# Using Dark Globular Cluster and Dwarf Galaxy Data to Constrain the Properties of the Dark Matter Particle

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Peter Biermann (MPI, Univ. of Bonn, Univ of AL), Zech Miller, Hunter Somers, and Ben Woodall (Millikin)
and
Norma Sanchez for inviting me.

# OUTLINE

## Observational Trends for MW dSphs:

- Mass Modeling via velocity dispersion data
  - Determine best-fit Burkert halo parameters ($r_0$, $\rho_0$)
  - Find strong correlations between the half-light radii ($r_{hf}$) and $r_0$ and $\rho_0$
- Phase Space Density measurements
  - $r_{hf}$ correlations also found for stellar PSD
  - A model for $\sigma_{DM}/\sigma_*$
  - PSD of DM

## A Physical Mechanism for the $r_{hf}$-$r_0$ & $r_{hf}$-$\rho_0$ correlations:

- Baryonic infall & adibatic compression of DM

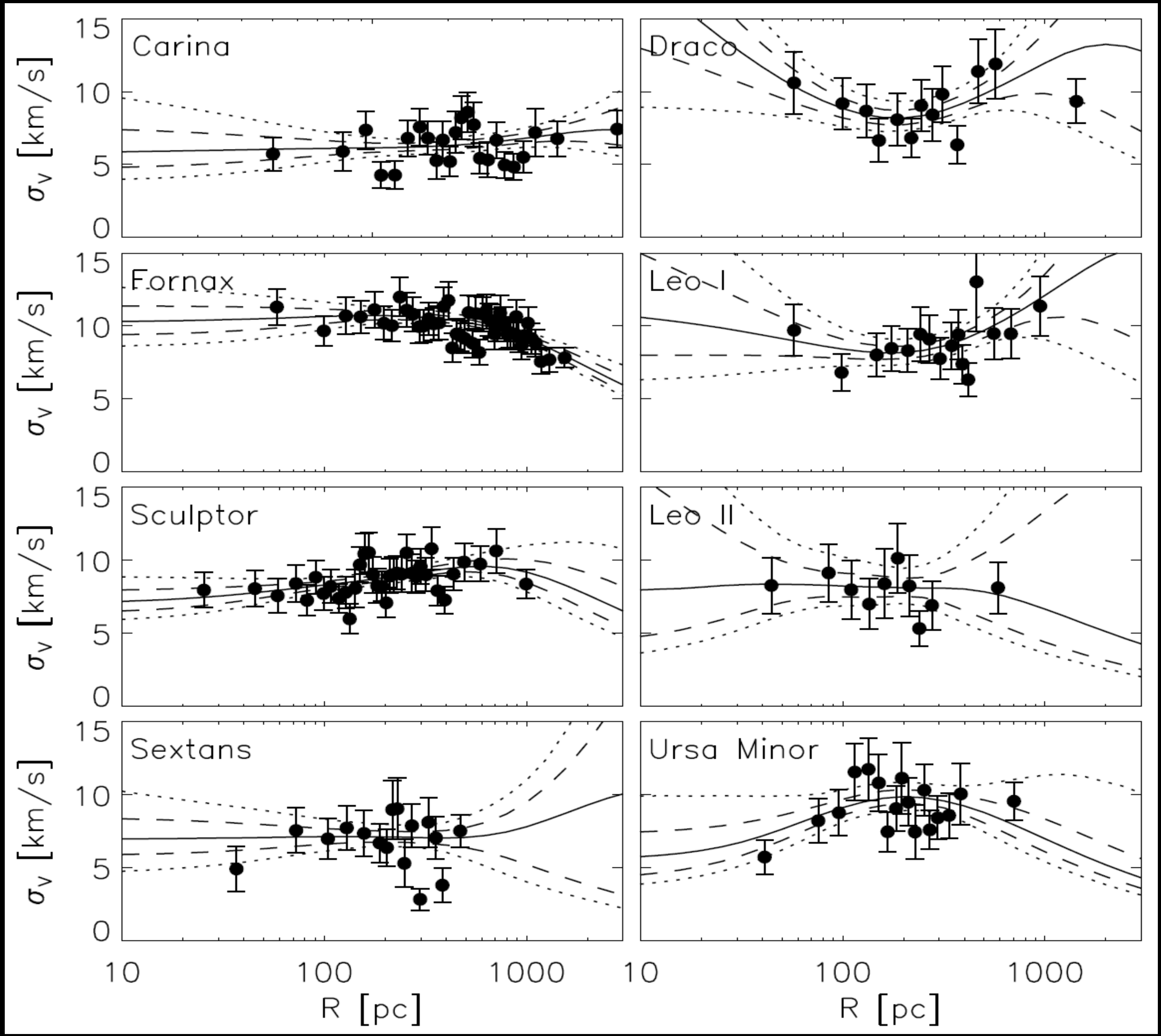
## Implications of the $r_{hf}$ correlations for the first galaxies:

- Observations of Dark Globular Clusters (DGCs) vs. Classical GCs
  - Evidence of DM (DGCs ) vs. No evidence of DM (GCs)
  - Simulations suggest DGCs originally ~$10^7$ $M_\odot$
  - Is $10^7$ $M_\odot$ a special scale? Yes!
  - Suggests $10^7$ $M_\odot$ = fundamental building block of galaxies (FSS)

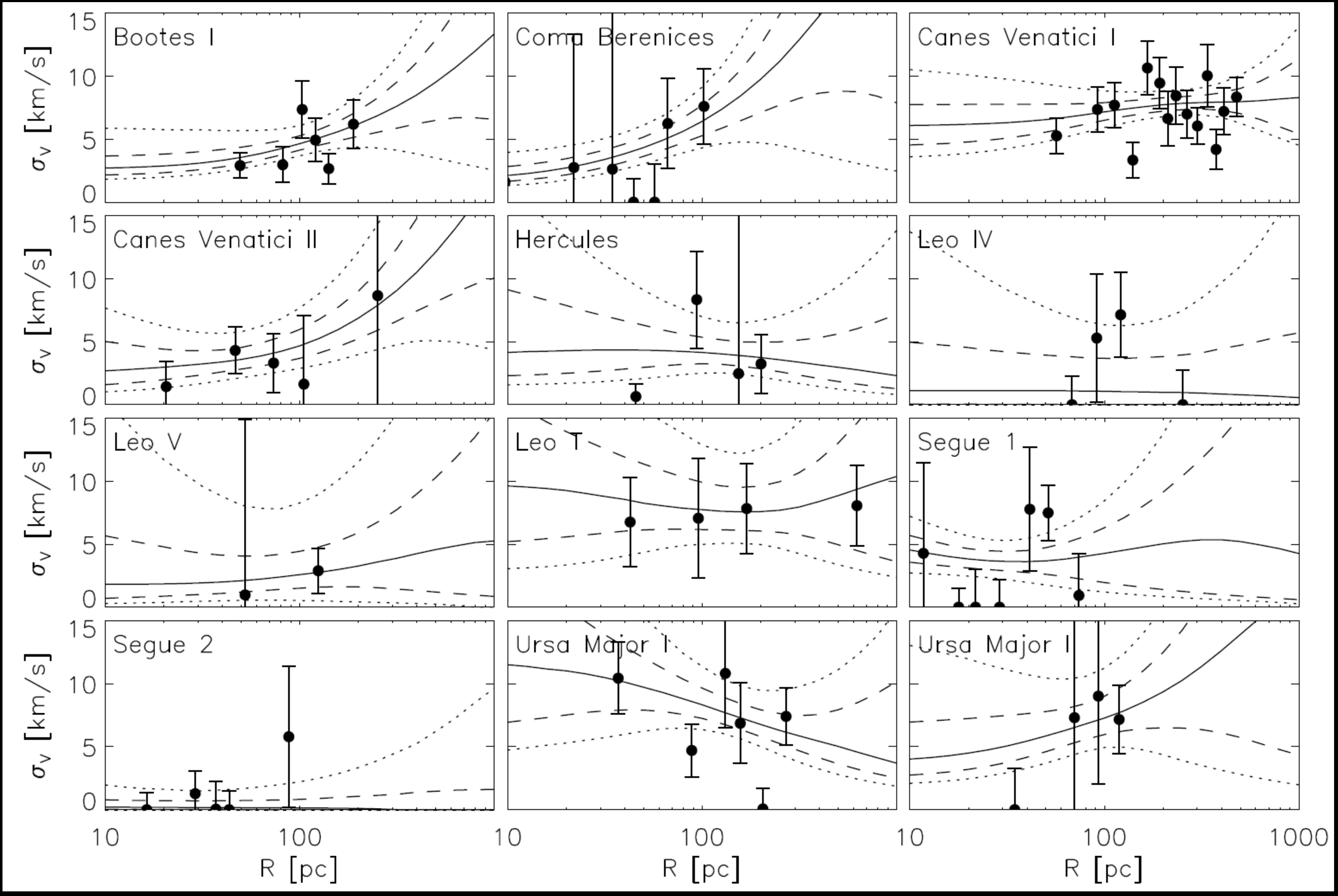
## Resulting FSS, LSS, & PSD limits all point to $m_{DM,thermal}$ ~ 2 keV.

# PART 1: Observational Trends

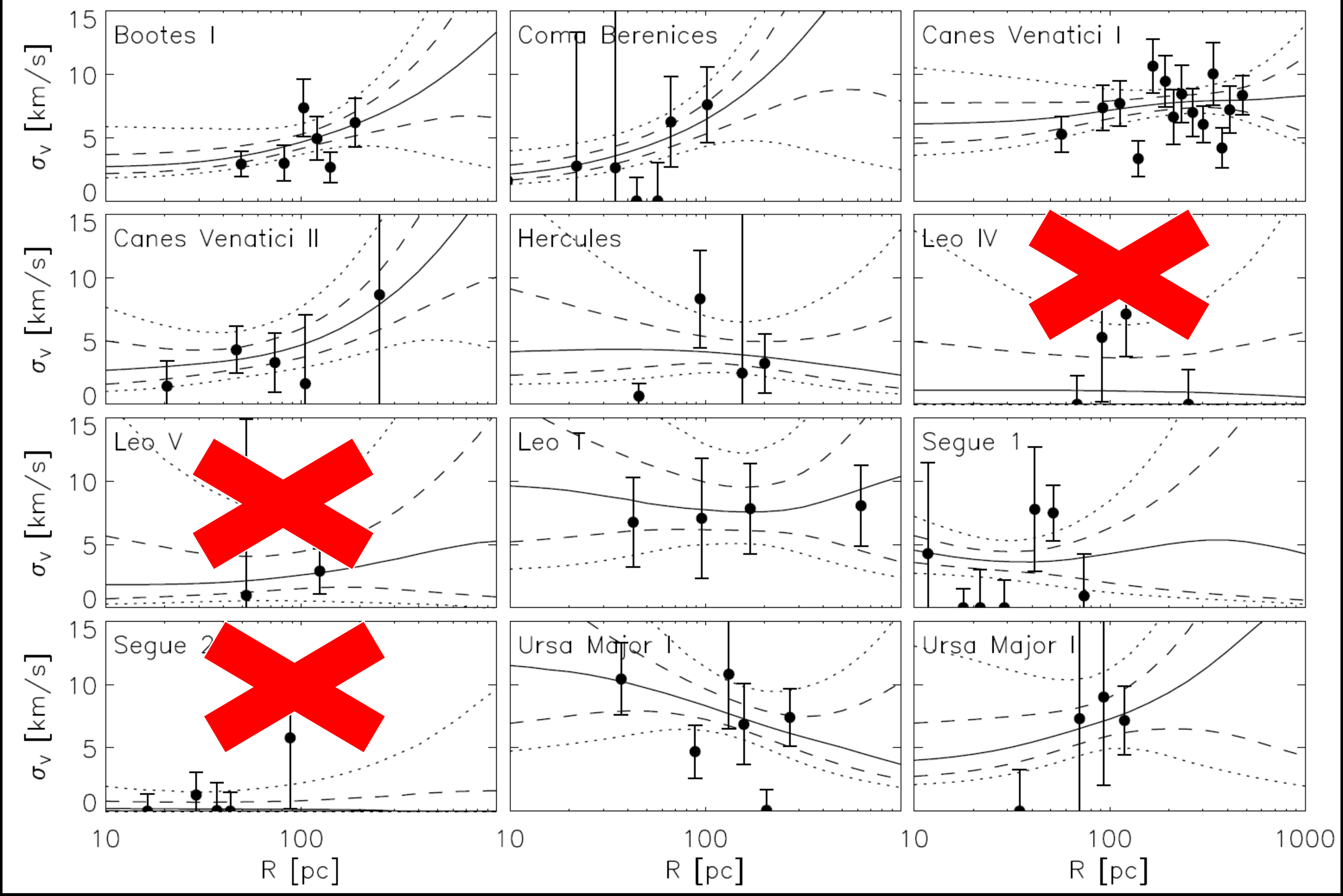
# MW Cl. dSphs Velocity Dispersions (Gerringer-Sameth et al. 2015)



