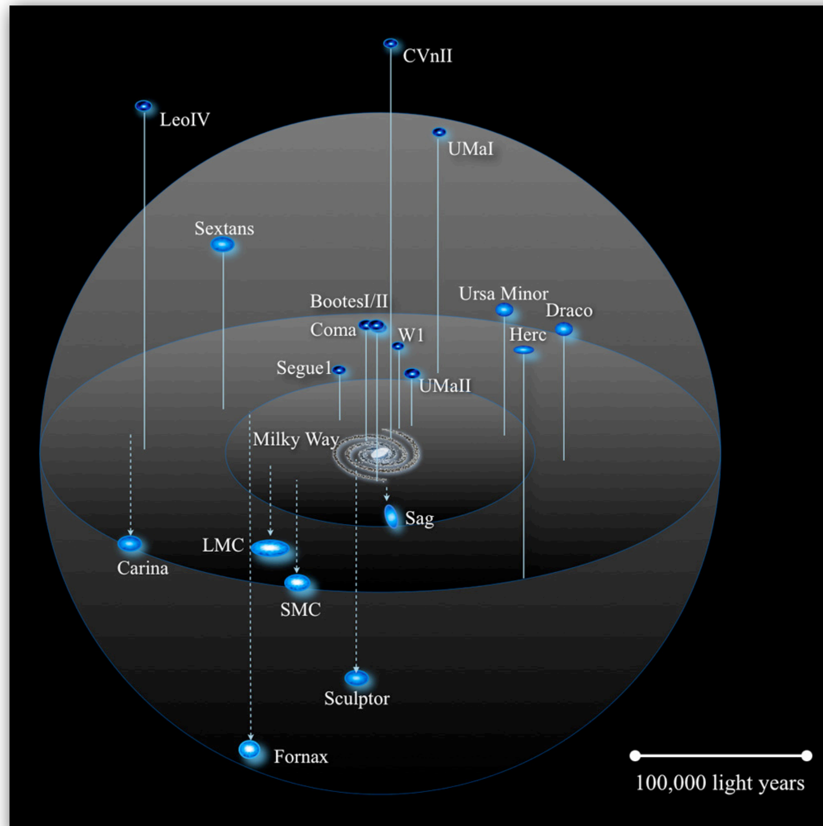
CDM and the Substructure Crisis

J. S. Bullock
XX Canary Islands Winter School, LG Cosmology



Theory: $N>10^{10}$ Observation: N~20

https://webfiles.uci.edu/bullock/Public/Canary2008/

Lecture 4: Revelations

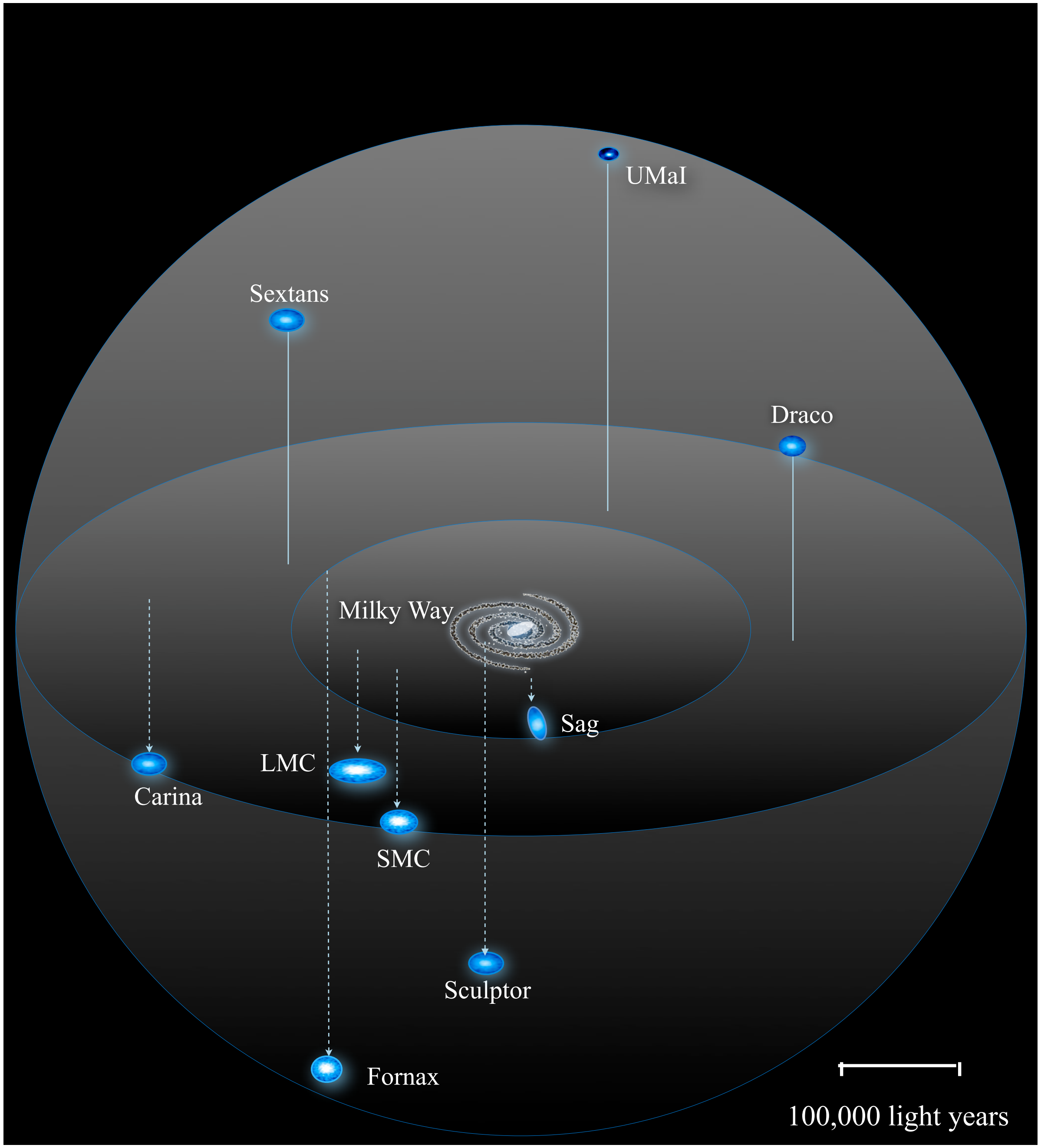
Thanks to: Erik Tollerud & Joe Wolf

https://webfiles.uci.edu/bullock/Public/Canary2008/

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
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994



Milky Way circa 2008

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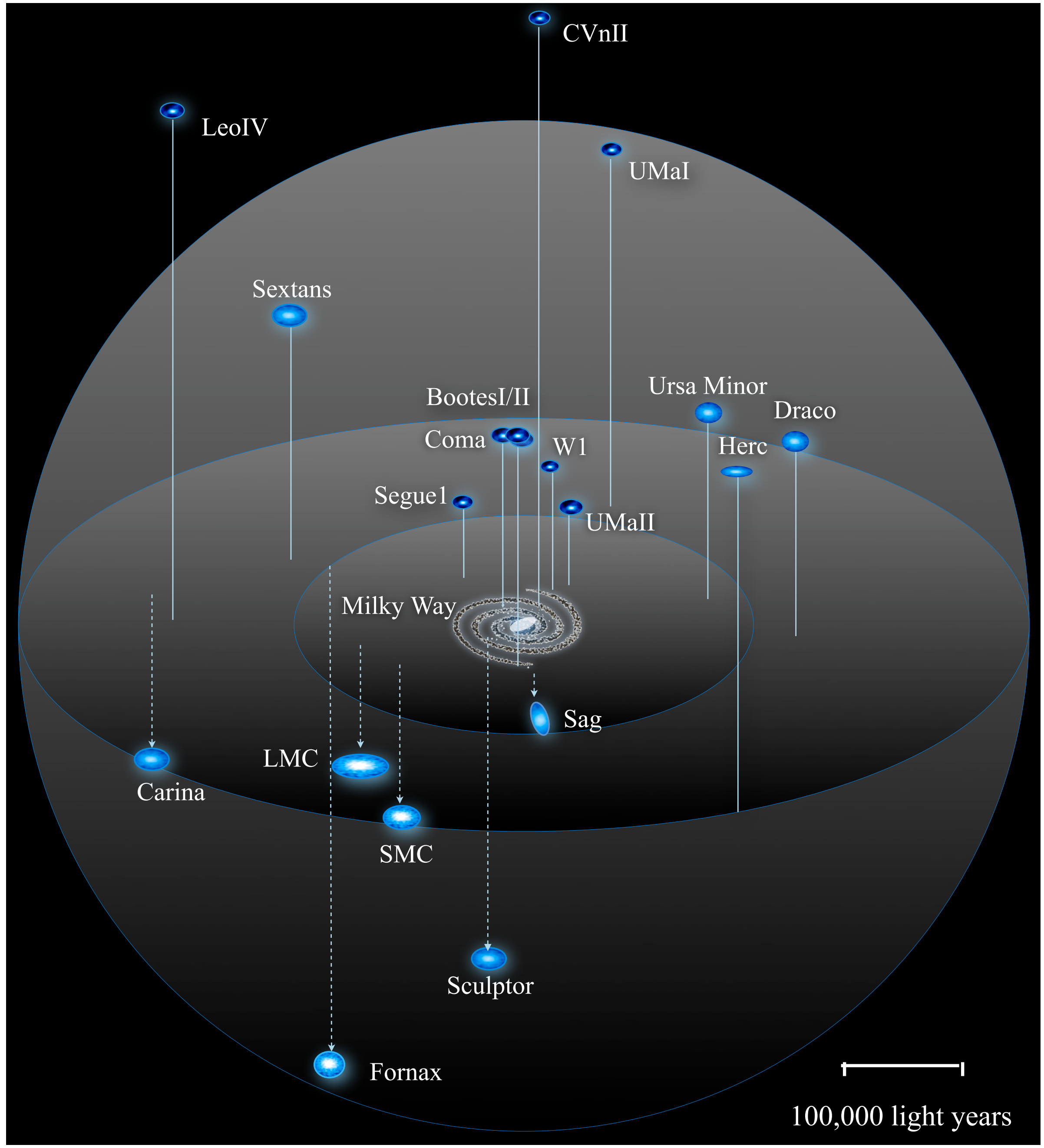
Carina	1977
Sextans	1990
Sagittarius	1994
Ursa Major I	**2005**
Willman I	**2005**
Ursa Major II	**2006**
Bootes	**2006**
Canes Venatici I	**2006**
Canes Venatici II	**2006**
Coma	**2006**
Segue I	**2006**
Leo IV	**2006**
Hercules	**2006**
Leo T	**2007**
Bootes II	**2007**
LeoIV	**2008**



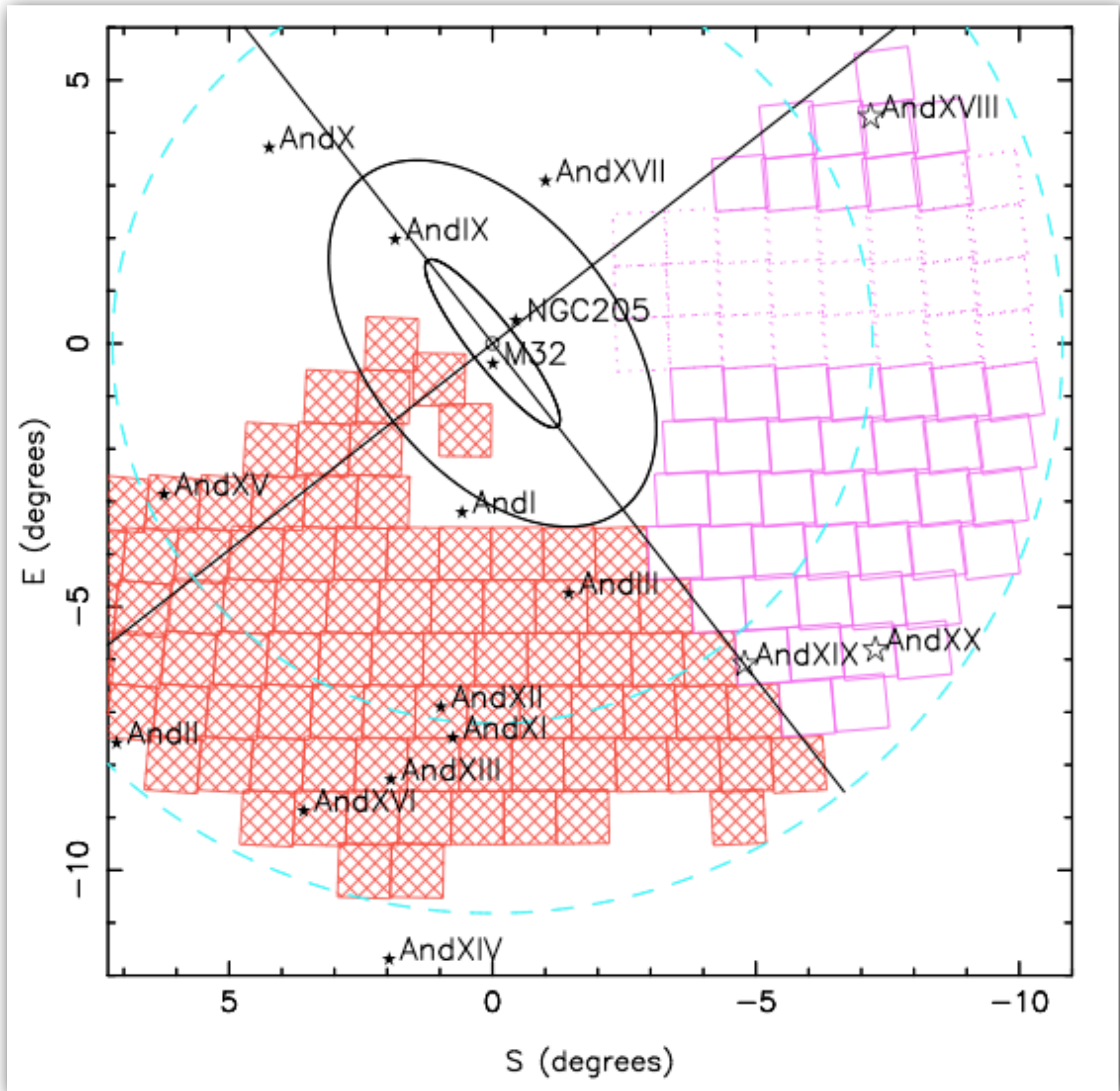
CENTER FOR COSMOLOGY

J. Bullock, UC Irvine

M31 circa 2004/2008

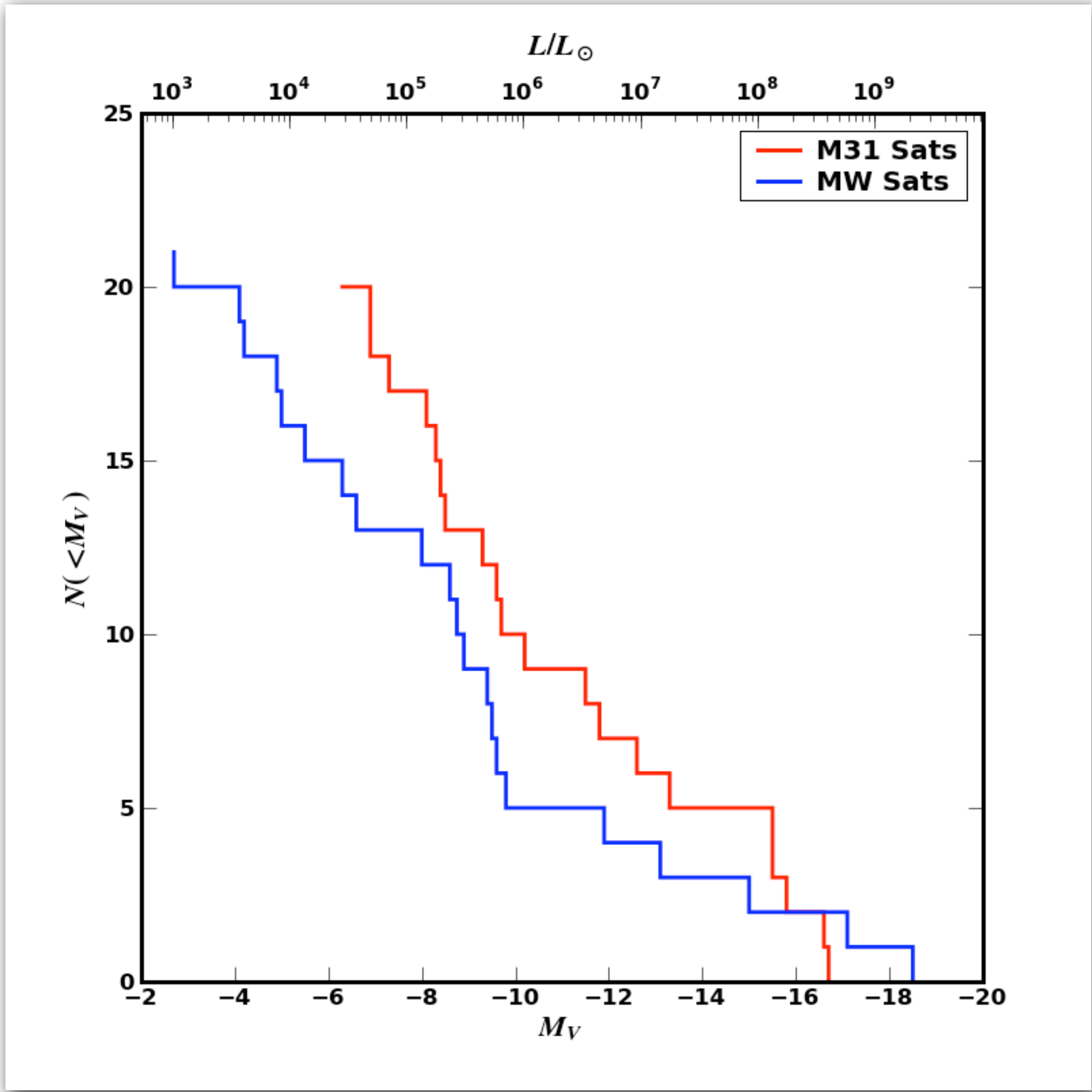
Name	Year Discovered
M32	1781
M33	1781
NGC 205	
NGC 185	
NGC 147	
And I	1972
And II	1972
And III	1972
And V	1998
And VI	1999
And VII	1999
And VIII	**2004**
And X	**2006**
And XI	**2006**
And XII	**2006**
And XIII	**2006**
And XIV	**2007**
And XV	**2007**
And XVI	**2007**
And XVII	**2008**
And XVIII	**2008**
And XIX	**2008**
And XX	**2008**

Alan McConnachie et al. 08



https://webfiles.uci.edu/bullock/Public/Canary2008/

current observed LF of M31 and MW satellites



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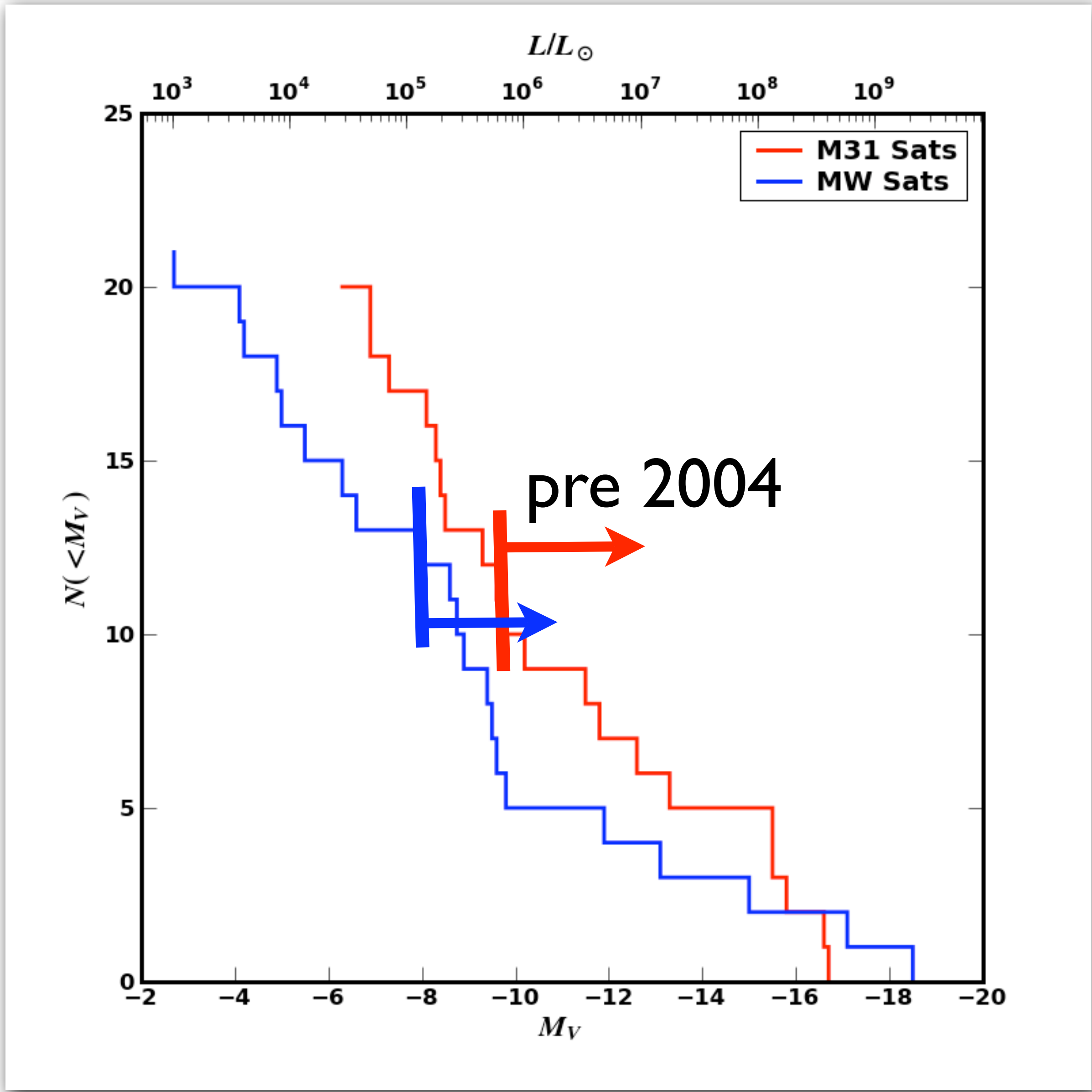

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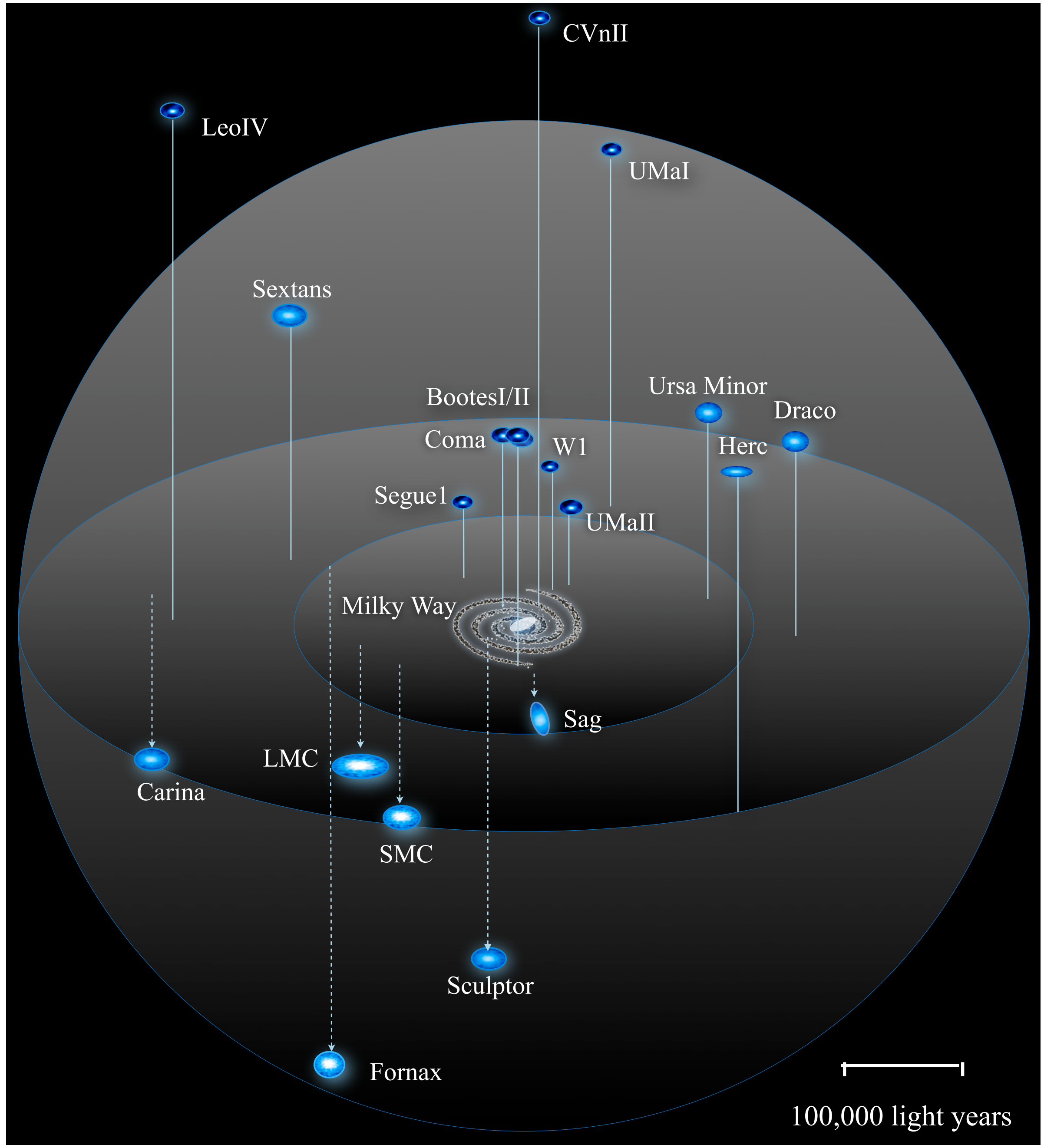

