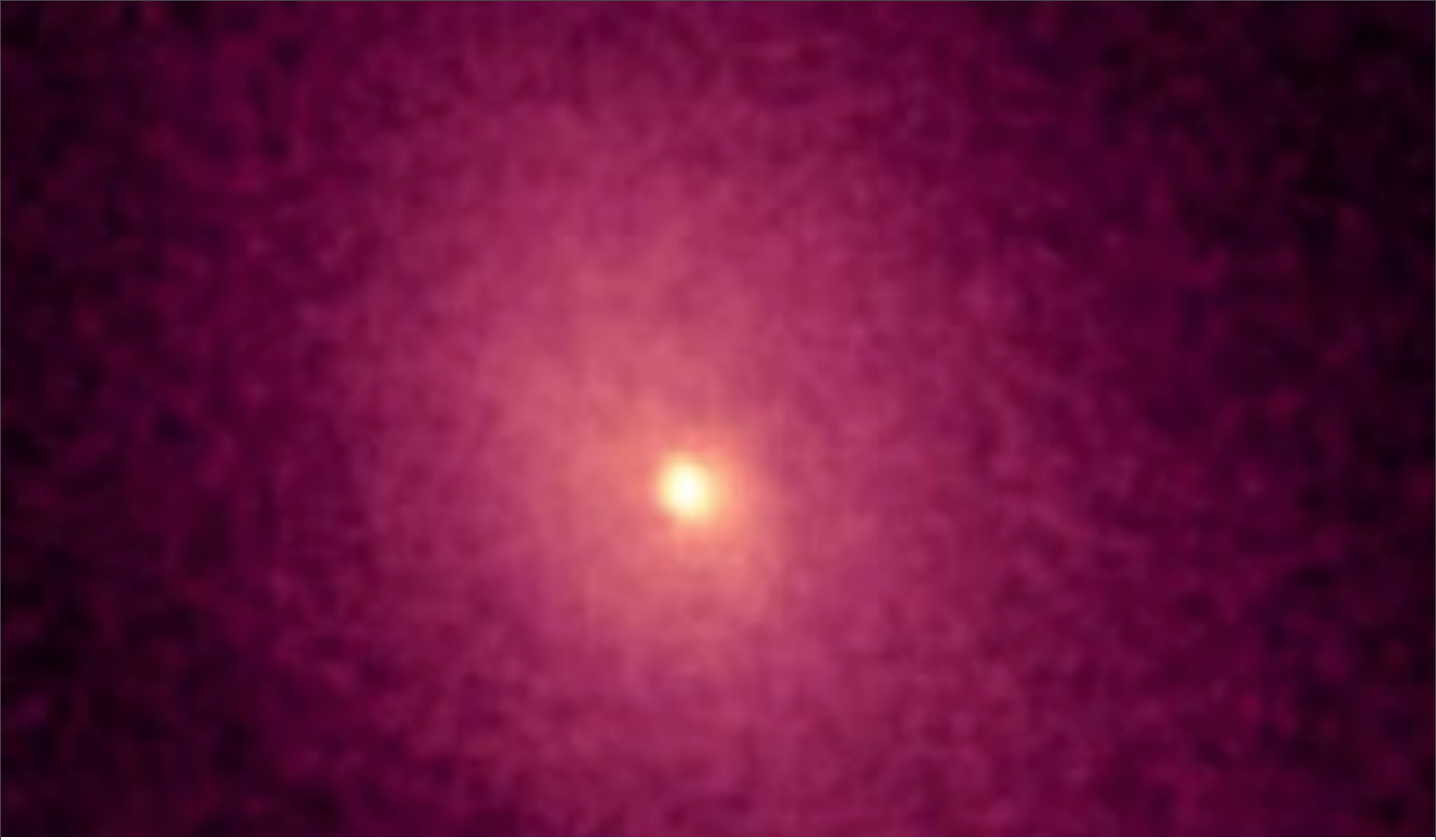


From Plasma Microphysics to Global Dynamics in Clusters of Galaxies

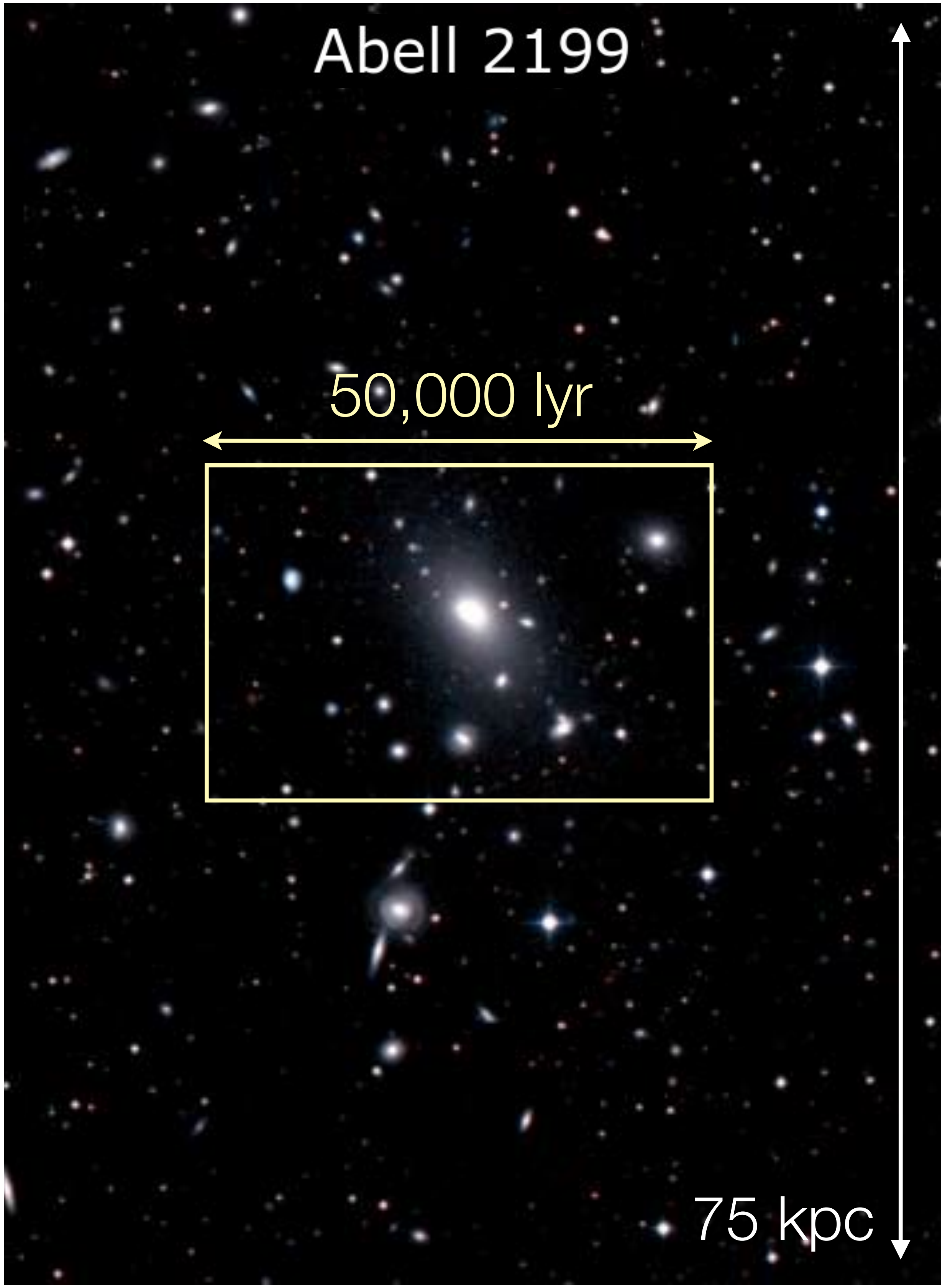
Matthew Kunz
28 Feb 2013

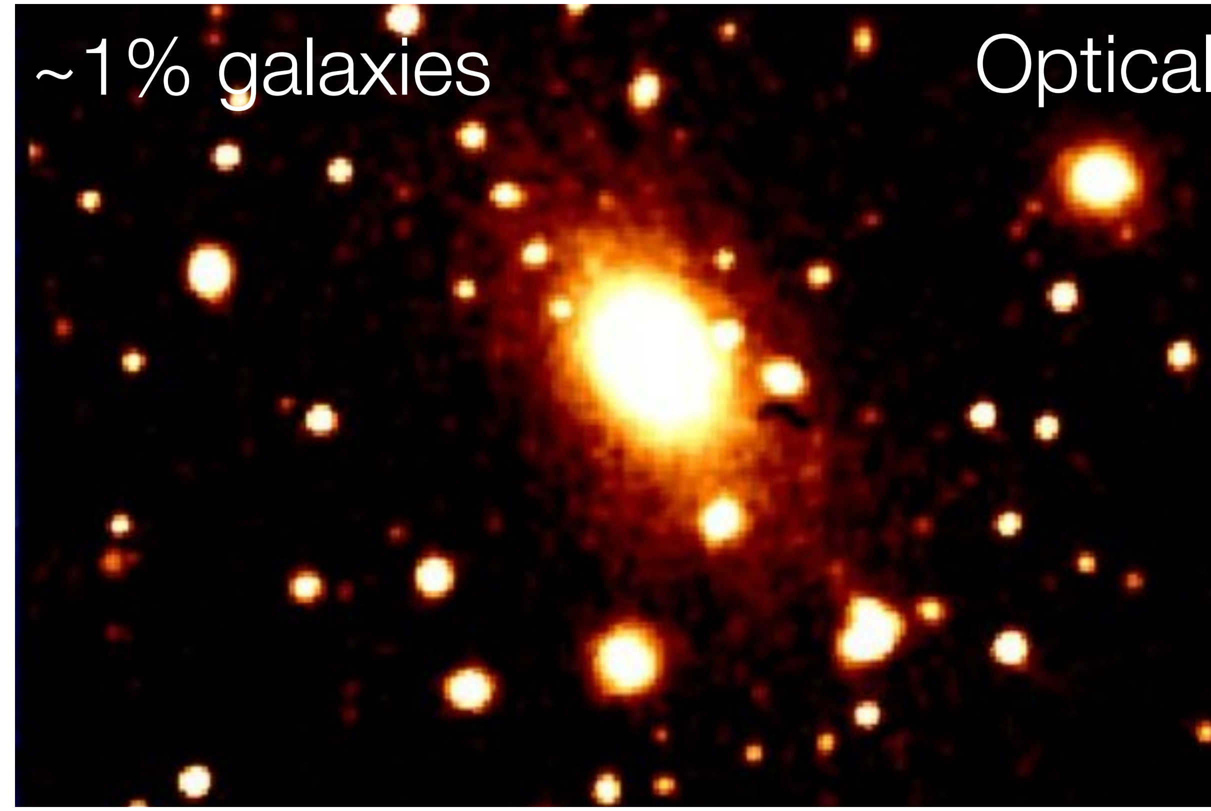
Picking up where we left off...

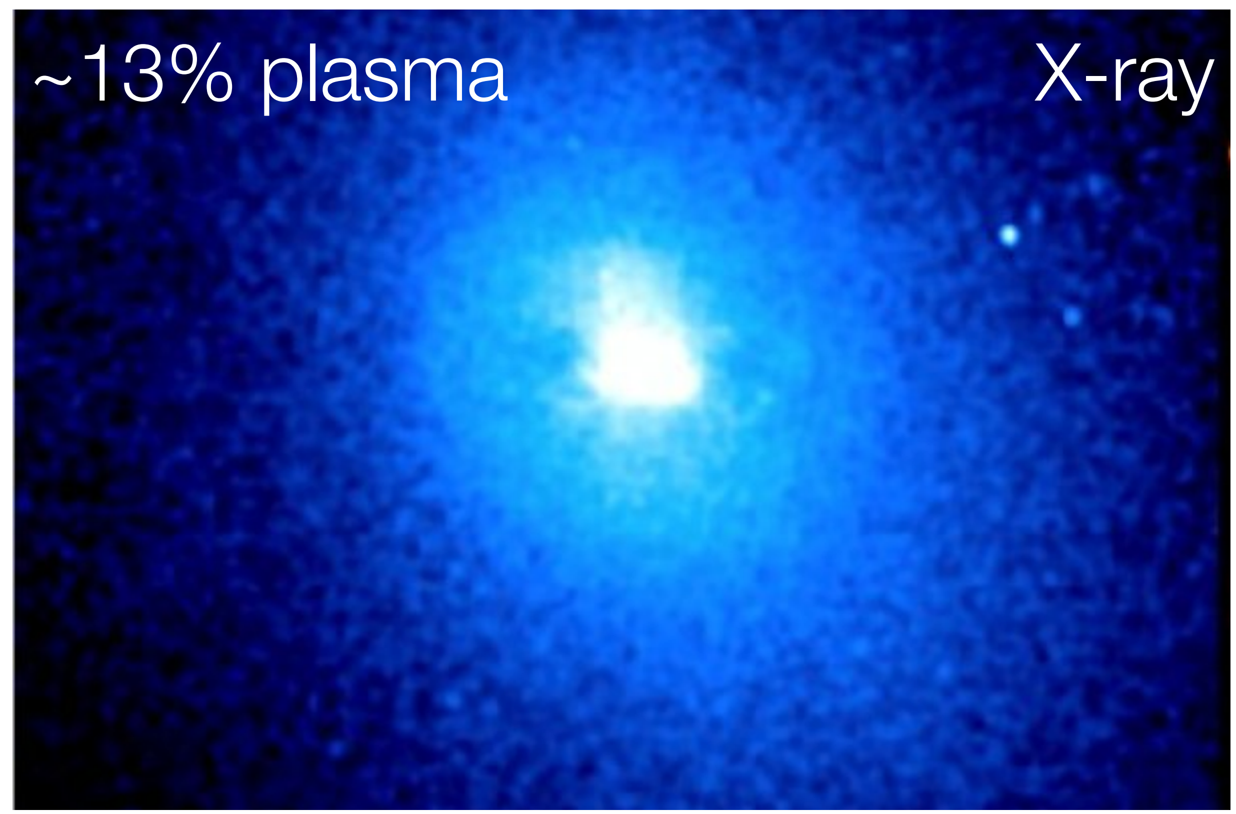
- We derived a system of equations that describe meso- and macroscale plasma physics in weakly collisional systems (including rotation, shear, gravity, thermal stratification).
- We discussed the physical interpretation of the kinetic-MHD closure.
- We applied these equations to elucidate the linear stability of weakly collisional accretion discs.

Galaxy Clusters

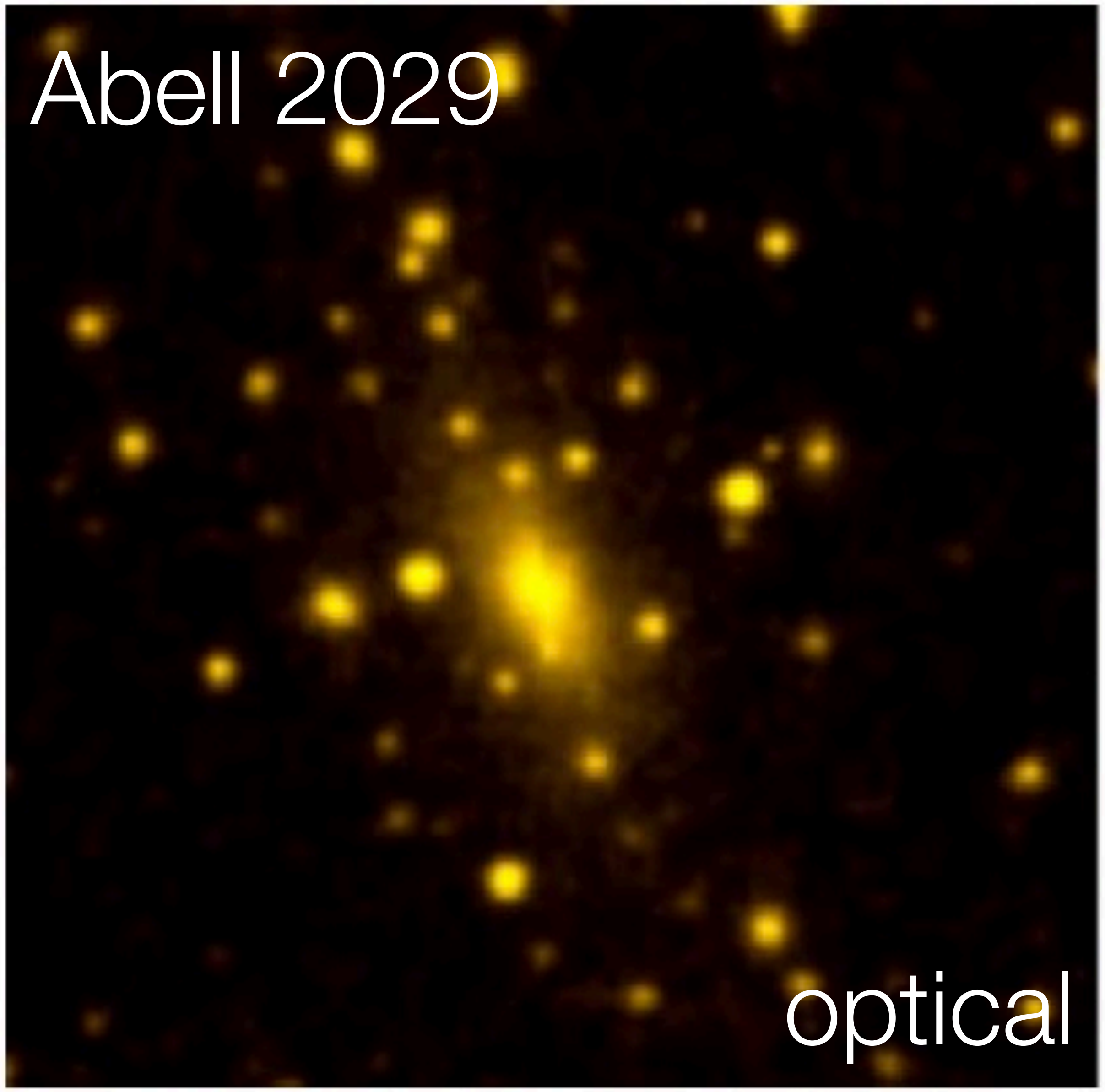
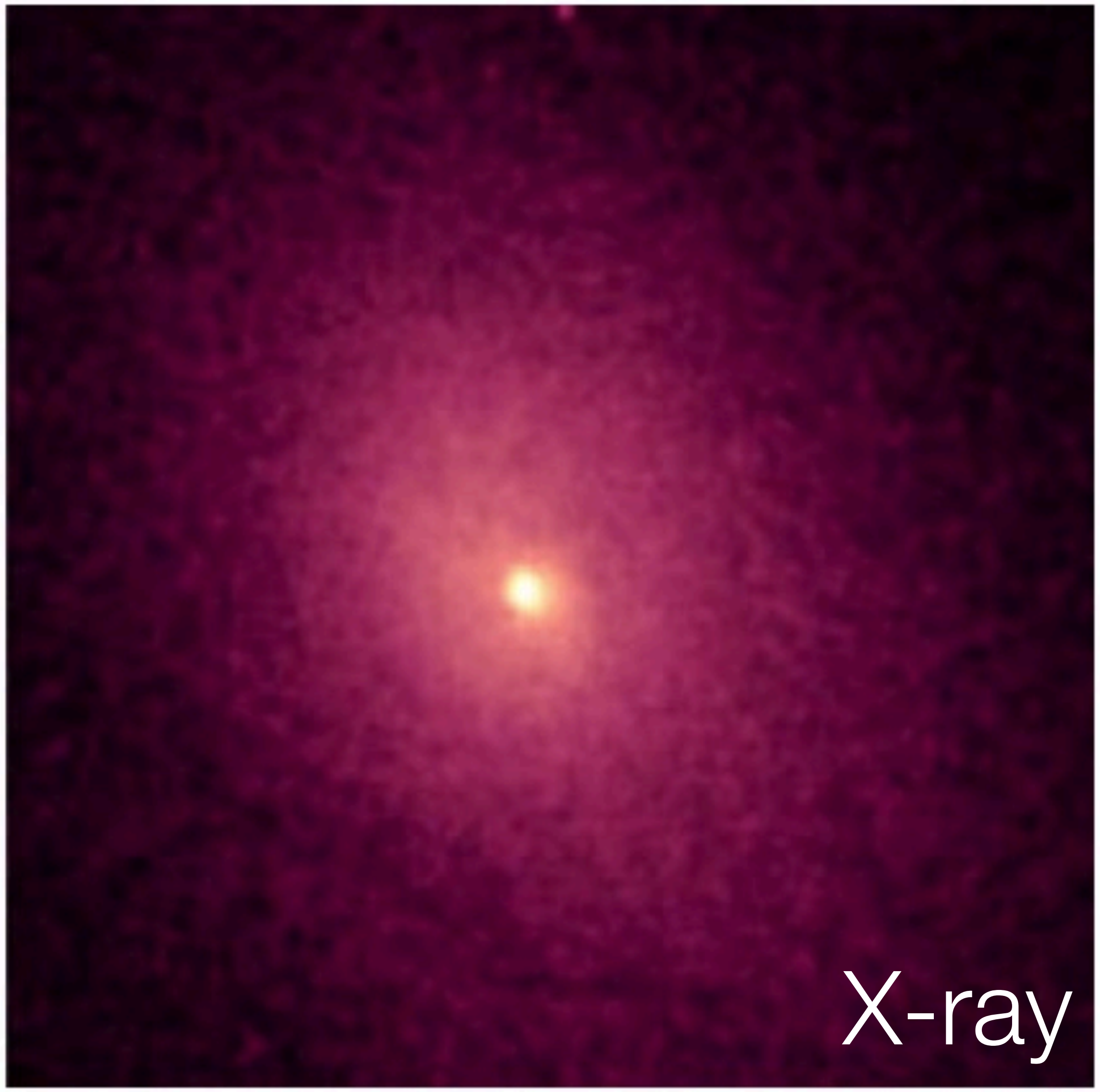
- We will learn the plasma parameters characterising these systems.
- We will investigate conduction, convection, and viscous dissipation in these systems.
- We will investigate the outstanding problems related to cluster plasma physics.
- We will look to the future and see what can be solved with current tools.

