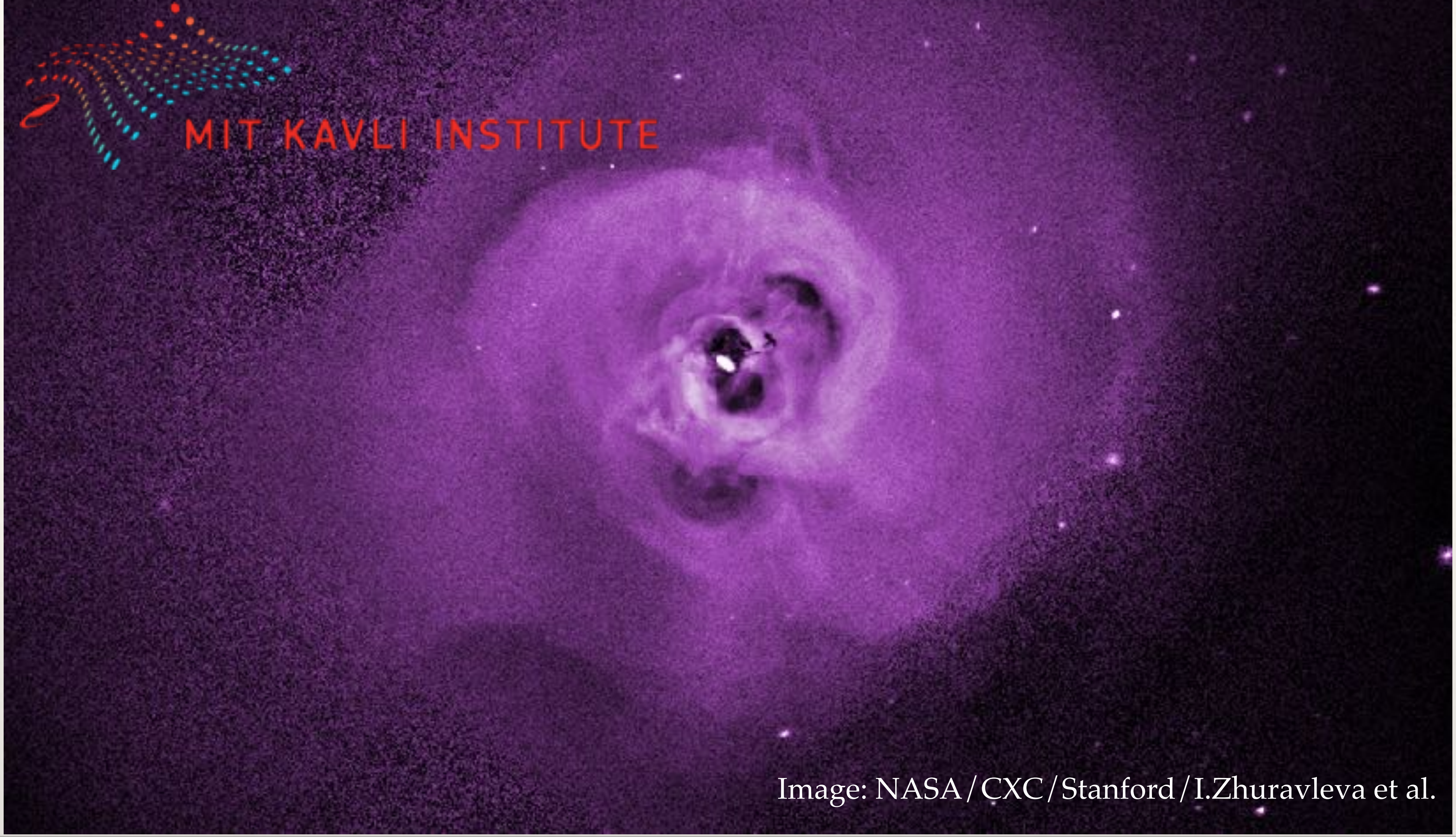


Quenching, AGN feedback and anisotropic thermal conduction

Rahul Kannan (MIT)

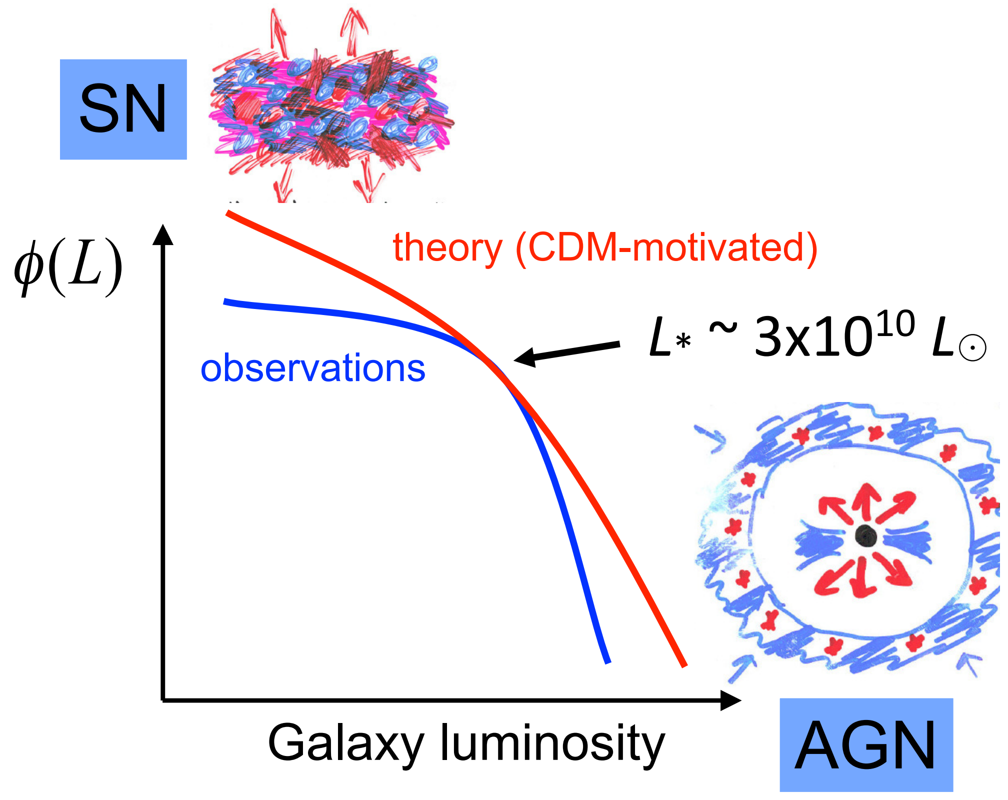
Collaborators : Mark Vogelsberger (MIT), Christoph Pfrommer (HITS), Rainer Weinberger (HITS), Volker Springel (HITS), Lars Hernquist (CfA), Ewald Puchwein (IoA), Ruediger Pakmor (HITS)

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

AGN winds on the Georgia Coast, Jekyll Island, June 29, 2017,

What decides the stellar mass of galaxies?

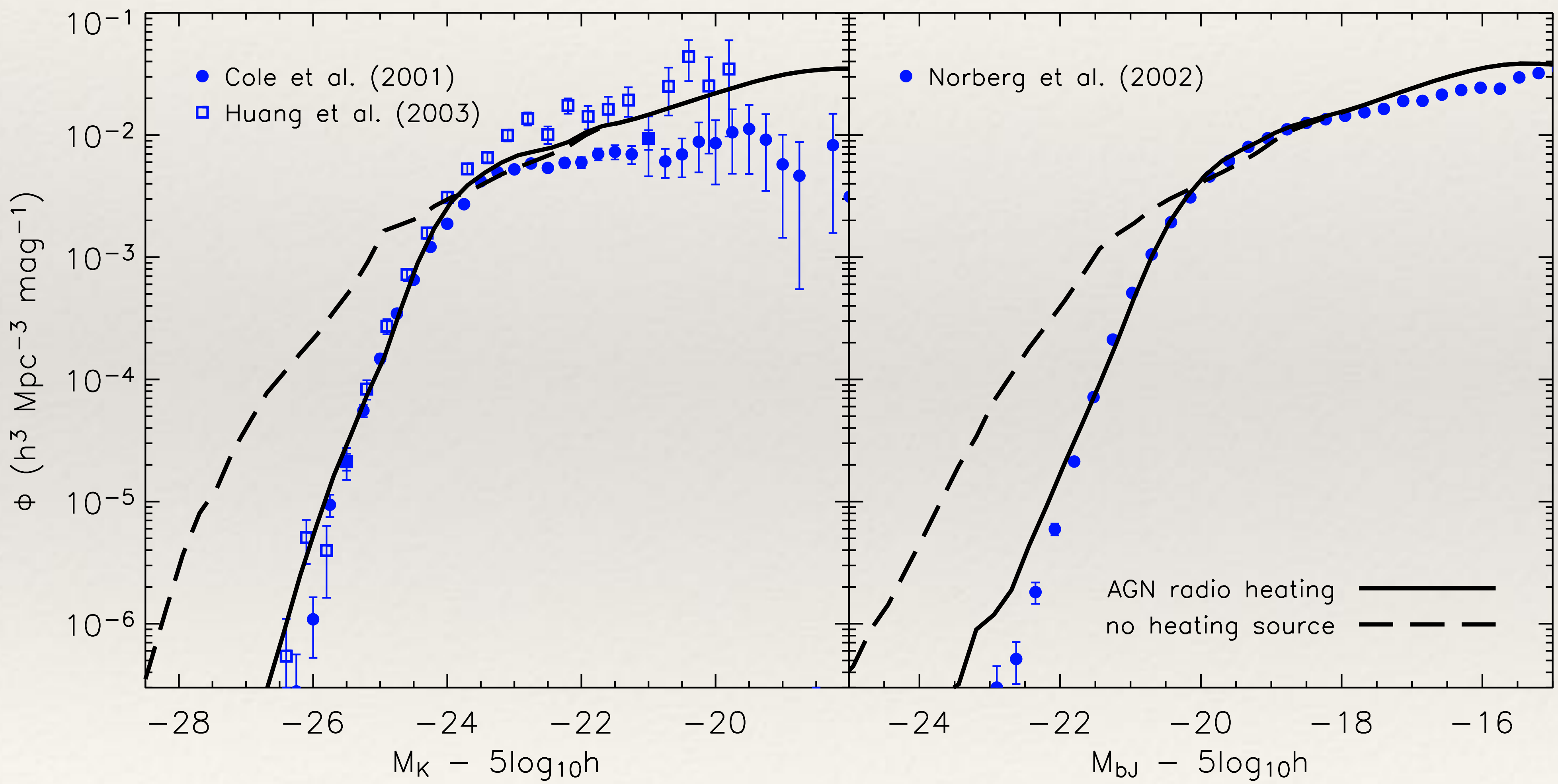
- DM mass function - galaxy luminosity function have different shapes
- Suppression in star formation in both high and low mass galaxies
- SNe feedback invoked to explain the discrepancy in low mass galaxies



Silk+2012

What decides the stellar mass of galaxies?

