Modeling mass independent of anisotropy

A comparison between Milky Way and Andromeda satellites
(and musings on density slope determinations)

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Extreme Star Formation in Dwarf Galaxies Ann Arbor, MI July 28 2009

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Collaborators

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
4. The skinny on slope determinations

Cardinal rule about dwarfs:

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

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)

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

Mass modeling of hot systems

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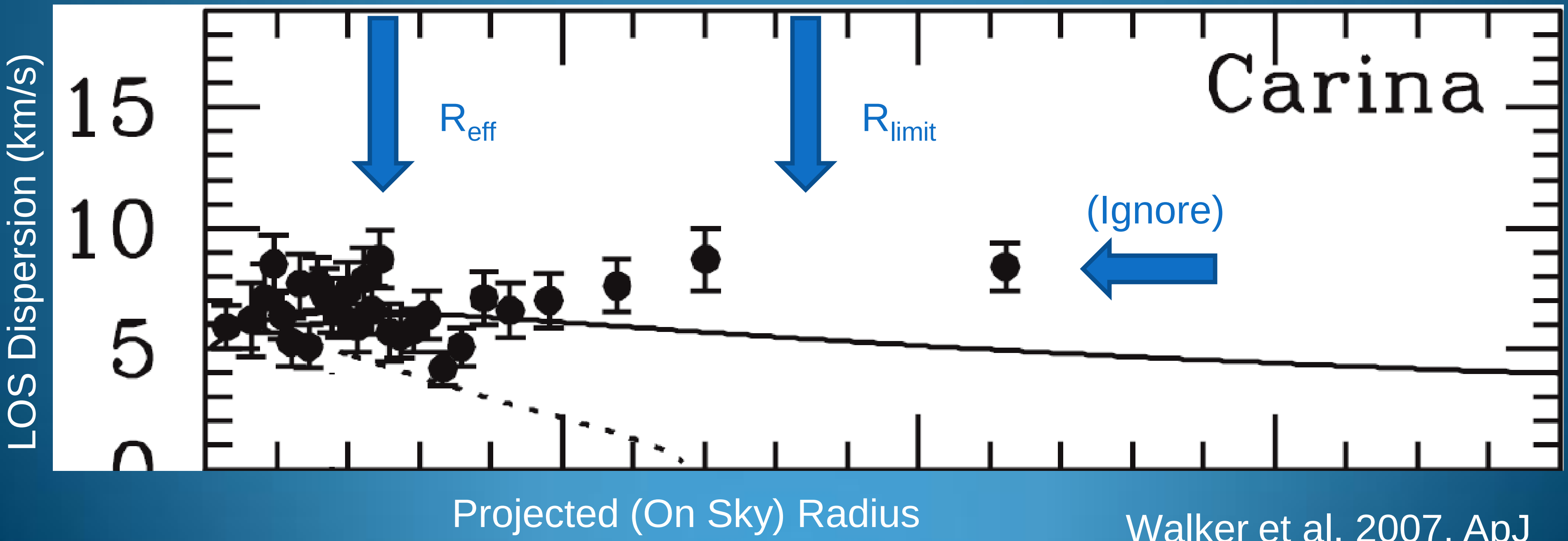
$$\rho(r) = \frac{\rho_s e^{-r/r_{cut}}}{(r/r_s)^c[1 + (r/r_s)^a]^{(b-c)/a}}$$

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…



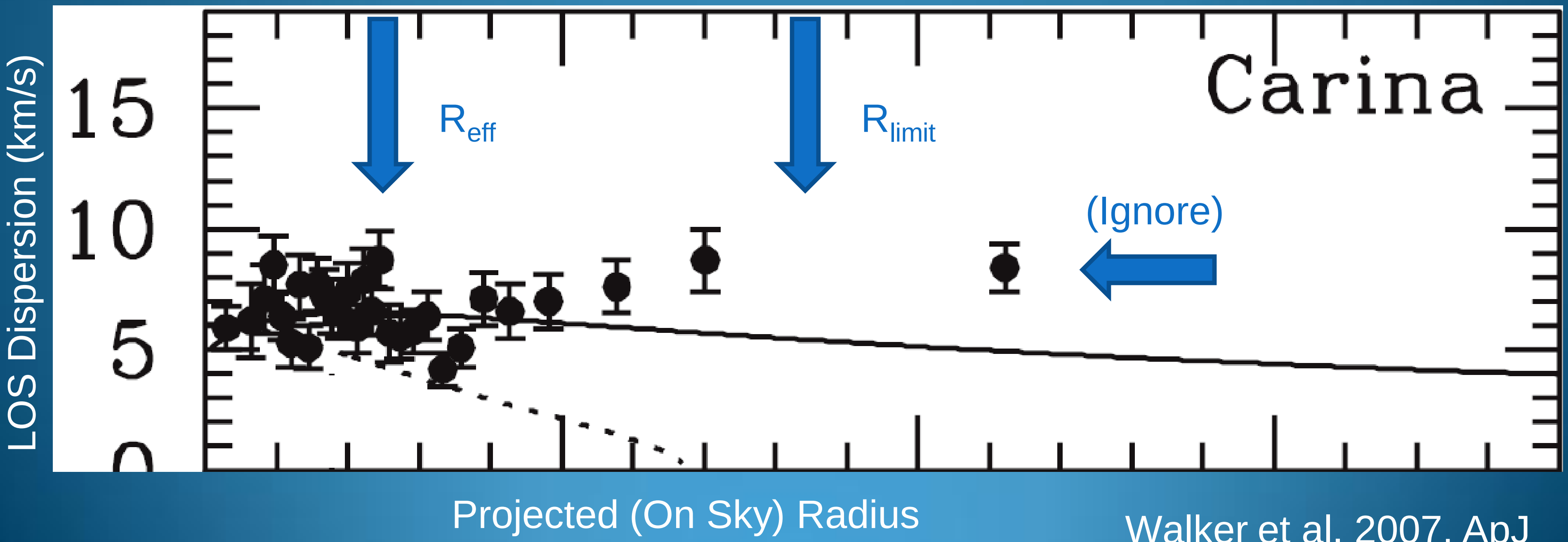
Walker et al. 2007, ApJ

Thought Experiment

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

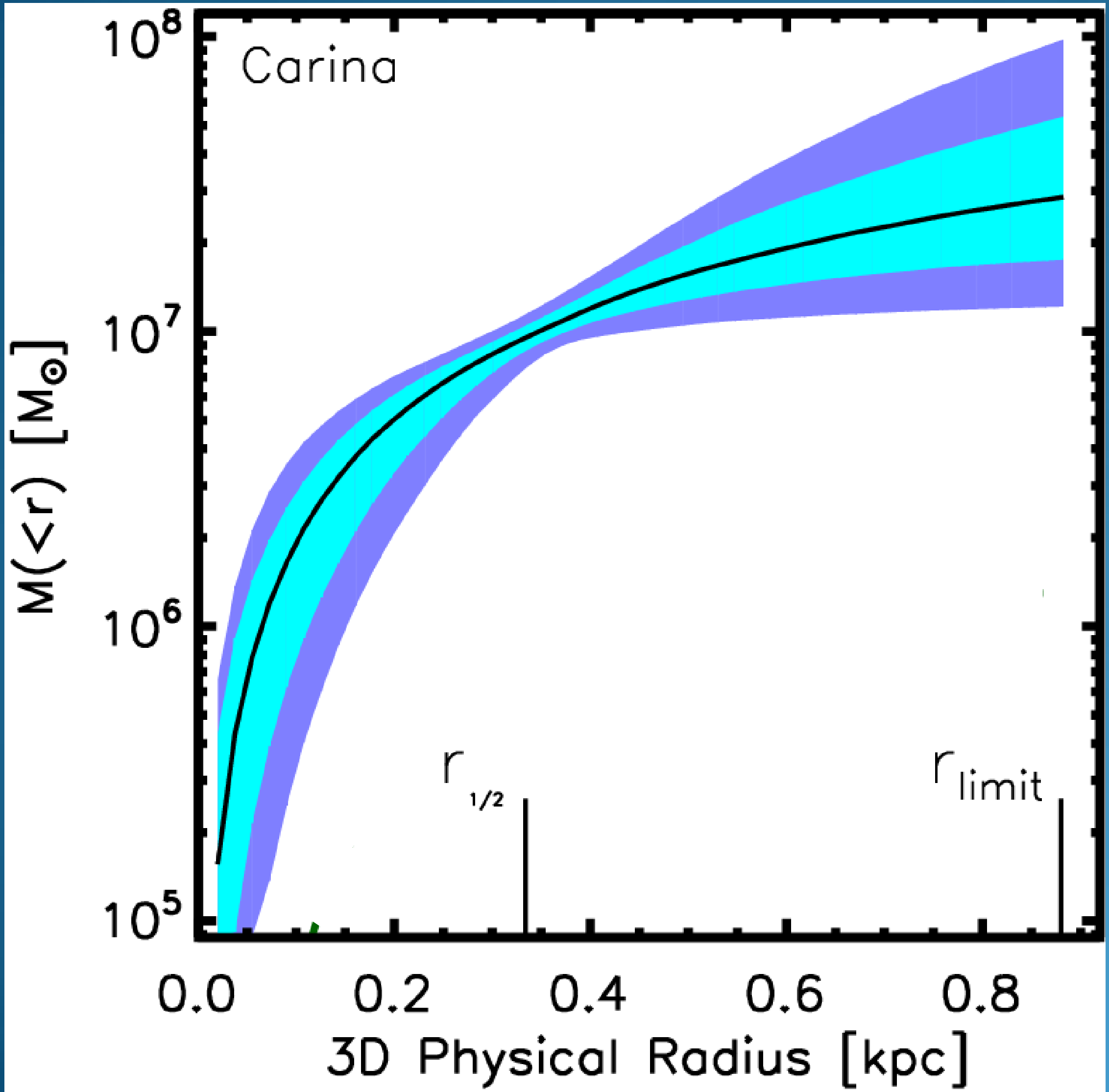
a) $0.5 * r_{1/2}$ b) $r_{1/2}$ c) $1.5 * r_{1/2}$

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…

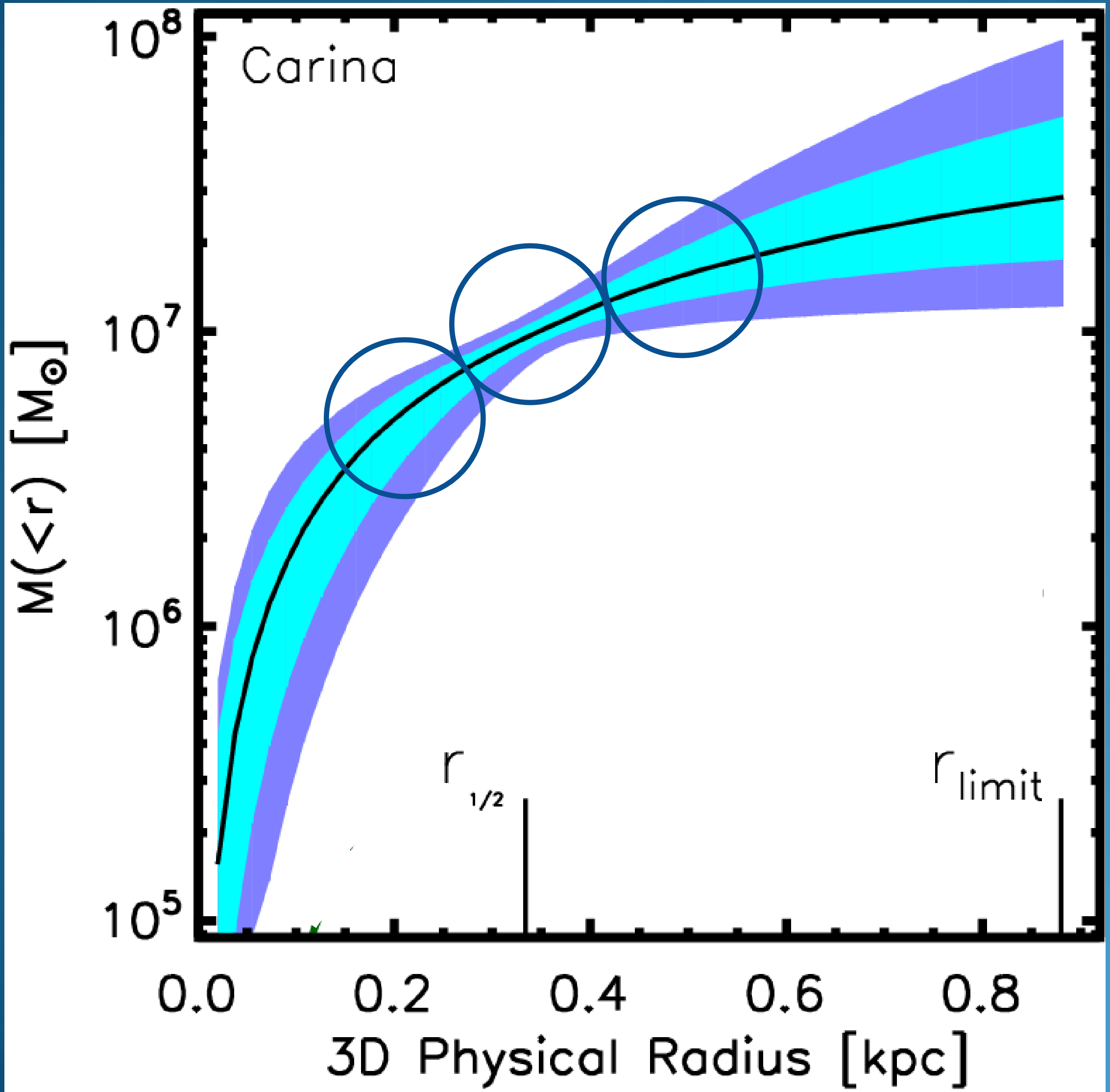


Confidence Intervals:
Cyan: 68%
Purple: 95%

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 $r > r_{1/2}$.



