Title: Dark Matter and the Milky Way

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Abstract: With the discovery of many new satellite galaxies, in recent years our understanding of the Milky Way environment has undergone a dramatic transformation. I will discuss what these discoveries are telling us about galaxy formation and the nature of dark matter itself. Issues I will focus on include: identifying the least luminous dark matter halo in the Universe, distinguishing between warm and cold dark matter, and indirect dark matter detection.

Dark Matter and the Milky Way

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Young Researchers Conference 2007

Perimeter Institute

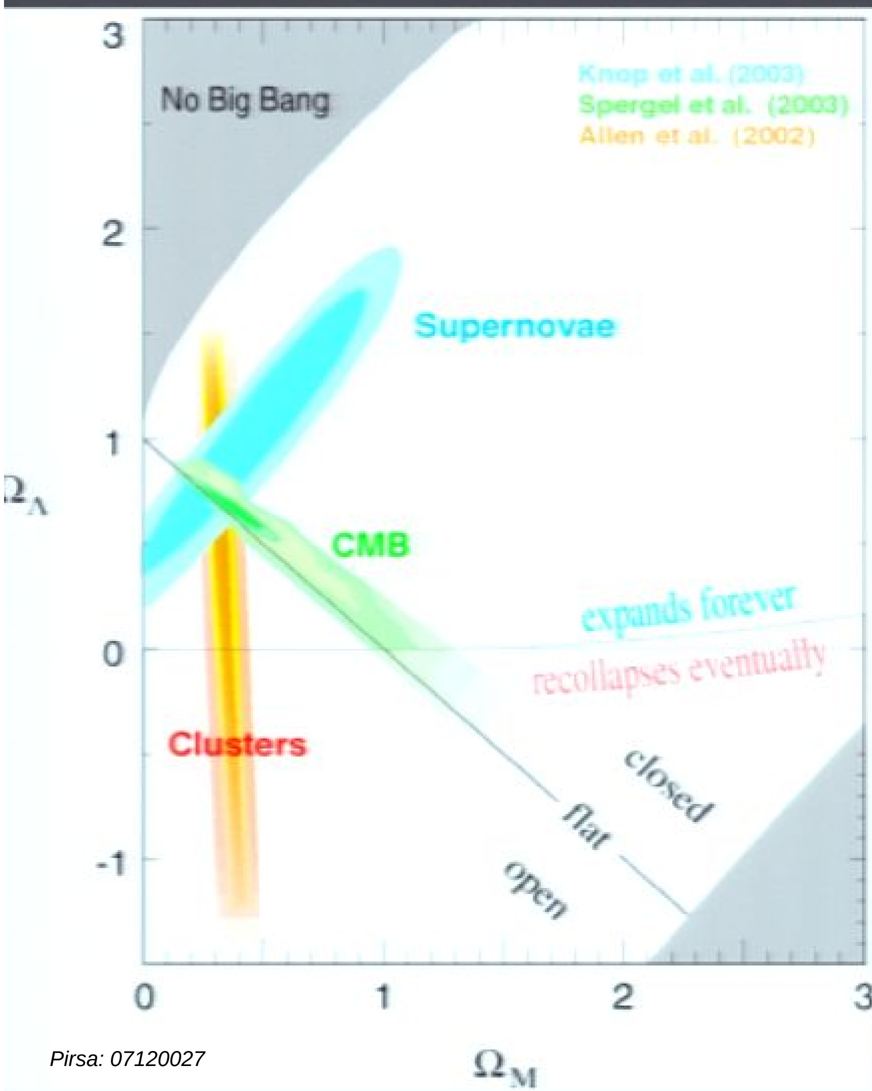
12.5.2007

Main Collaborators: James Bullock, Manoj Kaplinghat

Outline

- Introduction: Motivation for Dark Matter
  - Cosmology
  - Particle Physics
  - Astrophysics
- Review dark matter models
  - Including cold, warm, and non-thermal dark matter
- Astrophysical Probes of the Nature of Dark Matter
  - The minimum mass dark matter object
  - Dynamics of dark matter and galaxies
  - Indirect signals and speculations

Dark Matter in Cosmology



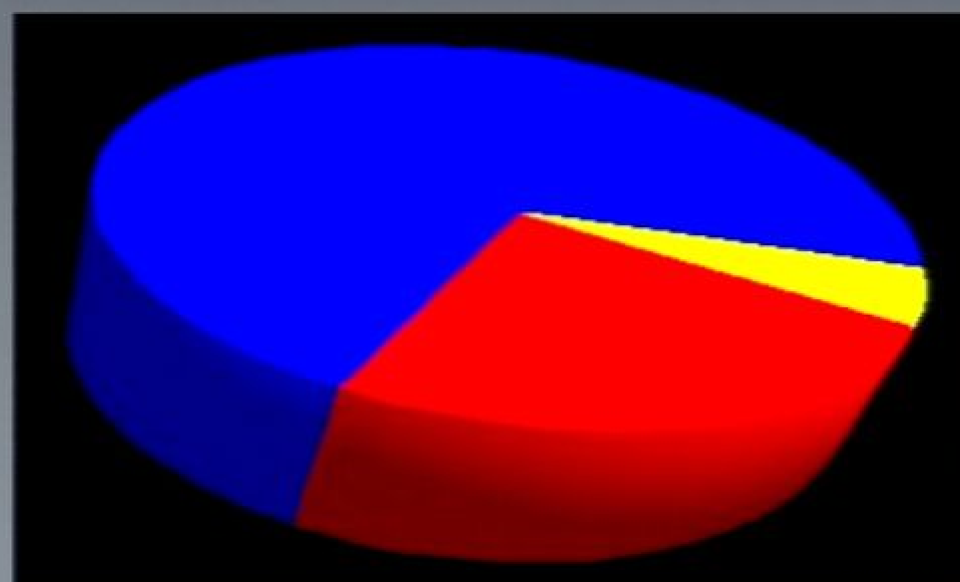
$$H^2 = H_0^2\left[\Omega_M(1+z)^3 + \Omega_R(1+z)^4 + \Omega_V - (\Omega - 1)(1+z)^2\right]$$

Critical density

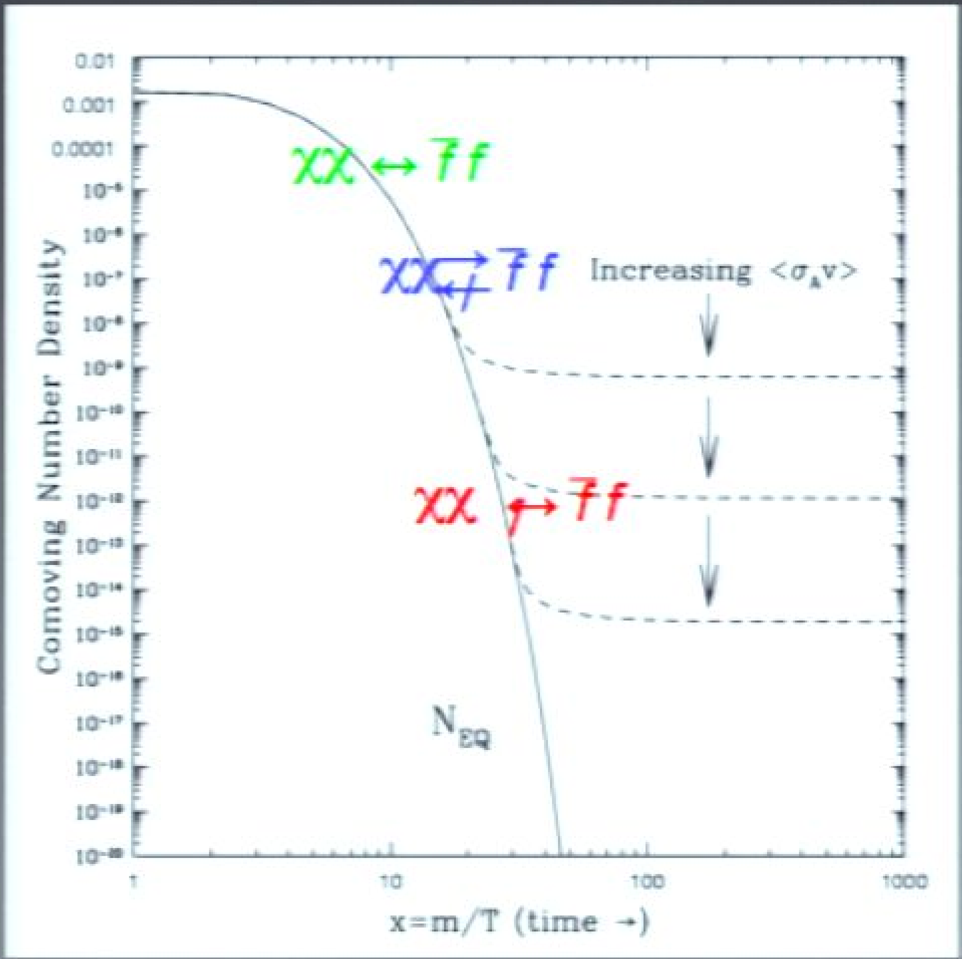
$$\rho_{CR} \equiv \frac{3H^2}{8\pi G}$$

Components

$$\Omega_x \equiv \frac{\rho_x}{\rho_{CR}}$$



Dark Matter ``Freeze-out"

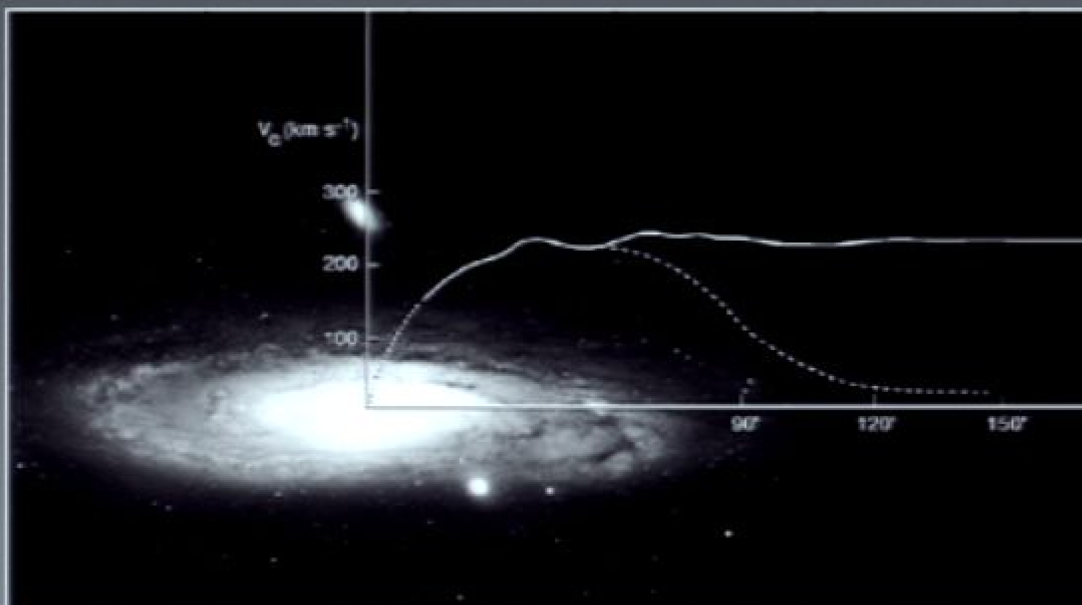


$\Omega_\chi \sim <\sigma_A v>^{-1}$

Since m/T is of order 20, we have ``Cold Dark Matter" (CDM)

Mass of particles required for electroweak symmetry breaking ~ 100 GeV -> the right amount of dark matter

