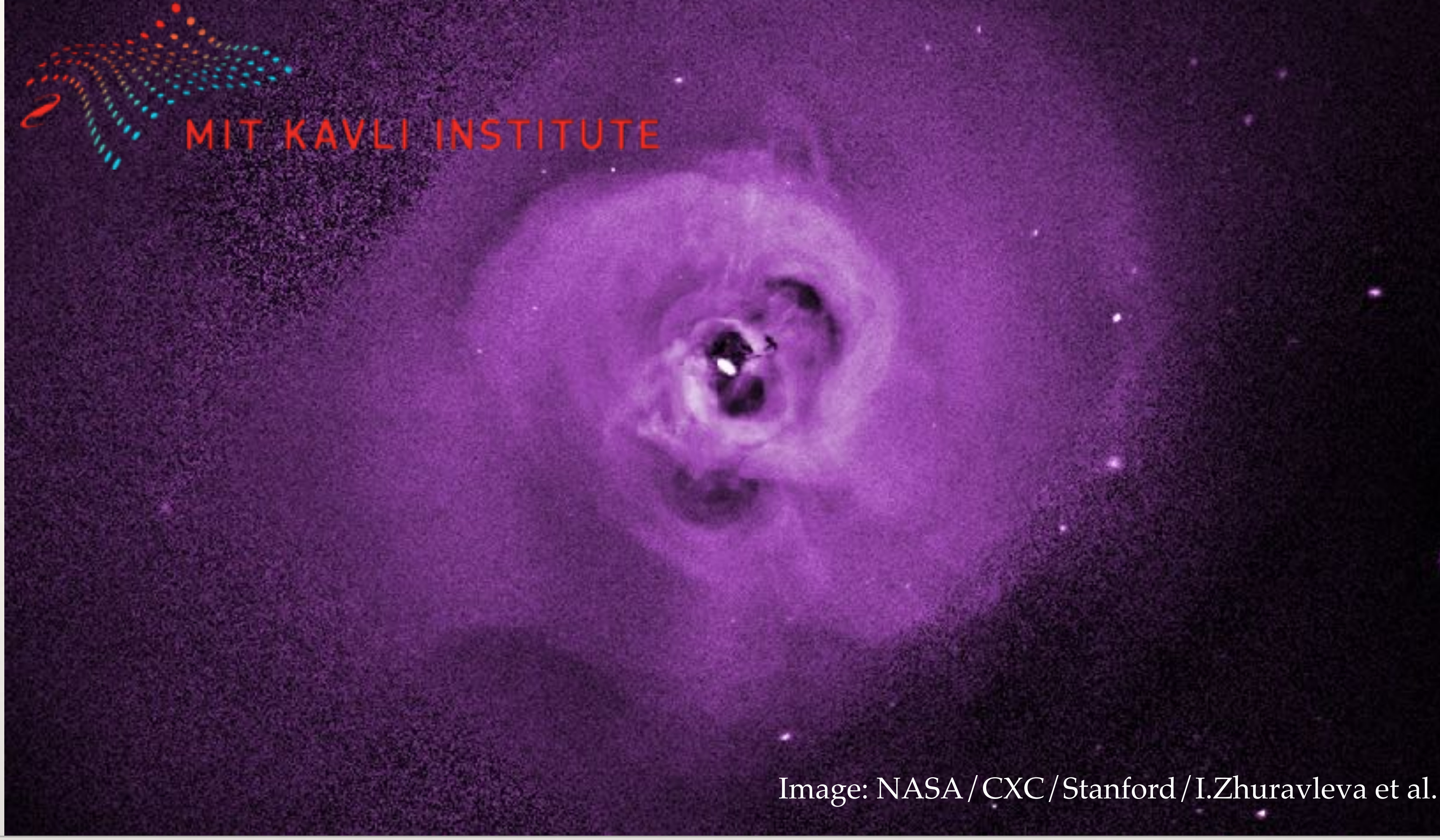


Image: NASA/CXC/Stanford/I.Zhuravleva et al.

Quenching, blackhole feedback and anisotropic thermal conduction

July 3, 2017, Galaxy Clusters 2017, Santander

Rahul Kannan (MIT)

Collaborators : Mark Vogelsberger (MIT), Christoph Pfrommer (HITS), Rainer Weinberger (HITS), Volker Springel (HITS), Lars Hernquist (CfA), Ewald Puchwein (IoA), Ruediger Pakmor (HITS)

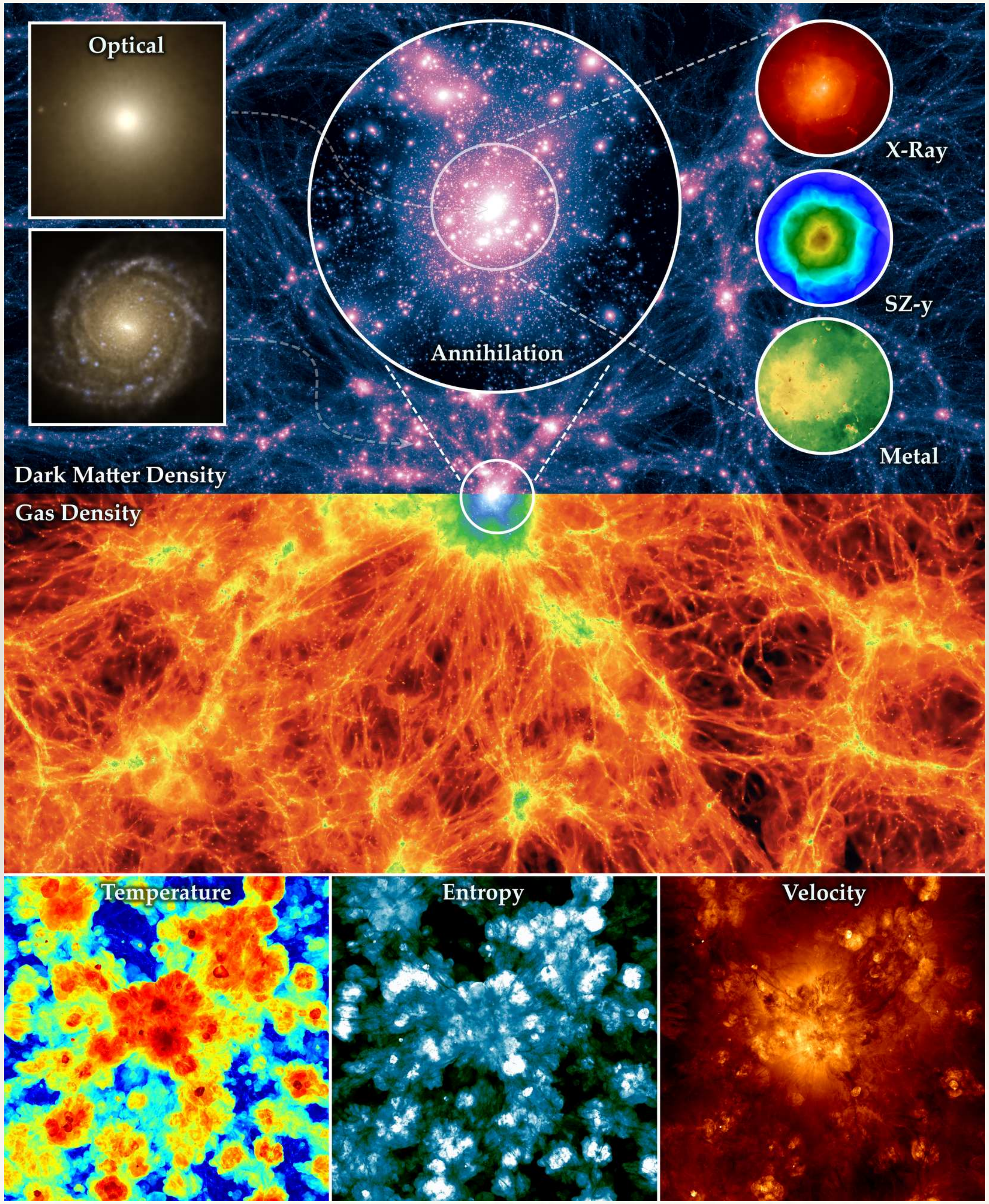
Based on Kannan et al.
2016 MNRAS 458, 410
2017 ApJ Lett. 837, L18

Introduction

- Galaxy clusters are the largest gravitationally bound objects in the Universe
- Cluster counts helps put important constraints on the cosmology
- Simulating these massive systems requires modeling complex physical processes like star formation, feedback, radiative cooling etc.

Attempt at modeling these processes

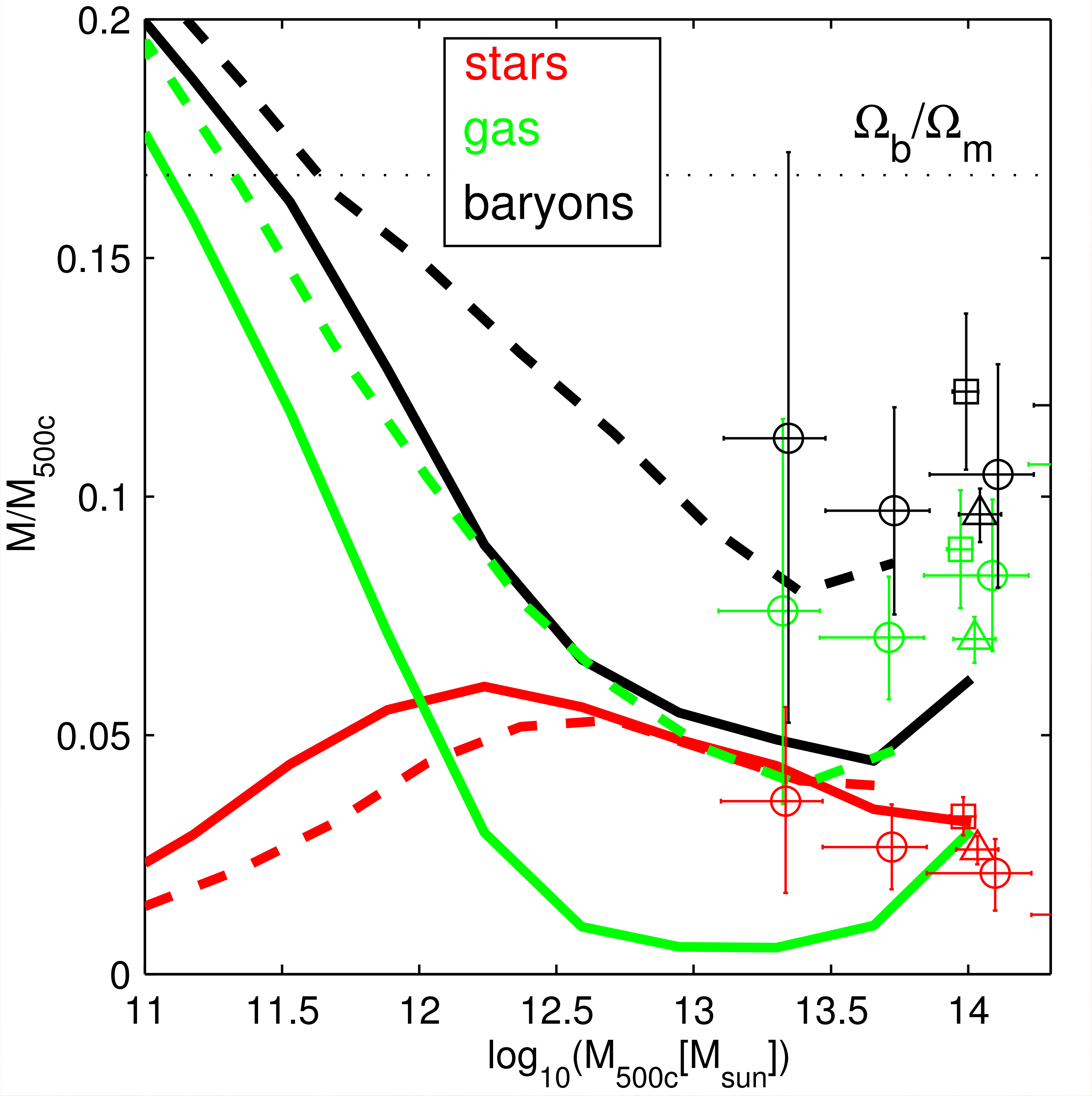
- Illustris simulation - Vogelsberger+2014
- 75 cMPc/h on a side box
- Resolution of 0.71 kpc
- All relevant physics - star formation, stellar feedback, AGN (radio+quasar) feedback, metal enrichment etc.



Vogelsberger+14

Attempt at modeling these processes

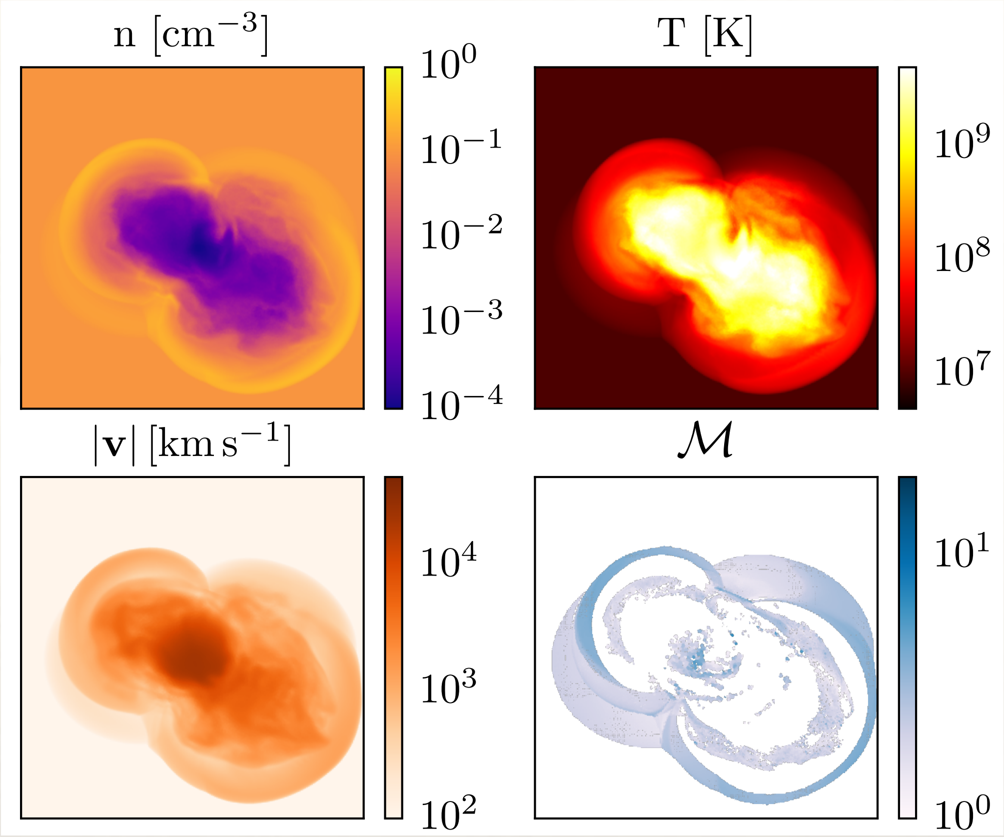
- Gas Fractions are way off
- Indicating that the coupling between the AGN feedback energy and the ICM is not modeled properly
- Only way to reduce star formation is to blow the gas out of the halo

