Dark Matter and Dwarf Galaxies: Evidence for a threshold mass in galaxy formation?

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UNIVERSITY OF CALIFORNIA, IRVINE

13th Paris Cosmology Colloquium
July 24, 2009

Collaborators

Manoj Kaplinghat (UC,Irvine)
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Marla Geha (Yale)
Josh Simon (Carnegie Obs)
Beth Willman (Haverford)

Greg **Martinez**

Erik **Tollerud**

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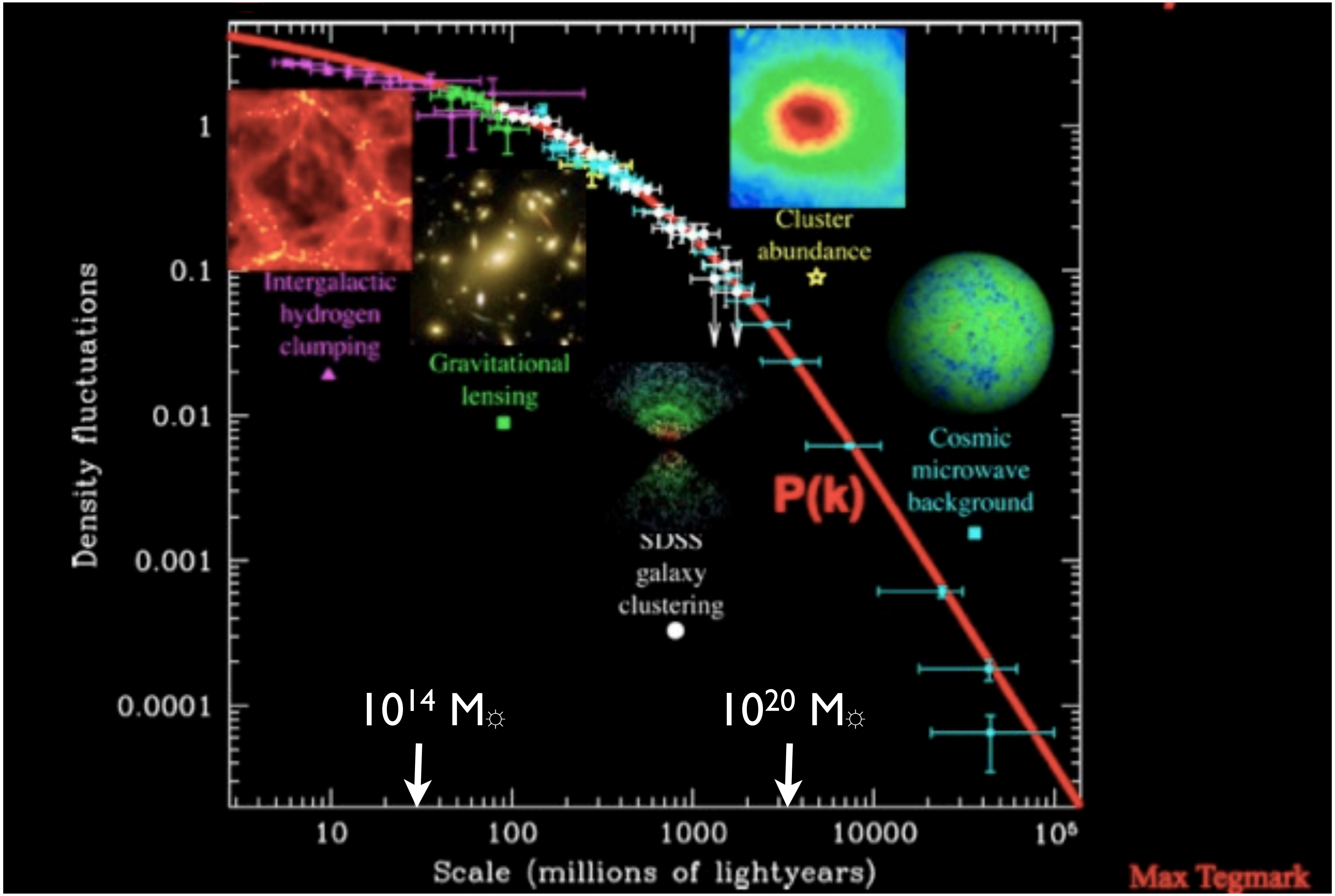
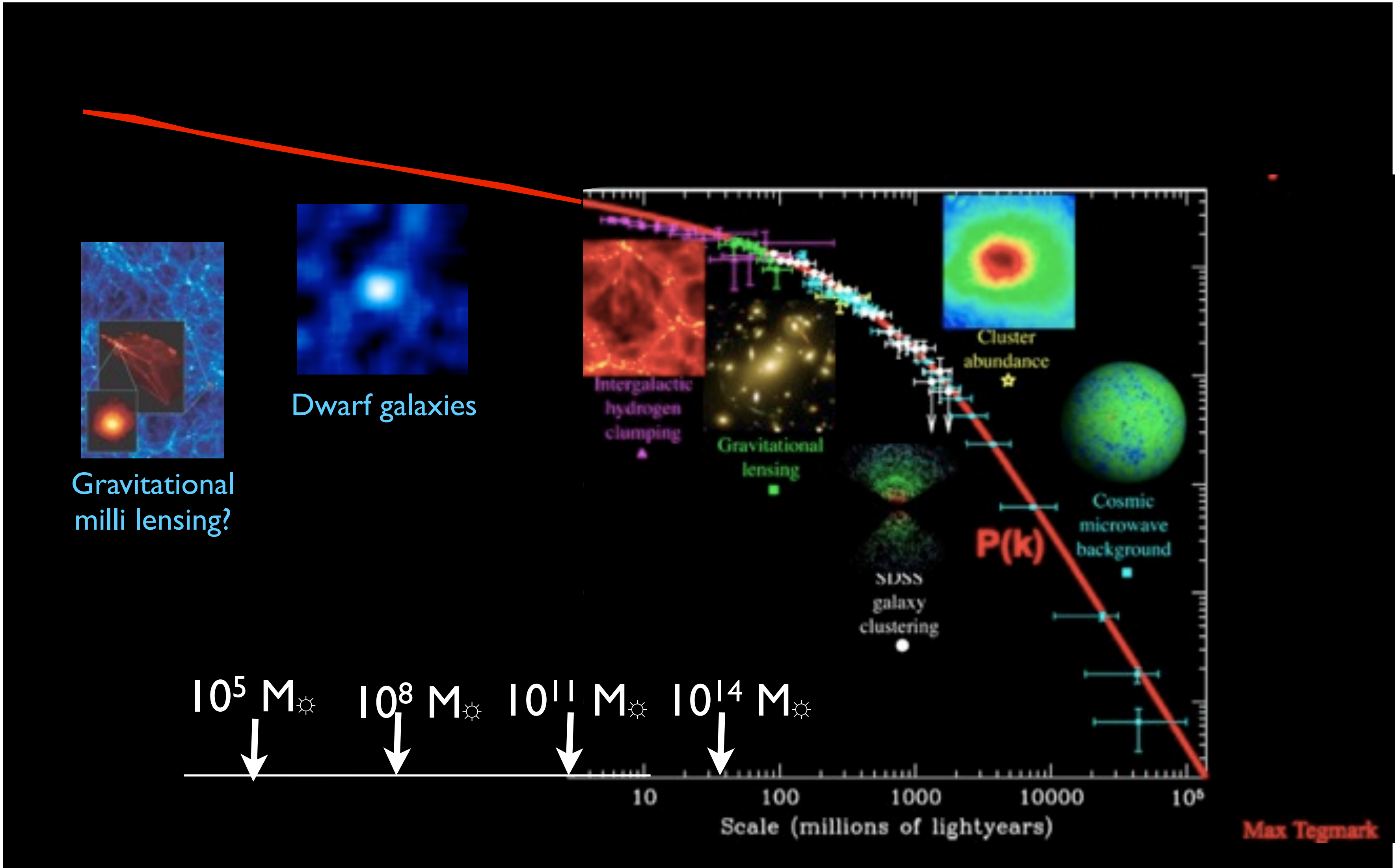
Plan of Talk

- **Motivation: Why dwarf spheroidal galaxies?**
- **How Many? -- Hundreds of Galactic Satellites?**
- **How Massive? -- A minimum mass for galaxy formation?**
- **Dark Matter Laboratories -- Indirect detection of DM**

Large-Scales: looks like CDM + Dark Energy



What about smaller scales?



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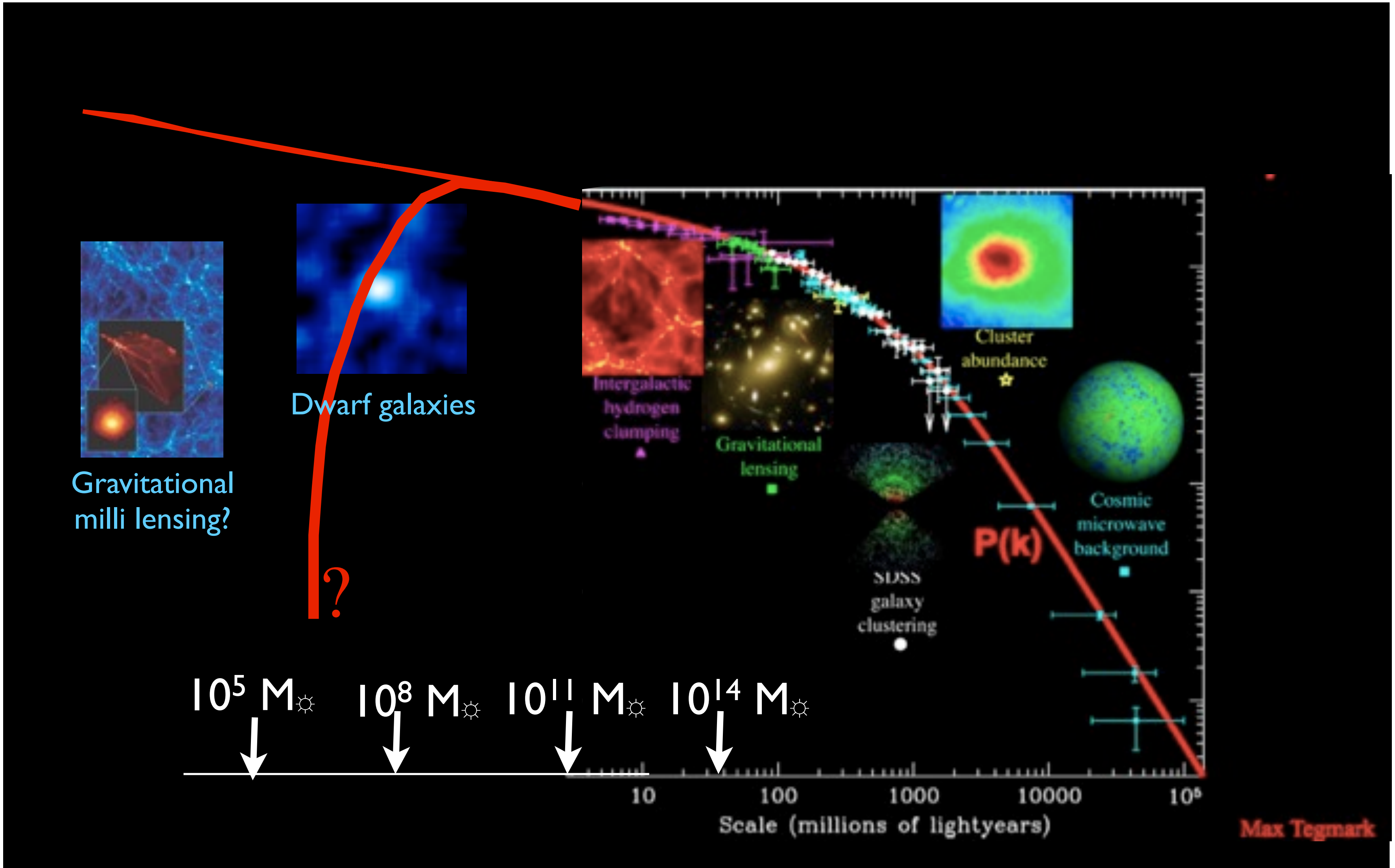


Dwarf Satellites of MW: Best DM Labs in the Universe

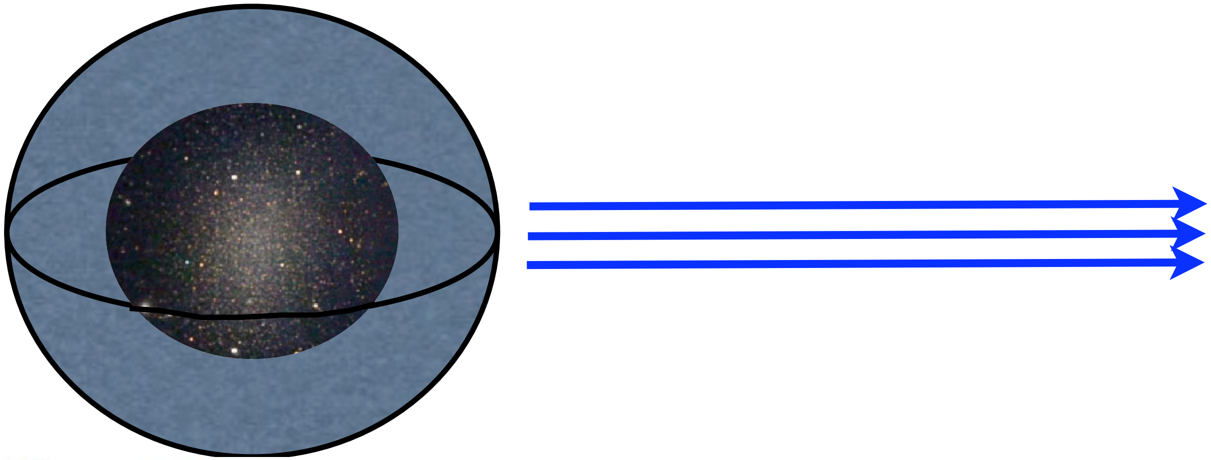
$$L \sim 10^5 - 10^6 L_\odot$$

$$M/L \sim 100$$

1. Dark Matter Dominated => Easy to interpret
2. Proximity (~100 kpc) => Individual Stellar Kinematics
3. Intrinsically high phase-space densities => Constrain WDM

dSphs ideal for SUSY-DM indirect detection

Virtually no astrophysical backgrounds



$$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \rightarrow \gamma + \gamma$$

Fermi

MW Dwarfs:
Galaxy formation in the extreme

$$M_{\rm vir} \sim 10^9 M_\odot$$

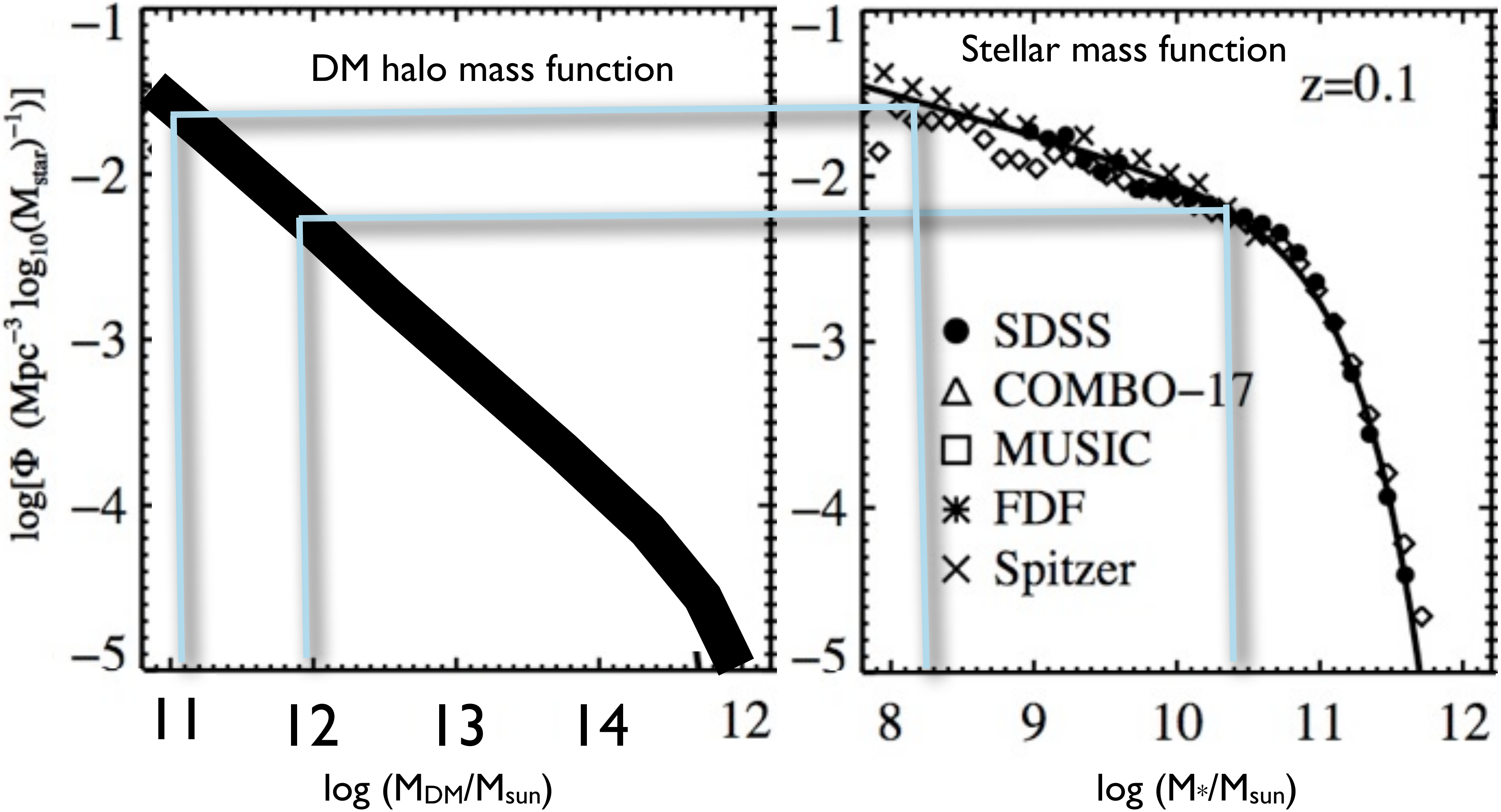
1. Low Mass ⇒ Early Forming

-- probes of early-collapse (low-mass) objects

2. Small number count

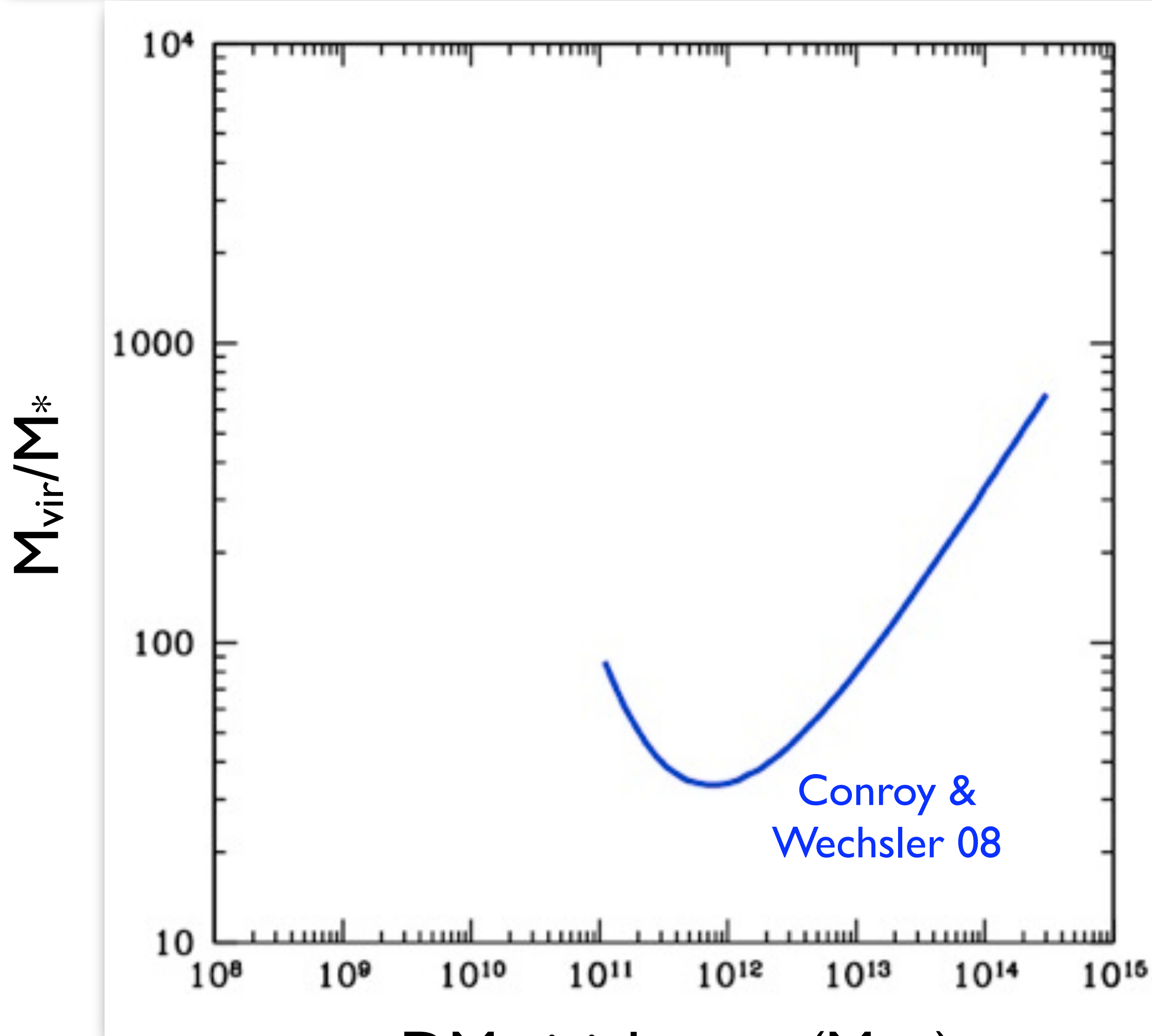
-- constrains nature of early/reionization star formation.

Given LCDM, we know galaxy formation is not efficient in small halos



compilation by Conroy & Wechsler 08

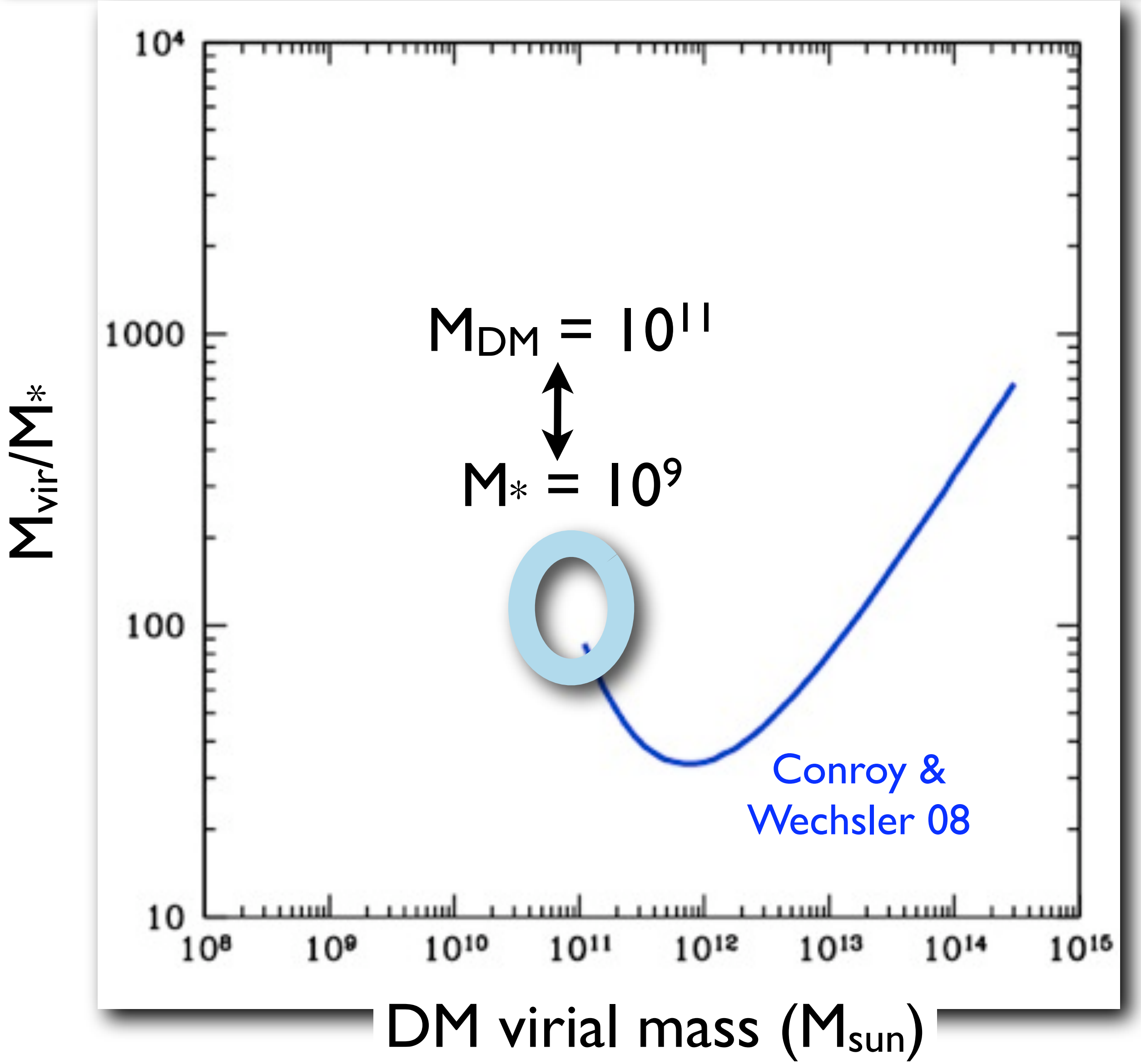
LCDM + Efficiency of Galaxy Formation



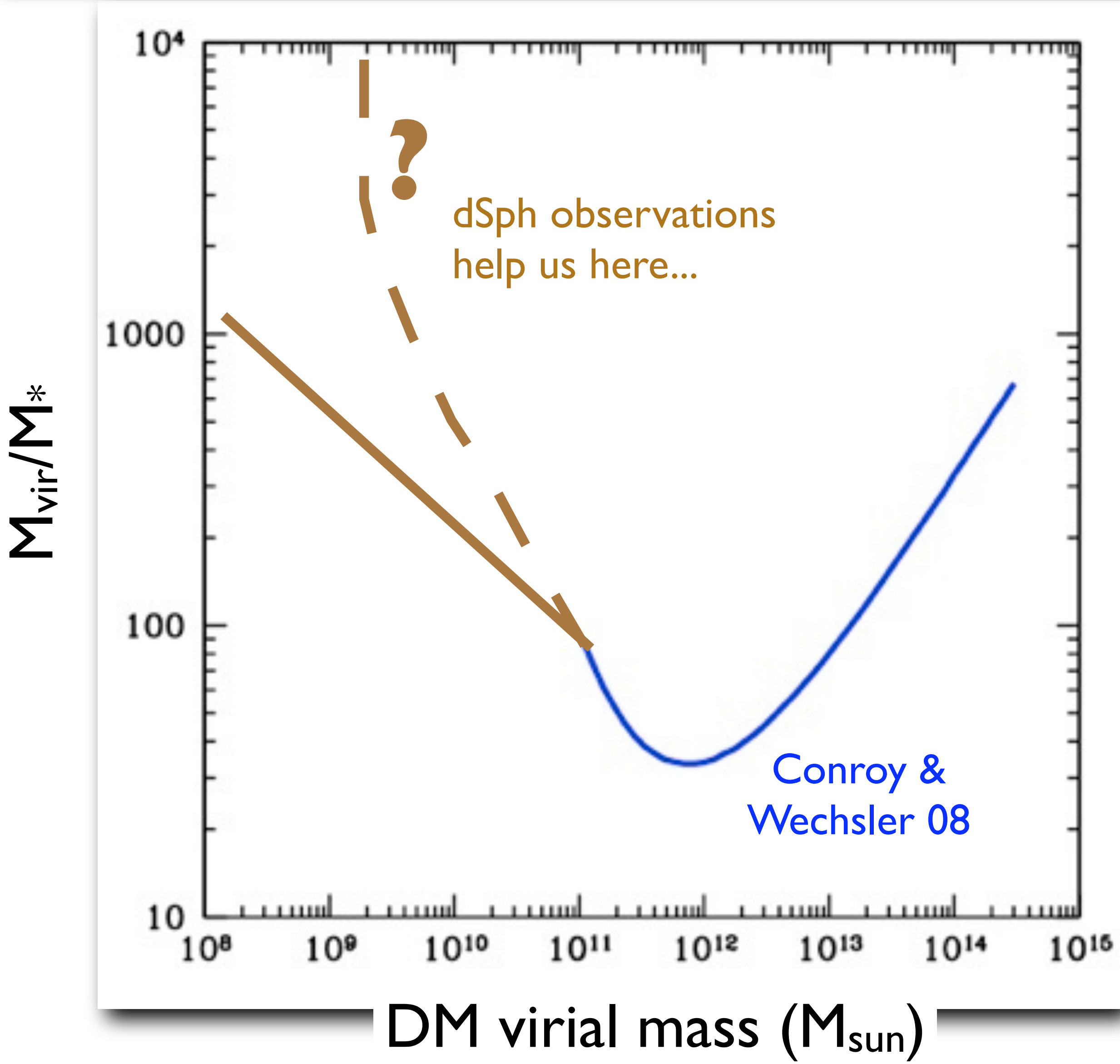
DM virial mass (M_{sun})

see also
van den Bosh et al. 03
Yang et al. 03
Kravtsov et al. 04
...
Purcell et al. 07

What is efficiency of galaxy formation in smallest halos?