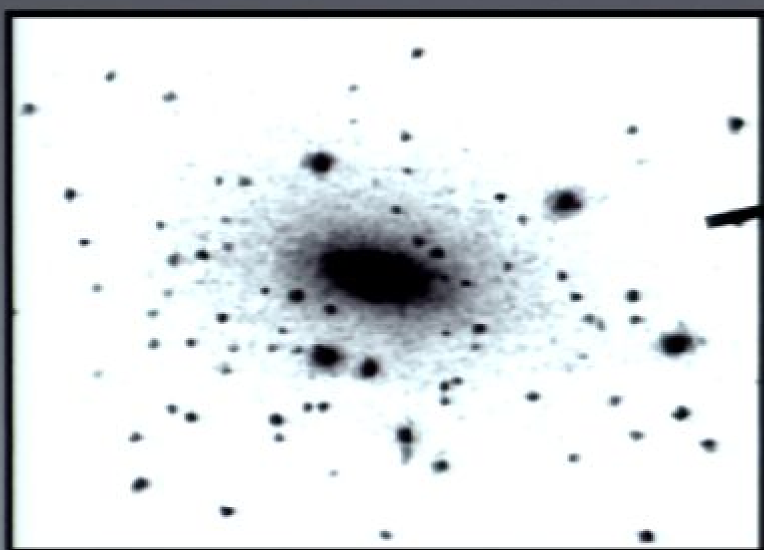
Dark Matter and Astrophysics

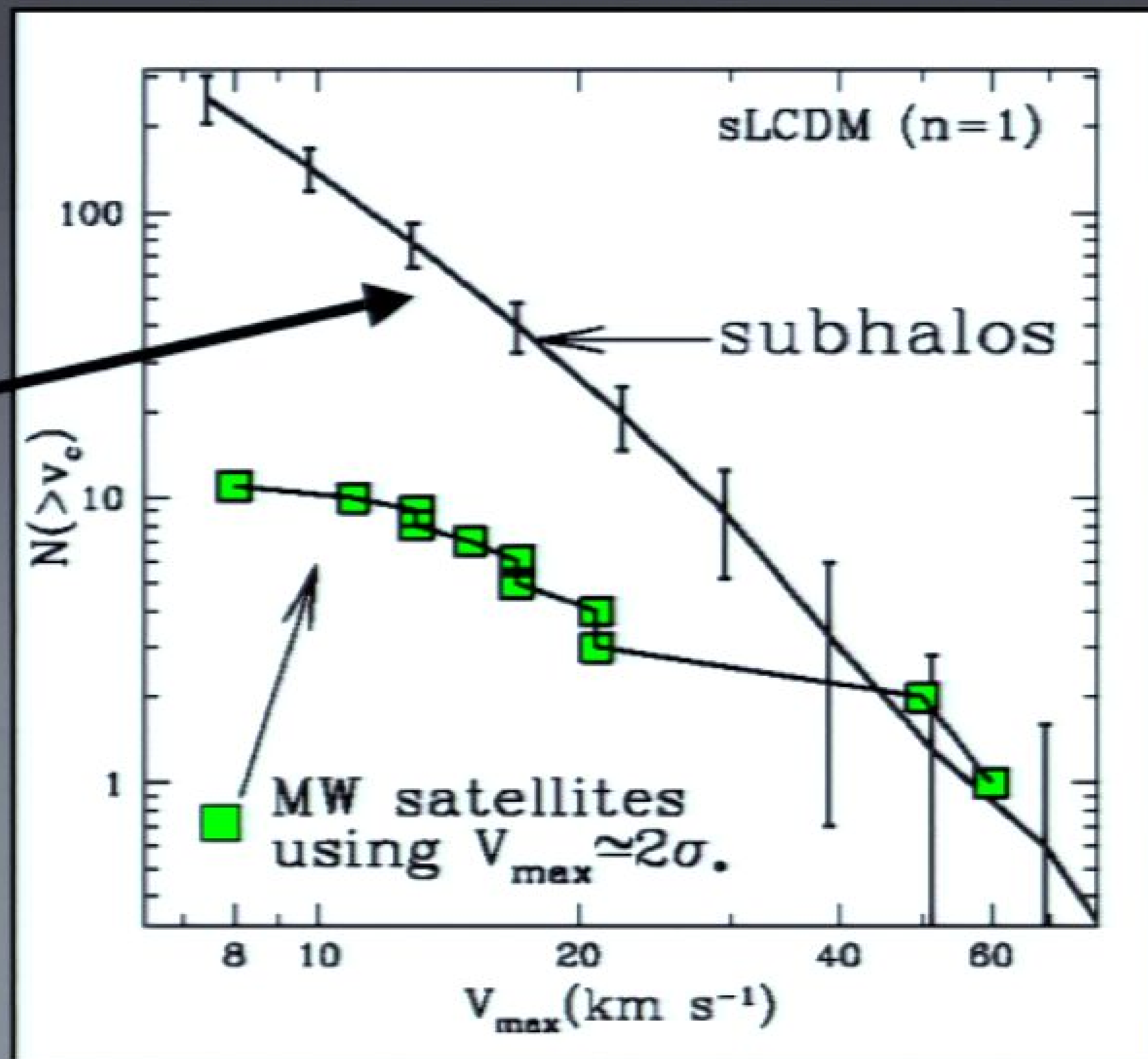


Rotating galaxies

Non-Rotating galaxies

Cold Dark Matter



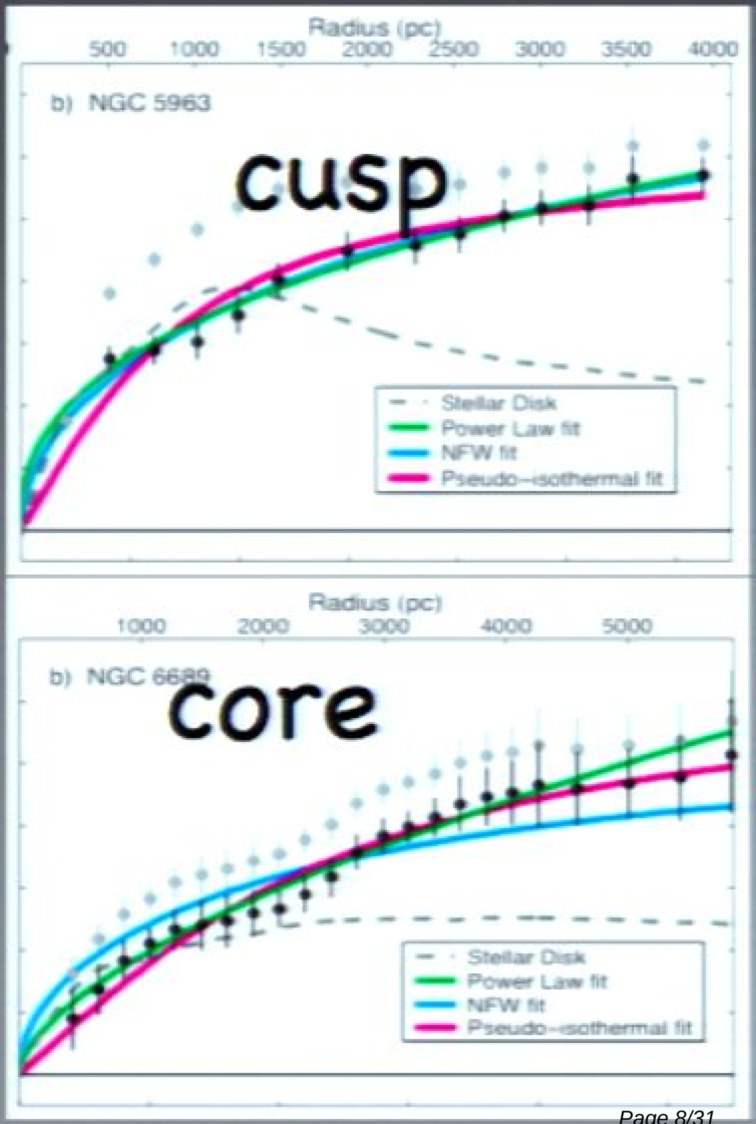


Cold Dark Matter

- Halo density profile scaling as 1/r in the central regions ``Cusps"
  [Navarro et al 2004, Diemand et al 2004]

- Q = physical density/(velocity dispersion)^3

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



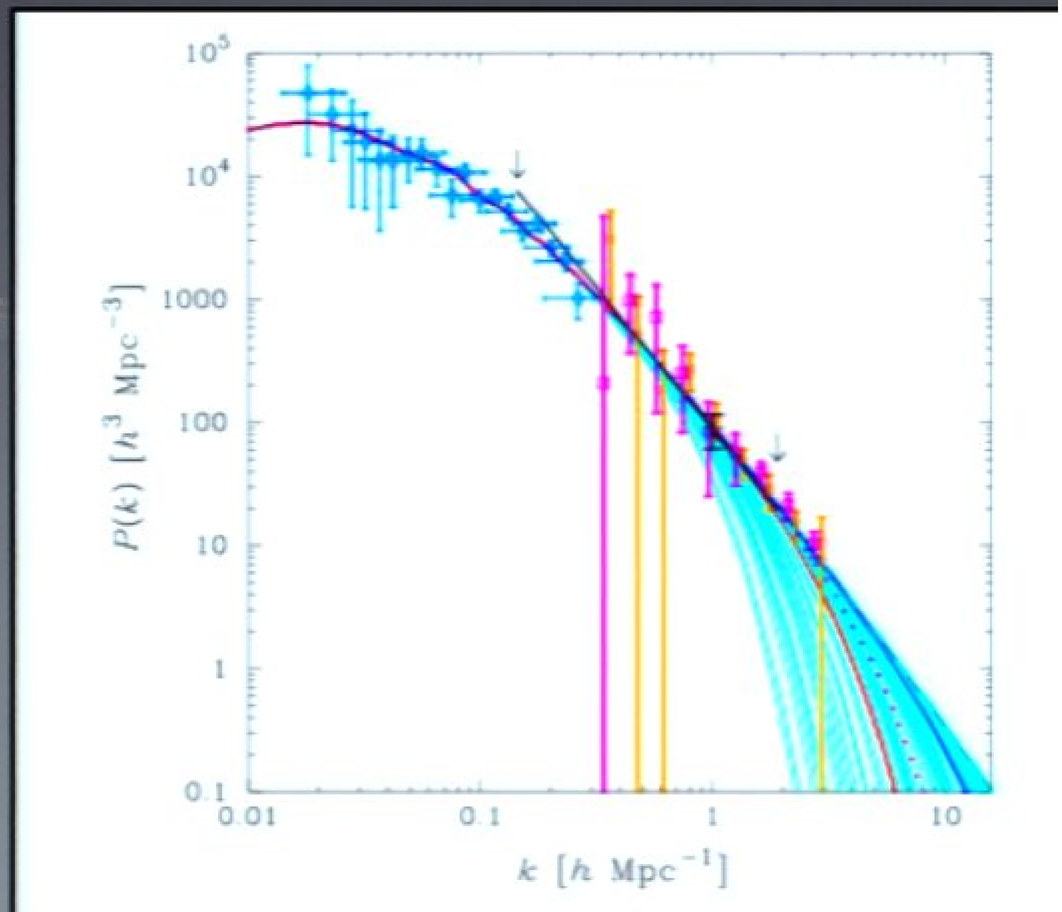
Simon et al. 2005, Kuzio de Naray 2006

Warm dark matter

- Dark matter freezes out with non-negligible velocities
- Free streaming: Reduces the number of small halos

Cosmological Constraints

Narayan et al 2000: $m_{WDM} > 750$ eV
Viel et al 2005: $m_{WDM} > 550$ eV



Abazajian 2006

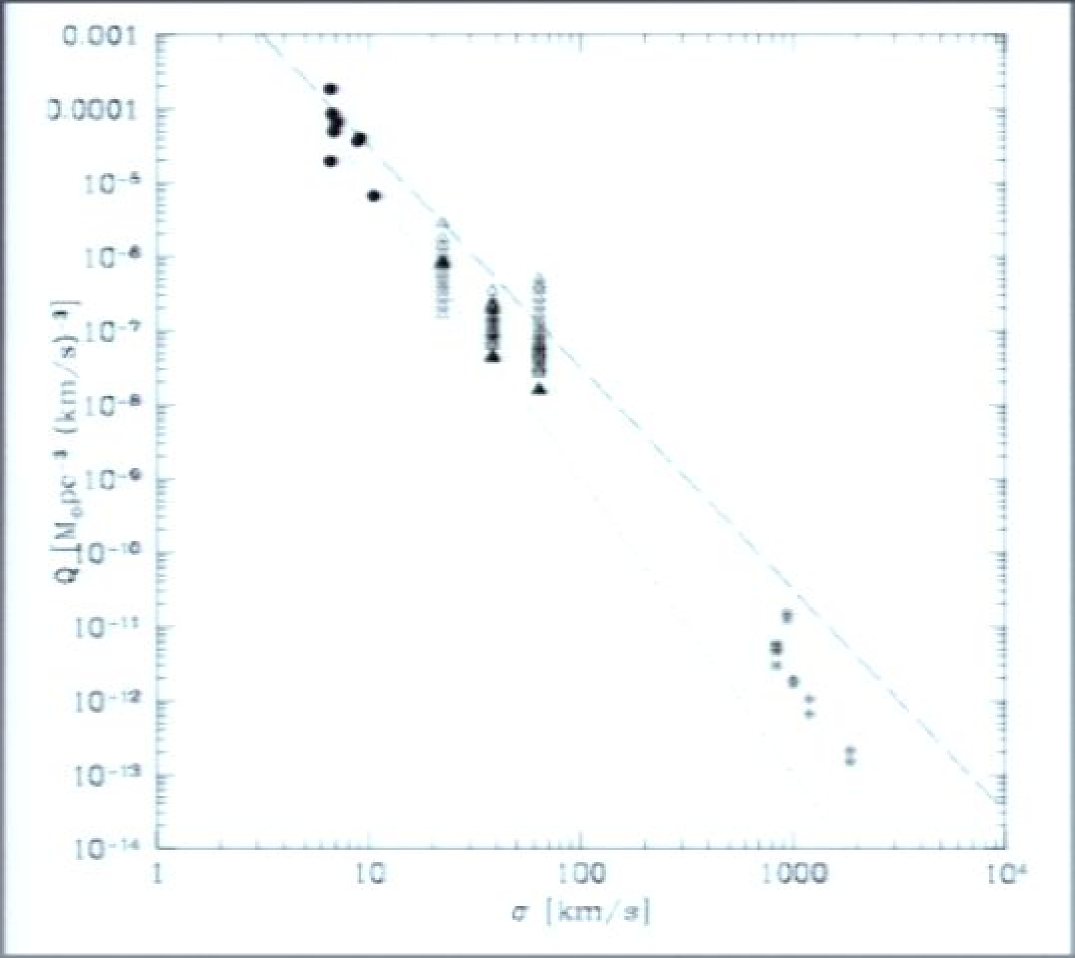
Warm dark matter

- Less dense dark matter halos
- Reduced phase space density

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

[Tremaine–Gunn Bound]

Are the dynamics of small galaxies set by dark matter physics?



