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Measuring Dark Matter Profiles Non-Parametrically in dSphs*

* (by dSphs I mean Draco)

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TACC

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"Dynamics Meets Kinematic Tracers"

Local Group dSphs

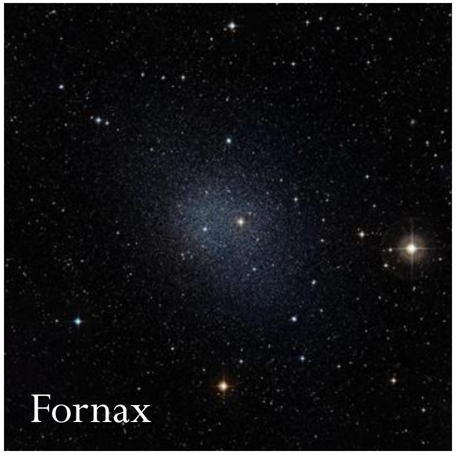
Why study Local Group dSphs?

DM dominated

Lowest mass products of galaxy formation

Large public data sets

Individual stars resolved



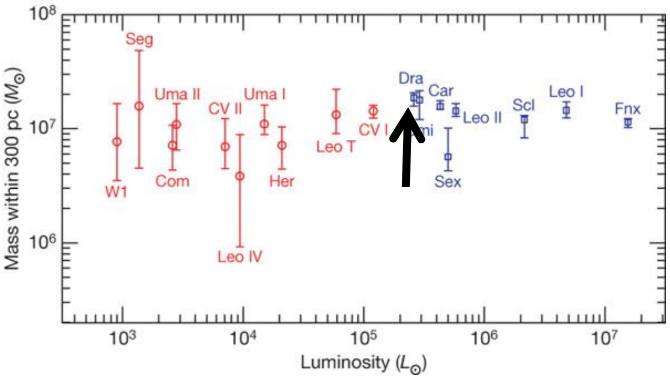
ESO/Digitized Sky Survey 2

"Dynamical" questions

What is the shape of the density profile?

What is the nature and degree of velocity anisotropy?

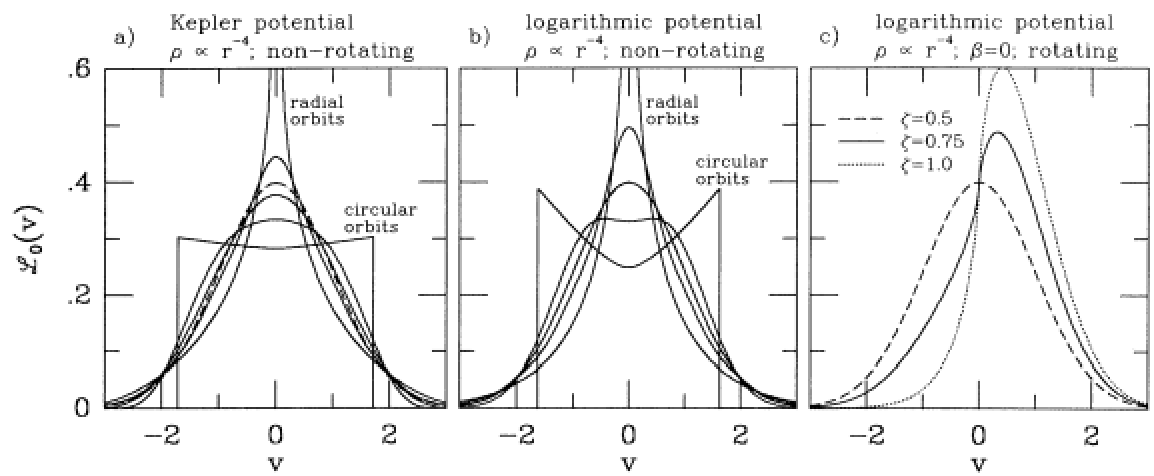
Are the dSphs consistent with the DM halos found in ΛCDM simulations?



Strigari+ (2008)

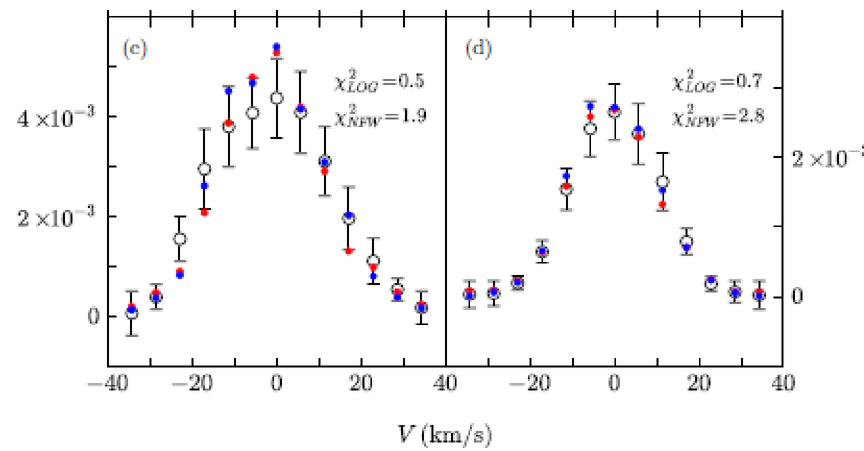
Why Schwarzschild Models?

Uses additional information in the LOSVDs to constrain anisotropy and break mass-anisotropy degeneracy



van der Marel & Franx (1993)

Our models must match the LOSVDs at each velocity bin



JJ & Gebhardt (2012)

Schwarzschild Modeling

1. Guess potential Φ

   guess $\rho(r)$ and solve for Φ

2. Build orbit library

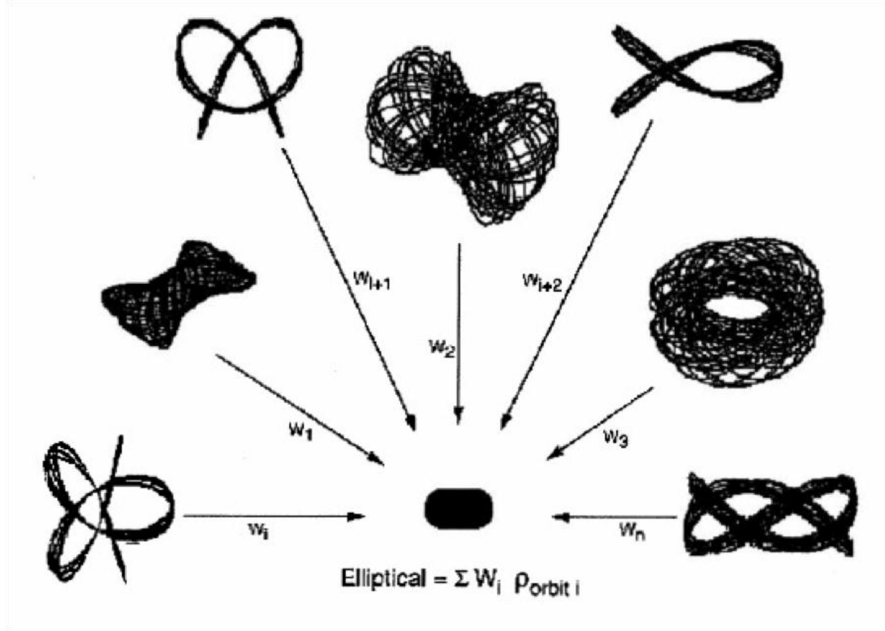
   launch orbits in Φ

3. Weight orbits to match projected kinematics & luminosity profile

   $\rightarrow \chi^2$ + max entropy constraint

4. Rinse, repeat

   choose new Φ (or $\rho(r)$) and repeat



(courtesy J. Kormendy)

How we choose $\rho(r)$ is the only major difference!

