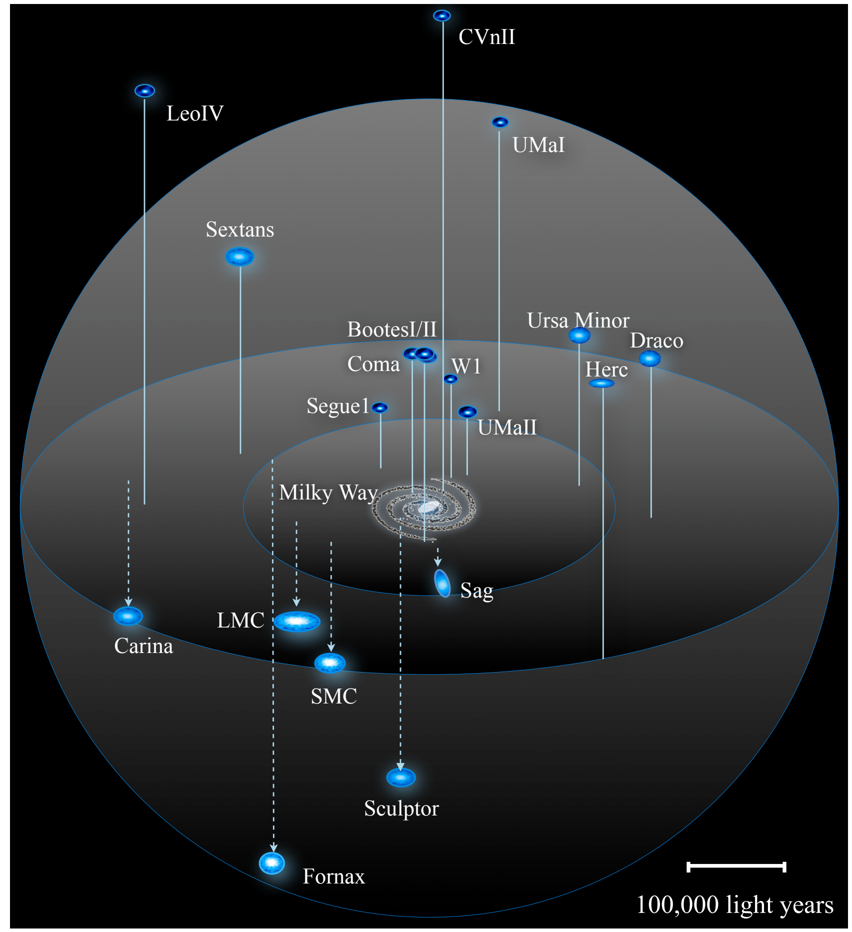
CDM and the Substructure Crisis

J. S. Bullock
XX Canary Islands Winter School, LG Cosmology



Theory: $N>10^{10}$ Observation: N~20

https://webfiles.uci.edu/bullock/Public/Canary2008/

Lecture 3:
First contact with observations

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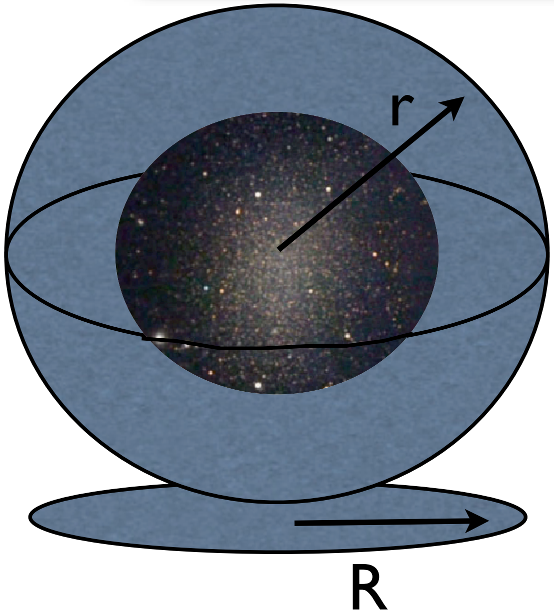
Interpreting Kinematics: Jeans Equation



Observables:

1. Line of sight velocity dispersion: $\sigma_{los}(R)$
2. Stellar distribution: $I_*(R) \longrightarrow \rho_*(r)$

$$\sigma_{los}^2(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\rho_* \sigma_r^2 r \mathrm{d}r}{\sqrt{r^2 - R^2}}$$

Infer 3d radial velocity dispersion of the stars: σ_r

unknown function

Jeans Equation: $$\rho_* \frac{\mathrm{d}\Phi}{\mathrm{d}r} = -\frac{\mathrm{d}(\rho_* \sigma_r^2)}{\mathrm{d}r} - 2\frac{\beta}{r}\rho_* \sigma_r^2$$

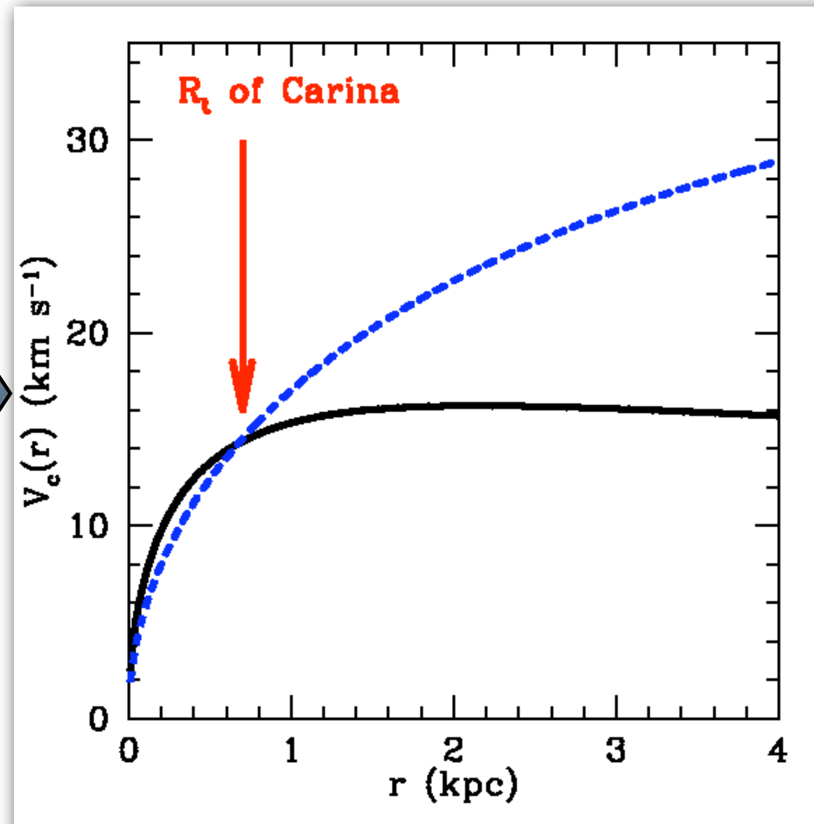
Global Potential - what we want to know

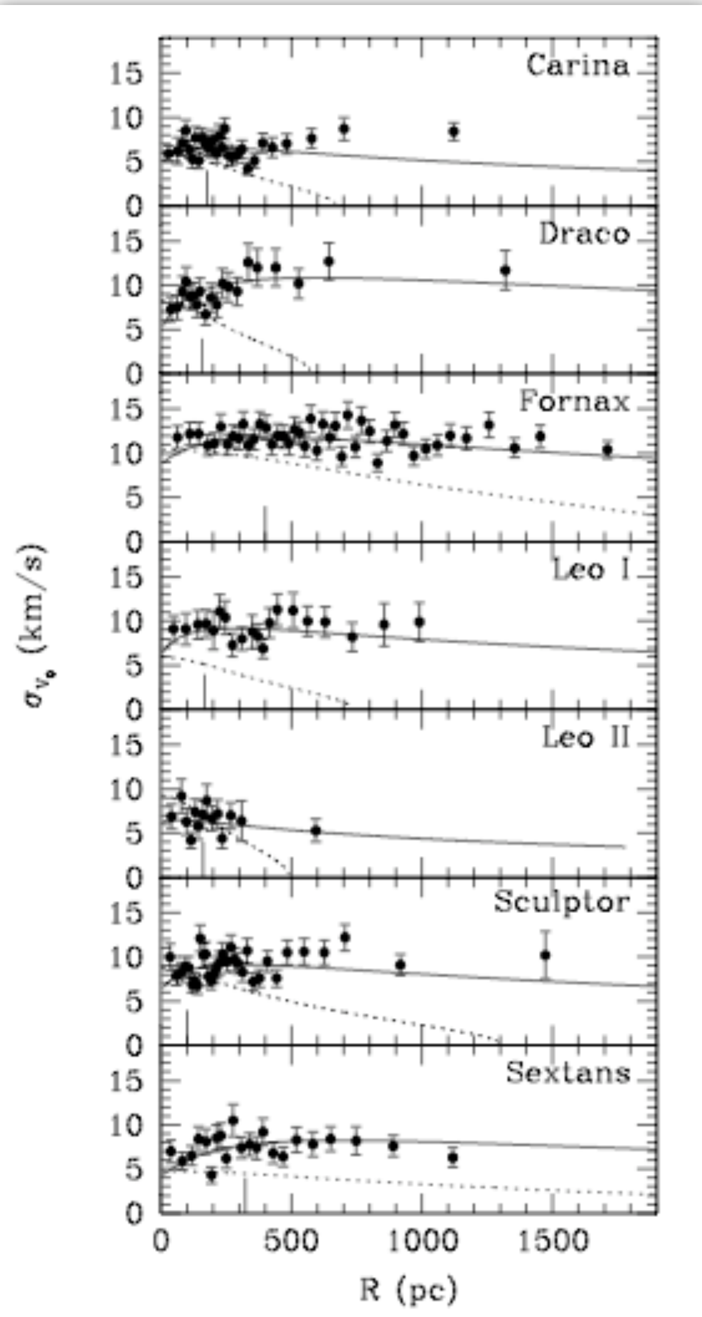
Counting Dwarfs

Halo maximum rotation speed poorly constrained by line-of-sight stellar velocity dispersion.

(Even if we assume stellar orbits are isotropic)

Both of these rotation curves reproduce observed velocity dispersion of Carina





Kinematics: Classical MW Satellites

Walker et al. 07

~1000 radial velocities per dSph
~5 km/s accuracy per star

- **Flat velocity dispersion profiles**
- **σ~5-10 km/s**
- **Mass-follows light strongly ruled out**

What are the masses of Milky Way Satellites?

1. Stellar kinematics
[Walker et al. 07; Munoz et al. 07;etc.]

2. Spherical Jeans equation. Marginalize over 8 parameter mass and velocity-anisotropy profiles.

generalized dm mass profile

$$\rho(r) = \frac{\rho_0}{(r/r_0)^a[1+(r/r_0)^b]^{(c-a)/b}}$$

stellar vel. anisotropy profile

$$\beta(r) = (\beta_\infty - \beta_0)\frac{r^2}{r_\beta^2 + r^2} + \beta_0.$$

$$P(\mathbf{v}|u,\sigma_t) = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left[-\frac{1}{2}\frac{(v_i - u)^2}{\sigma_i^2}\right]$$

N=# stars

$$\sigma_i^2 = \sigma_{t,i}^2 + \sigma_{m,i}^2$$

theory $\sigma(R=R_i)$ from Jeans equation

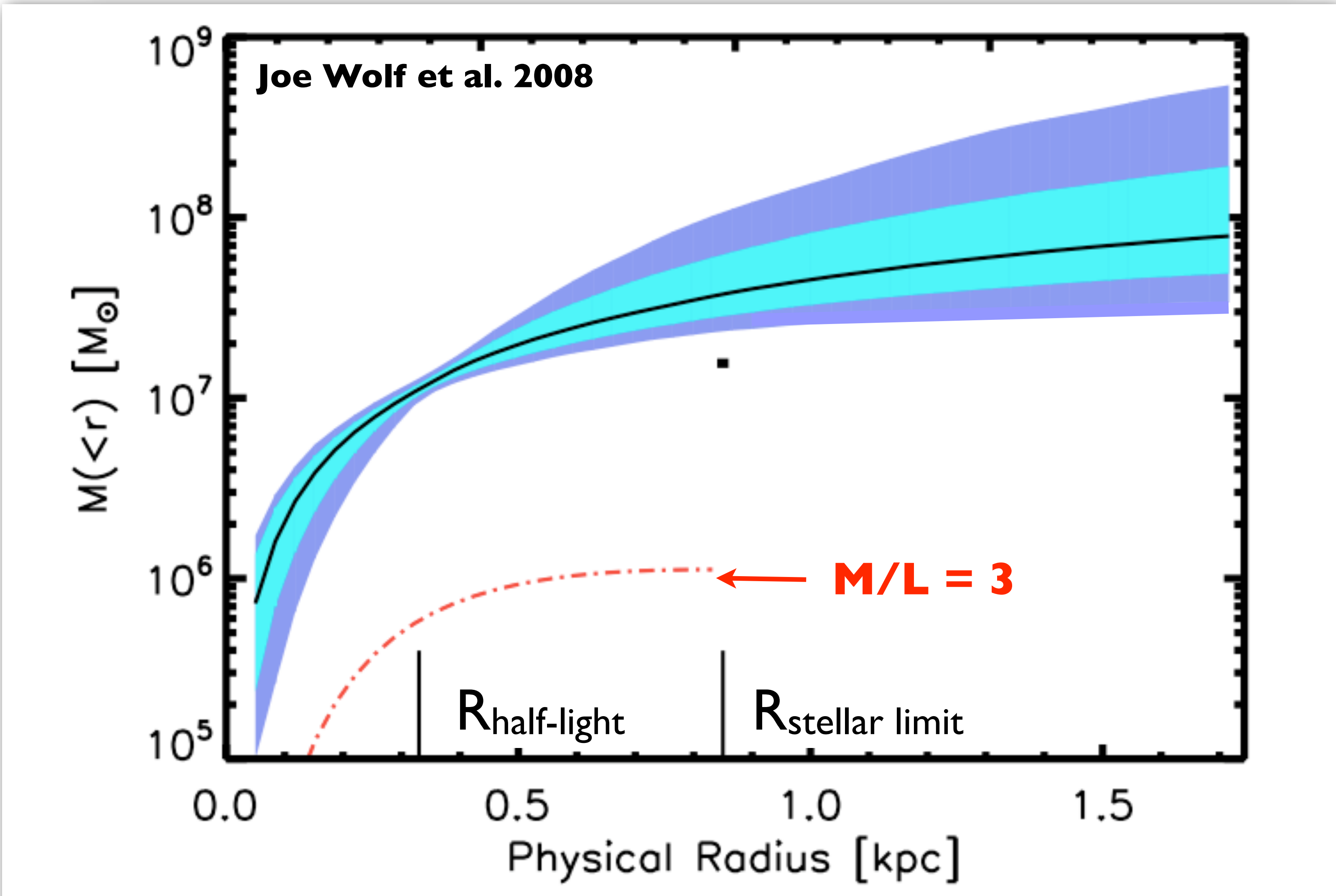
observ. error for star i

$$\mathcal{L}(m) \propto \int P[\mathbf{v}|u,\sigma_t(\vec{\theta})]\delta(m - M)d\vec{\theta}.$$

Determine the likelihood for some quantity (e.g. m = m(<600pc) by integrating the probability over all of the parameters: $\theta=(a,b,c,r_0, \rho_0, \beta_0, \beta_\infty, r_\beta)$

The Gaussian approximation provides a good estimation of the true distribution, though there may be some deviations from Gaussianity in the outer most regions of galaxies

Mass profile constraints for Carina: ~900 stars from Walker et al. 07



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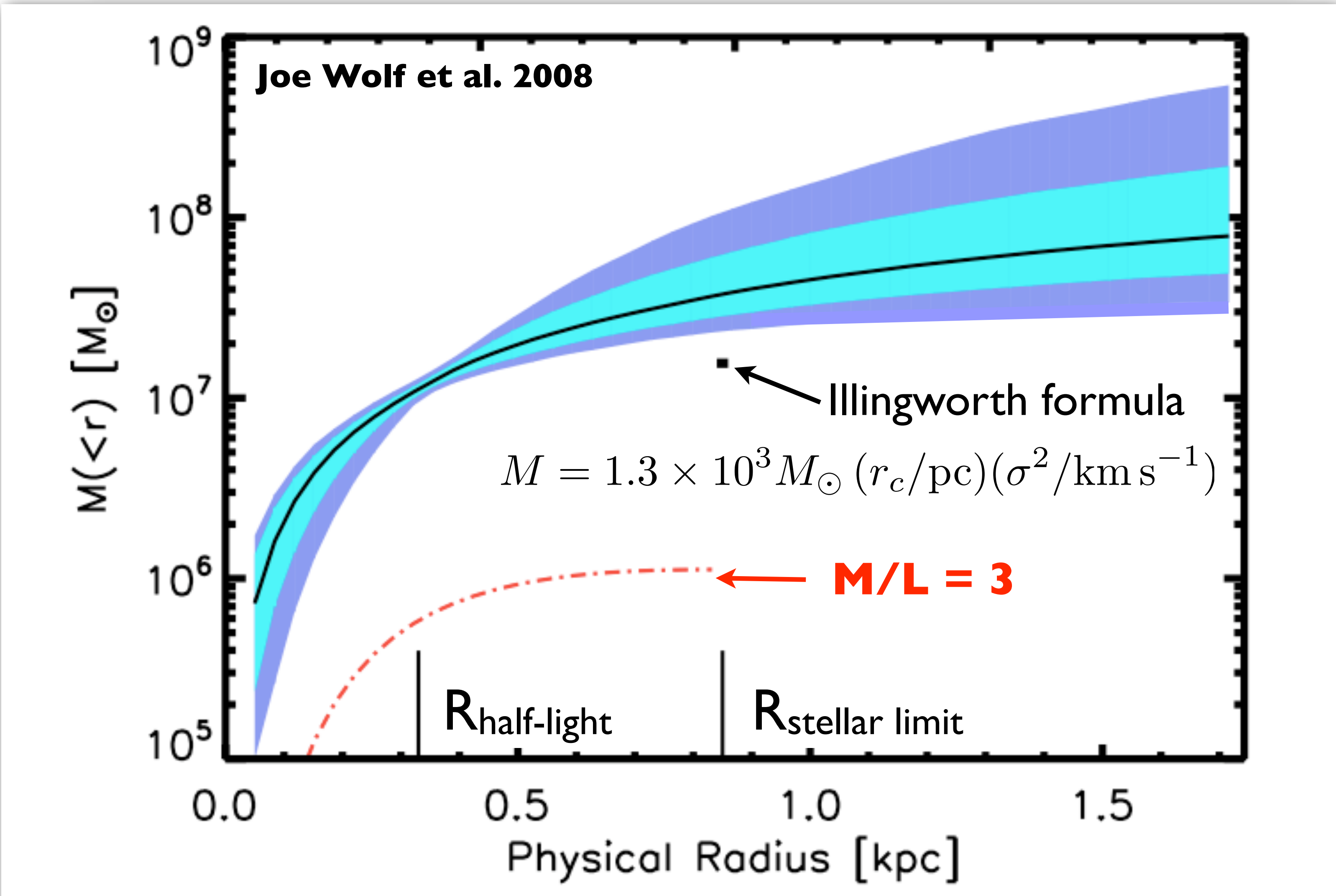


Side Note

- Please do not use the Illingworth formula for dSph masses. It was derived for self-gravitating King models (GC's) and is also concentration-dependent.