What is efficiency of galaxy formation in smallest halos?



Milky Way circa 2004

11 Dwarf Satellites

Name	Year Discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
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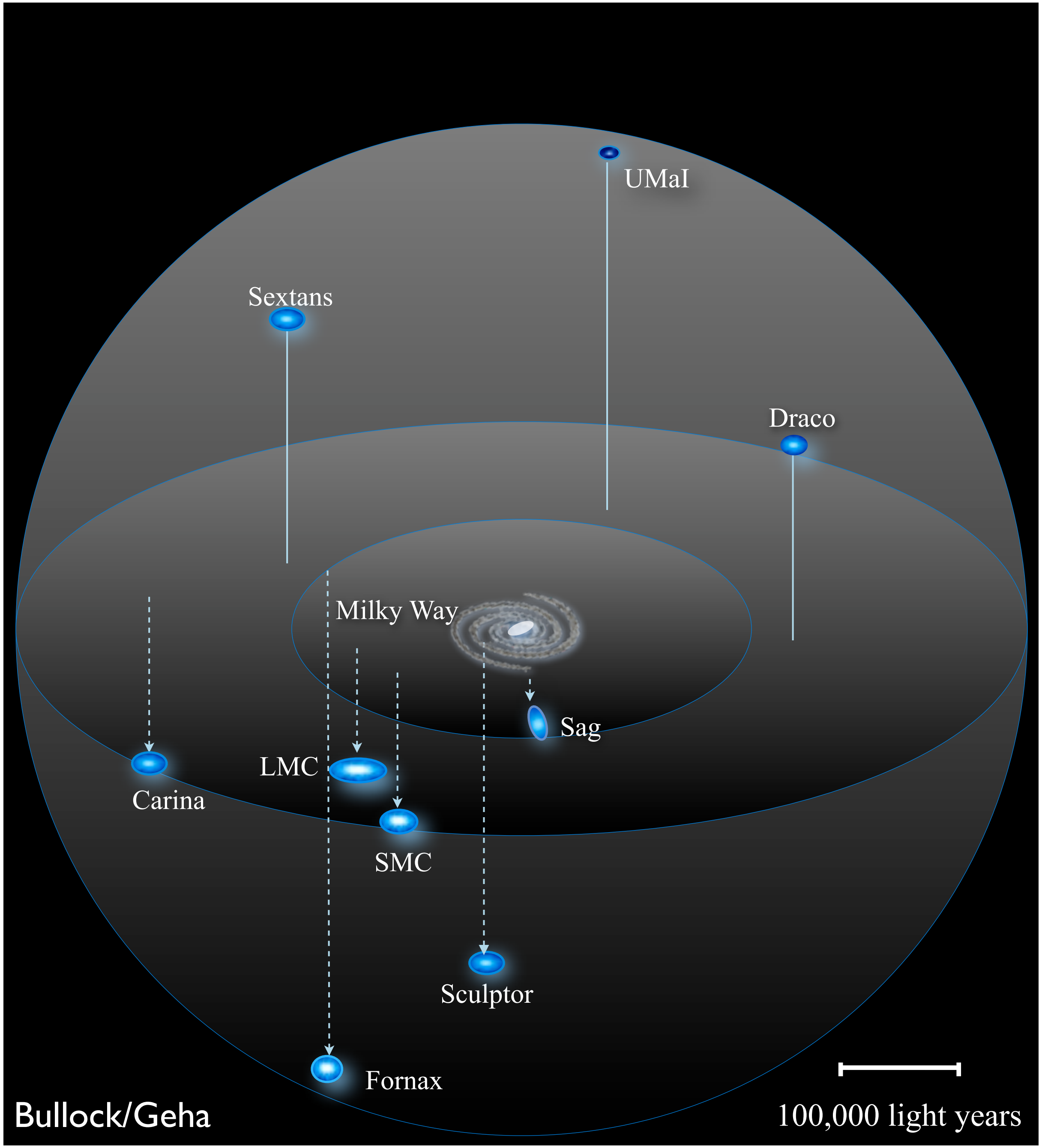

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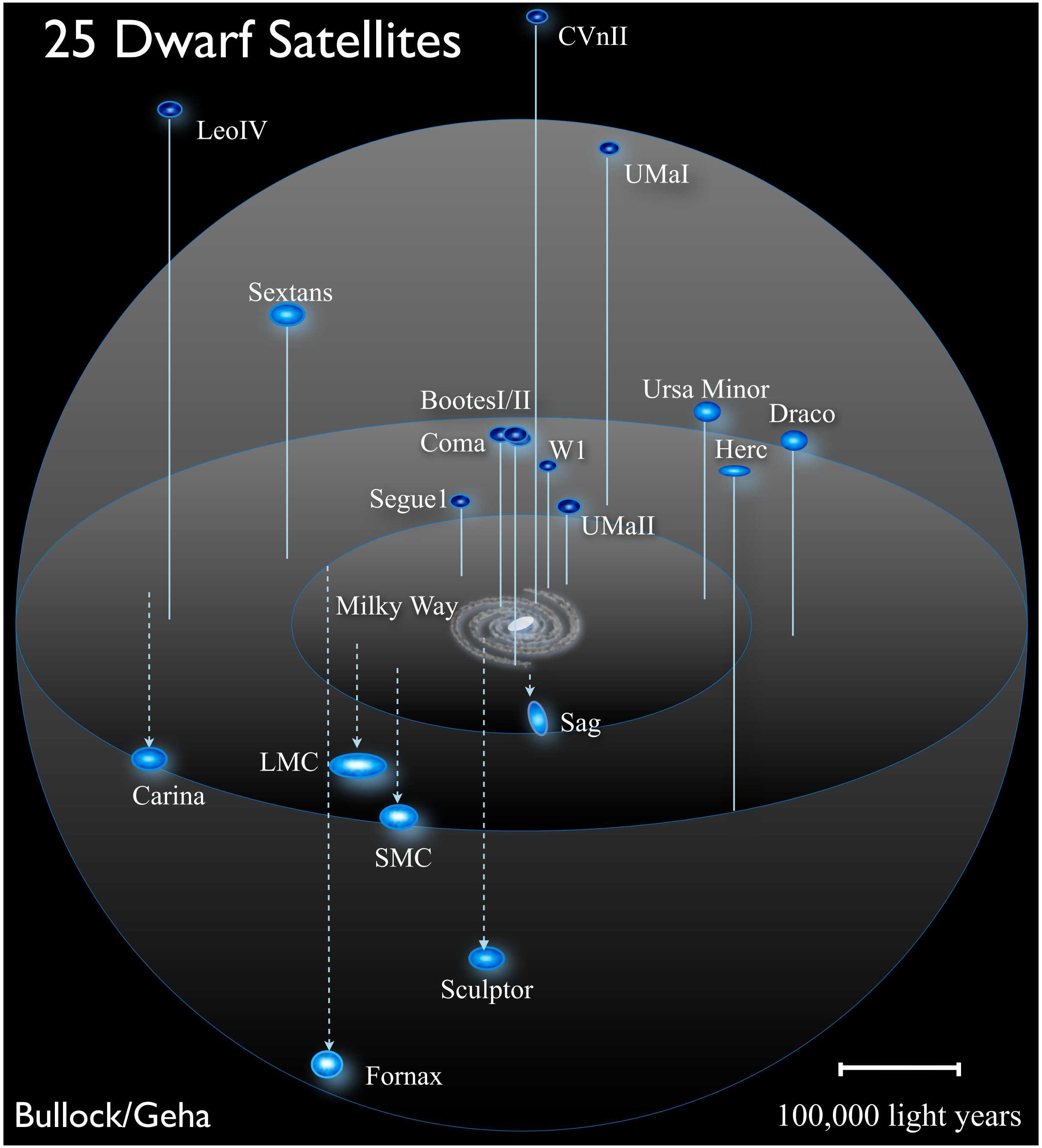


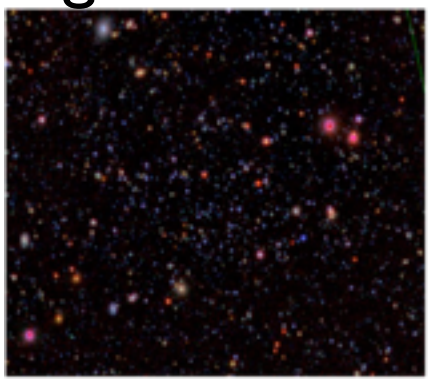
New MW dwarfs are NOT like old dwarfs...

Fornax

$L \sim 10^7\ L_{sun}$

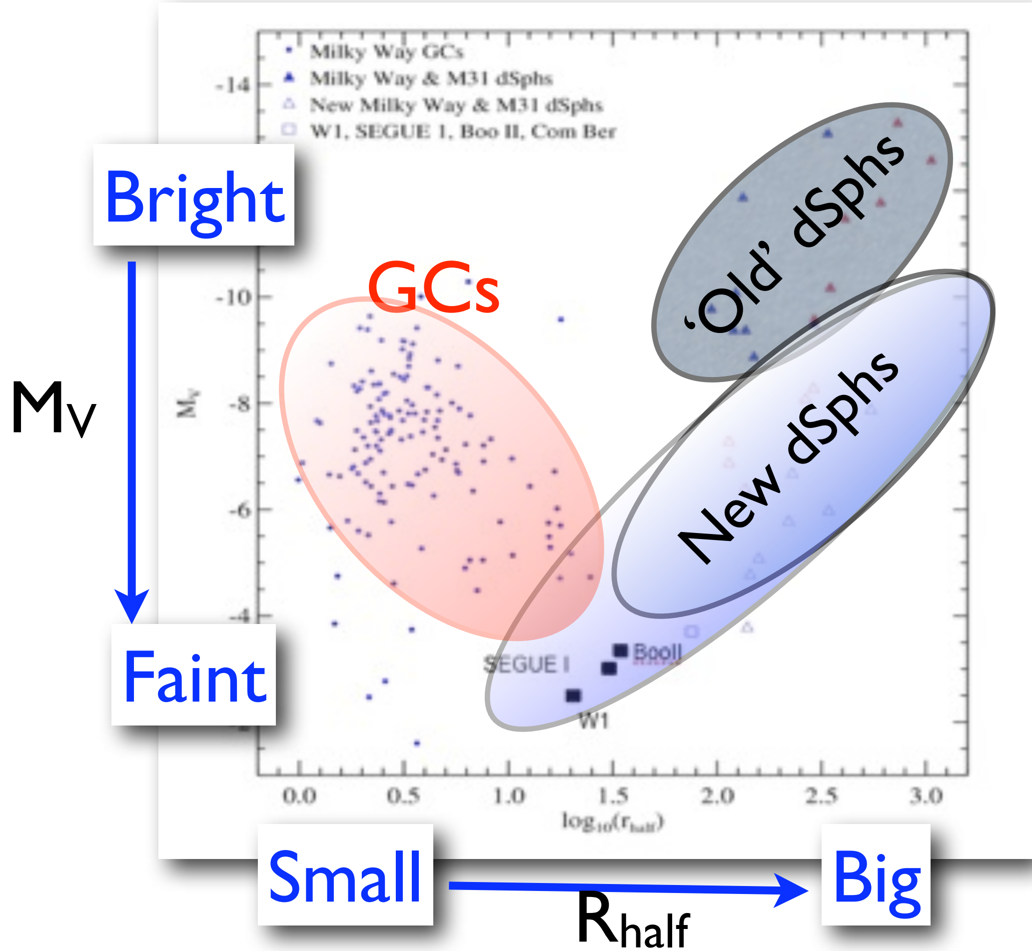
~3000 pc

Segue I



$L \sim 300\ L_{sun}$

~50 pc



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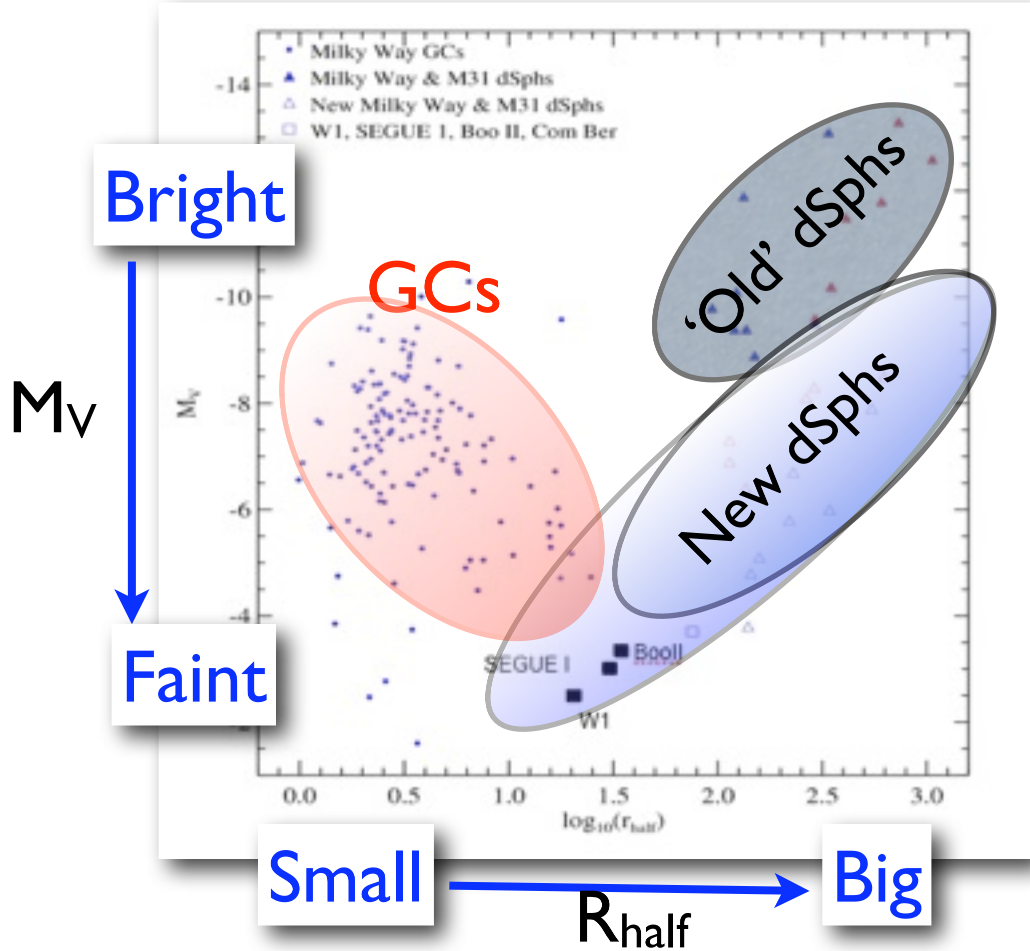
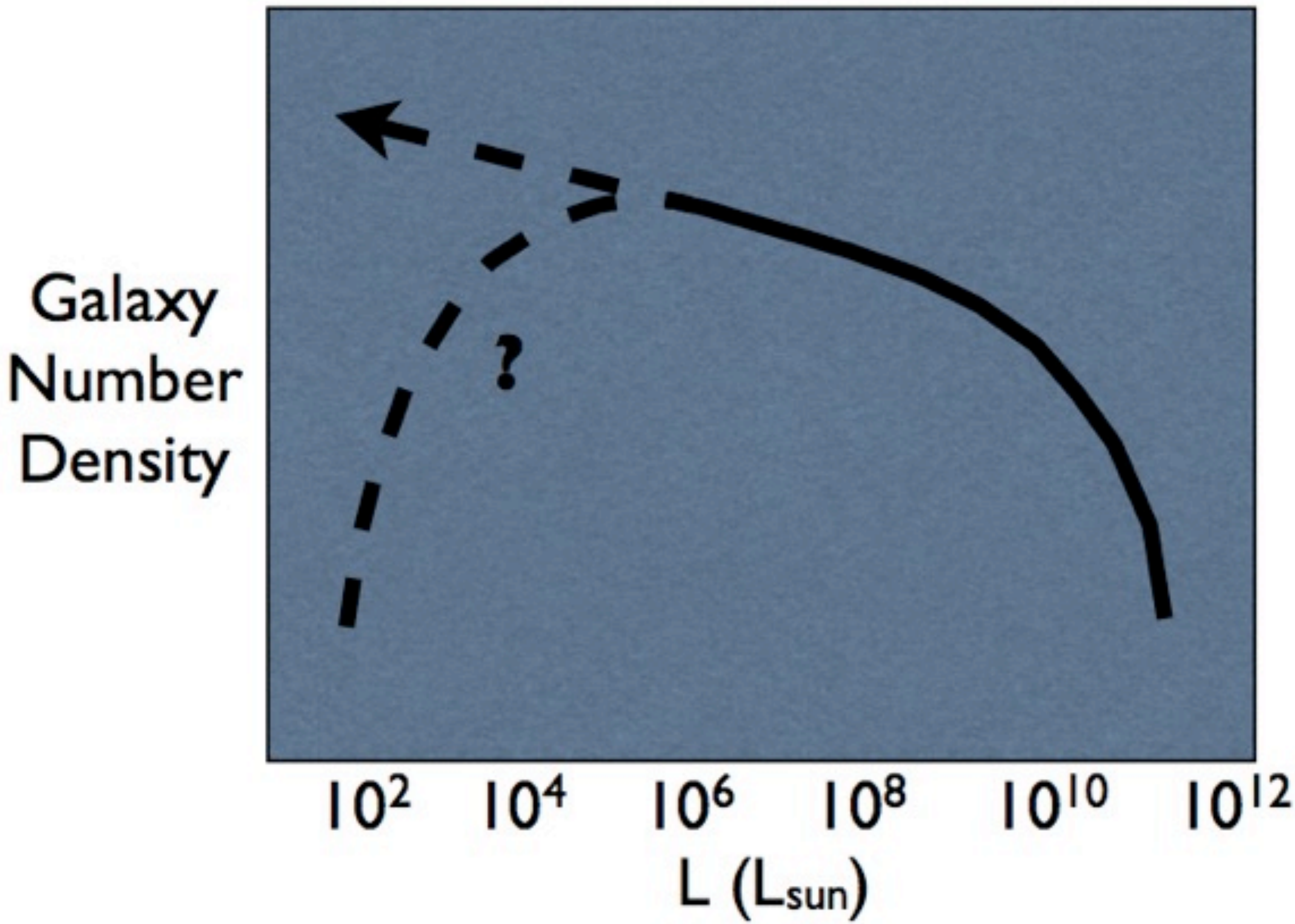
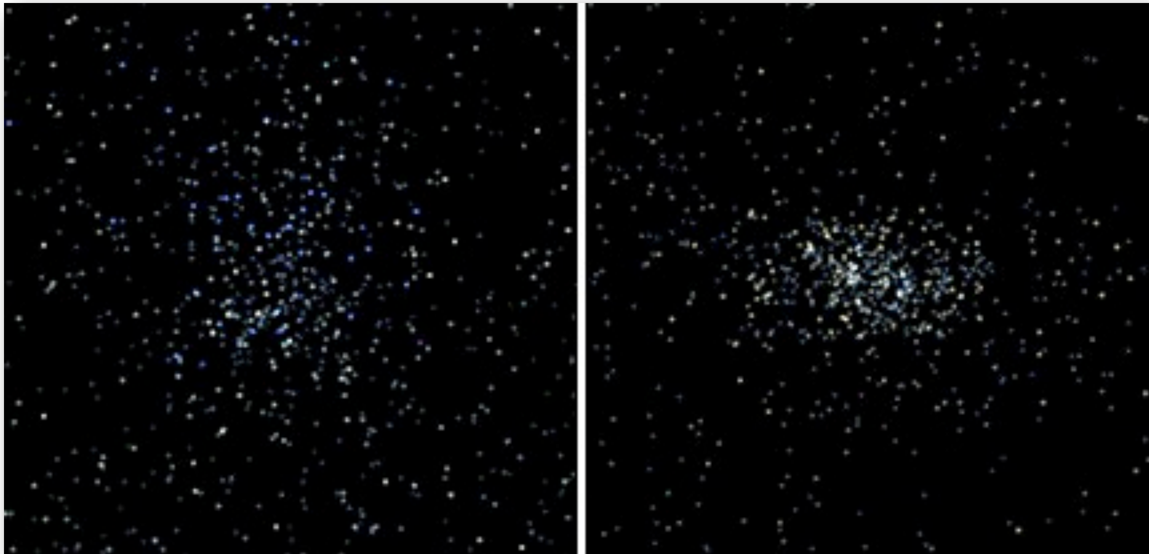


Friday, July 24, 2009

How faint is the faintest galaxy?

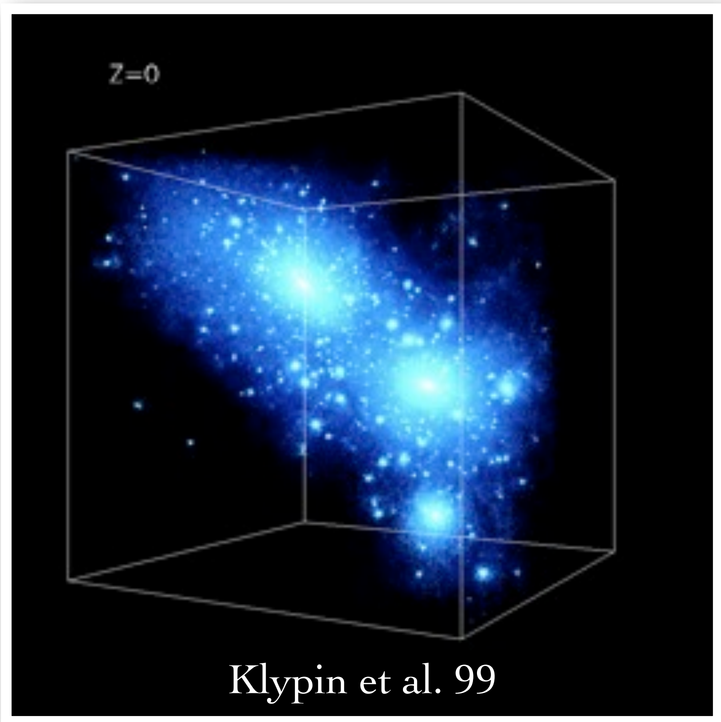


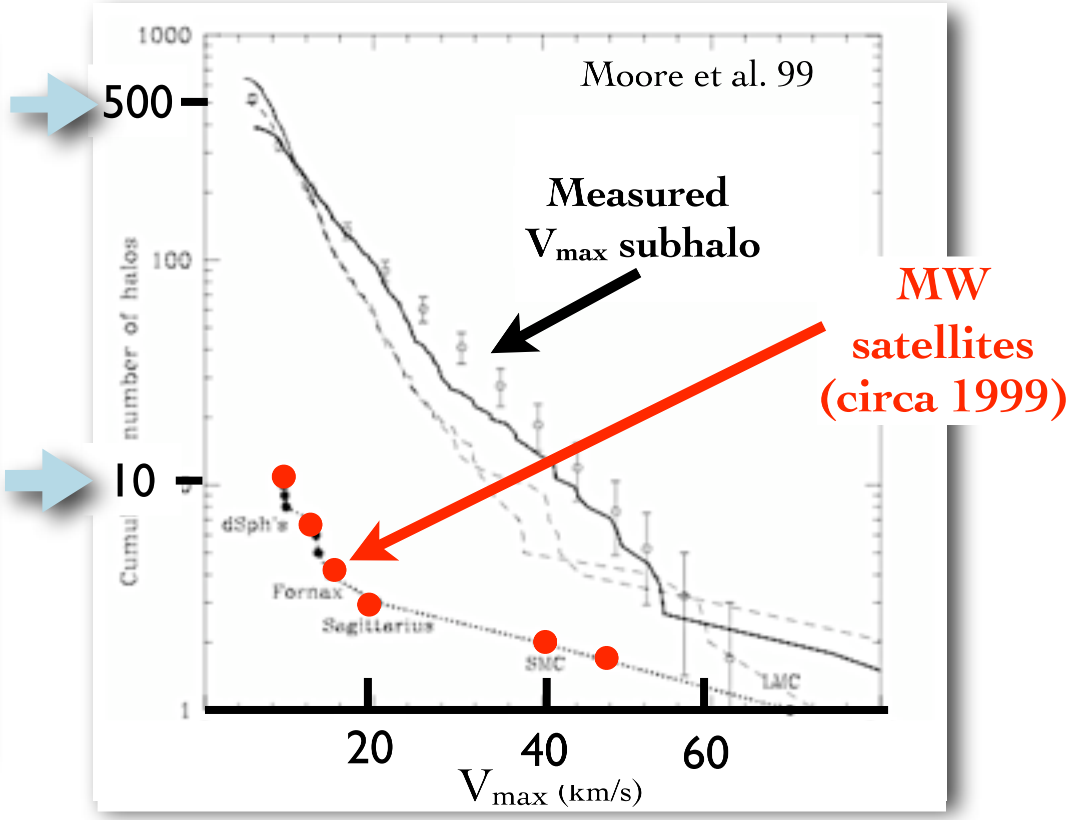
Cosmological Context?



