TI with conduction & turbulence

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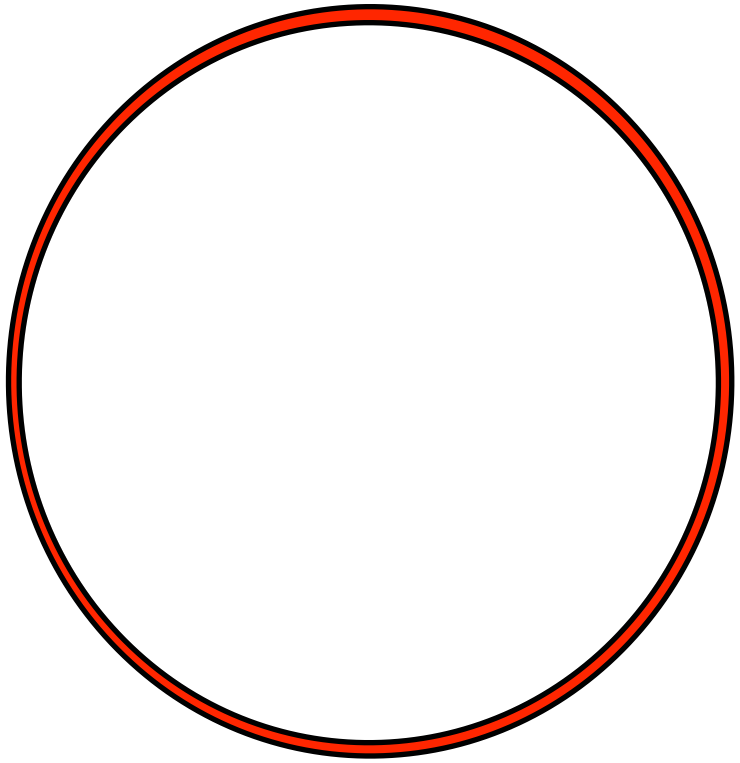
Wagh et al. 2014, MNRAS
Banerjee & Sharma 2014, MNRAS

TI paradigm

- cooling flows are absent; heating $\approx$ average cooling
- interplay of gravity & local TI in globally stable ICM
- behavior reproduced by realistic jets
- holds with anisotropic conduction
- role of turbulent heating/mixing

Toy model

heating~cooling at every radius
(must be true to some degree to prevent cooling flows)



$$q^+(r,t) = \langle n^2 \Lambda(T) \rangle$$

hydrostatic equilibrium: dp/dr = -ρg
gravity due to dark matter

how far can we go with this simple model?

“Entropy” ($K=T/n_e^{2/3}$)

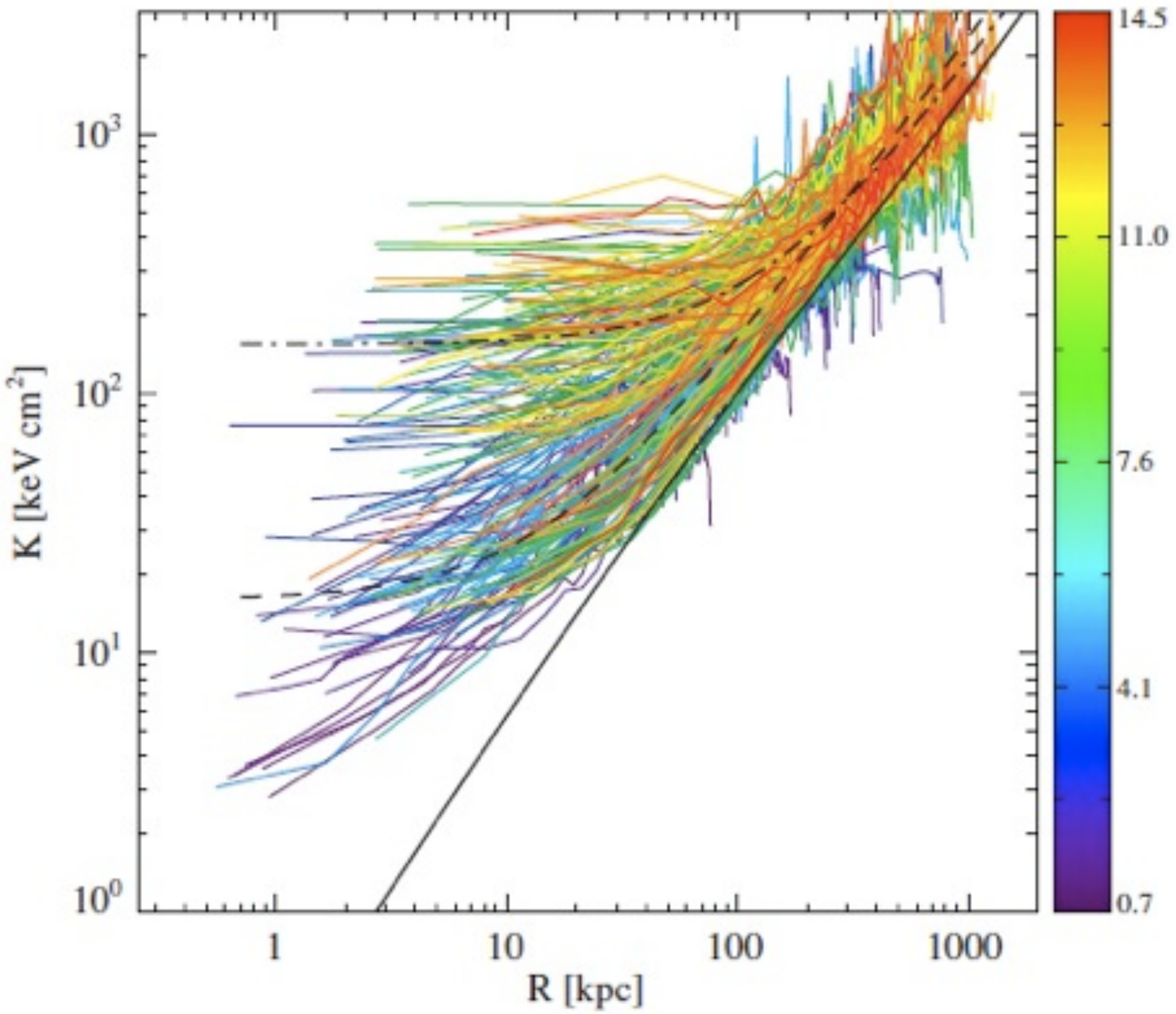
entropy tracks non-adiabatic htg./cooling

K(r): history of gas accn.

$$K(r) = K_0 + K_{100}(r/r_{100})^{\alpha}$$

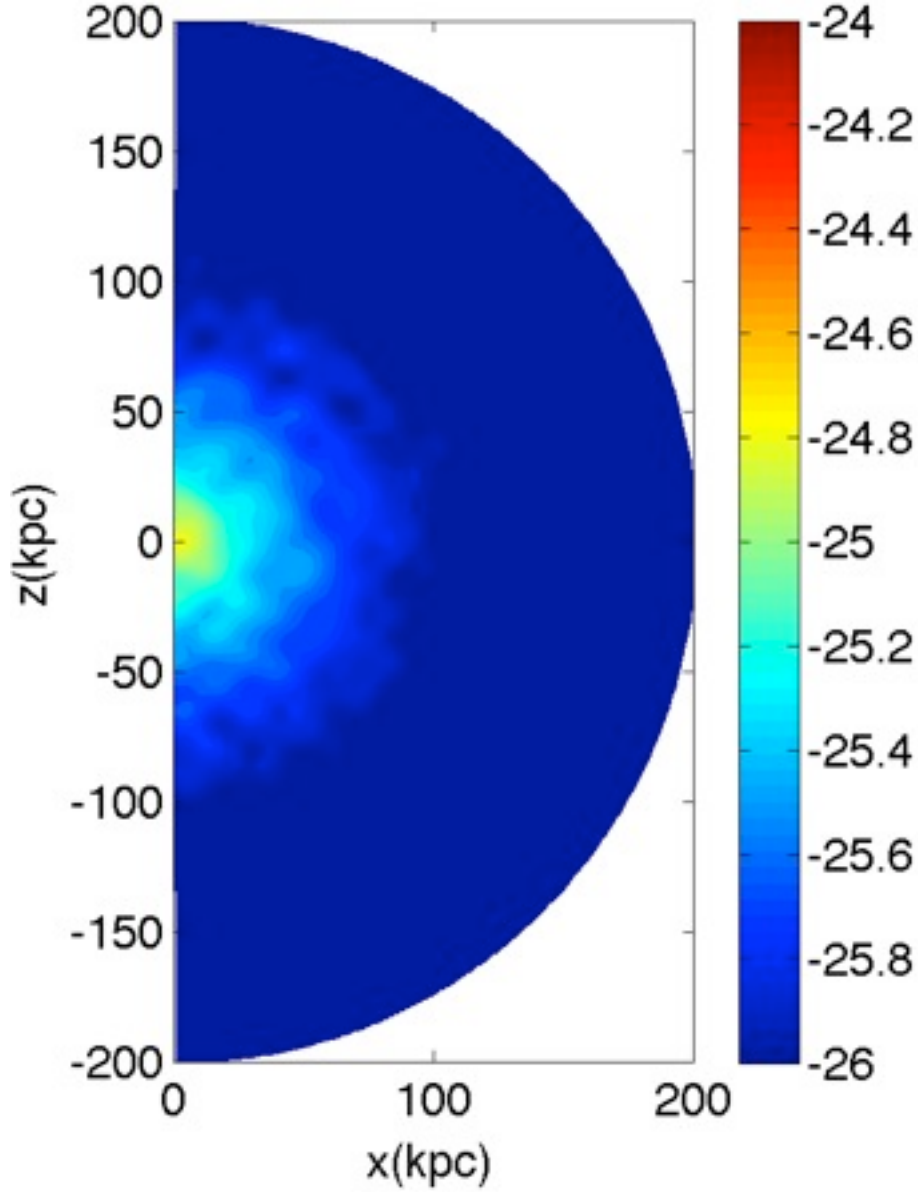
large K <=> low ICM density

[Cavagnolo et al. 2009]

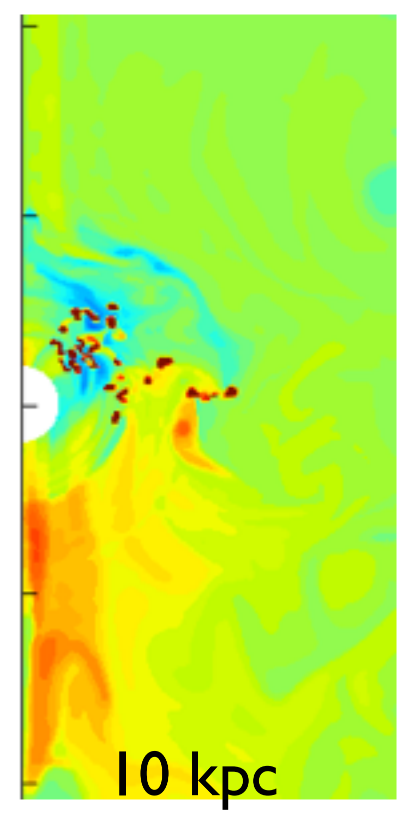


Spherical Sims. Clusters

Log_{10} density

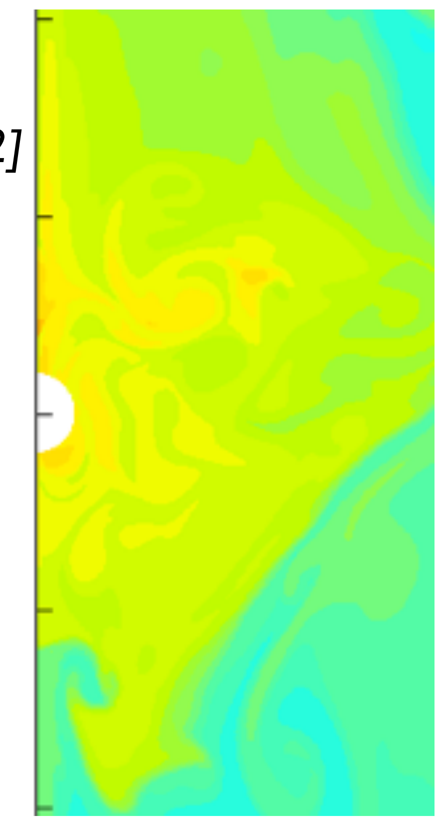


multiphase if t_{cool}/t_{ff} small!



