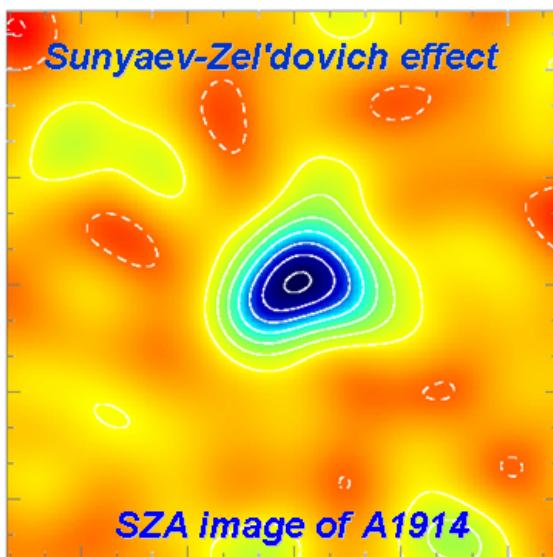
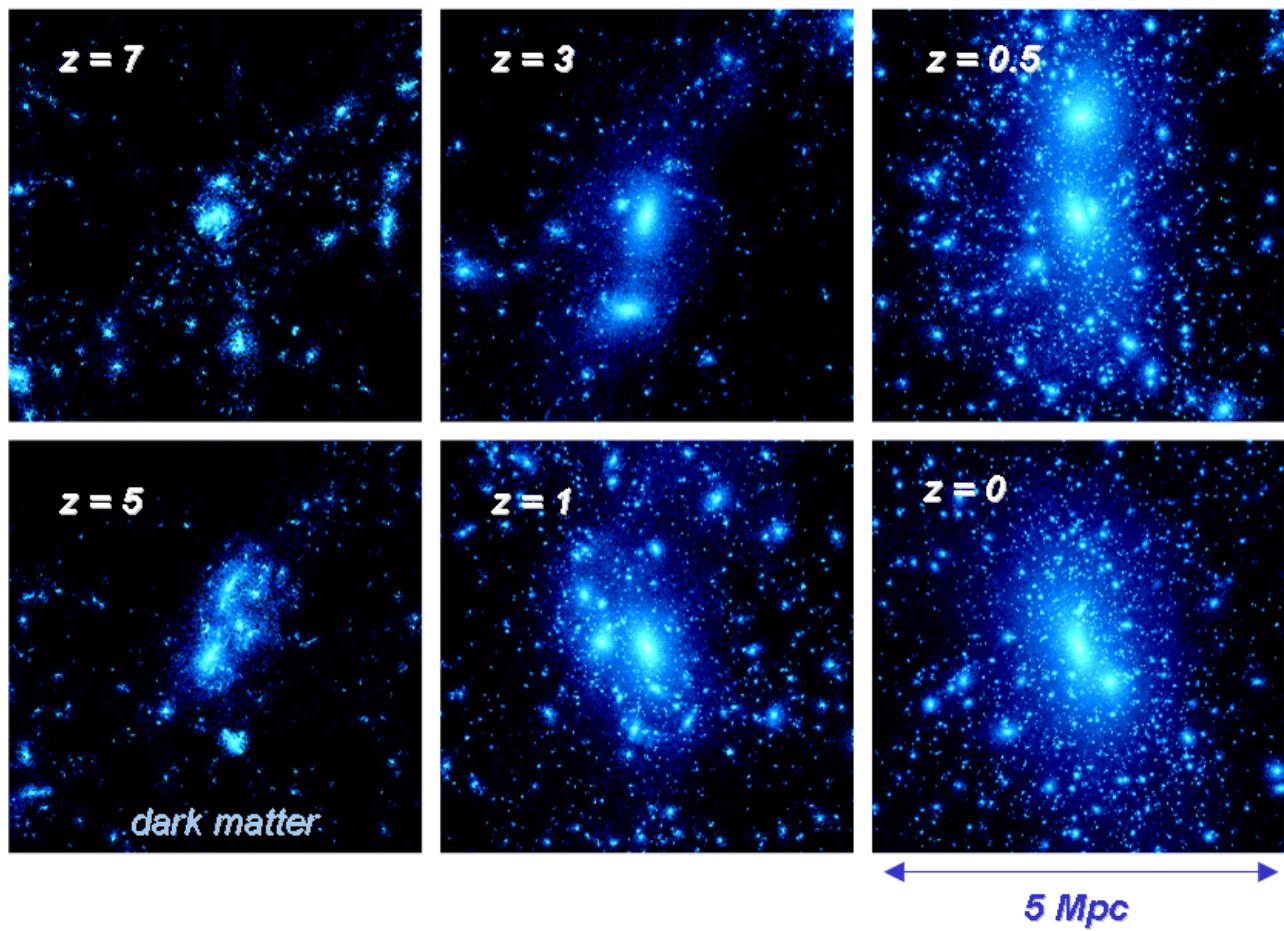


# Nearly Normal Galaxy Clusters

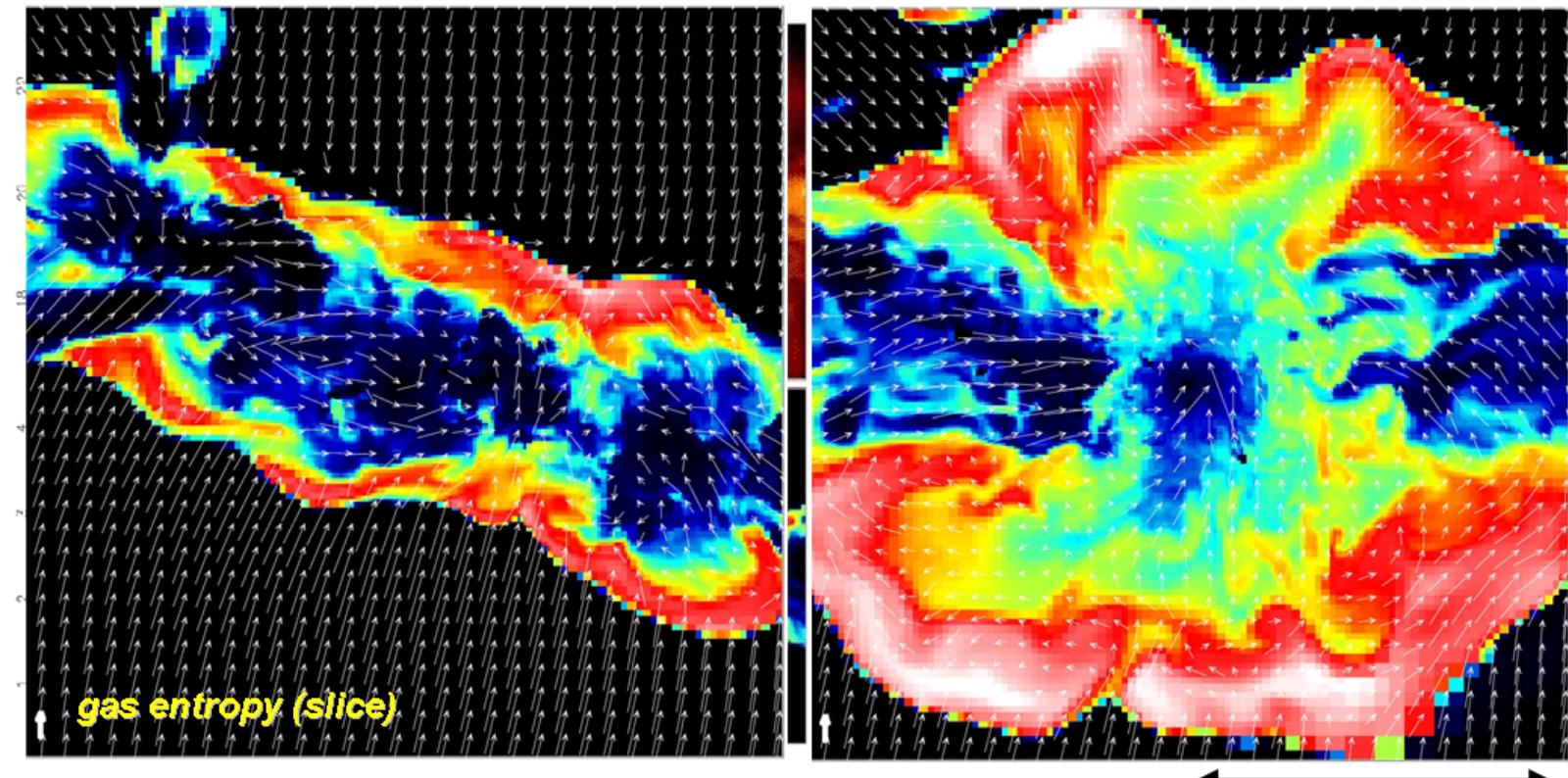
**Andrey Kravtsov**  
*The University of Chicago*



