The Effects of Baryons on Dark Matter Halos:
A Brief Summary

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Outline

1. Overview of Structure Formation
    1.1. Dark Matter Halos and Halo Structure
    1.2. Galaxies and Galaxy Formation
2. Baryonic Influences on Dark Matter Halos
    2.1. Halo Contraction
    2.2. Halo Shapes
    2.3. Halo Substructure (Subhalos)
3. Effect on *Dark Energy* Measurements
4. Summary & Future

Why Care?

1. Contraction affects tests of dark matter on a variety of scales, using a variety of techniques

   1.1. Rotation Curve Measurements

   1.2. Gravitational Lensing Tests

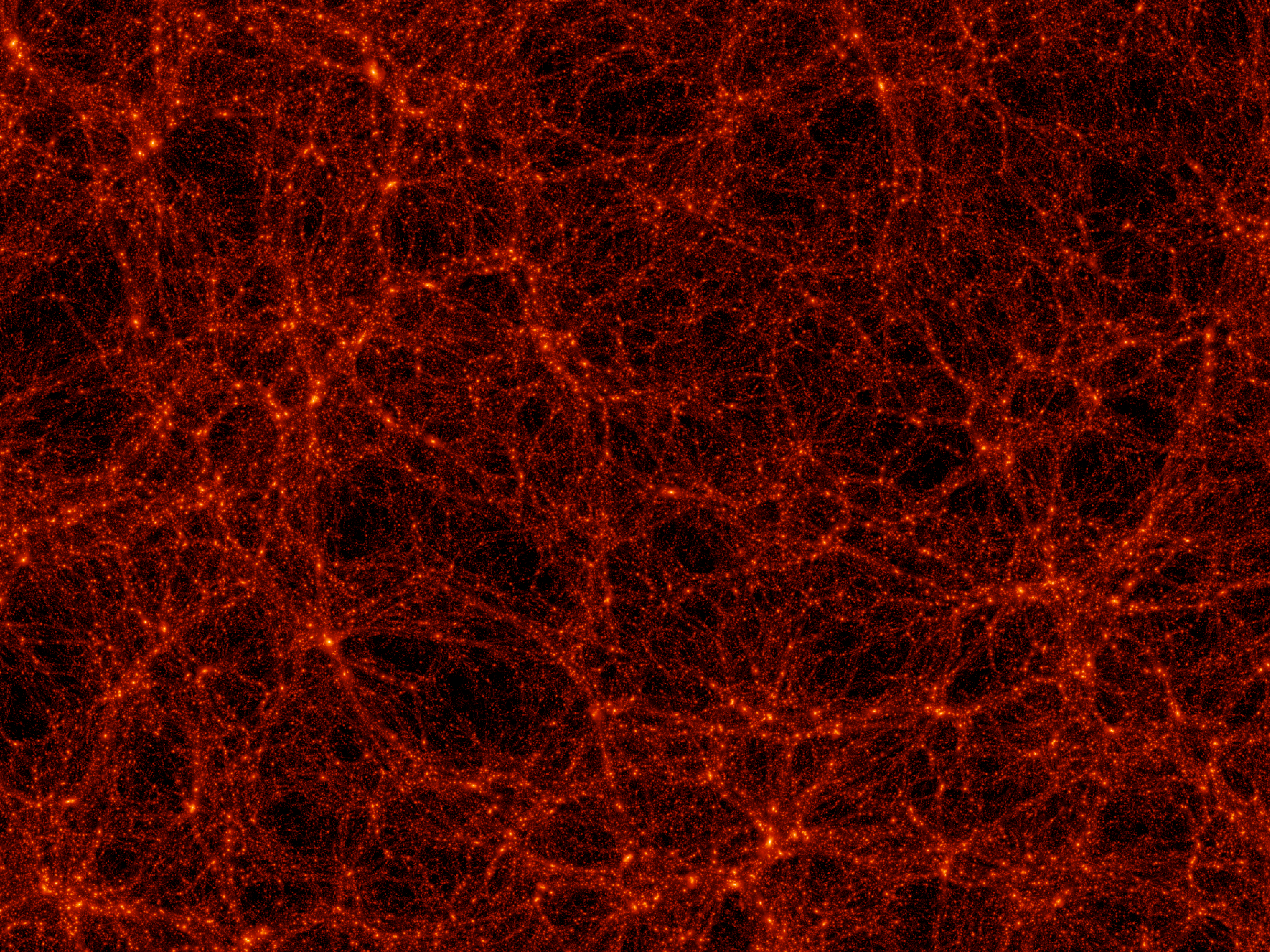
   1.3. Direct DM Search Signal Predictions

   1.4. Abundance of Halo Substructure (subhalos)

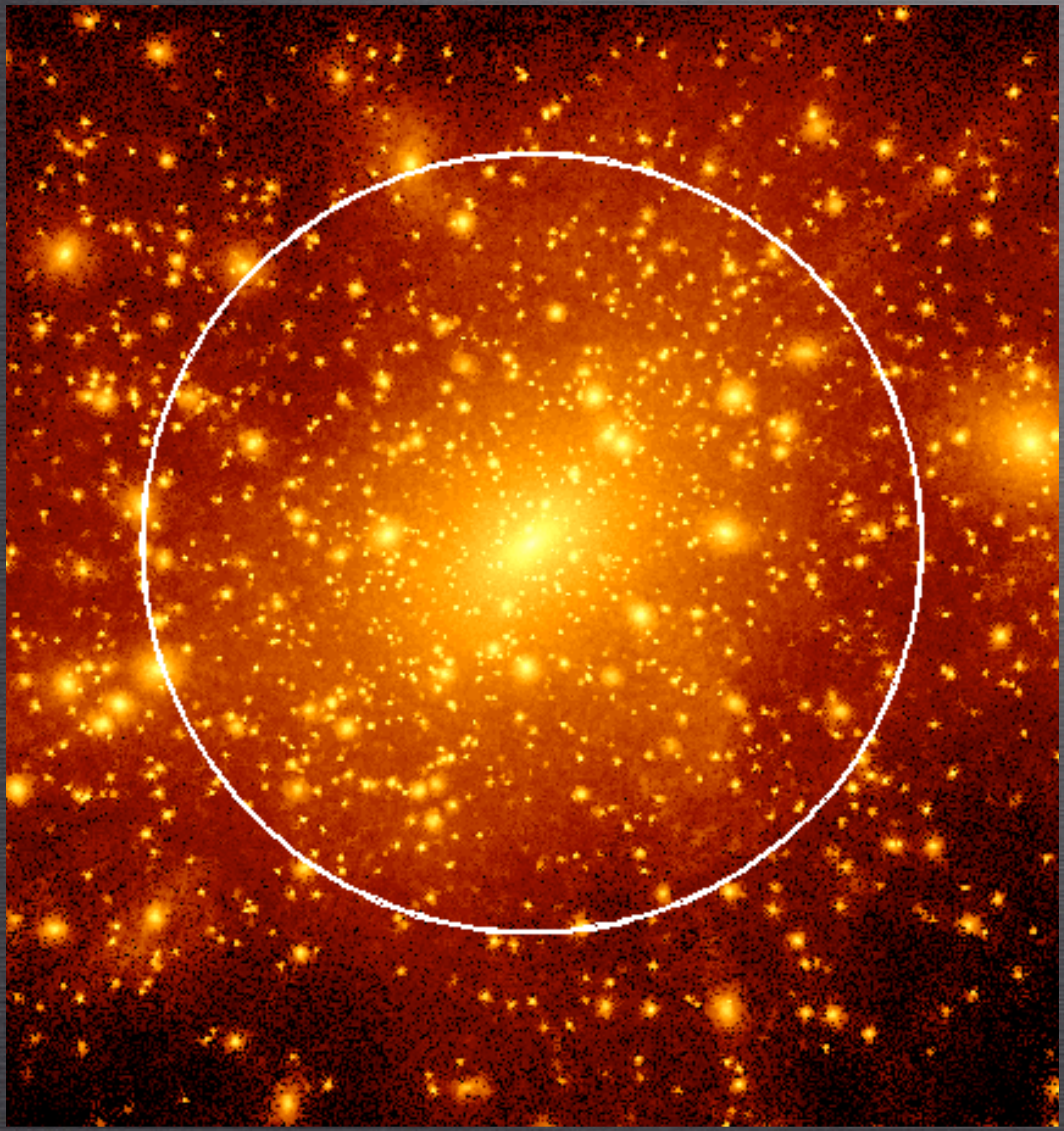
   1.5. Halo Shape Tests for DM Self-Interactions

   1.6. DM Annihilation Luminosities & Morphologies

Halo Structure



Dark Matter Halos

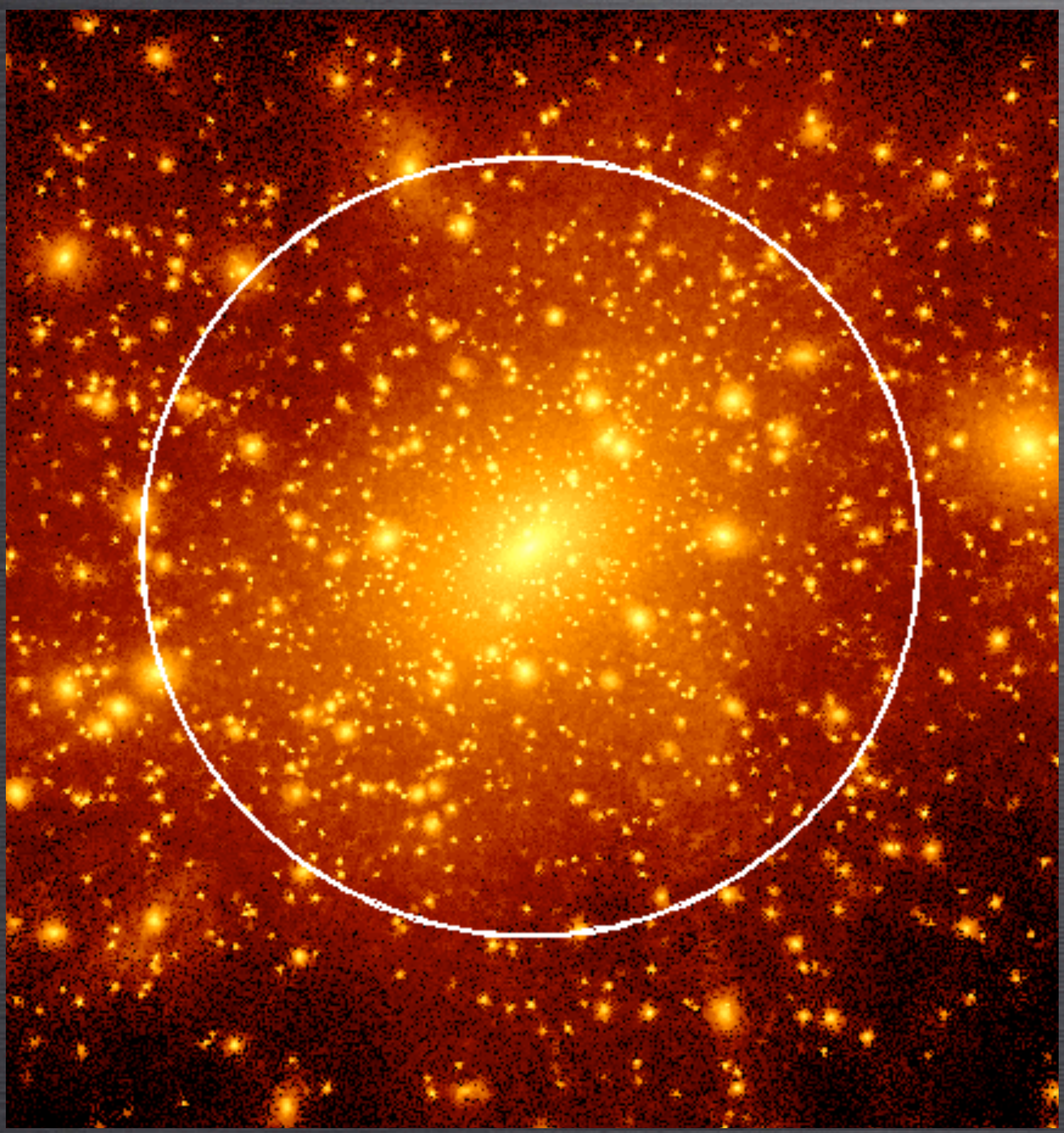


- Halos are "building blocks" of Nonlinear structure
- Virialized "Halos" have masses and radii...

$$M_{vir} = \frac{4\pi}{3}\,\Delta\langle\rho\rangle\,R_{vir}^3$$

$$\Delta \sim 200$$

Dark Matter Halos

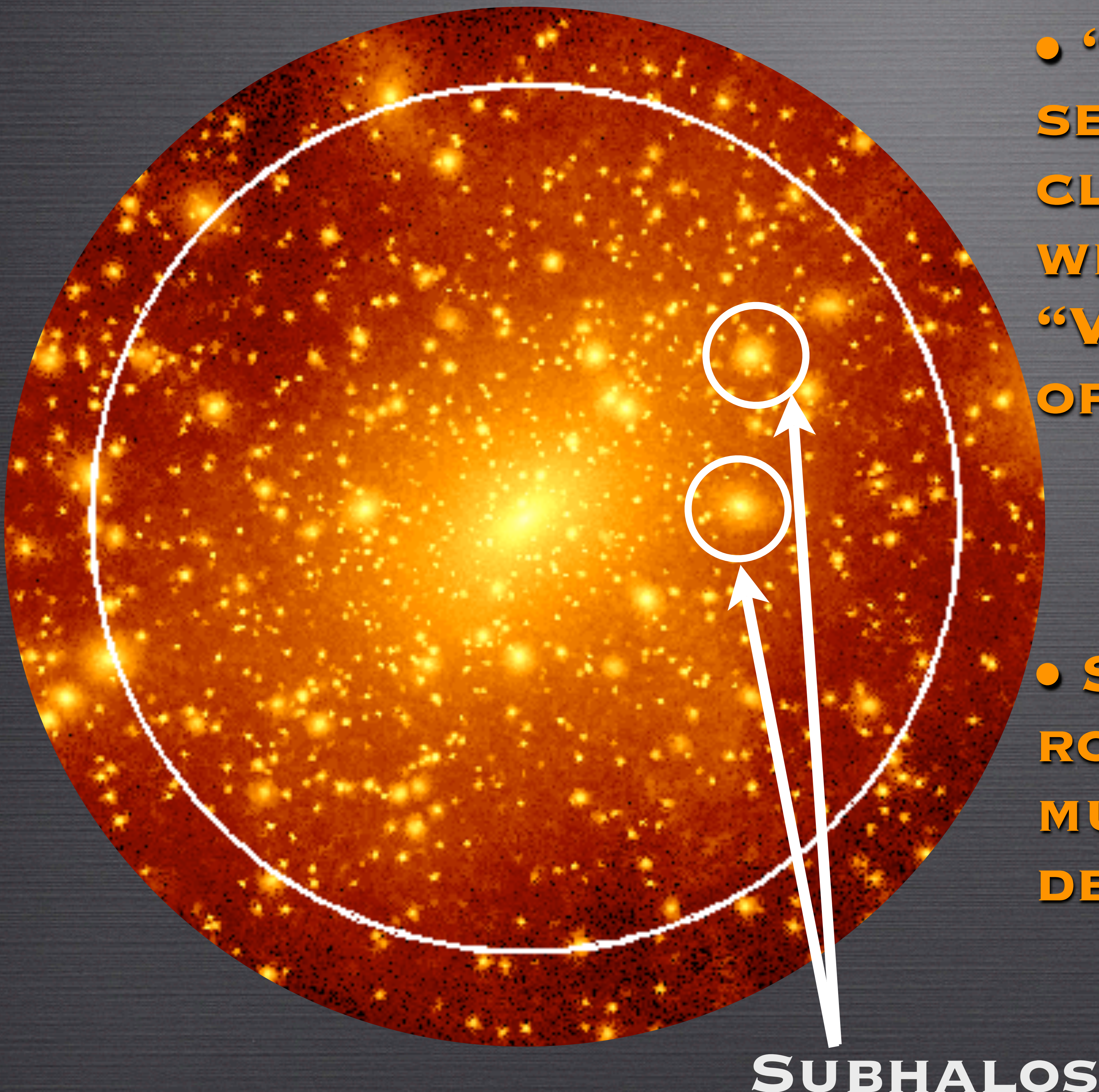


- Halos have spherically-averaged density structures...

$$\rho(\mathrm{r}) \propto \left(\mathrm{c}\frac{\mathrm{r}}{\mathrm{R_{vir}}}\right)^{-1}\left(1+\mathrm{c}\frac{\mathrm{r}}{\mathrm{R_{vir}}}\right)^{-2}$$

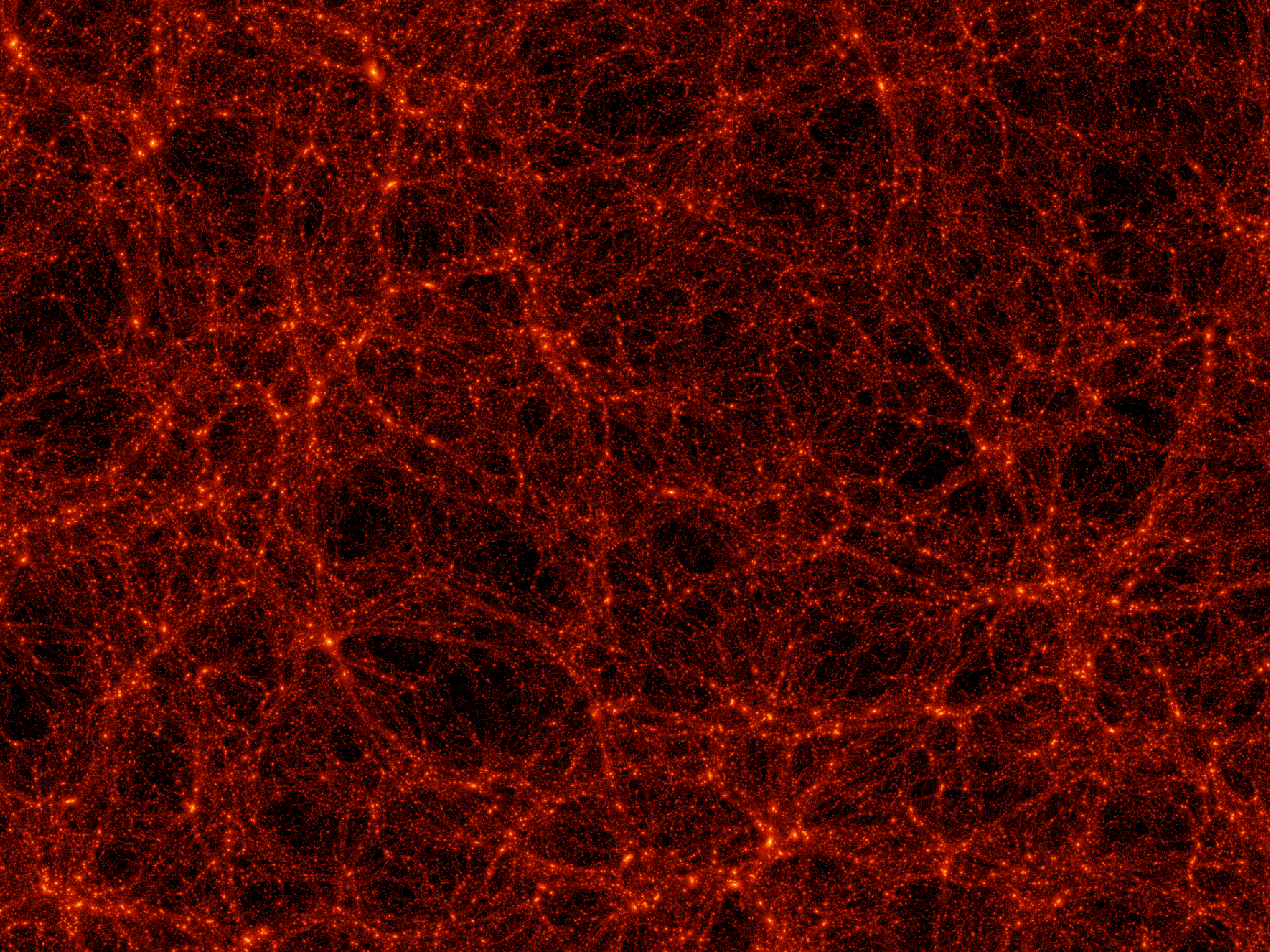
- The concentration parameter "c" specifies how centrally concentrated the dark matter is at fixed overall, M_{vir}

