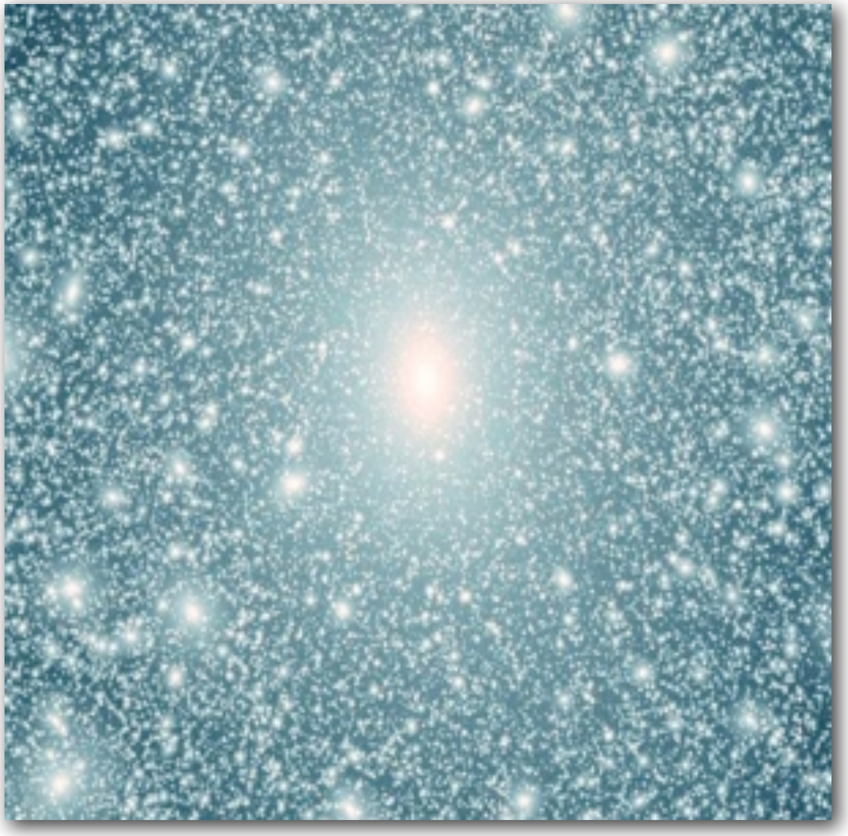
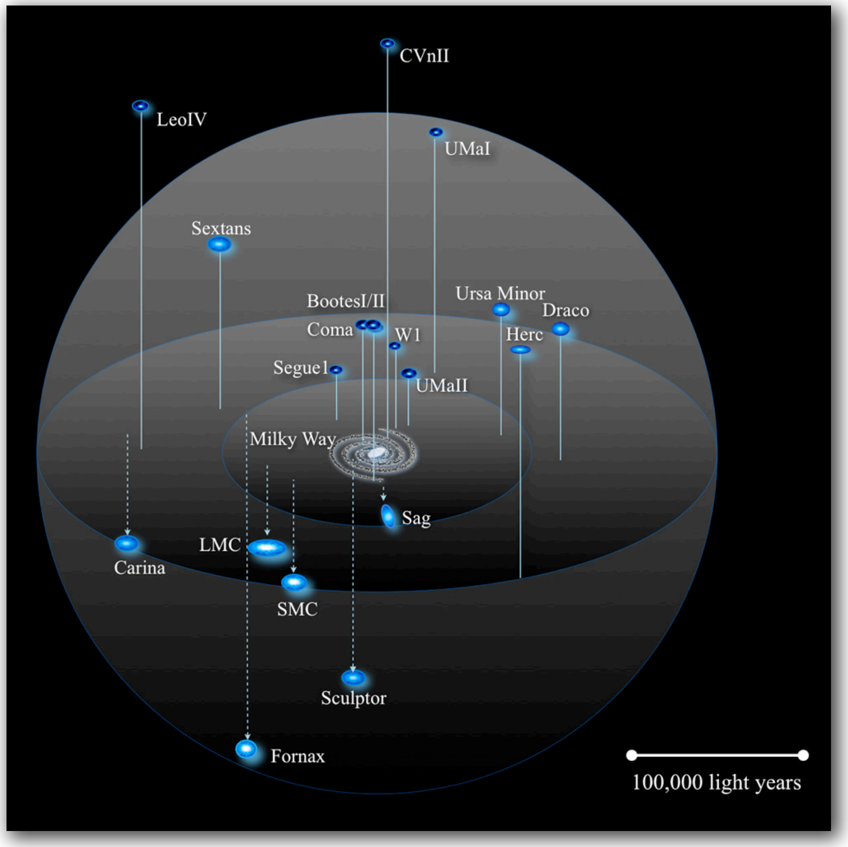
CDM and the Substructure Crisis

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



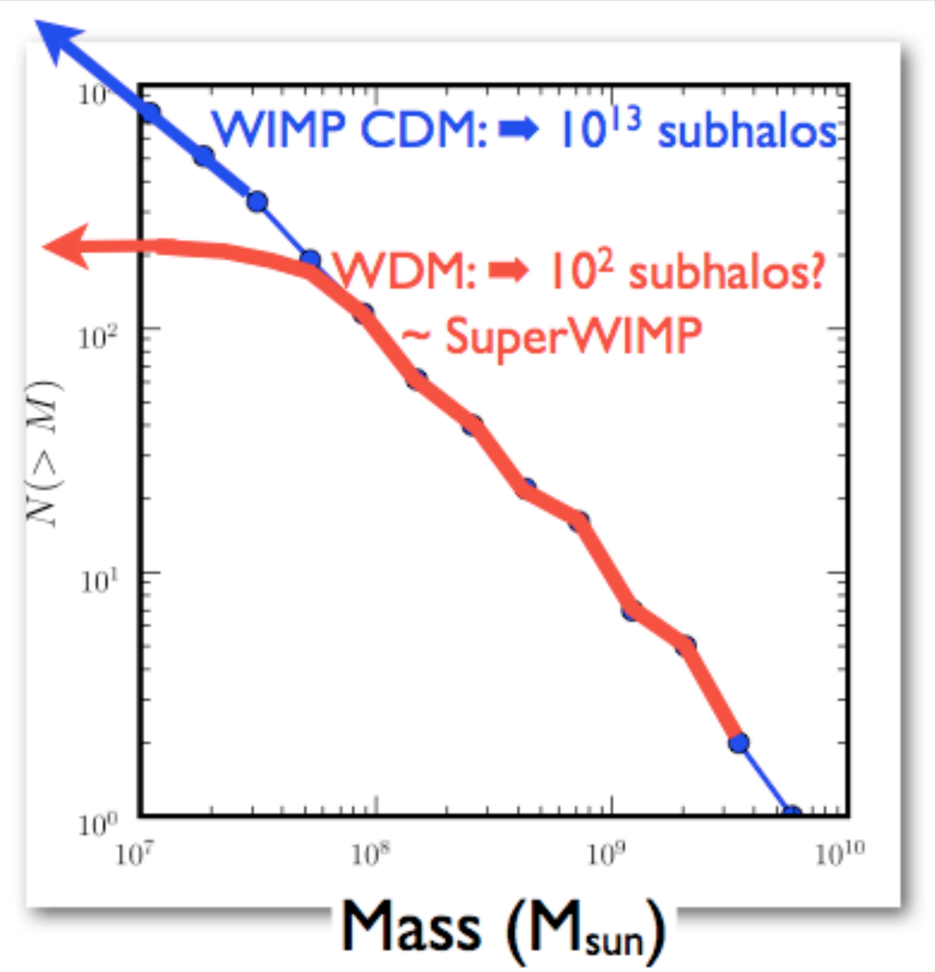


Theory: $N>10^{10}$

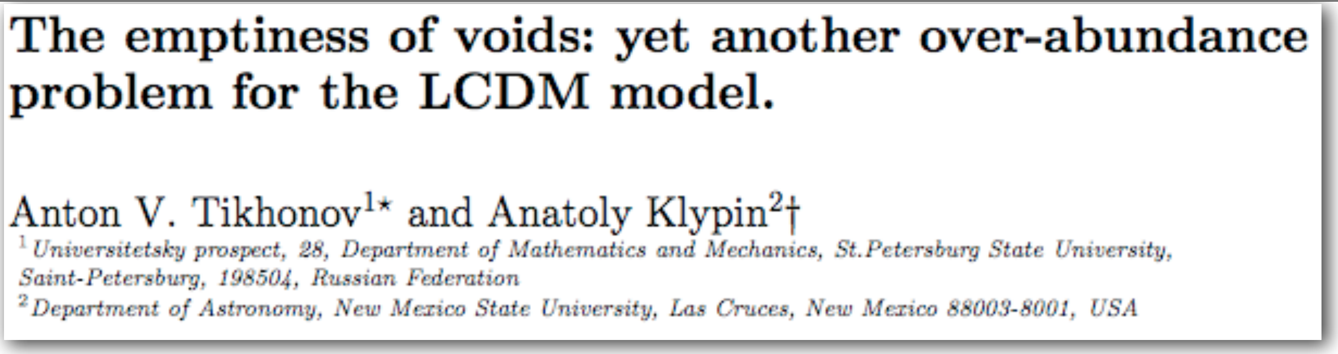
Observation: $N\sim20$

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

Lecture 5: Dwarf Galaxies as DM Labs



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

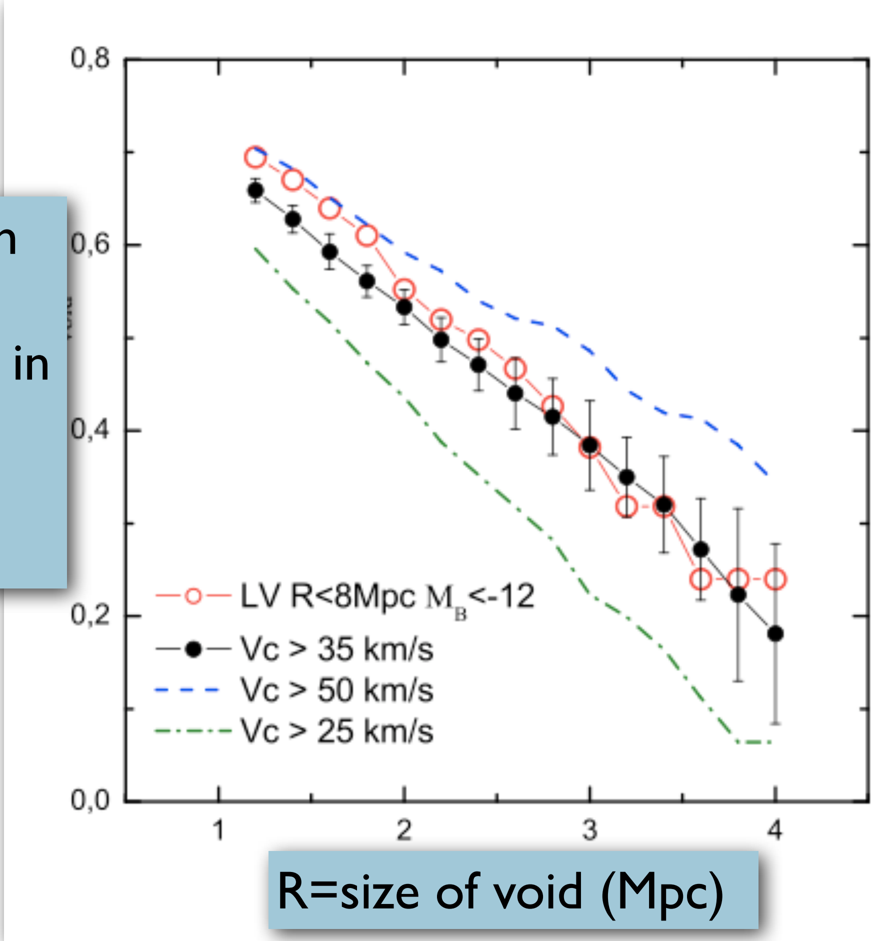


The emptiness of voids: yet another over-abundance problem for the LCDM model.

Anton V. Tikhonov[1]* and Anatoly Klypin[2]†

[1] *Universitetsky prospect, 28, Department of Mathematics and Mechanics, St.Petersburg State University, Saint-Petersburg, 198504, Russian Federation*

[2] *Department of Astronomy, New Mexico State University, Las Cruces, New Mexico 88003-8001, USA*



Fraction of local volume in voids bigger than R

R=size of void (Mpc)

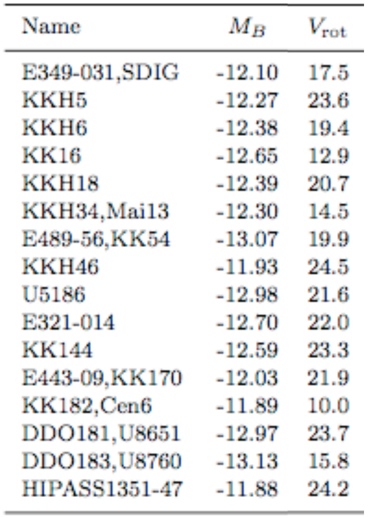
~Fornax's ~Leo I's

Voids are empty enough only if $M_B < -12$ galaxies are big:

$V_{max} > 35$ km/s

$M_{vir} \sim 10^{9.5}$ M_{sun}

$M_{300} \sim 10^{7.15}$ M_{sun}



Name	M_B	V_{rot}
E349-031,SDIG	-12.10	17.5
KKH5	-12.27	23.6
KKH6	-12.38	19.4
KK16	-12.65	12.9
KKH18	-12.39	20.7
KKH34,Mai13	-12.30	14.5
E489-56,KK54	-13.07	19.9
KKH46	-11.93	24.5
U5186	-12.98	21.6
E321-014	-12.70	22.0
KK144	-12.59	23.3
E443-09,KK170	-12.03	21.9
KK182,Cen6	-11.89	10.0
DDO181,U8651	-12.97	23.7
DDO183,U8760	-13.13	15.8
HIPASS1351-47	-11.88	24.2

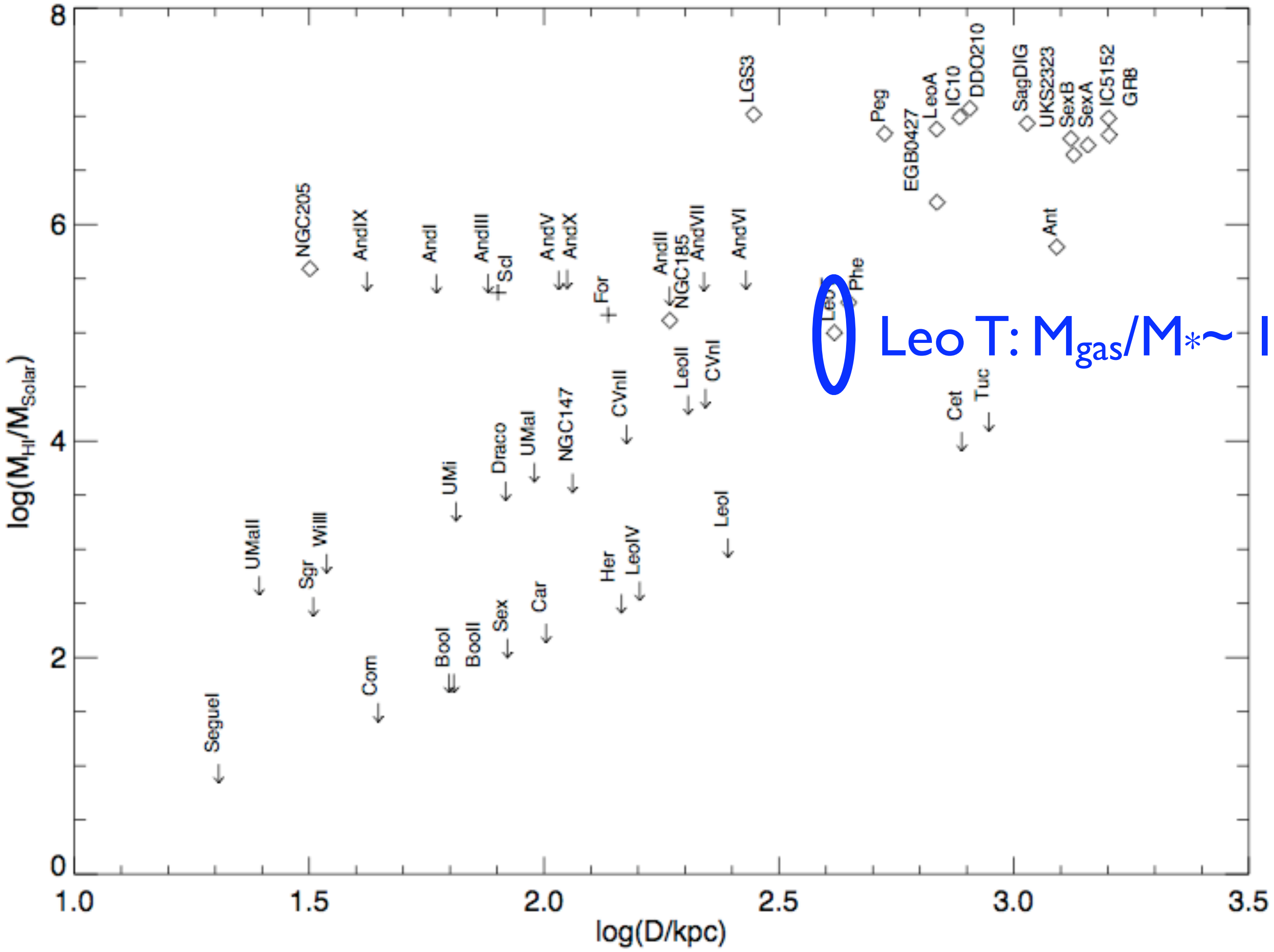
but: V_{HI} ~ 20 km/s

Lack of HI in MW dwarfs.

Putman, Grcevich, Peek 08

Ram Presssure?
-hot halo? missing MW baryons?

Is there bound/ionized gas?
-what about dSphs with recent SF?



Leo T: $M_{gas}/M_{*} \sim 1$

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

- Segue 1is the most dark-matter dominated object in the known universe.

