Dwarf Satellite Galaxies: How Dark and How Many?

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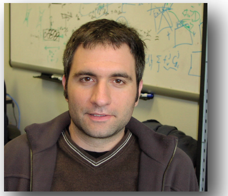
Back to the Galaxy II: UCSB, 2008

Team Irvine

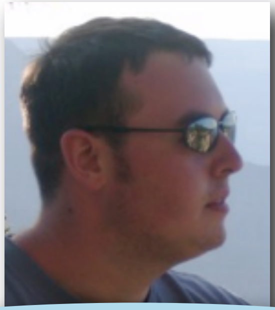
James **Bullock**

Manoj **Kaplinghat**



Louie **Strigari** (-> Stanford)

Erik **Tollerud**



Joe **Wolf**

Greg **Martinez**

Team Elsewhere

Beth **Willman**

Josh **Simon**

Marla **Geha**

Matt **Walker**

LG dSph Galaxies:
Best DM Labs in the Universe

$$L \simeq (10^3 - 10^7) L_\odot$$

$$M/L \simeq 10 - 10,000$$

1. Dark Matter Dominated - Easy to interpret

2. High phase-space densities - WDM vs CDM

3. Nearby - individual stellar kinematics

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Best Galaxy Formation labs in the Universe

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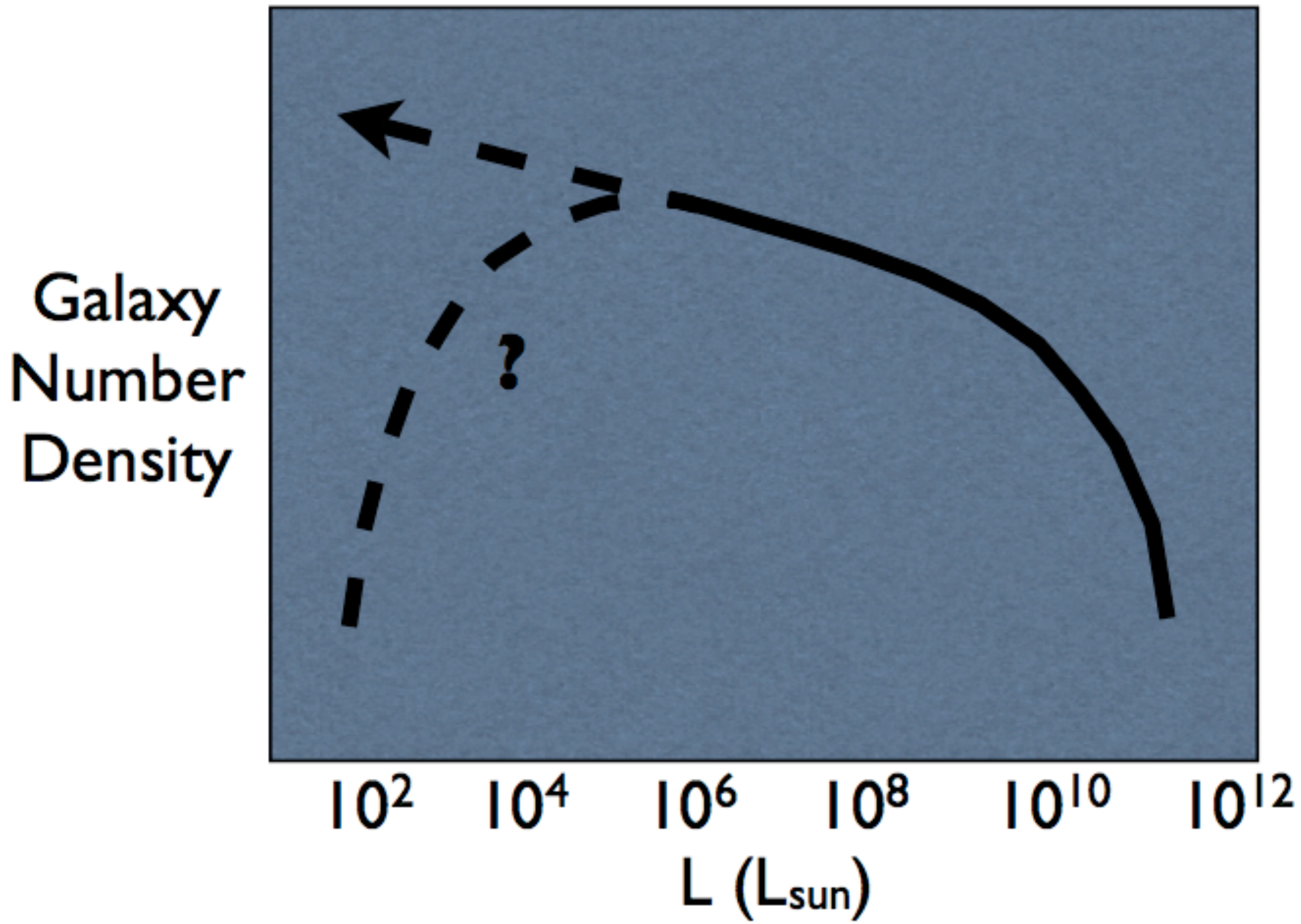
The least luminous and most metal poor galaxies known

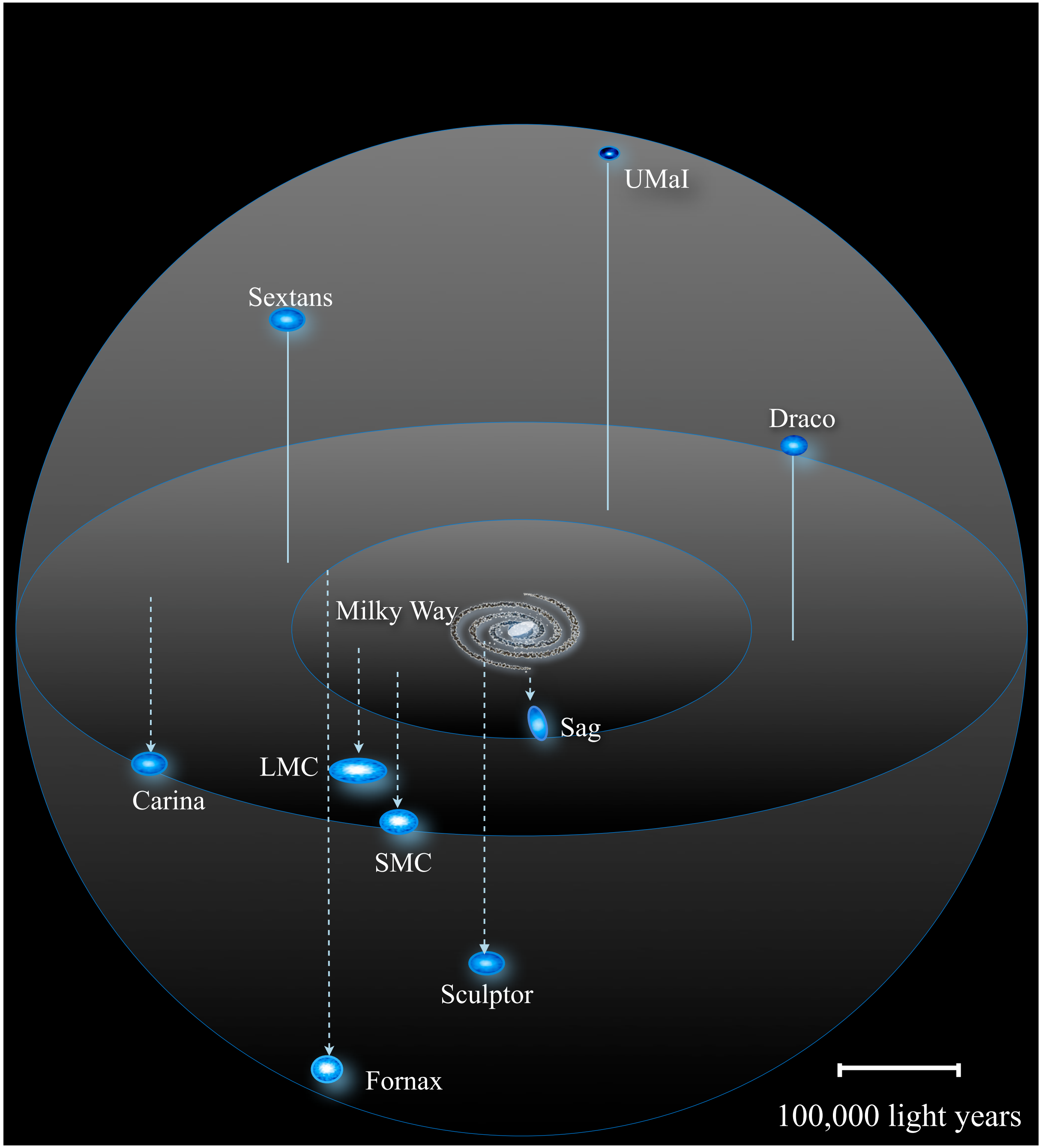
How faint is the faintest galaxy?



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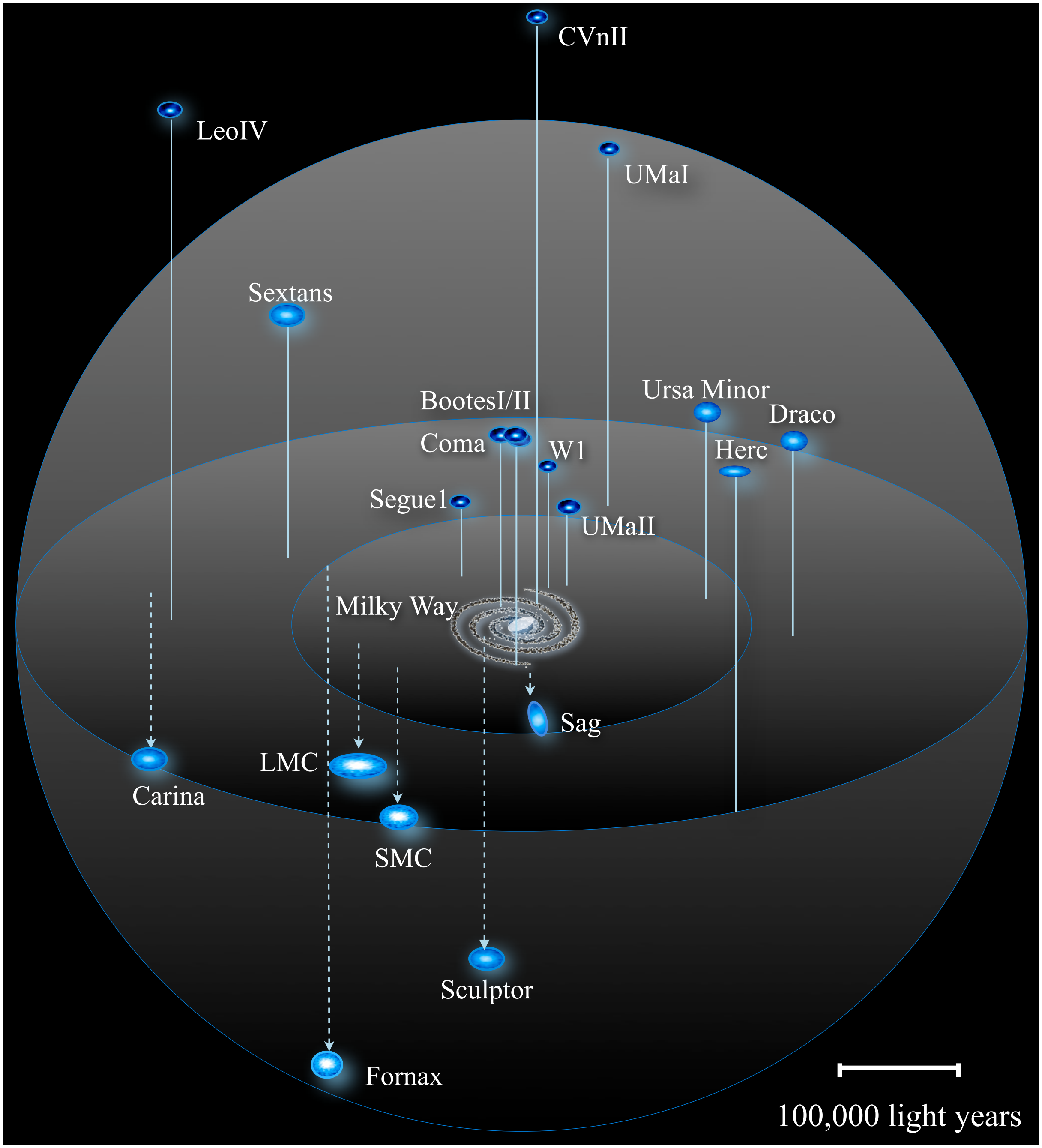
Sextans	1990
Sagittarius	1994
Ursa Major I	**2005**
Willman I	**2005**
Ursa Major II	**2006**
Bootes	**2006**
Canes Venatici I	**2006**
Canes Venatici II	**2006**
Coma	**2006**
Segue I	**2006**
Leo IV	**2006**
Hercules	**2006**
Leo T	**2007**
Bootes II	**2007**
Leo V	**2008**