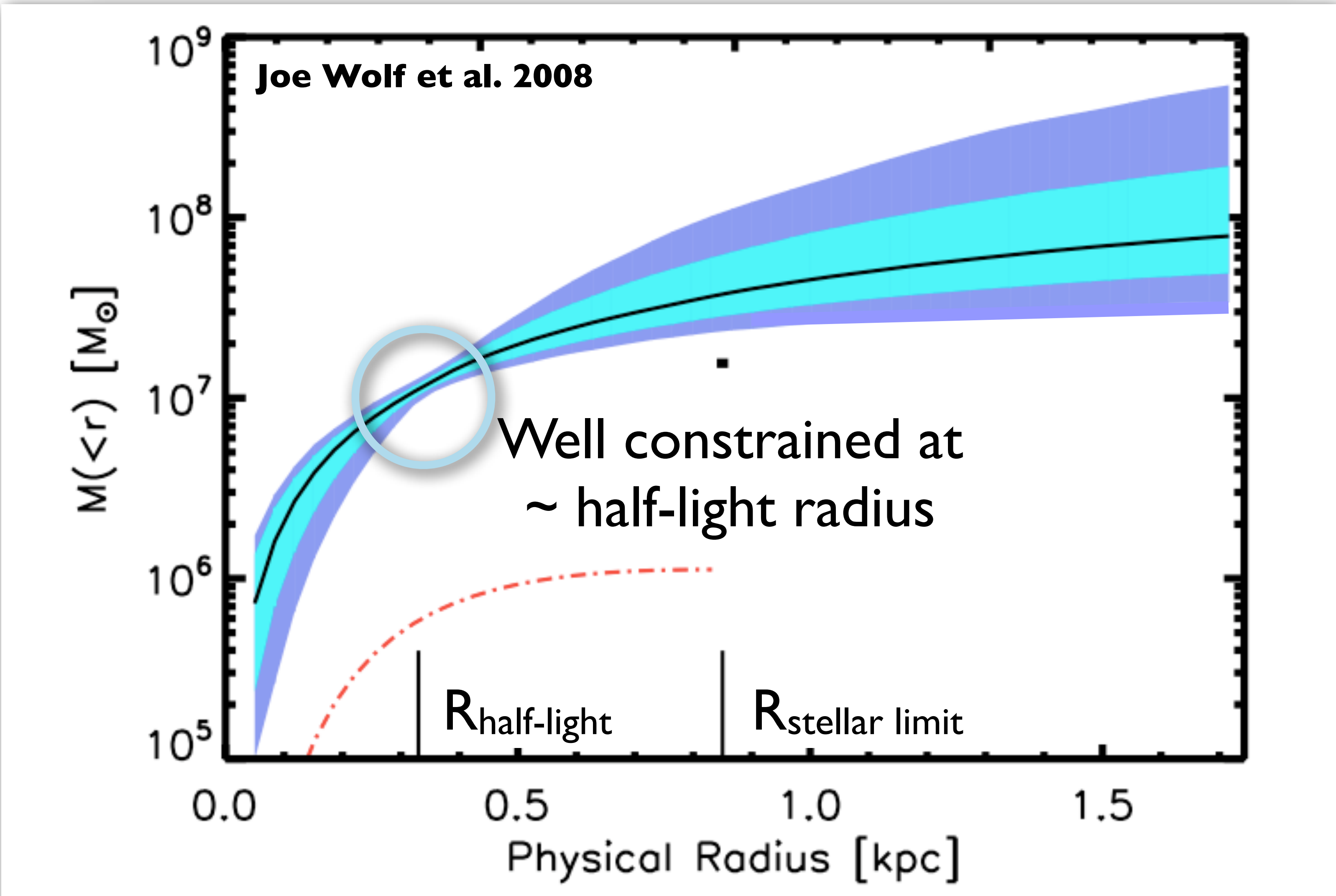
$$M = 1.3 \times 10^3 M_\odot (r_c/\mathrm{pc})(\sigma^2/\mathrm{km\,s^{-1}})$$

- If you want a simple approximation, this one is pretty good:

$$M(< r) = \frac{r\sigma_r^2}{G} \left| \frac{\mathrm{d}\ln \rho_*}{\mathrm{d}\ln r} \right|$$

$$\beta = 0 \quad \sigma_r = \mathrm{const} \simeq \sigma_{los}$$

Mass profile constraints for Carina: ~900 stars from Walker et al. 07

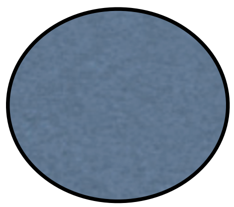


What can we determine?

Marginalize over >8 Parameters.

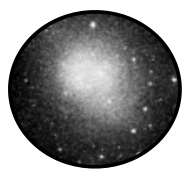
e.g. Dark Matter Halo (5)

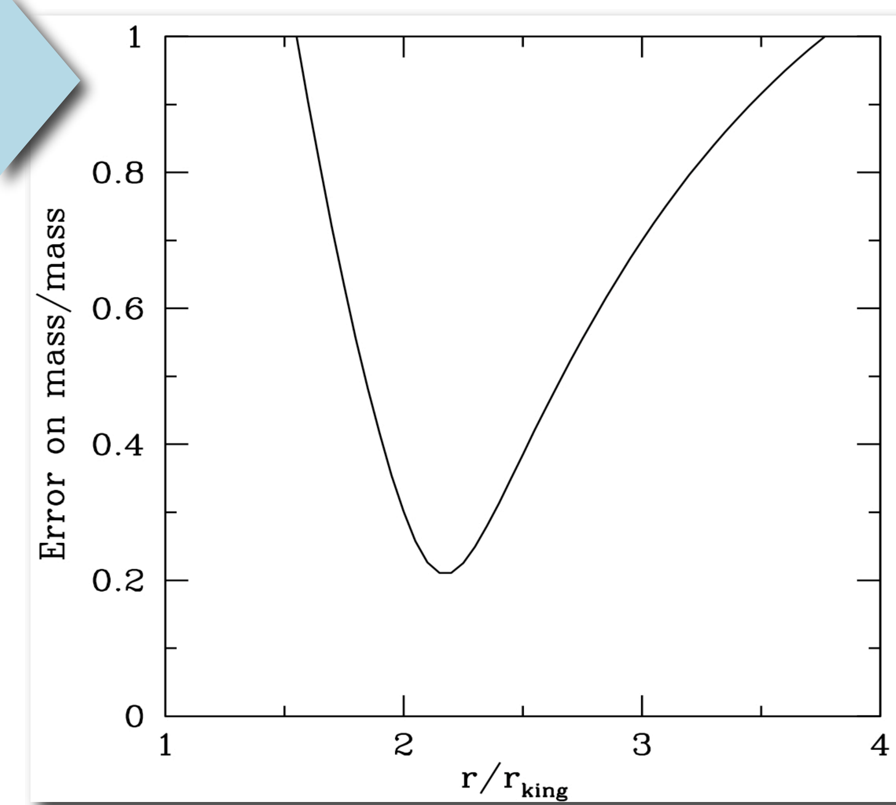
$$\rho(r) = \frac{\rho_0}{(r/r_0)^a[1+(r/r_0)^b]^{(c-a)/b}}$$



Stellar Vel. Anisotropy (3)

$$\beta(r) = \beta_0 + \frac{\beta_1 r^2}{r^2 + r_\beta^2}$$

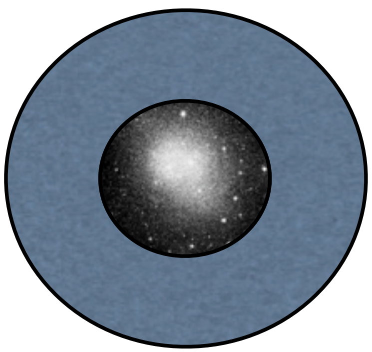


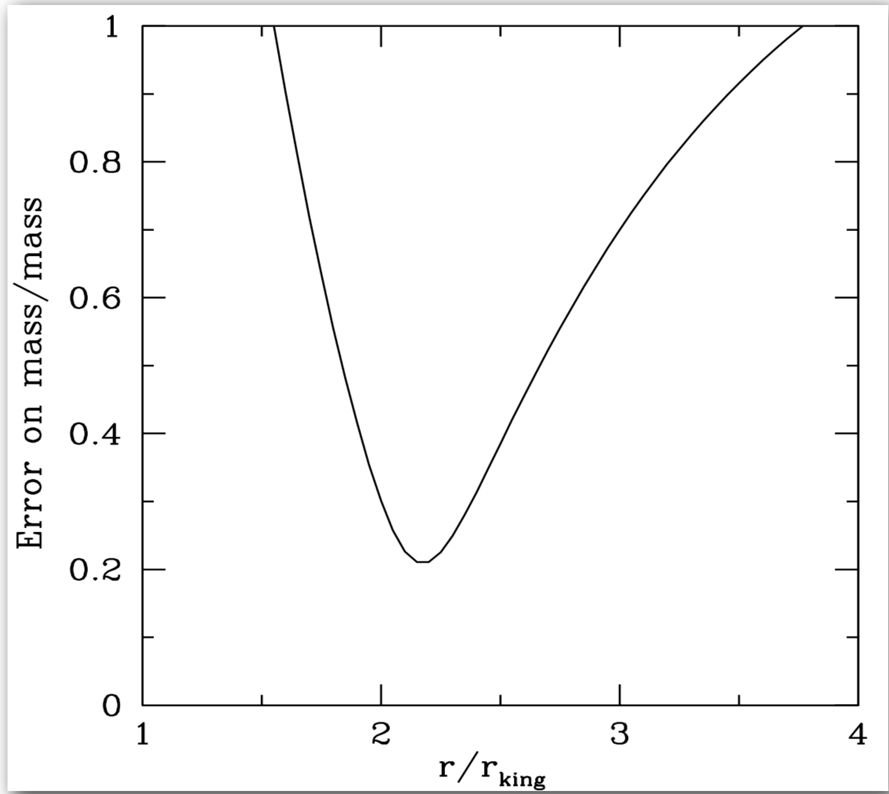


Strigari, JSB, Kaplinghat 07

What can we determine?

The total mass within the **stellar** radius





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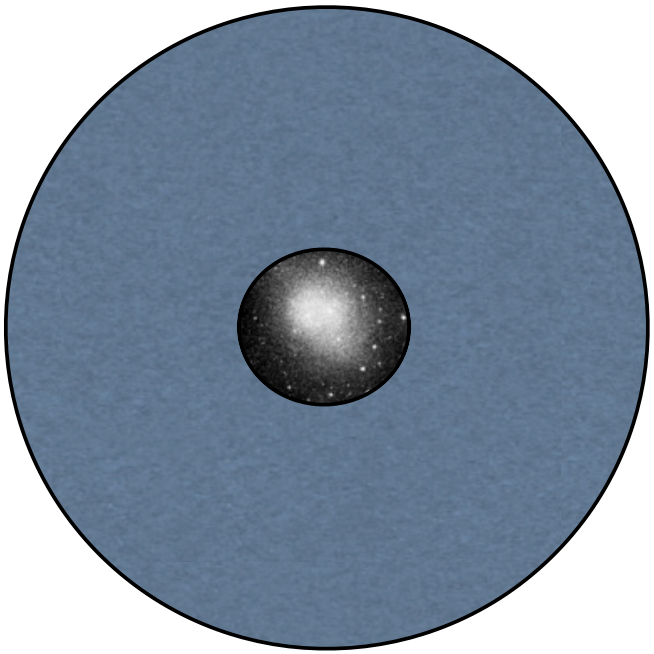

