Dark Matter, Small-Scale Structure, and Dwarf Galaxies

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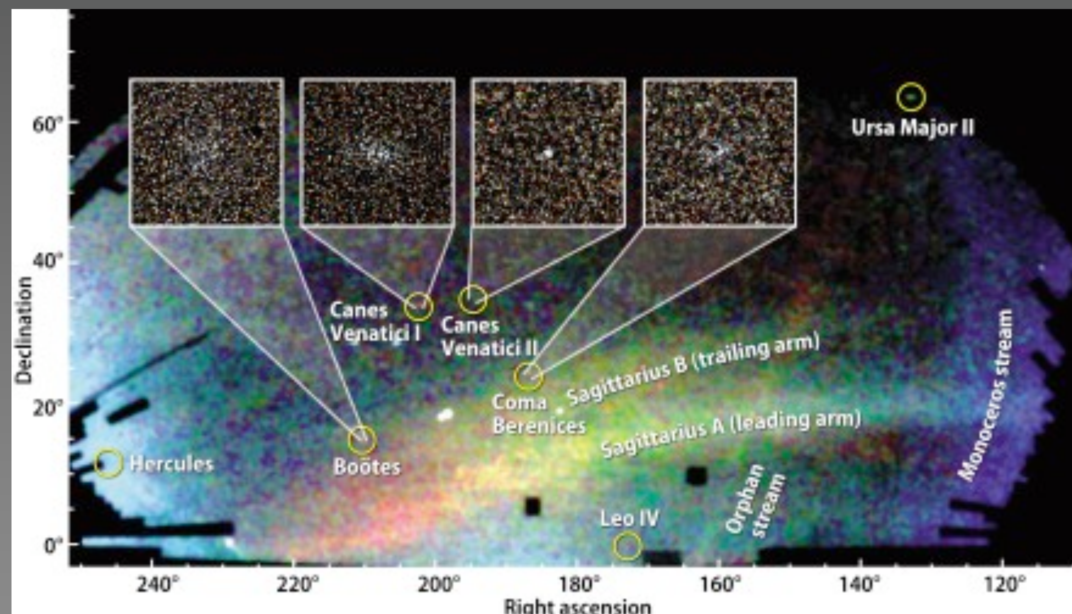
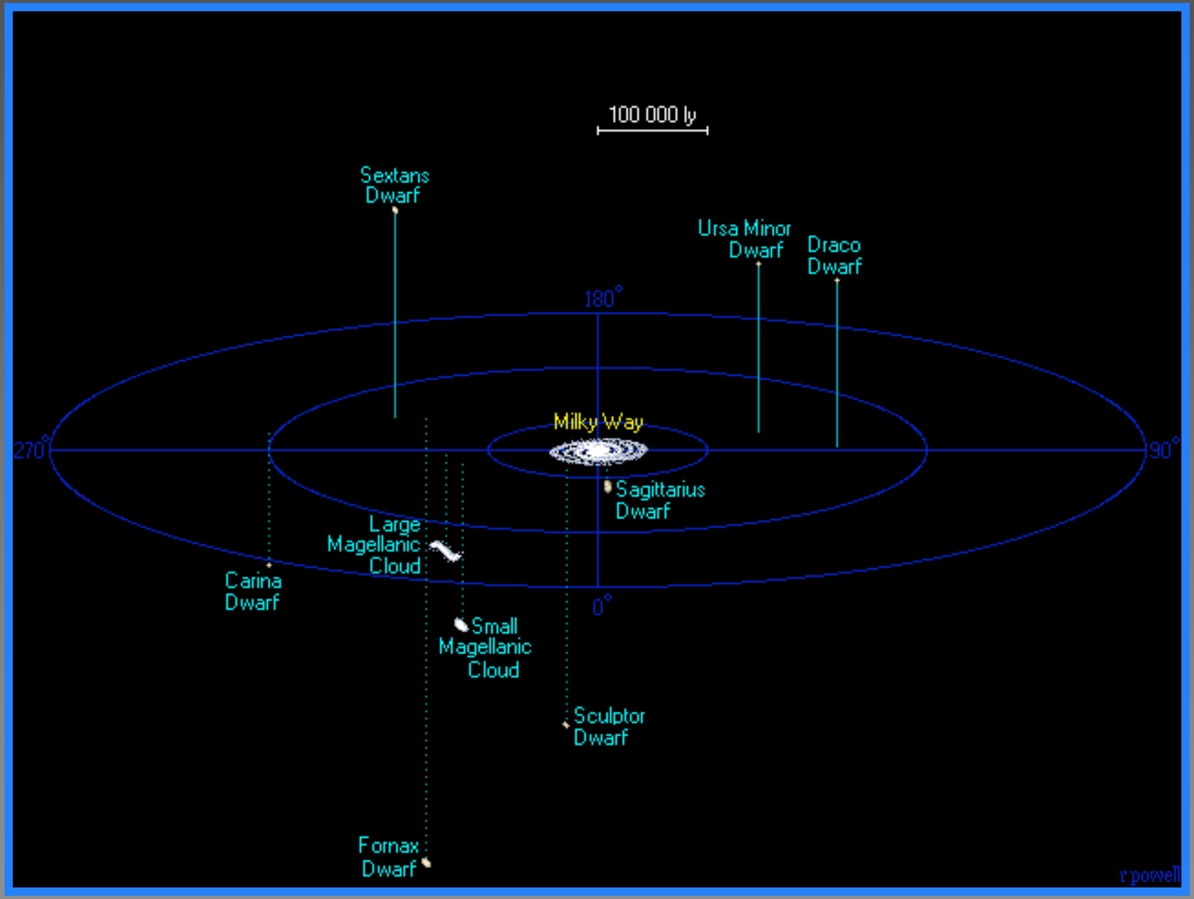
11.27.2007



Main Collaborators: James Bullock, Manoj Kaplinghat (UC Irvine)

Local Group circa 2003

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



- Possible that up to 3x more exist at these luminosities [e.g. willman et al 2004]
- About a dozen satellites of M31

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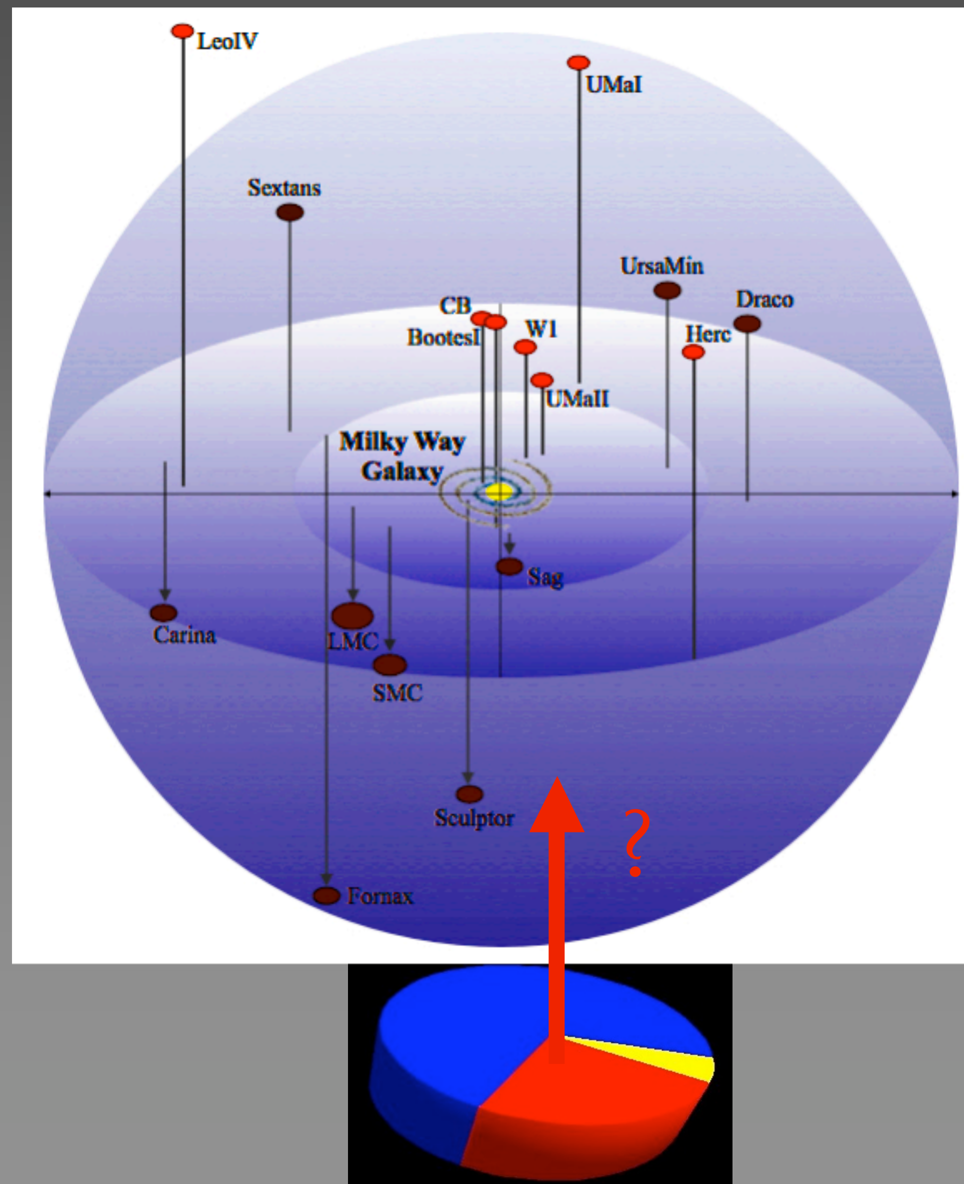
Local Group circa 2007

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
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



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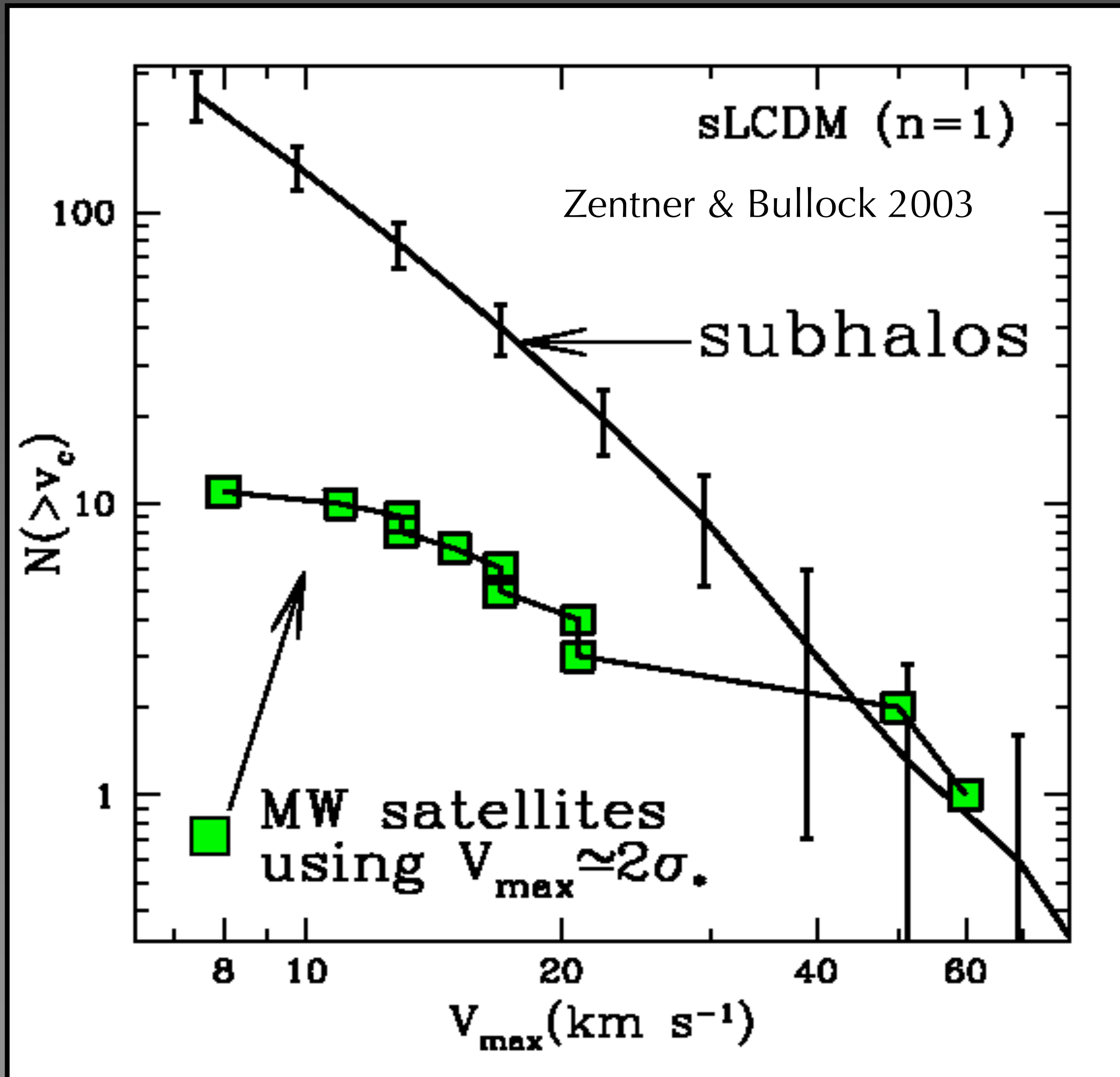
Questions to be addressed

- Is there a CDM missing satellites problem?
- What is the smallest dark matter system?
- Can we ever distinguish between cores and cusps?
- Viable alternatives to CDM? What are their phenomenological implications?

