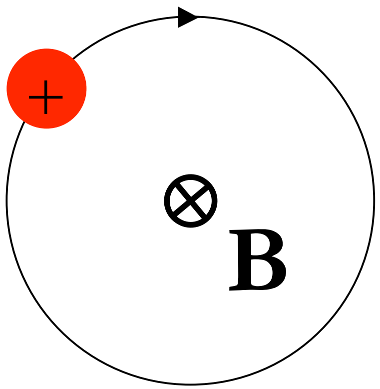
Modelling the Magnetised ICM: From Microscale Physics to What Matters to Astronomers

Alex Schekochihin *(Oxford)*
Matt Kunz *(Oxford)*
Steve Cowley *(CCFE)*
François Rincon *(Toulouse)*
Mark Rosin *(Cambridge)*

Schekochihin *et al.*, ApJ **629**, 139 (2005)
Schekochihin & Cowley, Phys. Plasmas **13**, 056501 (2006)
Schekochihin *et al.*, PRL **100**, 081301 (2008)
Schekochihin *et al.*, MNRAS **405**, 291 (2010)
Rosin *et al.*, MNRAS, submitted; arXiv:1002.4017
Kunz *et al.*, MNRAS, submitted; arXiv:1003.2719

$B = 1\ \mu\mathrm{G}$

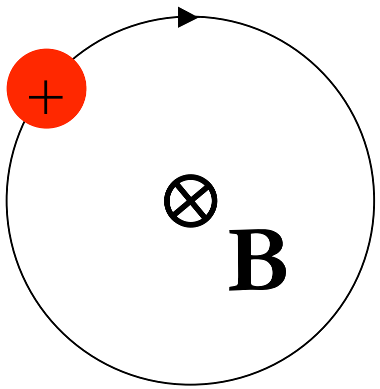
$T = 1\ \mathrm{keV}$



$$\rho_i = \frac{v_{\mathrm{th}i}}{\Omega_i} = \frac{c\sqrt{2Tm_i}}{eB} = 4.6 \times 10^9\ \mathrm{cm}$$

$B = 1\ \mu\text{G}$

$T = 1\ \text{keV}$



$$\rho_i = \frac{v_{\text{th}i}}{\Omega_i} = \frac{c\sqrt{2Tm_i}}{eB} = 4.6 \times 10^9\ \text{cm}$$

= 1.5 nanoparsec

Nanoastrophysics of Galaxy Clusters

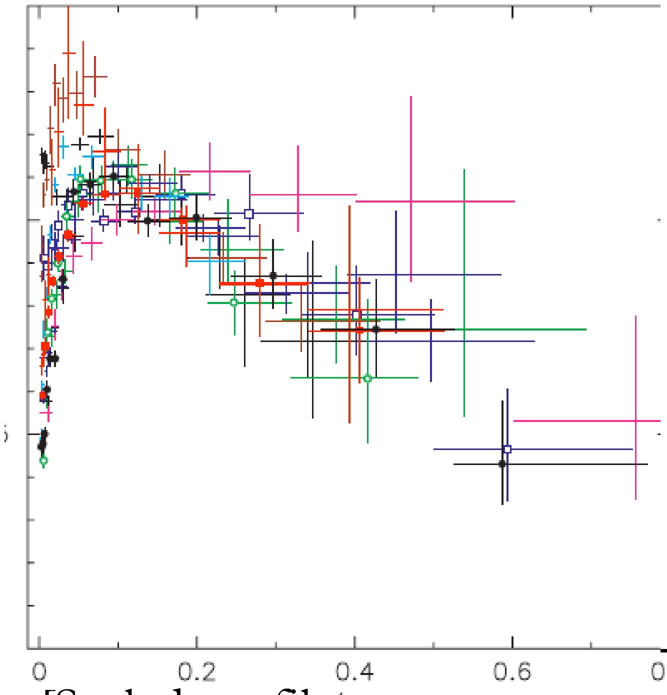
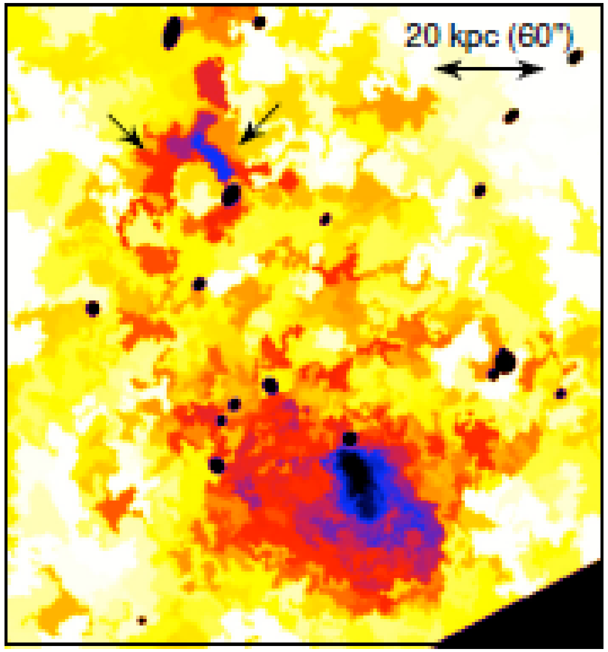
Alex Schekochihin *(Oxford)*
Matt Kunz *(Oxford)*
Steve Cowley *(CCFE)*
François Rincon *(Toulouse)*
Mark Rosin *(Cambridge)*

Schekochihin *et al.*, ApJ **629**, 139 (2005)
Schekochihin & Cowley, Phys. Plasmas **13**, 056501 (2006)
Schekochihin *et al.*, PRL **100**, 081301 (2008)
Schekochihin *et al.*, MNRAS **405**, 291 (2010)
Rosin *et al.*, MNRAS, submitted; arXiv:1002.4017
Kunz *et al.*, MNRAS, submitted; arXiv:1003.2719

ICM Dynamics: A 3-Scale Problem

GLOBAL (profiles, transport)	TURBULENCE (+ dynamo, fluid instabilities, etc.)	PLASMA (micro-instabilities)
100 kpc	1–10 kpc	*a few times* ρ_i 10^4–10^6 km **(1-100 npc)**
1 Gyr	10 Myr	*a fraction of* Ω_i 10 hours

ICM Dynamics: A 3-Scale Problem

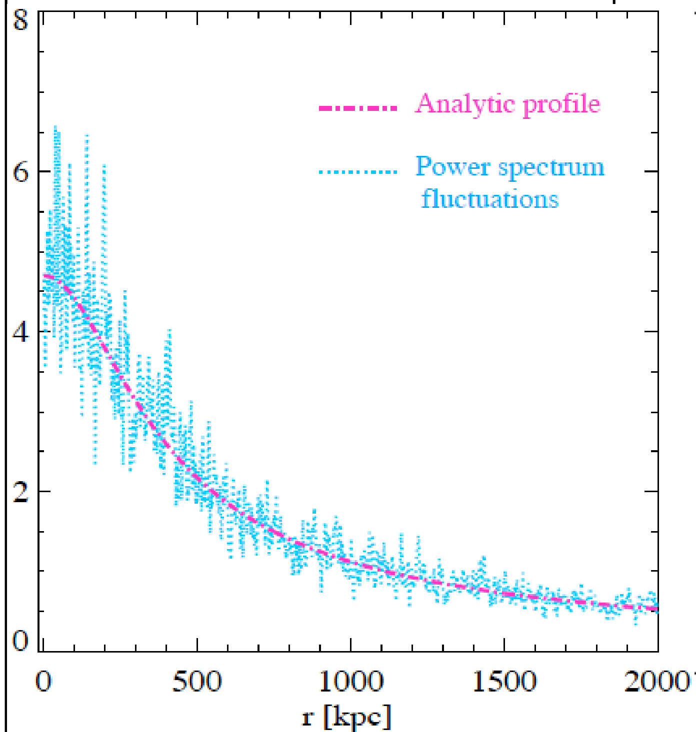
GLOBAL (profiles, transport)	TURBULENCE (+ dynamo, fluid instabilities, etc.)	PLASMA (micro-instabilities)
 [Scaled profiles, Vikhlinin et al. 2005]	 [A262, temperature map, Sanders et al. 2009]	*a few times* ρ_i 10^4–10^6 km **(1-100 npc)** *a fraction of* Ω_i 10 hours

ICM Dynamics: A 3-Scale Problem

Oxford Physics

GLOBAL

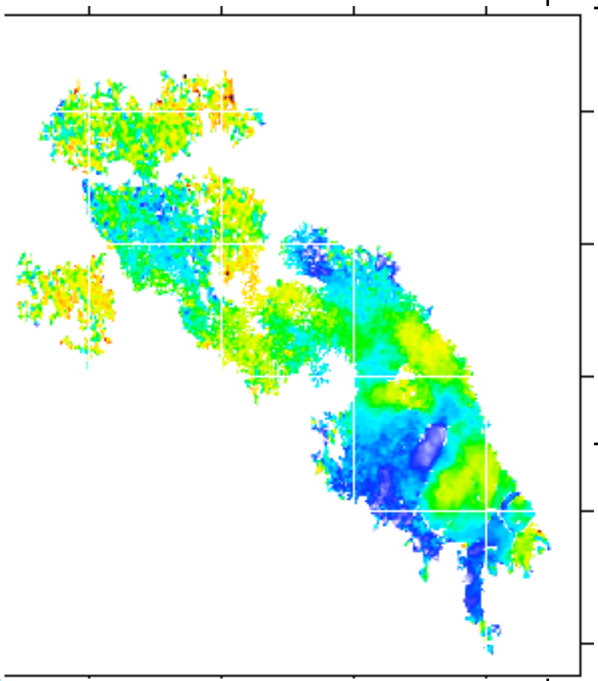
(profiles, transport)



[Magnetic field in Coma, Bonafede et al. 2010]

TURBULENCE

(+ dynamo, fluid instabilities, etc.)



[RM map, Hydra A, Vogt & Enßlin 2005]

PLASMA

(micro-instabilities)

a few times ρ_i

10^4–10^6 km

(1-100 npc)

a fraction of Ω_i

10 hours

Plasma Microinstabilities: Origin

First adiabatic invariant $\mu = \frac{mv_\perp^2}{2B}$ conserved provided $\Omega_i > \nu_{ii}$

holds already for $B > 10^{-18}$ G

$$\tau_{ii} \sim 23\ \text{kyr} \left(\frac{T_{\text{keV}}^{3/2}}{n_i \ \ln \Lambda} \right) \quad >> \quad \tau_{\text{ci}} \sim 14\ \text{min} \left(\frac{1}{B_{\mu\text{G}}} \right)$$

$$\lambda_{mfp} \sim 7\ \text{pc} \left(\frac{T_{\text{keV}}^{2}}{n_i \ \ln \Lambda} \right) \quad >> \quad \rho_i \sim 6\ \text{R}_\oplus \left(\frac{T_{\text{keV}}^{1/2}}{B_{\mu\text{G}}} \right)$$

Plasma Microinstabilities: Origin

First adiabatic invariant $\mu = \frac{mv_\perp^2}{2B}$ conserved provided $\Omega_i > \nu_{ii}$

holds already for $B > 10^{-18}$ G

Changes in field strength ⇔ pressure anisotropy

$$\sum_{\text{particles}} \mu = \frac{p_\perp}{B} = \text{const}$$

Plasma Microinstabilities: Origin

First adiabatic invariant $\mu = \frac{mv_\perp^2}{2B}$ conserved provided $\Omega_i > \nu_{ii}$

holds already for $B > 10^{-18}$ G

Changes in field strength ⇔ pressure anisotropy

$$\frac{1}{p_\perp}\frac{dp_\perp}{dt} \sim \frac{1}{B}\frac{dB}{dt} - \nu_{ii}\frac{p_\perp - p_\parallel}{p_\perp}$$

change in B drives anisotropy

anisotropy relaxed by collisions

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Plasma Microinstabilities: Origin

First adiabatic invariant $\mu = \frac{mv_\perp^2}{2B}$ conserved provided $\Omega_i > \nu_{ii}$

holds already for $B > 10^{-18}$ G

Changes in field strength ⇔ pressure anisotropy

$$\frac{d\Delta}{dt} \sim \frac{1}{B}\frac{dB}{dt} - \nu_{ii}\Delta \qquad \Delta \equiv \frac{p_\perp - p_\parallel}{p_\perp}$$

ignore evolution of $p_\parallel$ | change in B drives anisotropy | anisotropy relaxed by collisions

