Missing Satellite Problem and Dark Matter Models

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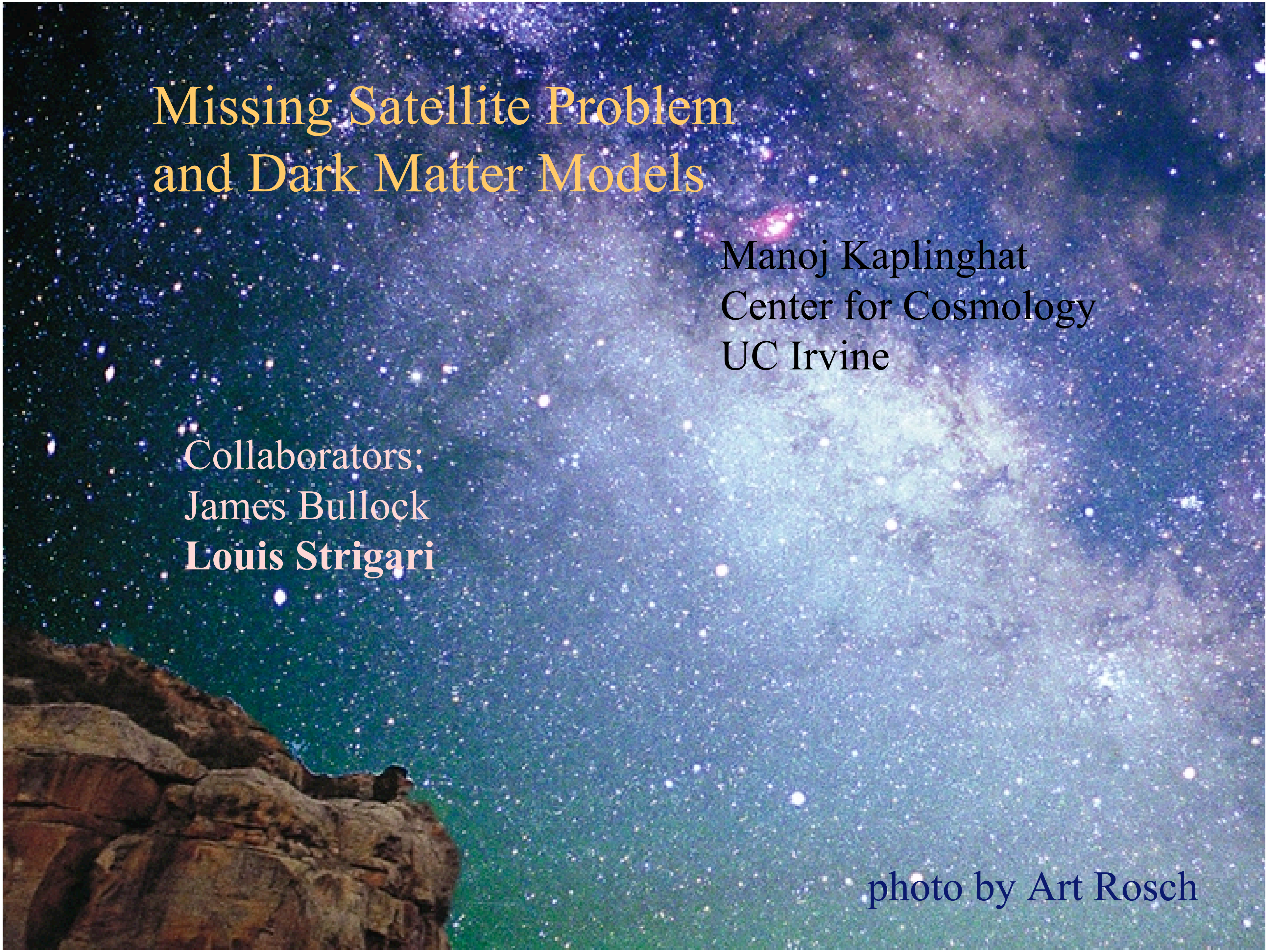


photo by Art Rosch

Properties of Dark Matter

- *Damping length* λ_d : Mean-free path before kinetic decoupling.
  - Depends on interactions (scattering off of the plasma) and early universe cosmology.
  - Example: Neutralinos (CDM) decouple from the standard model fermions at temperatures of order 10 MeV.

  Damping length ~ Horizon (10 MeV) / 3 ~ 3 pc

  Smallest mass halos ~ 3 Earth Mass

[Zaldarriaga and Loeb, Bertschinger]

Properties of Dark Matter

- *Free-streaming length λ_{fs}:* Average distance traveled by a dark matter particle before it falls into a potential well.
  - Depends on mean speed after decoupling and early universe cosmology
  - Example, Gravitino LSP (CDM) populated by the decay of the NLSP.

    Generic mechanism; depends on weak scale and G_N. Lifetimes around a month if $\Delta m \sim m \sim 100$ GeV.

    $v \sim c$ at T=keV (age ~ month)

    Free-streaming length ~ c month / a_d ln (t_{eq}/month) ~ Mpc

Properties of Dark Matter

- *Phase-space density Q*: Mass per unit phase space volume. The importance of this can be seen by noting that $S \sim -\ln Q$ and demanding that entropy should not decrease. This *implies* that Q should not increase. [Dalcanton and Hogan 2000, Kaplinghat 2005.]
  - Depends on mean squared speed.

CDM

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

Sterile neutrino

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

CDM from decays

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

Model space

- Warm Dark Matter (sterile ν, *Dodelson and Widrow 1993, Abazajian, Fuller and Patel 2001*)
- Cold Dark Matter born with large momentum (e.g., weak scale mass Gravitino LSP, *Kaplinghat 2005, Cembranos et al 2005*)
- Cold Dark Matter with stronger than weak interactions (e.g., MeV Dark Matter, *Hooper et al 2007*)
- Thermally populated Cold Dark Matter

  [Technically, a particle is cold if it decouples when non-relativistic.]

- Observations
  - Smallest mass halos < ~ 10^9 M_{sun} (Local group)
  - Cut-off in power spectrum on scales smaller than about 0.1 Mpc (*Seljak, Makarov, McDonald and Trac 2006*)

Thermally-populated Cold Dark Matter

- Most favored candidate is the WIMP. WIMPS are *massive*, *weakly interacting* and freeze-out when non-relativistic
- Free-streaming and damping lengths are small. Structure all the way to "earth mass halos"
- Phase space density is large

Set by annihilations

Set by scattering

$$Q \equiv \frac{\rho}{\langle v^2 \rangle^{3/2}}$$

[Dalcanton and Hogan, 2000]

$$Q_{\rm CDM} = 10^{14} \frac{\rm M_\odot}{\rm pc^3} \left(\frac{\rm km}{\rm s}\right)^{-3} \left(\frac{\rm M}{\rm 100GeV}\right)^{3/2}$$

Cold Dark Matter from Decays

WIMP

$\downarrow \Gamma \sim M_w^3/m_{pl}^2$

Dark Matter

- WIMPs have the right abundance because of their weak interactions

- $\rho_{DM} = \rho_{WIMP}\, m_{DM}/m_{WIMP}$

- If $m_{DM} \sim m_{WIMP}$, then the dark matter abundance today is naturally in the correct range.