2. High phase-space densities - WDM vs CDM

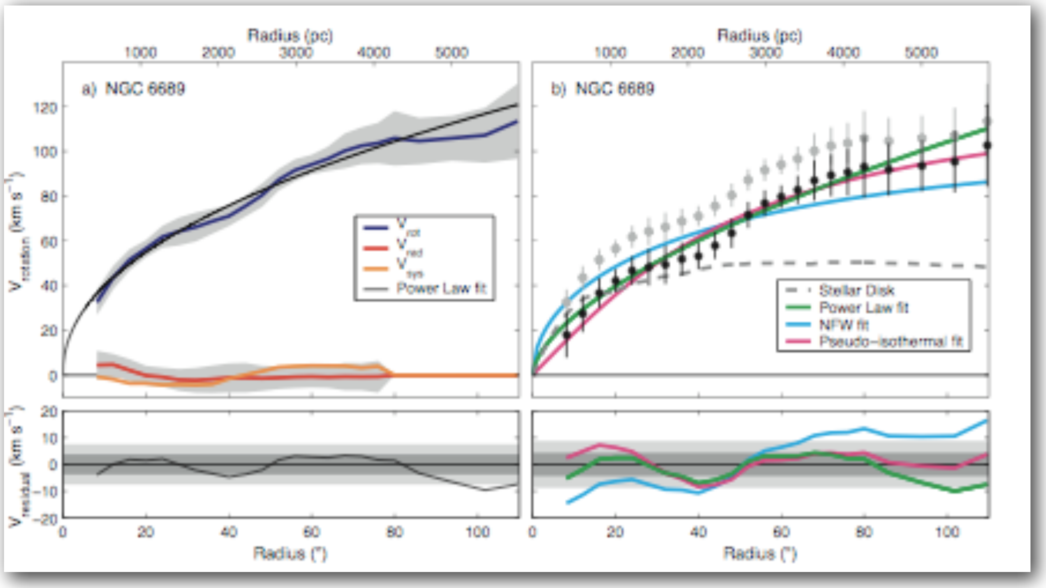
3. Nearby - individual stellar kinematics

Cusps vs Cores: 2D Velocity Maps

Galaxy rotation curves rise more slowly than CDM prediction

Simon et al. 05: (Ha & CO)
~3 of 6 look flatter than NFW

Dutton et al. 05: (Ha & HI)
3 of 6 flatter than NFW



Kuzio de Nary et al. 06, 07:
2d H-alpha ~13 of 17 look flatter than NFW

CONCERNS:
- astrophysics of ISM may affect interpretation (Valenzuela, Klypin et al. 07)
- non-spherical potentials may affect interpretation (Hayashi et al. 04)

* note: self-consistent non-spherical halo simulations of disk galaxies don't easily fix the problem (R. Kuzio de Naray & T. Kaufmann 08 - private communication)

WDM Phenomenology:

- Free Streaming: Suppresses P(k) on small scales
  - Free-streaming **does not** produce cores in halos
  - Free-streaming does reduce # of subhalos

$$\lambda_{FS} \simeq \int \frac{v(a)}{a}\, dt$$

- Low Phase Space Density: prevents sharp spatial density cusps?
  - Low primordial phase-space density will make cores
  - Low primordial phase-space density can also reduce # small subhalos

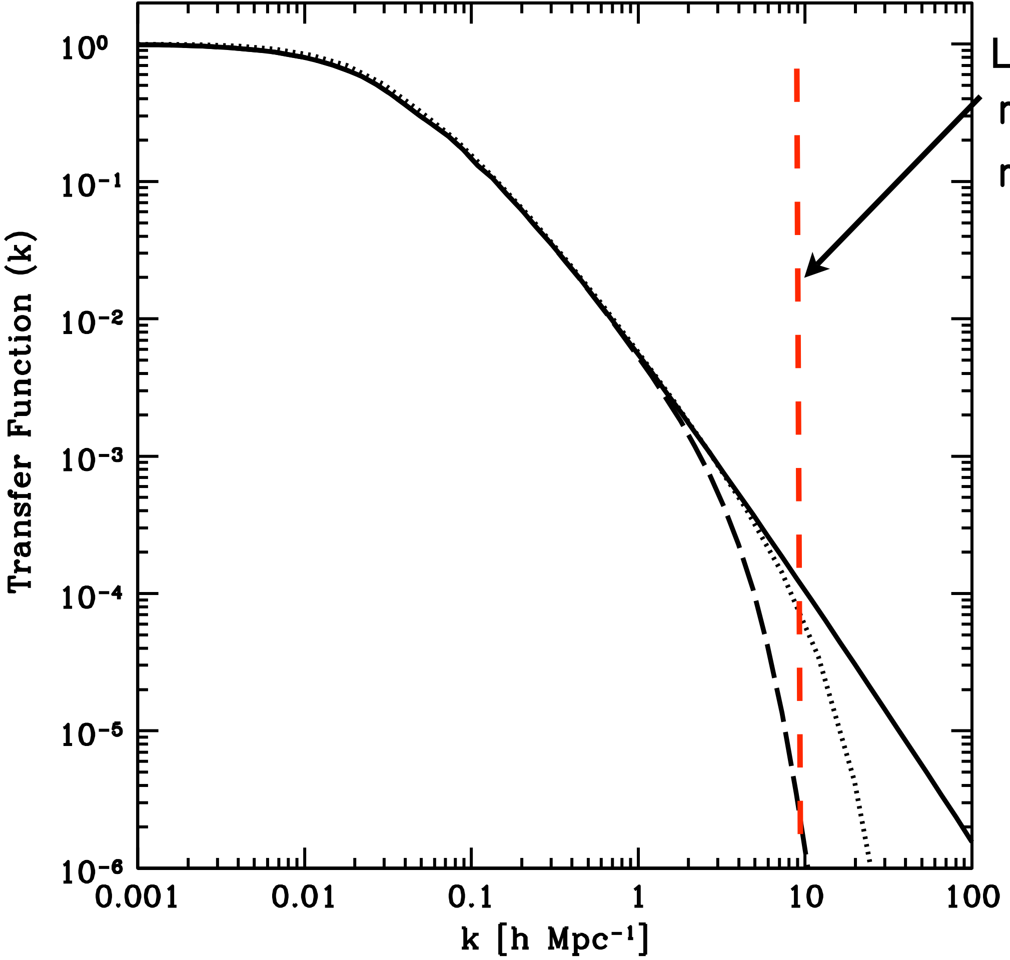
Effects must be considered separately!

Free Streaming:

IMPORTANT:
Free streaming does not make cores in halos.
It only reduces # and densities of small scales.

large scales small scales

$(P(k)/P(k)_{\text{primordial}})^2$



Lya forest:

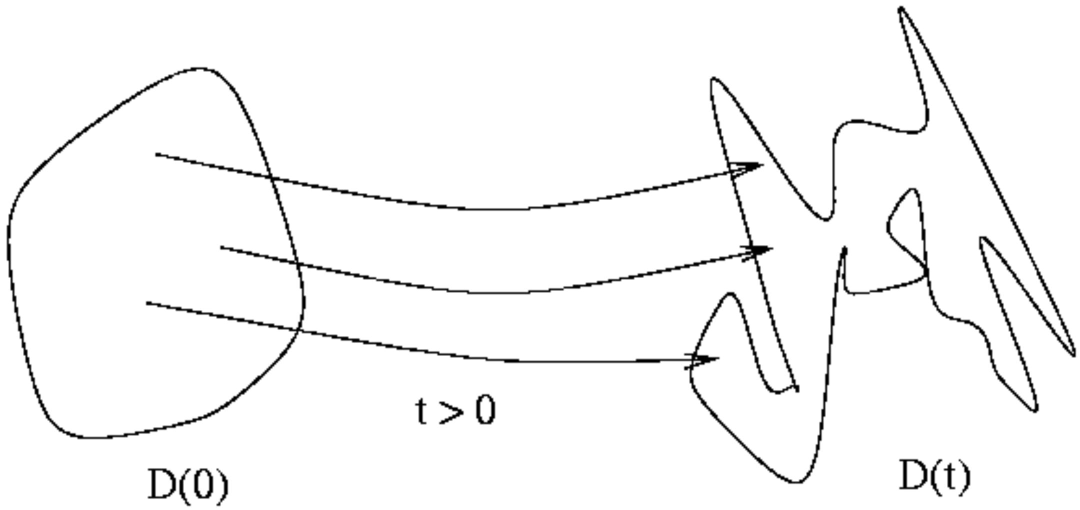
m_n > 750 eV Narayanan et al. 00

m_n > 550 eV Viel et al. 06

Seljak et al. 06

$$\lambda_{FS} \simeq \int \frac{v(a)}{a}\,dt$$

What can make cores? Phase Space Constraints



Tremaine & Gunn 79

Dalcanton & Hogan 00
ARZ & JSB 03, Kaplinghat 05

- For thermal fermionic dark matter, the primordial phase-space density freezes out as a Fermi-Dirac f(q), with a maximum value:

$$f_{\max} = 0.5 h_{pl}^{-3}$$

- Louivilles Theorem: For a collisionless particle, this maximum is never exceeded, no matter how gravity distorts the phase space sheets. See HWR lectures.
- Result: the course-grained phase space density must always be smaller than $f_{\max}$.

Tremaine & Gunn 79

Dalcanton & Hogan 00
ARZ & JSB 03, Kaplinghat 05

- Useful: Define a phase space variable $Q \equiv \frac{\rho}{\sigma^3}$

- Phase space constraint implies that any collapsed distribution of dark matter must obey:

$$Q < m_{\rm dm}^4 f_{\rm max}$$

For the case of thermal **WDM**, Q is related to the mass in a 1-to-1 way:

WDM →

$$Q_{\rm max} \simeq 5.2 \times 10^{-4} \left(\frac{m_{\rm dm}}{\rm keV}\right)^4 \frac{M_\odot/{\rm pc}^{-3}}{({\rm km\,s}^{-1})^3}$$

CDM →

$$Q_{CDM} \approx 7 \times 10^{14} \left(\frac{m_{cdm}}{100GeV}\right)^{3/2} M_{sun} pc^{-3} (km/s)^{-3}$$

The Story of Q

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

In order to have any observable effect on the density profiles of dark matter halos, the primordial Q_{dm} needs to approach the **maximum** Q that is inferred by stars in dSph's.

$$Q_{obs}(300pc) < \frac{M(300pc)/(300pc)^3}{4\pi\sigma_{los}^2} \simeq 10^{-4}\frac{M_\odot \mathrm{pc}^{-3}}{(\mathrm{kms}^{-1})^3}$$

Note: Q of the DM in dSph's *cannot be measured directly* because σ_{dm} cannot be measure direct -- Why? - we can't measure V_{max} and we need V_{max} to determine σ_{dm}. Here I have used $\sigma_{dm} < \sigma_{los}$.

WDM →

$$Q_{\max} \simeq 5.2 \times 10^{-4}\left(\frac{m_{\mathrm{dm}}}{\mathrm{keV}}\right)^4 \frac{M_\odot/\mathrm{pc}^{-3}}{(\mathrm{km\,s}^{-1})^3}$$

compare: CDM →

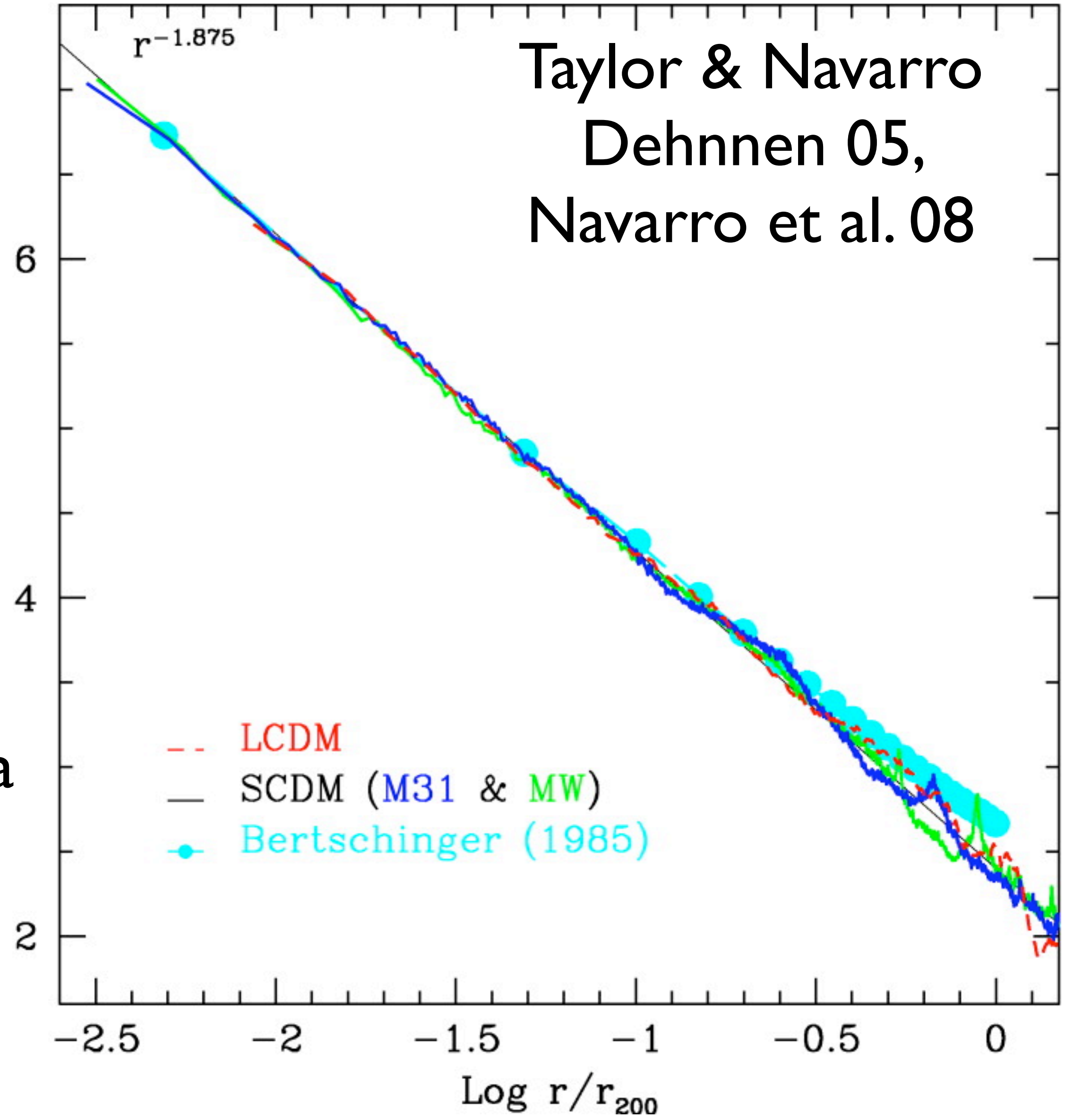
$$Q_{CDM} \approx 7 \times 10^{14}\left(\frac{m_{cdm}}{100GeV}\right)^{3/2} M_{sun}pc^{-3}(km/s)^{-3}$$

“Phase space” profile of CDM Halos

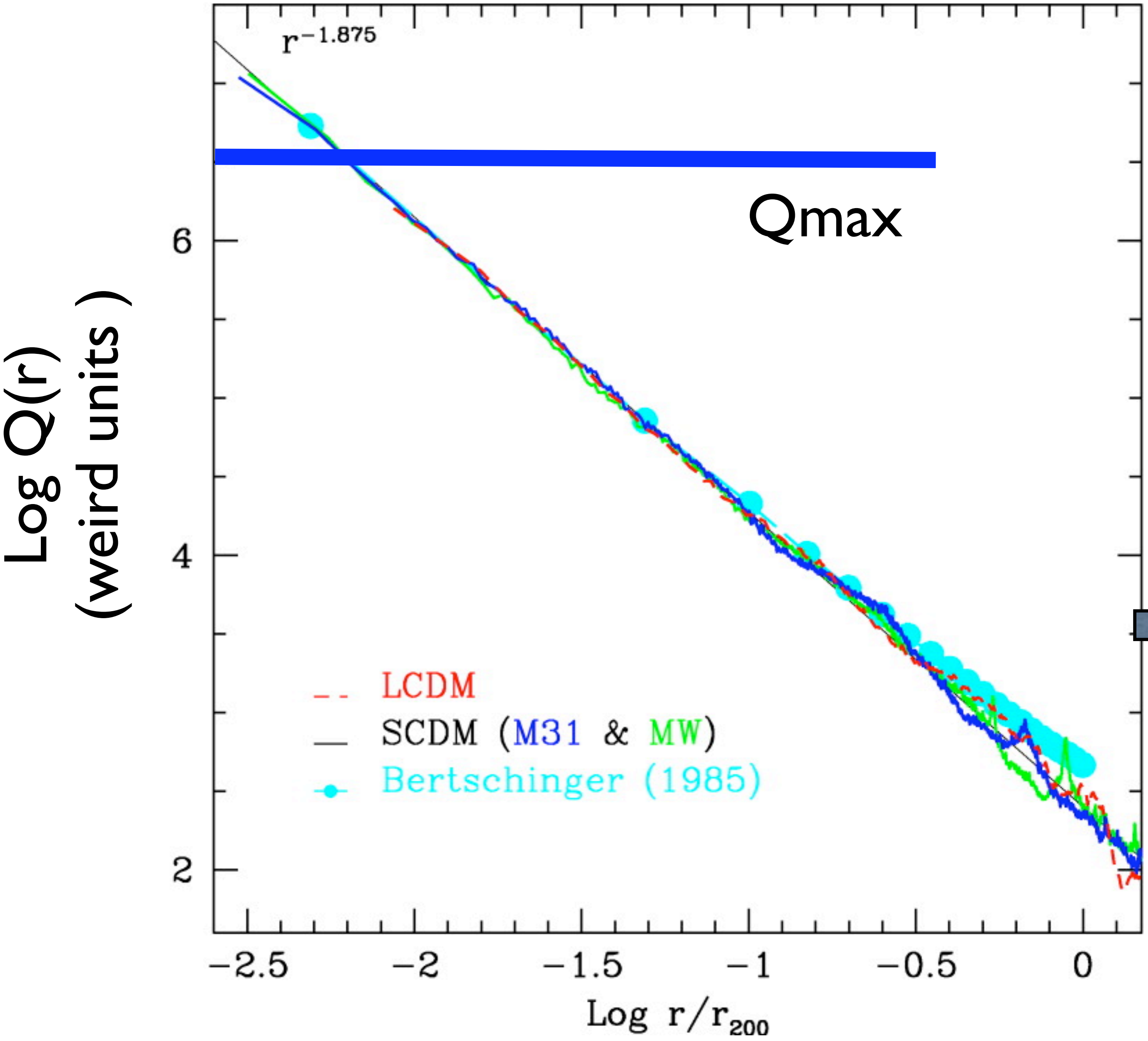
$$Q \equiv \frac{\rho}{\sigma^3}$$

Log Q(r)

Q rises as a power law.