## *Clusters form hierarchically*

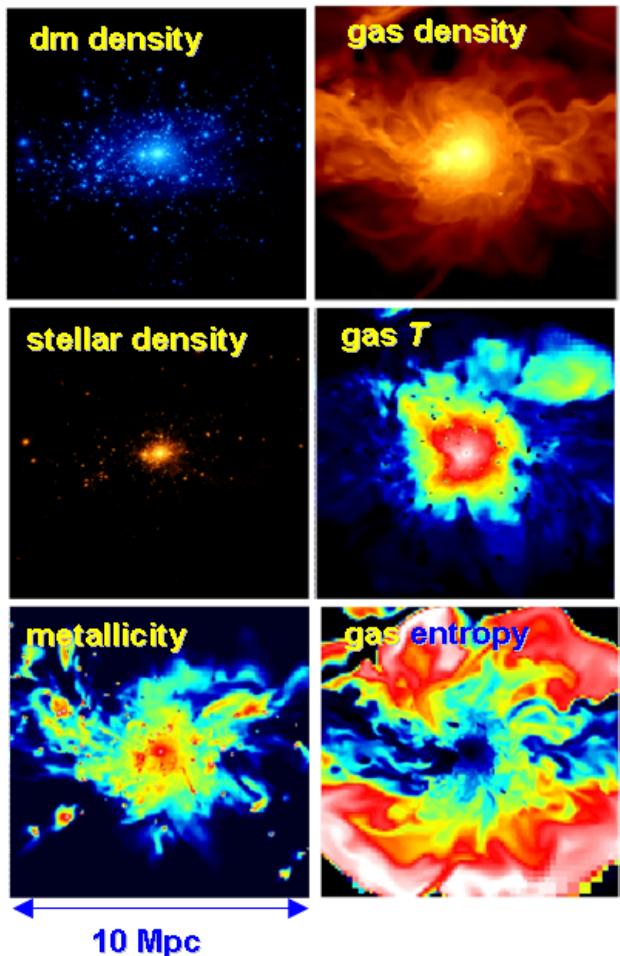


# *Accretion, Mergers → Shocks, Turbulence*



Norman & Bryan 1998  
Nagai, Kravtsov & Kosowsky 2003  
Sunyaev, Norman & Bryan 2003

## *Simulated cluster sample*



11 individual galaxy clusters simulated with and without cooling

virial masses from  $8 \times 10^{13}$  to  $10^{15} h^{-1}$  Msun

**Cosmological N-body+gasdynamics ART code**

(Kravtsov 1999, 2003; Kravtsov et al. 2002)

$m_{dm} = 3 \times 10^8 h^{-1}$  Msun,  $m_* \sim 10^6 h^{-1}$  Msun

peak resolution  $\sim 2 h^{-1}$  kpc

$2-4 \times 10^7$  mesh cells per cluster

**Gasdynamics:** Eulerian AMR (2<sup>nd</sup> 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

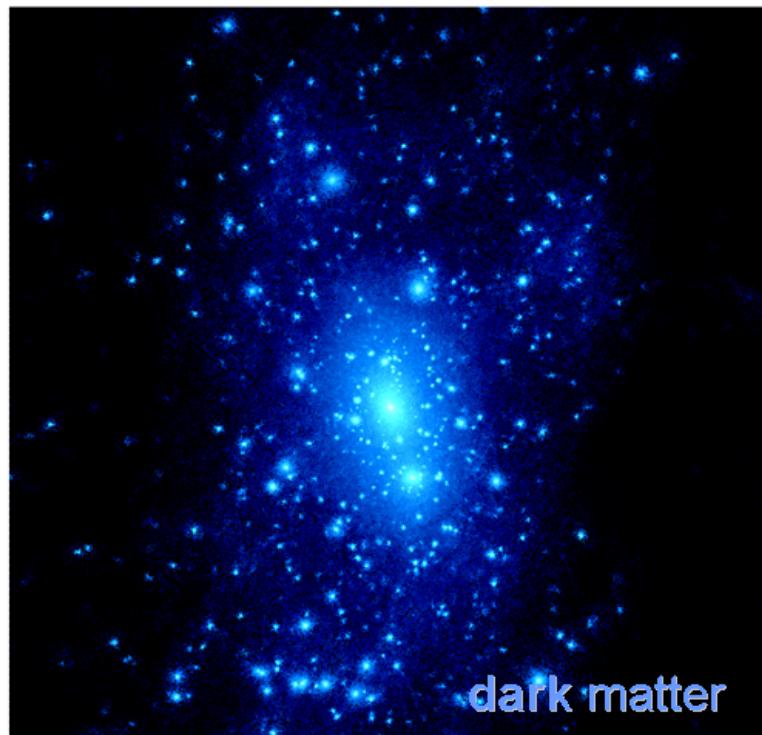
**Star formation** using the Kennicutt (1998) recipe

**Thermal stellar feedback**

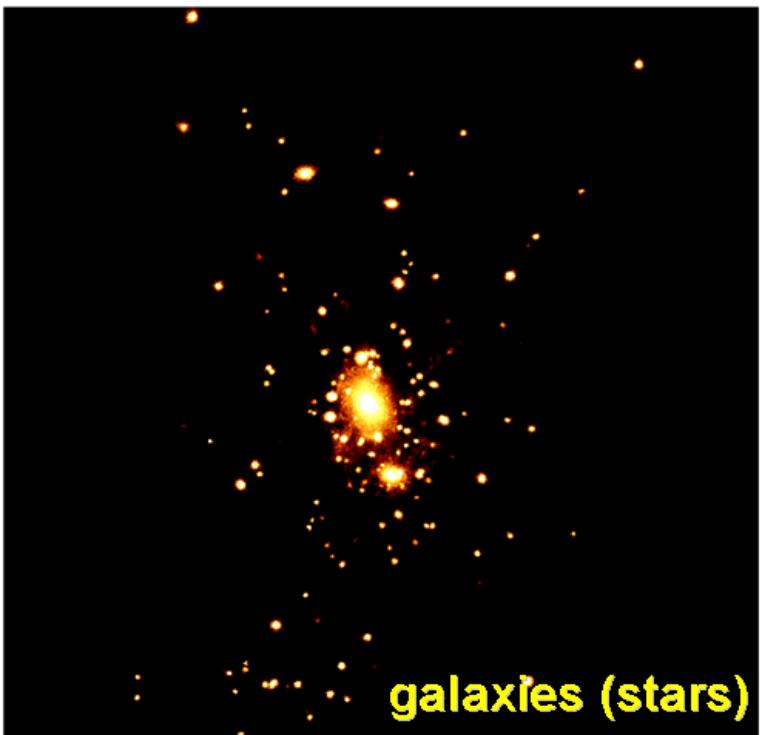
**Metal enrichment by SNIa + Advection of metals**

## High resolution allows us to actually simulate clusters of galaxies

- How galaxy formation affects the global cluster properties?
- How well simulations reproduce observations of clusters?



dark matter



galaxies (stars)

a Virgo-size cluster from our sample

## **Collaborators**

**Daisuke Nagai**

(University of Chicago -> Caltech)



**Alexey Vikhlinin**

(CfA, Harvard/ IKL)



