Dynamics & Energetics of the ICM

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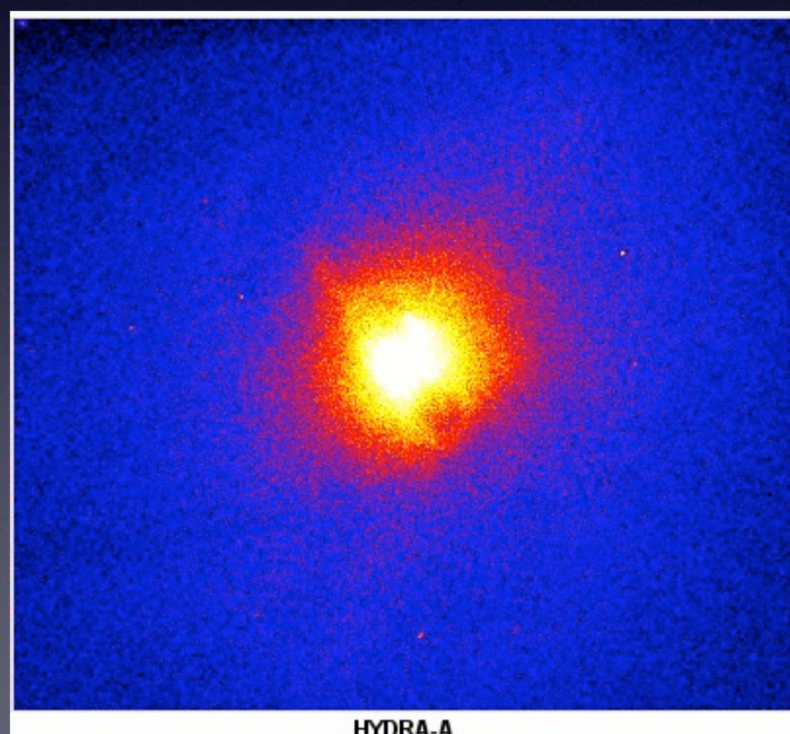
[+Ben Chandran, Eliot Quataert, Ian Parrish]



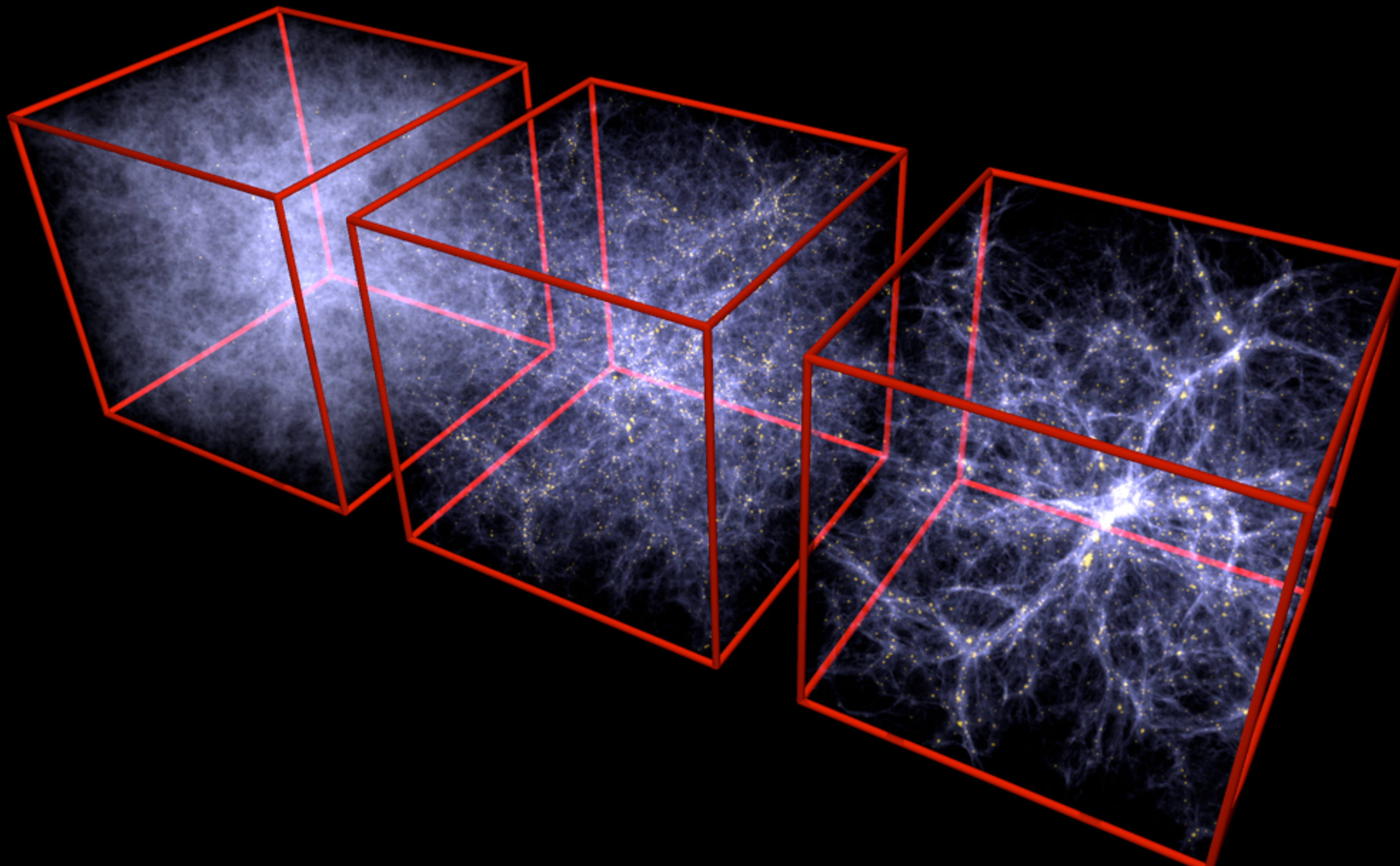
Outline

- Clusters: heating of ICM is required!
- conduction is along B field
- Mixing in the ICM: free vs. forced convection
- Thermal Instability in the ICM
- Implications

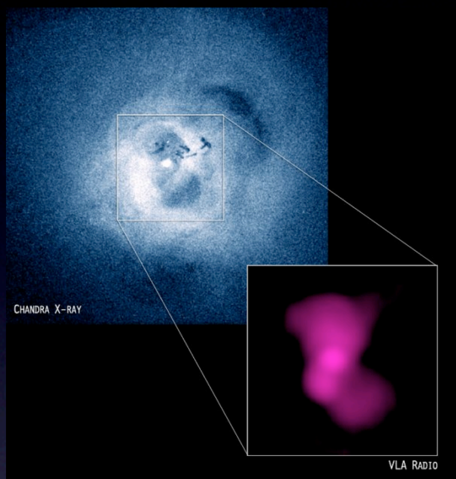
What is a cluster?