[Sharma et al. 2012]

only hot phase if t_{cool}/t_{ff} big!



cool filaments when $t_{TI}/t_{ff} < 10$

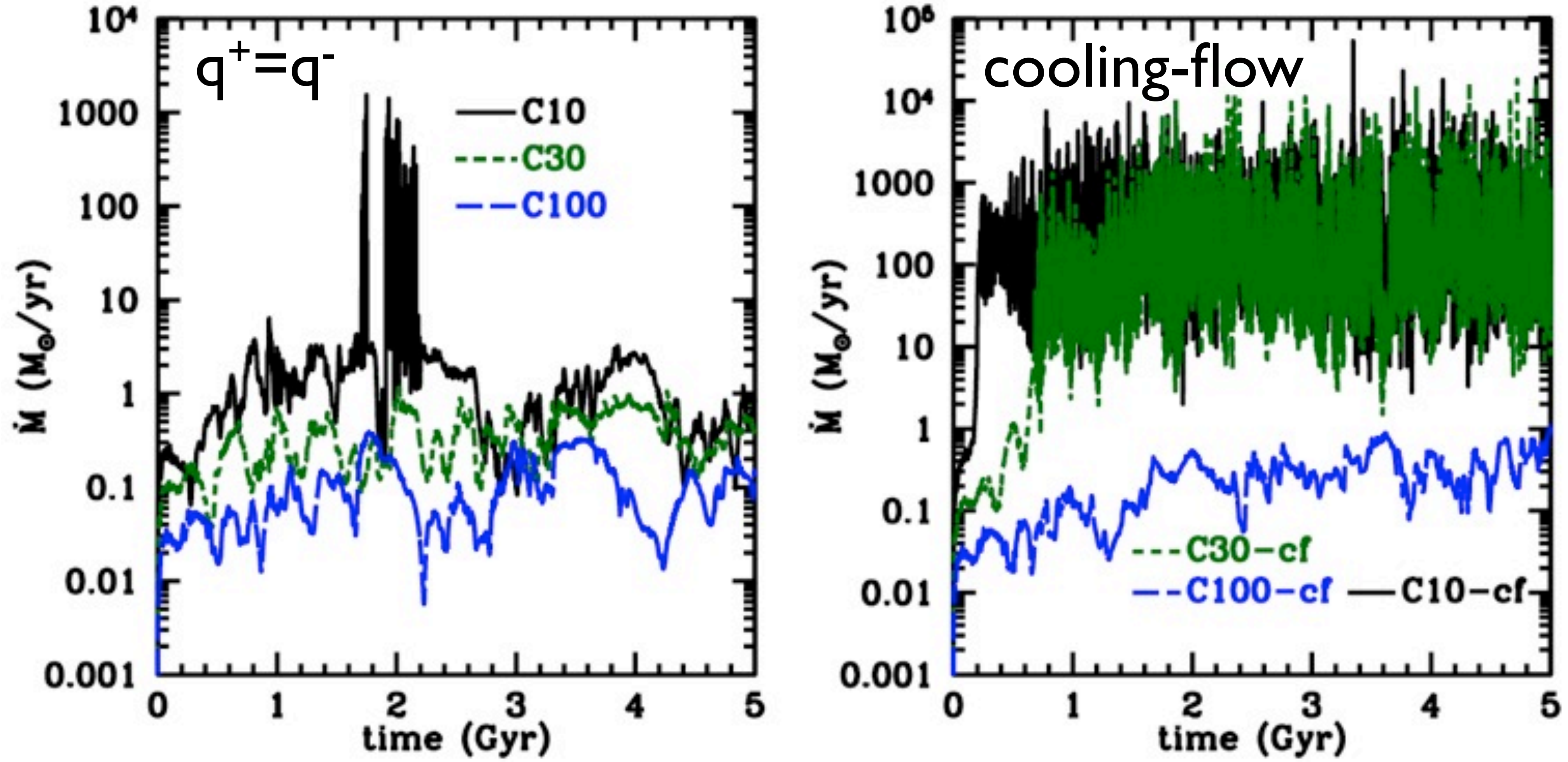
spherical compression is quantitatively imp.

need to understand this from analytic/phenomenological calculations

$q^+=q^-$ =>small dM/dt as observed

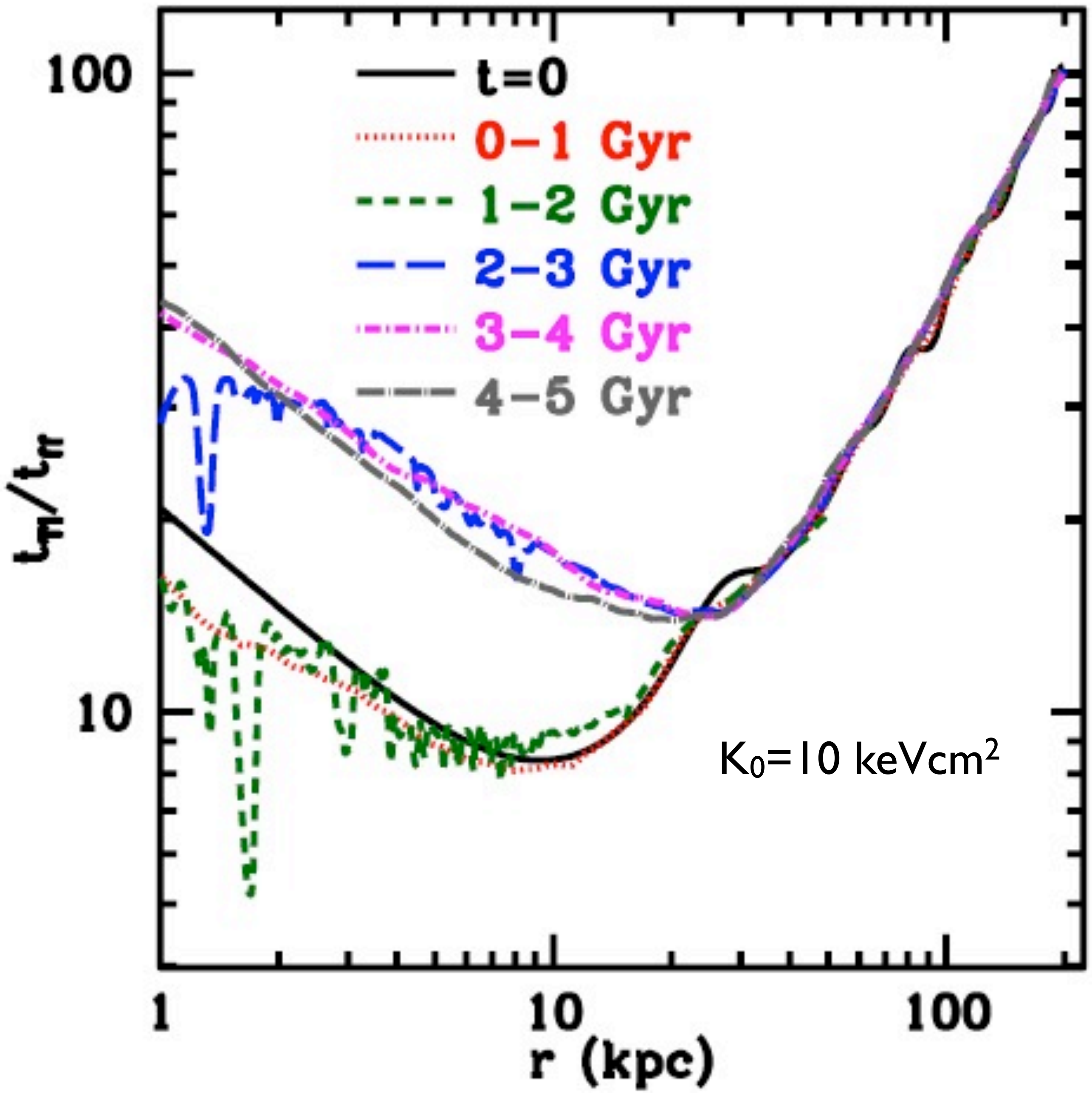
$\varepsilon \sim 10^{-3}$

[Sharma et al. 2012]



