Modeling mass independent of anisotropy

A tool to test galaxy formation theories

Joe Wolf
(UC Irvine)

CENTER FOR COSMOLOGY

UNIVERSITY OF CALIFORNIA, IRVINE

SF09 Cosmology Summer Workshop July 7 2009

Team Irvine:

Greg Martinez *James Bullock* *Manoj Kaplinghat* *Frank Avedo*

KIPAC: Louie Strigari Haverford: Beth Willman OCIW: Josh Simon

Heigh Ho...

Yale: Marla Geha Ricardo Munoz

Collaborators

Outline

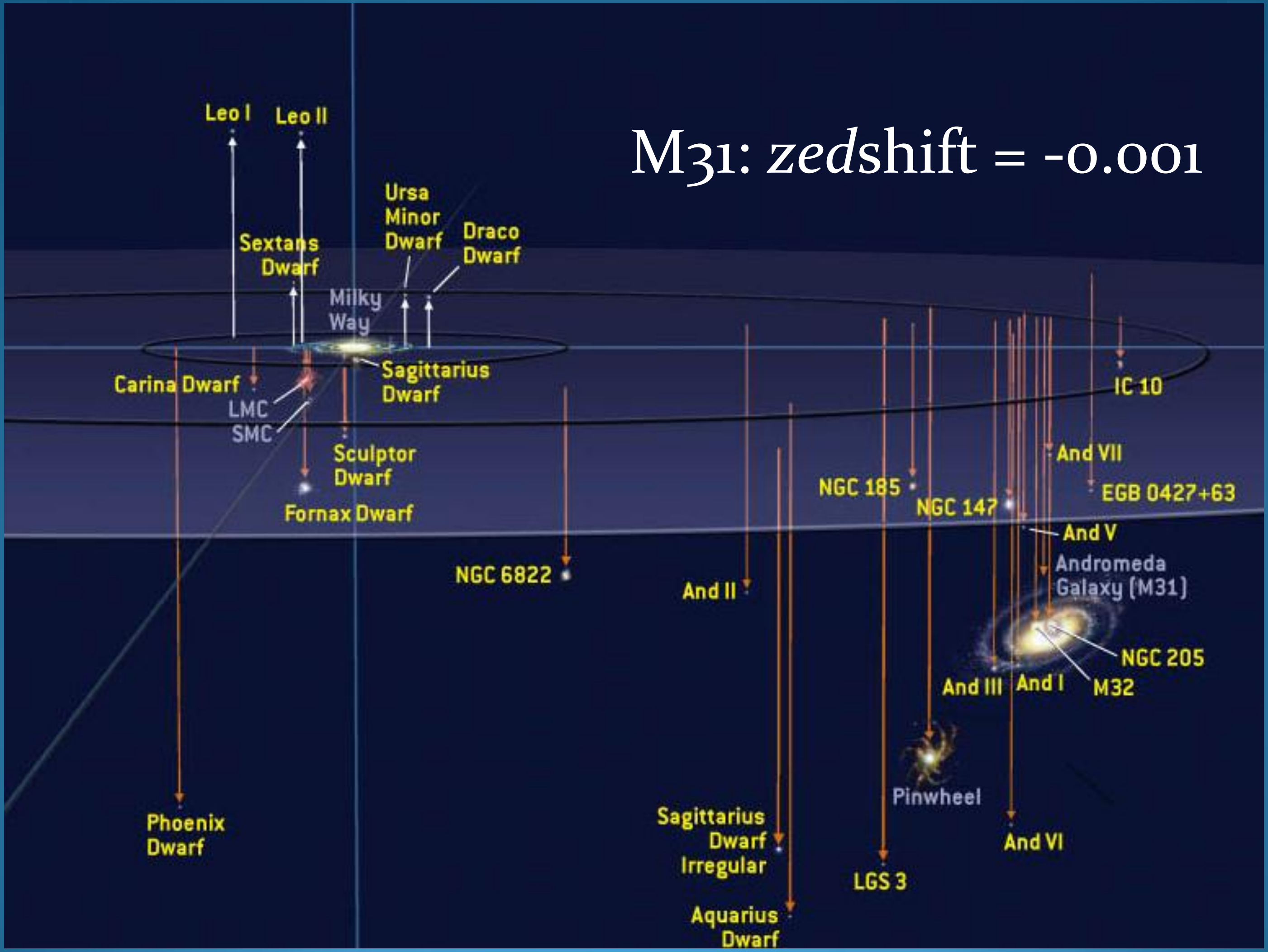
1. An introduction to the local group

2. A new mass estimator: accurate without knowledge of anisotropy/beta

3. Utilizing new mass estimator to probe galaxy formation scenarios

The Local Group

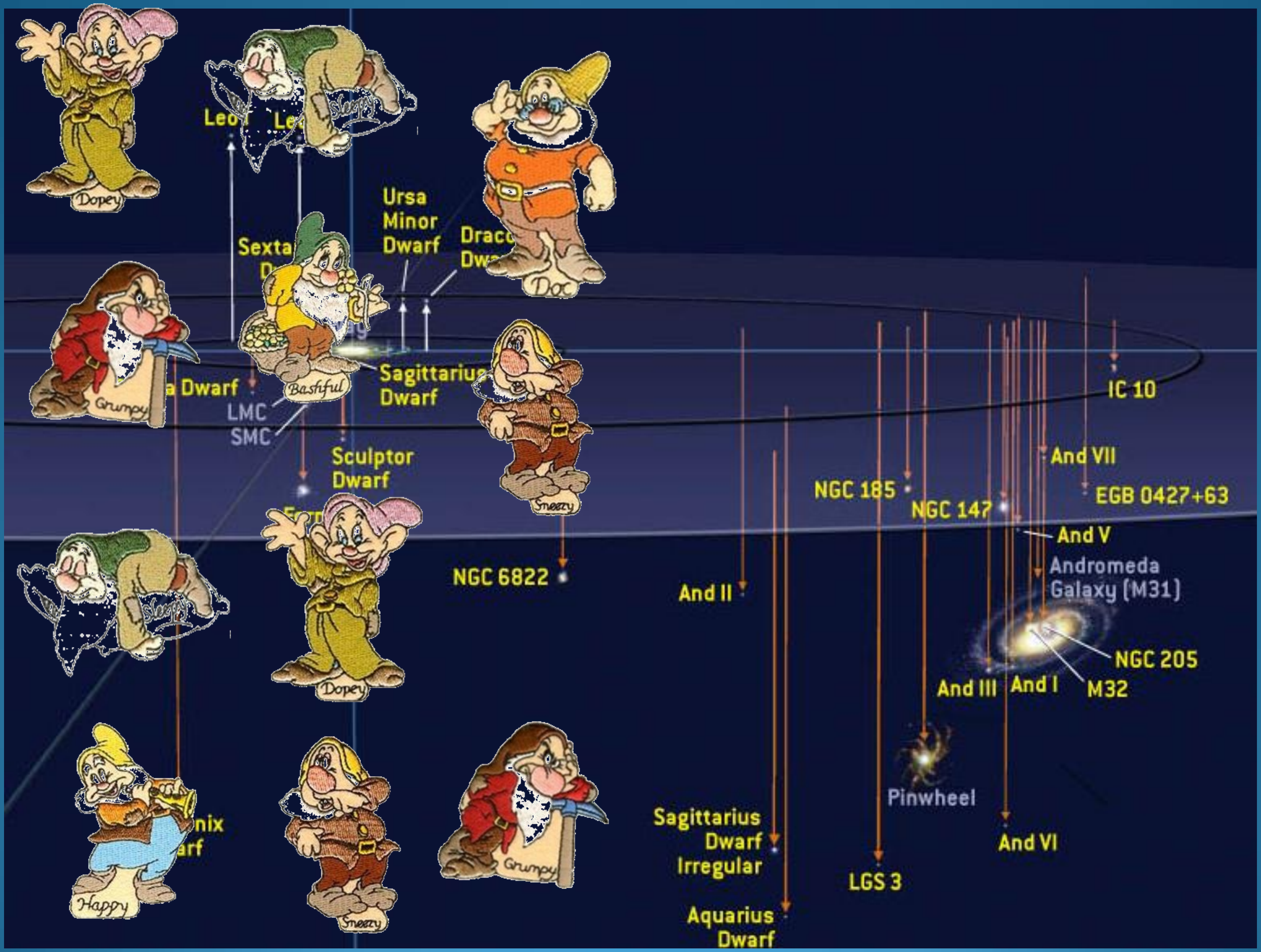
(So, what's "redshift" everyone keeps talking about?)



Roen Kelly / Astronomy

The Local Group

The new dwarf galaxy pond after SDSS:



Roen Kelly / Astronomy

Cardinal rule about dwarfs:

It's not the size of the boat, but the motion of the ocean…

Why study dwarfs?

