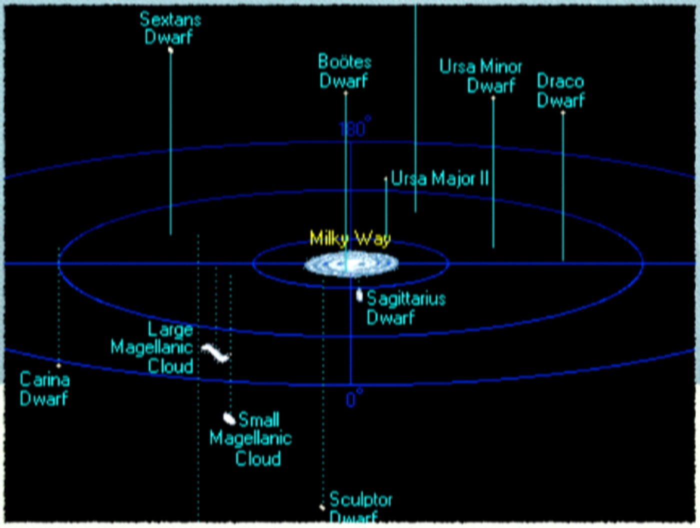
Title: TBA

Date: Jul 24, 2012 11:00 AM

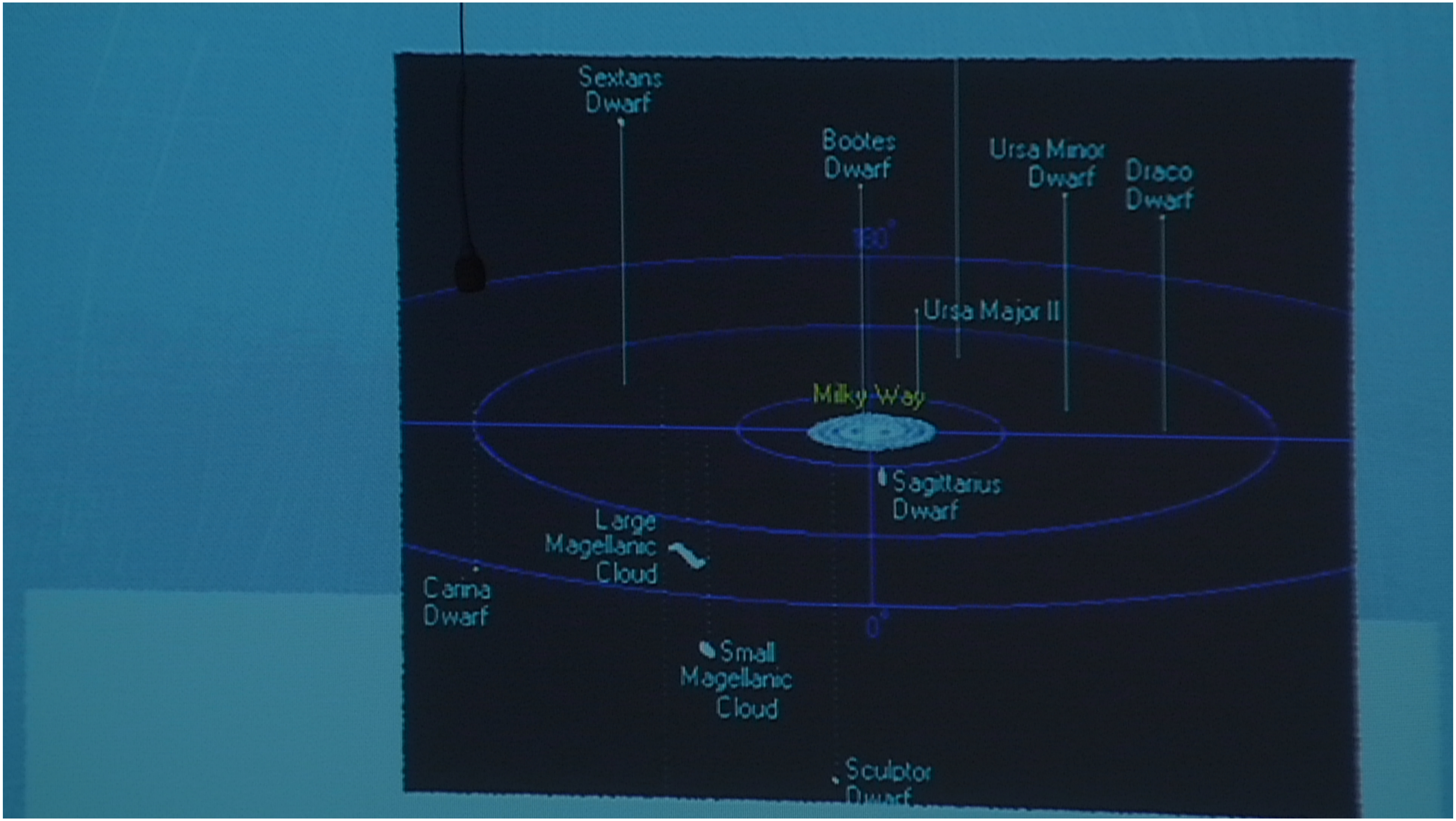
URL: http://pirsa.org/12070000

Abstract: TBA

Dark matter densities on small scales

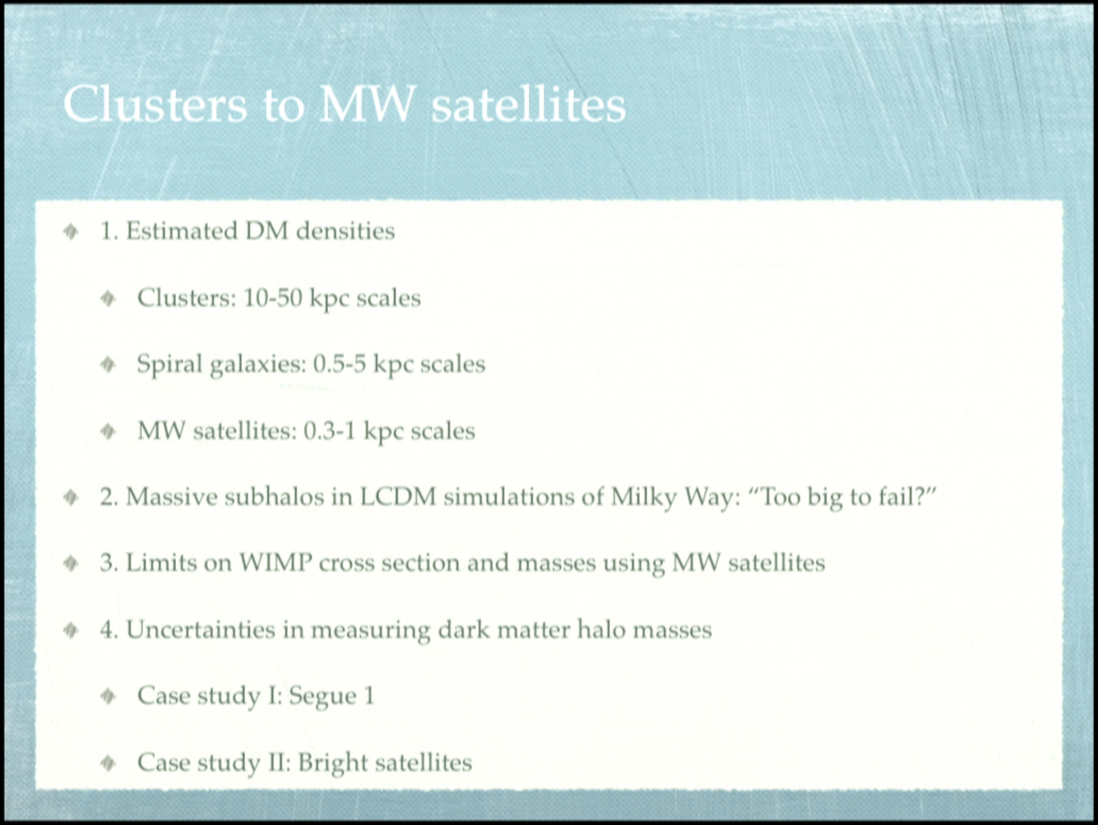


Manoj Kaplinghat, University of California, Irvine, USA


Sextans Dwarf
Bootes Dwarf
Ursa Minor Dwarf
Draco Dwarf
180°
Ursa Major II
Milky Way
Sagittarius Dwarf
Large Magellanic Cloud
Carina Dwarf
0°
Small Magellanic Cloud
Sculptor Dwarf

Clusters to MW satellites

- 1. Estimated DM densities
  - Clusters: 10-50 kpc scales
  - Spiral galaxies: 0.5-5 kpc scales
  - MW satellites: 0.3-1 kpc scales
- 2. Massive subhalos in LCDM simulations of Milky Way: “Too big to fail?”
- 3. Limits on WIMP cross section and masses using MW satellites
- 4. Uncertainties in measuring dark matter halo masses
  - Case study I: Segue 1
  - Case study II: Bright satellites



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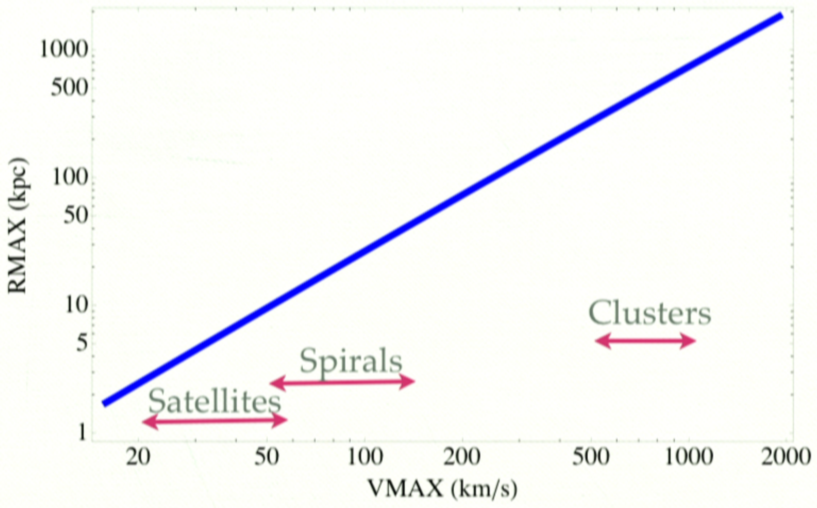
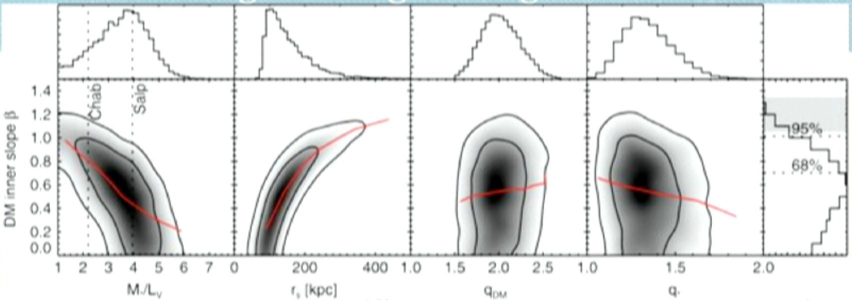
Size-Velocity (Mass) relation in hierarchical structure formation

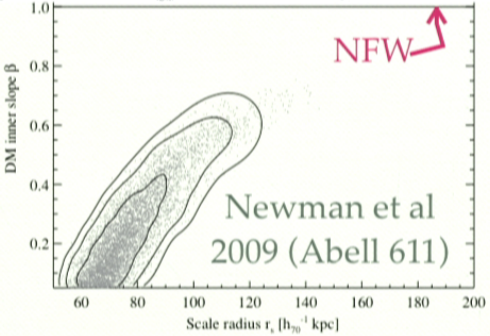


Clusters: weak lensing + strong lensing + kinematics



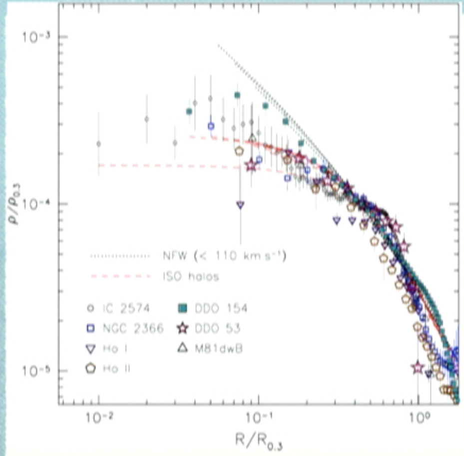
Newman et al 2011 (Abell 383)

These are both very massive clusters, with total mass in the vicinity of 10^{15} M_{sun}.