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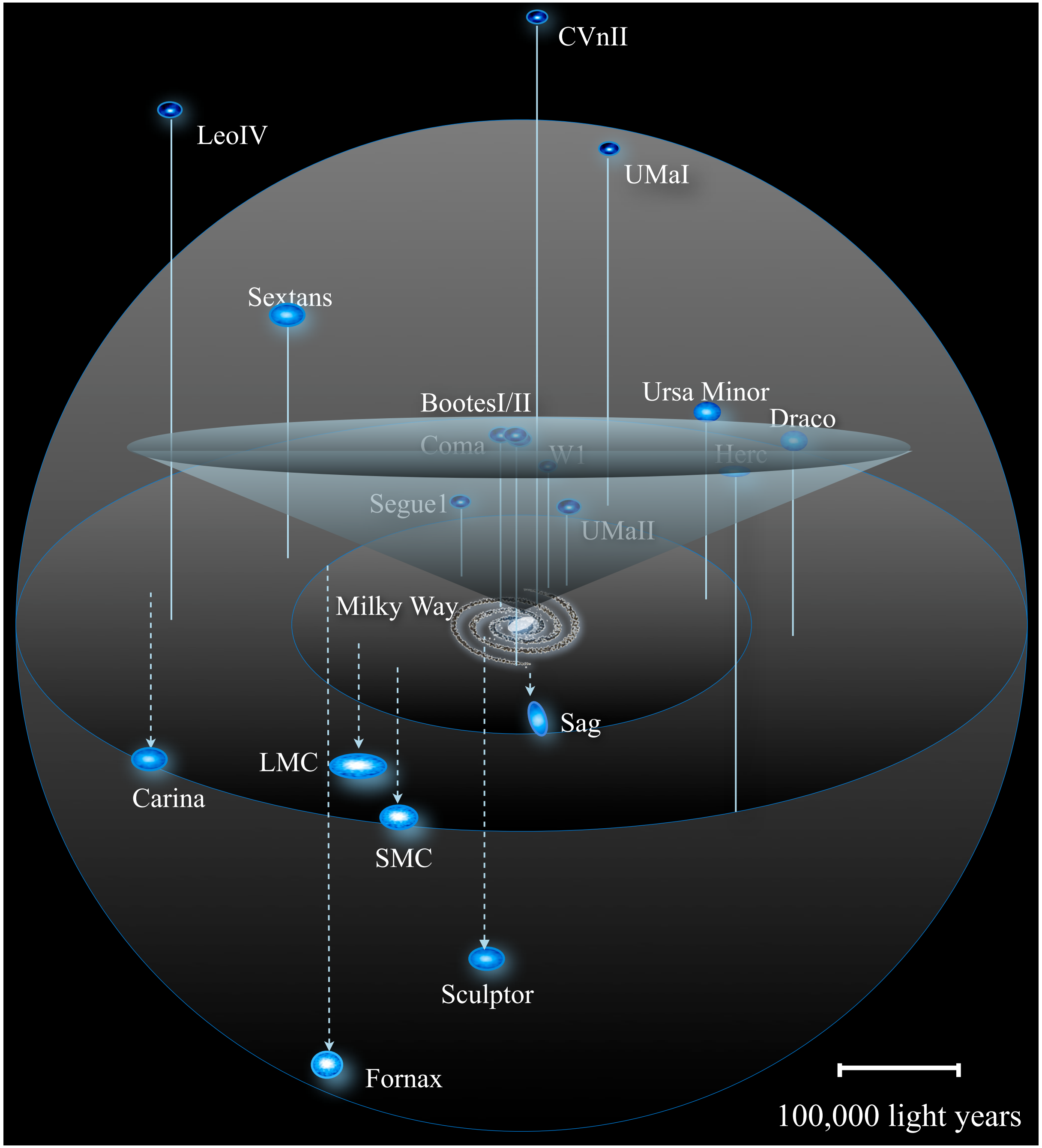
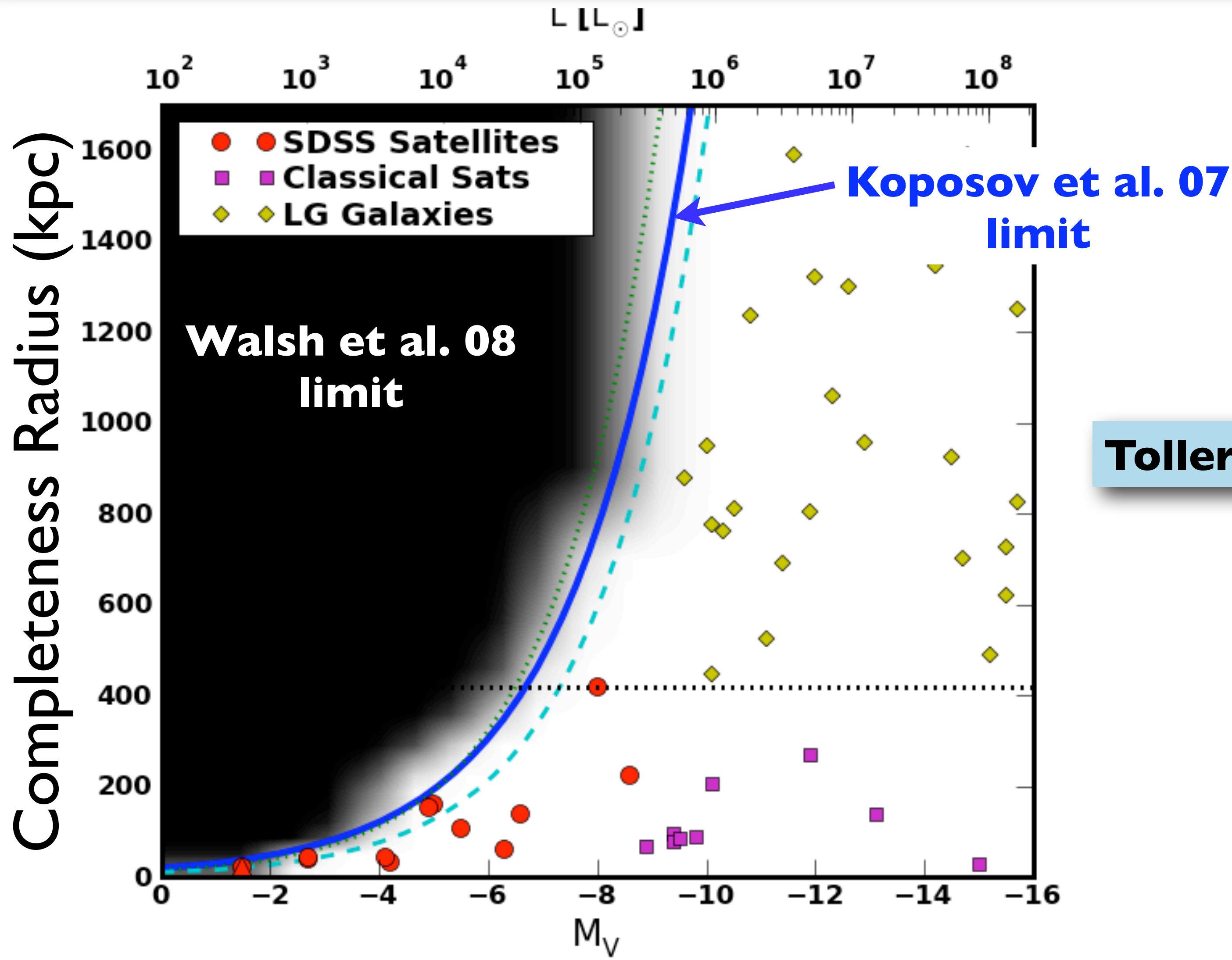


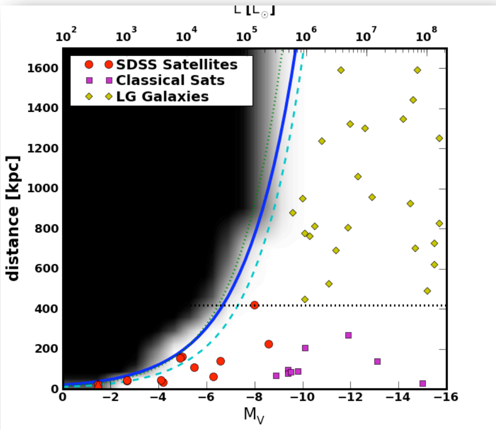
Many more to be discovered...



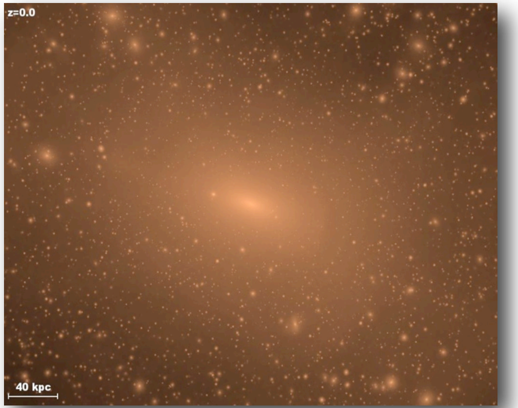
Tollerud et al. 08

Erik Tollerud, JSB, Strigari, Willman 08

How many Milky Way satellites?



1. Radial completeness limits for dwarf detection in SDSS (Koposov et al. 2007)



2. Radial (& angular) distribution of subhalos from the Via Lactea simulation (Diemand et al. 2007)

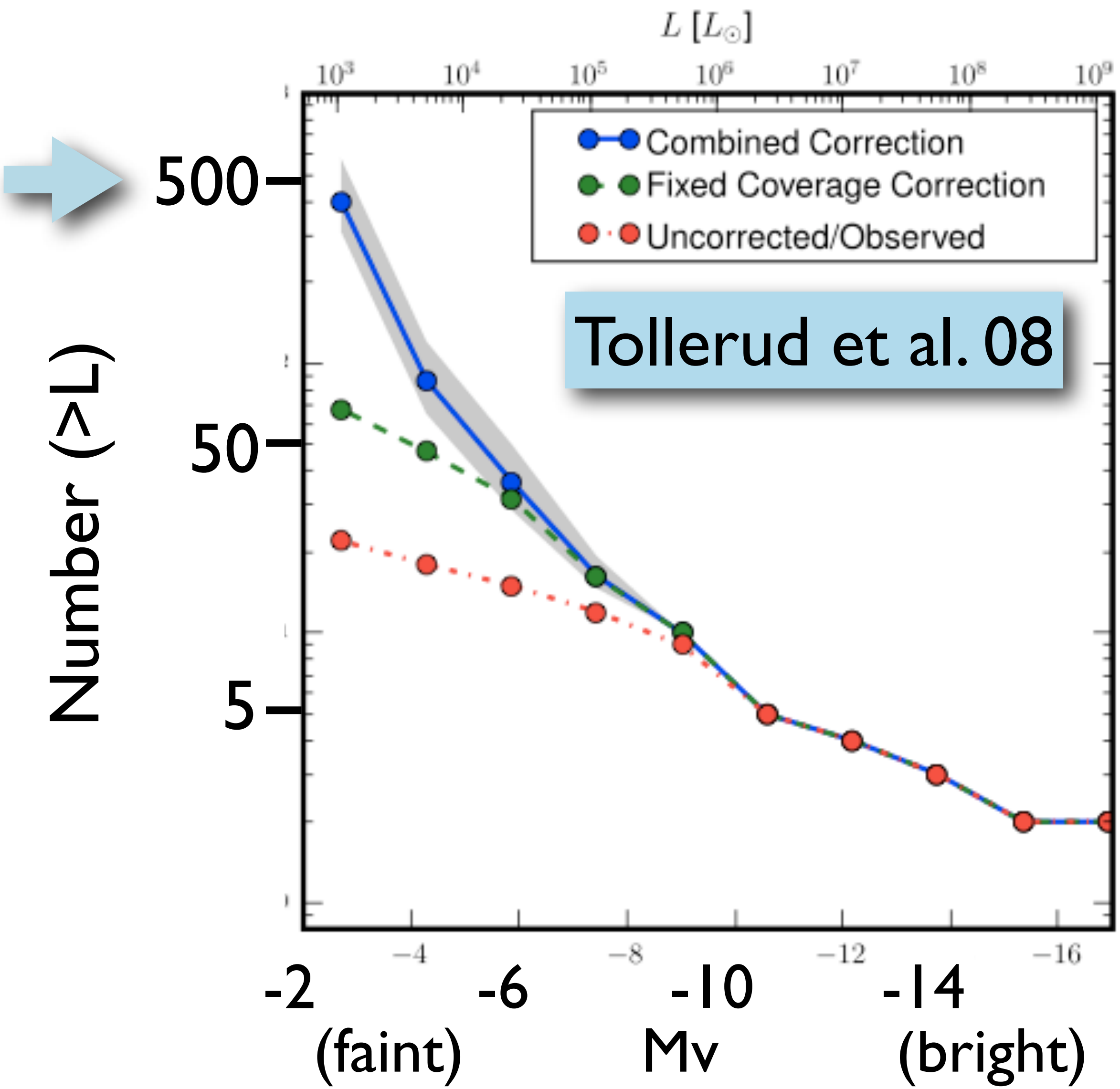
Erik Tollerud, JSB, Strigari, Willman 08

How many Milky Way satellites?

Only One Assumption:

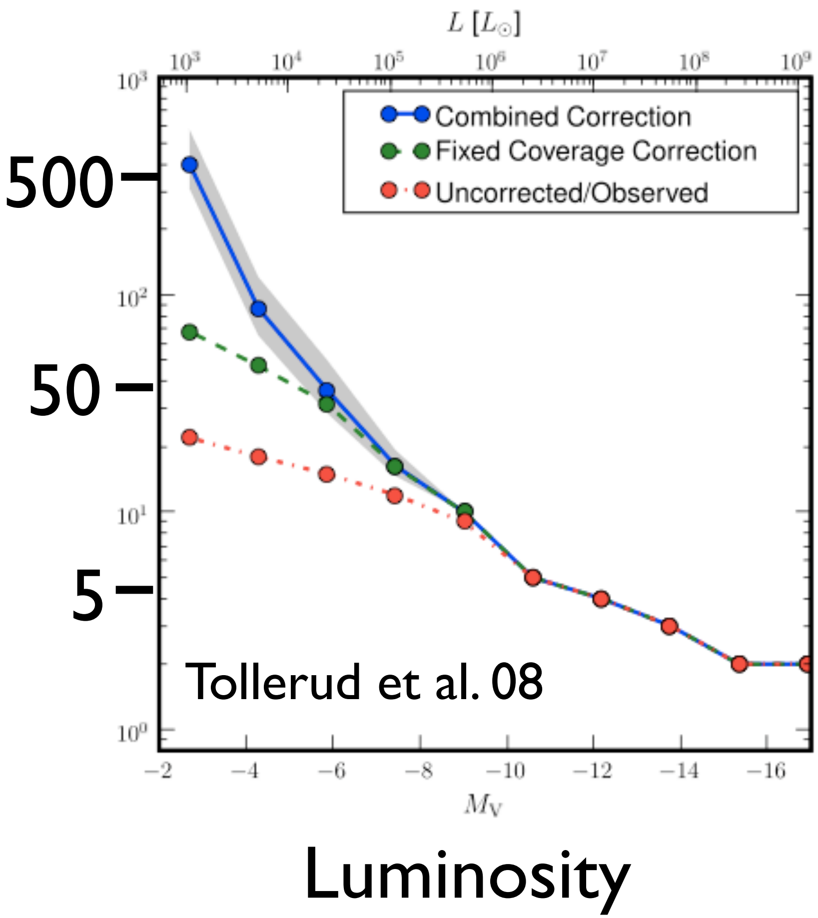
Radial & angular distribution of MW satellites matches that of subhalos in Via Lactea.

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



See poster by Tollerud

How could Tollerud et al. be wrong?



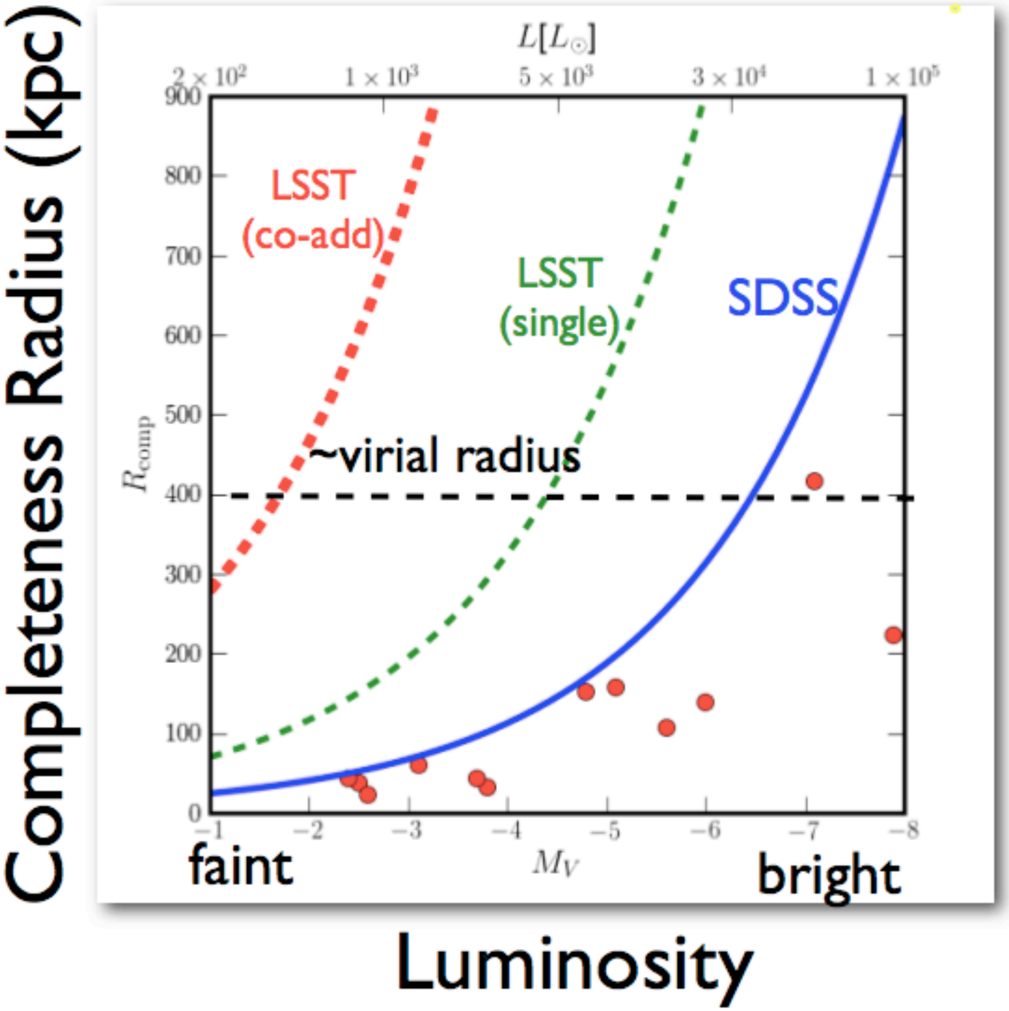
1. If subhalos near the Sun are more likely to host ultra-faints.