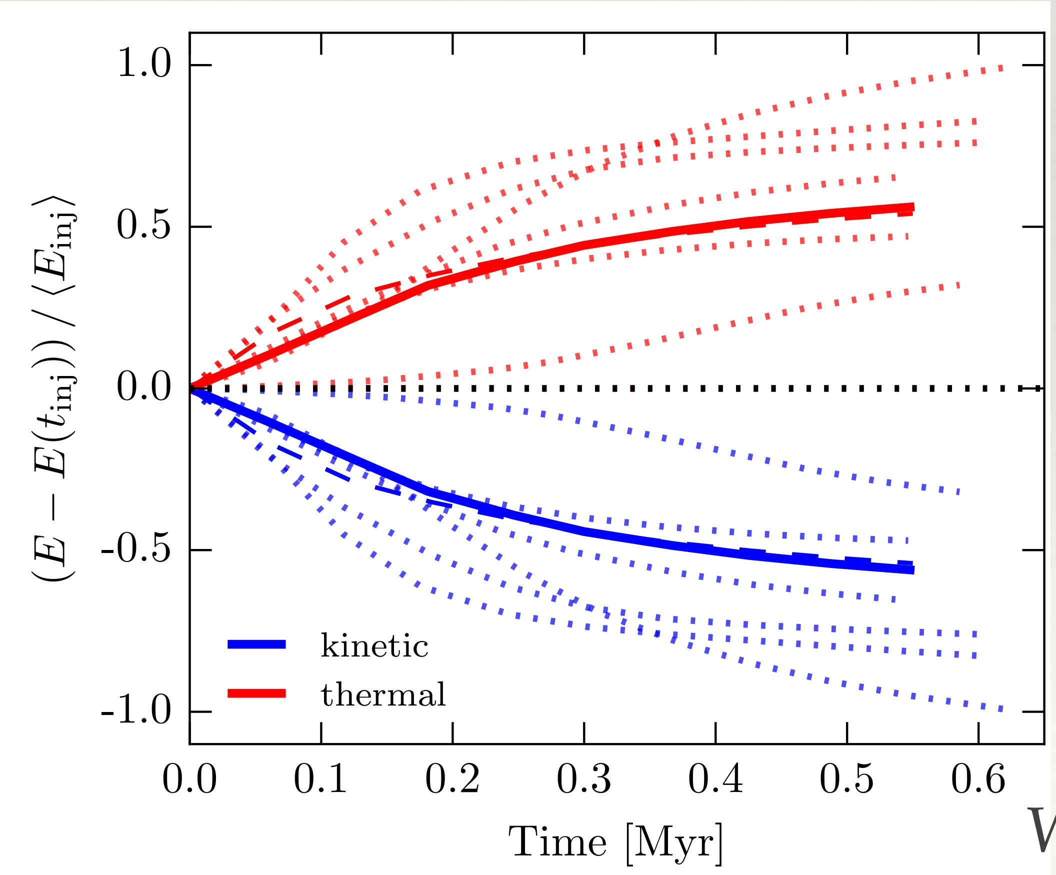


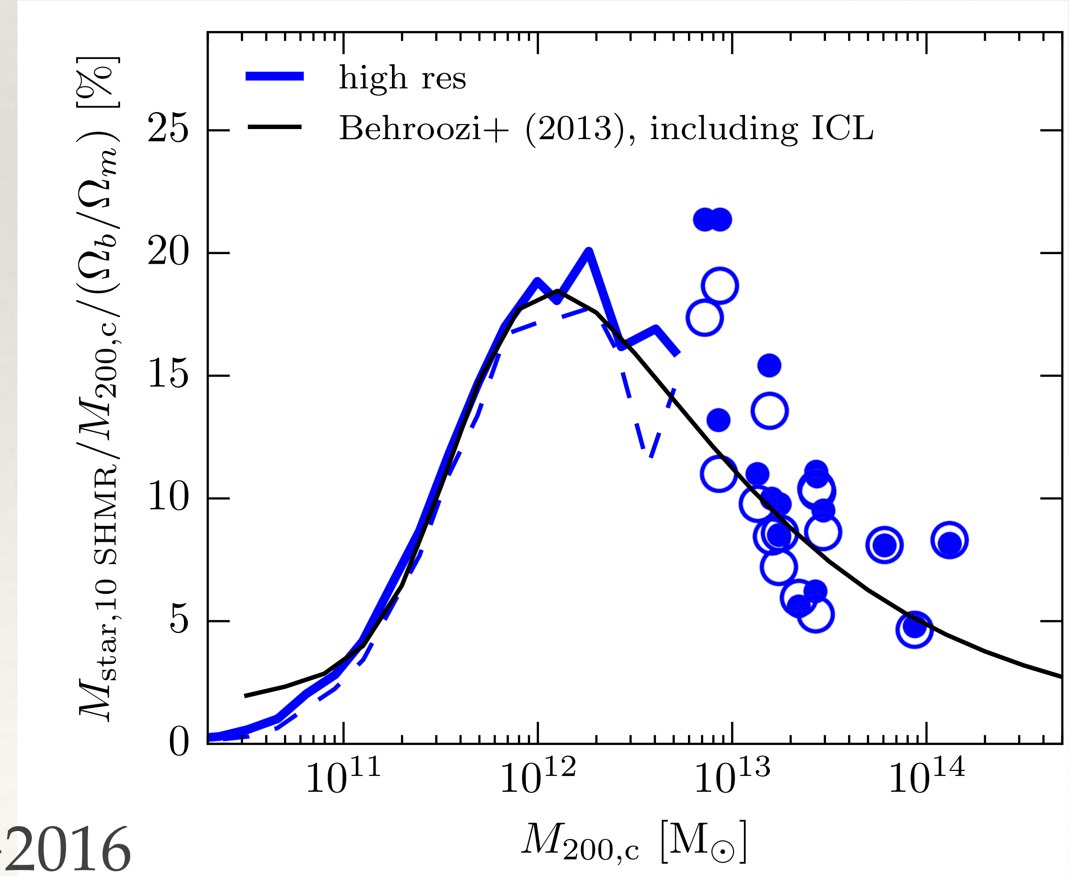
Genel+14

The (IllustrisTNG) AGN feedback model

- High accretion mode Quasar mode - Thermal dump of energy
- Low accretion mode Radio mode - Momentum kicks in random direction
- Half of the feedback energy that was initially in kinetic form is thermalized after 0.5 Myr.



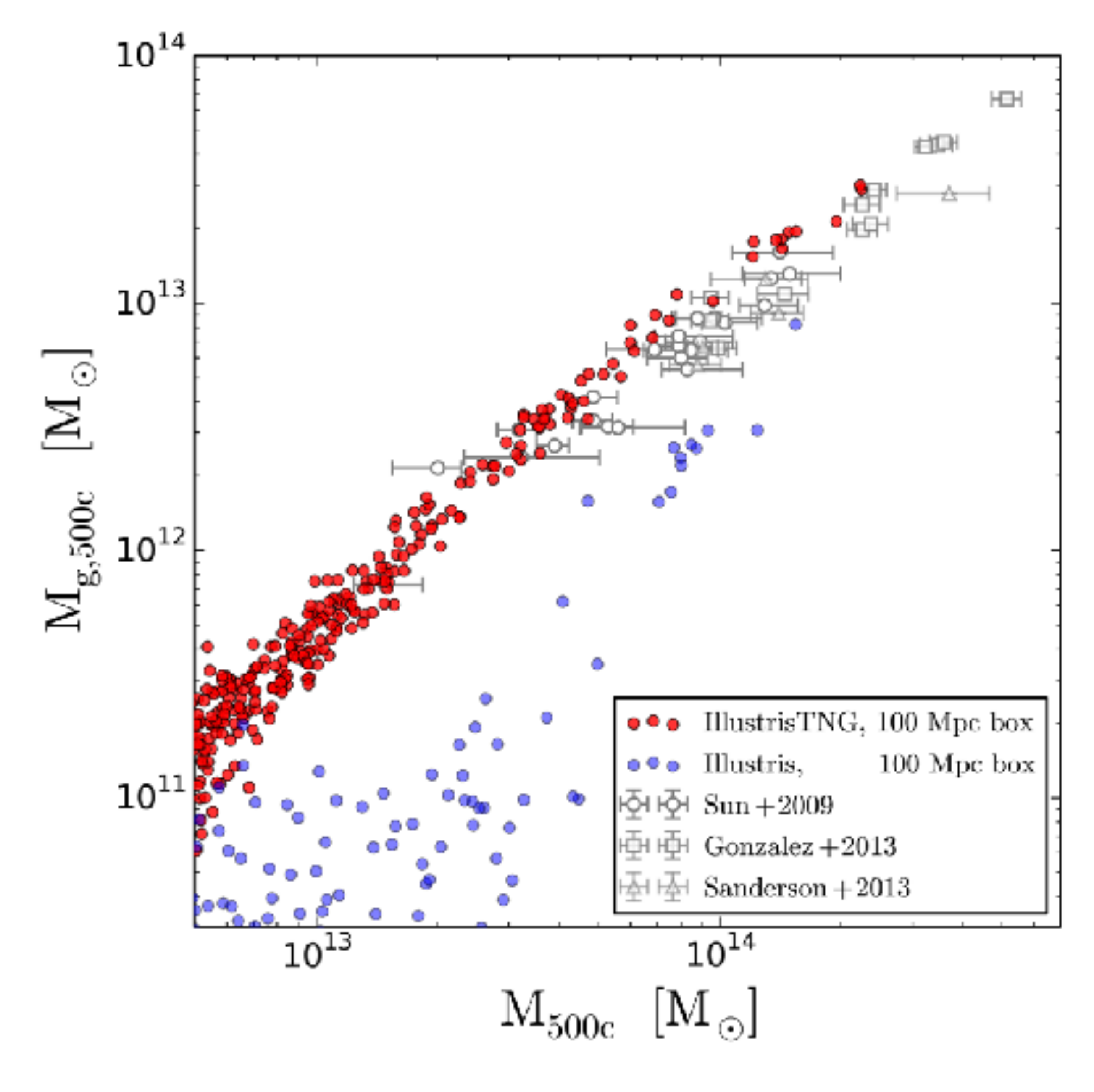




Weinberger+2016

IllustrisTNG (300 Mpc) - Gas fractions

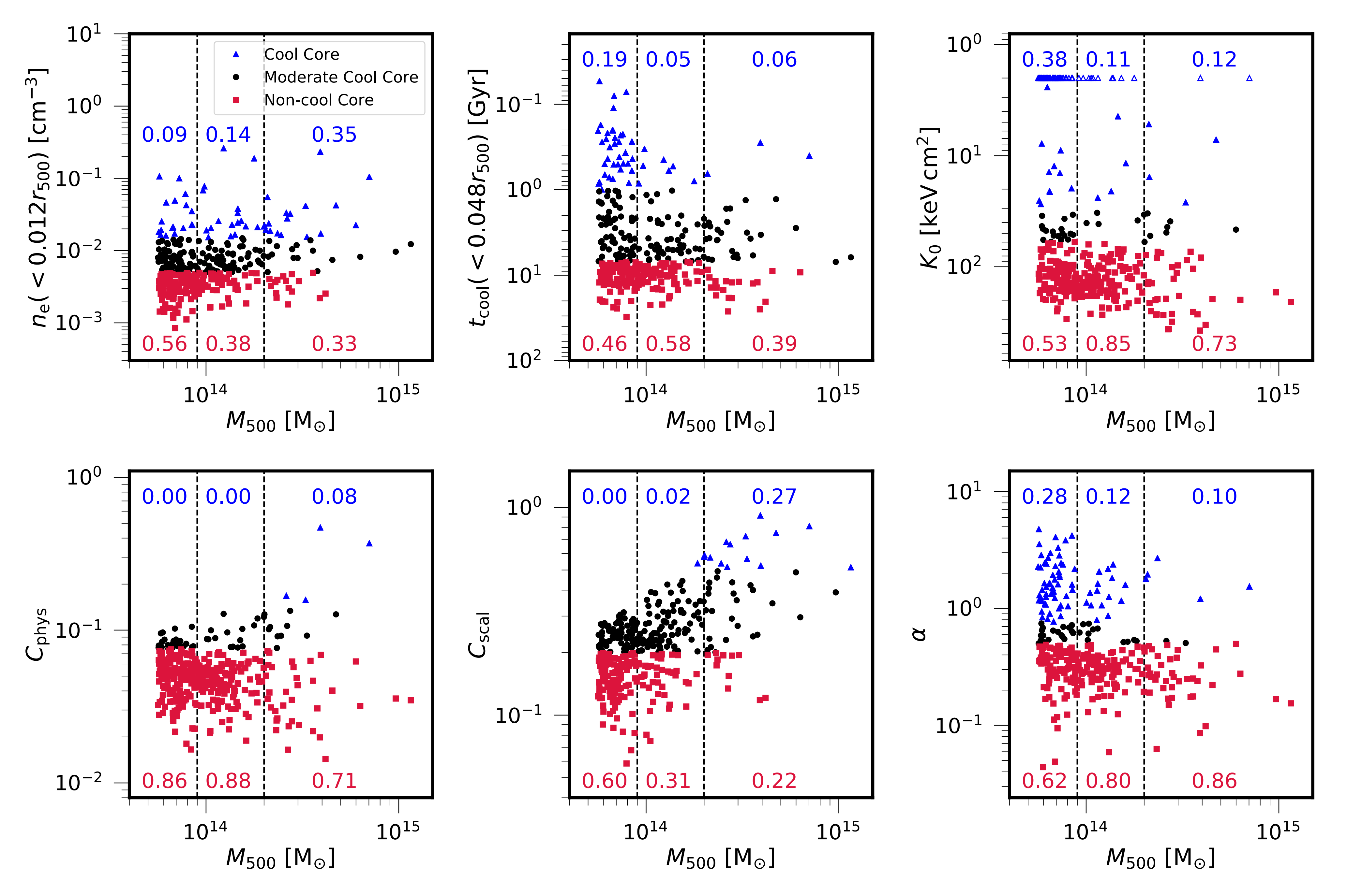
- ~400 clusters above 1e14 Msun - spatial resolution ~ 1 kpc/h
- Feedback is more gentle
- Manages to keep most of the gas in the halo
- Leads to better match with observed gas fractions, X- ray luminosities and thermal SZ signal



Pop, Hernquist, Kannan+, in prep
See also Ana-Roxana Pop's poster

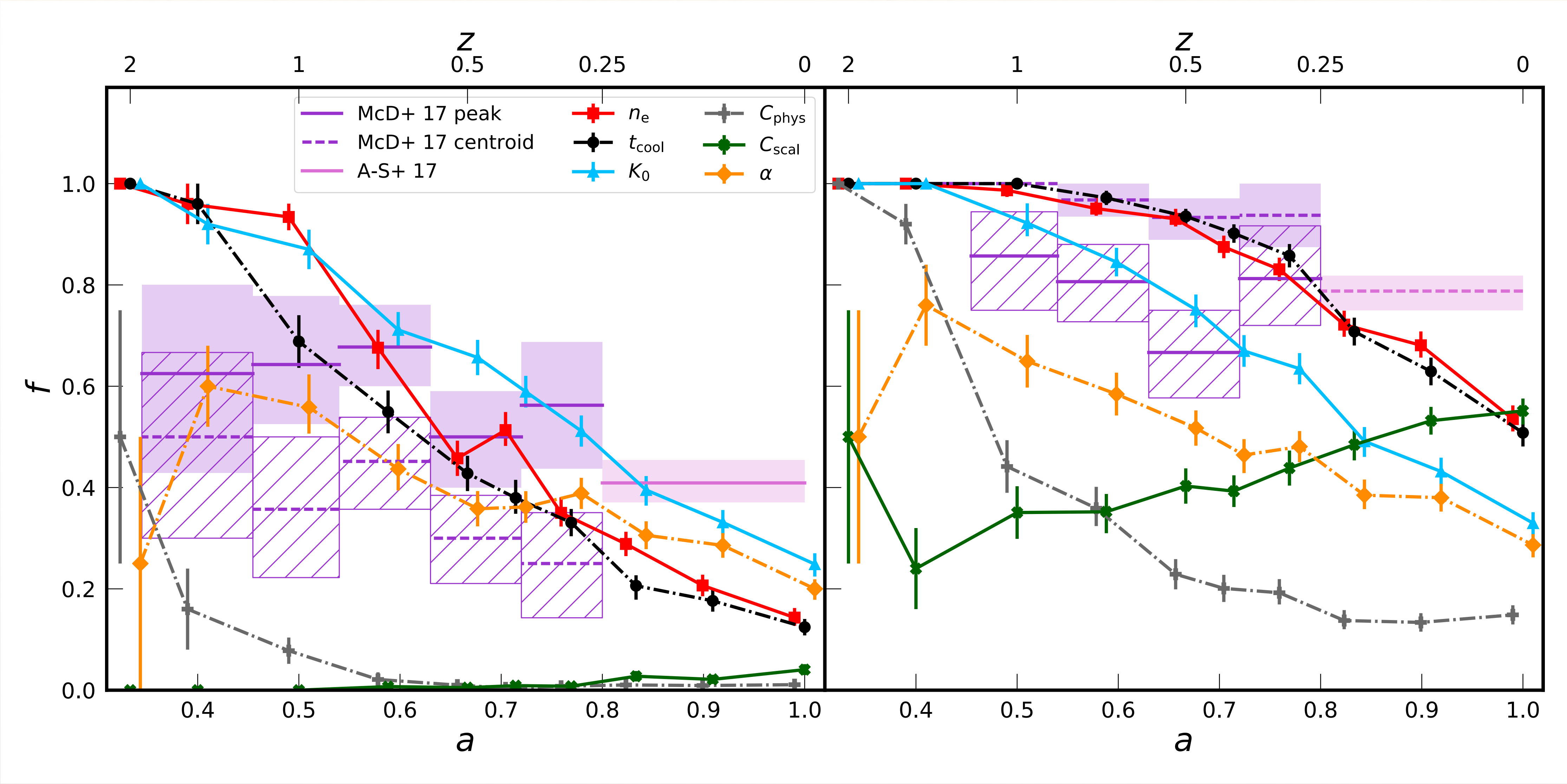
Cool core fractions

- Low cool cores fractions compared to observations
- Similar CC fraction as compared to Rasia+15 and Hahn+17 simulations
- Similar problems in other simulations such as EAGLES