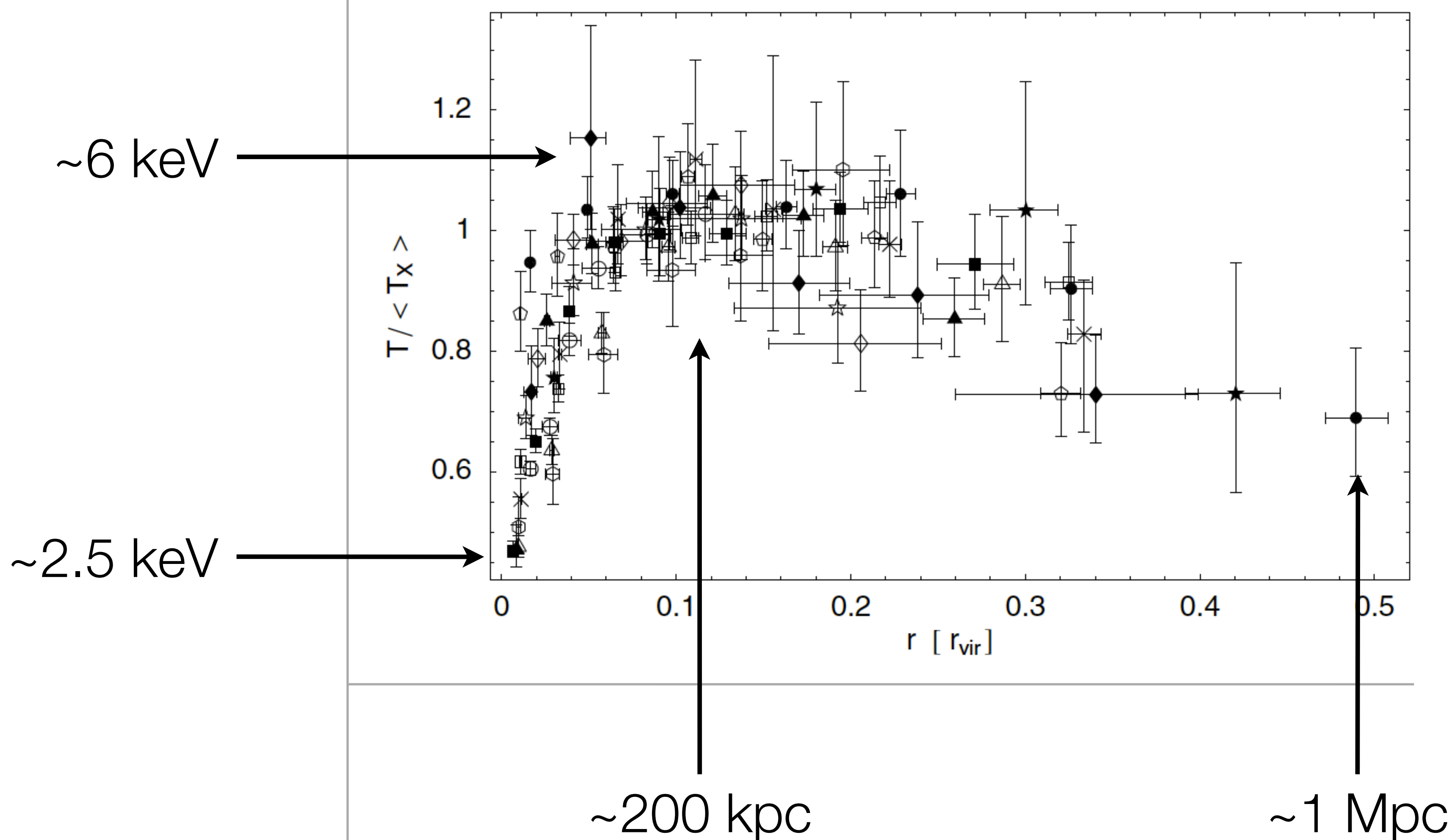


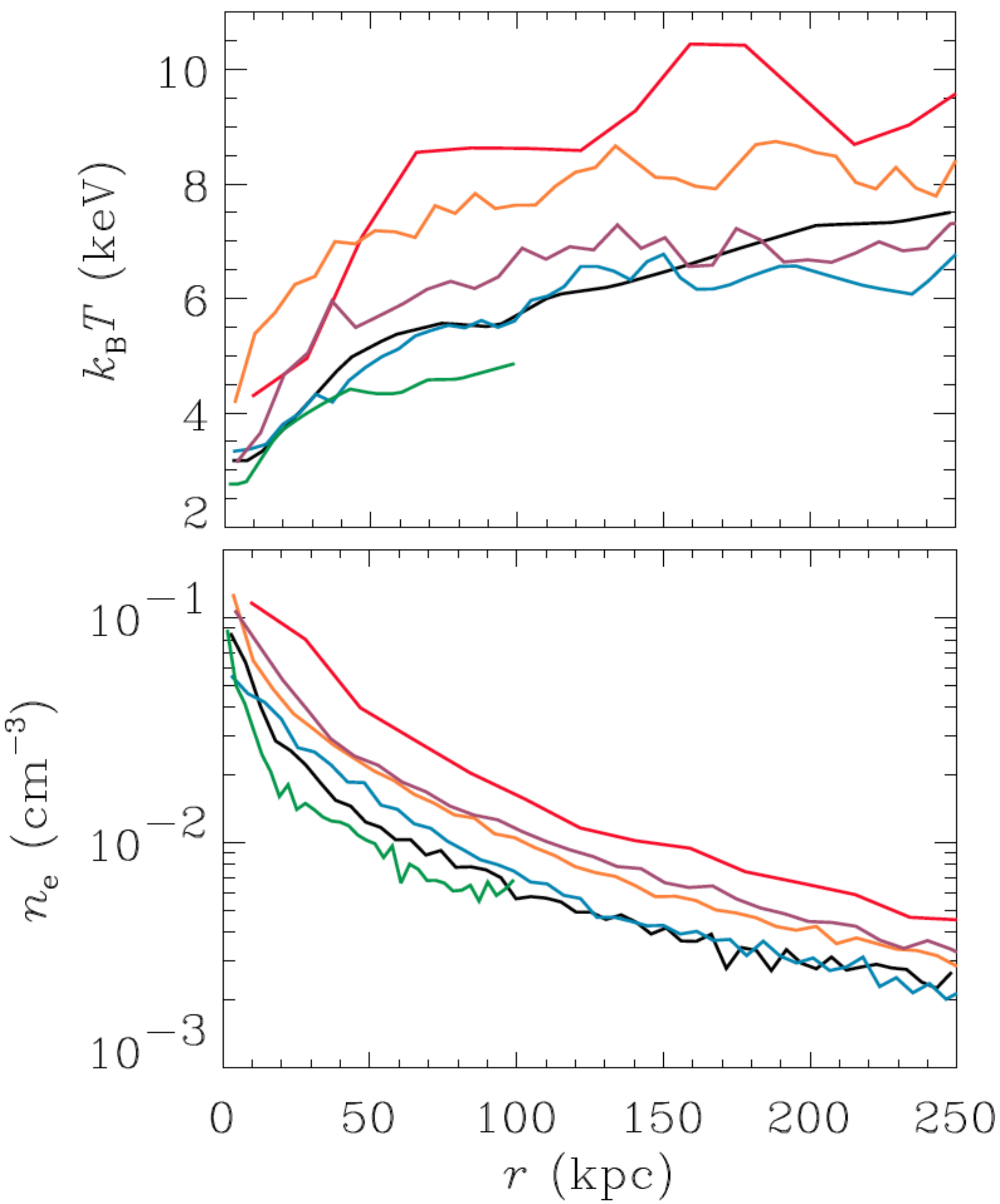


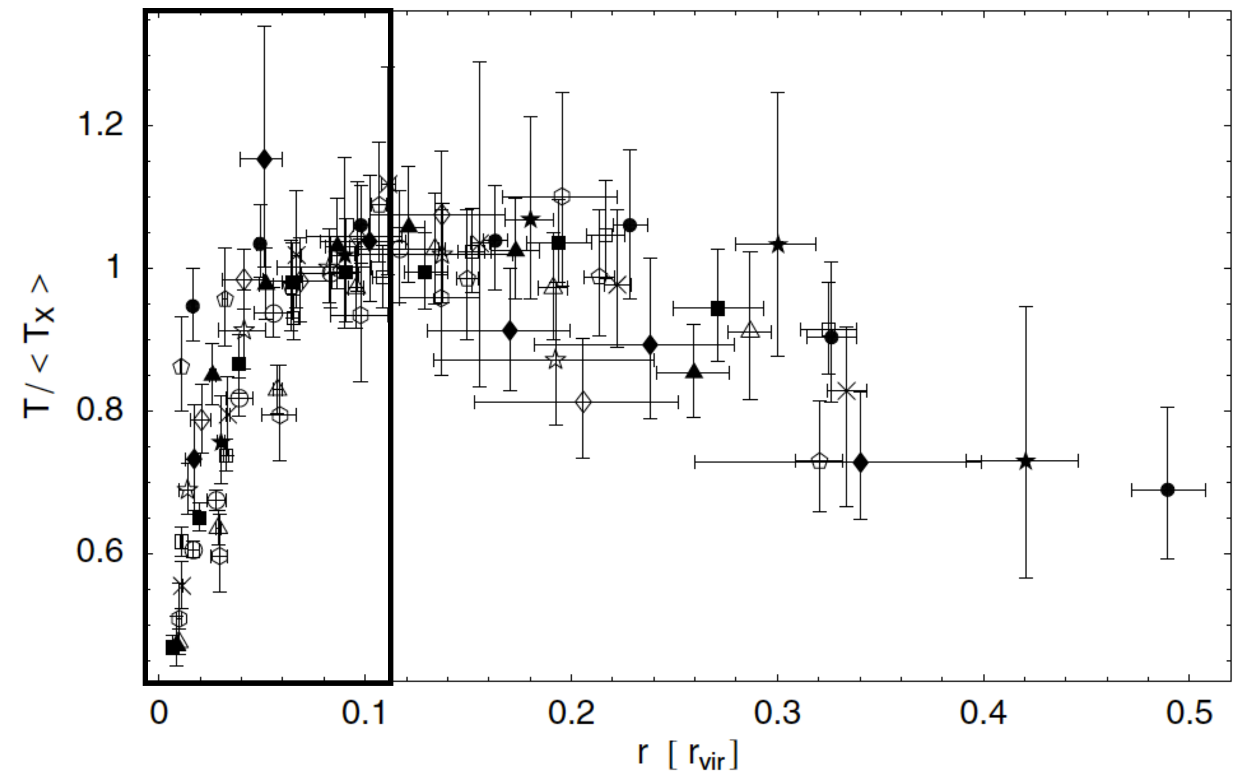


$M \sim 10^{14\text{-}15}\ M_\odot$ 100s of galaxies in ~1 Mpc


Abell 2029
optical

X-ray


~6 keV
~2.5 keV
~200 kpc
~1 Mpc
1.2
1
0.8
0.6
T / < T_X >
0
0.1
0.2
0.3
0.4
0.5
r [r_vir]

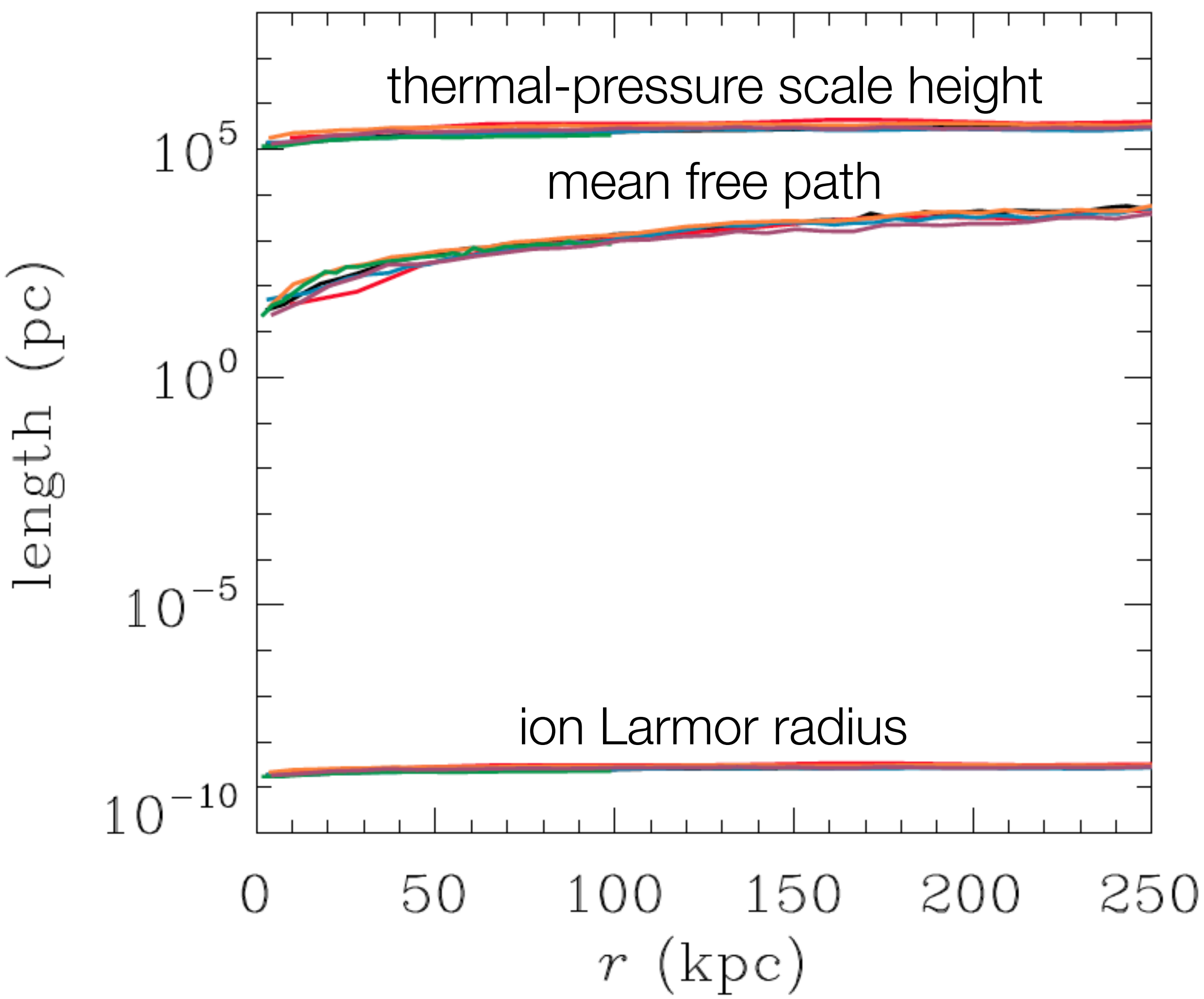




A85
A1835
A1795
A2029
A2199
A478

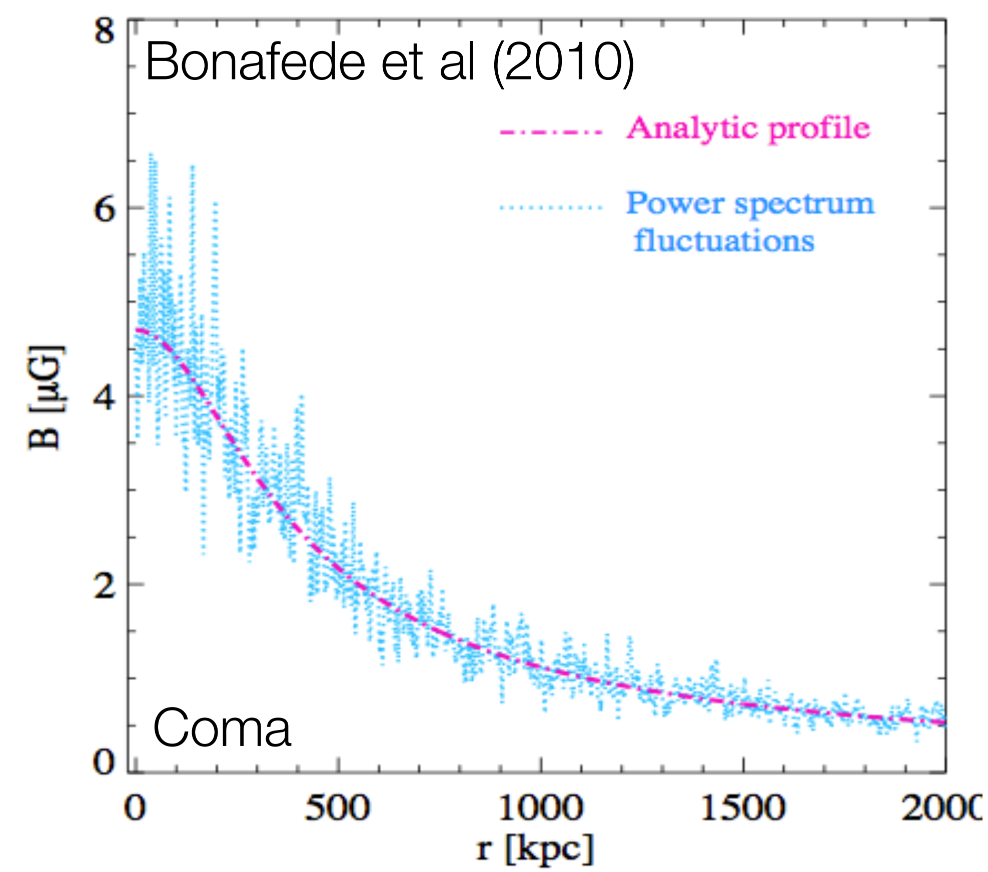
Cavagnolo et al 2009
http://www.pa.msu.edu/astro/MC2/accept/

ICM Dynamics:
A 3-scale problem

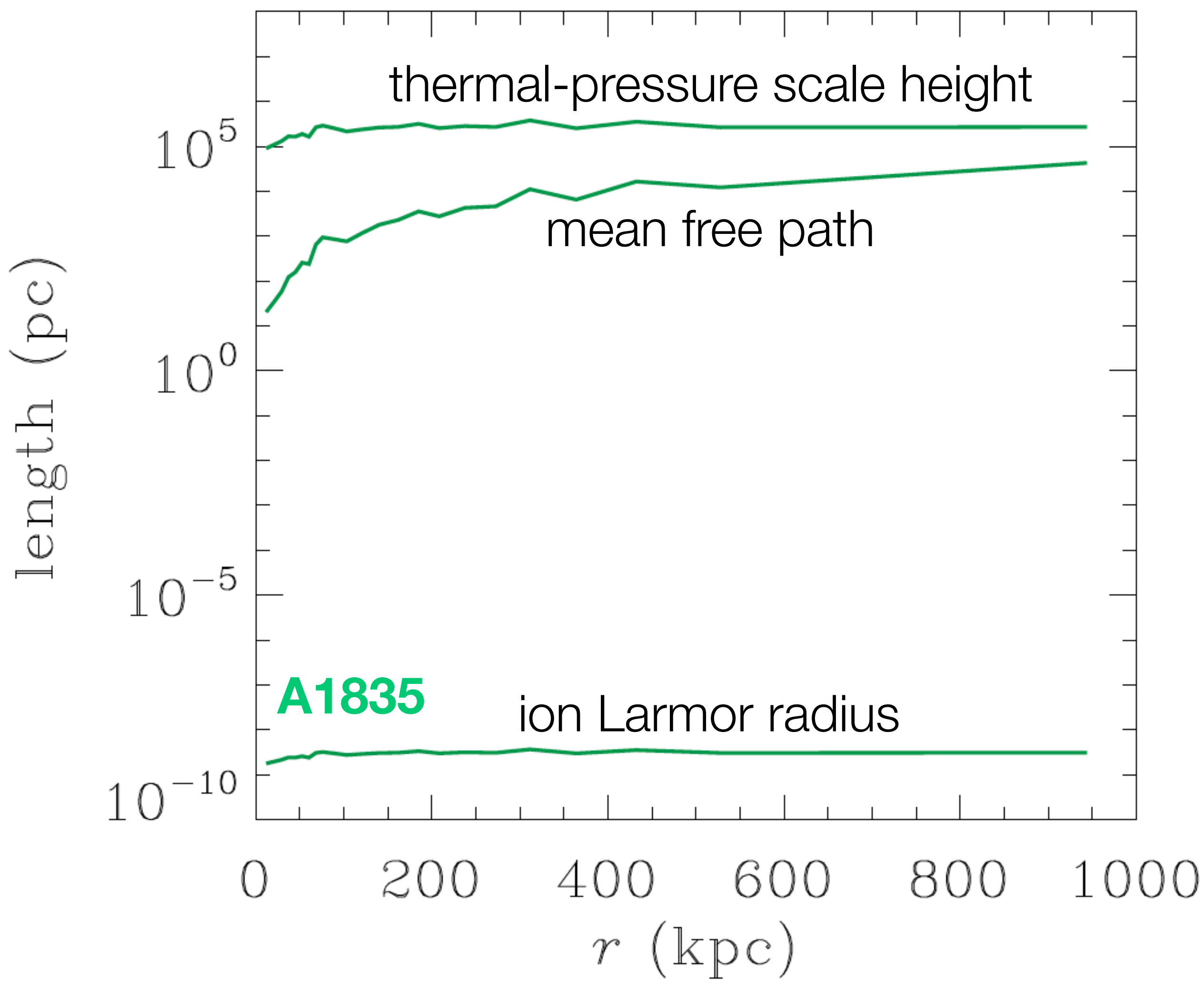


1 npc ~ 20,000 miles
~ 1 trip around the Earth

Cluster name	$n_{e,c}$ (10^{-2} cm^{-3})	T_c (keV)	$B_{c,obs}$ (μG)
	Cool-core clusters		
A1835	10	2.85	–
Hydra A	7.2	3.11	12[a]
A478	15.2	1.72	–
A2199	10	$\simeq 2$	15[b]
M87	10.8	1.62	35[b]
A1795	5.4	2.26	9.7[b]
Centaurus	9.5	1.24	8
A262	3.7	1.54	–



