The mass of the Milky Way halo and the identity of the dark matter

Carlos S. Frenk

Institute for Computational Cosmology, Durham

Conclusions

One of the strongest astrophysical constraints on the identity of the dark matter comes from:

the mass of the Milky Way halo!!

ICC

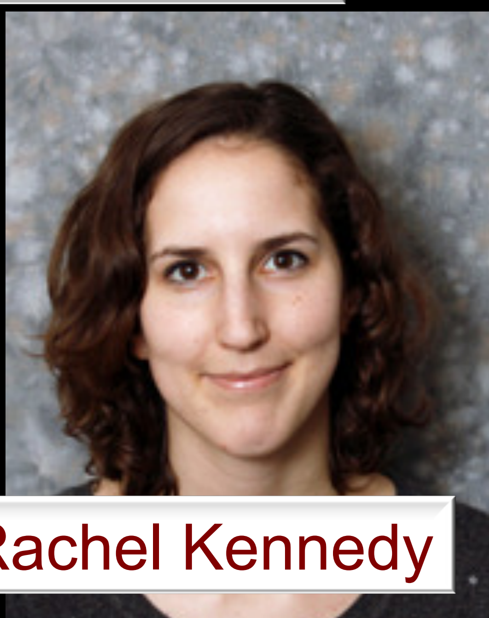
