

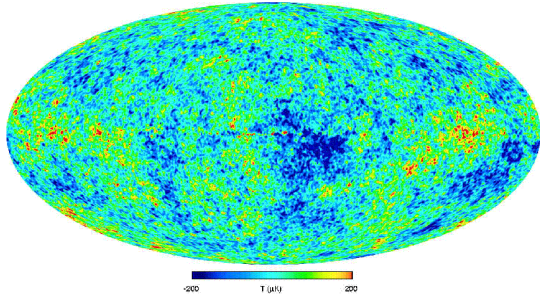


Decoding the identity of the dark matter from Milky Way data

Carlos S. Frenk
Institute for Computational Cosmology,
Durham



The cosmic power spectrum: from the CMB to the 2dFGRS

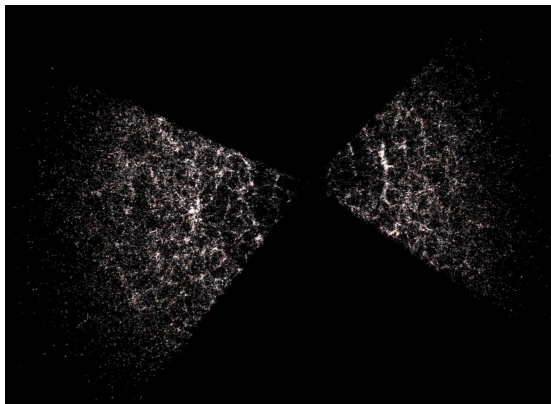


$z \sim 1000$

$\text{Log } k^3 P(k)$

wavelength k^{-1} (comoving h^{-1} Mpc)

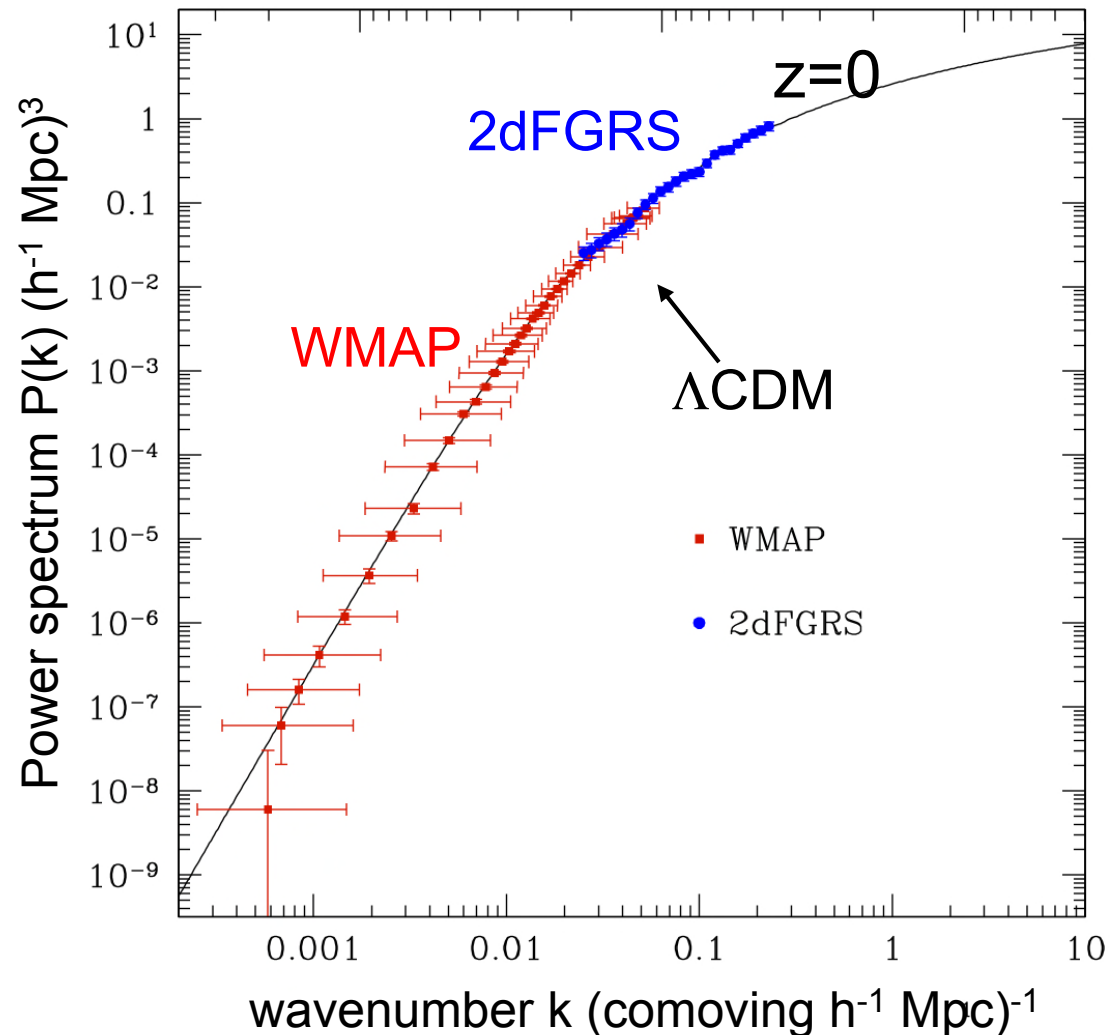
1 000 100 10



$z \sim 0$

$\Rightarrow \Lambda\text{CDM}$ provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06



The cosmic power spectrum: from the CMB to the 2dFGRS

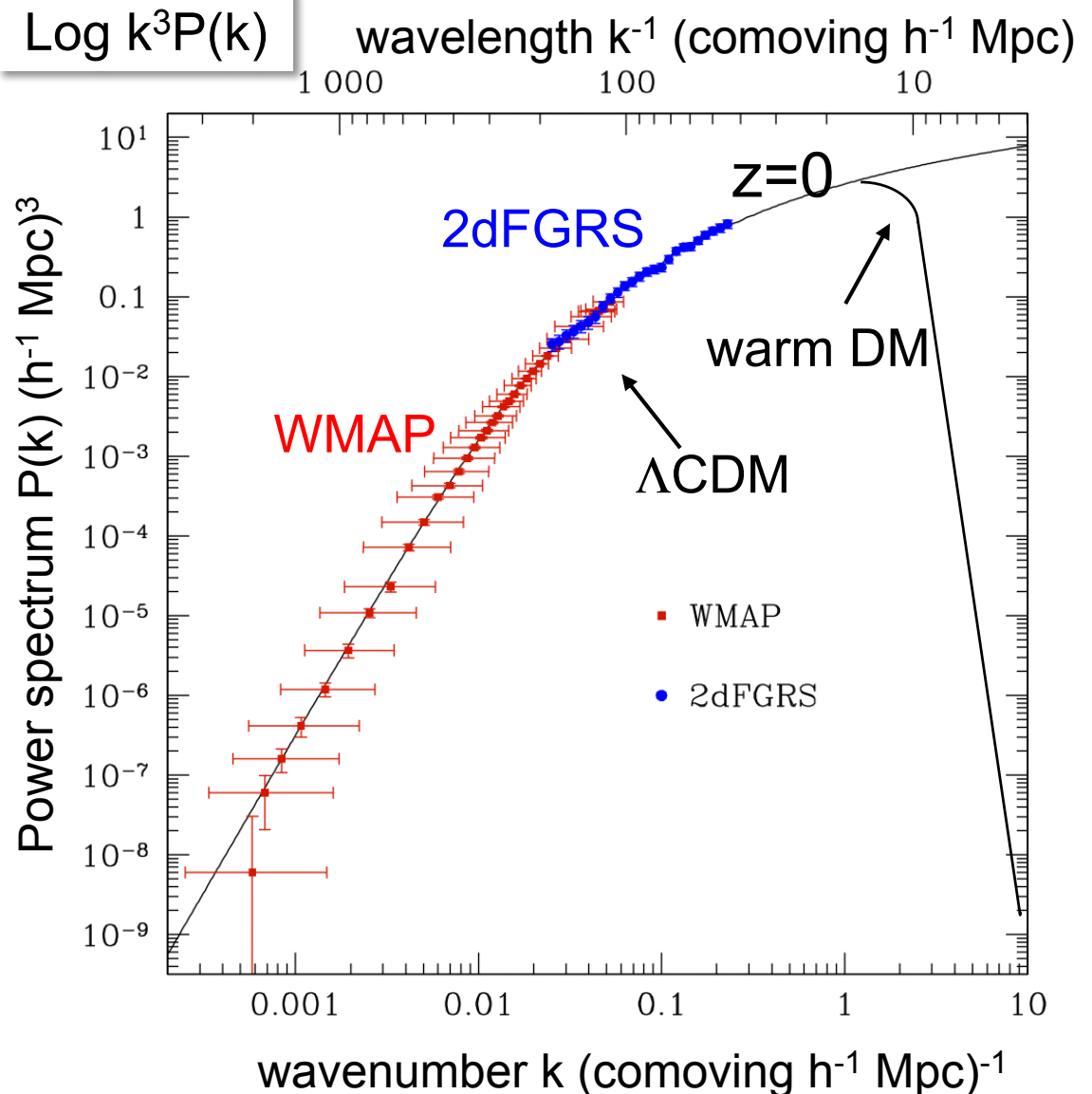
Free streaming →

$$\lambda_{\text{cut}} \propto m_x^{-1}$$

for thermal relic

$m_{\text{CDM}} \sim 100 \text{ GeV}$
 susy; $M_{\text{cut}} \sim 10^{-6} M_{\odot}$

$m_{\text{WDM}} \sim \text{few keV}$
 sterile ν ; $M_{\text{cut}} \sim 10^9 M_{\odot}$





The ν minimal standard model

- Neutrino Minimal Standard Model (ν MSM) proposed to explain neutrino masses (Asaka & Shaposhnikov '05)
- Adds three **sterile neutrinos** to the SM. The lightest of these would be the **dark matter**



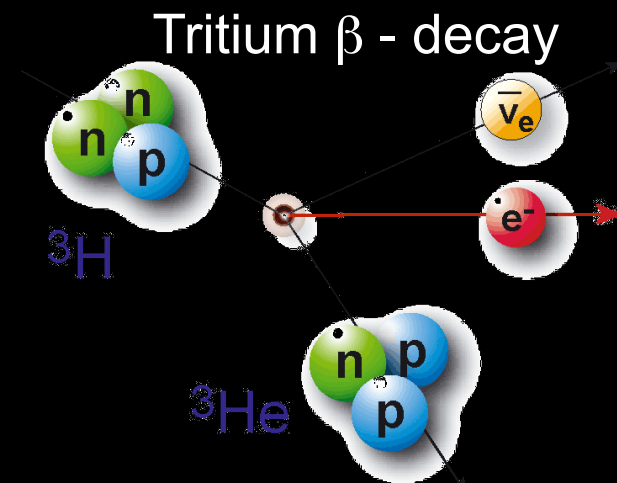
The ν minimal standard model

Sterile neutrino detection possible

Decay line in X-rays



Constellation X



The cosmic power spectrum: from the CMB to the 2dFGRS

Free streaming $\rightarrow$

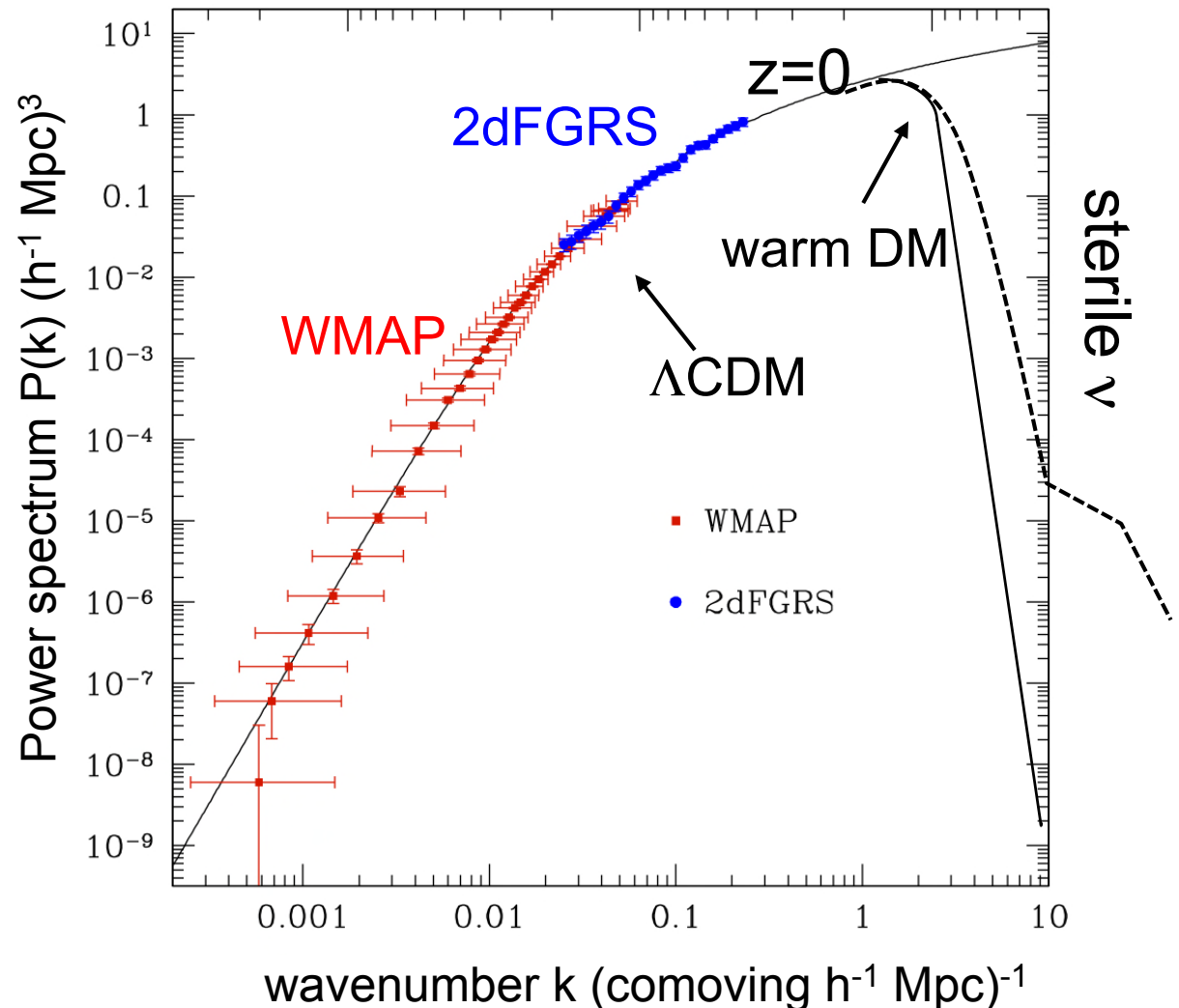
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Log $k^3 P(k)$ wavelength k^{-1} (comoving $h^{-1} \text{ Mpc}$)





Astrophysical key to identity of dark matter:

→ Subgalactic scales
(strongly non-linear)

Constraints from (mildly non-linear) Ly- α forest → Mateo Viel's talk

$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

The image shows a dark, textured field of purple and black, representing a simulated galaxy at a very early stage. The texture is grainy and noisy, with some faint, irregular patterns of slightly lighter purple. In the top left corner, the text "z = 48.4" is displayed. In the top right corner, the text "T = 0.05 Gyr" is displayed. At the bottom center, there is a horizontal scale bar with vertical end caps, and the text "500 kpc" is written below it.



