Biases in Mass Estimate of Galaxy Clusters

mainly on X-ray observations

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Introduction

- Mass of galaxy clusters
  → cosmological parameters (through mass function)

- Impact on cosmological parameters
  - σ_8 from cluster abundance (Shimizu et al., 2006)

$$\sigma_{8,\mathrm{true}} = \sigma_{8,\mathrm{cluster}} + 0.5(1 - \alpha_M) \quad \alpha_M = M_{\mathrm{est}}/M_{\mathrm{tot}} \ @r_{\mathrm{vir}}$$

- discrepancy between CMB & cluster abundance

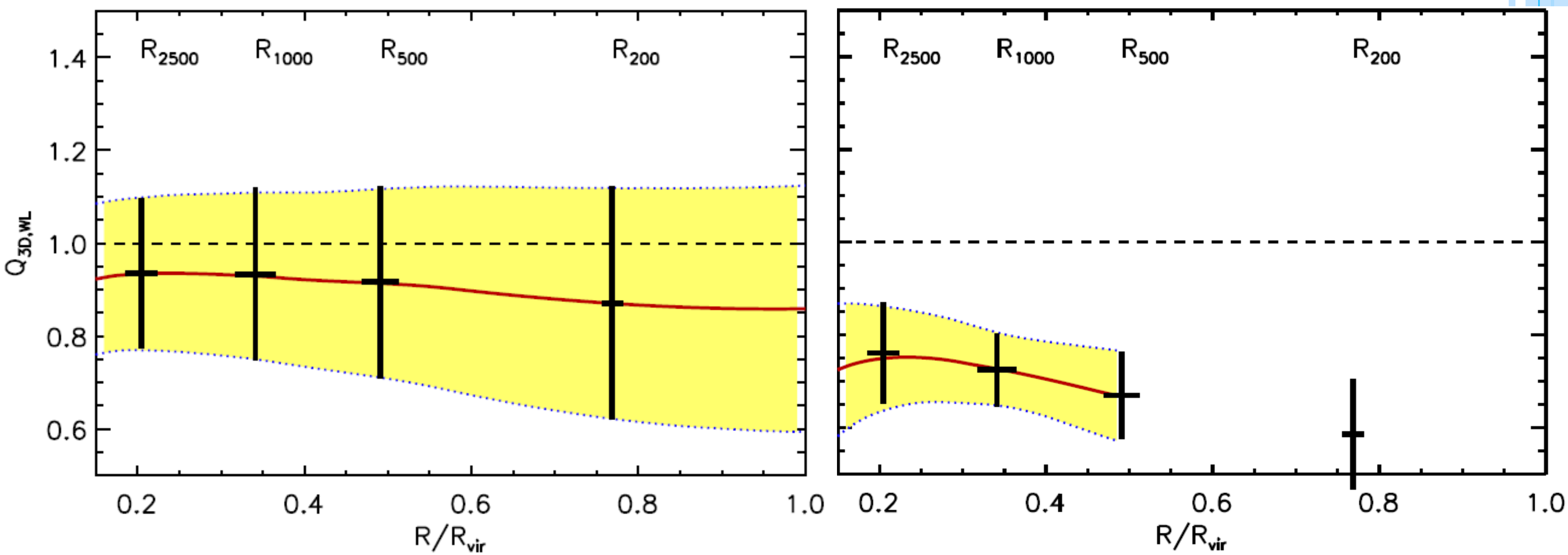
- Ongoing & future projects
  - ASTRO-H, eROSITA (X-ray)
  - Planck, SPT, ACT (Sunyaev-Zel'dovich effext)
  - Subaru HSC (Lensing)

  → Large sample of clusters
  Accurate mass measurement becomes more important!

Mock Observations

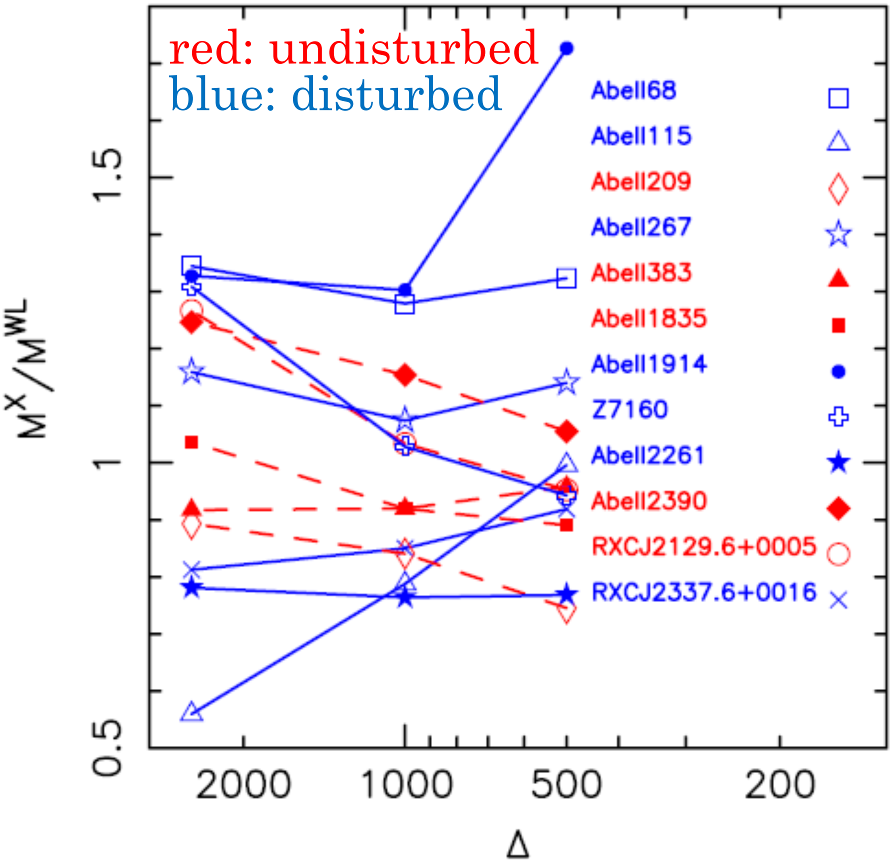
- Mock observations (Rasia et al., 2012)
  - 20 clusters × 3 directions
  - weak lensing (assuming HST) : more accurate, larger scatter
  - X-ray (assuming Chandra) : less accurate, smaller scatter