dM/dt ~ 0.01dM/dt CF, as observed

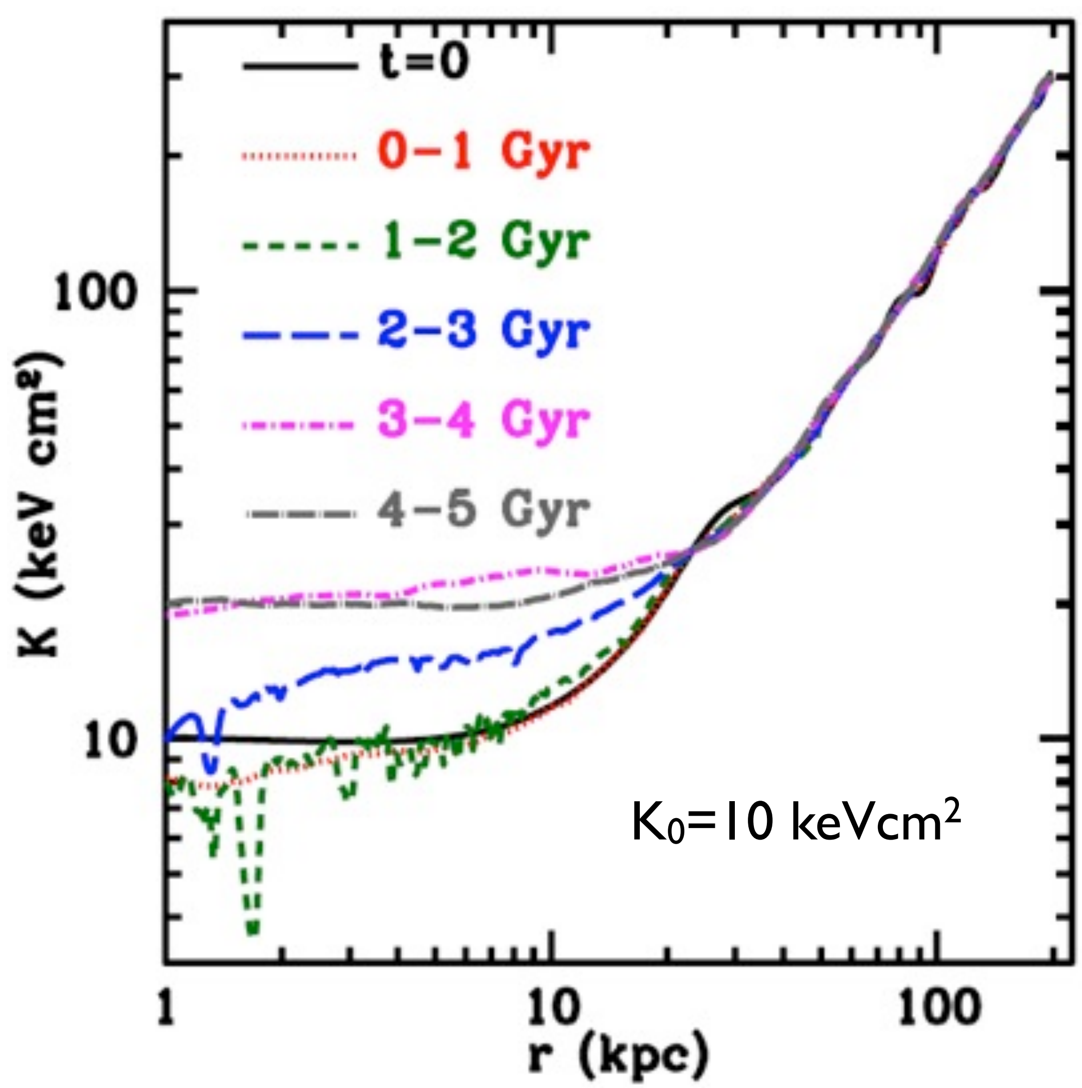
Self-Adjustment of ICM



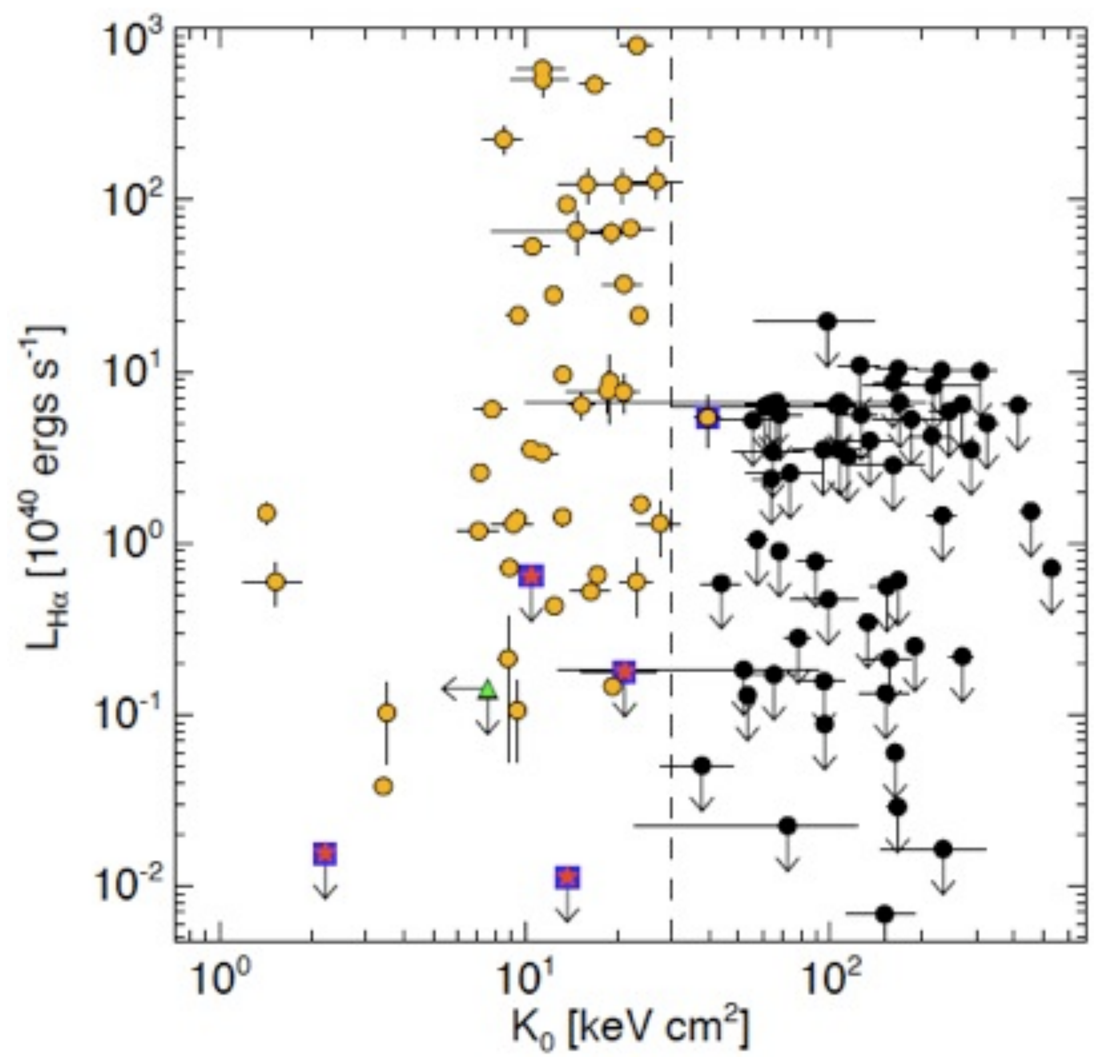
mass dropout if $t_{TI}/t_{ff}<10$
CC clusters at $t_{TI}/t_{ff}\sim 10$

even if we start w. much lower K_0 or t_{TI}/t_{ff}

Self-Adjustment of ICM



[Cavagnolo et al. 2008]



$t_{cool}/t_{ff} \approx 10$

CC/NCC division corresponds to our t_{cool}/t_{ff} criterion!

Core vs. halo mass

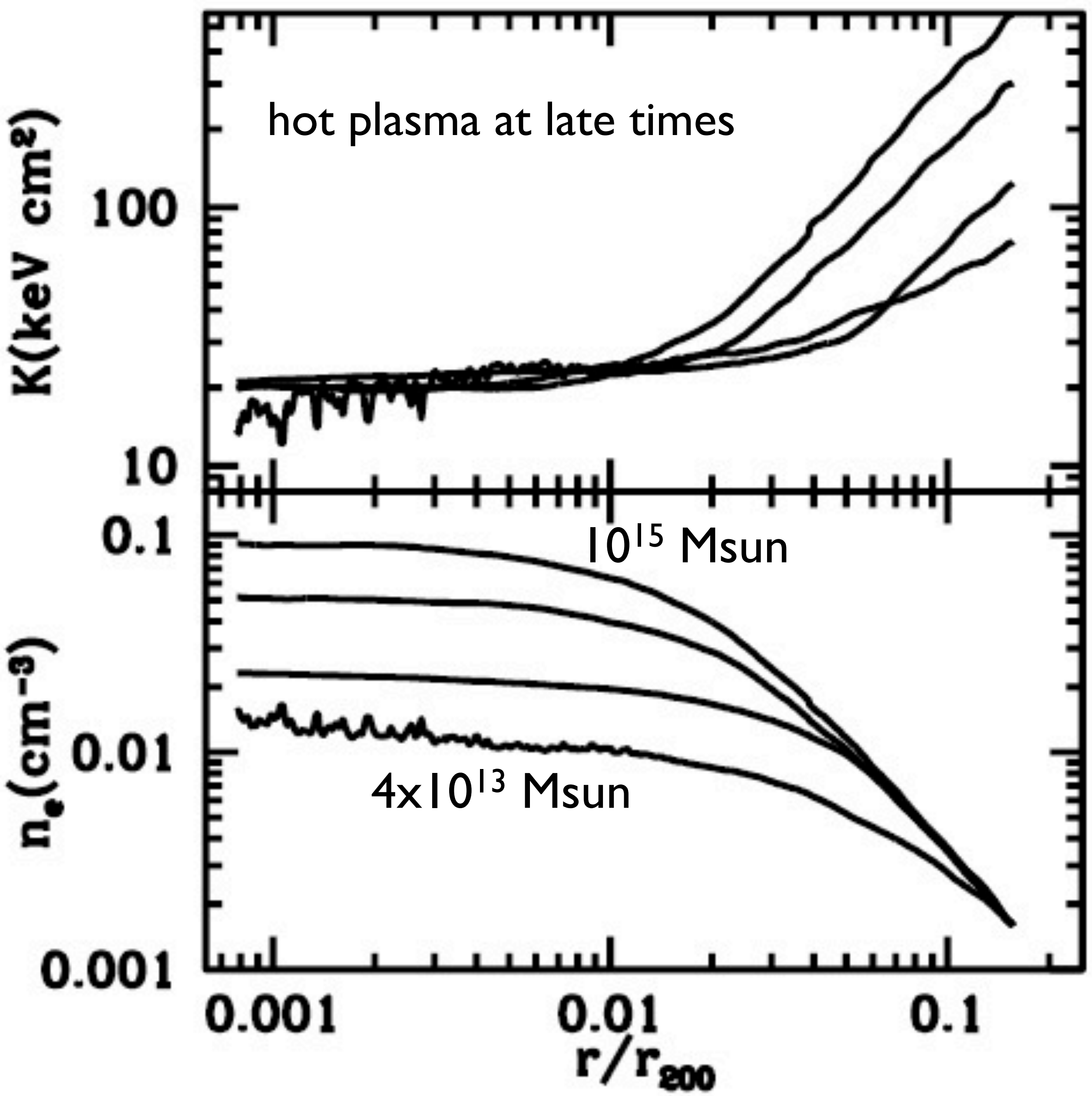
$t_{cool} \sim T/n\Lambda \sim T^{1/2}/n$
cooling more imp. for lower mass halos

bigger & lower density cores for groups vs. clusters

entropy almost the same for diff. halos => smaller halos overheated => steepening of L_X-T_X reln.