Cold Dark Matter

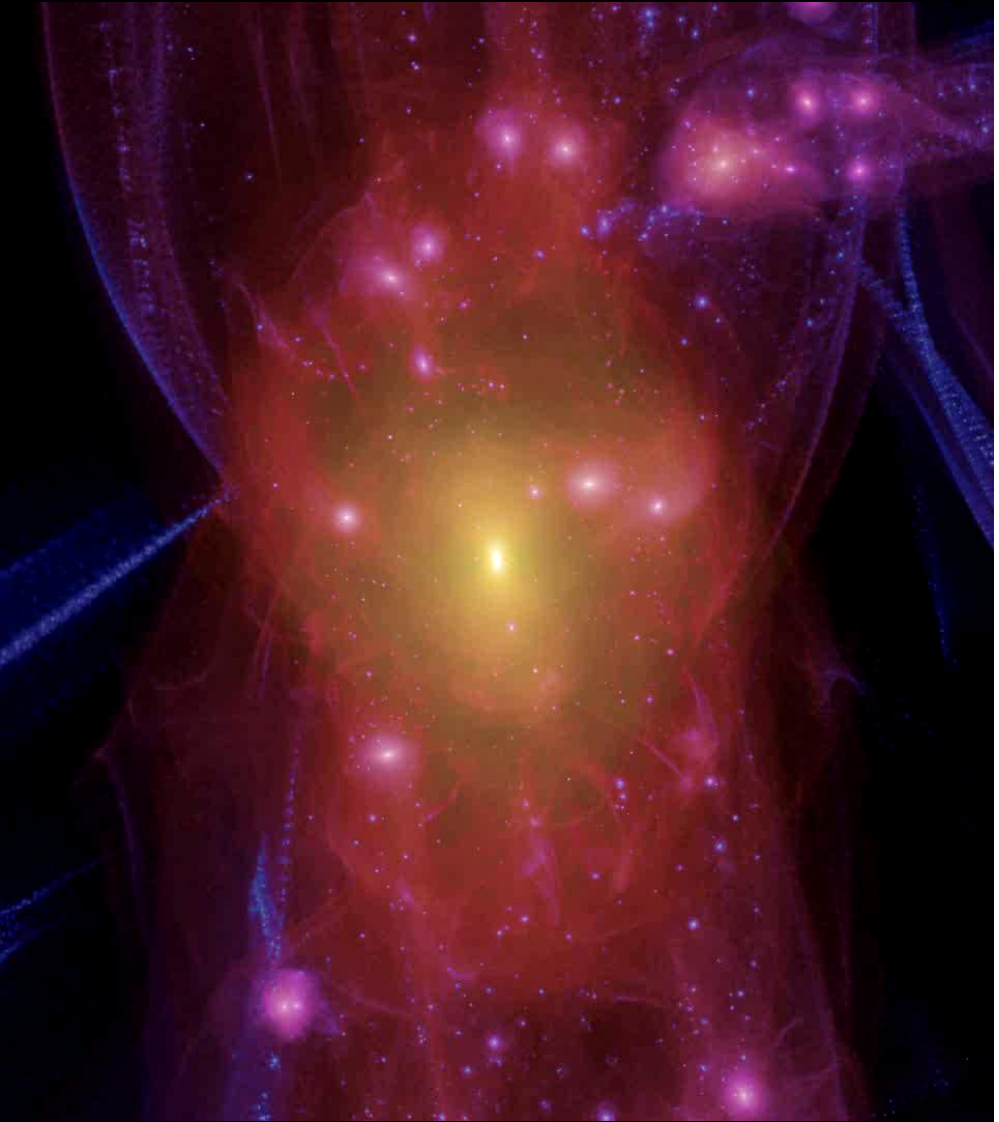
Warm Dark Matter

13.4 billion years ago

cold dark matter



warm dark matter

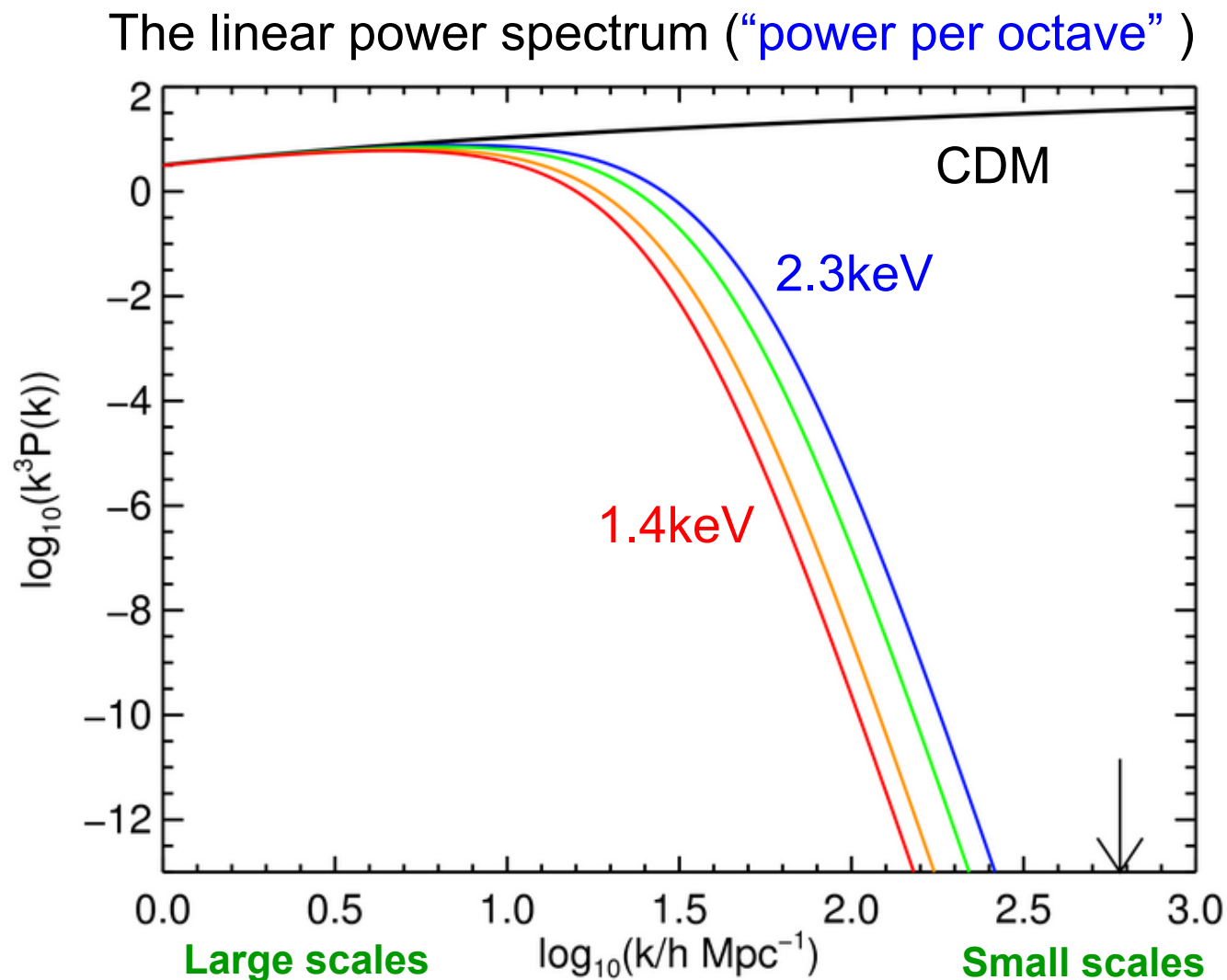


Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
BoyarSKI & Ruchayskiy '12

Warm DM: different ν mass

$$\lambda_{\text{cut}} \propto m_{\nu}^{-1}$$

- WDM
- 2.3 keV
- 2.0 keV
- 1.6 keV
- 1.4 keV



N-body simulations: CDM vs WDM

Simulations make 2 important predictions on galactic scales:

Cold dark matter

- Large number of self-bound substructures (**10% of mass**) survive
- The main halo and its subhalos have “cuspy” density profiles

Warm dark matter

- Far fewer self-bound substructures (**5% of mass**) survive
- Main halo profile identical to CDM; subhalos still “cuspy” but less concentrated than in CDM



Subhalo density profiles

CDM & WDM
subhalos have
cuspy profiles

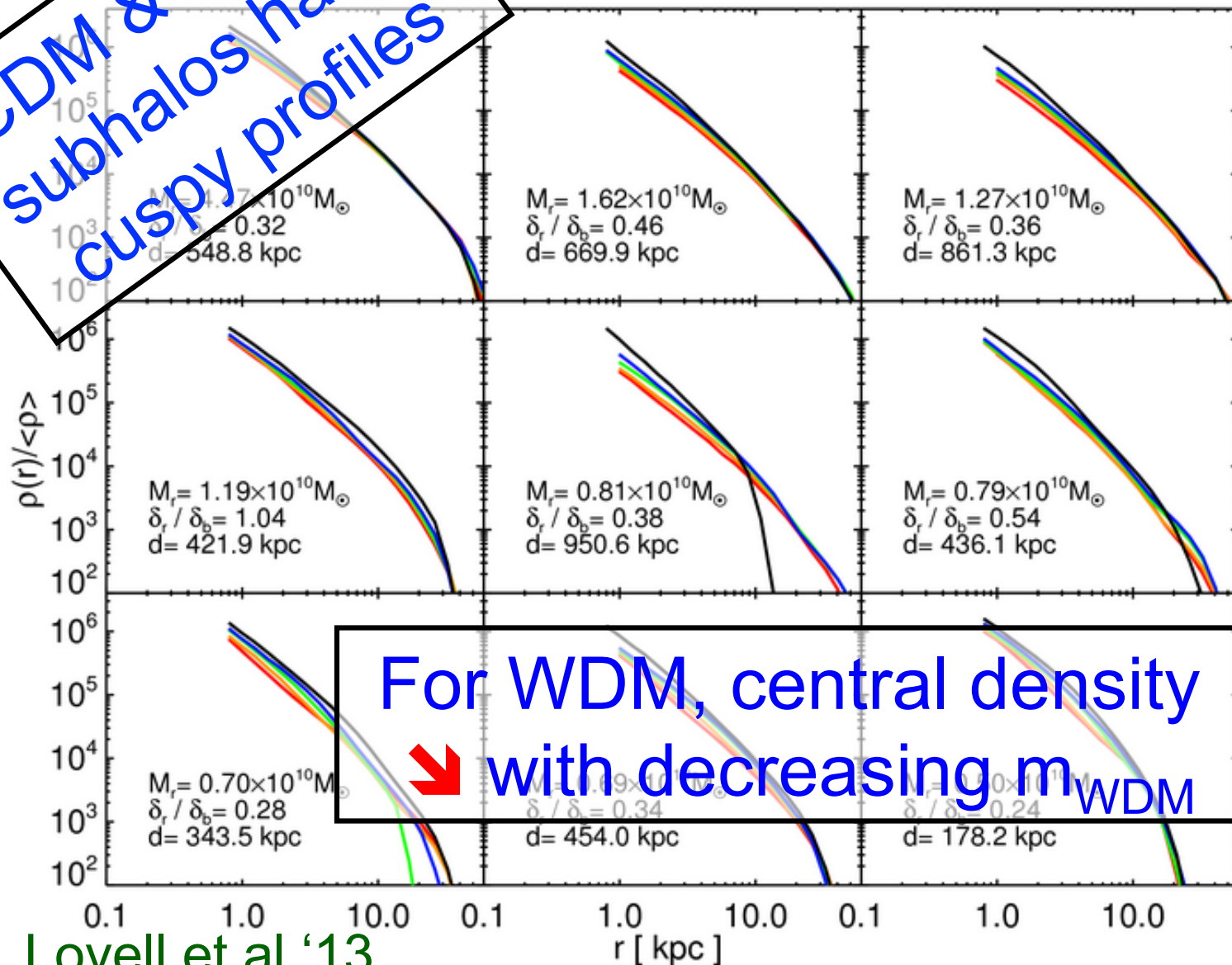
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV

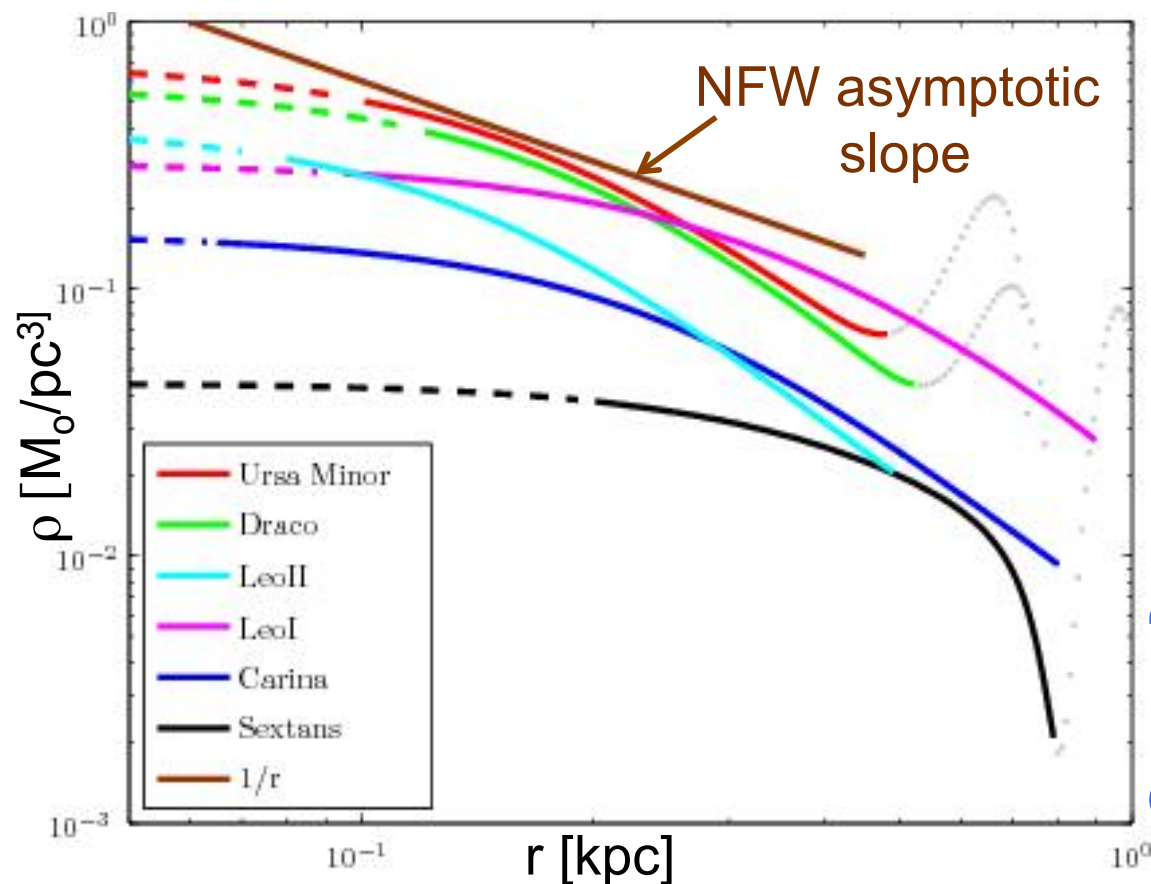


Lovell et al '13

The DM halos of dwarf spheroidals

Gilmore et al '07

Inferred density profiles for 6 dwarf spheroidals



“...dark matter forms cored mass distributions, with a core scale length of greater than about 100pc...”

“... (keV) sterile neutrino particles have been discussed as relevant in just the spatial and density range we have derived here.”

Core radii in WDM halos

The thermal velocities of WDM particles induce cores

see Shaun Cole's talk

Phase space arguments $\rightarrow$:

$$r_c = \frac{pc}{\left(\frac{m_x c^2}{8.2 \text{ keV}}\right)^2 \left(\frac{\sigma}{\text{km/s}}\right)^{1/2} \left(\frac{g}{2}\right)^{1/2}}$$

core radius

For $m_{\text{WDM}} > 1.5 \text{ keV}$, the core radii in WDM models are of **10 times smaller than the values** derived by Gilmore et al '07!

$\rightarrow$ core radii and NOT relevant in WDM models

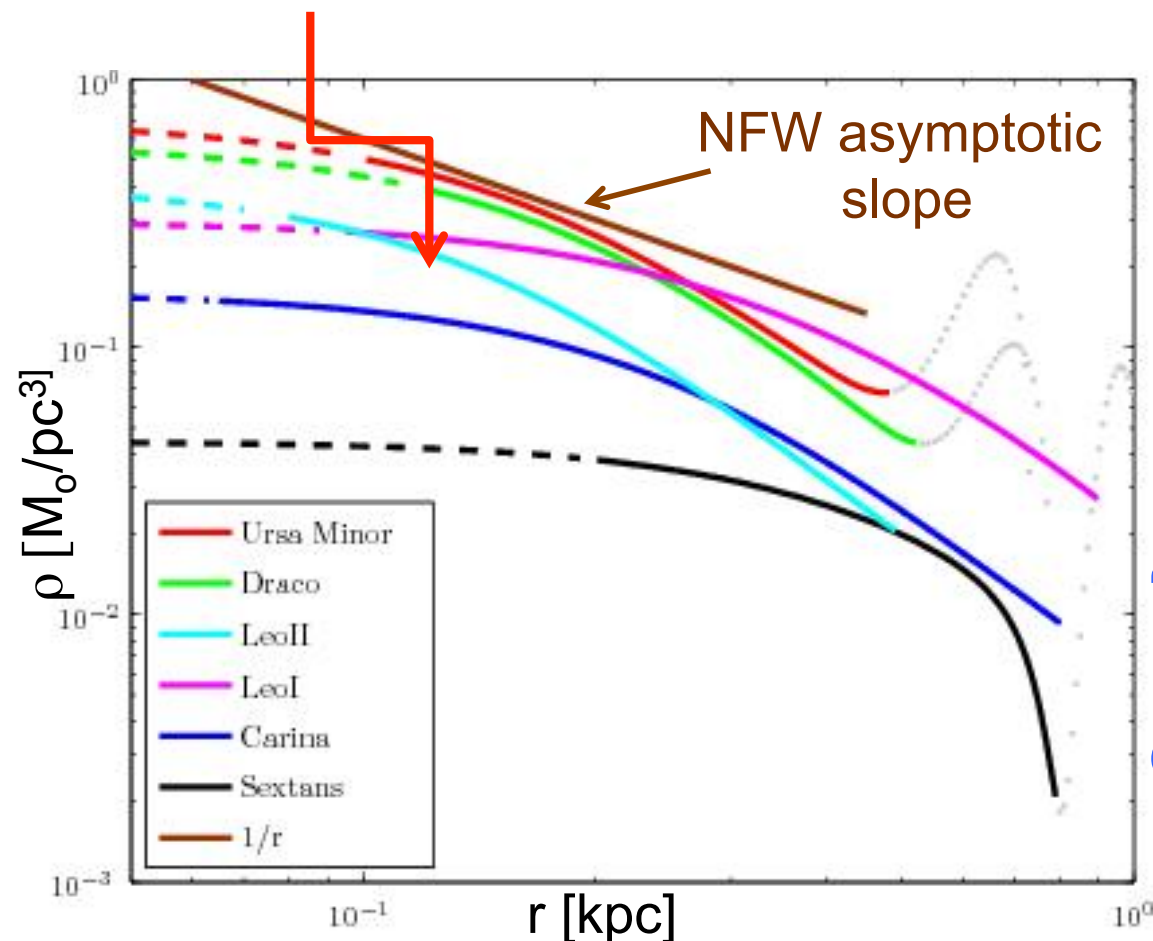
Shao, Gao, Theuns, Frenk '13
& Maccio et al '12

The DM halos of dwarf spheroidals

But what about these?

Gilmore et al '07

Inferred density profiles for 6 dwarf spheroidals



“...dark matter forms cored mass distributions, with a core scale length of greater than about 100pc...”

“... (keV) sterile neutrino particles have been discussed as relevant in just the spatial and density range we have derived here.”



