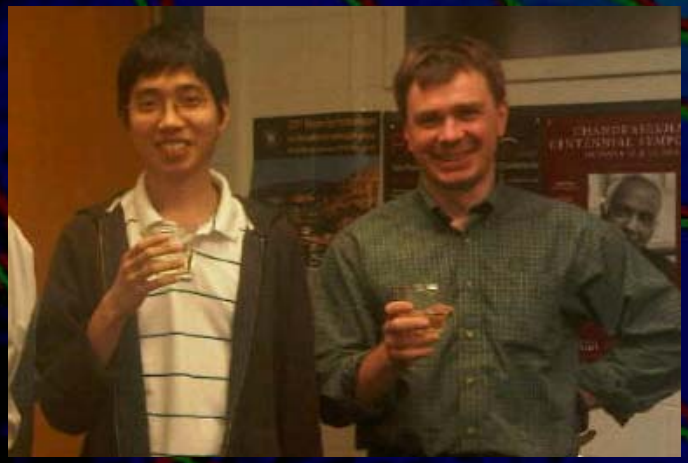
Constraints on the amount of turbulence and dissipation from the ellipticity of intracluster medium

Andrey Kravtsov

Department of Astronomy & Astrophysics
Kavli Institute for Cosmological Physics
The University of Chicago

with



Erwin Lau
U.Chicago

Alexey Vikhlinin
SAO/Harvard

Daisuke Nagai
Yale

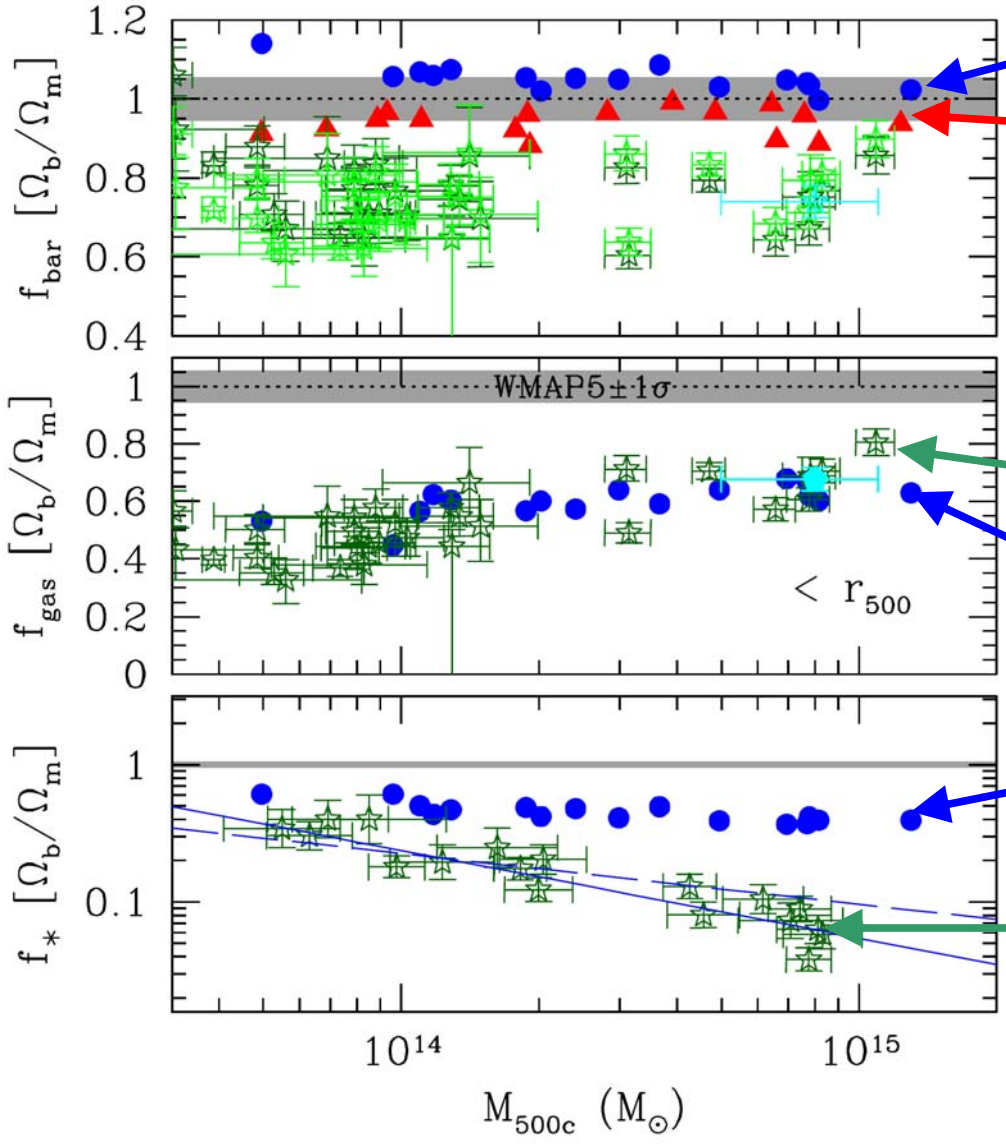
Andrew Zentner
U.Pitt

Testing two generic predictions of cosmological simulations of cluster formation

- Simulations generically *predict large fraction of baryons (30-50% within R_{vir}) cooling and converting into stars*. This is not confirmed by direct observations, but then there is baryon fraction puzzle. So this is worth checking using other means.

