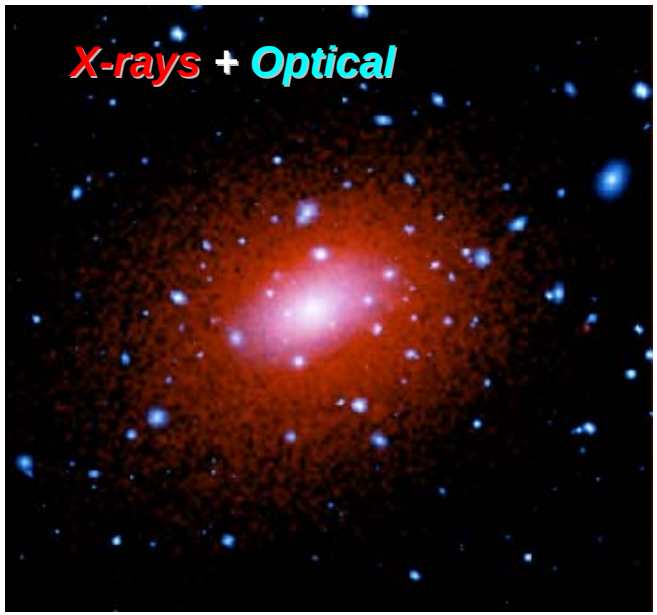
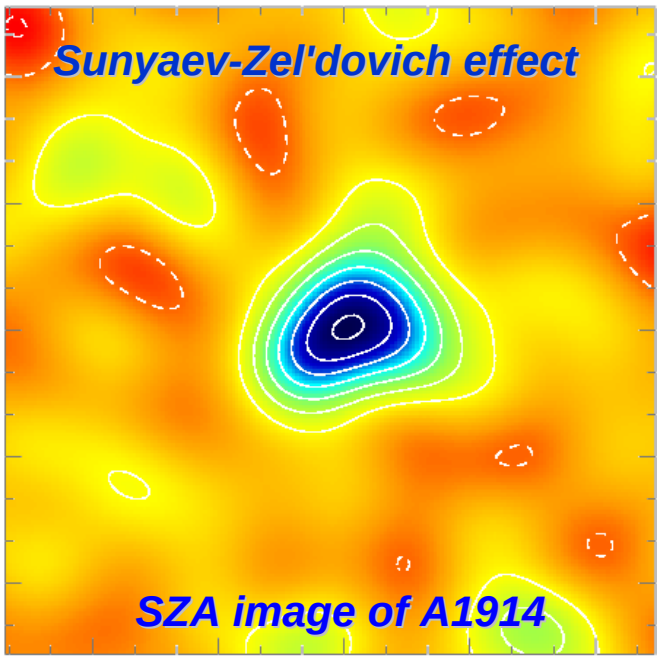


Lighting up the Dark Universe

Modelling the distribution and properties of baryons in galaxy clusters

Daisuke Nagai

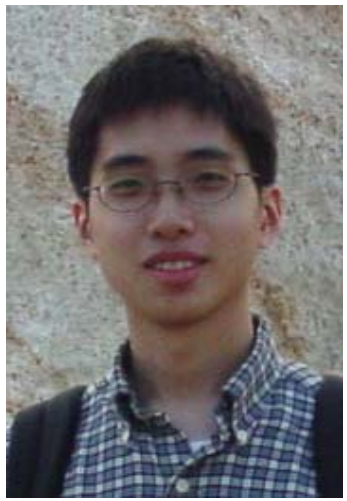
Caltech



Collaborators

Andrey Kravtsov
(U.Chicago)

Alexey Vikhlinin
(SAO Harvard, IKI Moscow)



Erwin Lau
(U.Chicago)

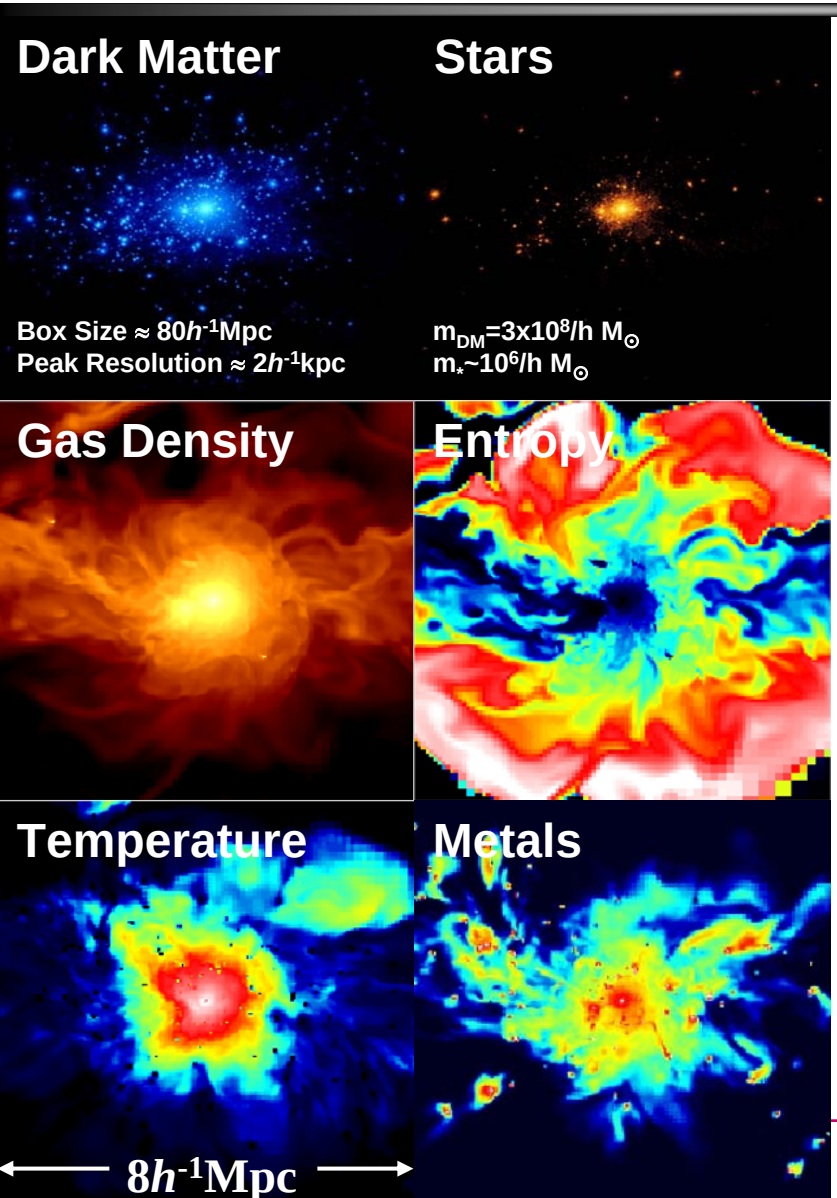
Michael Mortonson
(U.Chicago)

+ John Carlstrom,
Sam Laroque *(U.Chicago)* *+ …*

Outlines

- **Cosmological cluster simulations with baryons**
- **Effects of baryons on the mass distribution in groups and clusters & implications for lensing (a talk last week by Andrey Kravtsov)**
  - **The inner and outer mass profiles**
  - **The shapes of dark matter halos**
- **Properties of baryons in clusters (today's talk)**
  - **How realistic are the distribution and properties of baryons in simulated clusters?**
  - **How can observations of baryons (stars & gas) help with lensing studies?**

Cosmological Cluster Simulations with Baryons



N-body+Gasdynamics with ART code

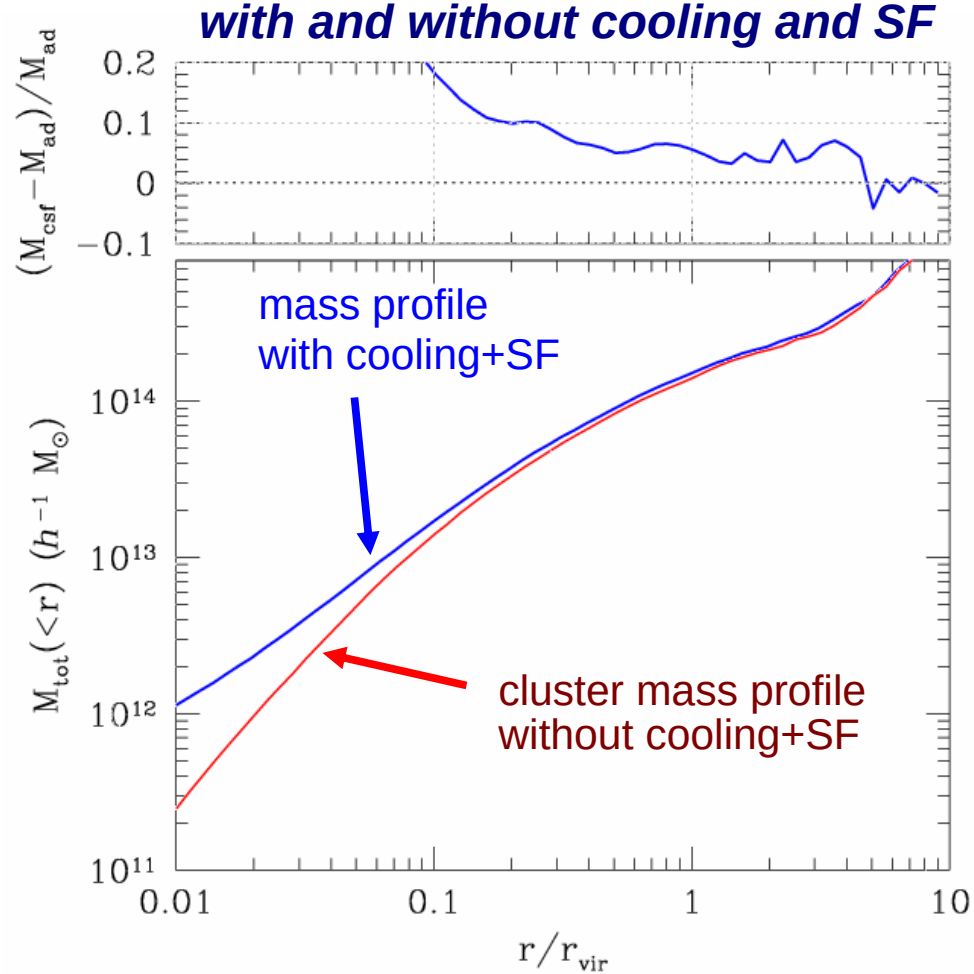
- **Collisionless dynamics** of DM and stars
- **Gasdynamics**: Eulerian Adaptive Mesh Refinement
- **Radiative cooling and heating of gas**: metallicity dependent net cooling/heating rates
- **Star Formation** using the Kennicutt (1998) recipe
- **Thermal stellar feedback**
- **Metal enrichment** by SNII/Ia
- **No AGN feedback, thermal conduction, magnetic field and cosmic rays**