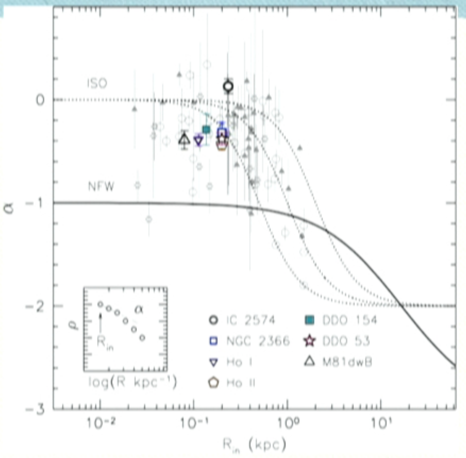


Newman et al 2009 (Abell 611)

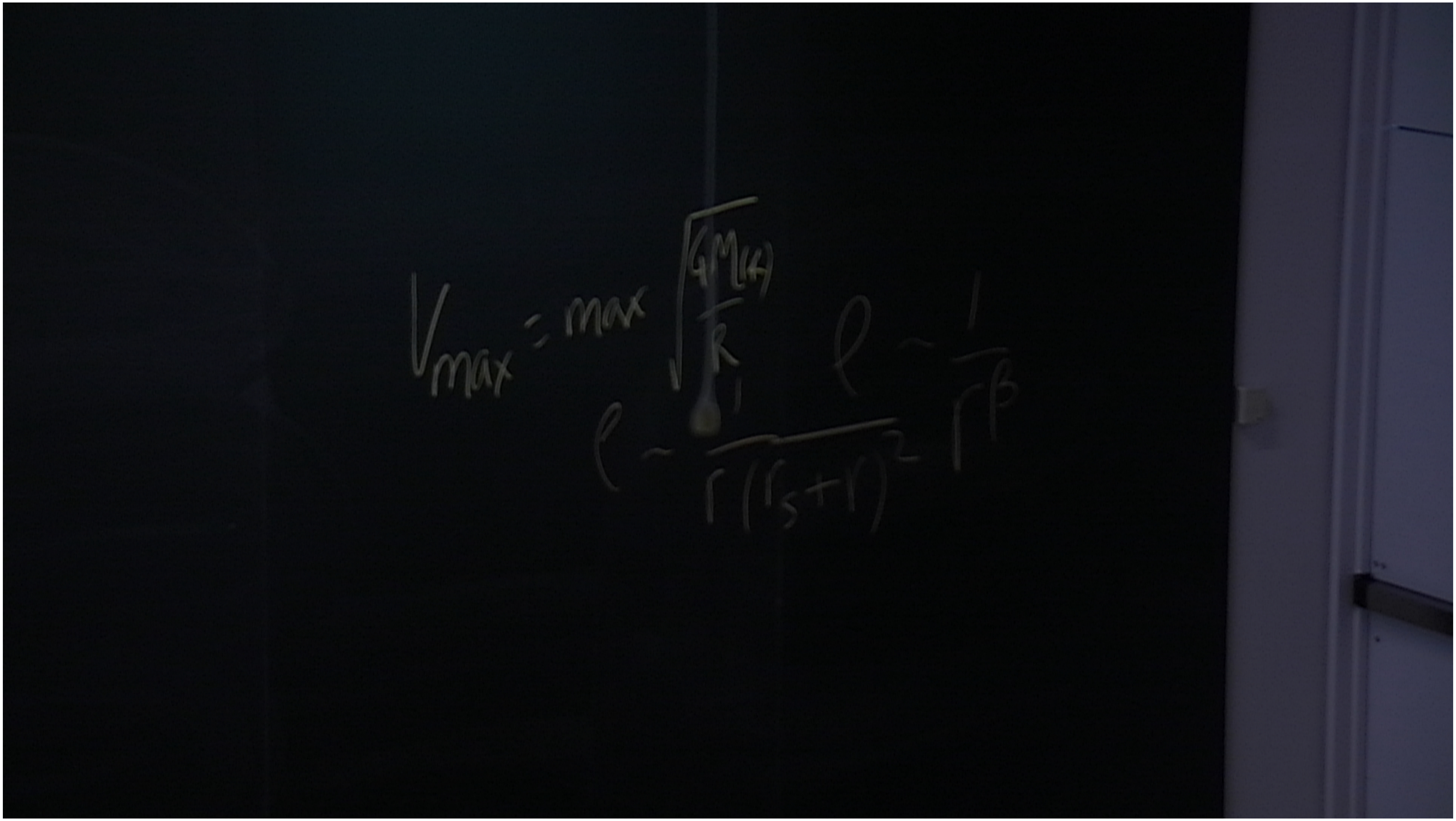
Nearby spiral galaxies



Oh et al 2011 (THINGS)



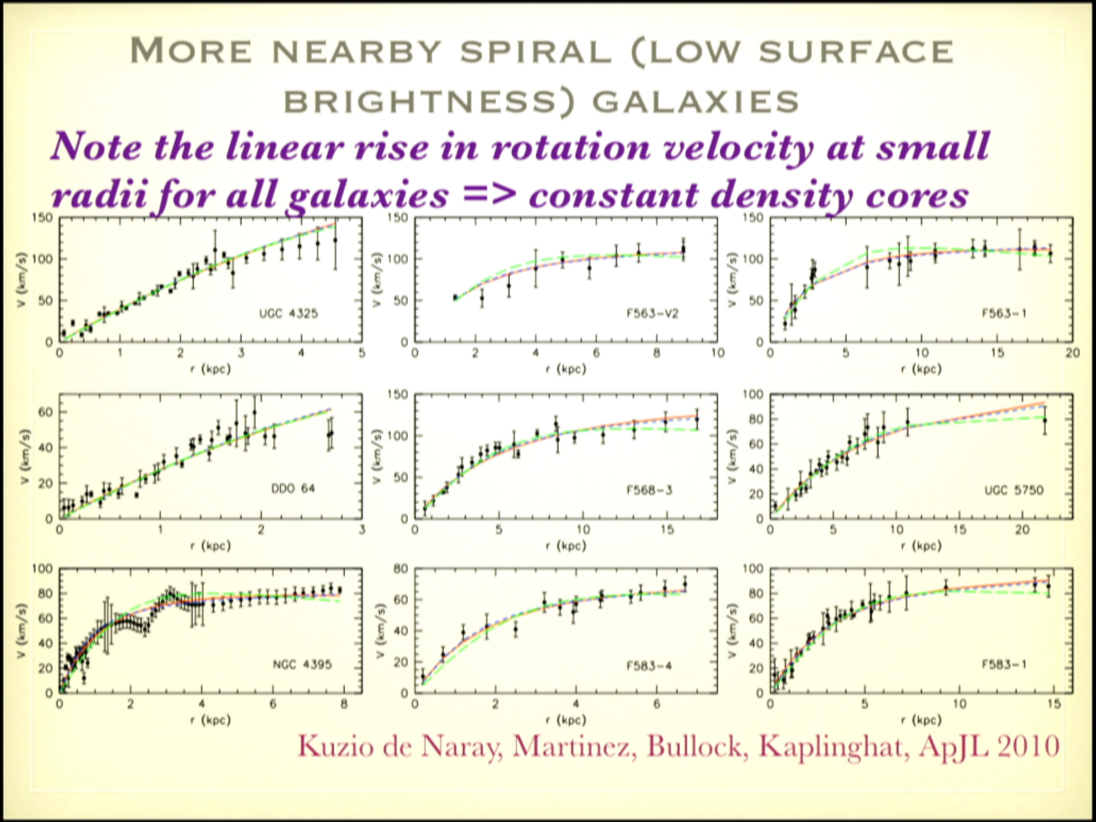
close-by (< 5 Mpc),
mostly DM dominated,
small (V ~ 30-100 km/s)



$$V_{max} = \max \sqrt{\frac{GM(r)}{r}}$$

$$\rho \sim \frac{1}{r(r_s+r)^2}$$

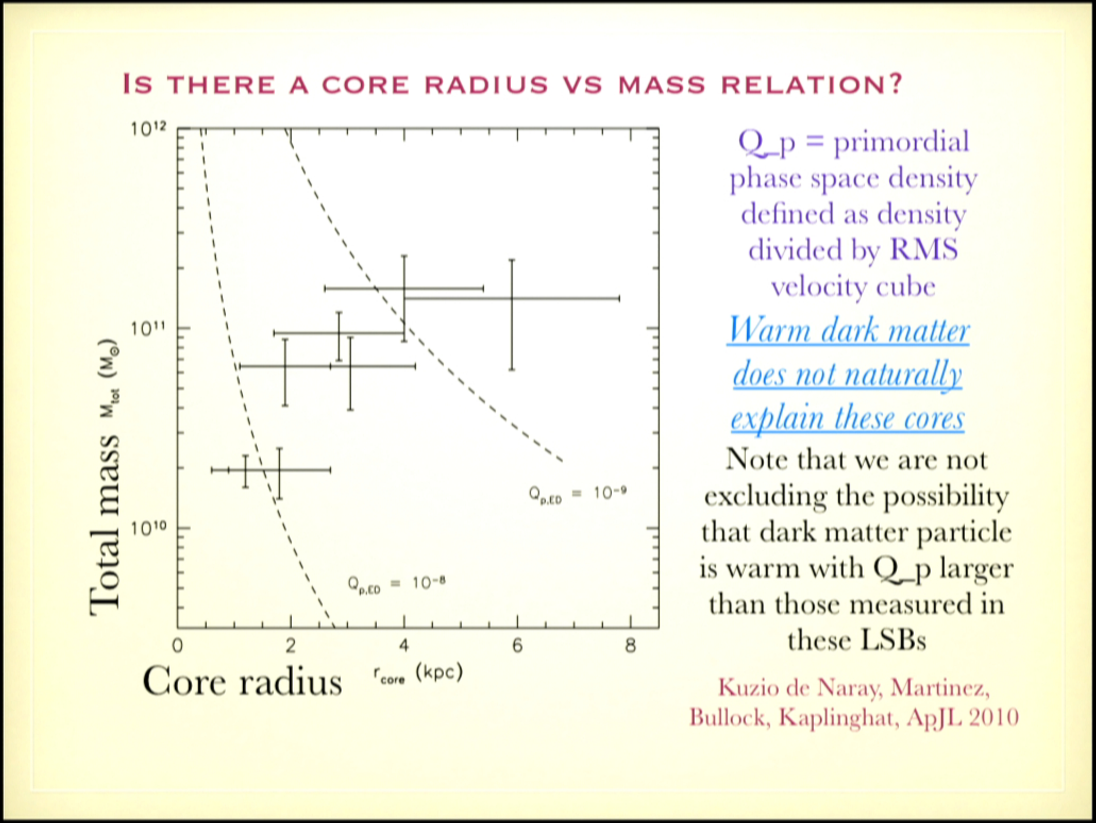
$$\rho \sim \frac{1}{r^\beta}$$



MORE NEARBY SPIRAL (LOW SURFACE BRIGHTNESS) GALAXIES

Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010



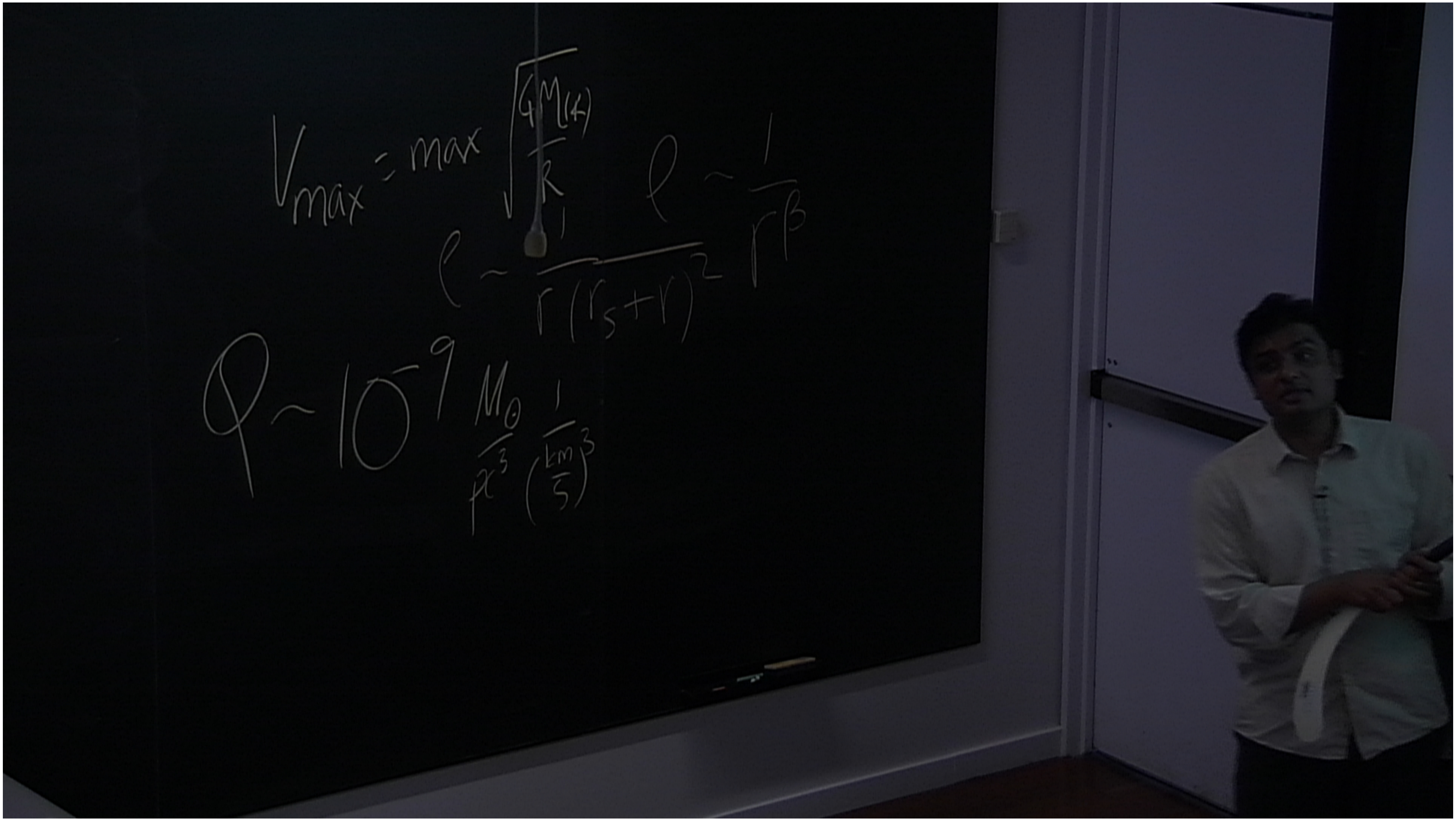
IS THERE A CORE RADIUS VS MASS RELATION?