- Simulations *predict ubiquitous subsonic turbulence*. Little observational evidence for it so far. So any way to probe for its presence is very welcome!

the baryon fraction puzzle



***mass** within radius enclosing overdensity of 500 times the critical density $\rho_{crit}(z)$*

bar fractions in simulations with cooling

bar fractions in simulations without cooling

[high-resolution Eulerian Adaptive Mesh Refinement N-body+gasdynamics simulations; Nagai, Kravtsov, Vikhlinin 2007]

Observed gas fractions (Chandra and XMM)

gas fraction in simulations (runs with cooling)

stellar fractions in simulations with cooling

Observed stellar fractions (Gonzalez et al. 2007 Giodini et al. 2009)

Ettori 2003, McCarthy et al. 2007, Kravtsov et al. 2009 (arXiv/0903.0388)

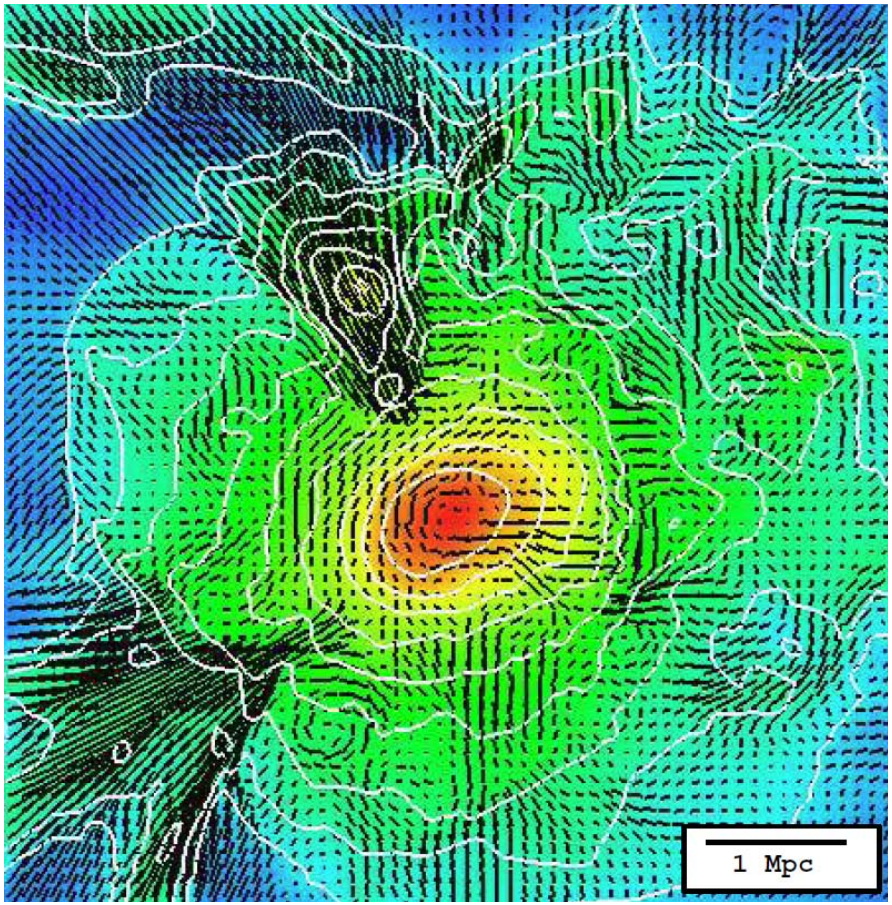
Testing two generic predictions of cosmological simulations of cluster formation

- Simulations generically *predict large fraction of baryons (30-50% within R_{vir}) cooling and converting into stars*. This is not confirmed by direct observations, but then there is baryon fraction puzzle. So this is worth checking using other means.

- Simulations *predict ubiquitous subsonic turbulence*. Little observational evidence for it so far. So any way to probe for its presence is very welcome!

simulations predict ubiquitous random gas motions in the ICM

Slice through gas density of ICM of a cluster formed in a cosmological simulation; short lines show magnitude and direction of gas velocity

