Modeling mass independent of anisotropy

A comparison between Milky Way and Andromeda satellites

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(UC Irvine)

Dark Matter in Early-Type Galaxies Rio de Janeiro, Brazil August 3rd, 2009

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Outline

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

2. Applications of new mass determinations for MW dSphs

3. Comparison between MW and M31 dSphs

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 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

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Mass Density (6 parameters)

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

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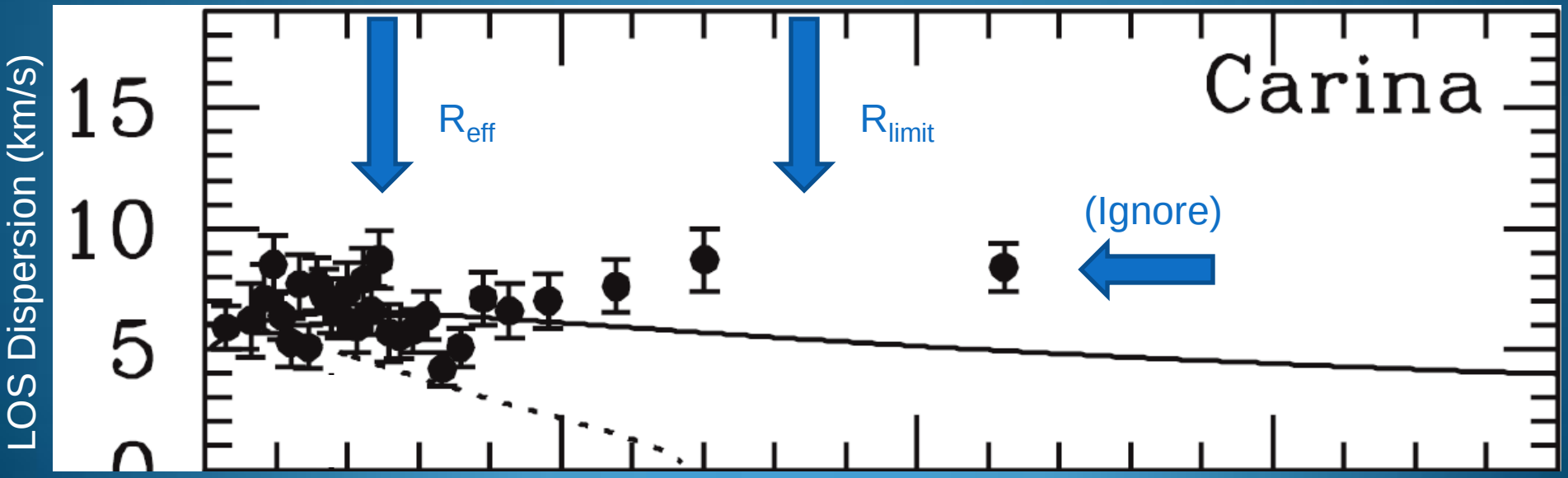
Using a Gaussian PDF for the observed stellar velocities, we marginalize over all free parameters (including photometric uncertainties) using a Markov Chain Monte Carlo (MCMC).

Thought Experiment

Given the following kinematics…



Projected (On Sky) Radius

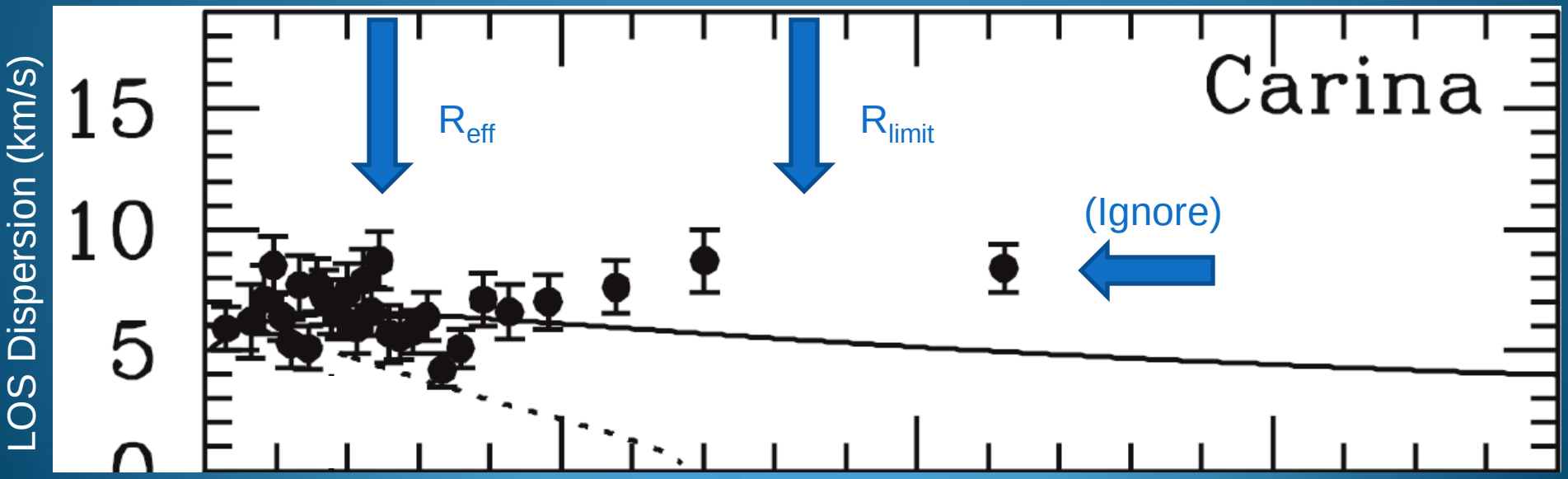
Walker et al. 2007, ApJ

Thought Experiment

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

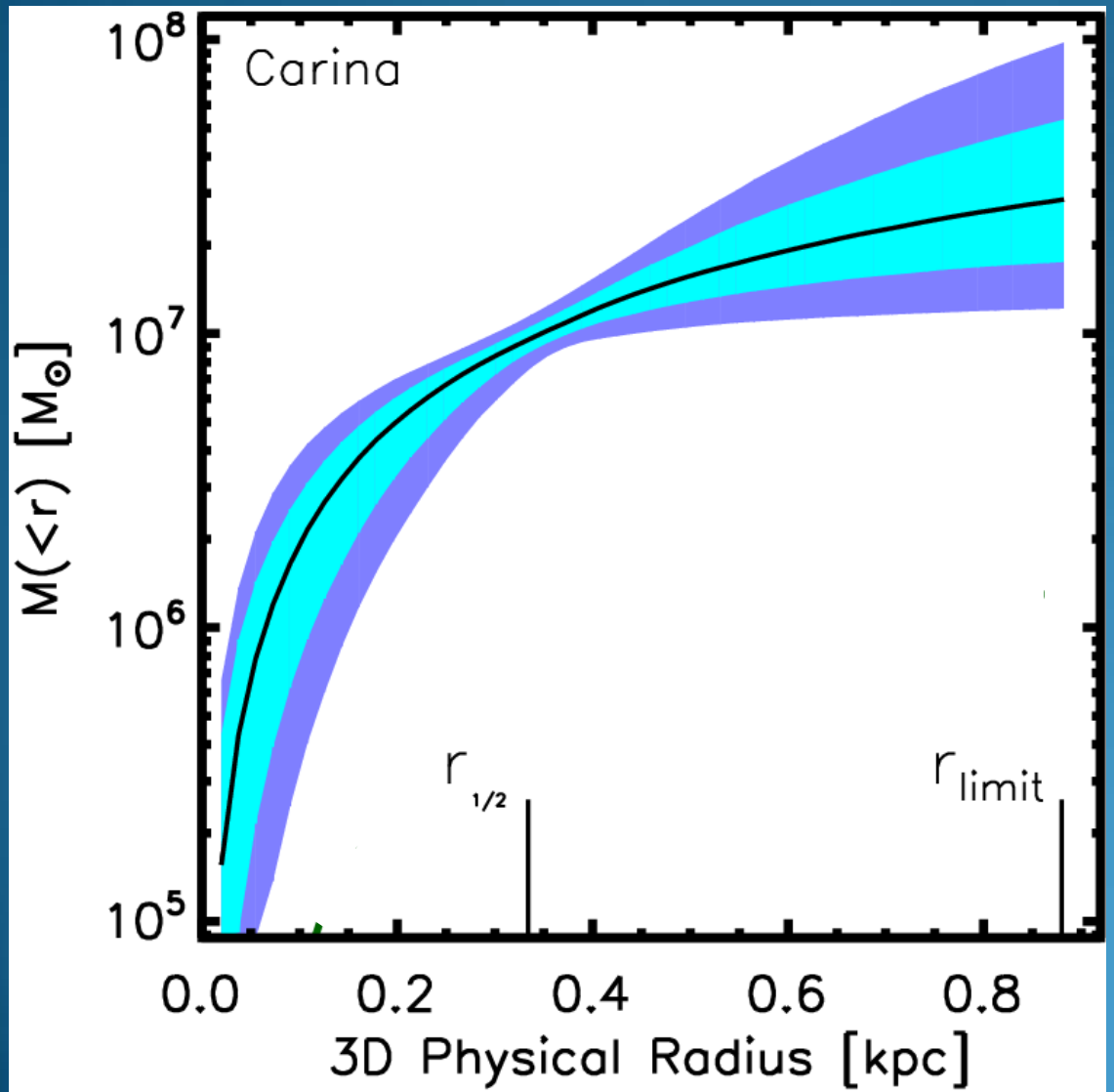
a) $0.5 * r_{1/2}$ b) $r_{1/2}$ c) $1.5 * r_{1/2}$

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...

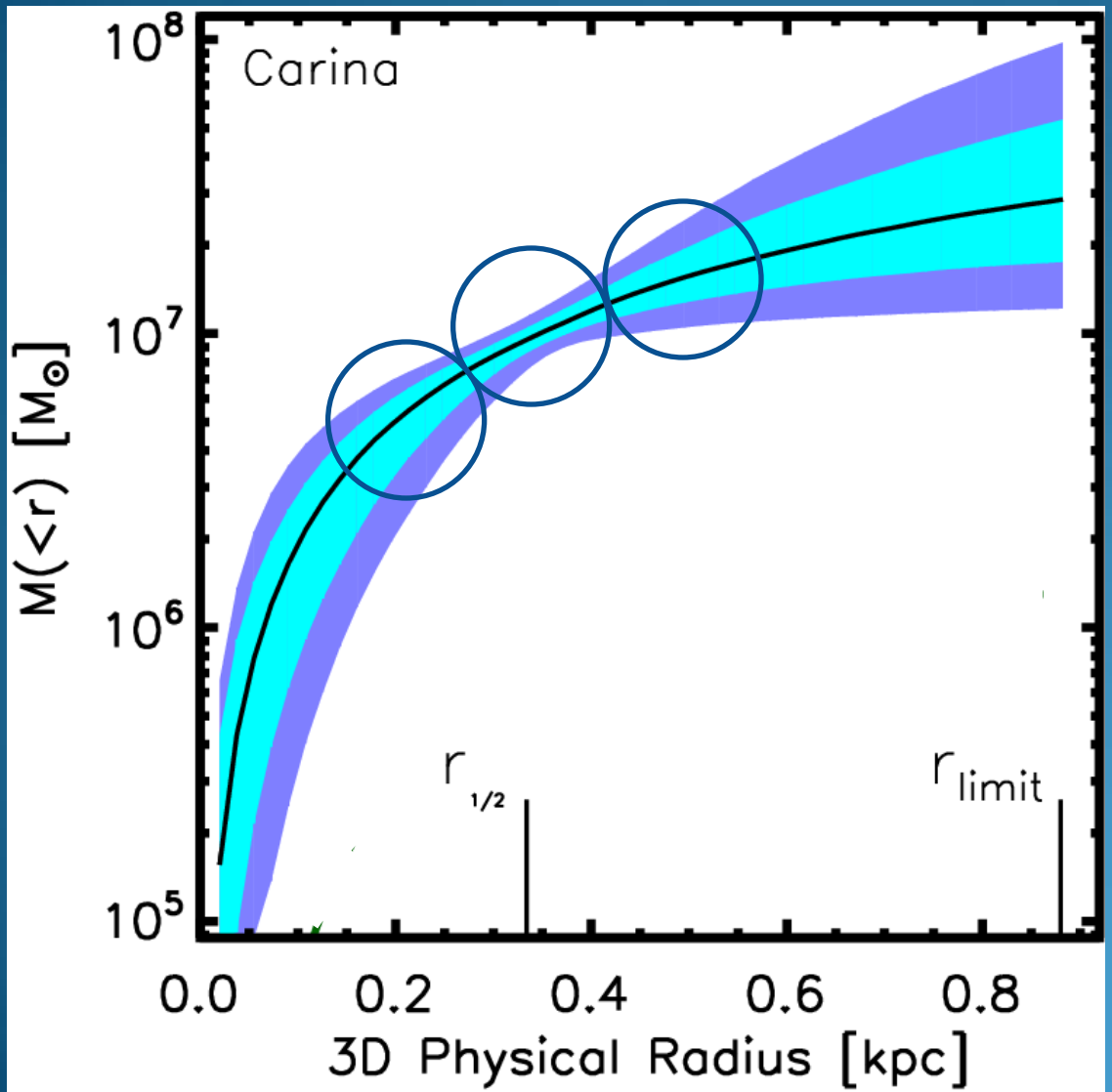


<u>Confidence Intervals:</u>
Cyan: 68%
Purple: 95%

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 $r > r_{1/2}$.



