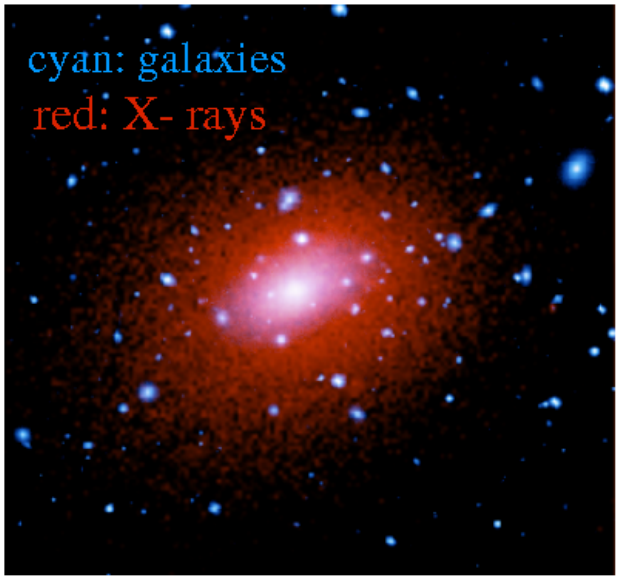
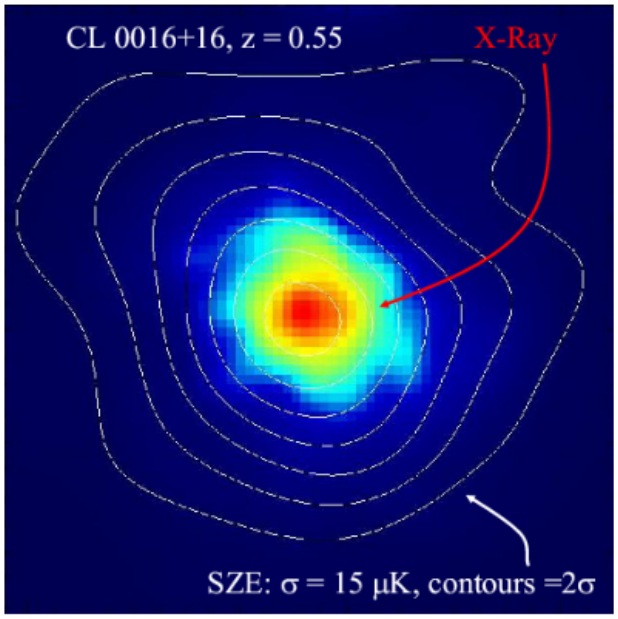
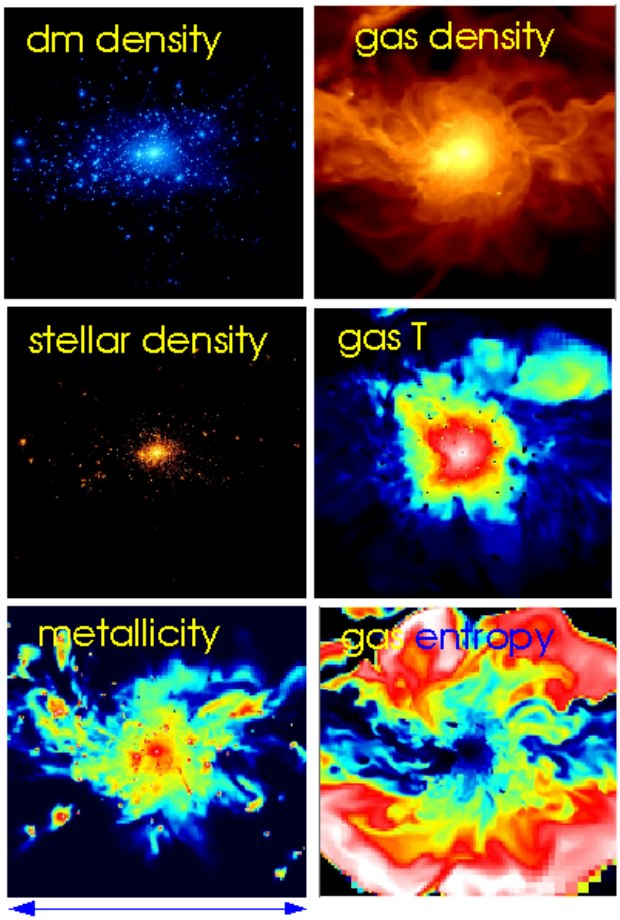


Modelling clusters of *galaxies*

Andrey Kravtsov
University of Chicago



Towards self - consistent simulations of cluster galaxies



$8h^{-1}$ Mpc

9 individual galaxy clusters
virial masses from 8×10^{13} to 9×10^{14} /h Msun

Cosmological N- body+gasdynamics ART code
(Kravtsov 1999, 2003; Kravtsov et al. 2002)
m_{dm}=3e8/h Msun, m_{*}~10^{6}/h Msun
peak resolution ~ 2/h kpc
2e7 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 by SNII/Ia + **Advection of metals**