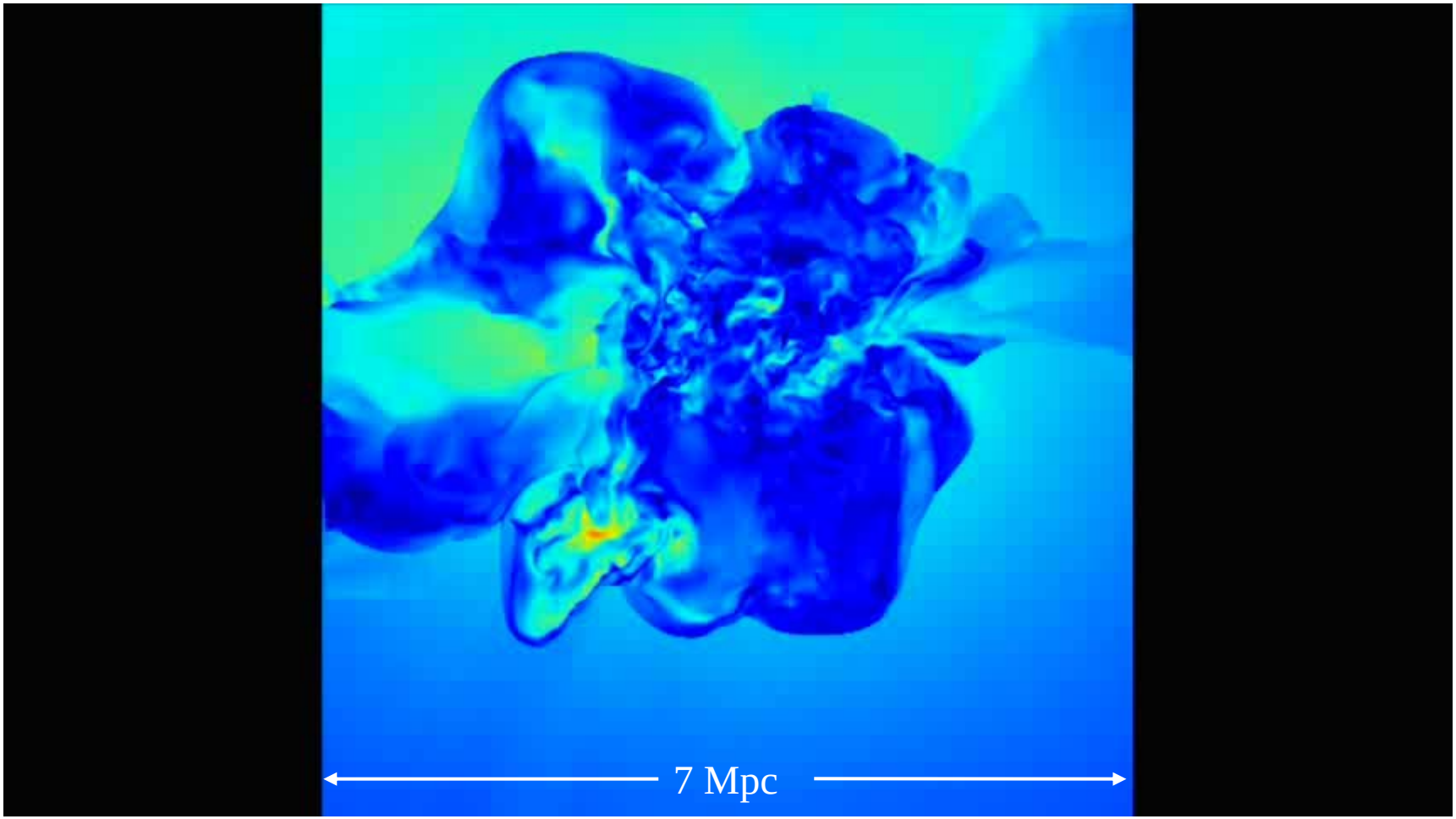


Norman & Bryan 1999

e.g., Evrard 1990; Norman & Bryan 1999; Nagai et al. 2003; Sunyaev et al. 2003; Rasia et al. 2004, 2006; Dolag et al. 2007; Vazza et al. 2008; Lau et al. 2009

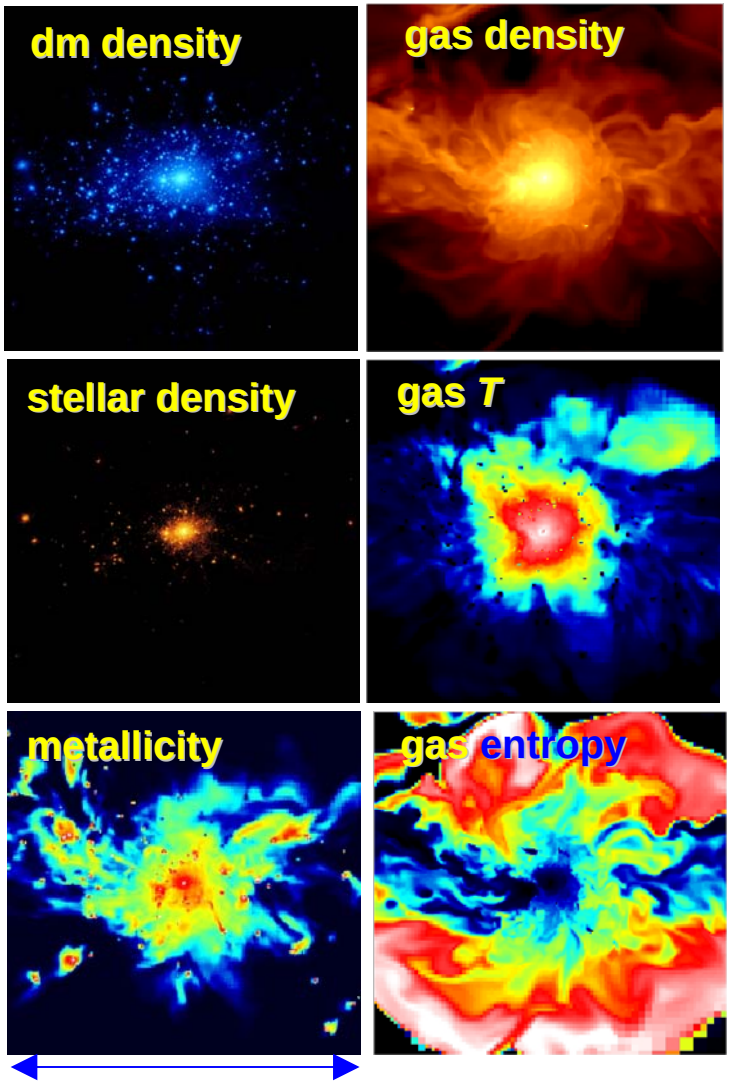
simulations predict ubiquitous random gas motions in the ICM

color = absolute value of gas velocity



Movie courtesy of Franco Vazza http://www.ira.inaf.it/~vazza/movies.html

simulated cluster sample



16 individual galaxy clusters simulated with and without cooling masses from 8×10^{13} to $10^{15}h^{-1}$Msun

Cosmological N-body+hydrodynamics ART code
(Kravtsov 1999, 2003; Kravtsov et al. 2002)
$m_{dm}=3\times10^{8}h^{-1}$ Msun, $m_{*}\sim10^{6\text{-}7}h^{-1}$ Msun
peak resolution ~ $2h^{-1}$ kpc
2-4 x 10^{7} mesh cells per cluster

Gasdynamics: Eulerian AMR (2^{nd} order Godunov)
N-body dynamics of DM and stellar particles

Radiative cooling and heating of gas:
metallicity dependent taking into account
atomic and molecular processes