Barnes, Vogelsberger, Kannan+, in prep

Cool core fraction evolution

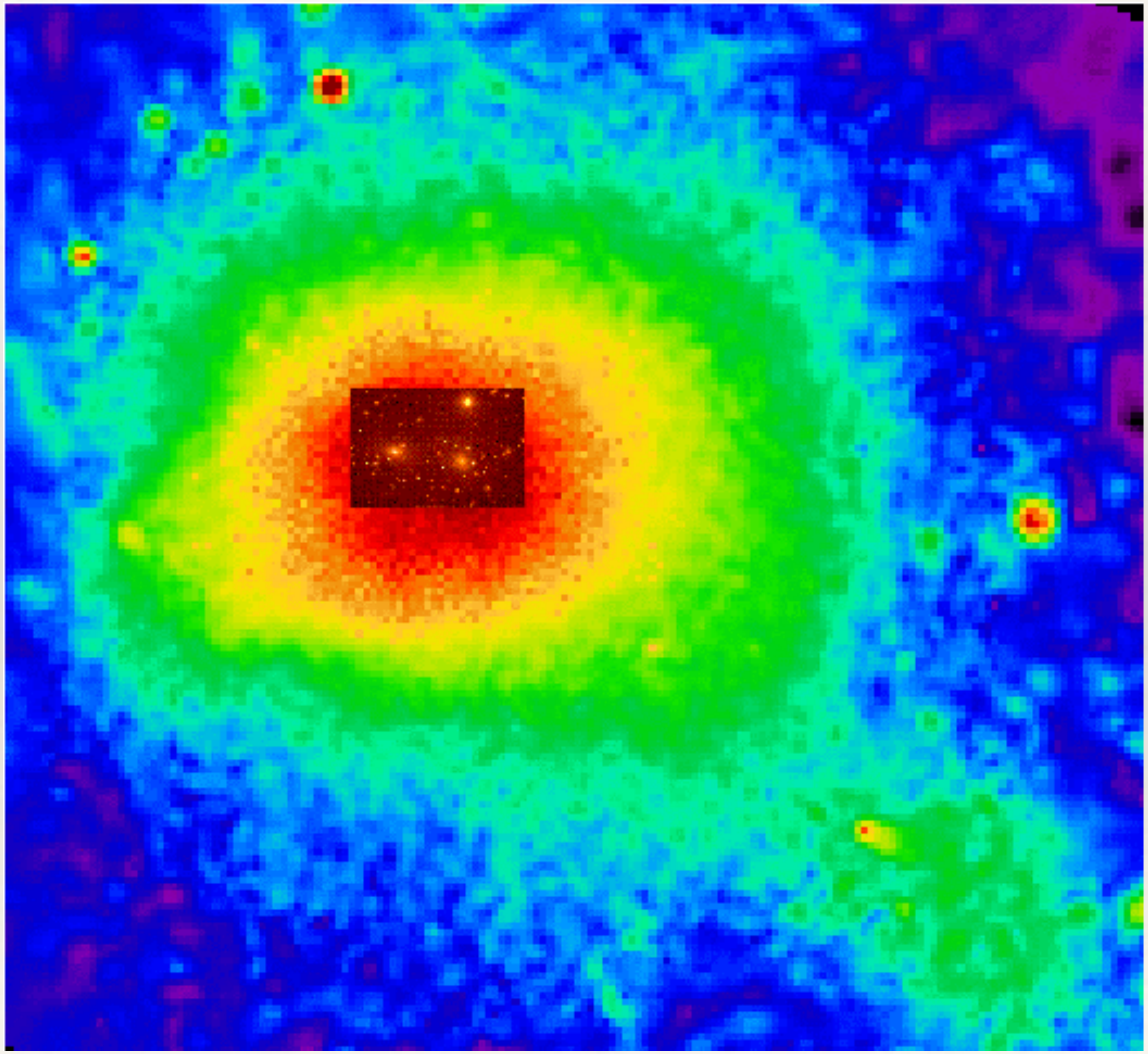


Barnes, Vogelsberger, Kannan+, in prep

- CC fraction in good agreement with z>0.3 results
- Too many cool cores getting destroyed at low redshift
- Are we missing something?

The rich physics in the ICM

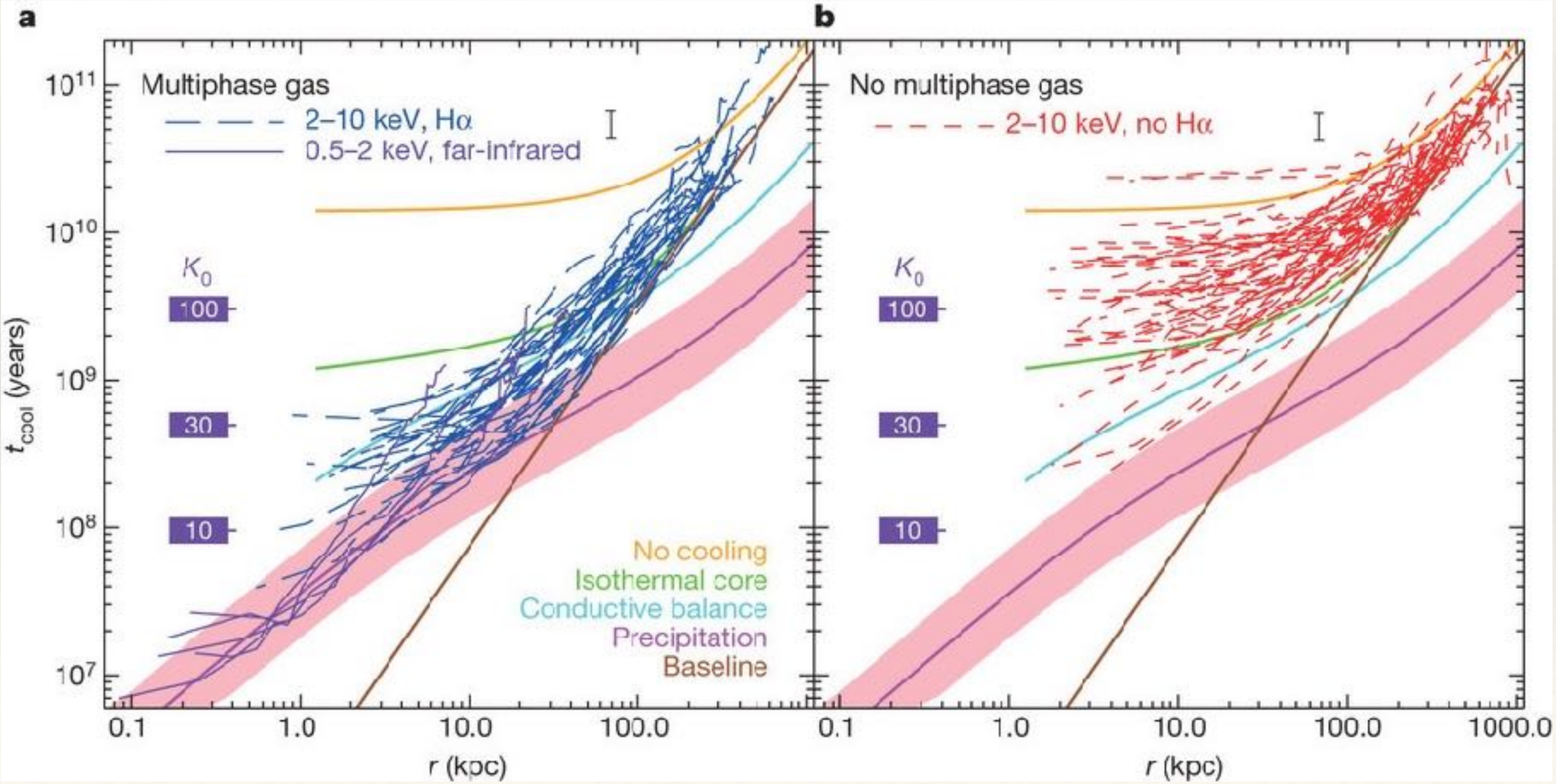
- The extreme temperatures and low density means that non traditional astrophysical processes become important
  - Magnetic fields
  - Thermal Conduction
  - Viscosity
- Need for efficient MHD and thermal conduction schemes
- Need high resolution in the ICM to resolve these processes
- Simulations unto now ignore these important processes



Thermal Conduction in clusters

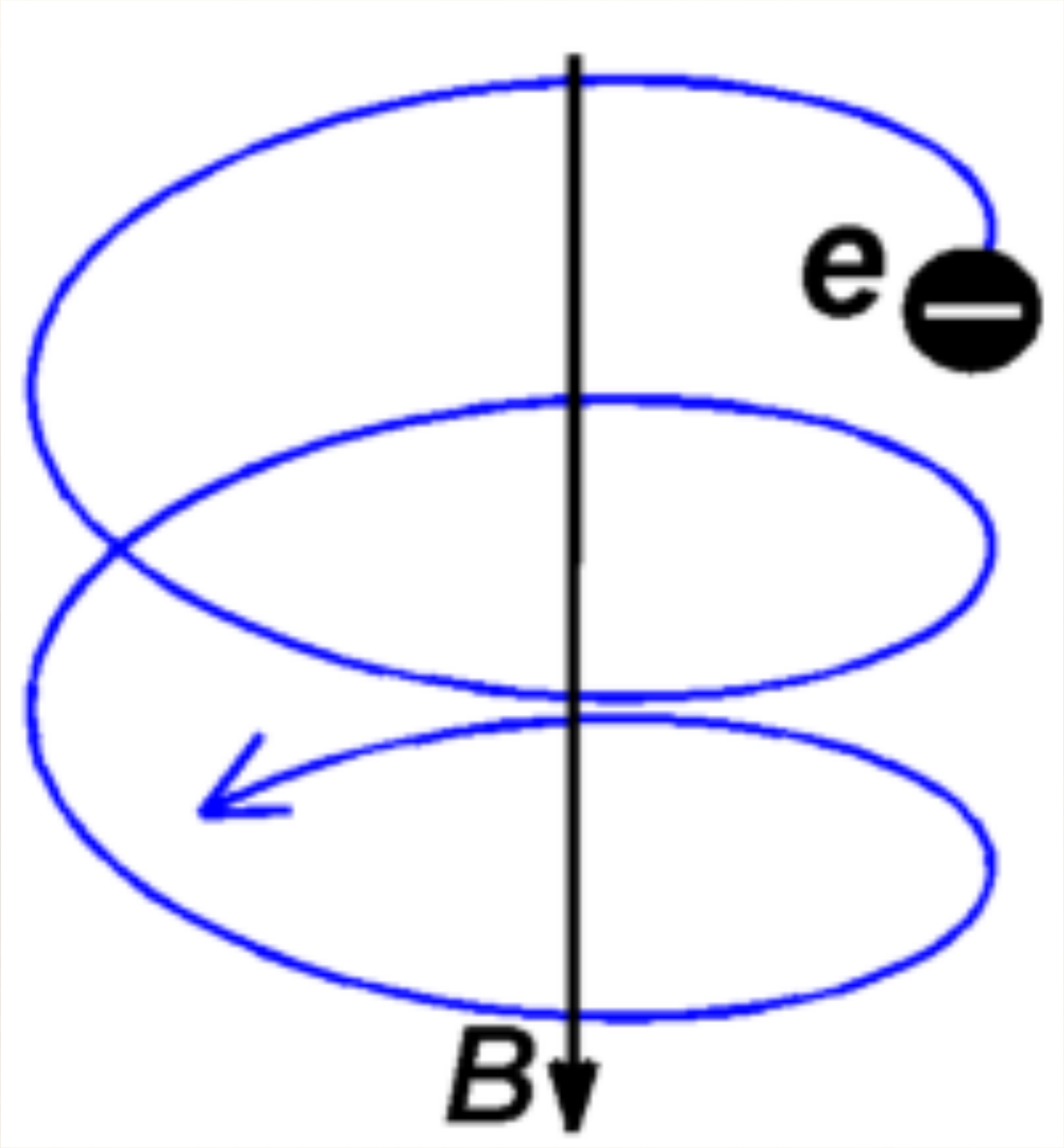
* Invoked by many to explain low cooling rates at the center of clusters(Voit+2015)

* However, many studies have shown that conductive heating alone cannot offset cooling loses in the core (eg. Yang & Reynolds 2016a)

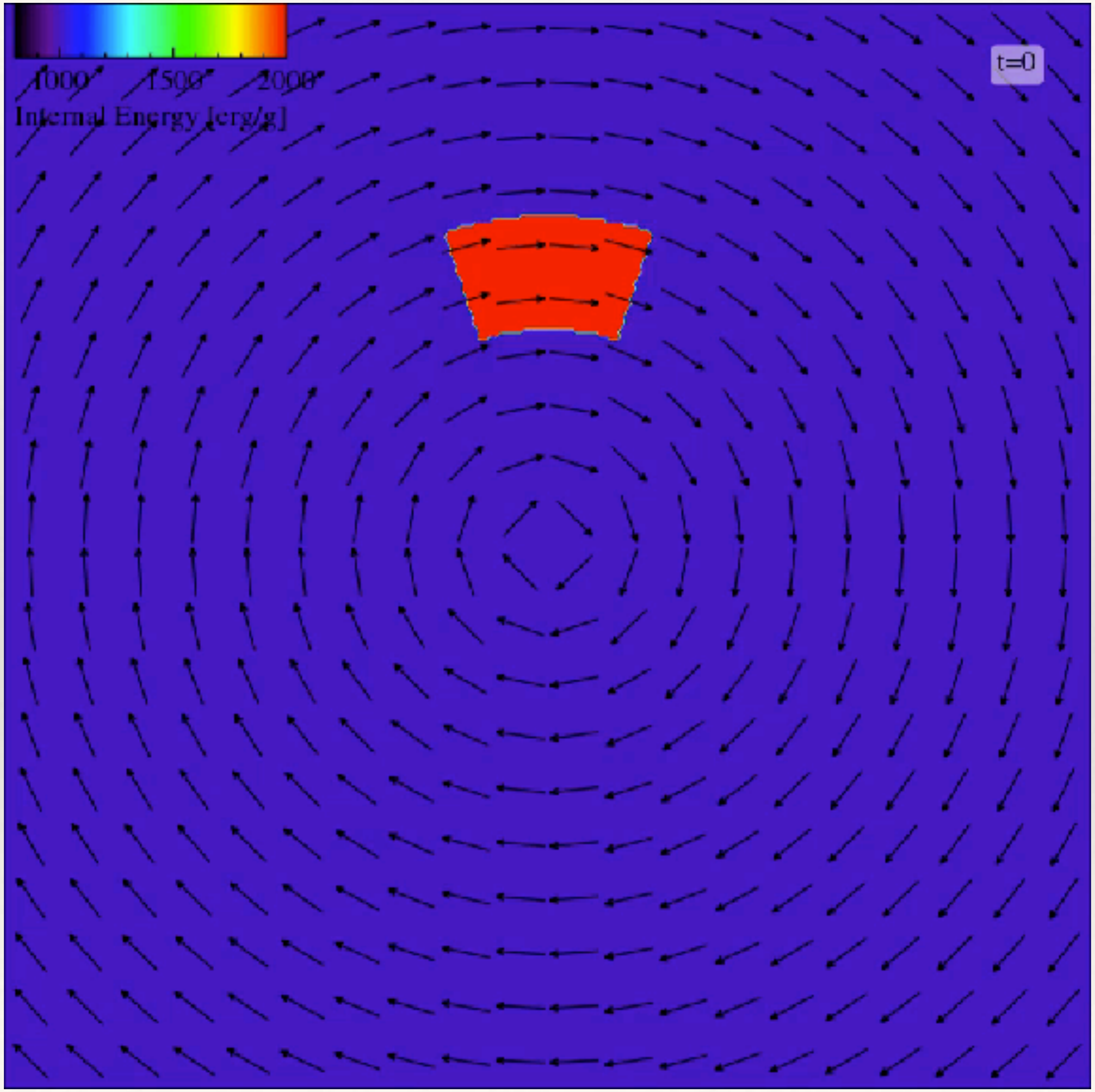


Thermal Conduction

- Diffusive transport of heat
- $\kappa \propto T^{5/2}$
- Mainly acts in high temperature systems where $t_{cond} << t_{dyn}$ as in clusters (will not affect Groups or MWs)
- Magnetic fields influence the direction of heat flow
- In general cluster plasma $l \sim 10^{12} r_g$
- Conduction across field lines strongly suppressed
- Leads to anisotropic transport of heat