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...

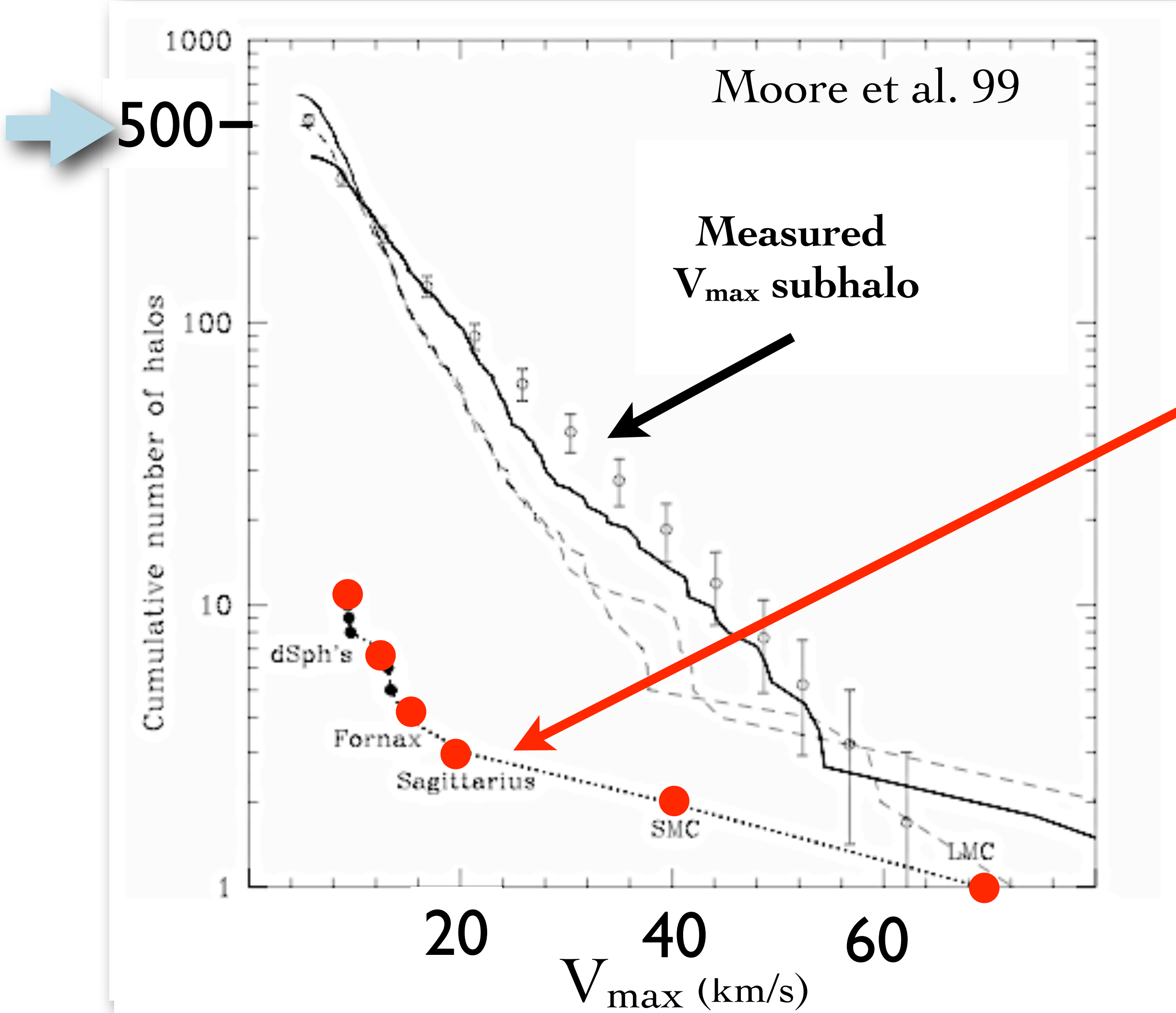
Skymapper/PanSTARRS/DES...



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

Tollerud et al. 08

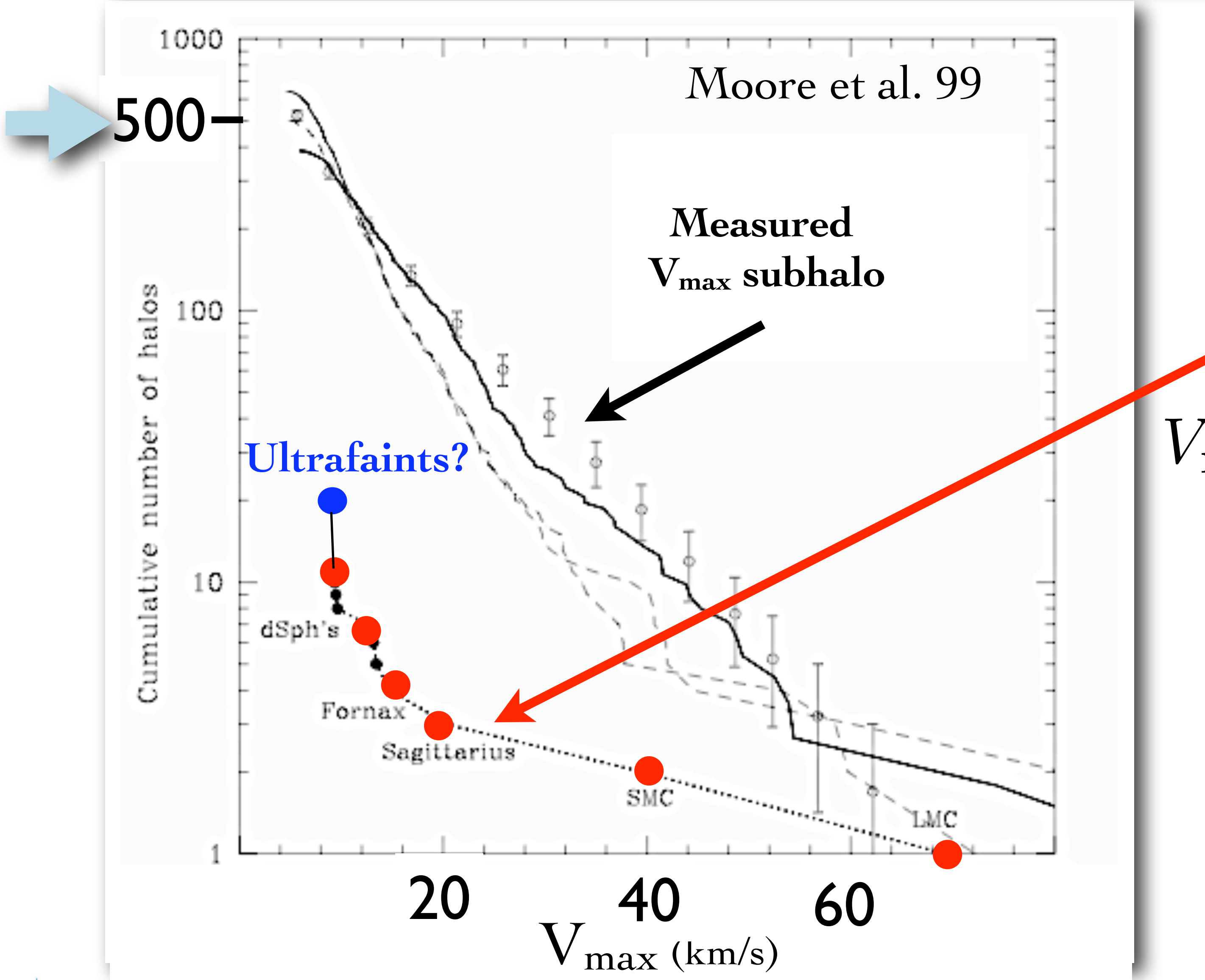
Missing Galactic Satellites?



Estimate:

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

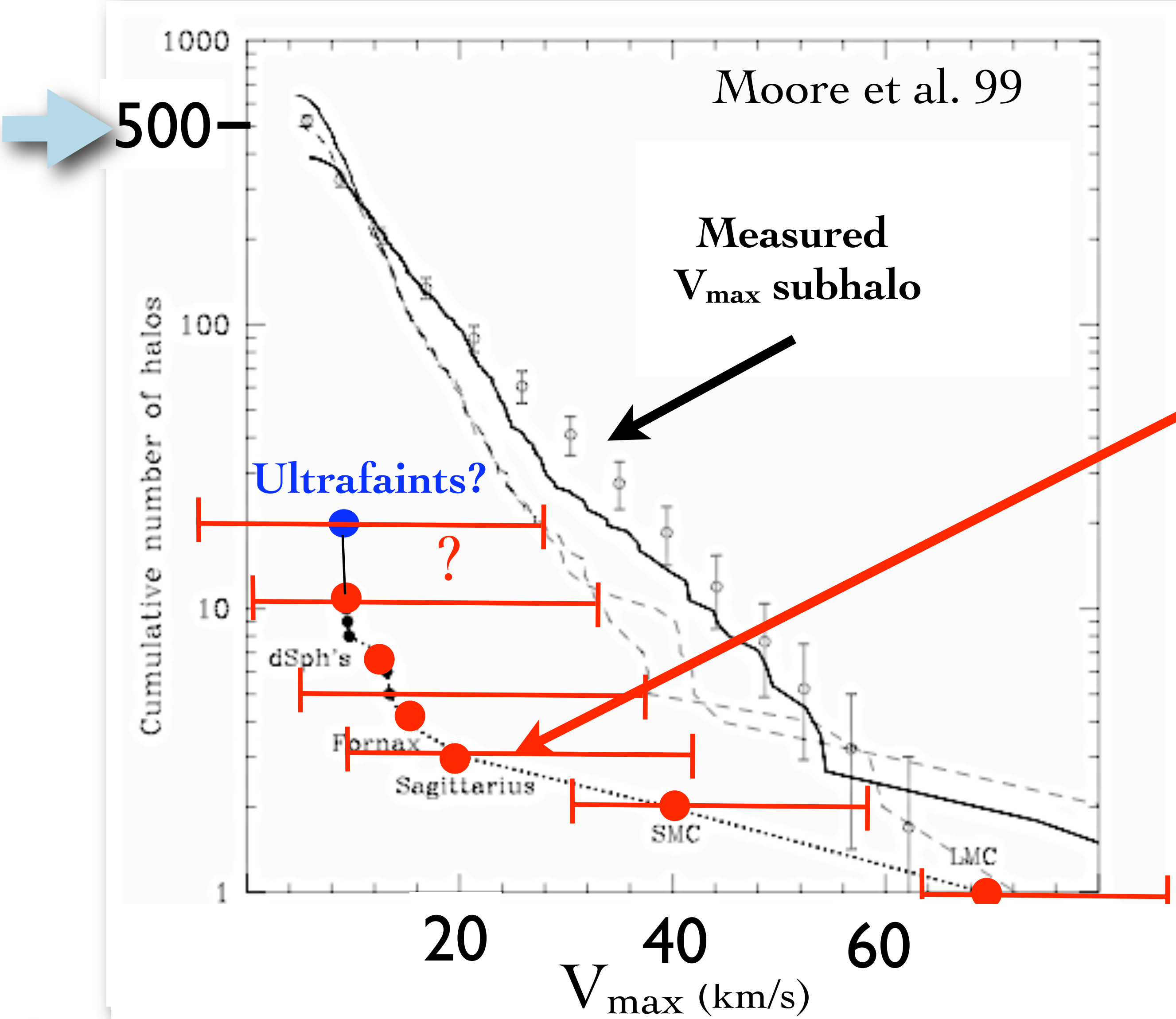
Missing Galactic Satellites?



Estimate:

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

What kind of subhalos host these satellites?



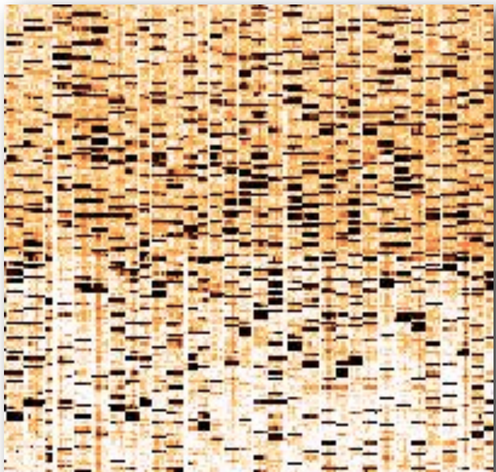
Estimate:

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

J. Bullock, UC Irvine

Strigari, JSB, Kaplinghat, Simon, Geha, Willman, Walker 2008

What are the masses of Milky Way Satellites?



1. Stellar kinematics for classical & ultrafaint dwarfs
[Walker et al. 07; Simon & Geha 07; Martin et al. 07; Willman et al. 08; Geha et al. 08]

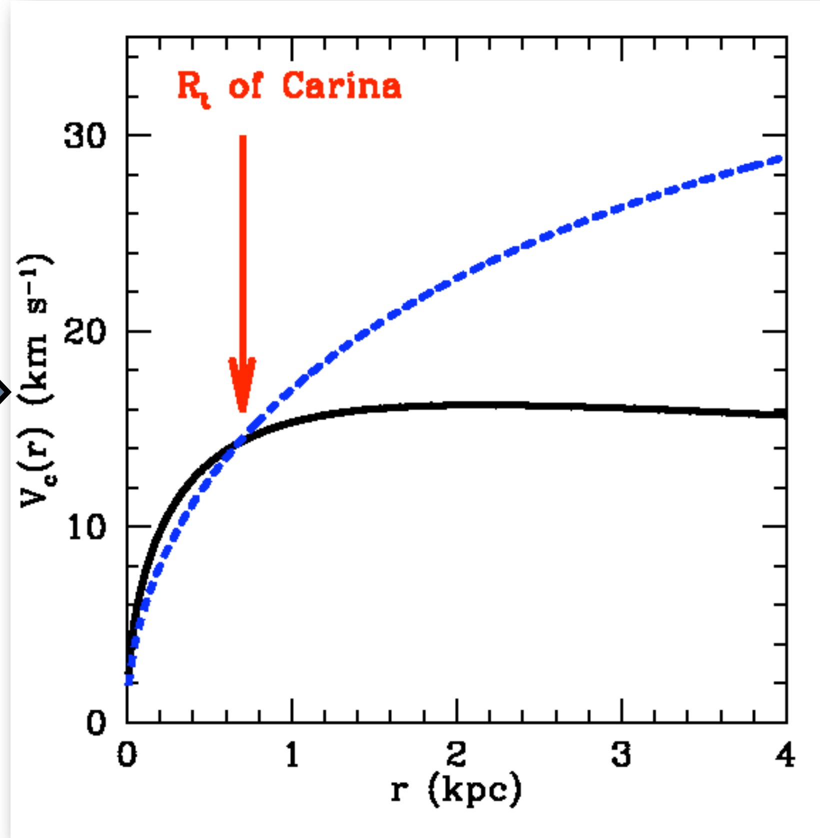
$$\rho(r) = \frac{\rho_0}{(r/r_0)^a[1 + (r/r_0)^b]^{(c-a)/b}}$$