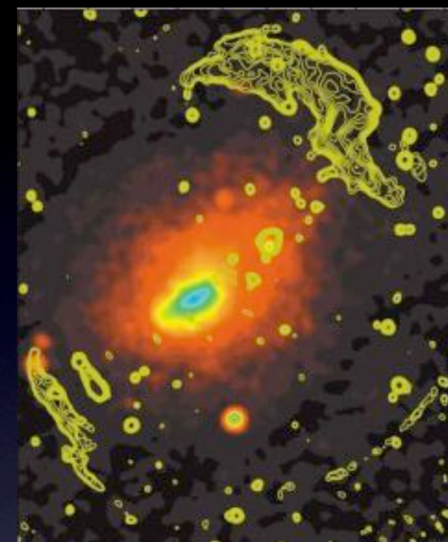
- DM halos > $10^{14} M_{\odot}$; most massive bound structures; structure formation in ΛCDM
- ~10% ICM, few% galaxies
- T$\gtrsim$1 keV =>X-rays via ff; R~few Mpc
- DM self-similarly (~NFW); gas does not! heating & cooling
- dlnn/dlnM(z,l) => $\sigma_8, \Omega_m, \Omega_\Lambda$; but accurate M

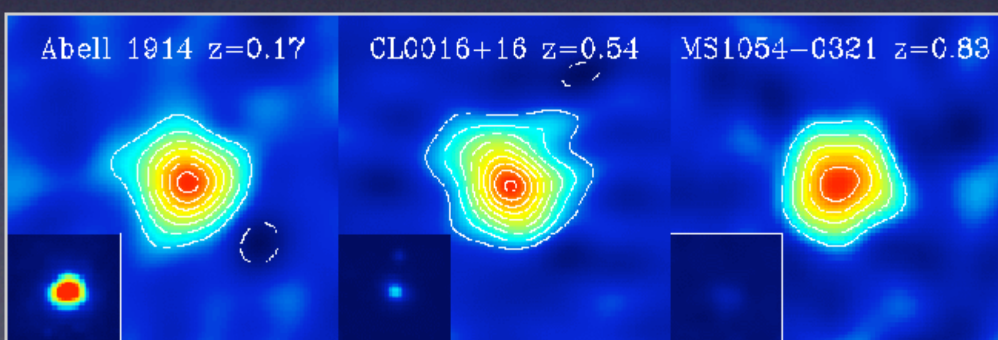
Structure Formation

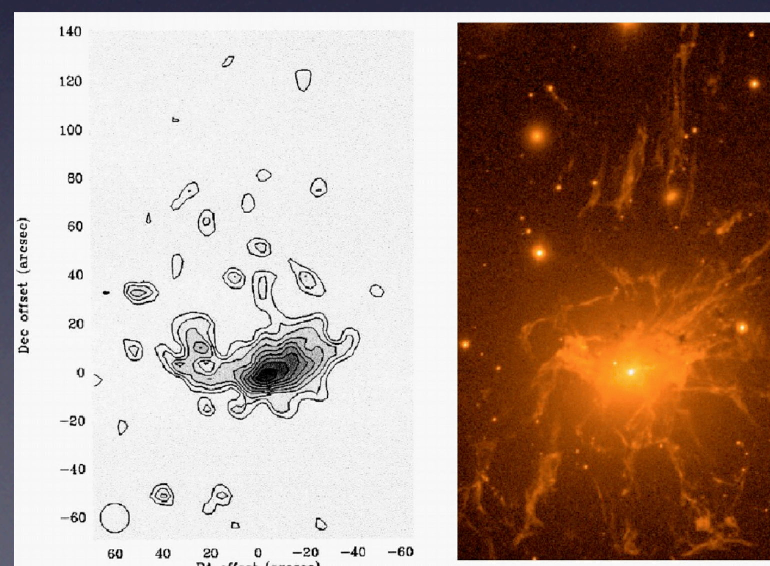


Observational Windows







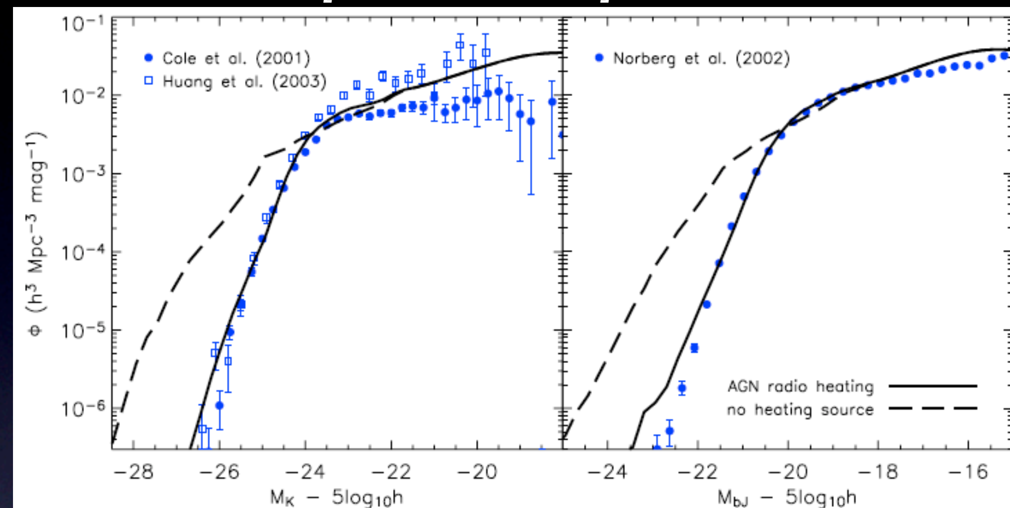


Puzzles

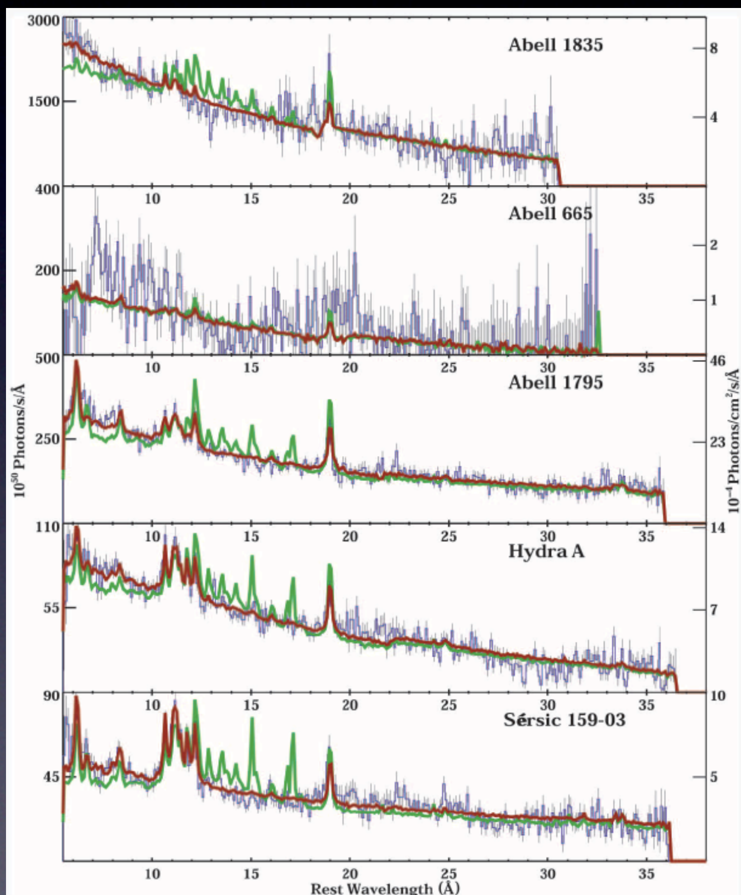
- overcooling problem: observed star formation too small!
- cooling flow problem: no catastrophic cooling; $t_{cool}<t_H$
