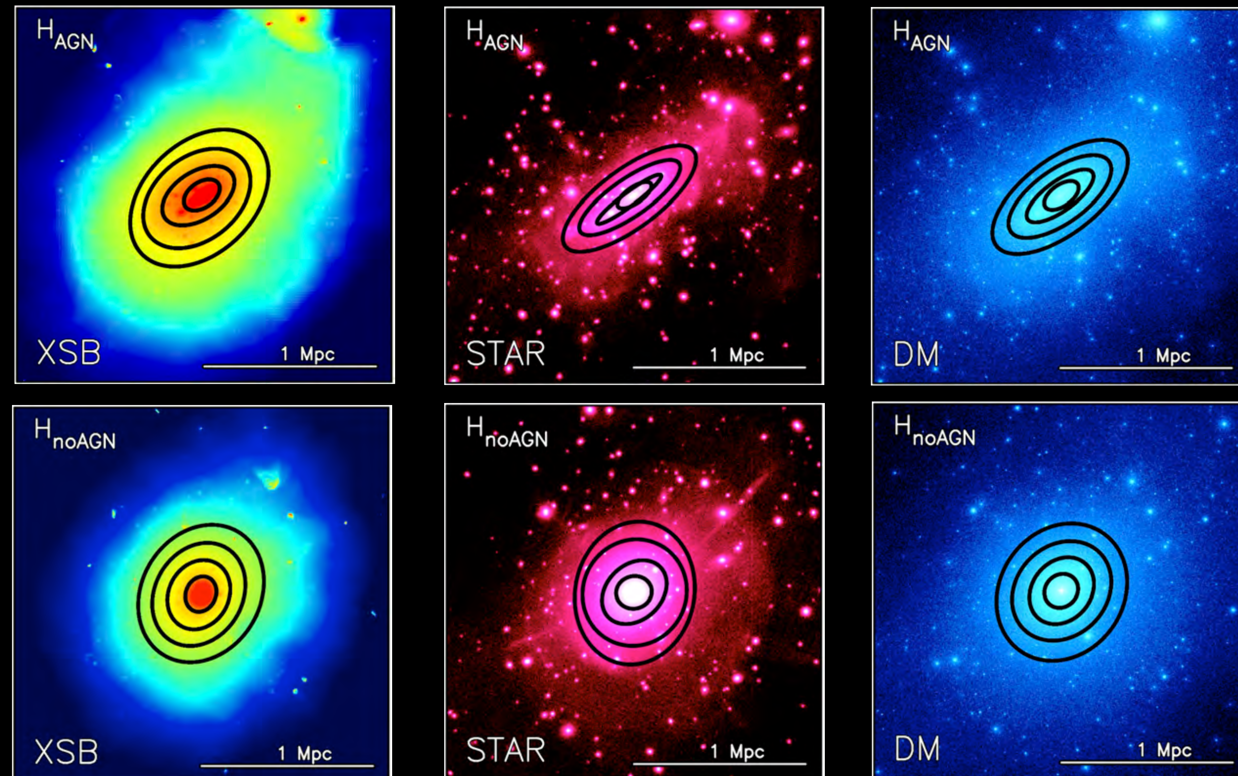
Non-sphericity of galaxy clusters and impact of baryon physics

Hydro-simulation with AGN feedback

Hydro-simulation without AGN feedback



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- *D.Suto et al. (2016a) PASJ, 68, 14*
- *D.Suto et al. (2016b) arXiv:1608.06494*
- *D.Suto et al. (2016c) submitted to PASJ*

1. Introduction
2. Comparison of spherical dust collapse model against N-body simulation
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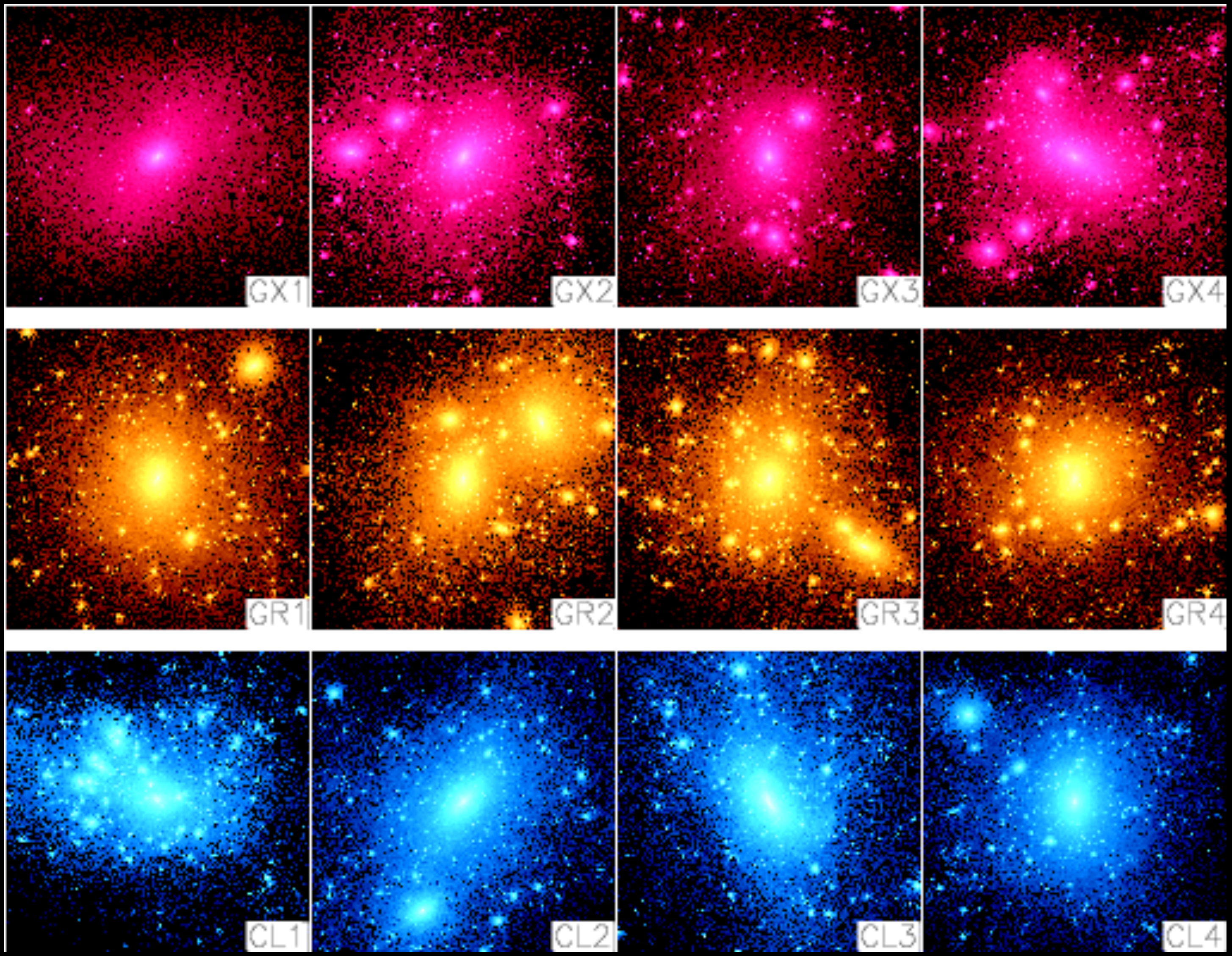
Shapes of dark matter halos: highly non-spherical