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Plasma Microinstabilities: Origin

First adiabatic invariant $\mu = \frac{mv_\perp^2}{2B}$ conserved provided $\Omega_i > \nu_{ii}$

holds already for $B > 10^{-18}$ G

Changes in field strength ⇔ pressure anisotropy

$$\frac{d\Delta}{dt} \sim \frac{1}{B}\frac{dB}{dt} - \nu_{ii}\Delta$$

ignore evolution of $p_{\|}$ | change in B drives anisotropy | anisotropy relaxed by collisions

$$\Delta \sim \frac{1}{\nu_{ii}}\frac{d\ln B}{dt} = \frac{\hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla\mathbf{u}}{\nu_{ii}}$$

because $\frac{1}{B}\frac{dB}{dt} = \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla\mathbf{u}$

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Plasma Microinstabilities: Taxonomy

First adiabatic invariant $\mu = \dfrac{mv_\perp^2}{2B}$ conserved provided $\Omega_i > \nu_{ii}$

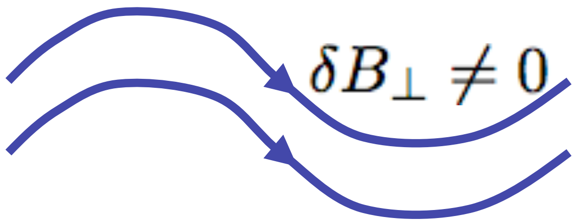
holds already for $B > 10^{-18}$ G

Changes in field strength ⇔ pressure anisotropy

$$\frac{d\Delta}{dt} \sim \frac{1}{B}\frac{dB}{dt} - \nu_{ii}\Delta \quad \Longrightarrow \quad \Delta \sim \frac{1}{\nu_{ii}}\frac{d\ln B}{dt} = \frac{\hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla\mathbf{u}}{\nu_{ii}}$$

Magnetic field decreases: $\Delta<0$

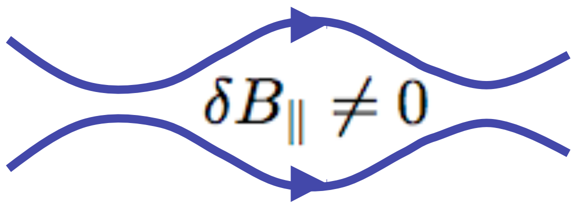
FIREHOSE: $\omega^2 = \dfrac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \dfrac{2}{\beta_i}\right)$



destabilised Alfvén wave

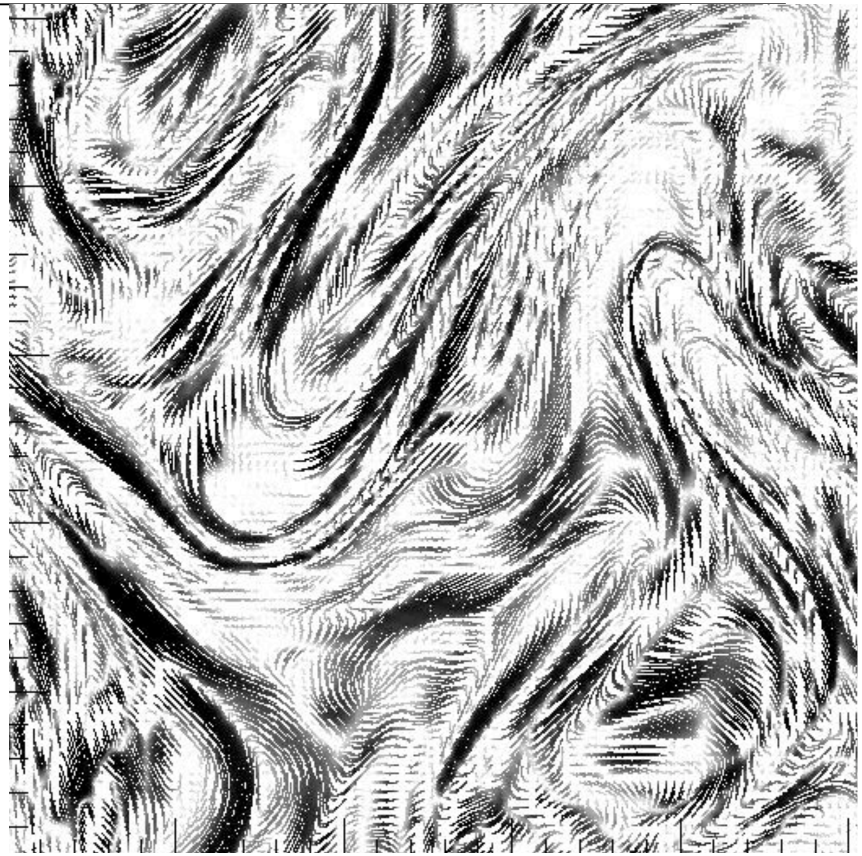
Magnetic field increases: $\Delta>0$

MIRROR: $\gamma = \dfrac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \dfrac{1}{\beta_i}\right)$



resonant instability

Plasma Microinstabilities: Where and When?



Typical structure of magnetic fields
generated by turbulence
(MHD simulations with Pm >> 1
by A. B. Iskakov & AAS)
for details see
Schekochihin *et al.* 2004,
ApJ **612**, 276

Magnetic field decreases: $\Delta<0$

FIREHOSE: $$\omega^2 = \frac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$$

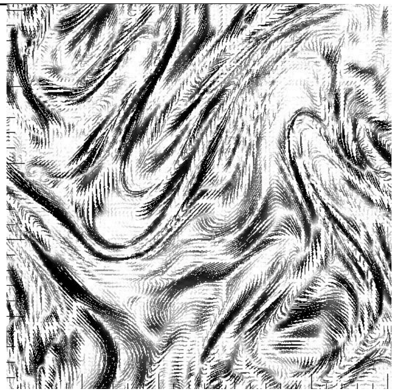
Magnetic field increases: $\Delta>0$

MIRROR: $$\gamma = \frac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$$

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Plasma Microinstabilities: Where and When?

Typical structure of magnetic fields generated by turbulence (MHD simulations with Pm >> 1 by A. B. Iskakov & AAS) for details see Schekochihin *et al.* 2004, *ApJ* **612**, 276

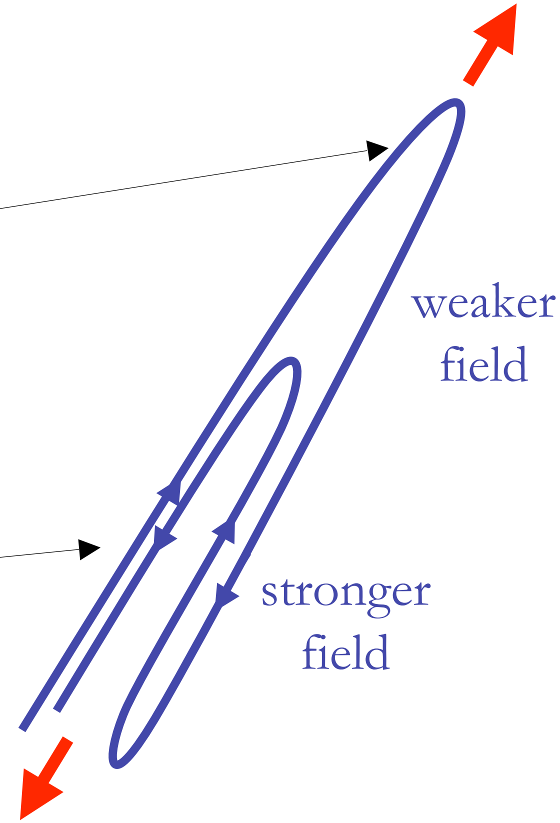


Magnetic field decreases: $\Delta<0$

FIREHOSE: $$\omega^2 = \frac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$$

Magnetic field increases: $\Delta>0$

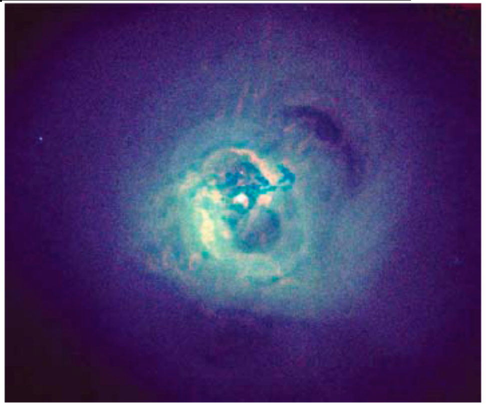
MIRROR: $$\gamma = \frac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$$



[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Plasma Microinstabilities in the ICM

For typical cluster parameters,



$$\Delta \sim 0.005 \left(\frac{n_e}{0.01\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T_i}{1\,\mathrm{keV}}\right)^{3/2} \left(\frac{\tau_\mathrm{turb}}{10\,\mathrm{Myr}}\right)^{-1}$$

$$\frac{2}{\beta} = 0.005 \left(\frac{B}{1\,\mu\mathrm{G}}\right)^{2} \left(\frac{n_e}{0.01\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T_i}{1\,\mathrm{keV}}\right)^{-1}$$

Magnetic field decreases: $\Delta<0$

Small, fast and furious…

FIREHOSE: $$\omega^2 = \frac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$$

$\gamma_\mathrm{peak}^\perp \sim |\Delta|^{1/2}\Omega_i \sim 10^{-3}\ \mathrm{s}^{-1}$ $\quad k_\parallel \rho_i \sim 1$

$\gamma_\mathrm{peak}^\parallel \sim |\Delta|\Omega_i \sim 10^{-4}\ \mathrm{s}^{-1}$ $\quad k_\parallel \rho_i \sim |\Delta|^{1/2}$

Magnetic field increases: $\Delta>0$

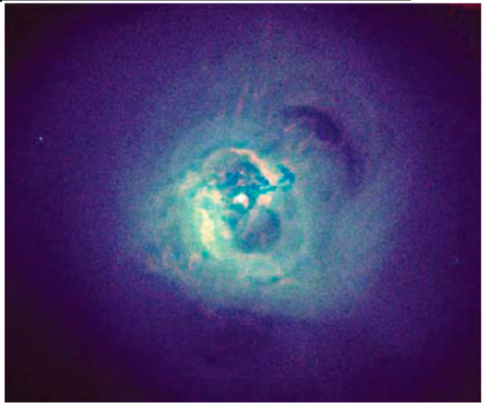
MIRROR: $$\gamma = \frac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$$

$\gamma_\mathrm{peak} \sim \Delta^2\Omega_i \sim 10^{-6}\ \mathrm{s}^{-1}$ $\quad k_\parallel \rho_i \sim \Delta$

$k_\perp \rho_i \sim \Delta^{1/2}$

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Plasma Microinstabilities in the ICM



For typical cluster parameters,

$$\Delta \sim 0.005 \left(\frac{n_e}{0.01\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T_i}{1\,\mathrm{keV}}\right)^{3/2} \left(\frac{\tau_{\mathrm{turb}}}{10\,\mathrm{Myr}}\right)^{-1}$$

$$\frac{2}{\beta} = 0.005 \left(\frac{B}{1\,\mu\mathrm{G}}\right)^{2} \left(\frac{n_e}{0.01\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T_i}{1\,\mathrm{keV}}\right)^{-1}$$

Magnetic field decreases: $\Delta<0$

FIREHOSE: $\omega^2 = \frac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$