Star formation using the Kennicutt (1998) recipe

Thermal stellar feedback

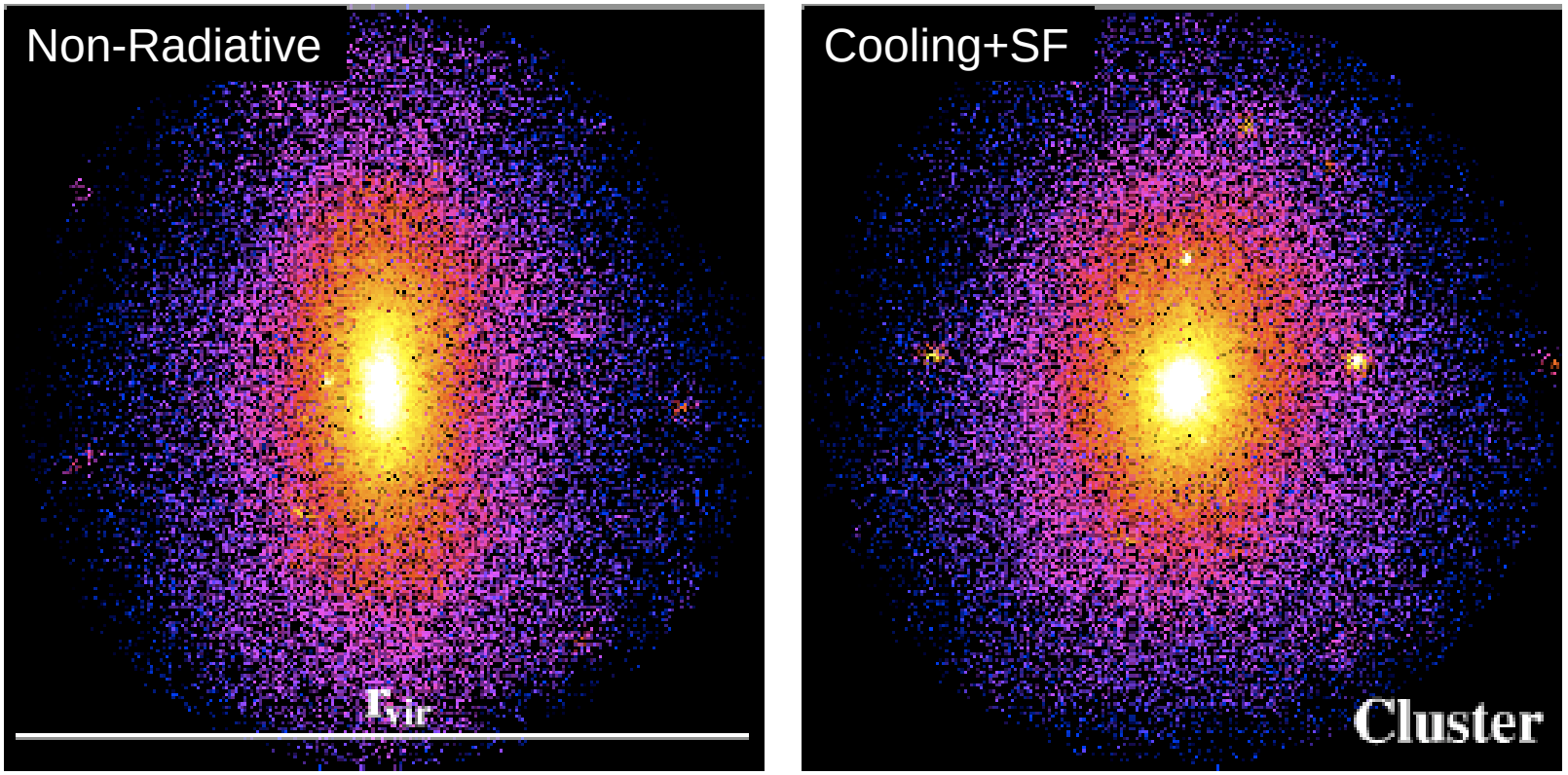
Metal enrichment by SNII/Ia + **Advection of metals**

Nagai (2006); Nagai, Kravtsov & Vikhlinin (2007)

