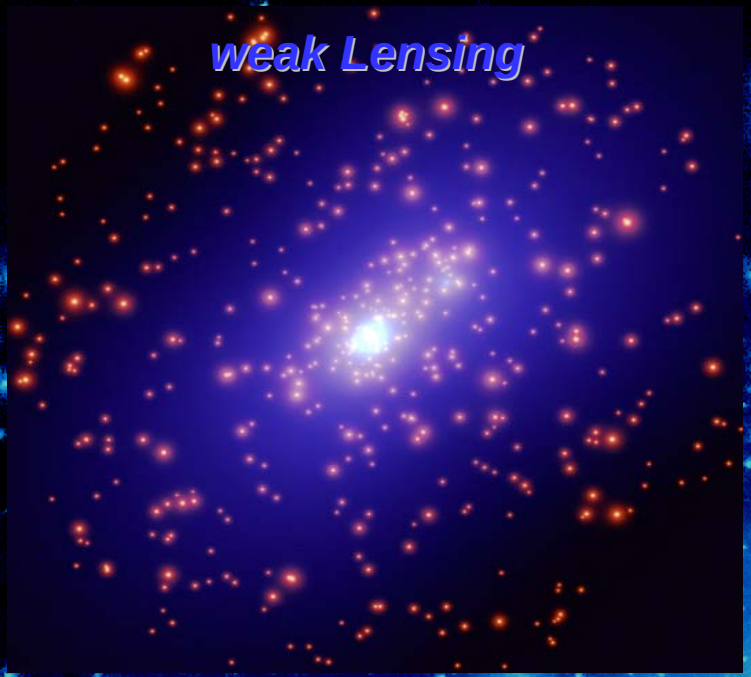
Effects of baryons on the mass distribution in groups and clusters: implications for lensing

Andrey Kravtsov
The University of Chicago

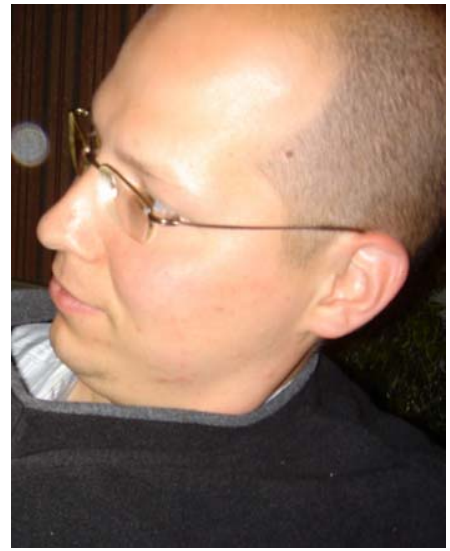


collaborators

Alexey Vikhlinin (SAO Harvard, IKI Moscow)

Daisuke Nagai (Caltech)

Douglas Rudd (U.Chicago)



Andrew Zentner (U.Chicago)

Oleg Gnedin (Michigan)

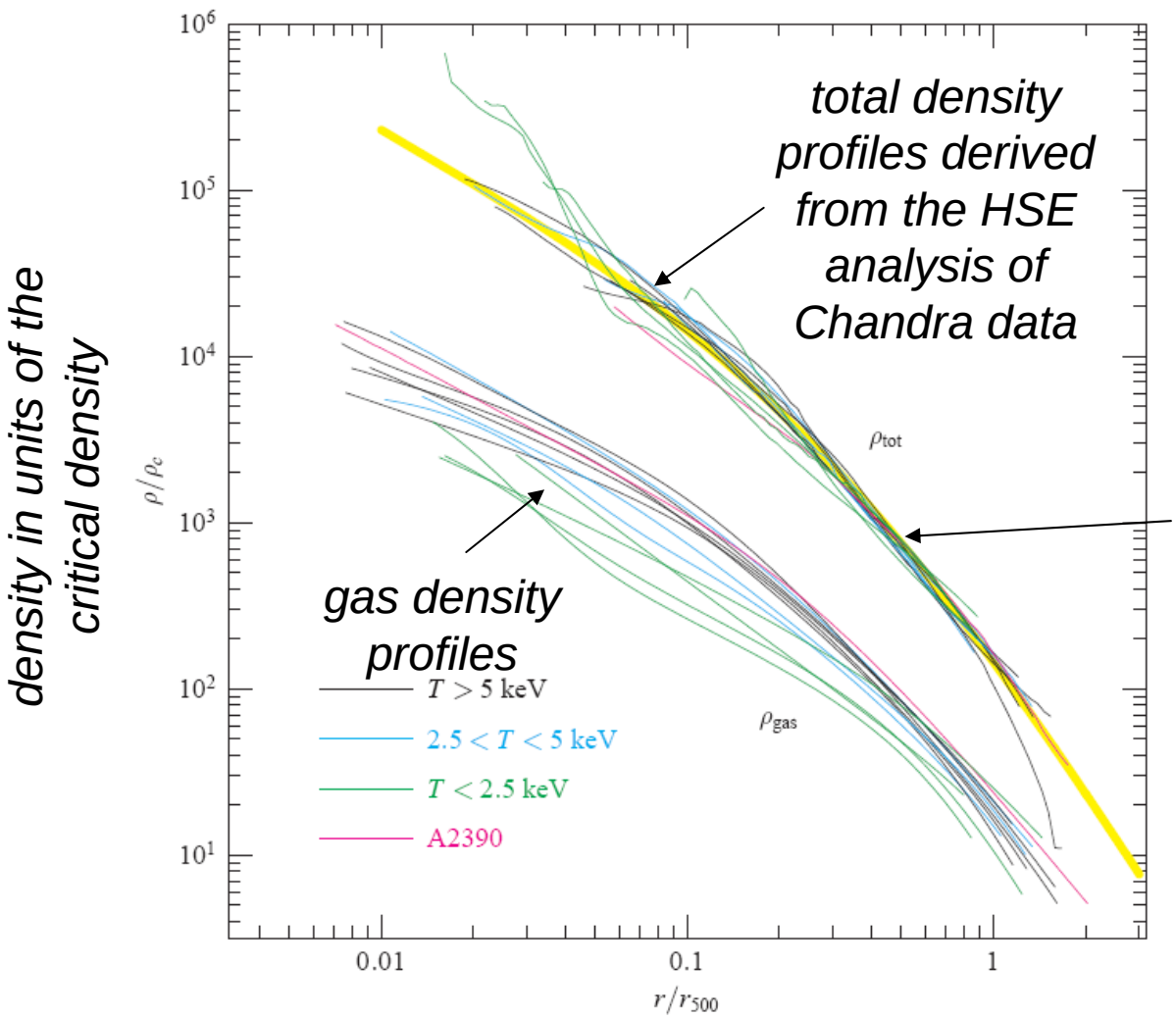
Anatoly Klypin (New Mexico State)

+ Stelios Kazantzidis (KIPAC, Stanford), Brandon Allgood, + …


A Virgo-sized cluster halo formed in LCDM cosmology

Cluster mass distribution is dominated by dark matter and is expected to approximately follow the NFW profile

Vikhlinin et al.
2006 ApJ 640, 691 (astro-ph/0507092)



radius in units of the radius r500c enclosing overdensity of 500 x ρ_{crit}

also:

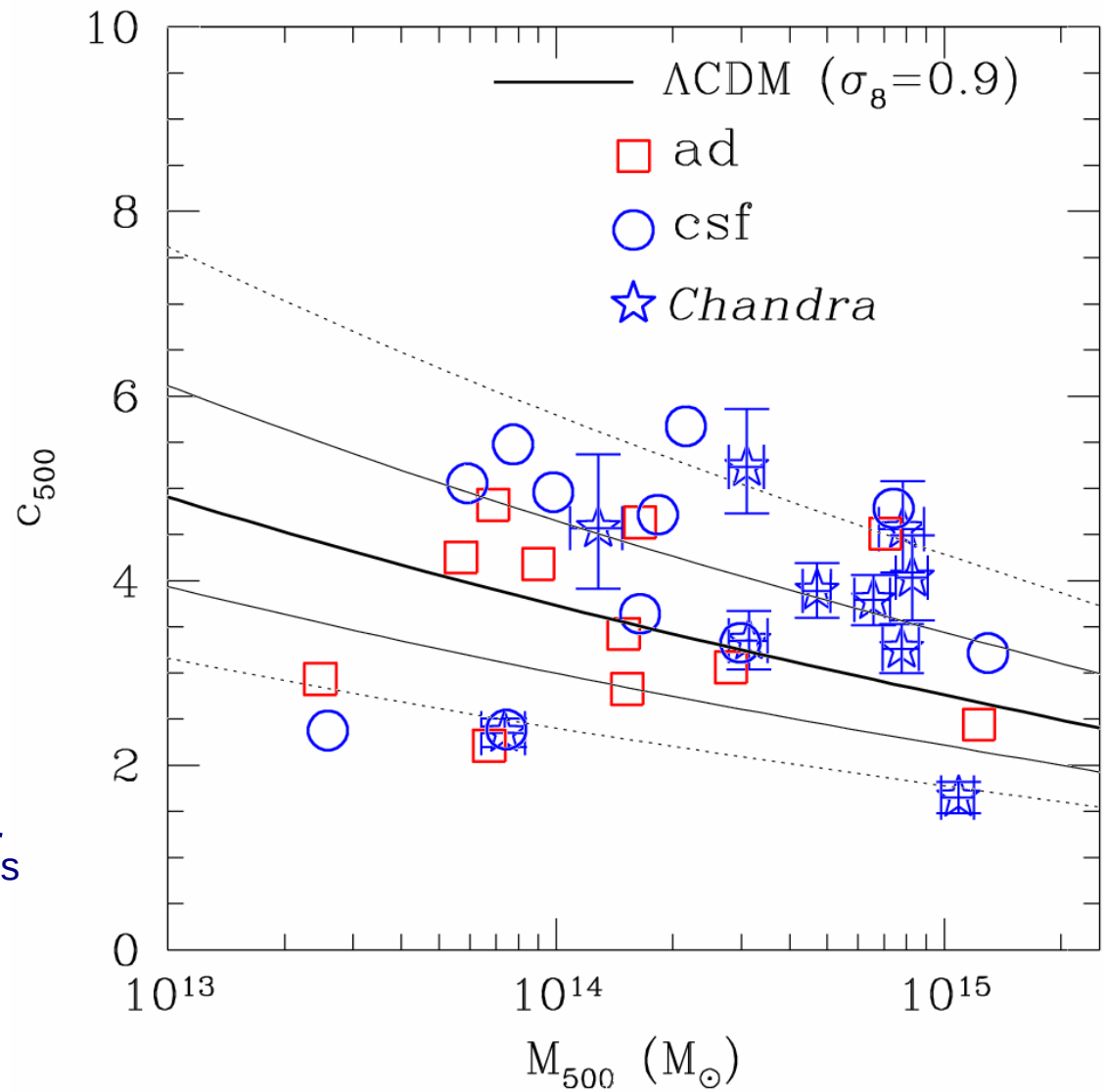
Pointecouteau et al. 2005
Humphrey et al. 2006

yellow line:
NFW profile with c=5

Cluster concentrations: theory vs data

$$\rho_{DM}(r) = \rho_{\rm DM}\left(c_{\rm vir}(M_{\rm vir})\frac{r}{R_{\rm vir}}\right)^{-1}\left(1 + c_{\rm vir}(M_{\rm vir})\frac{r}{R_{\rm vir}}\right)^{-2}$$

halo concentration



$c_{500} = r_{500}/r_s$

Chandra data:

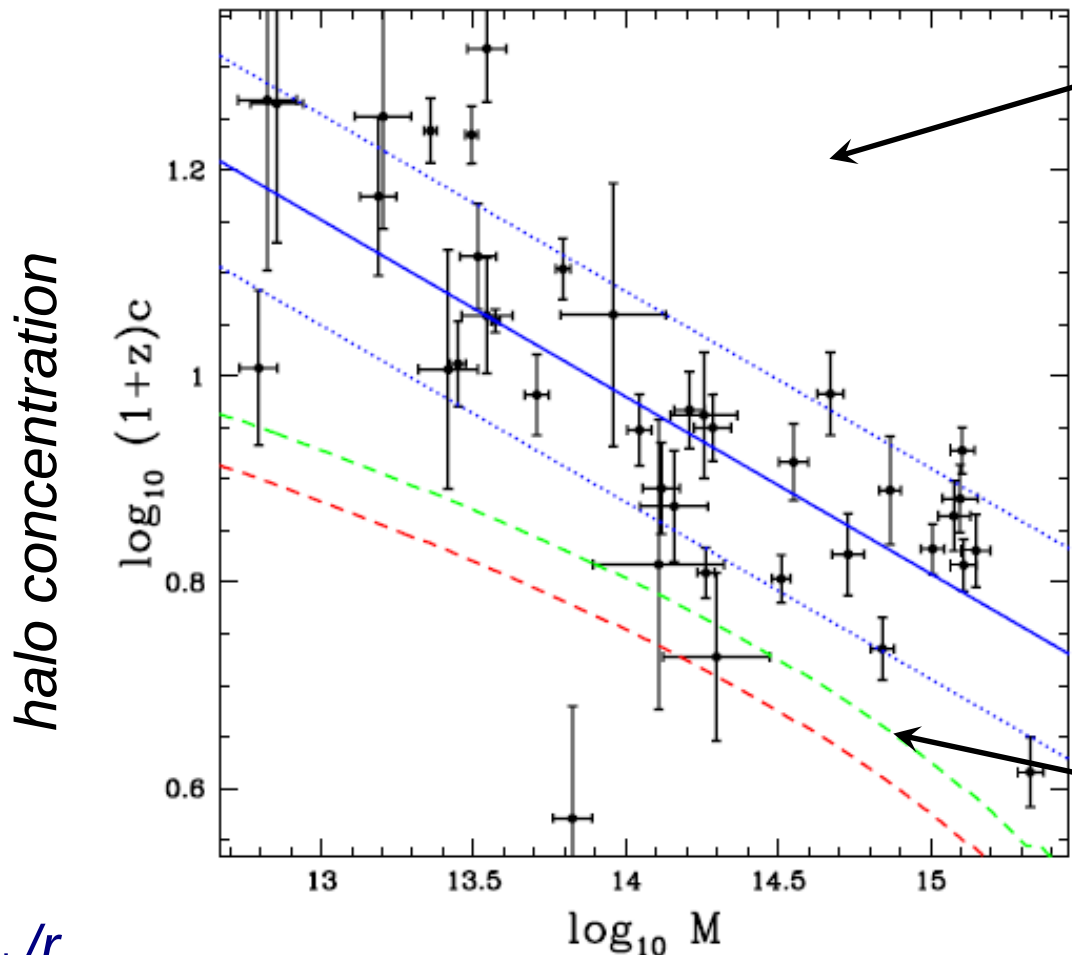
Vikhlinin et al. 2006, ApJ 640, 691

also,

Pointecauteau et al. 2005
Schmidt & Allen 2006
Buote et al. 2006

M_{500} - mass within radius enclosing overdensity of 500 x $\rho_{\rm crit}$

are observed cluster concentrations too high?



Buote et al. 2006
astro-ph/0610135

is evolution with redshift inconsistent with simulation predictions?
Schmidt & Allen 2006

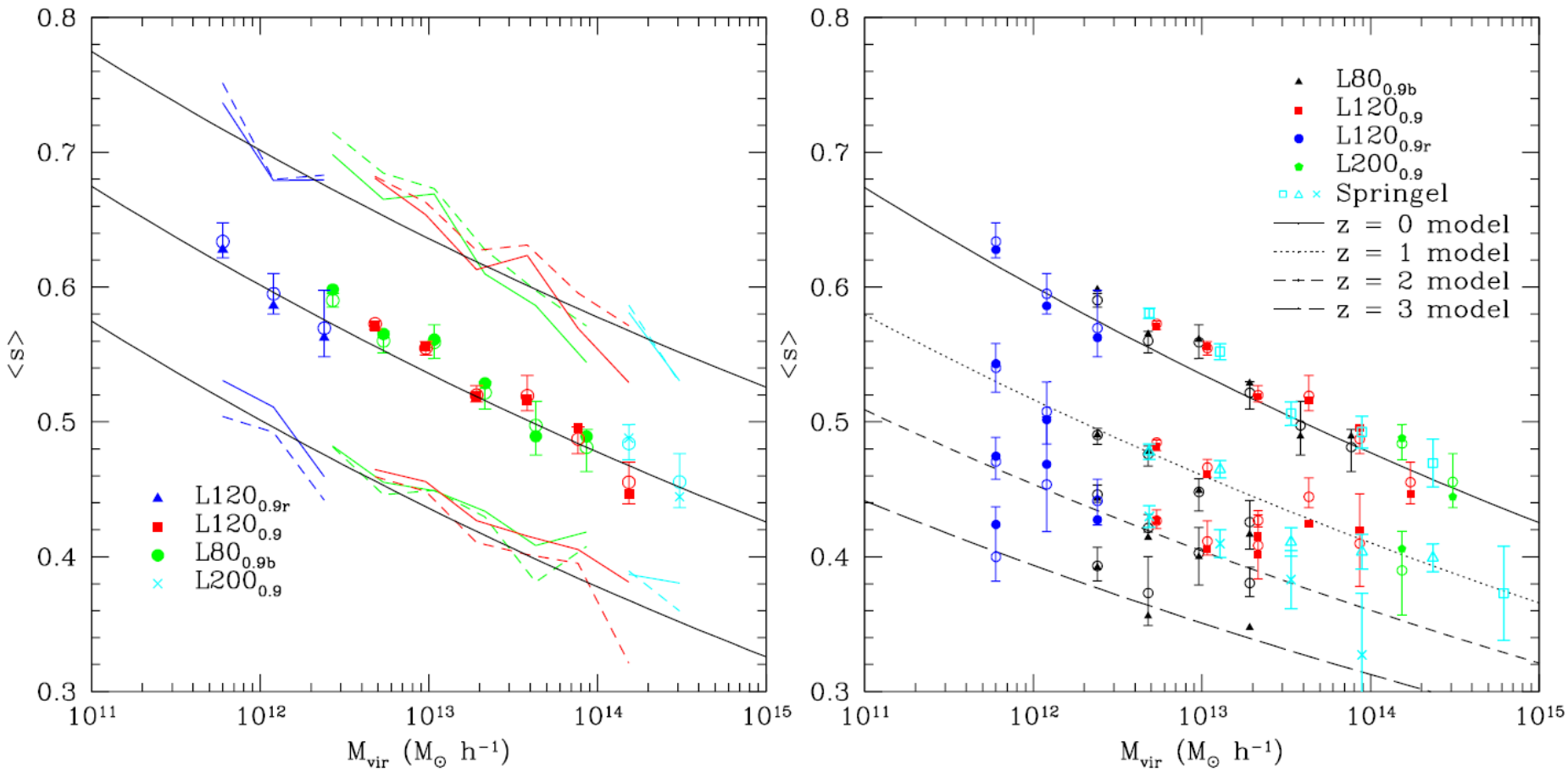
prediction for the WMAP 3 yr cosmology

$c_{vir} = r_{vir}/r_s$

M_{vir} - mass within radius enclosing overdensity of 340 x $<\rho>$

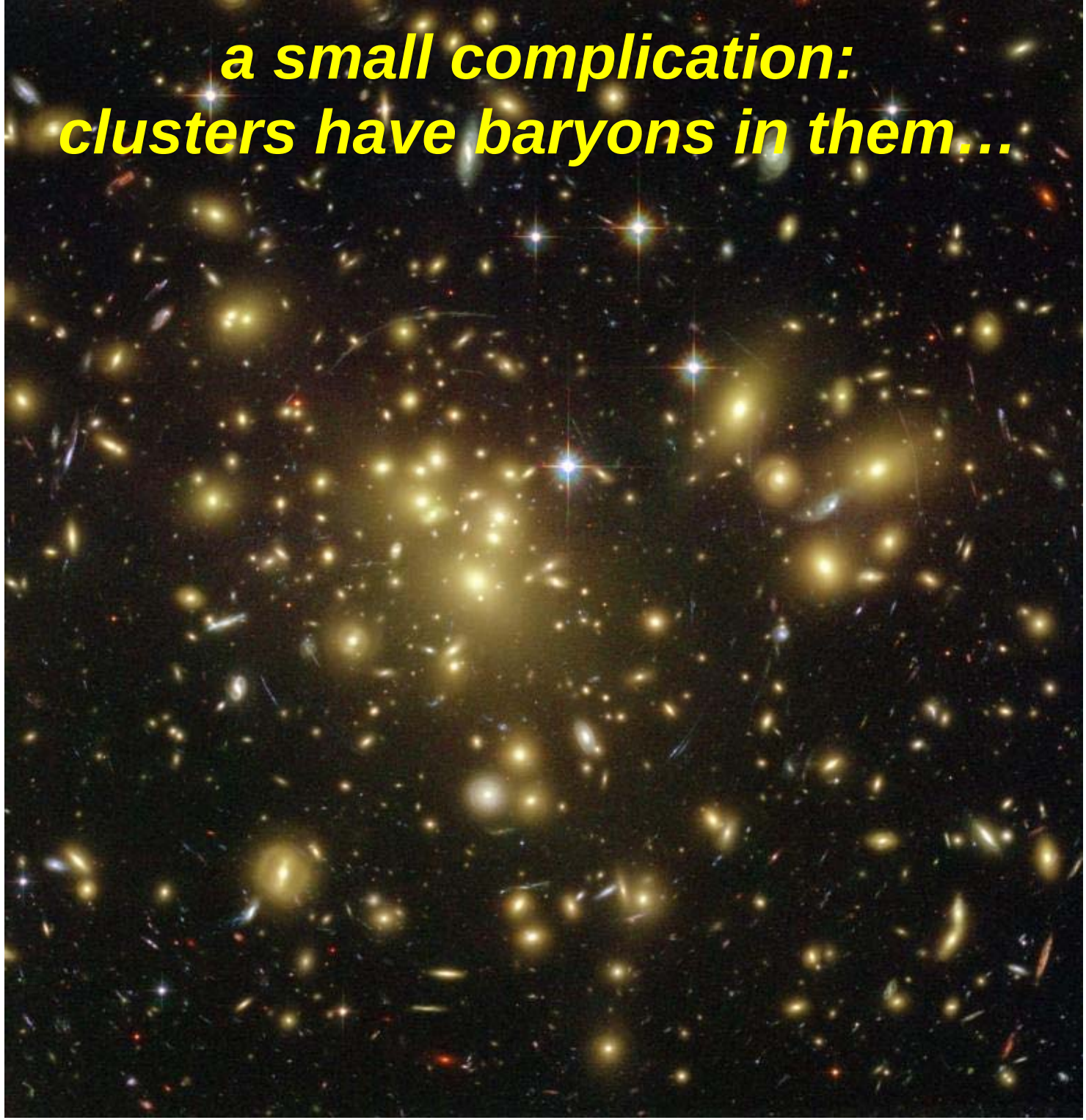
dark matter only simulations predict that clusters are highly triaxial and prolate with triaxiality increasing with z and for inner regions of clusters

