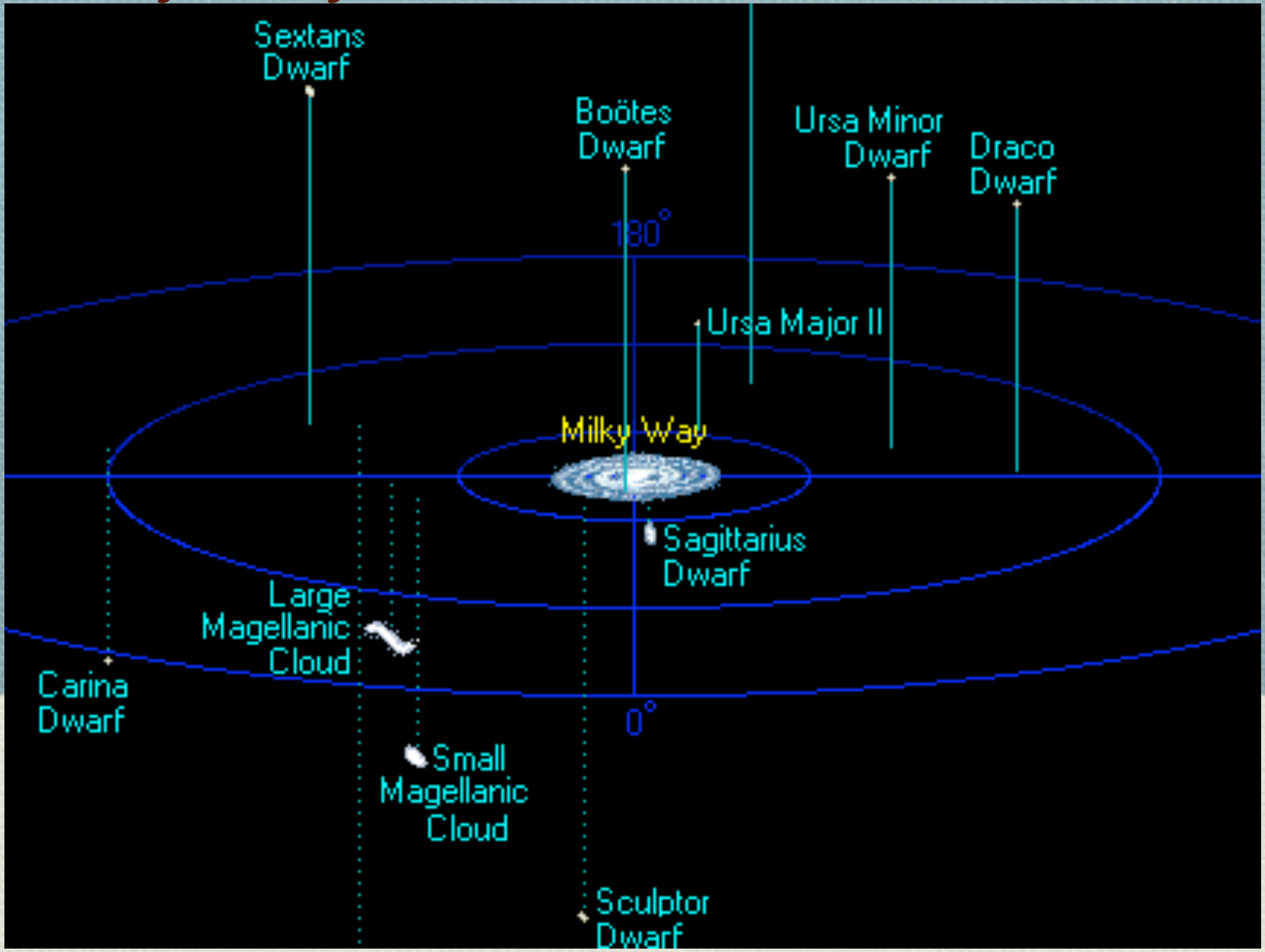
Indirect constraints on dark matter from Milky Way satellites



Manoj Kaplinghat, University of California, Irvine, USA

Milky Way satellites: served two ways

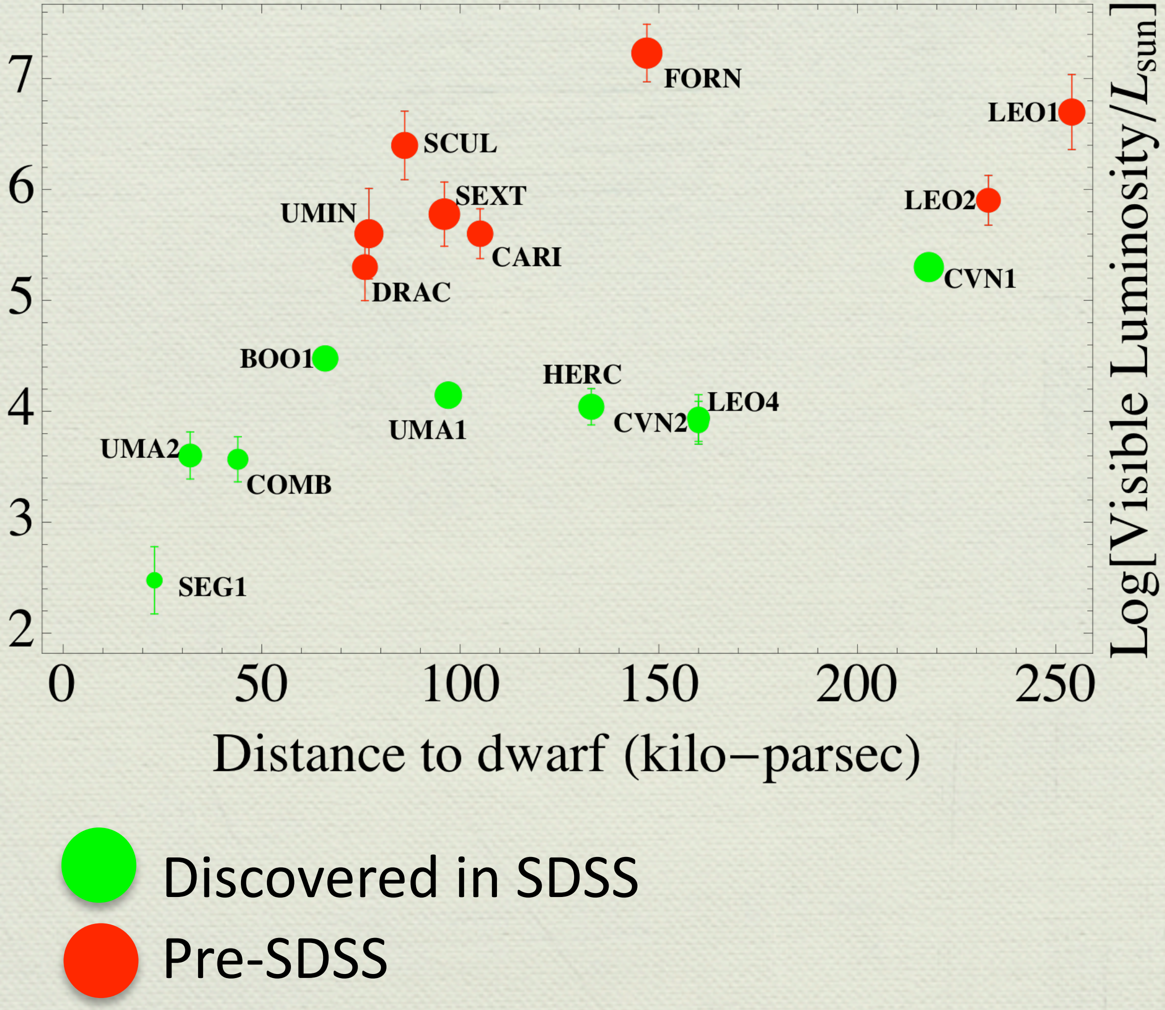
- 1. Massive subhalos in LCDM simulations of Milky Way: "Too big to fail?"
- 2. Limits on WIMP cross section and masses using dwarf spheroidal satellites of the Milky Way
- 3. Uncertainties in measuring dark matter halo masses
    - Case study I: Segue 1
    - Case study II: Bright satellites

Milky Way satellites

Name	Year Discovered
LMC	--
SMC	--
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994
Ursa Major I	2005
Willman I	2005
Ursa Major II	2006
Bootes	2006
Canes Venatici I	2006
Canes Venatici II	2006
Coma	2006
Segue I	2006
Leo IV	2006
Hercules	2006
Leo T	2007
Bootes II	2007
LeoIV	2008

Bright

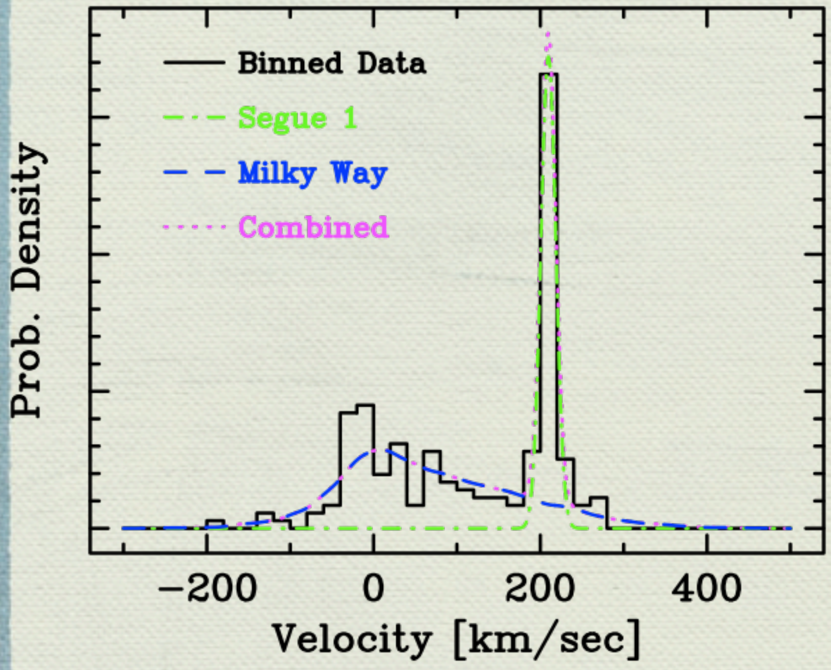
Faint

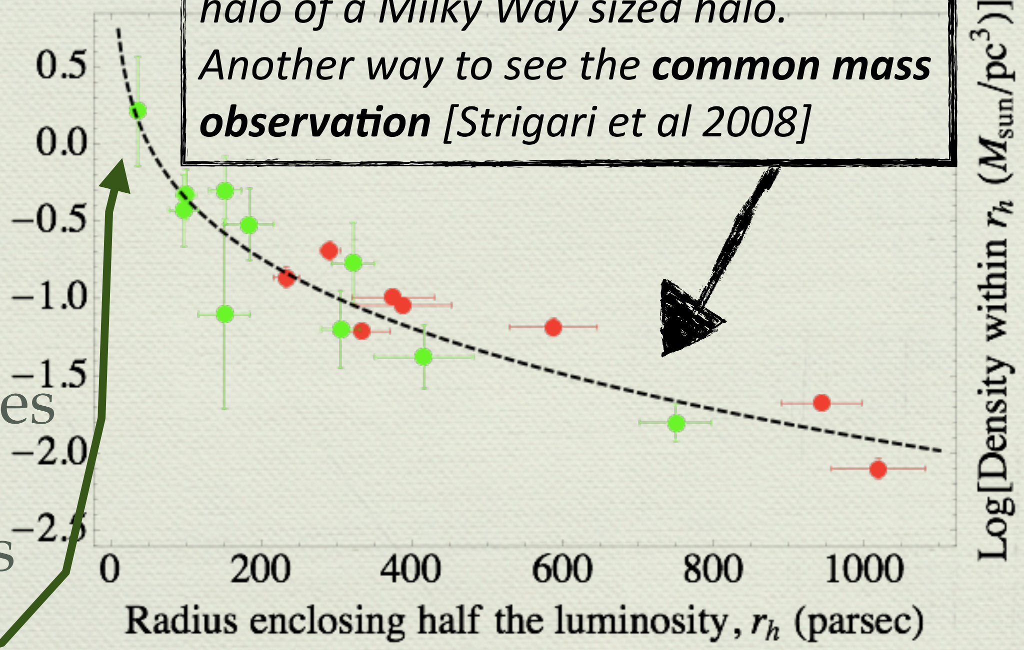


Mass of the optically visible satellites

Individual stellar velocity data gives the total mass within the half-light radius with very mild dependence on velocity dispersion anisotropy