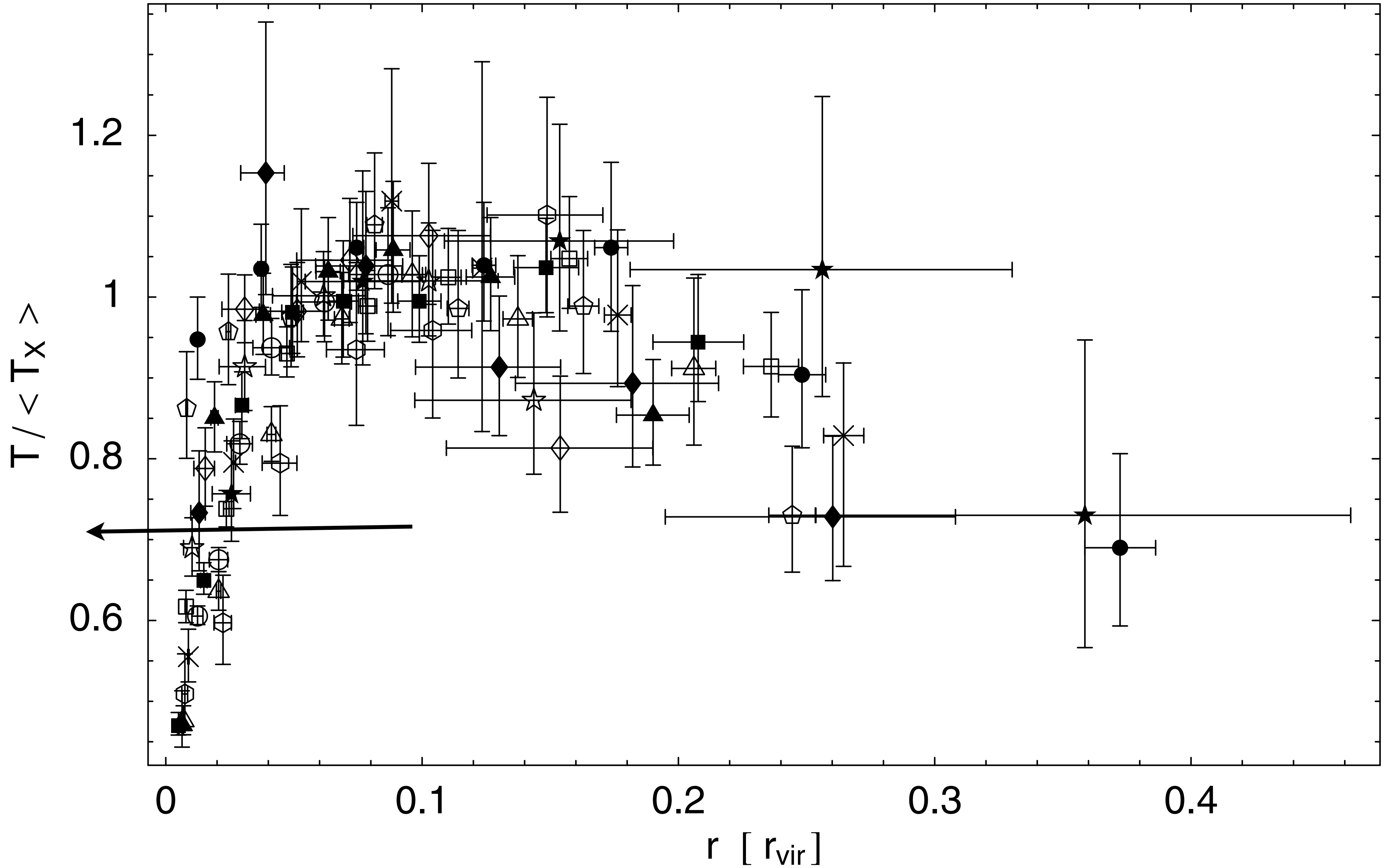
$t_{cool}/t_{ff} < 10$

[Sharma et al. 2012]



Effects of Conduction

[Piffaretti et al. 2005]

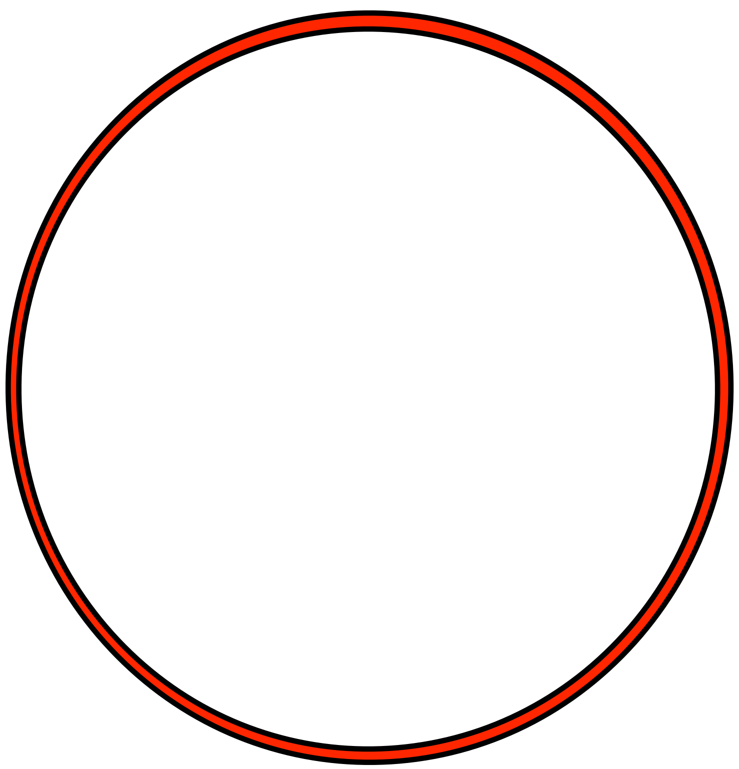


thermal conduction can, in principle, bring in heat from larger radii

Problems w. conduction

- globally unstable
- HBI shuts of conduction
- still can play a key role in energetics
- numerics: no MPI code for implicitly doing aniso. conduction

Conduction & cold gas



generalize the simple toy model but accounting conductive heating in energetics

$$q^+(r,t) = \langle n^2 \Lambda(T) \rangle + \nabla \cdot \vec{q}$$

How do isotropic & anisotropic conduction change the picture?

in addition to t_{cool}/t_{ff}, conduction is expected to suppress TI

Why conduction in core?

[Voit et al. 2008]

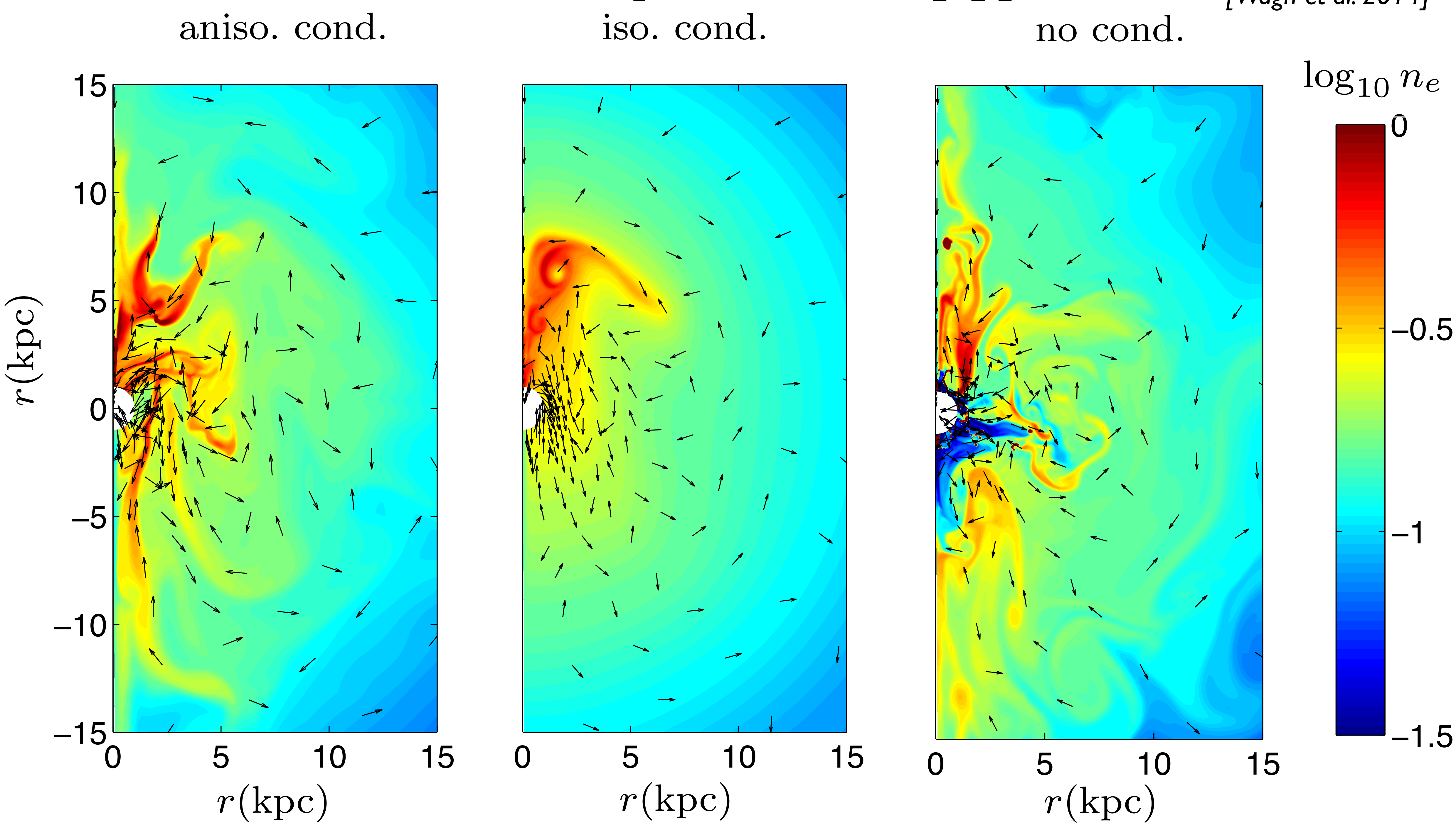
$$\lambda_F \equiv \left[\frac{T\kappa(T)}{n^2\Lambda(T)}\right]^{1/2} = 4 \text{ kpc } \left[\frac{K}{10 \text{ keV cm}^2}\right]^{3/2} f_c^{1/2}.$$

Field length, below which conducting prevents local TI

expect *isotropic* conduction to prevent condensation when Field length>core size; not so for *anisotropic*

Morphology

[Wagh et al. 2014]