$$\beta(r) = \beta_0 + \frac{\beta_1 r^2}{r^2 + r_\beta^2}$$

2. Spherical Jeans equation. Marginalize over 8 parameter mass and velocity-anisotropy profiles.

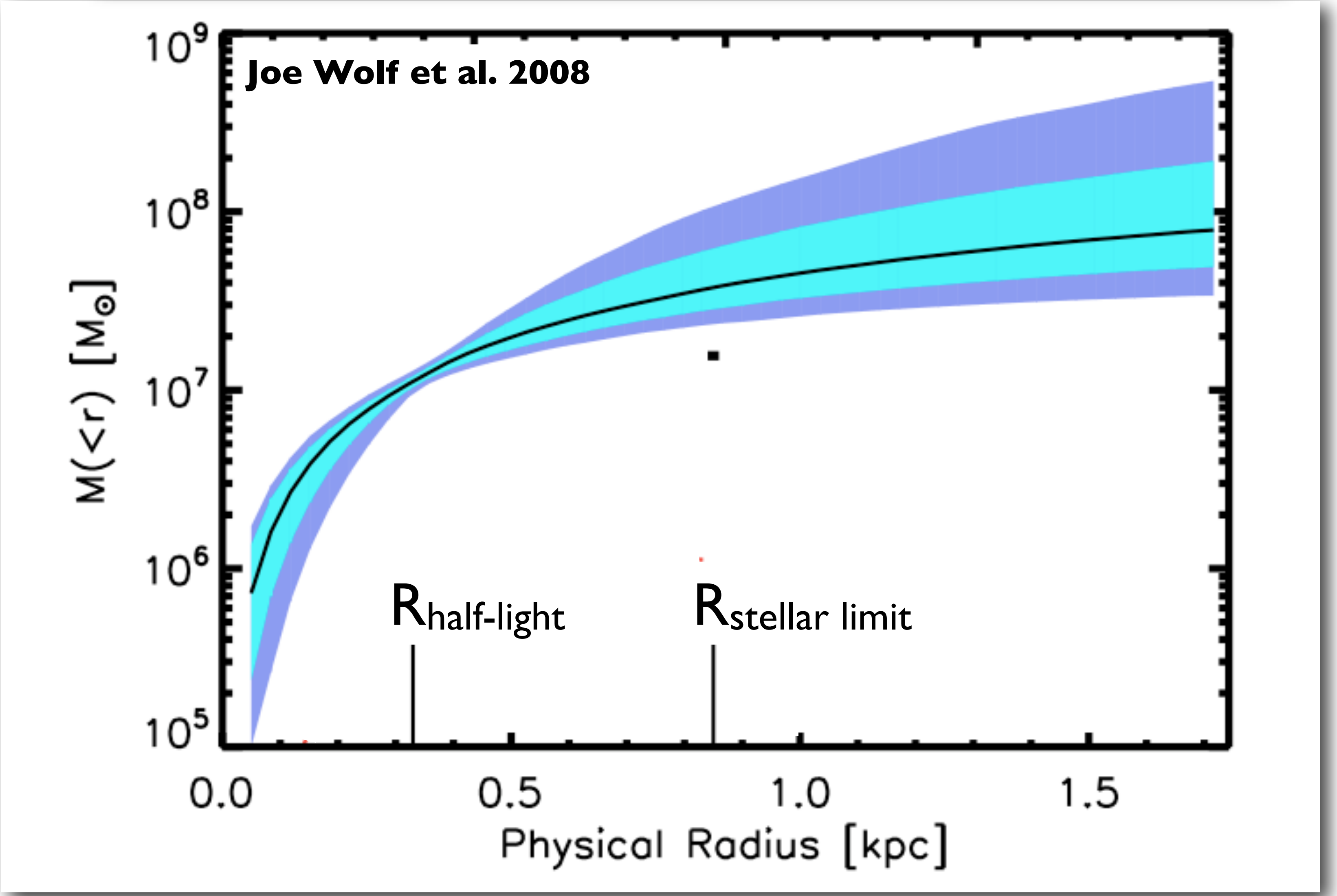
Dwarf V_{max} is hard/impossible to measure directly

Both of these rotation curves reproduce observed velocity dispersion of Carina



Zentner & JSB 03

Mass profile constraints for Carina: ~900 stars from Walker et al. 07



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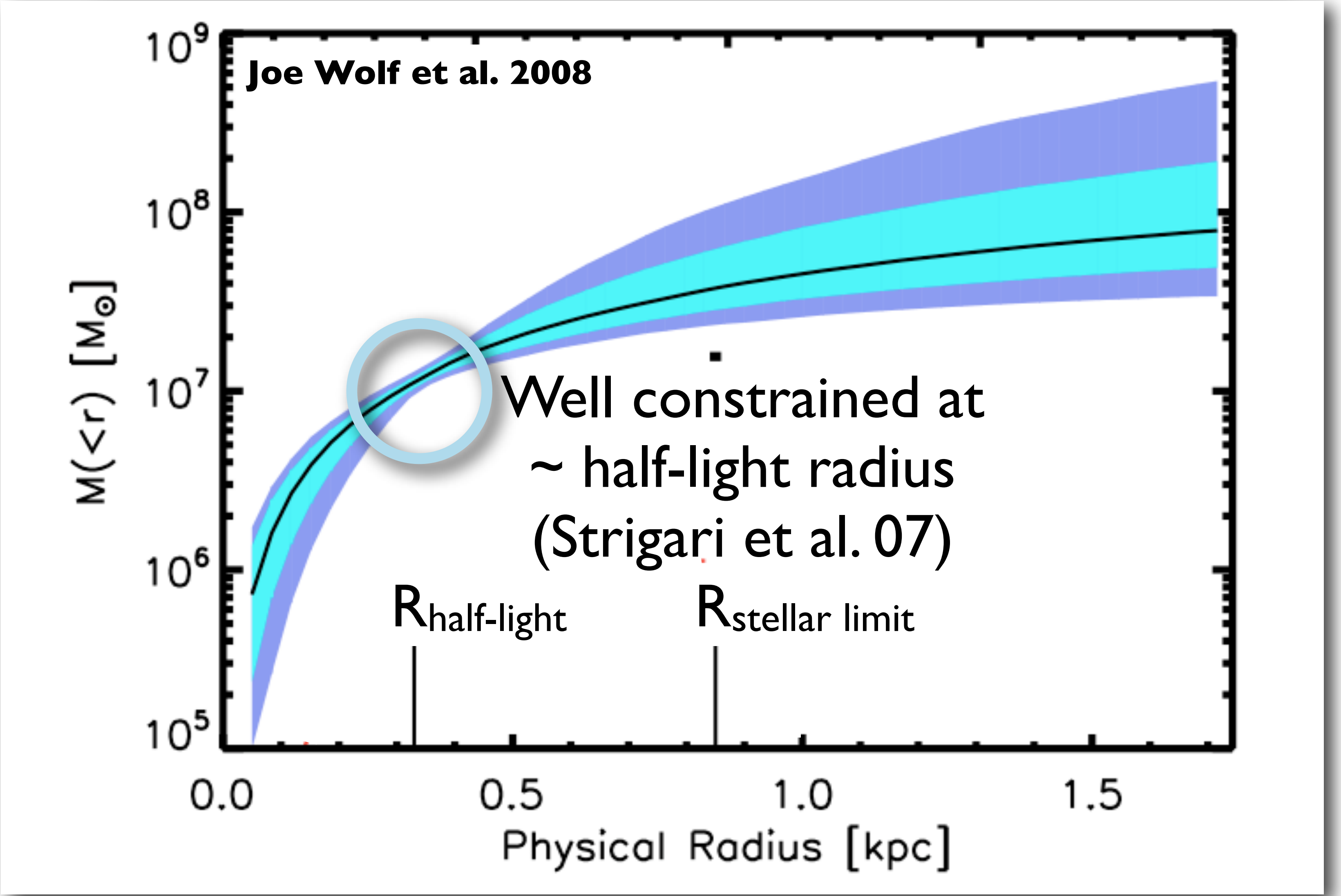
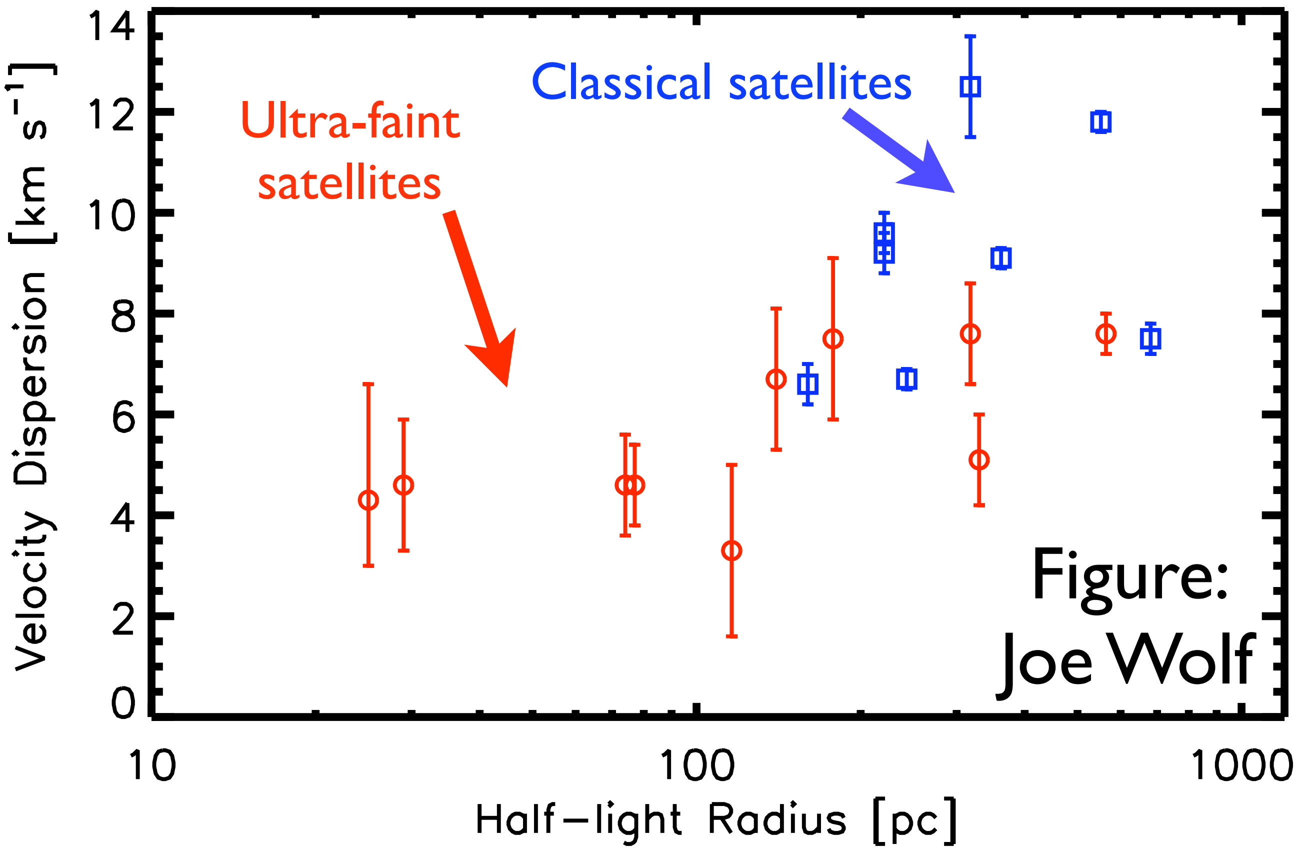


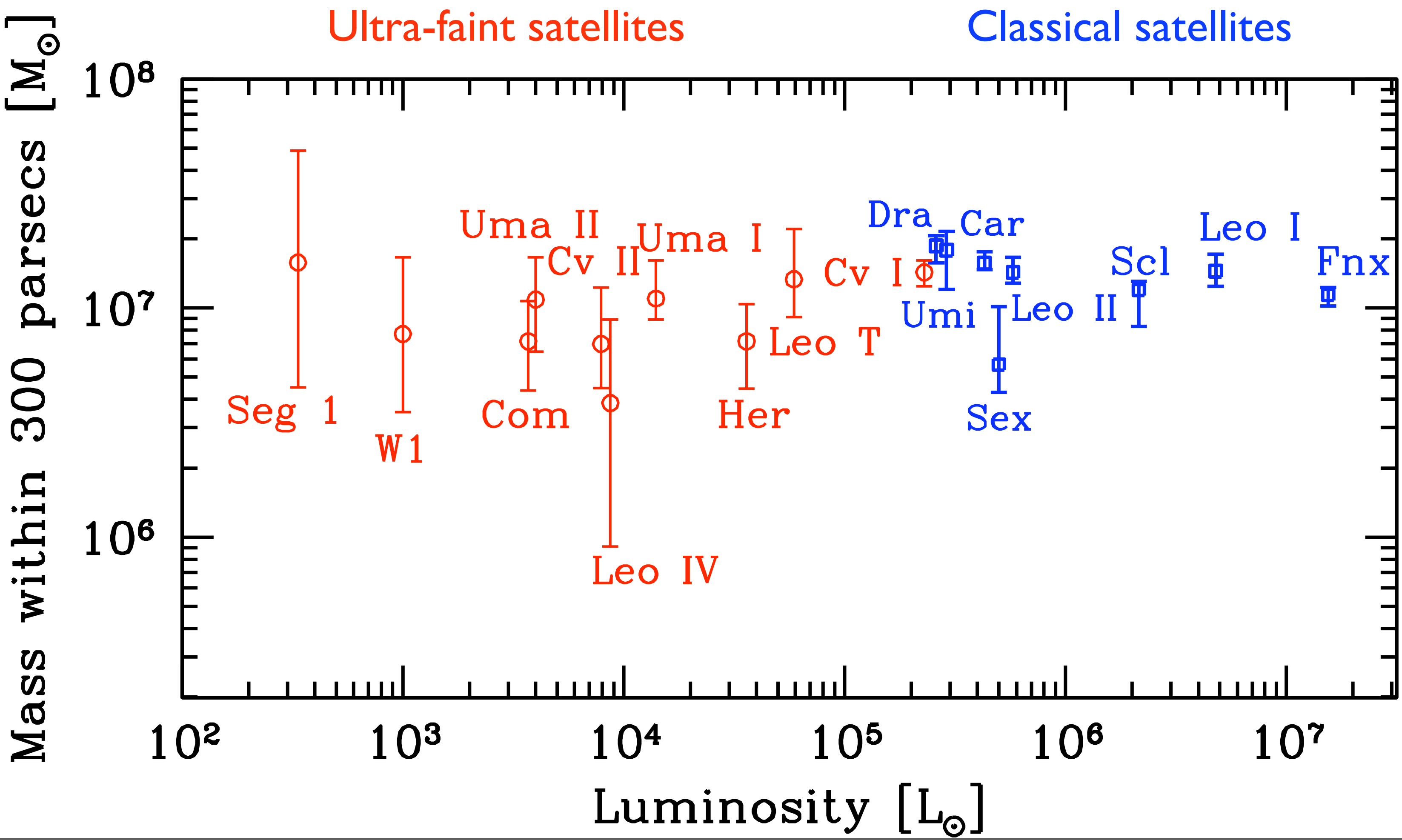
dSph radial velocities

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



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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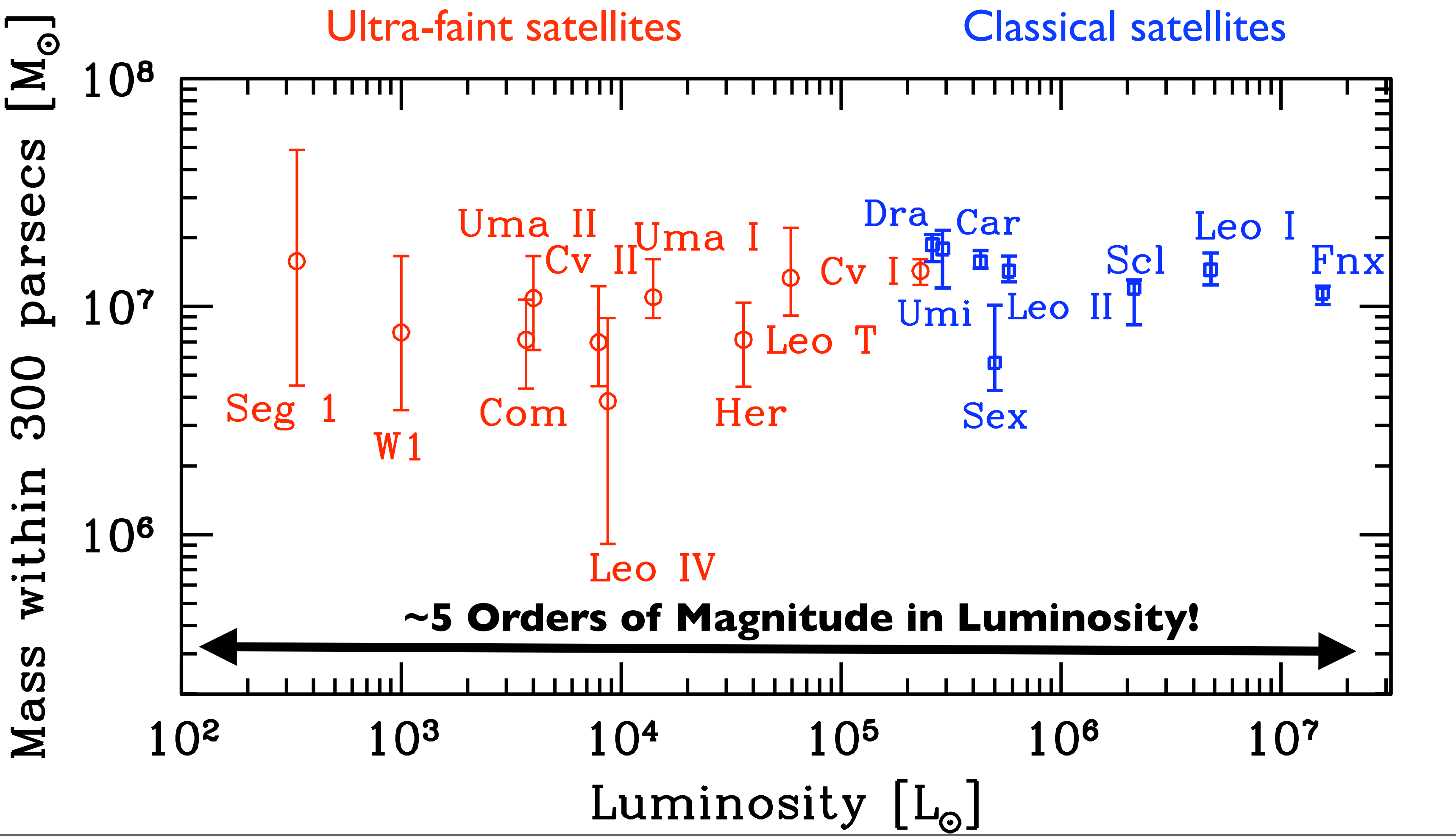