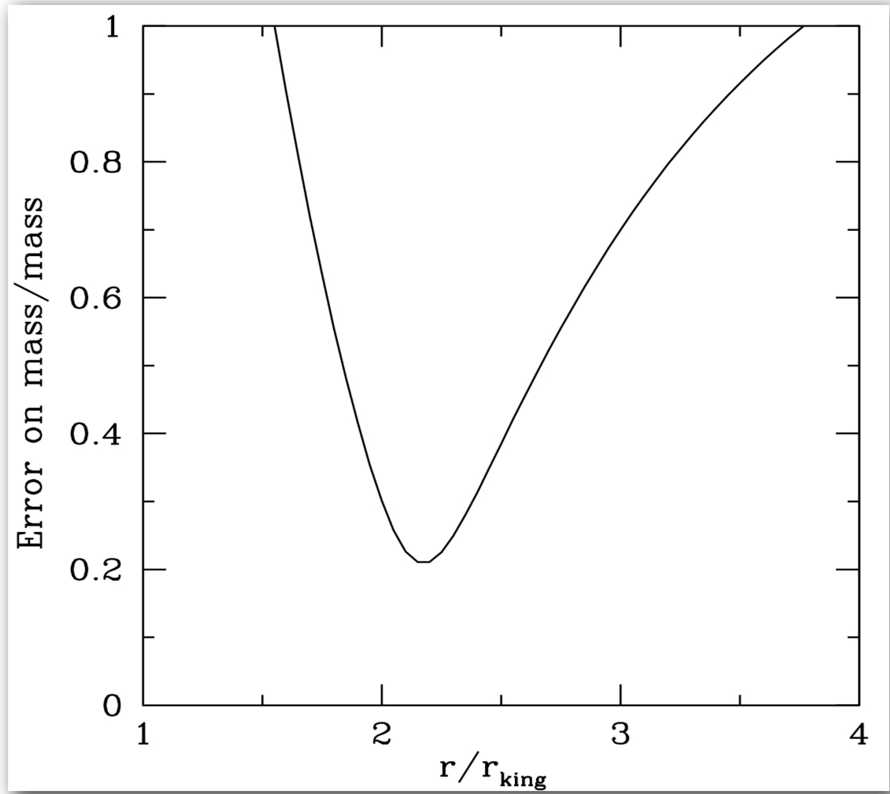

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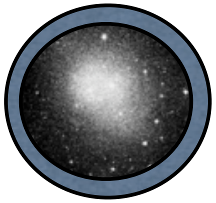
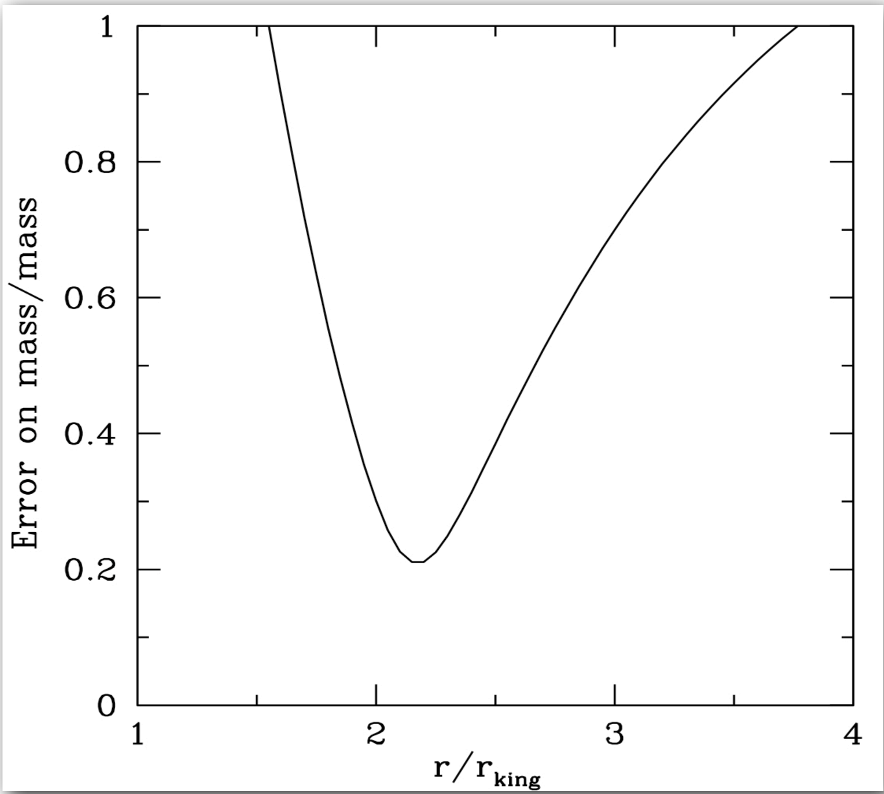
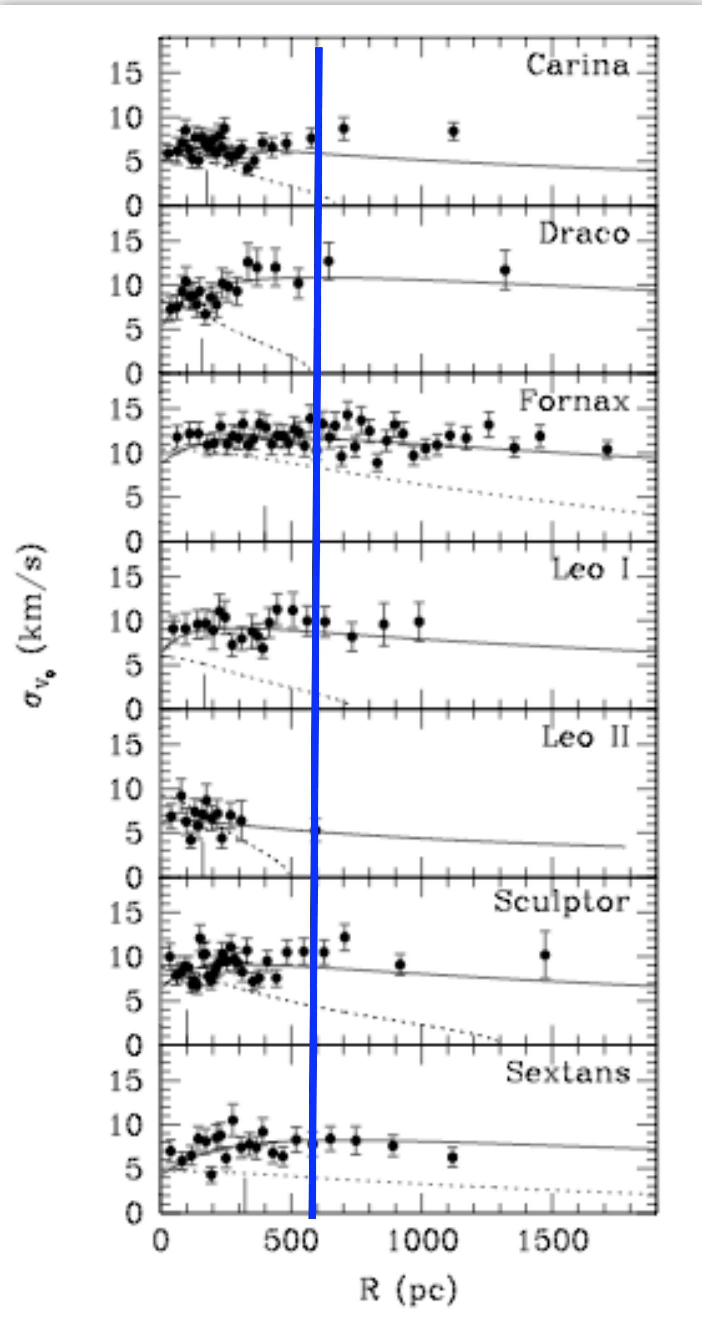




Strigari, JSB, Kaplinghat 07

Kinematics: Classical MW Satellites

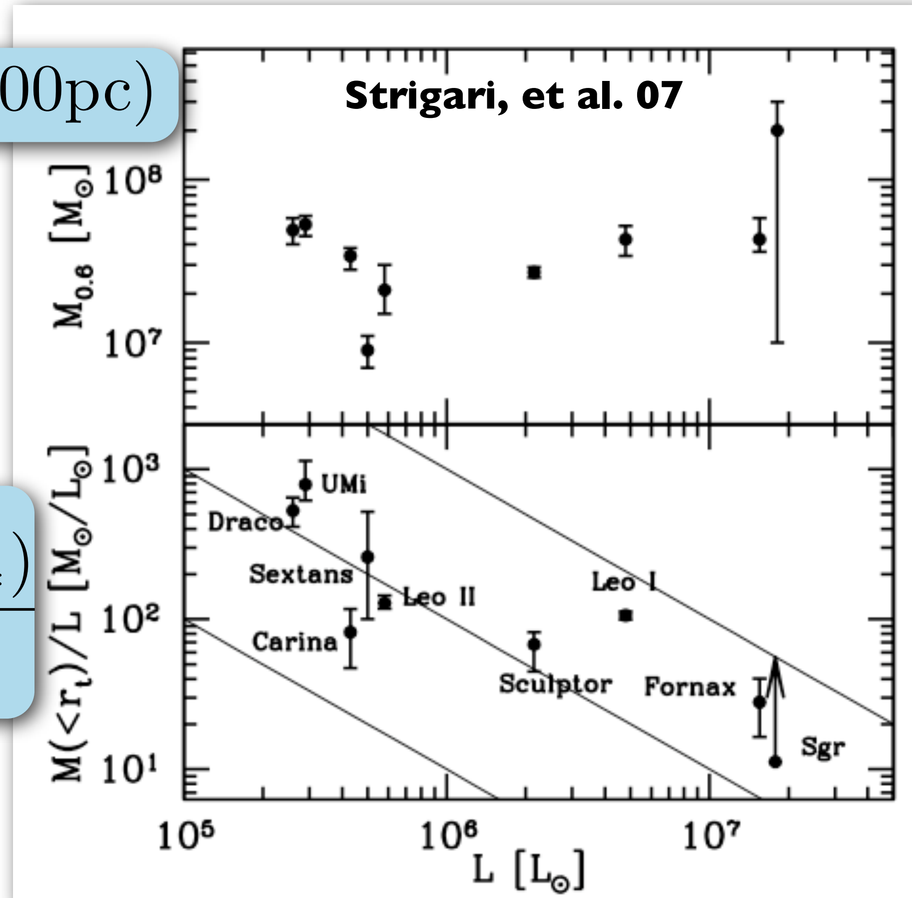


Walker et al. 07

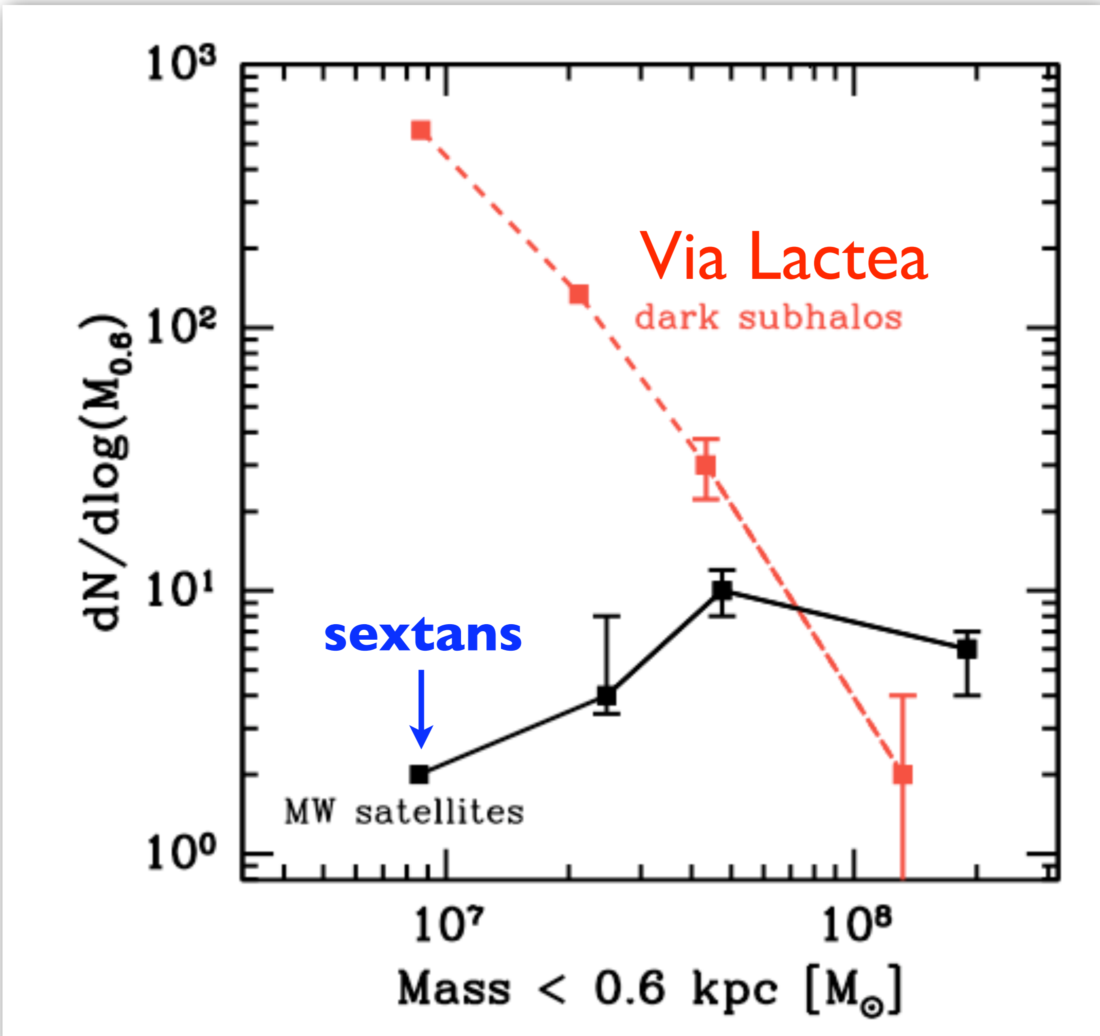
600 pc probed for all of them

$M(< 600\mathrm{pc})$

$$\frac{M(< r_*)}{L}$$

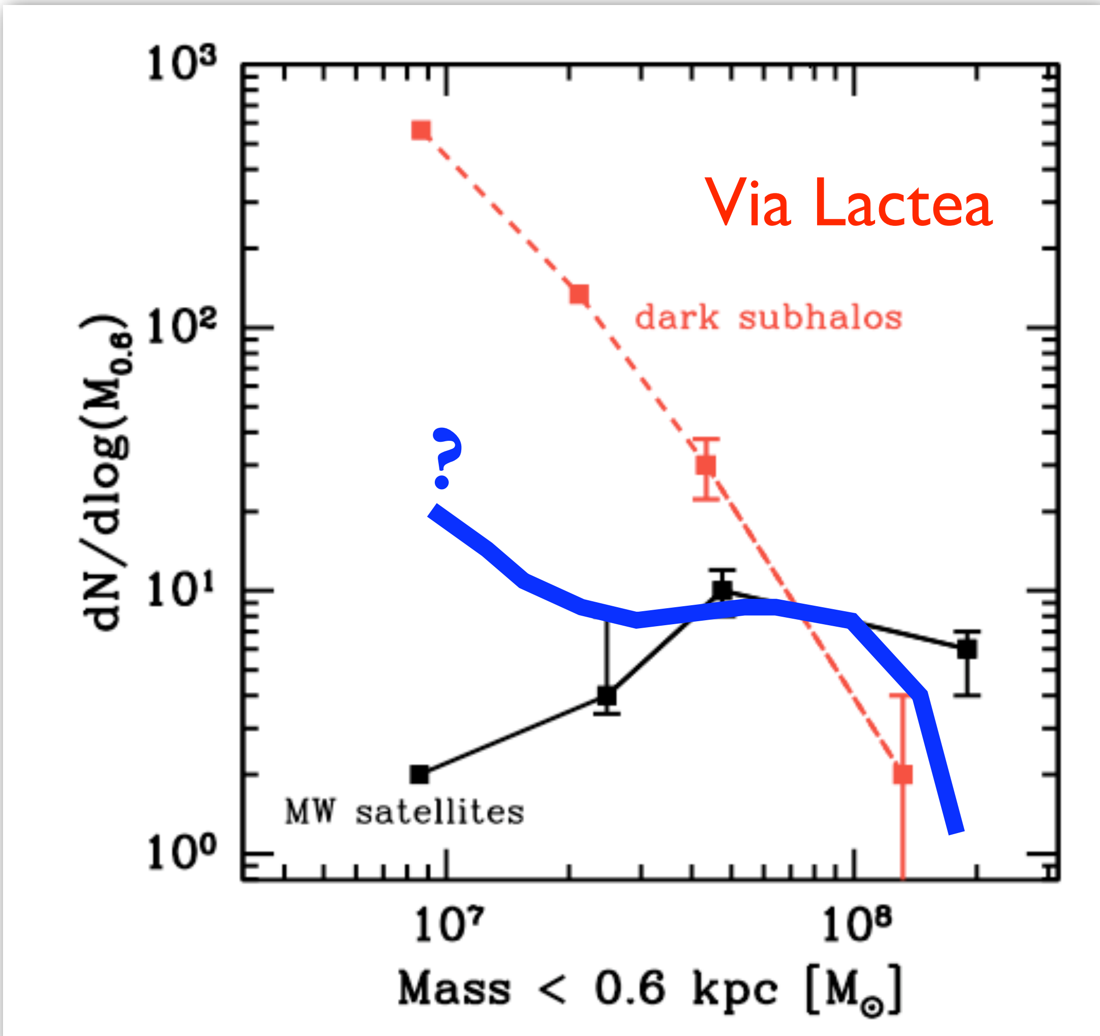


Classical Milky Way Satellites



Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau 07

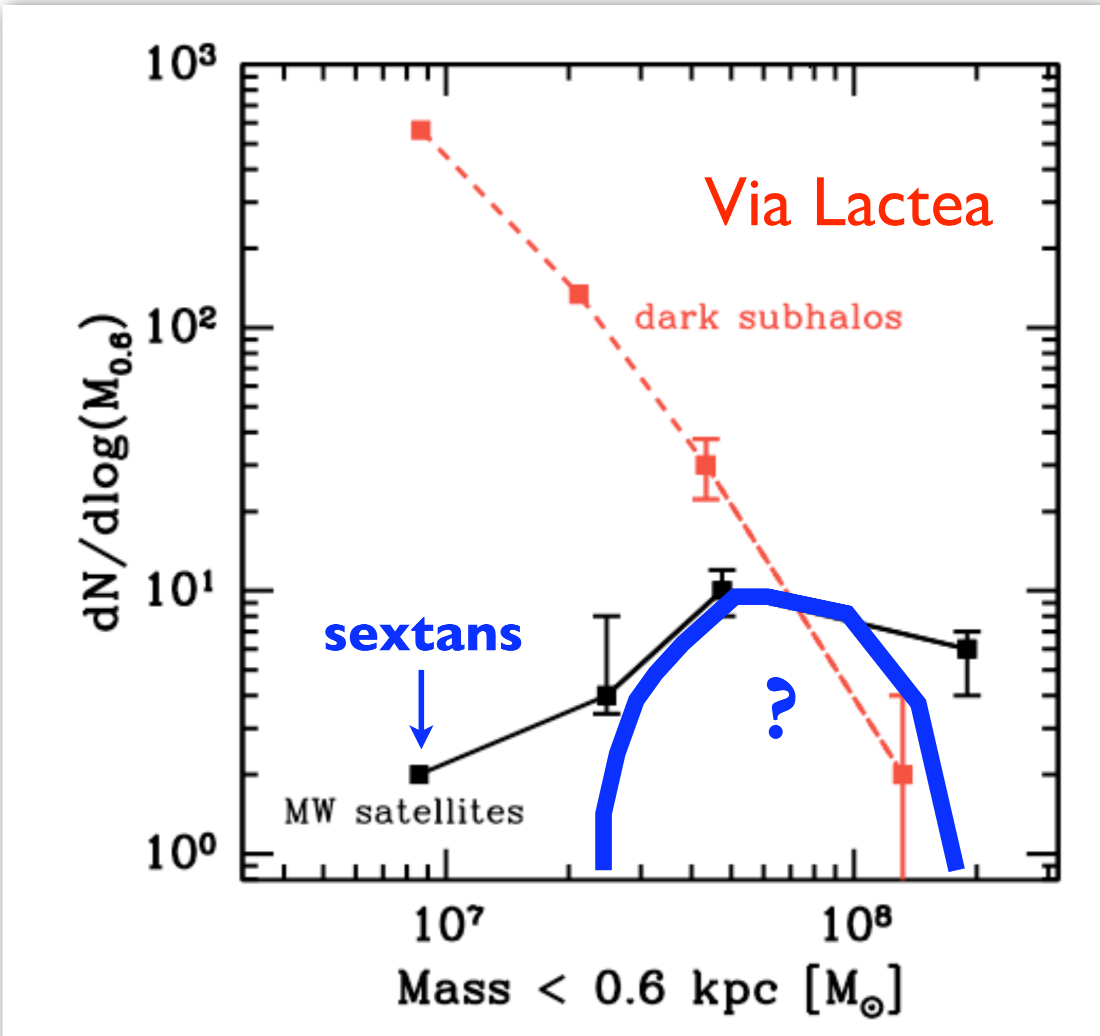
New Discoveries?



Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau 07

https://webfiles.uci.edu/bullock/Public/Canary2008/

New Discoveries?



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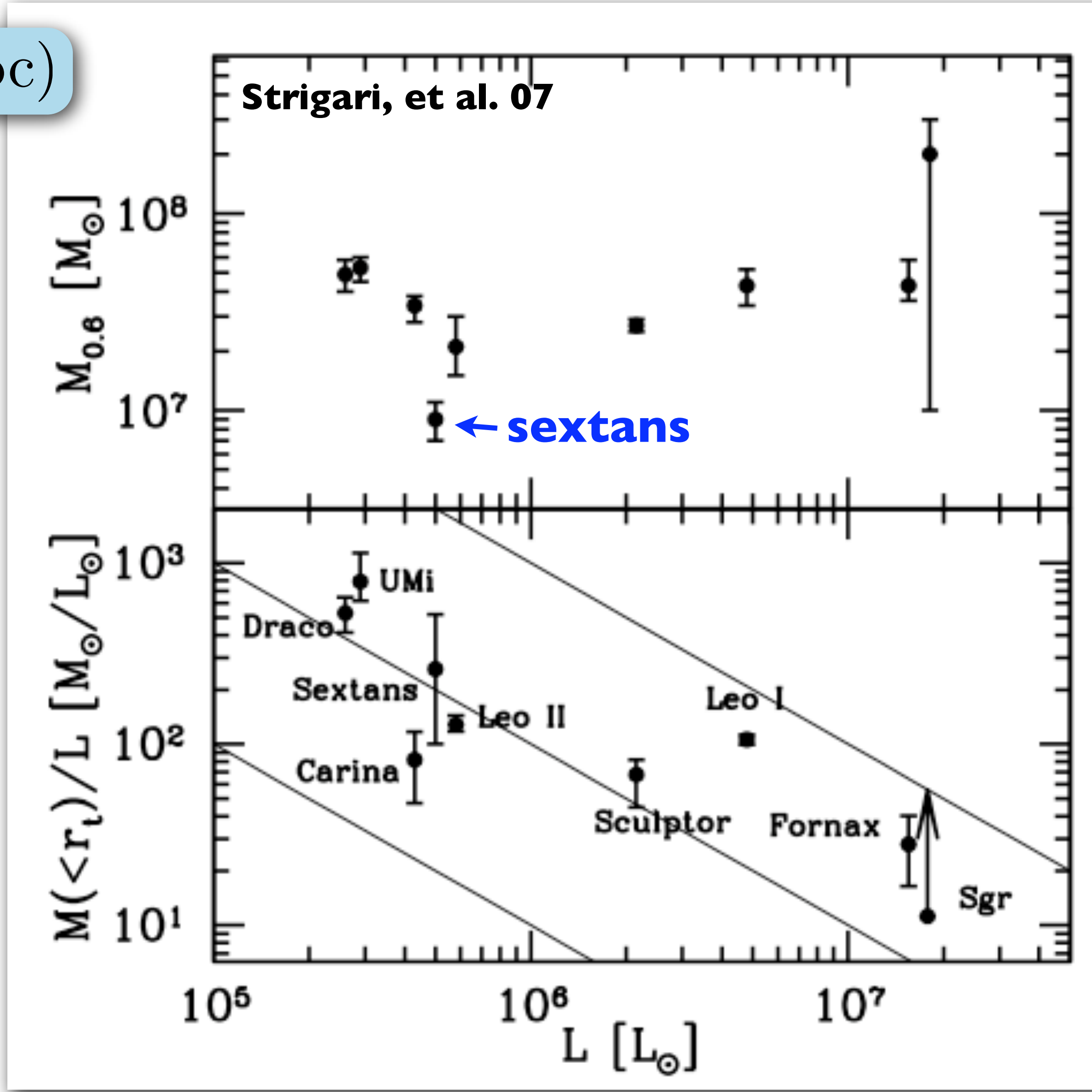
Why are these halos so dark?

$M(< 600\text{pc})$

$\frac{M(< r_*)}{L}$



Is dwarf galaxy formation suppressed by reionization?

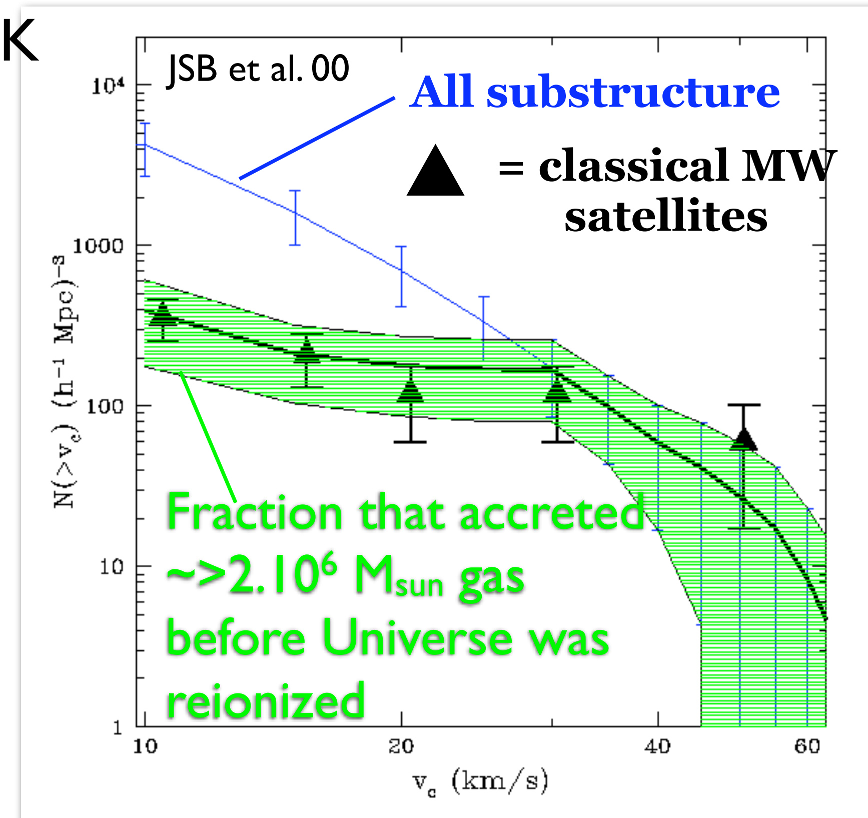
- Universe became reionized at $6 < z_{re} < 15$
- Ionizing background suppresses gas accretion in low-mass systems: V<~ 30 km/s, or $T \sim 10^4$ K

Efstathiou (92); Thoul & Weinberg; Gnedin (01); ...

↳ **Dwarf halos retain the gas they had before z_{re}.**

JSB, Kravtsov, & Weinberg (00)

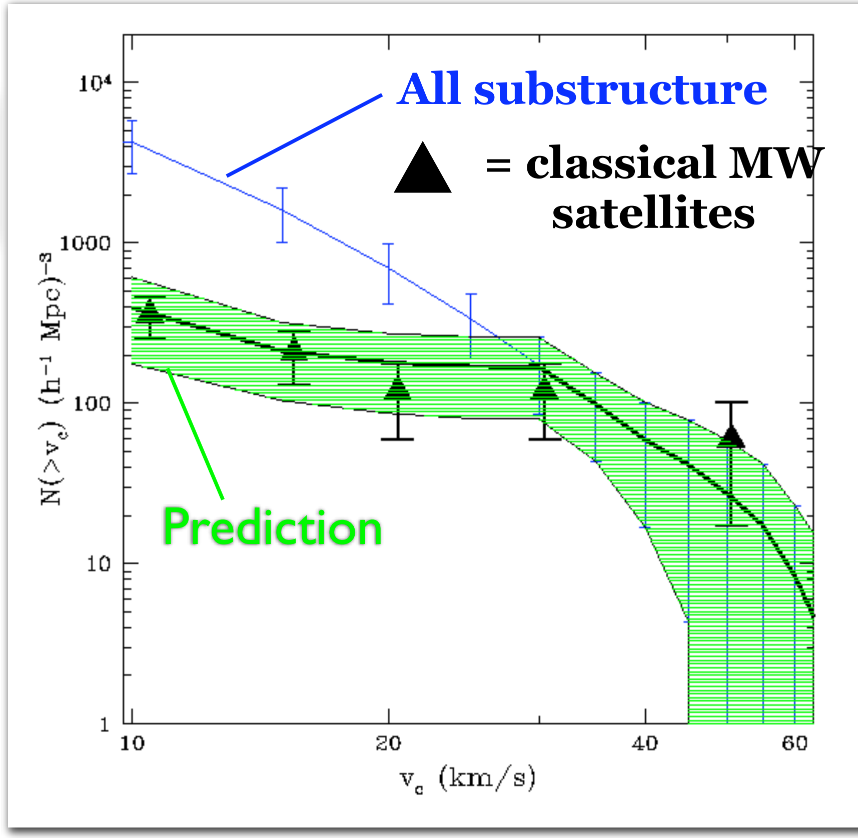
Somerville (01)
Benson et al. (01) Gnedin (01); ...
Moore et al. (06)



A forgotten prediction...

JSB, Kravtsov, & Weinberg (2000)

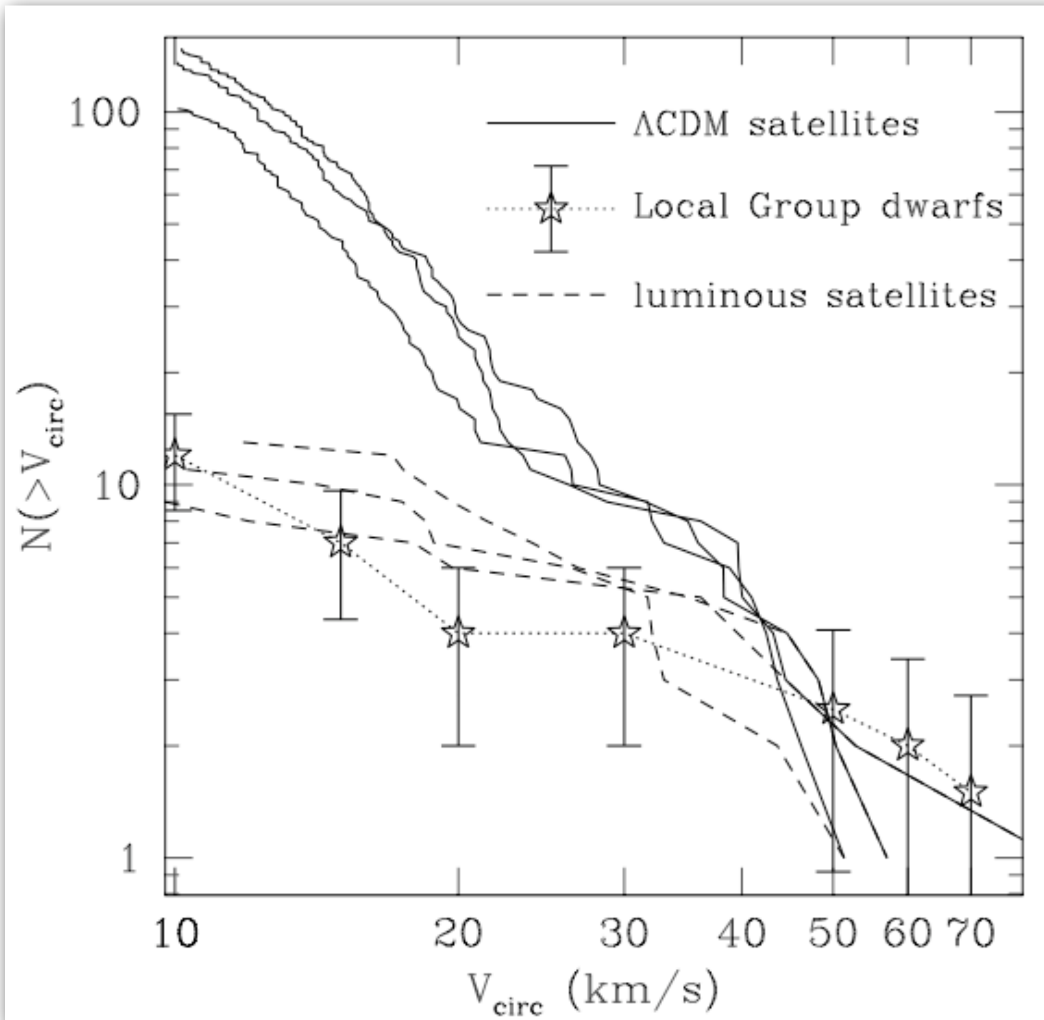
Dwarf halos retain the gas they had before z_{re}?



"If we assume that the model presented in §2.2 applies in all cases, then the observed dwarf satellites should be just the low M/L tail of the underlying population.... Reducing f (increasing M/L) by a factor of 7 raises the predicted number of satellites by a factor of 10... **Large area, deep imaging surveys may soon be able to reveal faint dwarf satellites that lie below current detection limits."**

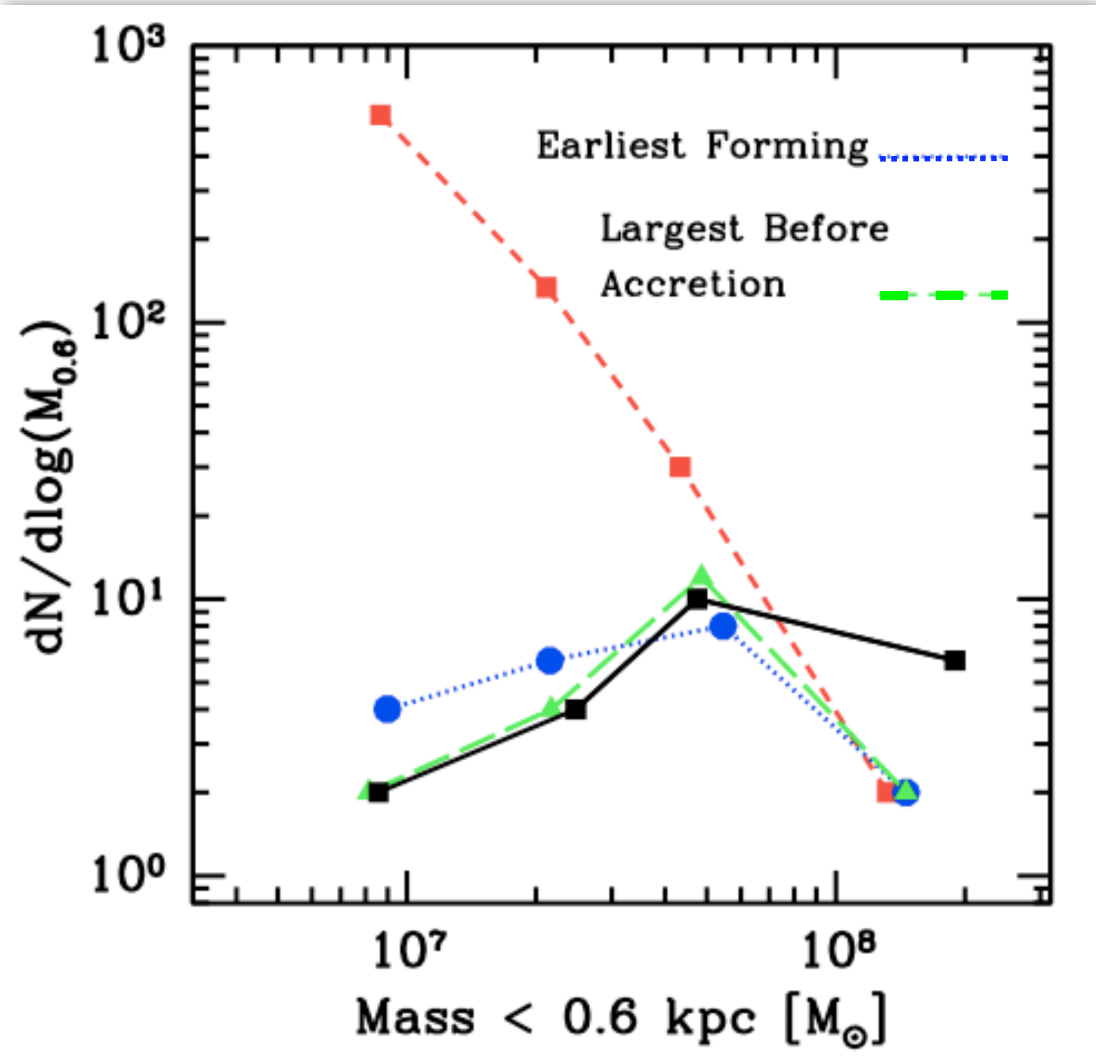
Dwarf suppression may set in at larger DM masses, but masses get whittled down after accretion

Kravtsov et al. 2004



- Galaxy formation inefficient in small halos because gas is puffy (shallow potential well depths)
- Some subhalos can have small V_{max} now even though it started of fairly large

Rough test of these ideas using via Lactea N-body simulation + robust mass measurements