Anisotropic Diffusion

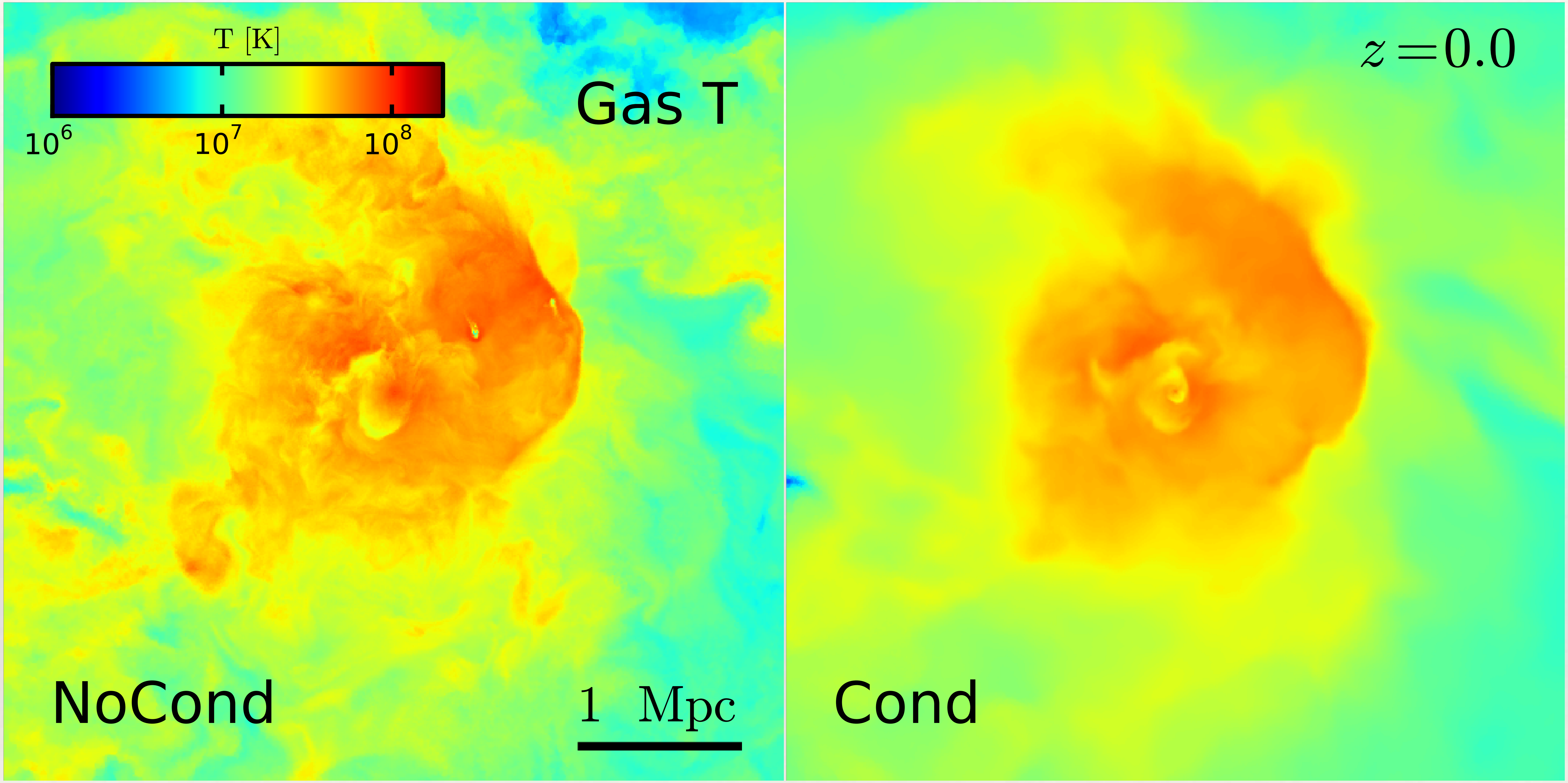


Conduction across magnetic field is highly suppressed

Kannan+2016b

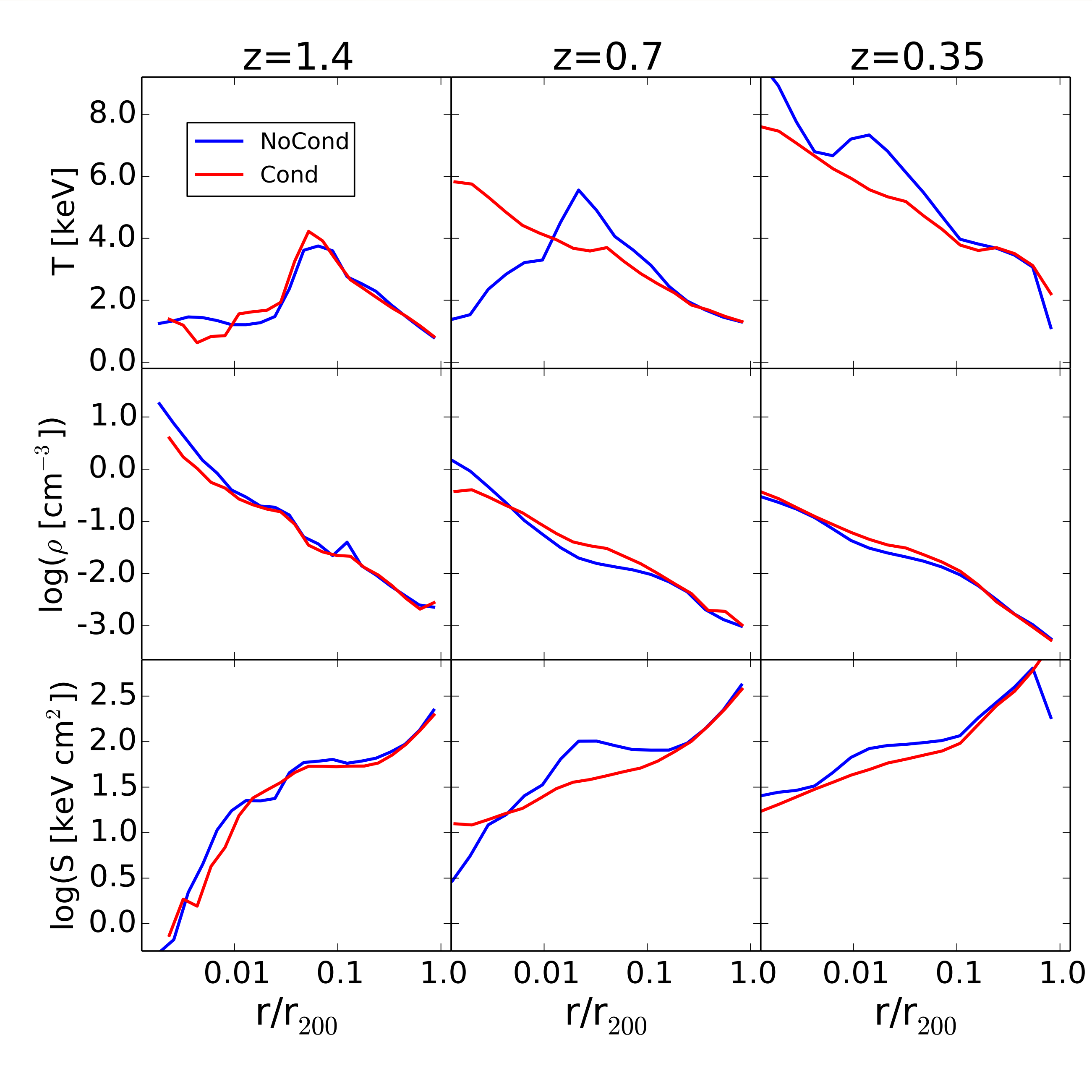
The AESTUS project

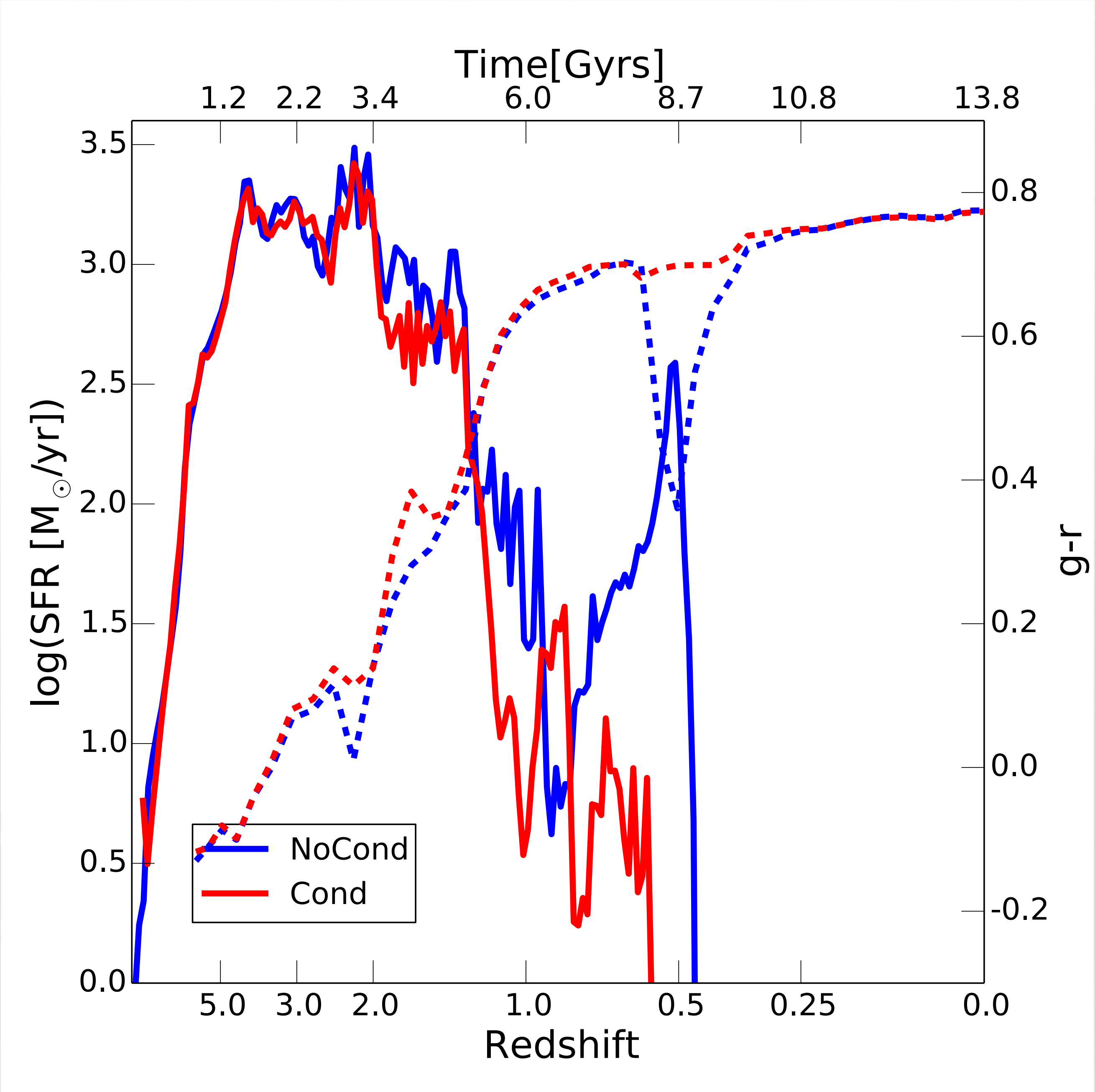
- Very high resolution simulations of a cluster ($\sim M_{200} = 6.5 \times 10^{14} M_{\odot}$) with the aim of resolving and simulating all the relevant ICM physics using Arepo
- ~1000 better Mass resolution ($6.8 \times 10^7 M_{\odot}$)
- ~30 times better Spatial resolution then previous simulations with ATC (1 kpc/h)
- All the relevant galaxy formation physics such as star formation, stellar (Vogelsberger+2013) and AGN (Weinberger+2016; Thermal quasar mode + kinetic radio mode) feedback included.
- Better physics and high resolution compared to the large scale simulations such as 'Illustris' (Vogelsberger+14), 'EAGLES' (Schaye+14) and even the new generation Illustris-TNG simulation suites.



Survival of cold fronts due to magnetic draping (Dursi+2009)

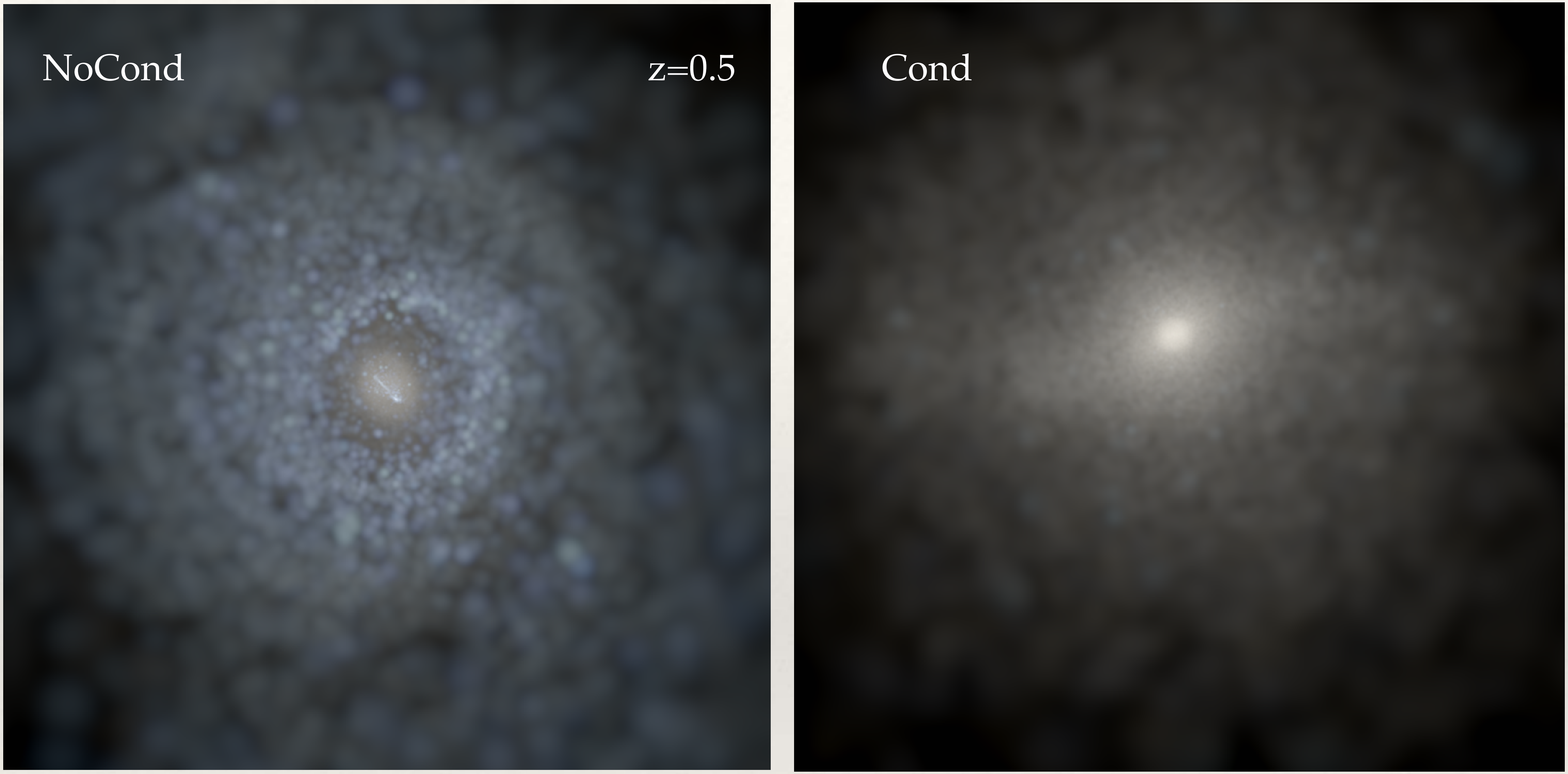
Better quenching





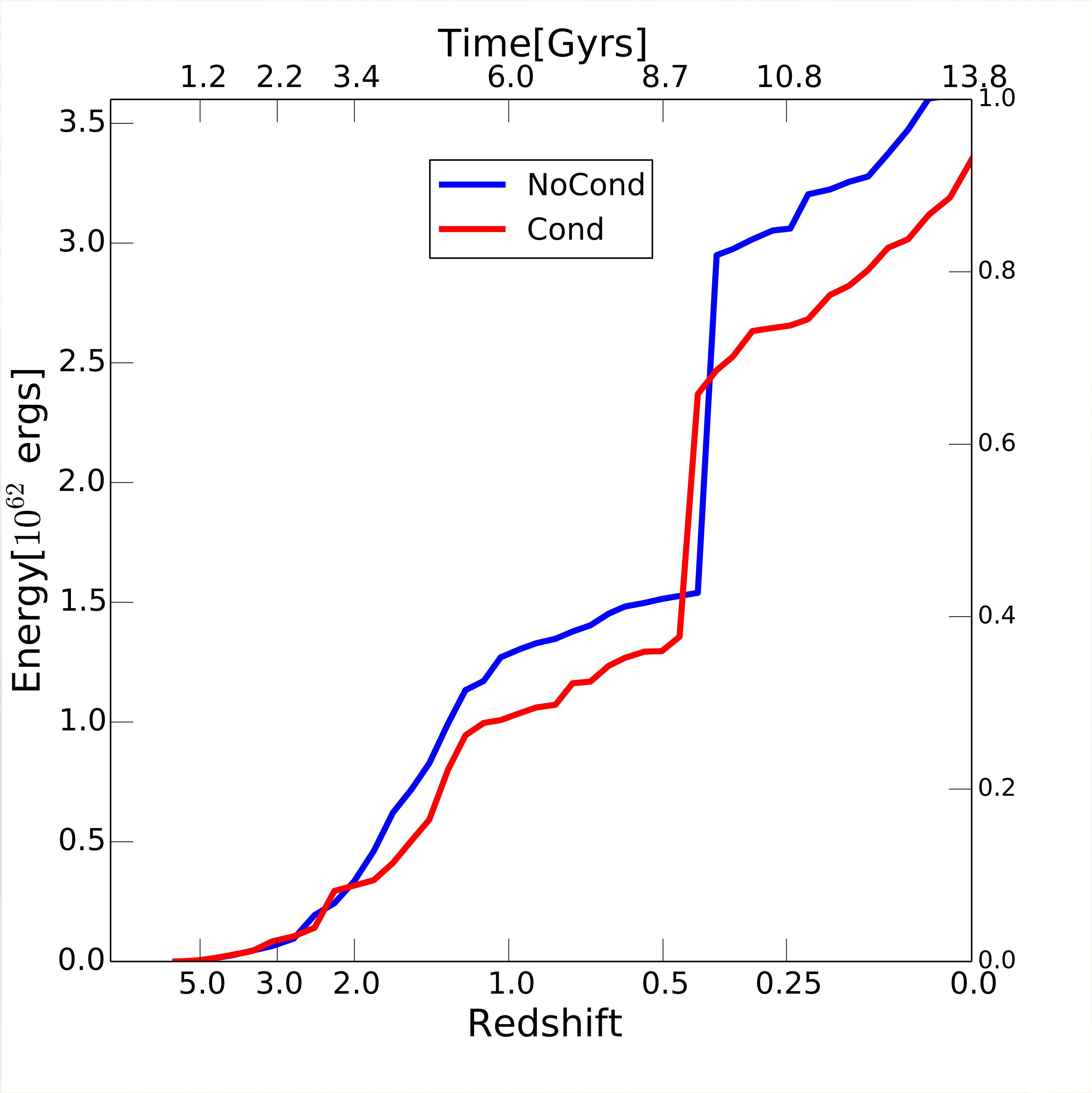
- Conduction converts a cool-core to a non cool core cluster earlier (merger driven)
- Reduces SFRs by more than an order of magnitude at low redshifts
- Completely quenches SF about 0.5 Gyrs earlier