Cosmological Cluster Simulations

- **High-resolution allows us to actually simulate clusters of galaxies**
- **Study the effects of galaxy formation**
  - **Sample of 16 clusters in ΛCDM model**
  - **Two sets of runs with Cooling & SF (CSF) and with adiabatic gasdynamics**

Effect of gas cooling on the mass profile

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



cluster -centric radius in units of the virial radius

at $r<0.1r_{vir}$ – gas cooling & contraction of dark matter

Eggen, Lynden-Bell & Sandage 1967; Zeldovich et al. 1980; Barnes & White 1984; Blumenthal et al. 1986; Ryden 1987; Gnedin et al. 2004

but the effect is actually non-zero all the way beyond r_{vir}

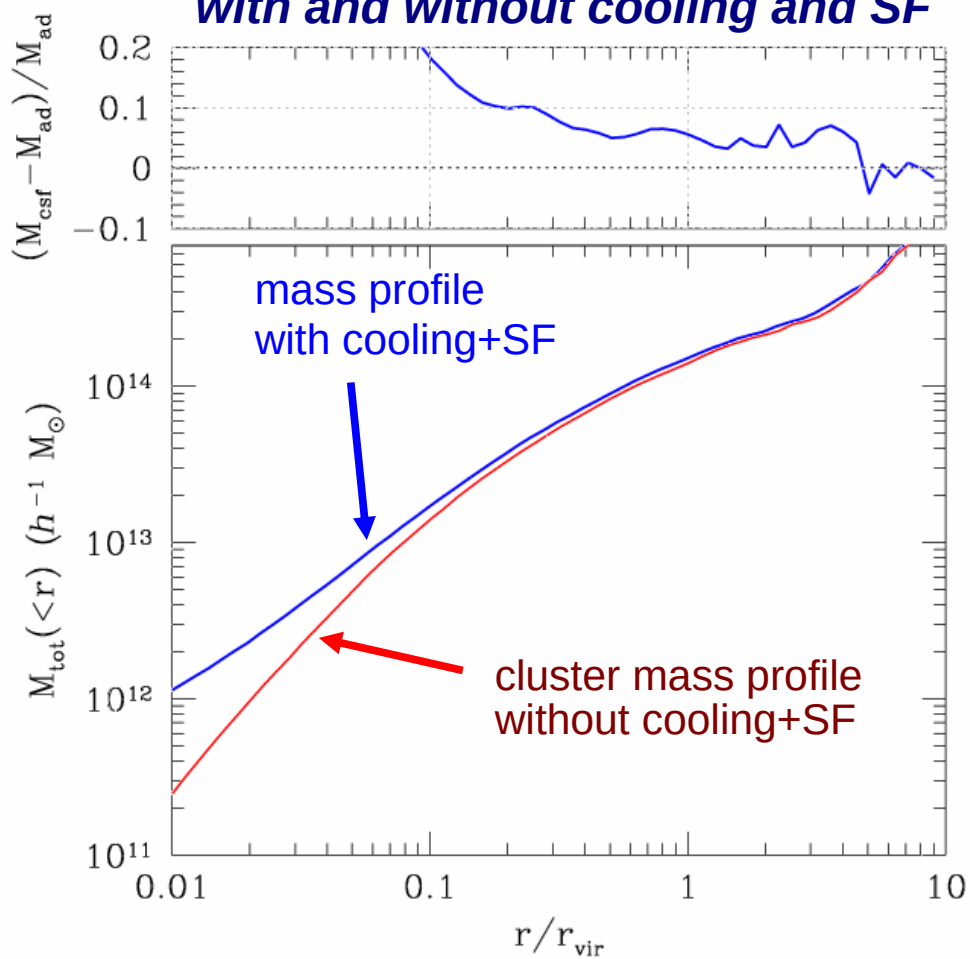
Nagai, Kravtsov,Vikhlinin 2006
Rudd, Zentner, Kravtsov 2006

Also, baryons make triaxial halos rounder

Katz 1991; Evrard et al. 1993; Dubinski 1994; Tissera et al. 1998; Springel 2004; Kazantzidis et al. 2004

Effect of gas cooling on the mass profile
Implications for lensing studies

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



cluster -centric radius in units of the virial radius

Strong lensing

"Changes in the inner mass distribution significantly affect strong lensing cross sections for tangential arcs."

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

Weak Lensing

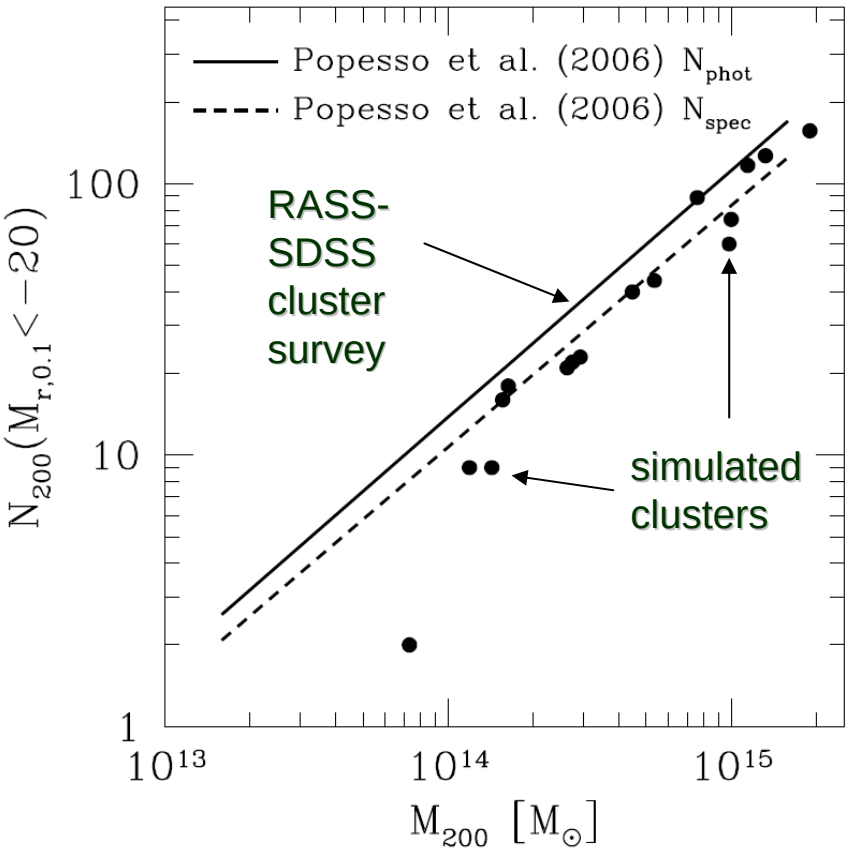
"Changes in the outer mass distribution have a non-negligible effect on the matter power spectrum on the scales where future weak lensing surveys have most statistical power."

Rudd, Zentner, Kravtsov 2006, in prep.

But, the magnitude of the effects depends on the details of baryonic physics in simulations.

How realistic are the properties of simulated galaxies?