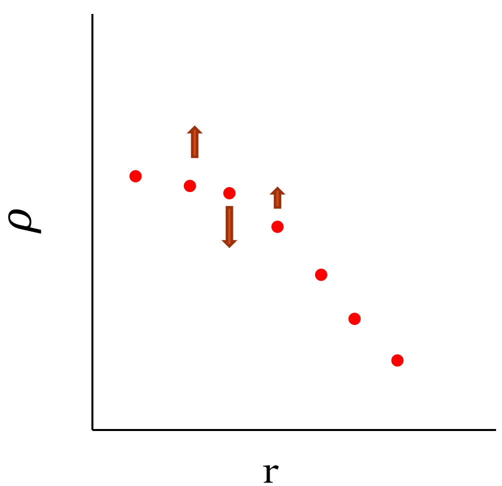
Non-parametric Schwarzschild Models

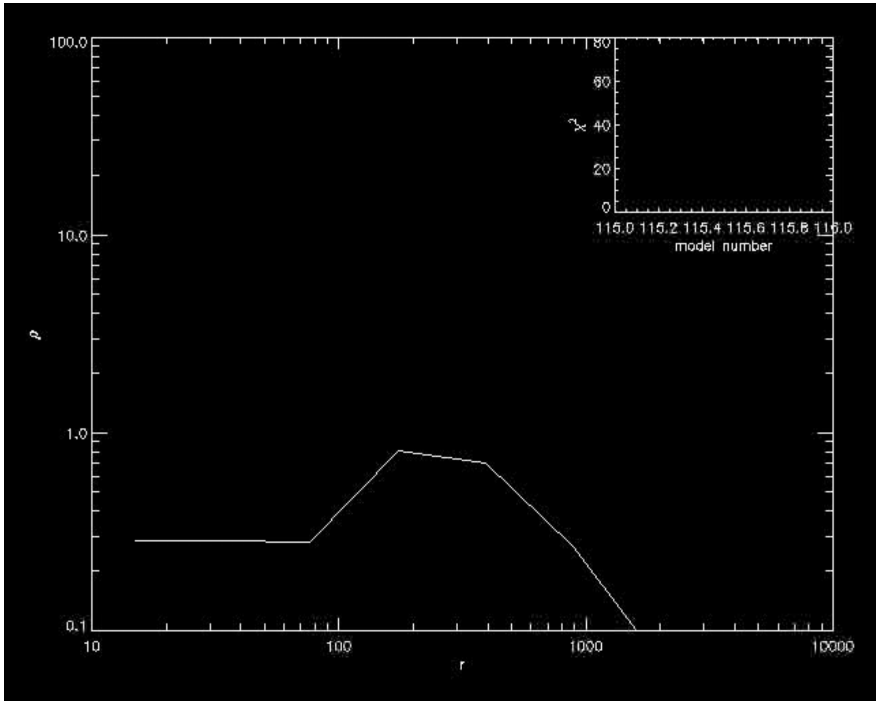
Traditional Schwarzschild modeling:

$$\rho(r) = \rho_*(r) + \rho_{DM}(r)$$

- NFW: c, r_s free parameters
- Logarithmic potential: V_c, $\mathrm{r_c}$ free parameters

Non-parametric Schwarzschild modeling:

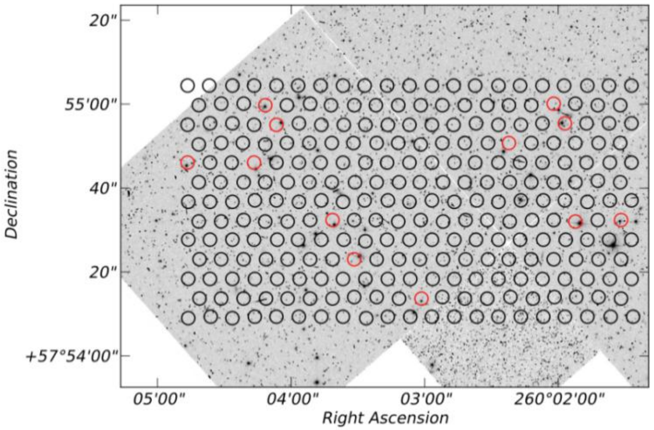




Then remove $\rho_* = \nu * \frac{M_*}{L_v}$ through some other constraint on $\frac{M_*}{L_V}$

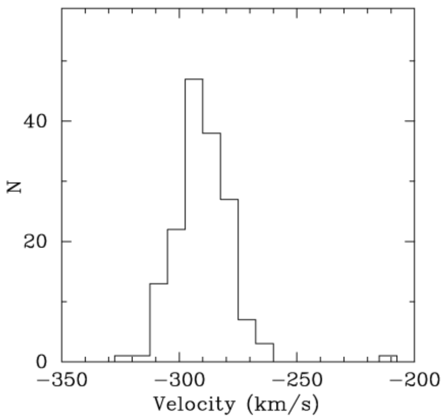
Draco: A test case

New VIRUS-W IFU observations (55" x 105")

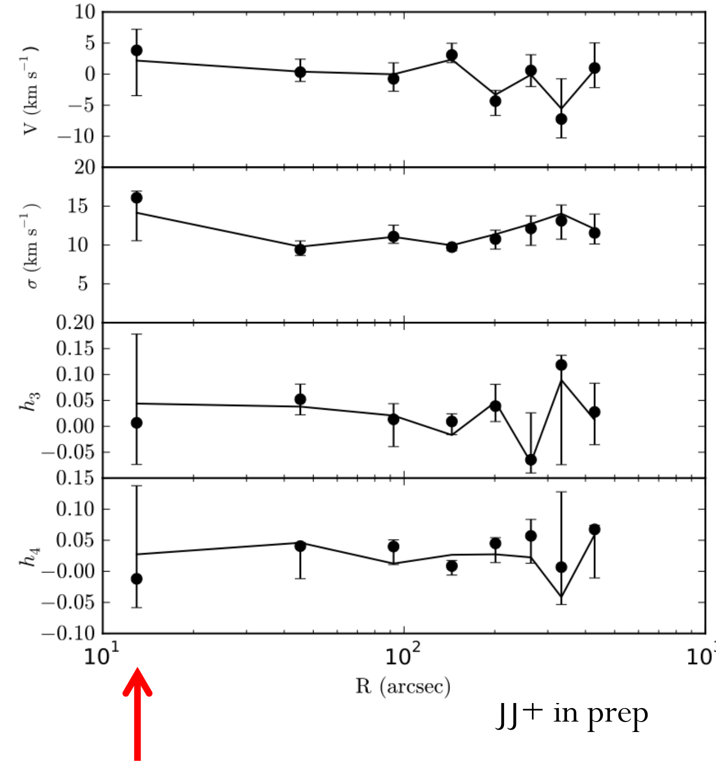


JJ+ in prep

Data from literature



Kleyna+ (2002)



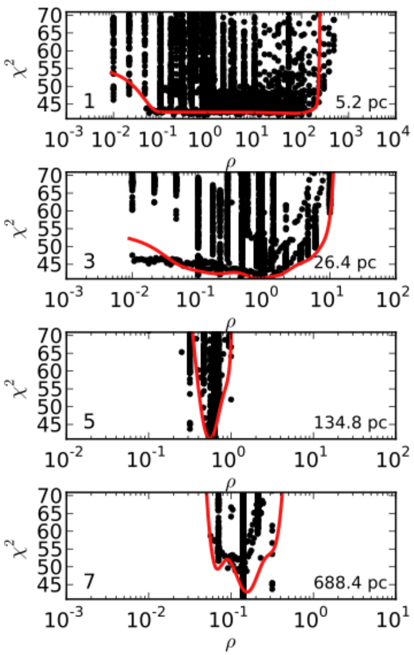
JJ+ in prep

New observations

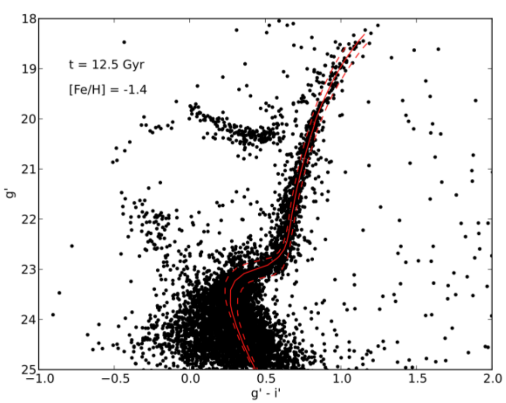
- 158 (from literature) + 12 (new) radial velocities
- 8 LOSVDs binned in annuli from 8 pc to 500 pc