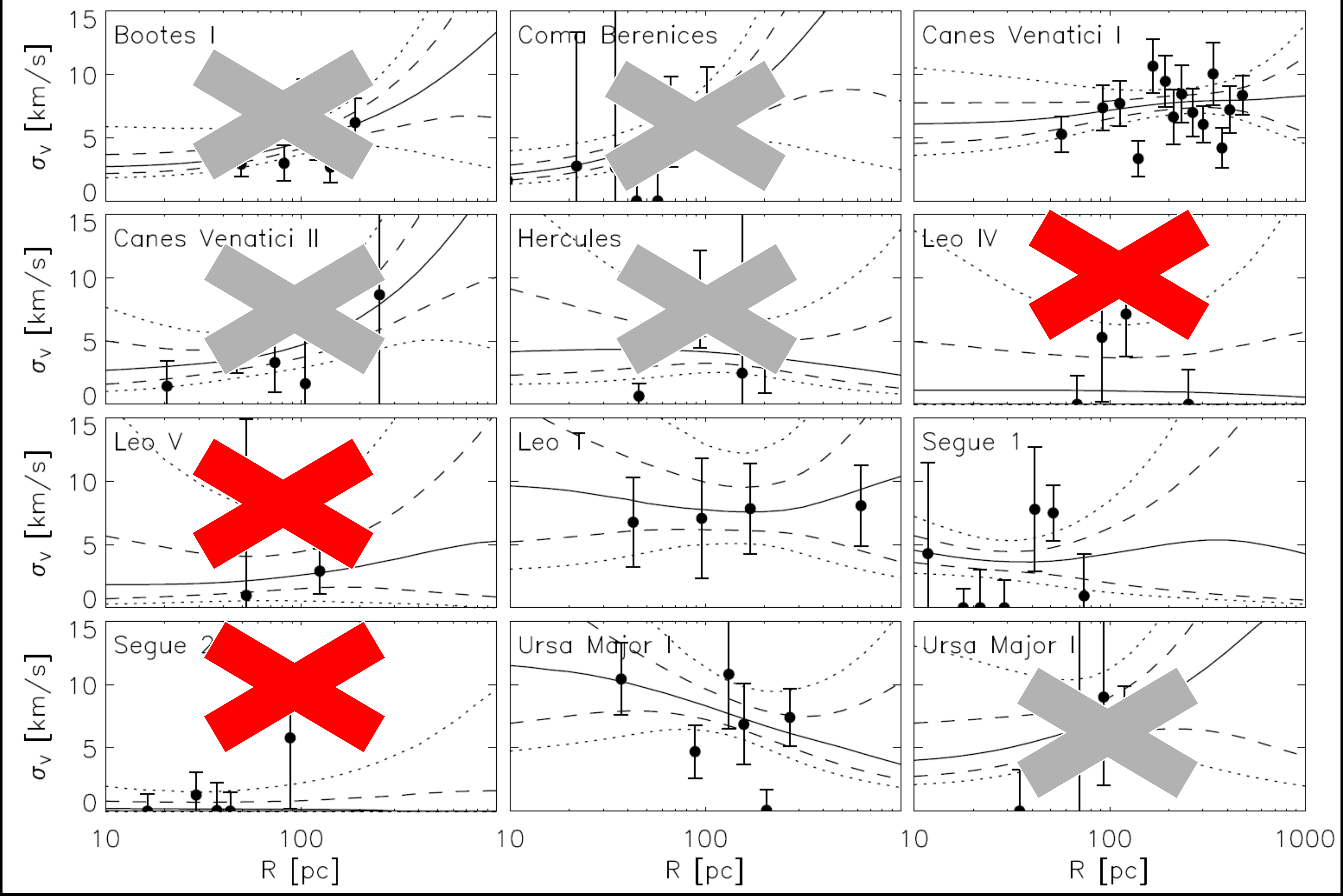
# MW UF dSphs Velocity Dispersions (Gerringer-Sameth et al. 2015)



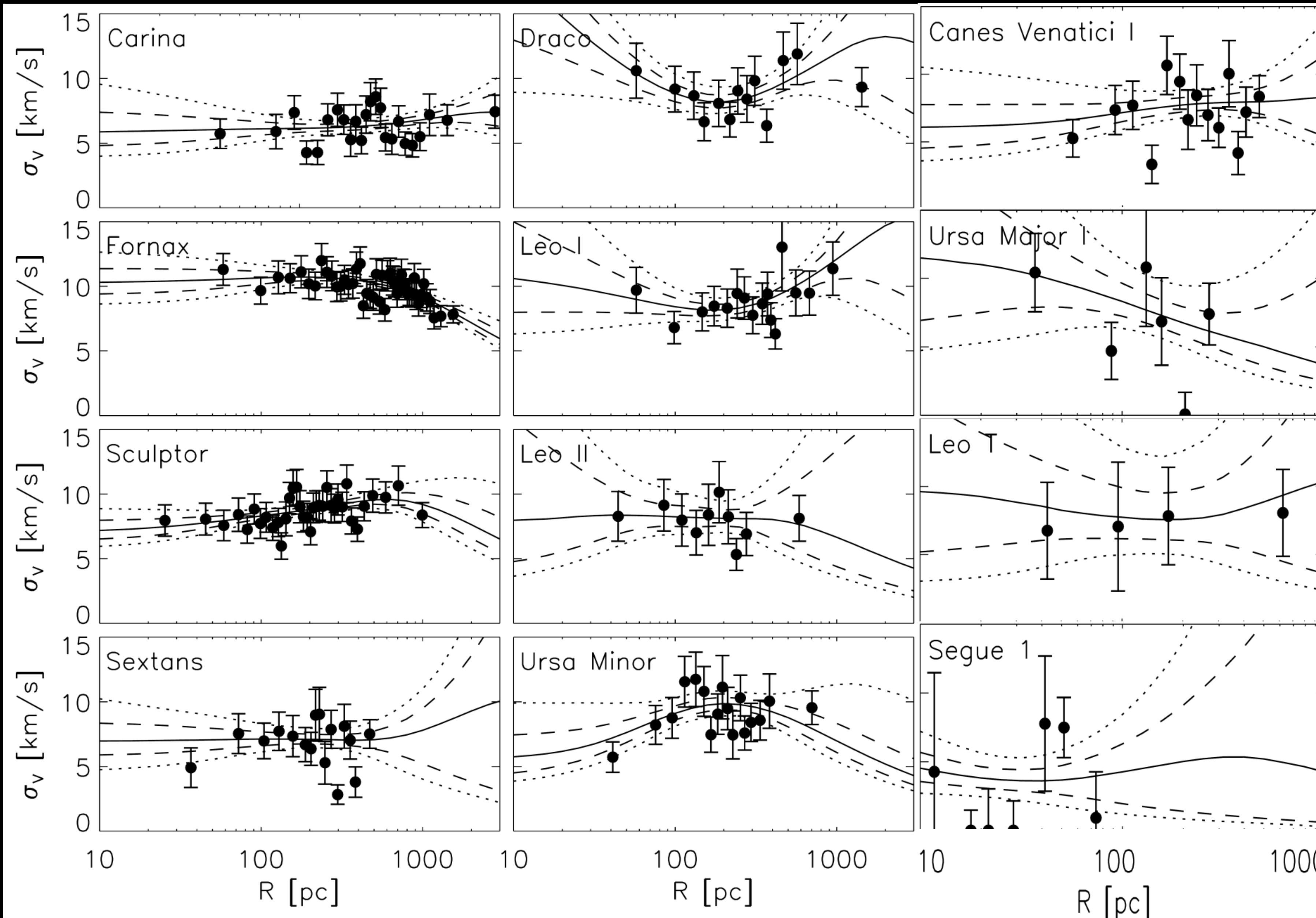
# Eliminated UF dSphs: Data



# Eliminated UF dSphs: Data & Tidal Disruption



# MW Classical + UF dSphs Data Set



# Mass Modeling: Jeans Analysis

$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

**Stellar Density - Plummer Profile:**

$$\nu(r) = 3L(4\pi r_{half}^3)^{-1}[1 + r^2/r_{half}^2]^{-5/2}$$

**For β ~ 0 and ~ flat velocity dispersion profiles:**

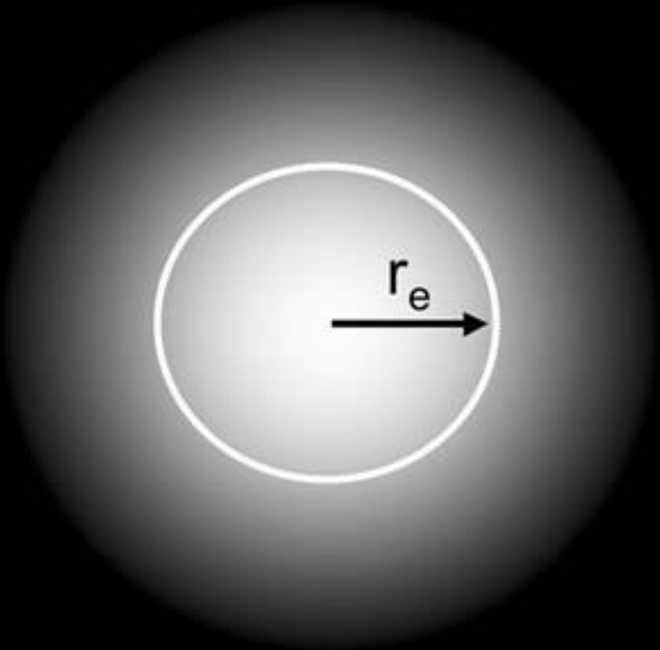
$$M(r) = -\frac{r^2\bar{v_r^2}}{G\nu}\frac{d\nu}{dr} = \frac{5r_{half}\sigma^2\left(\frac{r}{r_{half}}\right)^3}{G\left[1 + r^2/r_{half}^2\right]}$$