CDM: Cosmological Consequences



CDM: Predictions including ``astrophysics"

We are seeing:

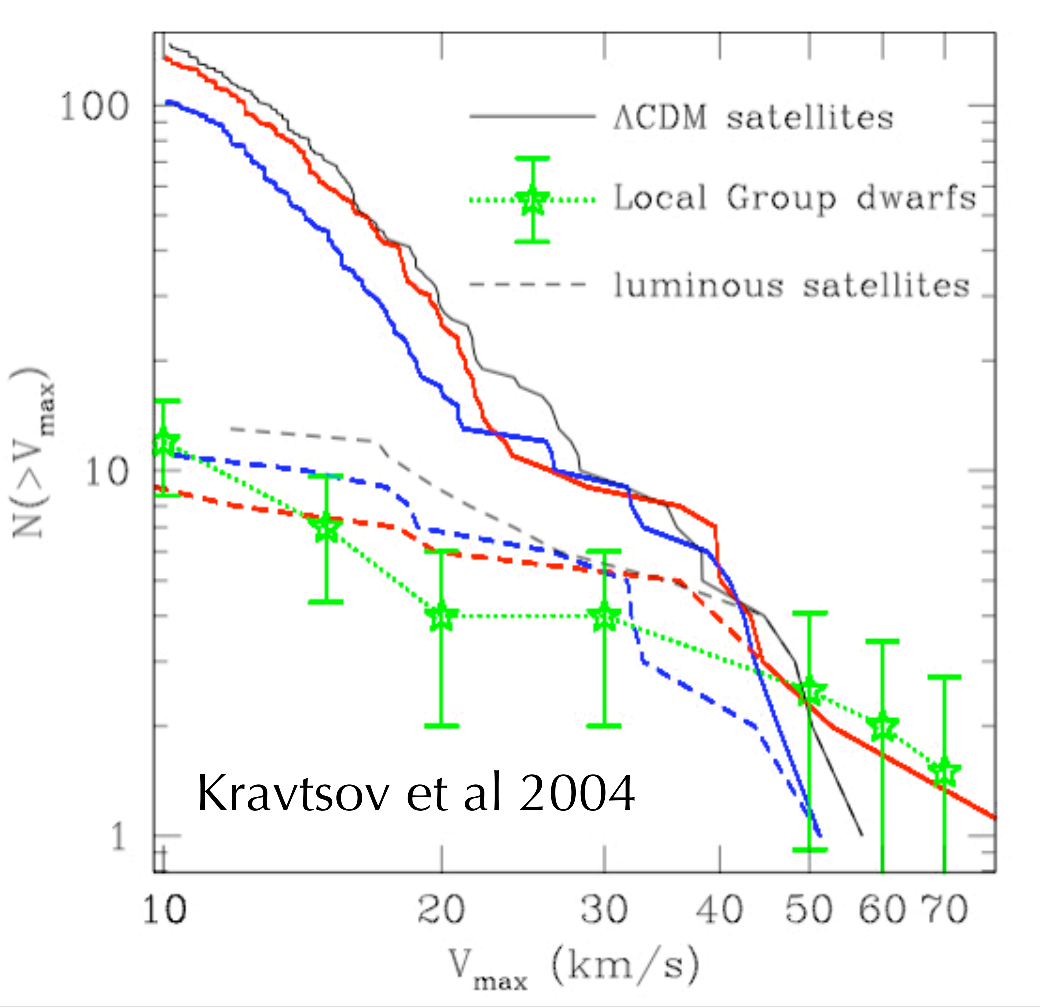
1) Earliest Forming halos

2) Largest before capture

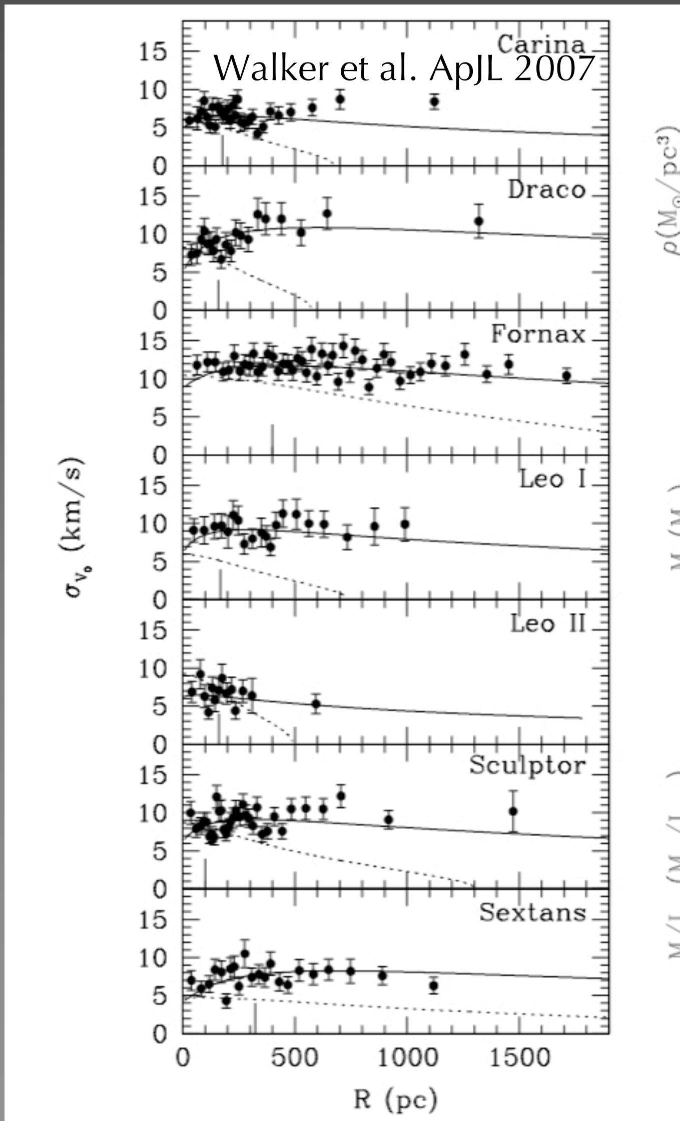
3) Most massive today

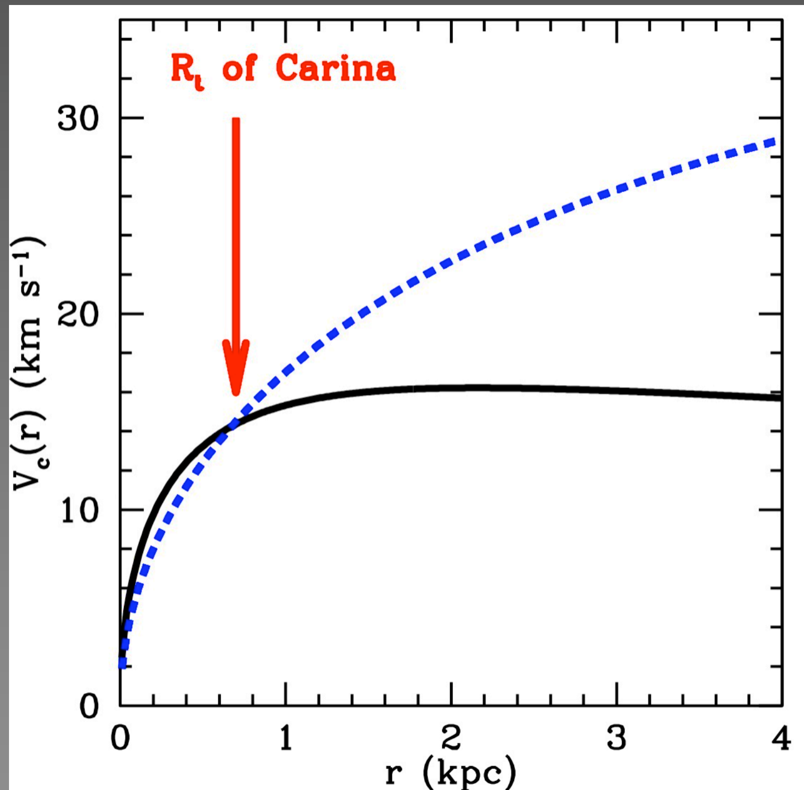
4) Some combination

Bullock et al. 2001; Chiu, Gnedin, Ostriker 2001; Somerville 200; Stoehr et al. 2002; Hayashi et al. 2003; Kravtsov et al. 2004; Gnedin & Kravtsov 2006; Diemand et al. 2006

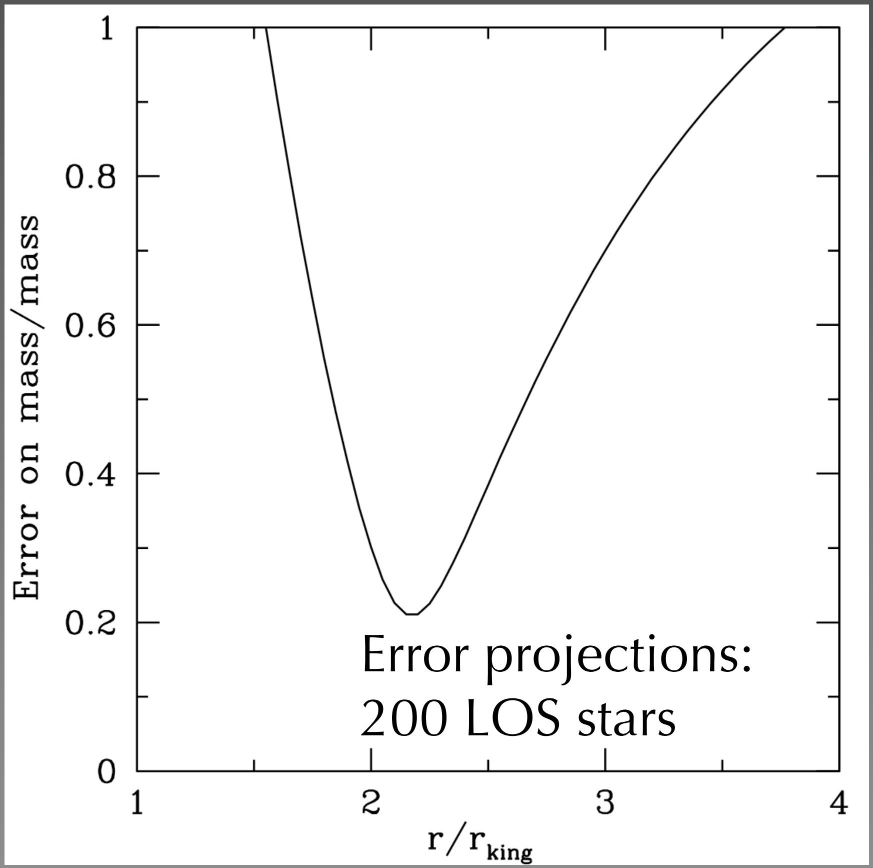


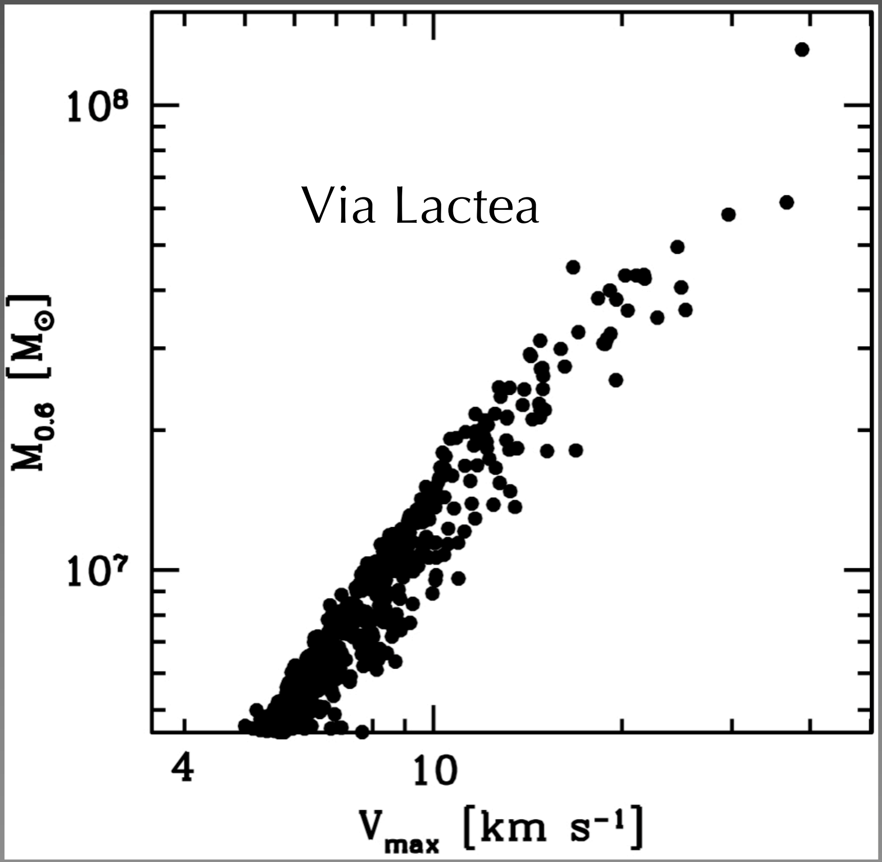
Maximum Circular Velocities?