+ Oleg Gnedin (OSU), Andrew Zentner, Stelios Kazantzidis  
(U.Chicago), Brandon Allgood (UCSC), Anatoly Klypin (NMSU)

## CONTRACTION OF DARK MATTER GALACTIC HALOS DUE TO BARYONIC INFALL<sup>1</sup>

GEORGE R. BLUMENTHAL AND S. M. FABER

Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz

RICARDO FLORES

Department of Physics, Brandeis University, Waltham, Massachusetts

AND

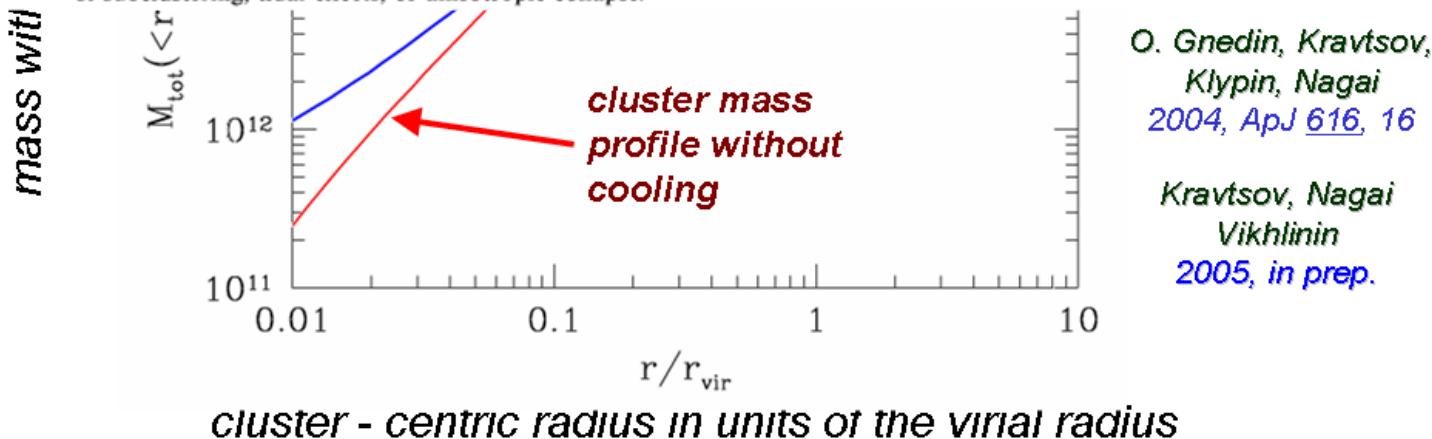
JOEL R. PRIMACK

Board of Studies in Physics, University of California, Santa Cruz

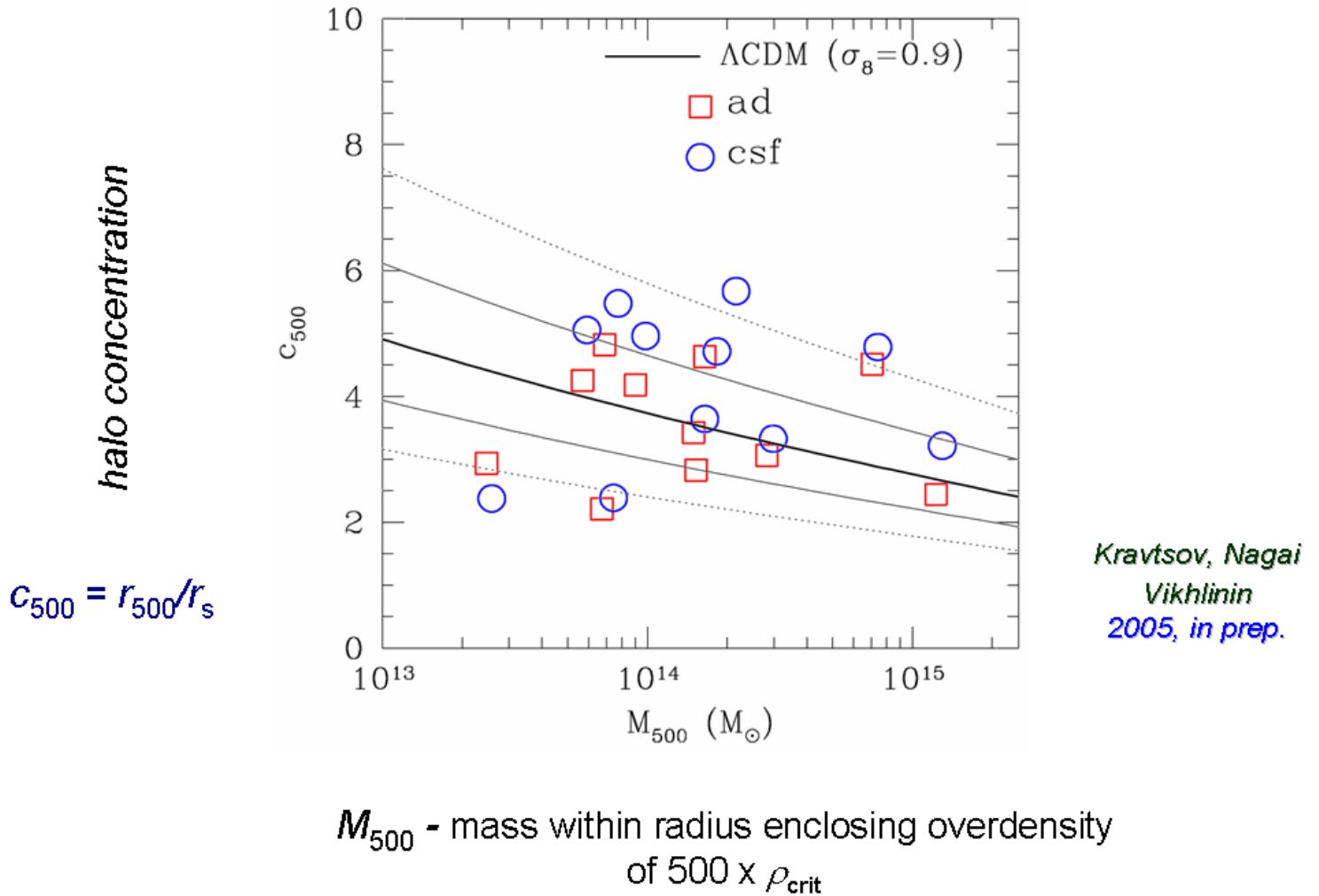
Received 1985 June 14; accepted 1985 July 9