Modeling Results

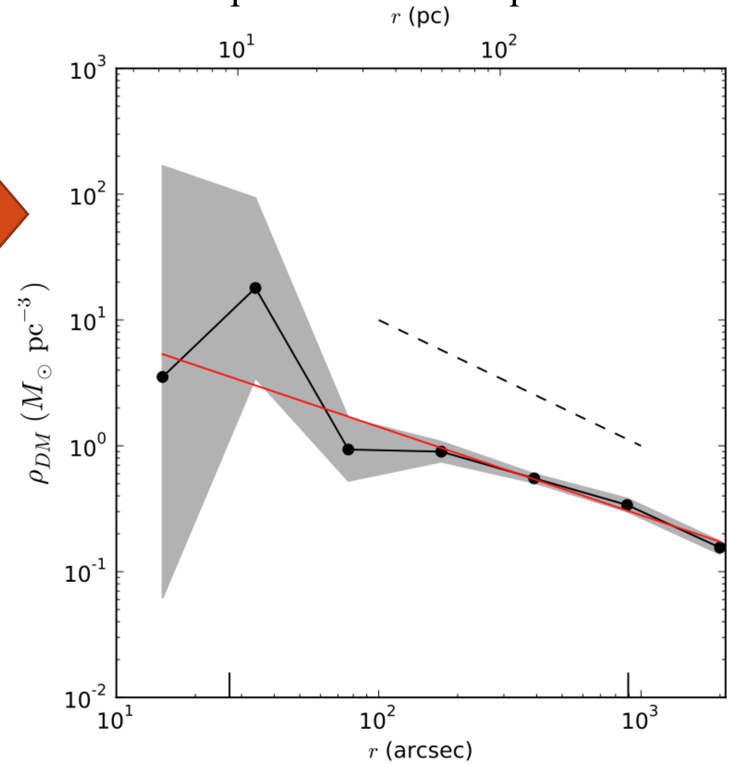
χ^2 curves constrain total ρ



Remove stellar density by determining $\frac{M_*}{L}$



Non-parametric DM profile

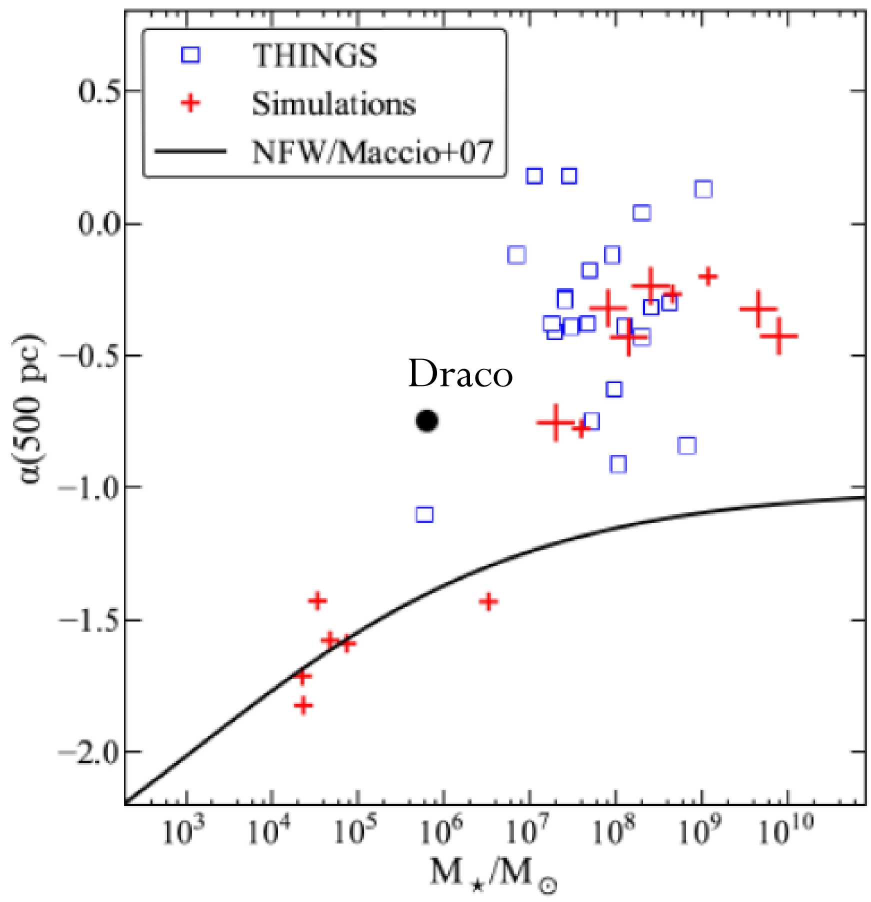


slope $\alpha = -0.7 \pm 0.1$
for $r > 30$ pc

And now for some wild speculation…

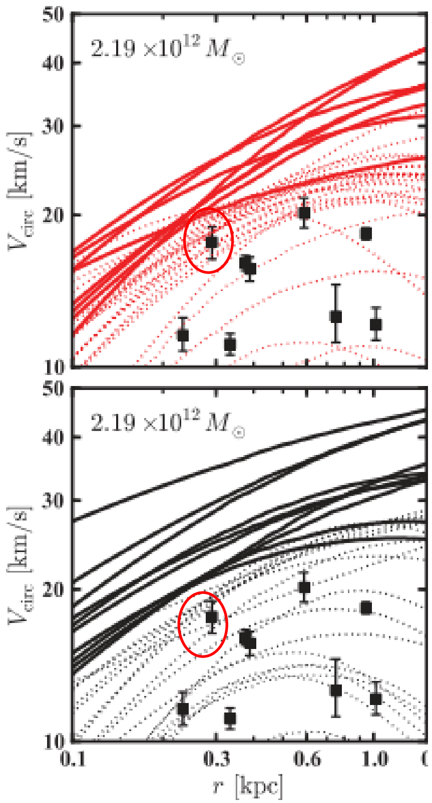
THINGS: HI survey of late-type field dwarfs

Simulations: Governato+ (2012) N-body/hydro cosmological simulations of THINGS-like dwarfs



Governato+ (2012) with Draco added

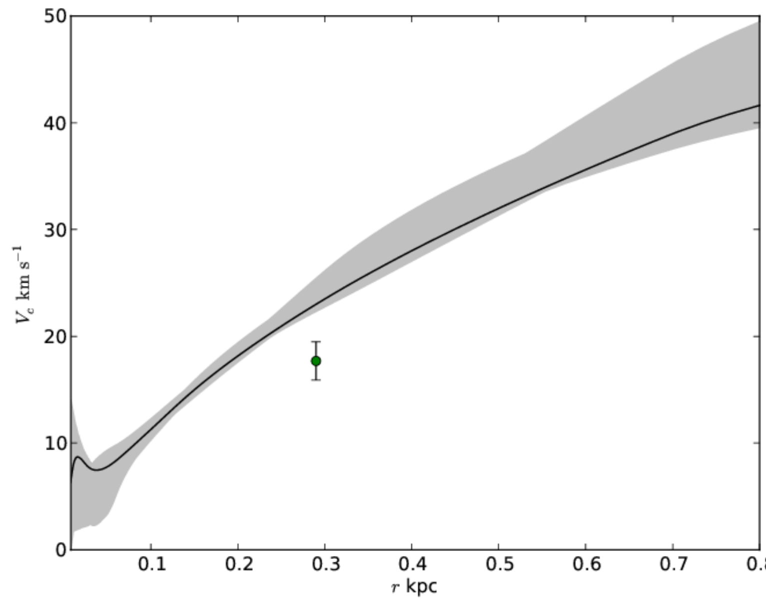
How does Draco compare to ΛCDM simulations?