Characteristic Mass of Satellites





0.6 kpc appropriate scale to characterize well-known MW satellites

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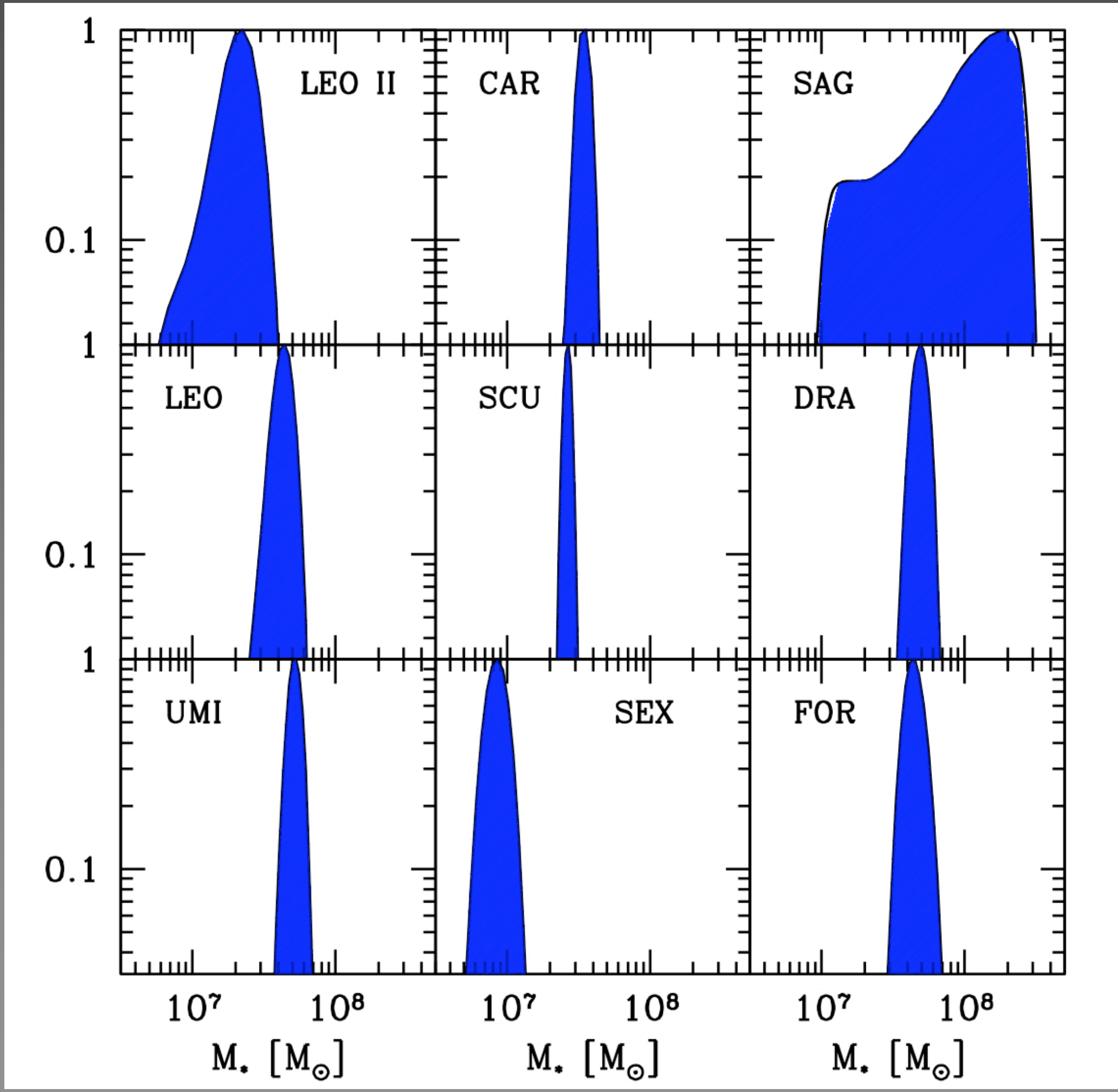
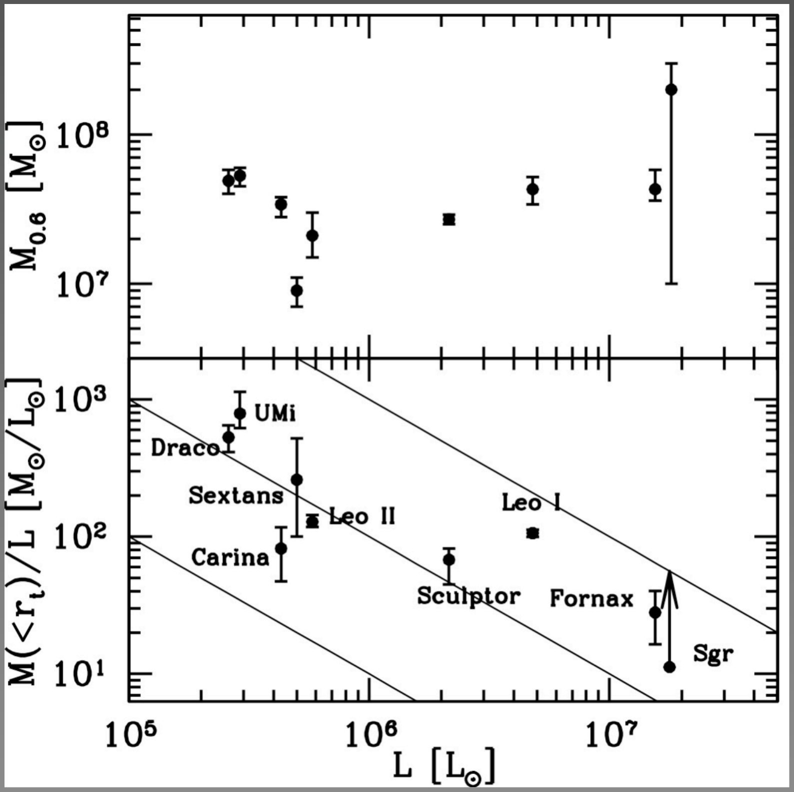
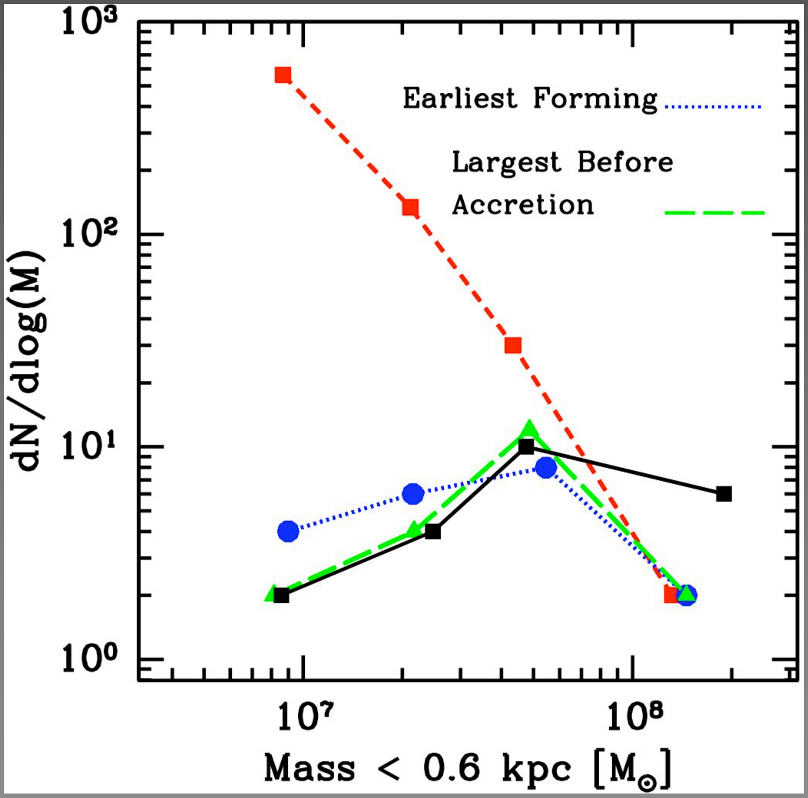
Mass Constraints: Take I



Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau ApJ 2007

Implications: Take I

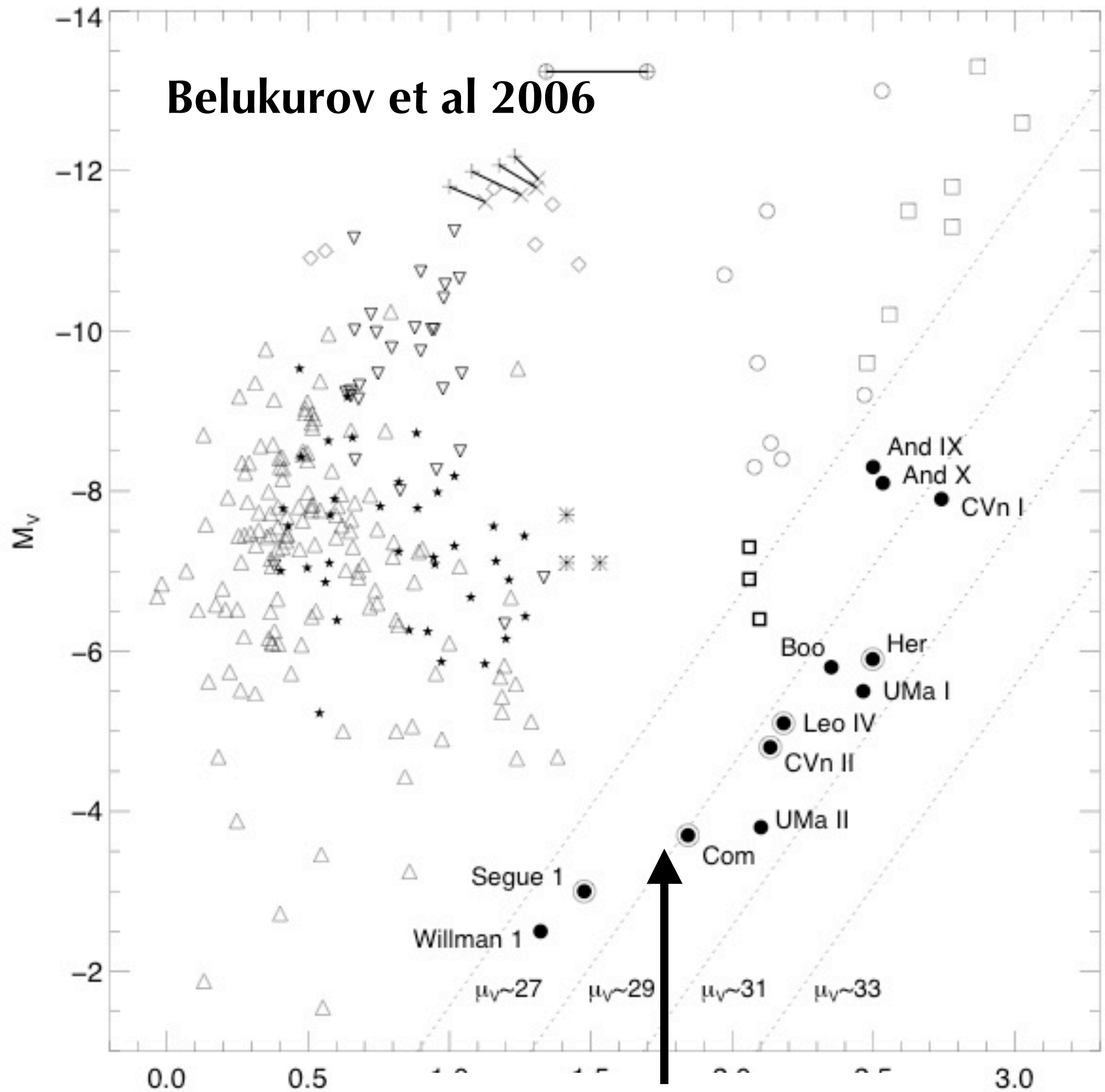




Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau ApJ 2007

Precise Mass function rules out most massive z=0 hypothesis

Belukurov et al 2006



A Pair of Boötes: A New Milky Way Satellite

S. M. Walsh[1], H. Jerjen[1], B. Willman[2]

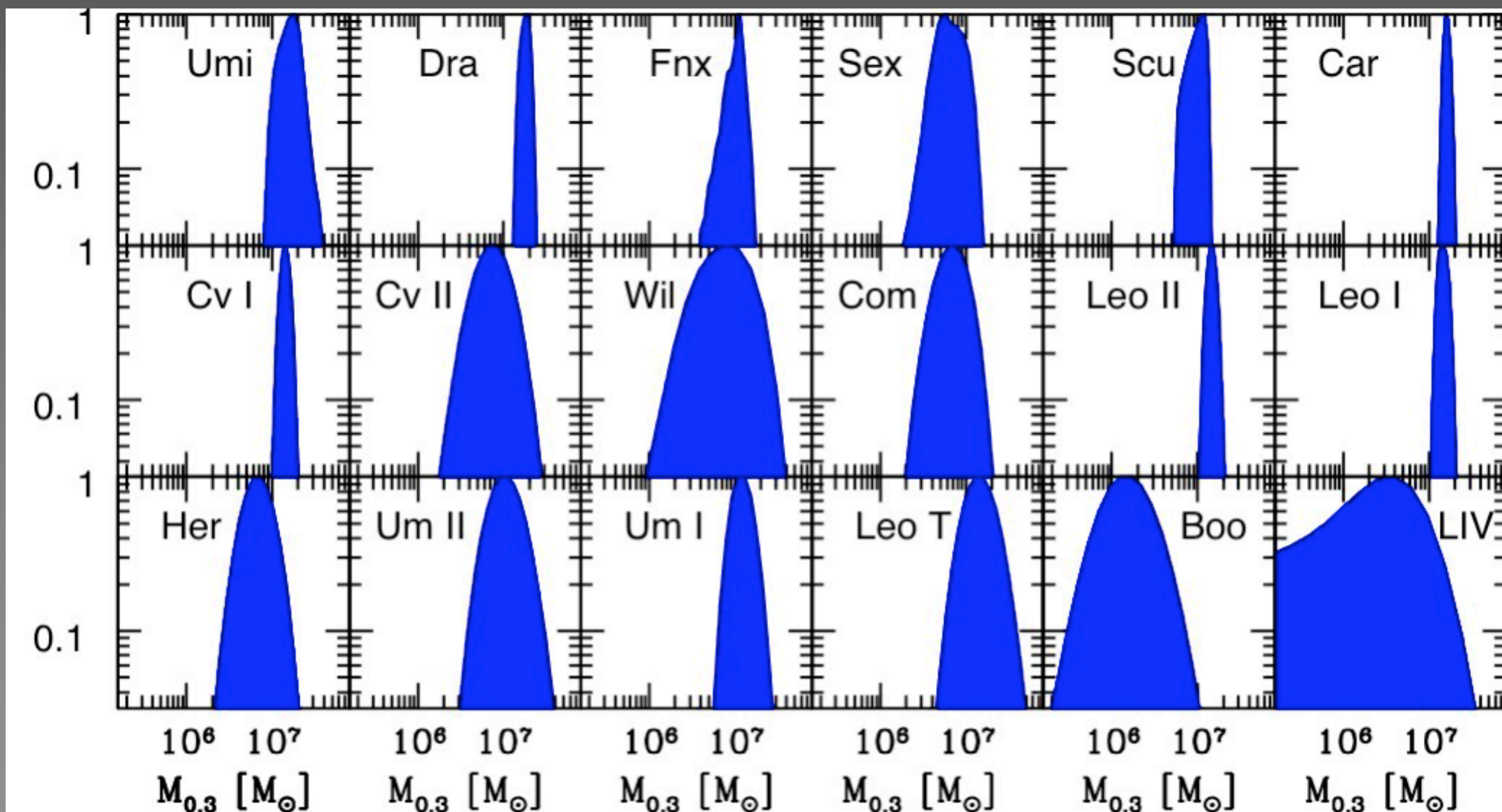
10 May 2007

ABSTRACT

As part of preparations for a southern sky search for faint Milky Way dwarf galaxy satellites, we report the discovery of a stellar overdensity in the Sloan Digital Sky Survey Data Release 5, lying at an angular distance of only 1.5 degrees from the recently discovered Boötes dwarf. The overdensity was detected well above statistical noise by employing a sophisticated data mining algorithm and

Mass Constraints: Take II

The Old and the New



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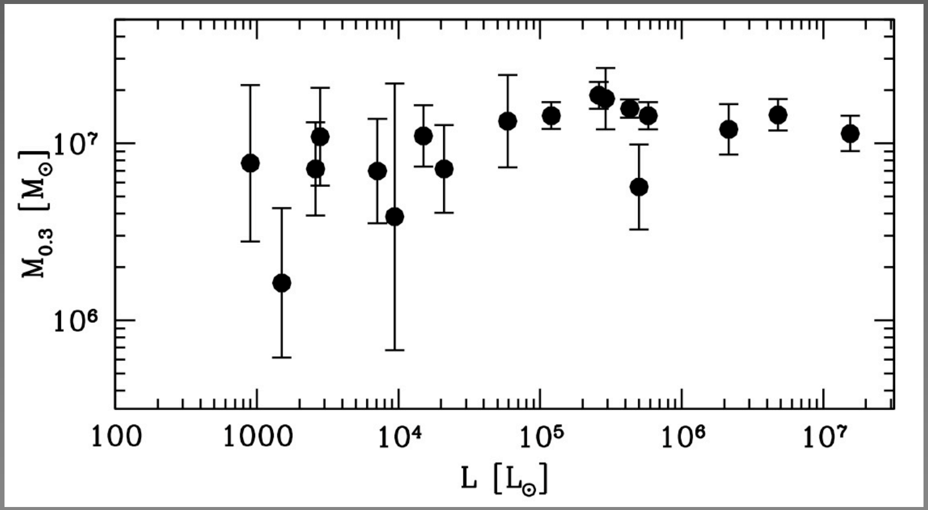
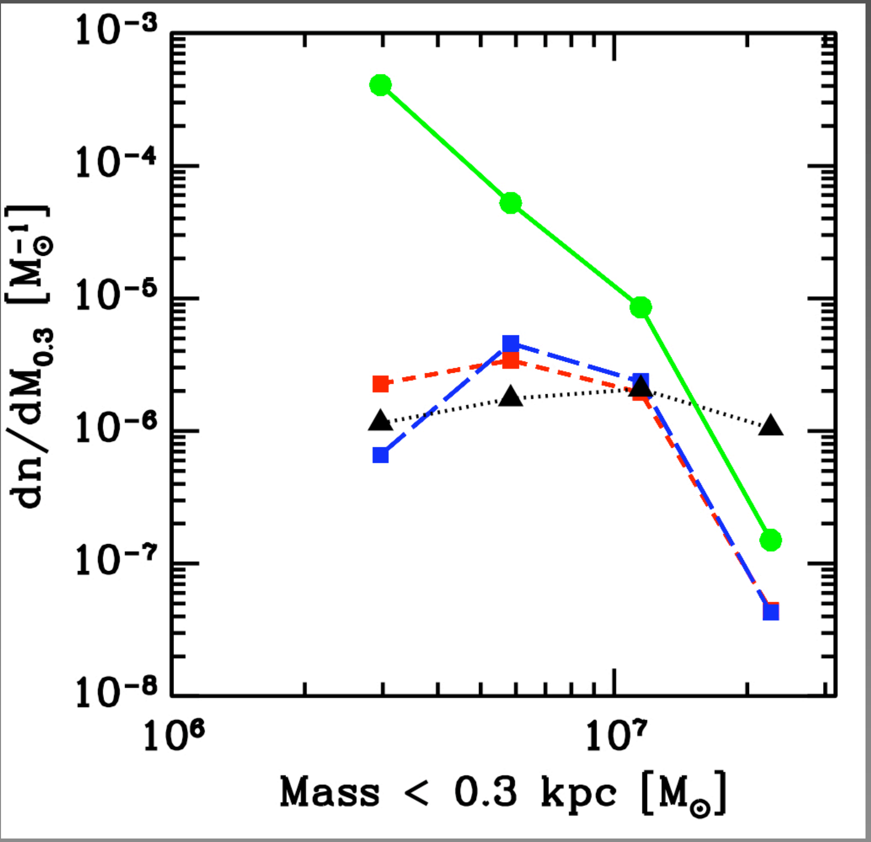
Implications: Take II



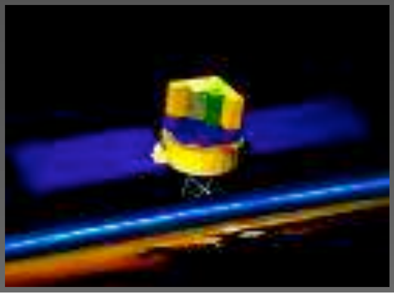
Strigari et al in prep

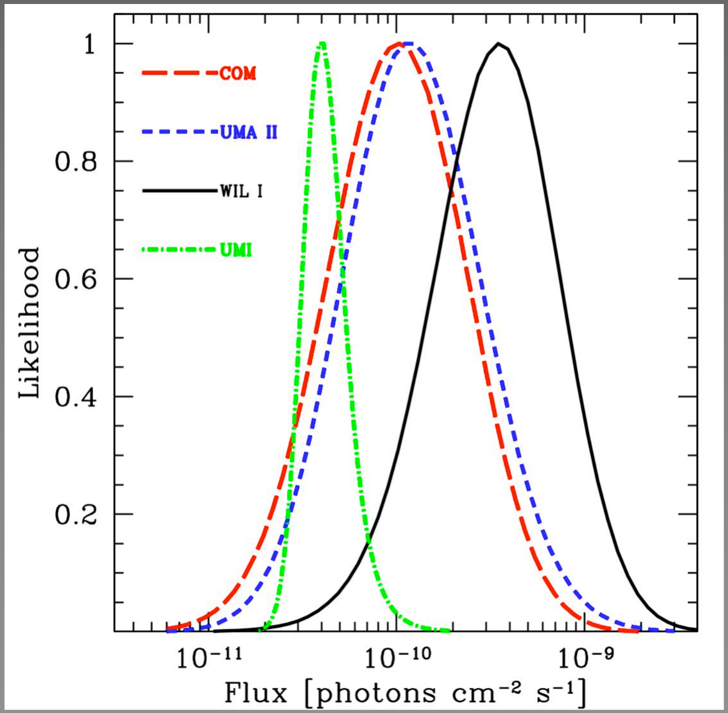


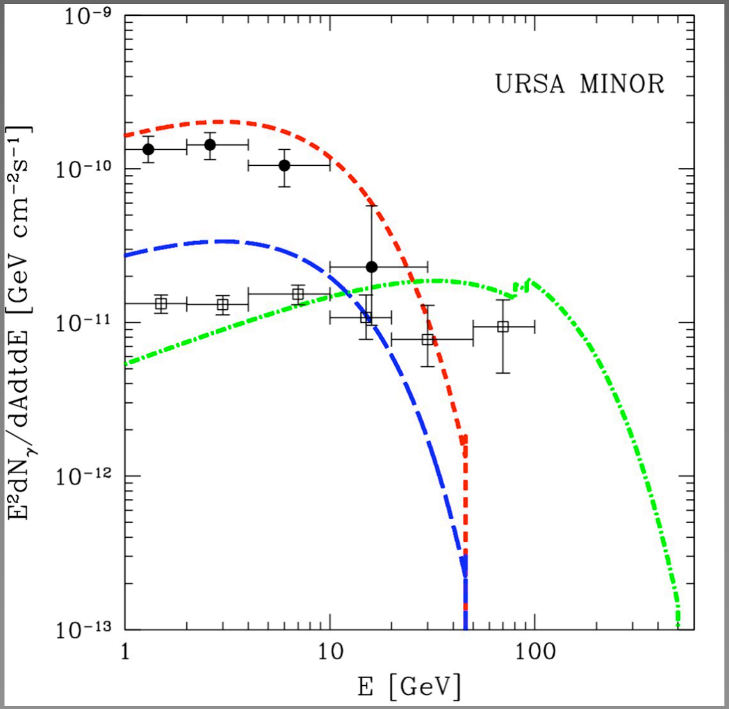
A characteristic mass scale for Milky Way satellites?

