Density profiles of MW dwarf spheroidals - cusp vs core

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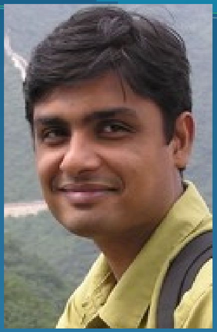
Joe Wolf
(UC Irvine)

Joelfest August 16, 2010 Santa Cruz, CA

Team Irvine:

Greg Martinez

James Bullock



Manoj Kaplinghat

Erik Tollerud

KIPAC: Louie Strigari

Haverford: Beth Willman

OCIW: Josh Simon

Yale: Marla Geha

Ricardo Munoz

Collaborators

Outline

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

2. Applications of new mass determinations for MW dSphs

3. The skinny on slope determinations: cusp vs. core

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

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

Assume known: 3D deprojected stellar density

Radial dispersion (depends on beta)

Free function

Mass modeling of hot systems

Jeans Equation

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Velocity Anisotropy (3 parameters)

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

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Mass Density (6 parameters)

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

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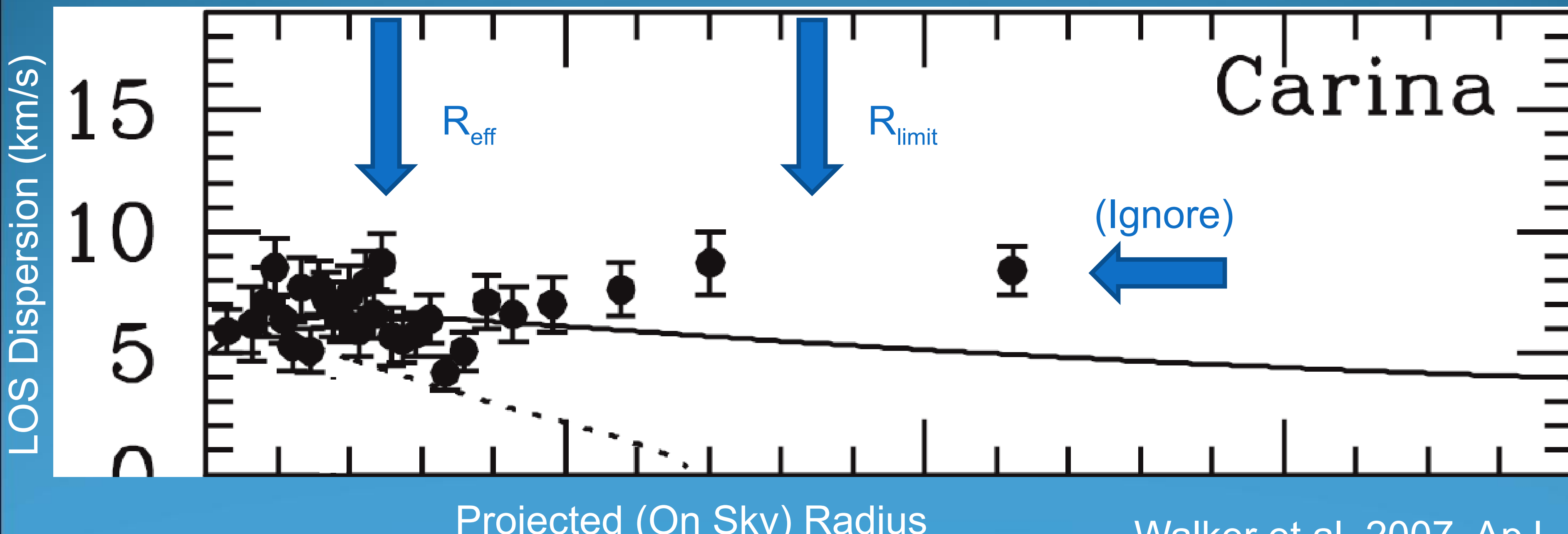
Using a Gaussian PDF for the observed stellar velocities, we marginalize over all free parameters (including photometric uncertainties) using a Markov Chain Monte Carlo (MCMC).

Thought Experiment

Given the following kinematics…



Walker et al. 2007, ApJ

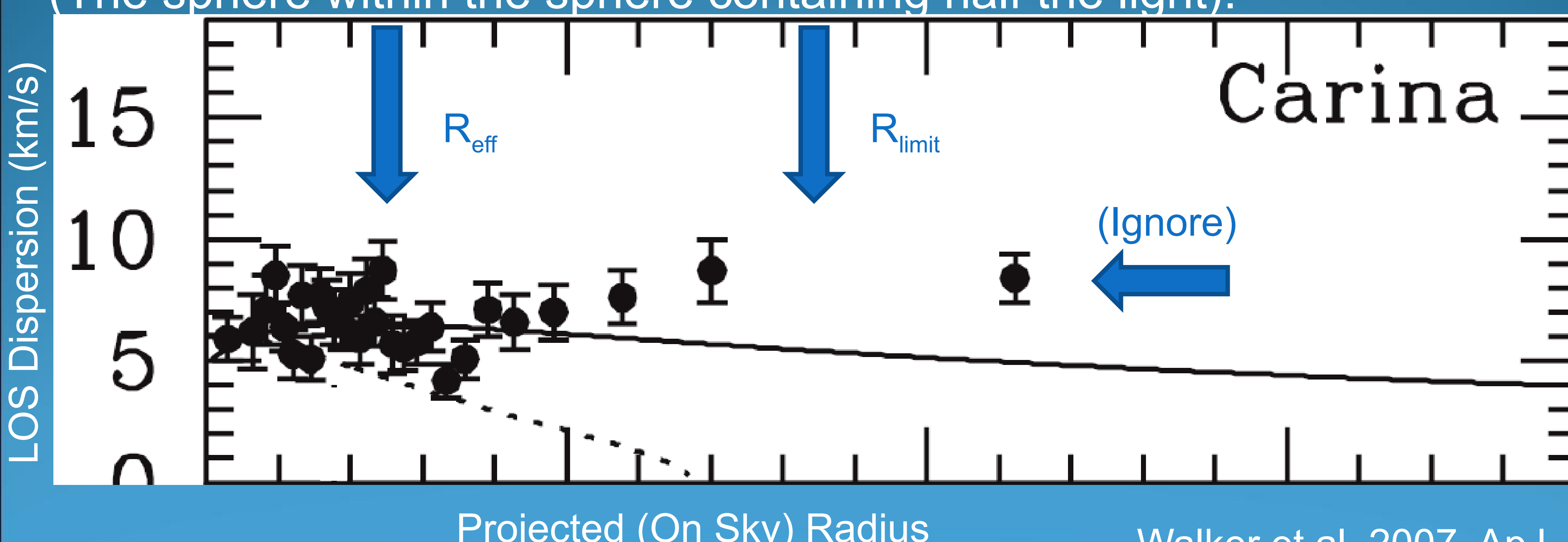
Thought Experiment

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) $1.5 * r_{1/2}$

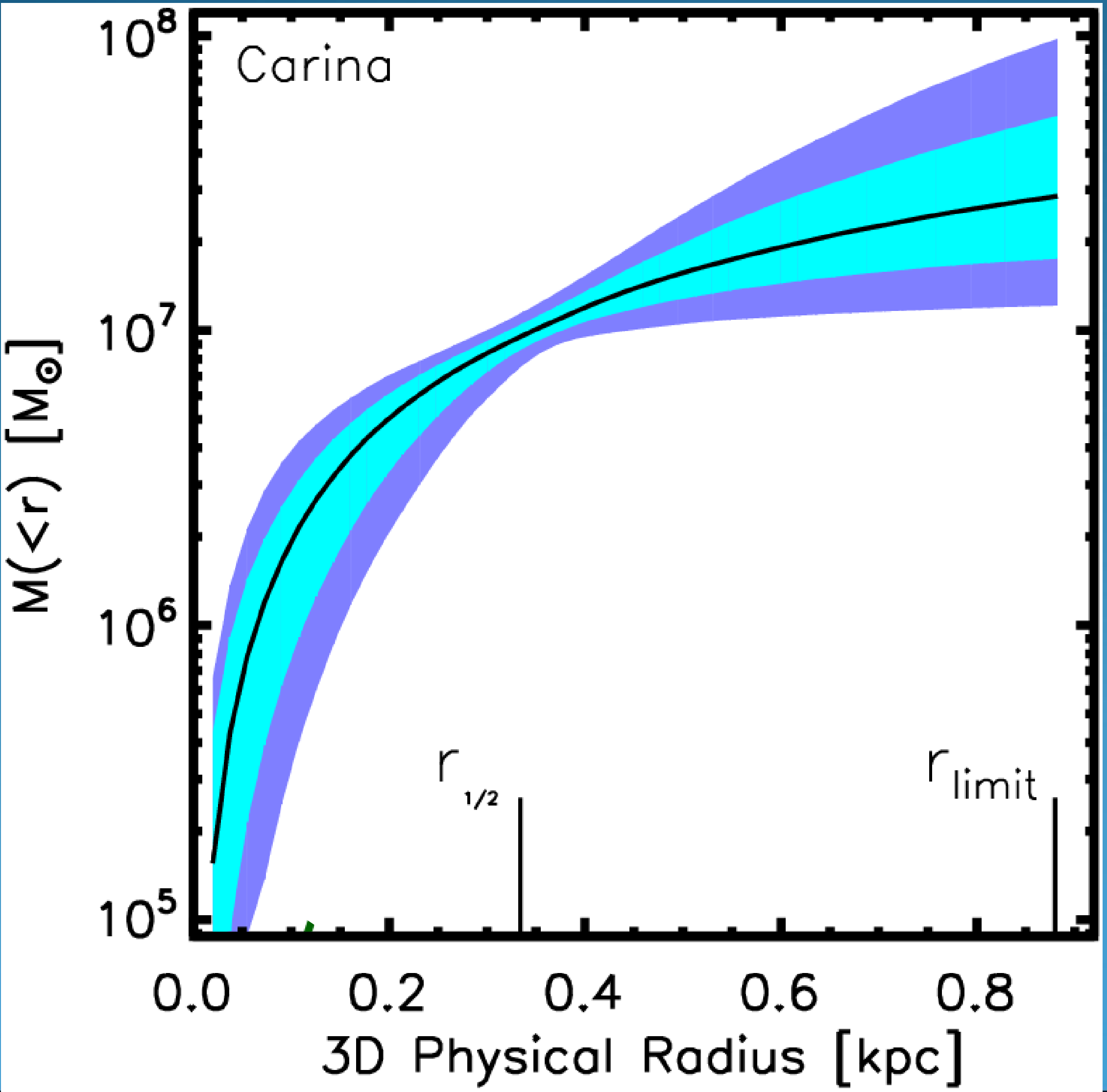
Where $r_{1/2}$ is the derived 3D deprojected half-light radius of the system.

(The sphere within the sphere containing half the light).