average longest to shortest axis ratio

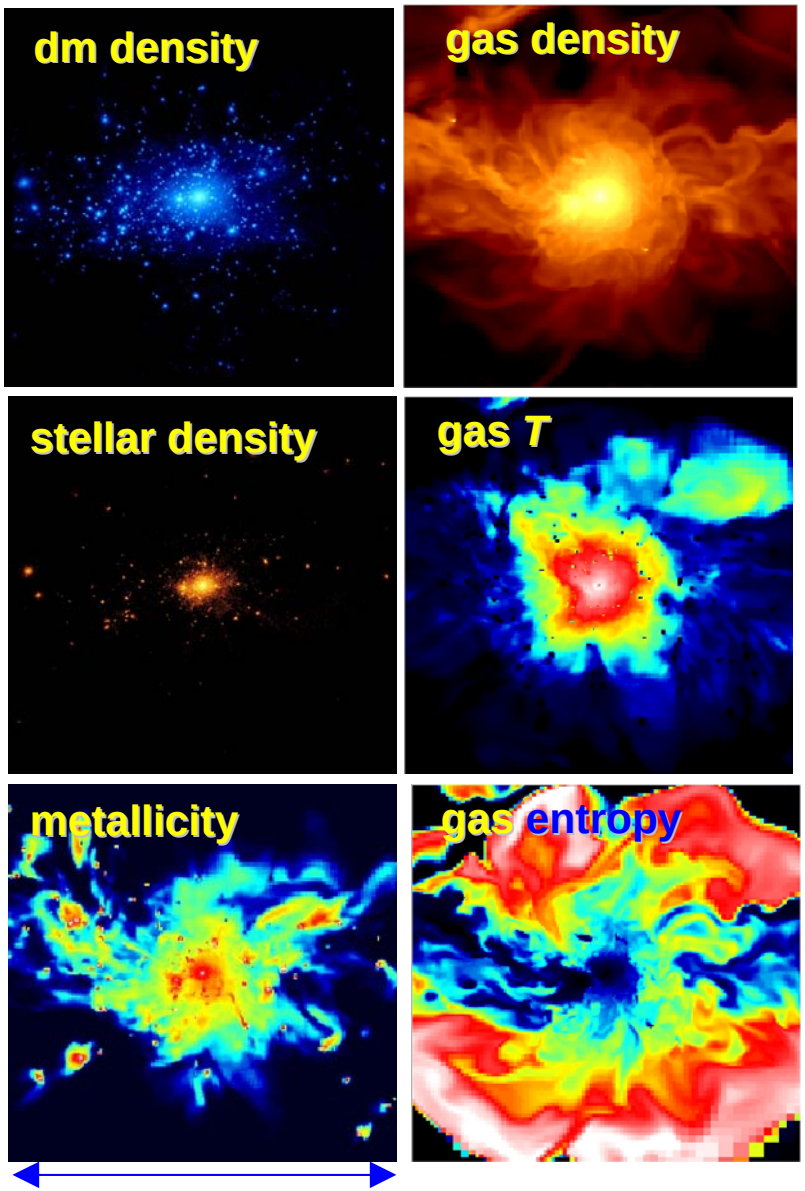


M_{vir} - mass within radius enclosing overdensity of 340 x $<\rho>$

Allgood et al. 2006, MNRAS 267, 1781


a small complication:
clusters have baryons in them…

simulations with baryons



16 individual galaxy clusters simulated with and without cooling (boxes of 80-120/h Mpc)
virial masses from 8×10^{13} to $10^{15}h^{-1}$ Msun

3 simulations of 60/h Mpc volume with uniform resolution, started from the same initial conditions but including different physical processes

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

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

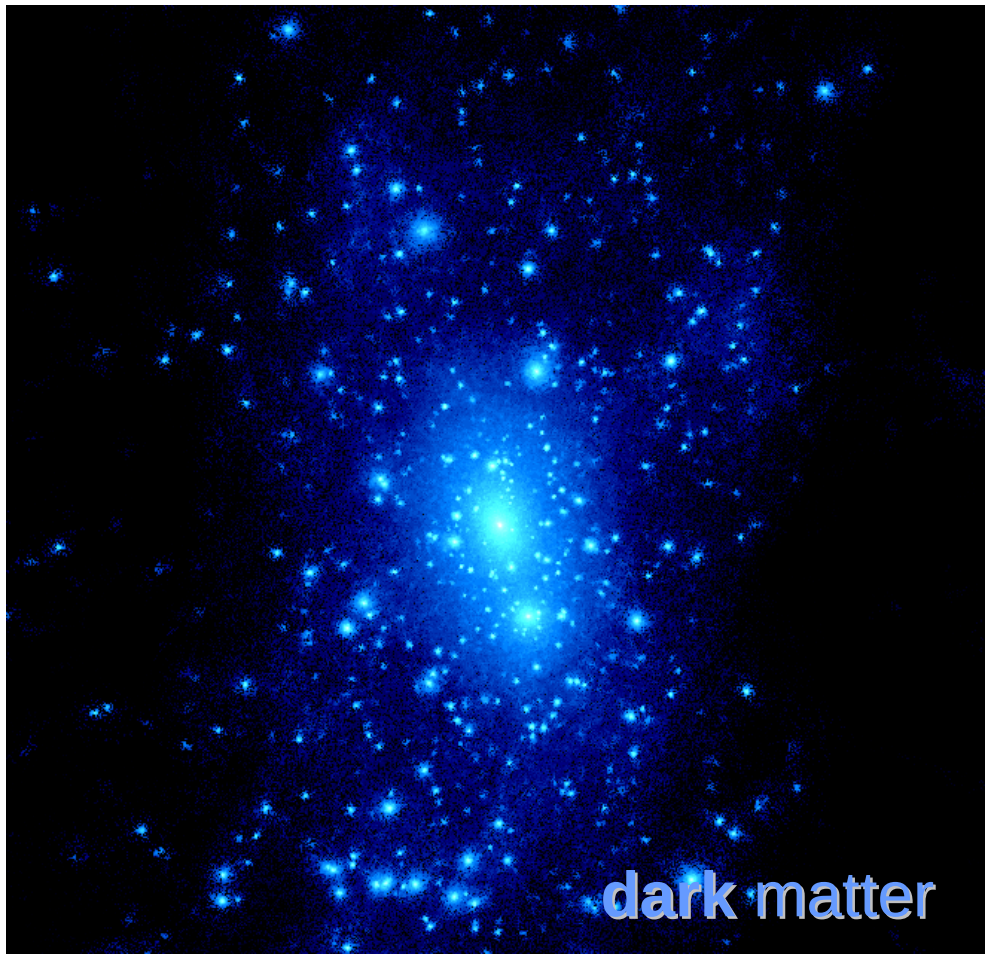
Radiative cooling and heating of gas:
metallicity dependent taking into account atomic and molecular processes

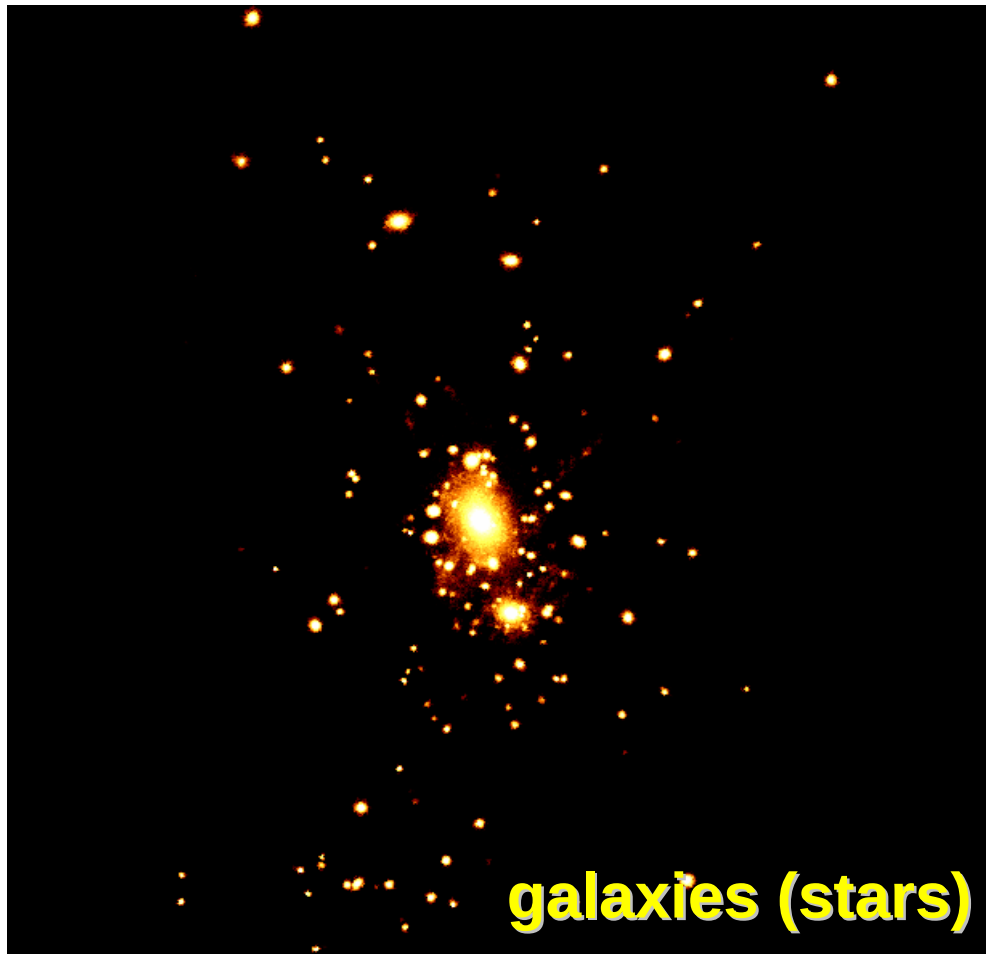
Star formation using the Kennicutt (1998) recipe

Thermal stellar feedback + **Metal enrichment**

High resolution allows us to actually simulate clusters of galaxies

- ➔ *how galaxy formation affects the mass distribution in clusters?*
- ➔ *what are the implications for lensing studies?*