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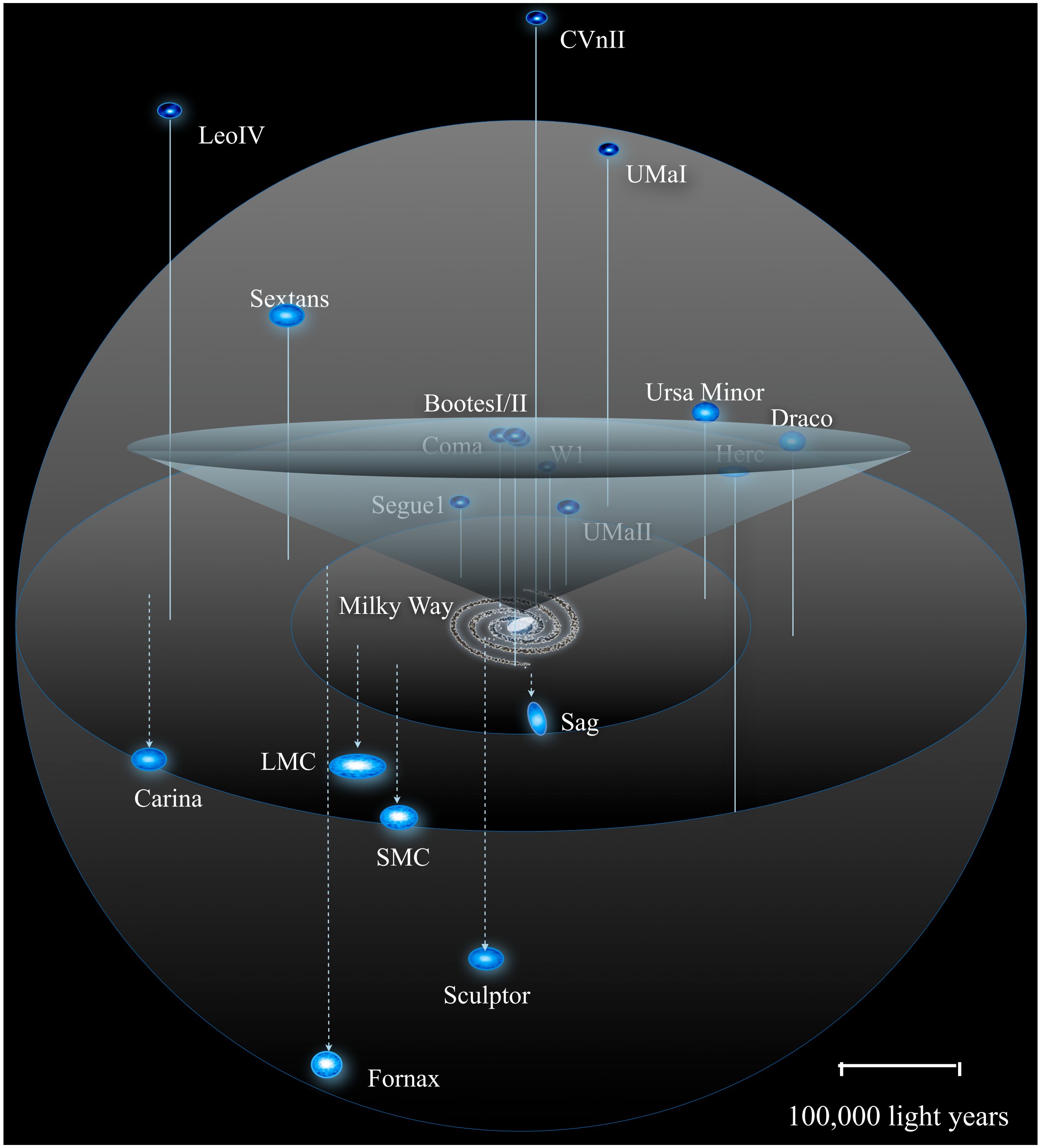
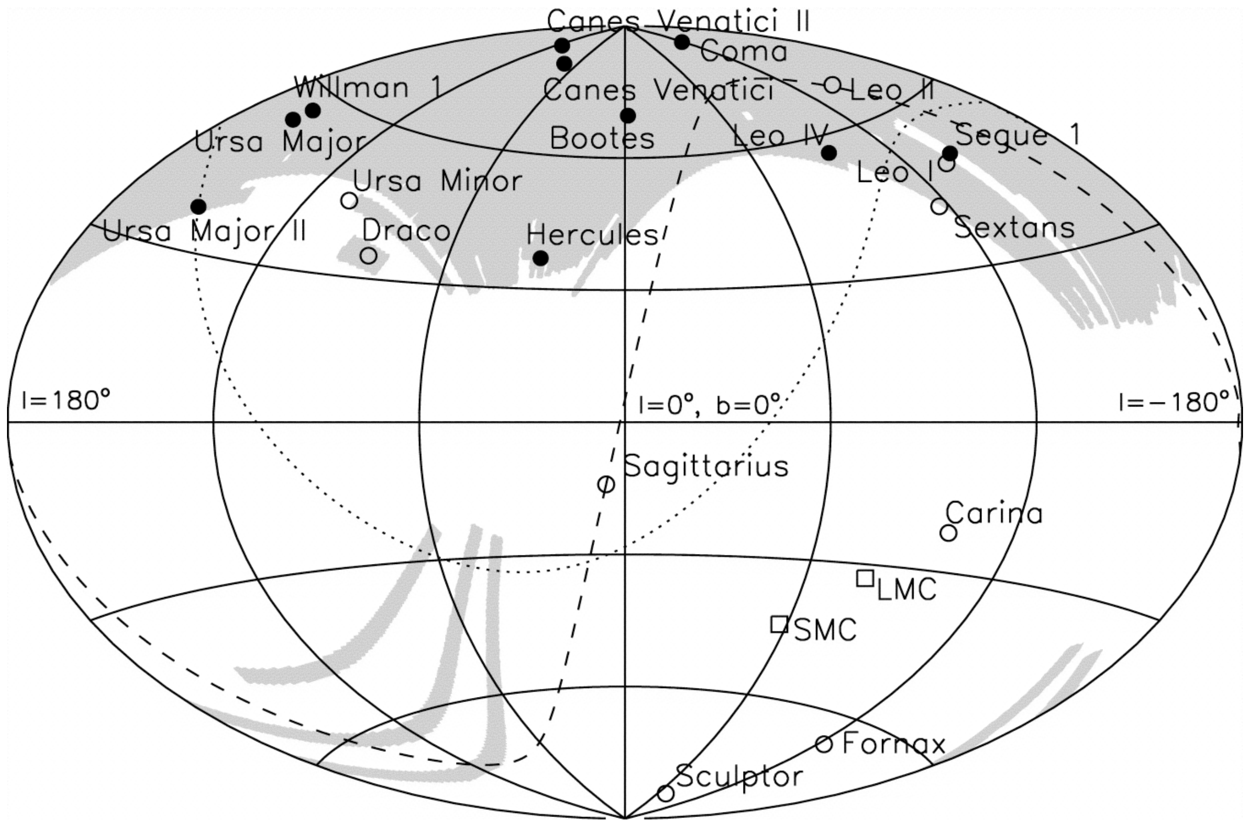


Many more to be discovered...

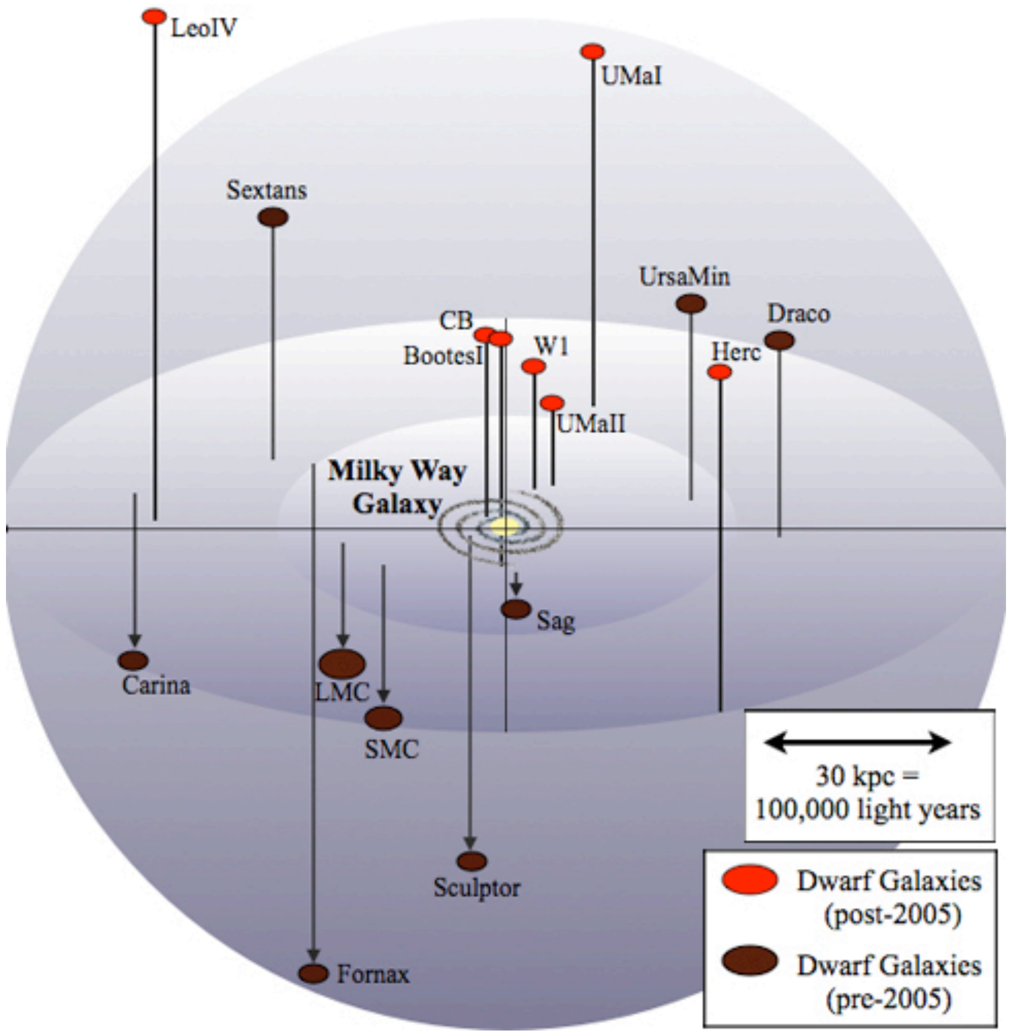


Willman et al.; Zucker et al.; Belokurov et al.;Koposov et al. 07...

See: Erik Tollerud et al. 2008

Faintest dwarfs, within ~40kpc, barely detectable by SDSS

Koposov et al. 08



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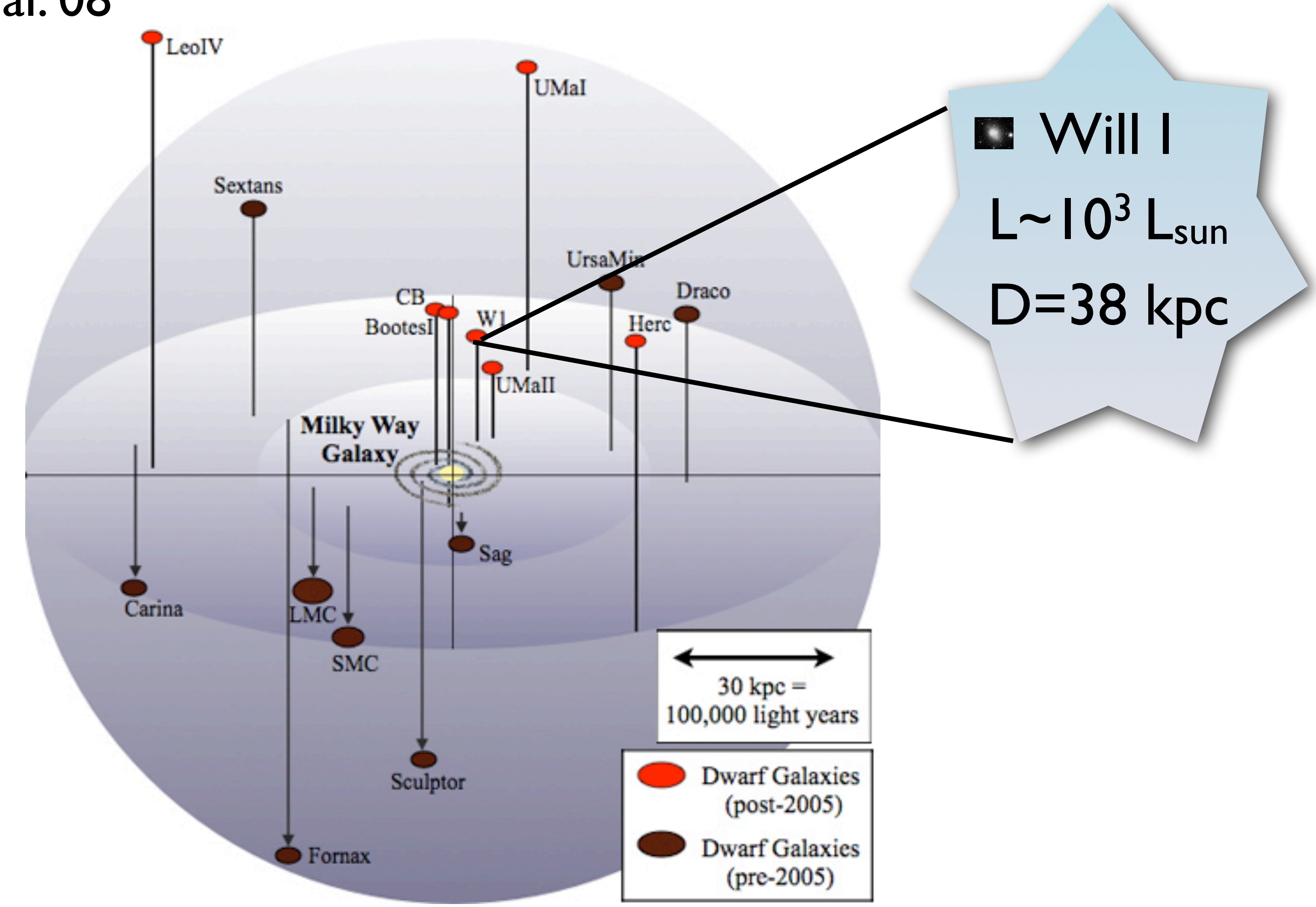

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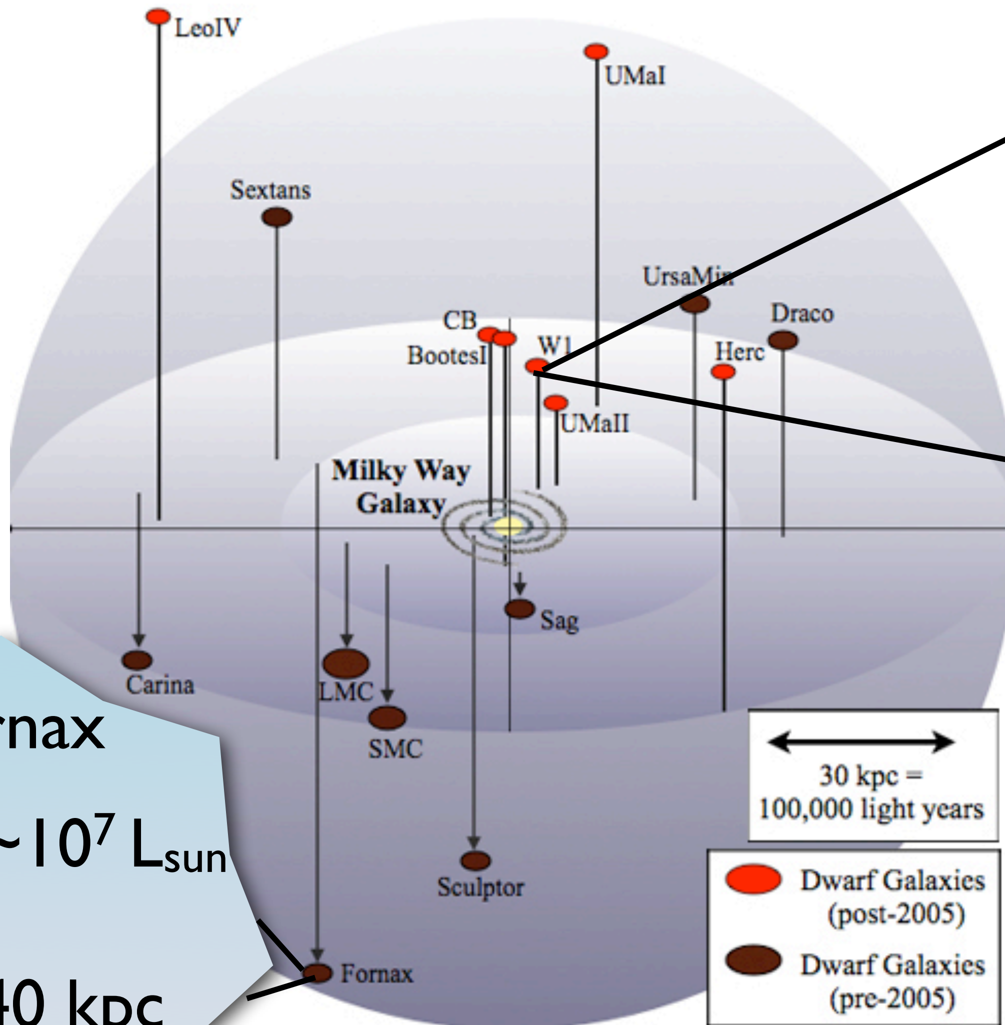
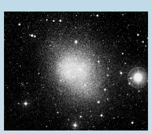


Will I

$L \sim 10^3\ L_{sun}$

D=38 kpc

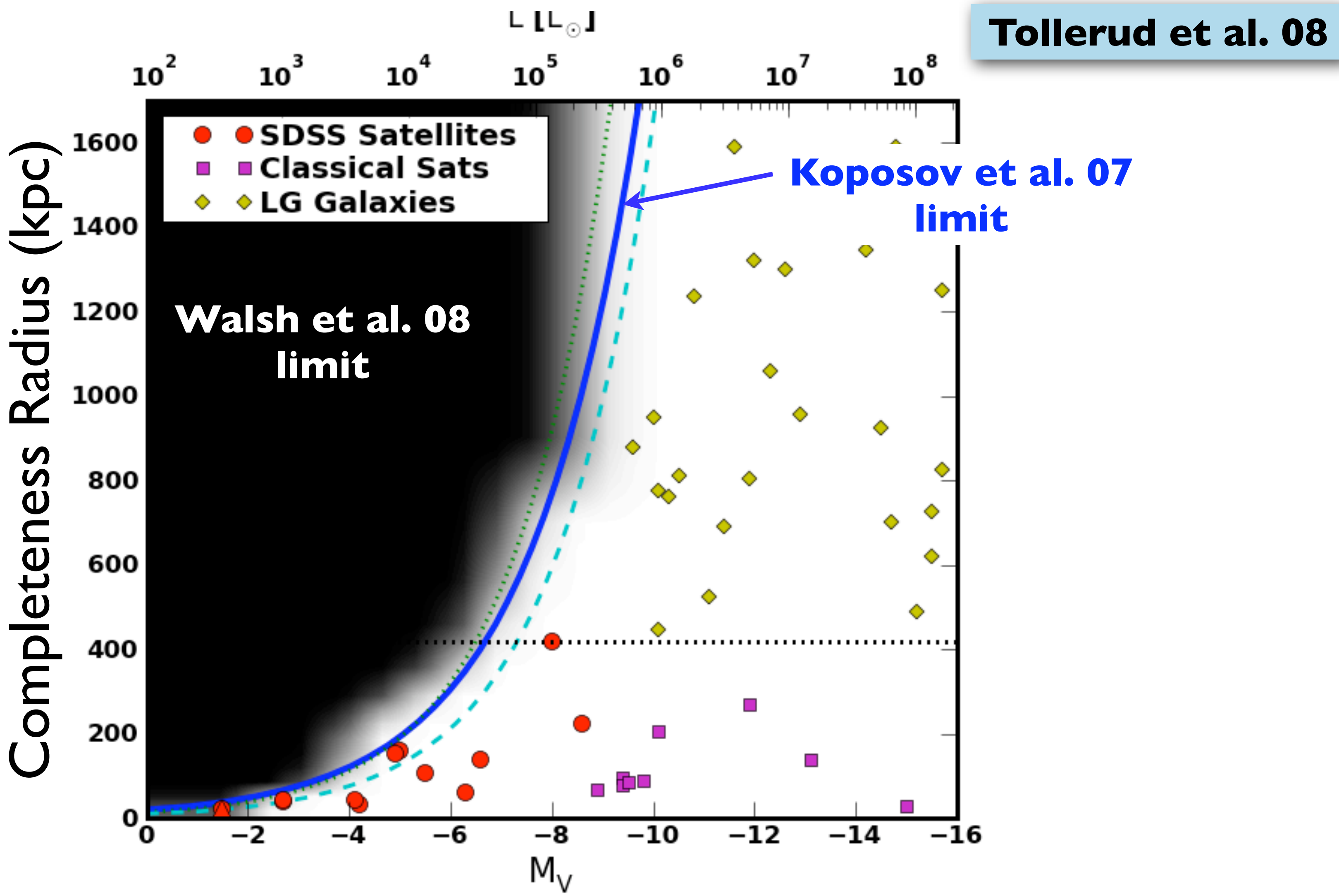
Fornax

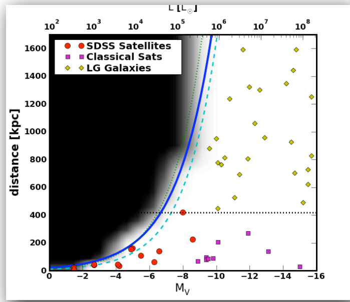


$L \sim 10^7\ L_{sun}$

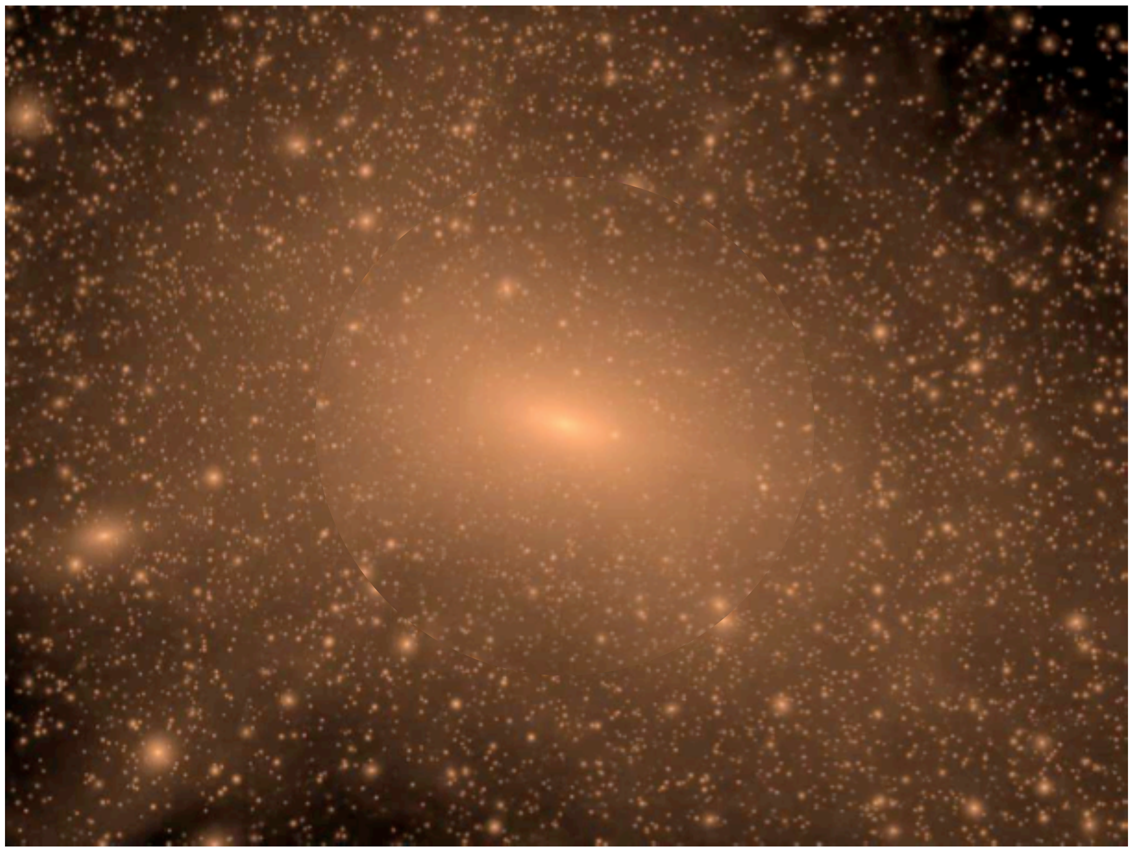
D=140 kpc

Many more to be discovered...