Phase space profile of WDM halos: must break @ small r



Martinez, JSB, Kaplinghat, Strigari, Simon, in prep

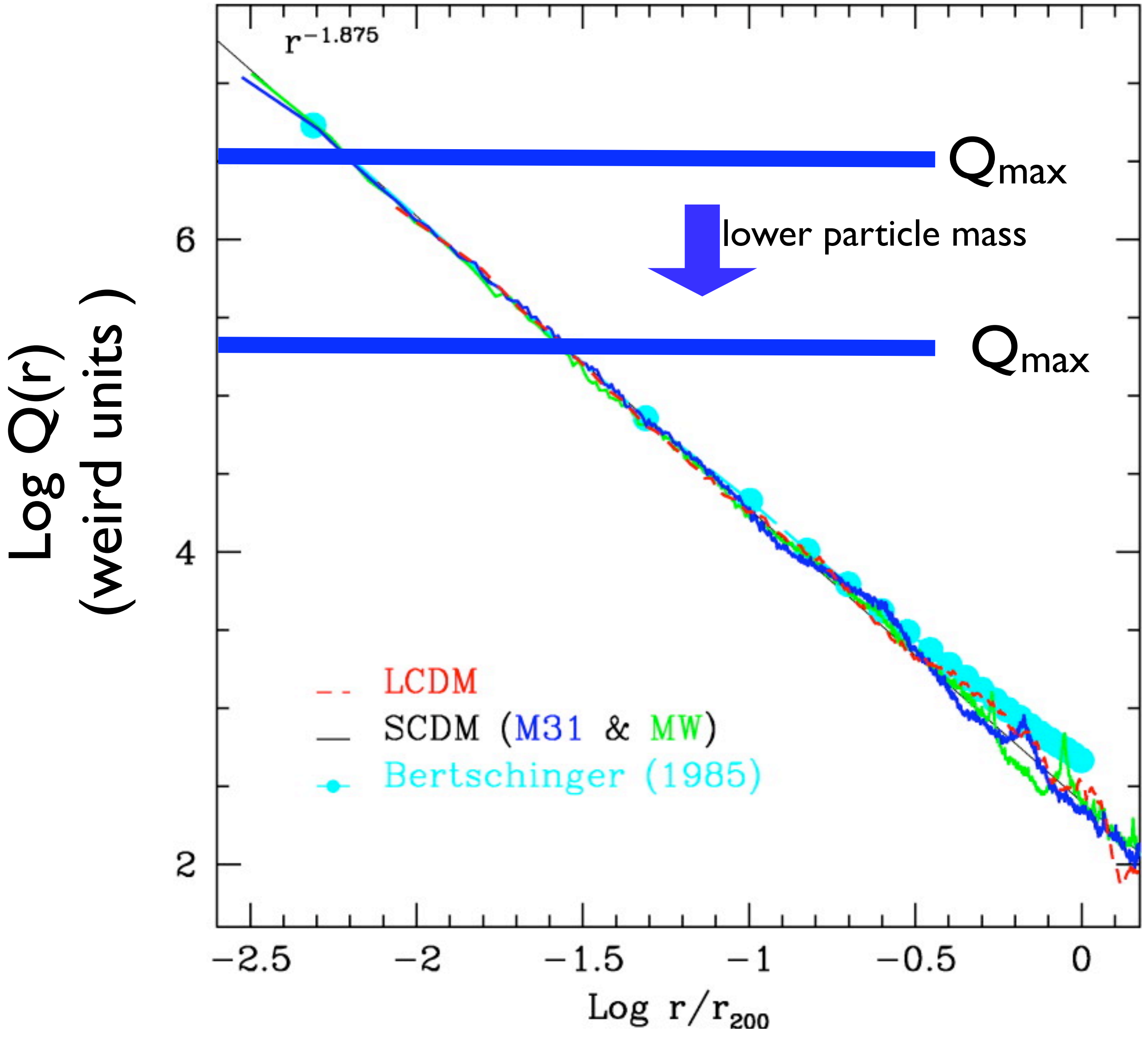
small r expect:

$$\sigma_0^B \simeq 0.55 V_{\max}$$

$$\rho \longrightarrow \text{const.}$$

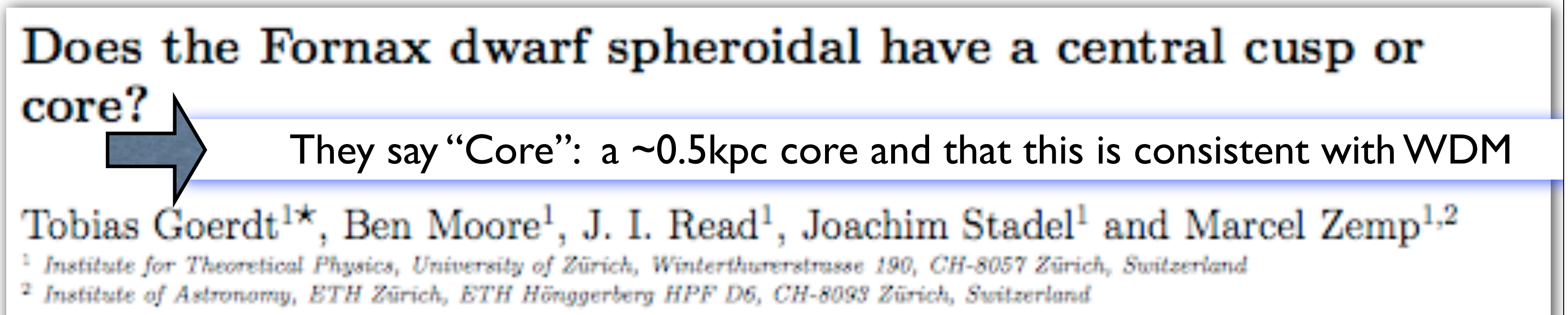
Central Core Density Profile

Phase space profile of WDM halos: must break @ small r



Martinez, JSB, Kaplinghat, Strigari, Simon, in prep

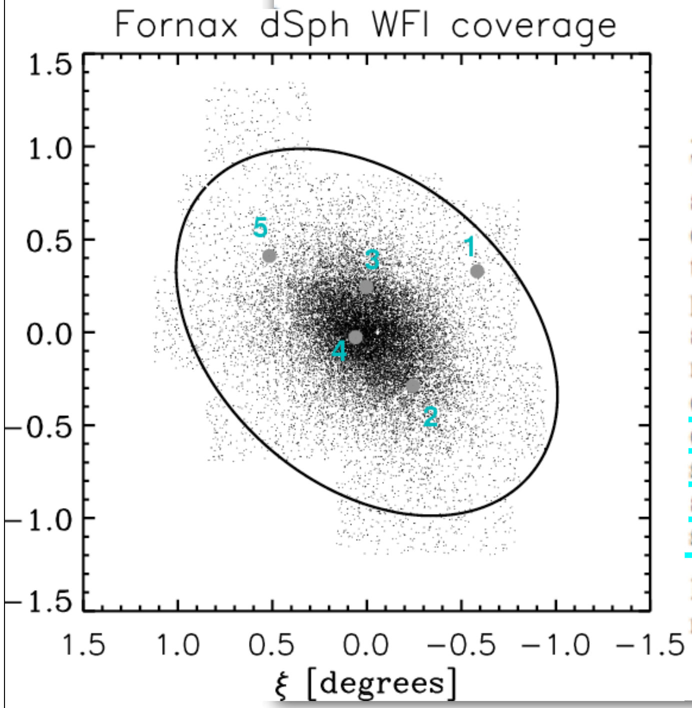
Note: self-consistent Q(r) profiles that have a maximum cannot be a power-law at large r. The figure to the left is just descriptive.

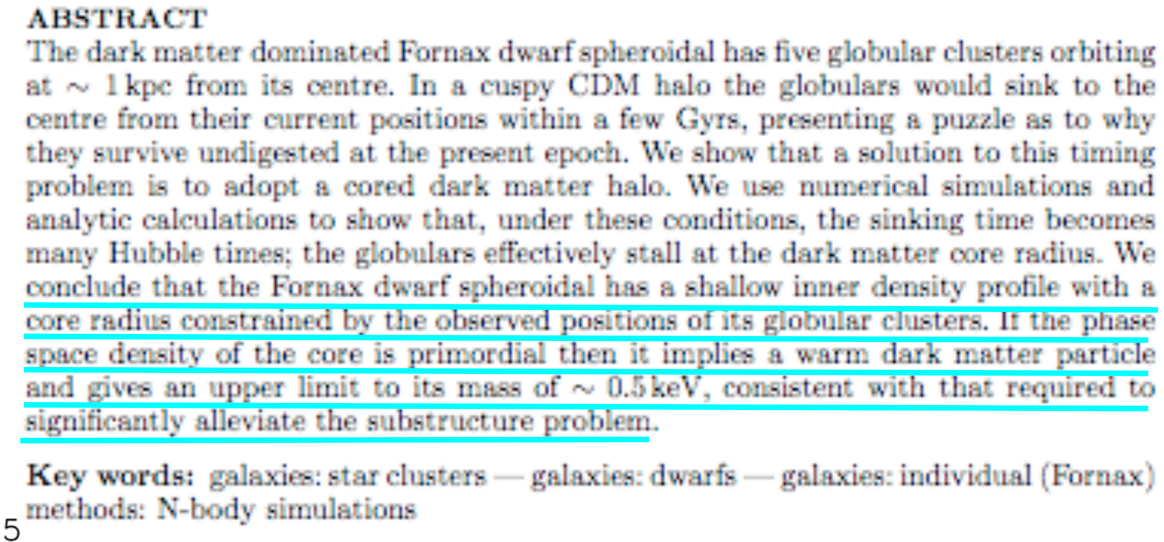


Does the Fornax dwarf spheroidal have a central cusp or core?

They say "Core": a ~0.5kpc core and that this is consistent with WDM

Tobias Goerdt[1★], Ben Moore[1], J. I. Read[1], Joachim Stadel[1] and Marcel Zemp[1,2]
[1] Institute for Theoretical Physics, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland
[2] Institute of Astronomy, ETH Zürich, ETH Hönggerberg HPF D6, CH-8093 Zürich, Switzerland



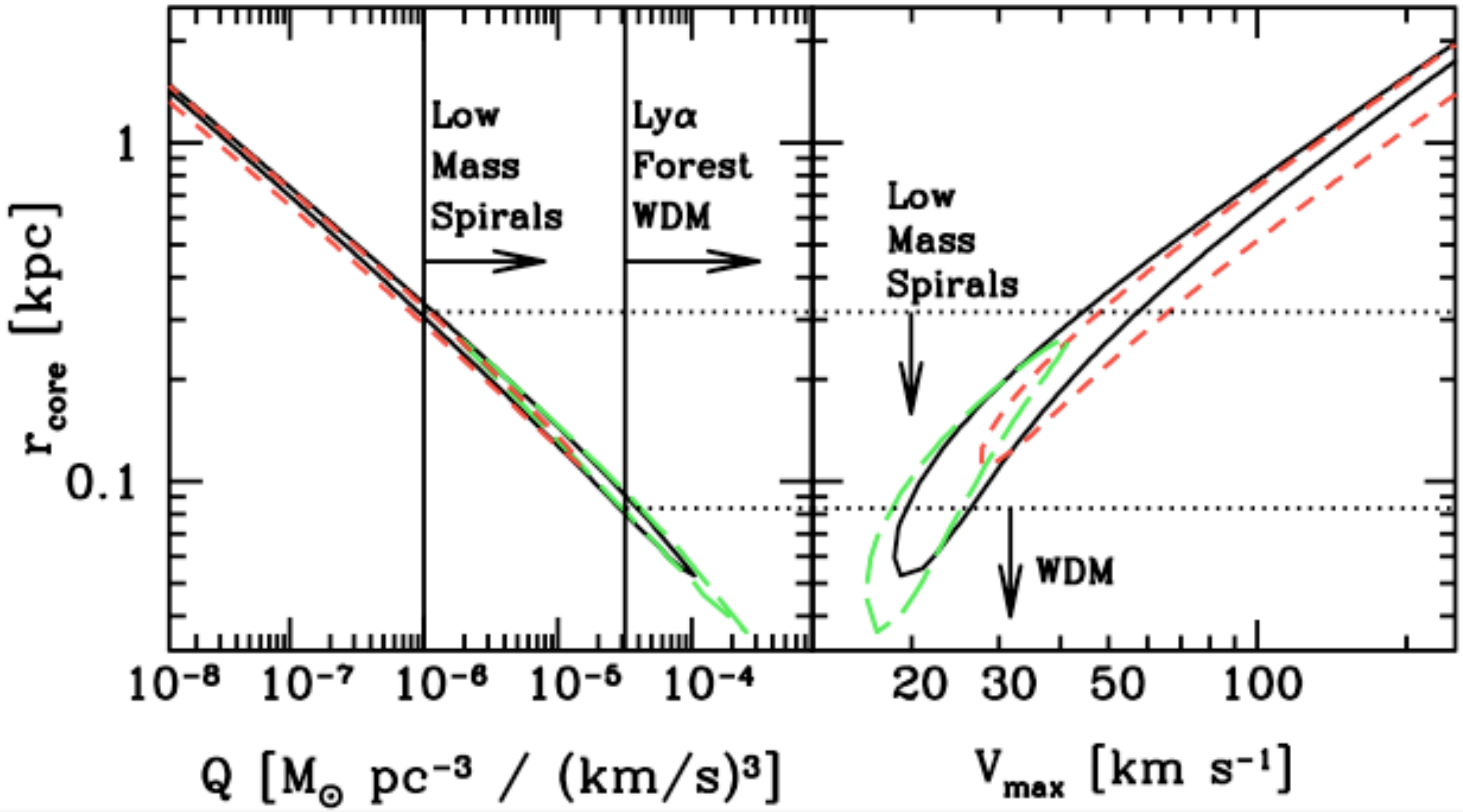


ABSTRACT
The dark matter dominated Fornax dwarf spheroidal has five globular clusters orbiting at ∼ 1 kpc from its centre. In a cuspy CDM halo the globulars would sink to the centre from their current positions within a few Gyrs, presenting a puzzle as to why they survive undigested at the present epoch. We show that a solution to this timing problem is to adopt a cored dark matter halo. We use numerical simulations and analytic calculations to show that, under these conditions, the sinking time becomes many Hubble times; the globulars effectively stall at the dark matter core radius. We conclude that the Fornax dwarf spheroidal has a shallow inner density profile with a core radius constrained by the observed positions of its globular clusters. If the phase space density of the core is primordial then it implies a warm dark matter particle and gives an upper limit to its mass of ∼ 0.5 keV, consistent with that required to significantly alleviate the substructure problem.

Key words: galaxies: star clusters — galaxies: dwarfs — galaxies: individual (Fornax) methods: N-body simulations

Strigari et al. 06

~0.5kpc core in Fornax requires an extremely low phase-space maximum Q~1.e-6.



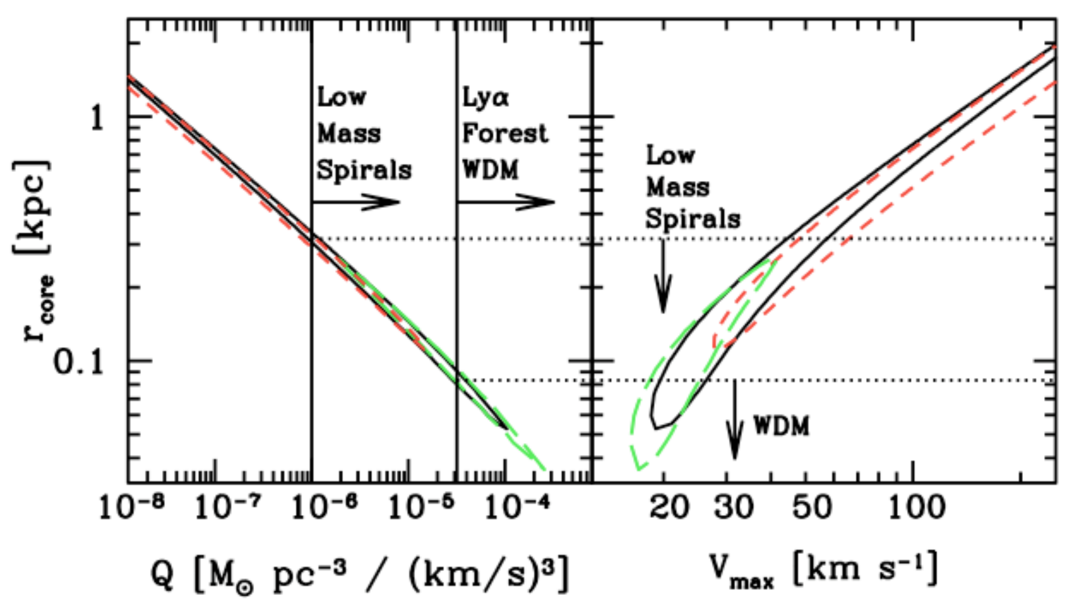
Thermal WDM of this type is strongly ruled out by Lya forest.

m_n > 600 eV => Q > 2e10^{-5}

Strigari et al. 06

~0.5kpc core in Fornax requires an extremely low phase-space maximum Q~1.e-6.

If ~0.5 kpc core is real need DM candidate with low Q and small free-streaming length...



Can we have such a DM particle?

YES. WE. CAN!