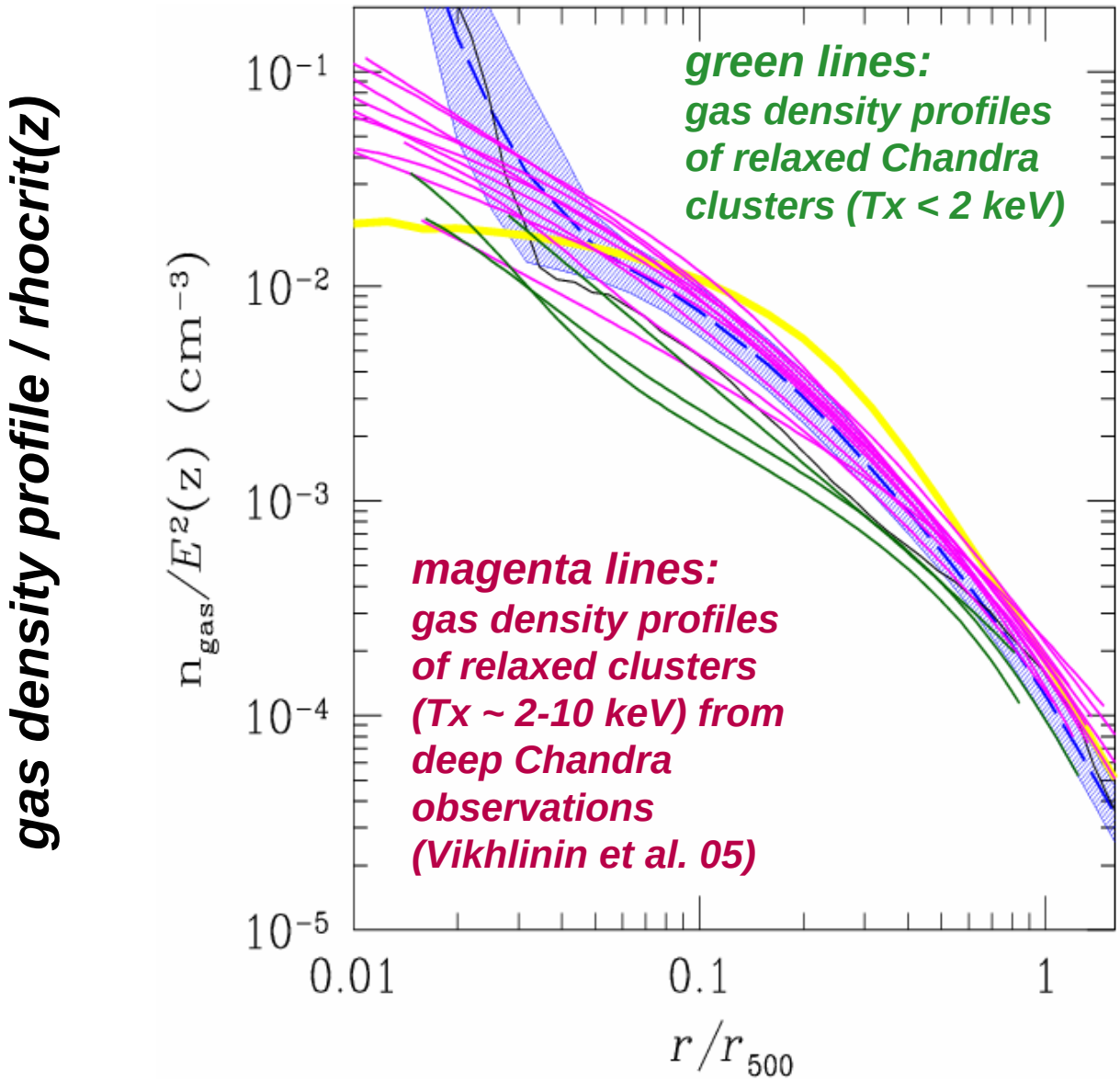




a Virgo-sized cluster from our sample

The Art and Science of

gas density profiles: simulations vs observations



Nagai, Kravtsov & Vikhlinin
2006, in preparation

yellow line:
mean gas density profile for clusters in adiabatic simulations

blue band:
mean gas density profile for clusters in simulations with cooling and star formation
width = rms scatter

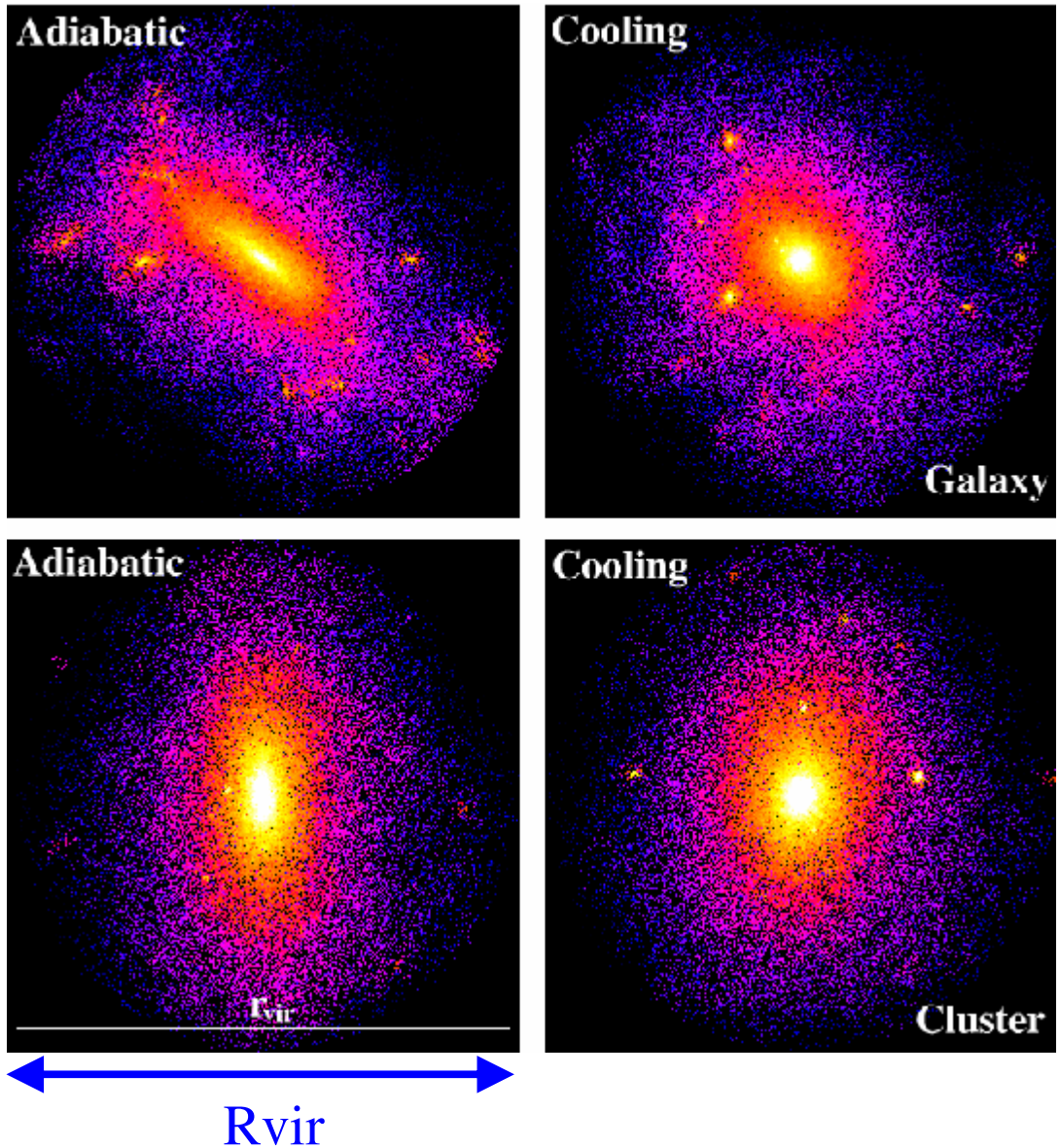
cluster-centric radius in units of r_{500} (500 wrt rho_crit)

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



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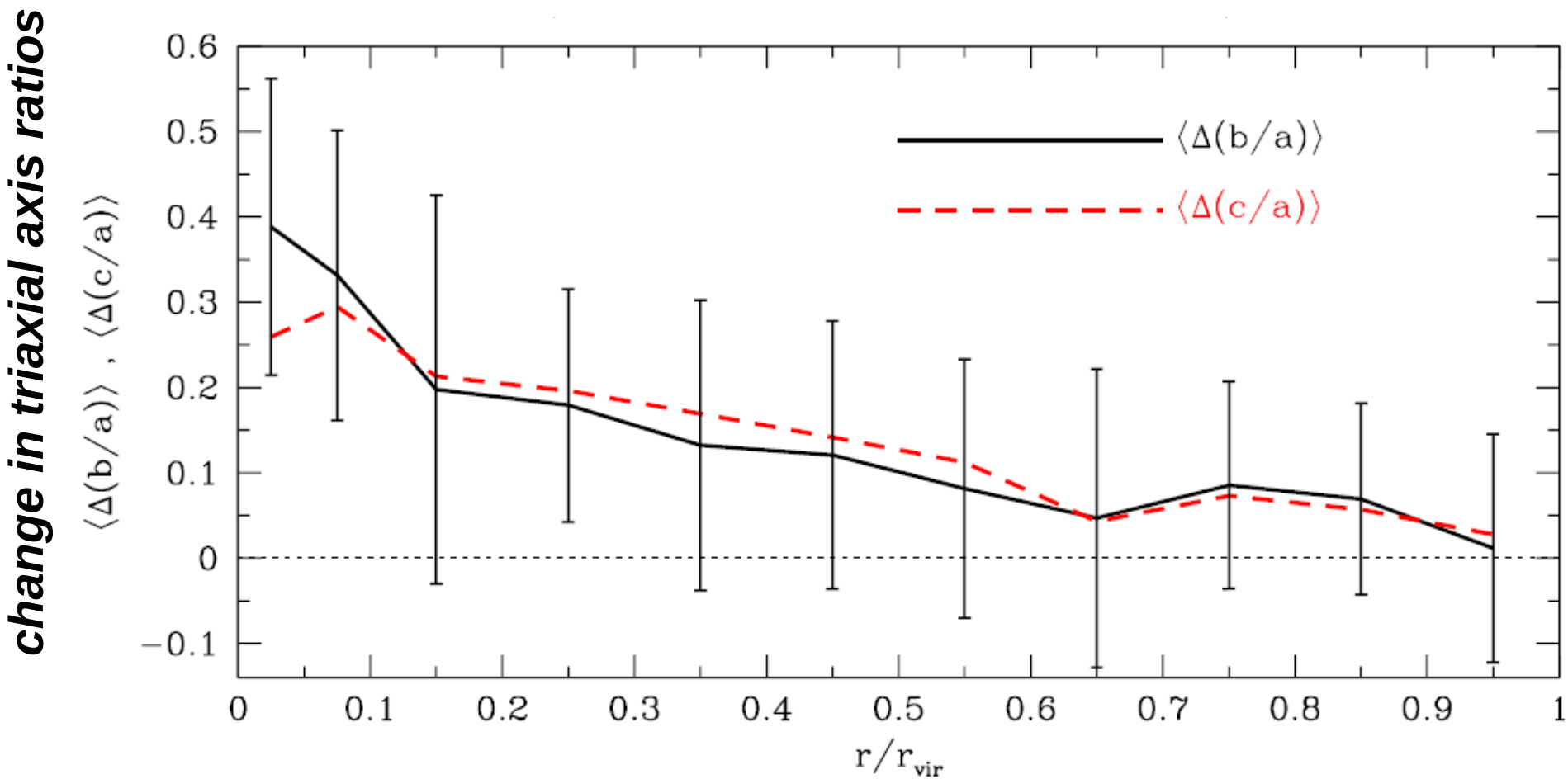
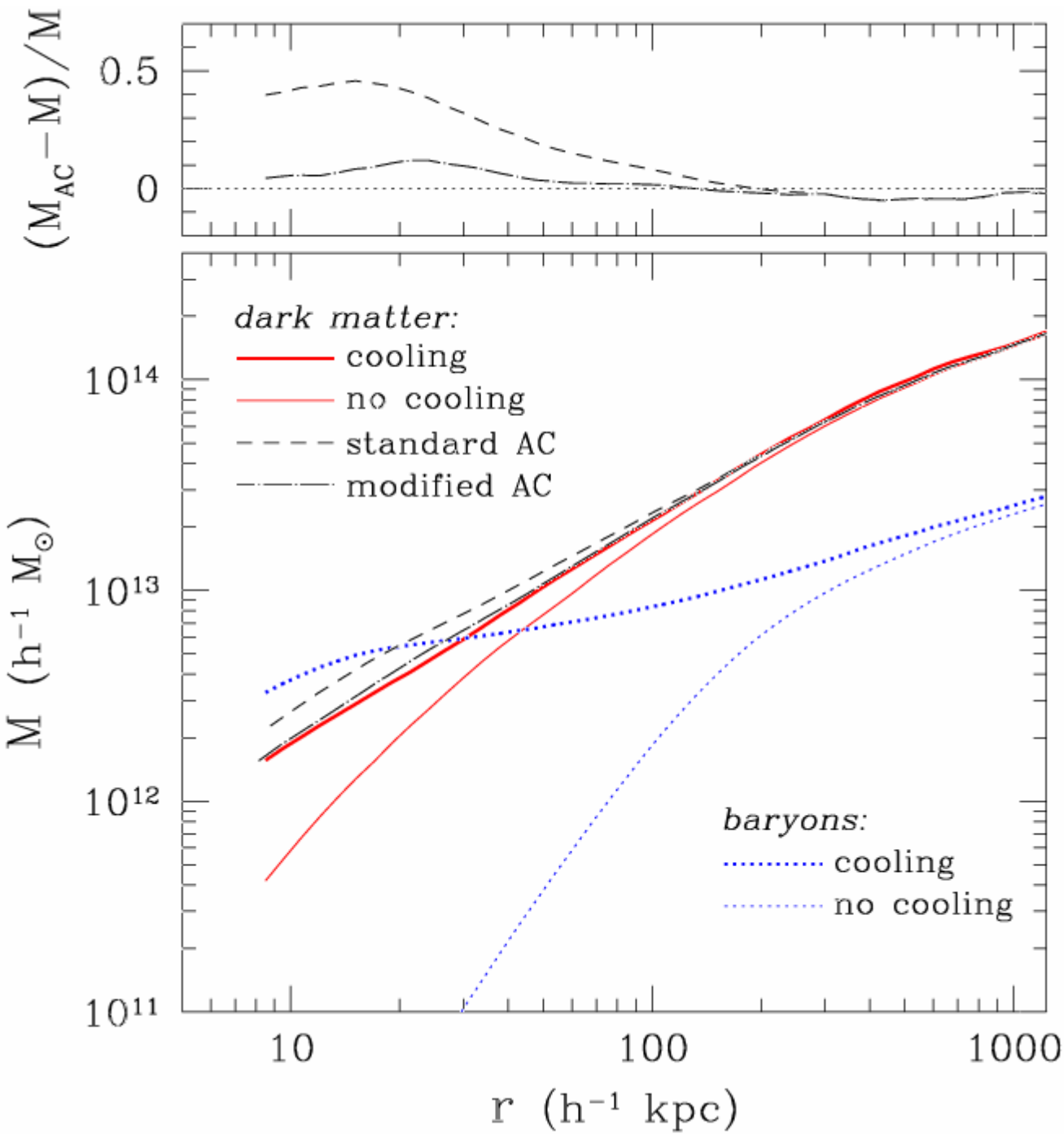