Q_p = primordial phase space density defined as density divided by RMS velocity cube

Warm dark matter does not naturally explain these cores

Note that we are not excluding the possibility that dark matter particle is warm with Q_p larger than those measured in these LSBs

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

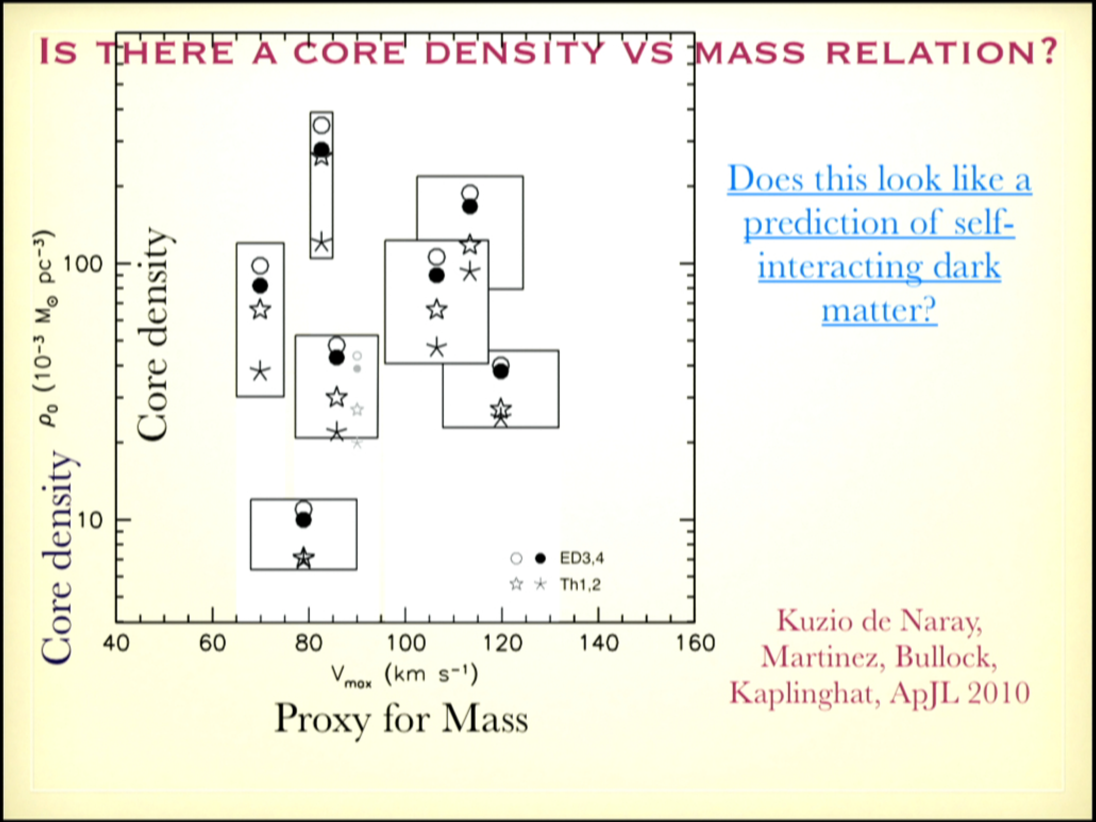


$$V_{max} = \max \sqrt{\frac{GM(r)}{r}}$$

$$\rho \sim \frac{1}{r^{\beta}}$$

$$\rho \sim \frac{1}{r(r_s+r)^2}$$

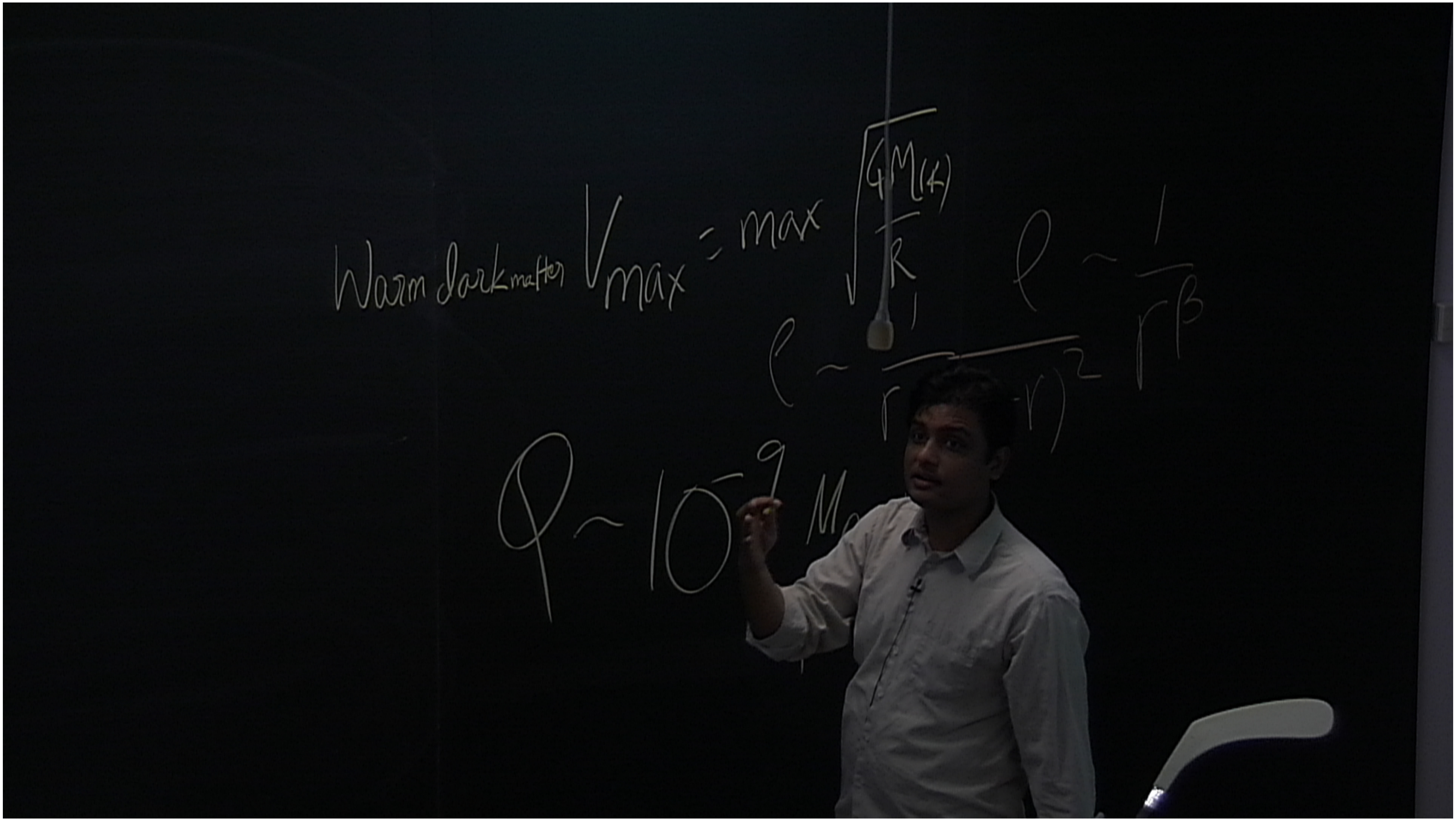
$$\phi \sim 10^{-9} \frac{M_\odot}{pc^3} \frac{1}{\left(\frac{km}{s}\right)^3}$$



IS THERE A CORE DENSITY VS MASS RELATION?

Does this look like a prediction of self-interacting dark matter?

