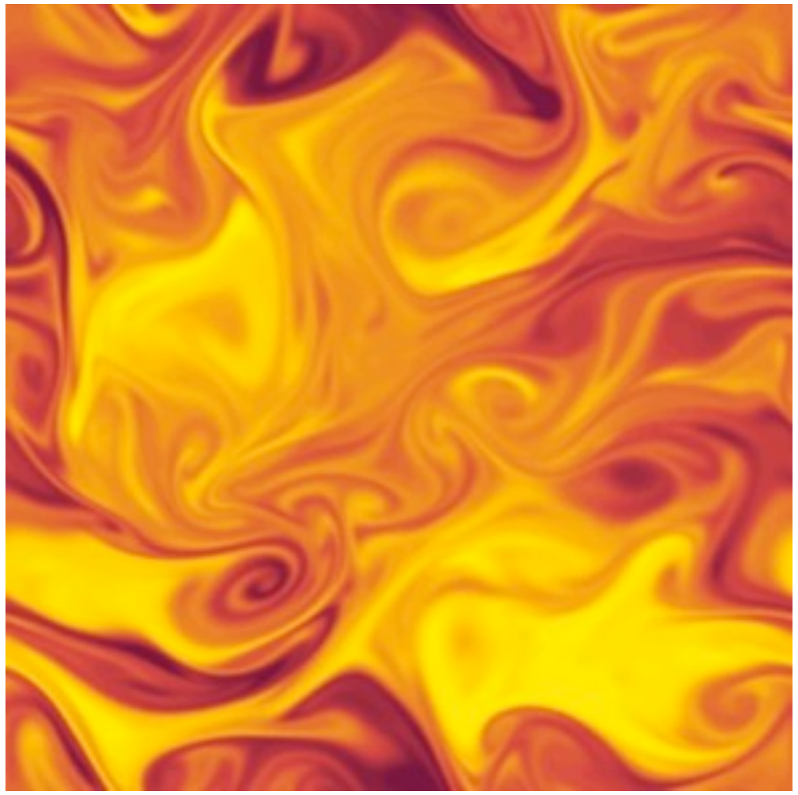
 

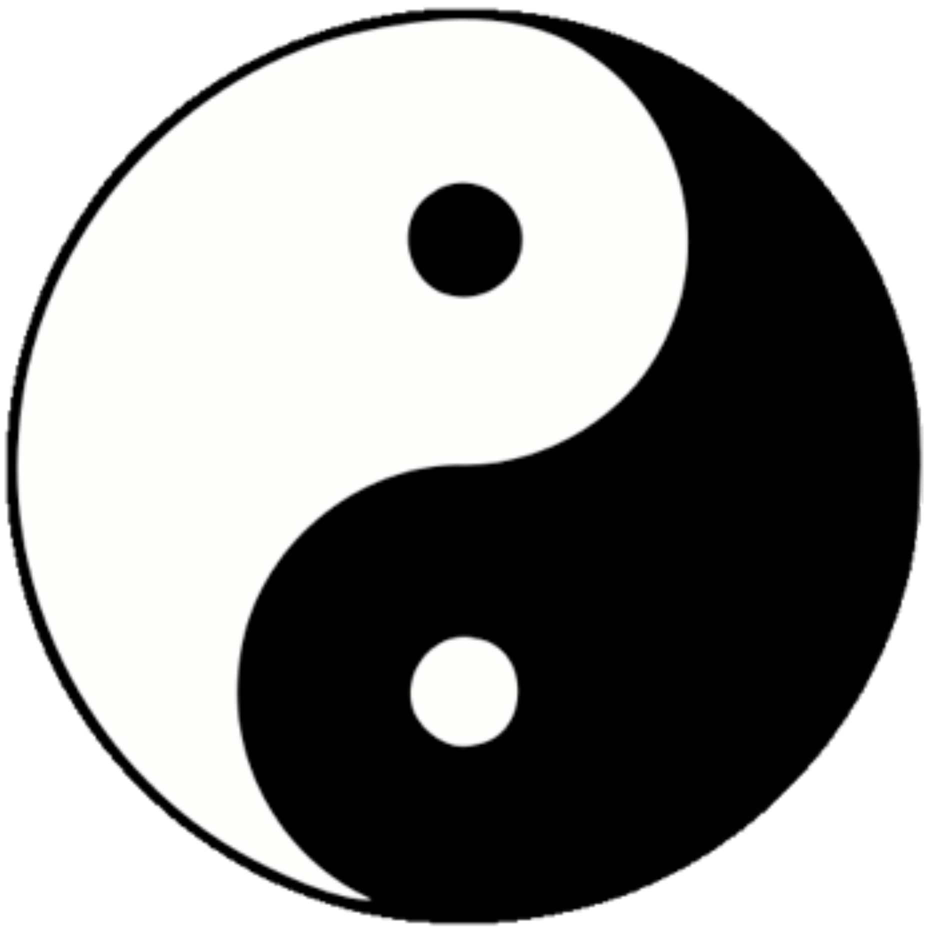
Turbulence and Conduction in Galaxy Clusters

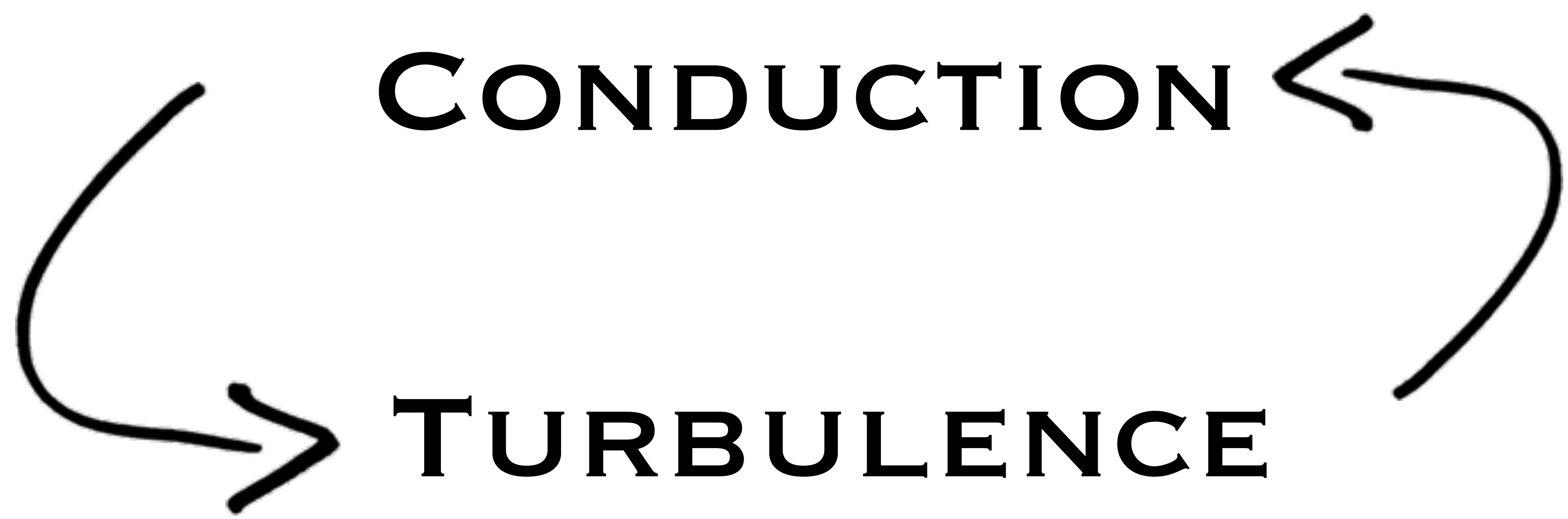
Peng Oh (UCSB)

Co-Conspirator

Comrade Ruszkowski

The Tao of Heat Transport



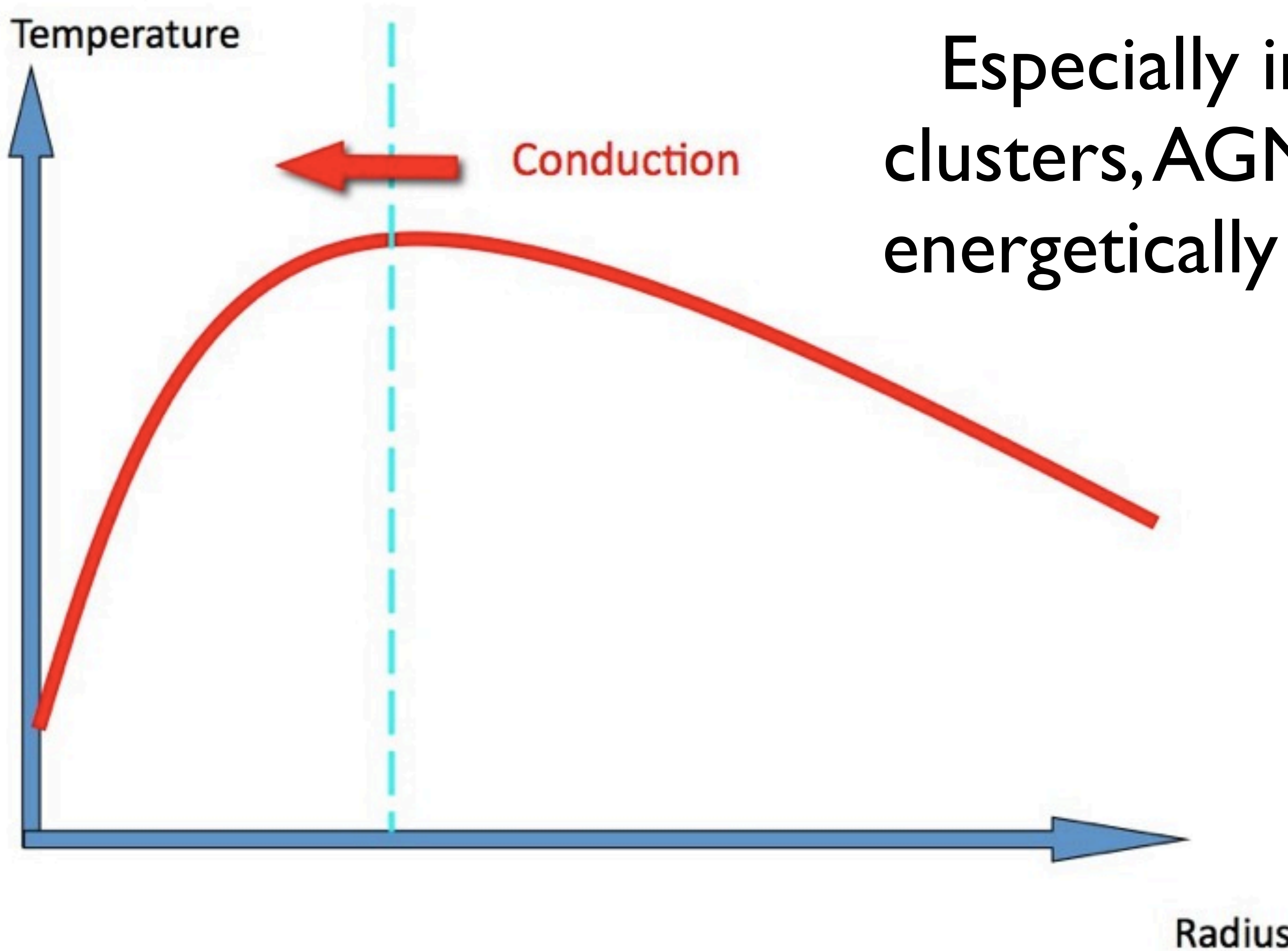


Shaken and Stirred: Turbulence and Conduction in Clusters

Ruszkowski & Oh, 2010, ApJ, 713, 1332

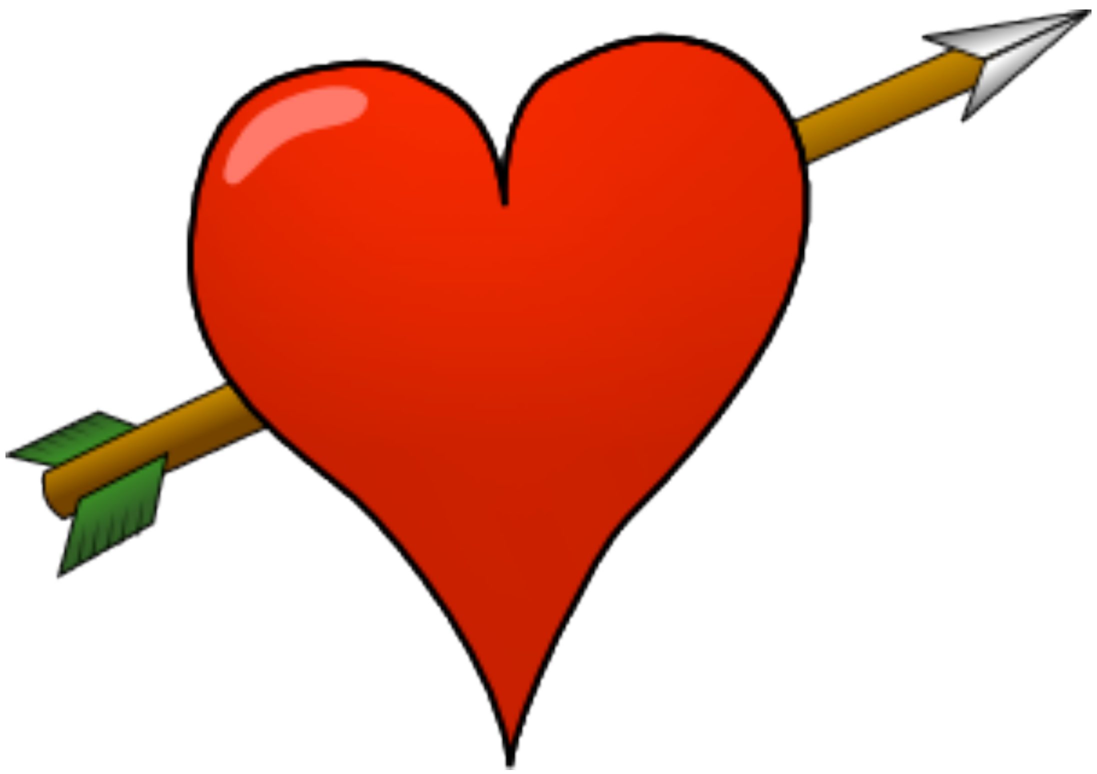
Also Parrish et al (2010)

Thermal Conduction can supply heat to cool core



Especially in massive clusters, AGN heating is energetically insufficient

Conduction is a fickle lover



Cluster becomes isothermal

Cooling catastrophe

There's a thin line between love and hate...

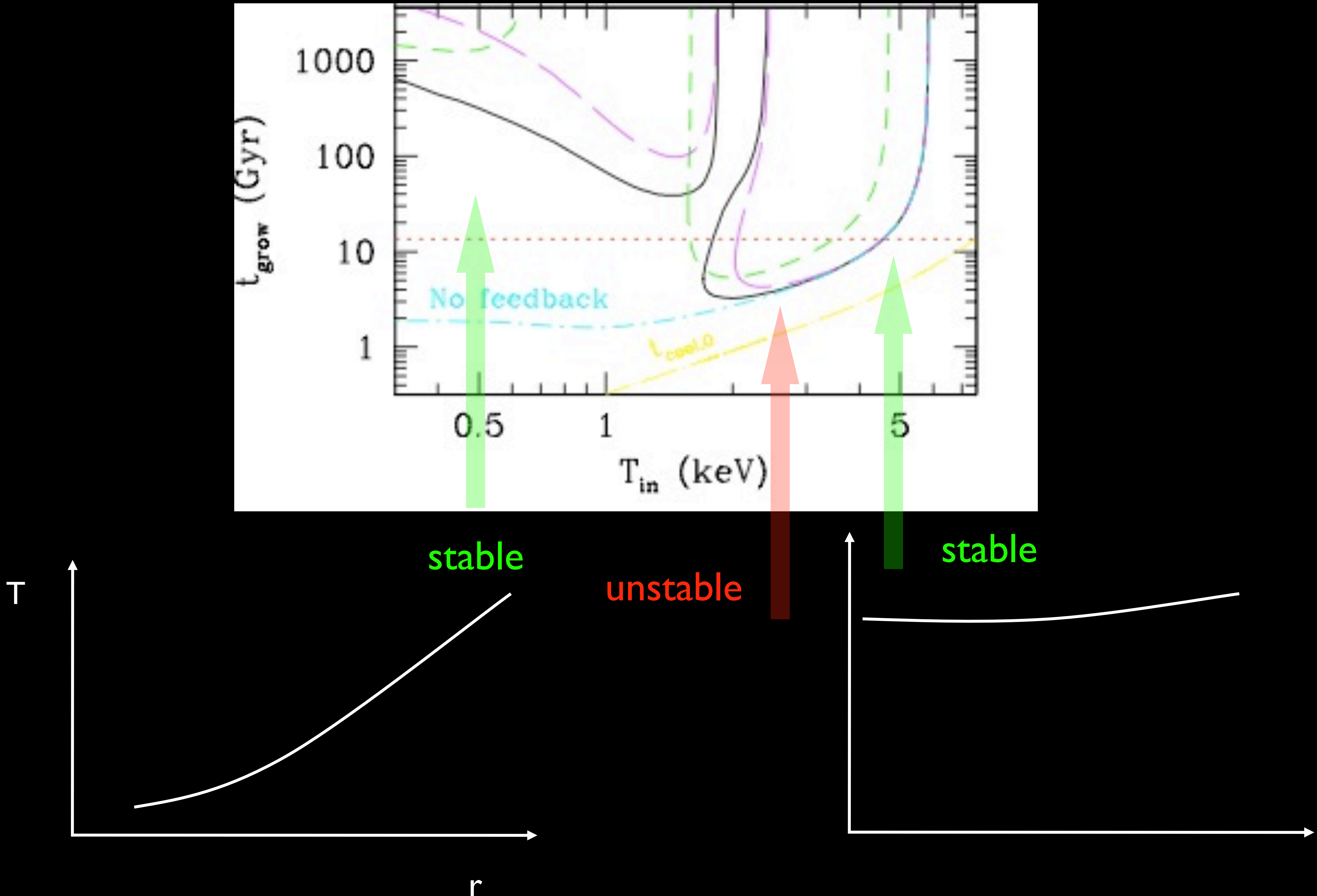
Use global stability analysis to understand

'Pick any two'

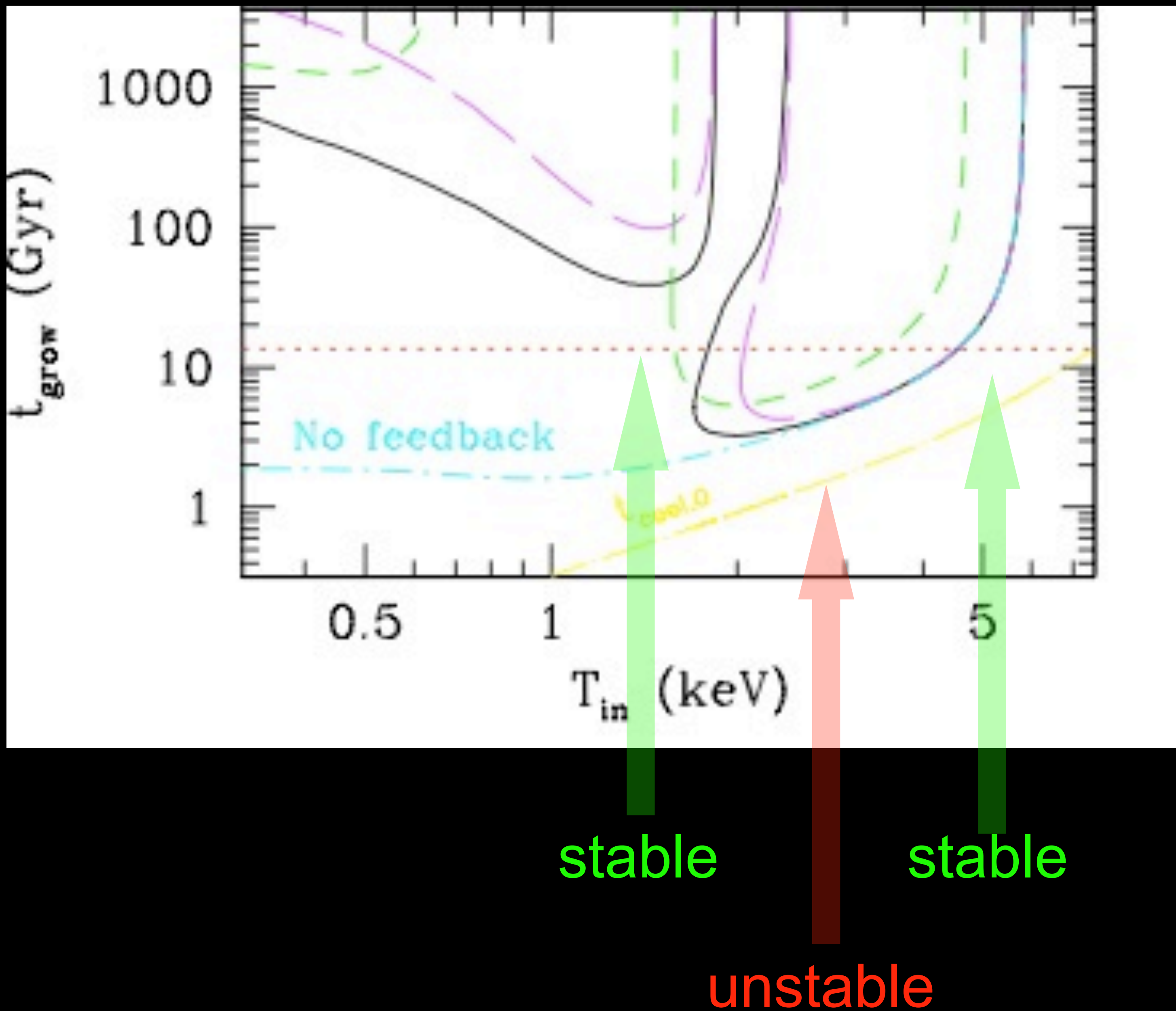
Semi-analytic study: Explore parameter space quickly

Set up equilibrium model, then study globally unstable modes

Guo, Oh & Ruszkowski (2008)



Stability is bimodal!

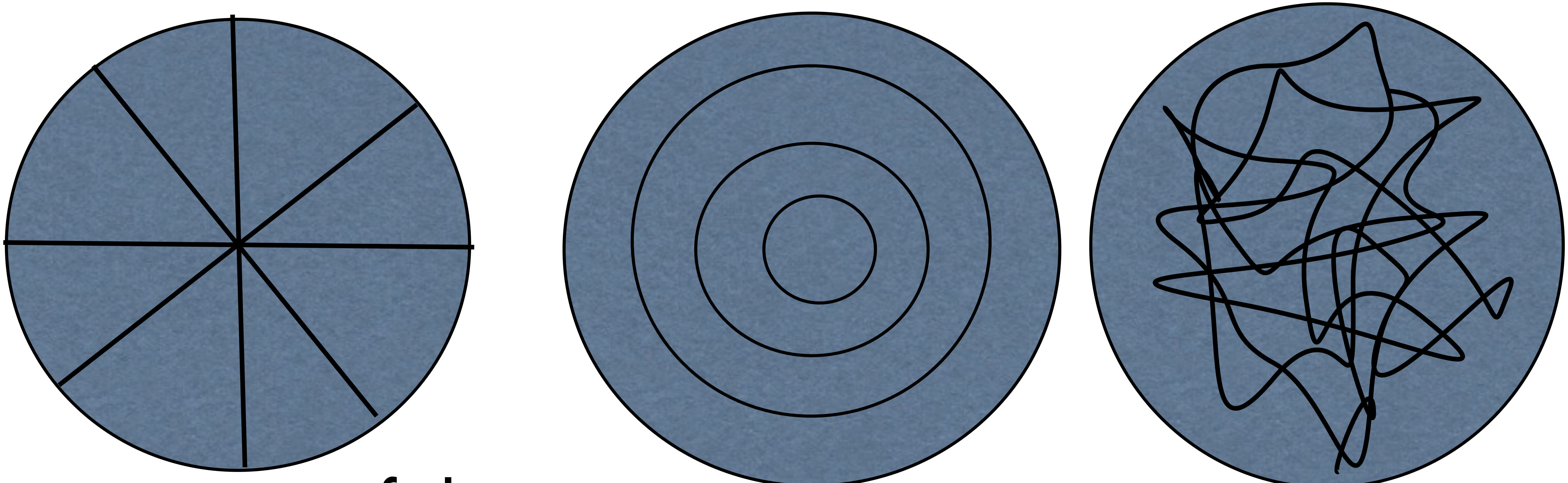


Bimodality !

cool core ← stabilized by AGN + conduction

non cool core ← stabilized by conduction

Efficiency depends on unknown B-field topology



f=1

f=0

$f = \langle \cos^2\theta \rangle = 0.33$

Note: this presumes $l_{\mathrm{T}} \gg l_{\mathrm{B}} \gg \lambda_e$

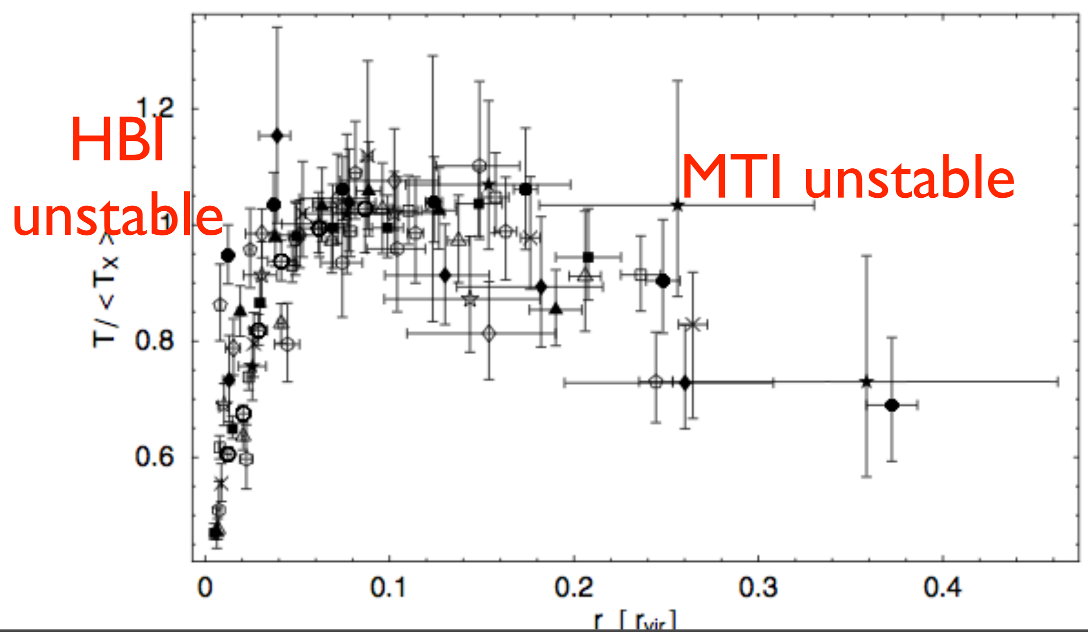
Buoyancy instabilities realign magnetic field

$\nabla T < 0$ → Magnetothermal Instability (MTI)
(Balbus 2000)

Radial magnetic fields

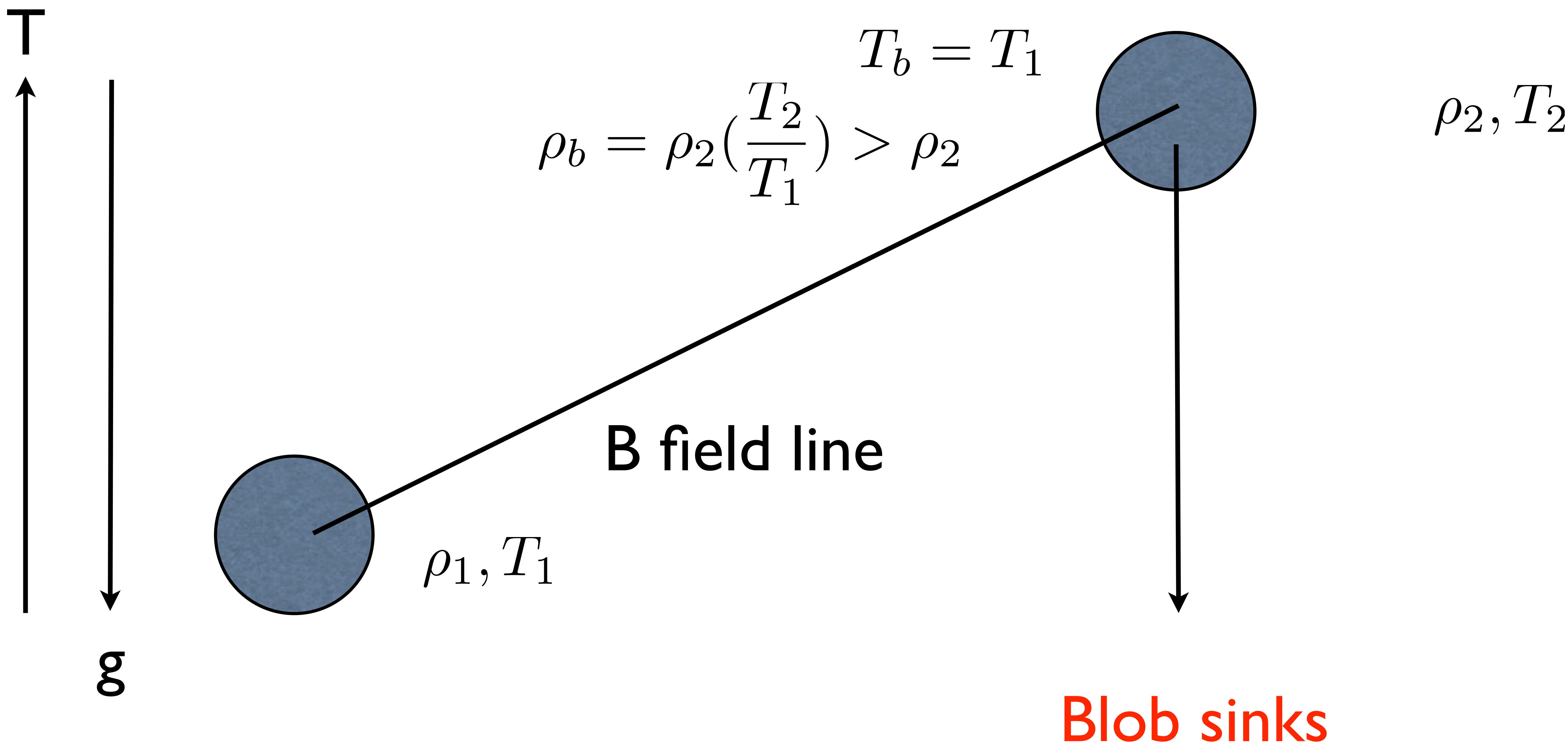
$\nabla T > 0$ → Heat buoyancy instability (HBI)
(Quataert 2008)