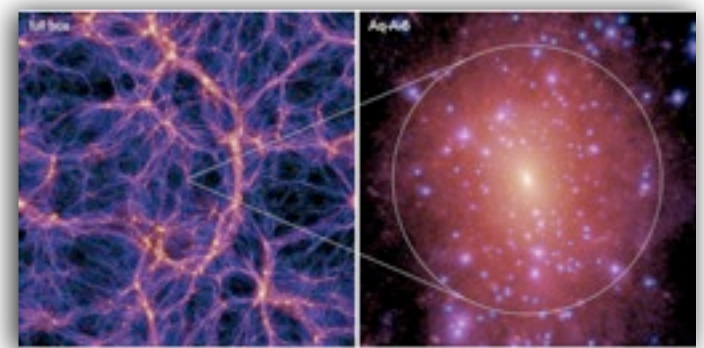
Missing Satellites Problem

Klypin et al. 99; Moore et al. 99

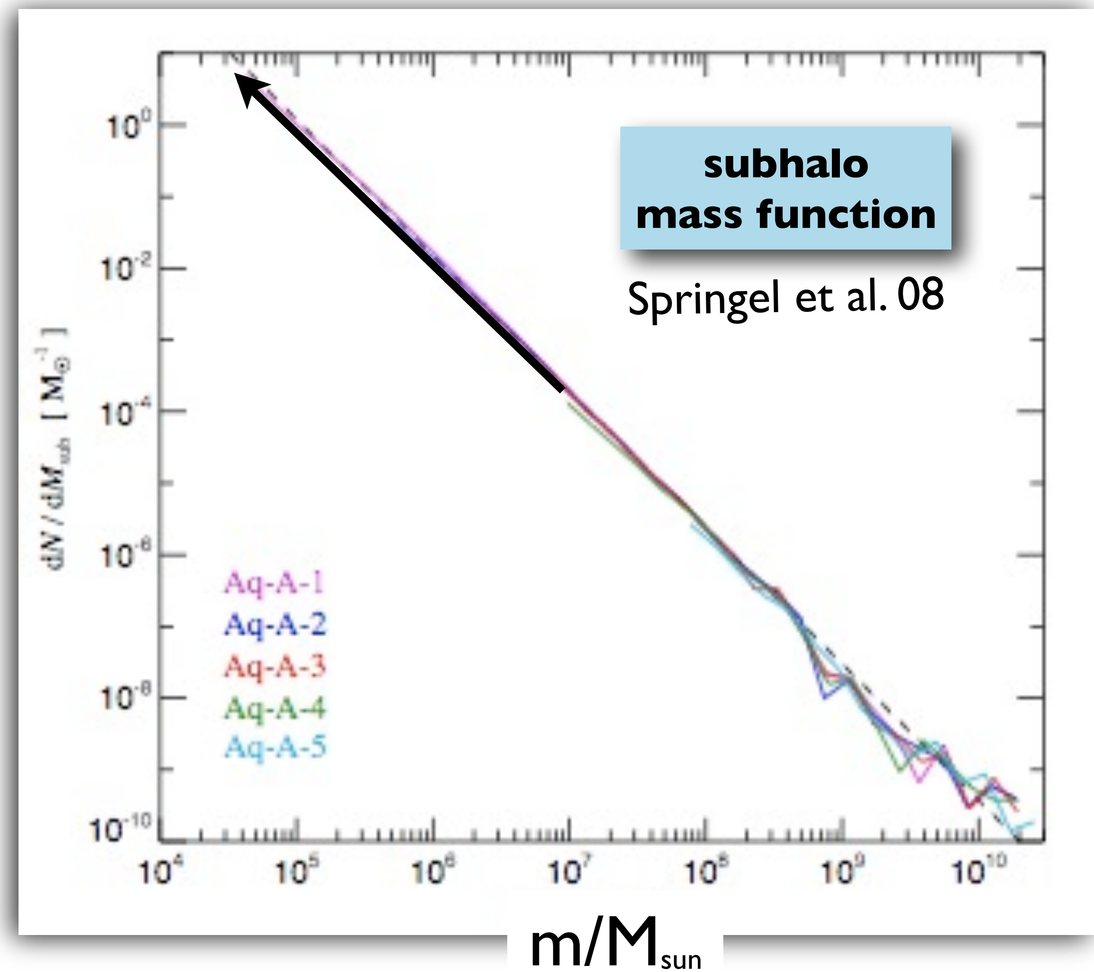





1600 kpc
via lactea II
Diemand, Kuhlen, Madau, Zemp, Moore, Potter, Stadel, 2008



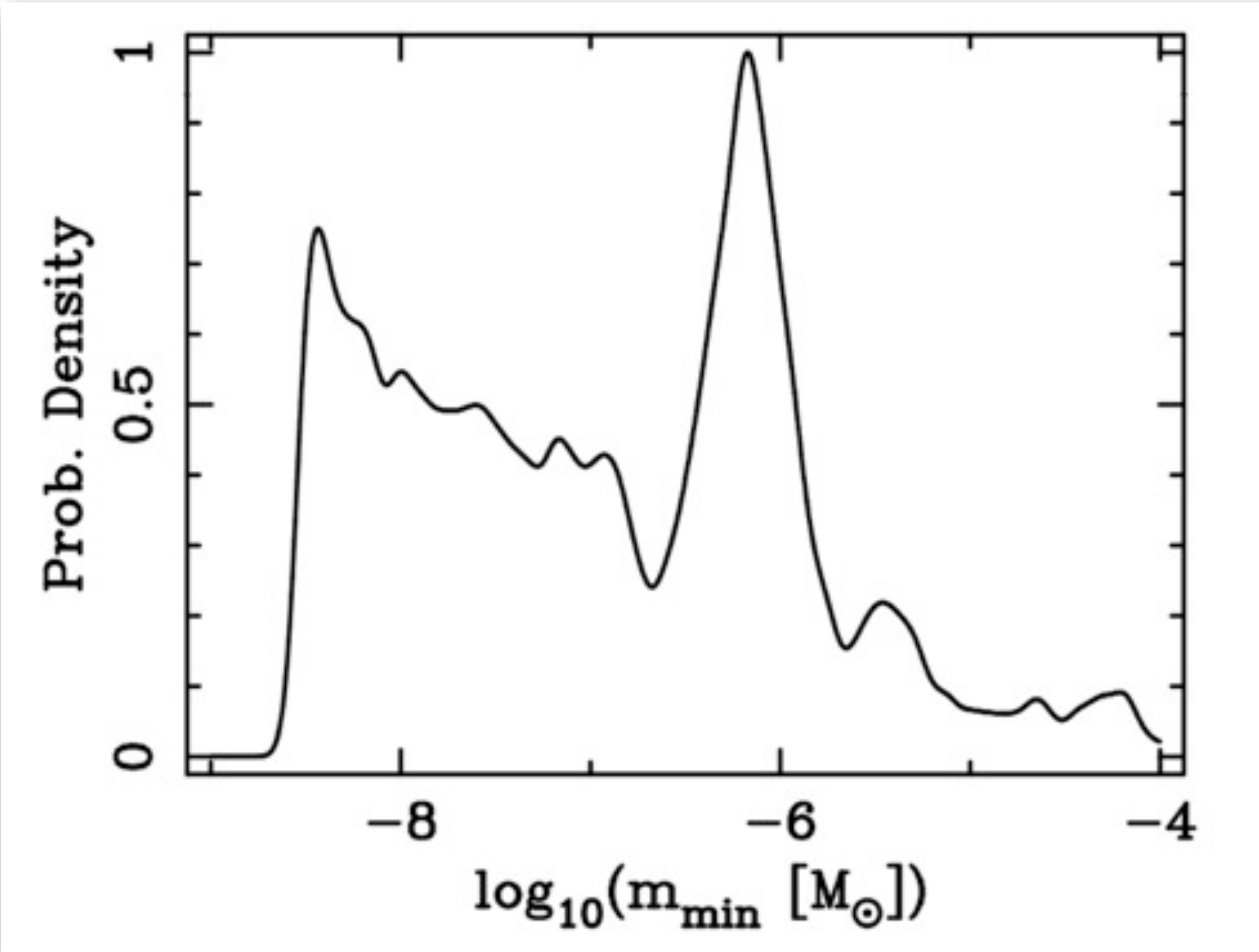
Subhalo Mass Function:
Better mass resolution just extends power law



Minimum Mass Halo ~ 10^{-8}-10^{-6} M_{sun}

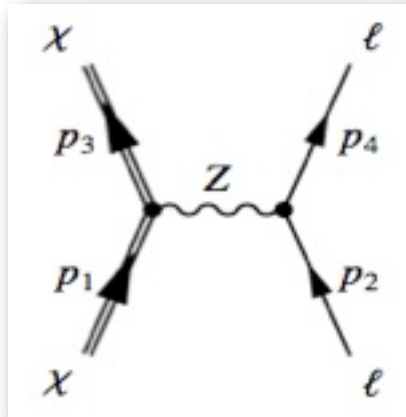
SuperBayeS - MCMC for Constrained Minimal Supersymmetric Standard Model

Martinez, JSB, Kaplinghat, Strigari, Trotta 09



Minimum mass set by horizon size at kinetic decoupling.

Decoupling depends on scattering rate with SM fermions.



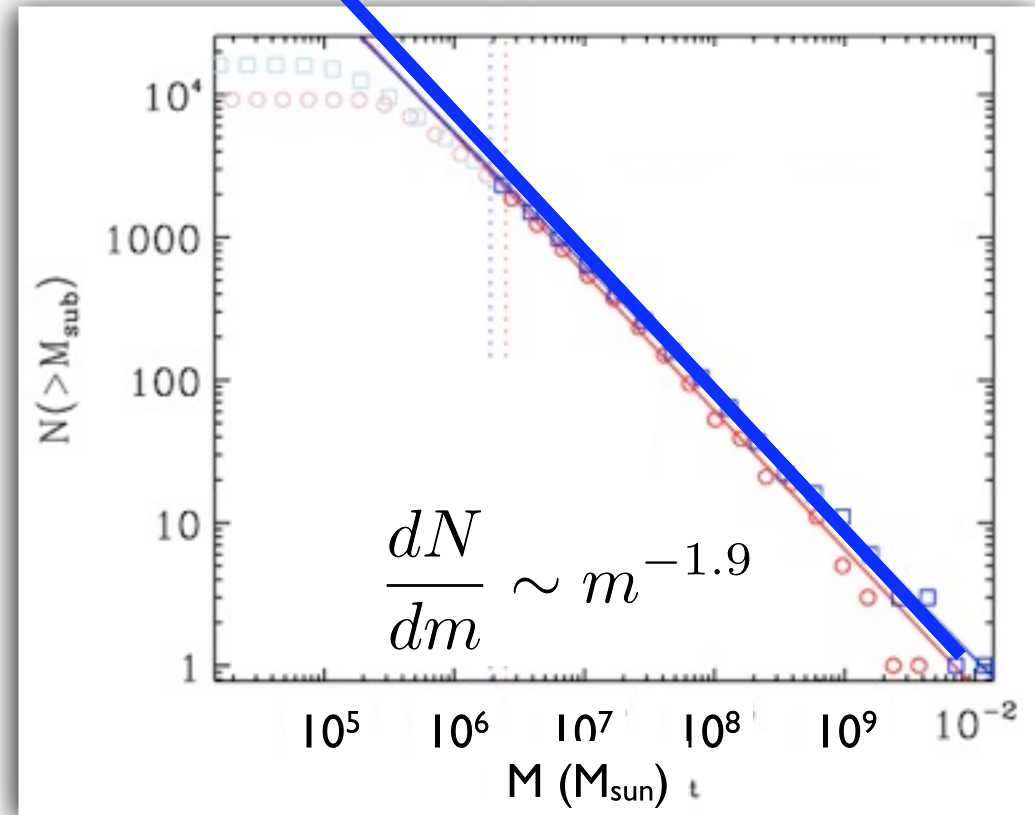
Calculated at every point in MCMC chain.

CDM Minimum Halo Mass ~ 10^{-7} M_{sun}

Martinez et al. 2009

Mass function of substructure should steadily increase down to tiny masses:

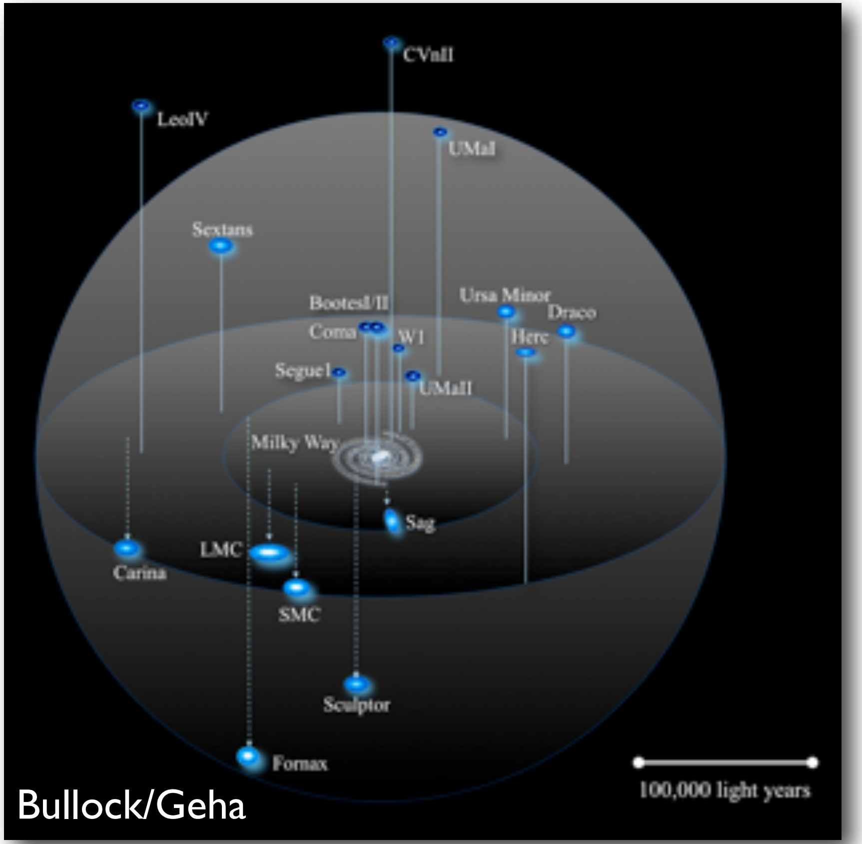
N(>10^{-7} M_{sun}) ~ 10^{17}



Madau, Diemand, Kuhlen 08

Theory: N>10^{17}

Observation: N~25



At least we're doing better than cosmological constant problem...

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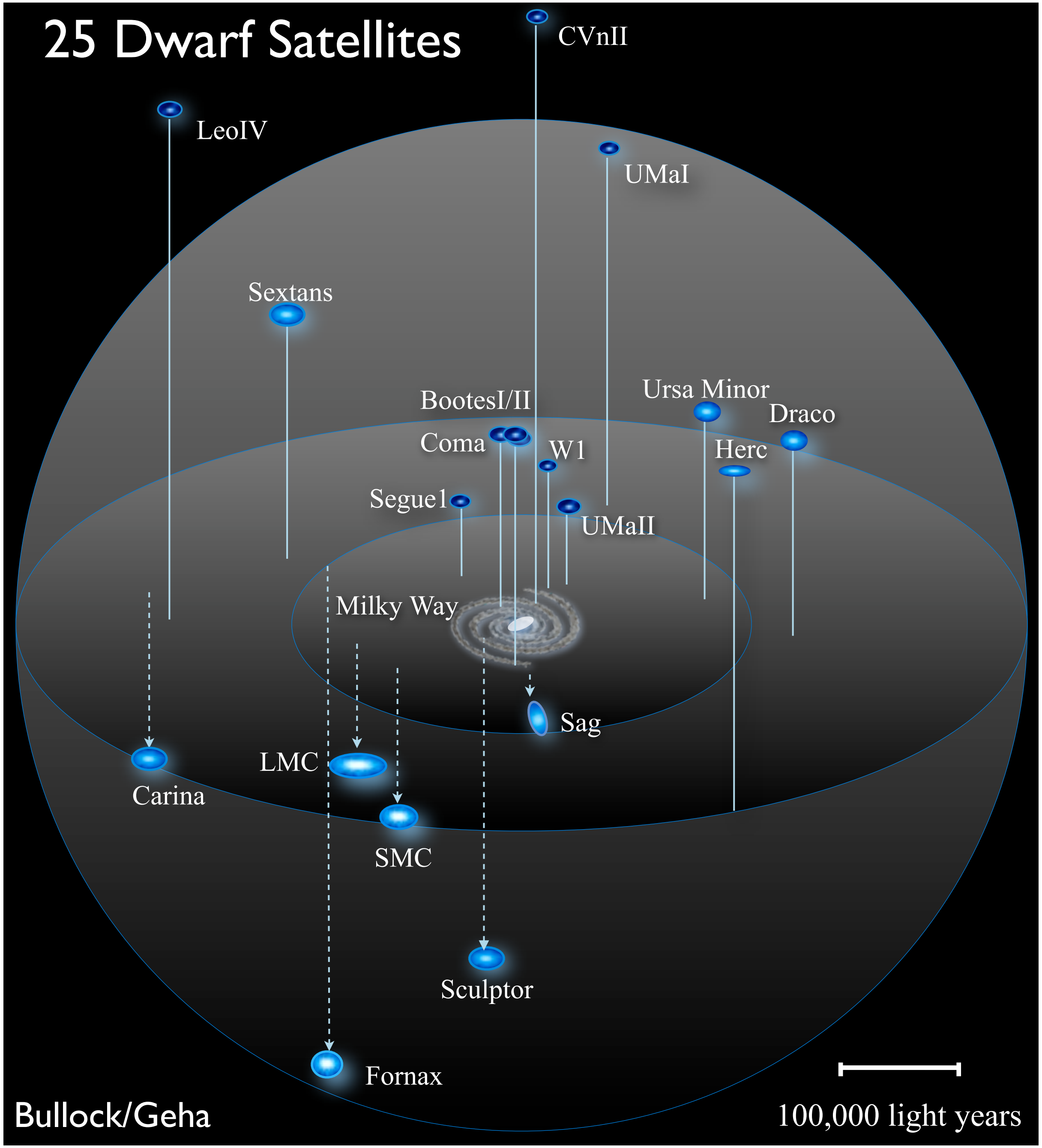

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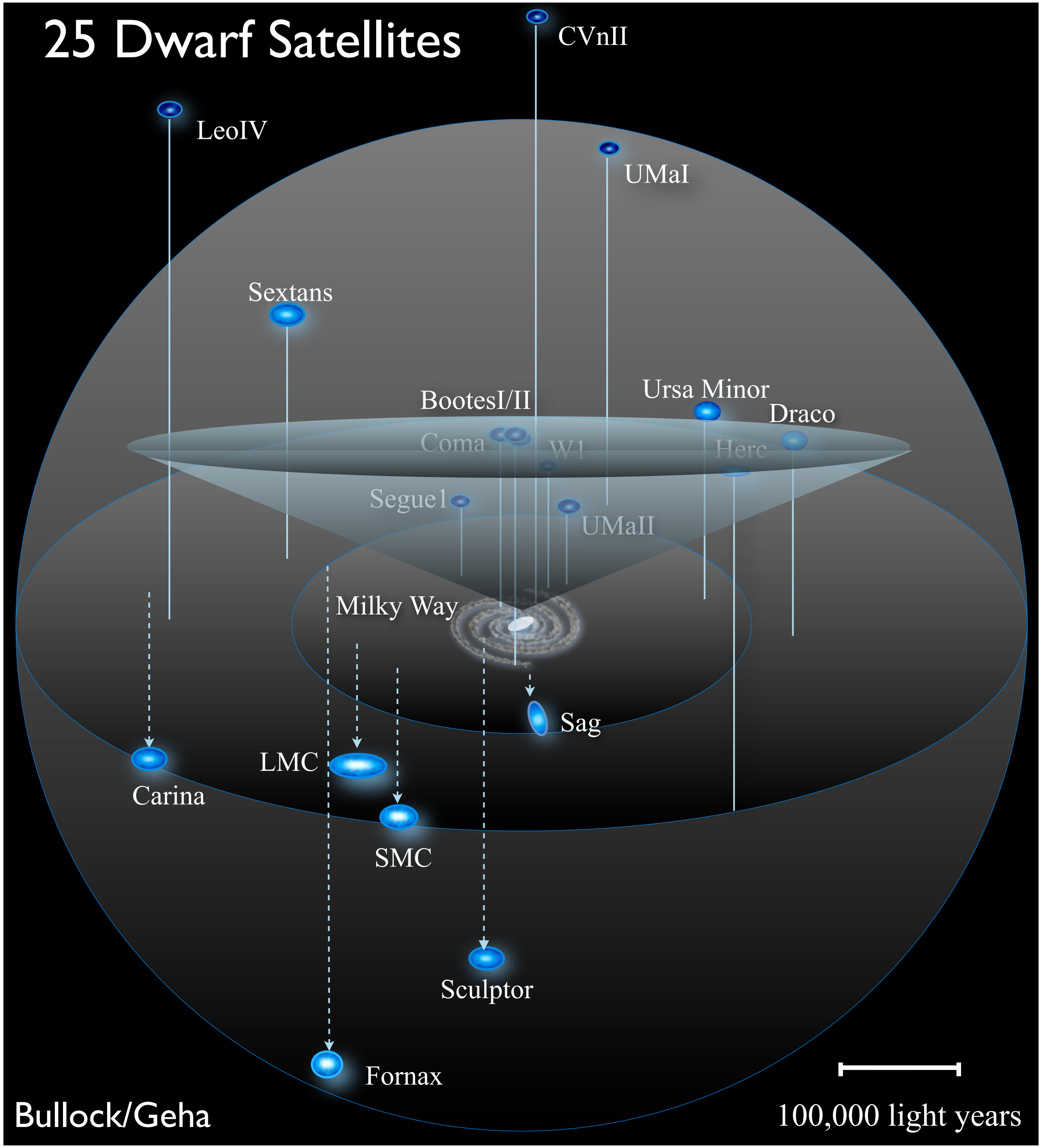
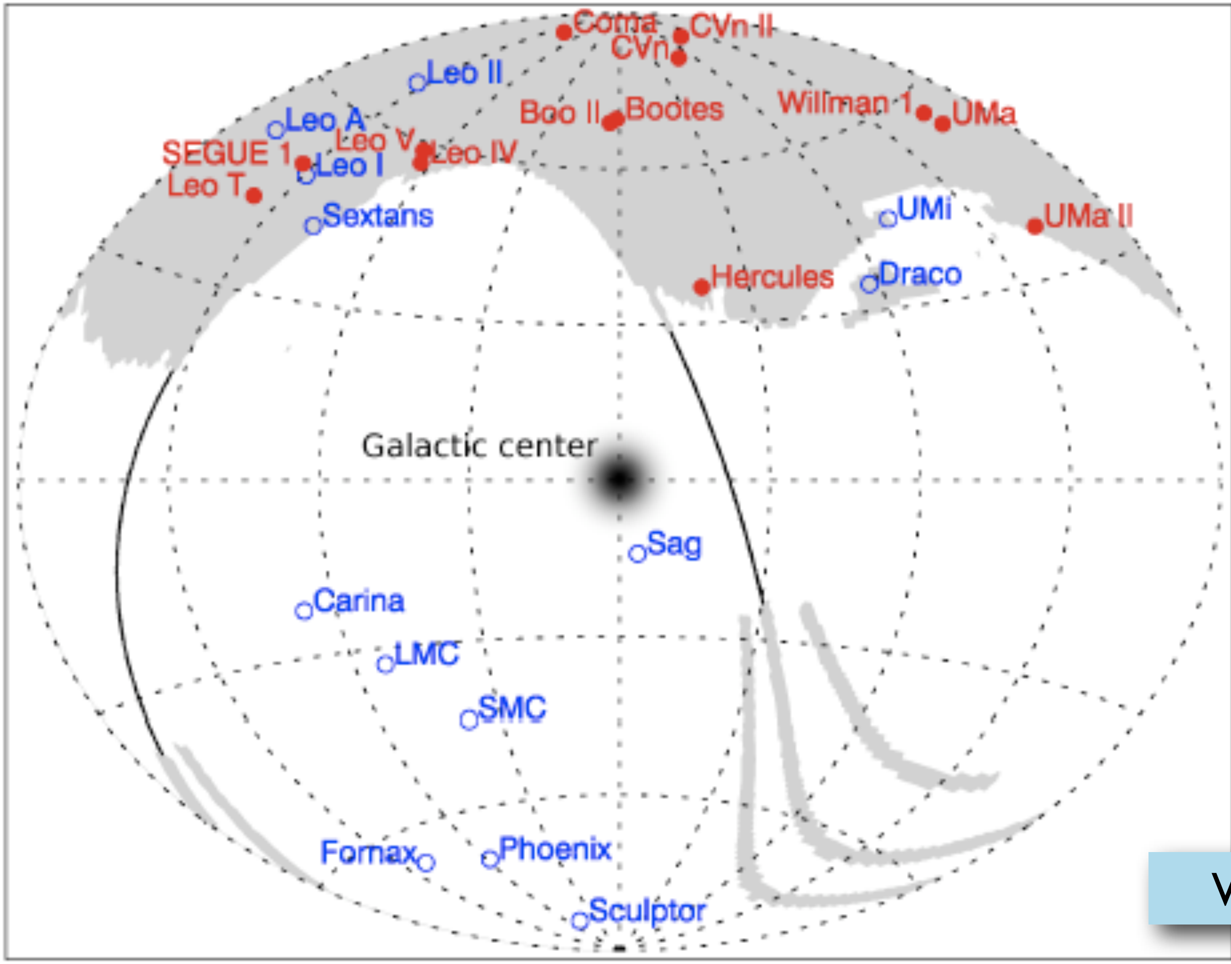


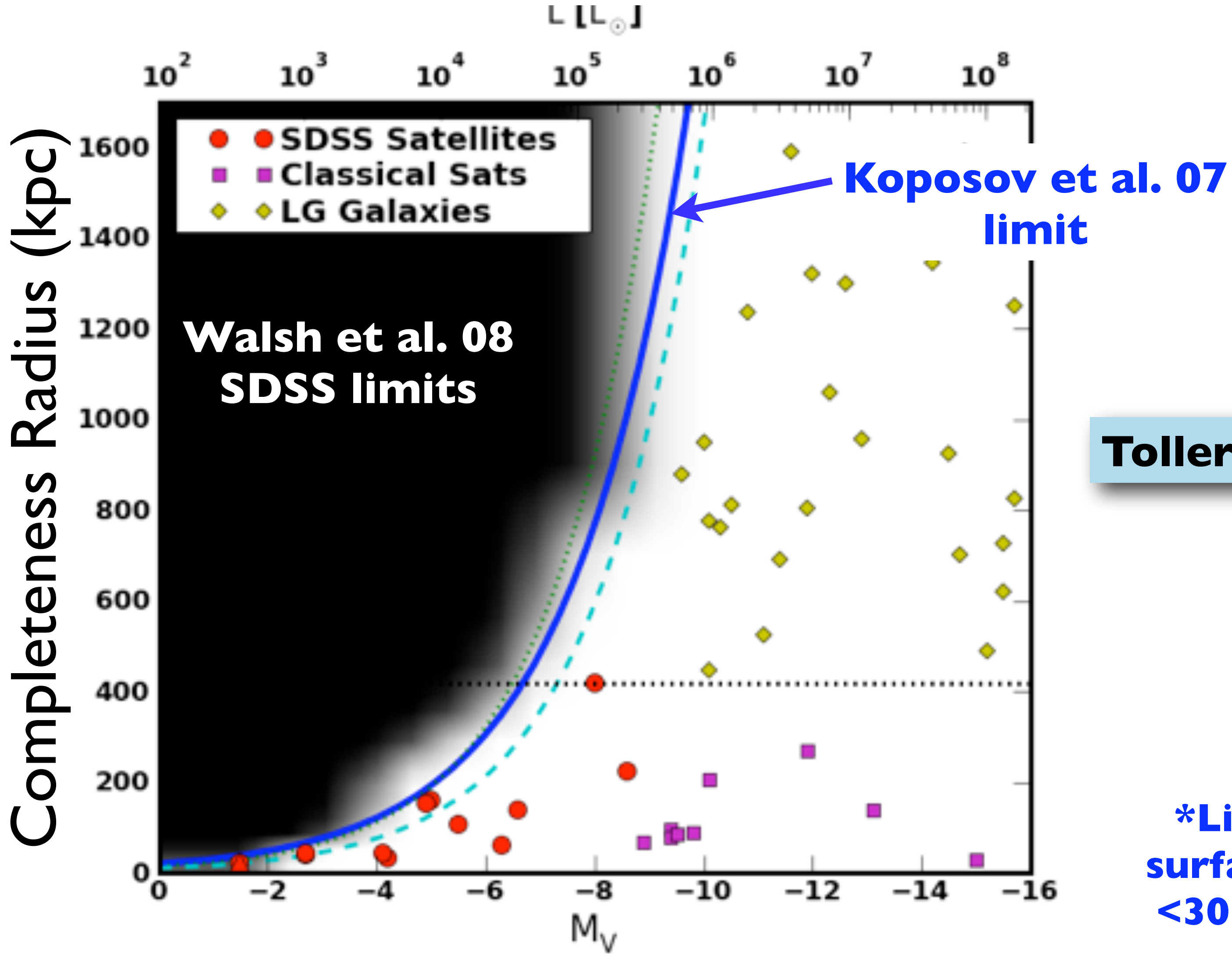
Many more to be discovered...