Number of galaxies brighter than M_r=-20 as a function of total cluster mass



# of galaxies brighter than Mr < -20 within r_{200}

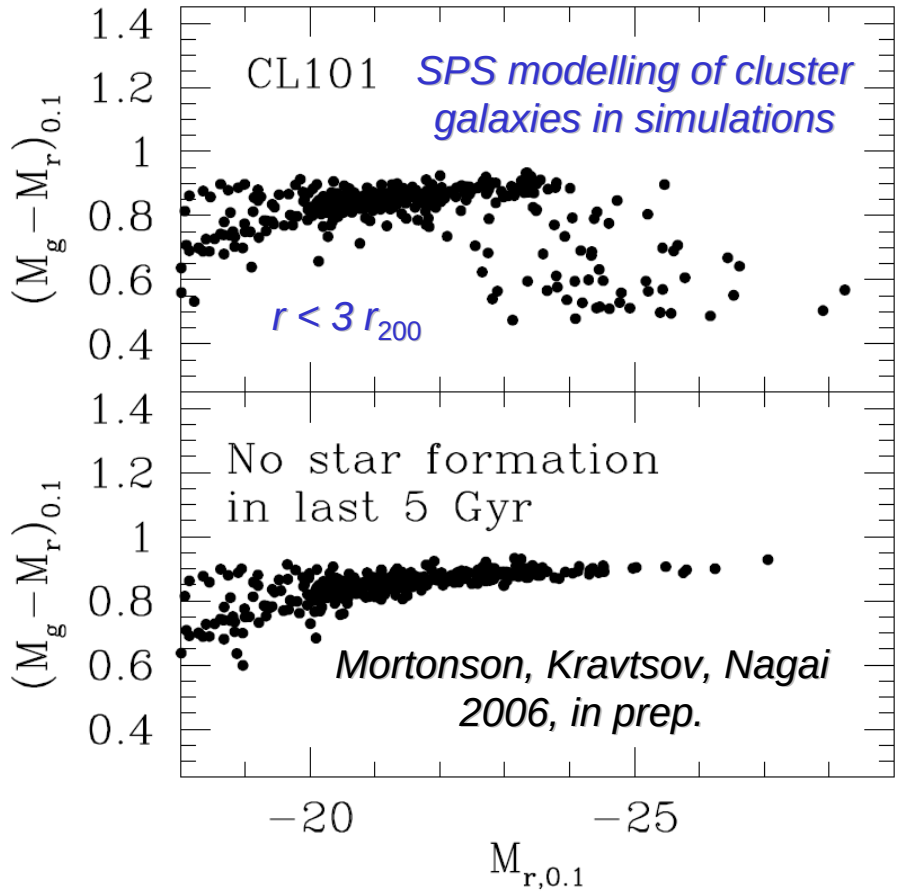
M_{200} - *mass within radius enclosing overdensity of 200 x* r_{crit}

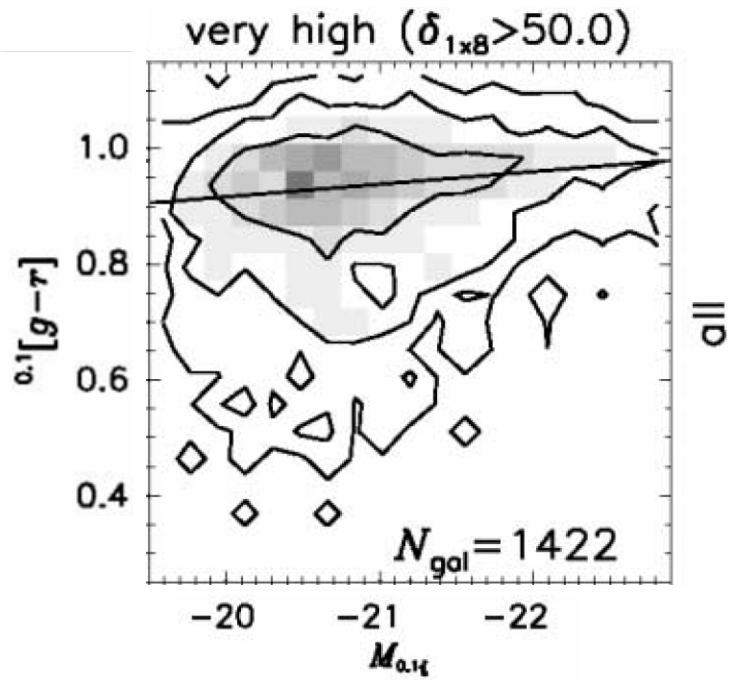
abundance of L* galaxies in clusters of different masses is in good agreement with the data

Mortonson, Kravtsov, Nagai *2006, in prep.*

What about galaxy colors and luminosities?

Recent (t<~5 Gyr) star formation makes massive galaxies in simulations too blue, but even without recent star formation they are already too massive



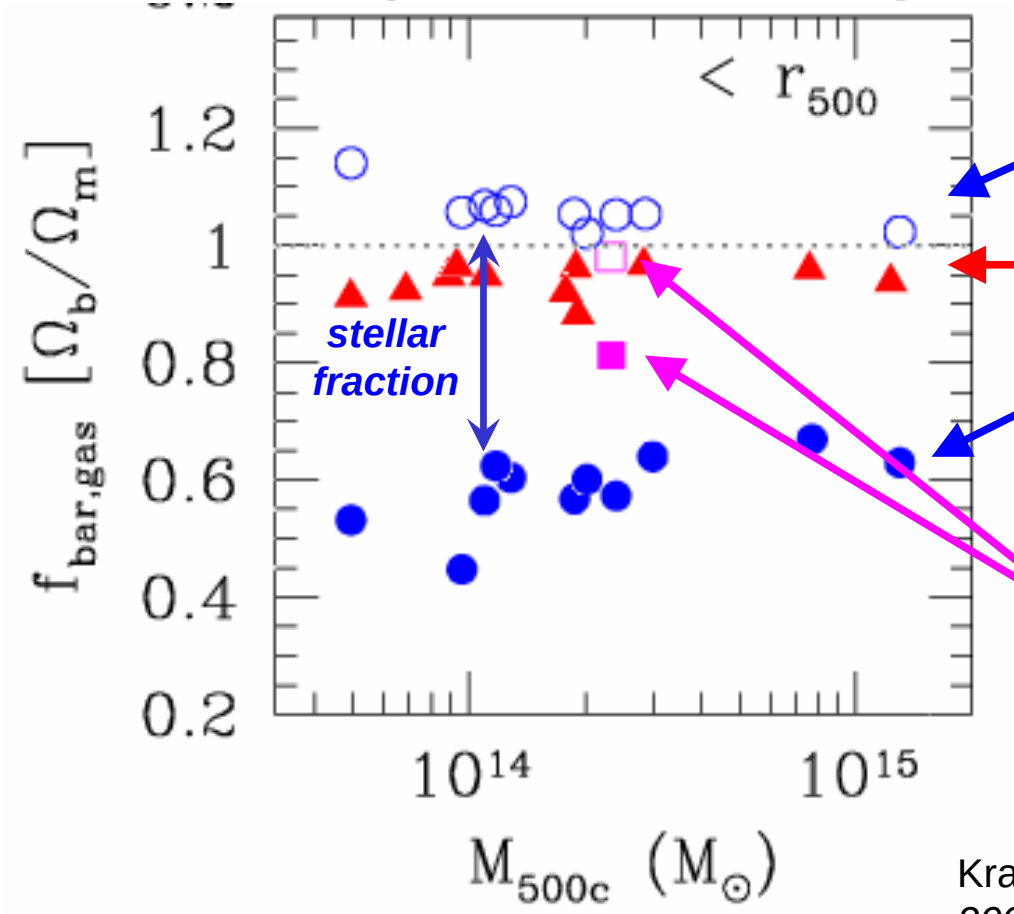


observed color-mag diagram of cluster galaxies in SDSS
Hogg et al. 2004

r-band absolute magnitude

Baryon budget in clusters

Baryon fractions in clusters are expected to be close to universal.
if stellar fractions are overpredicted, are the hot gas fractions underpredicted?



baryon and gas fraction in units of the universal value

virial mass

bar fraction (runs with cooling)

bar fraction (no cooling)

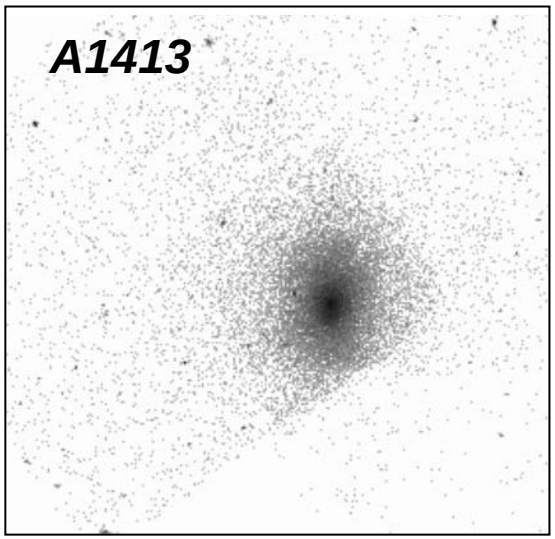
gas fraction (runs with cooling)

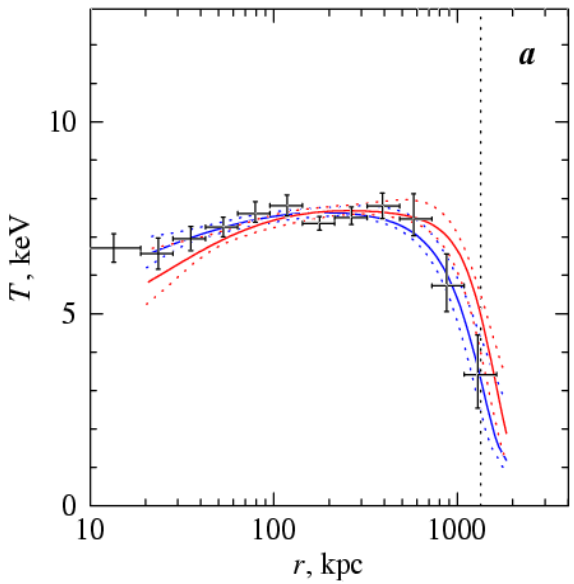
Re-simulation of one of the clusters with cooling artificially switched off at z<2