Walker et al. 2007, ApJ

Hmm…

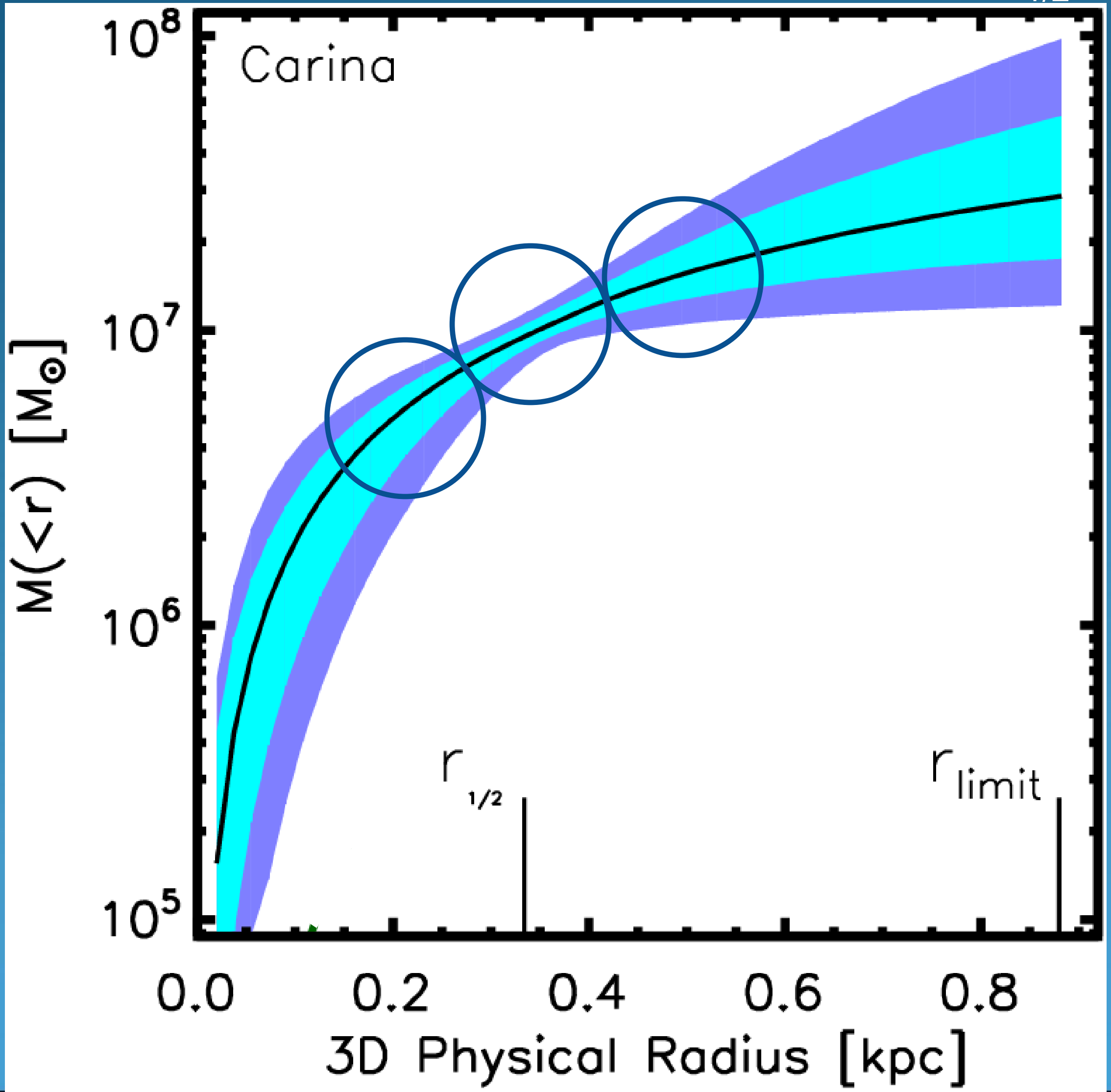


<u>Confidence Intervals:</u>
Cyan: 68%
Purple: 95%

Joe Wolf et al., 2010

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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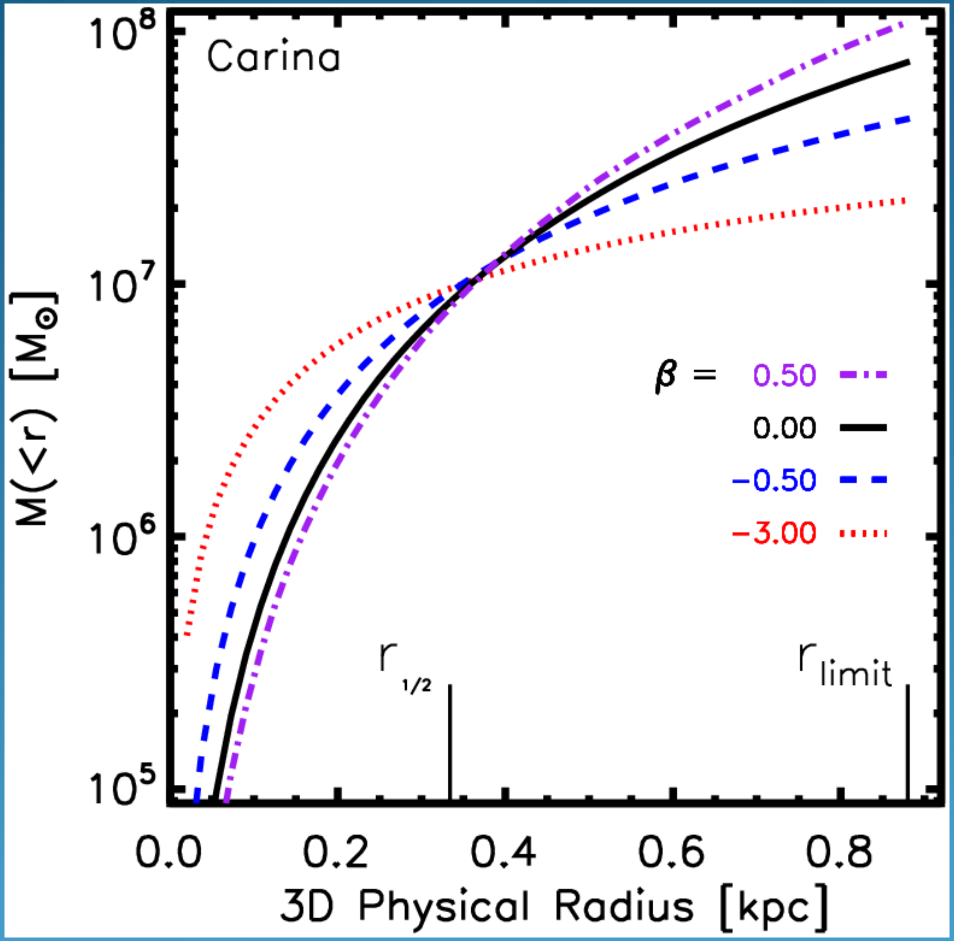
Anisotrwhat?



Radial Anisotropy

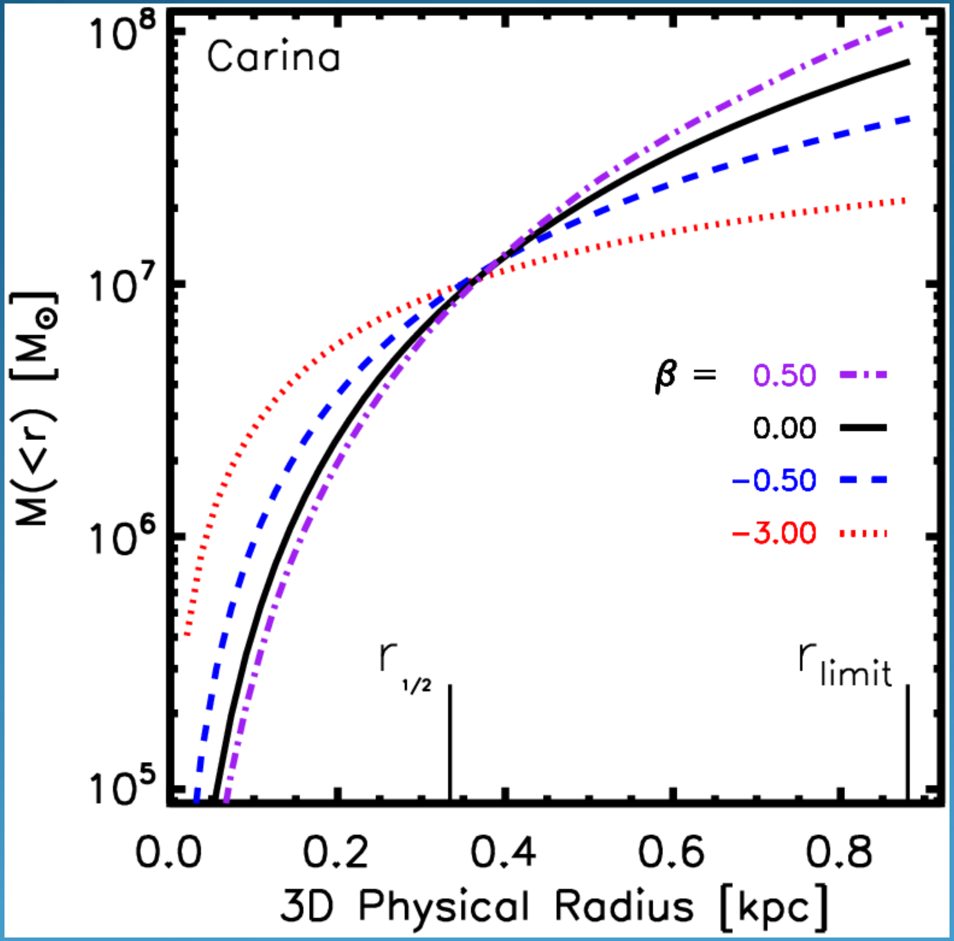
Isotropic

Tangential

Joe Wolf et al., 2010

Anisotrwhat?

Center of system:
Observed dispersion is radial



Edge of system: Observed dispersion is tangential

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Joe Wolf et al., 2010

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Center of system:
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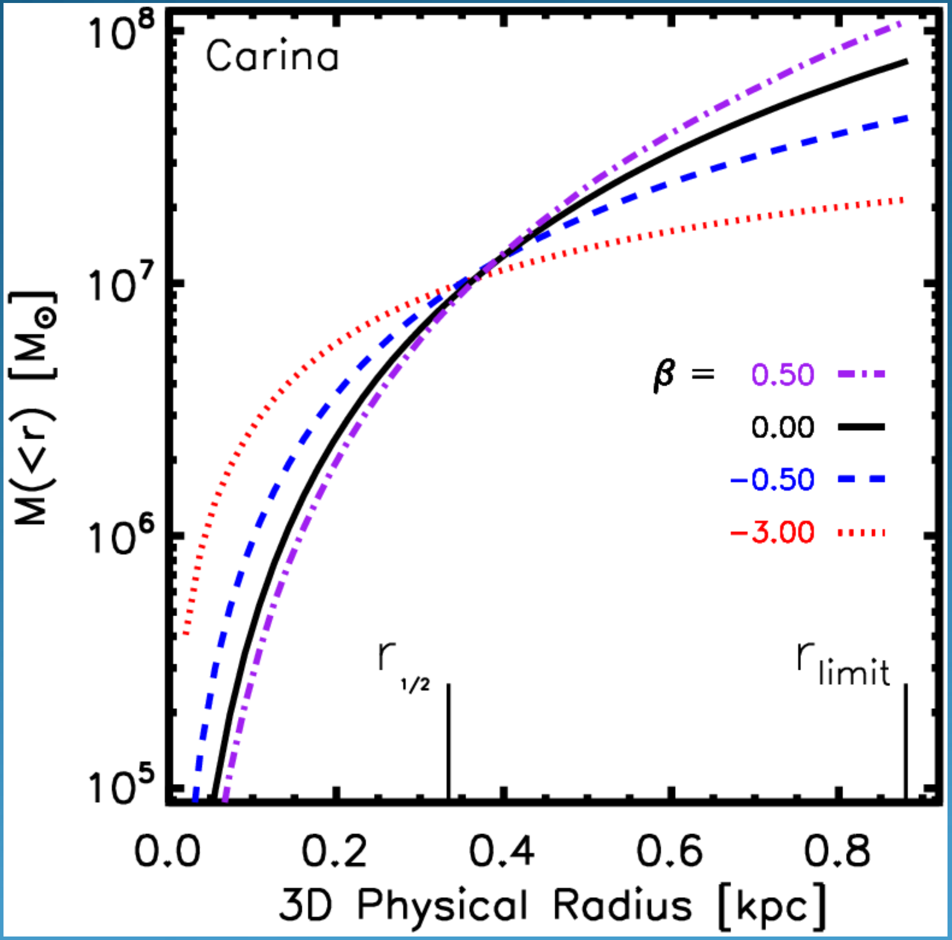

Joe Wolf et al., 2010

Edge of system: Observed dispersion is tangential

Radial Anisotropy

Isotropic

Tangential

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

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

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Derived equation under several simplifications:

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

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

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

Wait a second...