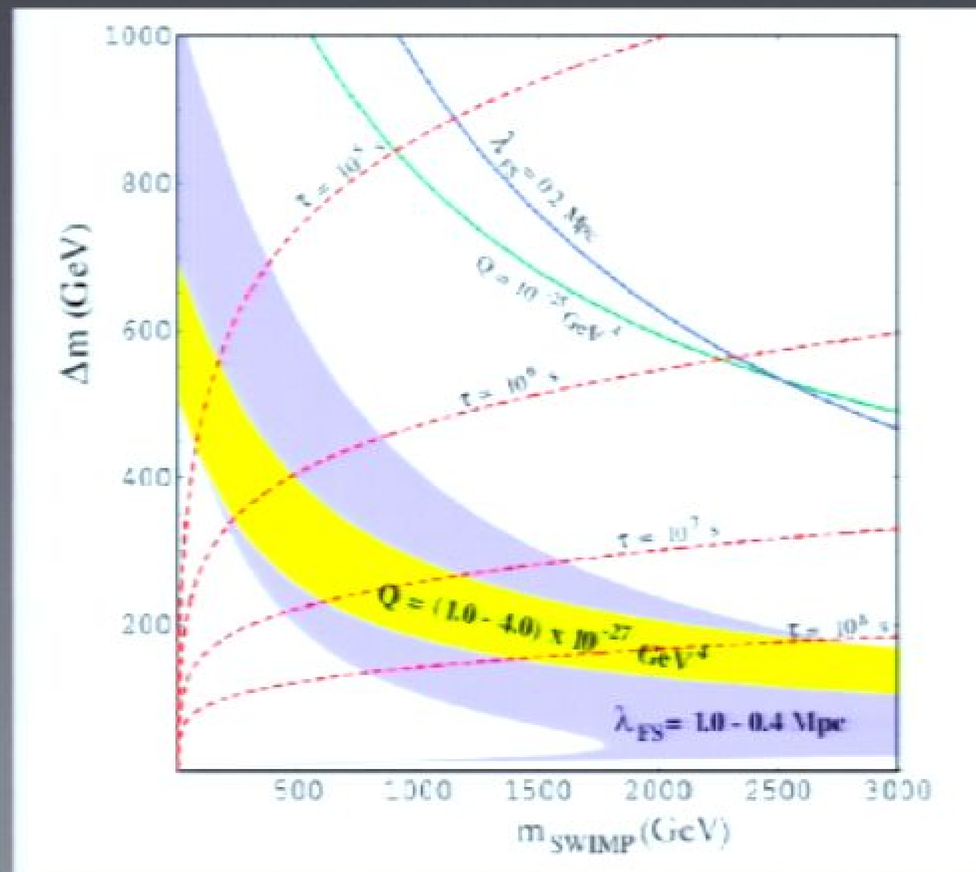
Hogan & Dalcanton 2000

Dark Matter from Decays

- Self-Interacting Dark Matter (Spergel & Steinhardt 2000)
- Annihilating Dark Matter (Kaplinghat, Knox & Turner 2001)
- Decaying Dark Matter (Sanchez-Salcedo 2003, Cen 2000)

- What if dark matter freezes-out, then decays to a `superweakly' interacting particle? [Feng, Rajaraman, Takayama 2003]
- Large velocity at production: 0.1-1c

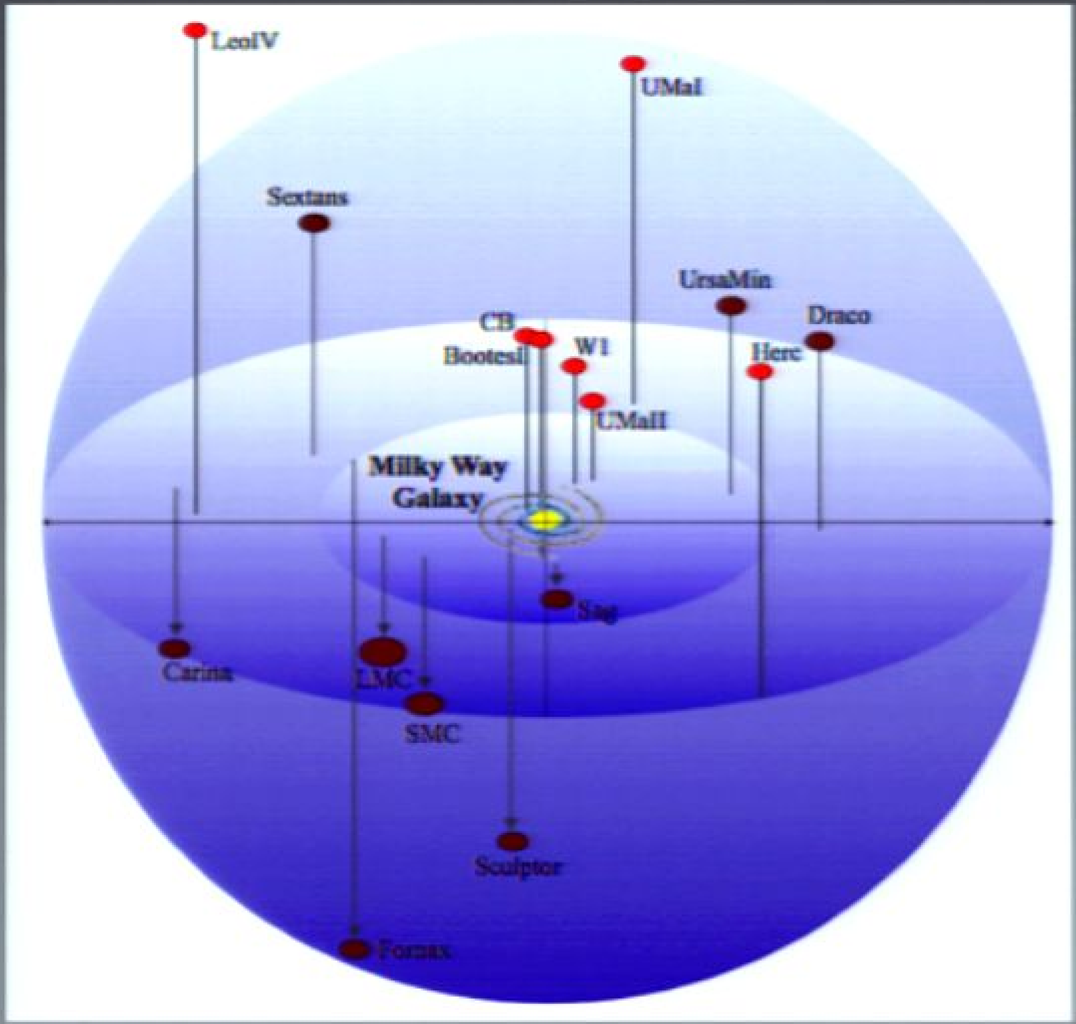
$$Q \approx 10^{-6}\left(\frac{10^{-3}}{\Delta m / m_{DM}}\right)^{3}\left(\frac{z_{decay}}{1000}\right)^{3} M_{sun}\, pc^{-3}(km/s)^{-3}$$

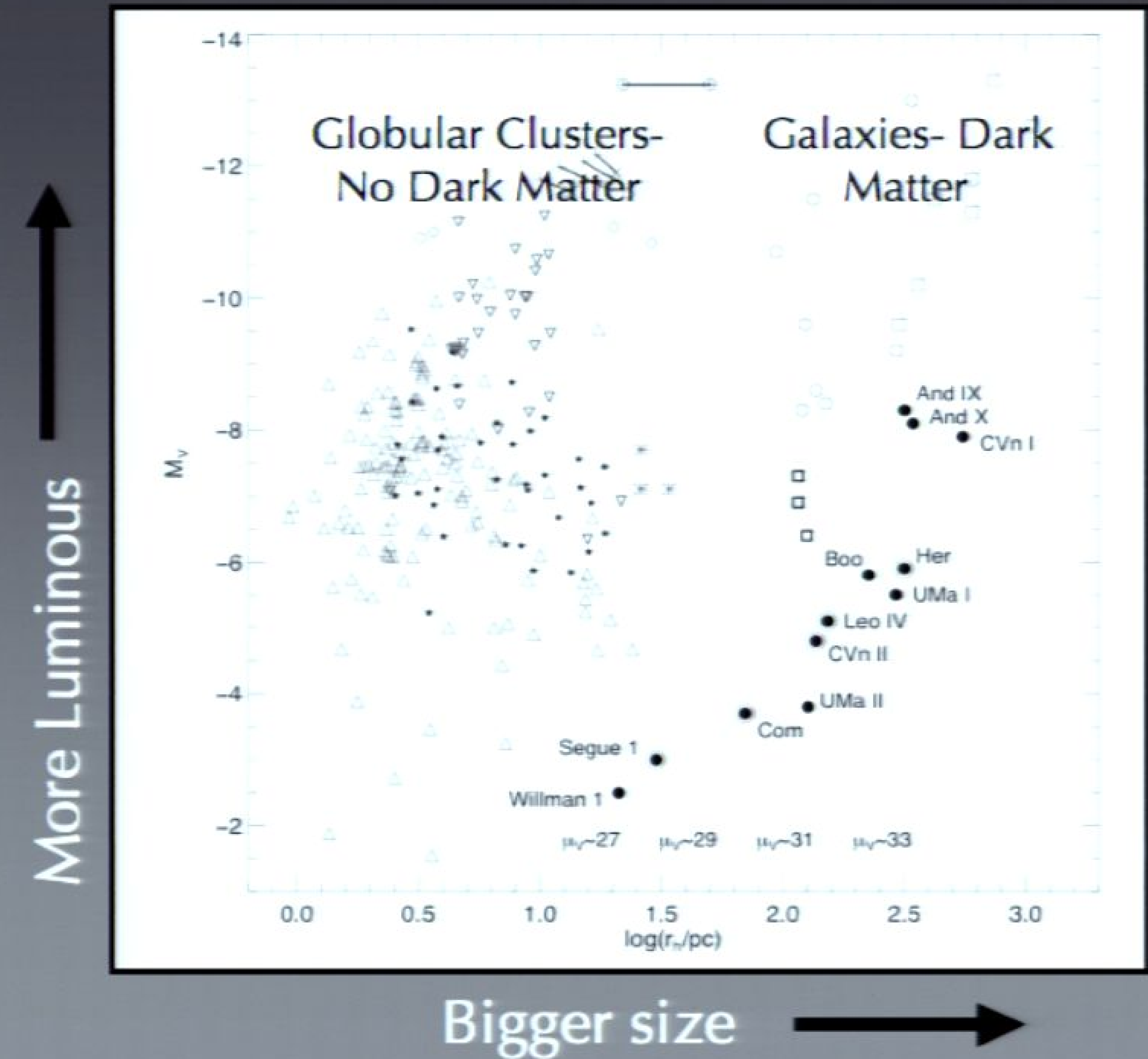


Cembranos et al., Kaplinghat (2005)

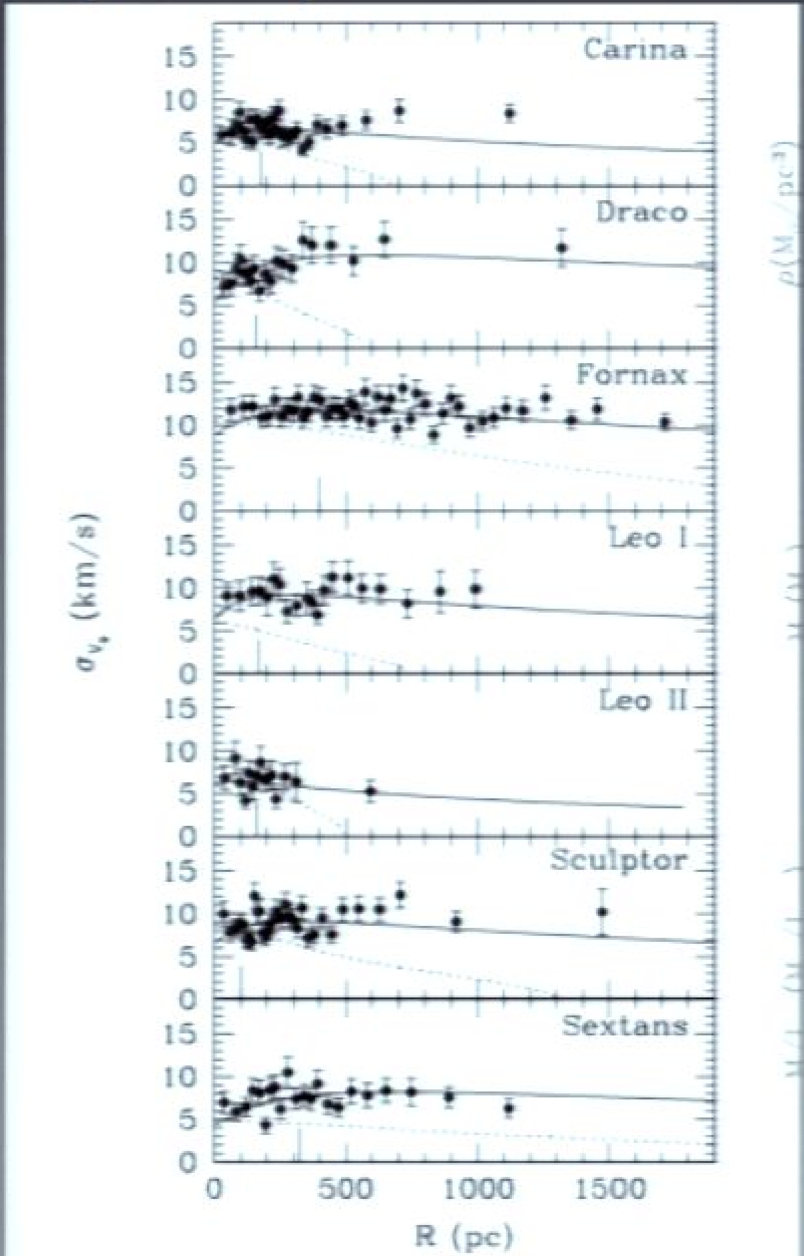
Local Group circa 2007

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




Globular Clusters-
No Dark Matter
Galaxies- Dark
Matter
And IX
And X
CVn I
Boo
Her
UMa I
Leo IV
CVn II
UMa II
Com
Segue 1
Willman 1
M_V
$\log(r_h/pc)$
More Luminous
Bigger size