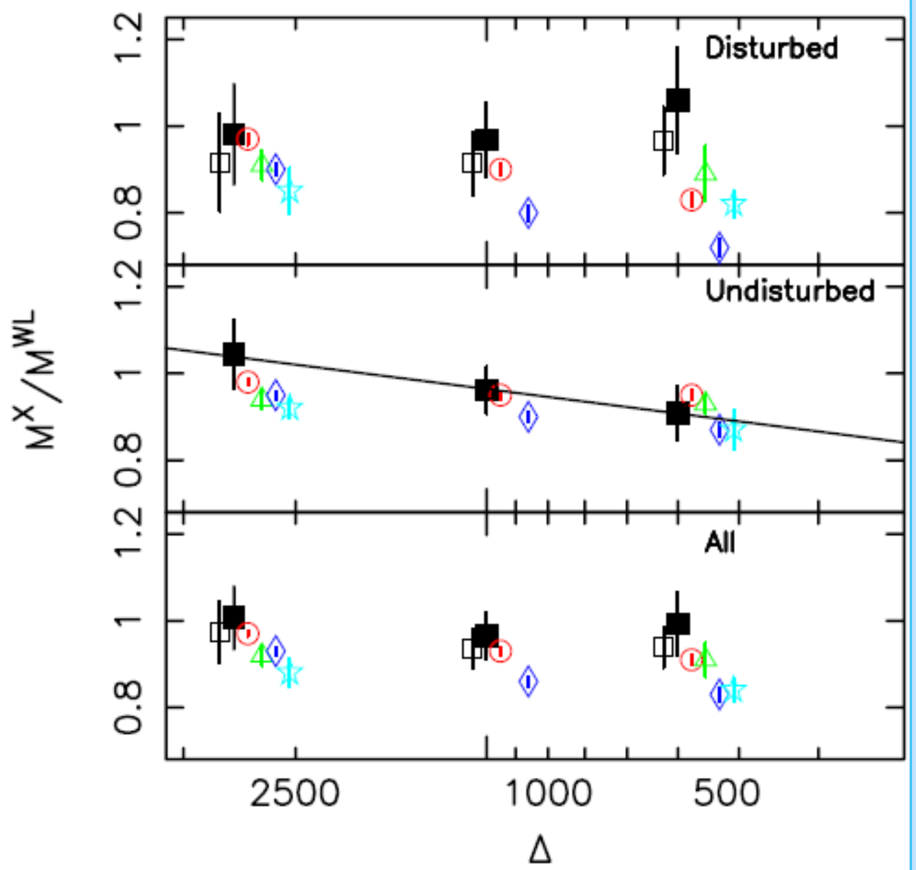
↓ M_{obs}/M_{true} **WL** **X**



X-ray vs. Weak Lensing

- 12 clusters observed in WL (Subaru) & X-ray (XMM-Newton) (Zhang et al., 2010)





Causes of the Bias

- Gravitational Lensing
  - substructure
  - non-sphericity
  - …
- X-ray & Sunyaev-Zel'dovich effect
  - assumption of hydrostatic equilibrium (HSE)
  - deprojection of gas properties from 2D observables
    (related to non-sphericity)
  - …

Hydrostatic Equilibrium (X-ray)

- Observables
  - surface brightness & spectroscopic (projected) temperature

  → gas density n(r) & (deprojected) temperature T(r)
- Hydrostatic Equilibrium (HSE)

$$-\frac{1}{\rho_{\rm gas}}\frac{dp}{dr} = \frac{GM}{r^2}$$

$$M_{\rm HSE} = -\frac{k_B T(r)}{\mu m_p G}\left[\frac{d\log n(r)}{d\log r} + \frac{d\log T(r)}{d\log r}\right]$$

The accuracy of X-ray mass estimate depends on the validity of HSE assumption

Hydrostatic Equilibrium (SZ)

- Observable

  Y ~ l.o.s. integral of gas pressure

  1. combined with gas density or temperature from X-ray

     → estimate mass under the HSE assumption

     OR

  2. Y-M scaling relation constructed by combining M-T relation with other scaling relations

  → scaling relations are calibrated by X-ray observations & simulations

Mass estimate of SZ effect is also based on HSE assumption.

Equation of Motion of Gas

↓ Gravitational Potential

$$\nabla\Phi = -\frac{1}{\rho_{\mathrm{gas}}}\nabla p - \frac{\partial \boldsymbol{v}}{\partial t} - (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}$$

HSE

Euler Eq. (simulations)

+ (terms neglected in simulations)

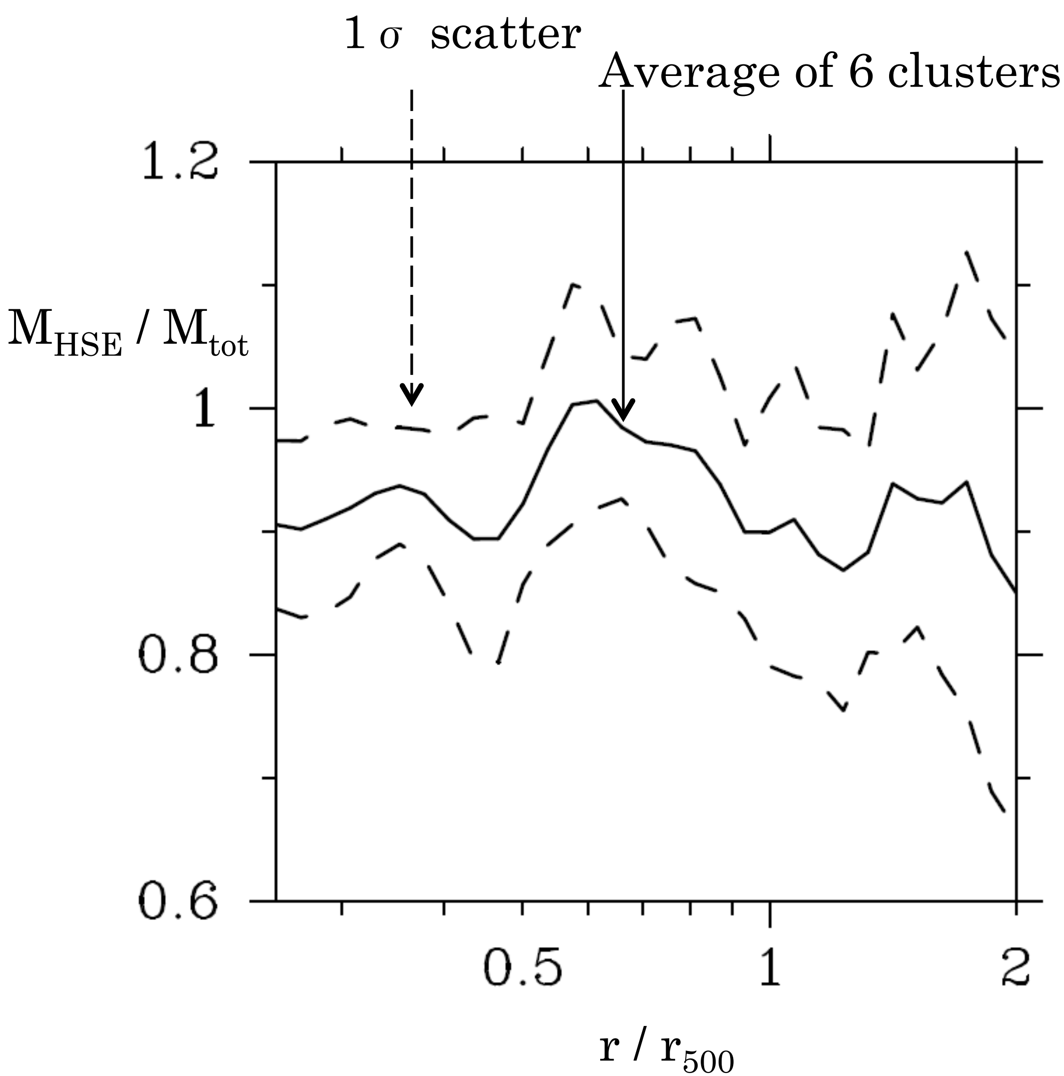
$\triangle\Phi = 4\pi G\rho_{\mathrm{tot}}$