- AGN feedback invoked at cluster scales



Croton+2006

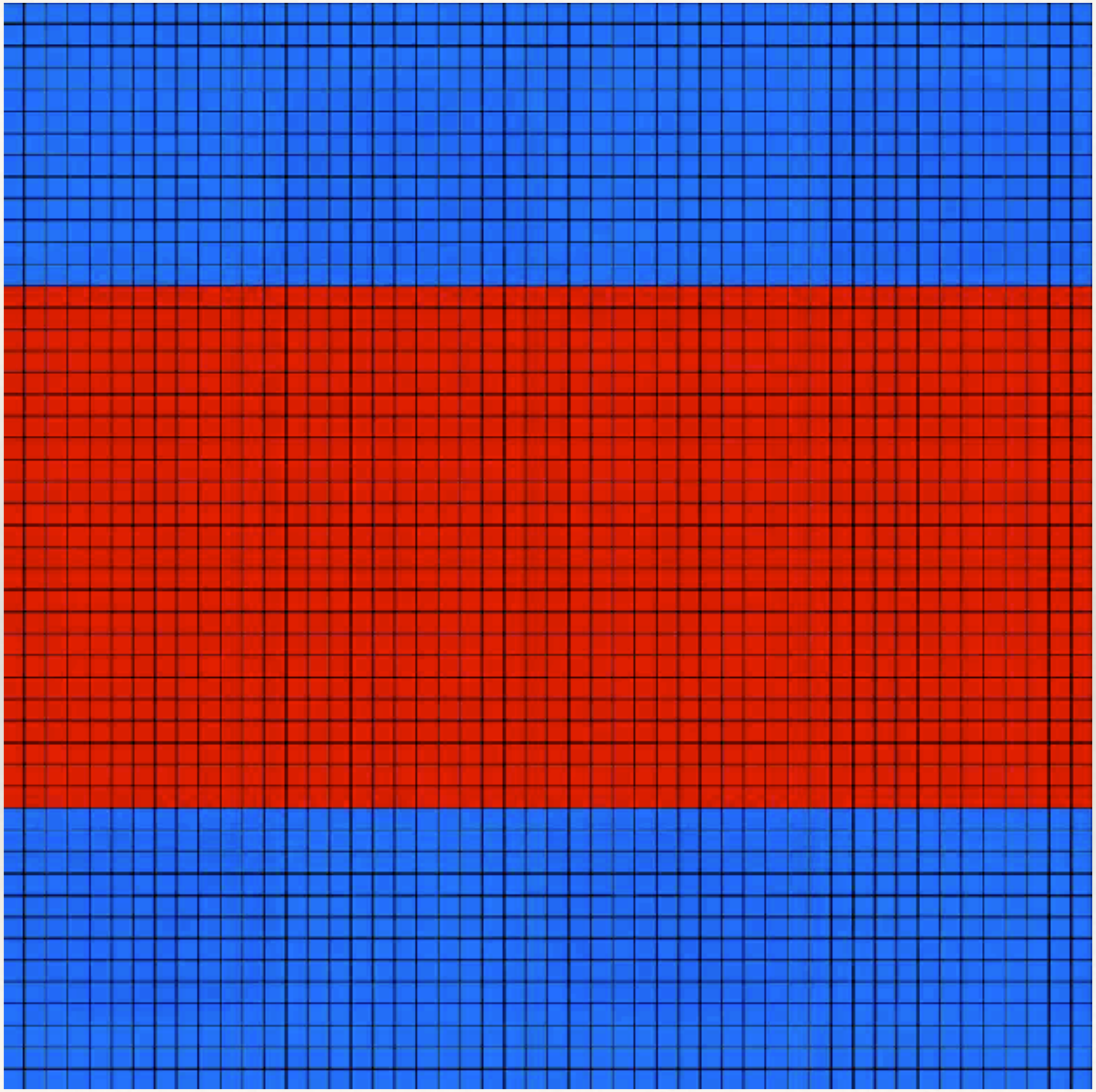
Cosmological simulations

- Typical resolution of state of the art cosmological cluster simulations ~ 0.5 kpc
- All the AGN feeding and outflow launching mechanisms happen below the resolution level
- Use sub-resolution treatments to mimic the effect on resolved scales
- Assumptions:
  - AGN feedback mechanisms are reasonably efficient
  - Their impact on large scales can be captured by depositing energy and momentum in the resolved region around the black holes

Moving mesh hydrodynamics

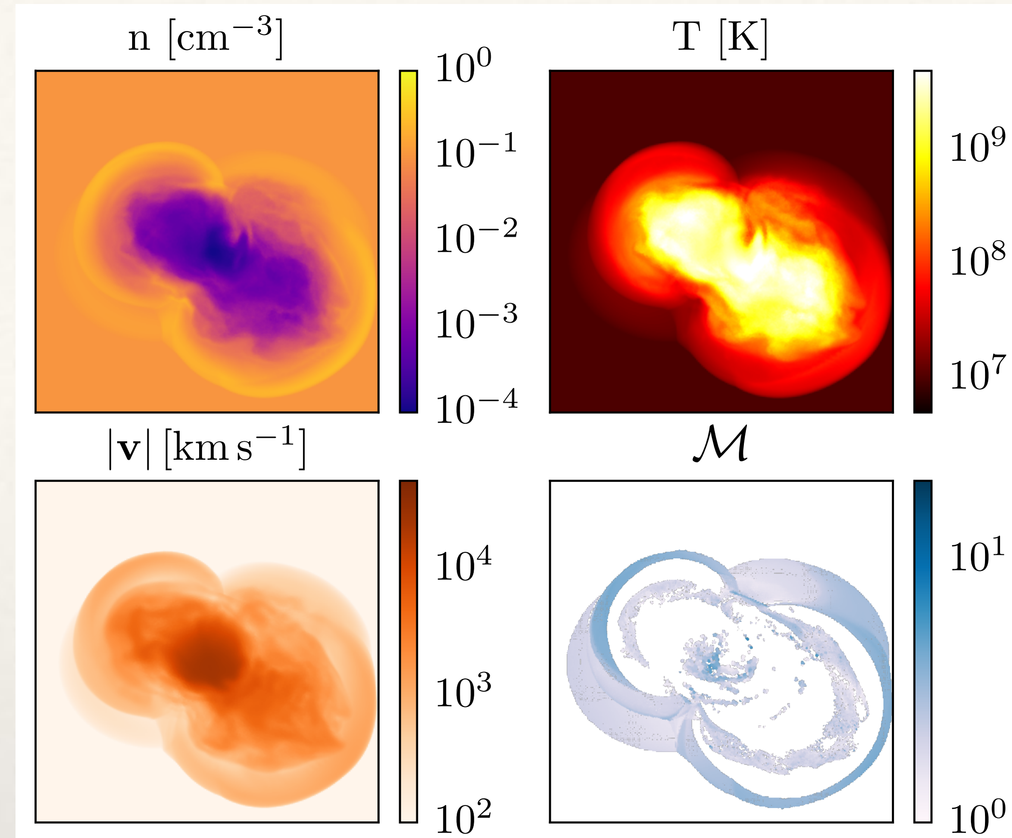
AREPO (Springel 2010)-
Moving mesh
hydrodynamics

- Solve the equations of motion in the frame of reference of the fluid
- Gets rid of numerical advection errors
- Automatically resolves high density regions