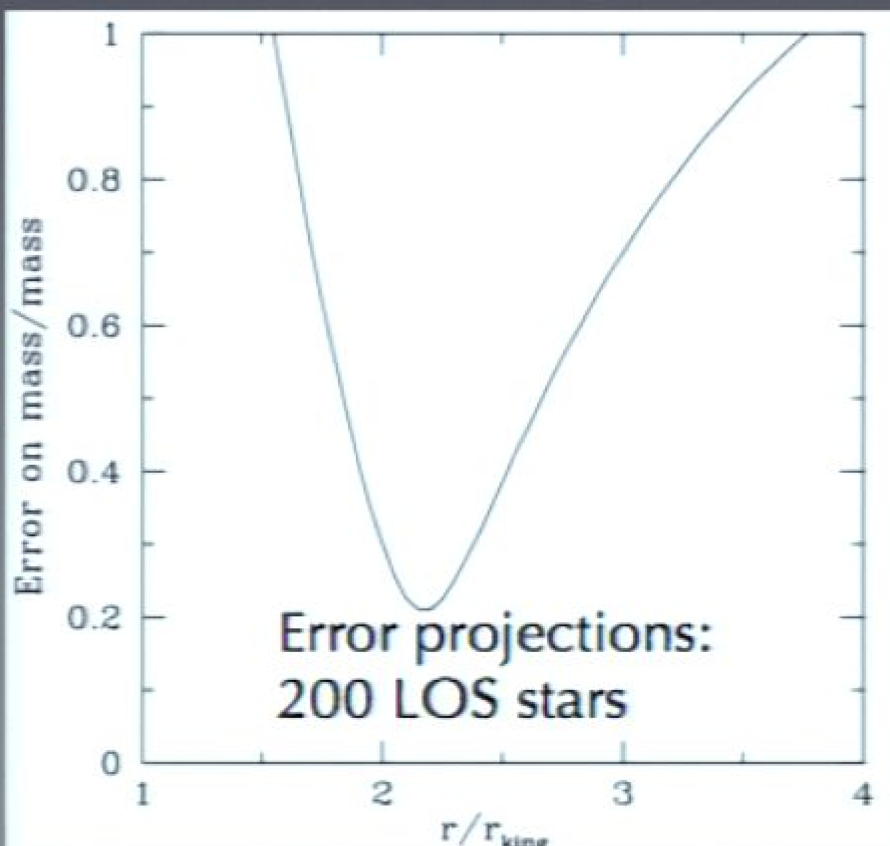
Milky Way satellite kinematics

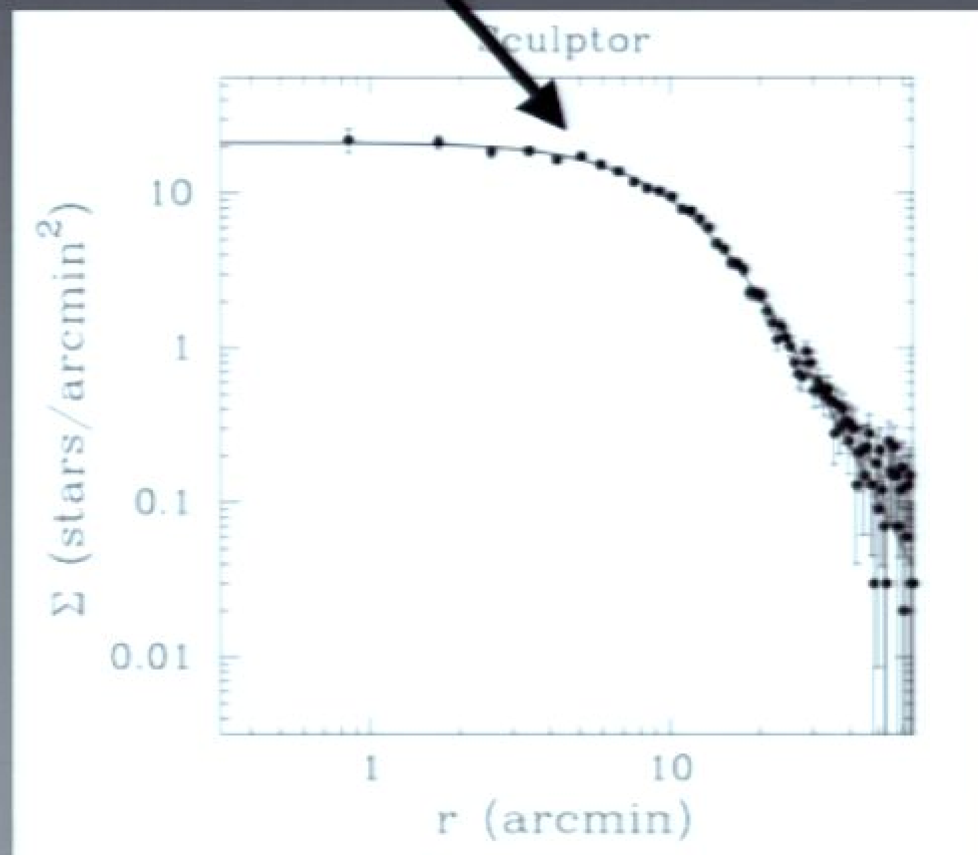


Walker et al. ApJL 2007

Observational Constraints

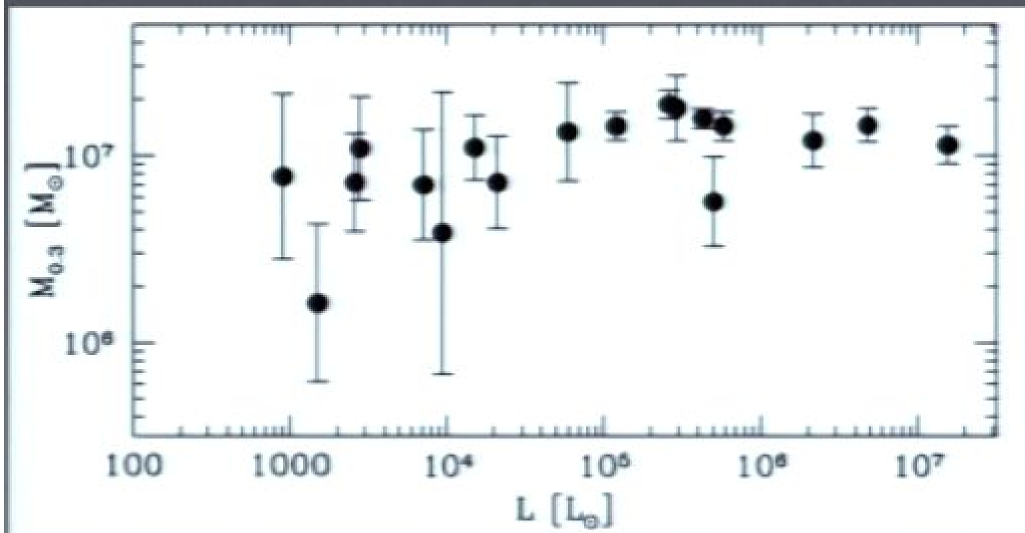
The best proxy is the mass within a few hundred parsecs

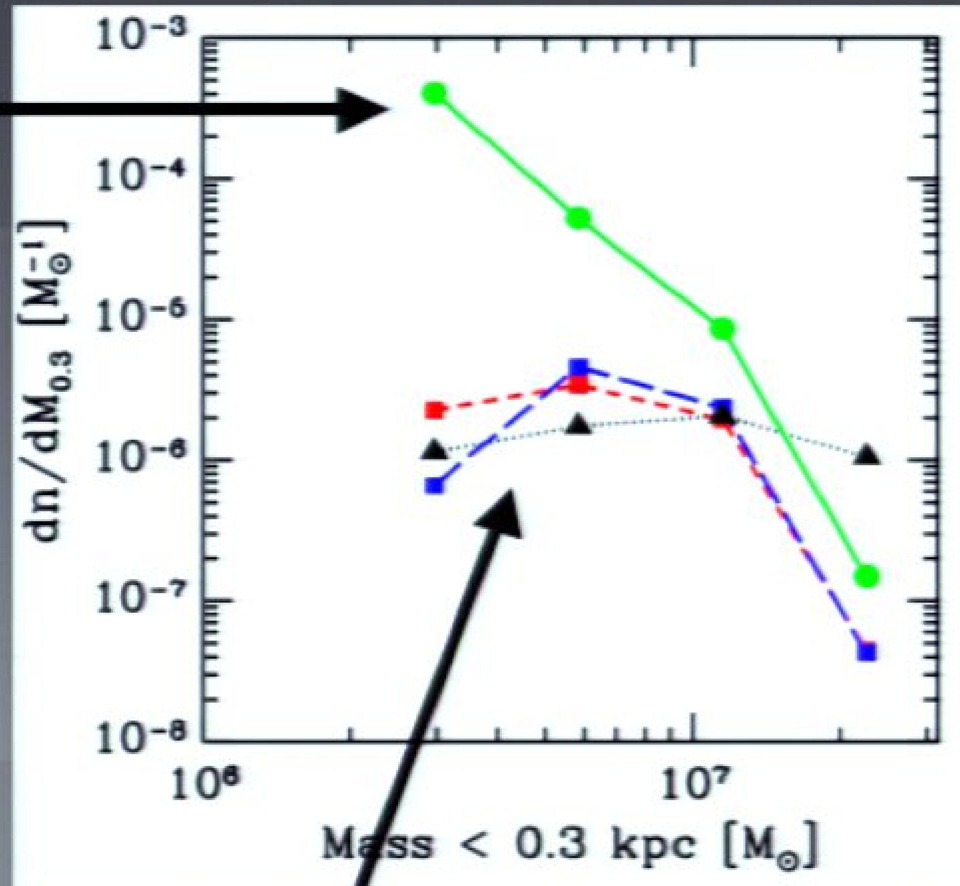




The mass scale for Milky Way satellites

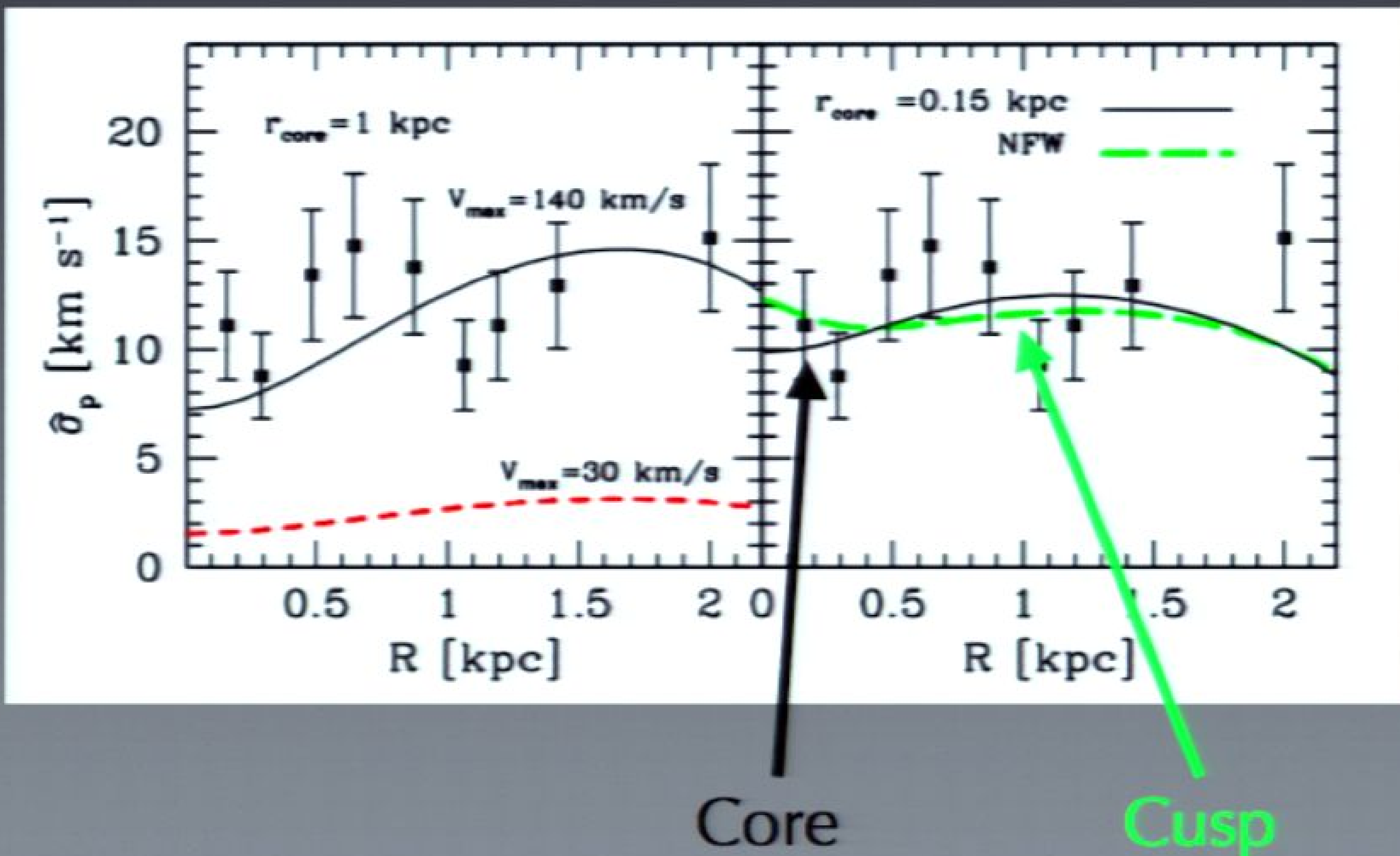
Entire predicted distribution of dark halos





In the context of CDM, the observed Milky Way satellites are likely the earliest forming dark matter halos in the Universe