Tangential magnetic fields

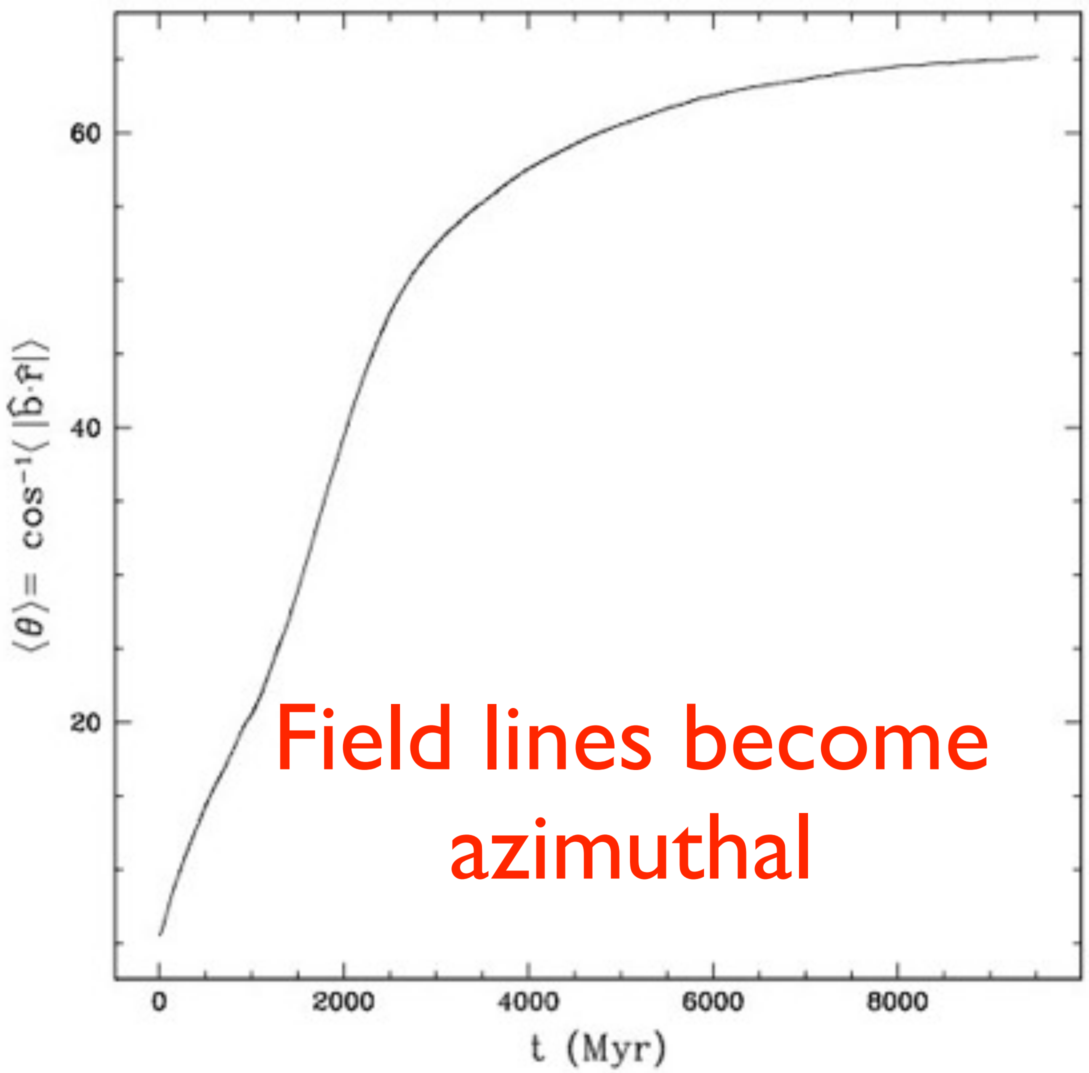


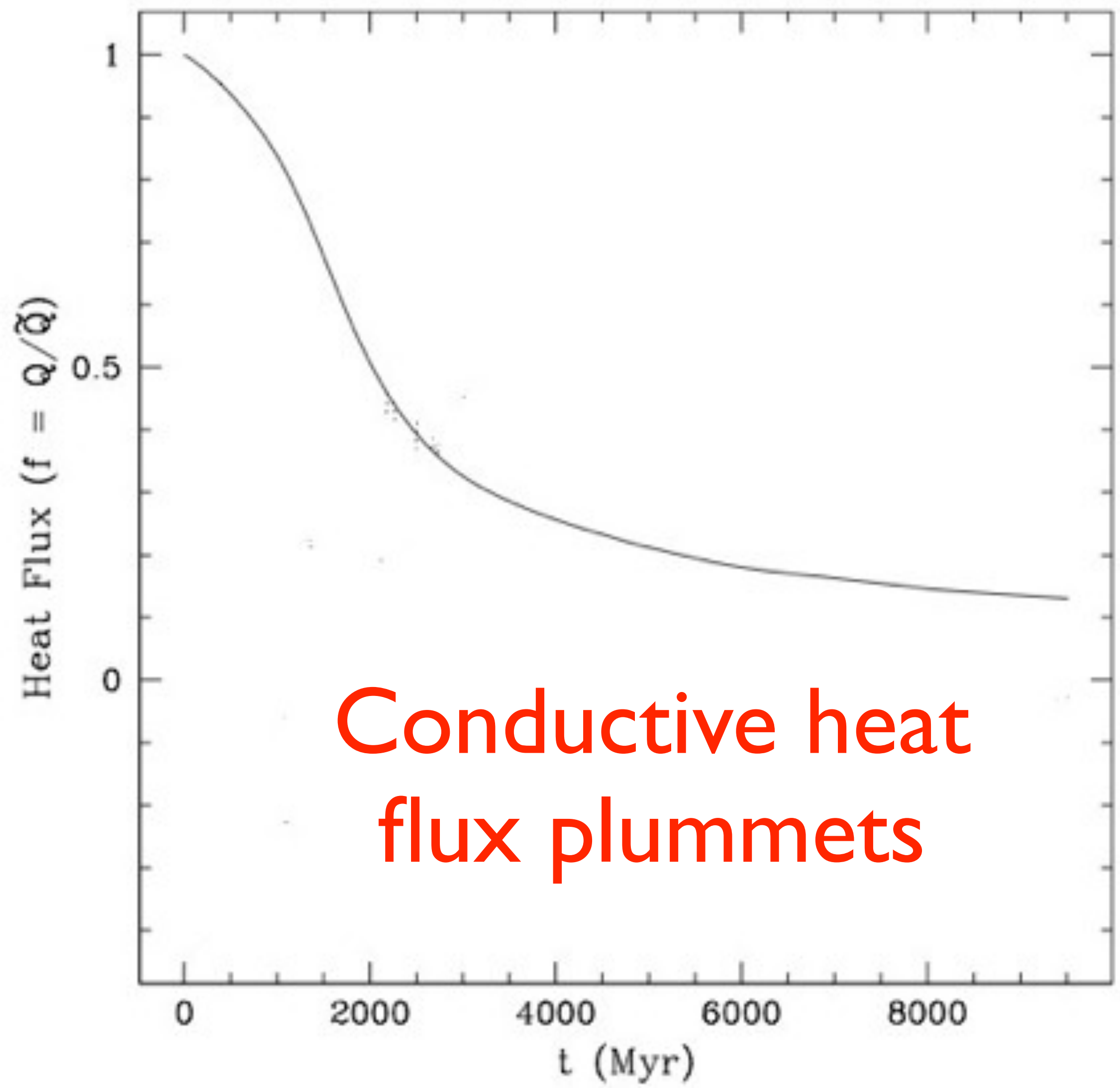
How does it work?

Consider HBI case



...this shuts off thermal conduction

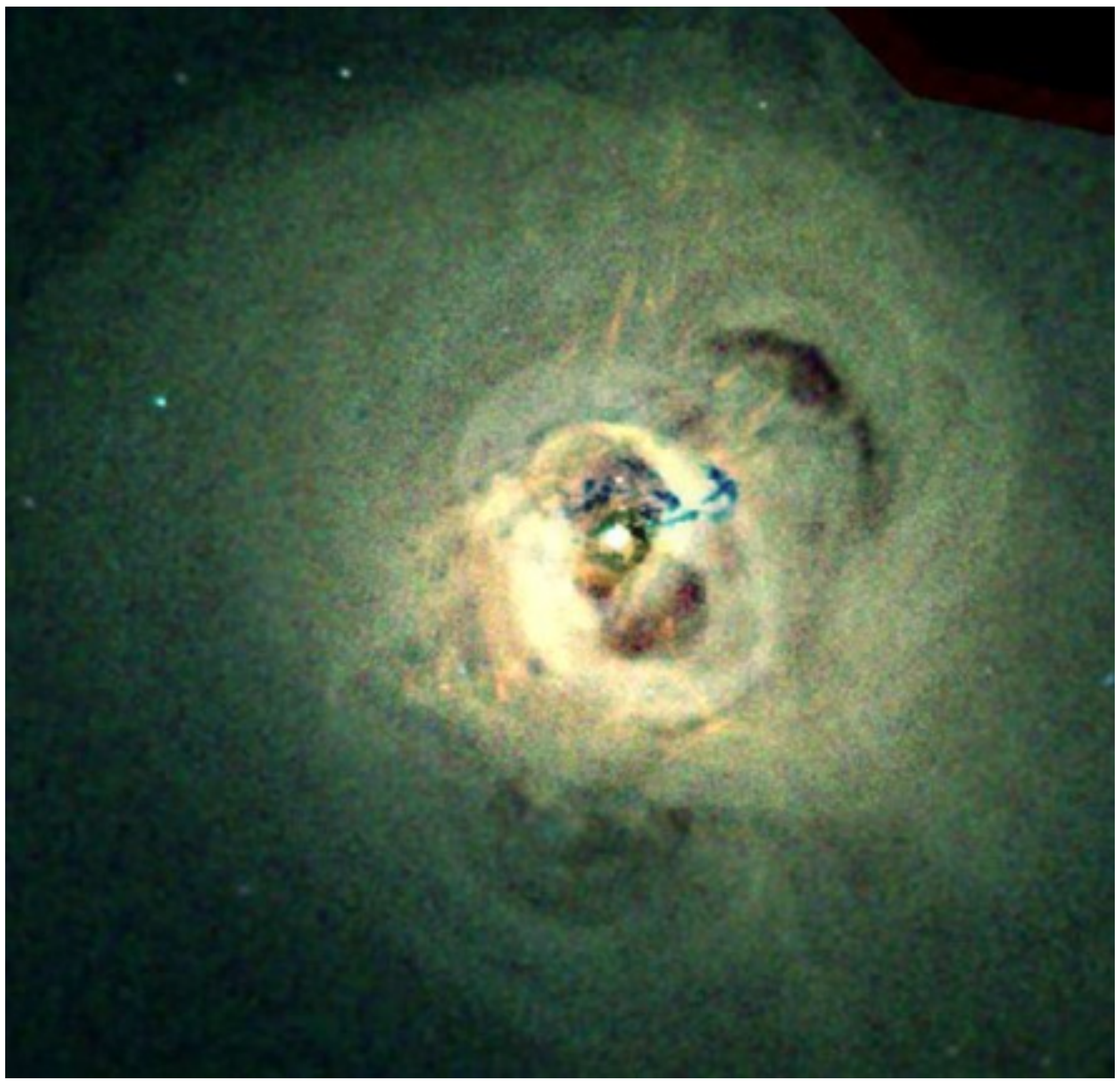




and brings on a cooling catastrophe

Parrish et al (2009) (see also Bogdanovic et al 2009)

We expect the ICM to be turbulent



Evidence from:

Lack of resonance scattering lines (Churazov et al 2004)

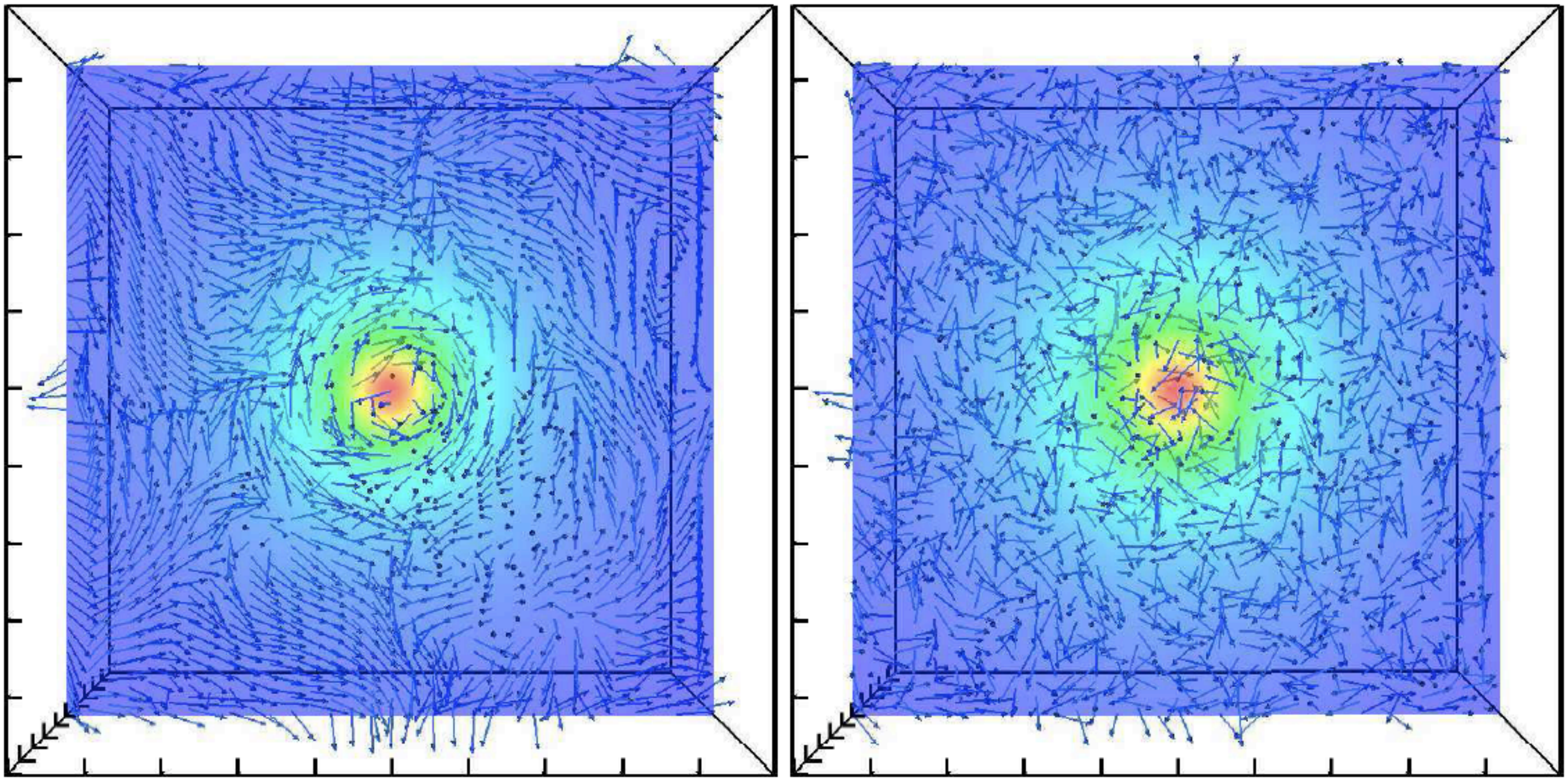
Analysis of pressure maps (Schuecker et al 2004)

Faraday rotation maps (Ensslin & Vogt 2006)

X-ray spectroscopy upper bounds (Sanders et al 2010)

Could turbulence randomize field lines and restore conduction?

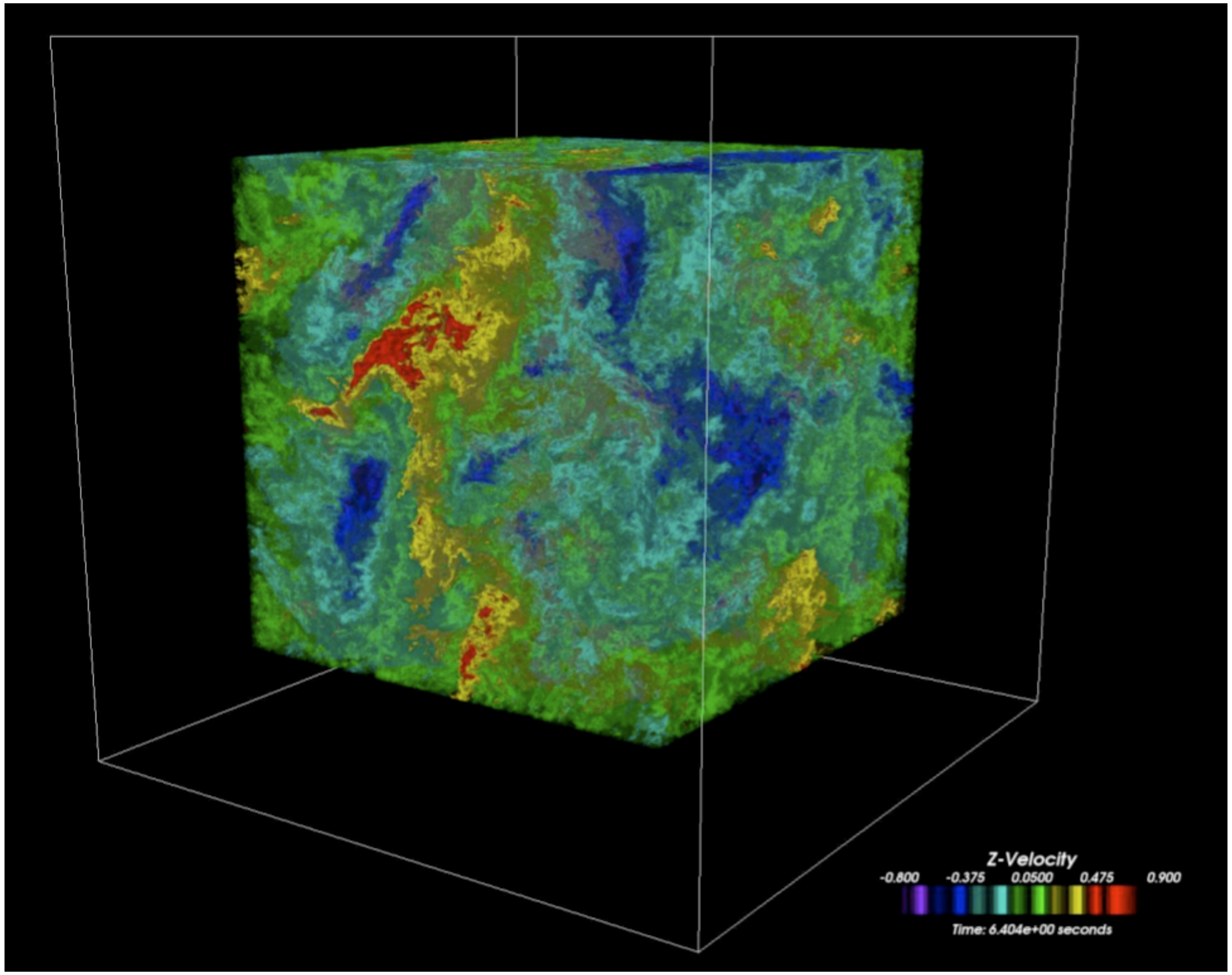
Bottom Line: YES



Ruszkowski & Oh (2010a), using FLASH

Similar results by Parrish et al (2010), using ATHENA

Simulation details



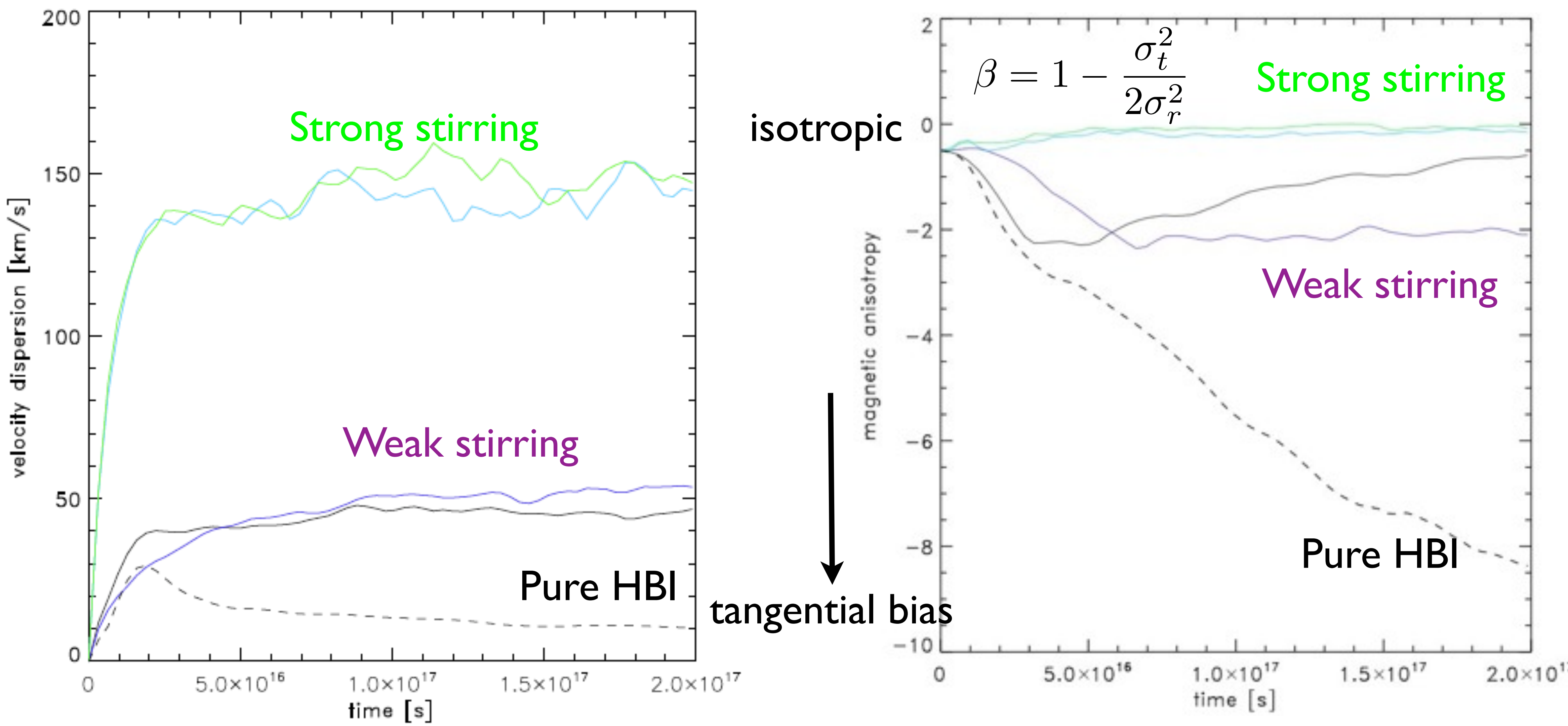
FLASH turbulence module
(Fisher et al 2008)

3D MHD FLASH simulations

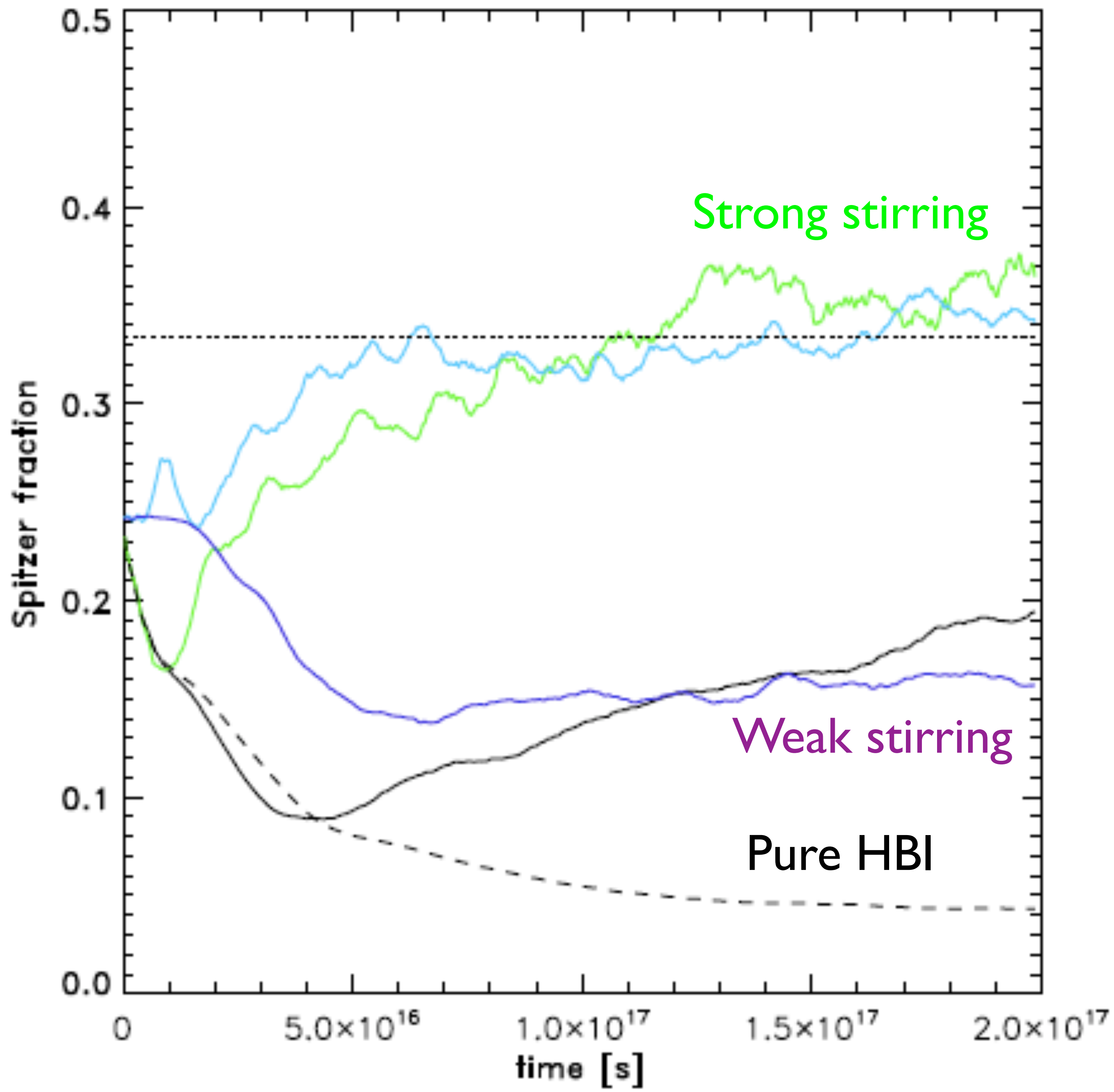
1 Mpc^3, max resolution 2.7 kpc h^{-1}

Spectral implementation of turbulent forcing (note: volume-filling by construction)

Required Amount of Turbulence is small



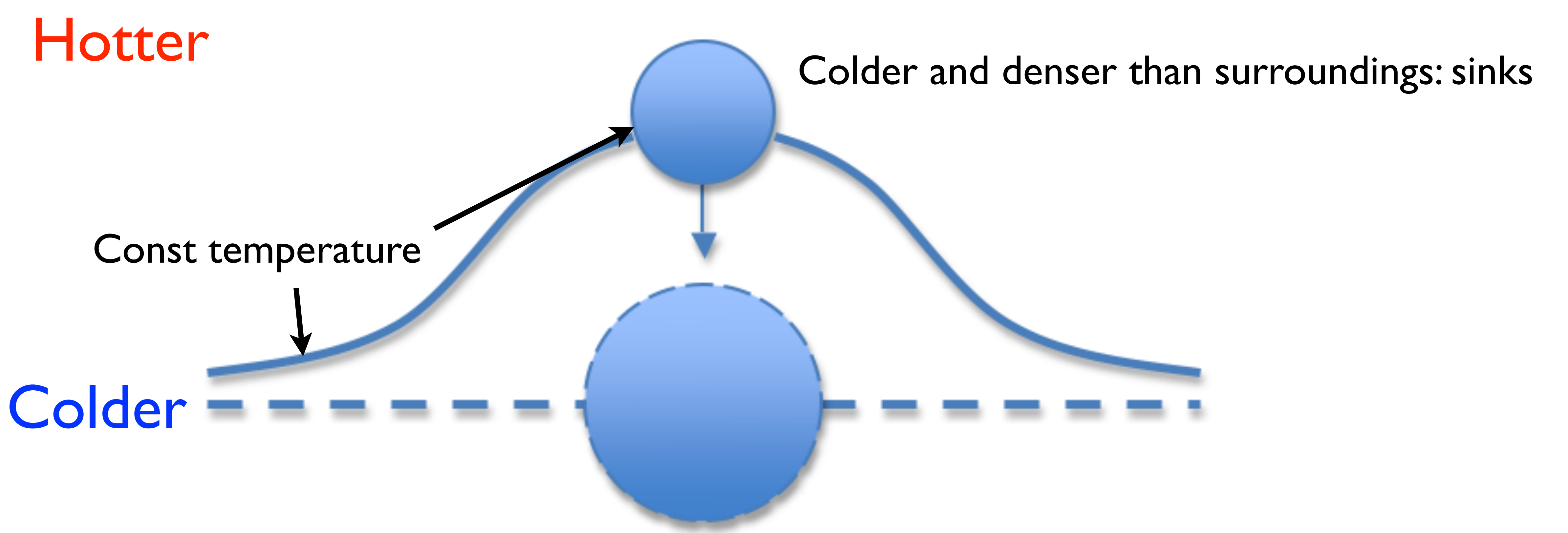
Highly subsonic (~10% of sound speed) motions overcome HBI, randomize fields



...and conduction is restored!

Why are such weak motions effective?

Stratified by temperature, rather than entropy.