Effects of dissipation on DM halo shape

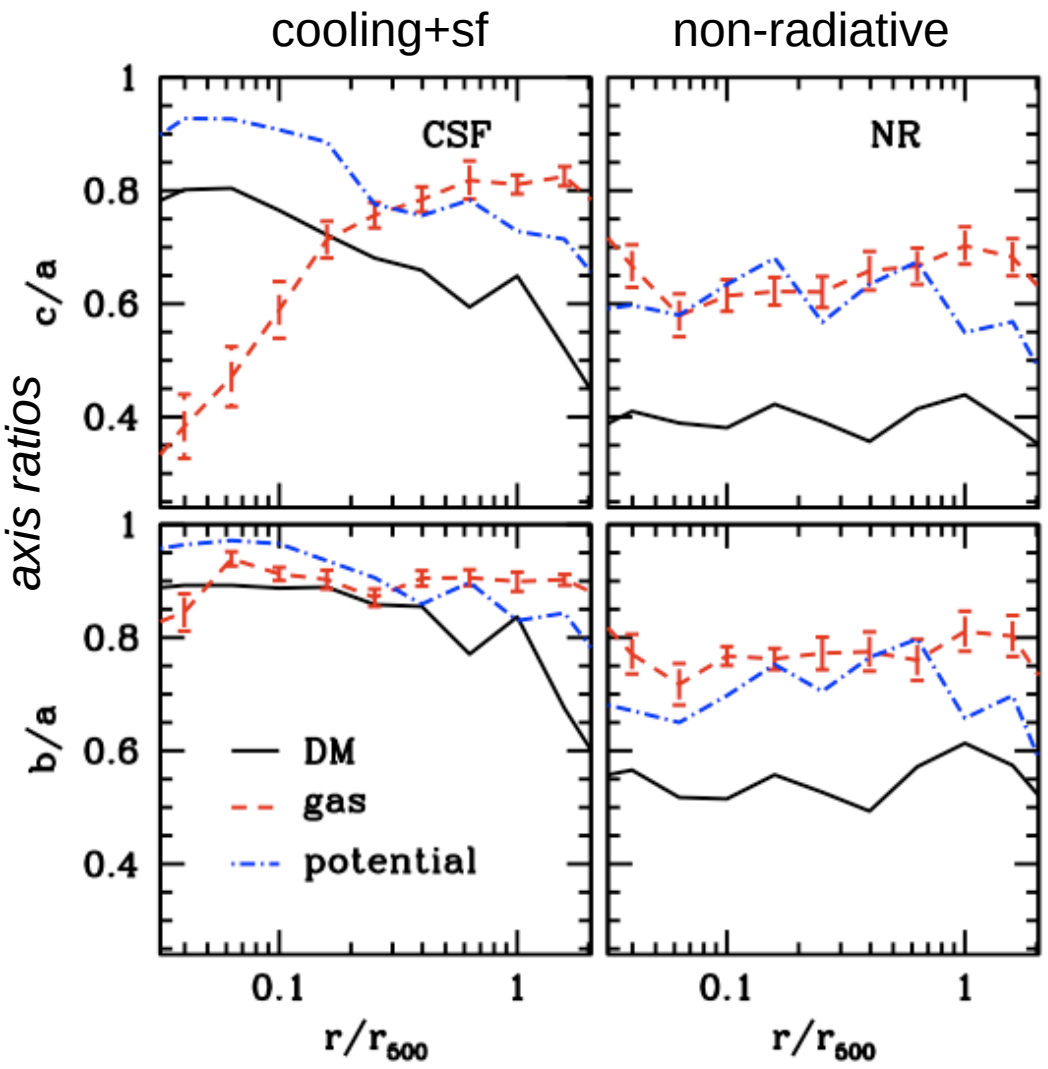
baryon condensation makes dark matter halos more spherical

halo simulated from the same initial conditions with and without baryon dissipation



e.g., Katz & Gunn '91, Evrard et al '94, Dubinski '94,
Kazantzidis et al. '04, Springel et al '04, Hayashi et al '07, Tissera et al '09

effect of dissipation on the 3d ICM shape



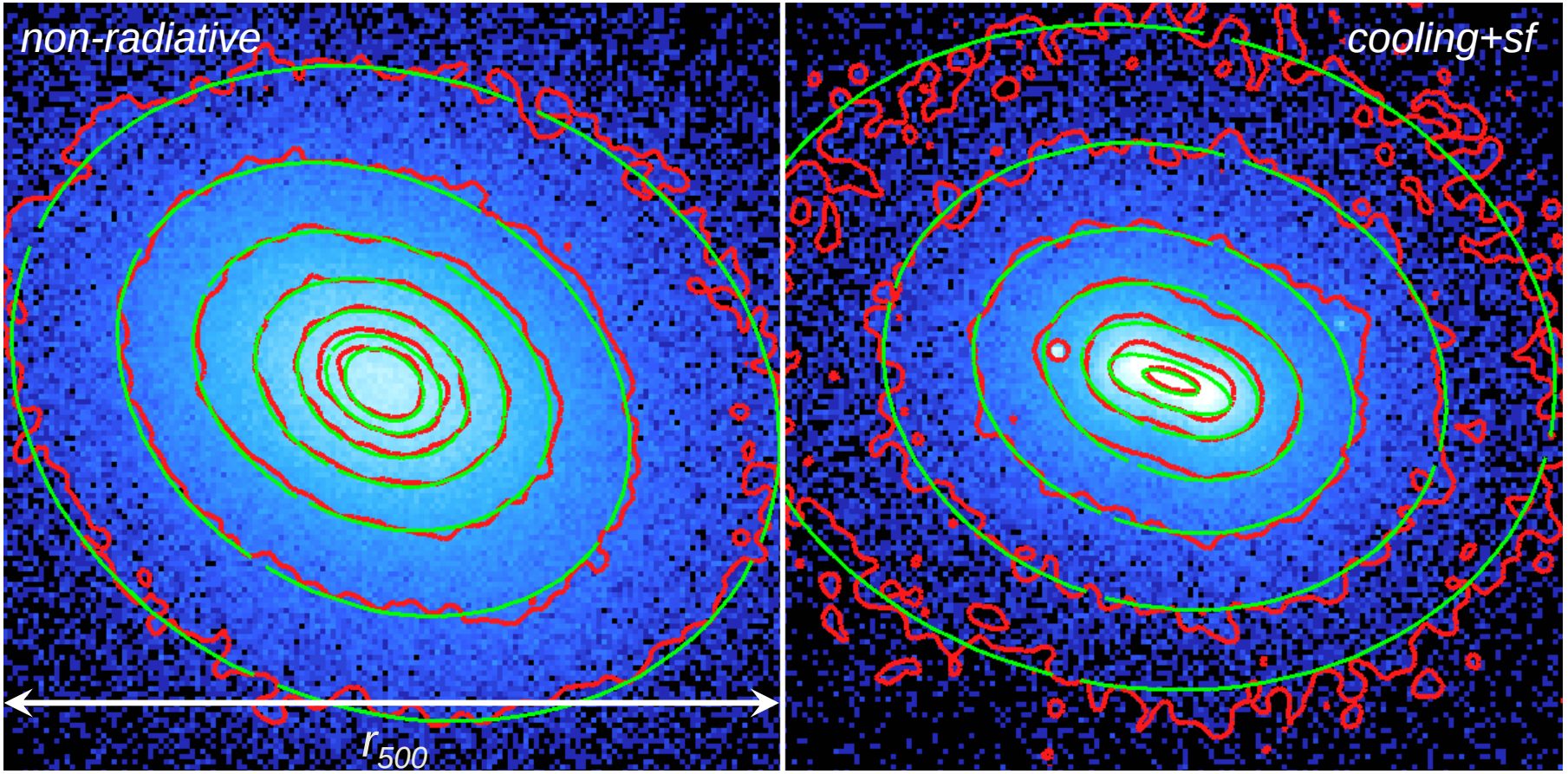
- Cooling: ICM is more spherical in the outer regions similar to DM
- ICM is more oblate in the inner regions
- Gas shape follows isopotential surfaces outside the cluster core