Dark Matter Cores and Cusps



Core and cusp model are not-distinguishable

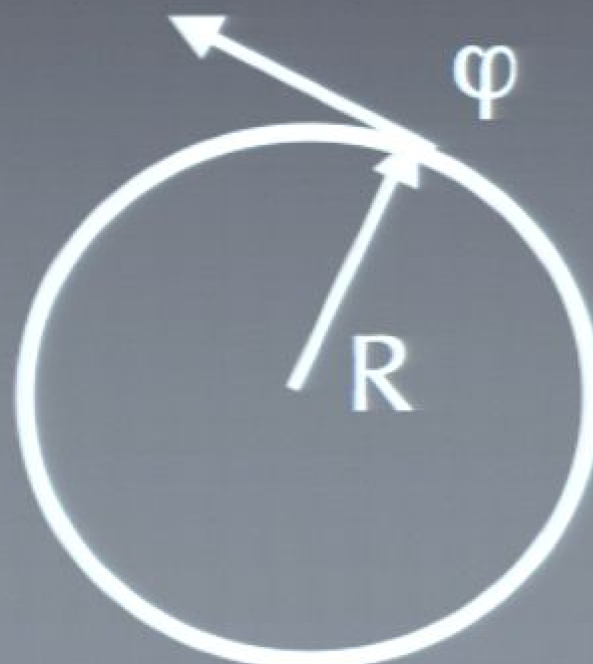
Proper Motions to measure the central density

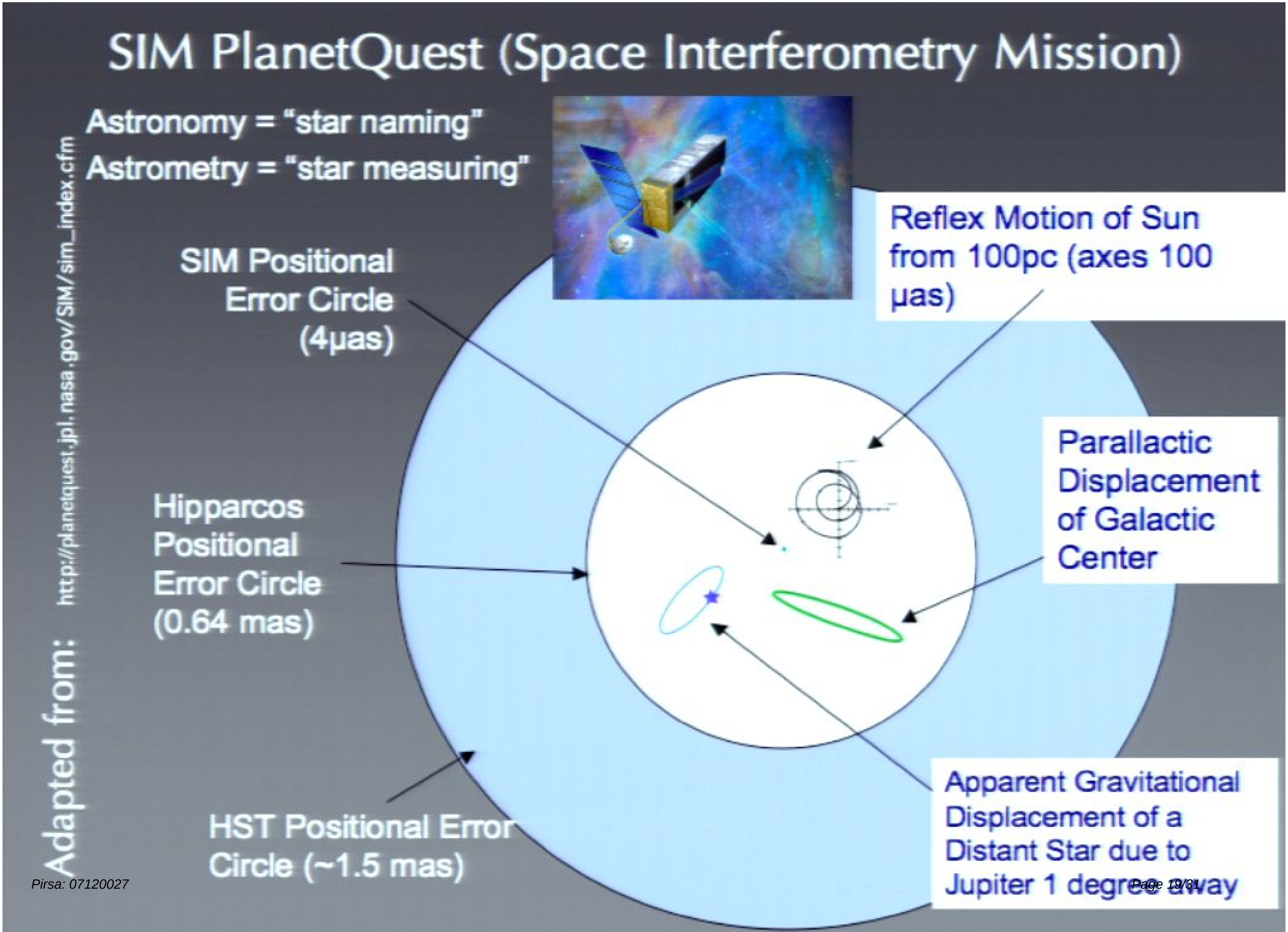
$$\sigma_{los}^2(R) = \frac{2}{I_\star(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}},$$

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

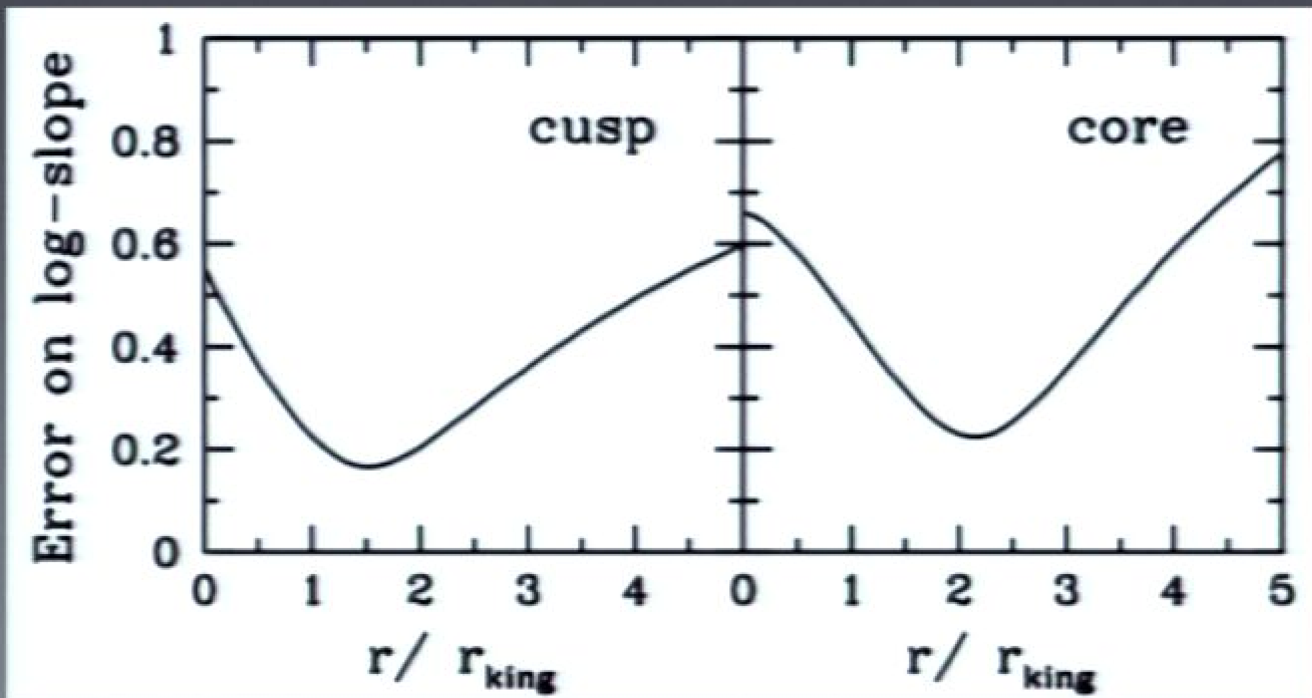
$$\sigma_t^2(R) = \frac{2}{I_\star(R)} \int_R^\infty (1 - \beta) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}.$$

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



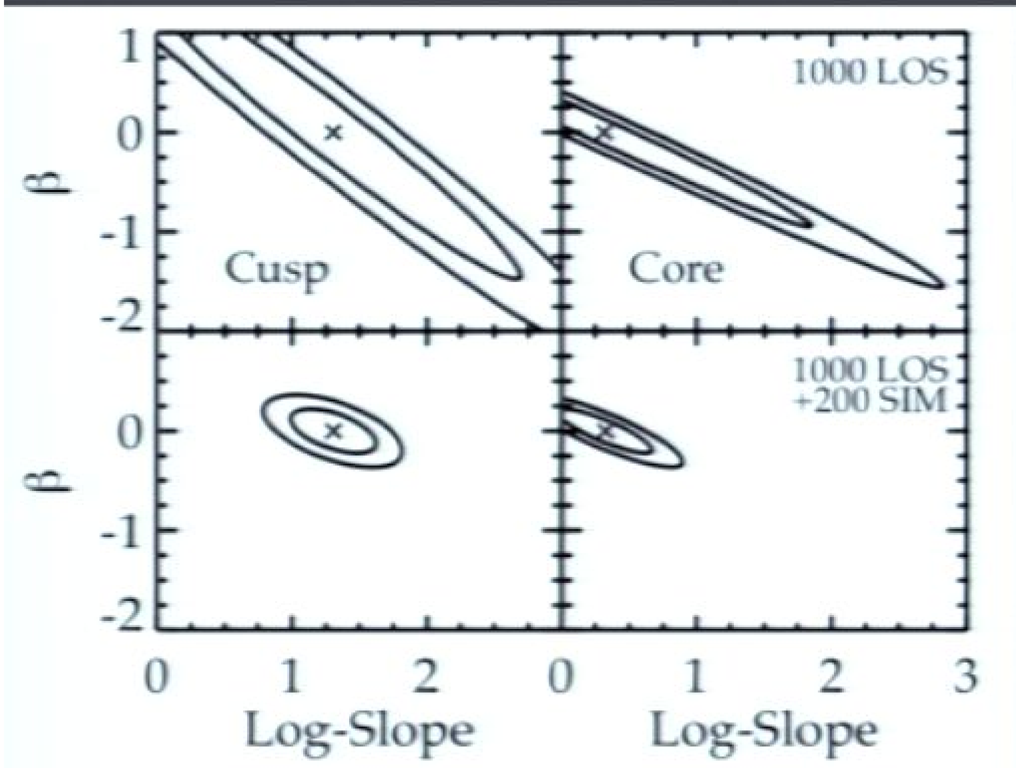

SIM PlanetQuest (Space Interferometry Mission)
Astronomy = “star naming”
Astrometry = “star measuring”
SIM Positional Error Circle (4μas)
Reflex Motion of Sun from 100pc (axes 100 μas)
Parallactic Displacement of Galactic Center
Hipparcos Positional Error Circle (0.64 mas)
HST Positional Error Circle (~1.5 mas)
Apparent Gravitational Displacement of a Distant Star due to Jupiter 1 degree away
Adapted from: http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm

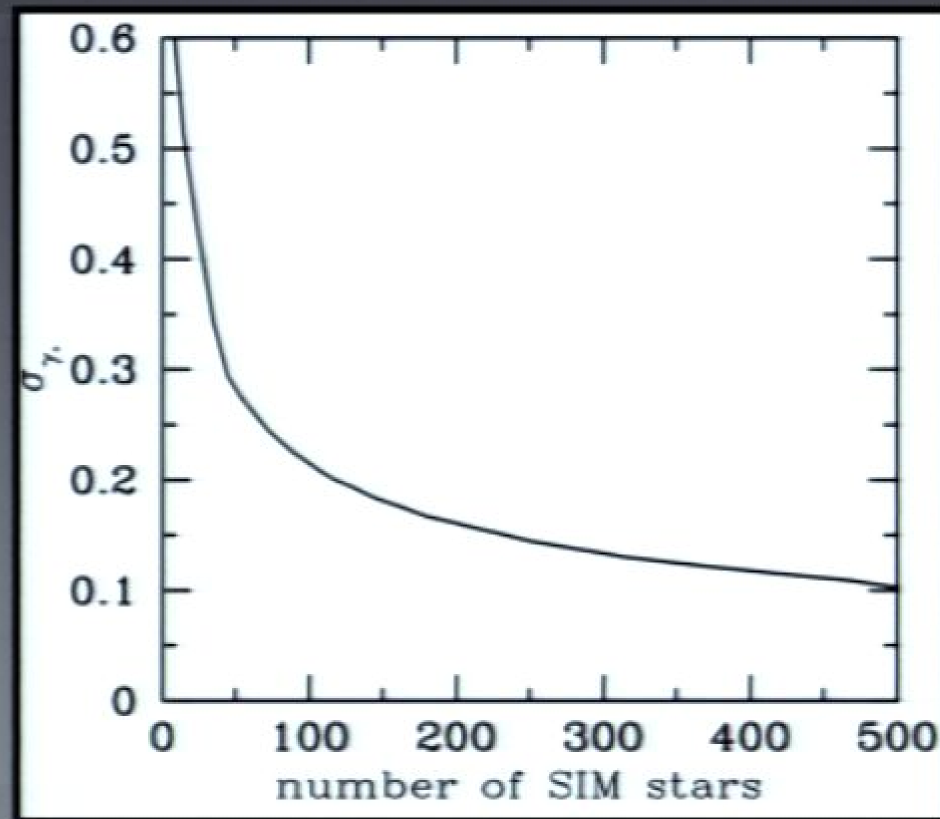
Constraints with SIM



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

Distinguishing Cores from Cusps





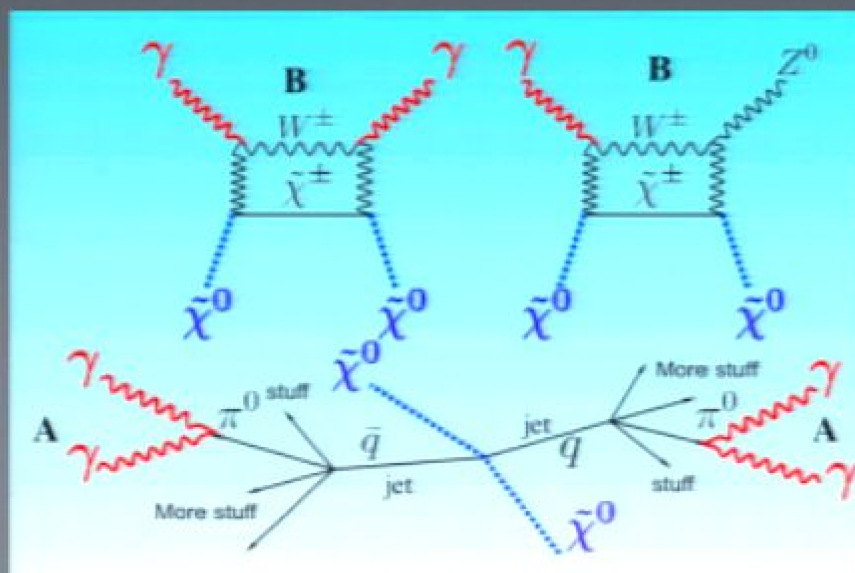
SIM key project would entail 1000 hrs of observing time and 200 stars from multiple dSphs