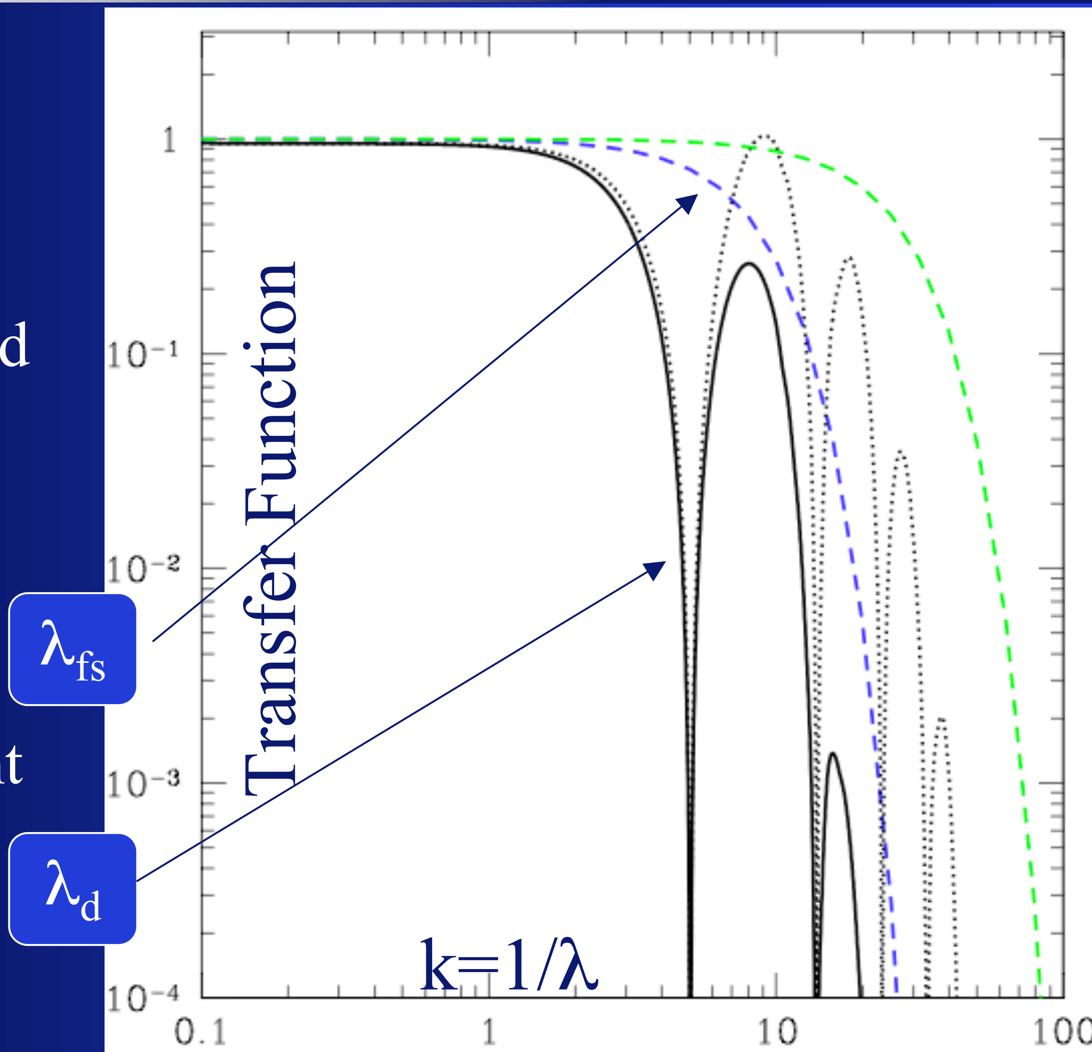
- Example: In super-gravity models, all super-partners have similar masses.