  (c.f., e.g. Buote & Tsai 94, 95, 96)

Lau, Nagai, Kravtsov & Zentner 2010, ApJ submitted (arXiv/1003.2270)

Mock Chandra maps

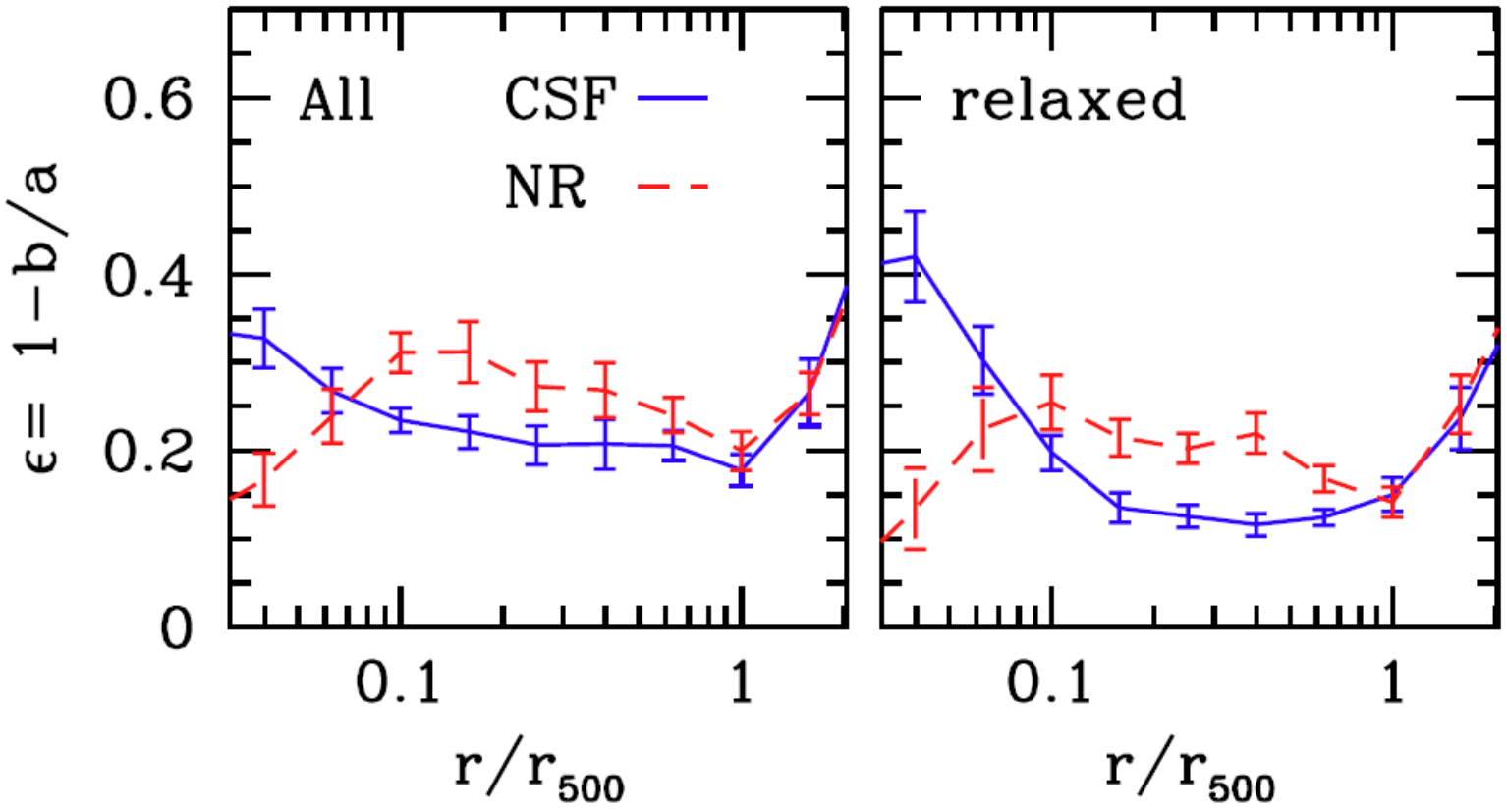
the differences in the ICM shape are still discernible in 2d X-ray emission