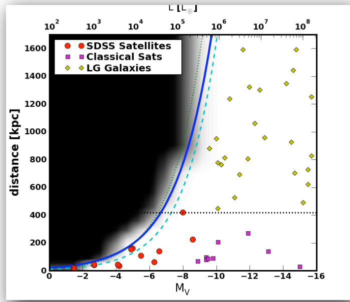




Faint galaxies can only be seen nearby



https://webfiles.uci.edu/bullock/Public/Canary2008/



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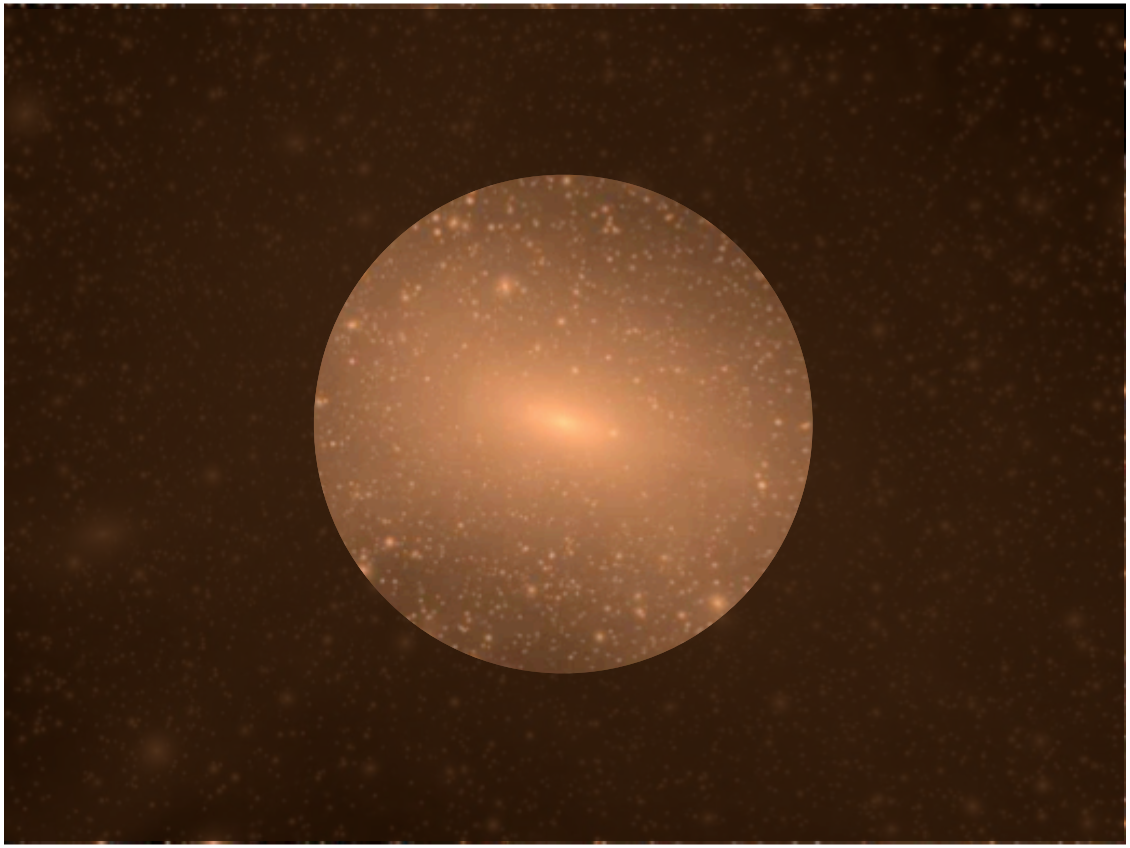

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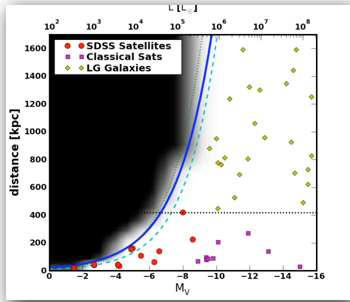

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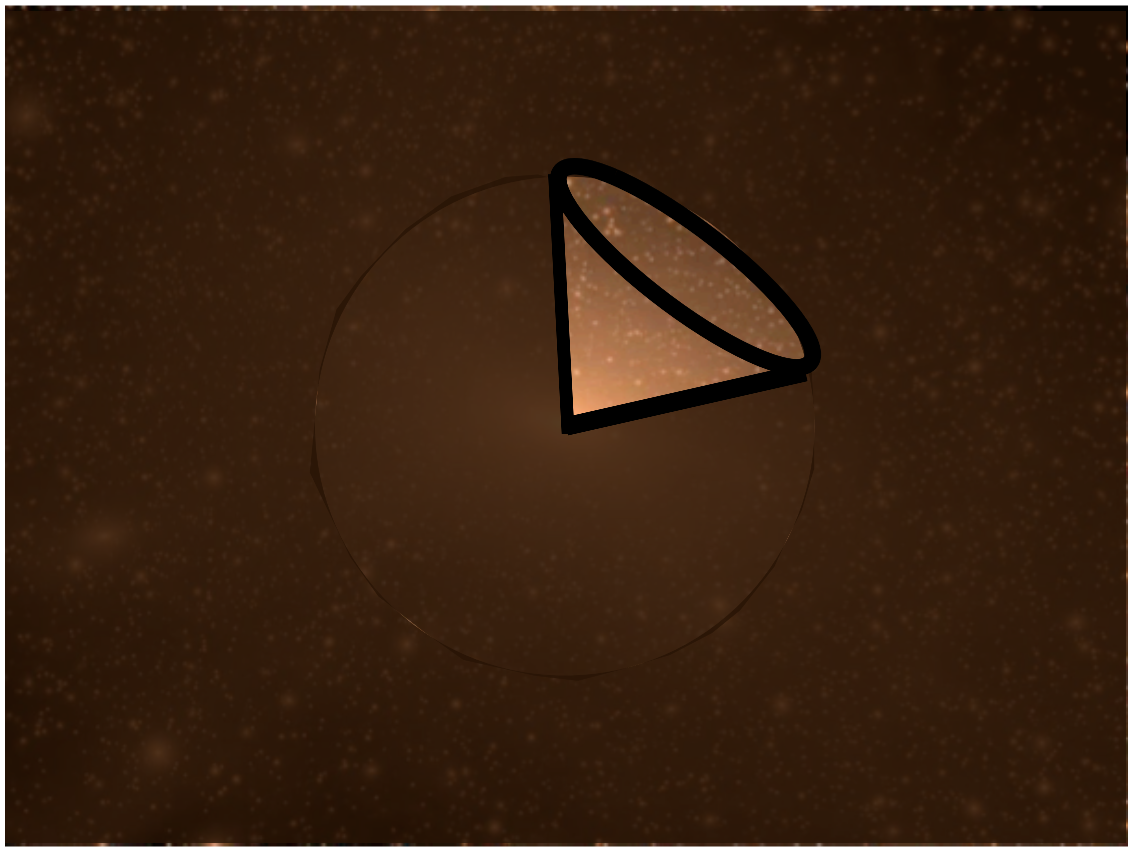
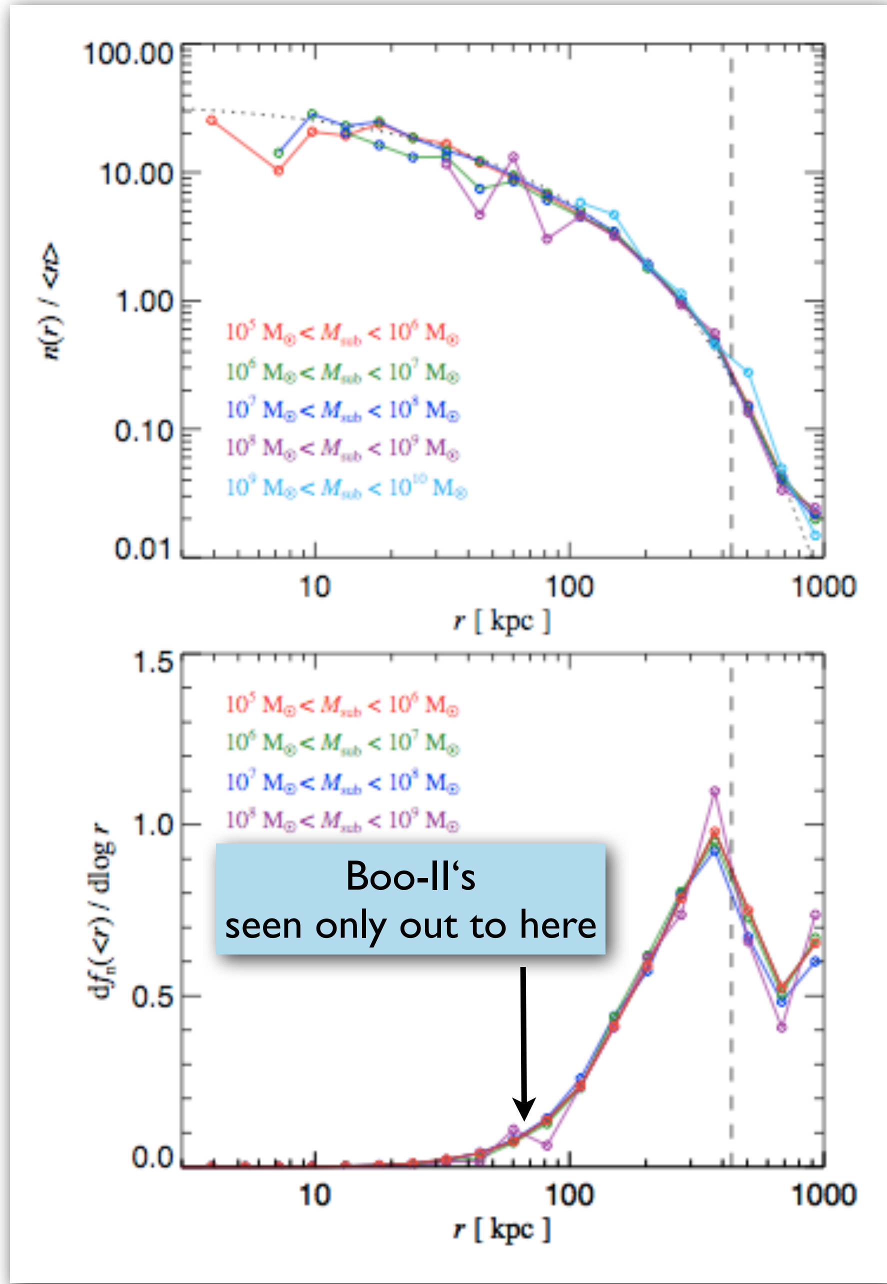
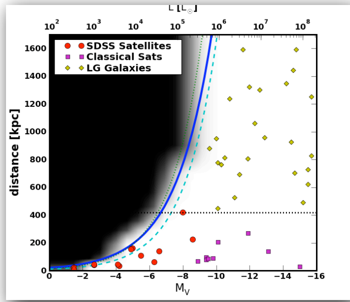


https://webfiles.uci.edu/bullock/Public/Canary2008/

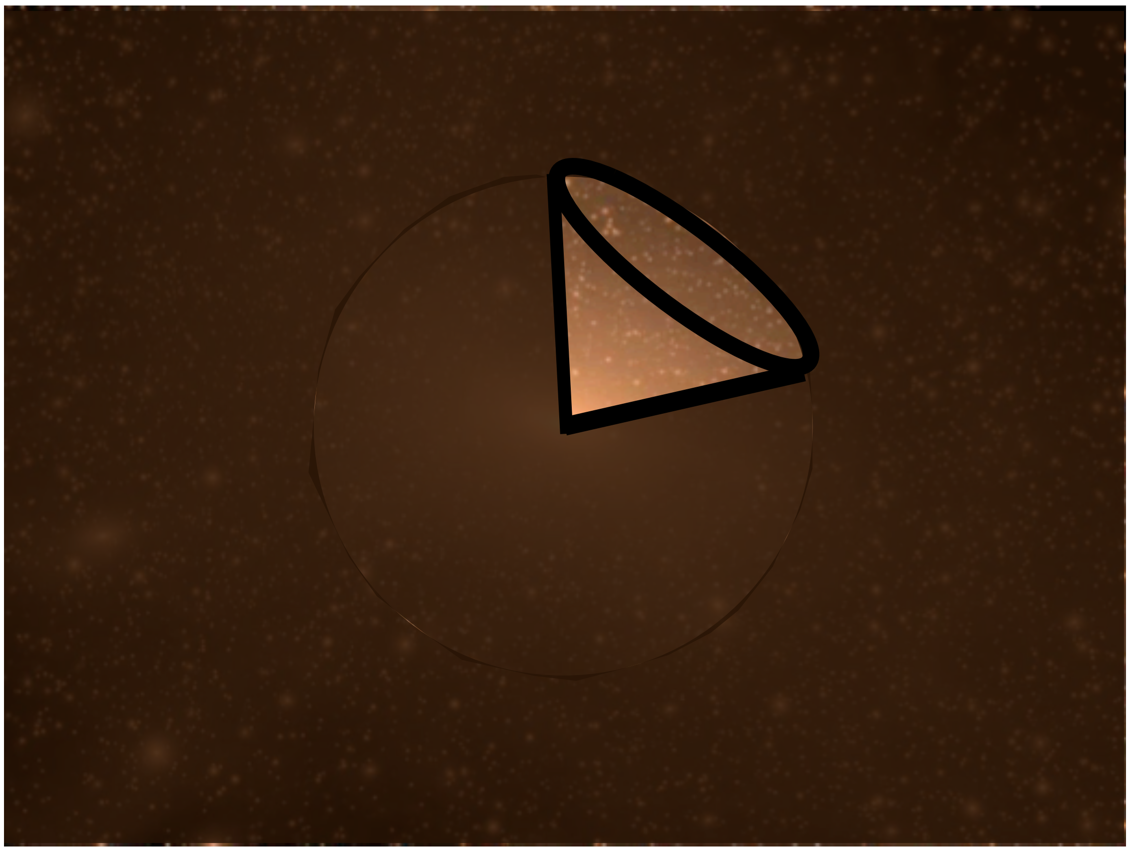
Radial distribution of subhalos in Aquarius simulation

Springel et al. 08





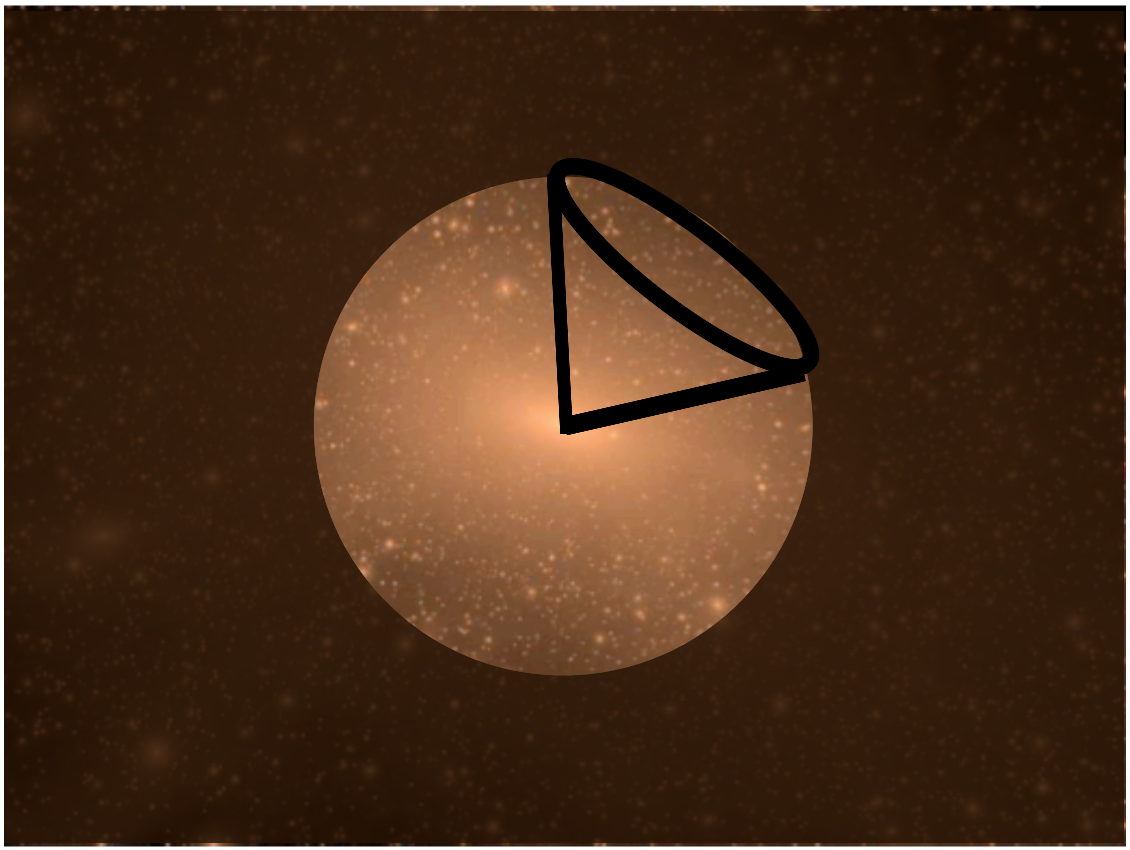
Plan: Use theoretical subhalo distribution to correct the observed count for luminosity bias.



https://webfiles.uci.edu/bullock/Public/Canary2008/

1. Angular sky-coverage correction.

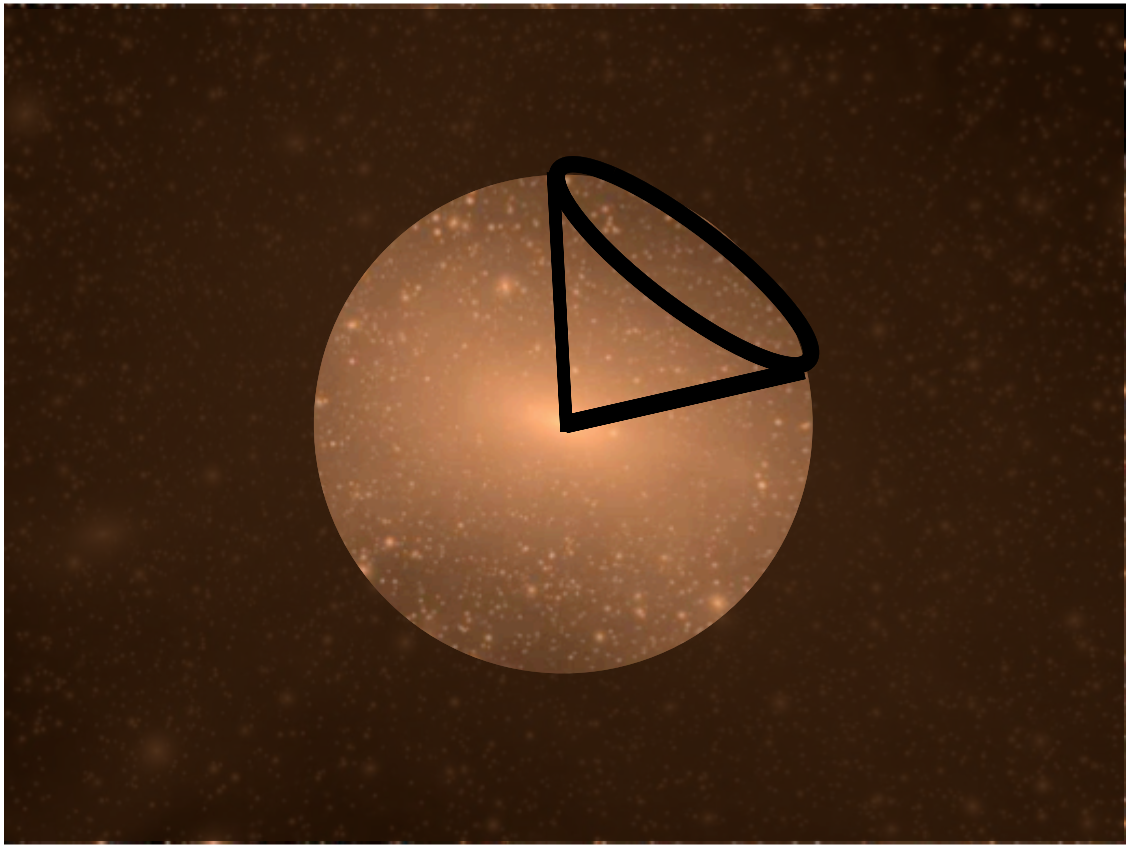
f_{sdss} ~1/5 sky => multiply observed count by 5



https://webfiles.uci.edu/bullock/Public/Canary2008/

1. Angular sky-coverage correction.

In detail, subhalo distribution is anisotropic. Correction depends on where SDSS is looking!



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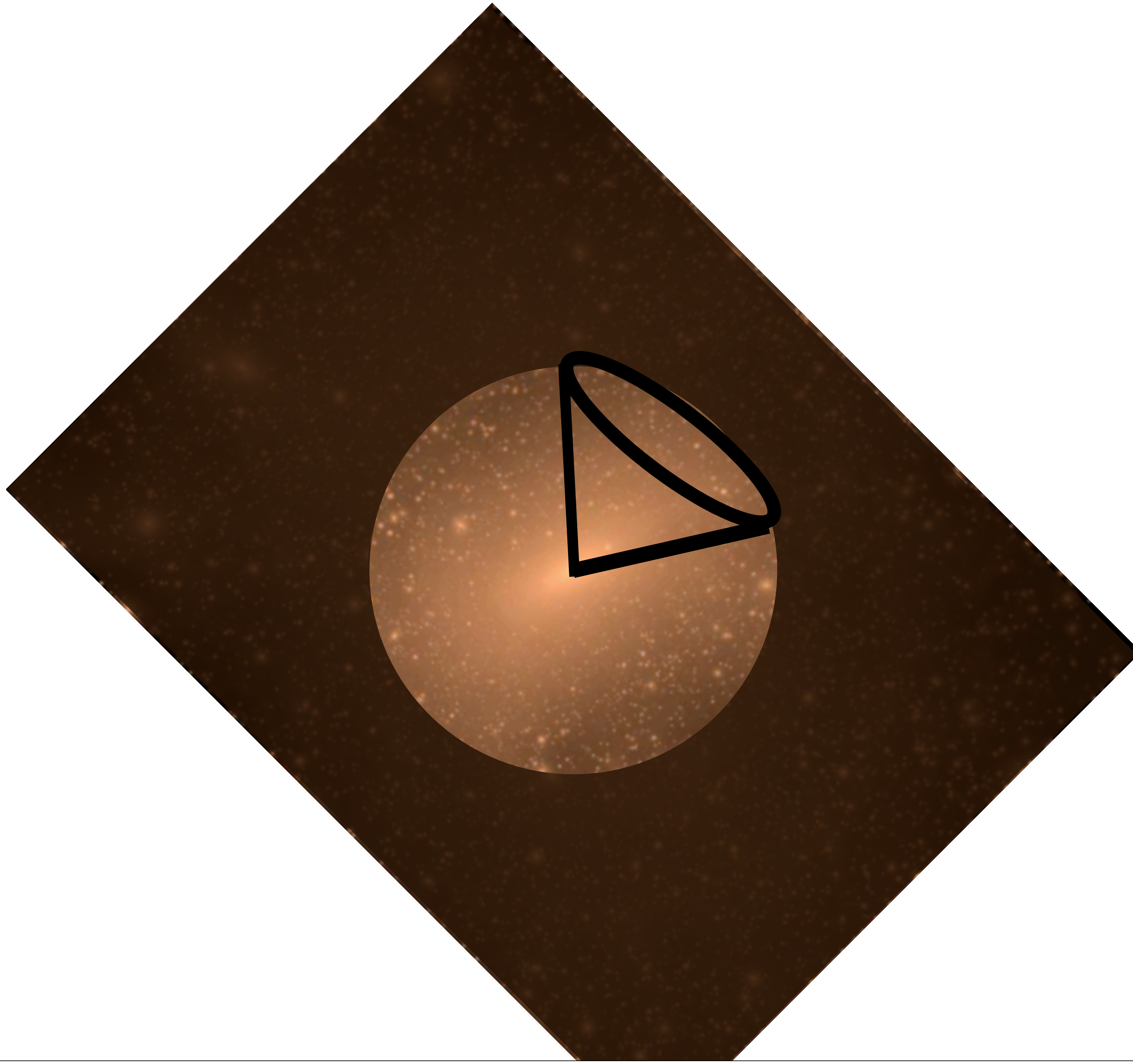
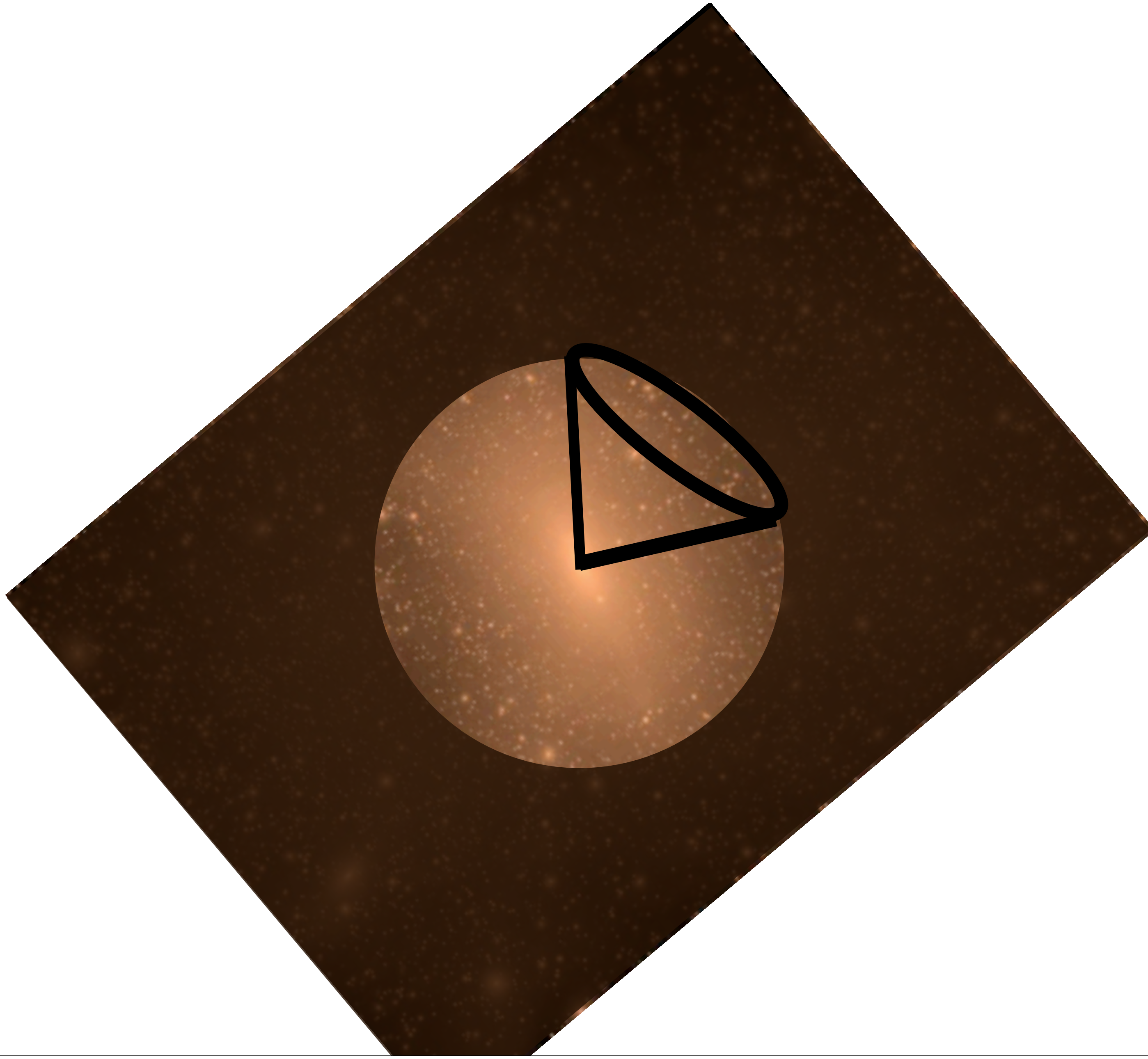
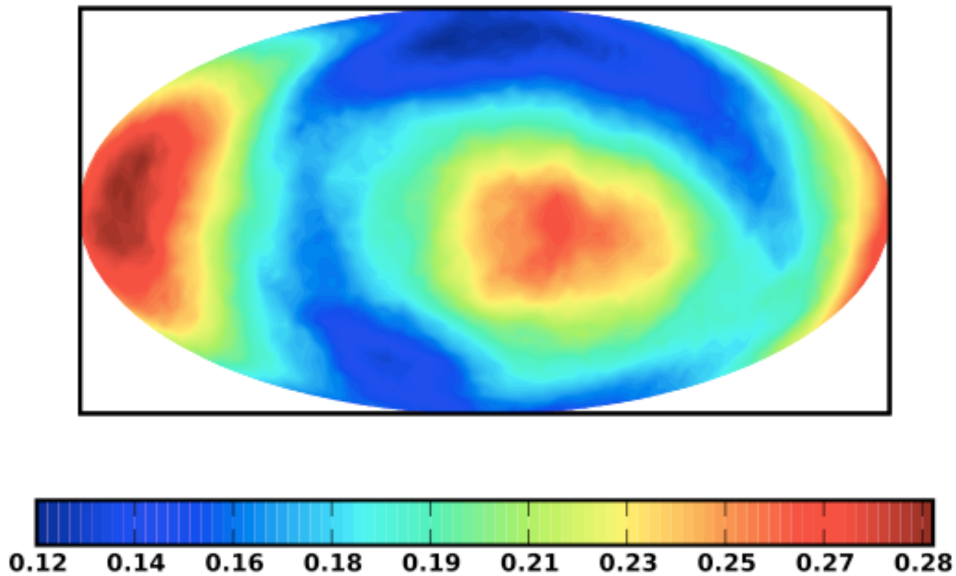