Redder galaxies

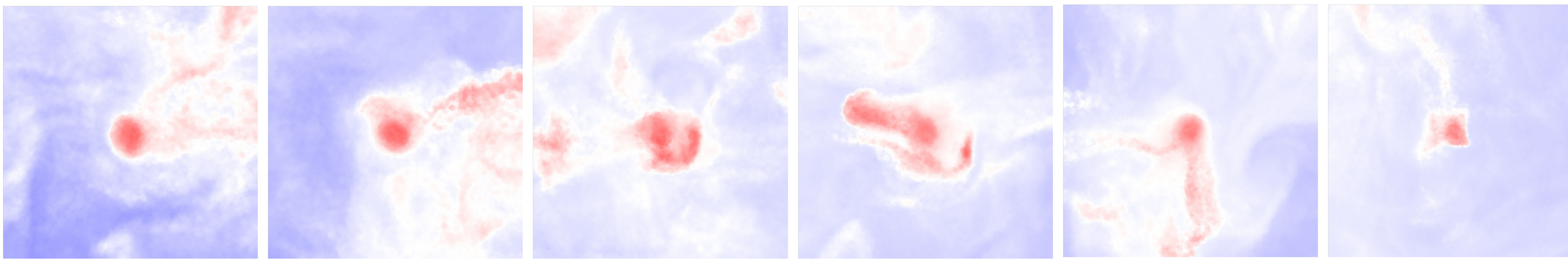


- Conduction converts a cool-core to a non cool core cluster earlier
- Reduces SFRs by more than an order of magnitude at low redshifts
- Completely quenches SF about 0.5 Gyrs earlier

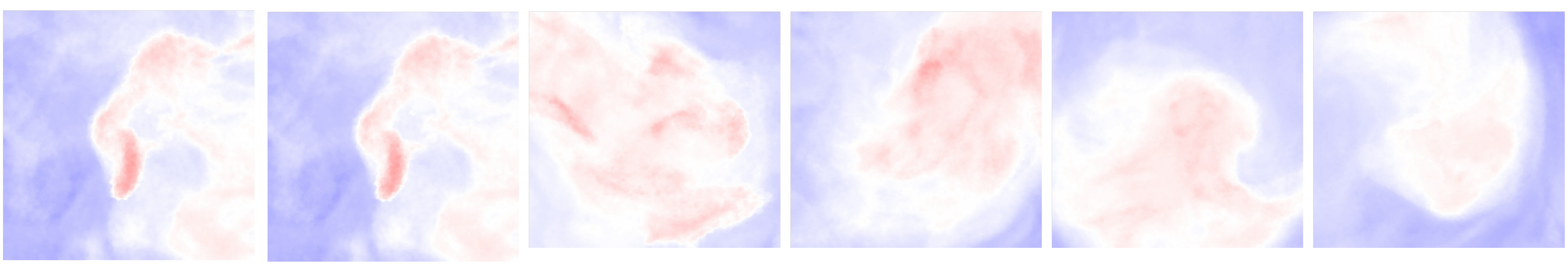
- Lower AGN feedback in the Cond but greater impact of SFRs
- Effect of conductive heating? -No because conductive heating is at most 10% of cooling losses
- Also cannot explain efficiency in NCC phase



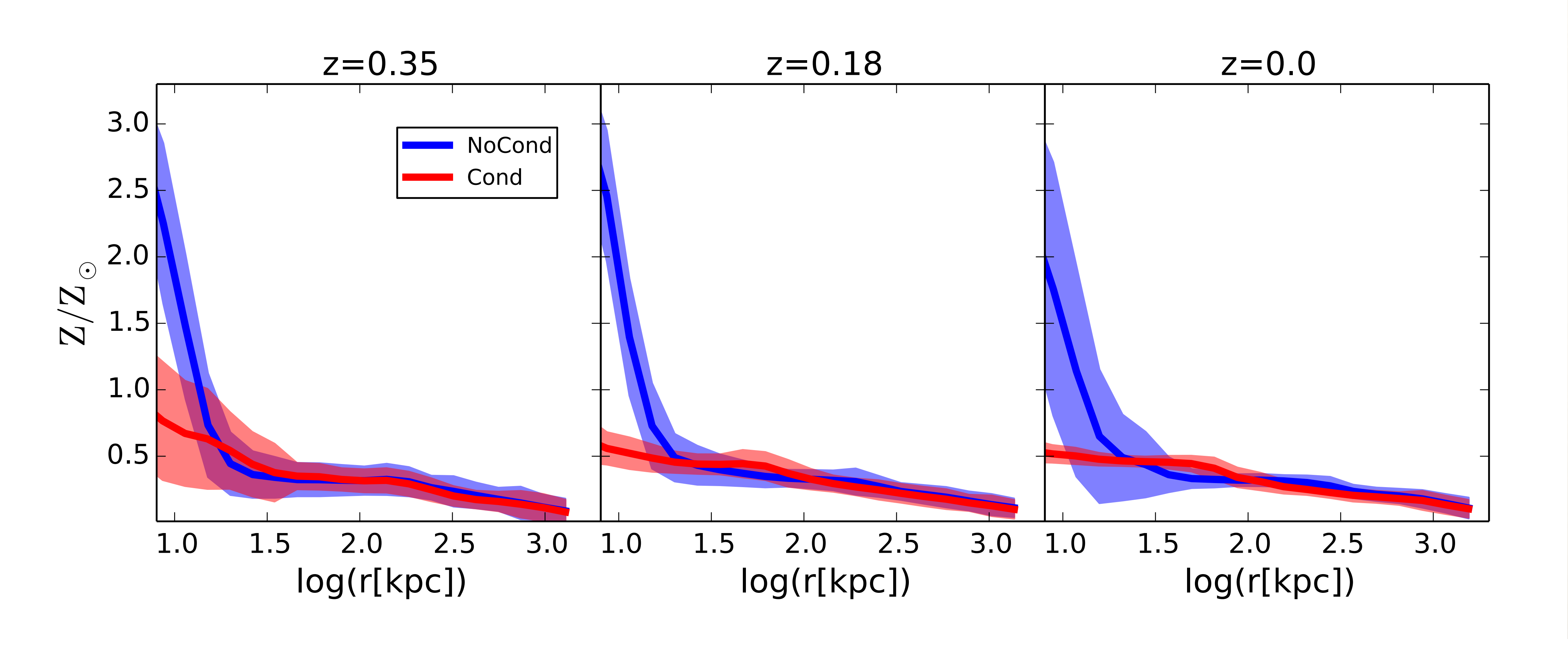
Increased Metal mixing



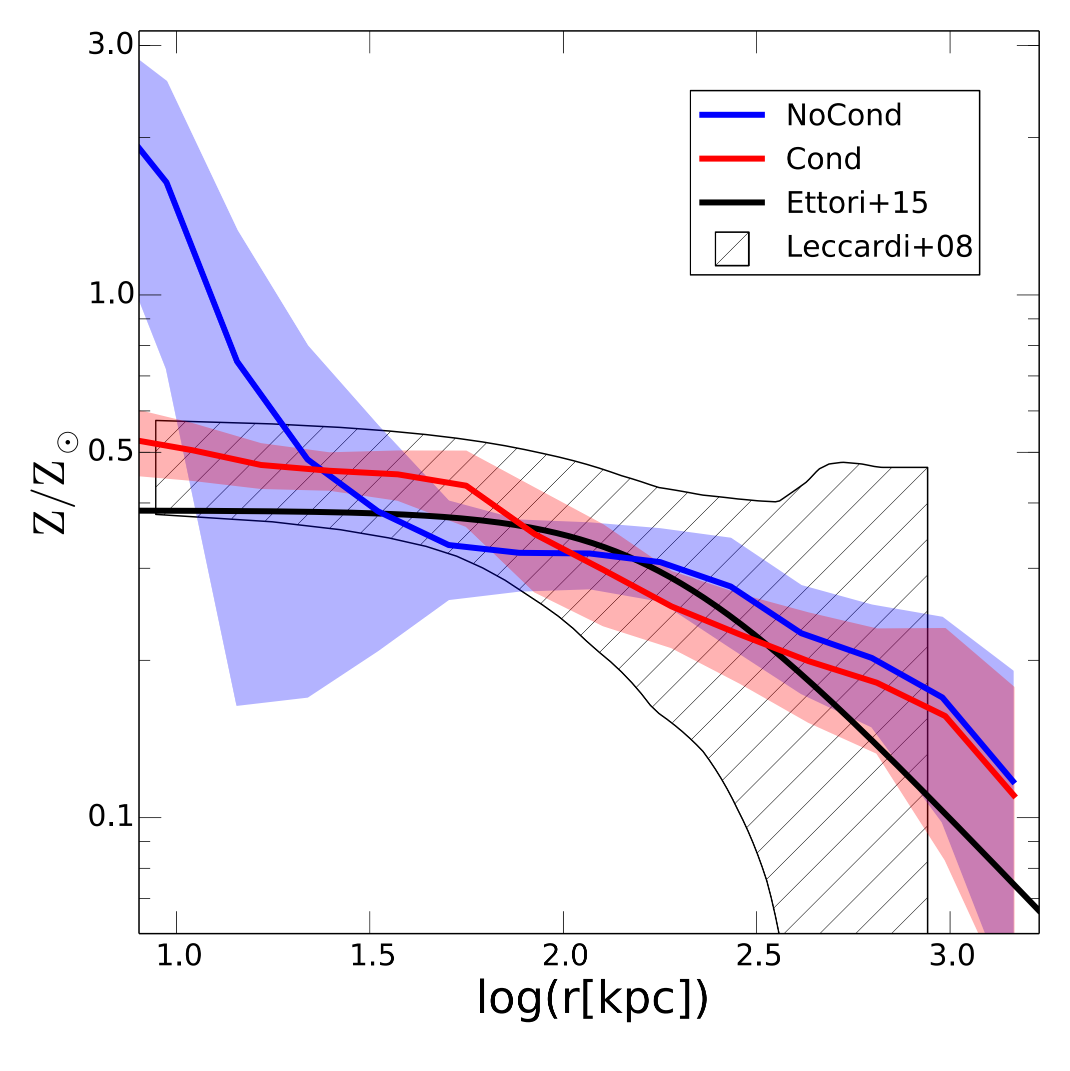
NoCond



Cond

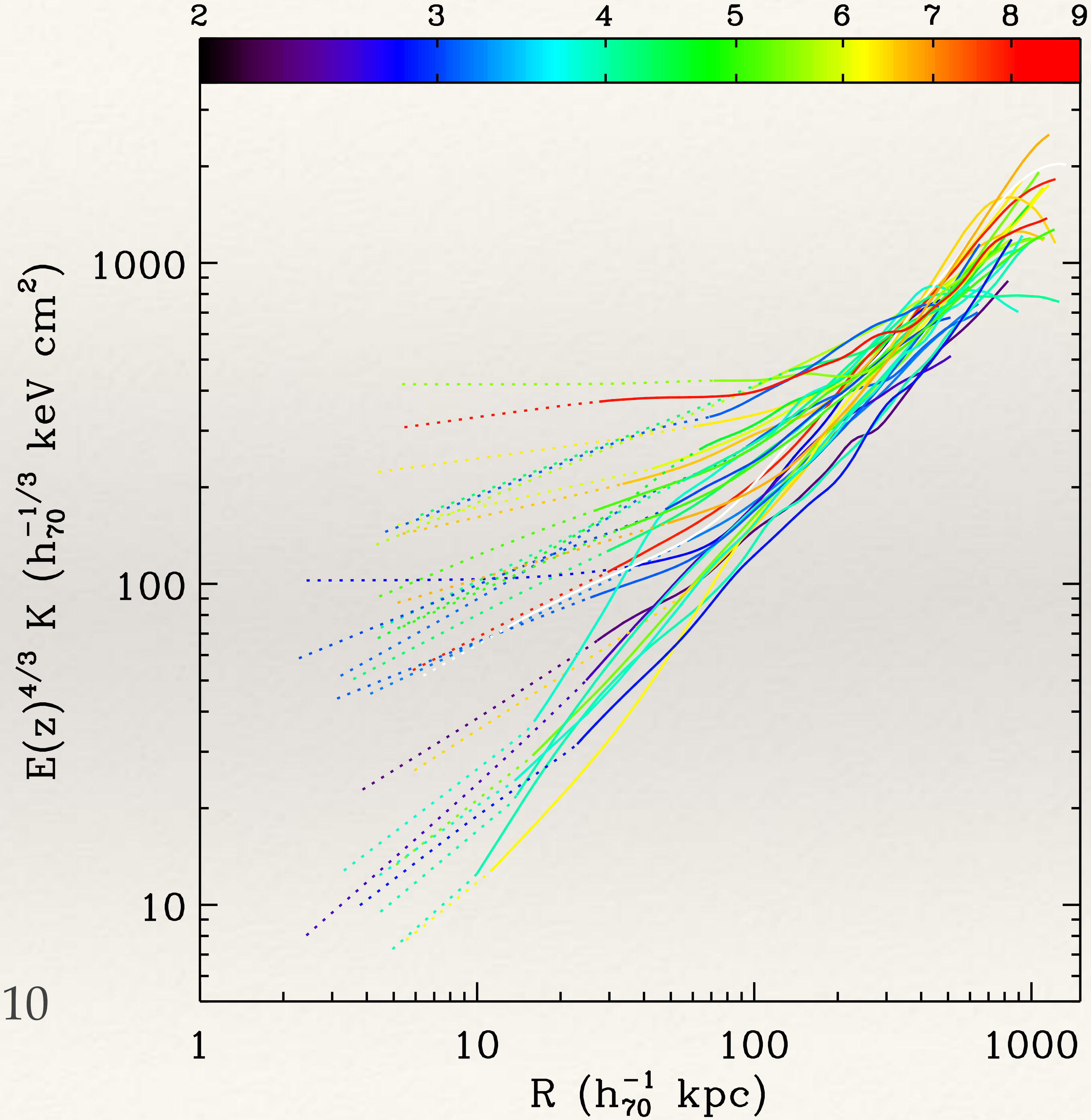


- Lowers the central metallicity
- Reduces the gradients
- Lowers dispersion
- Conduction run metallicity profiles match observations
- Conductive heating cannot explain this behavior
- Indicates efficient mixing in the conduction run



Convective stability of a pure hydrodynamic fluid

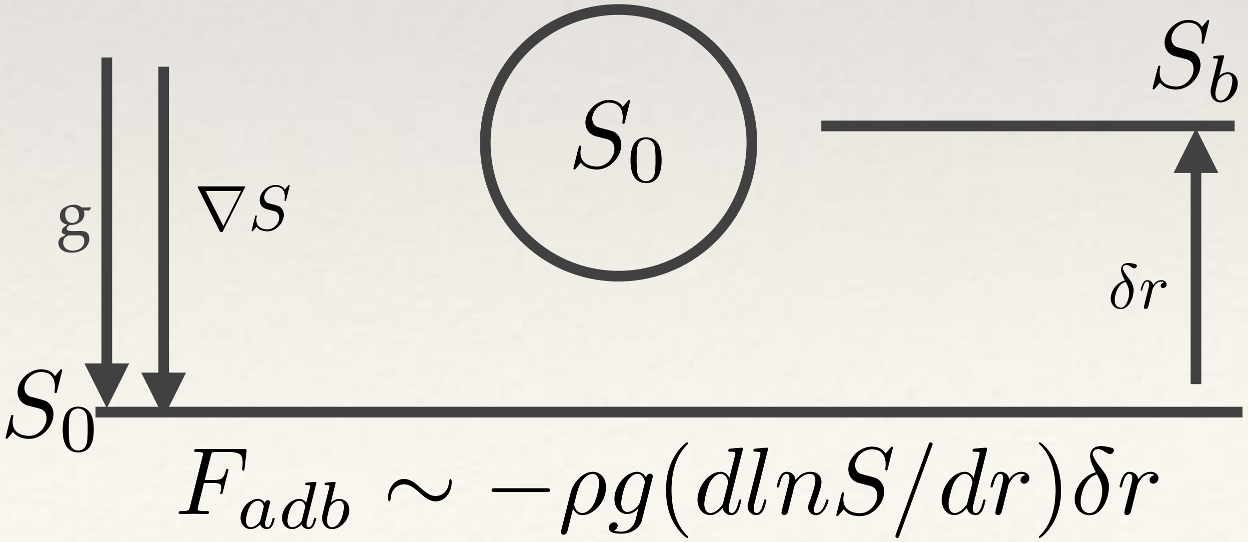
- Stable to convection as long as $dS/dr > 0$