ICM Dynamics:
A 3-scale problem



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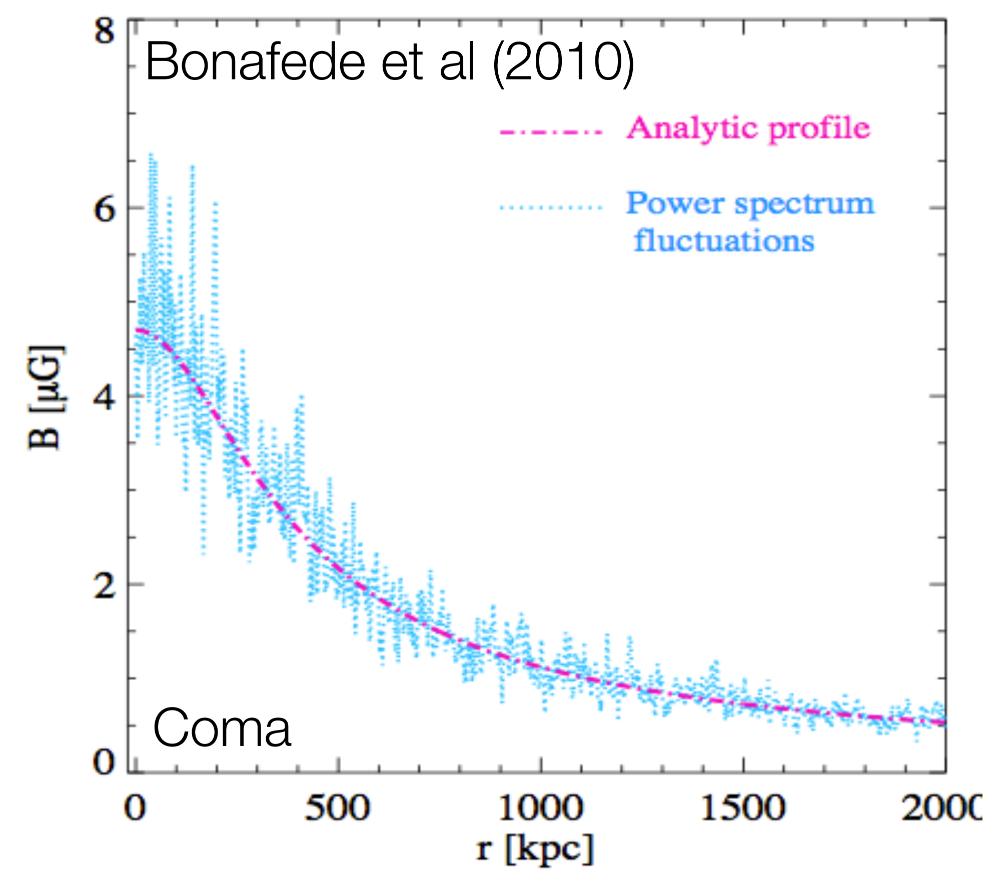


Braginskii-MHD equations

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla\cdot}(\rho \boldsymbol{v}) = 0$$

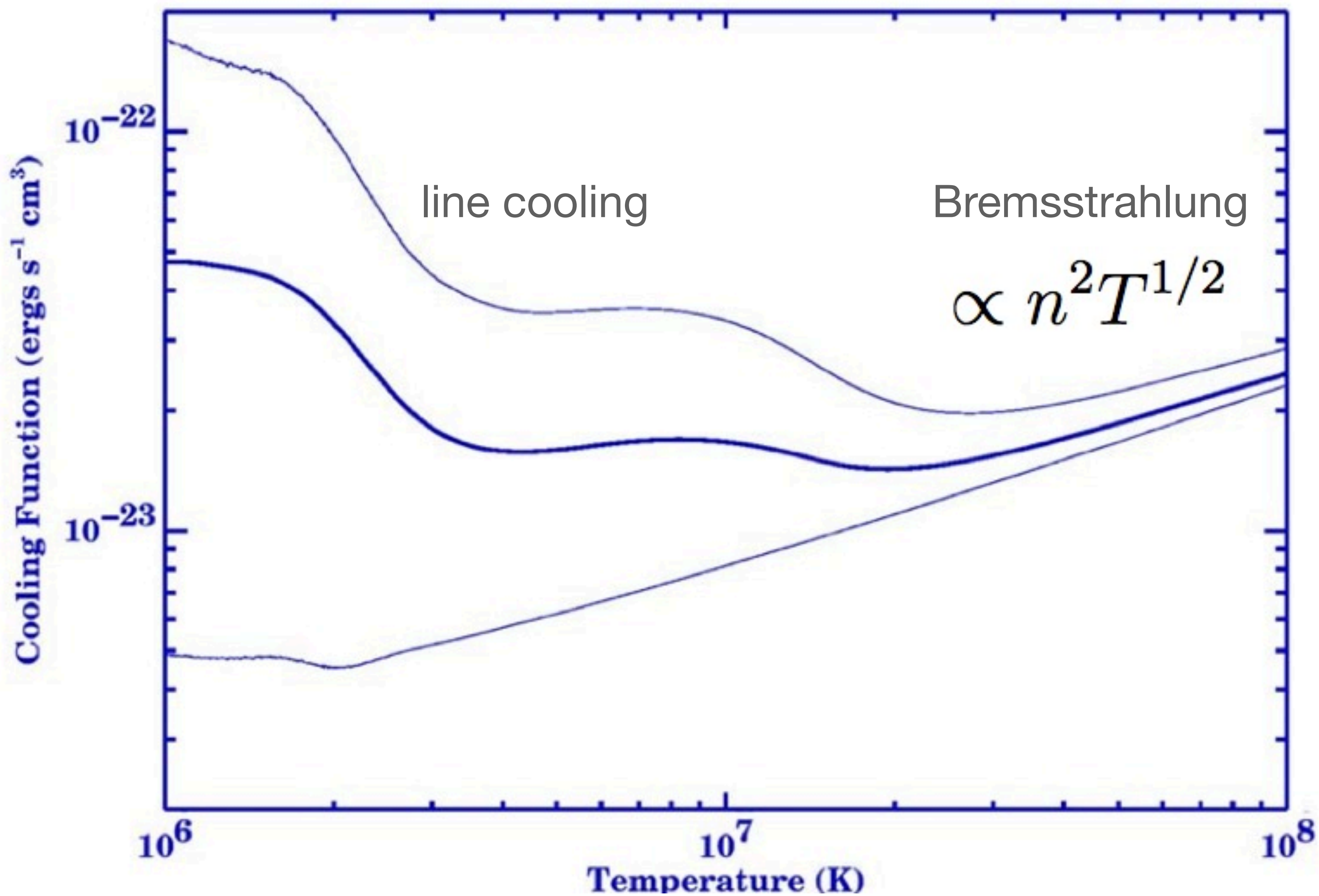
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \boldsymbol{\nabla\cdot}(\rho \boldsymbol{v}\boldsymbol{v}) = -\boldsymbol{\nabla} p - \rho \boldsymbol{\nabla}\Phi + \frac{1}{c}\boldsymbol{j}\times\boldsymbol{B} + \boldsymbol{\nabla\cdot}\left[\left(\hat{\boldsymbol{b}}\hat{\boldsymbol{b}} - \frac{1}{3}\mathbf{I}\right)(p_\perp - p_{||})\right]$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B}) = 0$$

$$\frac{3}{2} p \frac{\mathrm{d}}{\mathrm{d}t} \ln \frac{p}{\rho^{5/3}} = \rho\mathcal{L} + \boldsymbol{\nabla\cdot}\left(\chi_{||}\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\boldsymbol{\cdot\nabla} T\right) + (p_\perp - p_{||})\frac{\mathrm{d}}{\mathrm{d}t}\ln\frac{B}{\rho^{2/3}}$$

$$p_\perp - p_{||} = \frac{3}{2}\frac{\rho v_{\mathrm{th}}^2}{\nu_{\mathrm{i}}}\frac{\mathrm{d}}{\mathrm{d}t}\ln\frac{B}{\rho^{2/3}}$$

Cooling



line cooling
Bremsstrahlung
$\propto n^2 T^{1/2}$
10^{-22}
10^{-23}
Cooling Function (ergs s^{-1} cm^3)
10^6
10^7
10^8
Temperature (K)

Physical timescales

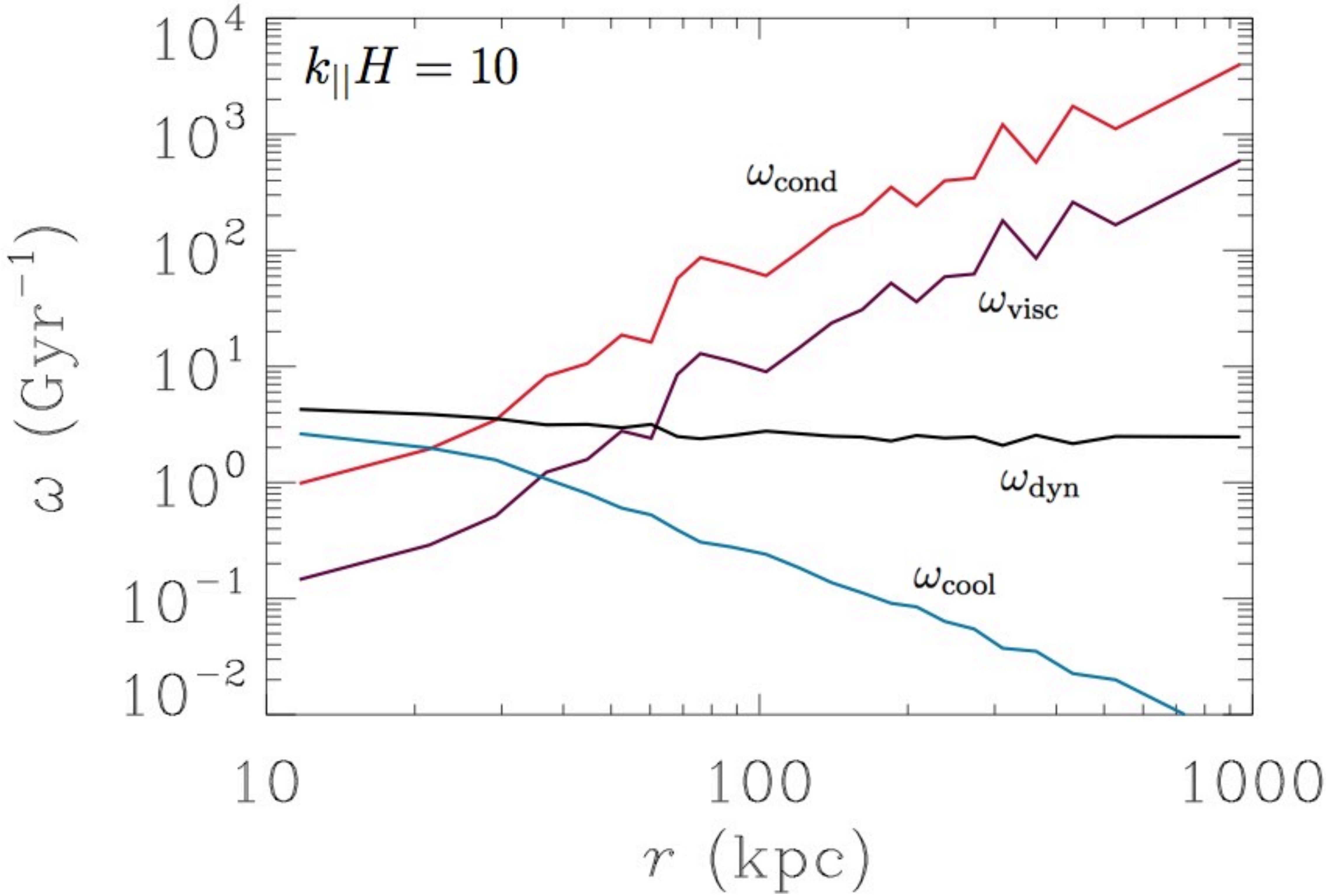
$$\omega_{\rm cond} \equiv 0.79 \times \frac{2}{5}\frac{k_{||}^2 v_{\rm th,e}^2}{\nu_{\rm e}} \approx 11 \left(\frac{k_{||}H}{10}\right)^2 \left(\frac{n_{\rm e}}{0.01~{\rm cm^{-3}}}\right)^{-1} \left(\frac{k_{\rm B}T}{3~{\rm keV}}\right)^{5/2}~{\rm Gyr^{-1}}$$

$$\omega_{\rm dyn} \equiv \left(\frac{g}{H}\right)^{1/2} \approx 4 \left(\frac{g}{10^{-8}~{\rm cm~s^{-2}}}\right) \left(\frac{k_{\rm B}T}{3~{\rm keV}}\right)^{1/2}~{\rm Gyr^{-1}}$$

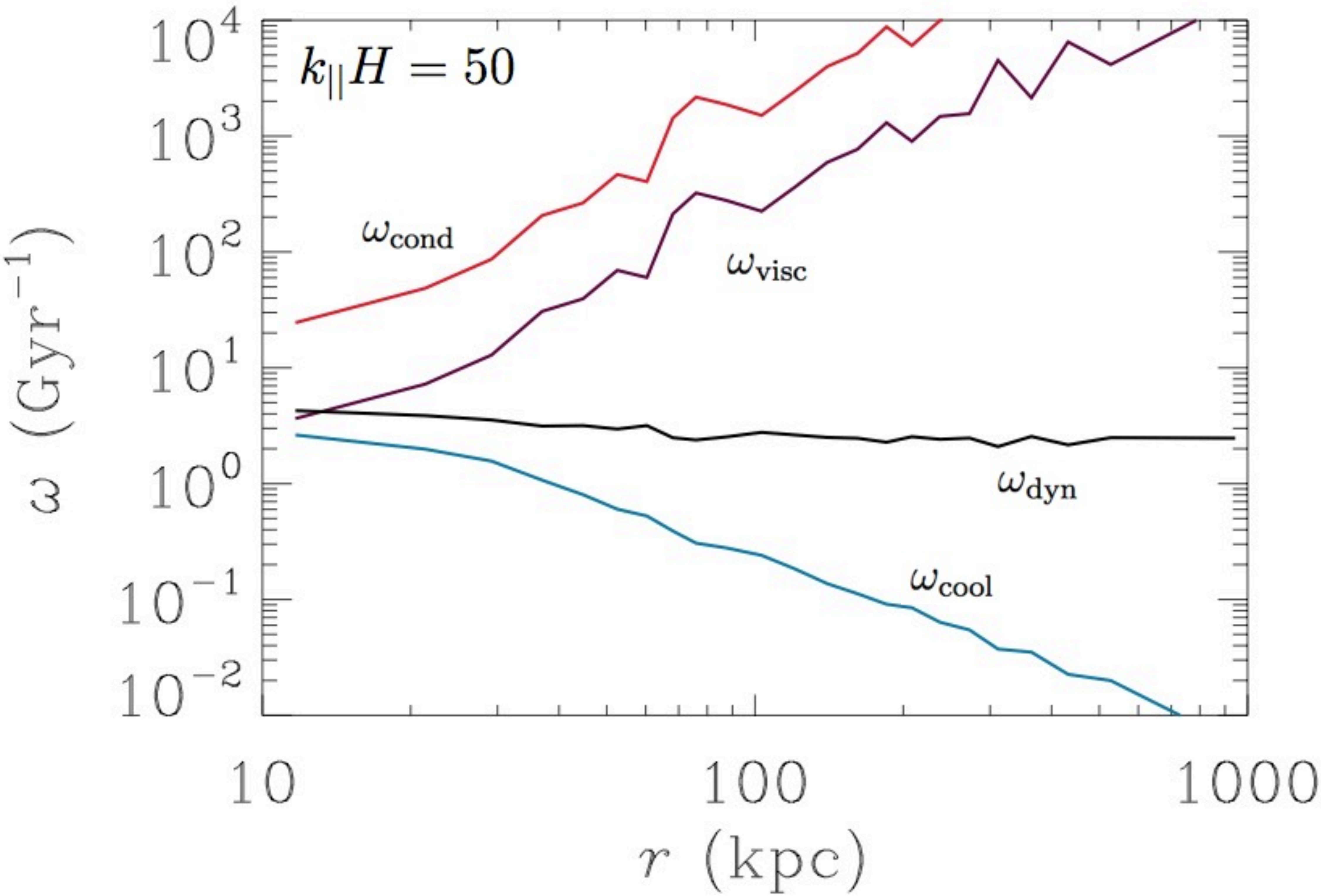
$$\omega_{\rm visc} \equiv 0.96 \times \frac{3}{2}\frac{k_{||}^2 v_{\rm th}^2}{\nu_{\rm i}} \approx 2 \left(\frac{k_{||}H}{10}\right)^2 \left(\frac{n_{\rm i}}{0.01~{\rm cm^{-3}}}\right)^{-1} \left(\frac{k_{\rm B}T}{3~{\rm keV}}\right)^{5/2}~{\rm Gyr^{-1}}$$

$$\omega_{\rm cool} \equiv -\frac{3}{5}\frac{\rho\mathcal{L}}{p} \approx -0.3 \left(\frac{n_{\rm e}}{0.01~{\rm cm^{-3}}}\right) \left(\frac{k_{\rm B}T}{3~{\rm keV}}\right)^{-1/2}~{\rm Gyr^{-1}}$$

Physical timescales



Physical timescales



Cooling flows

$$\rho\mathcal{L} \approx 10^{-25} \left(\frac{n_\mathrm{e}}{0.1\ \mathrm{cm}^{-3}}\right)^2 \left(\frac{T}{2\ \mathrm{keV}}\right)^{1/2} \ \mathrm{erg\ s^{-1}\ cm^{-3}}$$

$$t_\mathrm{cool} \equiv \frac{2}{3}\frac{\rho\mathcal{L}}{n_\mathrm{e}T} \sim 100 \left(\frac{n_\mathrm{e}}{0.1\ \mathrm{cm}^{-3}}\right) \left(\frac{T}{2\ \mathrm{keV}}\right)^{-1/2} \ \mathrm{Myr}$$

$$\ll t_\mathrm{age} \sim H_0^{-1}$$

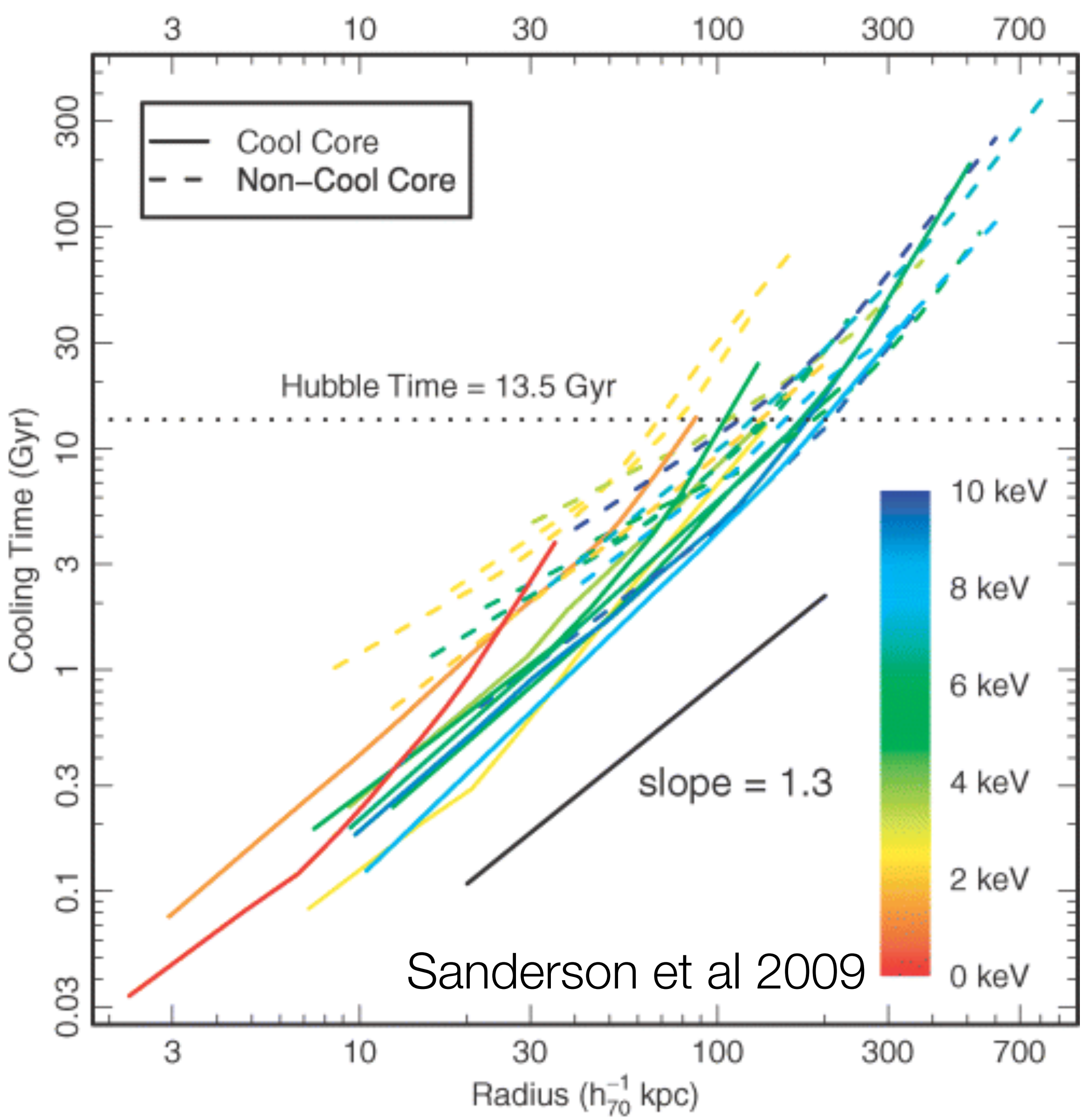
$$L_\mathrm{cool} = \frac{5}{2}\frac{\dot{M}}{\mu m} k_\mathrm{B} T \qquad \rightarrow \dot{M} \sim 100\ M_\odot\ \mathrm{yr}^{-1}$$

$k_\mathrm{B}T$: $\sim 3\ \mathrm{keV}$

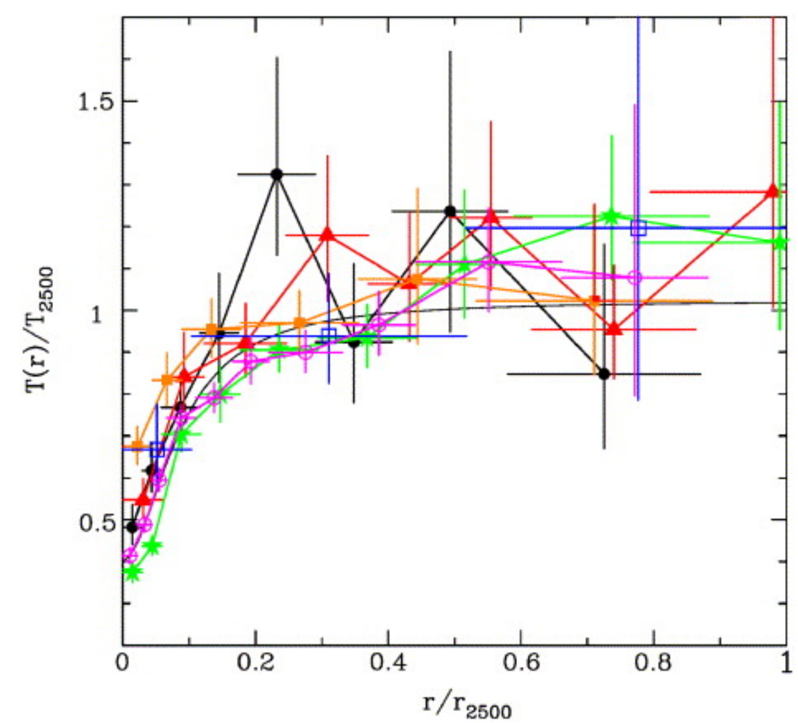
L_cool: $\sim 10^{44}\ \mathrm{erg\ s^{-1}}$

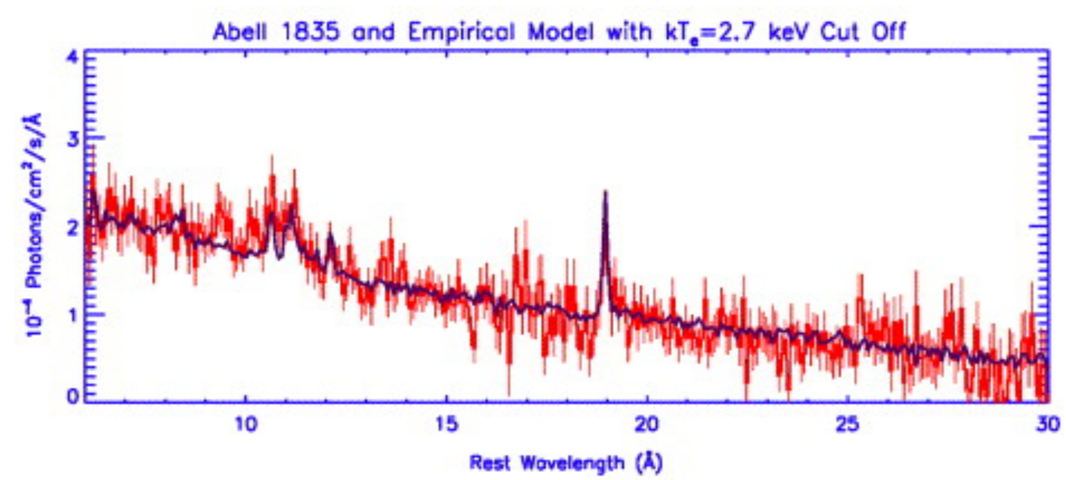
Cooling flows

expect lots of cold gas...