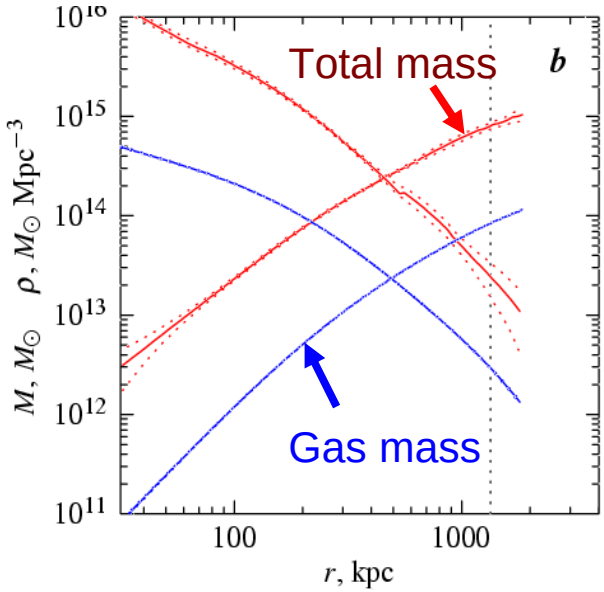
Kravtsov, Nagai & Vikhlinin *2005, ApJ,* 625, 588

Measurements of cluster gas fractions with deep Chandra X-ray observations

- 13 relaxed clusters with deep Chandra exposure of nearby clusters
  - Vikhlinin et al. 2005 ApJ, 628, 655 (astro-ph/0412406)
  - Vikhlinin et al. 2006 ApJ, 640, 691 (astro-ph/0507092)
- Observations are optimized to trace gas density profiles to ~r_{200c} and gas temperature profiles to ~r_{500c}
  - **accurate measurements of gas and total masses, temperature, gas fractions**

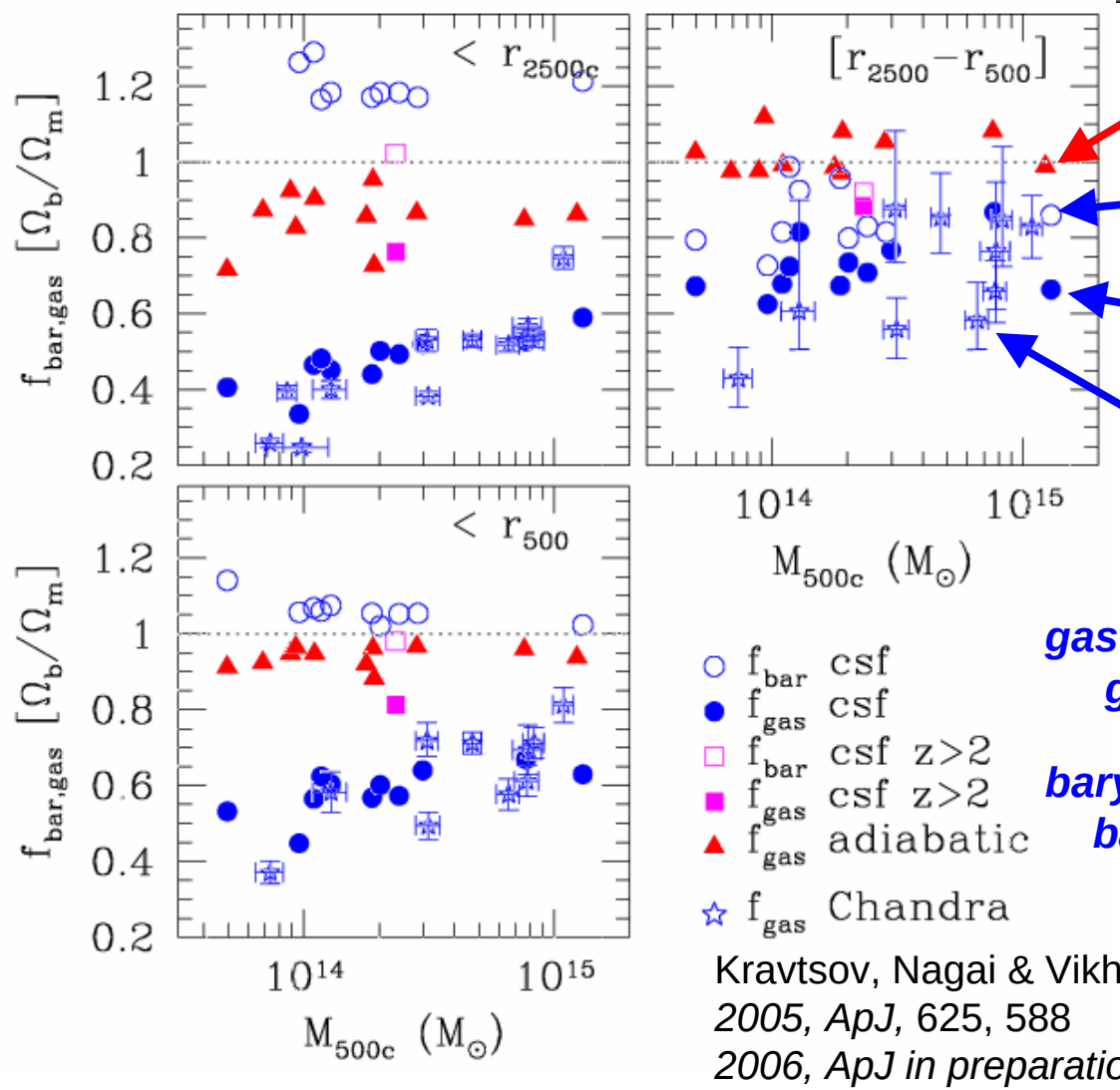






Baryon budget in clusters

Hot gas fraction in simulations and observations agree very well



bar fraction (no cooling)

bar fraction (runs with cooling)

gas fraction (runs with cooling)

Chandra data (Vikhlinin et al. 05)