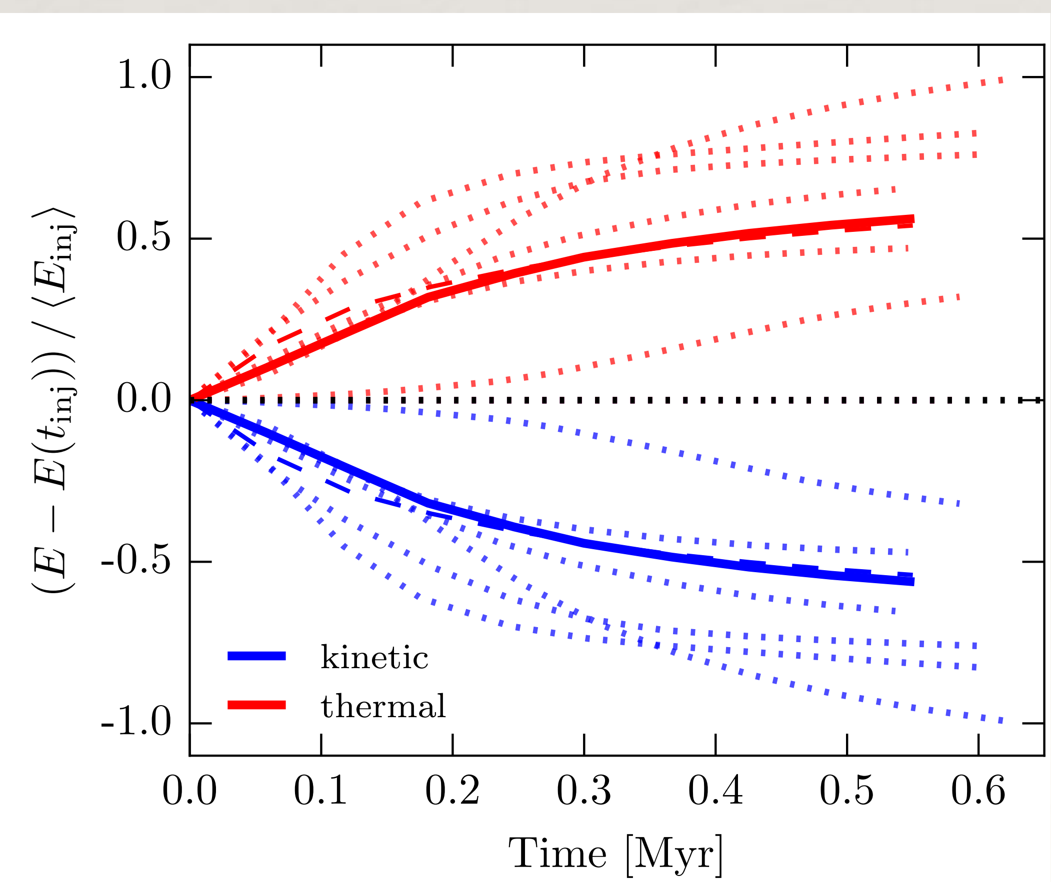


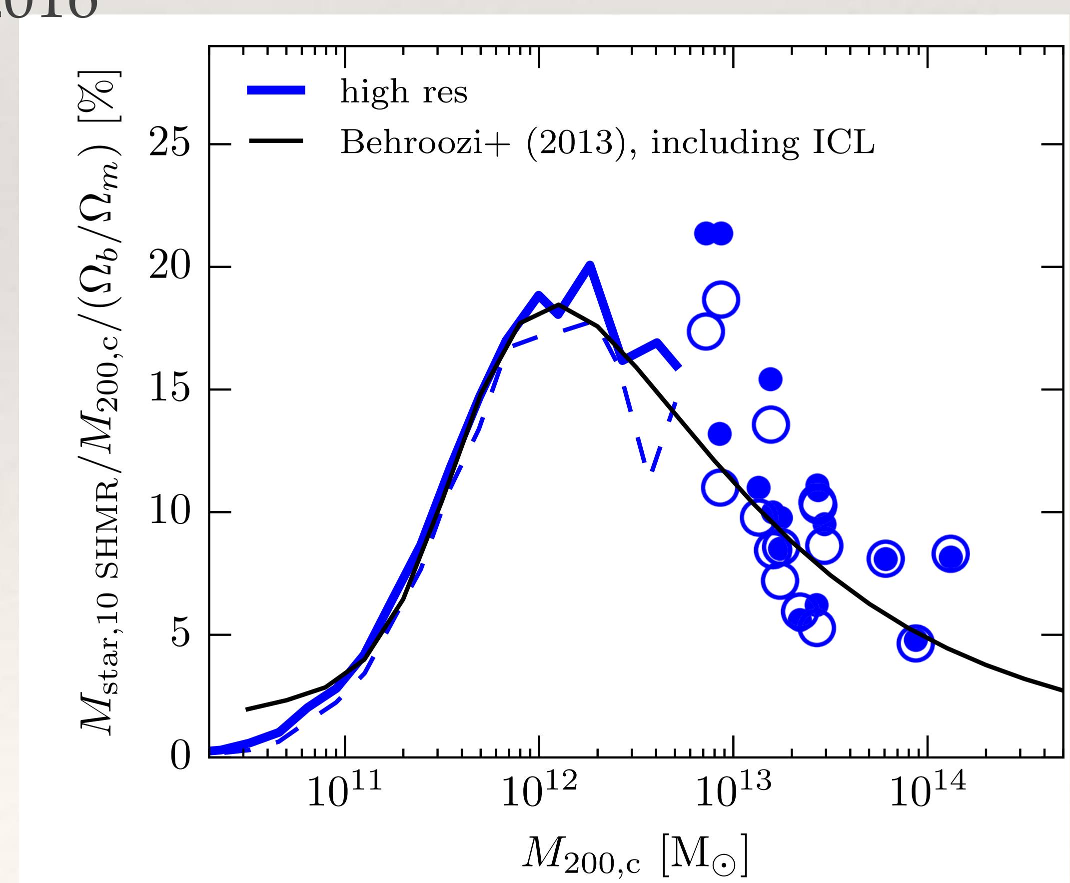
The AGN feedback model

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

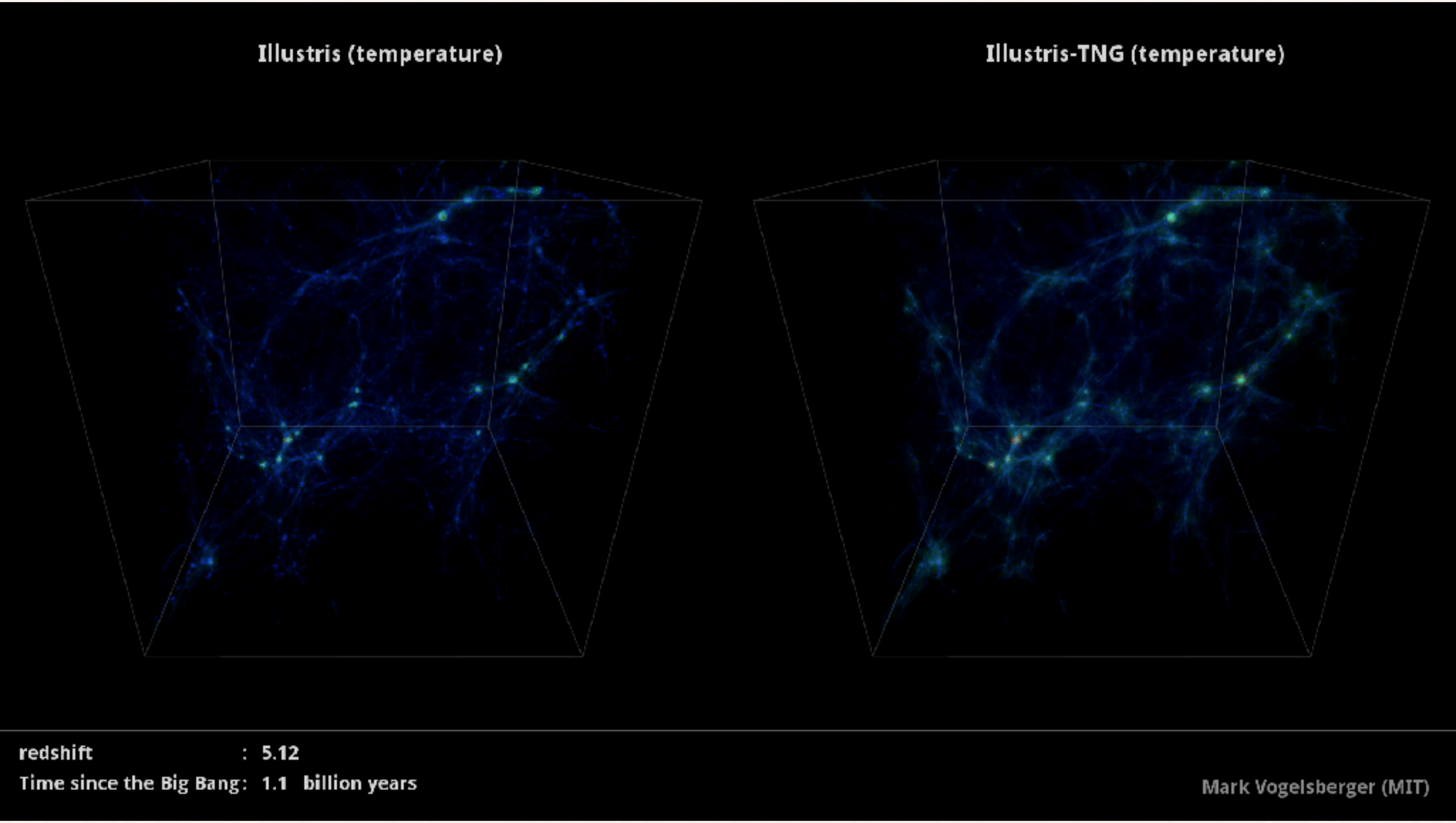


Weinberger+2016

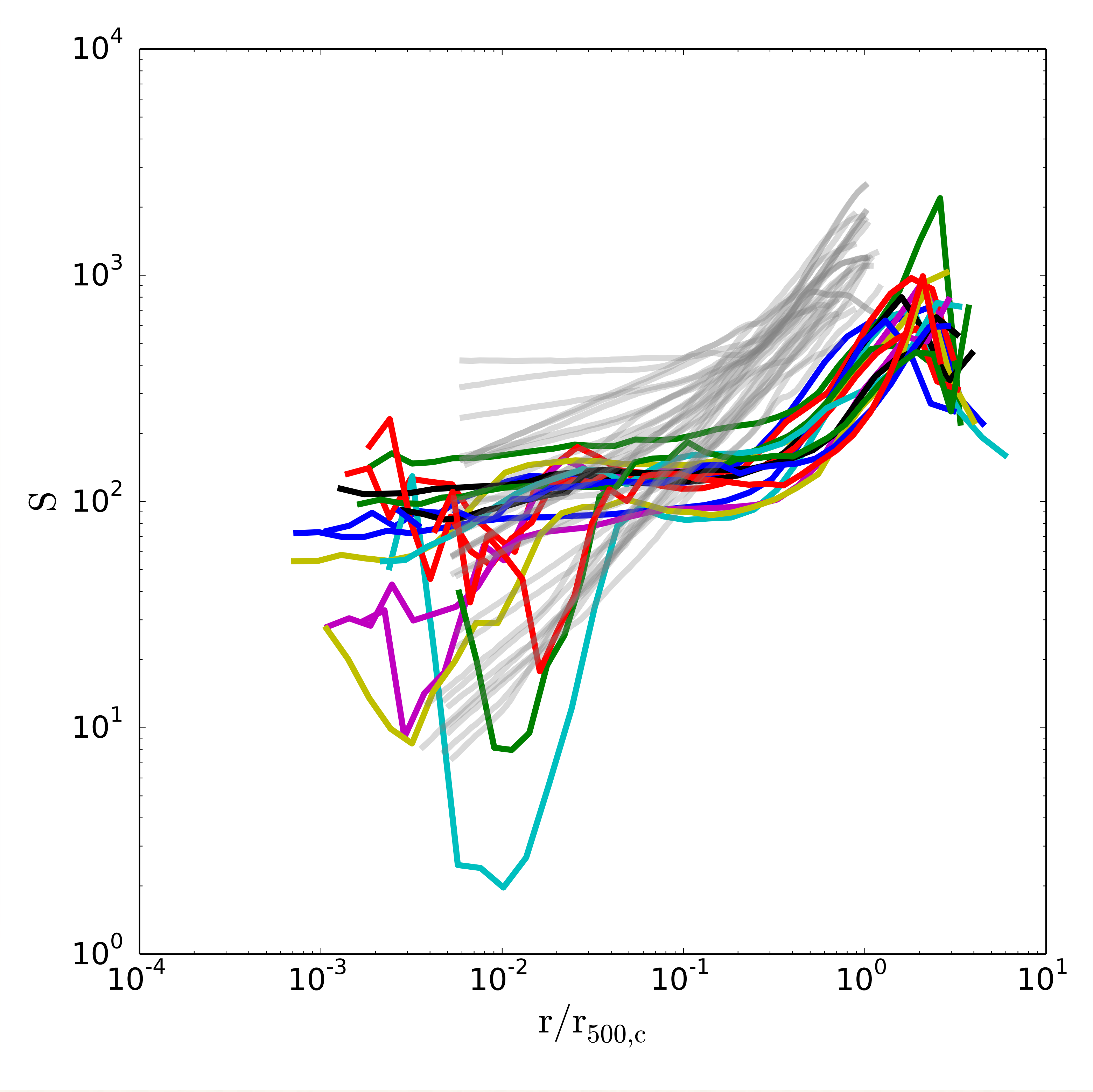




Large scale structure formation simulations



Entropy Profiles no CC -NCC dichotomy



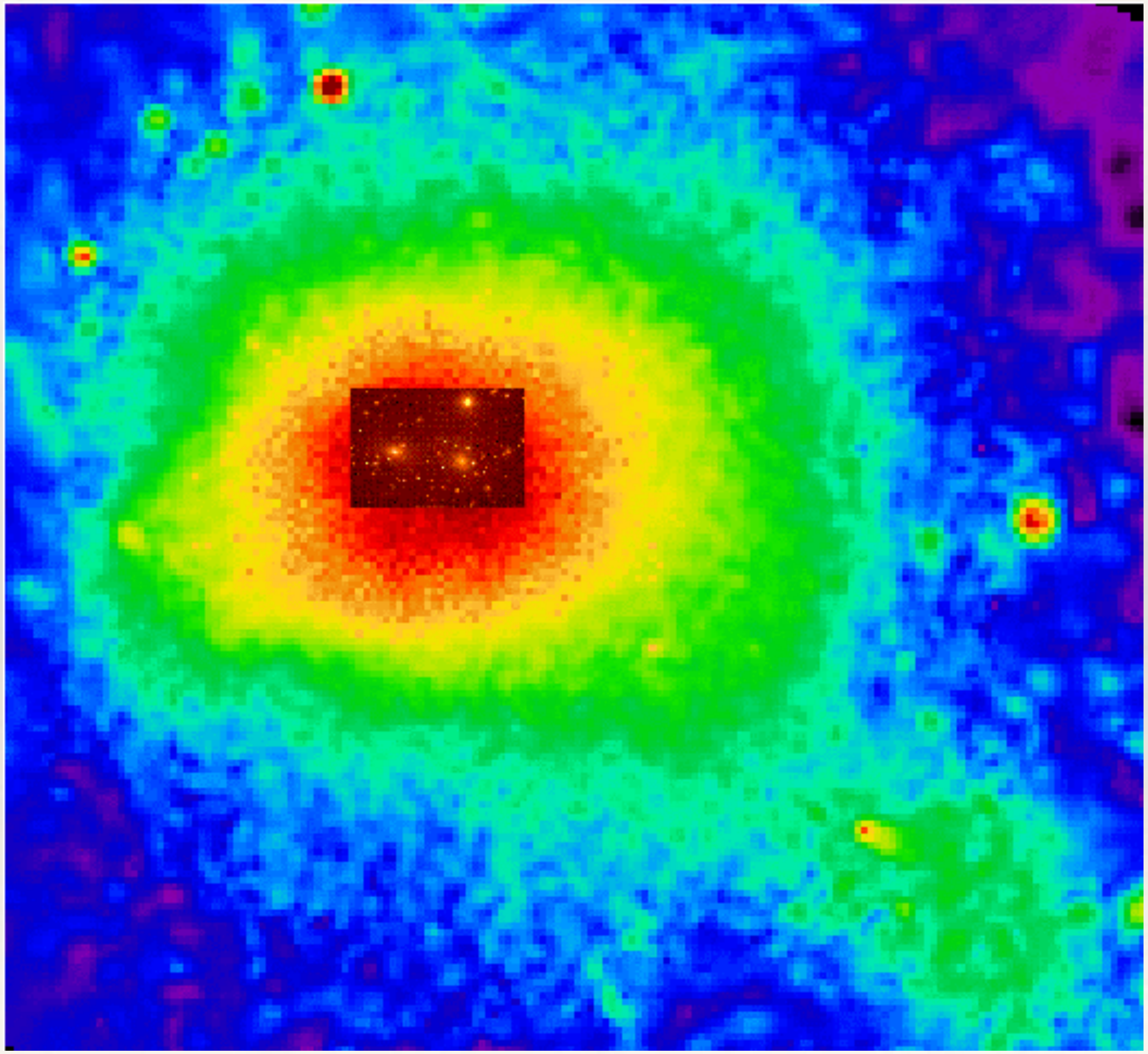
Entropy profiles of "clusters" in L75 box - Only group scale (<1e14 Msun) show cool core structure
Clusters are all non cool core

Still not able to accurately capture the coupling between AGN energy and ICM

<u>Extremely difficult to get CC in cosmological simulations</u>

The rich physics in the ICM

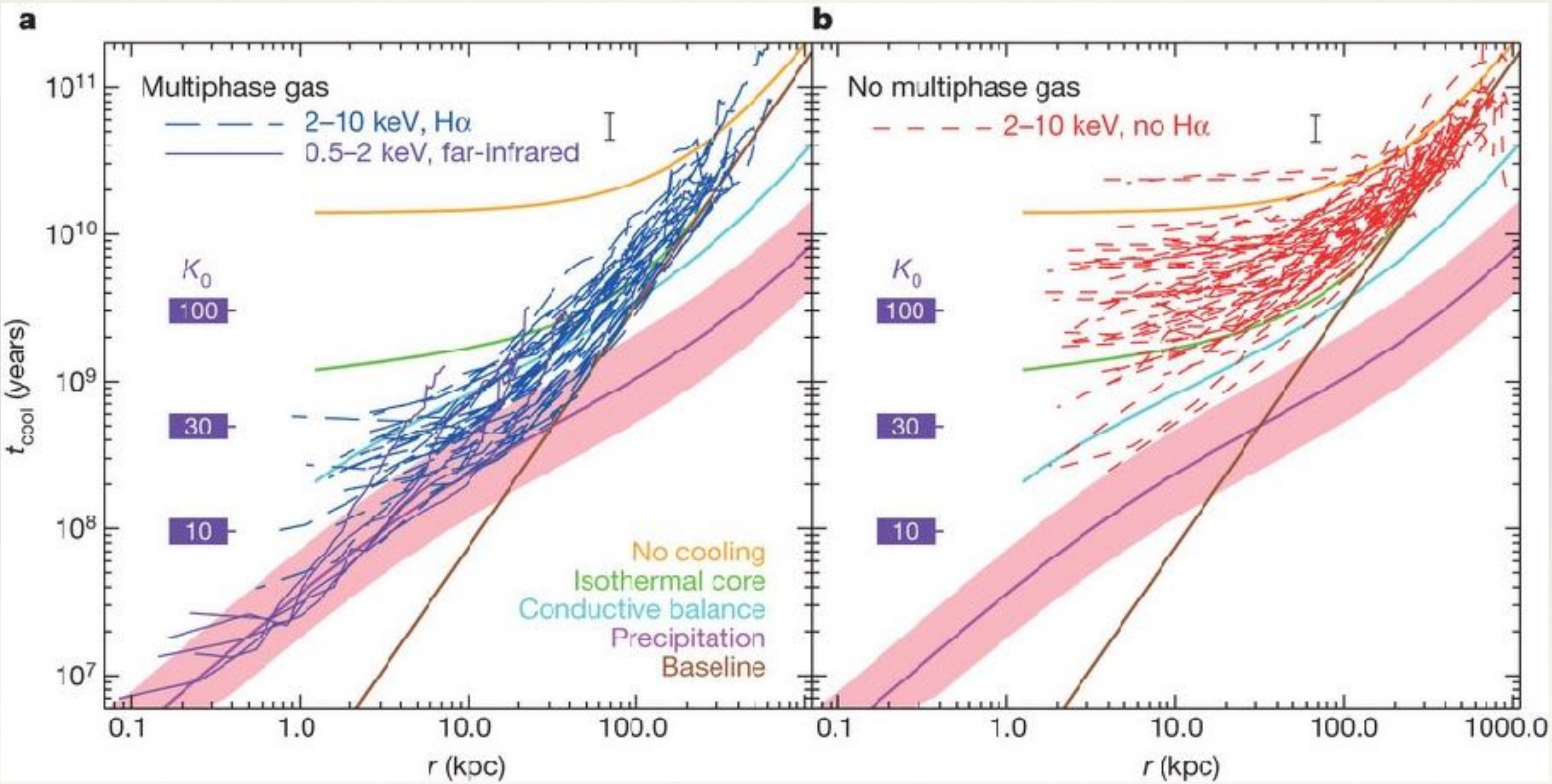
- The extreme temperatures and low density means that non traditional astrophysical processes become important
  - Magnetic fields
  - Thermal Conduction
  - Viscosity
- Need for efficient MHD and thermal conduction schemes
- Need high resolution in the ICM to resolve these processes
- Simulations unto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