- Downsizing: lack of massive spirals at z=0
- basically observed cooling (mainly in core) << expected

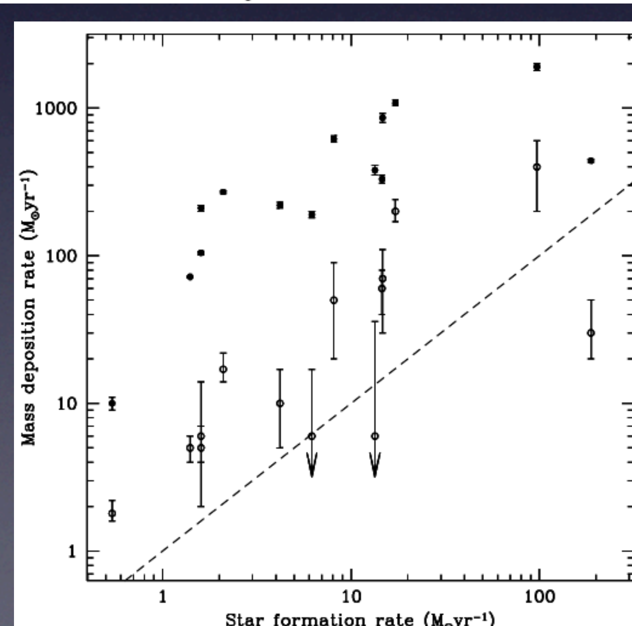
Evidence for heating

[Croton et al. 2003]



[Peterson et al. 2003]





[O'Dea et al. 2008]

Solution

Feedback

supernova winds (not enough)
quasar (only for short time)
AGN bubbles (anisotropic jets)
cosmic rays (isotropic? Fermi?)
sound waves (amplitude, viscosity?)
...

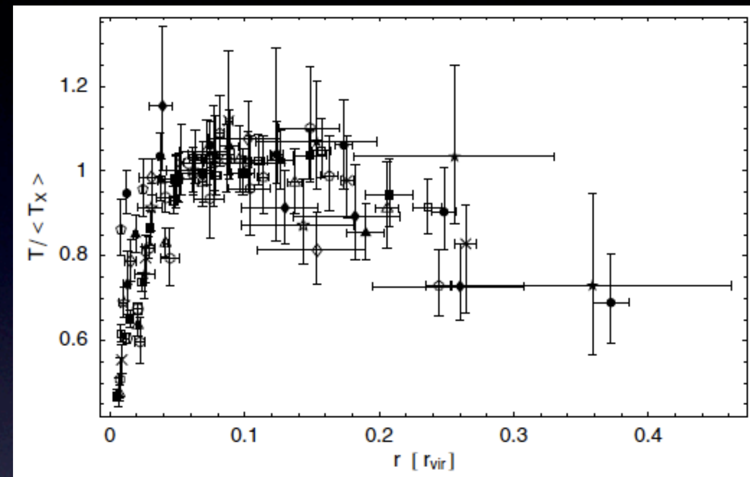
Non-feedback

thermal conduction (globally unstable, HBI, not enough for all)
galactic wake turbulence (not volume filling, efficiency?)
DM clumps (no observational constrains, efficiency?)
preheating (no justification, SF history?)
...