Lau, Nagai, Kravtsov & Zentner 2010, ApJ submitted (arXiv/1003.2270)

effect of cooling and gas turbulence on the observable ICM ellipticity

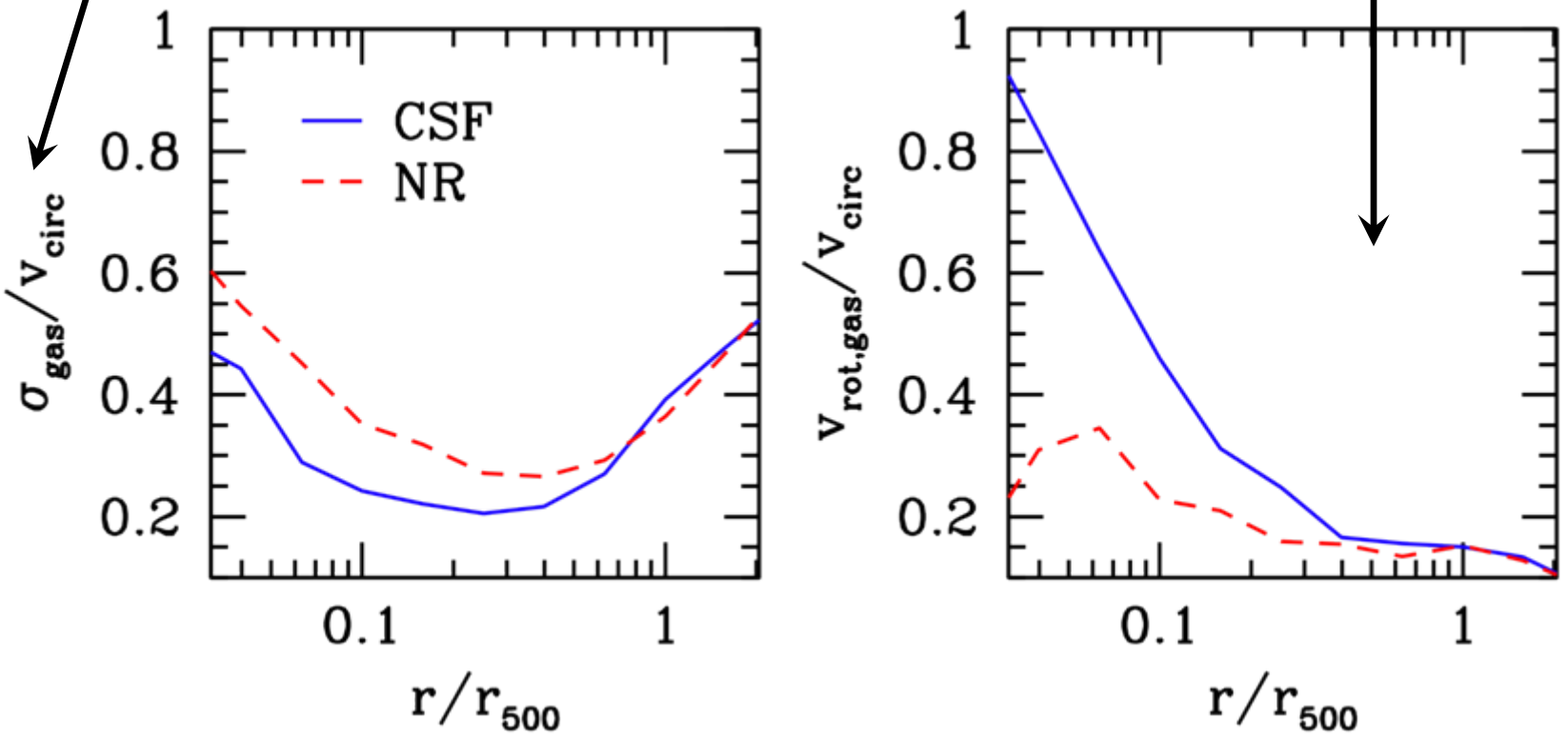
- at $0.1<r/r_{500}<1$ – the difference in the ICM shape between non-radiative and CSF simulations reflects the difference in DM halo shapes
- at $r/r_{500}<0.1$ – the difference is due to different gas motions (rotational motion in CSF, random, turbulent motion in the NR)



Lau et al. 2010, ApJ submitted (arXiv/1003.2270)

gas motions quantified

velocity dispersion of random component of gas motions and rotational velocity
Normalized to the circular velocity Vcirc(r)=sqrt(GM/r)