Thermal Conduction in clusters

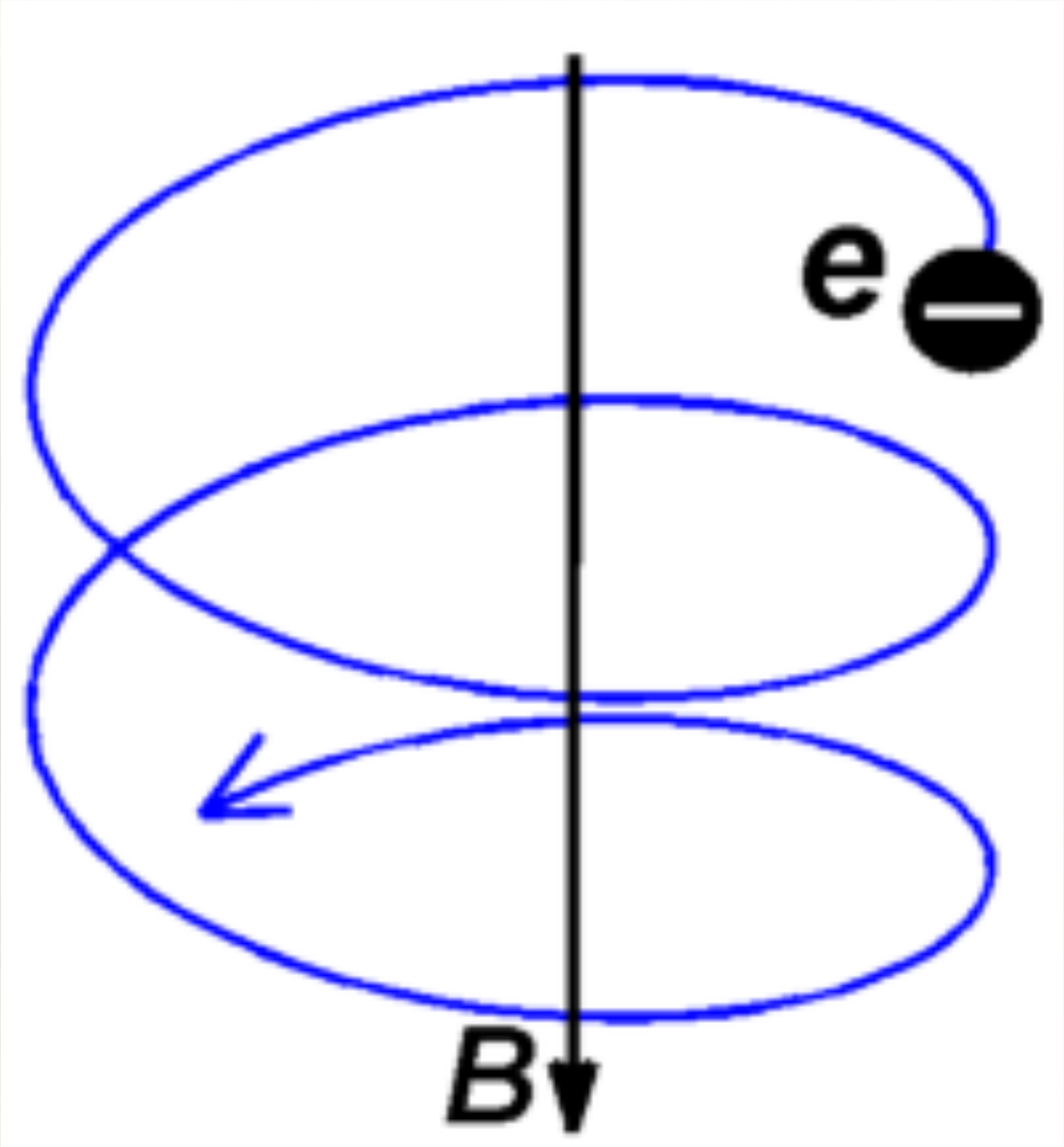
* Invoked by many to explain low cooling rates at the center of clusters(Voit+2015)