Dwarf galaxies around the Milky Way

A more rigorous analysis
(Strigari, Frenk & White '10)

Fornax

Sculptor

Leo I

© Anglo-Australian Observatory

Carina

Sextans

Sagittarius

Milky Way Dwarfs

Fit stellar surface density profile
with a 3D profile of the form:

$$\rho_*(r) \propto \frac{1}{x^a (1 + x^b)^{(c-a)/b}}$$

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

Milky Way Dwarfs

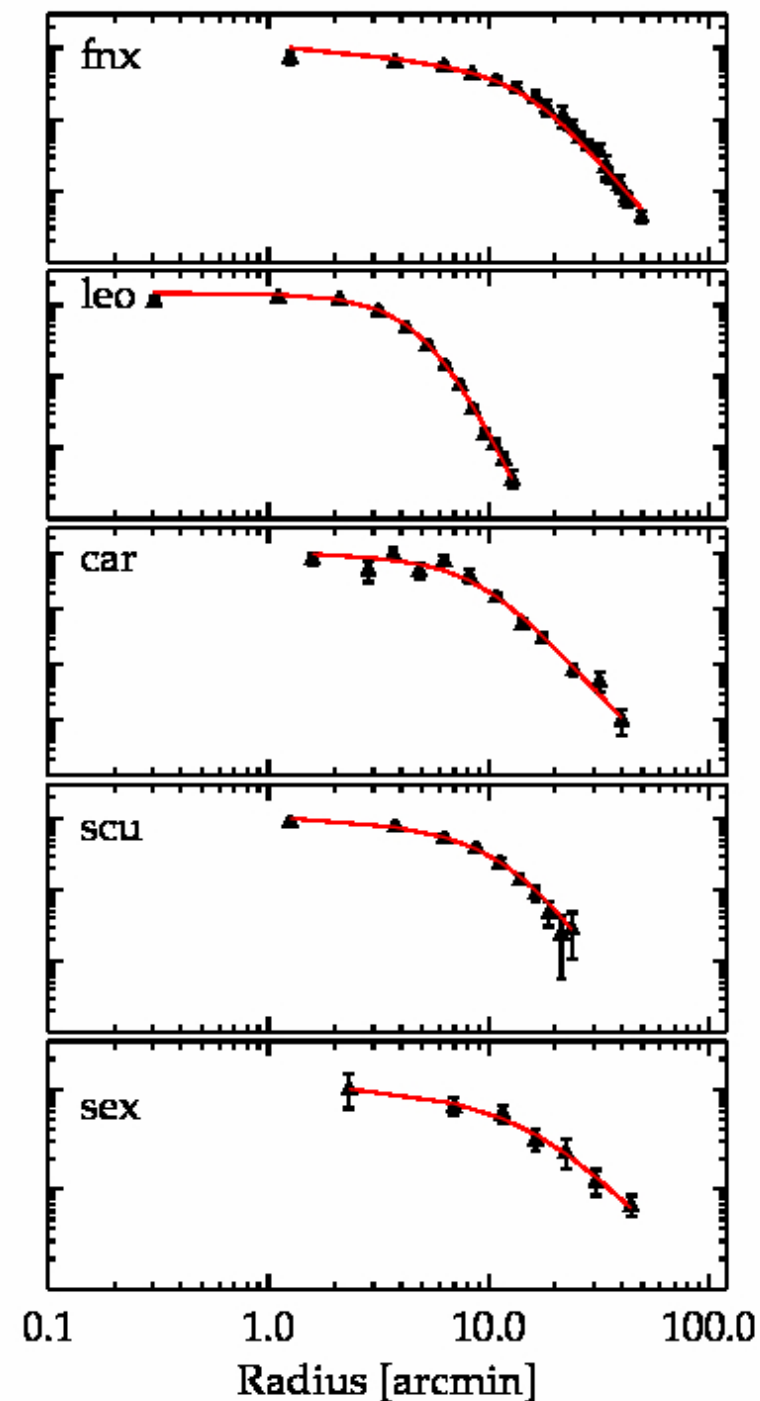
Fit stellar surface density profile with a 3D profile of the form:

$$\rho_*(r) \propto \frac{1}{x^a (1 + x^b)^{(c-a)/b}}$$

Satellite	a	χ^2 /d.o.f.
Fornax	1	1.0
Leo I	0	1.6
Carina	0.5	1.1
Sculptor	0.5	0.4
Sextans	0.5	01

Strigari, Frenk & White '10

Surface Density [Norm. arbitrary]



Dwarf sphs: cores or cusps?

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

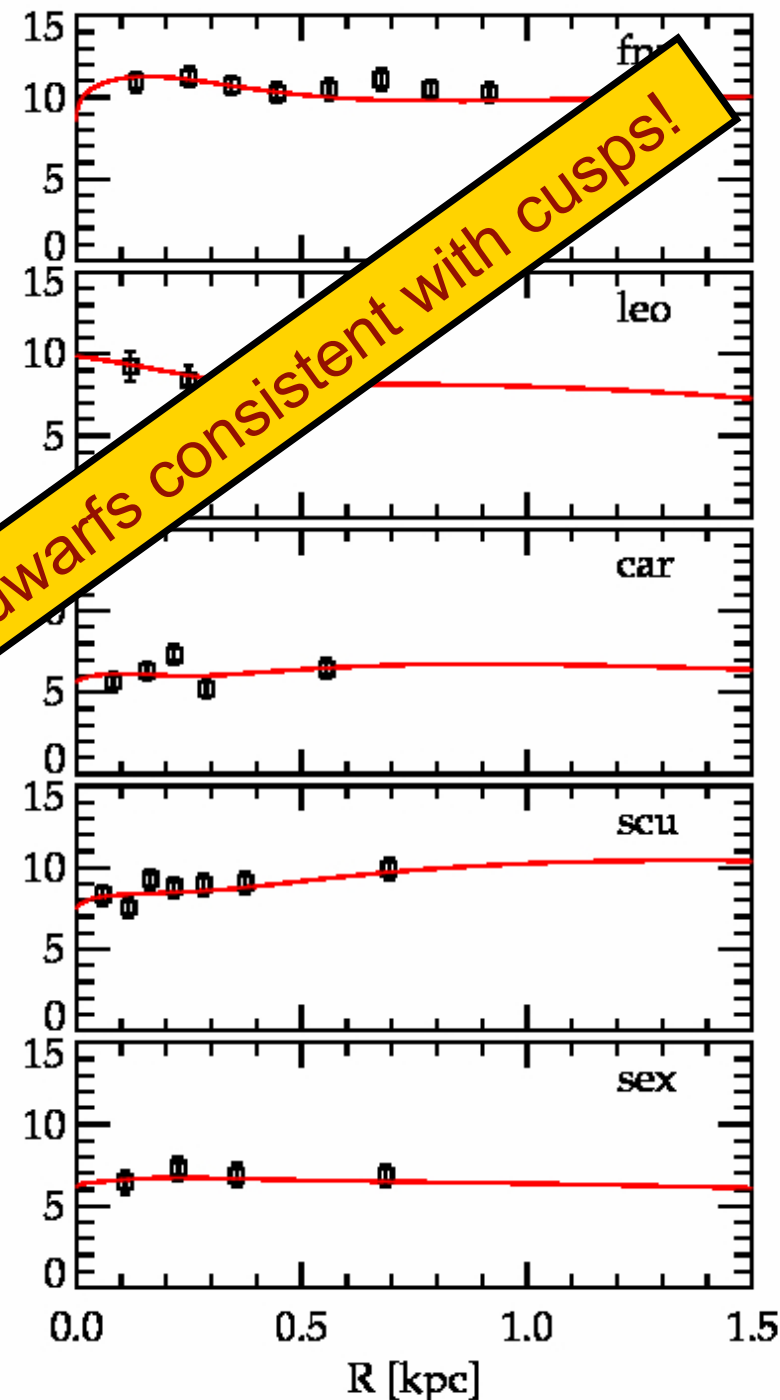
from Aquarius sim

Cuspy!

vel. an...

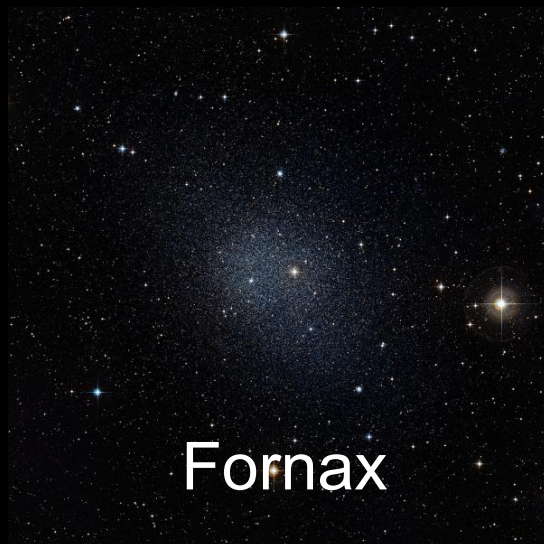
- Assume isotropic
- Solve for
- Compare with observed $\sigma_r(r)$
- "best fit" subhalo

Velocity dispersion [km s⁻¹]

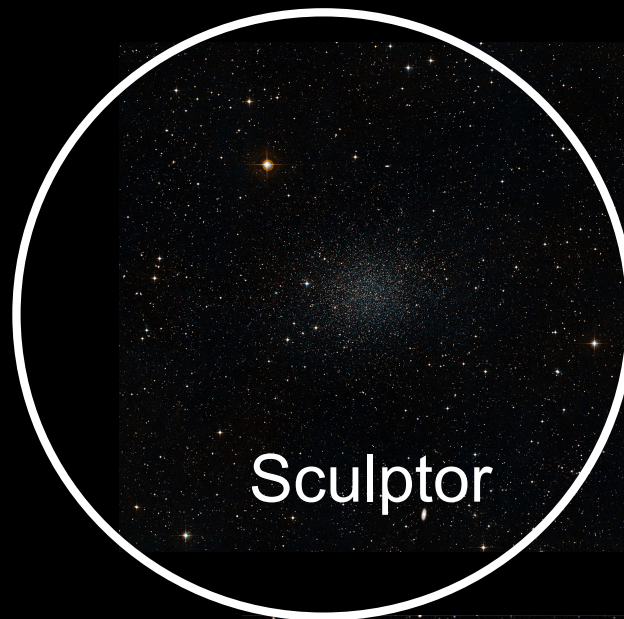




Dwarf galaxies around the Milky Way



Fornax



Sculptor



Leo I

© Anglo-Australian Observatory



Sextans



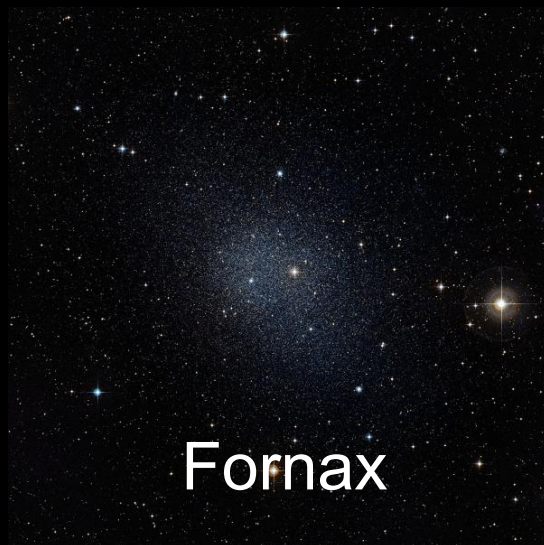
Carina



Sagittarius



Dwarf galaxies around the Milky Way



Fornax



Sculptor



Leo I

© Anglo-Australian Observatory



Sextans



Carina



Sagittarius

The DM halo of the Sculptor dwarf

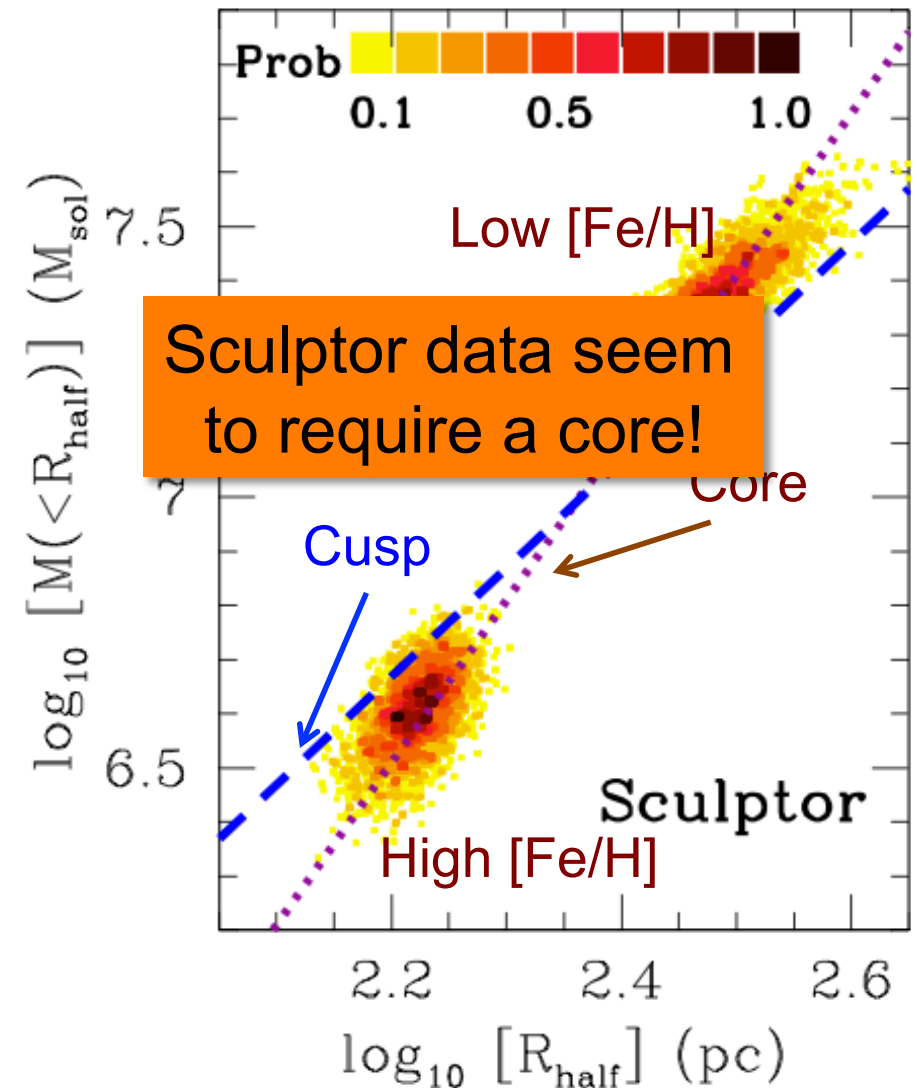
Sculptor has two stellar pops:

- (i) centrally concentrated, high [Fe/H]
- (ii) extended, low [Fe/H]

$$M(< r) = \mu \frac{r < \sigma_{los}^2 >}{G}$$

Wolf et al '10; Walker '10 →

if $r=r_{1/2}$, $\mu=2.5$, independently of model assumptions!

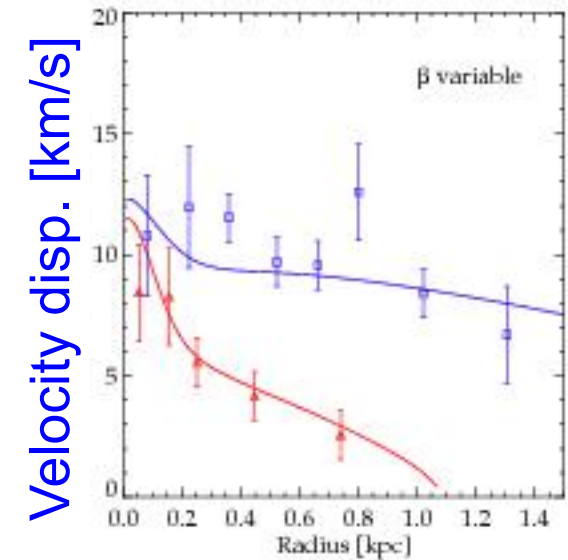
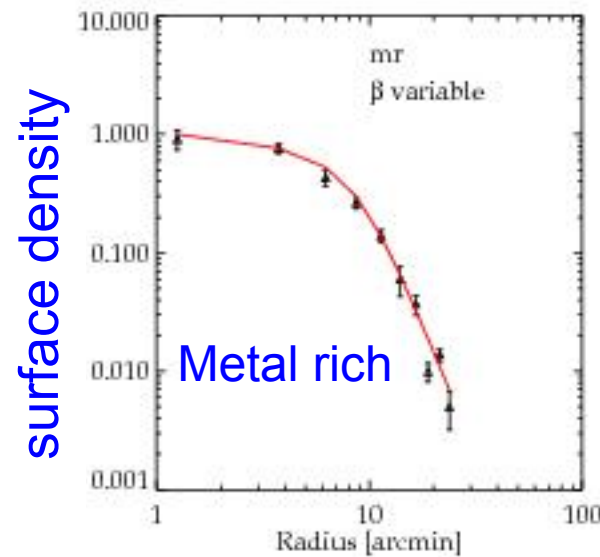
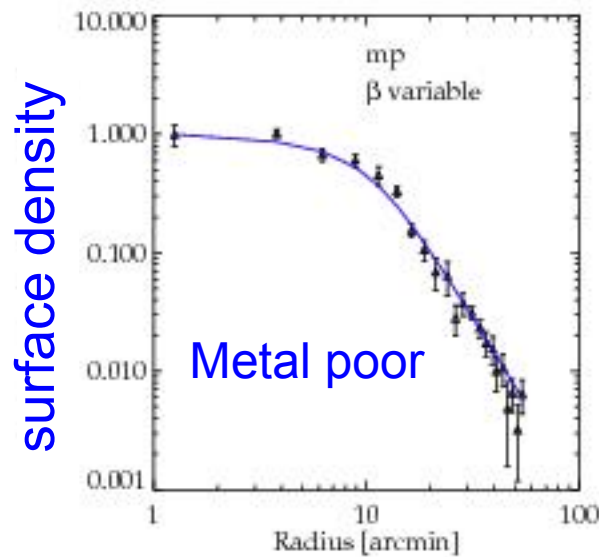


The DM halo of the Sculptor dwarf

Strigari, Frenk & White '13

When sufficiently general models for $\rho_*(r)$, $\sigma(r)$ are considered, do Sculptor data require a core or could they be consistent with NFW?