Feng, Rajaraman and Takayama 2003

Free-streaming and Damping: Power spectrum

Perturbations are erased below the free-streaming and damping lengths

Shown to the right is the transfer function at very early times

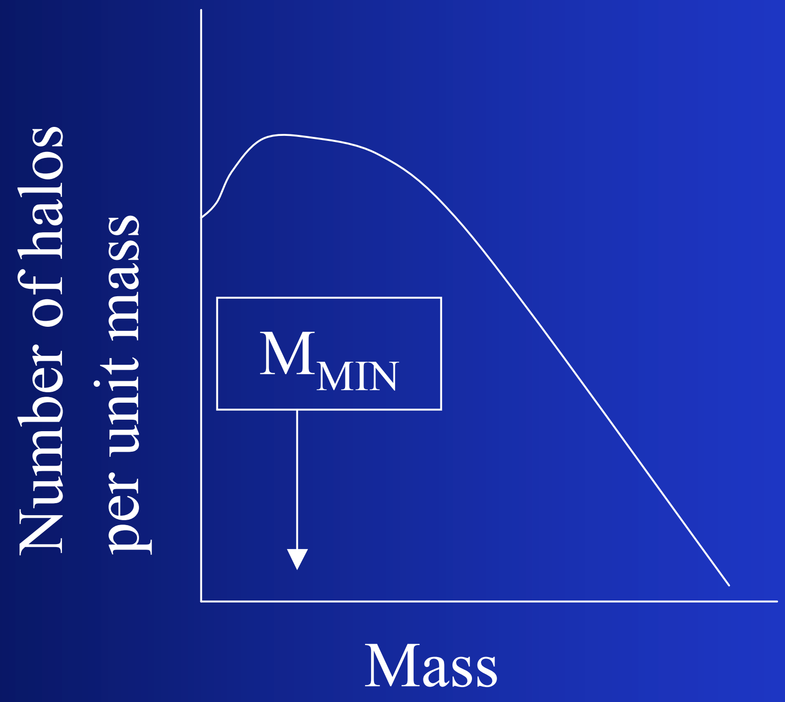


Zaldarriaga and Loeb 2005

Free-streaming and Damping: Mass function

Perturbations erased below λ_d and λ_{fs}

➔ Sets the mass of the smallest halos



Properties of Dark Matter

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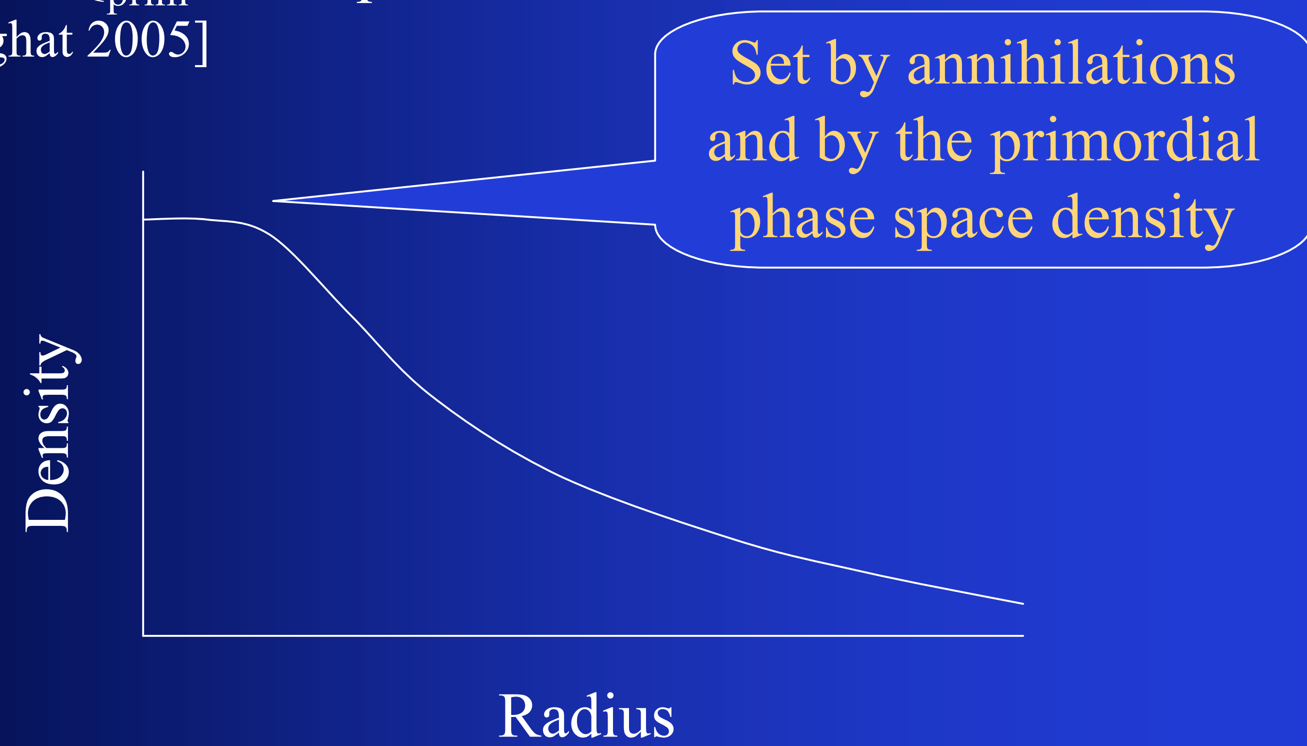
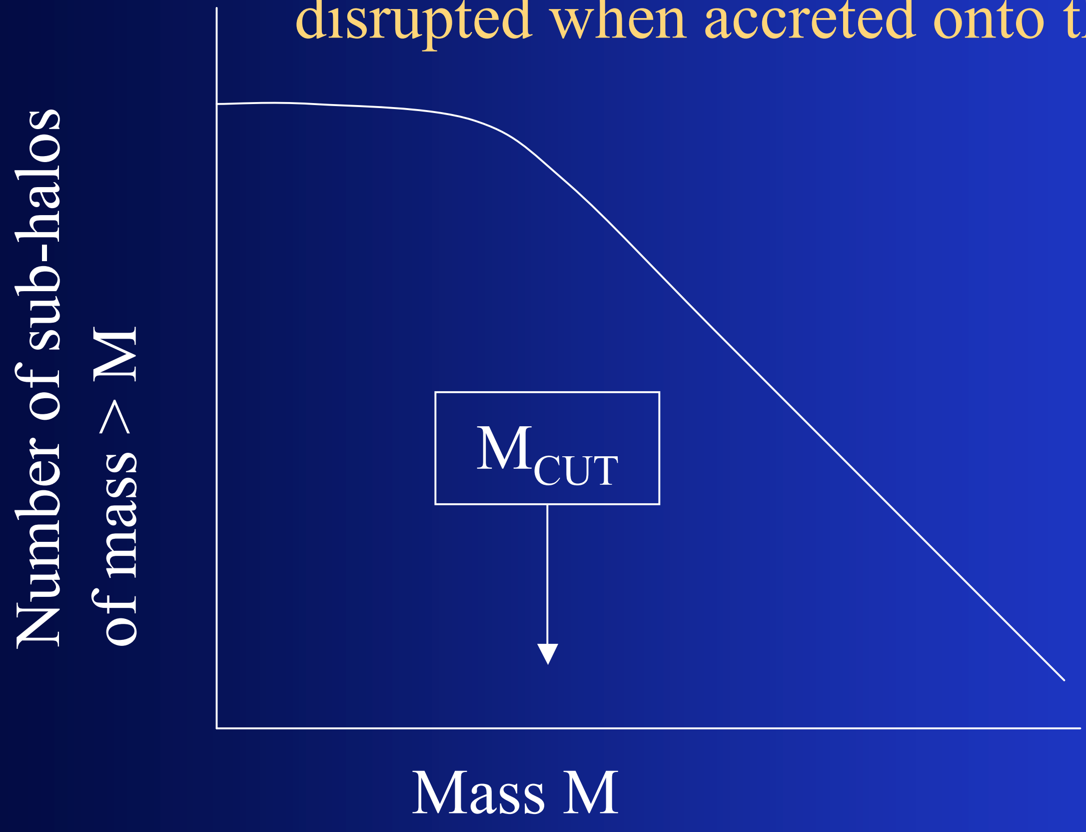
Phase space density: Cores

- Can’t stuff particles without limit into the center of dark matter halos. [Gunn and Tremaine]
- Incorrect to just use an average Q. WDM and CDM with the same Q_{prim} don’t predict the same small-scale structure. [Kaplinghat 2005]