The most dark matter dominated galaxies: Willman 1, Coma, Ursa Major II

These galaxies may be visible in gamma-rays with GLAST

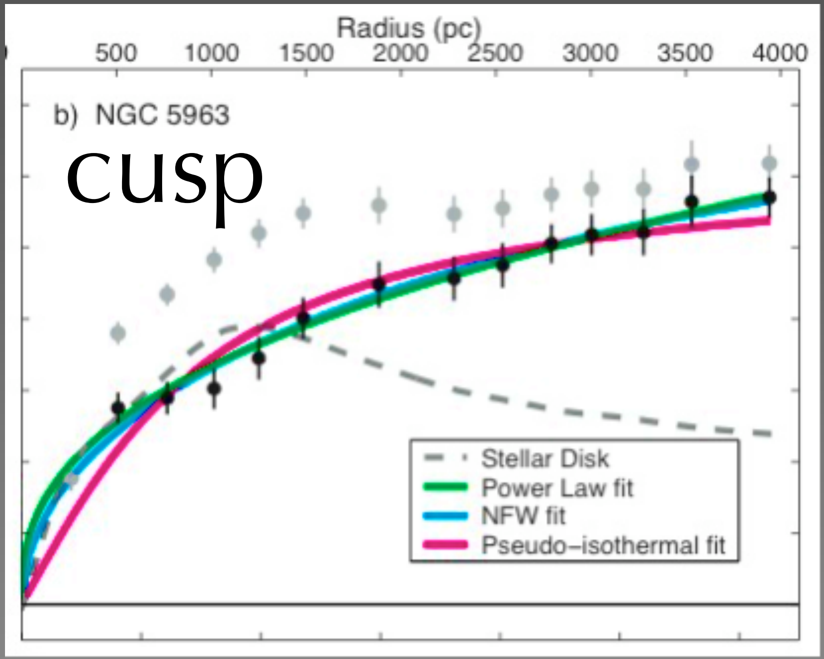


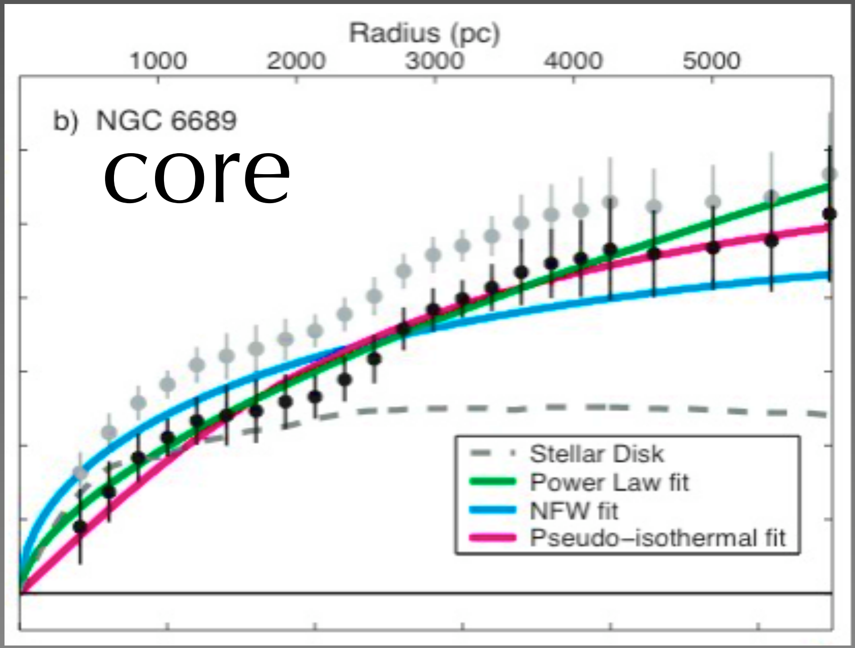




Dark substructure `boosts' the fluxes

CDM: Cosmological Consequences





Simon et al. 2005, Kuzio de Naray et al. 2006

Low mass dark matter halos are less `cuspy' than predicted in CDM

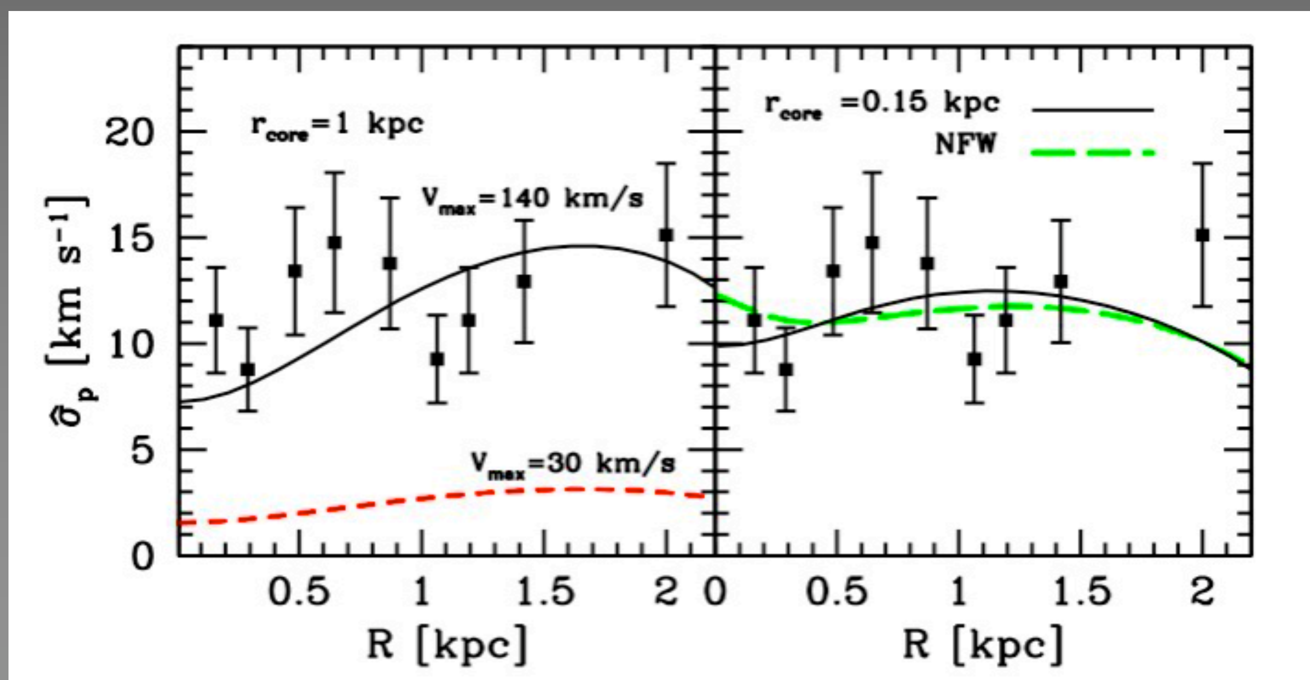
Dwarf kinematics (Circa 2005)

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

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*

Are survival of globular clusters in Fornax a sign of a kpc-sized core?

Gilmore et al 2007 find no- dSph requires the existence of central cusps, and there is a characteristic dark matter core density



Strigari et al. 2006

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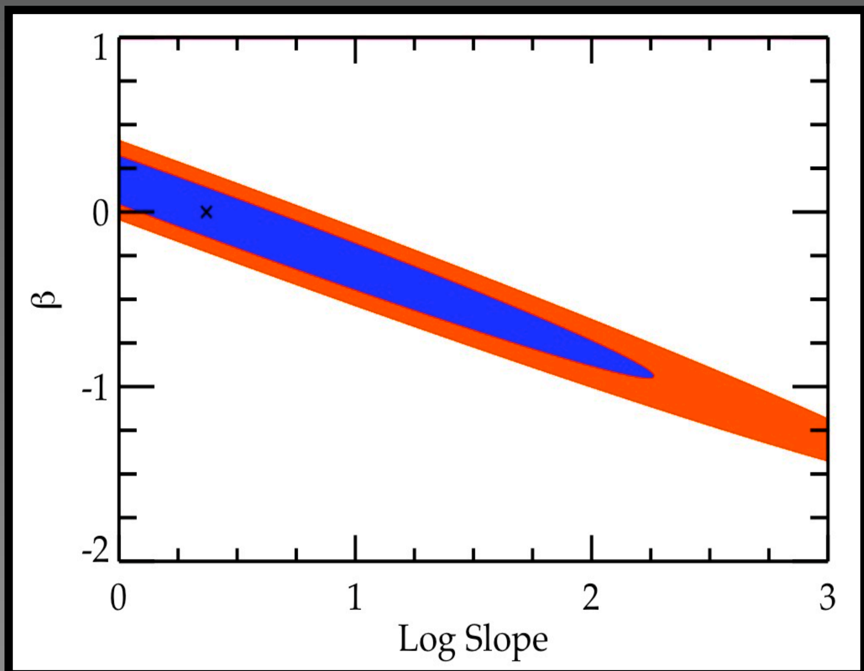
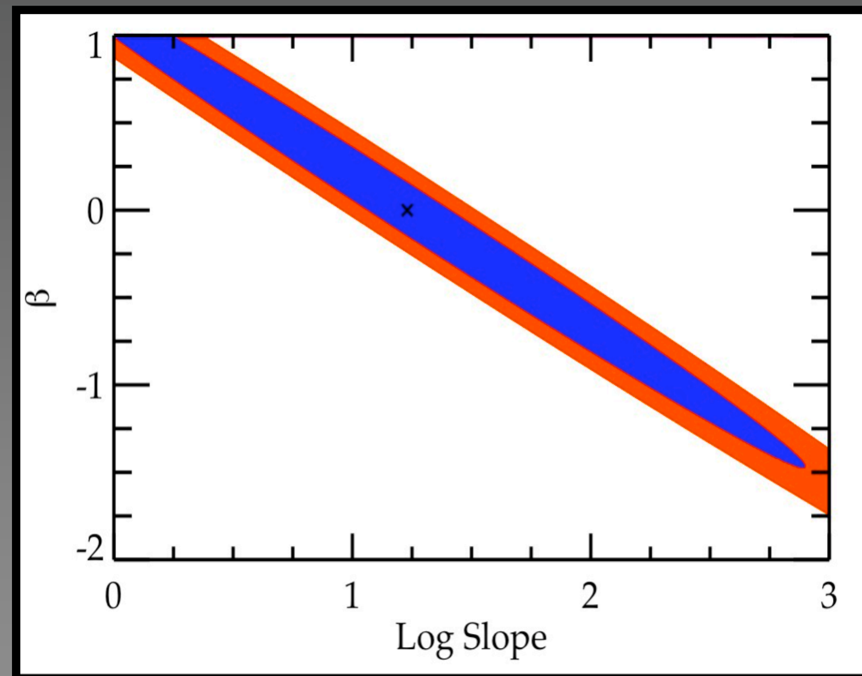
What can we learn from dwarfs?

Velocity Anisotropy



Truth = core



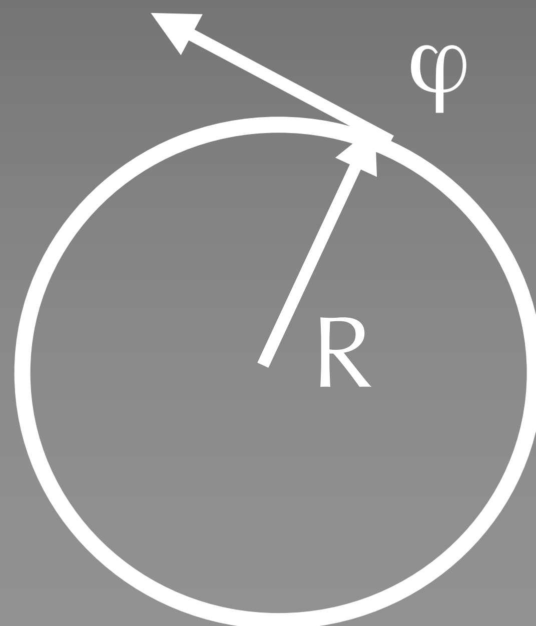
Truth = cusp

Proper Motions

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

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

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

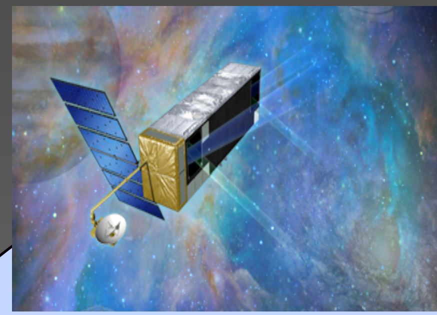


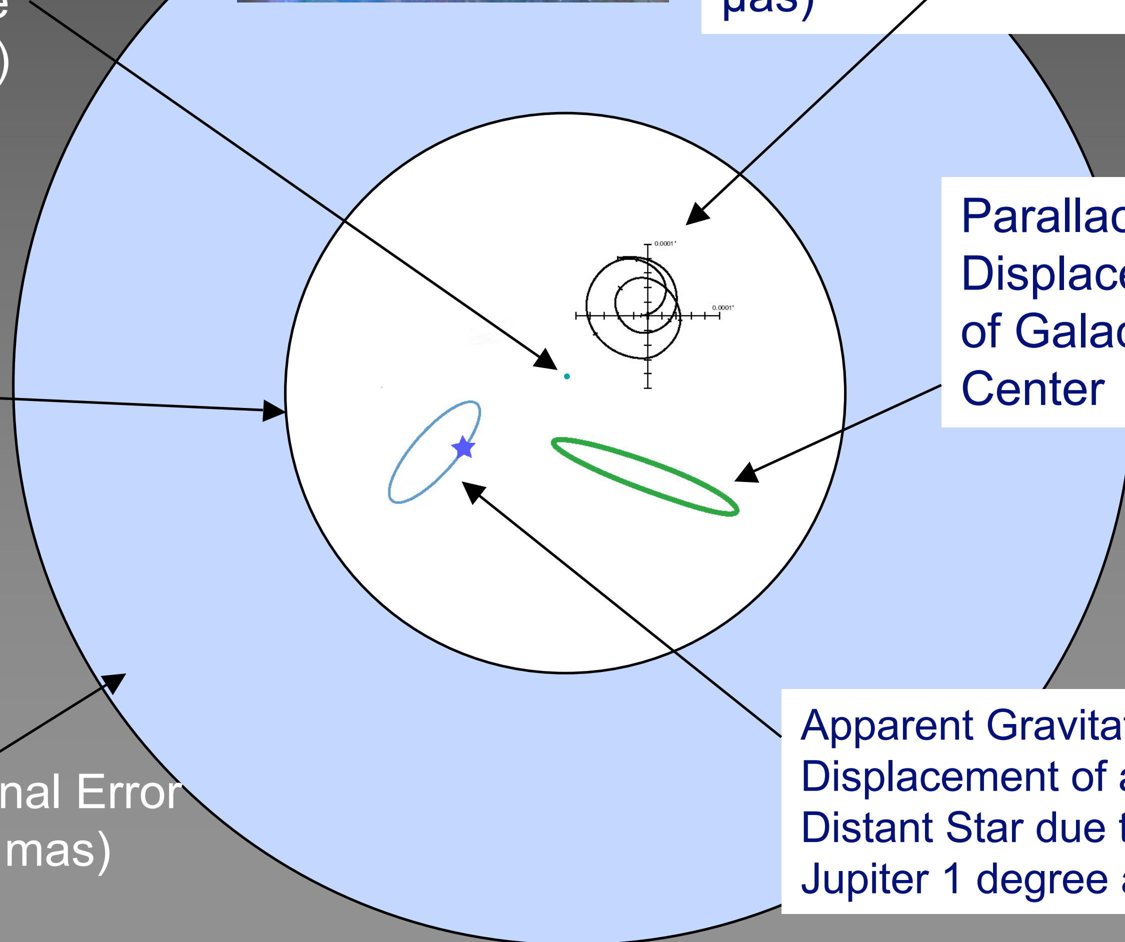
- Require accuracy on stellar transverse velocities of 5 km/s
- At < 100 kpc, this corresponds to accuracy 10 micro-arcseconds/yr