$$-\frac{1}{4\pi G}\int d\boldsymbol{S}\cdot\frac{\nabla p}{\rho_{\mathrm{gas}}} = M_{\mathrm{HSE}}$$

$$\int d^3x\ \rho_{\mathrm{tot}} = M_{\mathrm{tot}}$$

HSE Mass vs. Total Mass

- 1 AMR & 5 SPH simulated clusters (DS+13)
  (relaxed)



HSE Mass / Total Mass is
~ 0.9 @ r_{500}
& can be >30%@ larger radii

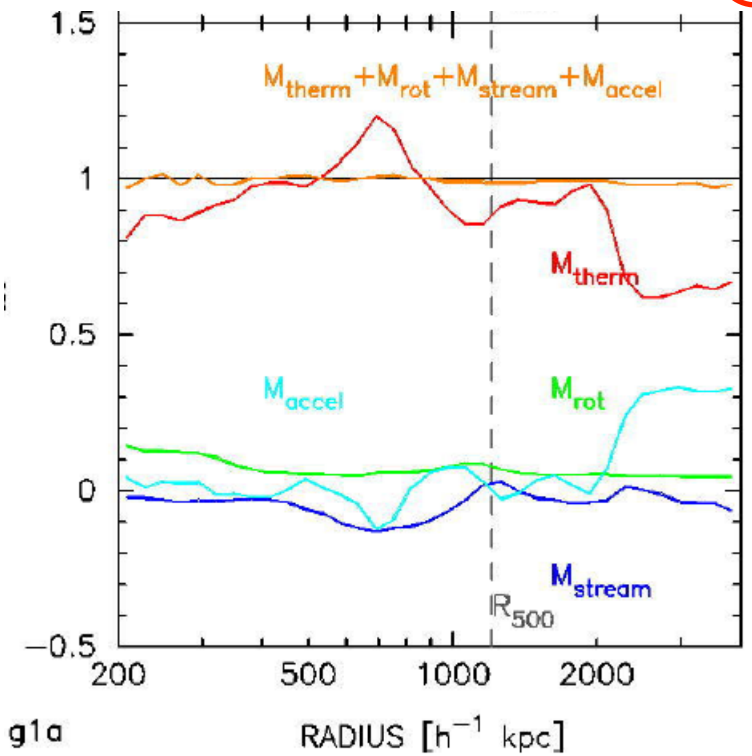
consistent with other studies

- Fang et al., 2009 (16 clusters)
- Lau et al., 2009 (16 clusters)
- Lau et al., 2013 (5 clusters)
- Nelson et al., 2013 (62 clusters)

Contribution from Other Terms (1)

$$\nabla\Phi = -\frac{1}{\rho_{\rm gas}}\nabla p - \frac{\partial \boldsymbol{v}}{\partial t} - (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}$$

$$\int d^3x\,\rho_{\rm tot} = \frac{1}{4\pi G}\int dS\left[-\frac{1}{\rho_{\rm gas}}\frac{\partial p}{\partial r} + \frac{v_\theta^2 + v_\varphi^2}{r} - (\boldsymbol{v}\cdot\nabla)v_r - \frac{\partial v_r}{\partial t}\right]$$



Acceleration is the most important (DS+13, 1 AMR & 5 SPH clusters)

Rotation is the most important (Fang et al, 2009; same analysis but different sample)

Contribution from Other Terms (2)

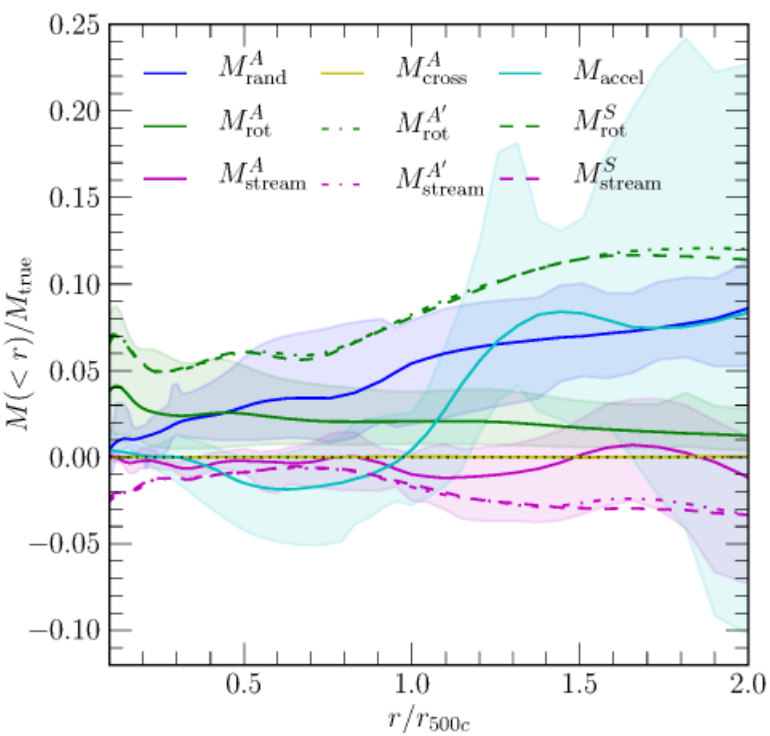
$$\nabla\Phi = -\frac{1}{\rho_{\rm gas}}\nabla p - \frac{\partial \boldsymbol{v}}{\partial t} - (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}$$