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

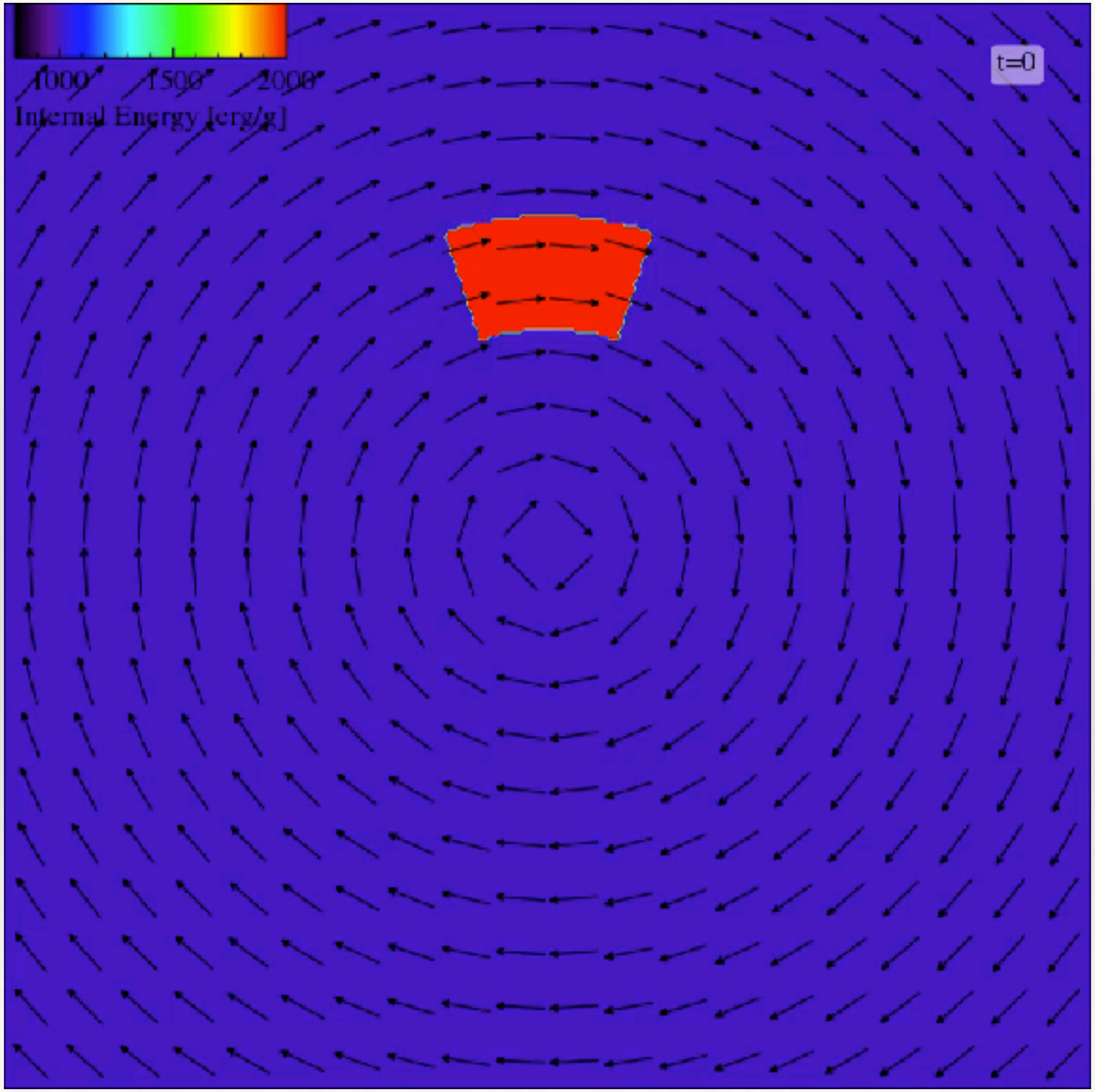


Thermal Conduction

- 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



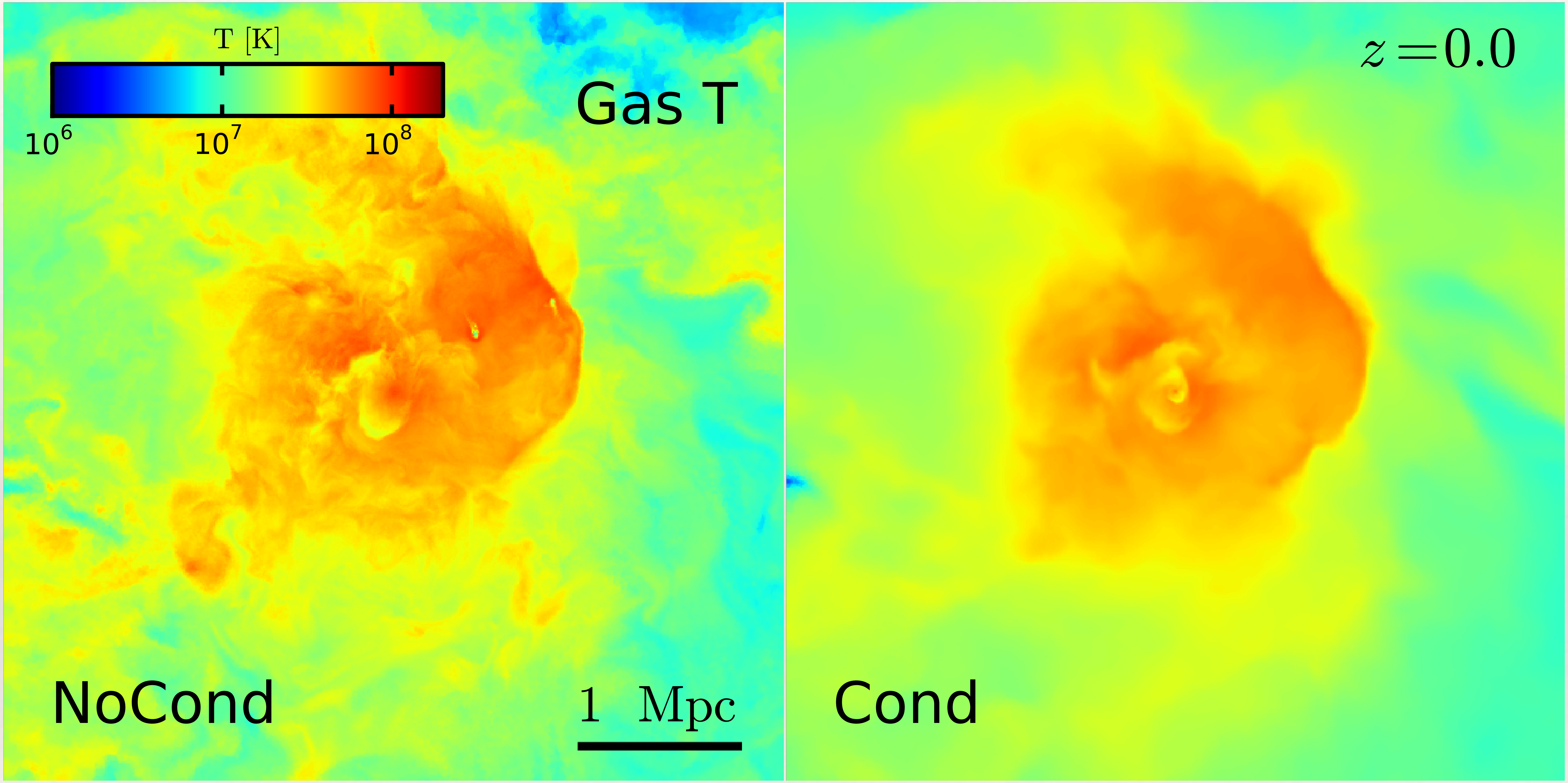
Anisotropic Diffusion



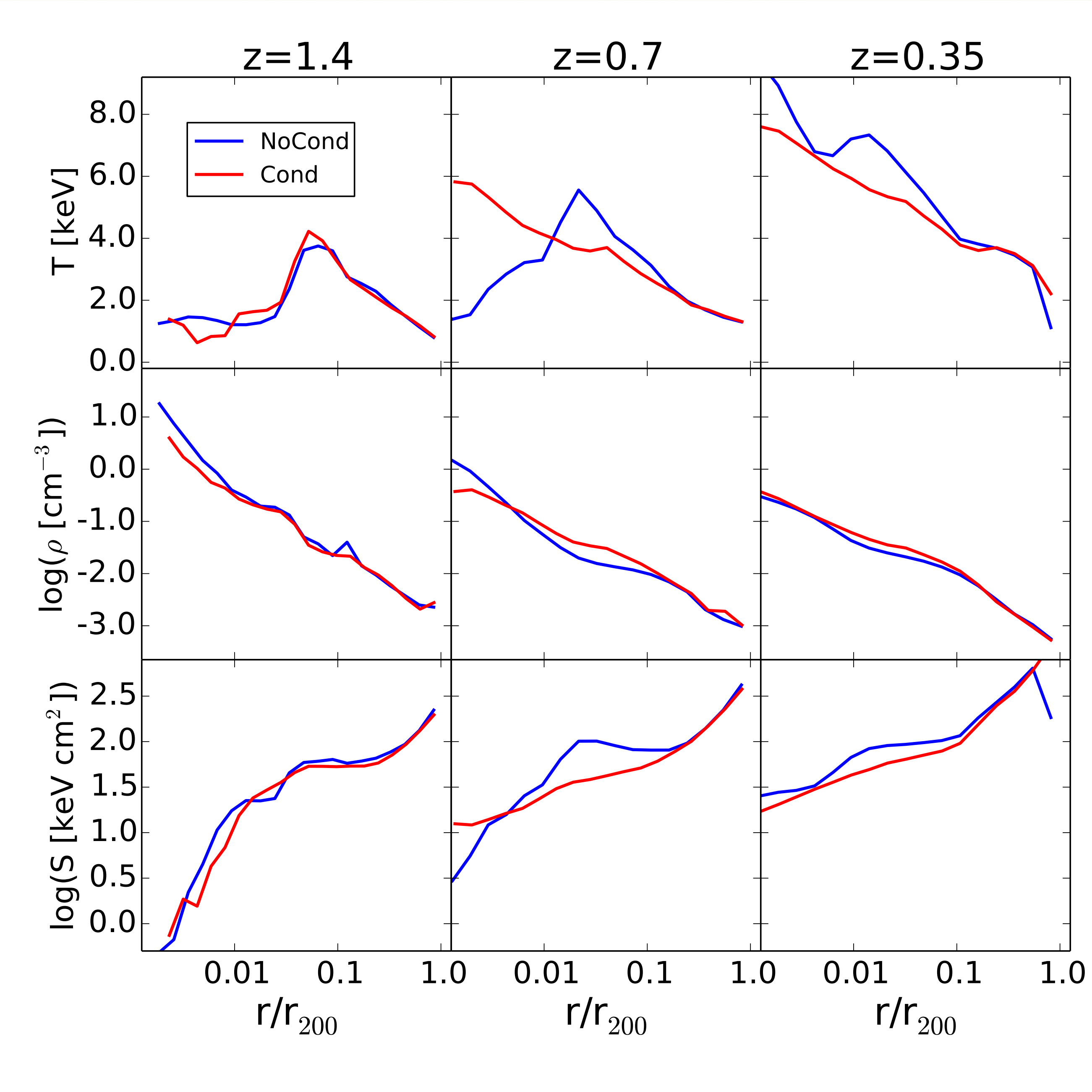
Conduction across magnetic field is highly suppressed

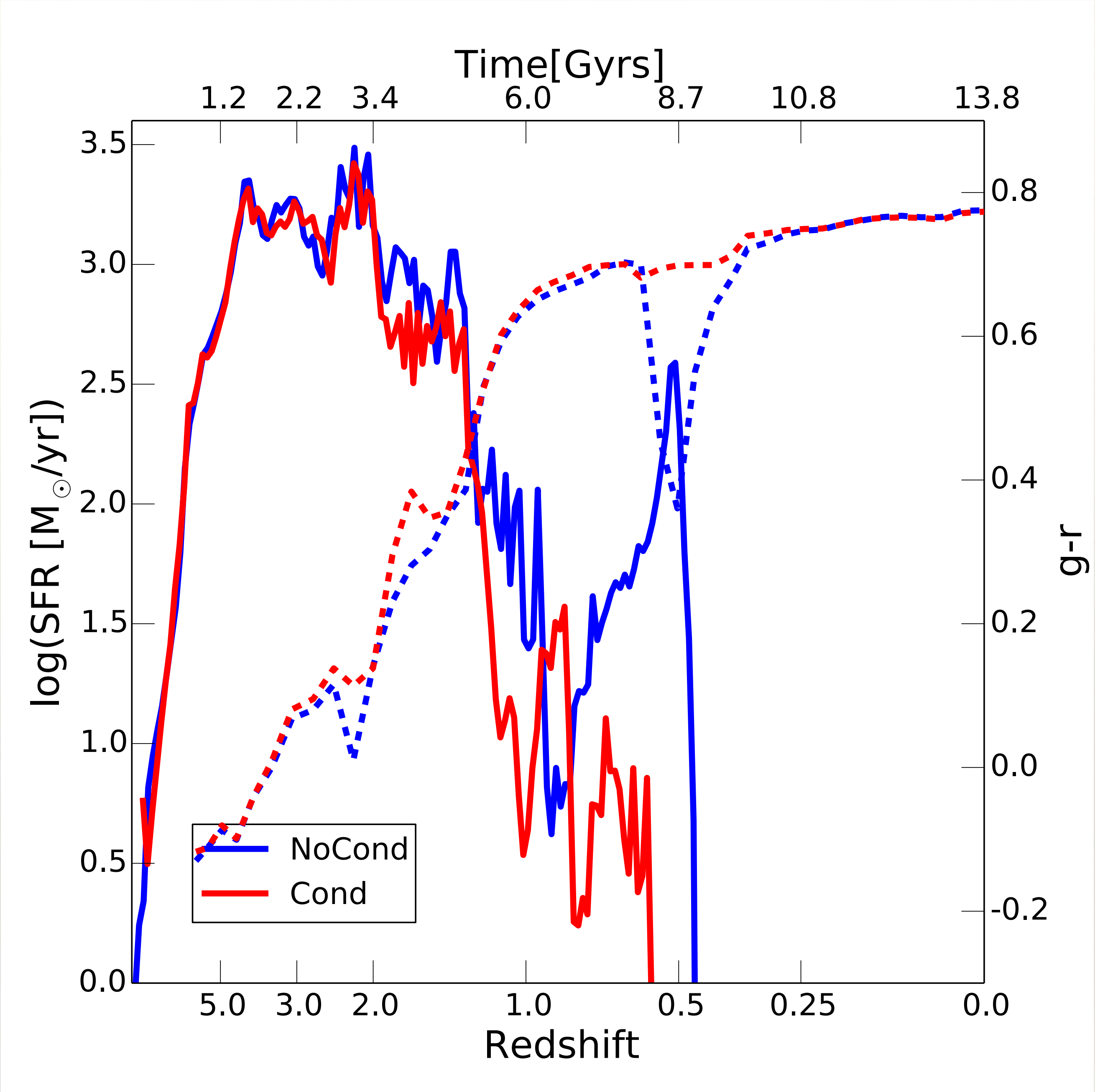
The simulations

- 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)



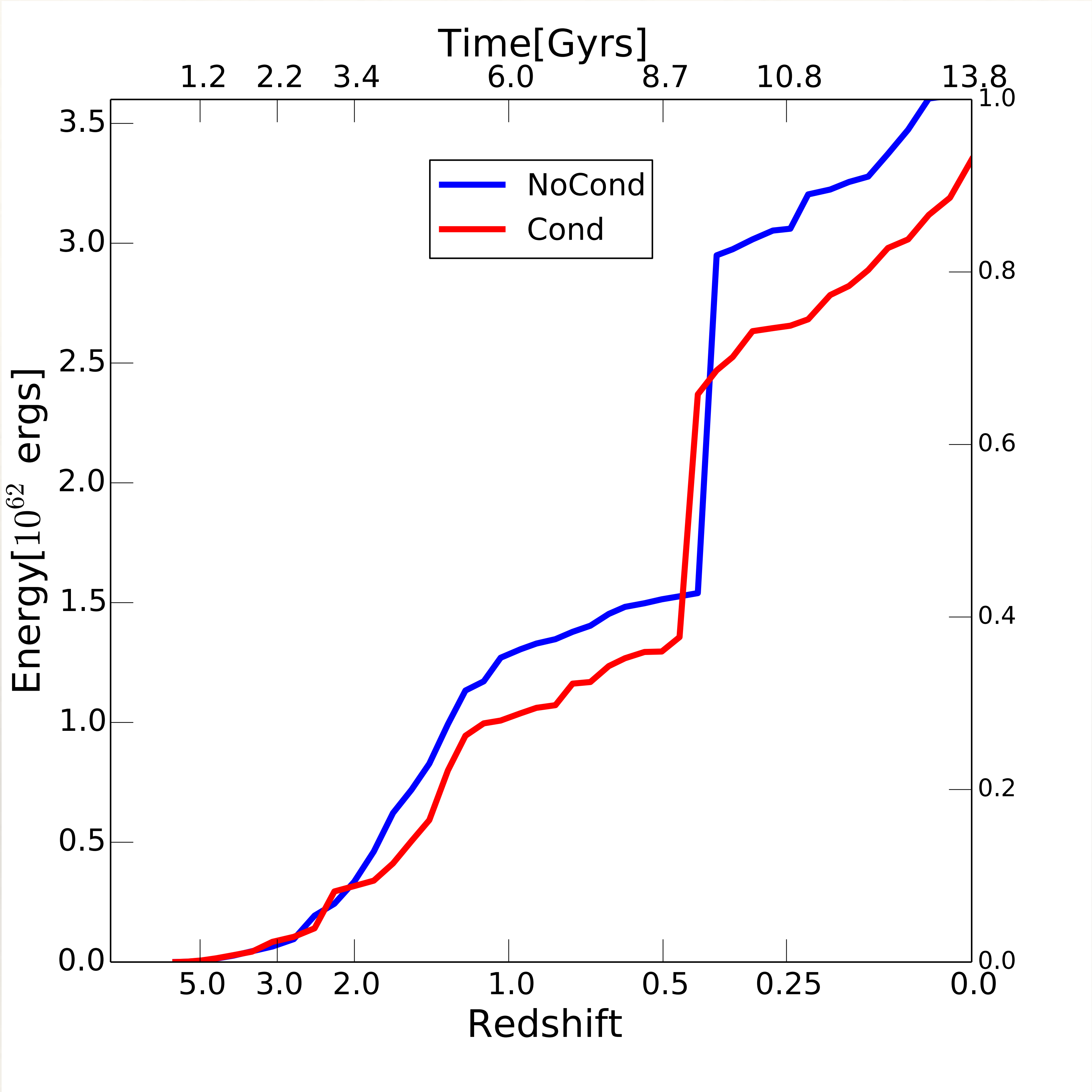


- Conduction converts a cool-core to a non cool core cluster earlier
- Reduces SFRs by more than an order of magnitude at low redshifts
- Completely quenches SF about 0.5 Gyrs earlier

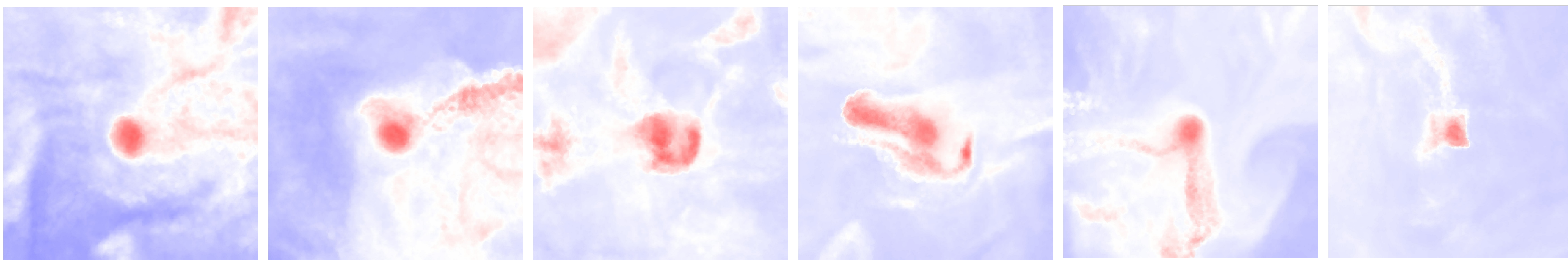
- Lower AGN feedback in the Cond but greater impact of SFRs