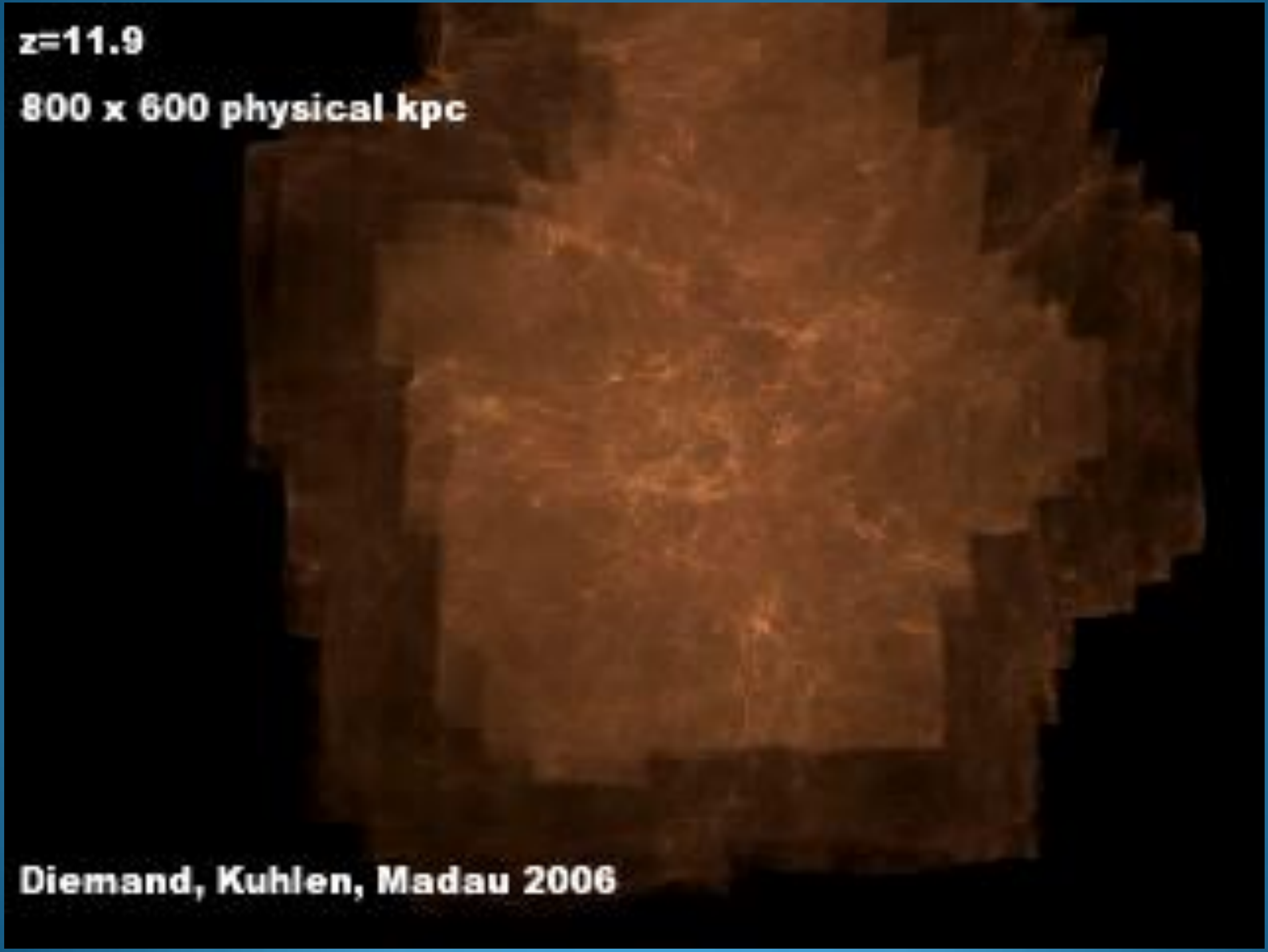
Galaxy formation

1. Subhalos merge to form galaxies

2. Surviving dwarfs are fossil relics of galaxies

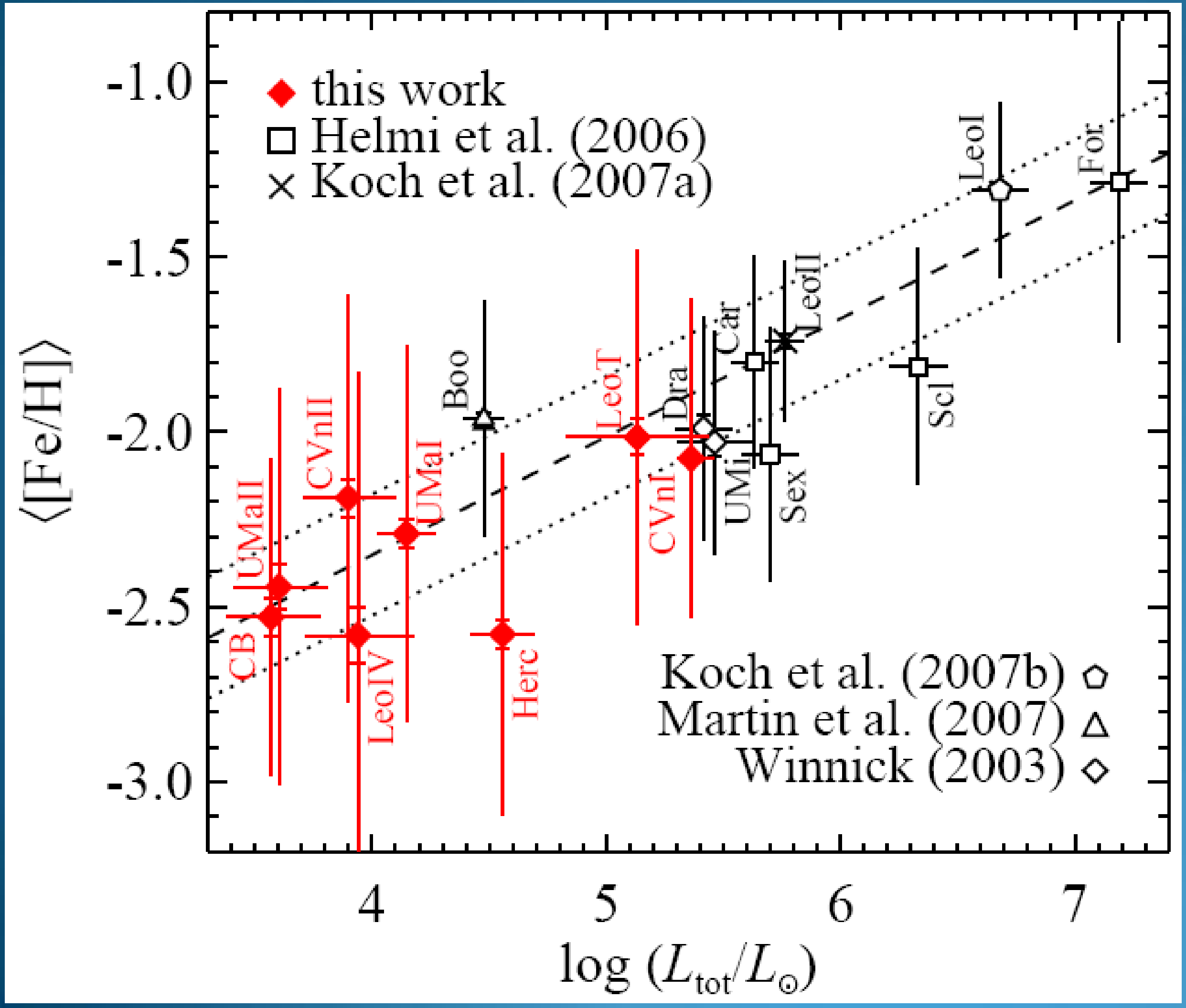
Hierarchical galaxy formation

Subhalos are the building blocks of all galaxies.



Galactic Archaeology

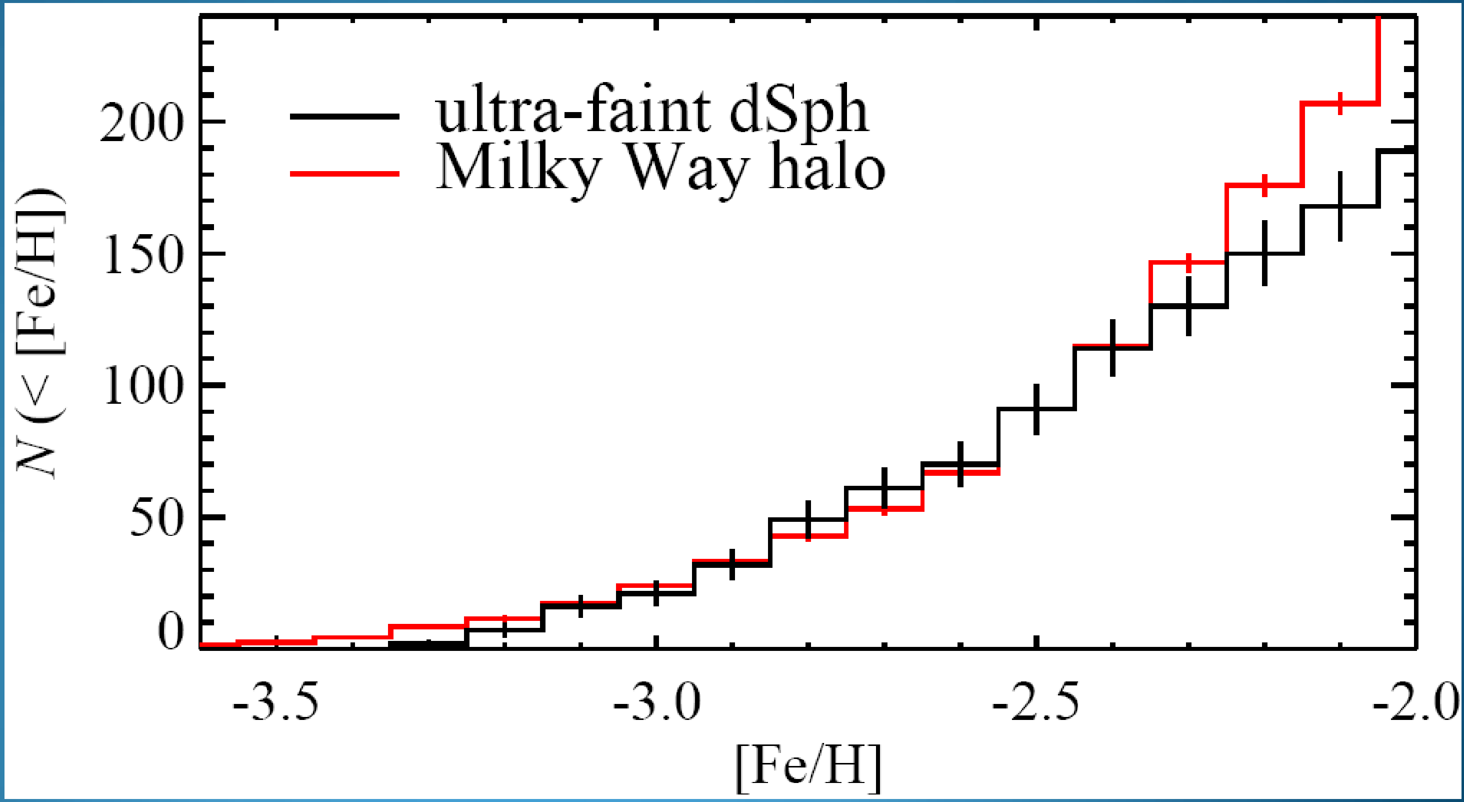
Today's population: Survivors + first infall



Evan Kirby et al. 2008

Galactic Archaeology

Today's population: Survivors + first infall



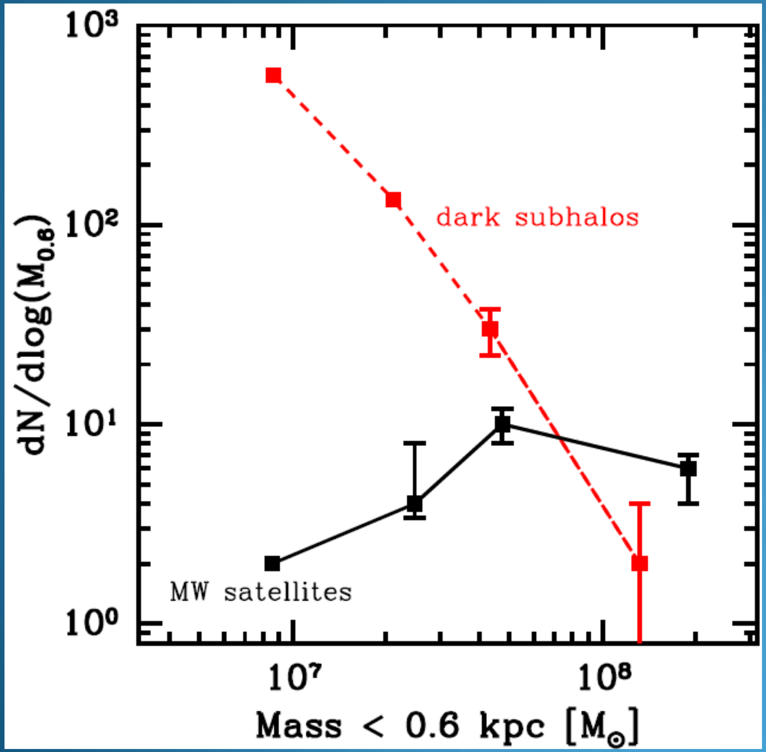
Evan Kirby et al. 2008

Why study dwarfs?

Two significant problems with ΛCDM on small scales:

1. Cusp vs core
2. Missing satellite problem

To test both galaxy formation scenarios and theories that try to solve these problems, we need accurate masses.



Strigari et al 2007

Mass modeling of hot systems

Many gas-poor dwarf galaxies have a significant, usually dominant hot component. They are dispersion supported, not rotation supported.

Consider a spherical, dispersion supported system whose stars are collisionless and are in equilibrium. Let us consider the Jeans Equation:

Unknown: Anisotropy

$$\beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

We want mass

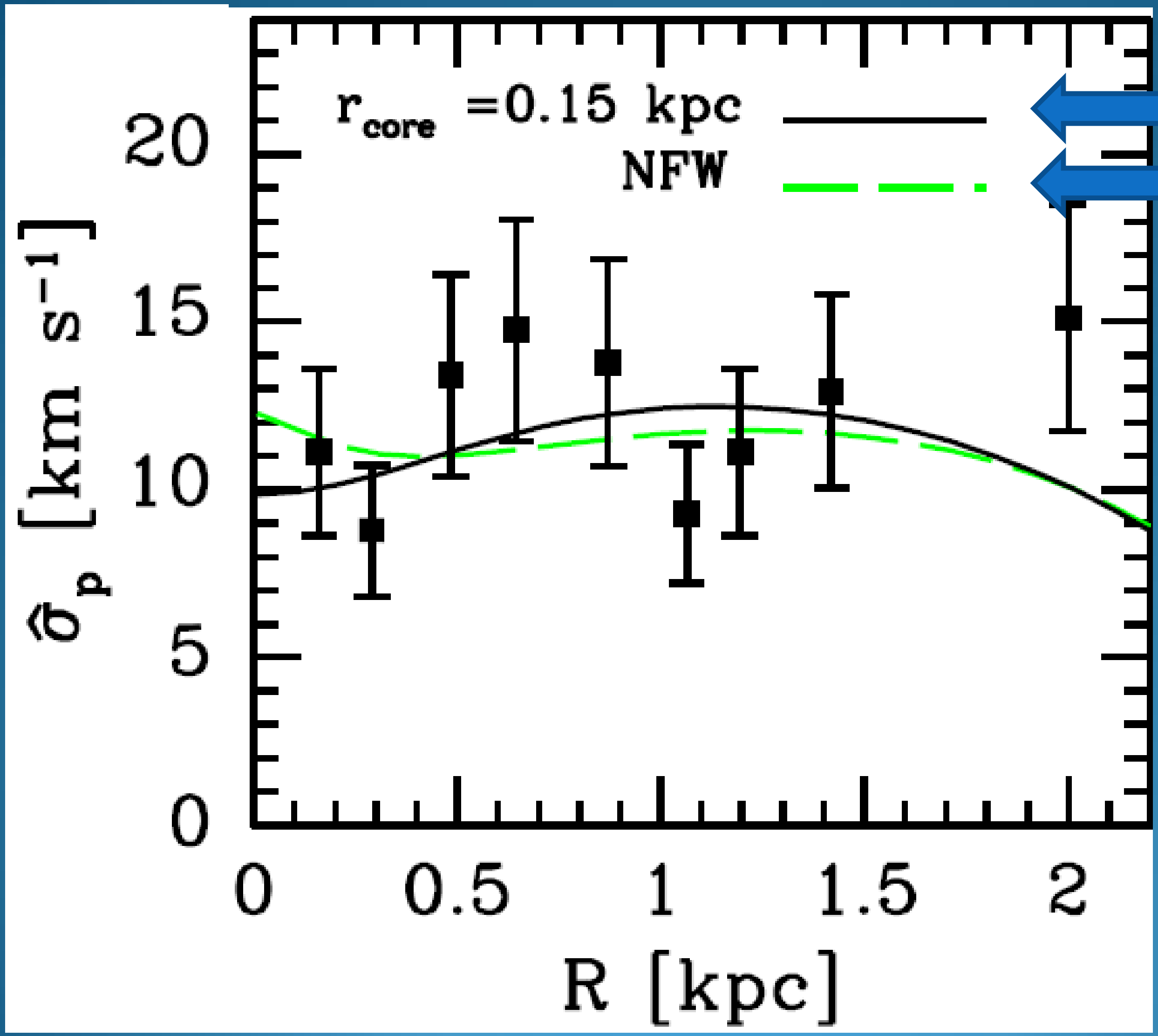
$$r\frac{d(\rho_\star \sigma_r^2)}{dr} = \frac{-GM(r)}{r}\rho_\star(r) - 2\beta(r)\rho_\star\sigma_r^2$$

Free function

Assume known: 3D deprojected stellar density

Radial dispersion (depends on beta)

Mass-Beta Degeneracy



Core

Cusp

Strigari et al. 2006, ApJ

Mass modeling of hot systems

Jeans Equation

$$r\frac{d(\rho_\star\sigma_r^2)}{dr} = \frac{-GM(r)}{r}\rho_\star(r) - 2\beta(r)\rho_\star\sigma_r^2$$

Velocity Anisotropy (3 parameters)

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

Mass modeling of hot systems

Jeans Equation

$$r\frac{d(\rho_\star \sigma_r^2)}{dr} = \frac{-GM(r)}{r}\rho_\star(r) - 2\beta(r)\rho_\star\sigma_r^2$$

Velocity Anisotropy (3 parameters)

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

Mass Density (6 parameters)

$$\rho(r) = \frac{\rho_s e^{-r/r_{cut}}}{(r/r_s)^c[1+(r/r_s)^a]^{(b-c)/a}}$$

Mass modeling of hot systems

Jeans Equation

$$r\frac{d(\rho_\star \sigma_r^2)}{dr} = \frac{-GM(r)}{r}\rho_\star(r) - 2\beta(r)\rho_\star\sigma_r^2$$

Velocity Anisotropy
(3 parameters)