Only ~20% of sky covered by SDSS searches ⇒ ≳ 70 total



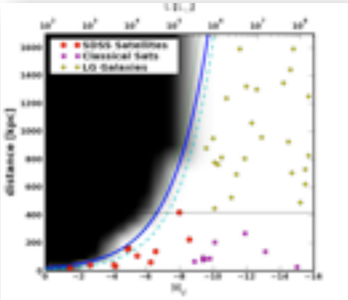
Walsh et al. 08

Luminosity bias: many more to be discovered

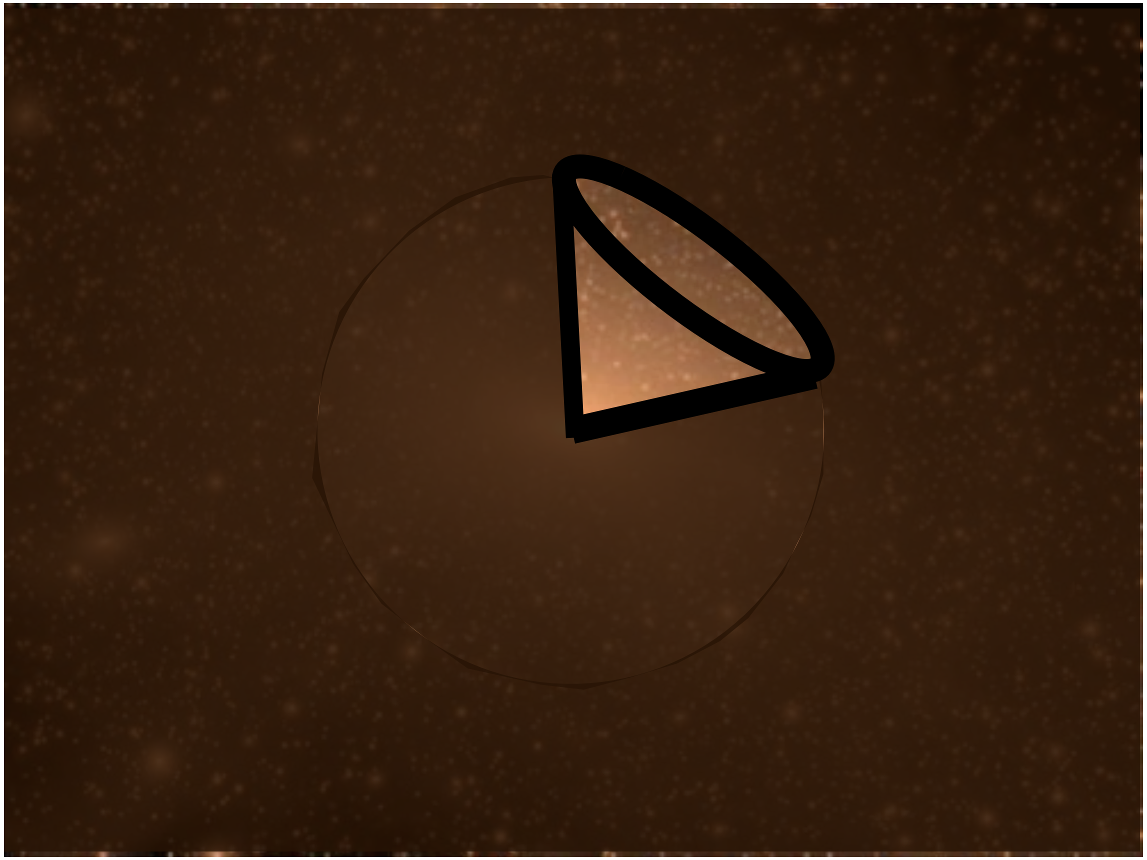


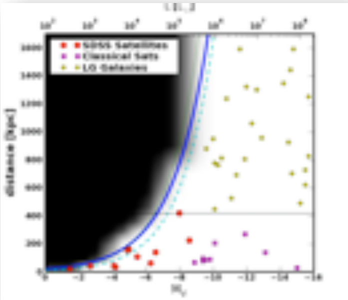
Tollerud et al. 08

***Limits assume surface brightness <30 mag/arsec^2**

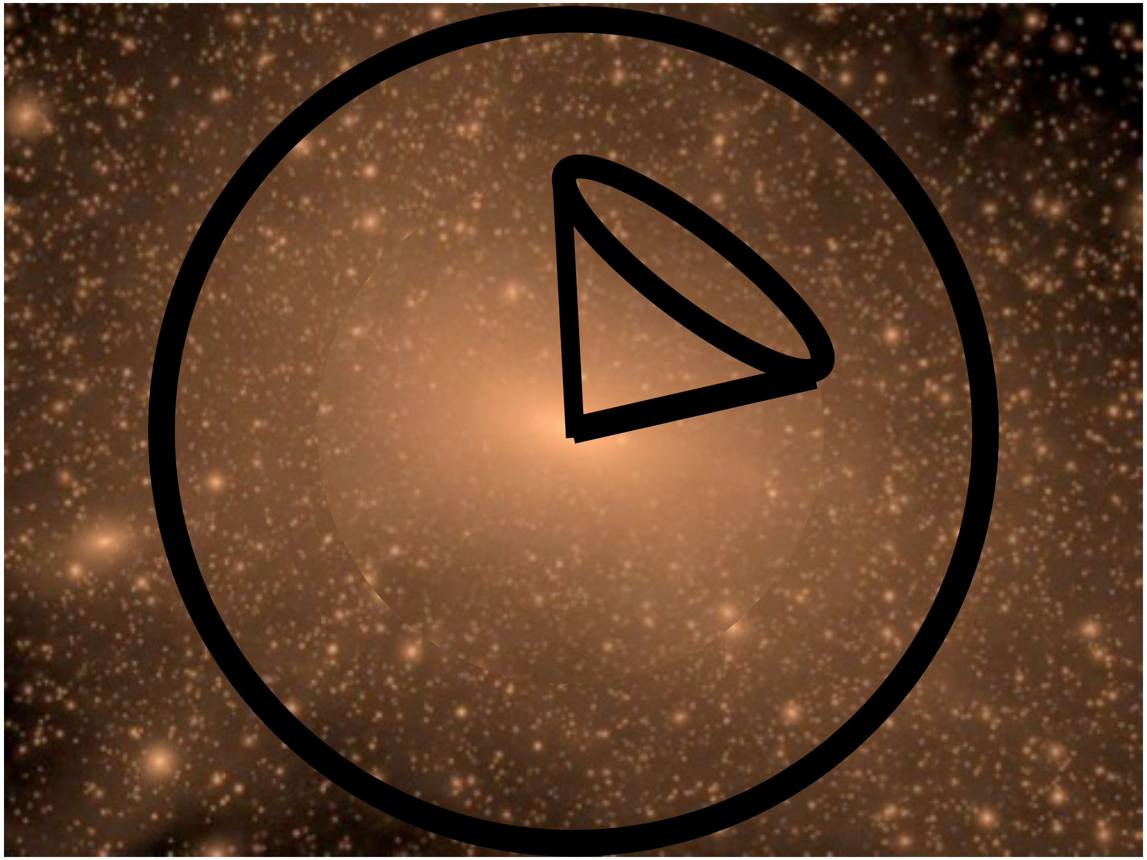


Faint galaxies can only be seen nearby

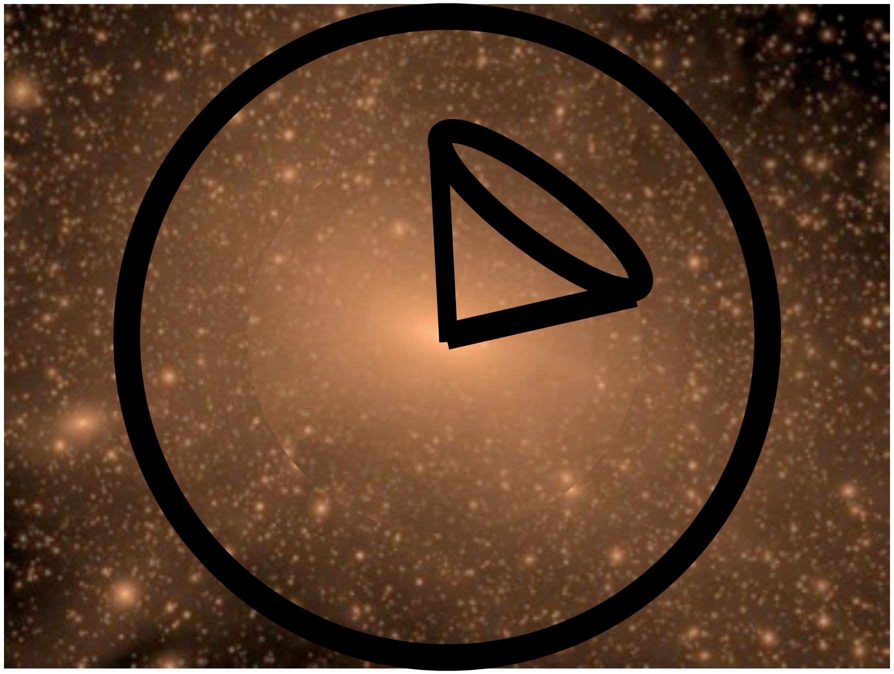




Full correction includes luminosity bias + angular coverage correction.



For every known dSph, how many did we miss?



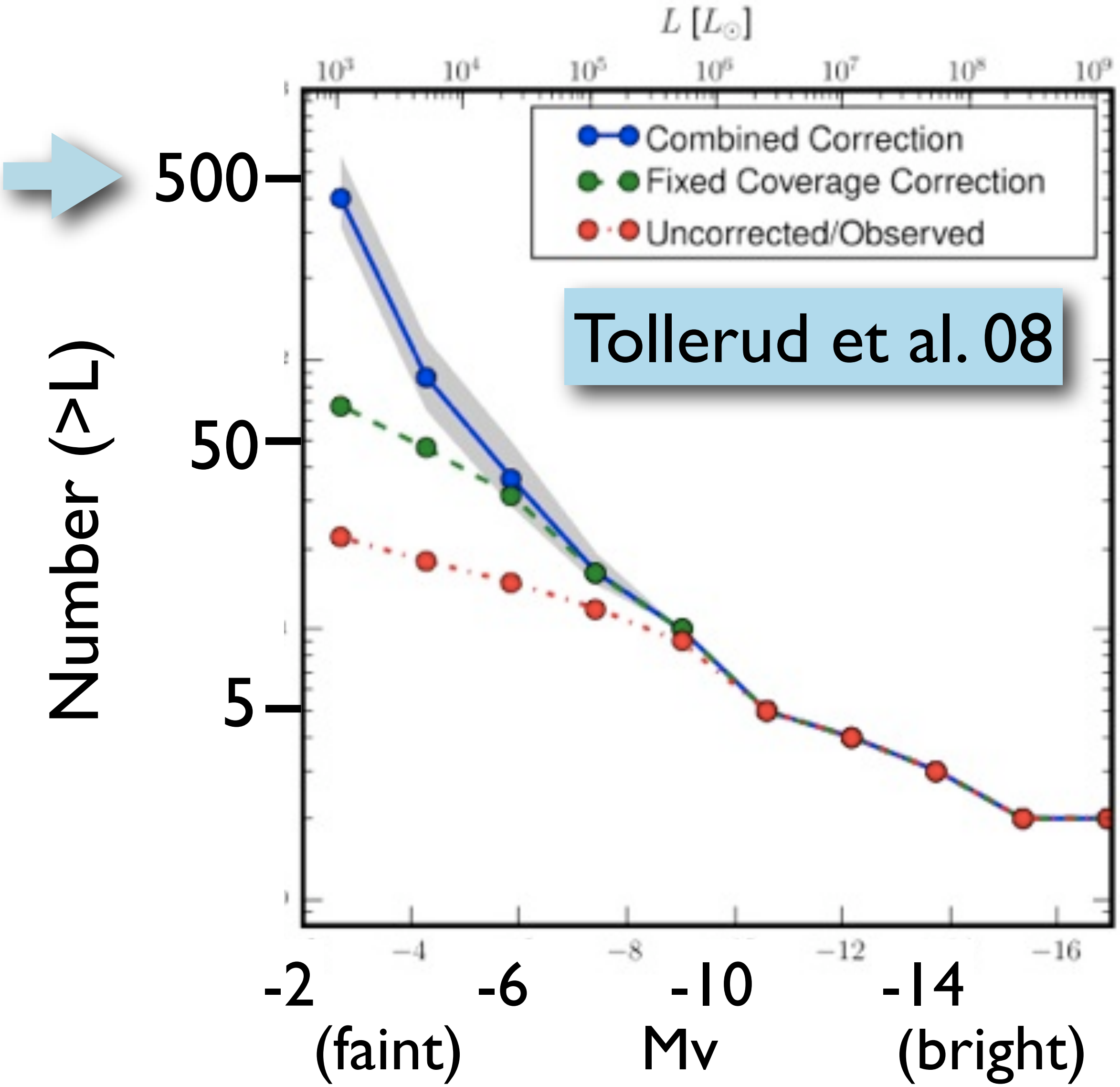
Erik Tollerud, JSB, Strigari, Willman 08

Only One Assumption:

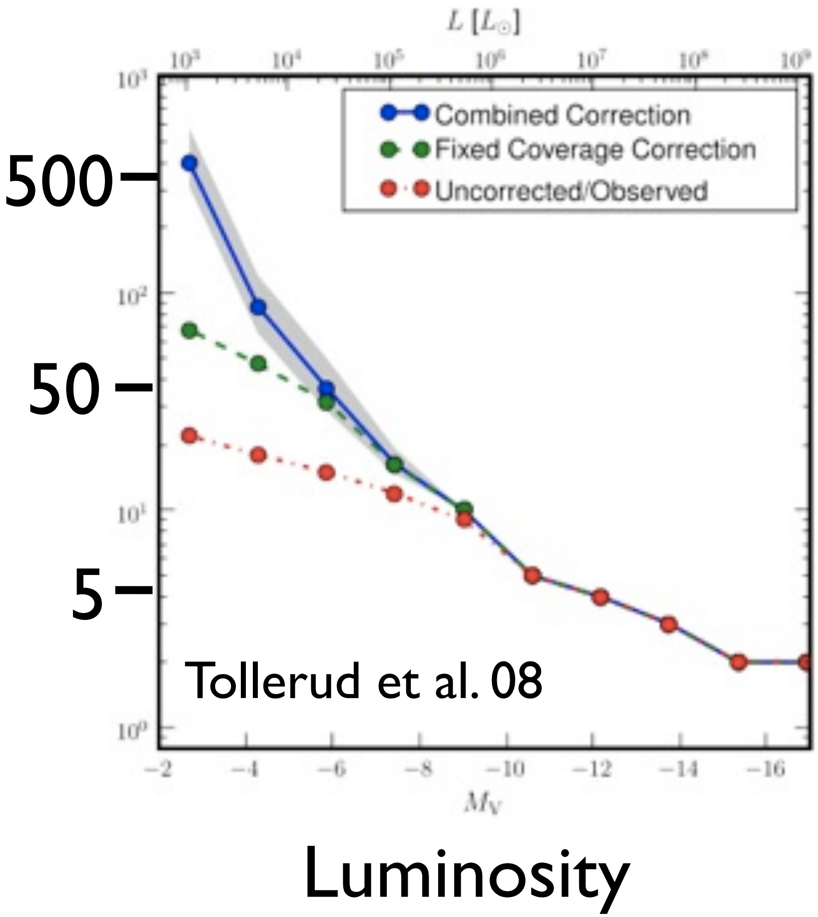
Radial & angular distribution of MW satellites matches that of subhalos.

→ No need to assign luminosities to individual subhalos.

~500 ultra-faint galaxies *within 400 kpc of the Sun*



How could Tollerud et al. be wrong?

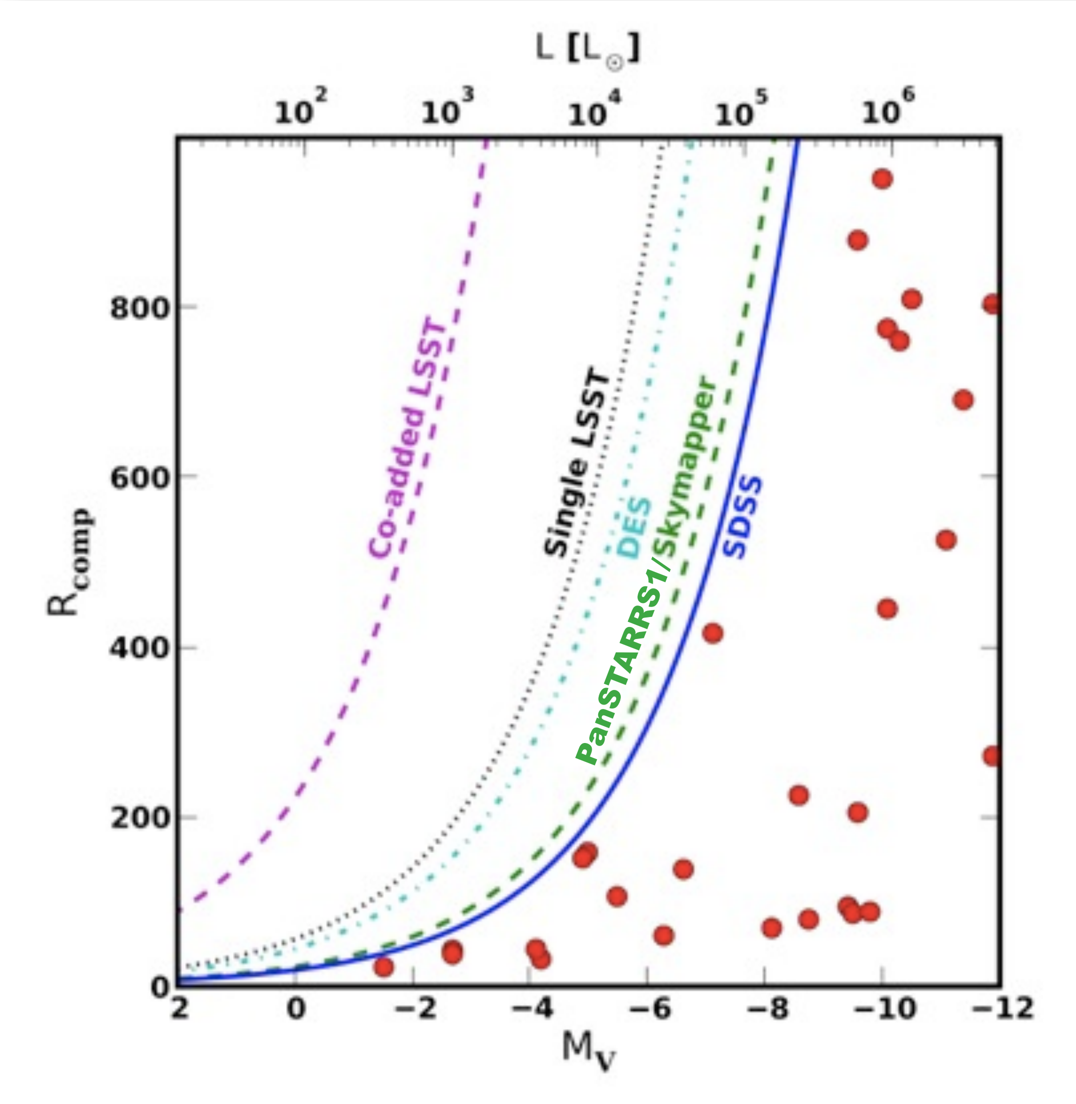


1. If subhalos near the Sun are more likely to host ultra-faint dwarfs.

2. If ultra-faint galaxies are not associated with DM halos at all...

3. If DM is not cold (i.e. subhalos are not there...)

Future surveys can test this

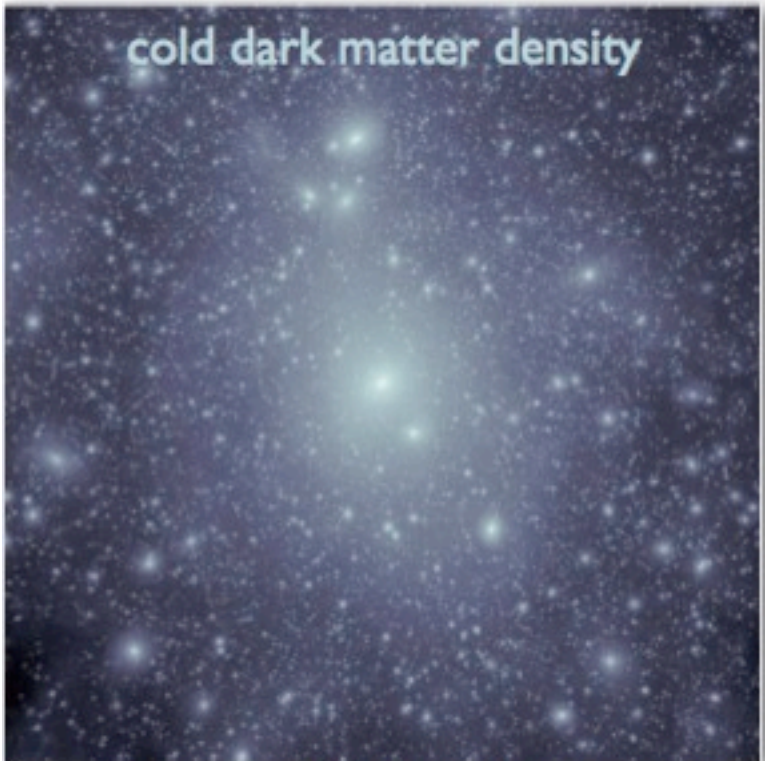


LSST can detect ultra-faint galaxies out beyond MW virial radius.

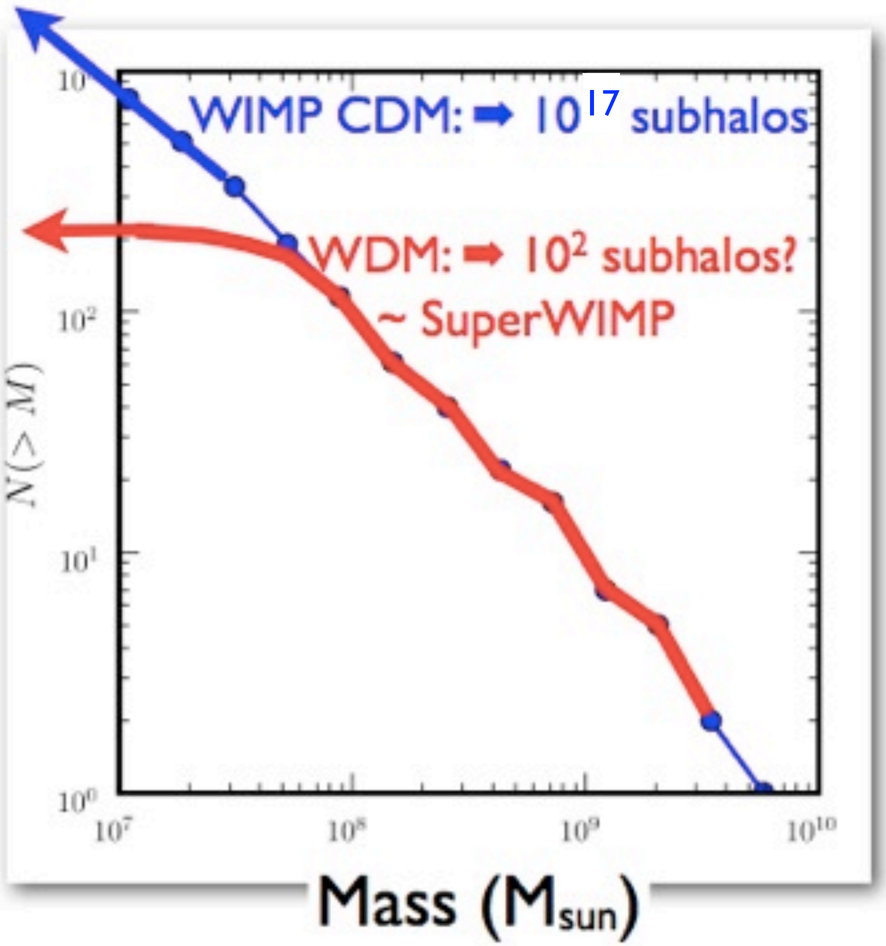
Tollerud et al. 08

How Cold is the Dark Matter?

An answer by simply counting dwarf galaxies!