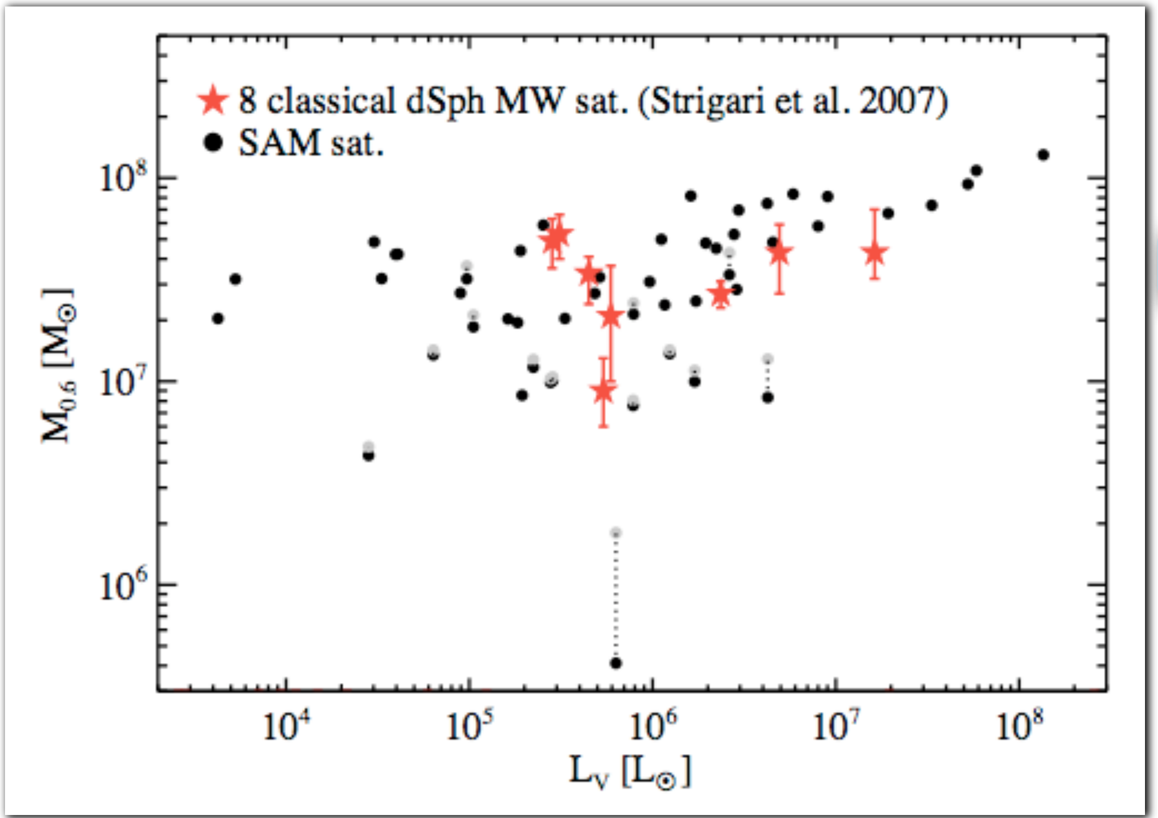
V_{max}>16 km/s @ z=10

V_{max}>37 km/s

Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau 07

Yang-Shian Li et al. 08

Hybrid sem-analytic N-body model



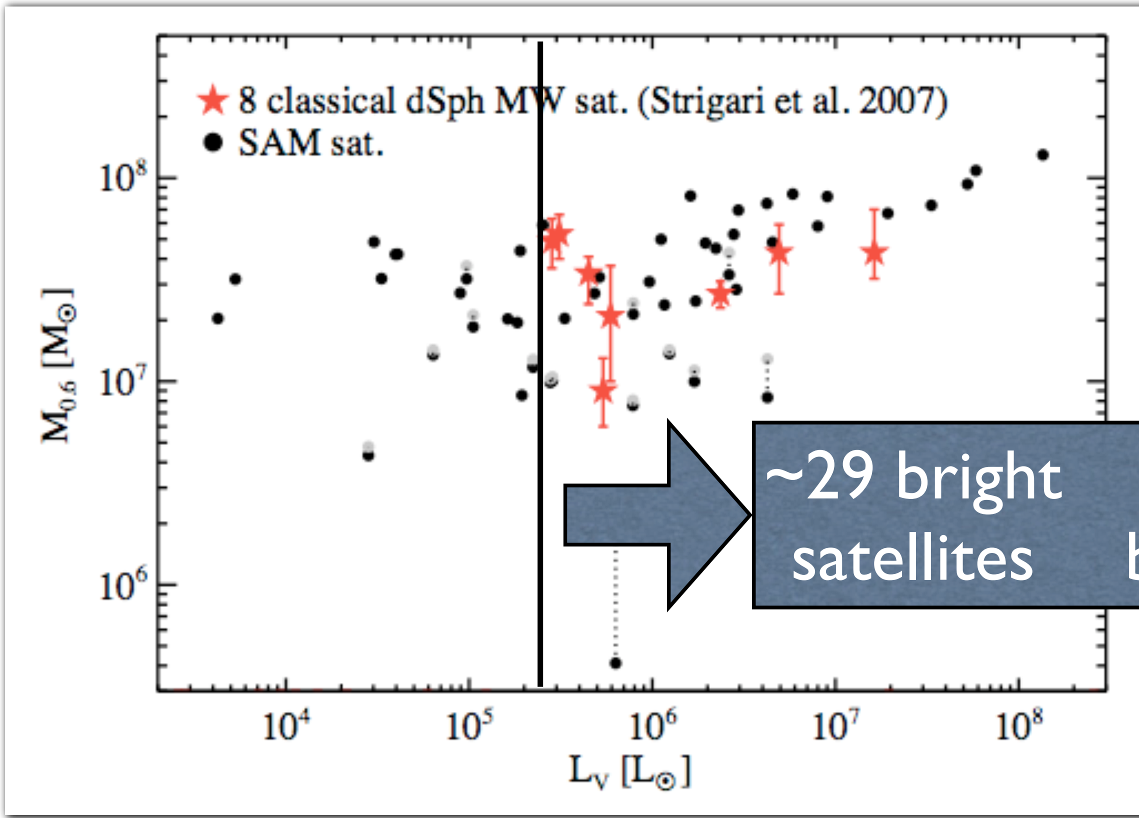
No cooling below 10^4K

+ reionization supression

Masses look good!

Yang-Shian Li et al. 08

Hybrid semi-analytic N-body model



No cooling below 10^4K

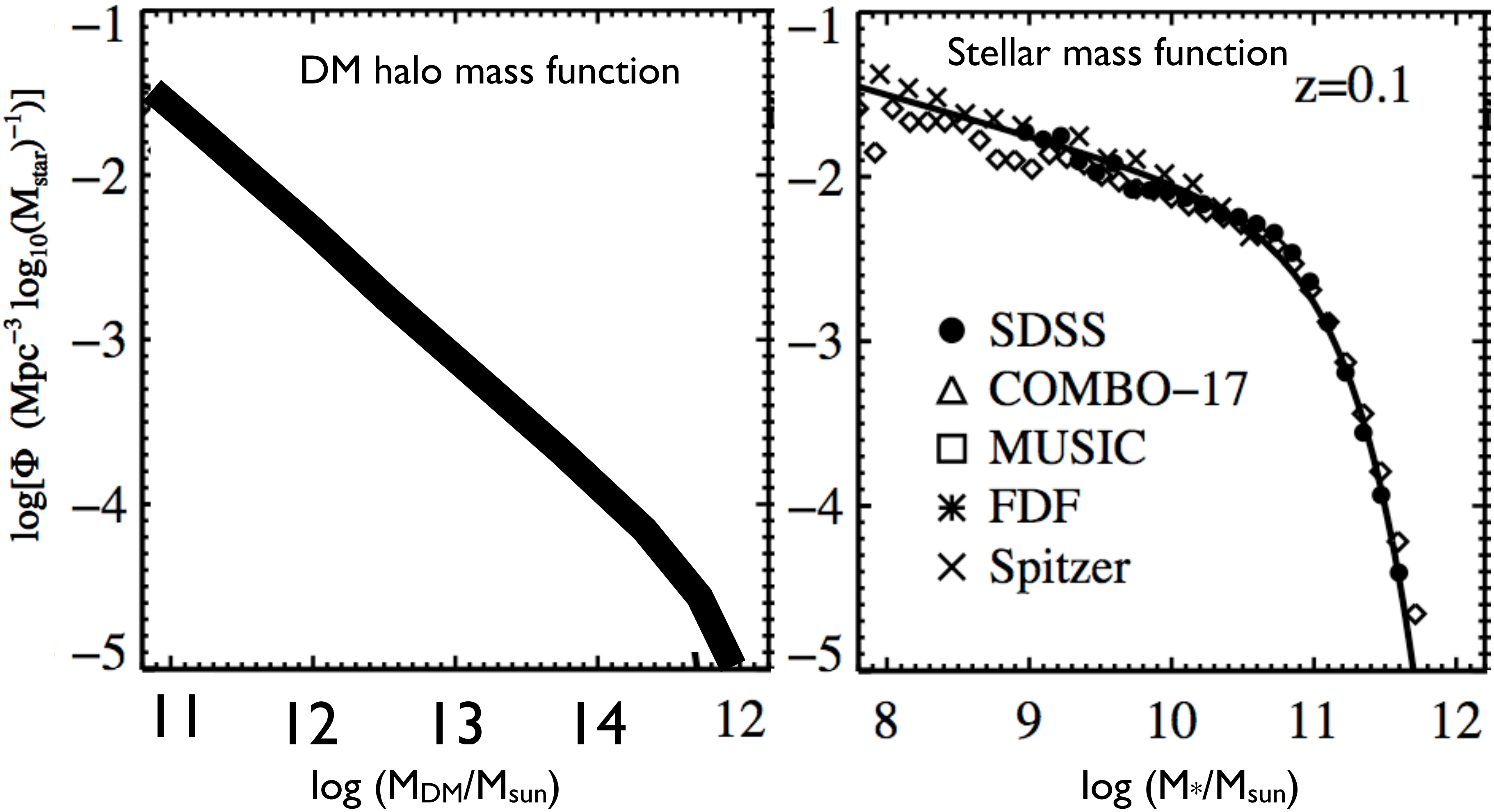
+ reionization supression

Masses look good!

~29 bright satellites

Too many for MW but maybe not for M31?

The need for high M/L halos should not surprise us...



compilation by Conroy & Wechsler 08

https://webfiles.uci.edu/bullock/Public/Canary2008/

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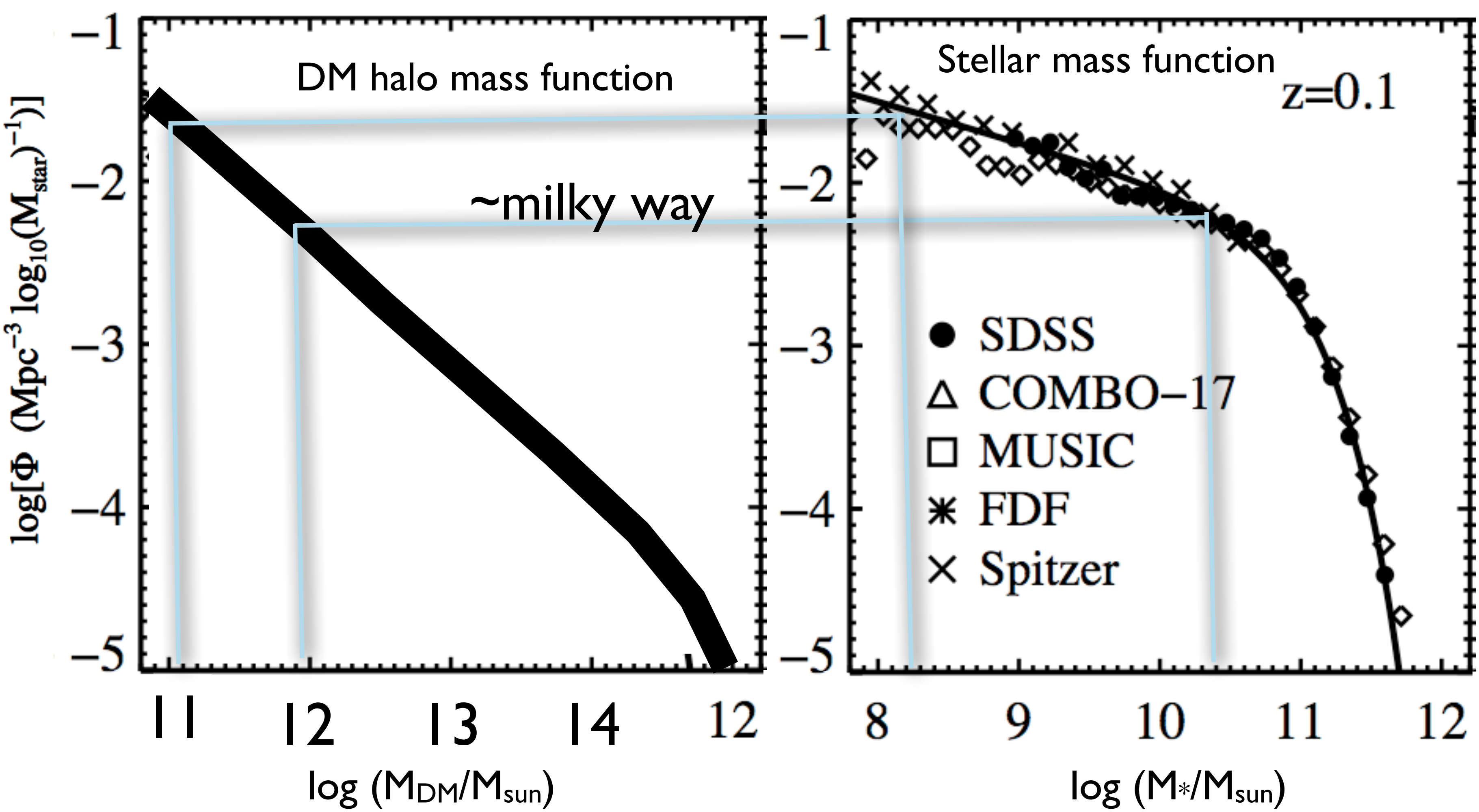


compilation by Conroy & Wechsler 08

https://webfiles.uci.edu/bullock/Public/Canary2008/

Strategy:

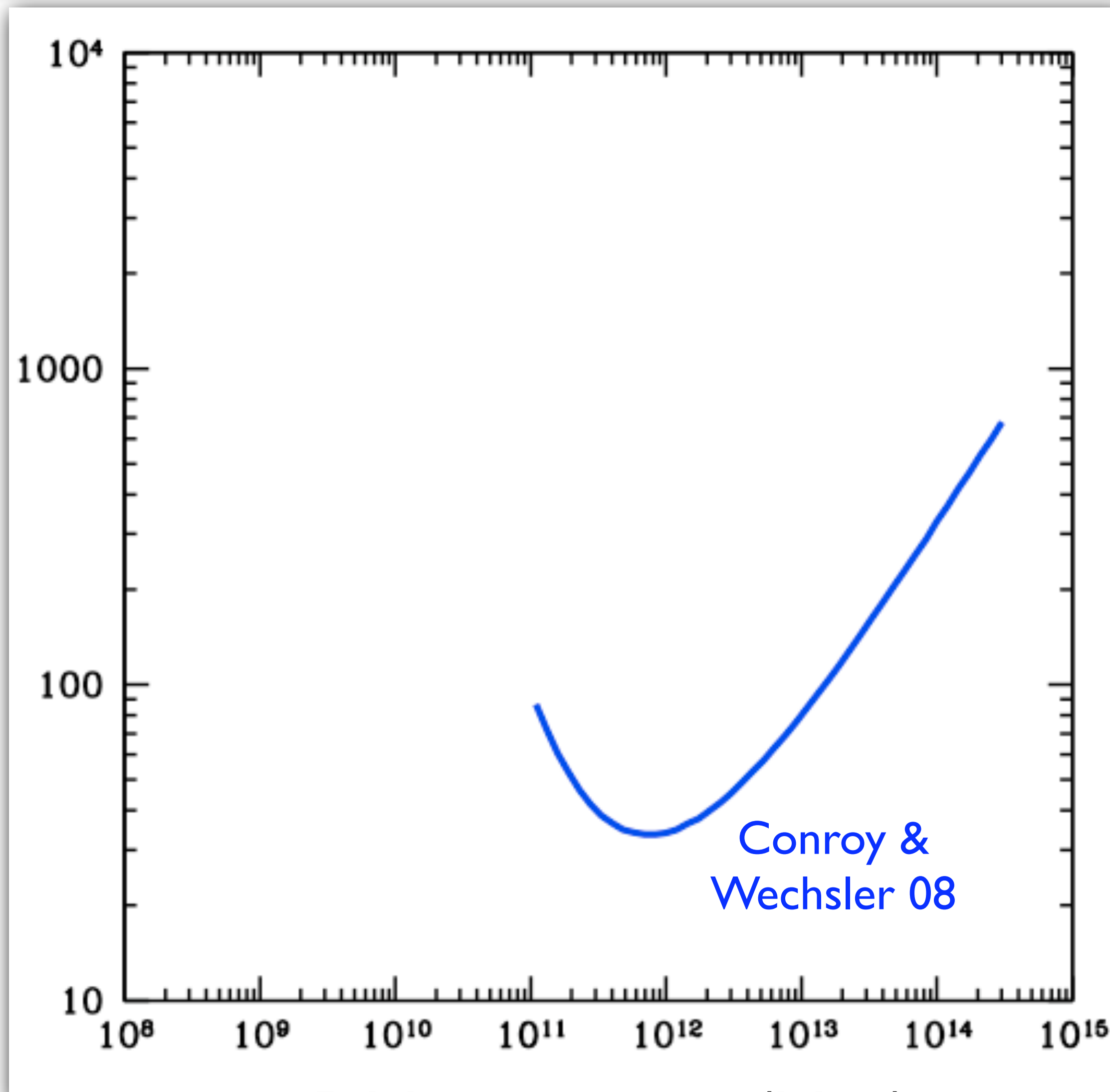
1. Rather than trying to reproduce the universe from first principles we assign stellar mass to halos with the values required in order to reproduce the observed stellar mass function.