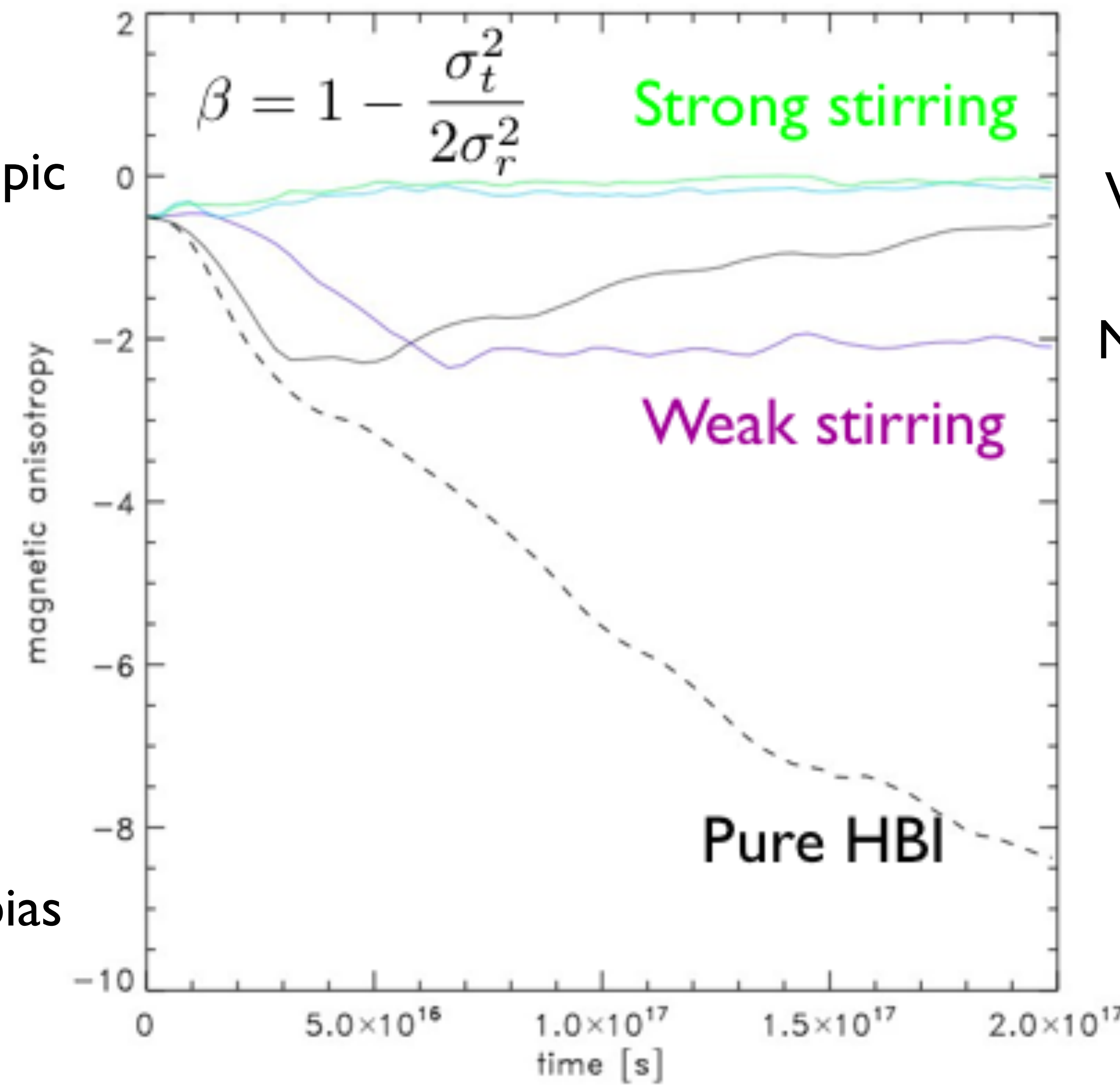


Oscillates with frequency $$(\omega_{\rm BV}^{\rm MHD})^2 = \frac{g}{r}\frac{d\ln T}{d\ln r},$$

Buoyancy forces are weaker in conducting plasma

We can see this already: different anisotropy for same amount of turbulence

isotropic



tangential bias

With conduction: more isotropic!

No conduction: more tangentially biased

Compare buoyancy force to inertial term (Richardson number, Froude number)

$$\frac{v_z}{v} \sim \left(\frac{\omega}{\omega_{\rm BV}}\right)^2$$

$\omega \ll \omega_{\rm BV} \Rightarrow$ Largely tangential motion

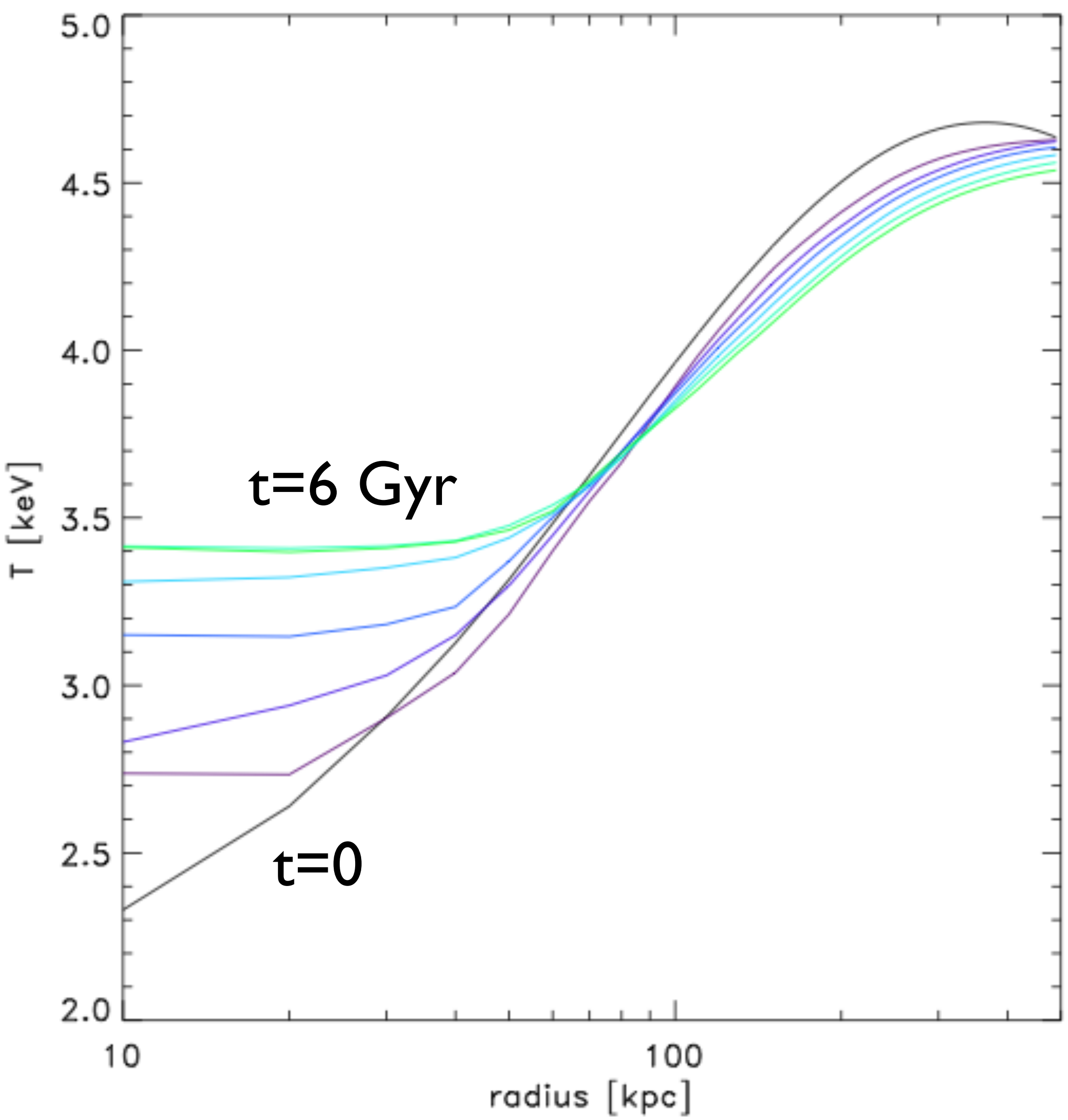
$\omega \gg \omega_{\rm BV} \Rightarrow$ Isotropic motion

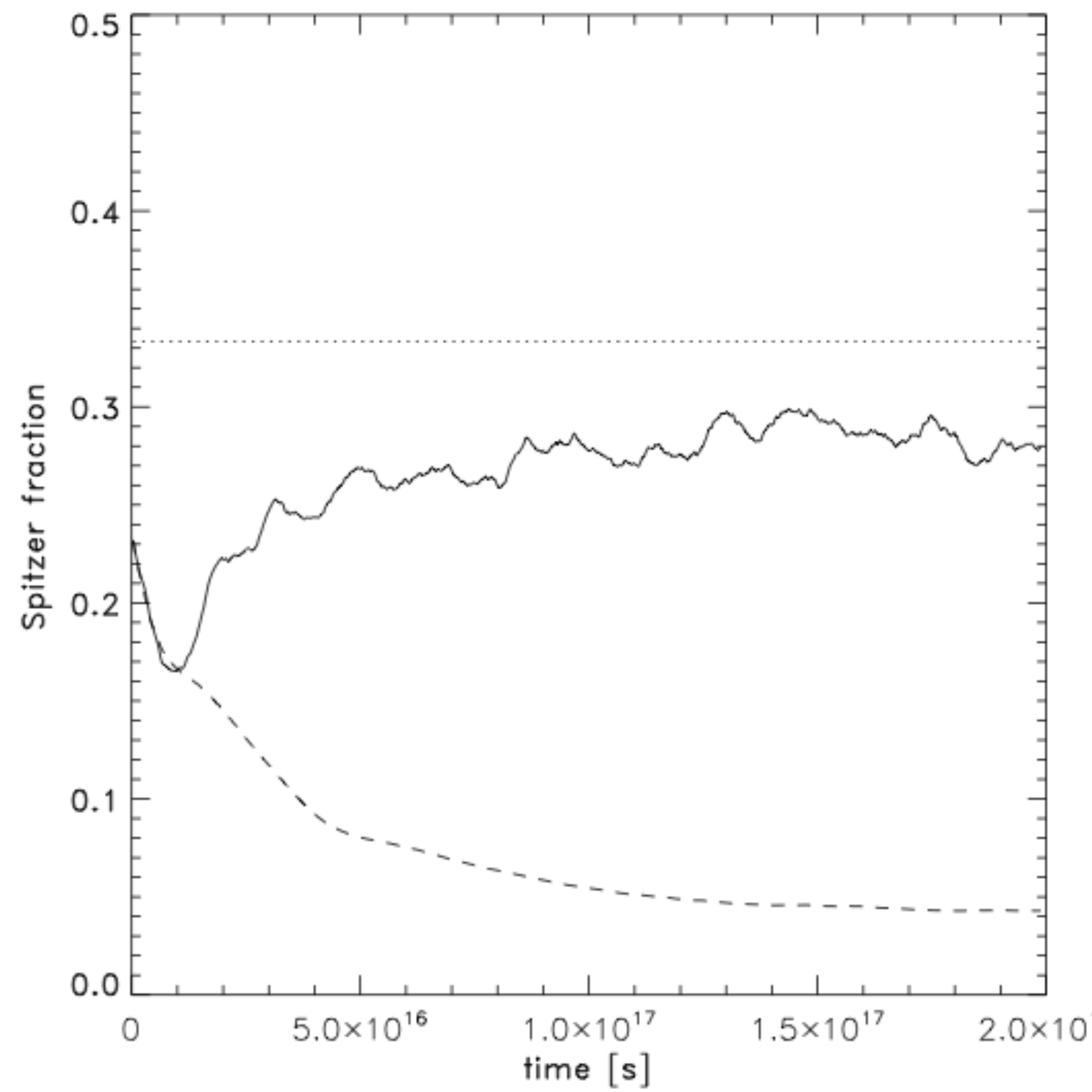
Required velocities are small

$$\sigma \approx 135\,{\rm km\,s^{-1}}\, g_{-8}{}^{1/2} r_{10}^{1/2} \left(\frac{d\ln T/d\ln r}{0.15}\right)^{1/2} \left(\frac{Ri_c}{0.25}\right)^{-1/2}$$

See also Sharma et al (2009)

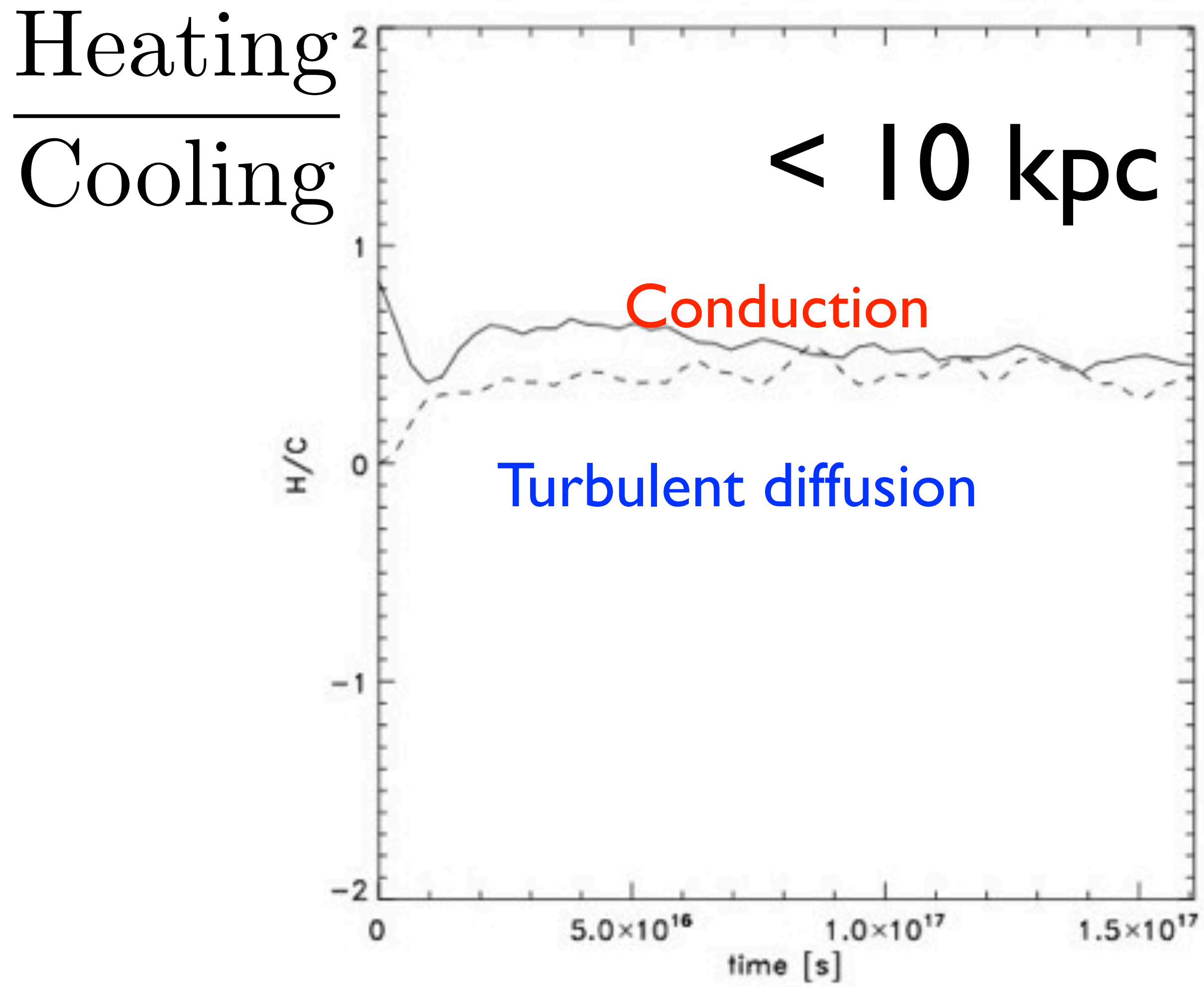
No cooling catastrophe!

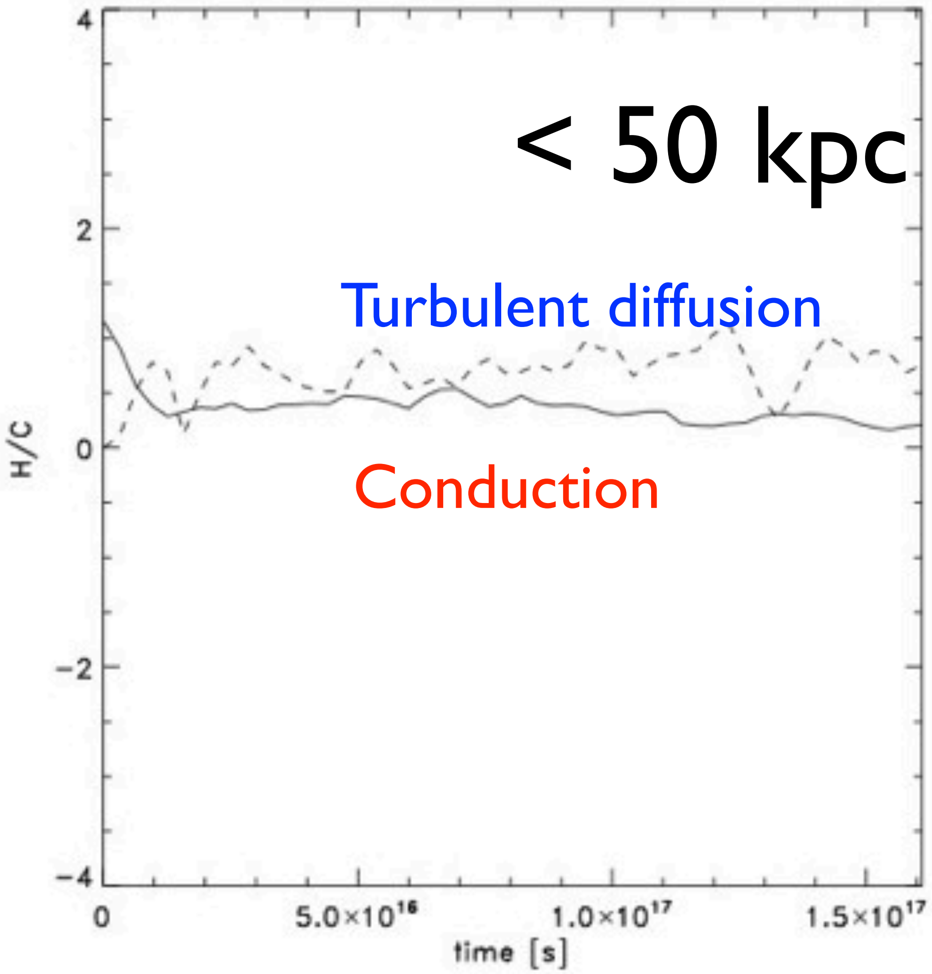




Cluster transitions from cool core to non cool core...

Turbulent heat diffusion is important...



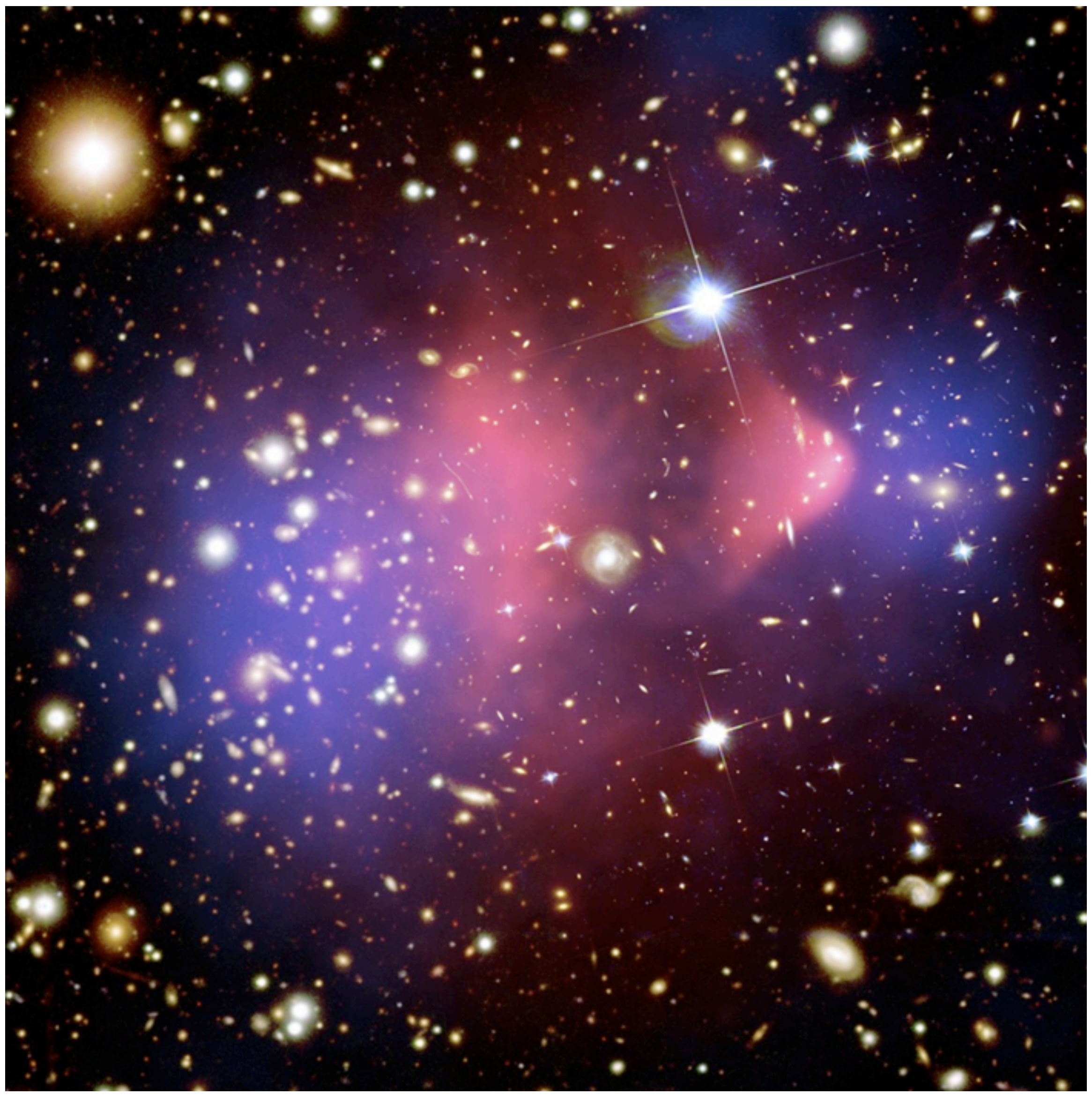


...but even when subdominant, conduction is crucial (more later)

Can we have sustained, volume-filling turbulence?

Ruszkowski & Oh (2010b, on astro-ph vvveerrrry soon...)

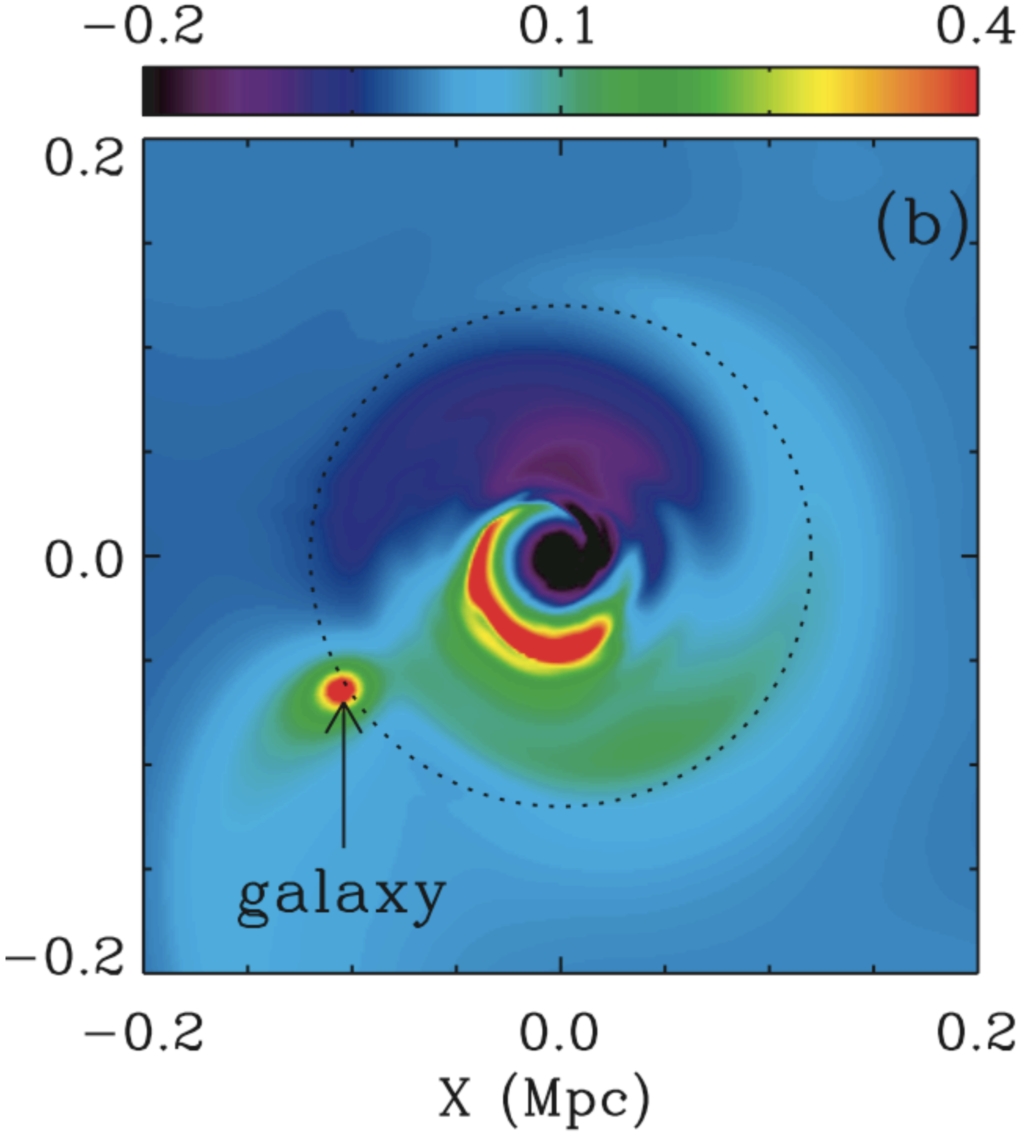
Most sources of turbulence are intermittent



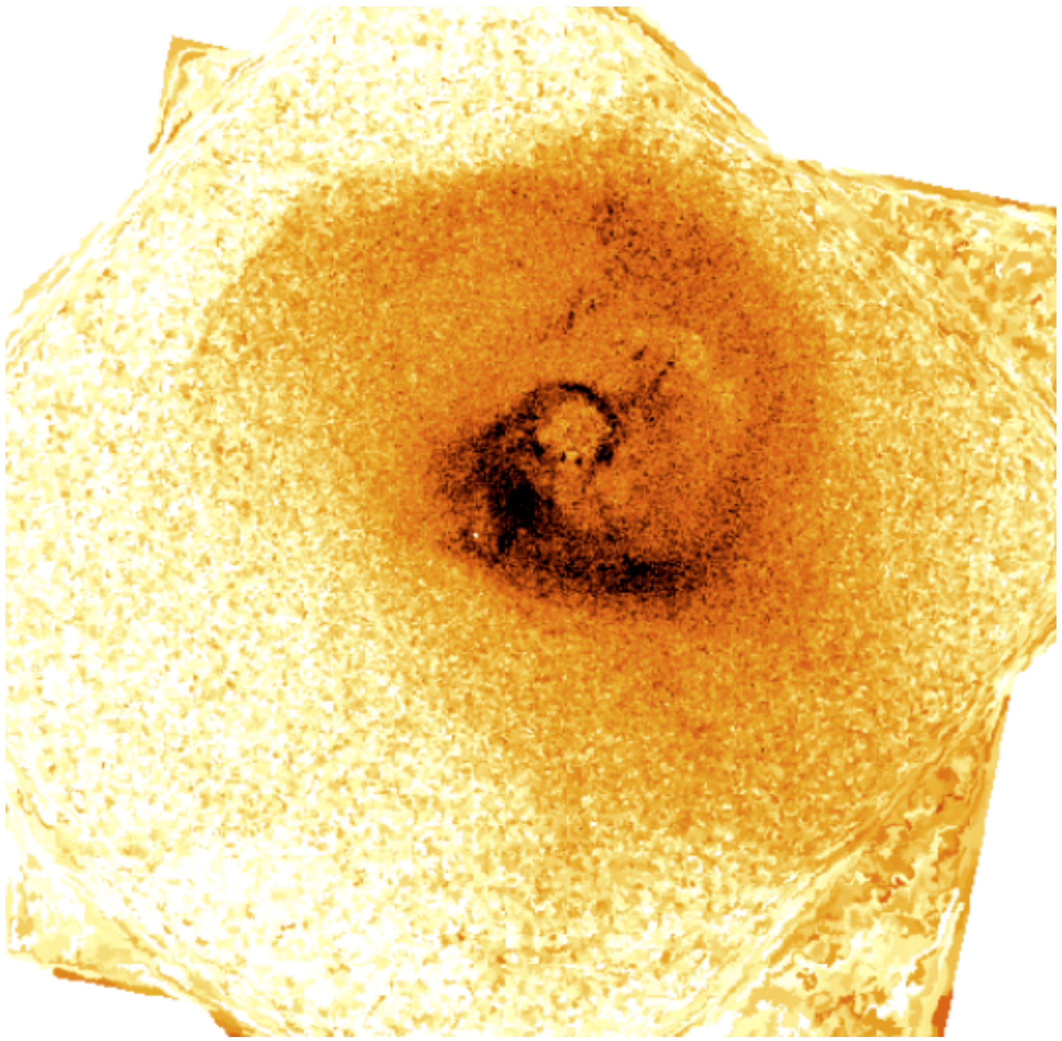
Mergers

AGN Outbursts

...except galaxy motions



Kim (2007)



Fabian (2005)