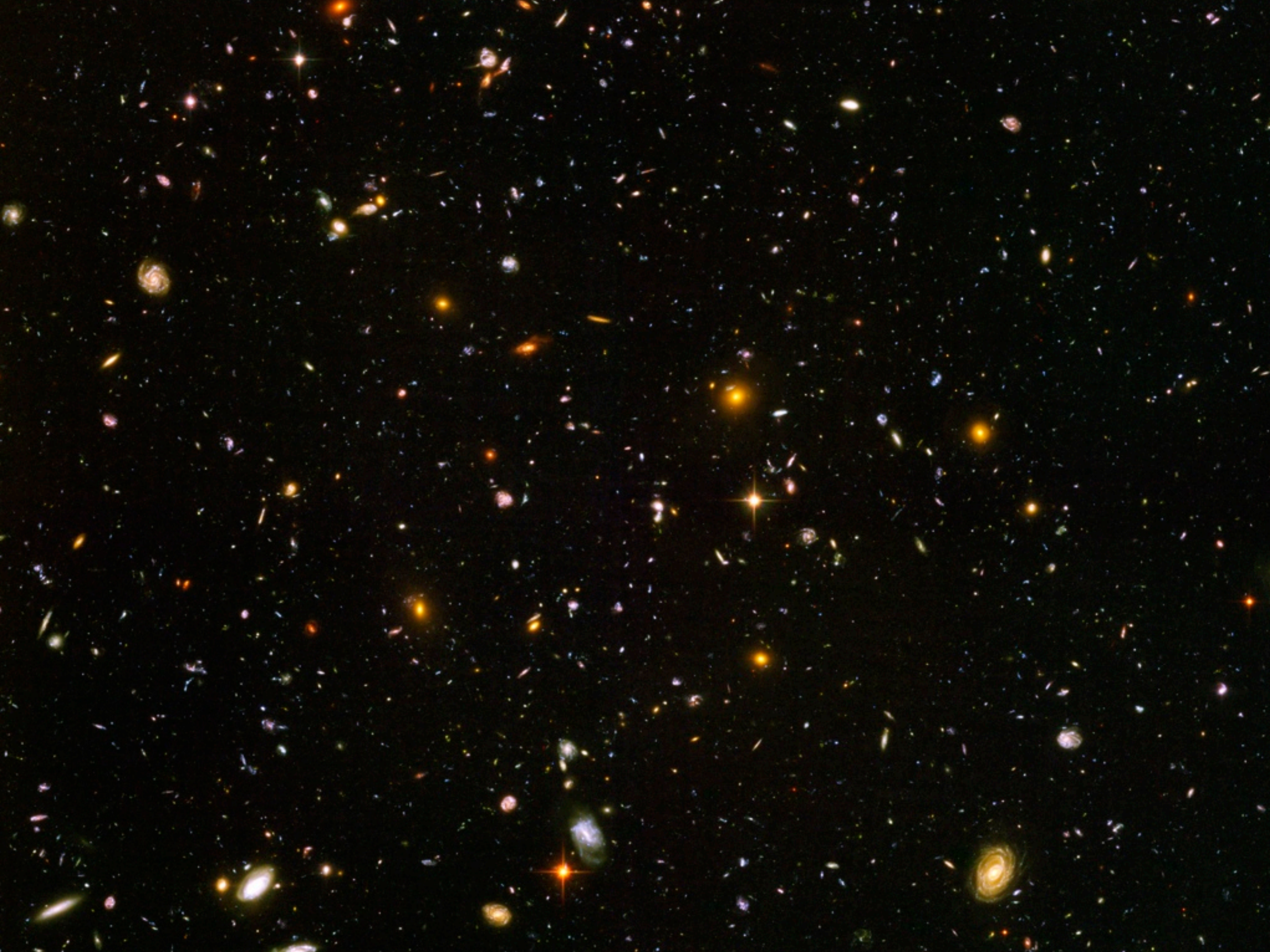
Subhalos



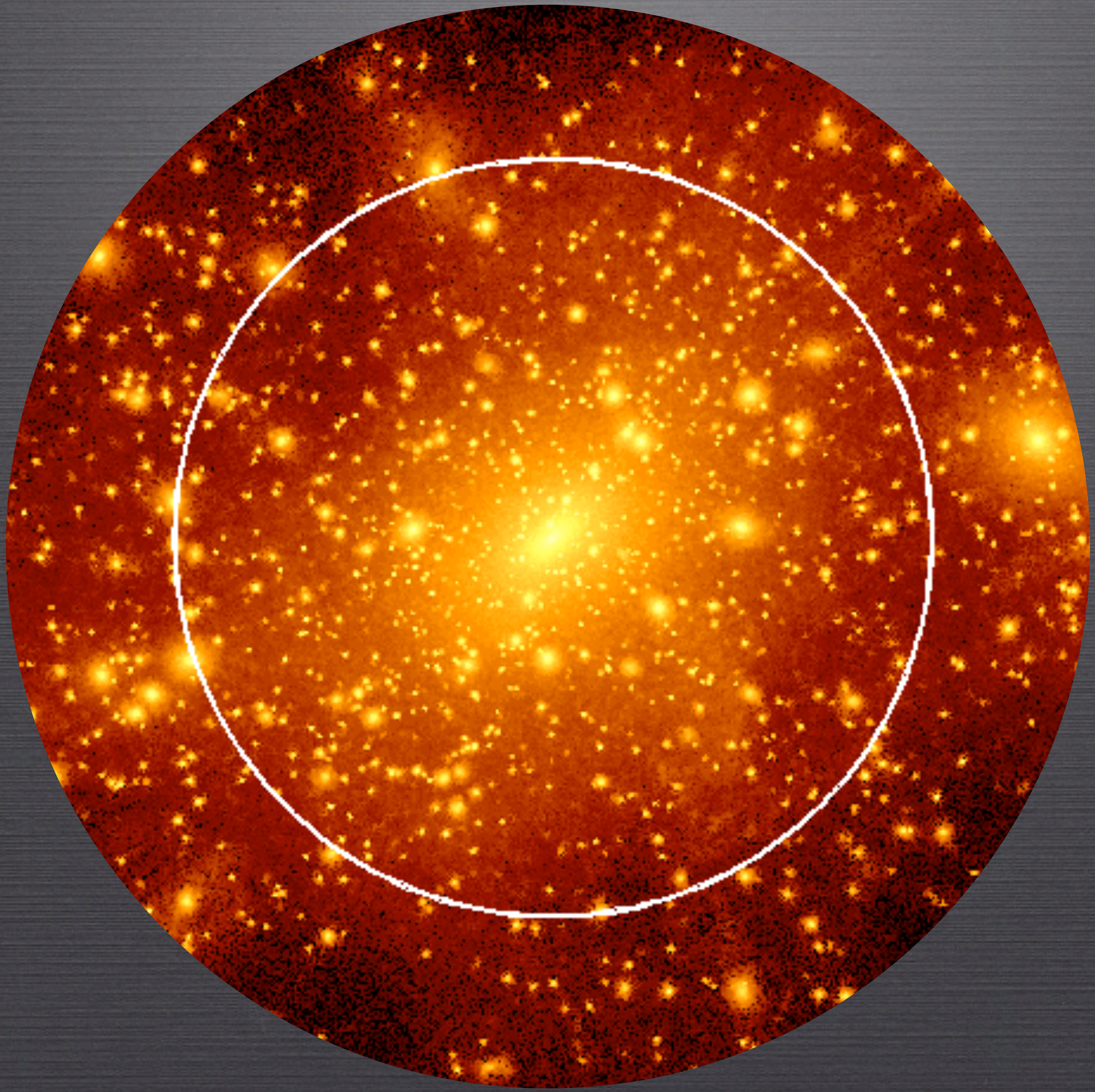
- "Subhalos" are the self-bound, smaller clumps the Lie within the "Virialized" regions of larger "Halos"