2. Follow the mergers and keep track of total amount and what happens to those accreted stars.

https://webfiles.uci.edu/bullock/Public/Canary2008/

Number density matching -> Efficiency of Galaxy Formation

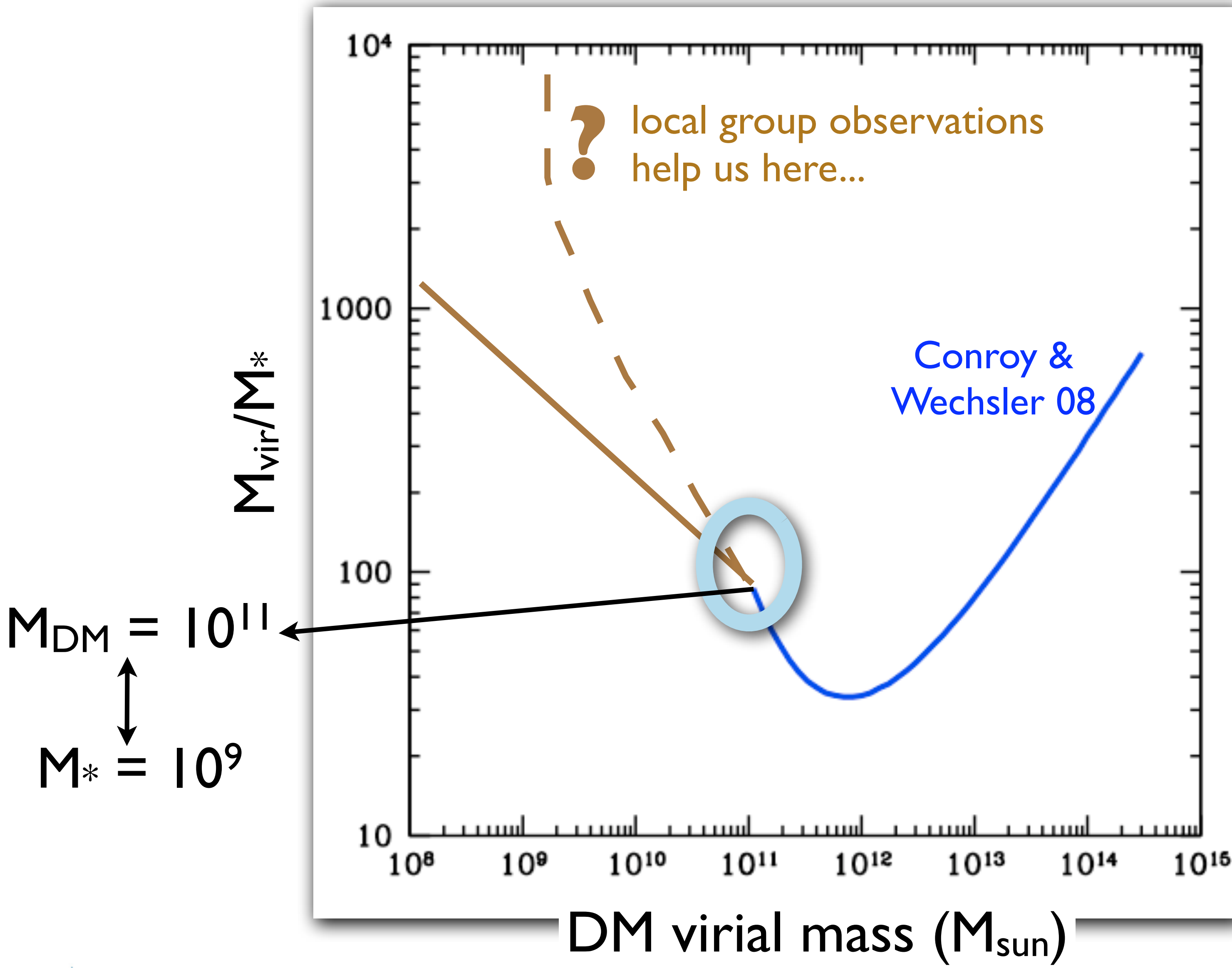
M_{vir}/M_{*}



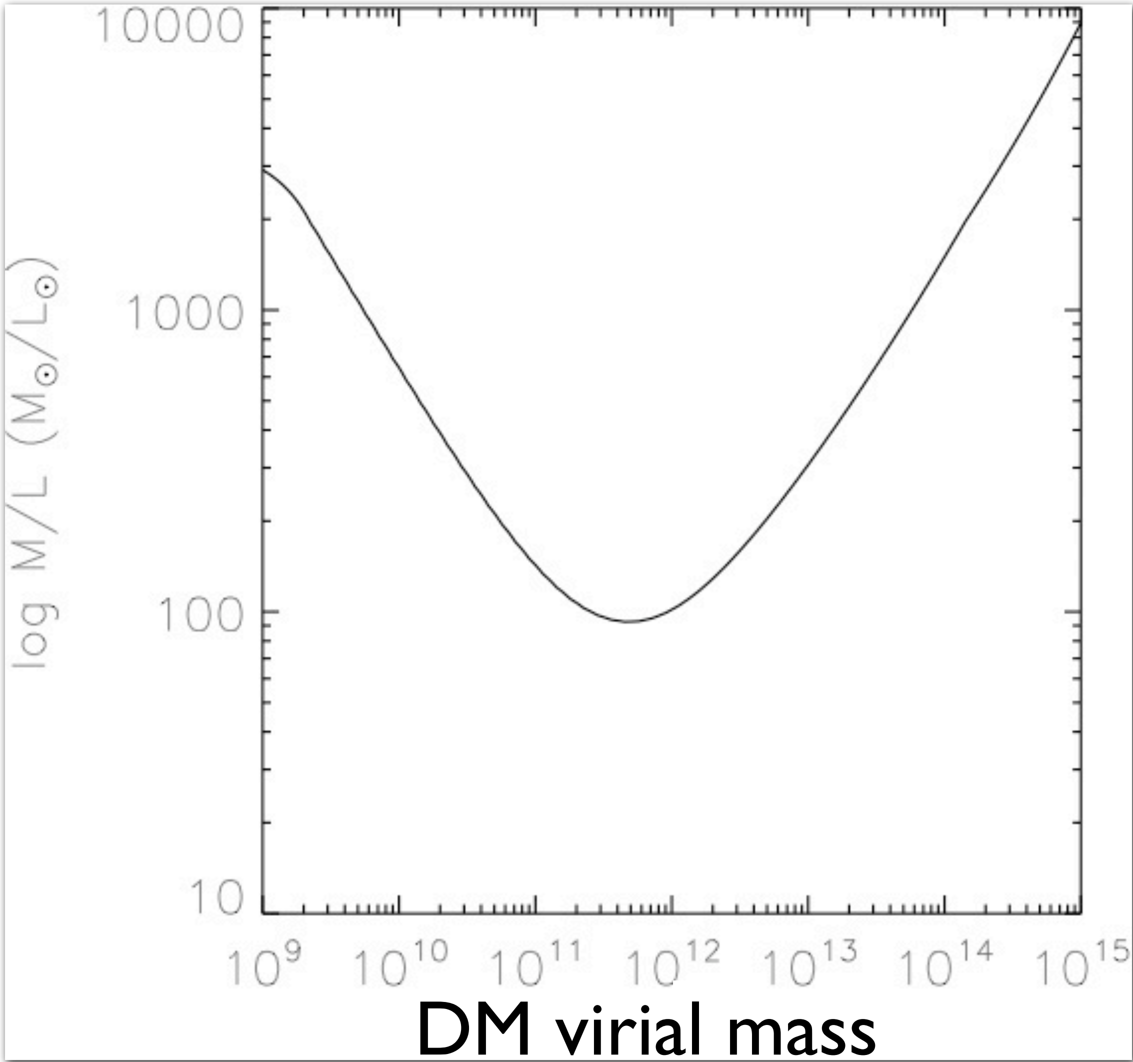
DM virial mass (M_{sun})

see also
van den Bosh et al. 03
Yang et al. 03
Kravtsov et al. 04
...
Purcell et al. 07

Efficiency of Galaxy Formation?



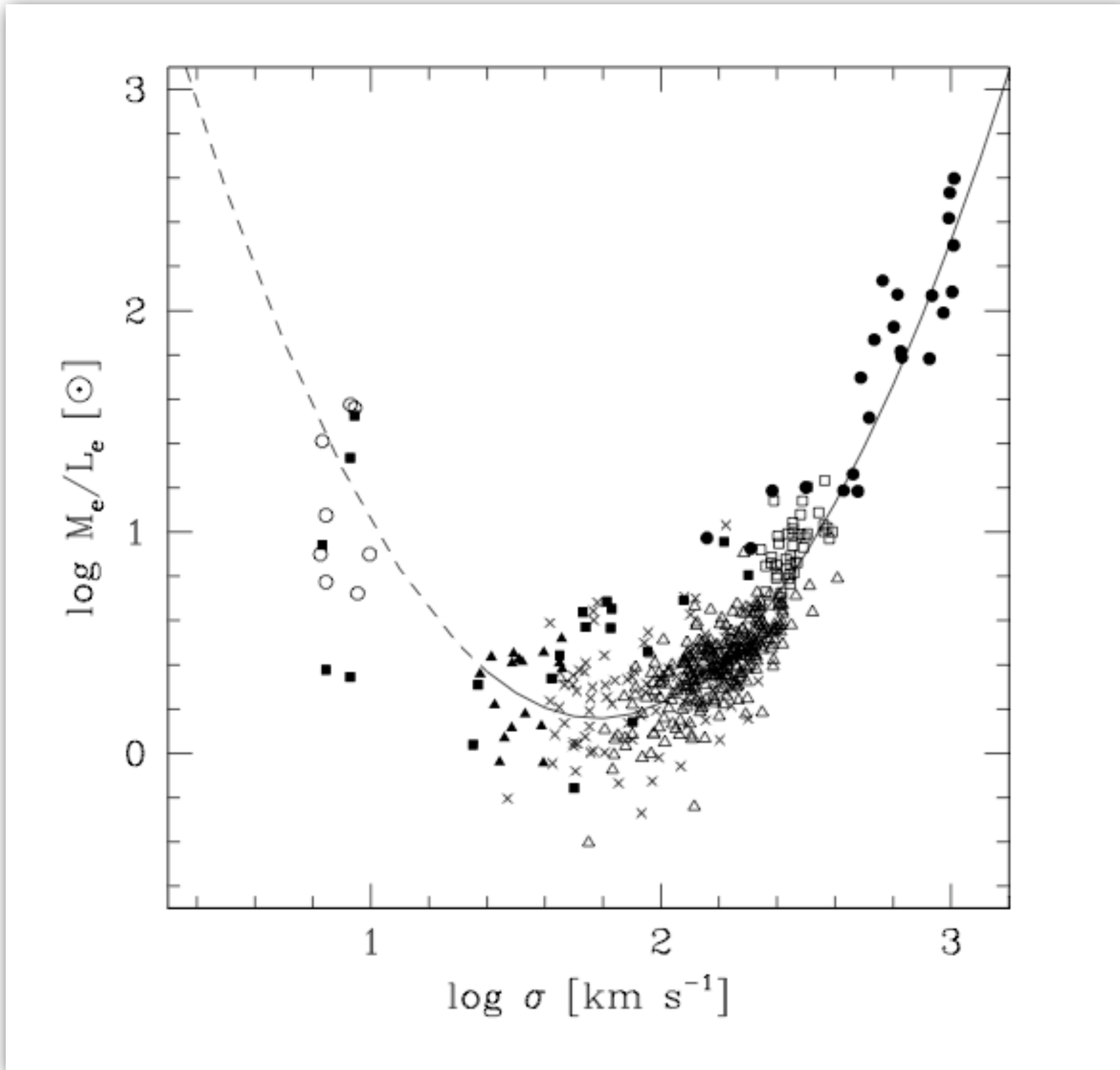
‘Conditional Luminosity Function’
Mass to (Central Galaxy) Light Ratios



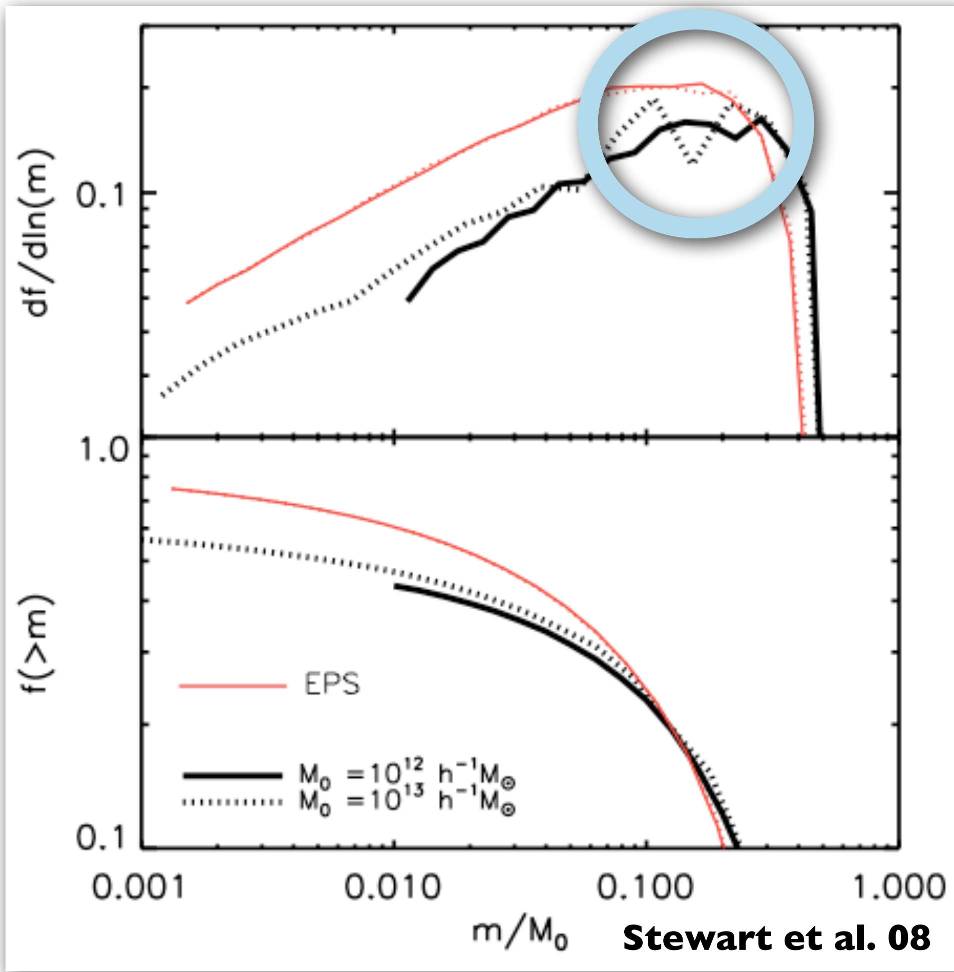
Yang, van den Bosch et al. 2003

https://webfiles.uci.edu/bullock/Public/Canary2008/

Dynamical Mass Estimates in Spheroids: Zaritsky, Gonzalez, & Zabludoff 06



How is mass accreted?



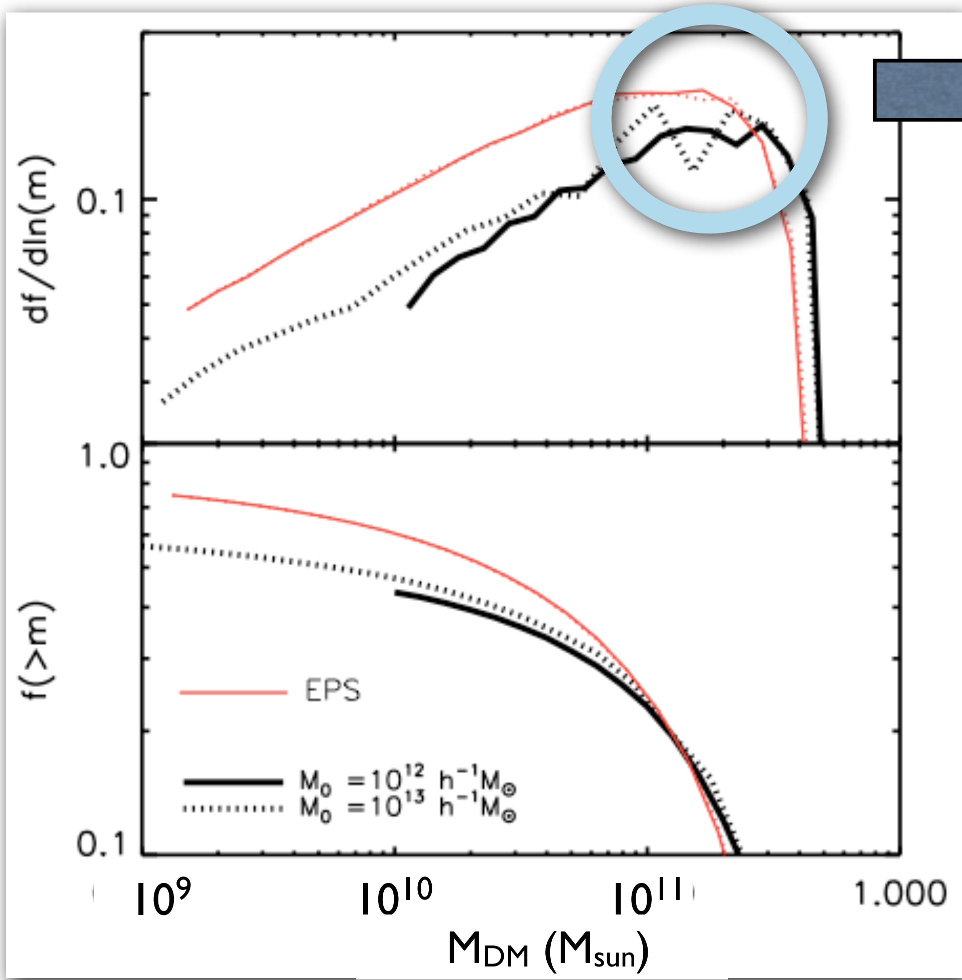
Mergers that are ~1/10 of the final halo mass dominate its mass growth.