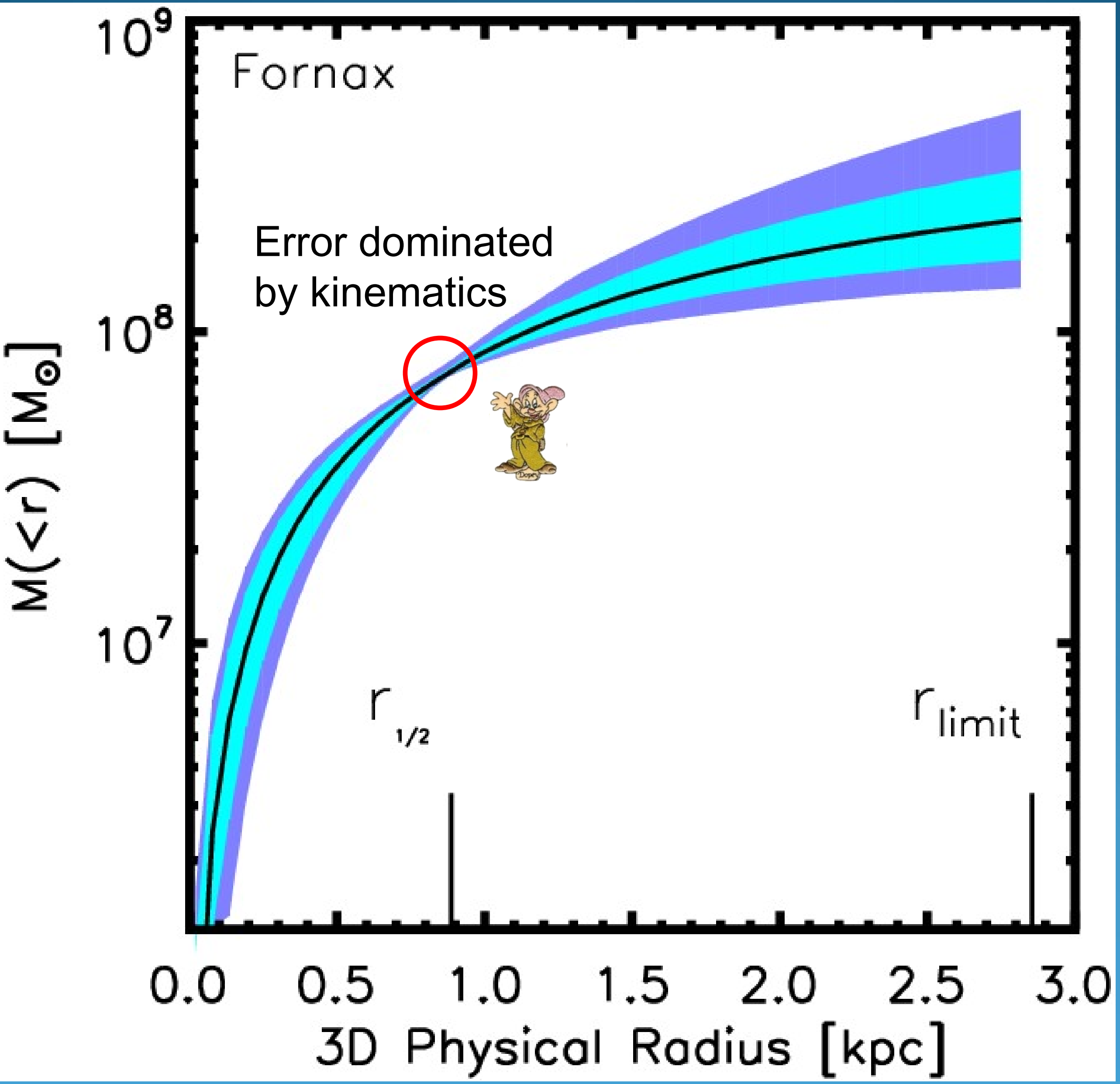
Isn't this just the scalar virial theorem (SVT)?

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

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.

Mass Errors: Origins



Joe Wolf et al., in prep

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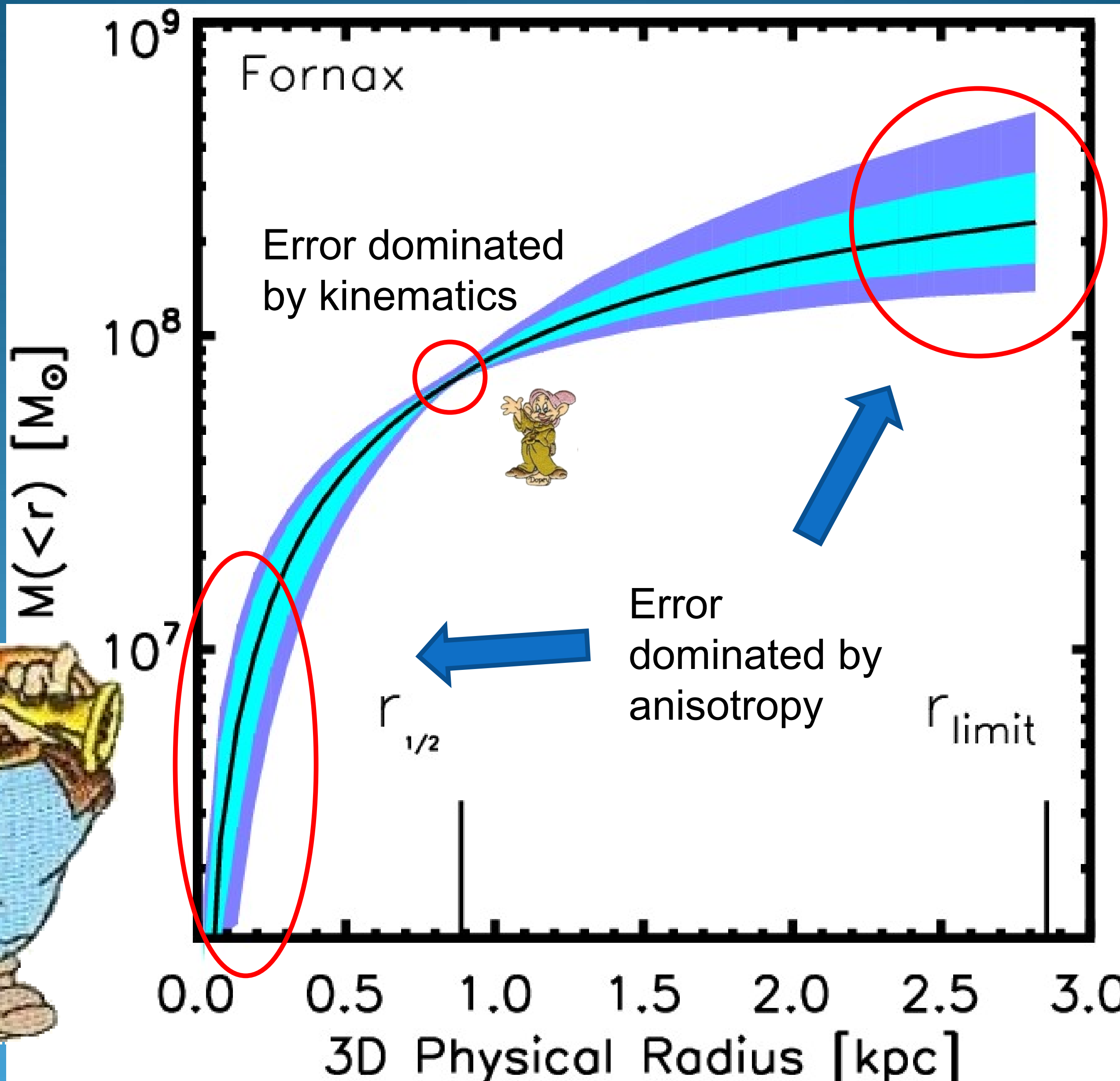

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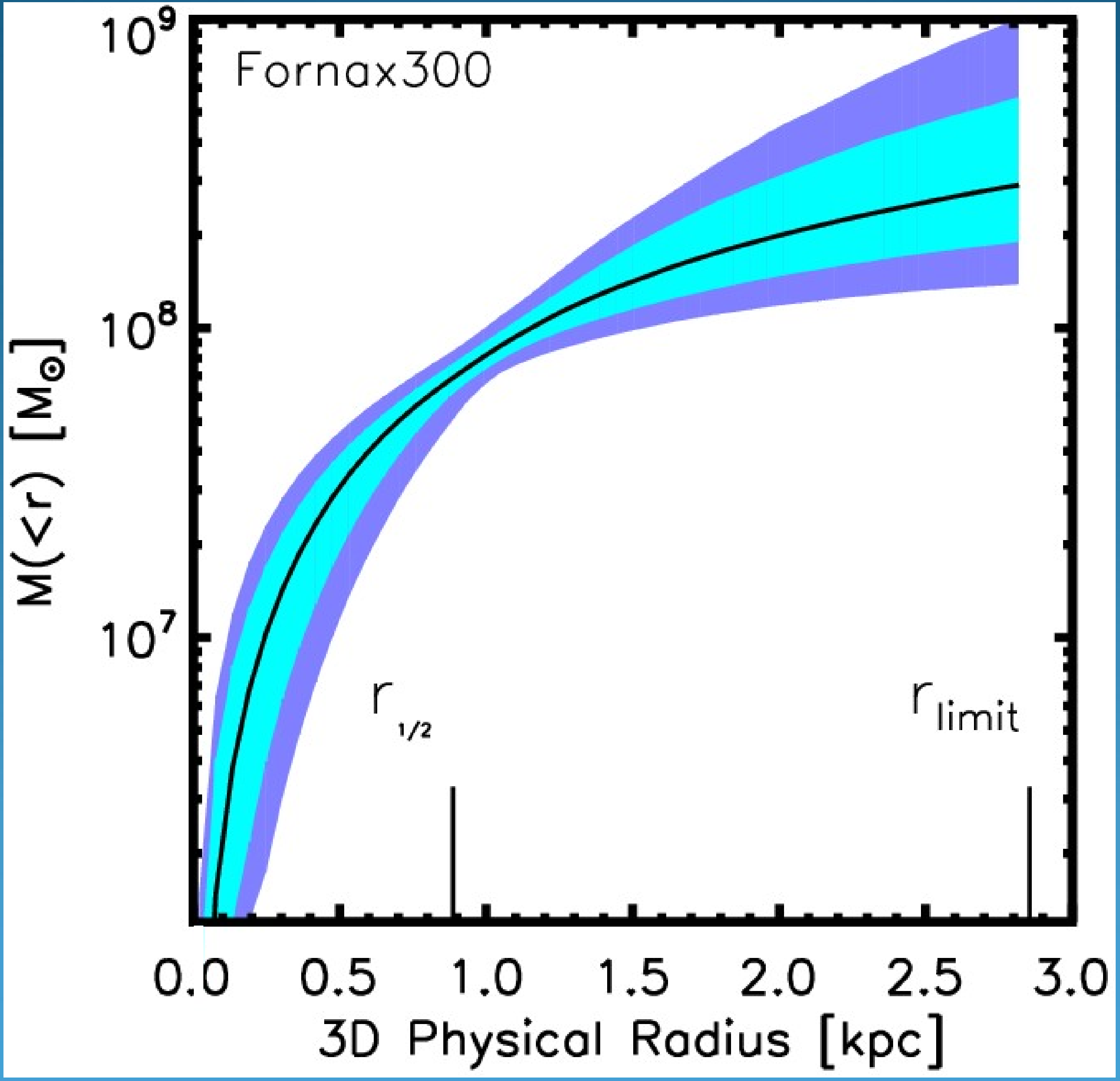
Mass Errors: 300 stars