$\langle\cdots\rangle$: mass average

$$M(<r) = \frac{-r^2}{G\langle\rho\rangle}\frac{\partial\langle P\rangle}{\partial r} \quad \frac{-r^2}{G\langle\rho\rangle}\frac{\partial\langle\rho\rangle\sigma^2_{\rho,rr}}{\partial r} - \frac{r}{G}\left(2\sigma^2_{\rho,rr} - \sigma^2_{\rho,\theta\theta} - \sigma^2_{\rho,\phi\phi}\right) \quad \frac{-r^2}{G}\frac{\partial\langle u_r\rangle_\rho}{\partial t}$$

$$+ \frac{r}{G}\left(\langle u_\theta\rangle^2_\rho + \langle u_\phi\rangle^2_\rho\right) \quad \frac{-r^2}{G}\left(\langle u_r\rangle_\rho\frac{\partial\langle u_r\rangle_\rho}{\partial r} + \frac{\langle u_\theta\rangle_\rho}{r}\frac{\partial\langle u_r\rangle_\rho}{\partial\theta} + \frac{\langle u_\phi\rangle_\rho}{r\sin\theta}\frac{\partial\langle u_r\rangle_\rho}{\partial\phi}\right)$$

$$\frac{-r^2}{G\langle\rho\rangle}\left(\frac{1}{r}\frac{\partial\langle\rho\rangle\sigma^2_{\rho,r\theta}}{\partial\theta} + \frac{1}{r\sin\theta}\frac{\partial\langle\rho\rangle\sigma^2_{\rho,r\phi}}{\partial\phi}\right) - \frac{r}{G}\left(\sigma^2_{\rho,r\theta}\cot\theta\right)$$



←average of 5 relaxed clusters (Lau et al., 2013)

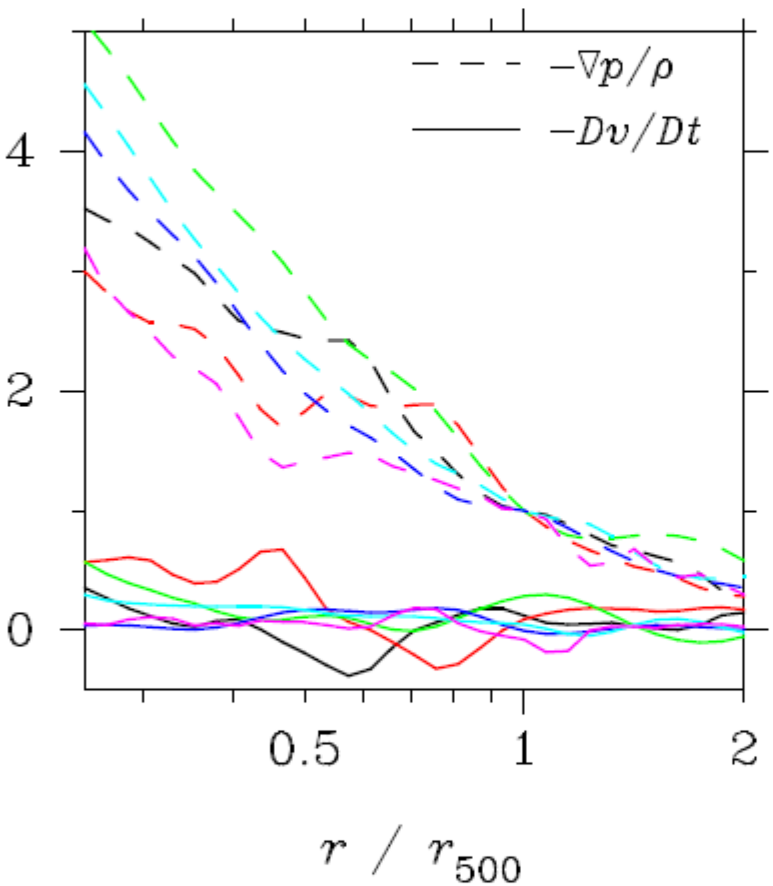
Random motion & acceleration have large contribution at large radii

Nelson et al., (2013)
Acceleration has small contribution (<3%) on average (12 relaxed clusters), but it produces a large scatter

Contribution from Other Terms (3)

$$\nabla\Phi = -\frac{1}{\rho_{\rm gas}}\nabla p - \frac{\partial \boldsymbol{v}}{\partial t} - (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\frac{D\boldsymbol{v}}{Dt}$$ (Lagrangian acceleration)

normalized by $|-\nabla p/\rho\,(r_{500})|$



- Dv/Dt is roughly constant compared to $\nabla p/\rho$
- Surface integral converges them to mass terms

→The contribution of Dv/Dt becomes more larger at larger radii

・velocity: will be observed with ASTRO-H (dynamical picture of clusters!)

・acceleration
・things neglected in simulations (e.g. non-thermal pressure from cosmic rays etc.)

Causes of the Bias

- Gravitational Lensing
  - substructure
  - non-sphericity
  - ...

- X-ray & Sunyaev-Zel'dovich effect
  - assumption of hydrostatic equilibrium (HSE)
    → ~10% @ r_{500}, >30% @ larger radii
  - deprojection of gas properties from 2D observables
    (related to non-sphericity of clusters)
  - ...

Deprojection Effect (1)

- Surface brightness I_X & spectroscopic temperature T_{spec}

→Radial profiles of density n(r) & temperature T(r)

deprojection process can produce another bias

DS+(in prep)

$$T_{\rm sl} = \frac{\int dl\ n^2 T^{1/4}}{\int dl\ n^2 T^{-3/4}}$$

- make I_X & spectroscopic-like temperature T_{sl} from simulation data (1 AMR and 5 SPH clusters)
- find n(r) & T(r) which best reproduce I_X & T_{sl} assuming

$$\widehat{n}(r) = n_0 \frac{(r/r_c)^{-\alpha/2}}{(1+r^2/r_c^2)^{3\beta/2-\alpha/4}} \quad \widehat{T}(r) = T_0 \frac{(r/r_t)^{-a}}{(1+(r/r_t)^b)^{c/b}}$$