Stellar mass loss based on population synthesis models

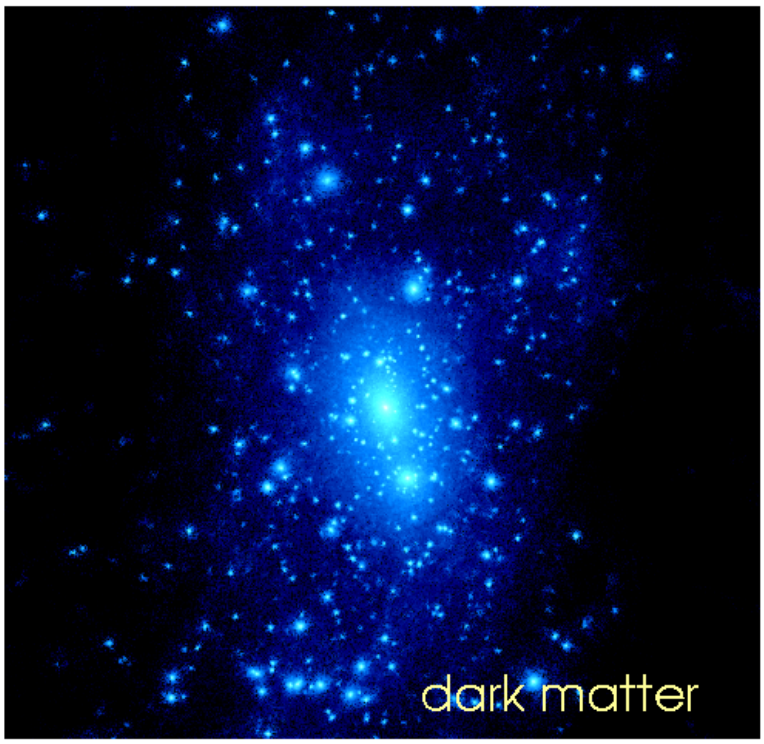
Collaborators

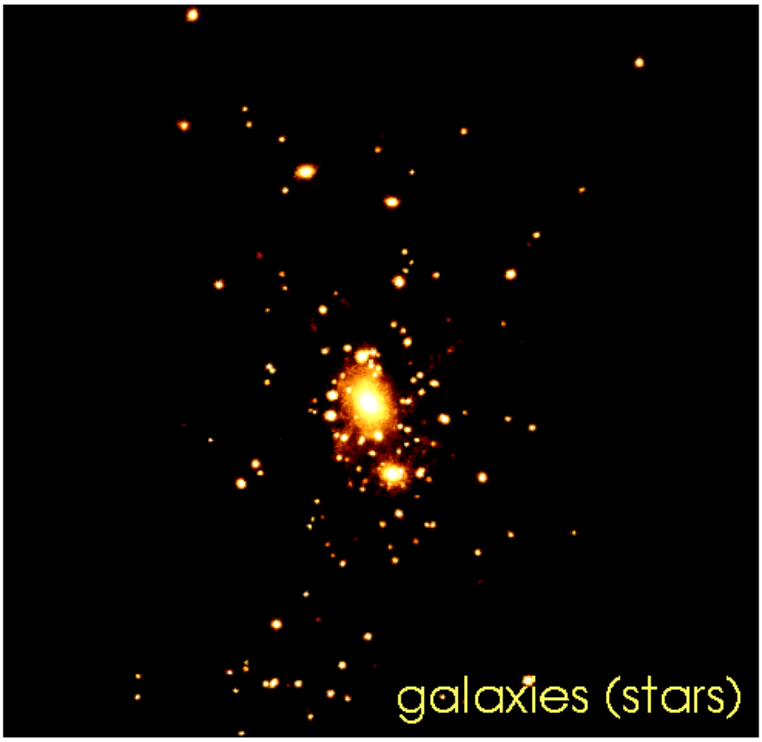
Daisuke Nagai
(University of Chicago)

Alexey Vikhlinin
(CfA, Harvard/ IKI)