galaxies
~ 5x10^{12}M$_{sun}$

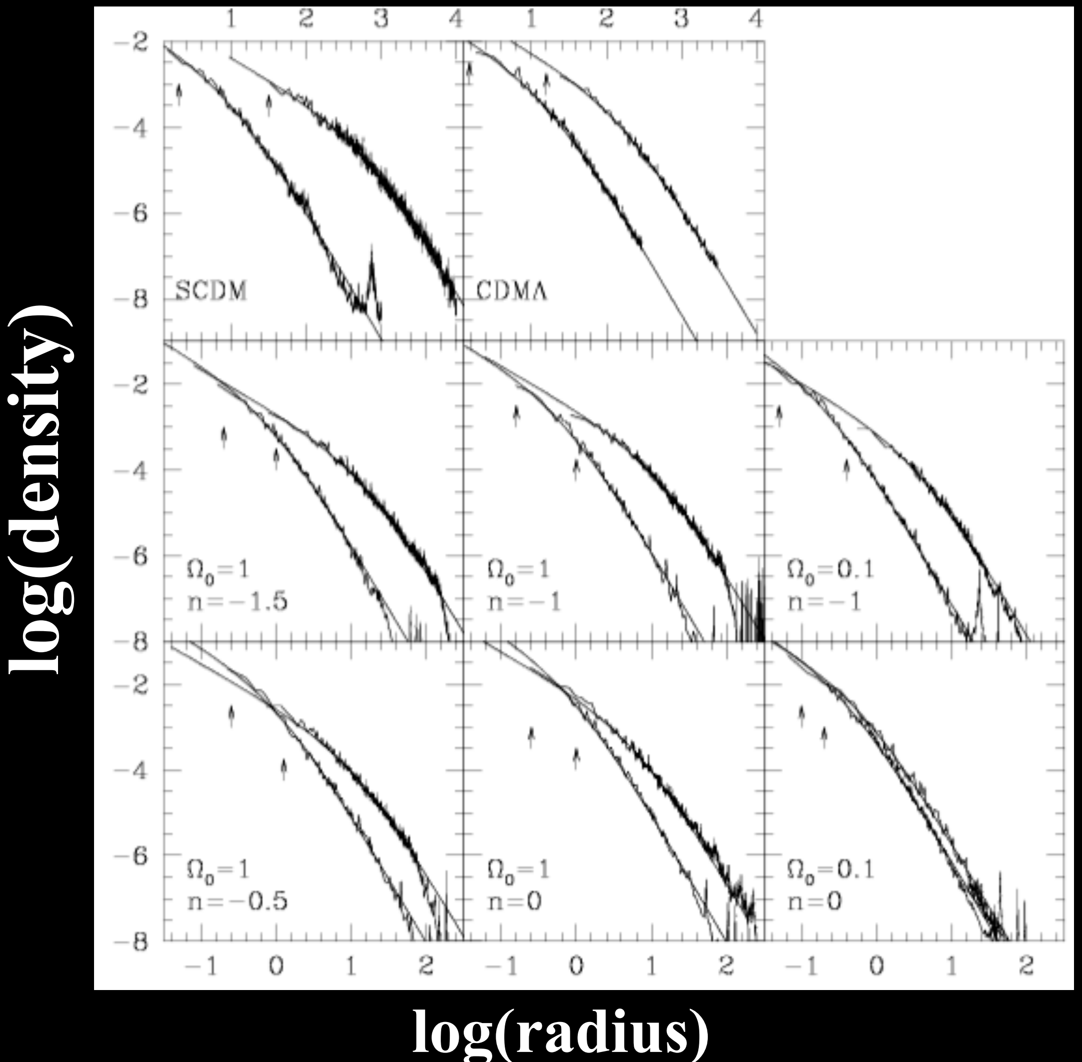
groups
~ 5x10^{13}M$_{sun}$

clusters
~ 3x10^{14}M$_{sun}$



N-body simulation by Jing & Suto (2000)

Amazing universality of ***spherically-averaged*** density profiles of halos



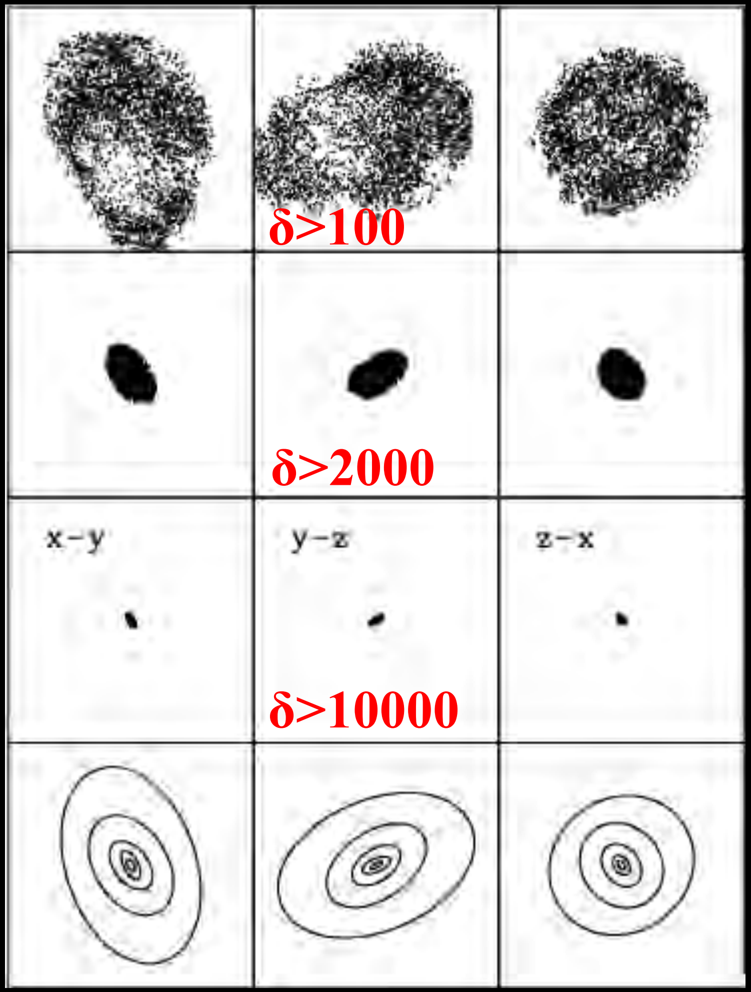
- **NFW profile**
  - Spherically-averaged density profiles of collisionless CDM halos

$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)(1+r/r_s)^2}$$

Navarro, Frenk & White (1997)

Dark matter halos are not spherical

Isodensity of a cluster-scale halo



- Triaxial modelling

$$\rho(R) = \frac{\delta_c \rho_{crit}}{(R/R_s)^{\alpha}(1+R/R_s)^{3-\alpha}}$$

$$R^2(\rho) \equiv \frac{X^2}{a^2(\rho)} + \frac{Y^2}{b^2(\rho)} + \frac{Z^2}{c^2(\rho)}$$

Jing & Suto ApJ 574 (2002) 538

- Halo non-sphericity is known to have impacts on halo mass function (Sheth & Tormen 2002), lensing probability (Oguri, Lee & Suto 2003), and thus important in precision cosmology.

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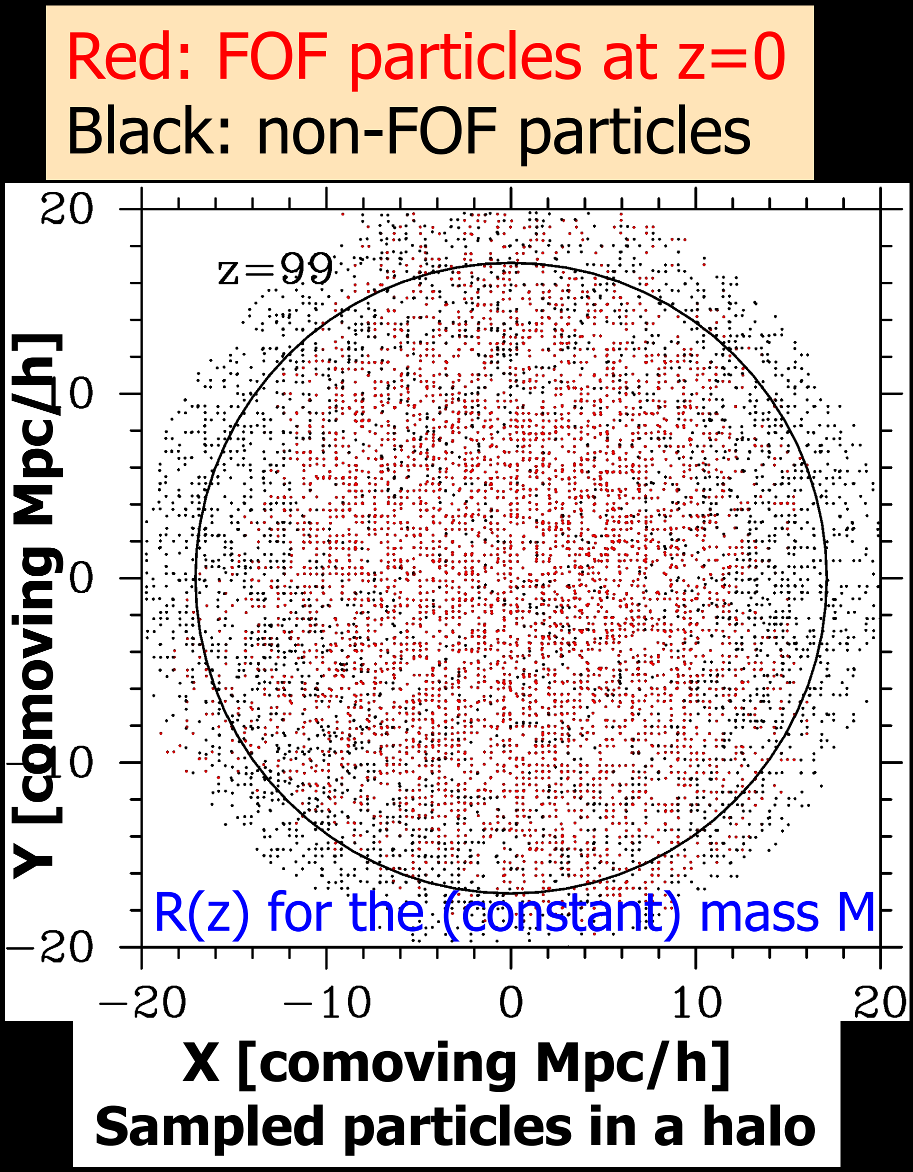
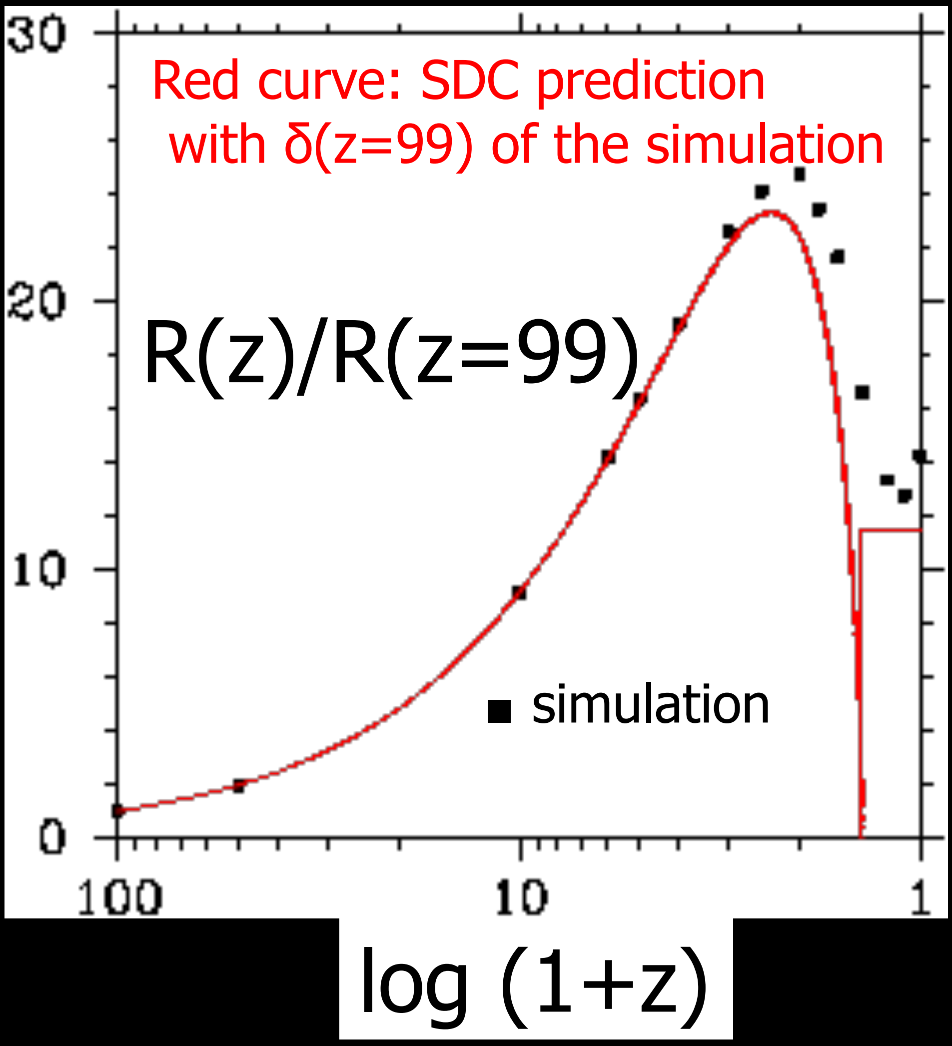
Comparison of the SDC model predictions against N-body results