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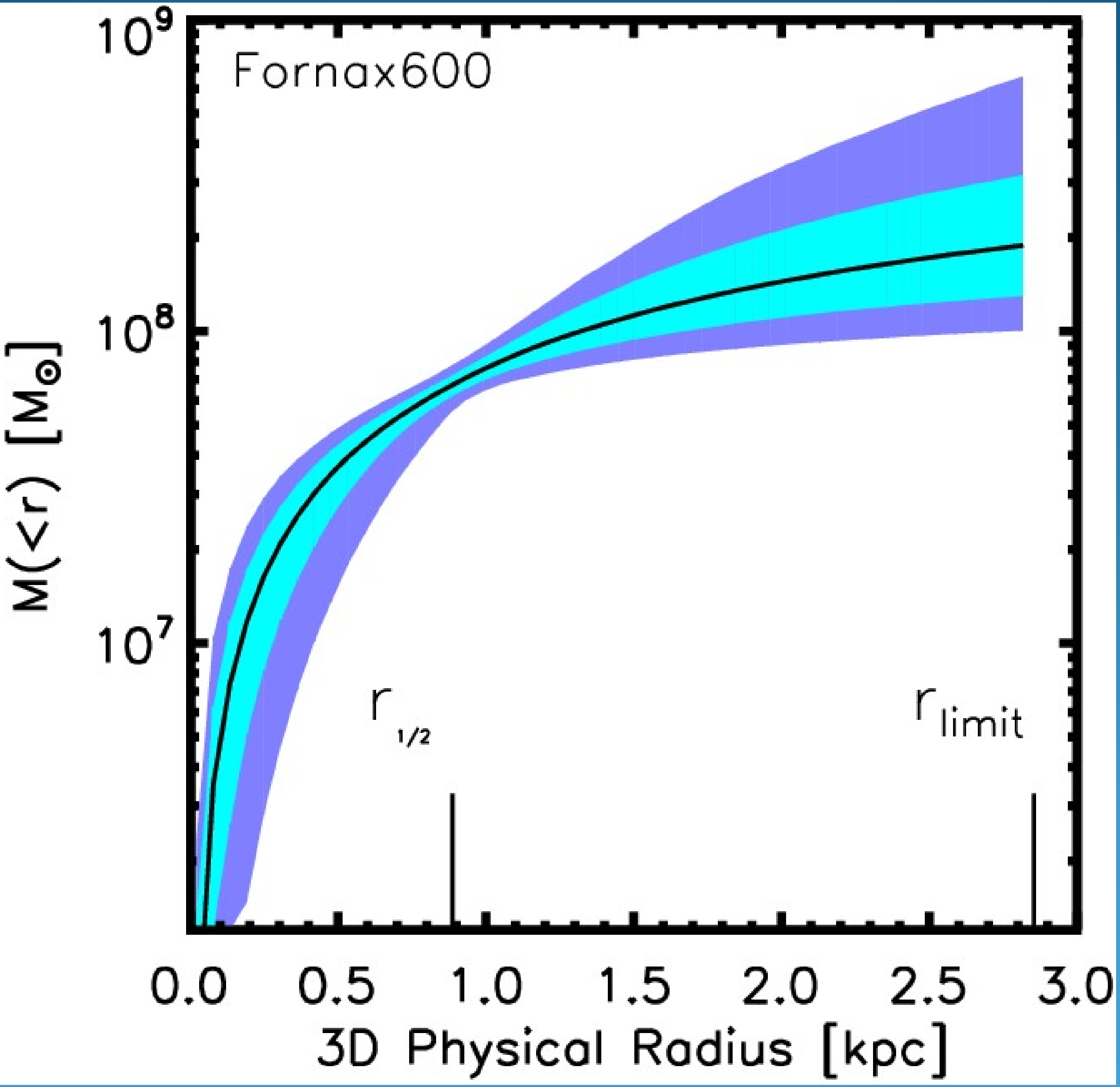
Mass Errors: 600 stars



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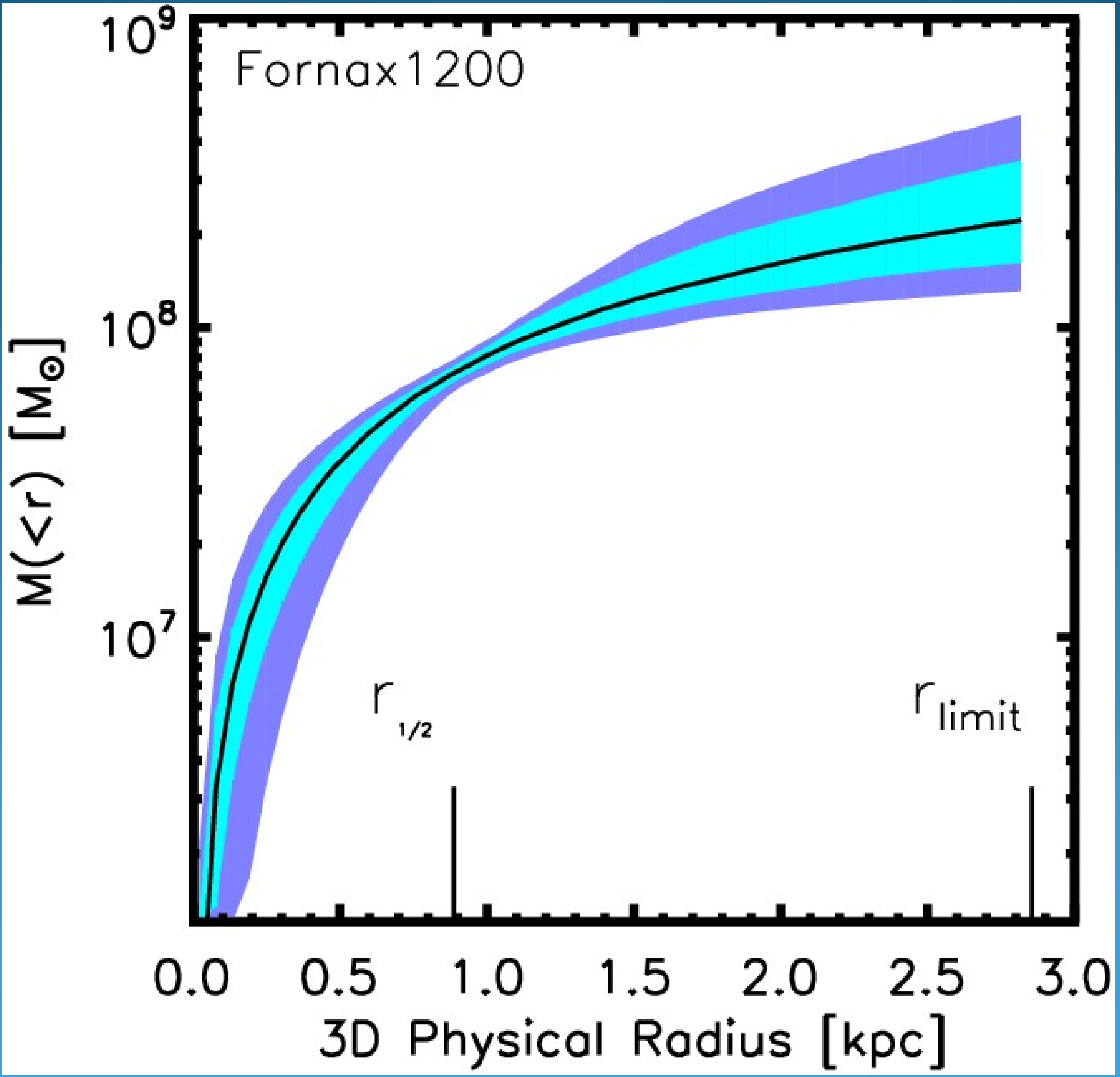
Mass Errors: 1200 stars



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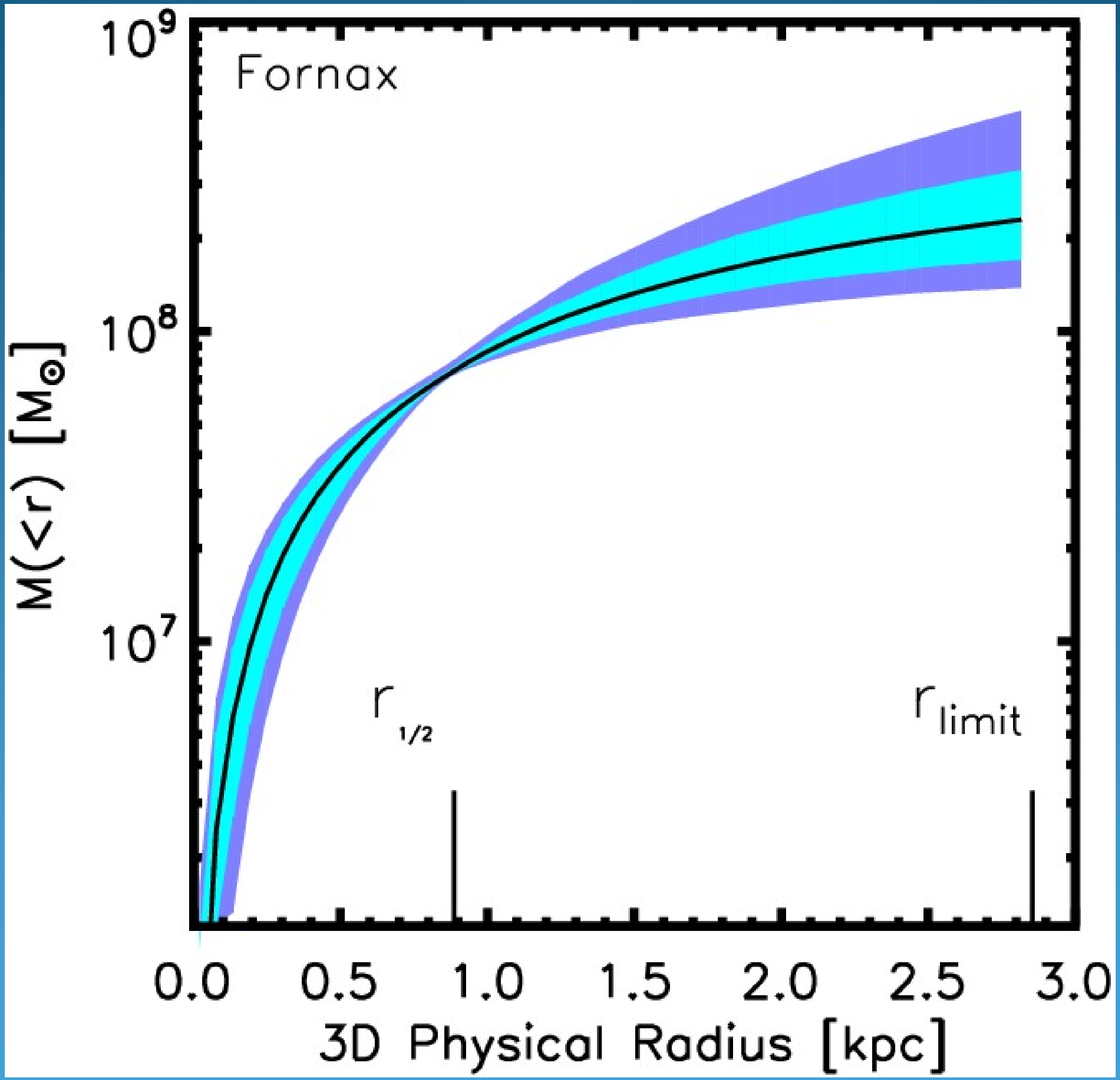
Mass Errors: 2400 stars



Joe Wolf et al., in prep

Outline

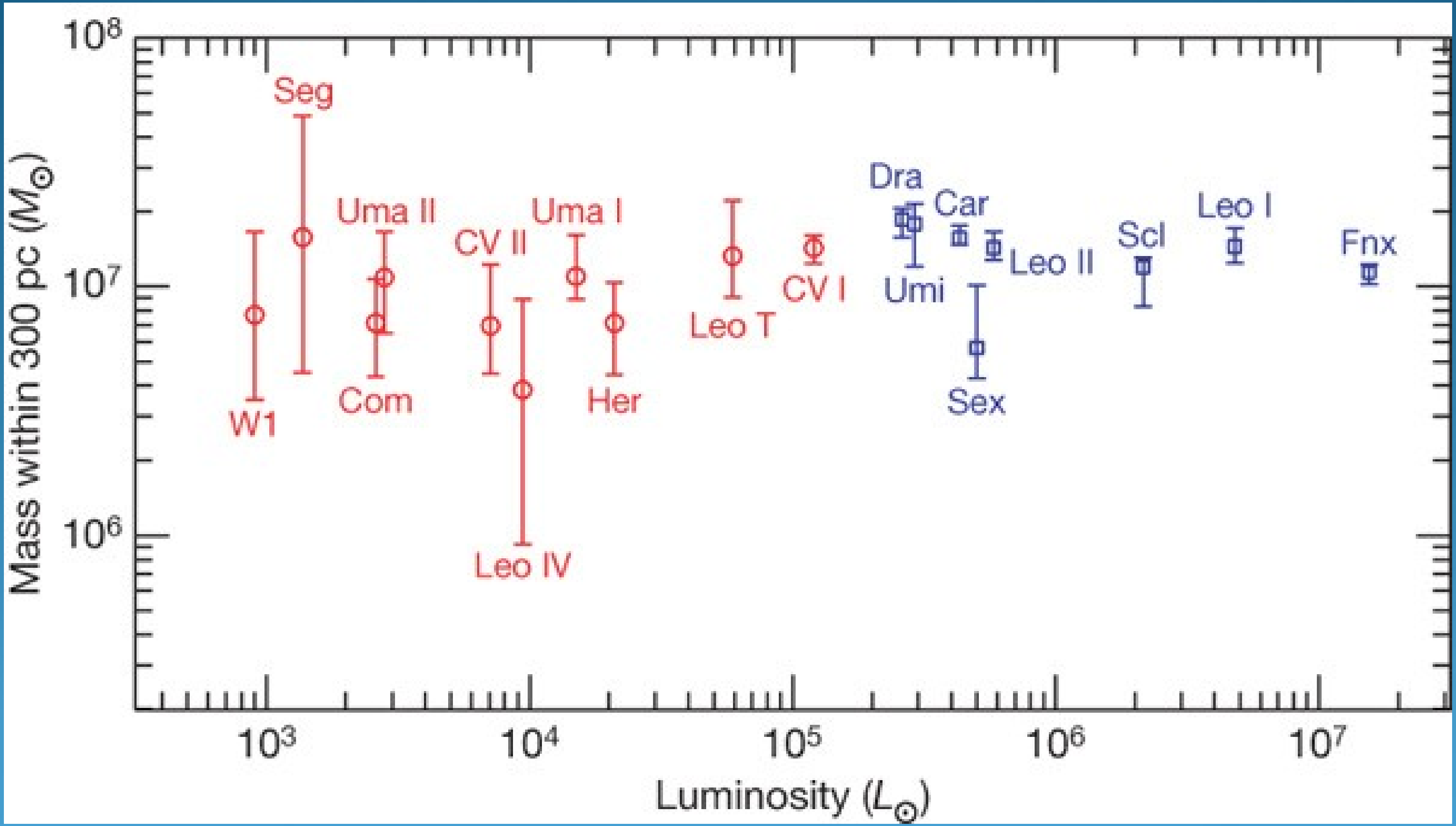
1. ~~A new mass estimator: accurate without knowledge of aniso~~tropy/beta

