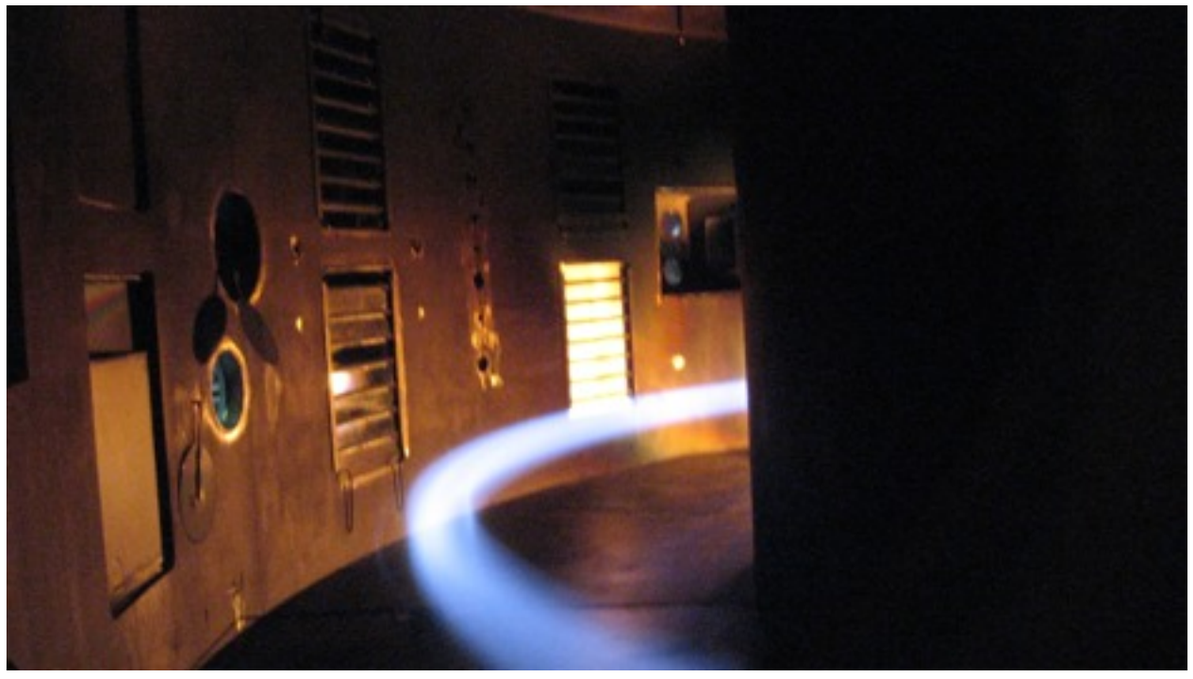
Clusters of Galaxies as Plasma Physics Laboratories

Peng Oh (UCSB)



Ongoing Cluster Workshop at KITP

Galaxy Clusters: the Crossroads of Astrophysics and Cosmology

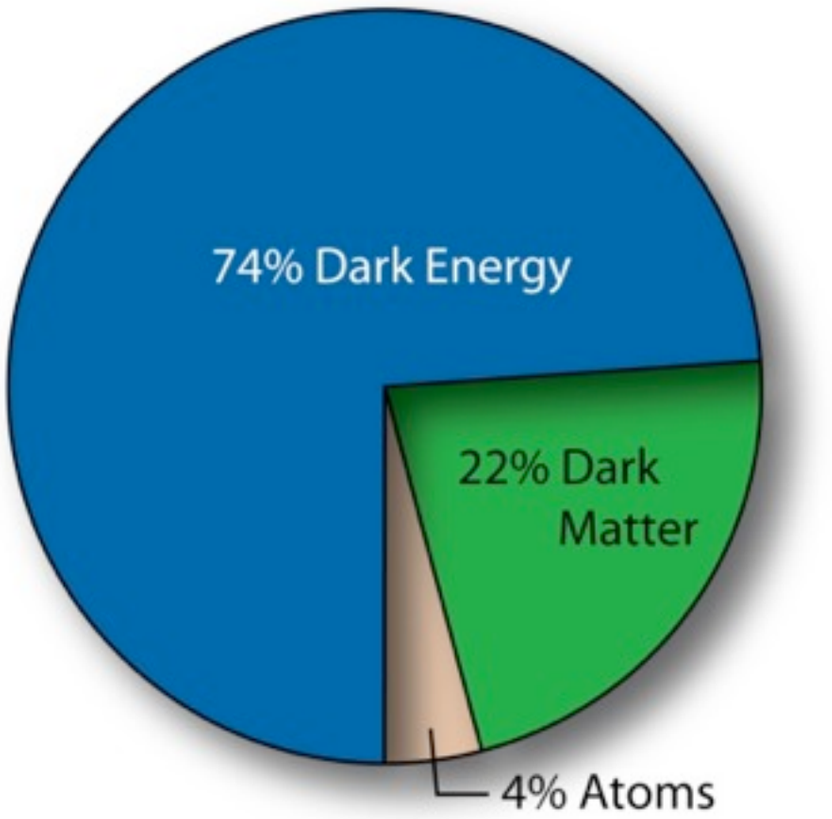
January 31 - April 22, 2011

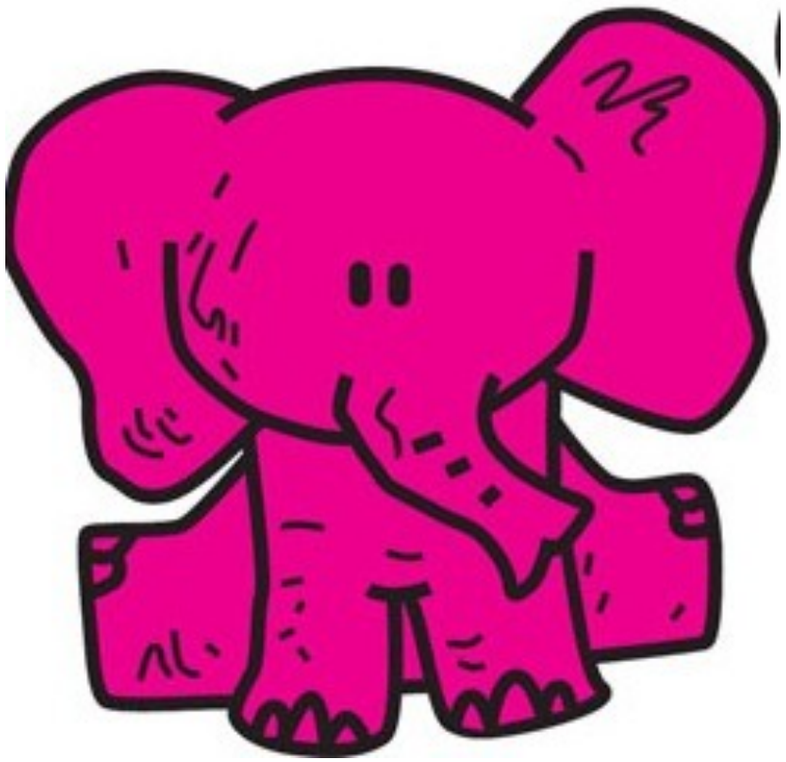
Coordinators: Andrey Kravtsov, Dan Marrone, and Peng Oh

Scientific Advisors: Maxim Markevitch, Megan Donahue, John Carlstrom, Richard Bond, Gus Evrard, and Mark Voit

Monsters, Inc.: Astrophysics and Cosmology with Galaxy ClustersConference: March 14-18, 2011

Use of Clusters for cosmology is well-known





Dark Energy

Non-Gaussianity

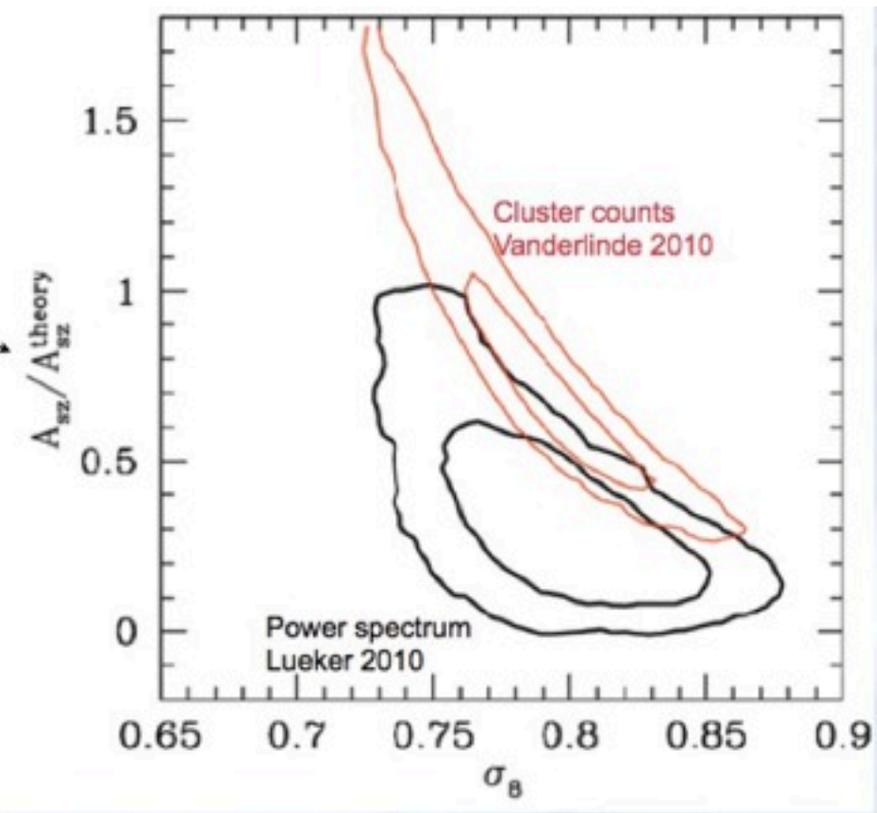
...but astrophysics gets in the way

Poster child : SZ power spectrum

slide from L. Shaw

SZ Power Ratio, Asz

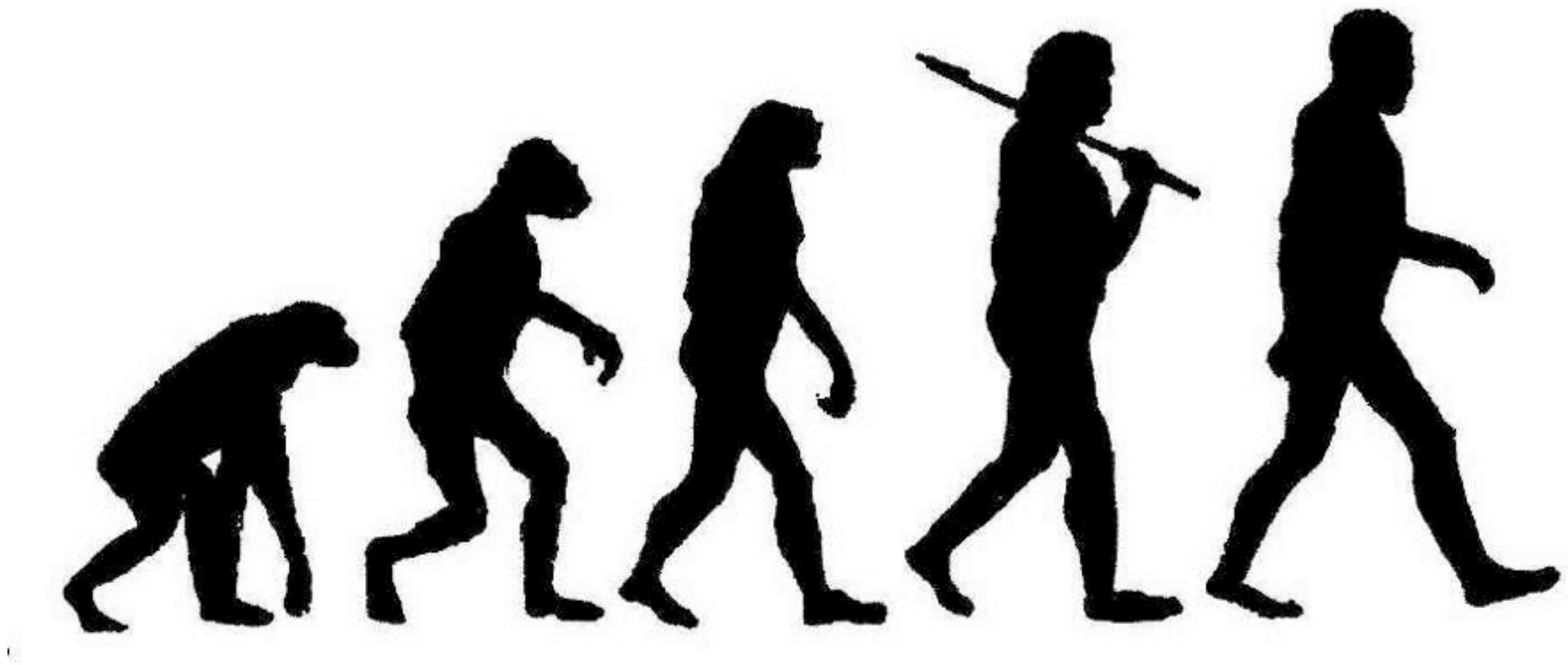
$$\frac{\text{(ratio of measured power)}}{\text{(power for given value of } \sigma_8\text{)}}$$



Detected power significantly below that predicted by simulations

Possible culprits: turbulent pressure in outskirts, feedback in groups

First Principles Calculations Possible in Clusters



IGM

No subgrid physics

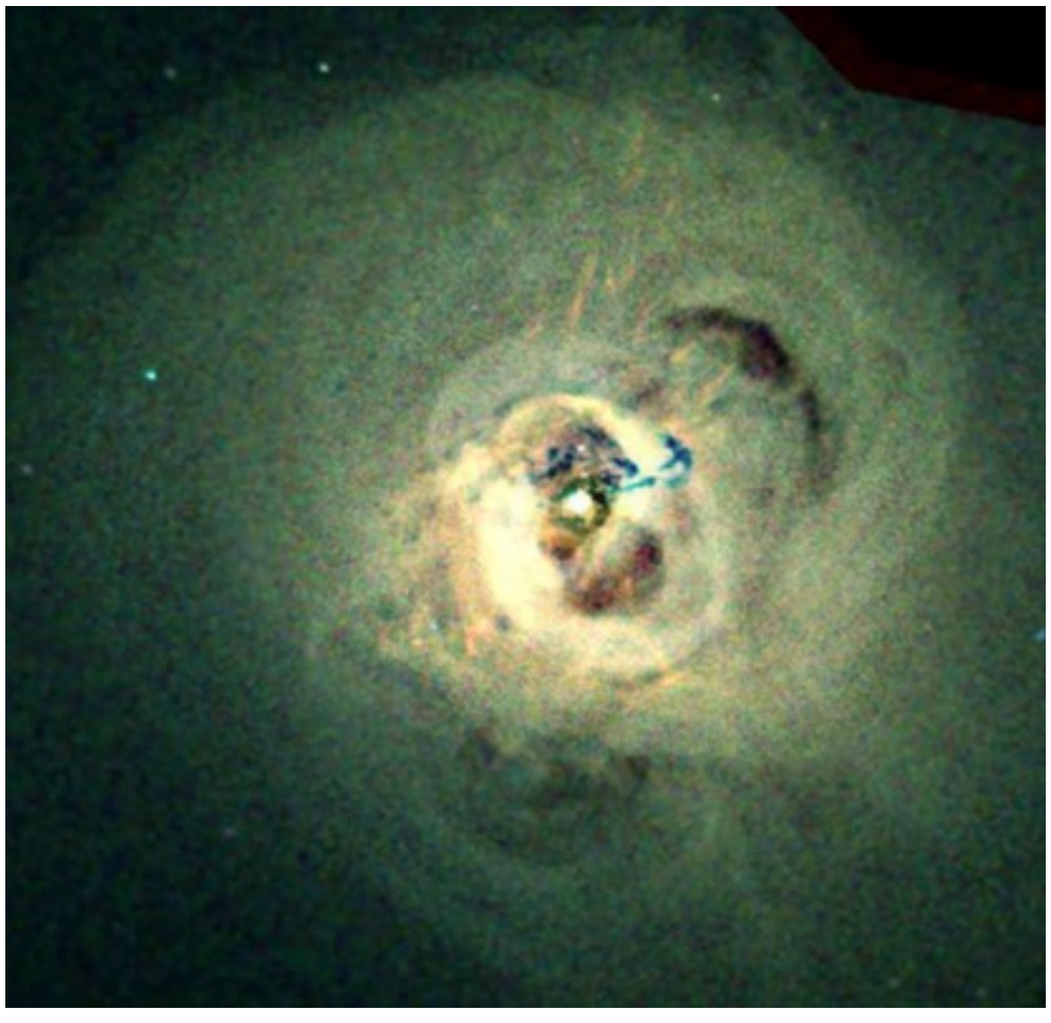
ICM

harder: B-fields, more complex physics

Galaxies

Hard!!