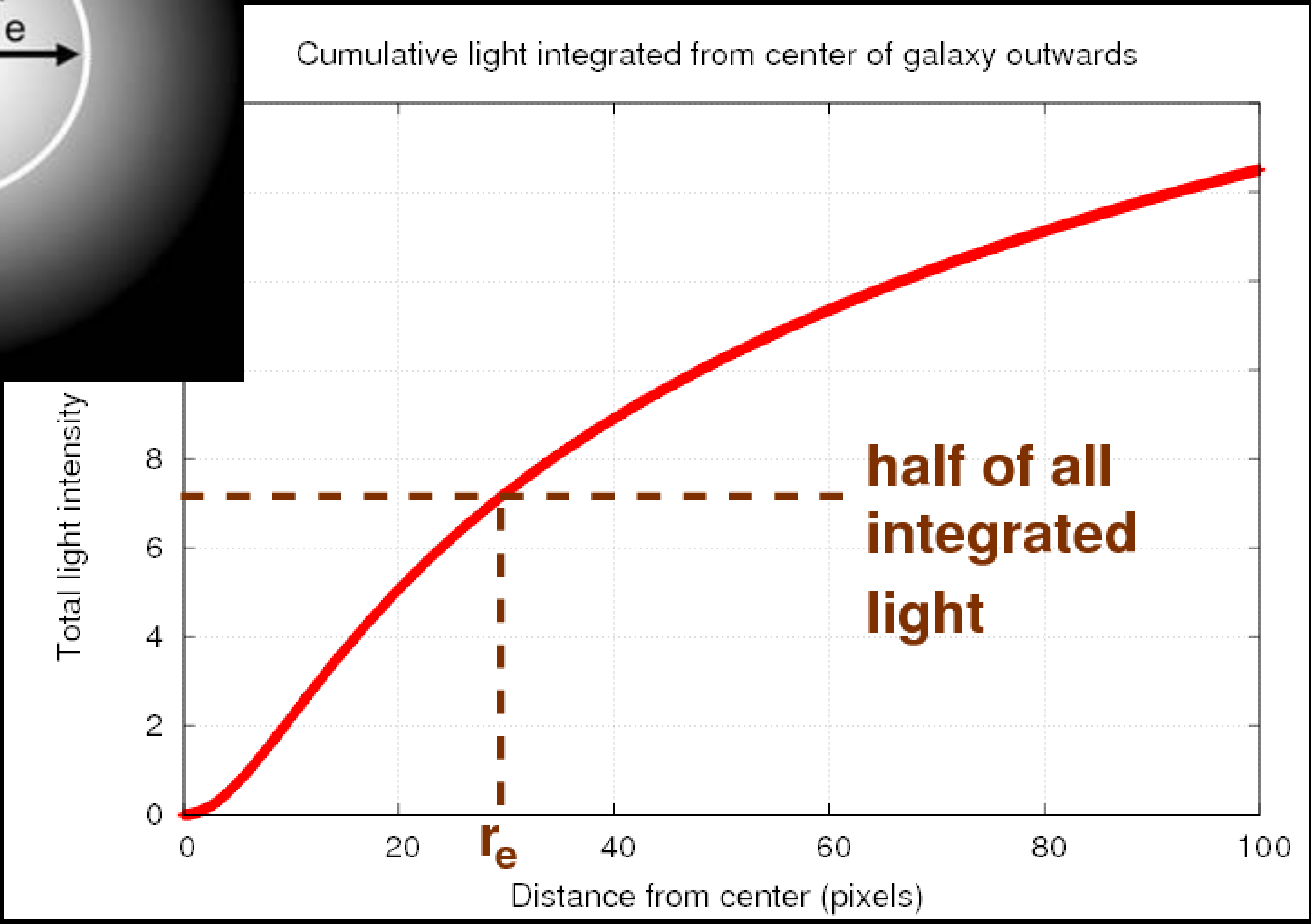
**Determine Best-fit Burkert Profile:**

$$M_B(r) = 4\pi\int_0^r s^2\rho_B(s)ds$$

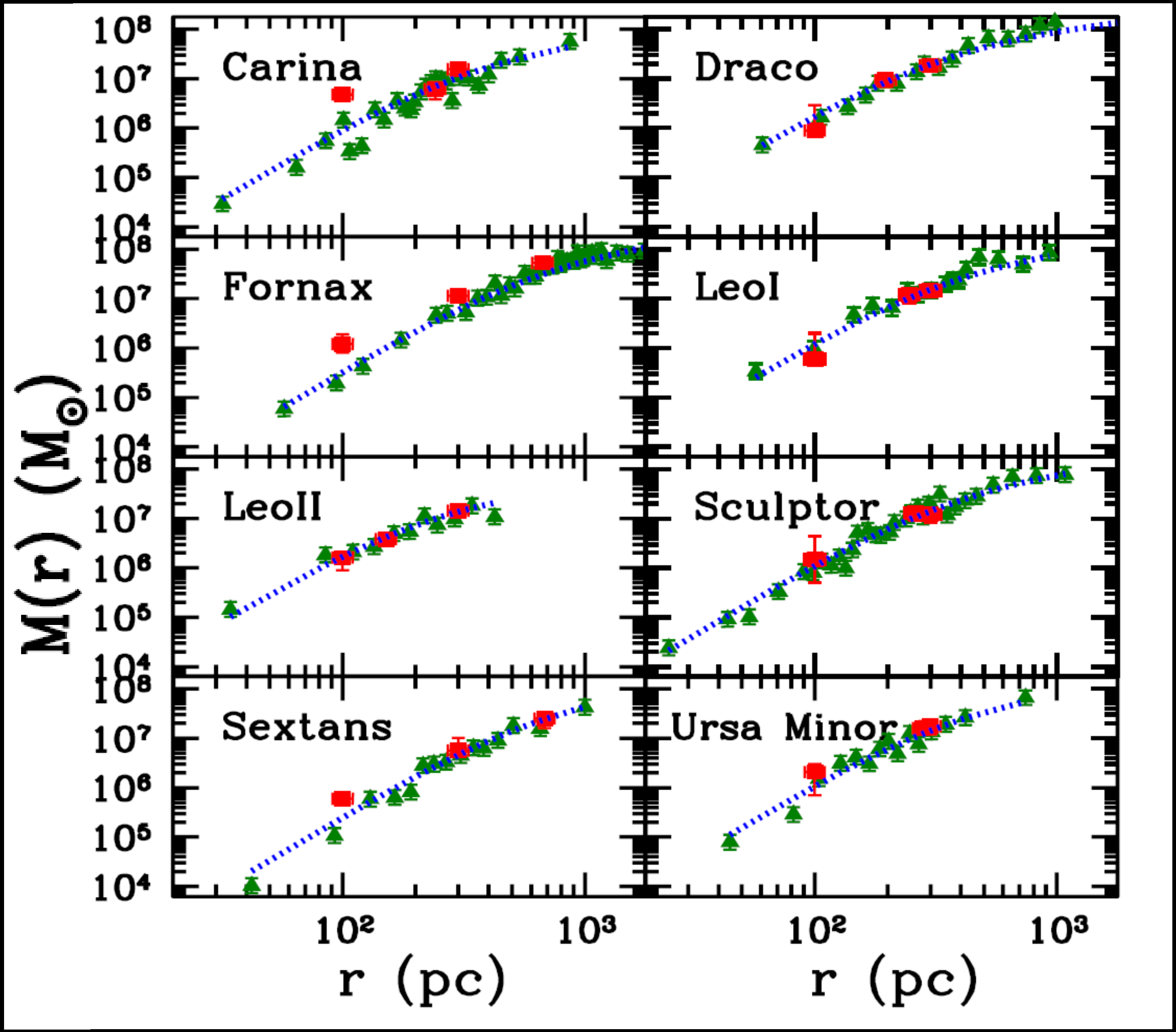
$$\rho_{\mathrm{B}}(r) = \frac{\rho_0}{(1+x)(1+x^2)}, \text{where } \mathrm{x} = \mathrm{r}/\mathrm{r}_0$$