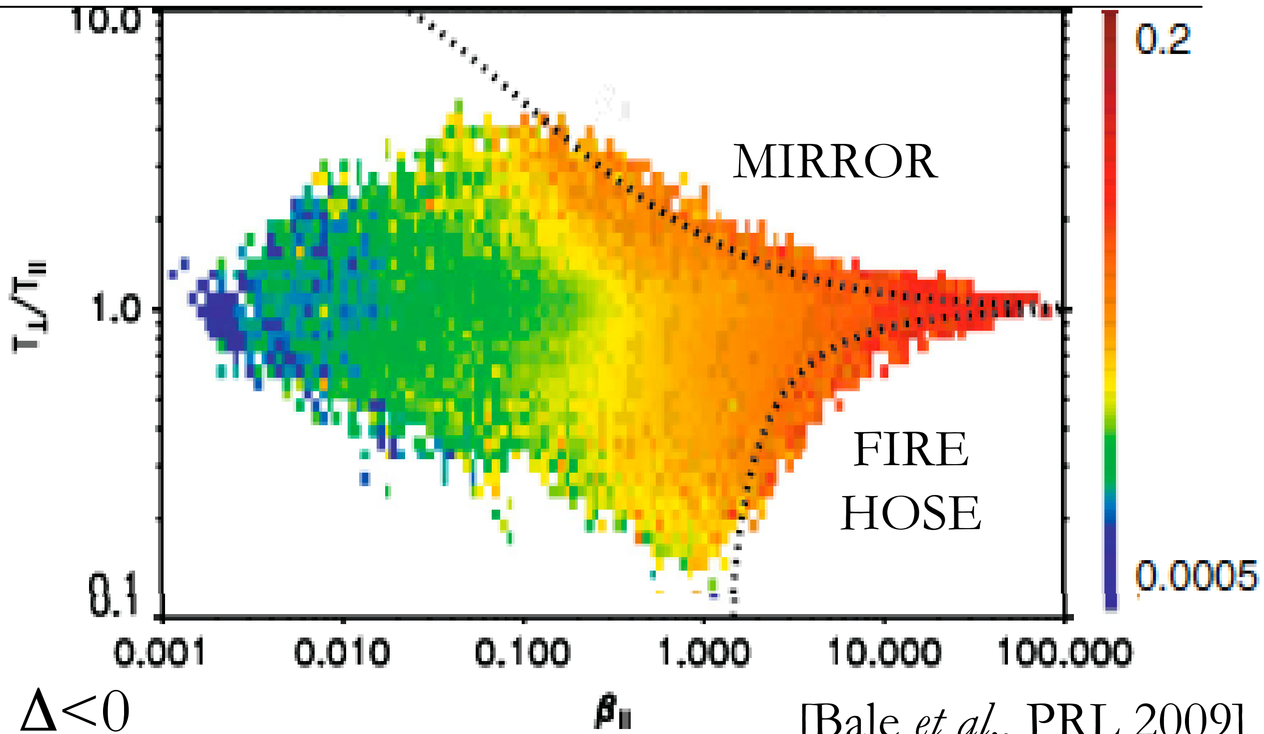
Magnetic field increases: $\Delta>0$

MIRROR: $\gamma = \frac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$

Is ICM in the marginal state with respect to plasma microinstabilities?

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Solar Wind: Laboratory for Nanoastrophysics



[Bale *et al.*, PRL 2009]

Magnetic field decreases: Δ<0

FIREHOSE: $\omega^2 = \frac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$

Magnetic field increases: Δ>0

MIRROR: $\gamma = \frac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$

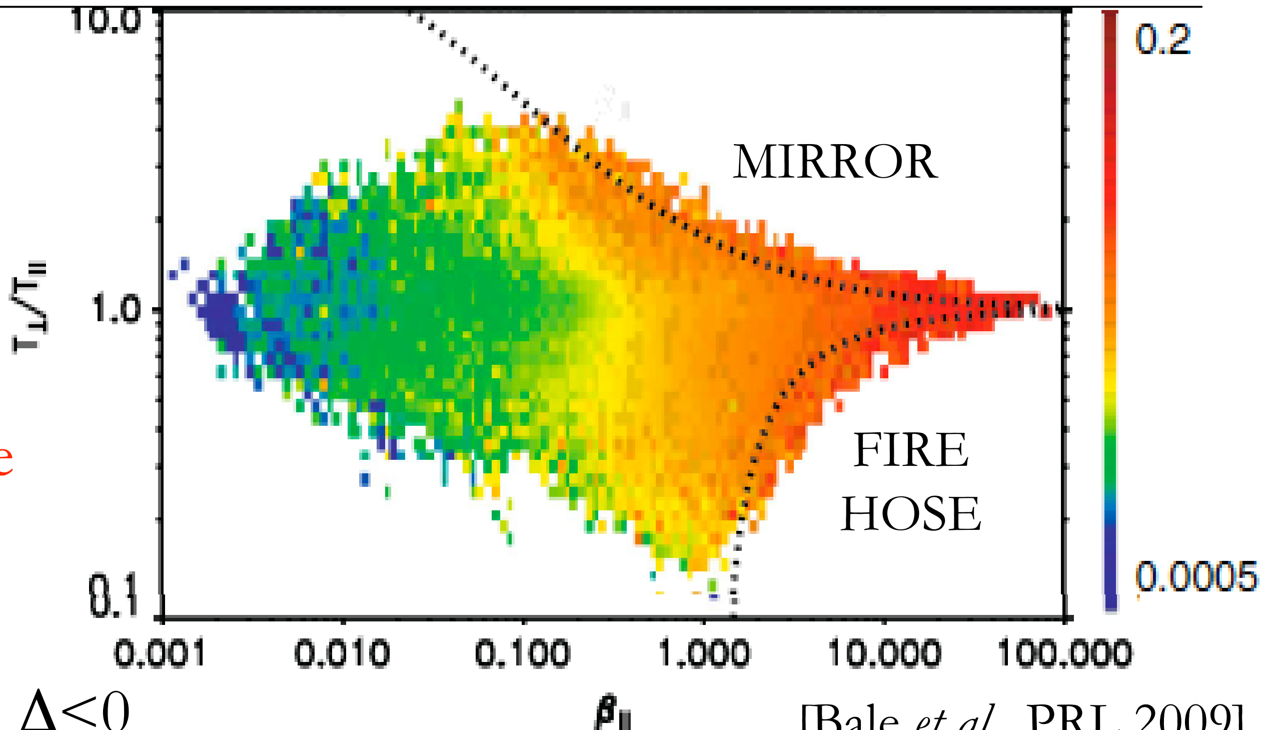
Is ICM in the marginal state with respect to plasma microinstabilities?

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

A Microphysical Dilemma

How is this achieved?

- Enhanced particles scattering isotropises pressure
  AND/OR
- Magnetic field structure and evolution modified to offset change



[Bale *et al.*, PRL 2009]

Magnetic field decreases: Δ<0

$$\text{FIREHOSE: } \omega^2 = \frac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$$

Magnetic field increases: Δ>0

$$\text{MIRROR: } \gamma = \frac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$$

Is ICM in the marginal state with respect to plasma microinstabilities?

[Schekochihin *et al.*, *ApJ* **629**, 139 (2005)]

Nonlinear Firehose

Principle of nonlinear evolution:

firehose fluctuations** (growing, fast, microscale)* ***cancel on average the change in the mean field** (decreasing, slow, macroscale)* ***to keep anisotropy at marginal level

$$\Delta \sim \frac{1}{\nu_{ii}} \frac{1}{B}\frac{dB}{dt} \sim \frac{1}{\nu_{ii}}\left(-\left|\frac{d\ln B_0}{dt}\right| + \frac{1}{2}\frac{d}{dt}\frac{\overline{|\delta \mathbf{B}_\perp|^2}}{B_0^2}\right) \to -\frac{2}{\beta_i}$$

macroscale field

microscale fluctuations

Schekochihin *et al.*, *PRL* **100**, 081301 (2008)
Rosin *et al.*, arXiv:1002.4017 (2010)

Magnetic field decreases: $\Delta<0$

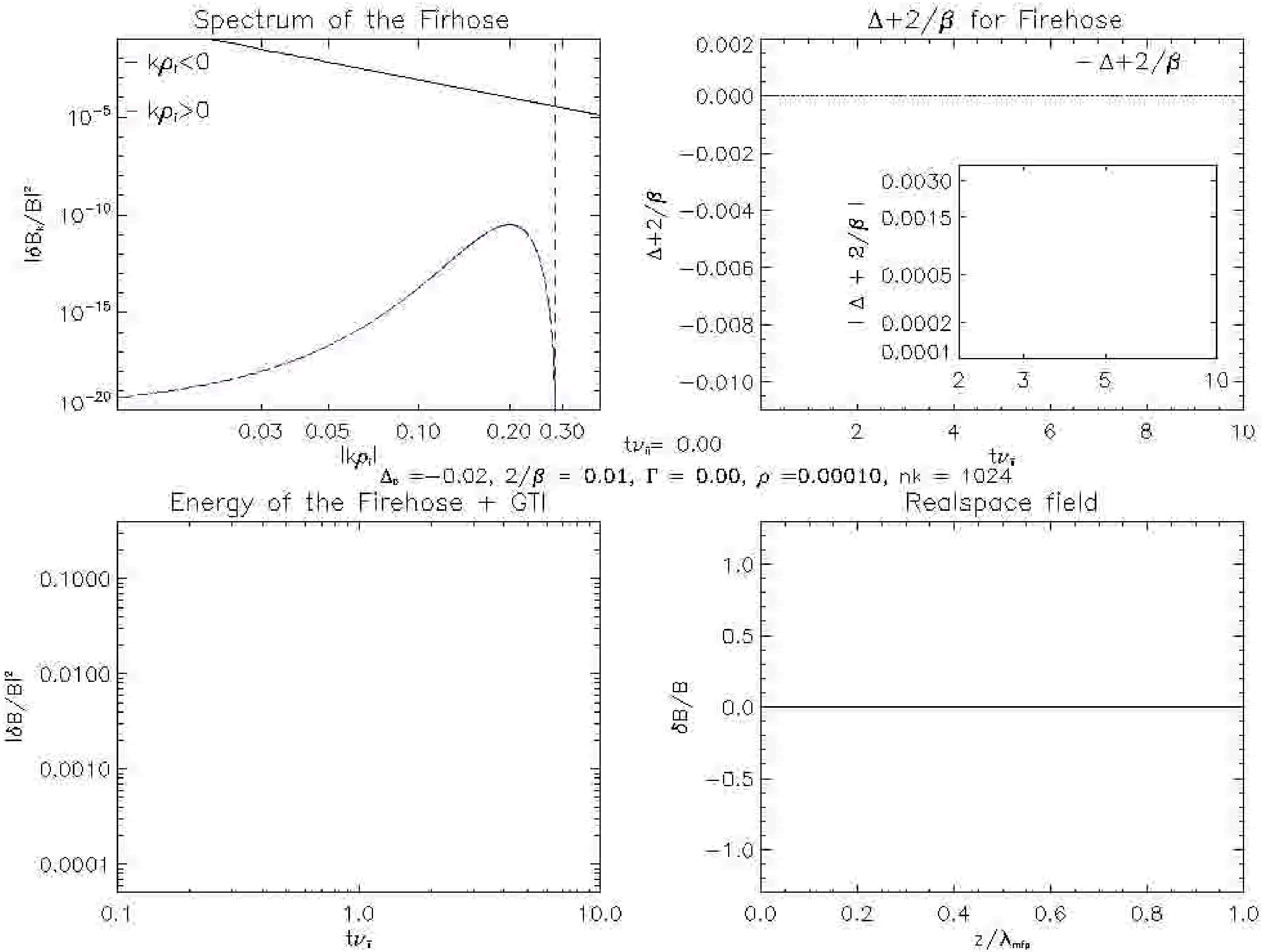
FIREHOSE: $\omega^2 = \frac{k_\parallel^2 v_{\mathrm{th}i}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$

Magnetic field increases: $\Delta>0$

MIRROR: $\gamma = \frac{|k_\parallel| v_{\mathrm{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$