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

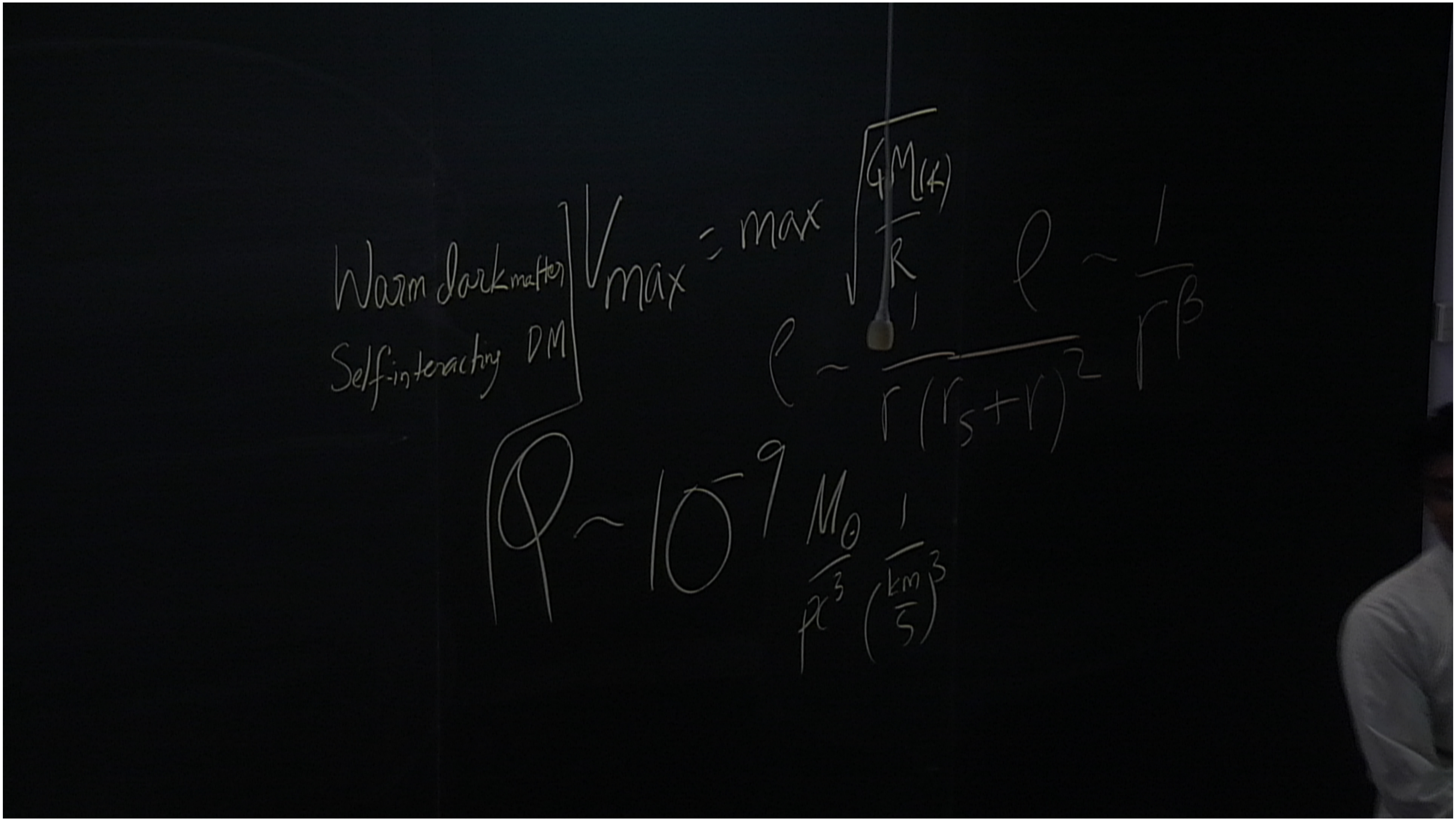


Warm dark matter $V_{max} = \max \sqrt{\frac{GM(r)}{r}}$

$\rho \sim \frac{1}{r^{\beta}}$

$\rho \sim \frac{1}{r \quad r)^2}$

$\rho \sim 10^{-9} M$



Warm dark matter

Self-interacting DM

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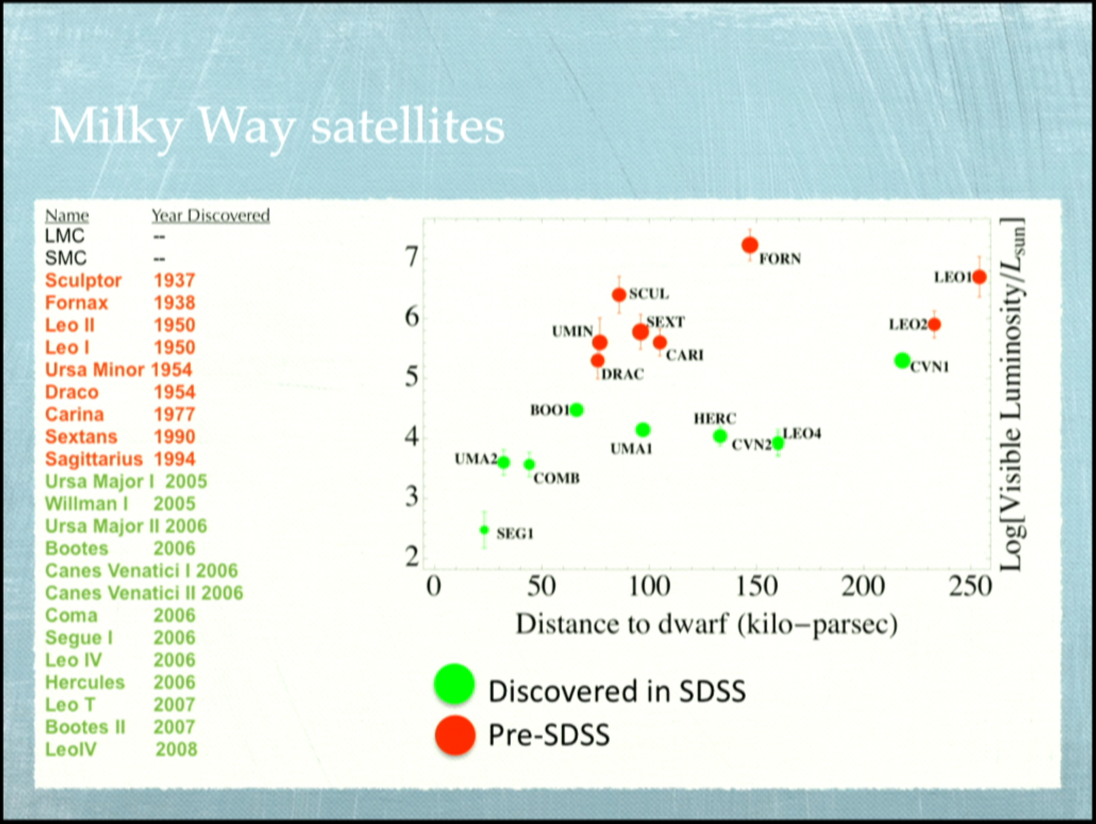
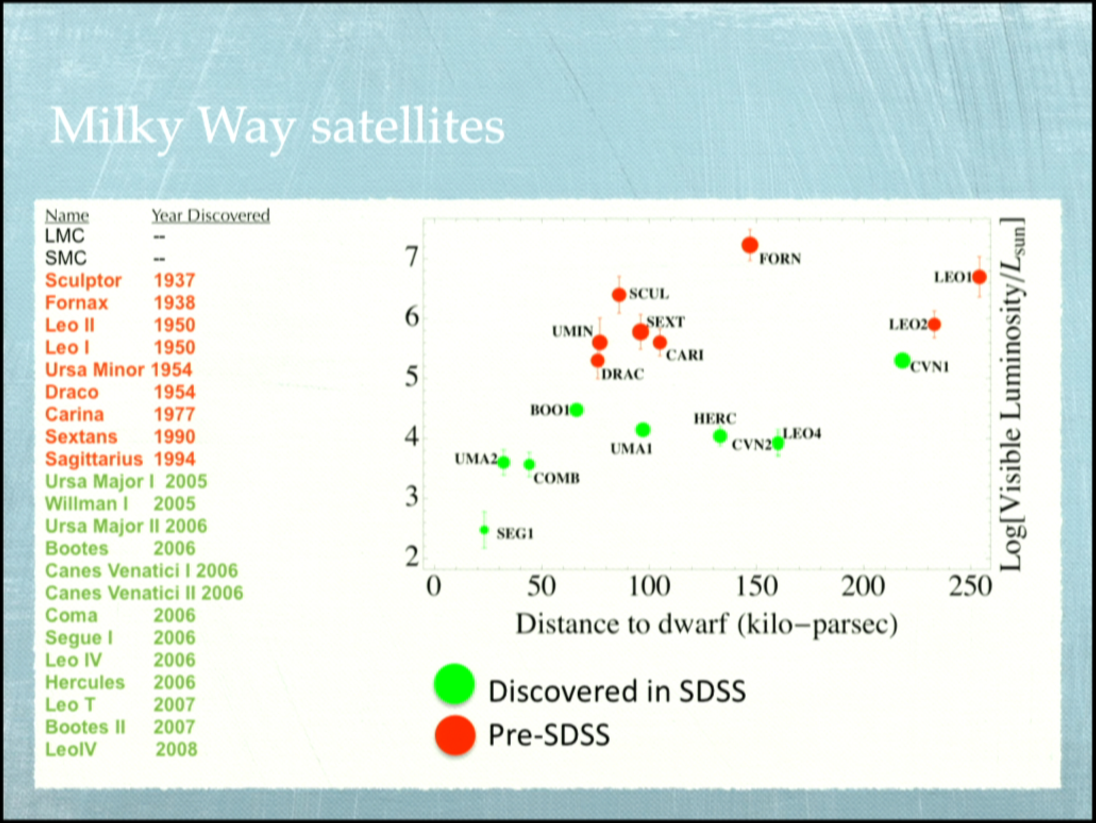


Milky Way satellites

Name	Year Discovered
LMC	--
SMC	--
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
LeoIV	2008

🟢 Discovered in SDSS

🔴 Pre-SDSS



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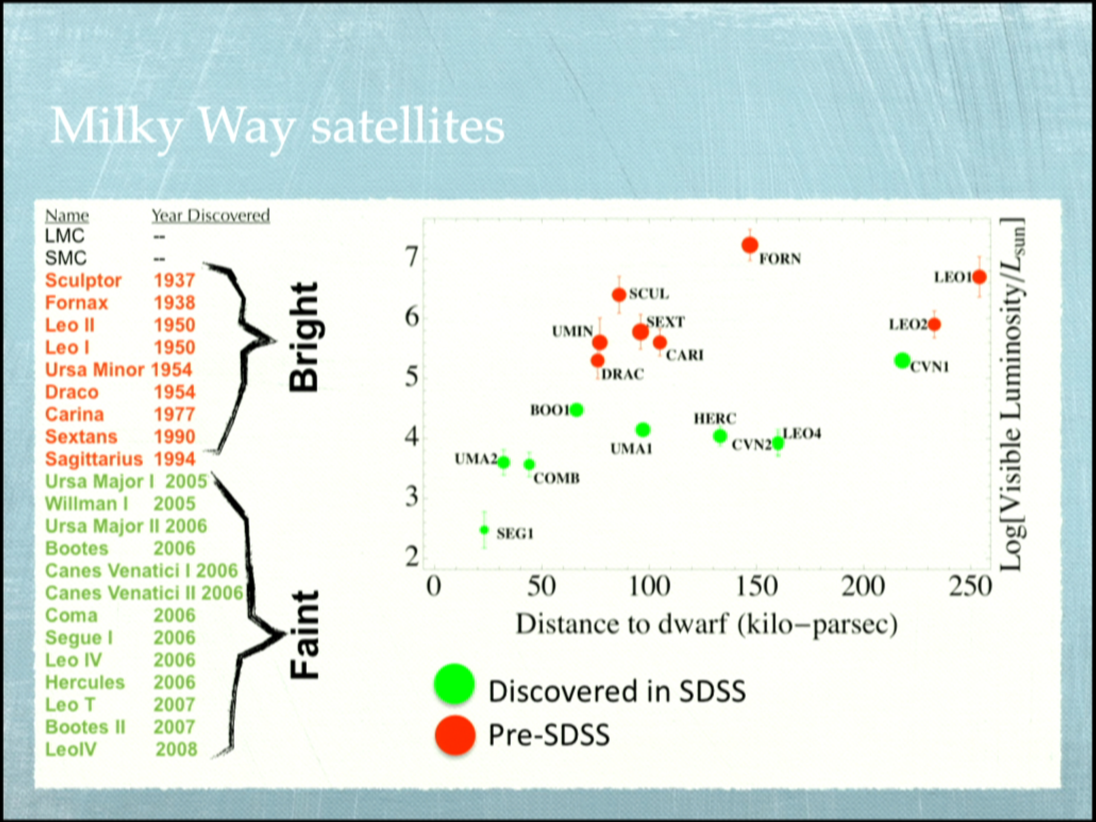

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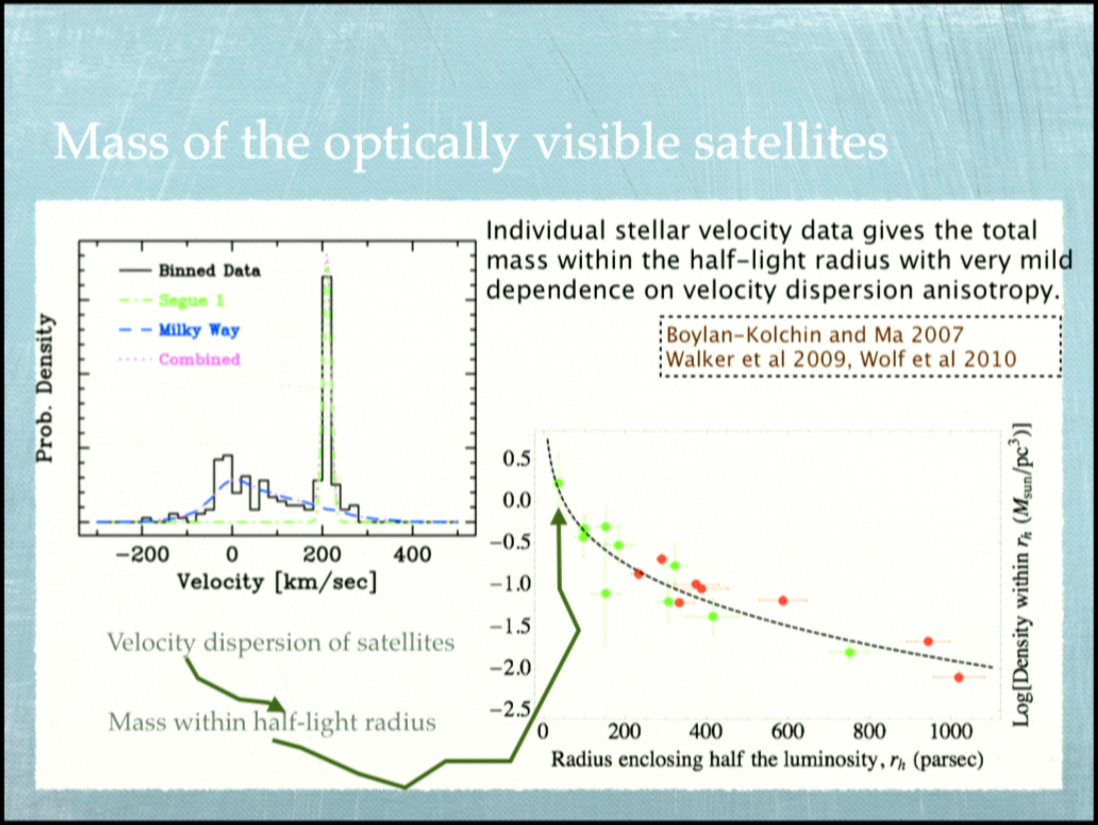
Bright

Faint

● Discovered in SDSS

● Pre-SDSS



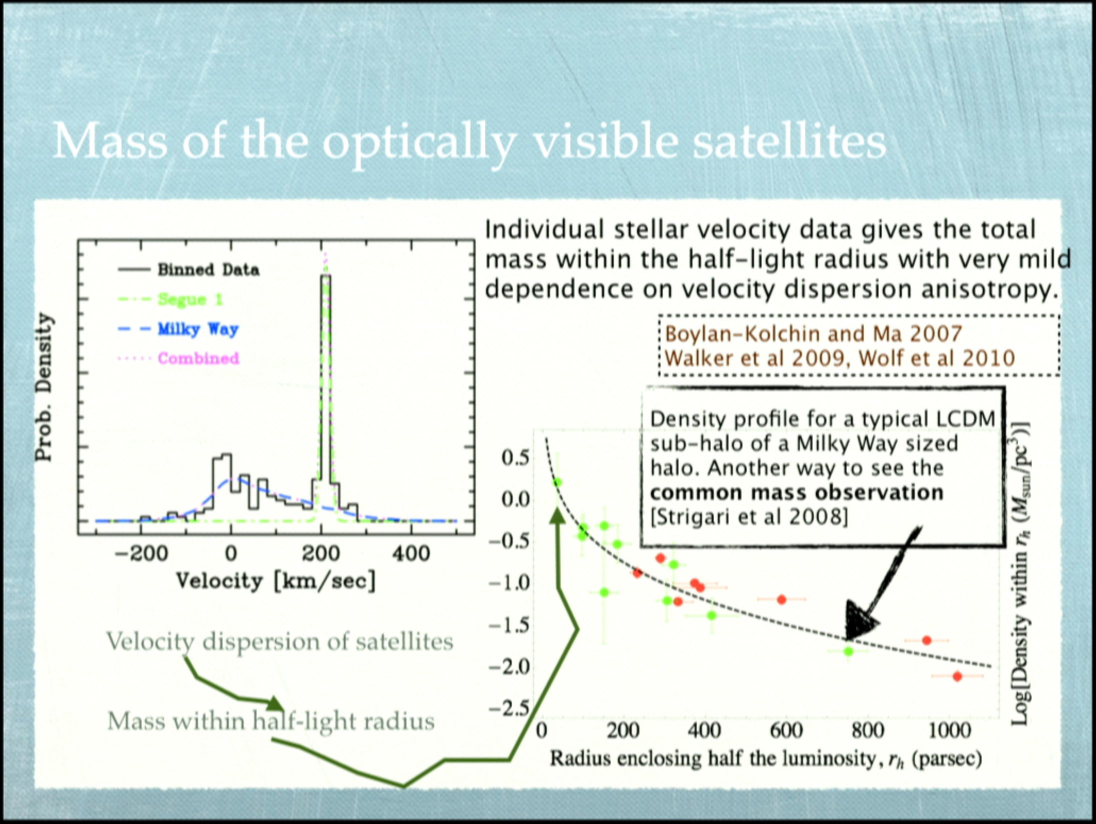
Mass of the optically visible satellites

Individual stellar velocity data gives the total mass within the half-light radius with very mild dependence on velocity dispersion anisotropy.