# The Half-Light Radius: $r_{hf}$ or $r_e$



# Best-Fit Burkert Mass Profiles

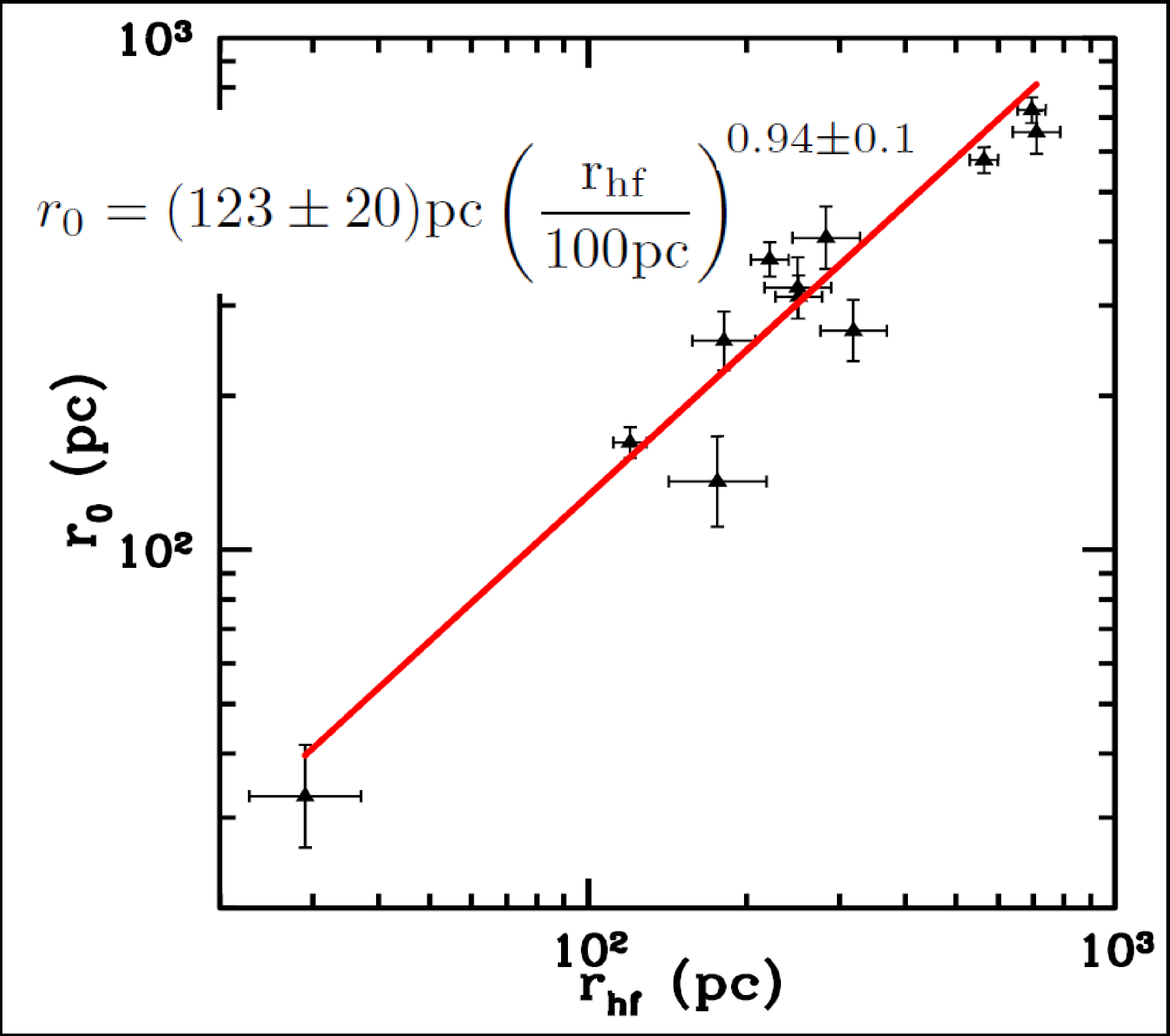



Best-Fit Burkert Profiles

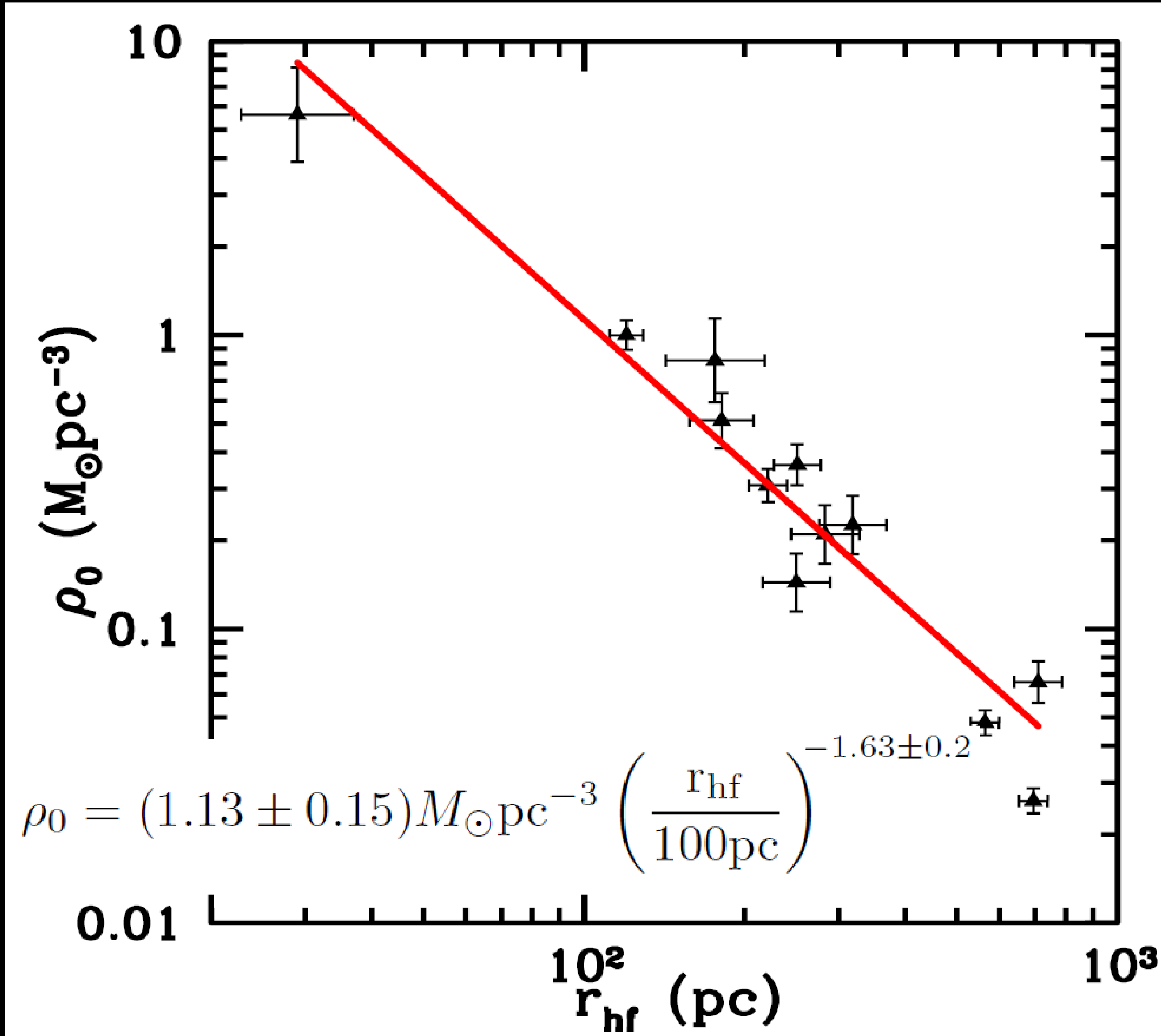
Strigari et al. (2009)

Gerringer-Sameth et al. (2014)

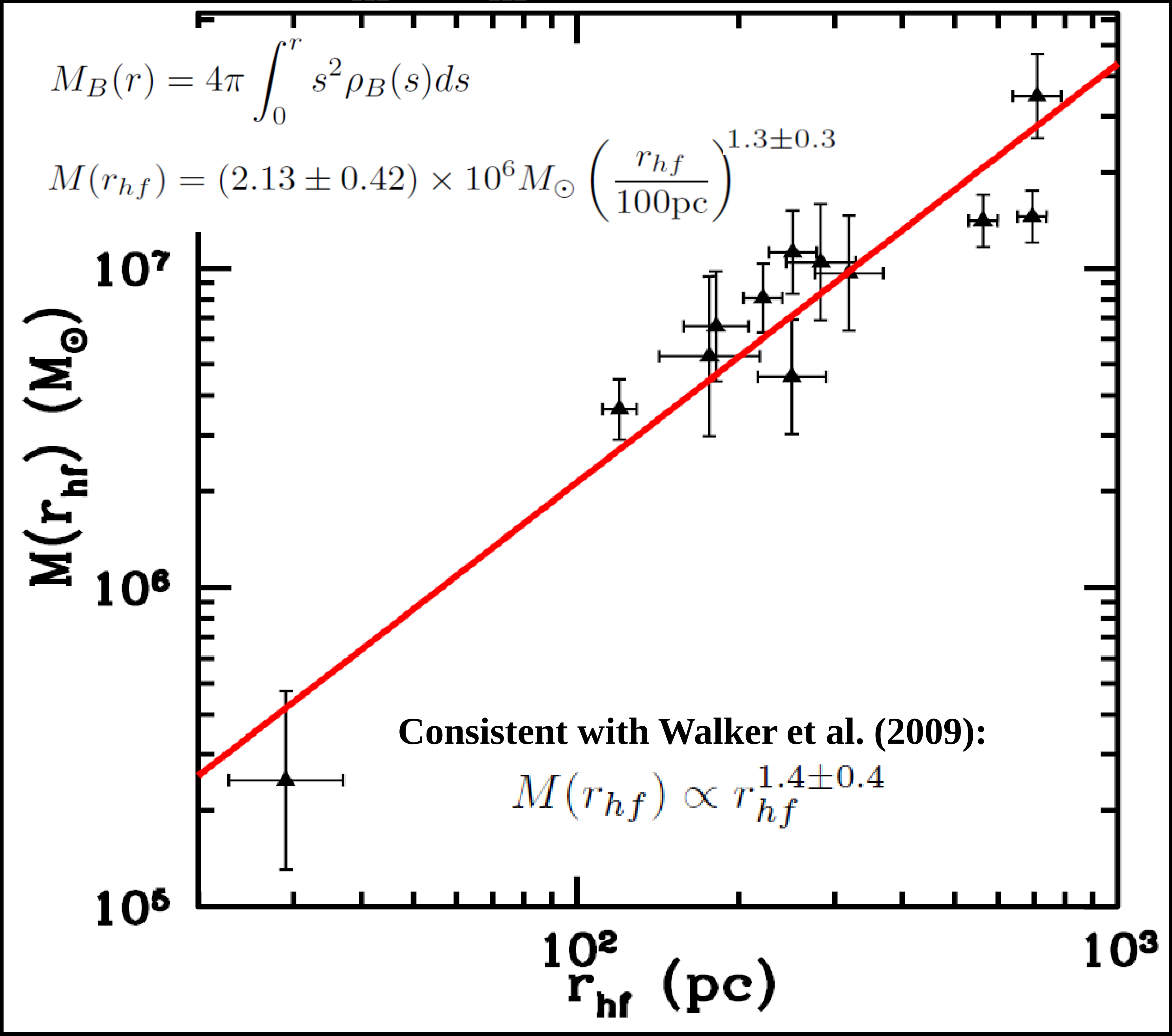
# The $r_0 - r_{hf}$ Correlation:



# The $\rho_0 - r_{hf}$ Correlation:



# The $M_{hf} - r_{hf}$ Correlation Test:



# Phase Space Density Overview I

$$Q \propto \frac{\rho}{\sigma^3}$$

- **For a fermionic thermal relic, Hogan & Dalcanton (2001) find:**

$$Q_{\mathrm{HD}} = \frac{\rho}{(3\sigma^2)^{3/2}} = AQ_* \left(\frac{m}{\mathrm{keV}}\right)^4$$

- **where A = 5 x 10$^{-4}$ and** $Q_* = \frac{M_\odot/pc^3}{(\mathrm{km\ s^{-1}})^3}$
- **adiabatic invariant**
- **strongly mass-dependent**

# Phase Space Density Overview II

- **Hogan & Dalcanton's assume a 1-D velocity disperson.**
- **As in Horiuchi et al. (2014), we assume MB:**

$$Q = \frac{\rho}{(2\pi\sigma^2)^{3/2}} \simeq 0.33 Q_{\mathrm{HD}}$$

$$Q_P = A Q_* \left(\frac{m}{\mathrm{keV}}\right)^4$$

- **where A = 1.65 x $10^{-4}$ and** $Q_* = \frac{M_\odot/pc^3}{(\mathrm{km\ s^{-1}})^3}$

# Connecting the Past to the Present

- **Galaxy formation processes alter Q by an unknown factor Z:**

$$Z = \frac{Q_P}{Q_0}$$

- **De Vega & Sanchez (2010) explored a number of analytical methods to find Z, concluding that**
  - **$1 \leq Z \leq 10^4$, in agreement with simulations**
  - **the mass of a thermal relic DM particle is ~ keV:**

$$\frac{m_{\rm th}}{\rm keV} = \left(\frac{Q_p}{A}\right)^{1/4} = \left(\frac{ZQ_0}{A}\right)^{1/4} \simeq 1 - 10$$

# PSD Goals

1. Determine Z directly from the dwarf galaxy data to produce a model-independent mapping between $Q_p$ and $Q_0$.
2. Use this empirical Z factor to determine the DM particle mass – both for thermal and non-thermal relics.
3. Identify primordial dwarf galaxies – i.e., systems for which $Q_0 \simeq Q_P$.
4. Draw insights from these primordial objects about the formation and evolution of galaxies.