Clusters are a great testbed for ideas about galaxy formation



Closed boxes

Large scales

Radiate profusely at many wavelengths

We can see what's going on!

Lower densities, longer timescales than galaxies

We can simulate it!

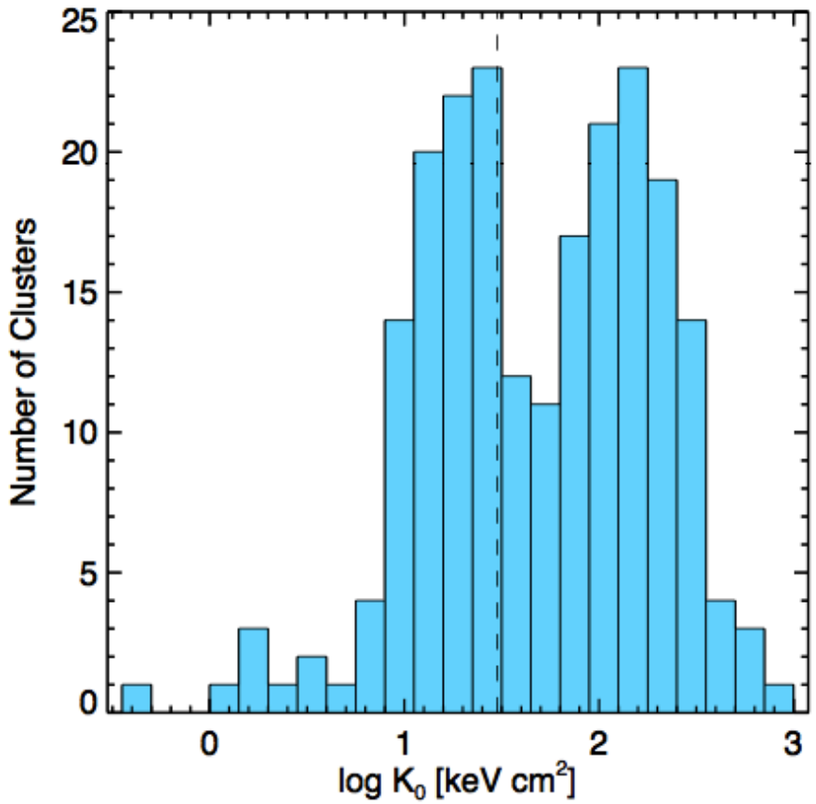
Some open questions

- How does AGN feedback actually work?
- What are the nature of diffuse transport coefficients (conduction, viscosity)?
- How do filaments form, what energizes them?
- What is the role of turbulence?
- Why are is there a bimodal population of cool-core and non-cool core clusters?
- Generation and role of B-fields, cosmic rays

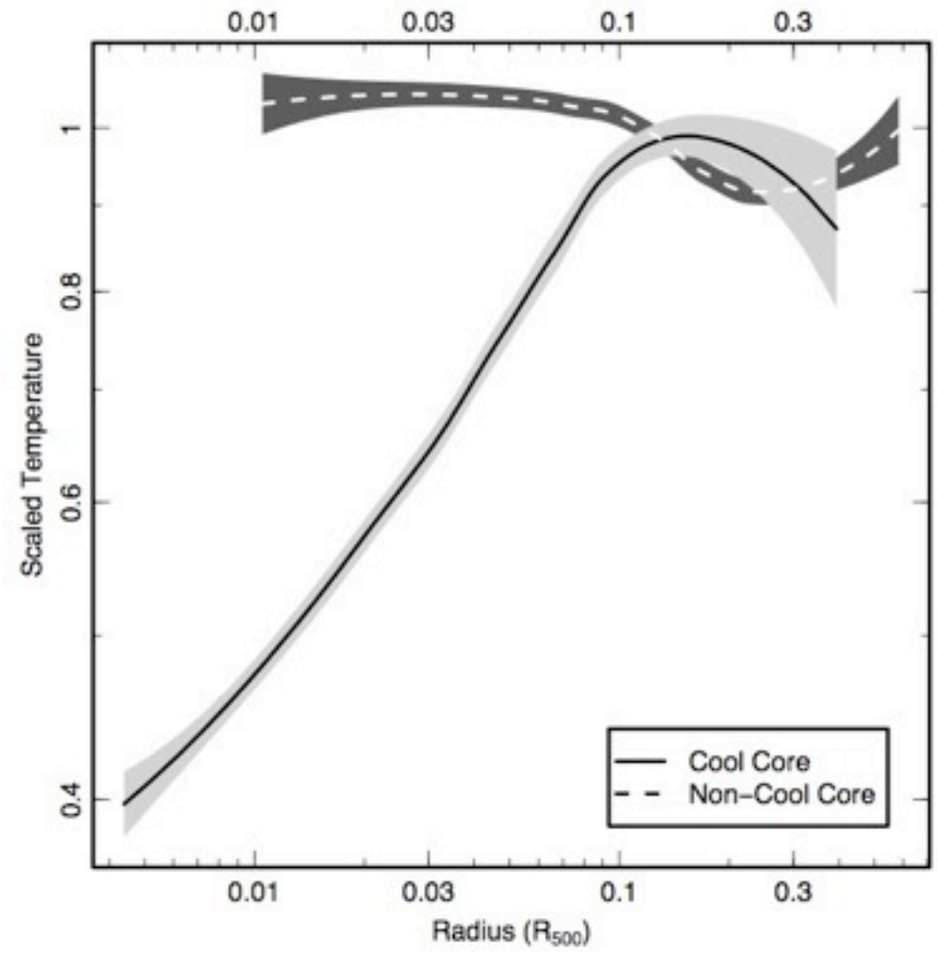
Some Examples

AGN Feedback

Observational puzzle: why are there two types of clusters?

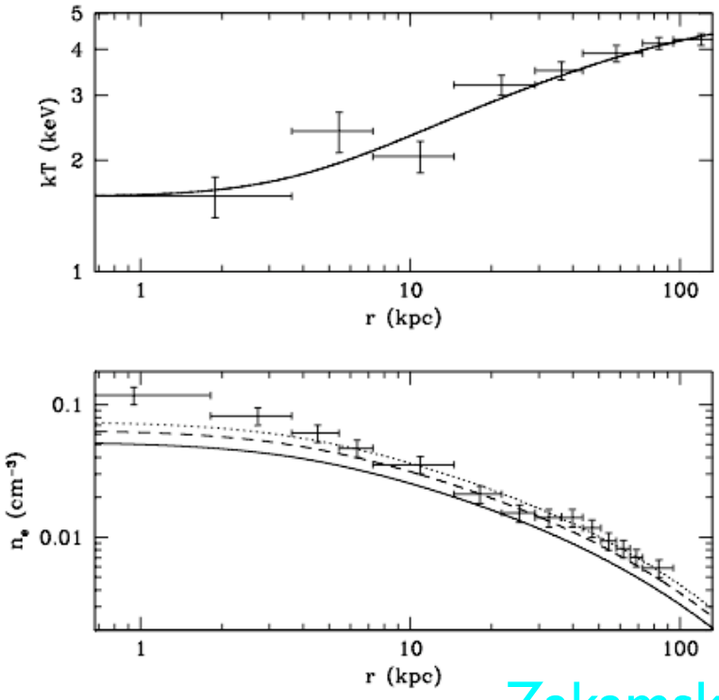


Cavagnolo, Donahue, Voit, Sun 2009



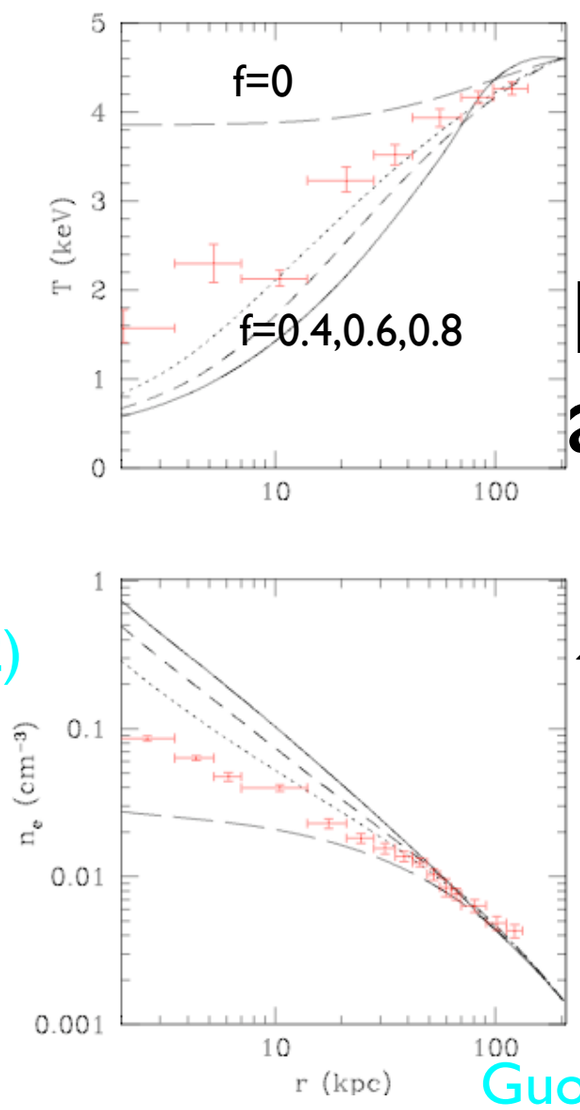
Sanderson et al (2006)

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

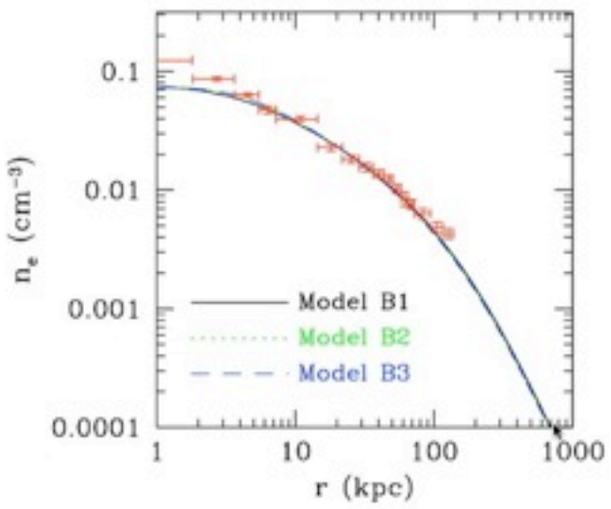
But have to tune parameters, and it won't evolve toward this state in general...

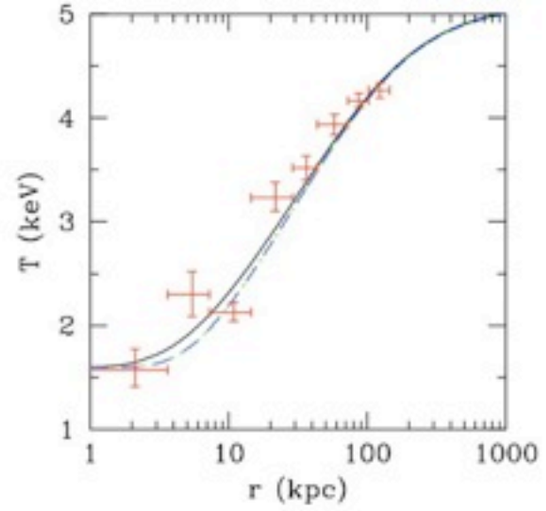
How to understand this?

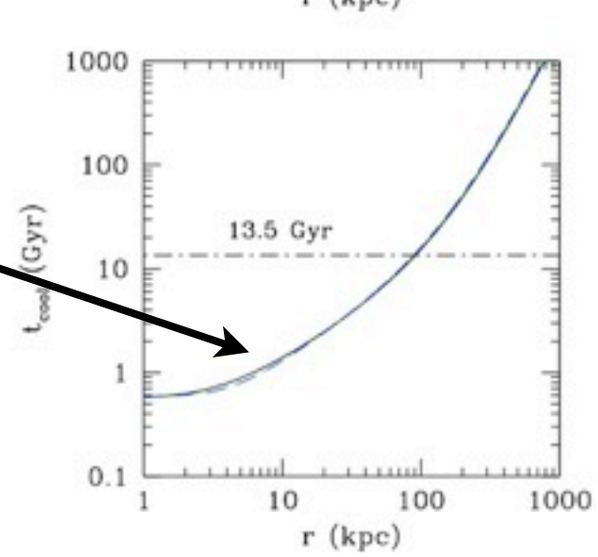
'Pick any two'

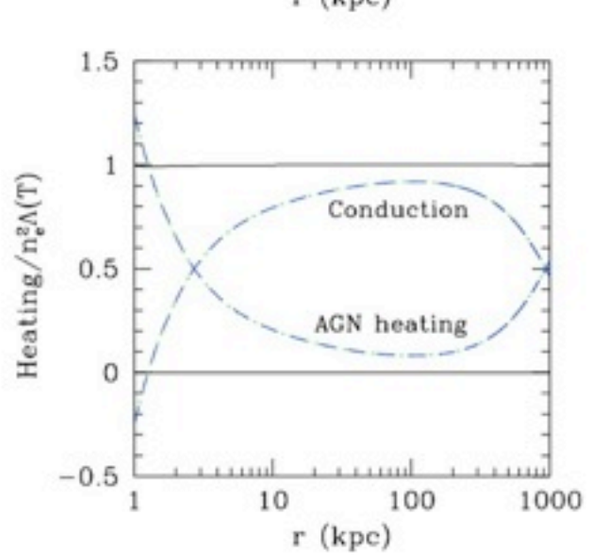
Semi-analytic model: Explore parameter space quickly
Aids in physical intuition

note short cooling time









First, build a background equilibrium solution

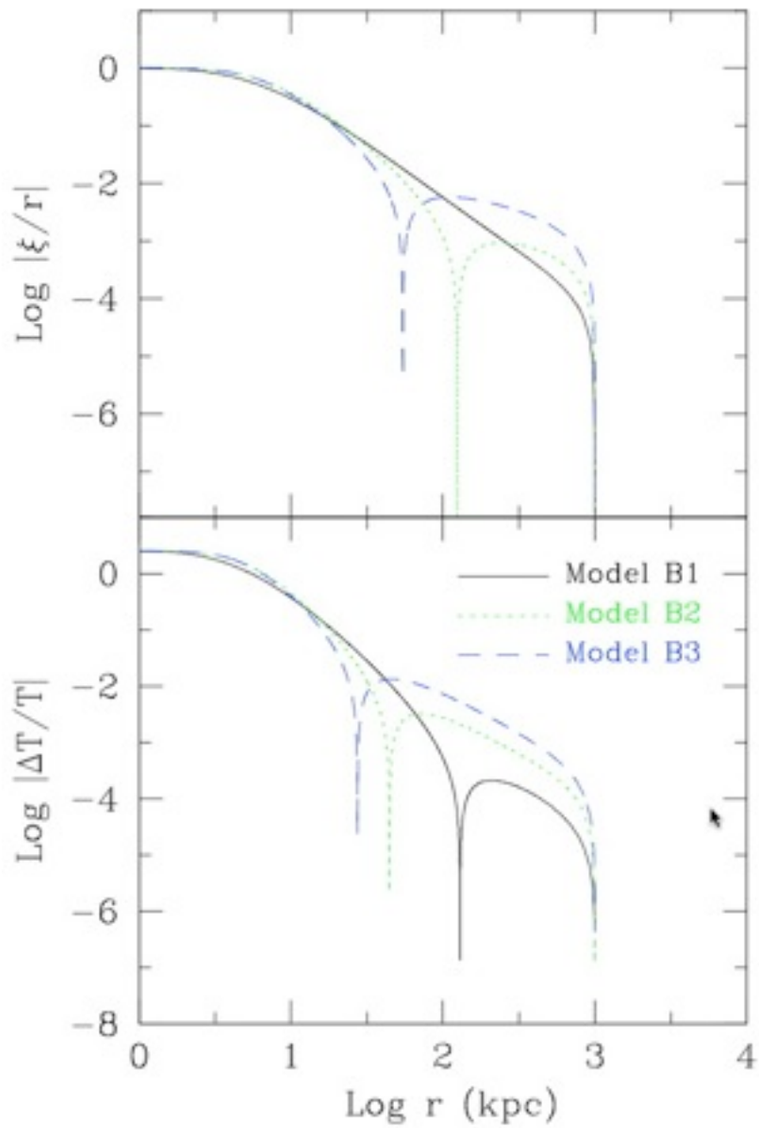
..and perform a global stability analysis

~~WKB~~

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

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

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



Growth rate is an eigenvalue of analysis

Explore parameter space rapidly!