- Effect of conductive heating? -No because conductive heating is at most 10% of cooling losses

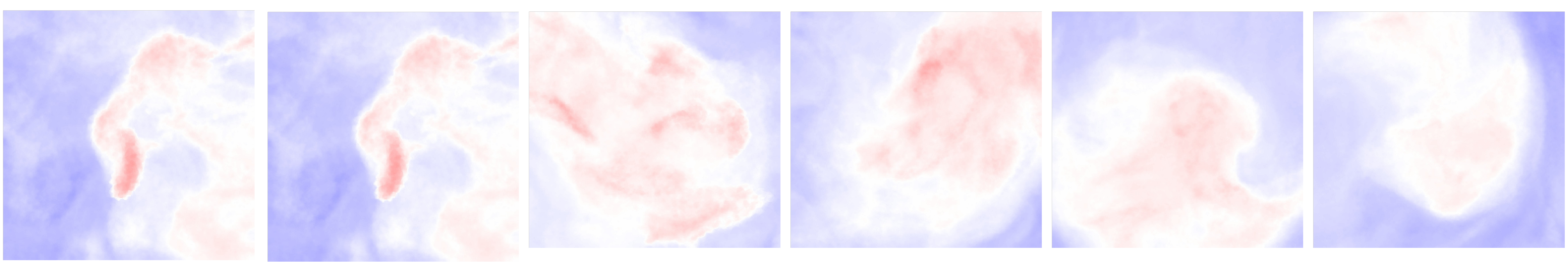
- Also cannot explain efficiency in NCC phase



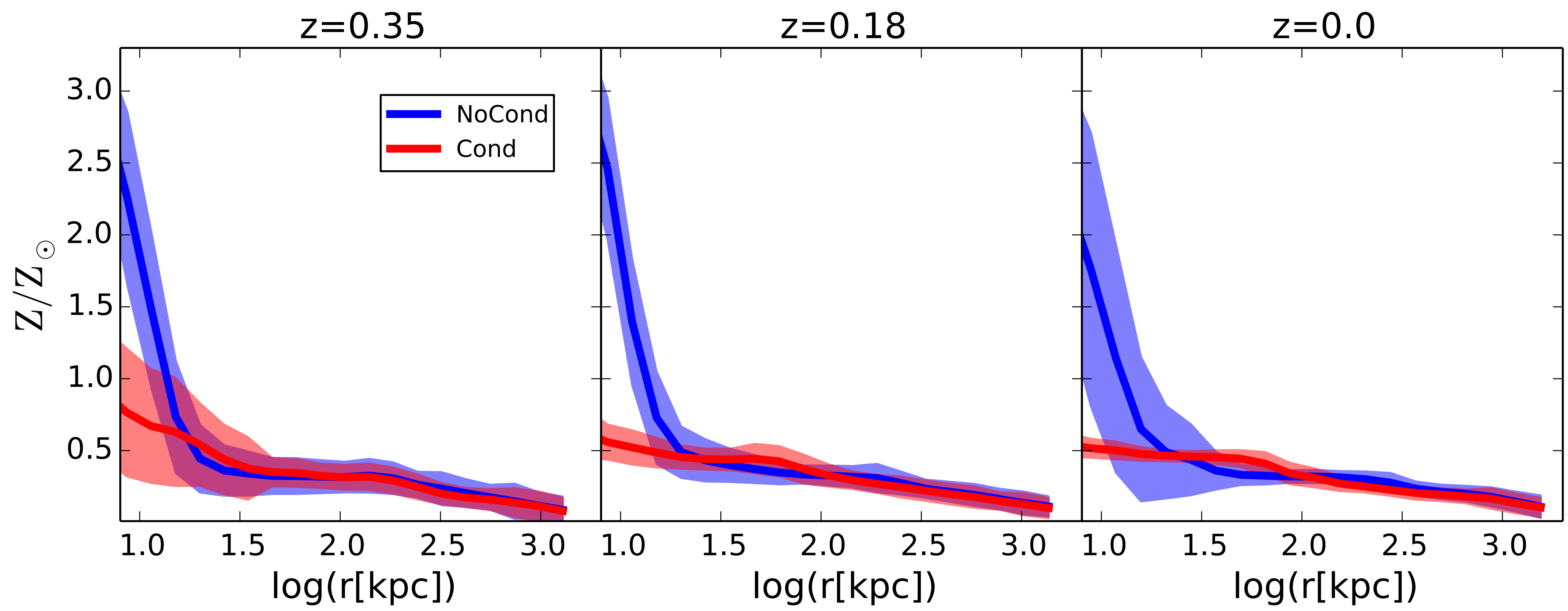
Increased Metal mixing



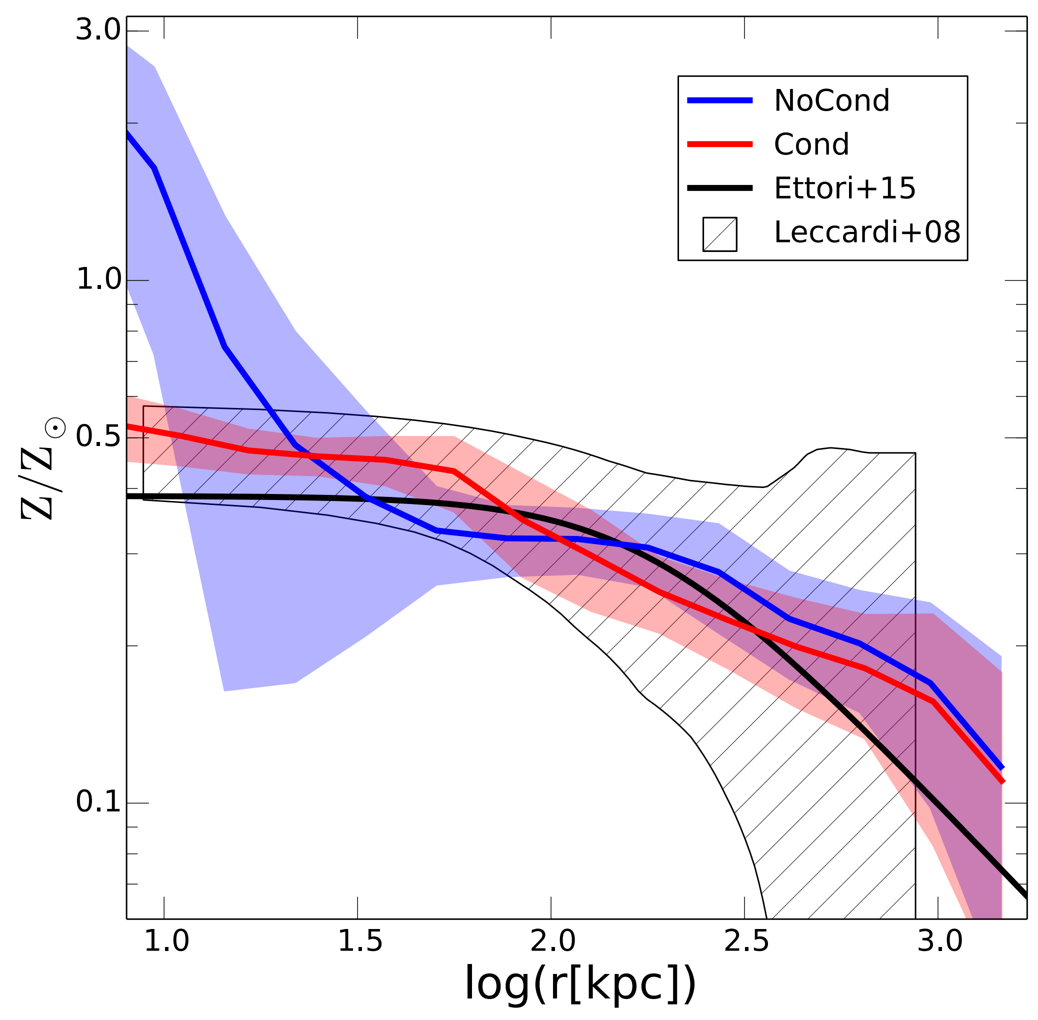
NoCond



Cond

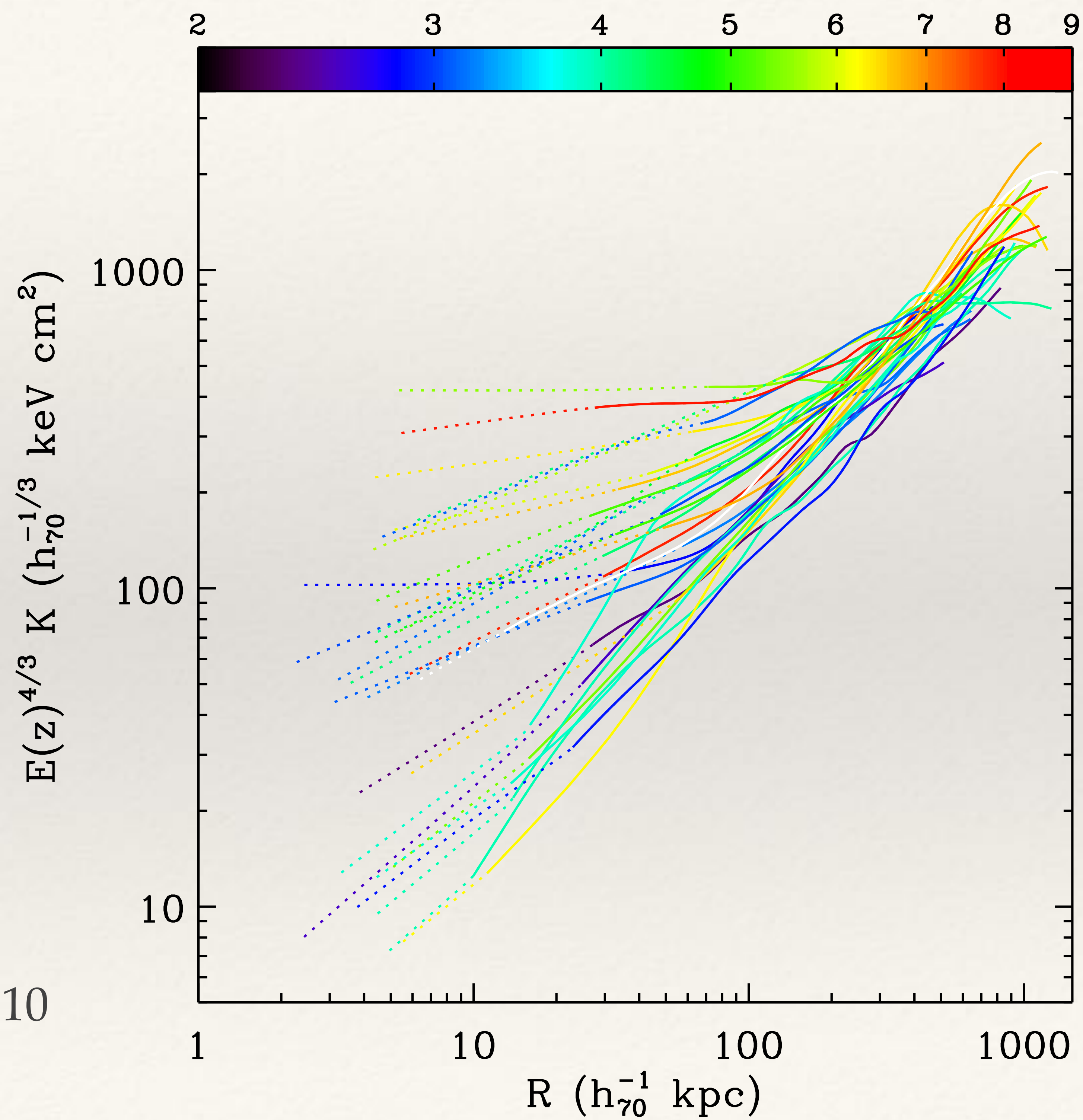


- Lowers the central metallicity
- Reduces the gradients
- Lowers dispersion
- Conduction run metallicity profiles match observations
- Conductive heating cannot explain this behavior
- Indicates efficient mixing in the conduction run



Convective stability of a pure hydrodynamic fluid

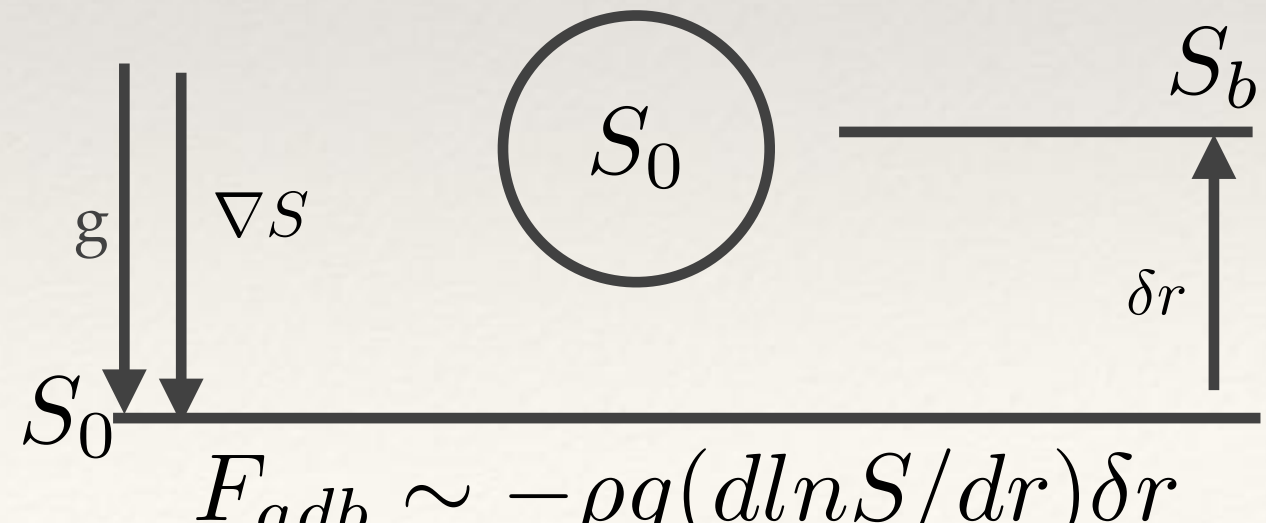
- Stable to convection as long as $dS/dr > 0$



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.