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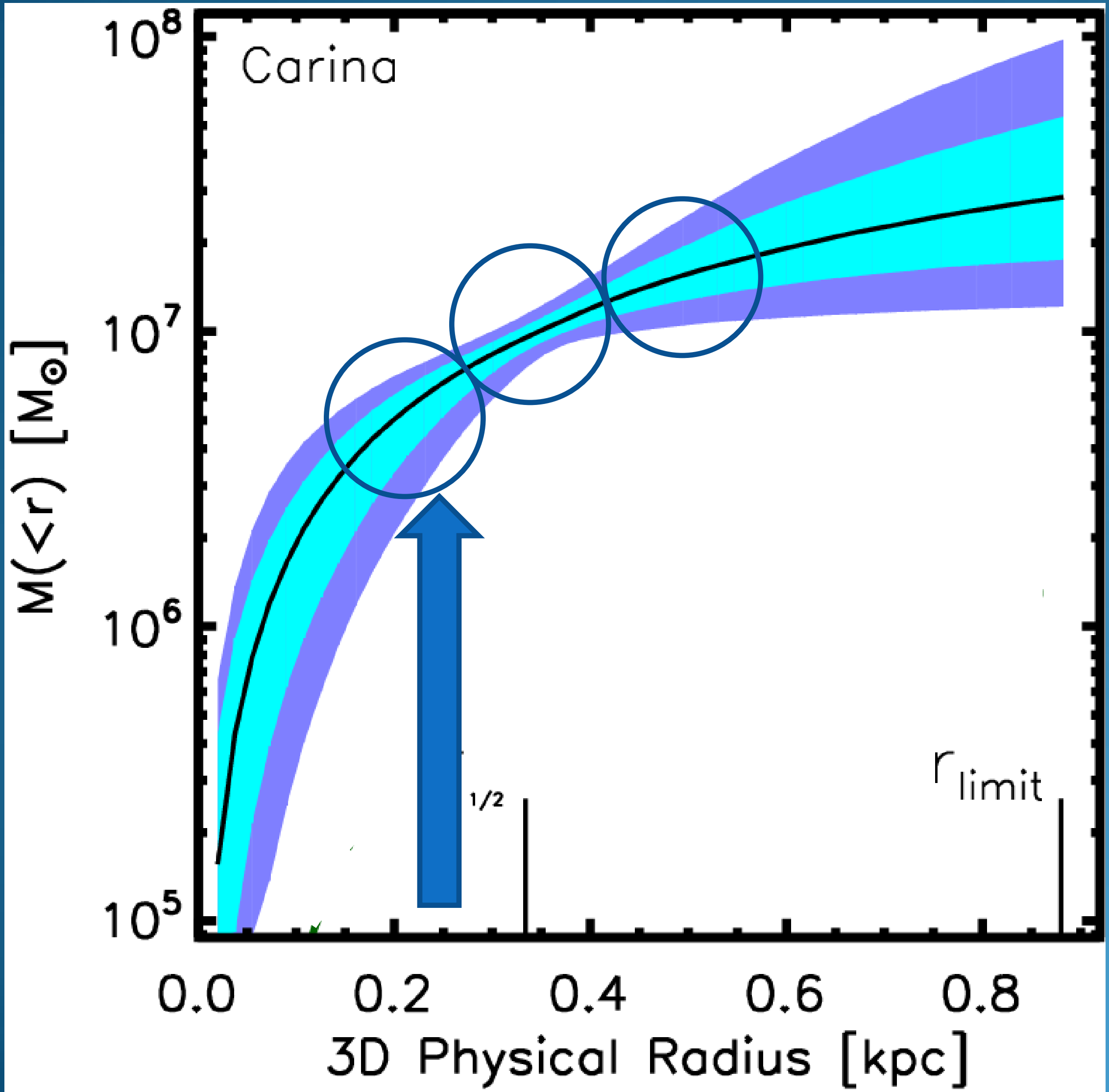

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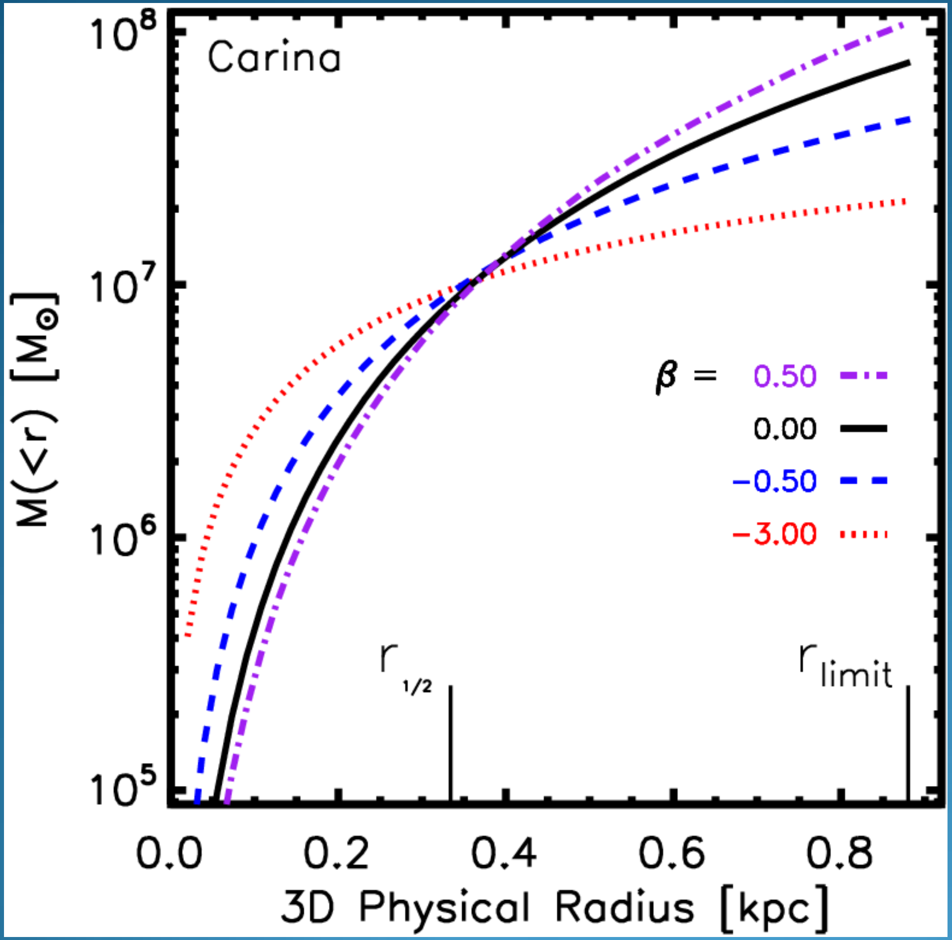
Joe Wolf et al., in prep

Anisotrwhat?



Radial Anisotropy

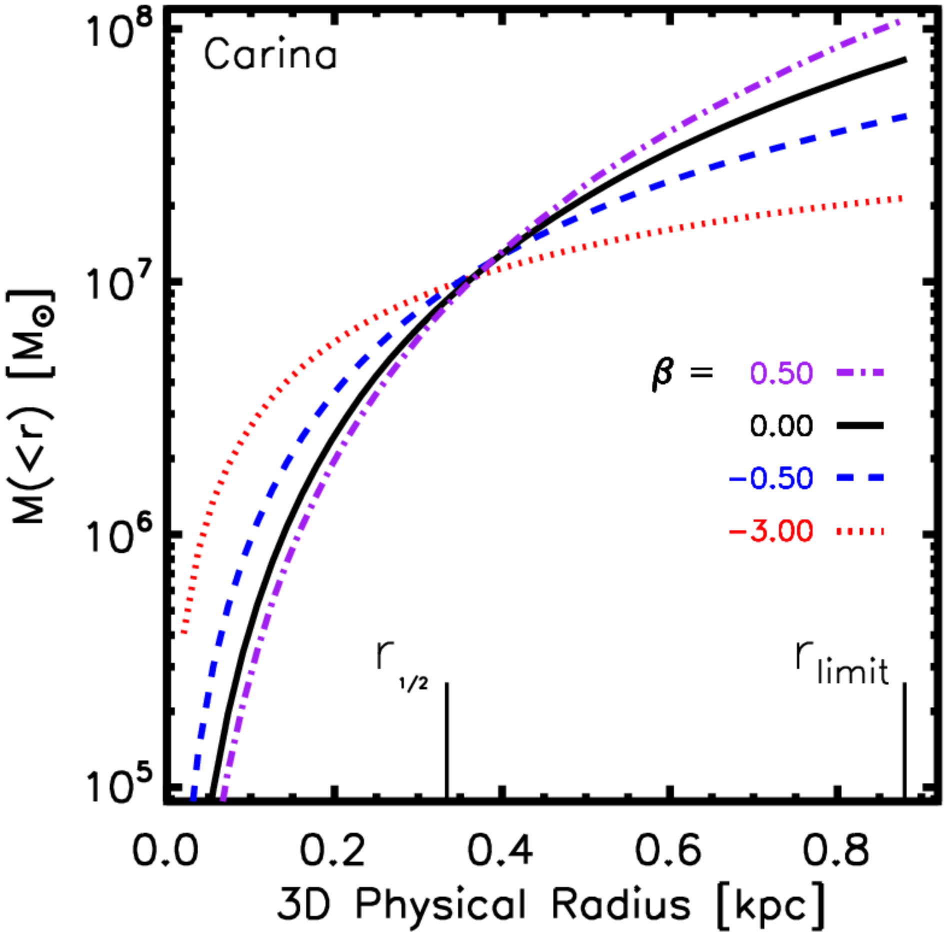
Isotropic

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

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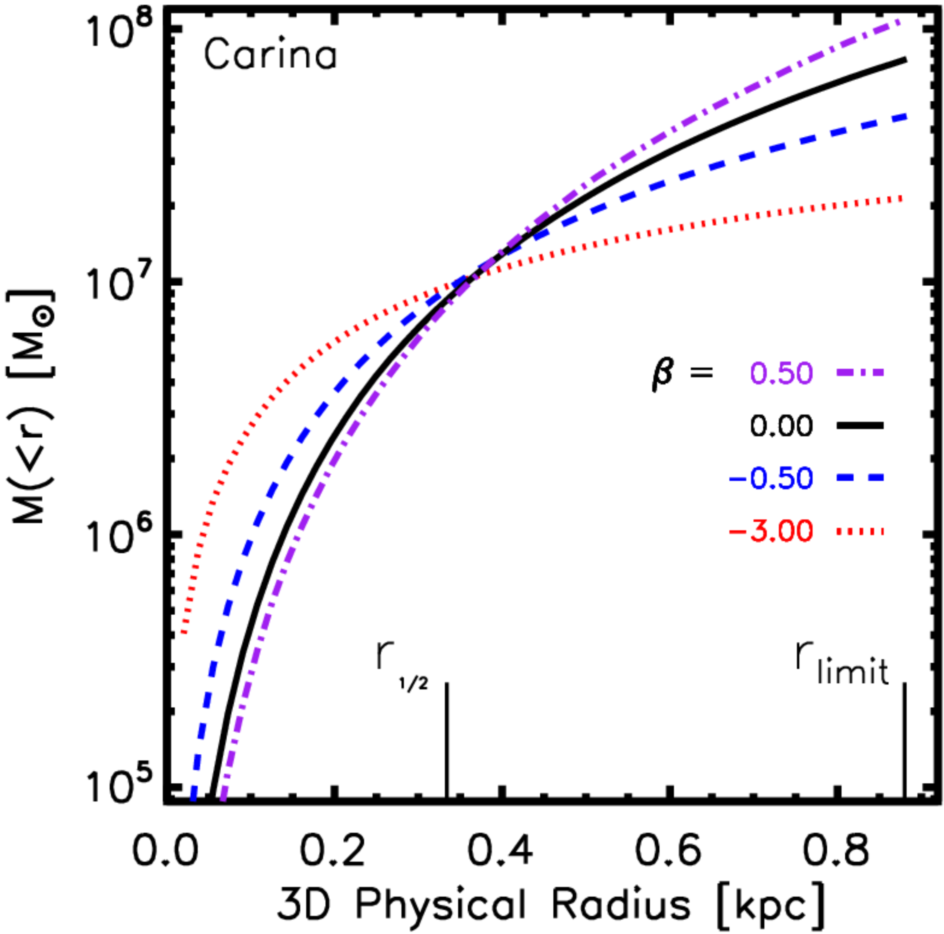
Joe Wolf et al., in prep

Anisotrwhat?

Center of system:
Observed dispersion is radial



Edge of system: Observed dispersion is tangential

Radial Anisotropy

Isotropic

Tangential

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

Joe Wolf et al., in prep

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

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

Derived equation under several simplifications:

$$\mathrm{M}_{1/2} = 3\,\mathrm{G}^{-1}\,\mathrm{r}_{1/2}\,\langle\sigma^2_{\mathrm{los}}\rangle$$

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

Derived equation under several simplifications:

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

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

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

Wait a second…

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

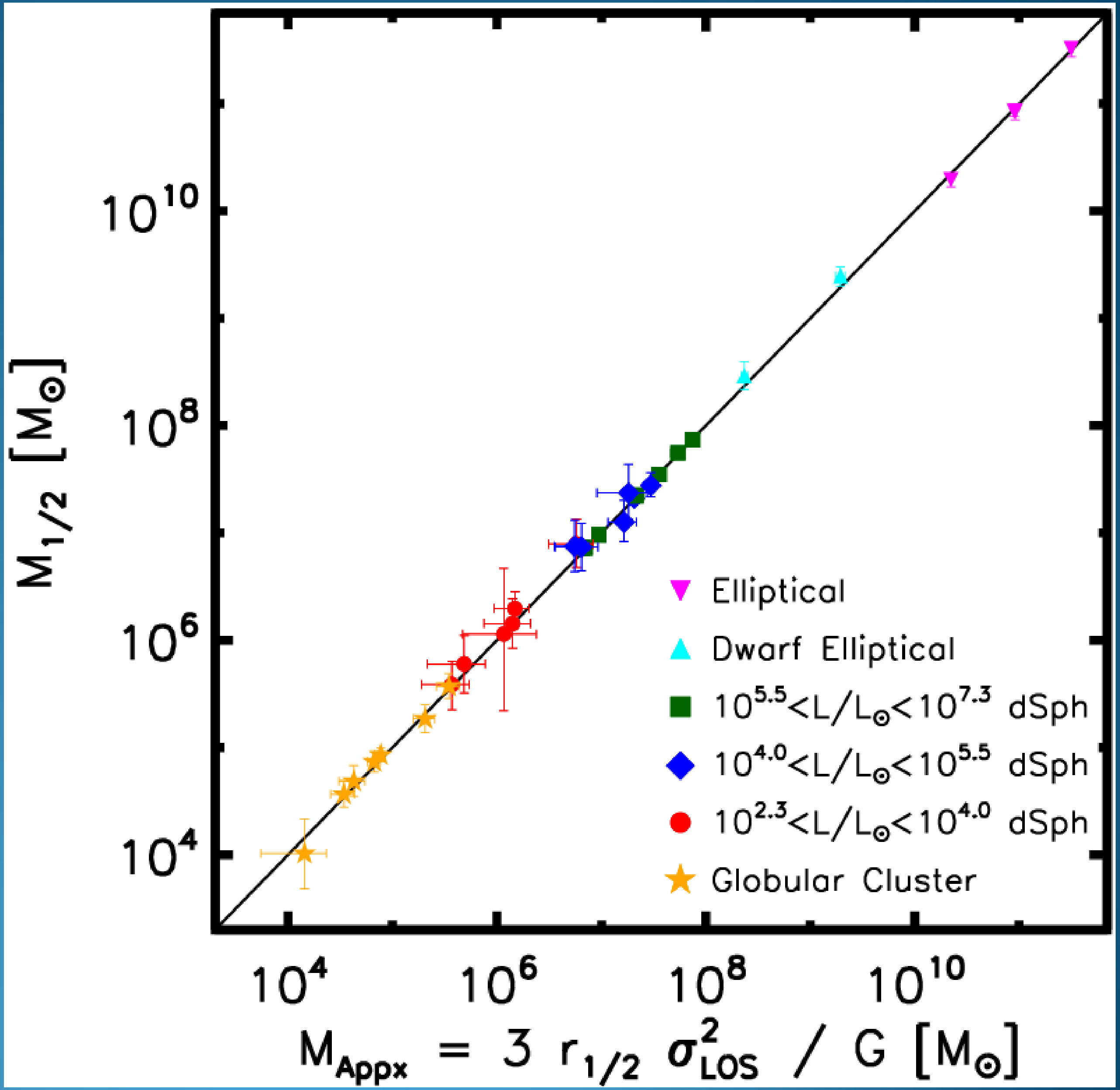
$$\mathrm{M}_{1/2} = 3\,\mathrm{G}^{-1}\,\mathrm{r}_{1/2}\,\langle \sigma_{\mathrm{los}}^{2} \rangle$$

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?