### ABSTRACT

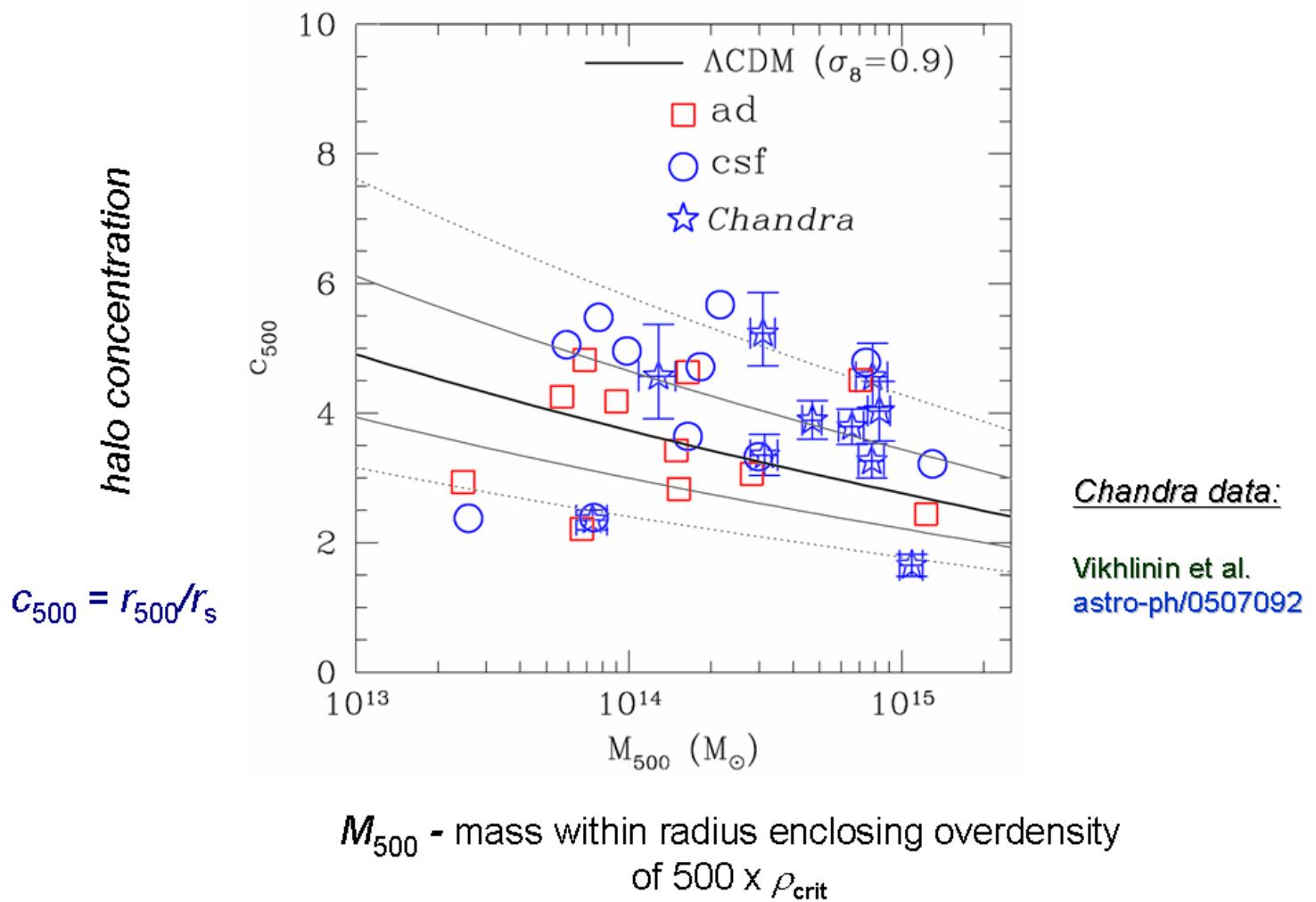
Varied evidence suggests that galaxies consist of roughly 10% baryonic matter by mass and that baryons sink dissipatively by about a factor of 10 in radius during galaxy formation. We show that such infall strongly perturbs the underlying dark matter distribution, pulling it inward and creating cores that are considerably smaller and denser than would have evolved without dissipation. Any discontinuity between the baryonic and dark matter mass distributions is smoothed out by the coupled motions of the two components. If dark halos have large core radii in the absence of dissipation, the above infall scenario yields rotation curves that are flat over large distances, in agreement with observations of spiral galaxies. Such large dissipationless cores may plausibly result from large internal kinetic energy in protogalaxies at maximum expansion, perhaps as a result of subclustering, tidal effects, or anisotropic collapse.



## ***Effect of cooling on halo concentrations***



## **Cluster concentrations: theory vs data**

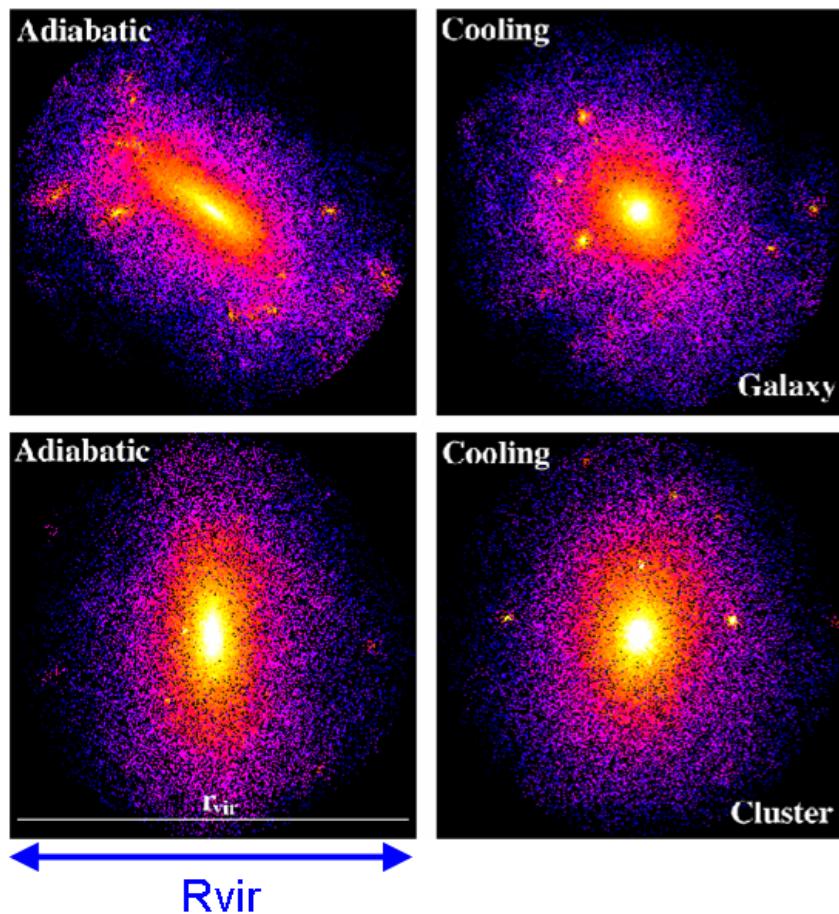


## ***Effect of dissipation on DM halo shape***

*Kazantzidis, Kravtsov, Zentner, Allgood, Nagai, Moore, 2004 ApJL 611, L73*

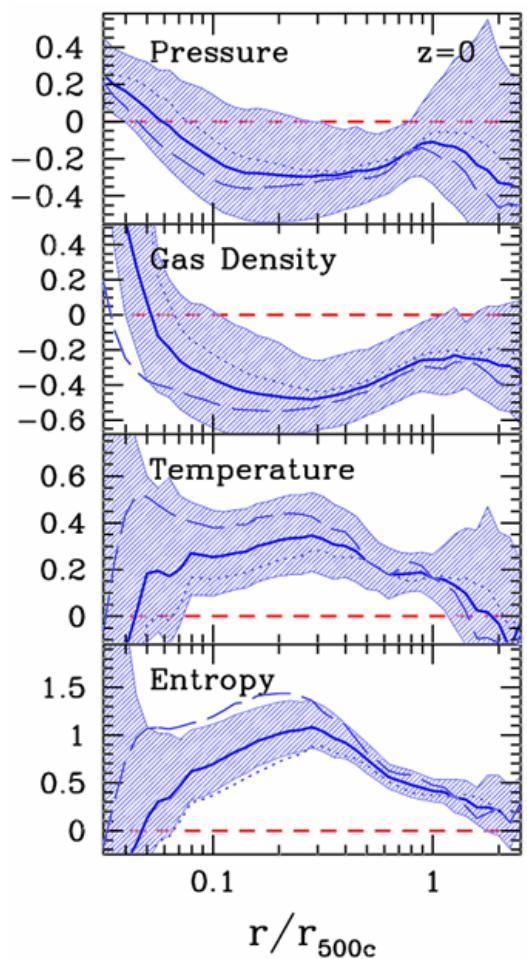
*also, Katz 1991; Evrard et al. 1993; Dubinski 1994; Tissera et al. 1998; Springel 2004*