For typical $10^{12}\ M_{sun}$ halo:

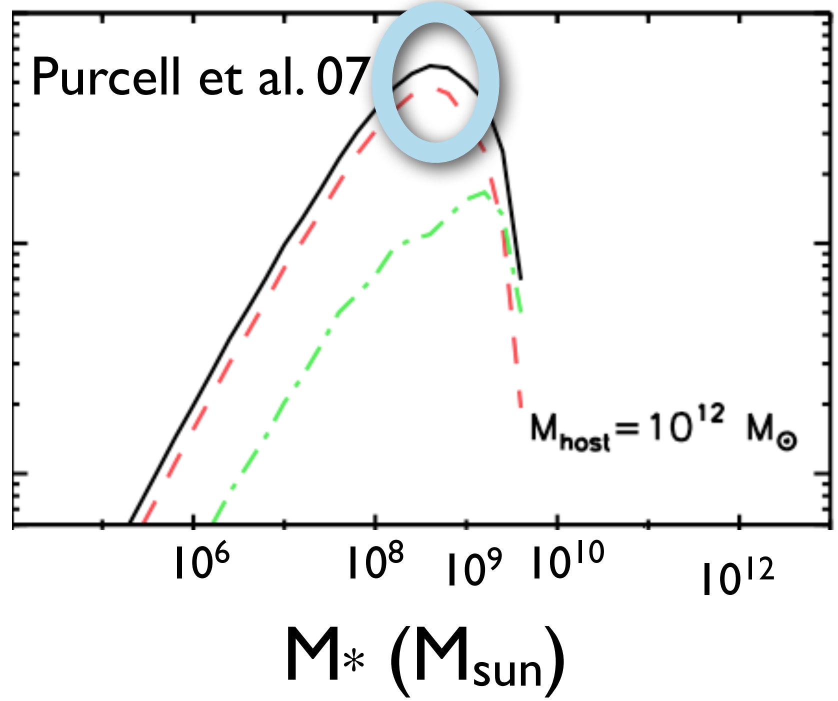
- $M \sim 10^{11}$ mergers dominate mass buildup.

Lacey & Cole 93; Zentner & JSB 03; Purcell et al. 07

How is **stellar** mass accreted?



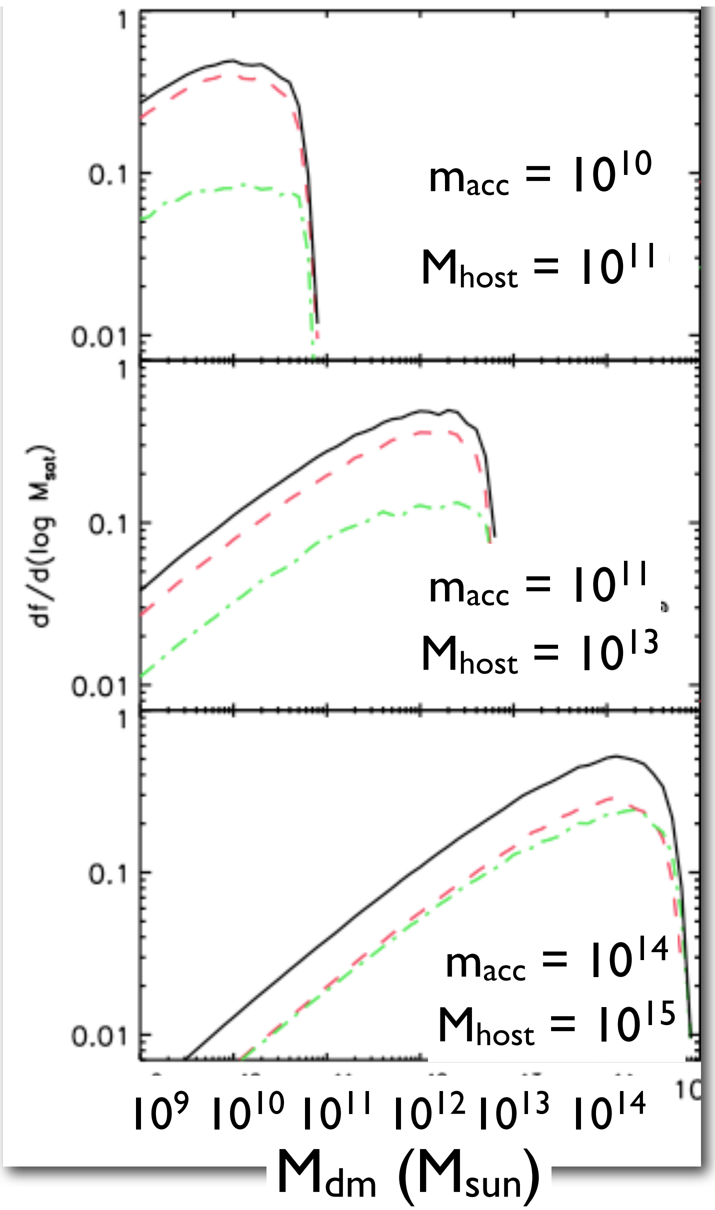
dominated by LMC's



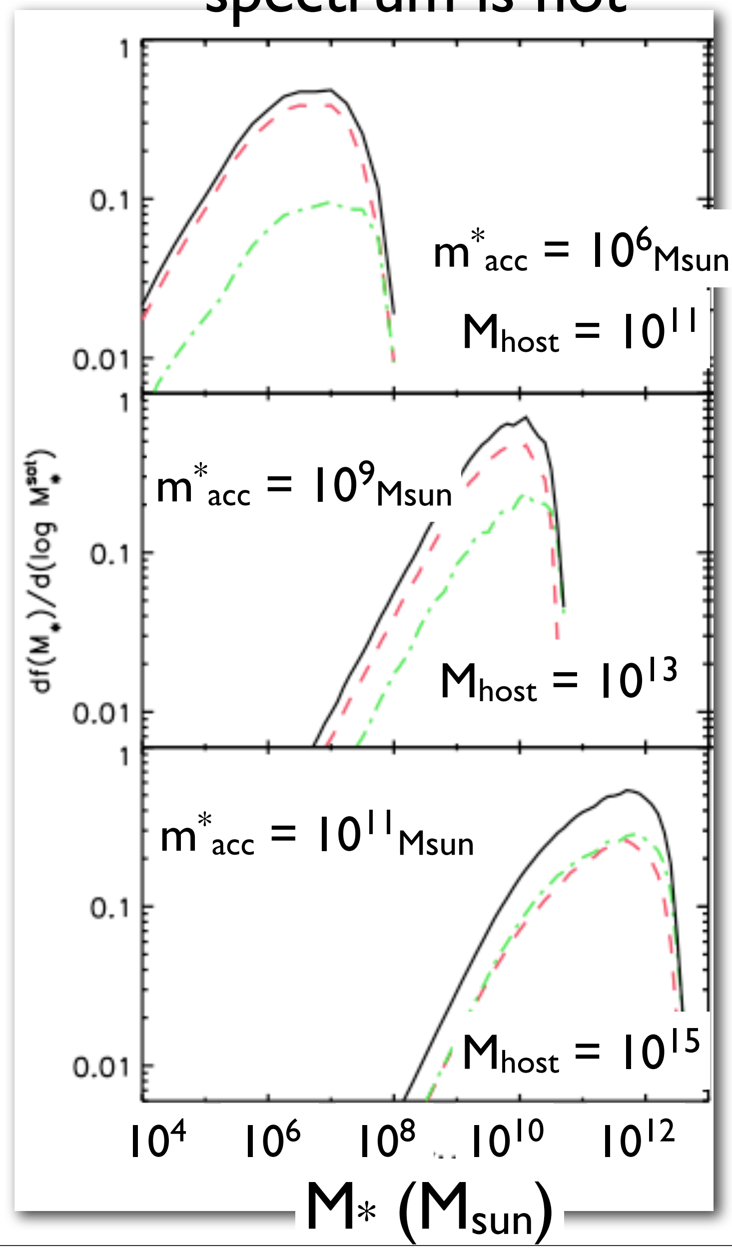
Stewart et al. 08

Lacey & Cole 93; Zentner & JSB 03; Purcell et al. 07

accreted DM halo mass spectrum: self similar



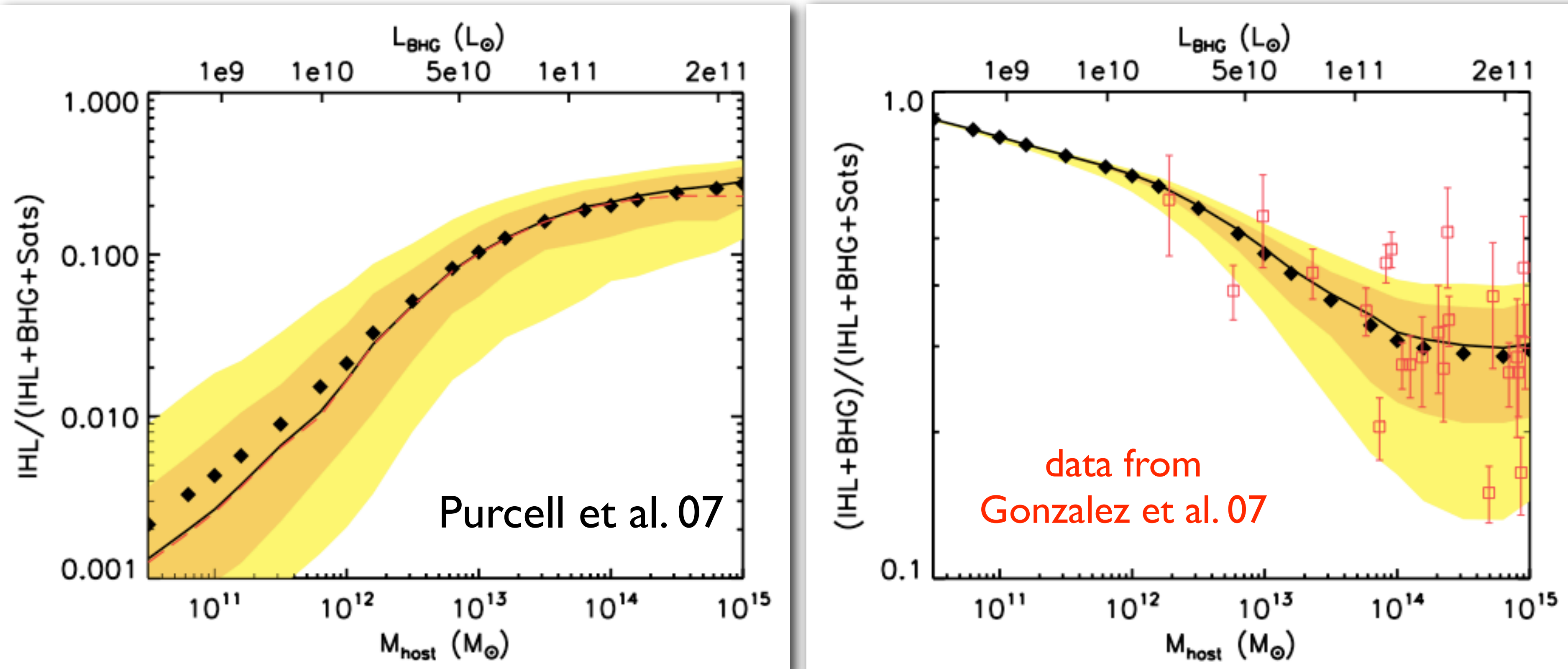
accreted galaxy stellar-mass spectrum is not



Accreted stellar mass fraction changes with DM halo mass even though DM accretion spectrum is ~ self-similar

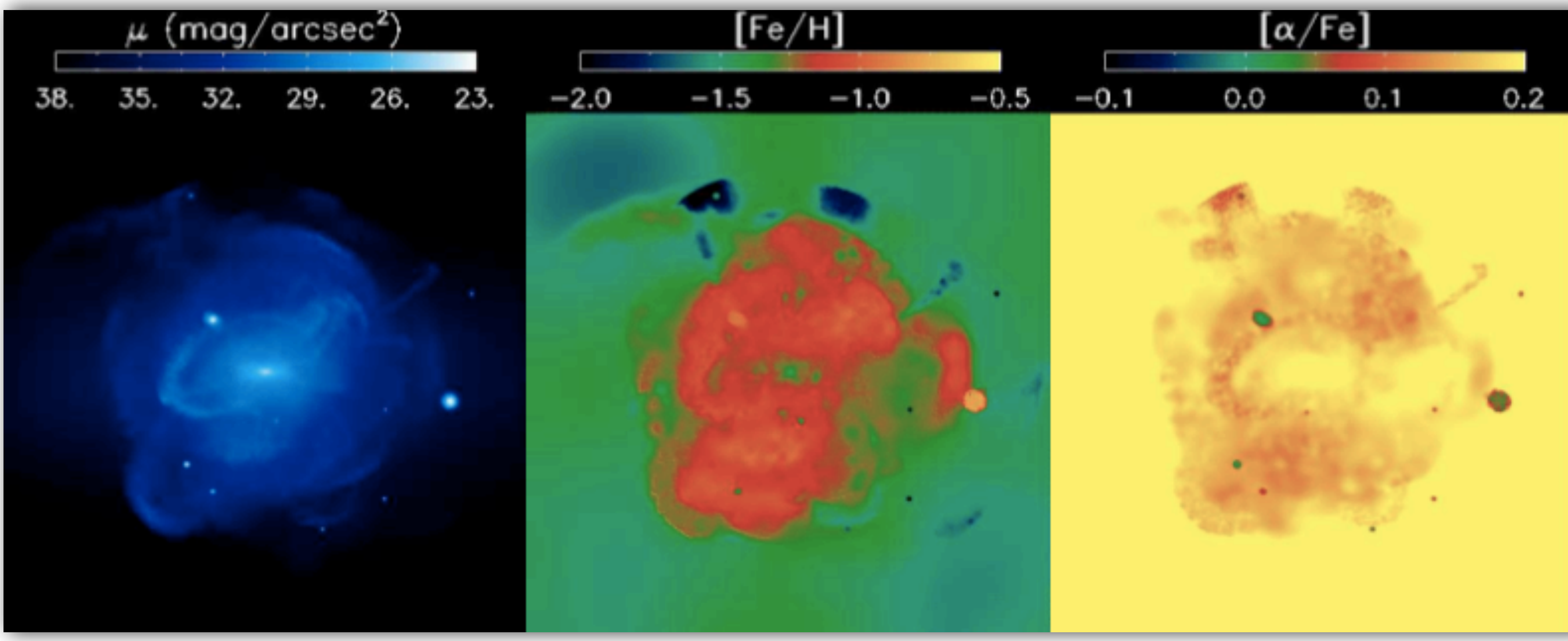
small galaxies: smaller relative fraction of diffuse light (stellar halos)

clusters/groups: lots of diffuse light (Intra-cluster light)



This kind of scenario produces fairly realistic (outer) stellar halos...