Boylan-Kolchin and Ma 2007
Walker et al 2009, Wolf et al 2010

Velocity dispersion of satellites

Mass within half-light radius



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Density profile for a typical LCDM sub-halo of a Milky Way sized halo. Another way to see the **common mass observation** [Strigari et al 2008]

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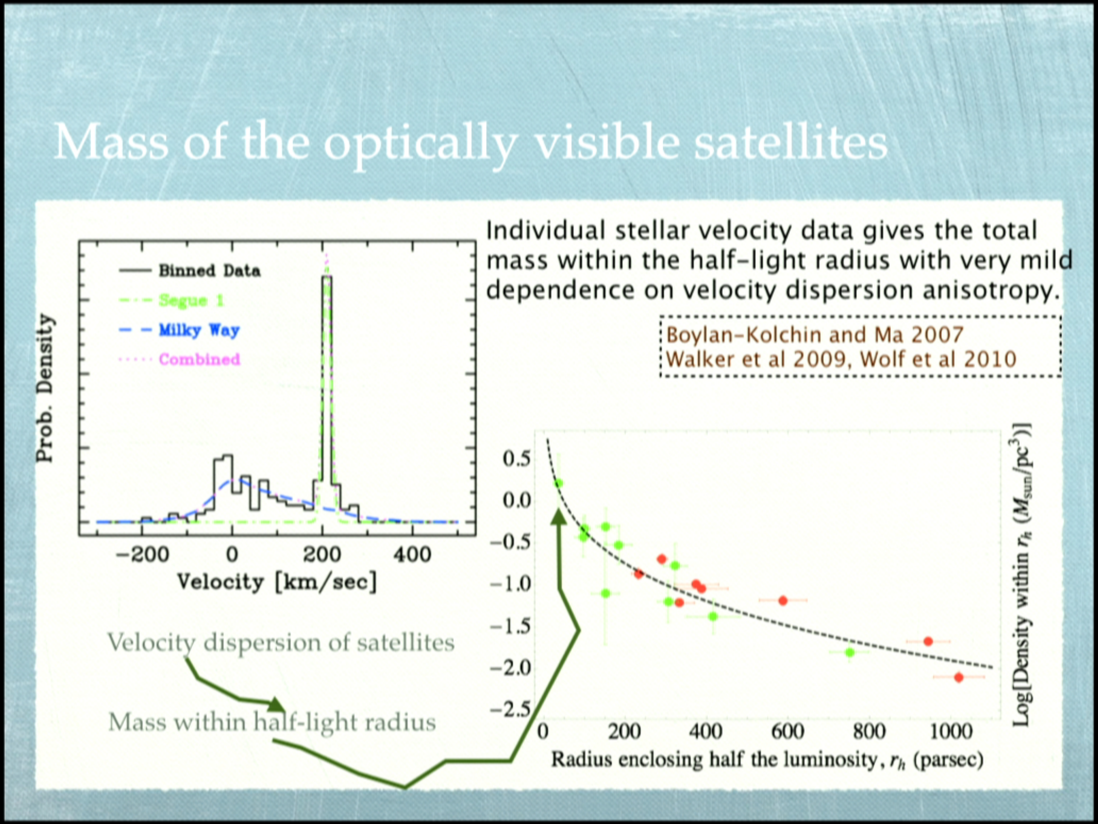

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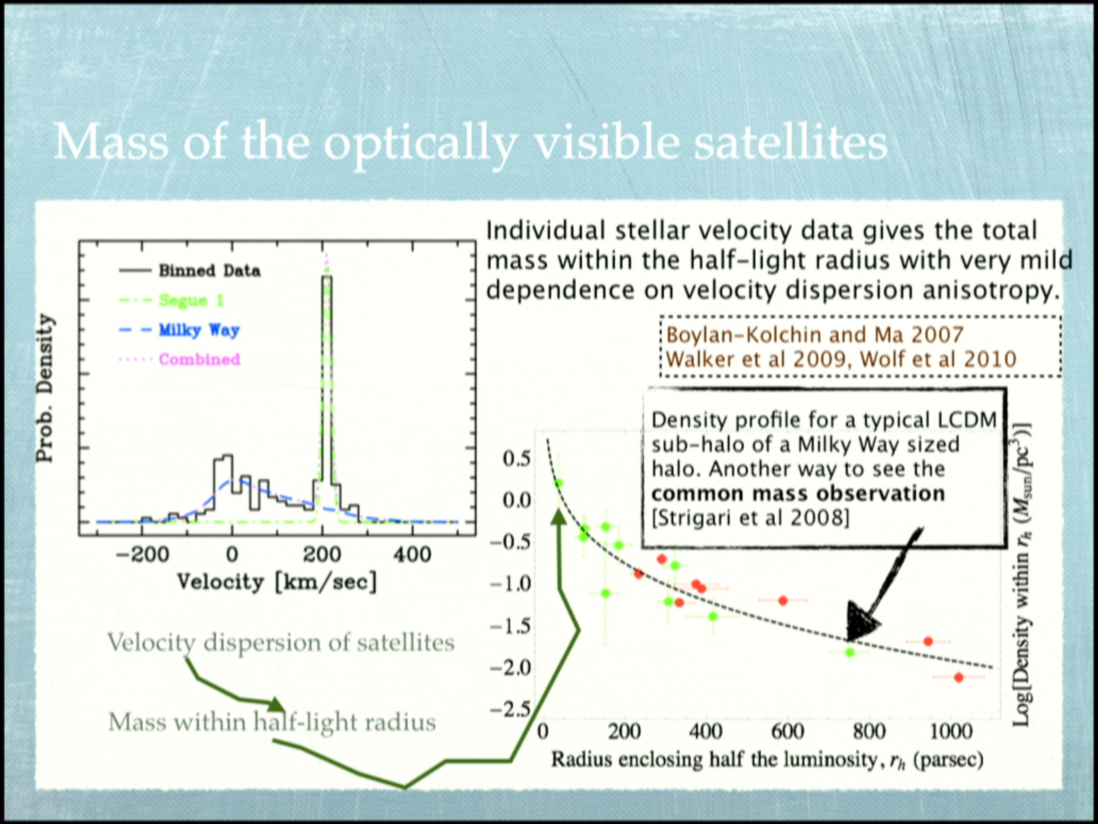

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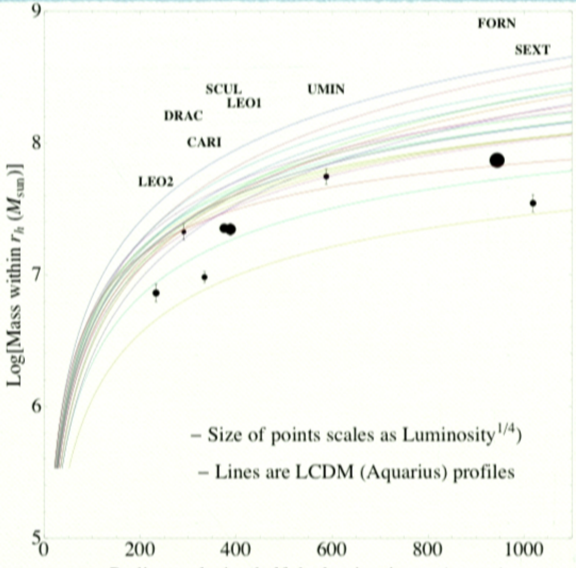
Velocity dispersion of satellites

Mass within half-light radius

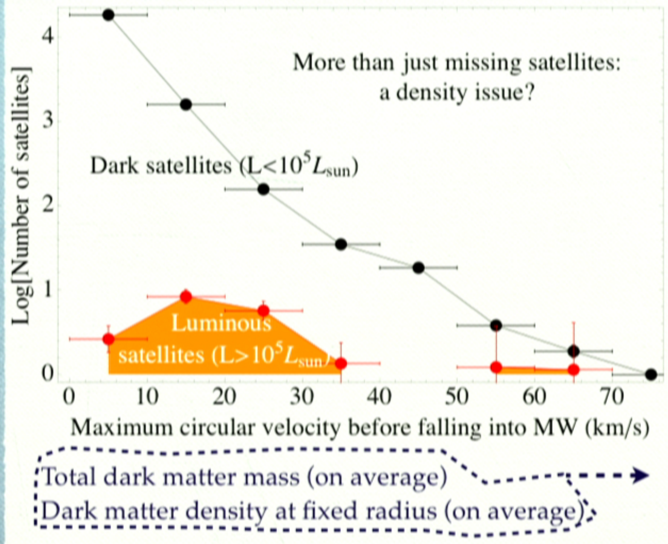
1: Too big to fail? The most massive apparently don't light up...

- NFW fits to mass profiles of the most massive subhalos from Aquarius simulation [Springel et al 2009] shown
- Bright satellites shown
- **Measured mass within half-light radius is too small to be consistent with the most massive subhalos**

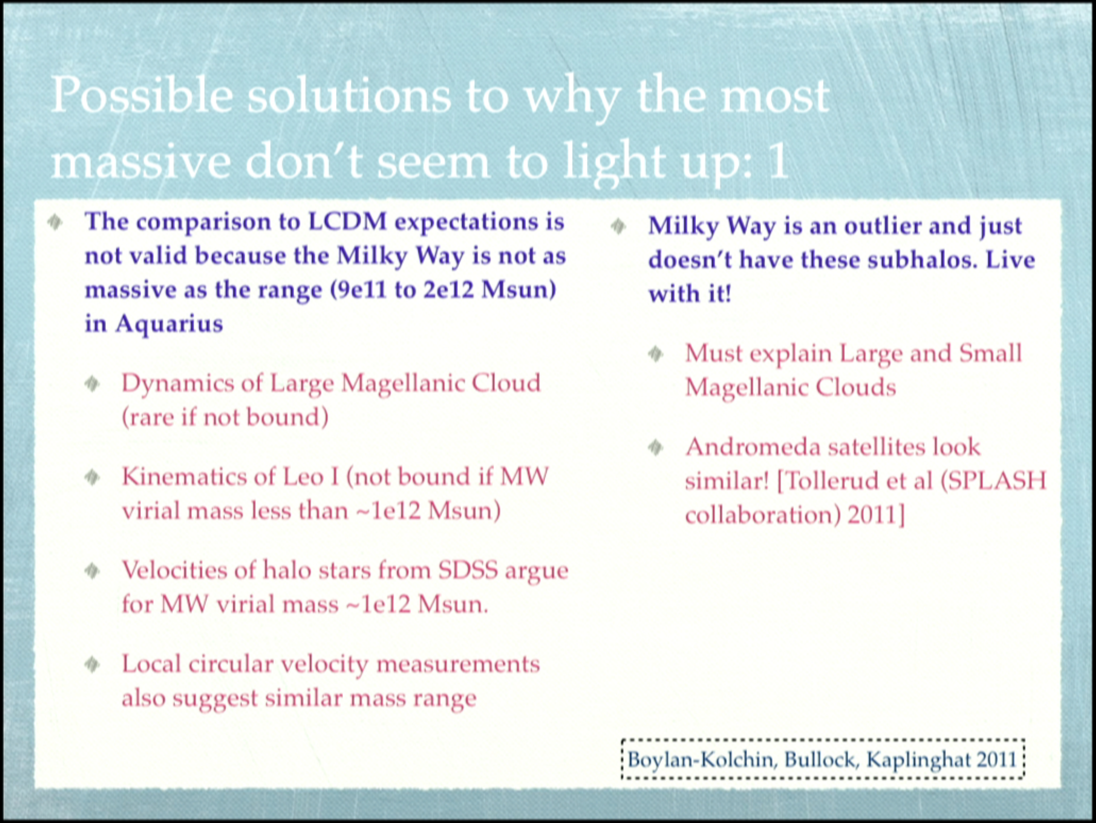
Boylan-Kolchin, Bullock, Kaplinghat 2011



Not the ``missing satellites" problem: observed satellites are not dense enough



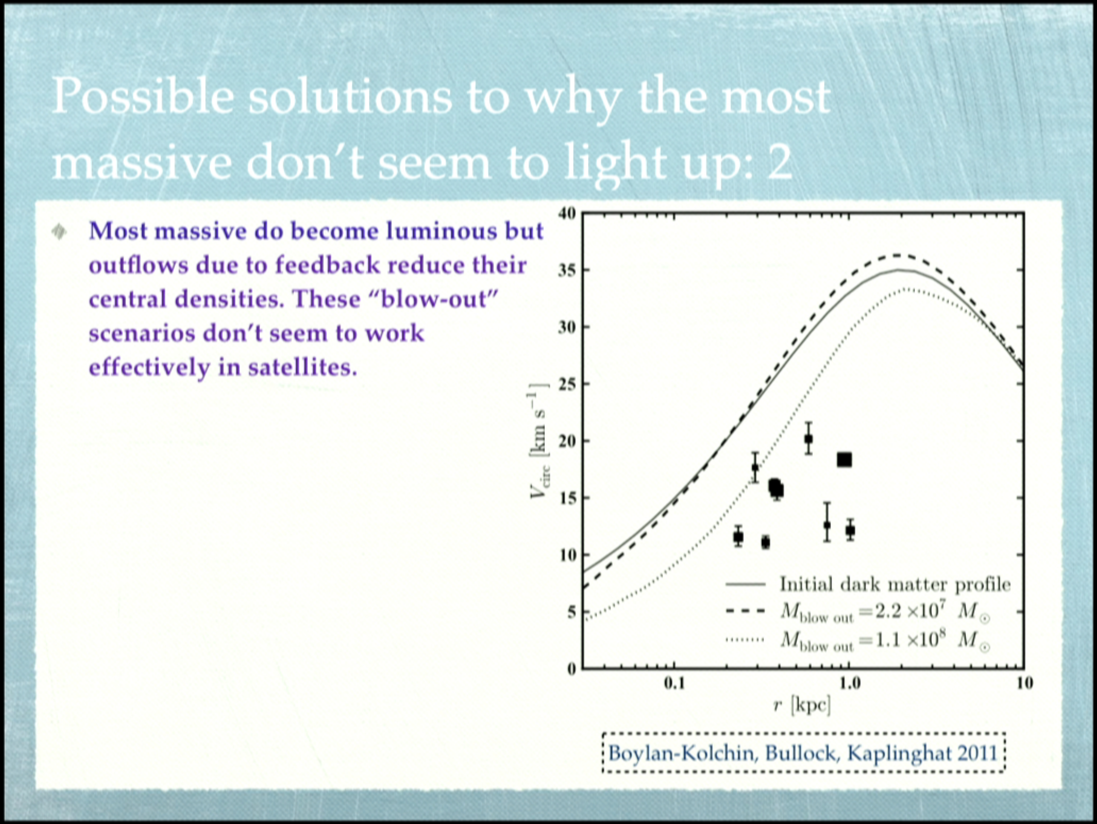
Brightest satellites are not dense enough in dark matter to inhabit the most massive subhalos predicted in LCDM.