- Dark matter only simulations with GADGET-2
  - ΛCDM with WMAP9 cosmological parameters
  - $N=1024^3$ in $(360h^{-1}\ \mathrm{Mpc})^3$
  - $m=3.4 \times 10^9\ M_\odot$
- FOF halos identified at $z=0$
  - compute the spherical mass M and radius R of spherical overdensity of $\Delta=\rho/\rho_m=355.4$
  - Identifies the center-of-mass of the $z=0$ FOF halo particles at z, and compute the radius R(z) enclosing the mass M at $0<z<z_{initial} = 99$

The most massive halo with $M=1.66\times10^{15}\ M_\odot$

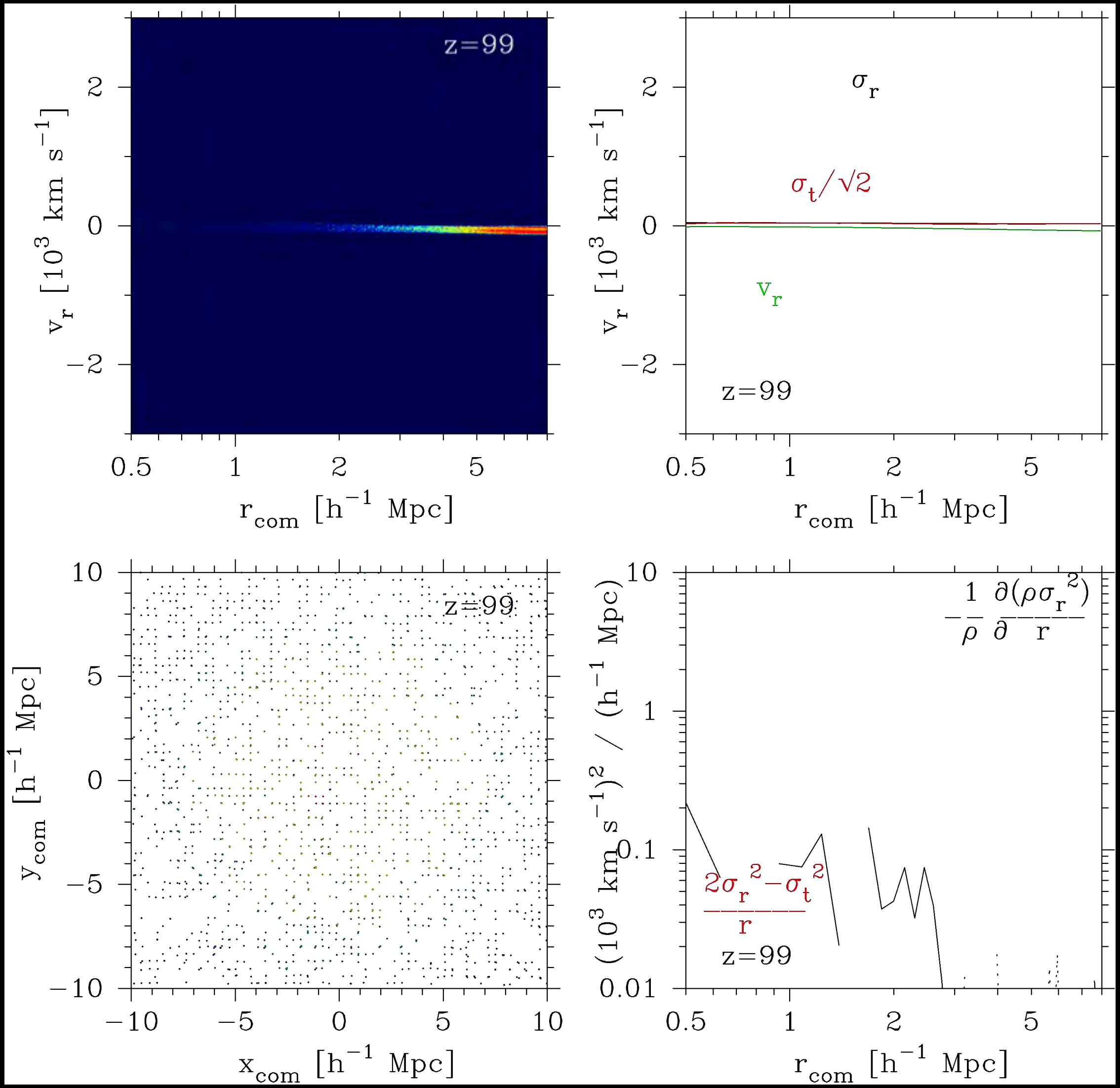




Generic trends from 100 simulated halos

- Very good quantitative agreement until the turn-around epoch
  - may be reasonable but not trivial at all, given the small-scale clumping, subhalo mergers inside, and/or the filamentary structure across the entire region
- Systematic difference relative to SDC predictions after the turn-around epoch
  - Delay of the turn-around epoch
  - Larger turn-around radius
  - Larger “virialized” radius

Evolution of a halo($M=1.66\times10^{15}\ M_{\odot}$) in phase space (comoving coordinate)



Effect of velocity dispersions

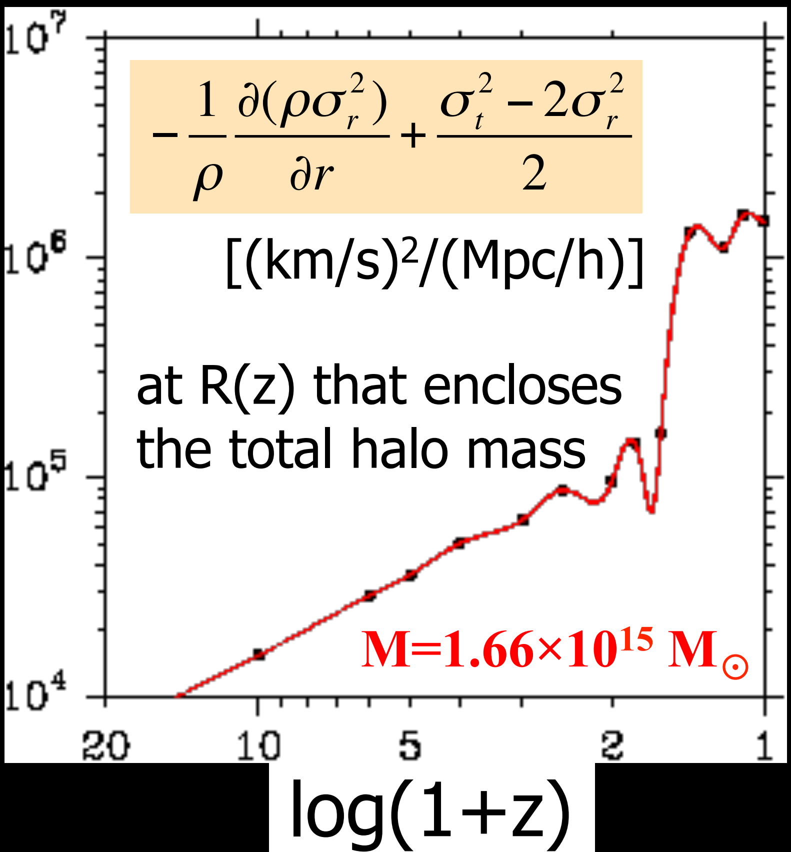
- Jeans equation for spherical collisionless system
  - radial velocity dispersion σ_r^2
  - tangential velocity dispersion σ_t^2