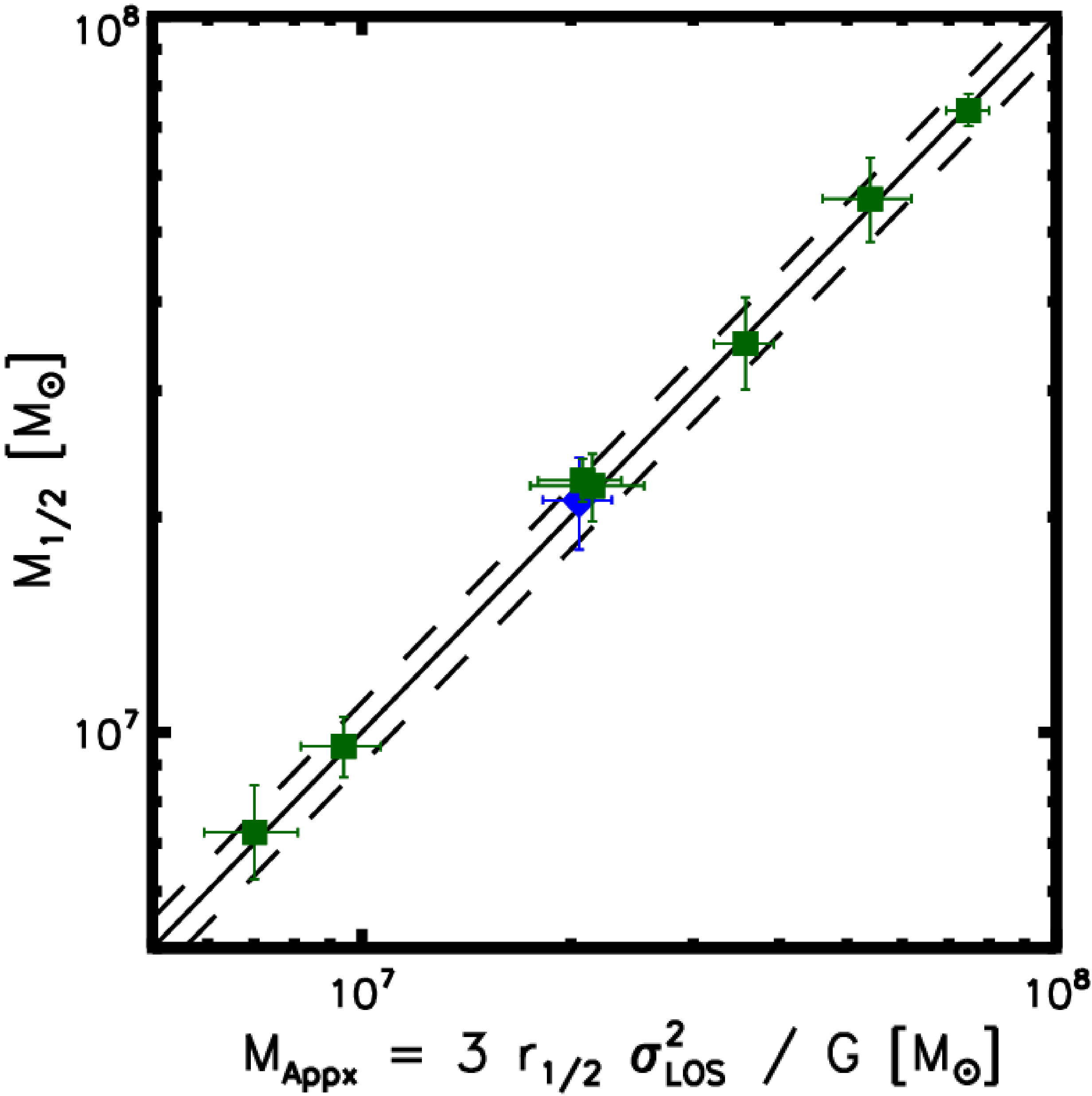
Boom!
Equation tested on systems spanning almost **eight** decades in half-light mass after lifting simplifications.



Joe Wolf et al., in prep

Boom!

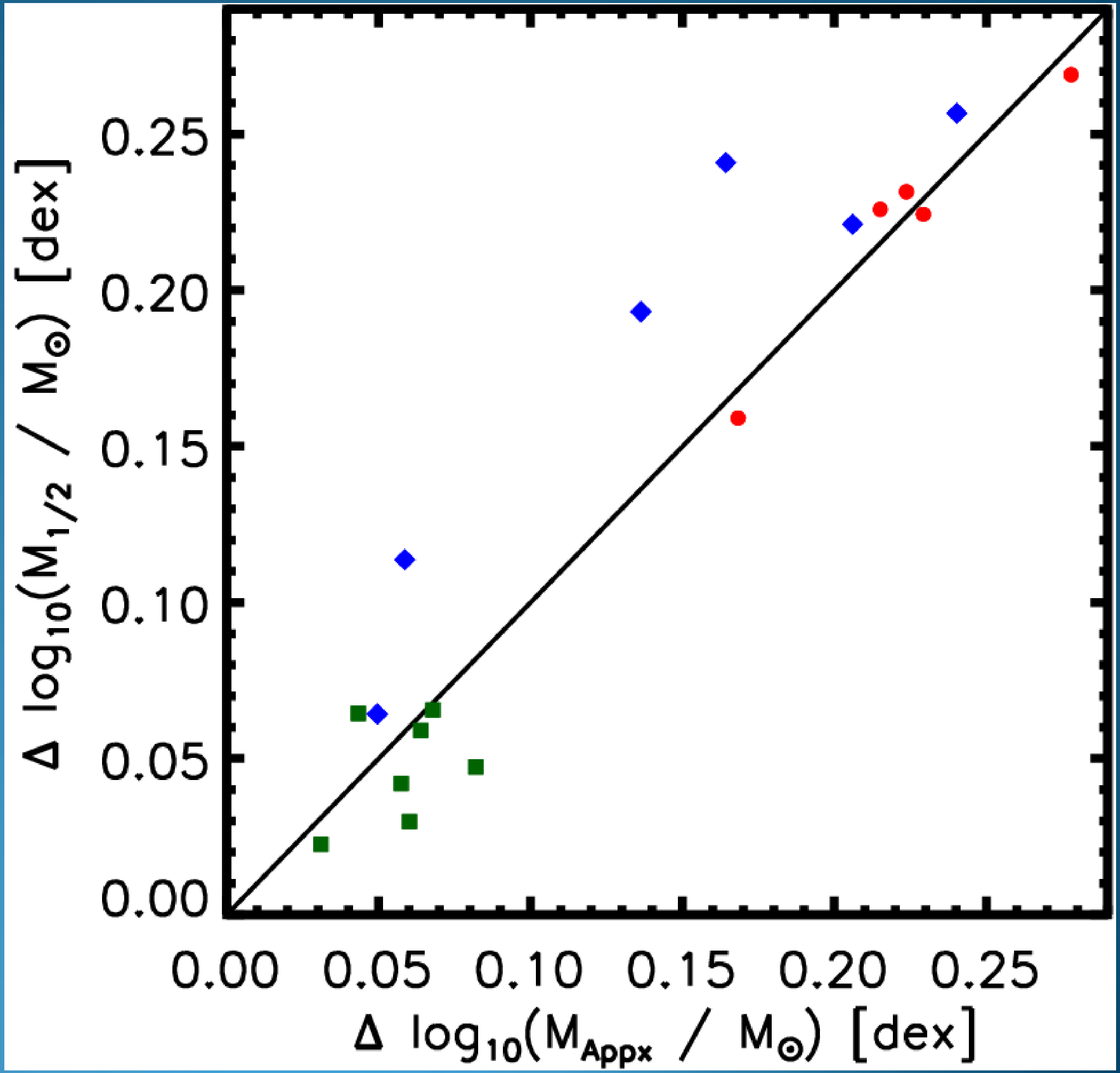
“Classical” MW dwarf spheroidals



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

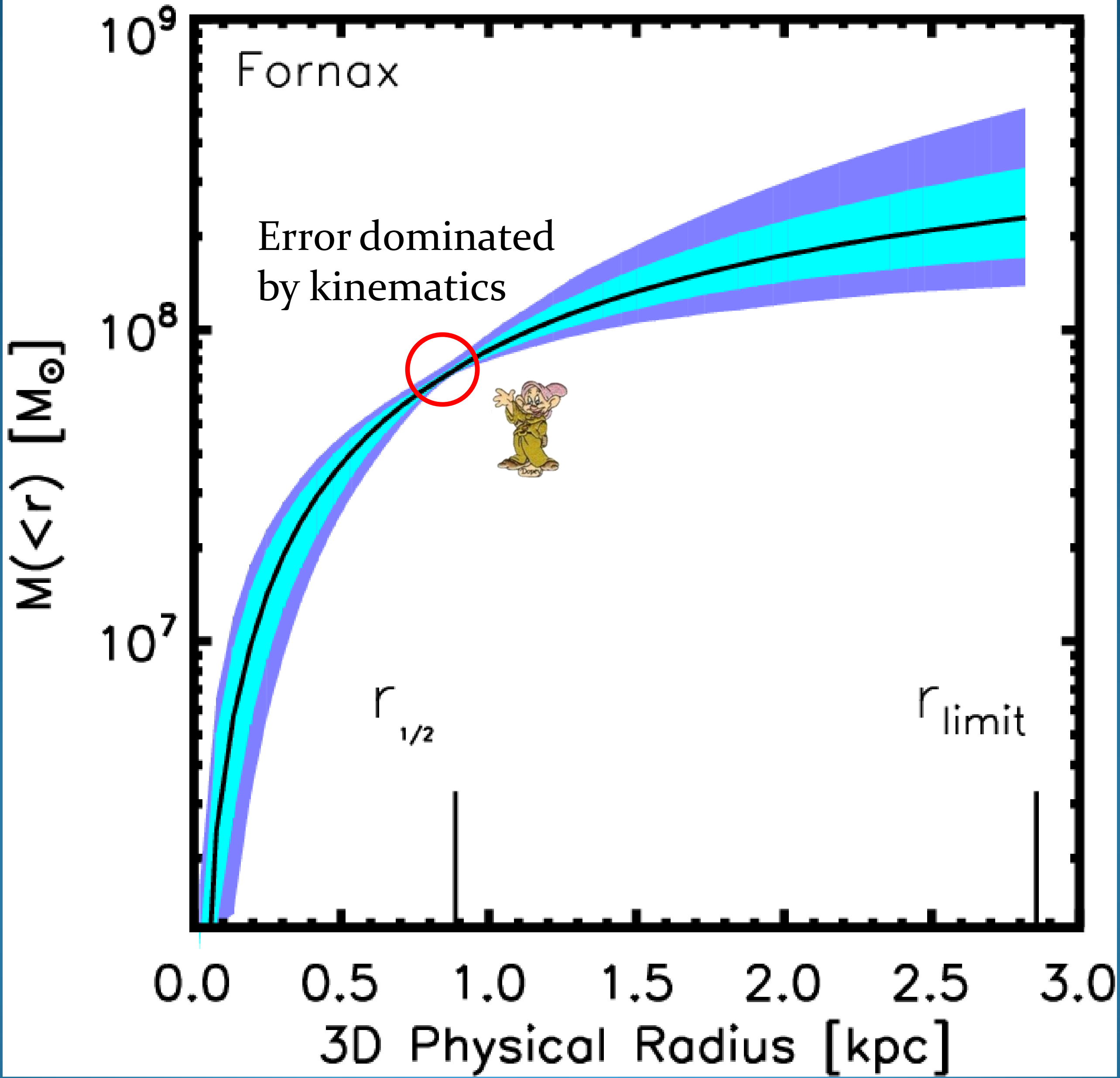
Joe Wolf et al., in prep

For Oleg (how *you* doin'?)