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

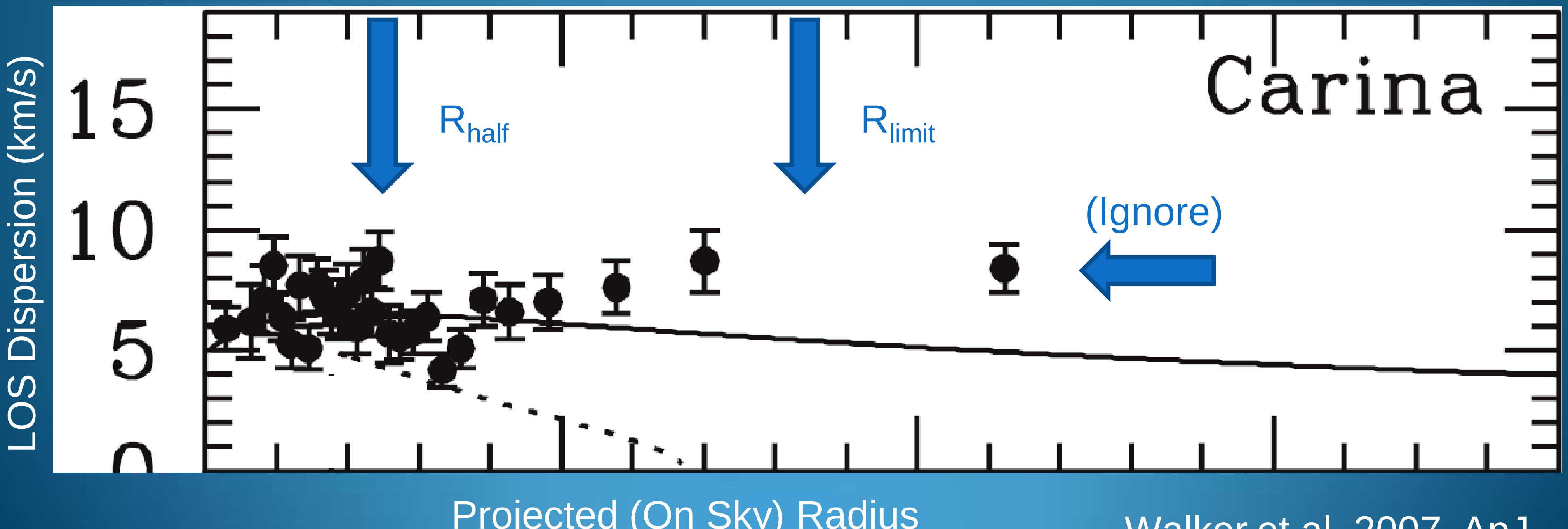
Mass Density
(6 parameters)

$$\rho(r) = \frac{\rho_s e^{-r/r_{cut}}}{(r/r_s)^c[1+(r/r_s)^a]^{(b-c)/a}}$$

Using a Gaussian PDF for the observed stellar velocities, we marginalize over all free parameters (including photometric uncertainties) using a Markov Chain Monte Carlo (MCMC).

Thought Experiment

Given the following kinematics…



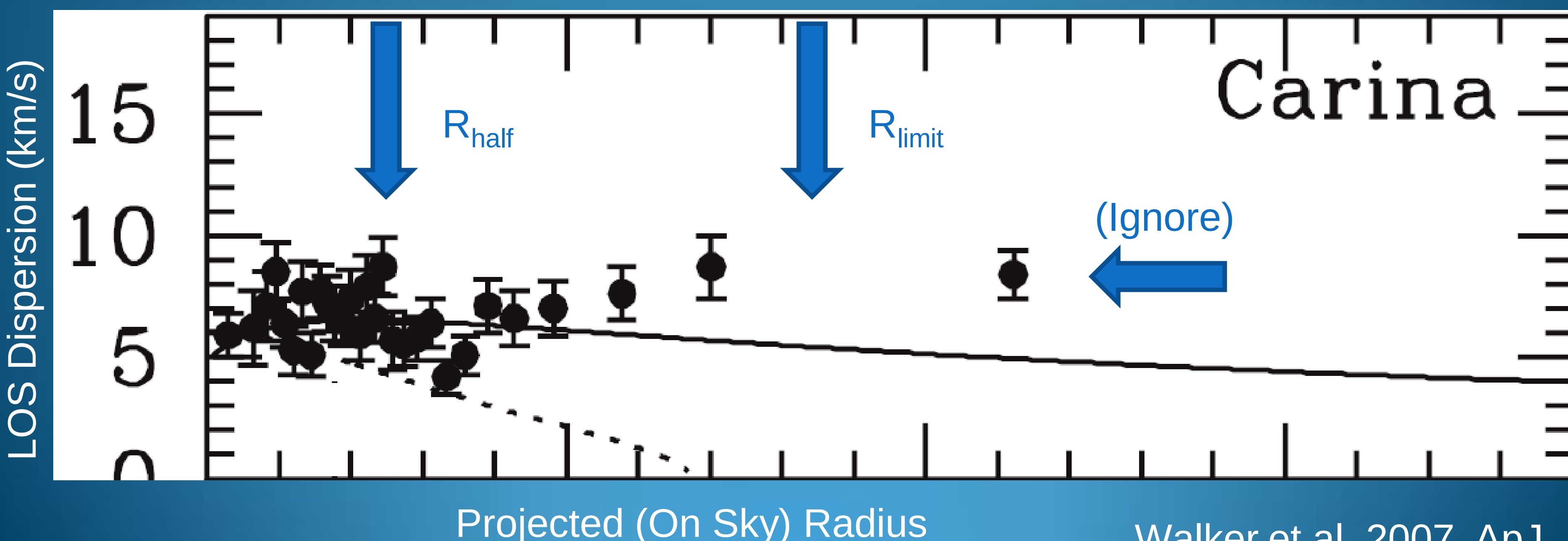
Walker et al. 2007, ApJ

Thought Experiment

Given the following kinematics, will you derive a better constraint on mass enclosed within:

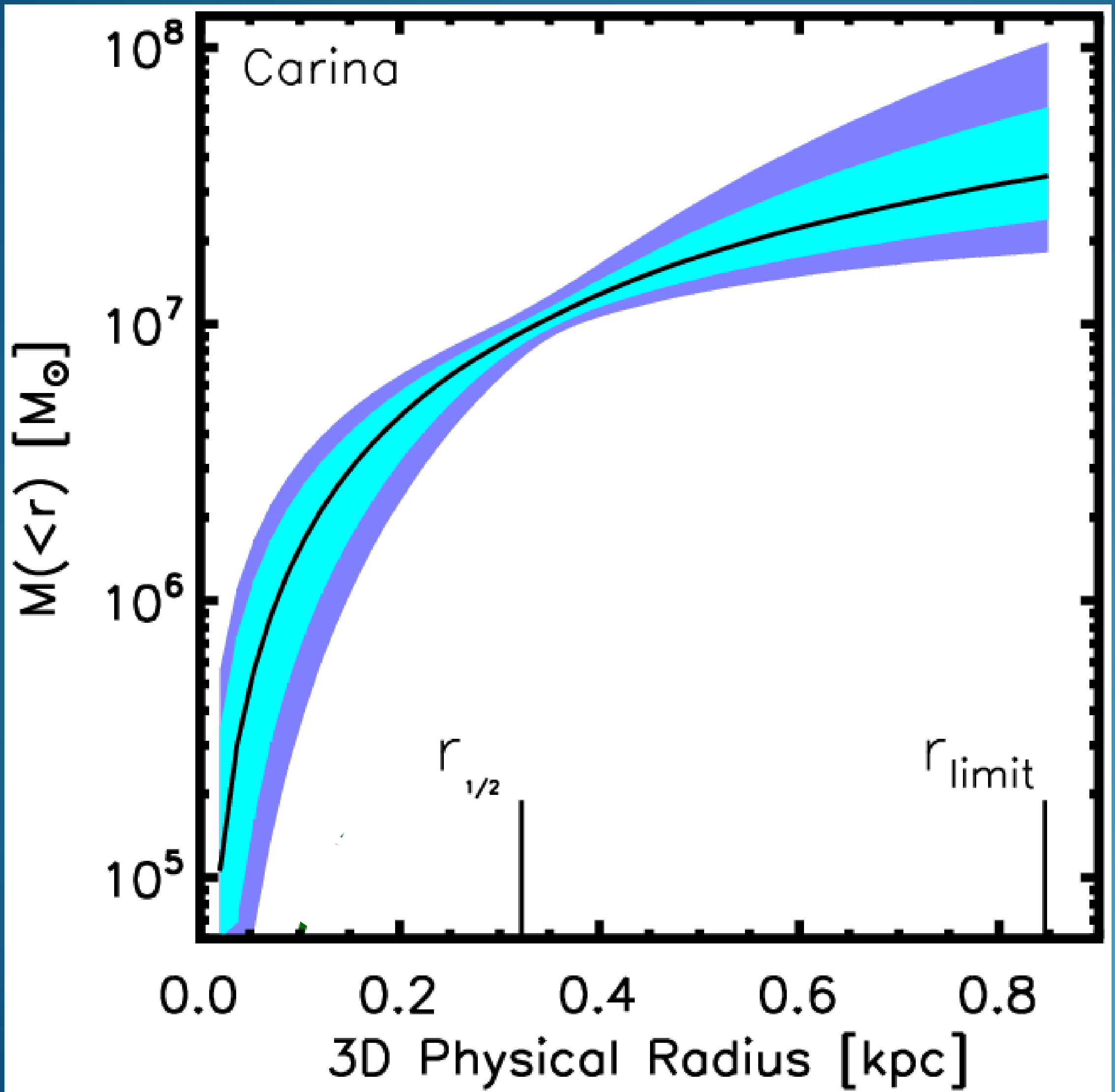
a) $0.5 * r_{1/2}$ b) $r_{1/2}$ c) $1.5 * r_{1/2}$

Where $r_{1/2}$ is the derived 3D deprojected half-light radius of the system. (The sphere within the sphere containing half the light).