Just as in Stellar Structure calculations...

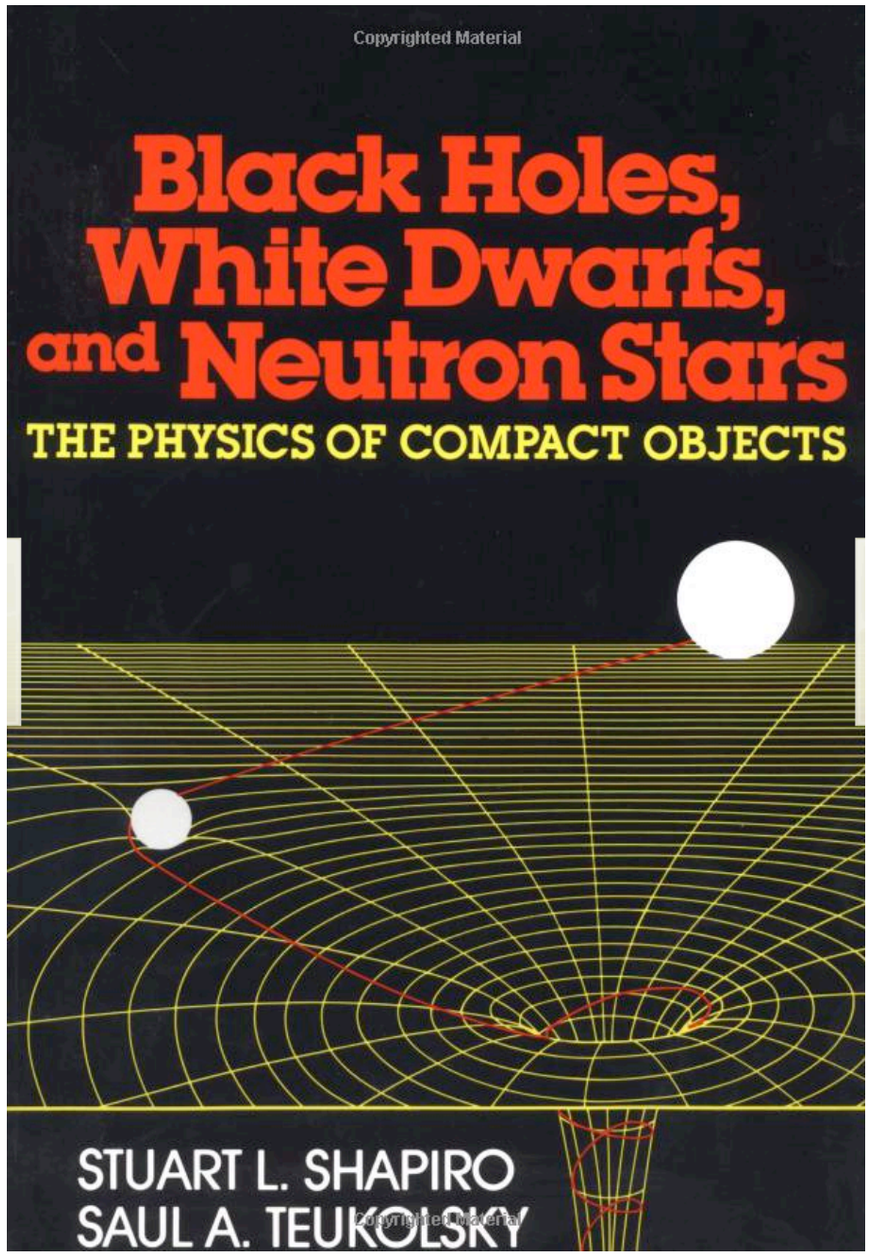
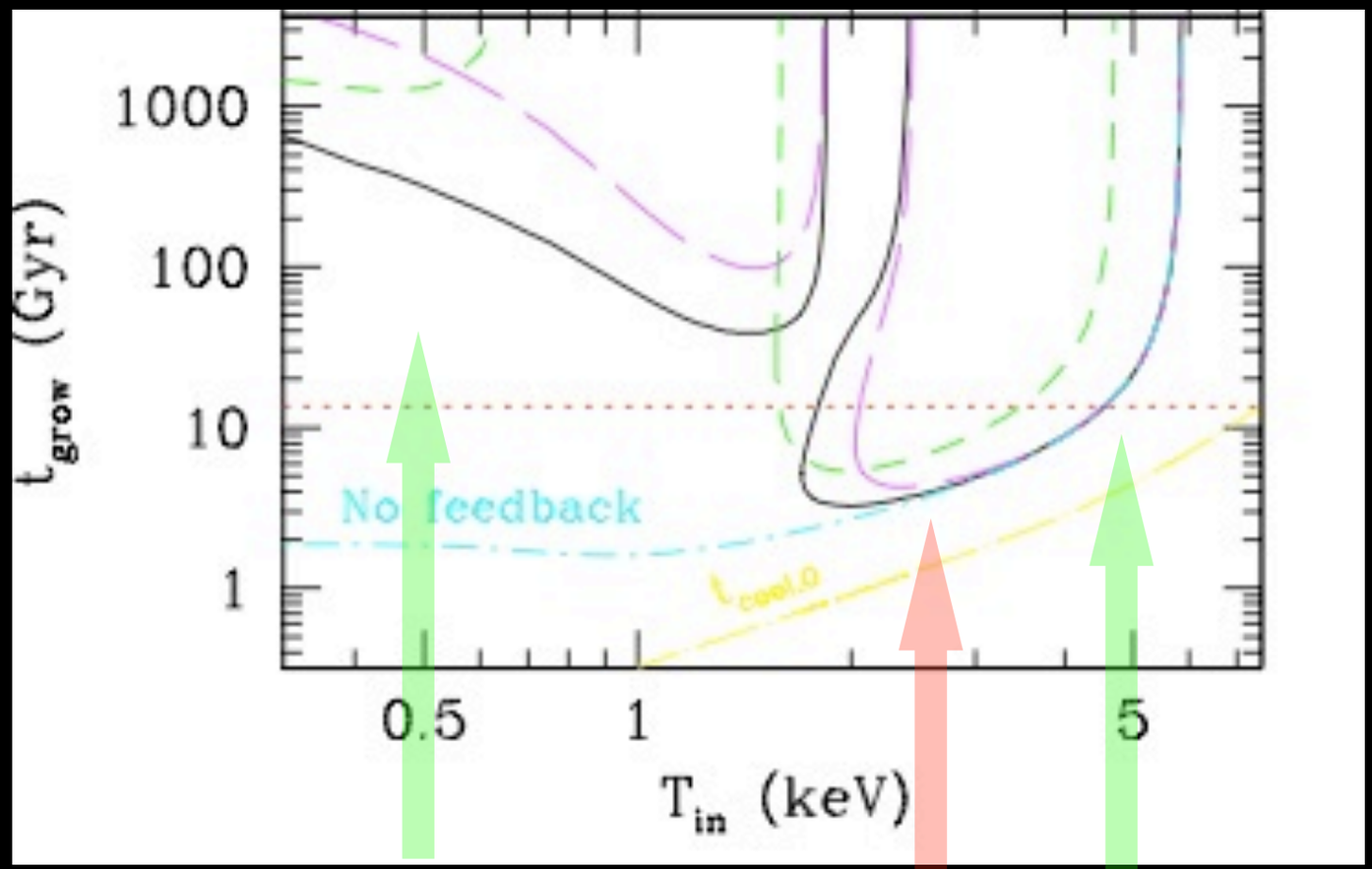


Fig from A. Piro



stable

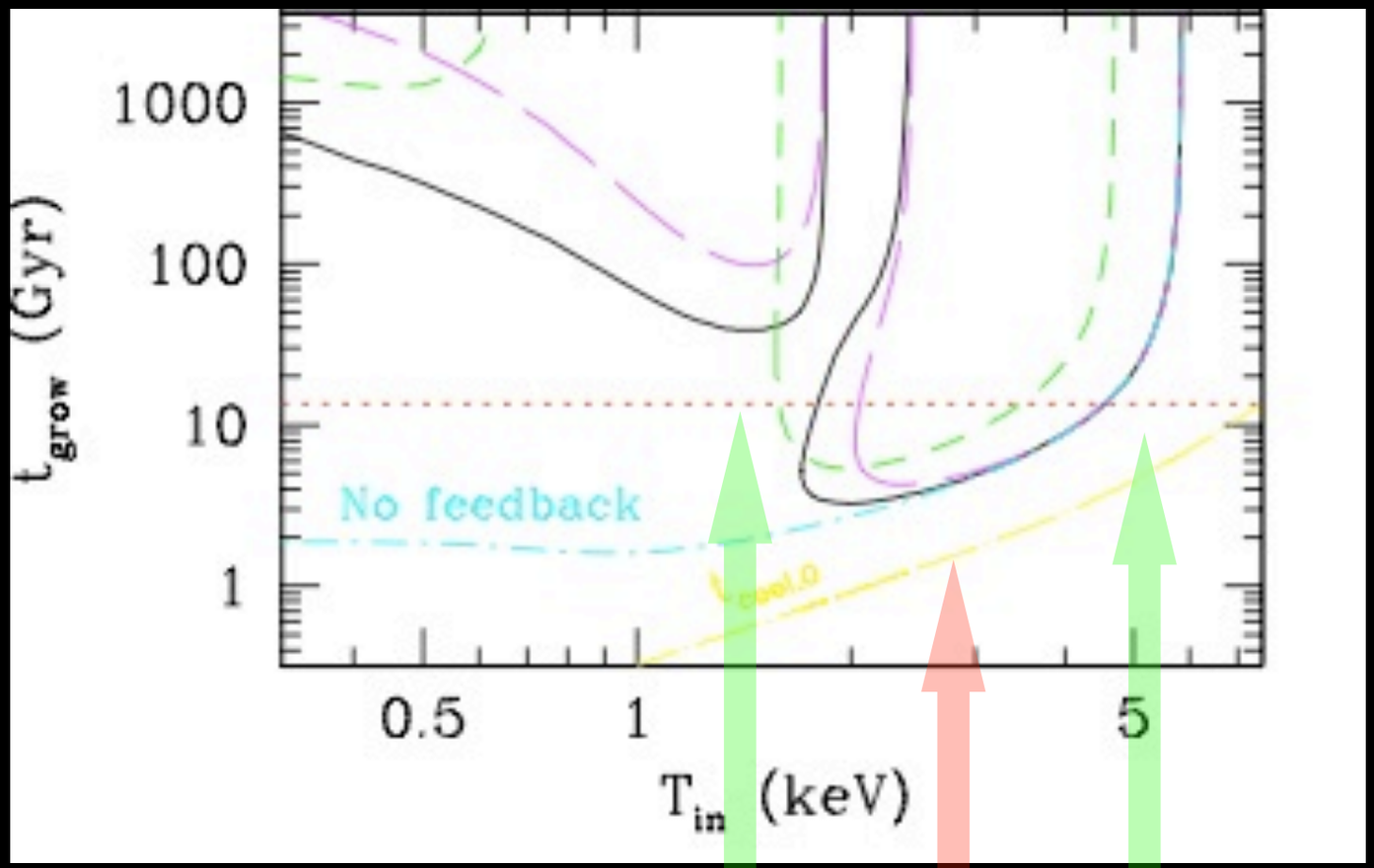
unstable

stable

T

r

Stability is bimodal!



stable

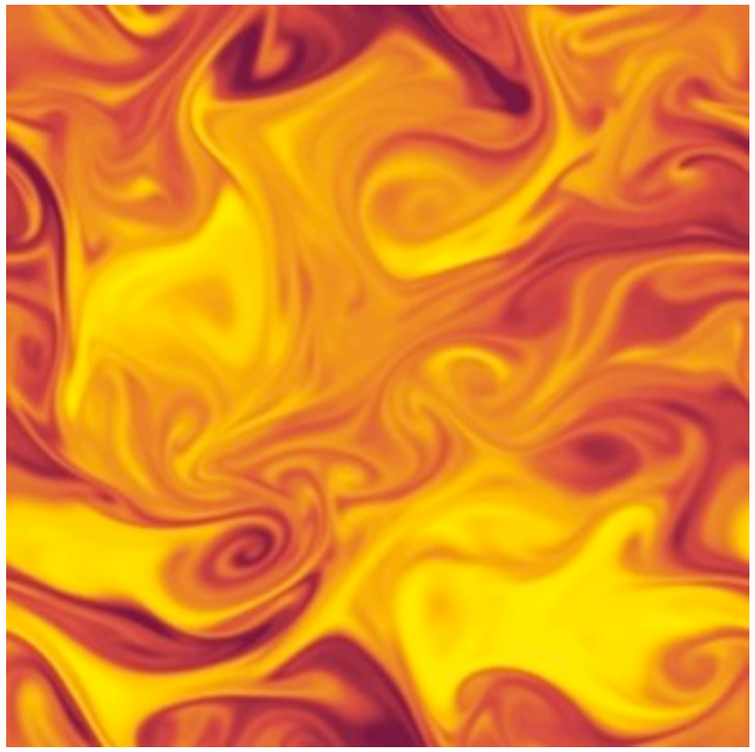
unstable

stable

Bimodality !