# Dwarf Galaxy Data (Sample)

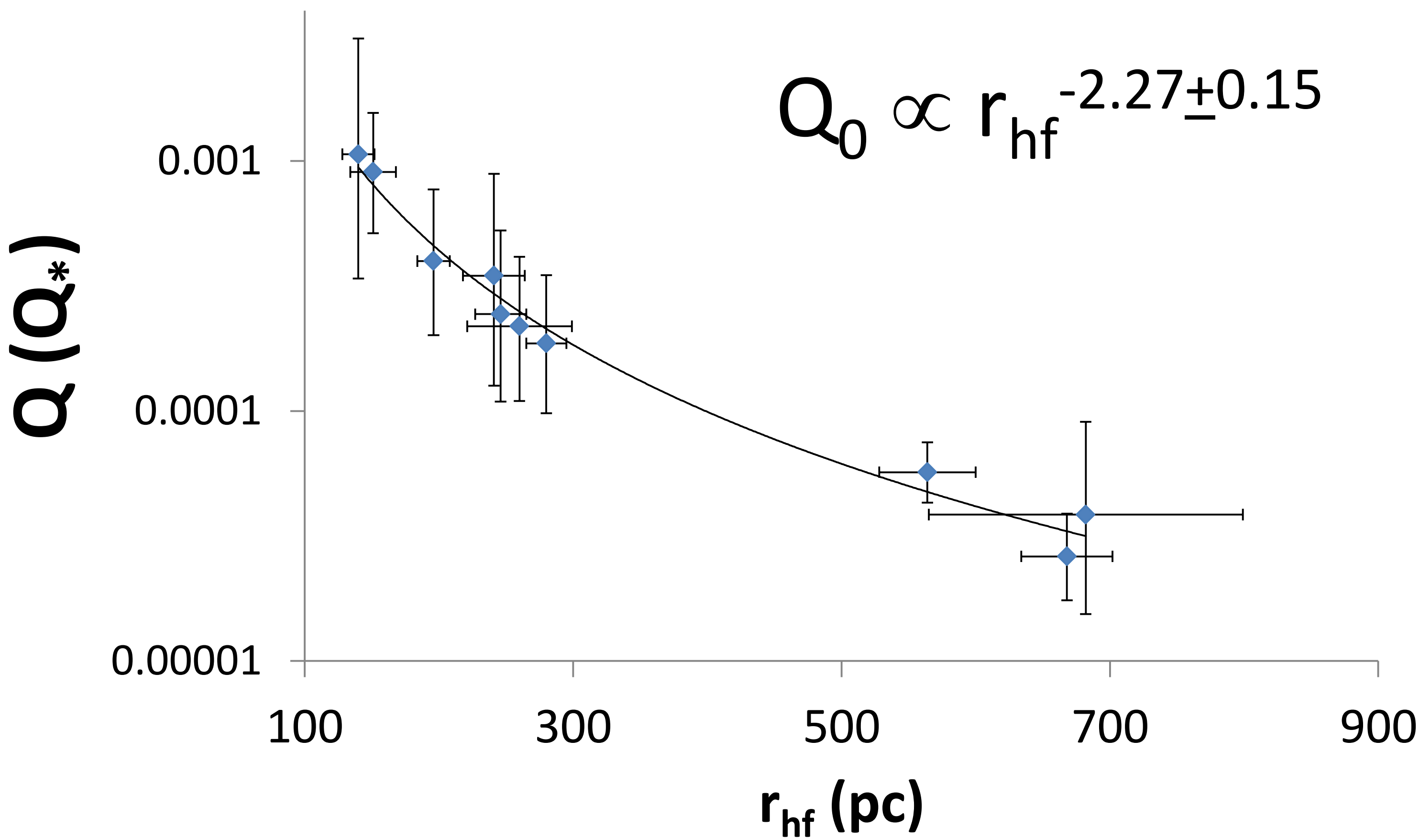
- **Data for 23 dSphs from Walker et. al. (2009)**

| Dwarf | $\sigma$ (km/s) | $\rho$ ($M_\Theta$ pc$^{-3}$) | $r_{hf}$ (pc) | $M(r_{hf})$ ($10^7\ M_\Theta$) |
|---|---|---|---|---|
| Carina | 6.6 ± 1.2 | 0.1 ± 0.04 | 241 ± 23 | 0.61 ± 0.23 |
| Draco | 9.1 ± 1.2 | 0.3 ± 0.08 | 196 ± 12 | 0.94 ± 0.25 |
| Fornax | 11.7 ± 0.9 | 0.042 ± 0.007 | 668 ± 34 | 5.3 ± 0.9 |
| Leo I | 9.2 ± 1.4 | 0.19 ± 0.06 | 246 ± 19 | 1.2 ± 0.4 |
| Leo II | 6.6 ± 0.7 | 0.26 ± 0.06 | 151 ± 17 | 0.38 ± 0.09 |
| Sculptor | 9.2 ± 1.1 | 0.17 ± 0.05 | 260 ± 39 | 1.3 ± 0.4 |
| Sextans | 7.9 ± 1.3 | 0.019 ± 0.007 | 682 ± 117 | 2.5 ± 0.9 |
| U Minor | 9.5 ± 1.2 | 0.16 ± 0.04 | 280 ± 15 | 1.5 ± 0.4 |
| C Ven I | 7.6 ± 0.4 | 0.025 ± 0.003 | 564 ± 36 | 1.9 ± 0.2 |
| U Ma II | 6.7 ± 1.4 | 0.32 ± 0.14 | 140 ± 25 | 0.36 ± 0.16 |

# $Q - r_{hf}$ Power-Law Relation

- **The power-law relations from Walker et al. (2009):**

$$\rho \propto r_{hf}^{-1.6}; \sigma \propto r_{hf}^{0.2} \rightarrow \quad Q \propto \frac{\rho}{\sigma^3} \propto r_{hf}^{-2.2}.$$



# Phase Space Density of the DM

- **$Q_0$ shown in the previous plot is based on *stellar* velocity dispersions, $\sigma_*$.**

- **What about the DM velocity dispersion, $\sigma$?**

- **Simulations show, e.g., Horiuchi et al. (2014)**

$$\eta \ = \sigma/\sigma_* = 1.5 \pm 0.2$$

- **What other constraints are possible?**

# A model for σ:

**Consider an equivalent form of the Jeans Equation for the stars:**

$$\frac{GM(r)}{r} = \langle\sigma_*^2\rangle(\gamma_* - 2\beta_* - \alpha)$$

$$\gamma_* = -d\log\nu/d\log r \qquad \alpha = d\log\langle\sigma_*^2\rangle/d\log r$$

**The LHS is the same for DM, so α must also be the same:**

$$\frac{GM(r)}{r} = \langle\sigma^2\rangle(\gamma - 2\beta - \alpha)$$

$$\gamma = -d\log\rho/d\log r \qquad \alpha = d\log\langle\sigma^2\rangle/d\log r$$

**It follows that:**

$$\frac{\langle\sigma^2\rangle}{\langle\sigma_*^2\rangle} = \frac{(\gamma_* - 2\beta_* - \alpha)}{(\gamma - 2\beta - \alpha)} \longrightarrow \frac{5}{3} \qquad \eta = \sigma/\sigma_* \sim 1.3$$

# Phase Space Density of DM – a model for σ:

**Simulations and observations suggest η ~ constant.**

**What are the implications from the Jeans equation?**

$$\sigma_*^2 = \left(\frac{\rho_*}{\rho^\eta}\right)^{1/\eta - 1} \; ; \quad \sigma^2 = \eta \sigma_*^2$$

$$\sigma_* = \sigma_0 \left( \frac{[(1+x)(1+x^2)]^\eta}{(1+y^2)^{5/2}} \right)^{1/2(\eta-1)} \; ; \quad x = \frac{r}{r_0}, \quad y = \frac{r}{r_{hf}}$$

$$\text{with } \eta = \frac{5 - 2\beta_* - \alpha}{3 - 2\beta \; - \alpha}.$$

**Test 1: agrees with numerical integration of Jeans equation with best-fit Burkert profile.**

# Test 2 for the constant η model:

$$\sigma_* = \sigma_0 \left( \frac{[(1+x)(1+x^2)]^\eta}{(1+y^2)^{5/2}} \right)^{1/2(\eta-1)} \quad ; \quad x = \frac{r}{r_0}, \quad y = \frac{r}{r_{hf}}$$

$$\text{with } \eta = \frac{5 - 2\beta_* - \alpha}{3 - 2\beta \ - \alpha}.$$

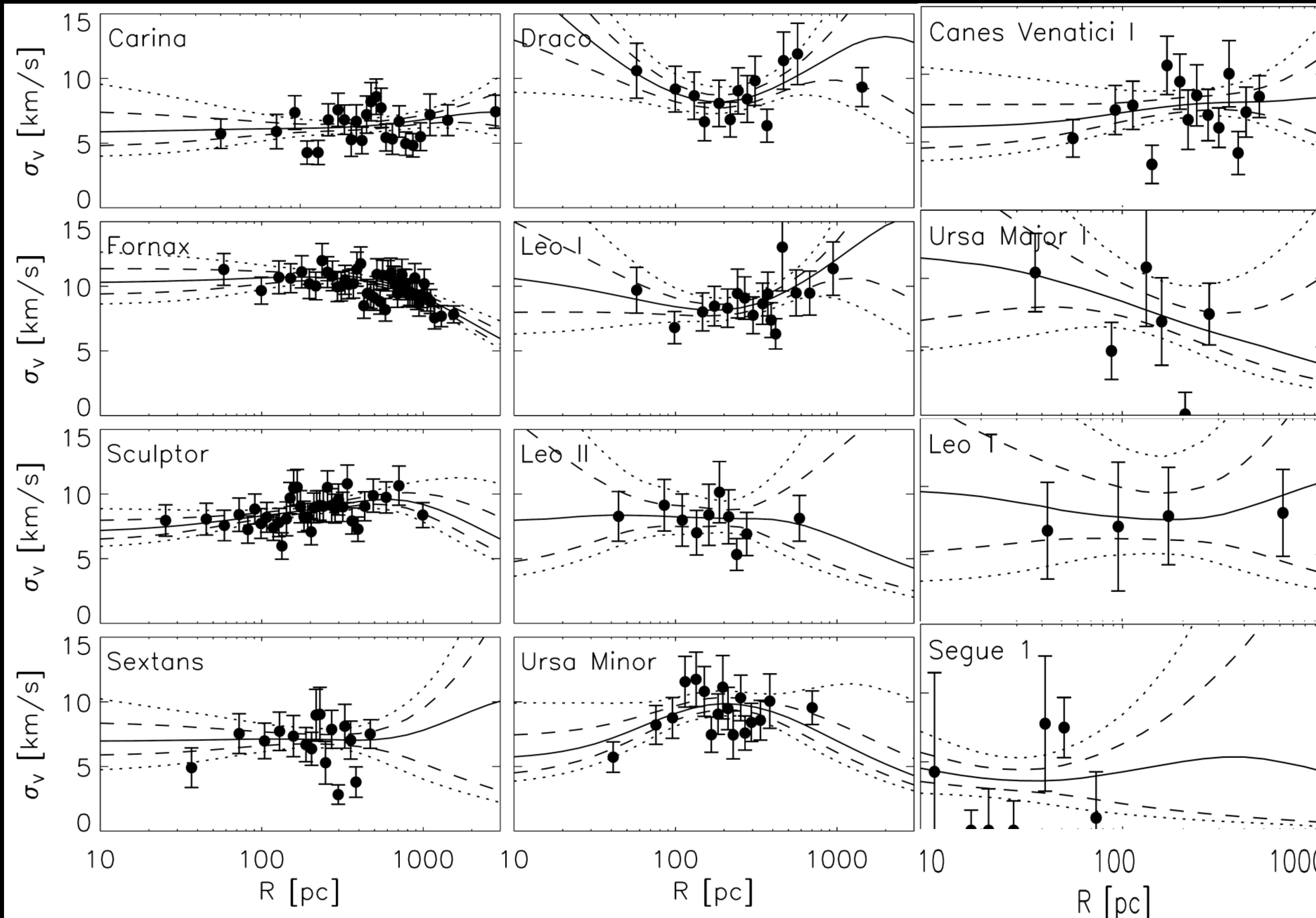
**Find the best-fit results for $\sigma_0$ and $r_0$ for the 12 MW dSphs:**