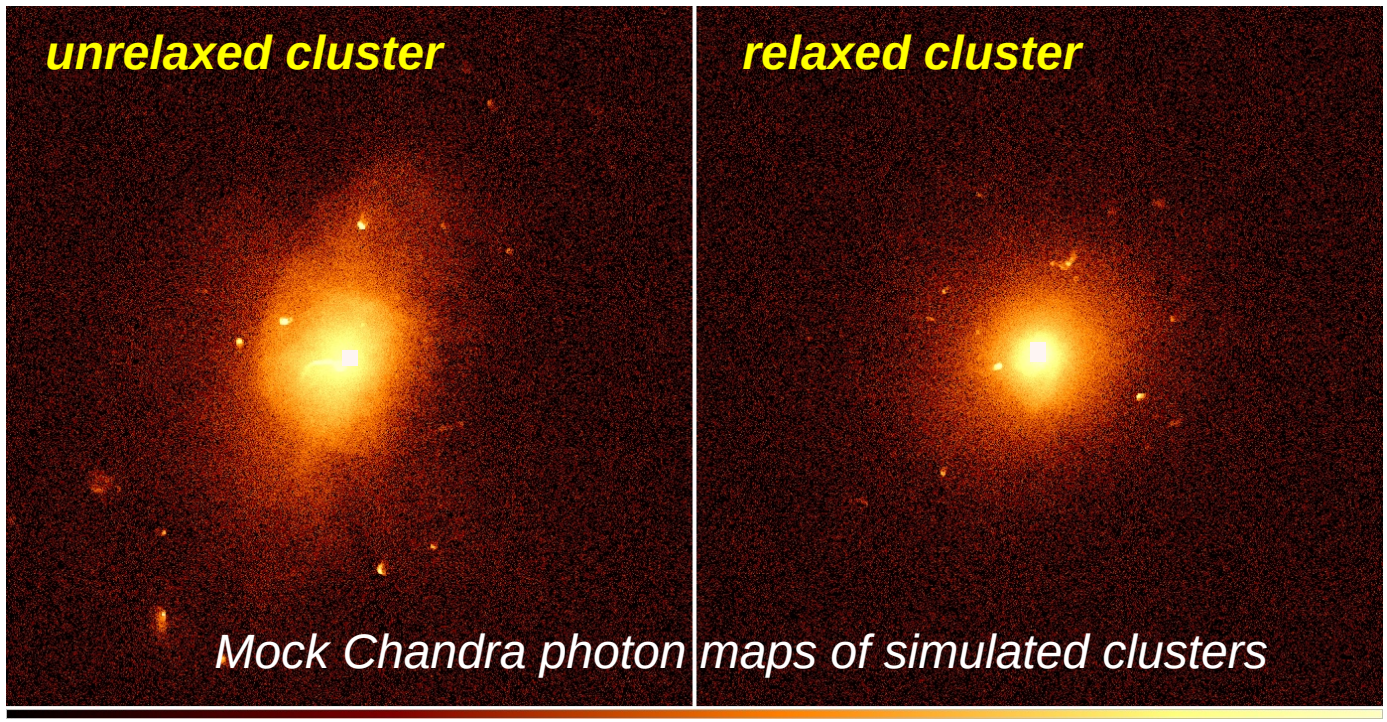
gas fraction = gas mass / total mass

baryon fraction = baryon mass / total mass

Kravtsov, Nagai & Vikhlinin
2005, ApJ, 625, 588
2006, ApJ in preparation

Testing Chandra measurements with mock observations of simulated clusters

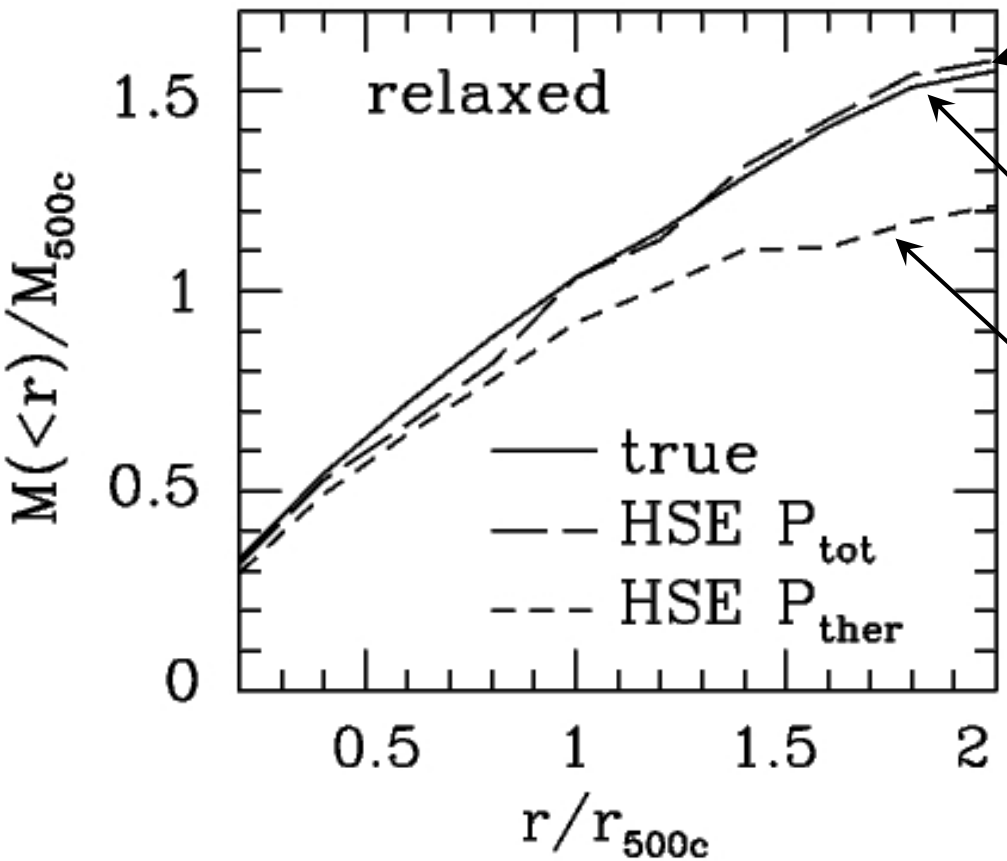
- generate “Chandra data” for clusters from cosmological simulations
- reduce with real data analysis pipeline
  - **gas mass accurate to ~3%, temperatures are accurate to <~10%**
  - **but, total mass biased by ~10%**



Nagai, Vikhlinin & Kravtsov 2006 (astro-ph/0609247)

Turbulent Pressure in Clusters

Turbulent pressure provides about ~10-15% of the total pressure support even in relaxed clusters



Mass profile from hydrostatic equilibrium taking into account turbulent pressure

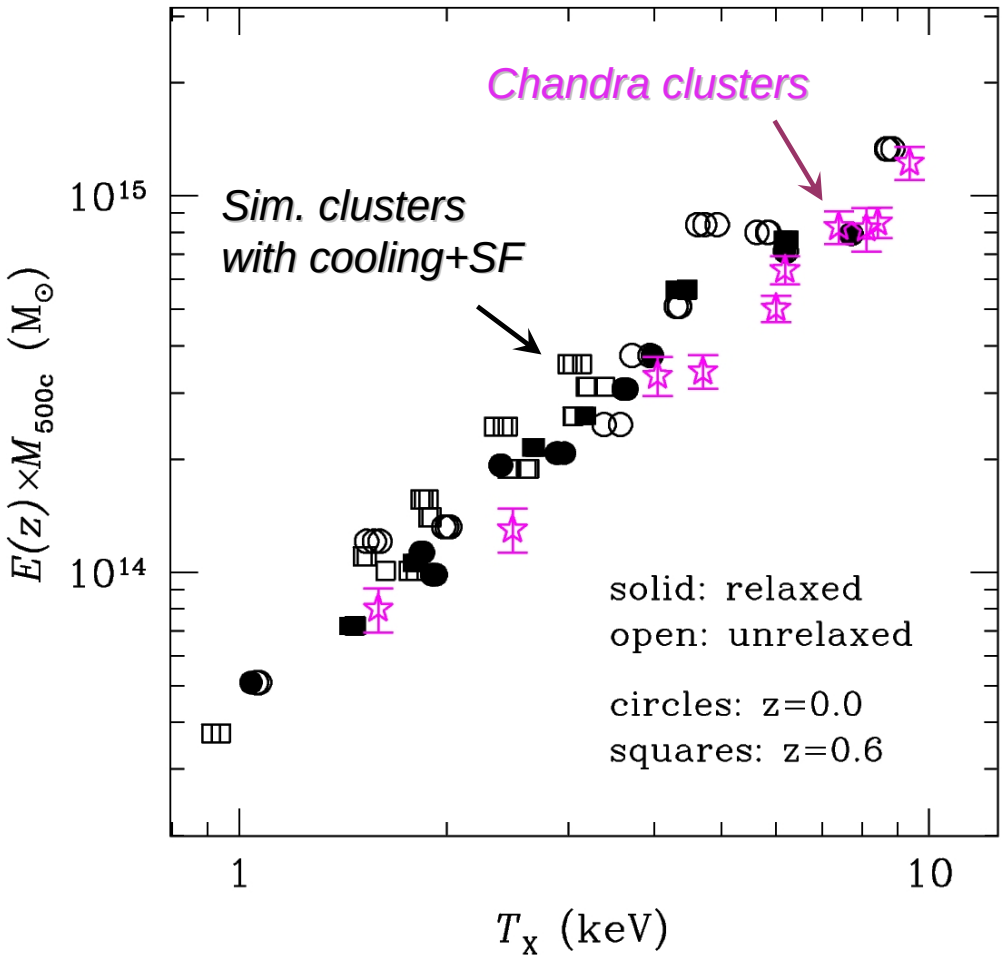
True mass profile in simulations

Mass profile from hydrostatic eqiulibrium neglecting turbulent pressure

Lau, Kravtsov, Nagai, 2006, in prep. Also, in Coma (Schuecker et al. 2004) & in SPH simulations (Rasia et al. 2006)

cluster-centric radius in units of r_{500c}

Mass – ICM temperature relation



Total mass M_{500c} scaled to z=0

X-ray spectral temperature excluding cluster cores ($r<0.15xr_{500c}$)

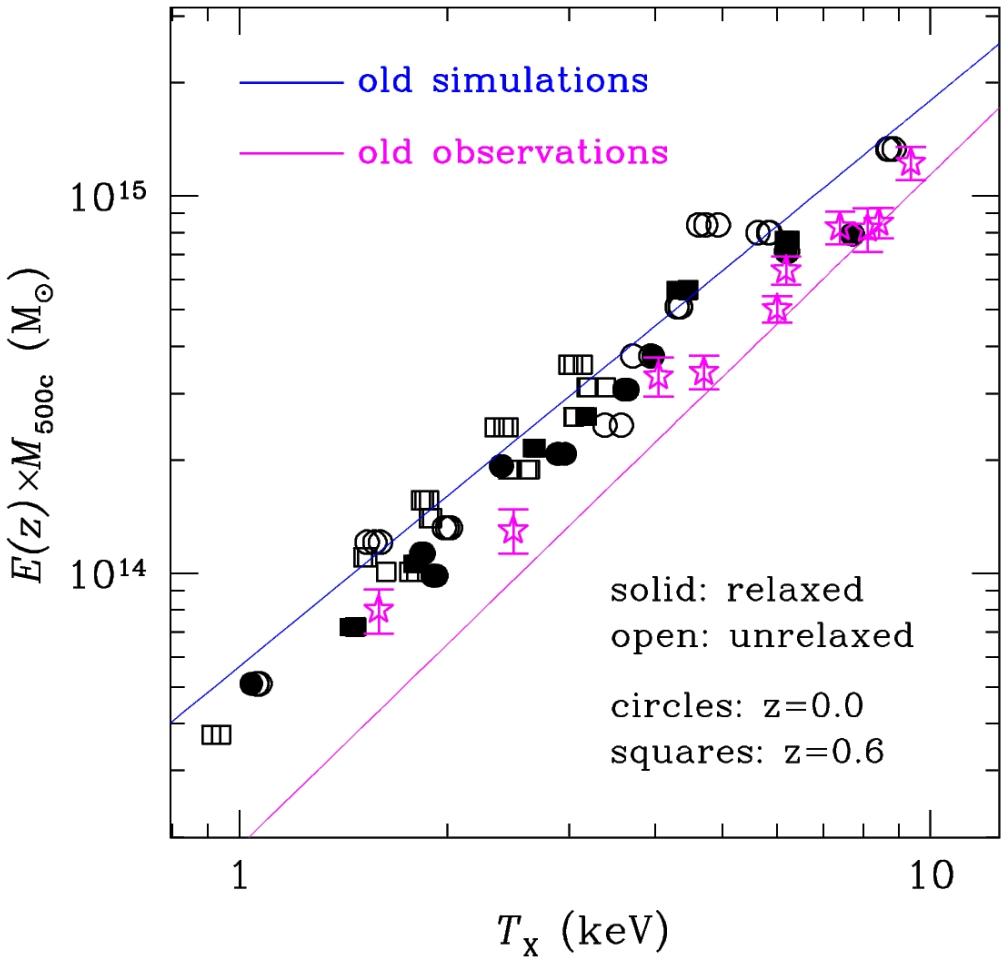
Scatter in M-Tx is ~20% in mass at a given Tx - the scatter is prmarily driven by unrelaxed systems