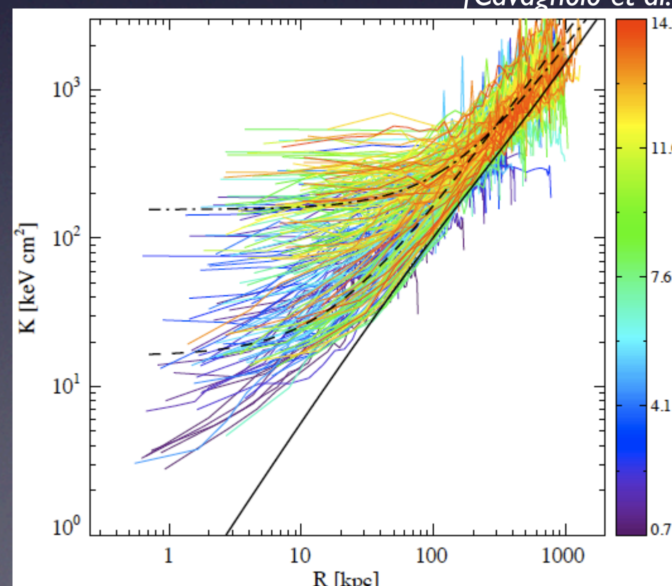
Typical (relaxed) Cluster

- rough hydrostatic equilibrium
- $T \sim T_v \sim$ keV => X-rays
- T, L_X=>M of most massive halo=>cosmology
- entropy a fn. of halo assembly
- lower entropy accreted earlier=>s inc. w. r (unlike stars)

[Piffaretti et al.]

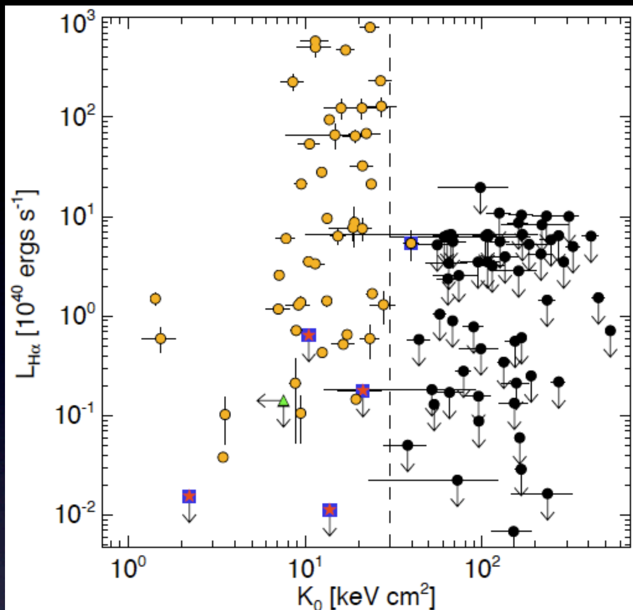


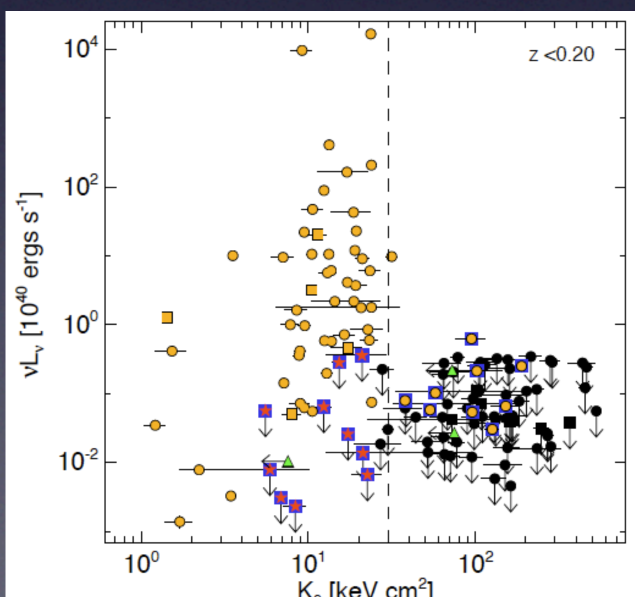
[Cavagnolo et al.]

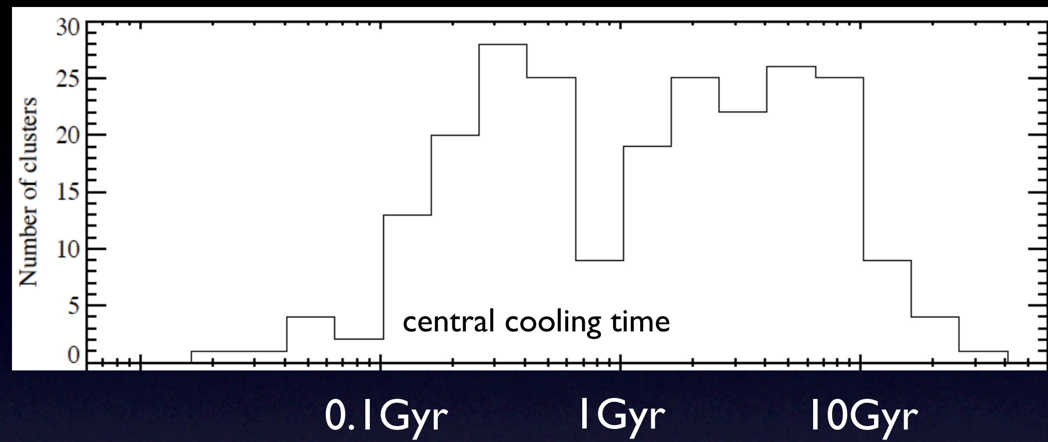


Bimodality

[Cavagnolo et al.]

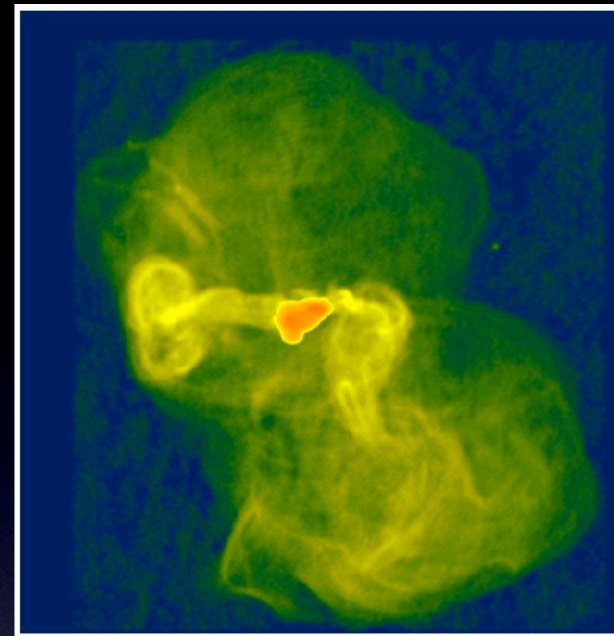






- cool-core vs. non-cool core
- entropy & cooling
- $j \sim n^2 T^{1/2}$ => inner r cool!