...but not observed

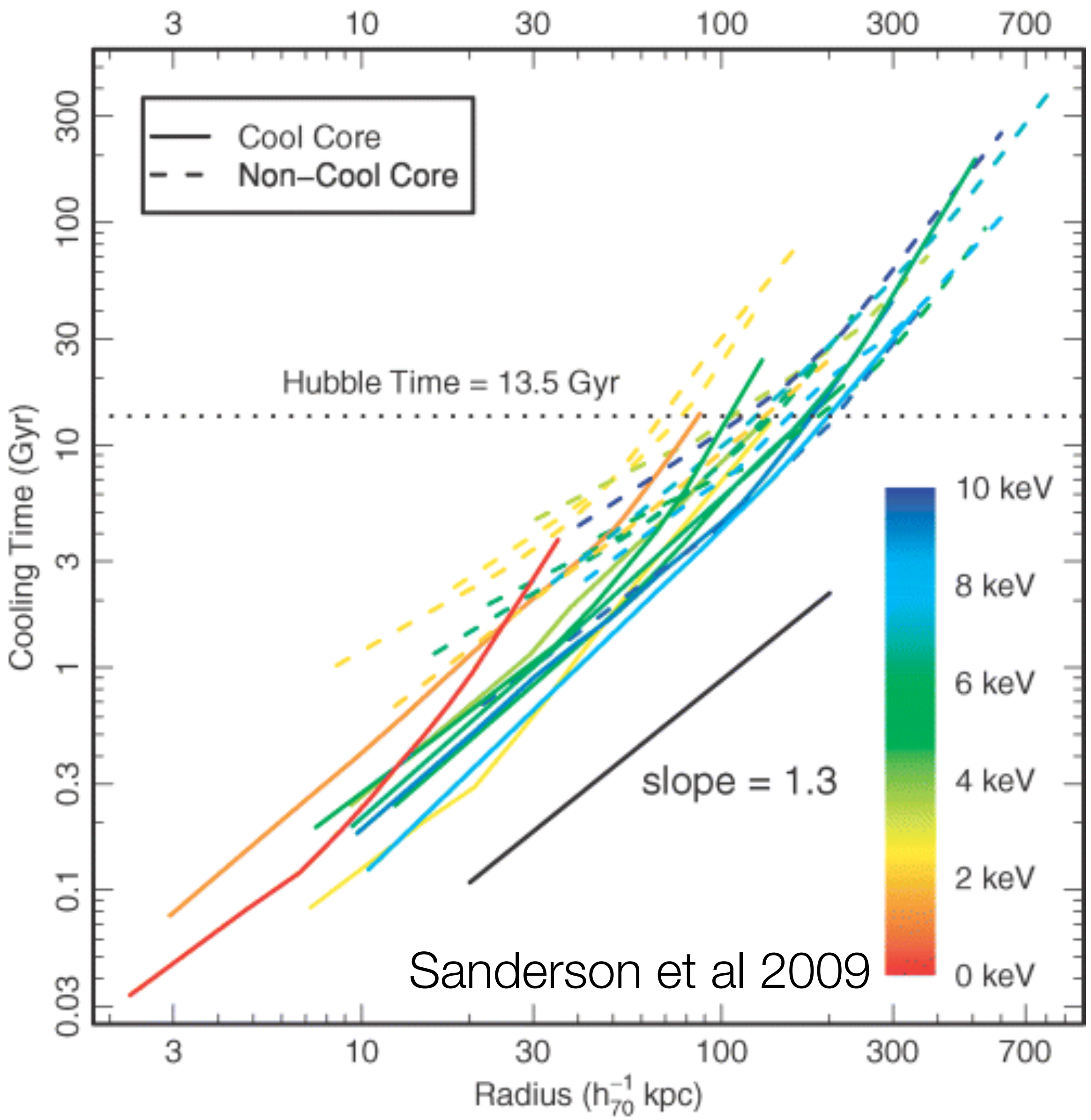


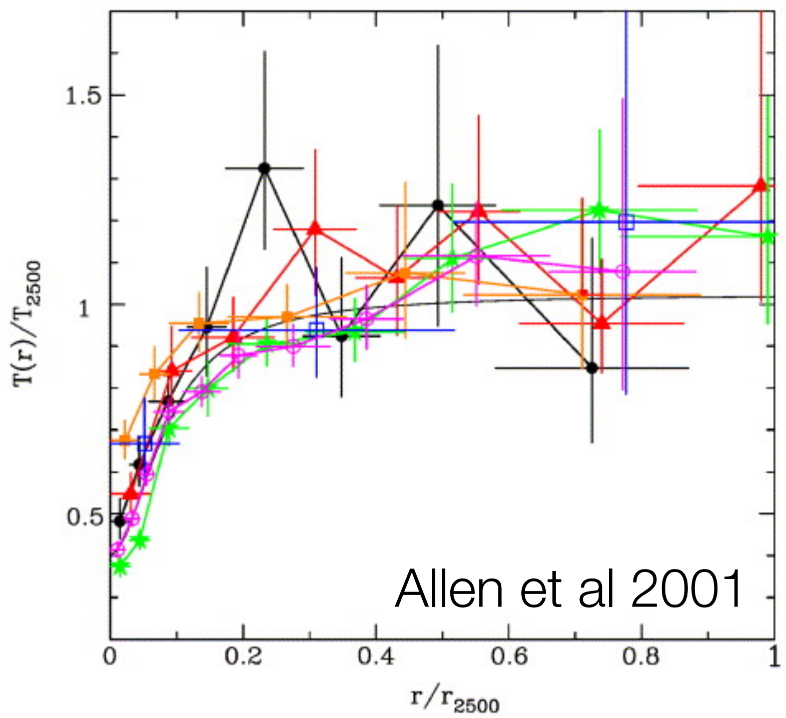


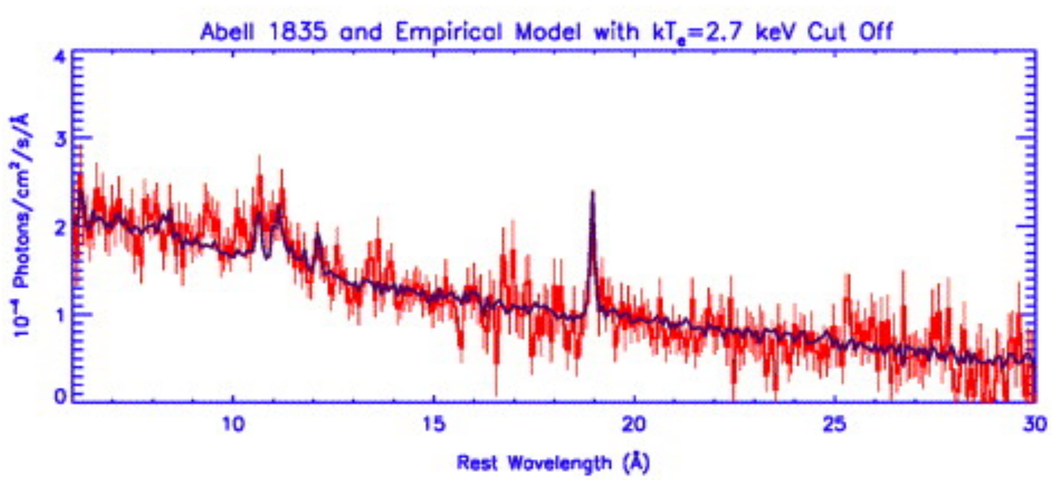
~~Cooling flows~~ "Cooling-flow problem"

expect lots of cold gas...

...but not observed

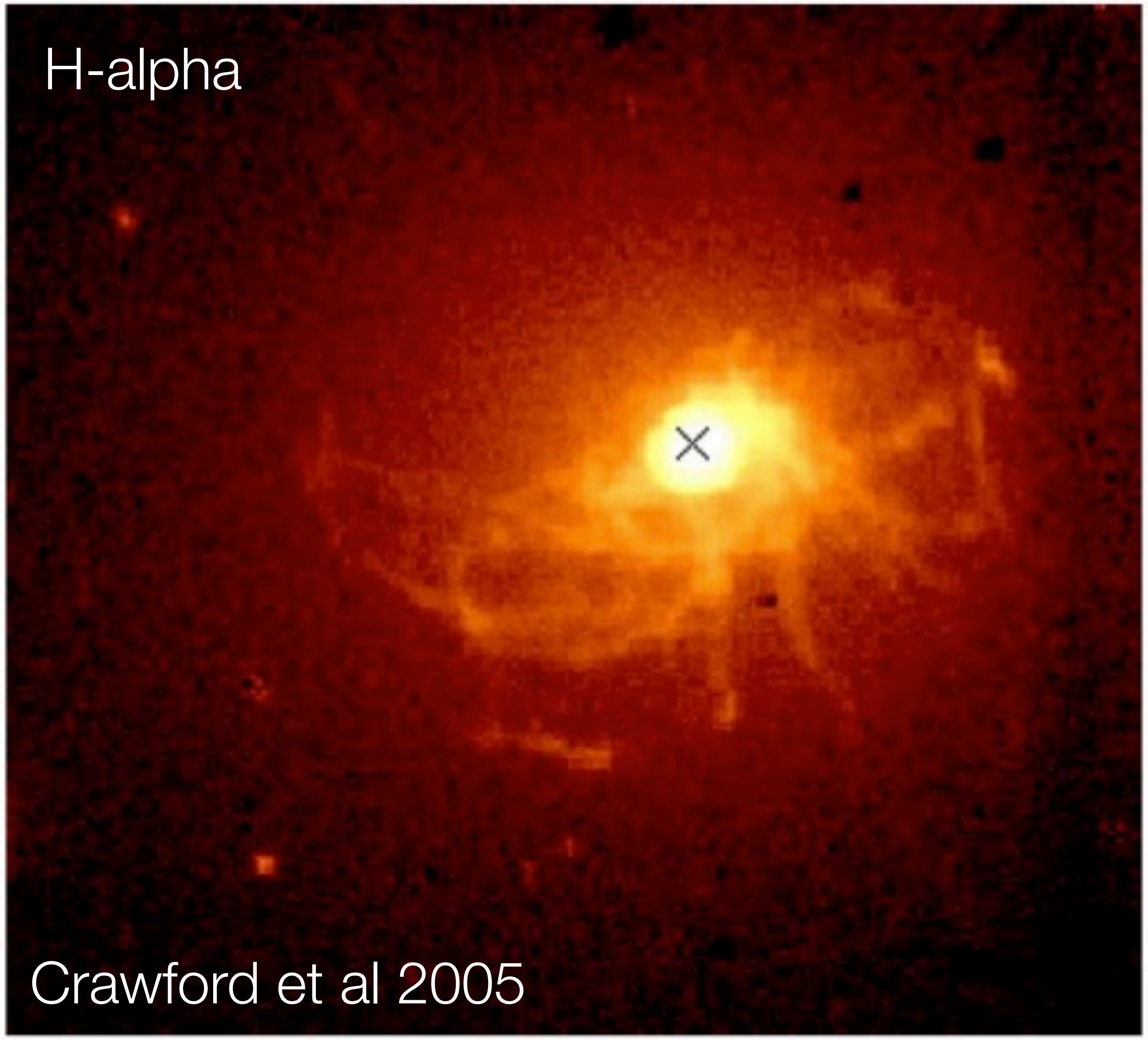






There is *some* cold gas...

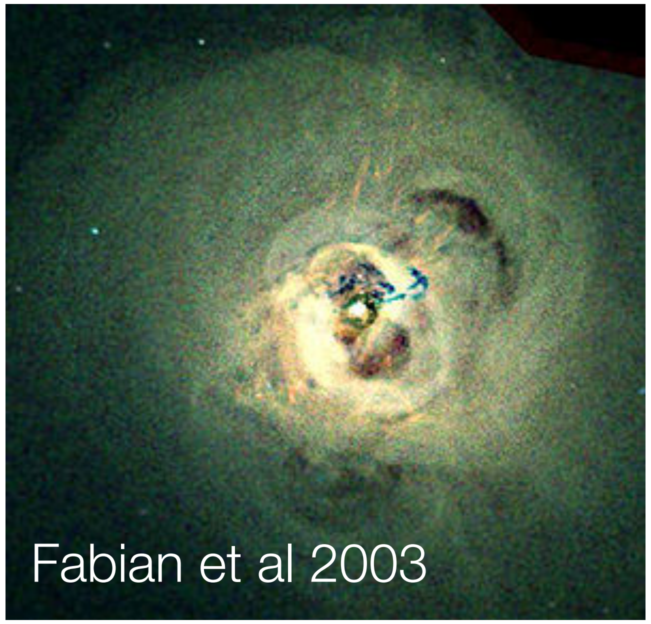
...mostly in filaments



God’s thermostat?

- Feedback from A(ctive) G(alactic) N(uclei)...

  ...but how does it know how much heat is needed?


Fabian et al 2003

$$\dot{M} \sim 4\pi n v_r r^2 \sim 4\pi \rho c_{\rm s} \left(\frac{GM}{c_{\rm s}^2}\right)^2$$

$$\propto \frac{1}{c_s^5} \text{ at constant pressure}$$

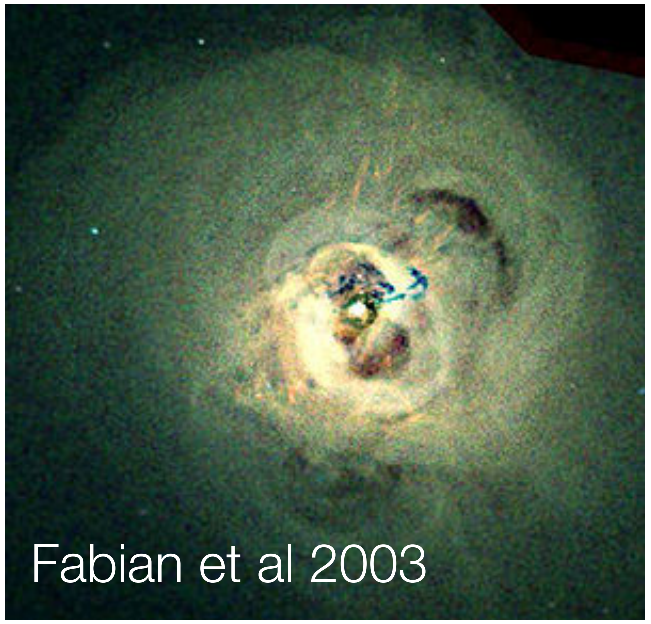
God’s thermostat?

- Feedback from A(ctive) G(alactic) N(uclei)...

  ...but how does it know how much heat is needed?

  ...and how is it thermalized and distributed?

  turbulence? sound waves? weak shocks? bubbles? cosmic rays?



Fabian et al 2003

$$\mathrm{Re} = \frac{u_{||}\ell_{||}}{\nu_{||}} \sim 10 - 100$$

God’s thermostat?

- Feedback from A(ctive) G(alactic) N(uclei)...

  ...but how does it know how much heat is needed?

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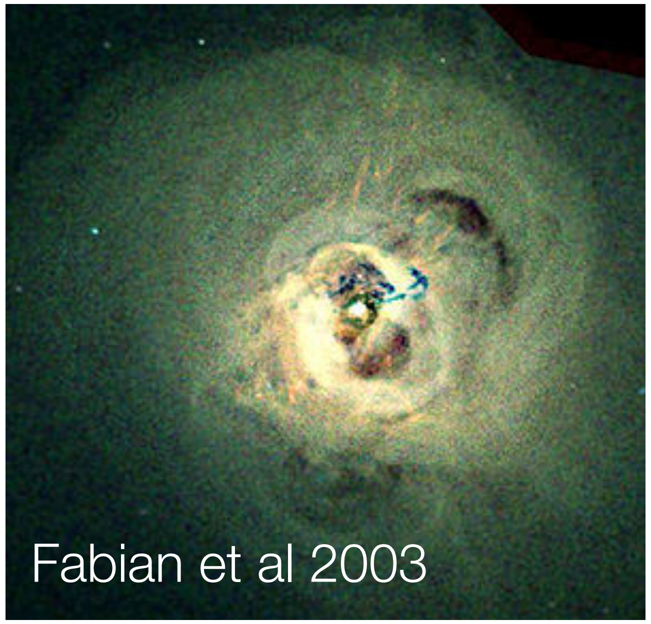
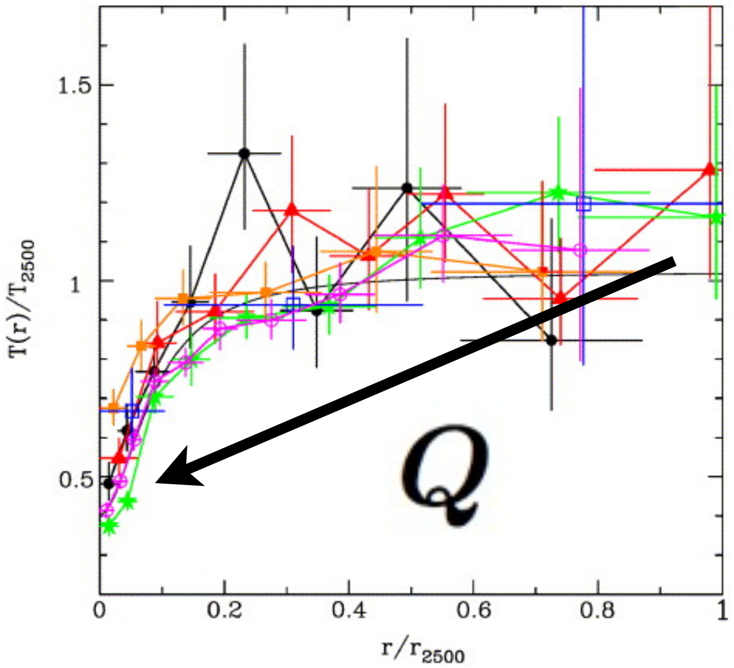

Fabian et al 2003

- Conduction inwards from bulk of cluster...

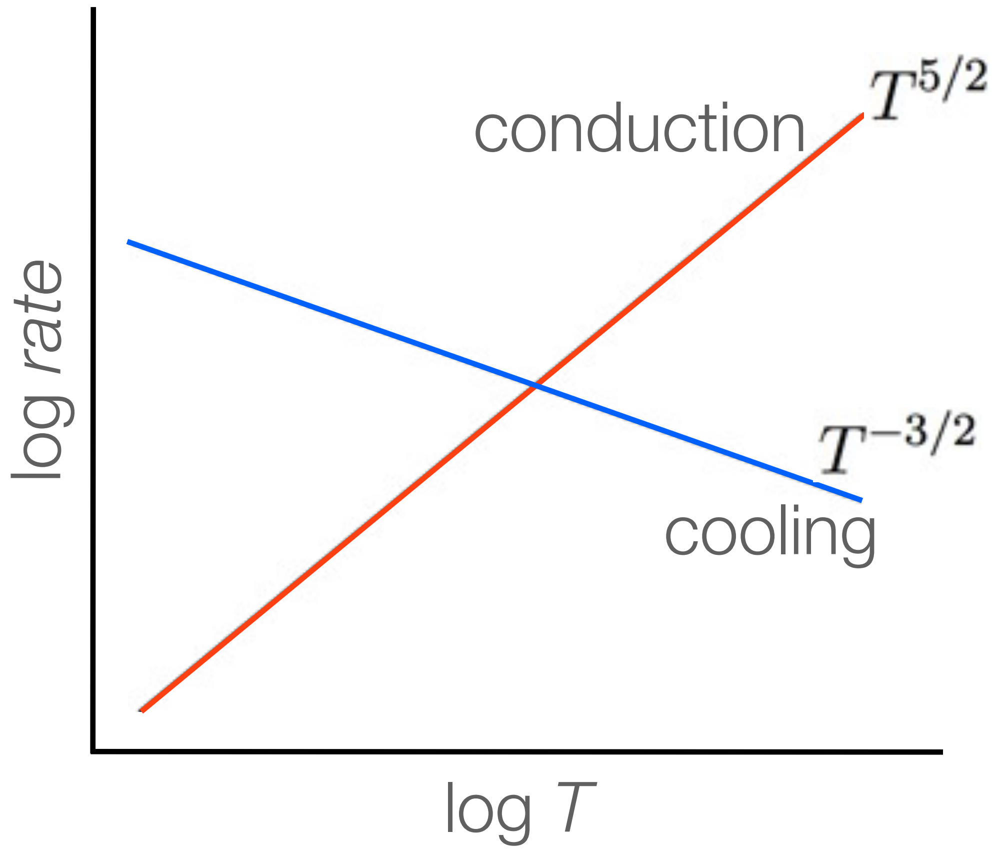
  ...but can it (stably) offset cooling? (e.g. Fabian et al 2002)

  ...and what is its efficiency?