Walker et al ApJ **704** (2009)
Wolf et al MNRAS **406** (2010)





Density profile for a typical LCDM sub-halo of a Milky Way sized halo. Another way to see the ***common mass observation*** *[Strigari et al 2008]*

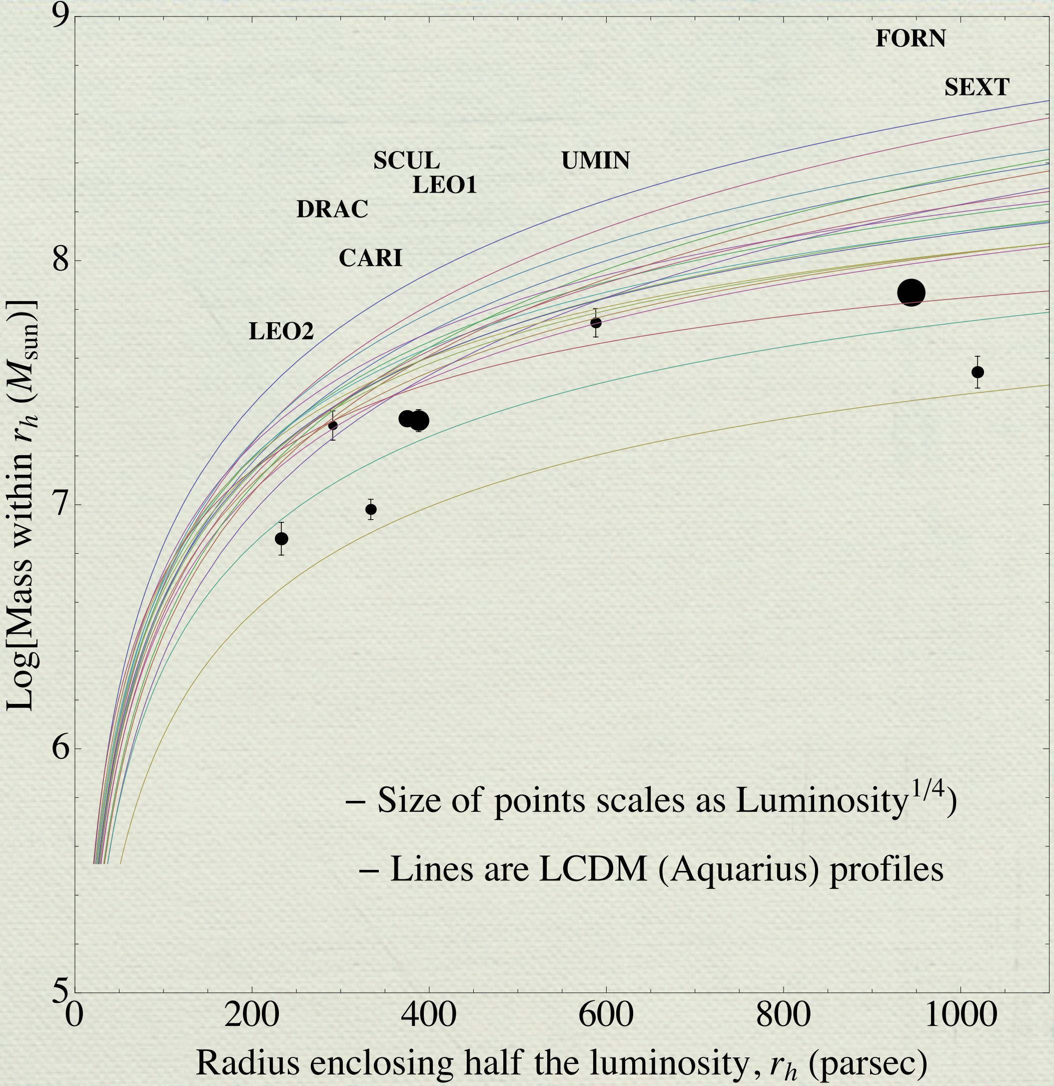
Velocity dispersion of satellites

Mass within half-light radius

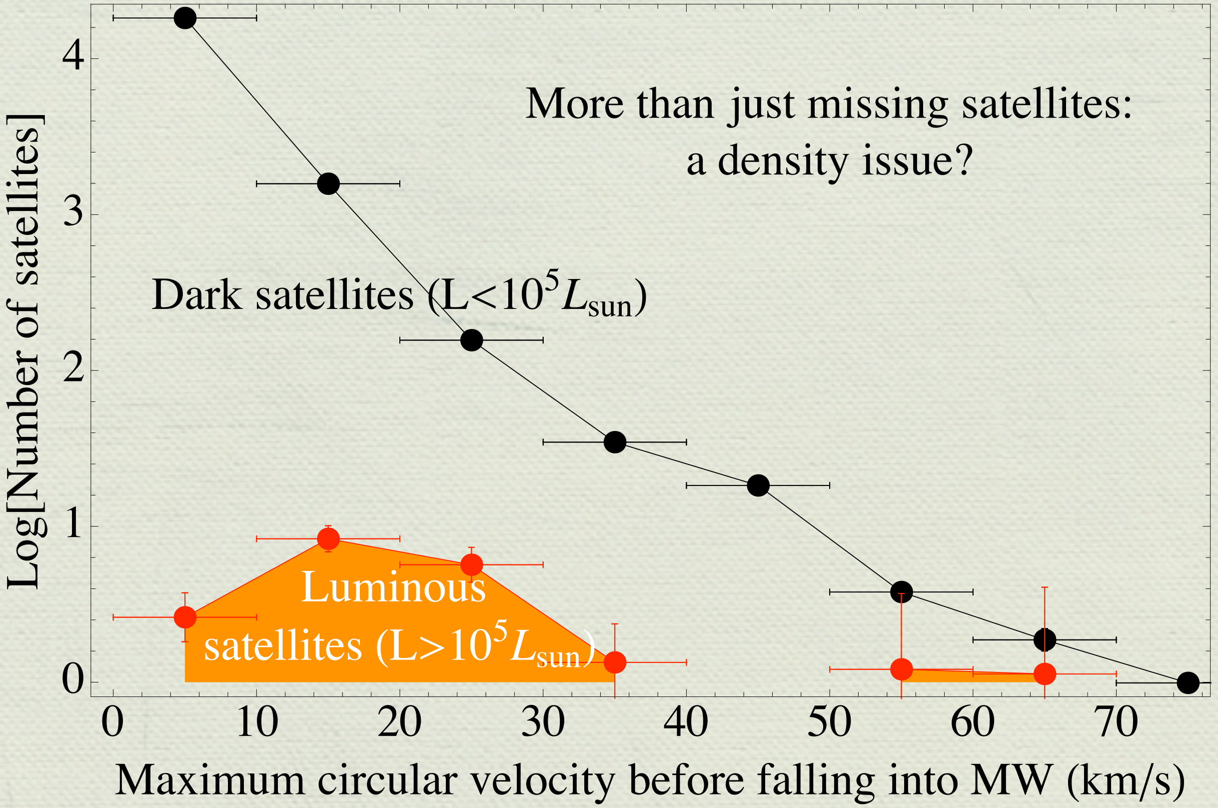
1: Too big to fail? The most massive apparently don’t light up...

- Fits to mass profiles of the most massive subhalos from Aquarius simulation [Springel et al 2009] shown
- Bright satellites shown
- **Measured mass within half-light radius is too small to be consistent with the most massive subhalos**

Boylan-Kolchin, Bullock, Kaplinghat 2011



Not the ``missing satellites" problem: observed satellites are not dense enough



Total dark matter mass (on average)
Dark matter density at fixed radius (on average)

Brightest satellites are not dense enough in dark matter to inhabit the most massive subhalos predicted in LCDM.

Possible solutions to why the most massive don't seem to light up: 1

- **The comparison to LCDM expectations is not valid because the Milky Way is not as massive as the range (9e11 to 2e12 Msun) in Aquarius**
  - Dynamics of Large Magellanic Cloud (rare if not bound)
  - Kinematics of Leo I (not bound if MW virial mass less than ~1e12 Msun)
  - Velocities of halo stars from SDSS argue for MW virial mass ~1e12 Msun.
  - Local circular velocity measurements also suggest similar mass range
- **Milky Way is an outlier and just doesn't have these subhalos. Live with it!**
  - Must explain Large and Small Magellanic Clouds
  - Andromeda satellites look similar! [Tollerud et al (SPLASH collaboration) 2011]

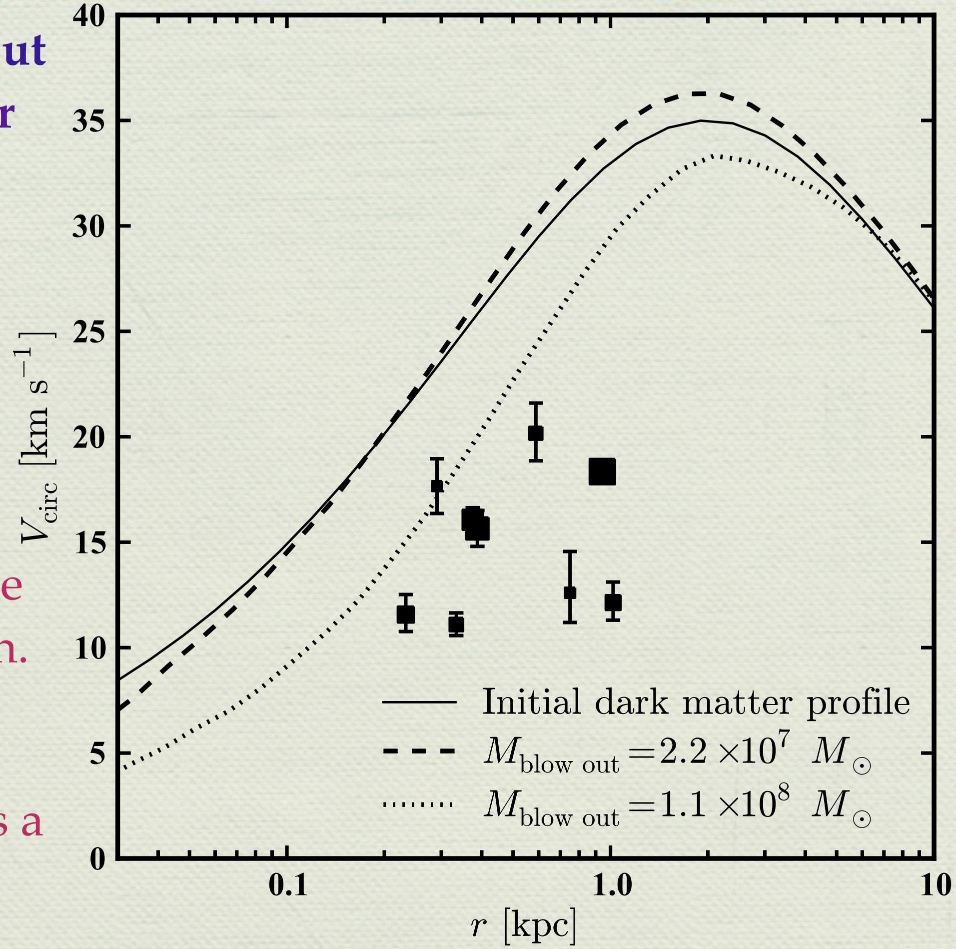
Boylan-Kolchin, Bullock, Kaplinghat 2011