AGN Feedback



Pros:

-Energetically sufficient
-self-adjusting; explains correlations
-kinetic feedback for low dM/dt (radiatively inefficient accretion)
-jets/radio bubbles seen for large L_X

Cons:

-anisotropic jets/bubbles; isotropic heating?
-exact mechanism? cosmic rays? turbulence?
-how are bubbles blown/disrupted? is microphysics important?
-simulations not there yet!

Transport in the ICM

-thermal conduction is important: $t_{cond} \lesssim t_{buoy} \lesssim t_{cool}$

-mean free path >> Larmor radius => parallel transport

-conduction is along B-lines => buoyancy instabilities (HBI/MTI)

g ↓ ↑ ∇T

cluster core

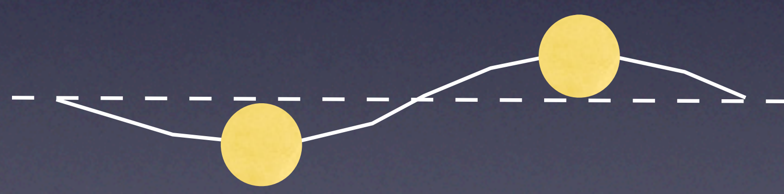
-magnetic field wants to be ⊥ to gravity *[Quataert]*

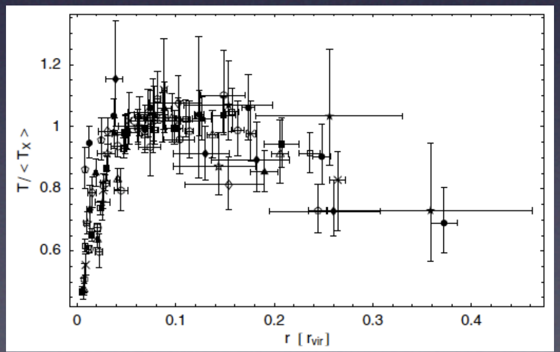
-shut off conduction *[Parrish et al.]*

-small velocities enough to rearrange B

g ↓ ↓ ∇T

beyond core

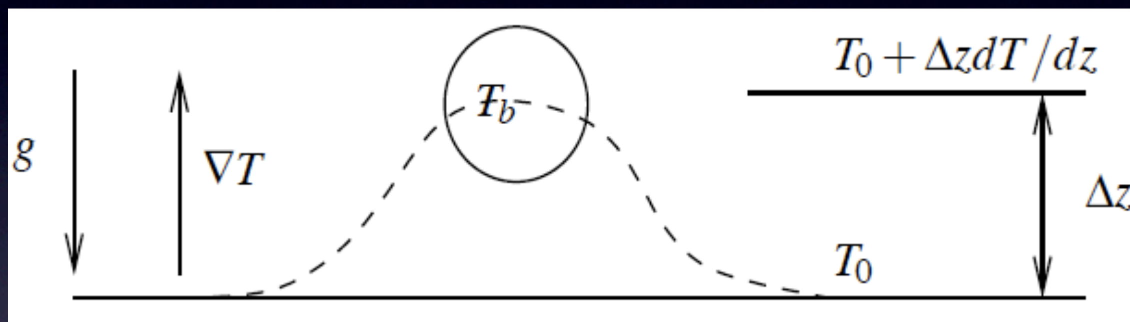




-magnetic field wants to be || to gravity *[Balbus]*

Anisotropically conducting plasma is convectively stable!

[PS et al., arxiv-0909.0270]



-buoyant restoring force ≈ $\rho g \Delta z$ dlnT/dz ($\rho g \Delta z$ dlnS/dz for convectively stable adiabatic fluid)

-similar restoring force for dT/dz<0!

-HBI/MTI are buoyancy instabilities *not* convective instabilities

Mixing in the ICM

conduction along B

adiabatic

[PS et al.]

For movies see: http://astro.berkeley.edu/~psharma/clustermovie.html

-adiabatic CRs with $ds/dr<0$ built up in time

-plasma becomes convectively unstable for $pcr/p \gtrsim 0.2$

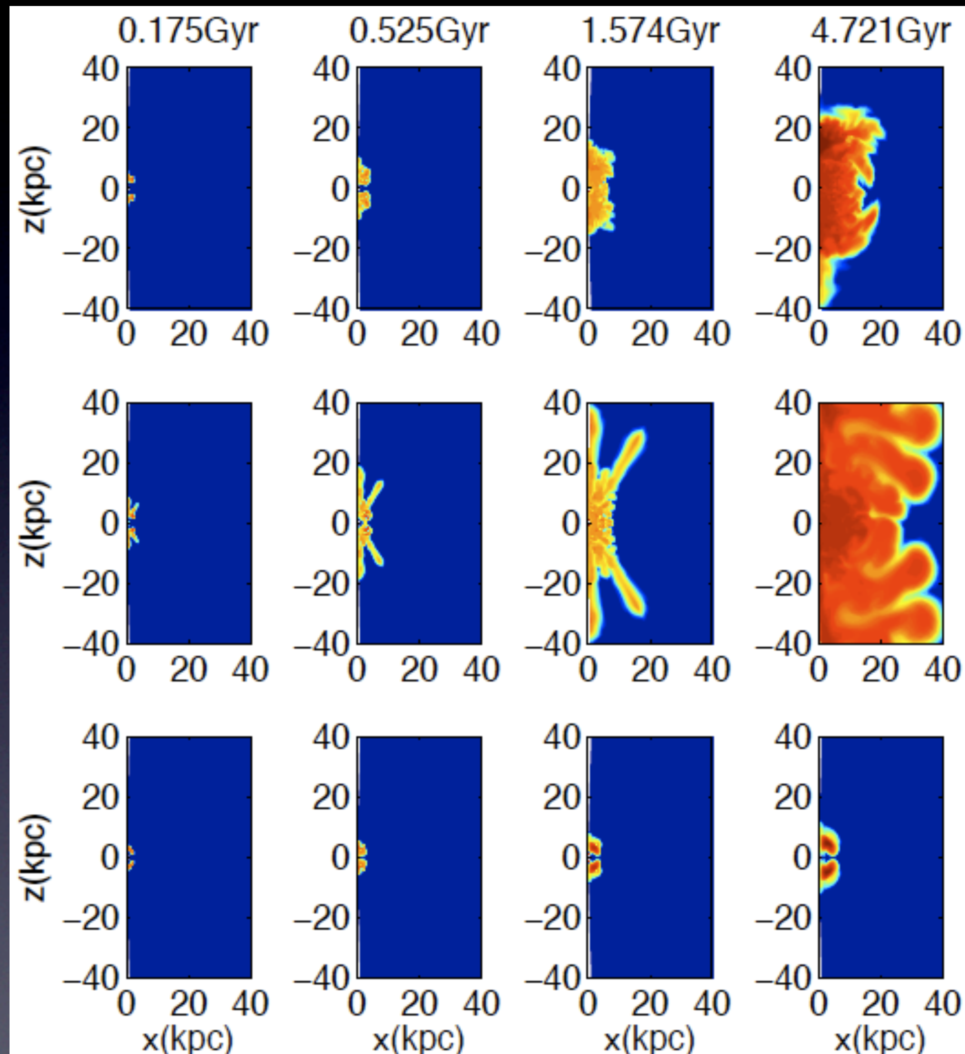
-easier to mix a conducting plasma than an adiabatic one!