Vikhlinin et al., 2006

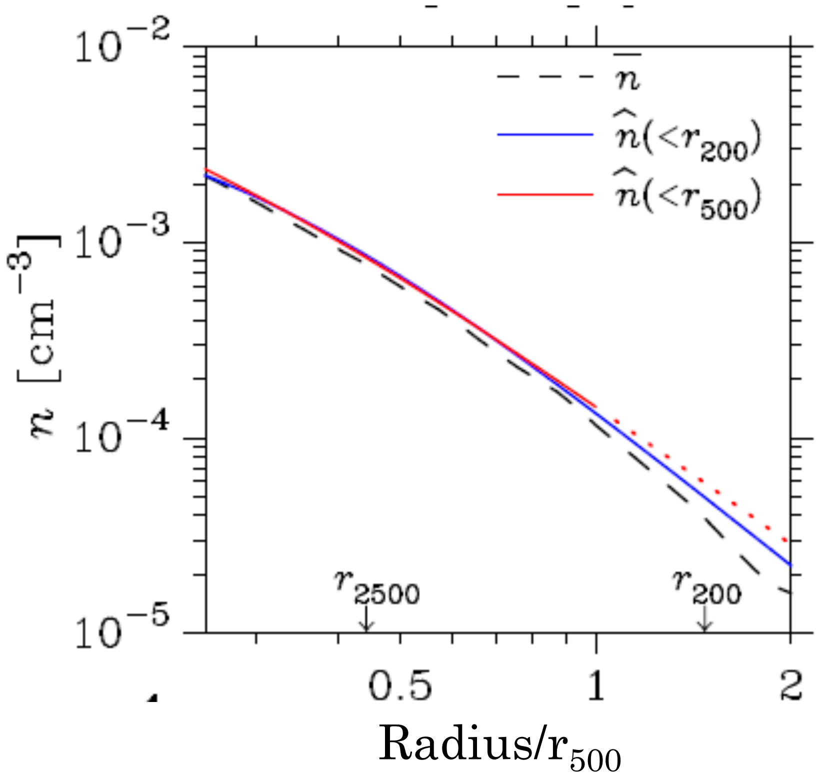
- calculate HSE mass

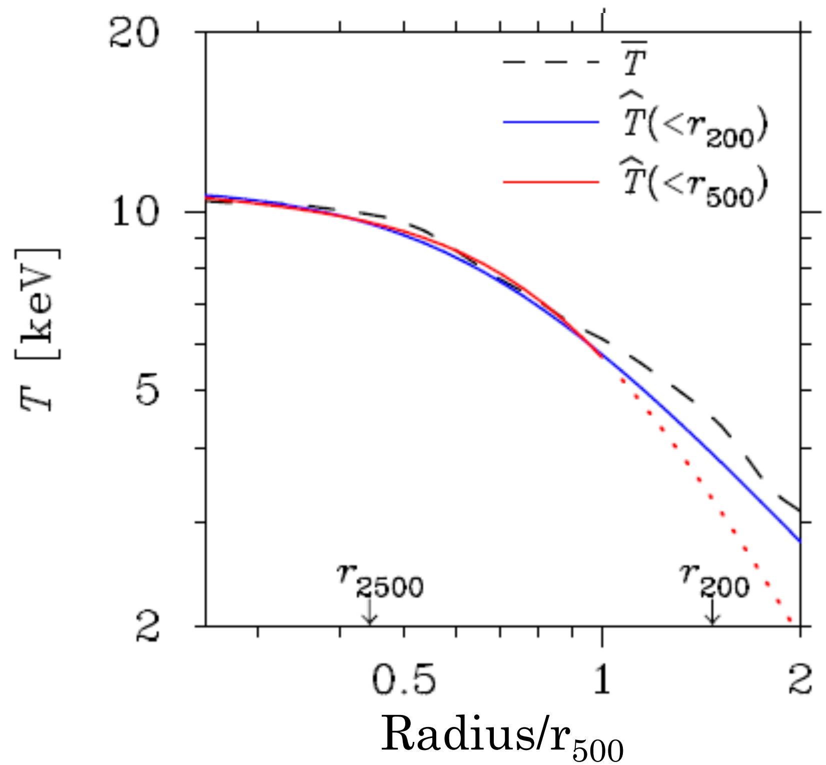
$$M_{\rm HSE} = -\frac{k_B T(r)}{\mu m_p G}\left[\frac{d\log n(r)}{d\log r} + \frac{d\log T(r)}{d\log r}\right]$$

Deprojection Effect (2)

- # of bins: arbitrary
- error bars: variance in the annulus

NOT considering some specific observation



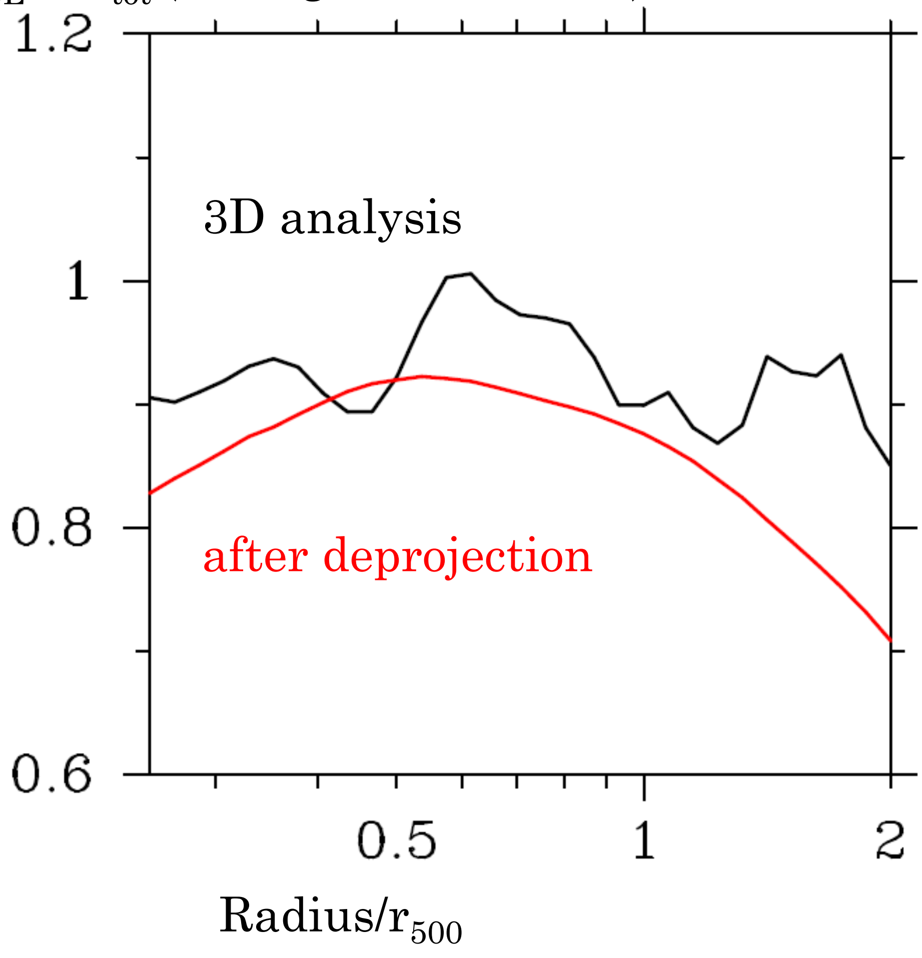


Density: tend to be overestimated (observables $\propto$ n^2)
Temperature: tend to be underestimated

Deprojection Effect (3)

$$M_{\rm HSE} = -\frac{k_B T(r)}{\mu m_p G}\left[\frac{d\log n(r)}{d\log r} + \frac{d\log T(r)}{d\log r}\right]$$

M_{HSE} / M_{tot} (average of 6 clusters)