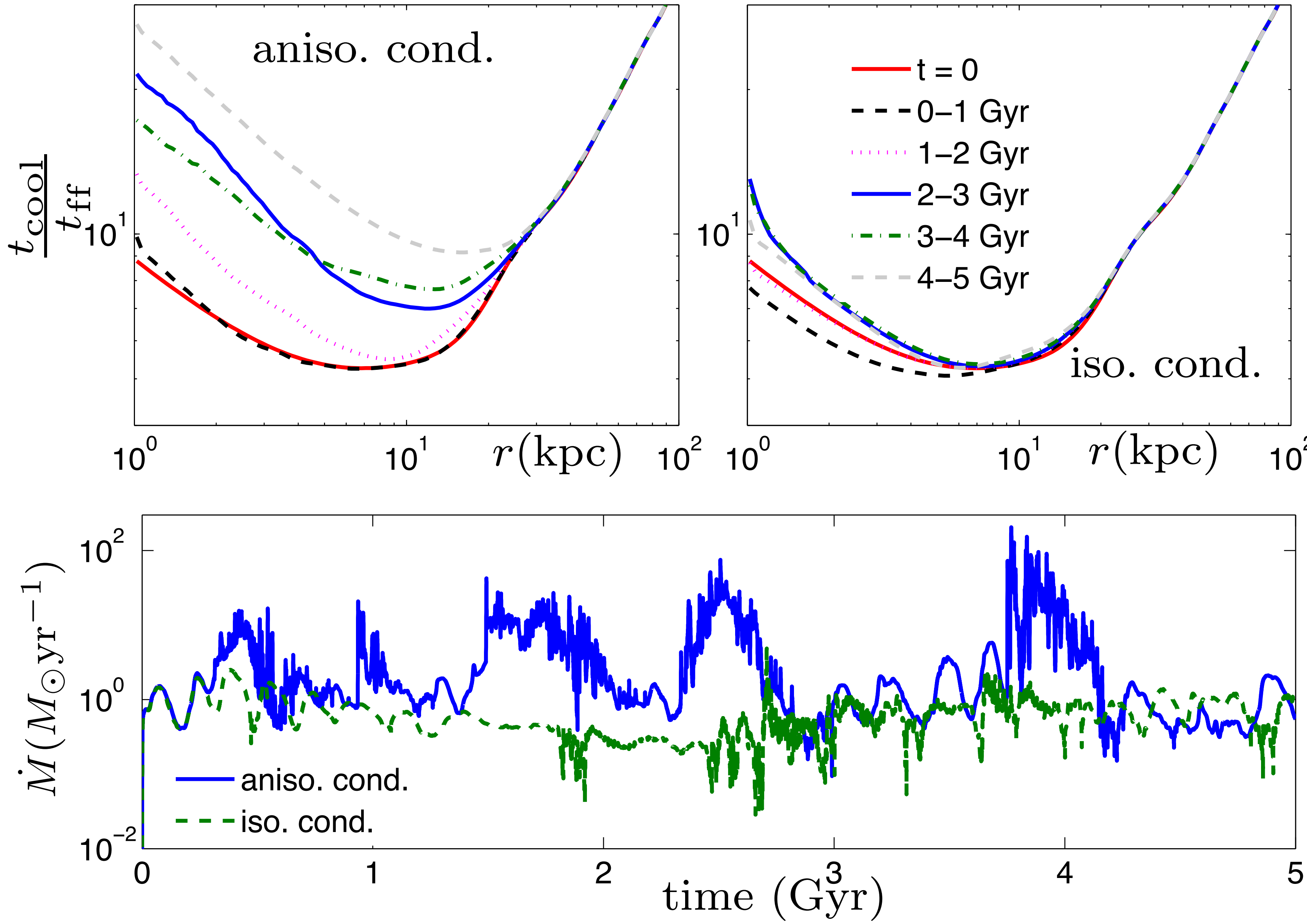


halo mass $3.8 \times 10^{14} M_{sun}$; split monopolar B~1 μG; K_0=5 keV cm^2

sim. with aniso. conduction much closer to hydro

Anisotropic vs Isotropic

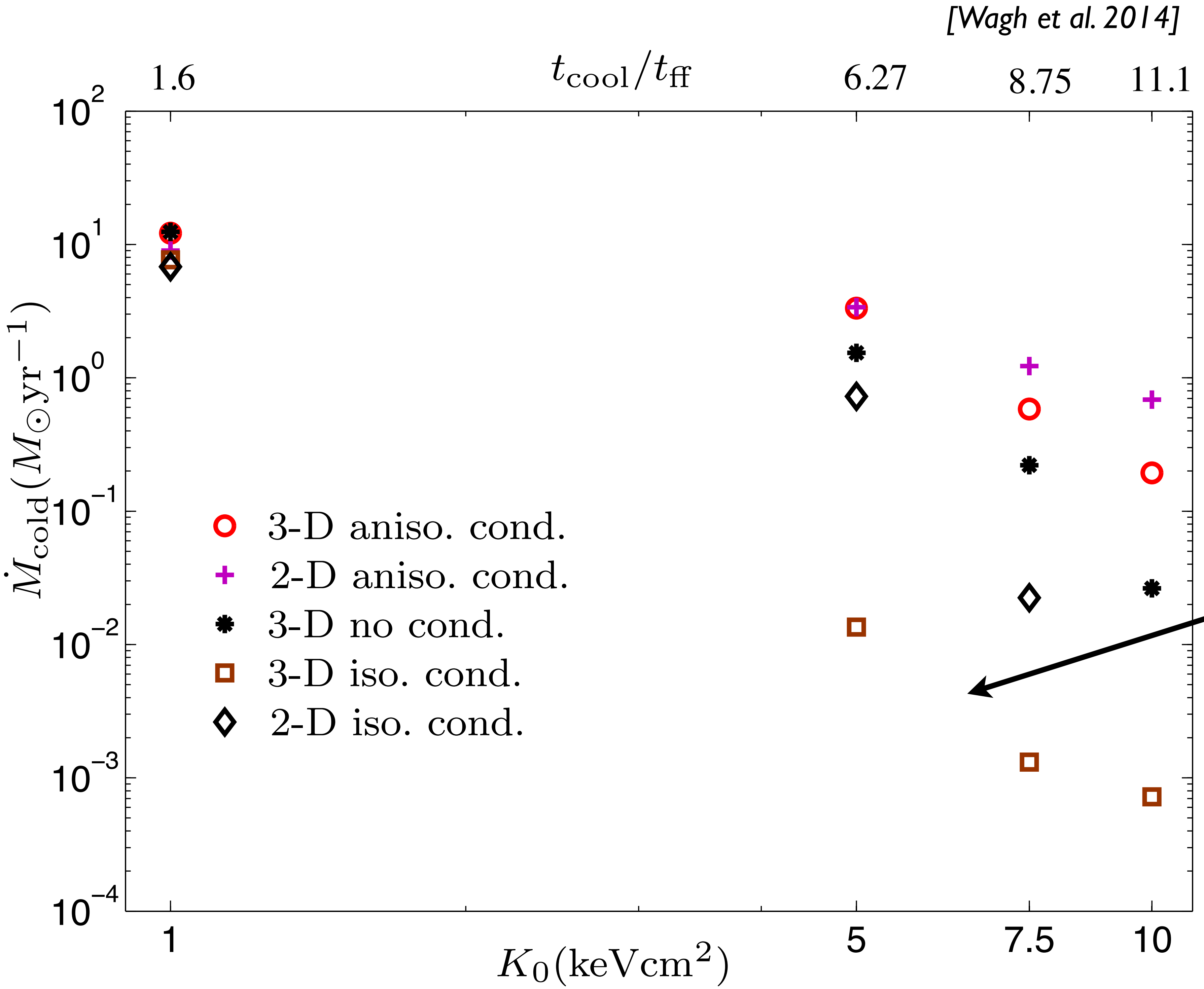
[Wagh et al. 2014]



K_0=5 keV cm^2

much smaller cold gas condenses with isotropic conduction
because of suppression of TI by conduction
difference is more pronounced for massive clusters

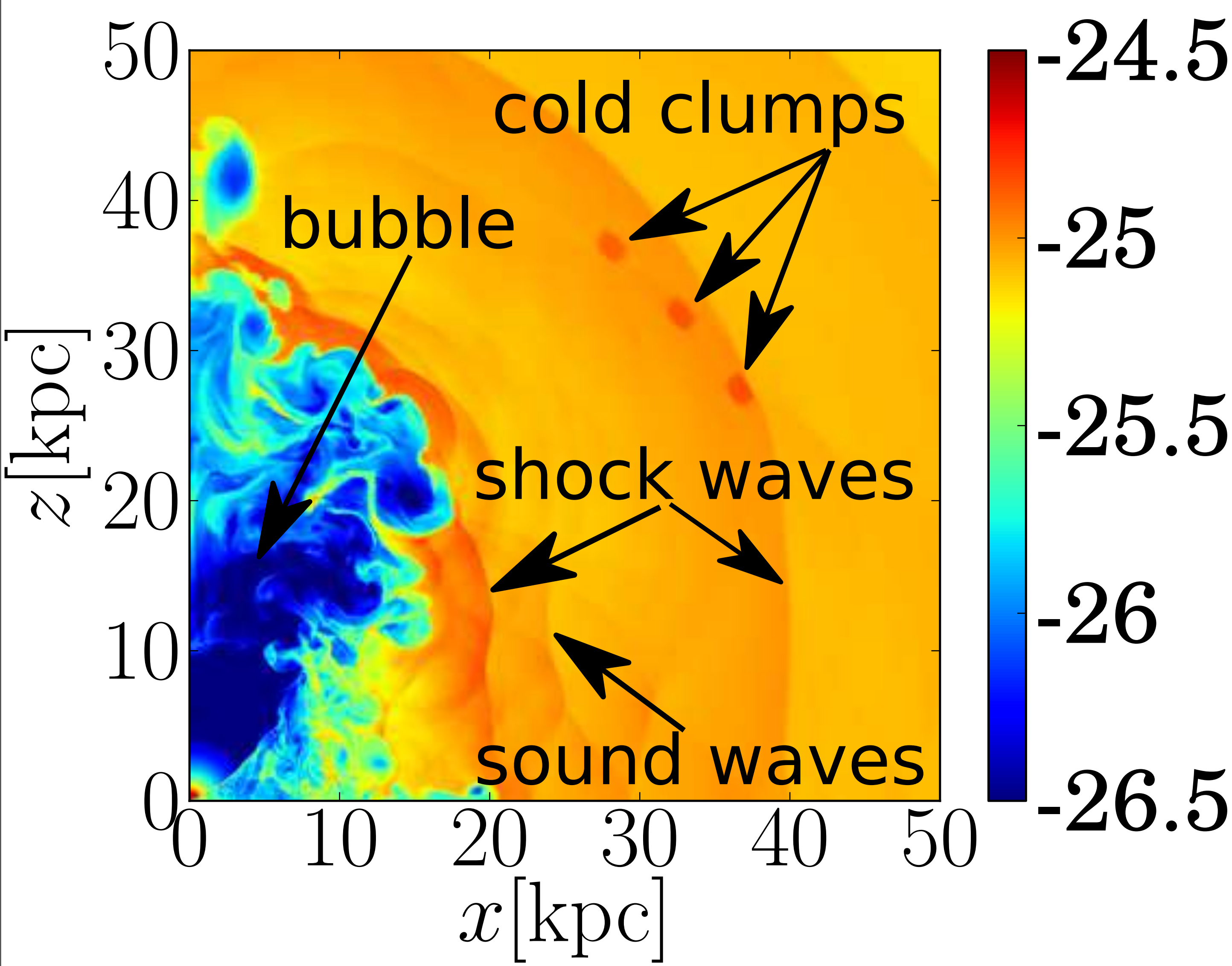
Cold gas accretion



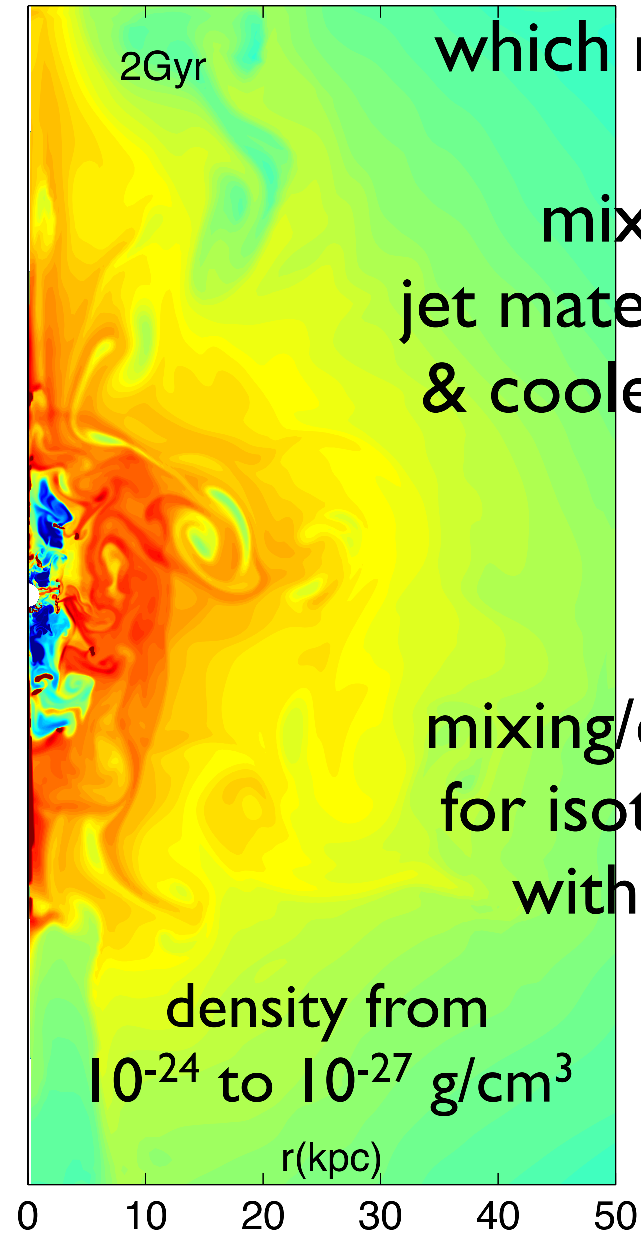
1-2 orders of magnitude lower cold gas with isotropic conduction at K0≳5 keV cm^2

What heats cool cores?