~10% agreement in the amplitude between observed and model M-Tx relations!

magenta pts: *Chandra data*
Vikhlinin et al. 2006 ApJ, 640, 691

Nagai, Kravtsov, Vikhlinin, 2006, ApJ [astro-ph/0603206]

Mass – ICM temperature relation



Total mass M_{500c} scaled to z=0

X-ray spectral temperature
excluding cluster cores ($r<0.15xr_{500c}$)

Scatter in M-Tx is ~20% in mass at a given Tx - the scatter is prmarily driven by unrelaxed systems

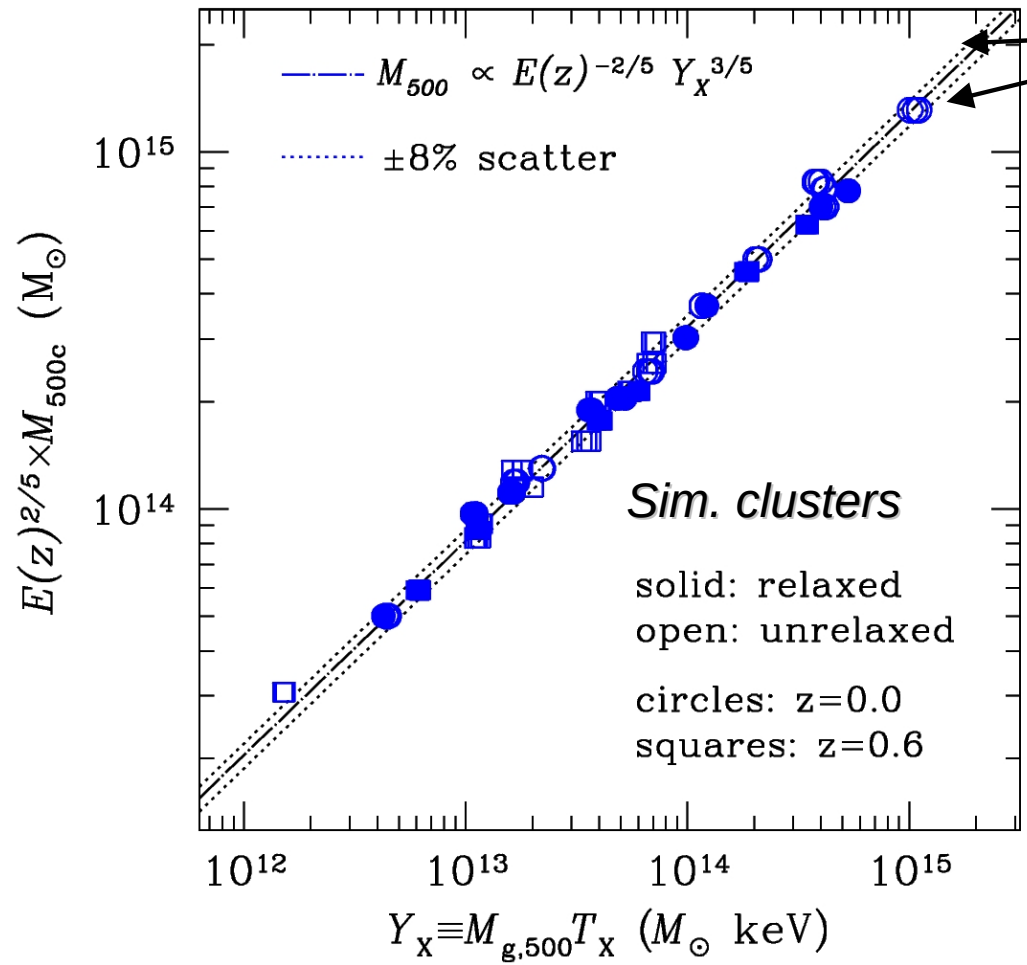
~10% agreement in the amplitude between observed and model M-Tx relations!

Compared to old comparisons both simulations and observations moved towards each other...

Kravtsov, Vikhlinin, Nagai 2006, ApJ [astro-ph/0603206]

Mass – Yx relation

a new X-ray mass proxy



M_{500c} scaled to z=0

Dotted lines show 8% deviation from the mean

Yx is an excellent mass proxy!

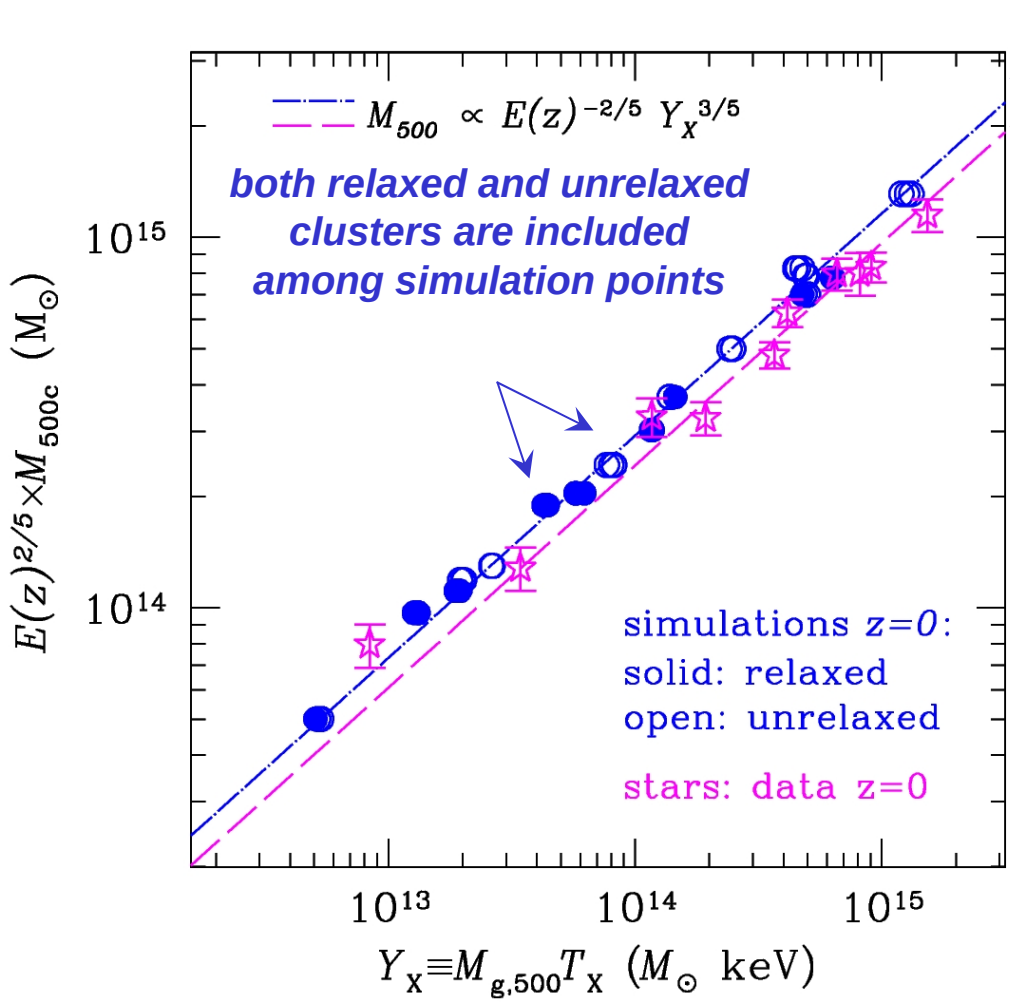
scatter in Yx-M is ~5% for both relaxed & unrelaxed systems and for low- & high-z

Kravtsov, Vikhlinin, Nagai 2006, ApJ [astro-ph/0603206]