metallicity

conduction along B

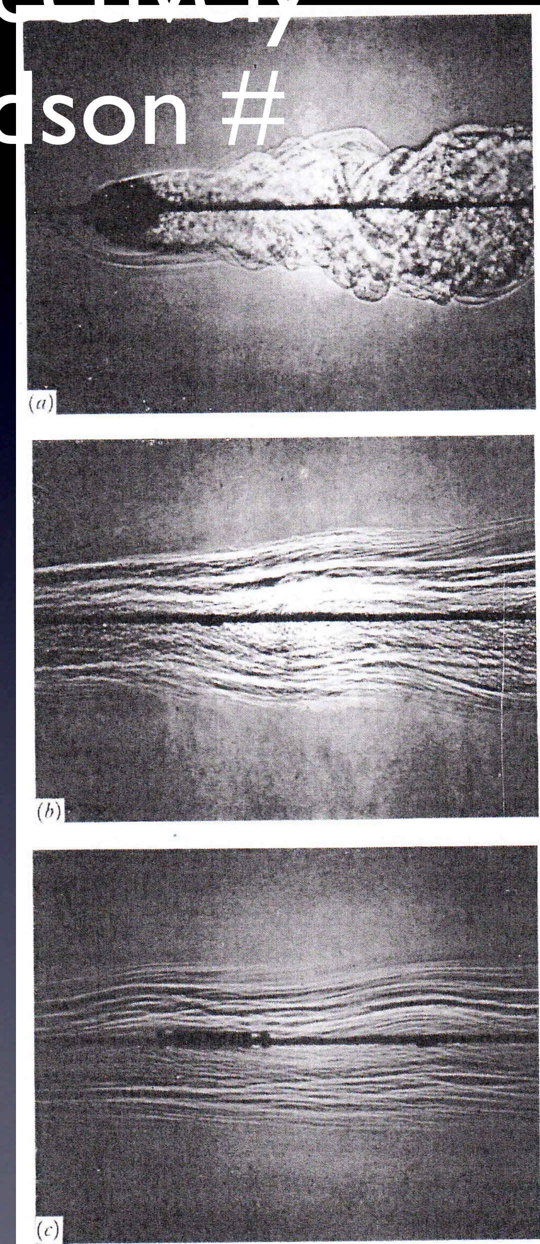
isotropic conduction

adiabatic



-easiest to mix isotropically conducting plasma!

Turbulent mixing in a convectively stable atmosphere: Richardson



Ri = stable buoyancy force/turbulent force
$\approx$[gdlnS/dz]/$|\nabla u|^2$ for adiabatic plasma

Ri$\gtrsim$1 buoyant stabilization; $\lesssim$1 turbulent

[Turner1973]

Turbulent mixing w. conduction along B: Richardson

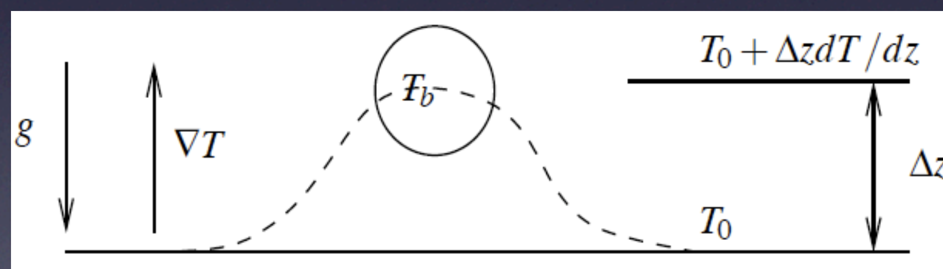
Ri = stable buoyant force/turbulent force

≈[gdlnT/dz]/$|\nabla u|^2$ for aniso. cond.

≈[gdlnS/dz]/$|\nabla u|^2$ for adiabatic

≈0 for iso. cond.

$$Ri \approx 3 g_{-8} r_{10} \frac{d \ln T / d \ln r}{u_{100}^2}$$



-vigorous mixing w. iso. conduction; dlnS/dz≈4dlnT/dz=>more mixing w. aniso. cond.

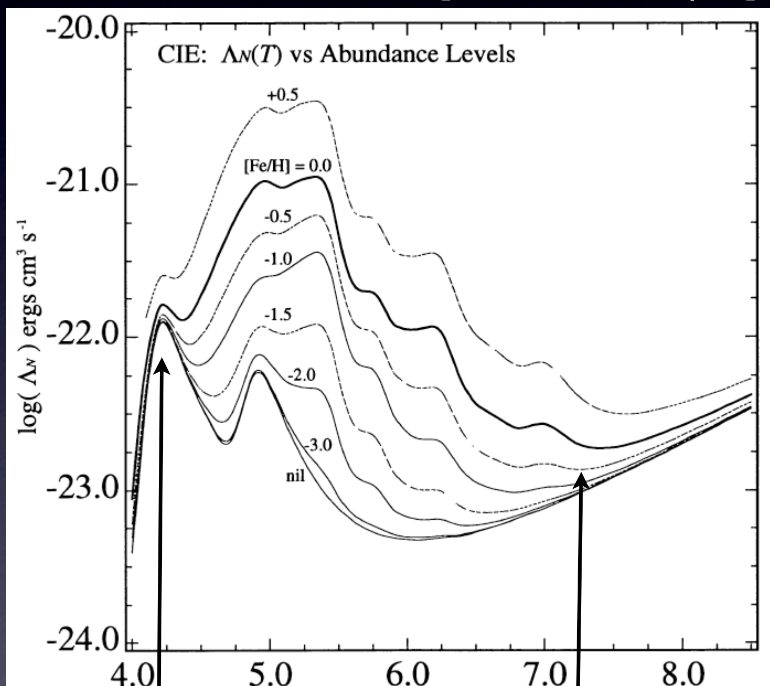
-strong mixing w. ~100 km/s turbulent velocities