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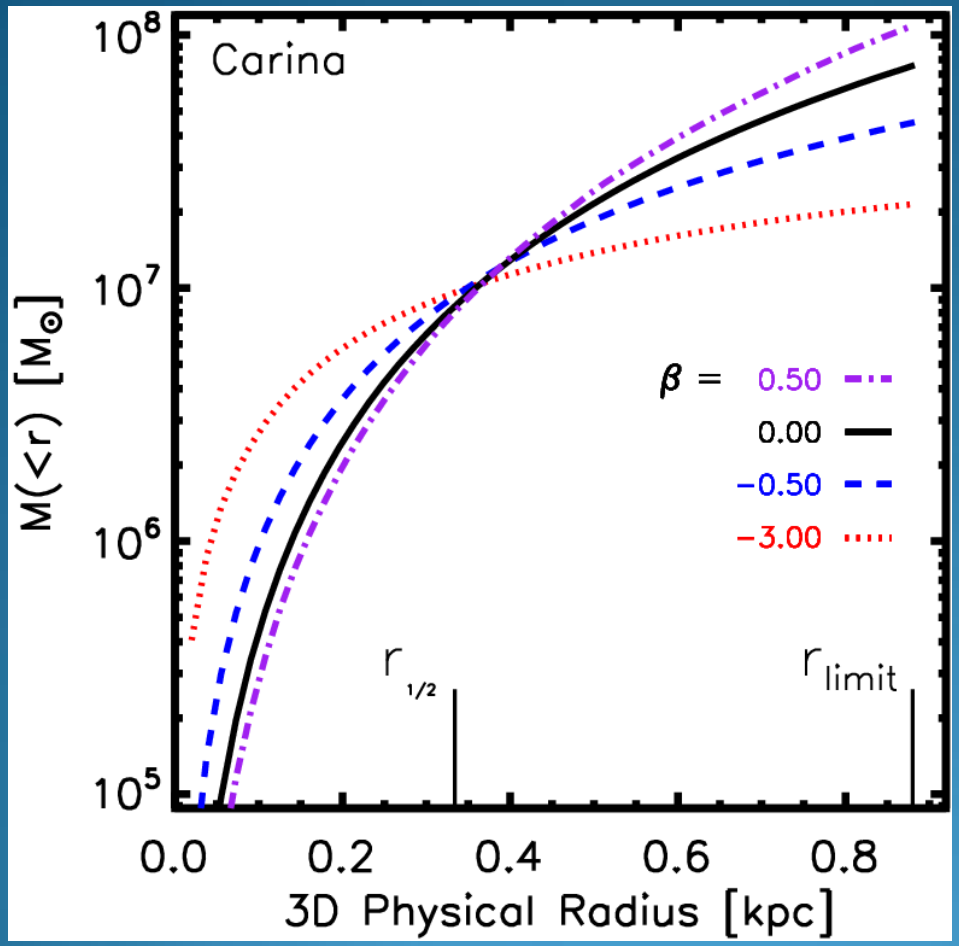
Joe Wolf et al., in prep

Anisotrwhat?



Radial Anisotropy

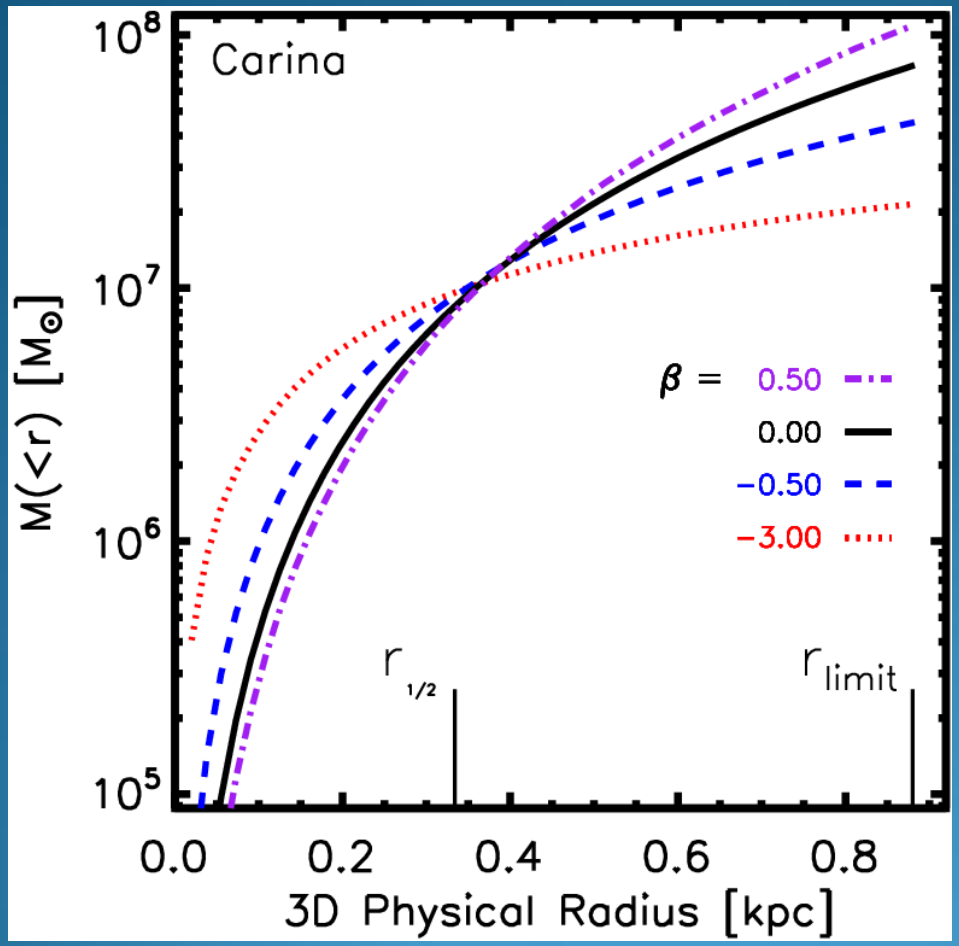
Isotropic

Tangential

Joe Wolf et al., in prep

Anisotrwhat?

Center of system:
Observed dispersion is radial



Edge of system: Observed dispersion is tangential

Radial Anisotropy

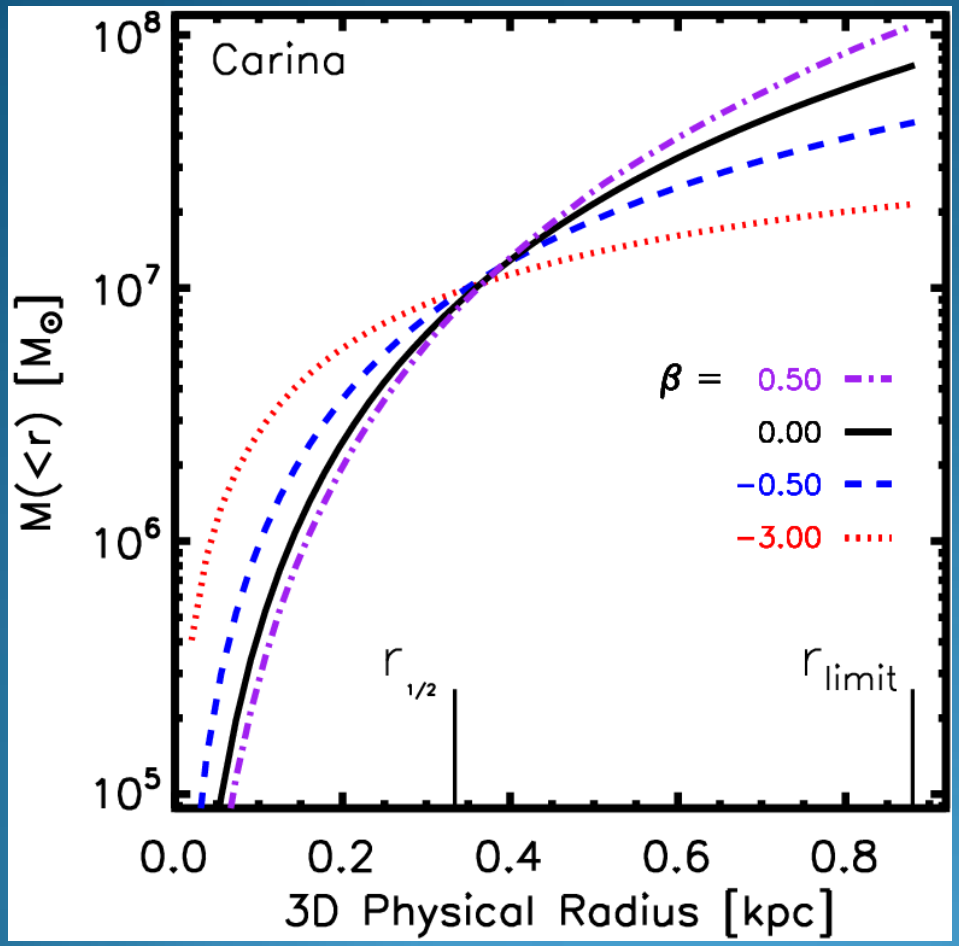
Isotropic

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 near $r_{1/2}$ for observed stellar densities:

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

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

Derived equation under several simplifications:

$$M_{1/2} = 3\, G^{-1}\, r_{1/2}\, \langle \sigma_{los}^2 \rangle$$

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Derived equation under several simplifications:

$$M_{1/2} = 3\, G^{-1}\, r_{1/2}\, \langle \sigma_{los}^2 \rangle$$

$$\frac{M_{1/2}}{M_\odot} \simeq 930\, \frac{R_{eff}}{pc}\, \frac{\langle \sigma_{los}^2 \rangle}{km^2\, s^{-2}}$$

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

Wait a second…

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

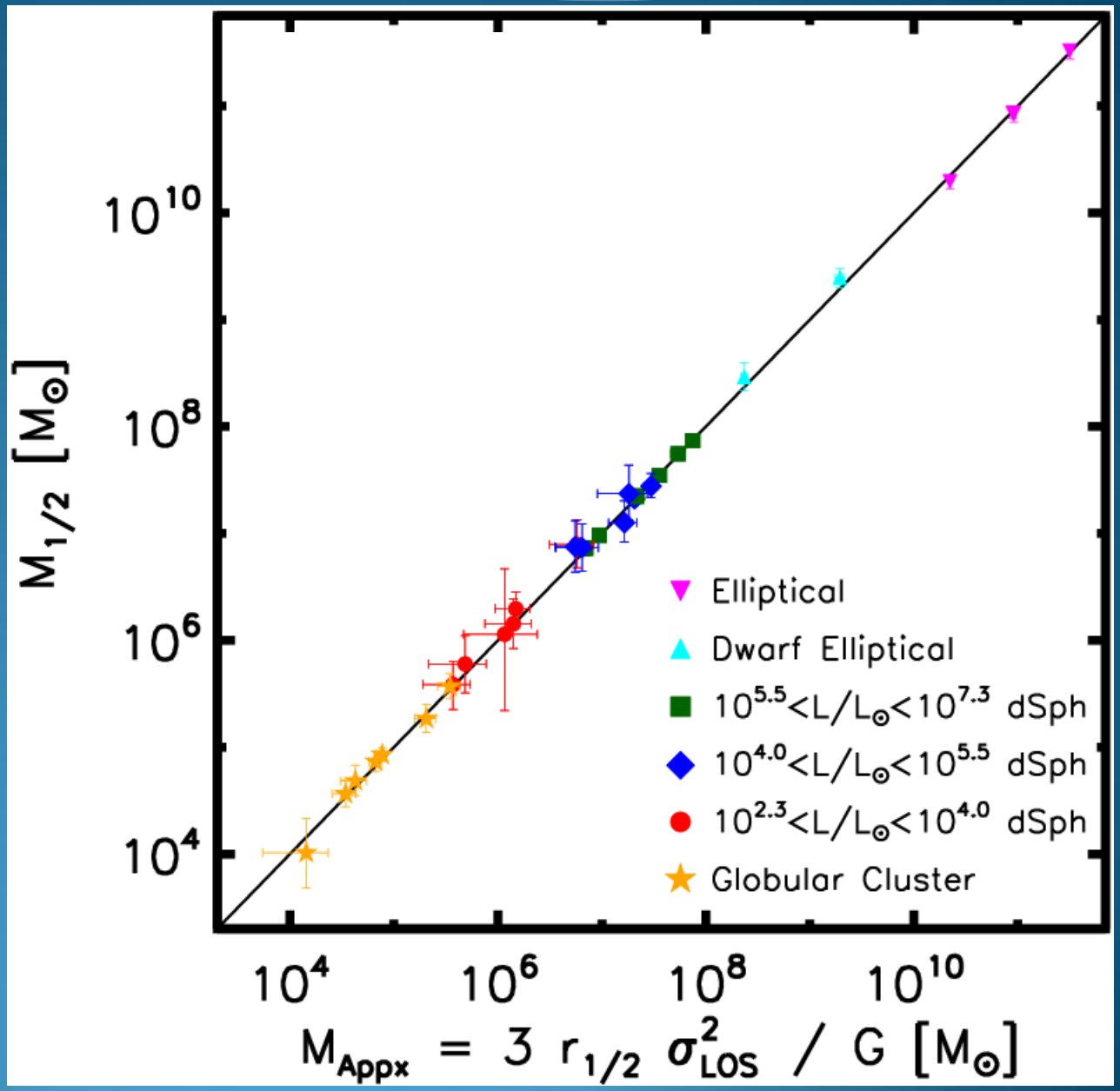
$$M_{1/2} = 3\,G^{-1}\,r_{1/2}\,\langle \sigma_{\rm los}^2 \rangle$$

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?