$$\sigma_0 = (5.2 \pm 1.1) \left( \frac{r_{hf}}{100\text{pc}} \right)^p \quad ; \quad p = (8.7 \pm 0.8) \times 10^{-2}$$

with $\beta = \beta_* = 0,\ \alpha = 0.7 \pm 0.4, \eta = 1.37 \pm 0.1,$

and ***the same*** $r_0$ - $r_{hf}$ relationship found for mass modeling!

# The combination of $\alpha$ and $r_0(r_{hf})$ reproduces all features



# Phase Space Density of the DM

- Based on the constant-η model, we can find $\eta(r_{hf})$ for the dSphs in the Walker et al. (2009) data set.

- Applying this correction factor to $Q_*$, yields

$$Q_{0,\mathrm{DM}} = (1.61 \pm 0.42) Q_* \left(\frac{r_{hf}}{\mathrm{pc}}\right)^{-n}$$

where $n = 2.27 \pm 0.15$ and $Q_* = \frac{M_\odot / pc^3}{(\mathrm{km\ s^{-1}})^3}$

# Using $Q(r_{hf})$ to find Z

- We can rewrite the $Q(r_{hf})$ power-law in terms of:
  - the unknown, primordial $Q_p$

  and

  - an unknown radial scale, $r_p$:

$$Q_0 = Q_P \left( \frac{r_p}{r_{hf}} \right)^n = Q_P / Z_{\rm em}$$

$$Z_{\rm em} = (r_{hf}/r_p)^n$$

- Thus, determining $r_p$ is the key to the empirical Z factor.

# Empirical Upper Limits on $r_P$

**Q can only decrease (Liouville's Theorem), so**

$$Z = (r_{hf}/r_p)^n \geq 1$$

$$r_p \leq r_{hf,min}$$

**Minimum $r_{hf}$ values:**

- **Willman 1: $r_{hf}$ = 25 ± 6 pc**
- **Segue 1: $r_{hf}$ = 29 ± 7 pc**
- **Segue 2: $r_{hf}$ = 34 ± 5 pc**

$$r_p \leq 19 - 39 \text{ pc}$$

# A physical foundation for the $r_{hf}$ correlations

- Consider baryonic infall, e.g., Blumenthal et al. 1986; Ryden & Gunn 1987, etc.
- Begin with pseudo-isothermal profiles for baryons and DM:

$$\rho_{b,i} = \frac{\rho_{b0,i}}{(1+q^2)}; \rho_{d,i} = \frac{\rho_{d0,i}}{(1+q^2)} \quad \ni \frac{\rho_{b0,i}}{\rho_{d0,i}} = \frac{\Omega_{b,0}}{\Omega_{d,0}}; q = \frac{r}{R_{vir}}.$$

- Allow baryons to evolve to a Plummer profile.
- Given $M_i$ $(R_{vir})$ = $M_f$ $(R_{vir})$,

  $M_{tot,\,i}$ – $M_{b,f\,(Plummer)}$ = $M_{d,f}$ matches $M_{d,f\,(Burkert)}$ when we assume $r_0$-$r_{hf}$ and $\rho_0$-$r_{hf}$ correlations.
- Correlations also simultaneously satisfy
  - $r_i M_i(r_i) = r_f M_f(r_f)$ (adiabatic invariant for spherically symmetric systems – e.g., Blumenthal et al. 1986)
  - $L_{i,d}(r_i) = L_{f,d}(r_f)$ (DM angular momentum)

# PART 2: Implications of DGC Observations and $r_{hf}$ correlations for the First Galaxies

# DGC Observations and the First Galaxies

## Dark Globular Clusters (DGCs - Taylor et al., 2015)

- **Recently found in Cen A**

- **Observations suggest they contain a significant amount of DM.**

- **Sizes and masses are intermediate between**

  **DM-free Classical GCs and DM-dominated dSphs**

- **Suggests DGCs and similar compact stellar structures (CSSs – e.g., Janz et al. 2015) may occupy the smallest dark matter halos that can form,**

- **i.e., they could be associated with the free-streaming scale (FSS) and be the fundamental building block of galaxies.**

# Are CSSs just stripped down relics of larger halos?

**Evidence of tidal stripping in CSSs:**

- **Directly observered tidal streams of stars (Huxor et al. 2013; Foster et al. 2014; Jennings et al. 2015)**
- **SMBHs expected for higher mass galaxies (Kormendy et al. 1997; Seth et al. 2014)**
- **Stellar populations like those of more massive galaxies (e.g. Chilingarian et al. 2009; Francis et al. 2012; Sandoval et al. 2015).**

**Evidence that CSSs are *not* tidally stripped remnants:**

- **Follow high mass extrapolations of GC luminosity function (LF) in galaxies with sufficiently rich GC populations (e.g. Fellhauer & Kroupa 2005; Hilker 2006; Norris & Kannappan 2011; Mieske et al. 2012).**
- **Some cEs follow low-mass extrapolations of the Ell. Galaxy LF (Kormendy et al. 2009)**
- **UCDs and cEs are found in all environments - from the field to dense clusters ((Norris & Kannappan 2011; Huxor et al. 2013; Paudel et al. 2014; Norris et al. 2014; Chilingarian & Zolotukhin 2015)**

**We will consider the origin of the latter objects – associating them with the $M_{fs}$ and the first, lowest mass galaxies.**

# DGCs and the Free-streaming mass scale: $M_{fs}$

## Observed DGC Masses in Cen A:

- **Range:** $5 \times 10^5 < M/M_\odot < 5 \times 10^6$ **; median** $\sim 10^6 M_\odot$

- **Simulations suggest tidal stripping removes 80-90% of original mass of small halos - e.g., Wang et al. (2015)**

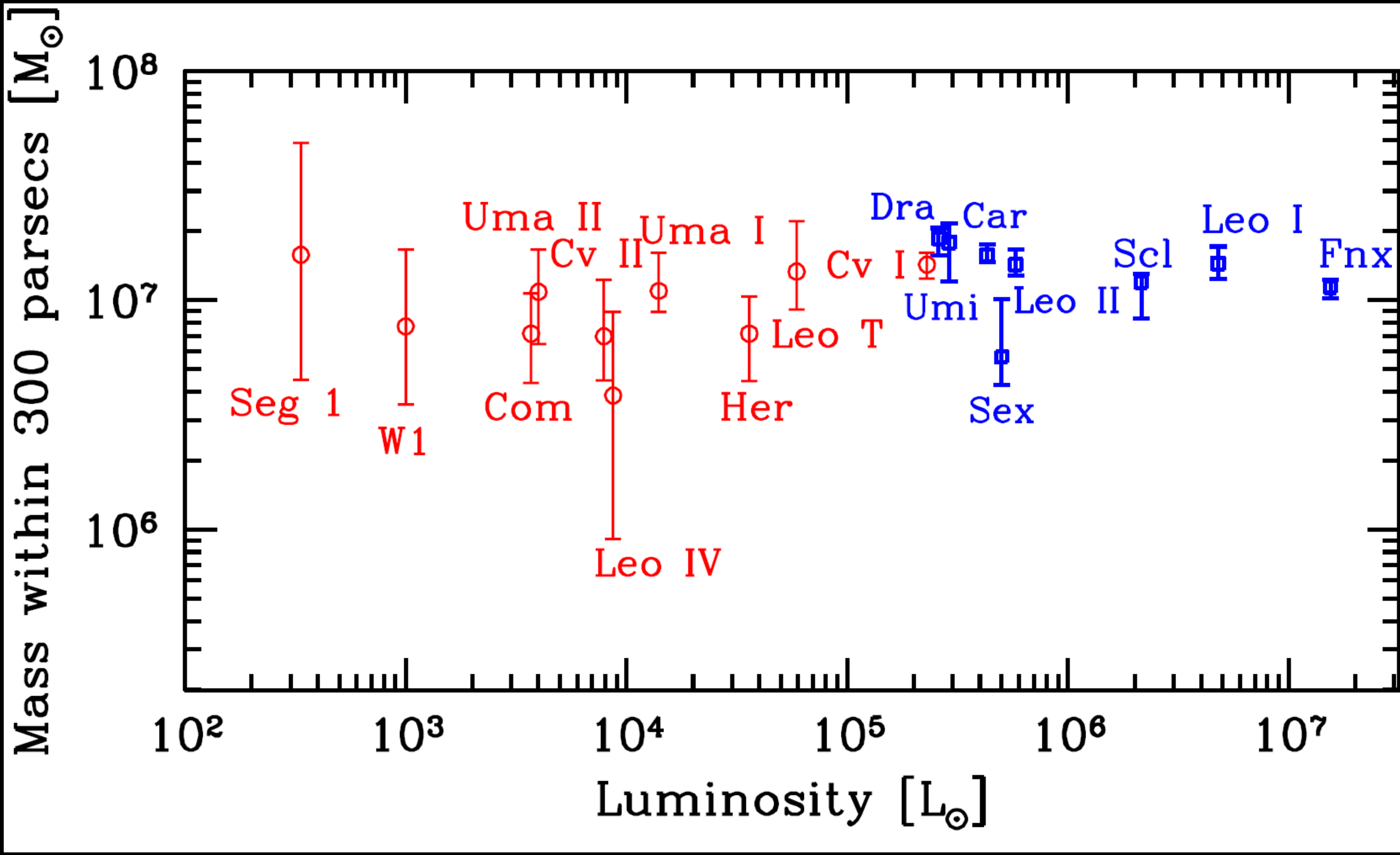
## Inferred Original/Peak Masses:

- **Range:** $5 \times 10^6 < M/M_\odot < 2.5 \times 10^7$ **; median** $\sim 10^7 M_\odot$

**If $M_{fs} \sim 10^7$ $M_\odot$, $10^7$ $M_\odot$ should be a special scale.**

**Strigari et al. (2009) found M(300 pc) $\simeq$ (0.4-2.0) x $10^7$ $M_\odot$ for 18 MW dSphs, despite variations of up to $10^6$ in luminosity.**