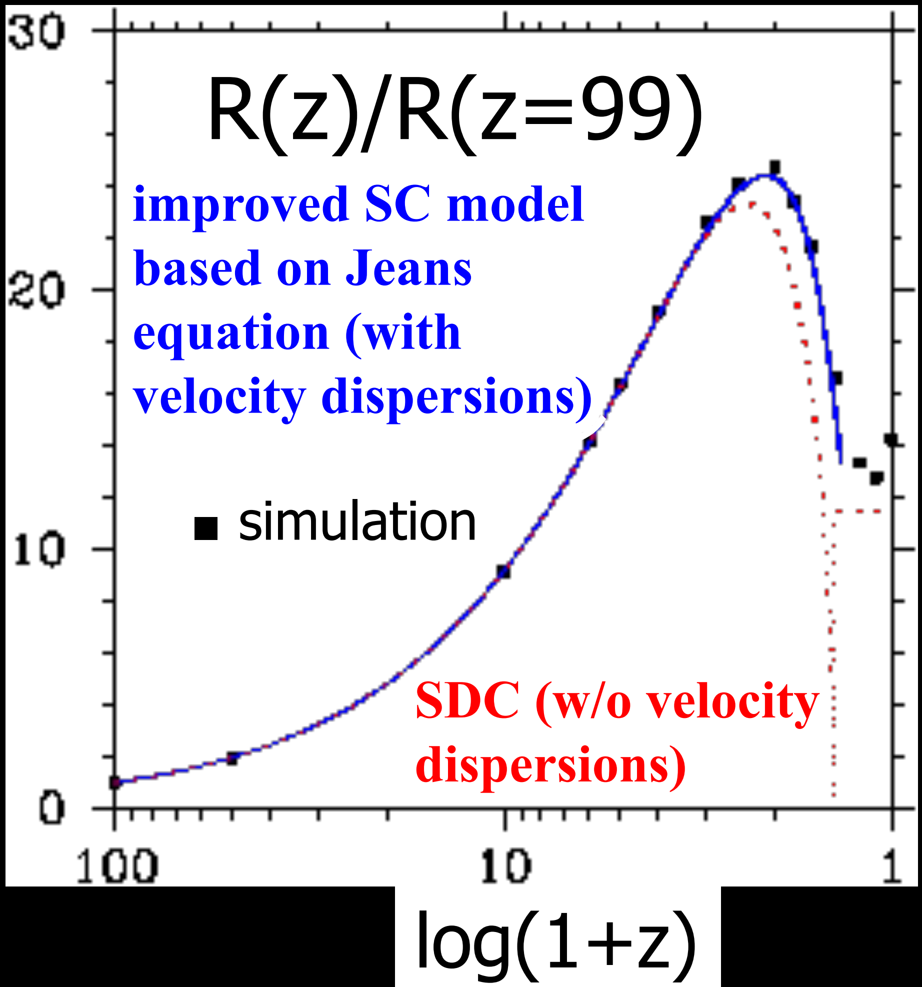
$$\frac{Dv_r}{Dt} = -\frac{1}{\rho}\frac{\partial(\rho\sigma_r^2)}{\partial r} + \frac{\sigma_t^2 - 2\sigma_r^2}{2} - \frac{GM}{r^2}$$

- SDC assumes an initially top-hat (homogeneous) sphere
  - neglects small-scale inhomogeneities, shell-crossing before turn-around, and thus no σ_r^2 or σ_t^2
- Larger $t_{\text{turn-around}}$ and R_{virial} than predicted by SDC

Improvement with velocity dispersions

- Evaluate the velocity dispersions from simulation data and solve the Jean equation
- Greatly improved !





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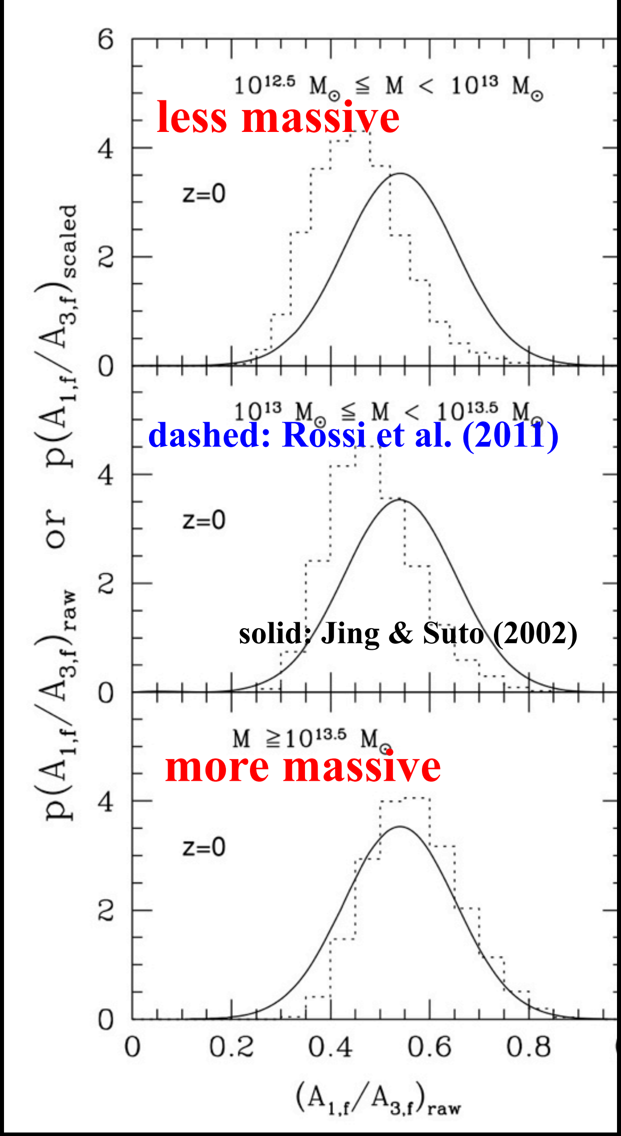
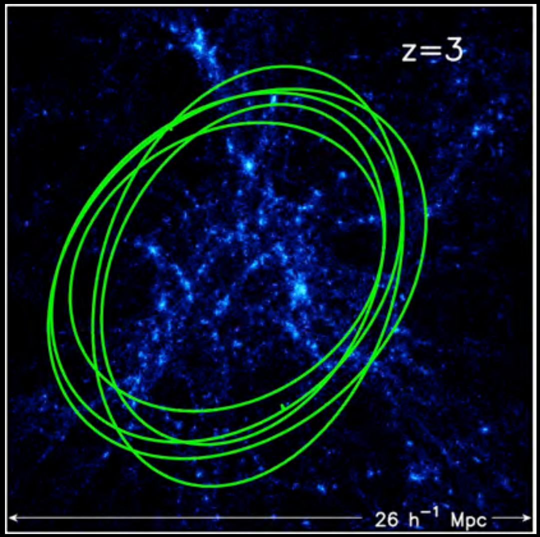
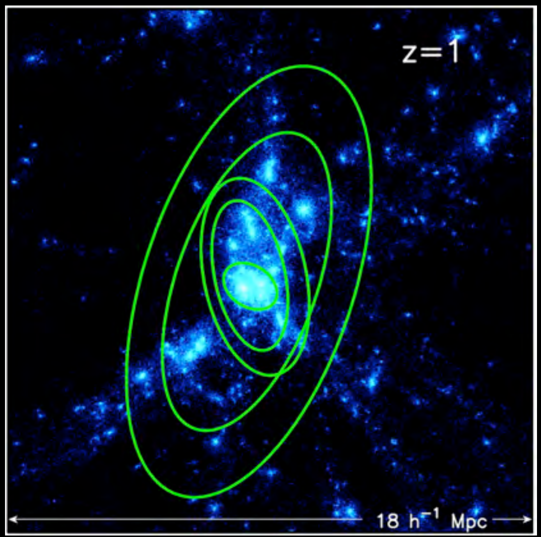
Does ellipsoidal collapse model fit better than spherical model ?