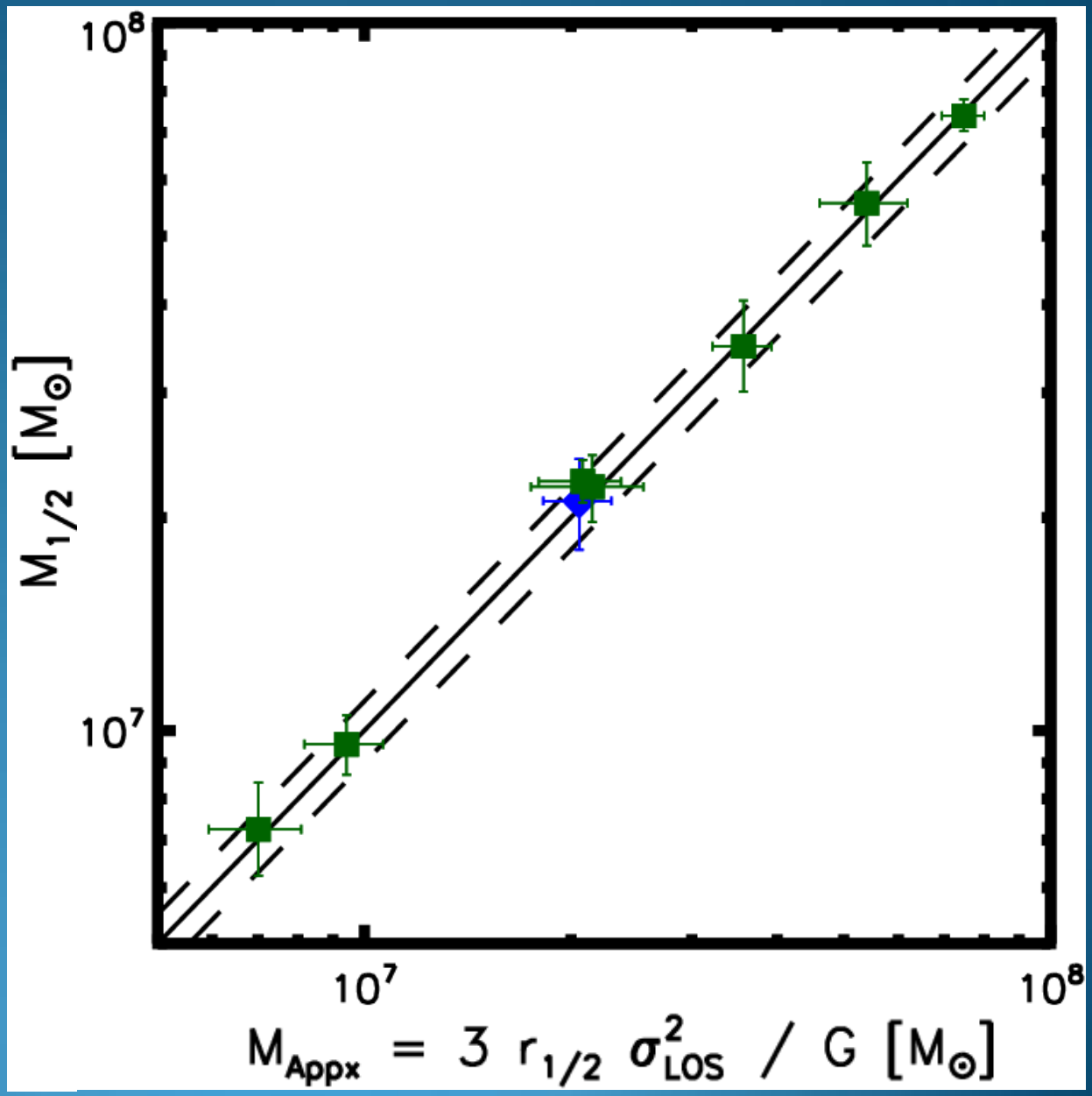
Boom!
Equation tested on systems spanning almost **eight** decades in half-light mass after lifting simplifications.



Joe Wolf et al., in prep

Boom!