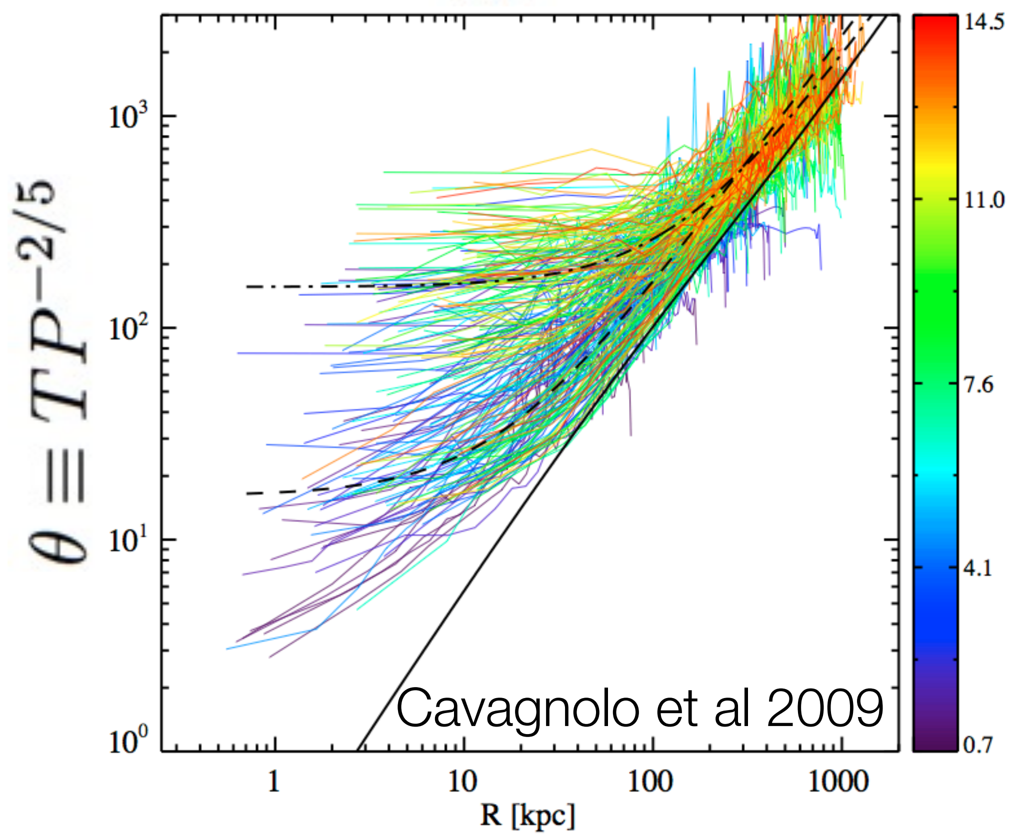
  (e.g. Chandran & Cowley 1998; Narayan & Medvedev 2001)



Conduction and convection— stability



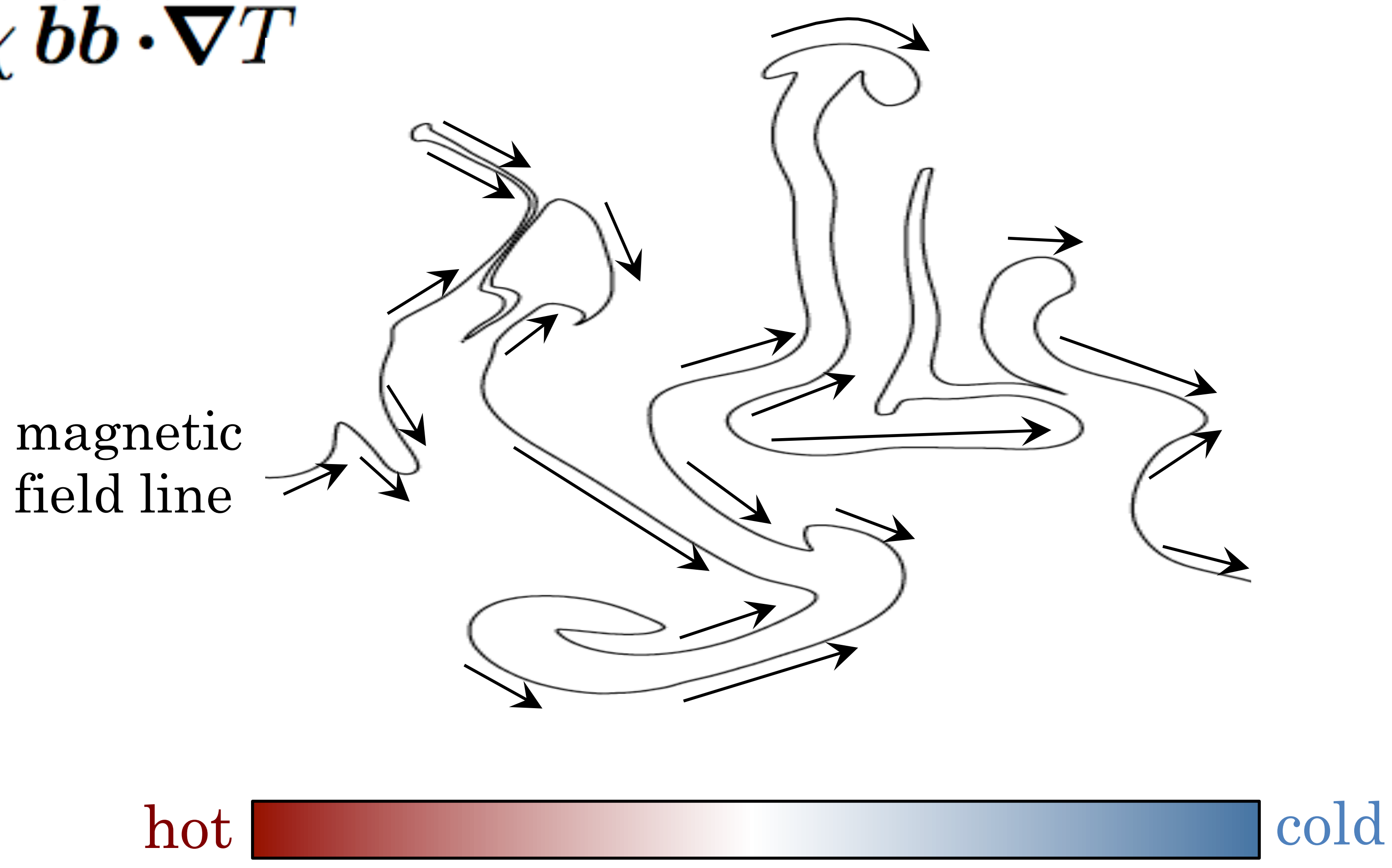
$$\frac{\mathrm{d}\ln\theta}{\mathrm{d}r} \geq 0$$



but it's a bit more subtle than this...

Heat conduction

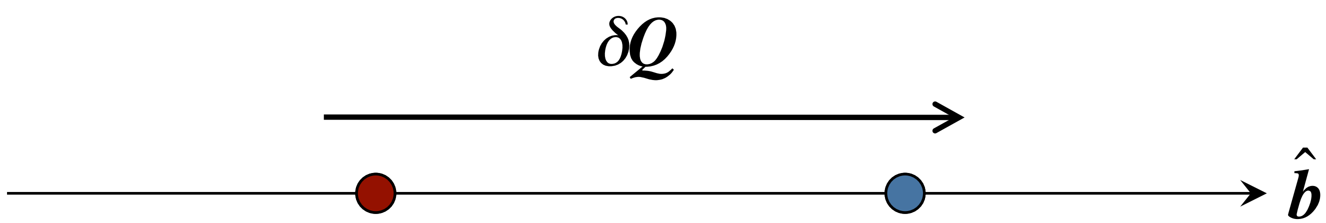
$$\boldsymbol{Q} = -\chi\, \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} T$$



$$\delta\boldsymbol{Q} = -\chi\, \boldsymbol{\nabla}\delta T \quad \text{vs.} \quad \delta\boldsymbol{Q} = -\chi\, \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla}\delta T - \chi\, \hat{\boldsymbol{b}}\,\delta\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} T - \chi\,\delta\hat{\boldsymbol{b}}\,\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} T$$

Heat conduction

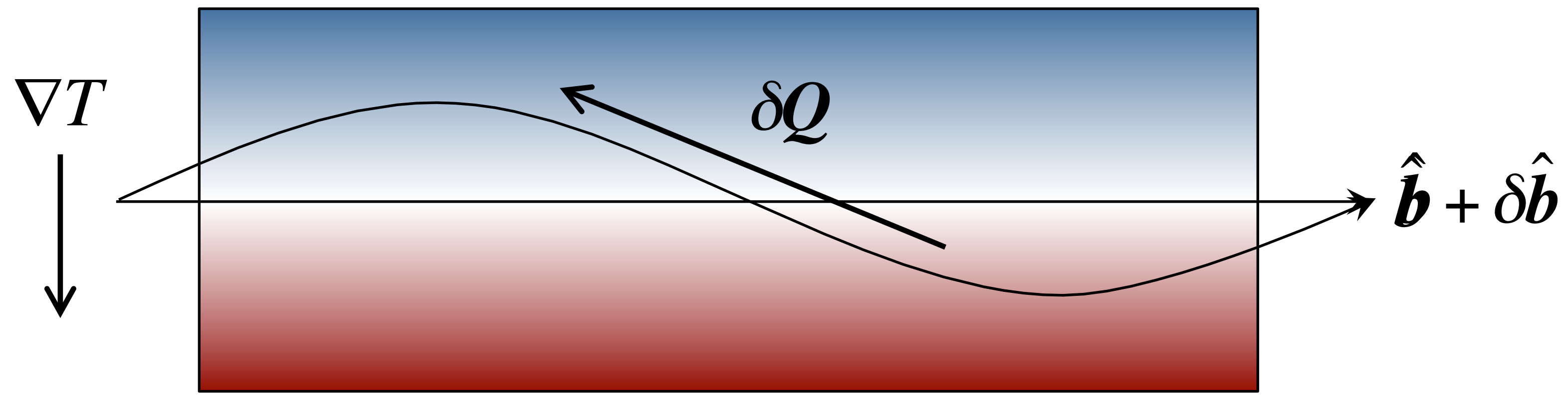
$$\delta \boldsymbol{Q} = \boxed{-\chi \, \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} \delta T} - \chi \, \hat{\boldsymbol{b}} \, \delta\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} T - \chi \, \delta\hat{\boldsymbol{b}} \, \hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} T$$



create a local temperature gradient along B,
create heat flux along B

Heat conduction

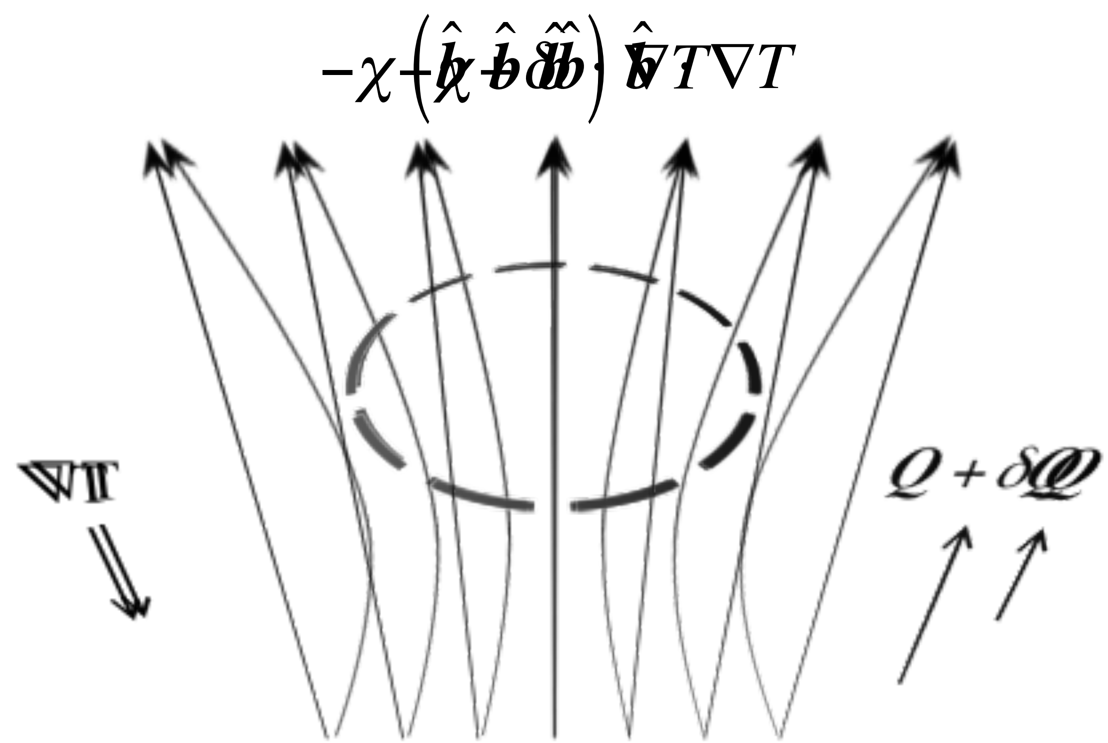
$$\delta \boldsymbol{Q} = -\chi\,\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\cdot\boldsymbol{\nabla}\delta T \boxed{-\chi\,\hat{\mathbf{b}}\,\delta\hat{\mathbf{b}}\cdot\boldsymbol{\nabla}T} - \chi\,\delta\hat{\mathbf{b}}\,\hat{\mathbf{b}}\cdot\boldsymbol{\nabla}T$$



align B with the background temperature gradient,
create heat flux along B

Heat conduction

$$\delta \boldsymbol{Q} = -\chi\, \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} \delta T - \chi\, \hat{\boldsymbol{b}}\, \delta\hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} T \boxed{- \chi\, \delta\hat{\boldsymbol{b}}\, \hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} T}$$

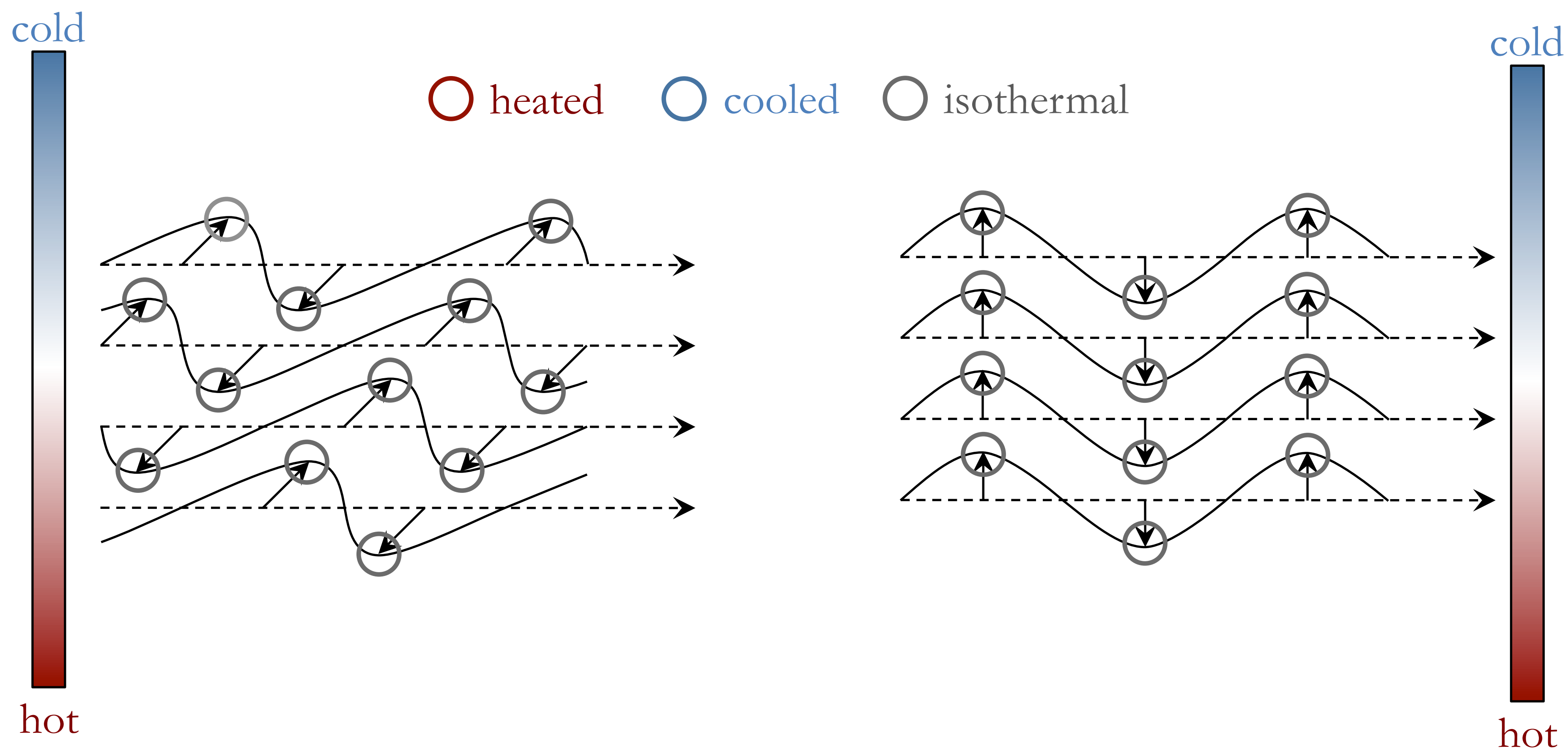


perturb B on which a heat flux is being channeled, increase/decrease that heat flux

When conduction is rapid...

$$\Delta T \simeq 2\xi_{||}\nabla_{||}T$$

i.e. compressions/rarefactions in ∇T -oriented field lines lead to heating/cooling