2. Applications of new mass determinations for MW dSphs

3. The skinny on slope determinations: cusp vs. core

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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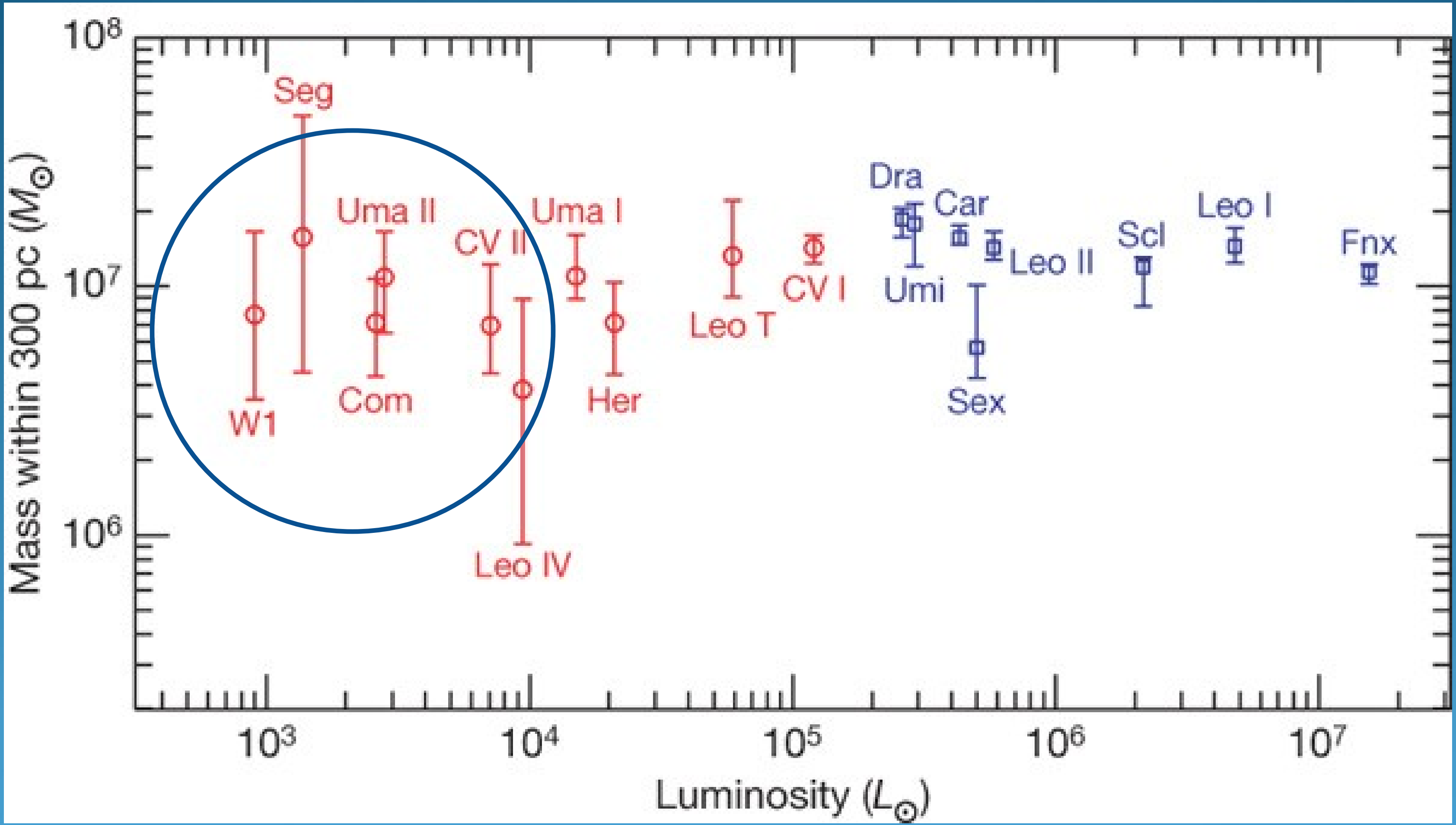

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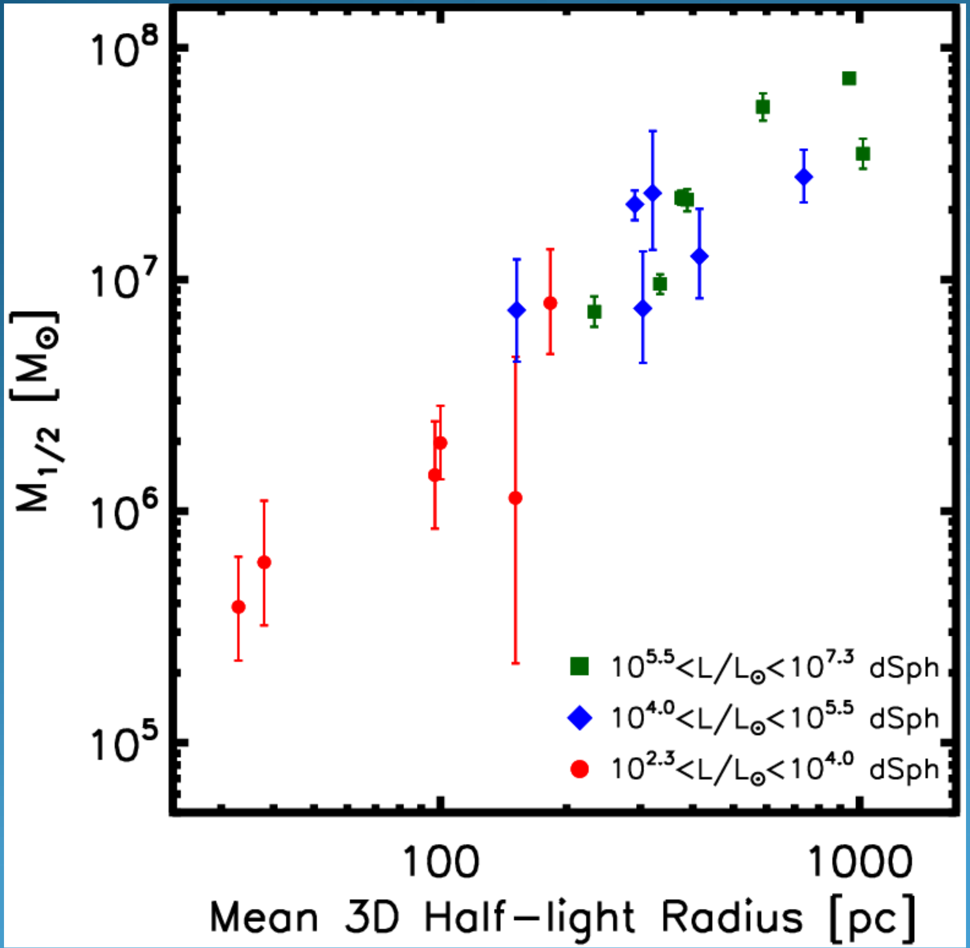
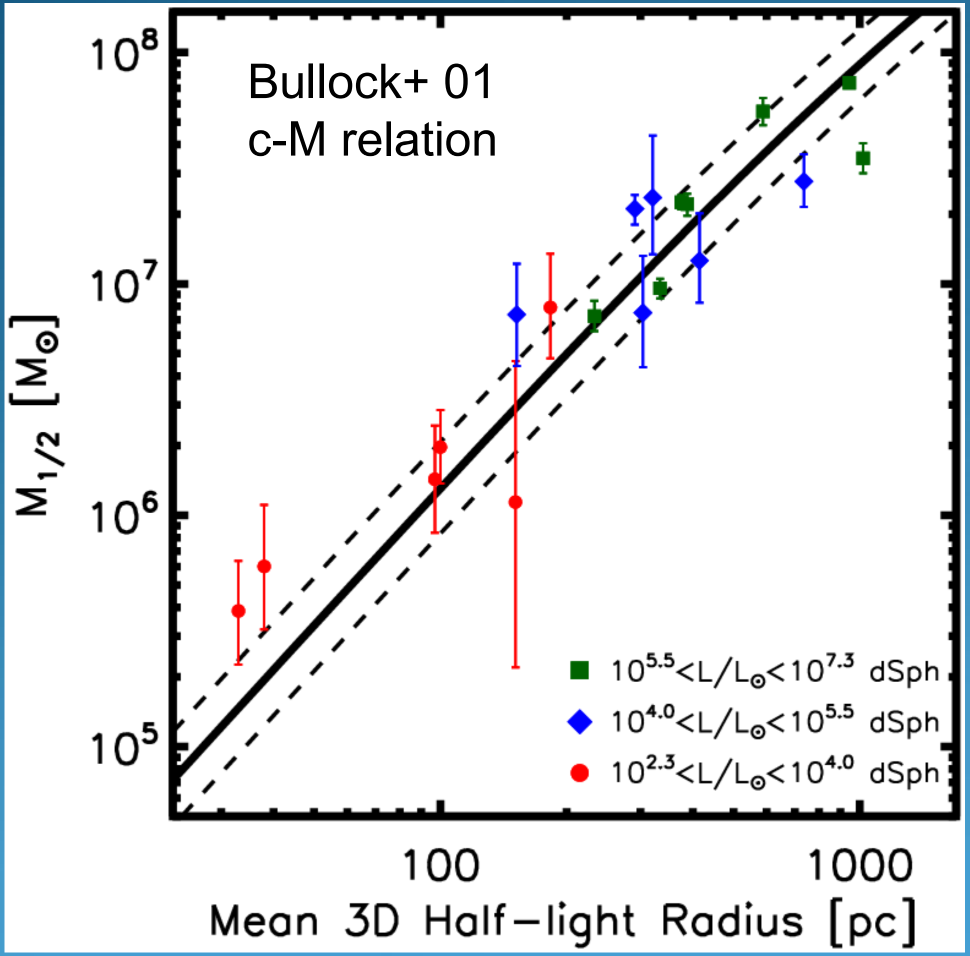