Mark Lovell

Marius Cautun

Jie Wang

Till Sawala

Matthieu Schaller



Rachel Kennedy

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

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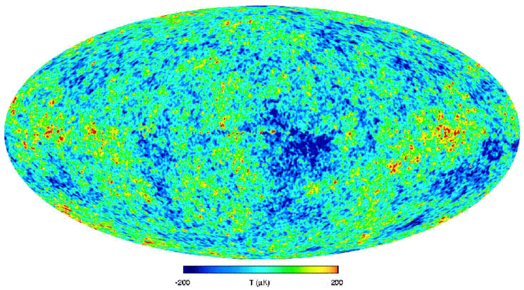
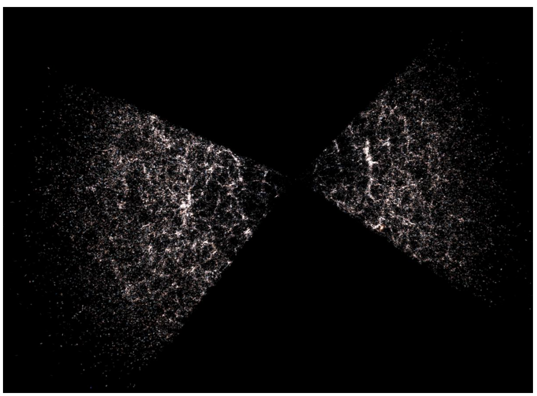
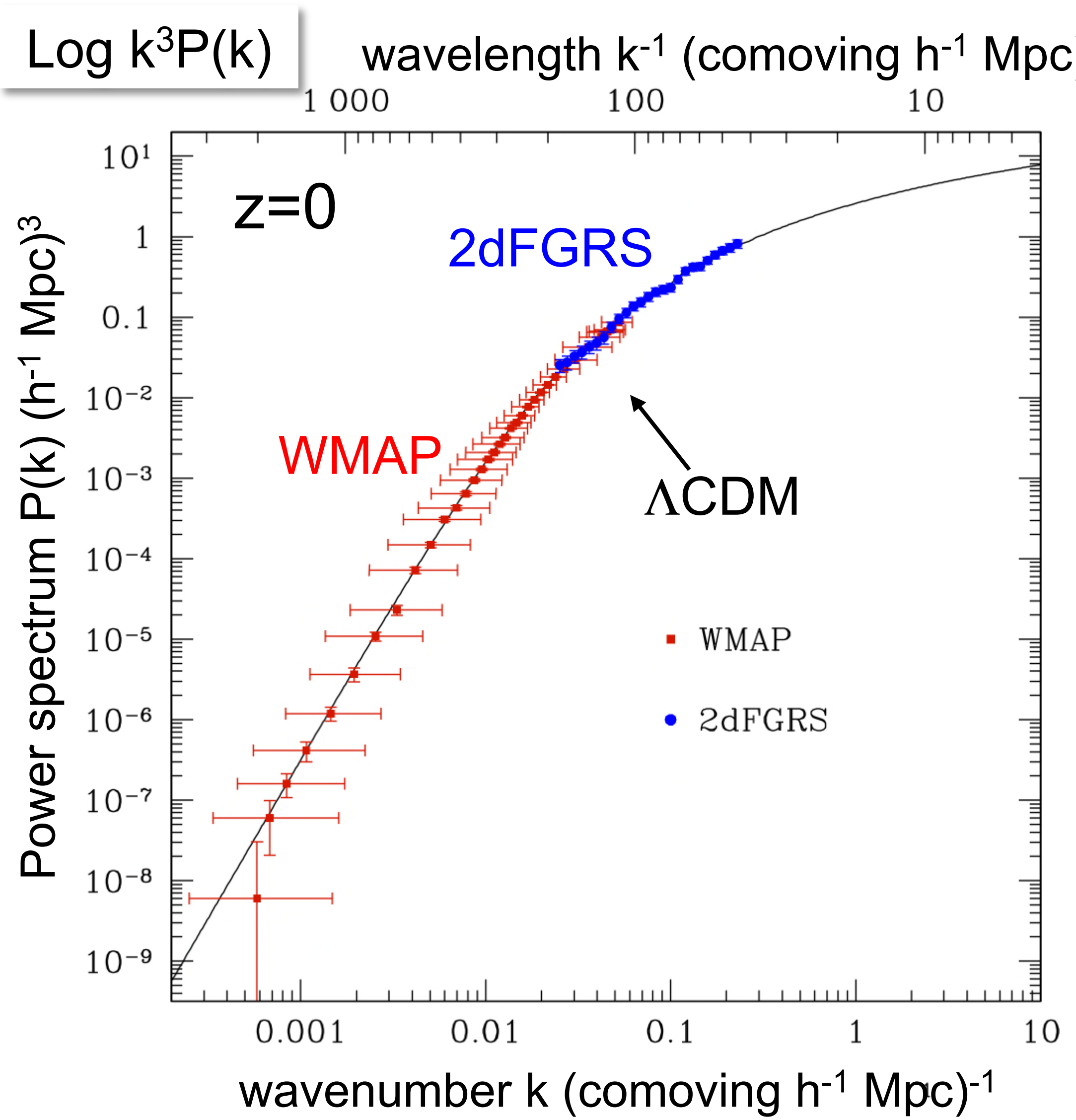