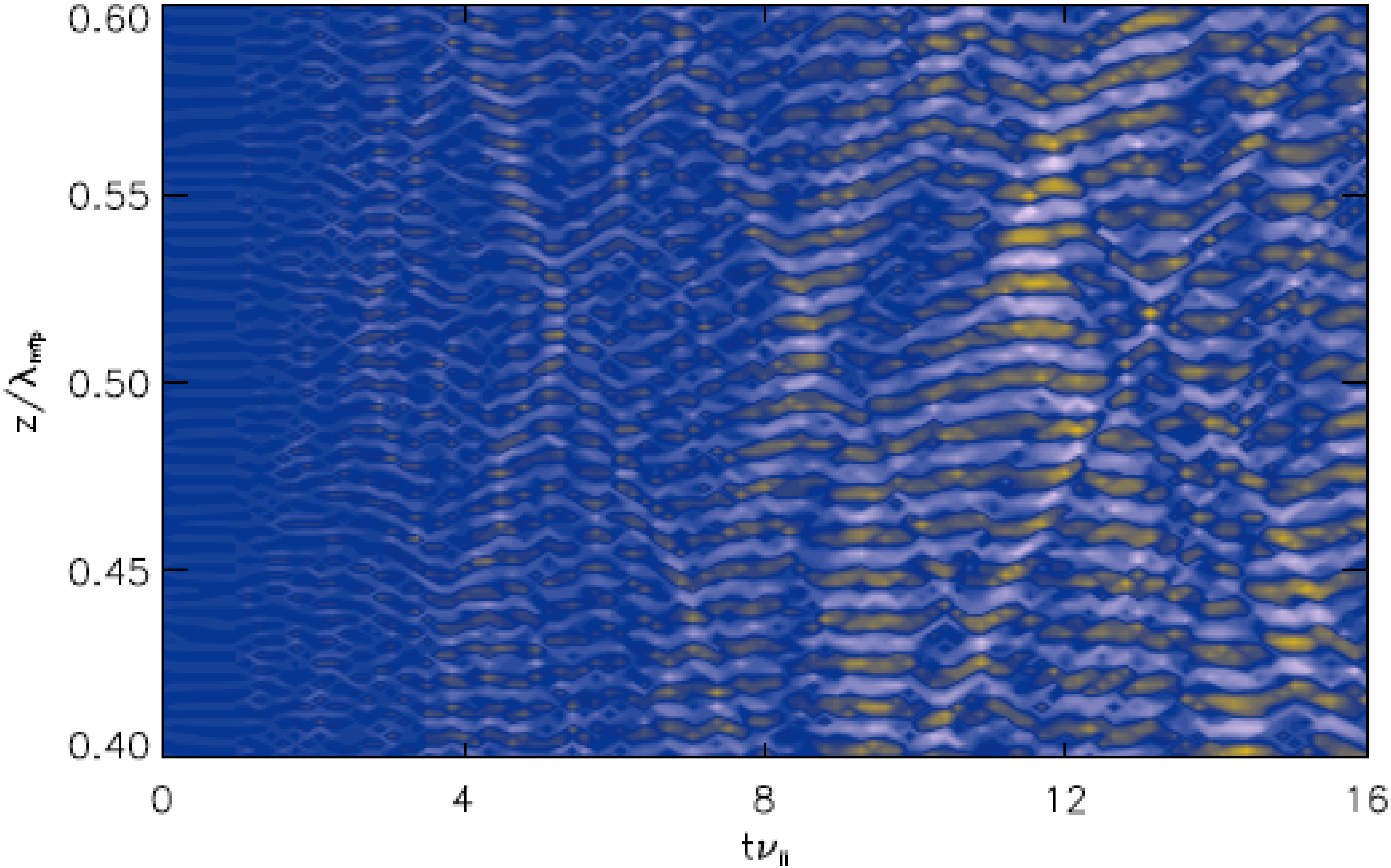
Is ICM in the marginal state with respect to plasma microinstabilities?

Nonlinear Firehose



[Rosin *et al.*, arXiv:1002.4017 (2010)]

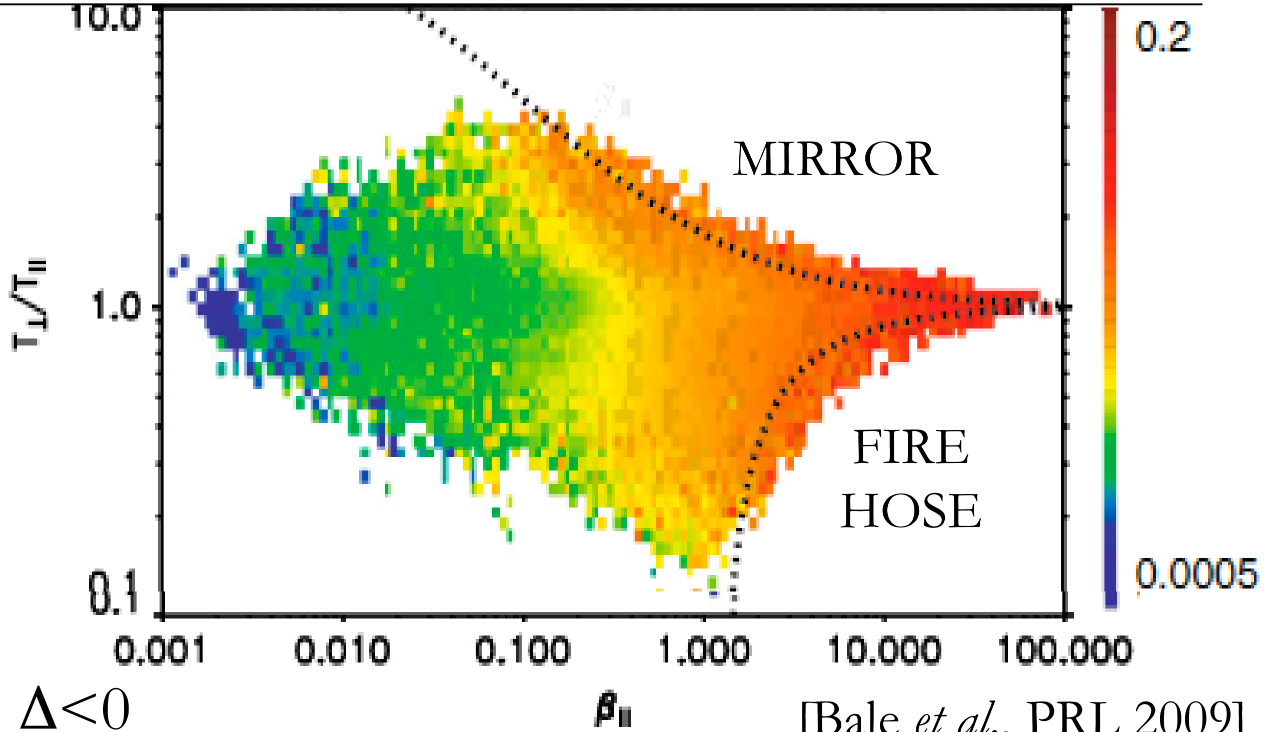
Nonlinear Firehose



[Rosin *et al.*, arXiv:1002.4017 (2010)]

A Macrophysical Fudge: Marginal ICM

Despite progress,
a complete *ab initio*
microphysical theory
of transport
is still a matter
of current work
and much difficulty



[Bale *et al.*, PRL 2009]

Magnetic field decreases: Δ<0

FIREHOSE: $\omega^2 = \frac{k_\parallel^2 v_{\rm thi}^2}{2}\left(\Delta + \frac{2}{\beta_i}\right)$

Magnetic field increases: Δ>0

MIRROR: $\gamma = \frac{|k_\parallel| v_{\rm thi}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$

To leapfrog having to do
an honest microphysical job,
simply assume closure (fudge)

$$\Delta = \frac{2\xi}{\beta_i}, \quad \xi \in [-1, 0.5]$$

[Kunz *et al.*, arXiv:1003.2719]

More Microphysics…

If one does microphysical theory (linear and nonlinear) carefully, there is always a chance of finding new things….

MRI, MVI, MTI, HBI…

So, for the aficionados of three-letter instabilities, I give you

GTI

(The GyroThermal Instability)

[Schekochihin *et al.*, *MNRAS* **405**, 291 (2010)]

Gyrothermal Instability: Equations

- Keep the gyroviscous terms in the "Braginskii" stress (this is valid even without collisions and is necessary to get the fastest growing mode for the firehose)
- Keep pressure anisotropies and parallel ion heat fluxes

$$mn\frac{d\boldsymbol{u}}{dt} = -\nabla\left(p_\perp + \frac{B^2}{8\pi}\right) + \nabla\cdot\left[\boldsymbol{bb}\left(p_\perp - p_\parallel + \frac{B^2}{4\pi}\right) - \mathsf{G}\right]$$

$$\mathsf{G} = \frac{1}{4\Omega}[\boldsymbol{b}\times\mathsf{S}\cdot(\mathsf{I}+3\boldsymbol{bb}) - (\mathsf{I}+3\boldsymbol{bb})\cdot\mathsf{S}\times\boldsymbol{b}] + \frac{1}{\Omega}[\boldsymbol{b}(\boldsymbol{\sigma}\times\boldsymbol{b}) + (\boldsymbol{\sigma}\times\boldsymbol{b})\boldsymbol{b}]$$

$$\mathsf{S} = (p_\perp\nabla\boldsymbol{u} + \nabla\boldsymbol{q}_\perp) + (p_\perp\nabla\boldsymbol{u} + \nabla\boldsymbol{q}_\perp)^T$$

$$\boldsymbol{\sigma} = (p_\perp - p_\parallel)\left(\frac{d\boldsymbol{b}}{dt} + \boldsymbol{b}\cdot\nabla\boldsymbol{u}\right) + (3q_\perp - q_\parallel)\boldsymbol{b}\cdot\nabla\boldsymbol{b}$$

- Consider just $\boldsymbol{k}_\perp = 0$ (Alfvénically polarised parallel-propagating modes – they decouple and can be calculated without knowing pressures or heat fluxes)

[Schekochihin *et al.*, *MNRAS* **405**, 291 (2010)]

Gyrothermal Instability: Linear Theory

Instability criterion:

$$\Lambda \equiv \Gamma_T^2 - \frac{(1-\delta)^2}{2}\left(\Delta + \frac{2}{\beta}\right) > 0$$

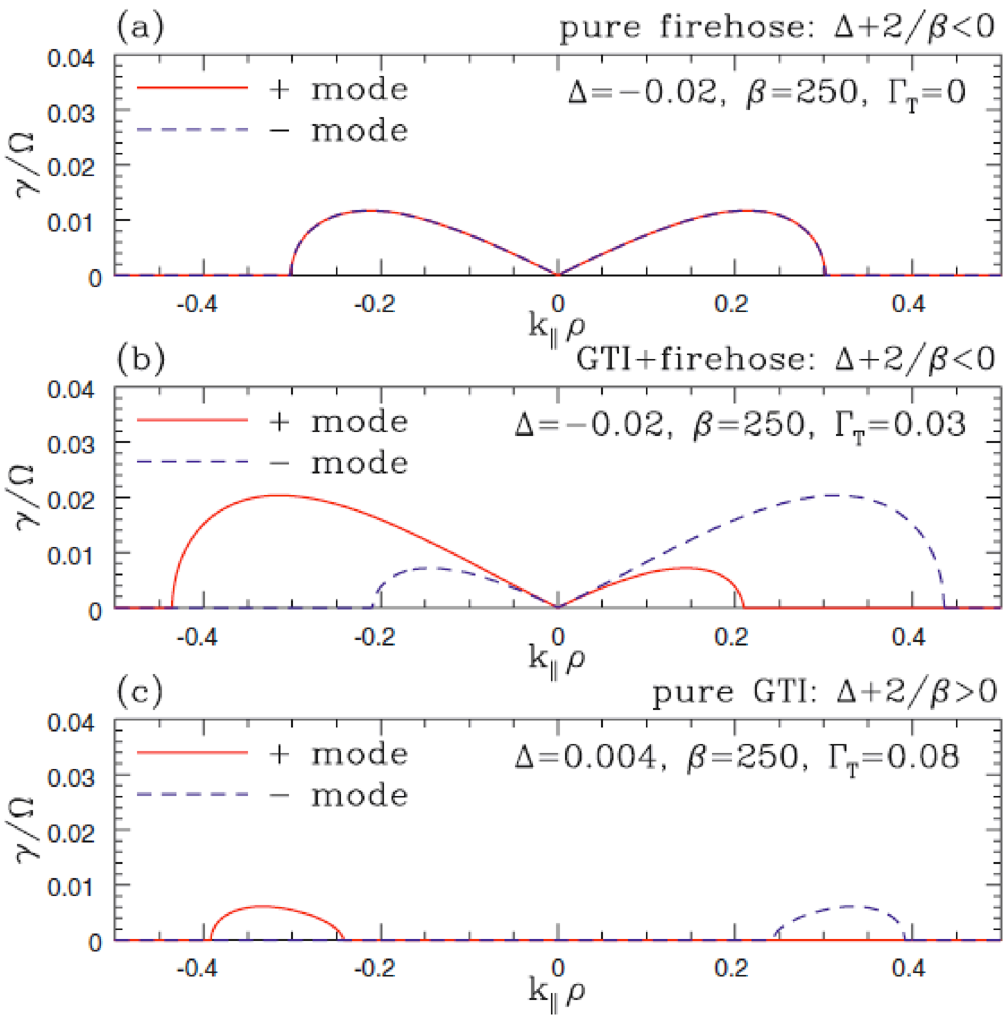
$$\Delta = \frac{p_{\perp i} - p_{\parallel i} + p_{\perp e} - p_{\parallel e}}{p_{\parallel i}}$$

$$\delta = \frac{p_{\perp i} - p_{\parallel i} - (p_{\perp e} - p_{\parallel e})}{p_{\parallel i}} - \frac{2}{\beta}$$

$$\Gamma_T = \frac{2q_{\perp i} - q_{\parallel i}}{p_{\parallel i} v_{\mathrm{th}}}$$