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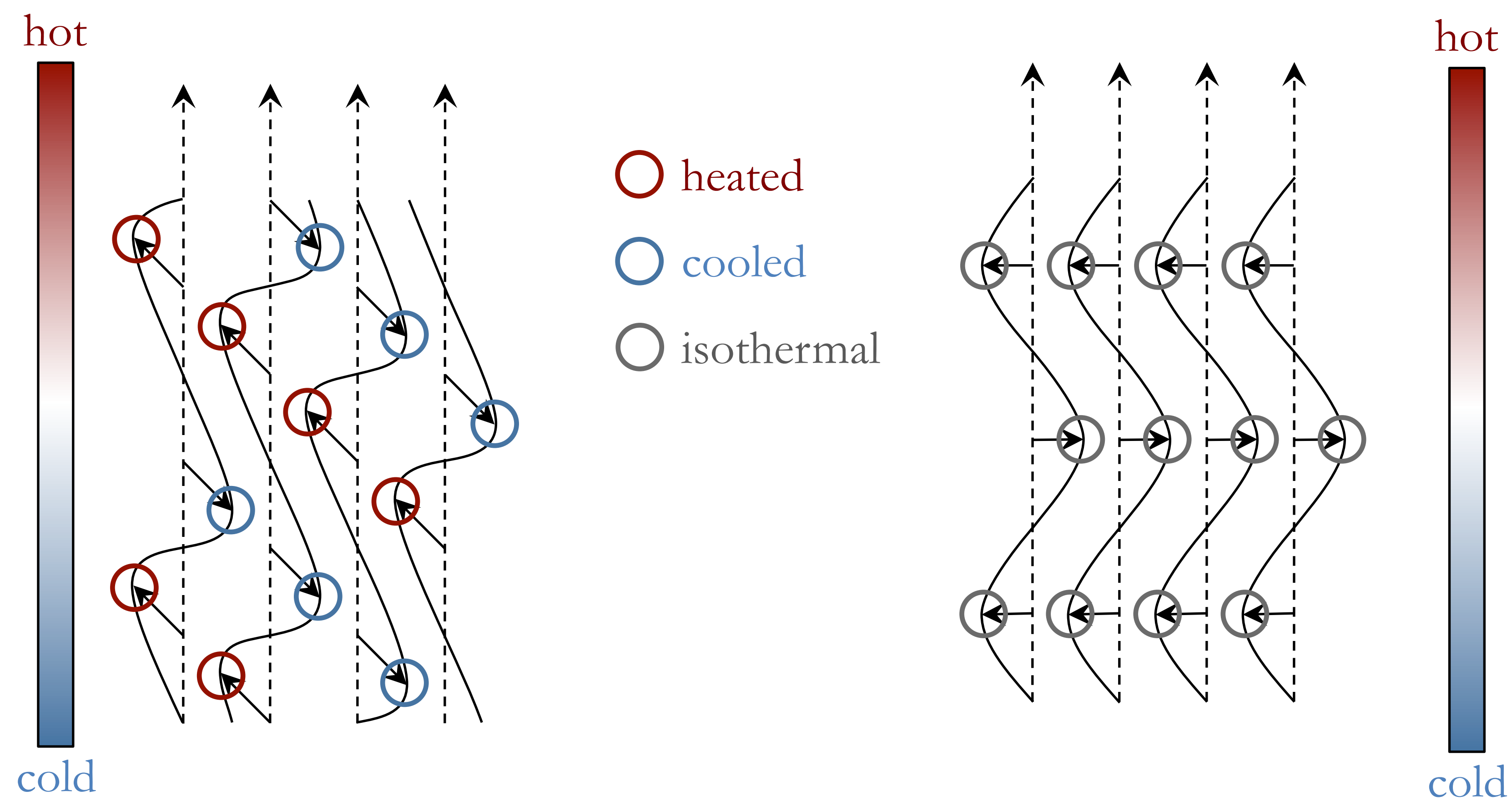
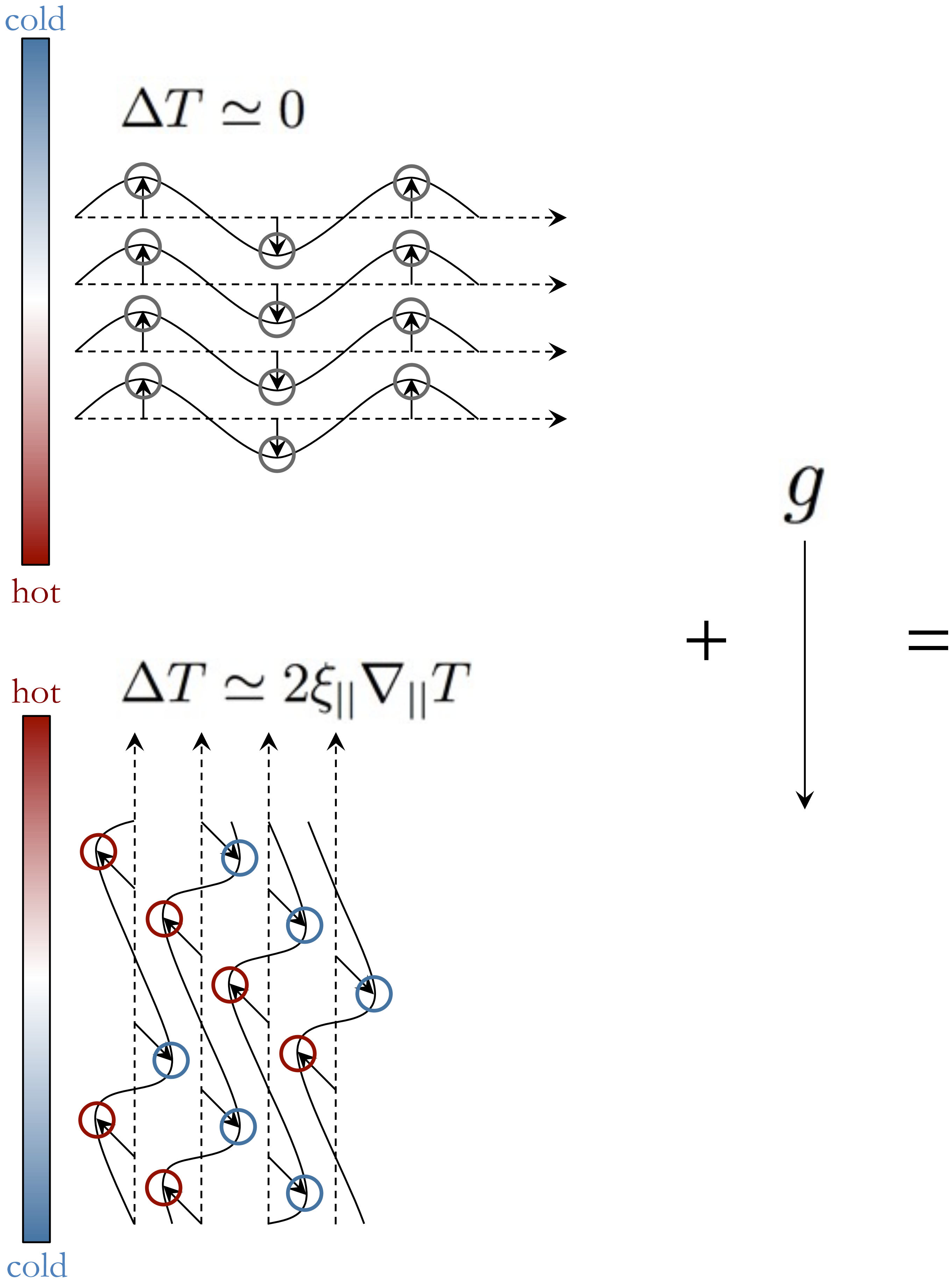


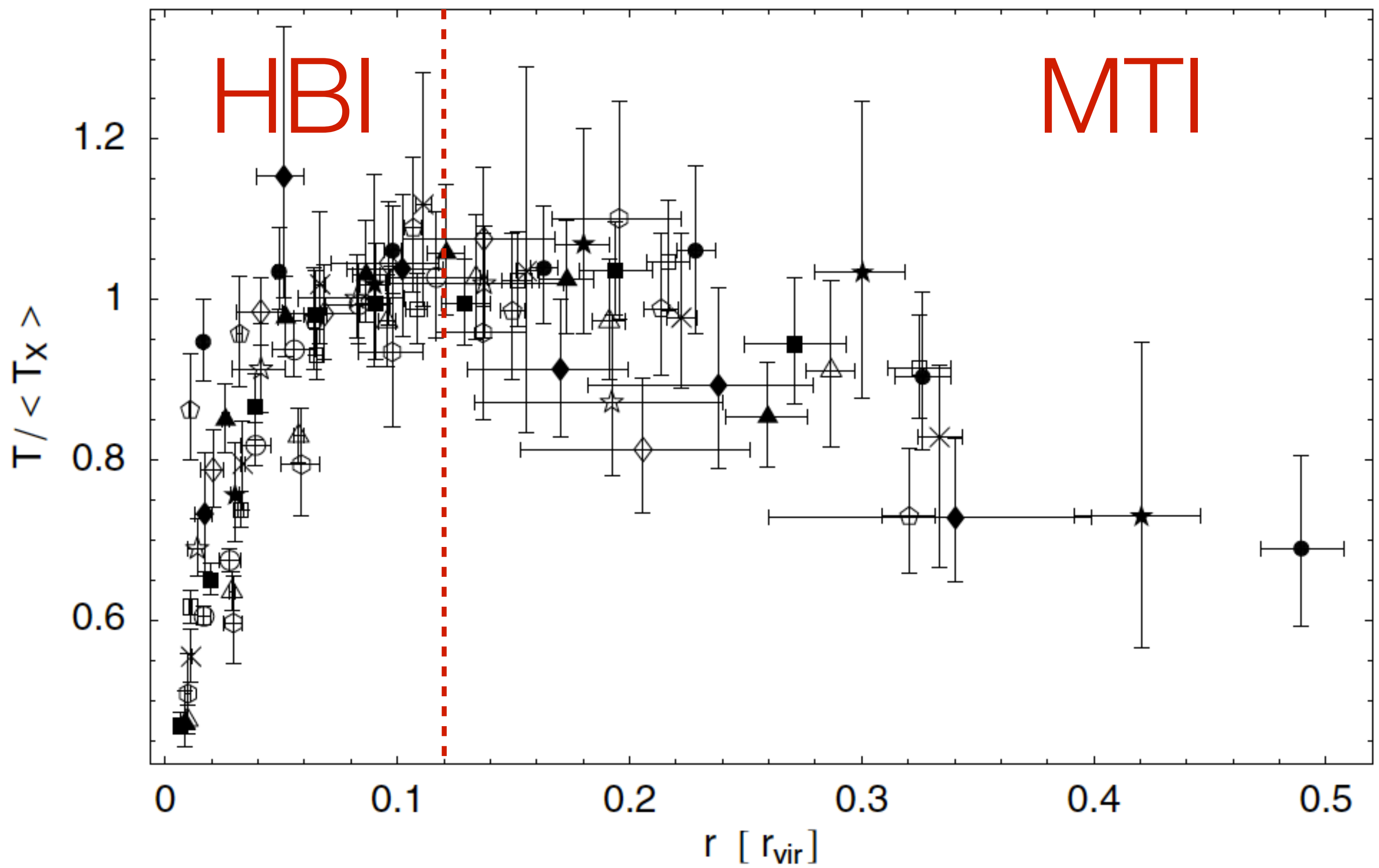


Magneto-Thermal Instability

(Balbus 2000; 2001)

Heat-flux-driven Buoyancy Instability

(Quataert 2008)



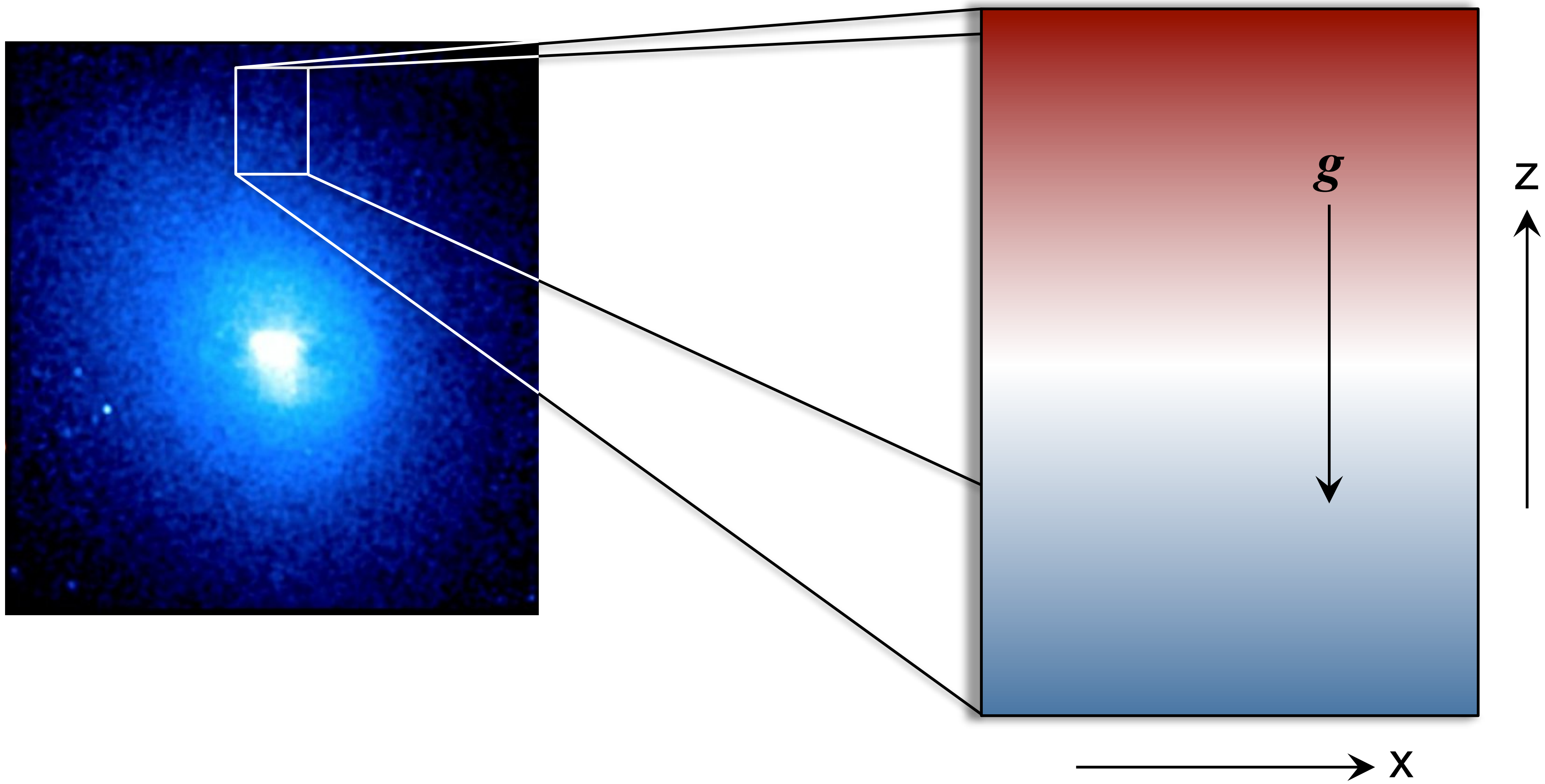
$$\boldsymbol{g}\cdot\boldsymbol{\nabla}\ln P\rho^{-\gamma} < 0 \longrightarrow \boldsymbol{g}\cdot\boldsymbol{\nabla}\ln T \neq 0$$

think by analogy:

$$\boldsymbol{g}\cdot\boldsymbol{\nabla}\ln R^4\Omega^2 < 0 \longrightarrow \boldsymbol{g}\cdot\boldsymbol{\nabla}\ln \Omega^2 < 0$$

Balbus (2001)

put a weakly collisional plasma in a gravitating, thermally stratified atmosphere



$$\boldsymbol{v} = \delta\boldsymbol{v} \qquad \boldsymbol{B} = B_{0,x}\hat{\boldsymbol{x}} + B_{0,z}\hat{\boldsymbol{z}} + \delta\boldsymbol{B} \qquad p = p_0(z) + \delta p \qquad T = T_0(z) + \delta T$$

$$\delta \propto \exp\left(\gamma t + i\boldsymbol{k}\cdot\boldsymbol{r}\right)$$

Dispersion relation (Kunz 2011)

$$-\omega_{\mathrm{visc}}\frac{k_\perp^2}{k^2} = \frac{\widetilde{\gamma}^2\left[\widetilde{\gamma}^2\left(\gamma+\omega_{\mathrm{cond}}\right)+\gamma\, g\,\frac{\mathrm{d}\ln\theta}{\mathrm{d}z}\,\frac{k_x^2+k_y^2}{k^2}+\omega_{\mathrm{cond}}\, g\,\frac{\mathrm{d}\ln T}{\mathrm{d}z}\,\frac{\mathcal{K}}{k^2}\right]}{\gamma\left[\widetilde{\gamma}^2\left(\gamma+\omega_{\mathrm{cond}}\right)+\gamma\, g\,\frac{\mathrm{d}\ln\theta}{\mathrm{d}z}\,\frac{b_x^2k_y^2}{k_\perp^2}+\omega_{\mathrm{cond}}\, g\,\frac{\mathrm{d}\ln T}{\mathrm{d}z}\,\frac{b_x^2k_y^2}{k_\perp^2}\right]}$$

$$\widetilde{\gamma}^2 \equiv \gamma^2 + \left(\boldsymbol{k}\cdot\boldsymbol{v}_{\mathbf{A}}\right)^2$$

$$\mathcal{K} \equiv (1-2b_z^2)(k_x^2+k_y^2) + 2b_xb_zk_xk_z$$

Dispersion relation (Kunz 2011)

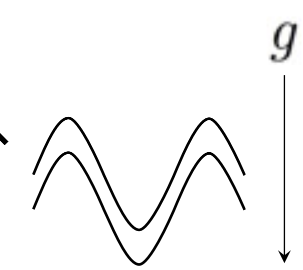
$$\omega_{\rm cond} = \omega_{\rm visc} = 0: \quad \gamma\, \widetilde{\gamma}^2 \left(\widetilde{\gamma}^2 + g \frac{\mathrm{d} \ln \theta}{\mathrm{d} z} \frac{k_x^2 + k_y^2}{k^2} \right) = 0$$

entropy mode

Alfvén wave

slow mode

buoyant response



Dispersion relation (Kunz 2011)

$$\omega_{\rm cond} = \omega_{\rm visc} = 0 : \quad \gamma\, \widetilde{\gamma}^2 \left(\widetilde{\gamma}^2 + g \frac{{\rm d} \ln \theta}{{\rm d}z} \frac{k_x^2 + k_y^2}{k^2} \right) = 0$$

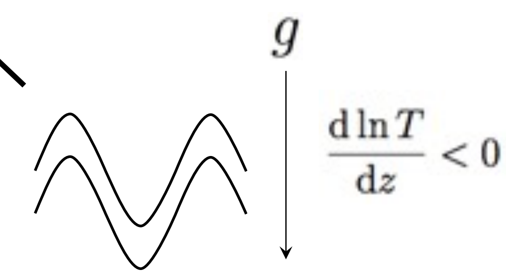
$$\omega_{\rm cond} \gg \omega_{\rm dyn} \gg \omega_{\rm visc} : \quad \widetilde{\gamma}^2 \left(\widetilde{\gamma}^2 + g \frac{{\rm d} \ln T}{{\rm d}z} \frac{\mathcal{K}}{k^2} \right) \approx 0 \qquad \gamma \approx -\omega_{\rm cond}$$

entropy mode

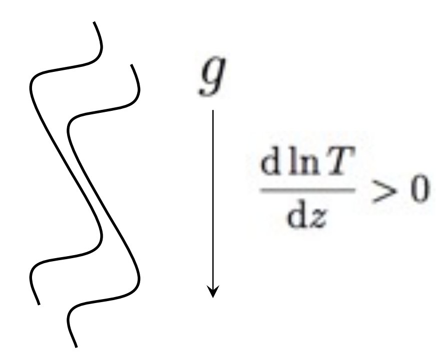
Alfvén wave

slow mode

altered
buoyant response



MTI



HBI

Dispersion relation (Kunz 2011)

$$\omega_{\rm cond} = \omega_{\rm visc} = 0 : \quad \gamma\, \widetilde{\gamma}^2 \left(\widetilde{\gamma}^2 + g \frac{{\rm d}\ln\theta}{{\rm d}z} \frac{k_x^2 + k_y^2}{k^2} \right) = 0$$

$$\omega_{\rm cond} \gg \omega_{\rm dyn} \gg \omega_{\rm visc} : \quad \widetilde{\gamma}^2 \left(\widetilde{\gamma}^2 + g \frac{{\rm d}\ln T}{{\rm d}z} \frac{\mathcal{K}}{k^2} \right) \approx 0 \qquad \gamma \approx -\omega_{\rm cond}$$

$$\omega_{\rm cond} \gg \omega_{\rm dyn} \sim \omega_{\rm visc} : \quad \widetilde{\gamma}^2 \left(\widetilde{\gamma}^2 + \gamma\, \omega_{\rm visc} \frac{k_\perp^2}{k^2} + g \frac{{\rm d}\ln T}{{\rm d}z} \frac{\mathcal{K}}{k^2} \right) \approx -\gamma\, \omega_{\rm visc}\, g \frac{{\rm d}\ln T}{{\rm d}z} \frac{b_x^2 k_y^2}{k^2}$$

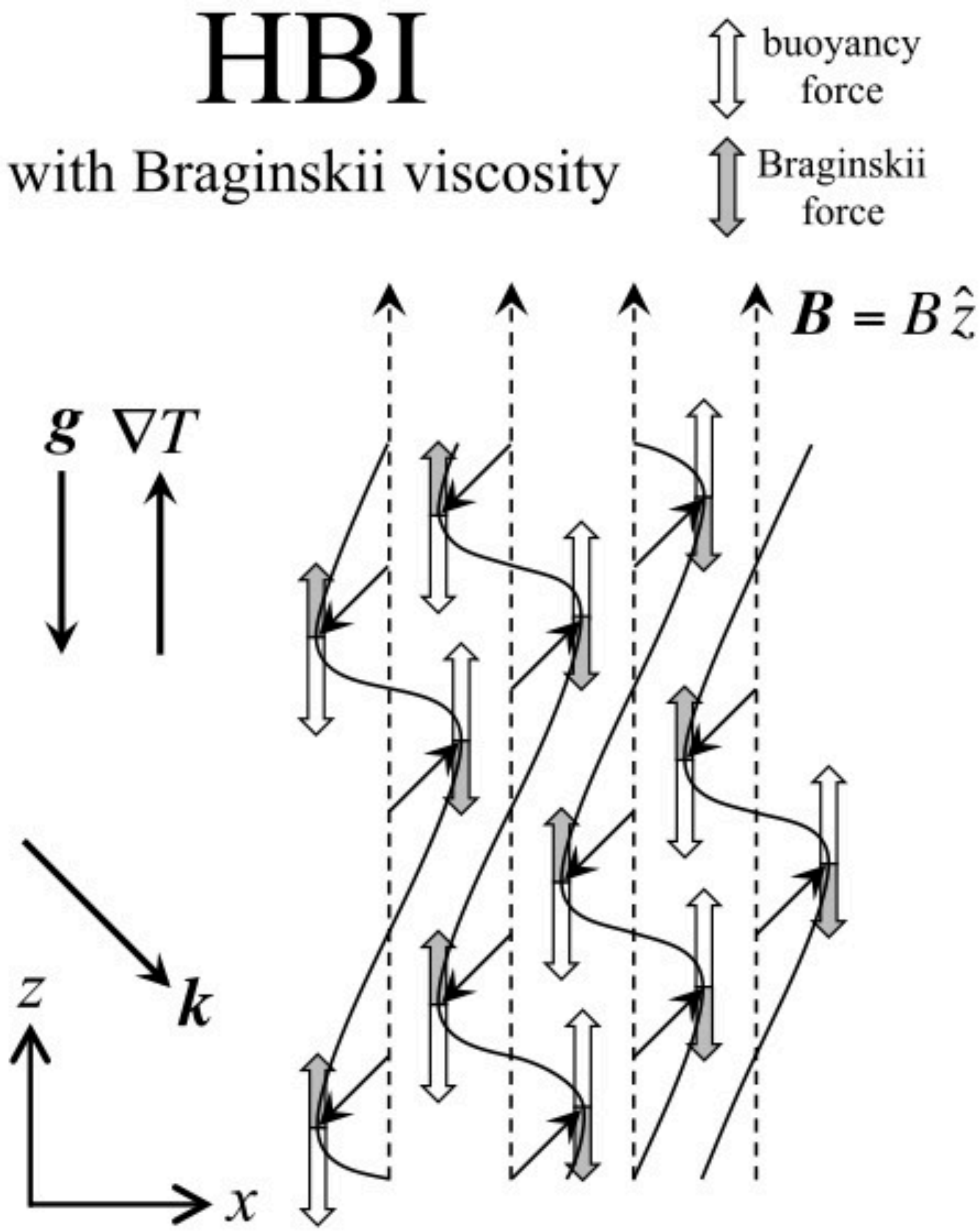
Alfvén wave

slow mode

anisotropic viscous damping

altered buoyant response

viscous coupling of slow & Alfvén modes



$$\Delta T \simeq 2\xi_{||}\nabla_{||}T$$

field-line compressions cause changes in temperature

but motions that cause field-line compressions are viscously damped

Dispersion relation (Kunz 2011)

$$\omega_{\rm cond} = \omega_{\rm visc} = 0: \quad \gamma\,\widetilde{\gamma}^2\left(\widetilde{\gamma}^2 + g\frac{{\rm d}\ln\theta}{{\rm d}z}\frac{k_x^2+k_y^2}{k^2}\right) = 0$$

$$\omega_{\rm cond} \gg \omega_{\rm dyn} \gg \omega_{\rm visc}: \quad \widetilde{\gamma}^2\left(\widetilde{\gamma}^2 + g\frac{{\rm d}\ln T}{{\rm d}z}\frac{\mathcal{K}}{k^2}\right) \approx 0 \qquad \gamma \approx -\omega_{\rm cond}$$