But galactic wakes have low volume-filling factor

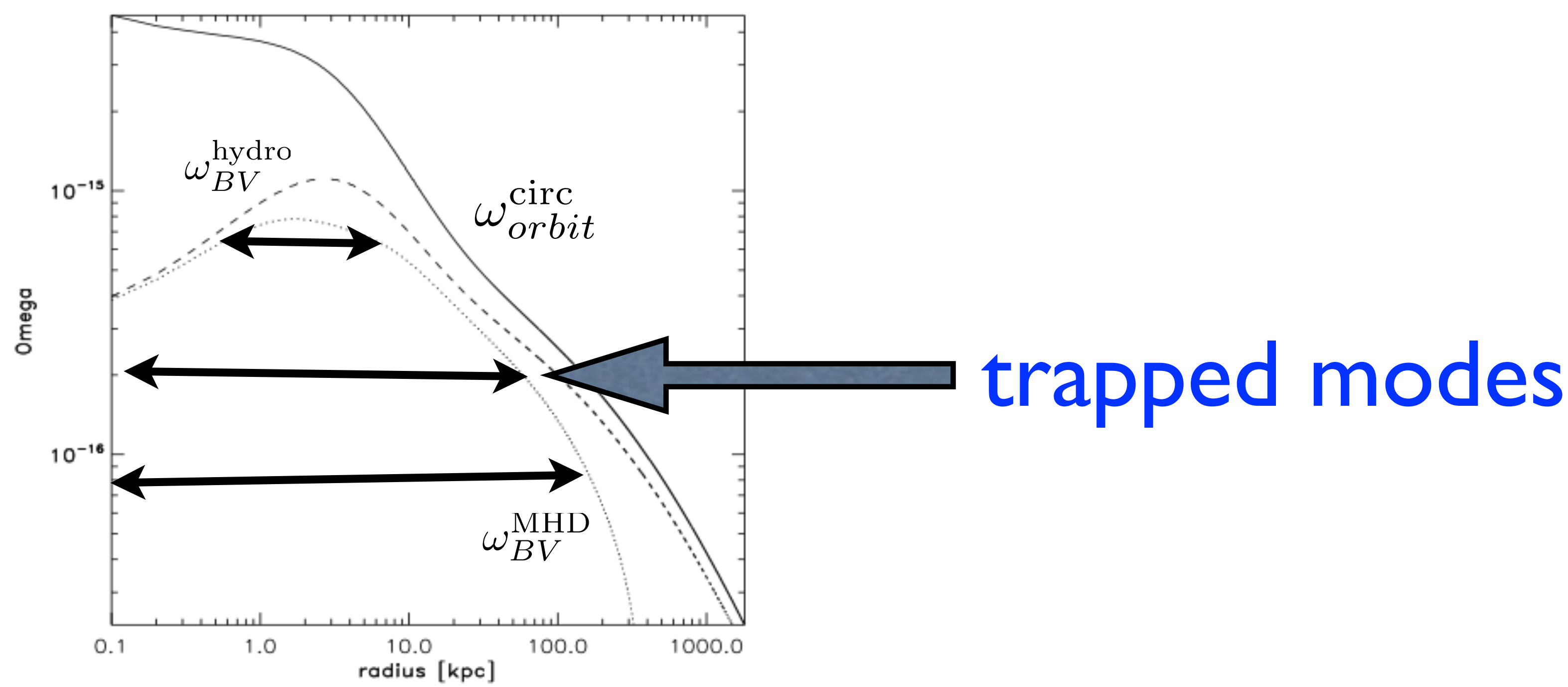
(Subramanian et al 2006, Iapichino & Niemeyer 2008)

Volume-filling only if can excite g-modes

(Lufkin et al 1995, Kim 2007)

This requires $\omega_{\rm turb} \sim v_{\rm turb}/\lambda < \omega_{\rm BV}$

cD galaxy contribution to potential is crucial



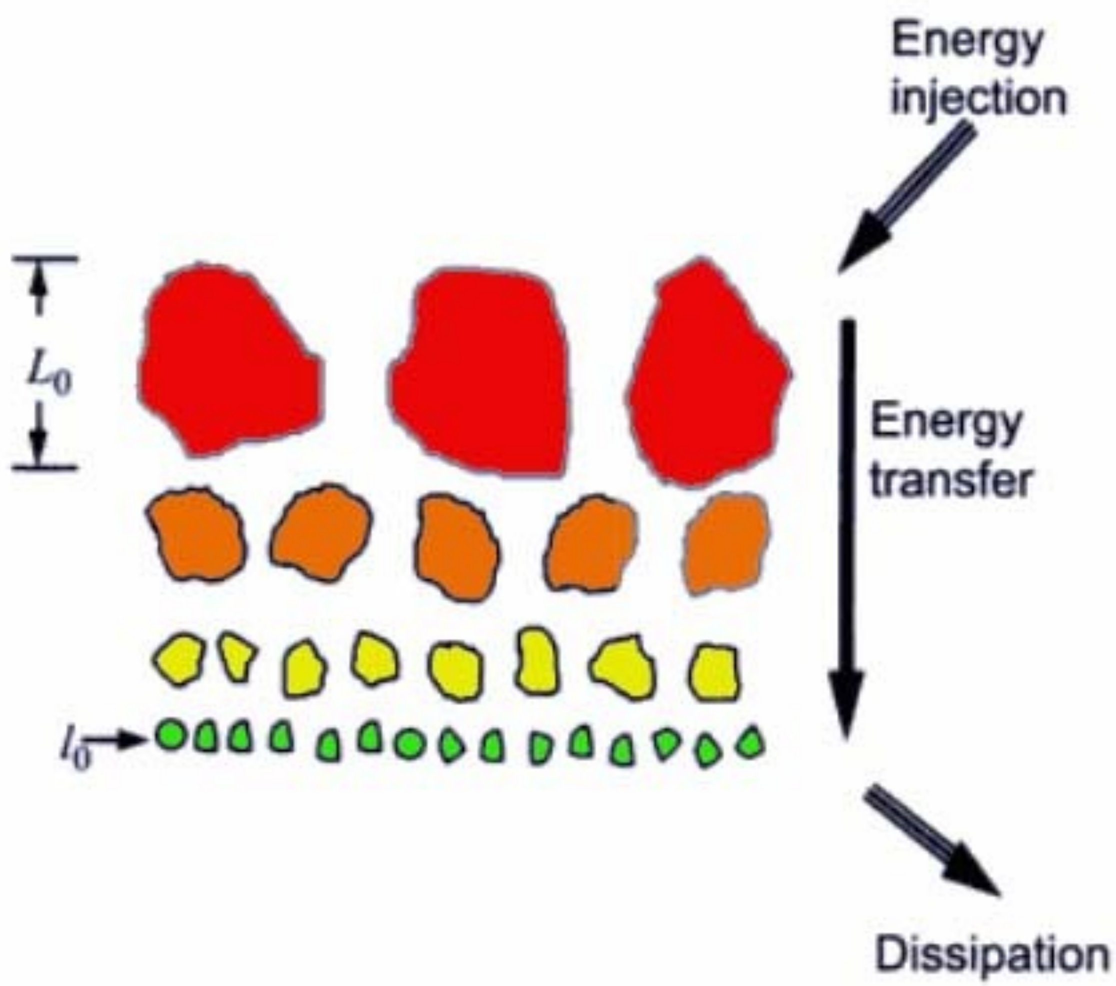
Contradictory requirements?

Trapping of g-modes requires $\omega_{\rm turb} < \omega_{\rm BV}$

Isotropic velocities requires $\omega_{\rm turb} > \omega_{\rm BV}$

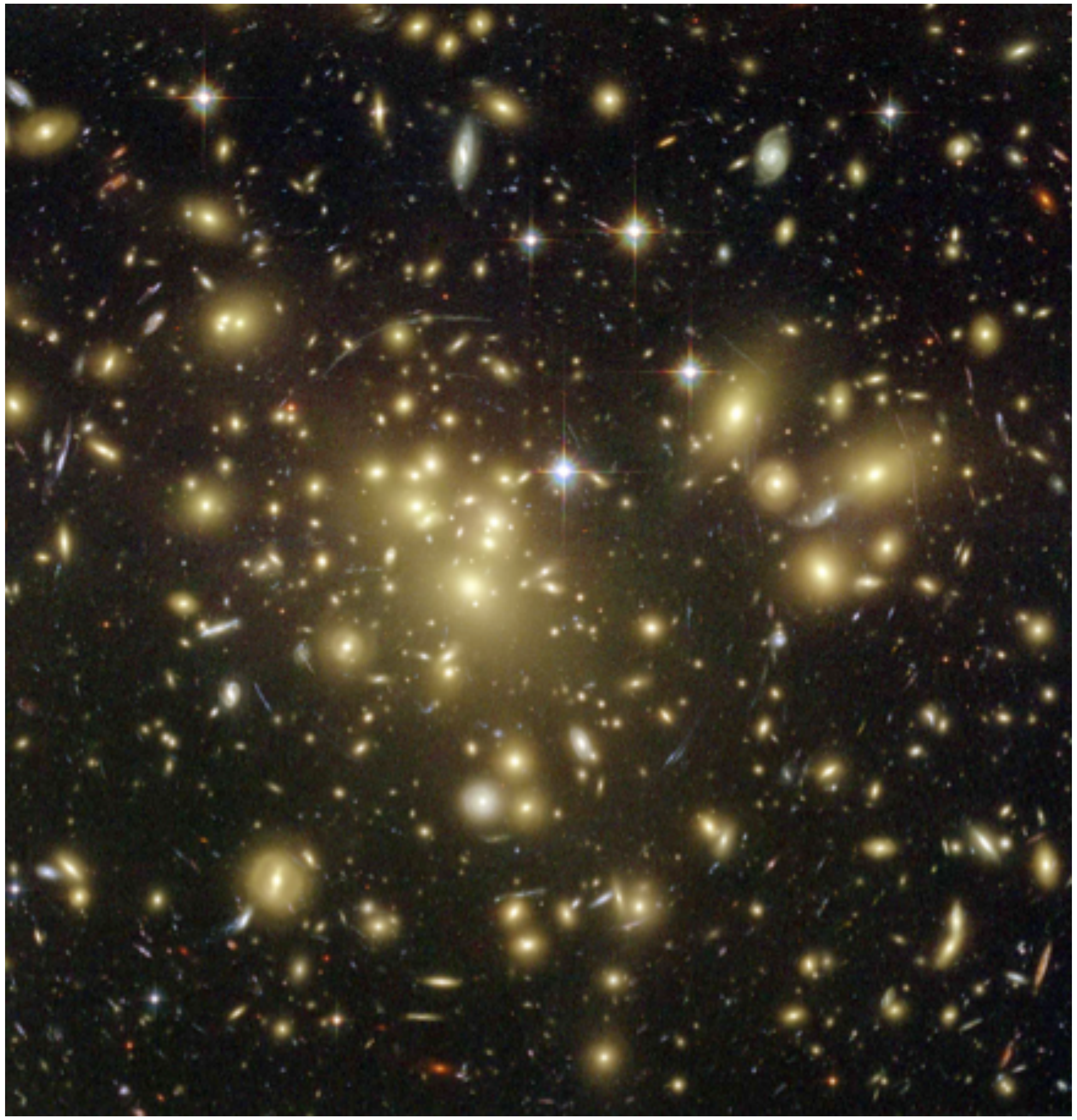
But recall $$\varepsilon \sim \frac{v^3}{l} \sim const$$

$$\omega \sim \frac{v}{l} \sim l^{-2/3}$$



Large eddies are trapped, smaller eddies isotropize

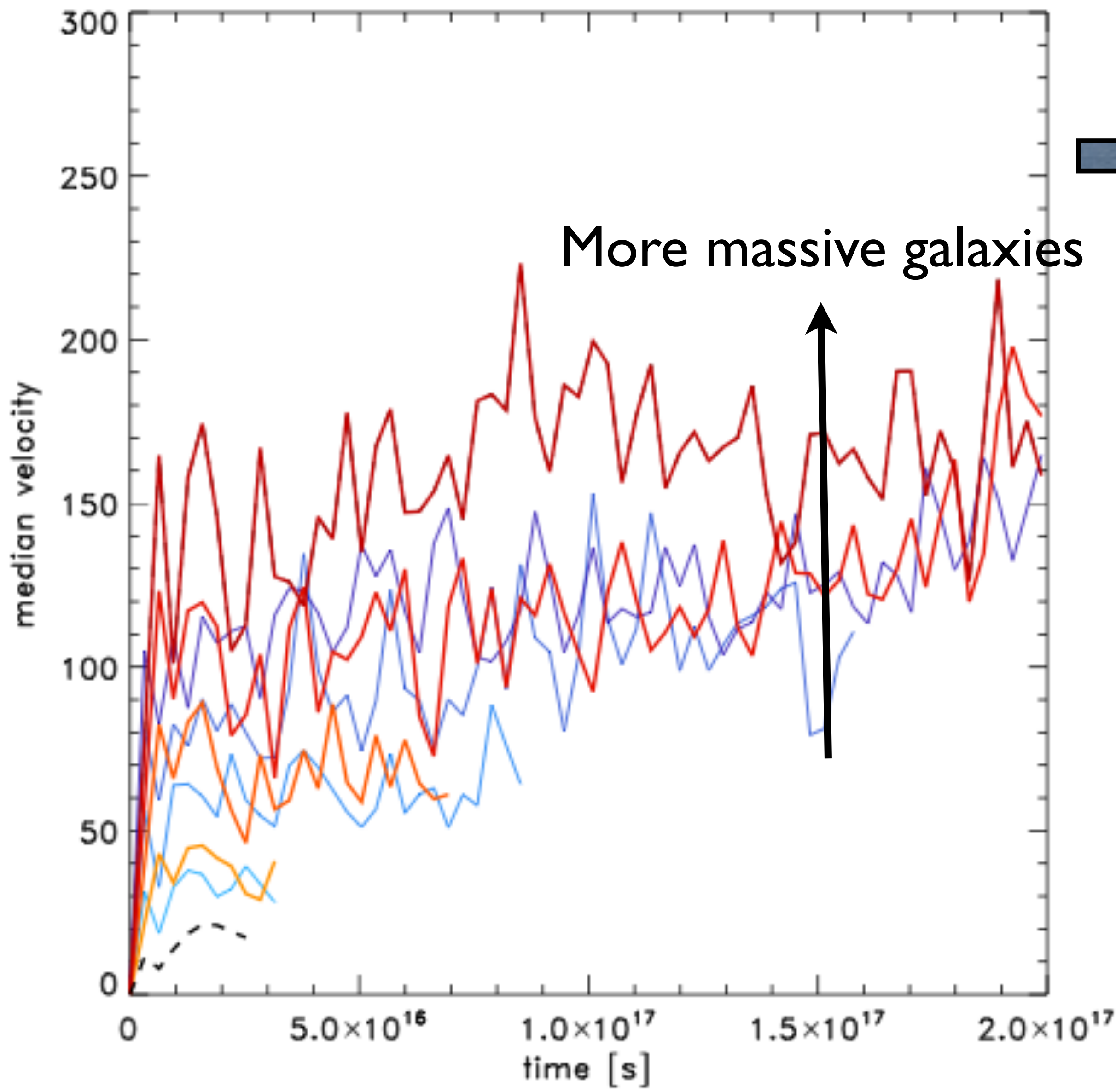
Simulate this!

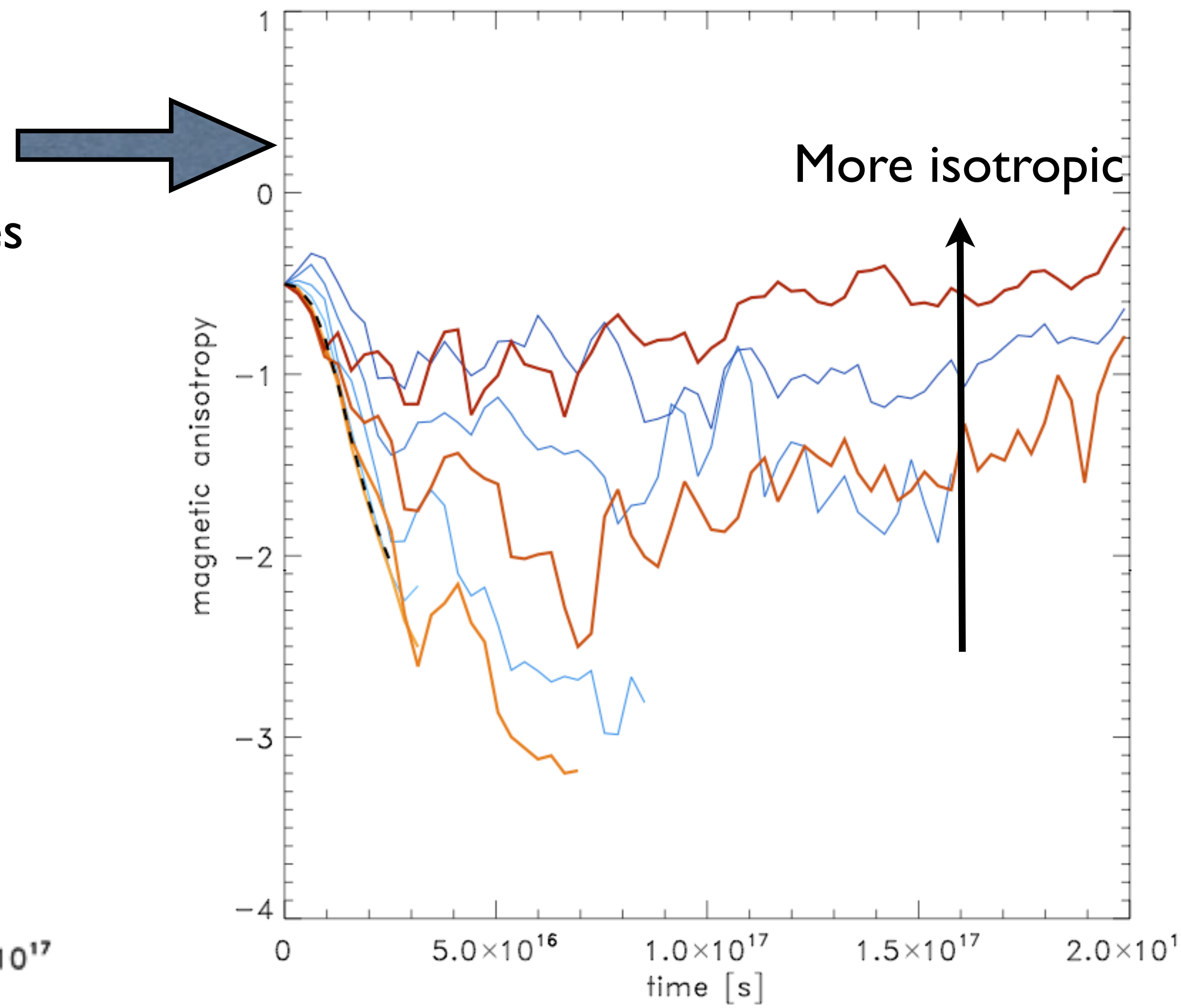


Assume galaxies trace NFW profile; solve Jeans equation to get velocities

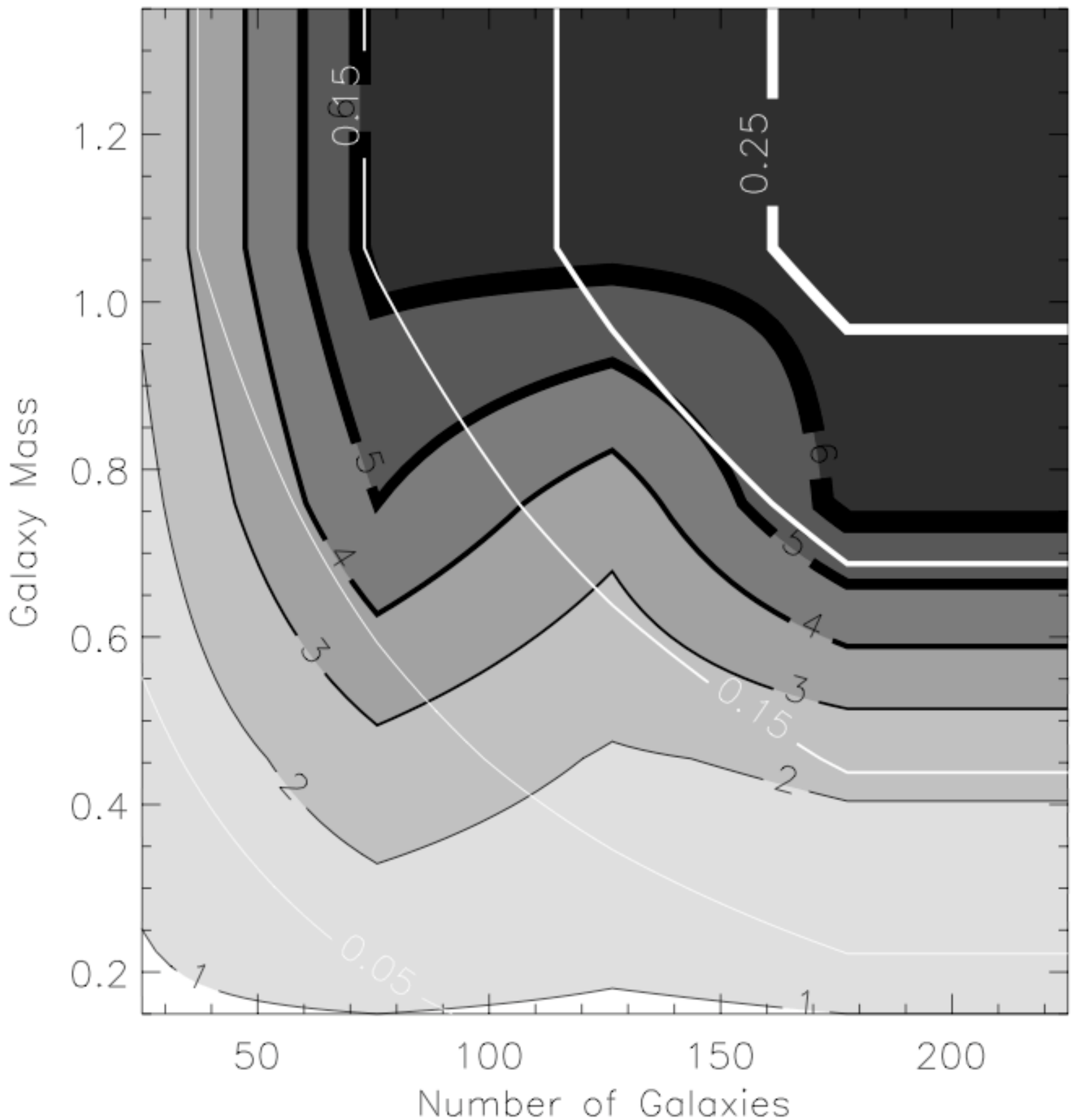
Mass in substructure from lensing studies (Natarajan et al 2008)

Magnetic fields are isotropized...





Note: no subgrid physics!

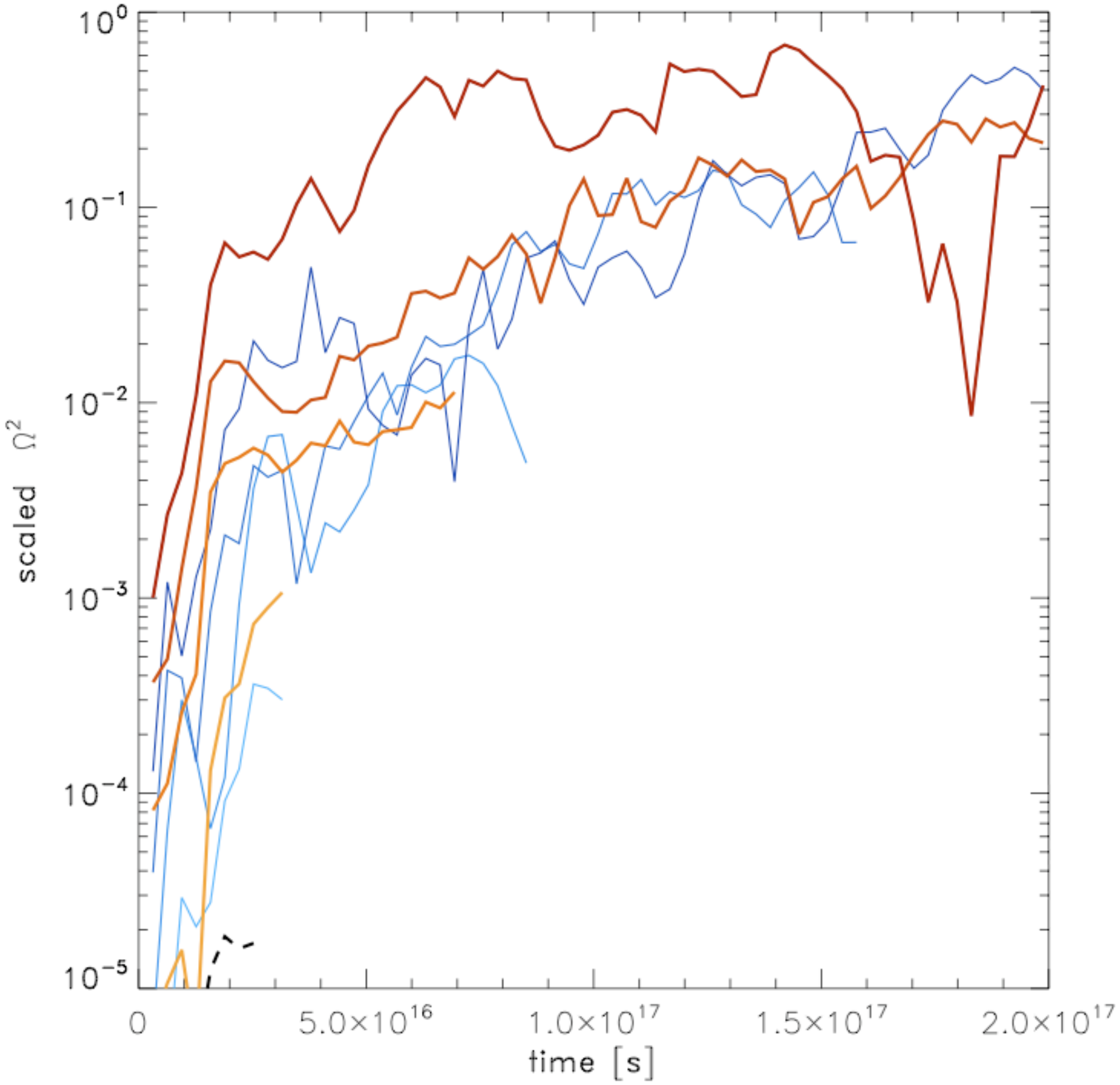


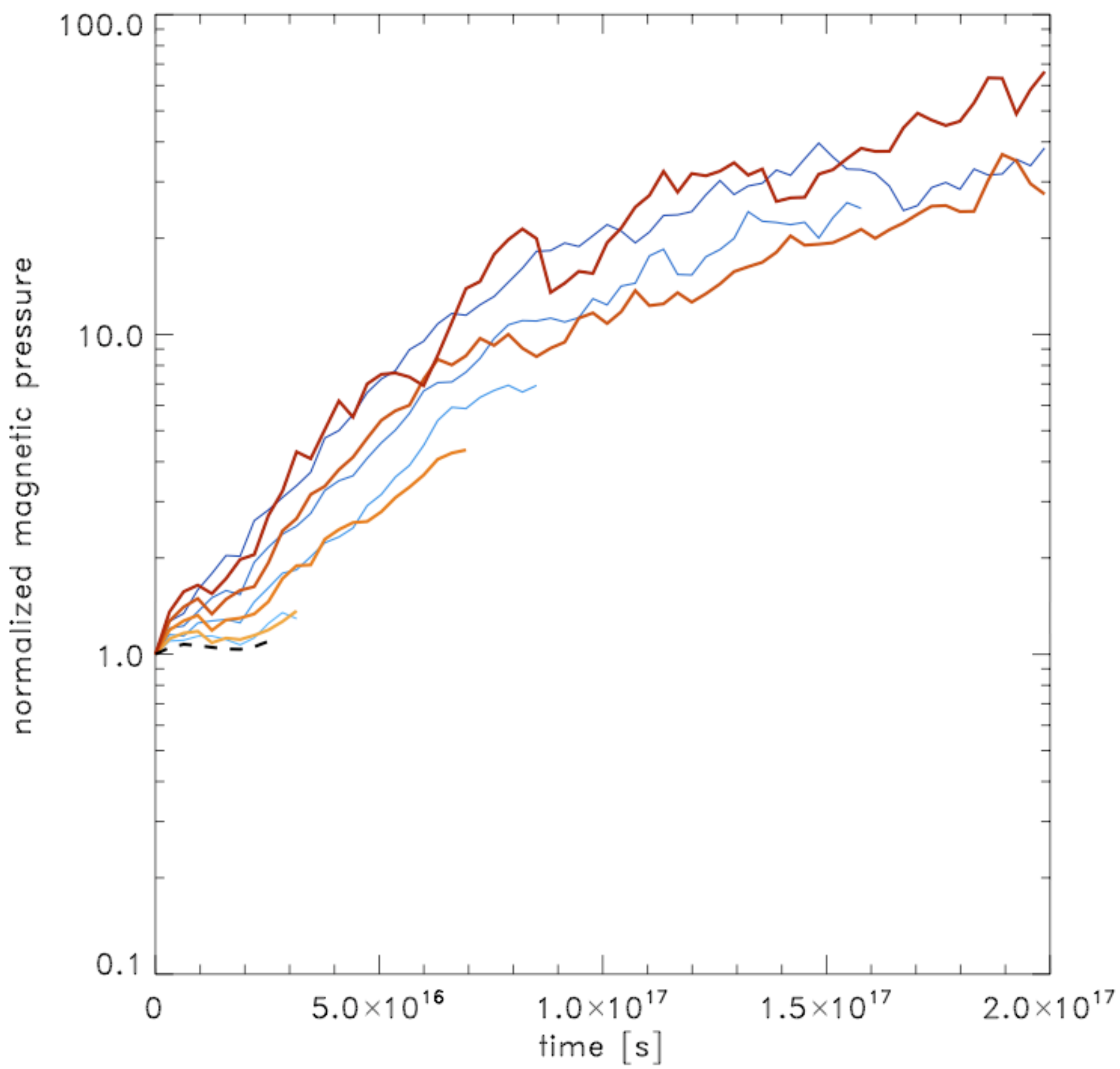
Black contours: Time to cooling catastrophe (6 Gyr=end of sim, stable)