z~1000



z~0



⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

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

Free streaming →

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

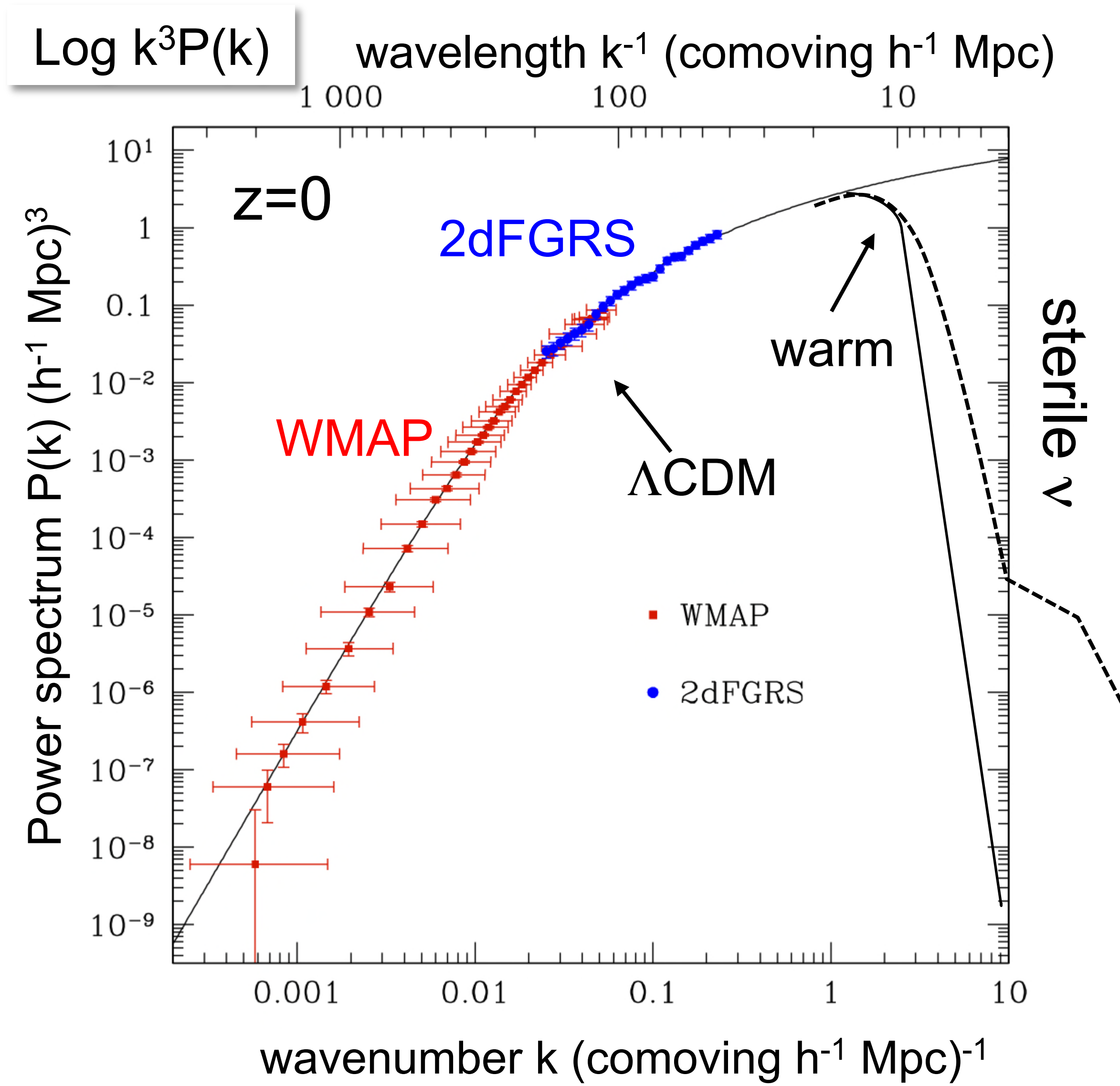
for thermal relic

$m_{CDM} \sim 100GeV$

susy; $M_{cut} \sim 10^{-6}\ M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$



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An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands

[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine

[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine

[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

arXiv:1402.4119v1 [astro-ph.CO] 17 Feb 2014

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

Submitted to ApJ, 2014 I

Preprint typeset using LaTeX

DETECTION OF AN U

Esra Bulbul[1,2], M

[1] Har

We detect a wea spectrum of 73 g independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum. The line is also detected at the same energy in the *Chandra* ACIS-S and ACIS-I spectra of the Perseus cluster, with a flux consistent with *XMM-Newton* (however, it is not seen in the ACIS-I spectrum of Virgo). The line is present even if we allow maximum freedom for all the known thermal emission lines. However, it is very weak (with an equivalent width in the full sample of only ~ 1 eV) and located within 50–110 eV of several known faint lines; the detection is at the limit of the current instrument capabilities and subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. Assuming that all dark matter is in sterile neutrinos with $m_s = 2E = 7.1$ keV, our detection in the full sample corresponds to a neutrino decay mixing angle $\sin^2(2\theta) \approx 7 \times 10^{-11}$, below the previous upper limits. However, based