In the collisional limit,

$$q_\perp = \frac{1}{3} q_\parallel = -\frac{1}{2} n \frac{v_{\mathrm{th}}^2}{\nu} \boldsymbol{b} \cdot \nabla T$$



[Schekochihin *et al.*, *MNRAS* **405**, 291 (2010)]

Gyrothermal Instability: Linear Theory

Instability criterion:

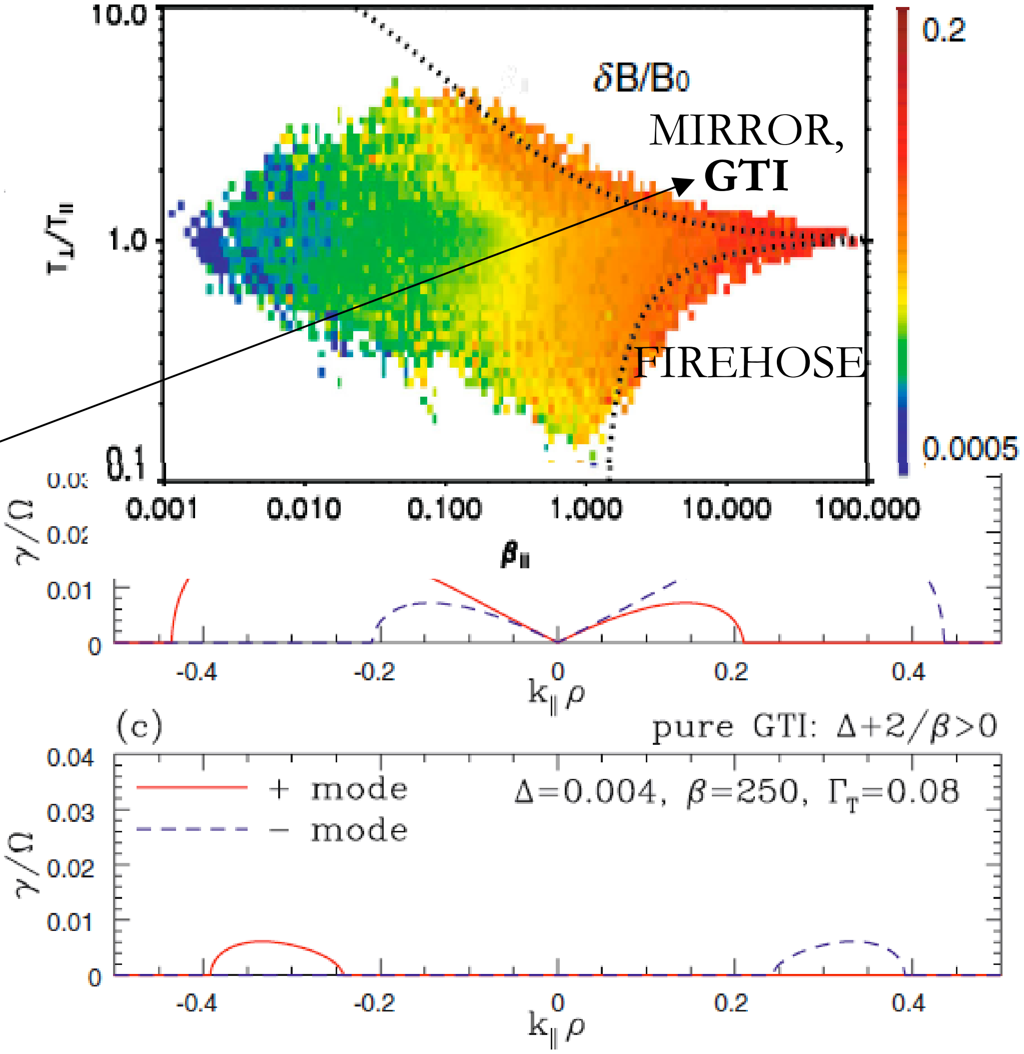
$$\Lambda \equiv \Gamma_T^2 - \frac{(1-\delta)^2}{2}\left(\Delta + \frac{2}{\beta}\right) > 0$$

So, Alfvénically polarised perturbations can be unstable at $\Delta > 0$!

$$\Gamma_T = \frac{2q_{\perp i} - q_{\| i}}{p_{\| i} v_{\rm th}}$$

In the collisional limit,

$$q_\perp = \frac{1}{3} q_\| = -\frac{1}{2} n \frac{v_{\rm th}^2}{\nu} \boldsymbol{b}\cdot\nabla T$$



[Schekochihin *et al.*, *MNRAS* **405**, 291 (2010)]

Gyrothermal Instability: Nonlinear Theory

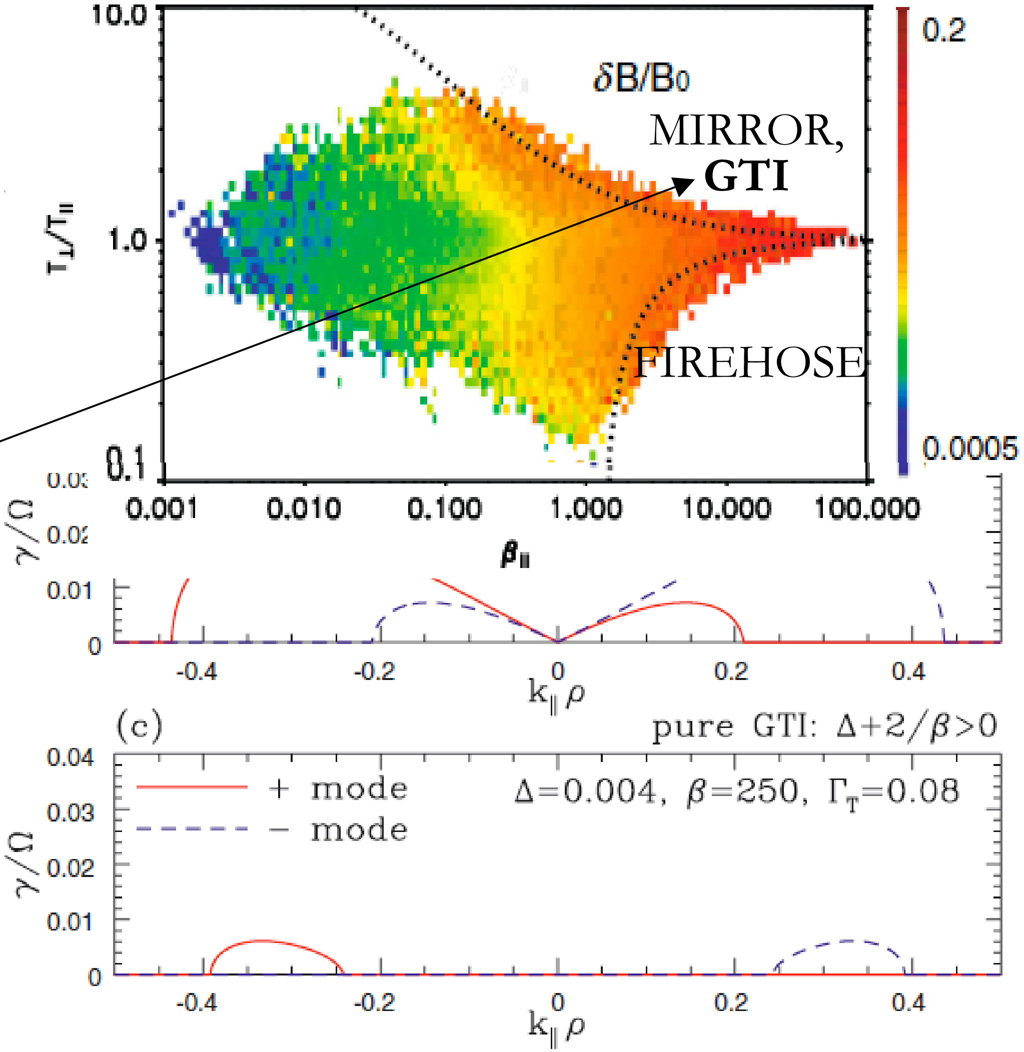
Instability criterion:

$$\Lambda \equiv \Gamma_T^2 - \frac{(1-\delta)^2}{2}\left(\Delta + \frac{2}{\beta}\right) > 0$$

So, Alfvénically polarised perturbations can be unstable at $\Delta > 0$!

GTI saturates by the same mechanism as the firehose: magnetic fluctuations adjusting (increasing) Δ

[It might actually destabilise mirror — no idea what then]



[Rosin *et al.*, arXiv:1002.4017 (2010)]

Gyrothermal Instability: Nonlinear Theory

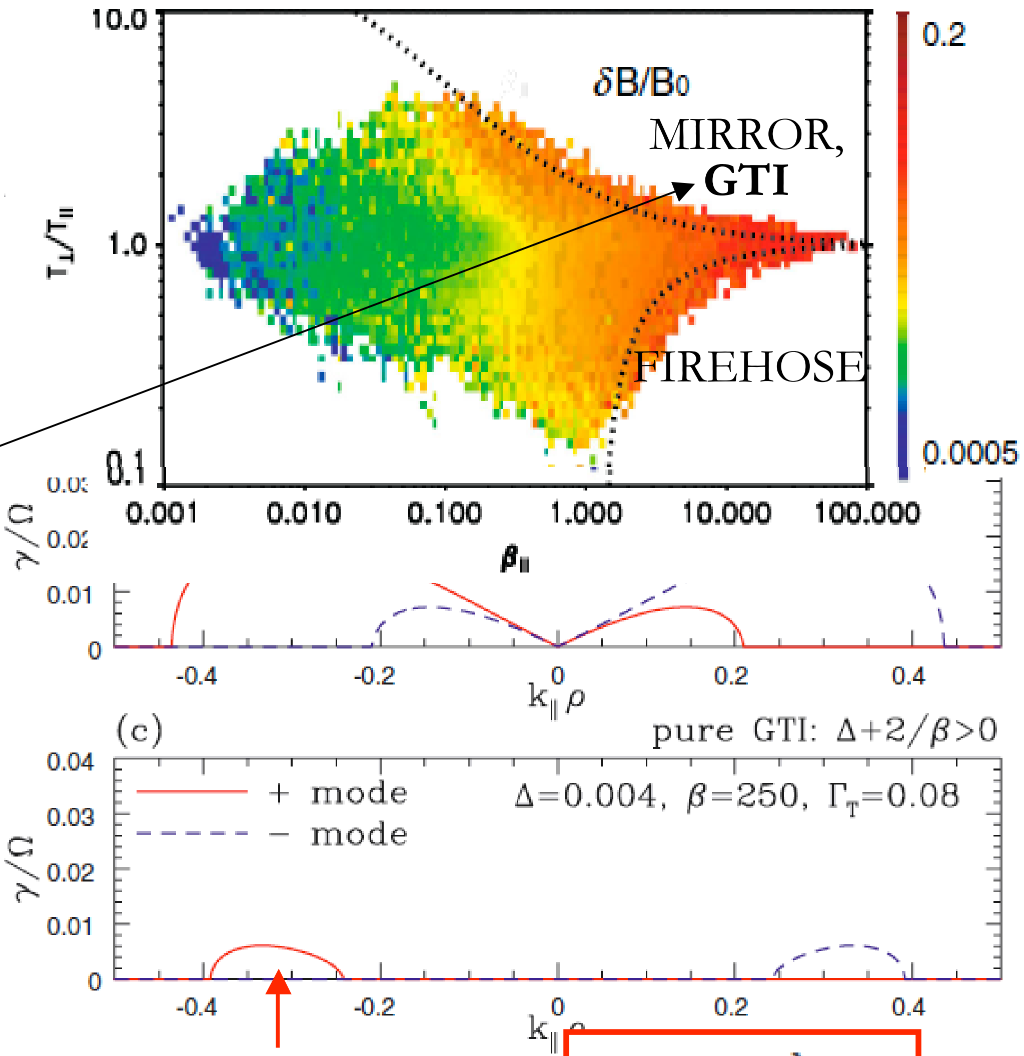
Instability criterion:

$$\Lambda \equiv \Gamma_T^2 - \frac{(1-\delta)^2}{2}\left(\Delta + \frac{2}{\beta}\right) > 0$$

So, Alfvénically polarised perturbations can be unstable at $\Delta>0$!