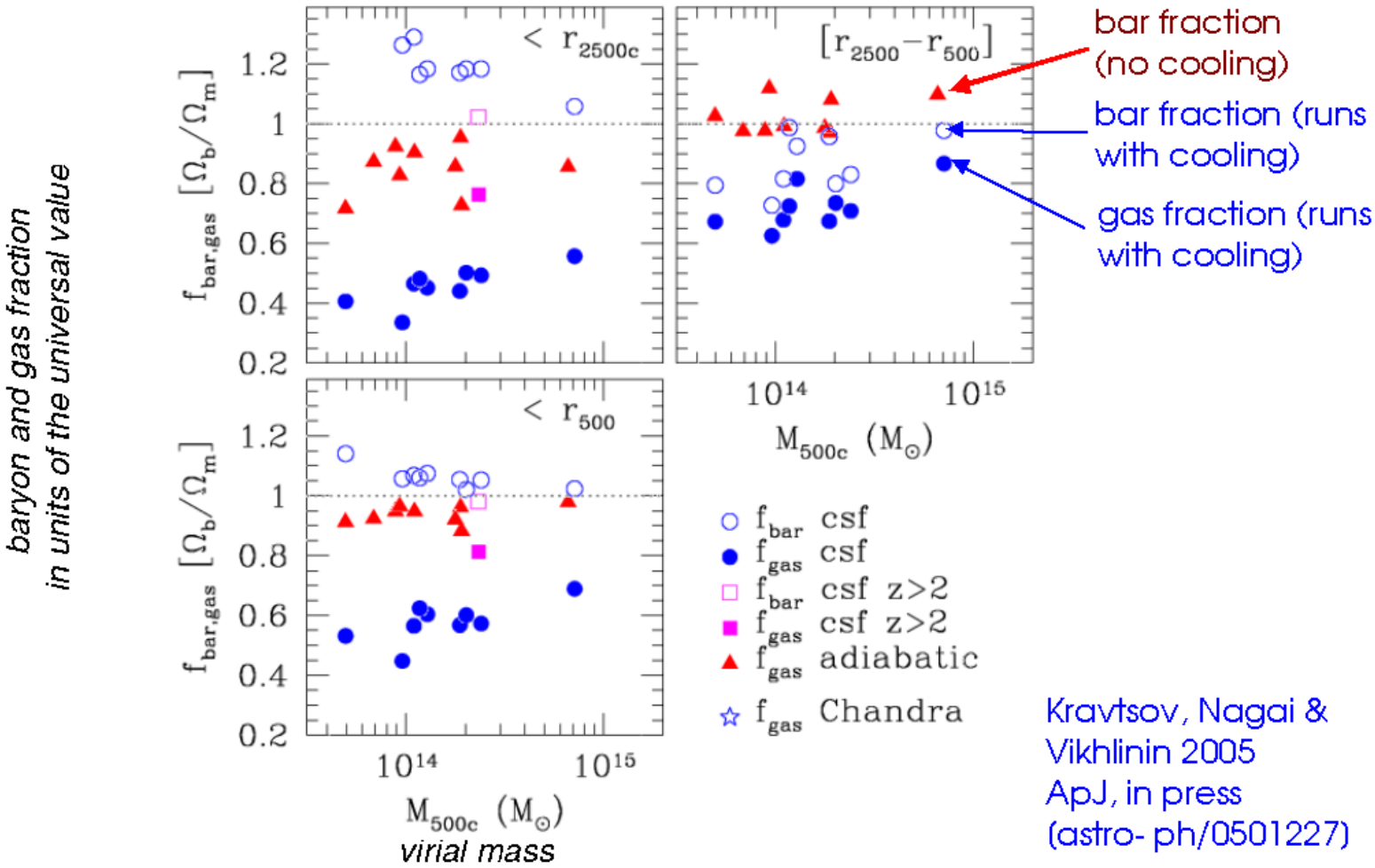
High resolution allows us to actually simulate clusters *of galaxies*