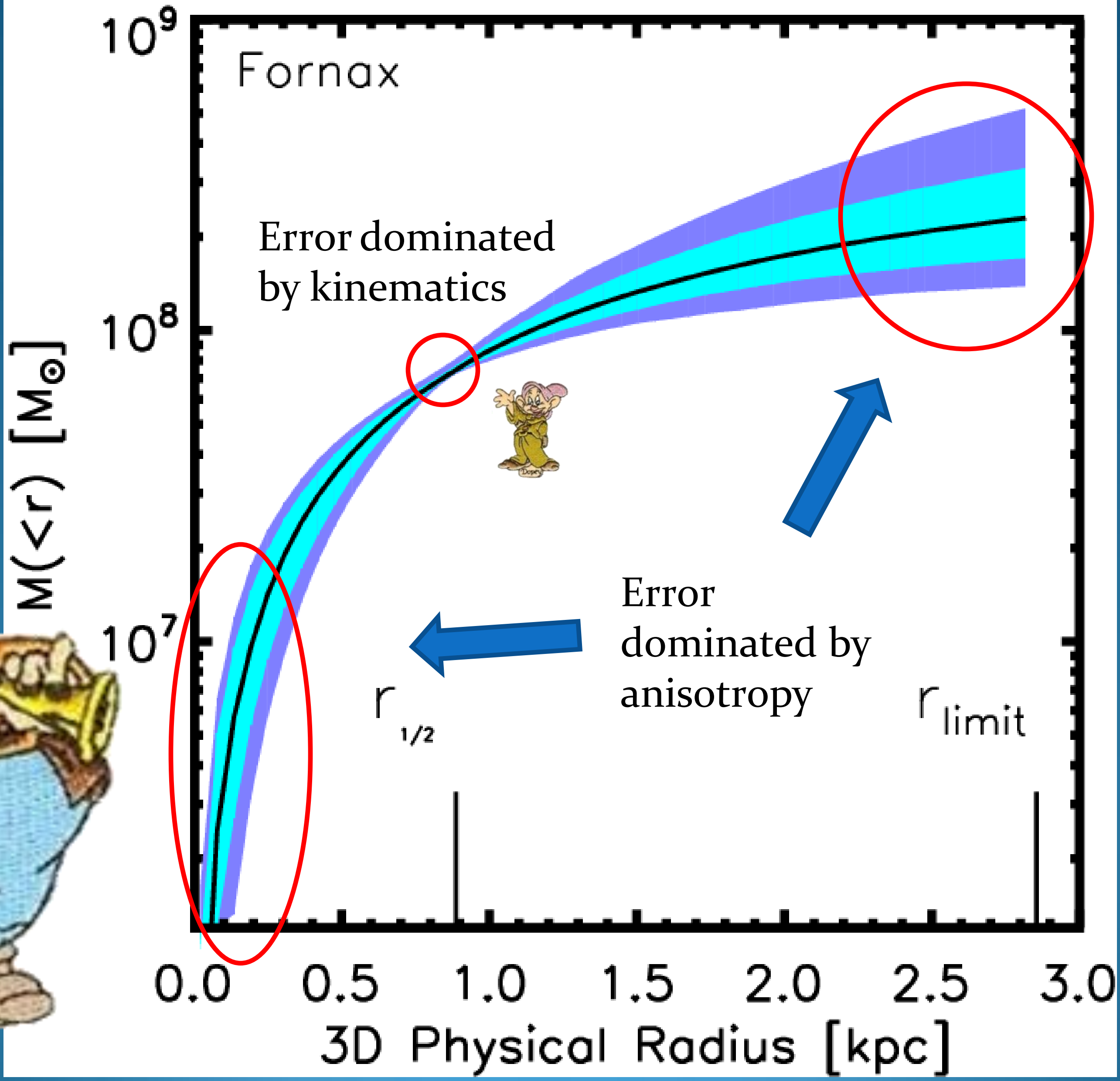
Joe Wolf et al., in prep

Mass Errors: Origins



Joe Wolf et al., in prep

Mass Errors: Origins

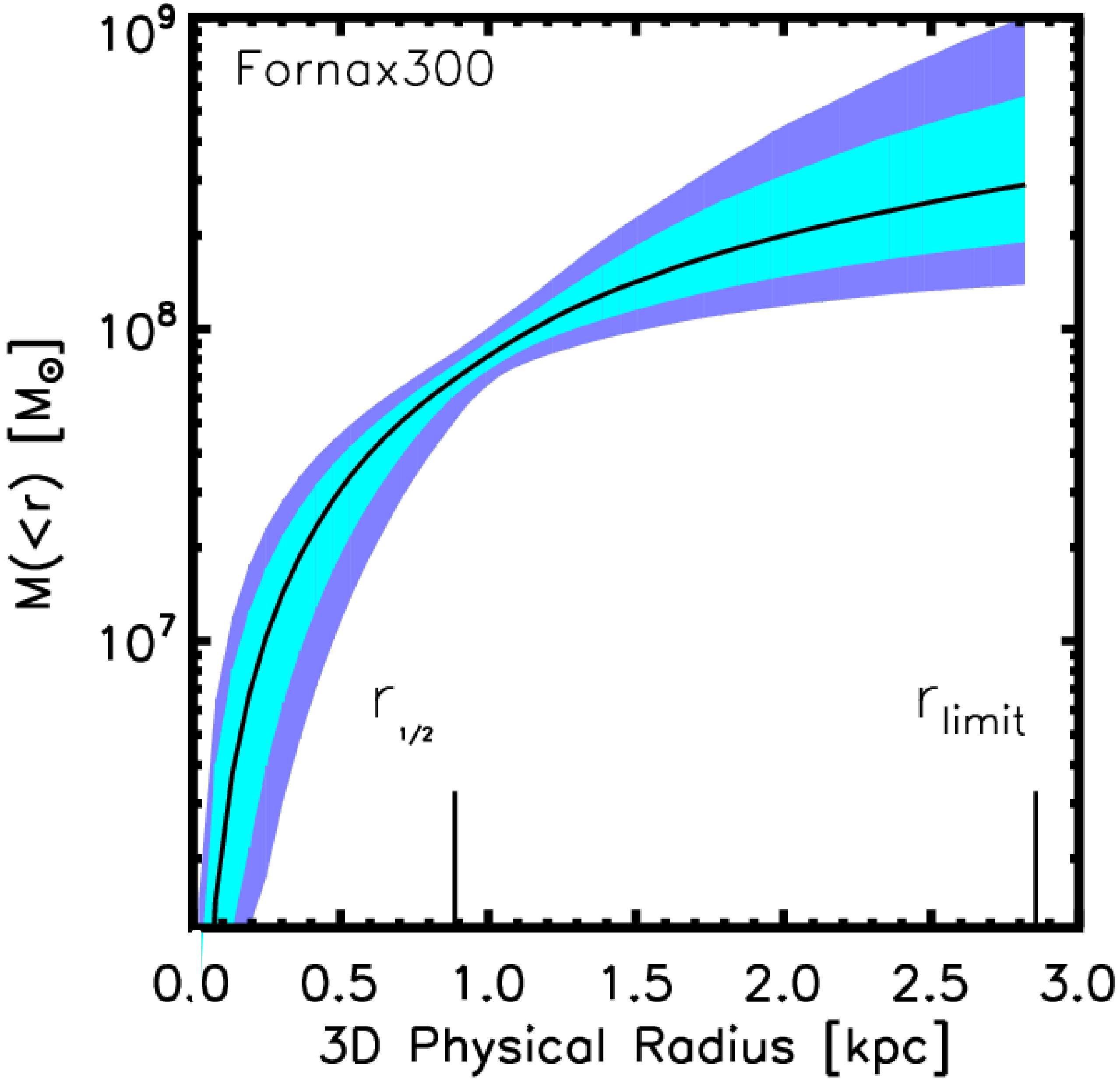


Error dominated by kinematics

Error dominated by anisotropy

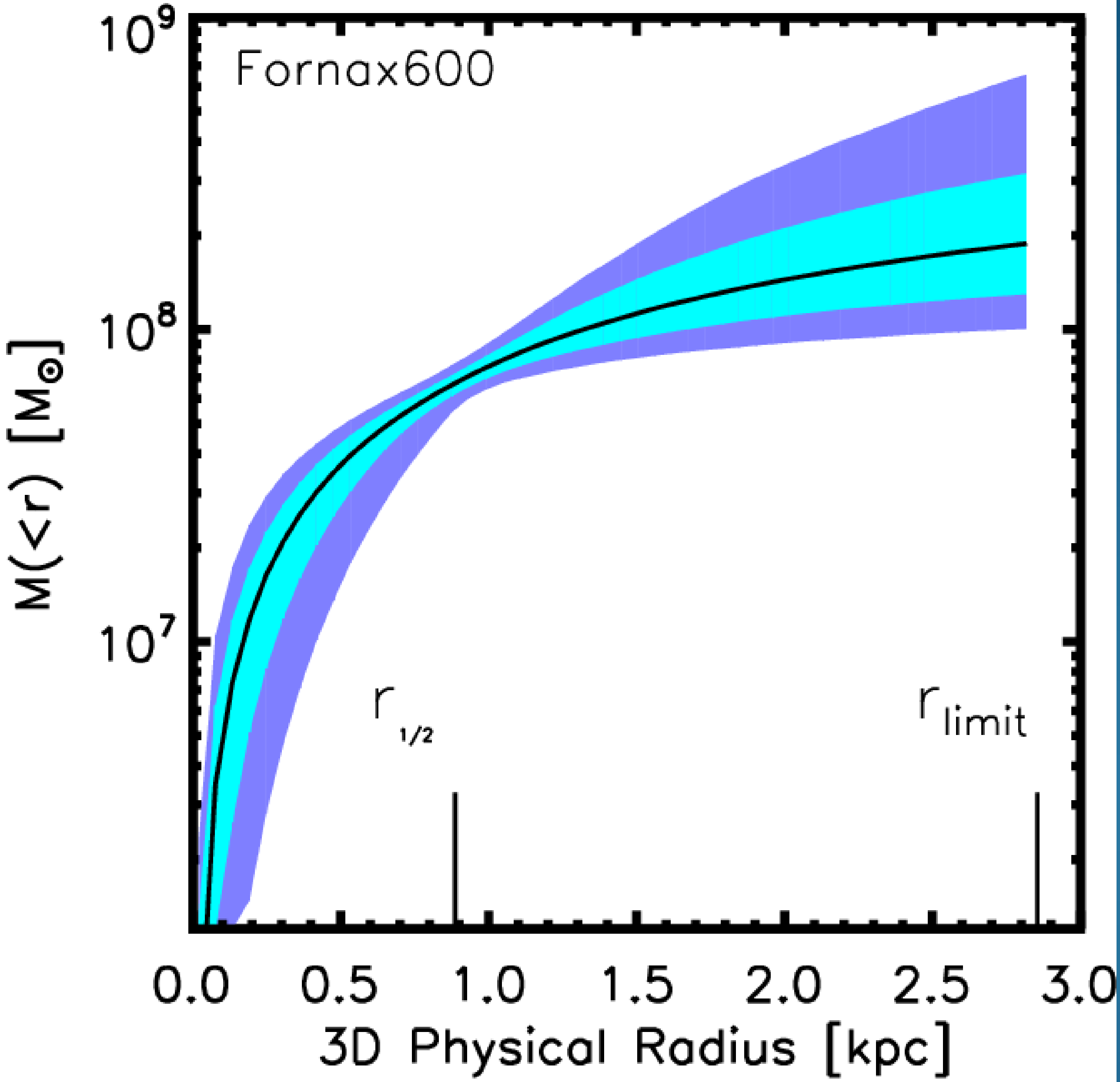
Joe Wolf et al., in prep

Mass Errors: 300 stars



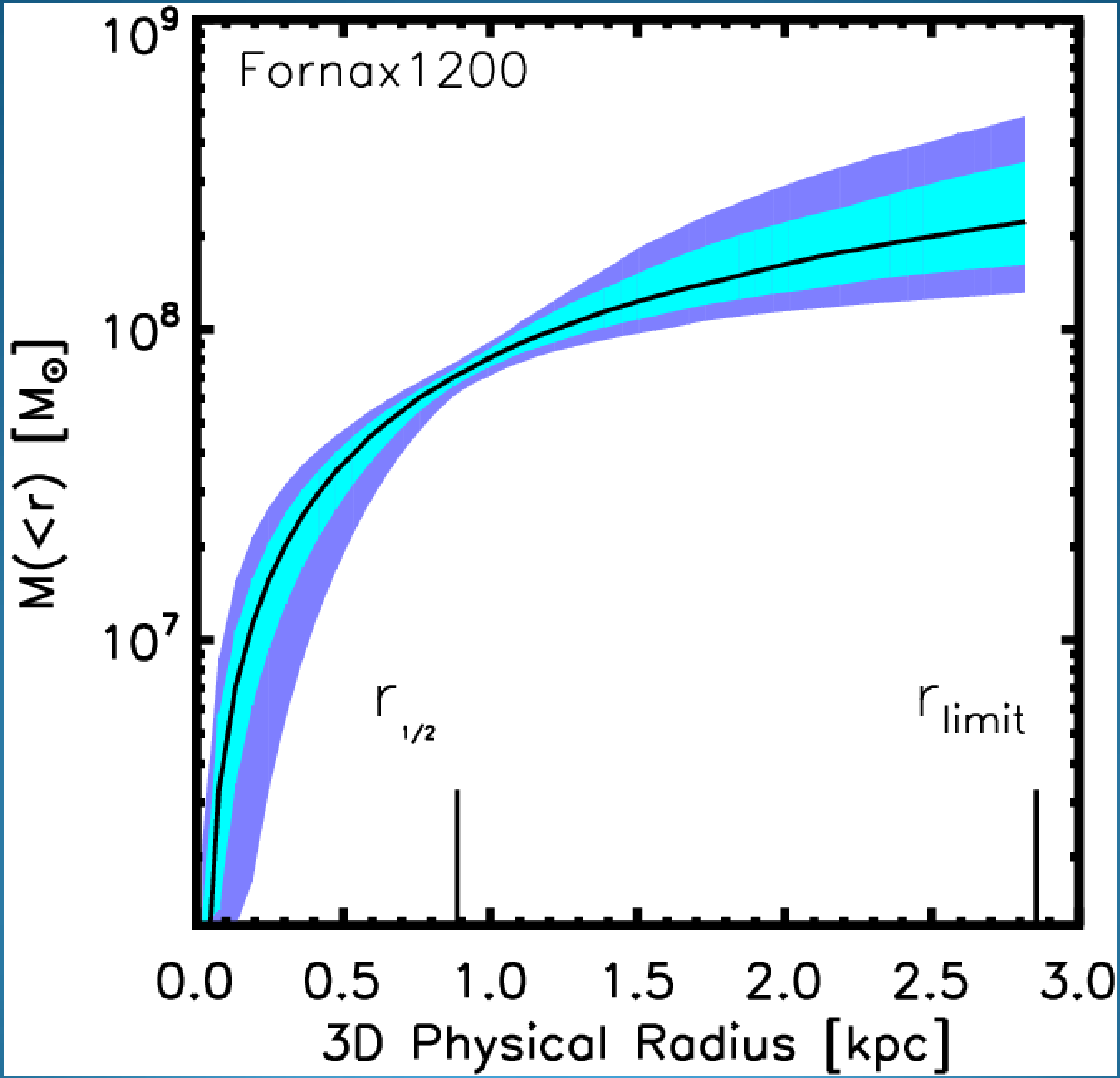
Joe Wolf et al., in prep

Mass Errors: 600 stars



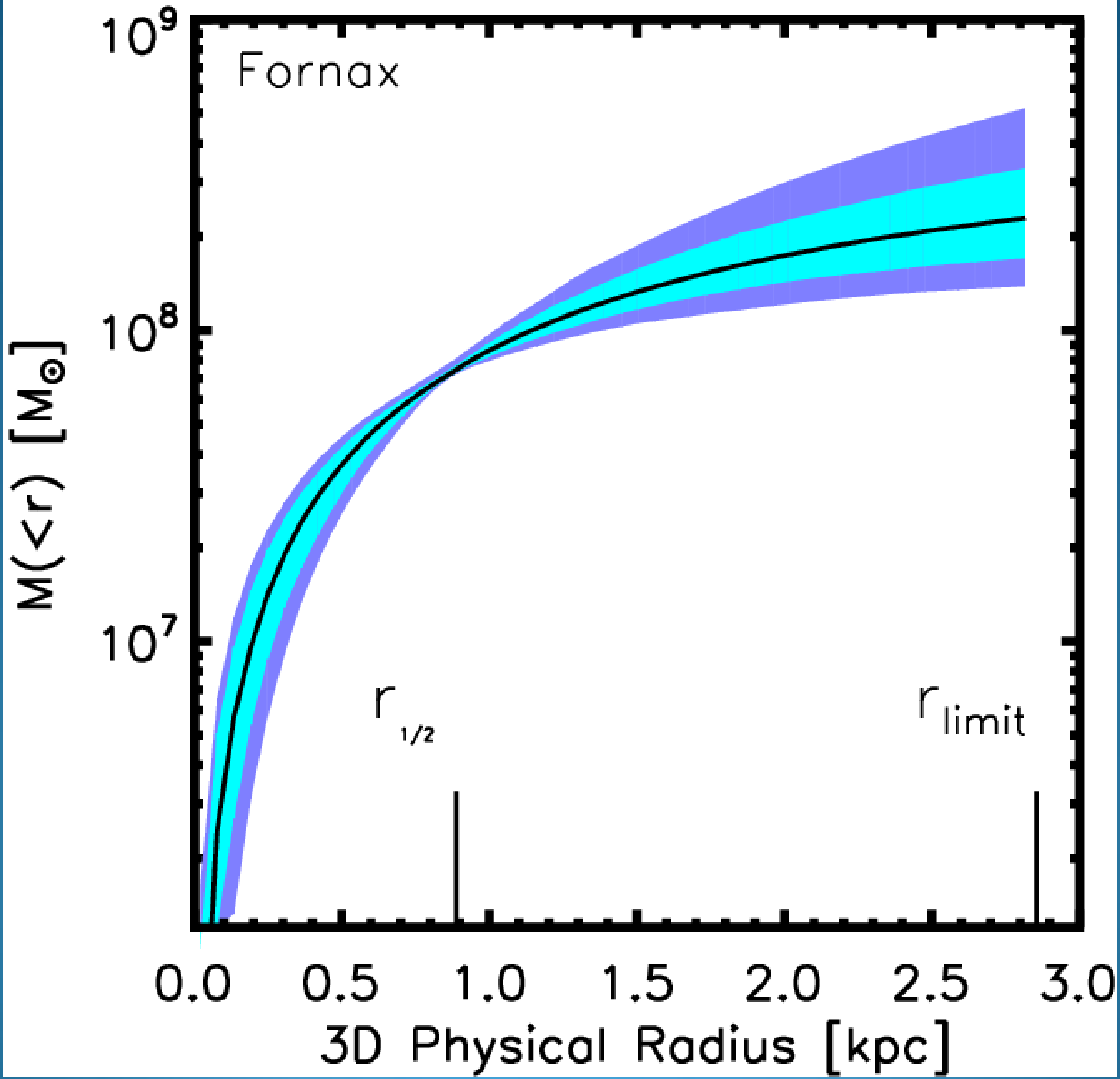
Joe Wolf et al., in prep

Mass Errors: 1200 stars



Joe Wolf et al., in prep

Mass Errors: 2400 stars



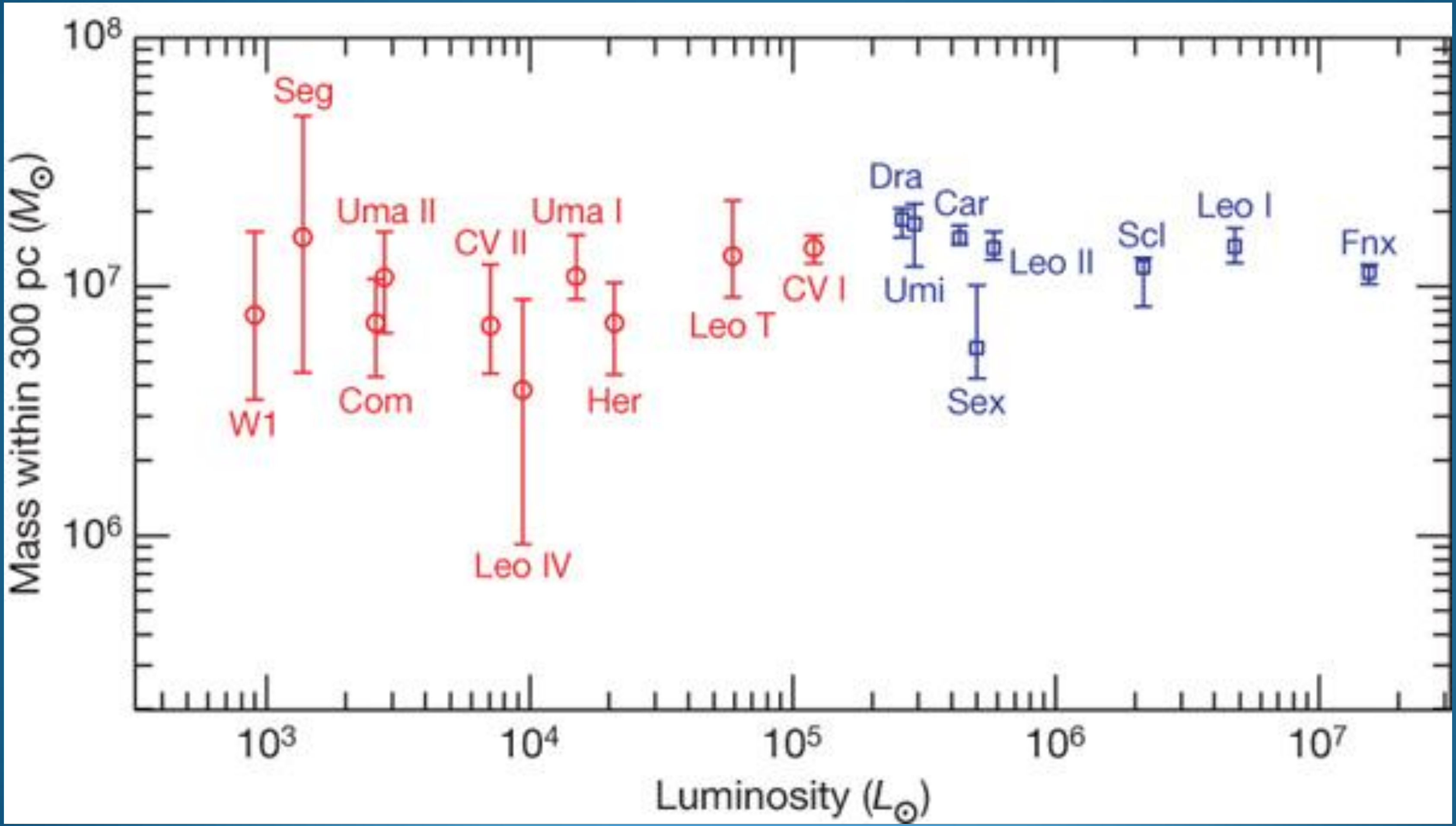
Joe Wolf et al., in prep

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
4. The skinny on slope determinations