- Subhalos are, to rough approximation, much like smaller, denser halos

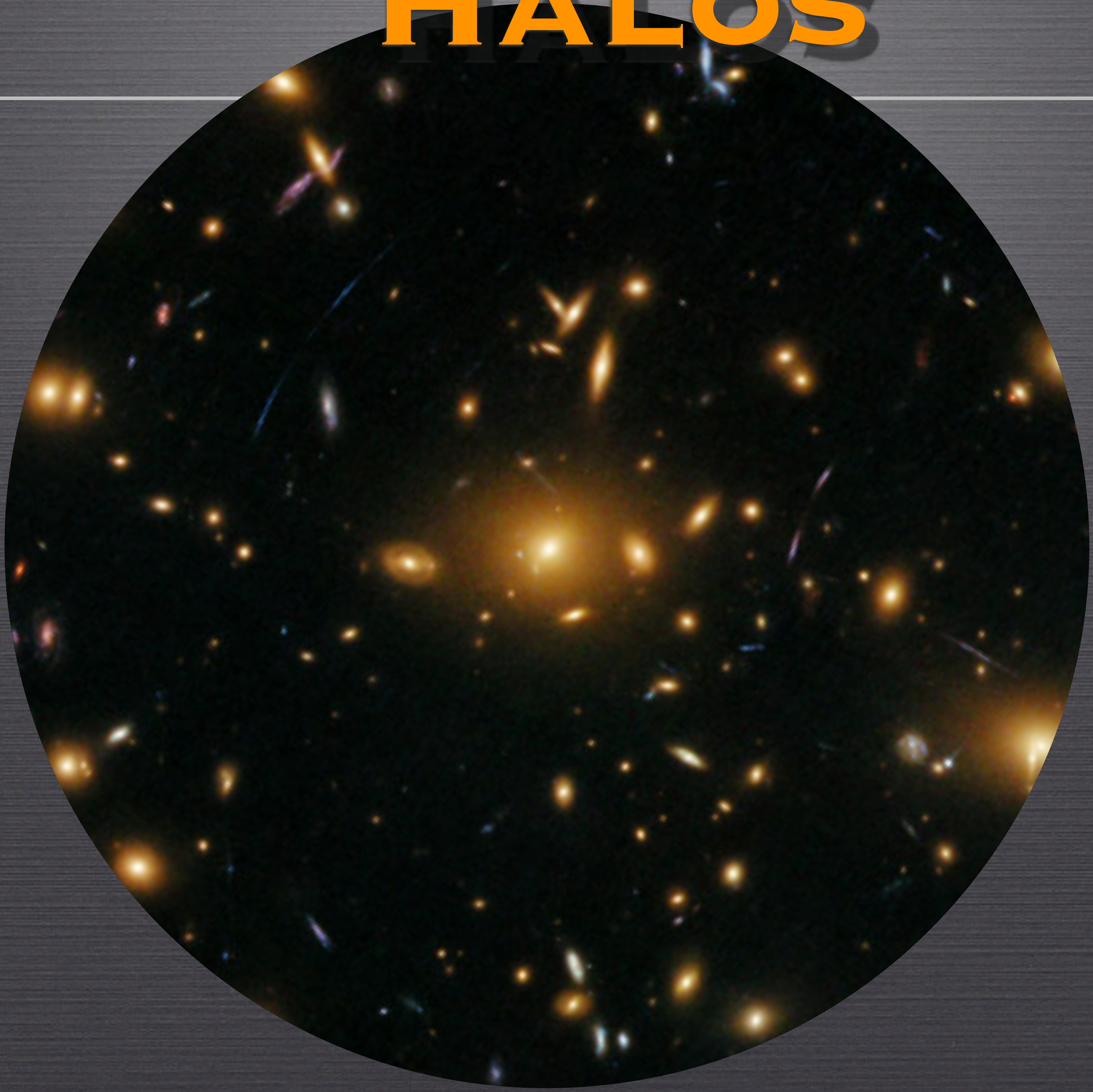




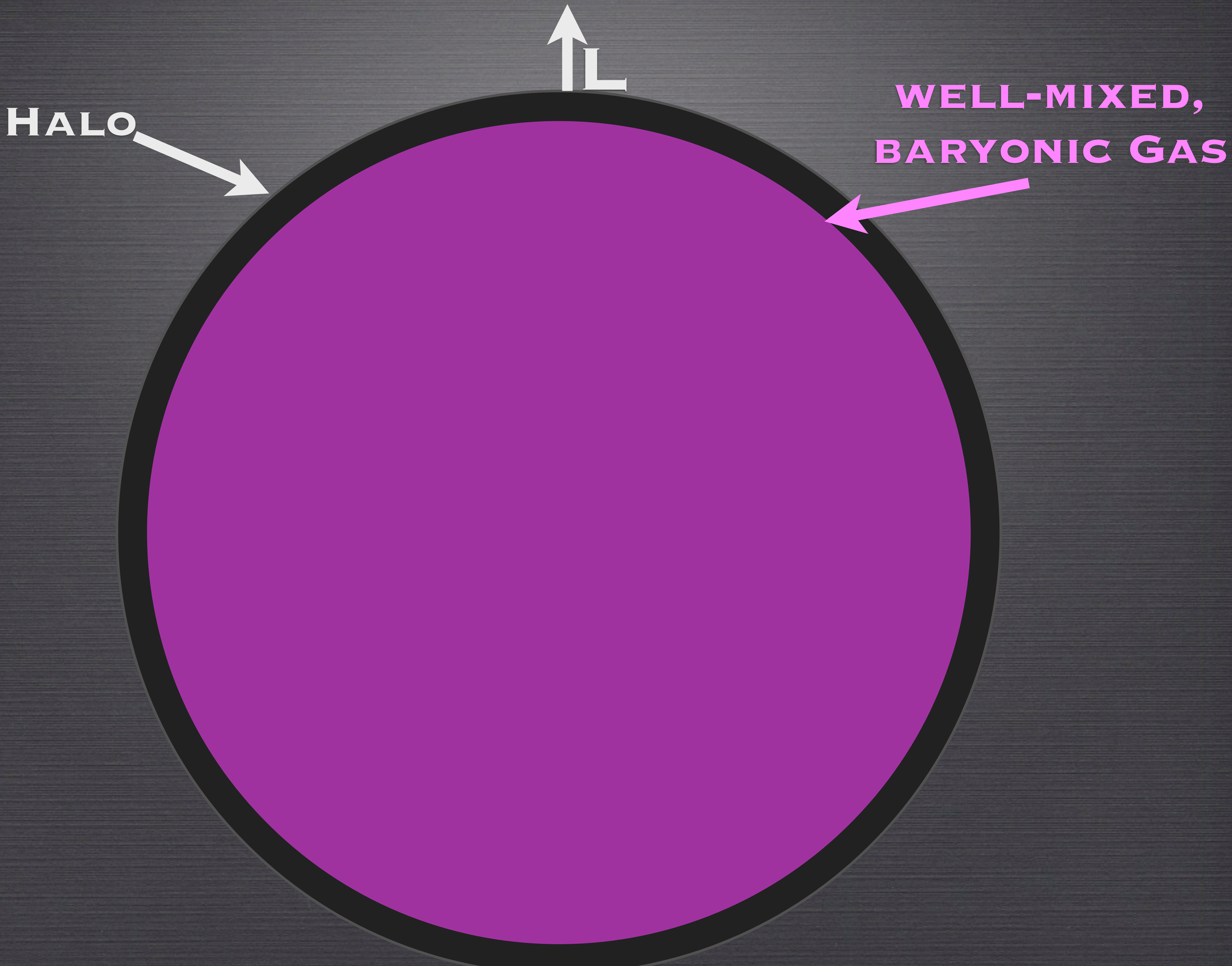
Dark Matter Halos

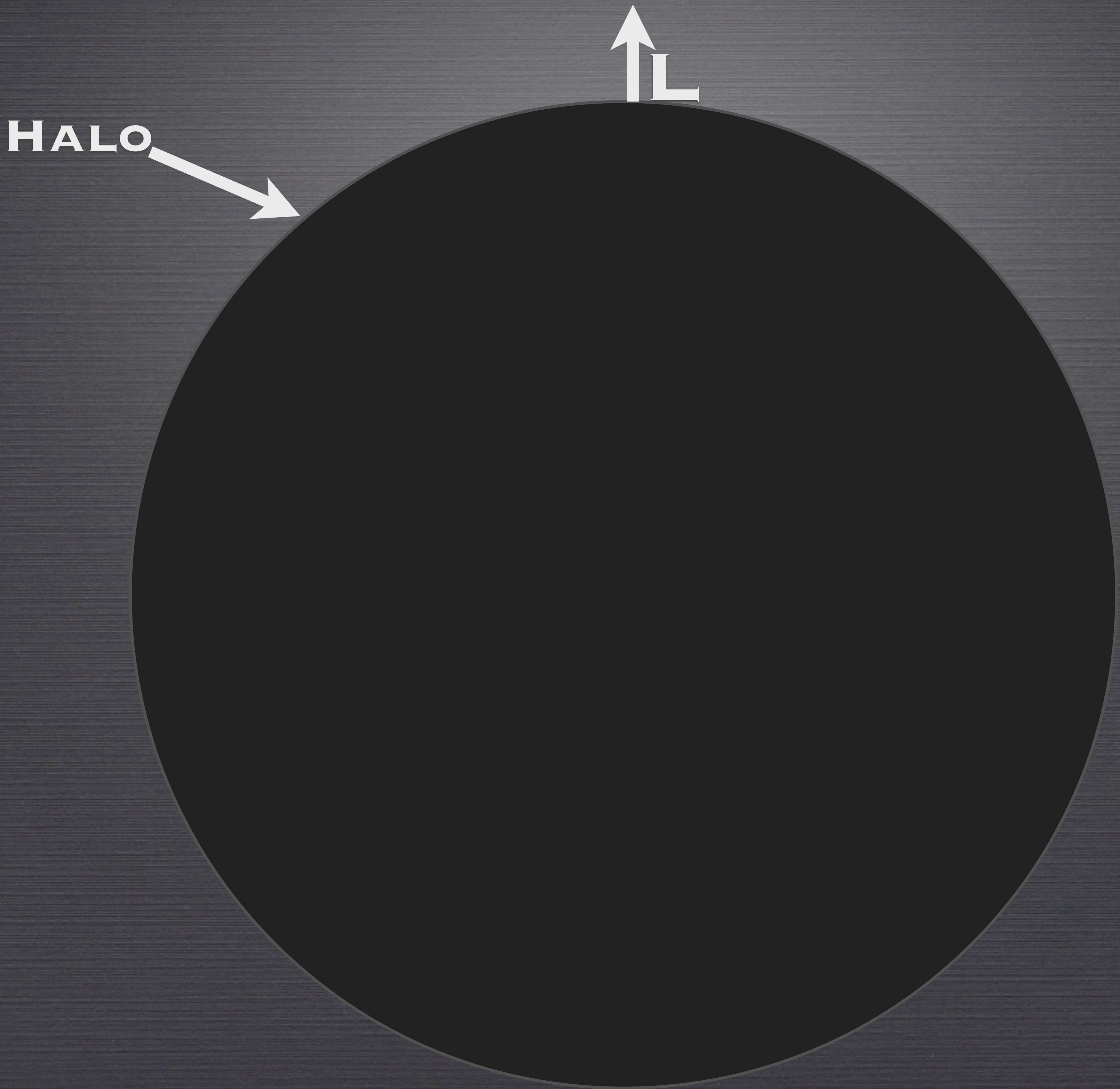


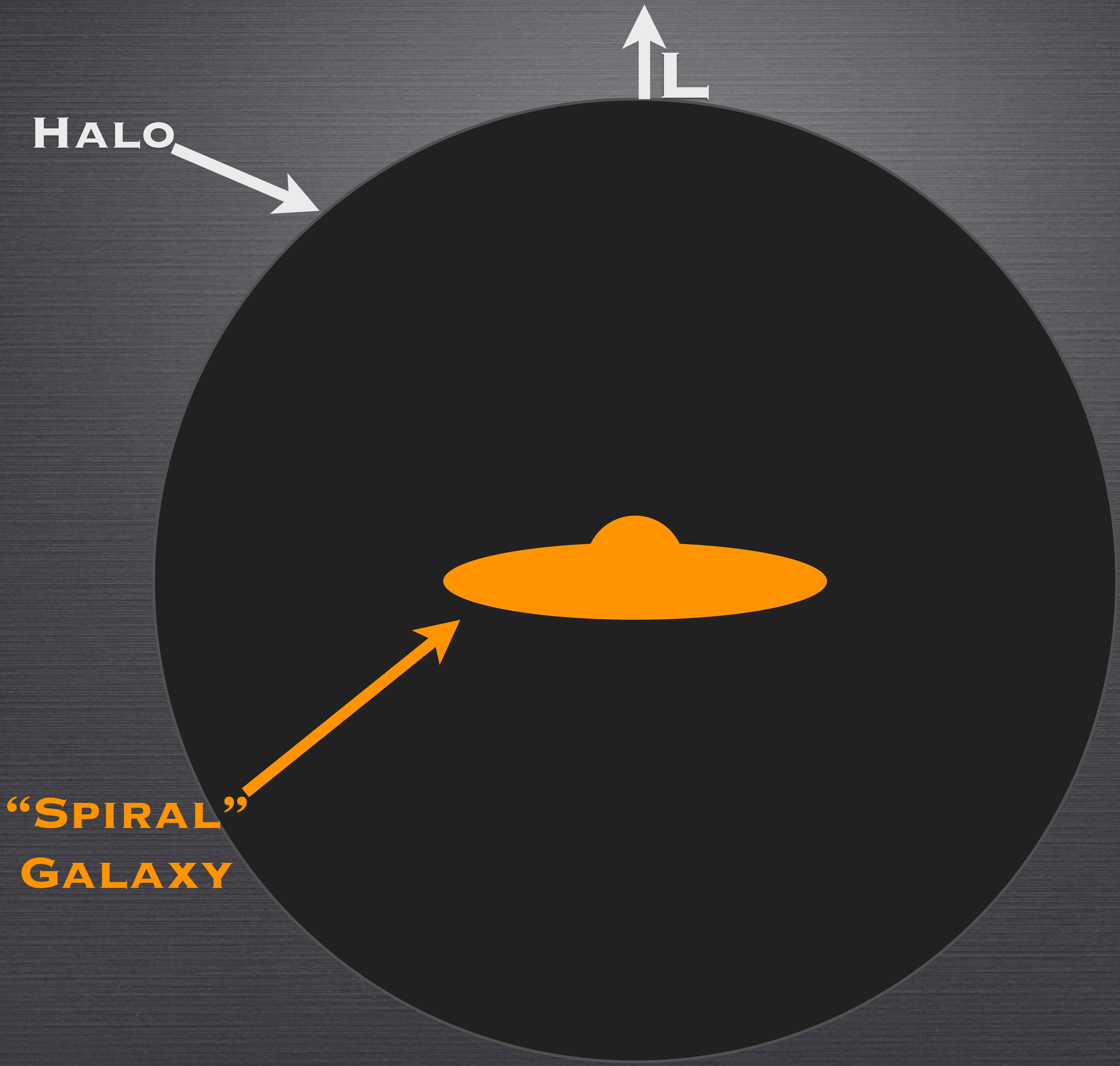
Galaxies Form in Halos

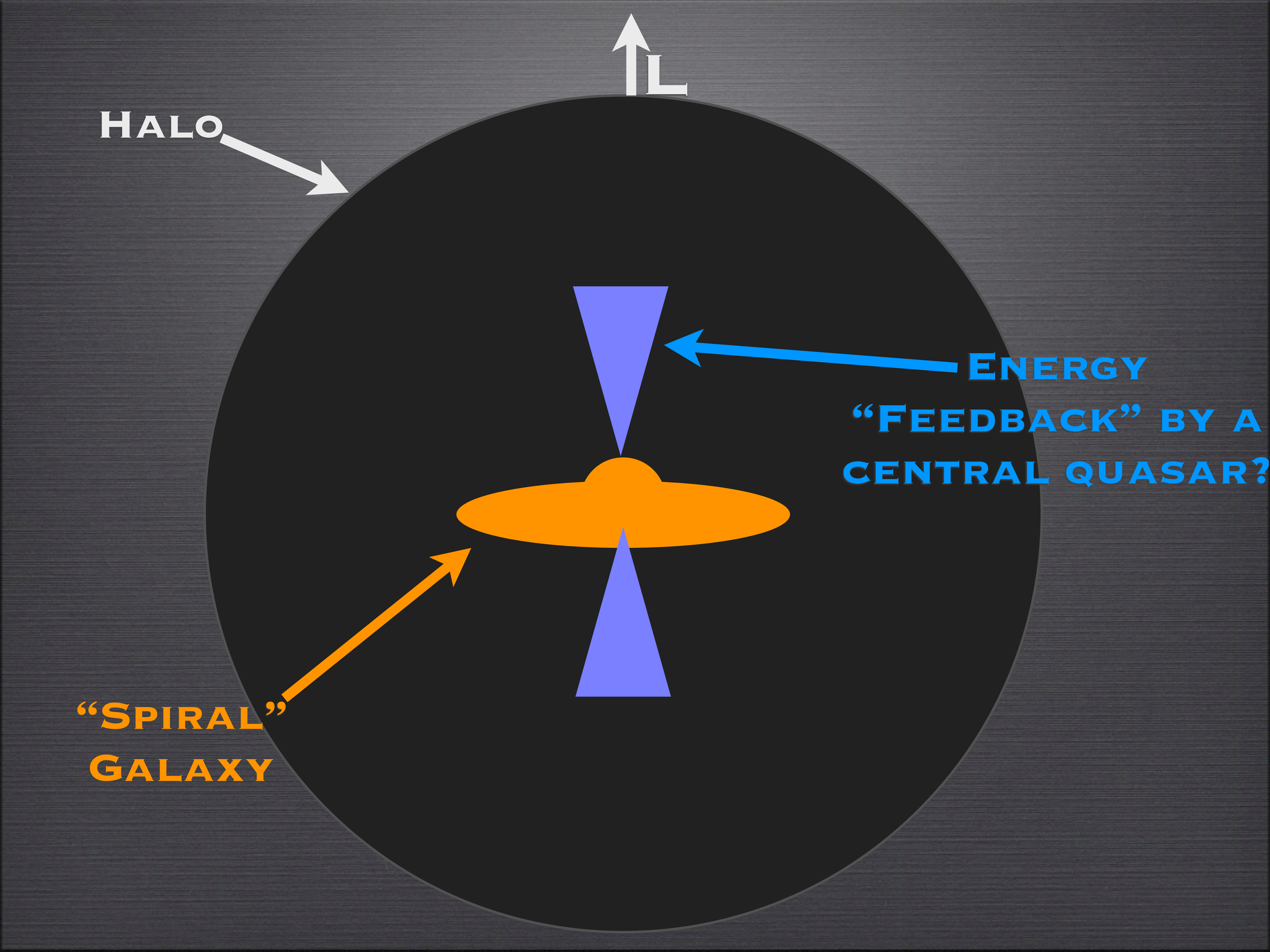


Galaxy Formation & Halo Contraction


L
Halo
well-mixed,
baryonic Gas

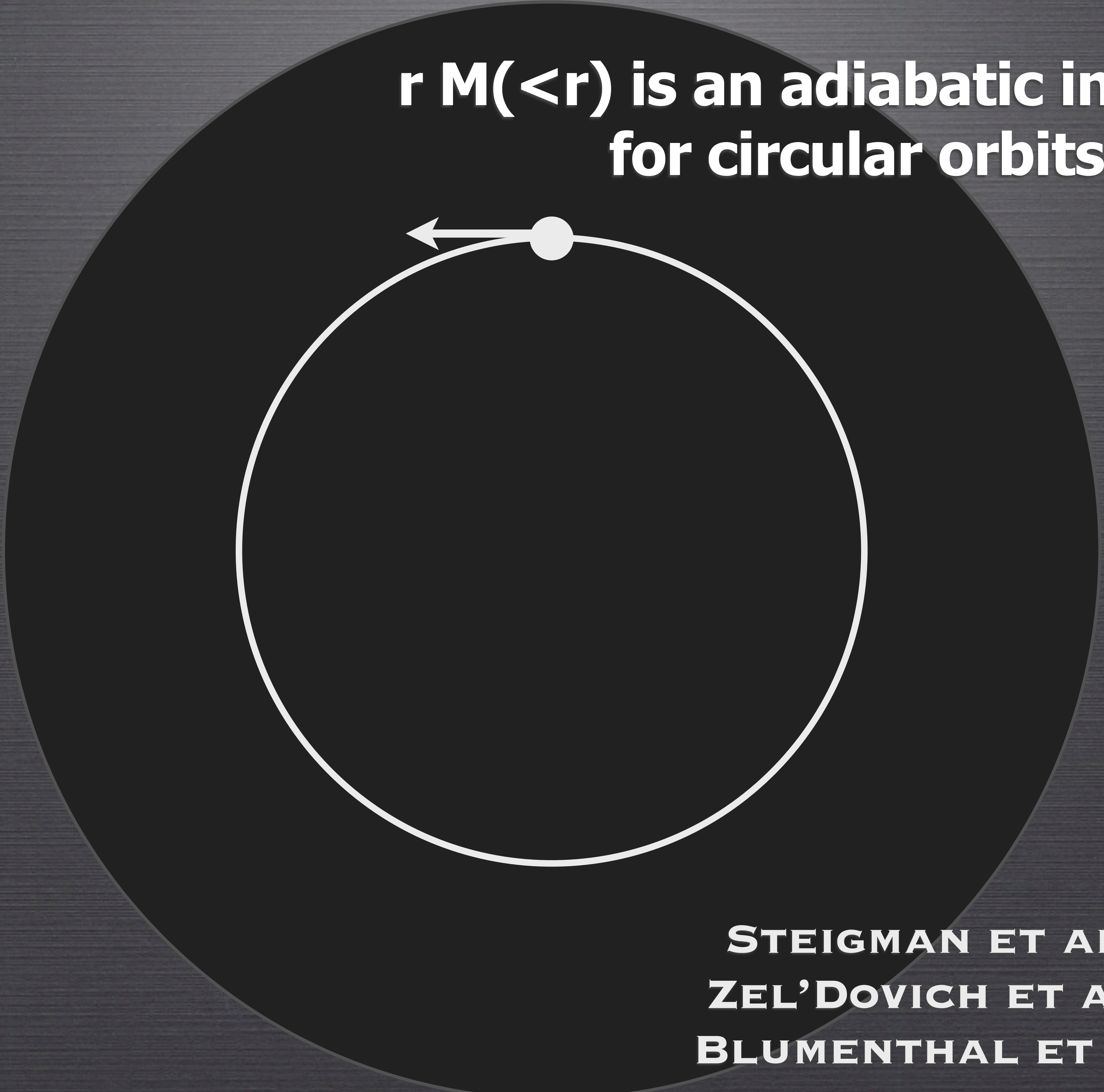

Halo
L


L
Halo
"Spiral"
Galaxy


L
Halo
Energy
"Feedback" by a
central quasar?
"Spiral"
Galaxy

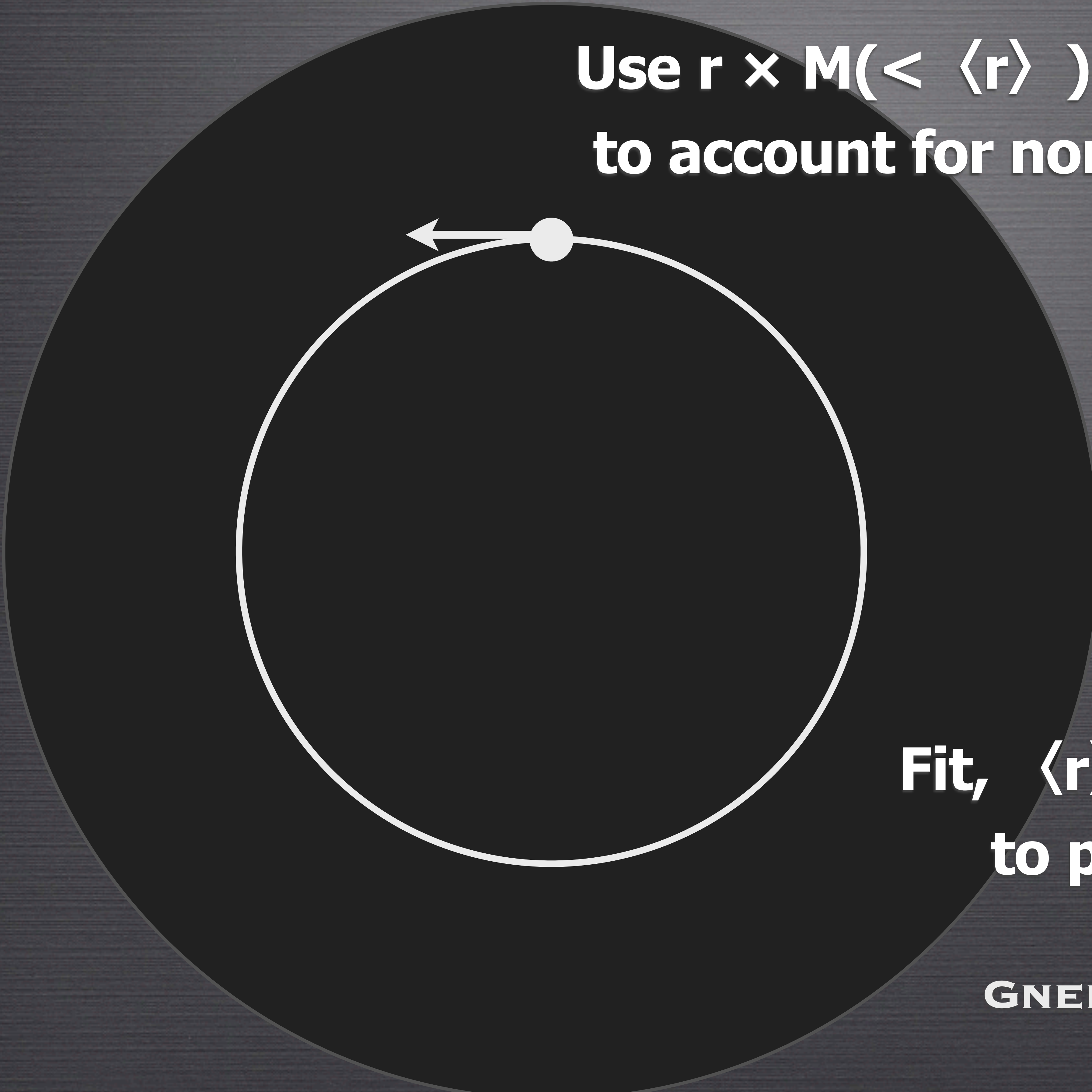
Adiabatic Contraction

r M(<r) is an adiabatic invariant for circular orbits



Steigman et al. 1978; Zel'Dovich et al. 1980; Blumenthal et al. 1986

Adiabatic Contraction



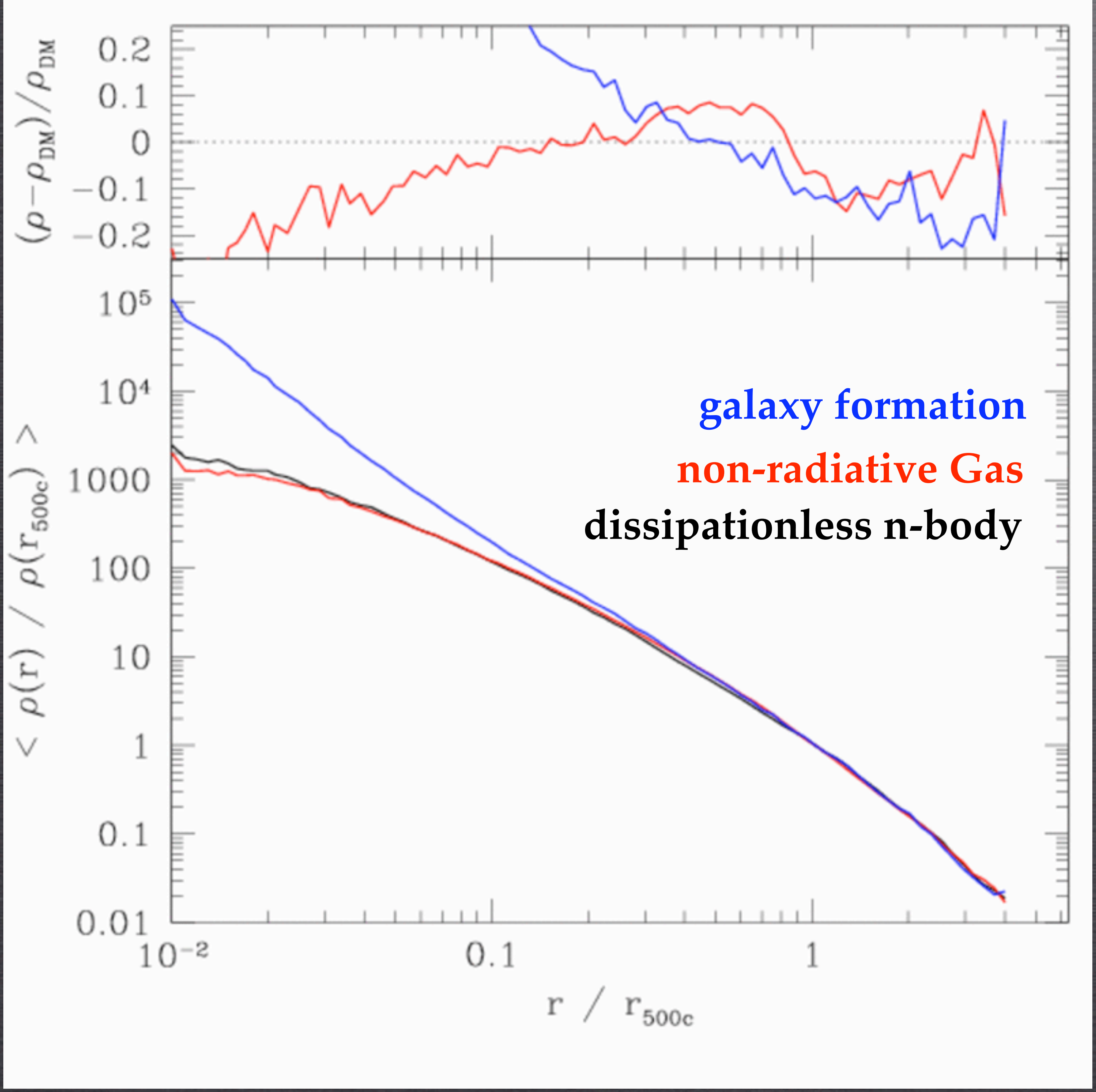
Use $r \times M(<\langle r \rangle)$ as an invariant to account for noncircular orbits

Fit, $\langle r \rangle = A r_{vir} (r/r_{vir})^{w}$ to particle orbits

Gnedin et al. 2005

Halos with Galaxies

Rudd et al. 2008



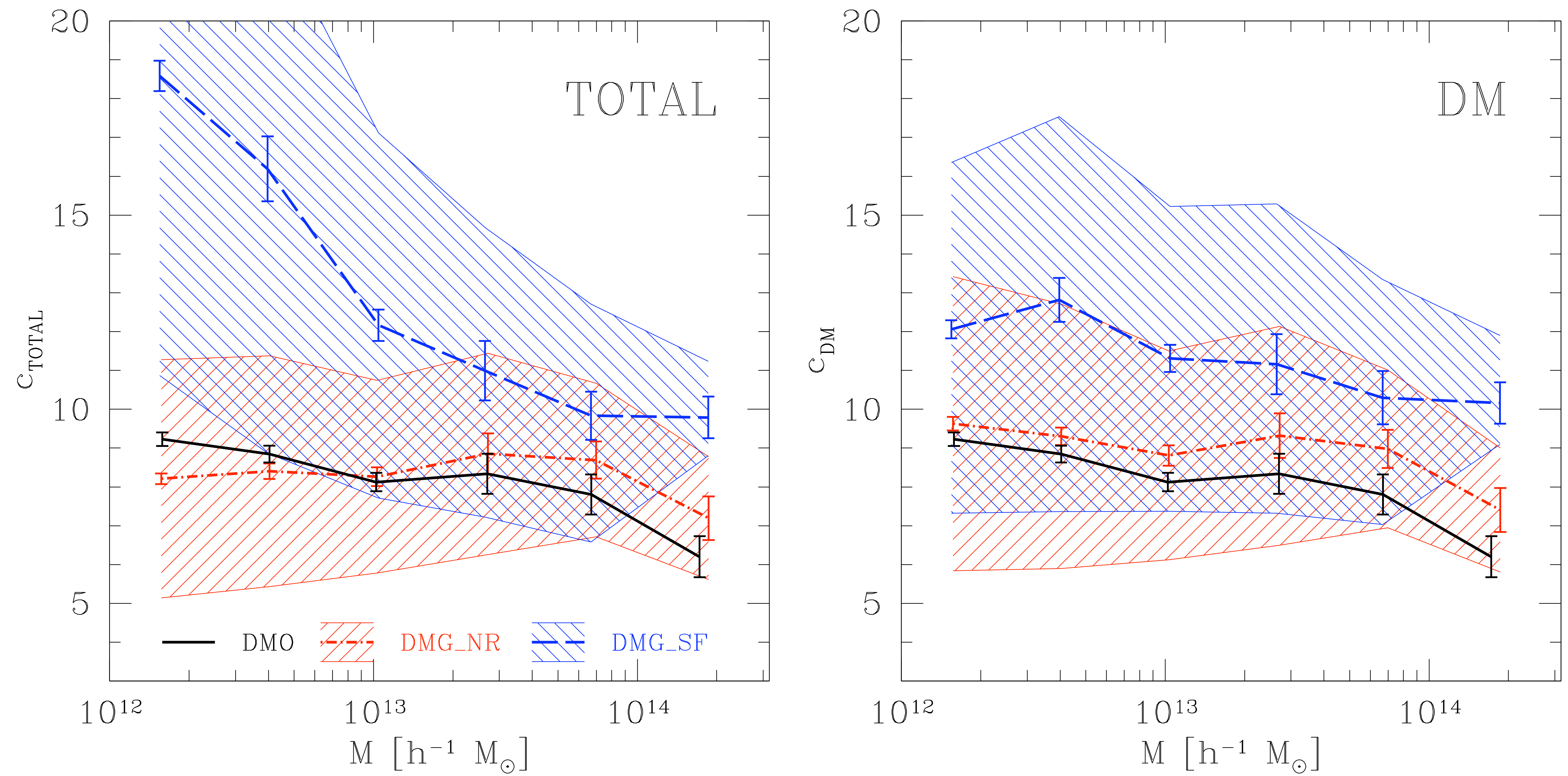
Modify Halo structure, account for contraction, compute lensing spectra