Possible solutions to why the most massive don't seem to light up: 2

- **Most massive do become luminous but outflows due to feedback reduce their central densities. These "blow-out" scenarios don't seem to work effectively in satellites.**

  [e.g., Navarro, Eke, Frenk 1996, Governato et al 2012]

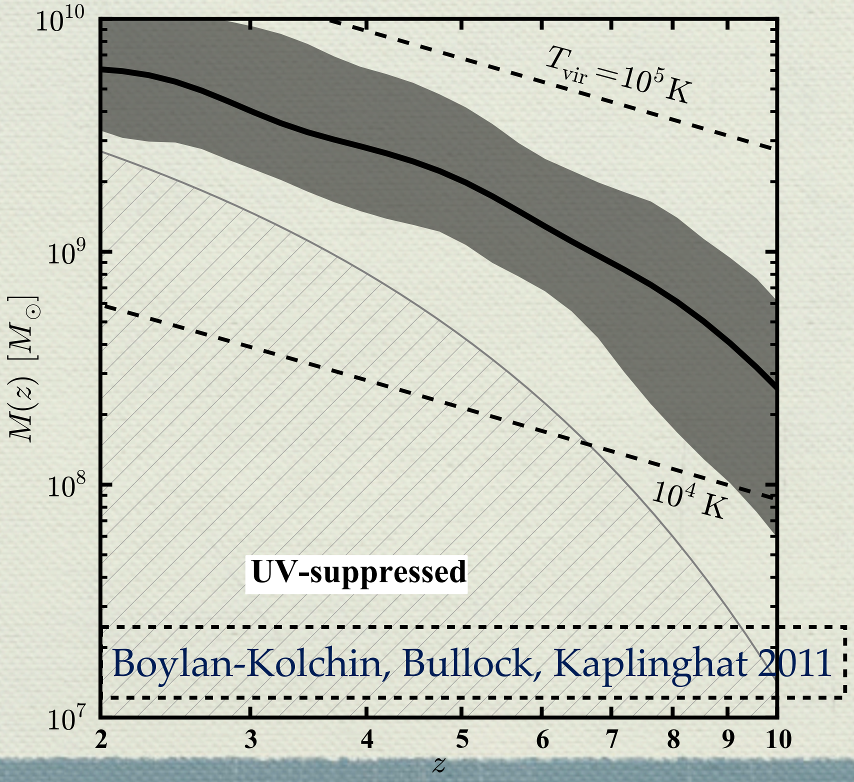
  - The meagre stellar content of the satellites is a stringent limitation.
  - At early times, the amount of baryons available to blow-out is a severe limitation.



Boylan-Kolchin, Bullock, Kaplinghat 2011

Possible solutions to why the most massive don't seem to light up: 3

- **Most massive do become luminous but dark matter microphysics sets an upper limit to the central density**
  - Must preserve the successes of LCDM on large scales and for more massive galaxies (around 100 km/s and higher.)
  - Not be in conflict with other measurements of shapes and densities of dark matter halos. There is a large diversity of behavior in galaxies!
  - [Subjective view] Must explain not just dwarfs but also problems on other scales.
- The dark matter microphysics solution **should not** be constrained to reduce substructure in MW sized halos. UV feedback will quench SF in low mass (V<20km/s) halos [Bullock et al 2001].



Boylan-Kolchin, Bullock, Kaplinghat 2011

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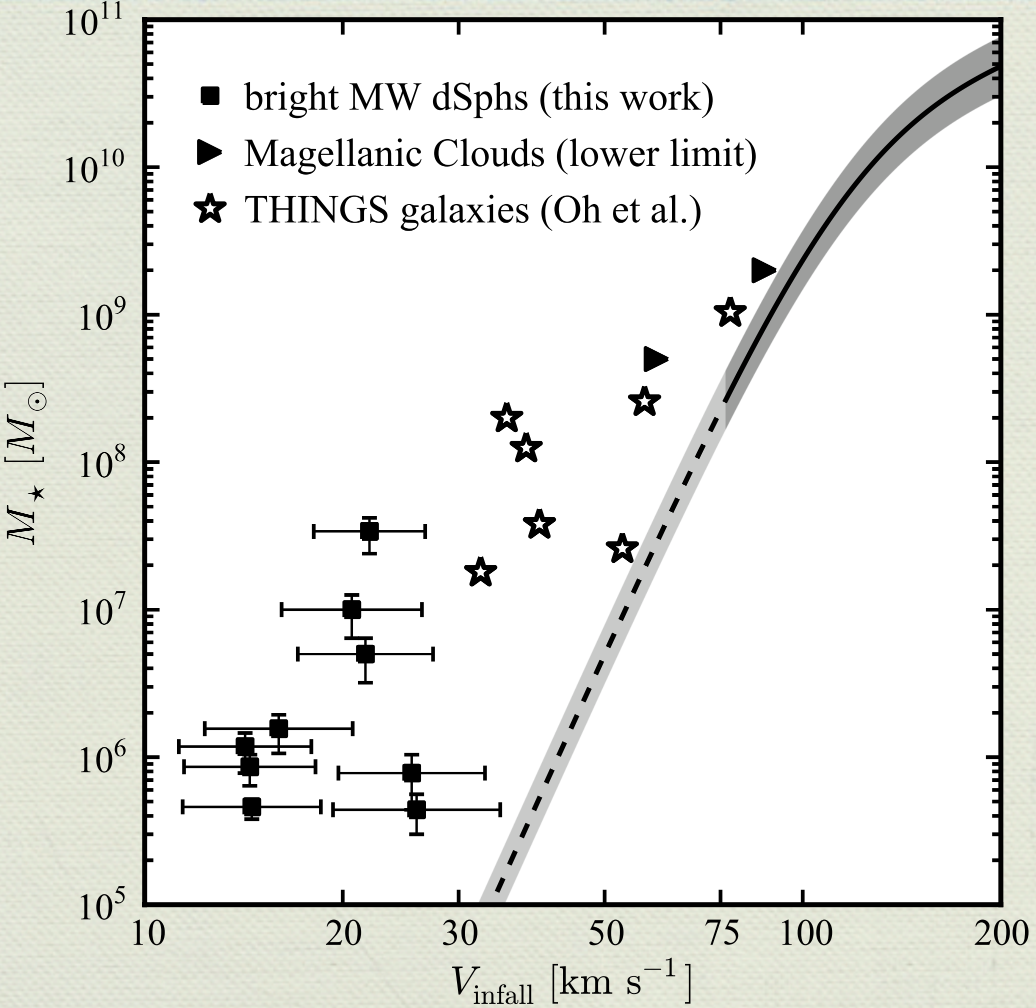
  - Not be in conflict with other measurements of shapes and densities of dark matter halos. There is a large diversity of behavior in galaxies!
  - Doesn't have to solve the "missing satellites" problem
- Warm dark matter [Gunn and Tremaine 1979, Bond, Efstathiou, Silk 1980]
  - Sterile neutrinos [Dodelson and Widrow 1994]
  - Weak-scale mass gravitinos [Kaplinghat 2005, Cembranos et al 2005]
- Self-interacting dark matter [Spergel and Steinhardt 2000, Firmani et al 2000]
  - Massive and massless force carriers [Feng, Kaplinghat, Yu, Tu 2009, Feng, Kaplinghat, Yu 2010, Loeb and Weiner 2011]

Galaxy formation looks stochastic at the faint end

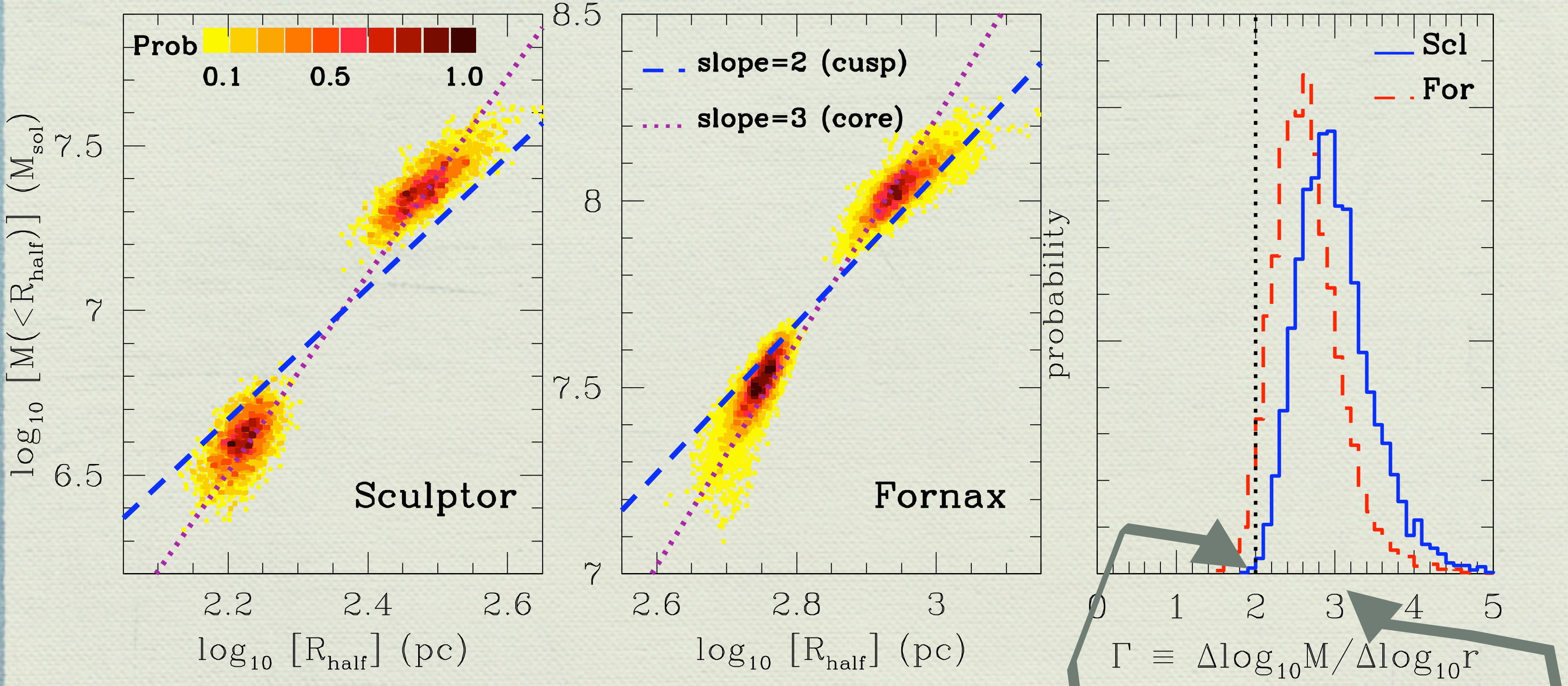
- Bright MW dwarfs and THINGS galaxies (tabulated in Oh et al. 2011) lie higher than the z = 0 abundance matching relation (solid curve), as well as its extrapolation to lower rotation velocities.
- The shaded region around the abundance matching relation shows allowed scatter in stellar mass.
- Something interesting is happening around 50 km/s!