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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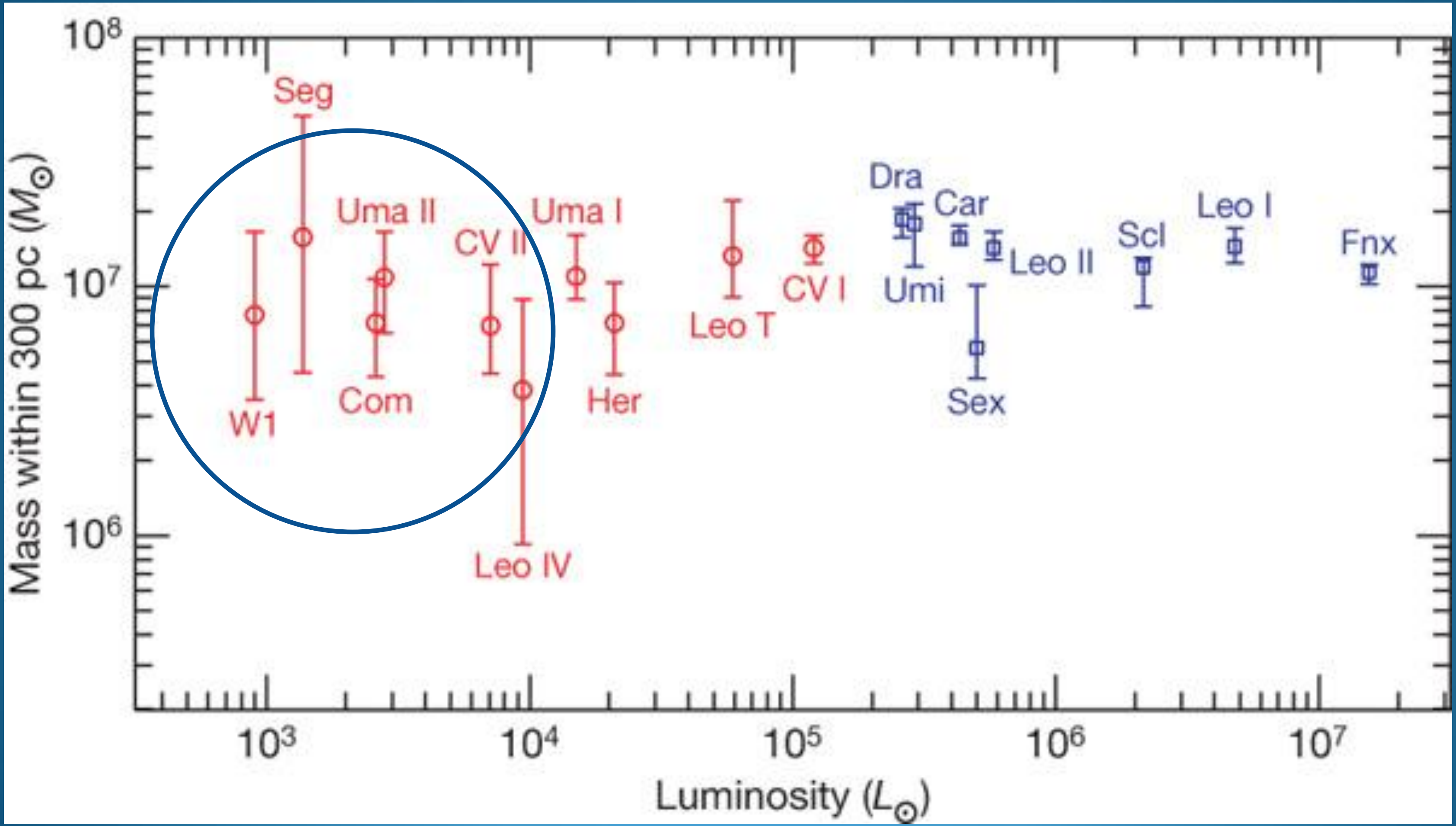

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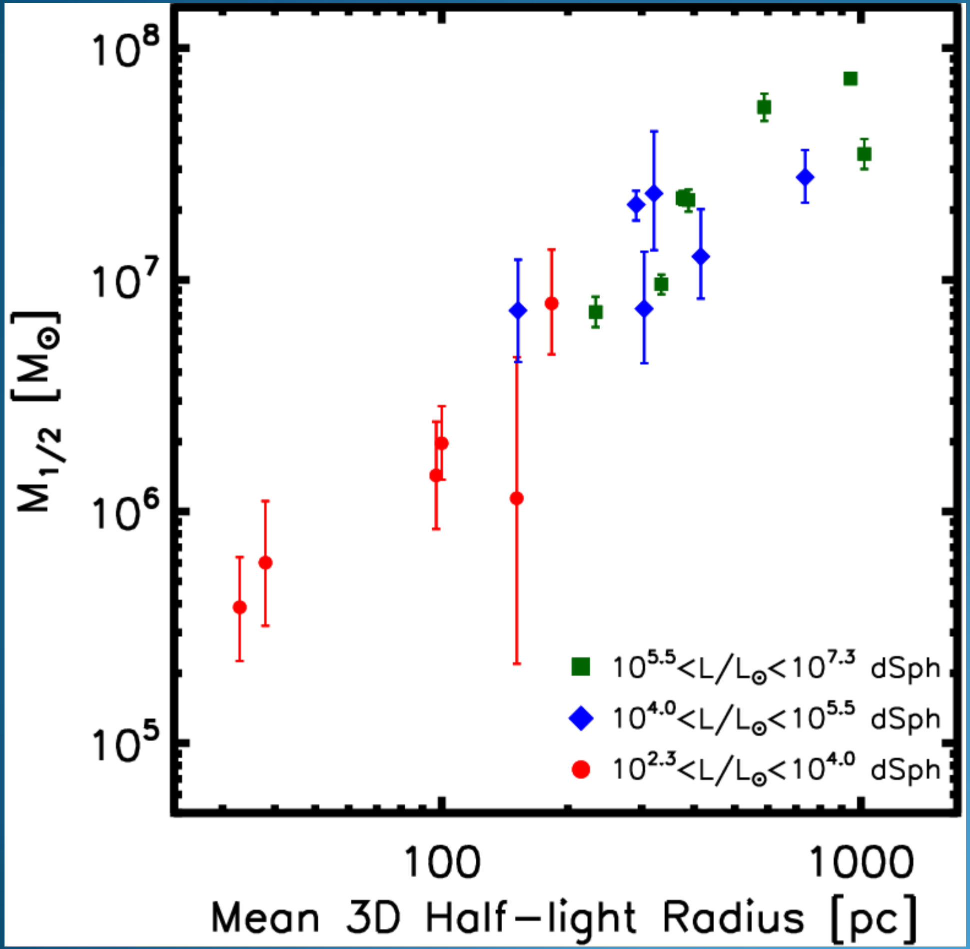
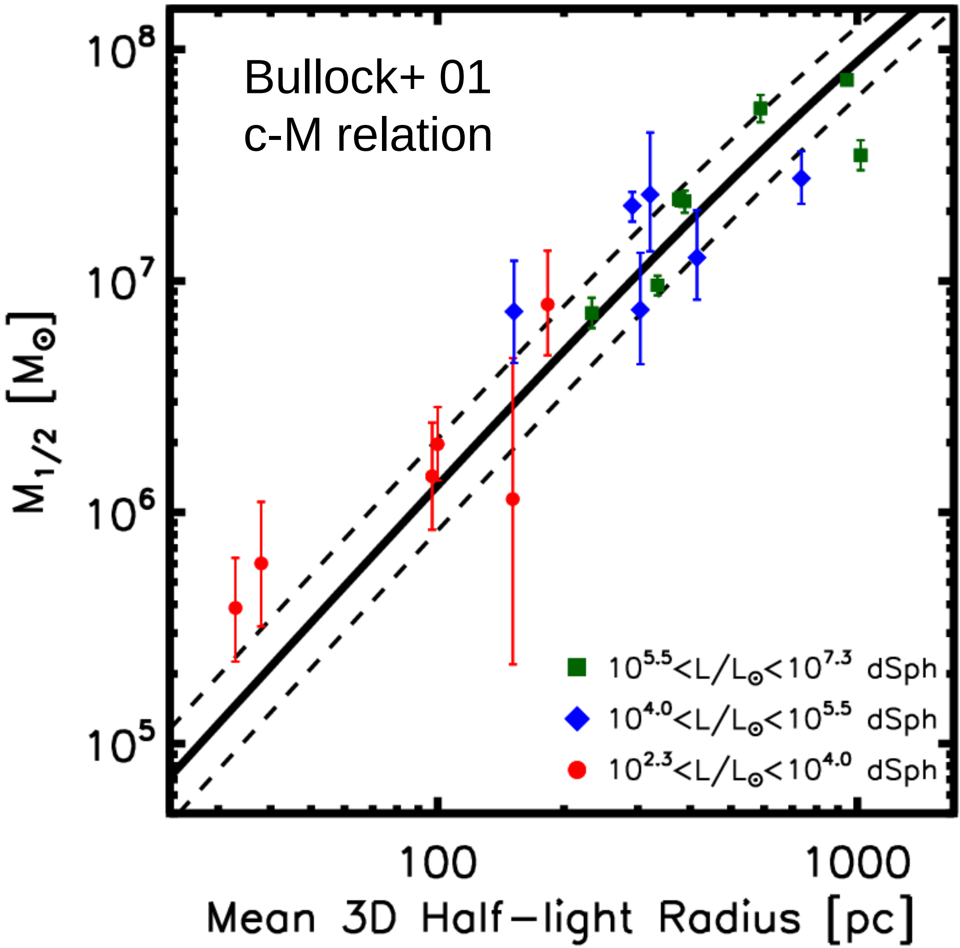


Joe Wolf et al., in prep

Applications: dSphs

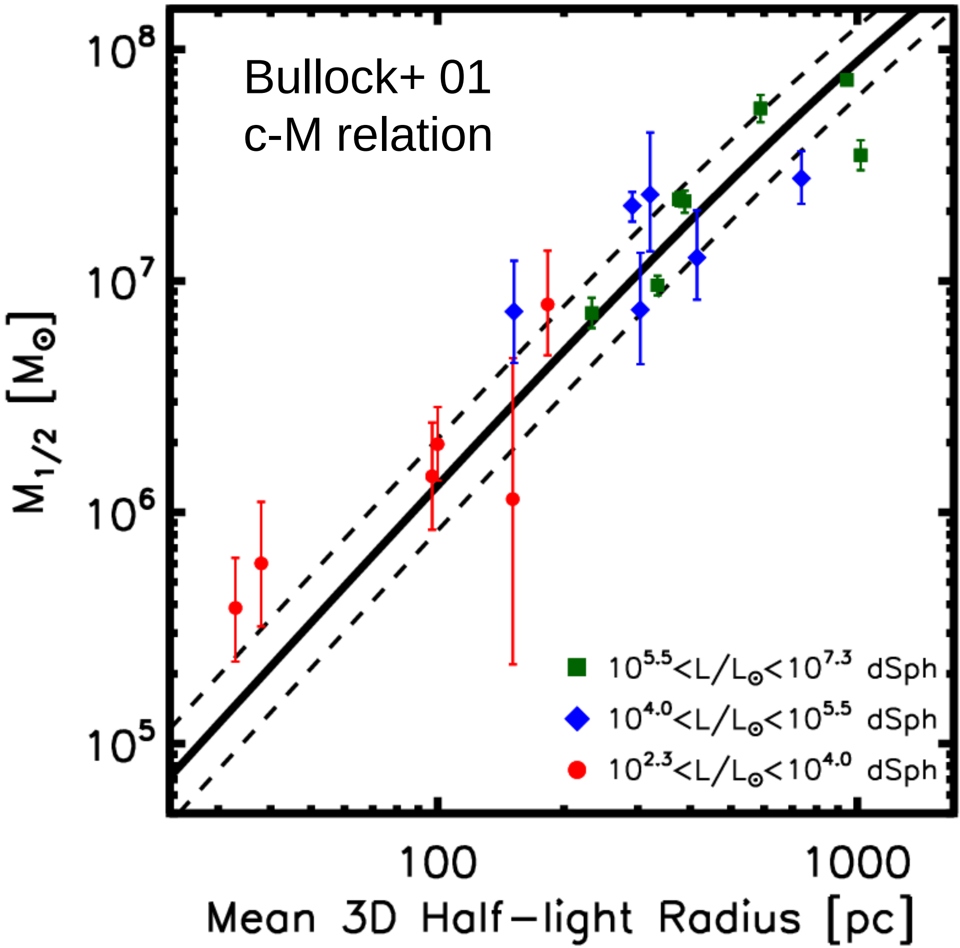
A common mass scale? Plotted: $M_{halo} = 3 \times 10^9 M_{sun}$

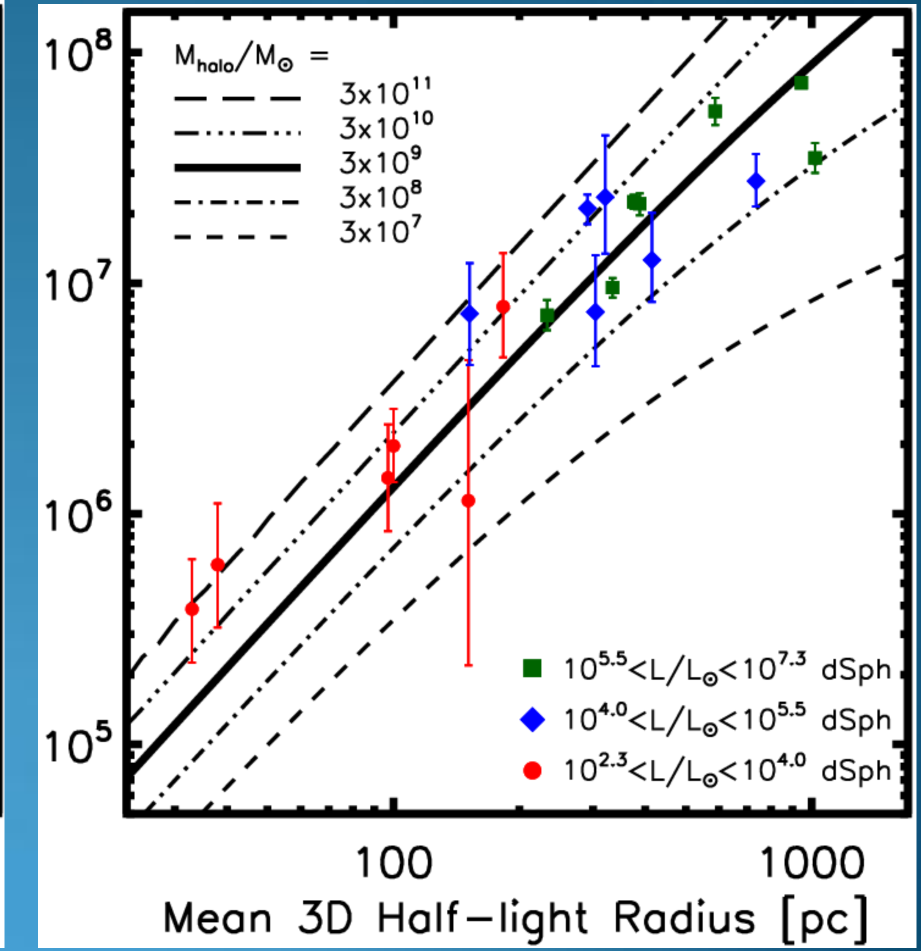


Joe Wolf et al., in prep

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)