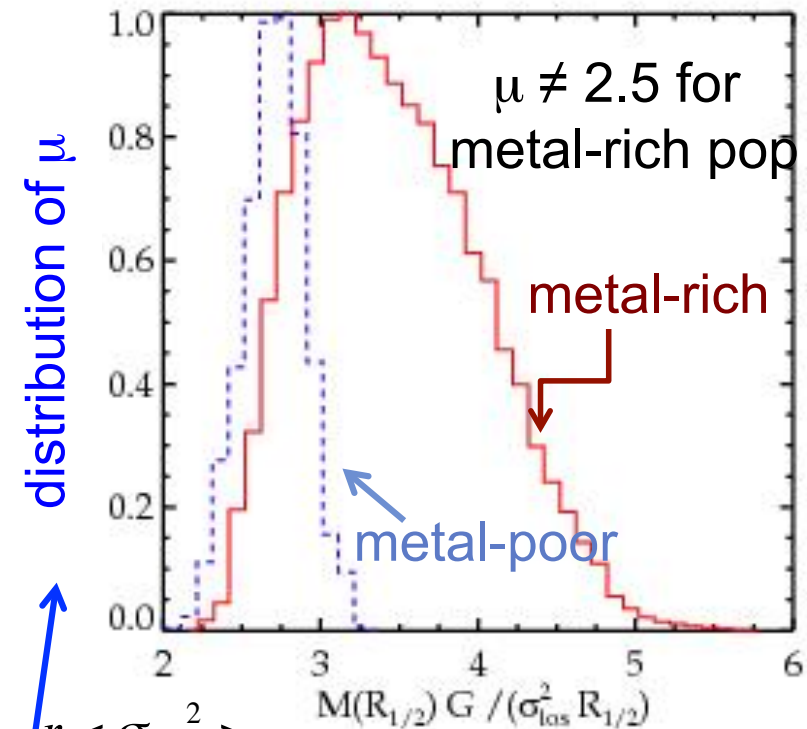
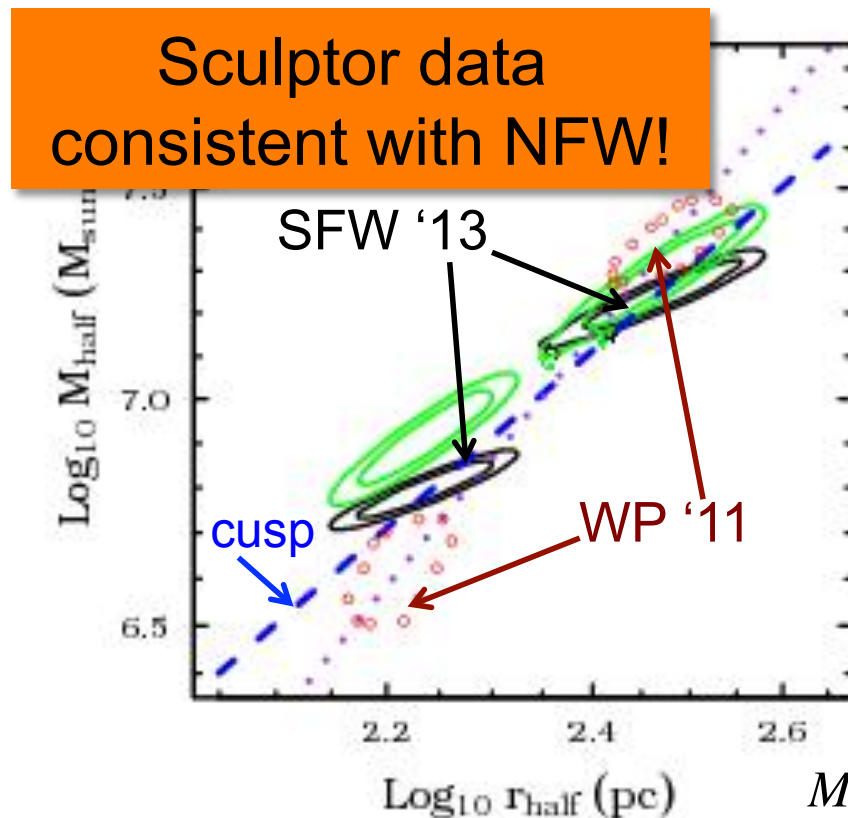
Fits to Sculptor metal-rich & metal-poor populations assuming NFW



The DM halo of the Sculptor dwarf

Strigari, Frenk & White '13

When sufficiently general models for $\rho_*(r)$, $\sigma(r)$ are considered, are the Sculptor data consistent with NFW?



$$M(< r) = \mu \frac{r < \sigma_{\text{los}}^2 >}{G}$$



Cores or cusps in the dwarf sph. satellites of the MW?

When sufficiently general models are considered, even best
data cannot distinguish cores from NFW cusps

N-body simulations: CDM vs WDM

Simulations make 2 important predictions on galactic scales:

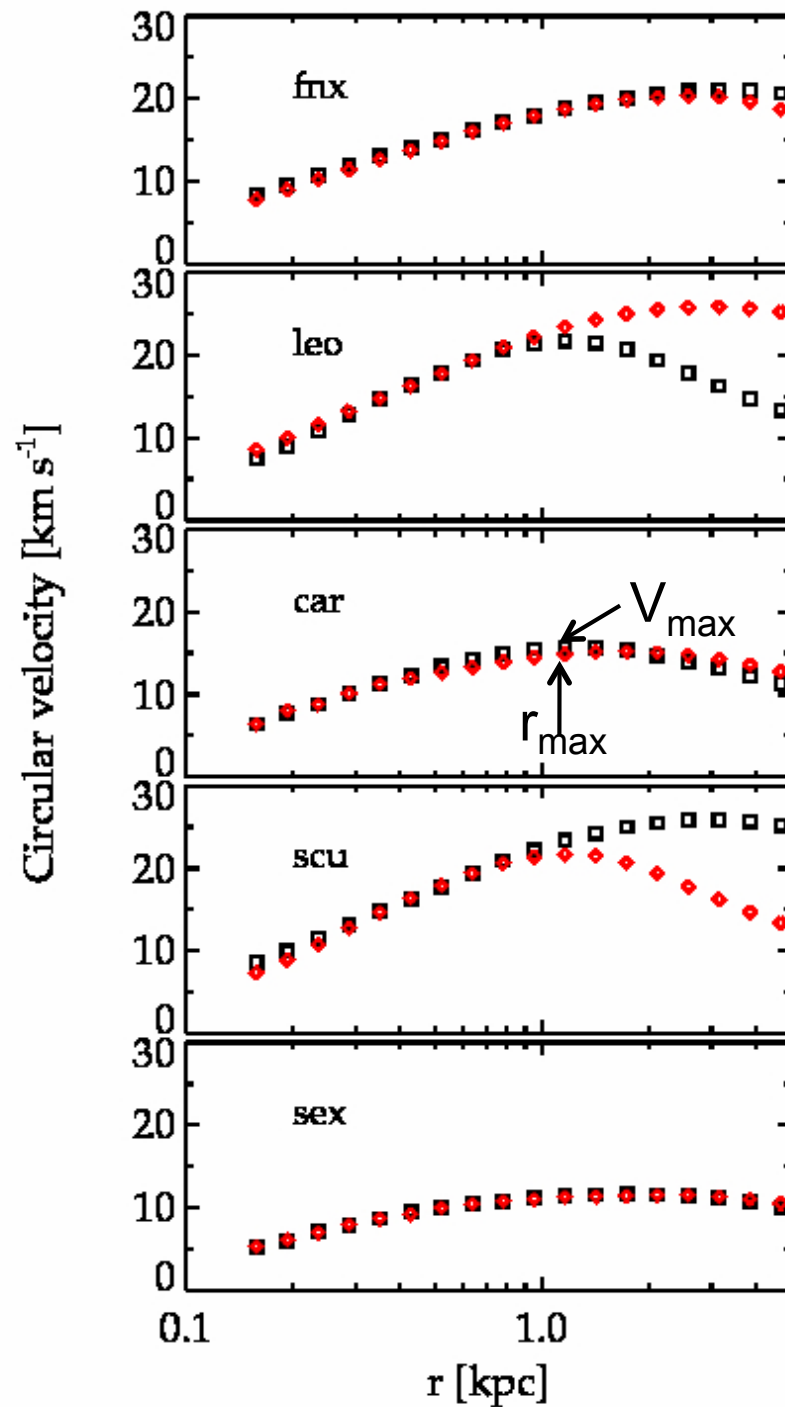
Cold dark matter

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Warm dark matter

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The structure of the Milky Way satellites

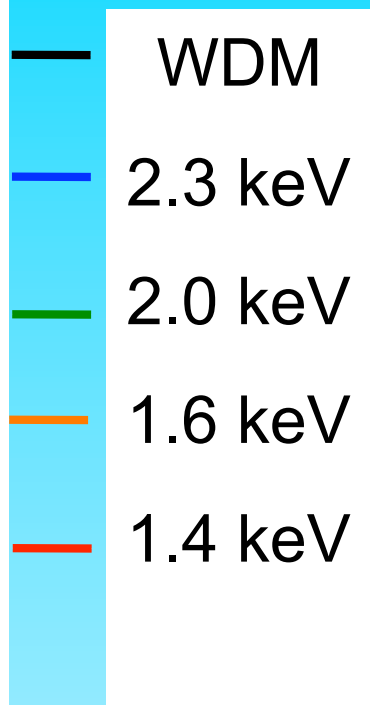


$$V_c = \sqrt{\frac{GM}{r}}$$

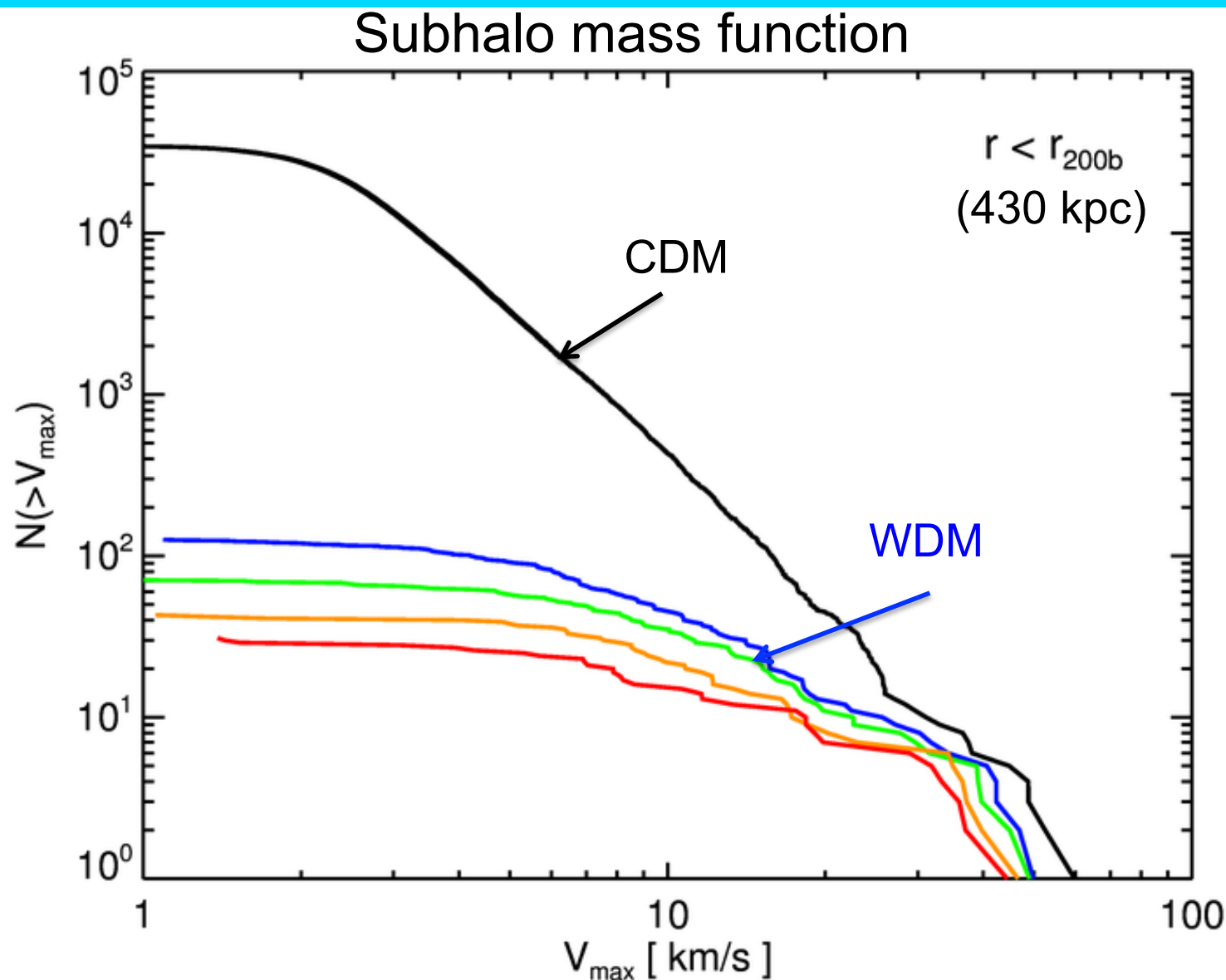
$$V_{\text{max}} = \max V_c$$

Strigari, Frenk & White 2010

The mass function of substructures



No of suhalos
 ↗ with m_{WDM}





How can we distinguish between CDM & WDM ?

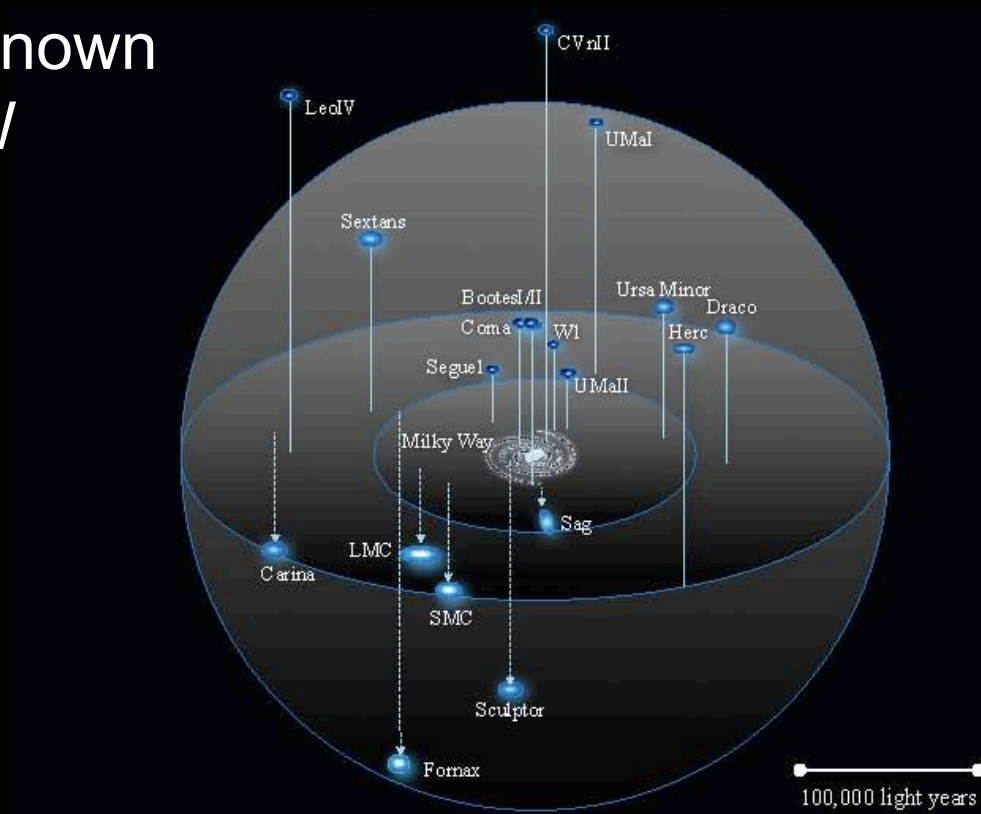


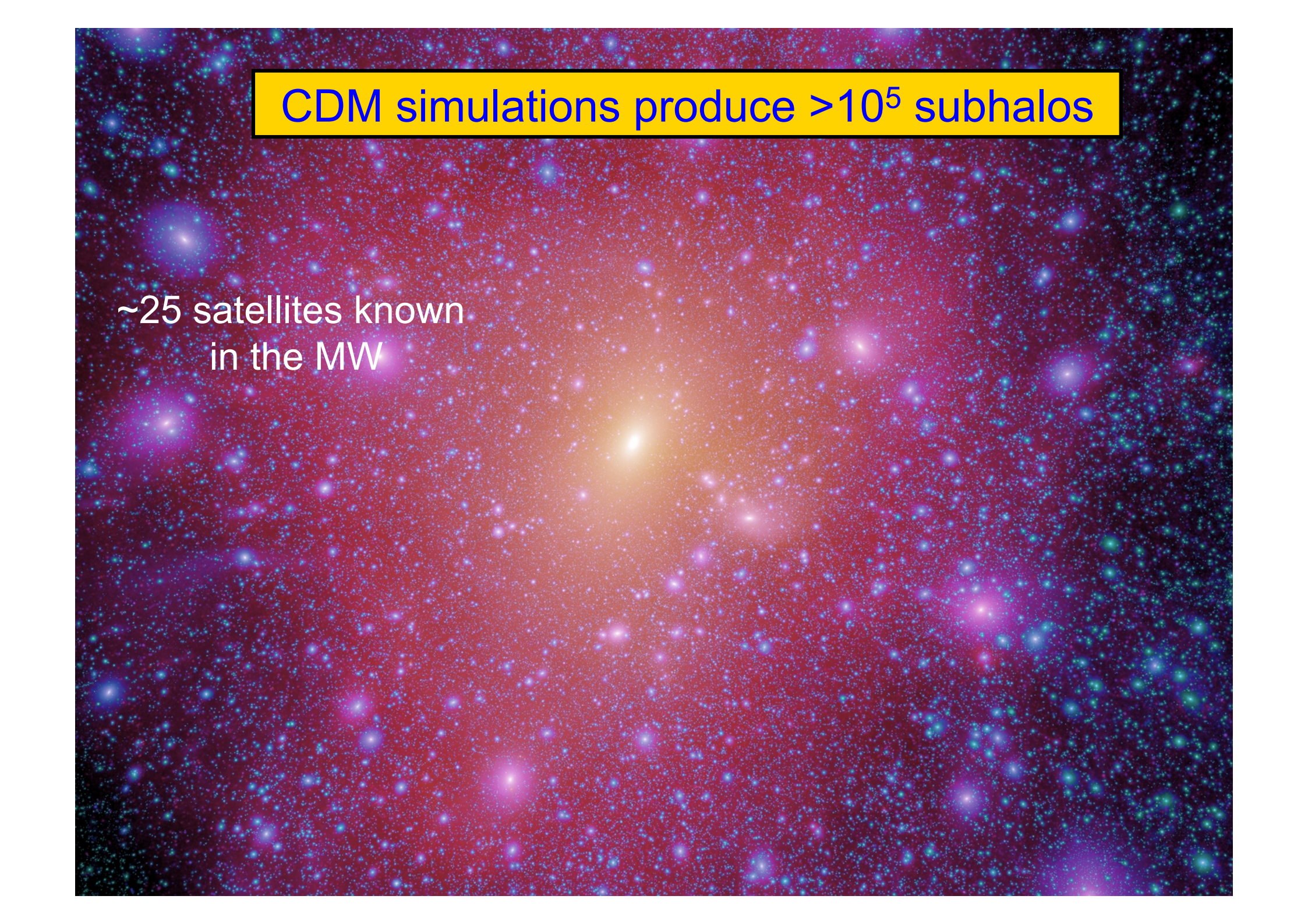
Cosmology on small scales

- The number of satellites (the “satellite problem”)
- The structure of satellites (the “too-big-to-fail” problem)