Phase Space Densities:

$Q = \rho/\sigma^3$

CDM

$$Q_{CDM} \approx 7\times10^{14}\left(\frac{m_{cdm}}{100GeV}\right)^{3/2} M_{sun}pc^{-3}(km/s)^{-3}$$

Neutrino WDM

$$Q \approx 5\times10^{-4}\left(\frac{m}{keV}\right)^{4} M_{sun}pc^{-3}(km/s)^{-3}$$

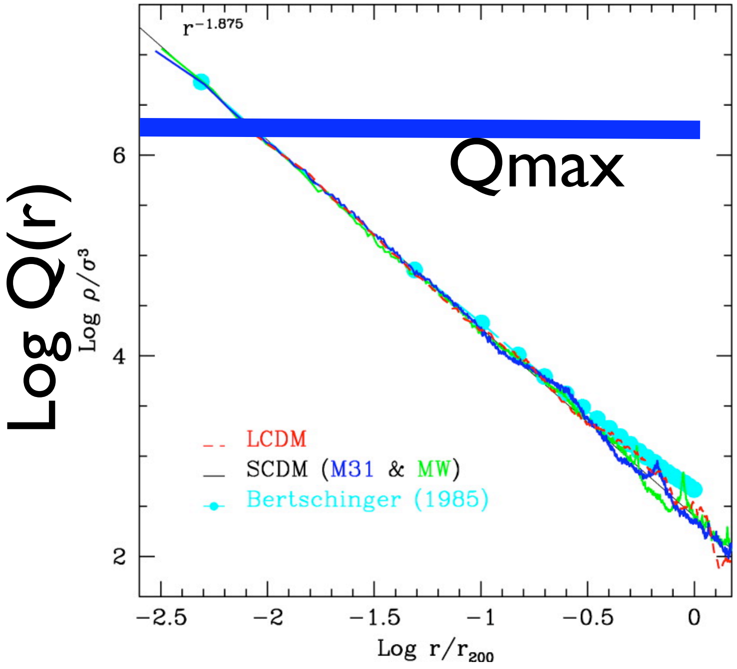
Dark matter from decays (non-thermal)

$$Q \approx 10^{-6}\left(\frac{10^{-3}}{\Delta m/m_{DM}}\right)^{3}\left(\frac{z_{decay}}{1000}\right)^{3} M_{sun}pc^{-3}(km/s)^{-3}$$

e.g. SuperWIMPS

Strigari, Kaplinghat, JSB 07

Phase space ceiling most important in the smallest galaxies.



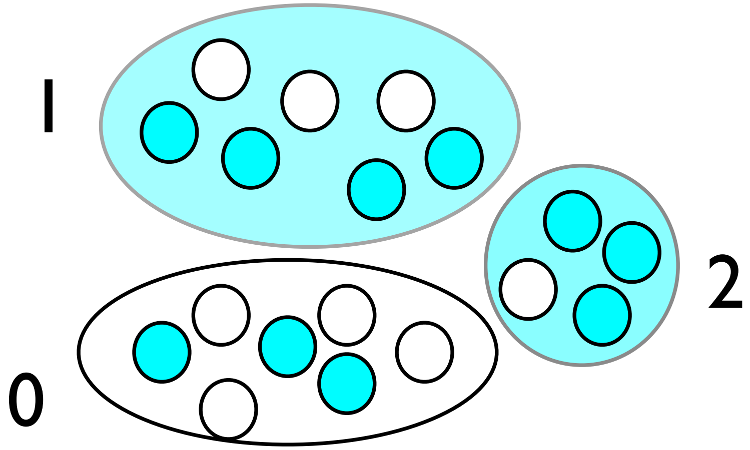
$$Q = \frac{\rho}{\sigma^3} \sim M_{\rm halo}^{-1}$$

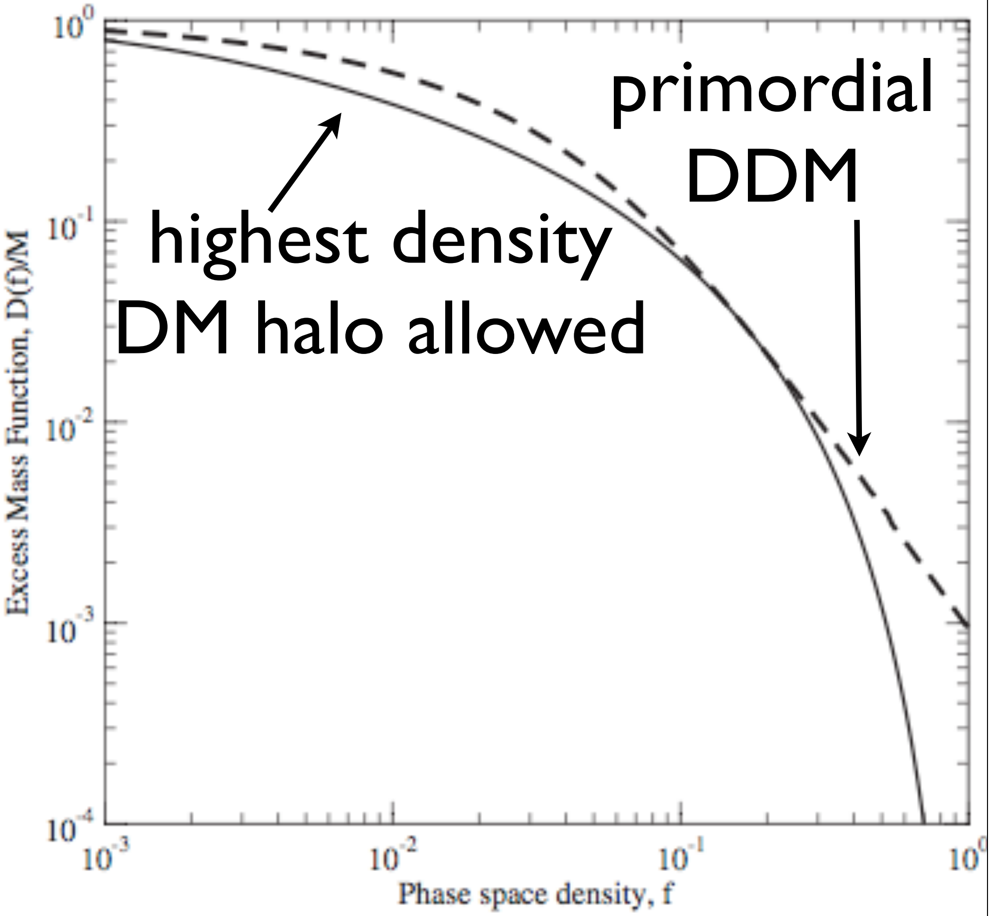
Kaplinghat 05

Generalizes Tremaine-Gunn bound for arbitrary (non-thermal) primordial phase space distribution

Dehnen 05:
There exists a function:
the "excess mass function" that always decreases as a result of coarse graining.

$$D(f) \equiv \int d^3x d^3q (F(\mathbf{x},\mathbf{q}) - f)\Theta(F(\mathbf{x},\mathbf{q}) - f)$$





primordial DDM

highest density DM halo allowed

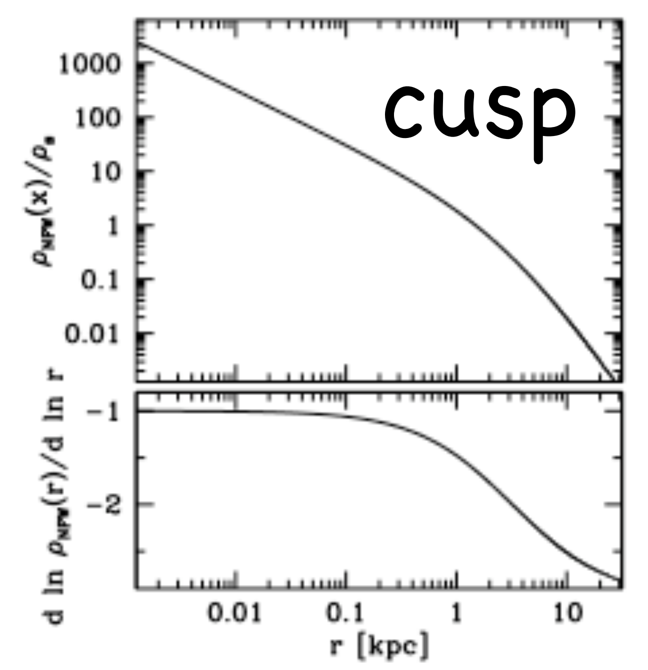
Large r ⟷ Small r

Dark Matter and Galaxy Central Densities

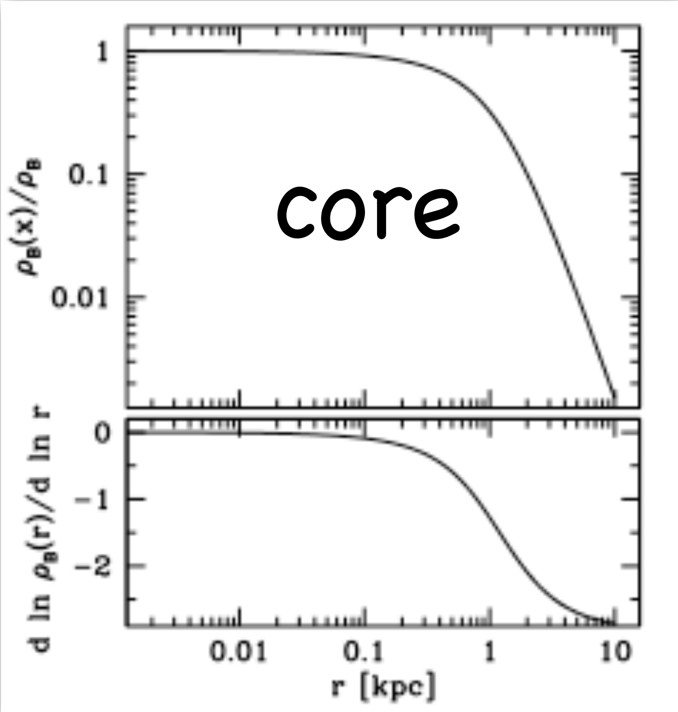
CDM WIMPs:
LSP neutrlino

WDM SuperWIMPs:
LSP gravitino

High phase-space density



Low phase-space density

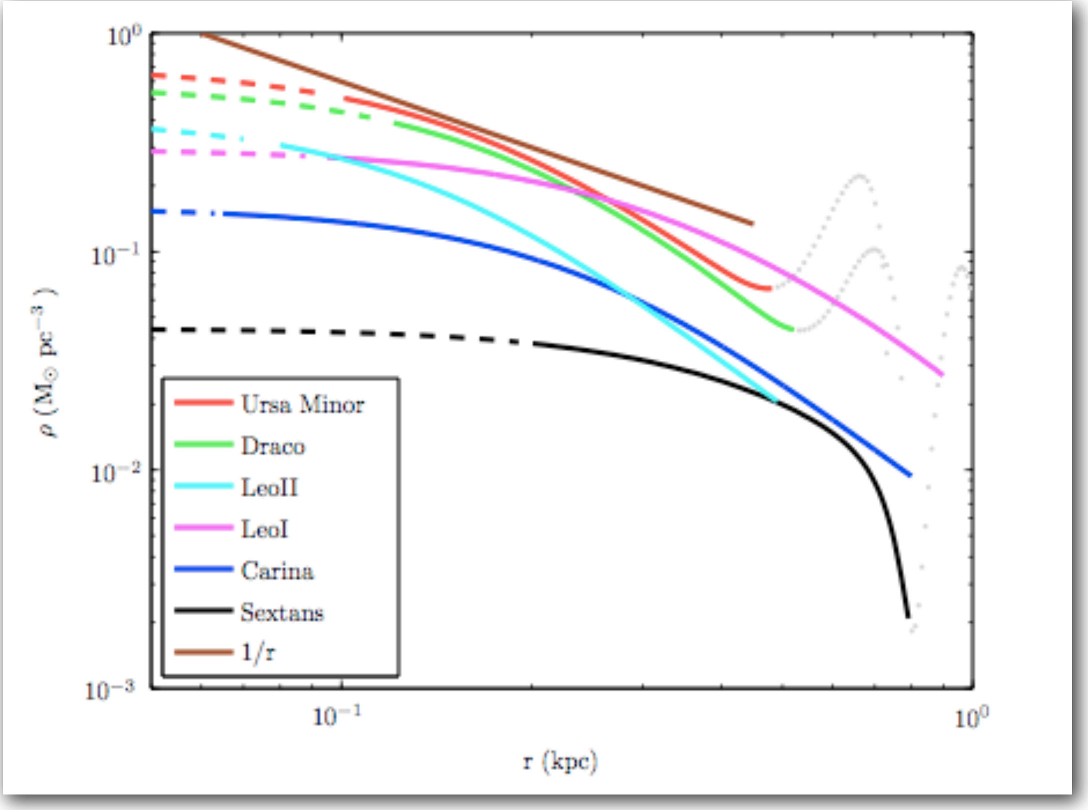


Looking for DM Cores...

Dwarf galaxies are potentially excellent laboratories:

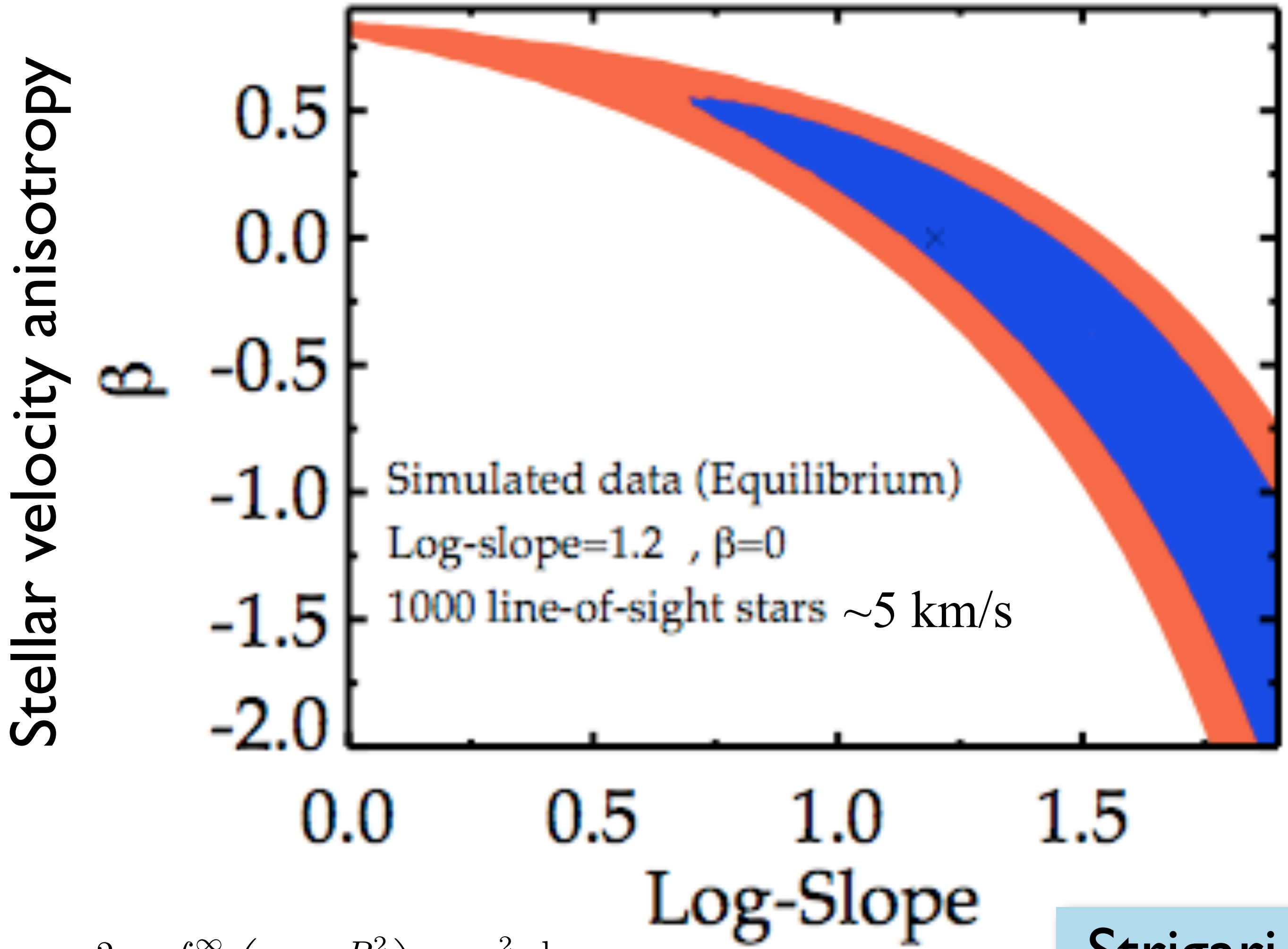
1. High Phase Space Densities
2. Stellar Dynamics => Probe DM distribution

Gilmore et al. 07:
Density profiles of dSph Galaxies - isotropic Jeans modeling



IF $\beta \equiv 1 - \frac{\sigma_\theta^2}{\sigma_r^2} = 0$ ➡ Cored profiles are better fits.