White contours: fraction of mass in substructure

No cooling catastrophe for plausible parameters consistent with lensing

Magnetic fields are amplified

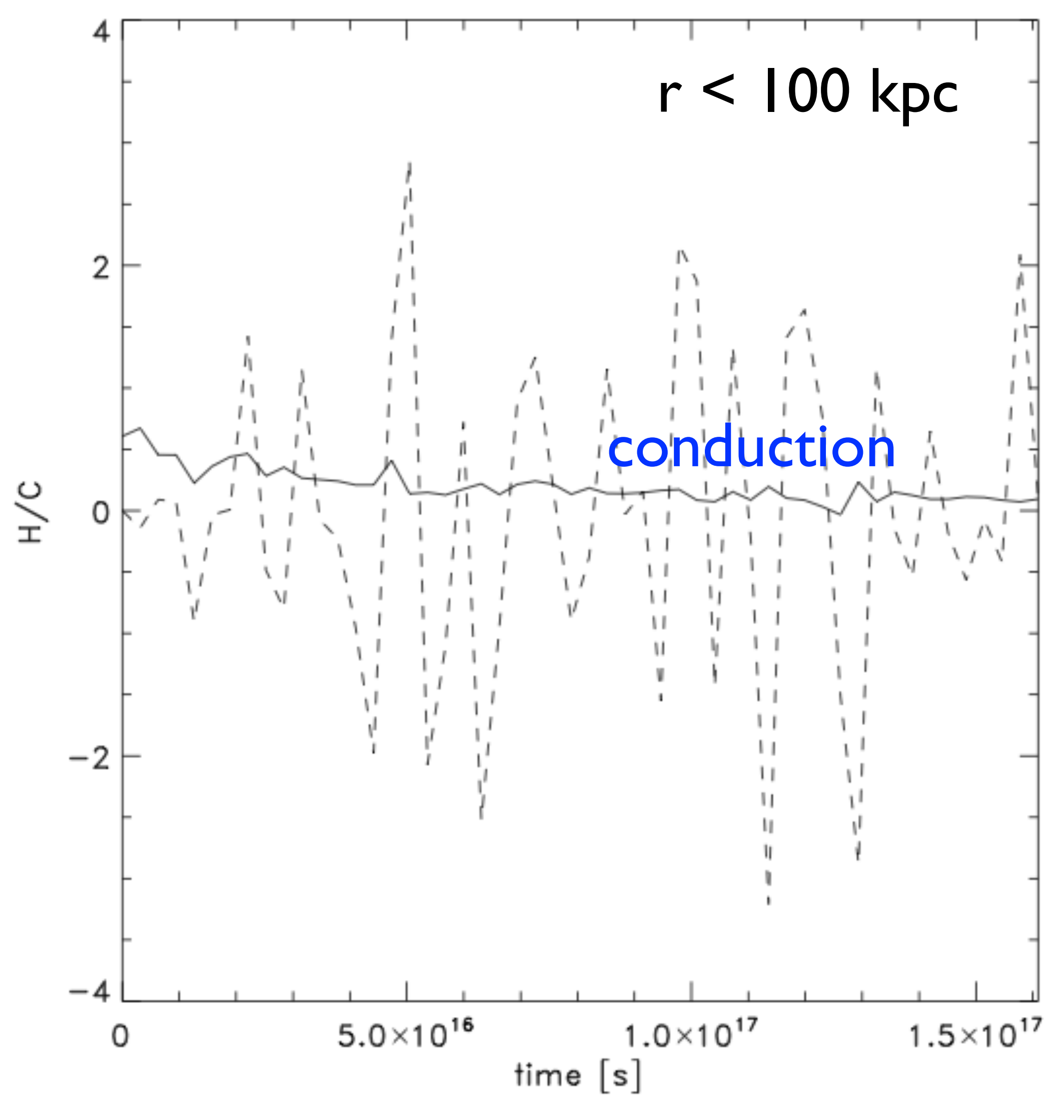


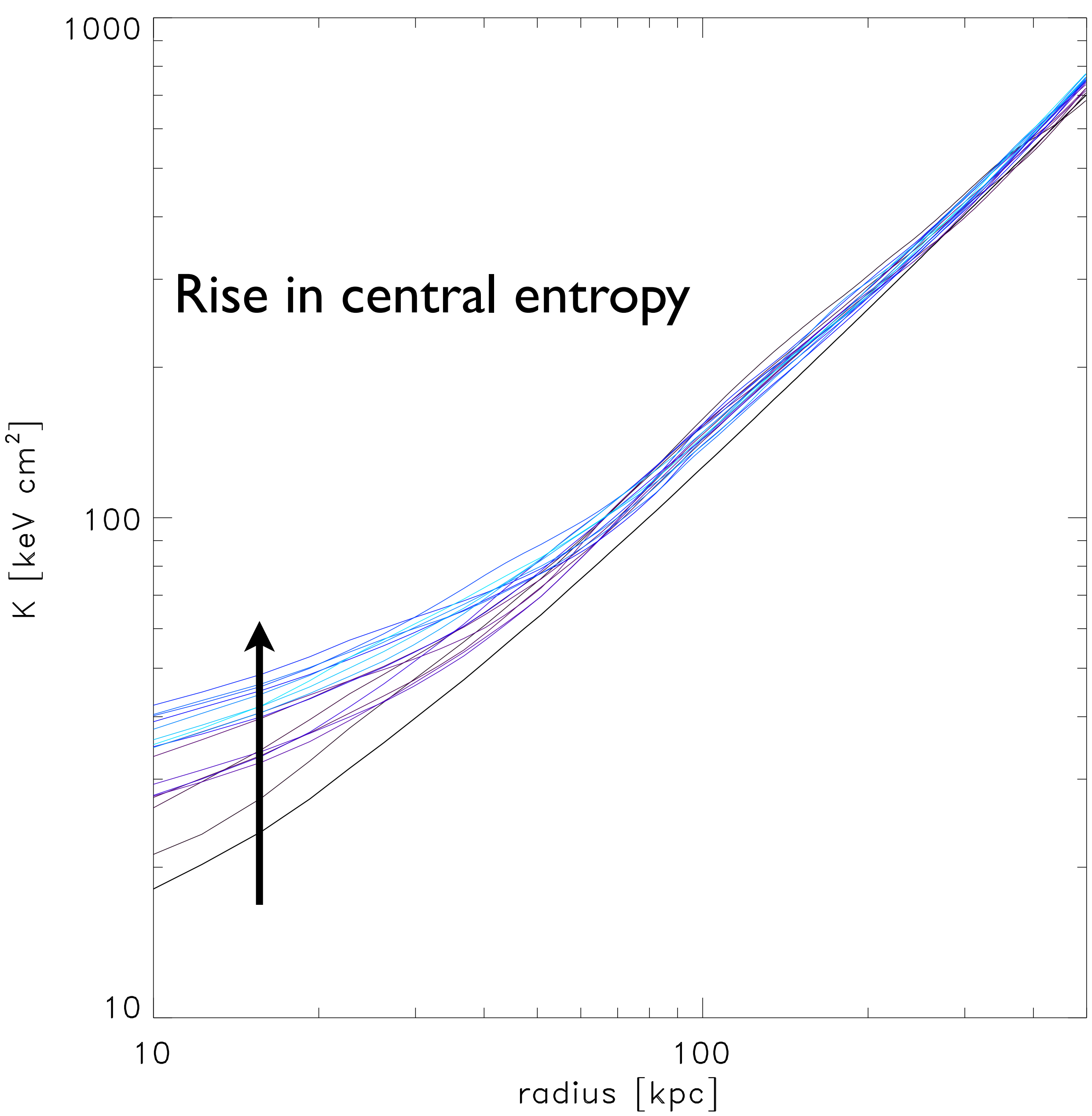


Vorticity growth → B-field growth

N.B. Magnetic tension negligible here

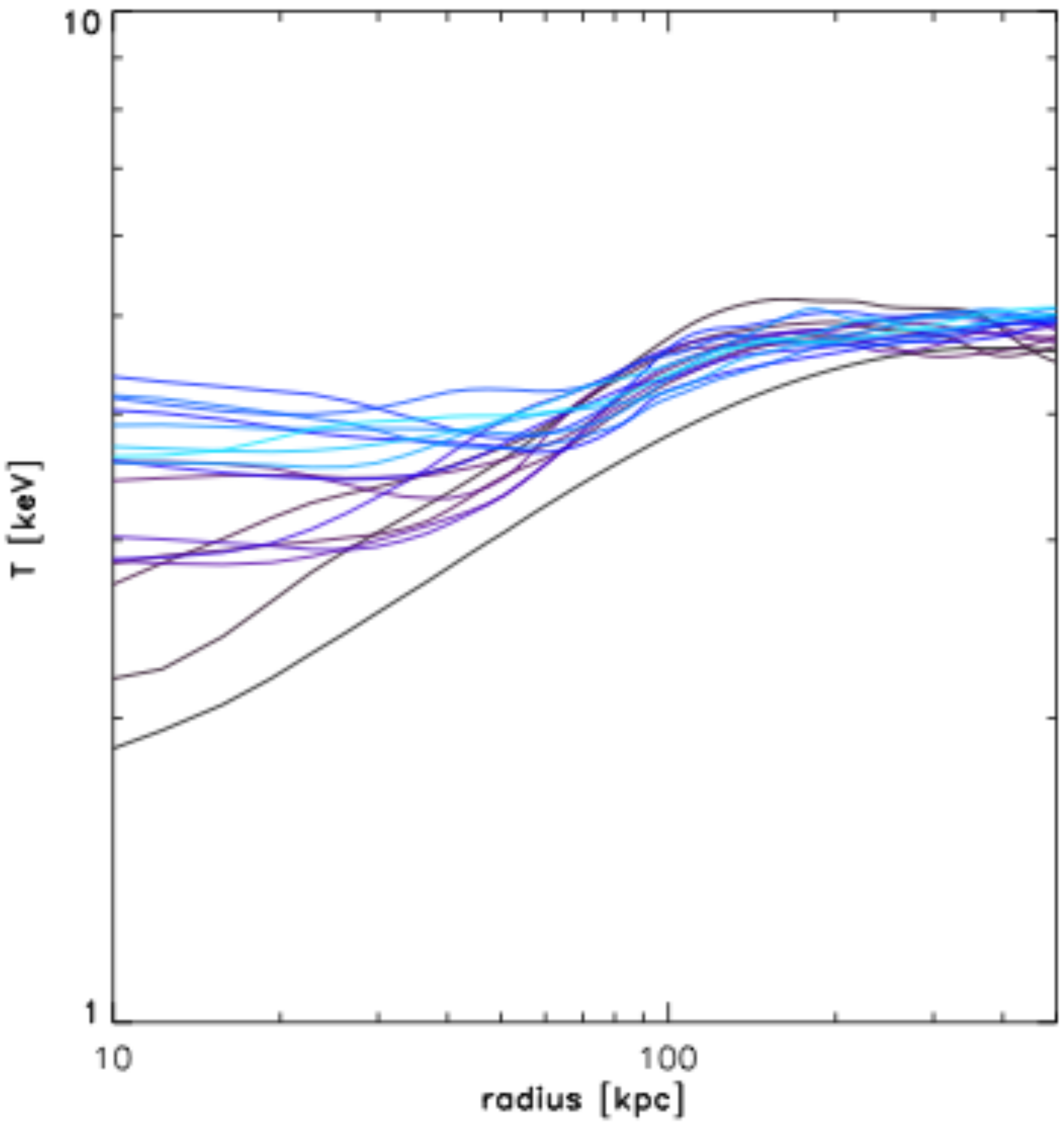
Conduction is at most ~50% of energy budget



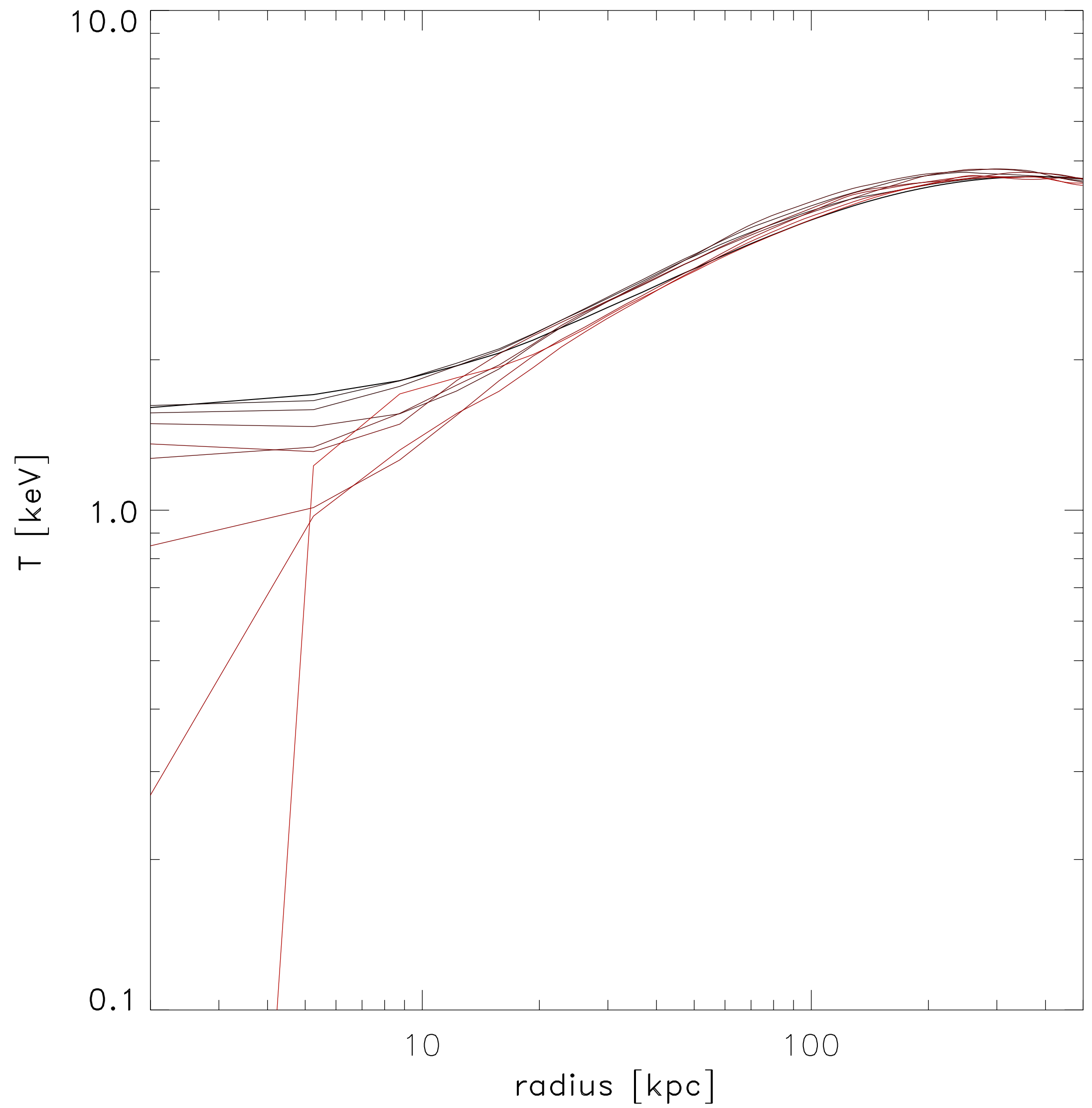


...but is a critical part of the story

MHD: stable

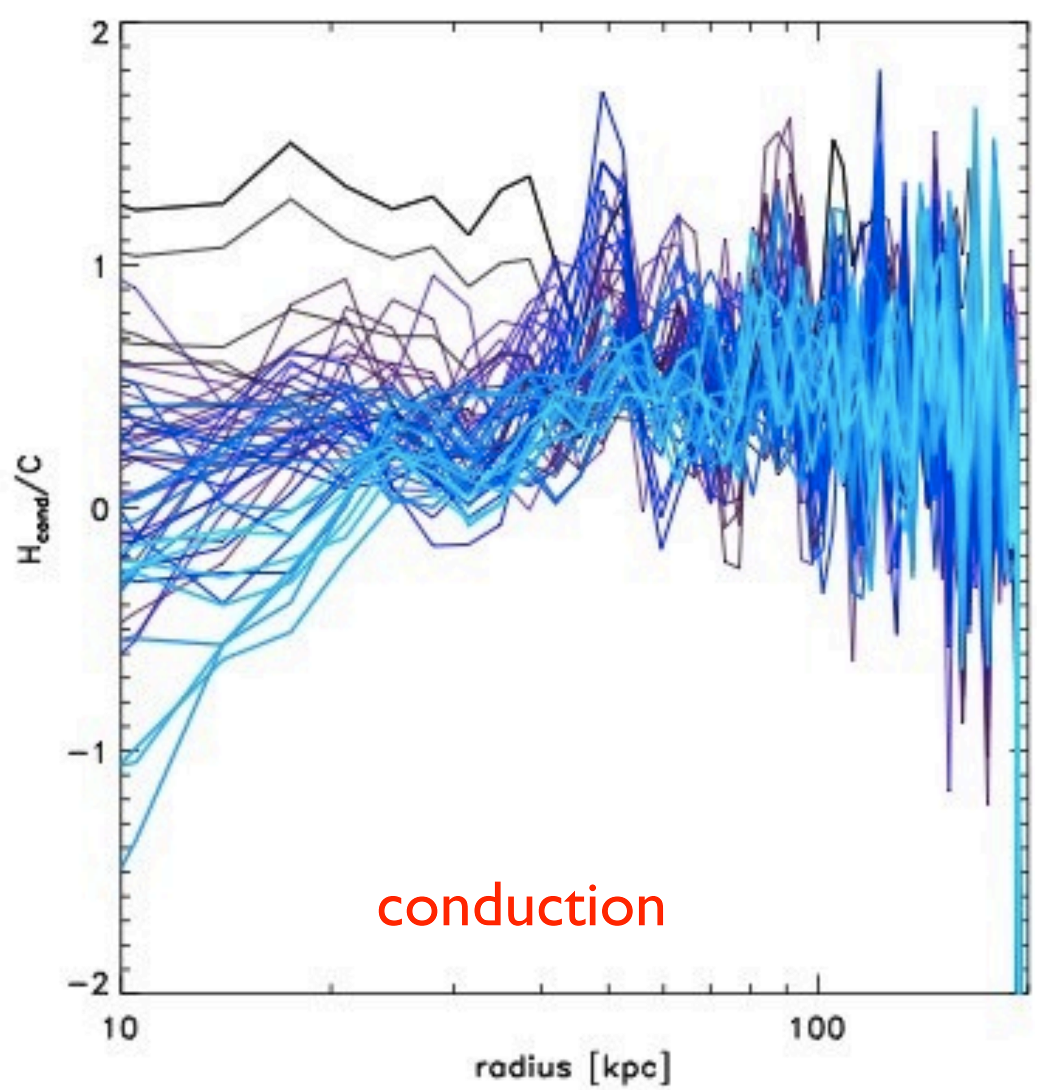


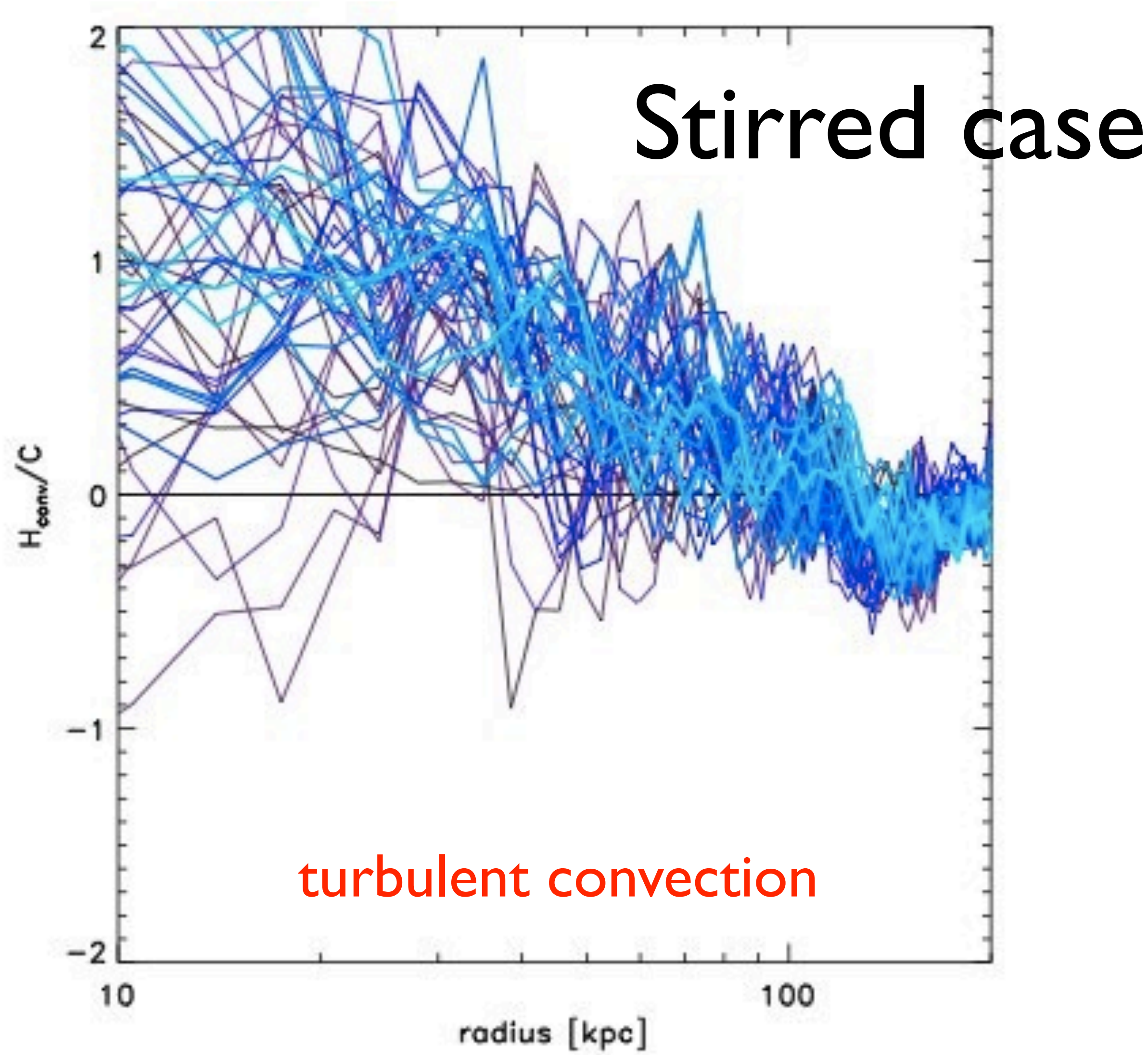
Pure hydro: cooling catastrophe



Likely that conduction facilitates turbulent diffusion

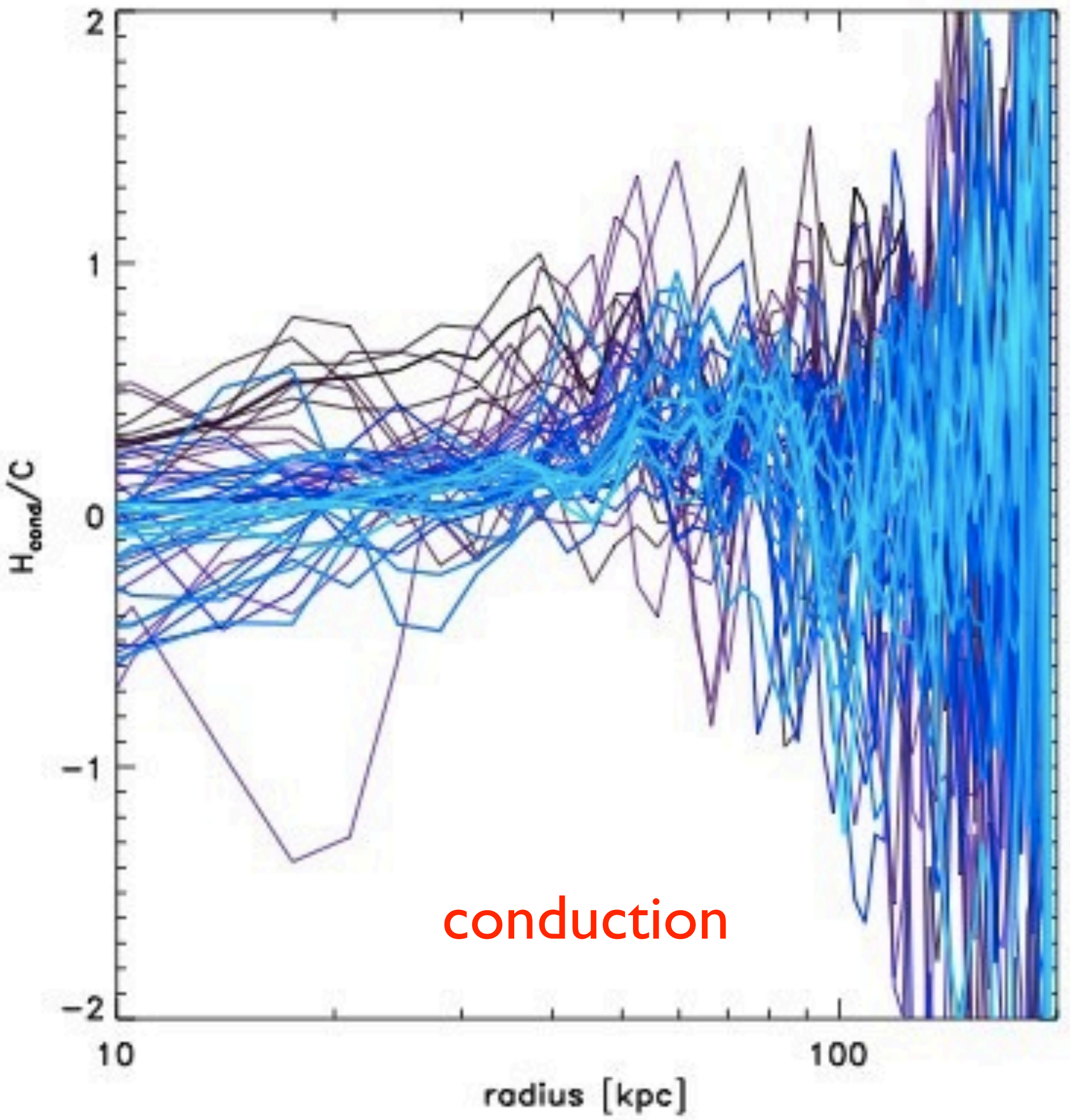
Conduction is more important in outer regions

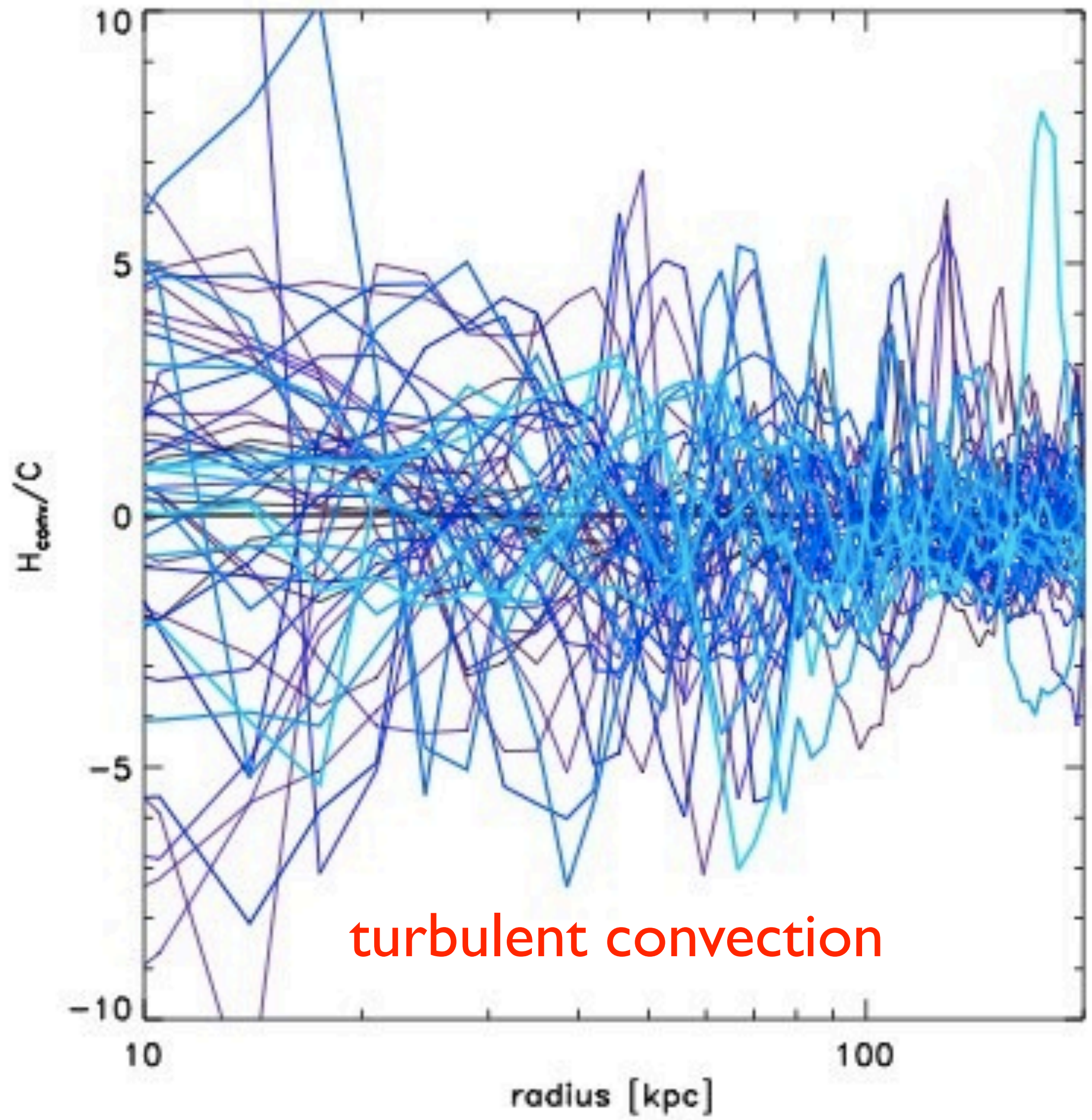




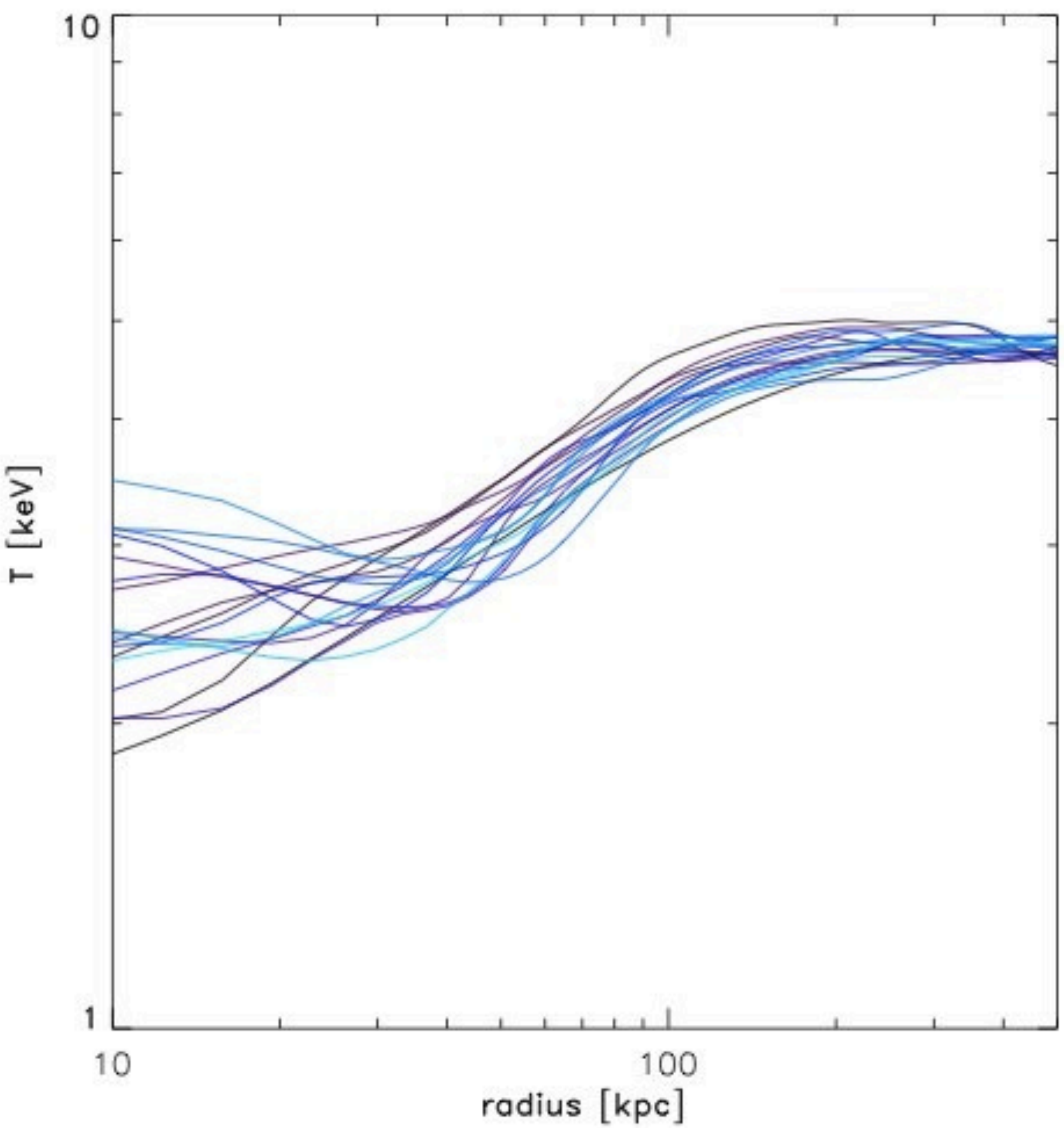
Turbulent heat transport more important in inner regions

galaxies case





So conduction-only solutions don't apply



Stable solutions don't have to be isothermal

Can have inverted temperature profiles near the center

Dissipation of turbulent motions is negligible

$$\Gamma = \frac{c_{\rm diss}\rho v_{\rm t}^3}{l} = \frac{c_{\rm diss}U_{\rm t}}{t_{\rm edd}}$$