cluster-centric radius in units of virial radius

effect of baryon cooling on inner mass distribution



Eggen, Lynden-Bell & Sandage 1967; Zeldovich et al. 1980; Barnes & White 1984

Standard Model

homologous contraction, circular orbits

Blumenthal et al. 1986
Ryden 1987

$$M(r)r = \text{const}$$

$$[M_{\rm dm}(r) + M_{\rm b}(r)]\, r = [M_{\rm dm}(r) + M_{\rm b}(r_f)]\, r_f$$

Improved Model

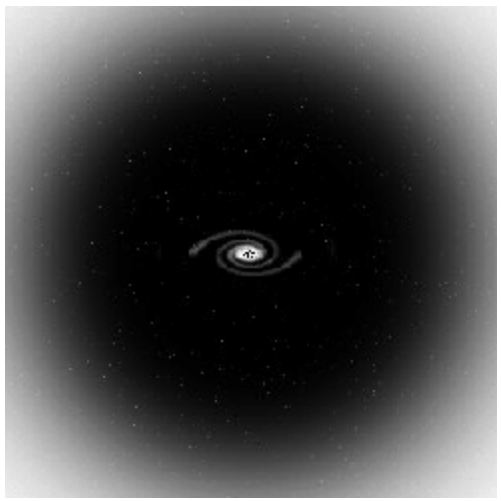
$$M(\bar{r})r = \text{const}$$

$$\bar{x} = Ax^w, \quad x \equiv r/r_{\rm vir}$$

[Gnedin et al. 2004]

Contra code implementing the improved AC model

http://www.astro.lsa.umich.edu/~ognedin/contra/



Contra is a publicly available code that calculates the contraction of a dark matter halo in response to condensation of baryons in its center. The code is based on the modified contraction model of Gnedin et al. (2004).

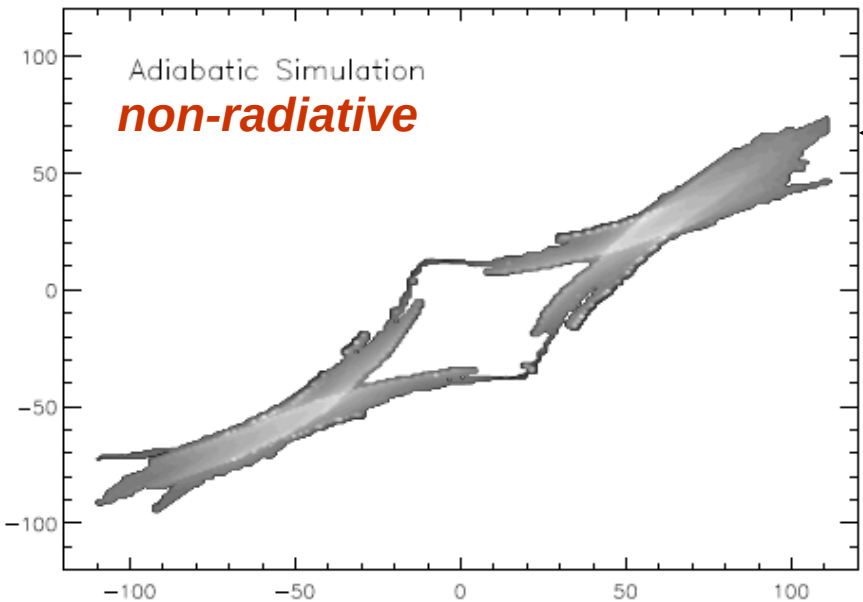
The code also calculates a line-of-sight velocity dispersion for a tracer population with a given density profile and velocity anisotropy (isotropic, constant, Osipkov-Merritt, or Mamon-Lokas model).

Tailored to lensing modeling during this workshop (ask Oleg)

effect of cooling on the abundance of arcs

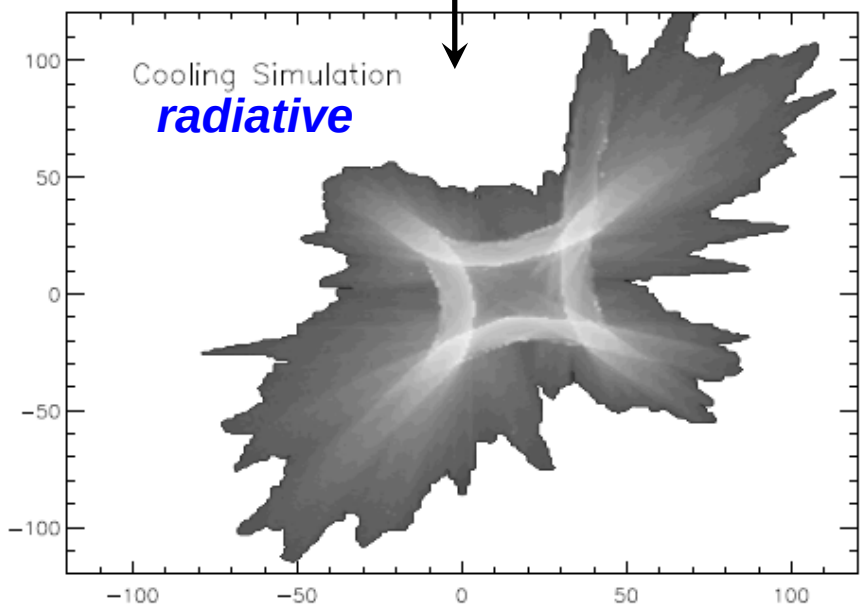
Rozo, Nagai, Keeton & Kravtsov 2006 (astro-ph/0609621)

maps of areas around the cluster center capable of producing arcs with length to width ratio larger than l (grayscale indicates value of l)



position in kpc wrt center of the cluster

the same cluster (simulated from the same initial conditions) with and without cooling



position in kpc wrt center of the cluster

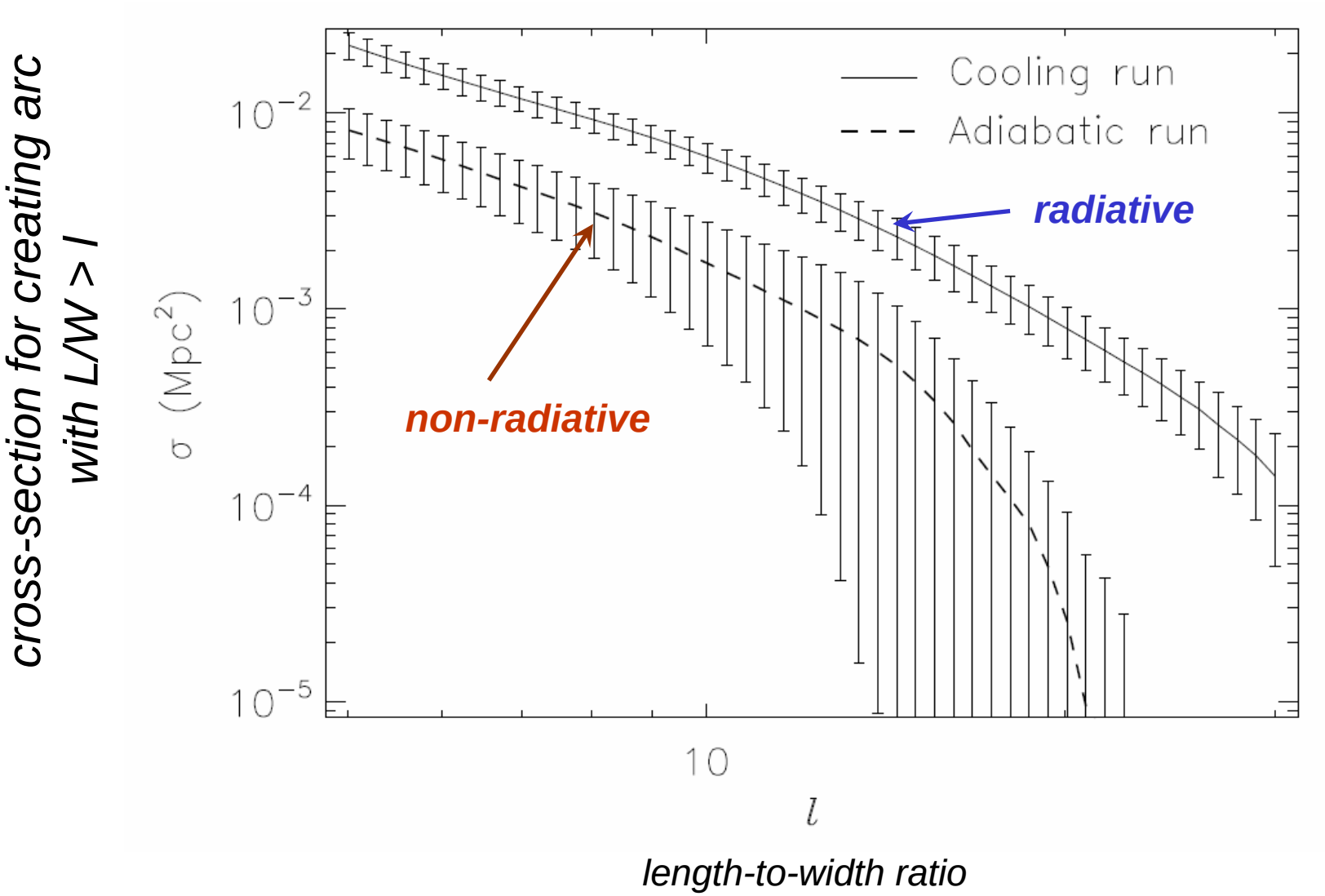
Cooling and associated condensation of baryons and steepening of the central density profile increase cross-section for long arcs substantially

effect of cooling on the abundance of arcs

Rozo, Nagai, Keeton & Kravtsov 2006 (astro-ph/0609621)