Walker et al. 2007, ApJ

Hmm…

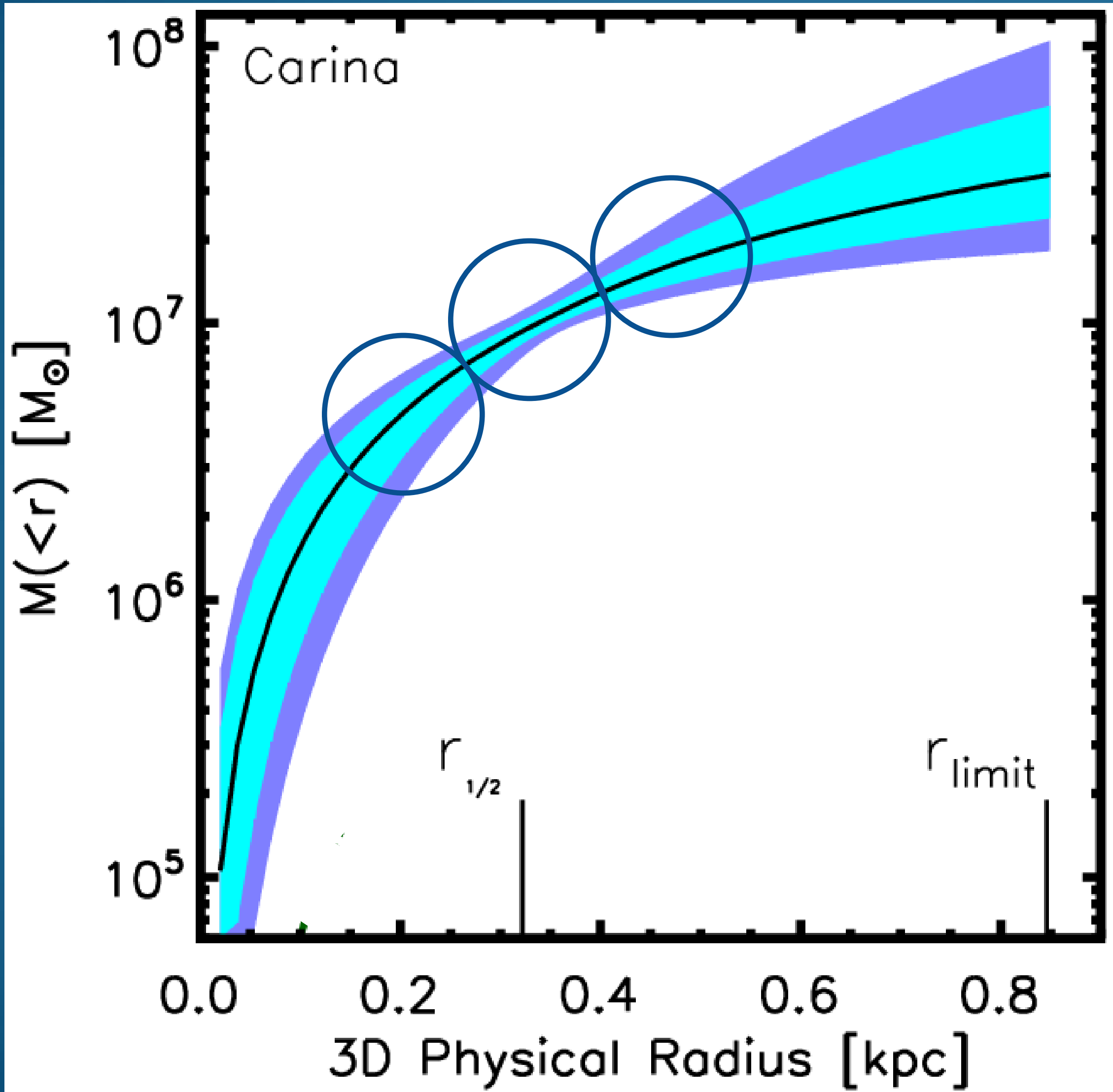


Confidence Intervals:
Cyan: 68%
Purple: 95%

Joe Wolf et al., in prep

Hmm…

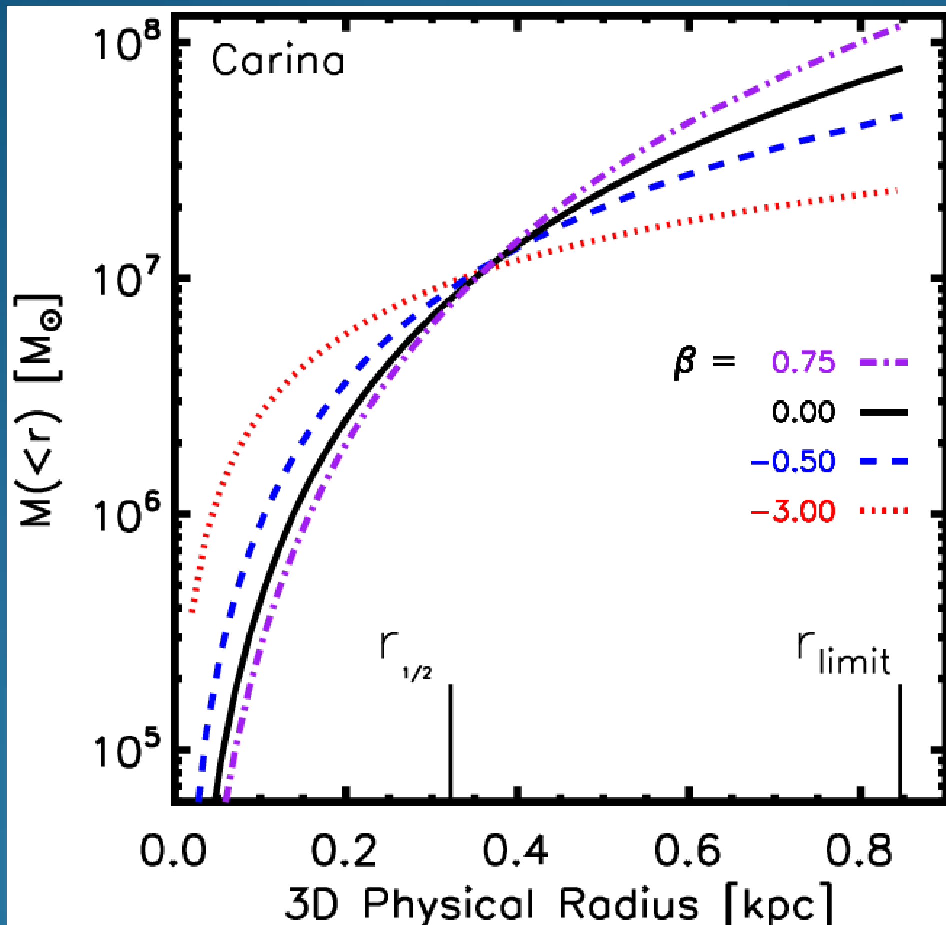
It turns out that the mass is best constrained within $r_{1/2}$, and despite the given data, is less constrained for $r < r_{1/2}$ than $r > r_{1/2}$.



Confidence Intervals:
Cyan: 68%
Purple: 95%

Joe Wolf et al., in prep

Anisotrwhat?



Radial Anisotropy

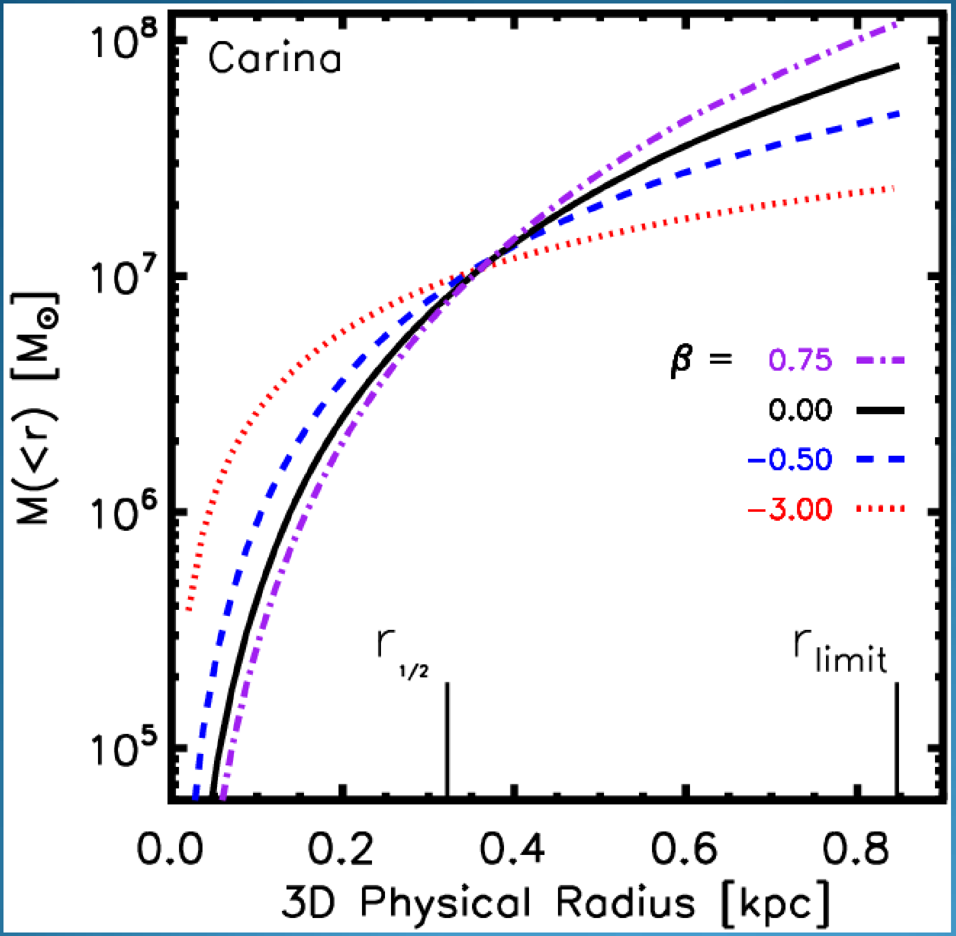
Isotropic

Tangential

Joe Wolf et al., in prep

Anisotrwhat?

Center of system:
Observed dispersion is radial



Edge of system: Observed dispersion is tangential

Radial Anisotropy

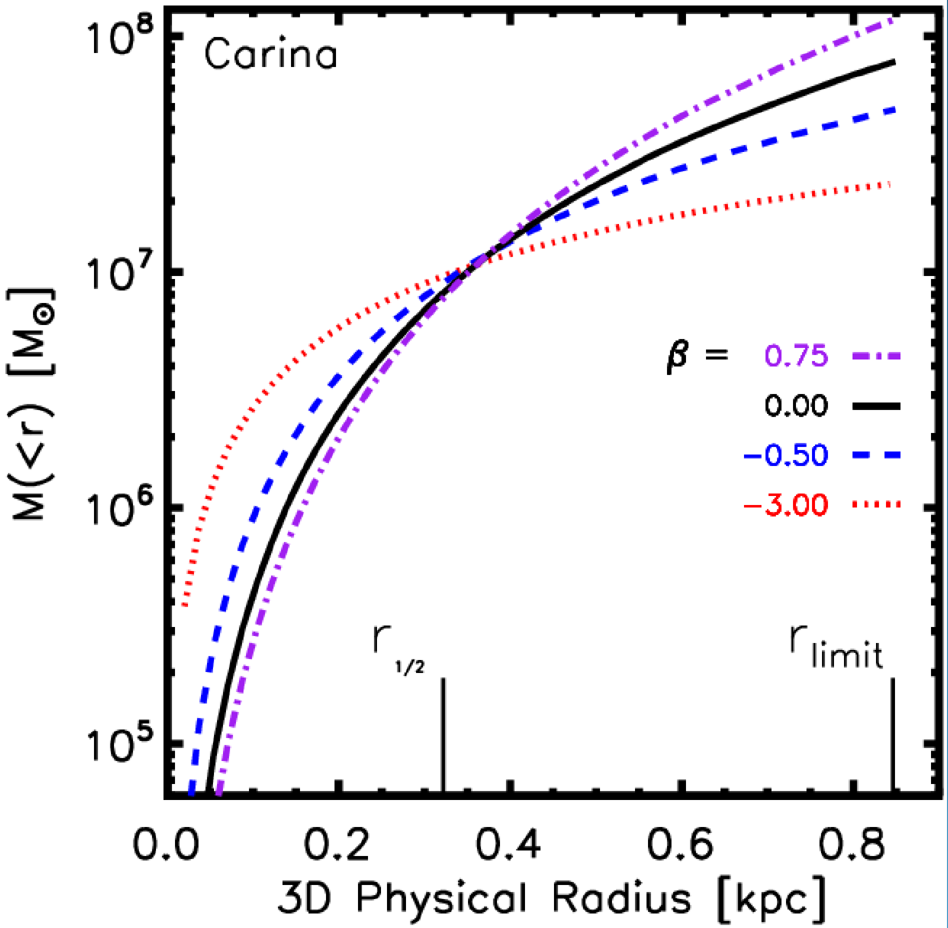
Isotropic

Tangential

Joe Wolf et al., in prep

Anisotrwhat?

Center of system:
Observed dispersion is radial



Joe Wolf et al., in prep

Edge of system: Observed dispersion is tangential

Radial Anisotropy

Isotropic

Tangential

Newly derived analytic equations **predict** that the effect of anisotropy is minimal $\sim r_{1/2}$. E.g.:

$$M(<r;0) - M(<r;\beta) = \frac{\beta(r)\, r\, \sigma_r^2(r)}{G}\left(\frac{d\ln\rho_\star}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + \frac{d\ln\beta}{d\ln r} + 3\right)$$

Mass-anisotropy degeneracy has effectively been *terminated* at $r_{1/2}$:

Derived equation under several simplifications:

$$M_{1/2} = 3\, r_{1/2}\, \sigma^2_{LOS}/G$$

Mass-anisotropy degeneracy has effectively been *terminated* at $r_{1/2}$:

Derived equation under several simplifications:

$$M_{1/2} = 3\, r_{1/2}\, \sigma^2_{LOS} / G$$

$$\frac{M_{1/2}}{M_\odot} \simeq 930\, \frac{R_{half}}{pc} \left(\frac{\sigma_{LOS}}{km/s} \right)^2$$

$r_{1/2} \approx 4/3 * R_{half}$

Wait a second…

Isn't this just the scalar virial theorem (SVT)?

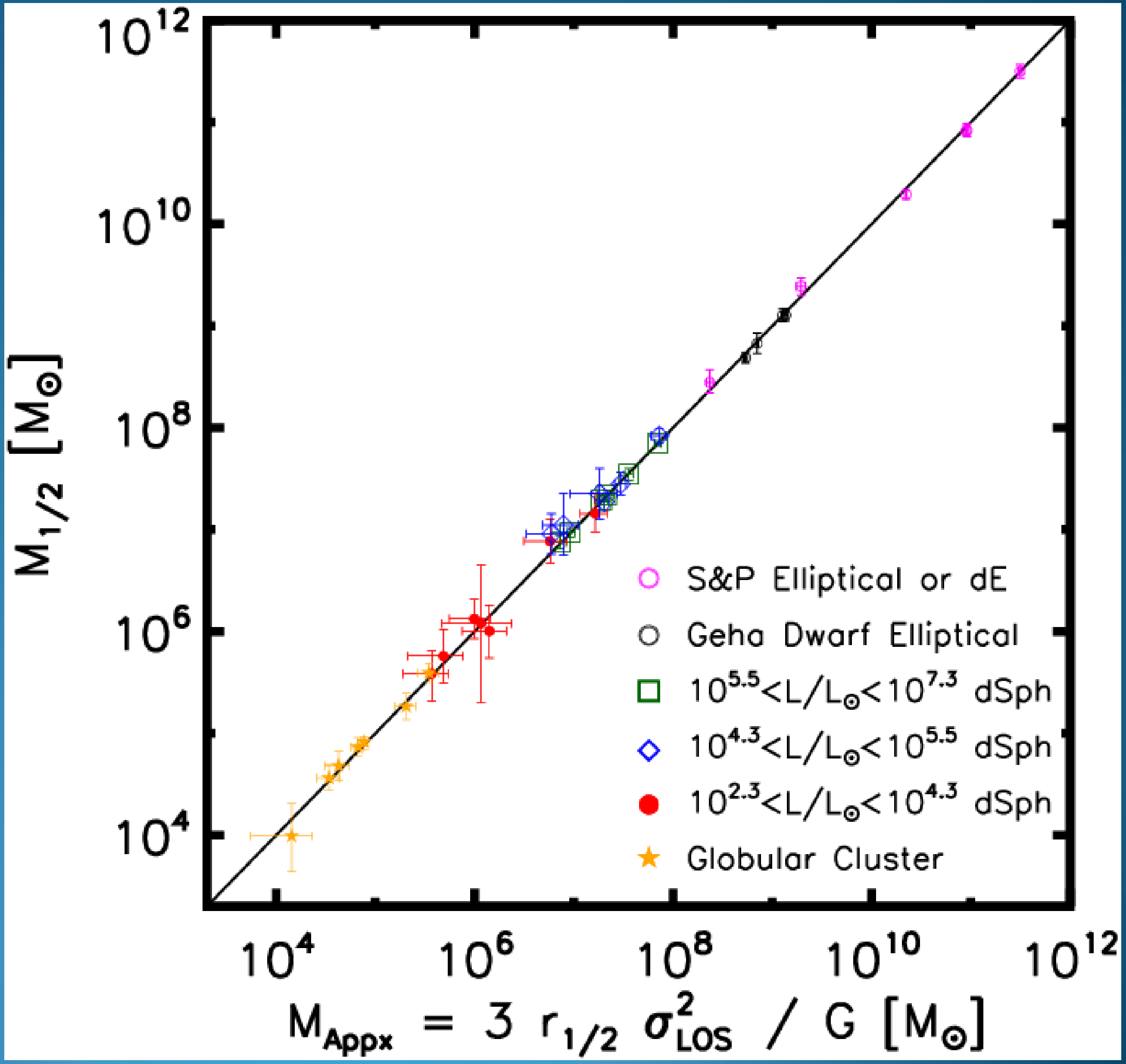
$$M_{1/2} = 3\, r_{1/2}\, \sigma^2_{LOS}/G$$

Nope! The SVT only gives you limits on the total mass of a system.

This formula yields the mass within $r_{1/2}$, the 3D deprojected half-light radius, and is accurate independent of our ignorance of anisotropy.

Really?

Boom!
Equation tested on systems spanning almost **eight** decades in half-light mass after lifting simplifications.