Possible solutions to why the most massive don't seem to light up: 1

- **The comparison to LCDM expectations is not valid because the Milky Way is not as massive as the range (9e11 to 2e12 Msun) in Aquarius**
  - Dynamics of Large Magellanic Cloud (rare if not bound)
  - Kinematics of Leo I (not bound if MW virial mass less than ~1e12 Msun)
  - Velocities of halo stars from SDSS argue for MW virial mass ~1e12 Msun.
  - Local circular velocity measurements also suggest similar mass range
- **Milky Way is an outlier and just doesn't have these subhalos. Live with it!**
  - Must explain Large and Small Magellanic Clouds
  - Andromeda satellites look similar! [Tollerud et al (SPLASH collaboration) 2011]

Boylan-Kolchin, Bullock, Kaplinghat 2011



Possible solutions to why the most massive don't seem to light up: 2

- **Most massive do become luminous but outflows due to feedback reduce their central densities. These "blow-out" scenarios don't seem to work effectively in satellites.**

Boylan-Kolchin, Bullock, Kaplinghat 2011

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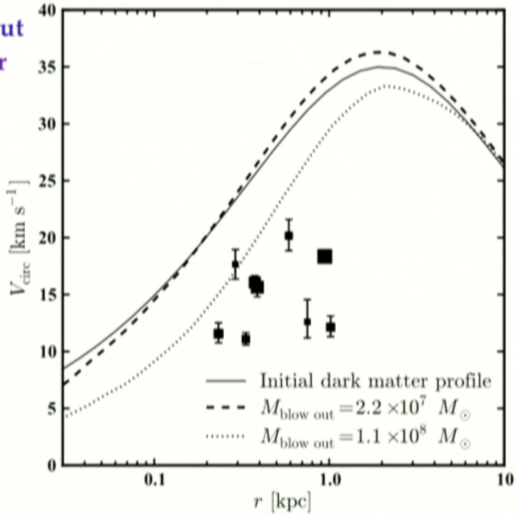

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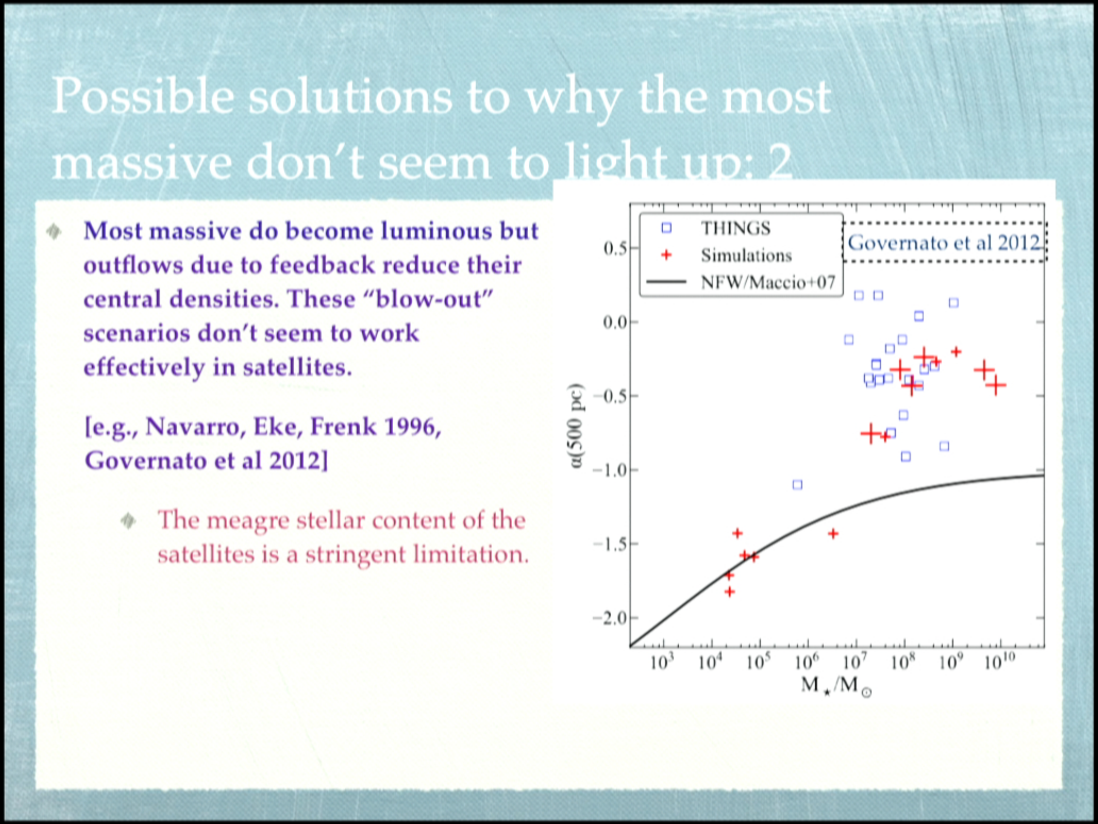

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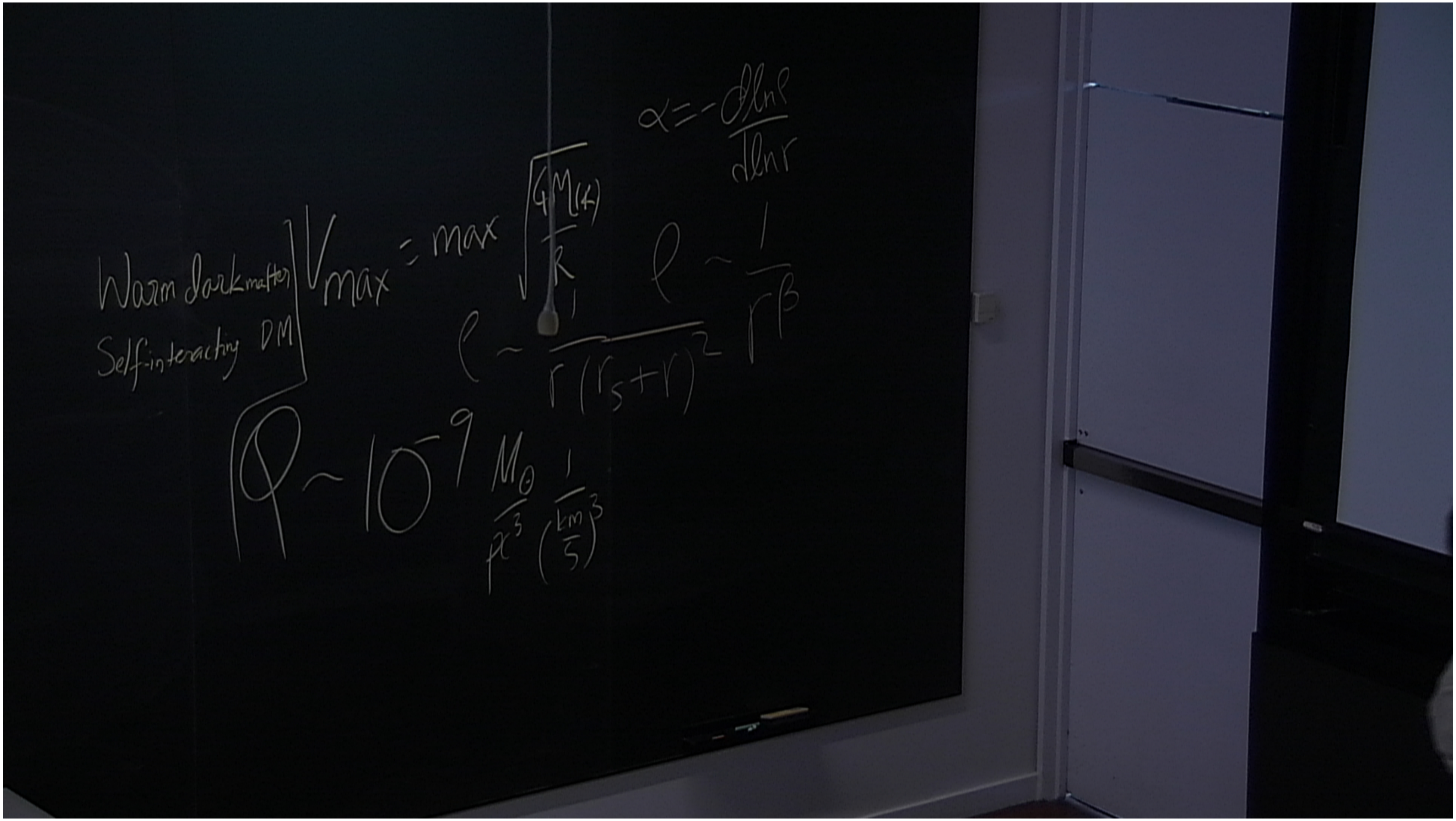

Warm dark matter

Self-interacting DM

$$V_{max} = \max \sqrt{\frac{G M(r)}{R}}$$

$$\alpha = -\frac{d\ln\rho}{d\ln r}$$

$$\rho \sim \frac{1}{r(r_s+r)^2} \qquad \rho \sim \frac{1}{r^\beta}$$

$$\rho \sim 10^{-9} \frac{M_\odot}{pc^3} \frac{1}{\left(\frac{km}{s}\right)^3}$$

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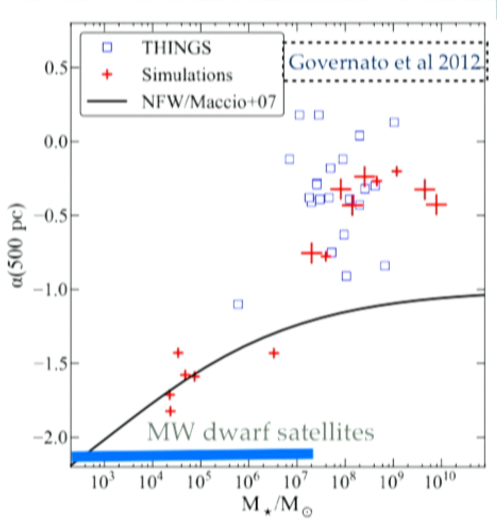