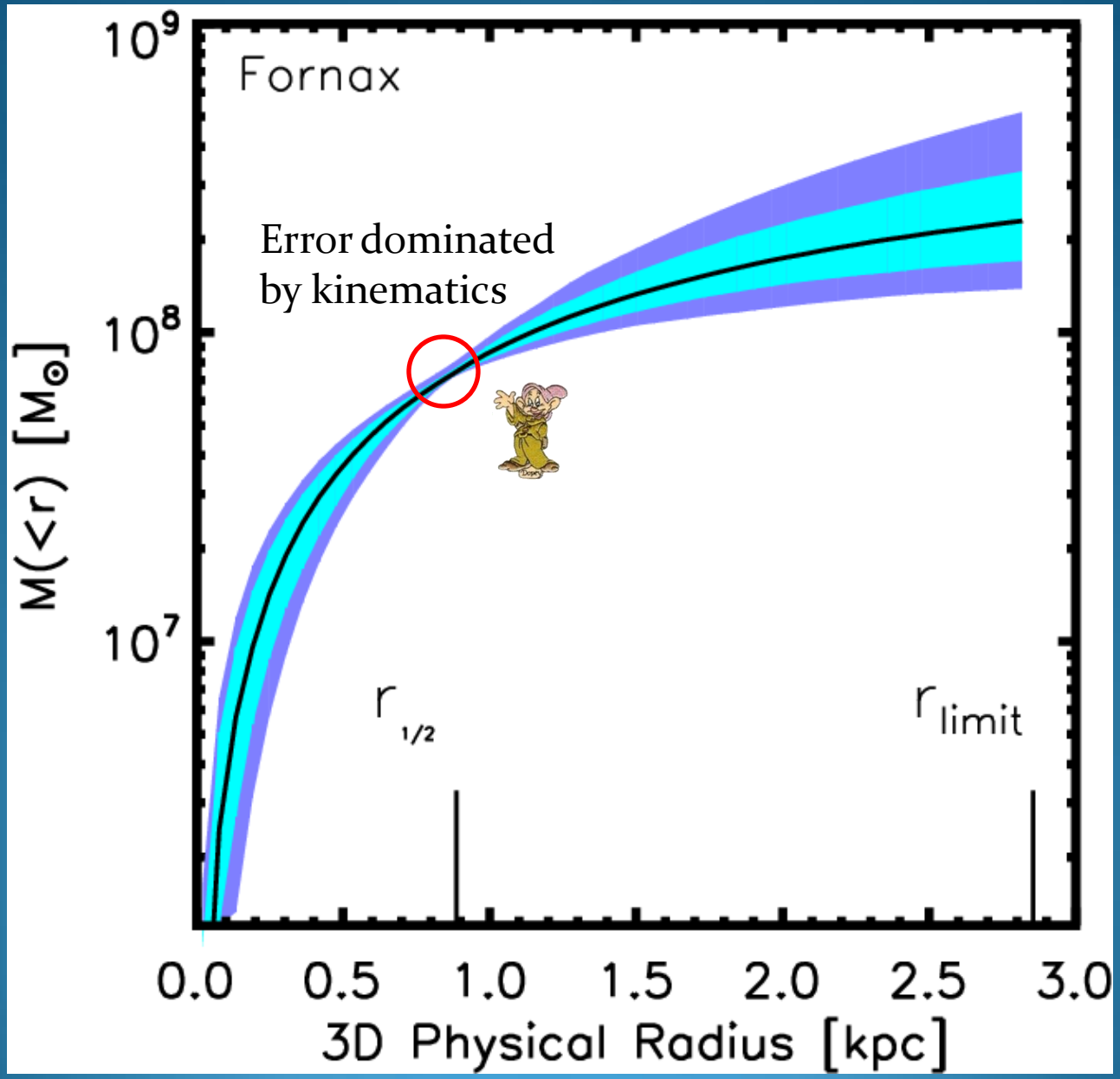
"Classical" MW dwarf spheroidals



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

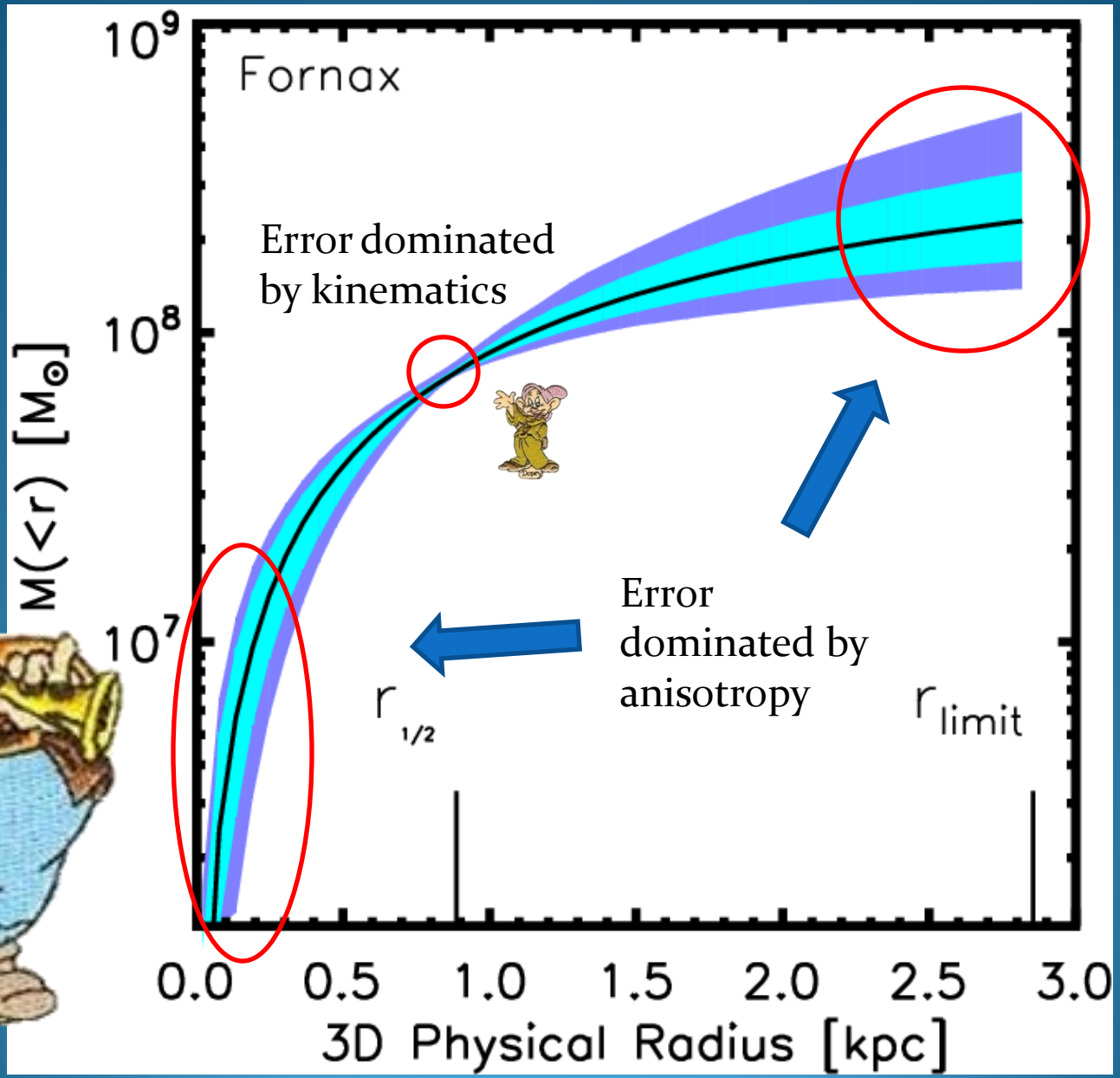
Joe Wolf et al., in prep

Mass Errors: Origins



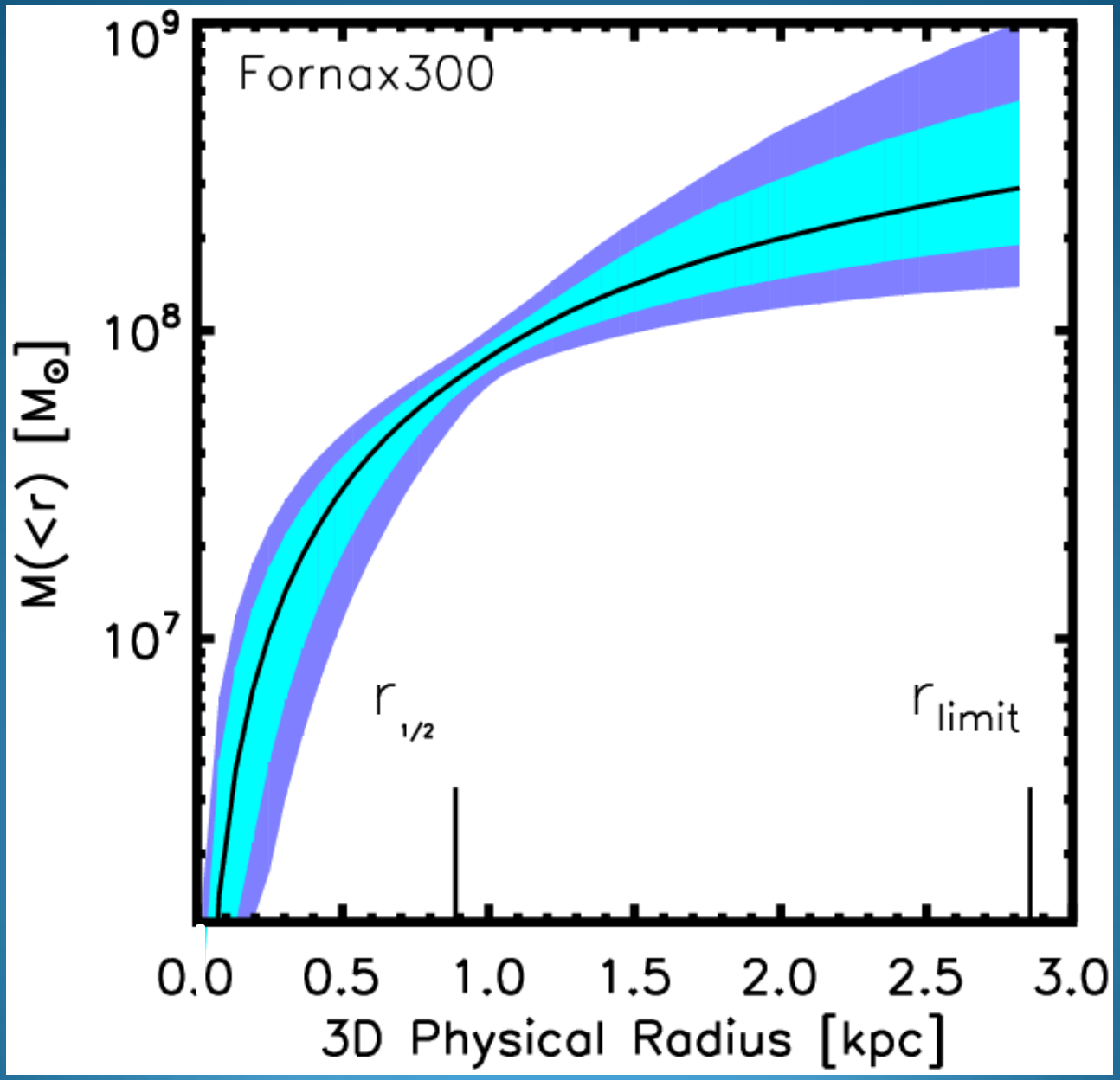
Joe Wolf et al., in prep

Mass Errors: Origins



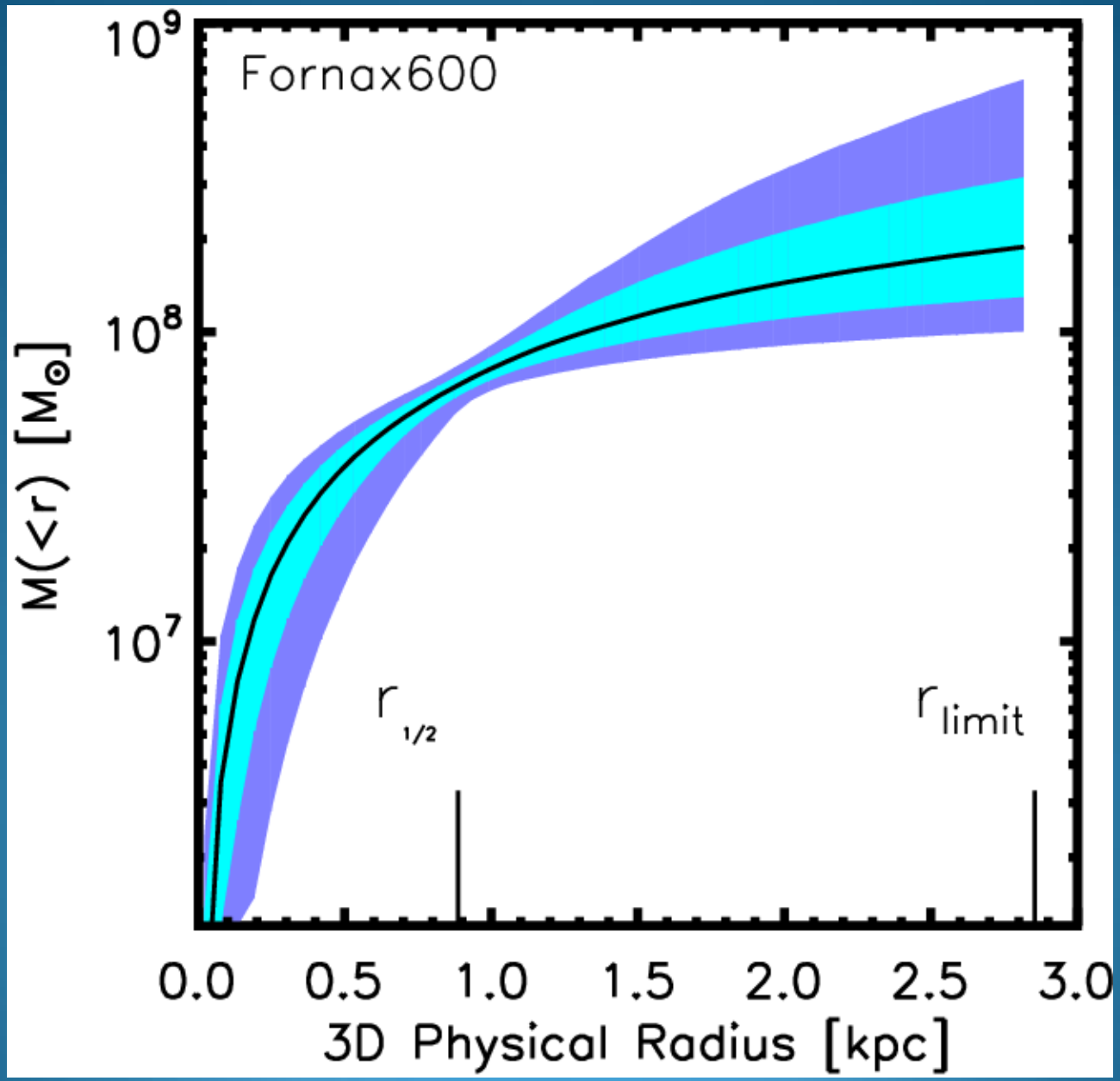
Joe Wolf et al., in prep

Mass Errors: 300 stars