Deprojection yields another ~10% underestimate of mass

Causes of the Bias

- Gravitational Lensing
  - substructure
  - non-sphericity
  - …

- X-ray & Sunyaev-Zel'dovich effect
  - assumption of hydrostatic equilibrium (HSE)
    → underestimate by ~10% @ r_{500}, >30% @ larger radii
  - deprojection of gas properties from 2D observables
    (related to non-sphericity of clusters)
    → another ~10% underestimate
  - …

Discussion

- assumption of hydrostatic equilibrium (HSE)
  → underestimate by ~10% @ r_{500}, >30% @ larger radii
- deprojection of gas properties from 2D observables
  (related to non-sphericity of clusters)
  → another ~10% underestimate

- consistent with Rasia et al. (2012)
  (~20% @ r_{500} underestimate with large scatter)
  larger radii?? things neglected in simulations??
  treatment of high energy physics in simulations?
- To better estimate mass…
  1. accurately measure gas density & temperature
     e.g. using variance in I_X to correct the bias in density ($\sqrt{n^2} \rightarrow n$)
     (Roncarelli et al., 2013)
  2. reconcile the discrepancy between HSE mass & total mass

Summary

- According to Rasia et al. (2012)
  - Lensing mass underestimates the true mass by <10% on average with large scatter
  - X-ray hydrostatic mass underestimates the true mass by >20% on average with small scatter

- Bias in X-ray observations
  - assumption of hydrostatic equilibrium (HSE)

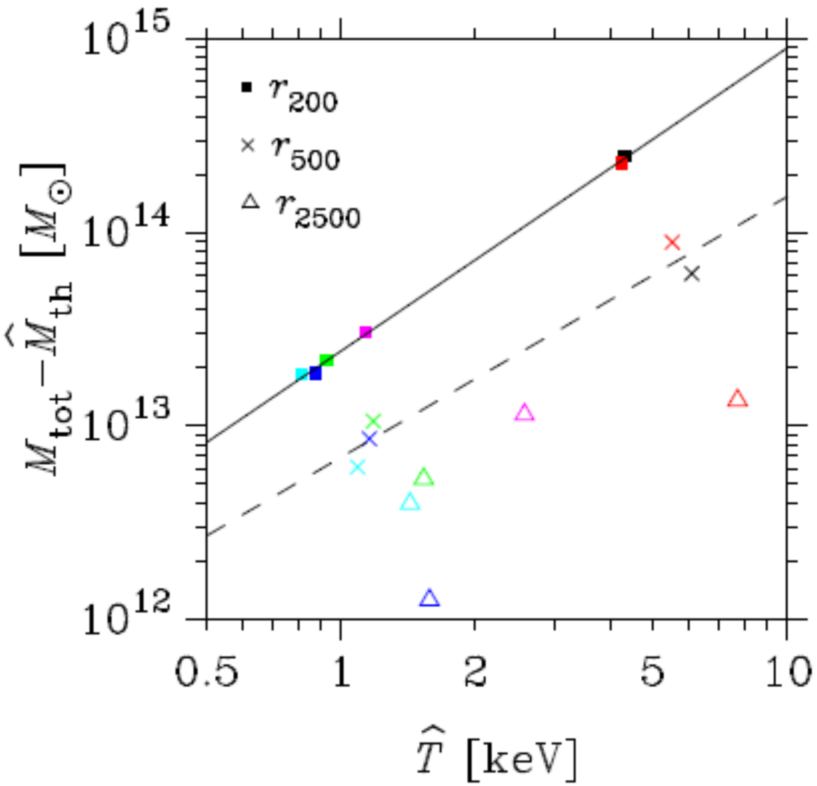
    → underestimate by ~10% @ r_{500}, >30% @ larger radii
  - deprojection of gas properties from 2D observables

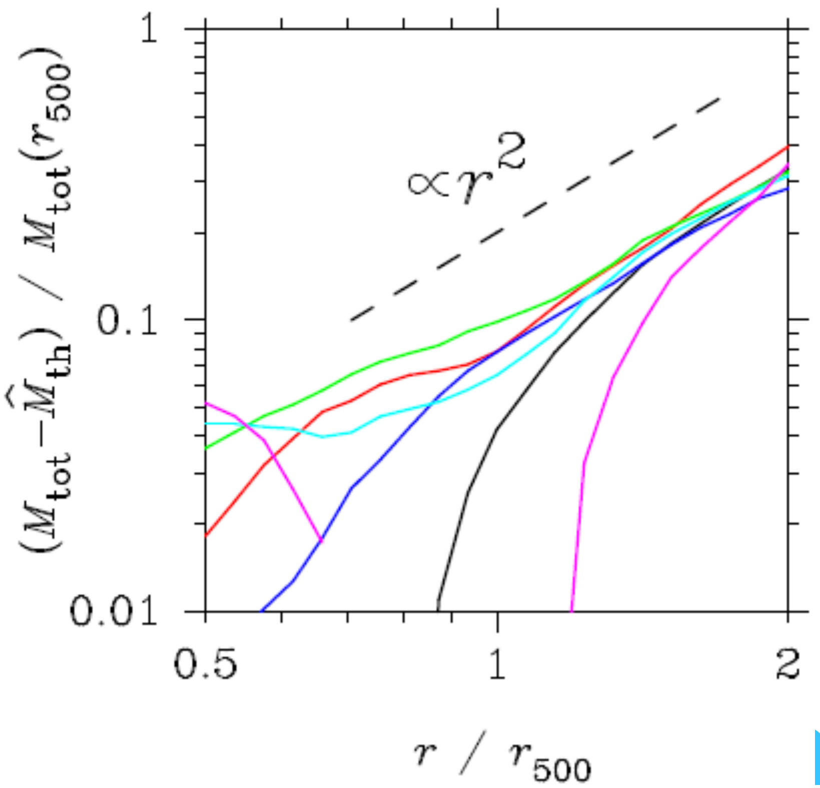
    (related to non-sphericity of clusters)

    → another ~10% underestimate
  - Effect neglected in simulations can be significant in real clusters

Correction Term

$$M_{\rm cor}^{\Delta} = A_{\Delta}\left(\frac{T(r_{\Delta})}{\rm keV}\right)^{B_{\Delta}}\left(\frac{r}{r_{\Delta}}\right)^{C_{\Delta}} M_{\odot}$$