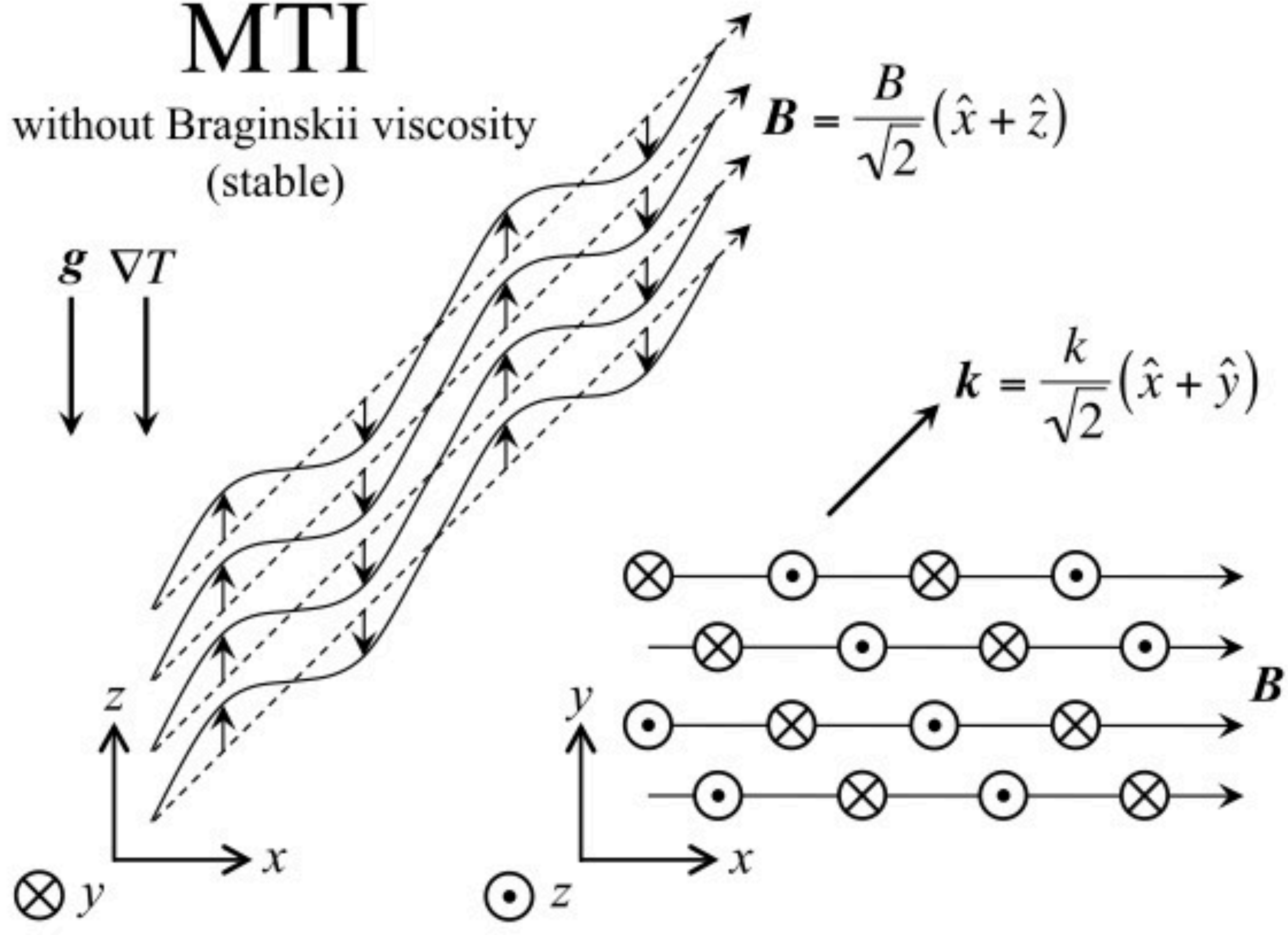
$$\omega_{\rm cond} \gg \omega_{\rm dyn} \sim \omega_{\rm visc}: \quad \widetilde{\gamma}^2\left(\widetilde{\gamma}^2 + \gamma\,\omega_{\rm visc}\frac{k_\perp^2}{k^2} + g\frac{{\rm d}\ln T}{{\rm d}z}\frac{\mathcal{K}}{k^2}\right) \approx -\gamma\,\omega_{\rm visc}\,g\frac{{\rm d}\ln T}{{\rm d}z}\frac{b_x^2k_y^2}{k^2}$$

$$\omega_{\rm cond} \gg \omega_{\rm visc} \gg \omega_{\rm dyn}: \quad \widetilde{\gamma}^2 \approx -g\frac{{\rm d}\ln T}{{\rm d}z}\frac{b_x^2k_y^2}{k_\perp^2}$$

(Alfvénic MTI)

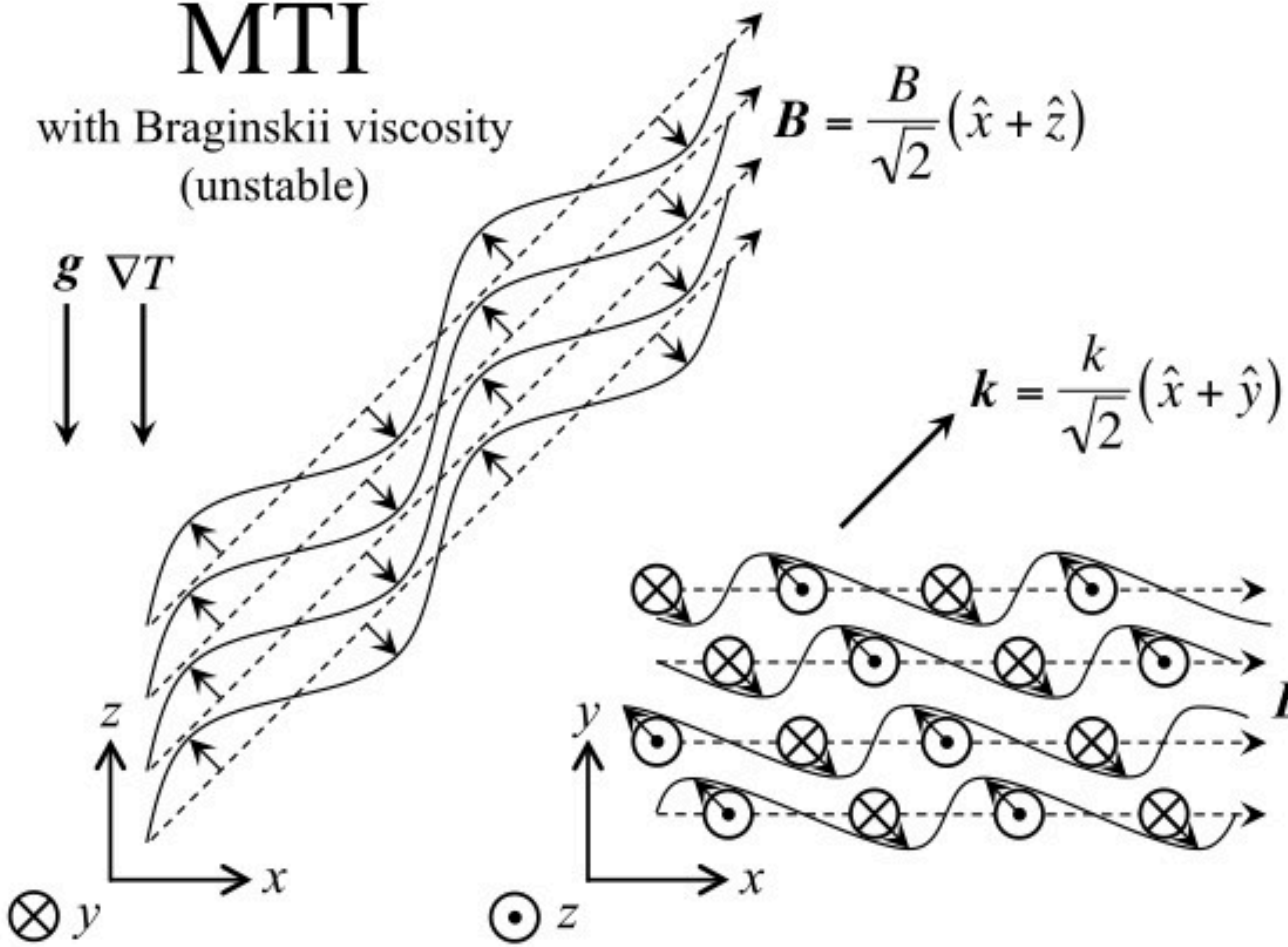
MTI

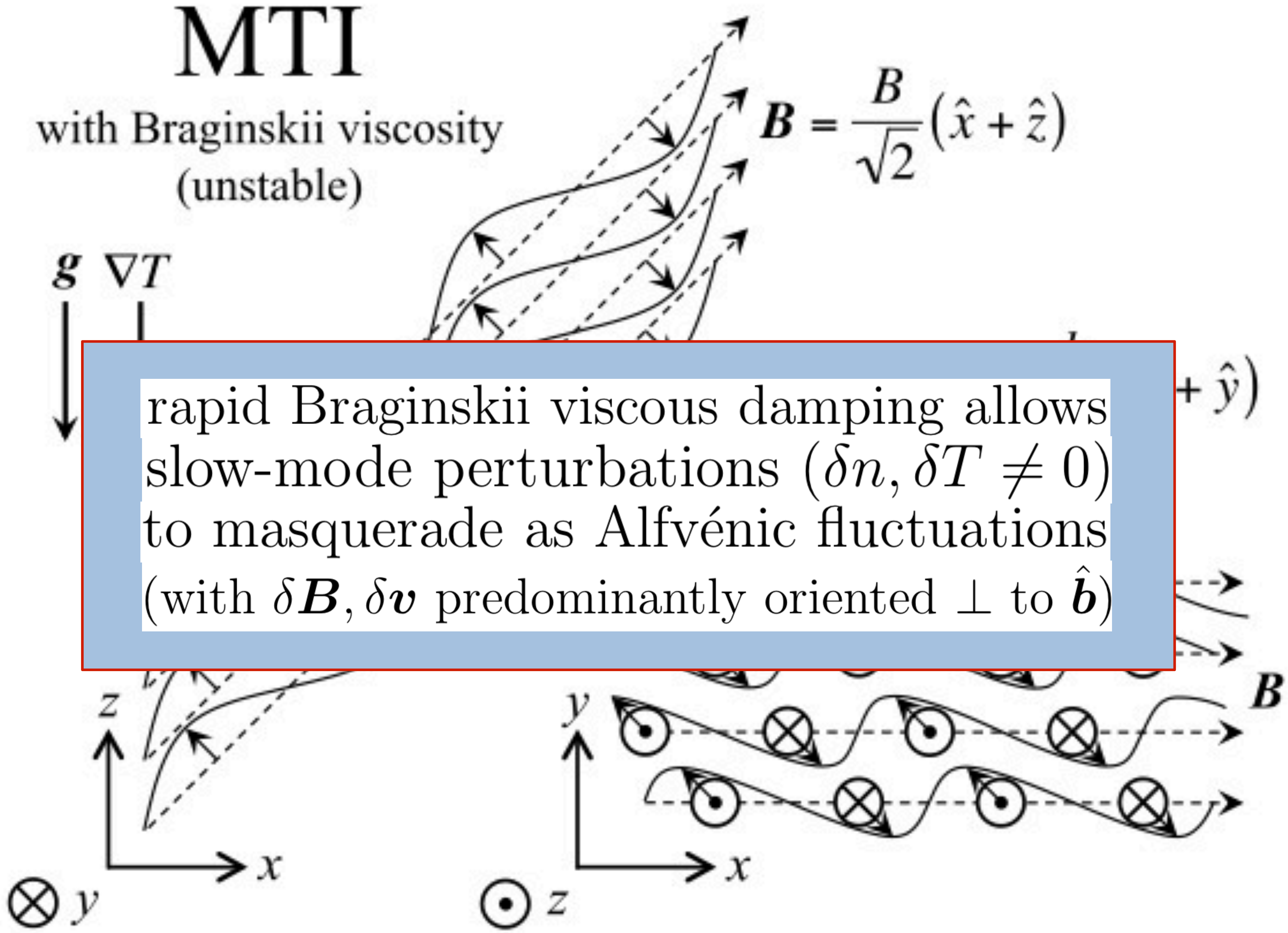
without Braginskii viscosity
(stable)



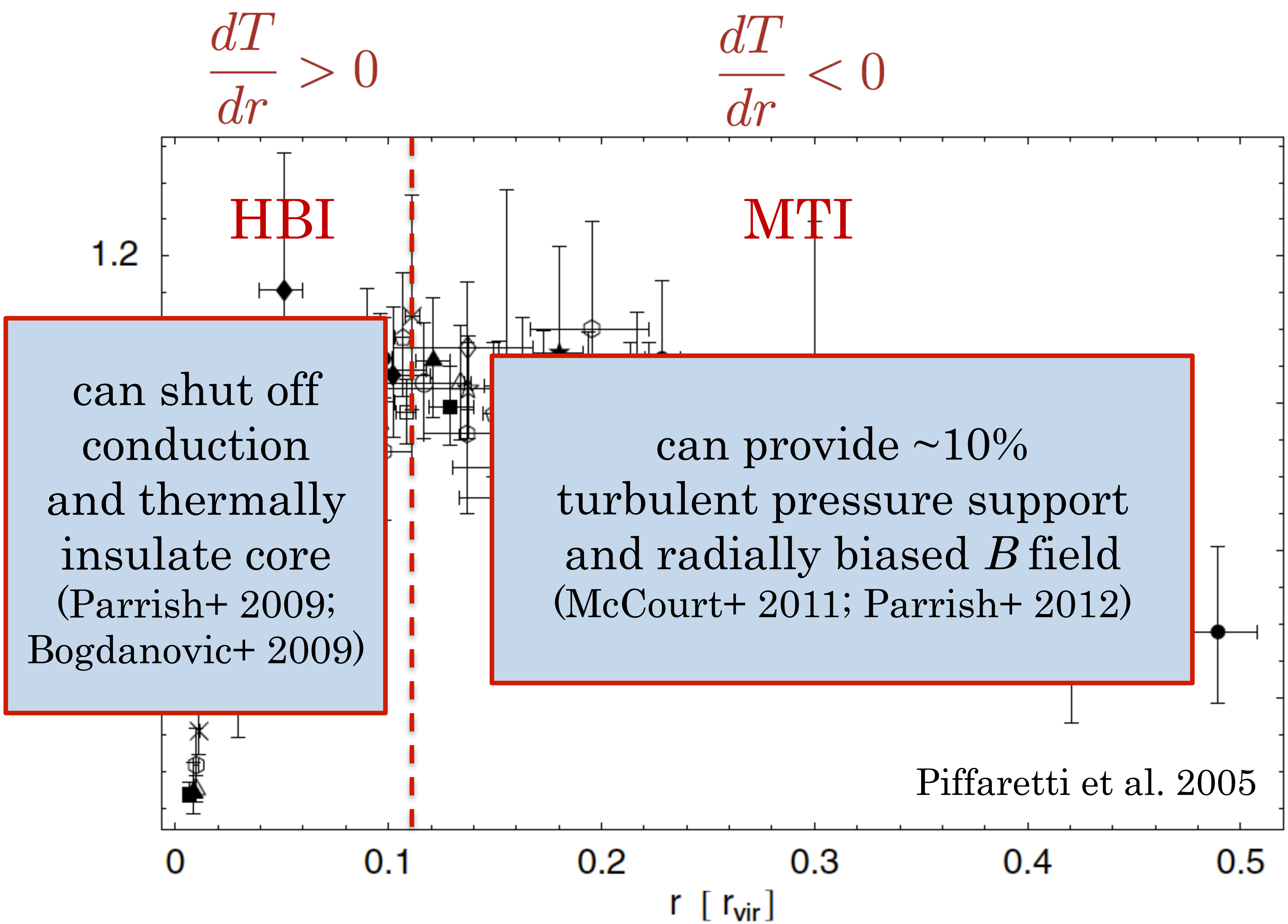
MTI

with Braginskii viscosity
(unstable)





rapid Braginskii viscous damping allows slow-mode perturbations ($\delta n, \delta T \neq 0$) to masquerade as Alfvénic fluctuations (with $\delta\boldsymbol{B}, \delta\boldsymbol{v}$ predominantly oriented $\perp$ to $\hat{\boldsymbol{b}}$)

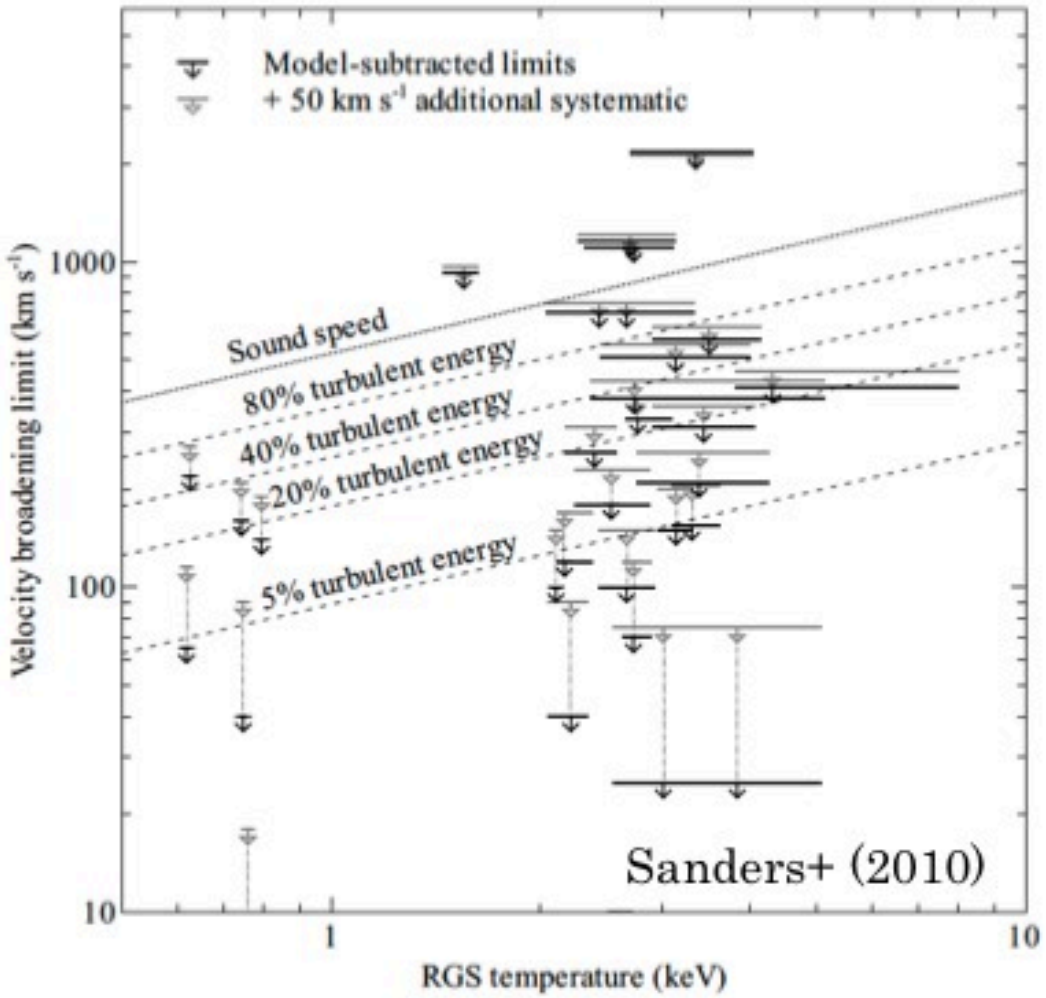

$\frac{dT}{dr} > 0$
$\frac{dT}{dr} < 0$
HBI
MTI
1.2
can shut off conduction and thermally insulate core
(Parrish+ 2009; Bogdanovic+ 2009)
can provide ~10% turbulent pressure support and radially biased B field
(McCourt+ 2011; Parrish+ 2012)
Piffaretti et al. 2005
0
0.1
0.2
0.3
0.4
0.5
r [r_{vir}]

This is all linear theory,
which means a lot...

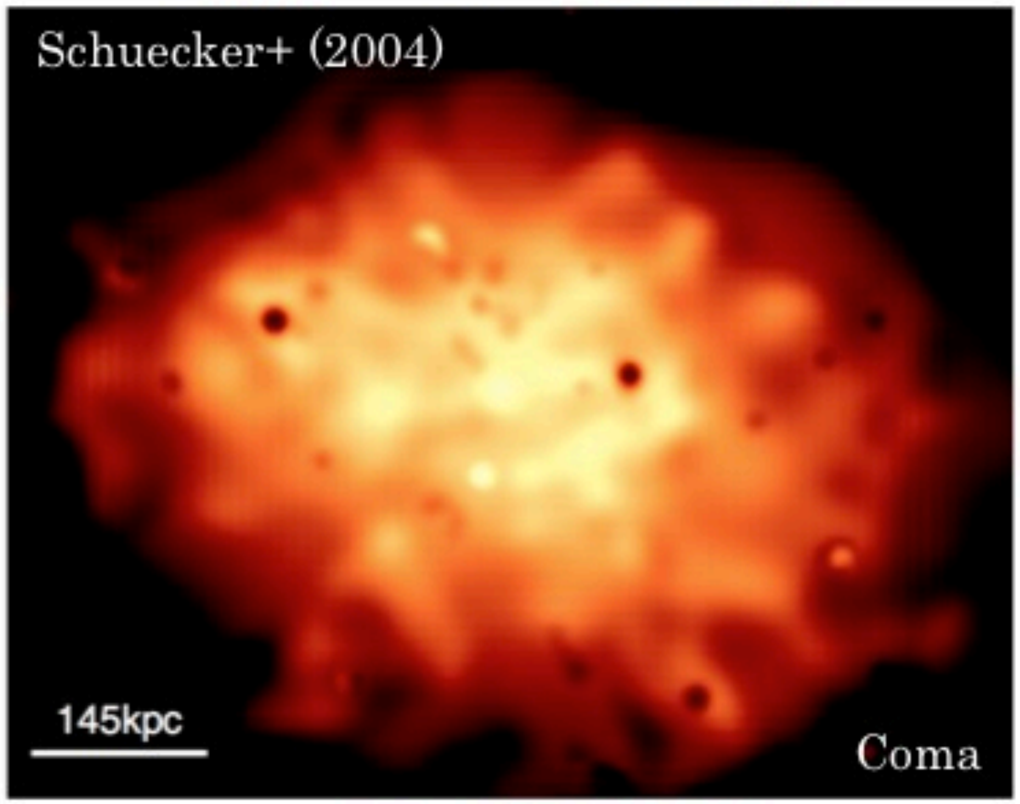
...but only for ~100 Myr.