Virgo - size cluster from our sample



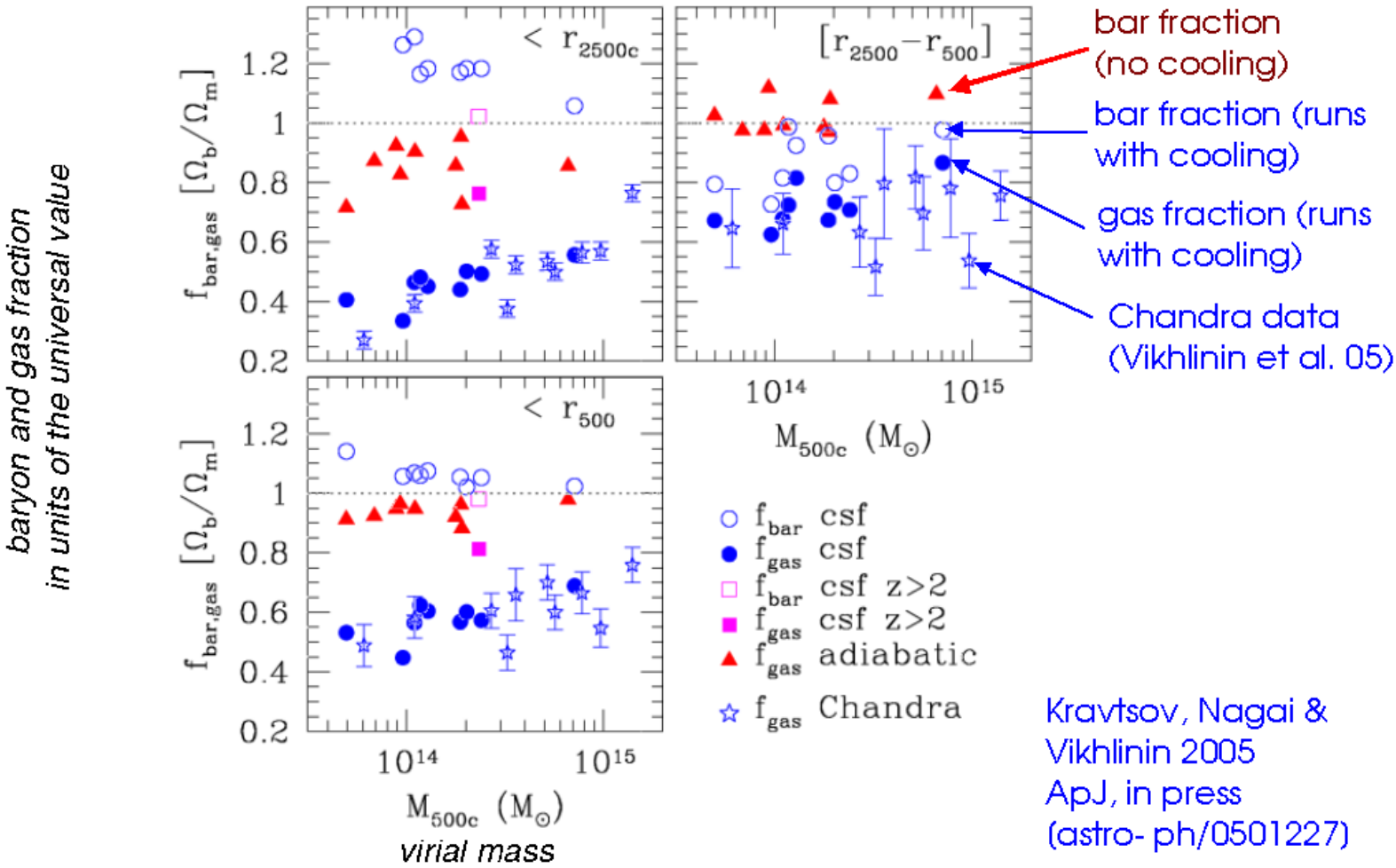


Effect of galaxy formation on the baryon and gas fractions in clusters



Kravtsov, Nagai & Vikhlinin 2005
ApJ, in press
(astro- ph/0501227)

Effect of galaxy formation on the baryon and gas fractions in clusters



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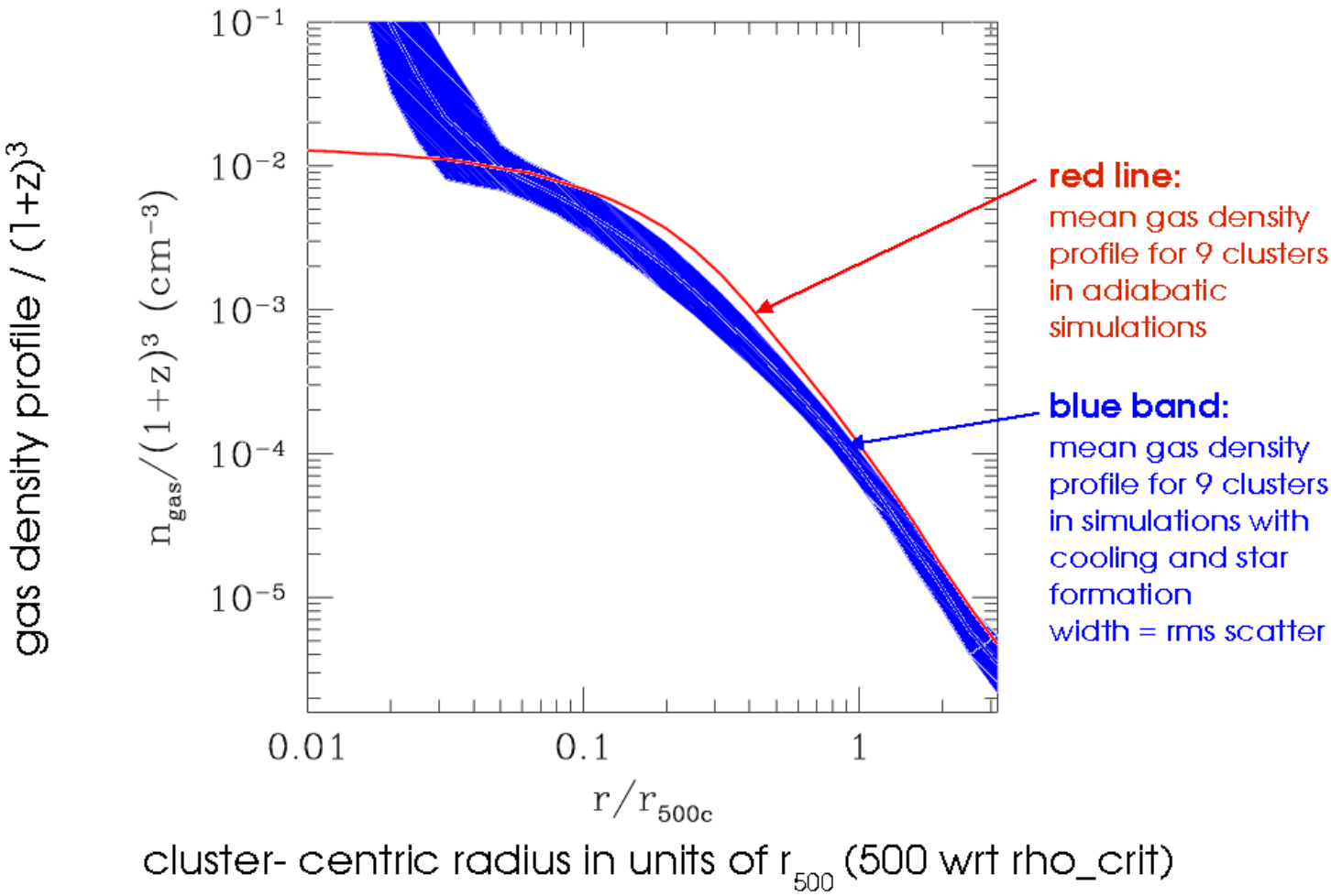
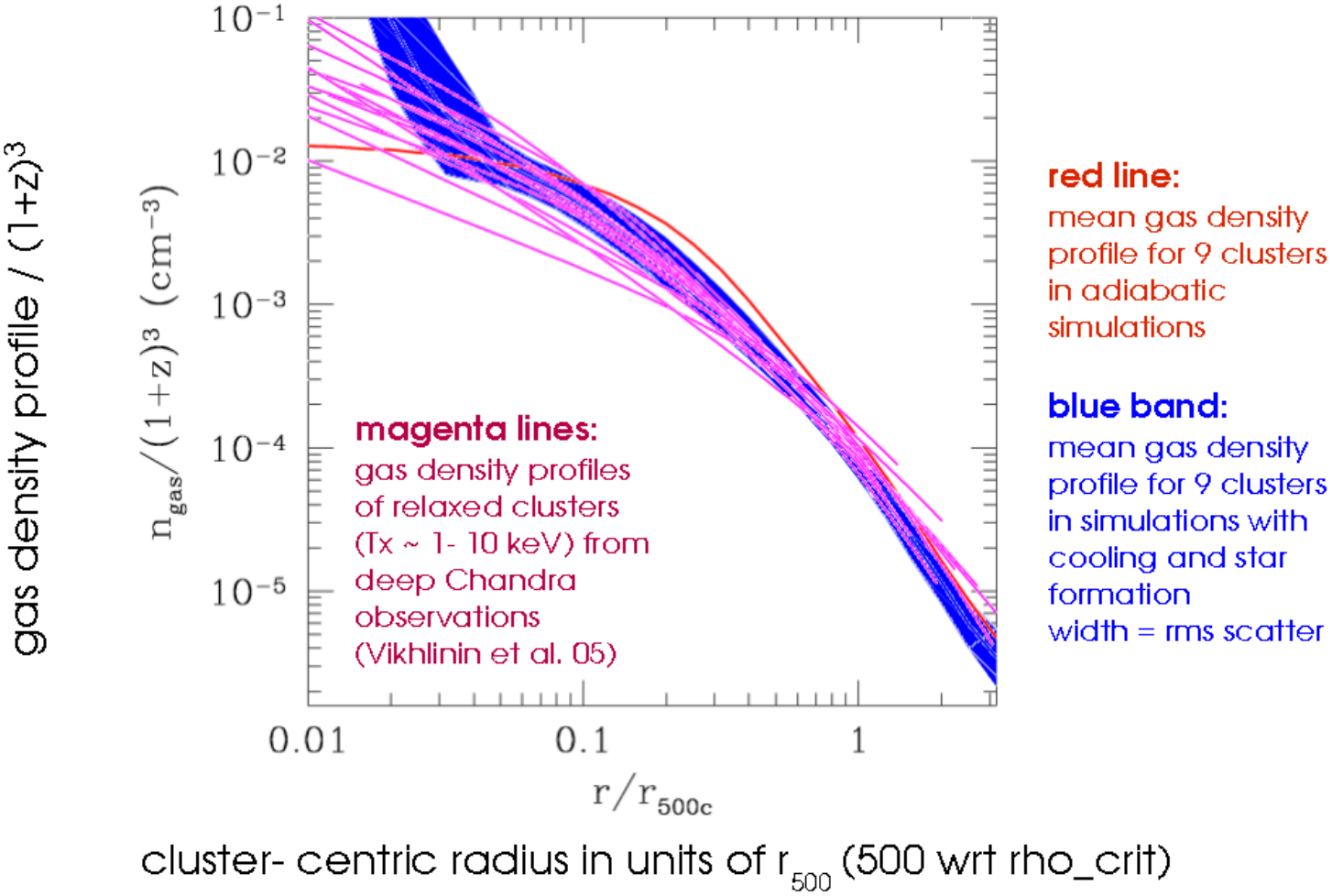
Effect of galaxy formation on the cluster gas density profile