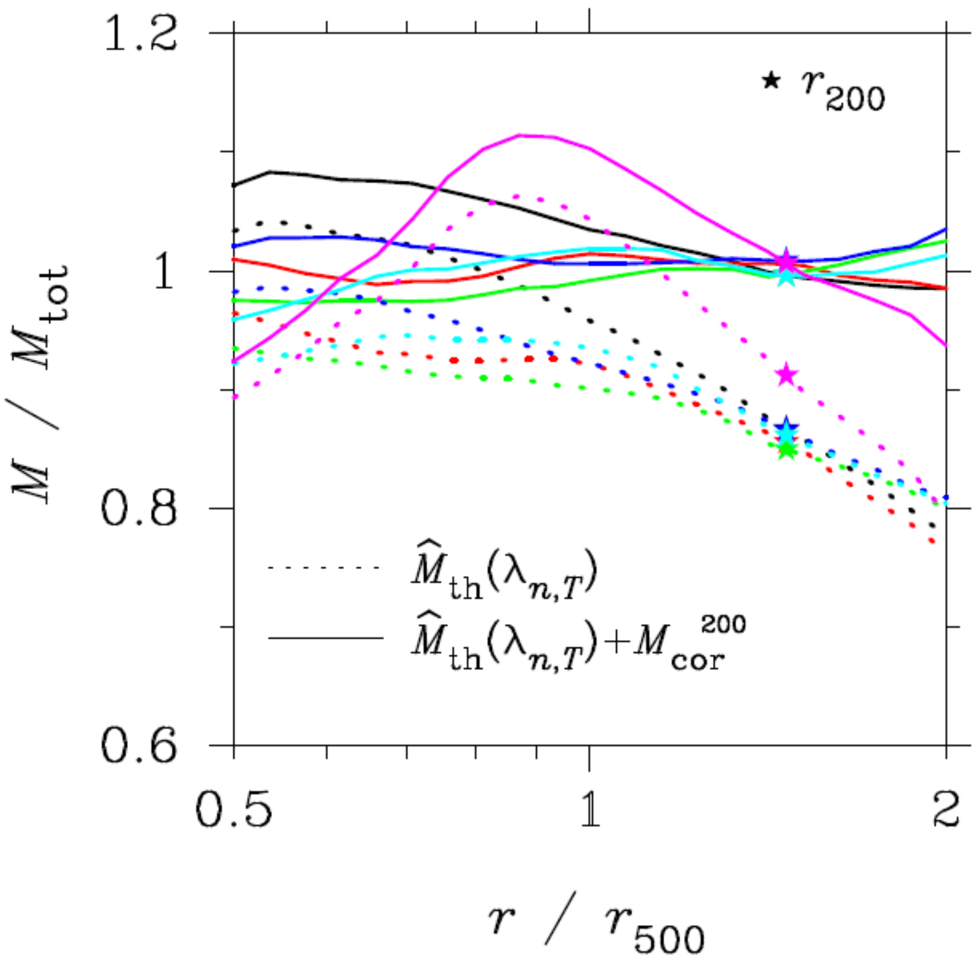


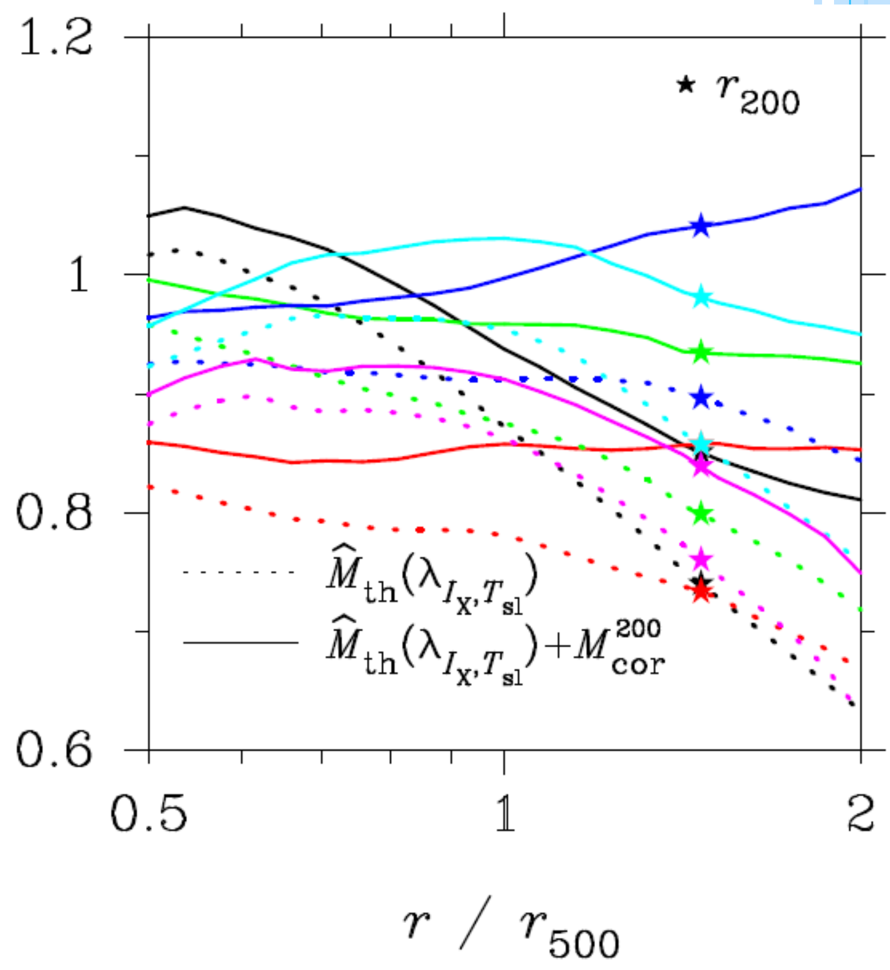


$$M_{\rm cor}^{200} = \left(\frac{\widehat{T}(r_{200})}{\rm keV}\right)^{1.75}\left(\frac{r}{r_{200}}\right)^{2} \times 10^{13.4}\ M_{\odot}$$

$$M_{\rm cor}^{500} = \left(\frac{\widehat{T}(r_{500})}{\rm keV}\right)^{1.35}\left(\frac{r}{r_{500}}\right)^{2} \times 10^{12.8}\ M_{\odot}$$