SIM PlanetQuest (Space Interferometry Mission)

Astronomy = “star naming”

Astrometry = “star measuring”

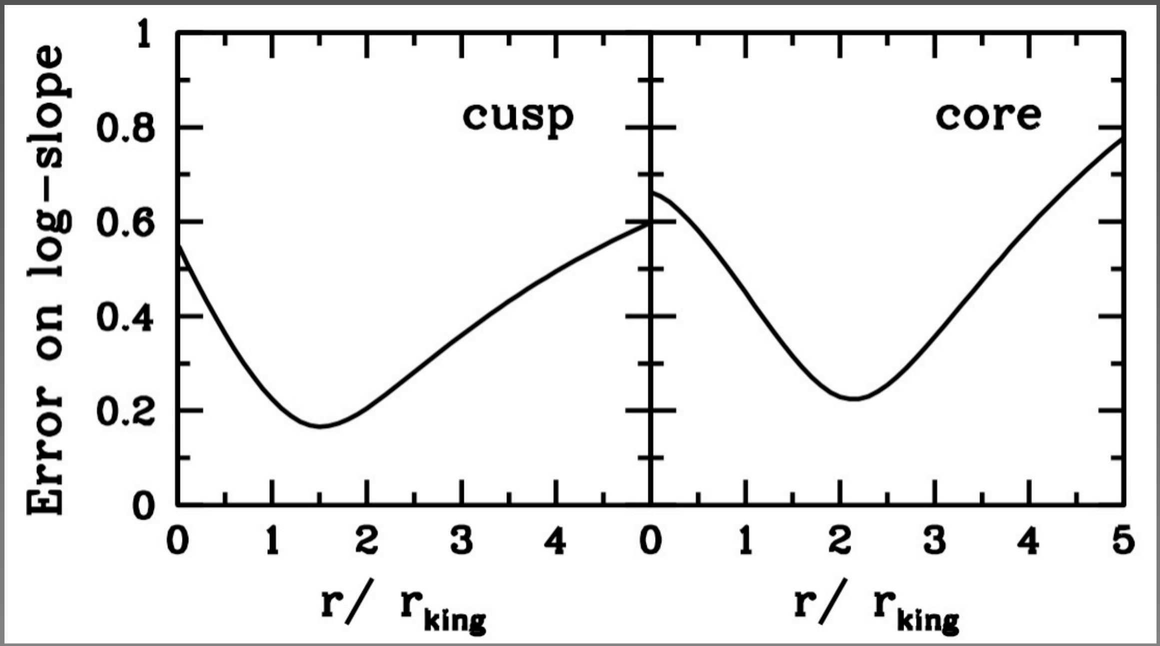




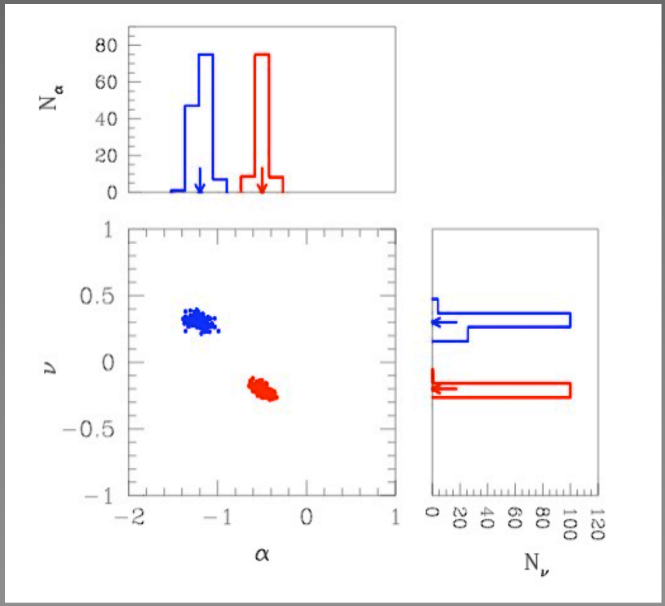
Adapted from: http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm

Constraints with SIM

Strigari, Bullock, Kaplinghat ApJL 2007

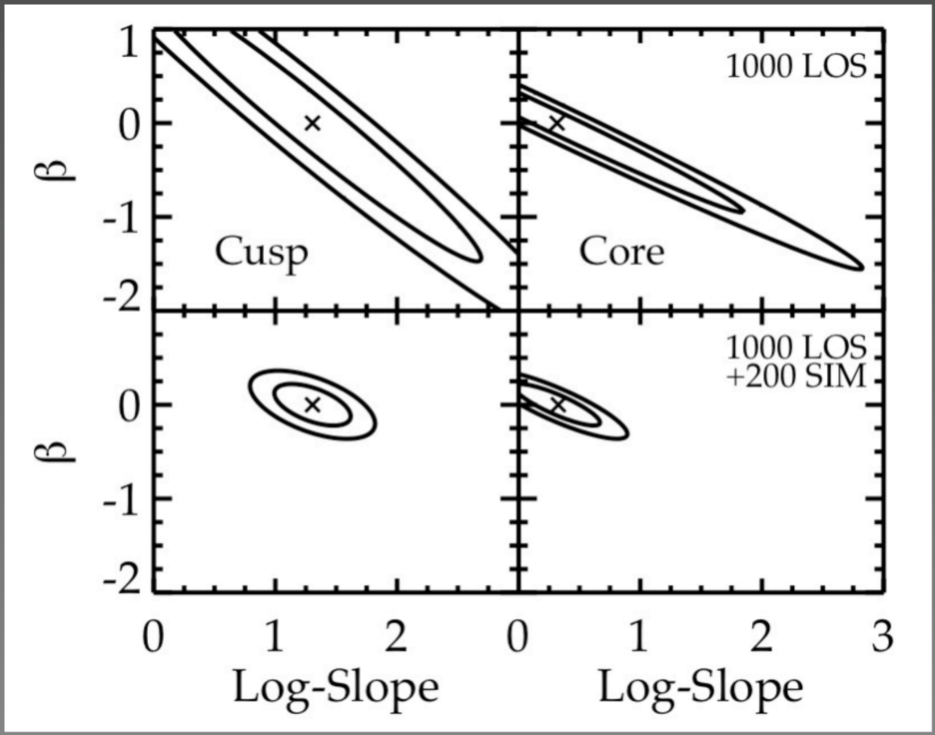


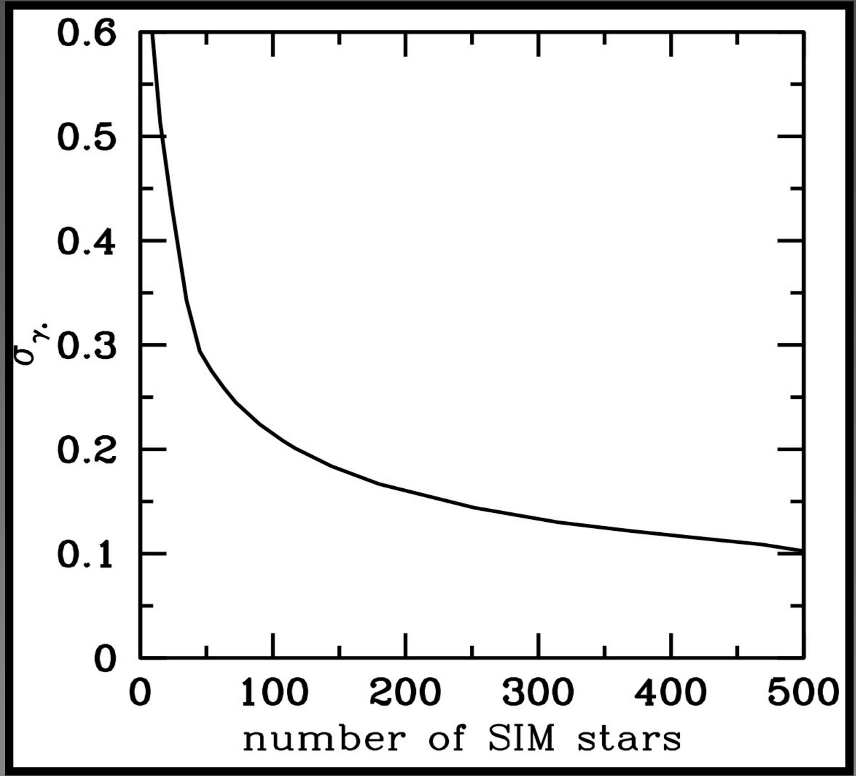
(Compare to Wilkinson et al 2000)



Inner slope is never well-constrained. However, log-slope at several hundred pc is constrained. *<u>This is sufficient to distinguish cores and cusps.</u>*

Distinguishing Cores from Cusps

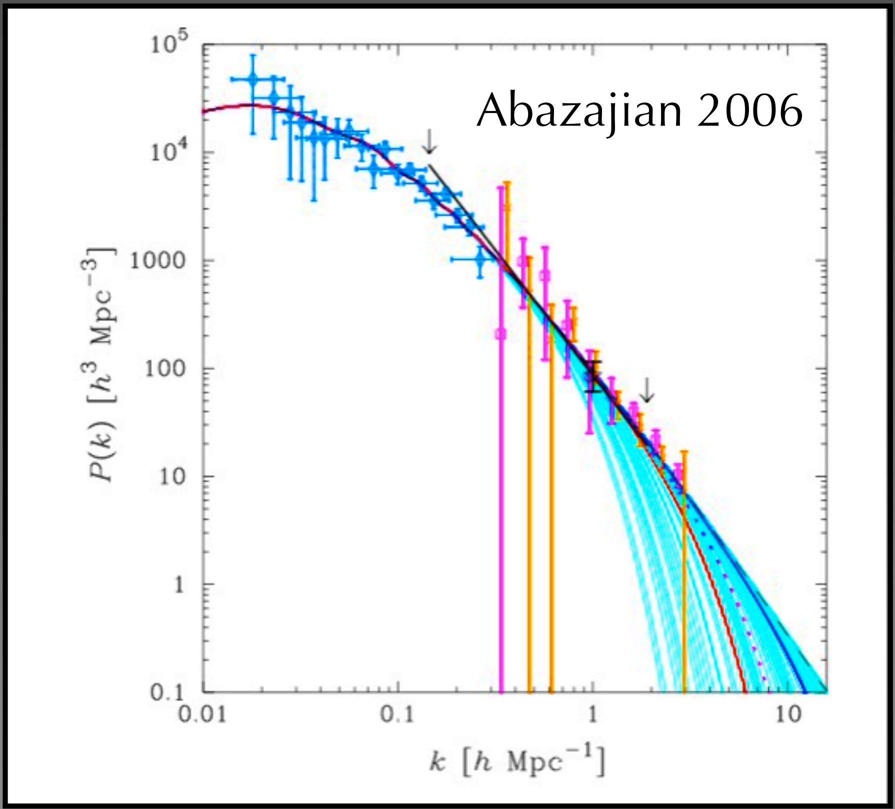


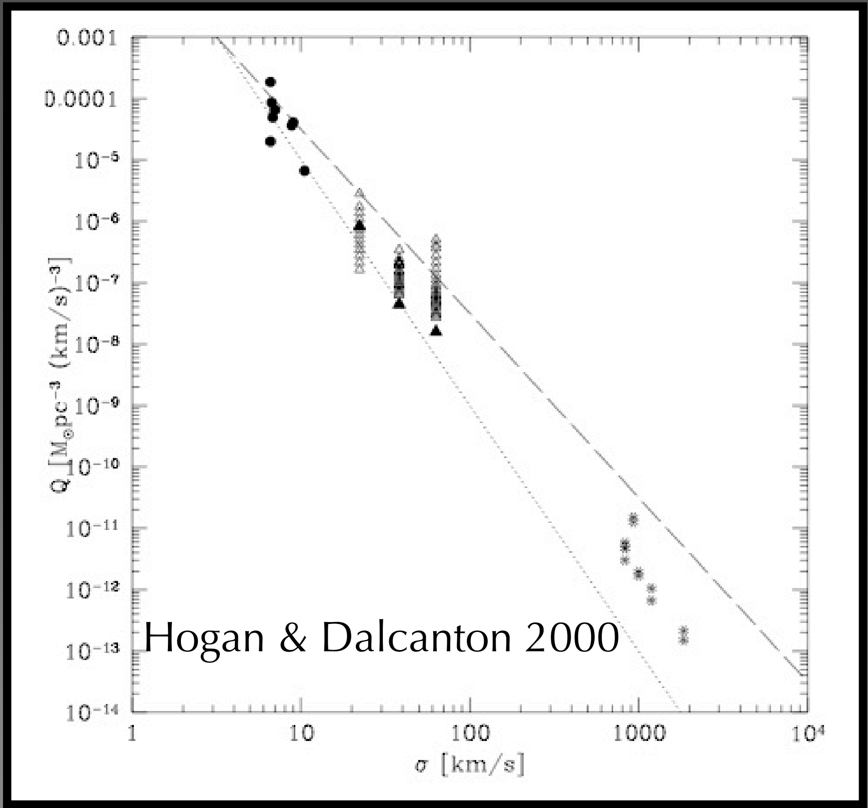


Strigari, Bullock, Kaplinghat ApJL 2007

SIM key project would entail 1000 hrs of observing time and 200 stars from multiple dSphs