Phase space density: Substructure

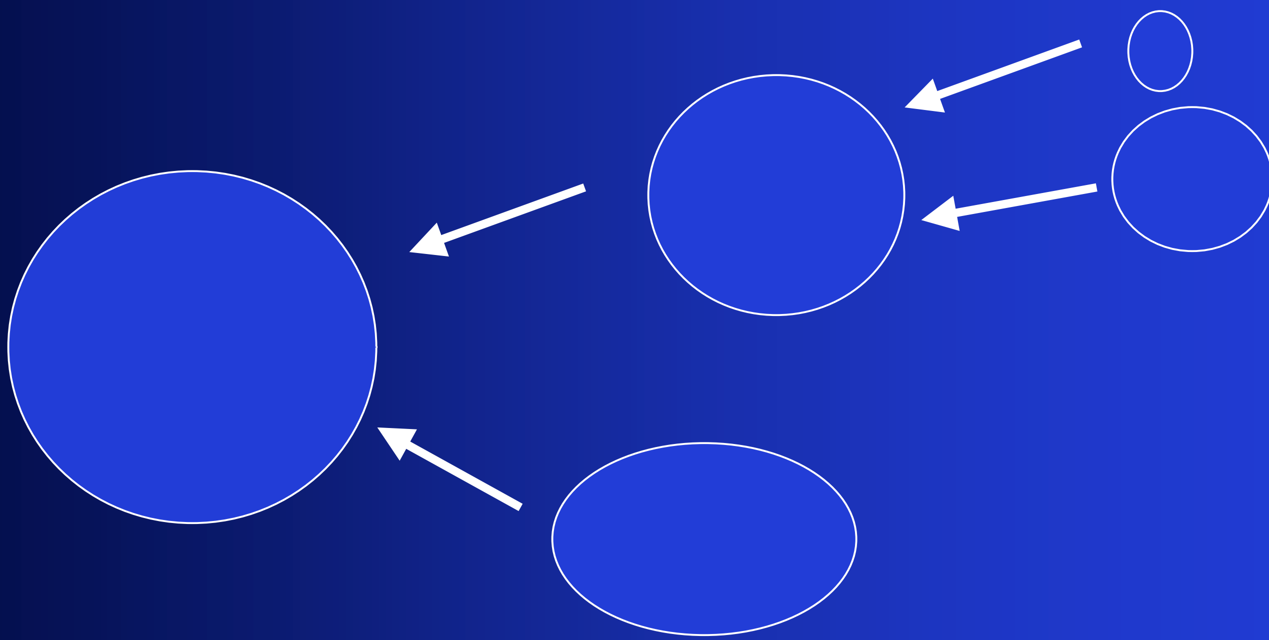
Cores set by phase space density are so large in halos below mass M_{CUT} that they are easily disrupted when accreted onto the large halo



$M_{CUT} \sim M_{MIN}$?

So what is the core size given a Q?

- This is a very hard question!
- Phase space arguments for collision-less particles give you a *minimum* core size.



Relation between Q and free-streaming

- The free-streaming scale and Q are related. For example, both are fixed by just specifying the mass of a warm dark matter particle like the sterile neutrino. Thus given the cut-off in the power spectrum, the size of cores in halos can be computed using numerical simulations. (Easier said than done! See Wang and White 2007.)
- For decays in the radiation dominated era, the relation between Q and free-streaming is similar. Despite appearances, there is effectively one free parameter.
- *However, for decays in the matter dominated era, one can have an "almost-CDM" like power spectrum but large cores in the local group dwarf galaxies!*

  Meta-CDM (Strigari, Kaplinghat and Bullock 2006)

Meta-CDM

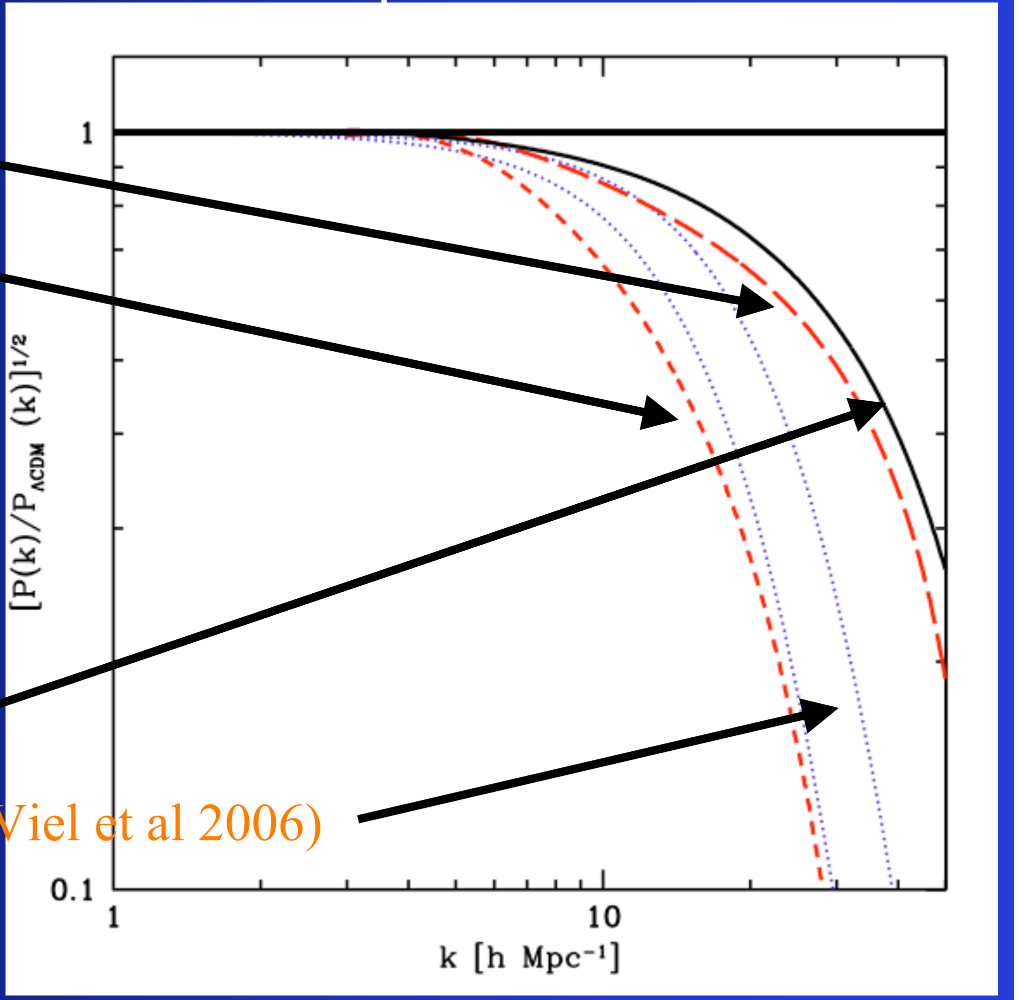
Q and Power spectrum cut-off decoupled.