Diemand, Kuhlen, Madau



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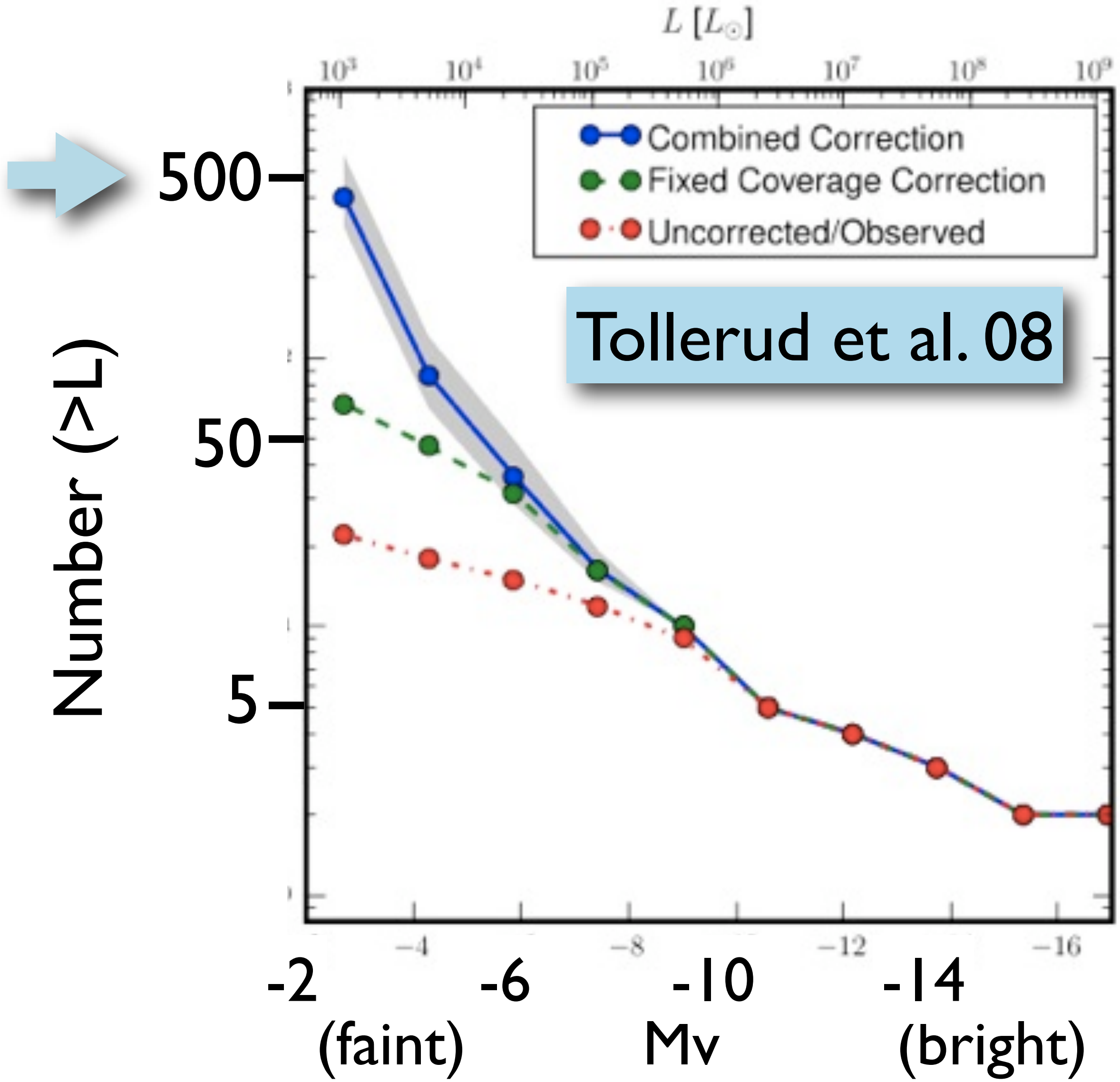
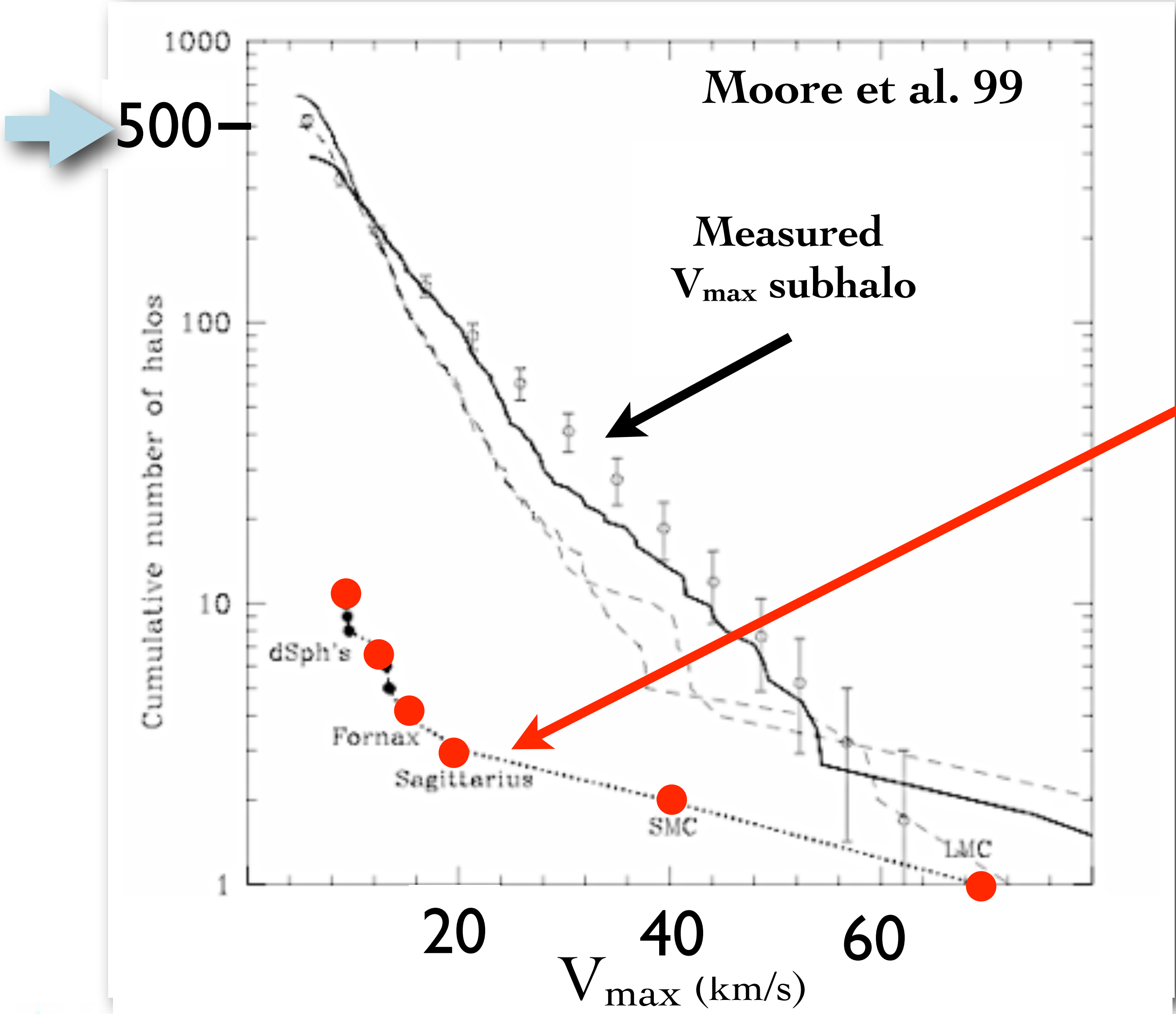


Missing Galactic Satellites?



Also:
Klypin et al. 99

Estimate:

$$V_{\rm max} = \sqrt{2}\sigma_*$$

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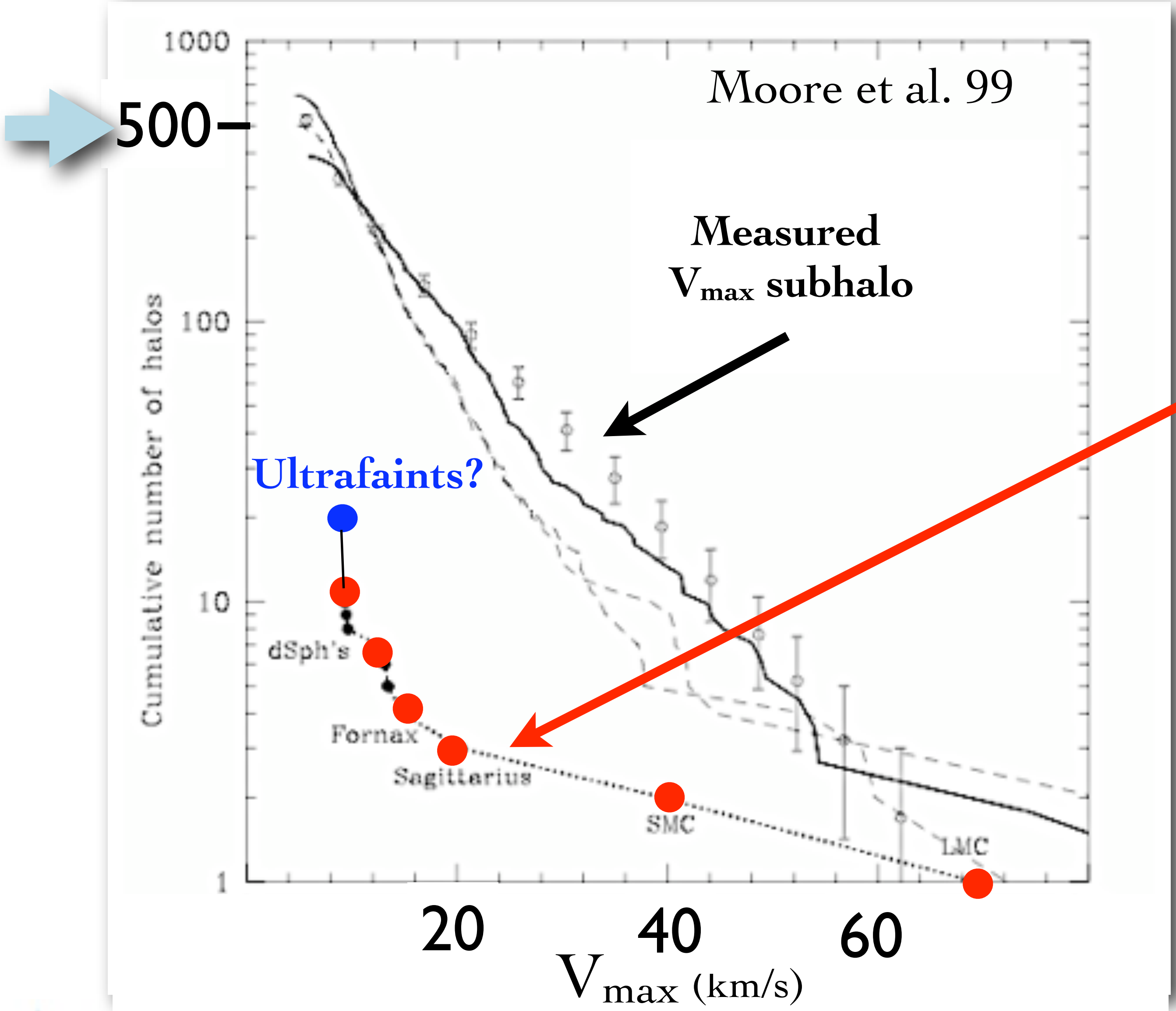

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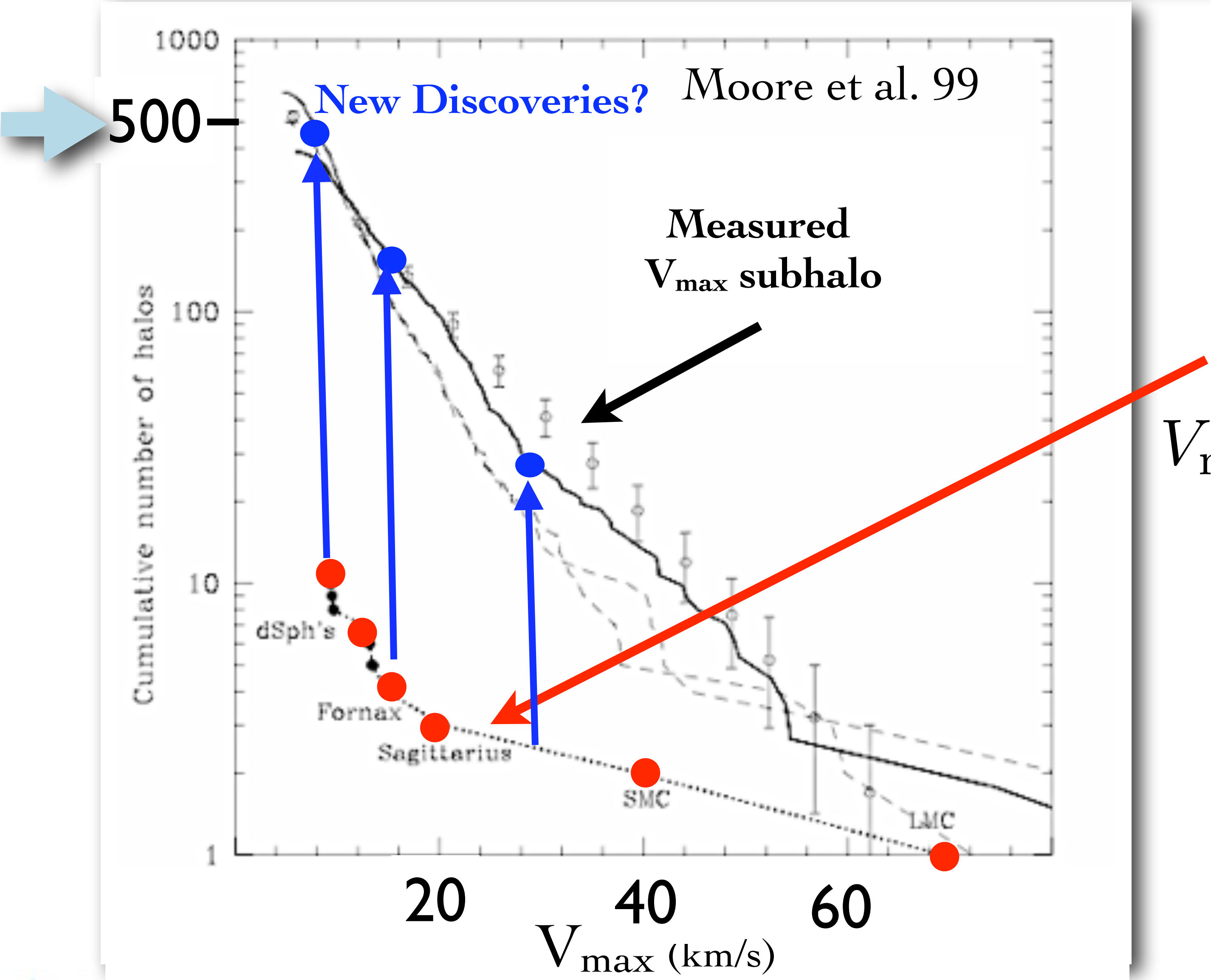
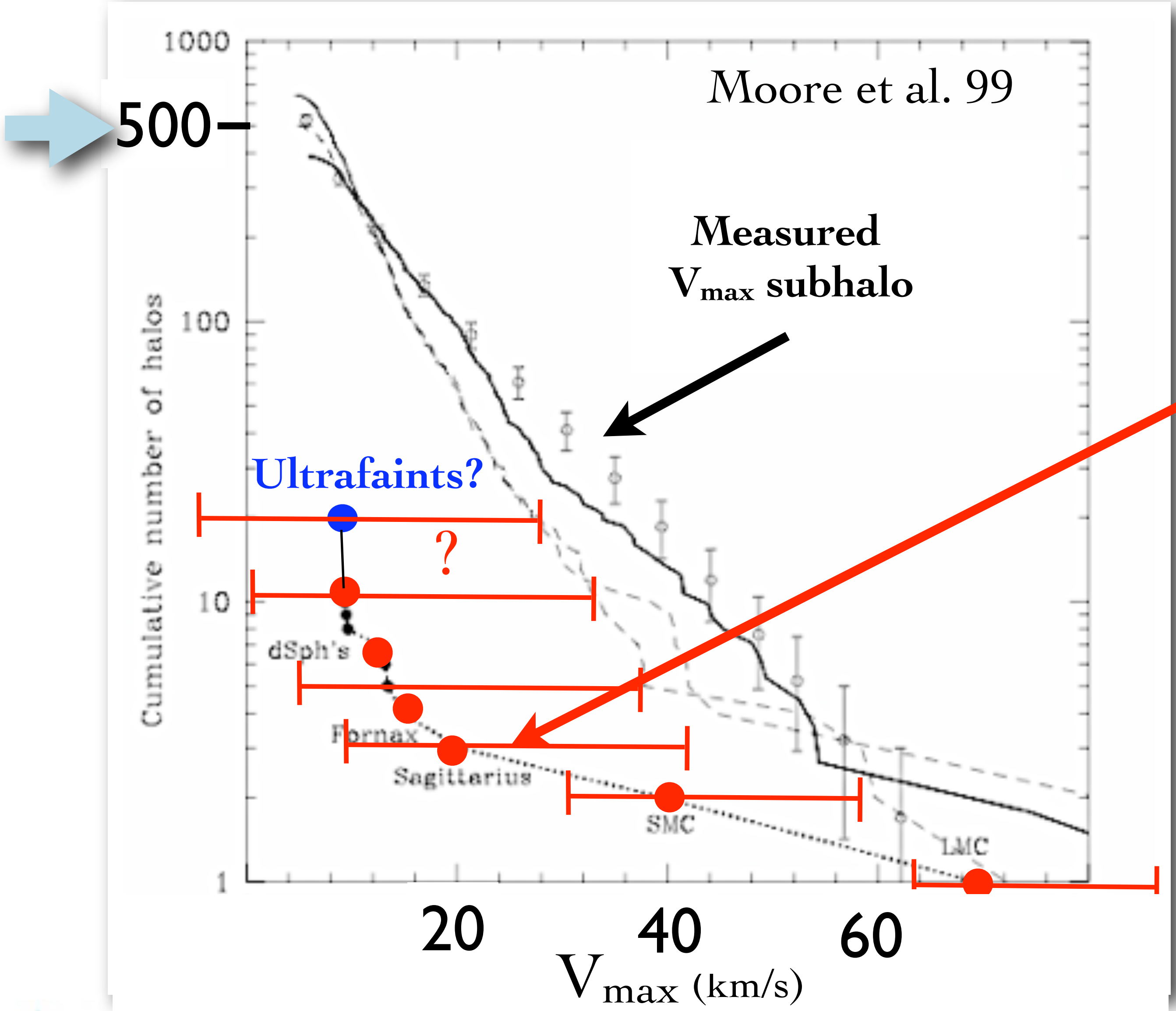


Estimate:

$$V_{\max} = \sqrt{2}\sigma_{*}$$

What kind of subhalos host these satellites?

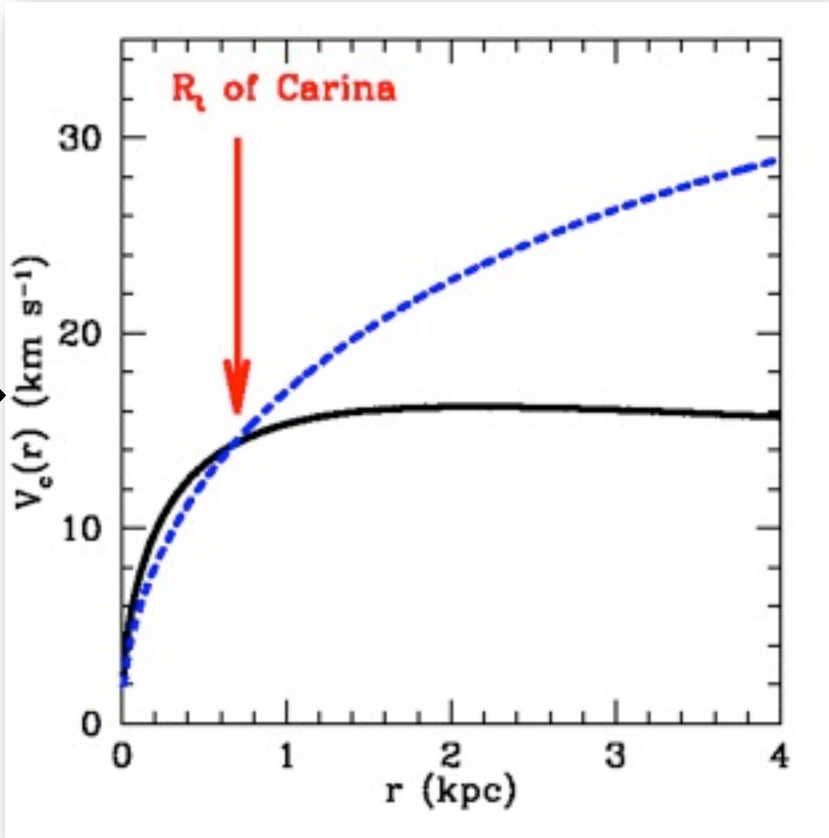


Estimate:

$$V_{\rm max} = \sqrt{2}\sigma_*$$

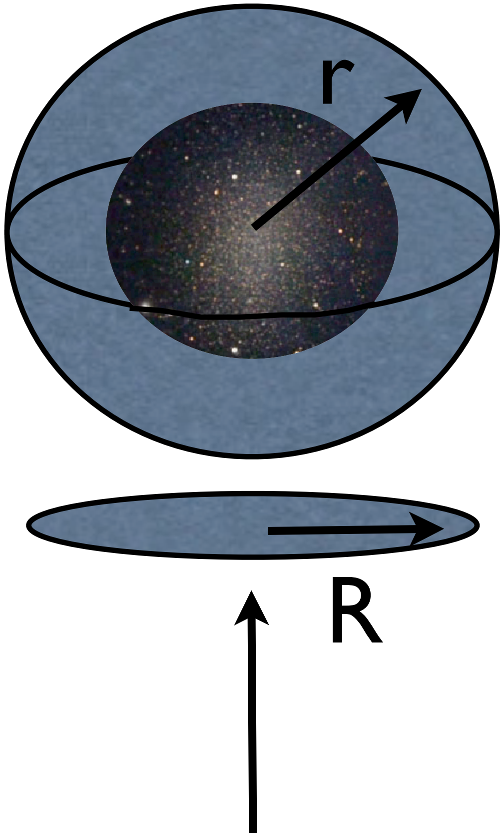
Dwarf V_{max} is hard/impossible to measure directly

Both of these rotation curves reproduce observed velocity dispersion of Carina



Zentner & JSB 03

Observables: $\sigma_{los}(R)$ & $I_*(R)$



$$\sigma^2_{los}(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right) \frac{\rho_* \sigma_r^2 r \mathrm{d}r}{\sqrt{r^2 - R^2}}$$

Spherical Jeans Equation:

$$M(<r) = \frac{r\sigma_r^2}{G}\left[-\frac{\mathrm{d}\ln\sigma_r^2}{\mathrm{d}\ln r} - \frac{\mathrm{d}\ln\rho_*}{\mathrm{d}\ln r} - 2\beta\right]$$

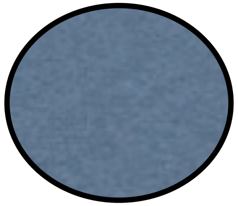
Key degeneracy: $\beta(r) = 1 - \sigma_t^2/\sigma_r^2$

Marginalize Over Uncertainties

Marginalize over 6+3+2 Parameters.

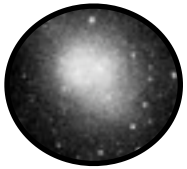
MCMC allows us to do the marginalization fast.