X-ray "pressure" = gas mass x temperature

Mass – Yx relation

robust and accurate X-ray mass proxy



M_{500c} scaled to z=0

Sim. clusters

Chandra clusters

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

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

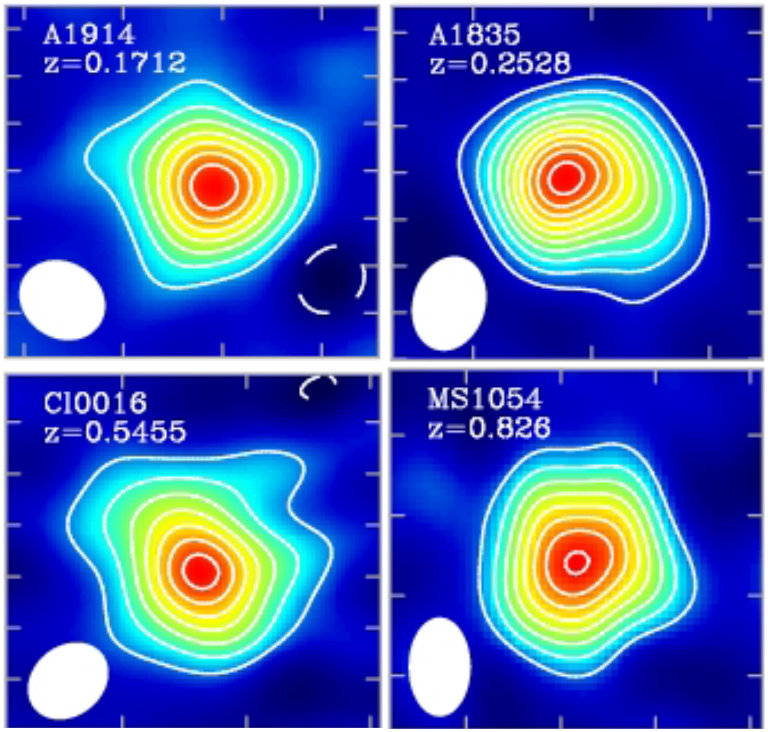
Kravtsov, Vikhlinin, Nagai 2006, ApJ [astro-ph/0603206]

X-ray "pressure" = gas mass x temperature

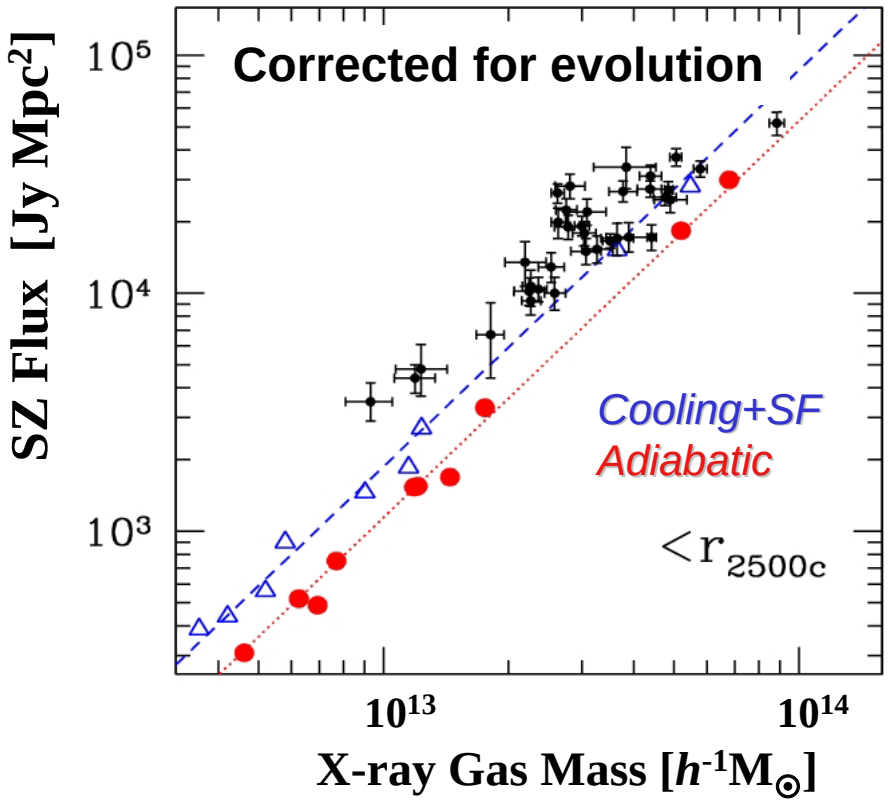
Sunyaev-Zel'dovich Effect

robust and accurate mass proxy

SZ Effect directly probes the integrated pressure

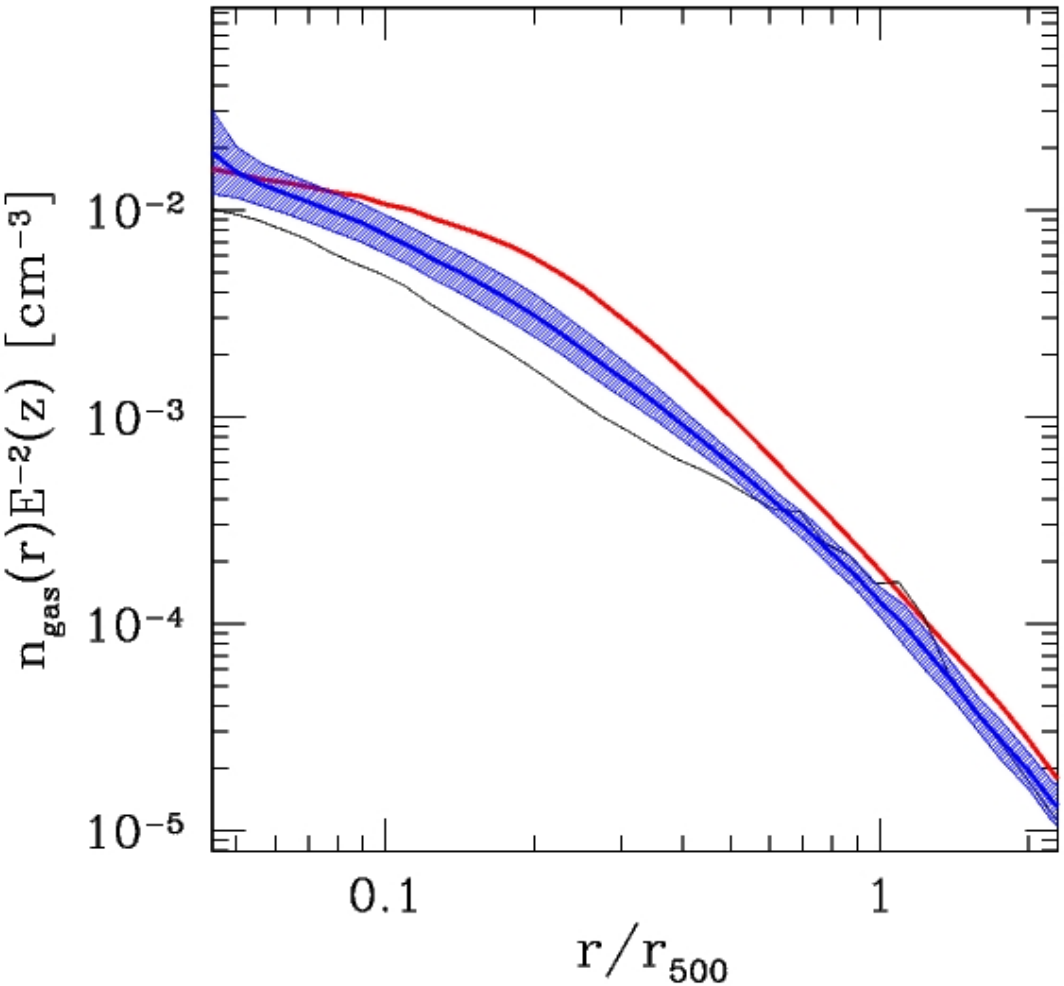


Sample of 38 BIMA/OVRO SZE+Chandra X-ray clusters at 0.14<z<0.89



Simulations: *Nagai 2006 (astro-ph/0512208), also Motl et al. 2005, da Silva et al. 2001*
Data: *LaRoque, Bonamente, Carlstrom, Joy, Nagai, Reese 2006, in prep.*