$Q=10^{-5}$, lifetime$=5\times10^{12}$s

$Q=10^{-6}$, lifetime$=5\times10^{12}$s

$Q=10^{-6}$, lifetime$=10^{14}$s

Lya limits (Seljak et al and Viel et al 2006)

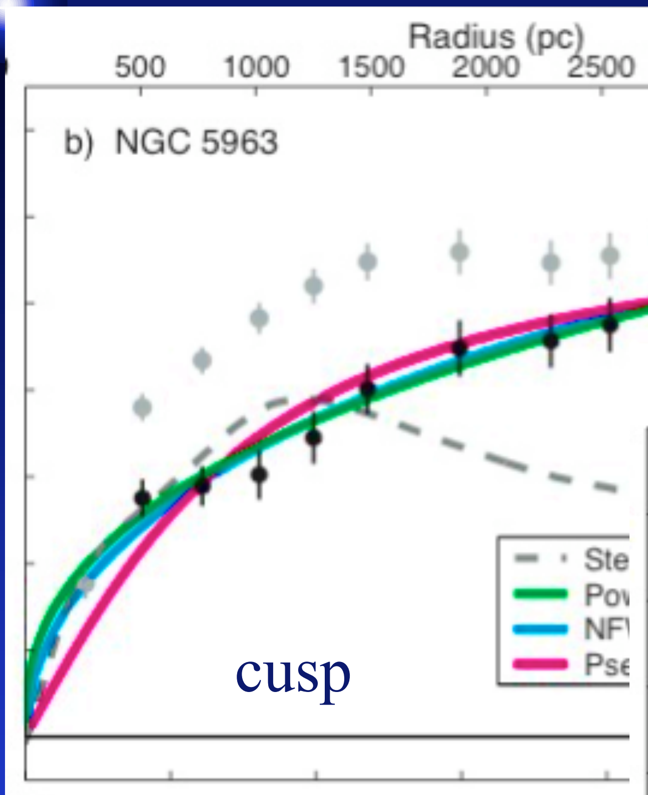


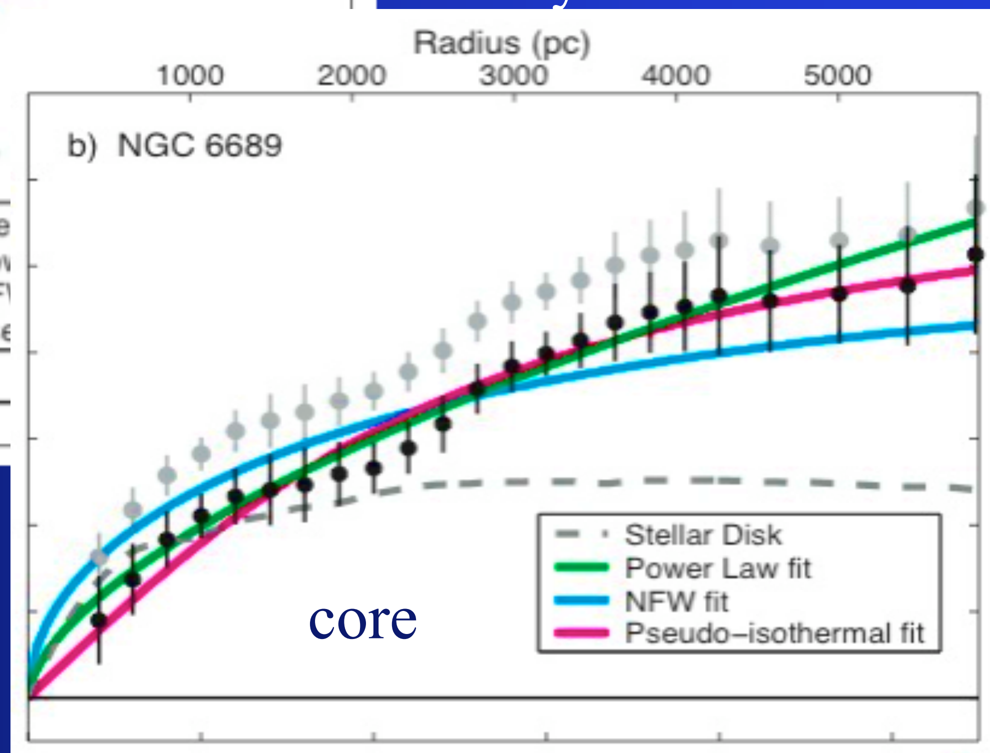
Review

- *Free-streaming and damping lengths:*
  - Truncates power on small scales
    ➔ No perturbations on small scales
    ➔ No halos below a minimum mass.
- *Phase space density:*
  - Limits density in the center of halos
    ➔ Makes small halos susceptible to disruption
    ➔ Limits sub-structure in large halos.
- *Well-motivated CDM models make a wide variety of predictions.*

Dark Matter halo central density

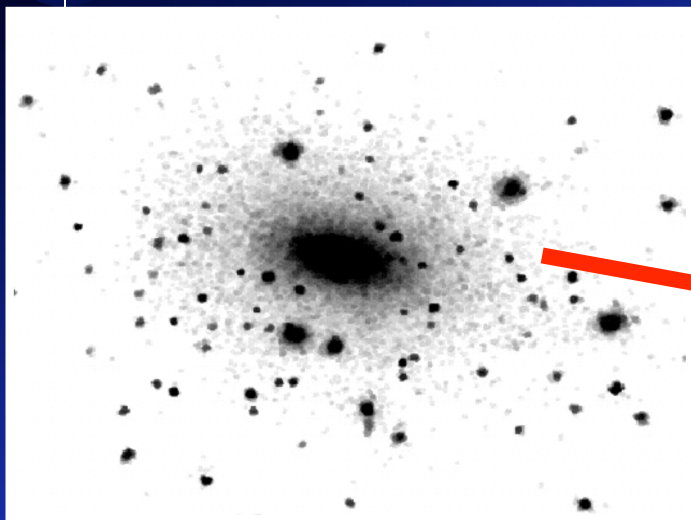
The generic expectation is that baryons will increase the concentration of dark matter halo central density.