Indirect Dark Matter Detection

Flux = Particle Physics x Astrophysics

$$\frac{dN_\gamma}{dAdt} = \frac{1}{4\pi}\mathcal{P}[\langle\sigma v\rangle, M_\chi, dN_\gamma/dE]\mathcal{L}(\rho_s, r_s, \mathcal{D}).$$

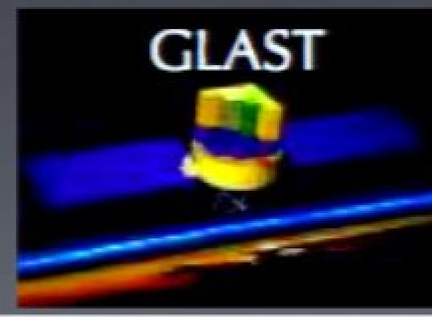
$$\mathcal{L} = \int_0^{\Delta\Omega}\left\{\int_{\rm LOS}\rho^2[r(\theta, \mathcal{D}, s)]ds\right\}d\Omega.$$

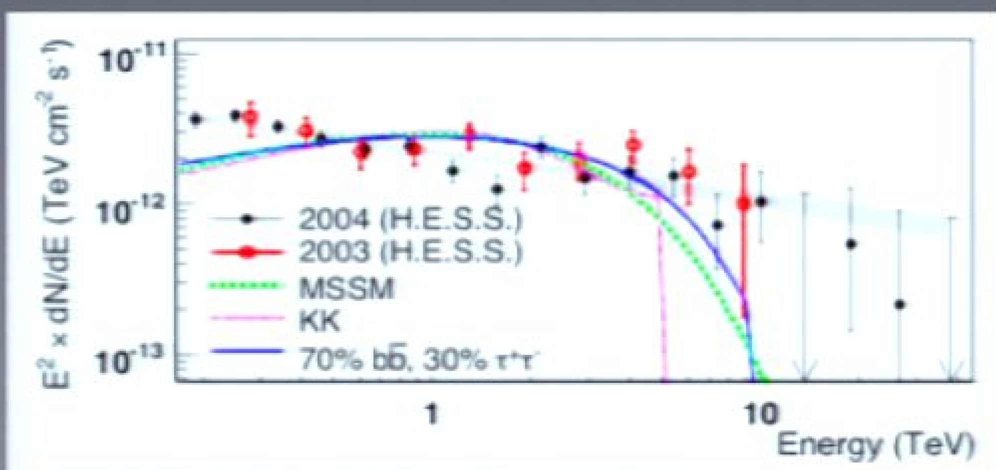


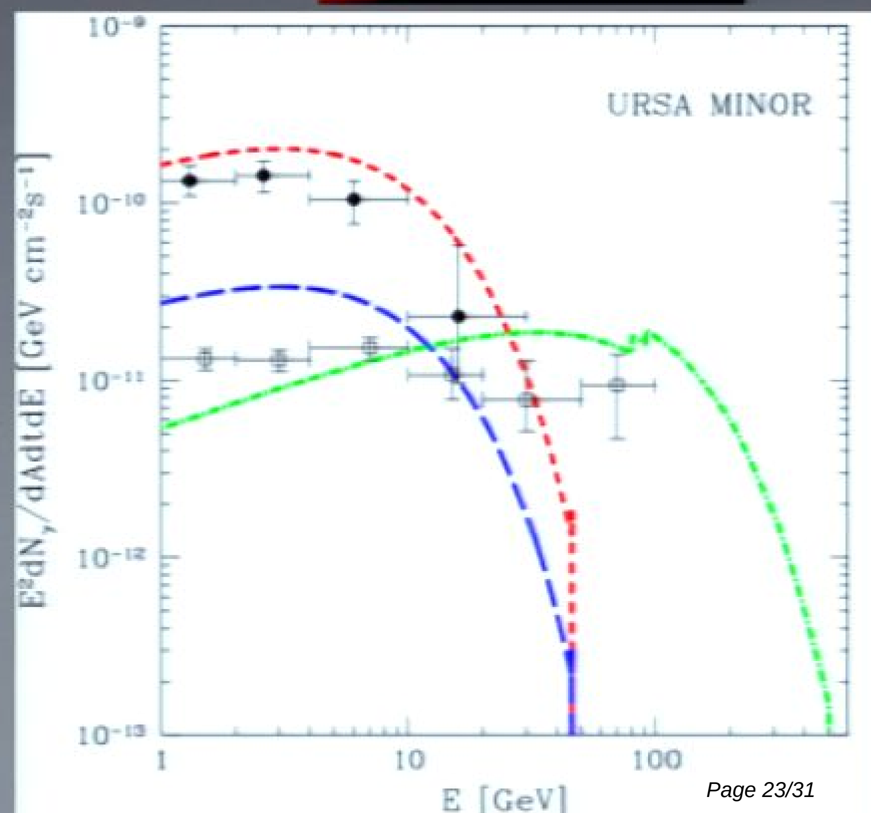
Contribution from line and continuum

Indirect Detection from the Milky Way

Two main sources are the center of our Galaxy or satellite galaxies



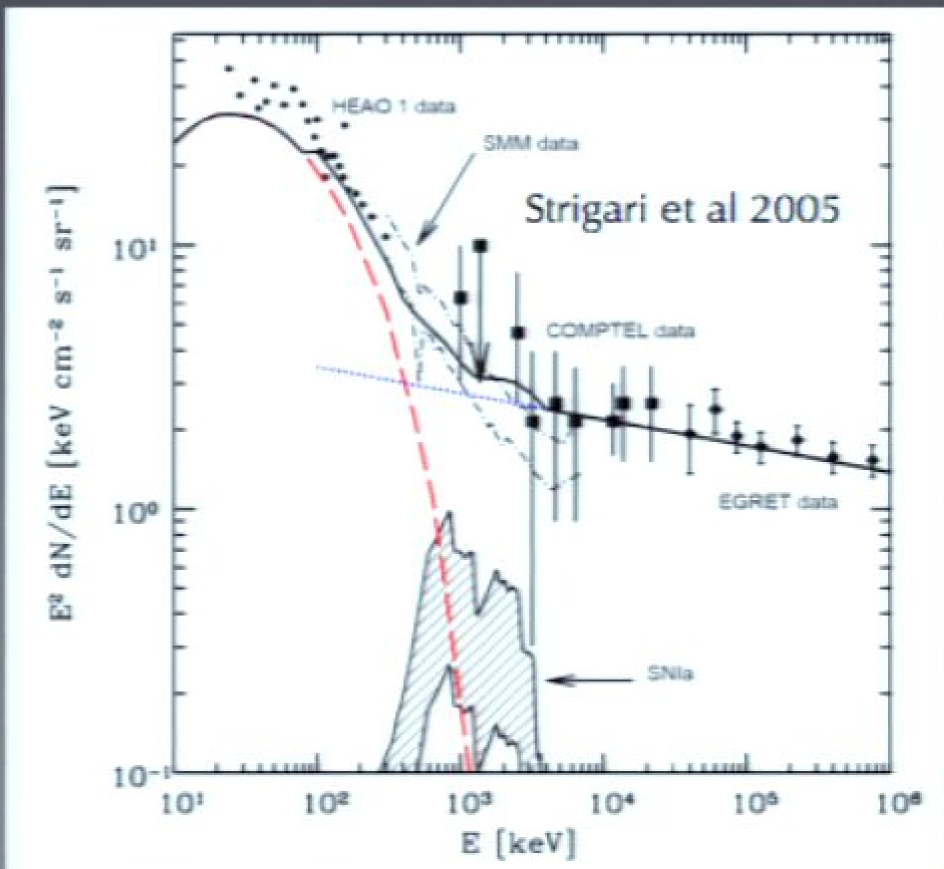


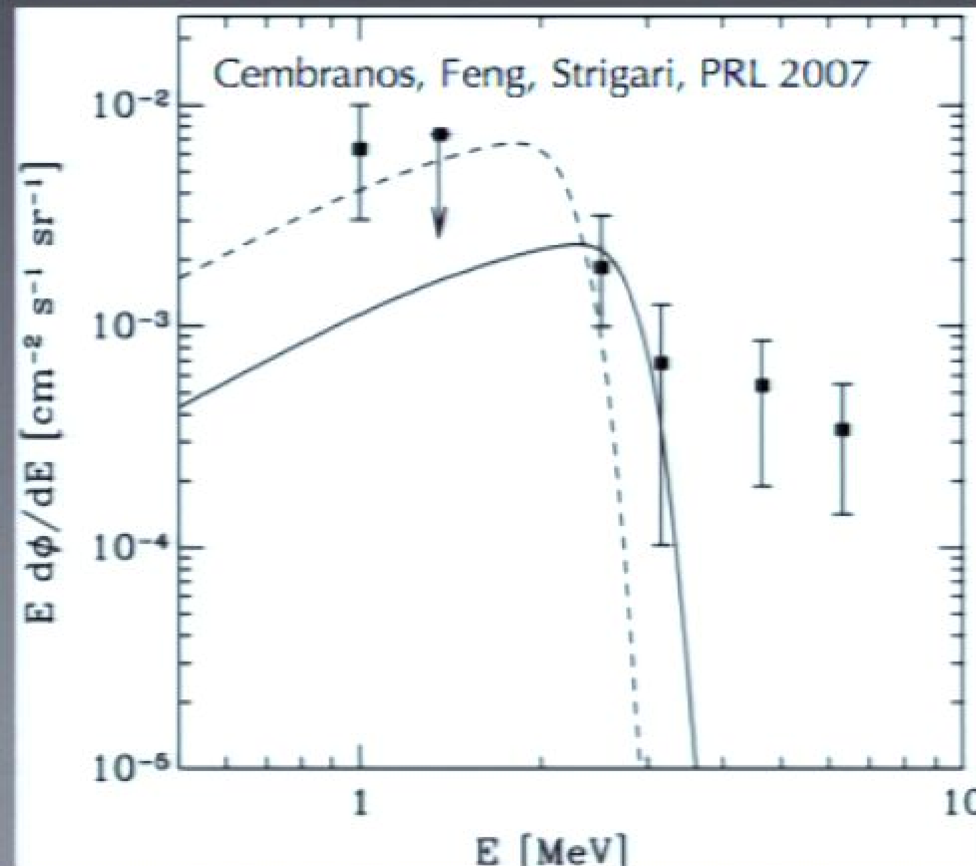


MeV gamma-ray background: Are WIMPs stable?