[Hillel & Soker 2014]



forward shock not efficient:
more like sound waves
which move out fast

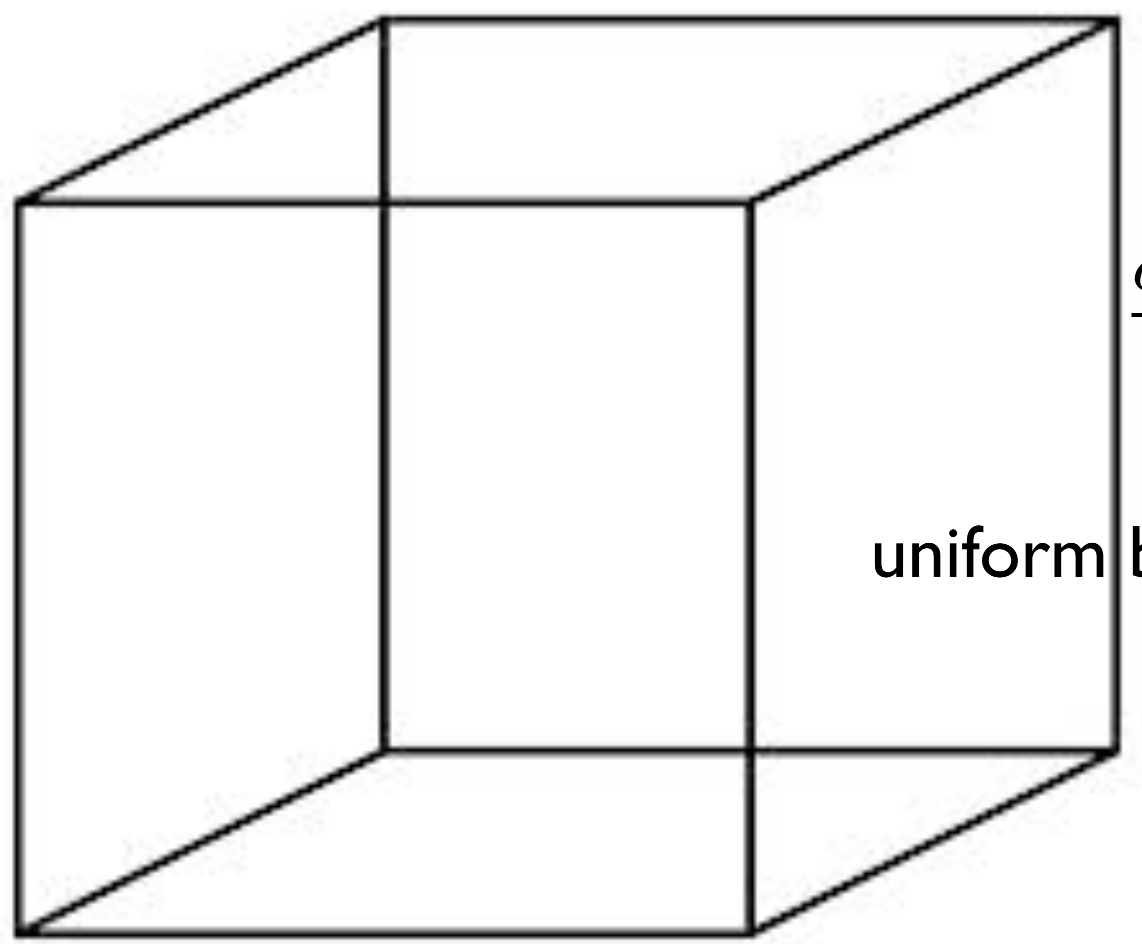


mixing of hot
jet material/outer ICM
& cooler ICM plasma

mixing/entrainment crucial
for isotropic heating even
with, say cosmic rays

N Experiments with Turbulent Heating/Mixing

[Banerjee & Sharma 2014]



$$\frac{\partial(\rho\vec{v})}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}\otimes\vec{v} + P^{*}I) = \vec{F},$$

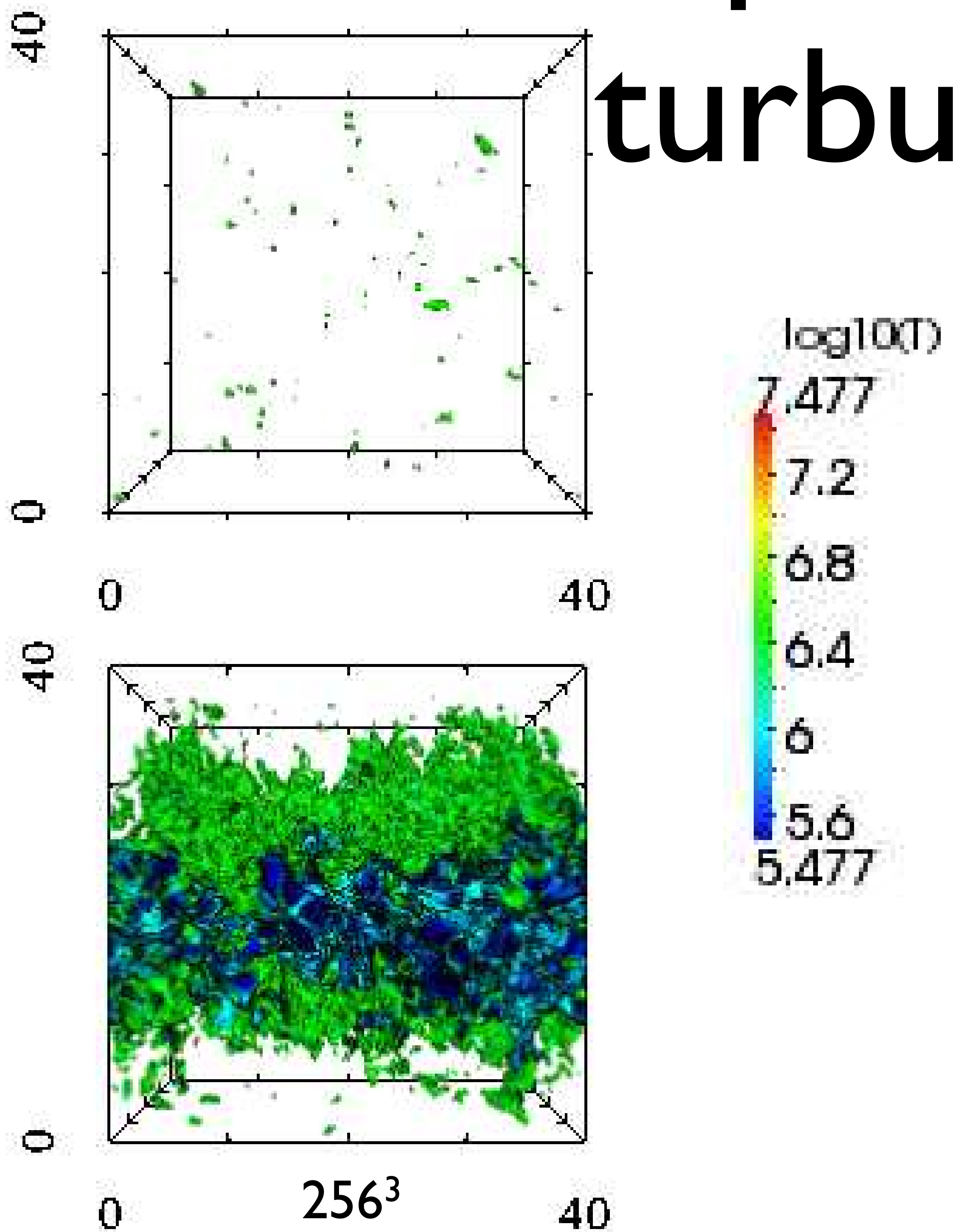
$$\frac{\partial E}{\partial t} + \vec{\nabla}\cdot\{(E + P^{*})\vec{v} + (\vec{B}\cdot\vec{v})\vec{B} + \vec{Q}\} = \vec{F}\cdot\vec{v} - \mathcal{L},$$

$$\langle\vec{F}\cdot\vec{v}\rangle = \langle\mathcal{L}\rangle$$

turbulence driven at 10 kpc

work done by turbulent force balances cooling over the box, on average mimicking heating due to jet-induced turbulence

Multiphase gas w. turbulence



only large-enough clouds can condense out smaller ones are mixed faster than they can cool

L =10 kpc is the driving scale

Scalings

L is the driving scale

$$\rho v_L^3/L = 2K/t_{\rm mix,L} \approx n^2\Lambda = U/t_{\rm cool}$$

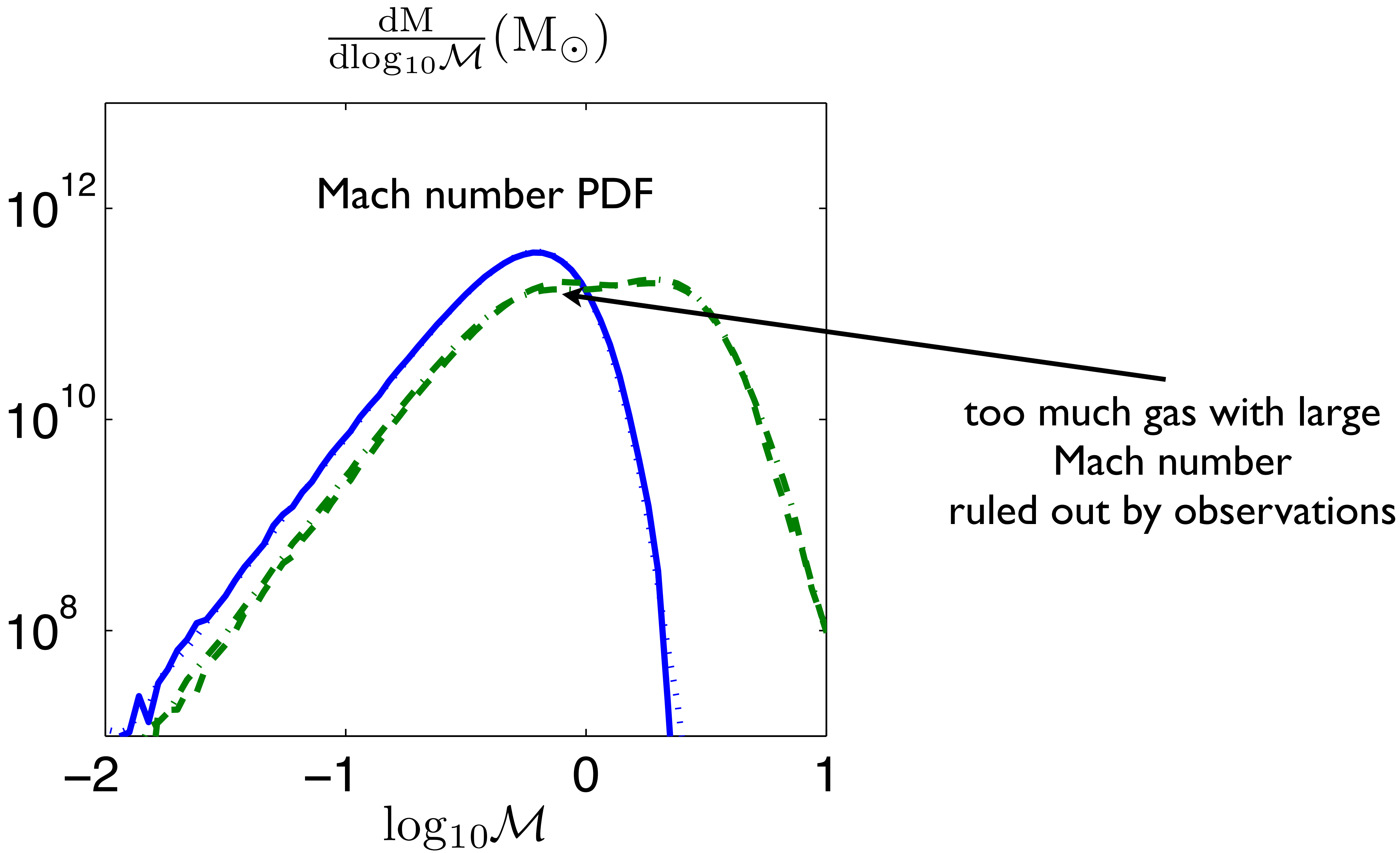
$$t_{\rm mix,L}/t_{\rm cool} \approx 2K/U \approx \mathcal{M}^2 \gtrsim 1$$ for condensation

implies that clouds condense out at large scales
& turbulence is close to sonic; ruled out for CCs!