Halos in baryonic simulations look like NFW halos with modified concentrations

Also: Guillet et al. 2009; Casarini et al. 2010

Halos with Galaxies

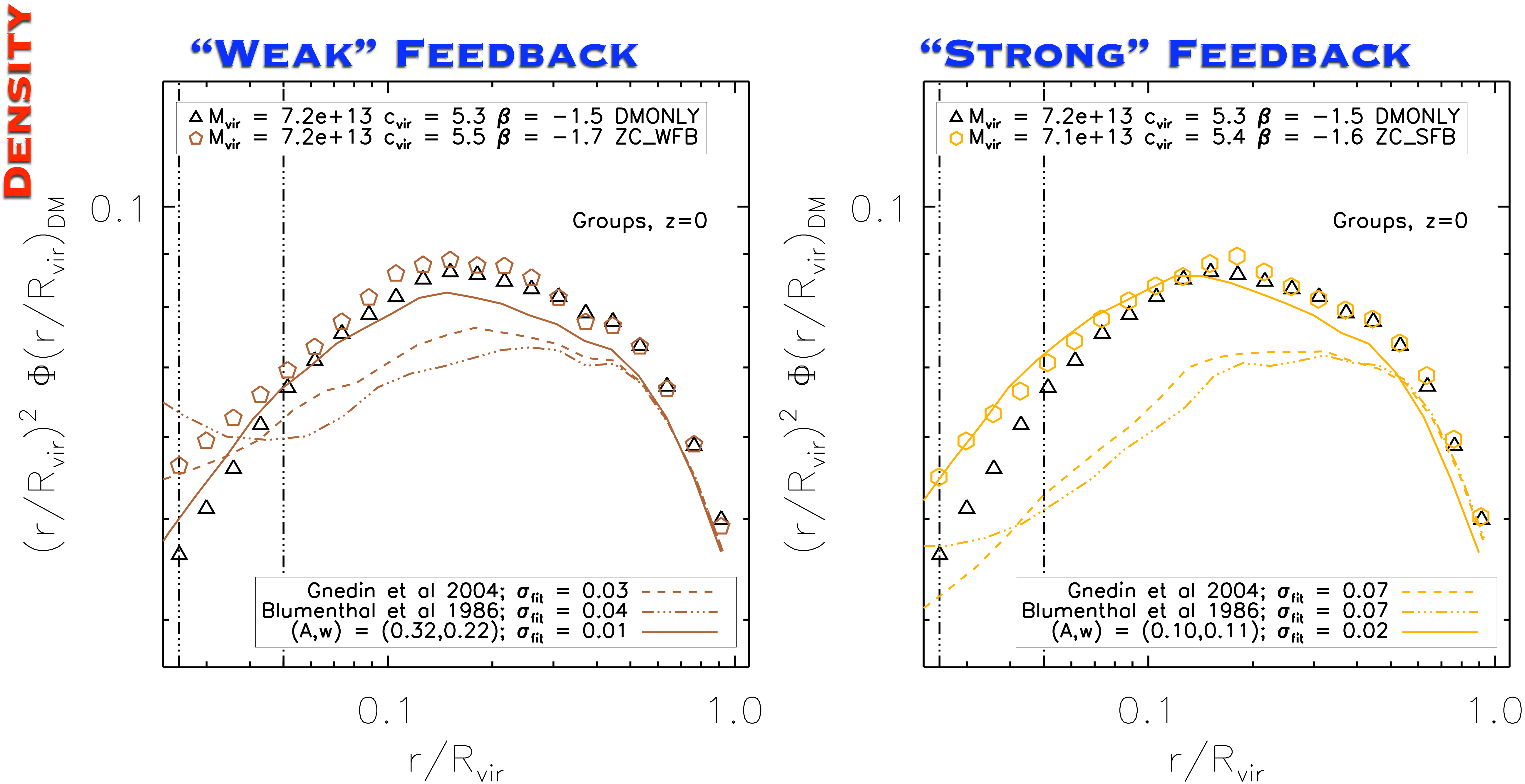
Rudd et al. 2008



- Modified Halo Concentration Relation Relative to the Standard N-Body Result

Example Contraction

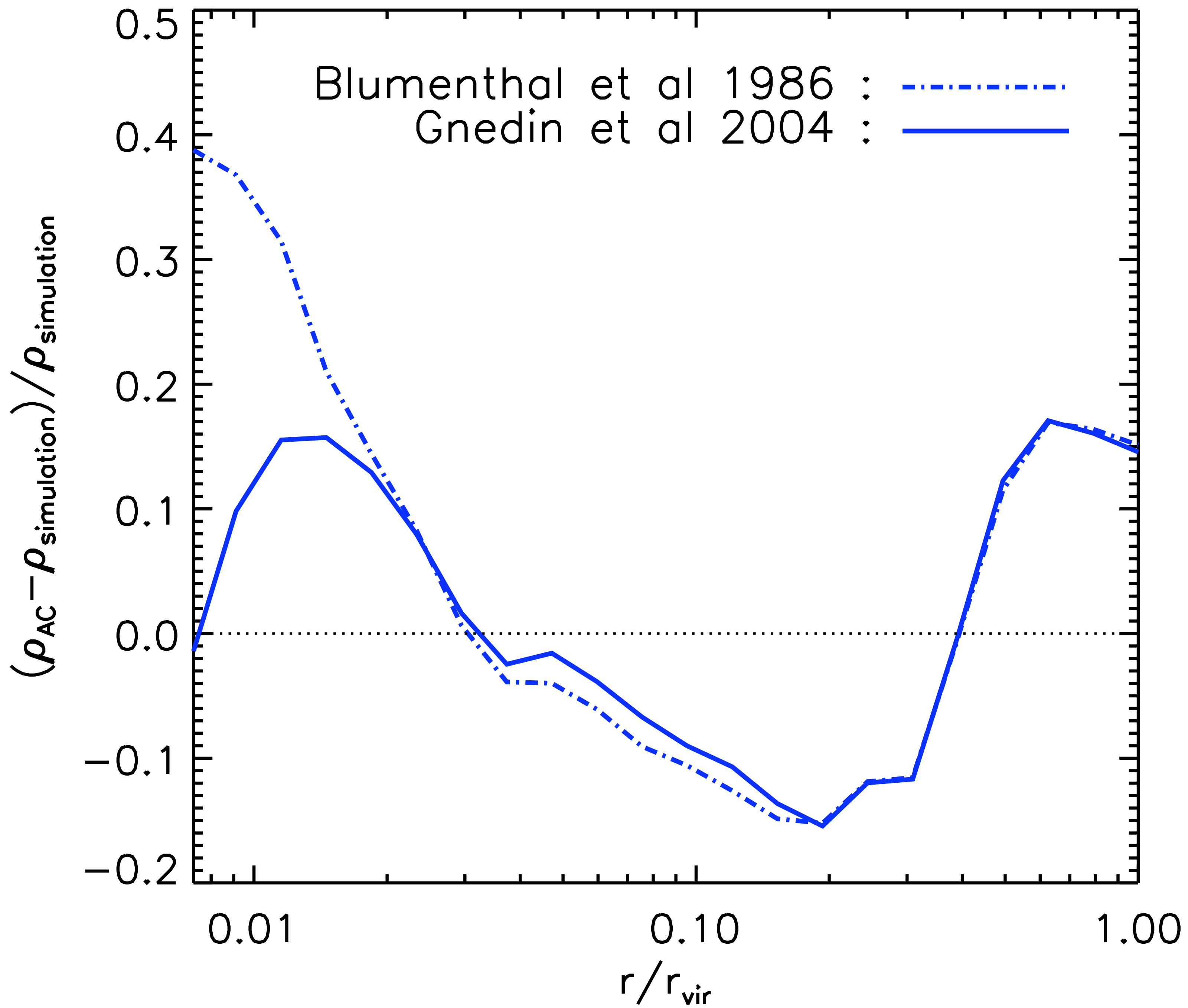
Duffy et al. 2010



See also: Gnedin+04; Gustafsson+06; Pedrosa+09; Tissera+10; Wang+10

Contraction Model Residuals

Wang et al. 2010

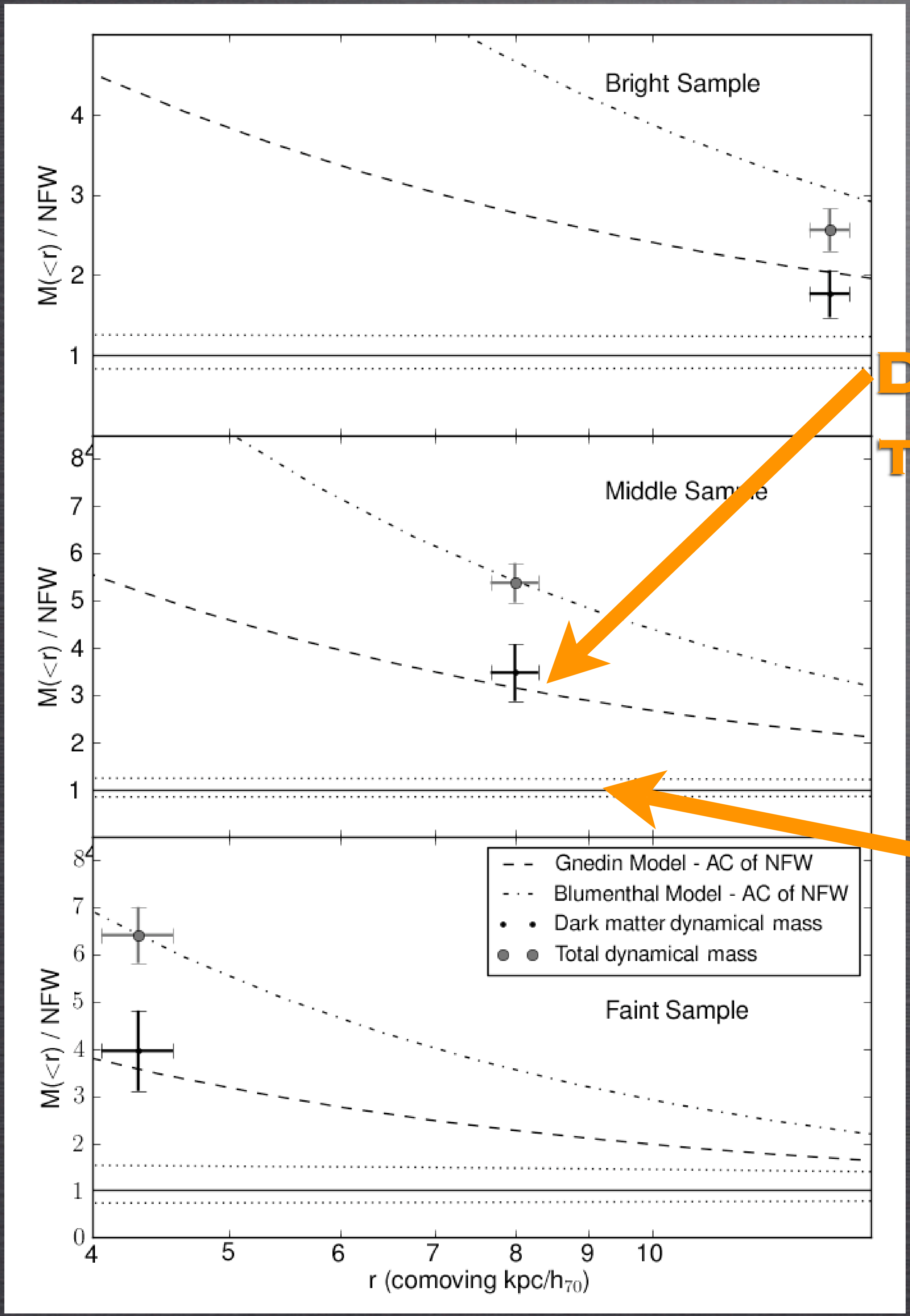


Similar: Gustafsson+06; Pedrosa+09; Tissera+10; Duffy+10

Is there evidence for contraction?

Yes?

Schulz et al. 2010

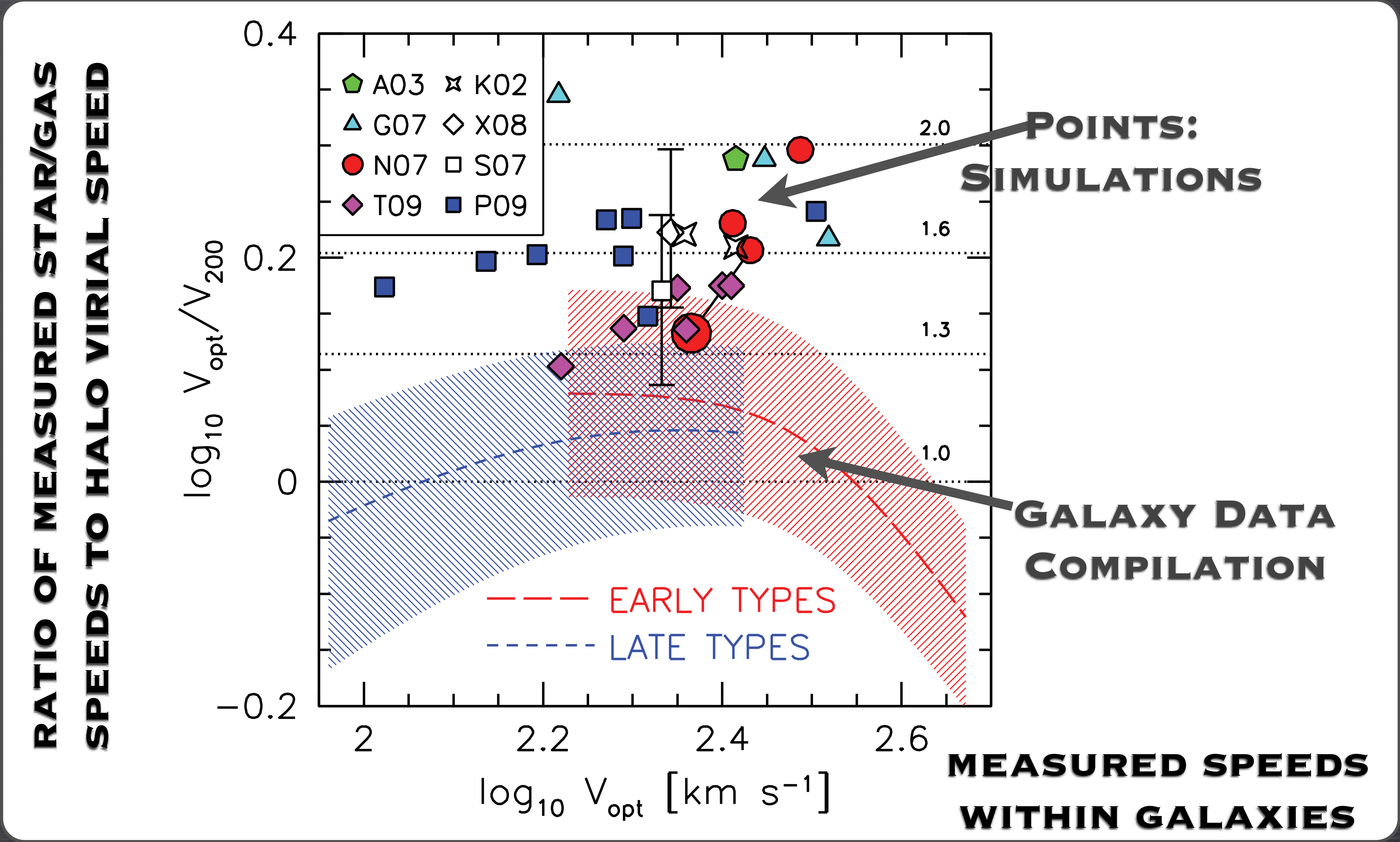


Dark matter contribution to mass based on velocity dispersions & stellar population modeling

Mass implied by weak lensing on large scales & NFW assumption for halo

No?

Dutton et al. 2010

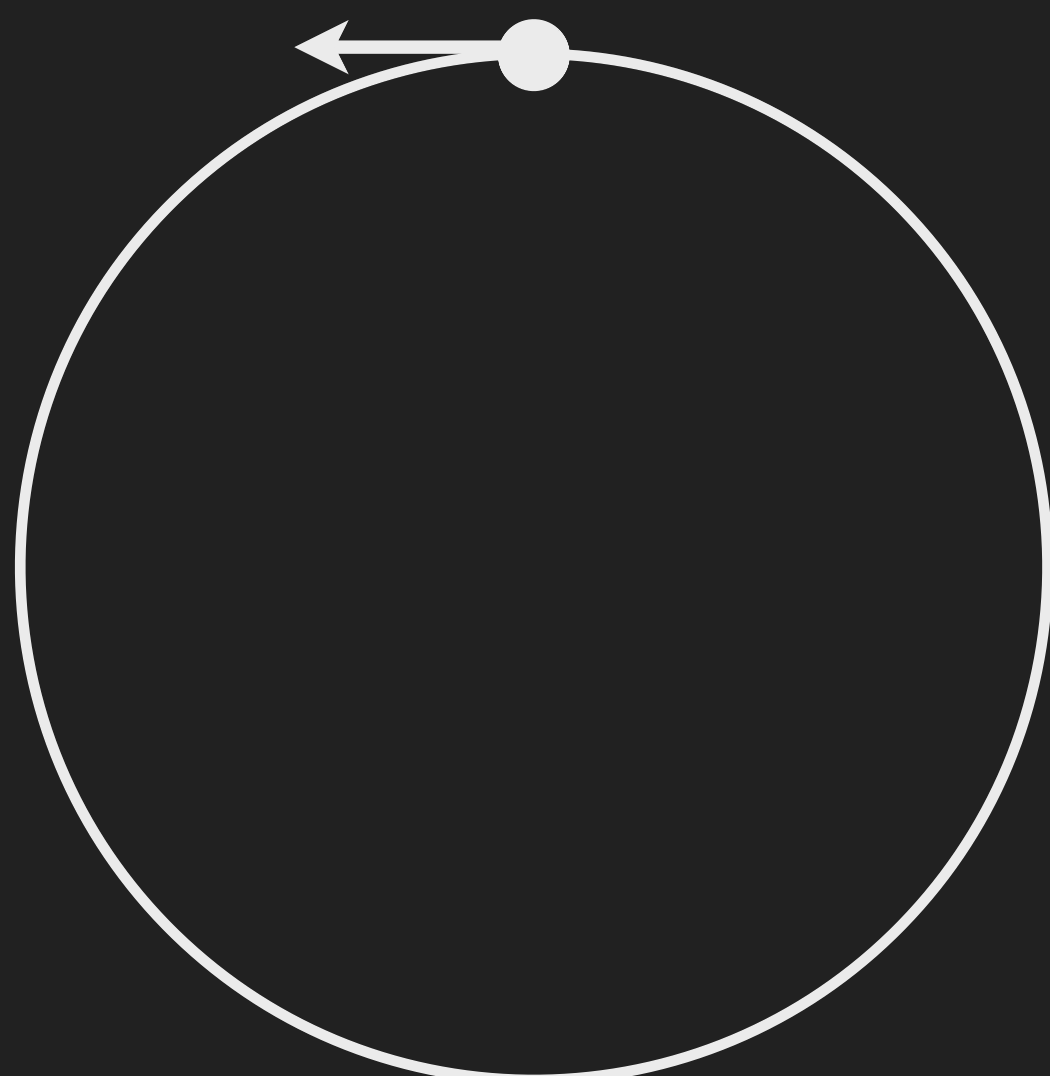


Also: Gnedin et al. 2006; Sand et al. 2008; Simon et al. 2008; Trachternach et al. 2008; de Blok et al. 2010...

Can the simple model be "Corrected"?

Adiabatic Contraction

Use $r \times M(<\langle r \rangle)$ as an invariant to account for noncircular orbits



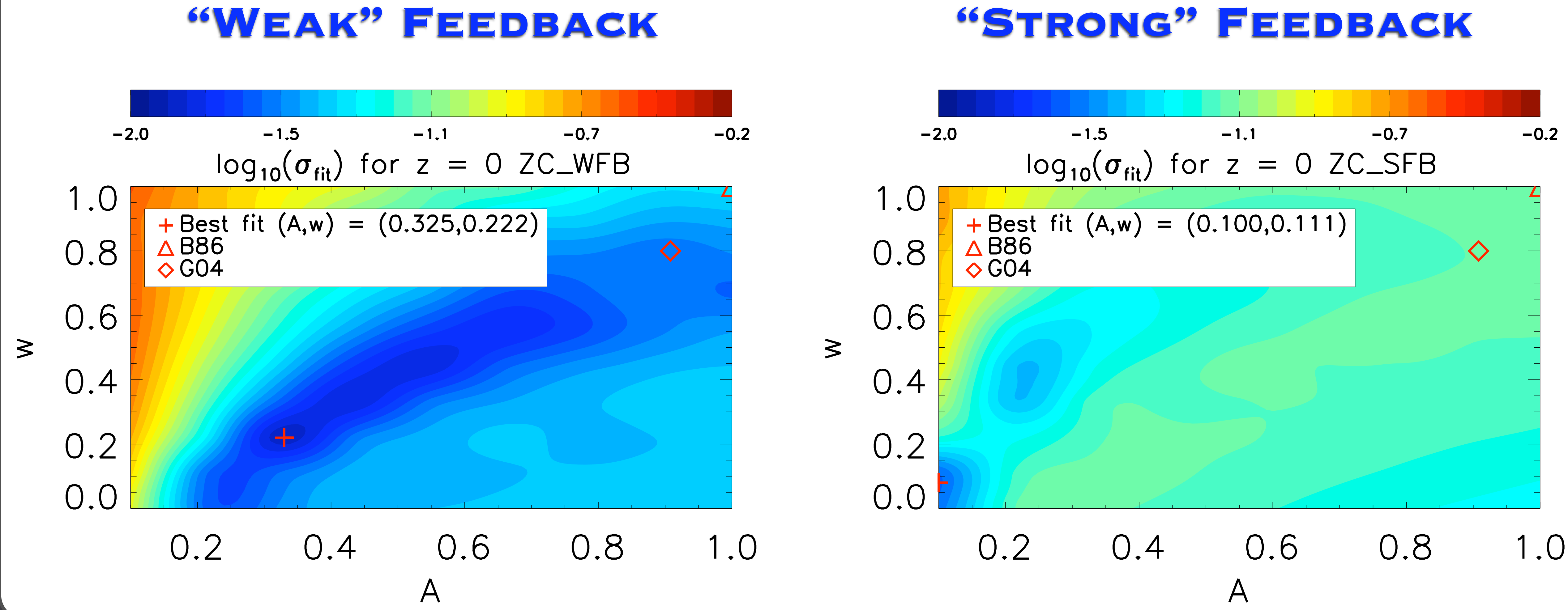
$$\langle r \rangle = A r_{vir} (r/r_{vir})^{w}$$

fit A & w to get better contraction model!

Gustafsson+06; Wang+10; Duffy+10

Orbit Correction?