Boylan-Kolchin, Bullock, & Kaplinghat (2012)

Estimate $V_c(r = r_{1/2})$ via $M_{1/2}$ mass estimator for each dSph (black points)

Compare to $V_c(r)$ curves of subhalos from Aquarius simulation (lines)

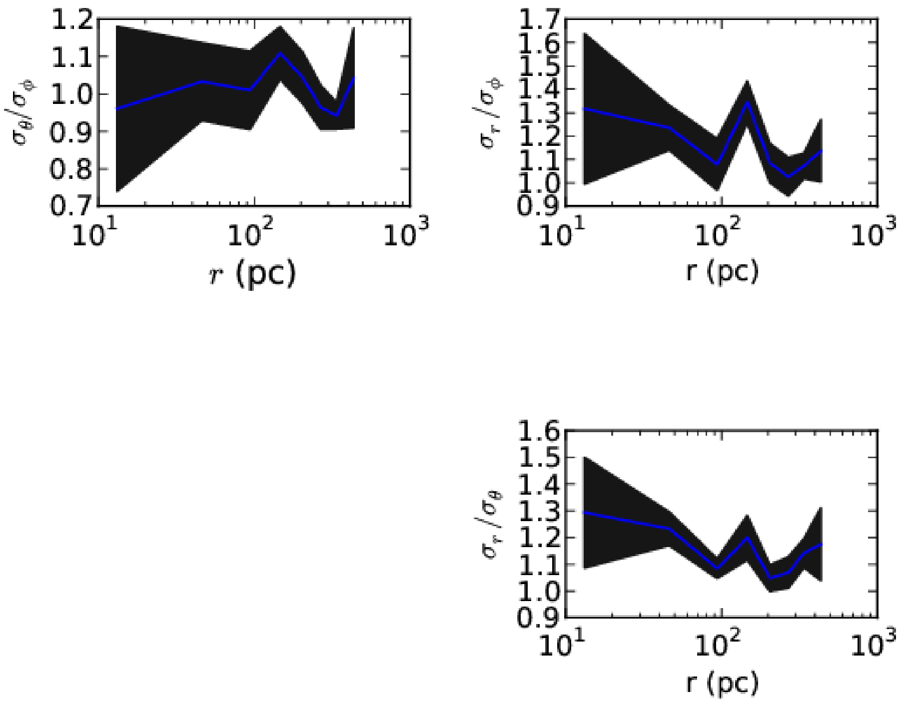


JJ+ in prep

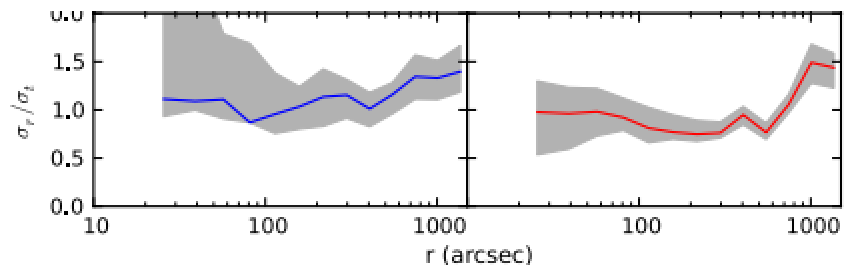
$M_{1/2}$ predicts about half as much mass as our model

Velocity anisotropy

Draco



Fornax (parameterized model)



JJ & Gebhardt (2012)

Orbits are more radially biased at large radii.

Consistent with tidal stirring scenarios (Łokas+, Kazantzidas+)

Draco summary

DM profile shape:

- NPSM constrains $\rho_{DM}(r)$ for $30 < r < 700$ pc
- well-fit by power law with $\alpha = -0.7 \pm 0.1$ over this range

Halo Mass:

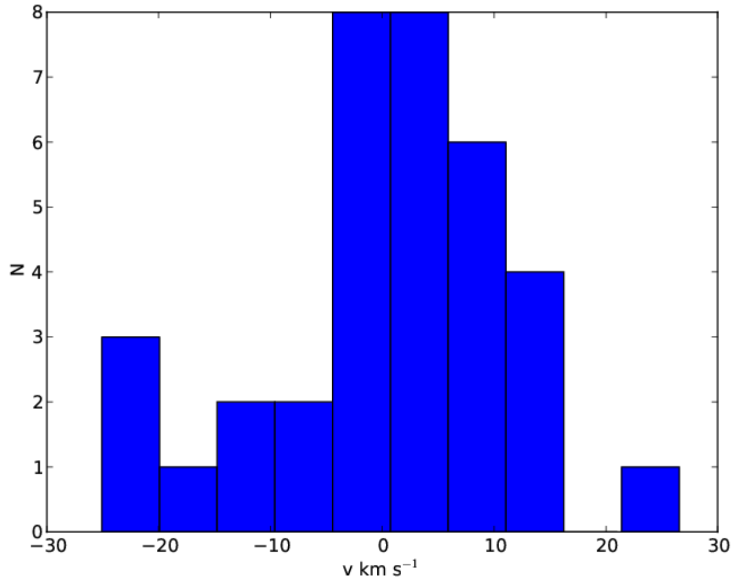
- $M(r_h) \sim 1.7 \times M_{1/2}$ estimator
- $V_c(r)$ profile indicates a more massive halo alleviating "massive failures" problem (at least for Draco)

<u>Things that aren't so great:</u>

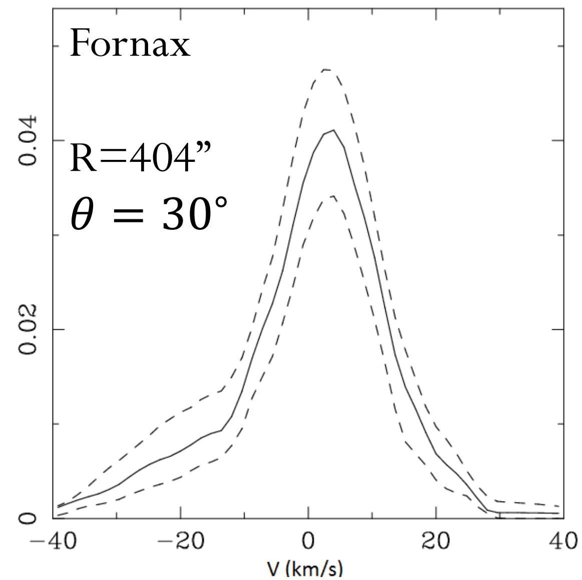
1. Binned velocities
2. "Non-Magorrian" treatment of best-fitting DF
3. Only 170 RVs in 8 LOSVDs