Warm Dark Matter





Seljak et al 2006, Viel et al 2006 find $m_{wdm} > 14$ keV

Spergel & Steinhardt 2000, Ostriker and Steinhardt 2003, Bode, Ostriker, & Turok 2001, Cen 2000, Sanchez-Salcedo 2003

[Tremaine-Gunn Bound]

$$Q \approx 5 \times 10^{-4} \left(\frac{m}{keV} \right)^4 M_{sun} pc^{-3} (km/s)^{-3}$$

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

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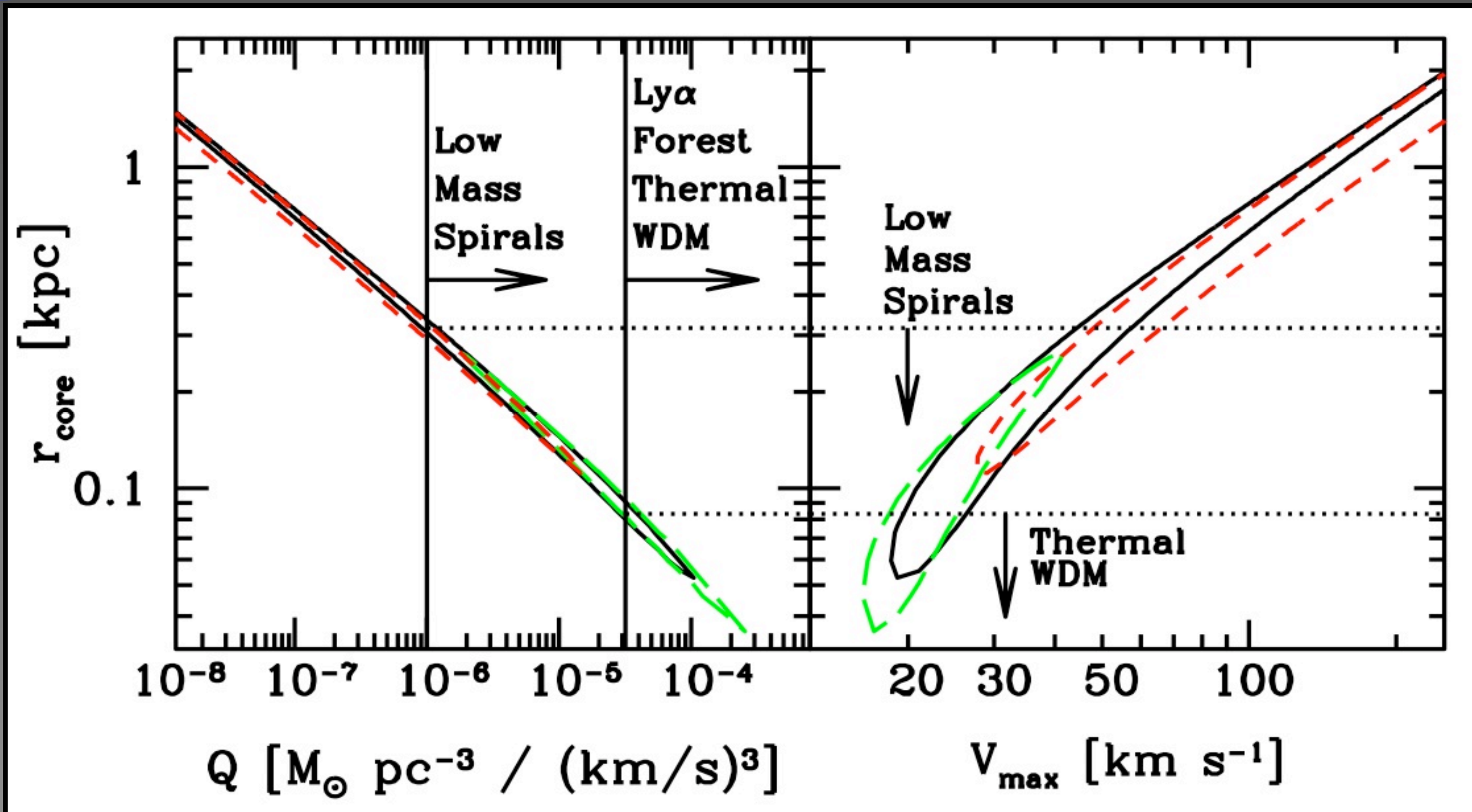
Warm Dark Matter

Fornax



Ly-alpha + velocity dispersion imply small WDM cores

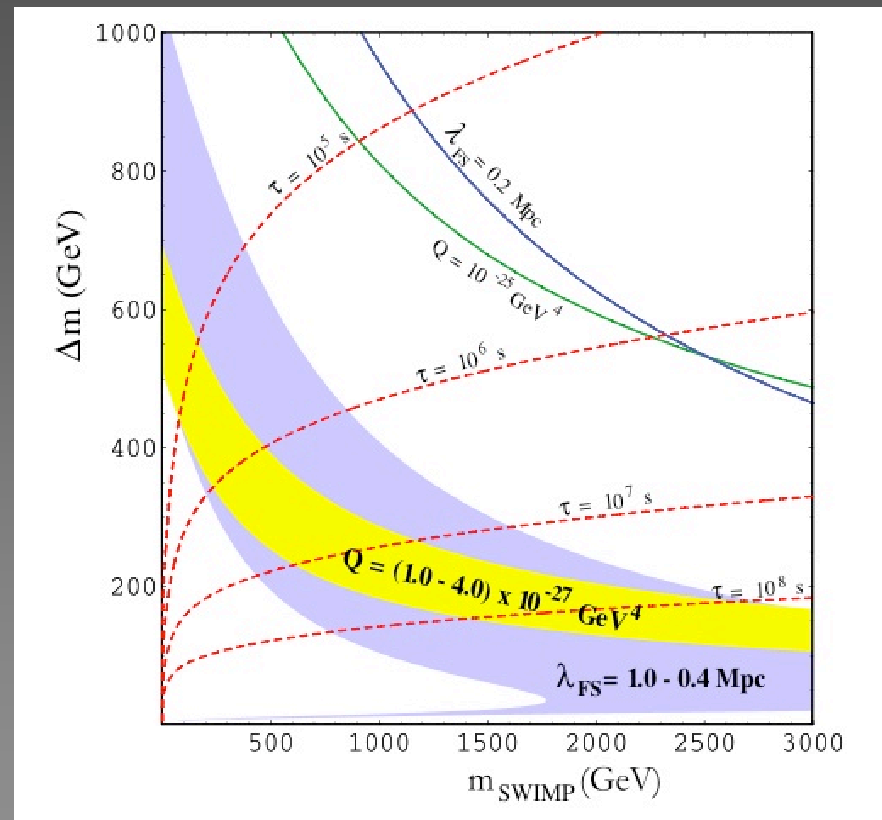
-Strigari et al ApJ 2006

Dark Matter from Early Decays

- ➢What if dark matter freezes-out, then decays to a `superweakly' interacting particle? [Feng, Rajaraman, Takayama 2003]
- ➢Large velocity at production: 0.1-1c
- ➢Free-streaming scale: $Q^{-1/3}$
- ➢Reduced Phase-Space Density

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

See also Kang, Kawasaki, Steigman 1993; Starkman, Kaiser, Malaney 1994



Cembranos et al., Kaplinghat (2005)

Is dark matter from decays just a one-parameter family of models?

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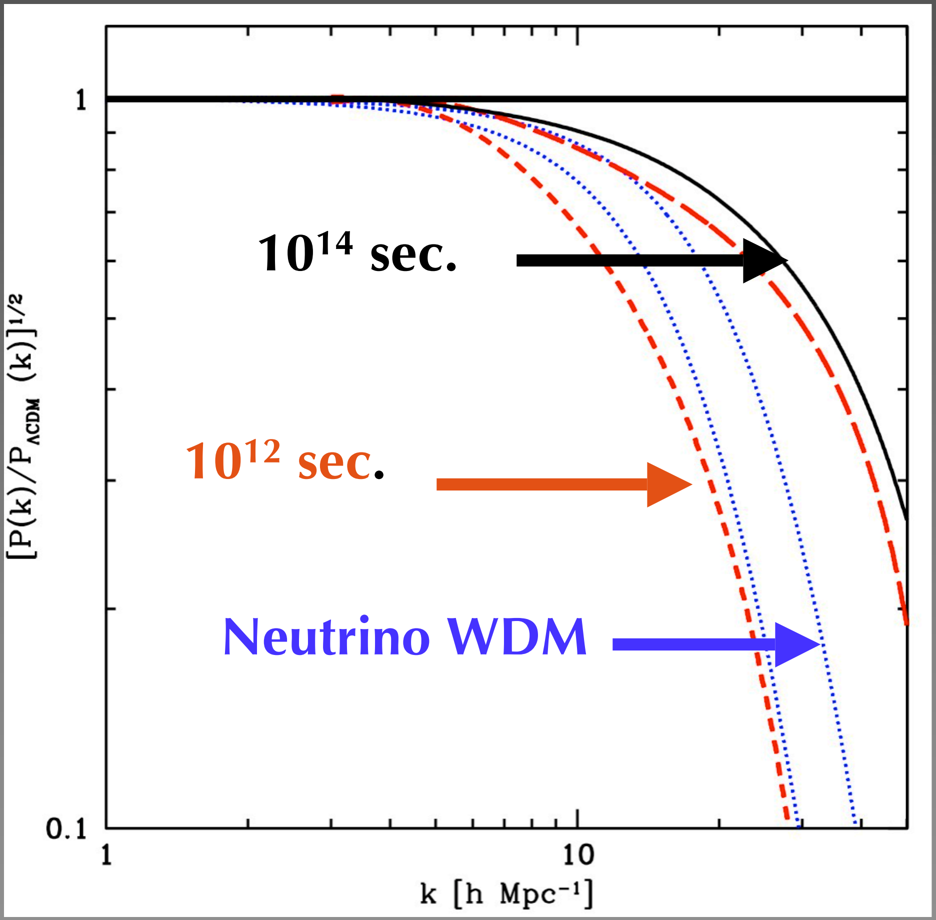
Dark Matter from Late Decays

➢Mass splitting is a free parameter: what if they are of order GeV? (Universal Extra Dimensions)

➢Free-streaming scale now depends on the lifetime: (Meta-CDM)

Distinguishing between cold and `warm' dark matter now requires separate investigation of dwarf galaxies and LSS