The satellites of the Milky Way

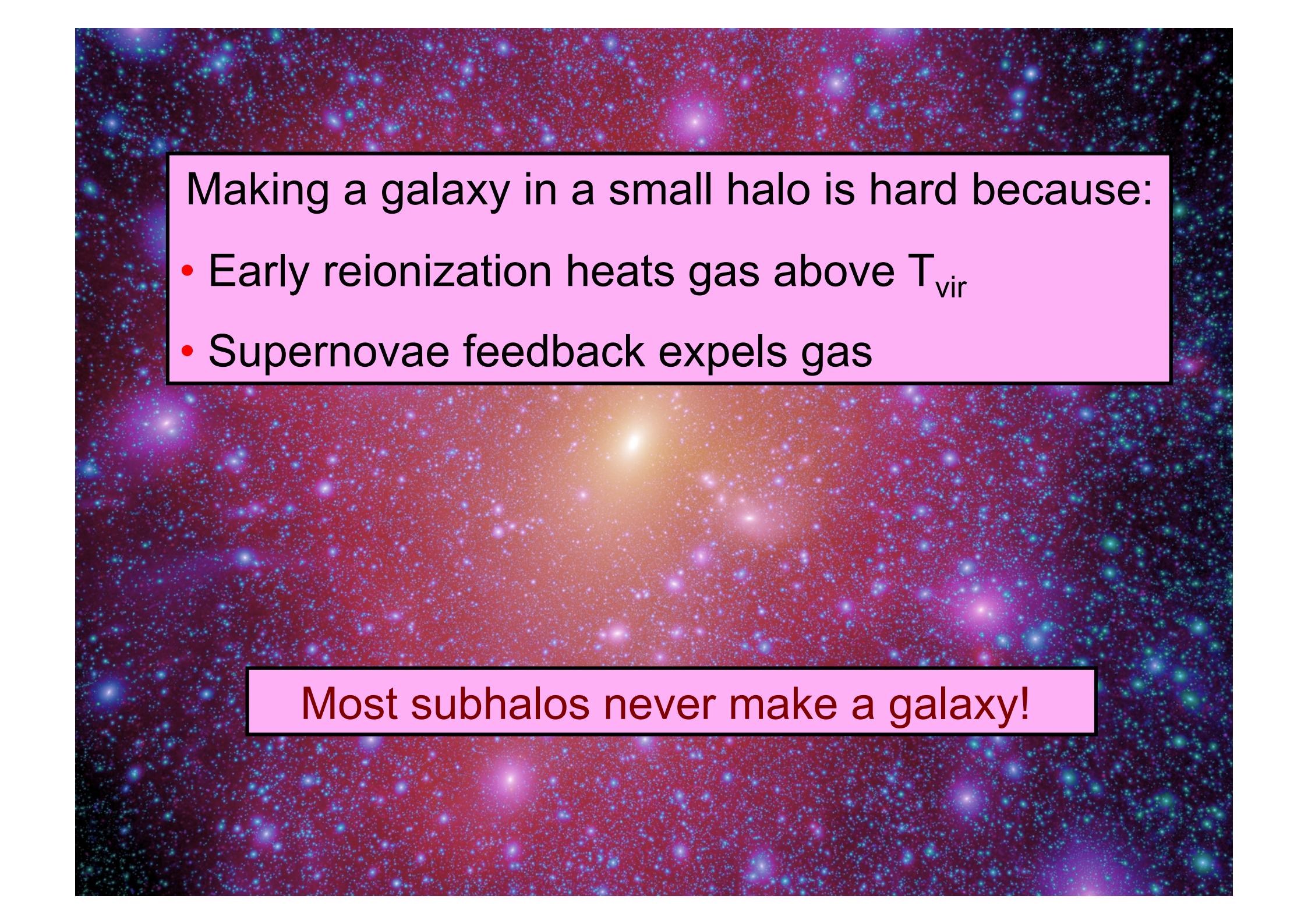
~25 satellites known
in the MW



The background of the slide is a deep space image showing a dense field of galaxies and galaxy clusters. A prominent yellow rectangular box is located at the top center, containing blue text. The overall color palette is dominated by the blues and purples of distant galaxies, with a bright yellow box providing a high-contrast area for the main title.

CDM simulations produce $>10^5$ subhalos

~25 satellites known
in the MW

The background of the slide is a deep space image showing a dense field of blue and white stars. In the center, there is a bright, glowing yellow-orange region, likely representing the core of a galaxy or a star-forming area. A semi-transparent pink rectangular box with a black border is positioned in the upper left quadrant, containing text and a bulleted list.

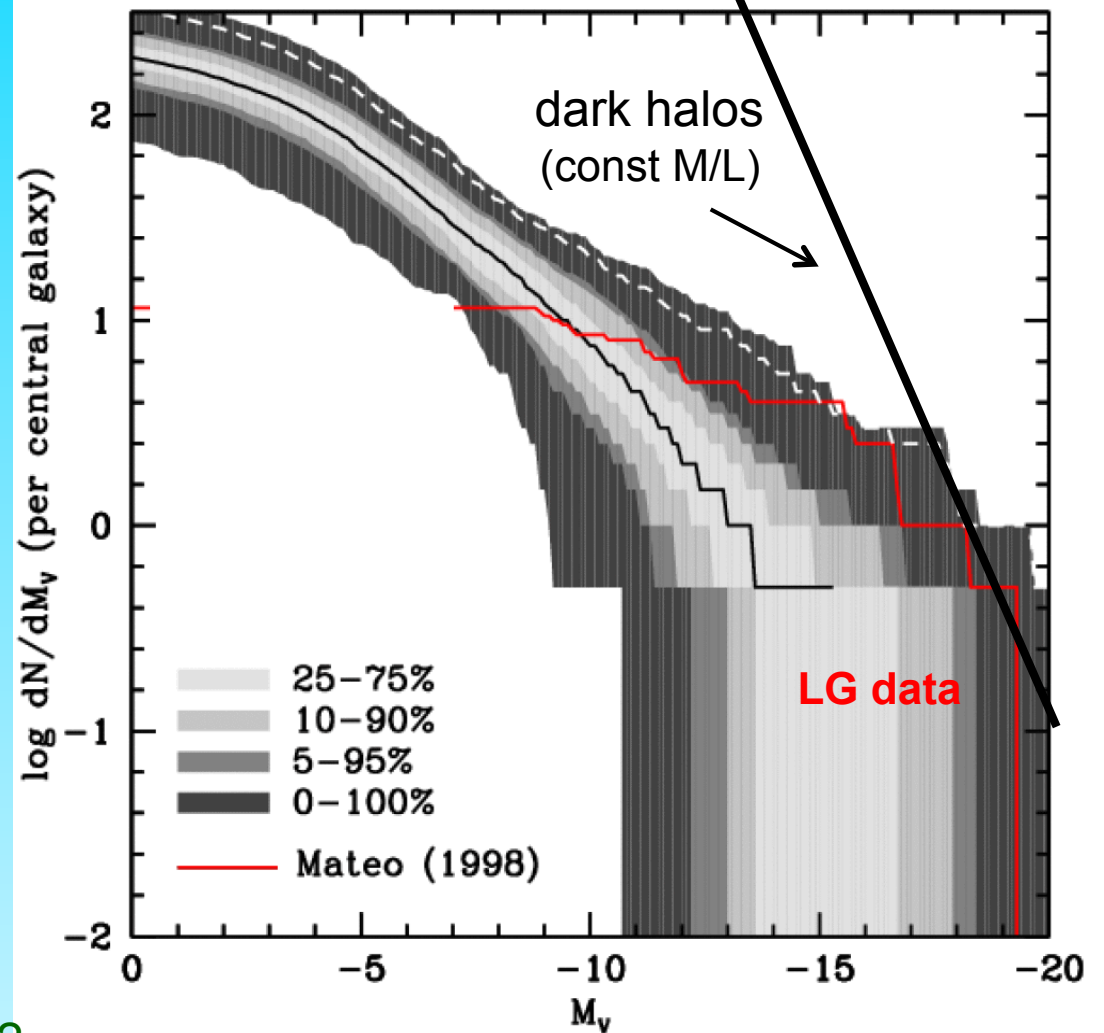
Making a galaxy in a small halo is hard because:

- Early reionization heats gas above T_{vir}
- Supernovae feedback expels gas

Most subhalos never make a galaxy!

Luminosity Function of Local Group Satellites

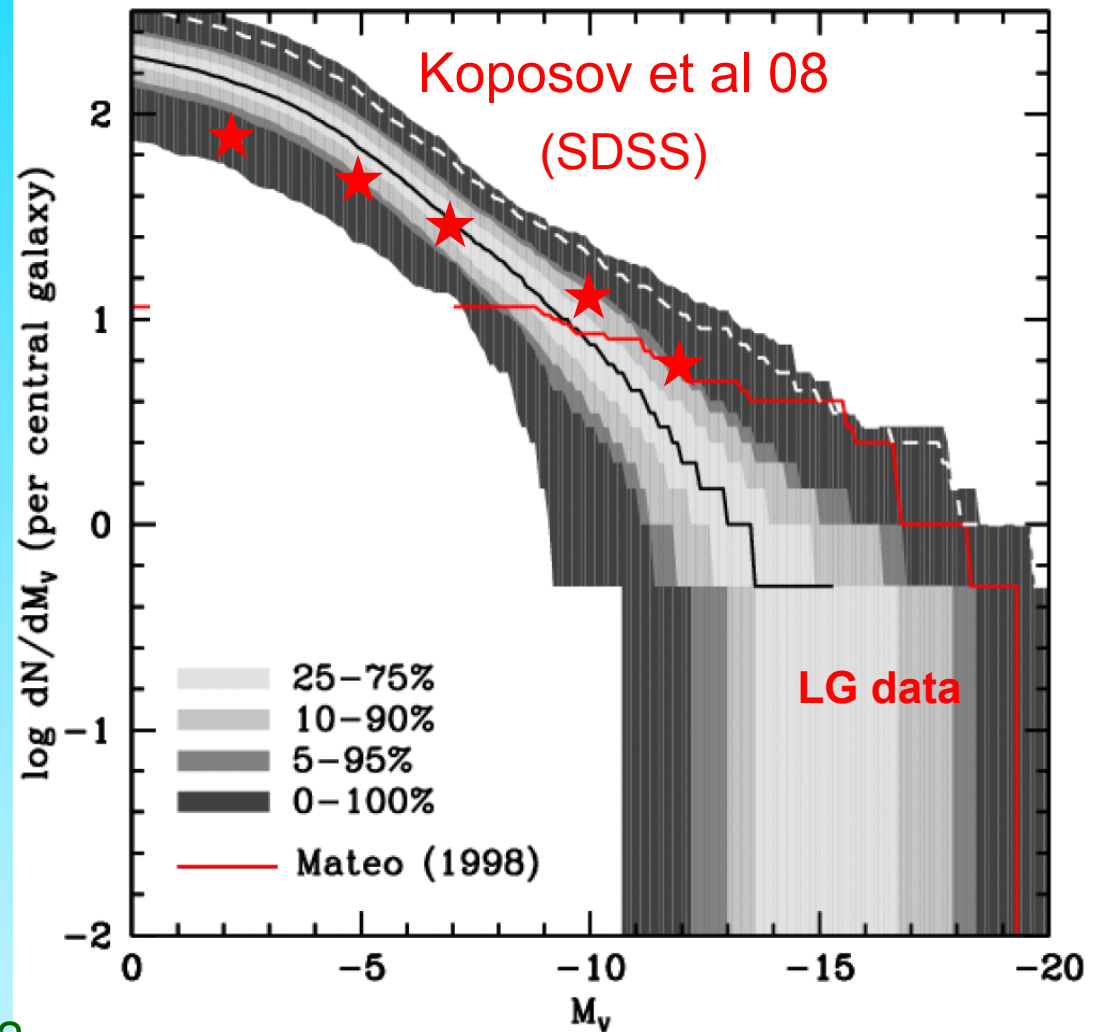
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

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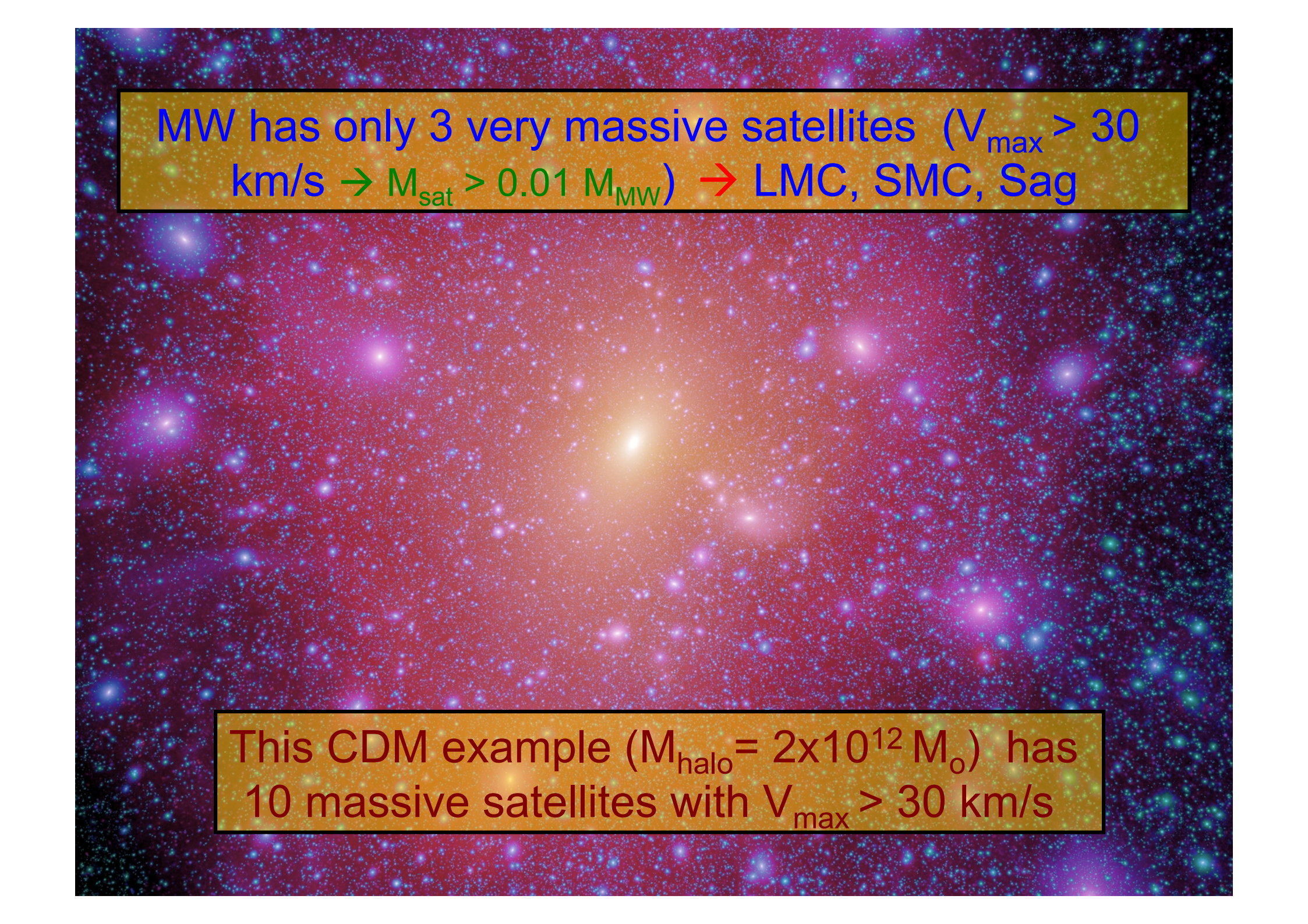


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)



Cosmology on small scales

- The number of satellites (the “satellite problem”)
- The structure of satellites (the “too-big-to-fail” problem)



MW has only 3 very massive satellites ($V_{\max} > 30$
km/s $\rightarrow M_{\text{sat}} > 0.01 M_{\text{MW}}$) $\rightarrow$ LMC, SMC, Sag