$2K/U \approx \mathcal{M}^2$ can be <1, but $t_{\rm mix,L} < t_{\rm cool}$ in this case

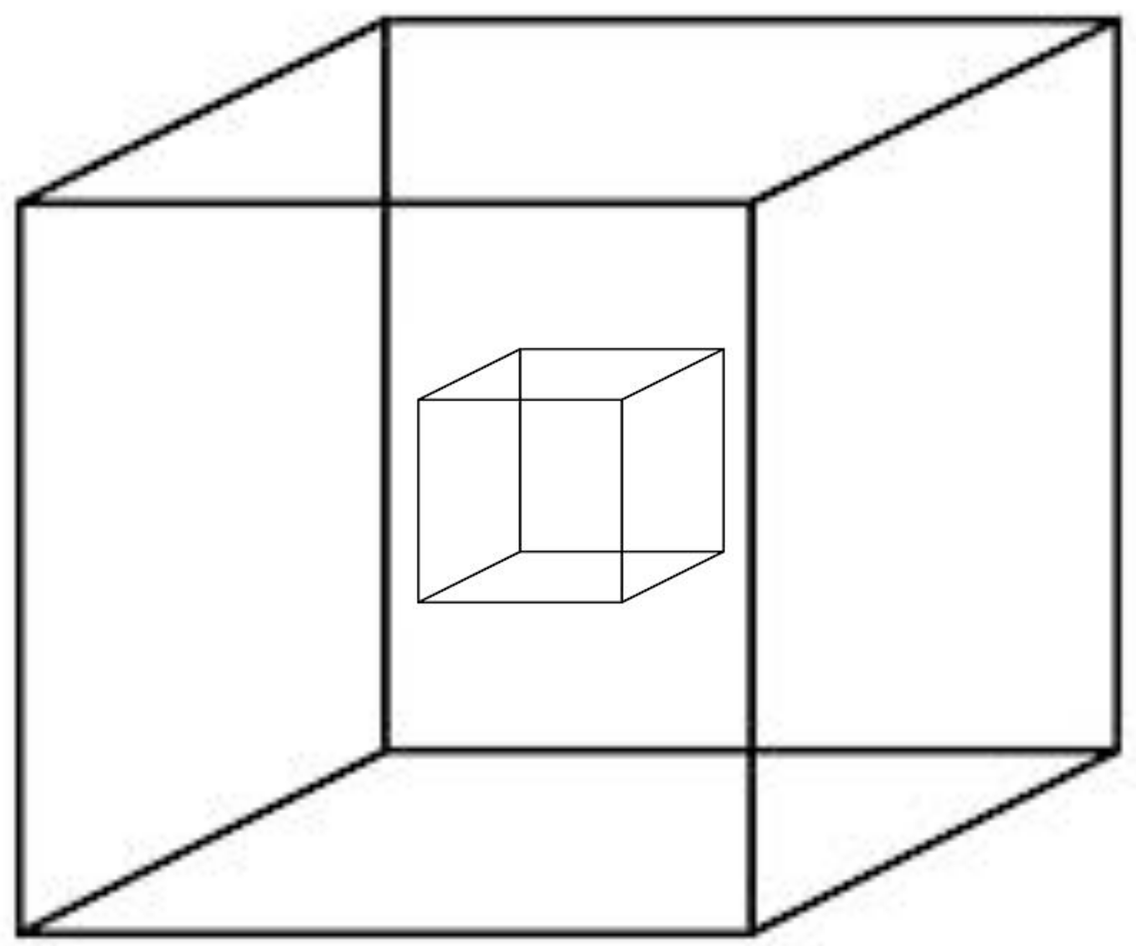
can't have condensation as seen in CCs

Turbulent htg. ruled out



Turbulent Mixing?

[Banerjee & Sharma 2014]



small box, represents the cool core

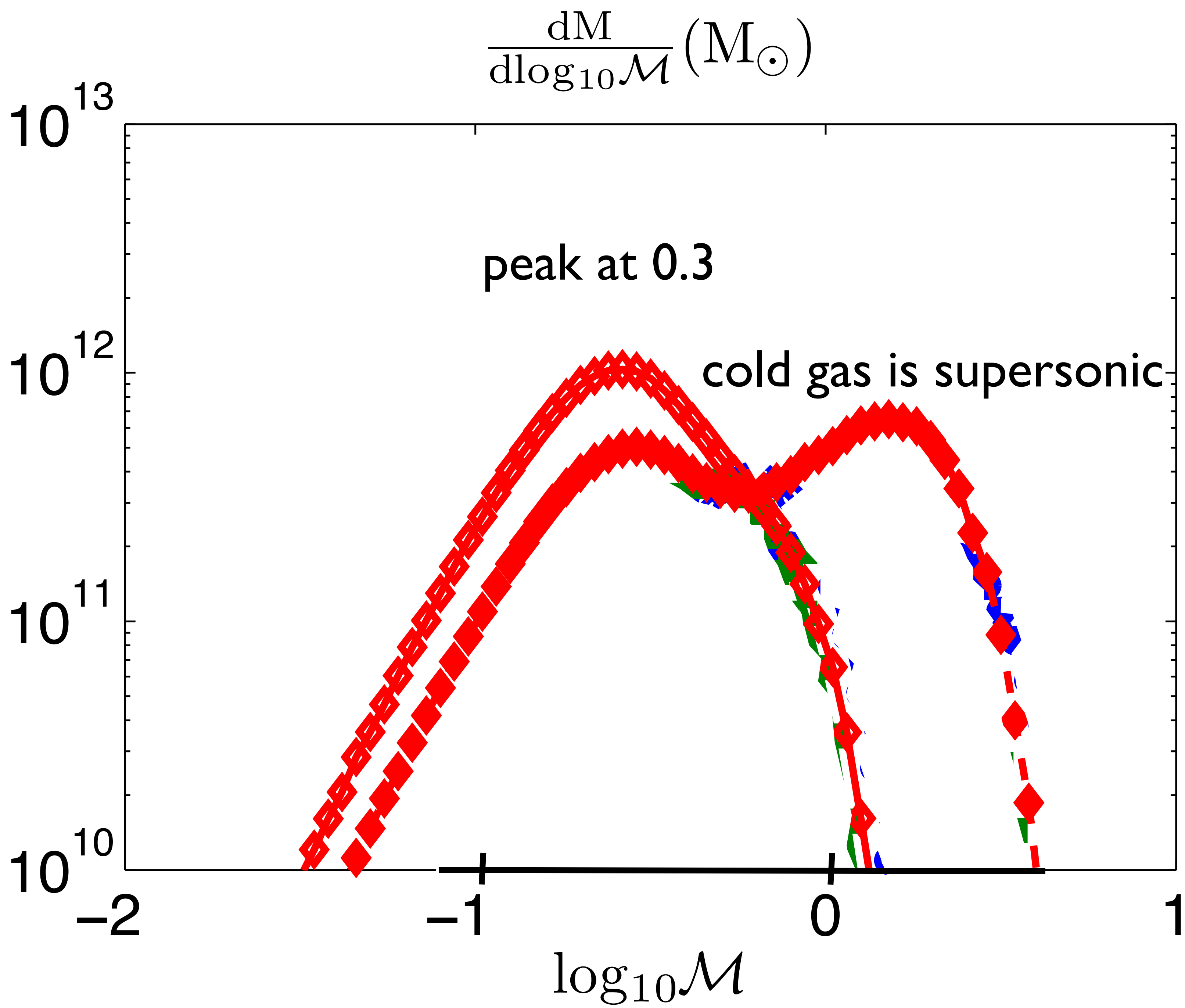
outer region is bubble material or hotter dilute regions of ICM

turbulence mixes the hotter gas with the denser core

$$\langle F \cdot v \rangle = \langle \mathcal{L} \rangle$$

still, but lower velocities because the dilute outer regions have longer cooling times & larger volume