GTI saturates by the same mechanism as the firehose: magnetic fluctuations adjusting (increasing) Δ

[It might actually destabilise mirror — no idea what then]

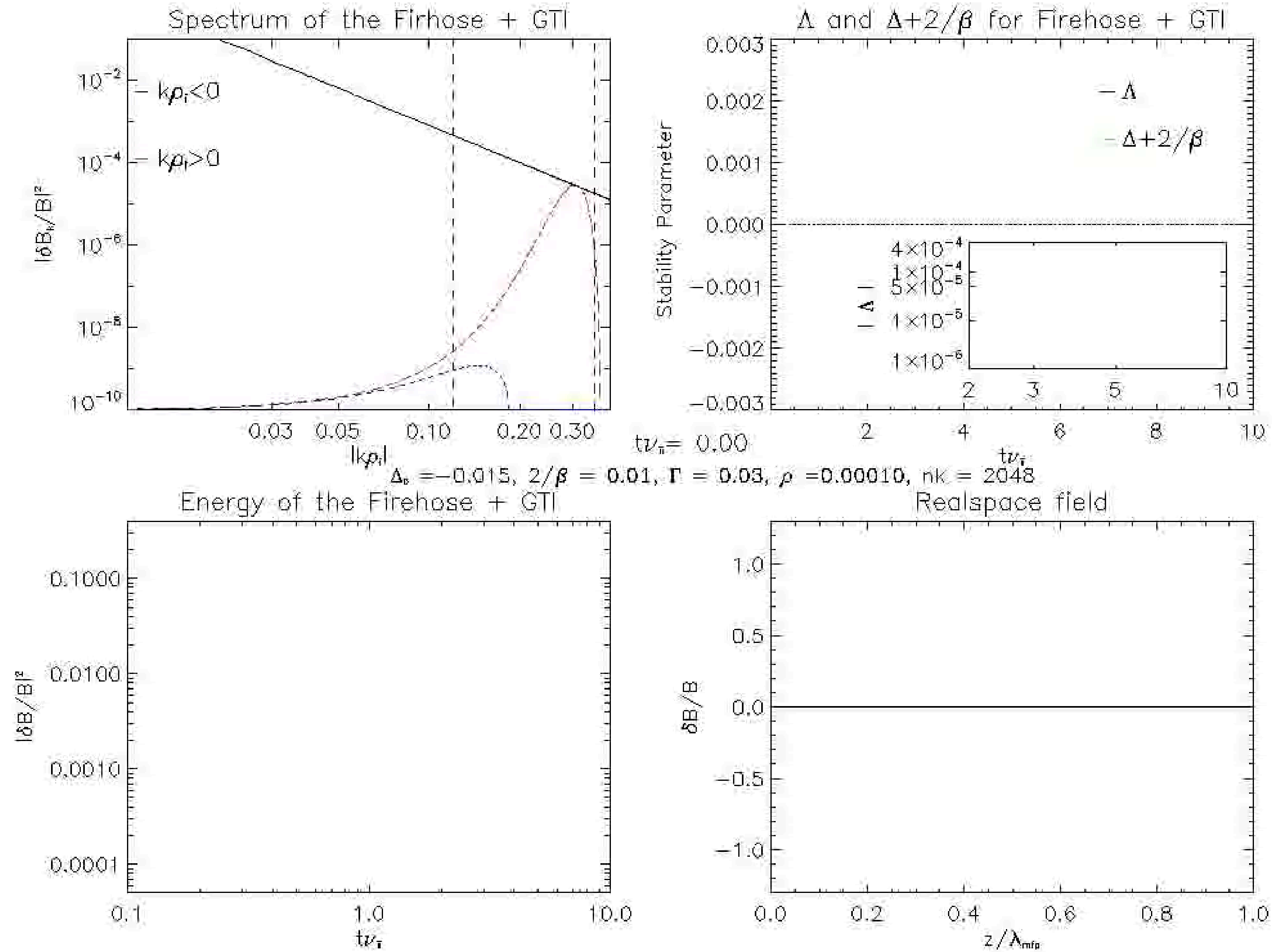


Preferred scale in marginal state:

$$k_\parallel \rho_i \sim \frac{\lambda_{\rm mfp}}{l_T}$$

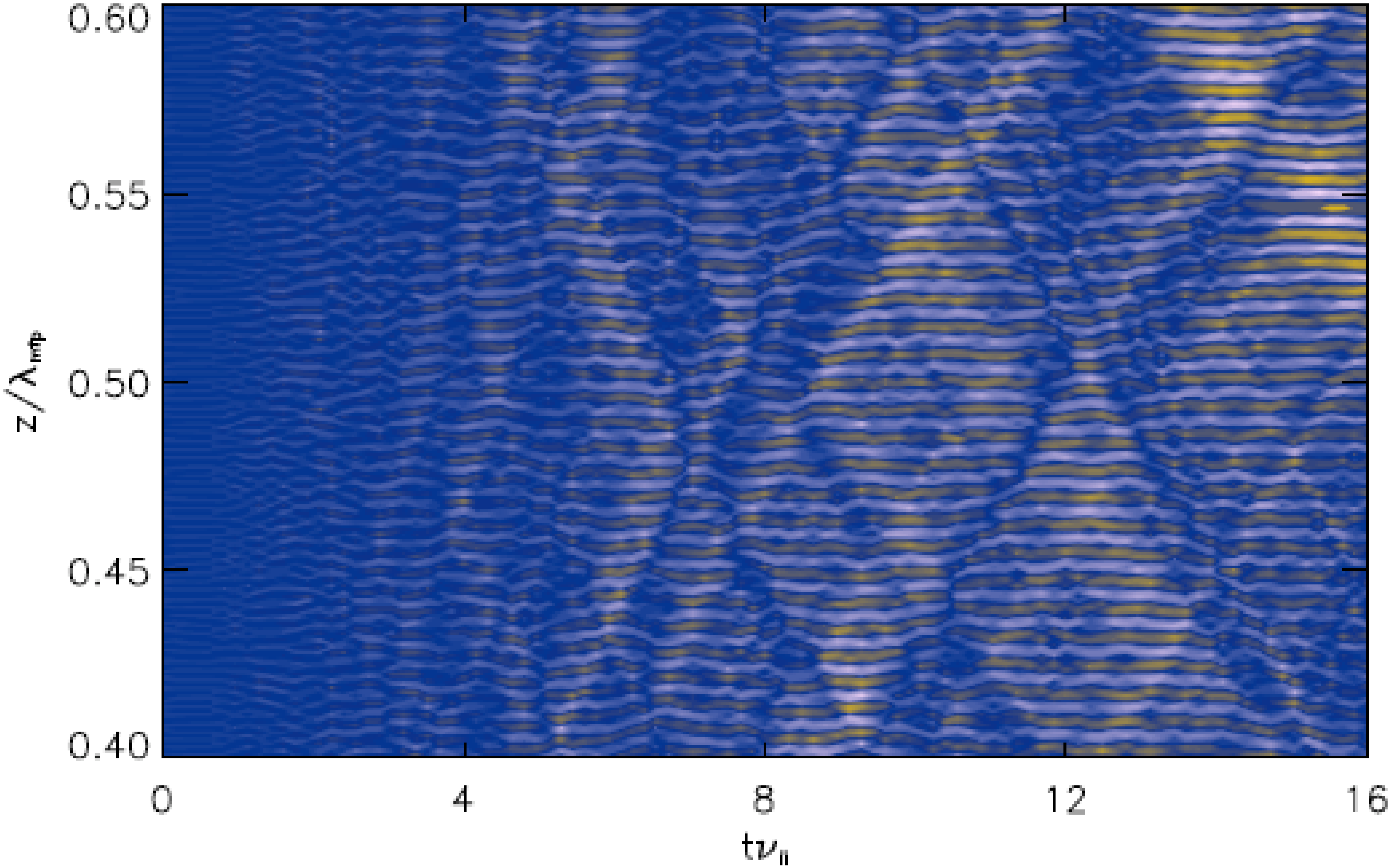
[Rosin *et al.*, arXiv:1002.4017 (2010)]

Nonlinear GTI



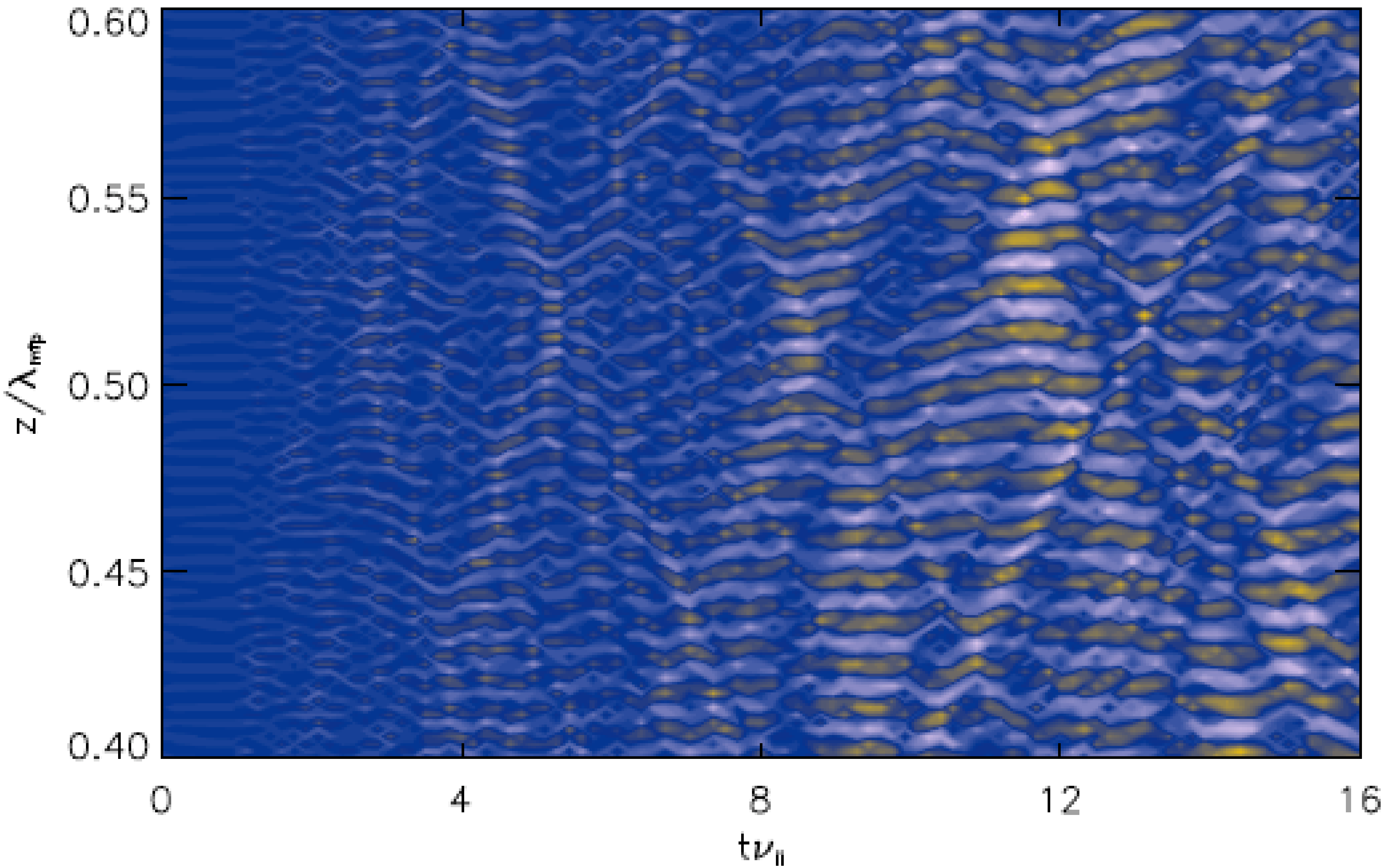
[Rosin *et al.*, arXiv:1002.4017 (2010)]