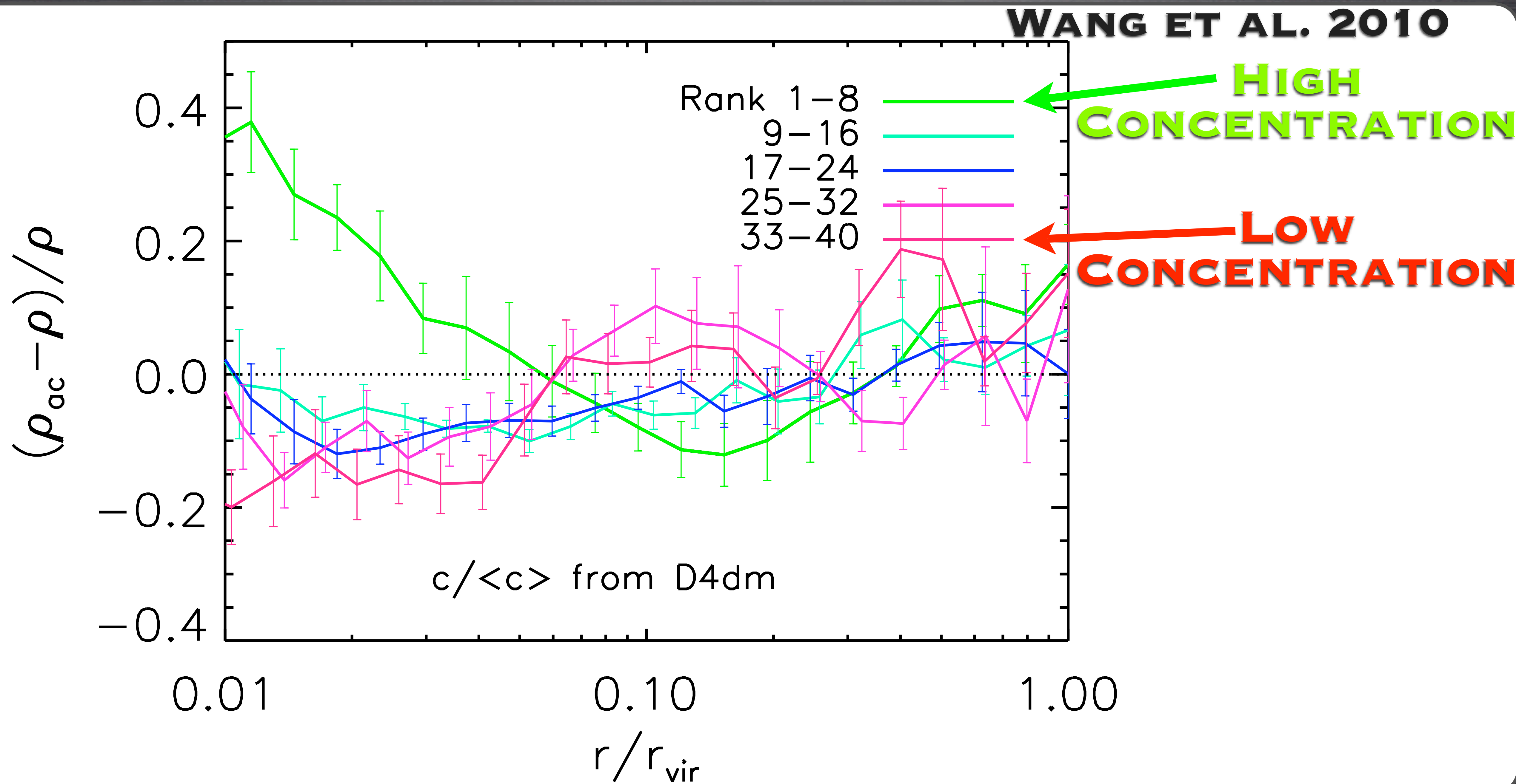
Duffy et al. 2010



1. "Best" model does not reflect particle orbits!
2. "Best" model depends upon baryonic feedback and assembly history: complicated!

Similar: Gustafsson+06; Wang+10

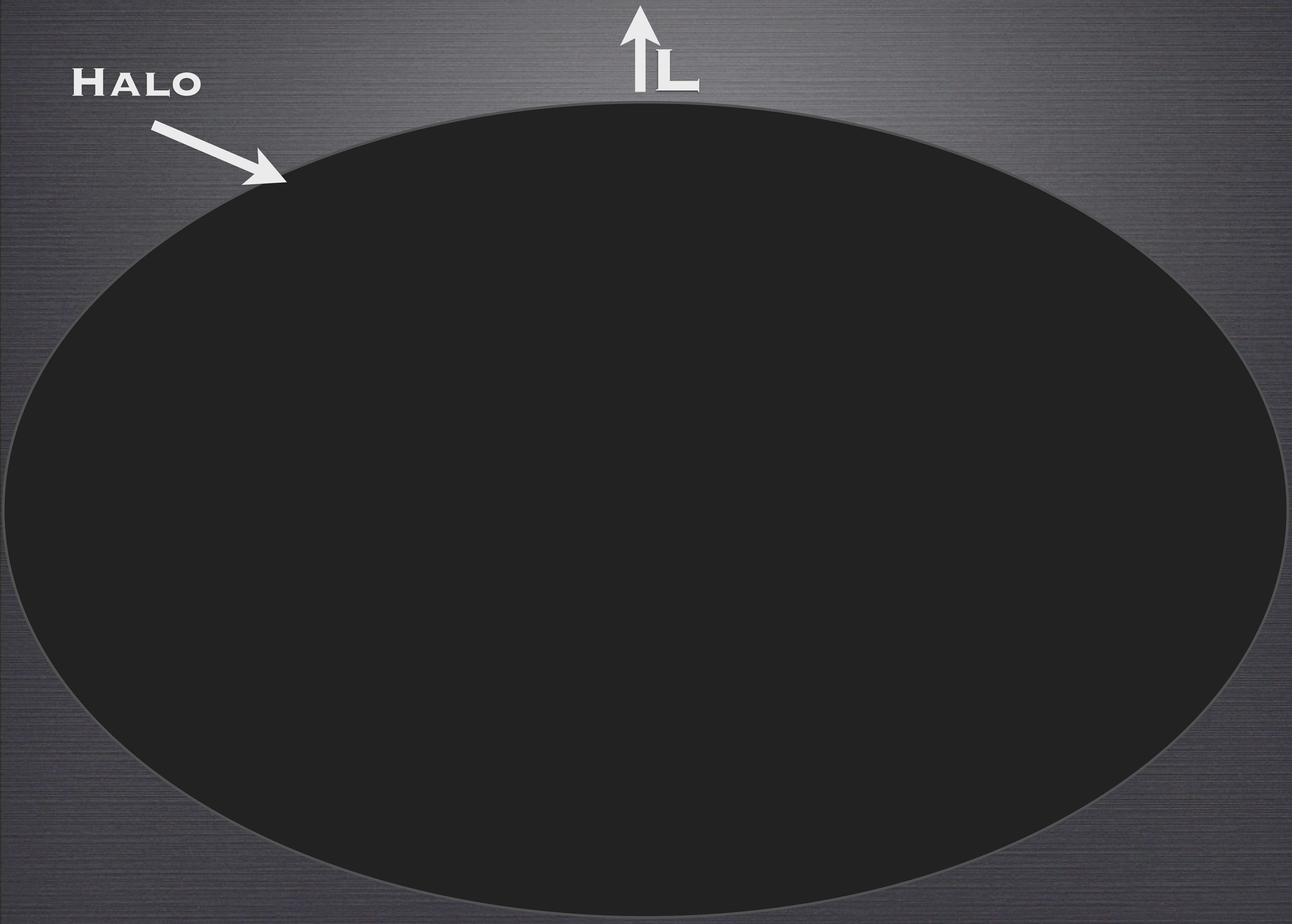
Halo Dependence?



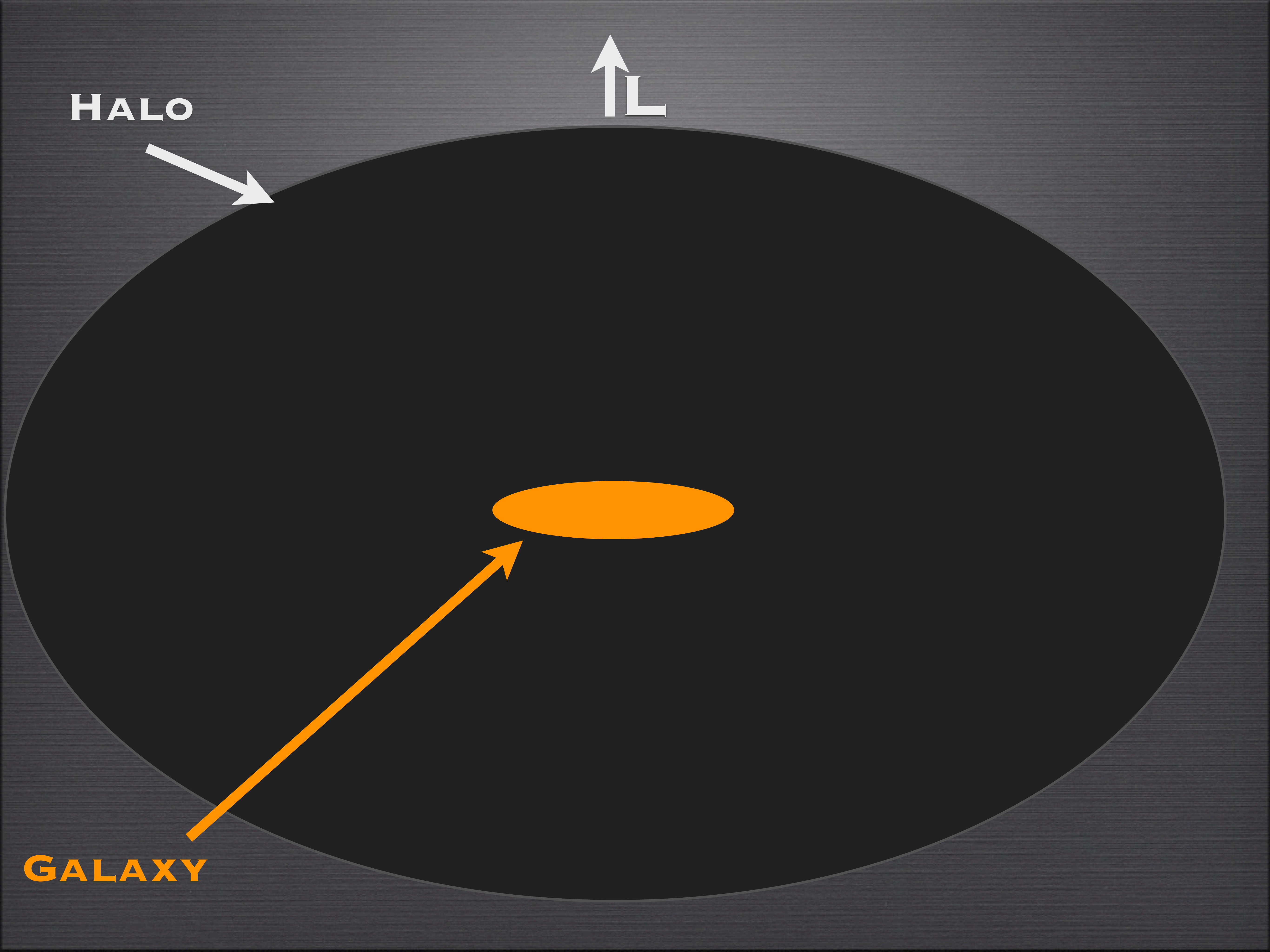
1. Residuals depend upon dark matter halo properties