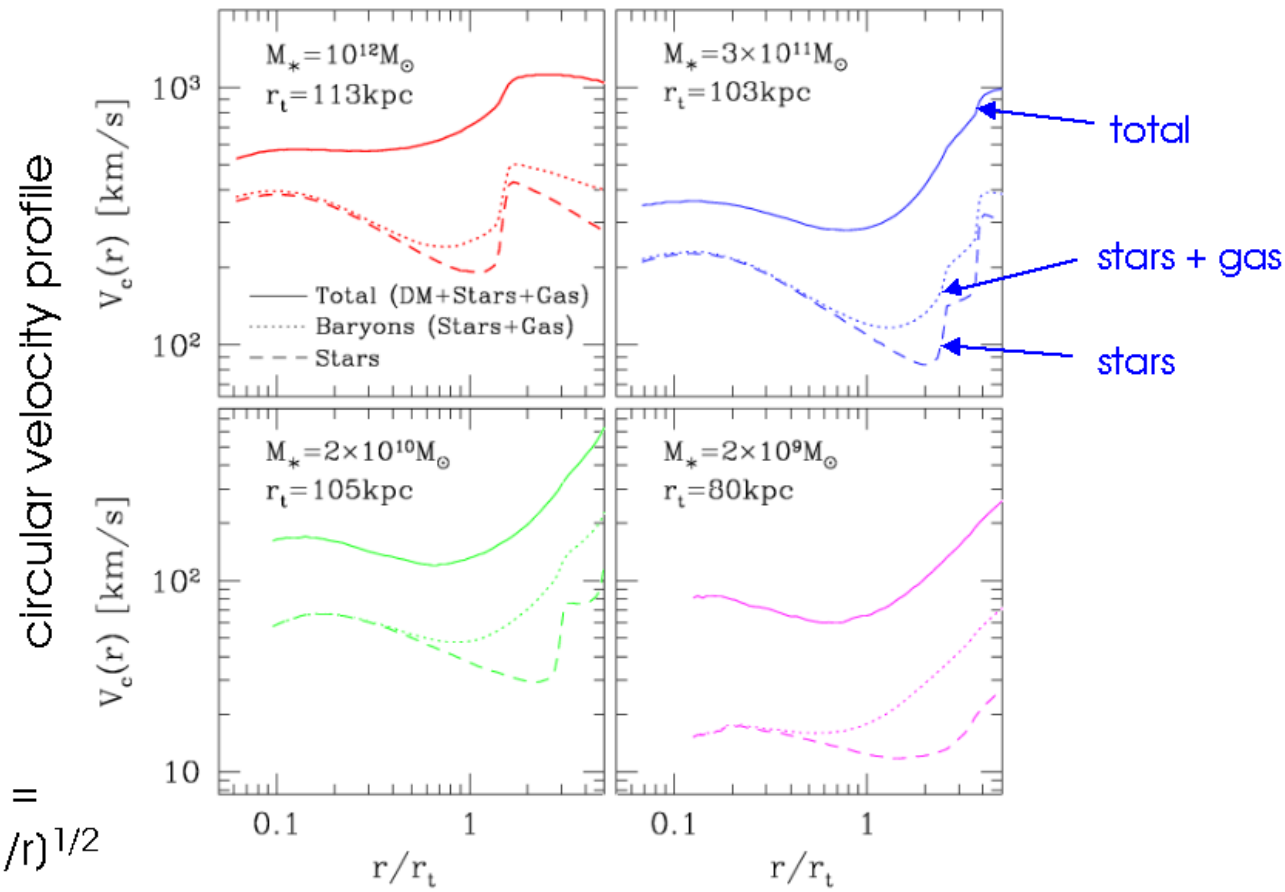
cluster- centric radius in units of r_{500} (500 wrt rho_crit)