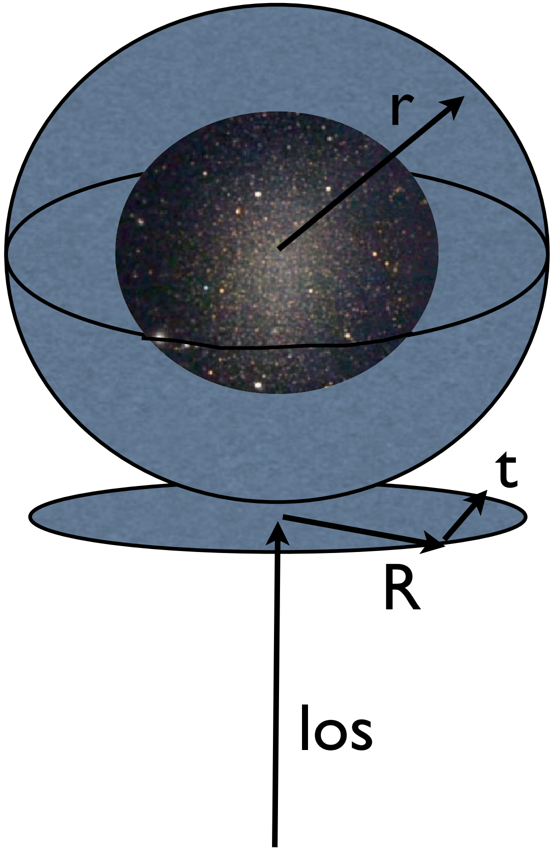
Without assumptions, Dark Matter Halo Slope is hard to measure even with radial velocities of ~1000s of stars

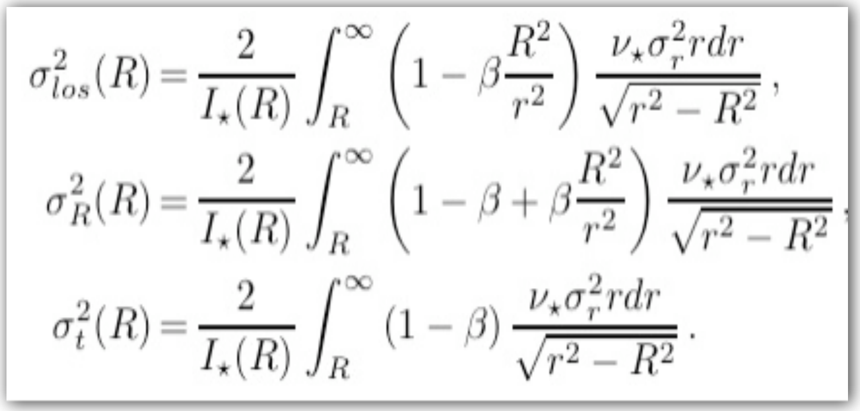


$$\sigma_{los}^2(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right) \frac{\rho_* \sigma_r^2 r \mathrm{d}r}{\sqrt{r^2 - R^2}}$$

Strigari, JSB, MK 07

Proper motions break the degeneracy





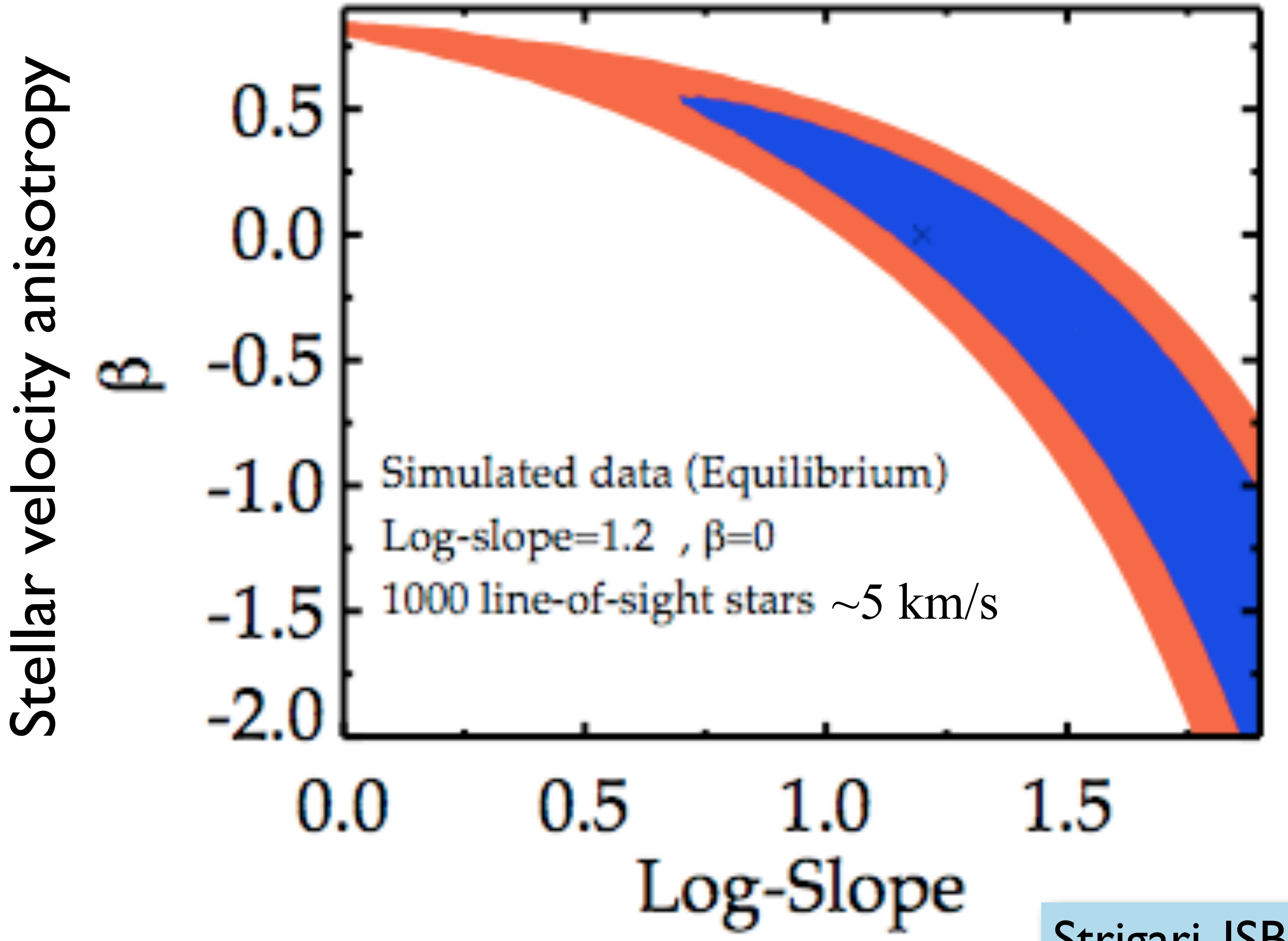
$$\sigma_{los}^2(R) = \frac{2}{I_\star(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}},$$

$$\sigma_R^2(R) = \frac{2}{I_\star(R)} \int_R^\infty \left(1 - \beta + \beta \frac{R^2}{r^2}\right) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$

$$\sigma_t^2(R) = \frac{2}{I_\star(R)} \int_R^\infty (1 - \beta) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}.$$

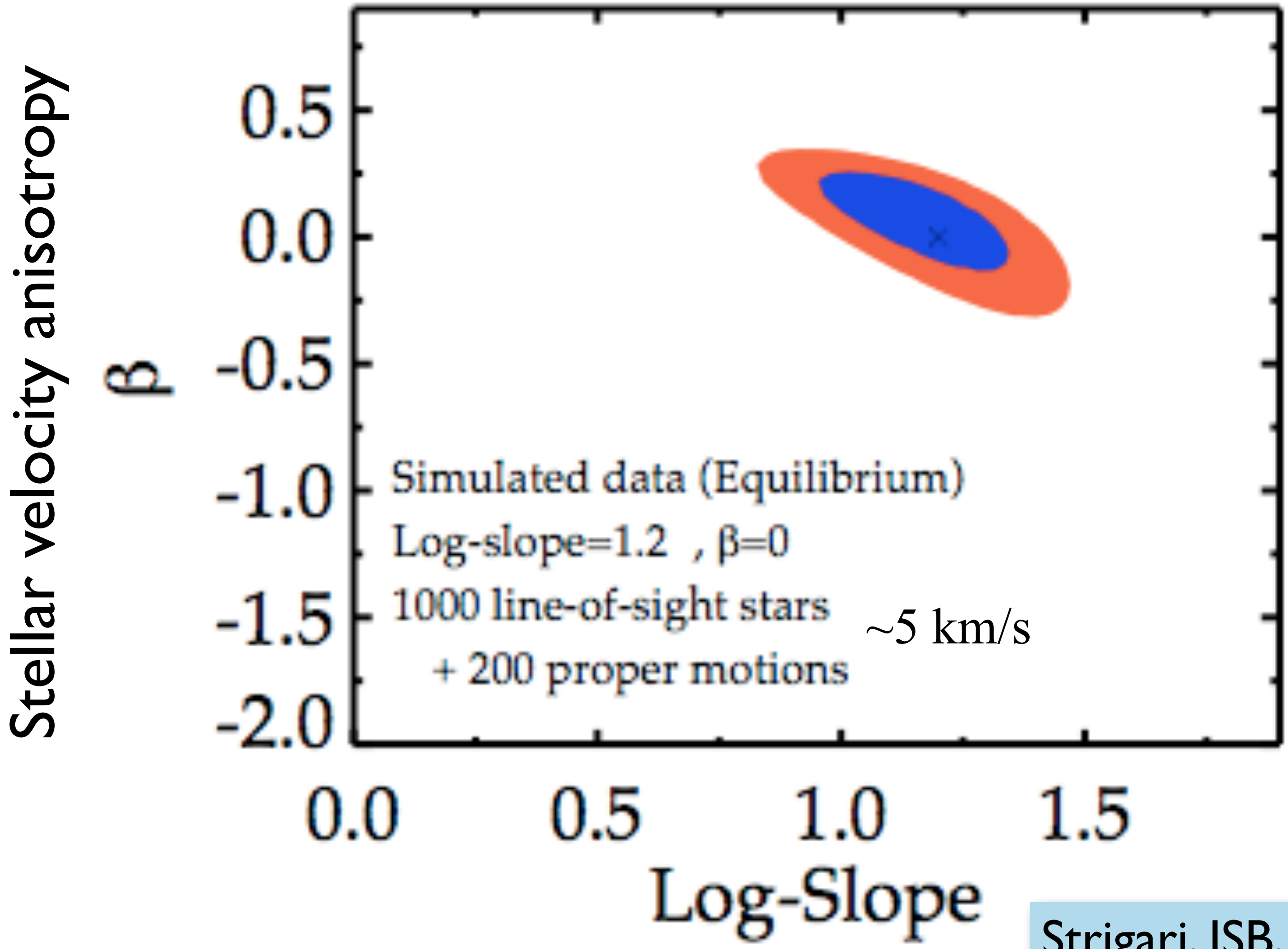
SIM PlanetQuest

Without assumptions, Dark Matter Halo Slope is hard to measure even with radial velocities of ~1000s of stars



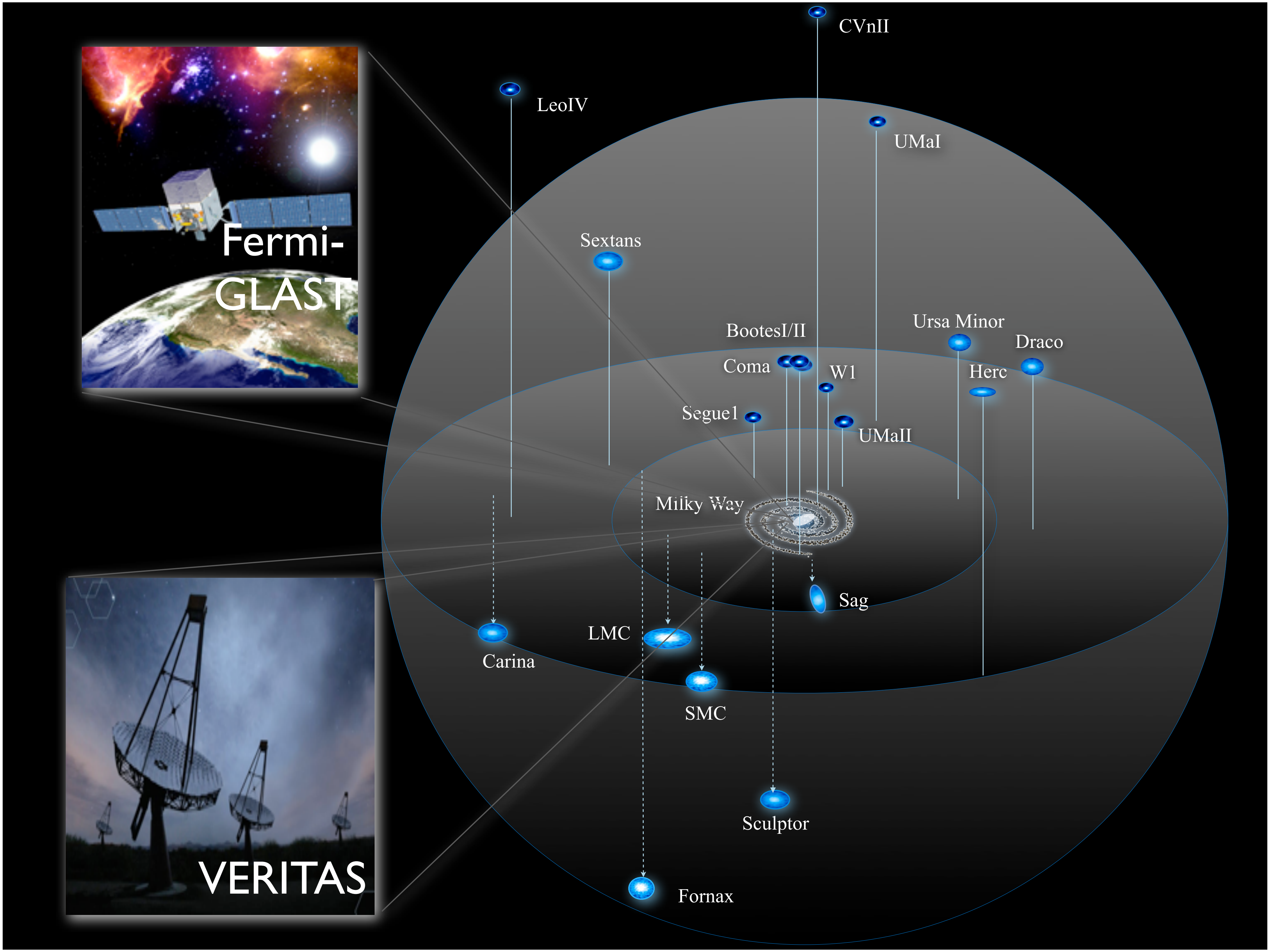
Strigari, JSB, Kaplinghat 07

Add Proper Motions (200 Stars from SIM)



~5 km/s

Strigari, JSB, Kaplinghat 07

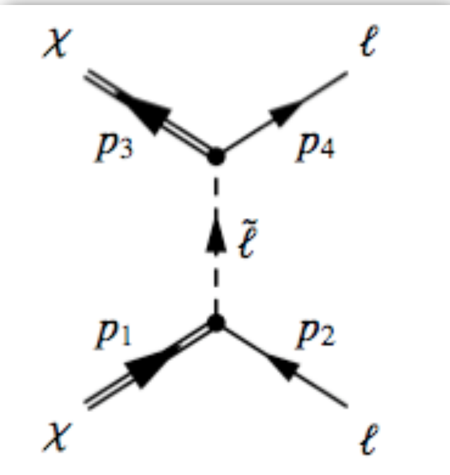

CVnII
LeoIV
UMaI
Fermi-GLAST
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
VERITAS
Fornax