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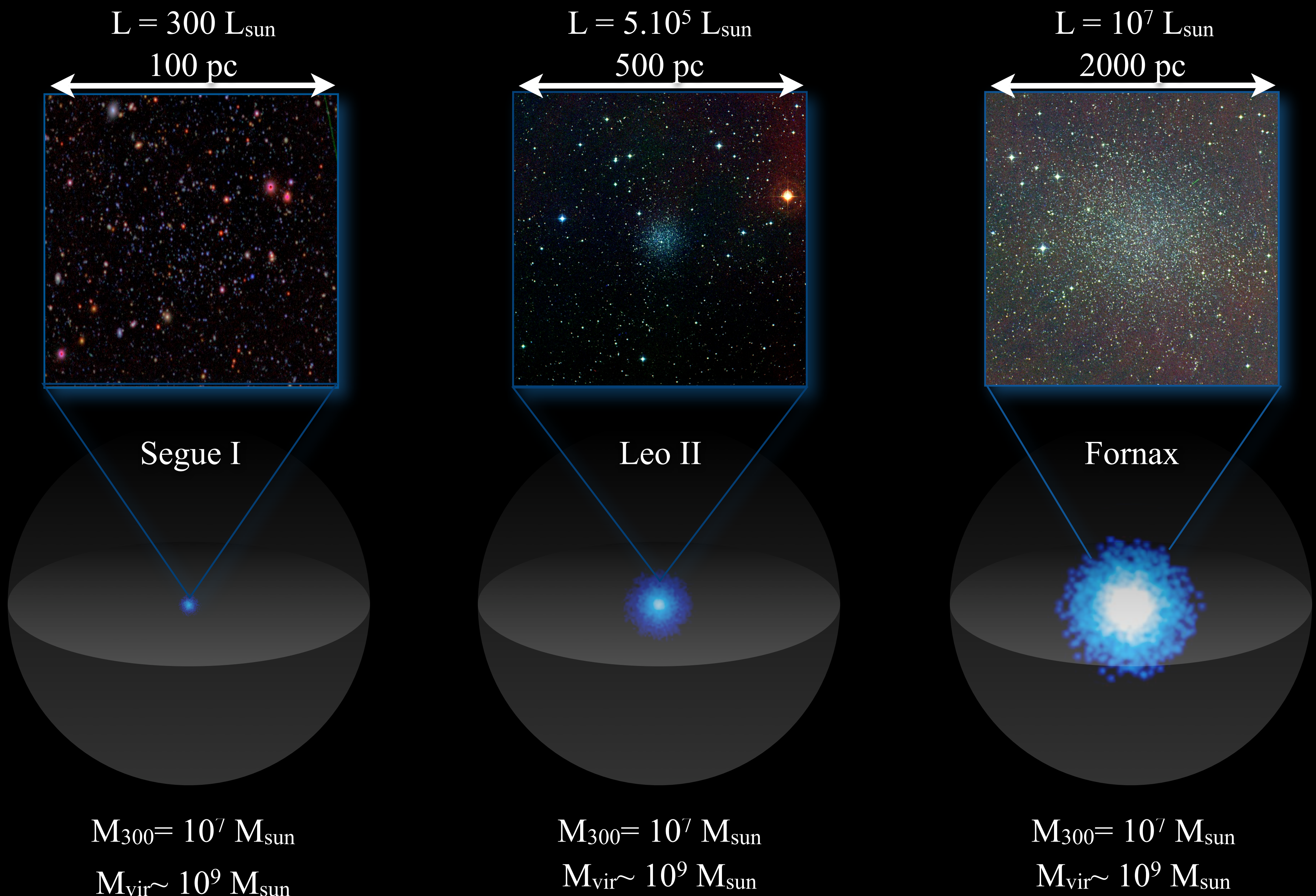

$L = 300\ L_{sun}$
100 pc
$L = 5.10^5\ L_{sun}$
500 pc
$L = 10^7\ L_{sun}$
2000 pc
Segue I
Leo II
Fornax
$M_{300} = 10^7\ M_{sun}$
$M_{vir} \sim 10^9\ M_{sun}$
$M_{300} = 10^7\ M_{sun}$
$M_{vir} \sim 10^9\ M_{sun}$
$M_{300} = 10^7\ M_{sun}$
$M_{vir} \sim 10^9\ M_{sun}$

A characteristic mass for Milky Way dwarfs:

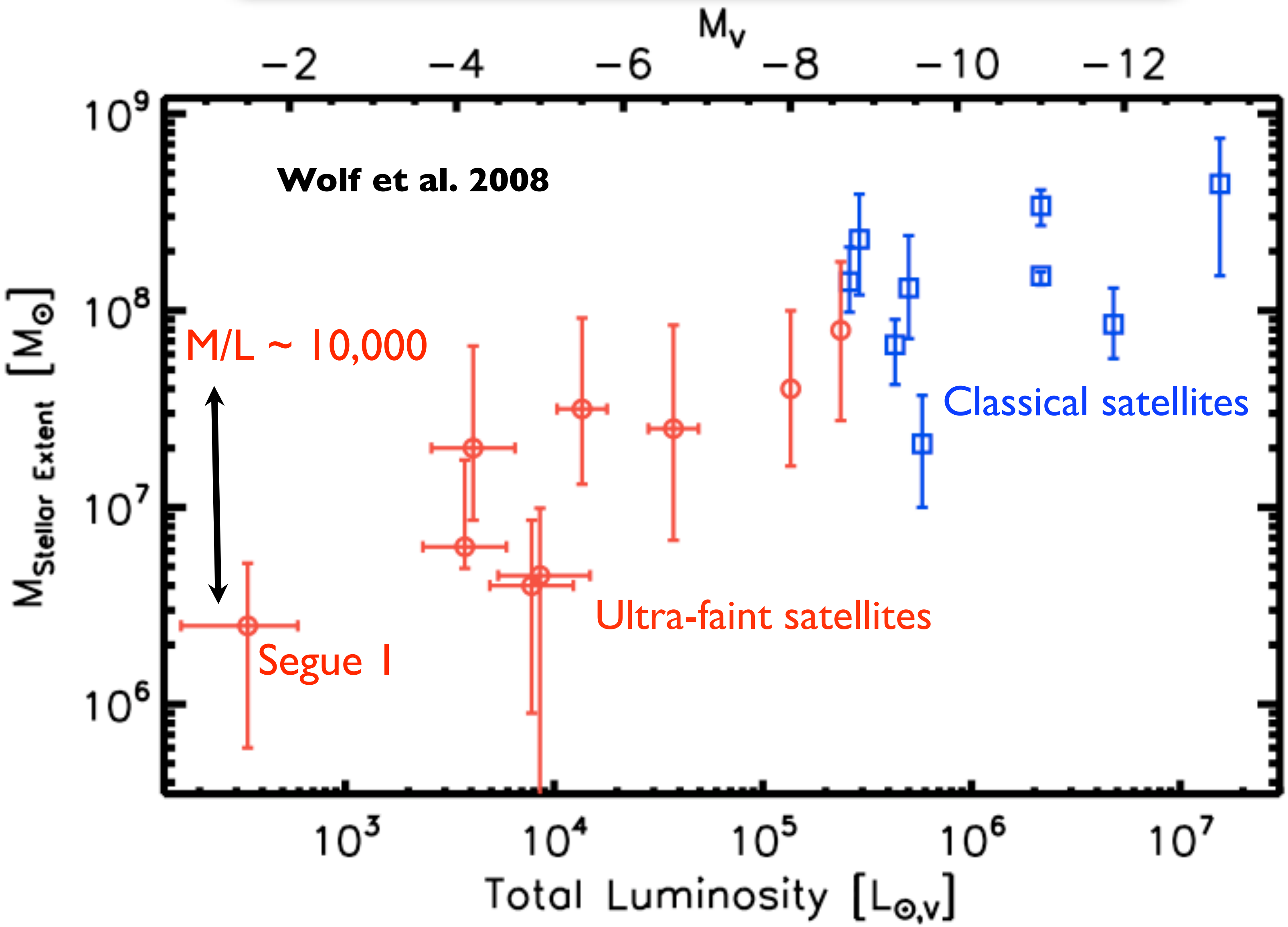
$$M(r < 300\text{pc}) \simeq 10^7 M_\odot$$

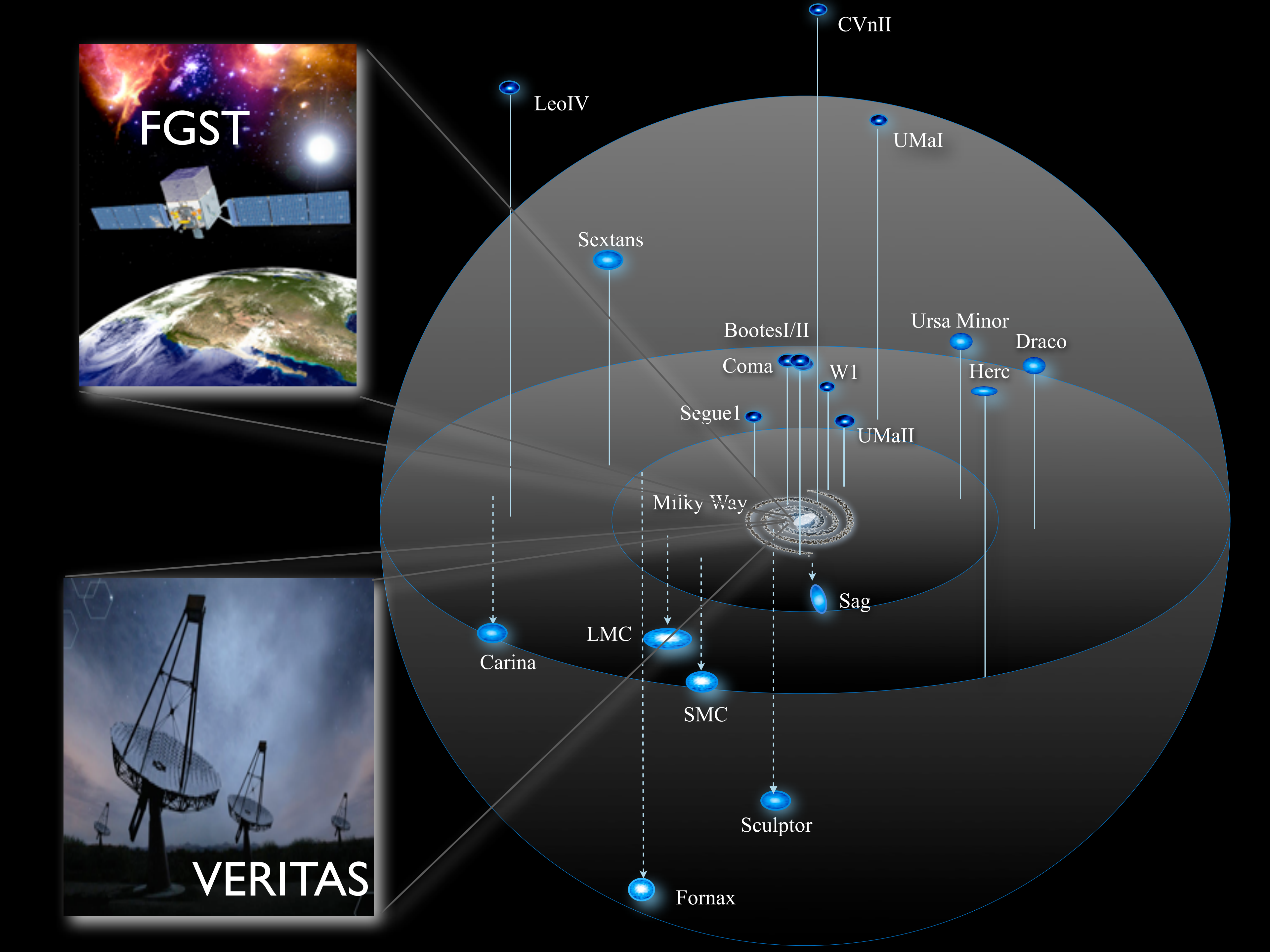
$$M_{\rm vir} \simeq 10^9 M_\odot \left(\frac{M_{300\rm pc}}{10^7 M_\odot} \right)^{0.35}$$

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

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

Total Mass within stellar extent





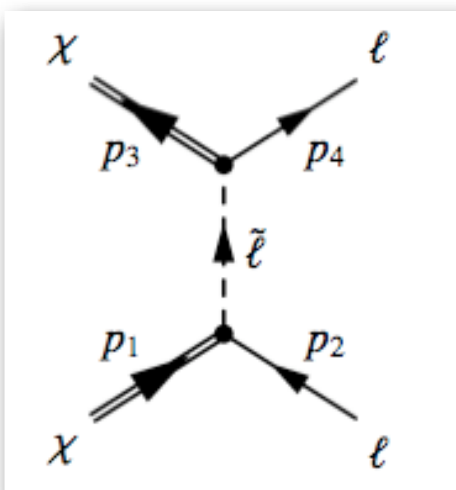
FGST
VERITAS
CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax

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

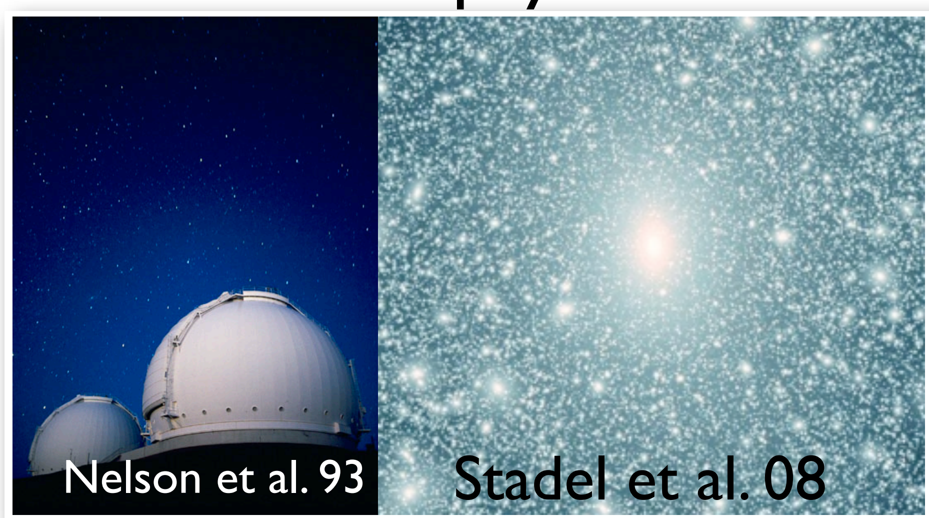
Dwarf Satellites and DM indirect detection