Joe Wolf et al. 2010

Applications: dSphs

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



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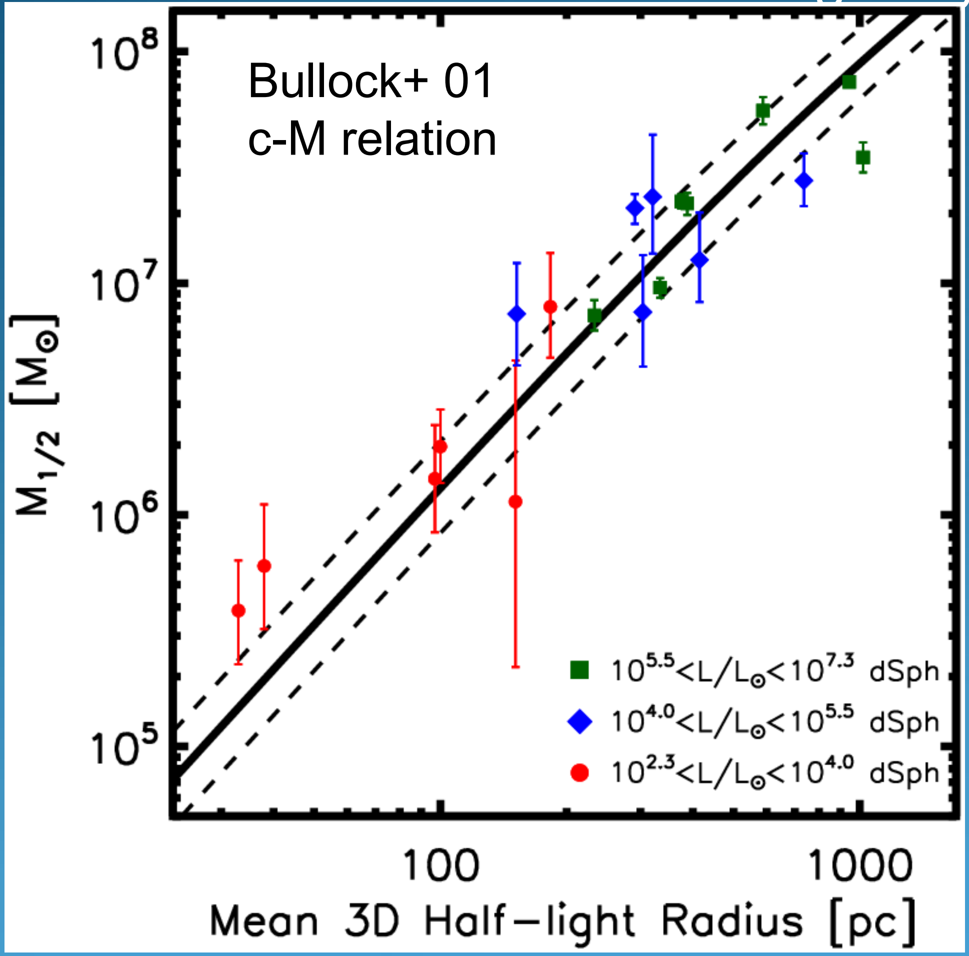
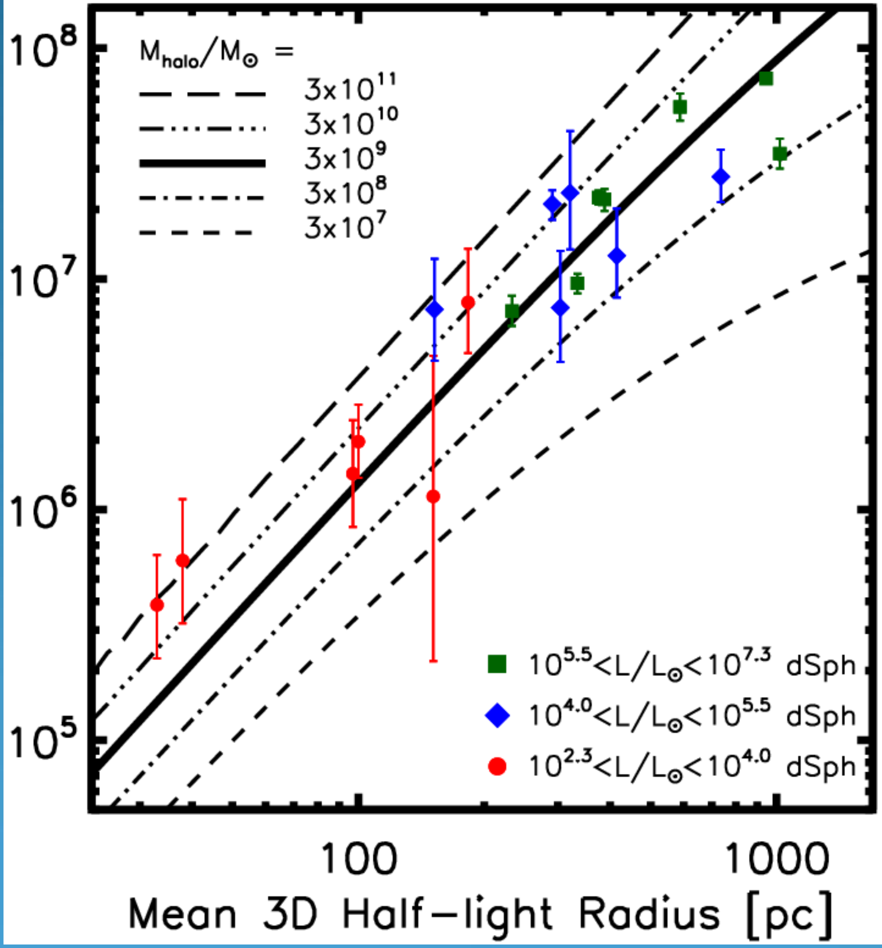
Applications: dSphs

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!

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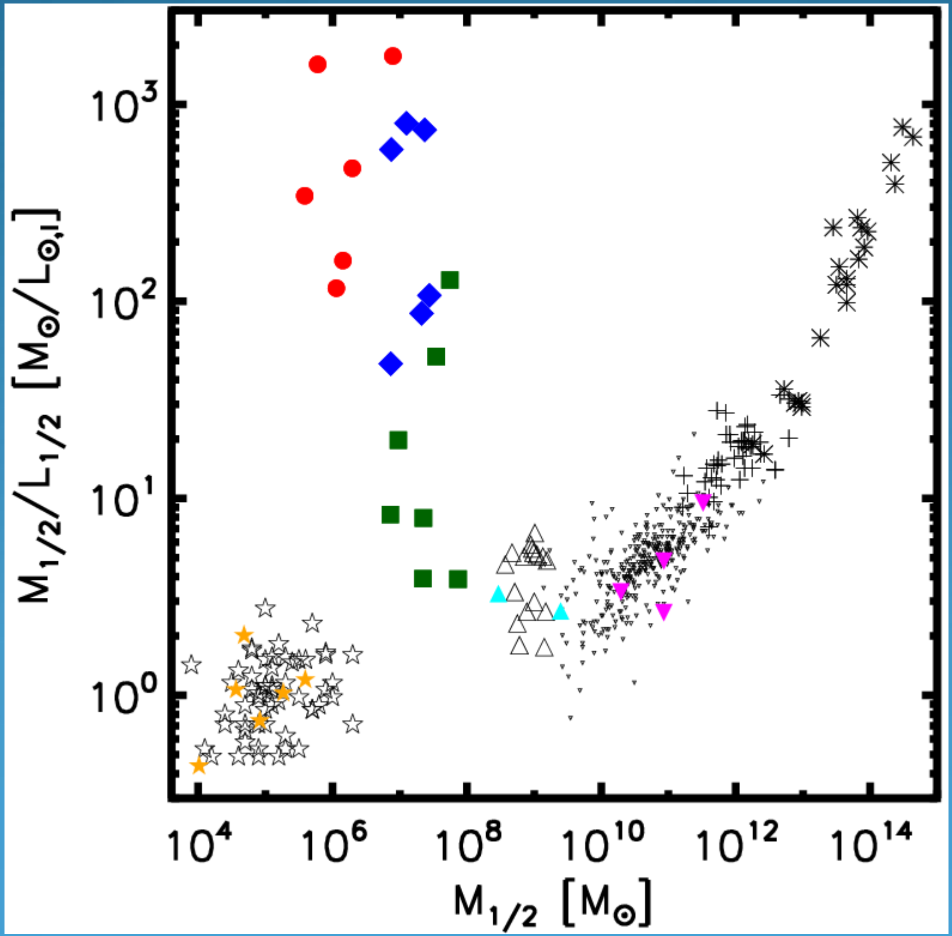
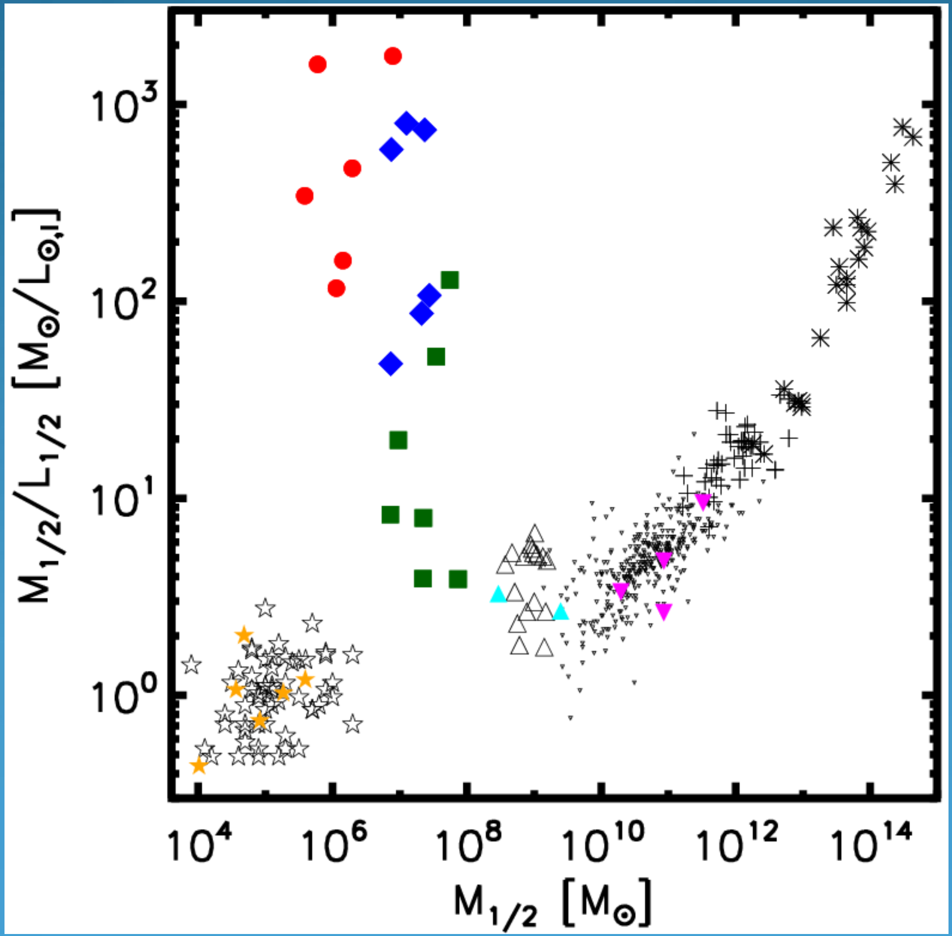
Applications: Global



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. 2010

Applications: Global

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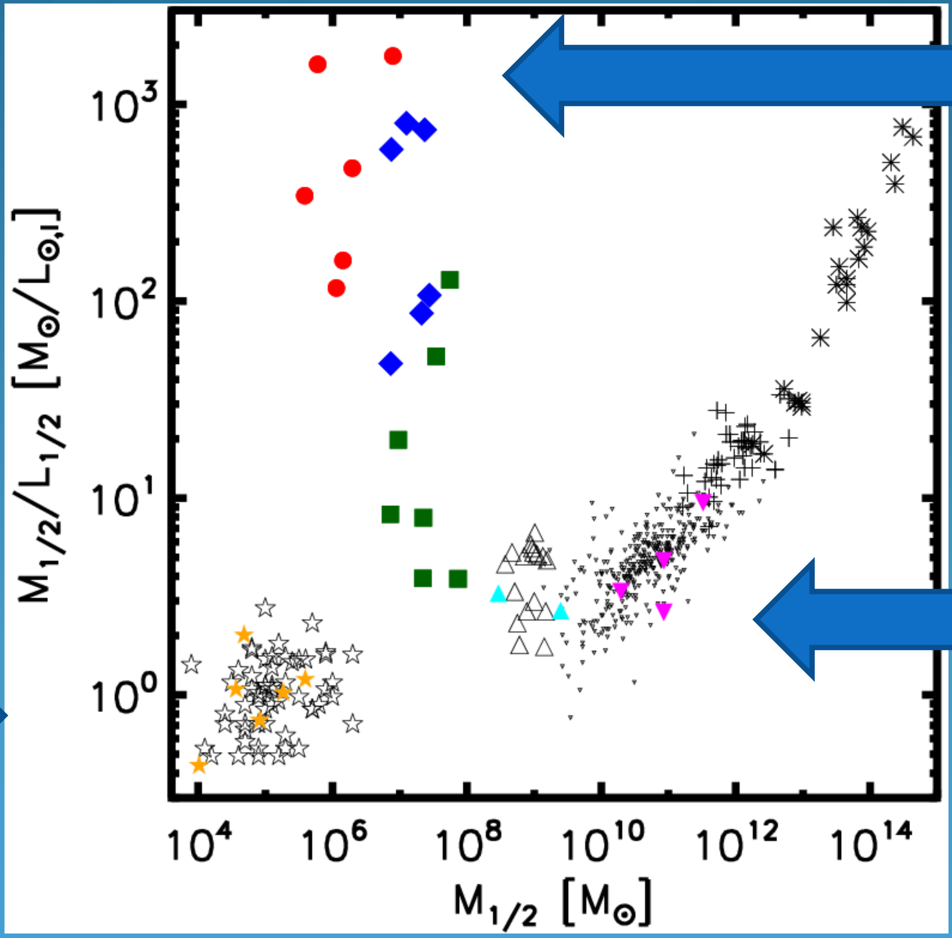
Ultrafaint dSphs: Most DM dominated systems known!