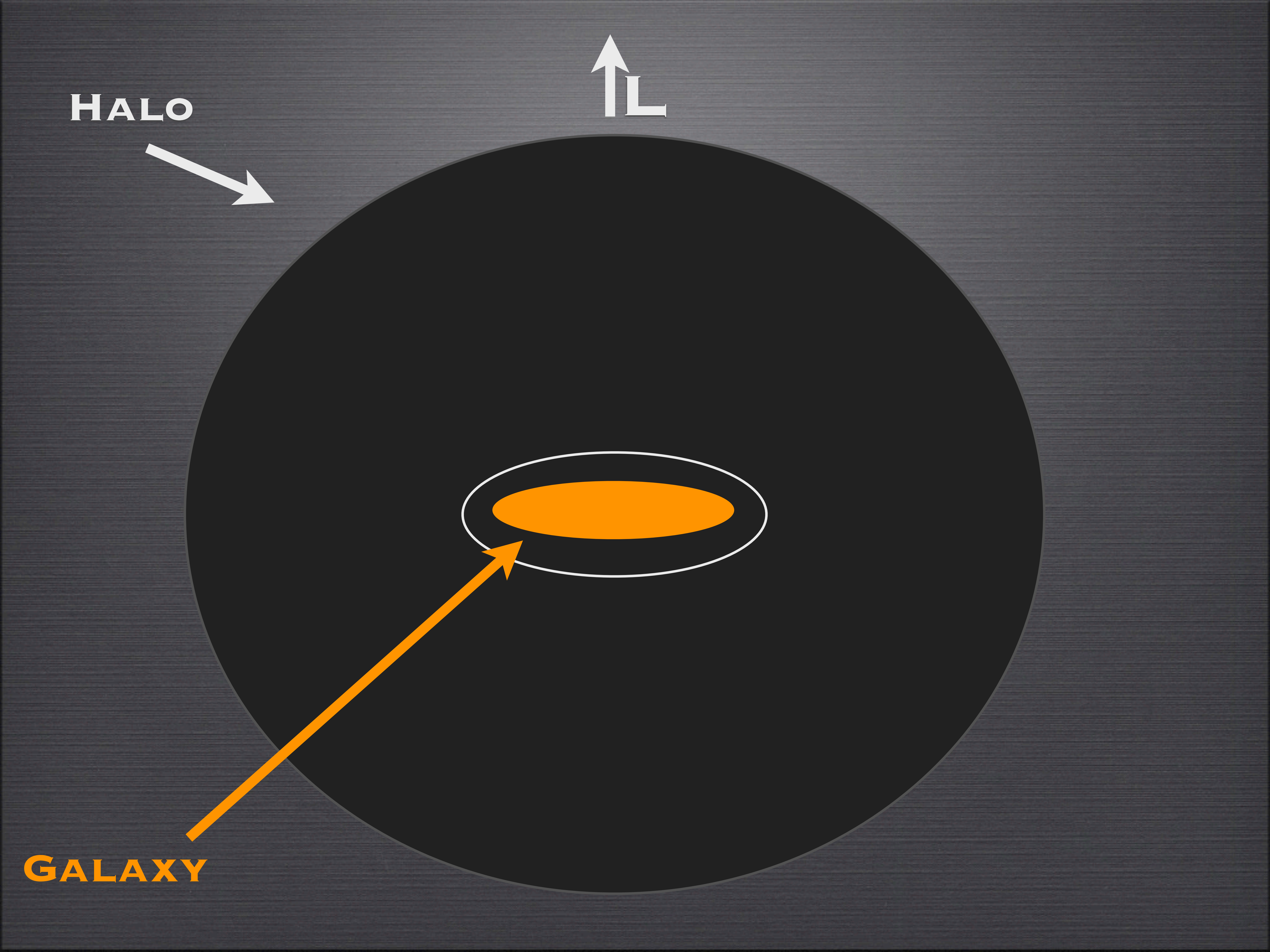
Failures are not surprising

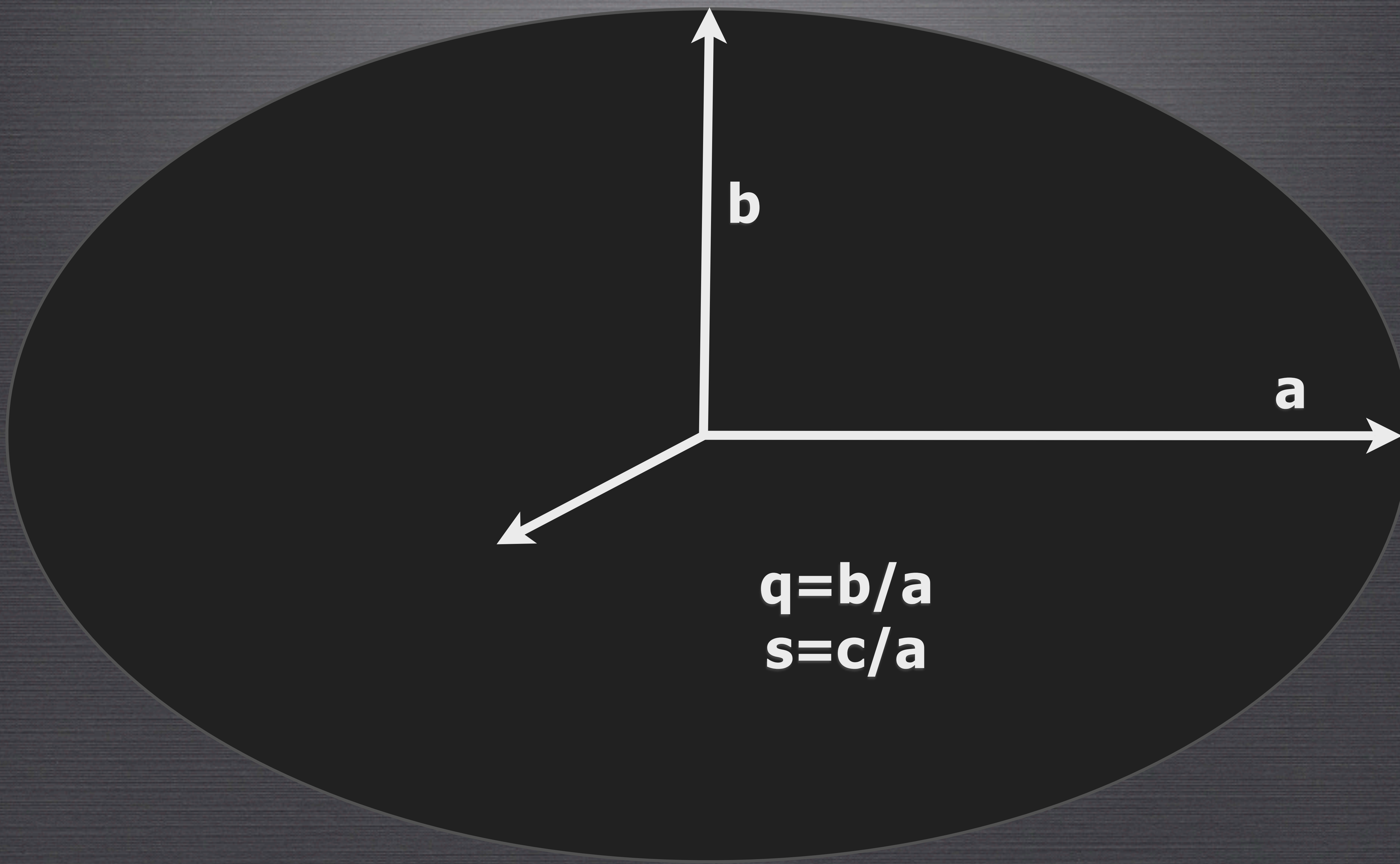
Halo Shapes

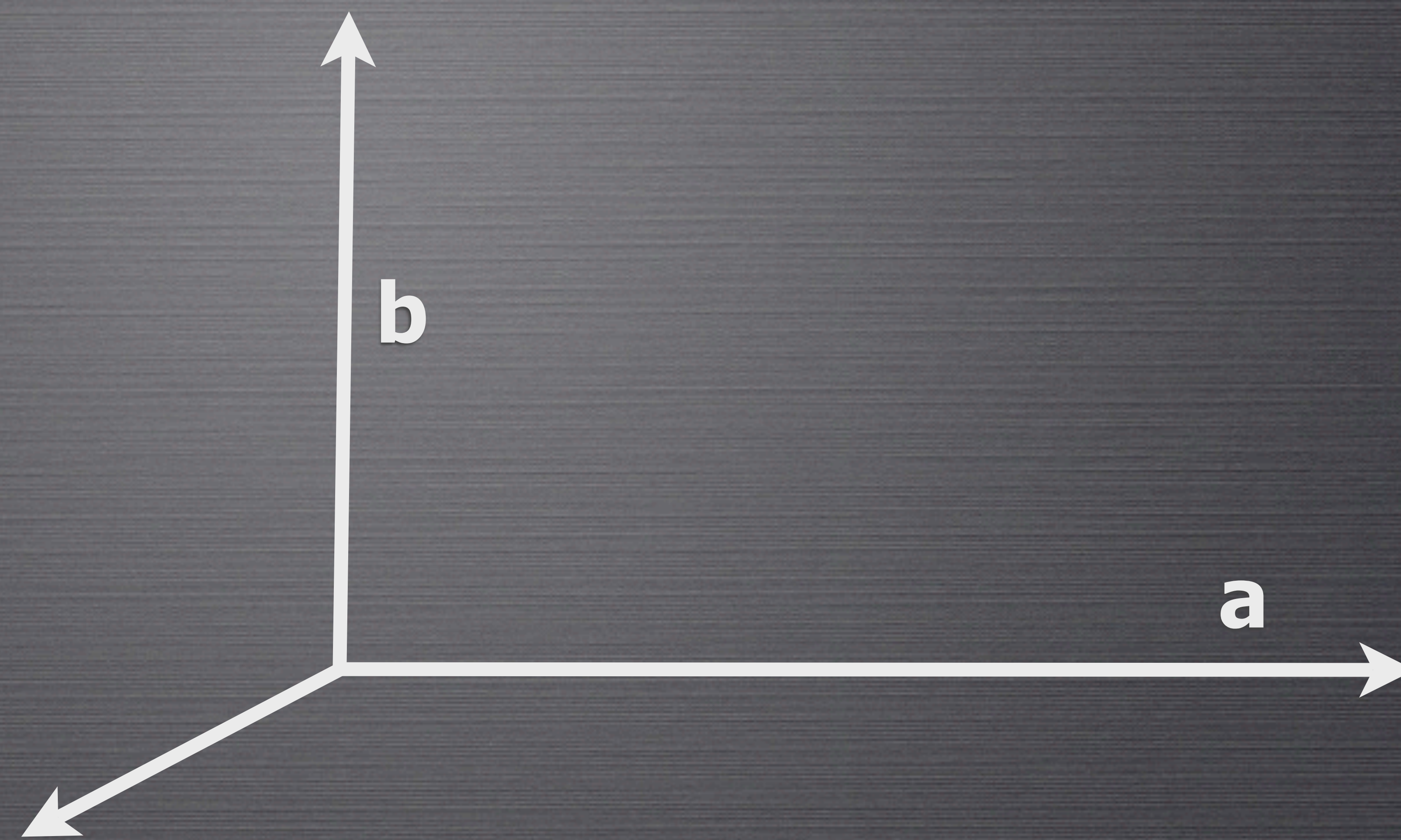

Halo
L


Halo
L
well-mixed,
baryonic Gas


L
Halo
Galaxy


Halo
L
Galaxy


b
a
q=b/a
s=c/a

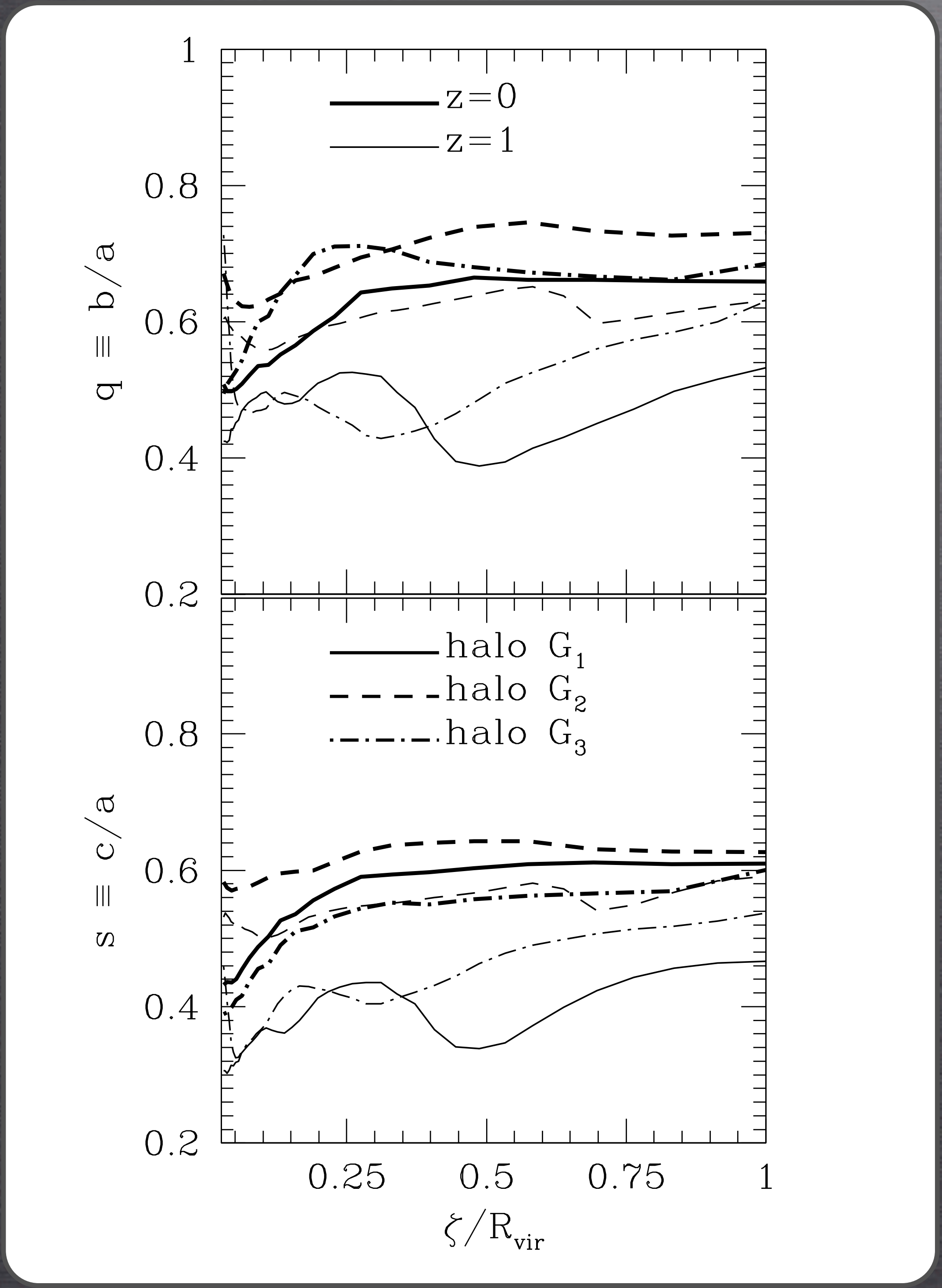


$q = b/a$

$s = c/a$

Shapes in DM-Only Halos

Zentner et al. 2005

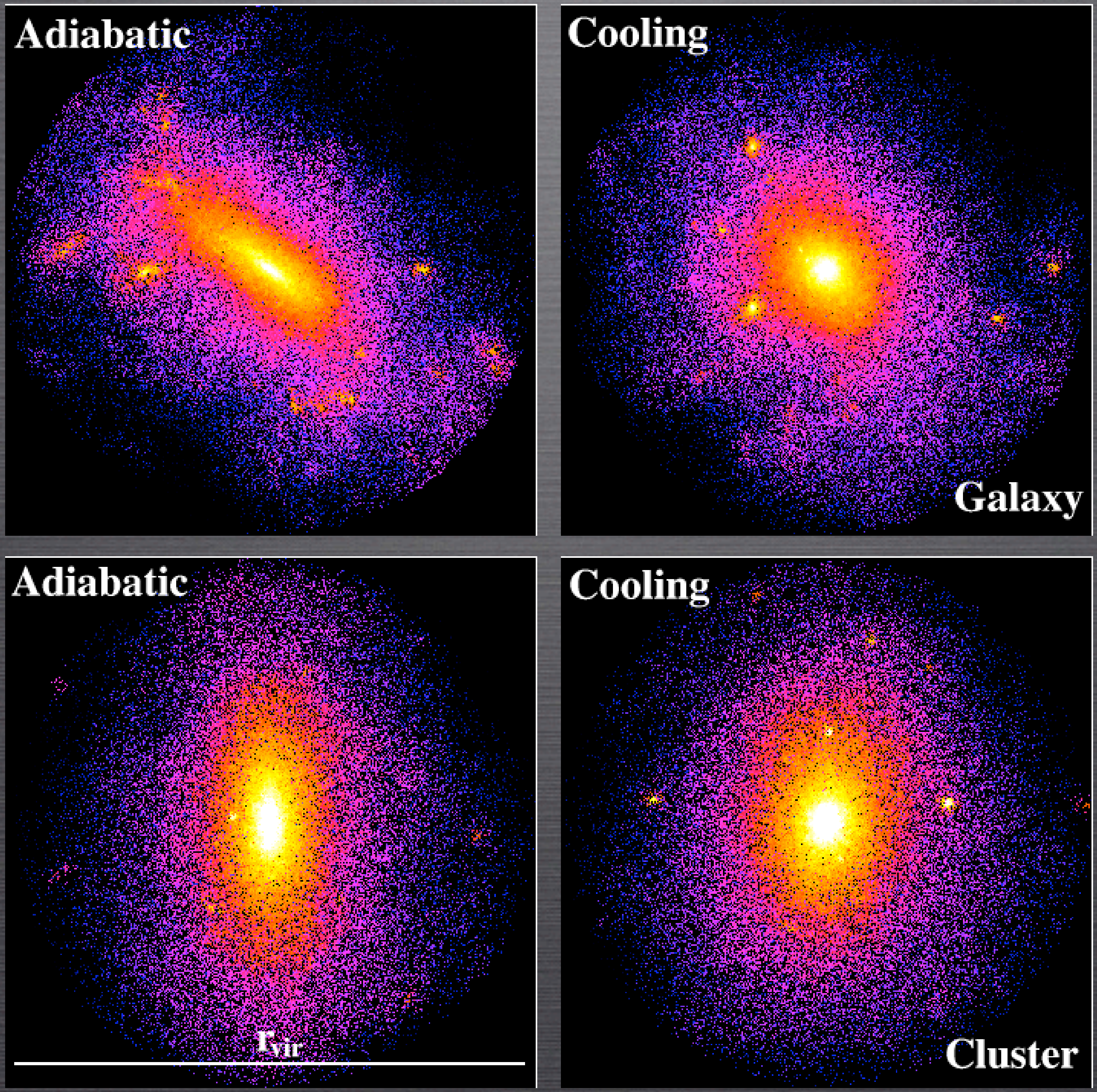


See also: Allgood et al. 2007

- Halos in DM-Only simulations typically are not round, q≈0.65 & s≈0.6
- However, many inferences drawn from local group data suggest a nearly spherical MW halo (Olling+00; Ibata+01; Majewski+03; Helmi+04; Johnston+07; Majewski+08; Smith+10)
- Distant galaxy halos as well... (Dubinski+91; Olling+00; Buote +02; Hoekstra+04; Mandelbaum +08; Buote+09)

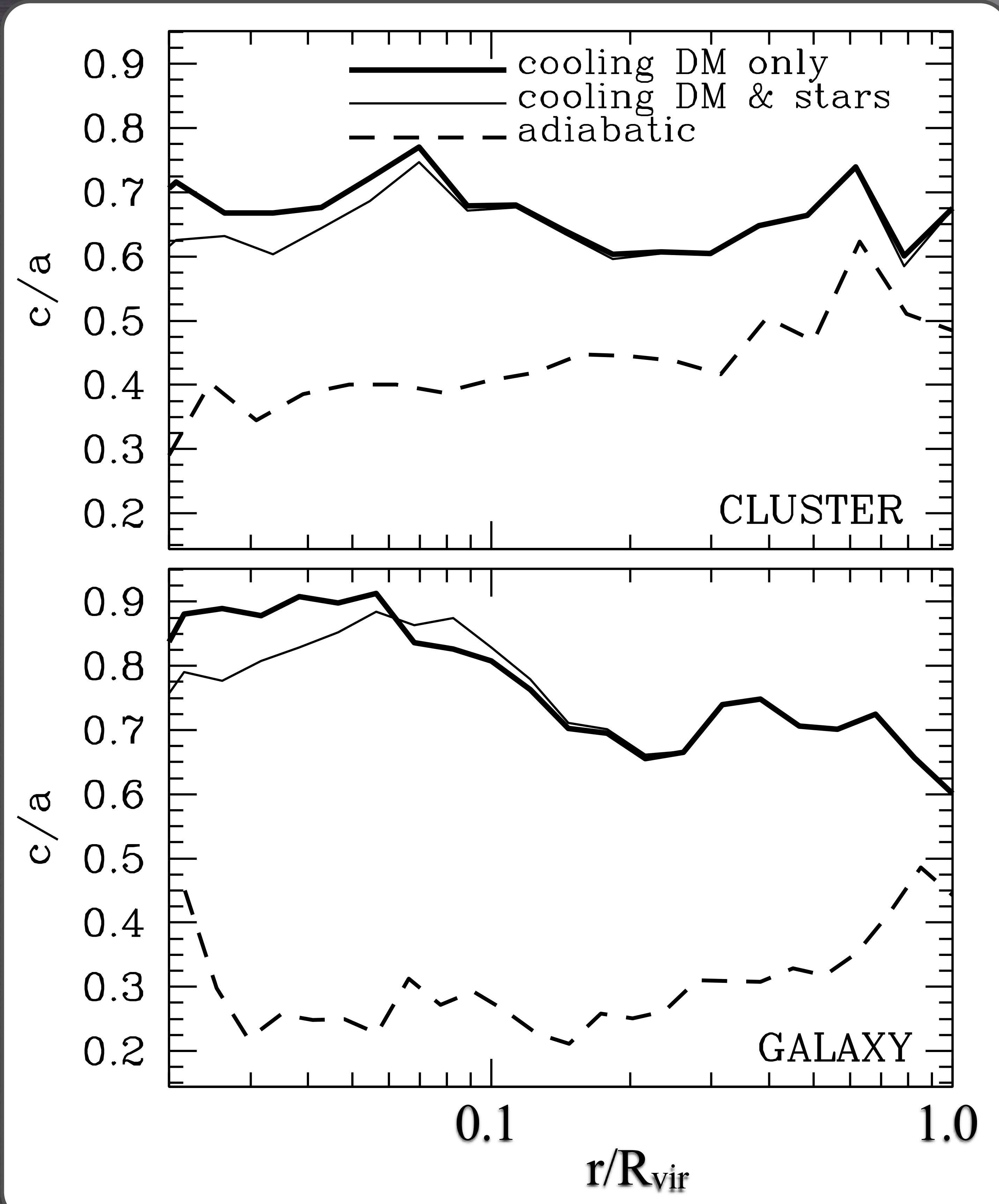
With Baryons

No Baryon cooling — With Baryon cooling



1. Halos become significantly more spherical when baryons cool and form galaxies

With Baryons

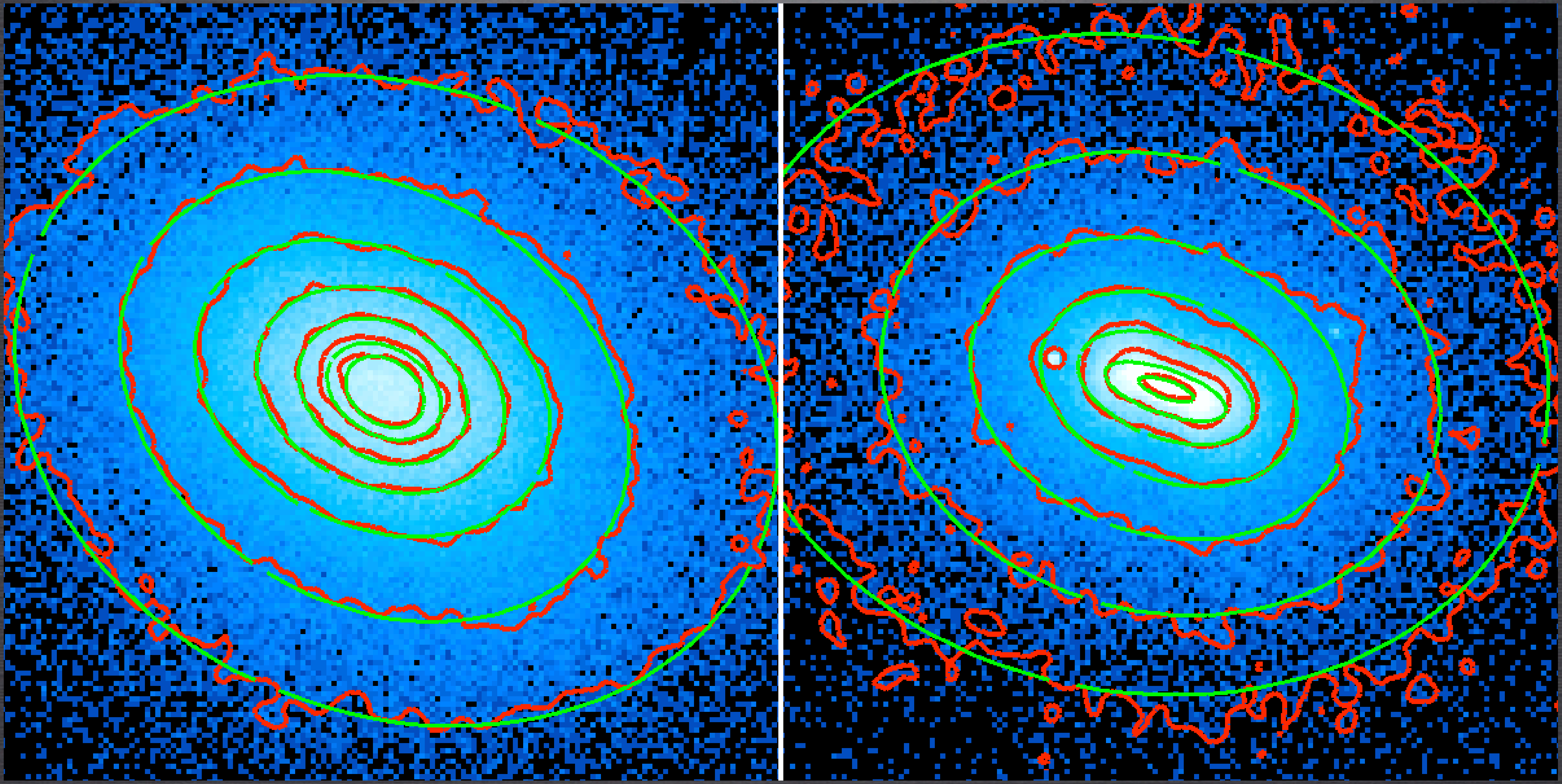


Kazantzidis et al. 2005

- Baryonic cooling in simulations gives dramatic changes in halo shape (but not velocity anisotropy; Tissera+2010)
- Changes as large as $\Delta(c/a) \approx 0.2$ are typical

Testing This

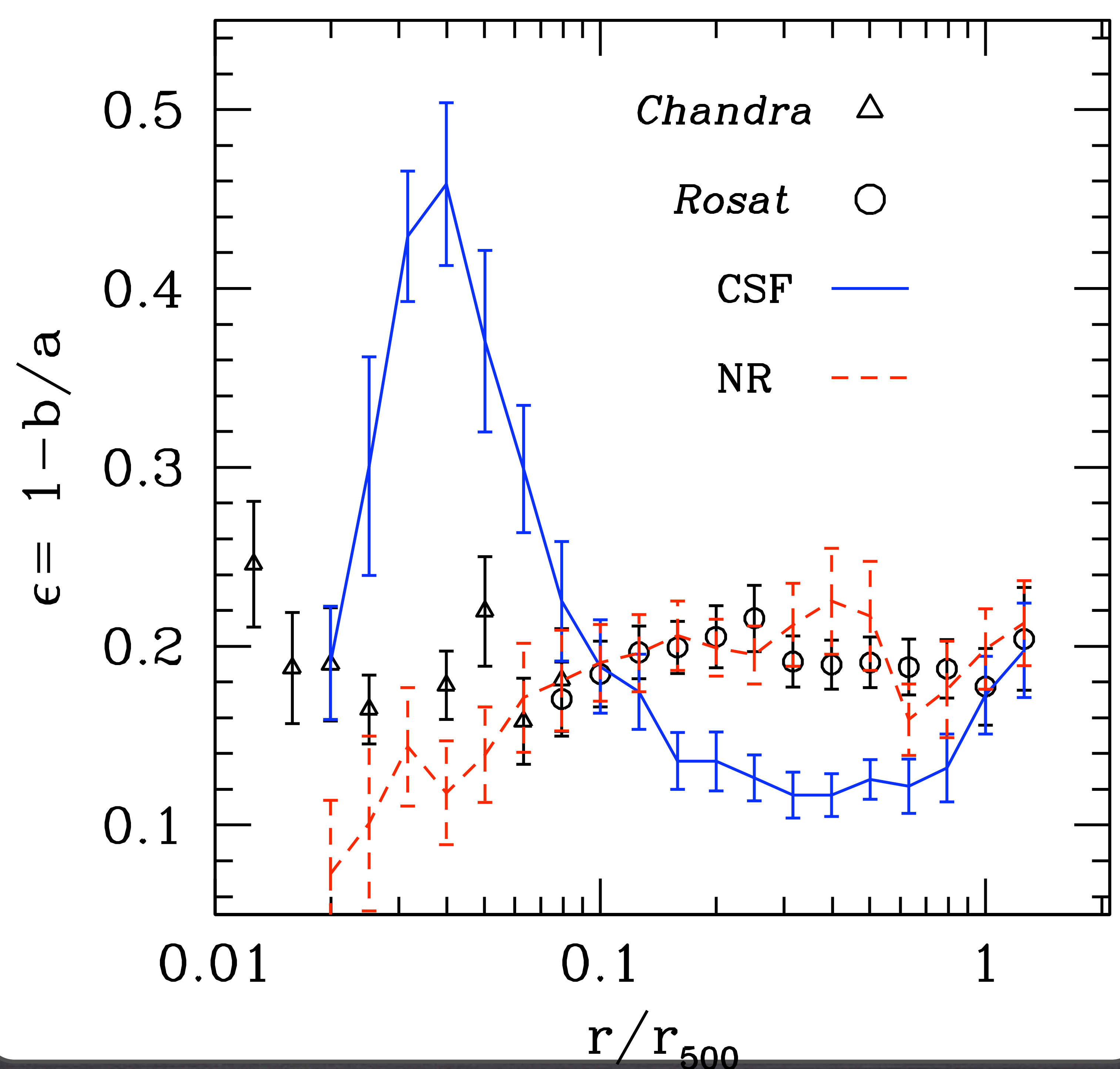
- Mock X-ray maps of simulated clusters



Lau et al. 2010

Testing This

- Mock X-ray maps of simulated clusters compared to data...