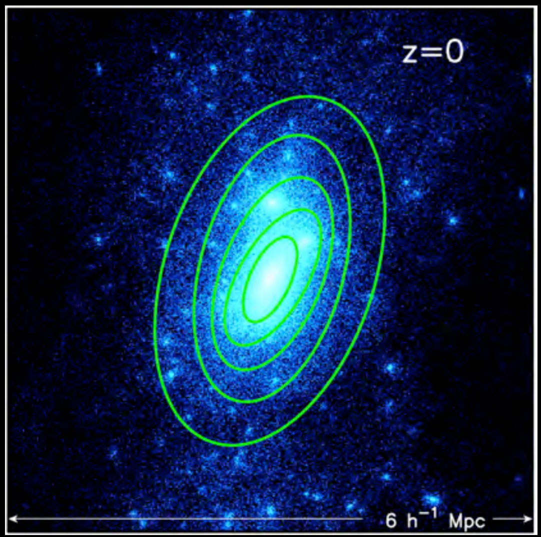
- Actually No!
- Ellipsoidal collapse model (Rossi, Sheth & Tormen 2011; dashed) predicts that more massive halos are more spherical
- N-body simulations (Jing & Suto 2002; solid) indicate that non-sphericity is fairly insensitive to mass

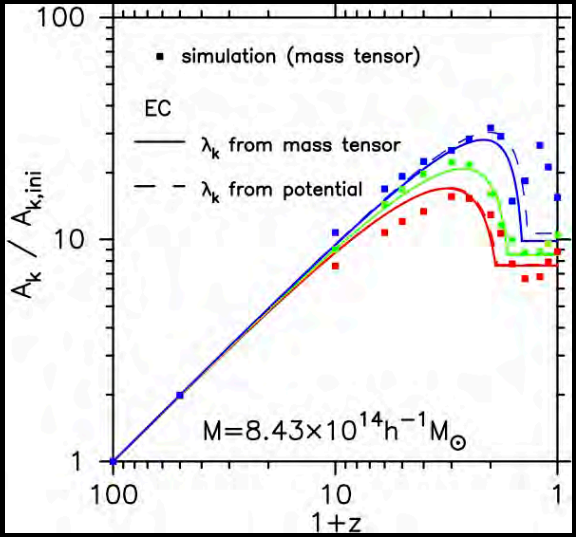


Evolution of non-sphericity: ellipsoidal collapse vs. N-body



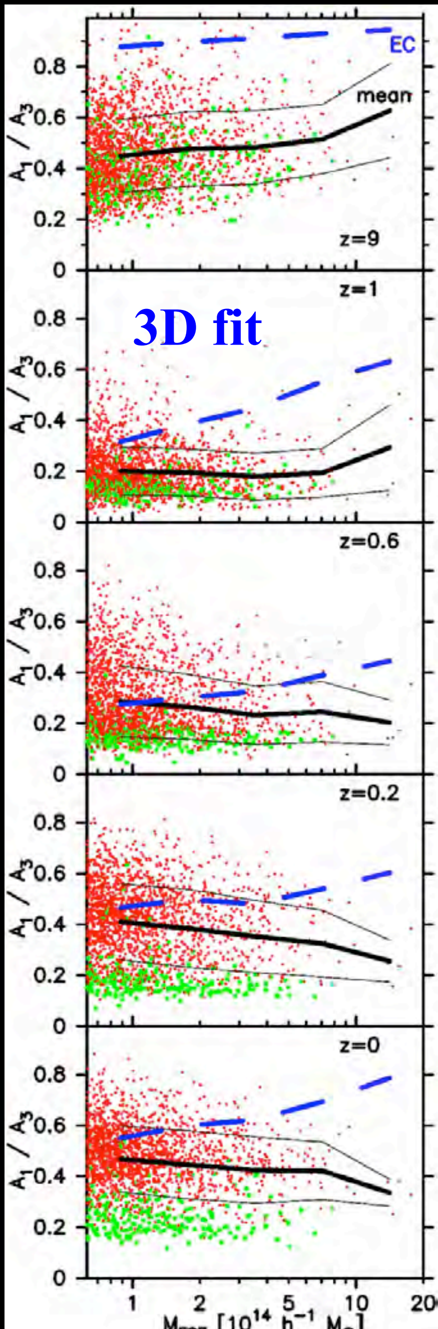




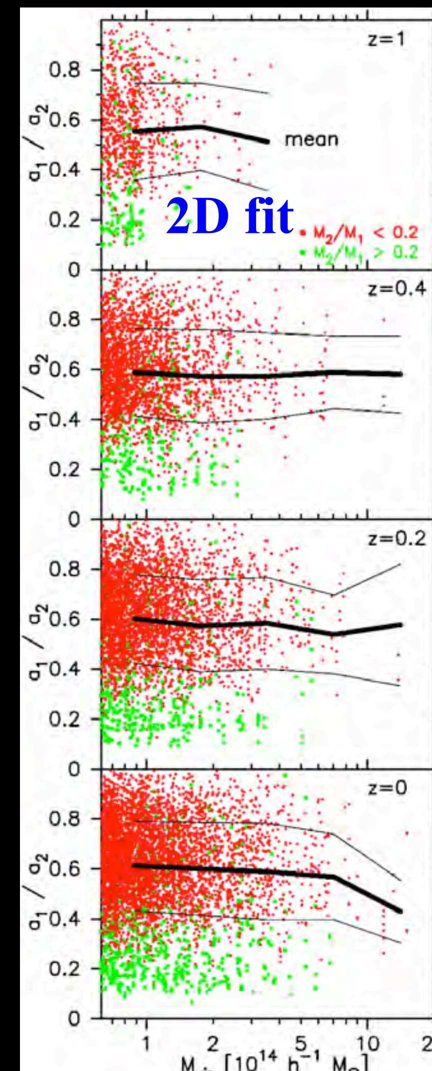


- Individual halo evolution is in reasonable, even if not good, agreement with ellipsoidal collapse before virialization
  - Suto et al. (2016b) PASJ, in press

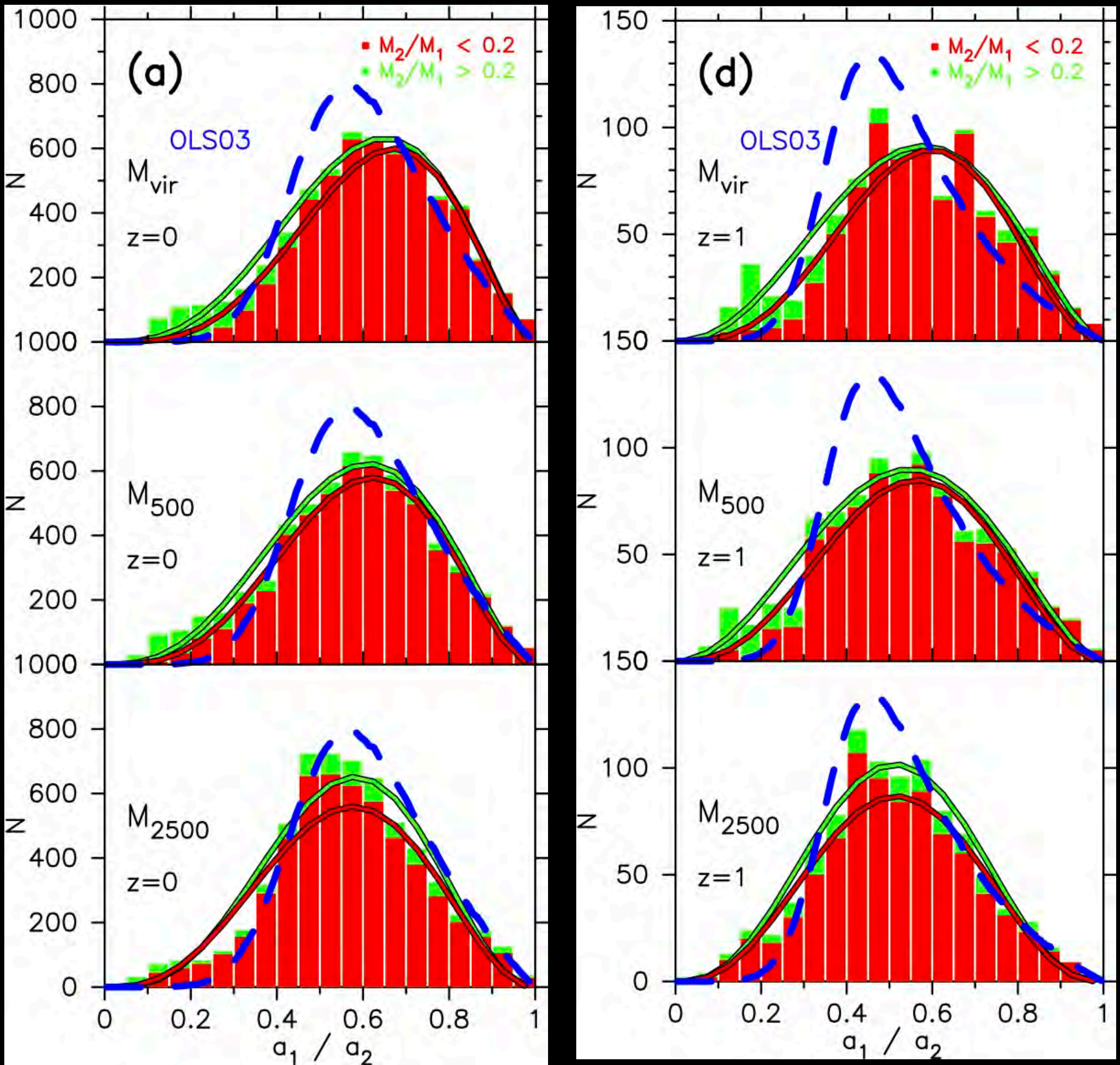
Axis ratio of 2004 halos: redshift and mass dependence



- 3D (left) and 2D (projected; right)
  - Becomes less spherical until turn-around, and then more spherical
  - Almost independent of mass (or very weakly less spherical for larger mass, which is opposite to ellipsoidal collapse prediction)