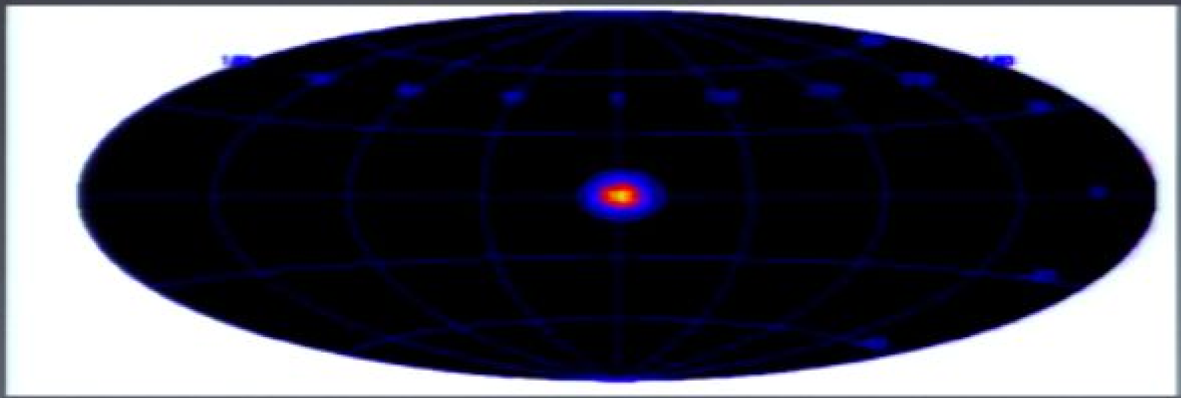
$$\chi \rightarrow \gamma G$$

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



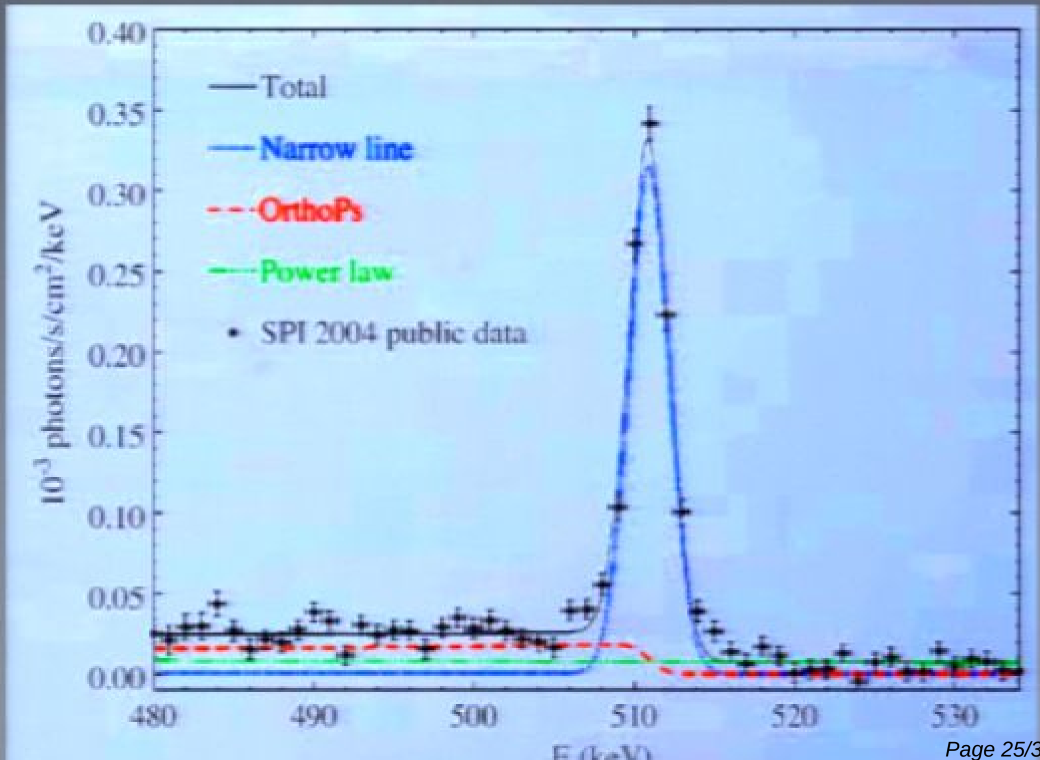


511 keV lines from Galactic center



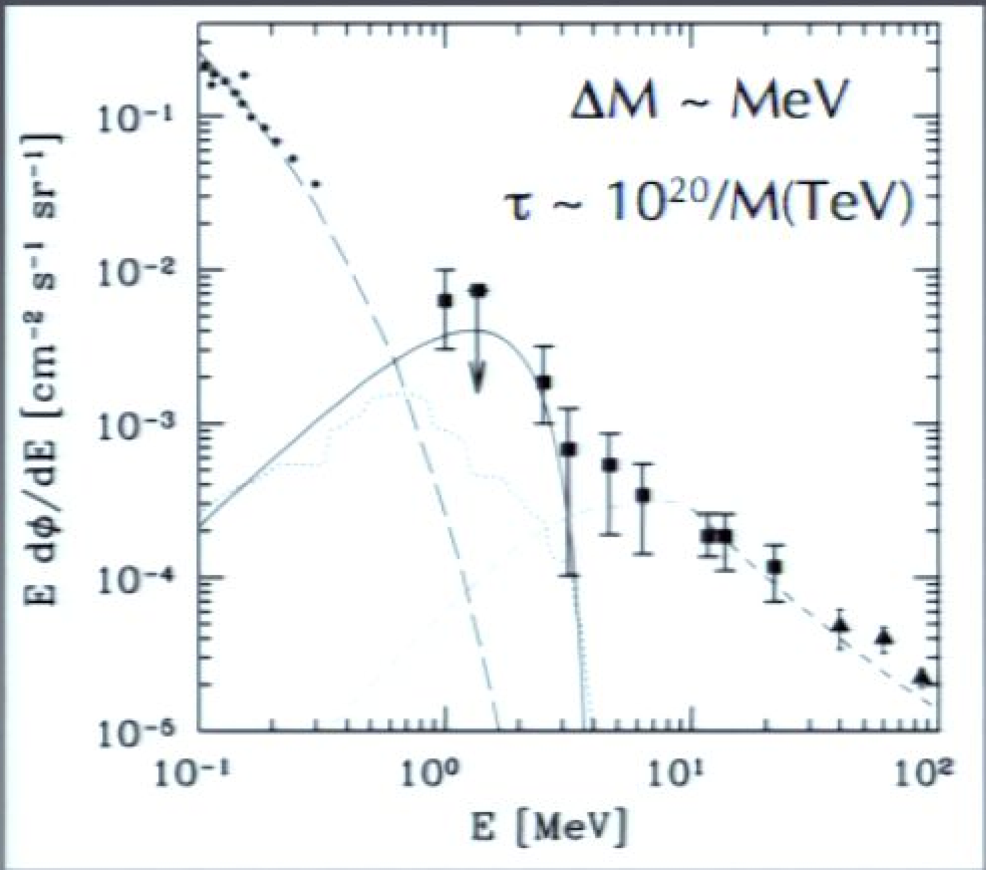
Could this be a sign of dark matter?

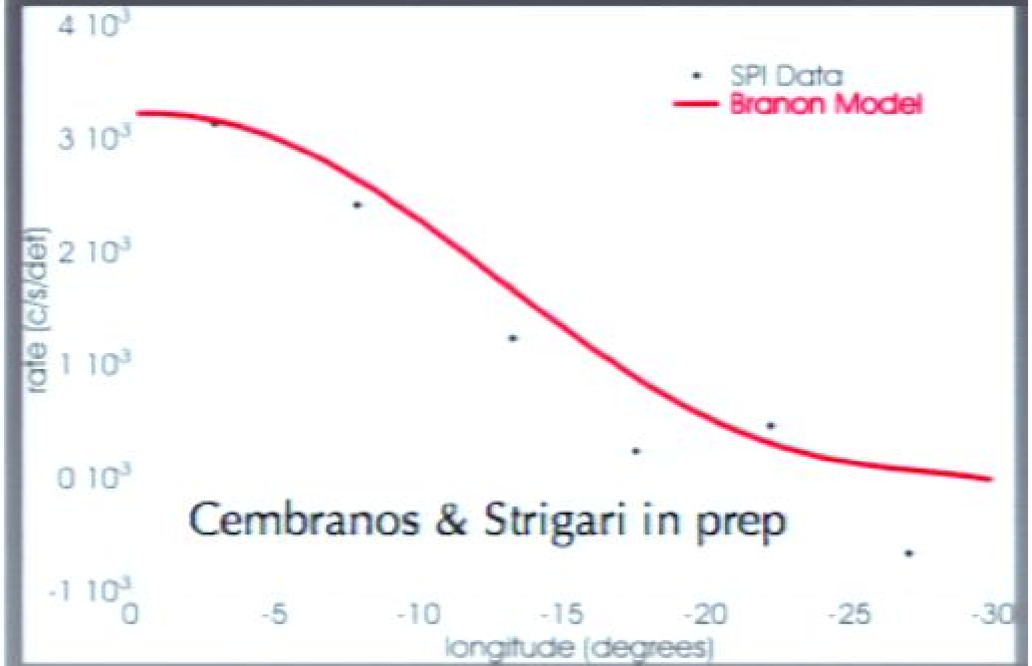
Boehm et al 2003, Picciotto & Pospelov 2005, Hooper & Wang 2005, Kasuya & Kawasaki 2006, Finkbeiner & Weiner 2007, Pospelov & Ritz 2007



Dark matter, gamma-rays, 511 keV photons

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





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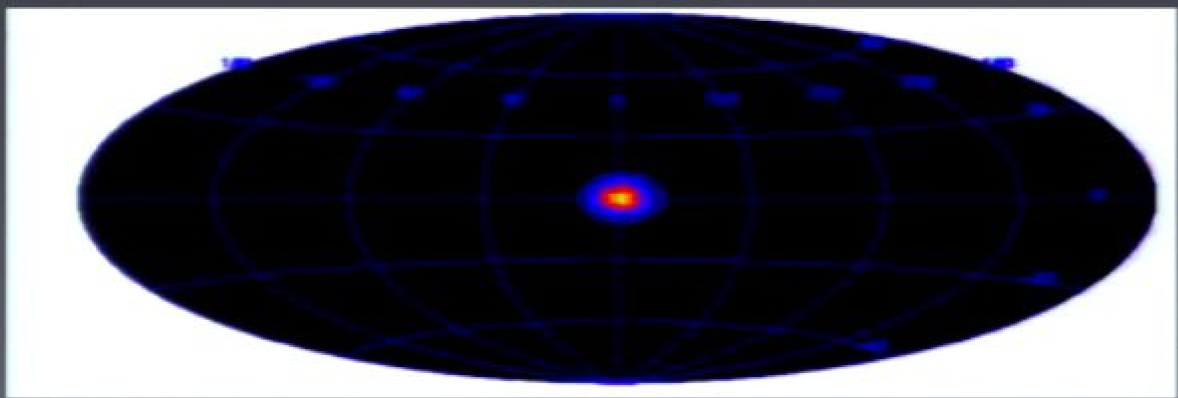

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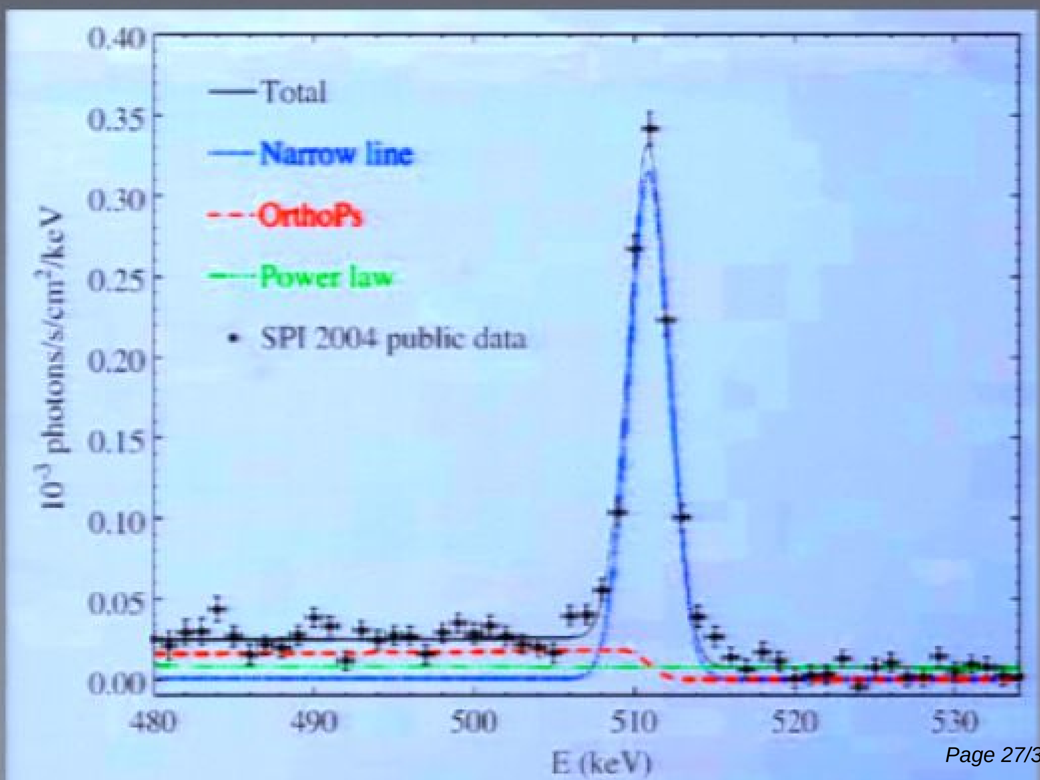

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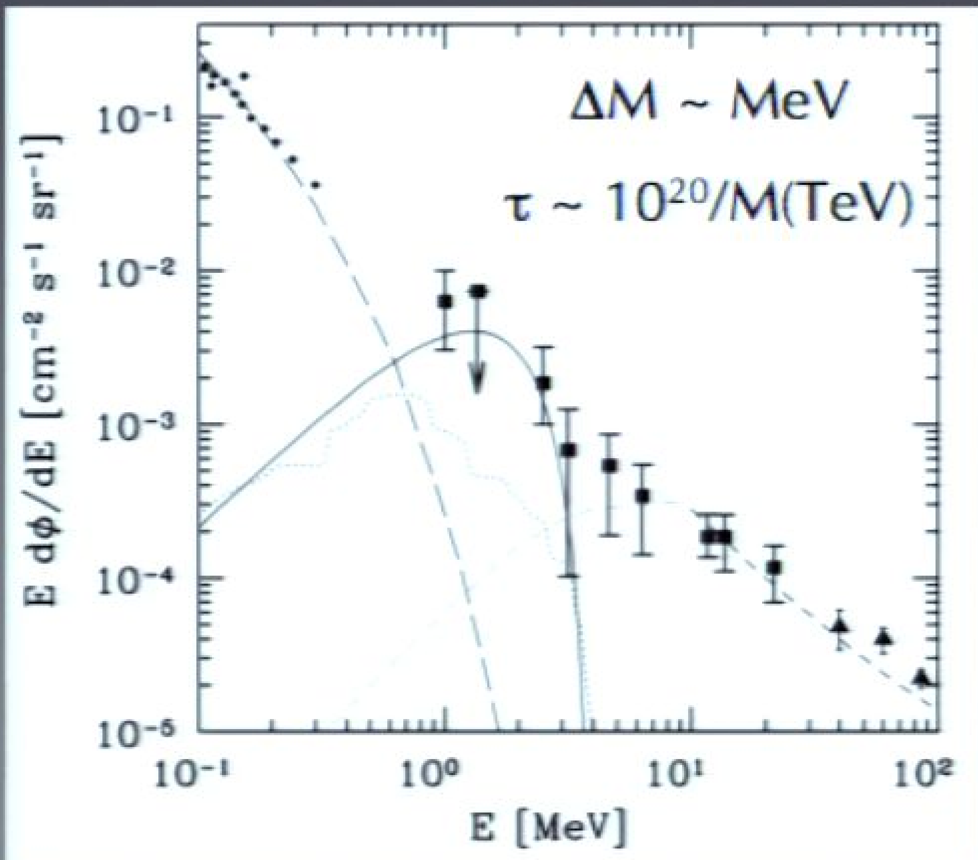