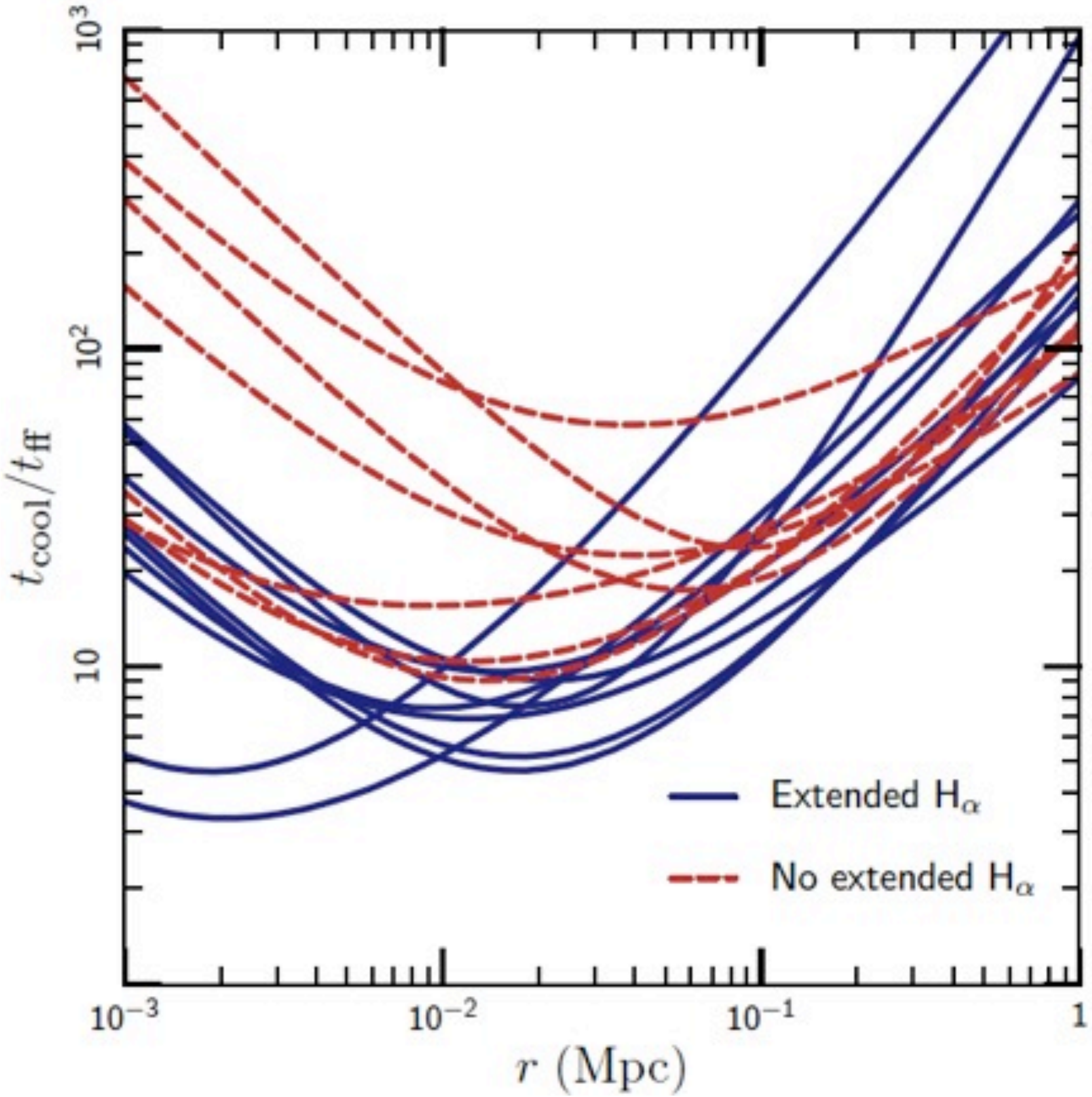
Mach no. with mixing



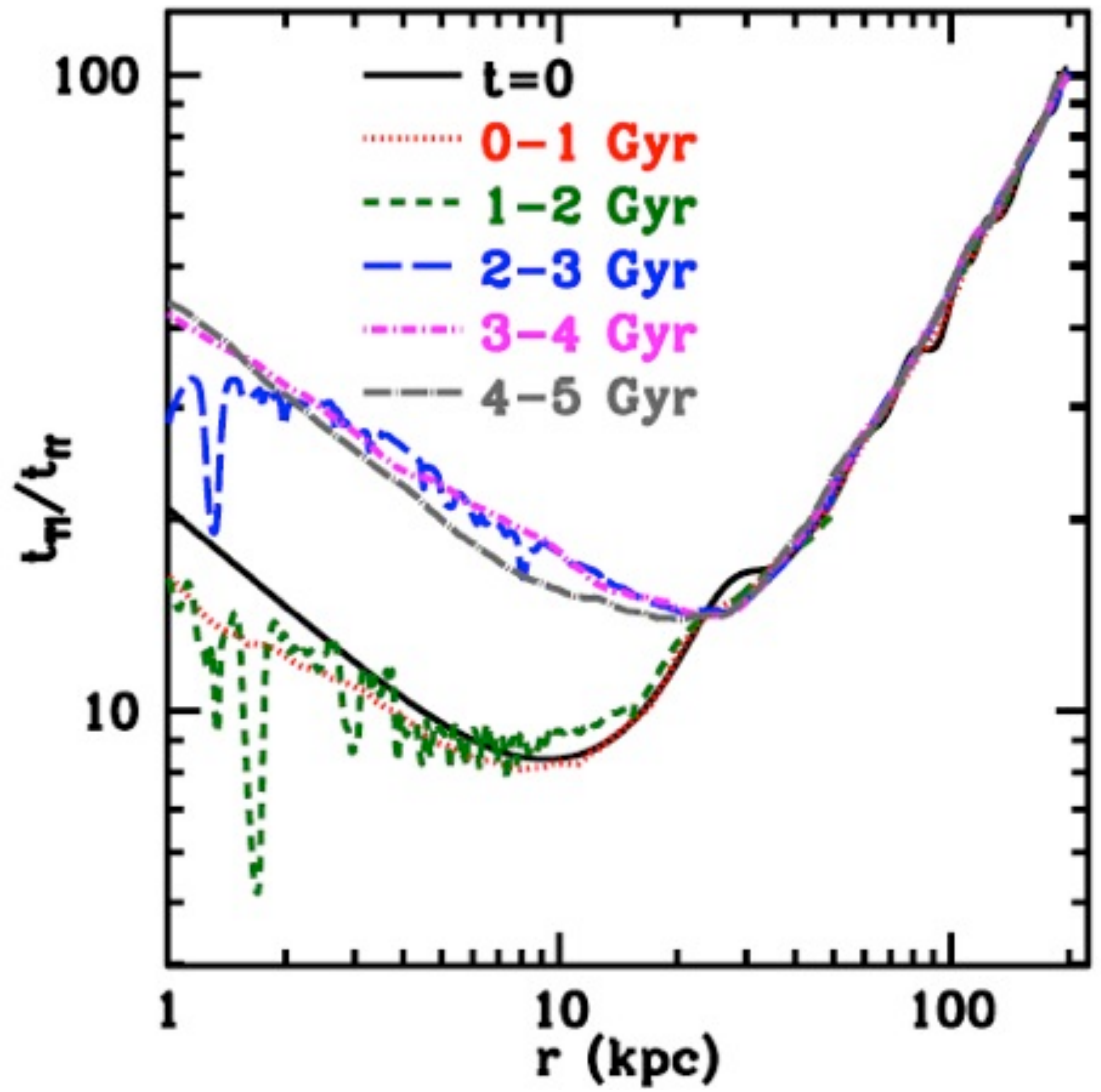
mixing gives a Mach number consistent with observations of cool core clusters

Data=>$t_{cool} \approx t_{TI}$

[McCourt et al. 2012]



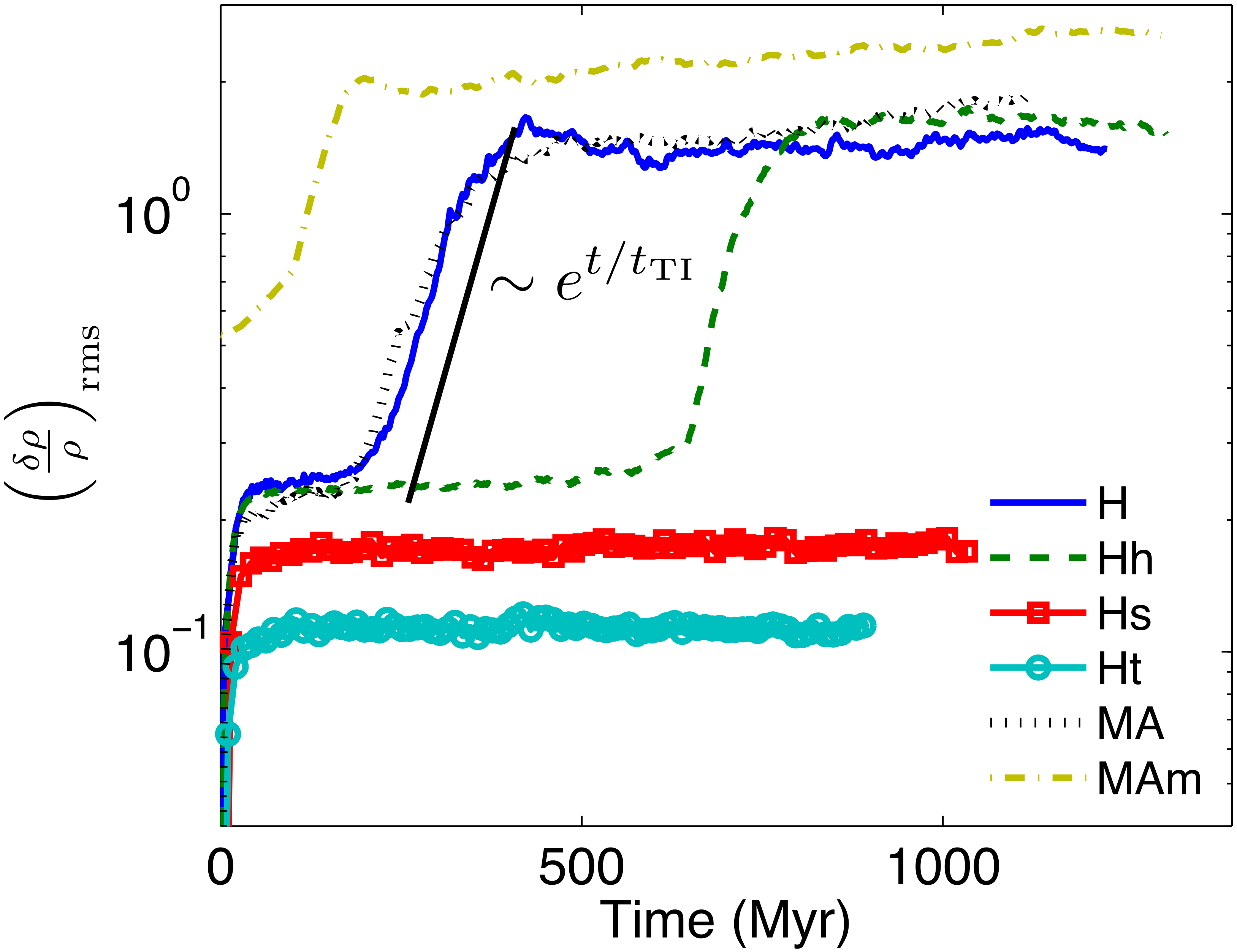
[Sharma et al. 2012]



$$q^+ \propto n^\alpha$$

$t_{TI} \approx t_{cool}$ or $\alpha \approx 0$ for observations to match idealized simulations

Measuring t_{TI}



measure the growth rate of density perturbations

measuring growth rate gives tTI and the density dependence of microscopic heating

$$q^+ \propto n^\alpha$$

α≈0 needed for agreement with observations

Measuring t_{TI}

Label †	Res.	L_x (kpc) $= L_y = L_z$	$\beta^{\ddagger}$	$\frac{\langle \text{heating} \rangle}{\langle \text{cooling} \rangle}$	$t_{\rm TI}$ range (Myr)	$\alpha^{\dagger\dagger}$ range
H*	128^3	40	...	1.0	59 to 116	-0.8 to 0.6
Hh	256^3	40	...	1.0	52 to 132	-1.2 to 0.7
Ht	128^3	40	...	1.0	...	...
Hs	128^3	20	...	1.0	...	...
Hl	128^3	80	...	1.0	100 to 117	0.3 to 0.6
Hm	128^3	80	...	1.0	66 to 87	-0.5 to 0.1
Hha	256^3	40	...	no cooling	...	...
M	128^3	40	100	1.0	67 to 69	-0.5 to -0.4
MA	128^3	40	100	1.0	73 to 93	-0.3 to 0.2
MAm	128^3	80	100	1.0	66 to 87	-0.5 to 0.1

$\alpha \approx 0$ agrees with the range observed from TI growth rate

$q^+ \propto n^\alpha$ too simplistic

Conclusions

- aniso. conduction much closer to runs without conduction
- *isotropic* conduction suppresses cold gas
- Turbulent heating is ruled out
- Turbulent mixing is viable
- $\alpha \approx 0$ for turbulent heating/mixing

Thank You!