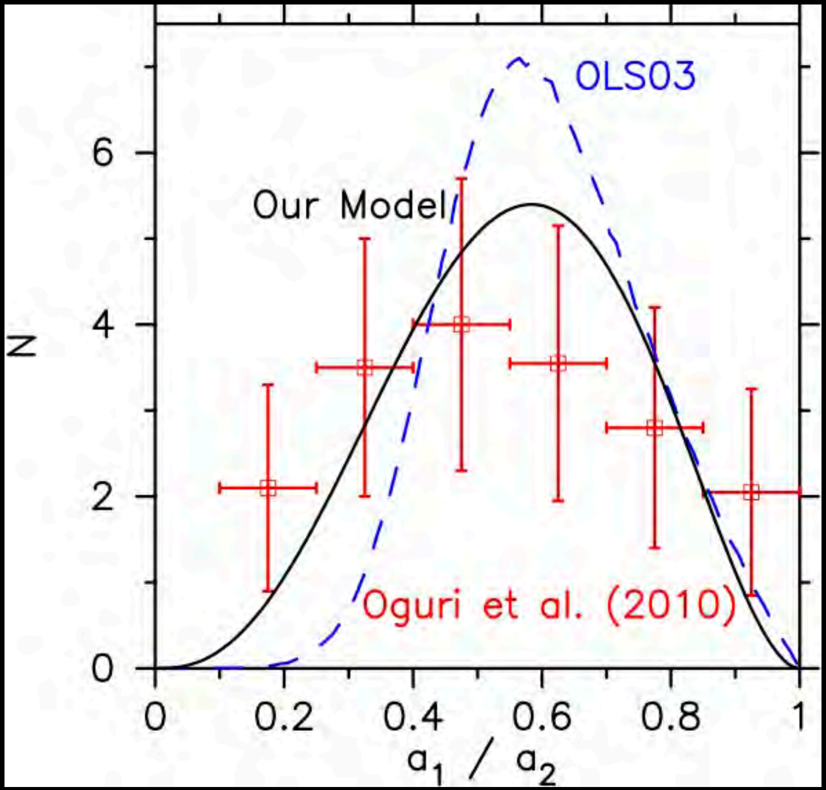


PDF of projected axis ratios



- insensitive to redshift
- Slightly less spherical towards inner region
- Very different from the self-similar projected model (Oguri, Lee & Suto 2003)
- Empirical fitted to β-distribution

Tentative comparison with observed axis ratio from weak lensing



- Subaru Suprime-Cam weak-lensing map for 18 massive clusters (Oguri et al. 2010, MNRAS 405, 2215)
- Our result fits the observed data better than the OLS03 prediction
- Promising for future comparison with Subaru Hyper Supreme-Cam data

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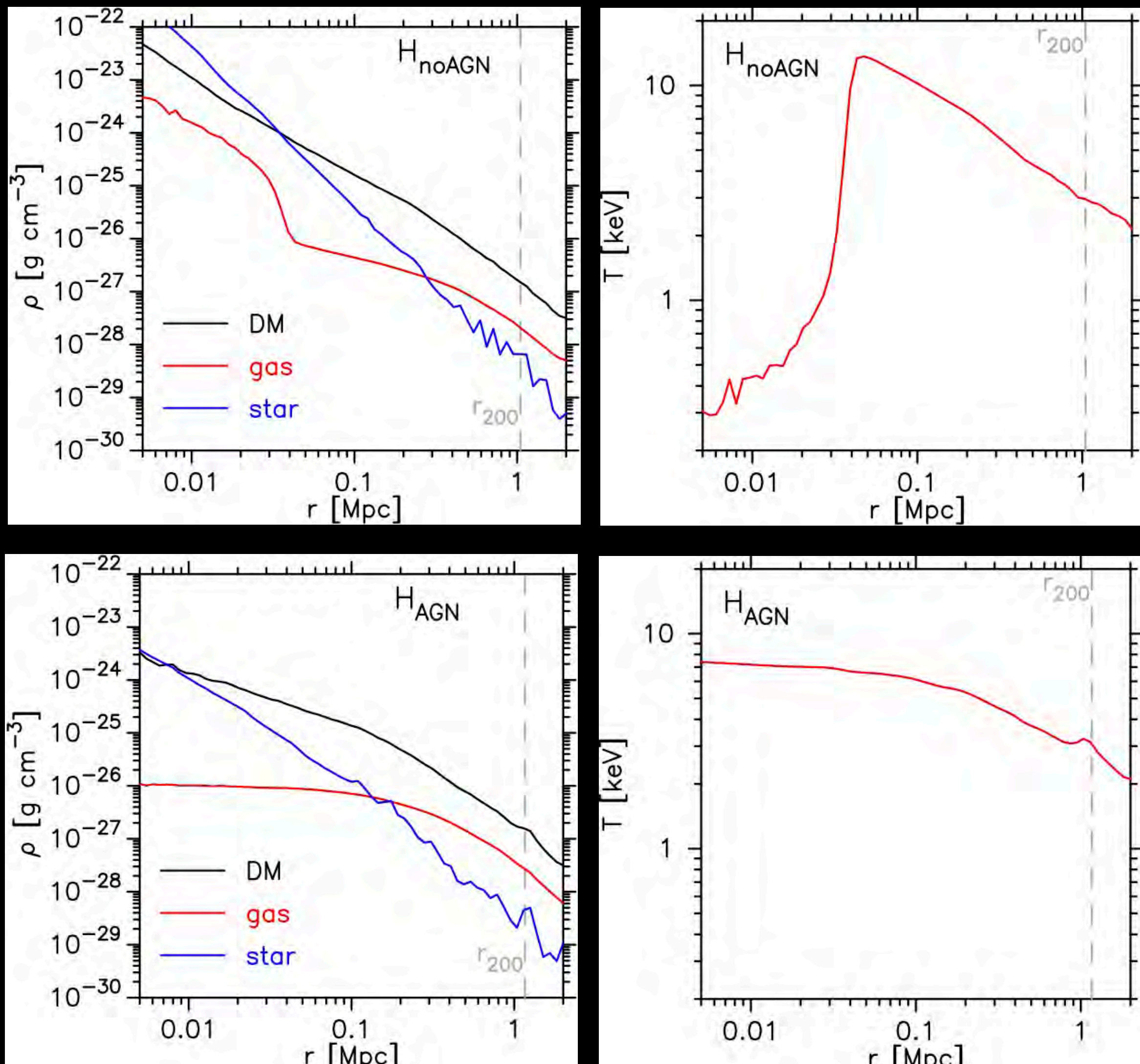
Horizon simulations

- Cosmological hydro-dynamical simulation (Dubois et al. 2014)
  - $N=1024^3$ dark matter particles in a cube of $(100h^{-1}\mathrm{Mpc})^3$; $m = 8.27\times10^7\,M_\odot$
  - Adaptive mesh refinement for gas with initial cell size of 136kpc (refine down to 1.06kpc)
    - Gas cooling, heating due to UV background, star formation, and feedback from stellar winds and type I and II SNe are included
  - H_{AGN} includes feedback from AGN as well by implementing the growth of central BHs