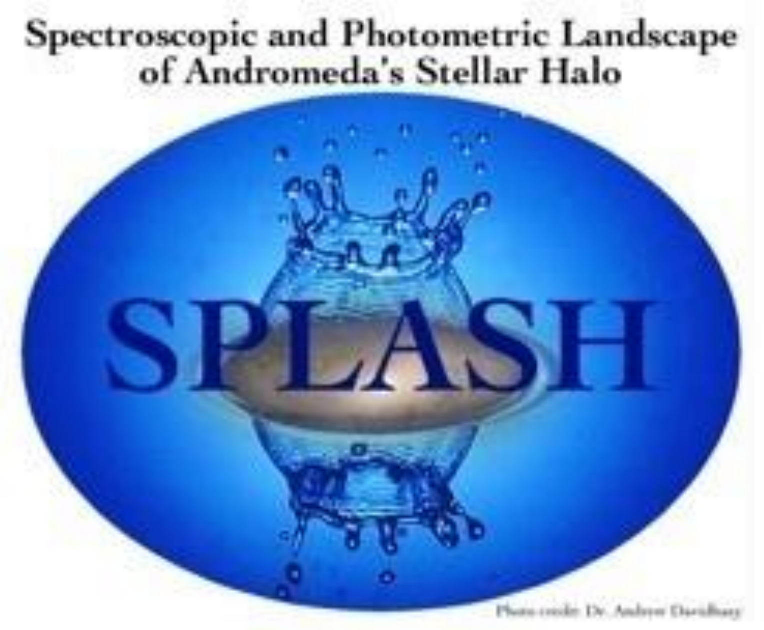
STScI: Jason Kalirai

Yale: Marla Geha

U. Washington: Karrie Gilbert

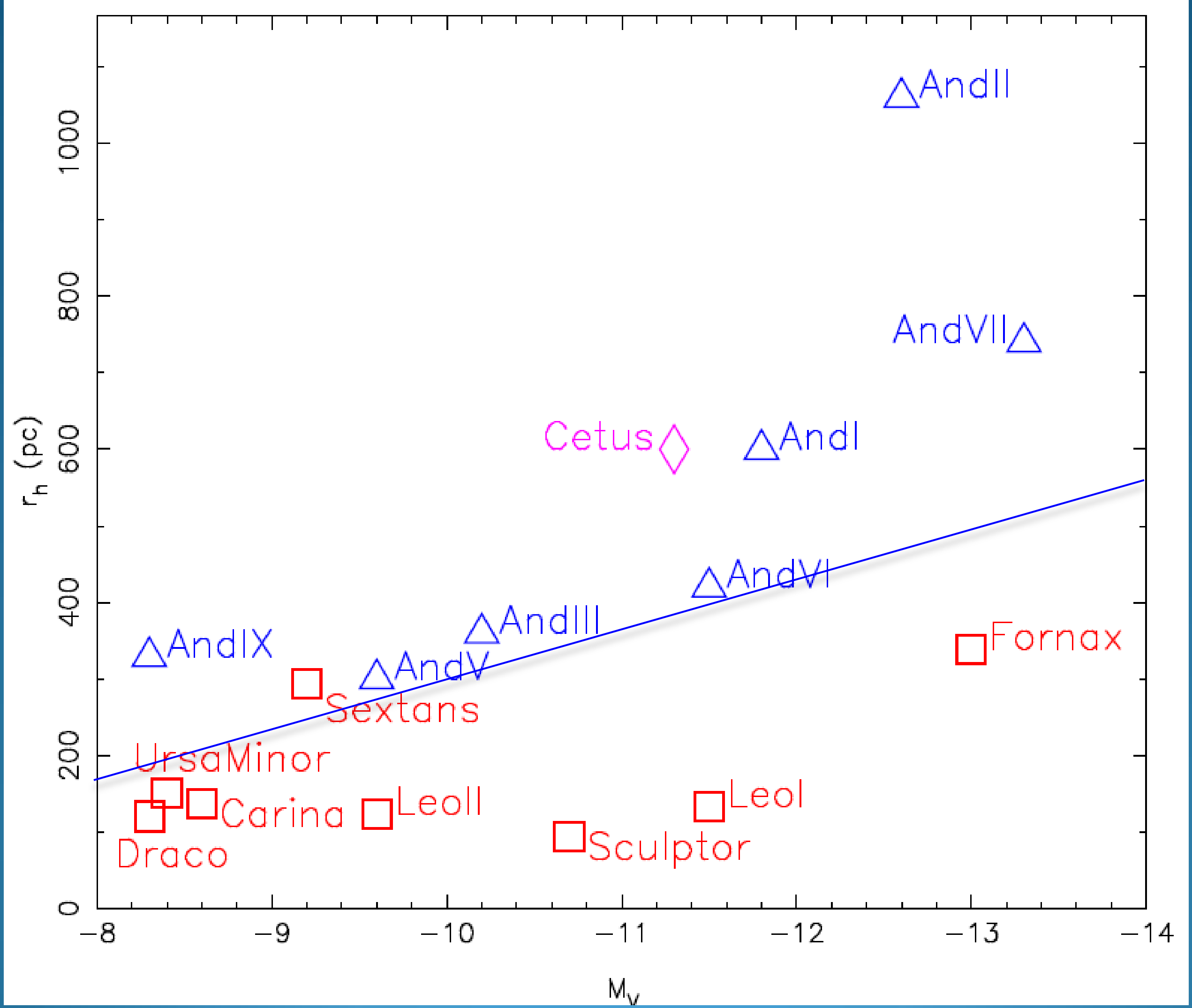
Caltech: Evan Kirby

And others involved in SPLASH →



M31 dSphs: Larger than MW dSphs

Observed half-light radius



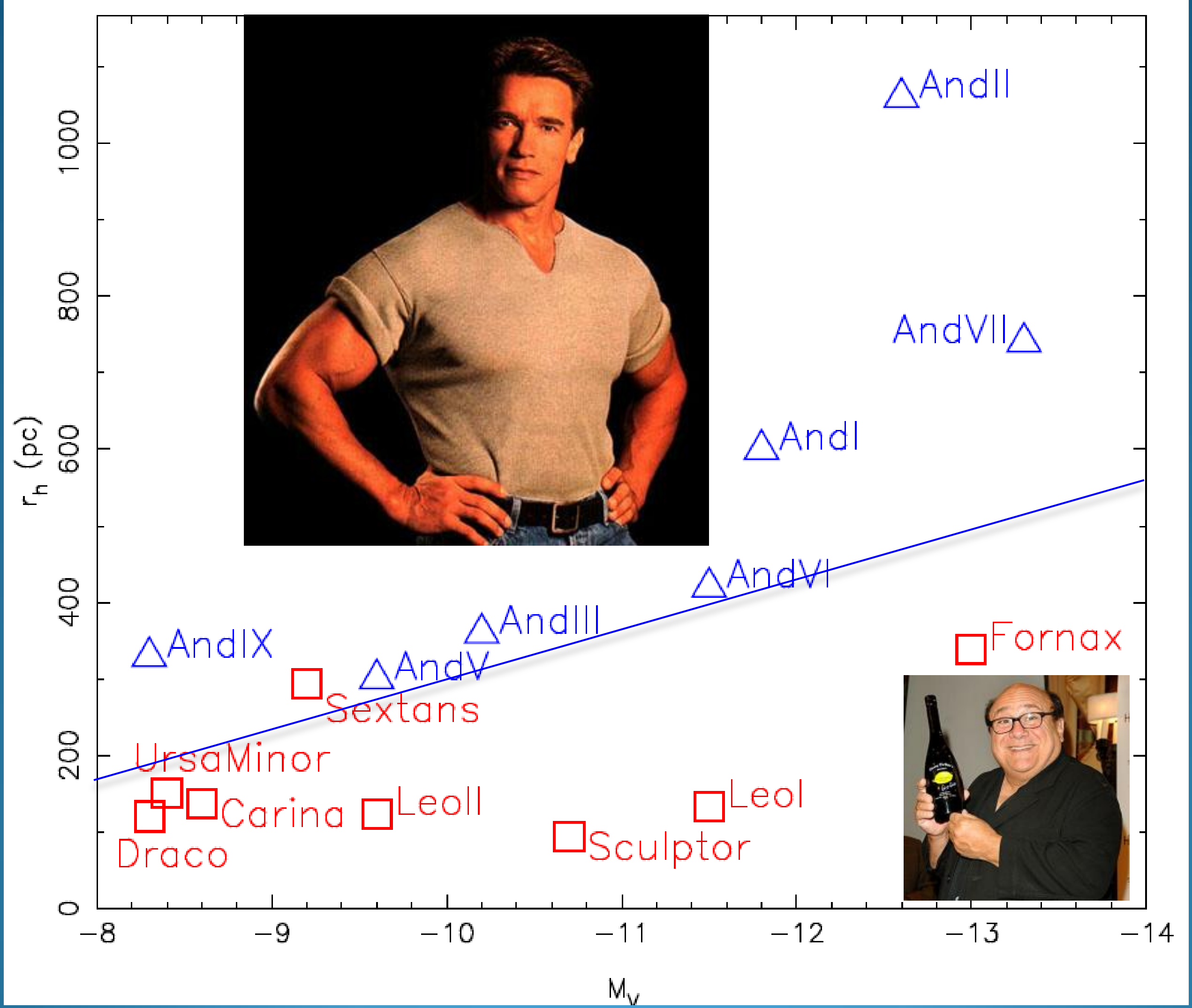
McConnachie & Irwin 2006, MNRAS

Dim

Luminosity

Bright

M31 dSphs: Larger than MW dSphs



Observed half-light radius

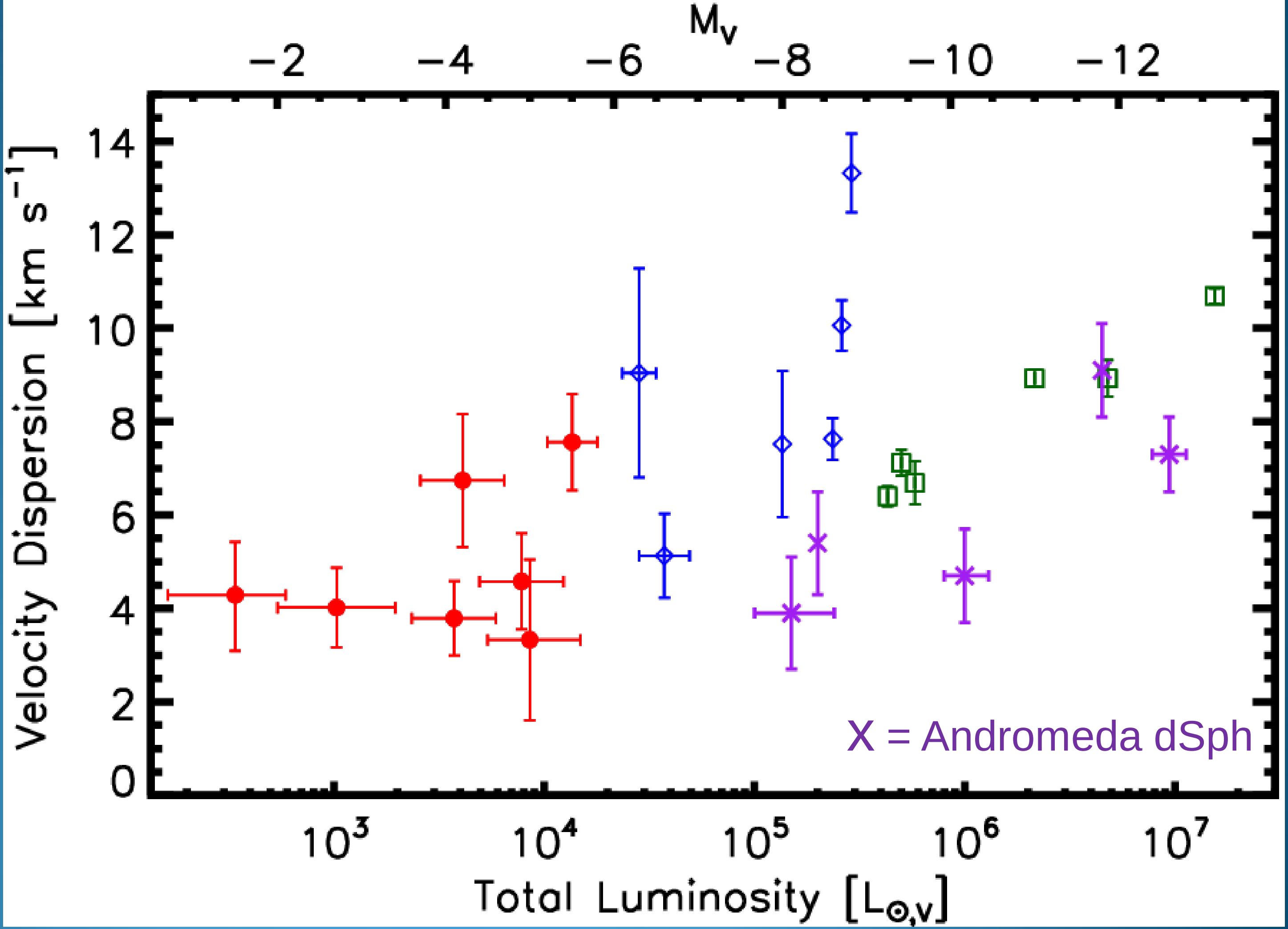
Dim Luminosity Bright

McConnachie & Irwin 2006, MNRAS

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



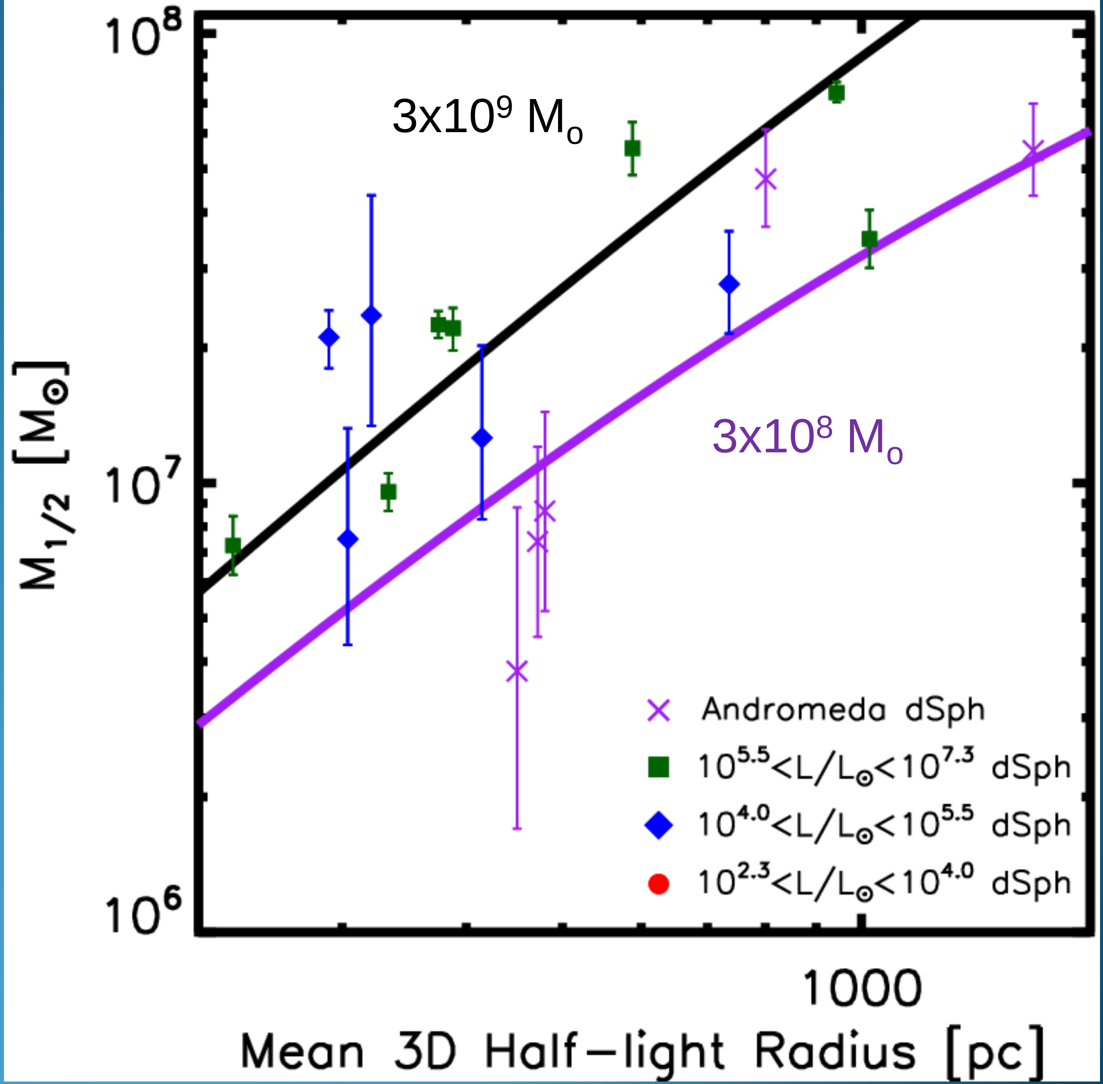
Dispersion data from Kalirai et al 2009, in prep