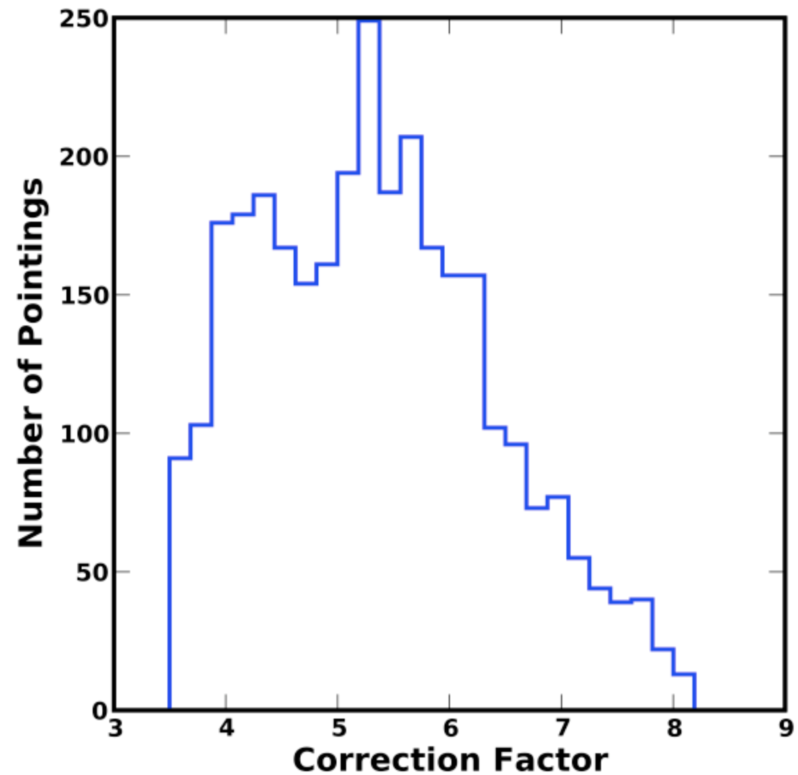
1. Range of angular sky-coverage correction factors as estimated from Via Lactea subhalos

Tollerud et al. 08

fraction of subhalos in 1/5 of sky



~8 correction factor ~3.5



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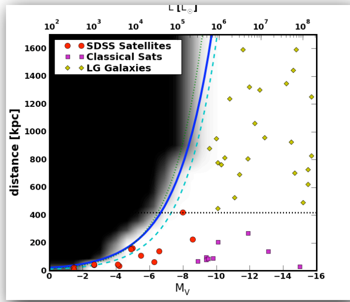
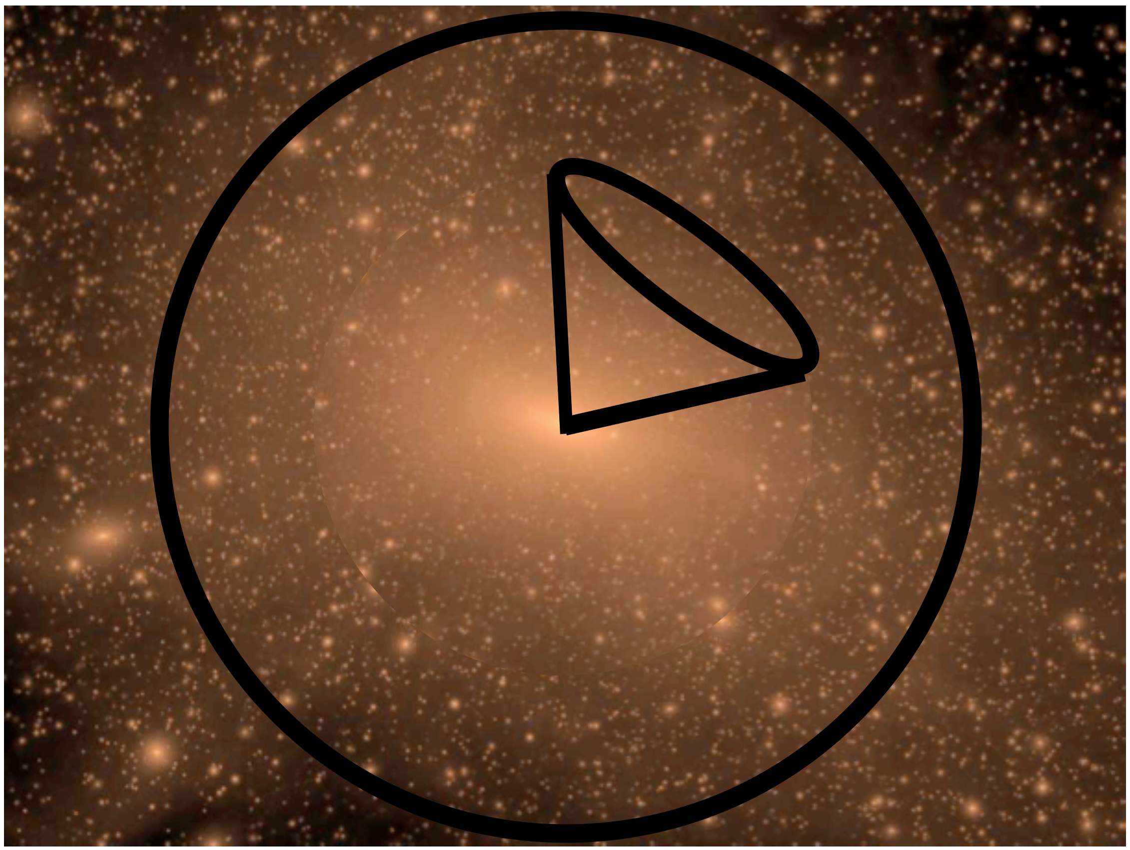
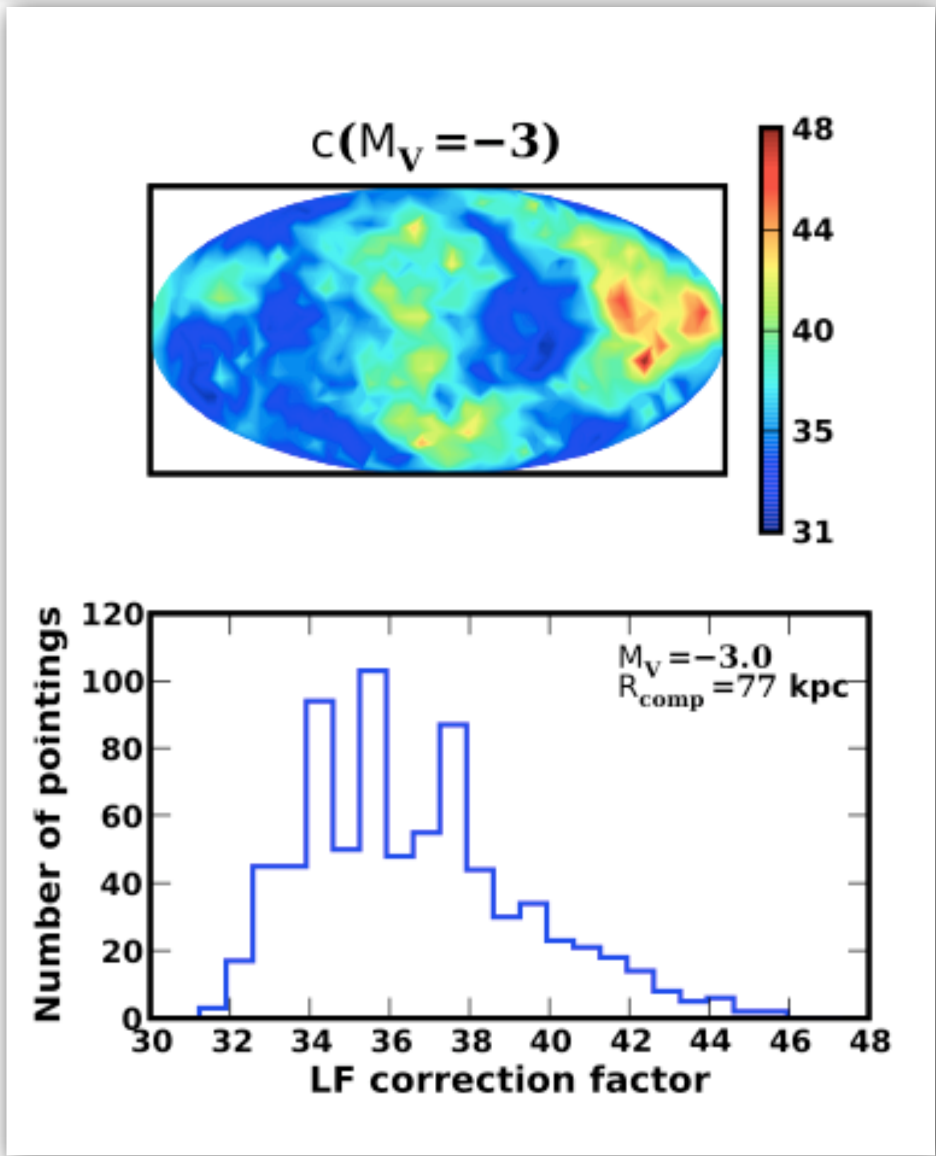


2. Full correction includes luminosity bias + angular coverage correction.



https://webfiles.uci.edu/bullock/Public/Canary2008/

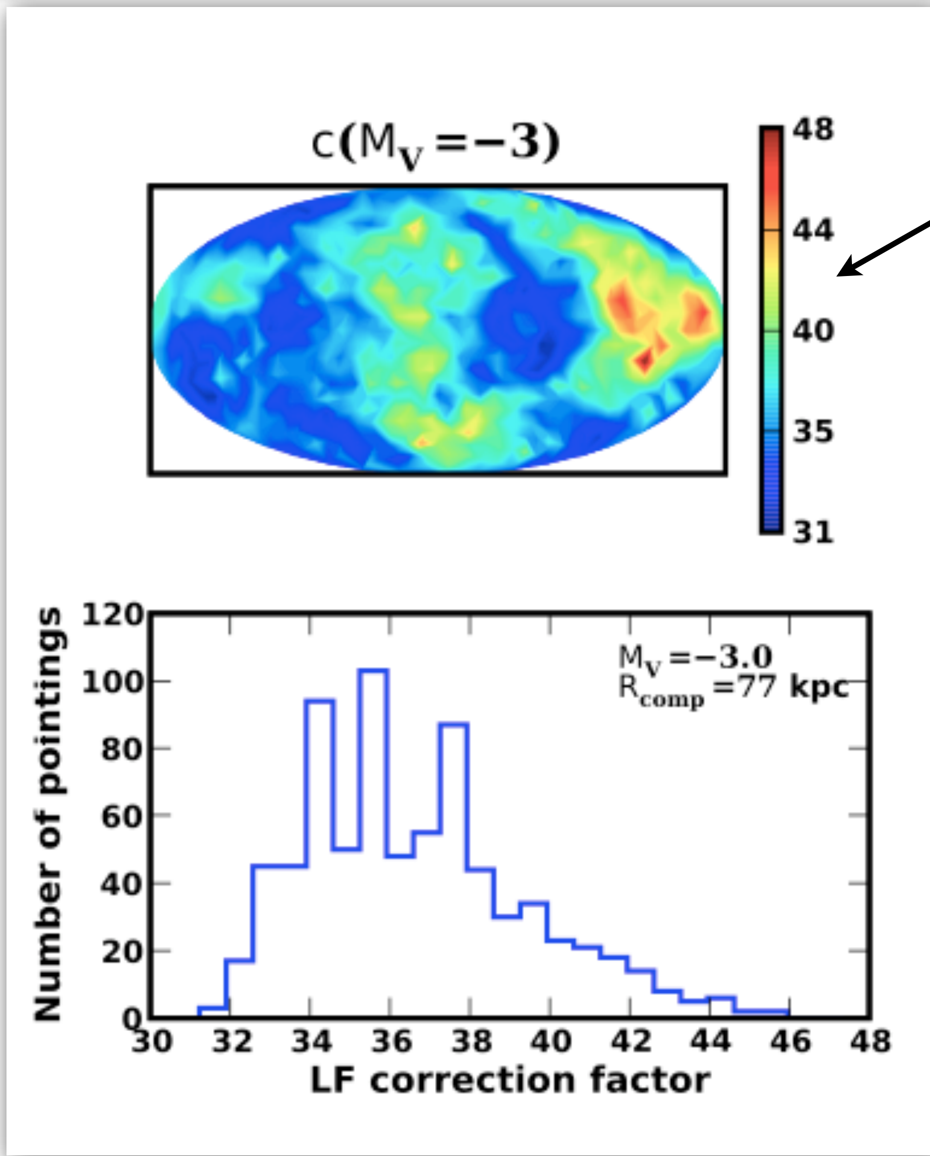
Total correction factor for Mv=-3 dwarfs, depending on where SDSS is looking in the sky



$N_{corr} = c \times N_{obs}$
$\sim 36 \times N_{obs}$

https://webfiles.uci.edu/bullock/Public/Canary2008/

Total correction factor for Mv=-3 dwarfs, depending on where SDSS is looking in the sky



We all know that Julio is dying to take a Fourier Transform of this map.

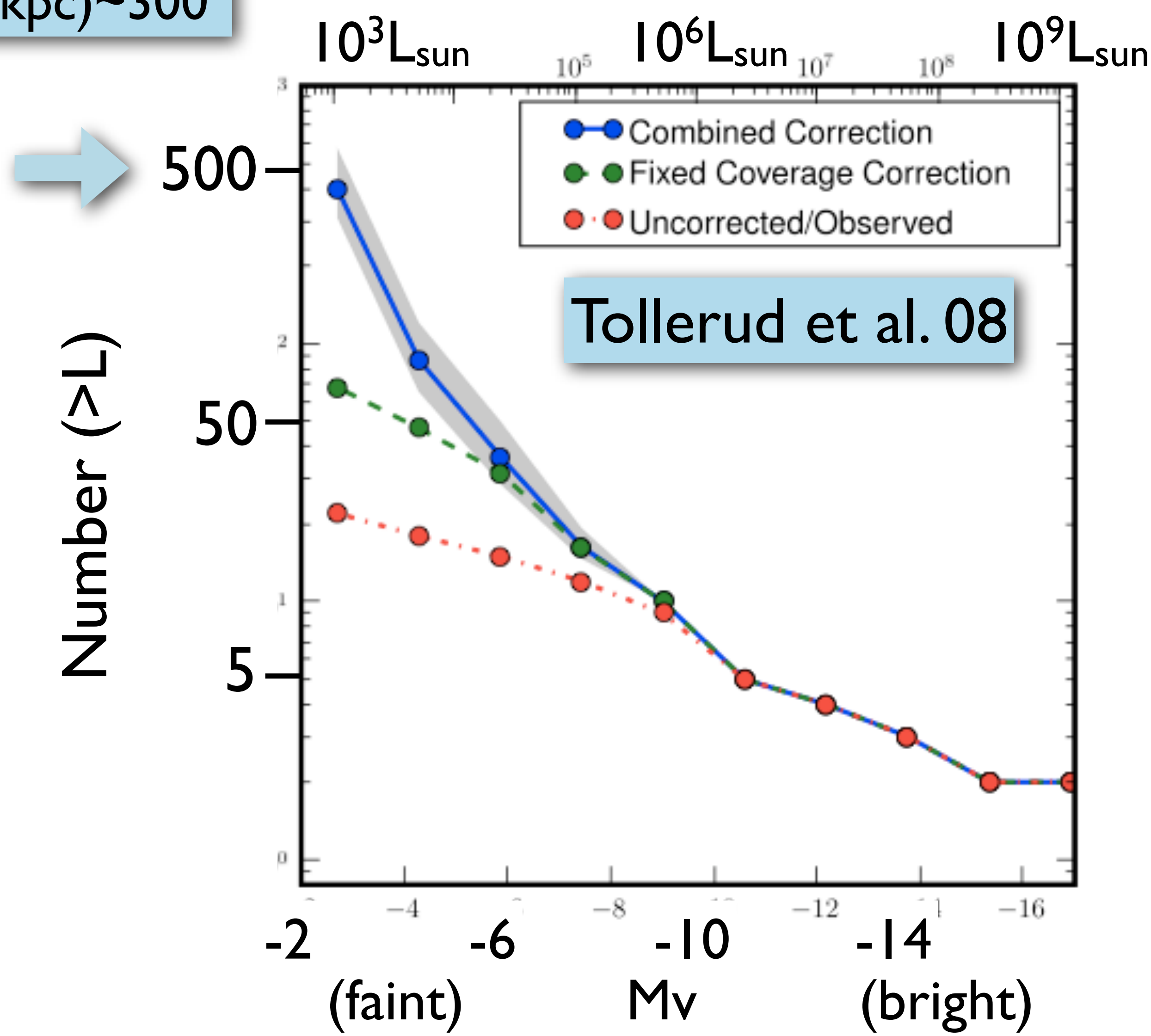
N_{corr} = c x N_{obs}

~36xN_{obs}

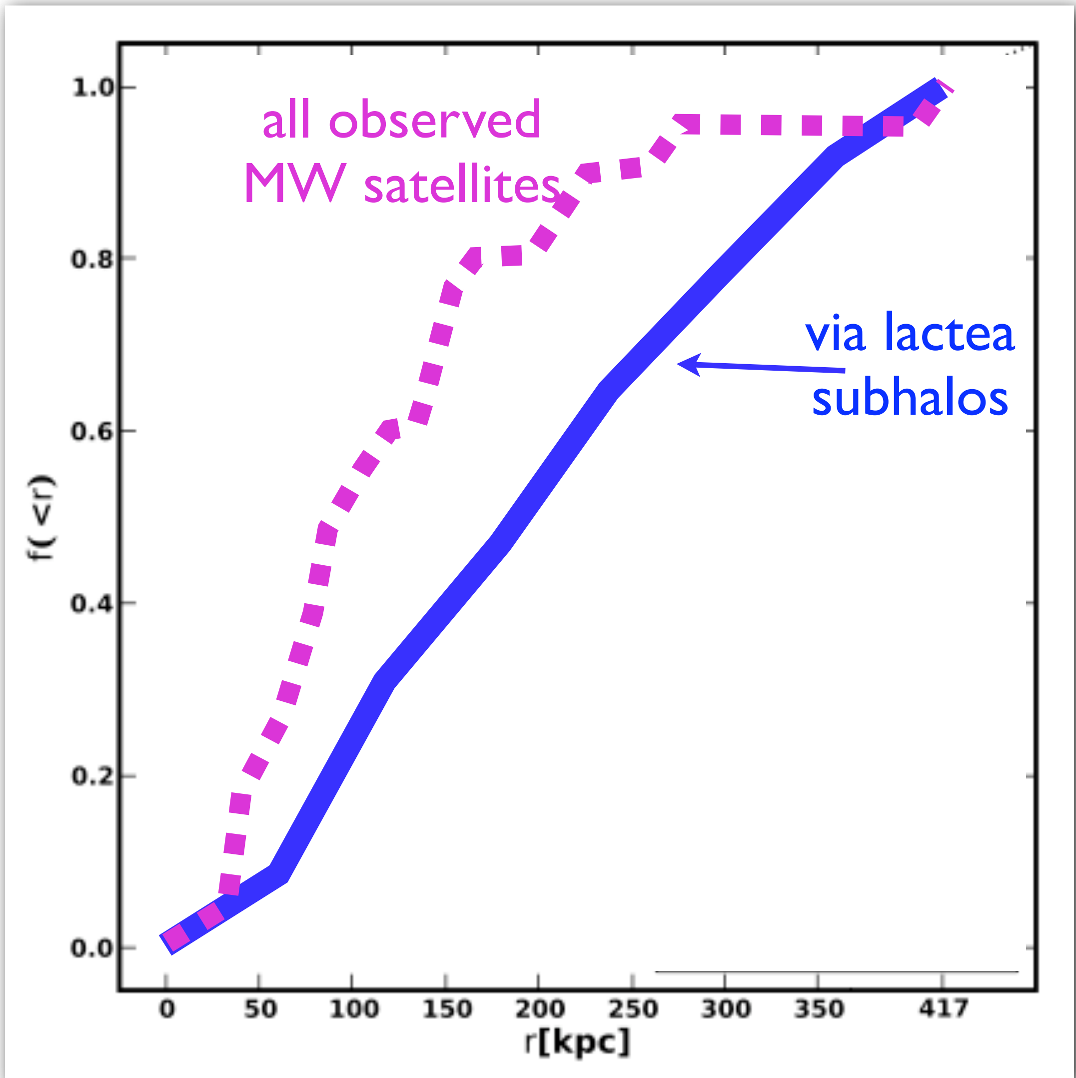
https://webfiles.uci.edu/bullock/Public/Canary2008/

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

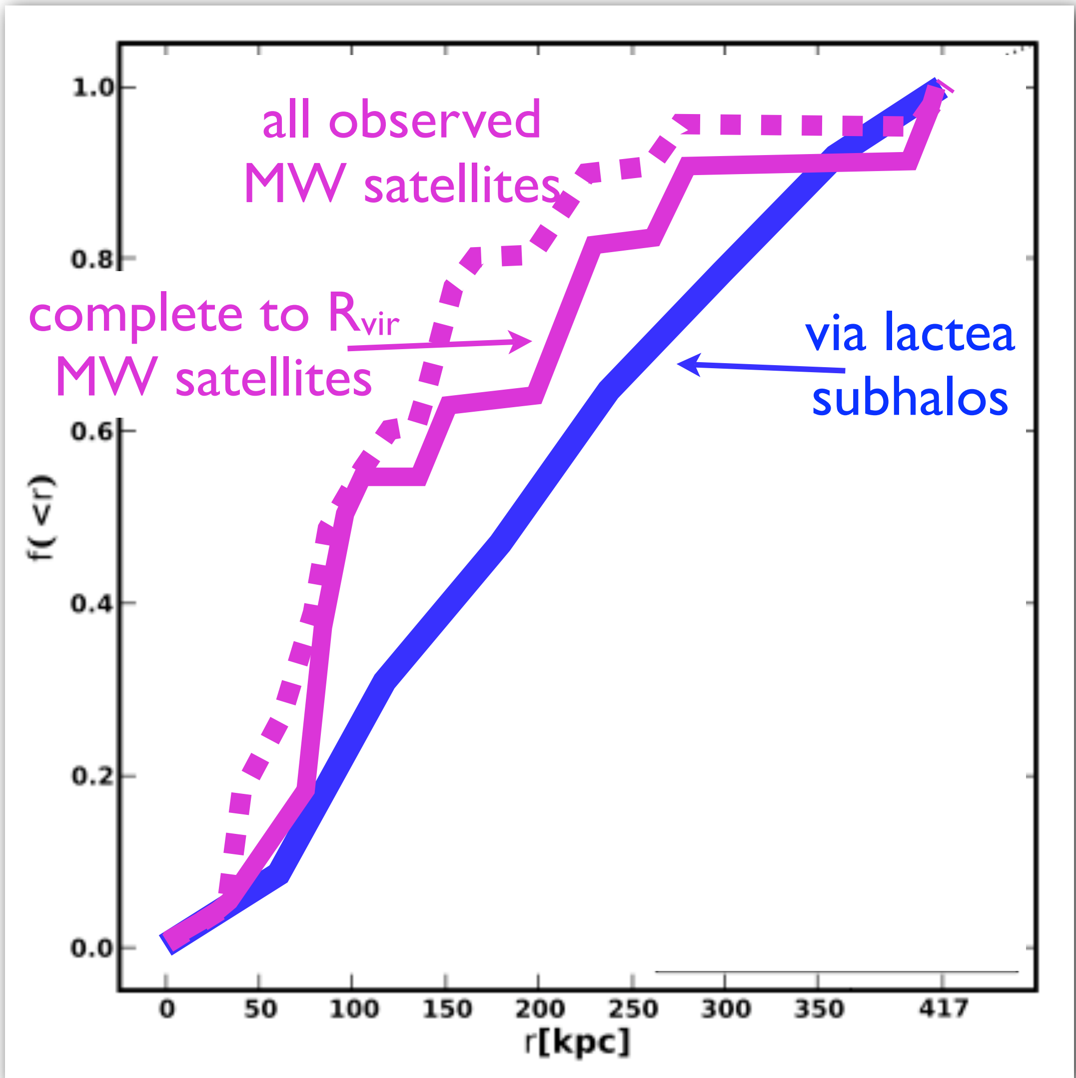
N(<200kpc)~300



Is the observed radial distribution self-consistent with this assumption?