Nonlinear GTI



[Rosin *et al.*, arXiv:1002.4017 (2010)]

[Recall: Nonlinear Firehose]



[Rosin *et al.*, arXiv:1002.4017 (2010)]

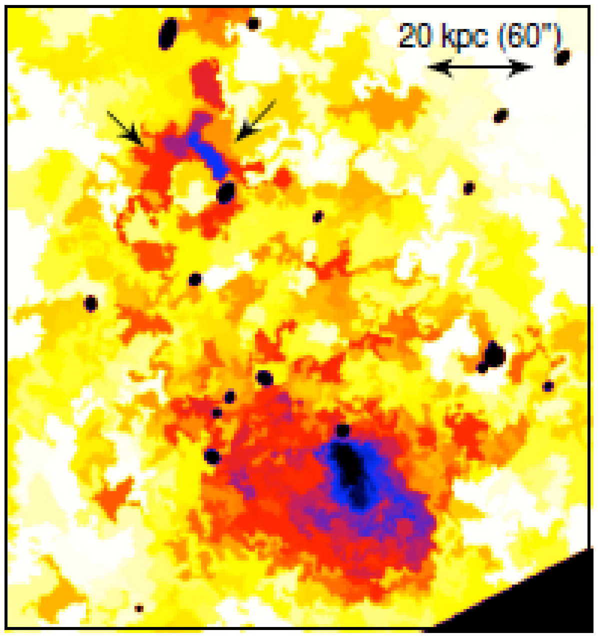
GTI in ICM?

Theoretical condition for GTI marginal stability $\Gamma_T^2 \lesssim 2/\beta$ translates into this: for the temperature scale $l_T^{-1} = \boldsymbol{b}\cdot\nabla \ln T$

$$l_T \gtrsim 0.3 \left(\frac{n_\mathrm{e}}{0.01\,\mathrm{cm}^{-3}}\right)^{-1/2} \left(\frac{T_\mathrm{i}}{1\,\mathrm{keV}}\right)^{5/2} \left(\frac{B}{1\,\mu\mathrm{G}}\right)^{-1} \mathrm{kpc},$$

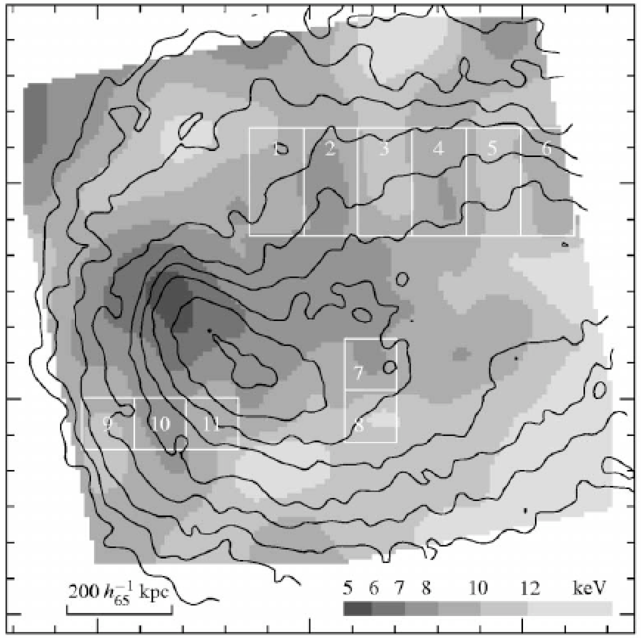
[Schekochihin *et al.*, *MNRAS* **405**, 291 (2010)]

CORES: ~1-10 kpc



A262, Sanders et al. (2010)

BULK: ~100 kpc



A754, Markevitch et al. (2003)

Elephant in the Room: ICM Dynamo

Important for:

• General understanding of magnetogenesis (nice word!)

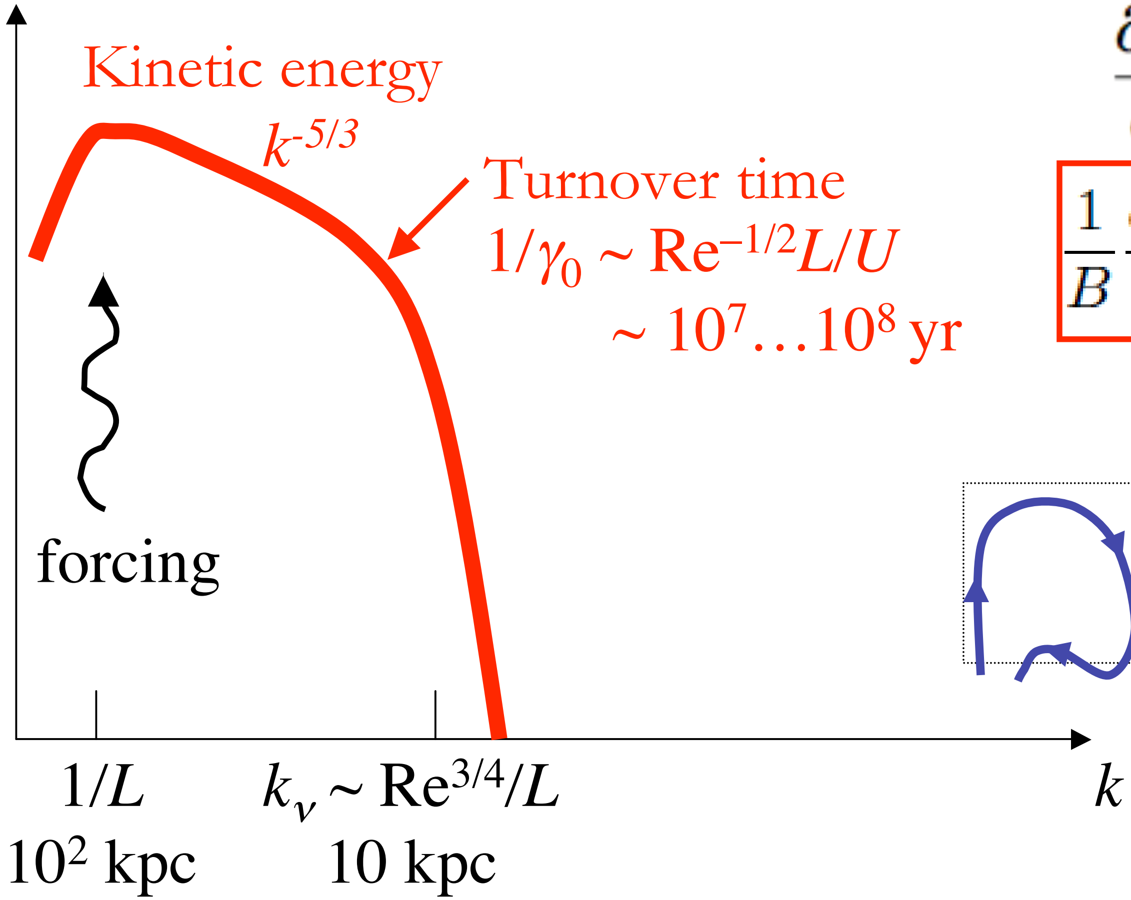
• Making sense of the size and structure of observed magnetic fields

• Now that we know magnetic field (via β_i) is likely to set the dissipation rate in the ICM, we also need it to calculate macro-scale dynamics (see M. Kunz's talk)

But

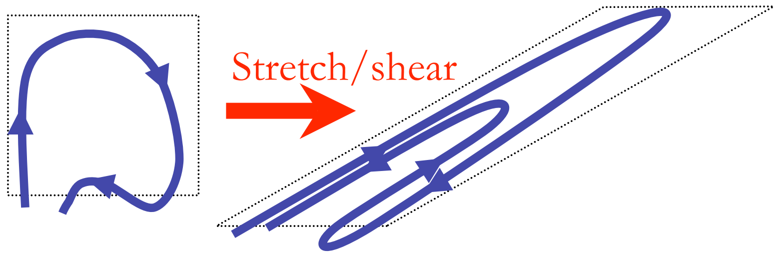
this is a complicated and very embarassing subject…

Fluctuation Dynamo in MHD



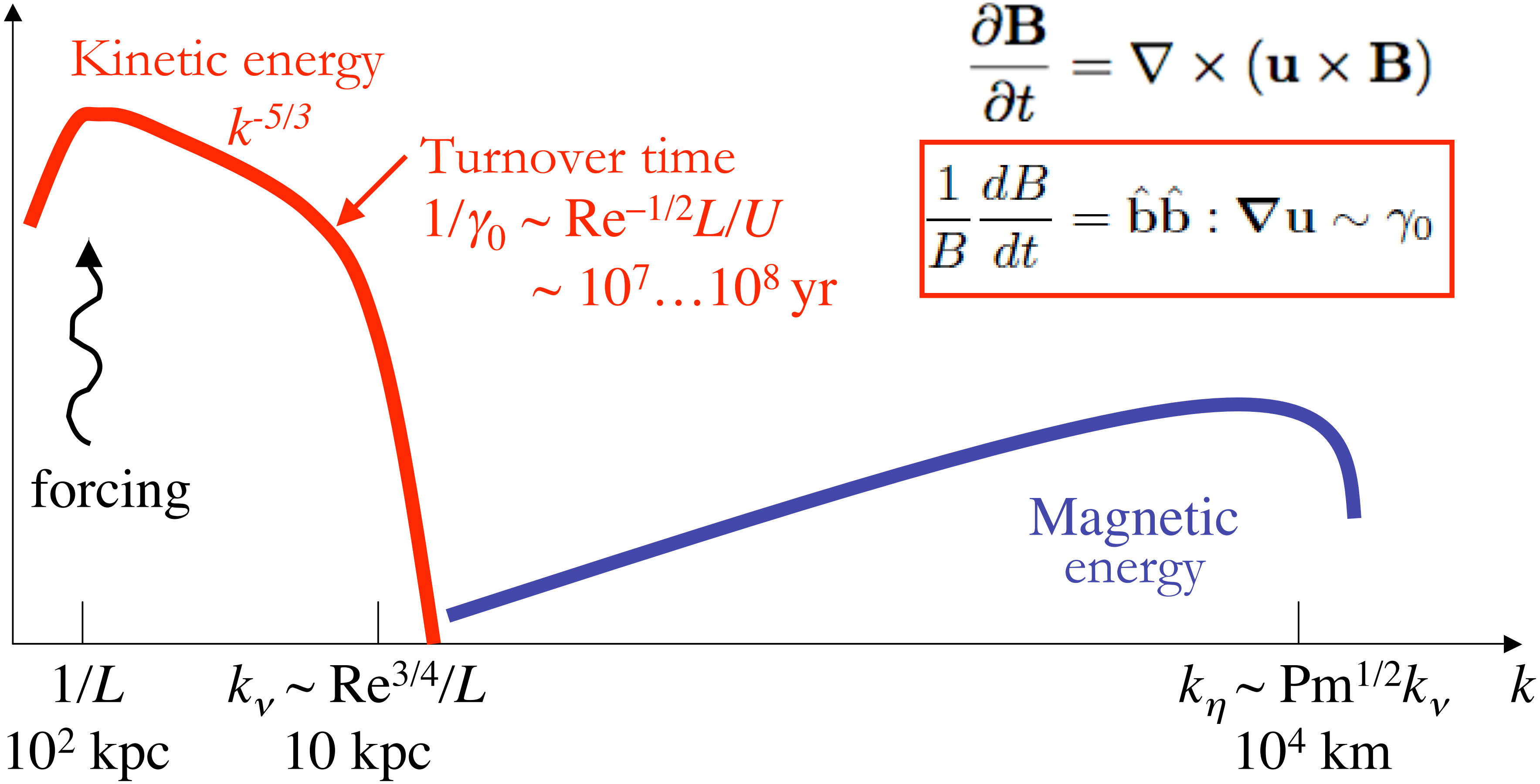
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

$$\frac{1}{B}\frac{dB}{dt} = \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{u} \sim \gamma_0$$