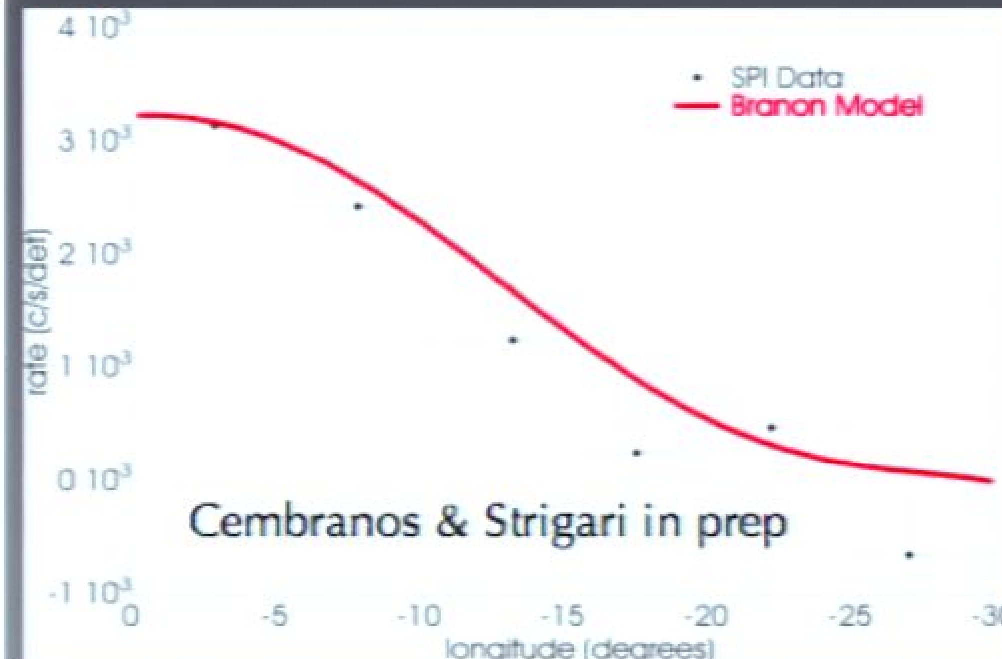

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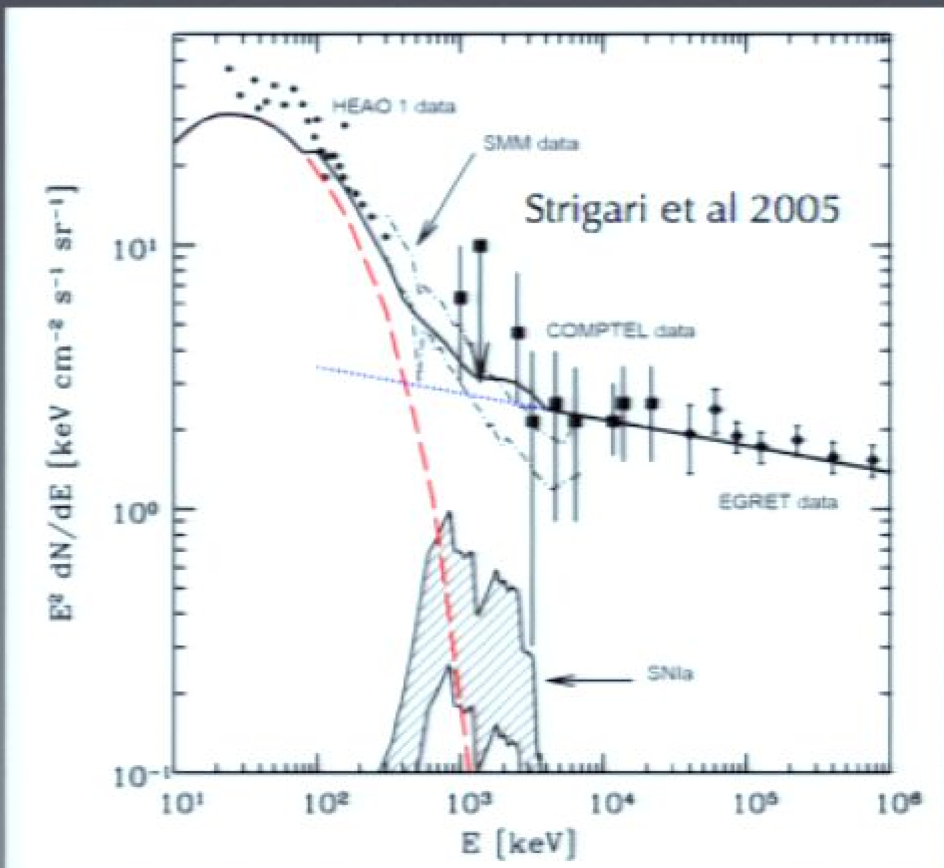

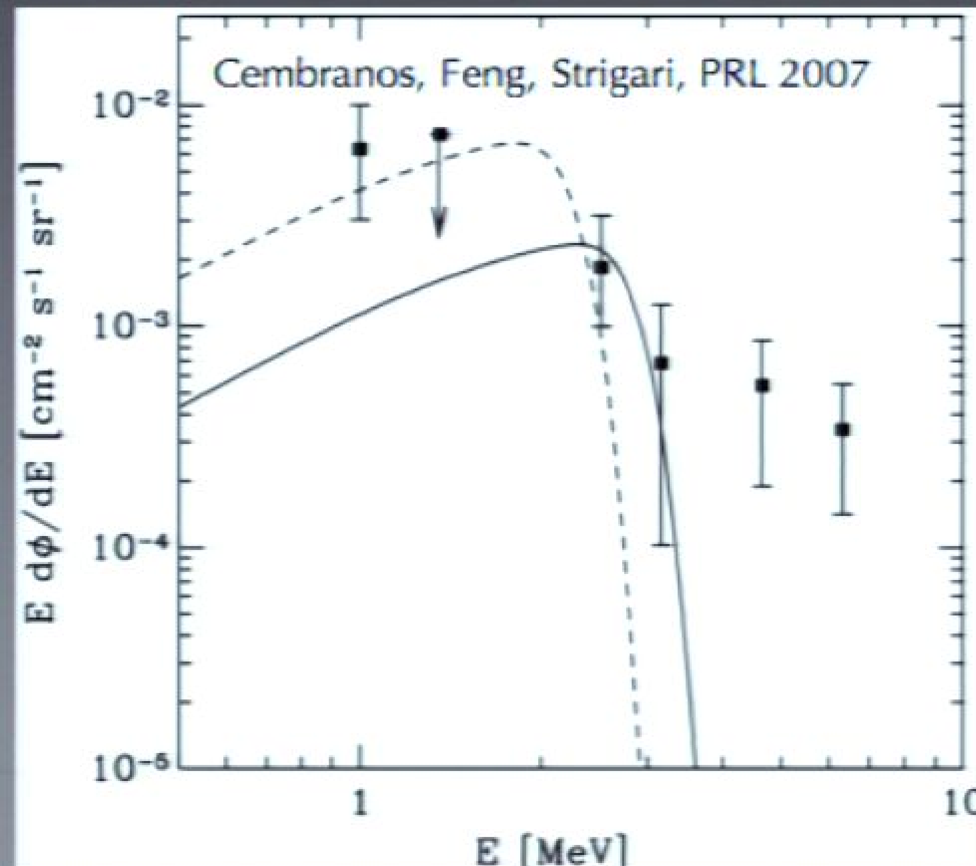

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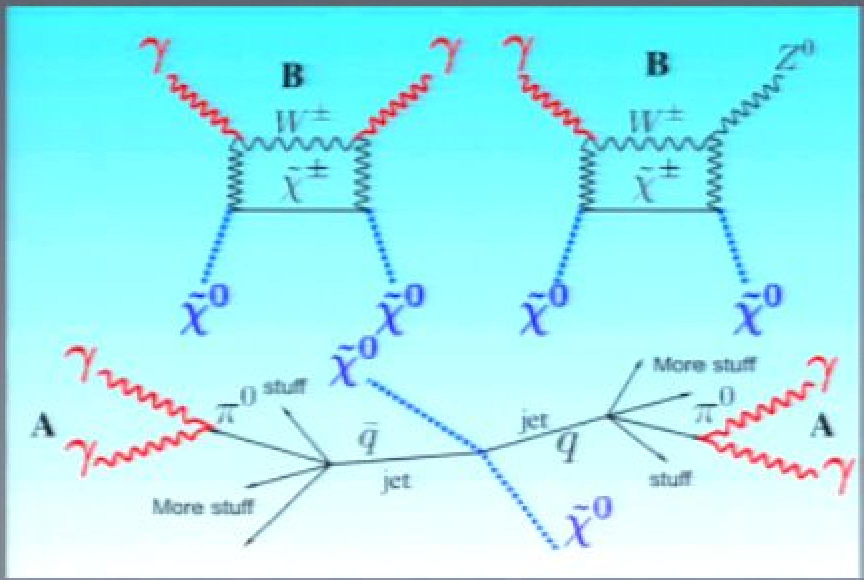

Contribution from line and continuum

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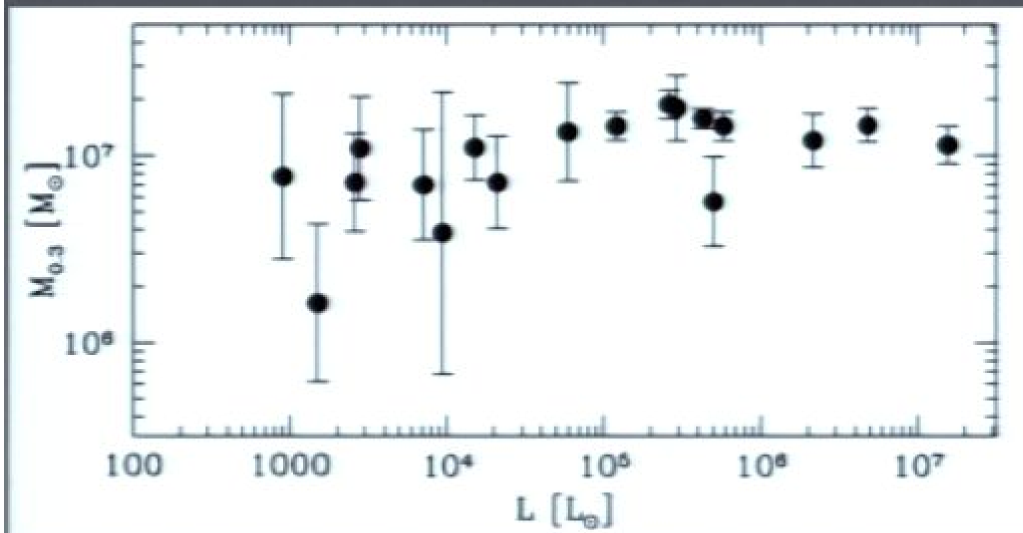
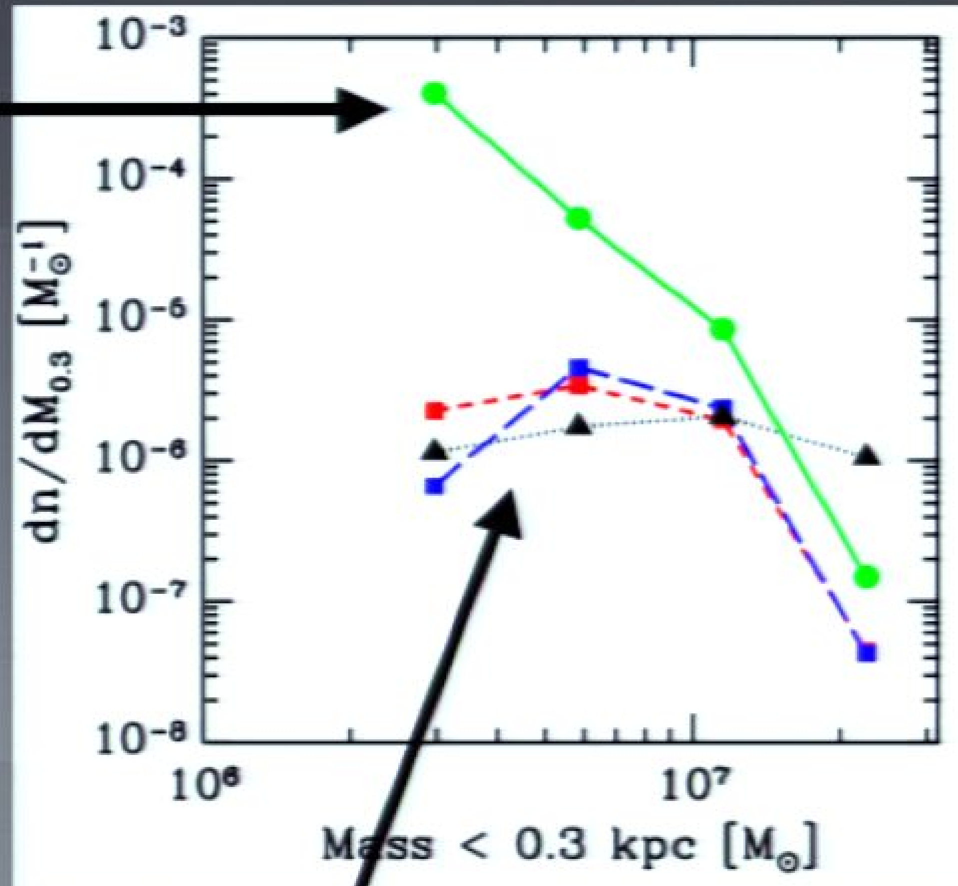
Entire predicted distribution of dark halos





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