Boylan-Kolchin, Bullock, Kaplinghat 2011

Cores in the dark matter halos of satellites

Walker and Penarrubia, ApJ 742 (2011)



NFW

Core

Having multiple stellar populations breaks degeneracies

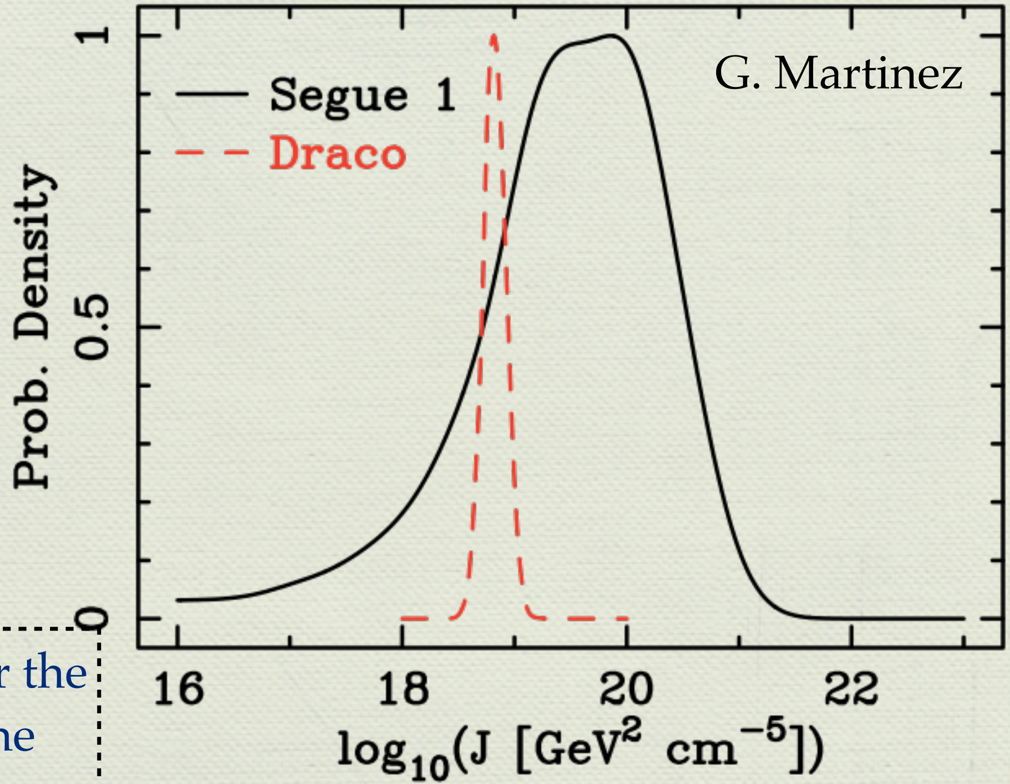
Battaglia et al MNRAS 383, 183 (2008)

Amorisco and Evans MNRAS 411, 2118 (2011)

2: Indirect detection
Faint vs Bright Satellites

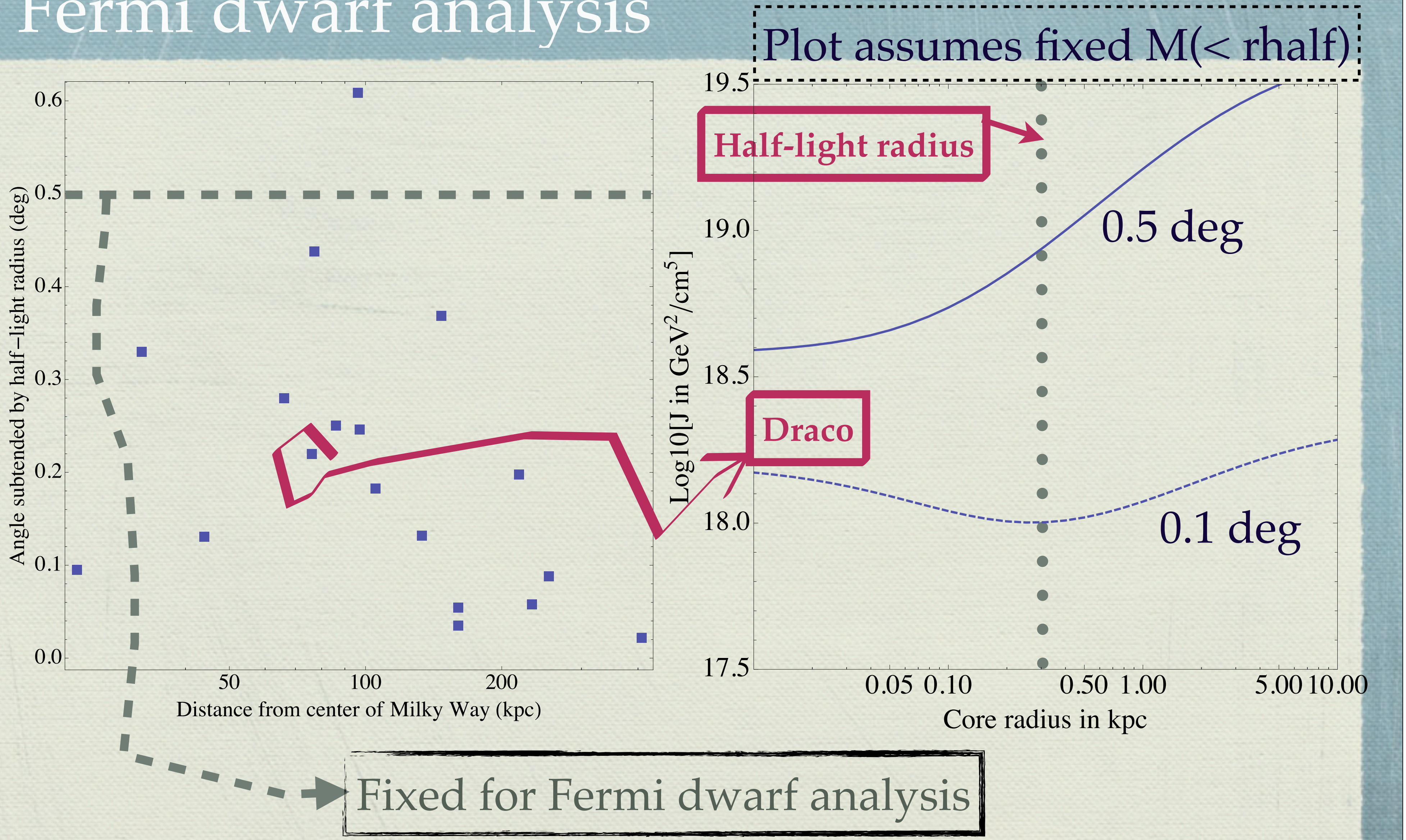
$$\Phi(E) = \frac{< \sigma \nu > N_\gamma(E)}{8\pi m_\chi^2} \int_{\theta'=0}^{\theta'=\theta_{\max}} d\Omega' \int d\Omega \mathcal{R}\,(\vec{\theta'} - \vec{\theta}) \int_{\ell_-}^{\ell_+} \rho^2_{DM}[\ell(\theta)] d\ell(\theta)$$

- Newly discovered ultra-faint satellites are great targets for indirect detection
- However, best limits (in case of no detection) on annihilation cross section from Draco and Ursa Minor



Segue 1 curve marginalizes over the contribution of binary stars to the velocity dispersion and the stellar density profile of the tracer stars

Cored profiles imply larger fluxes for Fermi dwarf analysis



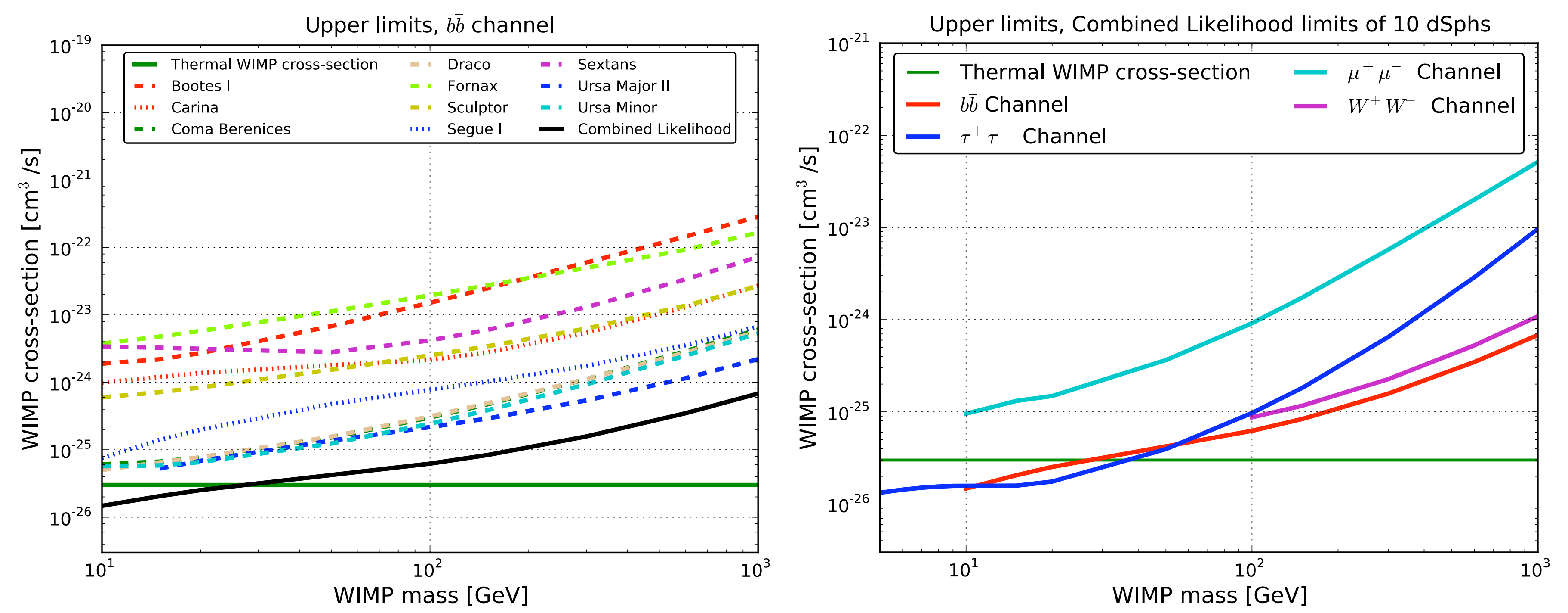
Plot assumes fixed M(< rhalf)

Half-light radius

Draco

Fixed for Fermi dwarf analysis

Stacking dwarfs



Navarro-Frenk-White profile for dark matter density vs radius assumed (density scales as 1/radius in the inner parts)