Globulars: Offset from L* by factor of three



Inefficient at galaxy formation

L*: Efficient at galaxy formation

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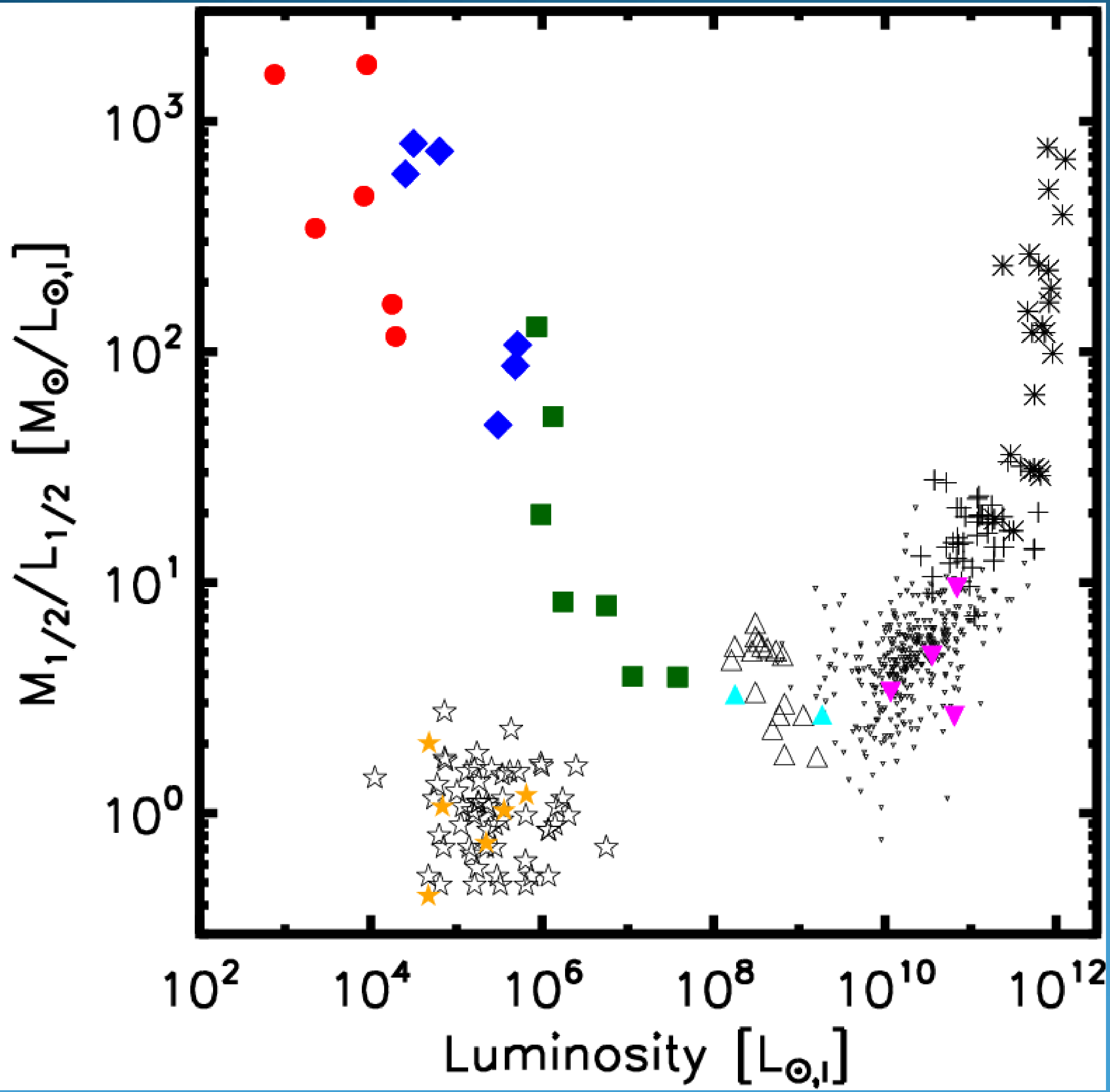
Applications: Global



Last plot:
Mass floor

This plot:
Luminosity ceiling

Joe Wolf et al. 2010

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3. The skinny on slope determinations: cusp vs. core

Slopes & Priors – Oh my!

LCDM does well at reproducing large scale structure. However, on small scales, two major problems:

1. Missing Satellites Problem
(Not as bad as we thought…see Tollerud et al. 2008)

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LCDM does well at reproducing large scale structure. However, on small scales, two major problems:

1. Missing Satellites Problem
(Not as bad as we thought…see Tollerud et al. 2008)

2. LCDM simulations predict cuspy inner slopes.
Observations strongly prefer cores.

Solution? Involve messy baryonic physics…and/or look at the most dark-matter dominated galaxies.

Slopes & Priors – Oh my!

Can the observed or potentially measurable velocity dispersions tell apart a cusp vs. a core in the centers of galaxies?

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Can the observed or potentially measurable velocity dispersions tell apart a cusp vs. a core in the centers of galaxies?

No…

Slopes & Priors – Oh my!

Can the observed or potentially measurable velocity dispersions tell apart a cusp vs. a core in the centers of galaxies?

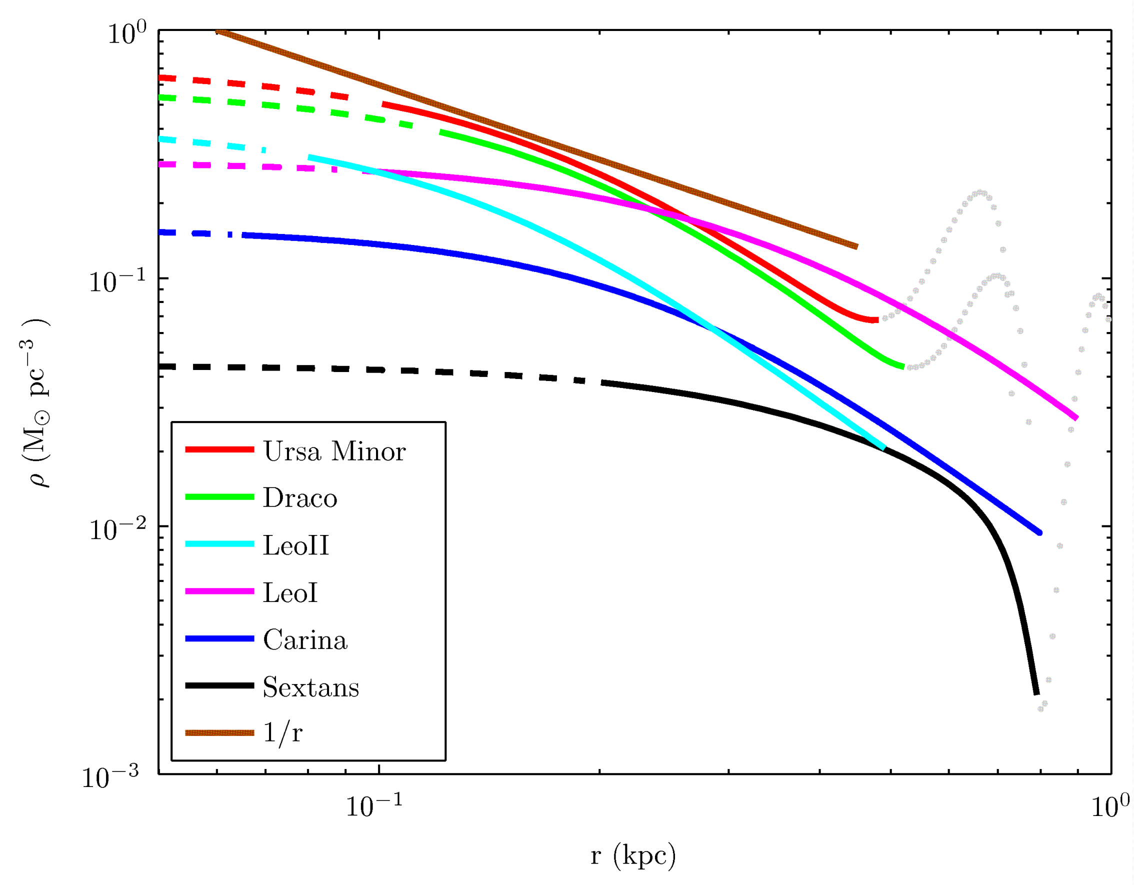
No…unless priors are assumed

The next two slides are copied directly from G. Gilmore’s 2007 Ann Arbor presentation (slides 14 and 15)

Derived mass density profiles:

Jeans' equation with assumed isotropic velocity dispersion: All consistent with

cores (similar results from other analyses)



CDM predicts slope of -1.3 at 1% of virial radius and asymptotes to -1 (Diemand et al. 04)

Need different technique at large radii, e.g. full velocity distribution function modelling.. And understand tides.

Conclusion two:

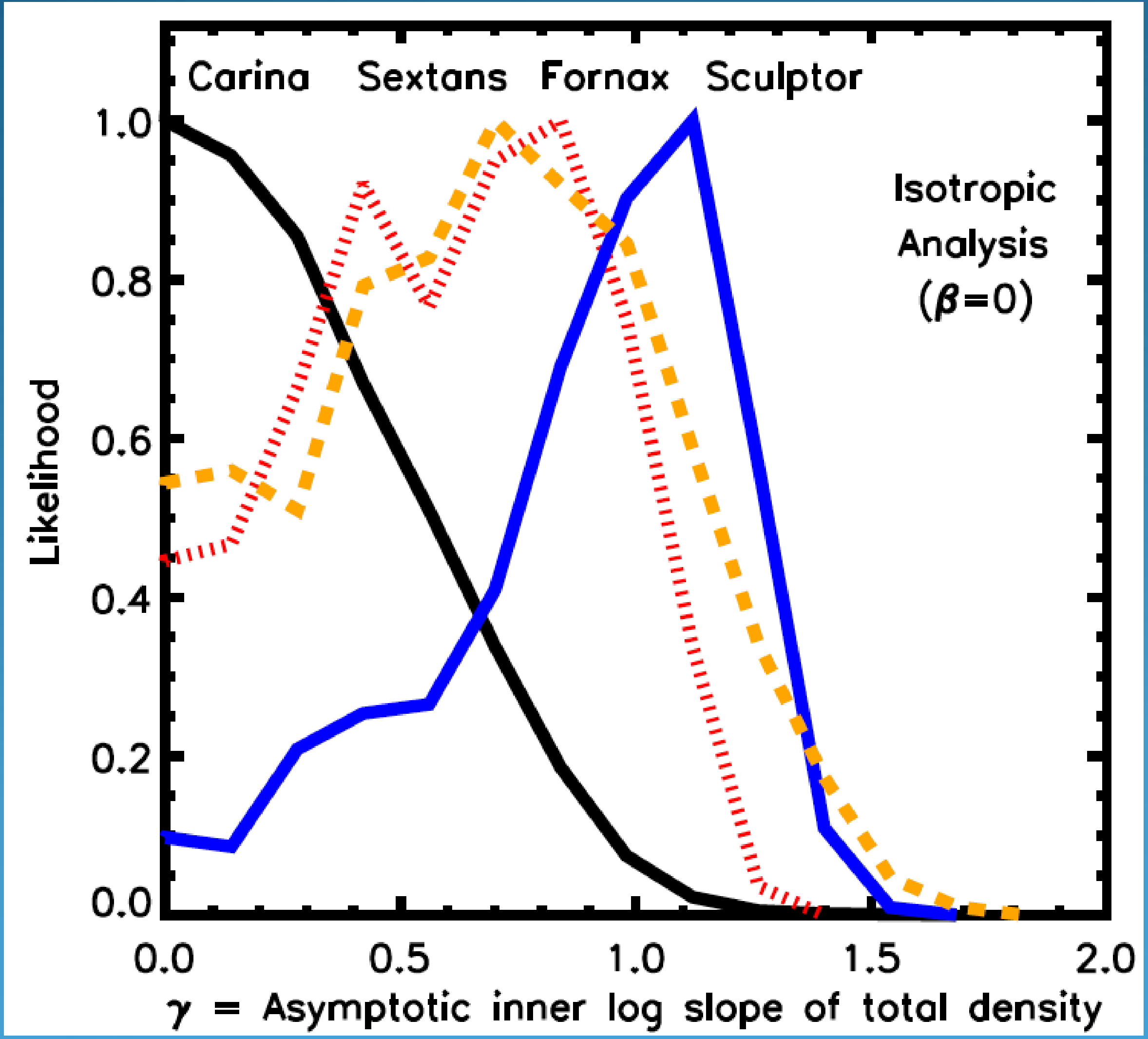
- High-quality kinematic data exist
- Jeans' analyses ➔ prefers cored mass profiles
- Mass-anisotropy degeneracy *allows* cusps
- Substructure, dynamical friction ➔ prefers cores
- Equilibrium assumption is valid inside optical radius
- More sophisticated DF analyses underway