***the same objects simulated with and without cooling***

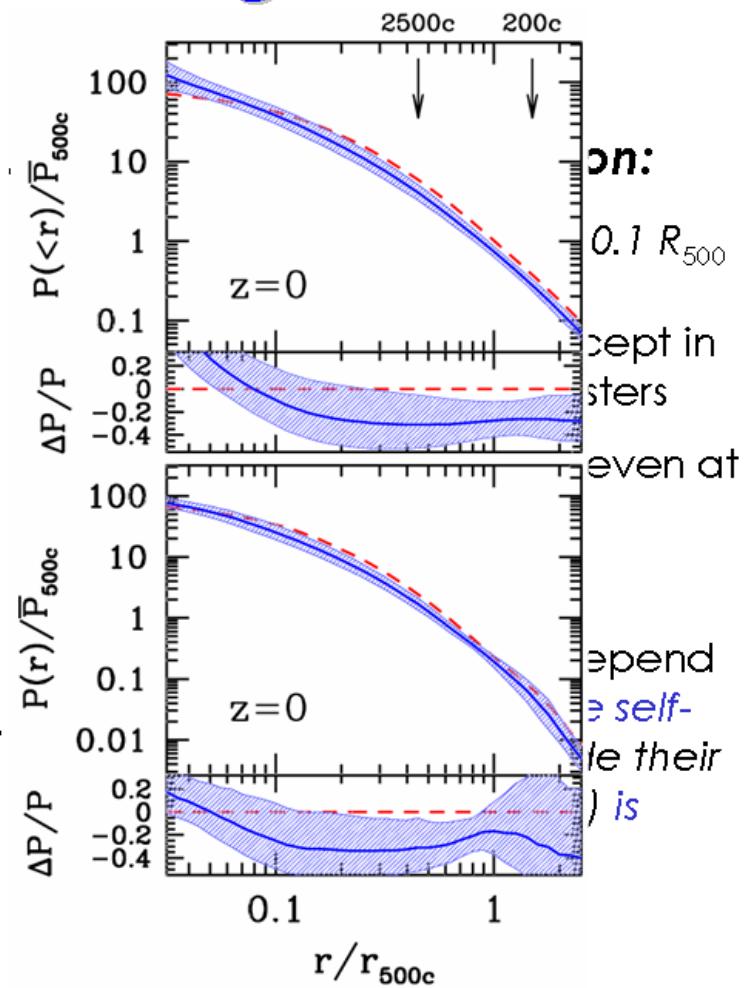


## Effect of galaxy formation on the intracluster gas

fractional difference between csf and adiabatic runs



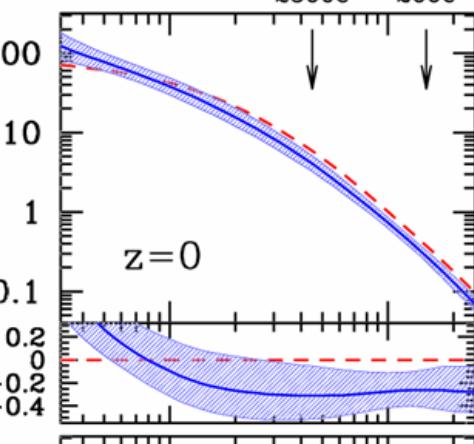
Integrated pressure



pressure

$P(r)/\bar{P}_{500c}$

$\Delta P/P$



on:

$0.1 R_{500}$

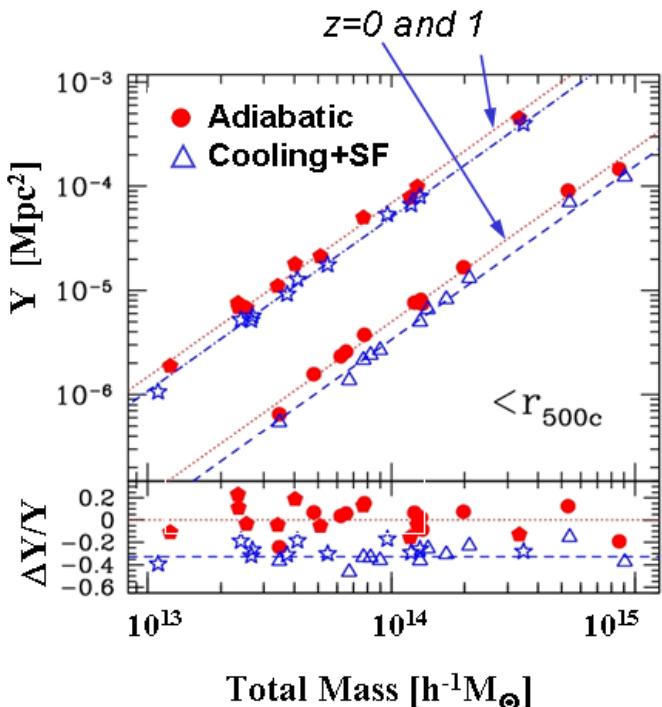
cept in clusters even at

spend self-

use their ) is

## SZ flux – total mass relation

$$Y \propto \int n_e T_e dV \propto f_{\text{gas}} T_m M_\Delta$$



Nagai 2005, ApJ submitted  
also, da Silva et al. 2004  
Motl et al. 2005

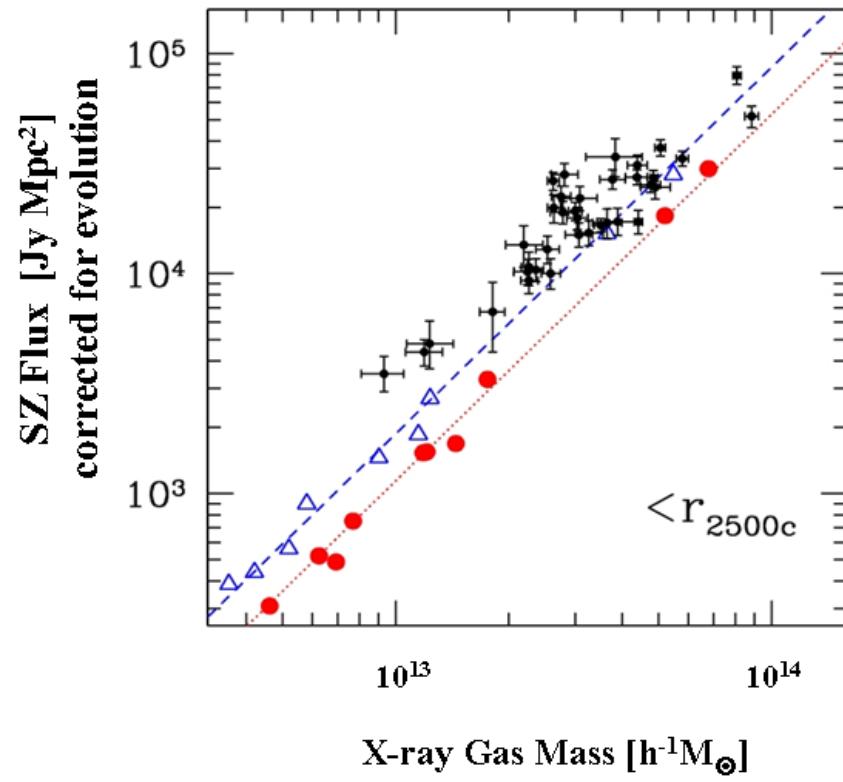
→ The relation is very tight

- The scatter is ~10-15% in both adiabatic and CSF runs
- The slope is consistent with the self-similar scaling law (slope  $\approx 5/3$ )

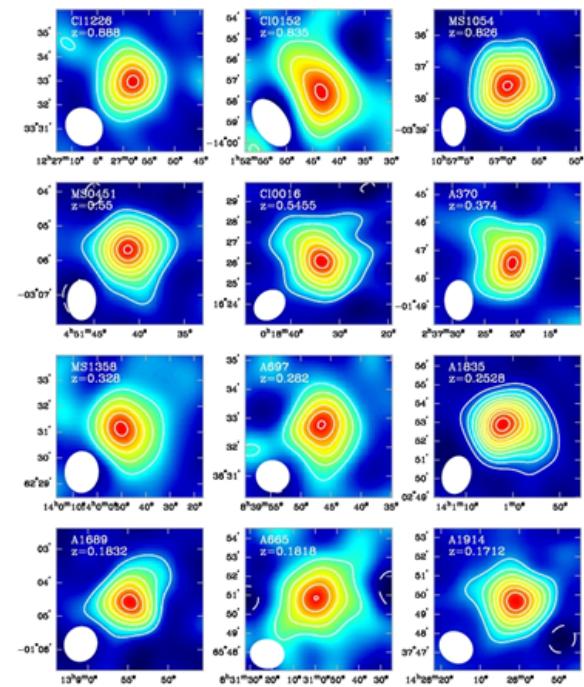
→ Effects of galaxy formation:

- The normalization is *lower*
  - by ~34% at  $R_{500c}$
  - by ~45% at  $R_{2500c}$  ( $\approx R_{500c}/2$ )
- Changes are in  $f_{\text{gas}}$ ,  $T_m$  and  $M_\Delta$ 
  - $\Delta f_{\text{gas}} \approx -38\%$  and  $\Delta T_m \approx +9\%$  at  $R_{500c}$
  - Also,  $\Delta M_{\text{vir}} \approx +7\%$  at  $R_{500c}$

# SZ flux - gas mass correlation: simulations vs observations



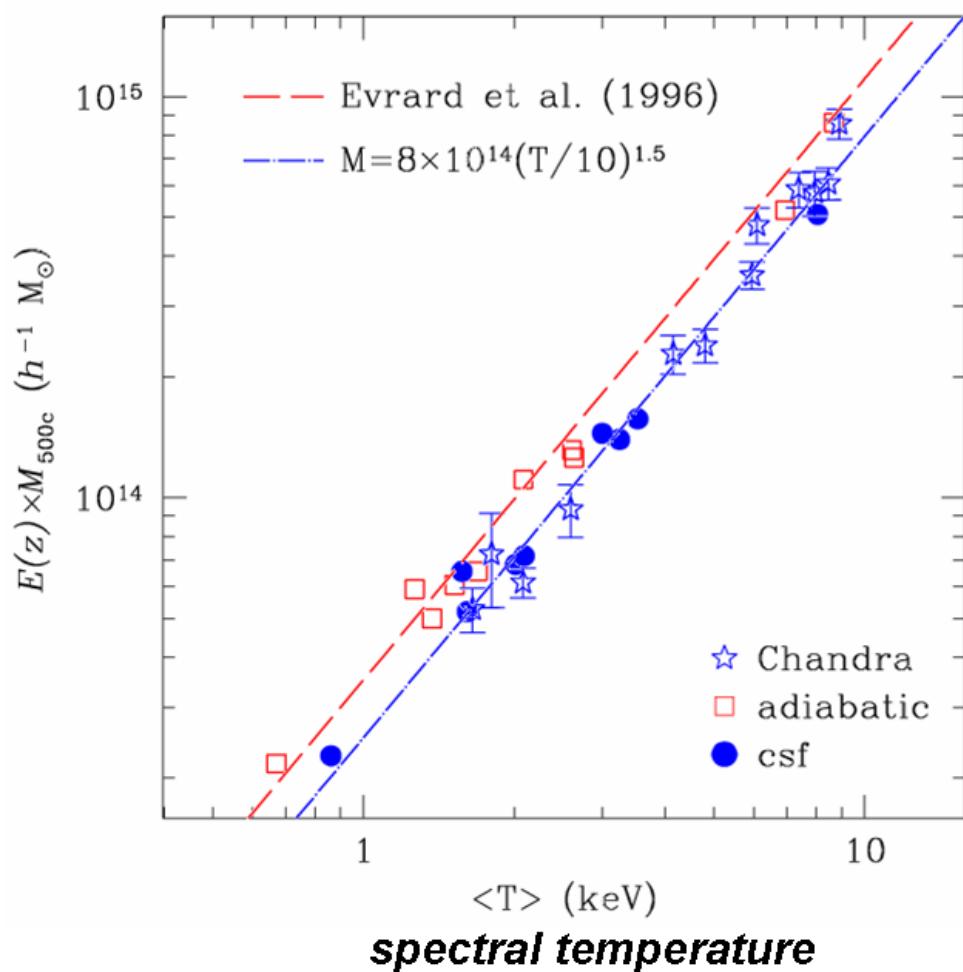
Nagai 2005, ApJ submitted  
(on astro-ph this week)



Sample of 36 clusters ( $0.14 < z < 0.9$ )  
with BIMA/OVRO SZE + Chandra X-ray  
observations

Data from John Carlstrom, Marshall Joy,  
Max Bonamente, Sam LaRoque

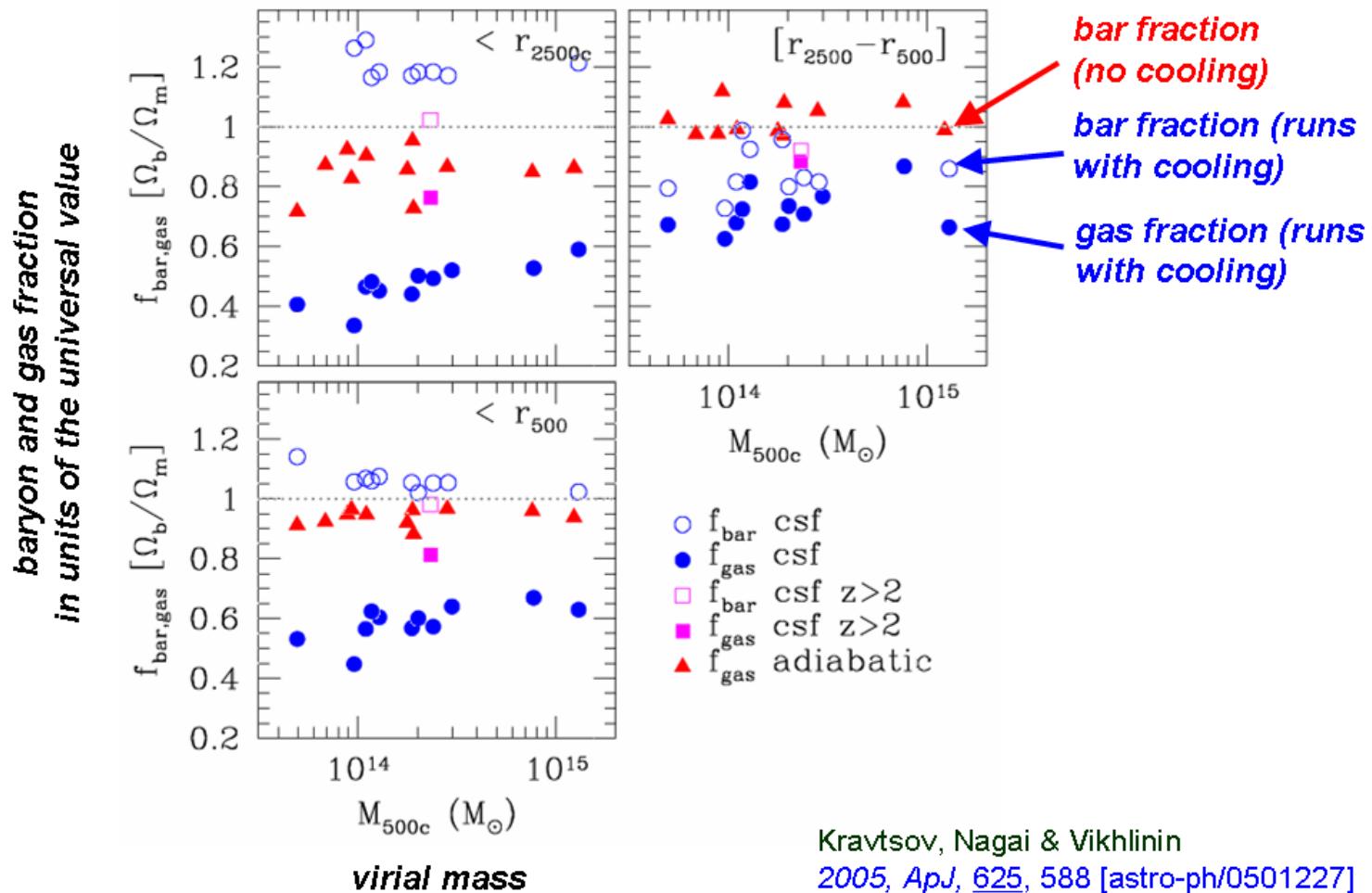
*M500 scaled to z=0*



Chandra data:

Vikhlinin et al.  
astro-ph/0507092

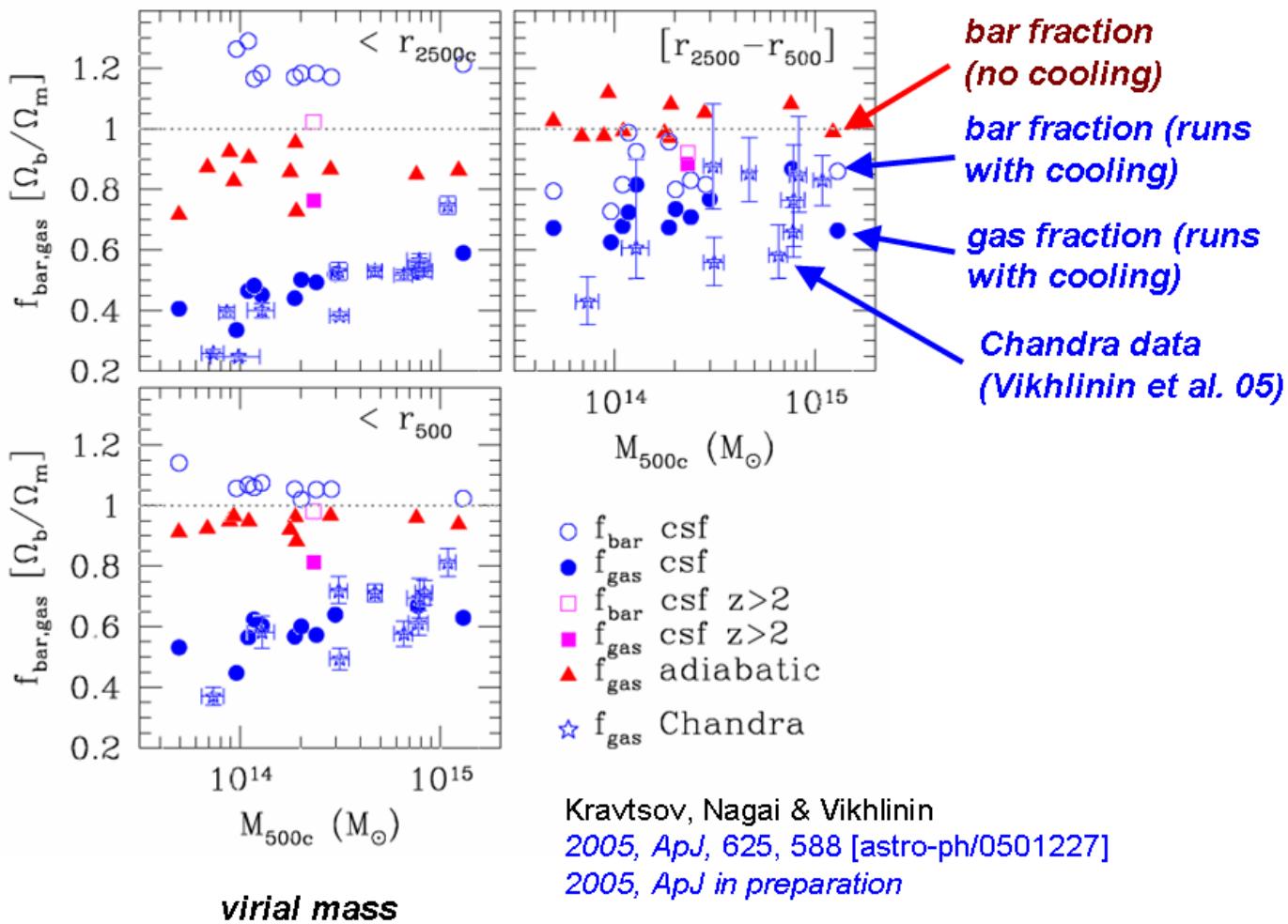
## baryon content of clusters: adiabatic vs cooling simulations



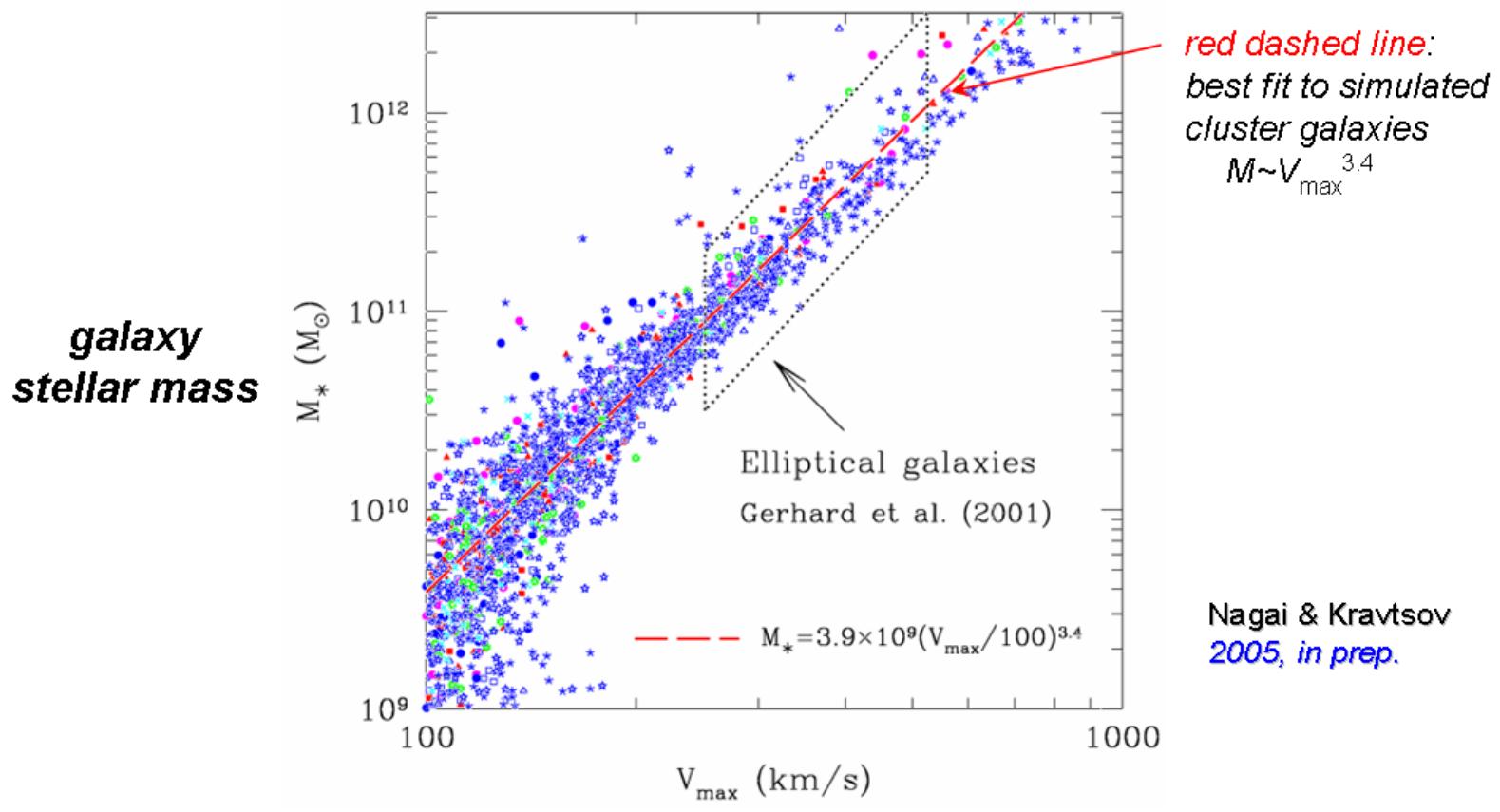
Kravtsov, Nagai & Vikhlinin  
2005, *ApJ*, 625, 588 [astro-ph/0501227]