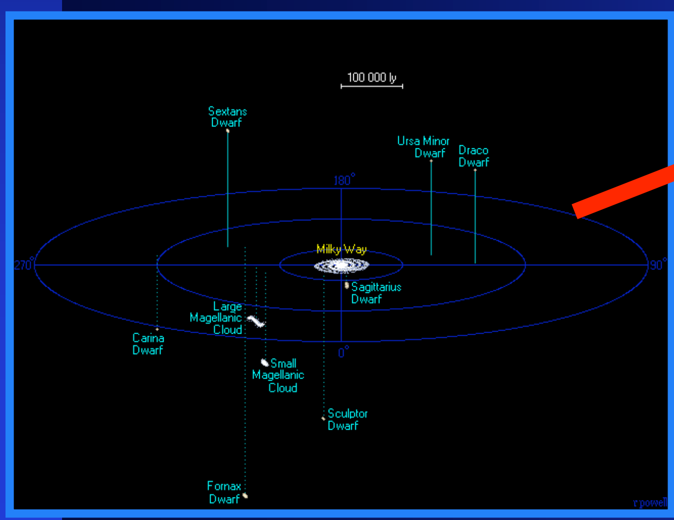




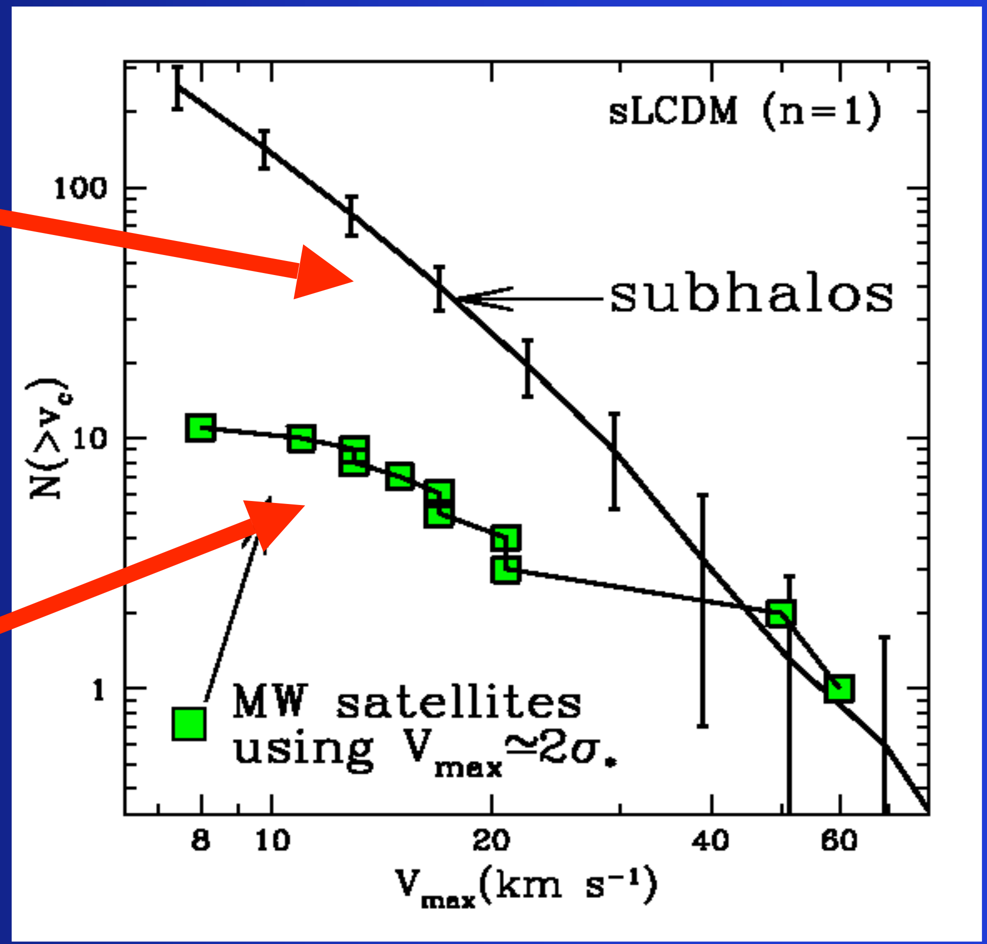
Simon et al 05

LCDM Missing satellite problem





Klypin et al. 99; Moore et al. 99



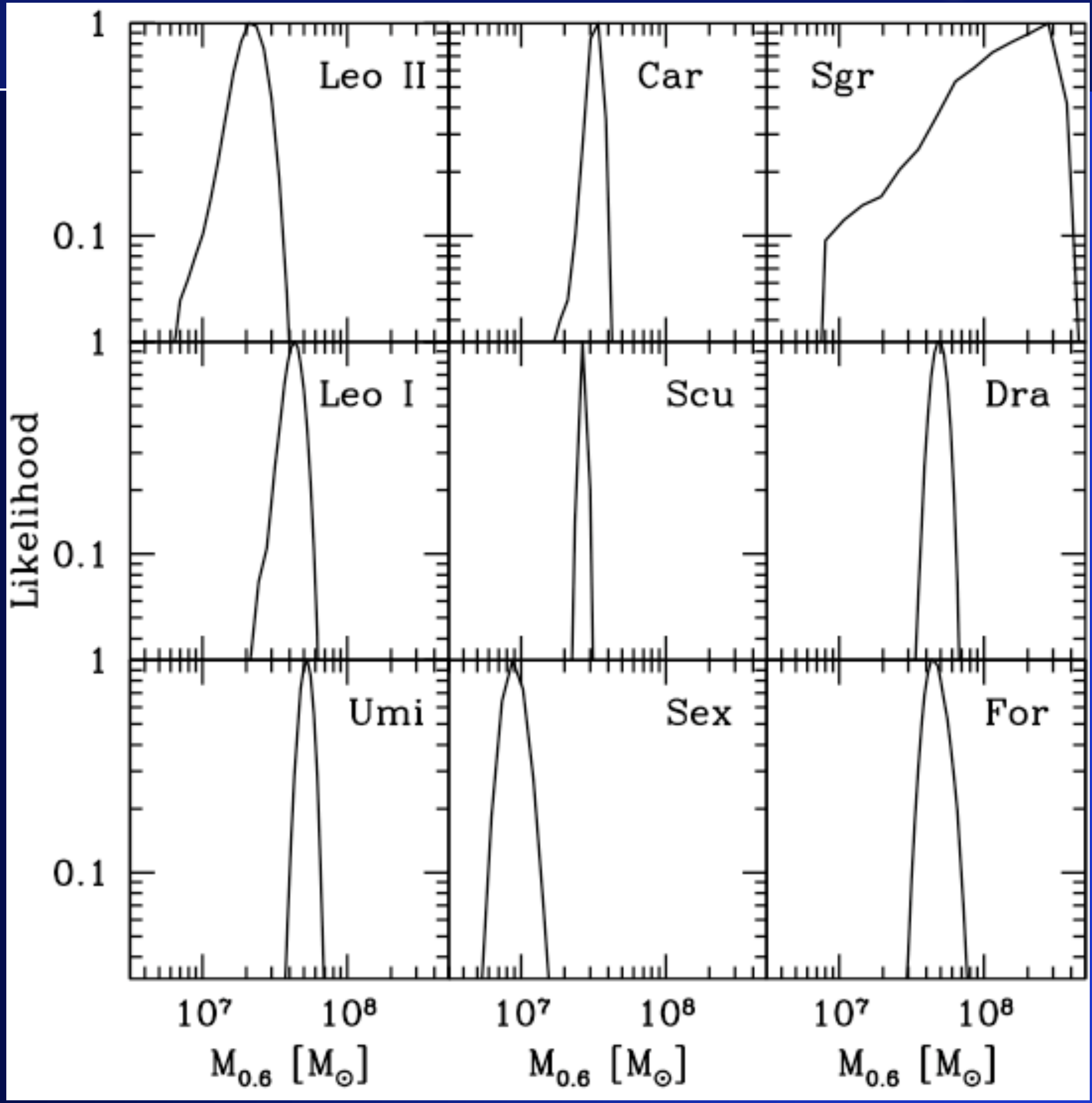
Trouble with V_{max}

- Large error bars. (V_{max} can be very large.)
- Solution … put theory prior on V_{max}
  (Bullock and Zentner 2003)
- Not simple … V_{max} depends, for example, on power spectrum.