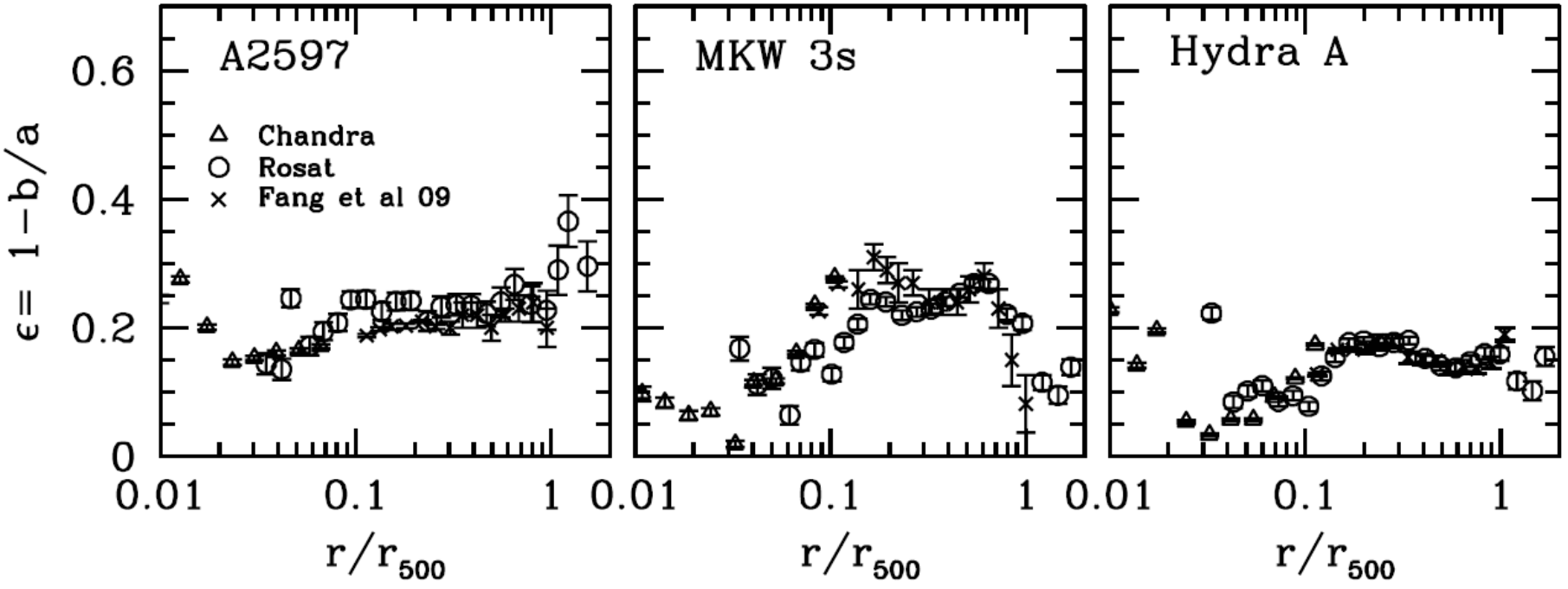


Lau et al. 2010, ApJ submitted (arXiv/1003.2270)

confronting simulations against observations

- Observations: sample of 31 local (z<0.1) clusters with ROSAT and Chandra images (25 of 31 clusters are classified as relaxed based on morphological appearance)
- Ellipticity profiles are constructed from the high-resolution Chandra images at small radii and ROSAT images at large radii

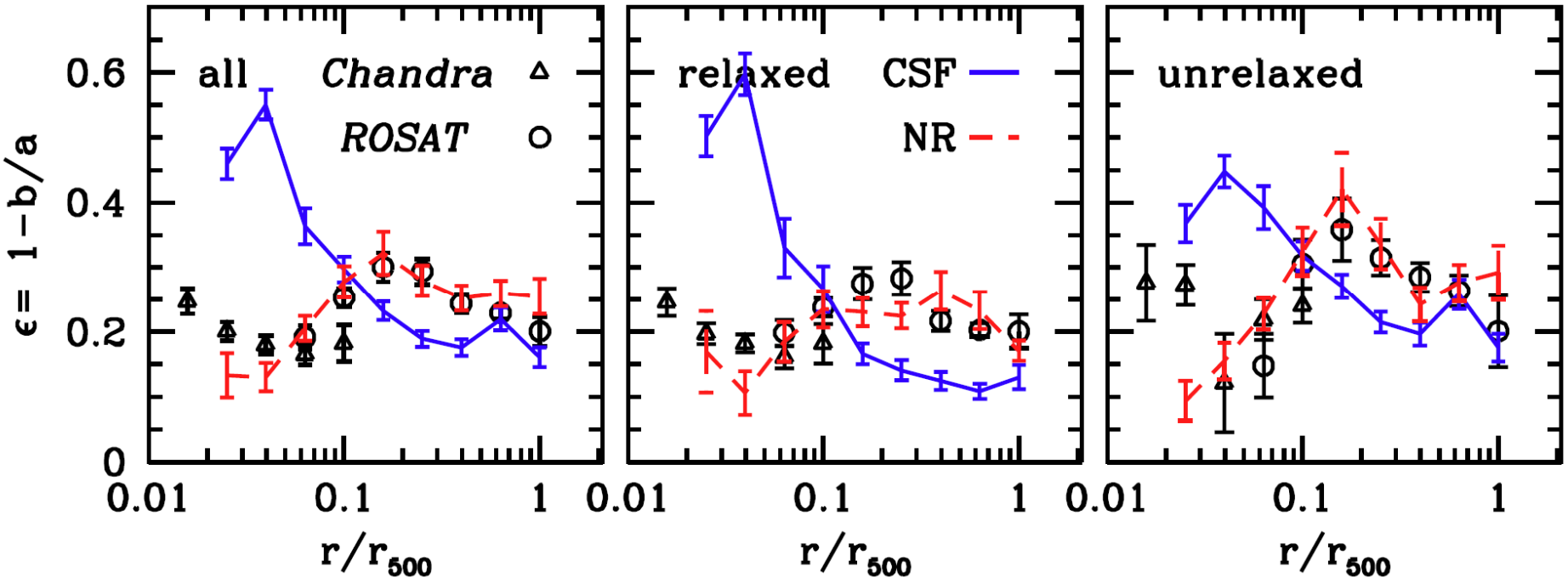
3 examples:



Lau et al. 2010, ApJ to be submitted

confronting simulations against observations

- at ***0.1<r/r_{500}<1*** – ellipticities of observed clusters indicates much smaller amount of baryon condensation than occurs in the CSF simulations
- at ***r/r_{500}<0.1*** – observed clusters do not exhibit strong flattening due to rotation; instead the inner profile is consistent with predictions of the NR simulations and shows signature of random gas motions



Lau et al. 2010, ApJ to be submitted

summary

- *effects of baryon dissipation on dark matter halo shape are also reflected in the observable ellipticity of the ICM at radii where gas is in hydrostatic equilibrium*

- *comparison of observed ellipticity profiles of nearby clusters and simulations indicates that the observed clusters experienced much smaller baryon dissipation during their formation than clusters in simulations*

- *the observed ellipticity profiles at $r<0.1r_{500}$ match the corresponding profiles predicted in non-radiative simulations and hint at the presence of random gas motions in cluster cores.*

Lau, Nagai, Kravtsov & Zentner 2010, ApJ submitted (arXiv/1003.2270)
Lau, Nagai, Kravtsov, Vikhlinin & Zentner 2010, ApJ to be submitted