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



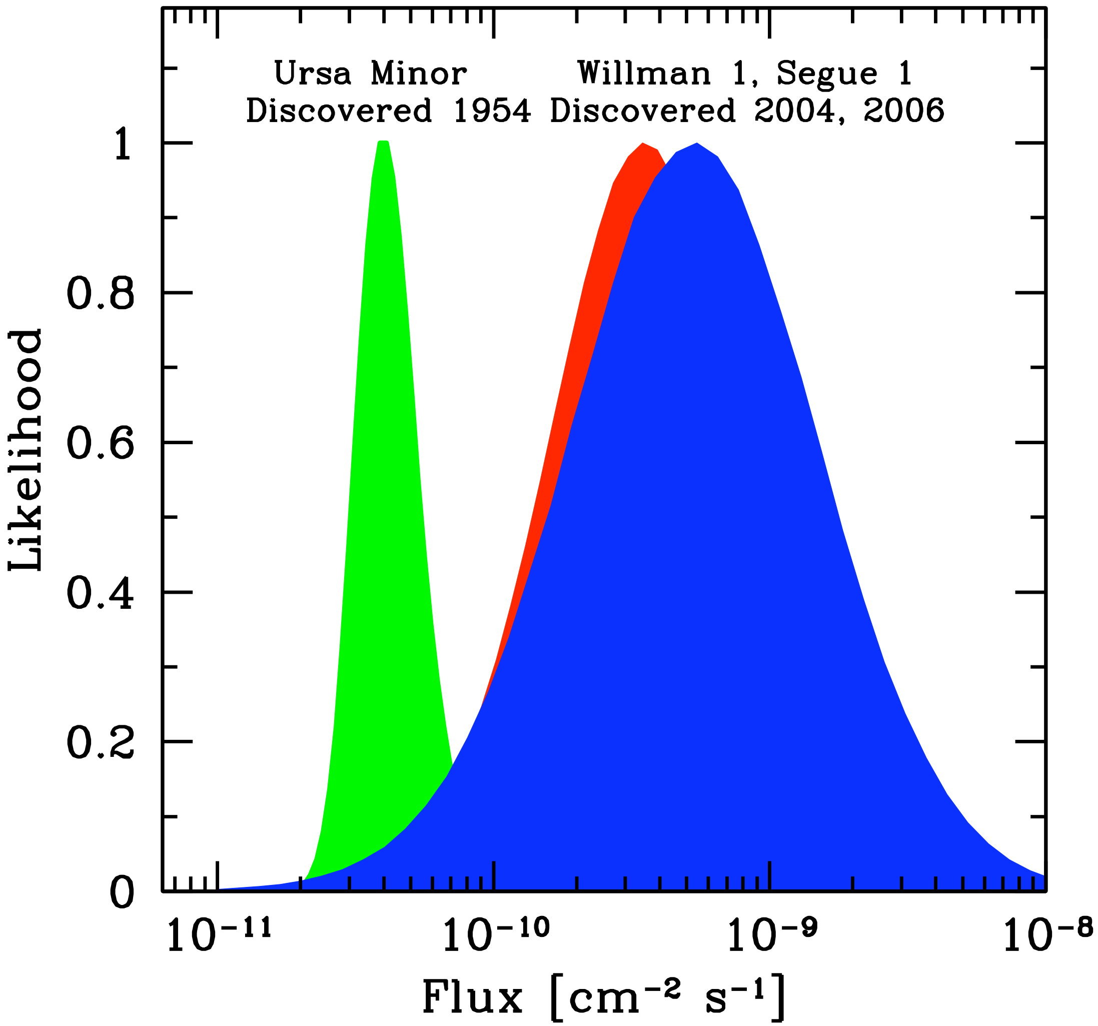
Astrophysics


Nelson et al. 93

Stadel et al. 08

Gamma-ray predictions

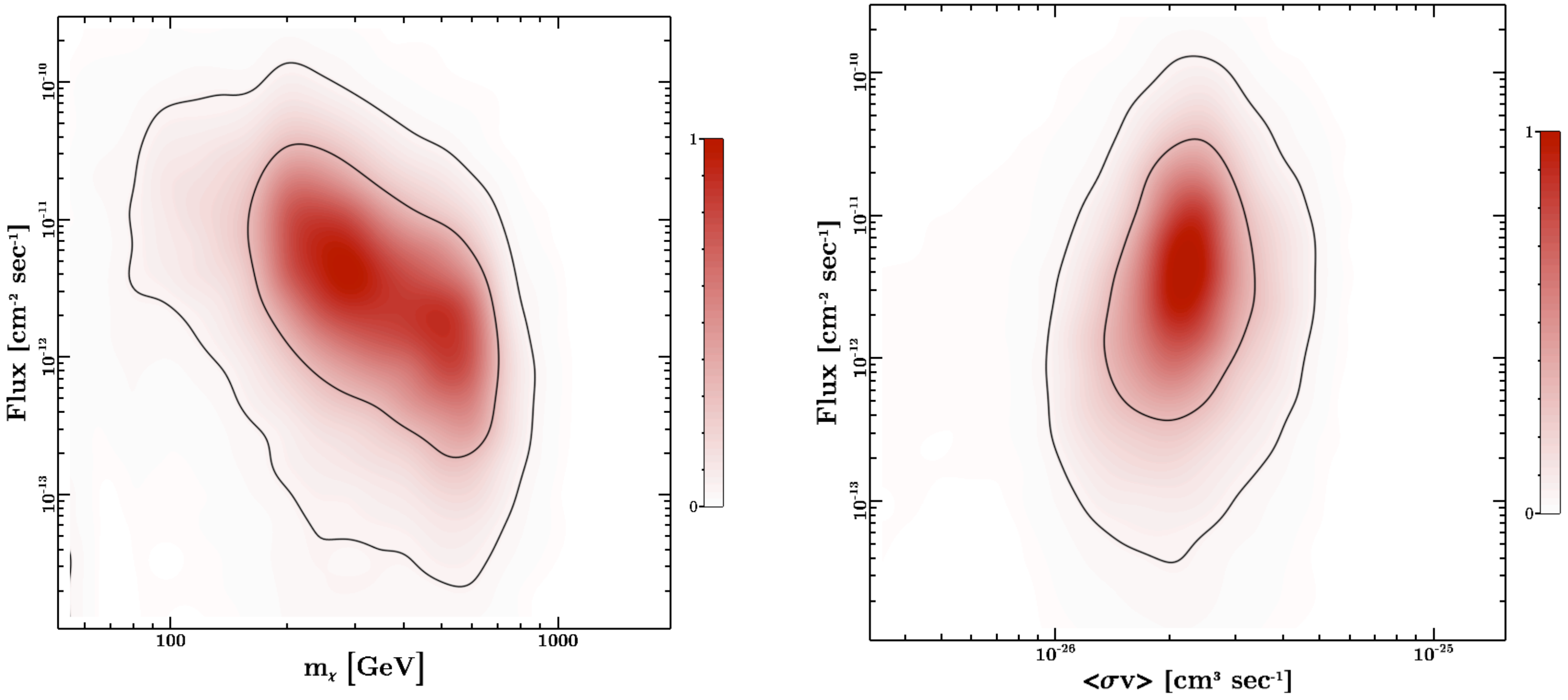
Strigari



Gamma-ray flux from Segue I

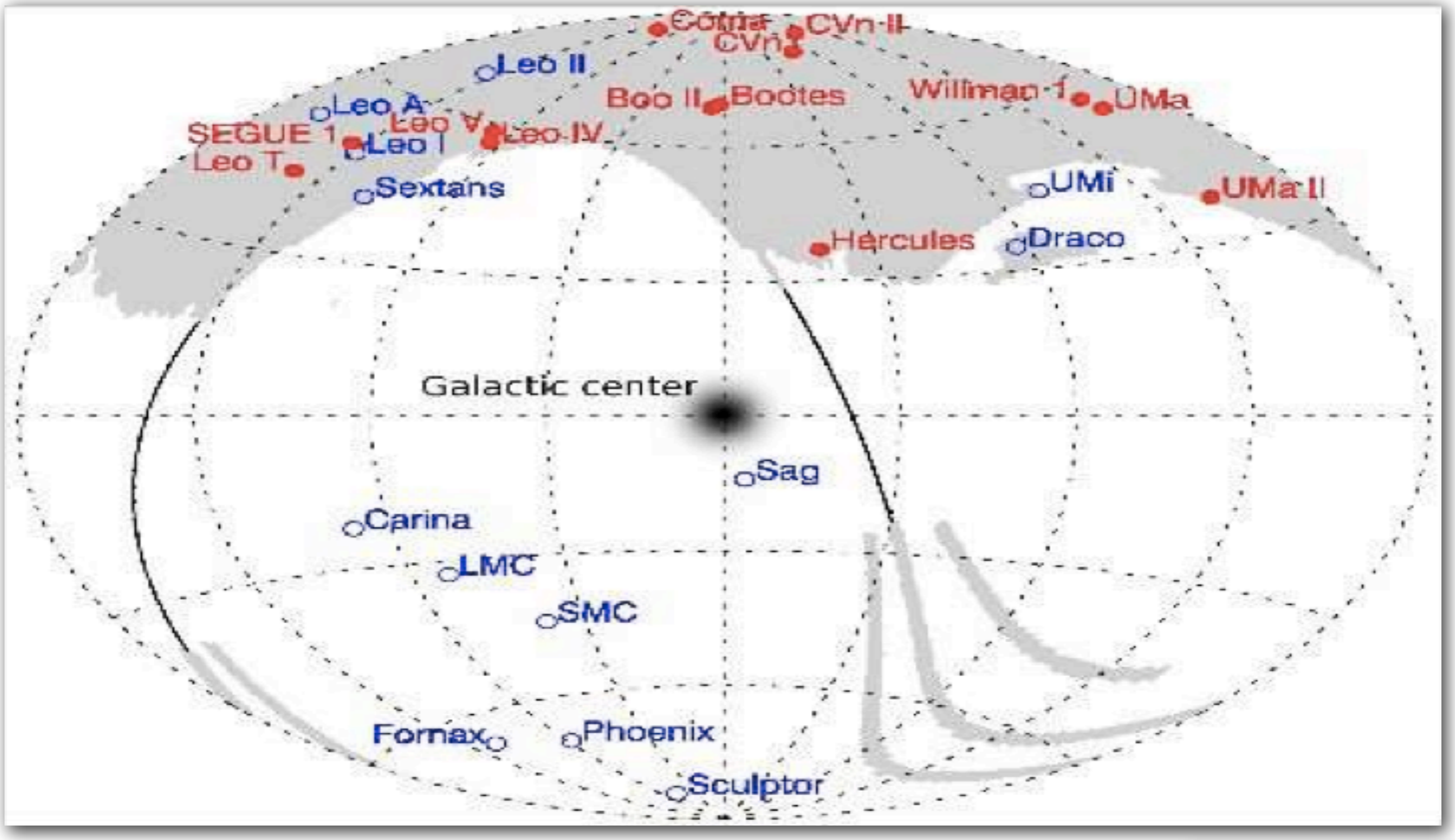
G. Martinez et al.
Constrained MSSM + Kinematic marginalization

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.

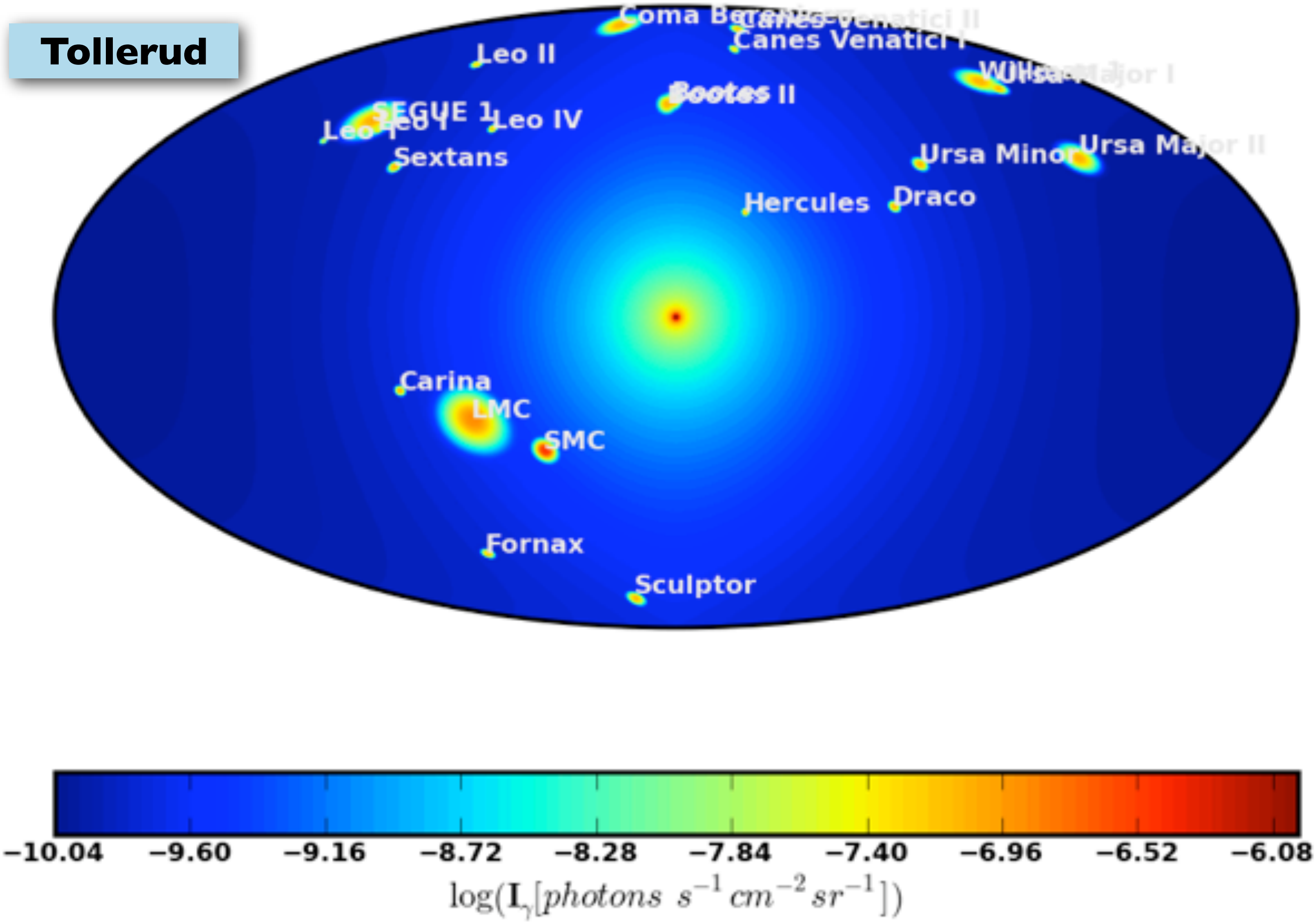
Milky Way Satellites



Walsh et al. 08

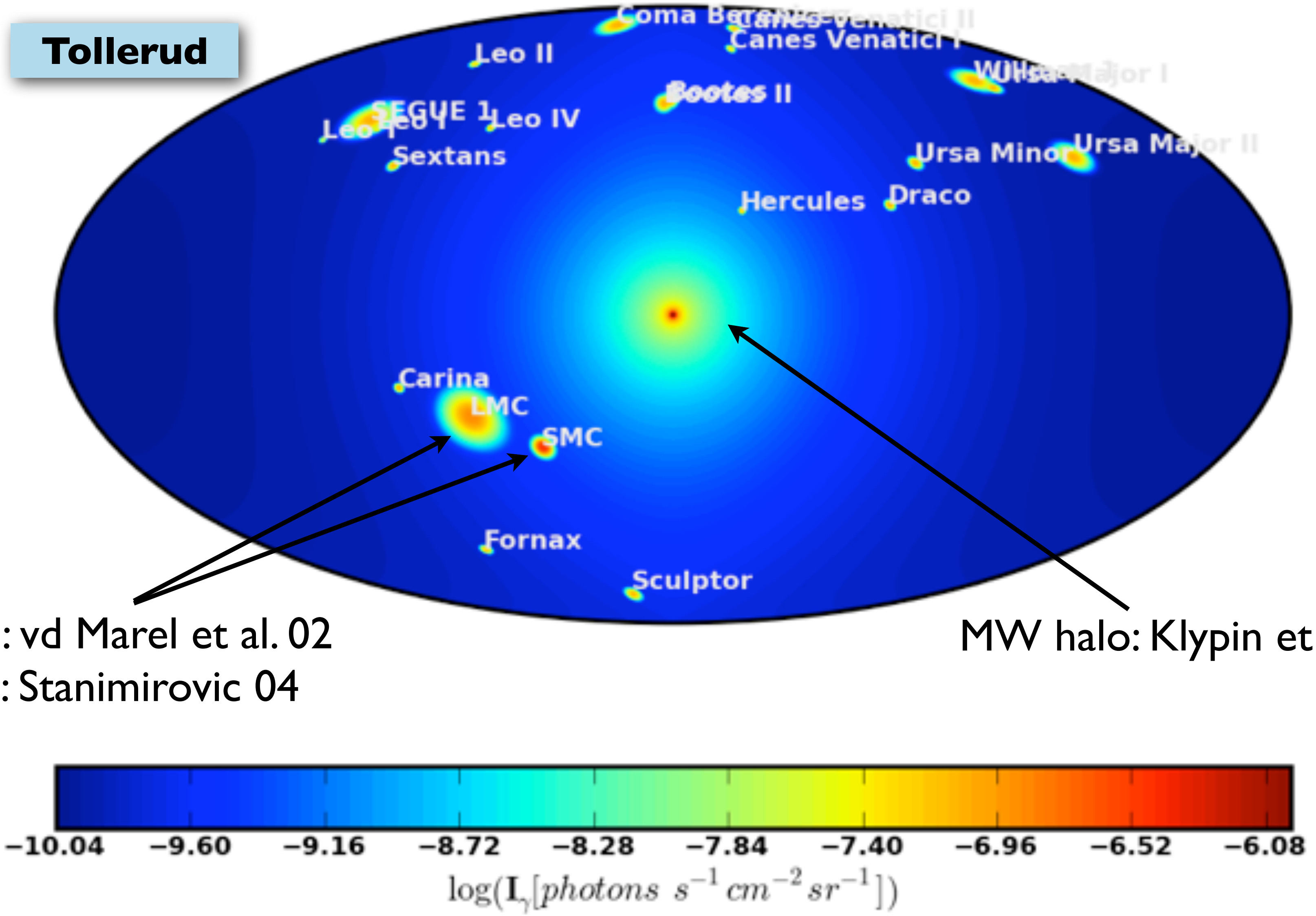
$E_\gamma > 1$ GeV Flux (optimistic particle model)

Tollerud



$E_\gamma > 1$ GeV Flux (optimistic particle model)