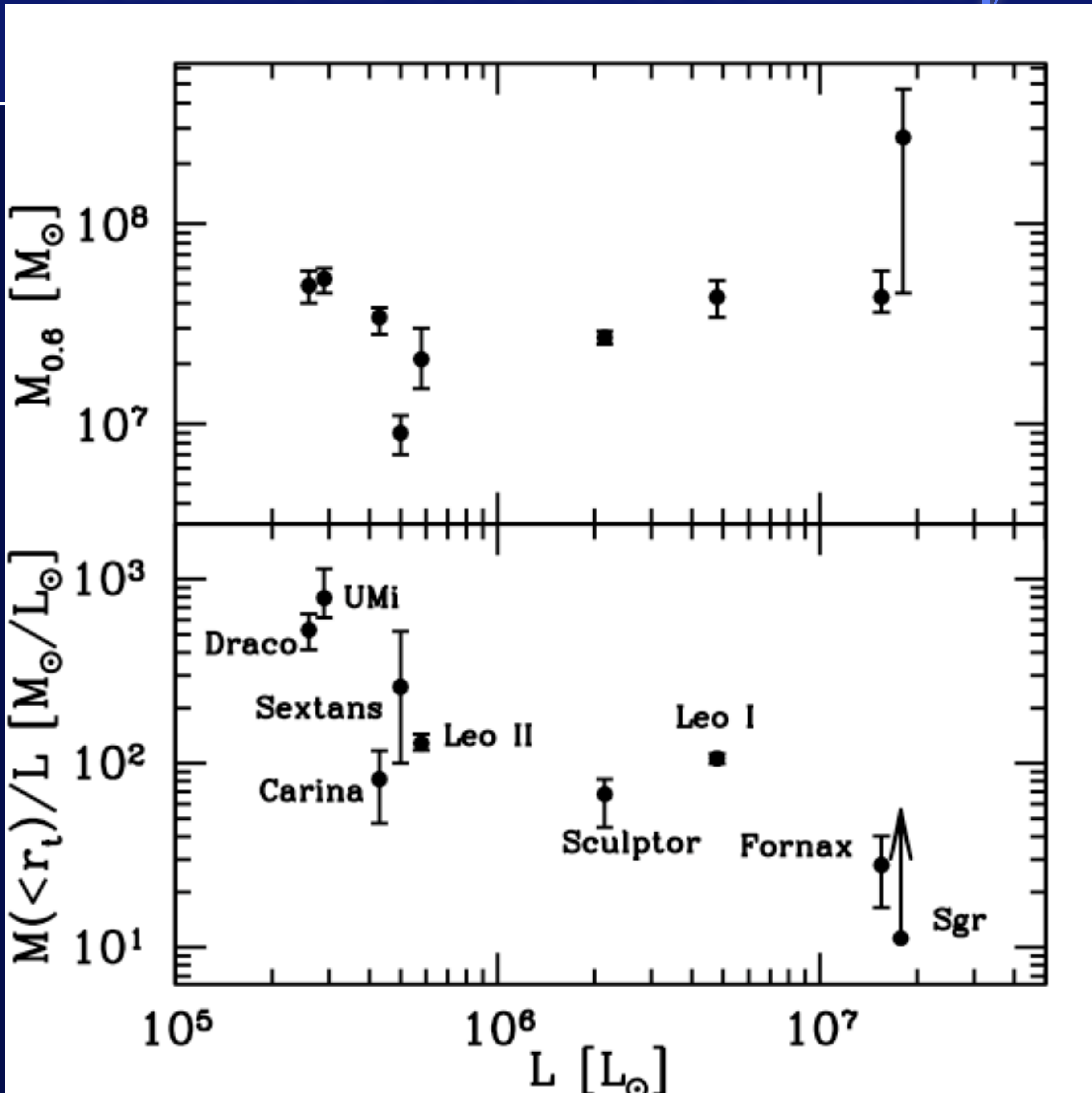
Another resolution

- Velocity dispersion data constrain the mass of the "old" dwarfs within about twice King core radius well.
- King radii similar and so we measure M(<0.6 kpc) very well.
- M(<0.6 kpc) does not depend on cosmology or the underlying dark matter model unlike V_{max}.
- Via Lactea simulation can resolve 0.6 kpc! Comparison easy now. [Diemand, Kuhlen and Madau 2006]