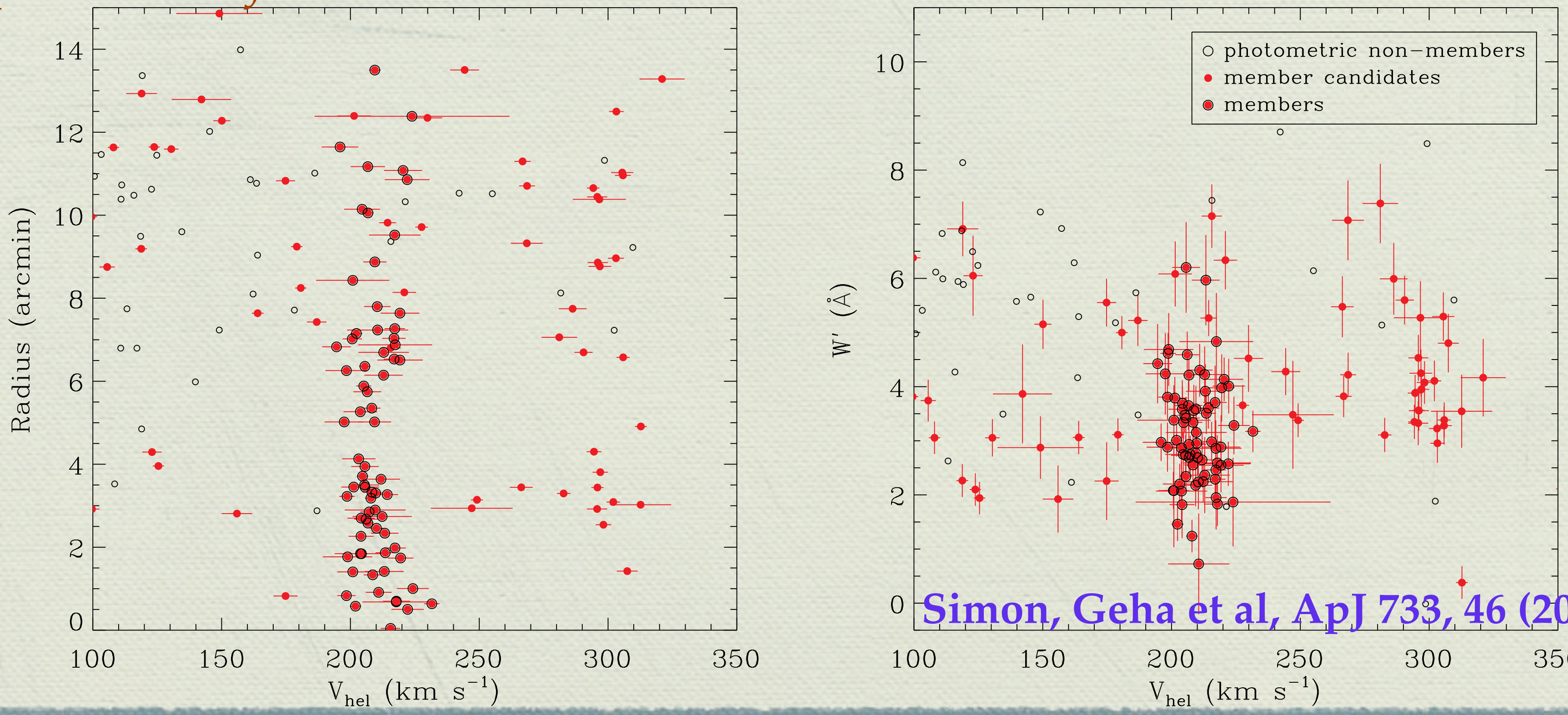
Fermi-LAT collaboration, Kaplinghat, Martinez 2011

Case study I: Segue 1 (found in SDSS at about 23 kpc)

Tidal radius without dark matter about the same as the radius that contains half the light.

At relative velocity of 4 km/s, stars will move apart about 400 pc in the time the dwarf takes to move about 20 kpc

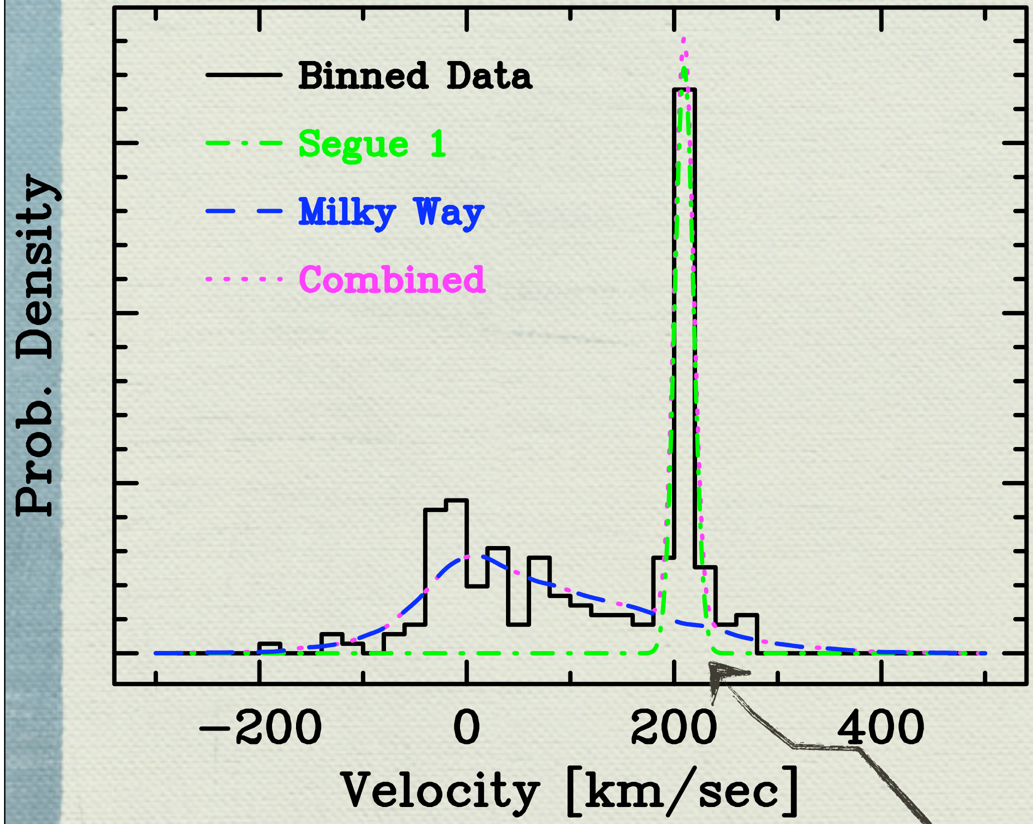
Existence of extremely metal poor stars and large metallicity spread: *not found in star clusters*



Simon, Geha et al, ApJ 733, 46 (2011)

Measuring mass in Segue 1

About 70 members with multi-epoch measurements for about half



Intrinsic dispersion
~3.8 km/s

$$M(r < r_{1/2}) = \frac{3 r_{1/2} \langle \sigma^2_{\mathrm{LOS}} \rangle}{G}$$

$$= \frac{3 \times 38\mathrm{pc} \times (3.8\mathrm{km/s})^2}{0.0043\,\mathrm{pc}\,\mathrm{M}_\odot^{-1}(\mathrm{km/s})^2}$$

$$= 3.8 \times 10^5\,\mathrm{M}_\odot$$

$$\rho(r < r_{1/2}) = 1.7\,\frac{\mathrm{M}_\odot}{\mathrm{pc}^3}$$

Simon, Geha et al, ApJ 733, 46 (2011)
Martinez, Minor ApJ 738, 55 (2011)

Segue 1 analysis: new method to handle membership and binaries

A fully Bayesian method that extends the method of Walker, Mateo, Olszewski, Sen, & Woodroofe, M. 2009, AJ, 137, 3109

Stellar populations:

$$\mathcal{L}(\mathscr{D}_i|\mathscr{M}) = F\mathcal{L}_{gal}(\mathscr{D}_i|\mathscr{M}_{gal}) + (1-F)\mathcal{L}_{MW}(\mathscr{D}_i|\mathscr{M}_{MW})$$

Separability:

$$\mathcal{L}_{gal,MW}(v,w,r) = \mathcal{L}_{gal,MW}(w)\mathcal{L}_{gal,MW}(v|r)\mathcal{L}_{gal,MW}(r)$$

No spatial bias:

$$\mathcal{L}(v,w|r) = f(r)\mathcal{L}_{gal}(w)\mathcal{L}_{gal}(v|r) + (1-f(r))\,\mathcal{L}_{MW}(w)\mathcal{L}_{MW}(v|r)$$

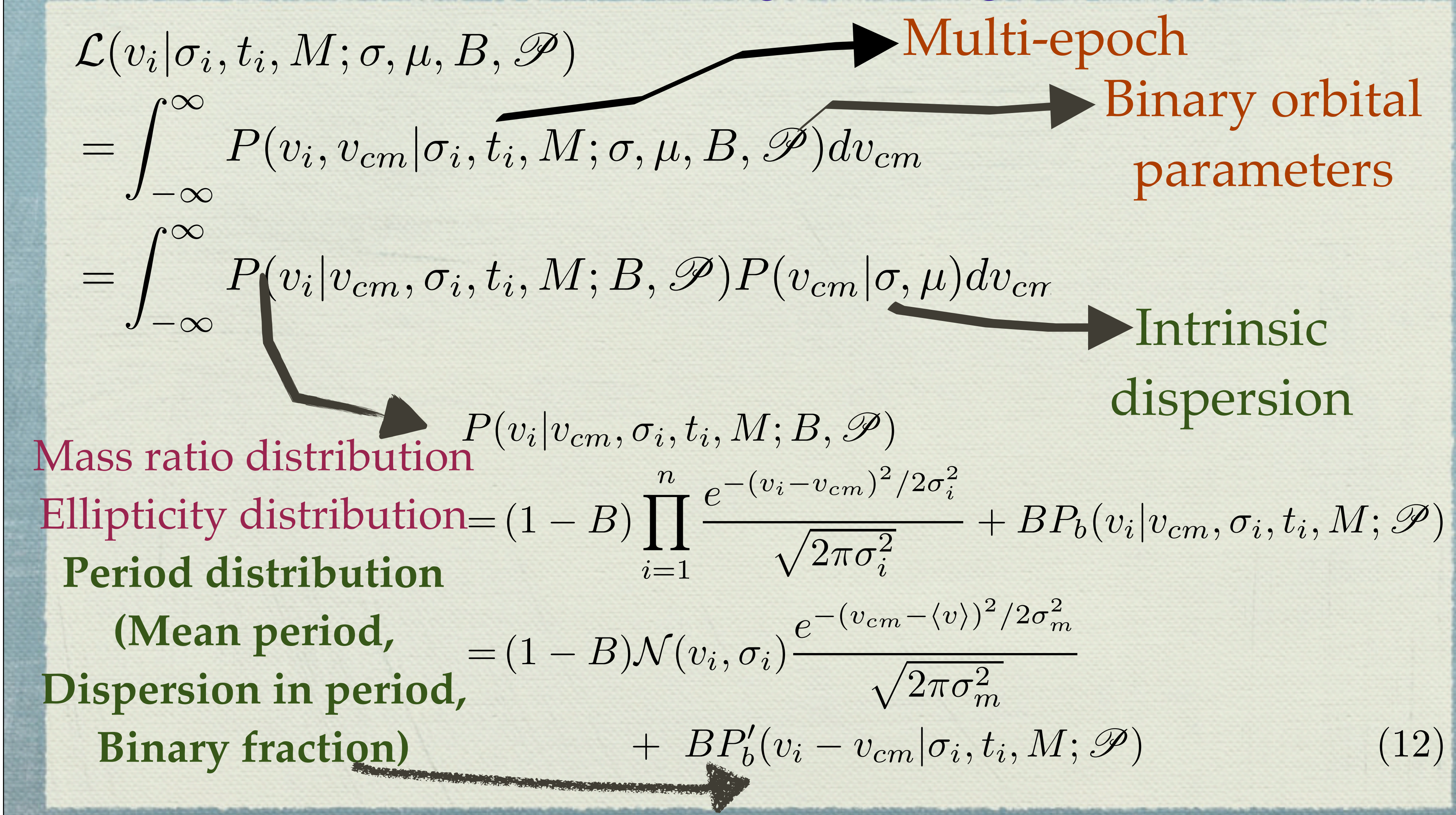
$$f(r) = \frac{n_{gal}(r)}{n_{gal}(r) + n_{MW}(r)}$$

$$n_{gal}(r) \propto \left(1 + (r/r_s)^2\right)^{-\alpha/2.0}$$

Can now constrain stellar profile independent of photometry

Segue 1 analysis essentials: binaries

Likelihood for each star assuming it is in Segue 1:



$$\mathcal{L}(v_i|\sigma_i,t_i,M;\sigma,\mu,B,\mathscr{P}) = \int_{-\infty}^{\infty} P(v_i,v_{cm}|\sigma_i,t_i,M;\sigma,\mu,B,\mathscr{P})dv_{cm}$$

$$= \int_{-\infty}^{\infty} P(v_i|v_{cm},\sigma_i,t_i,M;B,\mathscr{P})P(v_{cm}|\sigma,\mu)dv_{cm}$$