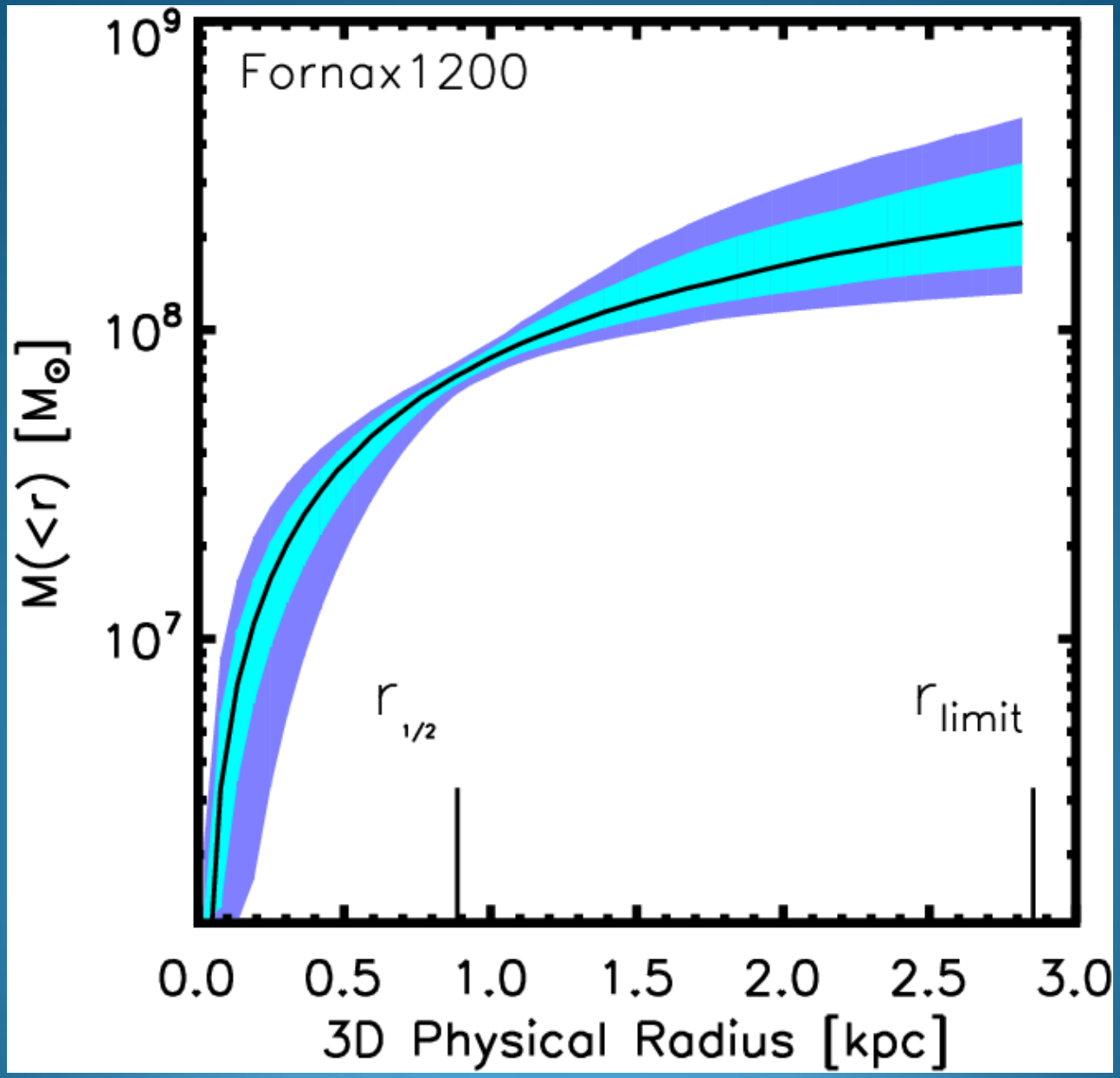
Joe Wolf et al., in prep

Mass Errors: 600 stars



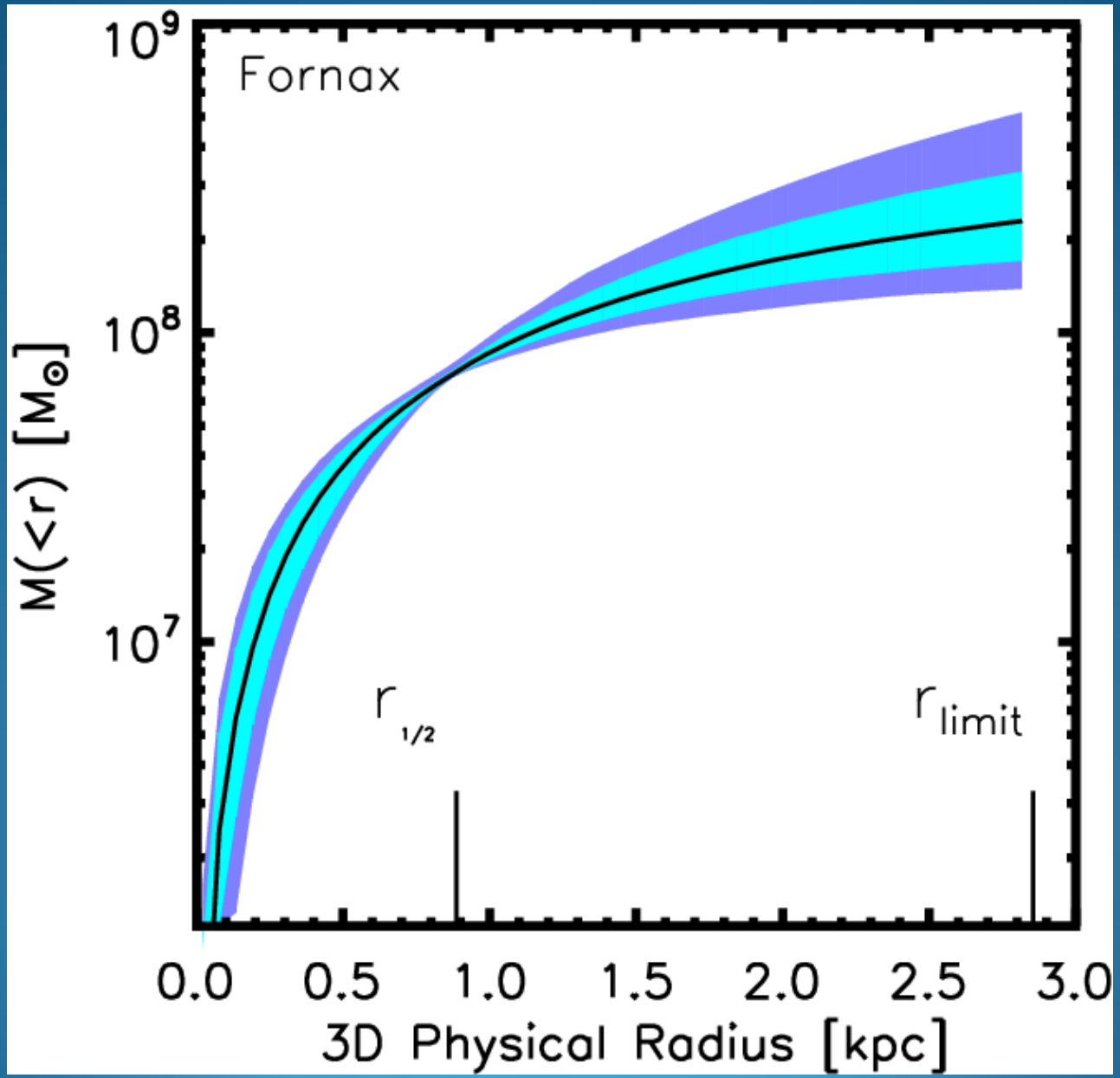
Joe Wolf et al., in prep

Mass Errors: 1200 stars



Joe Wolf et al., in prep

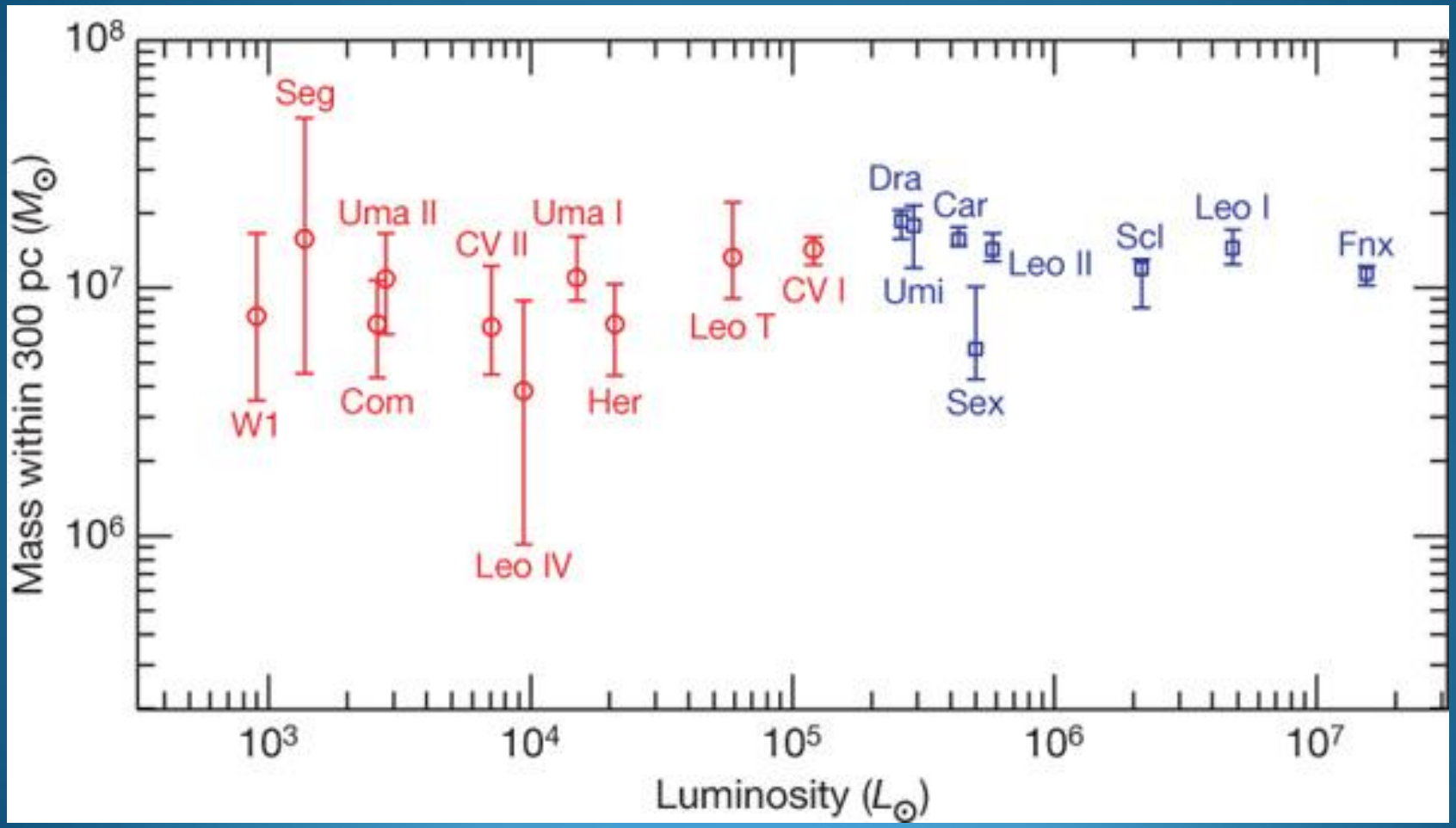
Mass Errors: 2400 stars



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

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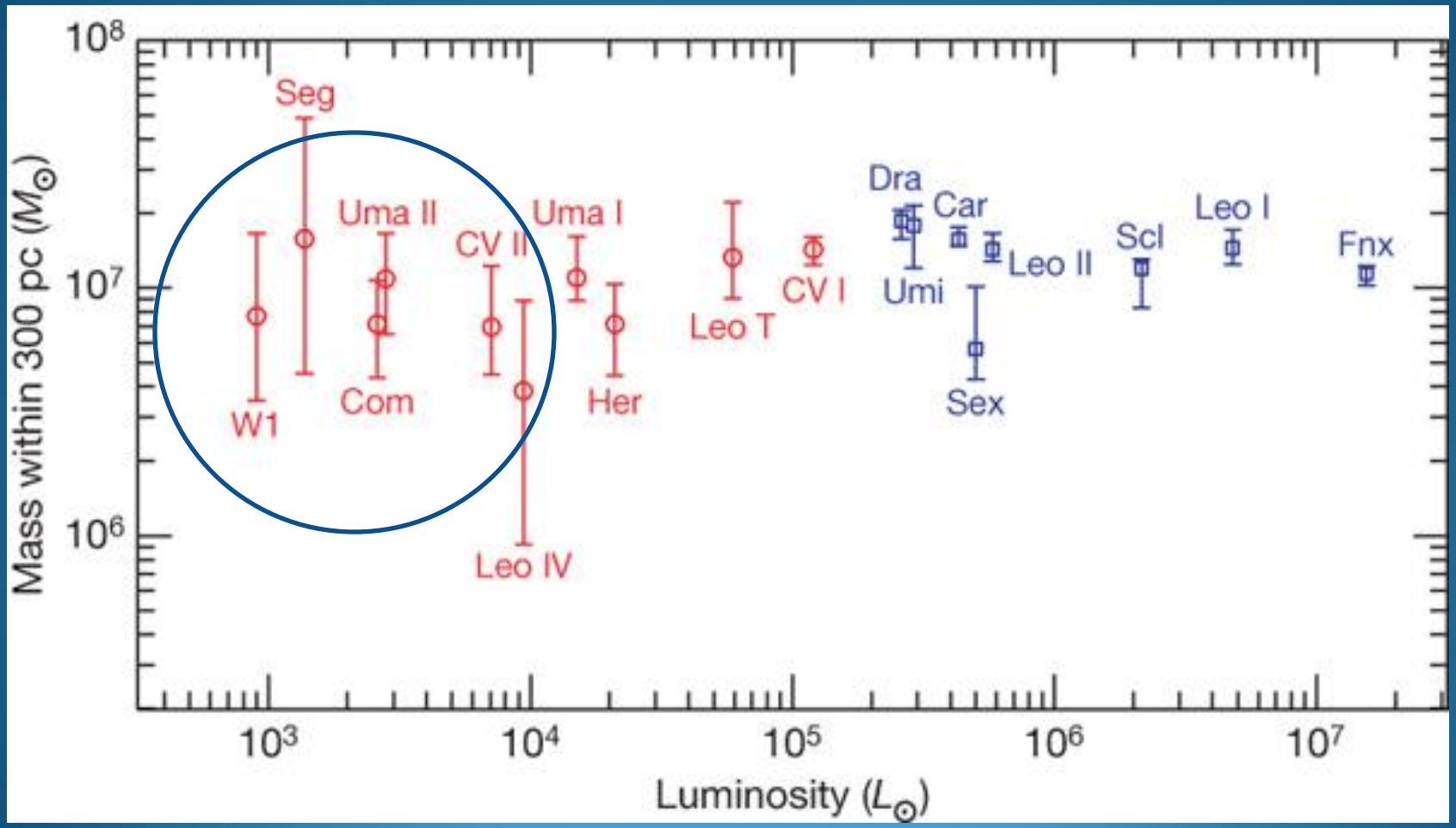