modified from Tollerud et al. 08



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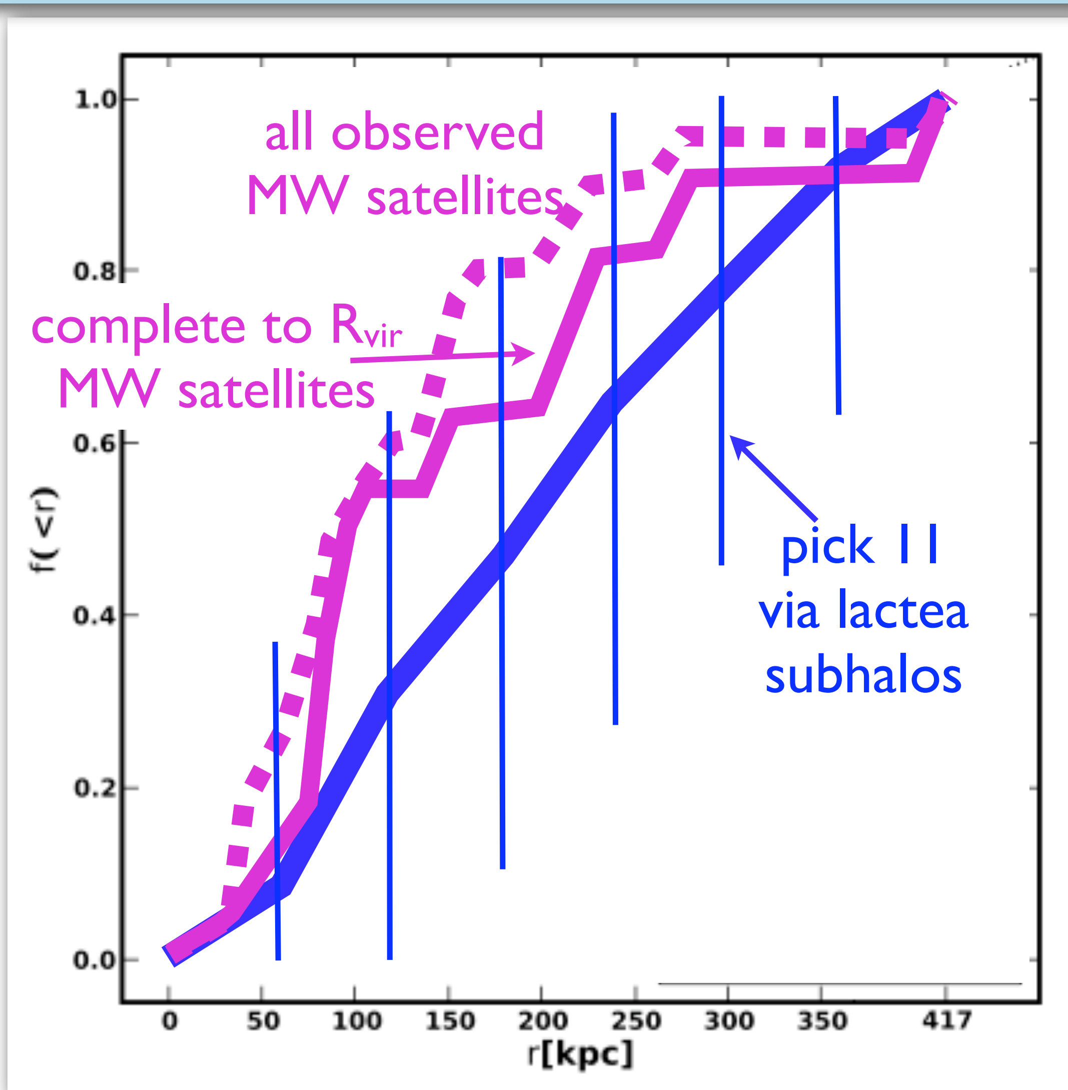
KS p-values are ~10%-90% depending on details. Bottom line is that distributions are consistent with satellites randomly sampling subhalo distribution.



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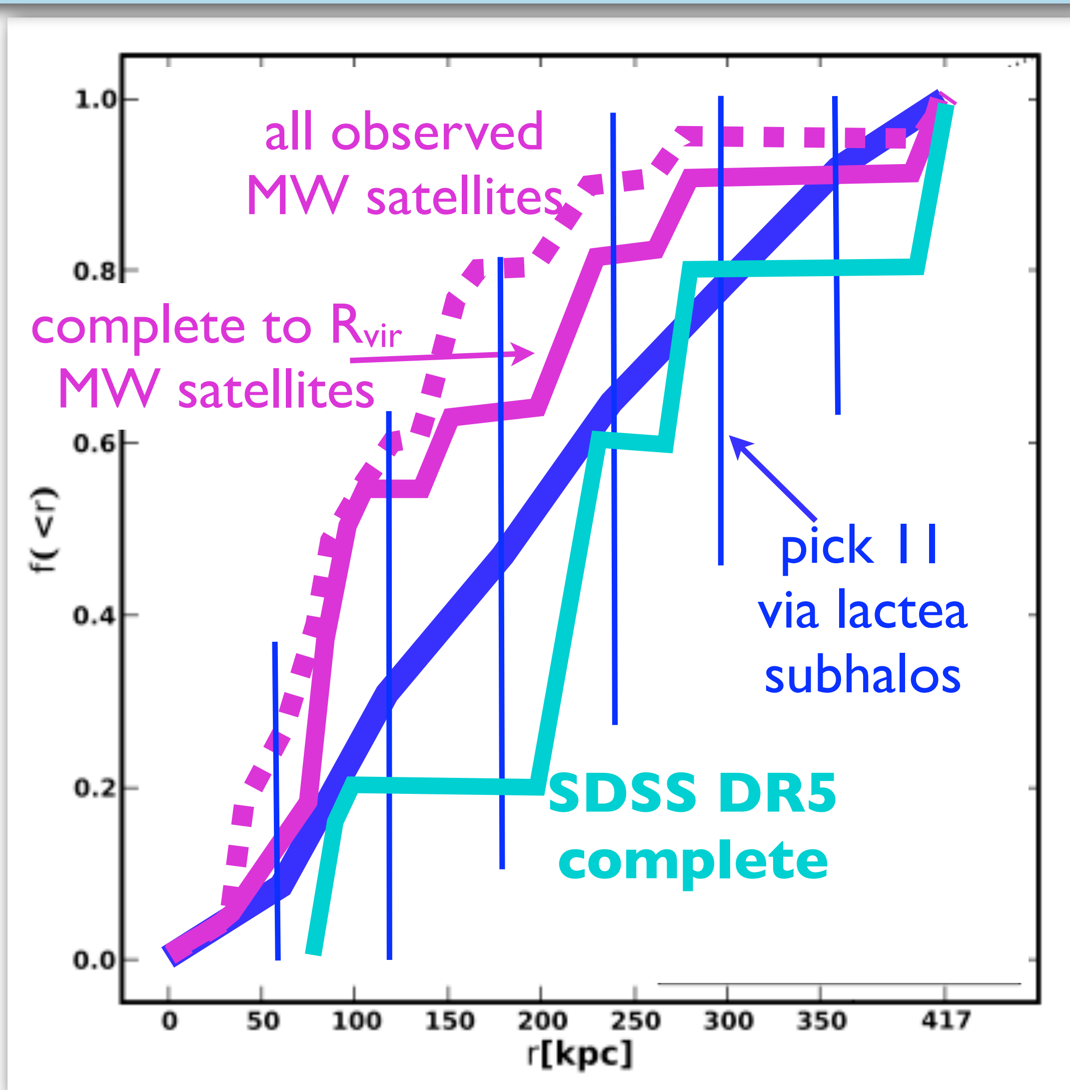

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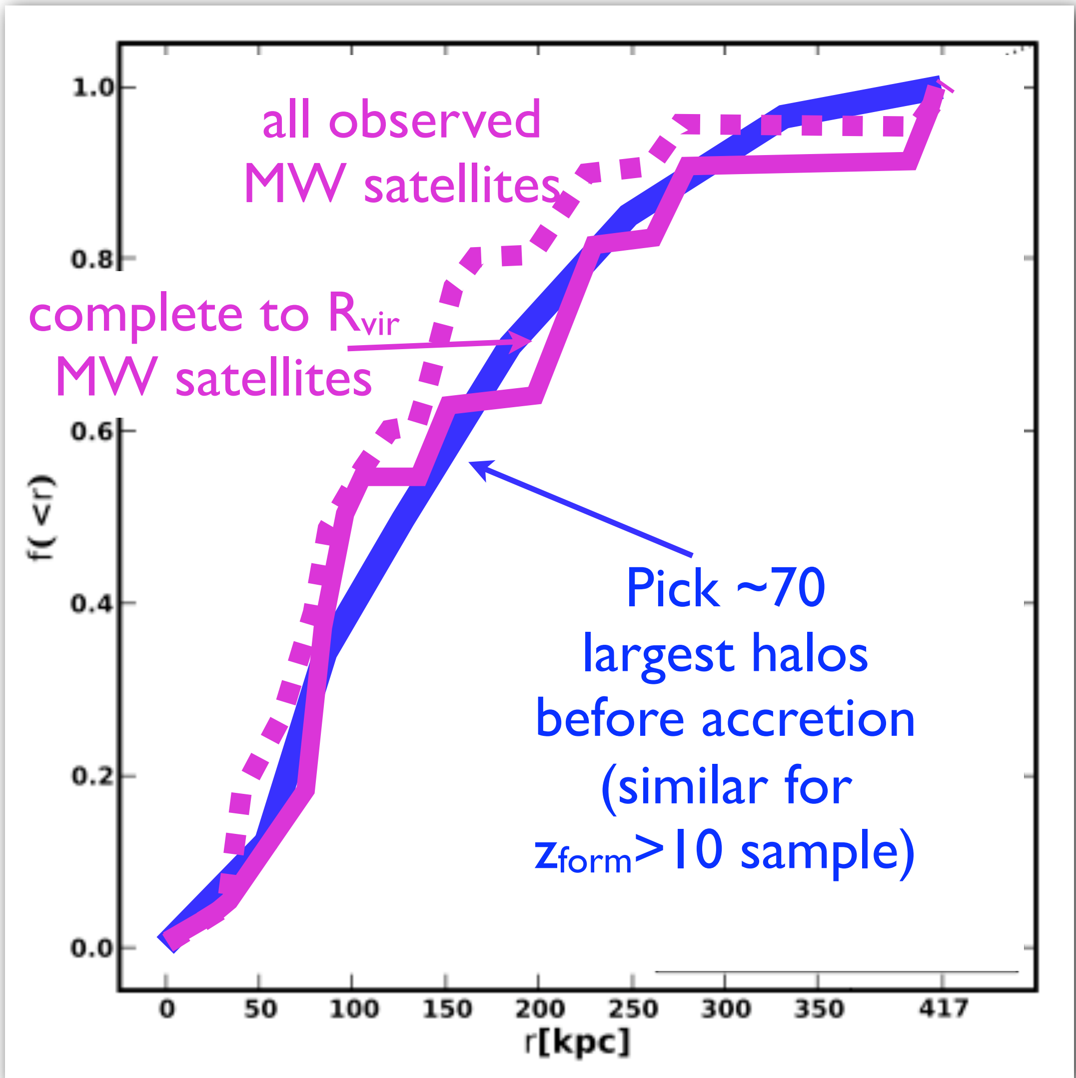
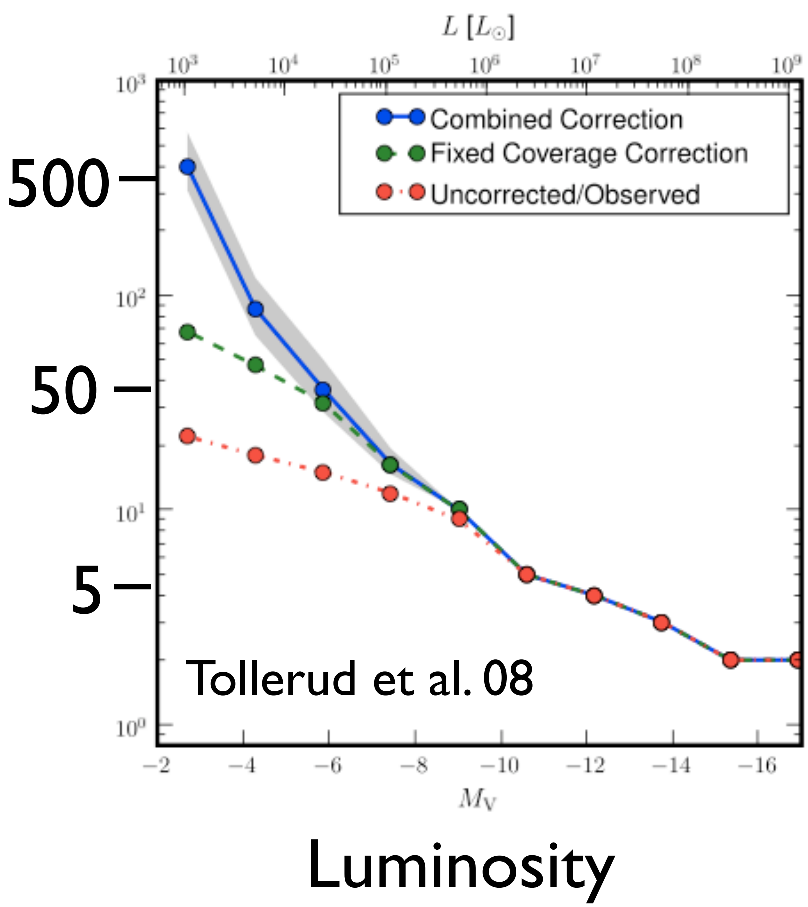


modified from Tollerud et al. 08

How could Tollerud et al. be wrong?



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

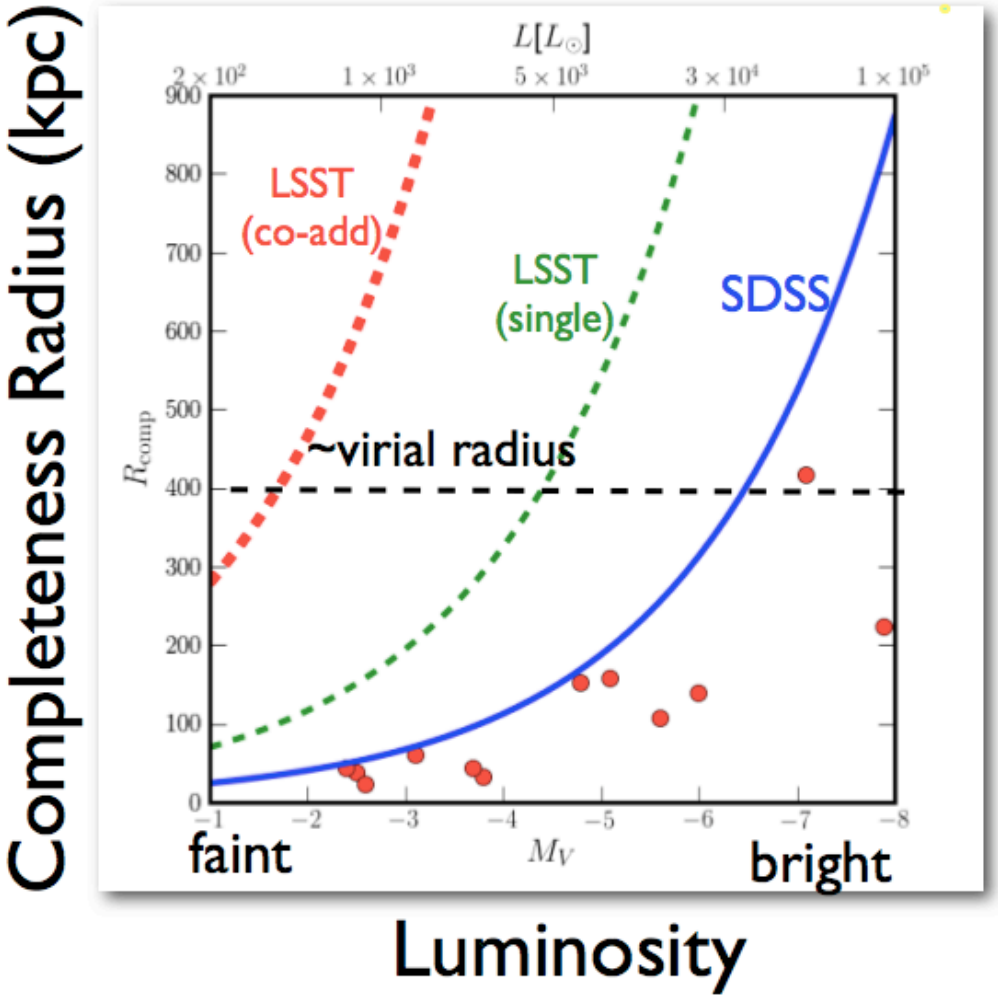
See Penarrubia et al. 08

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 will answer these questions...

Skymapper/PanSTARRS/DES...

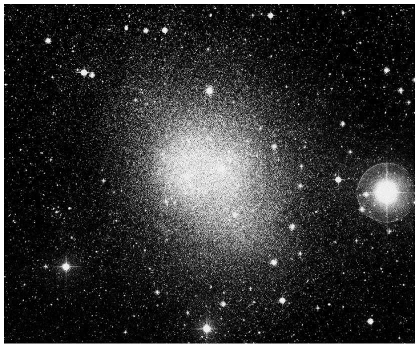


LSST will detect ultra-faint galaxies out beyond MW virial radius.

Tollerud et al. 08

New dwarfs are NOT your old dwarfs...

Fornax



~3000 pc

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

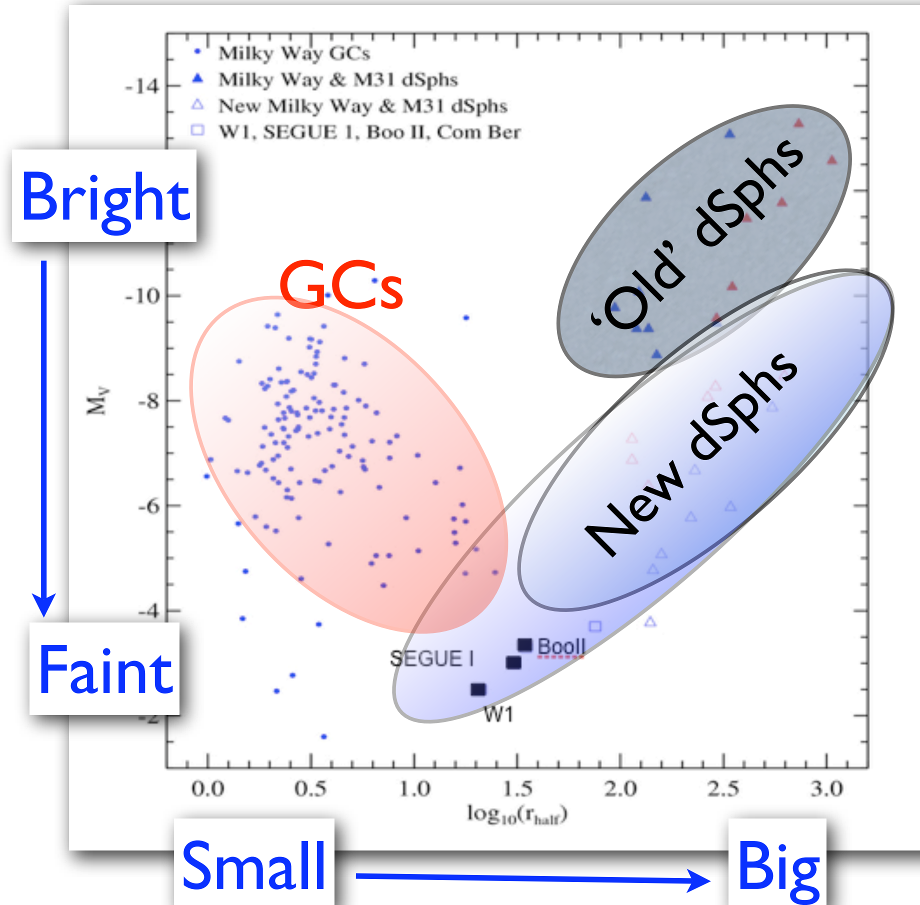
$\sigma_* \sim 11$ km/s

Will I

~80 pc

$L \sim 10^3 L_{sun}$

$\sigma_* \sim 5$ km/s



Compilation by Beth Willman.

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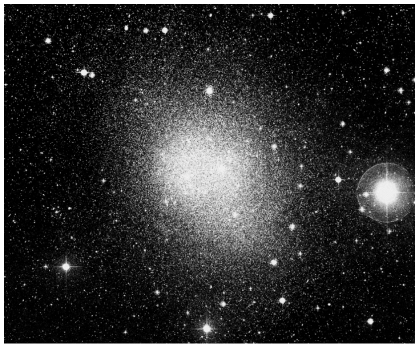

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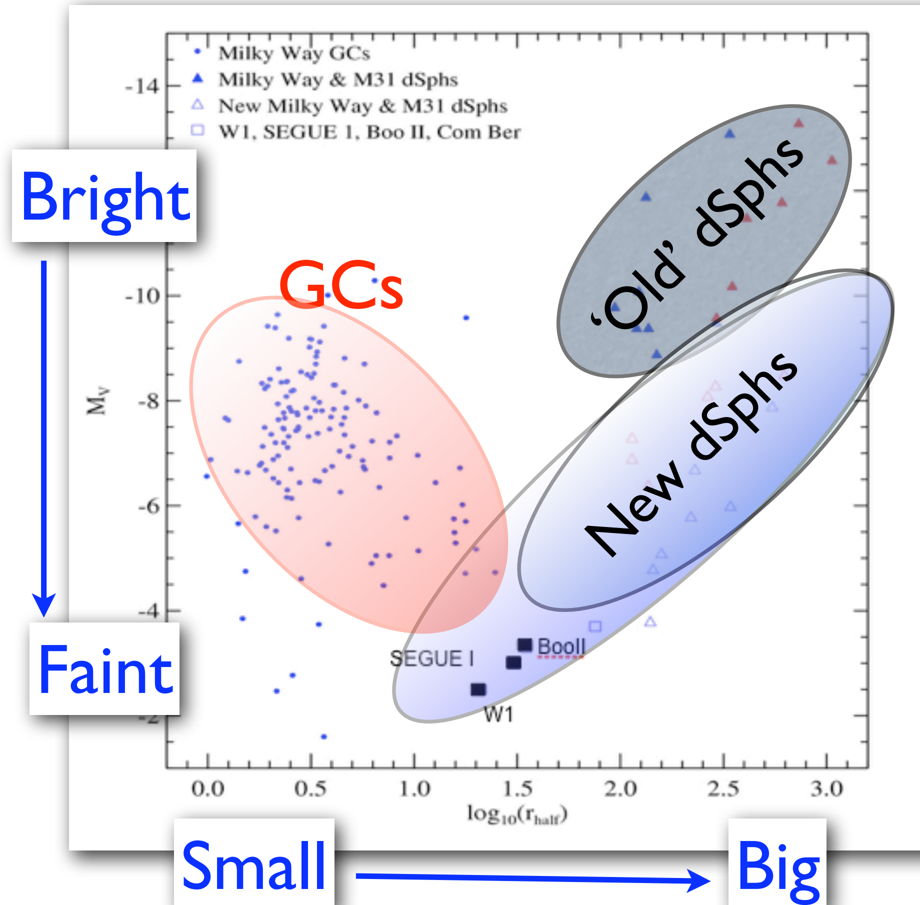
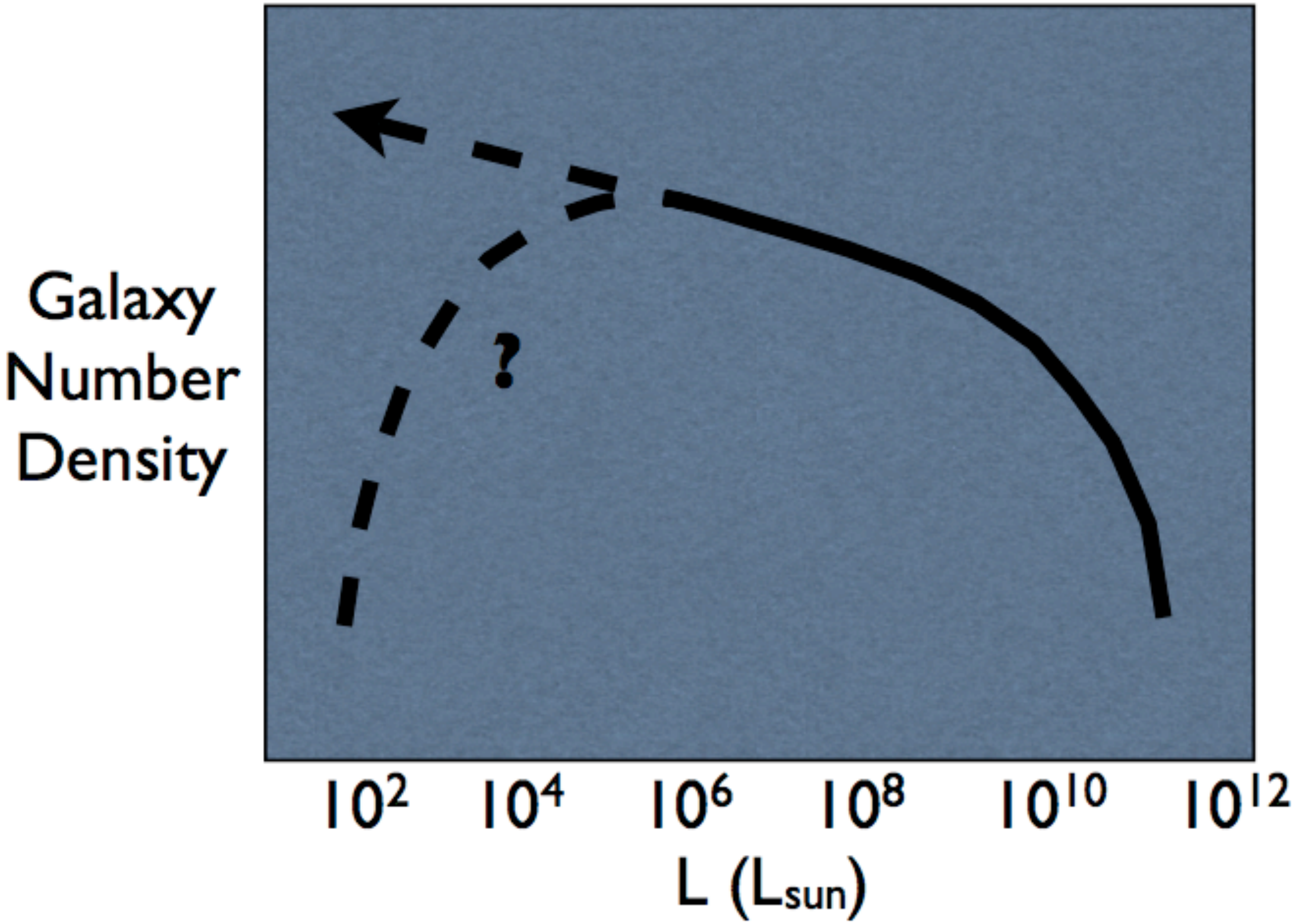