cool core ⟵ stabilized by AGN + conduction

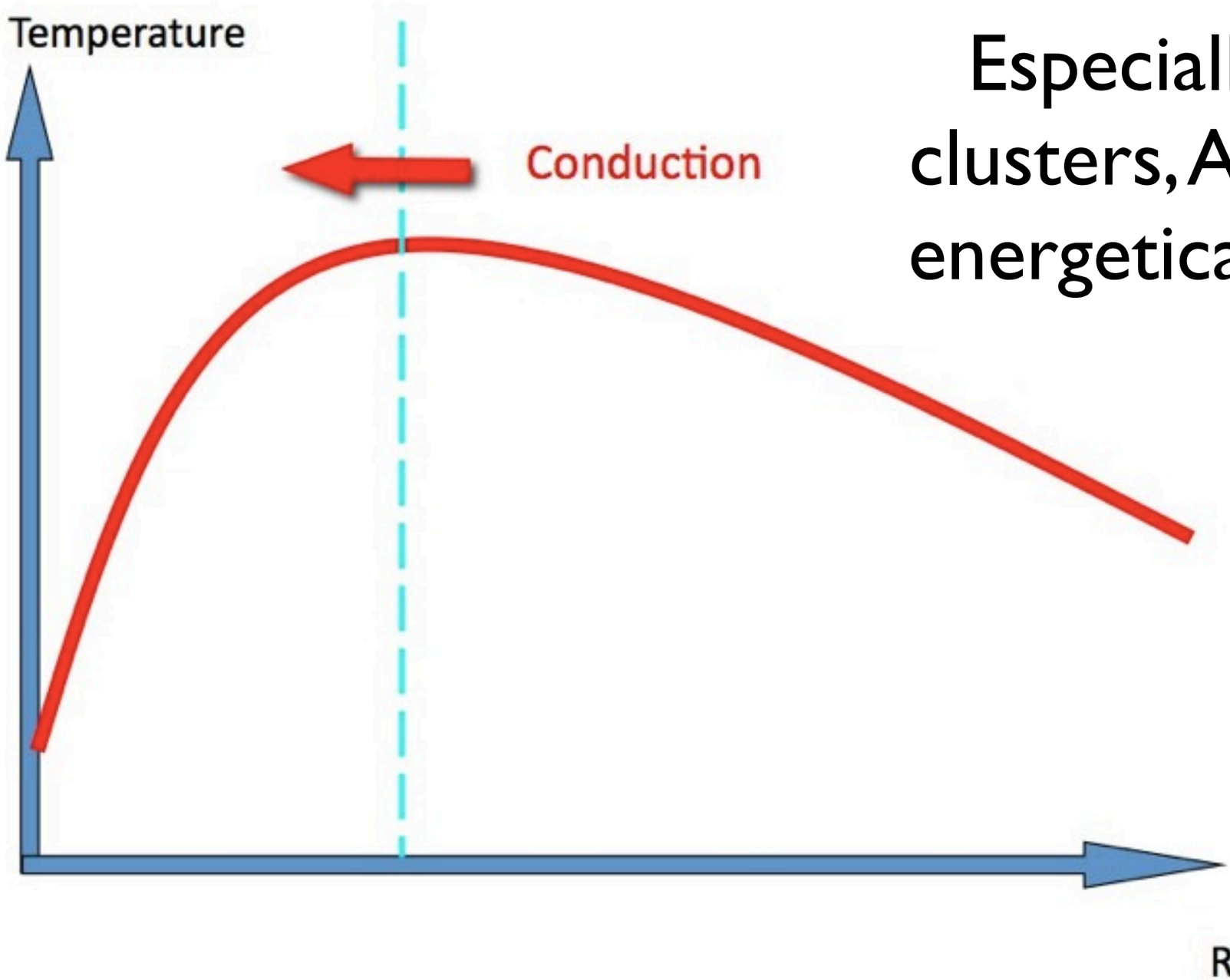
non cool core ⟵ stabilized by conduction



Turbulence and Conduction in Galaxy Clusters

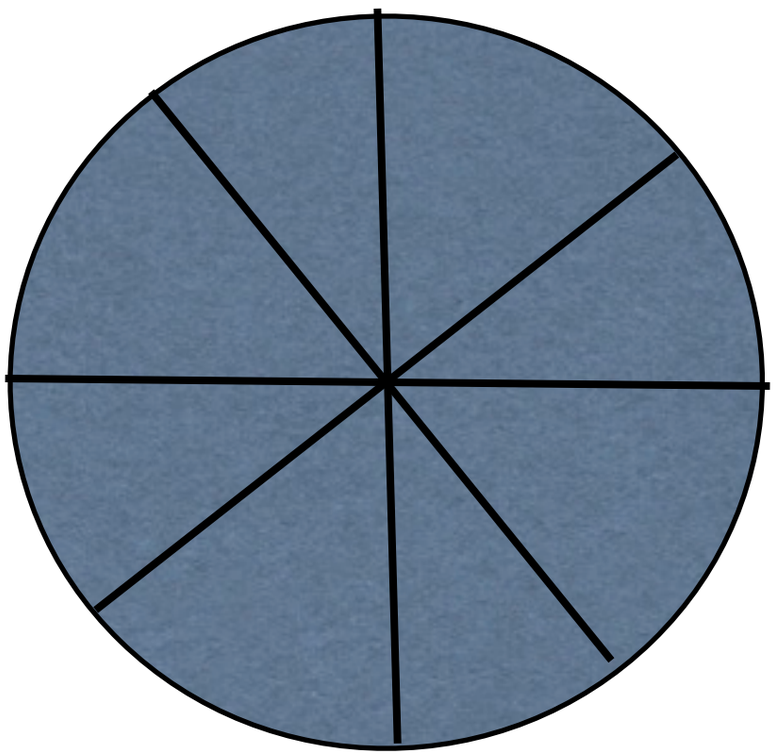
Collaborator: Mateusz Ruszkowski (Michigan)

Thermal Conduction can supply heat to cool core

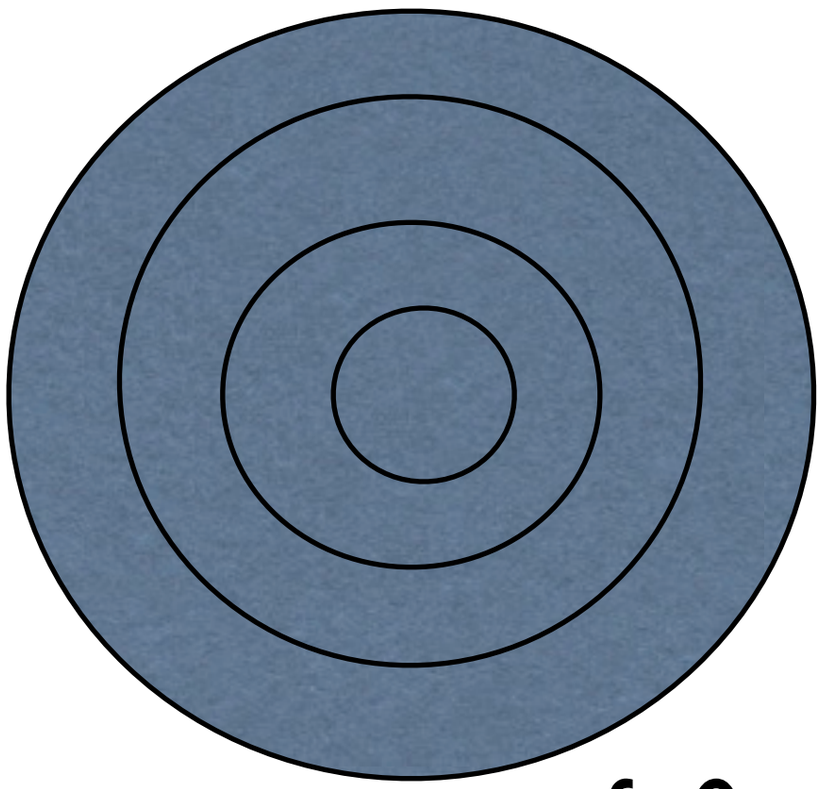


Especially in massive clusters, AGN heating is energetically insufficient

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)

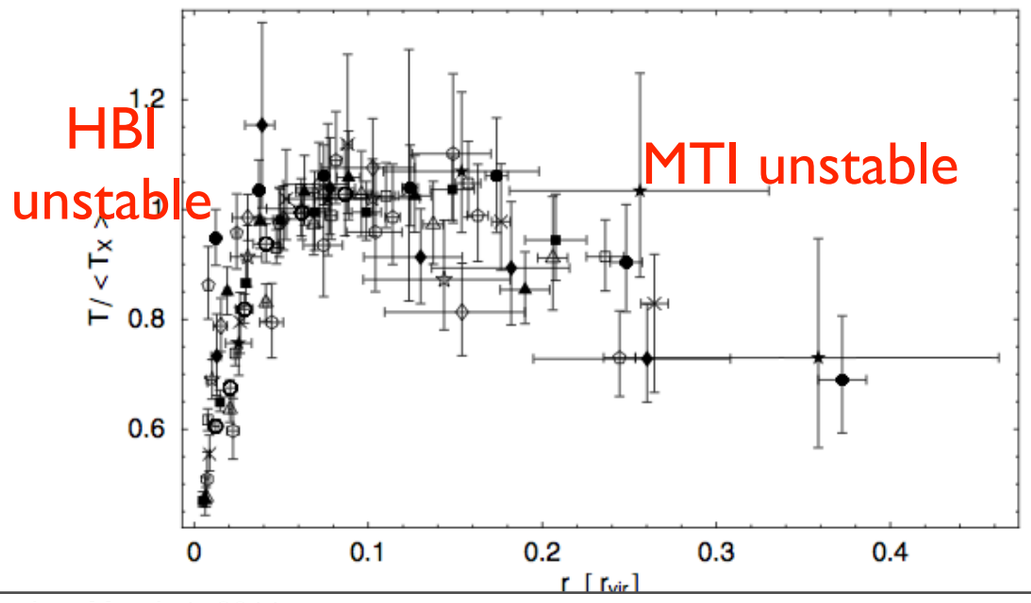
Radial magnetic fields

Enhances thermal conduction

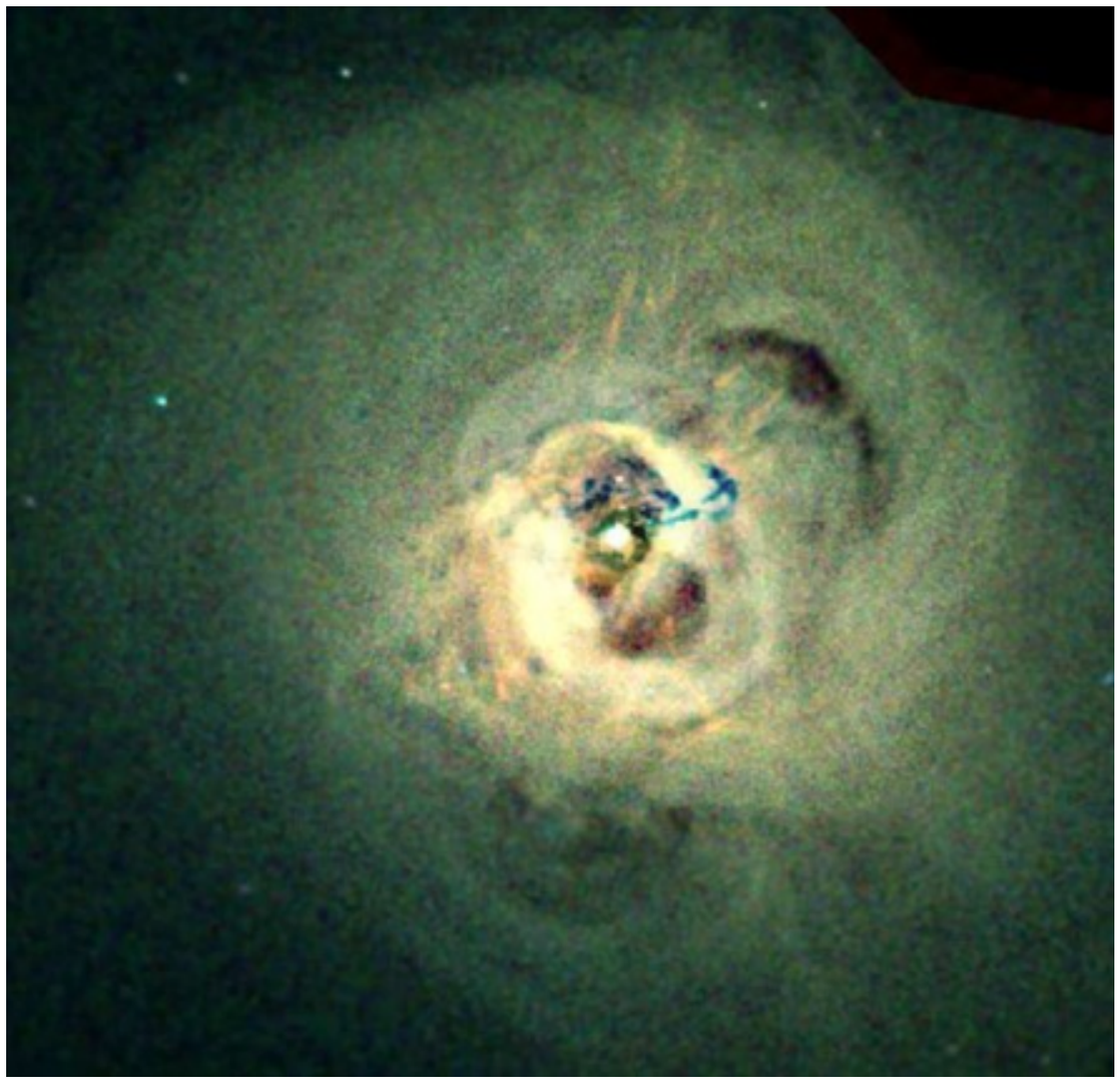
$\nabla T > 0$ → Heat buoyancy instability (HBI)
(Quataert 2008)

Tangential magnetic fields

Shuts off thermal conduction



We expect the ICM to be turbulent



Evidence from:

Lack of resonance scattering lines (Churazov et al 2004)

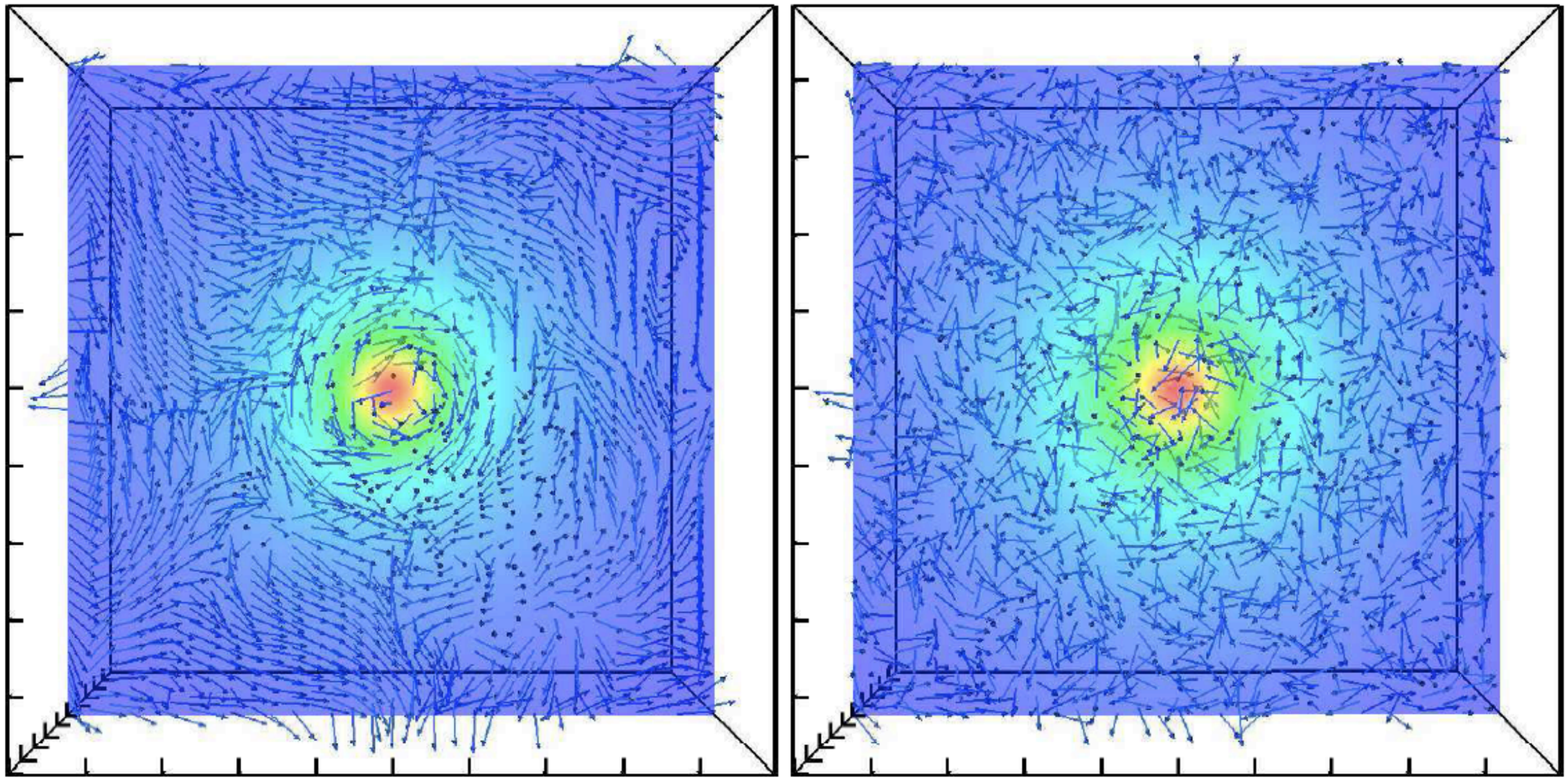
Analysis of pressure maps (Schuecker et al 2004)