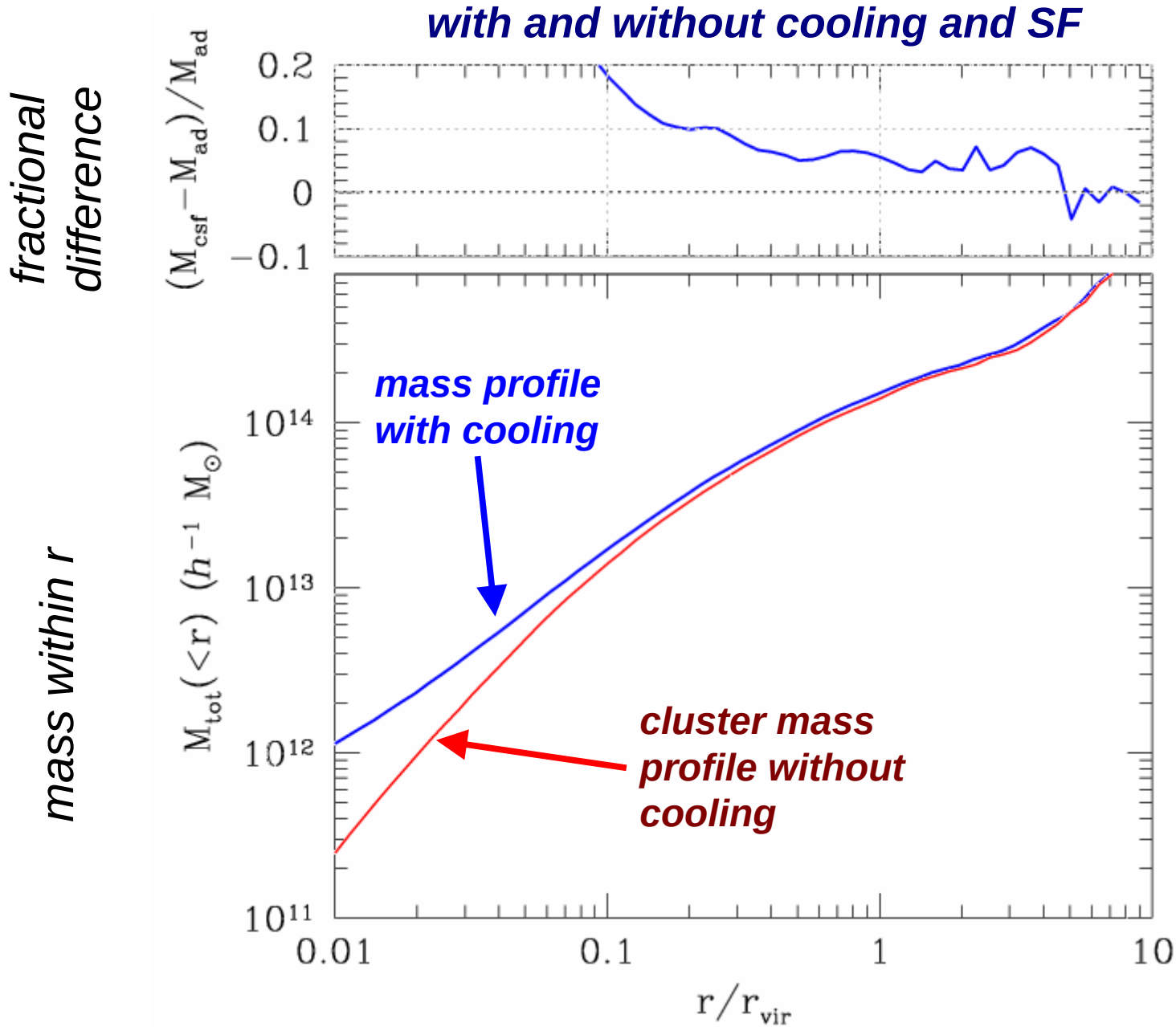
cross-section $\sigma(l)$ is defined as area of the source plane which is lensed by a cluster into an arc with length-to-width ratio larger than l:

$$dn_{arcs} = \sigma(l)\, dn_{source}$$



effect of dissipation on the overall mass profile

simulation of the same galaxy cluster with and without cooling and SF



cluster - centric radius in units of the virial radius

at r<0.1rvir – standard adiabatic contraction effect

but the effect is actually non-zero all the way beyond rvir

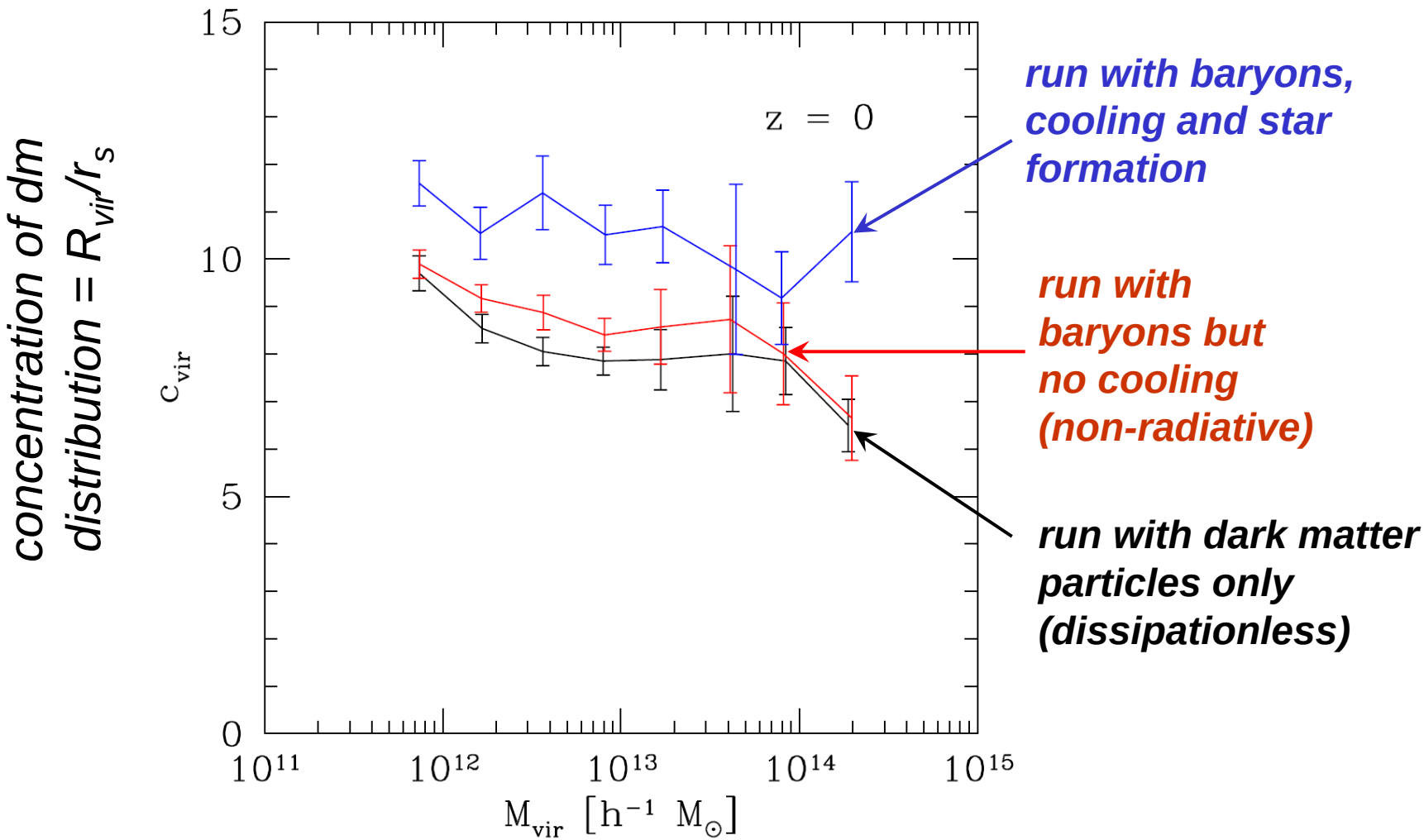
Nagai, Kravtsov Vikhlinin 2006, in prep.

Rudd, Zentner Kravtsov 2006, in prep.

effect of baryons on dm halo concentrations

Rudd, Zentner & Kravtsov 2006
also Lin et al. 2006

three runs started from identical initial conditions but run with different physics:

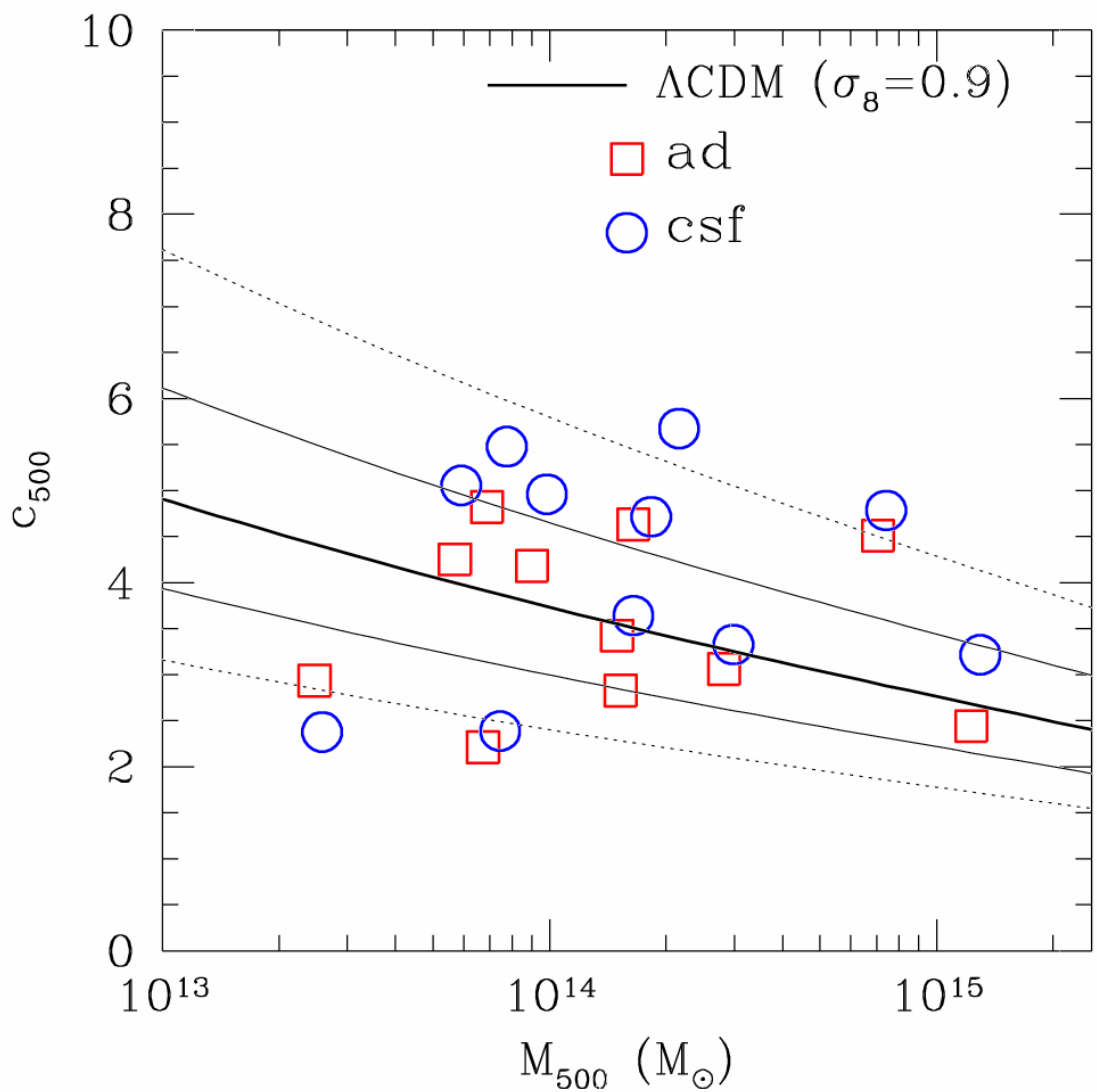


virial mass (overdensity of 337)

effect of cooling on halo concentrations

higher resolution cluster simulations

halo concentration



$c_{500} = r_{500}/r_s$

Nagai, Kravtsov Vikhlinin 2006, in prep.