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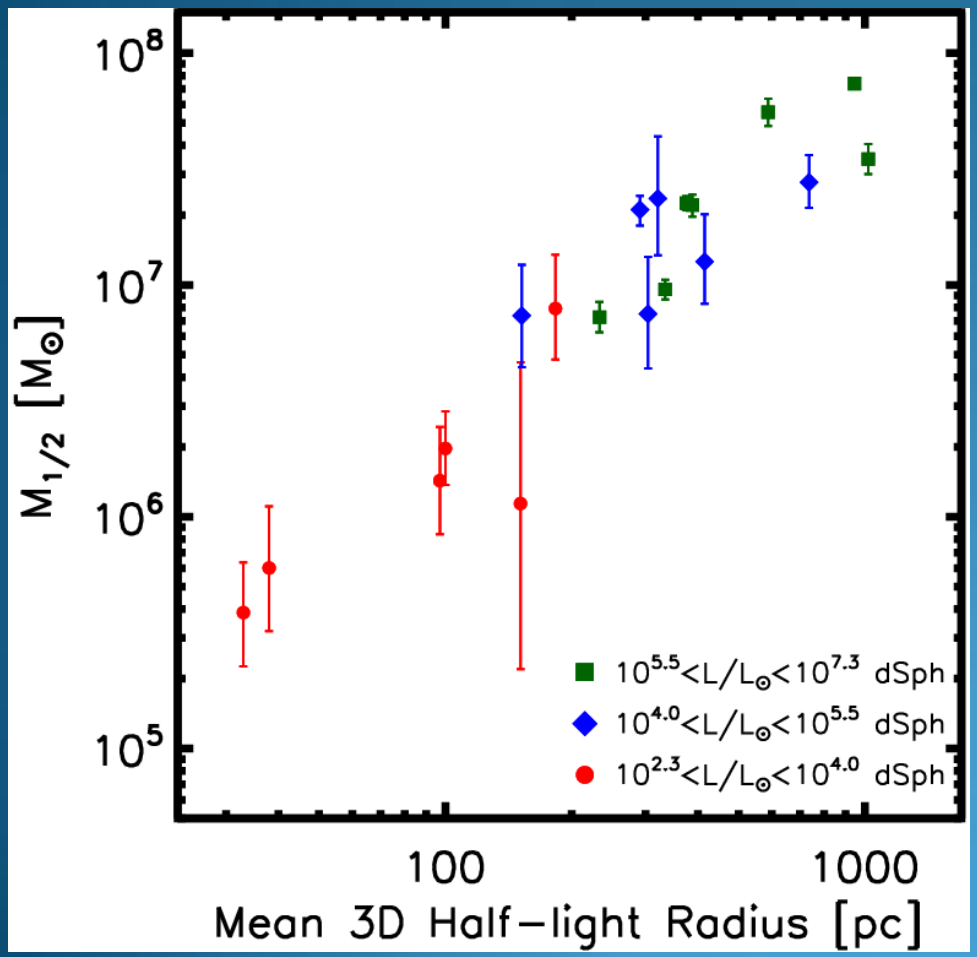
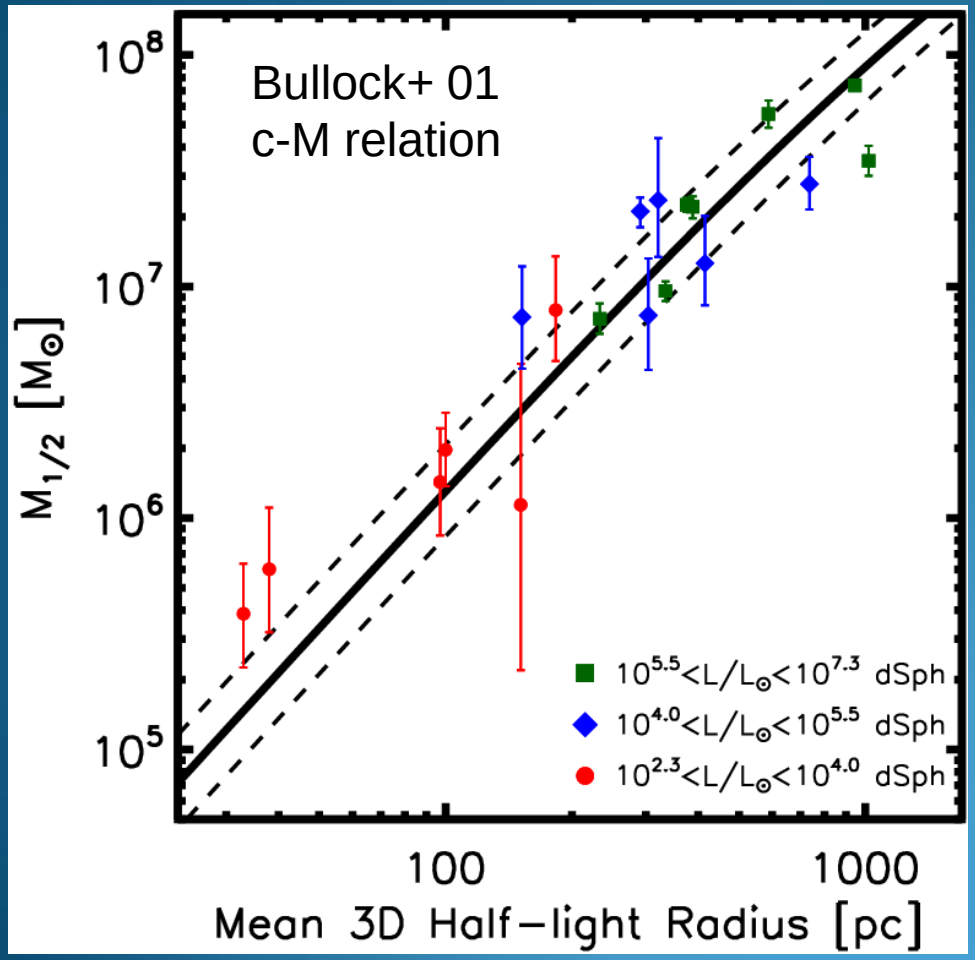


Joe Wolf et al., in prep

Applications: dSphs

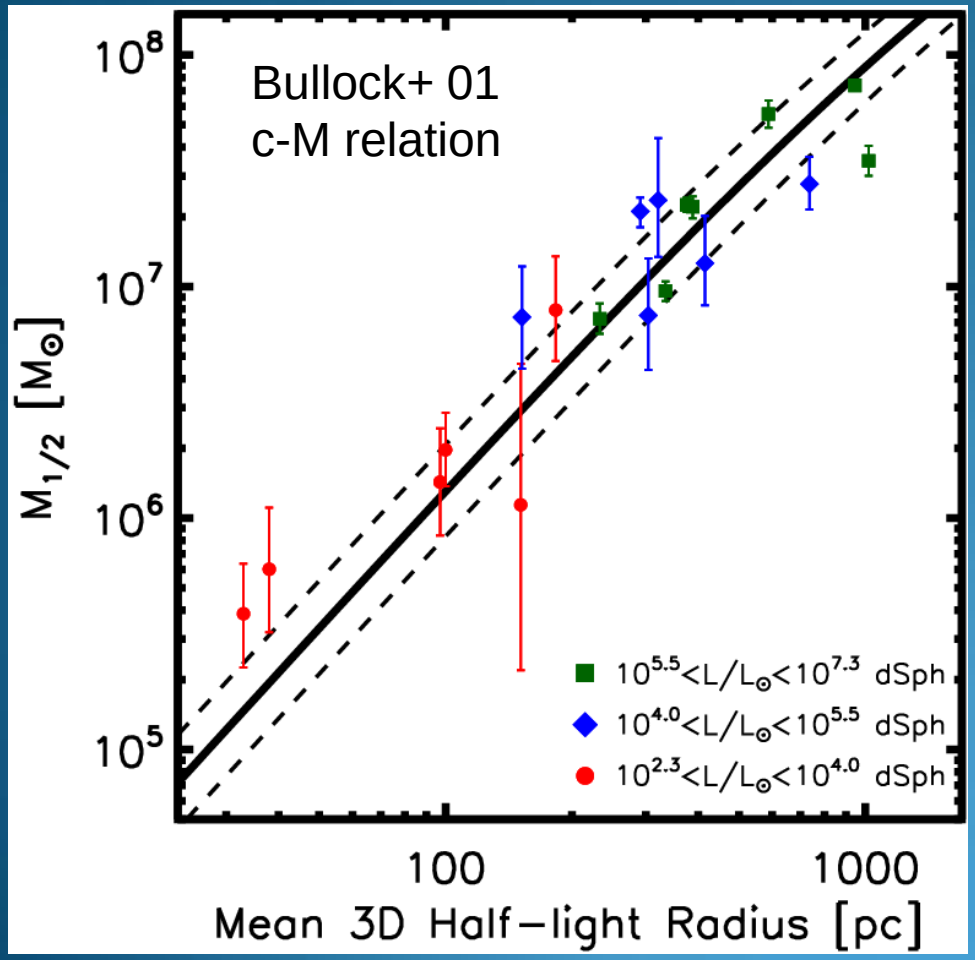
A common mass scale? Plotted: $M_{halo} = 3 \times 10^9 M_{sun}$

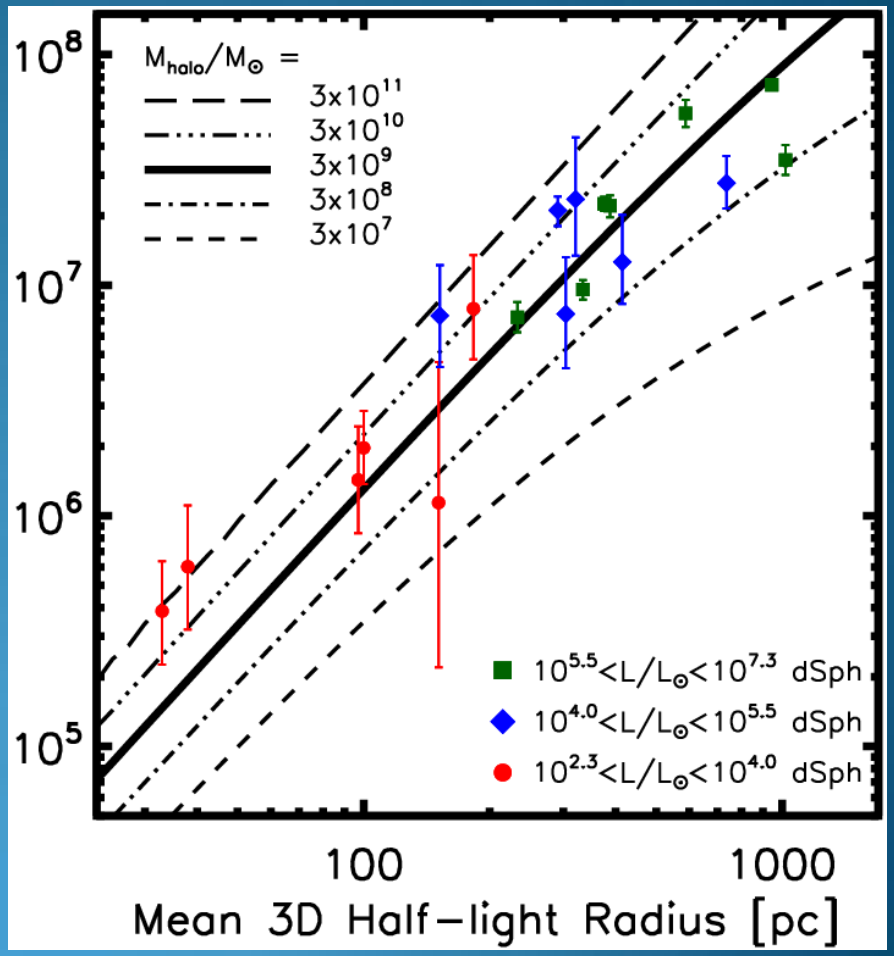


Joe Wolf et al., in prep

Applications: dSphs

A common mass scale? Plotted: $M_{halo} = 3 \times 10^9 M_{sun}$
Minimum mass threshold for galaxy formation?





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

Another dataset: M31

UC Irvine: James Bullock, Manoj Kaplinghat, Erik Tollerud, Joe Wolf, Basilio Yniguez

UC Santa Cruz: Raja Guhathakurta (SPLASH PI)