Multi-epoch

Binary orbital parameters

Intrinsic dispersion

$$P(v_i|v_{cm},\sigma_i,t_i,M;B,\mathscr{P})$$

$$= (1-B)\prod_{i=1}^{n}\frac{e^{-(v_i-v_{cm})^2/2\sigma_i^2}}{\sqrt{2\pi\sigma_i^2}} + BP_b(v_i|v_{cm},\sigma_i,t_i,M;\mathscr{P})$$

$$= (1-B)\mathcal{N}(v_i,\sigma_i)\frac{e^{-(v_{cm}-\langle v\rangle)^2/2\sigma_m^2}}{\sqrt{2\pi\sigma_m^2}} + BP_b'(v_i-v_{cm}|\sigma_i,t_i,M;\mathscr{P}) \qquad (12)$$

Mass ratio distribution

Ellipticity distribution

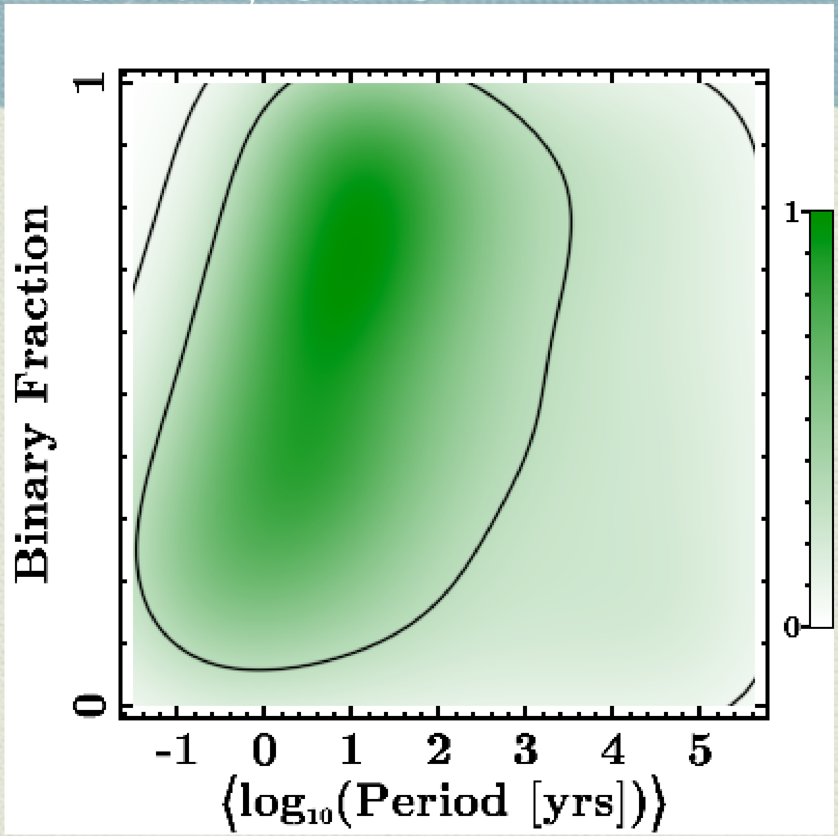
Period distribution

(Mean period,

Dispersion in period,

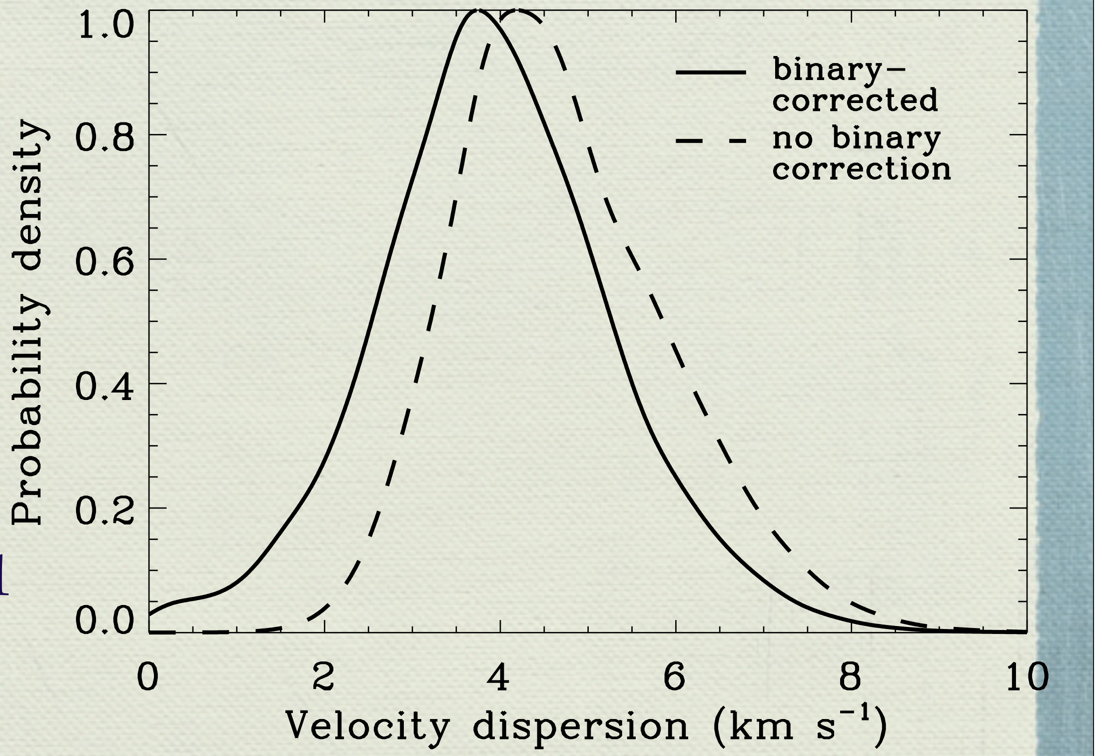
Binary fraction)

Measuring dark matter mass in Segue 1: effect of binary stars



Repeat measurements at about 1 year interval for many stars needed to constrain binary properties well enough to estimate dark matter mass

Velocity dispersion corrected for orbital motion in binary stars

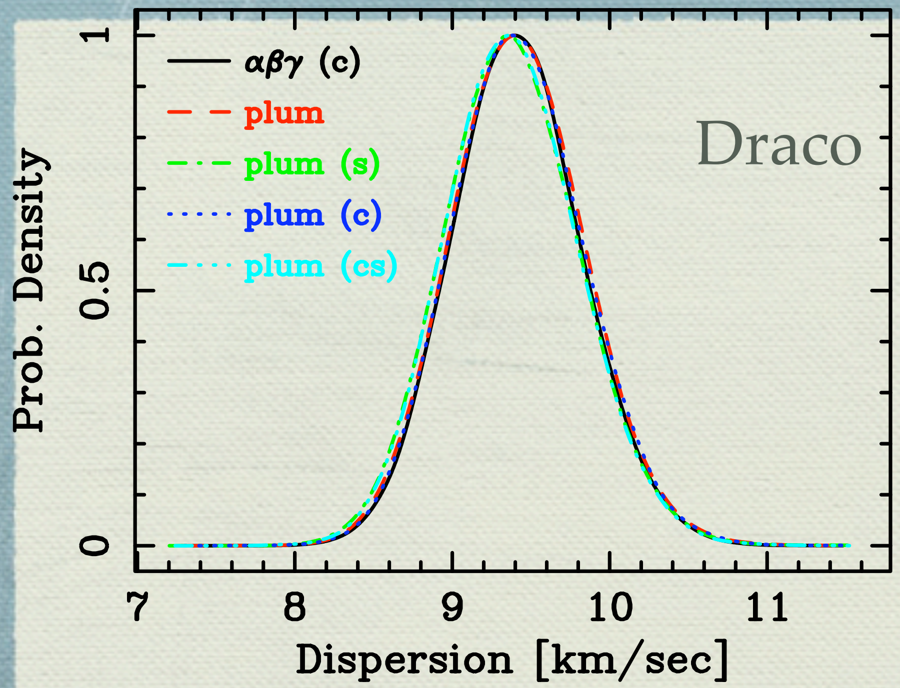


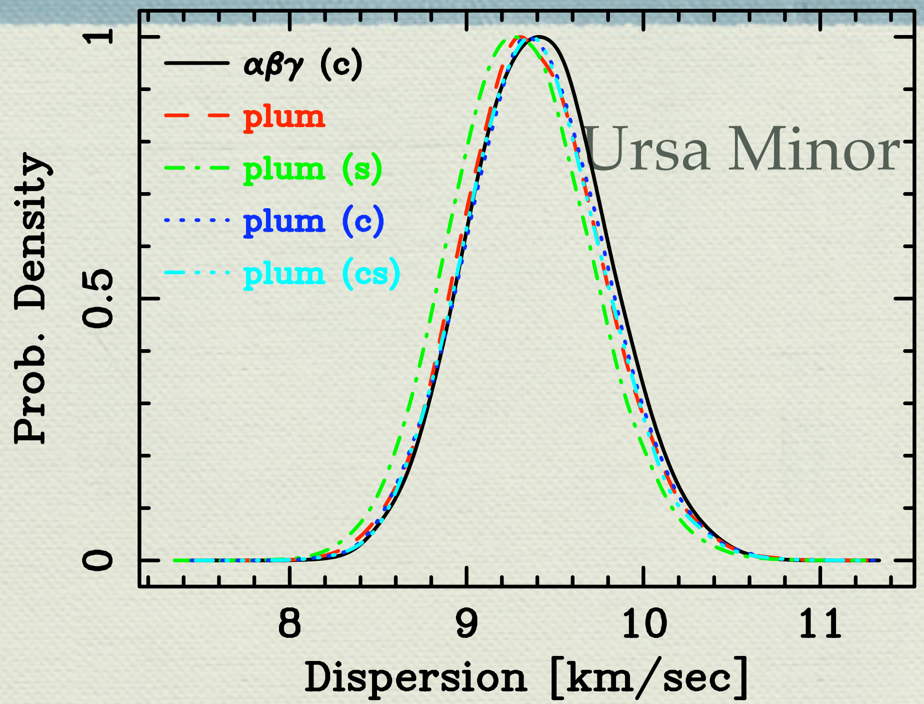
Simon, Geha et al, ApJ 733, 46 (2011)
Martinez, Minor ApJ 738, 55 (2011)

Segue 1 summary points

- Detailed Segue 1 analysis leads to the conclusion that it is a highly dark matter dominated galaxy with an intrinsic dispersion of about 3.7 (spread of about 1 km/s).
- Estimated central density within 40 pc has a mean value of about 1 Msun/pc^3 -- the highest density seen in the dwarfs. Interpreted in the context of LCDM, it should be among the brightest sources of dark matter annihilation products.