ICM is turbulent

15 clusters with $\mathcal{M}_{\rm turb} \lesssim 0.2$



$\ell_{\rm turb} \sim 10 - 100$ kpc



Pressure anisotropy

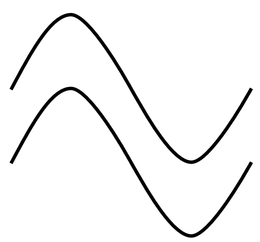
$$\frac{p_\perp - p_{||}}{p} \sim \frac{u}{v_{\rm th}} \frac{\lambda_{\rm mfp}}{\ell} \sim \text{few} \times 10^{-2}$$

$$\frac{1}{\beta} \sim \text{few} \times 10^{-2}$$

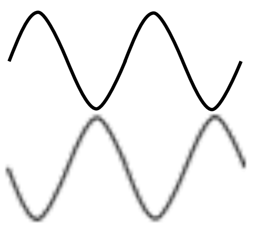
$$\frac{D\boldsymbol{u}_i}{Dt} = -\frac{1}{m_i n_i}\nabla\cdot\left[\mathsf{I}\left(p_\perp + \frac{B^2}{8\pi}\right) - \hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\left(p_\perp - p_{||} + \frac{B^2}{4\pi}\right)\right] + \boldsymbol{g}$$

↑ modifies magnetic tension

When $p_\perp - p_{||} < -\frac{B^2}{4\pi}$, Alfvén waves are FIREHOSE unstable.
growth time ~1 hr, wavelength ~10–100 npc

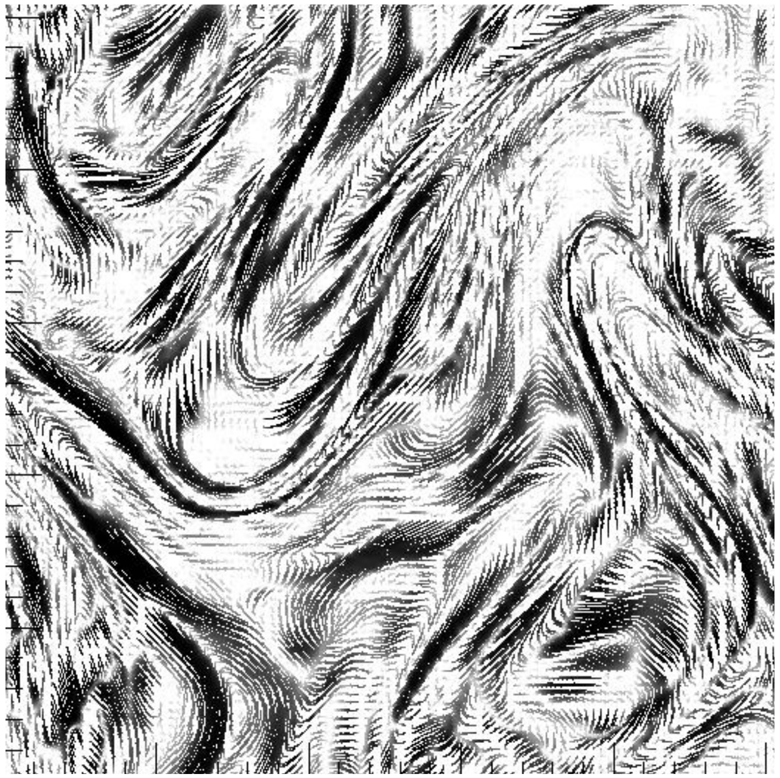


When $p_\perp - p_{||} > \frac{B^2}{8\pi}$, slow modes are MIRROR unstable.
growth time ~100 hr, wavelength ~10^2–10^3 npc



TRY CHANGING FIELD STRENGTH
AND EVERYTHING EXPLODES

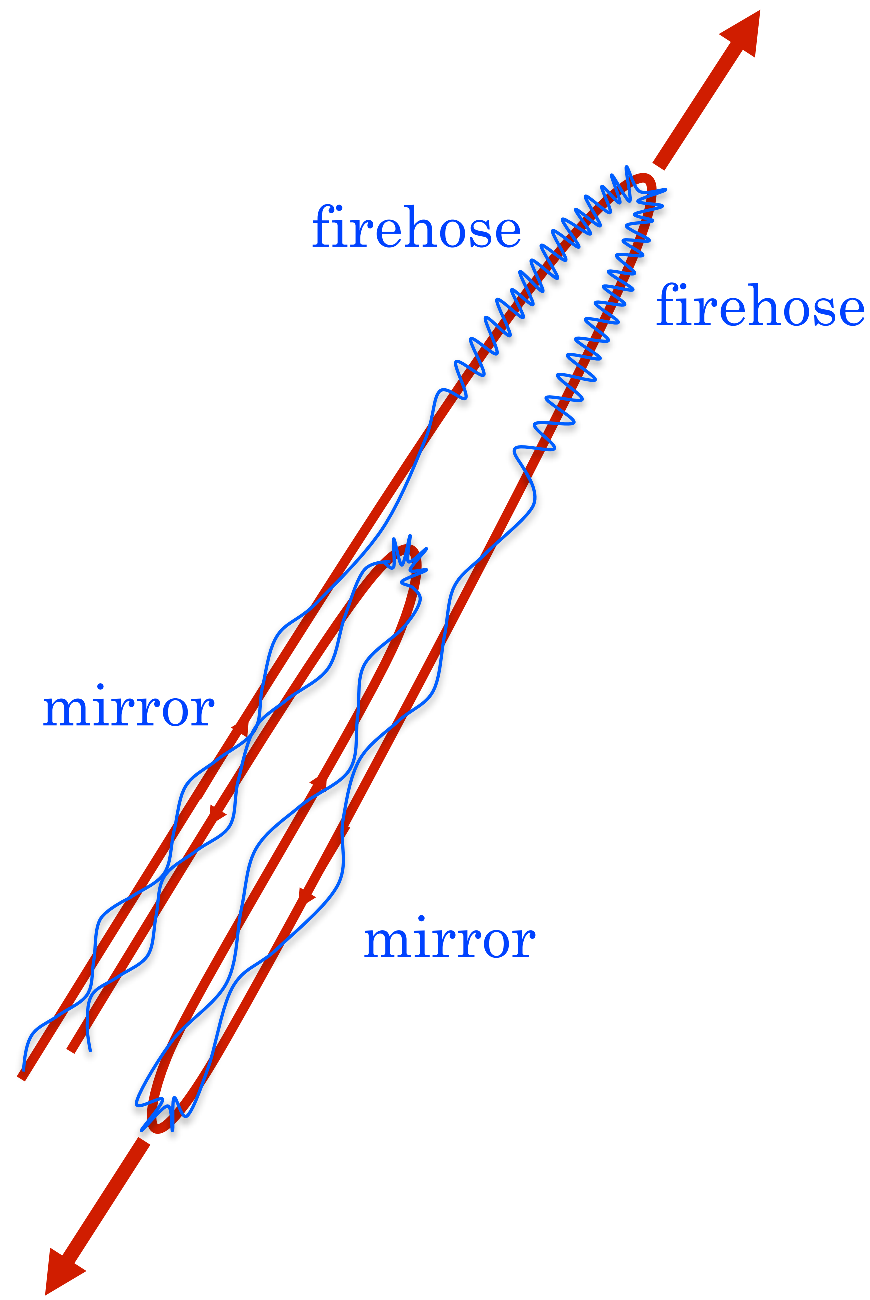
Where do they occur?



Typical structure of magnetic fields generated by turbulence from MHD simulations with (isotropic) Pm >> 1
Schekochihin+ (2004)

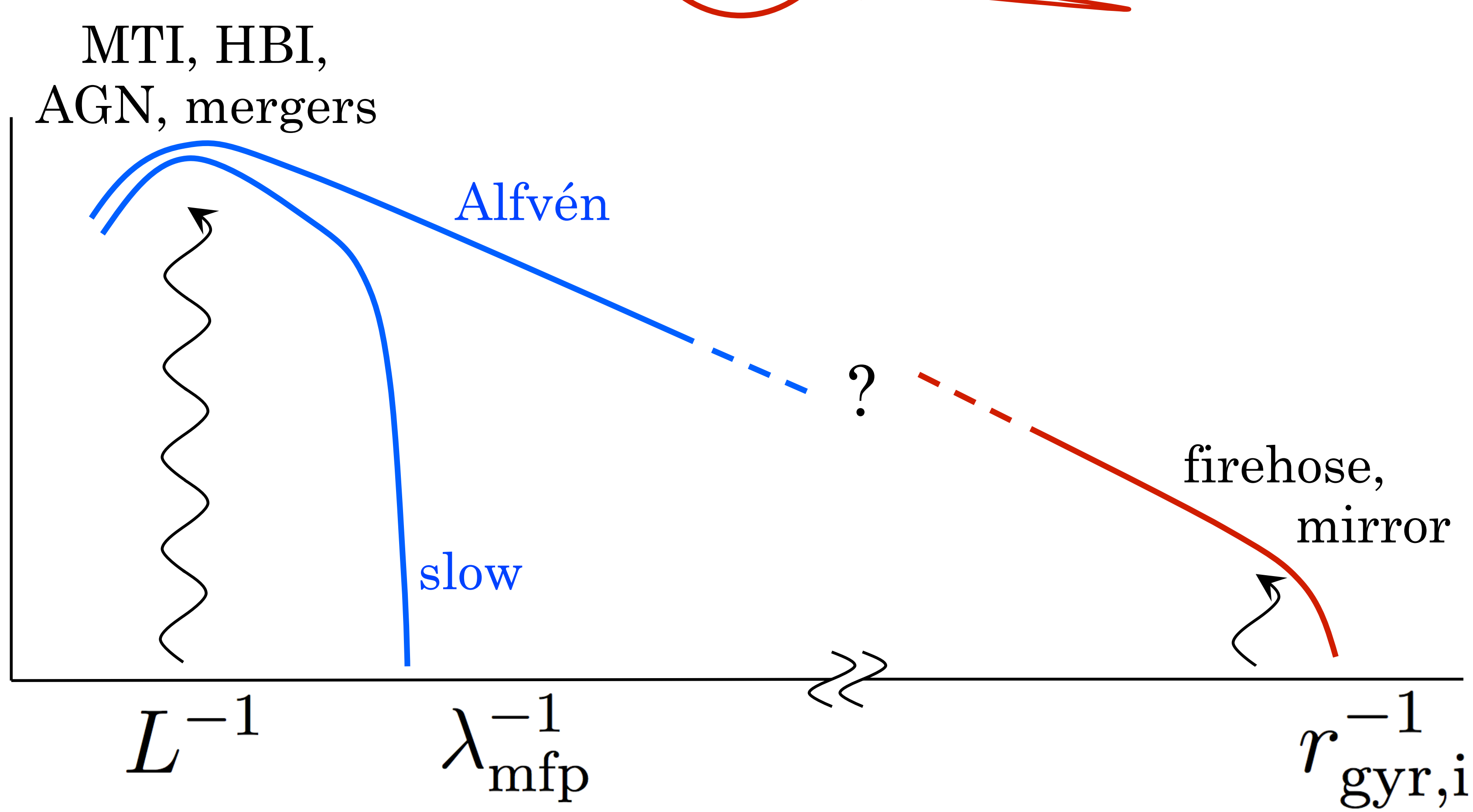
$$\ell_\perp \ll \ell_{||} \sim \ell_{\rm visc}$$

if weakly collisional with Pm >> 1:



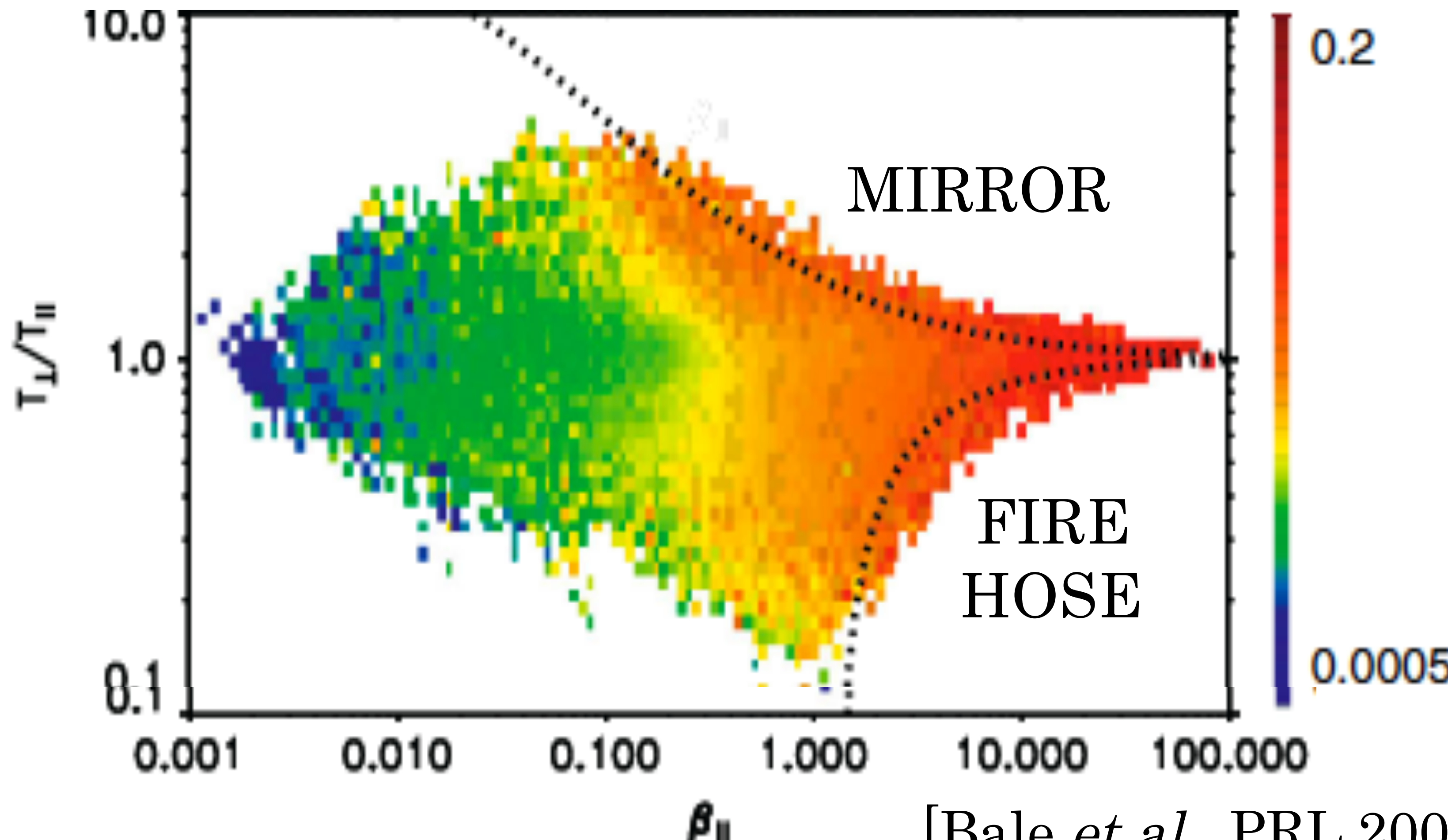
Do microinstabilities occur in ICM?

~10²–10⁴ (?) → $\beta \gtrsim \frac{\ell}{\lambda_{\rm mfp}} \frac{v_{\rm th}}{u}$? ← ~2–5 (?), ~10–100 (?)



What do these microinstabilities do?

Solar Wind:



[Bale *et al.*, PRL 2009]

perfect opportunity for synergy between space and astrophysics

How do they go marginal?

Option #1:

$$\frac{\mathrm{d}\ln B_0}{\mathrm{d}t} \text{ “}+\text{” } \begin{array}{ll} \text{firehose} & \dfrac{1}{2}\dfrac{\mathrm{d}}{\mathrm{d}t}\dfrac{\overline{|\delta \boldsymbol{B}_\perp|^2}}{B_0^2} \\ \text{mirror} & -\dfrac{\partial}{\partial t}\left(\dfrac{\overline{|\delta B_{||}|}}{B_0}\right)^{3/2} \end{array} \Longrightarrow \left|\frac{p_\perp - p_{||}}{p}\right| \to \sim \frac{1}{\beta}$$

How do they go marginal?

Option #1:

rate-of-strain is limited
(in a sense, **more** viscosity)

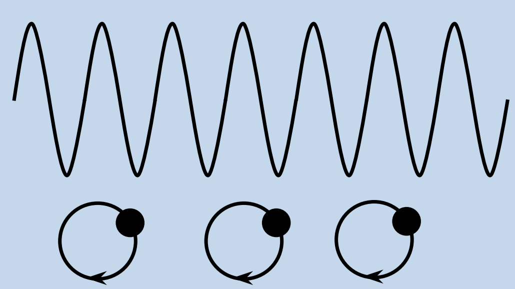
How do they go marginal?

Option #1:

rate-of-strain is limited
(in a sense, **more** viscosity)

Option #2:

$$\frac{\mathrm{d}\ln B_0}{\mathrm{d}t}$$



break mu

$$\Longrightarrow \left|\frac{p_\perp - p_{||}}{p}\right| \rightarrow \sim \frac{1}{\beta}$$

How do they go marginal?

Option #1:

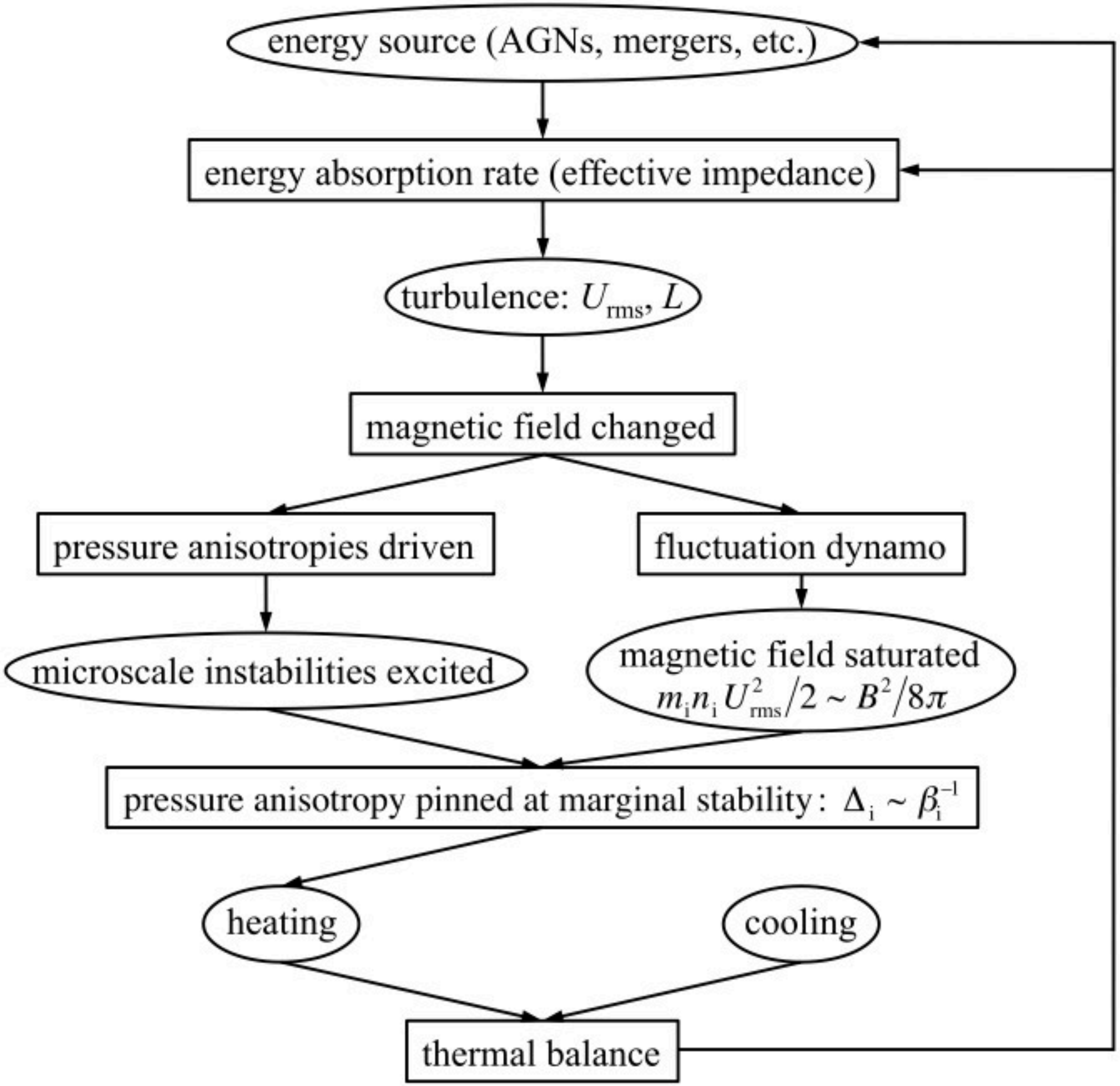
rate-of-strain is limited
(in a sense, **more** viscosity)

Option #2:

effective collisionality is enhanced
(in a sense, **less** viscosity)

Viscous heating

(done on board — see Kunz et al 2011)


energy source (AGNs, mergers, etc.)
energy absorption rate (effective impedance)
turbulence: U_{rms}, L
magnetic field changed
pressure anisotropies driven
fluctuation dynamo
microscale instabilities excited
magnetic field saturated
$m_i n_i U_{rms}^2/2 \sim B^2/8\pi$
pressure anisotropy pinned at marginal stability: $\Delta_i \sim \beta_i^{-1}$
heating
cooling
thermal balance