Effect of galaxy formation on the cluster gas density profile



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

Circular velocity profiles of four individual cluster galaxies

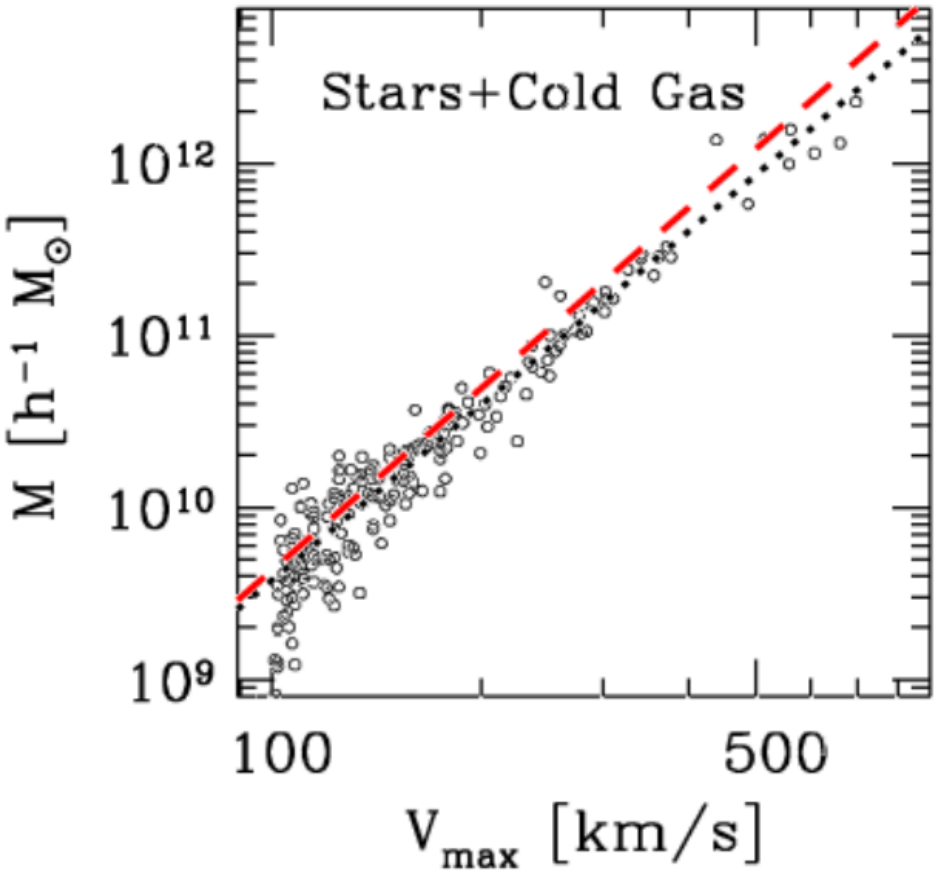


$Vc(r) = (GM(<r)/r)^{1/2}$

distance from the galaxy center in units of tidal radius

Galaxies in simulated clusters: the Mstar - Vmax ("Tully - Fisher") relation

galaxy mass (stars+ cold gas)



maximum circular velocity of galaxies

red dashed line:
field galaxies
(Bell & de Jong '01)