# Strigari et al. 2009 Results



# Analysis of the Free-Streaming Scale (FSS):

$$\lambda_{fs} = \frac{0.107\mathrm{Mpc}}{(1+z)} \left(\frac{\Omega_{m,0}h^2}{0.1371}\right)^{1/3} \left(\frac{m_{\mathrm{th}}}{\mathrm{keV}}\right)^{-4/3}$$

$$\begin{aligned} M_{fs} &= 4/3\pi\rho_{0,m}(1+z)^3 \left(\frac{\alpha\lambda_{fs}}{2}\right)^3 \\ &= 2.0 \times 10^8 M_{\odot} \left(\frac{\alpha}{2}\right)^3 \left(\frac{m_{\mathrm{th}}}{\mathrm{keV}}\right)^{-4}, \end{aligned}$$

**where $\alpha\lambda_{fs}/2$ is the scale at which significant suppression of galaxy formation occurs.**

**For $M_{fs} = (0.4 – 2.0) \times 10^7\ M_{\odot}$ , we find**

$$m_{\mathrm{th}} = 2.12^{+0.55}_{-0.34} \left(\frac{\alpha}{2}\right)^{3/4} \mathrm{keV}$$

**For $\alpha \sim 2$, $m_{th} \sim 2$ keV - as in many other studies (see conclusions).**

# Collapse Redshift of the First Galaxies

**Set $M_{fs} = M_{vir}$**

$$M_{\rm vir} = 4/3\pi(200\rho_{0,m}(1+z_{\rm coll})^3)R_{\rm vir}^3$$

**Choosing $R_{vir}$ = 300 pc, we find**

$$1 + z_{\rm coll} = 22 \pm 6$$

***This result is independent of $\alpha$.***

# Internal Properties of the First Halos – $r_{hf,fs}$

**Assume baryonic infall will lead to the same $r_{hf}$ correlations in the first galaxies:**

$$r_0 = (123 \pm 20)\mathrm{pc}\left(\frac{r_{hf}}{100\mathrm{pc}}\right)^{0.94\pm0.1}$$

$$\rho_0 = (1.13 \pm 0.15) M_\odot \mathrm{pc}^{-3}\left(\frac{r_{hf}}{100\mathrm{pc}}\right)^{-1.63\pm0.2}$$

**Integrate $\rho_{Burkert}(\rho_0, r_0)$ to $R_{vir}$ = 300 pc and set $M_{vir} = (1.0 \pm 0.3) \times 10^7\ M_\Theta$:**

$$M_{\mathrm{vir,B}}(r) = 4\pi \int_0^{R_{\mathrm{vir}}} r^2 \rho_B(r) dr$$
$$= \pi \rho_0 r_0^3 \left(\ln[(1 + c_{\mathrm{vir}}^2)(1 + c_{\mathrm{vir}})^2] - 2\arctan(c_{\mathrm{vir}})\right),$$

**where $c_{vir} = R_{vir}/r_0$.**

**Now, $M_{vir} = M_{vir}(r_{hf})$.**

# Internal Properties of the First Halos – $r_{hf,fs}$

**Solving $M_{vir} = M_{vir}(r_{hf})$ for $r_{hf,fs}$, we find:**

$$r_{hf,fs} = 40^{+37}_{-21}\mathrm{pc}$$

**Applying the $\rho_0(r_{hf})$ and $r_0(r_{hf})$ correlations yields:**

$$r_{0,fs} = 51^{+45}_{-22}\mathrm{pc}, \quad \rho_{0,fs} = 5.1^{+8.1}_{-3.4} M_\odot \mathrm{pc}^{-3}$$

$$c_{\rm vir} = R_{\rm vir}/r_0 = 5.8^{+4.3}_{-2.7}$$

# Associate $r_{hf,fs}$ with $r_P$ to find PSD mass limits

Recall $r_p \leq r_{hf,min}$

**Maximum $r_p$ values:**

– Willman 1: $r_{hf} = 25 \pm 6$ pc

**Sets ceiling on $r_{hf,\,fs}$:**

$$r_{hf,fs} = 40^{+37}_{-21}\mathrm{pc}.$$

**Limits on $r_p$:**

$$r_p = 25 \pm 6 \ \mathrm{pc}$$

# $Q_p$ + DM Particle Mass with $r_p = 25 \pm 6$ pc

- Max/Min $Q_0$ ratio is ~ $10^4$
- Max/Min $Q_p$ differ by ~ 4.5

$$Q_P = Z_{em} Q_0$$

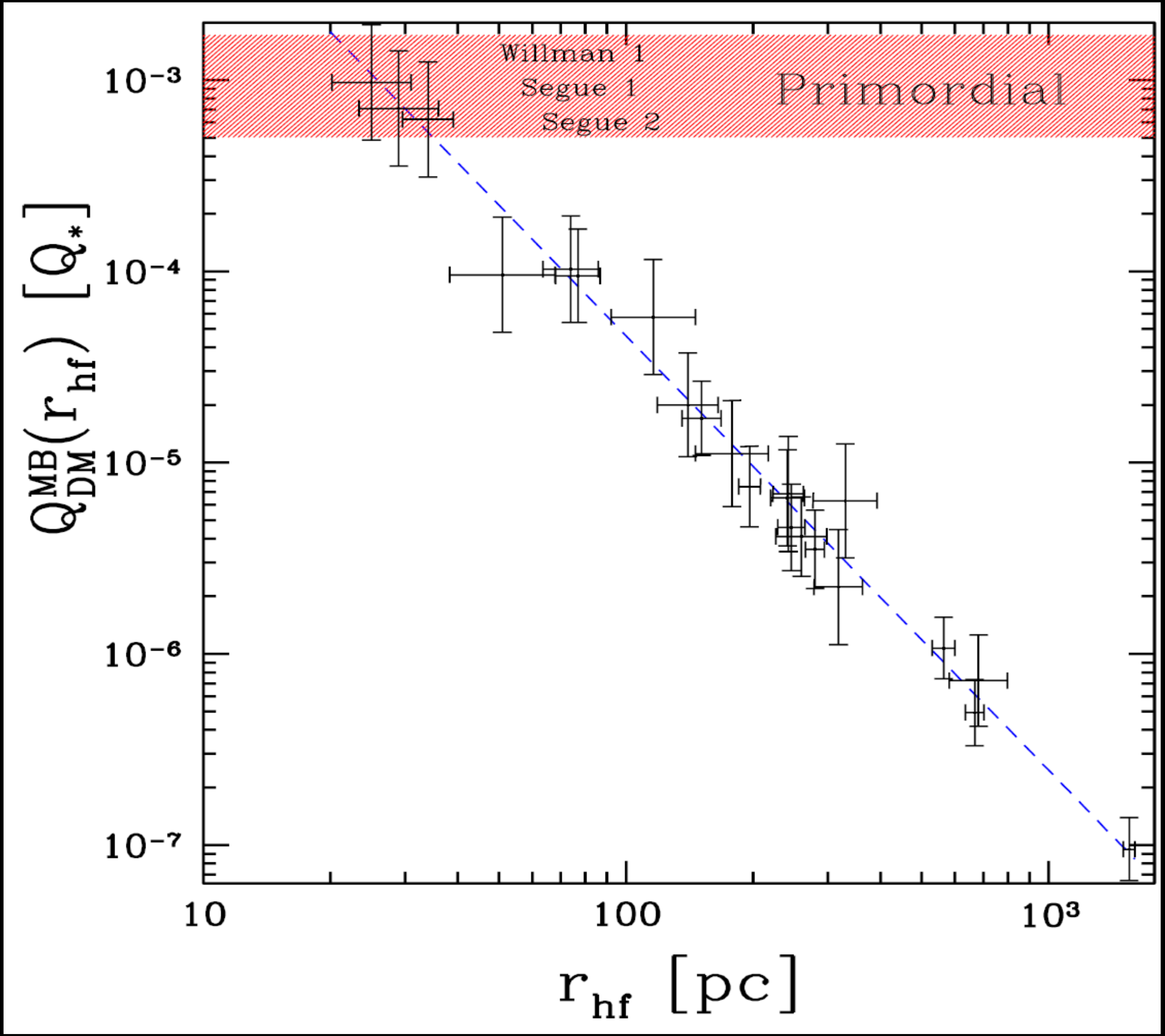
- Max/Min $m_{th}$ values differ by ~ 1.5

$$\frac{m_{\rm th}}{\rm keV} = \left(\frac{Z_{\rm em} Q_0}{A}\right)^{1/4} = \left(\frac{\left(\frac{r_{hf}}{r_p}\right)^n Q_0}{A}\right)^{1/4}$$

**Including all galaxy data uncertainties**

- $1 < Z < 10^4$
- $m_{\rm th} = 2.02 \pm 0.35$ keV

# PSD of DM



Willman 1
Segue 1
Segue 2
Primordial
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$Q_{DM}^{MB}(r_{hf})$ [$Q_*$]
10
100
$10^3$
$r_{hf}$ [pc]

# Internal Properties of the First Halos Refined

**With the refined limits on $r_{hf,fs}$ from the PSD analysis:**

$$r_{hf,fs} = 25 \pm 6\mathrm{pc}.$$

**Limits on $r_0(r_{hf})$, $\rho_0(r_{hf})$, and $c_{vir}$ now become:**

$$r_{0,fs} = 33.3 \pm 7.6\mathrm{pc},$$
$$\rho_{0,fs} = 10.7^{+6.0}_{-3.2} M_\odot \mathrm{pc}^{-3},$$
$$c_{\mathrm{vir,fs}} = R_{\mathrm{vir,fs}}/r_{0,fs} = 9.0 \pm 2.7$$

# Final Refinement – constraints from simulations

**For the 12 MW dSphs in our sample, we can use velocity dispersion data and the $r_{hf}$ correlations to explore:**

$$z_{\rm coll},\ M_{\rm vir},\ \text{and}\ c_{\rm vir}(M_{\rm vir}, z_{\rm coll})$$

**Compare to $c_{vir}(M_{vir}, z_{coll})$ found in the best simulations, e.g., Prada et al. (2011).**

**We find statistically self-consistent results for**

$$c_{\rm vir}(M_{\rm vir}, z_{\rm coll}) = 10.2 \pm 1.1$$

# Tightest Constraints on the First Halos

**With** $c_{\rm vir,fs} = 10.2 \pm 1.1$ **and** $r_{0,fs} = R_{\rm vir,fs}/c_{\rm vir,fs}$**,**

**we find**

$$r_{0,fs} = 29.3 \pm 3.5\mathrm{pc}.$$

$$r_{hf,fs} = 22 \pm 2.6\mathrm{pc}$$

$$\rho_{0,fs} = 13.4 \pm 2.6 M_\odot \mathrm{pc}^{-3}$$

**And applying the refined $r_{hf,fs}$ to the PSD data yields:**

$$m_{\rm th} = 2.19 \pm 0.35 \ \mathrm{keV}$$

# Galaxy Constraints Satisfied by 2 keV Thermal Dark Matter Particle (Abazajian 2014)

- **Local Group Phase Space Density and Subhalo Counts:**

  $m_{th} > 1.7$ keV (Horiuchi et al. 2014), $m_{th} \sim 2$ keV (de Vega & Sanchez 2010.12)