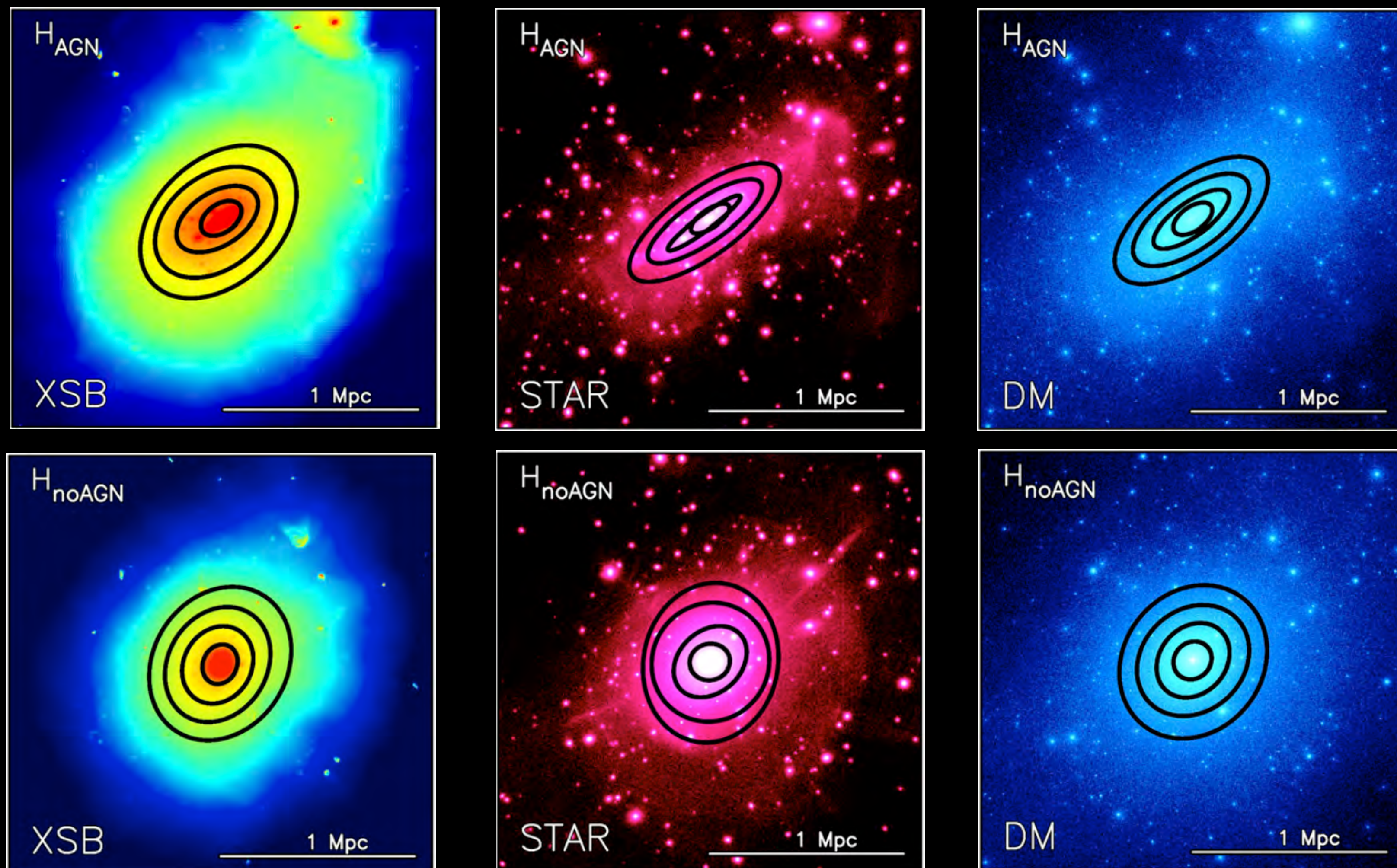
Baryonic effect inside galaxy clusters



- Both gas cooling and star+AGN feedback need to be properly included in simulation so as to reproduce the (spherically-averaged) properties of galaxy clusters

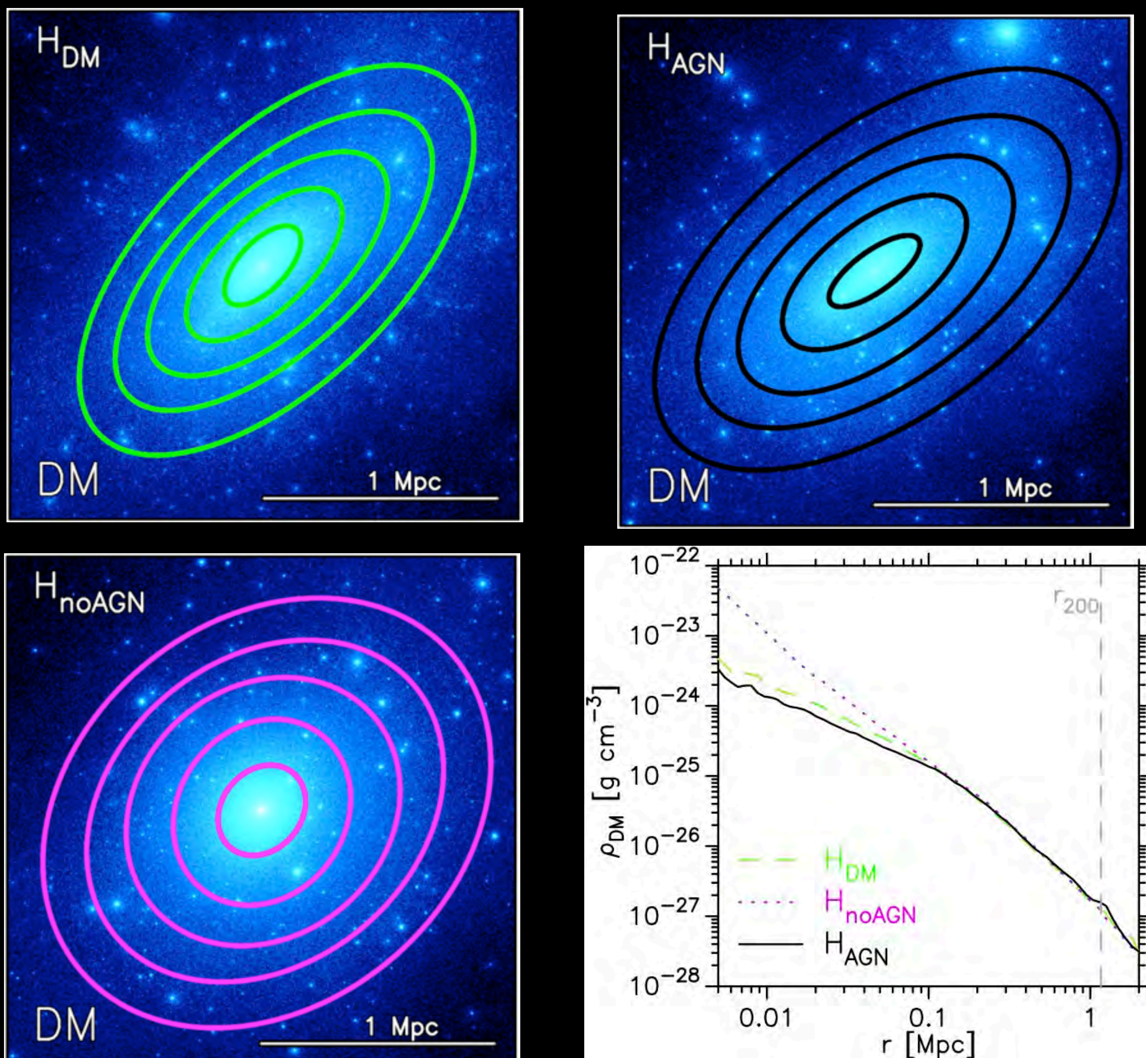
Shape of clusters probed by gas, stars, and dark matter