This CDM example ($M_{\text{halo}} = 2 \times 10^{12} M_{\odot}$) has
10 massive satellites with $V_{\max} > 30$ km/s

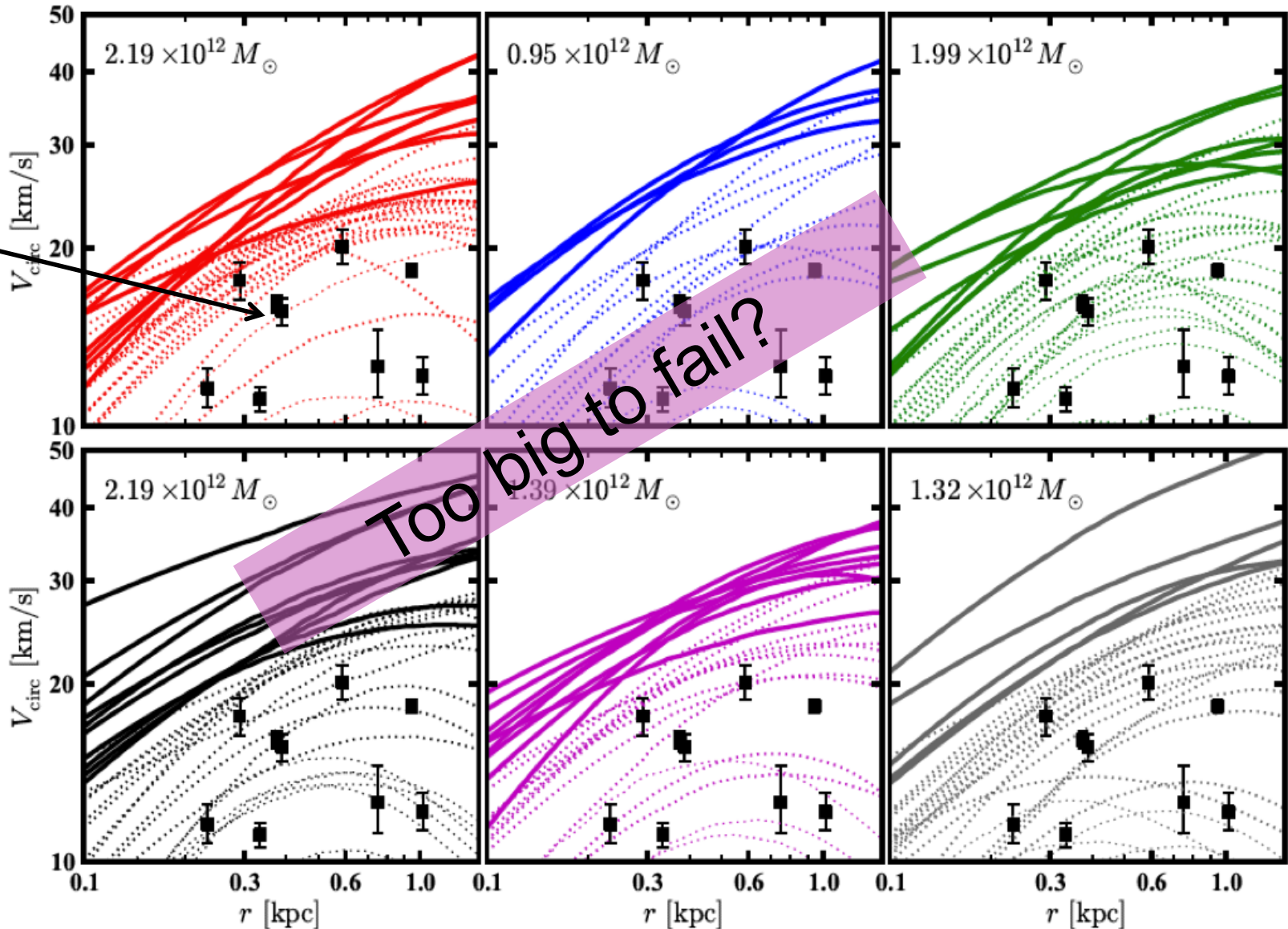
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11

$$V_c = \sqrt{\frac{GM}{r}}$$

9 dwarf
satellites of
Milky Way:
Mass within
half-light
radius

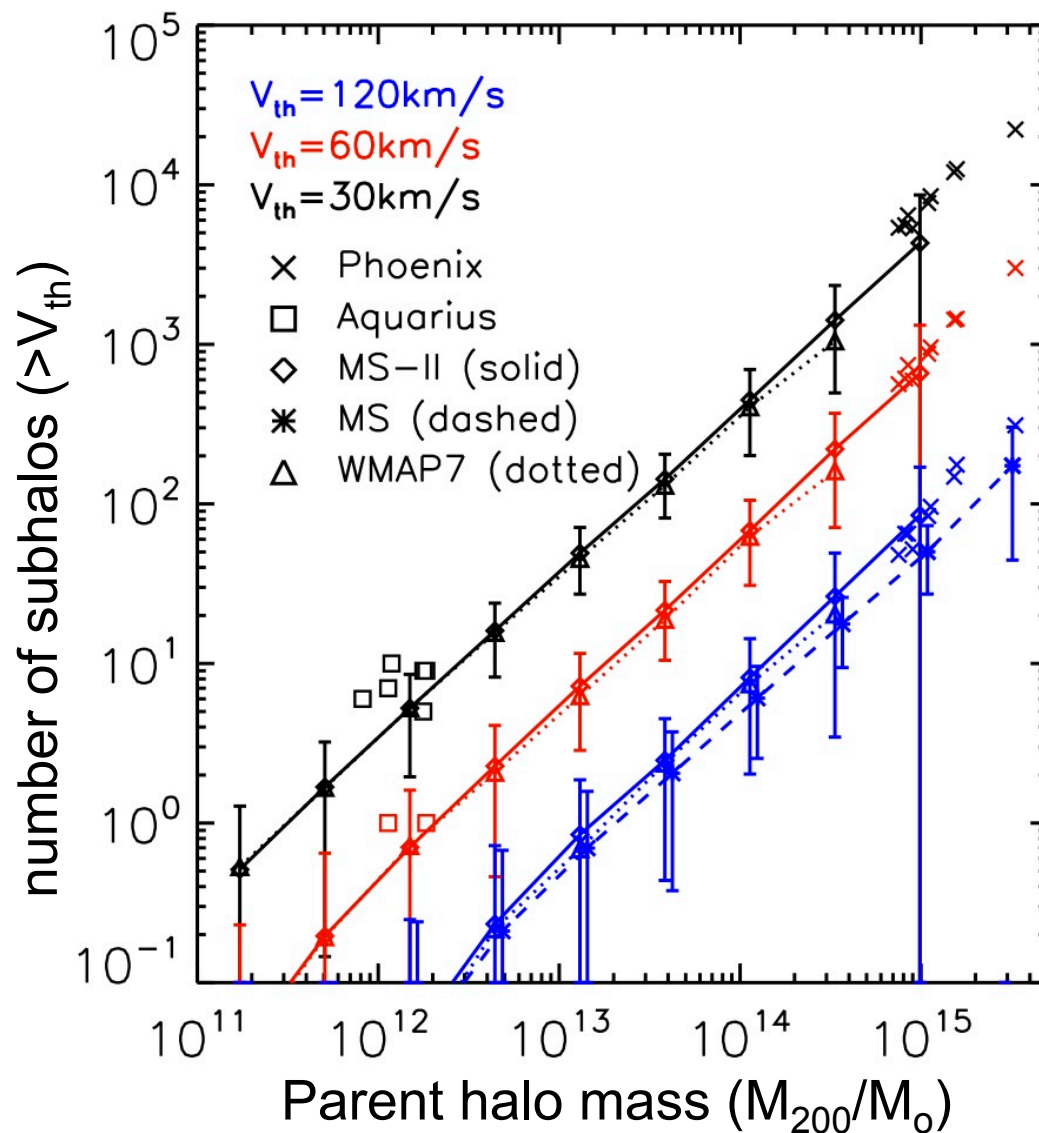
Excludes
LMC, SMC,
Sagittarius



Number of massive subhalos

Number of massive subhalos increases rapidly with halo mass

→ Milky Way halo mass cannot be too large if CDM is right!



Probability of massive subhalos

Probability of having no more than 3 subhalos with $V_{\max} > 30$ km/s

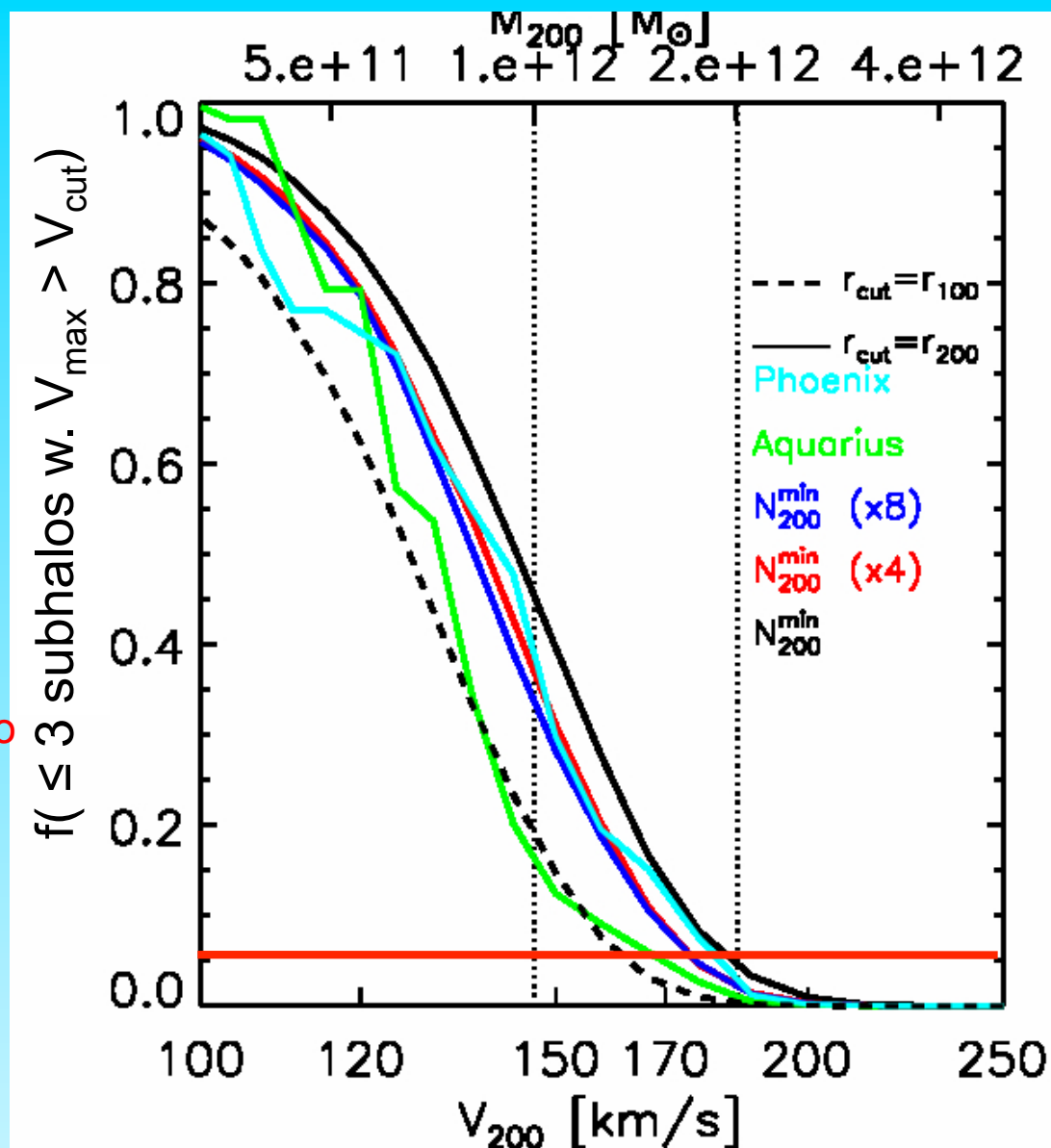
Depends strongly on M_{200} (and V_{cut})

If mass of MW halo $> 2 \times 10^{12} M_{\odot}$
pure CDM is ruled out

CDM requires

$M_{\text{halo}} < 1.5 \times 10^{12} M_{\odot}$ (95% confidence)

Wang, Frenk, Navarro, Gao '12

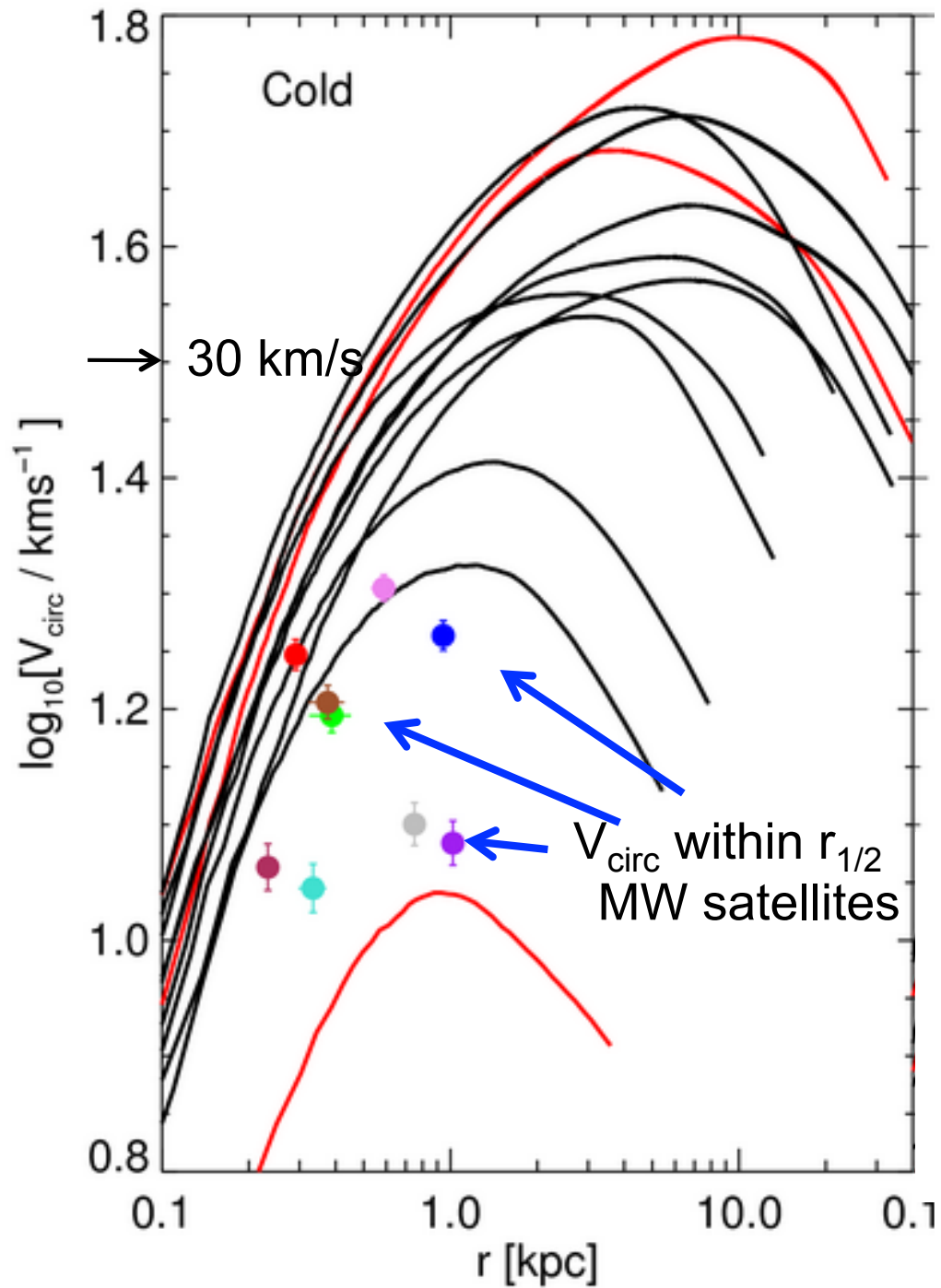




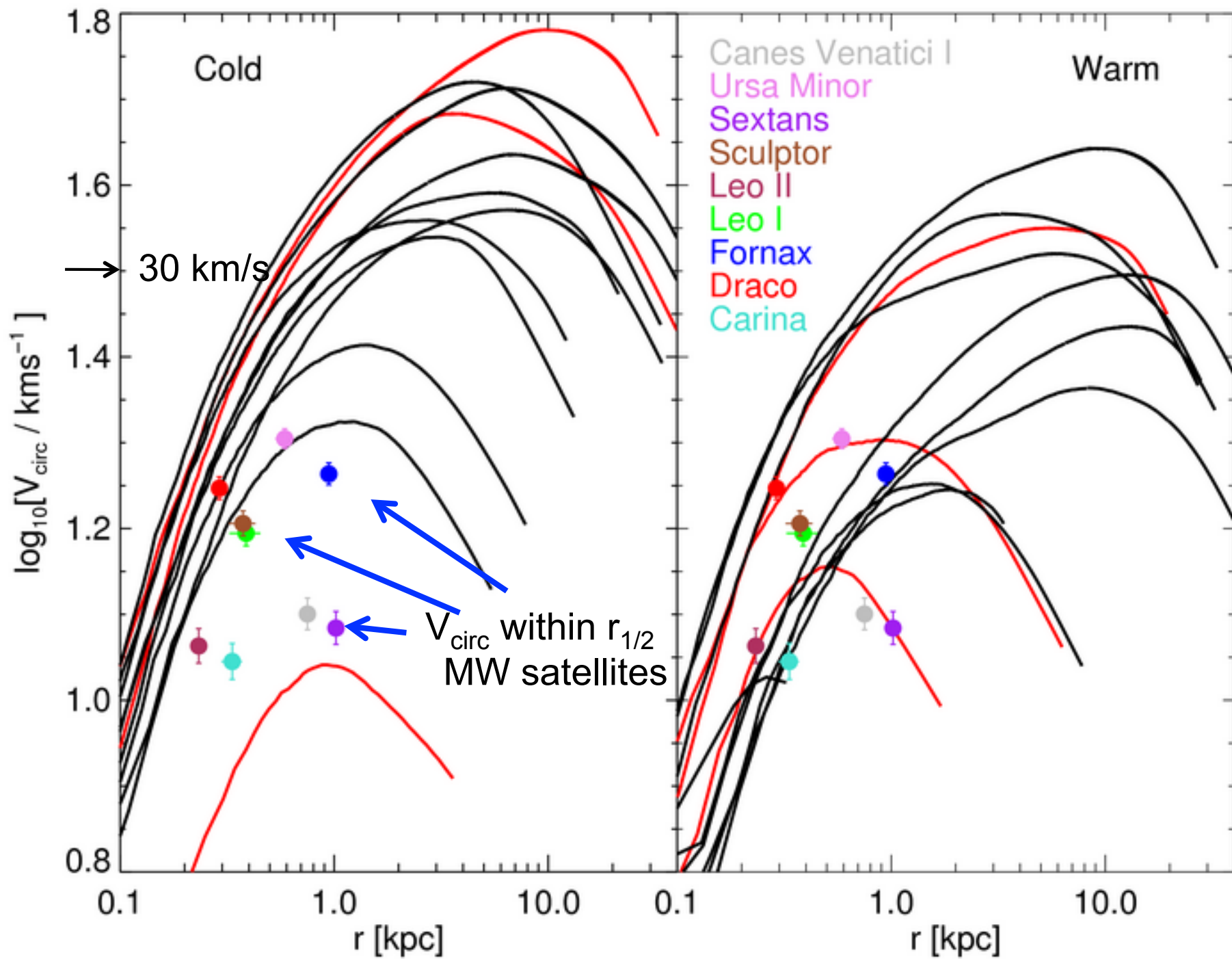
Cosmology on small scales

- The number of satellites (the “satellite problem”)
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How about WDM?