Extra Slides

Computing LOSVDs from histograms

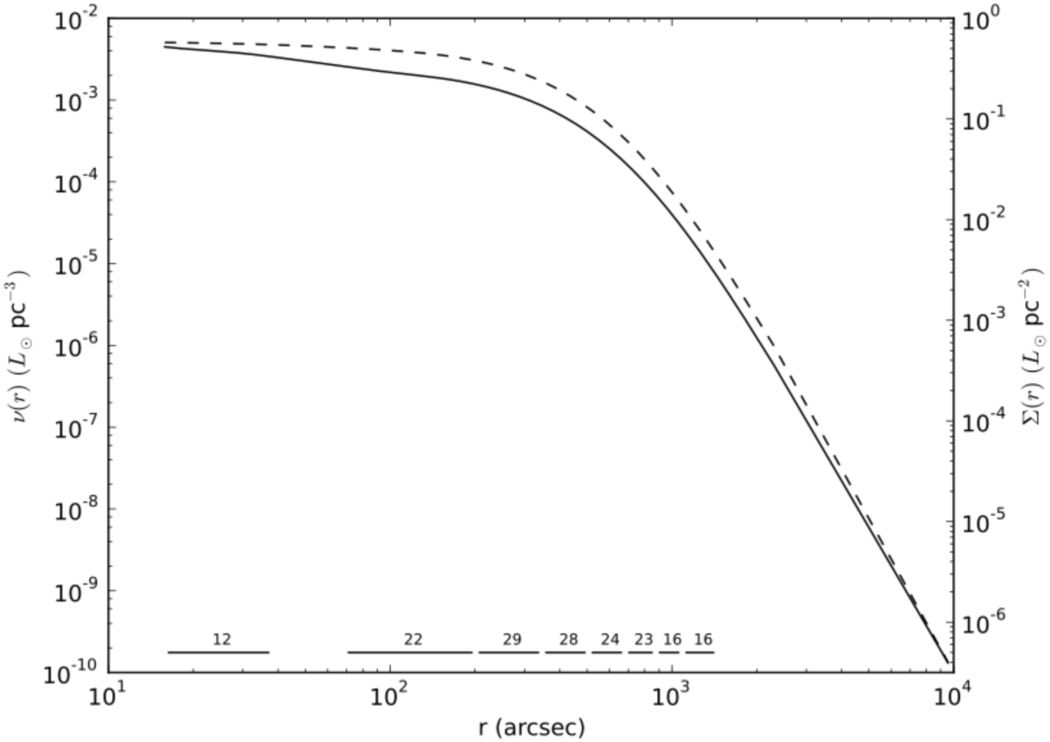


KDE smoothing



JJ & Gebhardt (2012)

Draco photometry



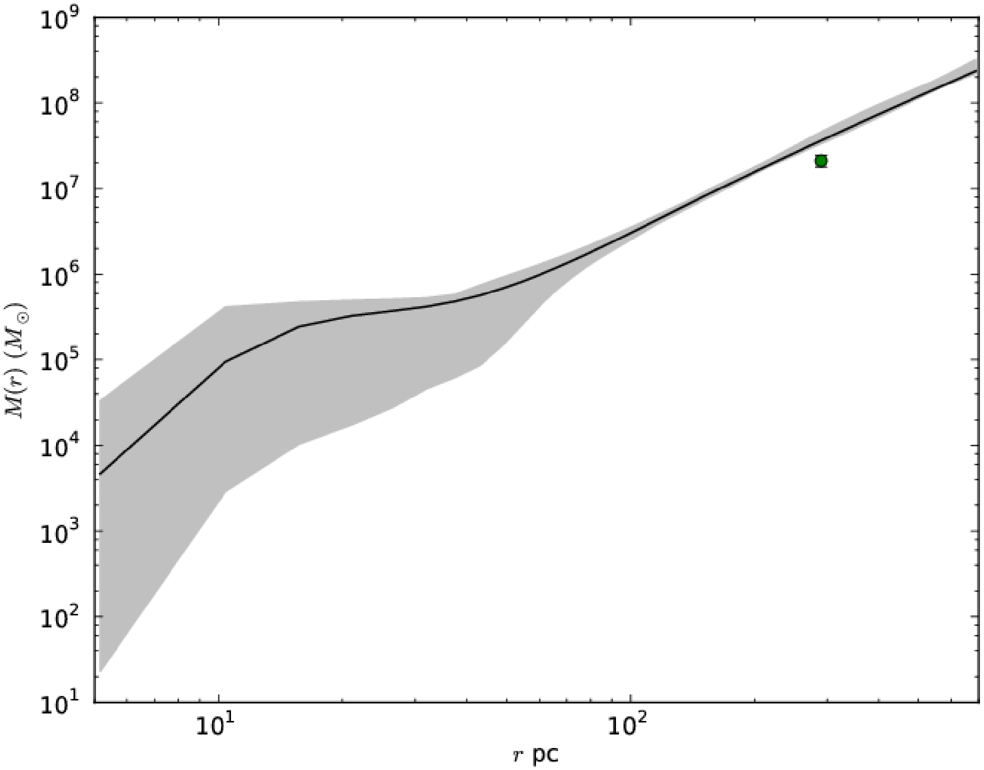
JJ+ in prep

Projected number density profile (dashed) from Ségall+ (2007)

Deprojected via Abel inversion for $i = 90°$ (solid)

$$\left\langle \frac{d \ln \nu}{d \ln r} \right\rangle \sim -0.4 \text{ for } r \leq 50 \text{ pc}$$

Draco's mass



Green point is

$$M_{1/2} = 4G^{-1}\langle\sigma_{LOS}^2\rangle R_e$$
$$M_{1/2} = 2.11 \pm 0.3 \times 10^7 M_\odot$$

Our model has:

$$M(r_h) = 3.6^{+0.92}_{-0.28} \times 10^7 M_\odot$$

Orbit sampling

- Orbits in axisymmetric potentials respect 3 isolating integrals of motion (E,L_z, I_3)
- For each (E,L_z):

$$v_{max} \equiv v_{r,i} = \sqrt{2[E - \Phi(r_l)] - \frac{L_z^2}{r_l^2}} \text{ (touches ZVC, } v_\theta = 0\text{)}$$

- Stepwise decrease $v_{r,i}$ and increase $v_{\theta,i} = \sqrt{2[E - \Phi(r_l)] - \frac{L_z^2}{r_l^2} - v_{r,i}^2}$

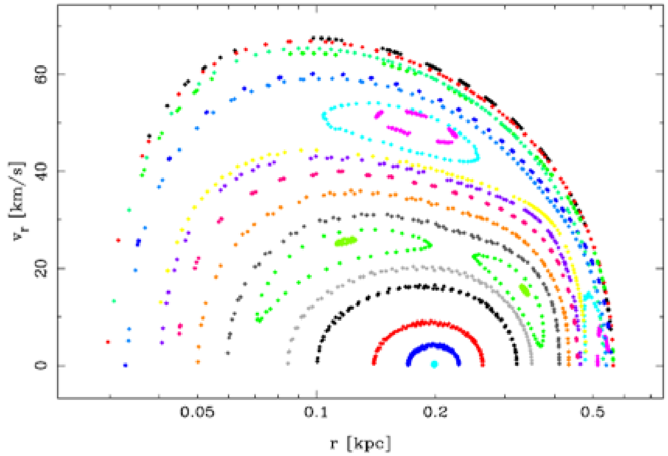


Figure 1. Example of a surface of section for a flattened Hernquist model (details in the text). All orbits have been integrated for $N_{SOS} = 80$ intersections with the SOS.

Each invariant curve represents an orbit. All orbits have same (E,L_z) and varying I_3 in this SOS.

(2004 MNRAS 353 391)

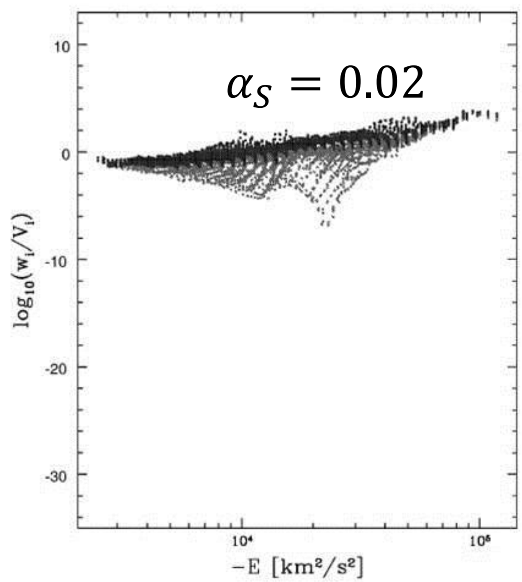
Maximum Entropy Regularization

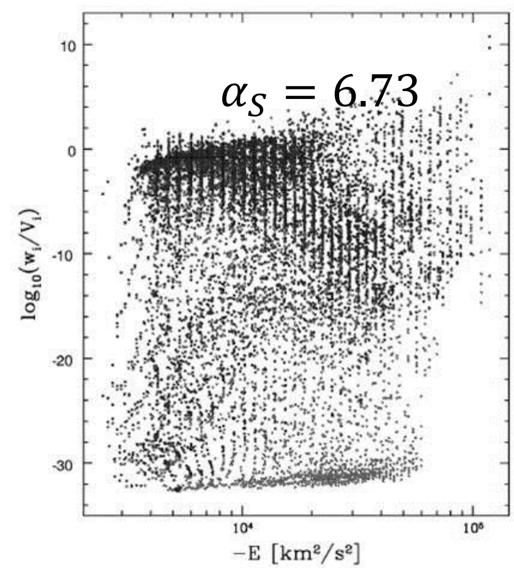
Typical models have >10,000 orbits and only 20 LOSVDS with 15 velocity bins (300 observables)