Faraday rotation maps (Ensslin & Vogt 2006)

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

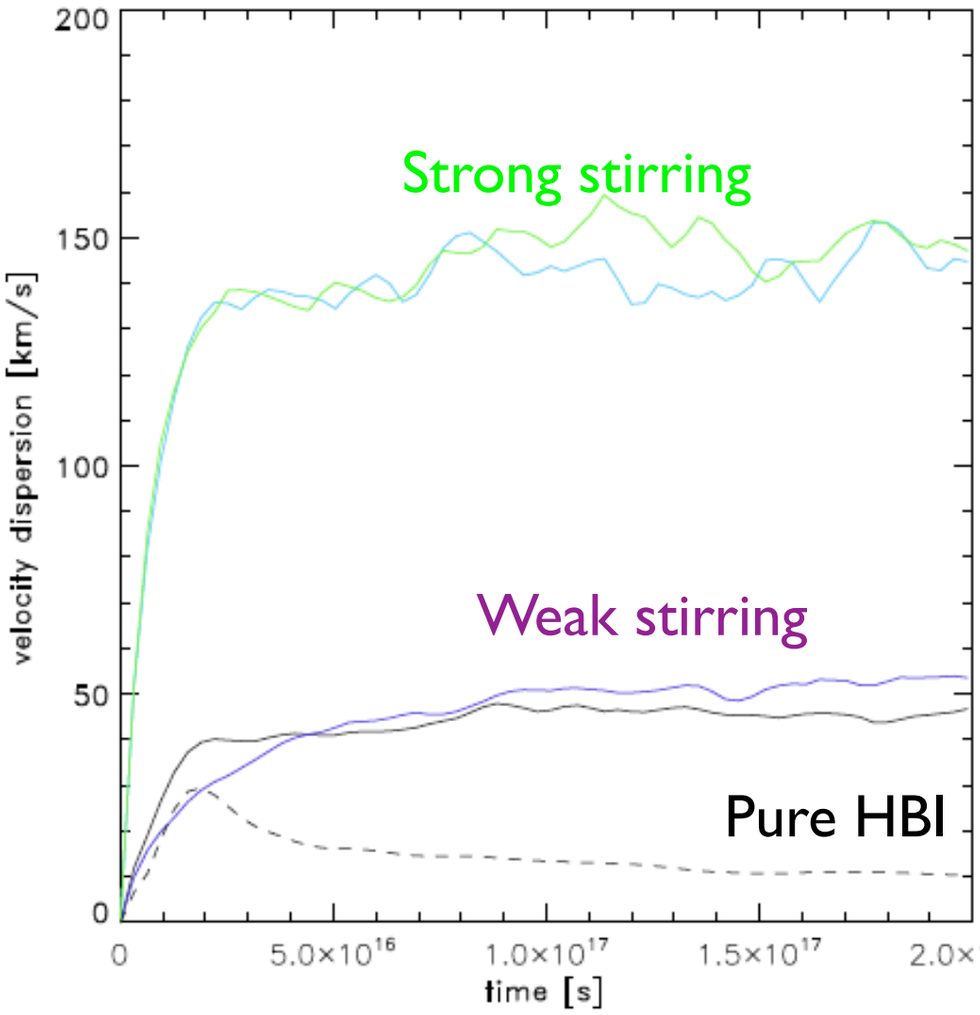
Could turbulence randomize field lines and restore conduction?