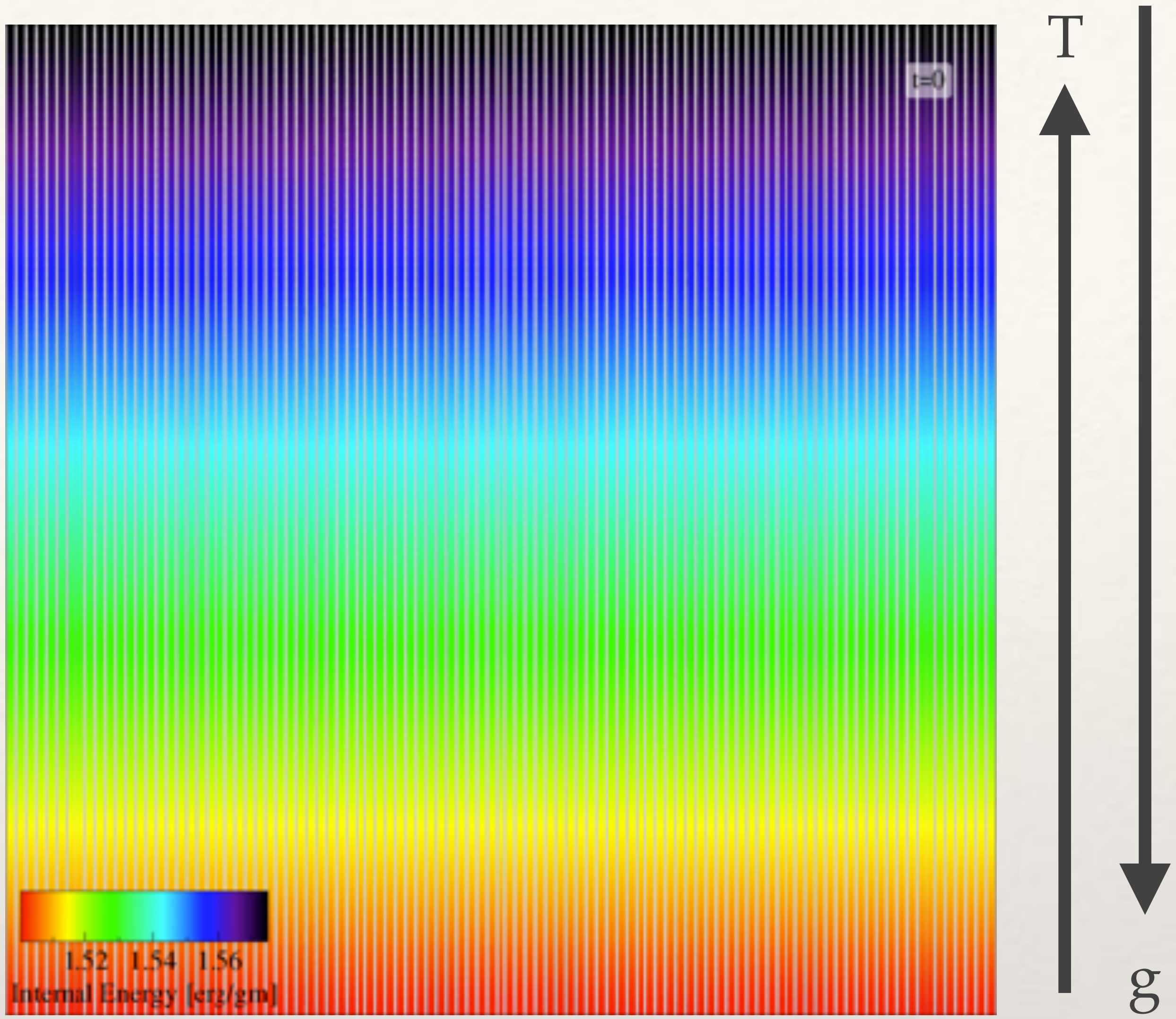
Convective stability of a anisotropically conducting fluid

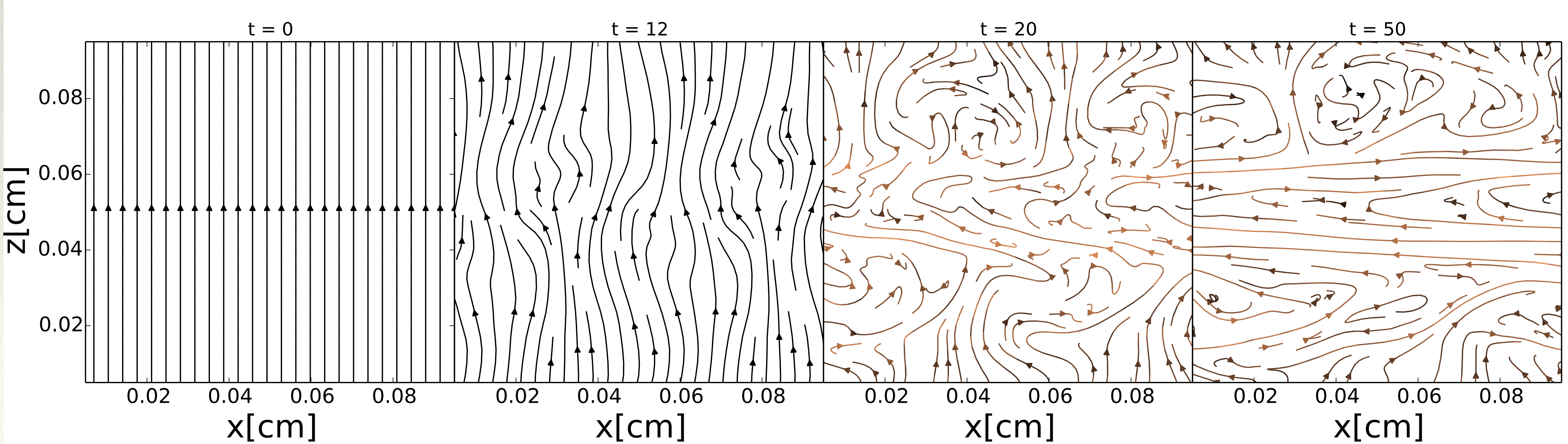
The dynamics of rapidly conducting plasma ($t_{dyn} >> t_{cond}$) very different