Instead, maximize $\hat{S} = S - \alpha\,\chi^2$

S: entropy

α_S: smoothing parameter





Thomas et al. (2005)

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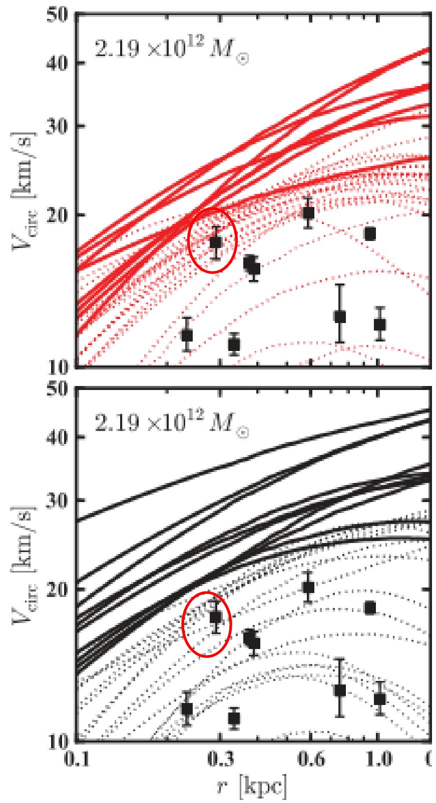
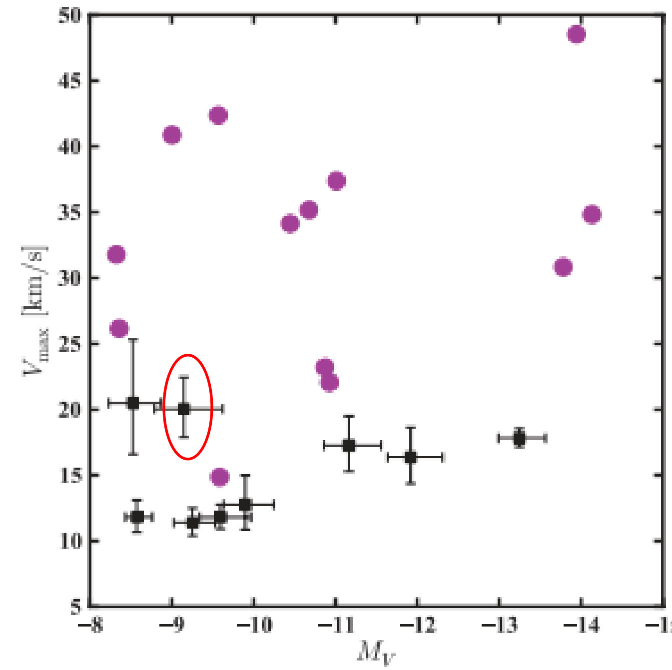
Compare to $V_c(r)$ curves of subhalos from Aquarius simulation (lines)

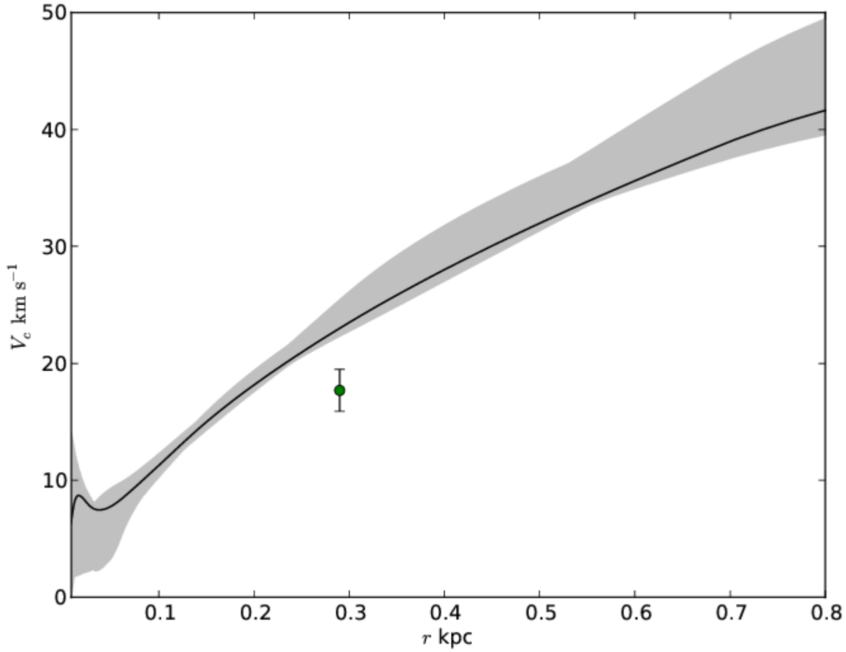


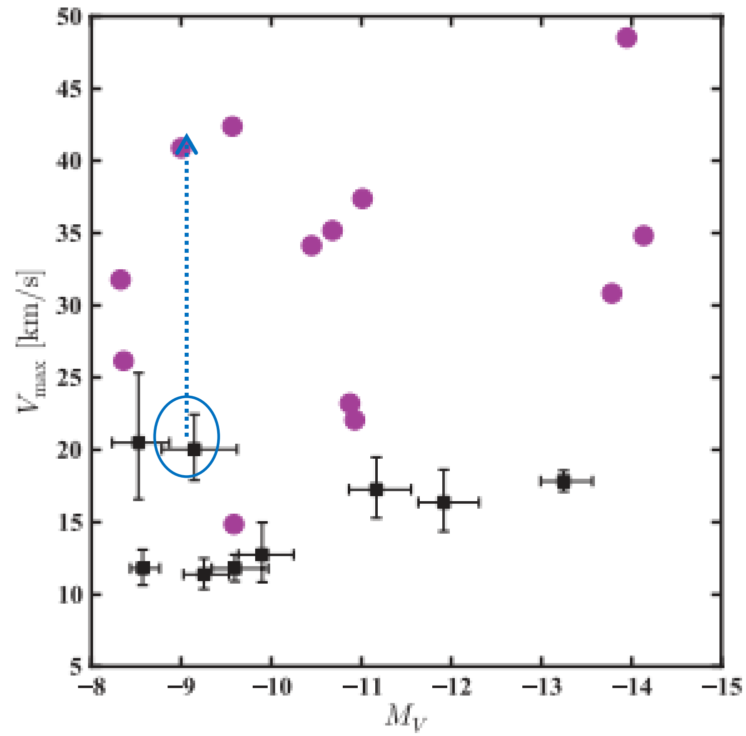


Scale $V_c(r_{1/2})$ to V_{max} and match (extrapolated) luminosity function to subhalo mass function from simulations

Boylan-Kolchin, Bullock, & Kaplinghat (2012)