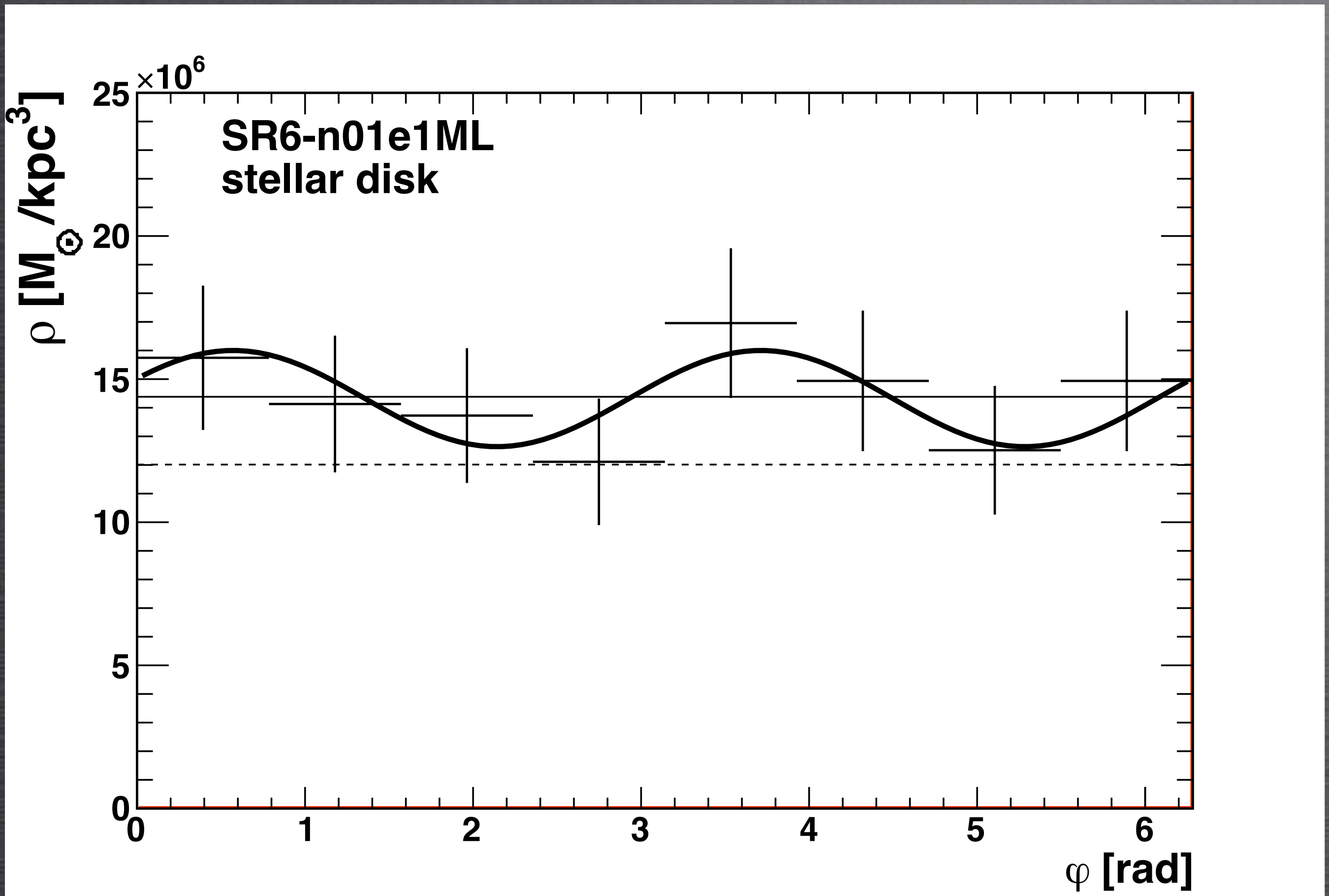


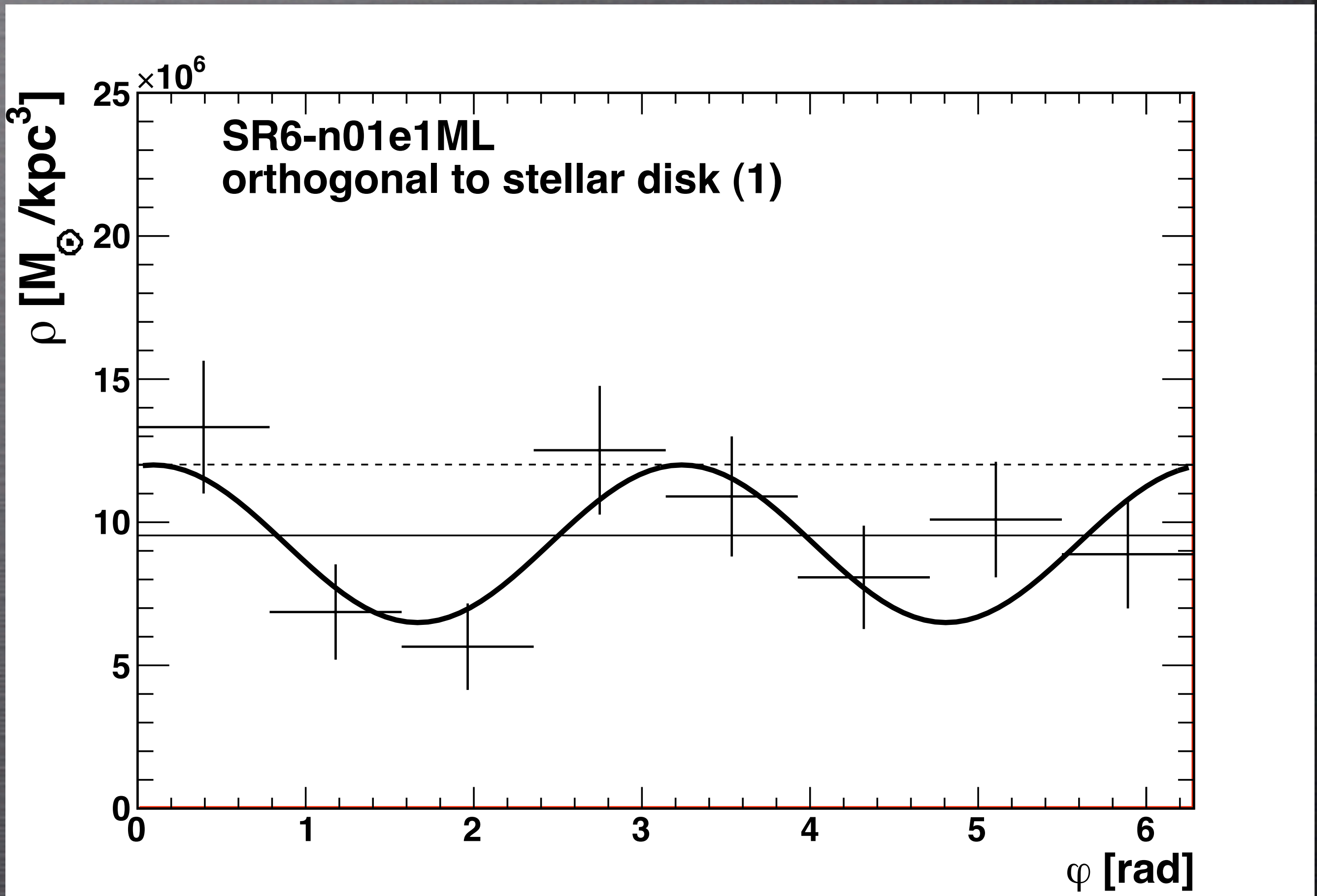
- Elliptical shapes of cluster suggest minimal shape transformation (and minimal cooling?)

Lau et al. 2010

Locally

- Shape of halo may have interesting consequences for direct and indirect search results locally...



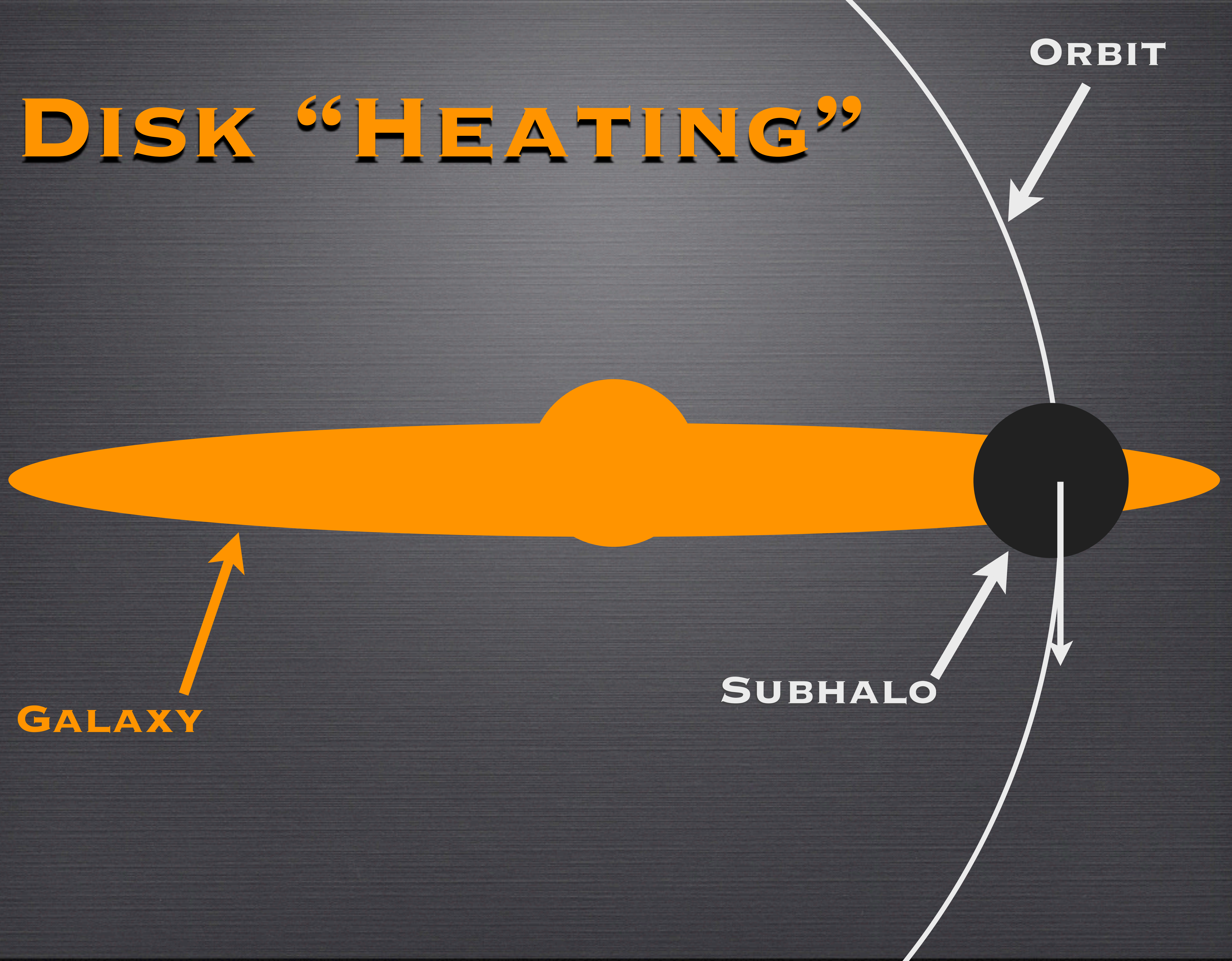


- Stellar disk enhances DM density in the plane (compared to measures that average spherically to derive DM density)
- Deviations from axial symmetry lead to time-dependent density along the Sun's orbit.

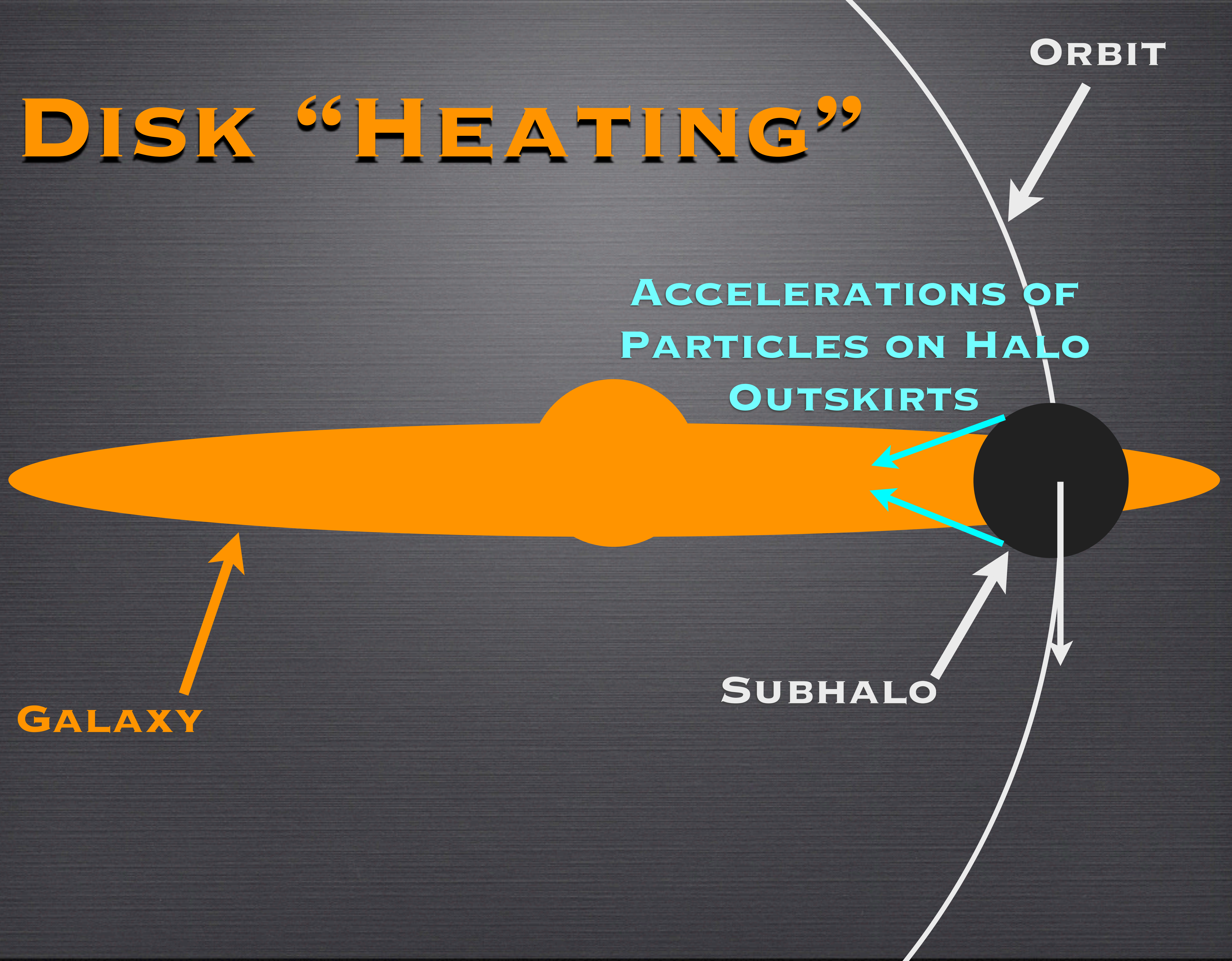
Pato et al. 2010

Halo Substructure with Baryons

Disk “Heating”

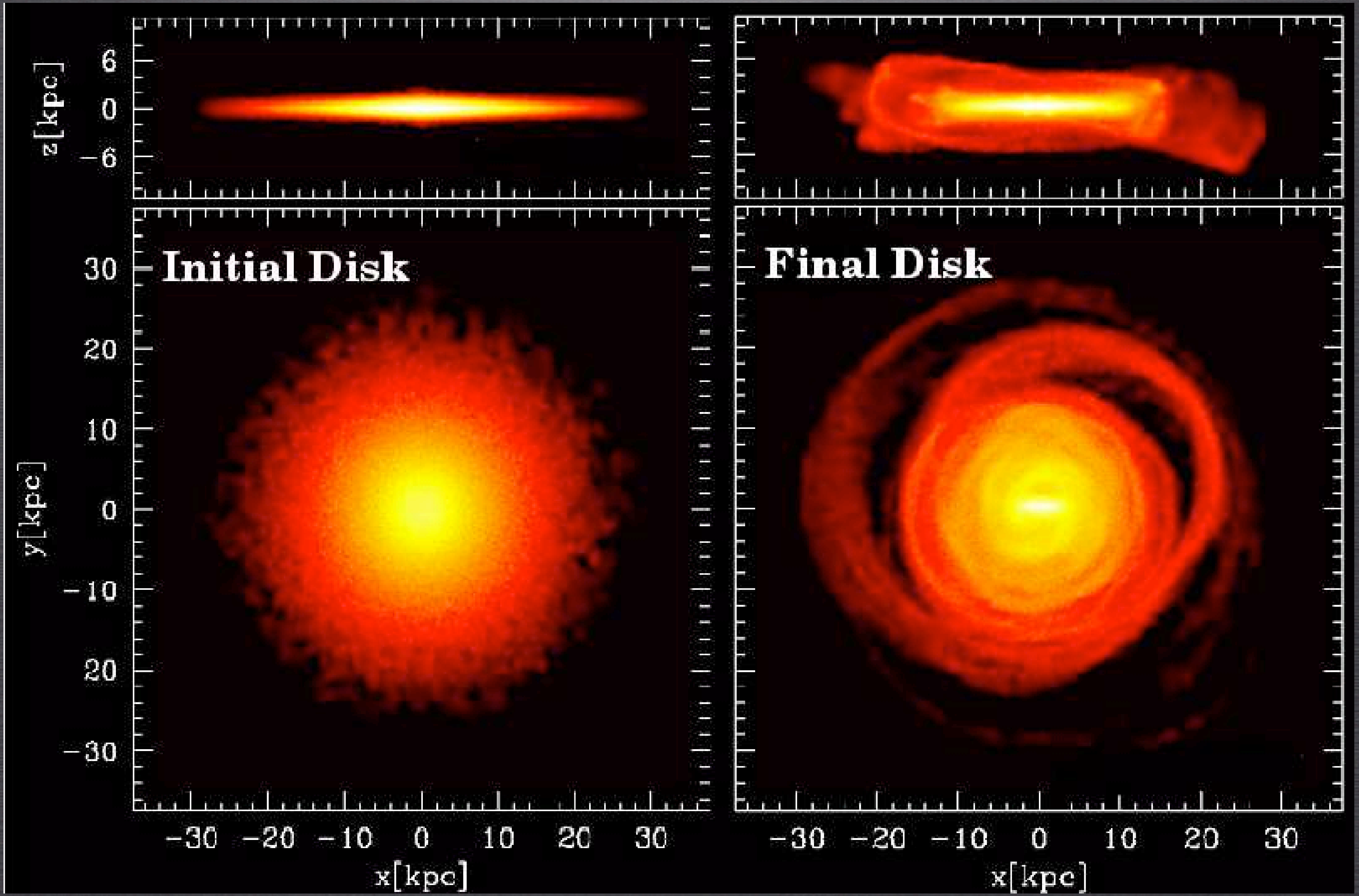


Disk "Heating"



Disk Consequences

- The disk is heated and disk “features” are generated...