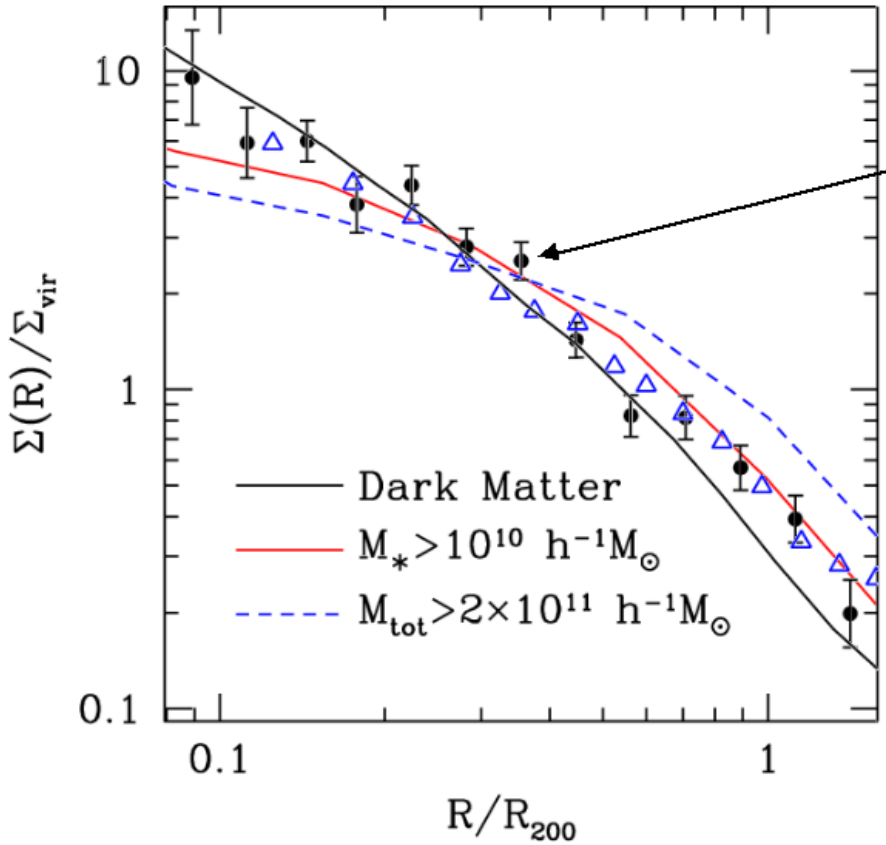
dotted line:
best fit to simulated cluster galaxies
$M \sim V_{max}^{3.4}$

Nagai & Kravtsov 2005 in preparation

Simulated cluster galaxies: no significant spatial or velocity bias (bv=1.1)

(if galaxies are selected using stellar mass)

surface density profile



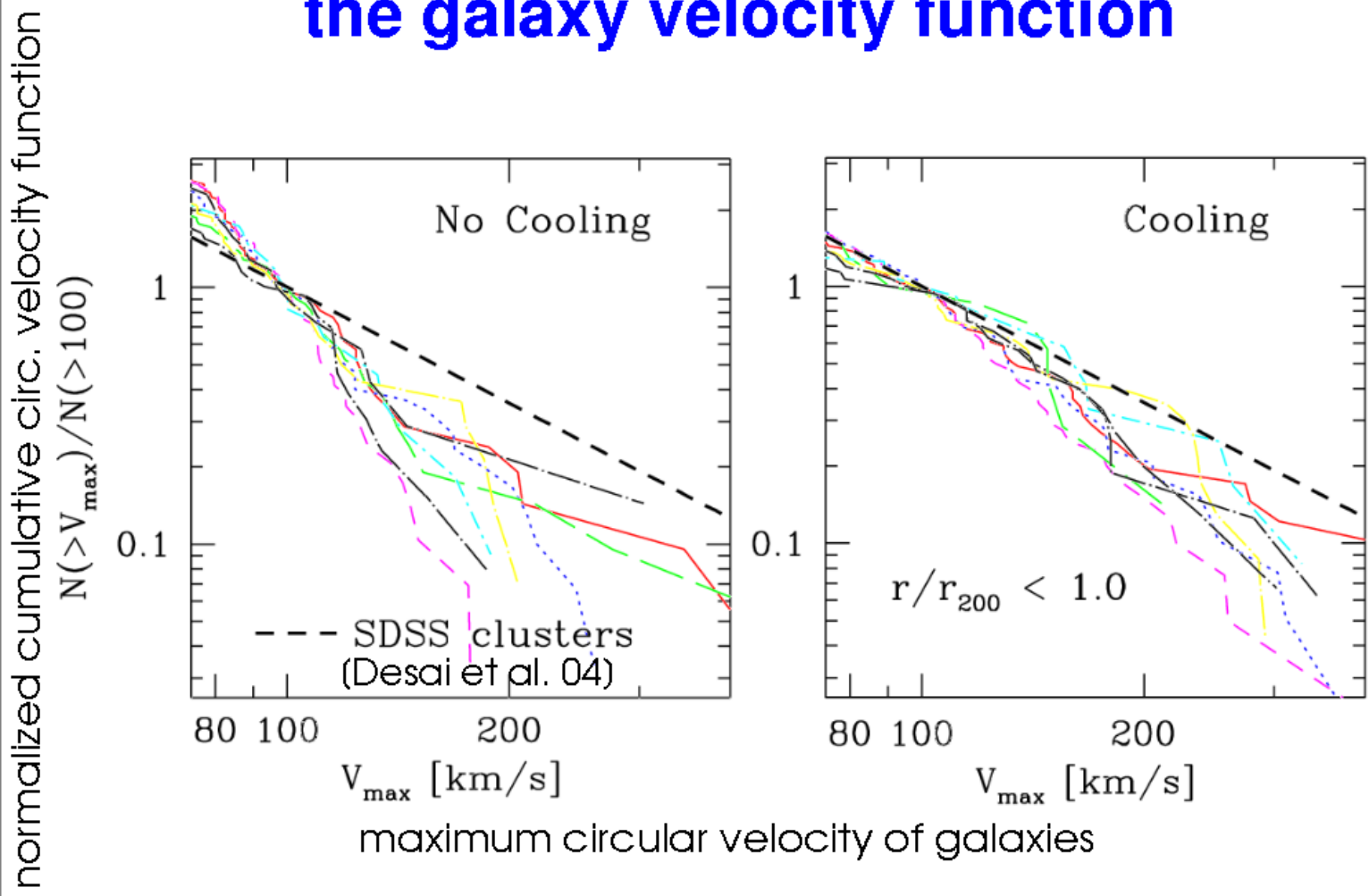
data:
CNOC - circles
(Carlberg ea 1997)
+
2MASS - triangles
(Lin & Mohr 2004)