Modeled $V_c(r)$





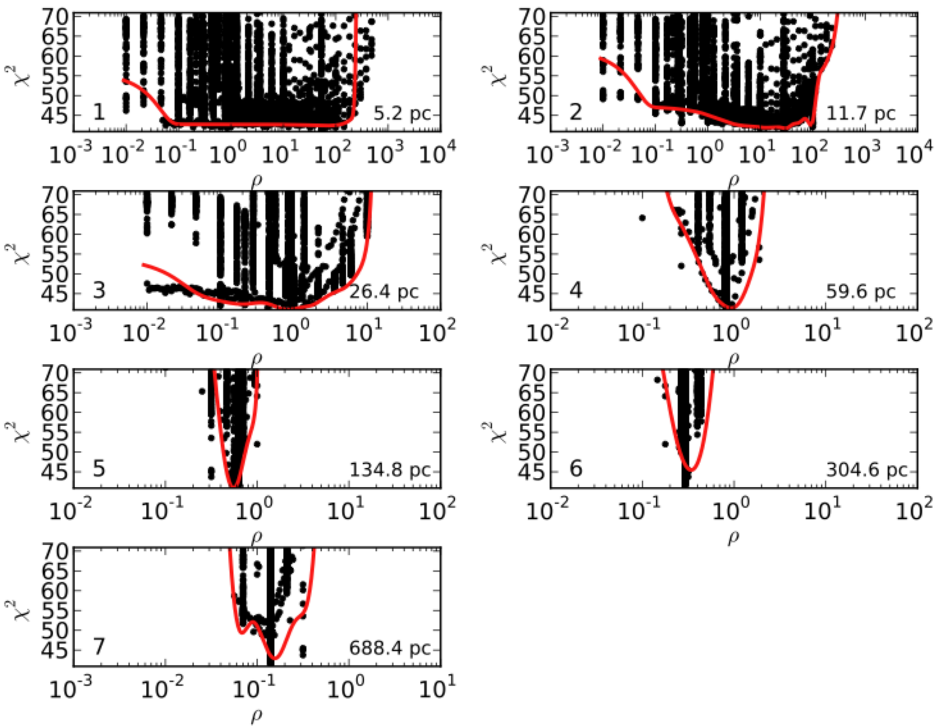
Green point is using

$$M_{1/2} = 4G^{-1}\langle\sigma^2_{LOS}\rangle R_e$$

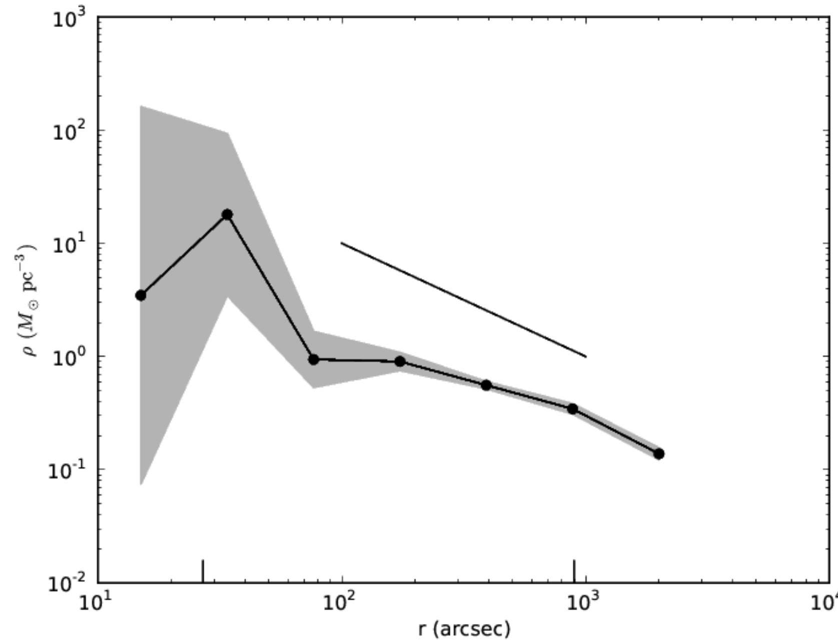
Our models have ~2x more mass than $M_{1/2}$ predicts

Could explain abundance matching discrepancy

Models



χ²
ρ
1
5.2 pc
2
11.7 pc
3
26.4 pc
4
59.6 pc
5
134.8 pc
6
304.6 pc
7
688.4 pc



ρ (M⊙ pc⁻³)
r (arcsec)

Stellar density subtraction

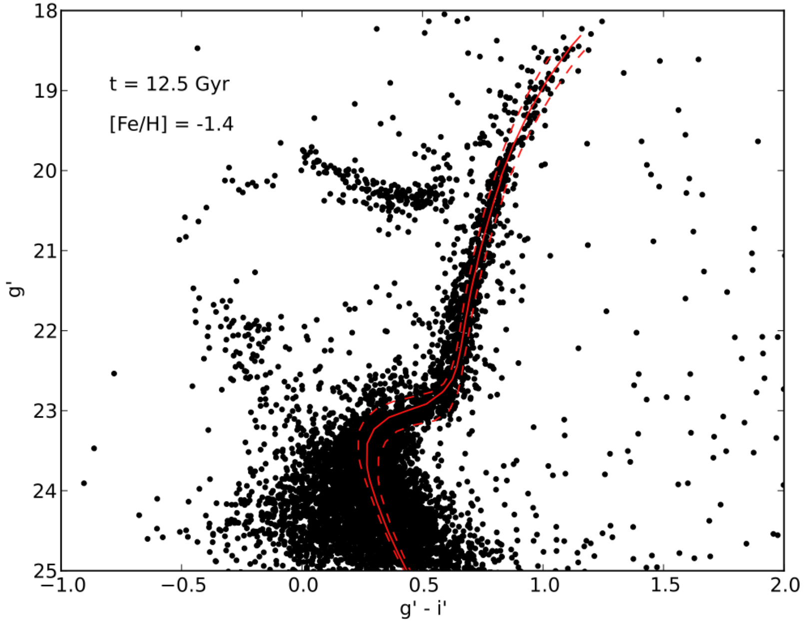
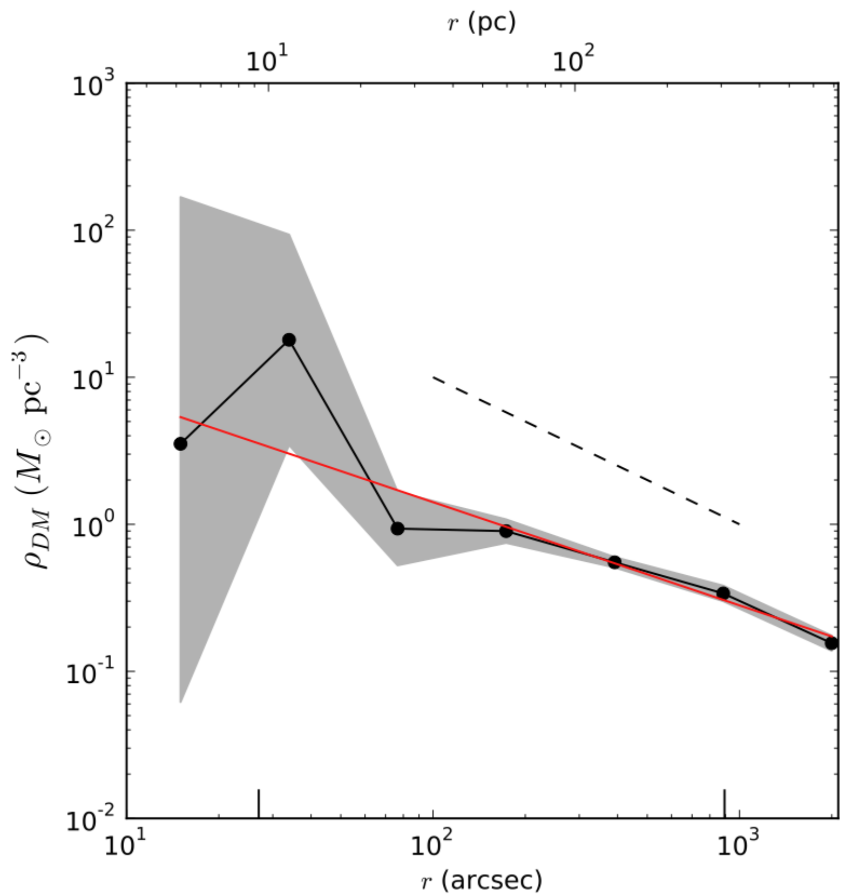