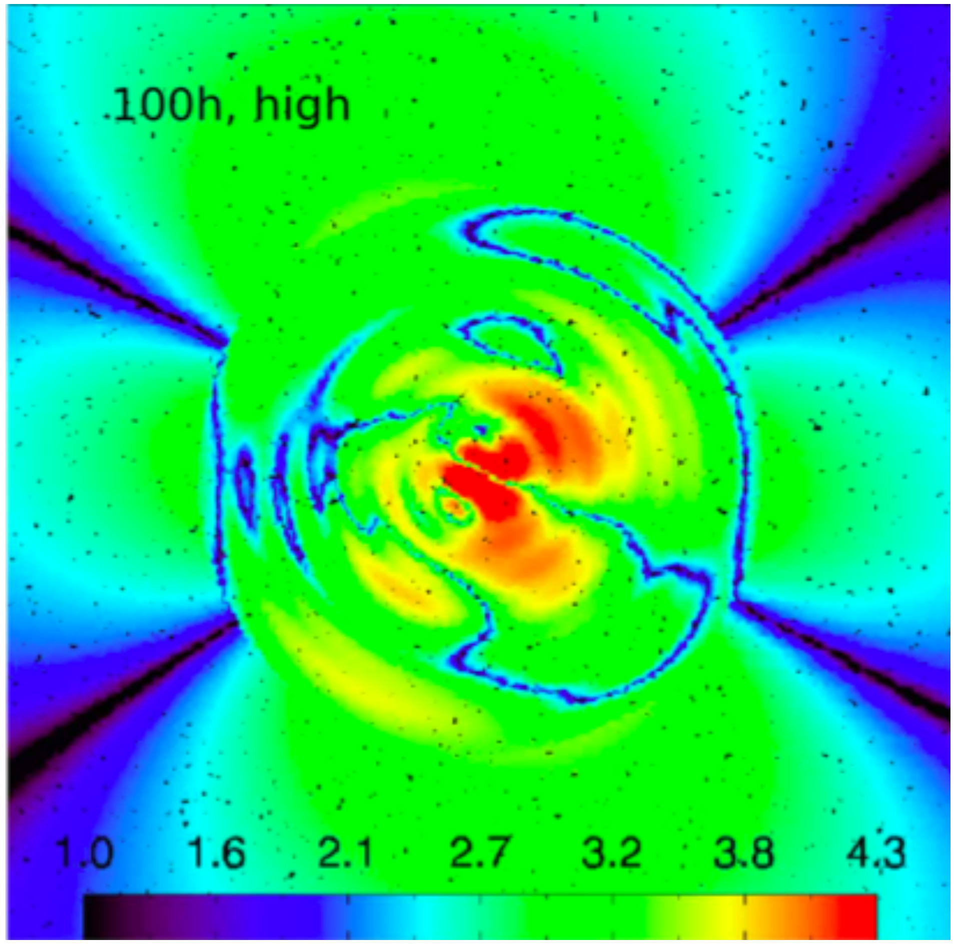
$$t_{\rm edd} \sim t_{\rm cool} \Rightarrow t_{\rm heat} = \frac{U_{\rm thermal}}{\Gamma} \approx \frac{U_{\rm thermal}}{U_{\rm turb}} t_{\rm cool} \sim 100 t_{\rm cool}$$

Dynamical friction heating unimportant in these simulations

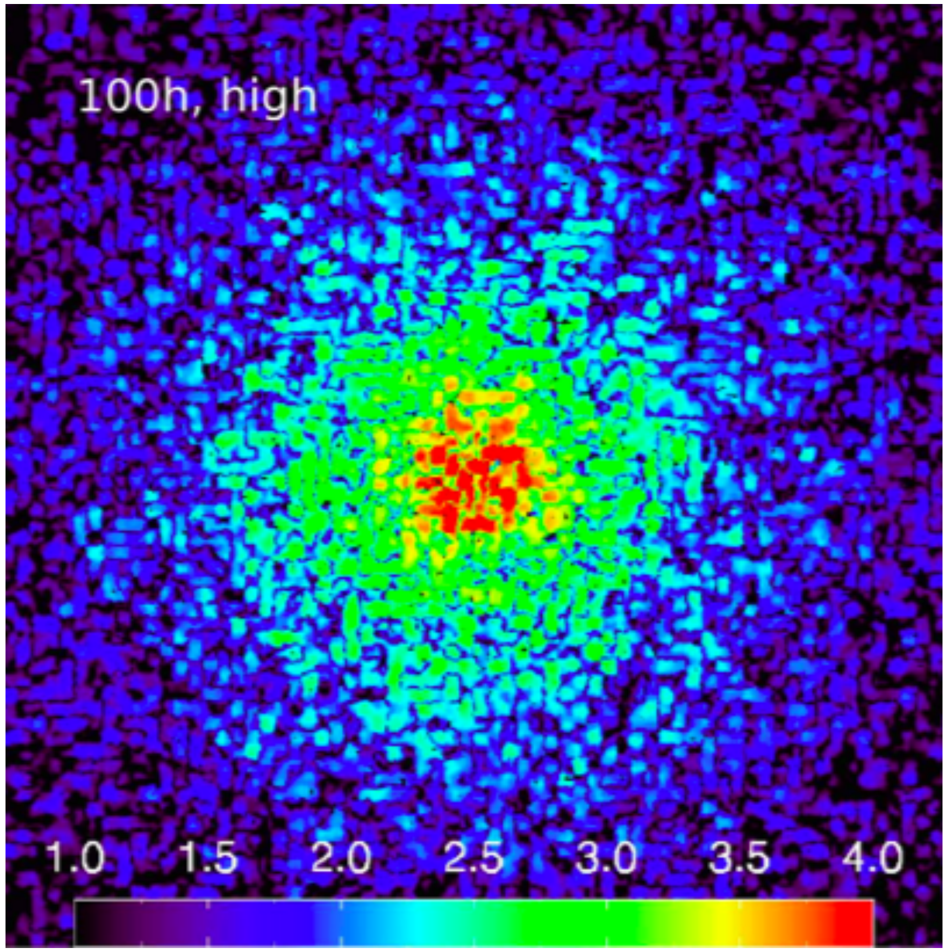
Implications

Faraday rotation could test field geometries

HBI/MTI dominated

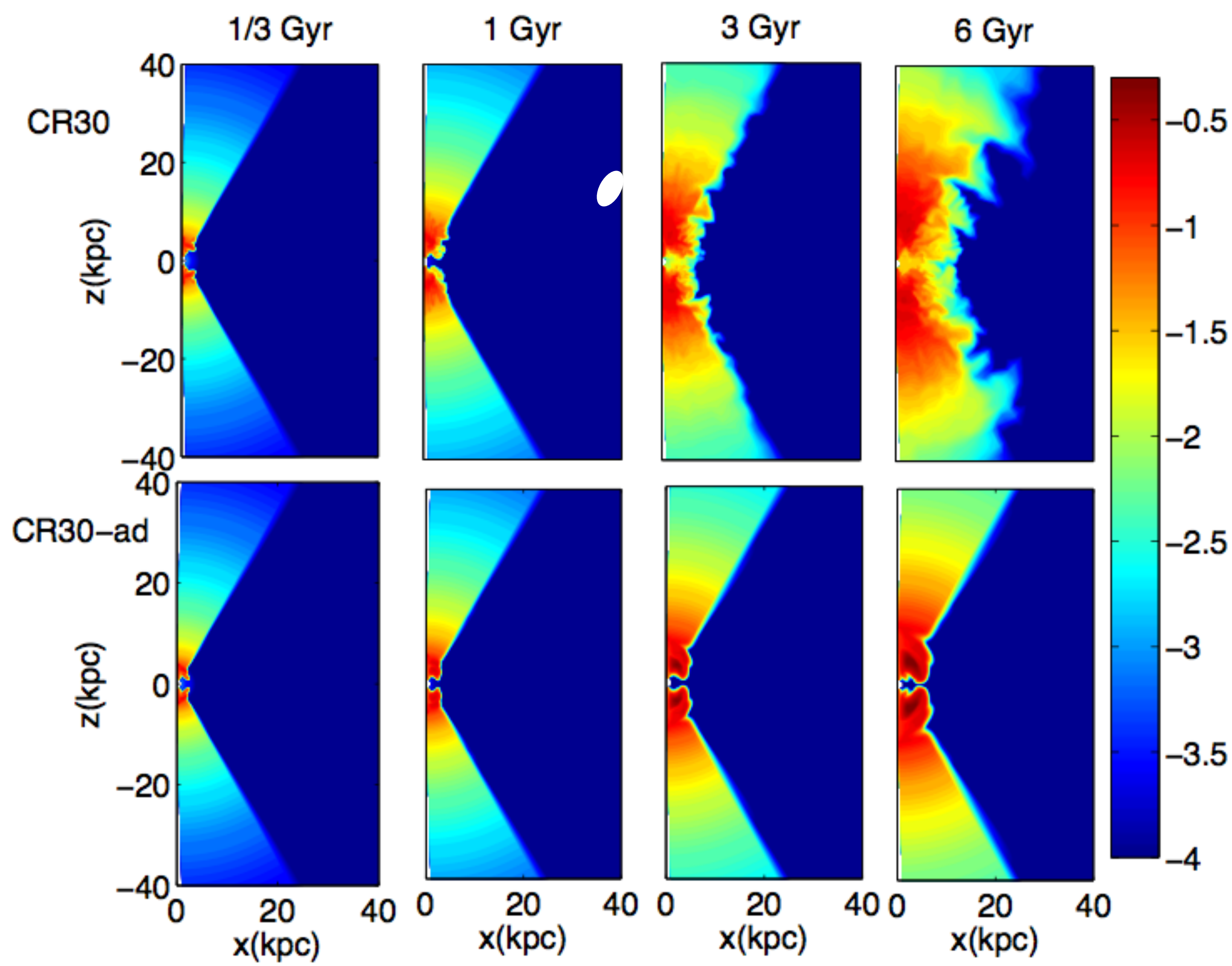


Turbulence dominated



Bogdanovic et al (2010)

Metal diffusion much more efficient with conduction

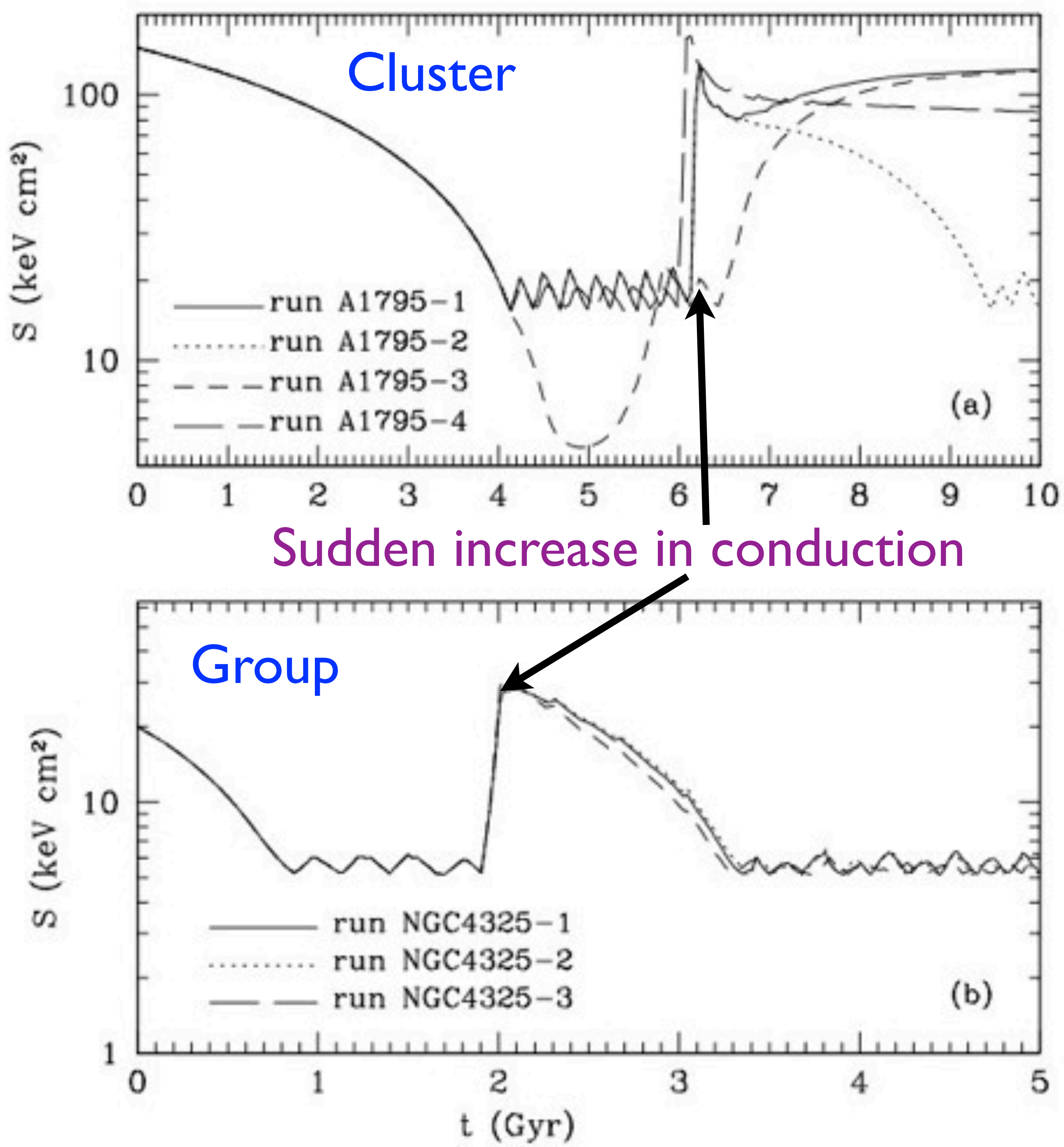


With conduction

No conduction

Sharma et al (2009)

Turbulence could regulate the CC to NCC transition...

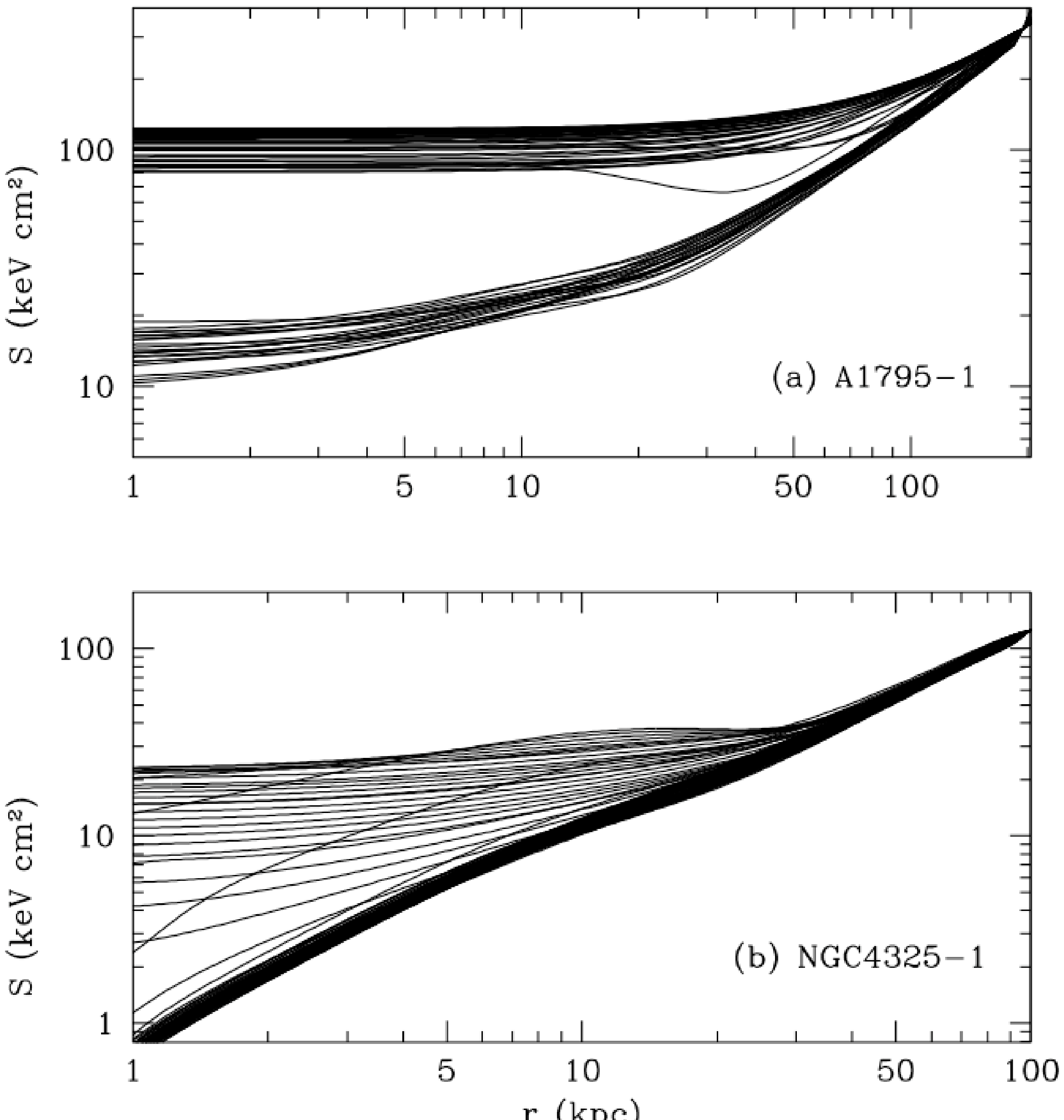


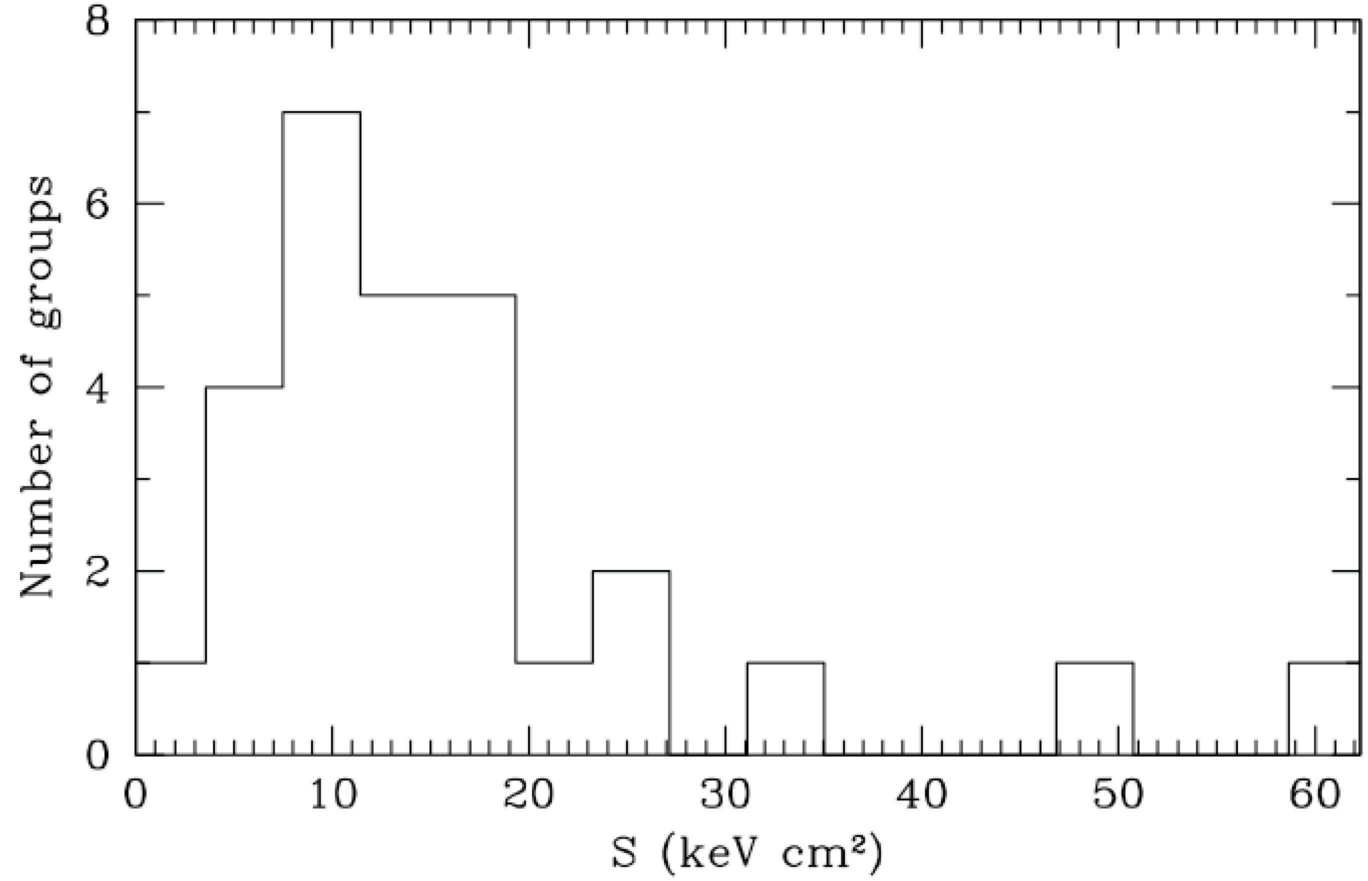
AGN or mergers could stimulate turbulence and change conductivity. Big impact on cluster profiles, even if their energetic contribution small

If this is right, should not see bimodality in groups

Guo & Oh (2009)

Guo & Oh (2009)



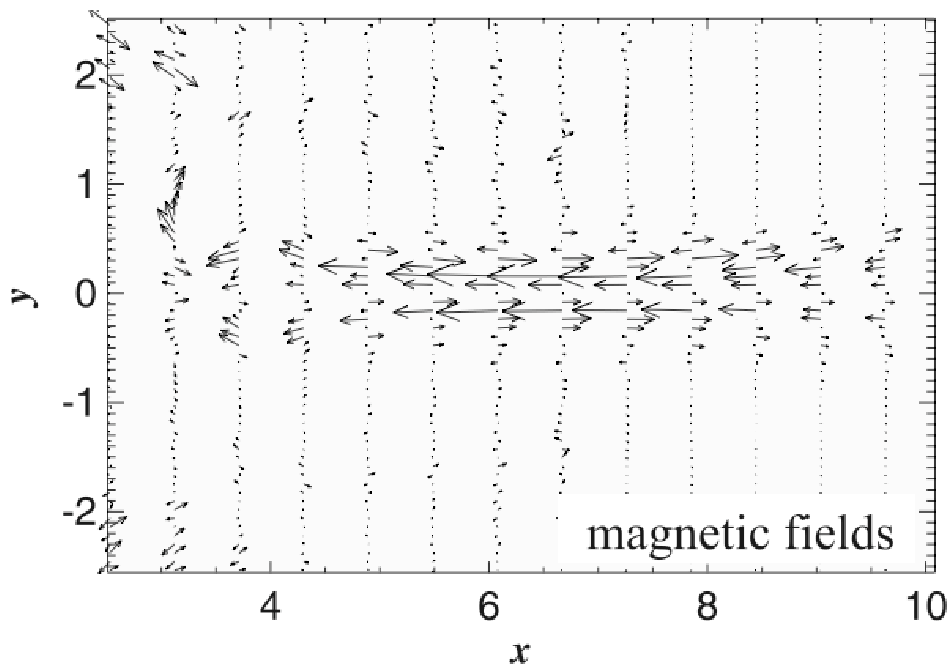


(group data from Johnson et al 2009)

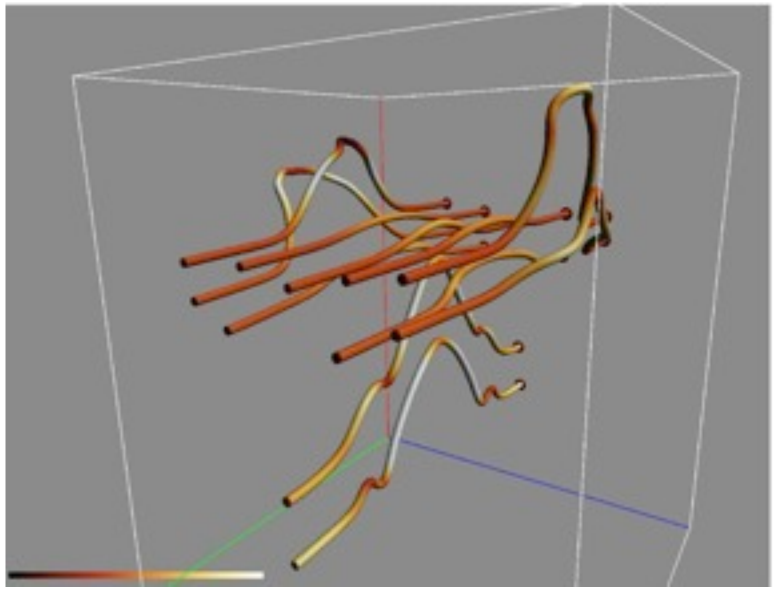
Groups are a useful test: cannot be stabilized by conduction, we predict no bimodality

...although role of turbulent heat transport in groups needs to be investigated

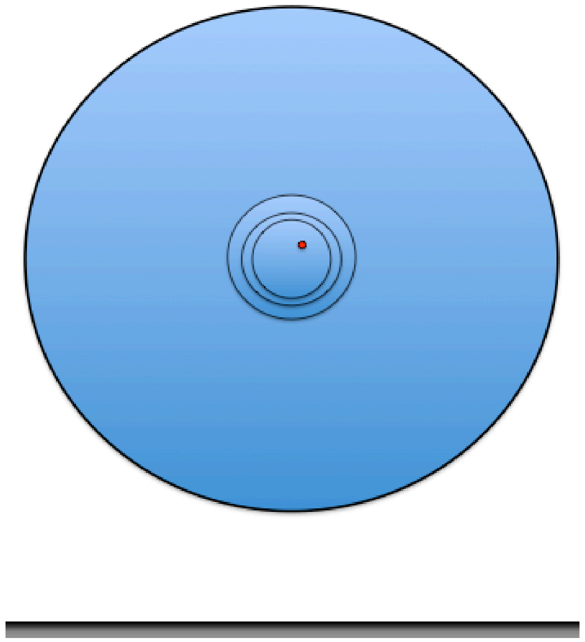
Could rising bubbles straighten field lines?

