the race is on

Mogavero & AAS, *MNRAS* **440**, 3226 (2014) [arXiv:1312.3672]
Kunz, AAS & Stone, *PRL* **112**, 205003 (2014) [arXiv:1402.0010]

Conclusions So Far

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  - **No scattering** ➔explosive growth, but long time to get going

    $t \sim \beta_0/2\nu$ scales with collision time and initial field
  - **Efficient scattering** ➔secular growth, but very fast

    $t \sim l/u$ one large-scale turnover time
- Driven **firehose** saturates at low amplitudes, scatters particles
- Driven **mirror** grows to $\delta B/B \sim 1$ without doing much scattering (marginal state achieved via trapped population in mirrors)
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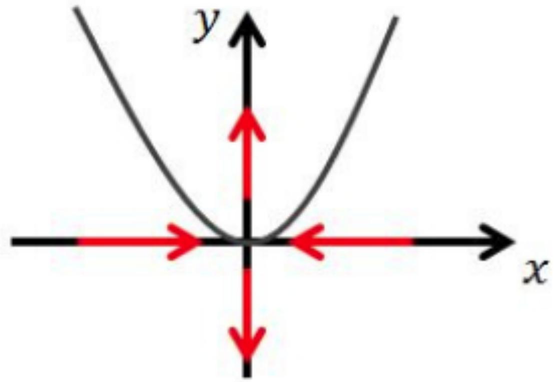
WE DON'T REALLY KNOW (YET) HOW MAGNETISED, HIGH β PLASMA MOVES

Effects of Magnetic Field

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



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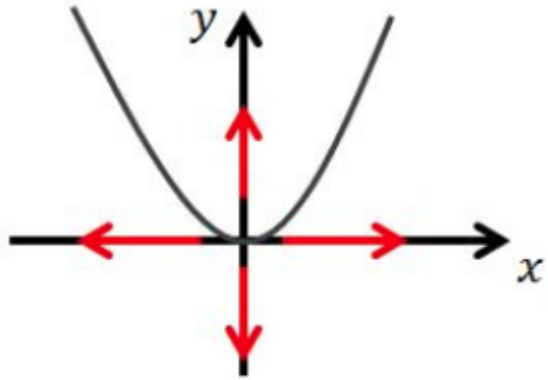

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