Dark Matter Halo (6)



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

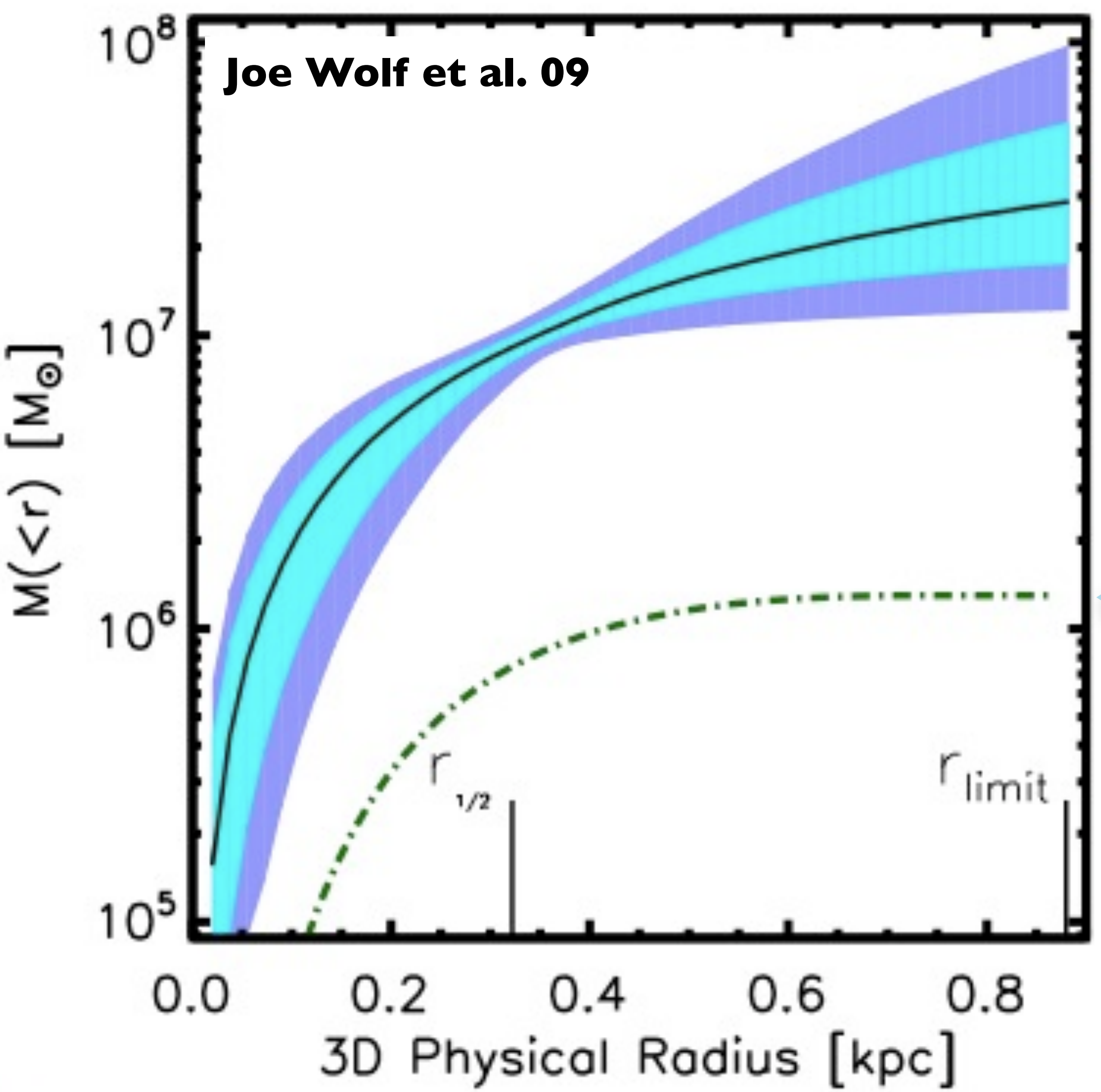
Stellar Vel. Anisotropy (3)



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

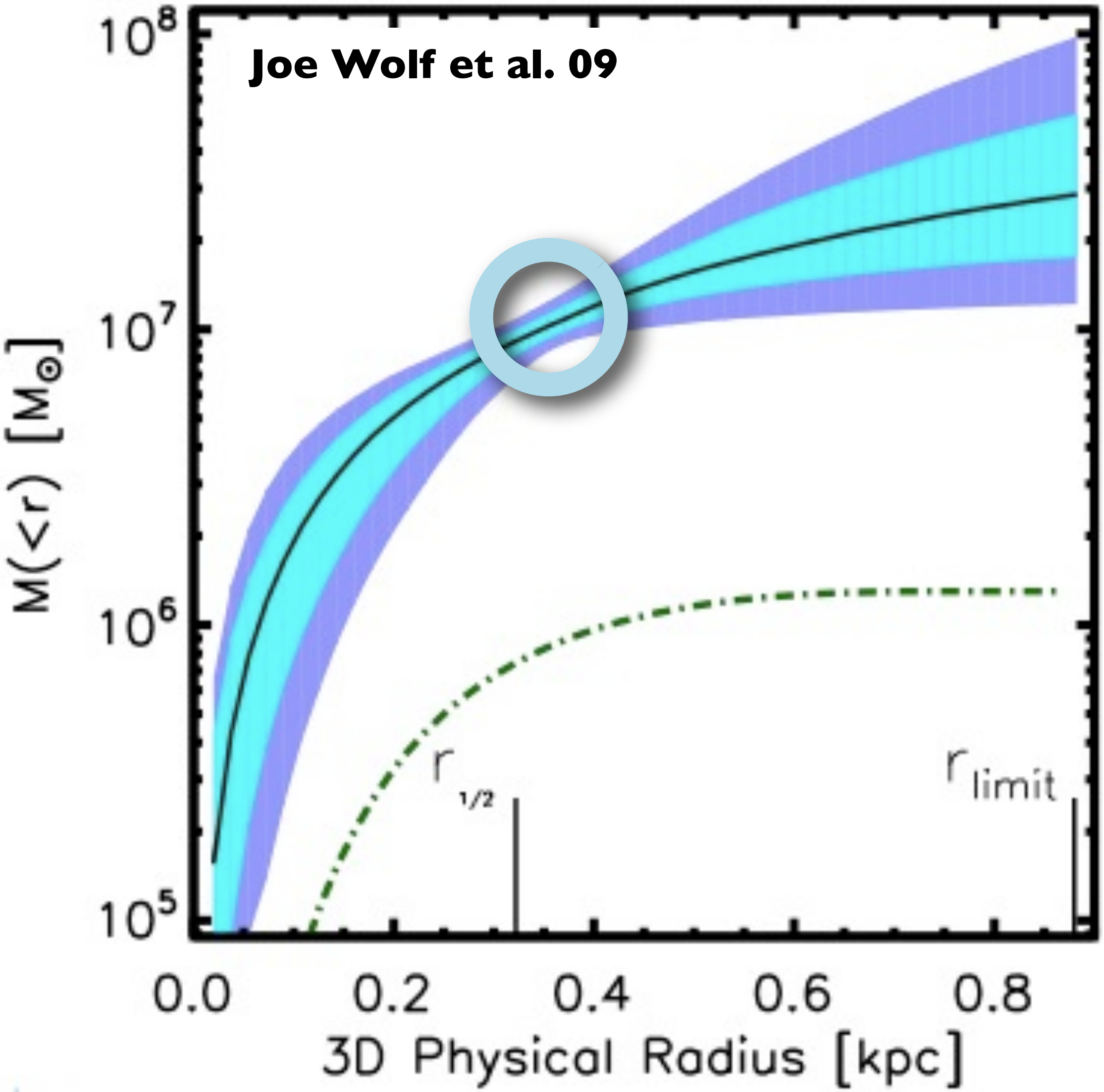
+ 2 photometric uncertainties in the light profile

Carina: 900 stars from Walker et al.



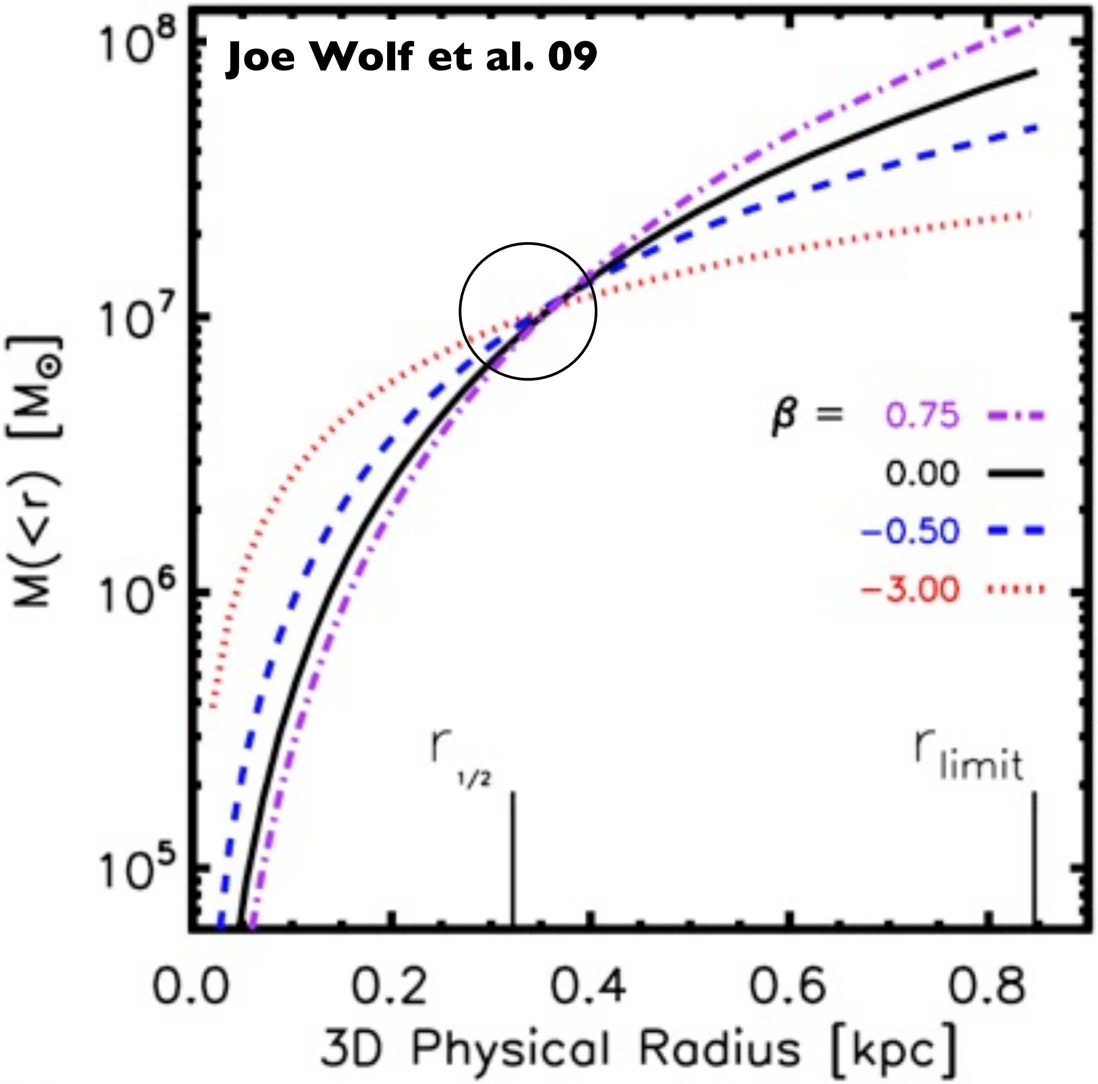
$M_*/L = 3$

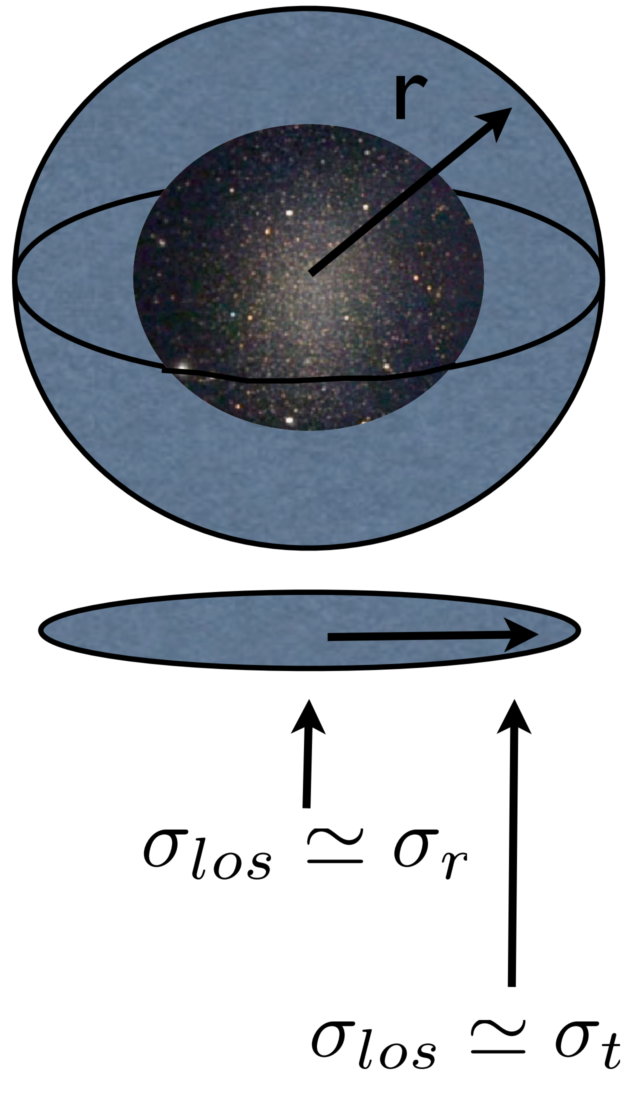
Carina: 900 stars from Walker et al.



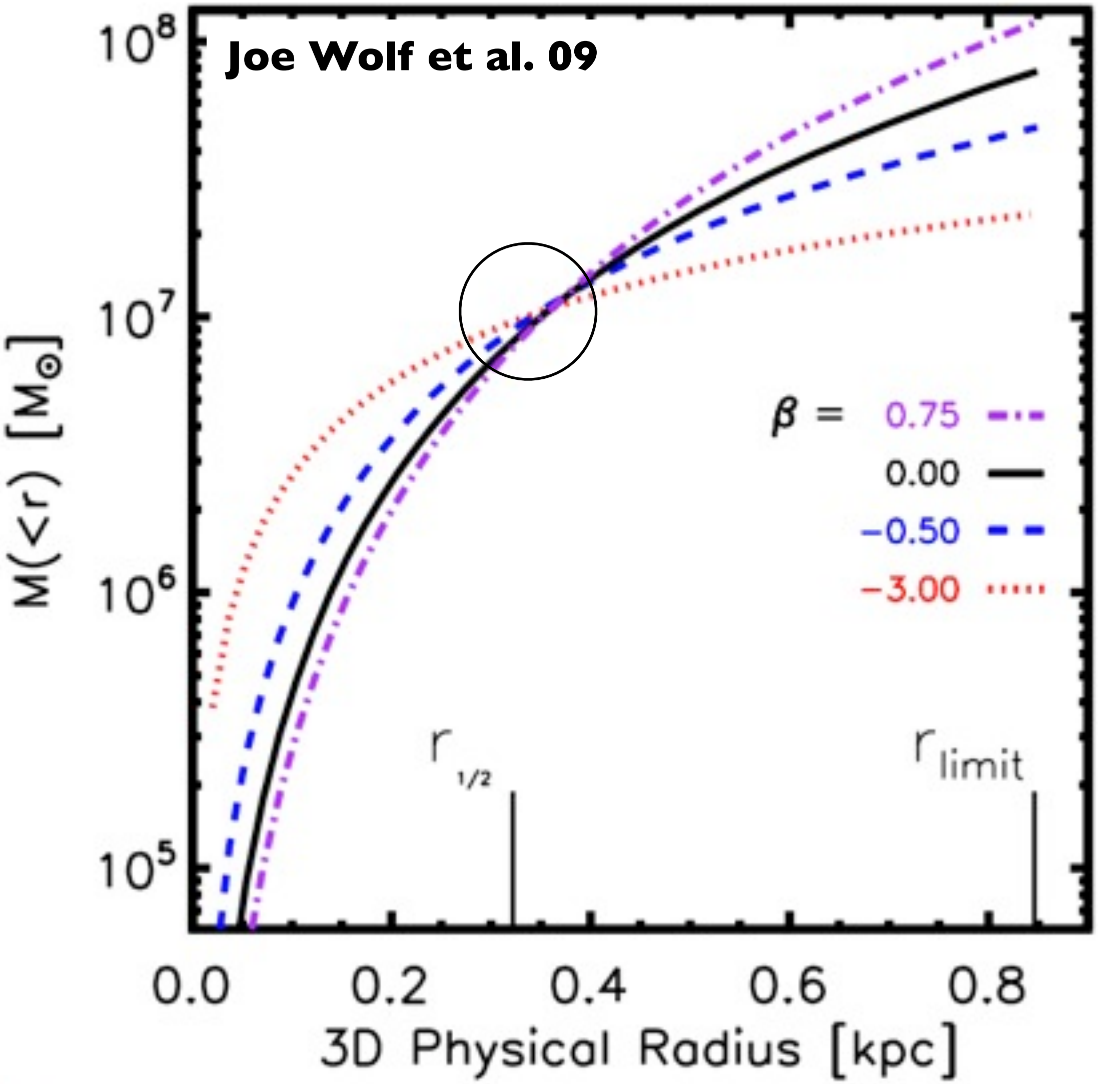
Mass is best constrained at the 3d half-light radius

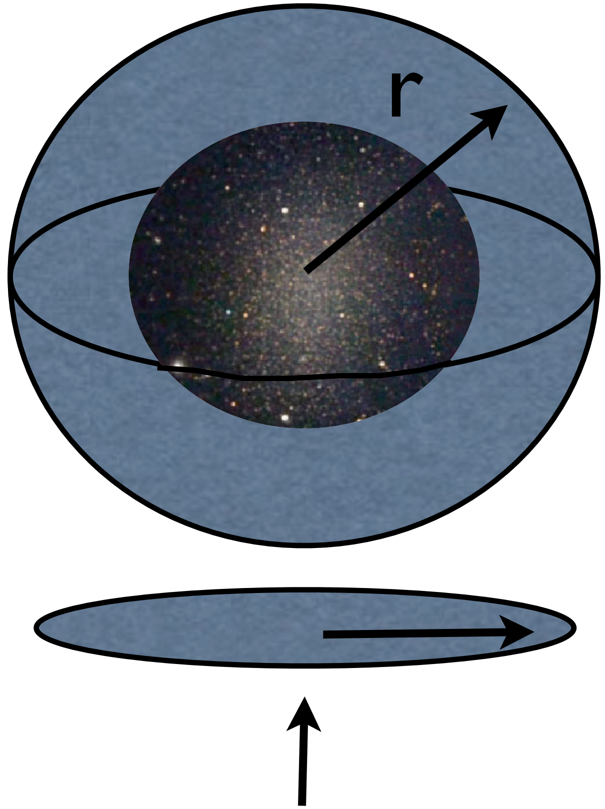
Same data: force a fixed β





Same data: force a fixed β





At small R, σ_{los} measures ~σ_r
- if β<0, M increases
- if β>0, M decreases

Where is β uncertainty minimized?

Wolf, Martinez, JSB, Kaplinghat et al. 09

Can Show:

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

$$\frac{d\,\ln\rho_\star}{d\ln r}(r_{\rm eq}) = 3$$

→

$$M(<r_{\rm eq};\beta) = M(<r_{\rm eq};0)$$

↓

$$r_{\rm eq} \simeq r_{1/2}$$

→

$$M(<r_{1/2}) = 3\,G^{-1}\,r_{1/2}\,\sigma_{los}^2$$

Where is β uncertainty minimized?

Wolf, Martinez, JSB, Kaplinghat et al. 09

Jeans Equation:

$$M(<r) = \frac{r\sigma_r^2}{G}\left[-\frac{\mathrm{d}\ln\sigma_r^2}{\mathrm{d}\ln r} - \frac{\mathrm{d}\ln\rho_*}{\mathrm{d}\ln r} - 2\beta\right]$$

Rewrite, absorbing β into the total (3d) velocity dispersion:

$$\sigma_{tot}^2 = (3-2\beta)\sigma_r^2$$

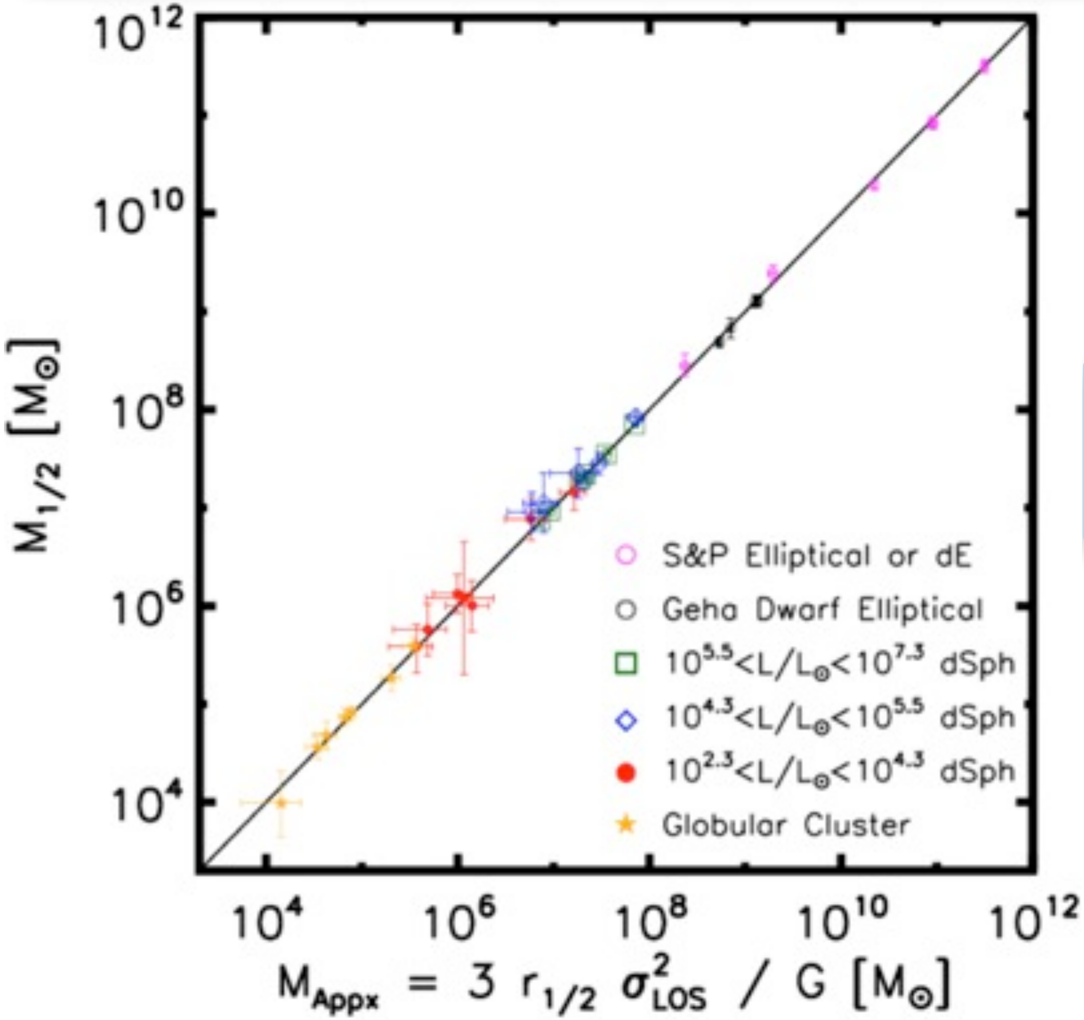
$$M(<r) = \frac{r\sigma_{tot}^2(r)}{G} - \frac{r\sigma_r^2(r)}{G}\left[\frac{d\,\ln\rho_\star}{d\ln r} + \frac{d\,\sigma_r^2}{d\ln r} + 3\right]$$

$$\left(\frac{d\,\ln\rho_\star}{d\ln r} + \frac{d\,\sigma_r^2}{d\ln r}\right)\Bigg|_{r=r_3} \equiv -3 \quad \Rightarrow \quad M(r_3) = \frac{r_3\square_{tot}^2(r_3)}{G}$$

if σ is flatter than ρ★

$$r_3 \simeq r_{1/2} \quad \Rightarrow \quad M(r_{1/2}) = \frac{r_{1/2}\sigma_{tot}^2(r_{1/2})}{G} \simeq \frac{3\,r_{1/2} < \sigma_{los}^2 >}{G}$$

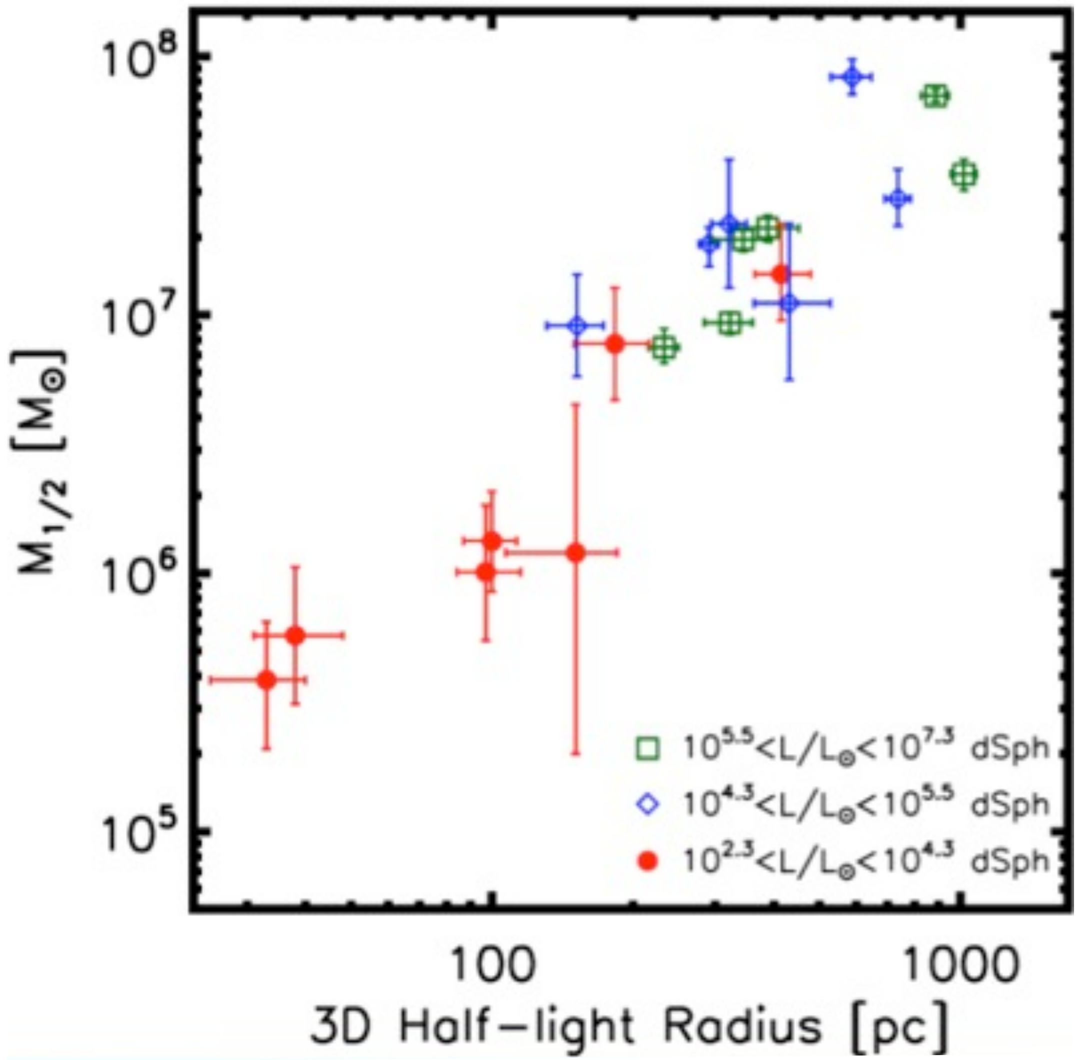
Formula works to 20% over 8 orders of magnitude in half-light mass



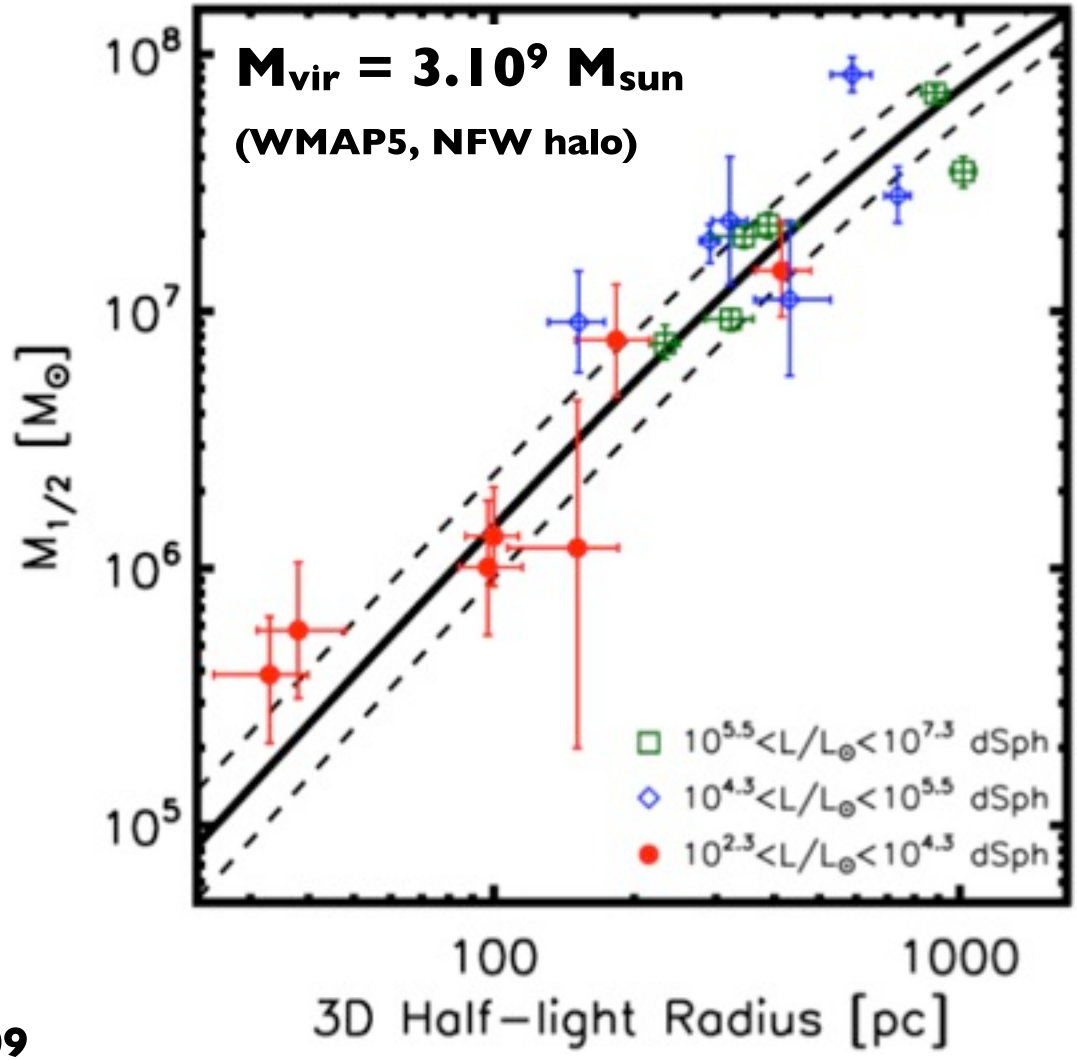
$$M(< r_{1/2}) = 3\,G^{-1}\,r_{_{1/2}}\,\sigma^2_{los}$$