Pratt+2010

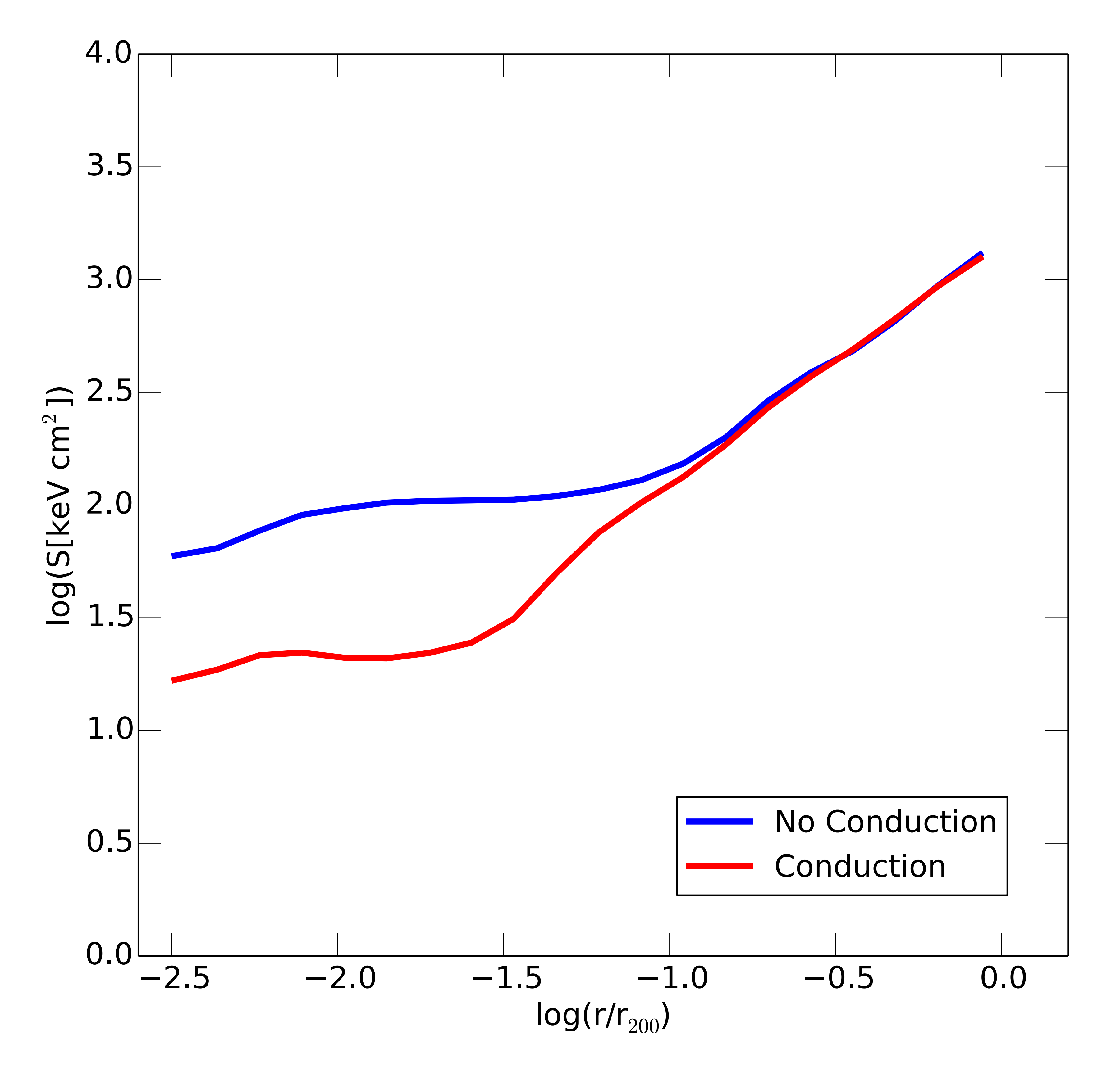
Convective stability of a pure hydrodynamic fluid

- Stable to convection as long as $dS/dr > 0$
- Buoyant restoring force $F_{adb} \sim -\rho g(dlnS/dr)\delta r$
- If injected turbulent force is $F_{turb} < F_{adb}$ then the fluid element oscillates with the classical Brunt-Vaisala frequency.
- If $F_{turb} > F_{adb}$ then you effectively induce mixing in the plasma
- The restoring force depends on the entropy gradient
- If the gradient is lower then you get more mixing with less turbulent velocity.



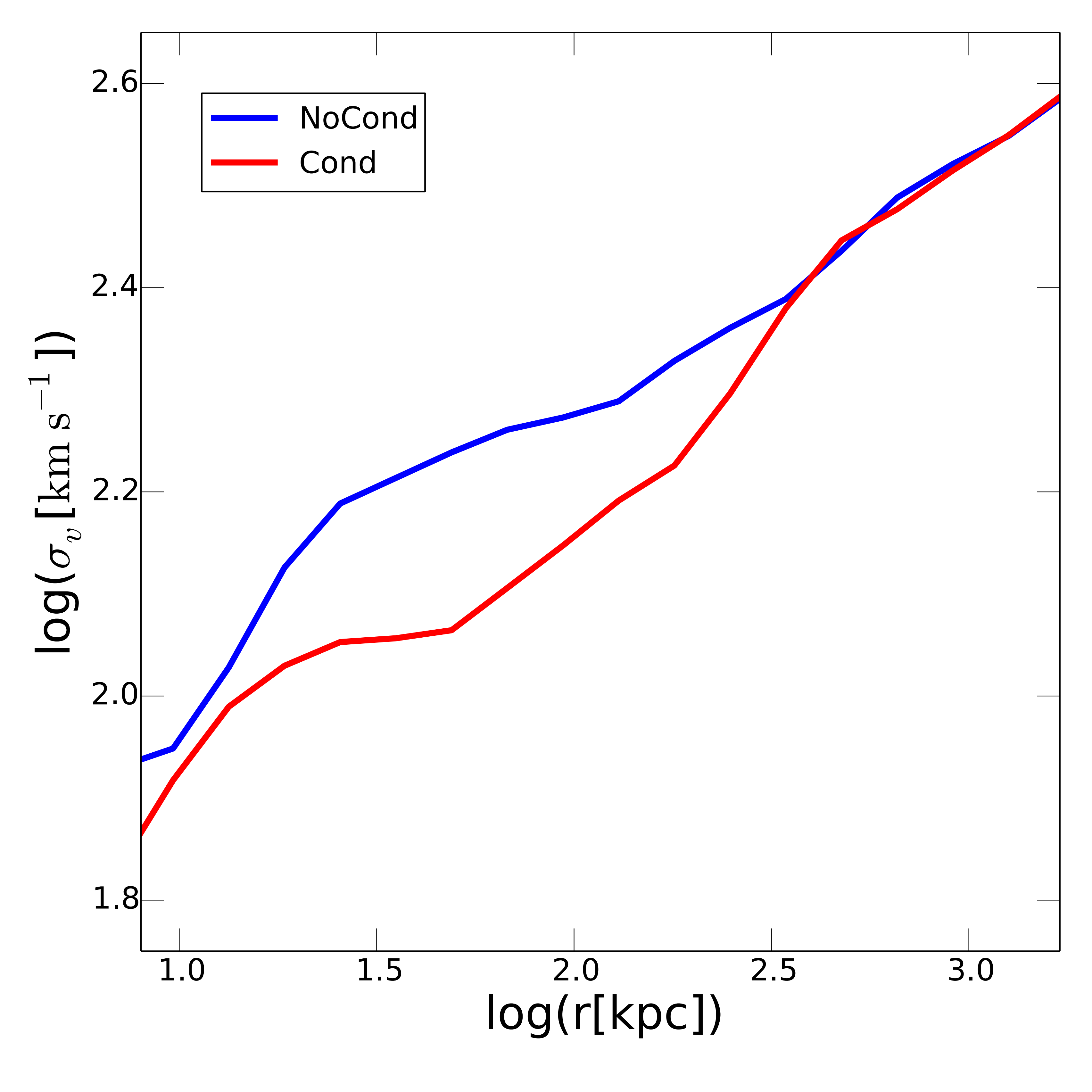
Convective stability of a pure hydrodynamic fluid

- Entropy gradient shallower in the Cond run.
- Suggesting that there is more mixing despite higher restoring force



Turbulent Mixing?

- 1D velocity dispersion lower in the Conduction run
- Paradoxically, this seems to suggest more plasma mixing in spite of lower turbulence velocities.



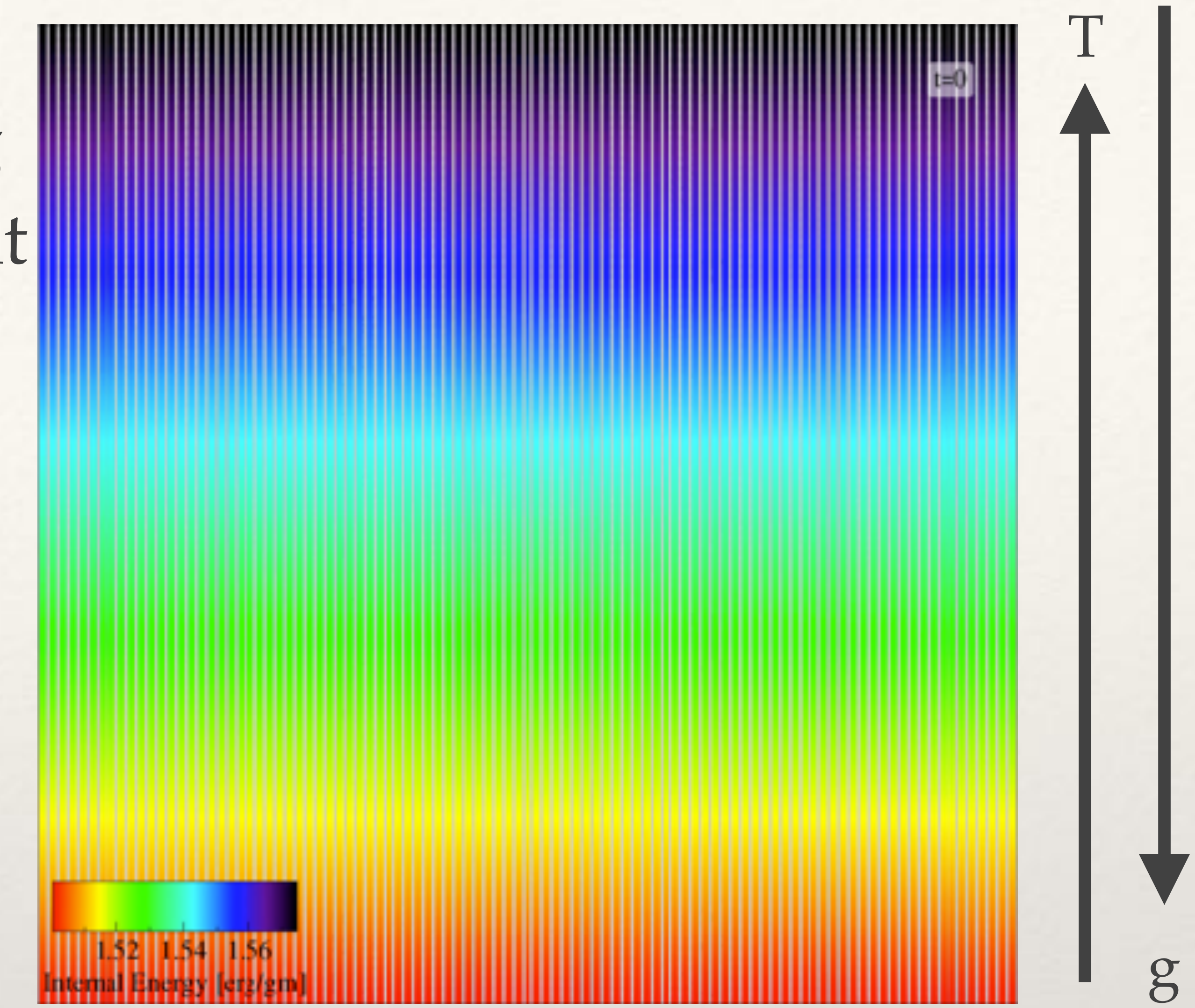
Convective stability of a anisotropically conducting fluid

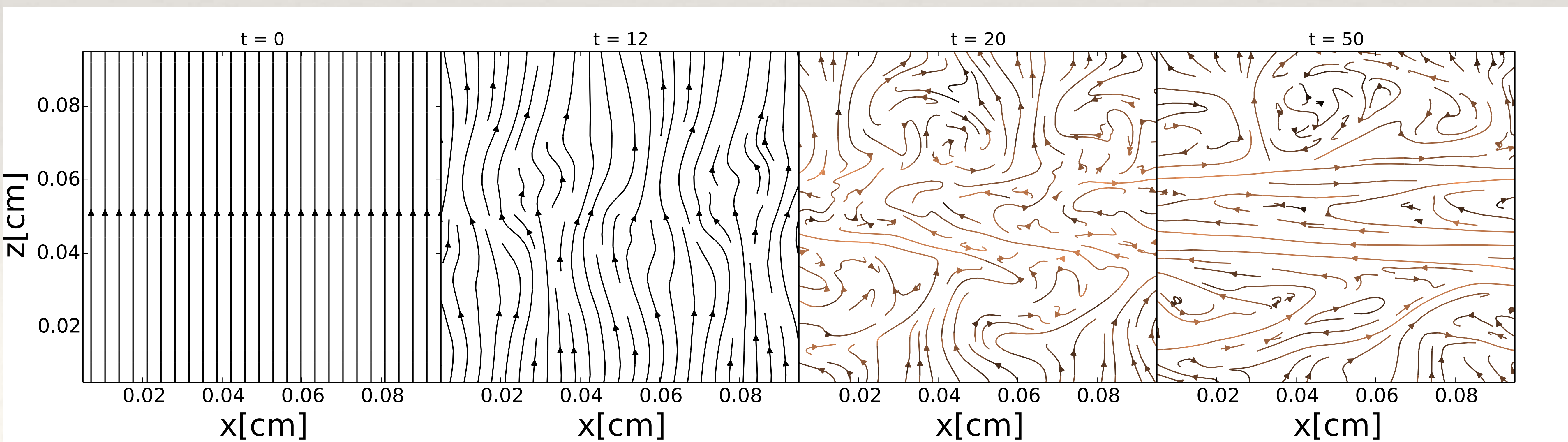
The dynamics of rapidly conducting plasma ($t_{dyn} >> t_{cond}$) very different