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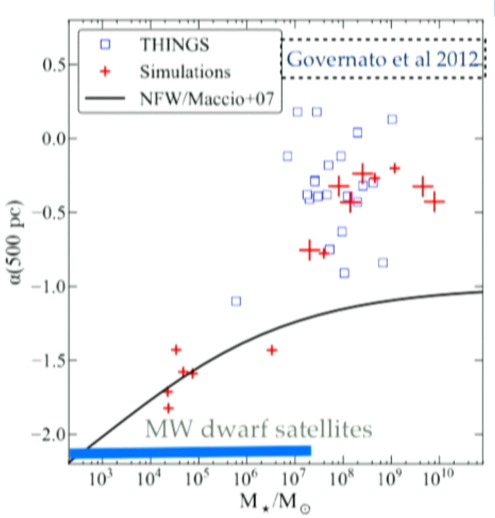
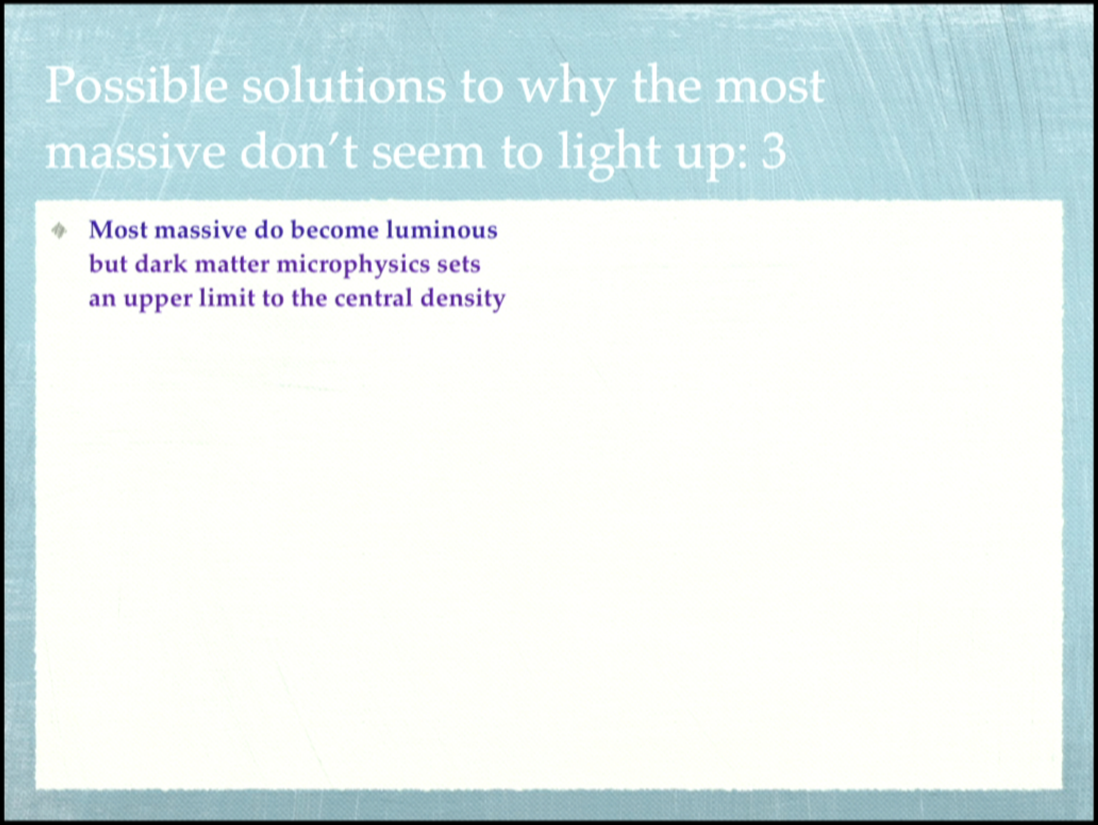
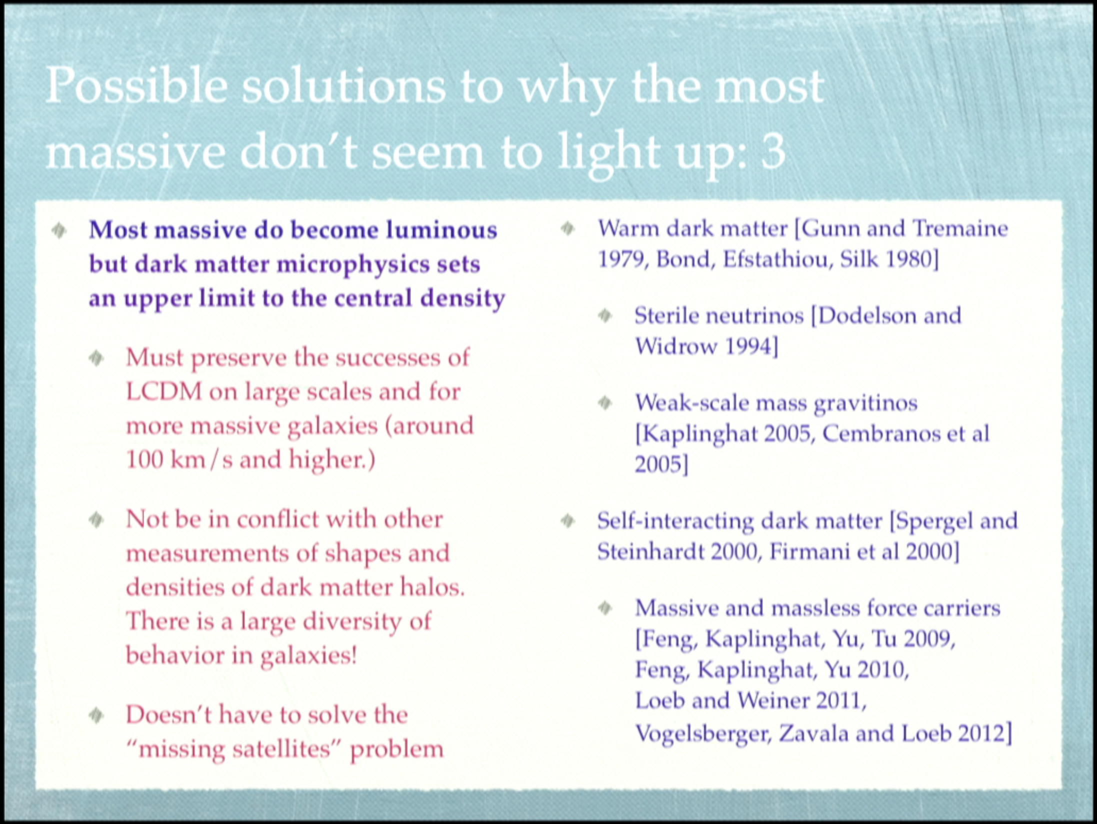


Simulation	Galaxies stellar masses $M_\odot$	DM part. mass $M_\odot$	Star part. mass ($M_\odot$)	Softening (pc)	Overdensity $\Delta\rho/\rho$	Particles within R_{vir}	V_{peak} km s^{-1}
Fields 1 & 2	10^{10}-10^8	1.6×10^5	8×10^3	170	0.38 – 0.03	3.4-0.05×10^6	100-40
Field 3 & 4	3×10^8-10^5	2×10^4	10^3	85	0.58 – -0.07	2-0.05×10^6	55-30
Field 5	10^8-$10^{3.5}$	6×10^3	4.2×10^2	64	0.01	2-0.05×10^6	35-10



Possible solutions to why the most massive don’t seem to light up: 3

- **Most massive do become luminous but dark matter microphysics sets an upper limit to the central density**

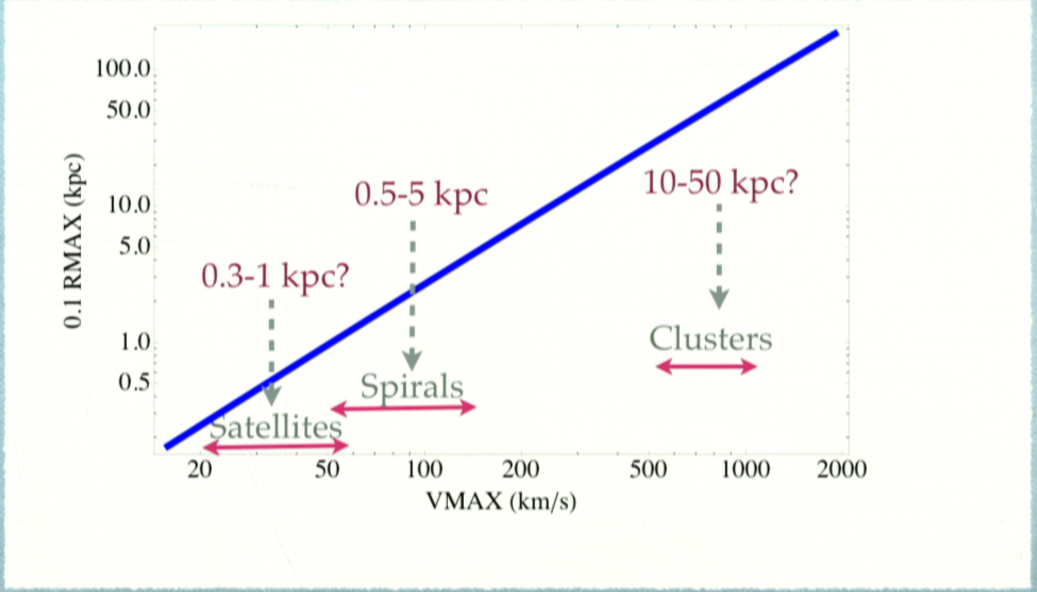


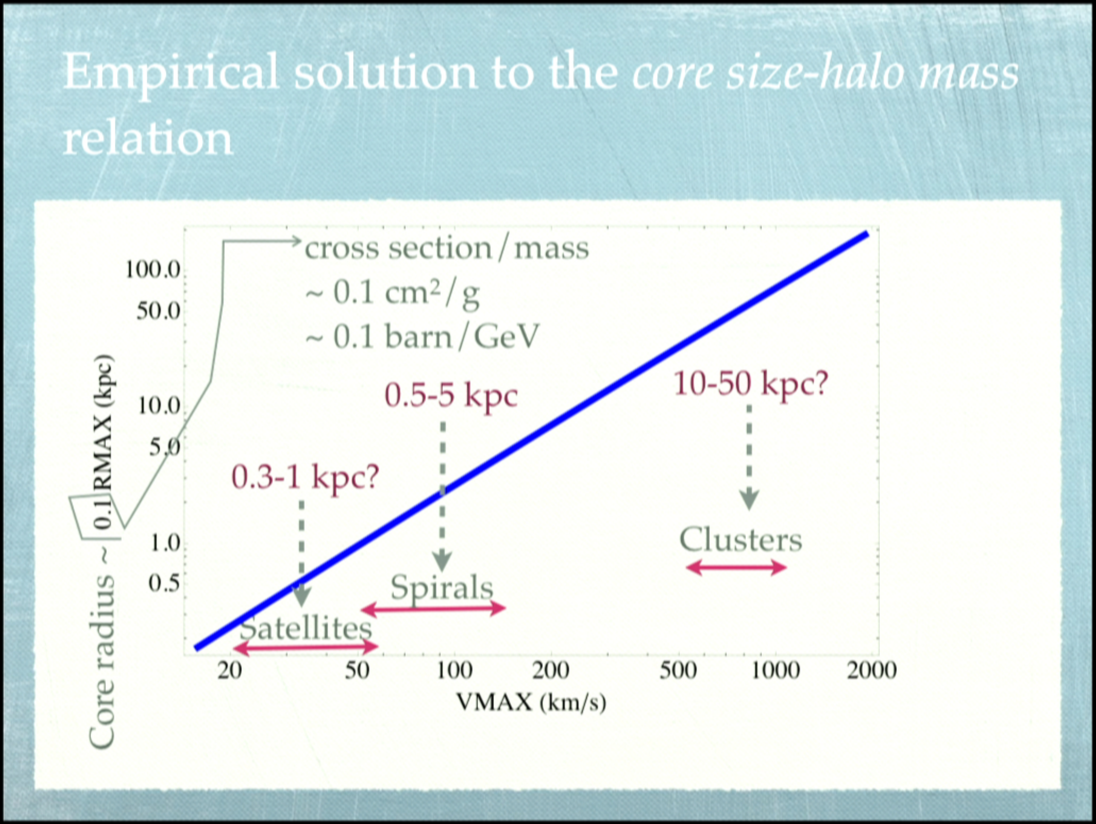
Possible solutions to why the most massive don't seem to light up: 3

- **Most massive do become luminous but dark matter microphysics sets an upper limit to the central density**
  - Must preserve the successes of LCDM on large scales and for more massive galaxies (around 100 km/s and higher.)
  - Not be in conflict with other measurements of shapes and densities of dark matter halos. There is a large diversity of behavior in galaxies!
  - Doesn't have to solve the "missing satellites" problem

- Warm dark matter [Gunn and Tremaine 1979, Bond, Efstathiou, Silk 1980]
  - Sterile neutrinos [Dodelson and Widrow 1994]
  - Weak-scale mass gravitinos [Kaplinghat 2005, Cembranos et al 2005]
- Self-interacting dark matter [Spergel and Steinhardt 2000, Firmani et al 2000]
  - Massive and massless force carriers [Feng, Kaplinghat, Yu, Tu 2009, Feng, Kaplinghat, Yu 2010, Loeb and Weiner 2011, Vogelsberger, Zavala and Loeb 2012]

Empirical solution to the *core size-halo mass* relation





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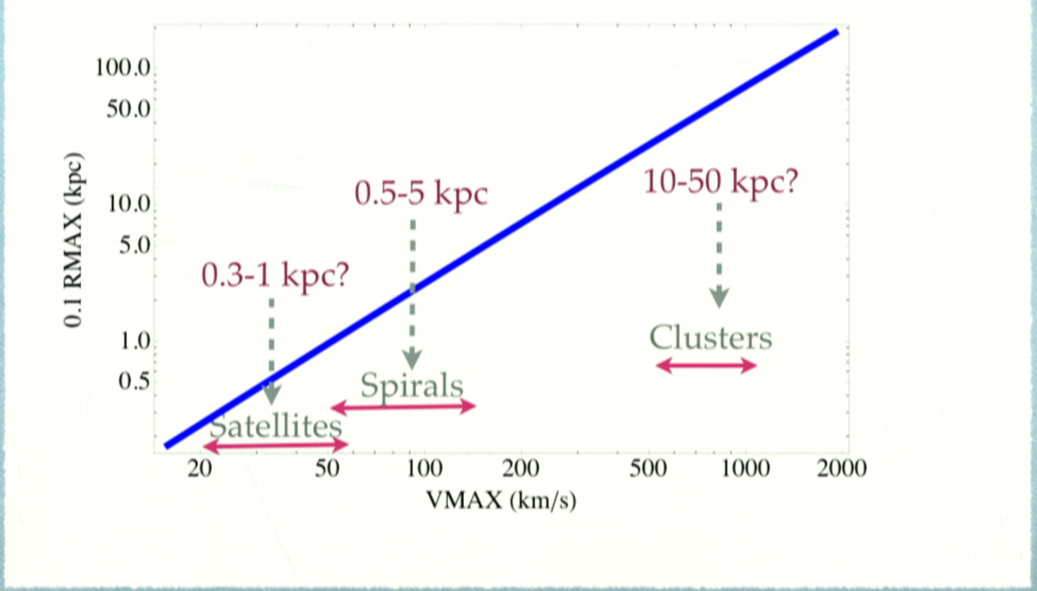
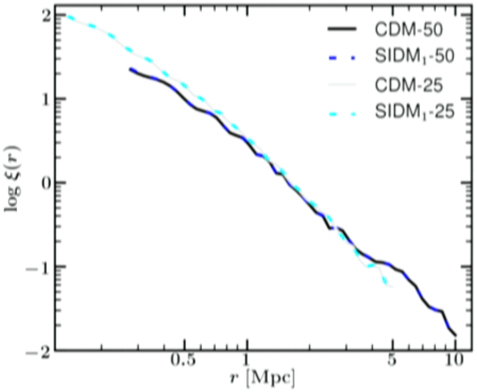
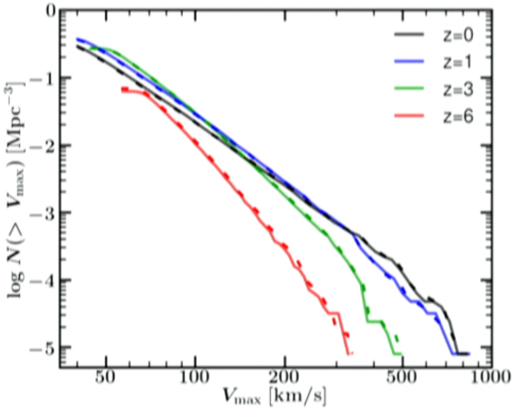
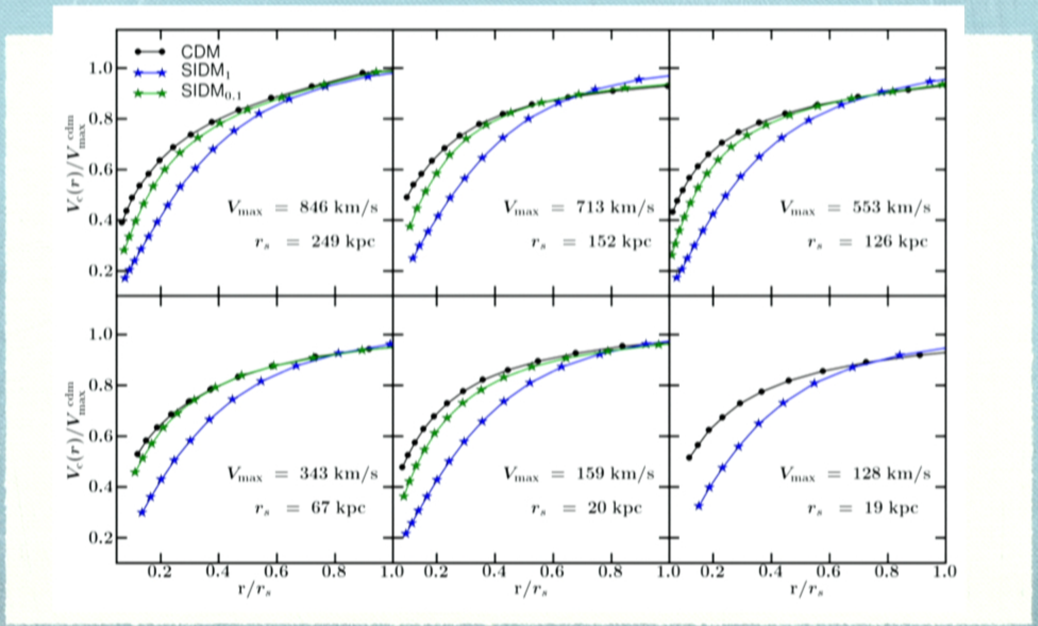