Wolf, Martinez, JSB, Kaplinghat et al. 09

MW Dwarf Spheroidals: $M_{1/2}$ vs $r_{1/2}$

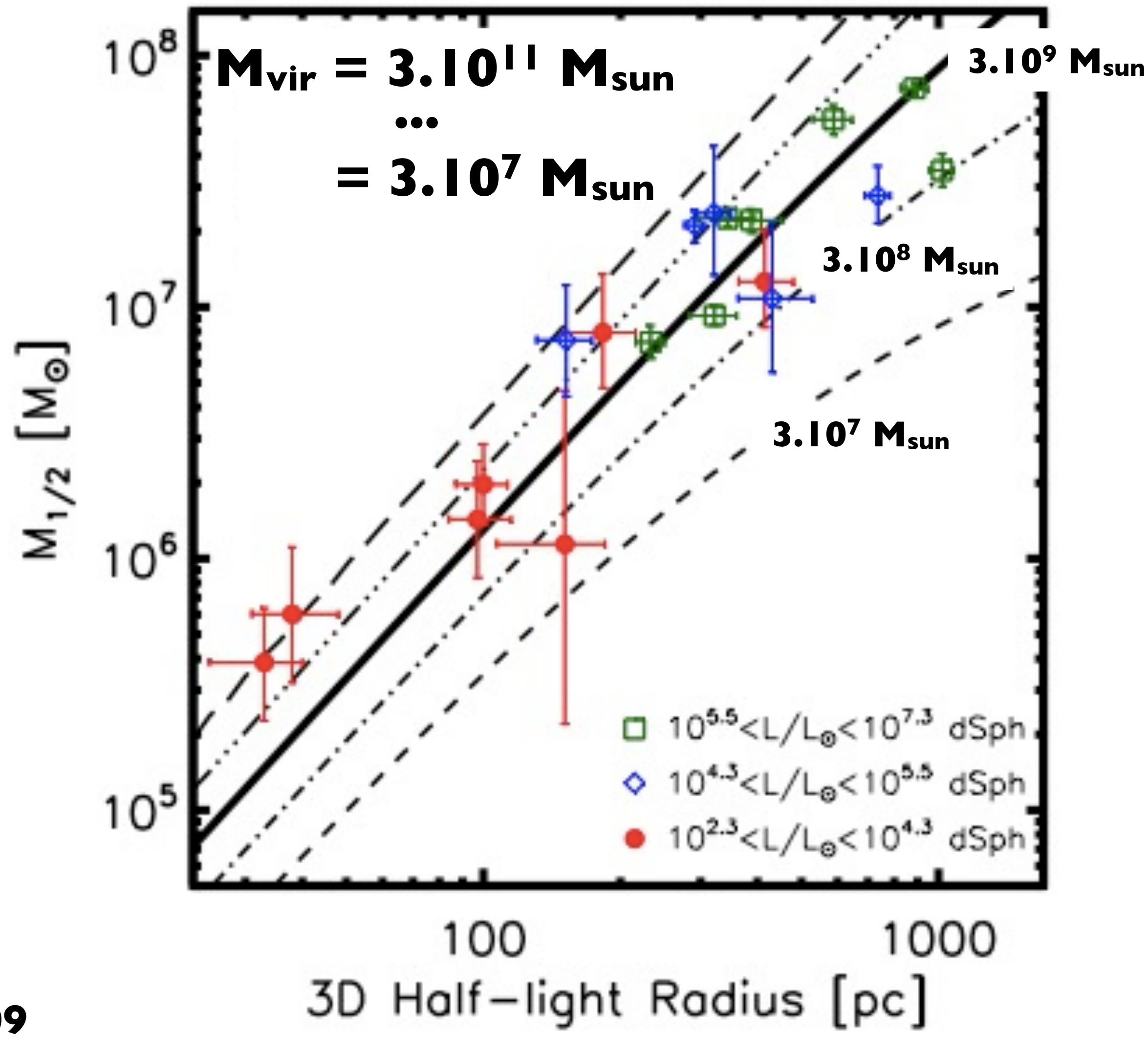


MW Dwarf Spheroidals: $M_{1/2}$ vs $r_{1/2}$



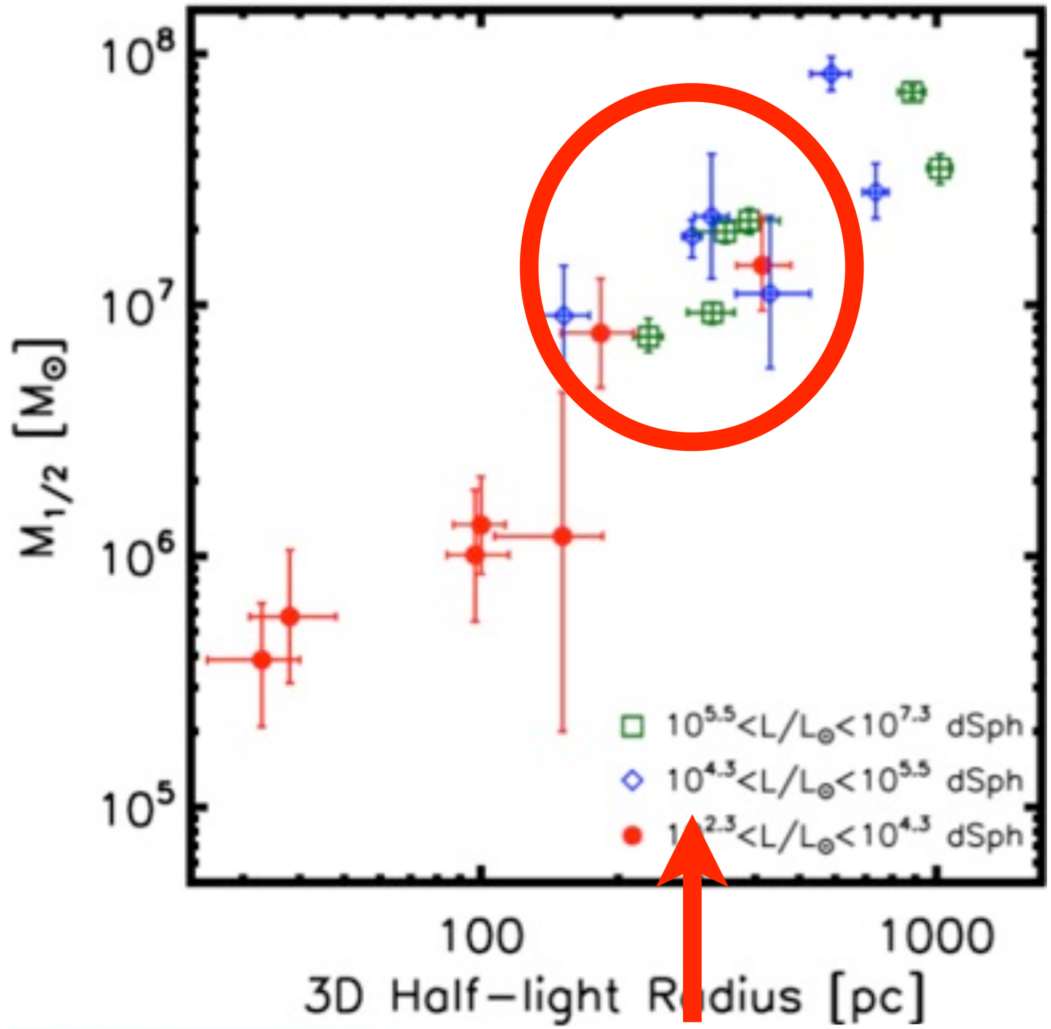
Joe Wolf et al. 09

All systems have $M_{vir} > 10^8\ M_{sun}$ + No evidence for M_{vir} trend with Luminosity

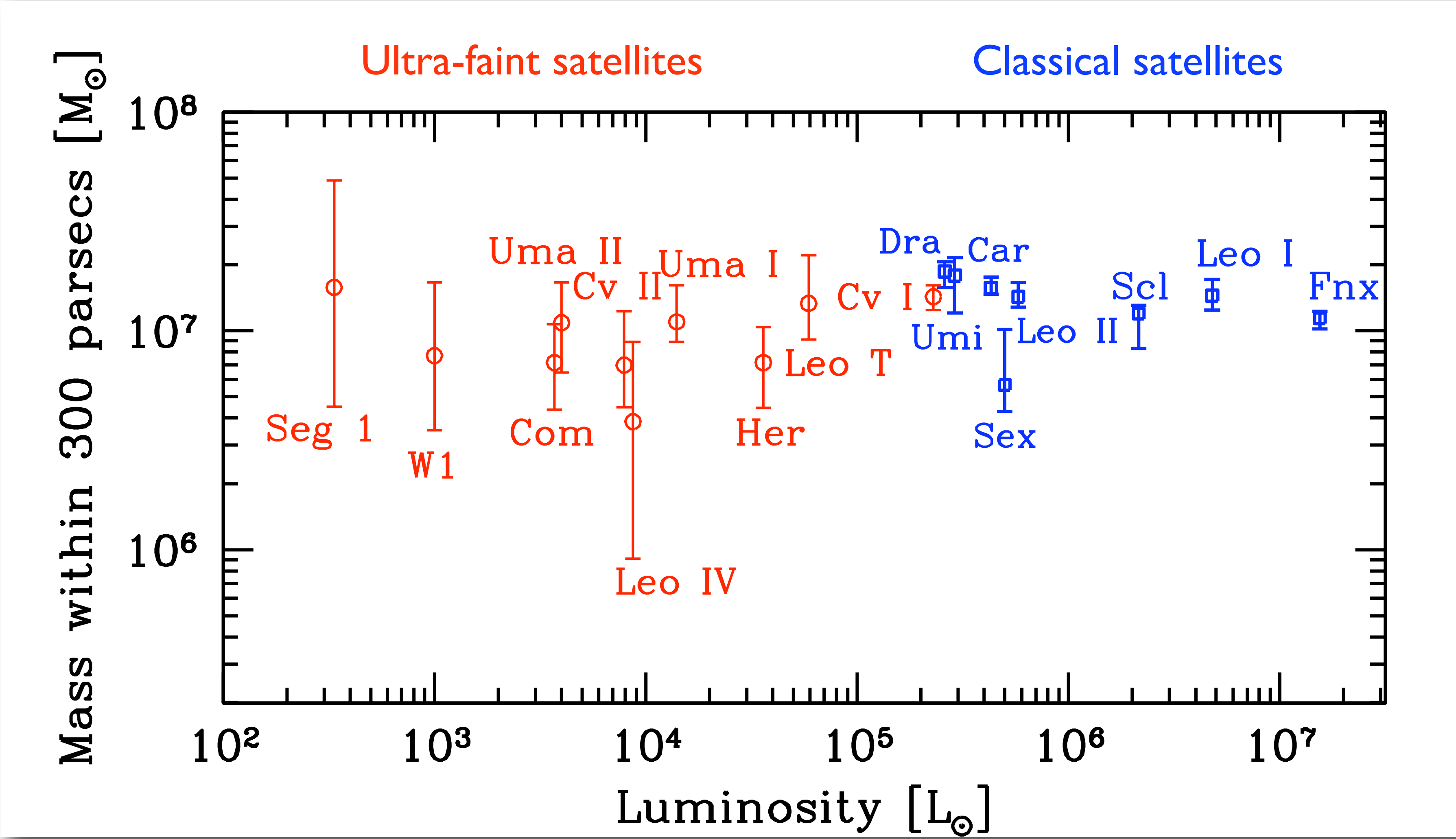


Joe Wolf et al. 09

Look at mass within typical radius: $r_{1/2} \sim 300$pc



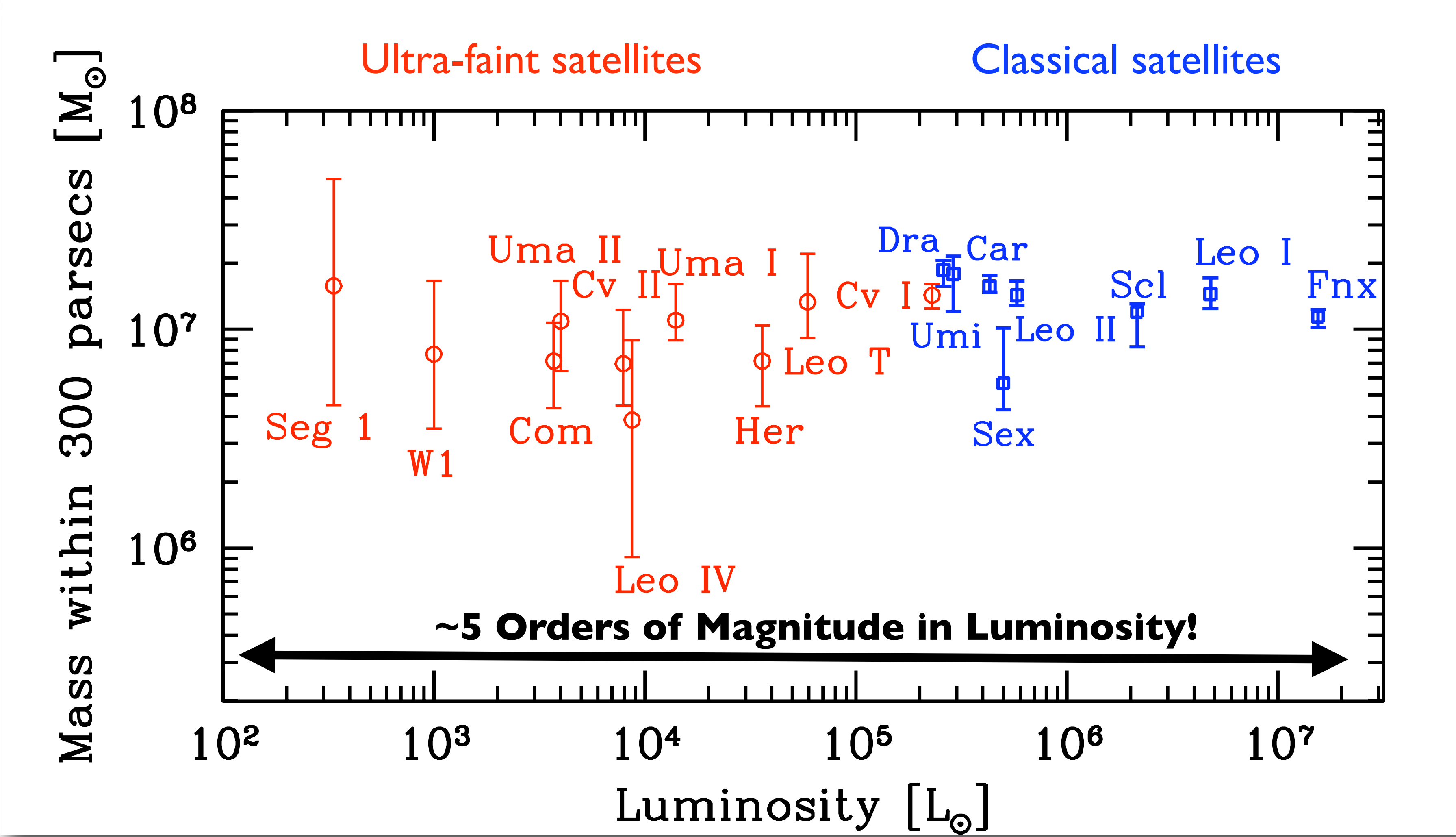
A Common Mass for MW Satellite Galaxies



L. Strigari, J. Bullock, M. Kaplinghat, J. Simon, M. Geha, B. Willman, M. Walker,

[Nature, Aug 28, 2008]

A Common Mass for MW Satellite Galaxies



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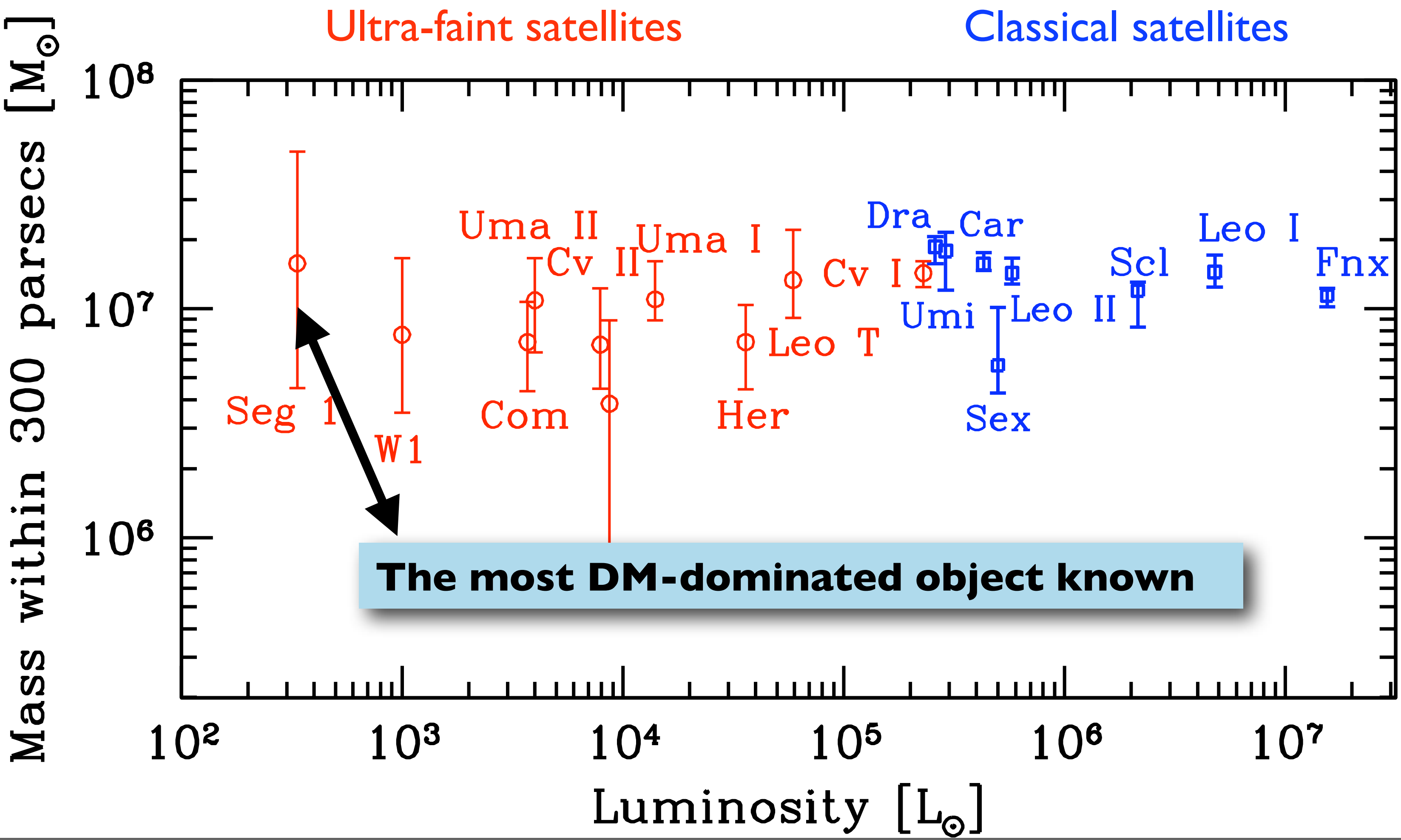


L. Strigari, J. Bullock, M. Kaplinghat, J. Simon, M. Geha, B. Willman, M. Walker,

[Nature, Aug 28, 2008]

A characteristic mass for Milky Way dwarfs:

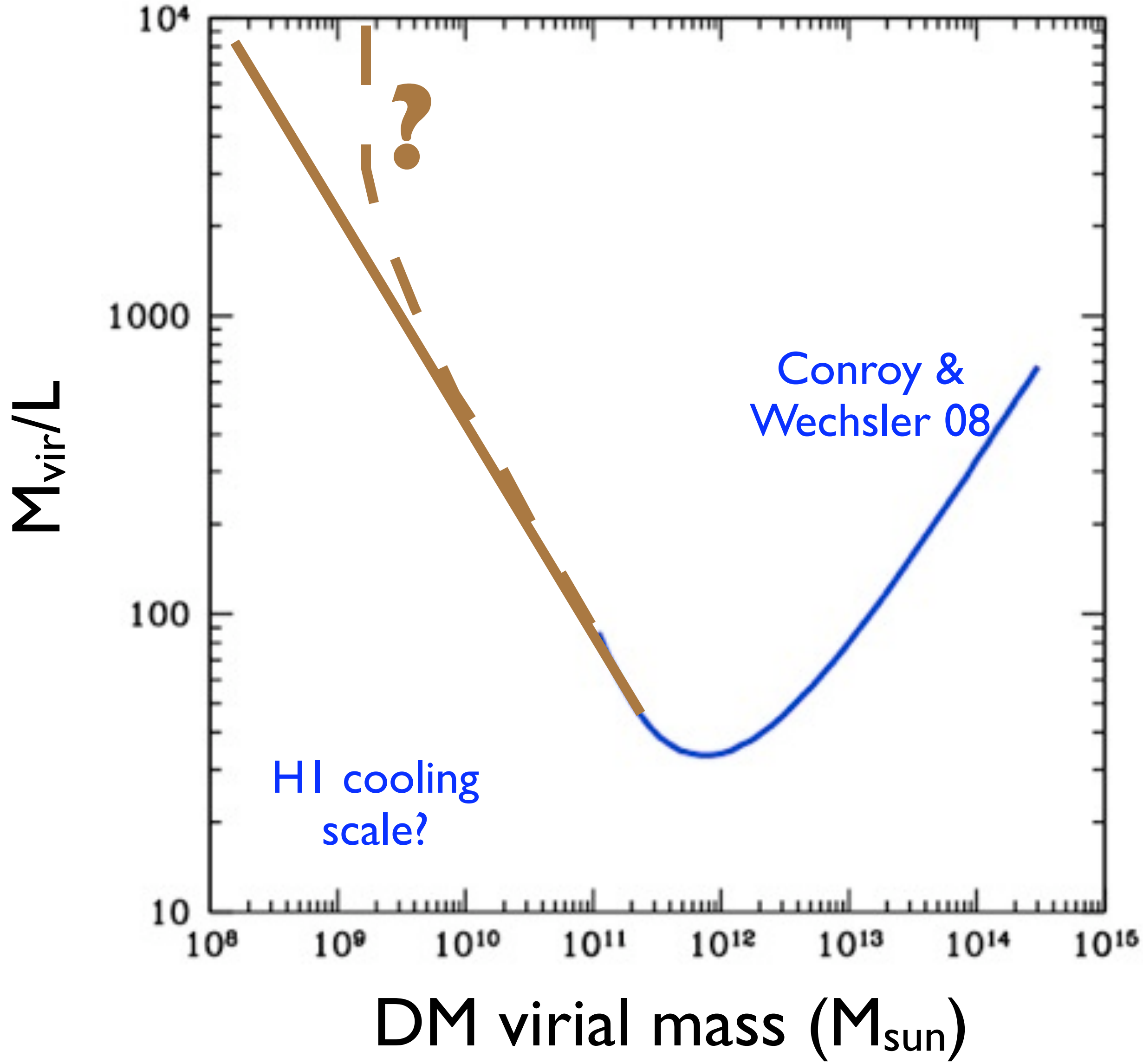
$$M(r < 300\mathrm{pc}) \simeq 10^7 M_\odot$$

$$M(< 300\mathrm{pc}) \simeq 10^7 M_\odot \left(\frac{M_{\mathrm{vir}}}{10^9 M_\odot} \right)^{1/3}$$

$$M_{\mathrm{threshold}} \simeq 10^9 M_\odot \ \ \mathbf{?}$$

~ Atomic cooling limit.
~10^4 K radiative feedback scale
~$M_{\text{free-stream}}$ for ~1KeV neutrinos

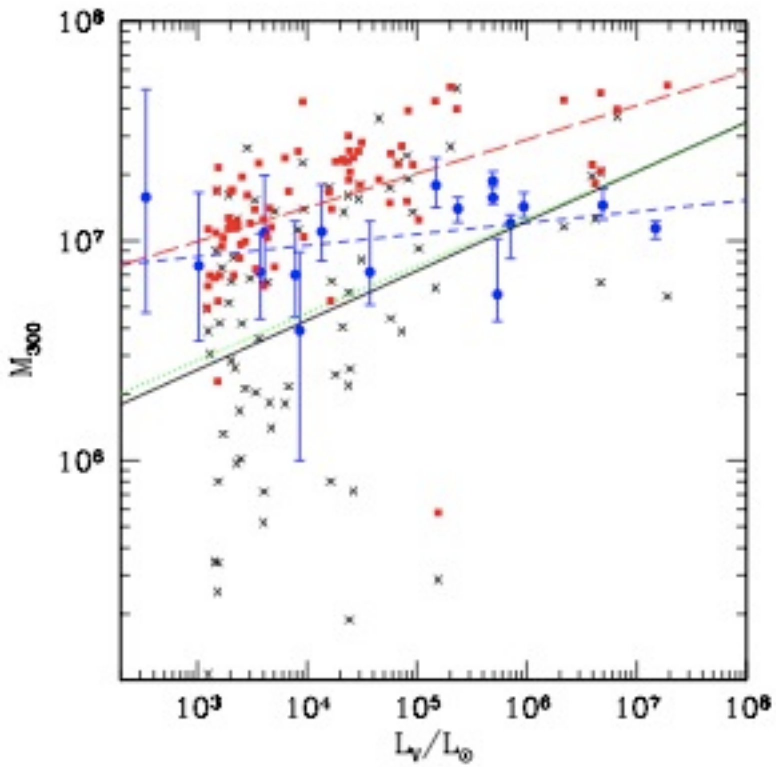
Efficiency of Galaxy Formation?