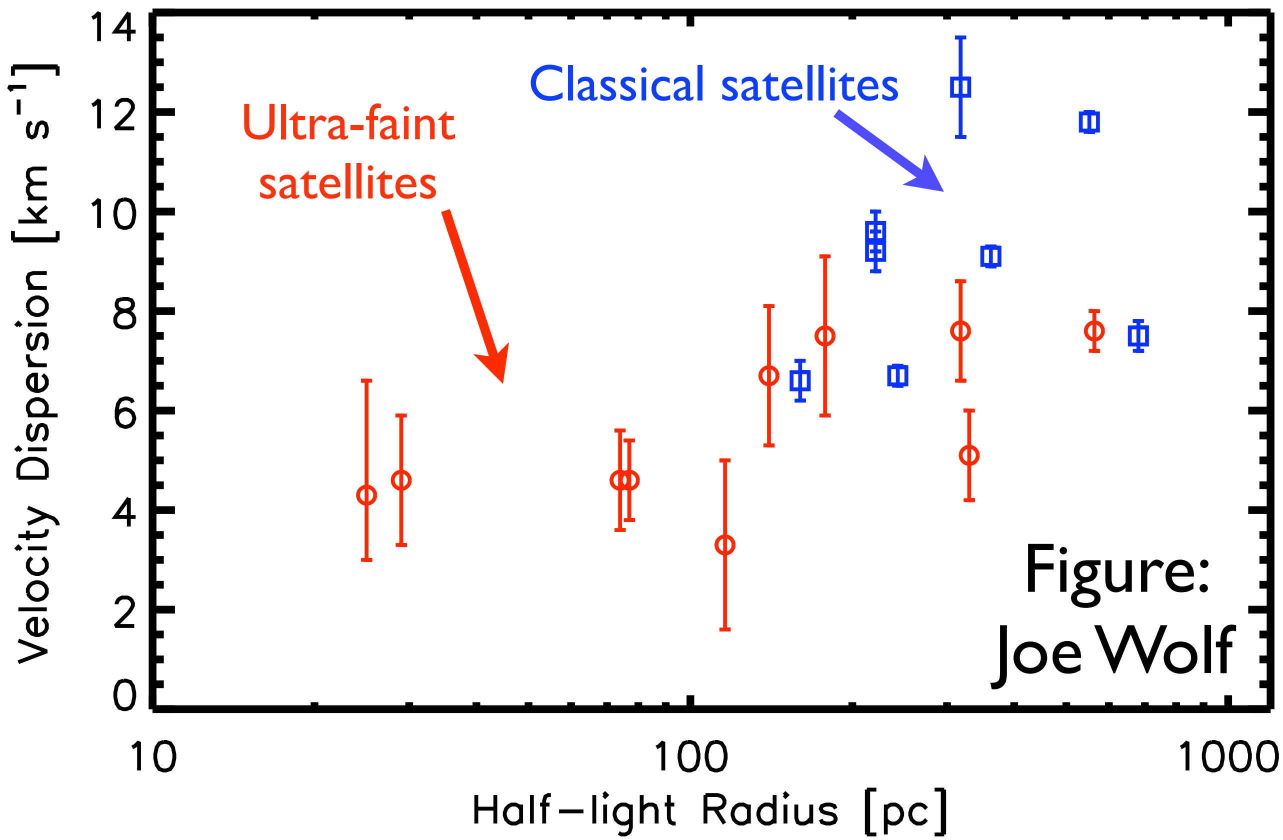
Compilation by Beth Willman.

How faint is the faintest galaxy?

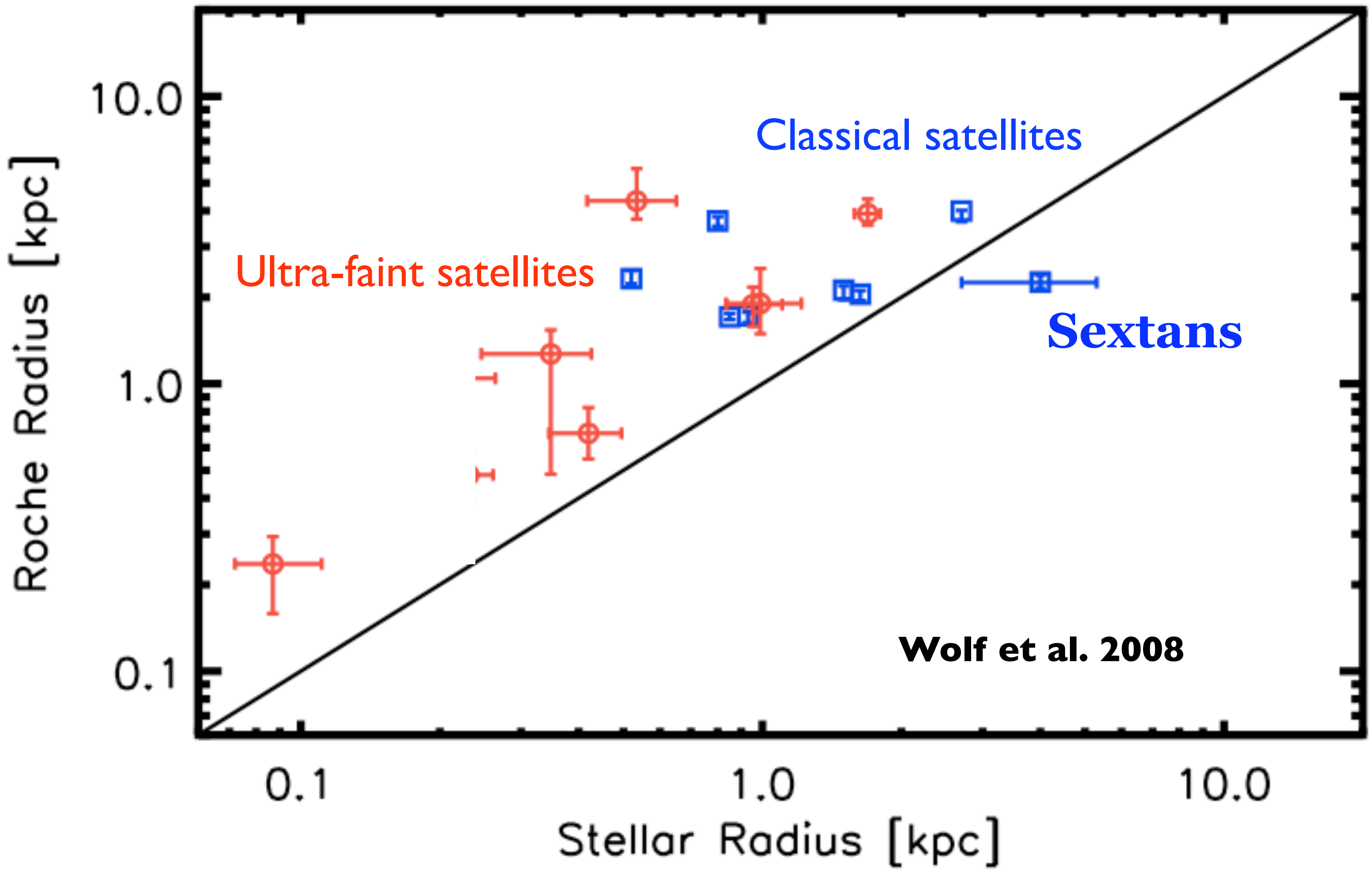


dSph radial velocities

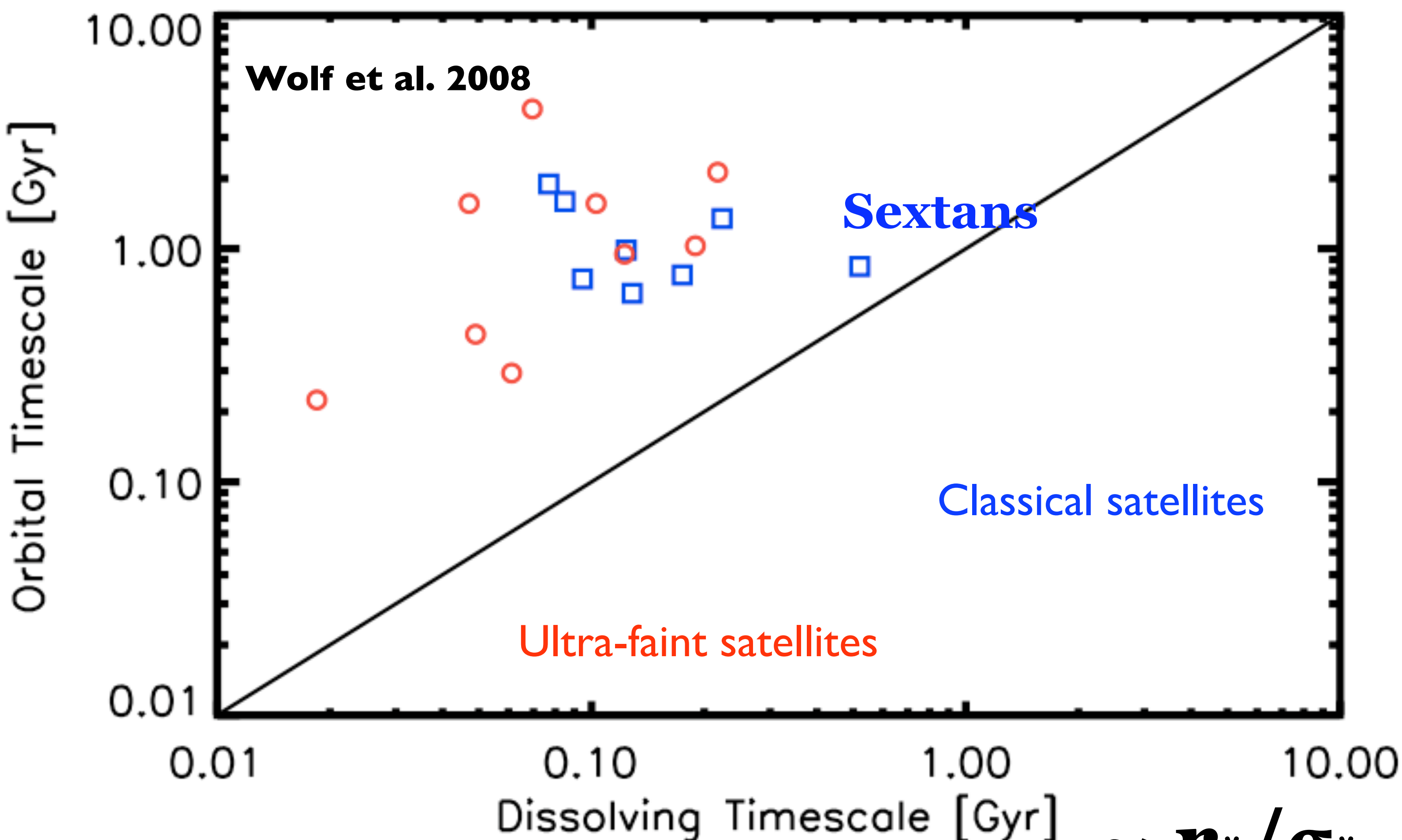
Walker et al. 07; Simon & Geha 07; Munoz et al. 06; Martin et al. 07; Willman et al. 08; Geha et al. 08



Instantaneous tidal radius vs. stellar radius

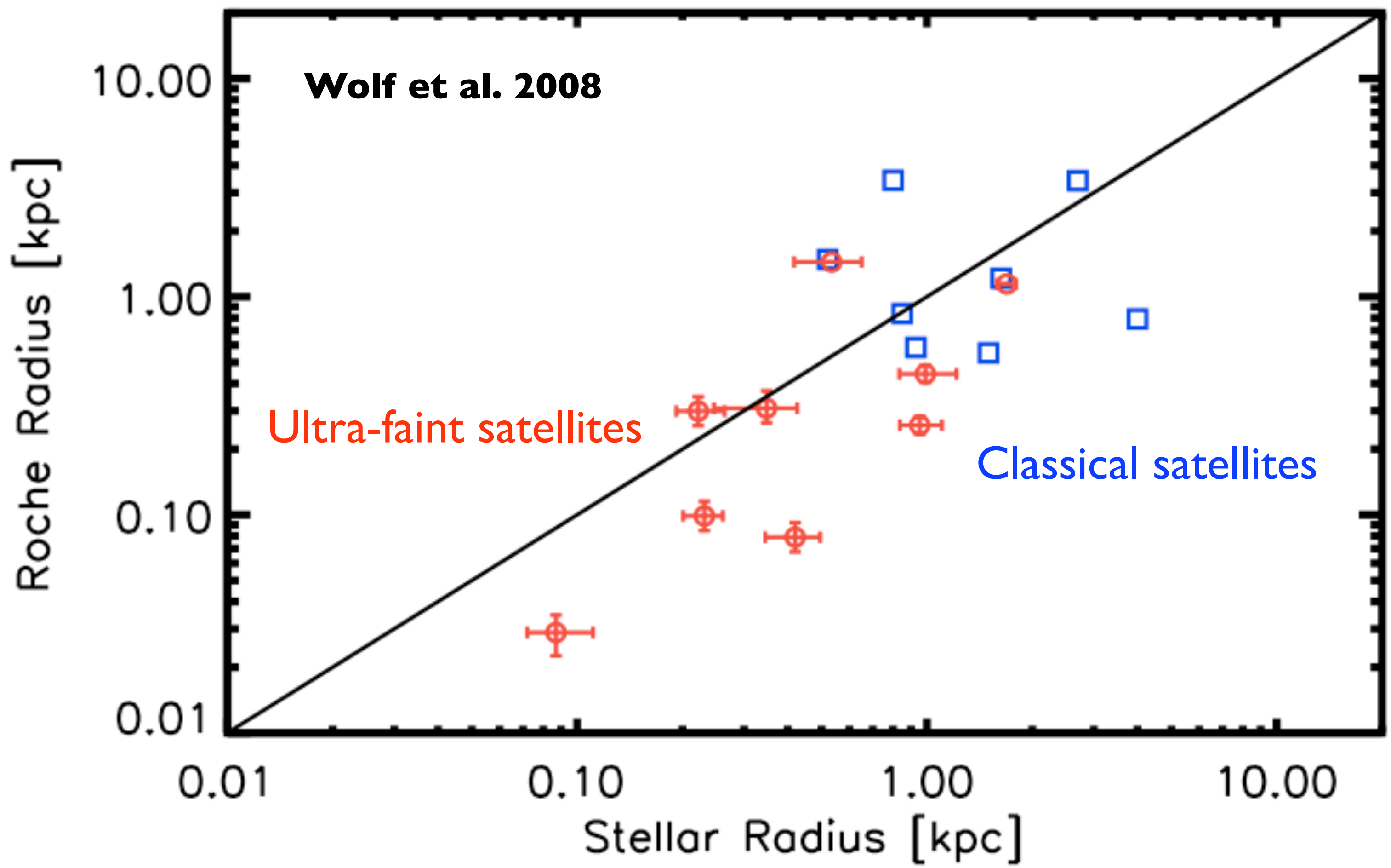


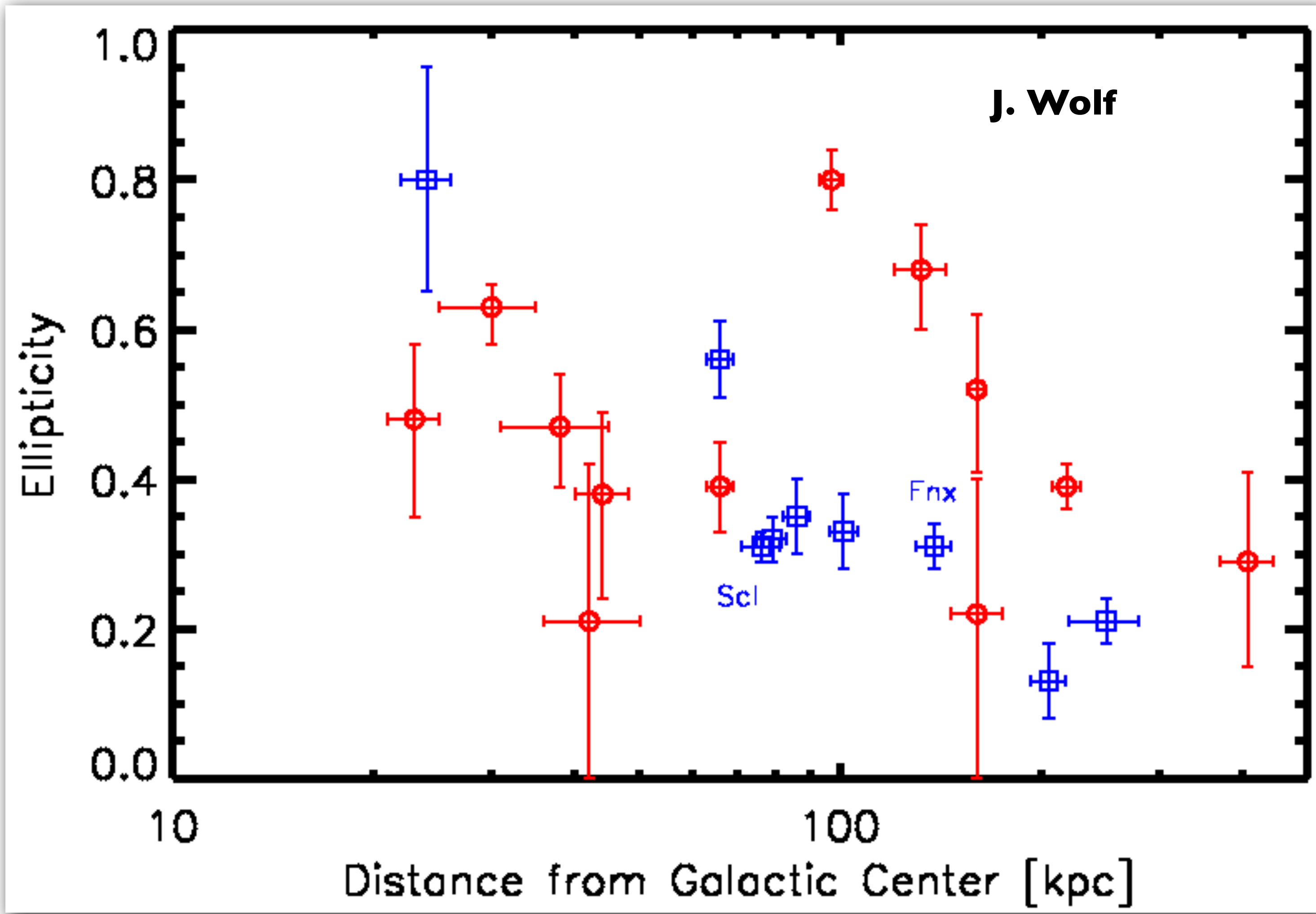
How quickly dissolve if not bound?



$\sim r_*/\sigma_*$

Instantaneous tidal radius vs. stellar radius (no dark matter)





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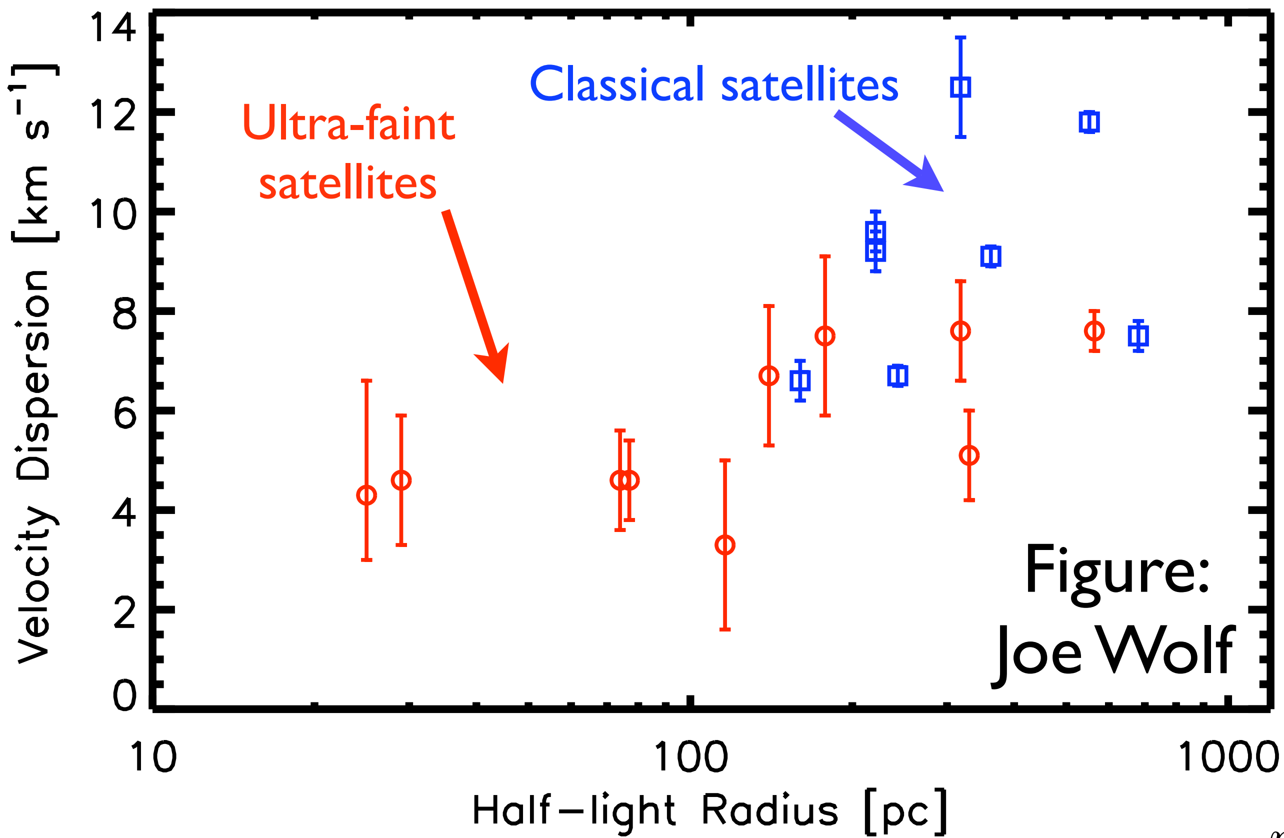
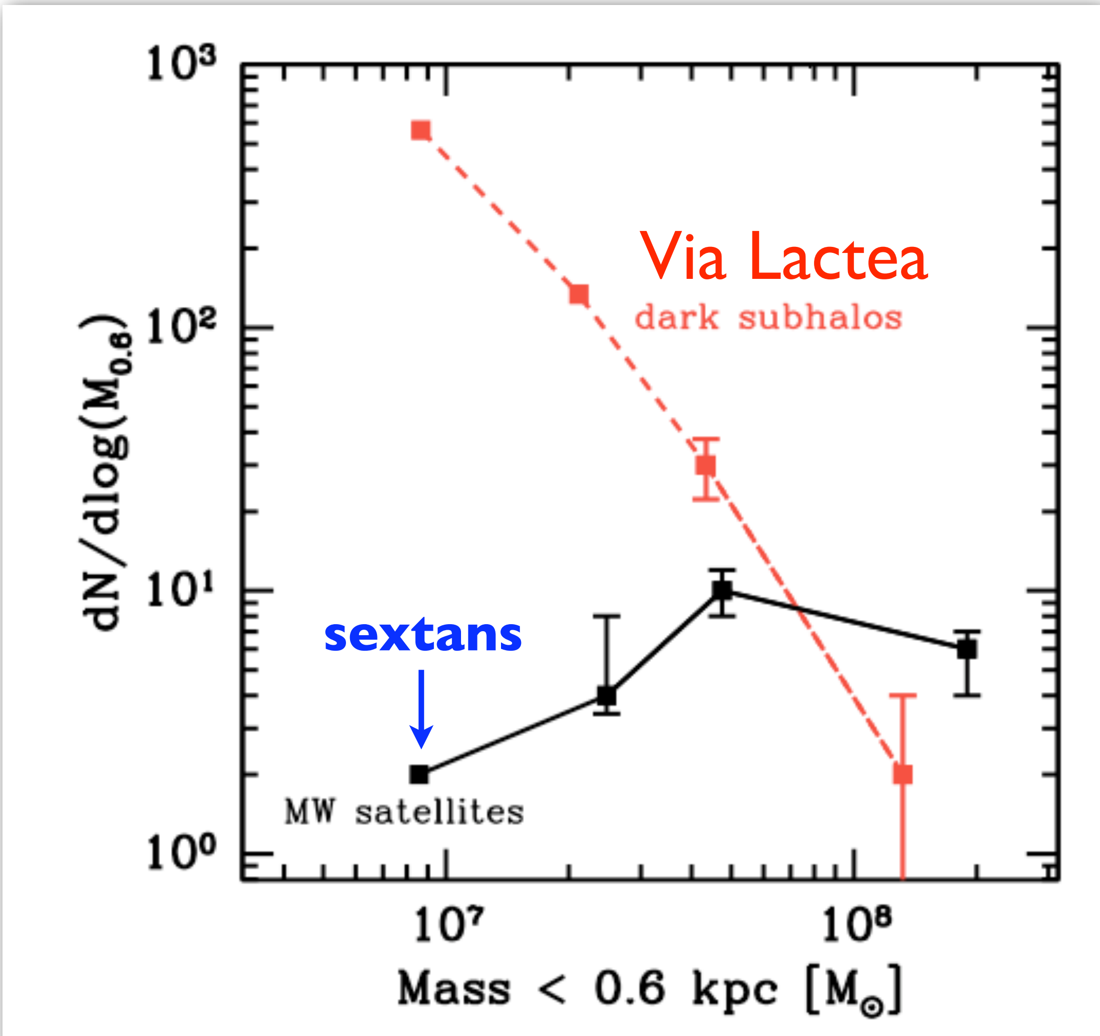