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

Particle Physics

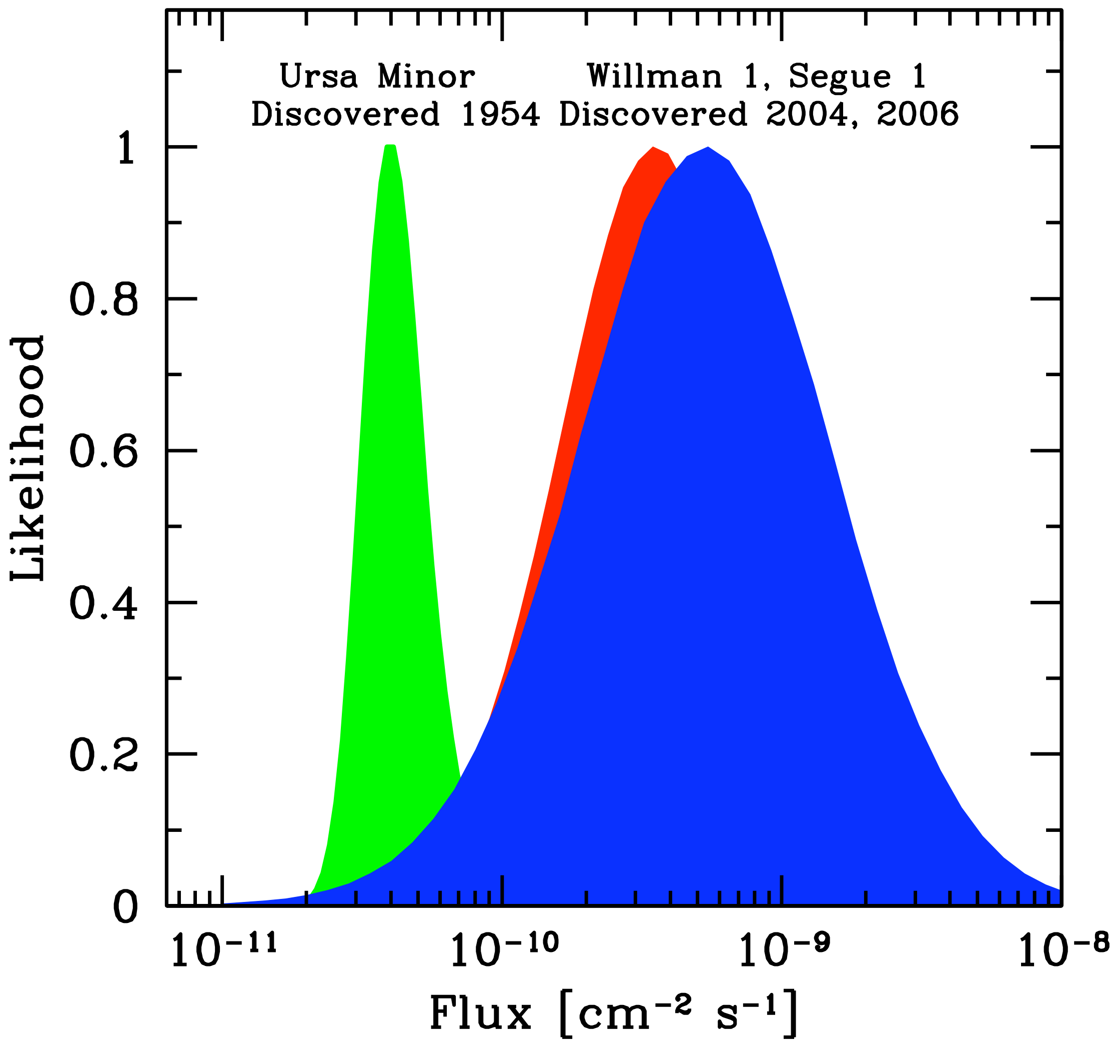


Astrophysics

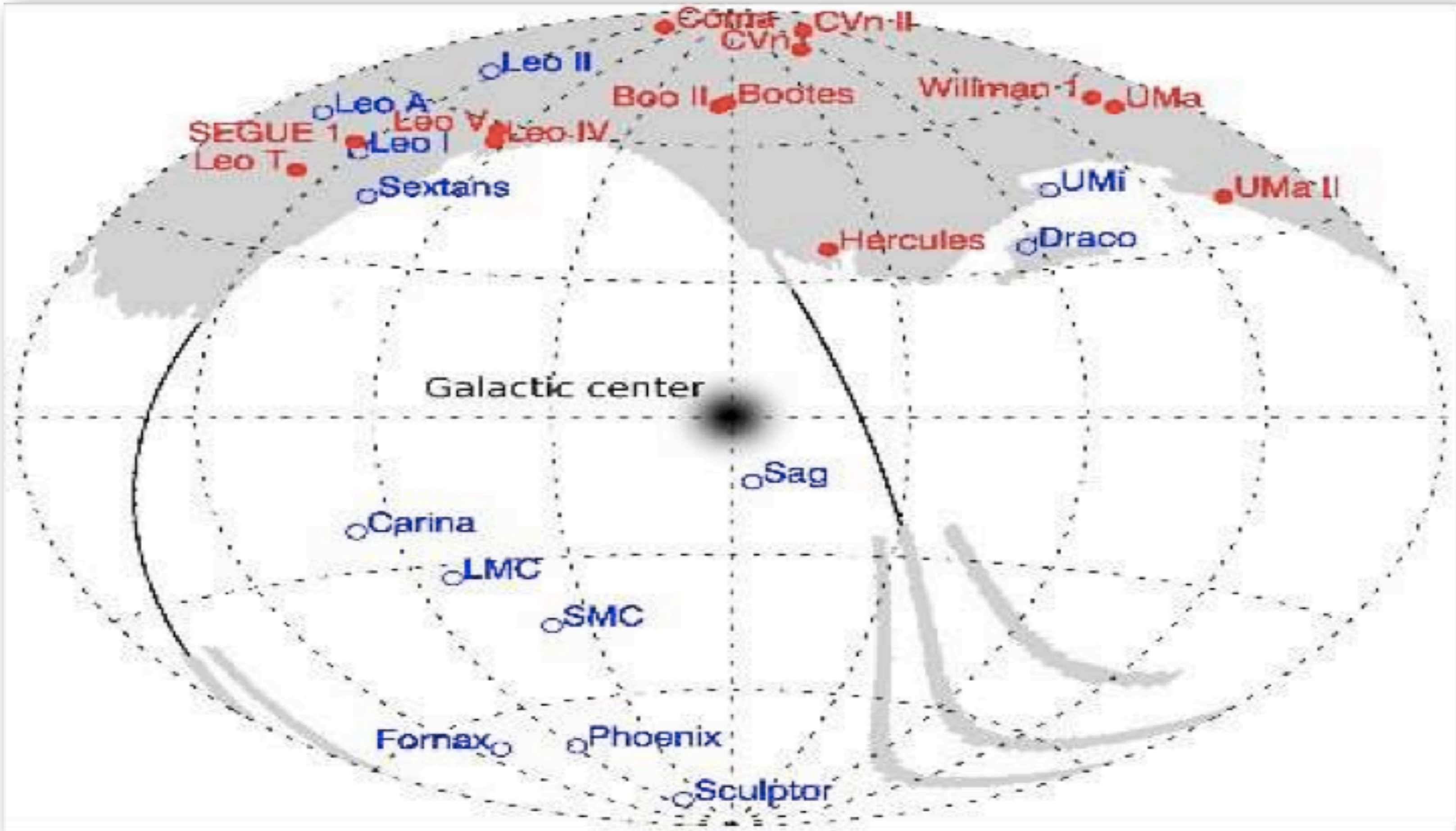


Gamma-ray predictions

Strigari



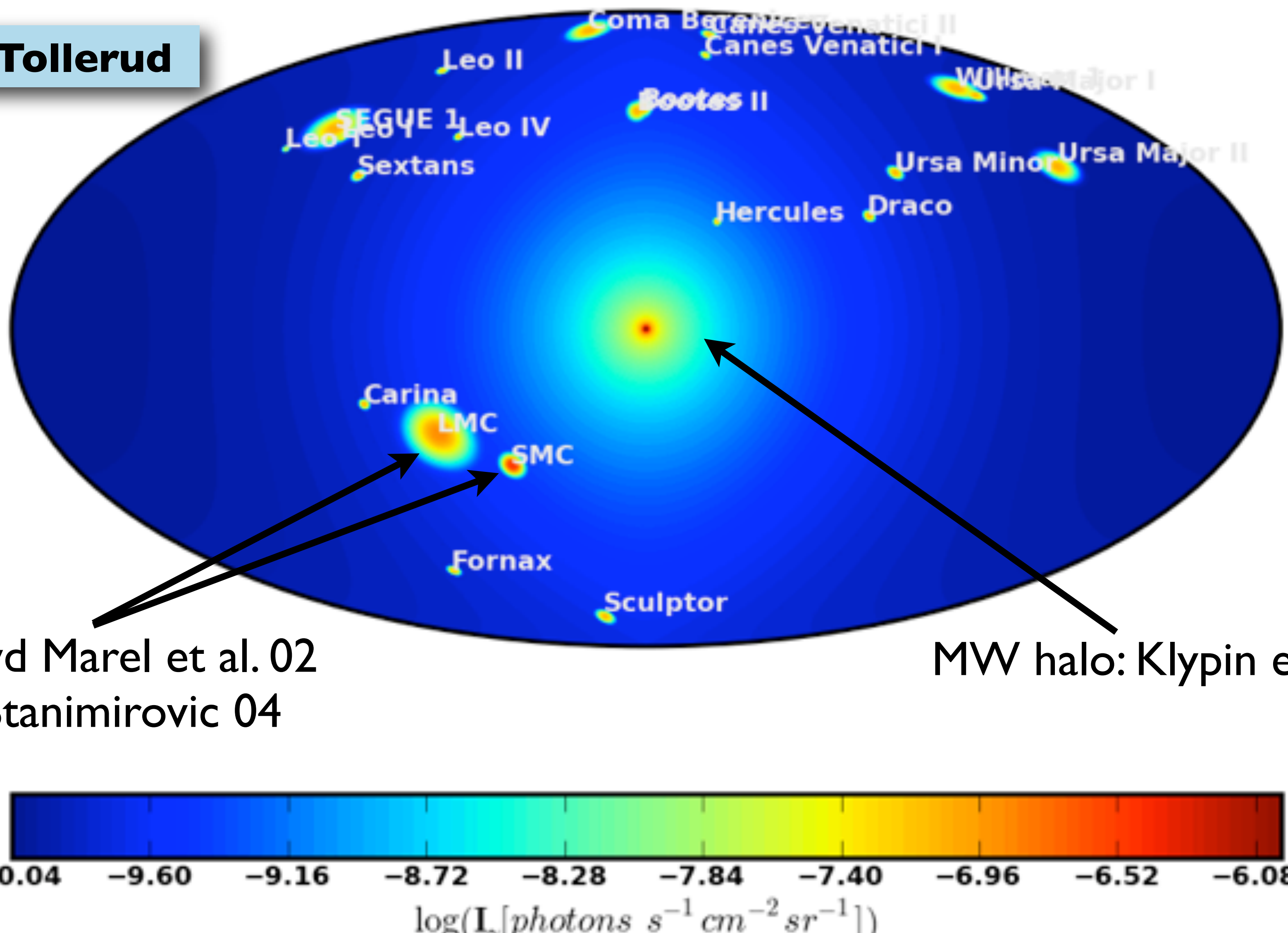
Milky Way Satellites



Walsh et al. 08

Eγ>1 GeV Flux (optimistic particle model)