Lovell, Eke, Frenk, Gao,
Jenkins, Wang, White, Theuns,
BoyarSKI & Ruchayskiy '11





Cosmology on small scales

- The number of satellites (the “satellite problem”)
- The structure of satellites (the “too-big-to-fail” problem)

How about WDM?



Tests of the nature of the DM

cold dark matter



warm dark matter



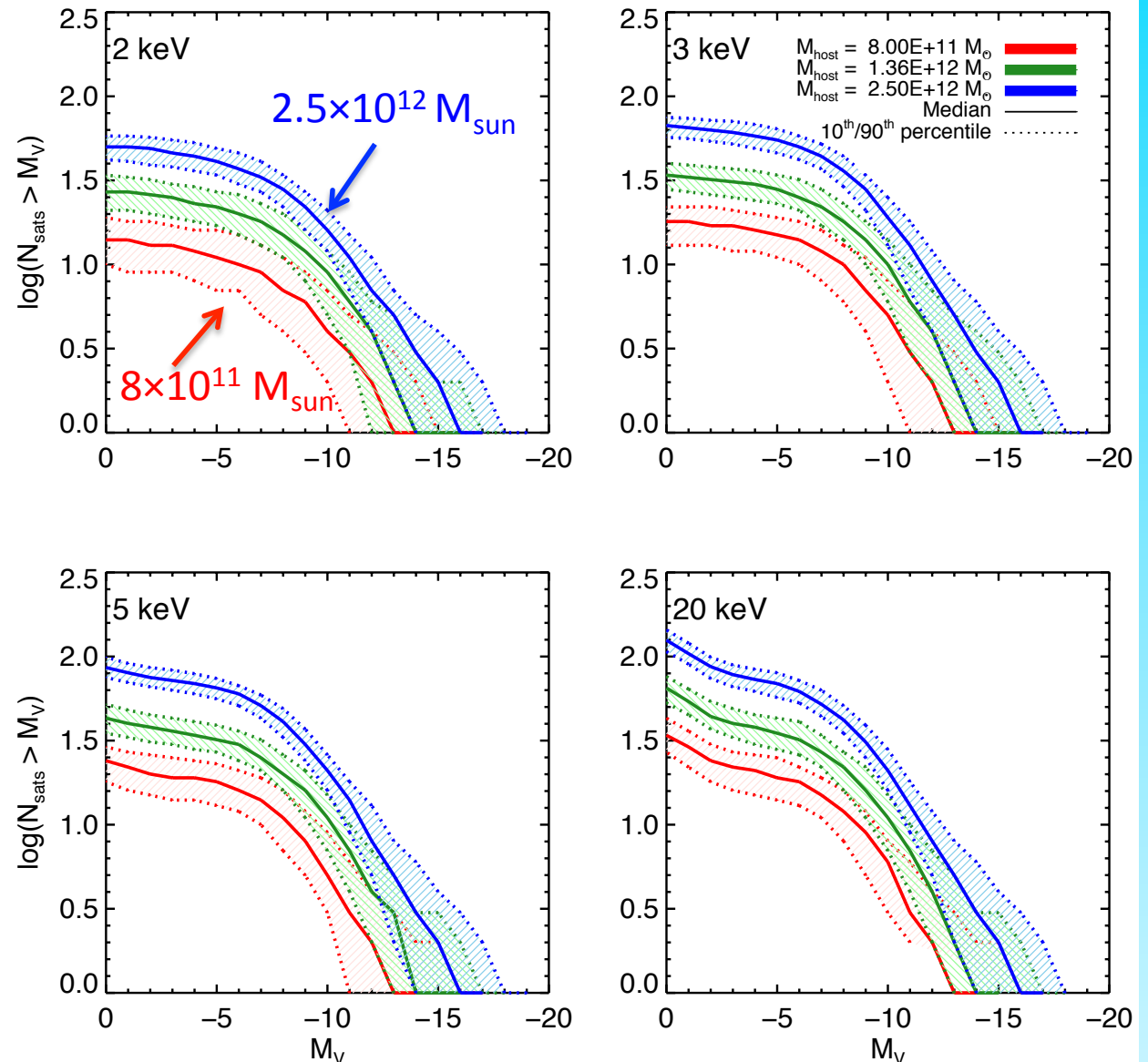
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

Institute for Computational Cosmology

Luminosity Function of Local Group Satellites in WDM

No of sats $\nearrow$ with:

- host halo mass
- WDM particle mass

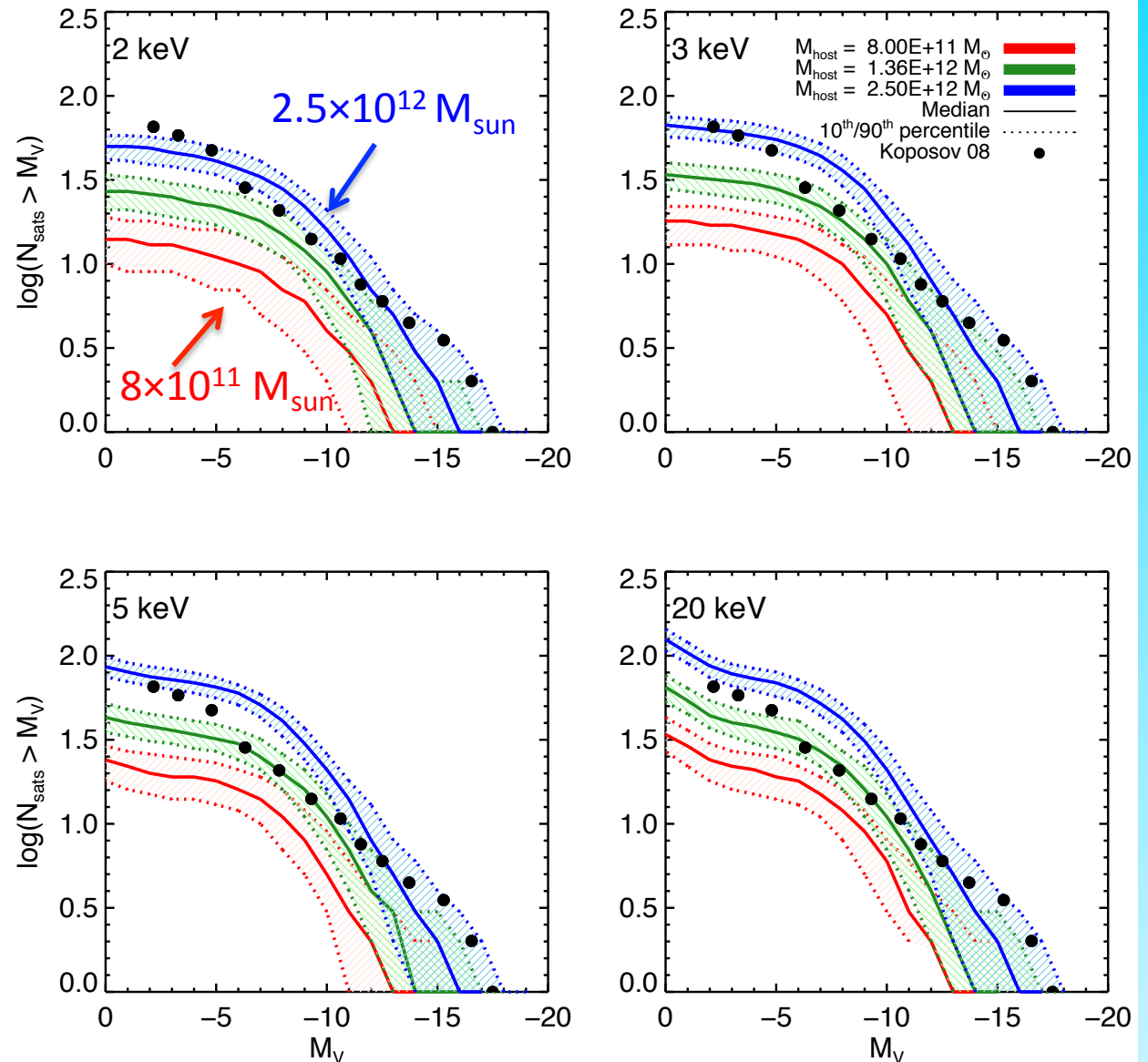


Kennedy, Cole & Frenk '13

Luminosity Function of Local Group Satellites in WDM

No of sats $\nearrow$ with:

- host halo mass
- WDM particle mass



Kennedy, Cole & Frenk '13

Limits on WDM particle mass

For given m_{wdm} model must predict **at least** observed no of sats

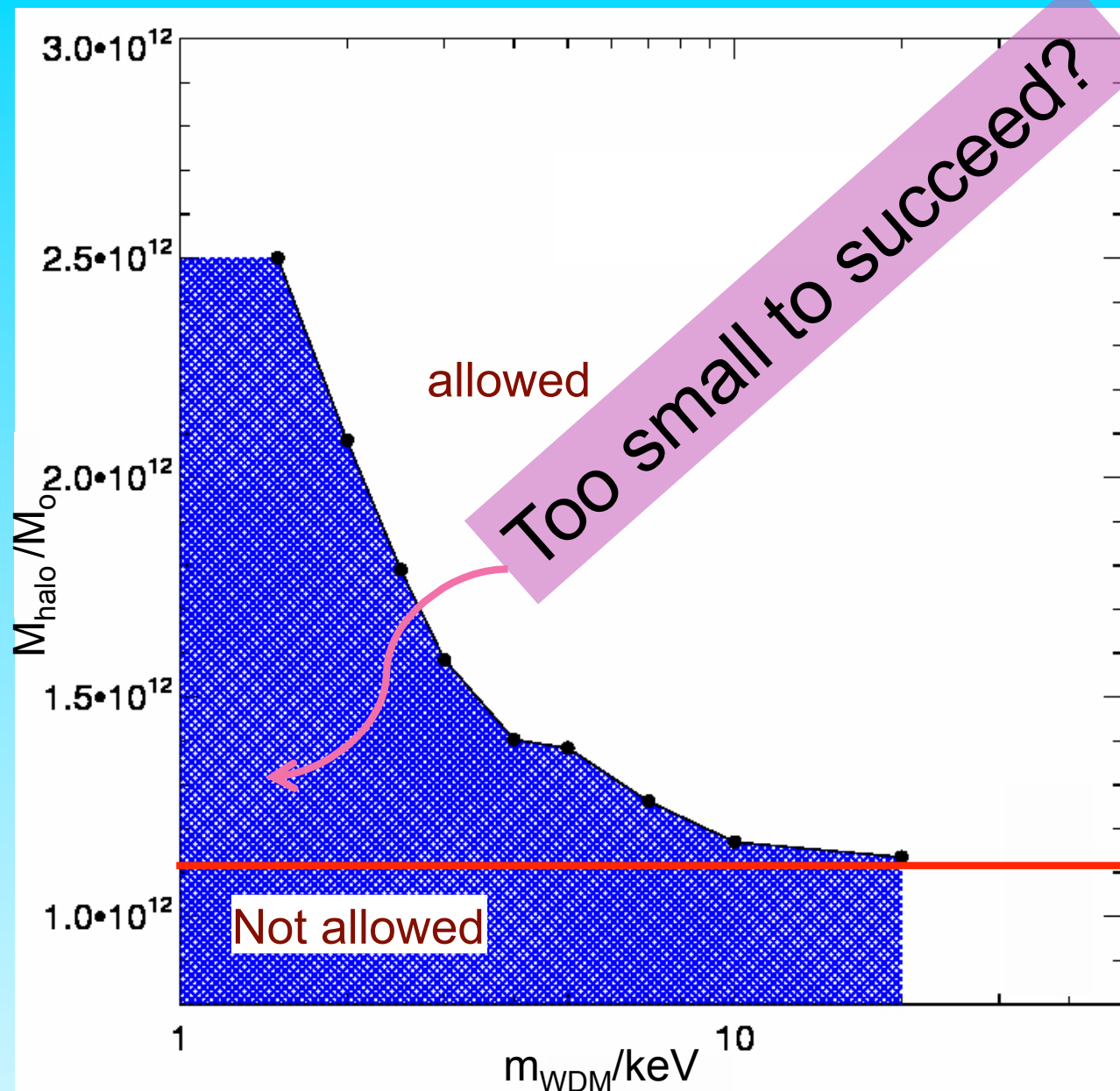
→ lower limit on m_{wdm}

Limits on WDM particle mass

Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

For standard galaxy formation model, WDM ruled out if $M_{\text{halo}} < 1.1 \times 10^{12} M_{\odot}$

Kennedy, Cole & Frenk '13



Estimates of the MW halo mass

- Li & White $\rightarrow M_{200} = 2.4 \times 10^{12} M_{\odot}$; $M_{200} > 8 \times 10^{11} M_{\odot}$ at 95% CL
- Guo et al $\rightarrow 8 \times 10^{11} M_{\odot} < M_{200} < 4.7 \times 10^{12} M_{\odot}$
- Deason et al $\rightarrow 5 \times 10^{11} M_{\odot} < M_{150\text{kpc}} < 1 \times 10^{12} M_{\odot}$
- Xue et al $\rightarrow 8 \times 10^{11} M_{\odot} < M_{100} < 1.3 \times 10^{12} M_{\odot}$
- Battaglia et al $\rightarrow 6 \times 10^{11} M_{\odot} < M_{100} < 3 \times 10^{12} M_{\odot}$

Constraints on CDM & WDM from the Milky Way satellites

With our standard assumptions: at 95% confidence

Cold dark matter :

Ruled out unless $M_{\text{halo}} < 1.5 \times 10^{12} M_{\odot}$

(from abundance of massive satellites)

What about baryon effects?

Warm dark matter :

Ruled out unless $M_{\text{halo}} > 1.2 \times 10^{12} M_{\odot}$

(from abundance of satellites)

From X-ray decay limit, for resonantly produced sterile vs

→ need $m_{\text{WDM}} < 5\text{keV}$ and $M_{\text{halo}} > 1.4 \times 10^{12} M_{\odot}$

The cores of dwarf galaxy haloes

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Accepted 1996 September 2. Received 1996 August 28; in original form 1996 June 26

ABSTRACT

We use N -body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.