- **Cores always preferred, but not always required**
- **Central densities always similar and low**
- **Consistent results from available DF analyses**

- Extending analysis to lower luminosity systems difficult due to small number of stars
- Integrate mass profile to enclosed mass:

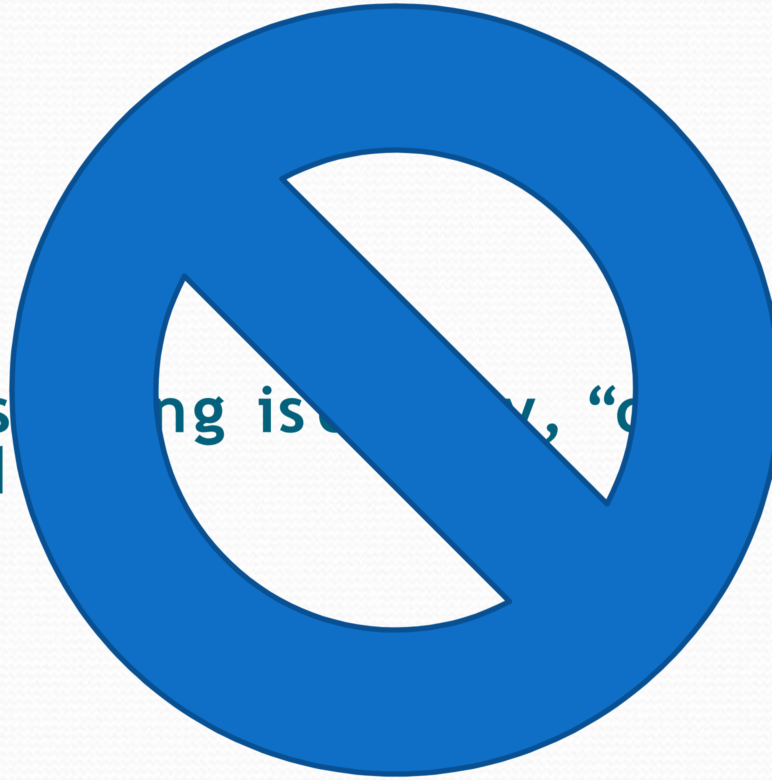
Story Time: A New Ending

Forcing isotropy: 4 of the 8 classical dSphs show no preference for either cores or cusps, and Sculptor strongly prefers a cusp.



Joe Wolf et al., in prep

- When assuming isotropy, “cores always preferred”

- When ass  ng is , “c s always preferred

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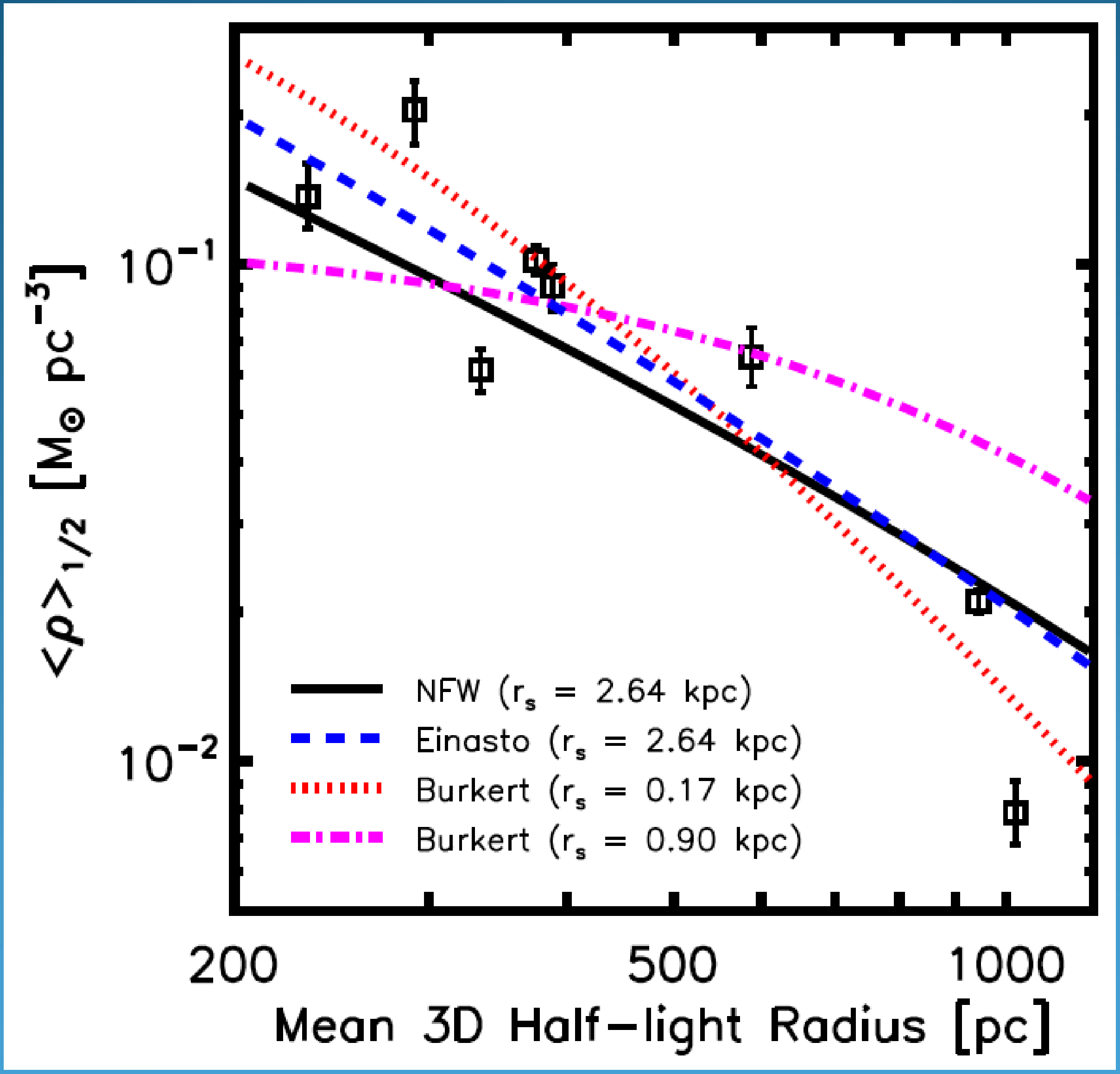
Can a common cored halo fit the data?



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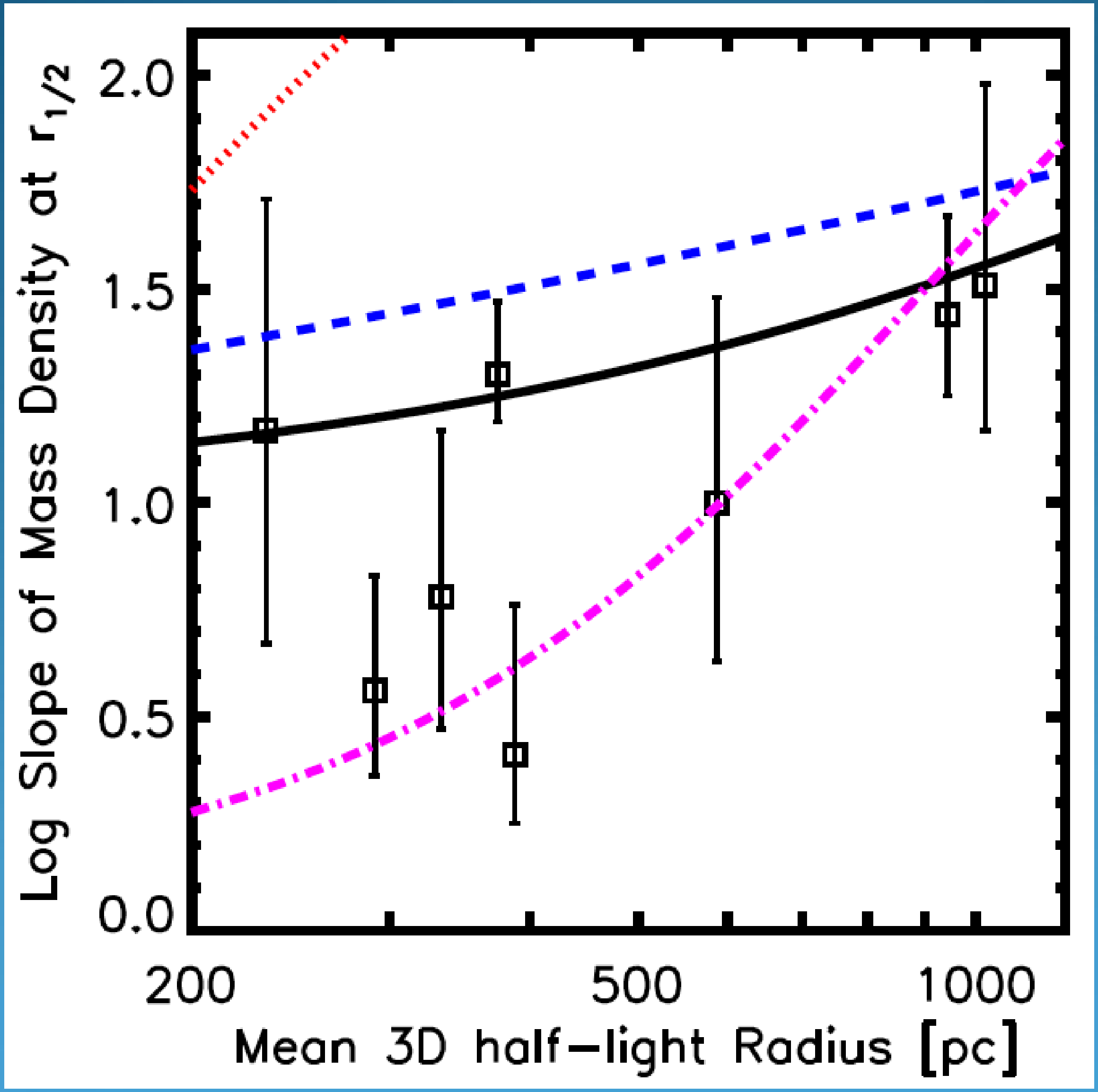

Joe Wolf et al., in prep

Take-Home Messages

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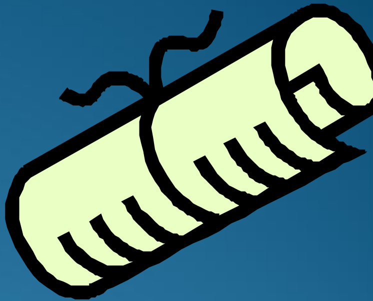

Wolf et al. 2010 (arXiv:0908.2995)

- 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

- Inner slopes of dSphs **cannot** be determined with only LOS kinematics.

- **Jeans modeling w/isotropy does not *always* prefer cores**