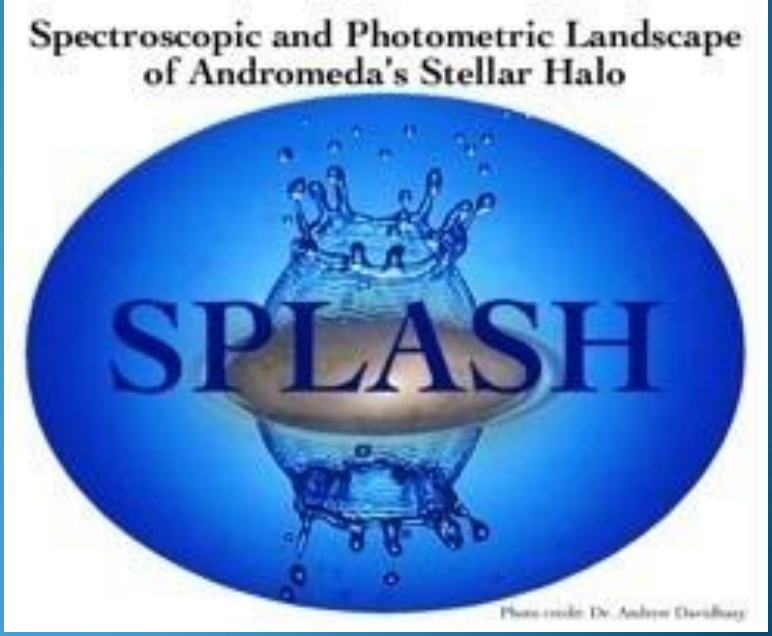
STScI: Jason Kalirai

Yale: Marla Geha

U. Washington: Karrie Gilbert

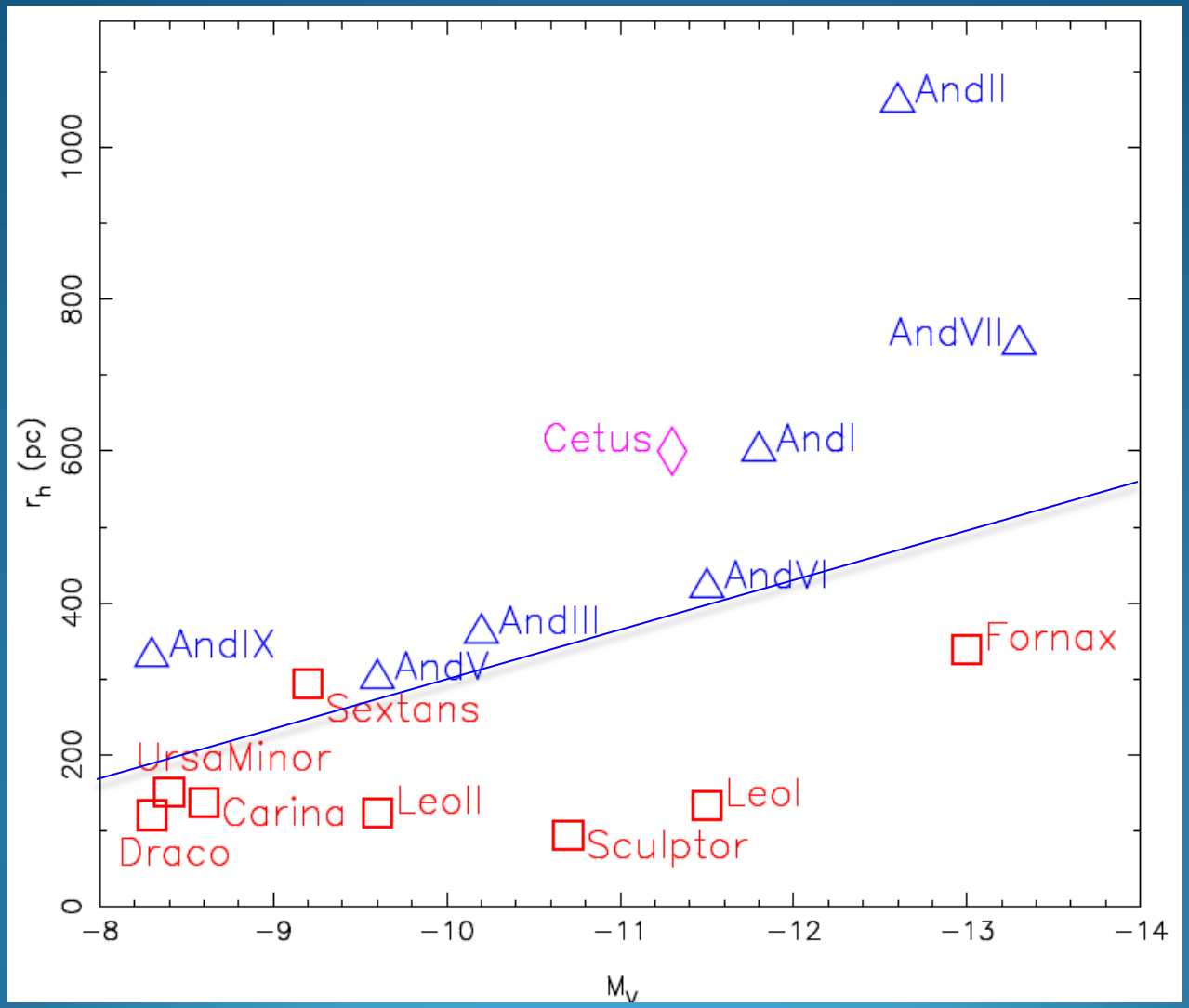
Caltech: Evan Kirby

And others involved in SPLASH →



M31 dSphs: Larger than MW dSphs

Observed half-light radius



Dim Luminosity Bright

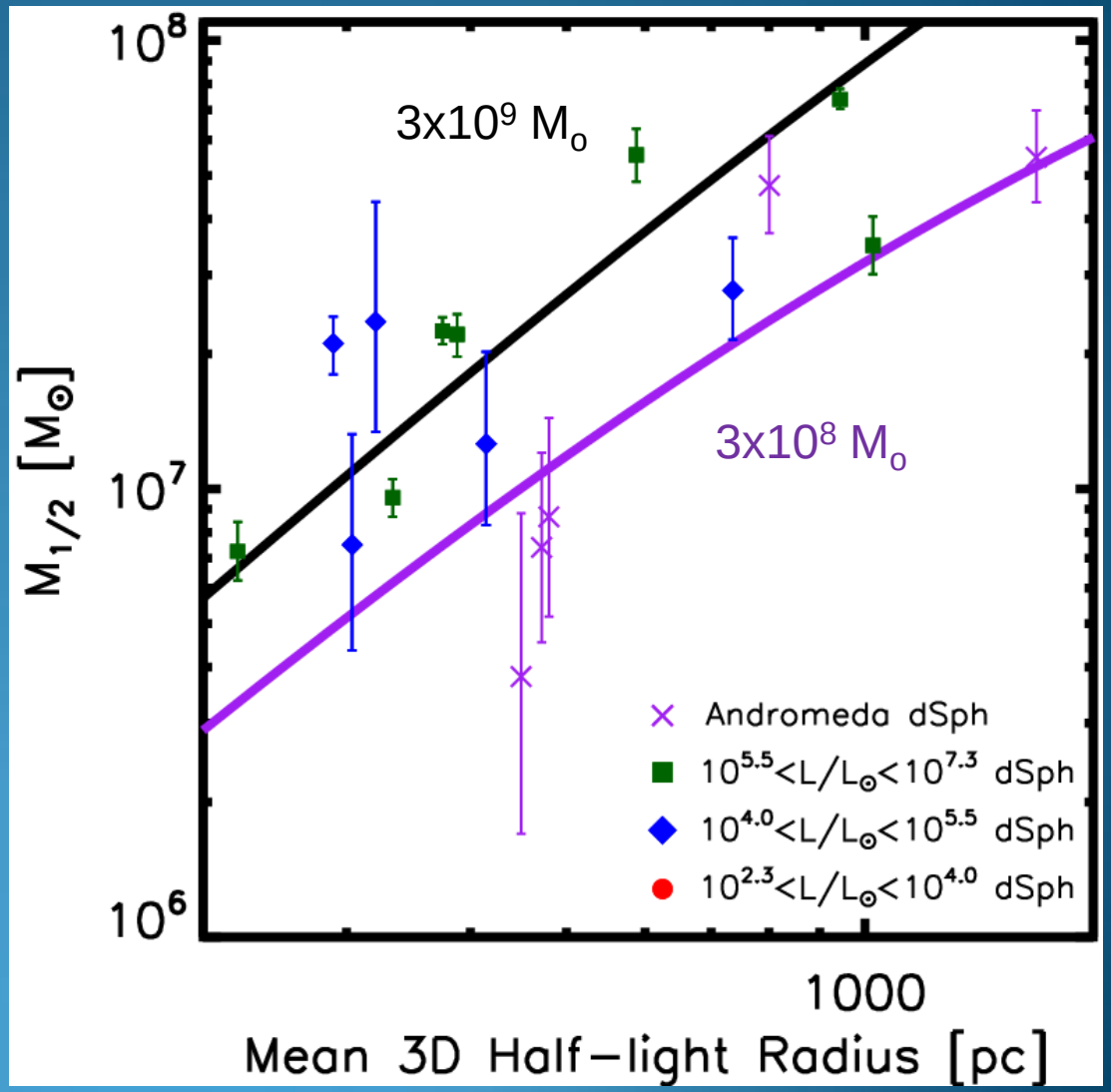
McConnachie & Irwin 2006, MNRAS

M31 dSphs: Bigger but less massive!

Spectroscopic data from Keck/DEIMOS.

DM halo mass offset by ~10.
M(<300 pc) offset by ~2.

Joe Wolf et al., in prep



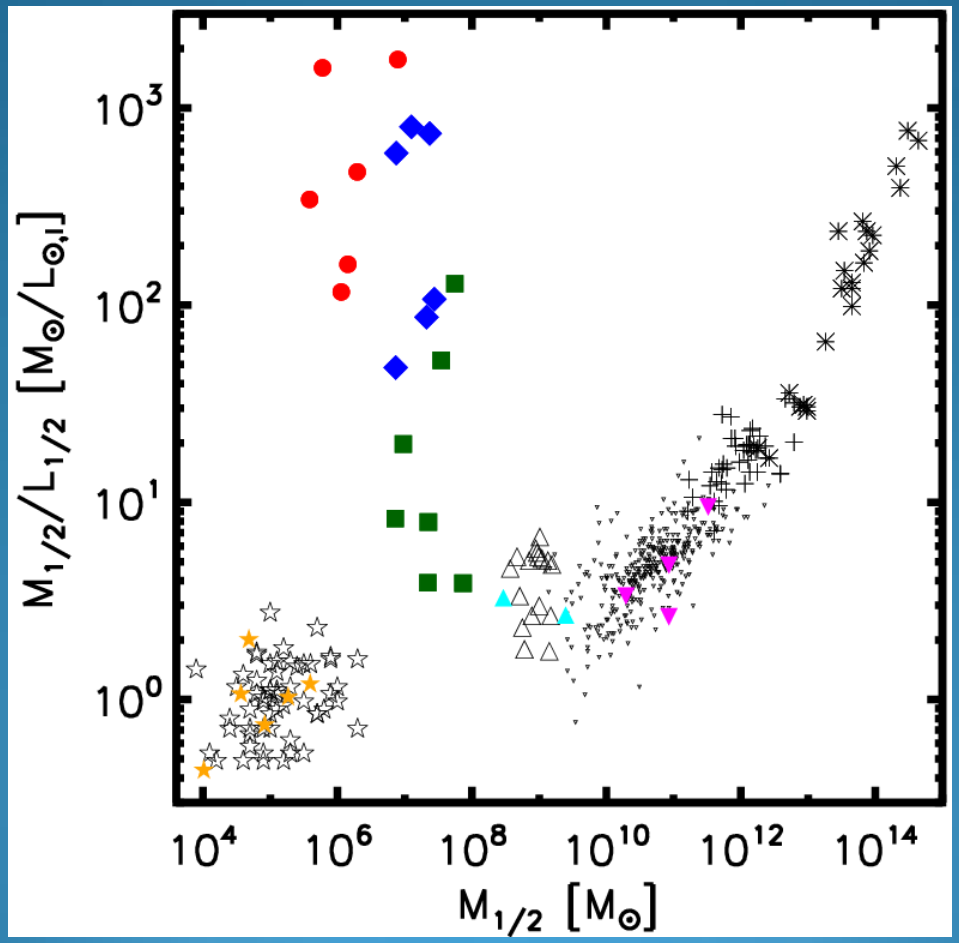
M31: Different Environment?

If M31's DM halo collapsed later → Less dense substructure & later forming star formation.

Interesting:

Brown et al. 2008 find that portion of investigated M31 stellar halo is younger (on average) than MW's.