Case study II: Measuring velocity dispersion in bright dSphs





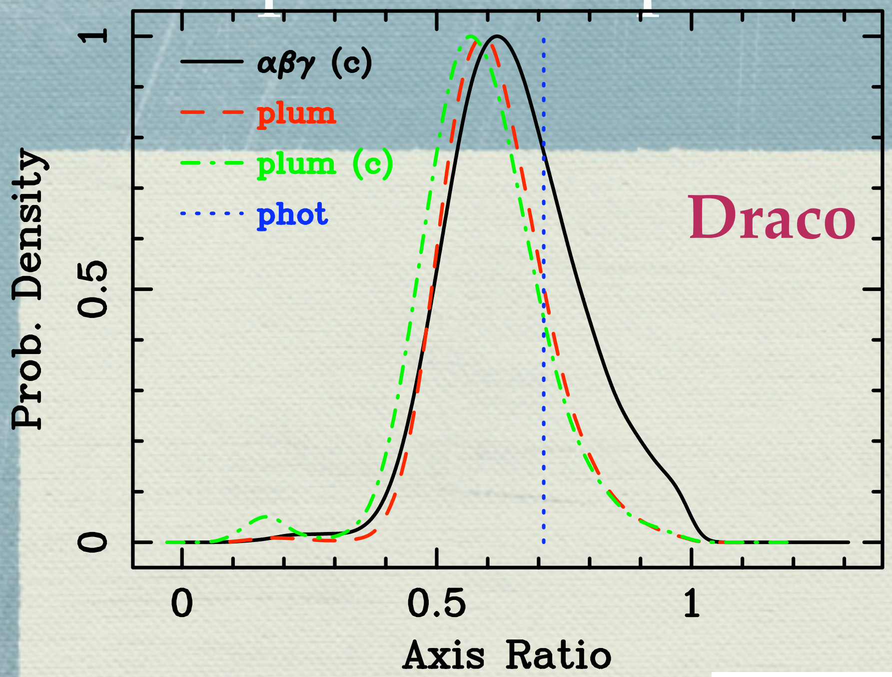
Martinez, Geha, Kaplinghat, Kirby, Strigari, in preparation

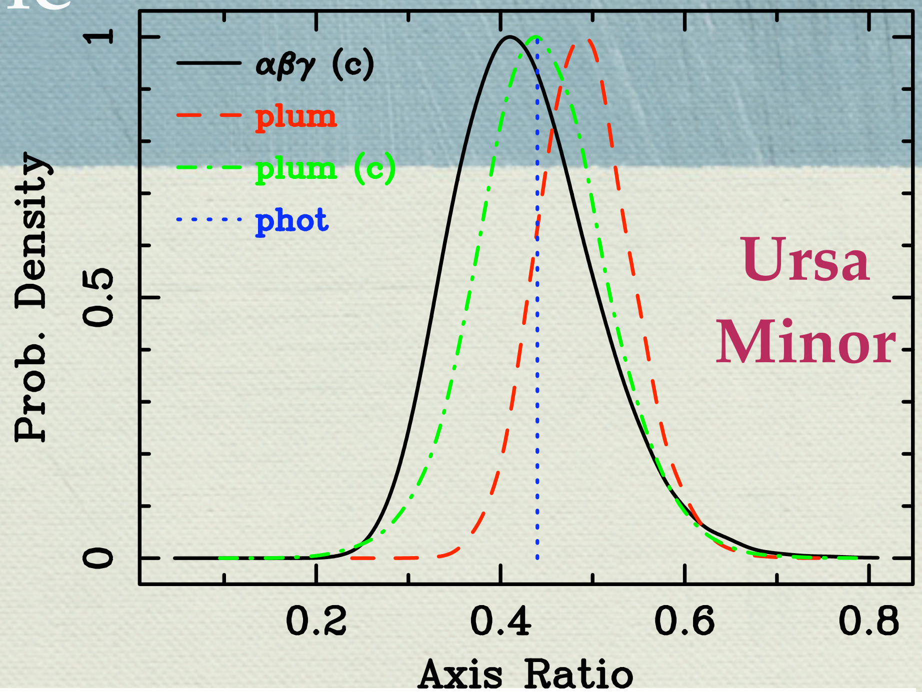
Caution: This is work in progress and the slides in section are preliminary!

The velocity dispersion posterior includes uncertainties in position of center, density profile, position angle and ellipticity of stars.

Axisymmetric modeling gives results consistent with spherical M(rhalf) estimates, e.g., Thomas et al MNRAS 415, 545 (2011), Jardel and Gebhardt ApJ 2012.

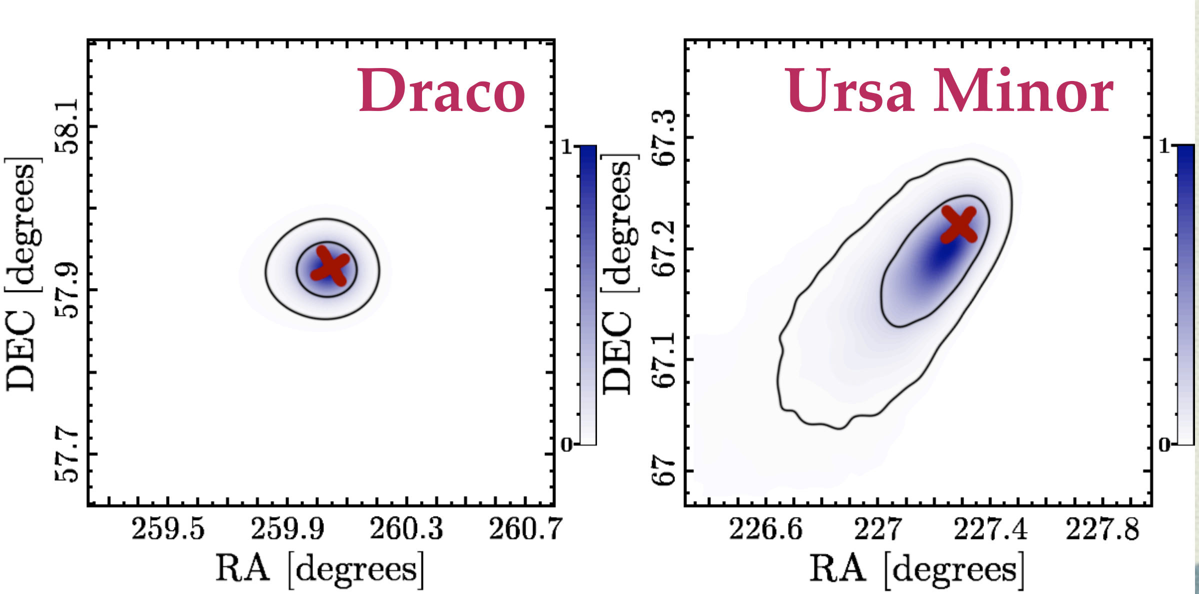
Case study II: Elliptical stellar profile from the spectroscopic sample



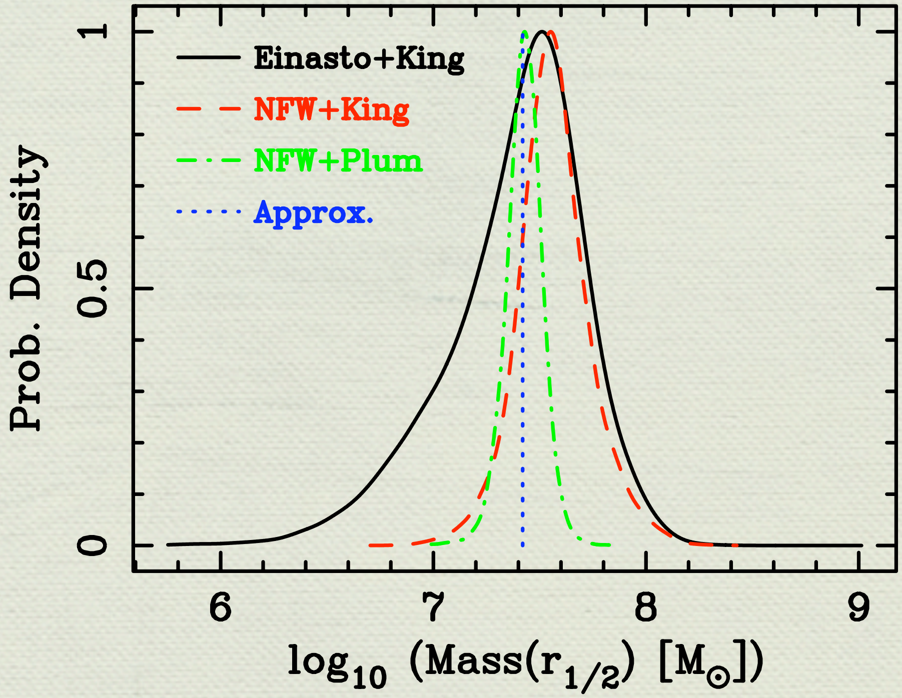


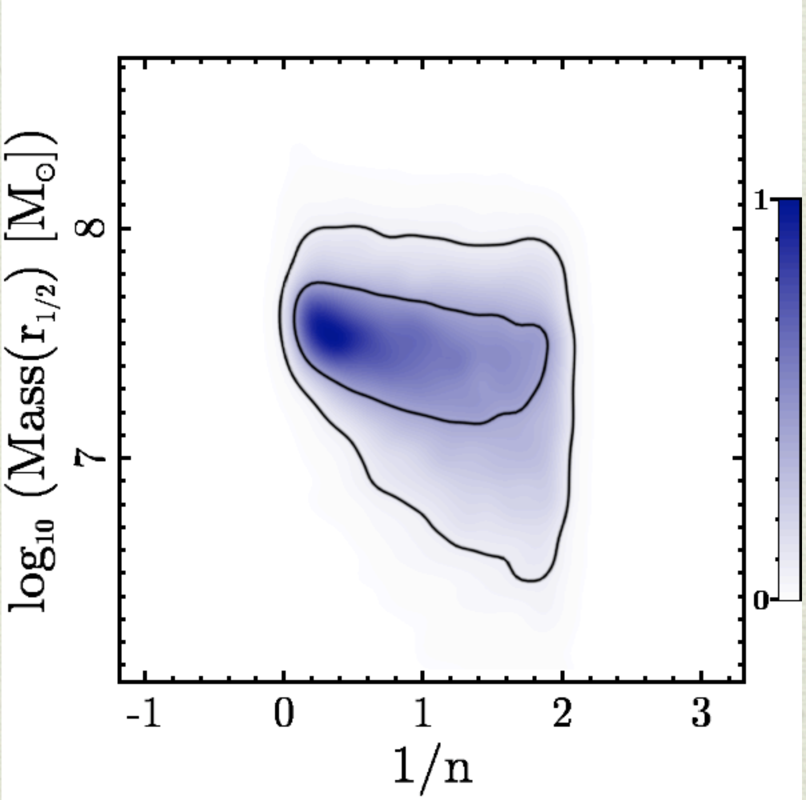
Keep in mind that the stellar profile of the kinematics sample (RGB stars typically) don't have to be exactly the same as that derived from photometry.