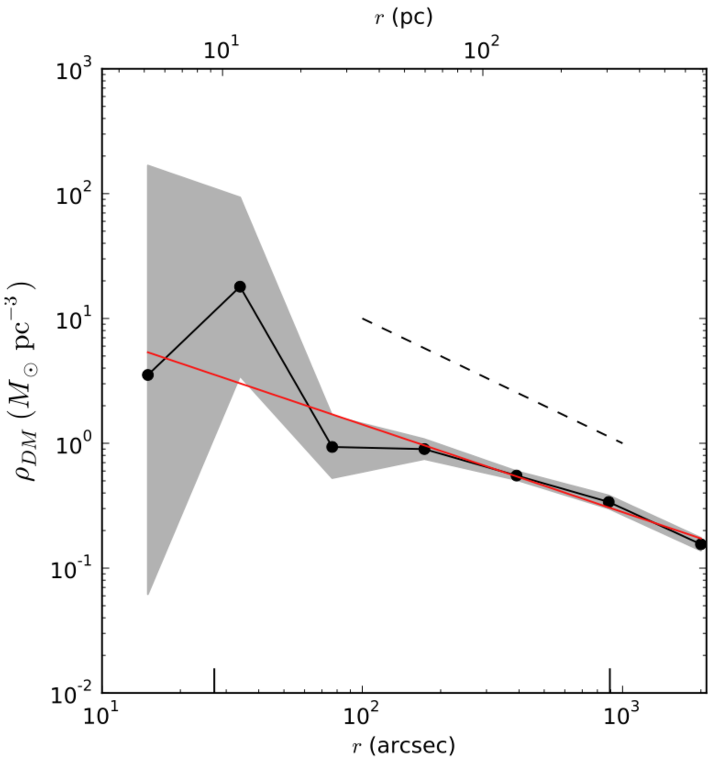
FIG. 7.— Color-magnitude diagram of stars within the central 5′of Draco. From left to right, we plot isochrones of ($t_{age} \times 10^9$yr, $[Fe/H]$) = (11.5, −1.6), (12.5, −1.4), and (13.5, −1.3). The solid red line is the (12.5, −1.4) isochrone we use when determining M_*/L_V.

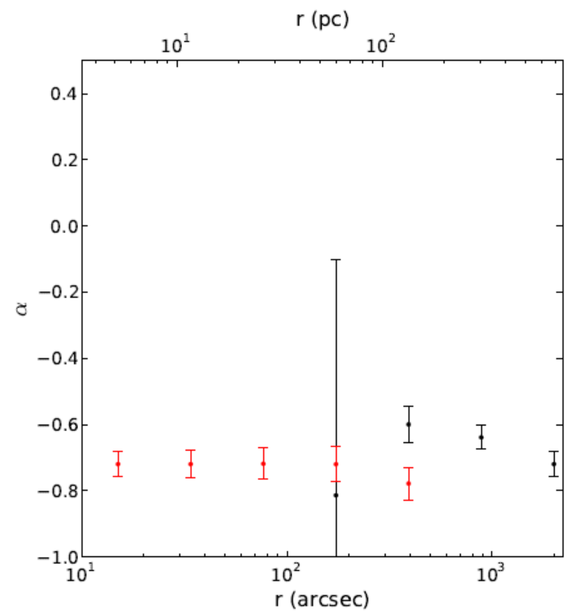
JJ+ in prep



SSP models with t = 12.5 Gyr and [Fe/H] = -1.4 give $\frac{M_*}{L_V} = 2.9 \pm 0.6$

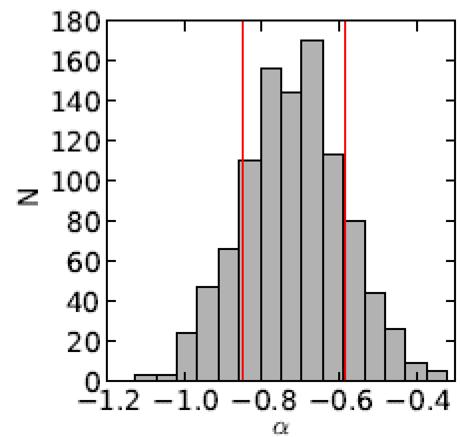
Fit to the non-parametric profile





Varying number of points in fit

$\alpha = -0.7 \pm 0.1$ from outer 4 points



MC fit with simulated noise

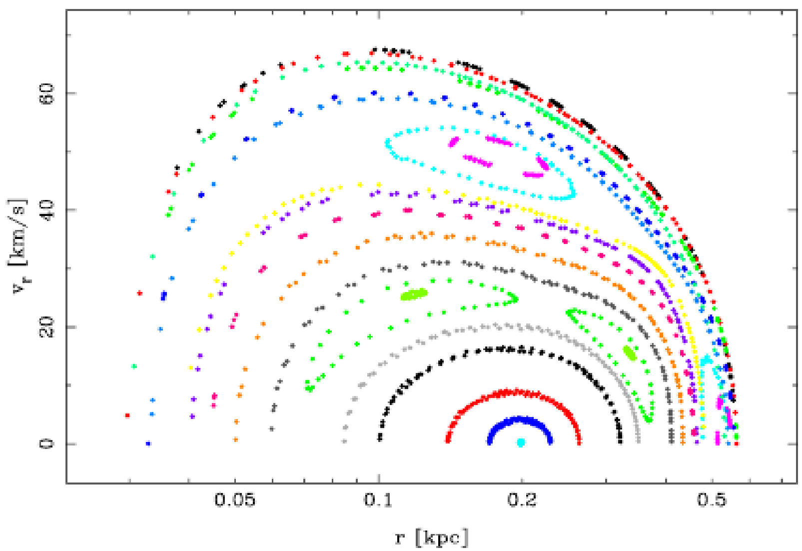
Calculating Phase Space Volumes

Evaluating the integral $$V \approx \Delta L_z \Delta E \int_{SOS} T(R, v_R) dR dv_R$$

Voronoi Tessellation

Enclose each point (site) in SOS inside a polygon

Area contains all points which lie closer to site in consideration than another



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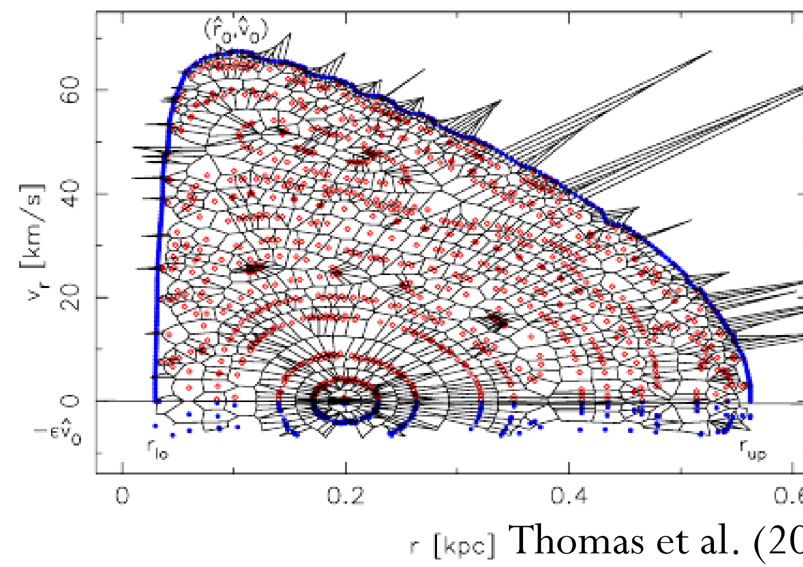

Thomas et al. (2004)

Figure 2. A Voronoi tessellation of the SOS of Fig. 1. Open circles mark individual intersections of orbits with the SOS; solid dots are points added to make the Voronoi cells well behaved at the boundaries.