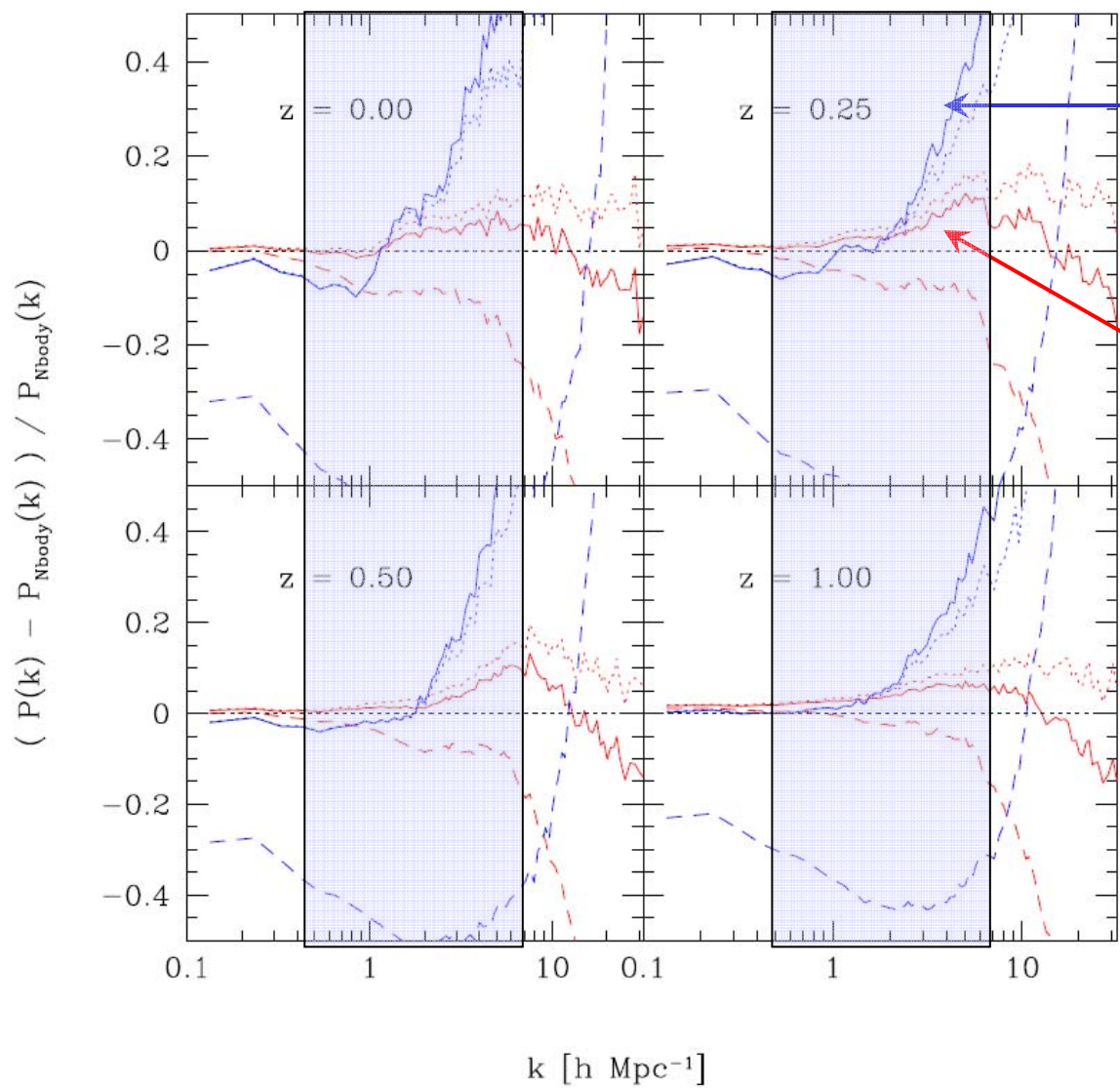
M_{500} - mass within radius enclosing overdensity of 500 x ρ_{crit}

effect of baryons on matter power spectrum

Rudd, Zentner & Kravtsov 2006; Jing et al. 2006

three runs started from identical initial conditions but run with different physics:

fractional difference in P(k) from the dark matter only simulation



wavenumber

run with baryons, cooling and star formation

run with baryons but no cooling (non-radiative)

lines:

solid – total mass spectrum

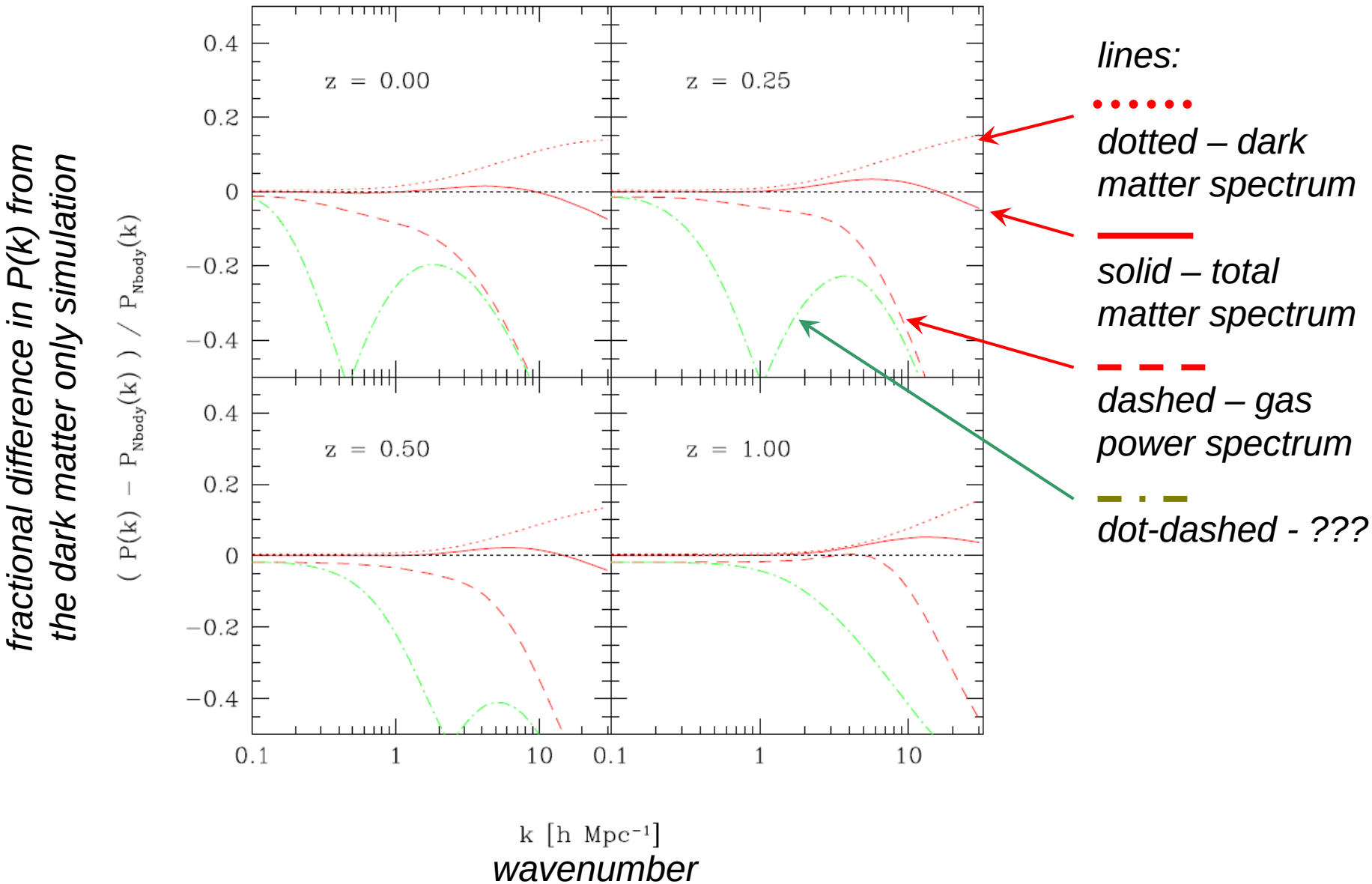
dotted – dark matter spectrum

dashed – gas power spectrum

effect of baryons on matter power spectrum

halo model – non-radiative case

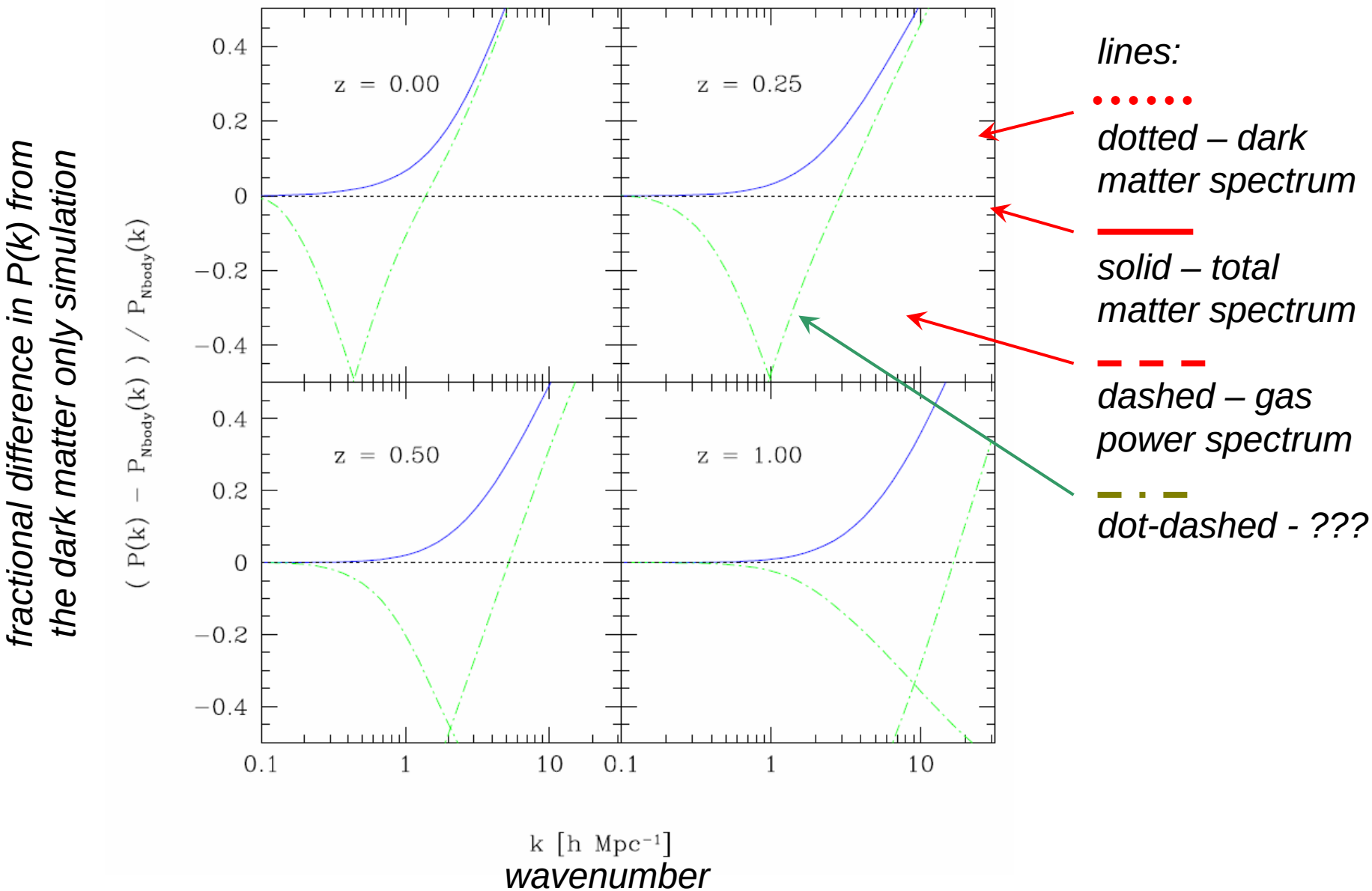
Rudd, Zentner & Kravtsov 2006



effect of baryons on matter power spectrum

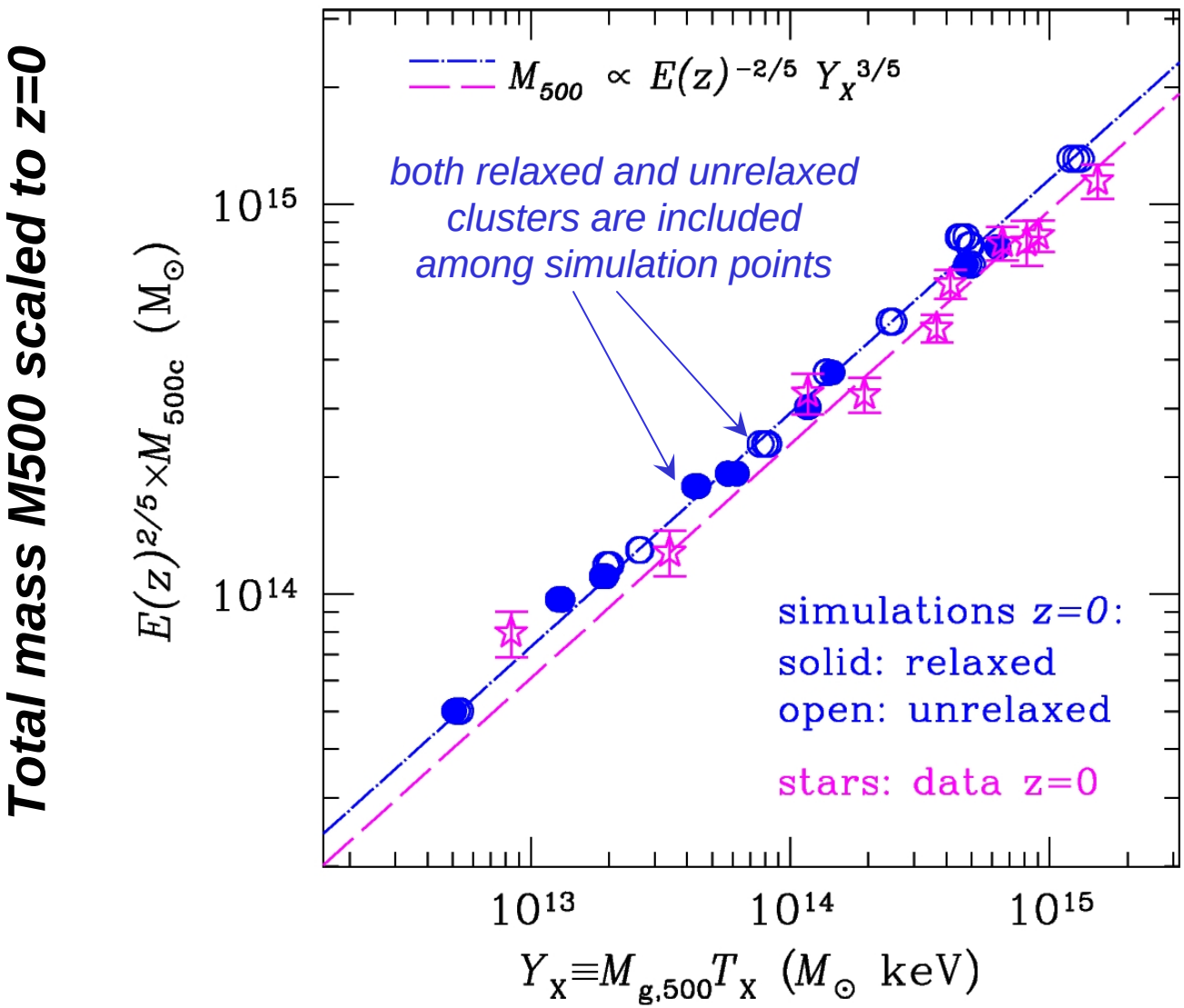
halo model – radiative case

Rudd, Zentner & Kravtsov 2006



robust and accurate X-ray mass indicator

X-ray masses can be used for cross-comparison with lensing masses even for unrelaxed systems



Normalizations of the model and observed Yx-M relations agree to ~10%

Kravtsov, Vikhlinin, Nagai
2006, ApJ 650, 128
astro-ph/0603205

X-ray "pressure" = Yx = gas mass x temperature

Summary

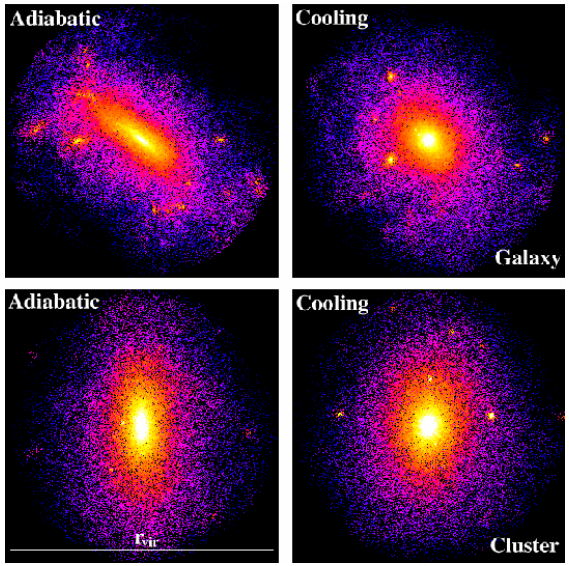
- Gas cooling and star formation affect the global distribution of dark matter within halos: in particular the slope of the inner cusp and overall concentration of matter distribution

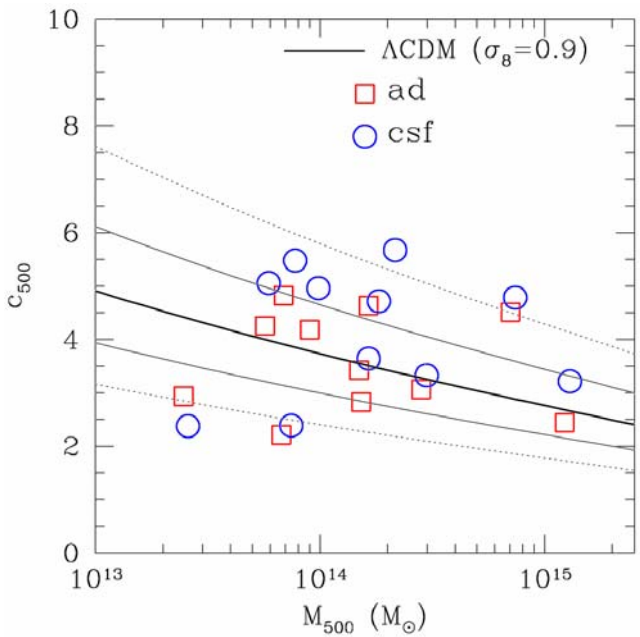
- Changes in the mass distribution significantly affect strong lensing cross sections for tangential arcs and have a non-negligible effect on the matter power spectrum on the scales where future weak lensing surveys have most statistical power.

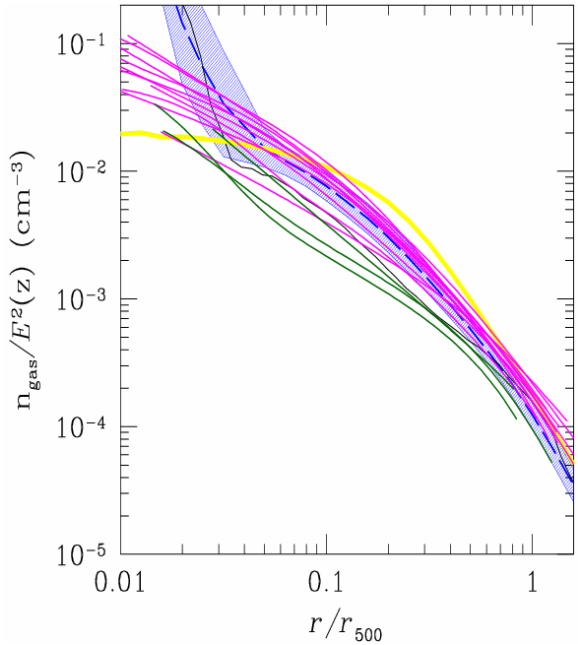
- The magnitude of the effects depends on the correct treatment of baryonic physics in simulations, but non-trivial effects are present even in non-radiative simulations with minimum physics.

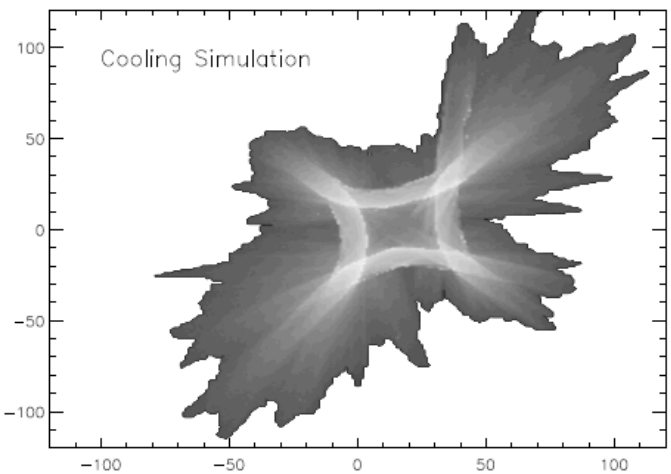
- This complicates usage of lensing statistics for precision cosmology but opens the possibility of constraining physics of galaxy formation

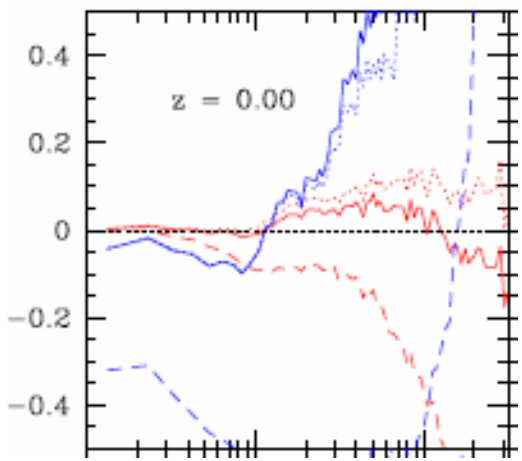
Summary (pictorial version)

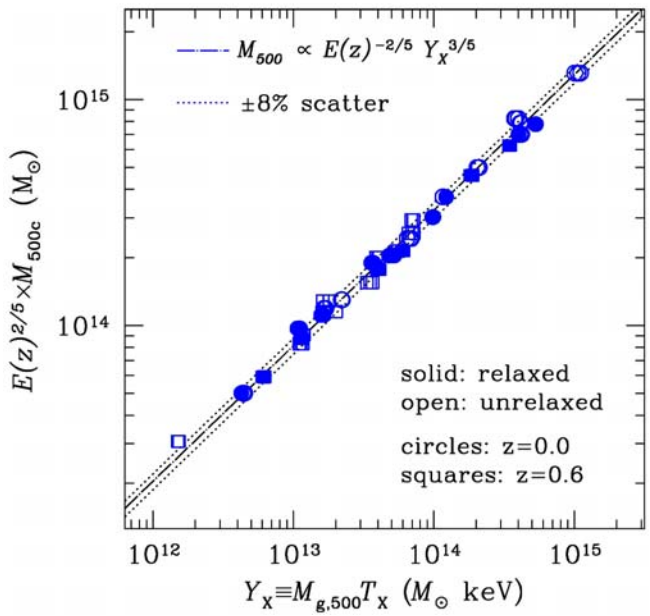












A·S·P·E·N Center for Physics

"Clusters of galaxies as cosmological probes"

Aspen, Colorado, Feb 12-16 2007

SOC: A. Kravtsov, J. Carlstrom, C. Jones, T. McKay, J. Mohr, A. Vikhlinin

http://astro.uchicago.edu/~andrey/clcp07

application deadline – November 1