Cold Dark Matter | Warm Dark Matter

13.4 billion years ago

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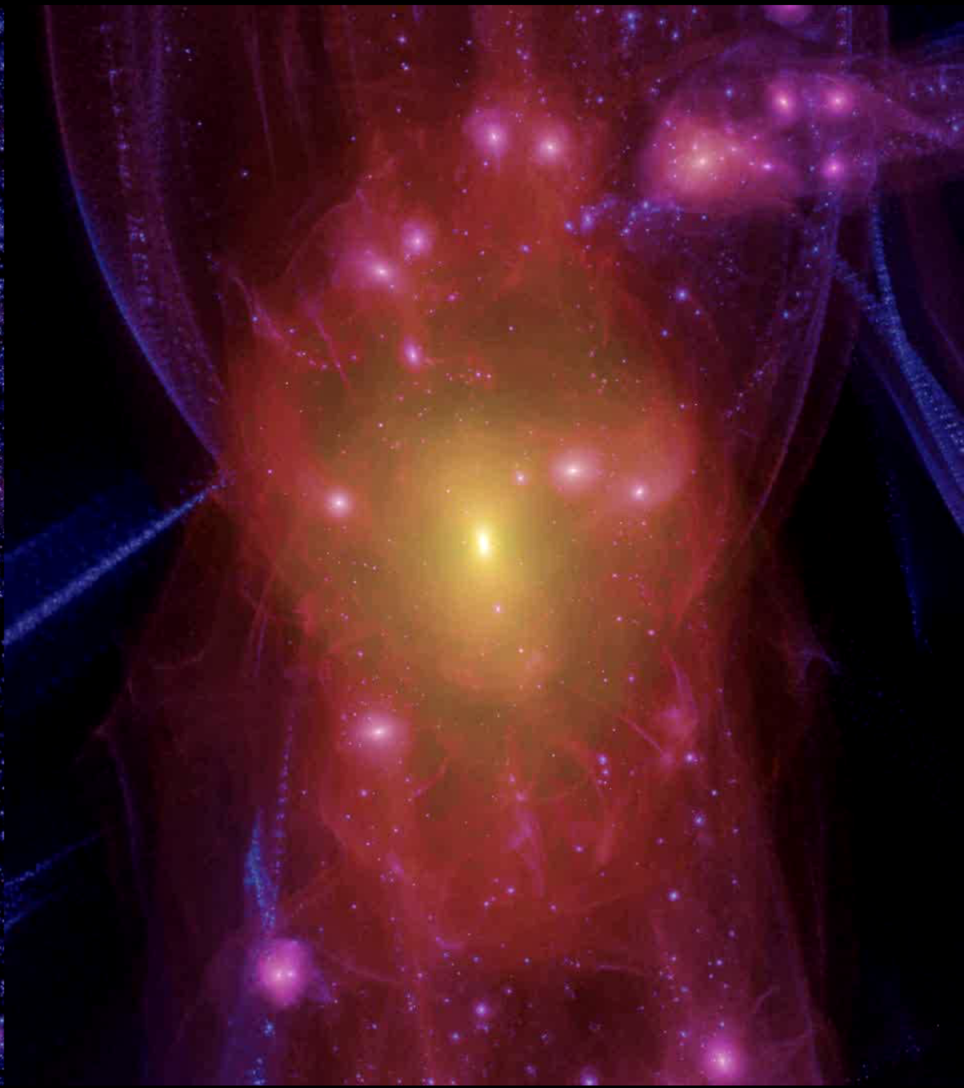
cold dark matter

warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '14

Warm DM: different ν mass

z=3

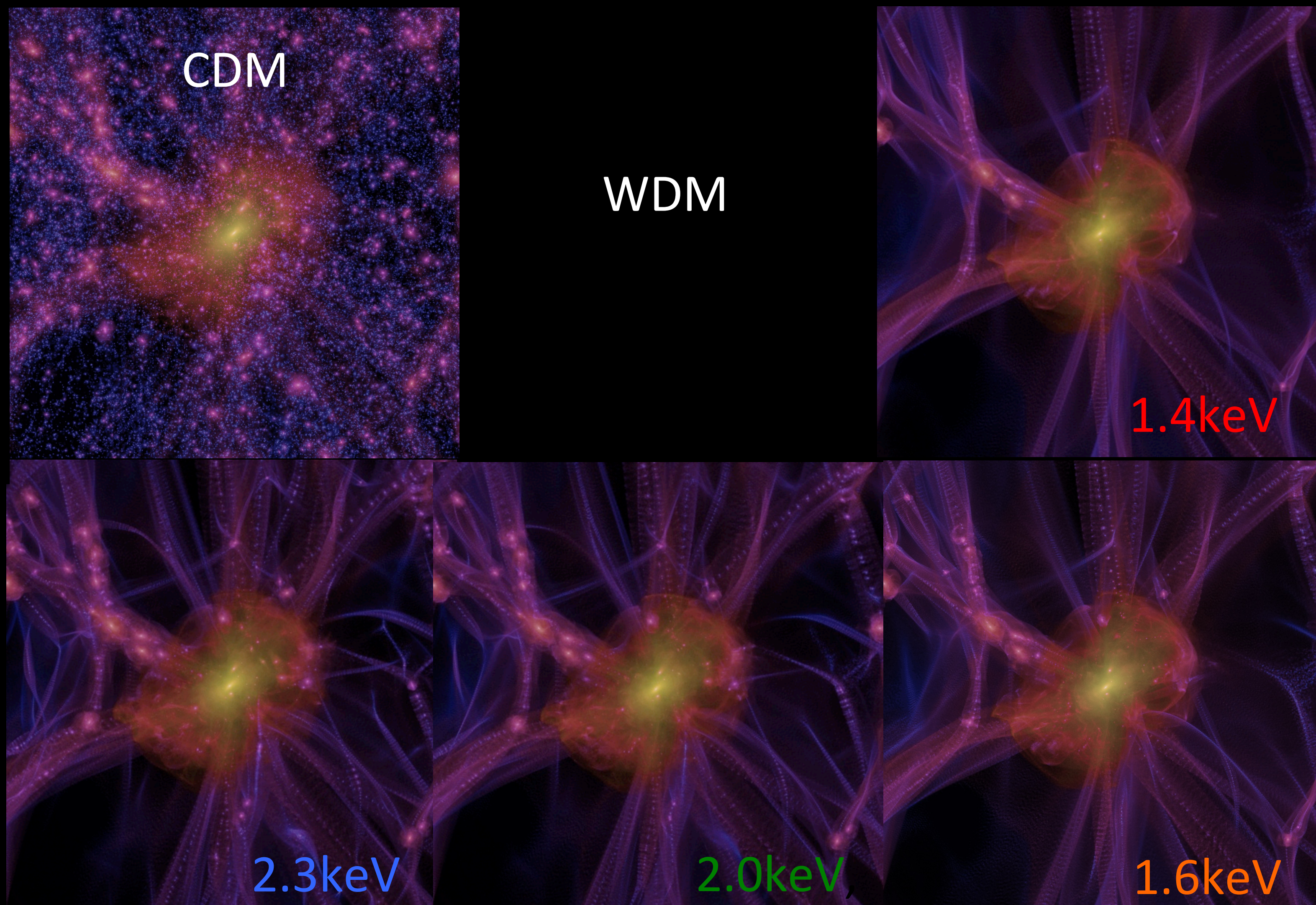
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



Number of massive subhalos

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Number of massive subhalos increases rapidly with halo mass