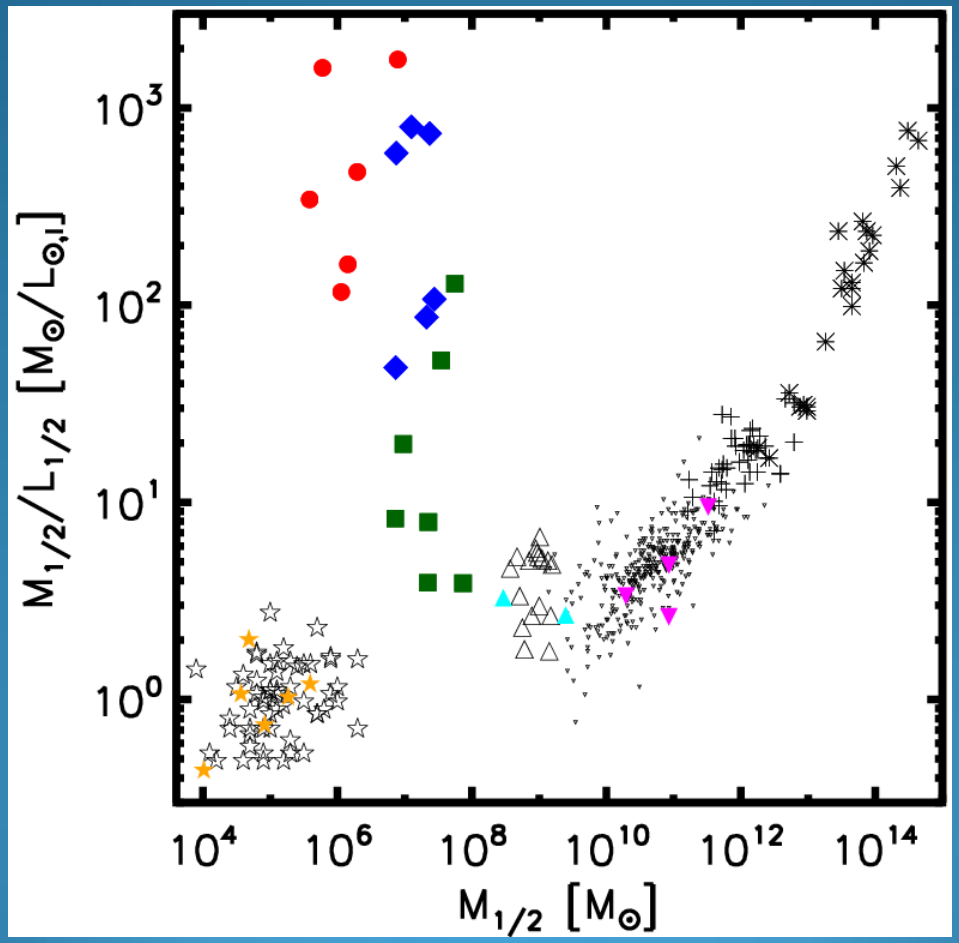
Applications: Global



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

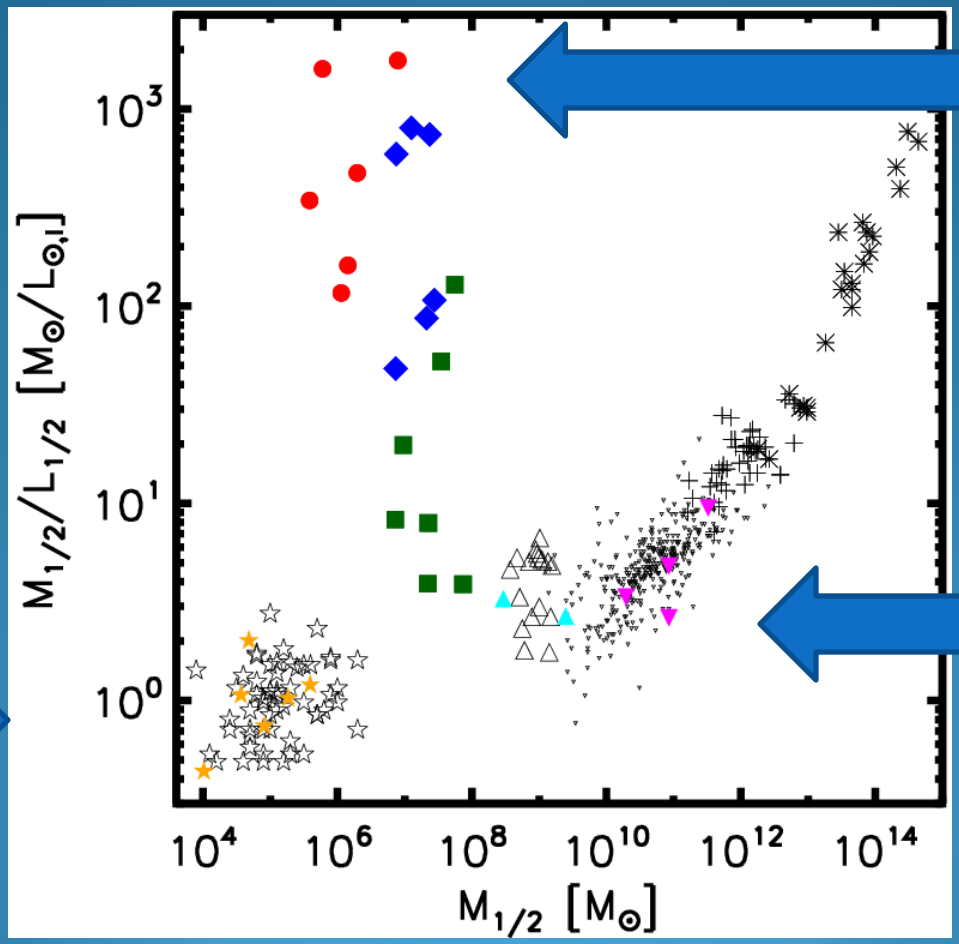
Applications: Global

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: Offset from L* by factor of three

(Hmm…)

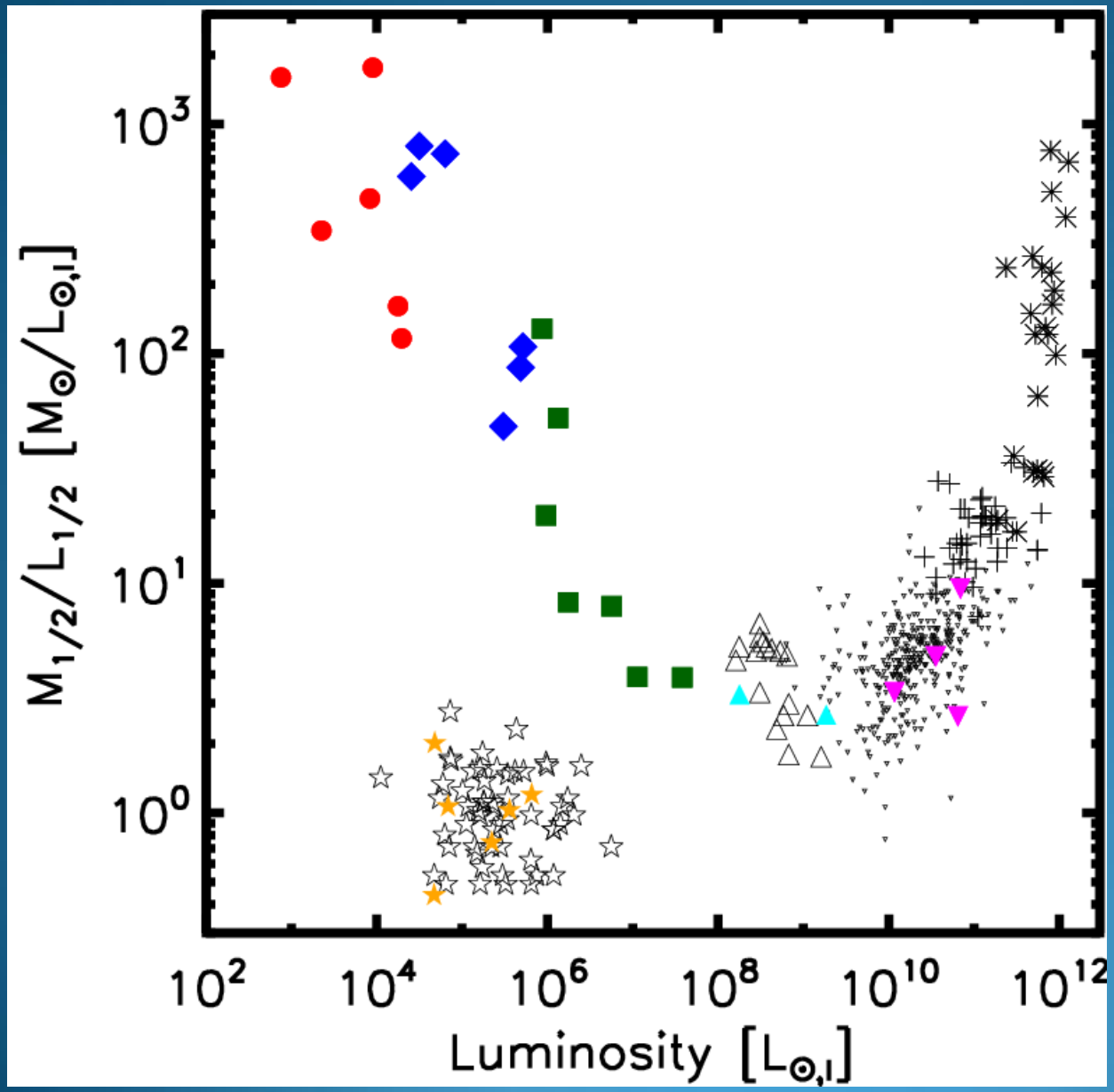


Inefficient at galaxy formation

L_*: Efficient at galaxy formation

Joe Wolf et al., in prep

Applications: Global



Last plot:
Mass floor

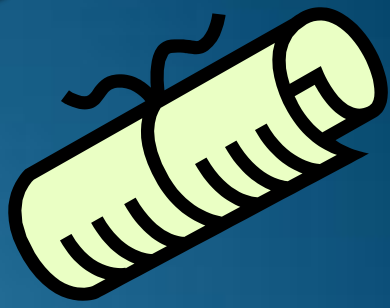
This plot:
Luminosity ceiling

Joe Wolf et al., in prep

Take-Home Messages

$$M_{1/2} = 3\, G^{-1}\, r_{1/2}\, \langle \sigma_{los}^2 \rangle$$

$$\frac{M_{1/2}}{M_\odot} \simeq 930\, \frac{R_{eff}}{pc}\, \frac{\langle \sigma_{los}^2 \rangle}{km^2\, s^{-2}}$$



Take-Home Messages

$$M_{1/2} = 3\, G^{-1}\, r_{1/2}\, \langle \sigma^2_{los} \rangle$$

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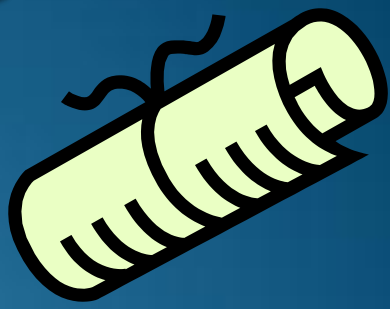


- M31 dSphs: Offset mass scale. What the *&%#?!

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

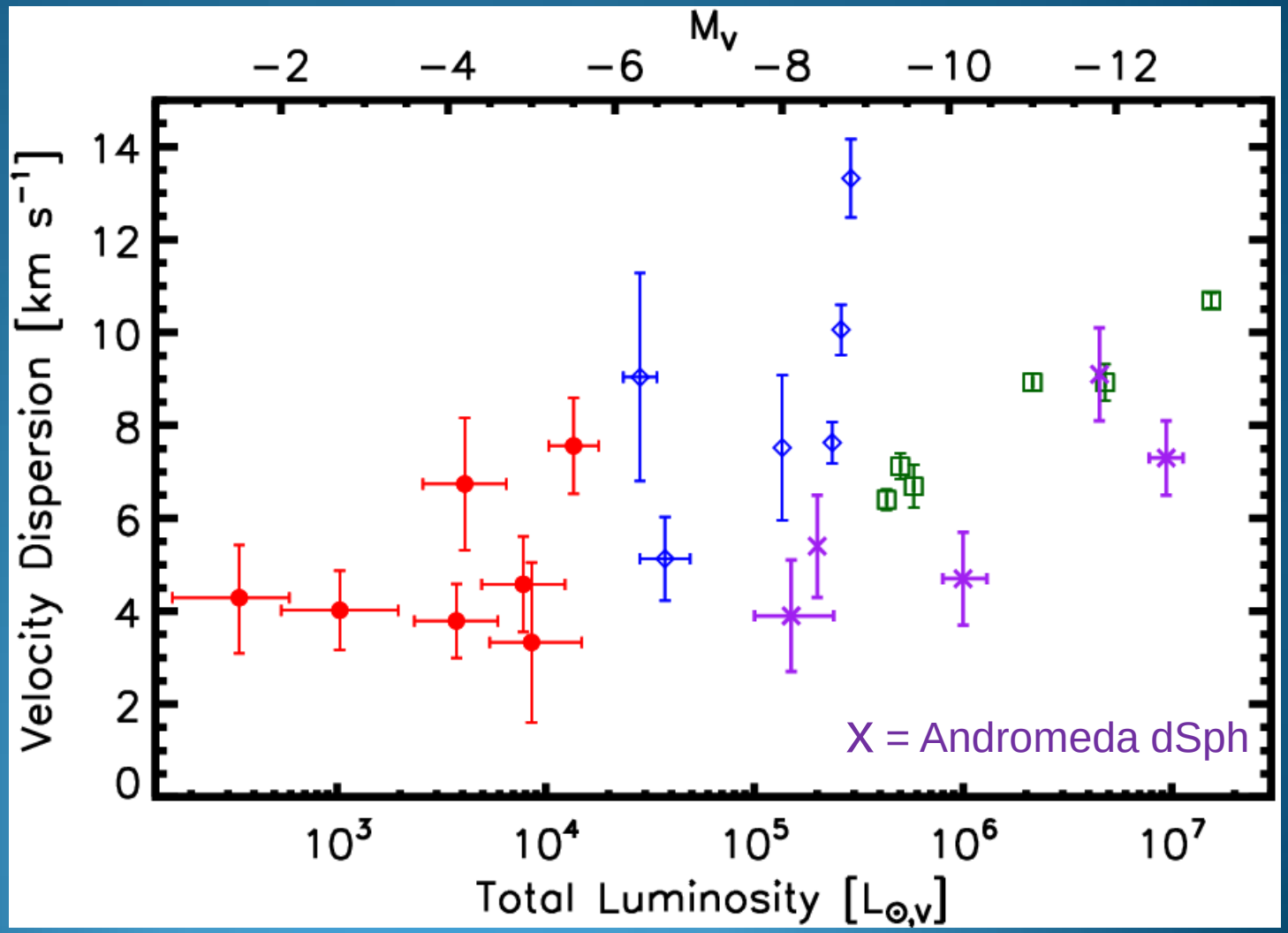
- Future simulations must be able to reproduce these results

- GCs vs L*: M/L ratios are offset…hmm?

Dispersion vs Luminosity

Keck/DEIMOS

And	#	σ km/s
I	76	9.1 ± 1.0
II	95	7.3 ± 0.8
III	43	4.7 ± 1.0
X	22	3.9 ± 1.2
XIV	38	5.4 ± 1.1



Dispersion data from Kalirai et al 2009, in prep