Tollerud

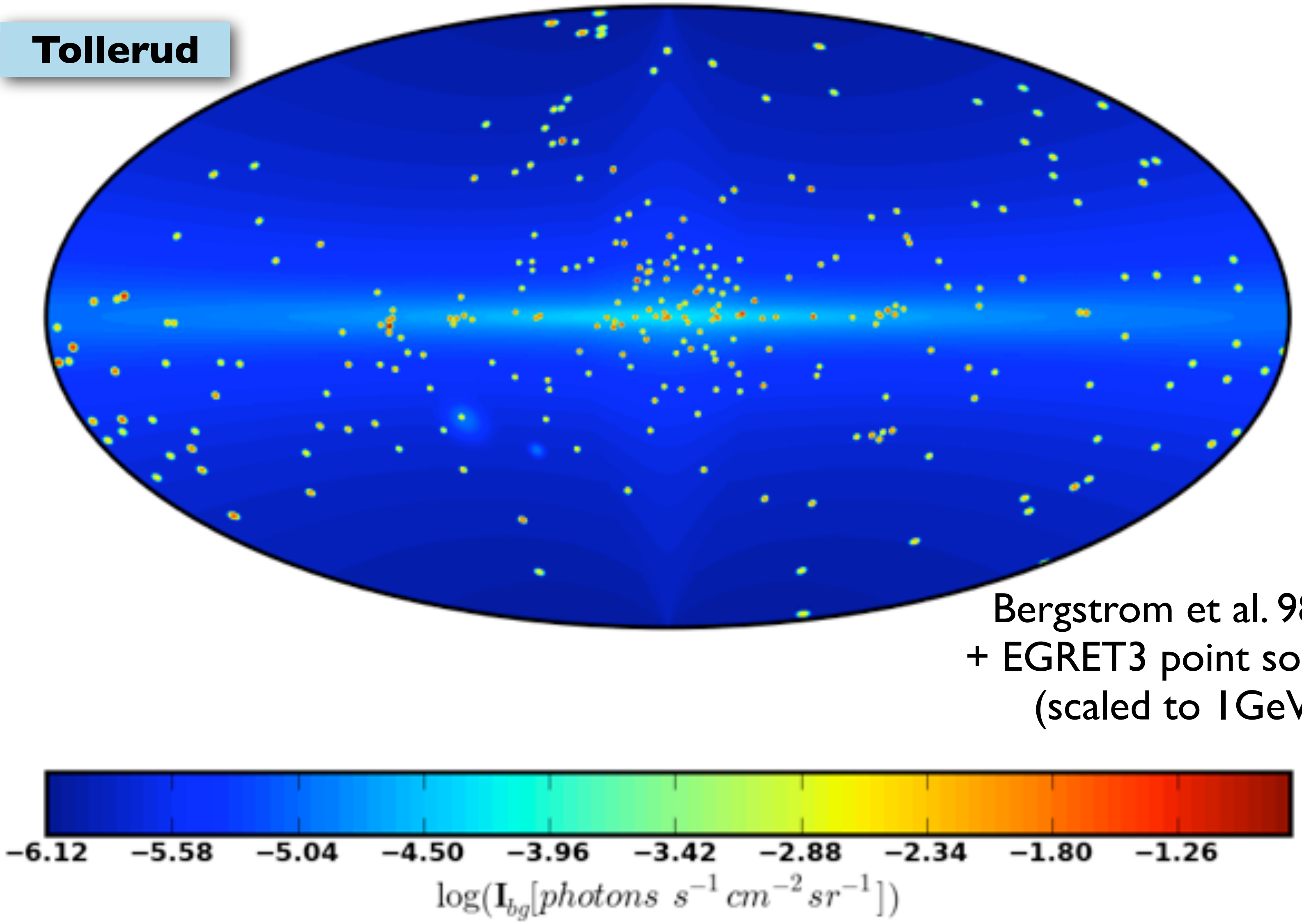


LMC: vd Marel et al. 02
SMC: Stanimirovic 04

MW halo: Klypin et al. 01

EGRET Background

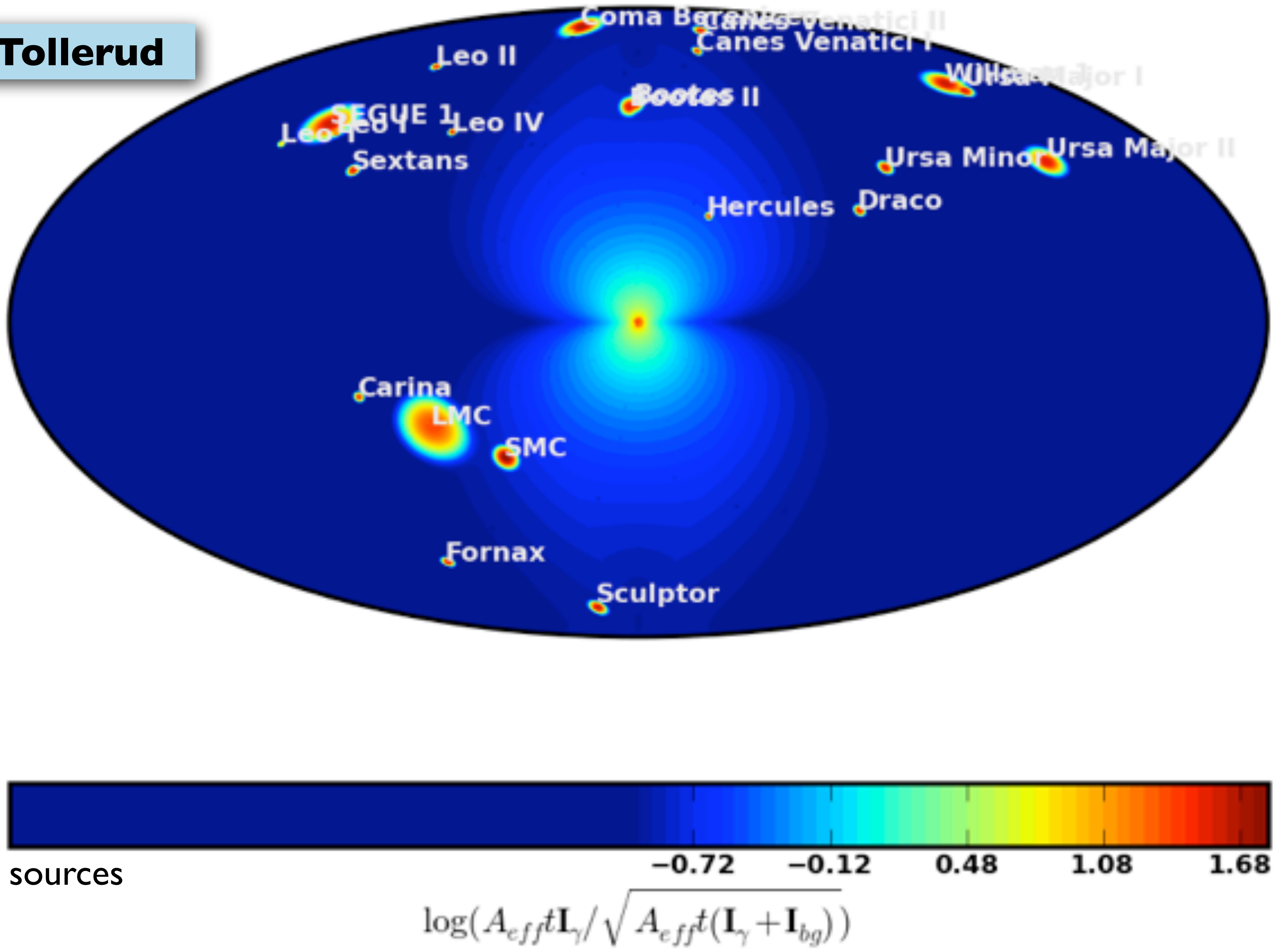
Tollerud



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

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

Tollerud

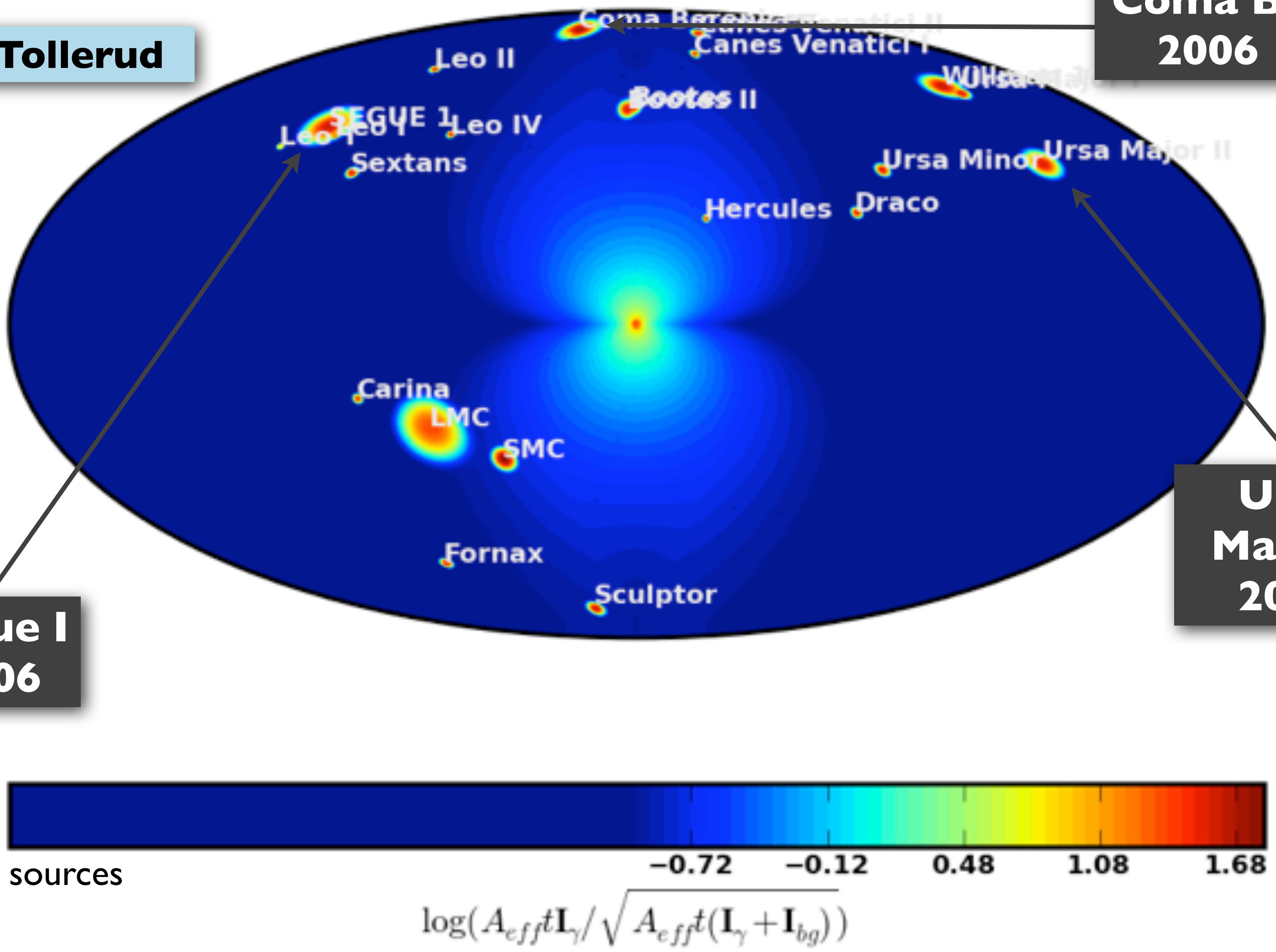


point sources

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

Tollerud

Coma Br
2006

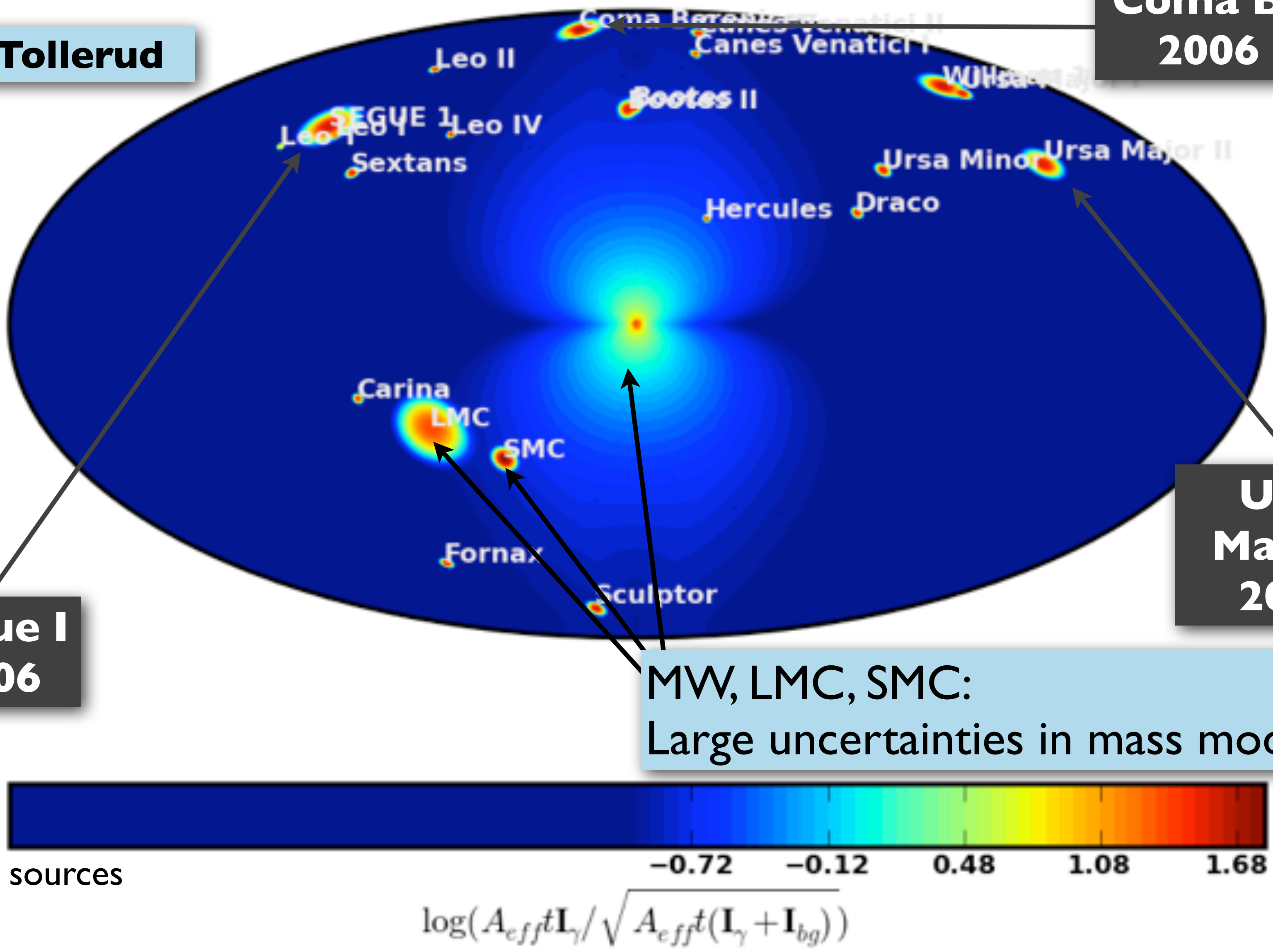


Ursa Major I
2005

Segue I
2006

point sources

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



Tollerud

Coma Br 2006

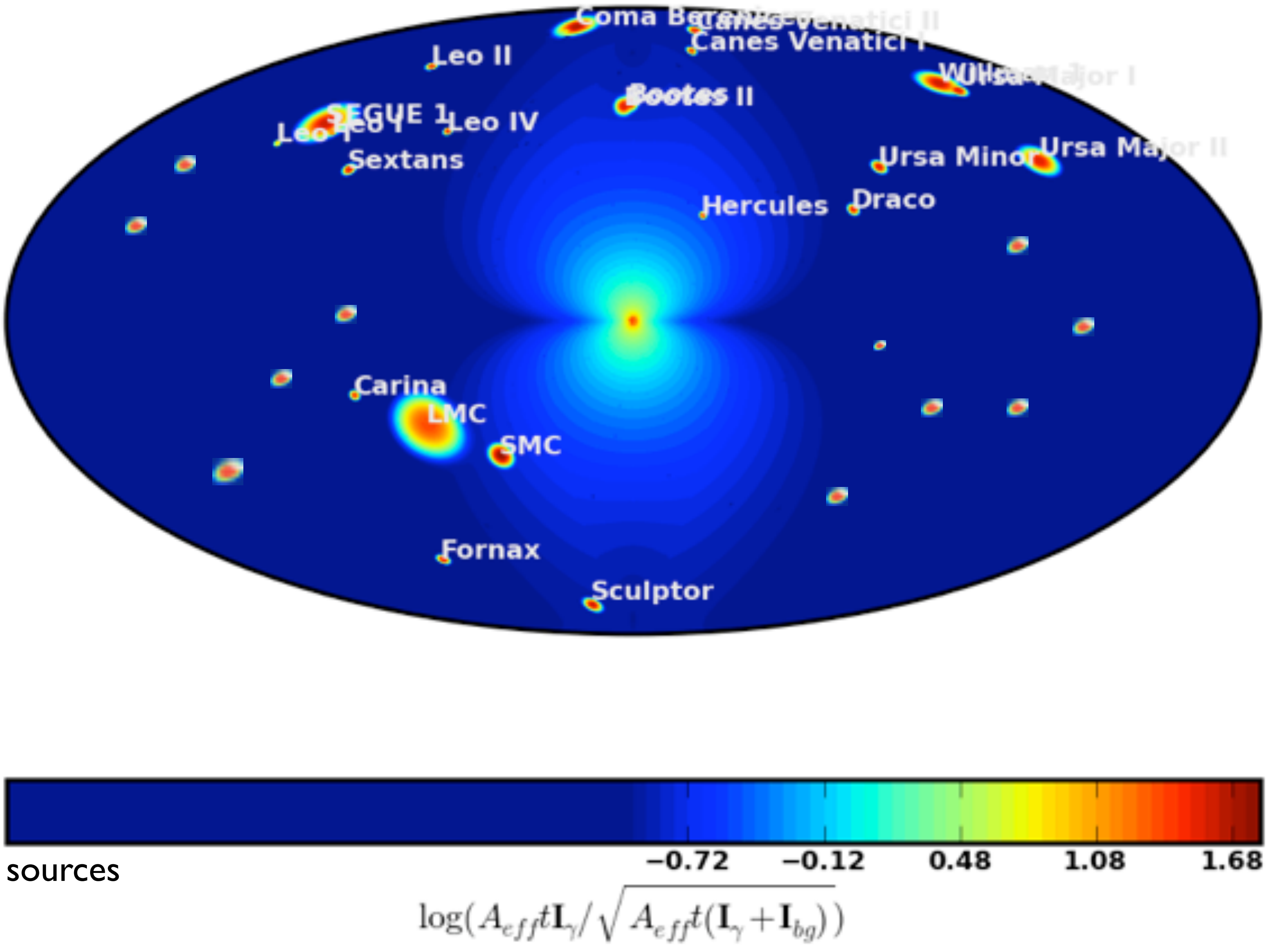
Ursa Major I 2005

Segue I 2006

MW, LMC, SMC:
Large uncertainties in mass models!