Correction Term



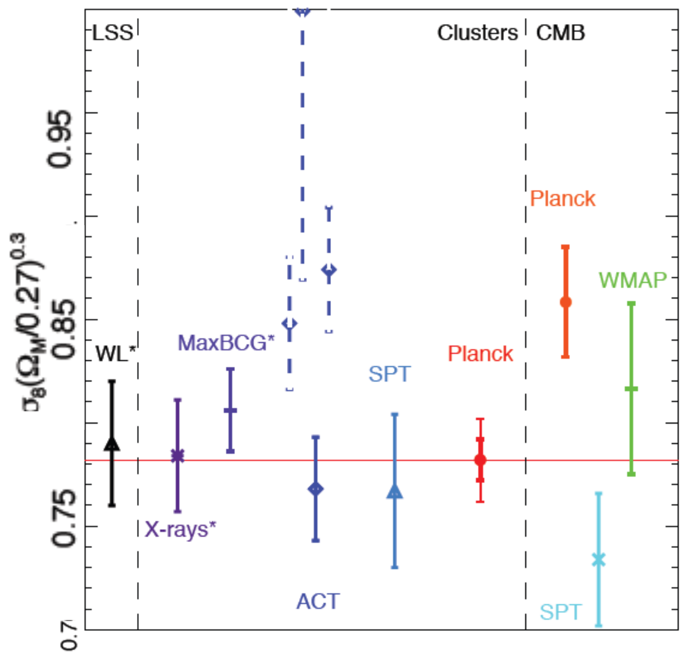


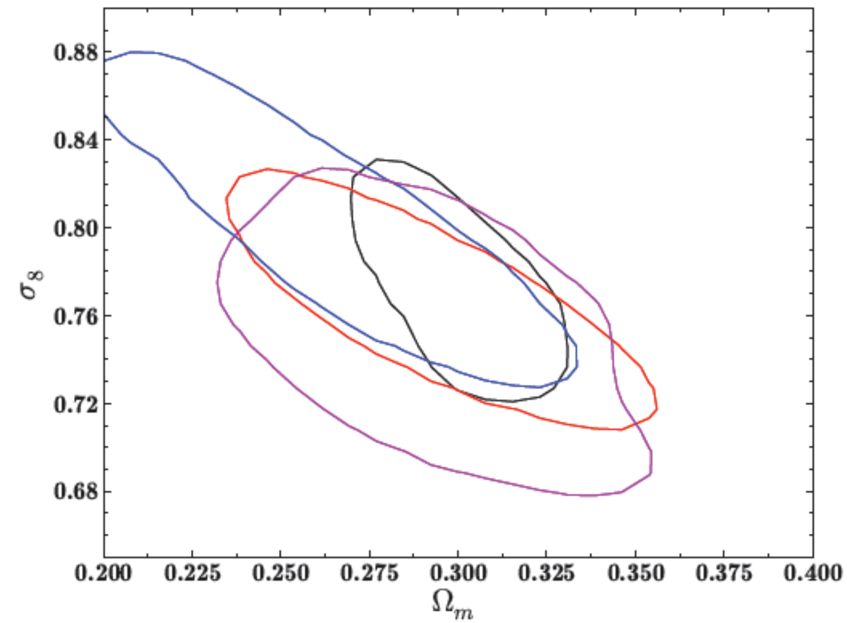
Introduction

- Impact on cosmological parameters
  - σ_8 from cluster abundance (Shimizu et al., 2006)

$$\sigma_{8,\mathrm{true}} = \sigma_{8,\mathrm{cluster}} + 0.5(1-\alpha_M) \quad \alpha_M = M_{\mathrm{est}}/M_{\mathrm{tot}}$$

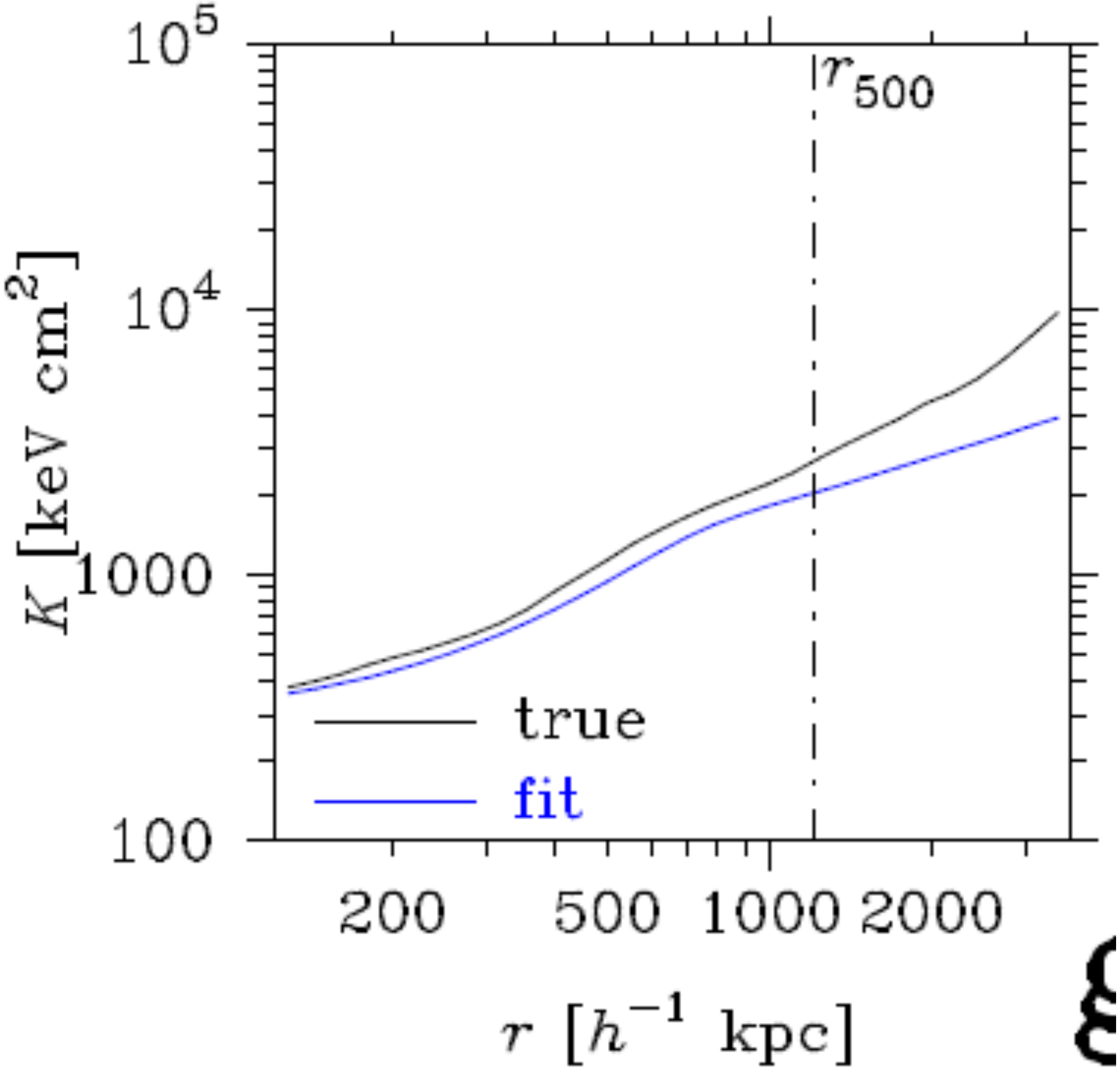
- Cluster abundance vs. CMB anisotropies





Planck Collaboration, 2013

Entropy



10^5
10^4
1000
100
K [keV cm^2]
r_{500}
true
fit
200
500
1000
2000
r [h^{-1} kpc]