Nagai & Kravtsov 2005 ApJ 618, 557

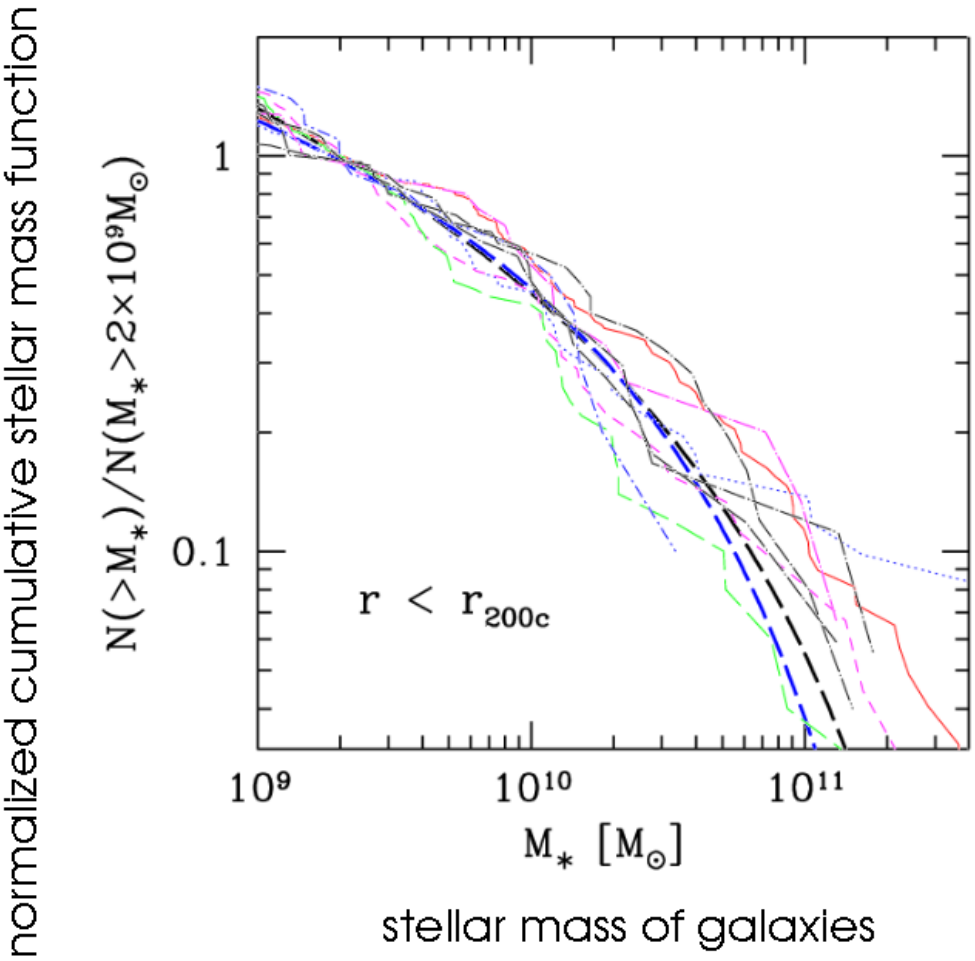
Faltenbacher, Kravtsov, Nagai & Gottloeber 2005 MNRAS 358, 139 astro-ph/0408488

projected cluster-centric radius in units of R_{200}

Effect of cooling on the galaxy velocity function



Cumulative stellar mass function



thick dashed lines:
blue - composite stellar mass function of cluster galaxies (2MASS data; Lin et al. 2003)
black - Abell 85 (SDSS; Mesheriakov & Vikhlinin 2005)

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

scaling with mass:
Kravtsov et al. 2004
Zentner et al. 2005

Summary

- Gasdynamics + N- body cluster simulations with galaxy formation remedy some of the problems of dissipationless simulations and reasonably reproduce key observations:

  - *gas density profiles*
  - *Tully- Fisher relation*
  - *radial distribution of galaxies*
  - *circular velocity function*
  - *the shape of the stellar mass function*

- Galaxy formation has a fairly dramatic effect on cluster gas and baryon fractions

- fgas(simulated clusters) ~ fgas(observed clusters).
  Just how bad is the overcooling problem?