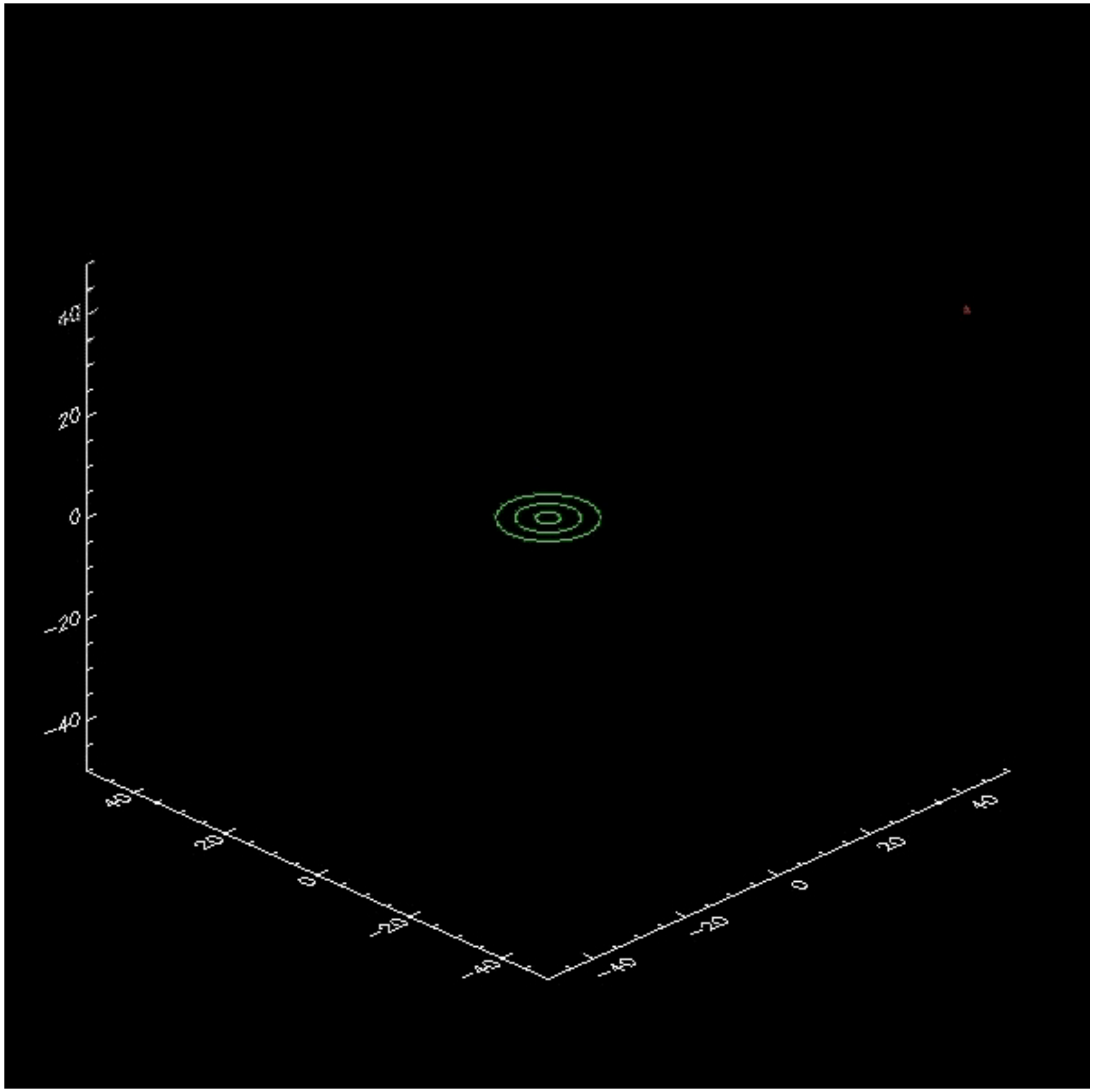
$M \sim 10^9 \, M_{sun}$



JSB & Kathryn Johnston 05 + Robertson et al. 06 + Font et al. 07 + Sanjib Sharma visualization

+ Helmi et al. 2007

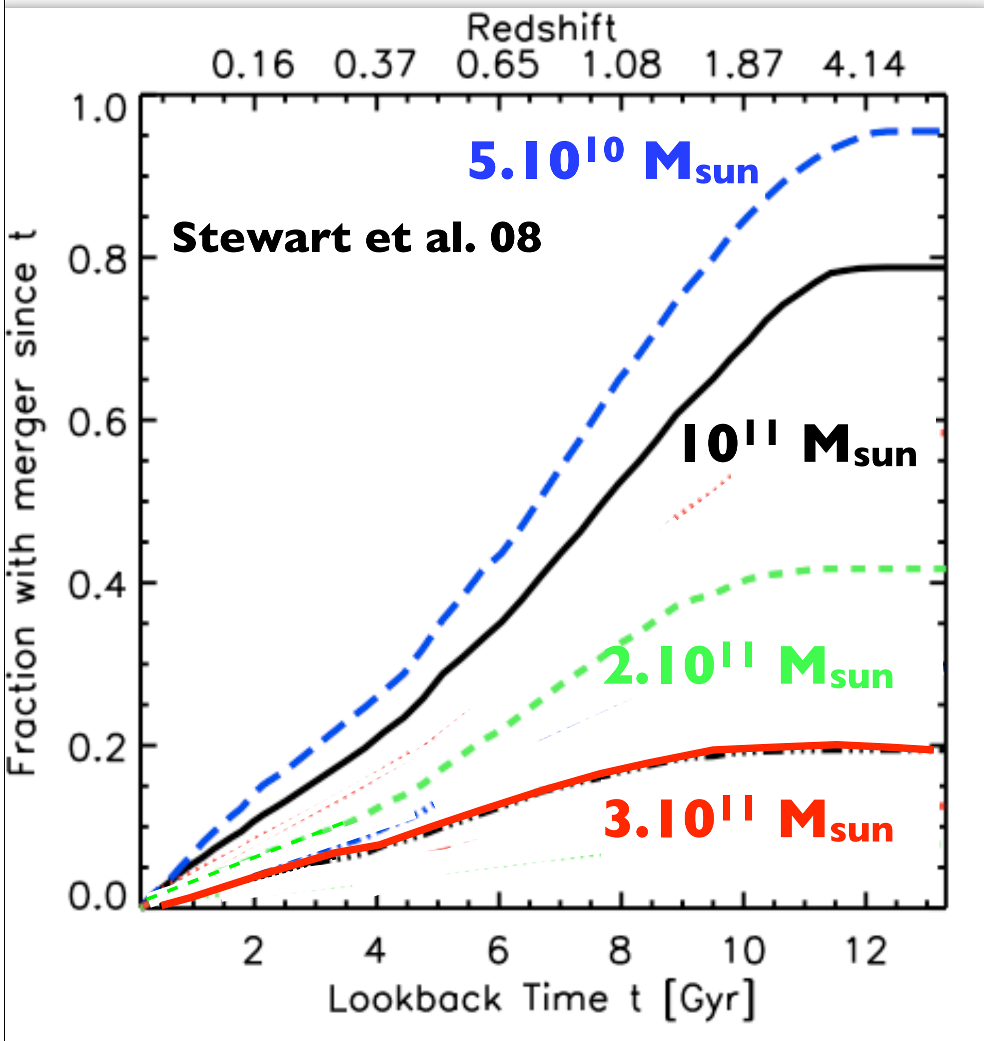
Note: Simulations that do not get the faint luminosity function right are doomed to failure
-- they will always over-predict the mass fraction accreted in stars (halos & spheroids too massive)
-- it's hard to build a high angular-momentum disk out of accreted stars



JSB & Kathryn Johnston 05

What happens to the disk during all of this?

10^{12} M_{sun} Halo Merger histories



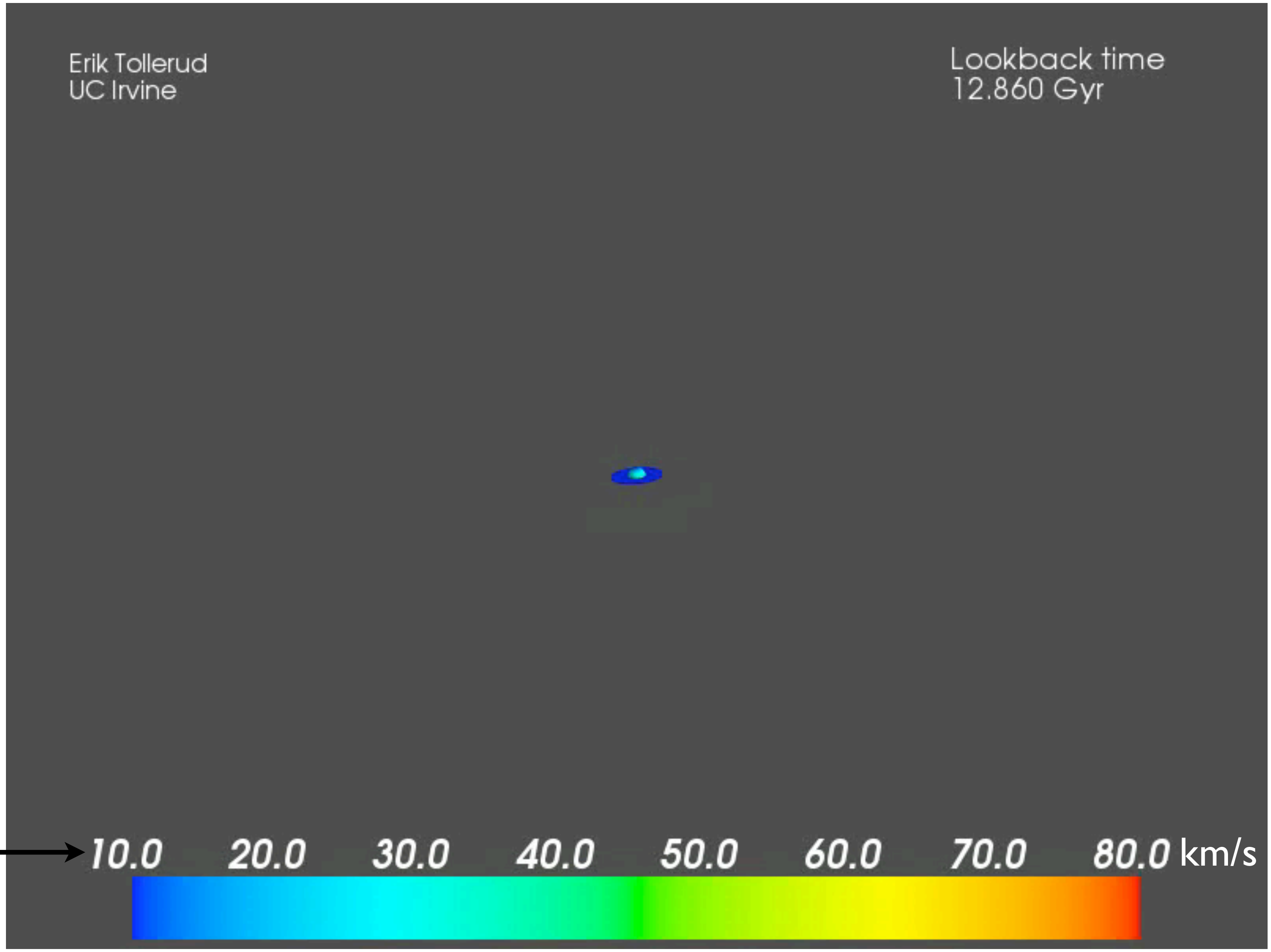
In Last 10 Gyr:

- ~95% have 5.10^{10} M_{sun} merger
- ~70% have 10^{11} M_{sun} merger
- ~40% have 2.10^{11} M_{sun} merger

m/M > 0.3 events are rare.

The Via Lactea Simulation Simplified.
Dark matter halos + 'toy' disk galaxy (to scale)

Erik Tollerud

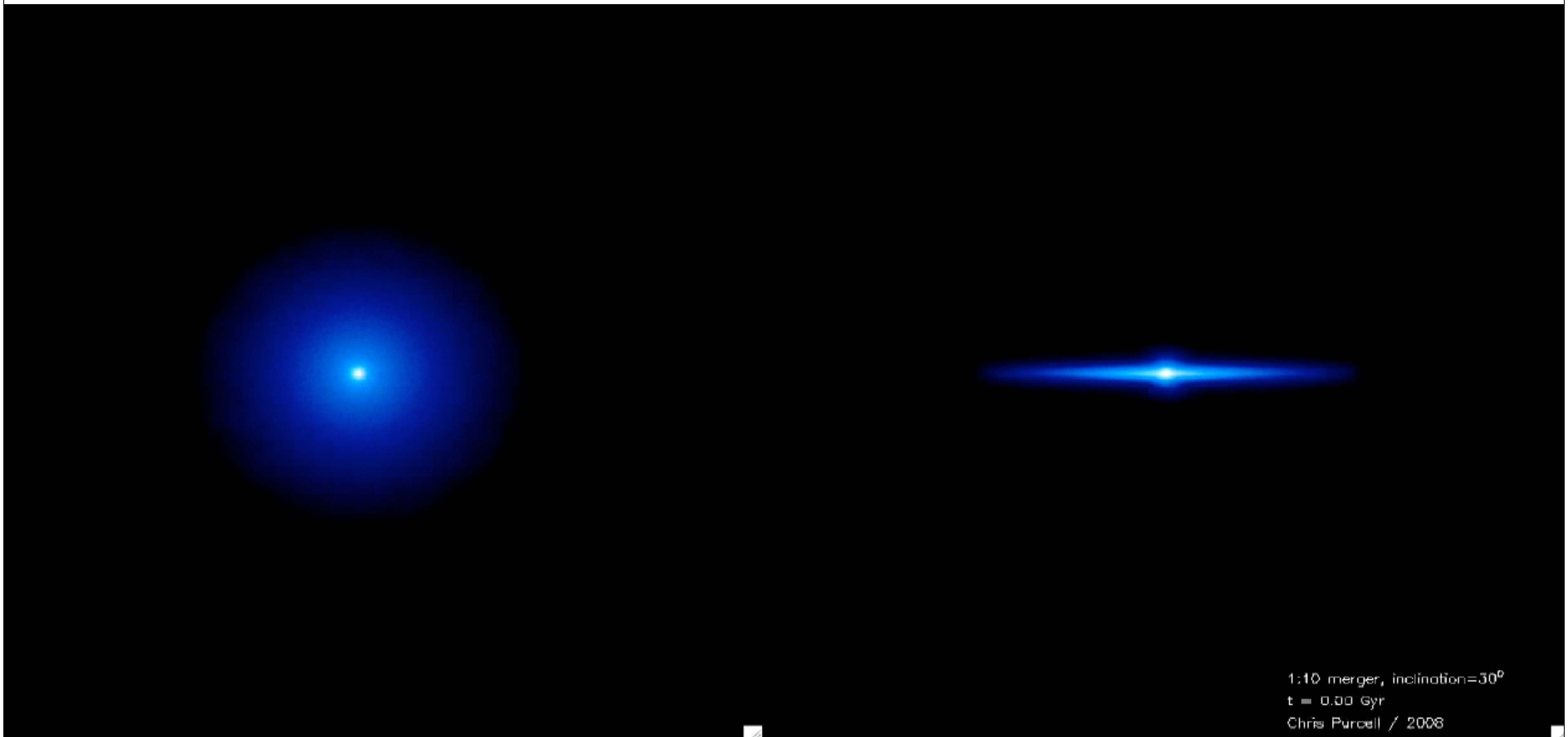


$\mathbf{V_{max}}$ → $\mathbf{V_{max}}$

$\sim 10^{8.3}\ M_{sun}$ $\sim 10^{11}\ M_{sun}$

PKDGRAV

Purcell, et al. 08



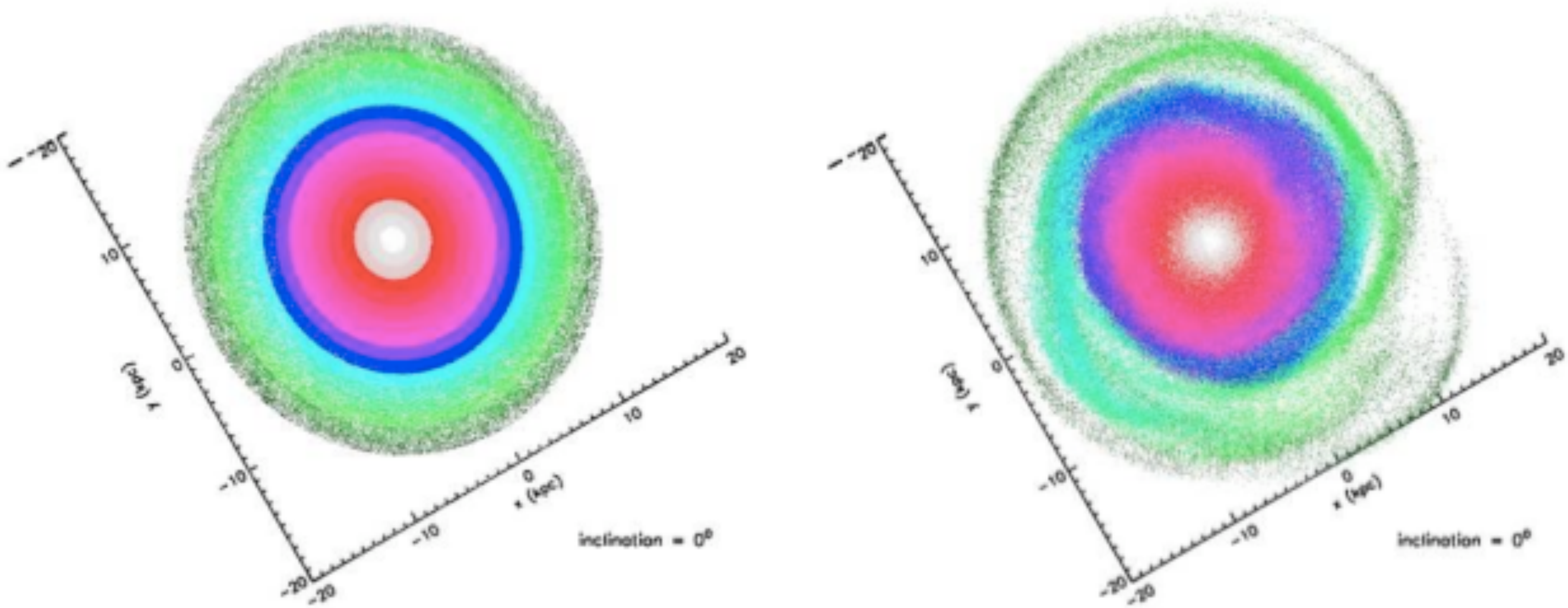
mag/arcsec^2

30

20

Merger with $M=2.10^{10}\ M_{sun}$ secondary

⟶ $M_{*} \sim 2.10^{8}\ M_{sun}$~giant stream progenitor



Purcell, JSB, Johnston, Kazantzidis 08

<u>Main point</u>: we know that these mergers are happening (witness large tidal streams) -- it’s likely that they are generating structure in disks... even if the disks to not get destroyed.

End Lecture 3