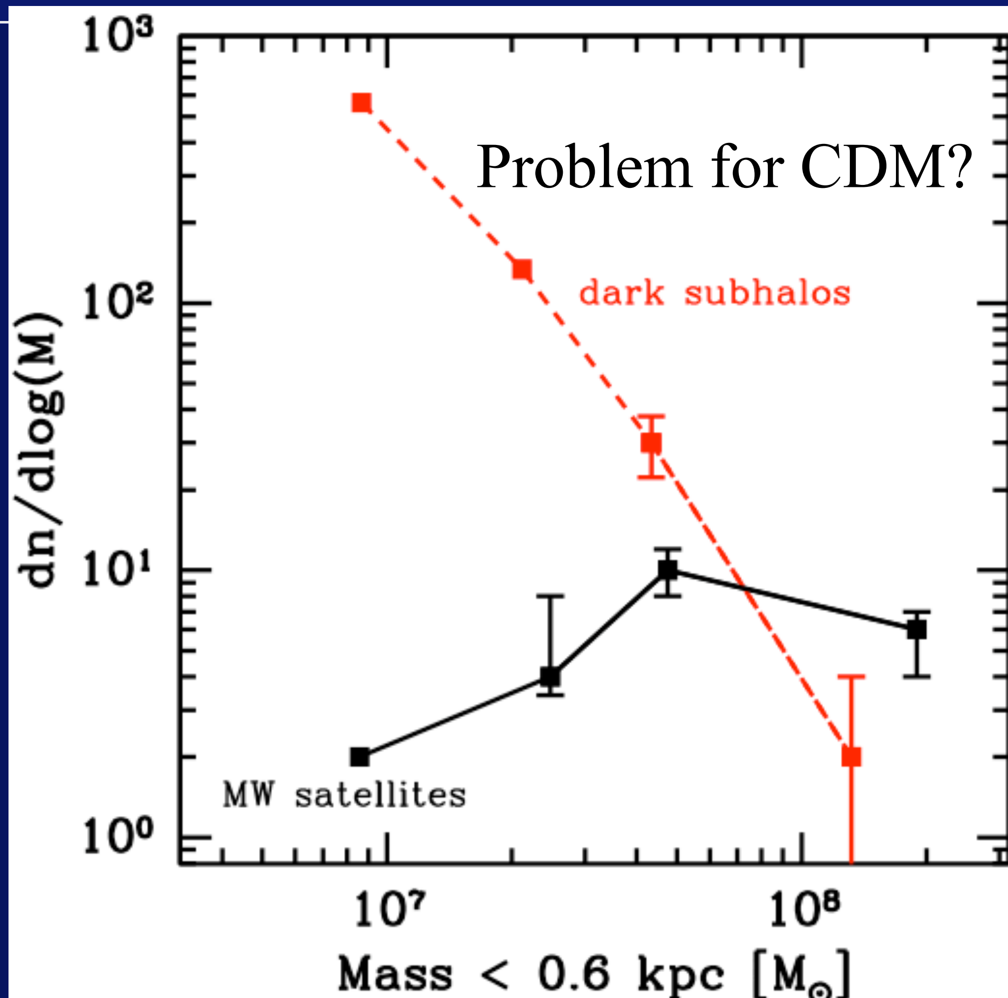
Likelihoods for Mass(<0.6 kpc)



Luminous satellites summary

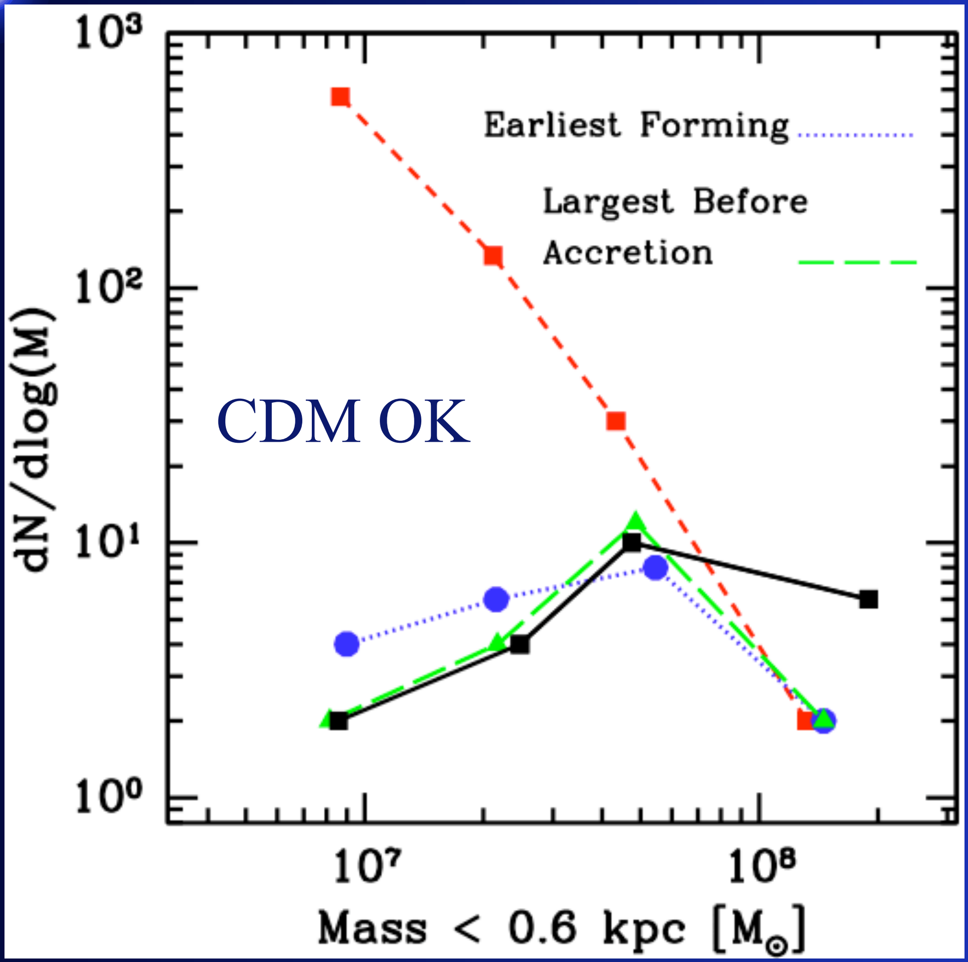


Local Group Mass Function



Strigari et al 2007

Comparison to CDM



Strigari et al 2007

The real model will combine the physics implicit in both LBA and EF samples.

Bullock et al 2000
Kravtsov, Gnedin and Klypin 2004.

Constraints on DM clustering? Issues

- Mass measured in the Milky Way is probably very different (smaller) than the mass before infall.

  [Kravtsov, Gnedin and Klypin 2004]
- No “warm dark matter” simulation. This is hard but can be done.

  [Wang and White 2007]
- Could we use Press-Schechter like arguments?

  [Dalal 2007]
- Some guidance from the Diemand et al simulations that include WIMP damping. However, this is for a much *lower mass regime* and for *sub-halos* and do not include *large initial velocities*.

Summary

- From the theory side, there is good motivation to look at dark matter clustering on small scales -- 1-100 kpc scale linear power spectrum.

- A promising way to test the CDM paradigm is using the dwarf galaxies in the local neighborhood of Milky Way. Dwarf counts doubled by SDSS. A full sky survey will almost certainly reveal more.

- Other tests of dark matter clustering
  - Strong lensing
  - 21cm maps