Similar results for position angle



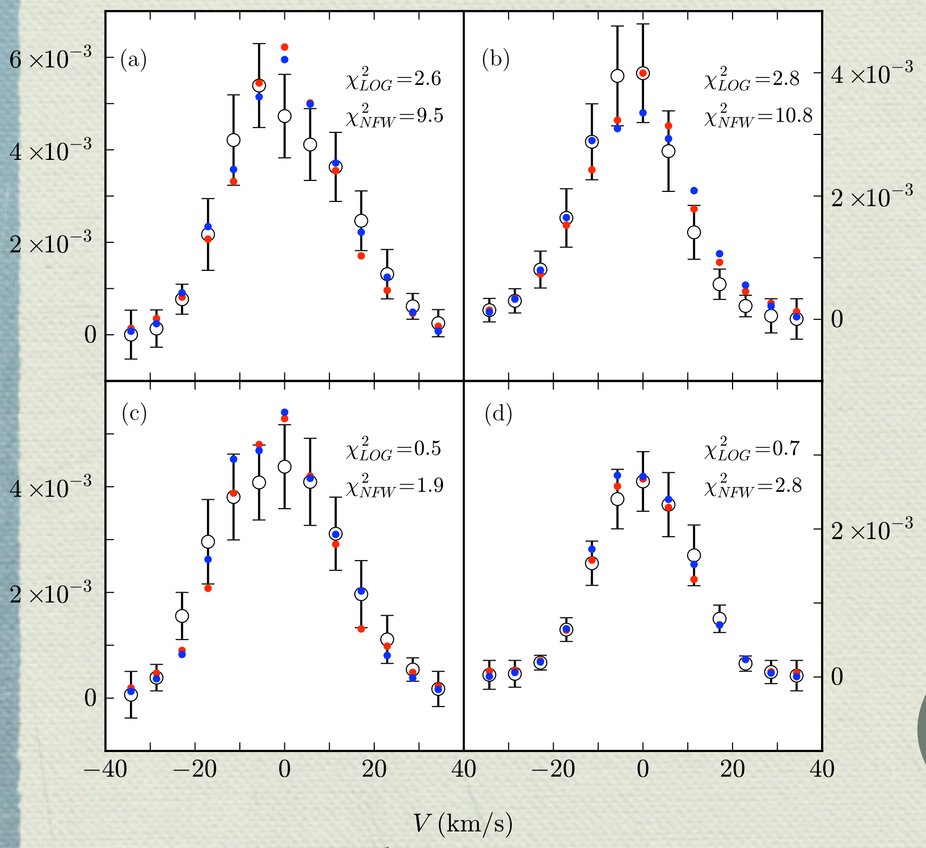
Case study II: Ursa Minor halo mass within half-light radius



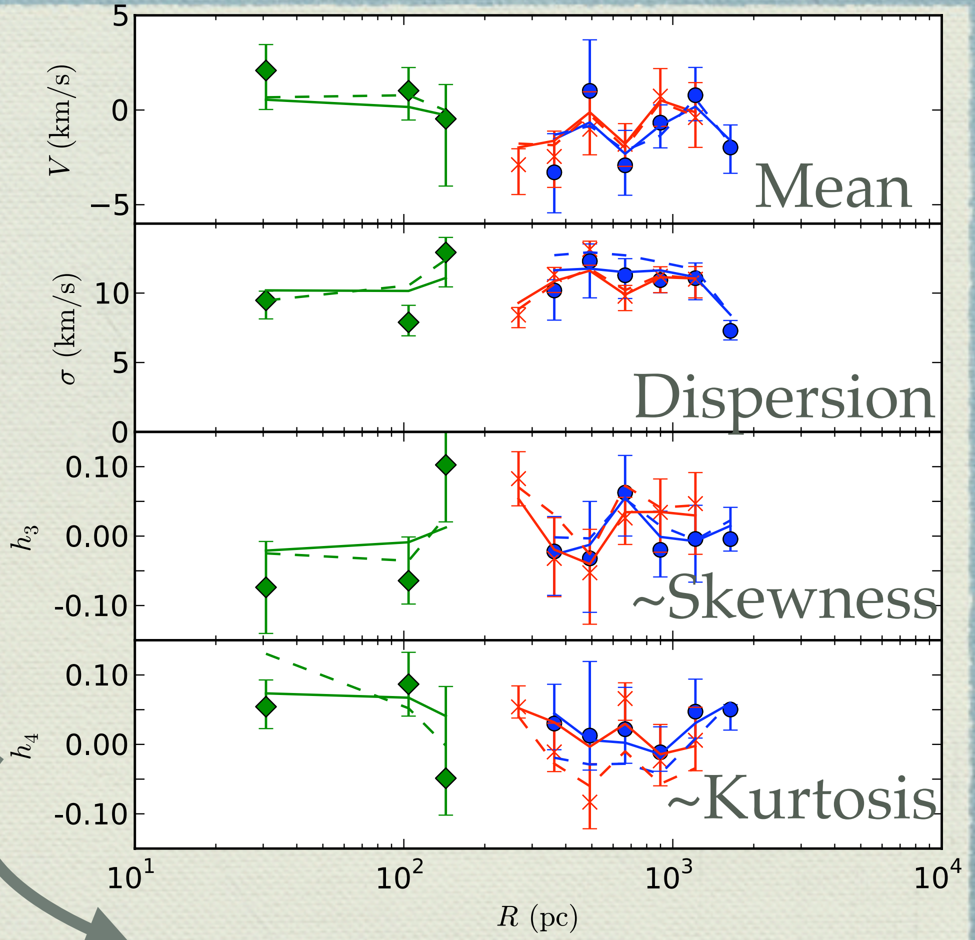


Case study II: dynamical information from higher order moments?

Fornax

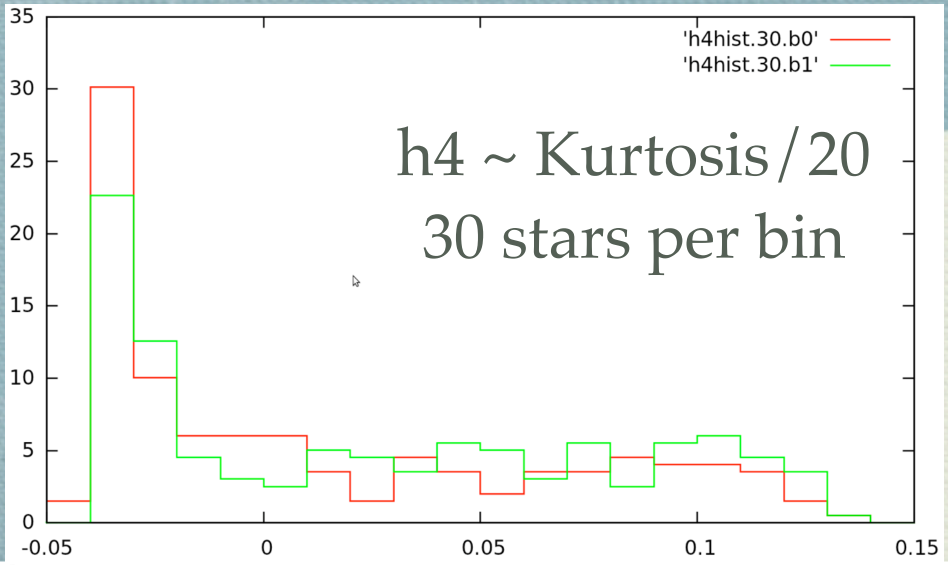


Jardel and Gebhardt, ApJ 2012

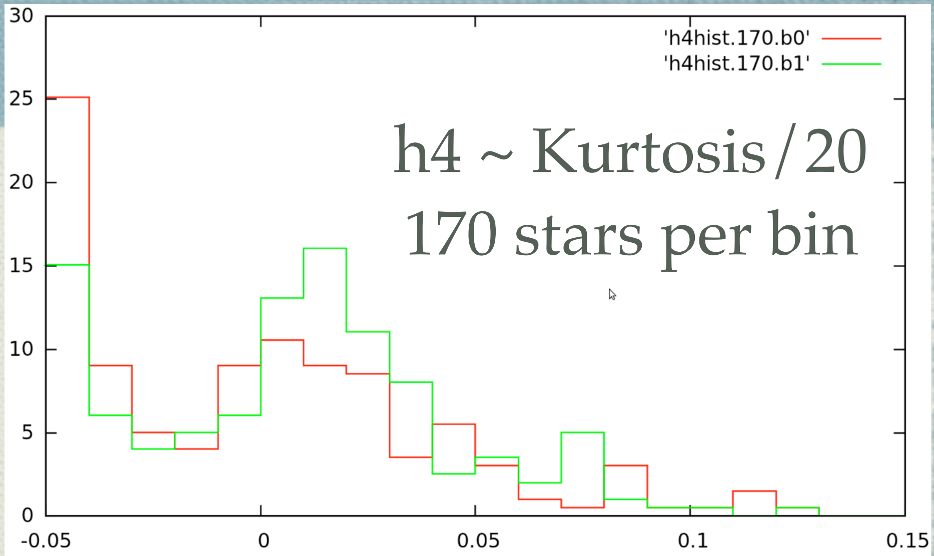


Sensitive to binary orbital motion and membership cuts

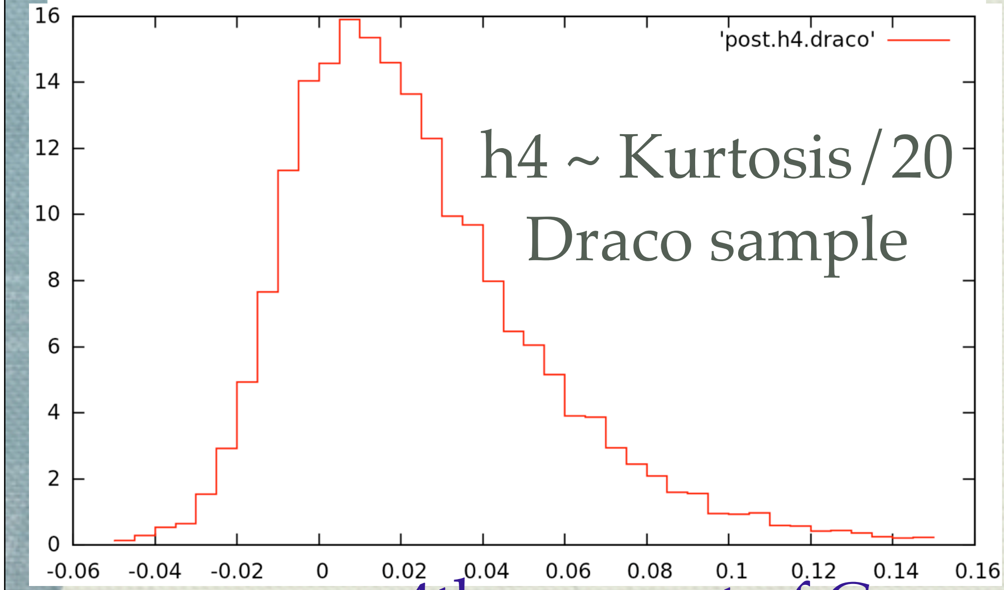
Binaries and “Kurtosis”


h4 ~ Kurtosis/20

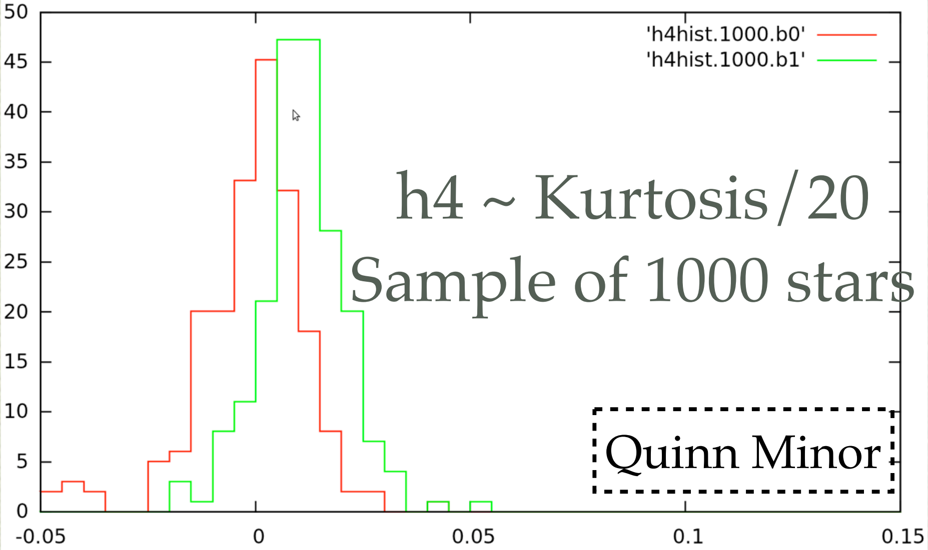
30 stars per bin


h4 ~ Kurtosis/20

170 stars per bin


h4 ~ Kurtosis/20

Draco sample


h4 ~ Kurtosis/20

Sample of 1000 stars

Quinn Minor

4th moment of Gauss-Hermite decomposition

Summary

- Central dark matter densities of Milky Way dwarfs are not compatible with existing LCDM predictions.
- Searching for gamma-rays from the dwarfs has ruled out models with canonical thermal relic cross-section for masses below about 30 GeV.
- Most of the uncertainties (stellar profile, binary stars) affecting dark matter halo mass estimates have either been included or will be in the next year or so.