Implications for ICM

- easier to redistribute energy in θ, Φ
- 100 km/s stirring is enough to isotropize B-fields => conductivity~Spitzer/3 (negligible conduction for smaller stirring!)
- source of turbulent motions: jets/bubbles, galaxy wakes,...

Thermal Instability

[Sutherland&Dopita]



$\log_{10} T$

thermally stable Hα filaments

hot ICM is thermally unstable;
like the hot phase of the ISM

$$\frac{d\ln(\Lambda/T^2)}{d\ln T} > 0$$ for isobaric thermal stability

$$\frac{d\ln\Lambda}{d\ln T} > 0$$ for isochoric thermal stability

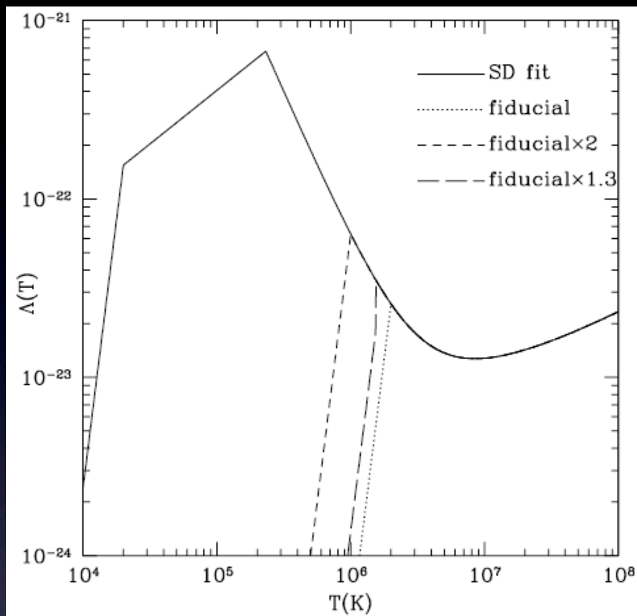
valid when $p_{cr}/p \gg 1$ or $\beta \ll 1$

TI stabilized by conduction at scales smaller than $L_F \approx 10$ kpc $T_{keV}^{7/4} n_{0.1}^{-1}$

Conduction along B => filaments along B!

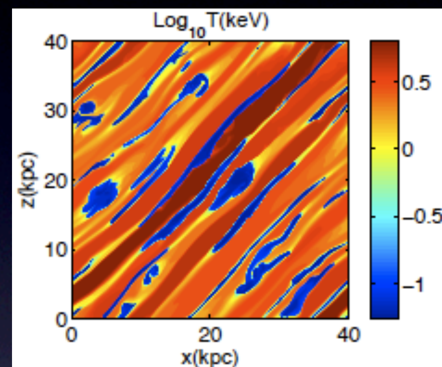
Temperature

modified c.f.

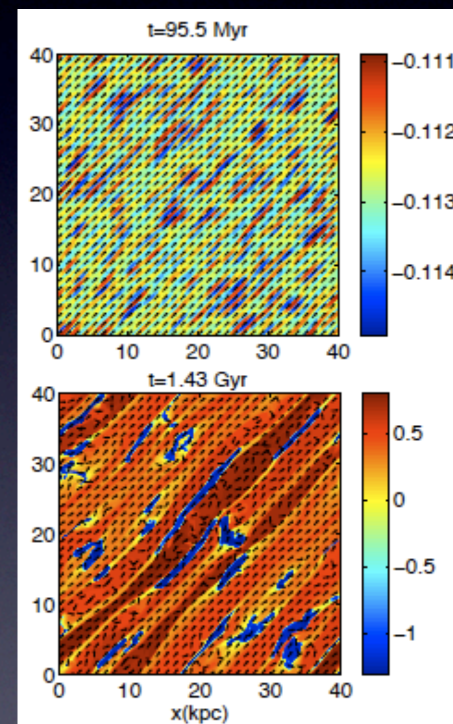


CRs may help explain 10s of kpc long filaments!