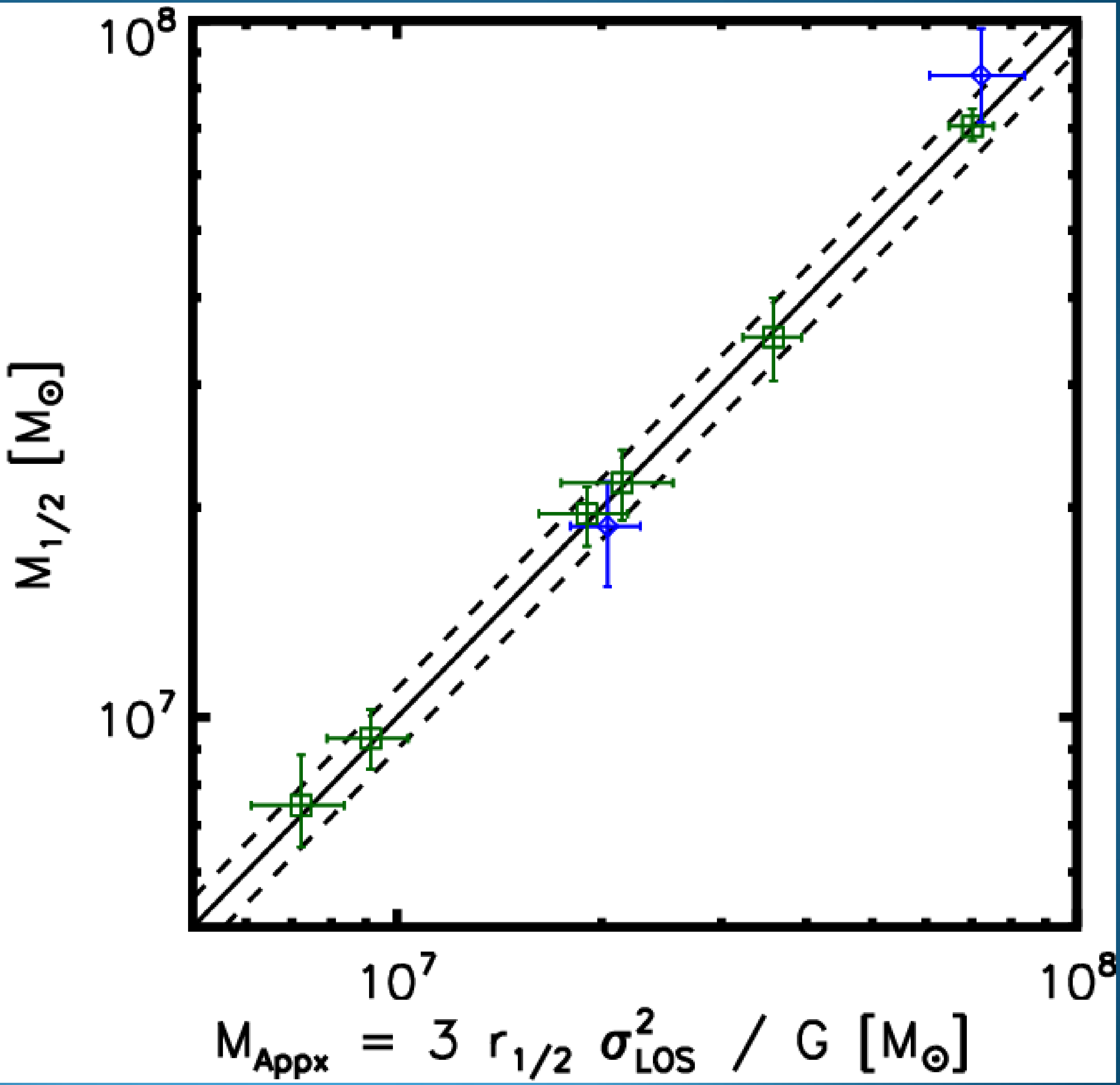


Joe Wolf et al., in prep

Boom!

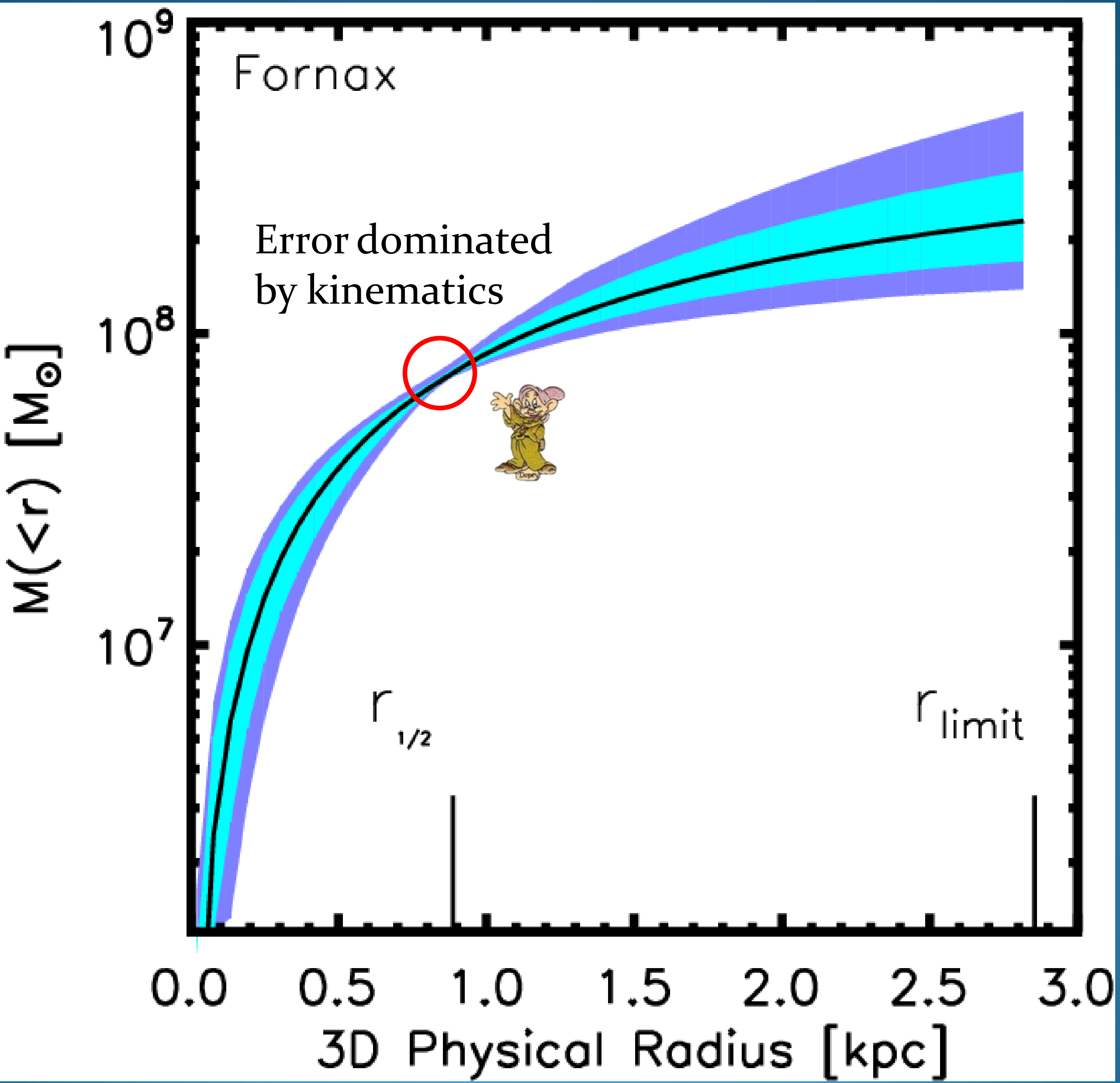
Dotted lines:
10% variation in
factor of 3 in M_{Appx}