SIDM is the same as CDM on large scales





SIDM predictions for rotation speed



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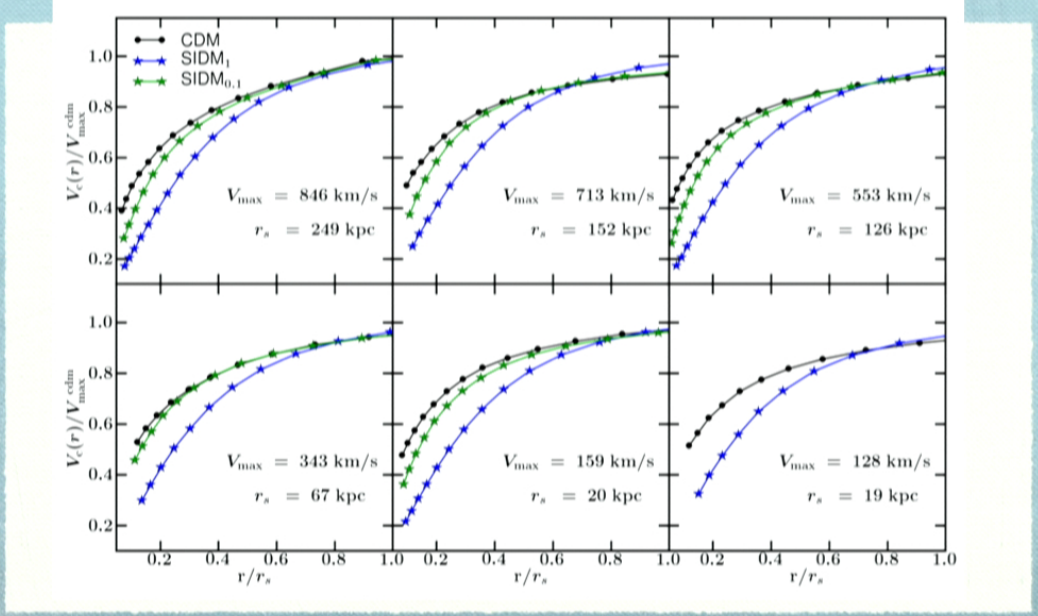
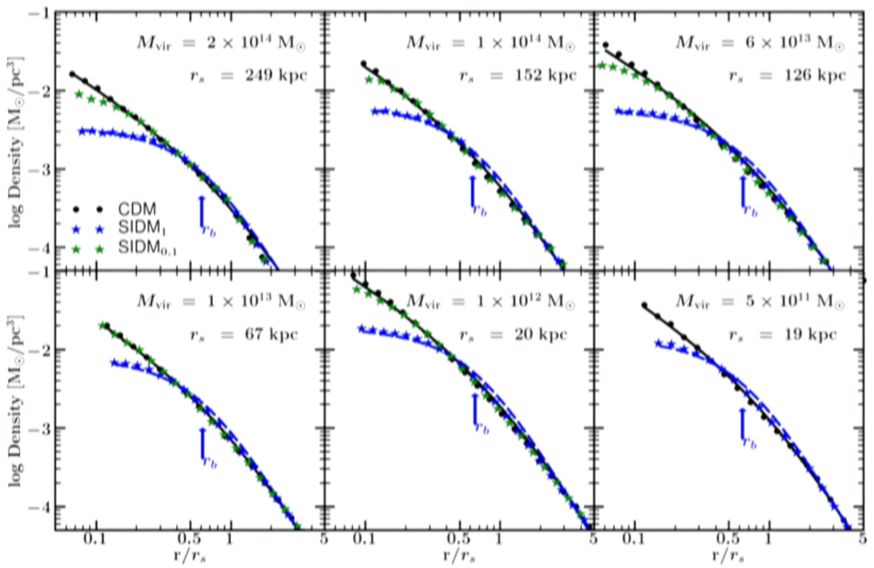


SIDM predictions for density profile



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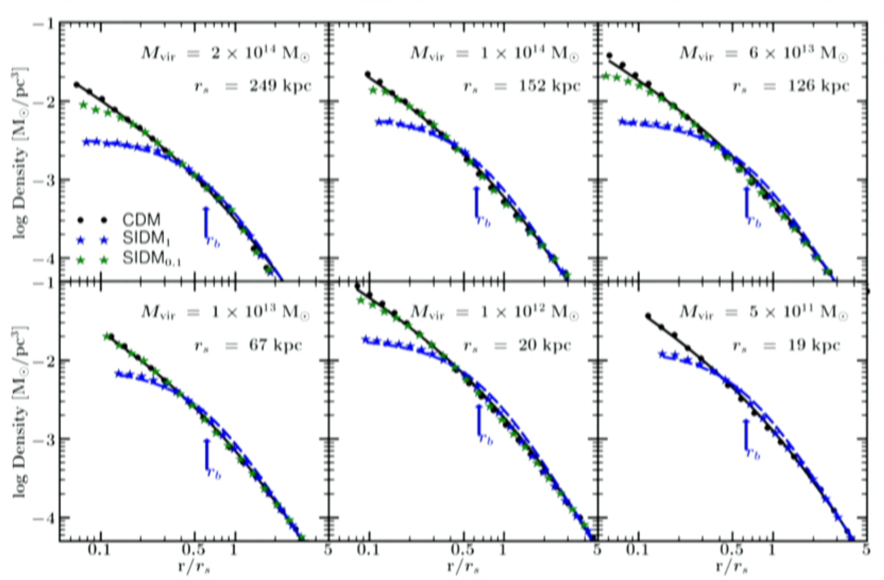
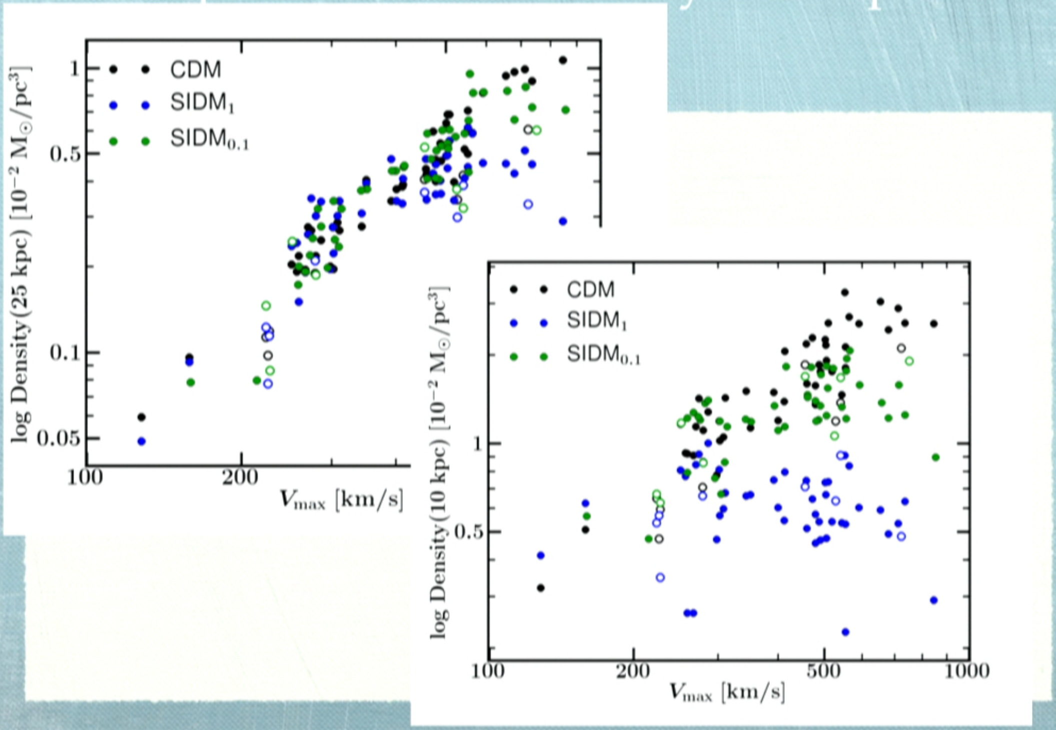
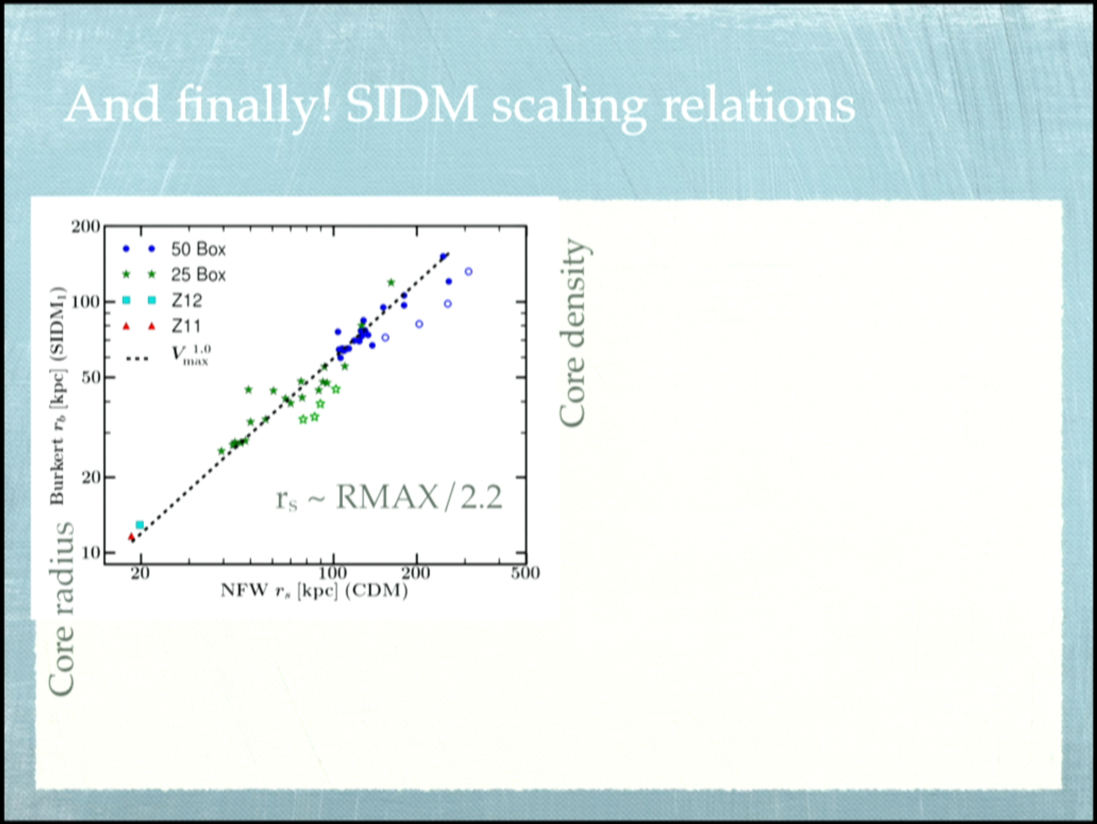


SIDM predictions for density at 25 kpc





And finally! SIDM scaling relations

Core radius

Core density

$r_s \sim$ RMAX/2.2

And finally! SIDM scaling relations