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



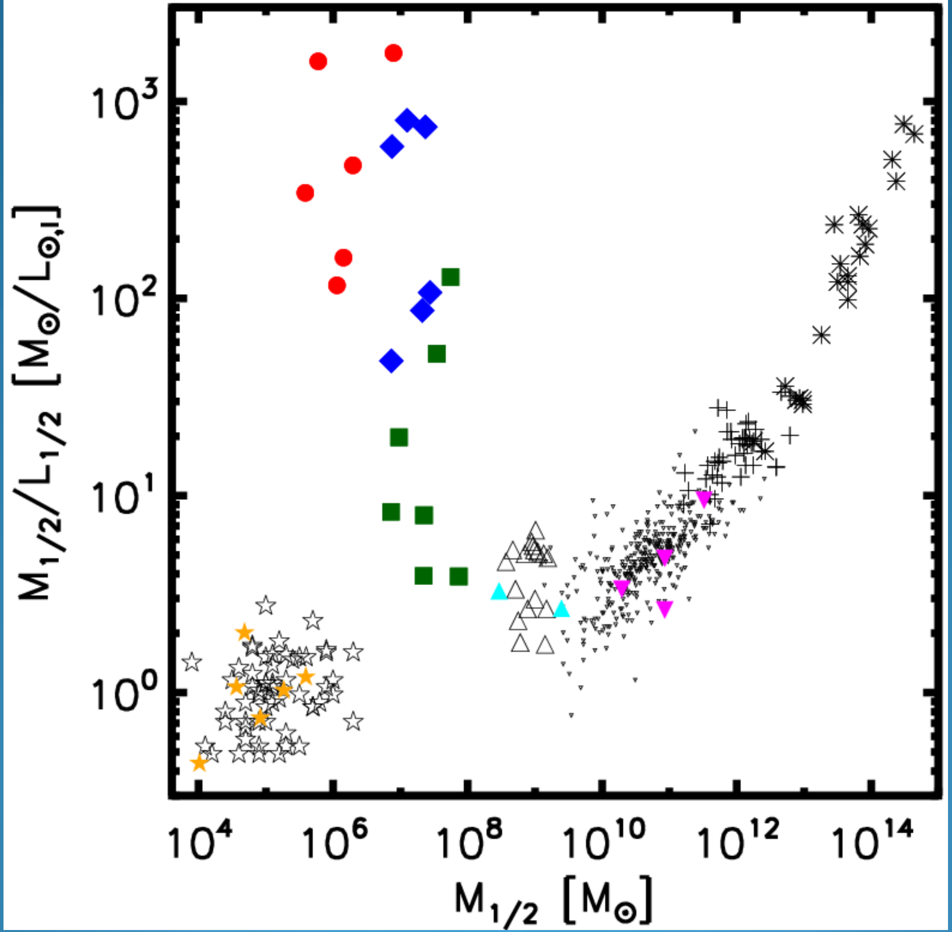
M31: Different Environment?

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.

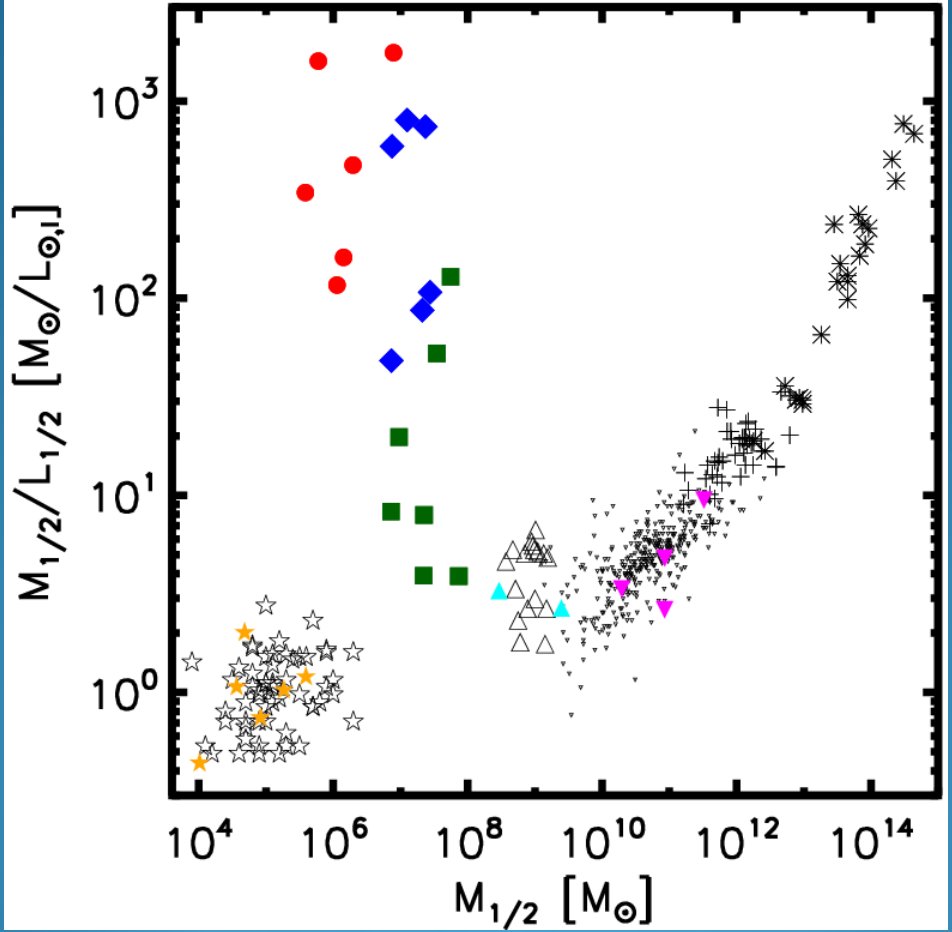
Applications: Global



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

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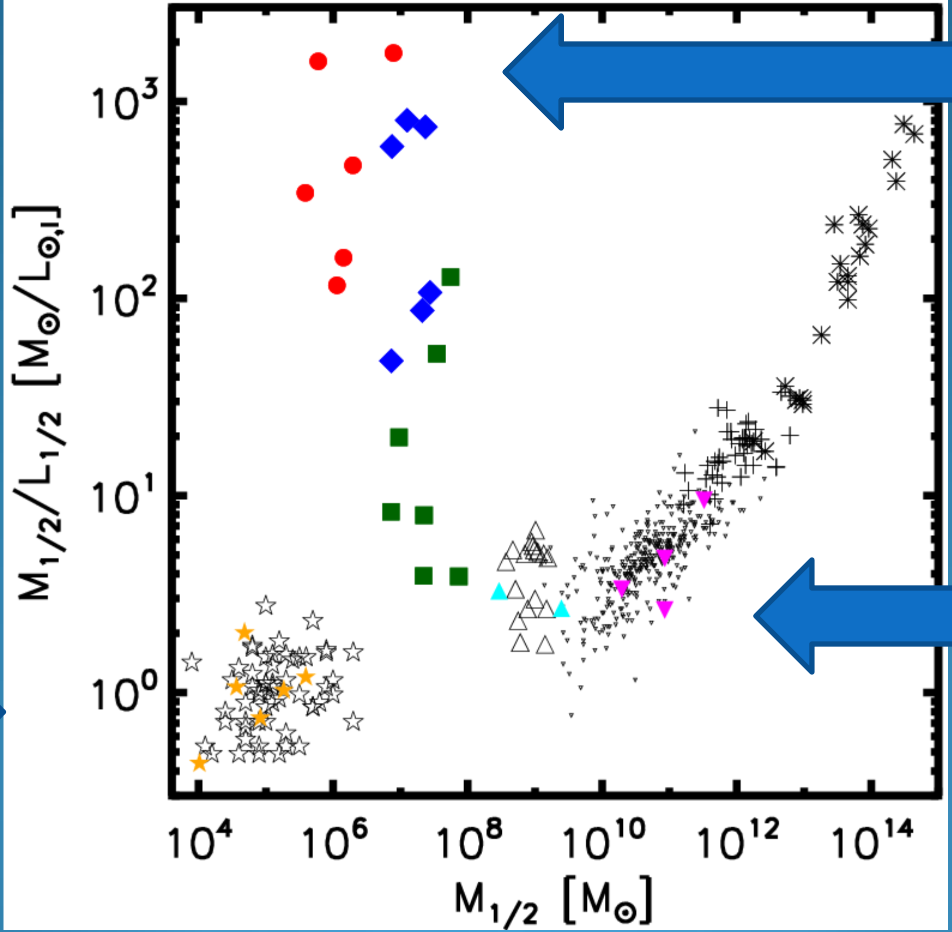
Ultrafaint dSphs: Most DM dominated systems known!

Globulars: Offset from L* by factor of three

(What the $%#*?!)

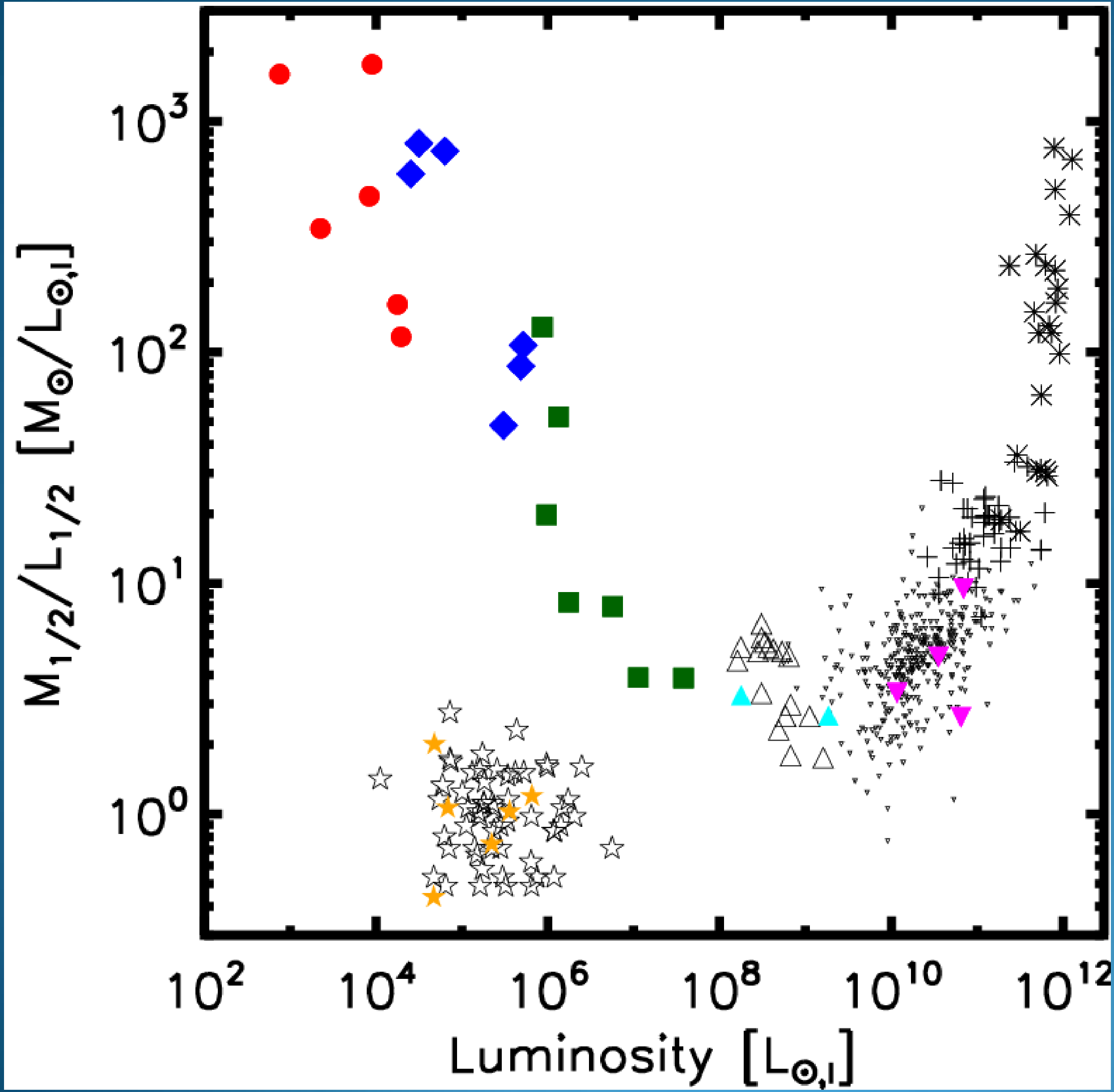


Inefficient at galaxy formation

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

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Slopes & Priors – Oh my!

“Can the observed or potentially measurable velocity dispersions tell apart a cusp vs. a core in their centers?” – Conference Website

Slopes & Priors – Oh my!

“Can the observed or potentially measurable velocity dispersions tell apart a cusp vs. a core in their centers?” – Conference Website

No.

Slopes & Priors – Oh my!

“Can the observed or potentially measurable velocity dispersions tell apart a cusp vs. a core in their centers?” – Conference Website

No.
(At least not with LOS kinematics alone.)

Slopes & Priors – Oh my!