Bottom Line: YES



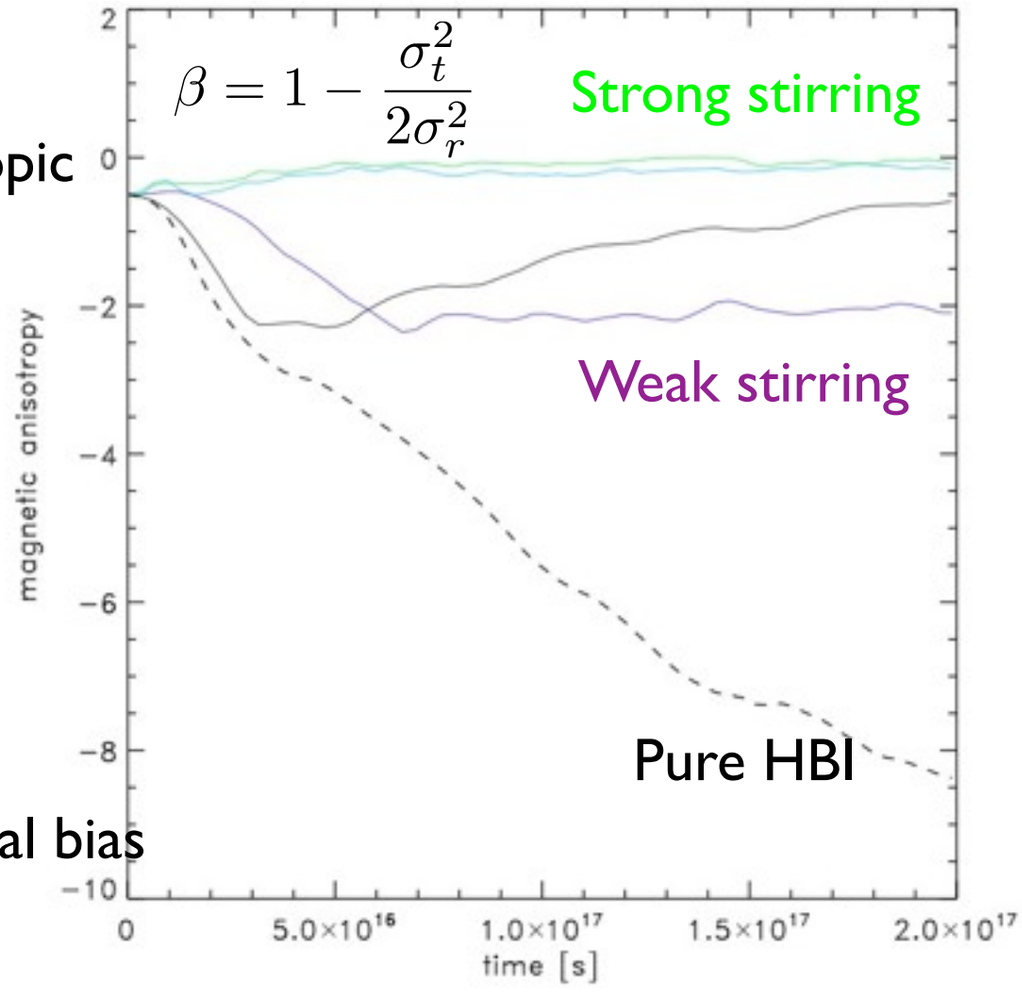
Ruszkowski & Oh (2010), using FLASH

Required Amount of Turbulence is small



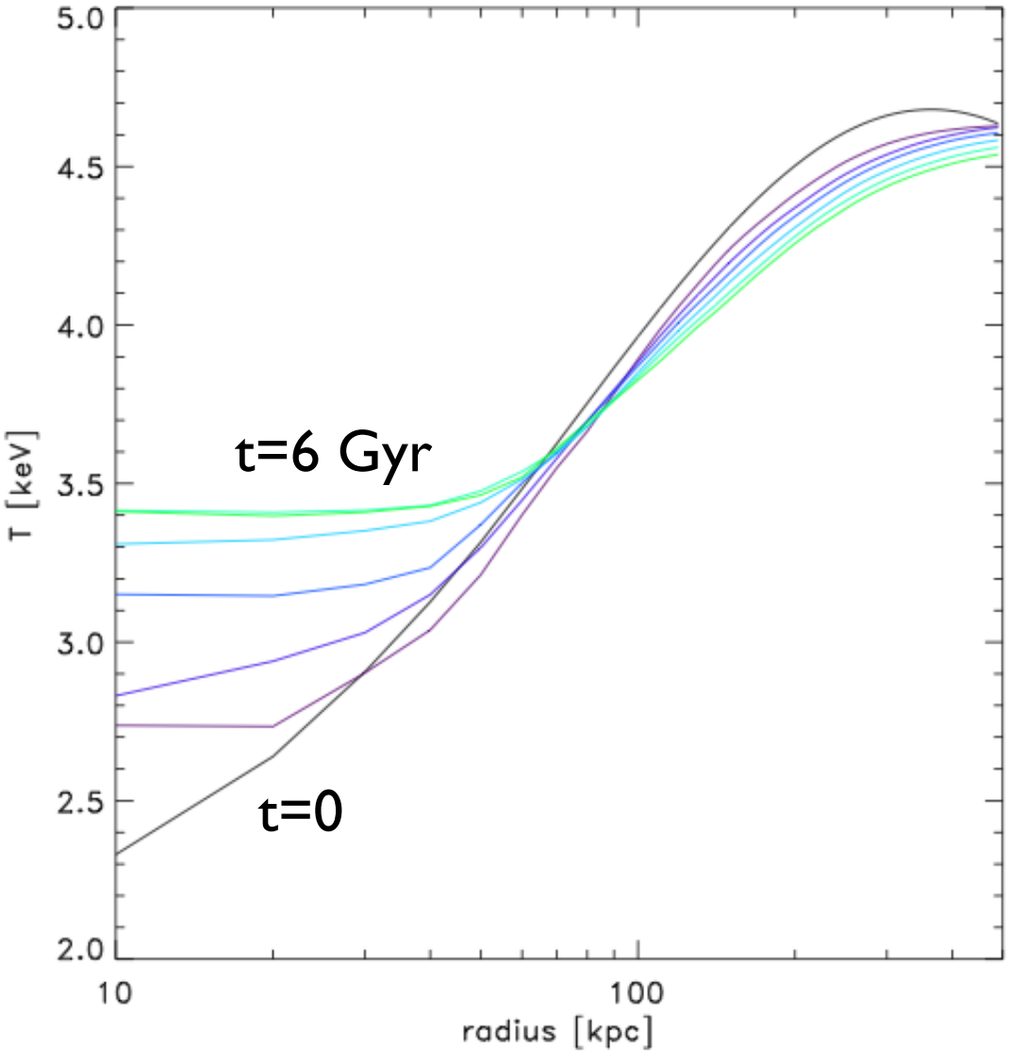
isotropic

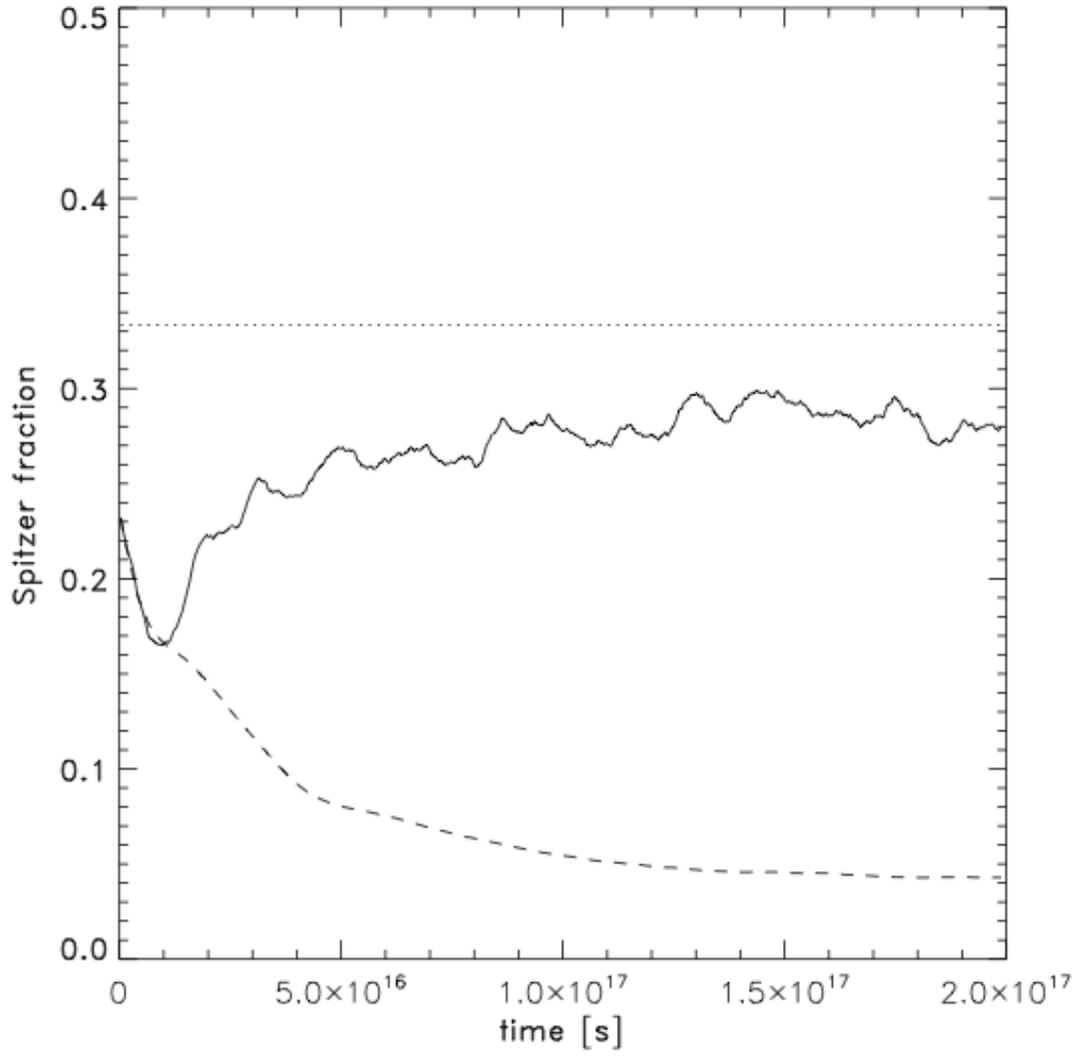
tangential bias



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

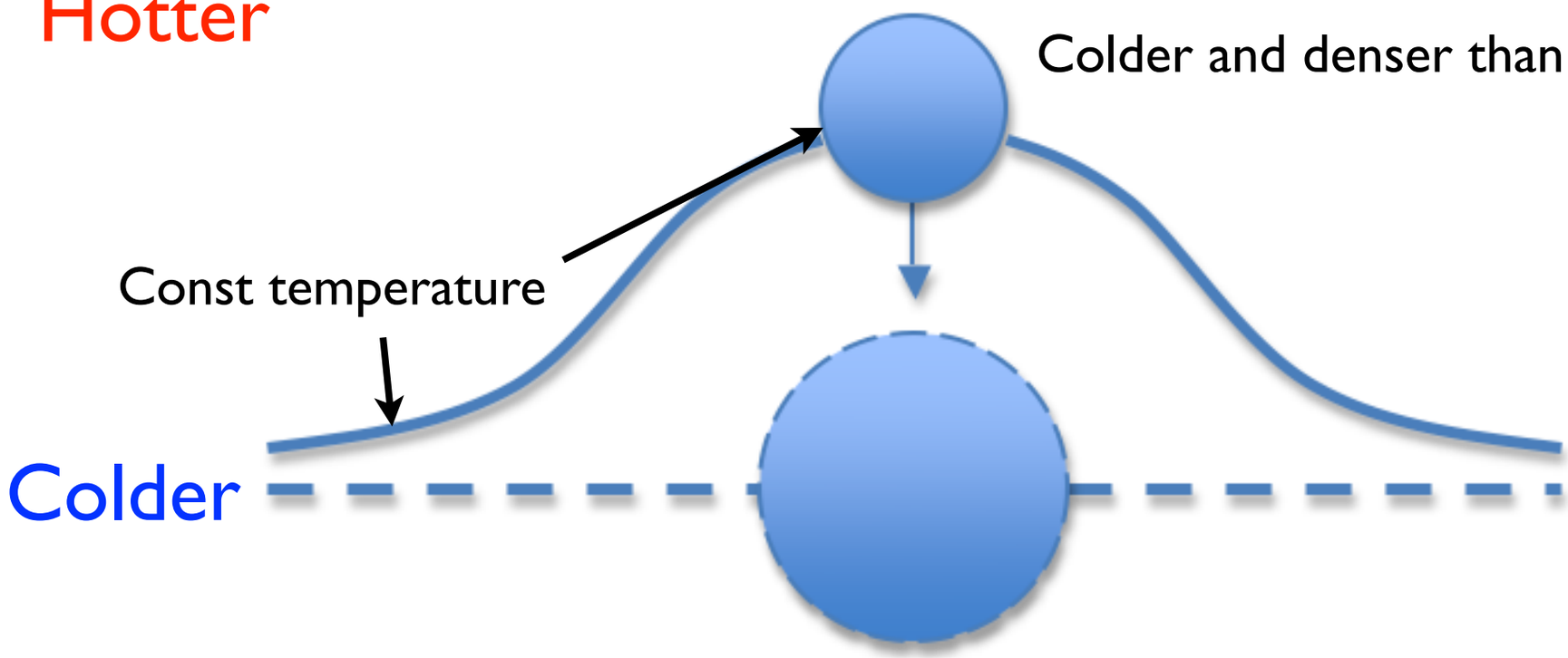
No cooling catastrophe!





Why are such weak motions effective?

Stratified by temperature, rather than entropy.



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

Buoyancy forces are weaker in conducting plasma

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

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

See also Sharma et al (2009)

Can galaxy motions excite volume filling turbulence?

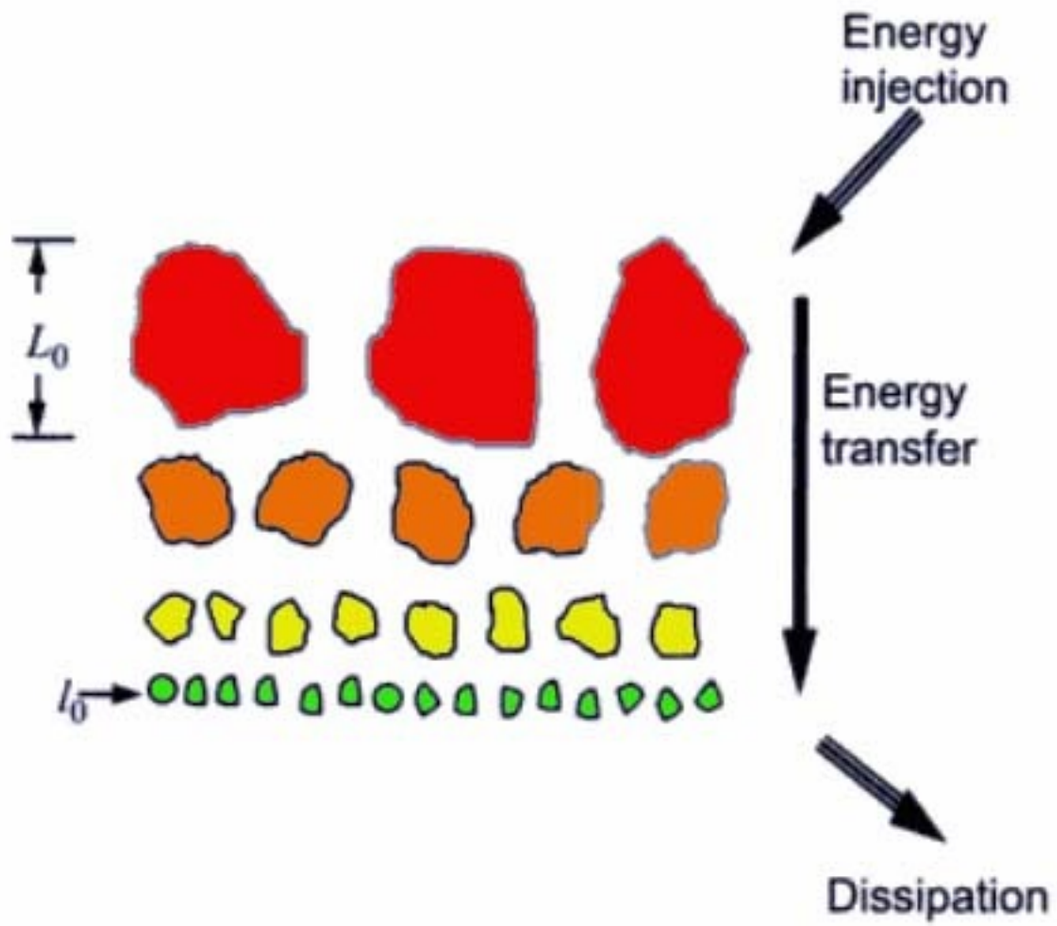
Wakes not volume-filling; need to excite g-modes