Tollerud

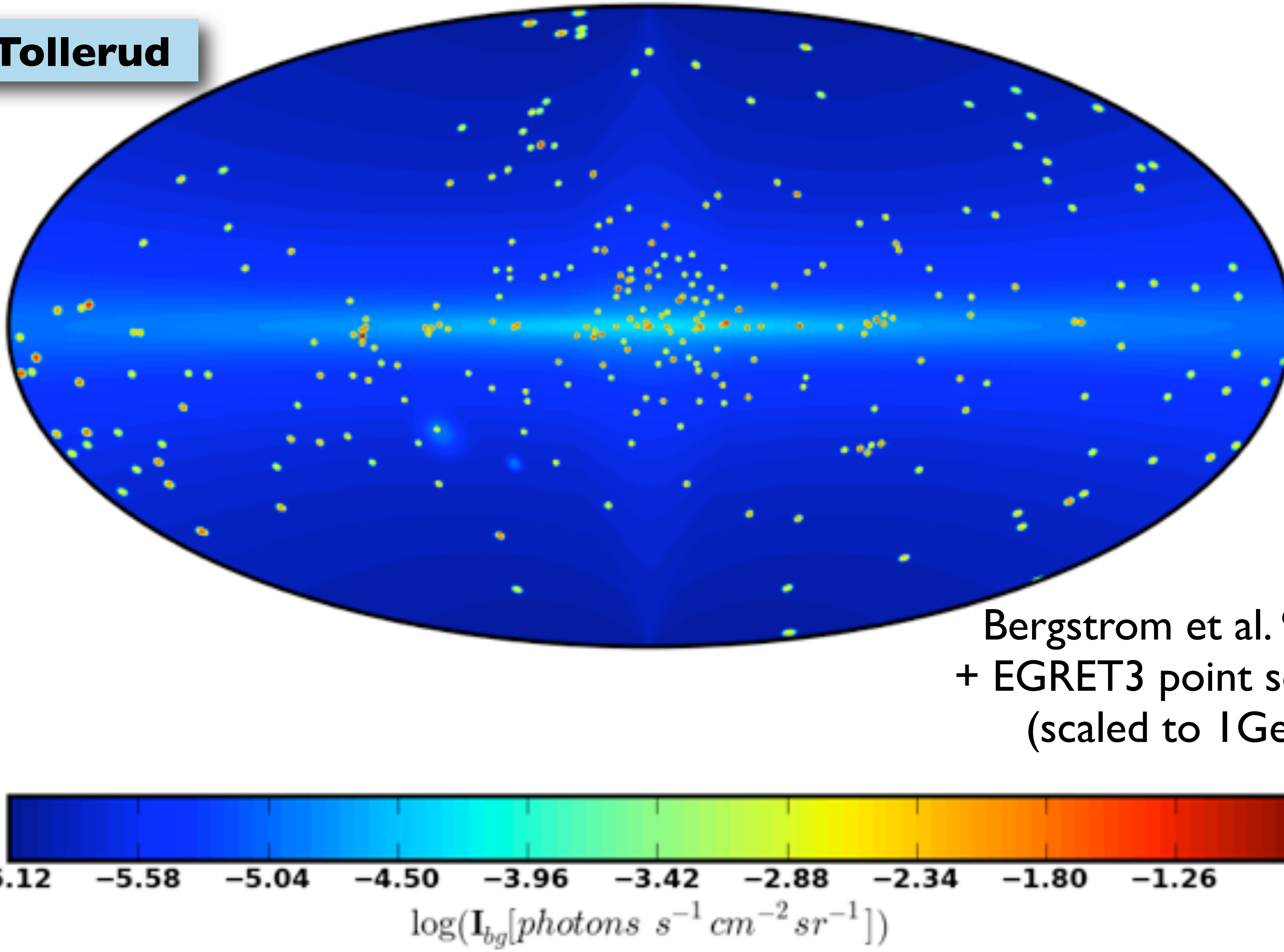


LMC: vd Marel et al. 02
SMC: Stanimirovic 04

MW halo: Klypin et al. 01

EGRET Background

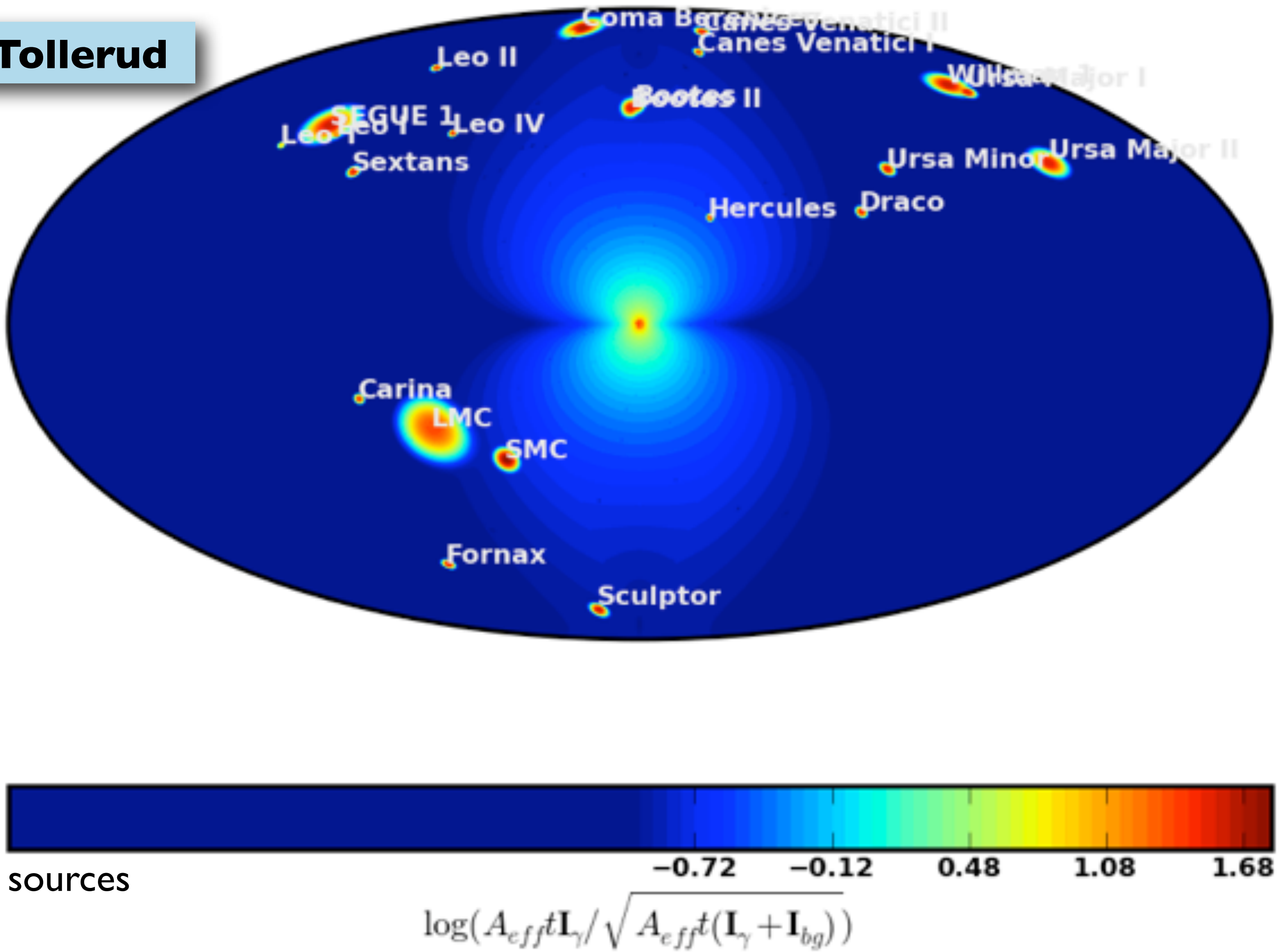
Tollerud



Bergstrom et al. 98 fit
+ EGRET3 point sources
(scaled to 1GeV)

Significance Map ~ $N_\gamma / (N_\gamma + N_{bg})^{1/2}$

Tollerud



point sources

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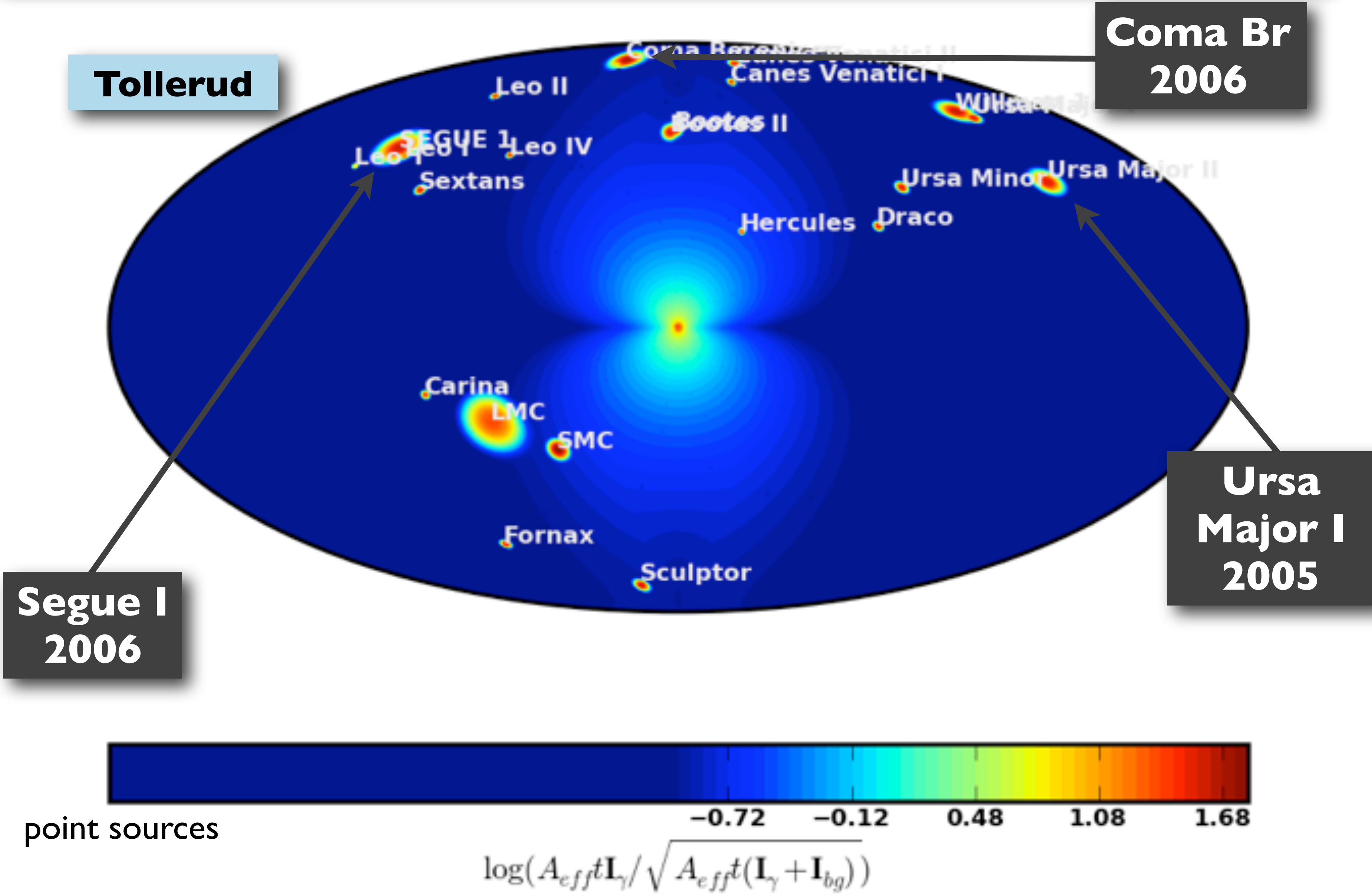

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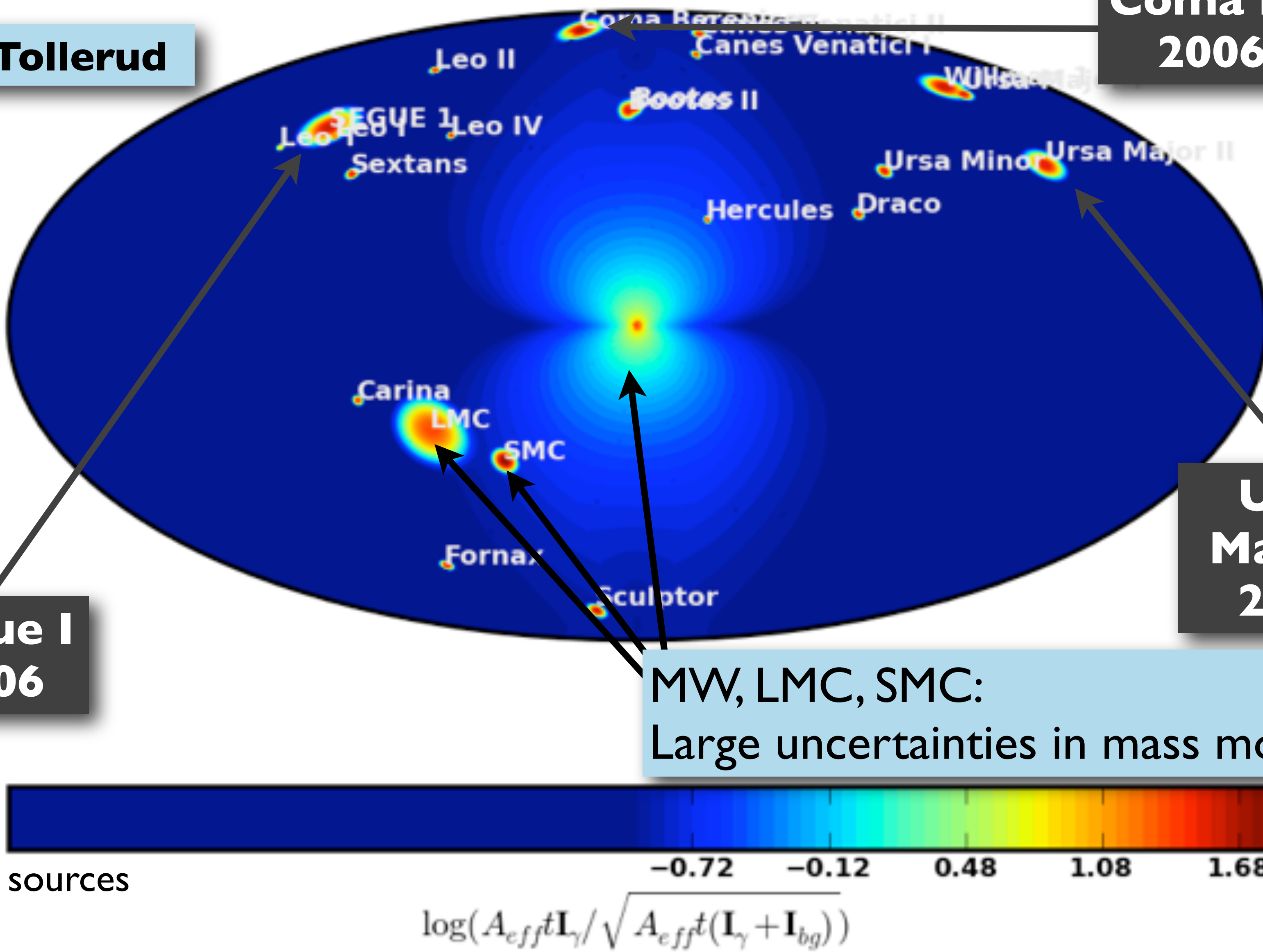
Tollerud

Coma Br 2006



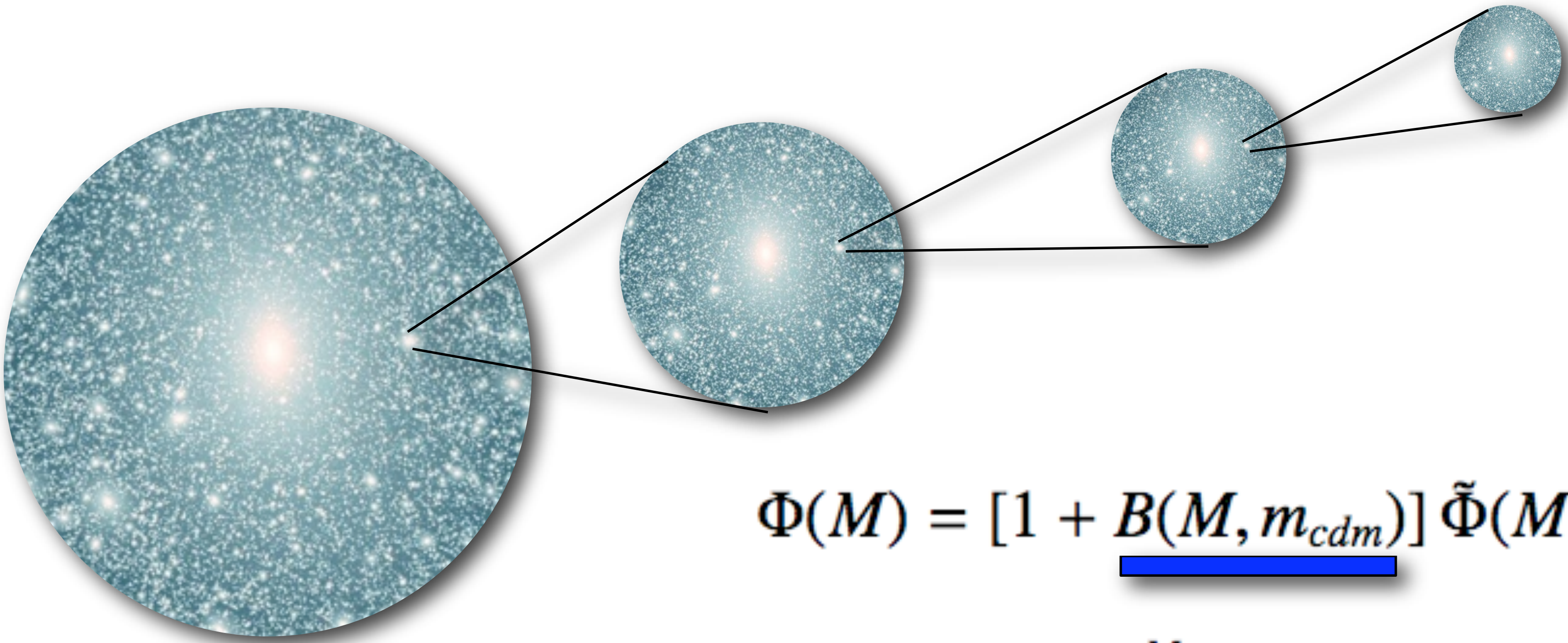
Ursa Major I 2005

Segue I 2006

MW, LMC, SMC:
Large uncertainties in mass models

point sources

The substructure boost



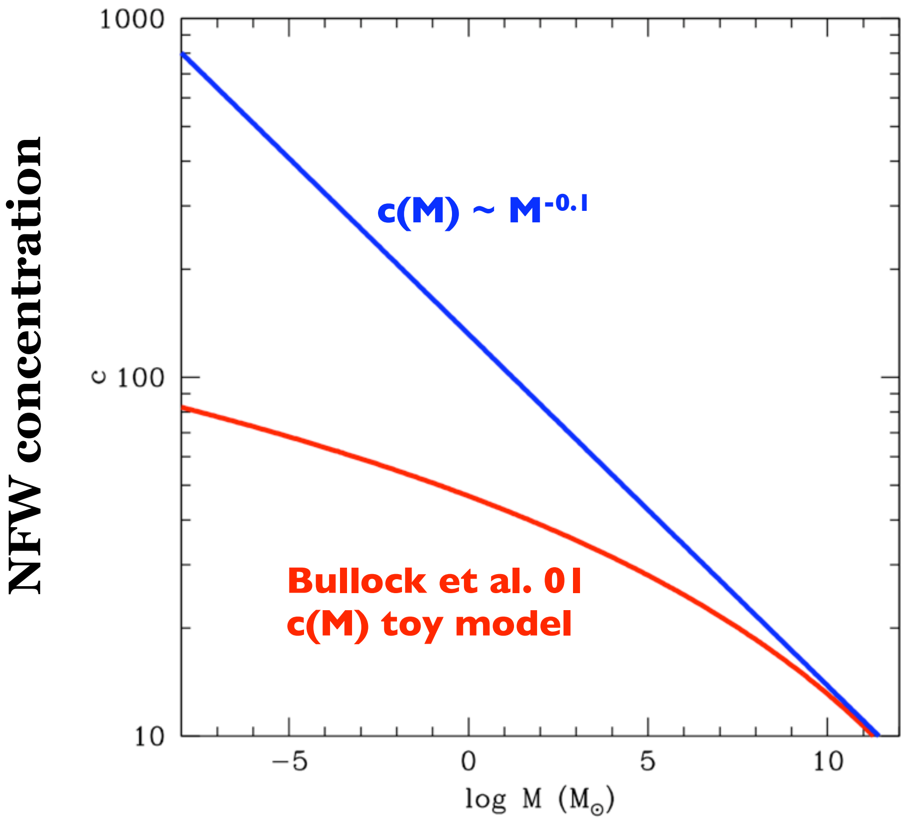
$$\Phi(M) = [1 + B(M, m_{cdm})]\,\tilde{\Phi}(M).$$