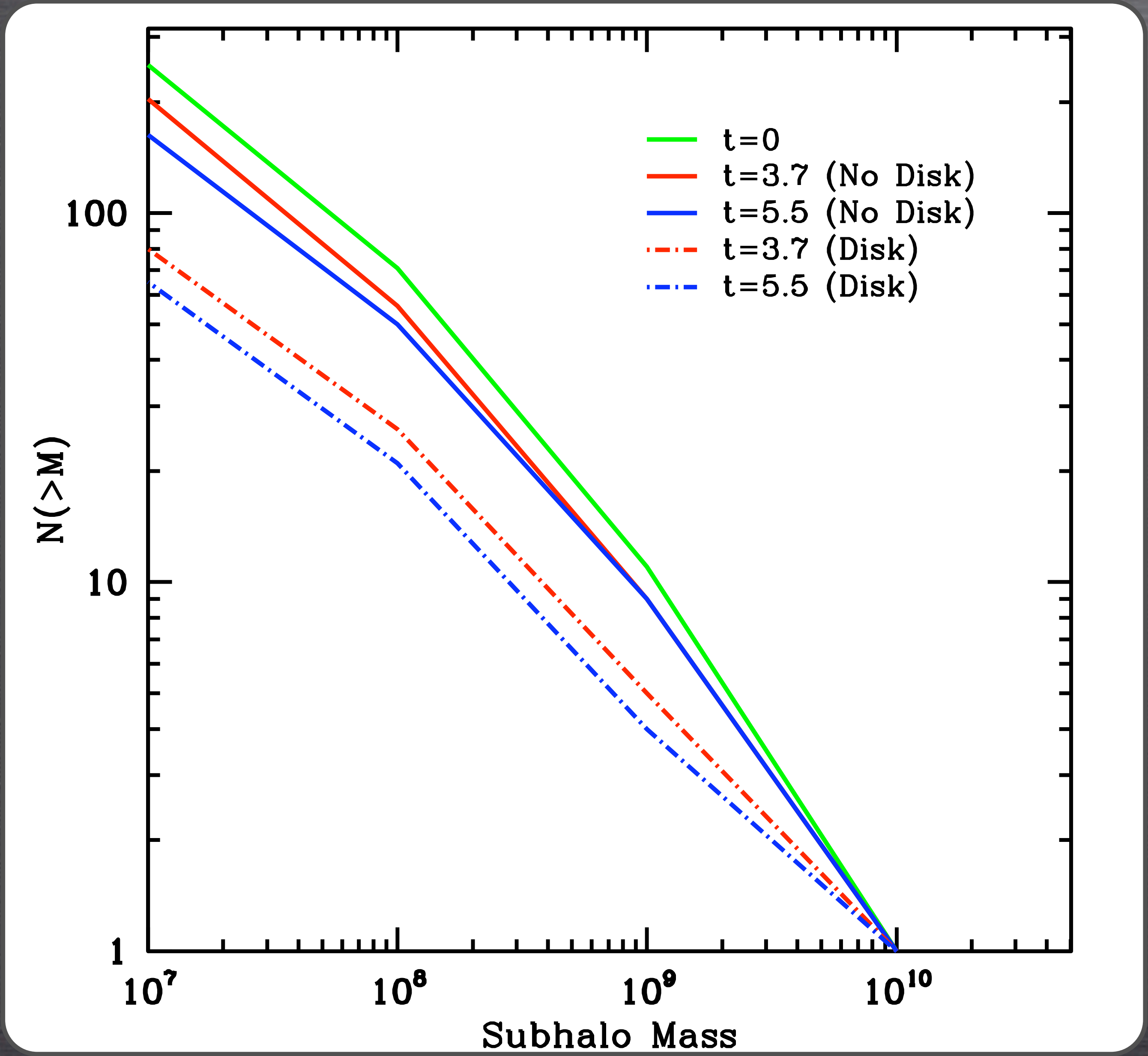


Kazantzidis et al. 2010

Subhalo Consequences

- The disk "heats" substructure and serves to destroy them more efficiently than N-body only simulations

D'Onghia et al. 2010

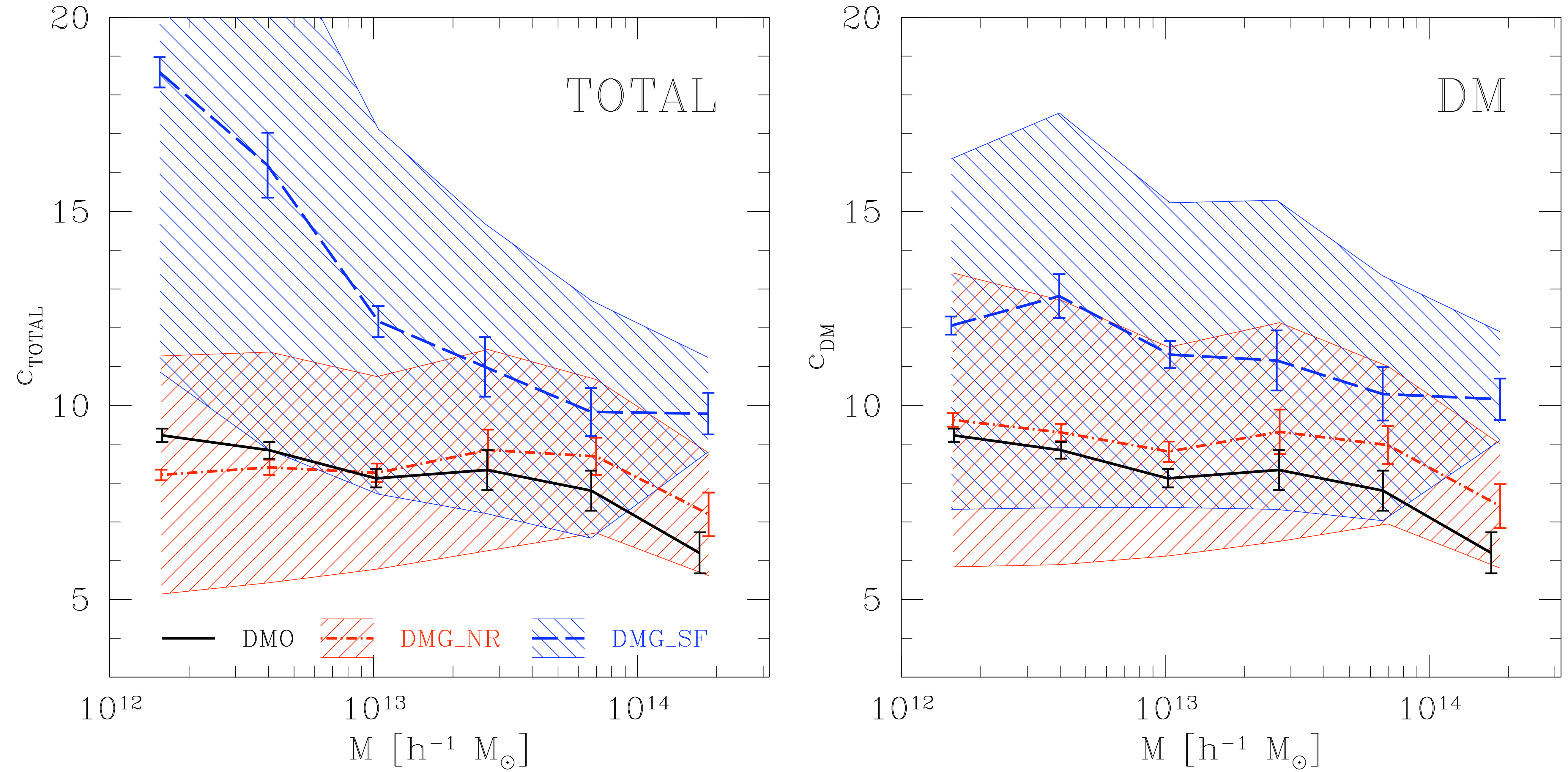


Also: Kazantzidis et al. 2009

Dark Energy?

Halos with Galaxies

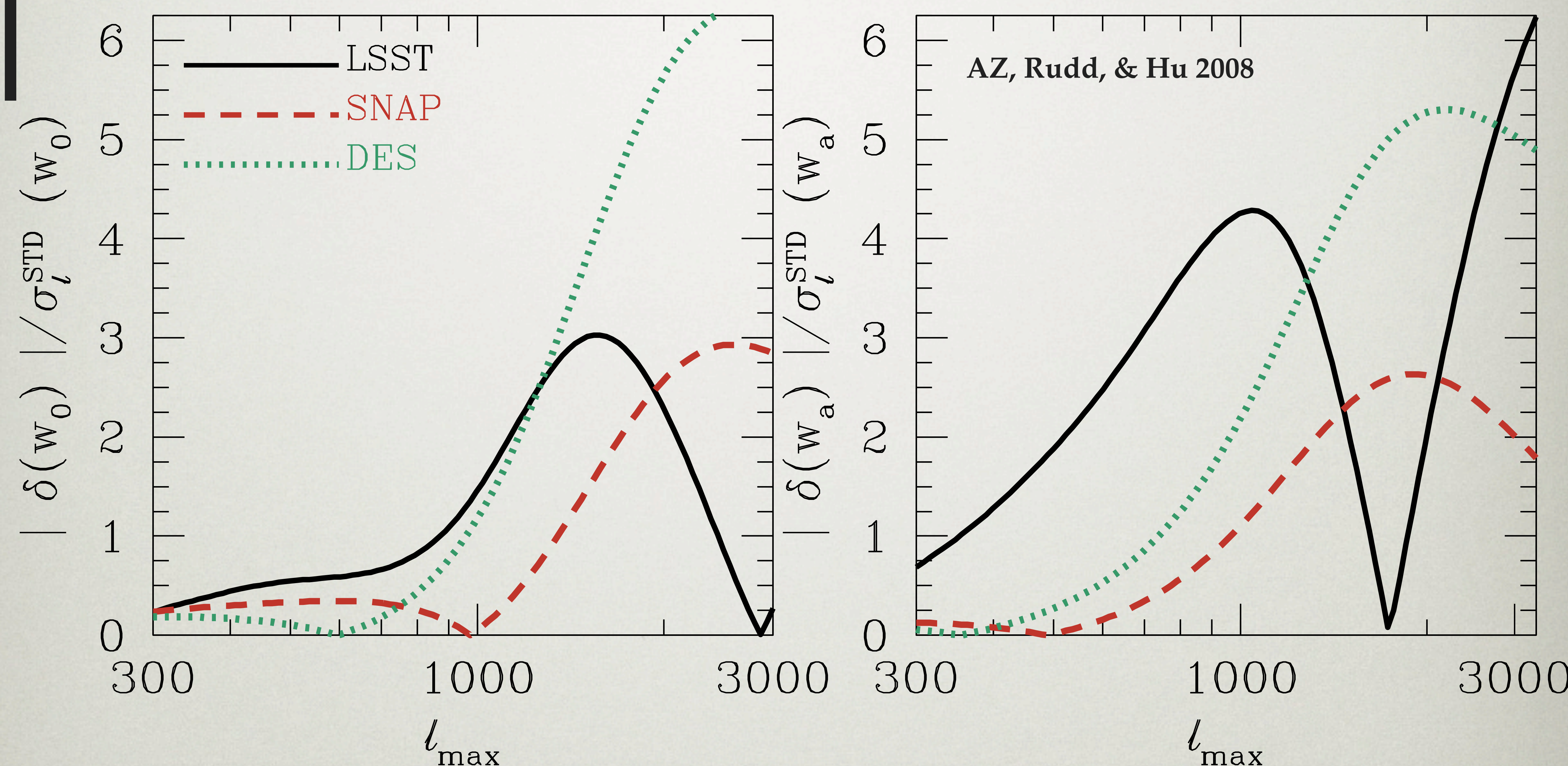
Rudd et al. 2008



- Modified Halo Concentration Relation Relative to the Standard N-Body Result

Parameter Biases

Parameter Bias Relative to Statistical Uncertainty



Maximum Multipole Under Consideration

“Conclusions”

1. Some Halo Contraction Likely Happens, but it is hard to assess the degree and it depends upon messy details of galaxy formation
2. Baryonic Contraction likely makes halos rounder (altering, in principle, constraints on SIDM), but the degree is again hard to assess
3. The presence of galaxies should reduce the prevalence of substructure, but the degree is hard to assess

The Correlation Function

- **Excess probability of finding a galaxy a distance r, from another:**

$$\mathrm{d}P = \bar{n}_\mathrm{g}\mathrm{d}V_1 \times \bar{n}_\mathrm{g}[1 + \xi(r)]\mathrm{d}V_2$$

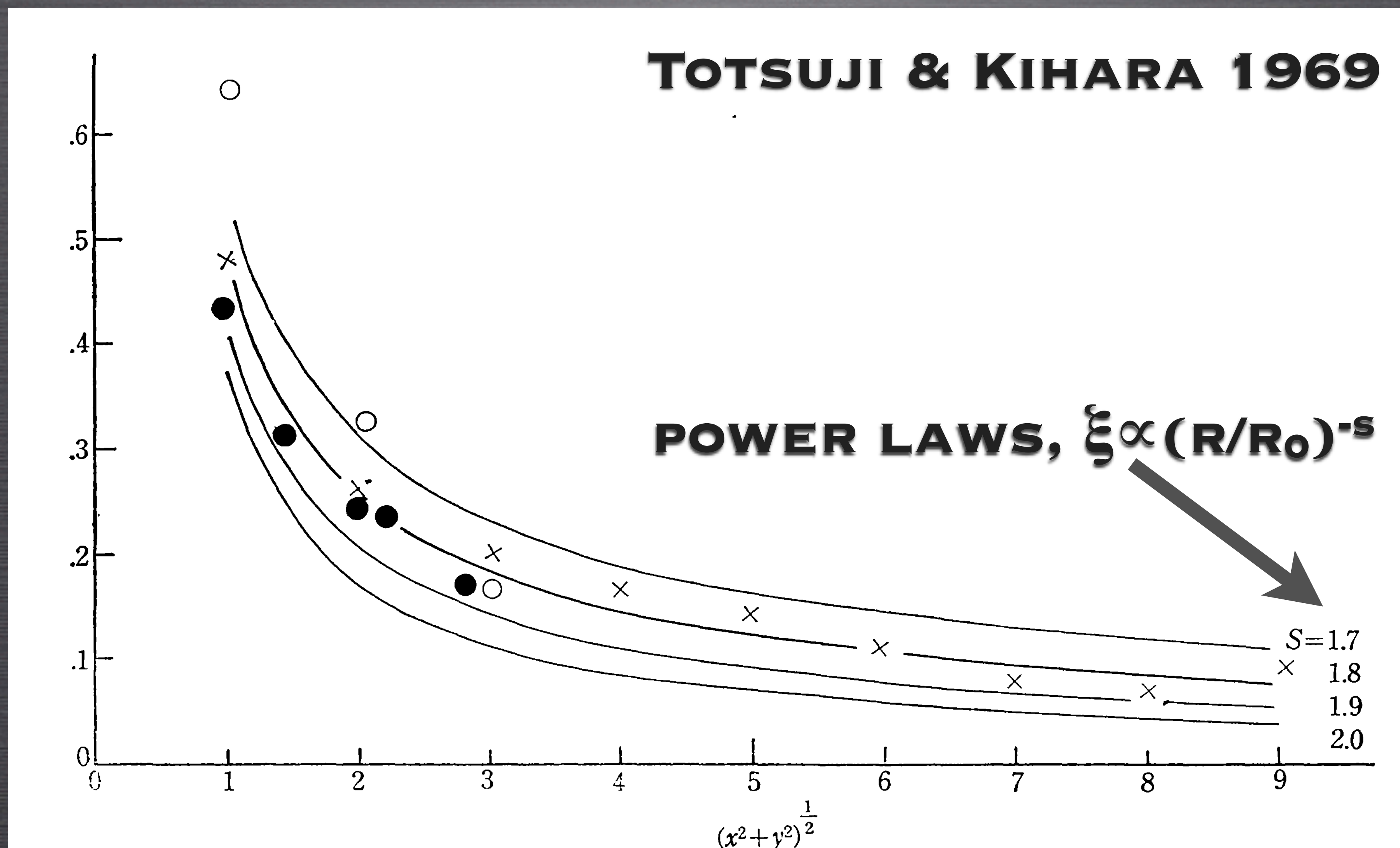
- **If the local galaxy density is $n_g = \bar{n}_g [1+\delta(x)]$, then:**

$$\mathrm{d}P = \bar{n}_\mathrm{g}^2 \langle [1 + \delta(\vec{x}_1)][1 + \delta(\vec{x}_1 + \vec{r})] \rangle \, \mathrm{d}V_1 \mathrm{d}V_2$$
$$= \bar{n}_\mathrm{g}^2 [1 + \langle \delta(\vec{x}_1)\delta(\vec{x}_1 + \vec{r}) \rangle] \mathrm{d}V_1 \mathrm{d}V_2$$

- **and:** $$\xi(r) = \langle \delta(\vec{x}_1)\delta(\vec{x}_1 + \vec{r}) \rangle$$

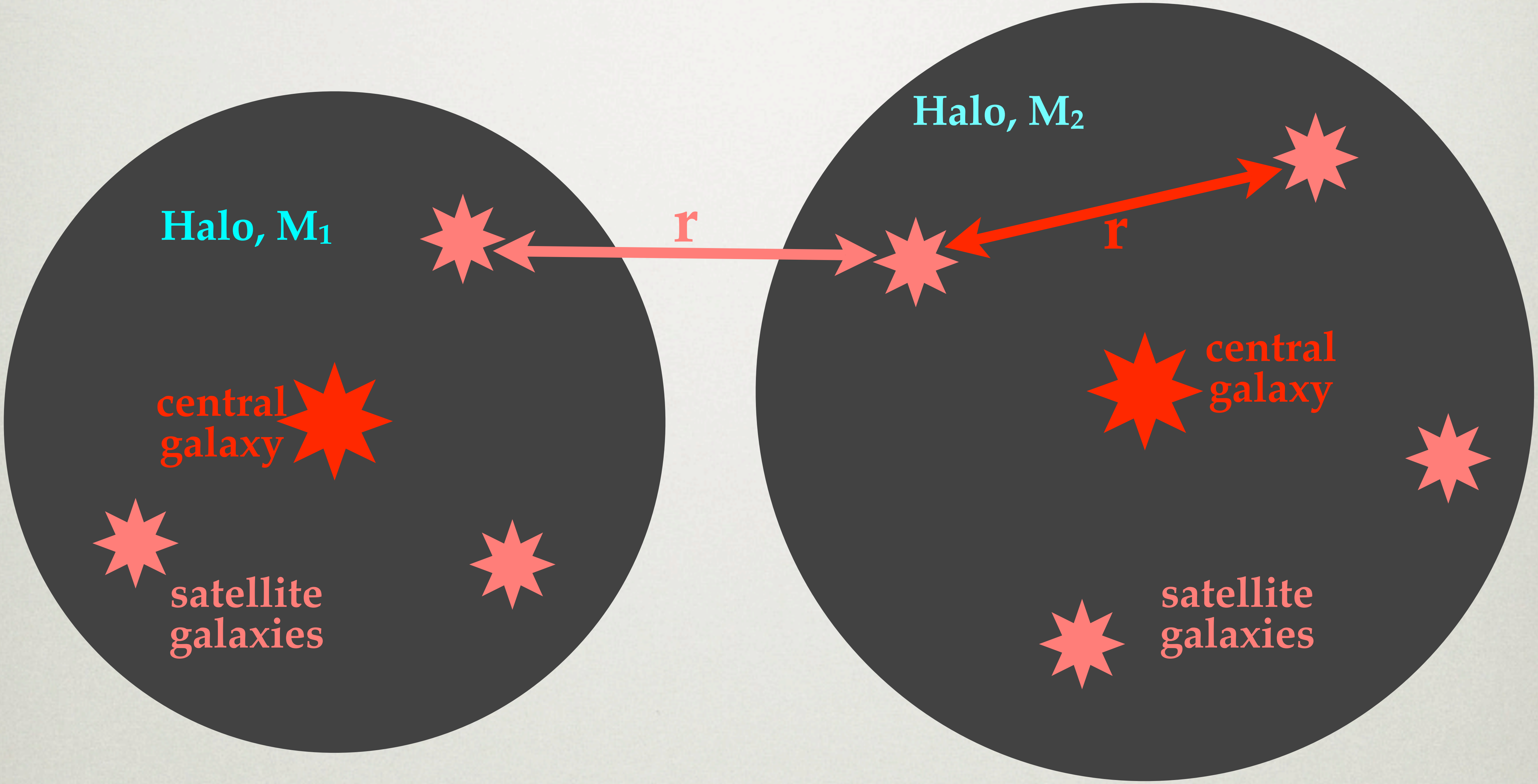
Correlation Function

Correlation function



Angular separation

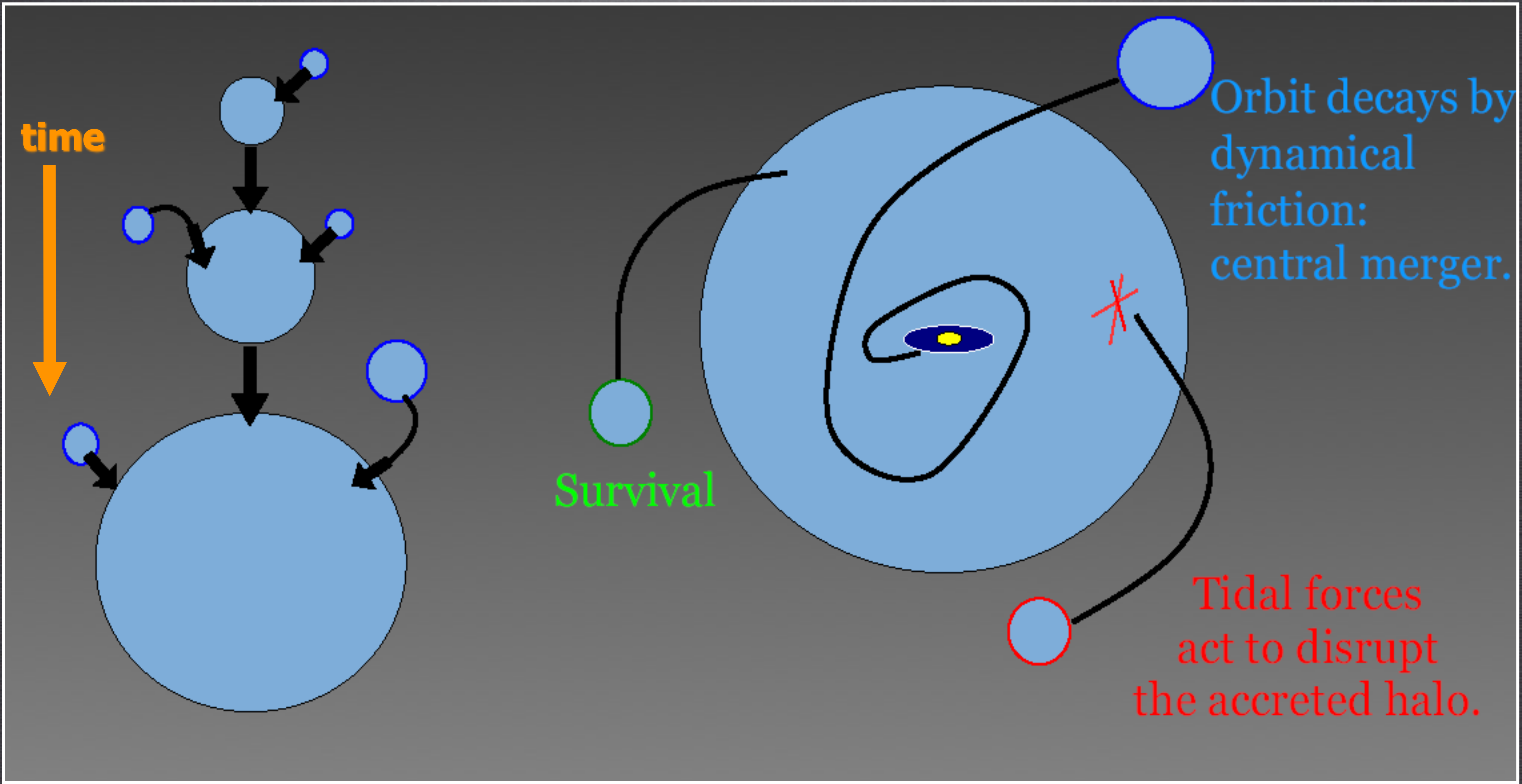
The Halo Model



- Compute correlation statistics using halos as the fundamental unit of structure: $\xi(r)=\xi^{1H}(r)+\xi^{2H}(r)$

Analytic Method

Modeling Framework



Gnedin & Ostriker 1999; Gnedin, Ostriker, & Hernquist 2000; Taffoni et al. 2002;
Taylor & Babul 2002; Zentner & Bullock 2003; Zentner et al. 2005a,2005b