# a baryon content crisis?

baryon and gas fraction  
in units of the universal value



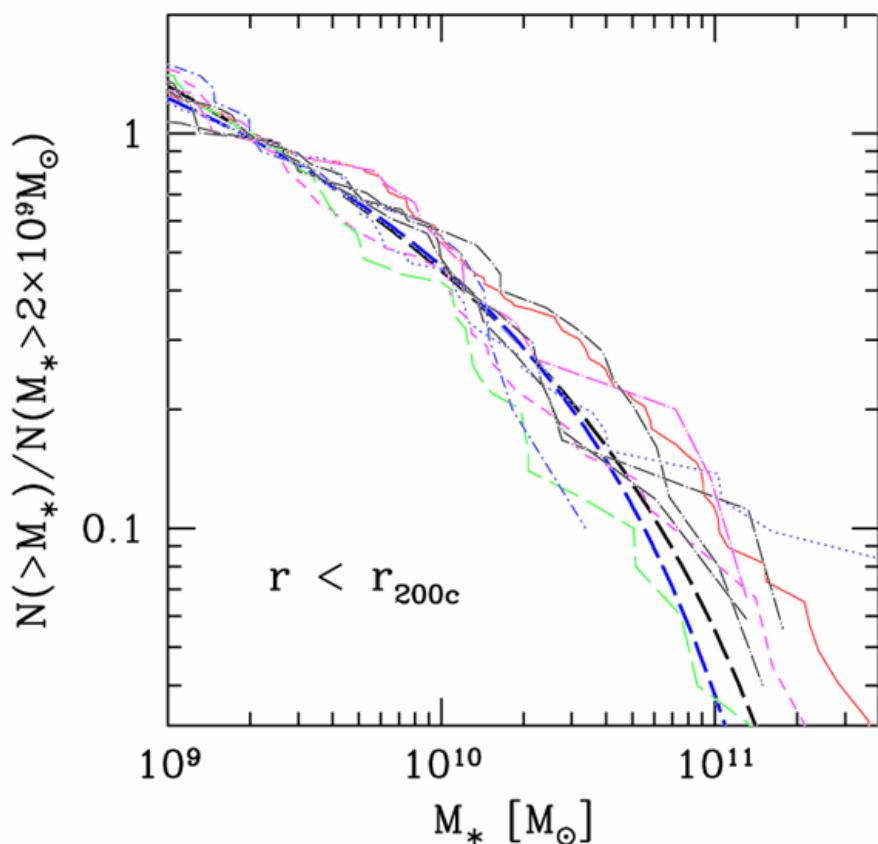
## Galaxies in simulated clusters: the Mstar - Vmax relation



$$\text{maximum of the circular velocity profile} = (GM(\langle r \rangle)/r)^{1/2}$$

# Cumulative stellar mass function

*normalized cumulative stellar mass function*



**thick dashed lines:**  
blue - composite  
stellar mass function  
of cluster galaxies  
[2MASS data; Lin et al 03]

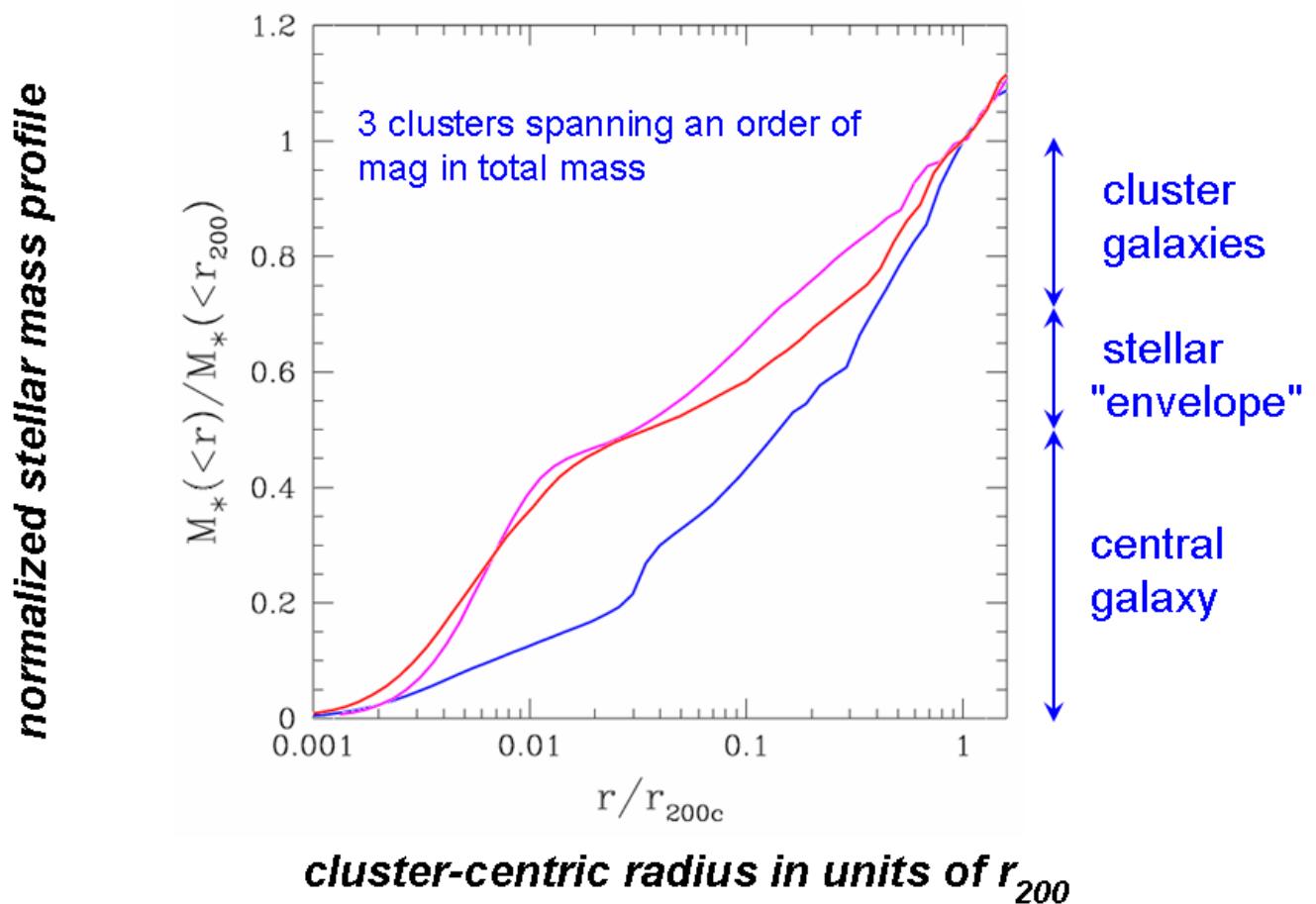
black – mean of 4 cls.  
(SDSS; Mesheriakov &  
Vikhlinin 2005)

**thin color lines:**  
stellar mass functions  
of galaxies in individual  
simulated clusters  
(Nagai & Kravtsov  
2005, in preparation)

*stellar mass of galaxies*

# **Where are the extra (or missing) stars?**

→ in the central galaxy and its envelope



## Summary

- Gas cooling and star formation affect the global distribution of dark matter within the clusters, as well as gas density and temperature profiles (and hence pressure and entropy).
  - However, *outside their cores* ( $r > 0.05R_{\text{vir}}$ ) *clusters remain approximately self-similar. This is consistent with Chandra observations.*
  - Galaxy formation can significantly affect normalization of the  $Y_{\text{tot}} - M_{\text{tot}}$  and  $T_x - M_{\text{tot}}$  relations, but not their slope and scatter.
  - *The hot gas fractions in simulated clusters match the observed gas fractions very well, but stellar mass appears to be overestimated by a factor of  $\sim 2\text{-}3$ :*
- *Are cluster baryon fractions significantly smaller than universal value?*  
*(If so, what process(es) suppress  $f_{\bar{b}}$ ?)*
- *Or are we missing baryons in clusters? (if so, in what form?)*