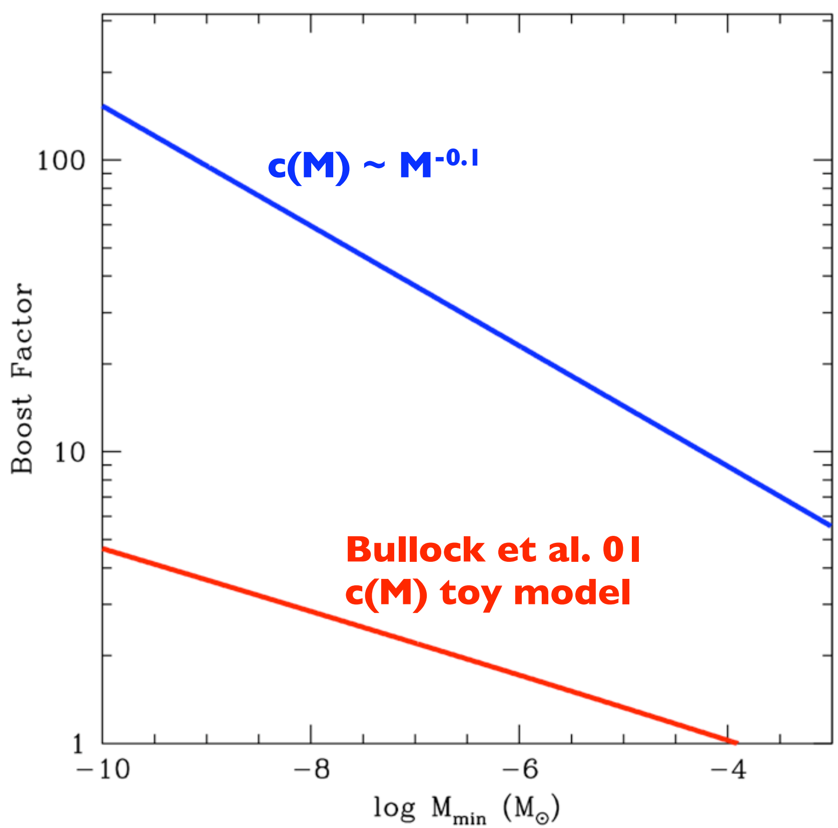
$$B(M, m_{cdm}) = \frac{1}{\tilde{\Phi}(M)} \int_{m_{cdm}}^{M} \frac{dN}{dm} \Phi(m) dm$$

$$\propto m^{-0.9}\, c(m)^{2.2}\, \mathrm{d}m$$

The substructure boost

Unfortunately, the boost factor depends sensitively on the density structure of the smallest subhalos

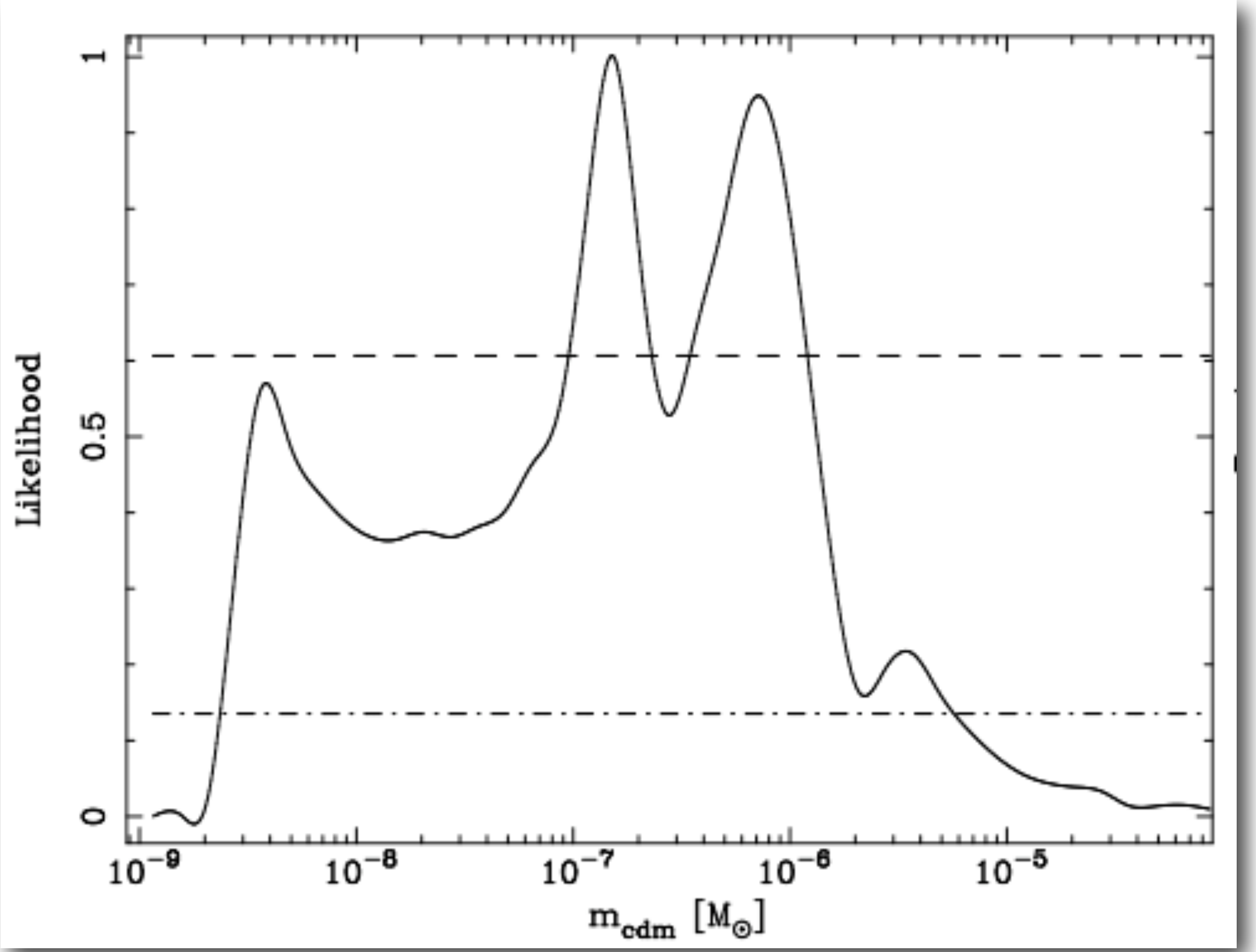




Greg Martinez et al. 2008

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

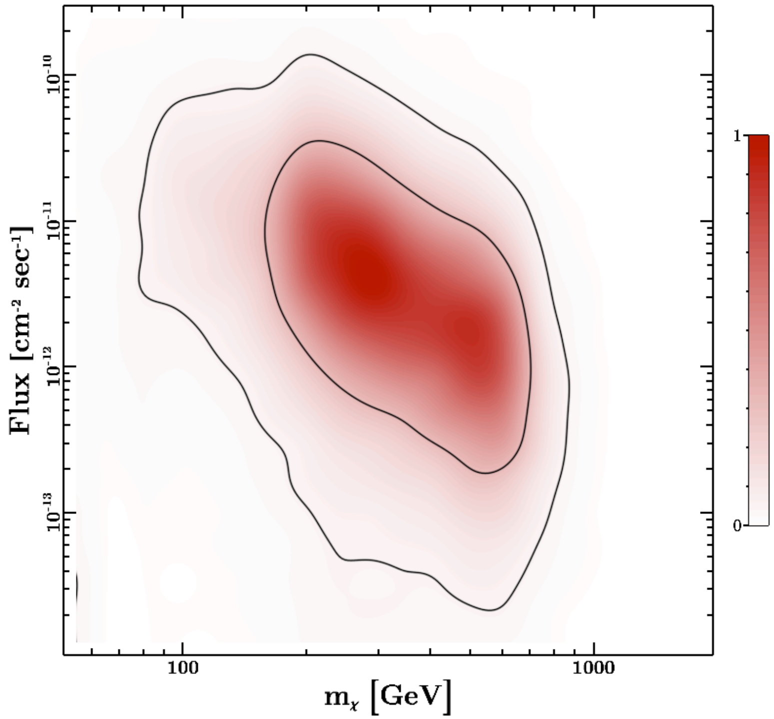
Greg Martinez et al. 2008:
generalizes Bertschinger 2006 calculation

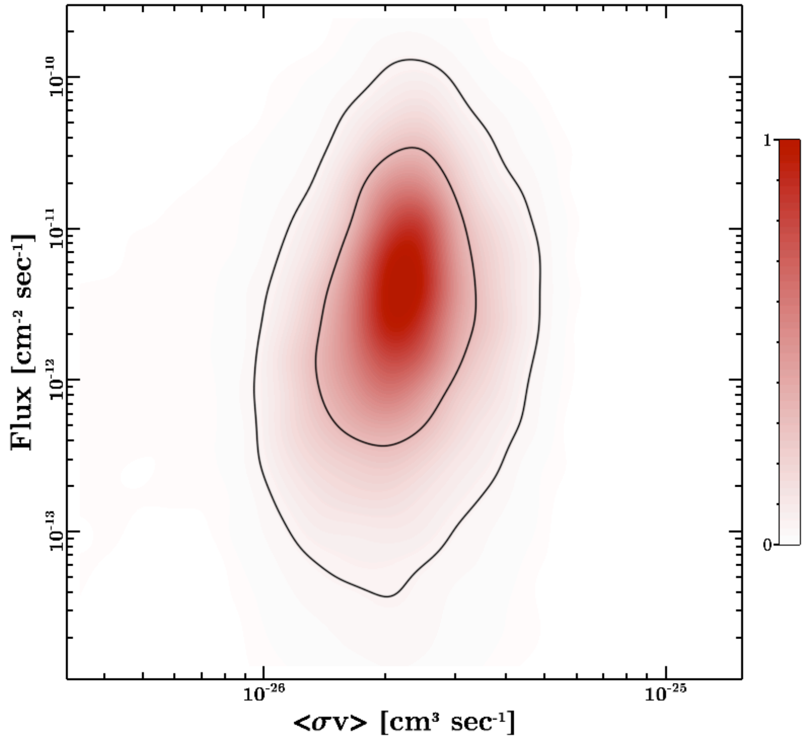


Gamma-ray flux from Segue1

G. Martinez et al.
Constrained MSSM + Kinematic marginalization

Particle Physics + Astrophysics now both fully marginalized





Likelihoods use SuperBayes MCMC code [Ruiz de Austri, Trotta, Roszkowski 2005].
Kinematics of dwarfs are now coupled with DarkSUSY [Gondolo et al.]
G. Martinez et al.

Conclusions

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

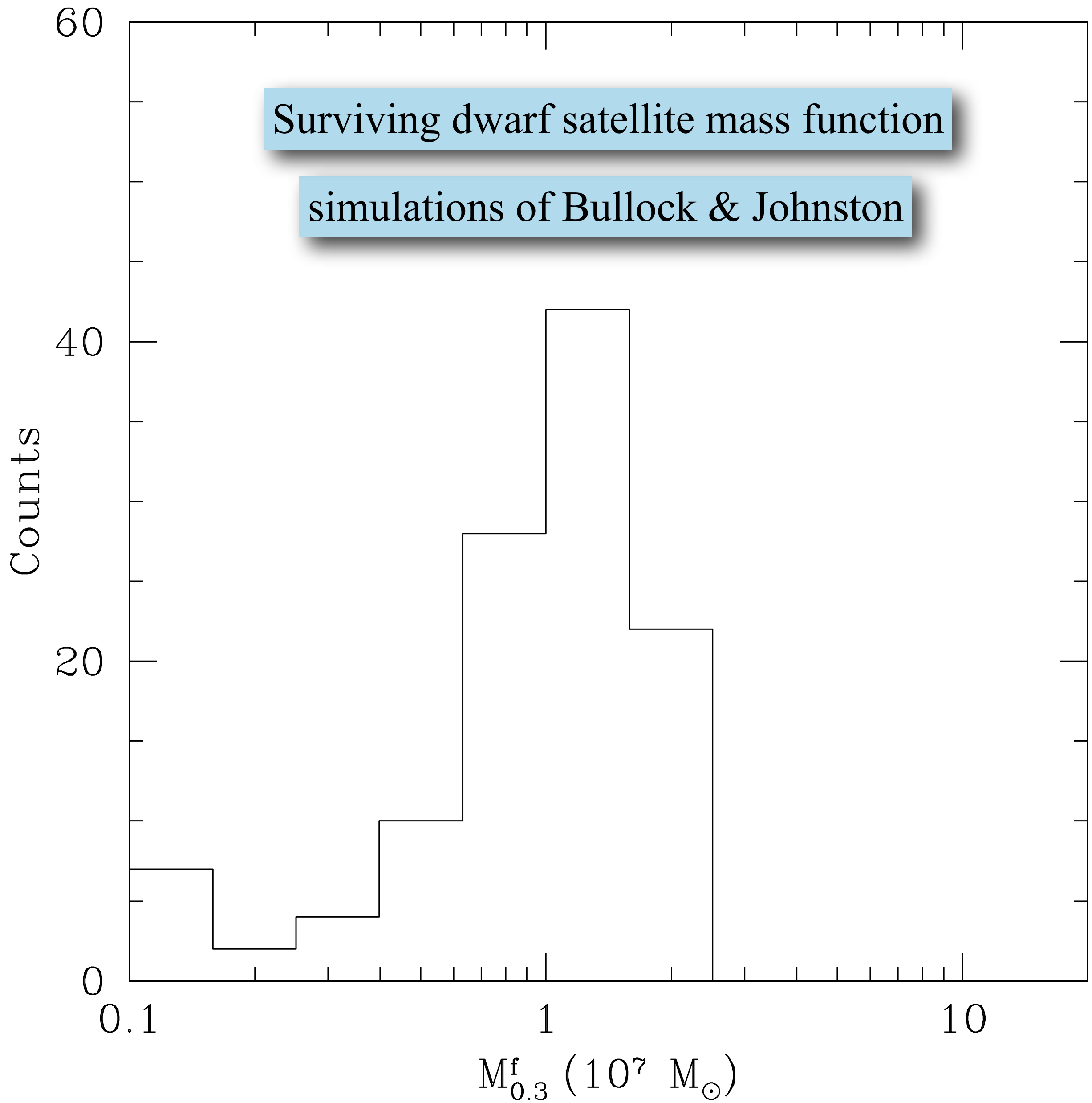
$$M(r < 300\mathrm{pc}) \simeq 10^7 M_\odot \longrightarrow M_{\mathrm{threshold}} \simeq 10^9 M_\odot \textbf{?}$$

- **~500 Galactic Satellites?**

LSST will discover them.

- **MW Dwarf satellites as DM laboratories.**

Best prospects for **unambiguous** detection of gamma-ray signals


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