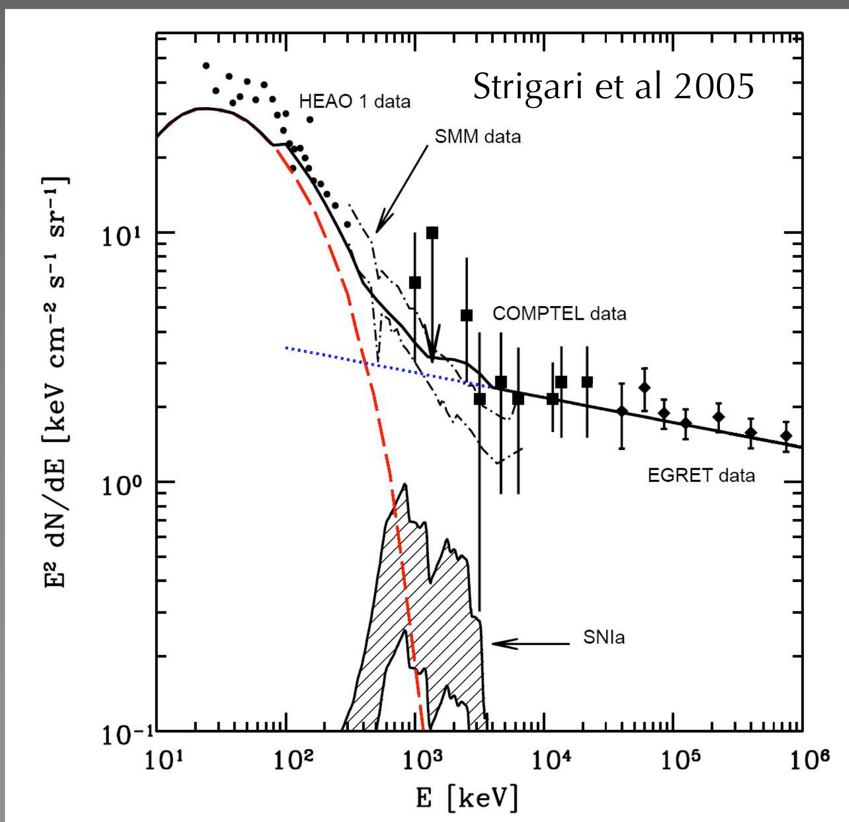


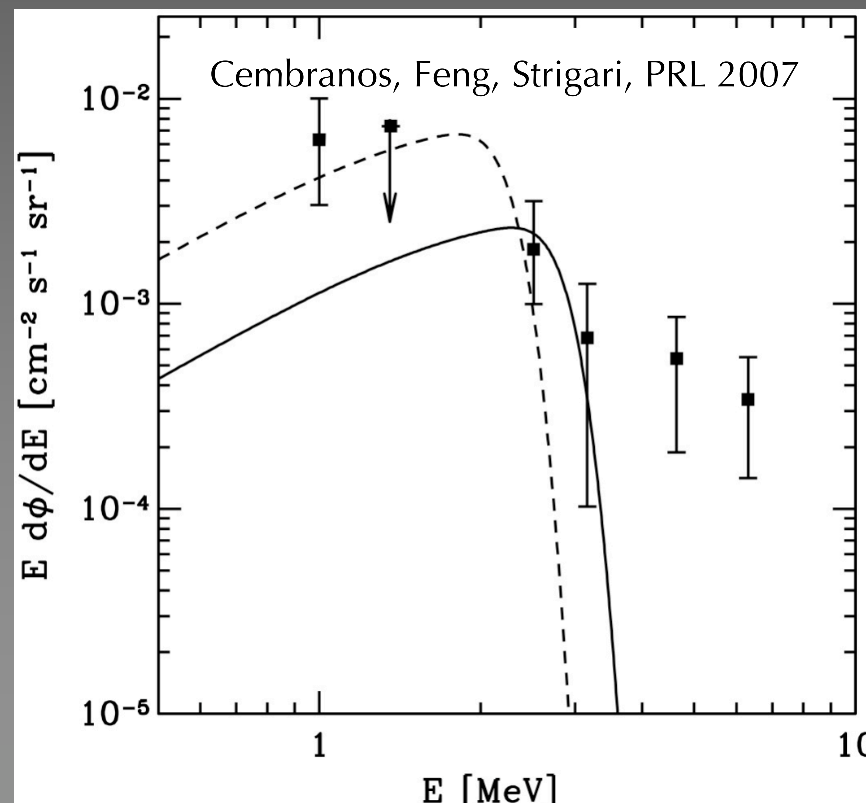
Strigari, Kaplinghat, Bullock PRD 2006

MeV gamma-ray background: Are WIMPs stable?

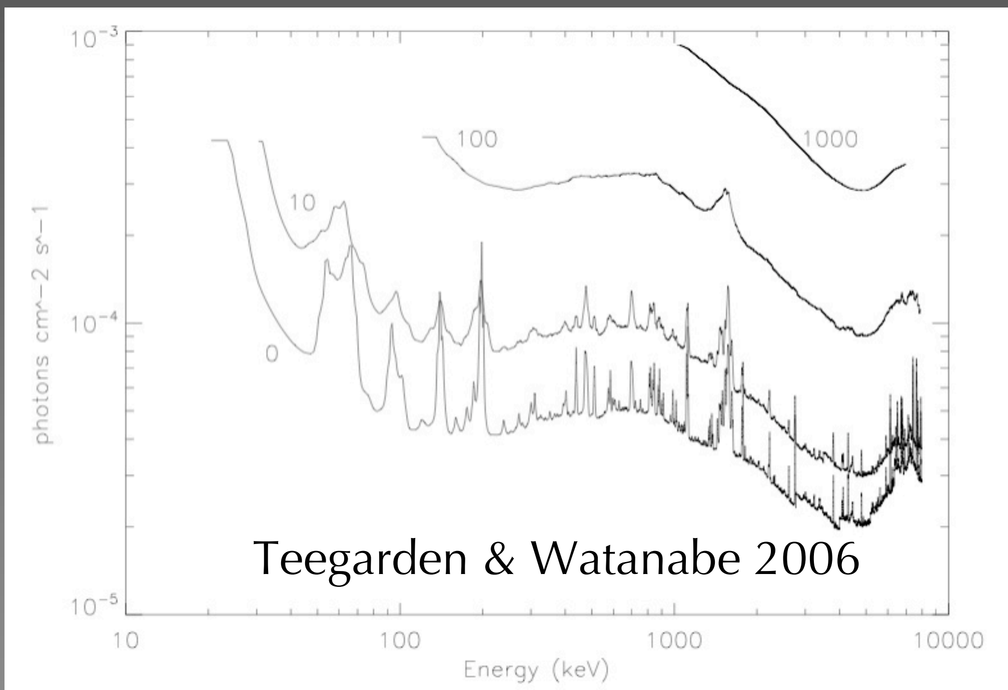
$\chi \rightarrow \gamma G$

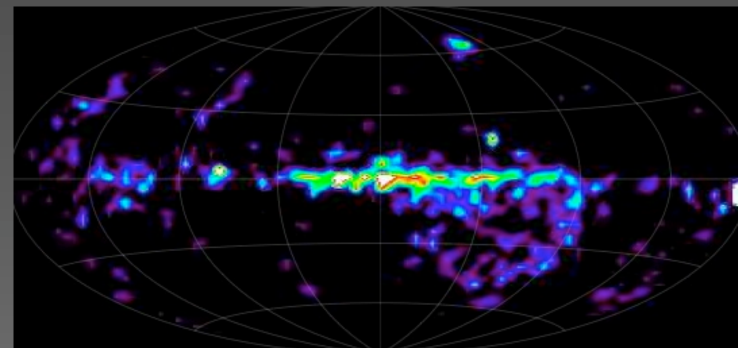
$$\tau \simeq \frac{3\pi}{b \cos^2 \theta_W} \frac{M_P^2}{(\Delta m)^3} \simeq \frac{4.7 \times 10^{22}\ \mathrm{s}}{b} \left[\frac{\mathrm{MeV}}{\Delta m}\right]^3$$

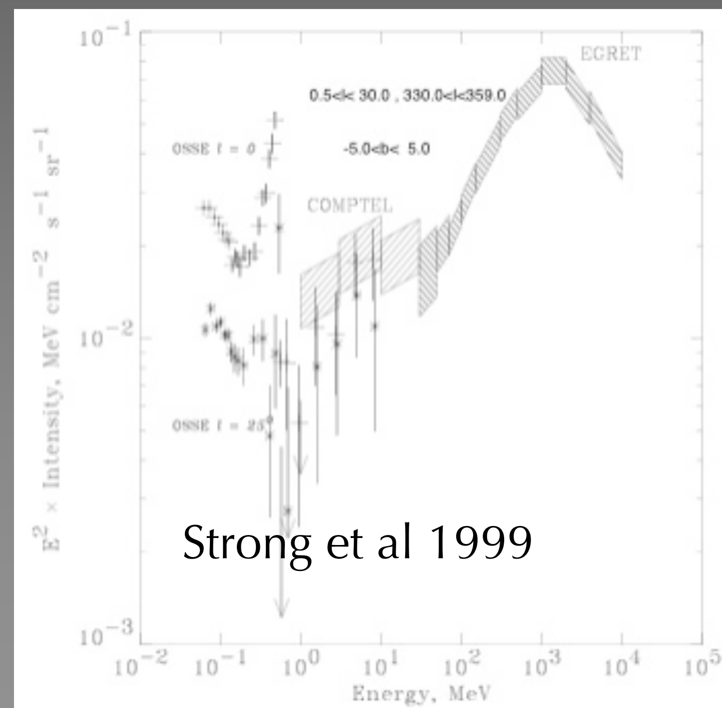




Galactic gamma ray constraints



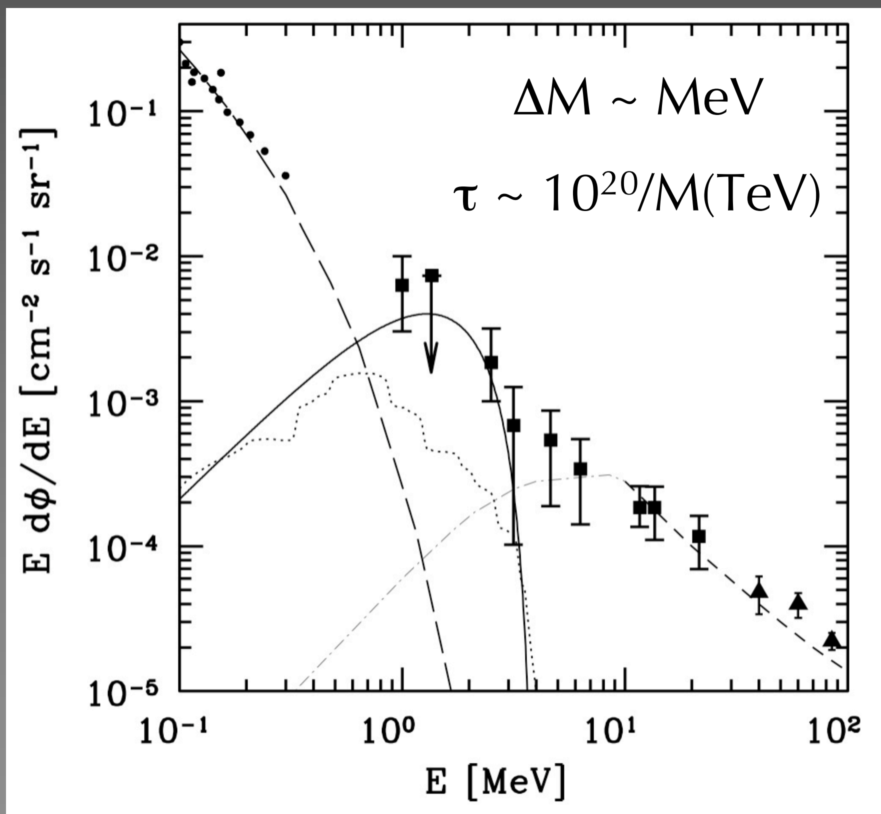


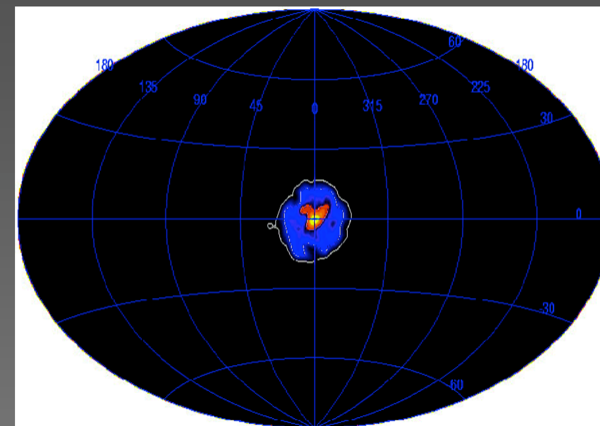


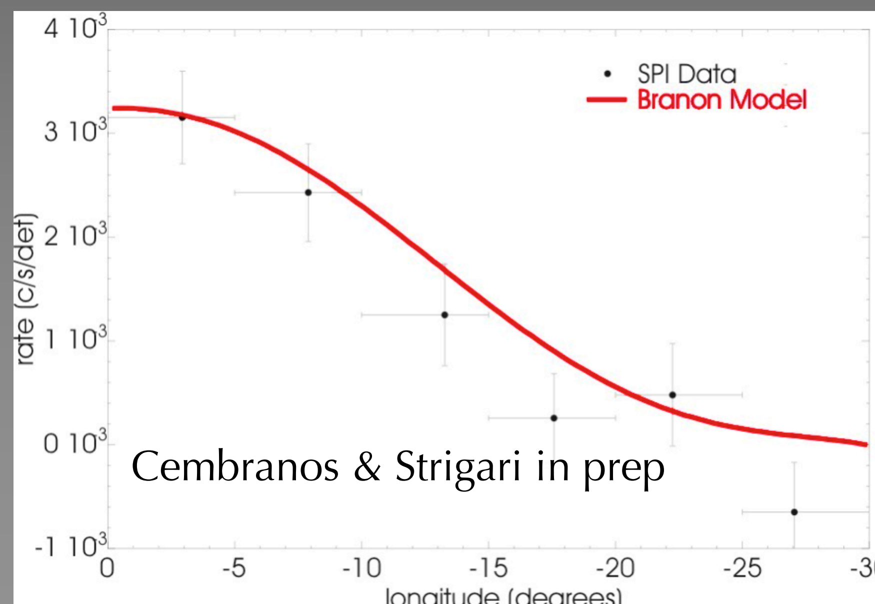
Constraints depend on dark matter density profile [Yuksel & Kistler 2007]

Dark matter, gamma-rays, 511 keV photons

$\text{NLP} \rightarrow \text{LP} + \gamma + \gamma, \ \text{NLP} \rightarrow \text{LP} + e^+ + e^-$







Picciotto & Pospelov 2005, Hooper & Wang 2005, Kasuya & Kawasaki 2006, Finkbeiner & Weiner 2007, Pospelov & Ritz 2007