- **High Redshift Galaxy Counts:**

  $m_{th} > 1.3$ keV (Schultz et al. 2014)

- **Abundance, Radial Distribution, and Inner Density Profile Crises of Milky Way Satellites solved if:**

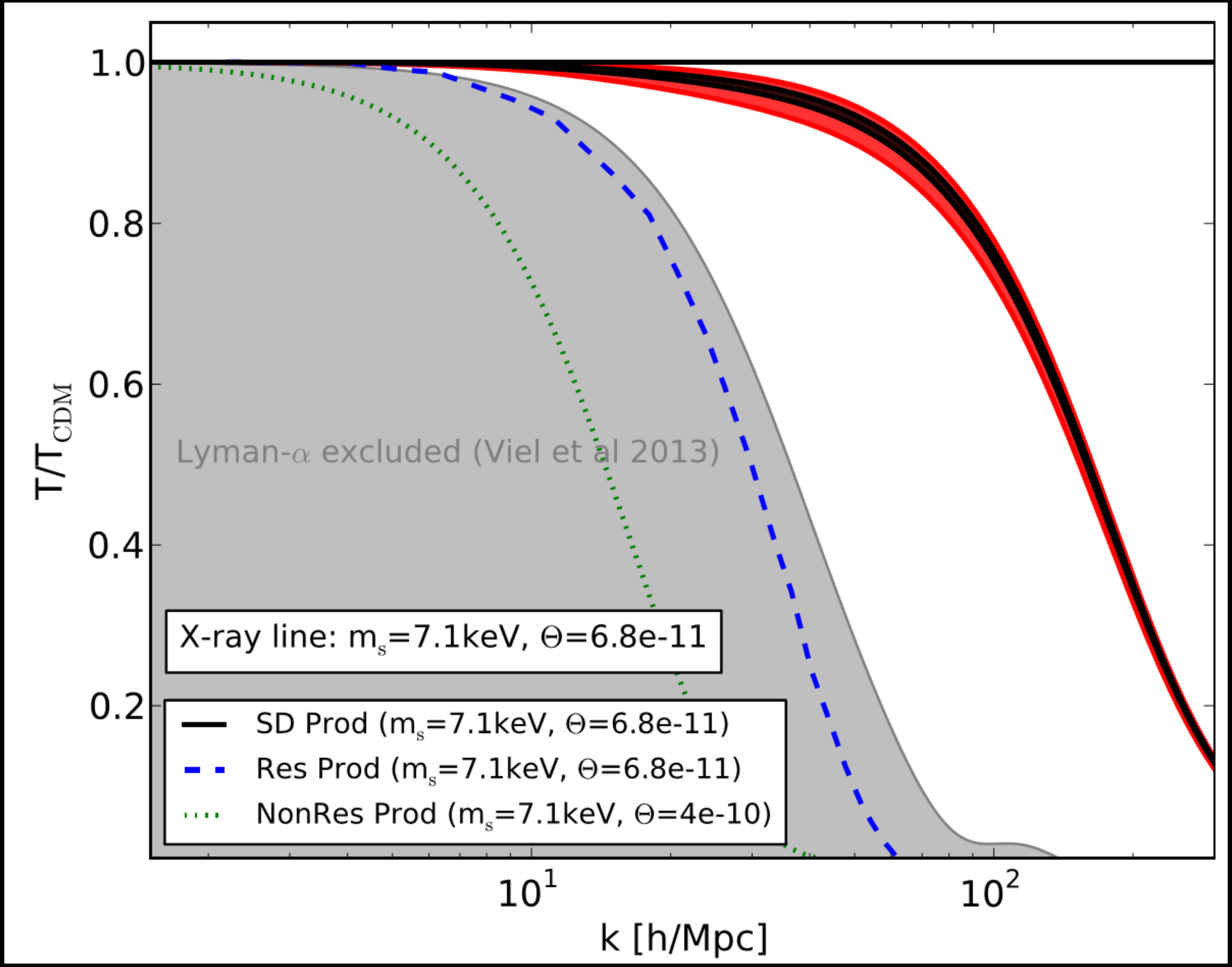
  $m_{th} \simeq 2$ keV (e.g., Lovell et al. 2012 and Abazajian 2014 for additional references)

- **A *non*-thermal particle can produce similar LSS:**
- **For instance, a 7.14 keV Shi-Fuller $\nu_s$ with $L = 7 \times 10^{-4}$**

  **behaves like $m_{th} \simeq 2$ keV.** (Abazajian 2014 )

# $\nu_s$ Transfer Functions II: Ly$\alpha$ Constraints

## Scalar Decay, Shi-Fuller, DW (Merle & Schneider 2014)



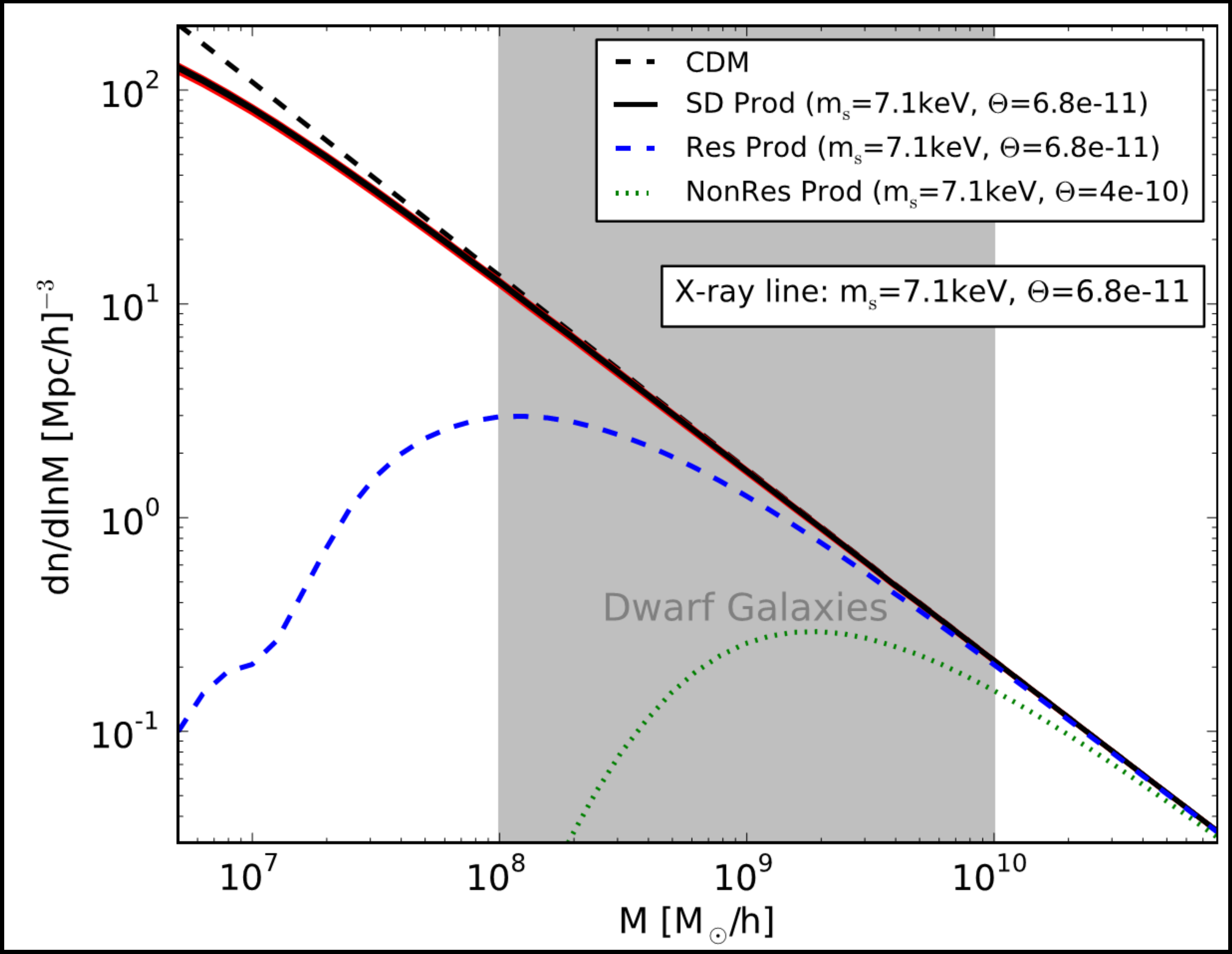

SD

SF

DW

# $\nu_s$ Halo Mass Function:

## Scalar Decay, Shi-Fuller, DW (Merle & Schneider 2014)




SD

SF

DW

# Summary and Conclusions

## Observational Trends for MW dSphs:

- **Mass Modeling via velocity dispersion data**
  - **Determined best-fit Burkert halo parameters ($r_0$, $\rho_0$) for 12 MW dSphs**
  - **Found strong correlations between the half-light radii ($r_{hf}$) and $r_0$ and $\rho_0$**
- **Phase Space Density measurements**
  - **$r_{hf}$ correlations also found for stellar PSDs.**
  - **Constant $\eta = \sigma_{DM}/\sigma_*$ model for $\sigma_{DM}$ obeys same $r_0$-$r_{hf}$ correlations**
  - **Determined PSD of DM**

## Discussed foundation for the $r_{hf}$-$r_0$ & $r_{hf}$-$\rho_0$ correlations:

- **Baryonic infall & adibatic compression of DM**

## Applied $r_{hf}$ correlations to study the first galaxies:

- **Interpretted *some* DGCs/CSSs as the lowest mass halos (FSS)**
  - **Suggests ~ $10^7$ $M_\Theta$ is the fundamental building block of galaxies (FSS)**

## Resulting FSS, LSS, & PSD limits all point to $m_{DM,thermal}$ ~ 2 keV.

# Non-thermal DM

- If the DM particle is a sterile neutrino, we can use the following transformation equations (e.g., Viel et al. 2005; Abazajian 2014) to find the corresponding non-thermal limits:

$$m_{s,\mathrm{DW}} = 4.27\mathrm{keV}\left(\frac{\mathrm{m_{th}}}{\mathrm{keV}}\right)^{4/3}\left(\frac{\Omega_{\mathrm{m,0}}\mathrm{h}^2}{0.1371}\right)^{-1/3} \simeq 1.5 m_{s,\mathrm{SF}}$$

- Applying these transformations, we find:

2.9 < m/keV < 22.1 (Dodelson-Widrow) X (Watson et al. 2012)

1.9 < m/keV < 14.7 (Shi-Fuller) Bulbul et al. (2014) OK

- Alternative transformations (deVega & Sanchez 2013):

$$m_\nu^{\mathrm{DW}} = 2.85\mathrm{keV}\left(\frac{m_{\mathrm{th}}}{\mathrm{keV}}\right)^{4/3};\, m_\nu^{\mathrm{SF}} \cong 2.55 m_{th}$$

1.9 < m/keV < 14.7 (Dodelson-Widrow) X (Horiuchi et al. 2014)

1.9 < m/keV < 8.6 Shi-Fuller Bulbul et al. (2014) OK