"Classical" MW dwarf spheroidals



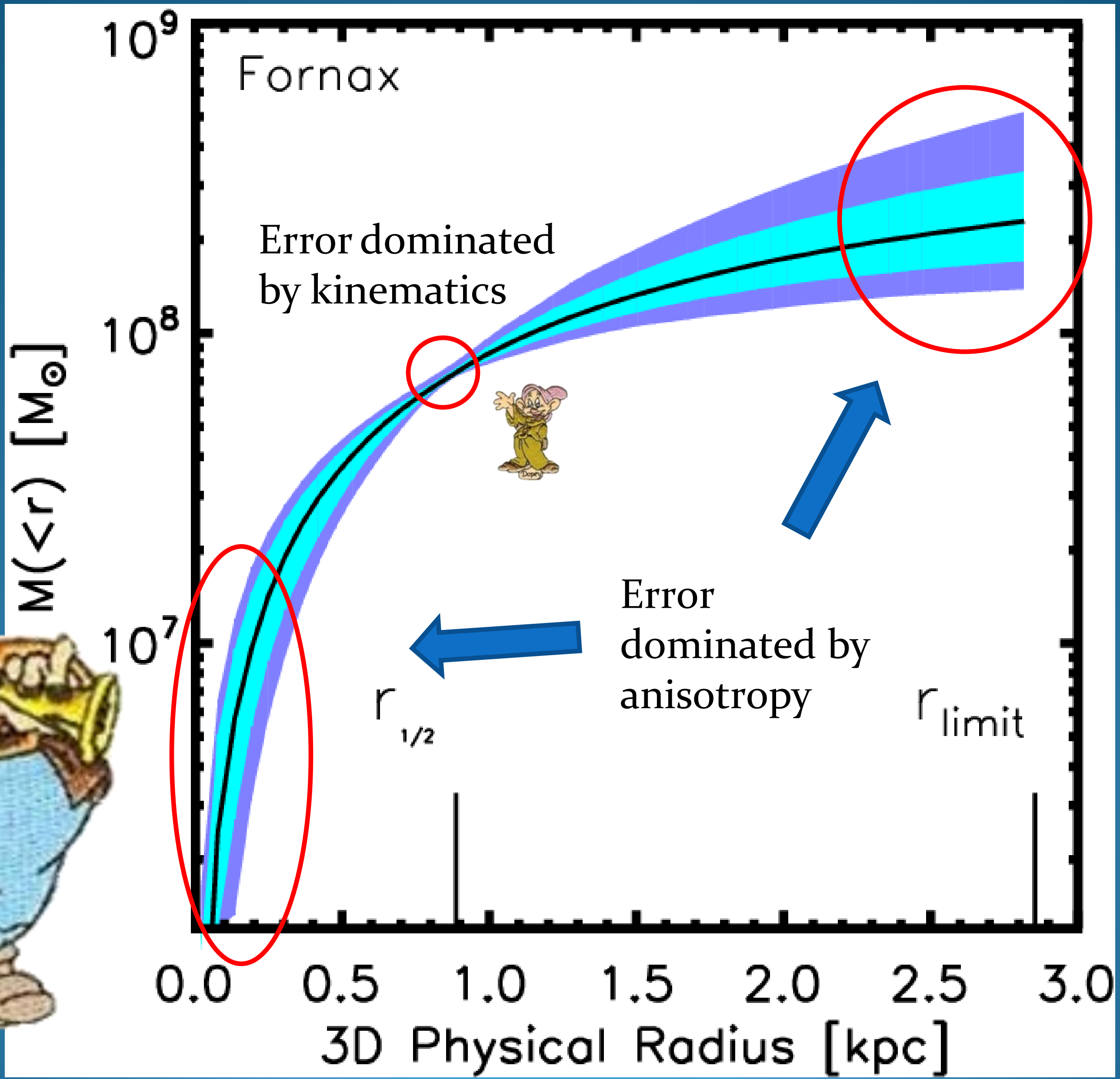
Joe Wolf et al., in prep

Mass Errors: Origins



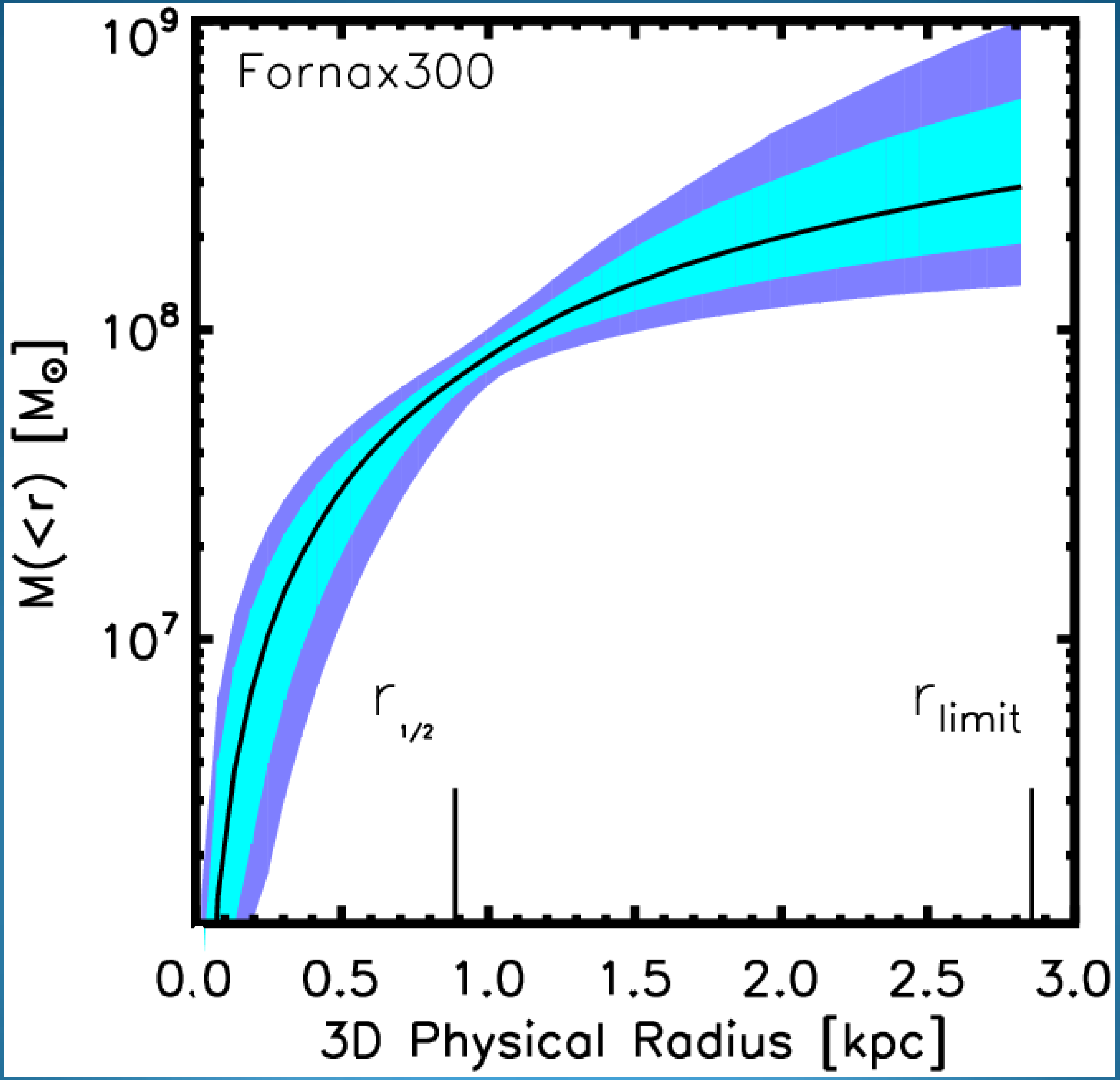
Joe Wolf et al., in prep

Mass Errors: Origins



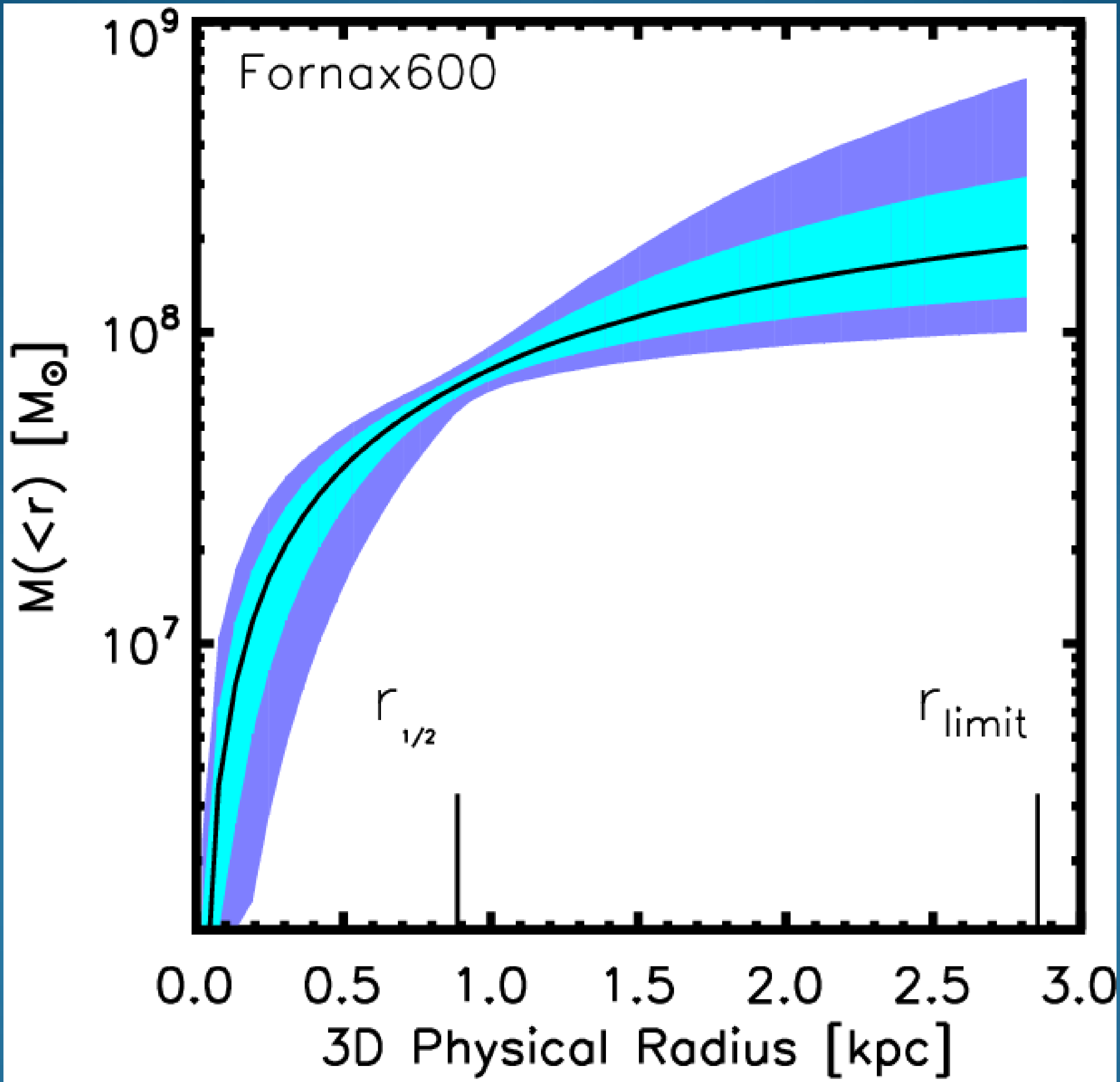
Joe Wolf et al., in prep

Mass Errors: 300 stars



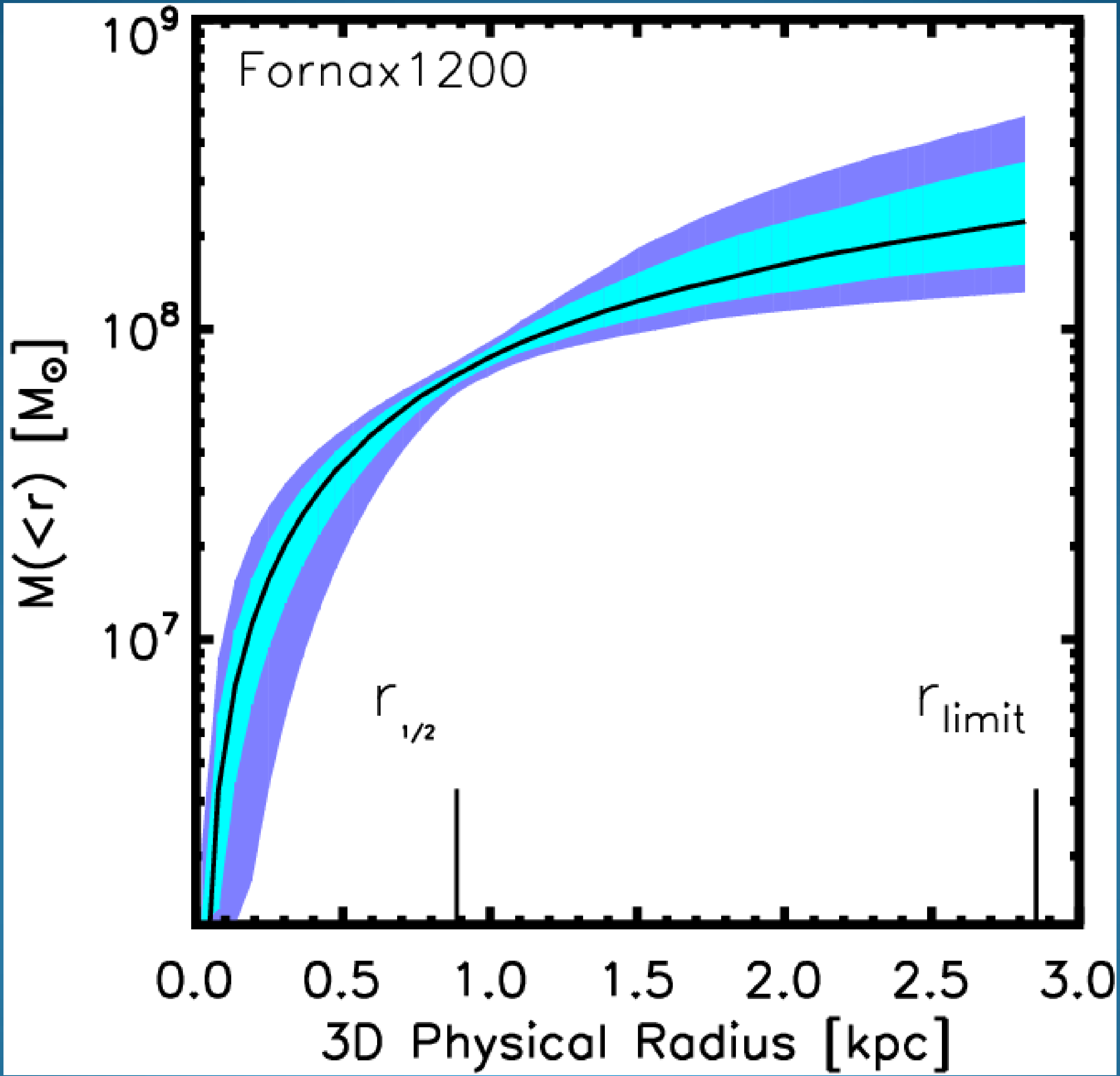
Joe Wolf et al., in prep

Mass Errors: 600 stars



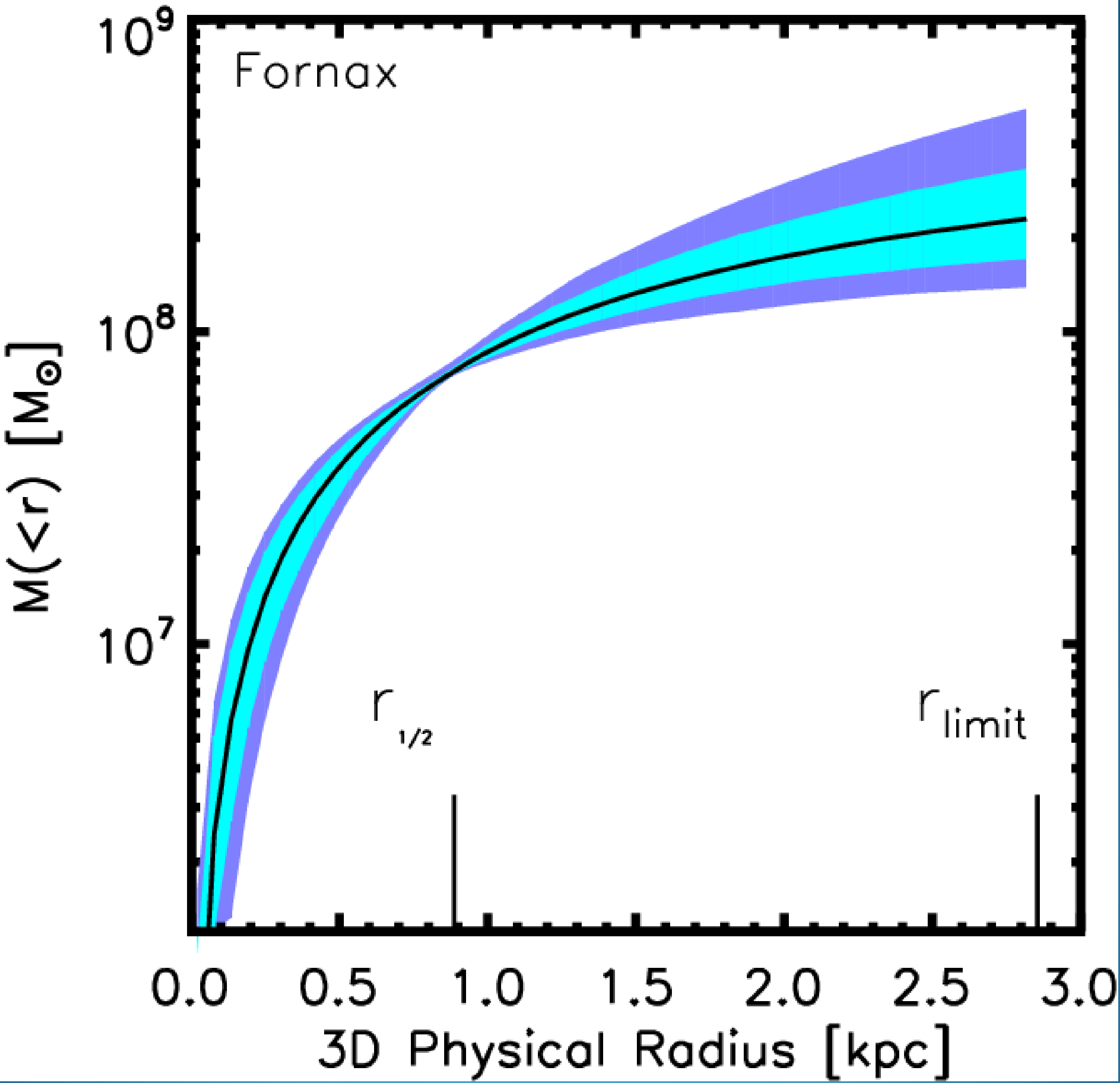
Joe Wolf et al., in prep

Mass Errors: 1200 stars



Joe Wolf et al., in prep

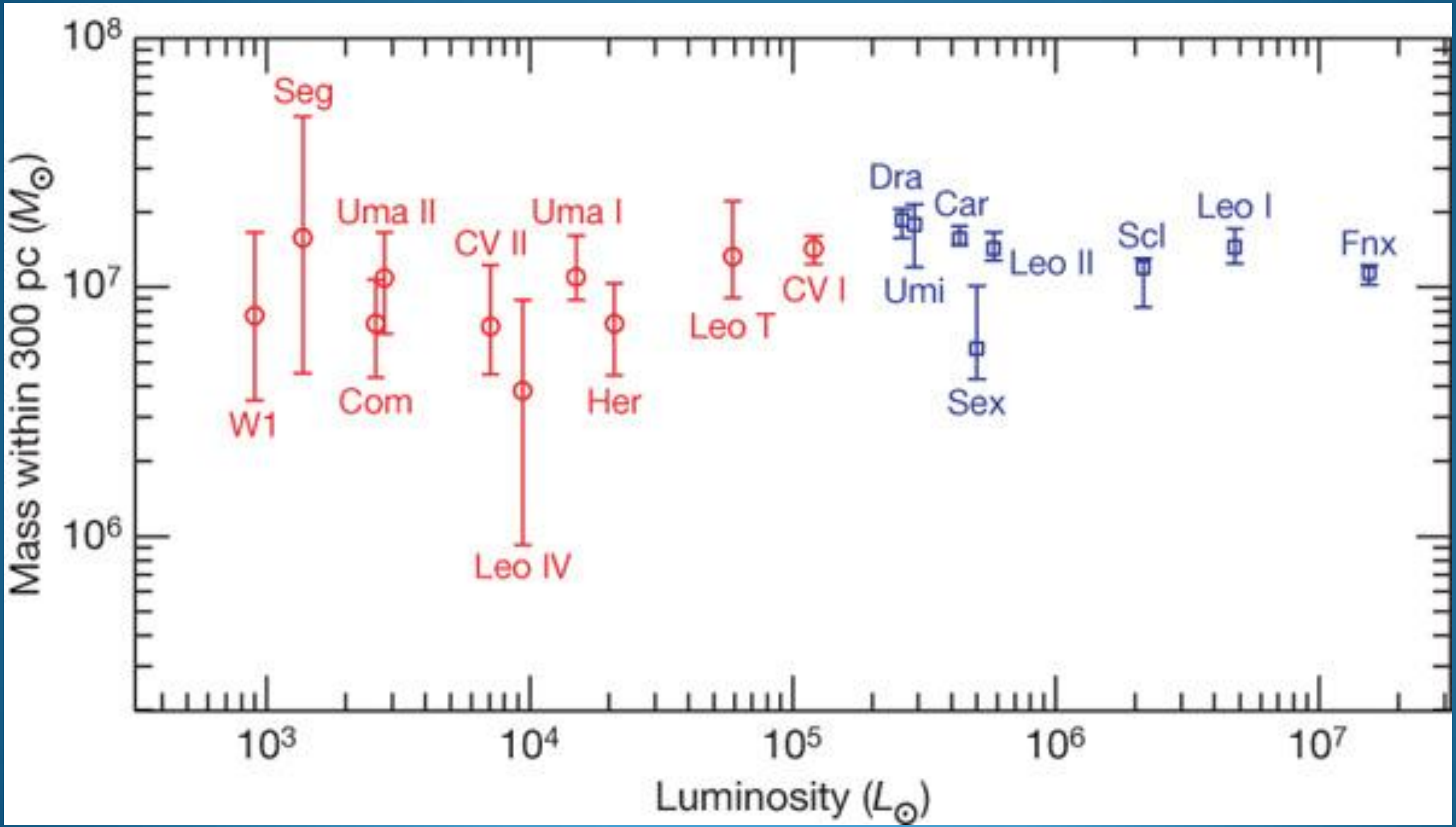
Mass Errors: 2400 stars



Joe Wolf et al., in prep

Applications: dSphs