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

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

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

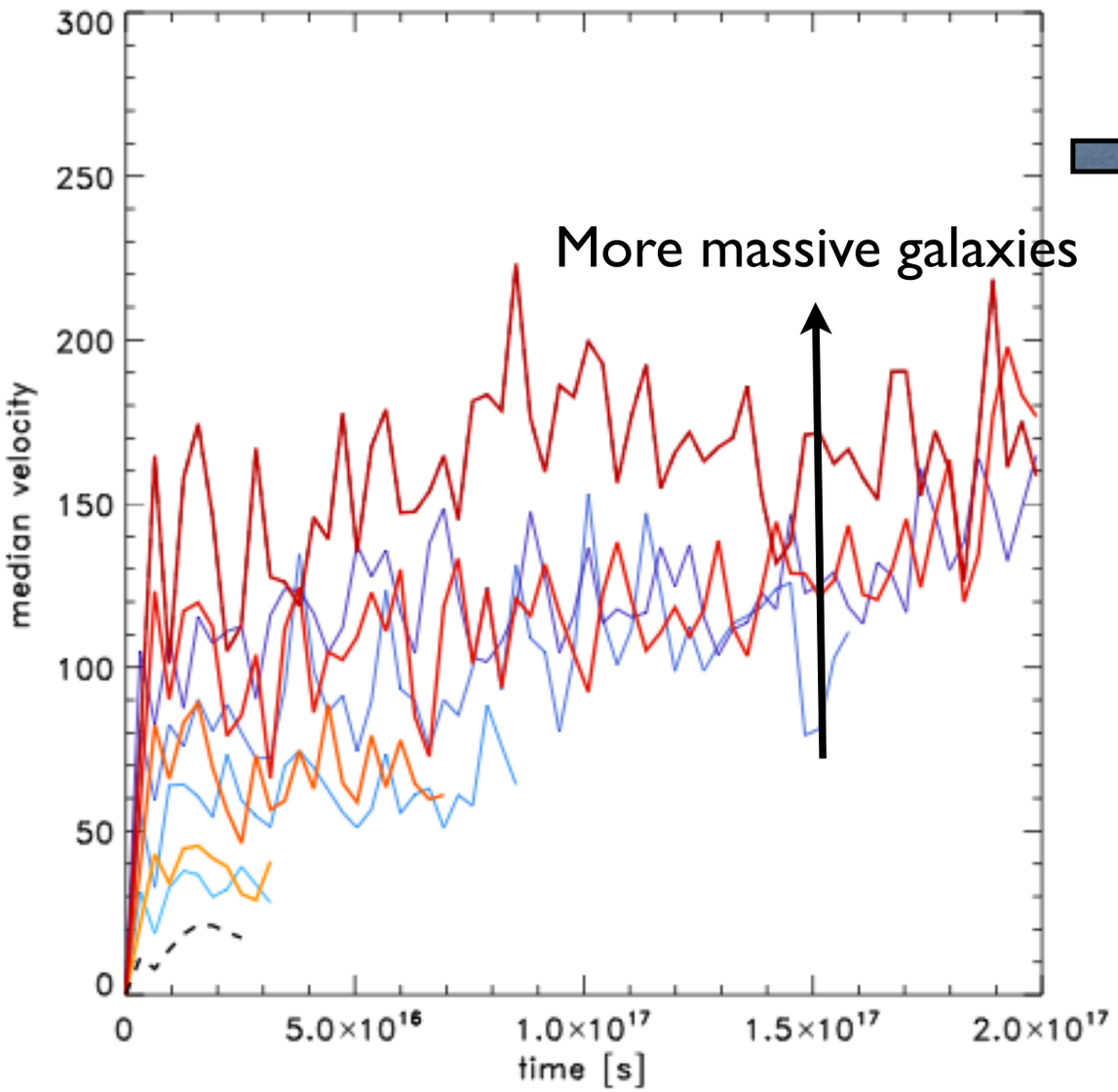
$\omega \sim \frac{v}{l} \sim l^{-2/3}$

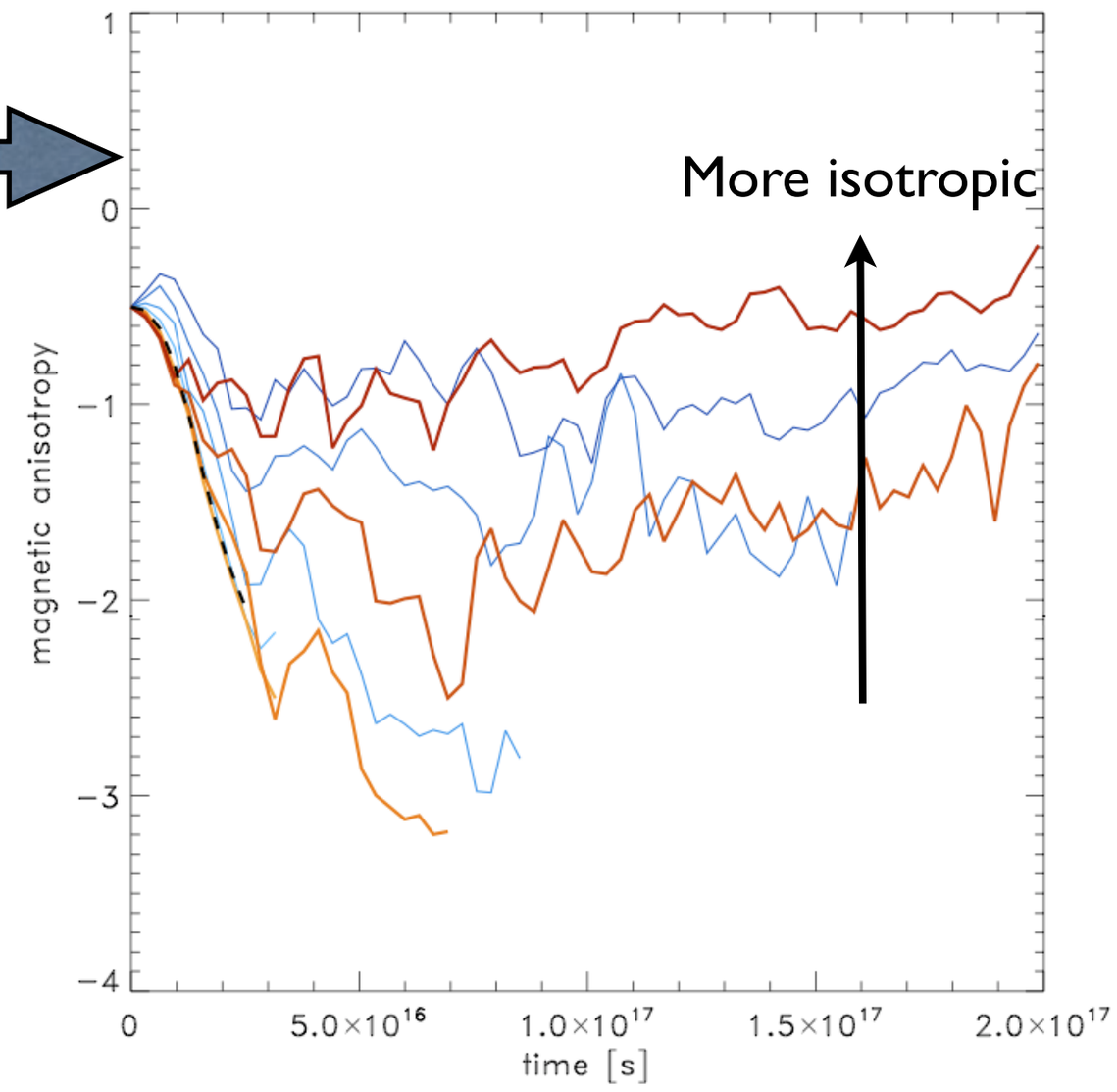


Large eddies are trapped, smaller eddies isotropize

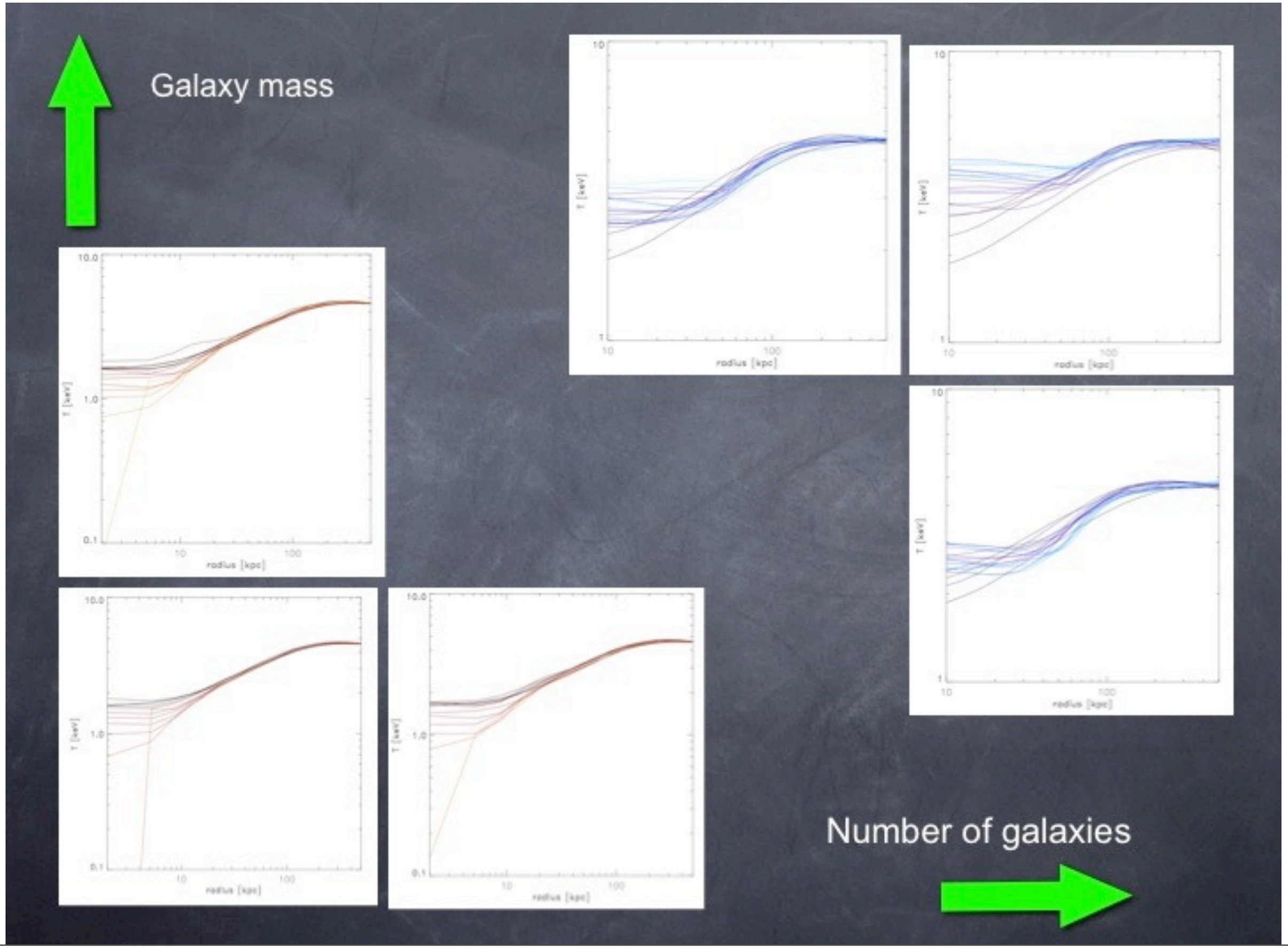
Ruszkowski & Oh (2011)

Magnetic fields are isotropized...

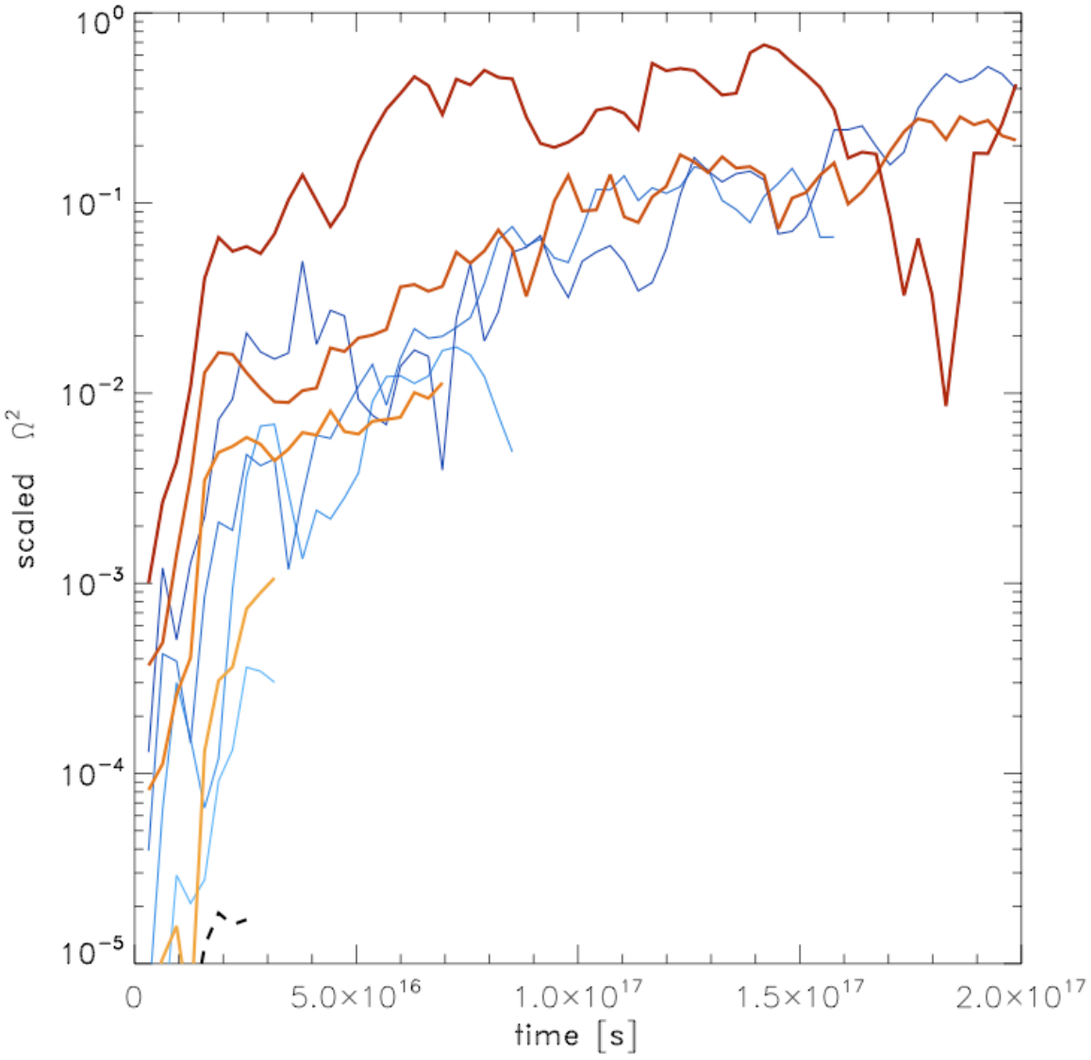


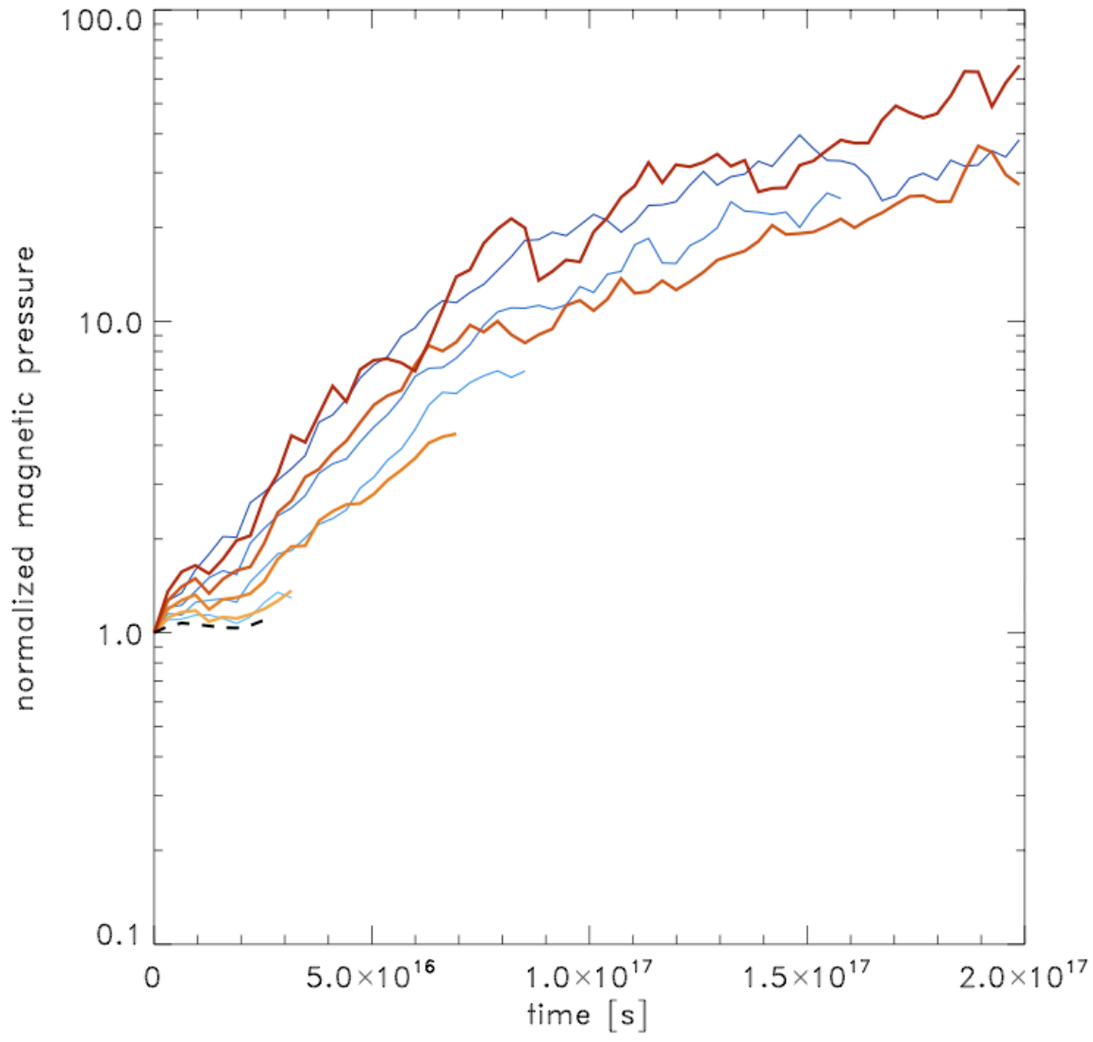


No cooling catastrophe. Note: no subgrid physics!



Magnetic fields are amplified

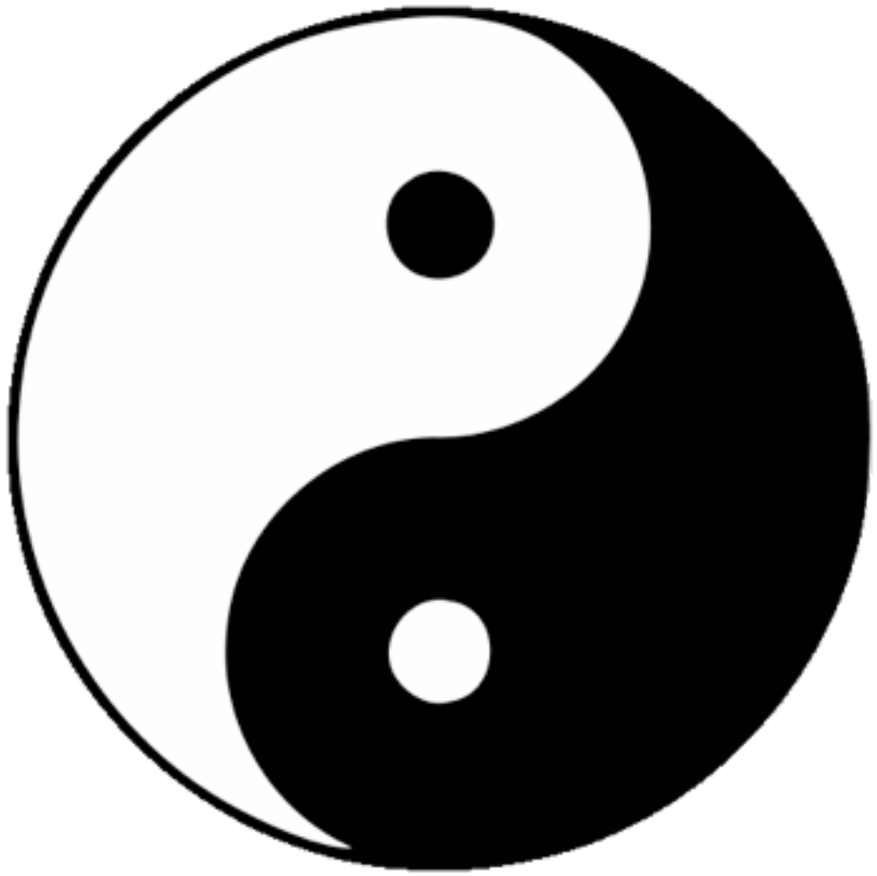




Vorticity growth → B-field growth

N.B. Magnetic tension negligible here

The Tao of Heat Transport



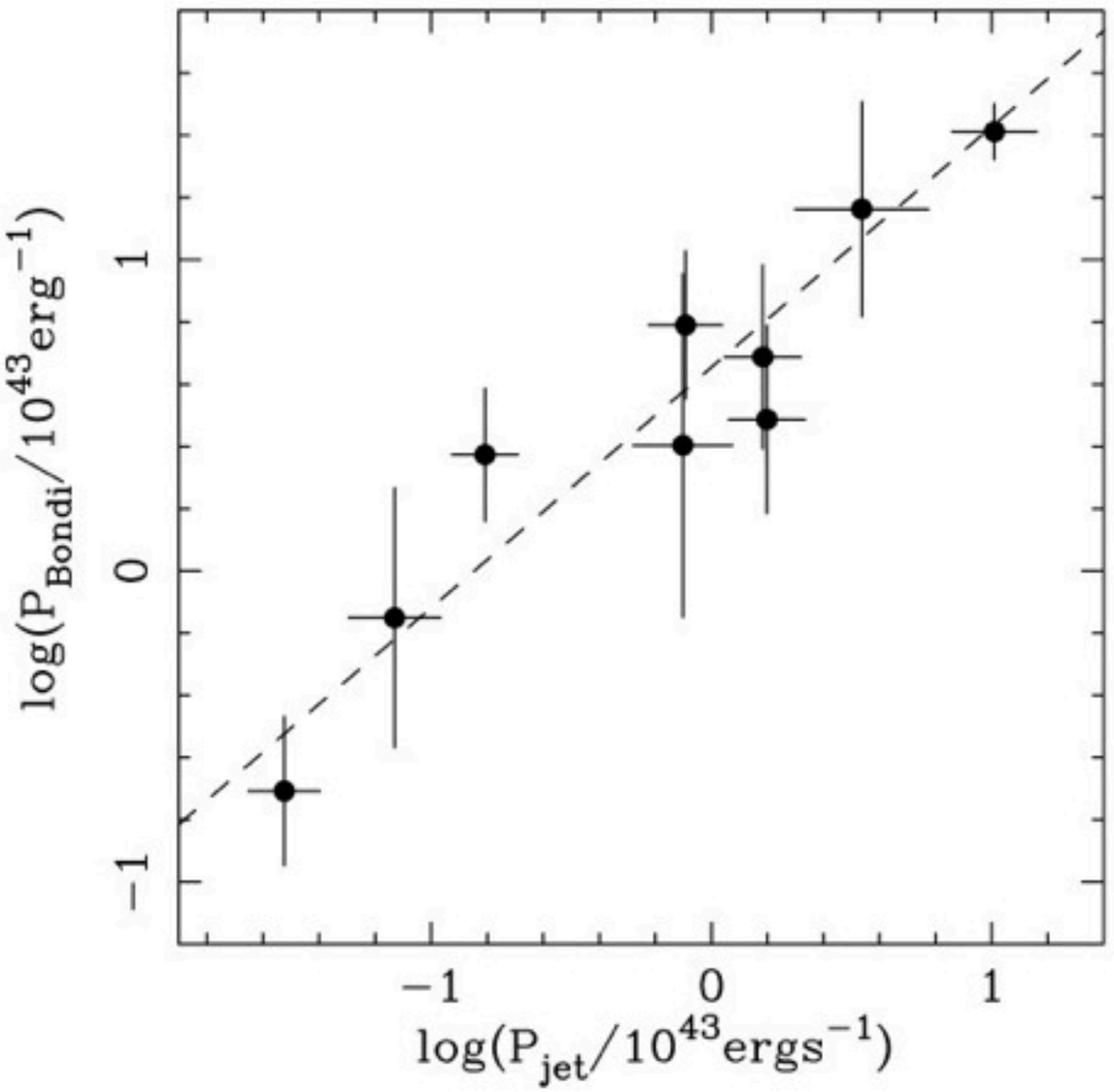
Conduction

Turbulence

Even if you don't care about clusters...