Gas density profiles: Effects of Galaxy Formation



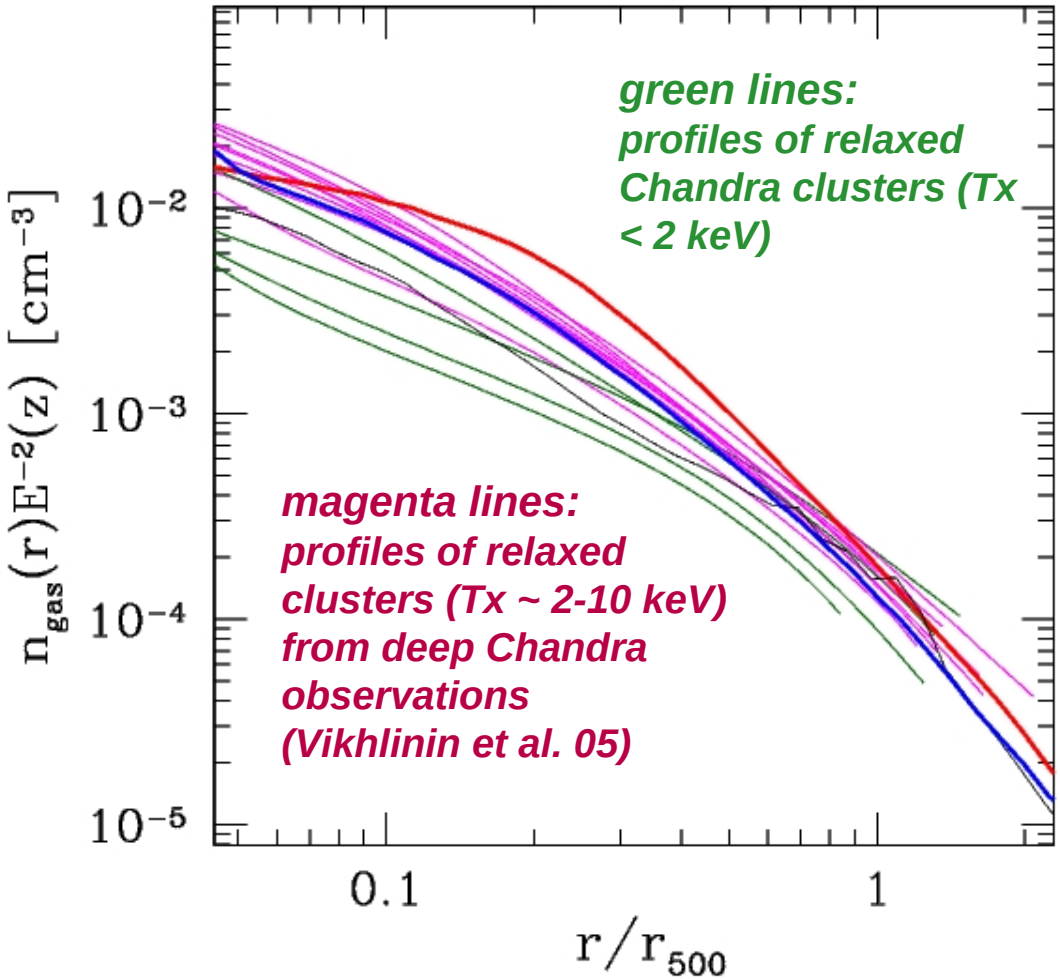
red line:
mean profile for relaxed clusters in adiabatic simulations

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

black line – profile for the coolest cluster (Tx~1 keV)

Nagai, Kravtsov, Vikhlinin, 2006, in preparation

Gas density profiles: simulations vs observations



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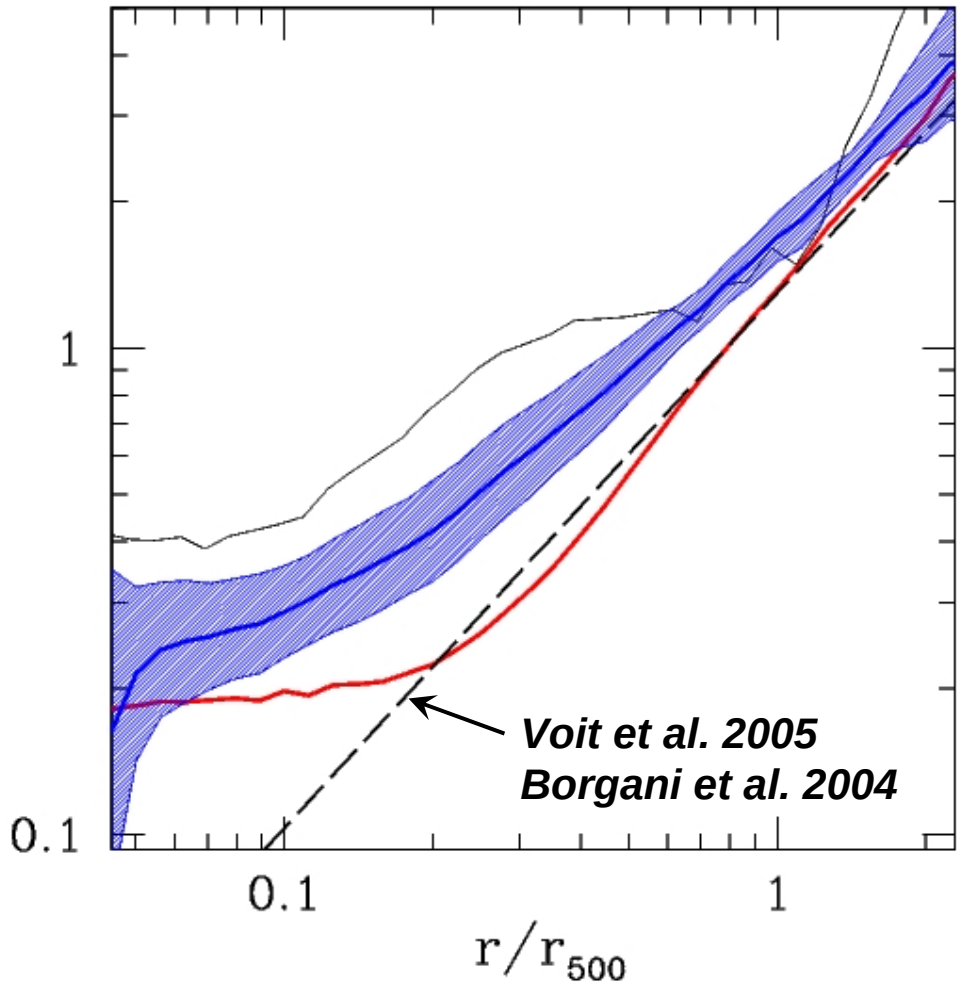
Gas entropy profiles: simulations vs observations



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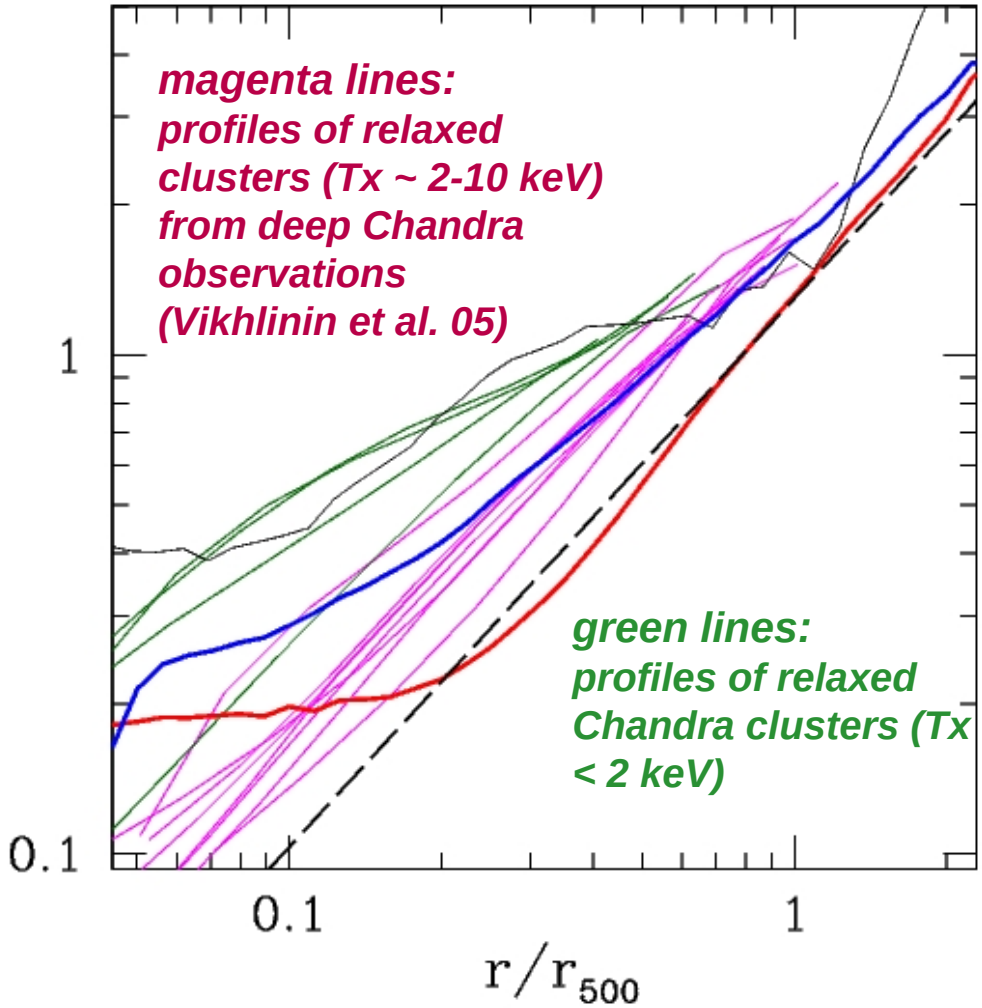
Gas entropy profiles: simulations vs observations



Normalized gas entropy profile

cluster-centric radius in units of r_{500c}

red line:
mean profile for clusters in adiabatic simulations

blue band:
mean profile for clusters in simulations with cooling and star formation

black line – profile for the coolest cluster (Tx~1 keV)

Nagai, Kravtsov, Vikhlinin, 2006, in preparation

Summary

- ***Baryons have important effects on the mass distribution of groups and clusters and hence interpretations of both strong and weak lensing observations. But, the magnitude of the effects depends on the treatment of baryonic physics in simulations.***
- ***Properties of baryons in clusters***
  - **Cooling+SF simulations reproduce the properties of X-ray emitting intracluster medium outside the cores in quite detail**
  - **X-ray and SZ derived masses (based on Yx and Ysz) can be used for cross-comparisons with lensing mass even for unrelaxed systems**
- ***Problems & Challenges:***
  - ***Disagreement between simulations and observations in massive galaxies and cluster cores***
    - Need for additional physical processes (e.g., AGN feedback, thermal conduction, magnetic field & cosmic-rays etc.)