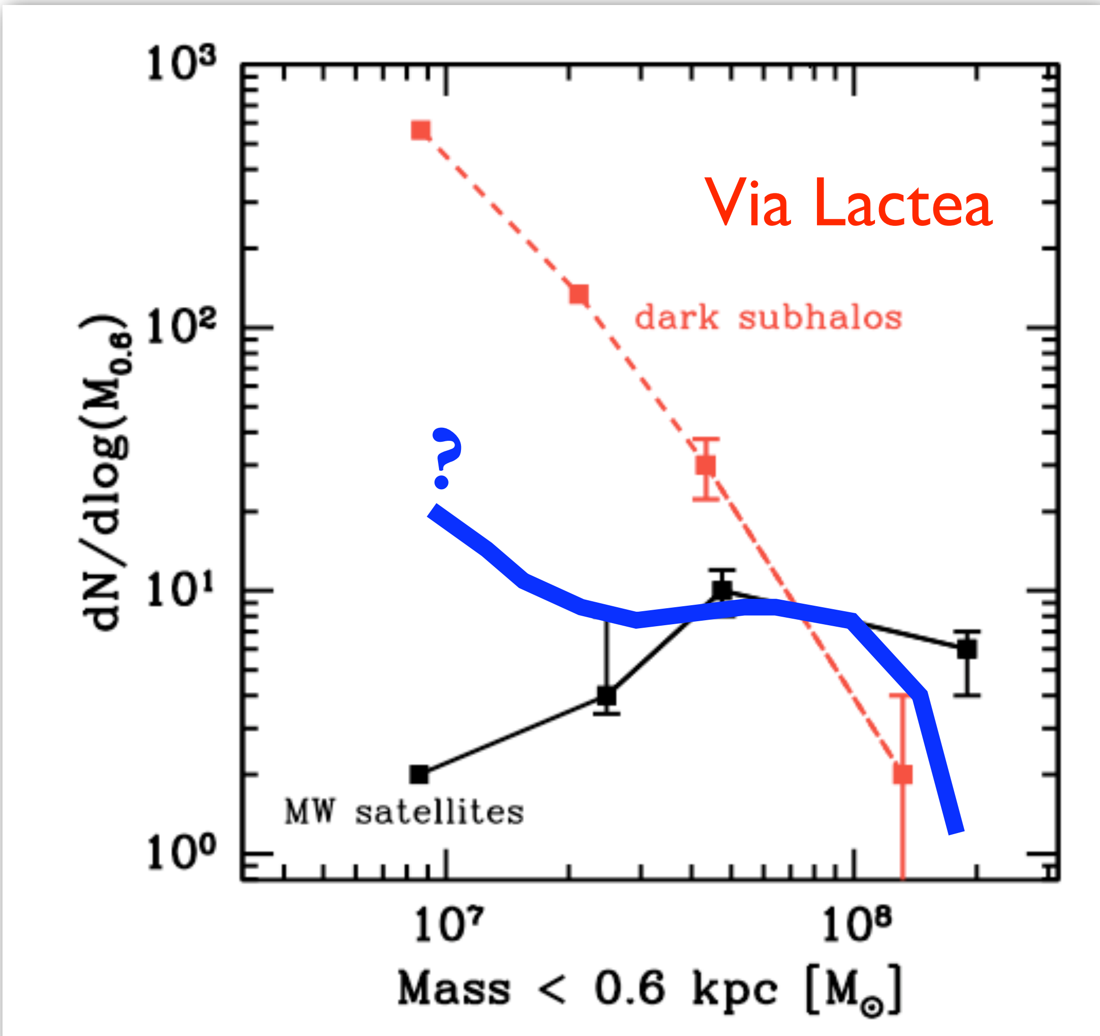
$$M(<r) = \frac{r\sigma_r^2}{G}\left|\frac{\mathrm{d}\ln\rho_*}{\mathrm{d}\ln r}\right|$$

M(<600pc) for Classical Milky Way dSphs



Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau 07

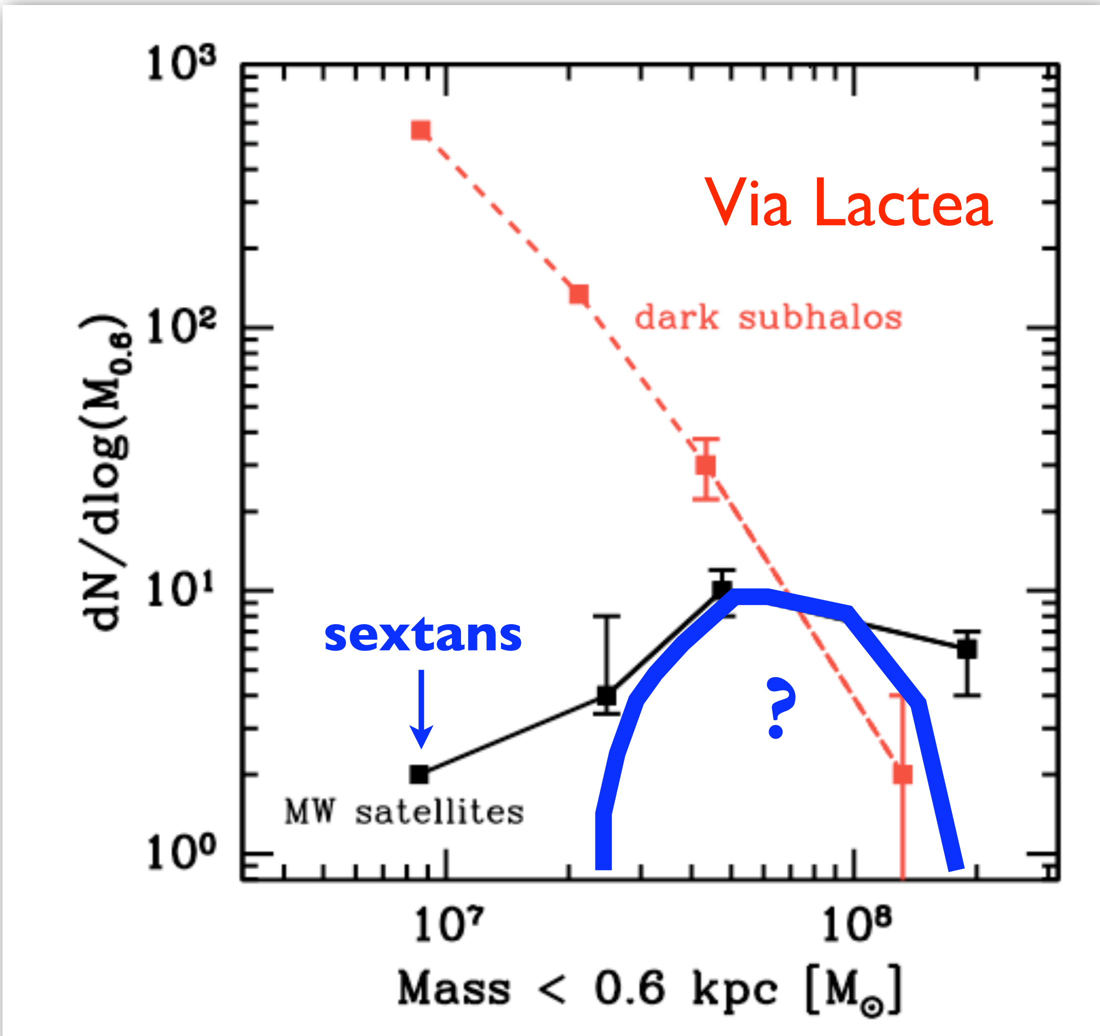
New Discoveries?



Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau 07

https://webfiles.uci.edu/bullock/Public/Canary2008/

New Discoveries?



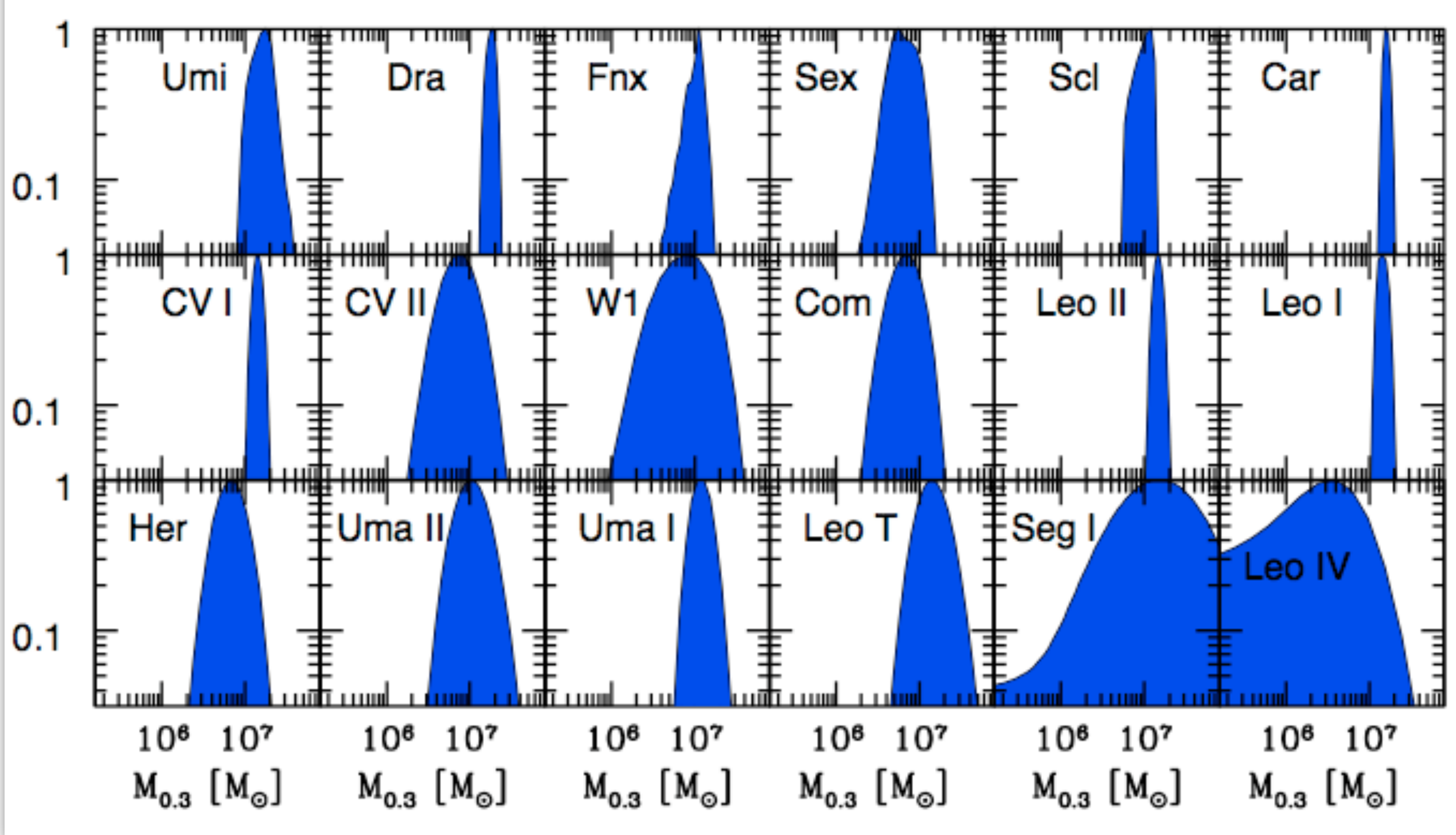
Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau 07

https://webfiles.uci.edu/bullock/Public/Canary2008/

L. Strigari et al., 2008

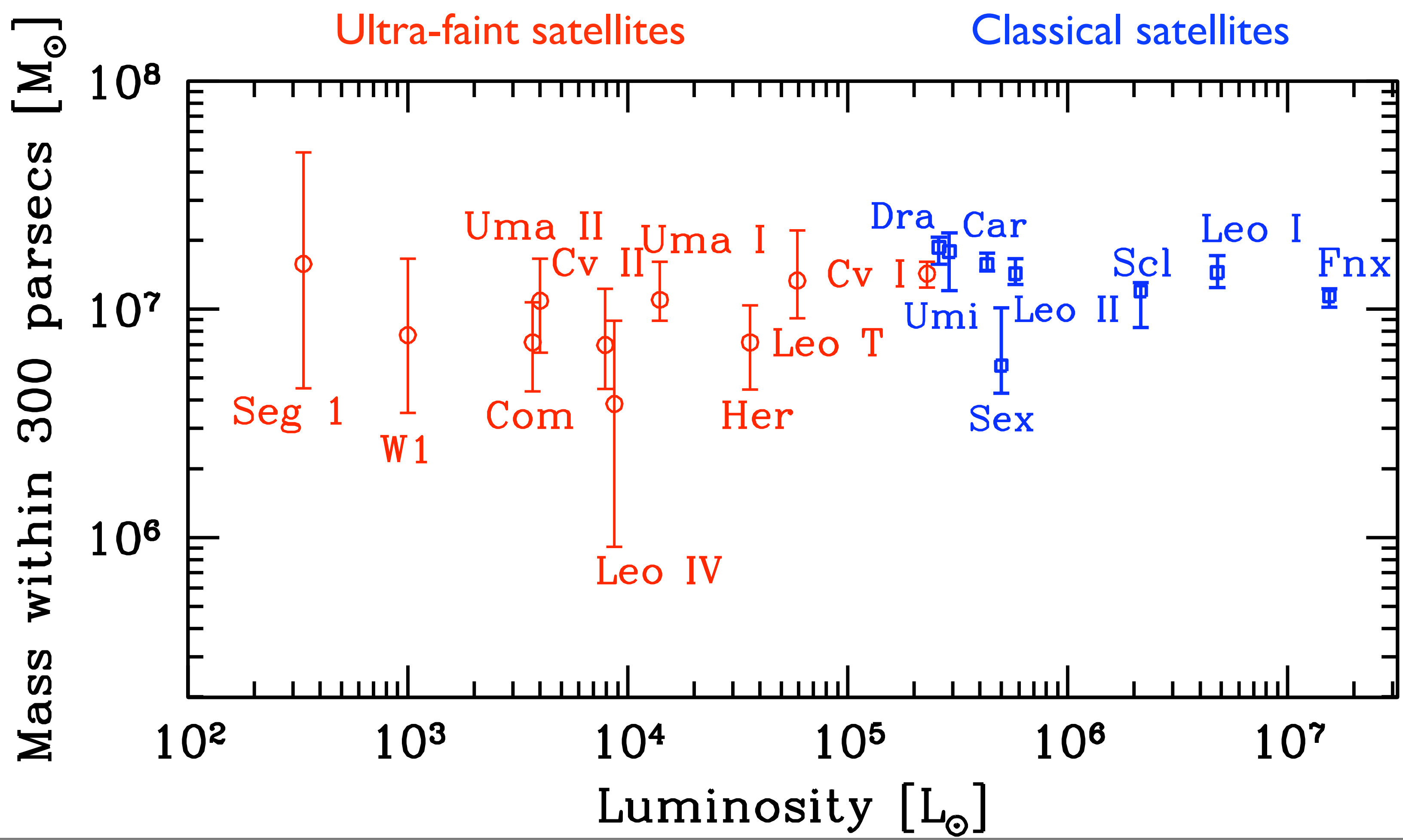
Find M(<300pc)

Note: allow **cusps and cores** and range of velocity anisotropies



https://webfiles.uci.edu/bullock/Public/Canary2008/

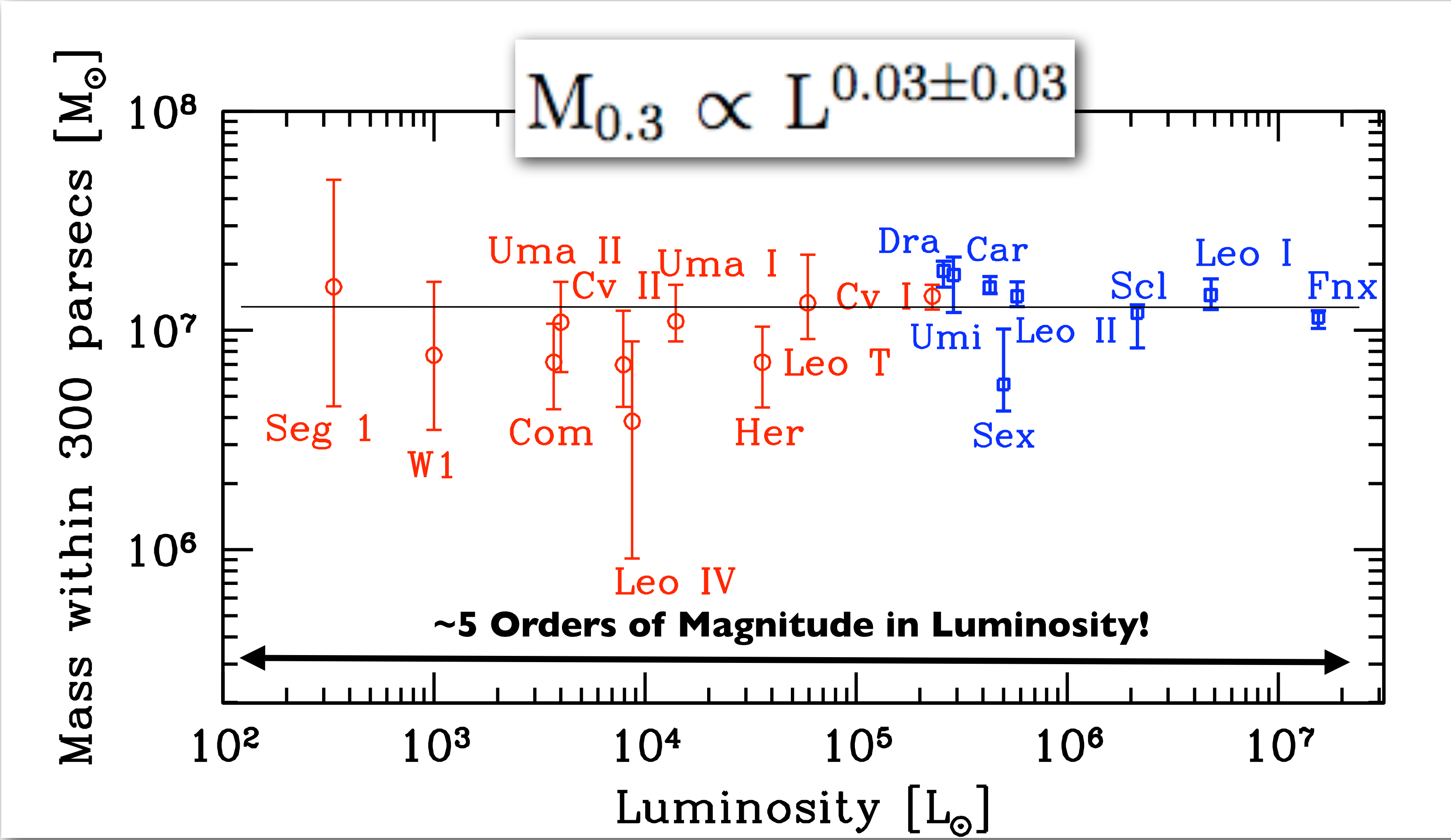
A Common Mass for MW Satellite Galaxies



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



L. Strigari, J. Bullock, M. Kaplinghat, J. Simon, M. Geha, B. Willman, M. Walker,
[Nature, Aug 28, 2008]

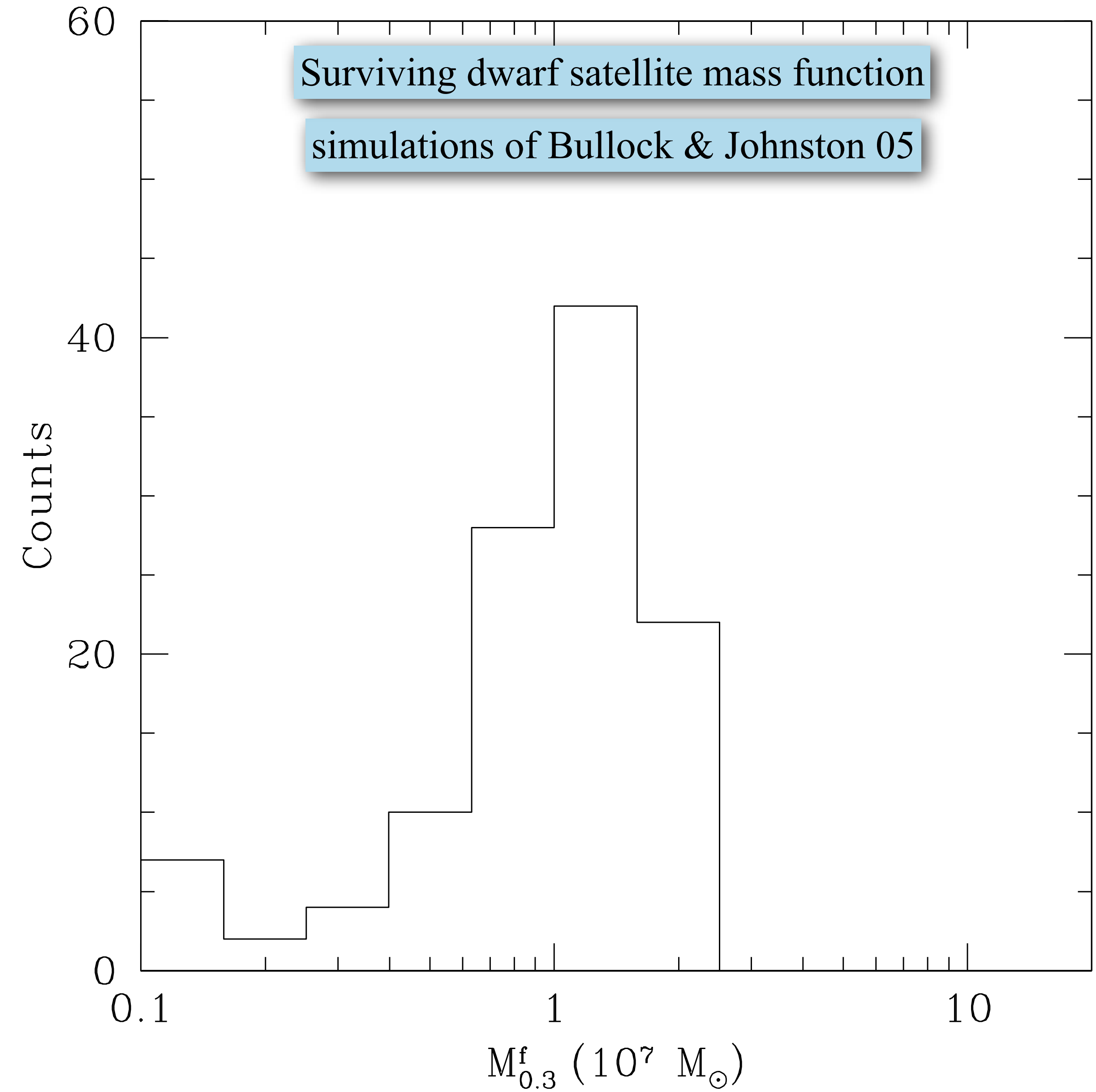
A characteristic mass for Milky Way dwarfs:

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

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

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

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

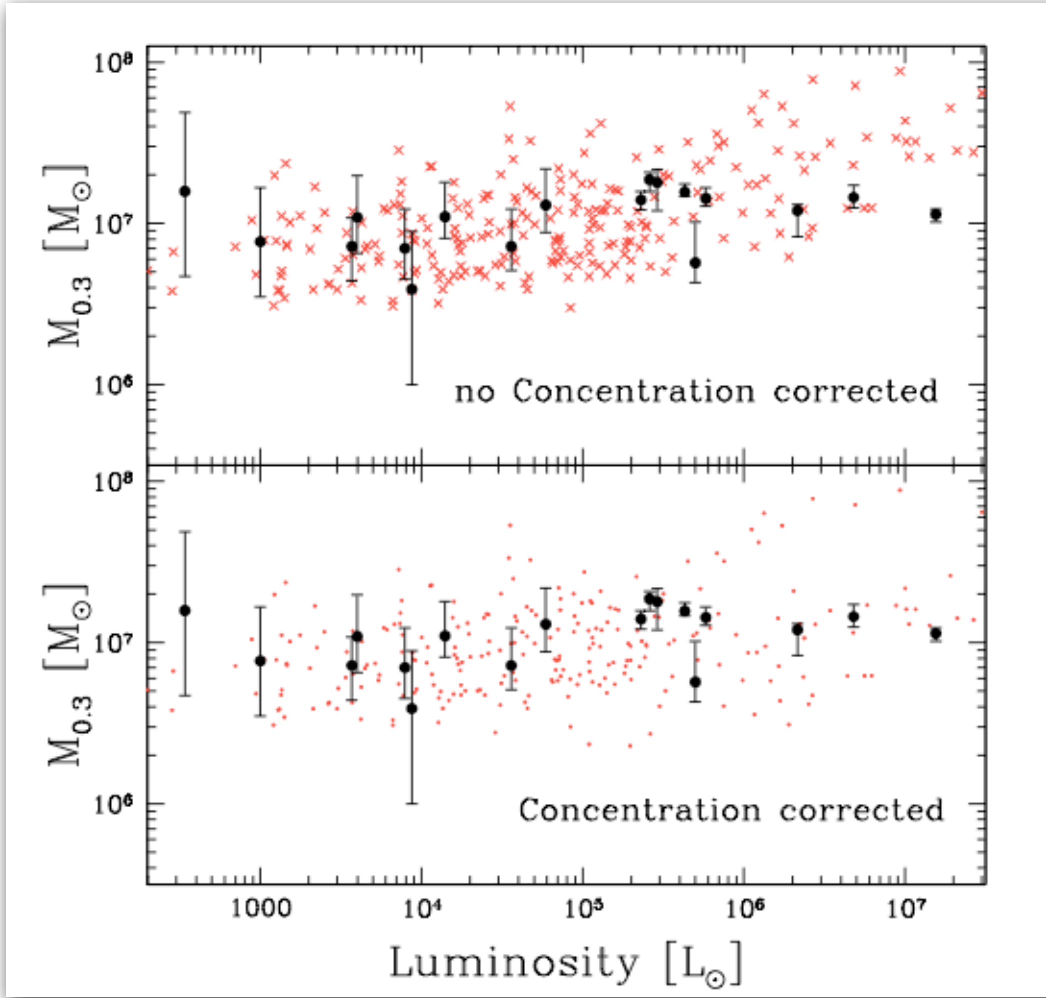


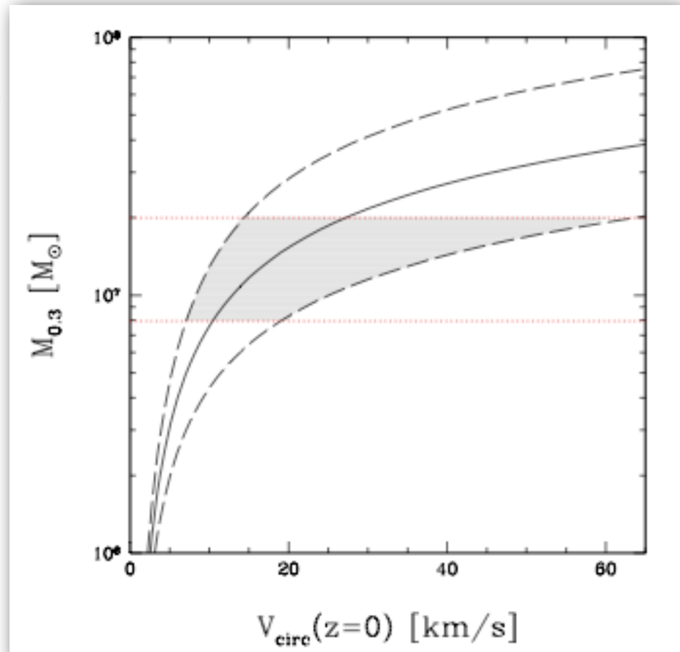
Surviving dwarf satellite mass function
simulations of Bullock & Johnston 05
Counts
0
20
40
60
0.1
1
10
$M^{f}_{0.3}$ (10^7 $M_\odot$)

Maccio et al. 08

No cooling below Tv=10^4K
+ reionization supression

(see Li et al. 08)



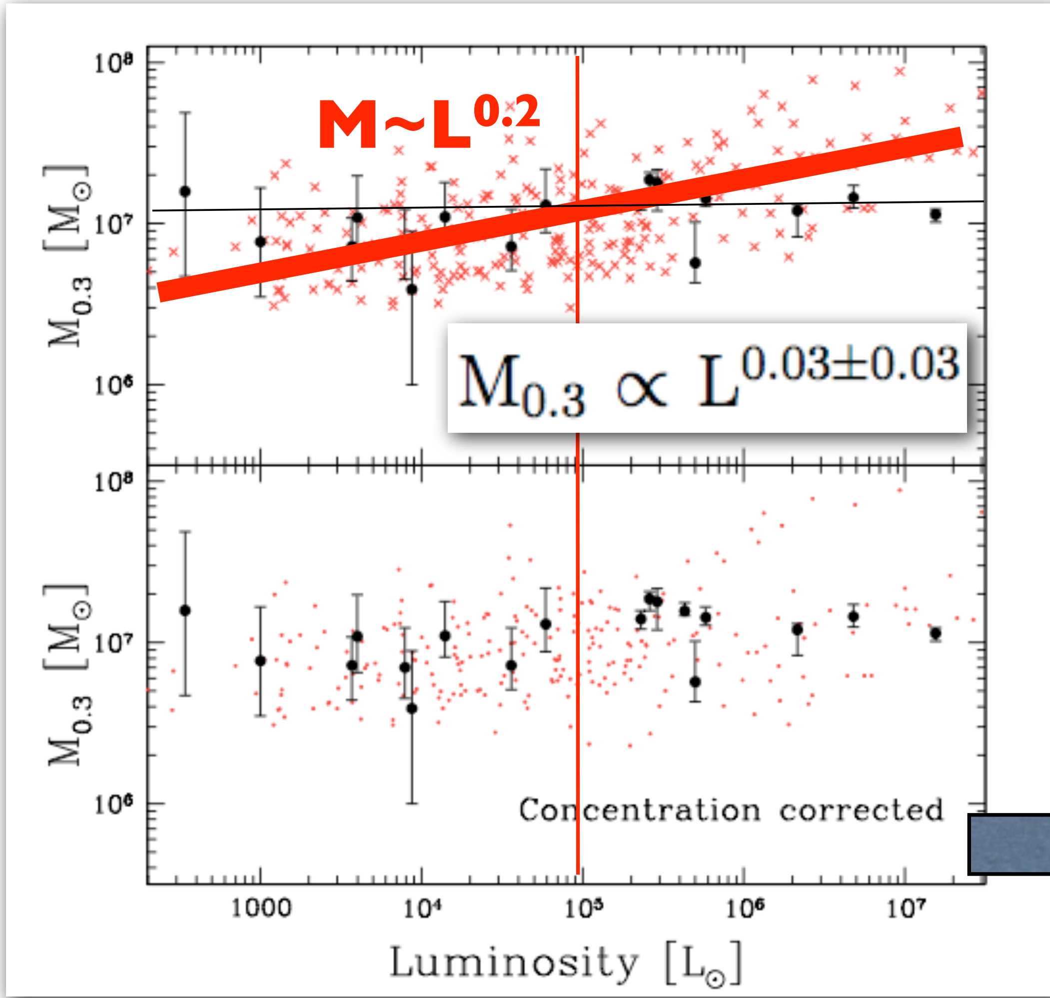


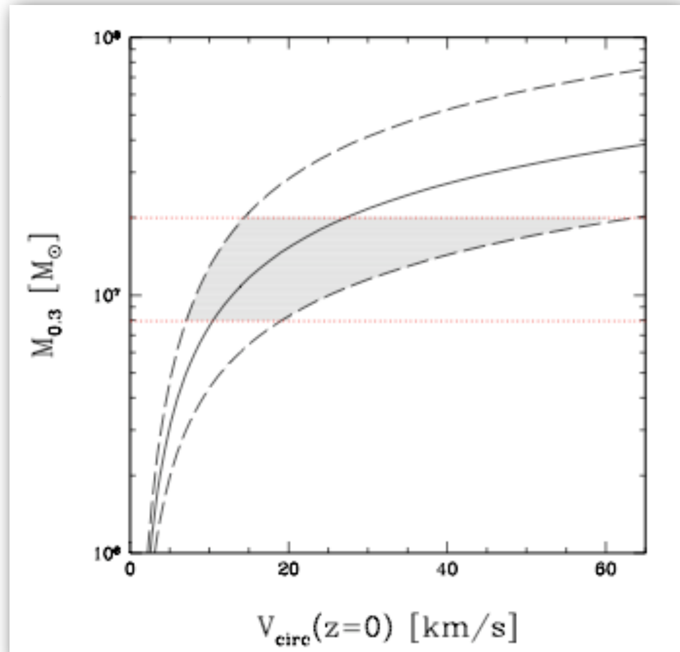
Scatter in L at fixed M
is caused by range of
accretion/formation times

Maccio et al. 08

No cooling below Tv=10^4K
+ reionization supression

(see Li et al. 08)

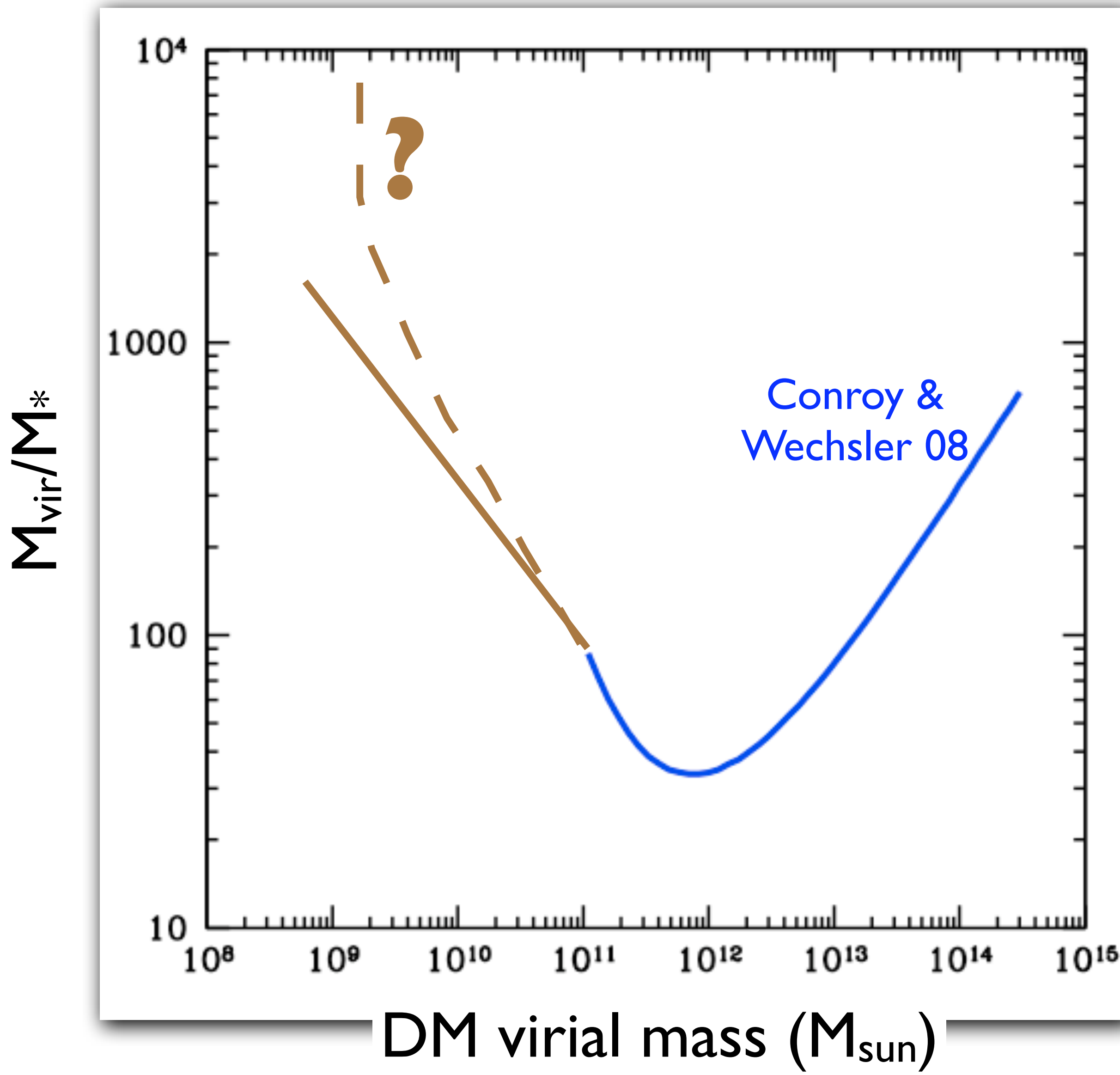




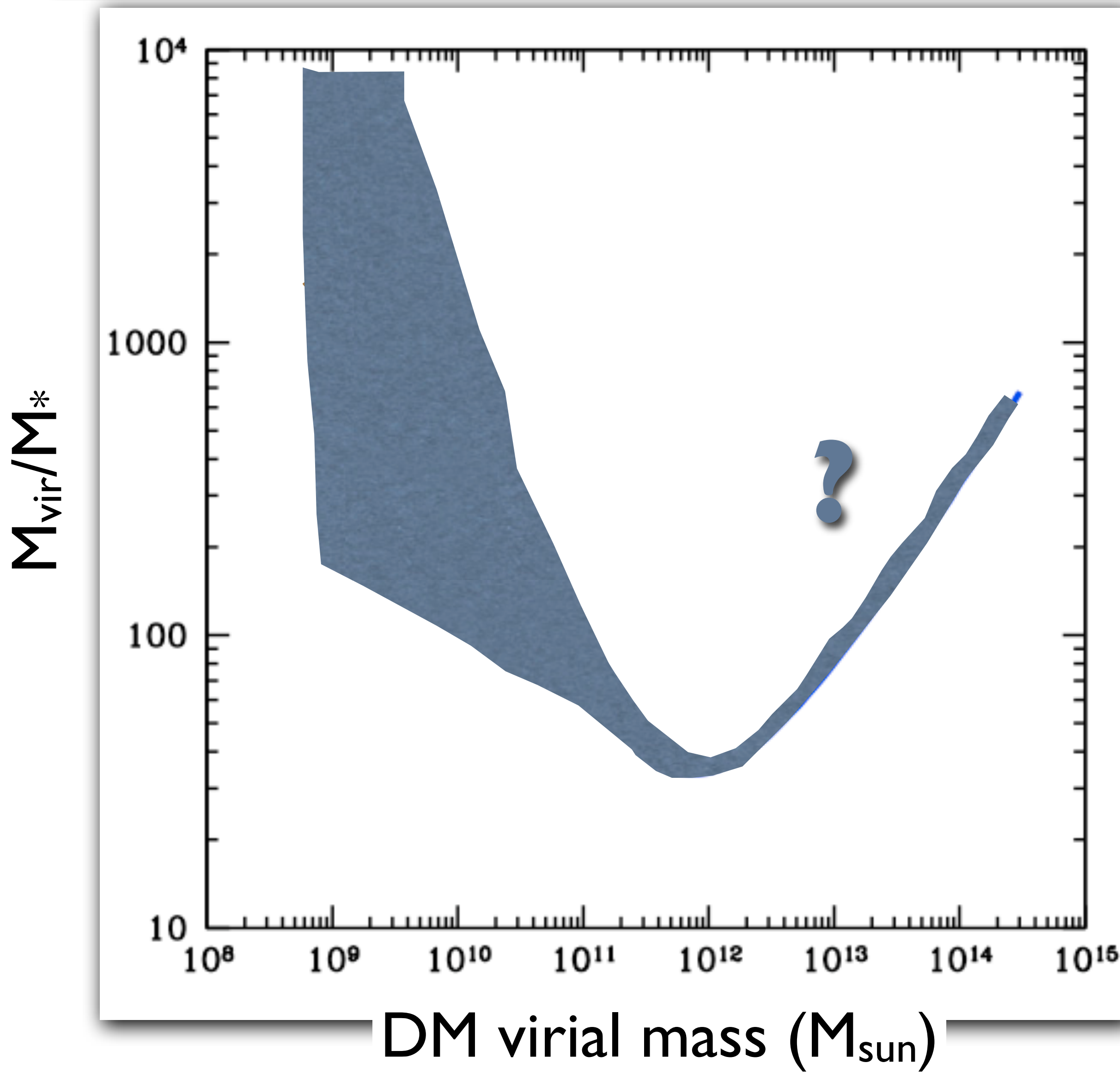
Scatter in L at fixed M
is caused by range of
accretion/formation times

~20 classical
satellites per halo
(too many)

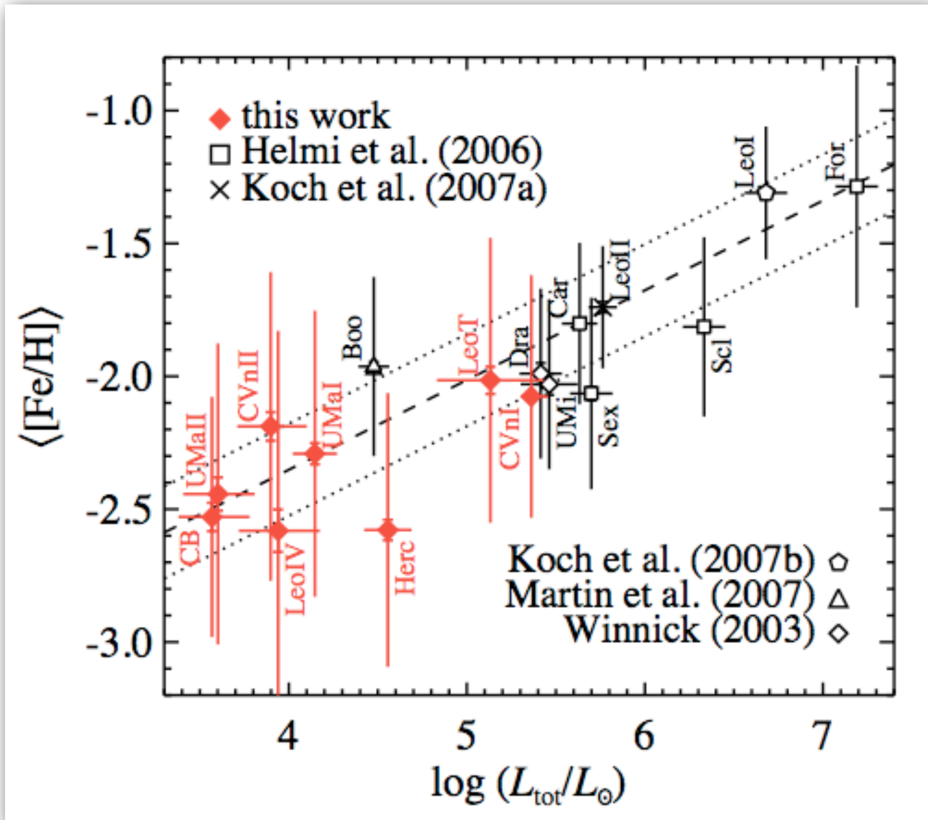
Efficiency of Galaxy Formation?

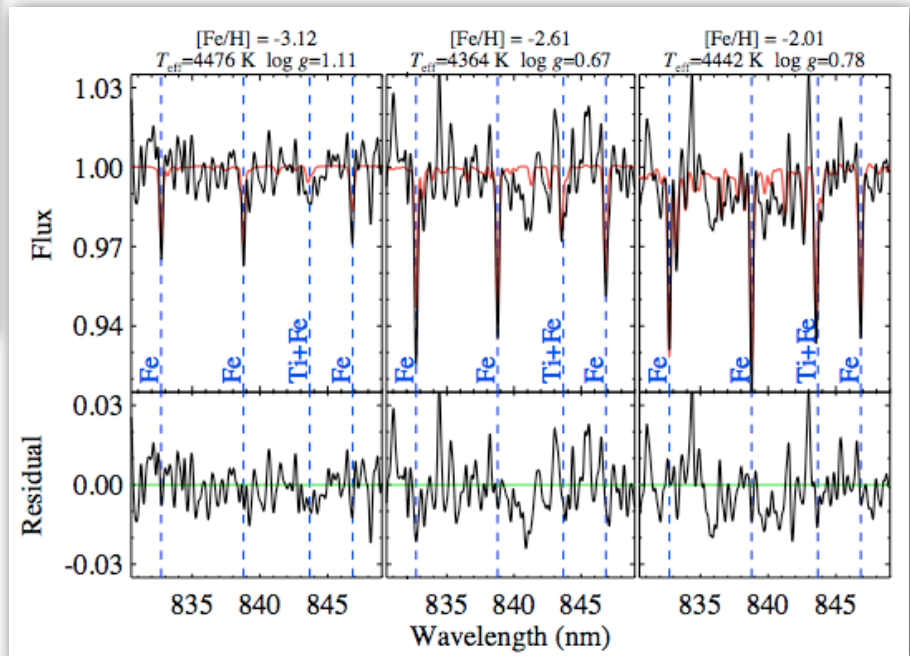


Scatter in Efficiency of Galaxy Formation?



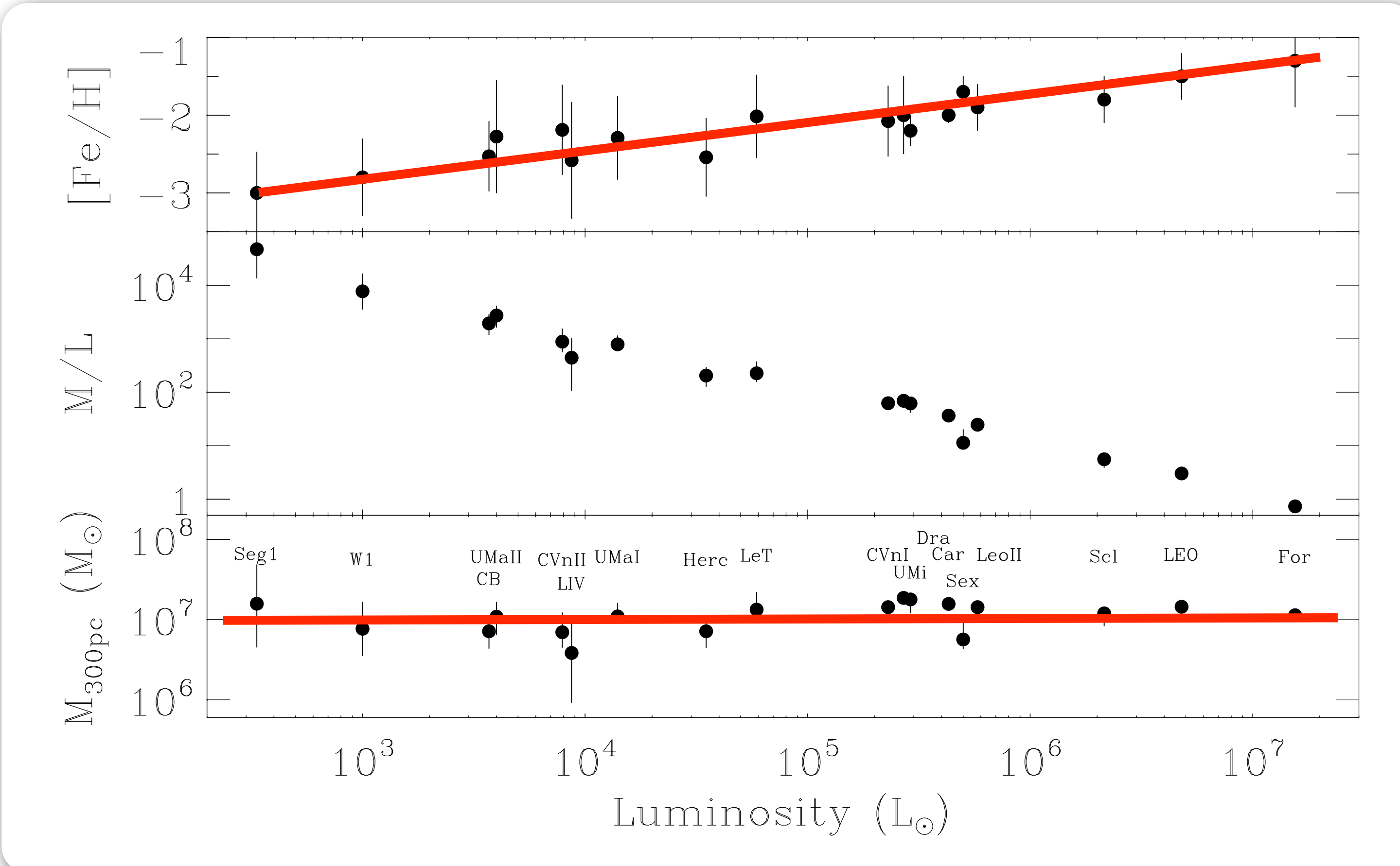
Evan Kirby, J. Simon et al. 2008





https://webfiles.uci.edu/bullock/Public/Canary2008/

Kirby, Simon et al 2008; Geha et al. 2008



Metallicity-Luminosity Relationship NOT set by potential well depth?

A characteristic mass for Milky Way dwarfs:

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

$$\Rightarrow \quad \rho(300\mathrm{pc}) \simeq 0.1 M_\odot\,\mathrm{pc}^{-3}$$

Julio: "Pericenter required for tidal destruction ~ 6 kpc"

End Lecture 4