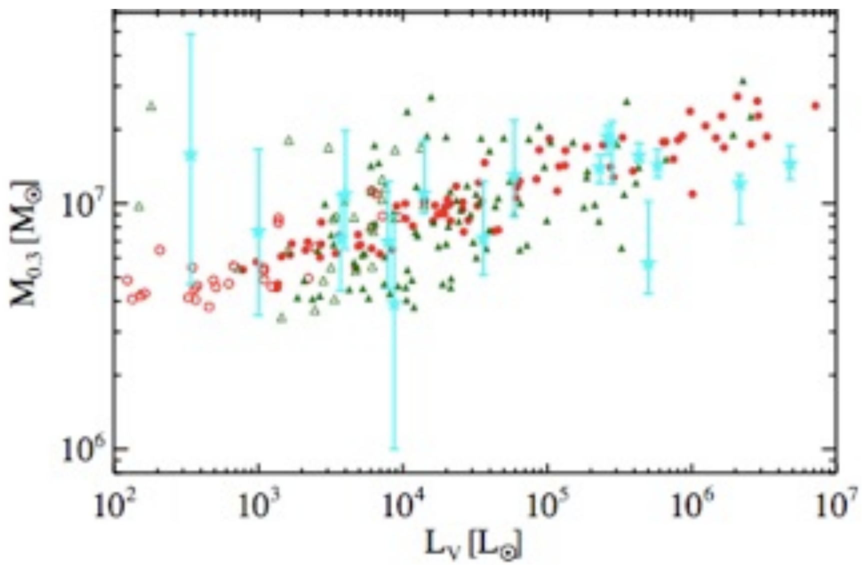
A comparison to models

$M_{300} \sim 10^9\ M_{sun}$ = Generally good news for CDM
But lack of trend with L is hard to reproduce...

Munoz, Madau, Loeb, Diemand 09

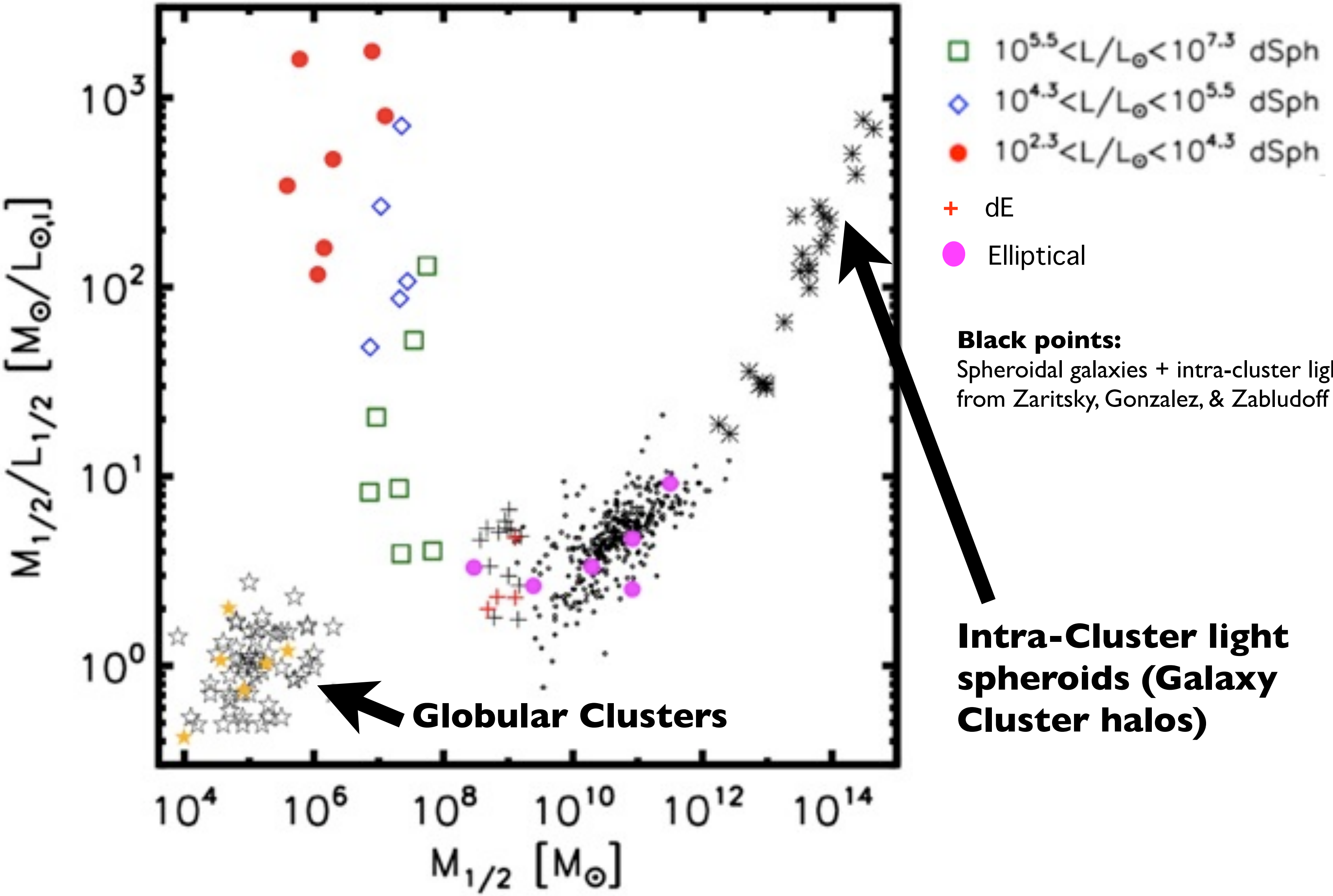


Busha et al. 09



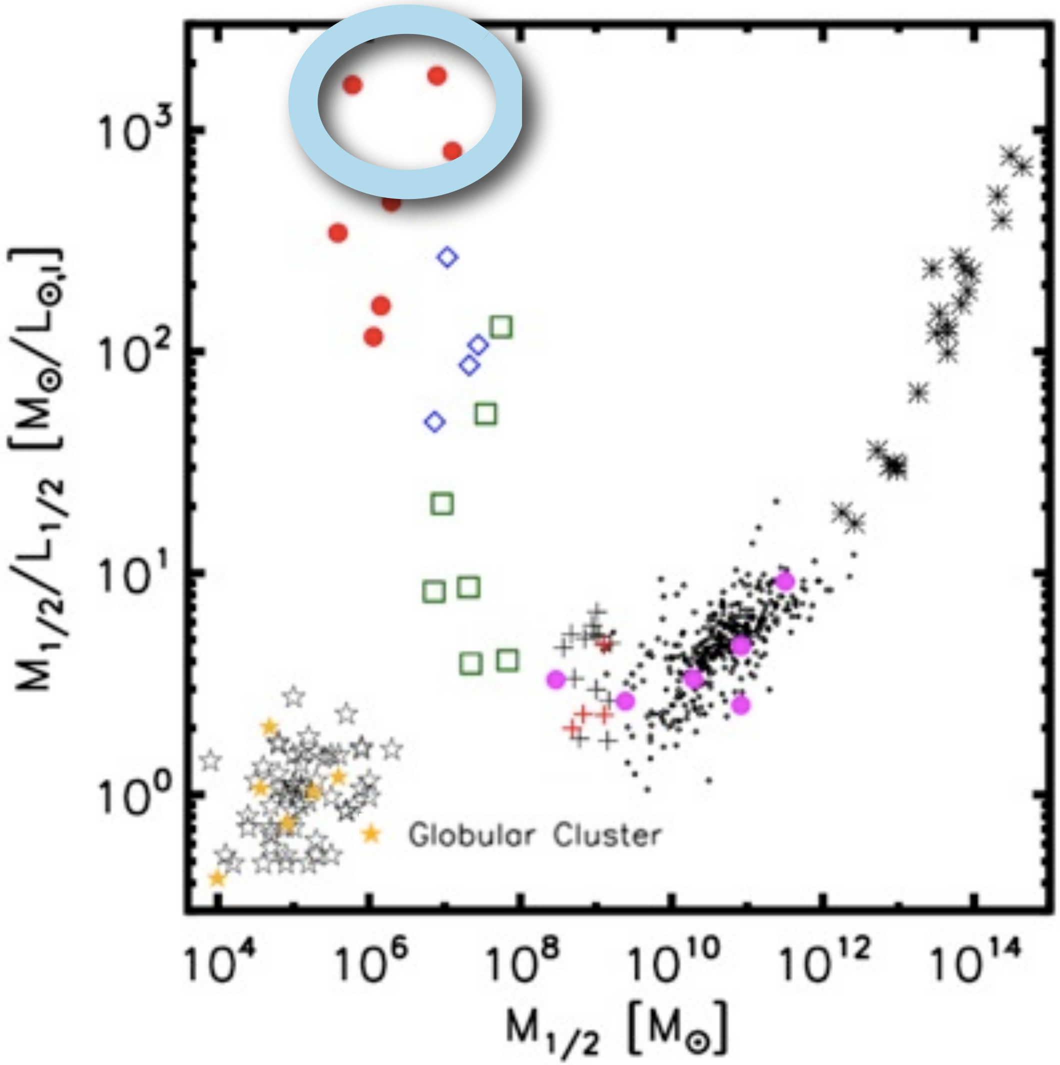
Similar results by
Koposov et al. 09 & Li et al. 08

dSphs vs. Global Population of Spheroids



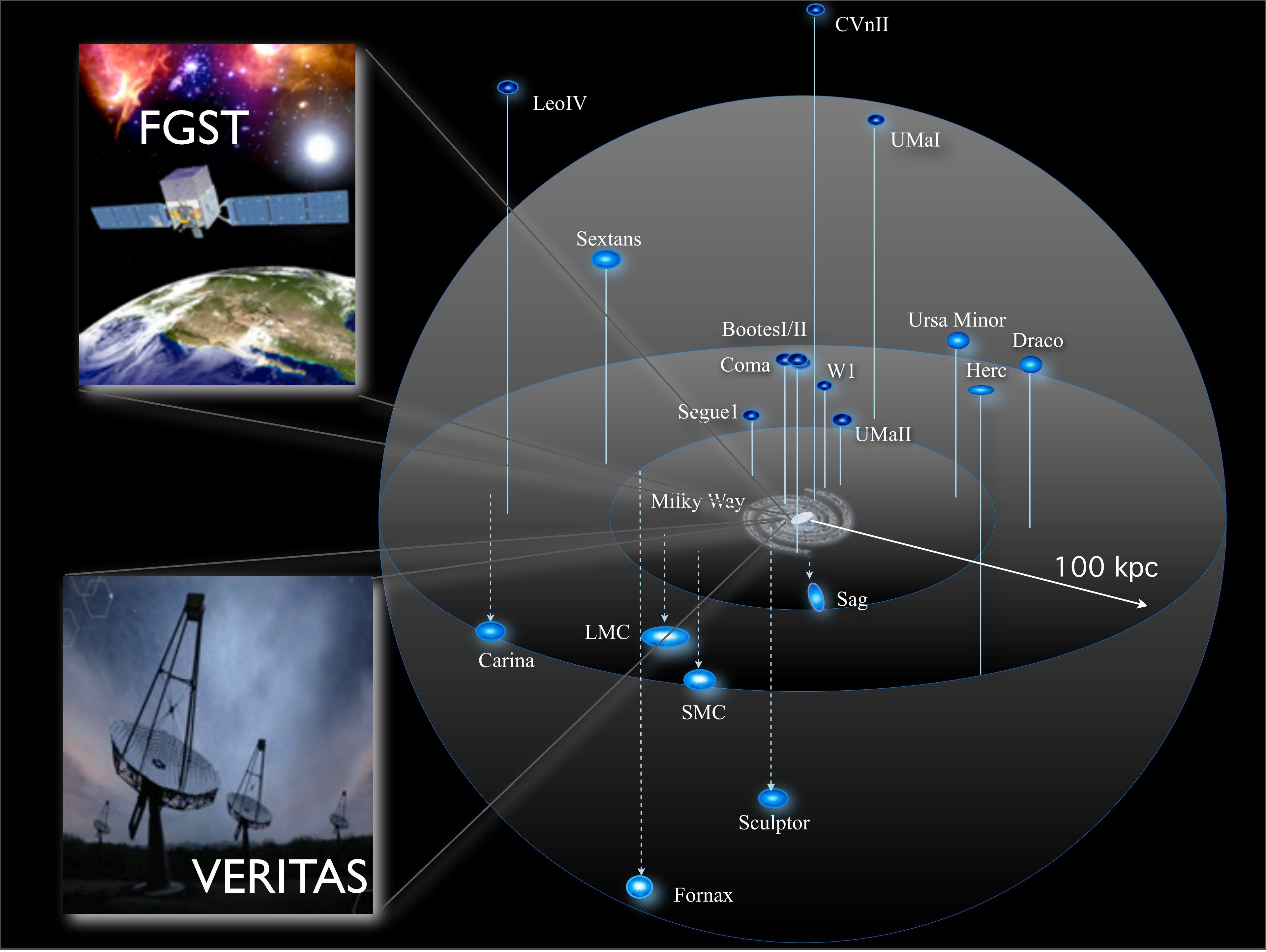
Black points:
Spheroidal galaxies + intra-cluster light from Zaritsky, Gonzalez, & Zabludoff 06

dSphs vs. Global Population of Spheroids



$(M/L_I)_{1/2}$ ~1500

Ultra-faint dSphs
Highest M/L of any known objects
- even compared to galaxy clusters
- within half-light radius

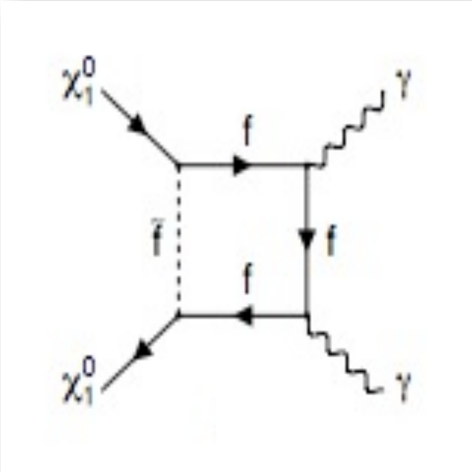

FGST
VERITAS
CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
100 kpc
Sag
LMC
Carina
SMC
Sculptor
Fornax

Strigari et al. 2007, 2008; **Martinez** et al. 2009

Dwarf Satellites and DM indirect detection

$$\Phi(E) = \frac{<\sigma v> N_\gamma(E)}{2m_\chi^2} \int_0^{\psi_{max}} \sin\psi d\psi \int_{\ell_-}^{\ell_+} \rho_{DM}^2(\ell(\psi)) d\ell(\psi)$$

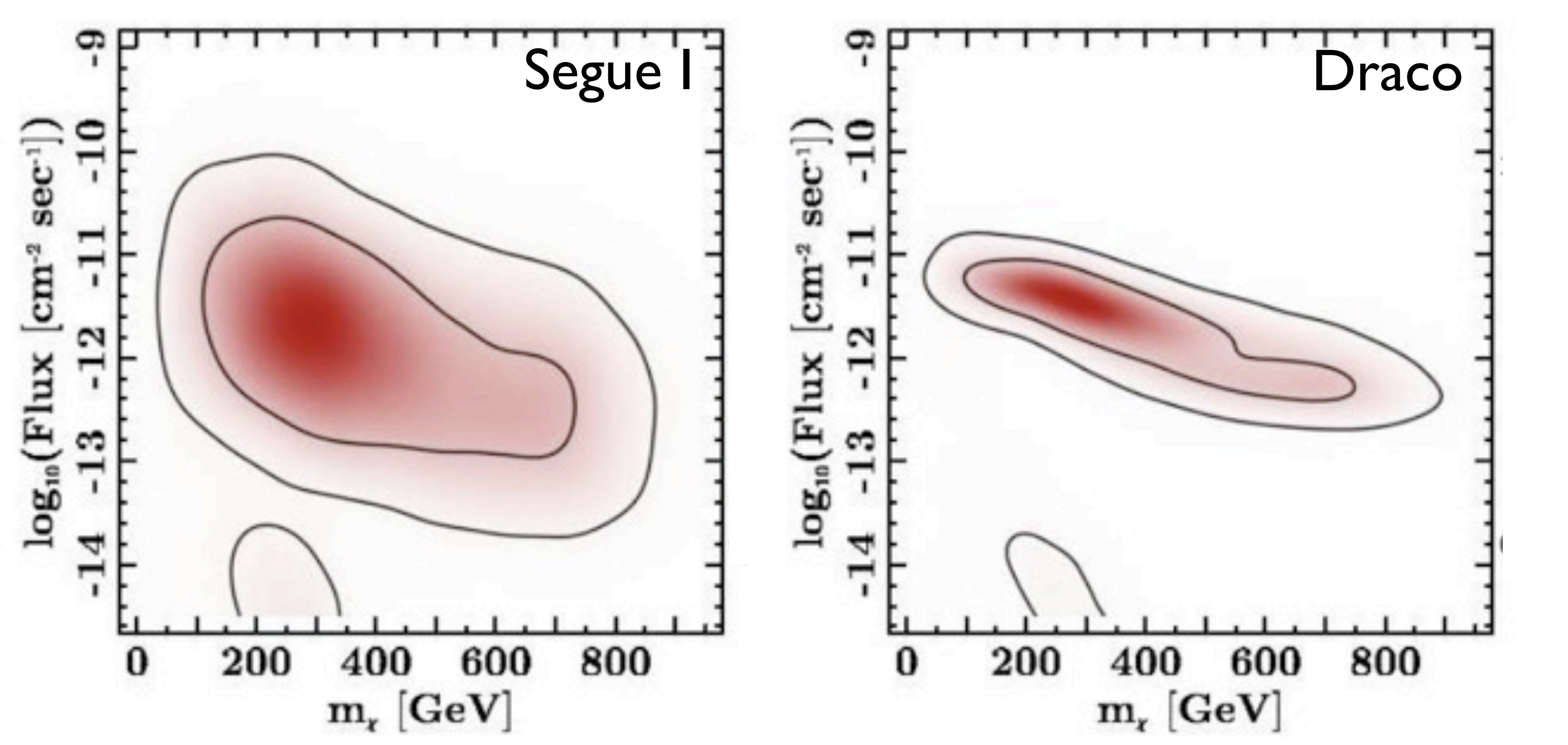
Particle Physics



Astrophysics

Joint expectations from supersymmetry + astrophysics

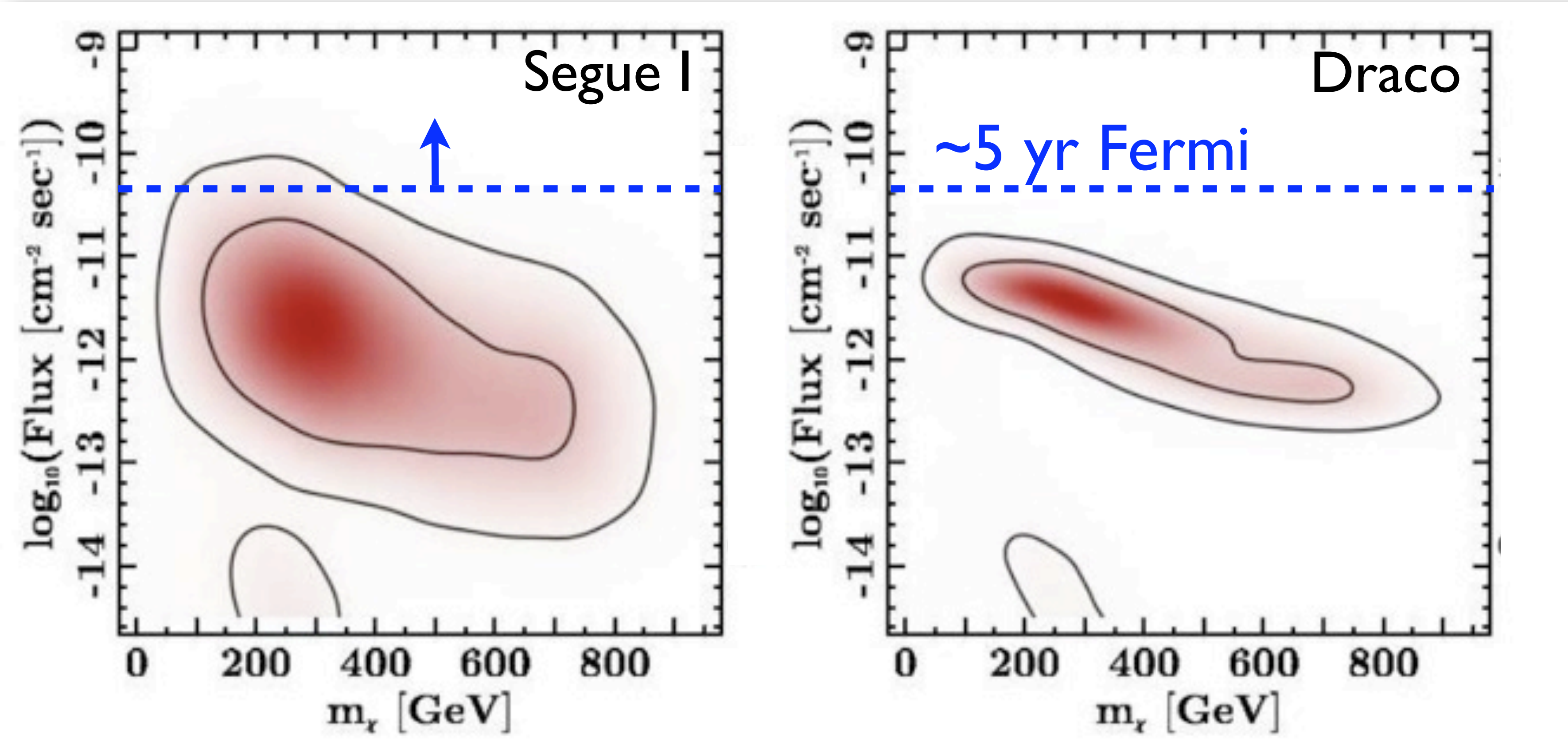
Combined MCMC chains for CMSSM + dSph mass models



Eγ>1GeV flux from **Martinez et al. 2009**

Joint expectations from supersymmetry + astrophysics

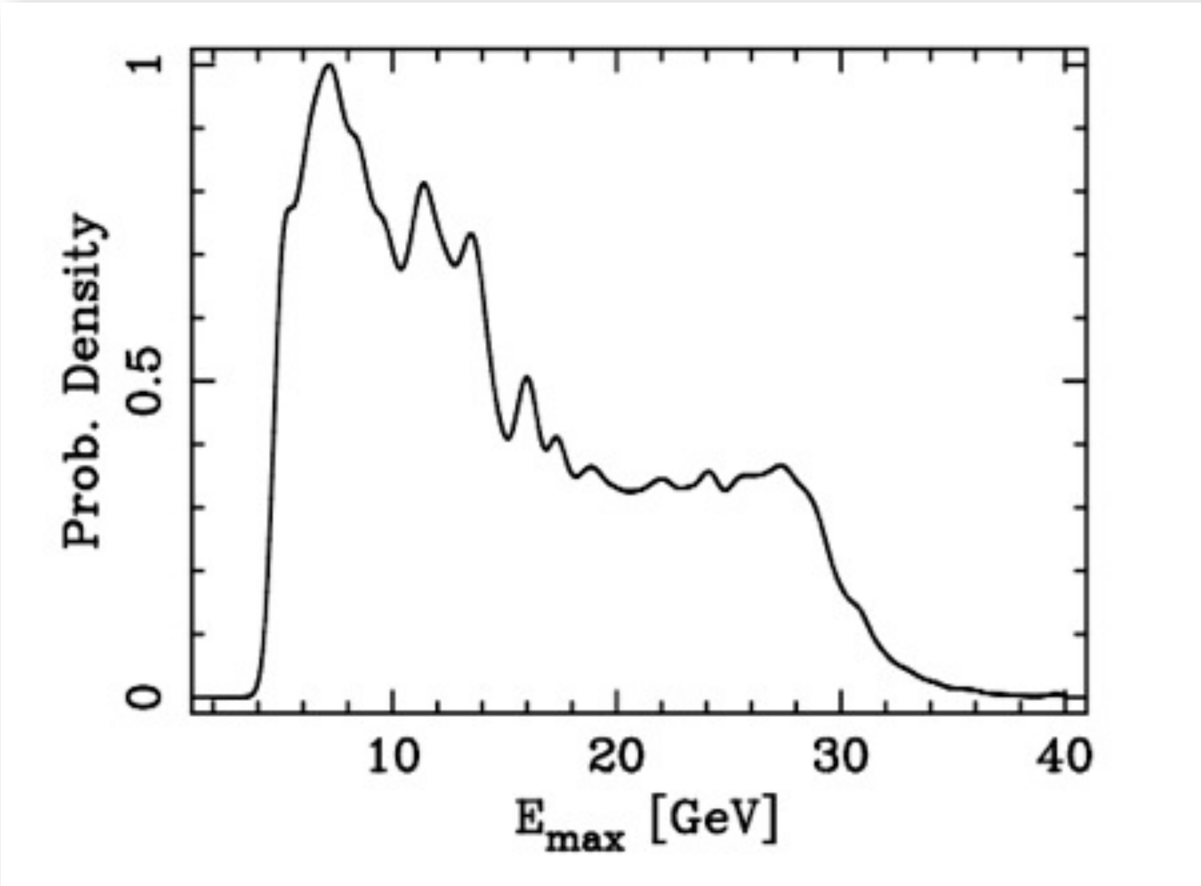
Combined MCMC chains for CMSSM + dSph mass models



E$_\gamma$>1GeV flux from **Martinez et al. 2009**

best way to extract DM annihilation signal above background is to know input spectrum

Peak of expected Energy Spectrum ~E^2 dN/dE



CMSSM:

E_{peak}~10 GeV

Martinez et al. 2009

Dwarf Satellites and DM indirect detection

$$\Phi(E) = \frac{<\sigma v> N_\gamma(E)}{2m_\chi^2} \int_0^{\psi_{max}} \sin\psi d\psi \int_{\ell_-}^{\ell_+} \rho_{DM}^2(\ell(\psi)) d\ell(\psi)$$

Let this be free

Rank by DM density signal

Dwarf Satellites and DM indirect detection

$$J(<\Psi_{max}) = \int_0^{\psi_{max}} \sin\psi d\psi \int_{\ell_-}^{\ell_+} \rho_{DM}^2(\ell(\psi))d\ell(\psi)$$

Ratio of signal from dwarf to dwarf is well-constrained:

$$J_{\rm Draco}(<1^\circ) = (3 \pm 1) \times 10^{-4} ({\rm GeV}^2/{\rm cm}^6)\,{\rm kpc}$$

Ursa Minor ~ 0.5 Draco

Sculptor ~ 0.2 Draco

Sextans ~ 0.05 Draco

Fornax ~ 0.05 Draco

Dwarf Satellites and DM indirect detection

$$J(<\Psi_{max}) = \int_0^{\psi_{max}} \sin\psi d\psi \int_{\ell_-}^{\ell_+} \rho_{DM}^2(\ell(\psi))d\ell(\psi)$$

Ratio of signal from dwarf to dwarf is well-constrained:

$$J_{\rm Draco}(<1^\circ) = (3 \pm 1) \times 10^{-4} ({\rm GeV}^2/{\rm cm}^6)\,{\rm kpc}$$

Fermi should be able to rule out DM models with Sommerfeld-enhanced cross sections of the type proposed to address PAMELA/ATIC data

Conclusions

- **A common mass scale for the satellite galaxies of the Milky Way.**

$\Rightarrow$ $M(r < 300\text{pc}) \simeq 10^7 M_\odot \longrightarrow M_{\text{threshold}} \simeq 10^9 M_\odot$ **?**

- **~400 Galactic Satellites?**

$\Rightarrow$ LSST and other planned surveys can discover them.

- **Dark Matter Indirect Detection**

$\Rightarrow$ Ratio of DM signal from dwarf to dwarf is well-constrained. No Astrophysical backgrounds.