Gas isothermal along magnetic field lines under these conditions

System unstable even if $dS/dr > 0$

HBI - Heat flux driven buoyancy instability (Quataert 2008) - $dT/dr > 0$

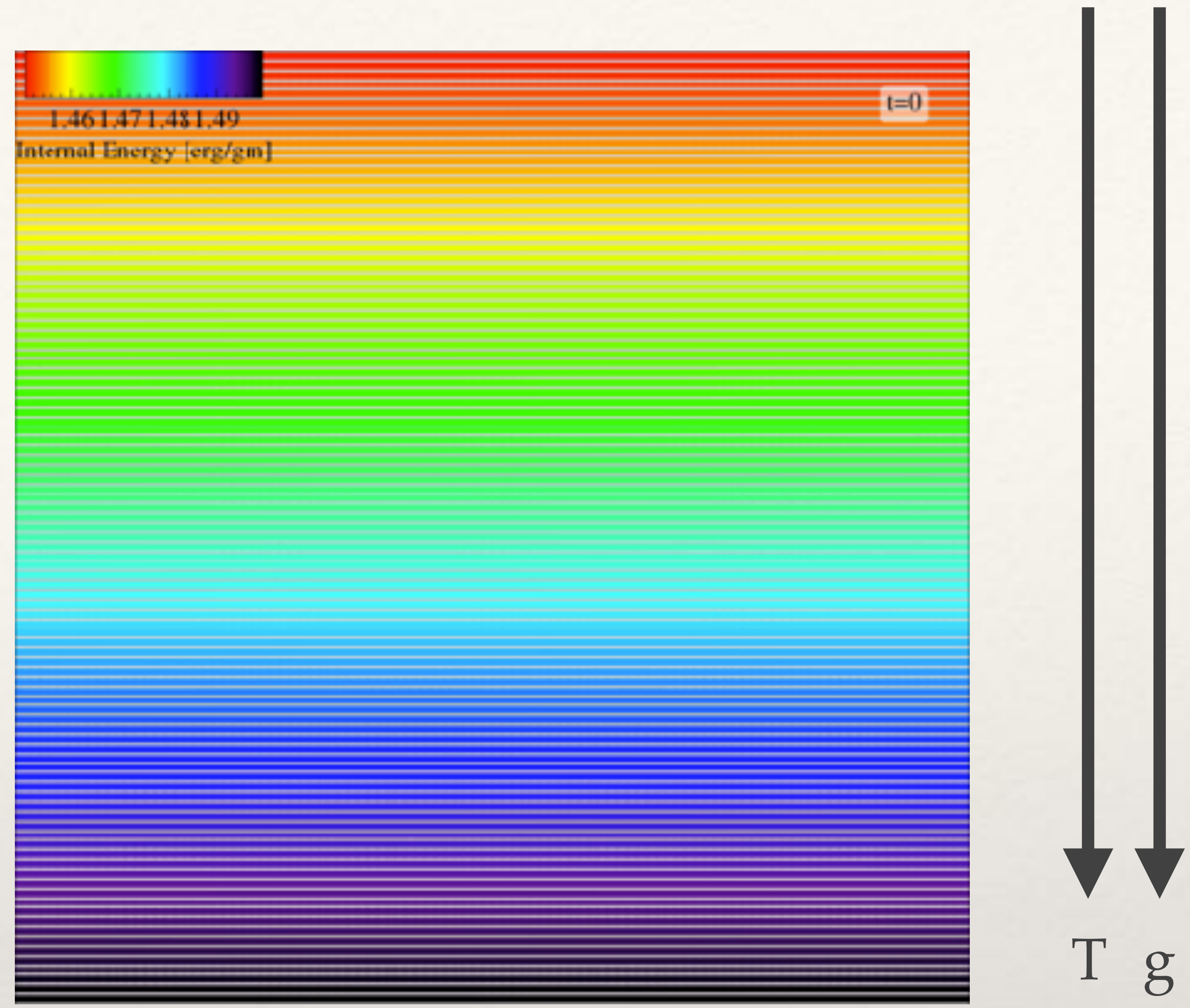


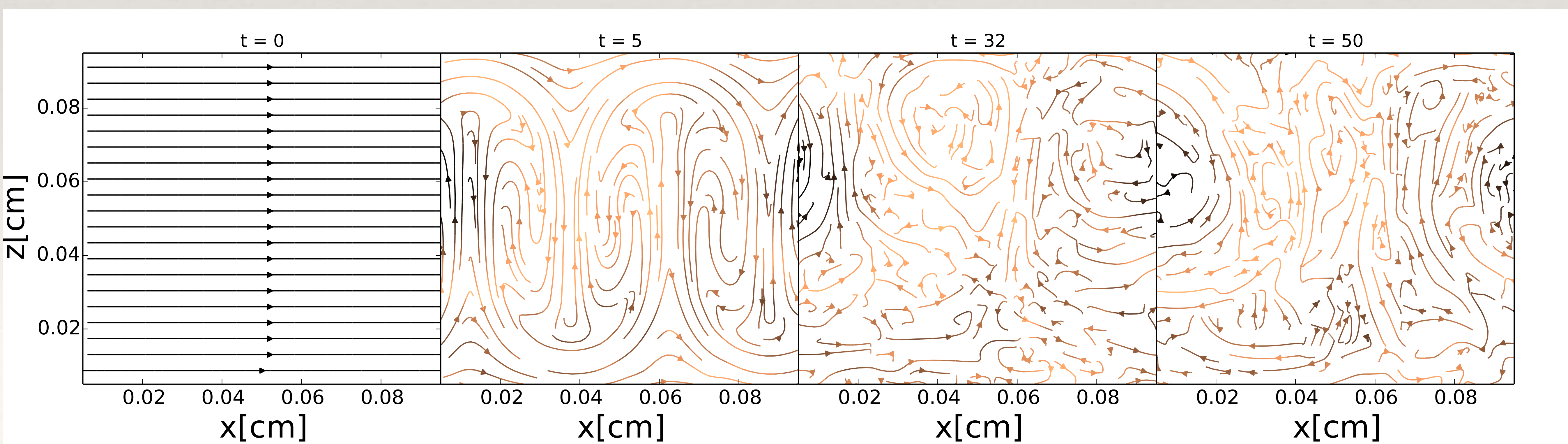


Convective stability of a anisotropically conducting fluid

MTI - Magneto thermal instability (Balbus 2001) - $dT/dr < 0$

Main take away point - The entire cluster ICM is convectively unstable - making it prone to mixing (Zero restoring force)!!



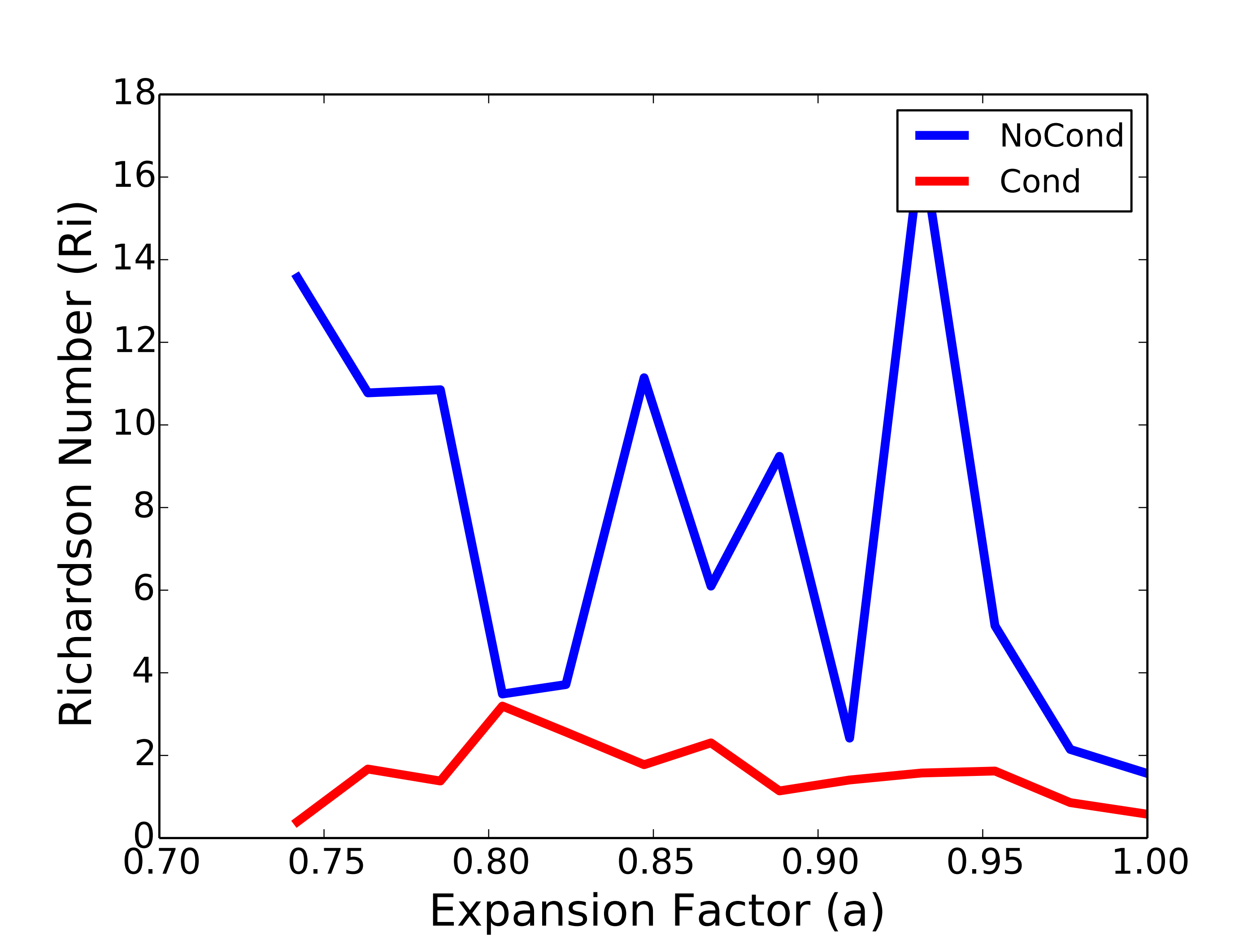


Response of a stratified plasma to external turbulence

- Lower forces mean are mixing for a given the same amount of turbulent driving
- However, the turbulent velocities are lower in the Cond run.
- To correct for this we look at the Richardson number.

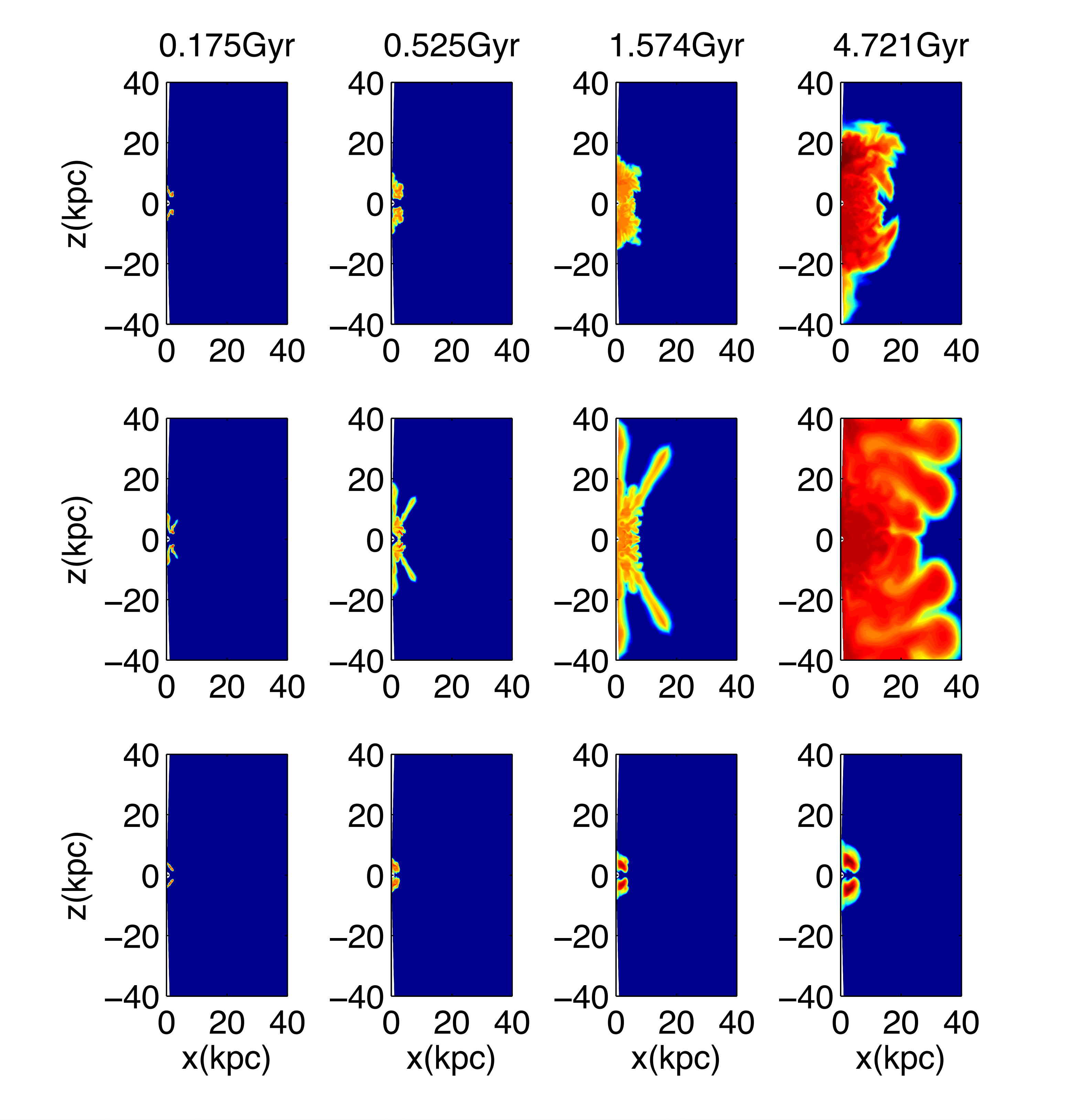
$$Ri(\mathrm{NoCond, Cond}) = \rho \mathrm{r_i}\ [\mathrm{dln(S,T)/dlnr}]/\mathrm{u_o^2}$$

- Ri in Cond run hovers around 1 meaning there is efficient mixing
- Not the case for the NoCond run.



Increased Mixing

- Conduction can increase mixing in a stratified plasma (Sharma+2009a,b)



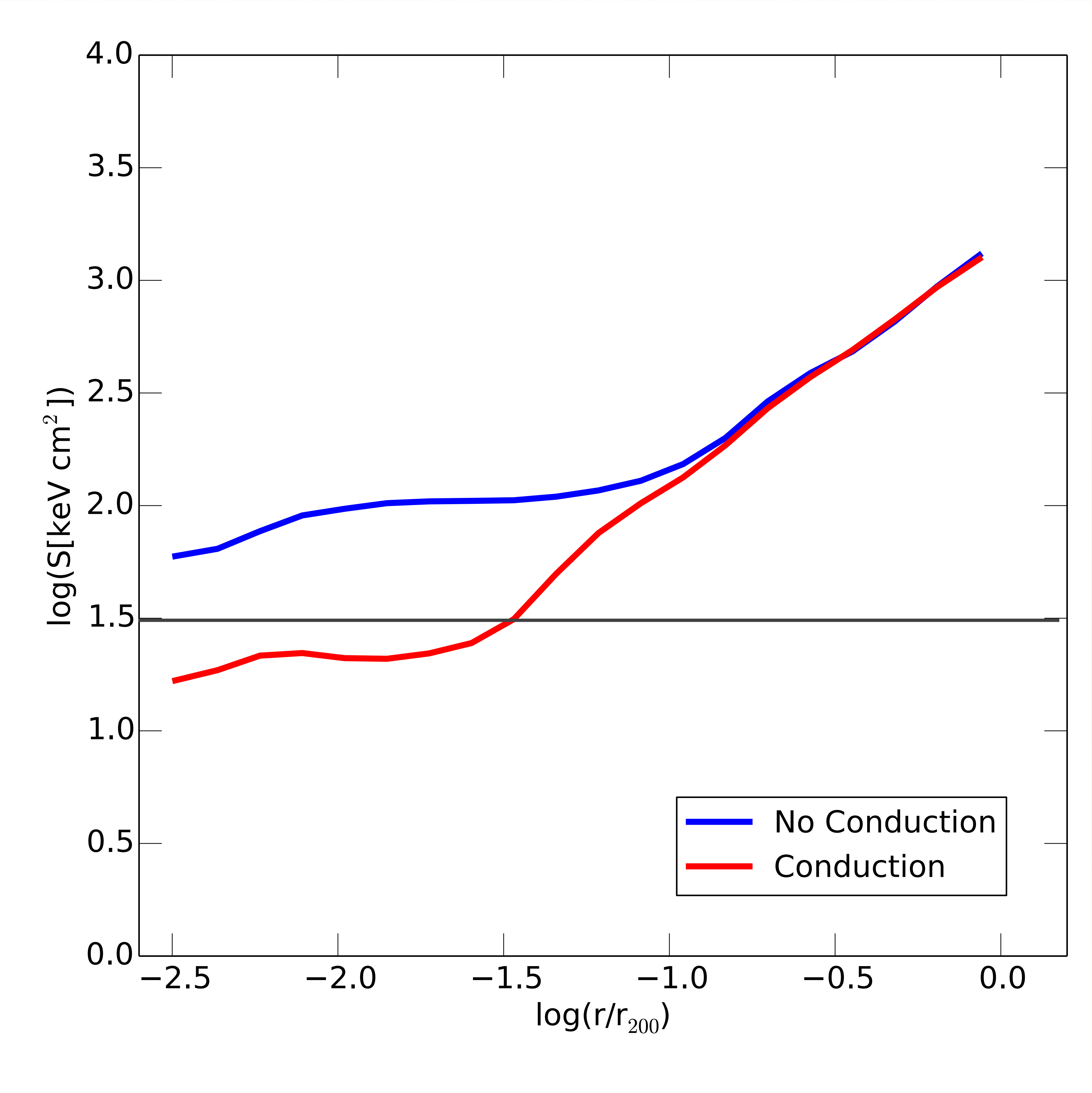
Anisotropic Conduction

Isotropic Conduction

Adiabatic

Impact of efficient coupling

- Entropy gradient shallower in the Cond run.
- Formation of a cool core in Cond run?