with AGN feedback



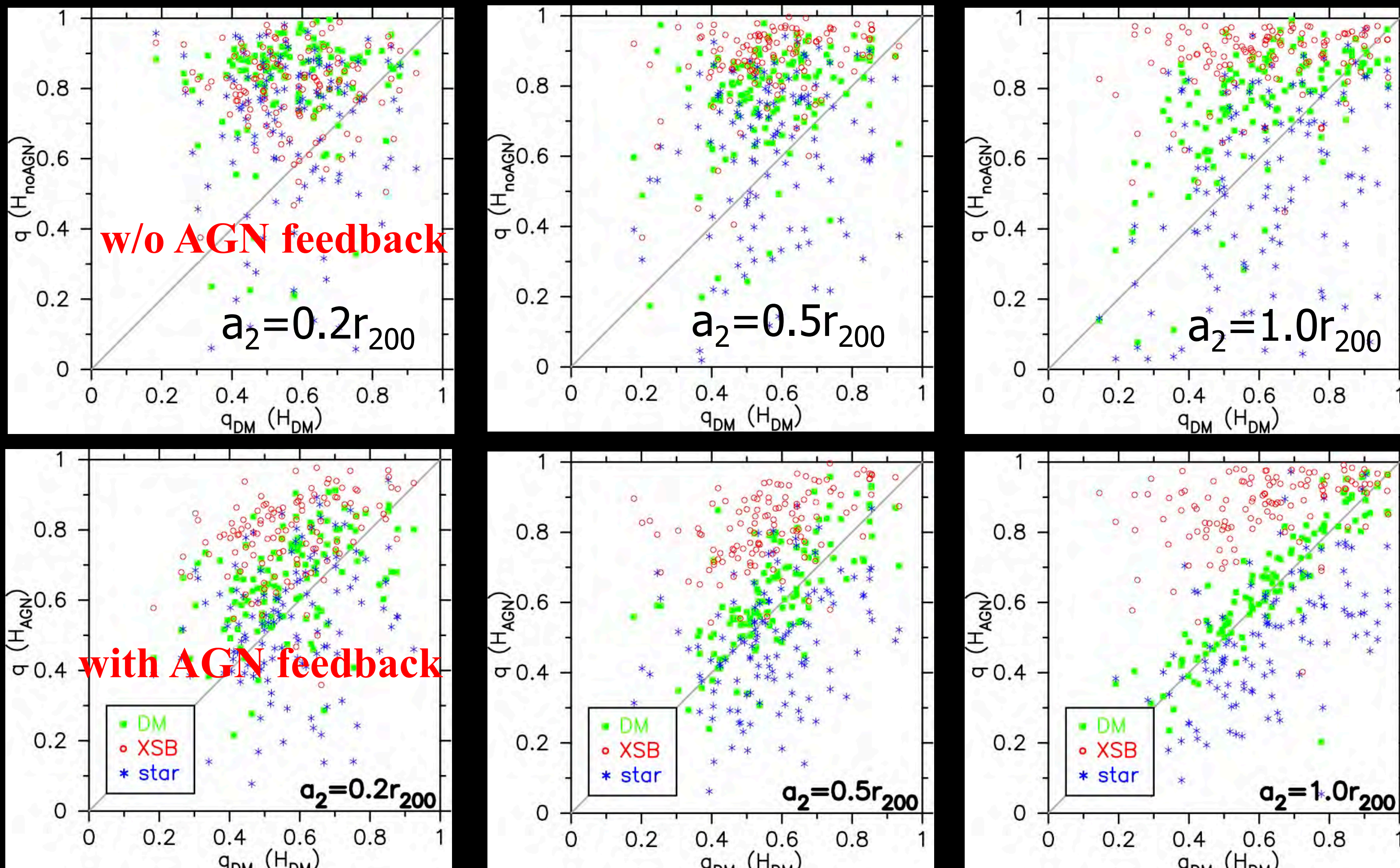
without AGN feedback

Effect of baryons on the shape of dark matter distribution

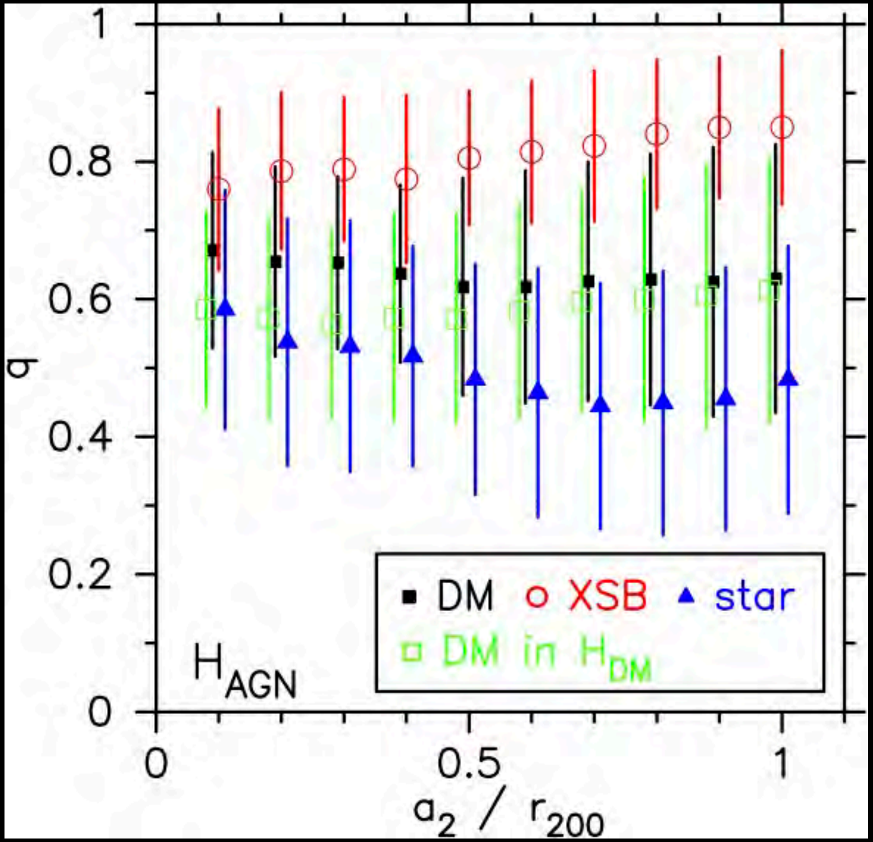


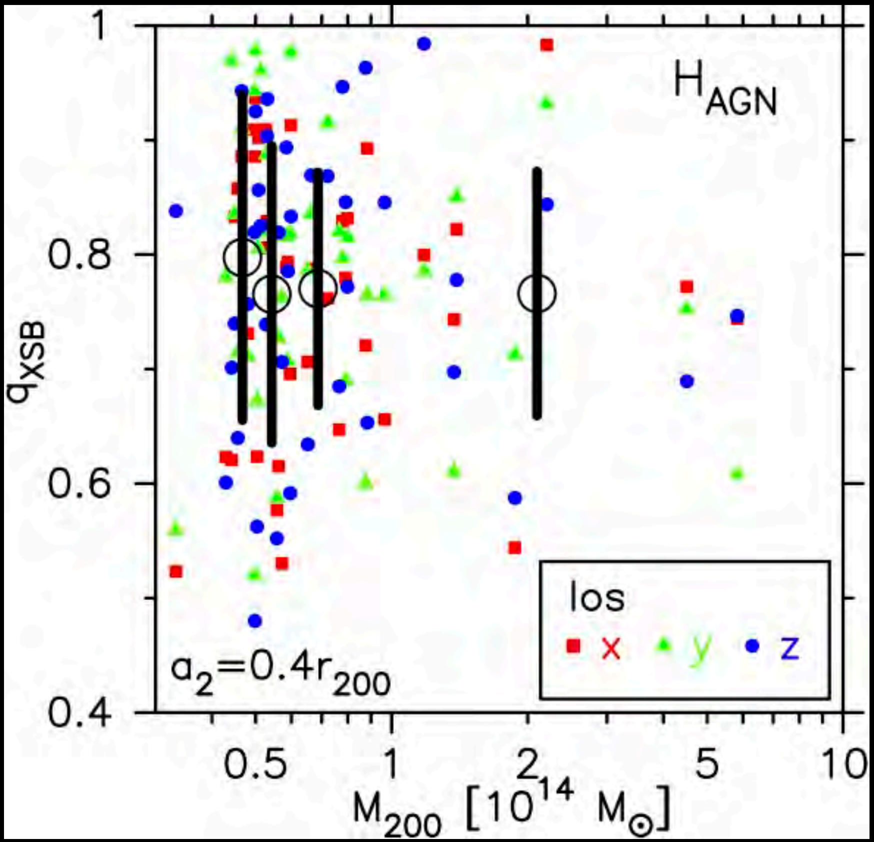
- spherical profile unchanged for $r>0.1r_{vir}$
- significant impact even up to $0.5r_{vir}$!

Axis ratios of 40 simulated clusters with/without baryon physics



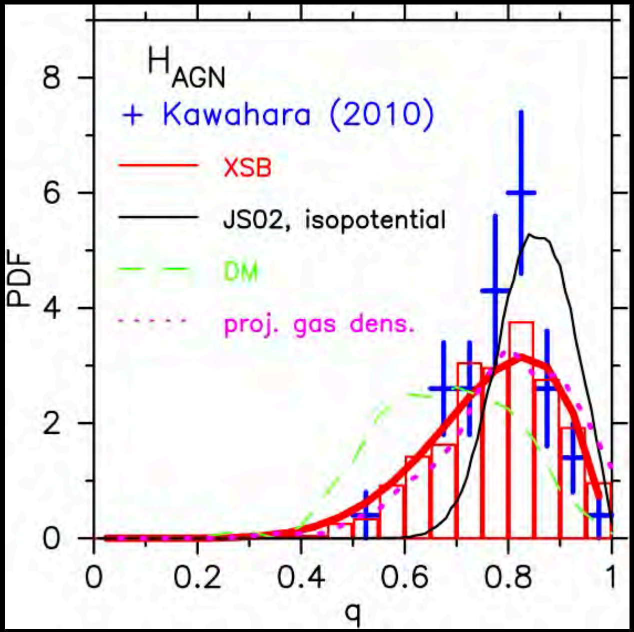
Radial and mass dependence of axis ratio



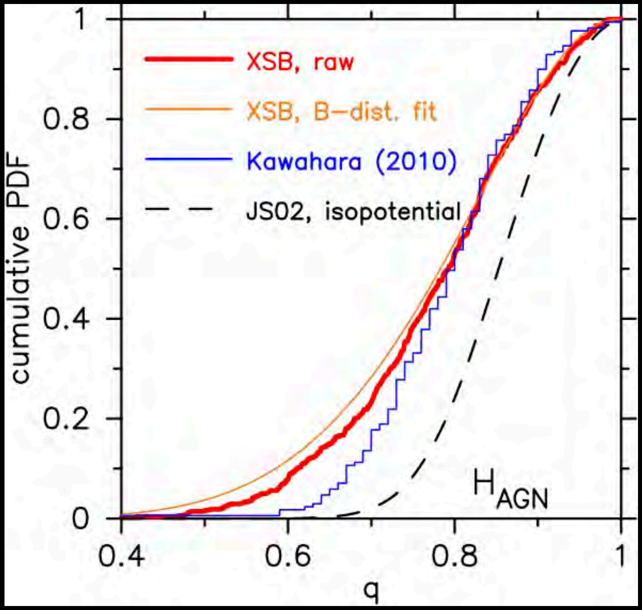


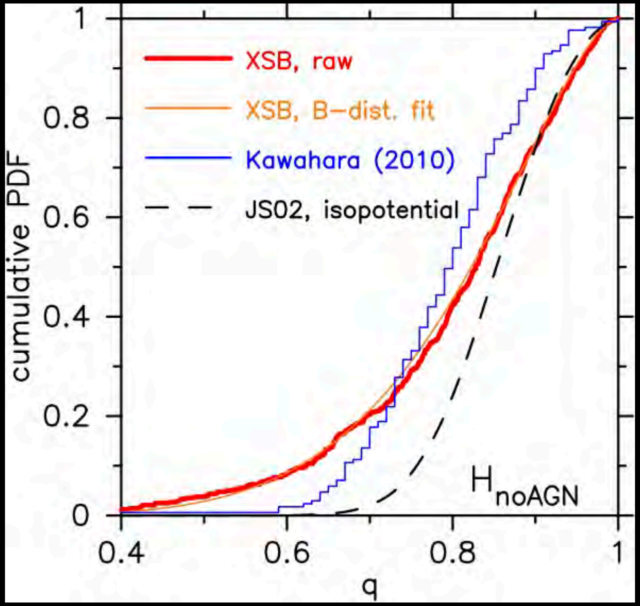
- $q_{XSB} > q_{DM} > q_{star}$
- no significant mass dependence of axis ratio

Comparison with X-ray observation



- axis ratios of 70 X-ray clusters fitted by Kawahara (2010)
- simulated clusters with AGN feedback reasonably agree with the observed data





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Summary

- Galaxies and galaxy clusters are highly non-spherical, but their non-sphericity is not easy to model/interpret theoretically
- Reliable simulations with various baryon physics are required for observational confrontation
- Current simulations reasonably reproduce the observed axis ratios from weak lensing and X-ray data
- Interesting and complementary probes of cosmology with future data