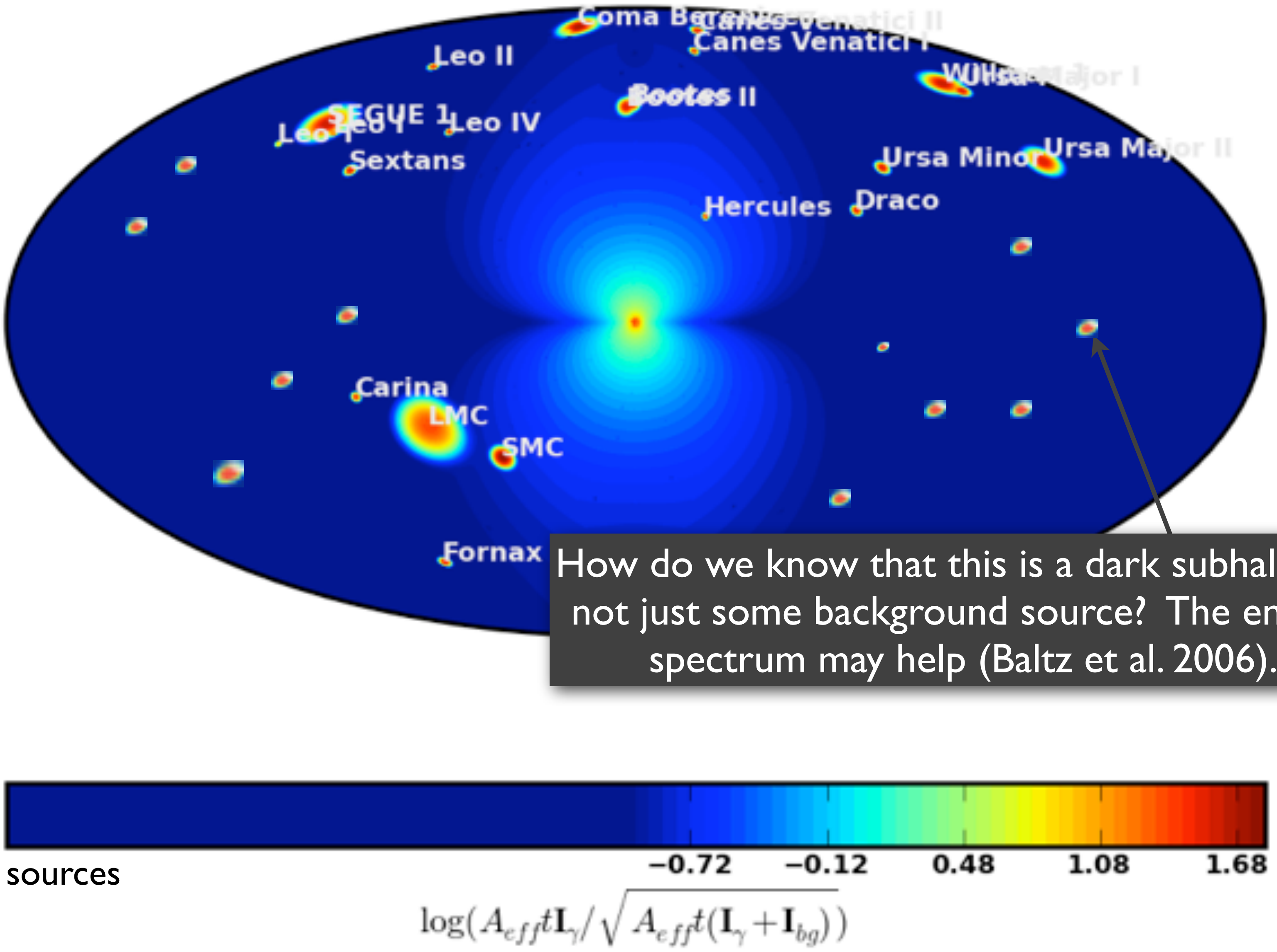
point sources

GLAST may discover some sources without corresponding galaxies
they may even be brighter (see Kuhlen et al. 08 vs Springel et al. 08)



point sources

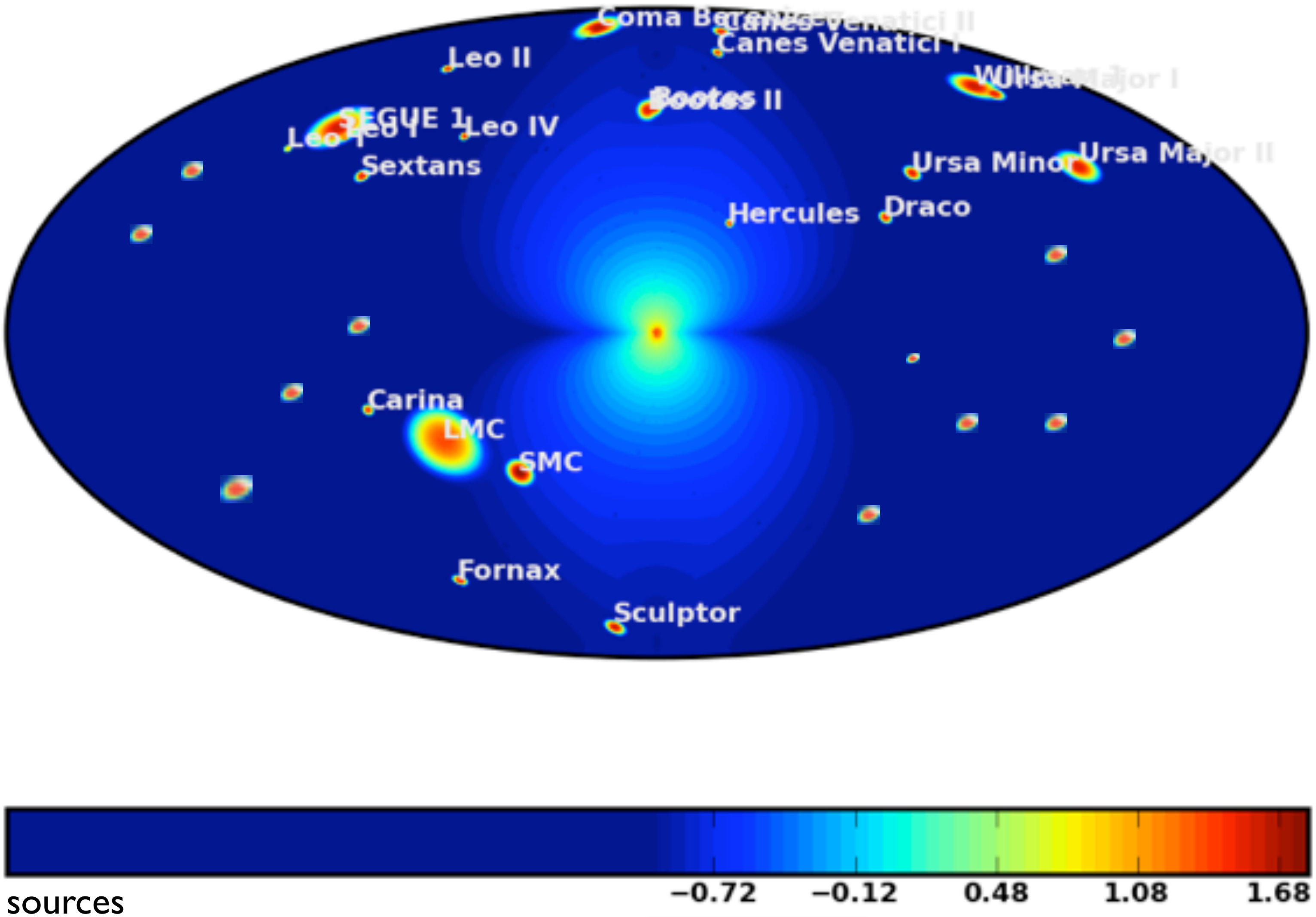
GLAST may discover some sources without corresponding galaxies they may even be brighter (see Kuhlen et al. 08 vs Springel et al. 08)



How do we know that this is a dark subhalo and not just some background source? The energy spectrum may help (Baltz et al. 2006).

point sources

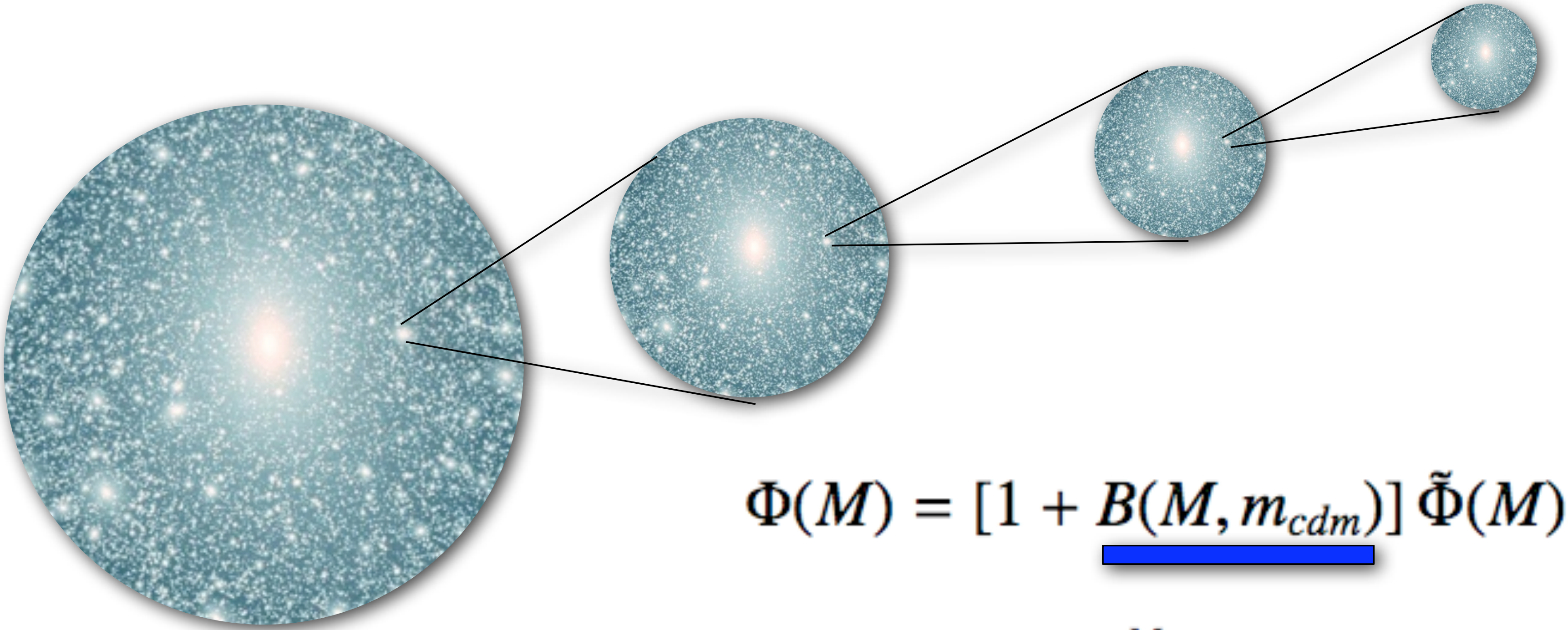
Air Cerenkov Telescopes (ACTs) like VERITAS/HESS/MAGIC and future instruments will **need to know where to point**.



point sources

$$\log(A_{eff} t \mathbf{I}_{\gamma} / \sqrt{A_{eff} t (\mathbf{I}_{\gamma} + \mathbf{I}_{bg})})$$

The substructure boost



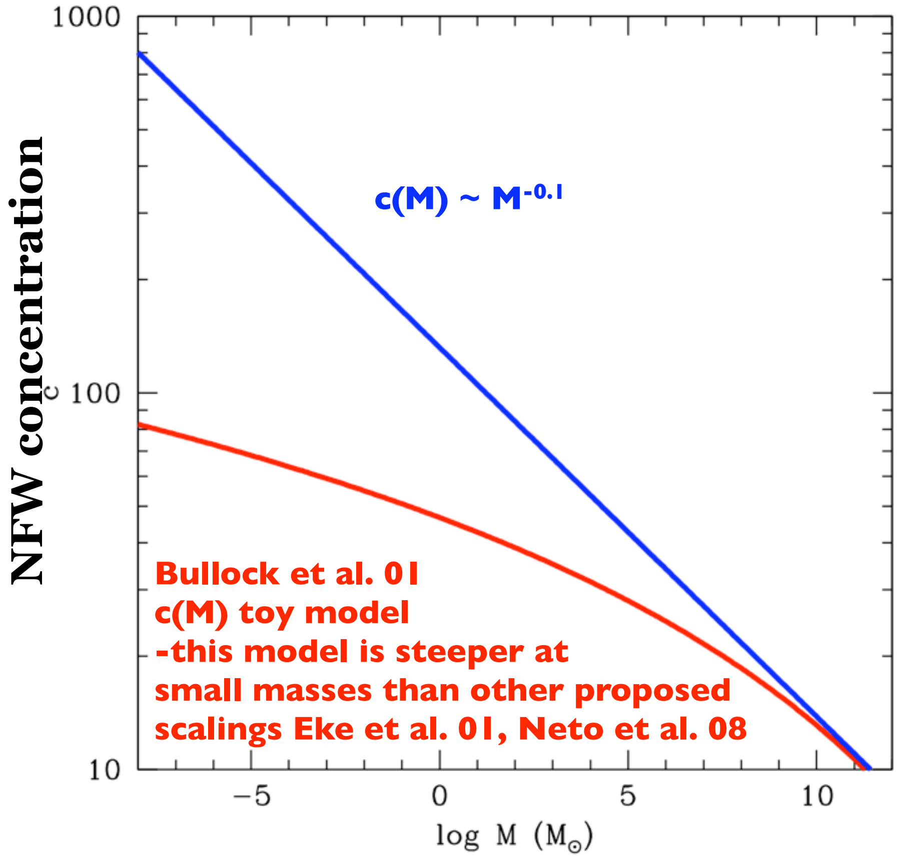
$$\Phi(M) = [1 + \underline{B(M, m_{cdm})}]\, \tilde{\Phi}(M).$$

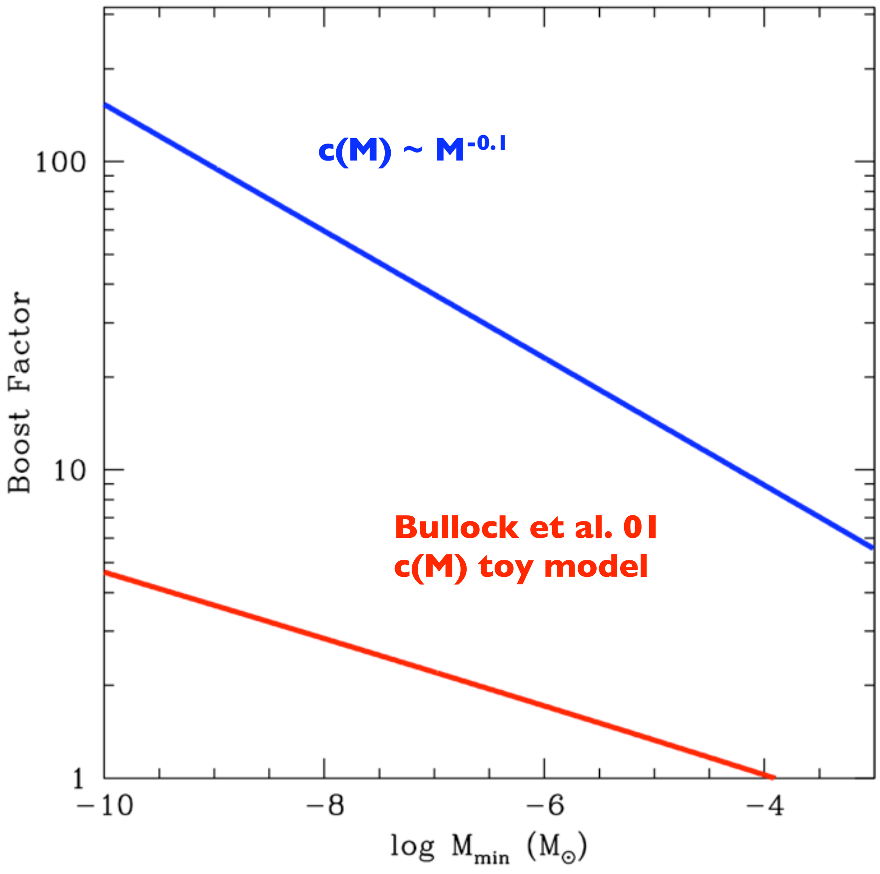
$$\underline{B(M, m_{cdm})} = \frac{1}{\tilde{\Phi}(M)} \int_{m_{cdm}}^{M} \underline{\frac{dN}{dm} \Phi(m) dm}$$

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

The substructure boost

Unfortunately, the boost factor depends sensitively on the density structure of the smallest subhalos. if c(M) maintains a power-law, then we could have boosts ~100. This seems unlikely -- most likely c(M) will roll off and give boost~5 at most.

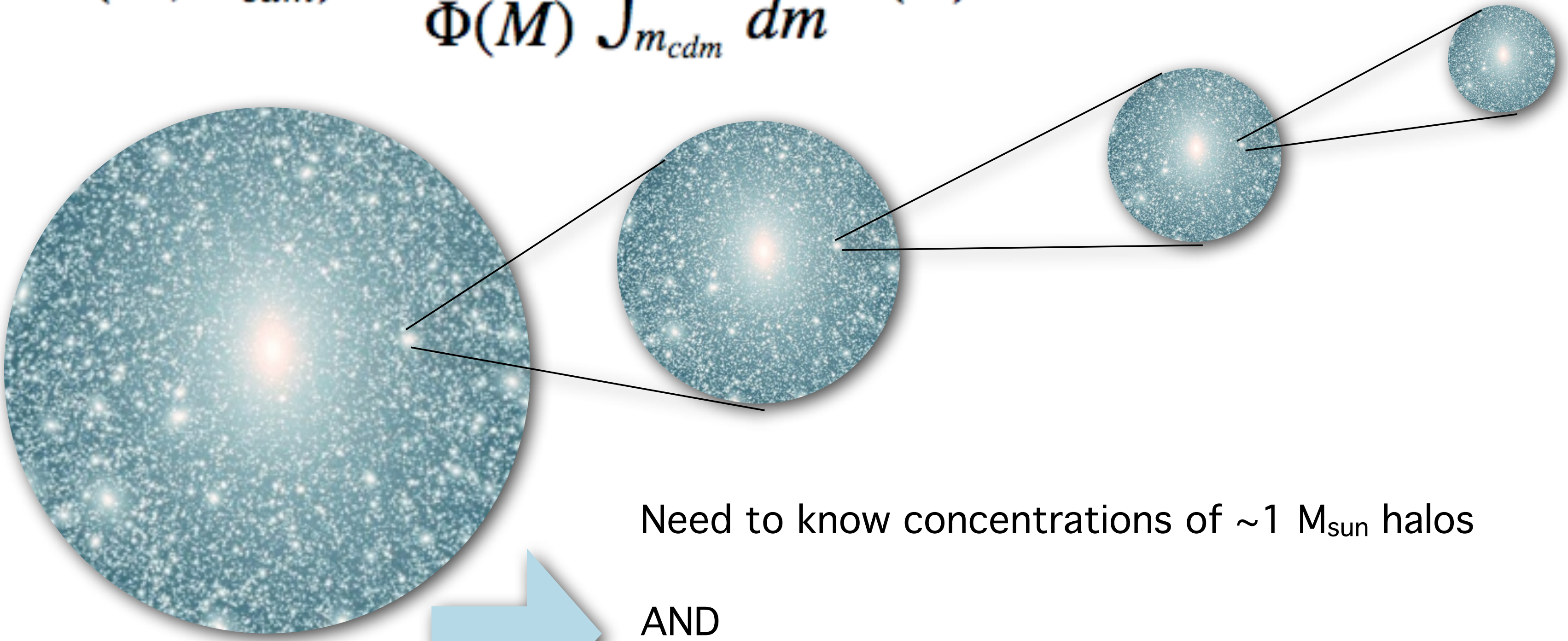




Greg Martinez et al. 2008

Boost integral is teetering on the edge of divergence at small scales....

$$B(M, m_{cdm}) = \frac{1}{\tilde{\Phi}(M)} \int_{m_{cdm}}^{M} \frac{dN}{dm}\Phi(m)dm \qquad \propto m^{-0.9}\, c(m)^{2.2}\, \mathrm{d}m$$



Need to know concentrations of ~1 M_{sun} halos

AND

Radial profile n(r) for ~ 1 M_{sun} halos (see discussion in Springel et al. 08)

End Lecture 5