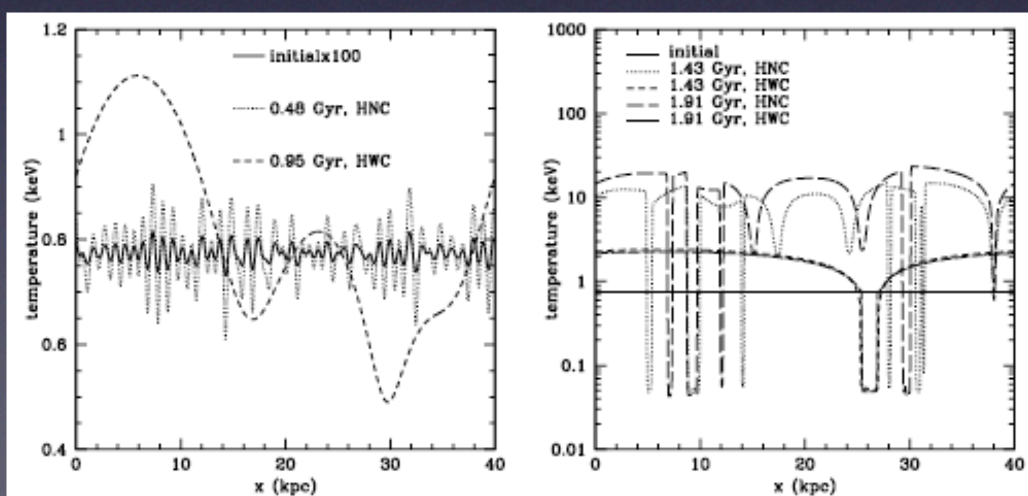
w. CRs



no CRs



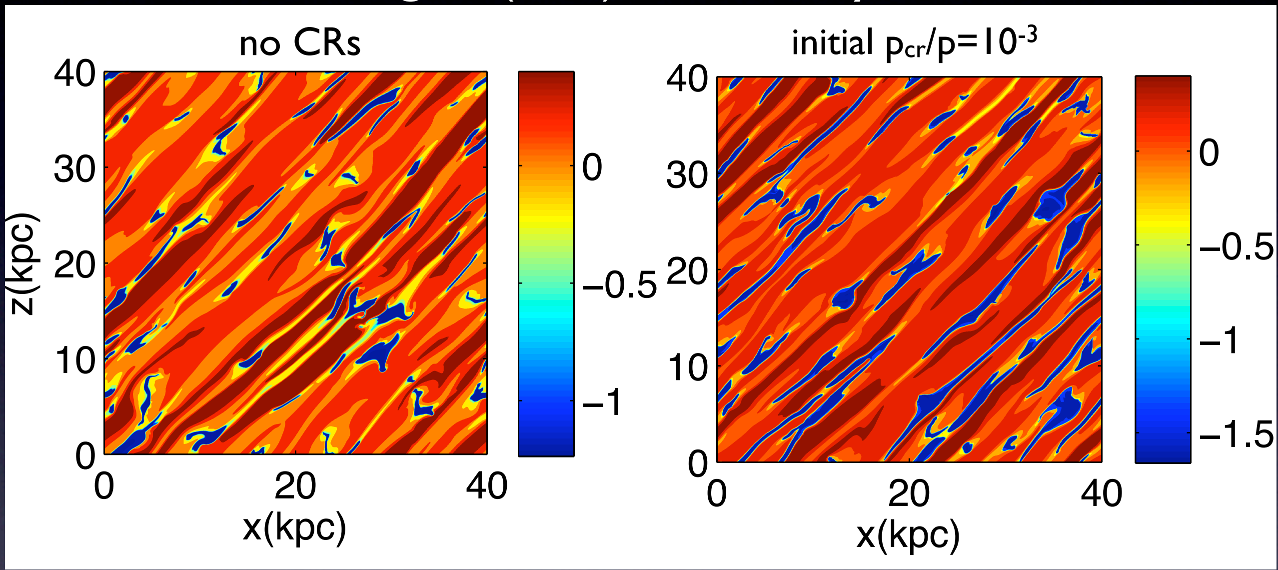
1D



need to resolve L_F !

CRs prevent || compression

$Log_{10}T$(keV) at 0.95 Gyr



-CRs needed to explain large ΔE emission lines *[Ferland et al.]*

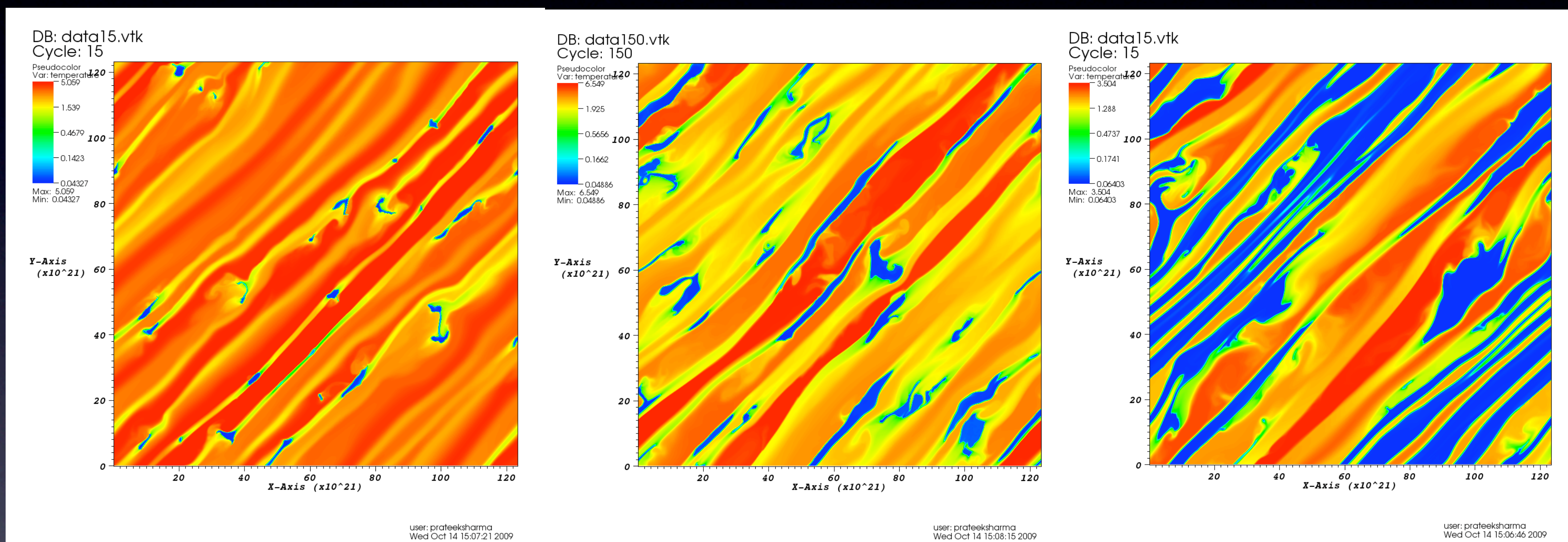
-lack of star formation in molecular filaments!

-10^9-$10^{10}M_\odot$ molecular gas *[Salomé et al.]*

-Are CRs and B fields preventing gravitational collapse?

Is heating≈cooling?

t=1.43Gyr



yes! statistically over many cooling times, else either hot/cold phase

Implications

- ICM easier to mix than adiabatic sims. suggest => easy to redistribute jet/bubble kinetic energy
- ICM is convectively stable! Richardson# criterion
- how ICM is heated isotropically still unknown!
- Hα, molecular filaments due to TI; elongated because of anisotropic conduction (+CRs??); suppressed star formation
- not a cooling flow but heating≈cooling & TI