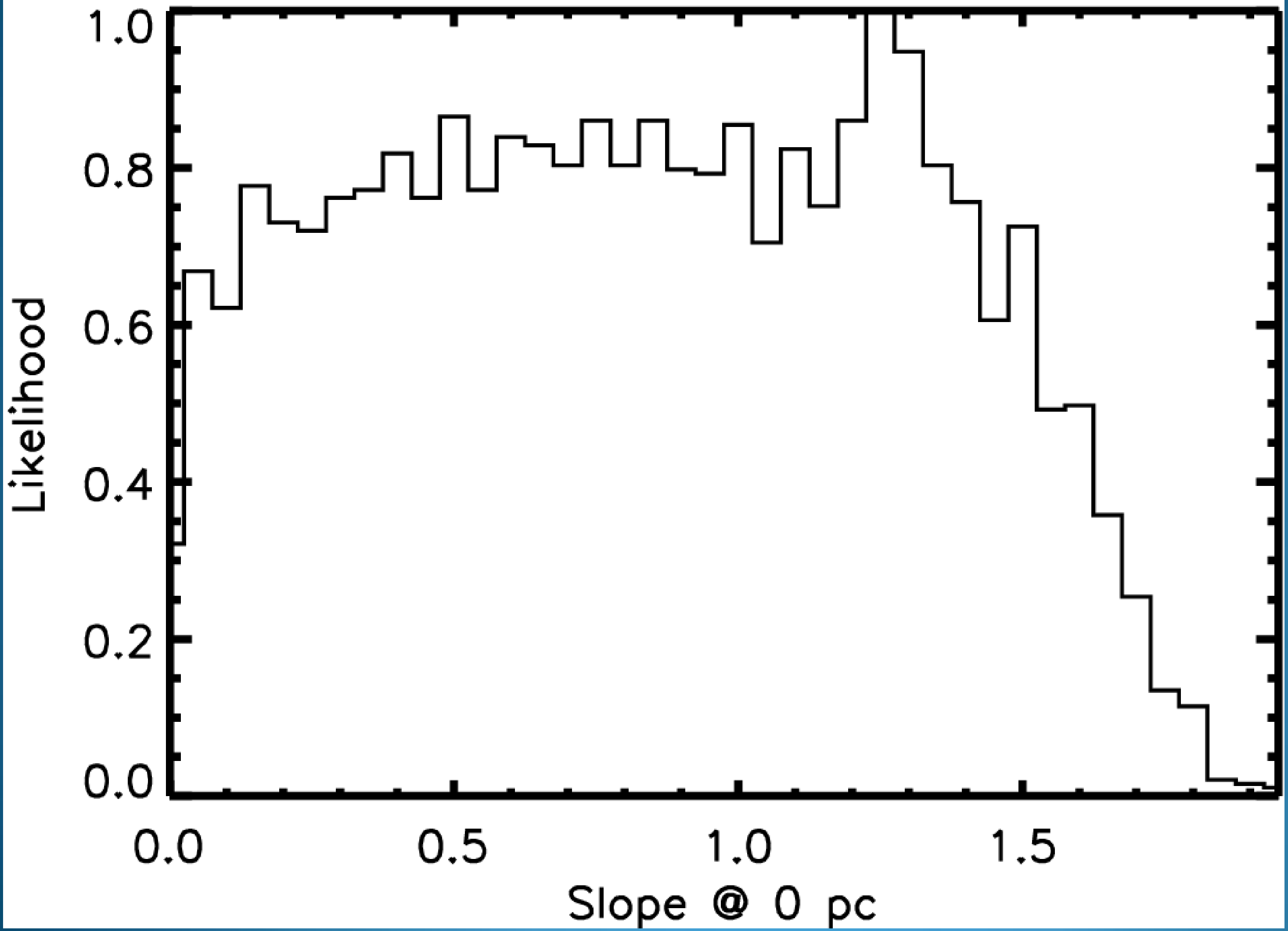
An e-mail from my advisor when I told him what I was planning on presenting:

James Bullock to me

What radius are you quoting the log slope at? r1/2 I hope. Please don't tell me you're using gamma.

Slopes & Priors – Oh my!

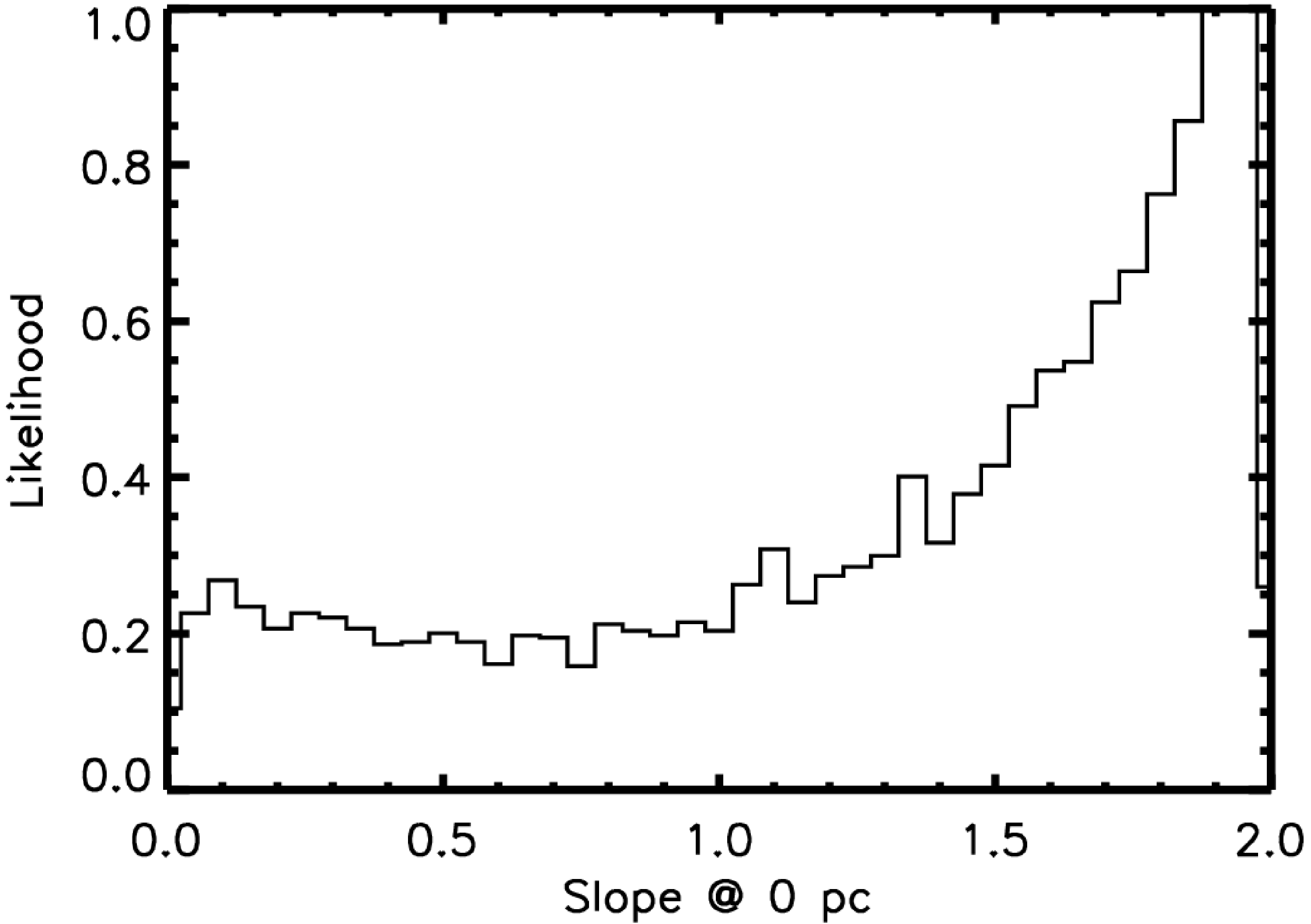
Beta prior #1: Constant beta that is flat from -10 to 0.91.
Gamma = Log slope of Carina at 0 pc



Joe Wolf et al., in prep

Slopes & Priors – Oh my!

Beta prior #2: Constant beta that is as likely to be negative as positive (ranging from -10 to 0.91).



Joe Wolf et al., in prep

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

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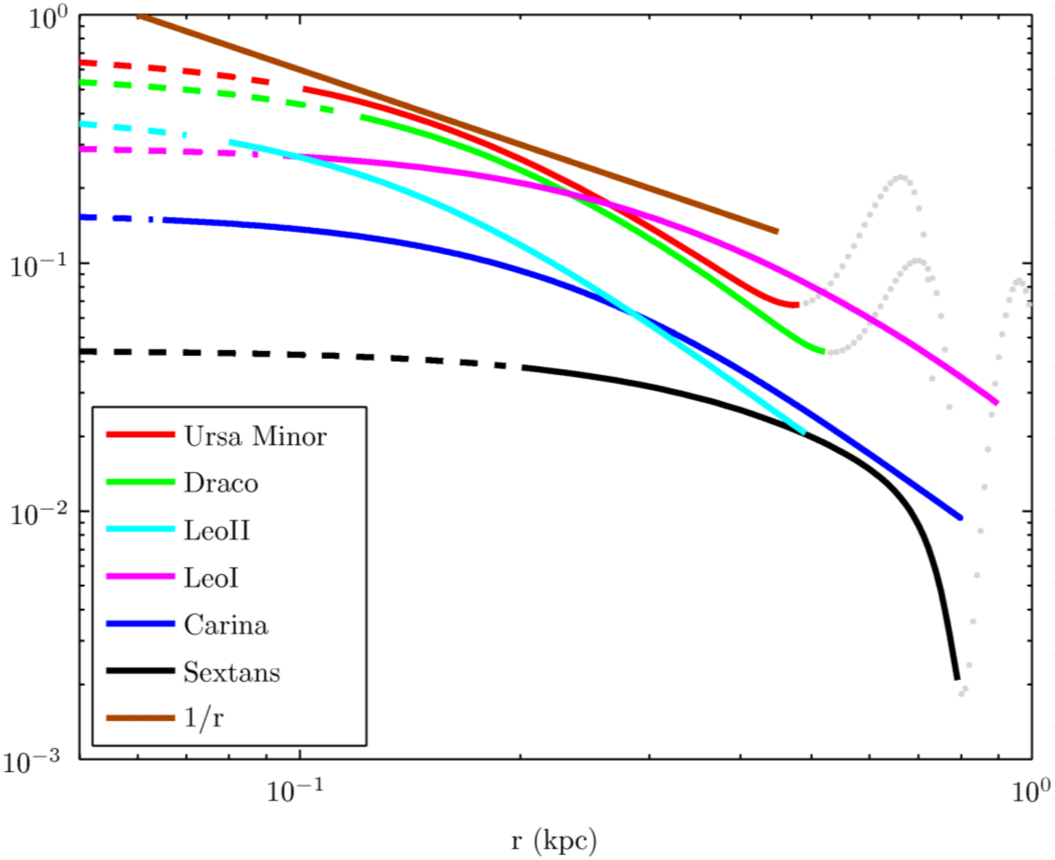
Except for his pink backgrounds

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:

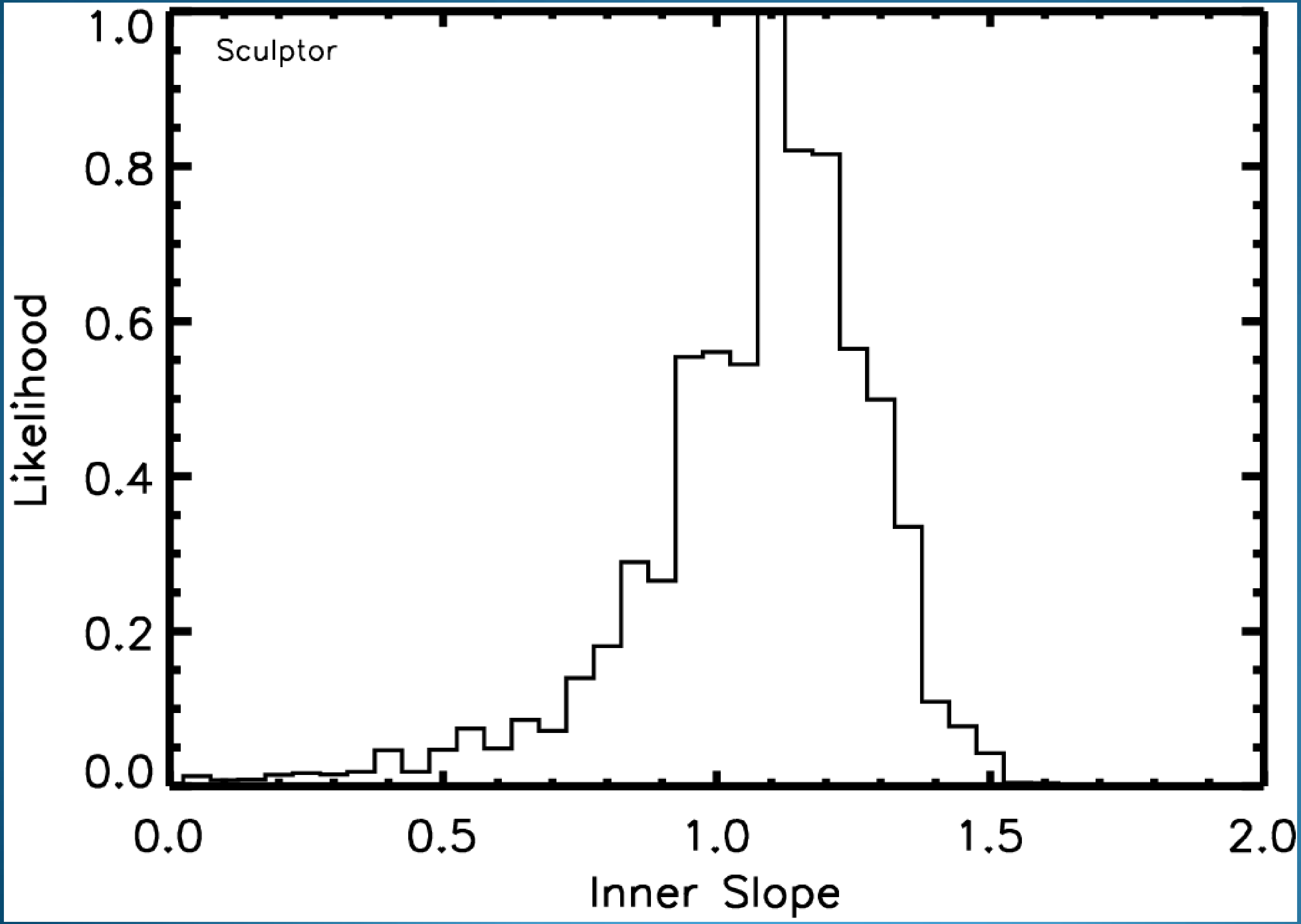
- High-quality kinematic data exist
- Jeans' analyses ➔ prefers cored mass profiles
- Mass-anisotropy degeneracy *allows* cusps
- Substructure, dynamical friction ➔ prefers cores
- Equilibrium assumption is valid inside optical radius
- More sophisticated DF analyses underway

- **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:

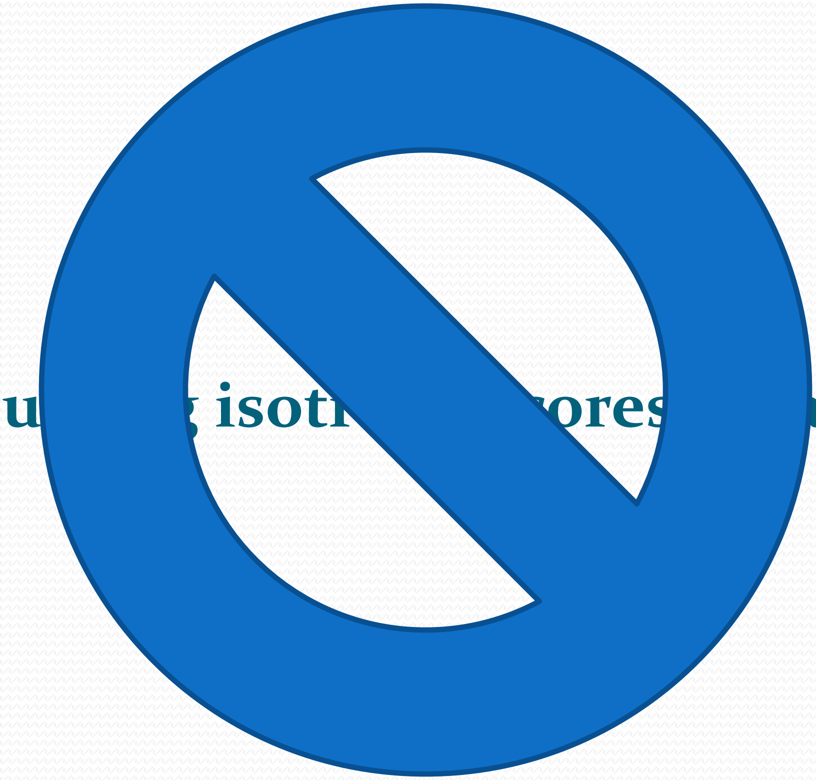
Story Time: A New Ending

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”**

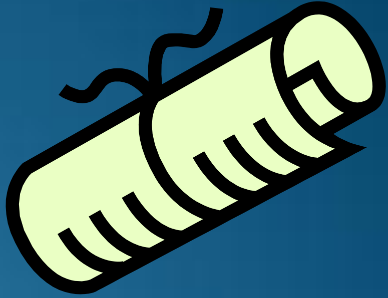


- **When assu g isotr ores ys preferred”**

Take-Home Messages

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

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



- 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…hmm?
- Inner slopes of dSphs **cannot** be determined with only LOS kinematics.
- **Jeans modeling w/ isotropy does not *always* prefer cores**