[chatty historical review for bed-time reading:
Schekochihin & Cowley, astro-ph/0507686]

Fluctuation Dynamo in MHD



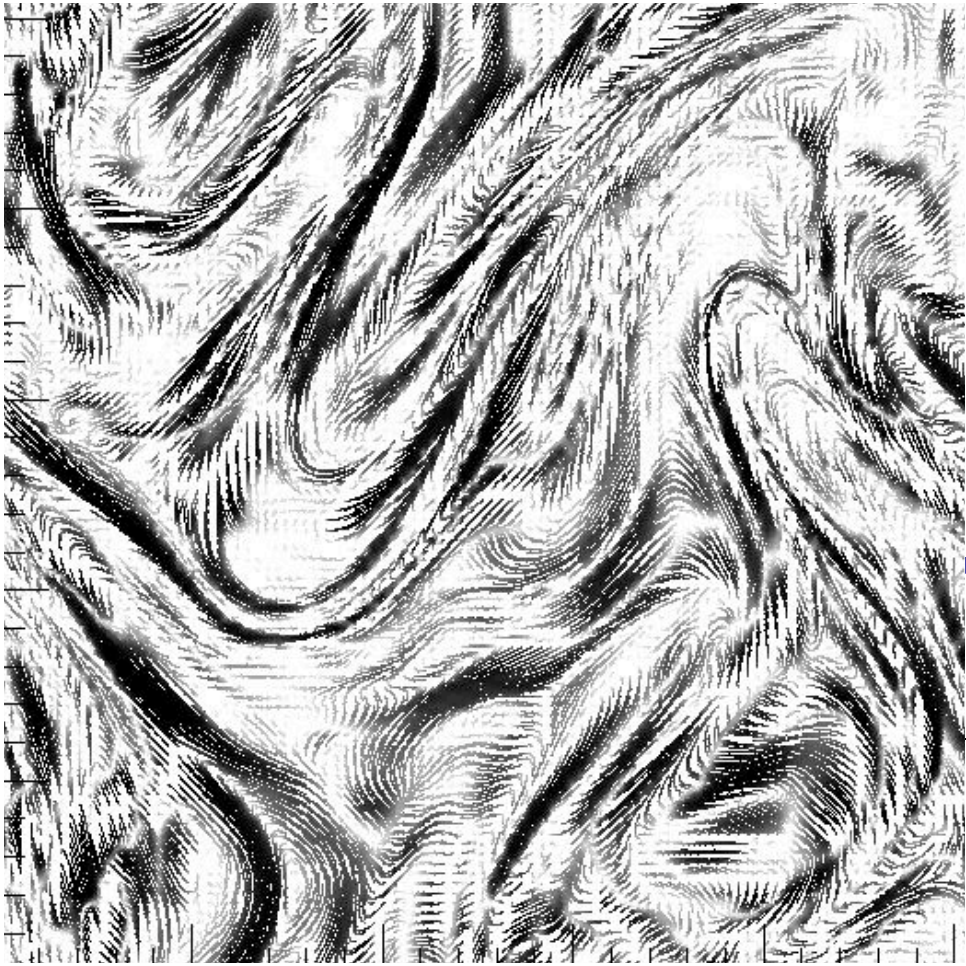
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

$$\frac{1}{B}\frac{dB}{dt} = \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{u} \sim \gamma_0$$

The field grows at the resistive scale and, as far as we know, saturates with energy at the smallest scales available to it.
All simulations will likely have magnetic field at the Nyquist scale.

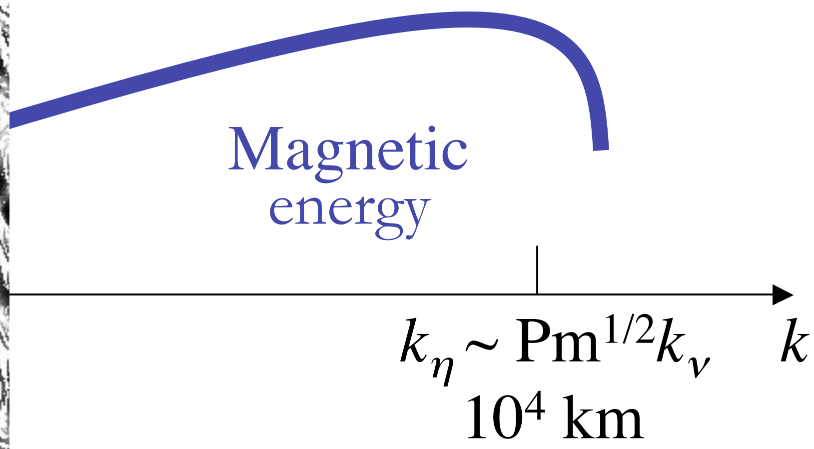
[Schekochihin *et al.*, *ApJ* **612**, 276 (2004)]

Fluctuation Dynamo in MHD



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

$$\frac{1}{B}\frac{dB}{dt} = \hat{\mathbf{b}}\hat{\mathbf{b}} : \boldsymbol{\nabla}\mathbf{u} \sim \gamma_0$$



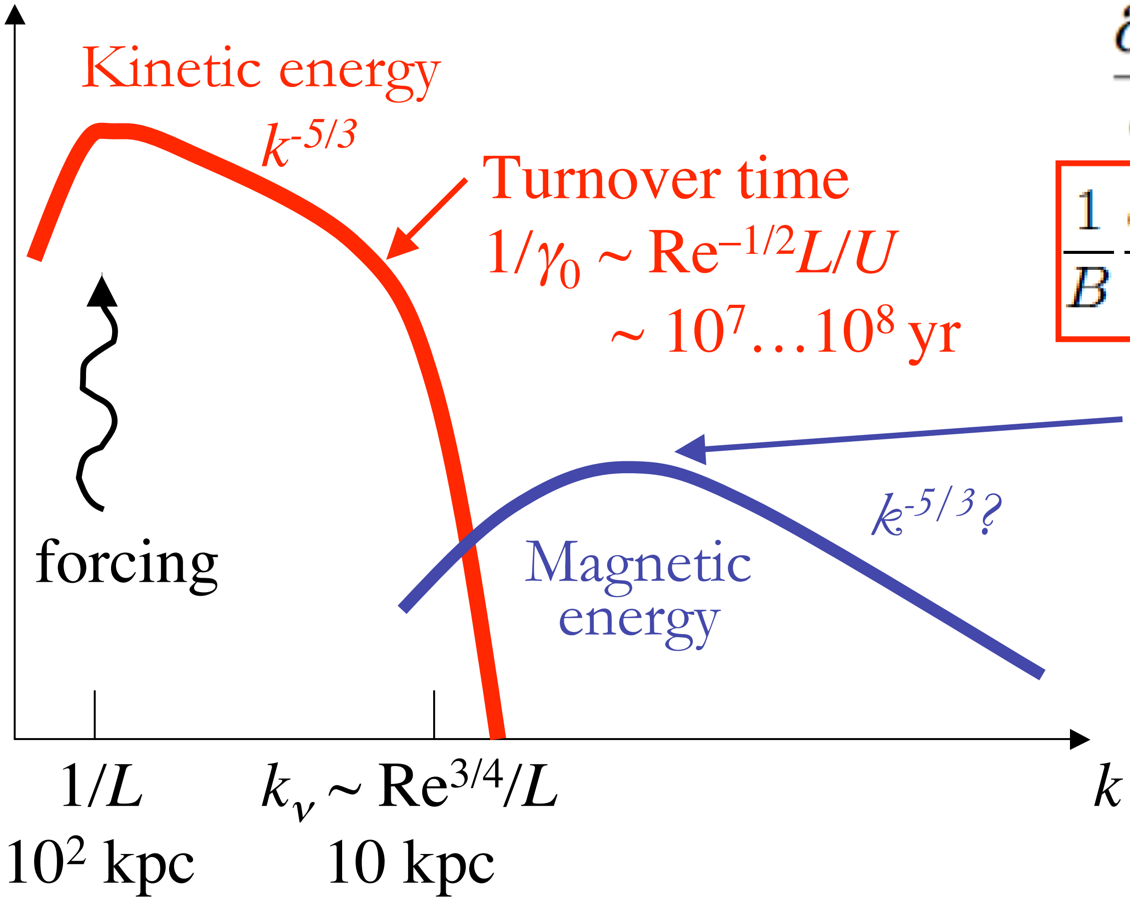
The field grows at the resistive scale and, as far as we know, saturates with energy at the smallest scales available to it ("folds"). All simulations will likely have magnetic field at the Nyquist scale.

[Schekochihin *et al.*, *ApJ* **612**, 276 (2004)]

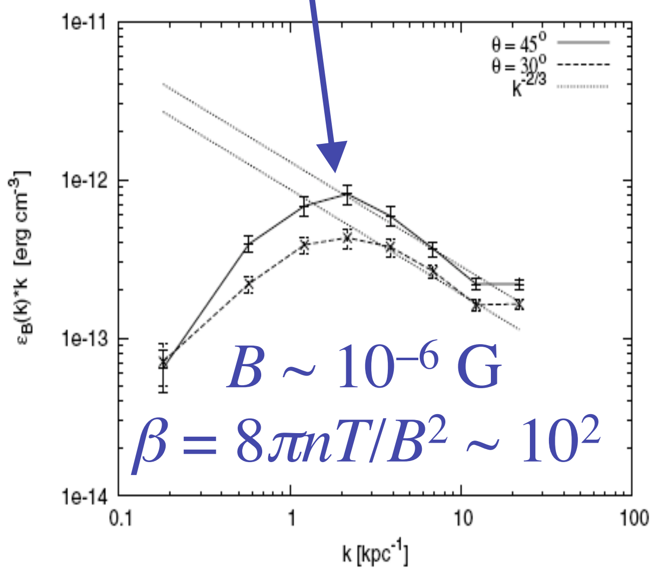
Fluctuation Dynamo in the ICM

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

$$\frac{1}{B}\frac{dB}{dt} = \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{u} \sim \gamma_0$$



What determines this scale is unclear



[Vogt & Enßlin 2005, *A&A* **434**, 67]

In contrast, observationally, while folded fields are seen, the reversal scale is not that small…

Fluctuation Dynamo in the ICM

Nobody knows how fluctuation dynamo works in a weakly collisional plasma — and numerics can't answer this because we can't do a kinetic simulation of dynamo (HUGE computing resources required for that).

However, on general grounds, it must work somehow: indeed, anywhere we look (ISM, ICM, old clusters, young clusters, cool-core clusters, unrelaxed clusters, etc.), we find ~1-10 μG fields, or, more importantly,

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

In MHD numerical simulations, there can be a factor <1, which, however, seems to increase with magnetic Prandtl number

[Schekochihin *et al., ApJ* **612**, 276 (2004)]

Fluctuation Dynamo in the ICM

Nobody knows how fluctuation dynamo works in a weakly collisional plasma — and numerics can't answer this because we can't do a kinetic simulation of dynamo (HUGE computing resources required for that).

However, on general grounds, it must work somehow: indeed, anywhere we look (ISM, ICM, old clusters, young clusters, cool-core clusters, unrelaxed clusters, etc.), we find ~1-10 μG fields, or, more importantly,

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

It is easy to argue hand-wavingly that this will happen FAST:

$$\frac{1}{B}\frac{dB}{dt} \sim \nu_{ii}\Delta \sim \frac{\nu_{ii}}{\beta_i} \propto B^2$$

So, **explosive growth**? (If true, no need to count *e*-folding times!)
We still have no idea what sets the field's scale…

[Schekochihin & Cowley 2006, *Phys. Plasmas* **13**, 056501]

Conclusion

For astronomers:

- See Matt Kunz's talk on the cooling flow regulation

For theoreticians:

- Microscale instabilities determine transport, heating, etc. *Ab initio* theory still incomplete (and painful, but interesting)

- Assuming **pressure anisotropies are pinned at marginal values** is supported by SW data and gives reasonable results for ICM
- Special cases that we have worked out suggest this happens via field modification, not enhanced particle scattering (but who knows)
- New instabilities lurking: GTI… (could set the temperature fluctuation scale in ICM?)
- Magnetogenesis/ICM dynamo is a great open problem

Further reading:

- Schekochihin *et al.*, MNRAS **405**, 291(2010)
- Rosin *et al.*, MNRAS, submitted; arXiv:1002.4017