Ask not...what you can do for clusters, but what clusters can do for you

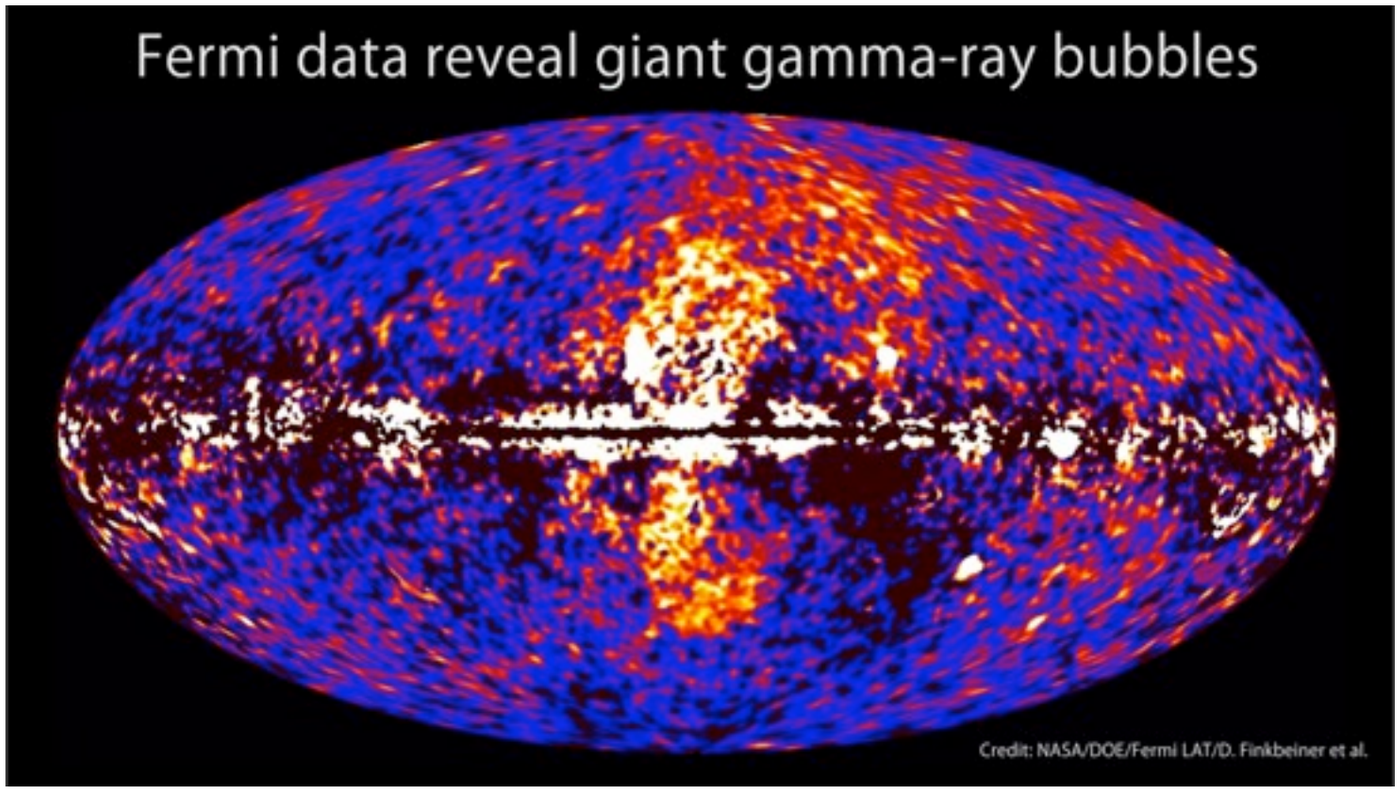
AGN Fueling



Allen et al 2006

We don't believe in Bondi accretion....but why does it seem to work??

Feedback by Winds



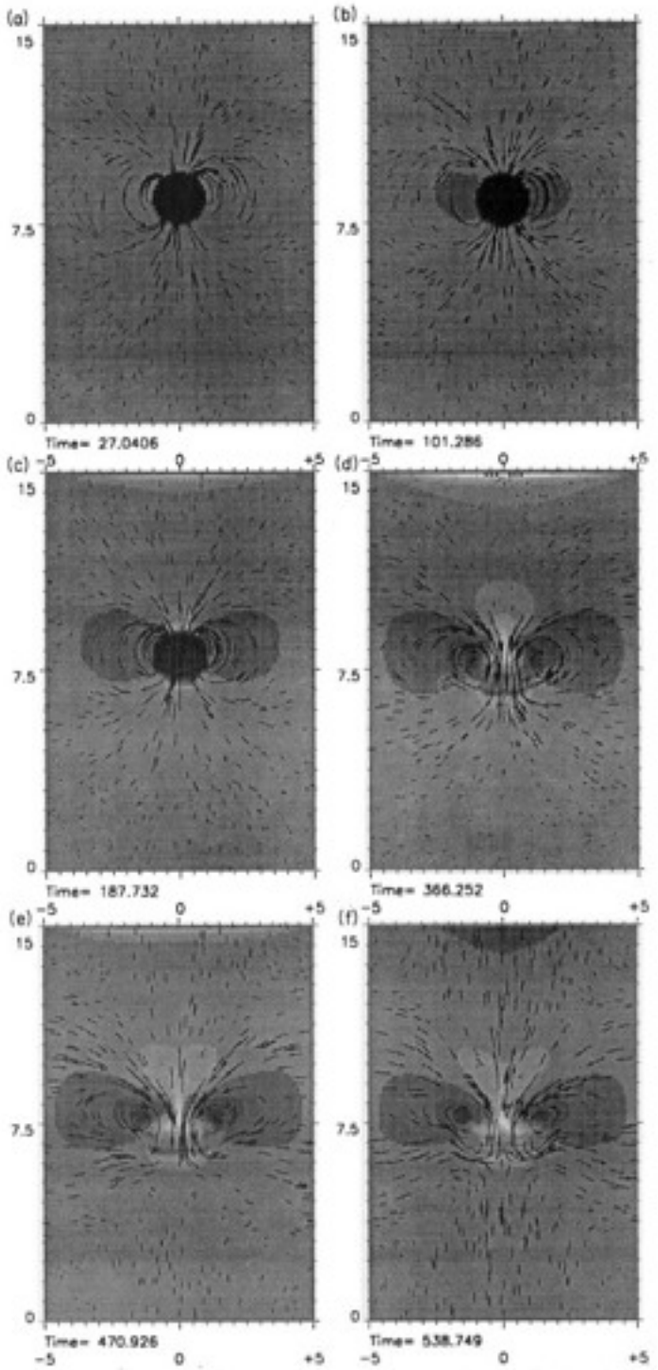
Our Galaxy

Hydra A

Why aren't bubbles disrupted by Kelvin-Helmholz instabilities?

How do they heat their surroundings?

Thermal Instability in Stratified Atmospheres

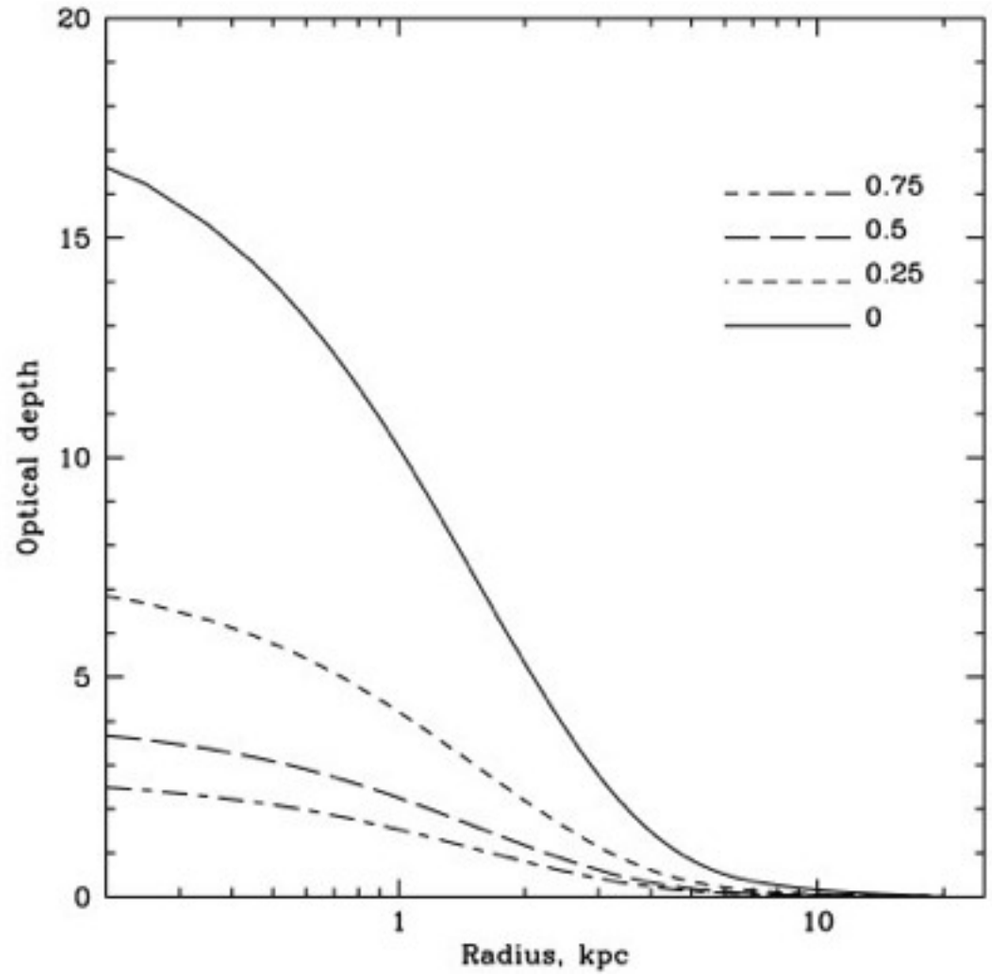


Simple Field Criterion not correct in stratified atmospheres---cooling blobs subject to overstable oscillations

Will limit efficiency of HVC formation in galactic coronae

Malagoli, Rosner & Fryxell 1990

Resonant Line Transport in Turbulent Medium



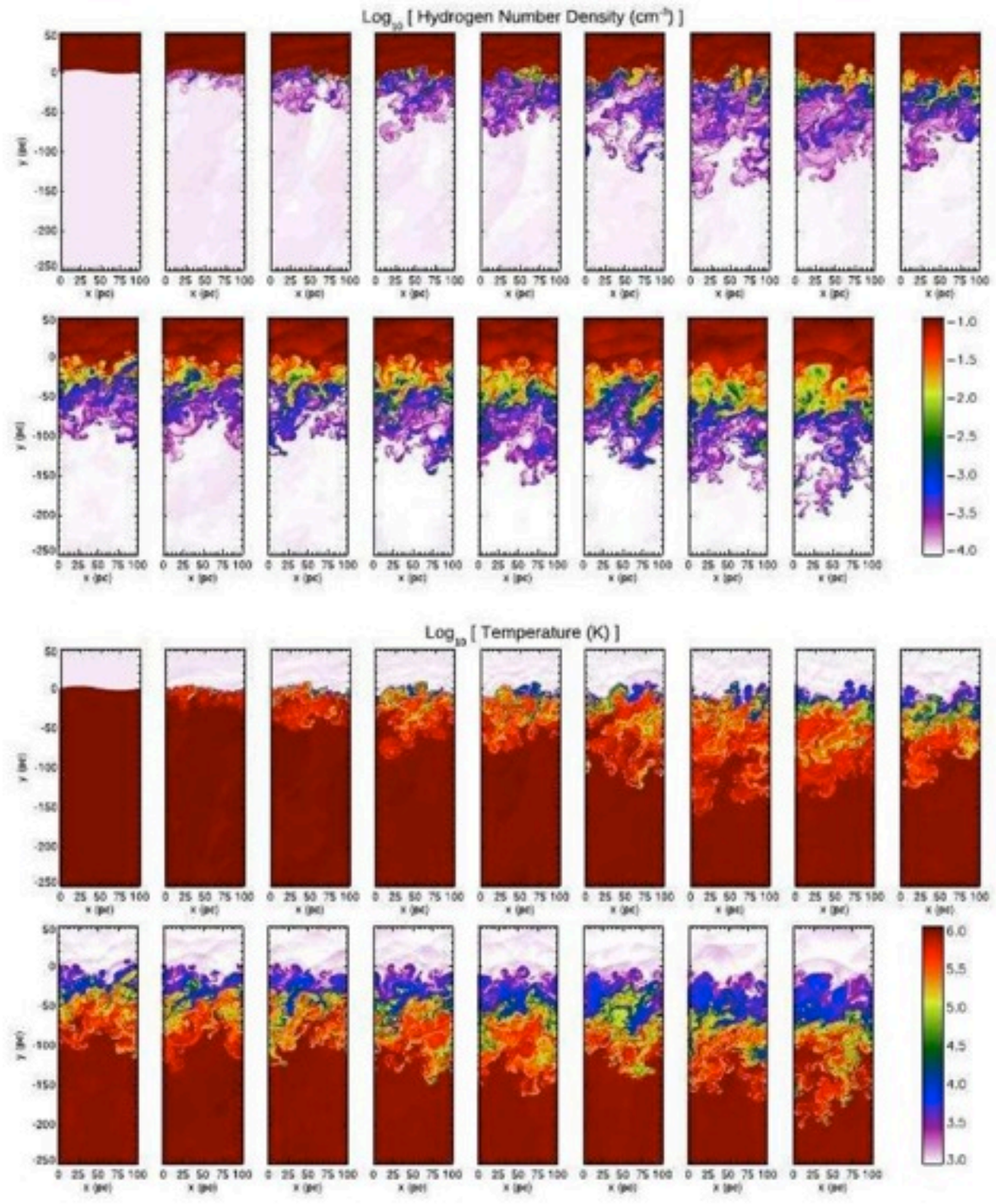
Line profiles broadened by turbulence---reduce optical depth for scattering

Used in clusters to constrain turbulence

Werner et al (2009)

We need to include turbulence in our Ly-alpha radiative transfer codes!

Turbulent Mixing Layers



Possible means of powering filament emission in clusters

Could also be partially responsible for OVI, CIV emission in galaxies

Kwan & Shelton 2010

Cosmic Ray/Wave Heating

Collisional heating as the origin of filament emission in galaxy clusters*

G. J. Ferland,[1,2]† A. C. Fabian,[1] N. A. Hatch,[3] R. M. Johnstone,[1] R. L. Porter,[1,2]
P. A. M. van Hoof[4] and R. J. R. Williams[5]

EVIDENCE FOR AN ADDITIONAL HEAT SOURCE IN THE WARM IONIZED MEDIUM OF GALAXIES

R. J. Reynolds, L. M. Haffner, and S. L. Tufte[1]
Department of Astronomy, University of Wisconsin–Madison, 475 North Charter Street,
Madison, WI 53706; reynolds@astro.wisc.edu, haffner@astro.wisc.edu
Received 1999 July 9; accepted 1999 August 26; published 1999 September 29