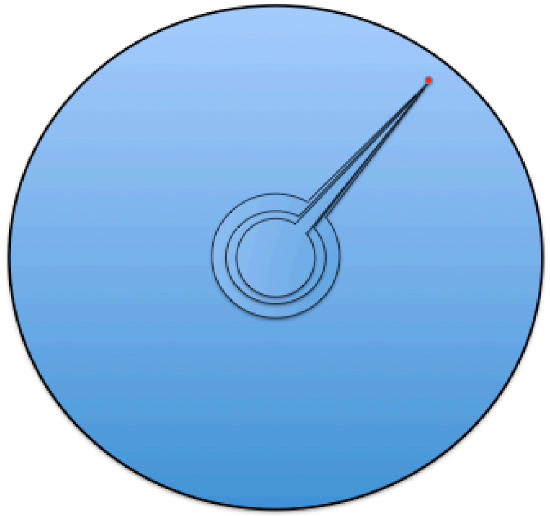


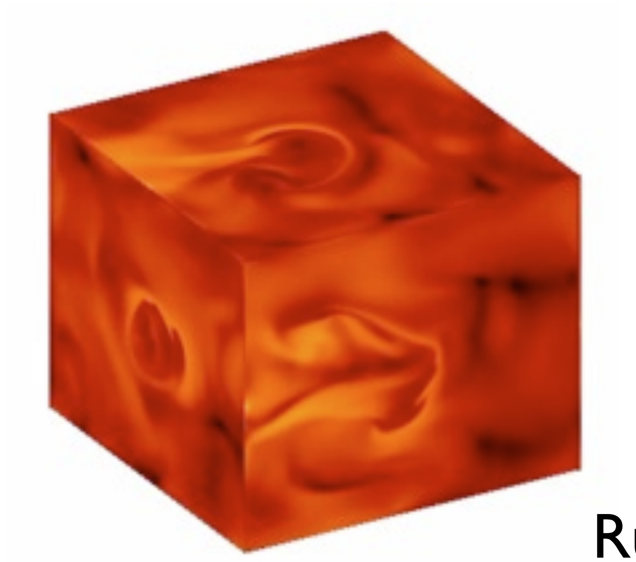
Asai et al (2007)



O'Neill et al (2009)

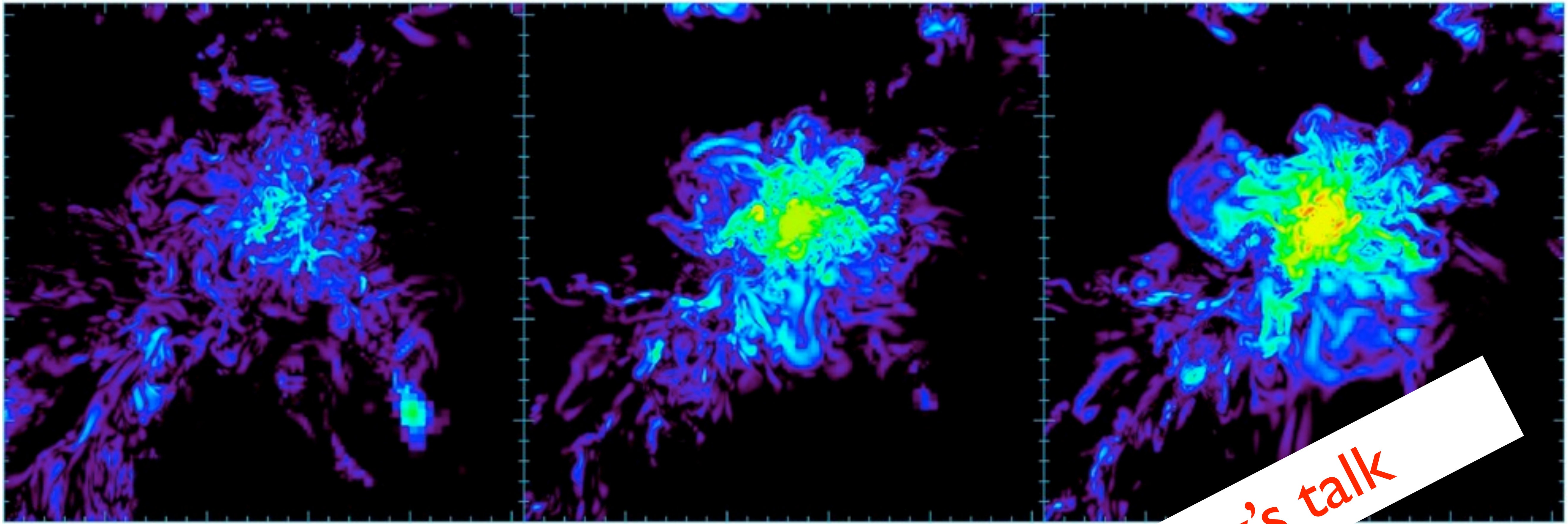






Ruszkowski et al (2007)

Can turbulence overwhelm the MTI?

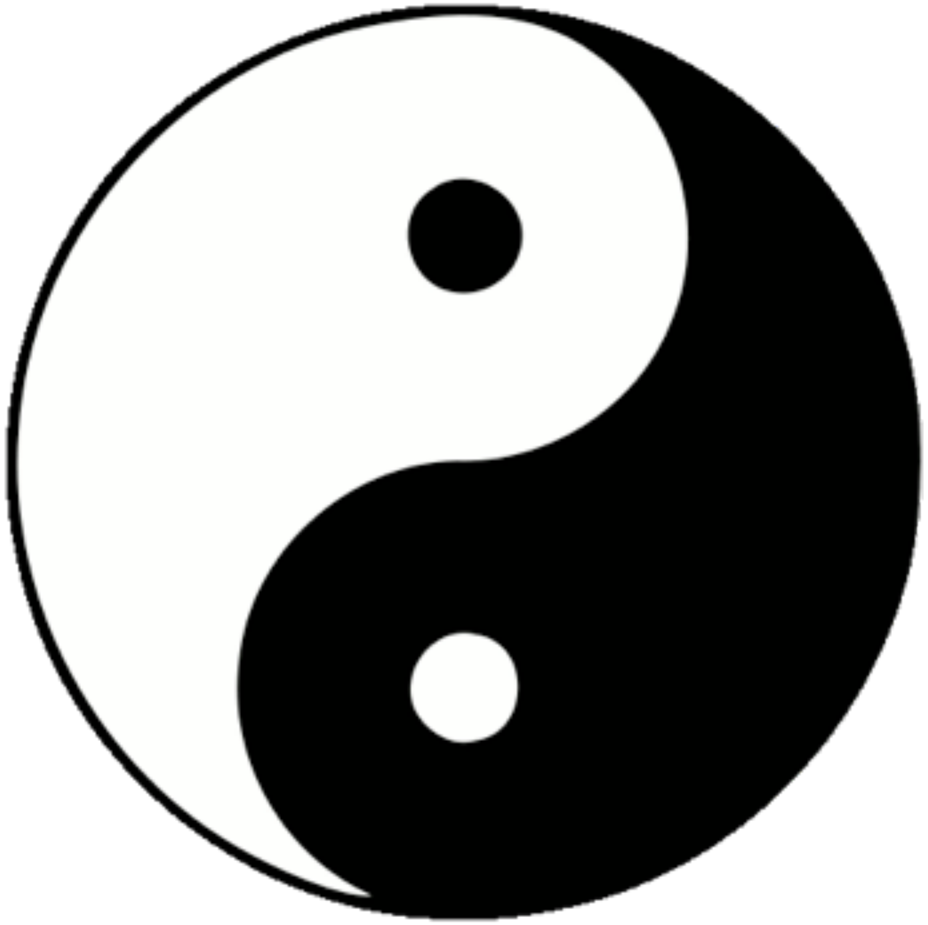


See Mateusz's talk

Conclusions

- Conduction reduces buoyancy forces
- Mild, subsonic turbulence is sufficient to overcome HBI and isotropize magnetic field, restoring conduction
- Galaxies which excite g-modes can provide this volume-filling turbulence
- Turbulent heat diffusion is important, but may be aided by conduction

The Tao of Heat Transport



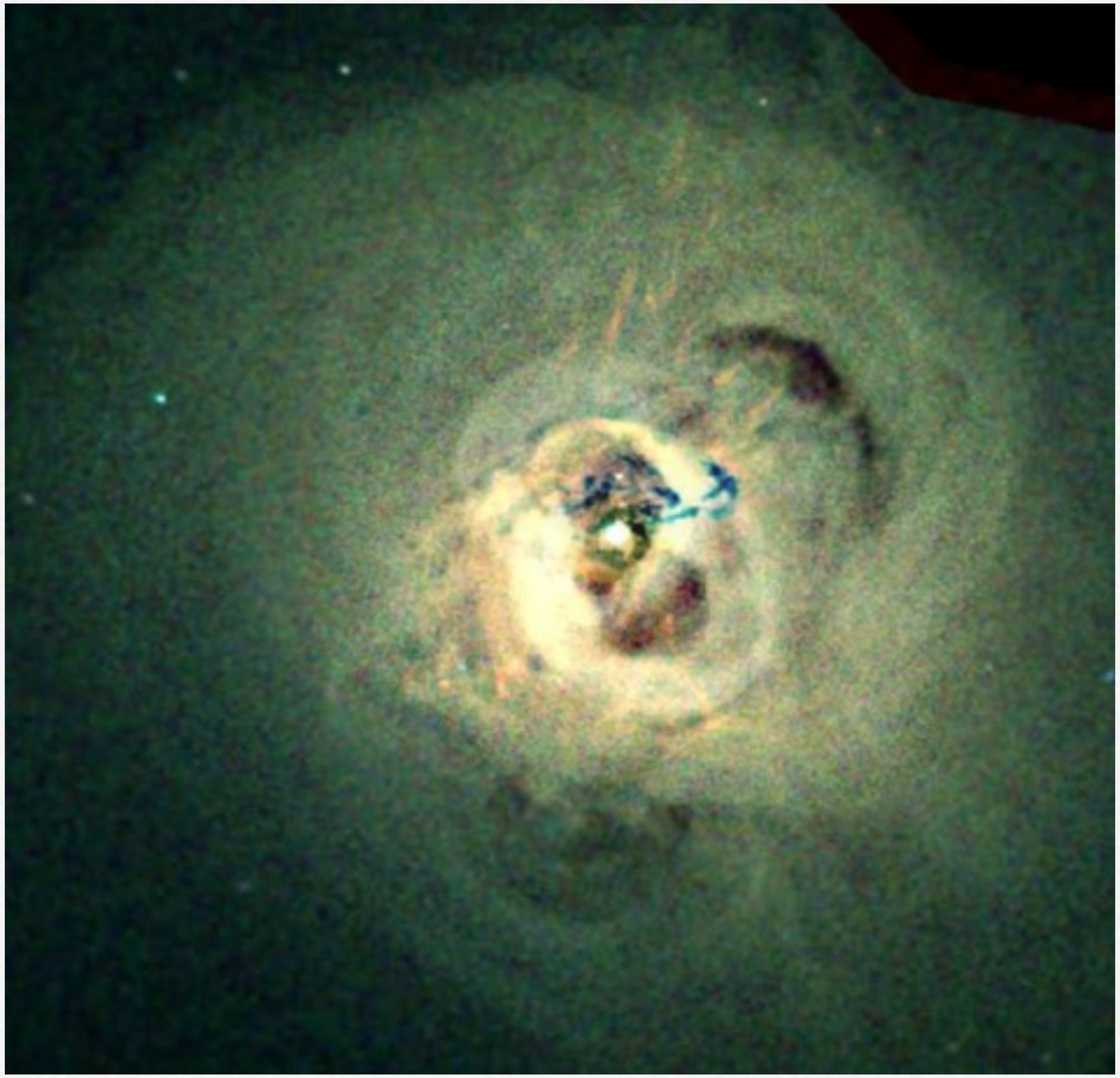
Conduction

Turbulence

Other stuff

AGN/radio galaxy heating

See review by McNamara & Nulsen (2007)



Chandra image, Perseus cluster

Bubbles observed in ICM, filled with hot/relativistic plasma

Maybe: entrain cold gas

pdV work

This talk: cosmic ray heating

(Guo & Oh 2008)

A key problem: CR transport is slow

$$\boldsymbol{F}_{\rm c} = \gamma_{\rm c} E_{\rm c}(\boldsymbol{u} + \boldsymbol{v}_{\rm A}) - \boldsymbol{n}\kappa_{\rm c}(\boldsymbol{n} \cdot \boldsymbol{\nabla} E_{\rm c}), \qquad \text{(A14)}$$

$$\frac{\partial E_{\rm c}}{\partial t} = (\gamma_{\rm c} - 1)(\boldsymbol{u} + \boldsymbol{v}_{\rm A}) \cdot \boldsymbol{\nabla}\, E_{\rm c} - \boldsymbol{\nabla} \cdot \boldsymbol{F}_{\rm c} + \bar{Q}. \qquad \text{(A15)}$$

Diffusive and other CR transport timescales are long

Leads to overpressured center with insufficient heating at outskirts (though may drive turbulent convection: Chandran & collaborators)

Method

- 1D Zeus code: solve time-dependent hydrodynamic equations + CR heating & transport equations
- calculate steady steady CR spectrum, assuming Coulomb, hadronic and Alfven-wave energy loses (latter dominates):

$$\Gamma_{wave} = v_A \frac{dP_c}{dr}$$

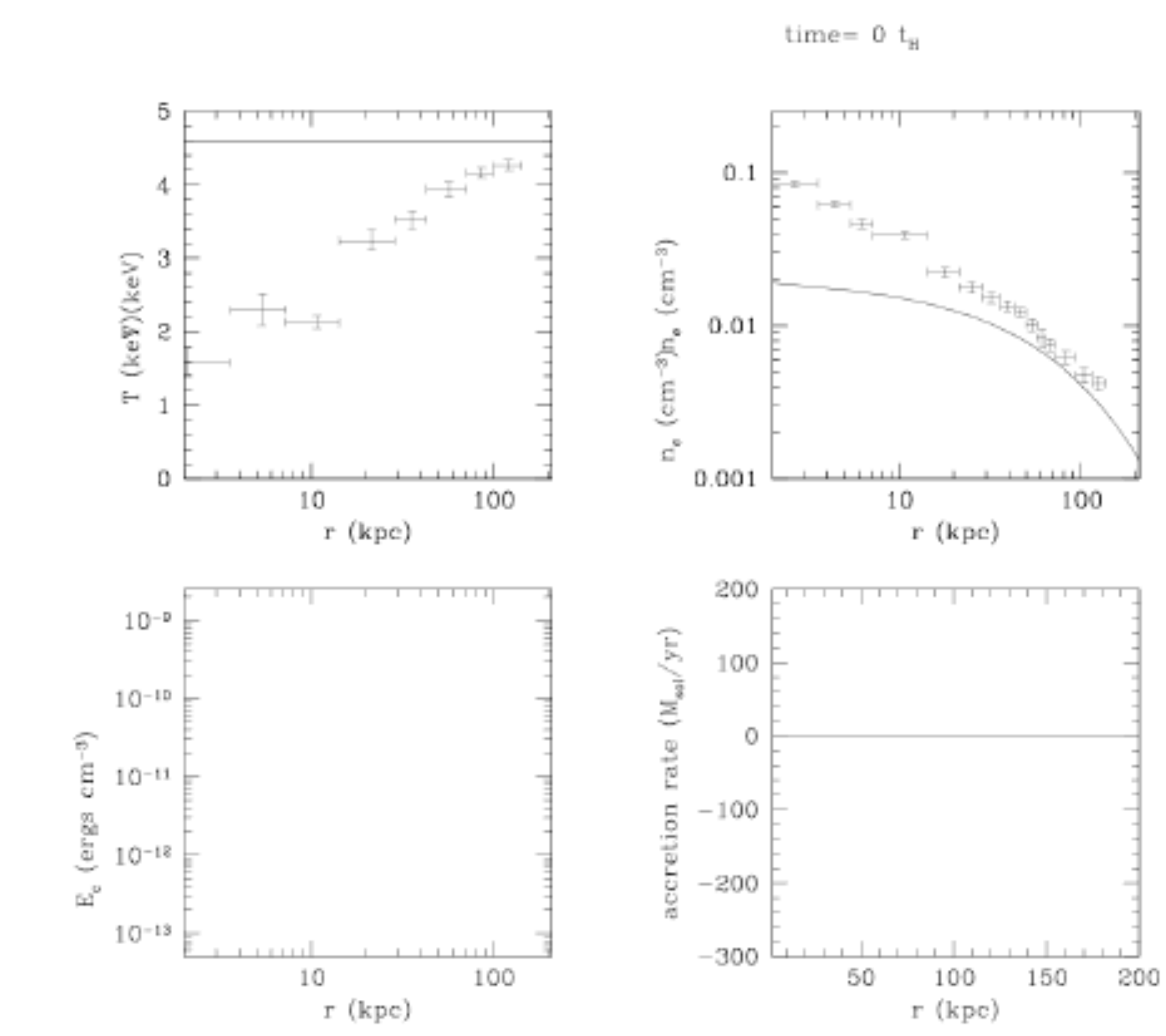
- Assume energy density in bubbles is a power-law with radius (note: CR injection rate depends on gas cooling---feedback effect)

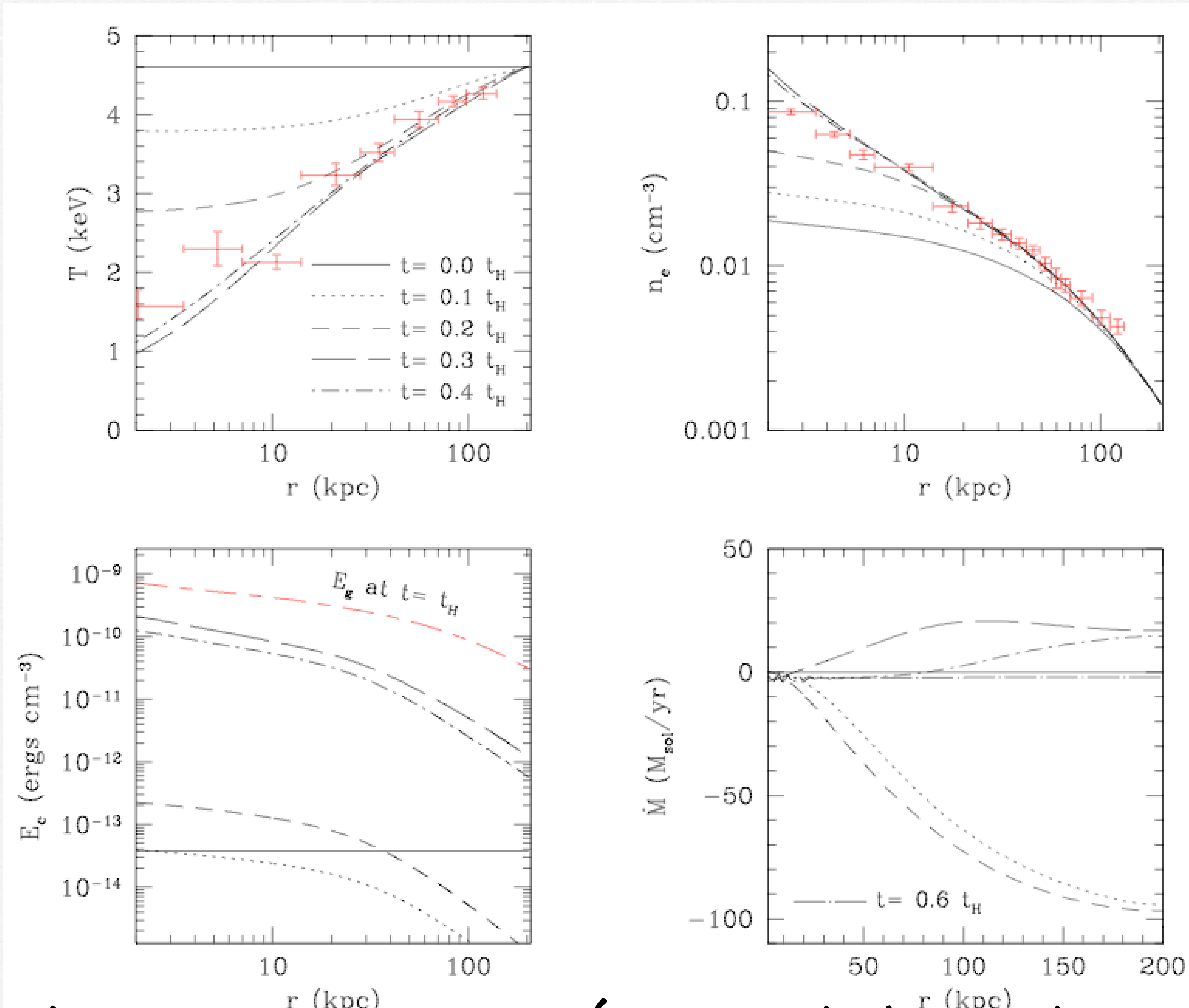
$$L_{\rm bubble} \sim -\epsilon \dot{M}_{\rm in} c^2 \left(\frac{r}{r_0}\right)^{-\nu} \quad \text{for } r > r_0,$$

$$\begin{aligned} Q_{\rm c} = \nabla \cdot \mathbf{F}_{\rm bubble} &\sim -\frac{1}{4\pi r^2} \frac{\partial L_{\rm bubble}}{\partial r} \left[1 - e^{-(r/r_0)^2}\right] \\ &\sim -\frac{\nu \epsilon \dot{M}_{\rm in} c^2}{4\pi r_0^3} \left(\frac{r}{r_0}\right)^{-3-\nu} \left[1 - e^{-(r/r_0)^2}\right], \end{aligned} \quad (19$$

Slope is free parameter, implicitly specifies bubble disruption rate

Bottom line: it works!

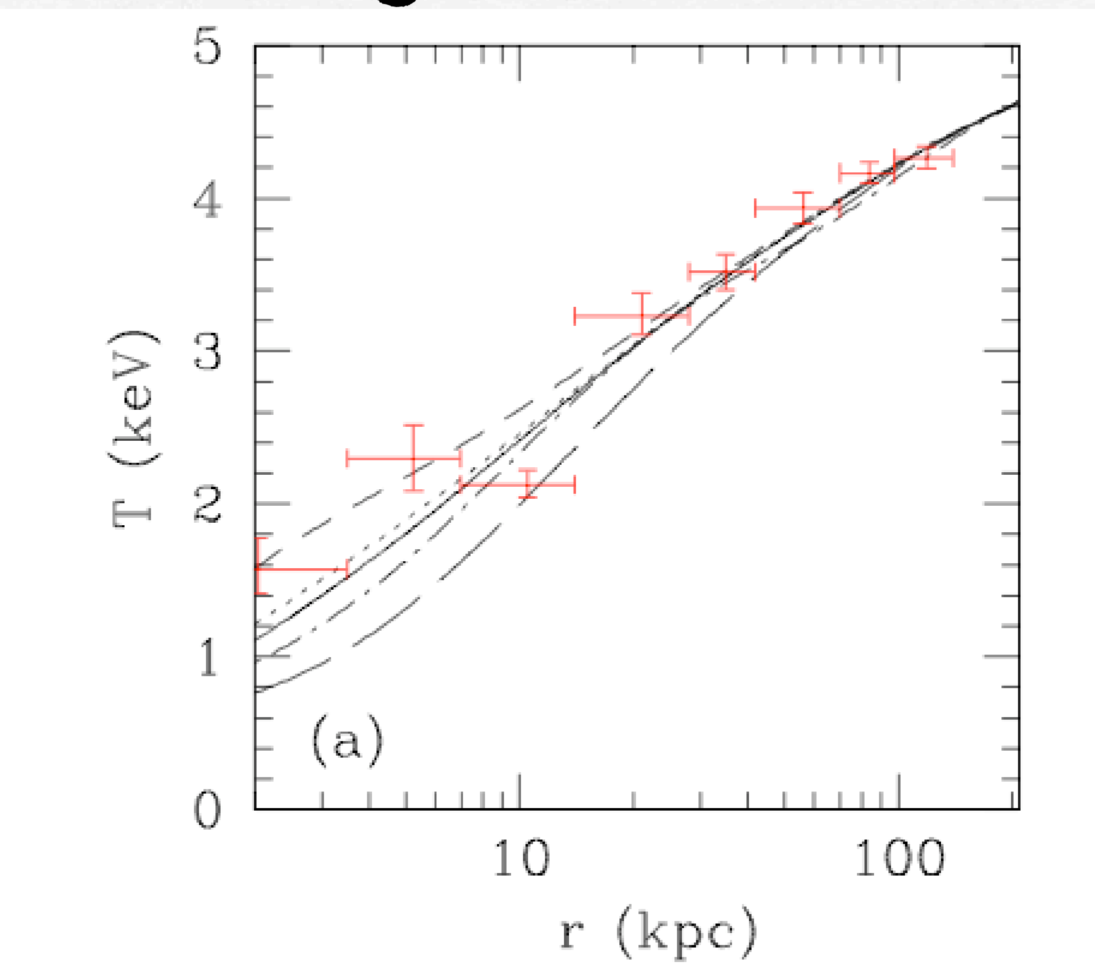




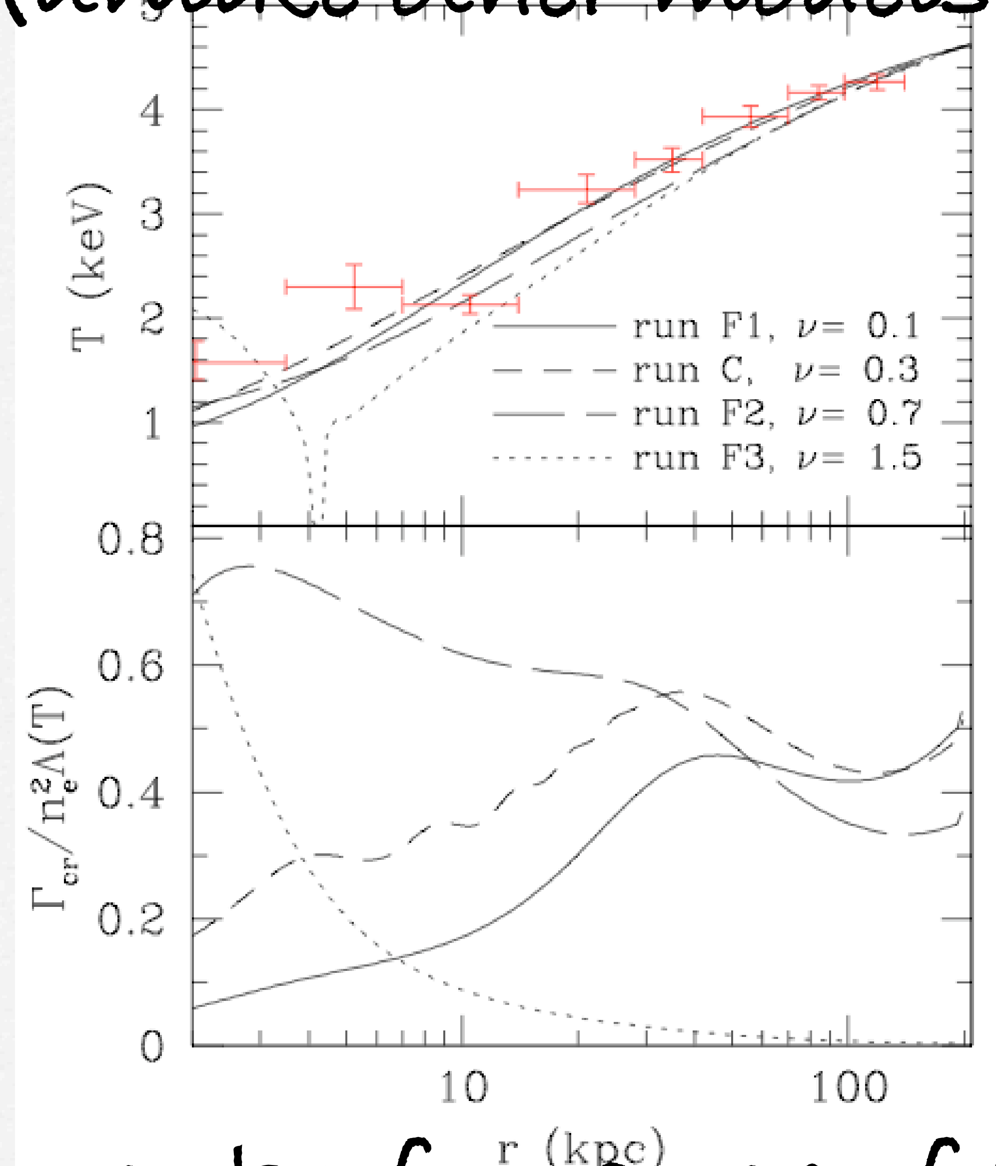
Note that CR pressure is much less than thermal pressure

No fine tuning

Works (i.e., no massive cooling flow) starting from arbitrary initial conditions (unlike other models...)