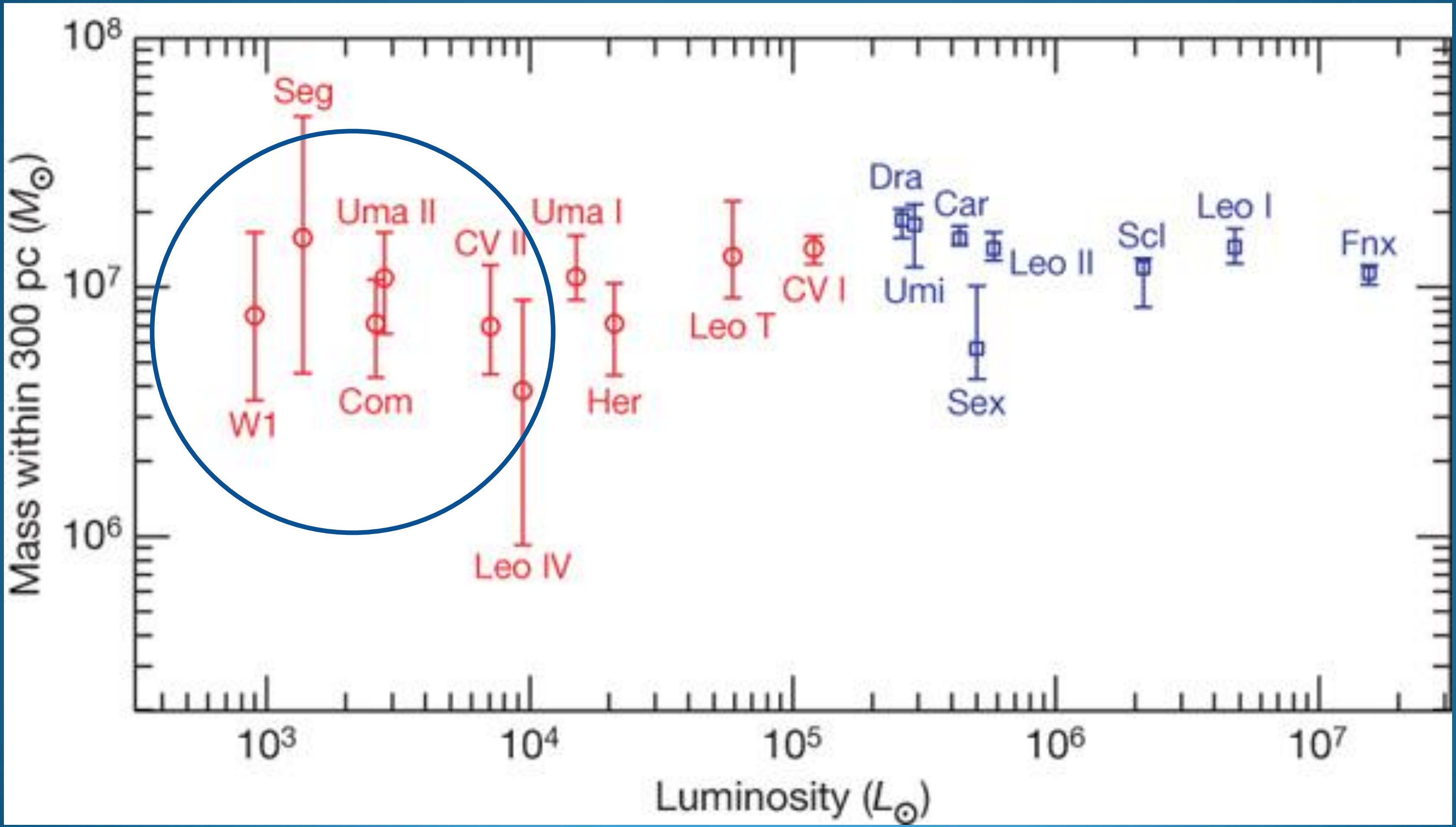
A common mass scale? $M(<300) \sim 10^7\ M_{sun} \rightarrow M_{halo} \sim 10^9\ M_{sun}$



Strigari, Bullock, Kaplinghat, Simon, Geha, Willman, Walker 2008, Nature

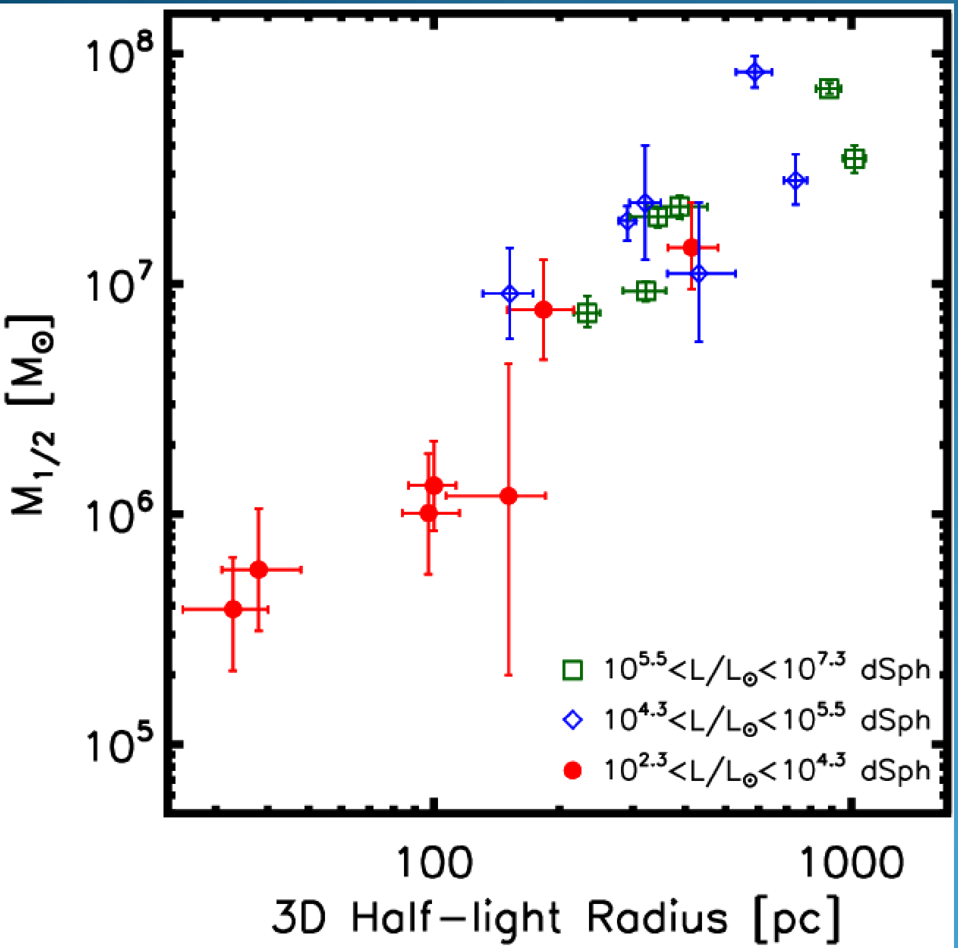
Applications: dSphs

A common mass scale? $M(<300) \sim 10^7\ M_{sun} \rightarrow M_{halo} \sim 10^9\ M_{sun}$



Strigari, Bullock, Kaplinghat, Simon, Geha, Willman, Walker 2008, Nature

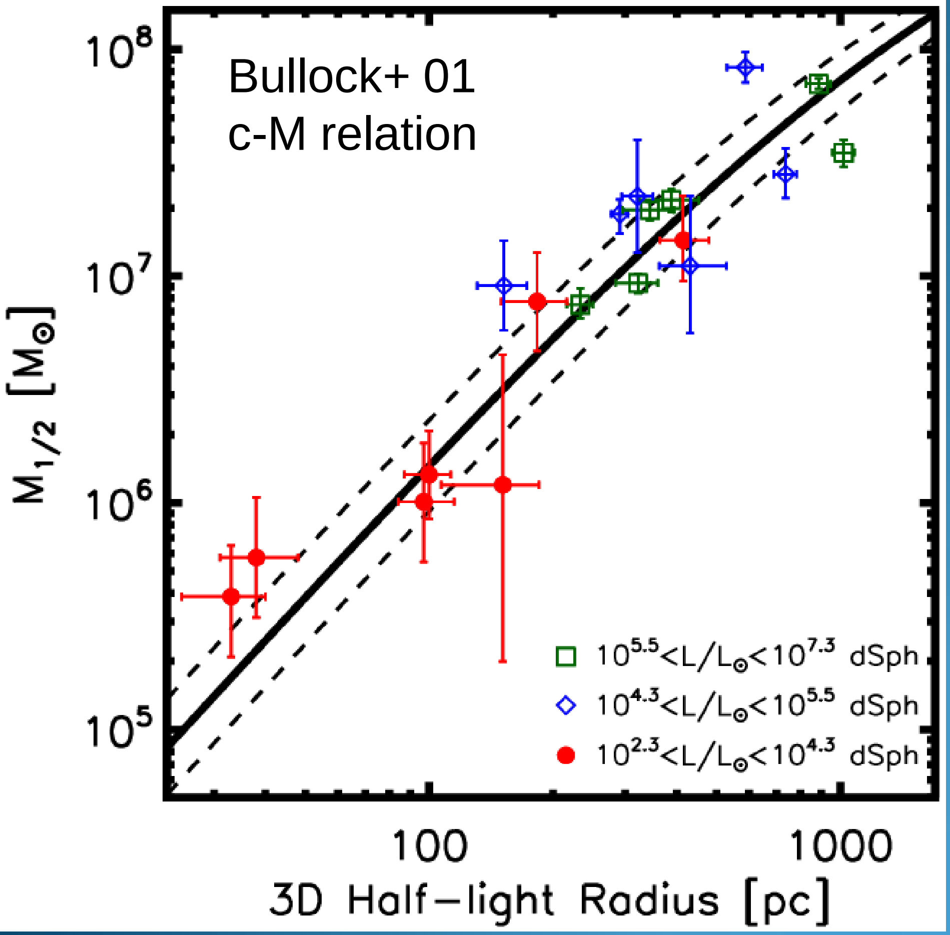
Applications: dSphs



Joe Wolf et al., in prep

Applications: dSphs

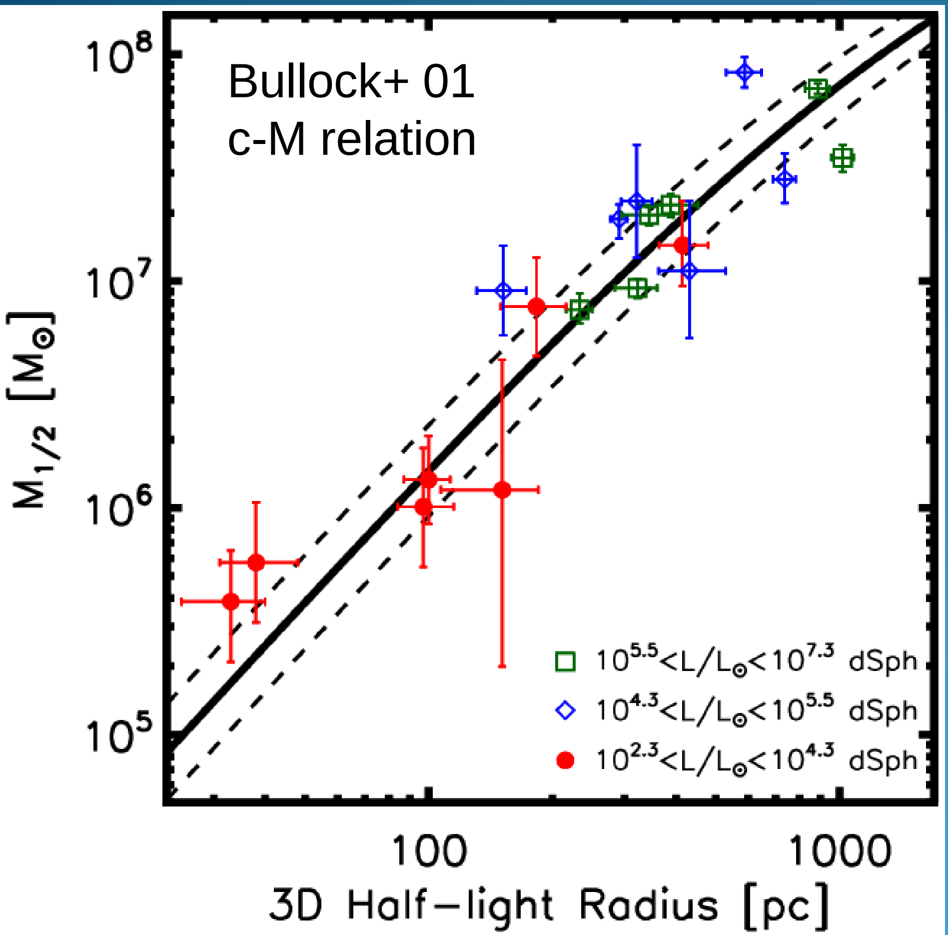
A common mass scale? Plotted: $M_{halo} = 10^9\ M_{sun}$