Gas isothermal along magnetic field lines under these conditions

System unstable even if $dS/dr > 0$

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

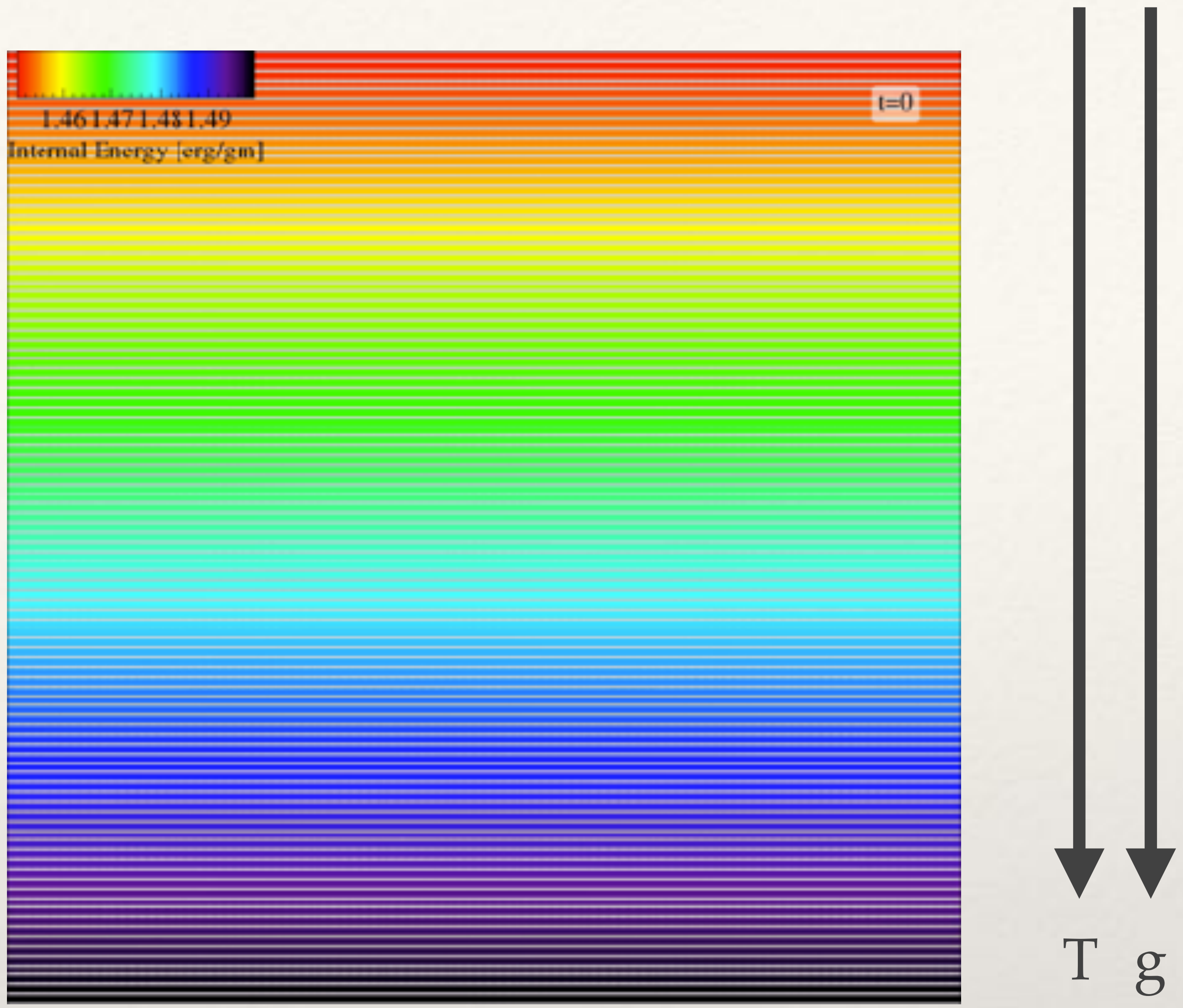


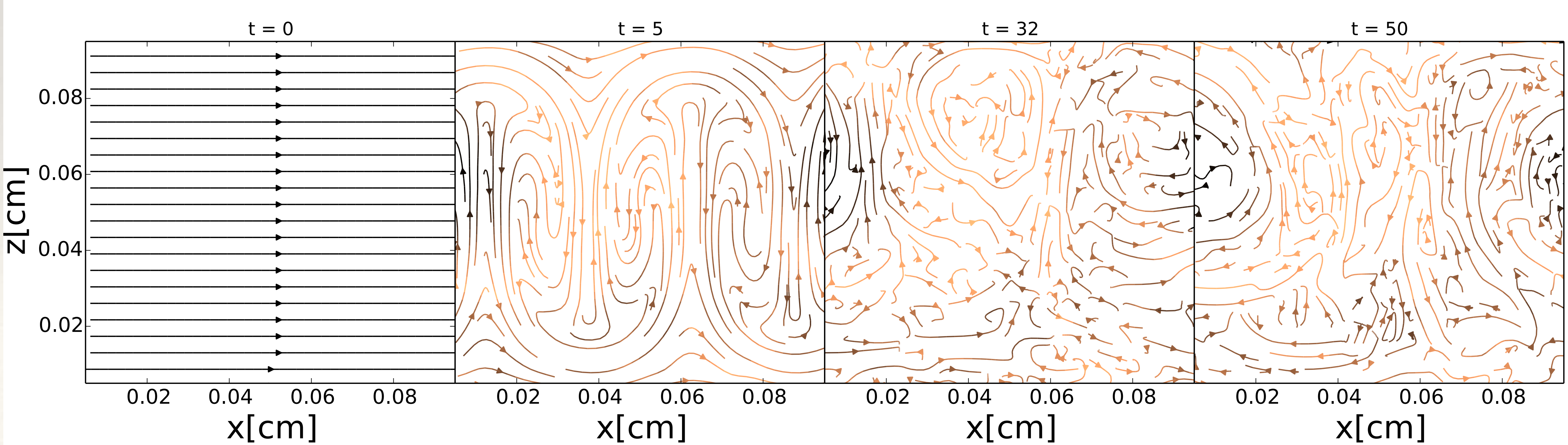


Convective stability of a anisotropically conducting fluid

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

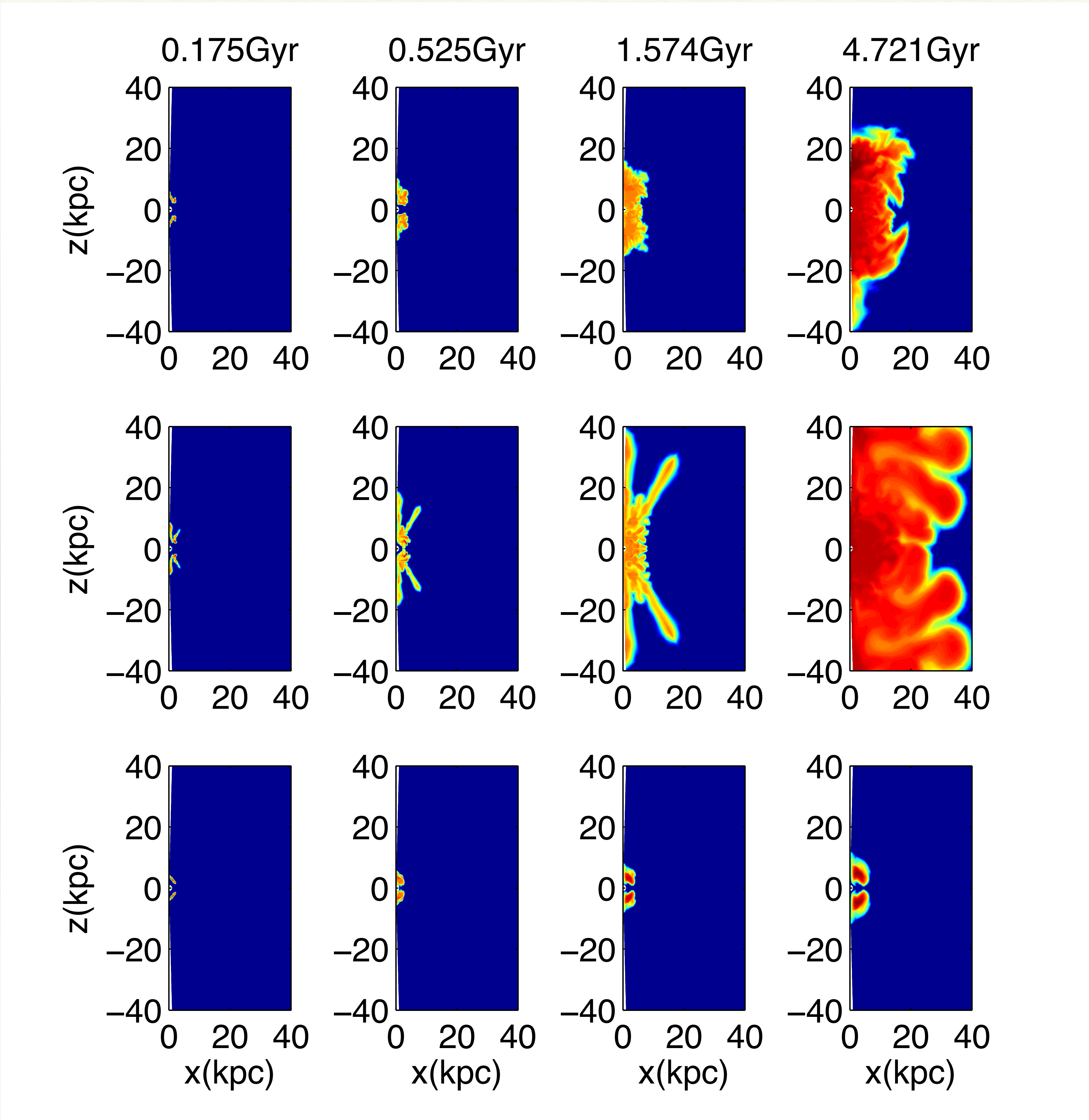
Main take away point - The entire cluster ICM is convectively unstable - making it prone to mixing (Zero restoring force)!!





Increased Mixing

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

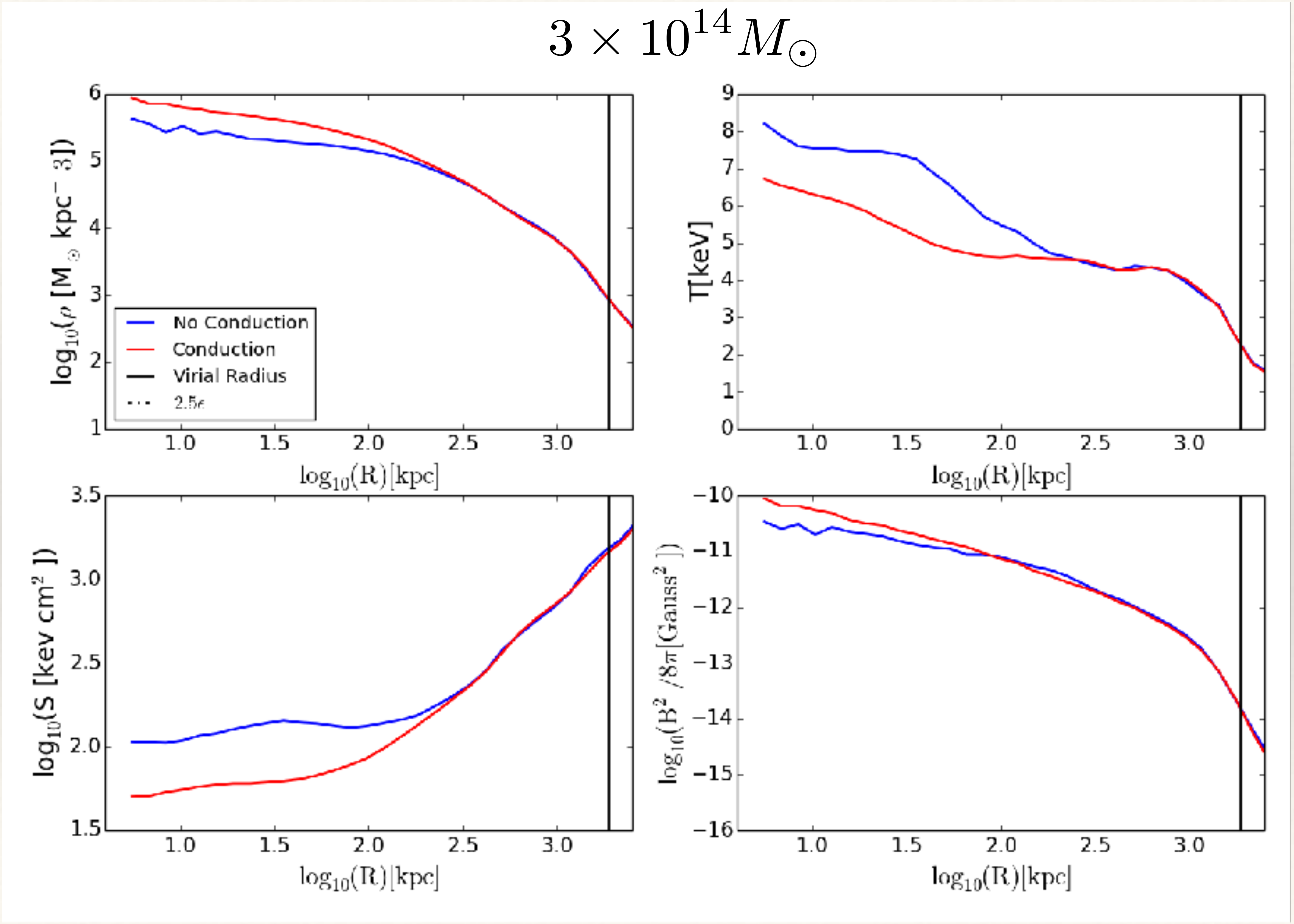


Anisotropic Conduction

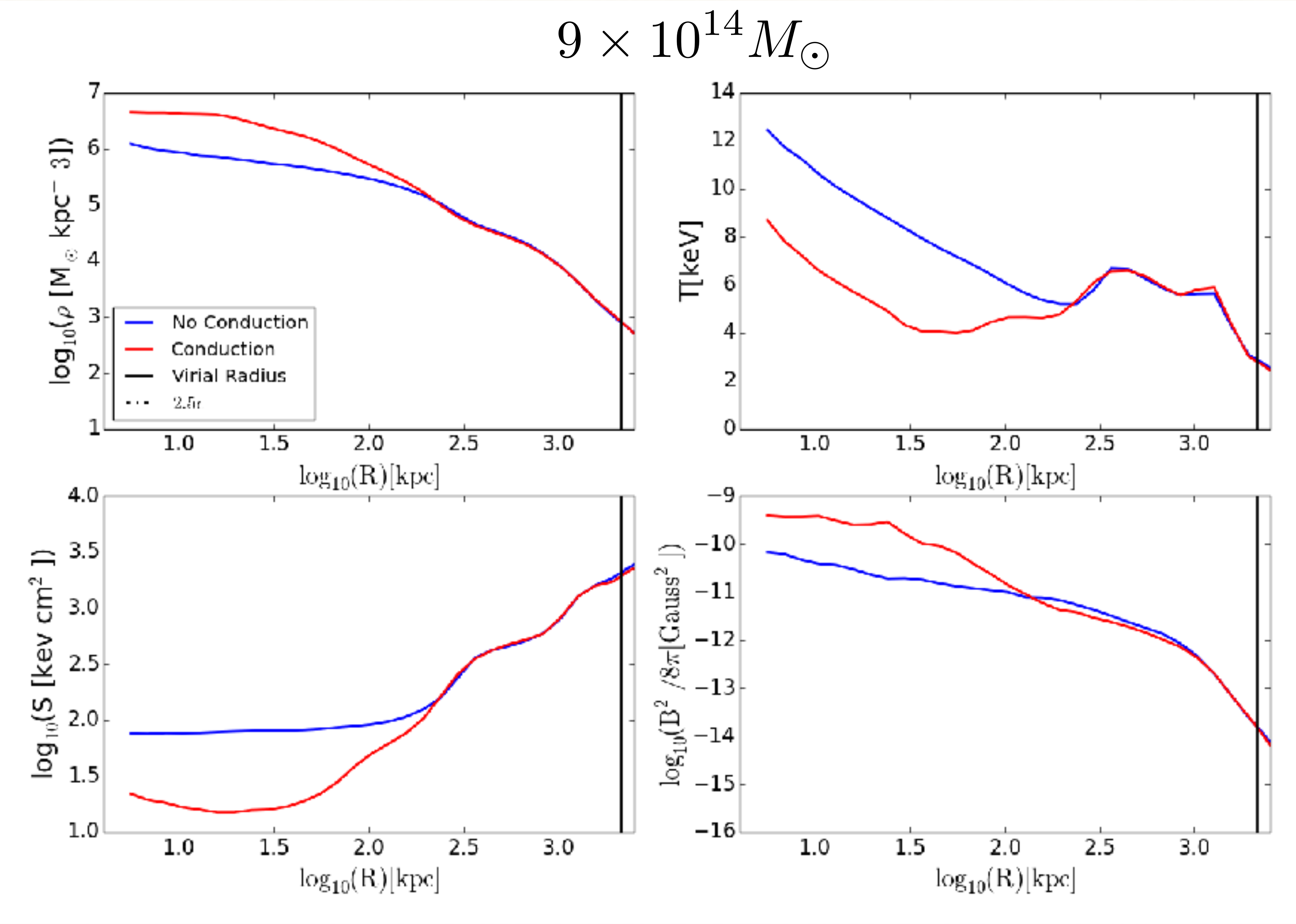
Isotropic Conduction

Adiabatic

Impact of efficient coupling



Impact of efficient coupling



Conclusions

- Anisotropic conduction makes the entire ICM unstable and prone to 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
- Leads to flatter metallicity profiles and matches observations
- Main effect of conduction is turbulent mixing and not conductive heating in clusters

Future Work - Cluster simulation suite

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