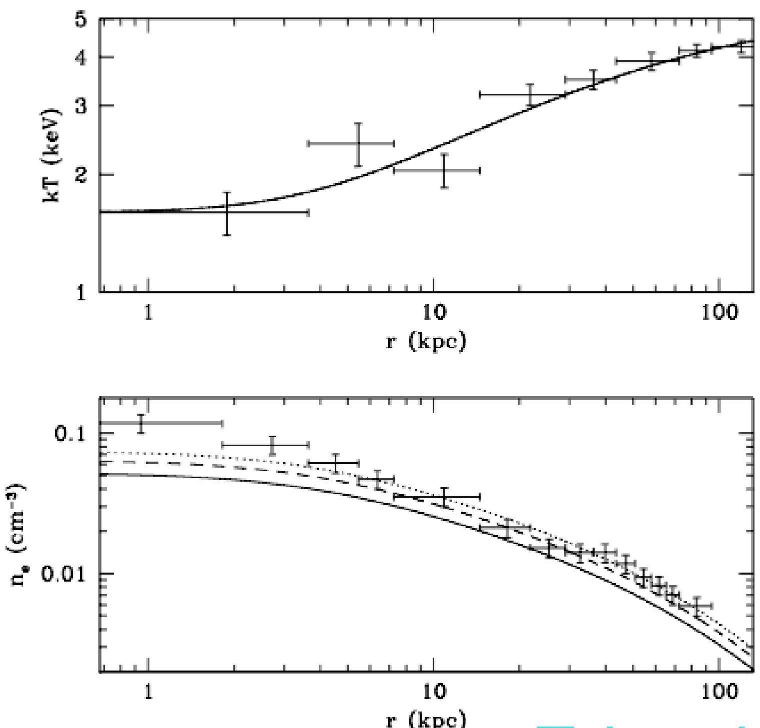


works for range of AGN + conduction parameters



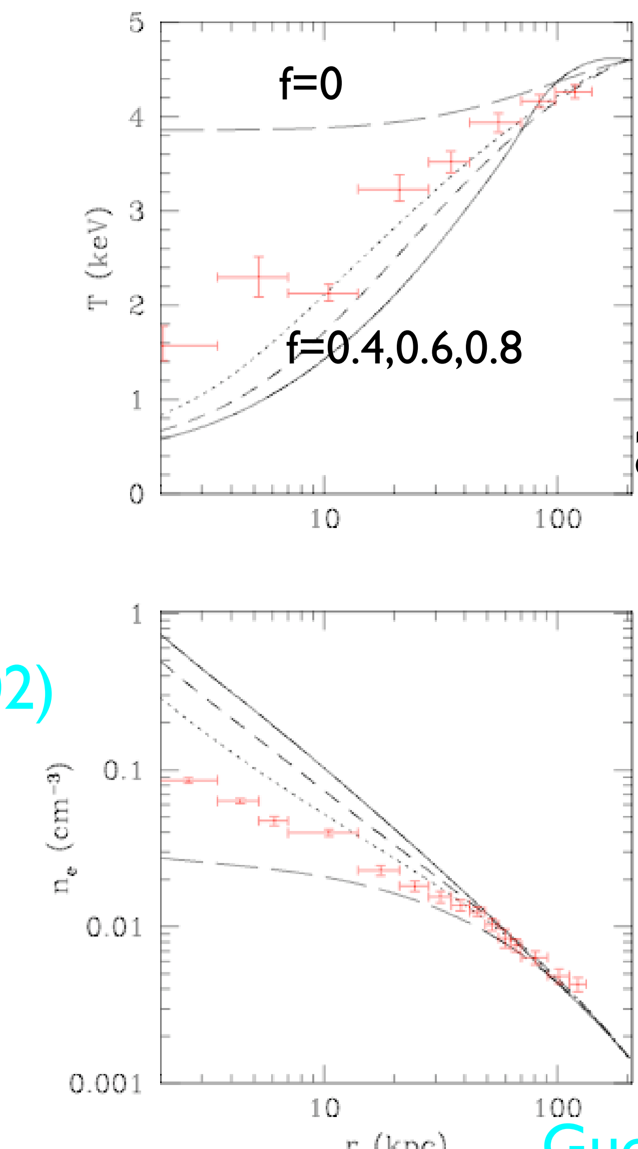
works for range of CR profiles

Theoretical Puzzle: How to Guarantee Stability and Avoid Fine Tuning ?



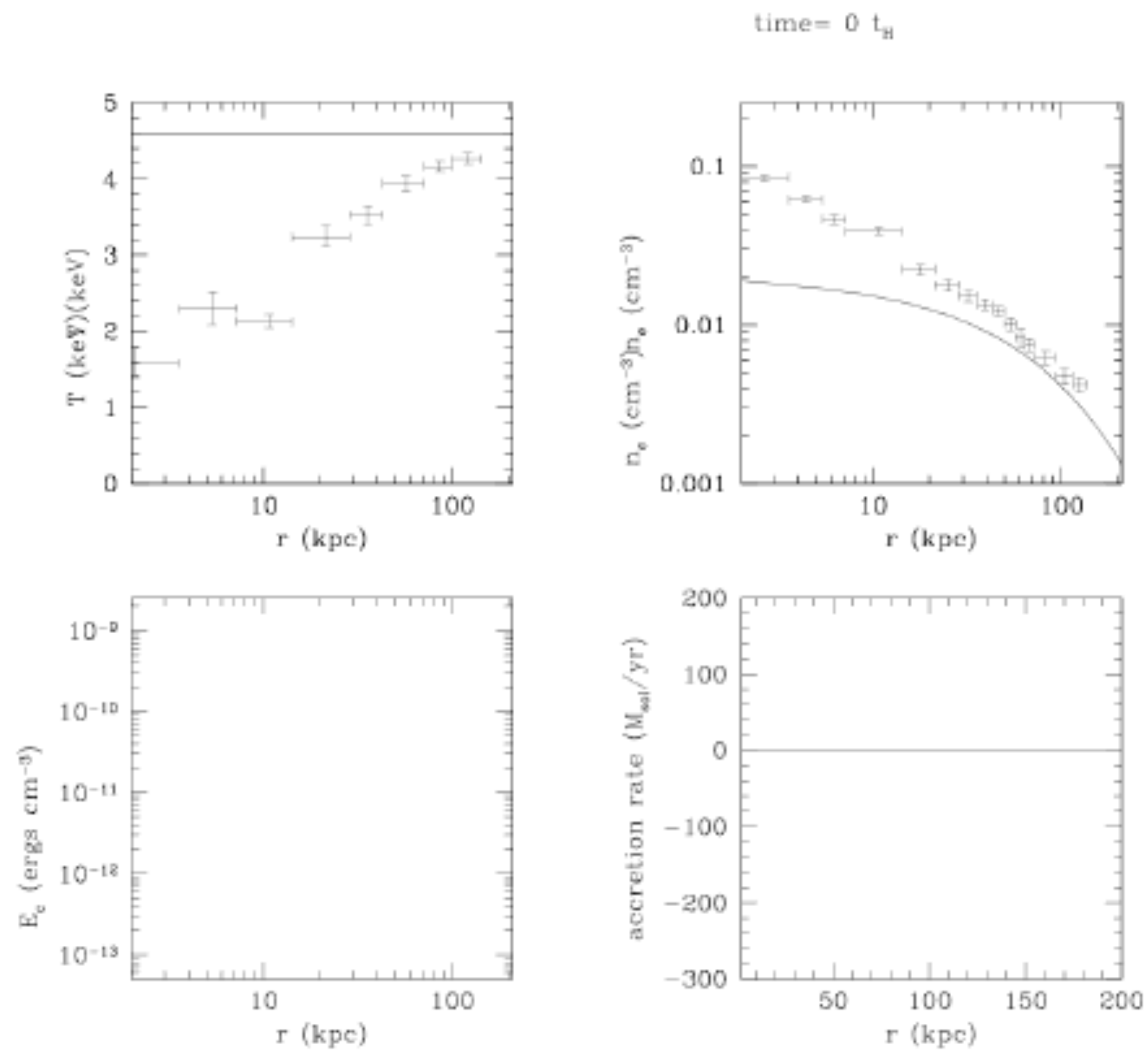
Zakamska & Narayan (2002)

Conduction only model can fit observations (solve eigenvalue problem)



Guo & Oh 2008

But have to tune parameters, and it won't evolve toward this state in general...



Guo & Oh (2008) -- see also Ruszkowski & Begelman (2002)

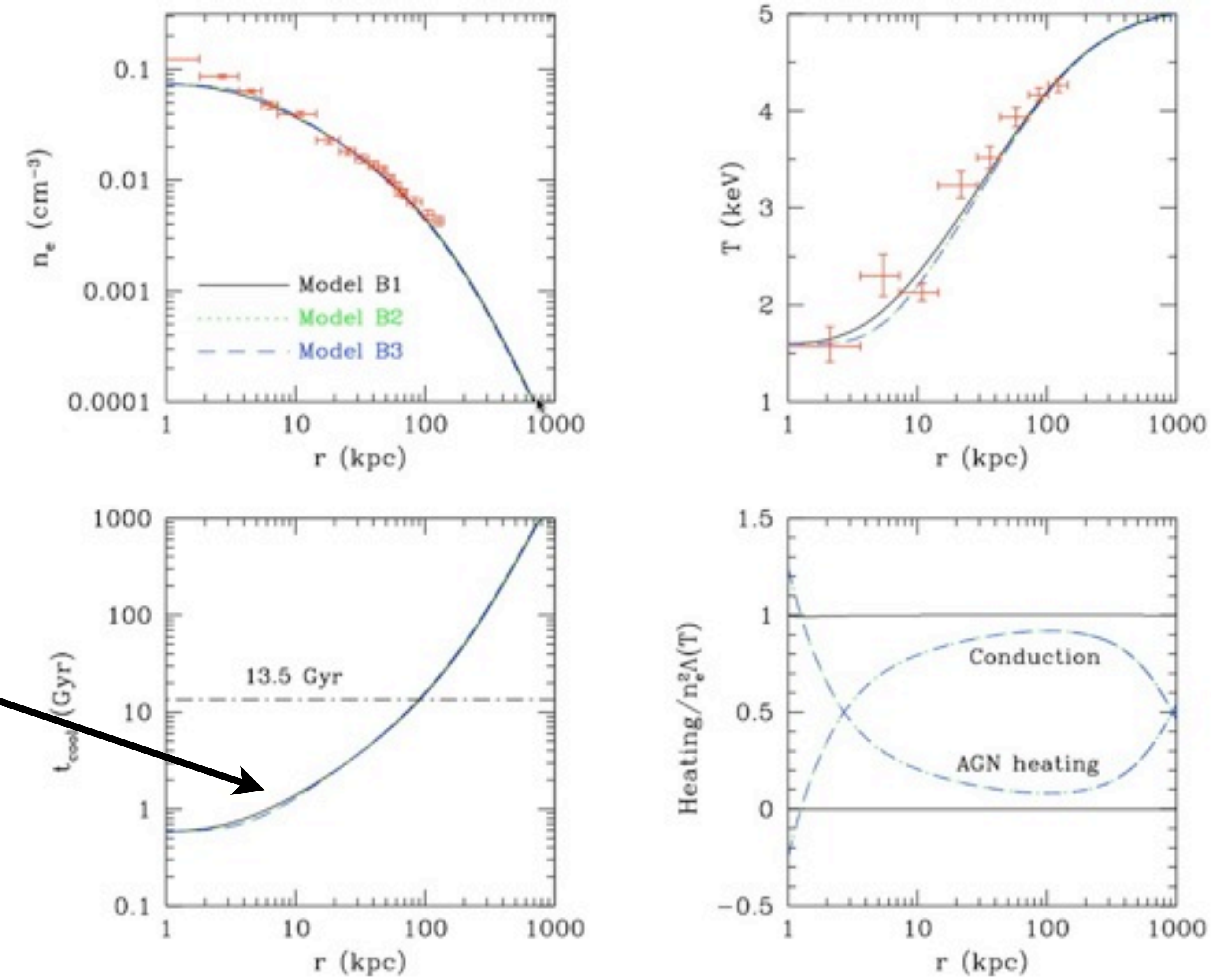
2) Observed profiles are an attractor solution

How to understand this?

'Pick any two'

Semi-analytic model: Explore parameter space quickly
Aids in physical intuition

note short cooling time



First, build a background equilibrium solution

..and perform a global stability analysis

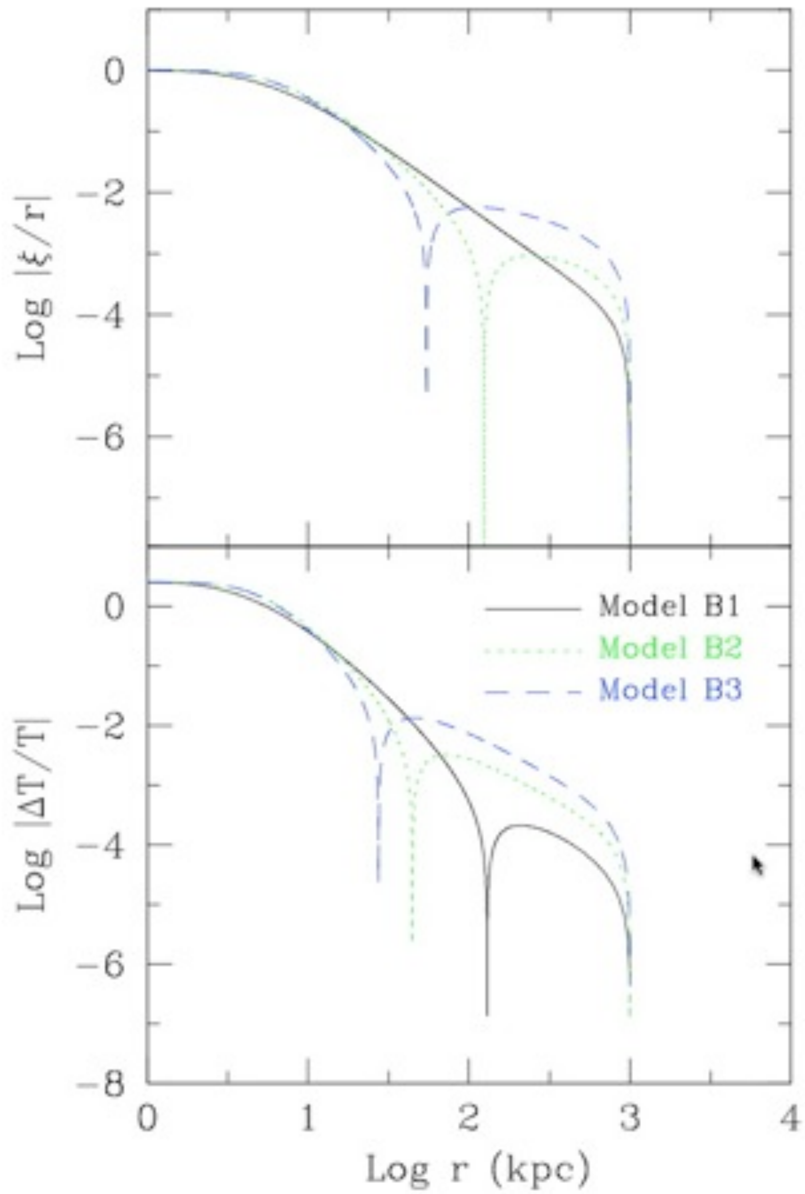
~~WKB~~

Done for conduction only case by Kim & Narayan (2003)

$$\left(\frac{P}{\rho} - v^2\right)\frac{d}{dr}(\nabla\cdot\boldsymbol{\xi}) = \left(r\sigma^2 + r\frac{d^2\Phi}{dr^2}\right)\frac{\xi}{r} + \frac{1}{\rho}\frac{d}{dr}\left(P\frac{\Delta T}{T}\right) - 2v^2\frac{d}{dr}\left(\frac{\xi}{r}\right) + \left(2\sigma v + v\frac{dv}{dr} - \frac{1}{\rho}\frac{dP}{dr}\right)\frac{d\xi}{dr} \quad (33)$$

$$\kappa T\frac{d}{dr}\left(\frac{\Delta T}{T}\right) = F\left[\frac{7}{2}\frac{\Delta T}{T} - r\frac{d}{dr}\left(\frac{\xi}{r}\right) + \frac{\xi}{r}\right] + \frac{\Delta L_r}{4\pi r^2} \quad (34)$$

$$\frac{1}{4\pi r^2}\frac{d}{dr}\Delta L_r = (P\sigma - \rho^2\mathcal{L}_\rho - \mathcal{H})(\nabla\cdot\boldsymbol{\xi}) - \Delta\mathcal{H} + \left(\frac{P\sigma}{\gamma-1} + \rho T\mathcal{L}_T + \frac{v}{\gamma-1}\frac{dP}{dr} - \frac{\gamma v}{\gamma-1}\frac{P}{\rho}\frac{d\rho}{dr}\right)\frac{\Delta T}{T} + Pv\frac{d}{dr}(\nabla\cdot\boldsymbol{\xi}) + \frac{Pv}{\gamma-1}\frac{d}{dr}\left(\frac{\Delta T}{T}\right) \quad (35)$$



Growth rate is an eigenvalue of analysis

Explore parameter space rapidly!

Guo, Oh & Ruszkowski 2008

Just as in Stellar Structure calculations...

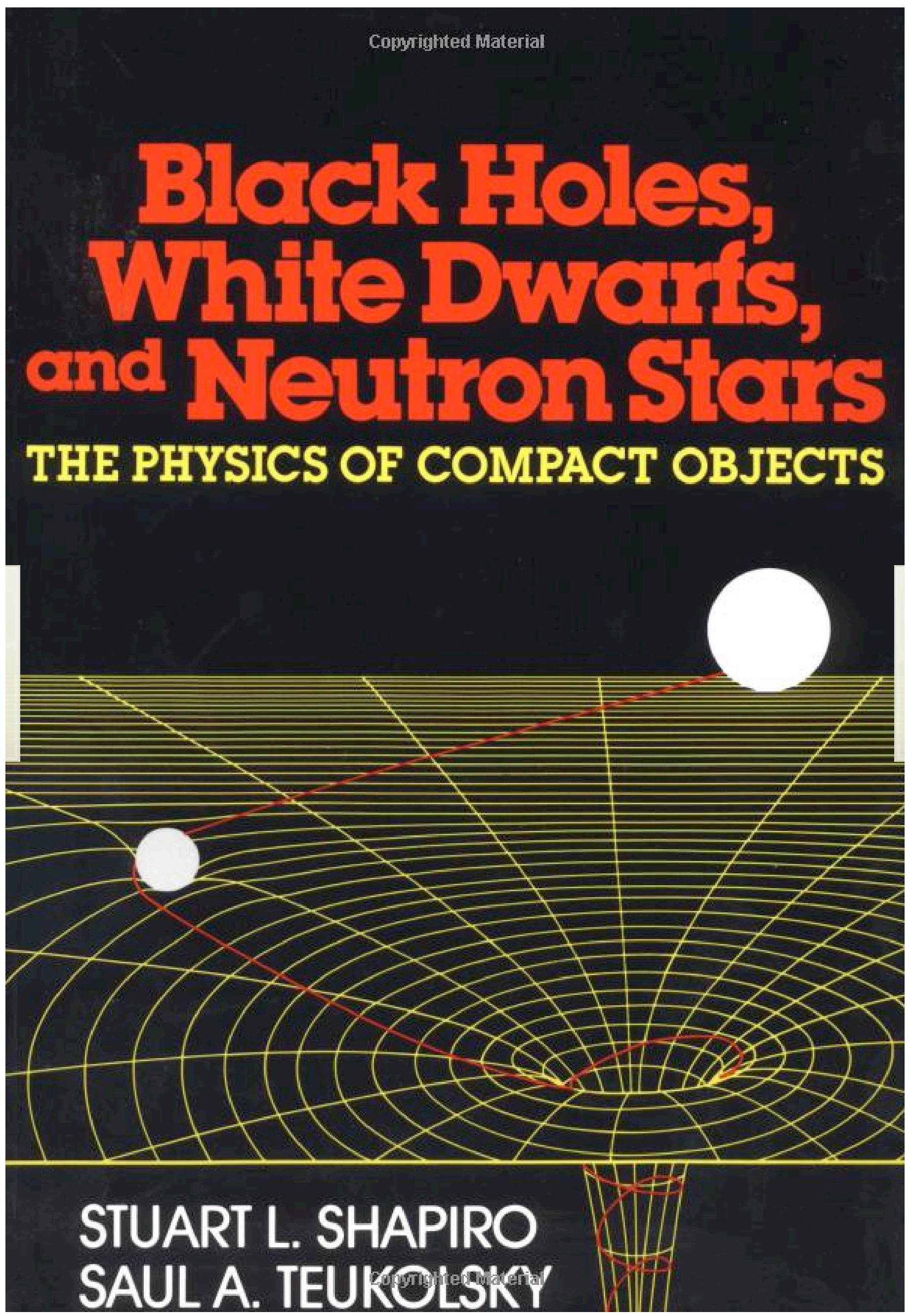
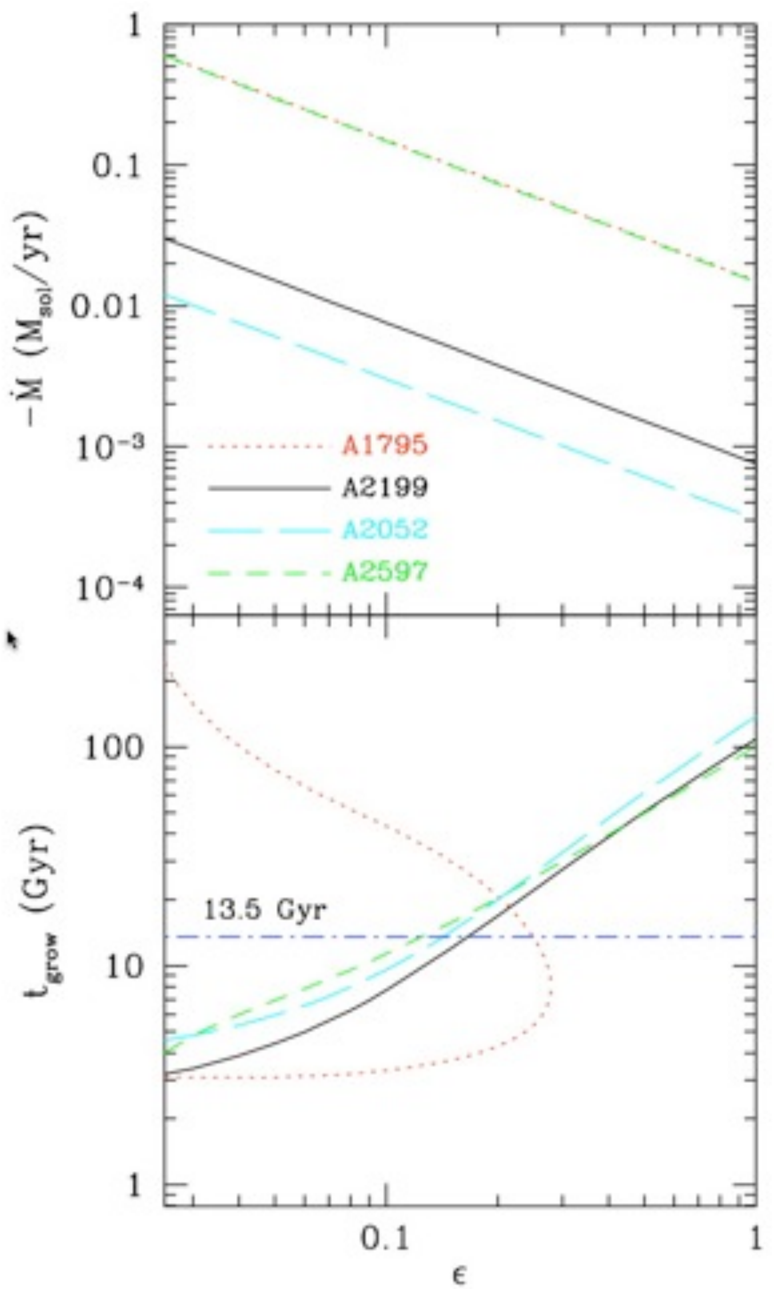


Fig from A. Piro

Global unstable modes suppressed with AGN!

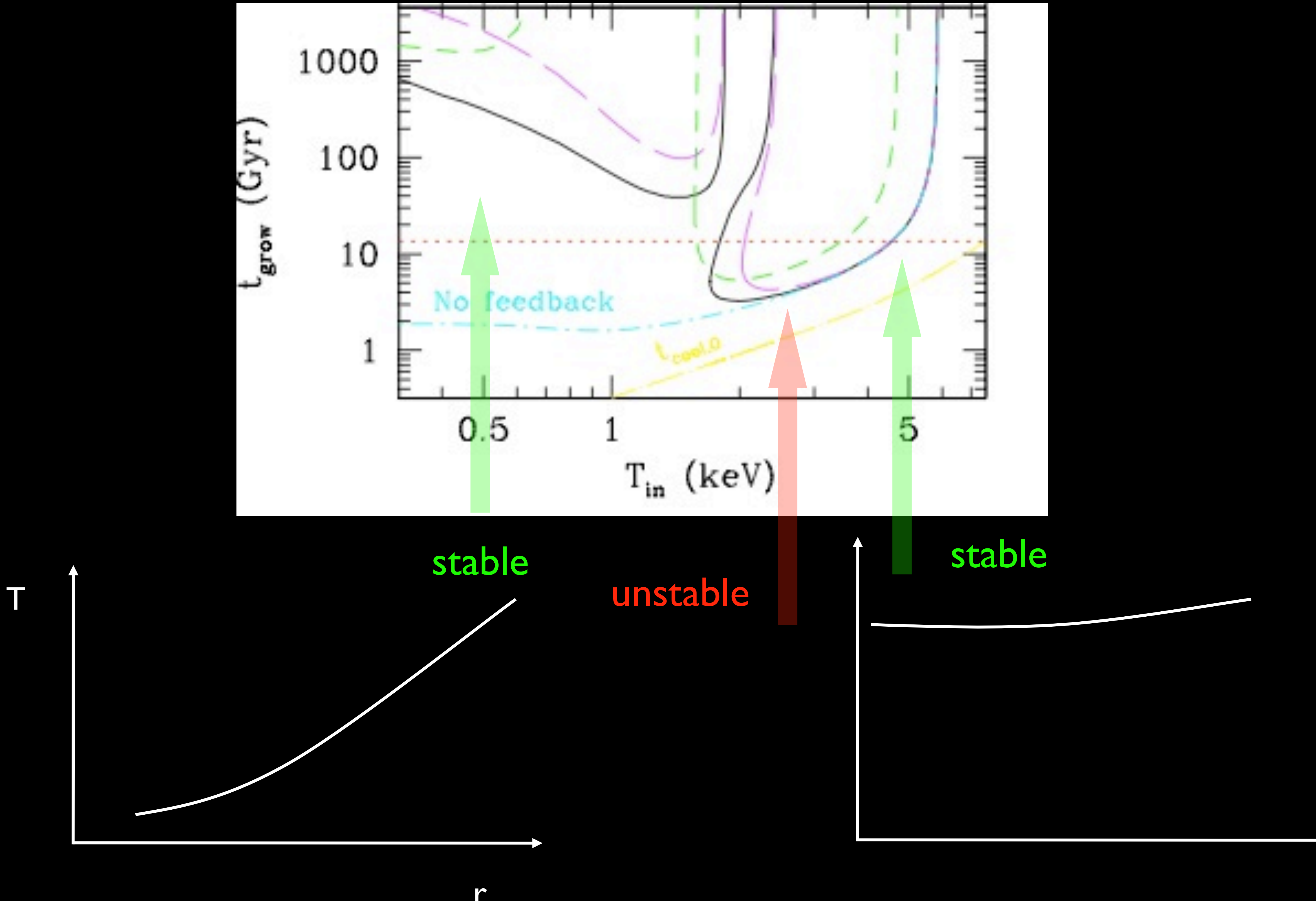


Suppression depends on efficiency

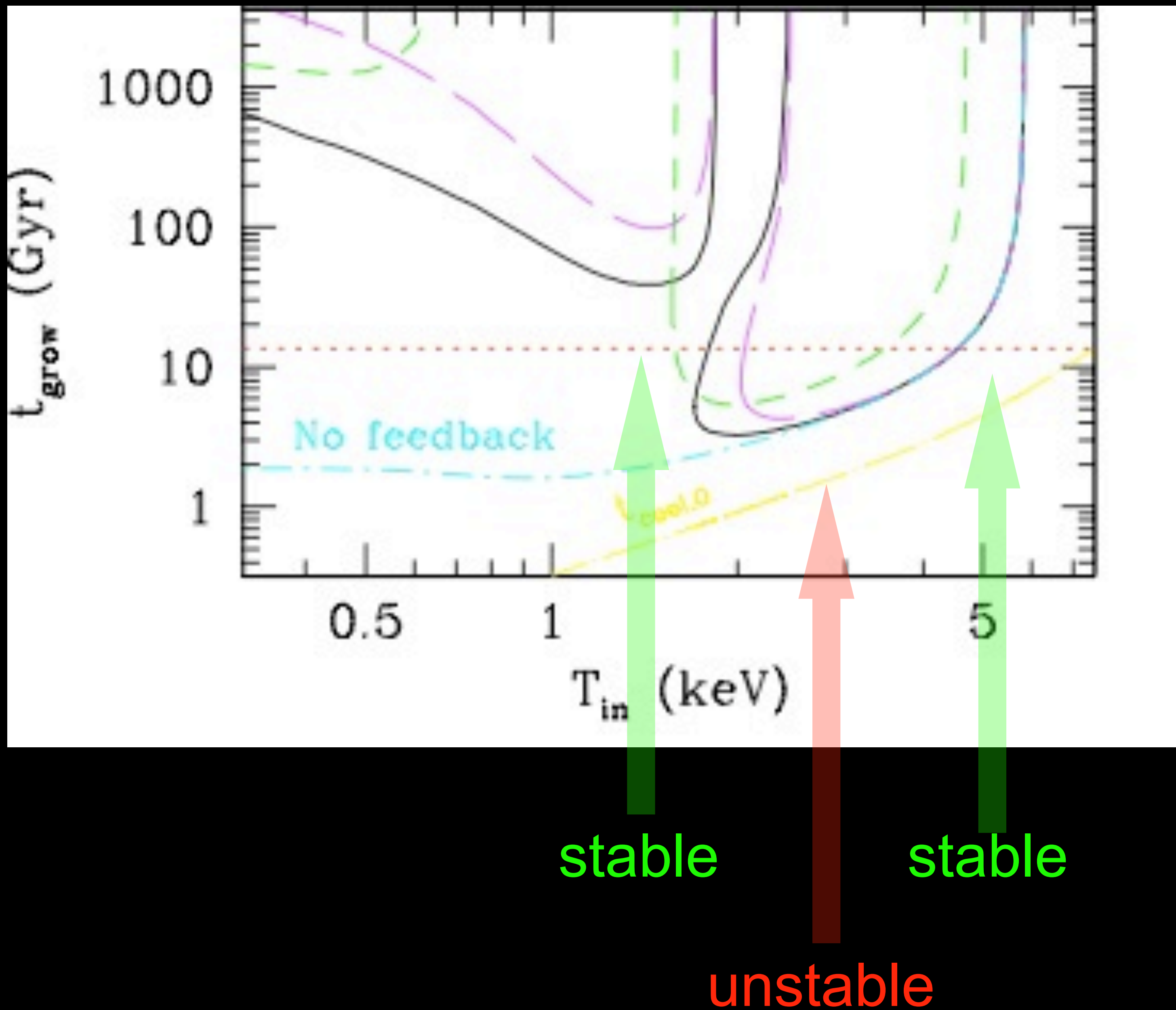
$$L_{\rm agn} = -\epsilon \dot{M}_{\rm in} c^2,$$

The crucial term: feedback

$$\Delta\mathcal{H}_{\rm feed} \equiv \mathcal{H}\Delta\dot{M}(r_{\rm in})/\dot{M}_{\rm in} = \frac{\mathcal{H}\sigma}{v_0}\xi(r_{\rm in}) \ ,$$



Stability is bimodal!



<u>Bimodality !</u>

cool core ← stabilized by AGN + conduction

non cool core ← stabilized by conduction