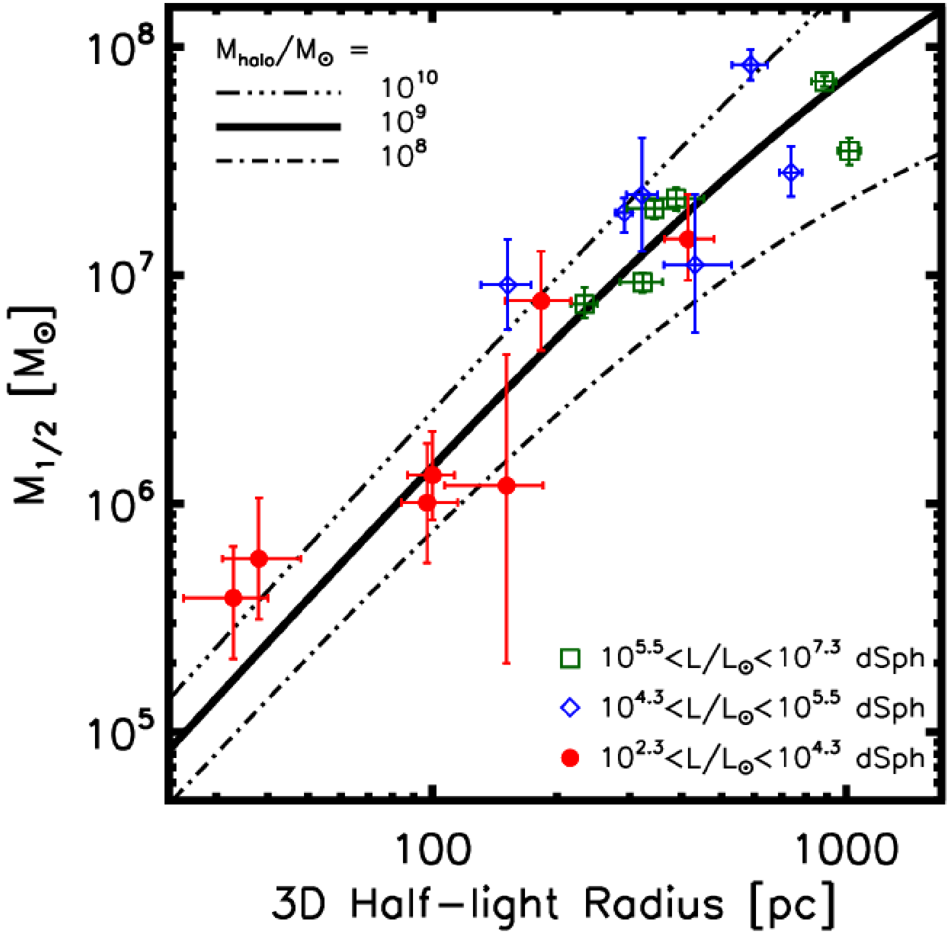


Joe Wolf et al., in prep

Applications: dSphs

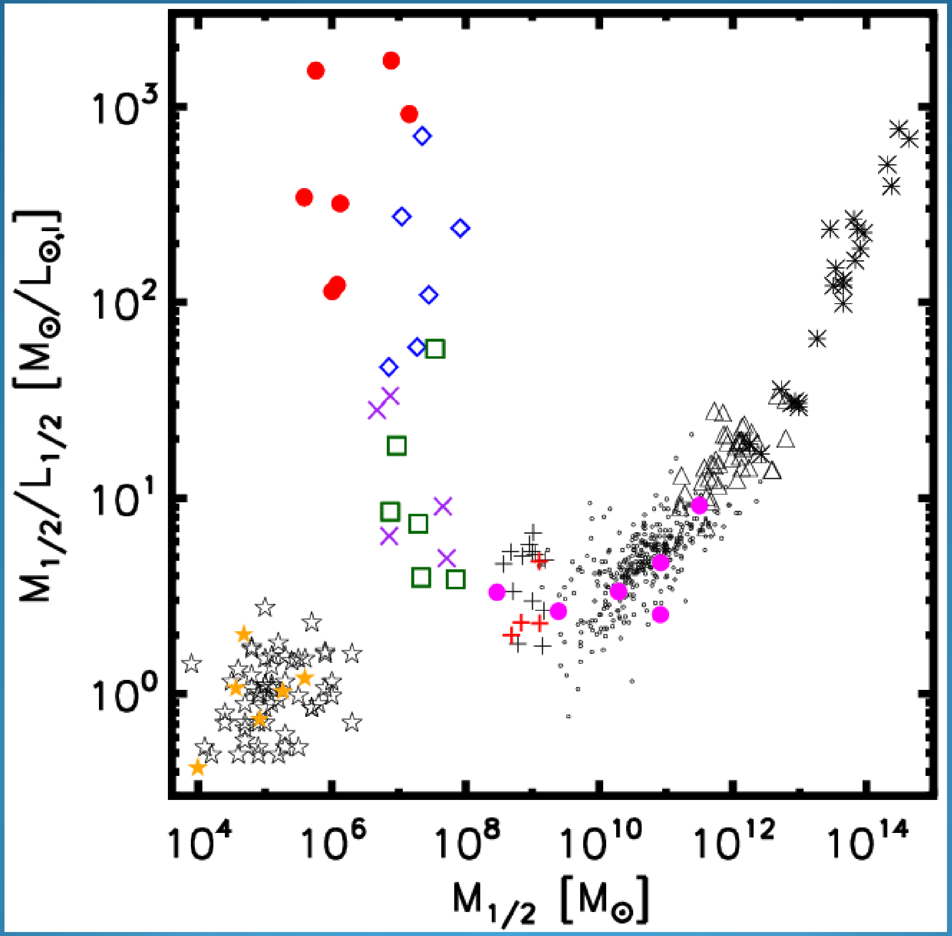
A common mass scale? Plotted: $M_{halo} = 10^9\ M_{sun}$
Minimum mass threshold for galaxy formation?





Notice: No trend with luminosity, as might be expected! Joe Wolf et al., in prep

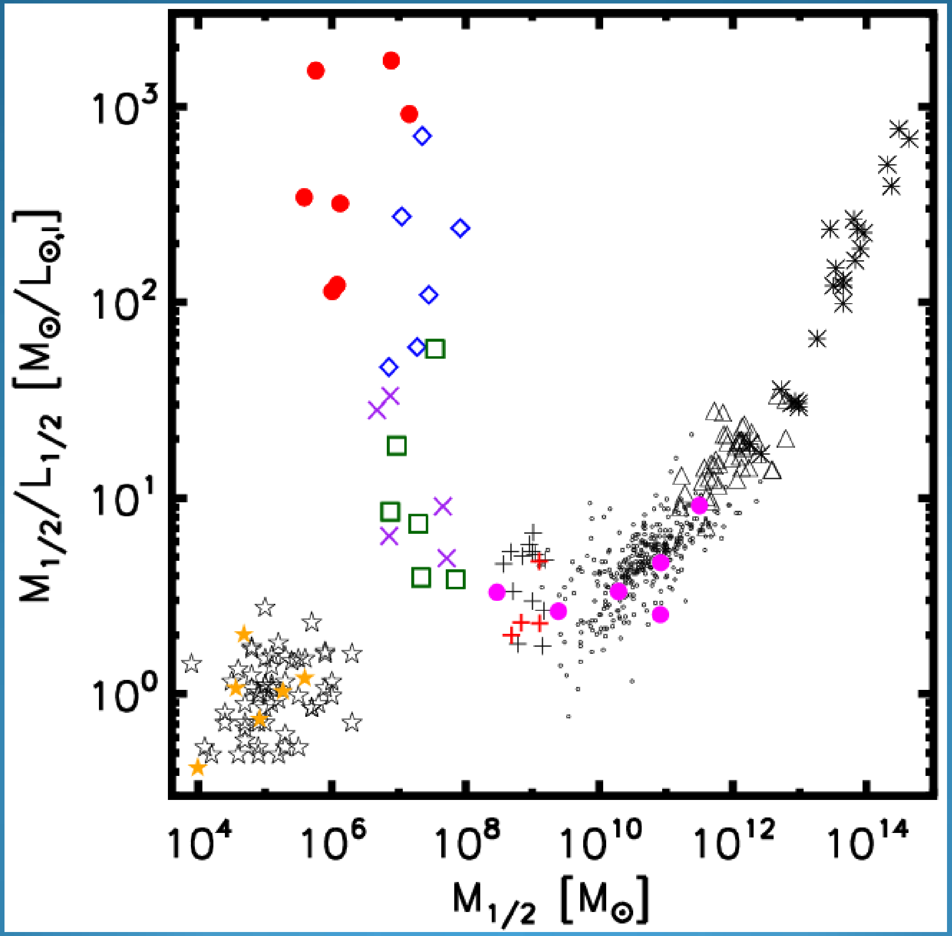
Applications: Global



Joe Wolf et al., in prep

Applications: Global

Much information about feedback & galaxy formation can be summarized with this plot. Also note similar trend to number abundance matching.



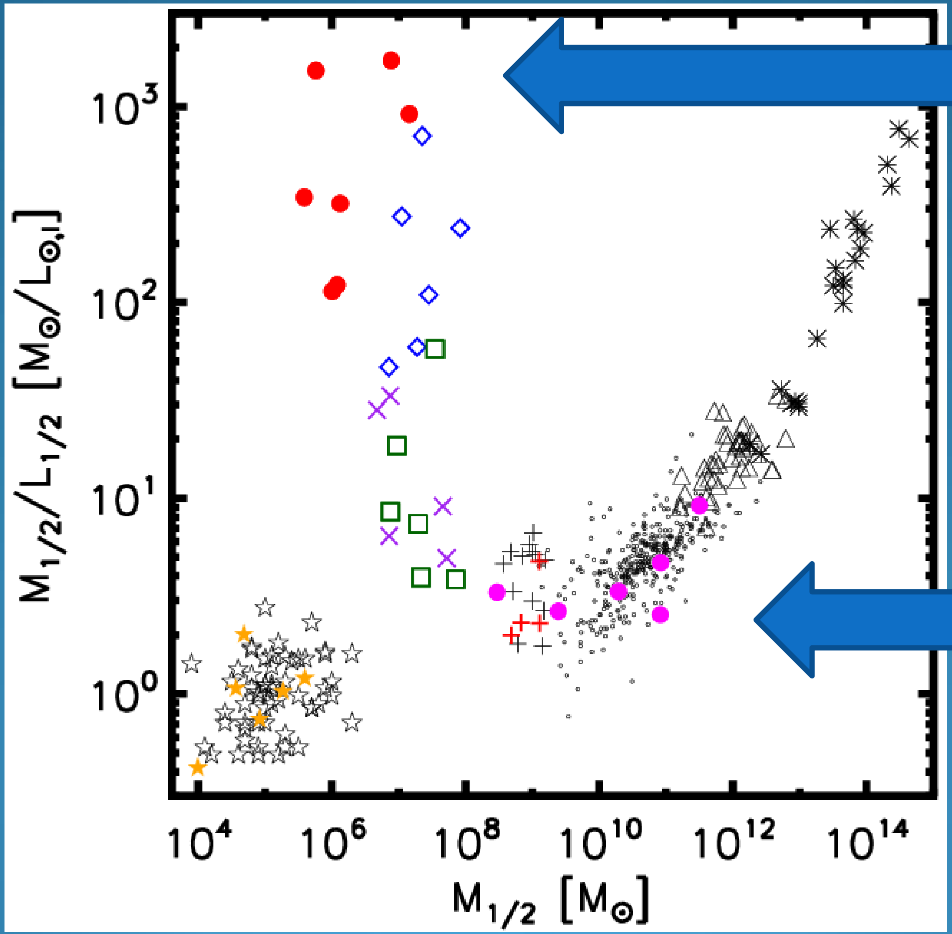
Joe Wolf et al., in prep

Applications: Global

Much information about feedback & galaxy formation can be summarized with this plot. Also note similar trend to number abundance matching.

Ultrafaint dSphs: most DM dominated systems known!

Globulars: Little to no dark matter



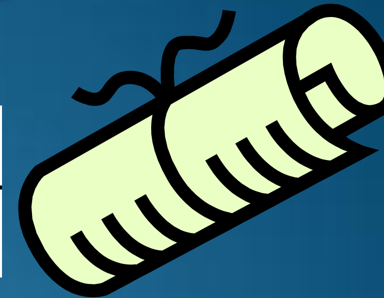
Inefficient at galaxy formation

L_*: Efficient at galaxy formation

Joe Wolf et al., in prep

Take-Home Messages

$$M_{1/2} = 3\, r_{1/2}\, \sigma^2_{\rm LOS}/G$$



$$\frac{M_{1/2}}{M_\odot} \simeq 930\, \frac{R_{\rm half}}{\rm pc} \left(\frac{\sigma_{\rm LOS}}{\rm km/s} \right)^2$$

- Knowing $M_{1/2}$ accurately without knowledge of anisotropy gives a new constraint for galaxy formation theories to match

- Future simulations must be able to reproduce these results

- arxiv.org/abs/0907.stay tuned!