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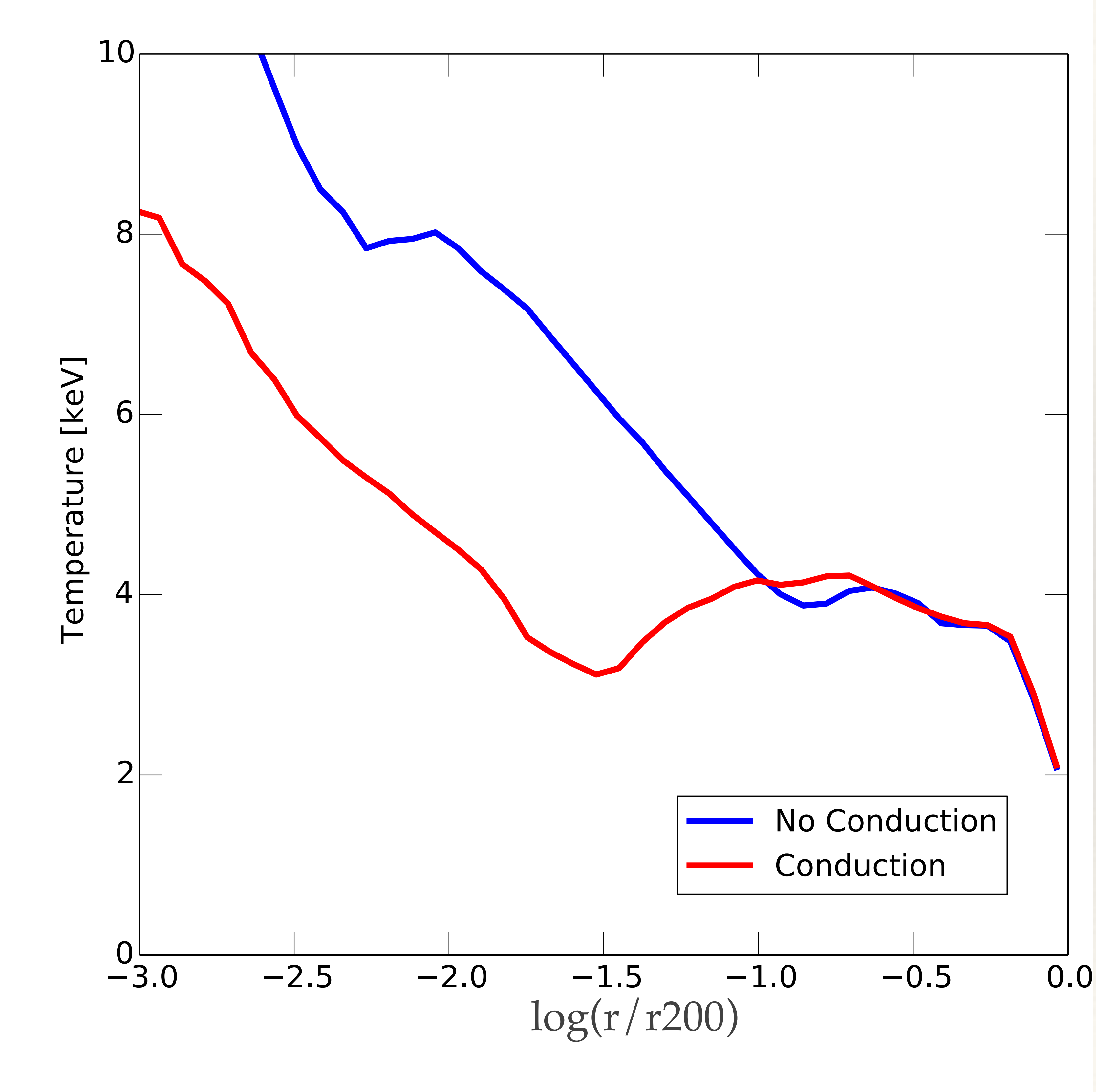
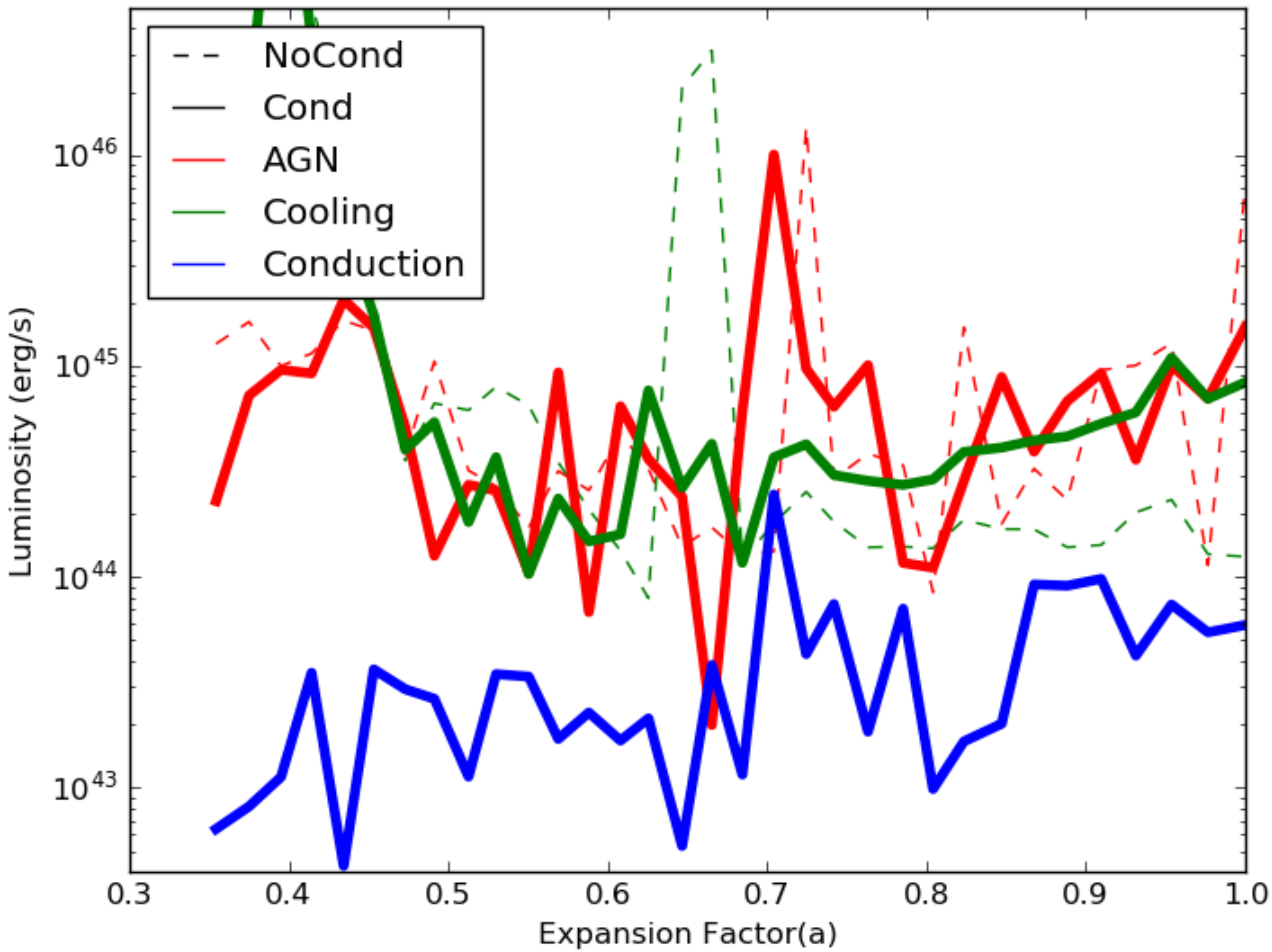
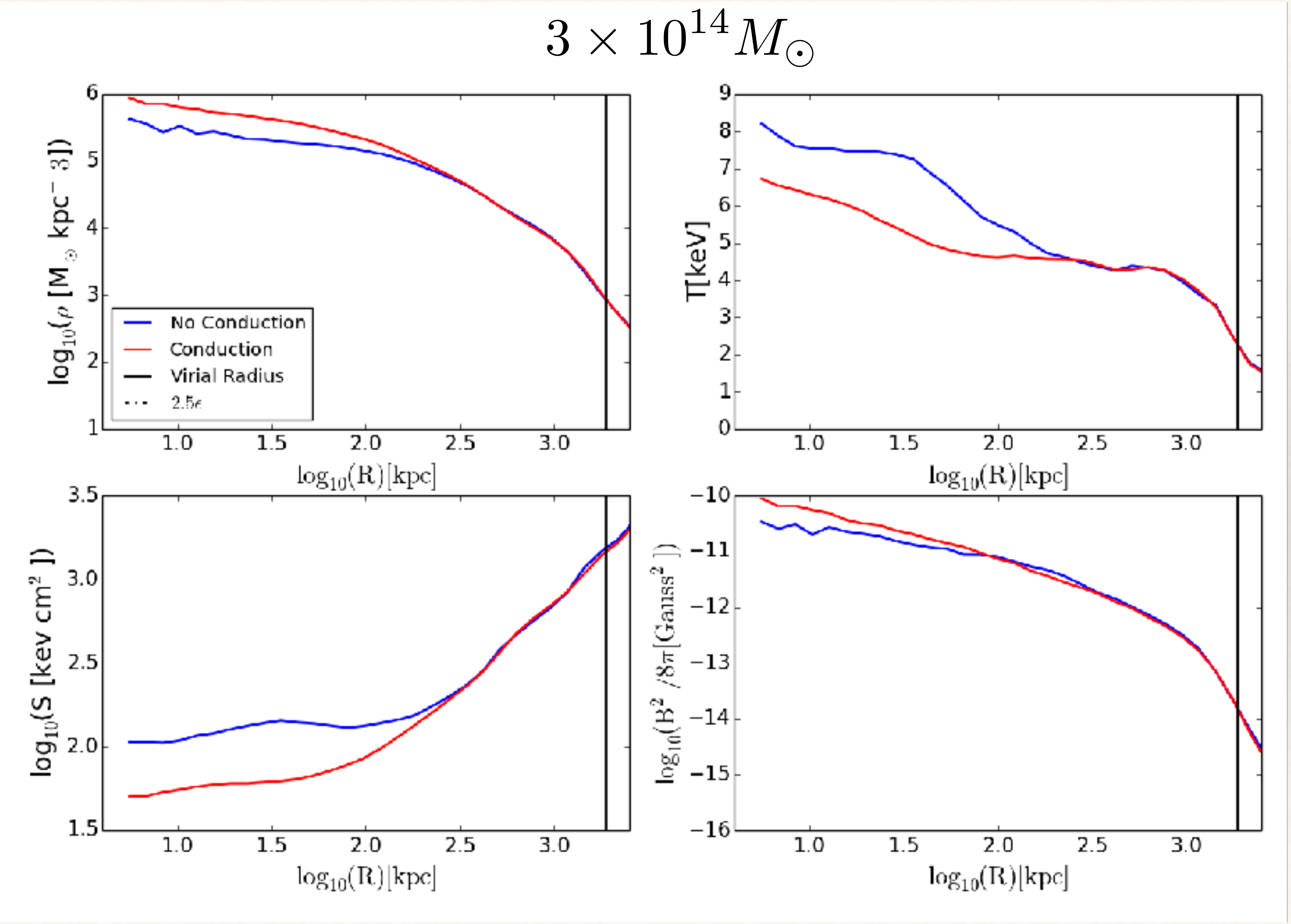


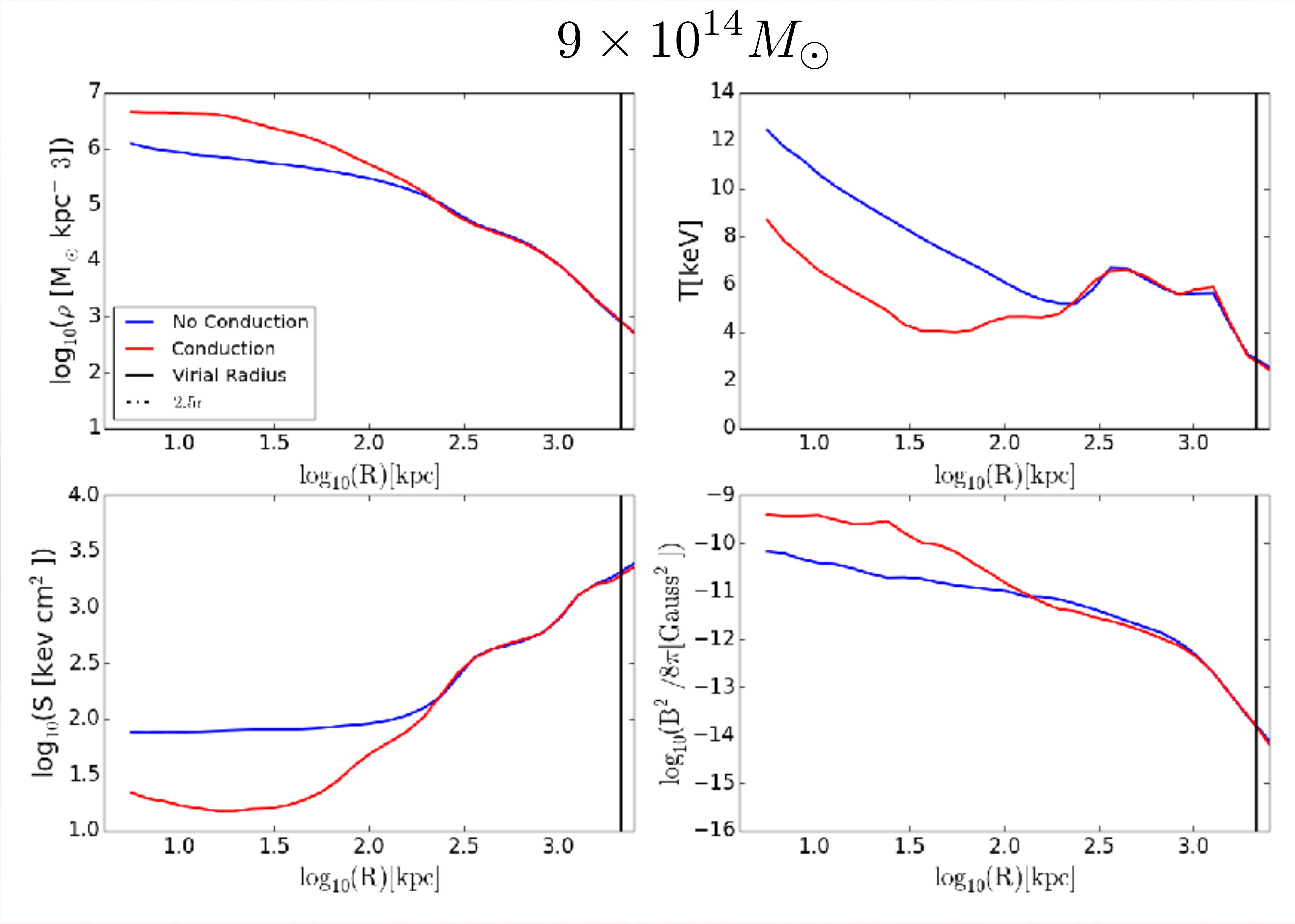
Impact of efficient coupling



Impact of efficient coupling



Impact of efficient coupling

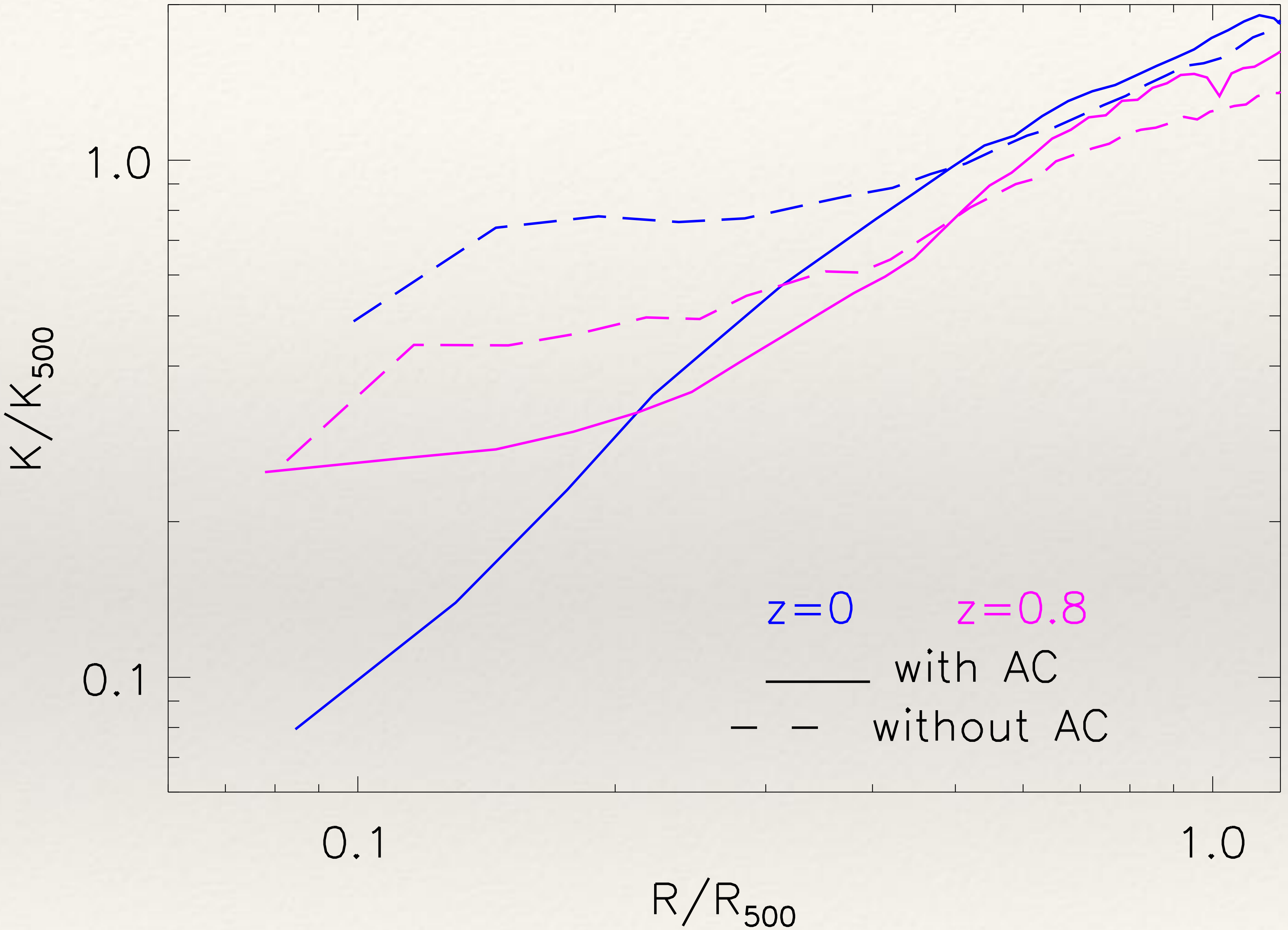


Artificial Conduction produces cool cores

Rasia+15

Artificial conduction introduced to increase the accuracy of SPH causes cool cores.

Done to increase mixing!!



Conclusions

- Anisotropic conduction makes the entire ICM unstable and prone to mixing
- **Conduction enables mixing**
- Leads to efficient isotropizaton of injected AGN energy, making quenching more efficient
- Efficient coupling leads to generation of low entropy cores - important implications for CC/NCC dichotomy
- Purely hydrodynamic treatment does not fully describe the complex physics of the ICM

Future Work - Cluster simulation suite

10 clusters between 10^14 and 2x10^15 Msun