Let baryons cool and condense to the galactic centre

Rapid ejection of large fraction of gas during starburst can lead to a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

Governato et al. '12

Pontzen & Governato '12

Brooks et al. '12

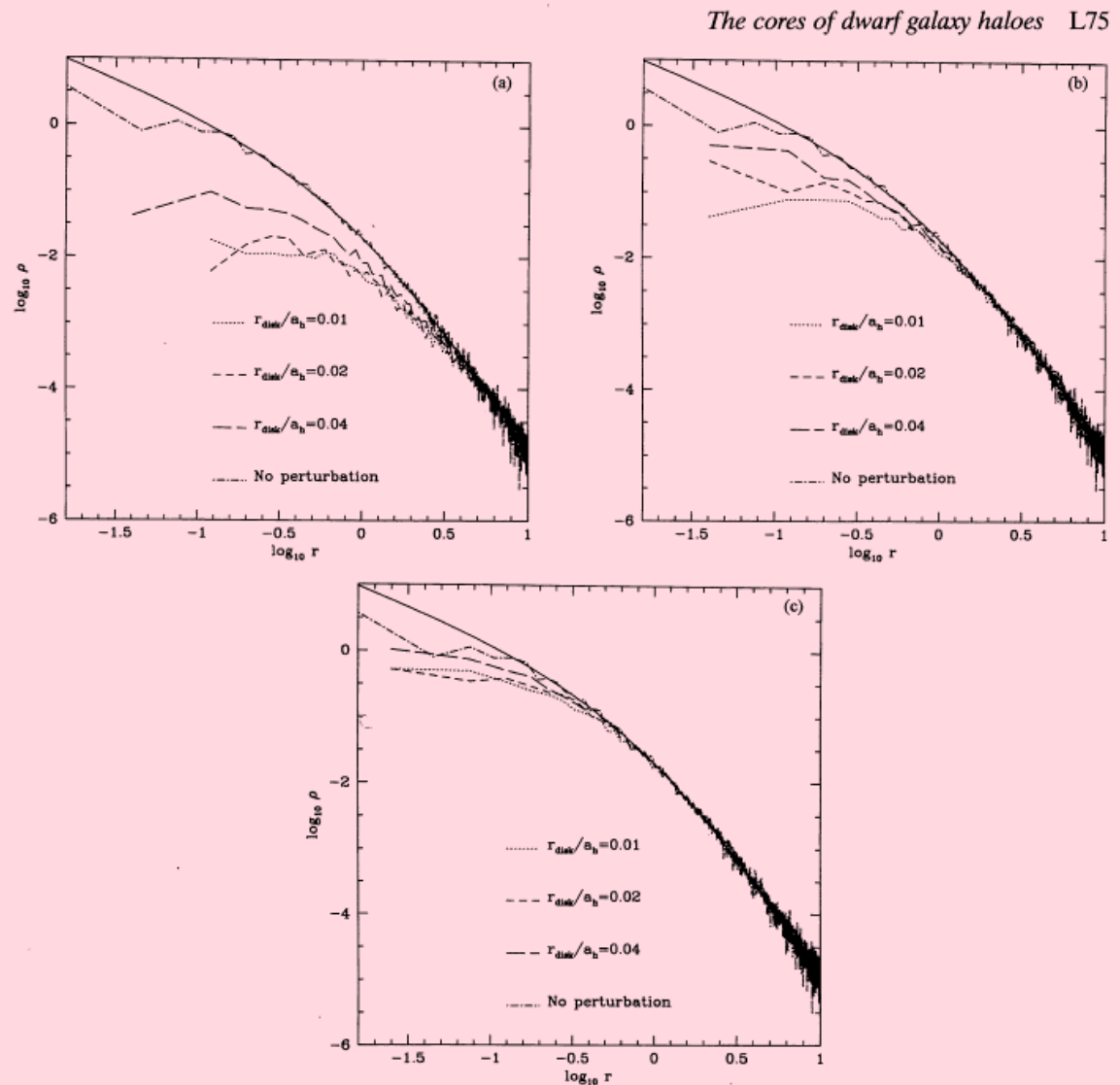


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{\text{disc}}=0.2$. (b) $M_{\text{disc}}=0.1$. (c) $M_{\text{disc}}=0.05$.

Cores in dwarf galaxies

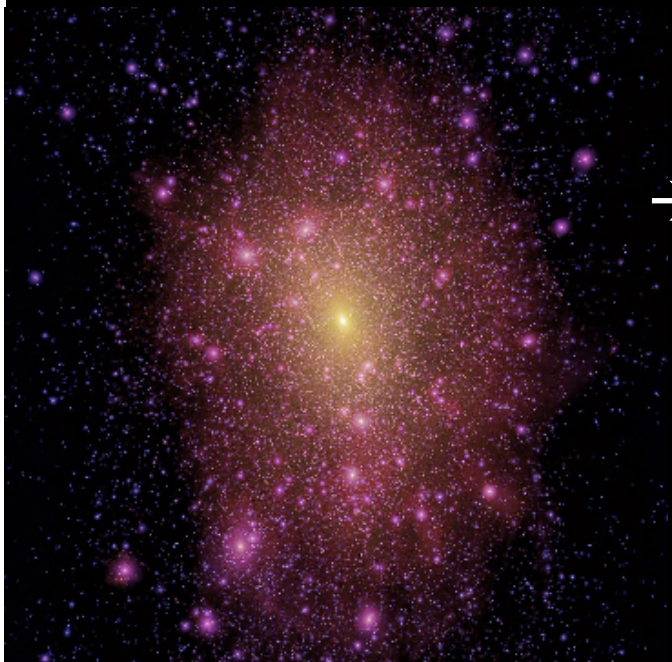
Recent tsunami of papers on simulations that produce cores:

Governato et al '10, '12, Parry et al '12, Pontzen & Governato '13,
Zolotov et al '12, Brooks et al '13 ... and more

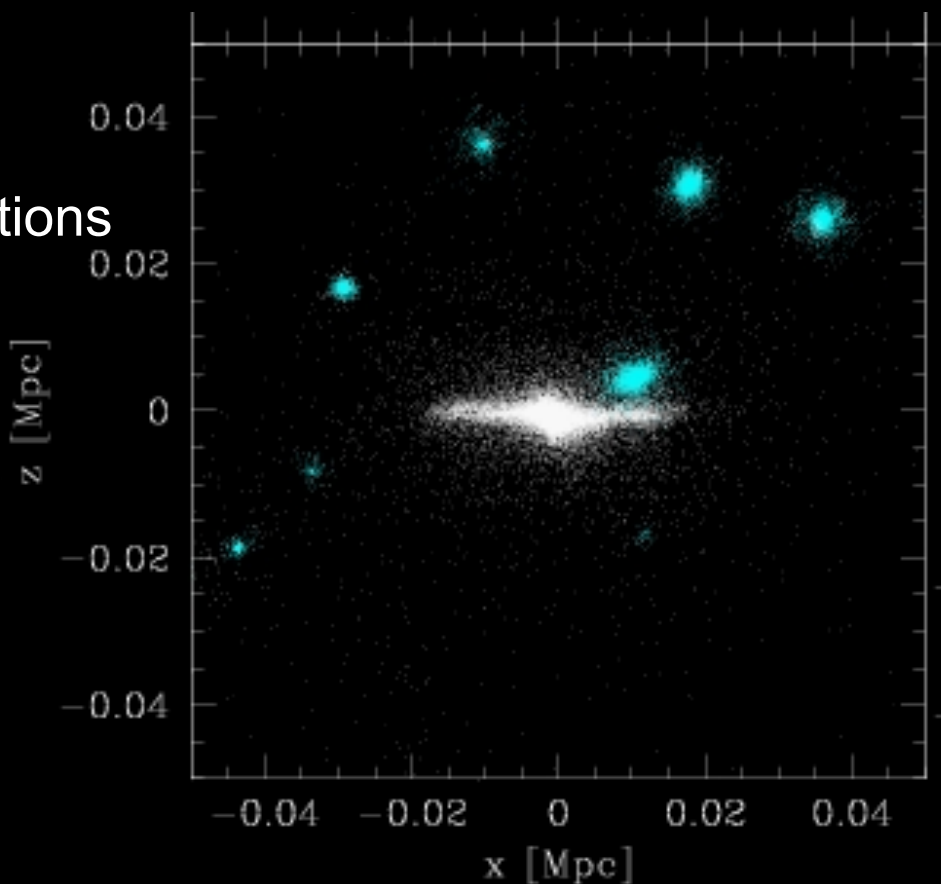


The satellites of the Milky Way

SPH simulations of galaxy formation in
three Aquarius halos

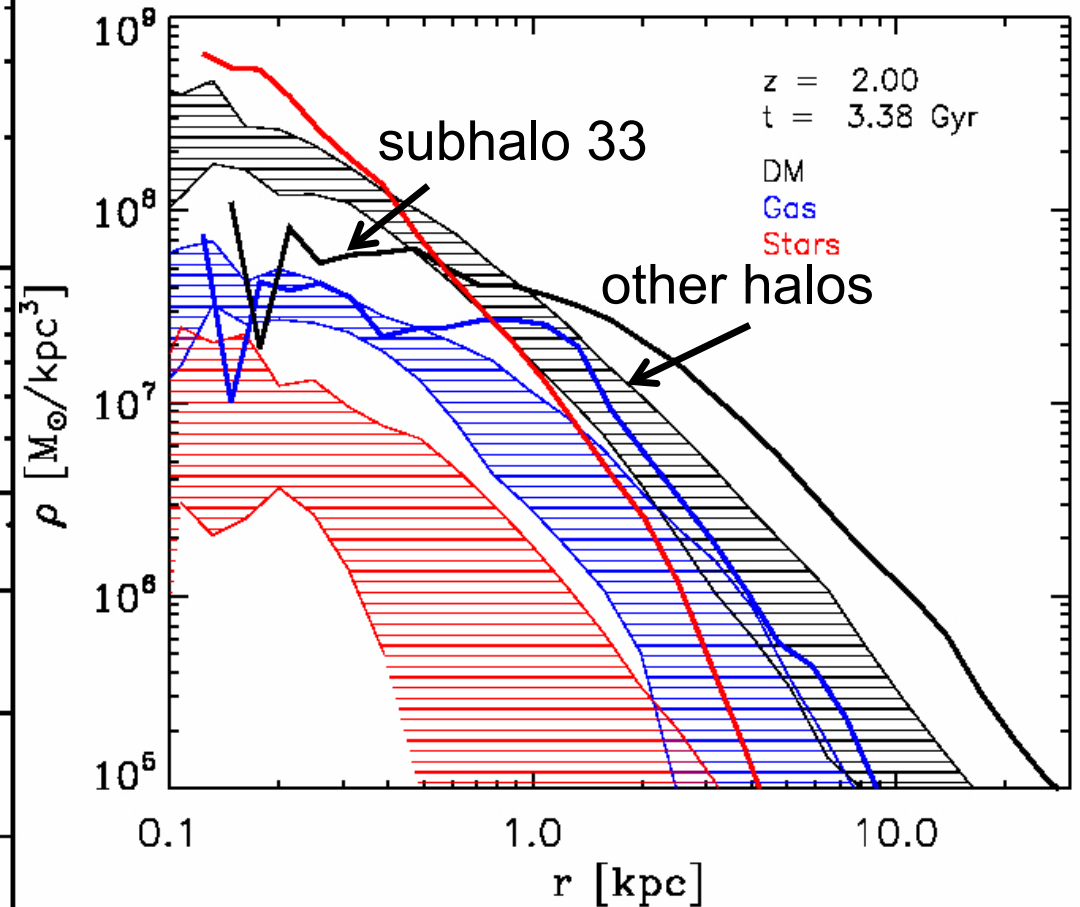
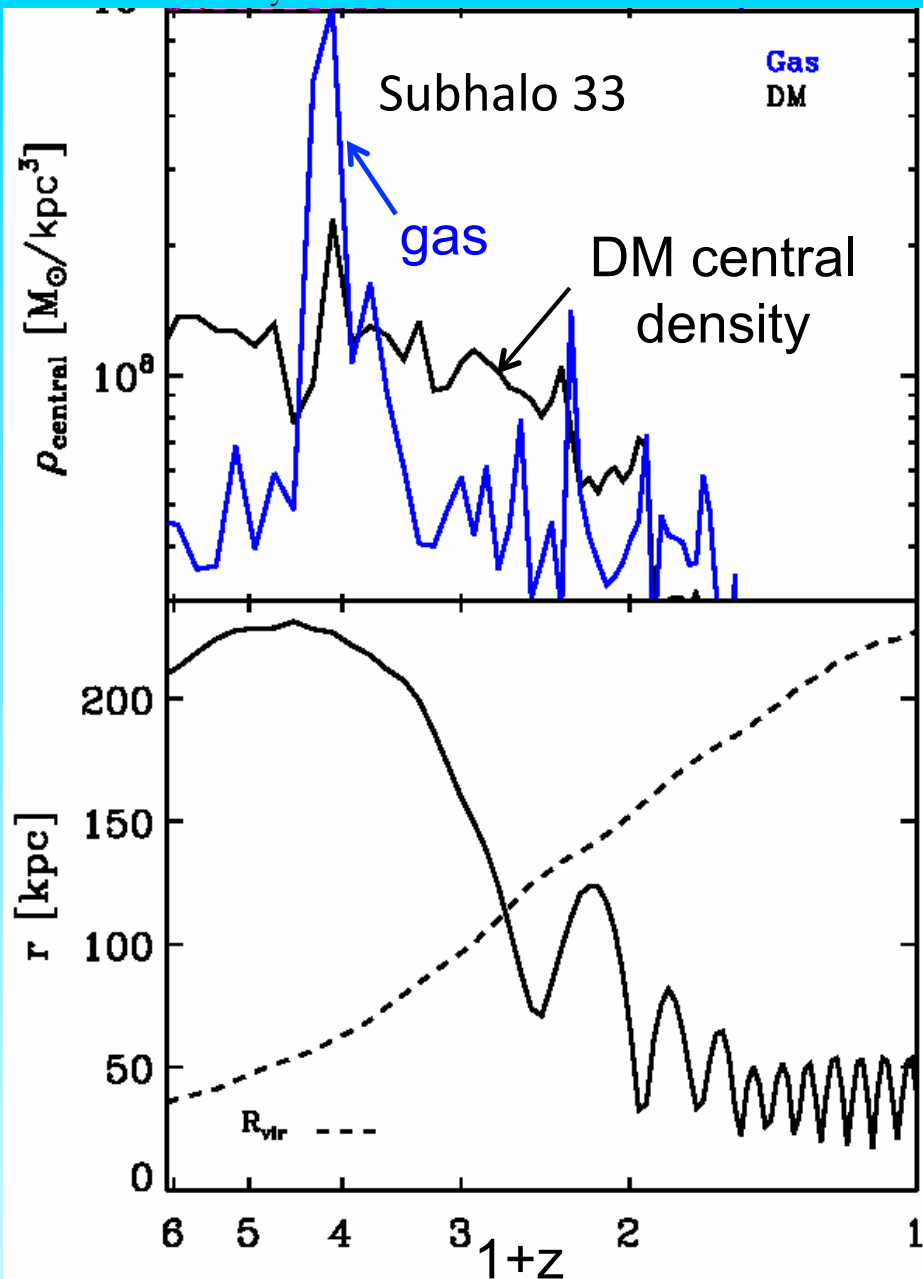


→ gas simulations



Parry, Eke, Frenk & Okamoto '11

Baryon effects in the MW satellites

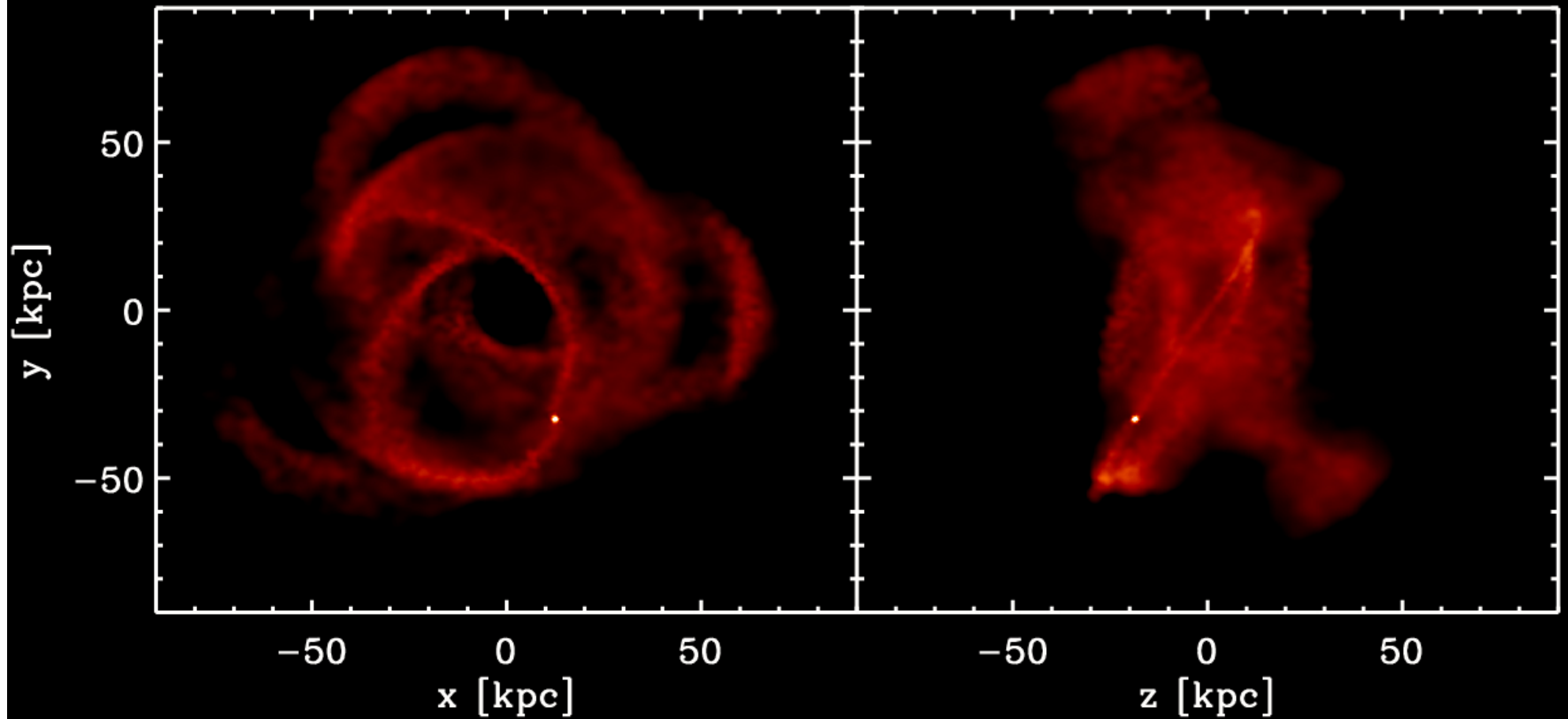


Parry, Eke & Frenk '11



Baryon effects in the MW satellites

Subhalo 33





Baryon effects → unlikely in dwarf satellite gals

either:

- they are tidally disrupted (Parry et al '12)
- or there is are not enough SNe (Governato et al '20)

DM & sats of the MW: conclusions

- The **core** radii in **WDM** halos are **tiny** - **not** astrophysically **relevant**
- There is **no evidence** for **cores** in the dwarf sph **sats** of the MW
- Abundance and kinematics of MW sats set **strong constraints** on **nature** of dark matter

Model	Sat Lum Fn	Massive sats	Comments
CDM	OK	$M_{\text{halo}} < 1.5 \times 10^{12} M_{\odot}$	Unless baryon effects reduce central density
WDM	$M_{\text{halo}} > 1.2 \times 10^{12} M_{\odot}$	OK	Predicted to have very small core radii