V_{max} = maximum of

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

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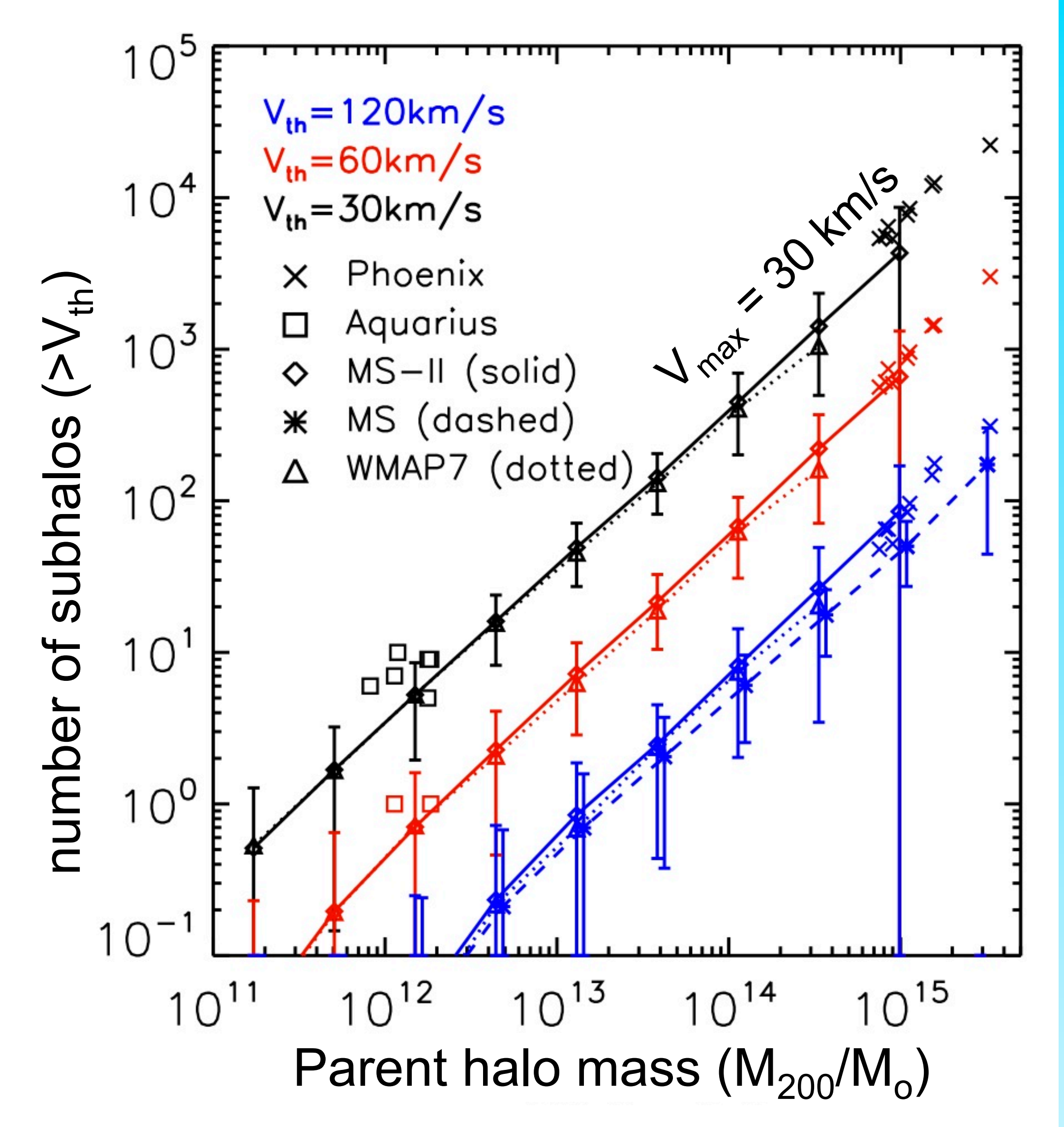
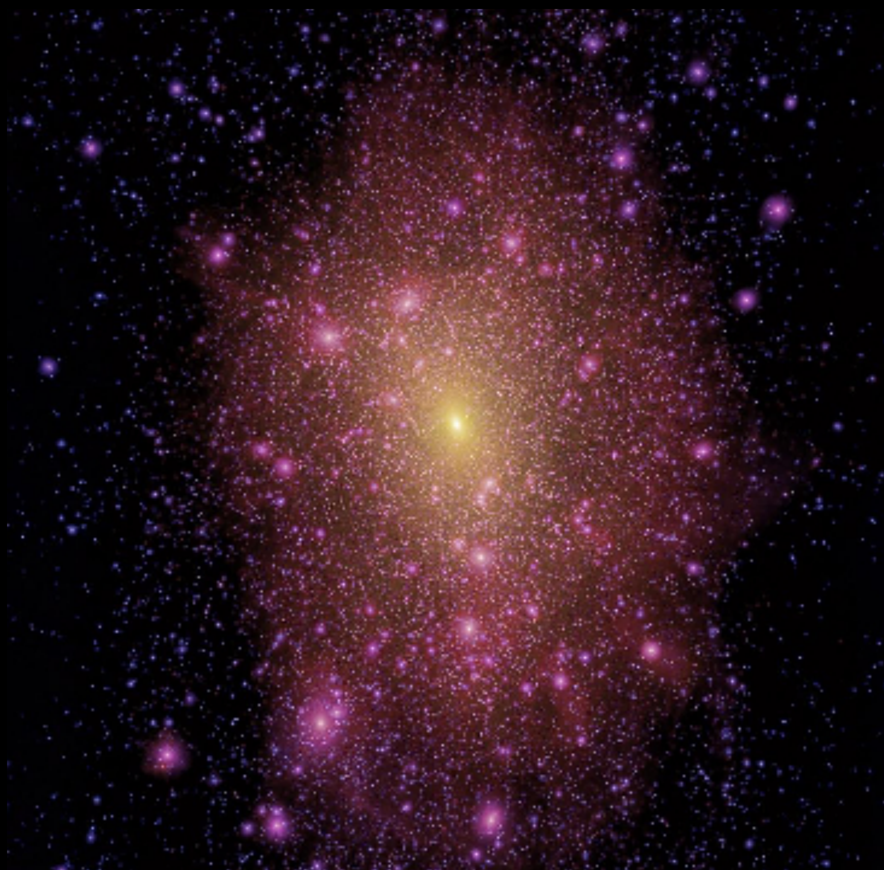


Wang, Frenk, Navarro, Gao ‘12

ICC VIRGO

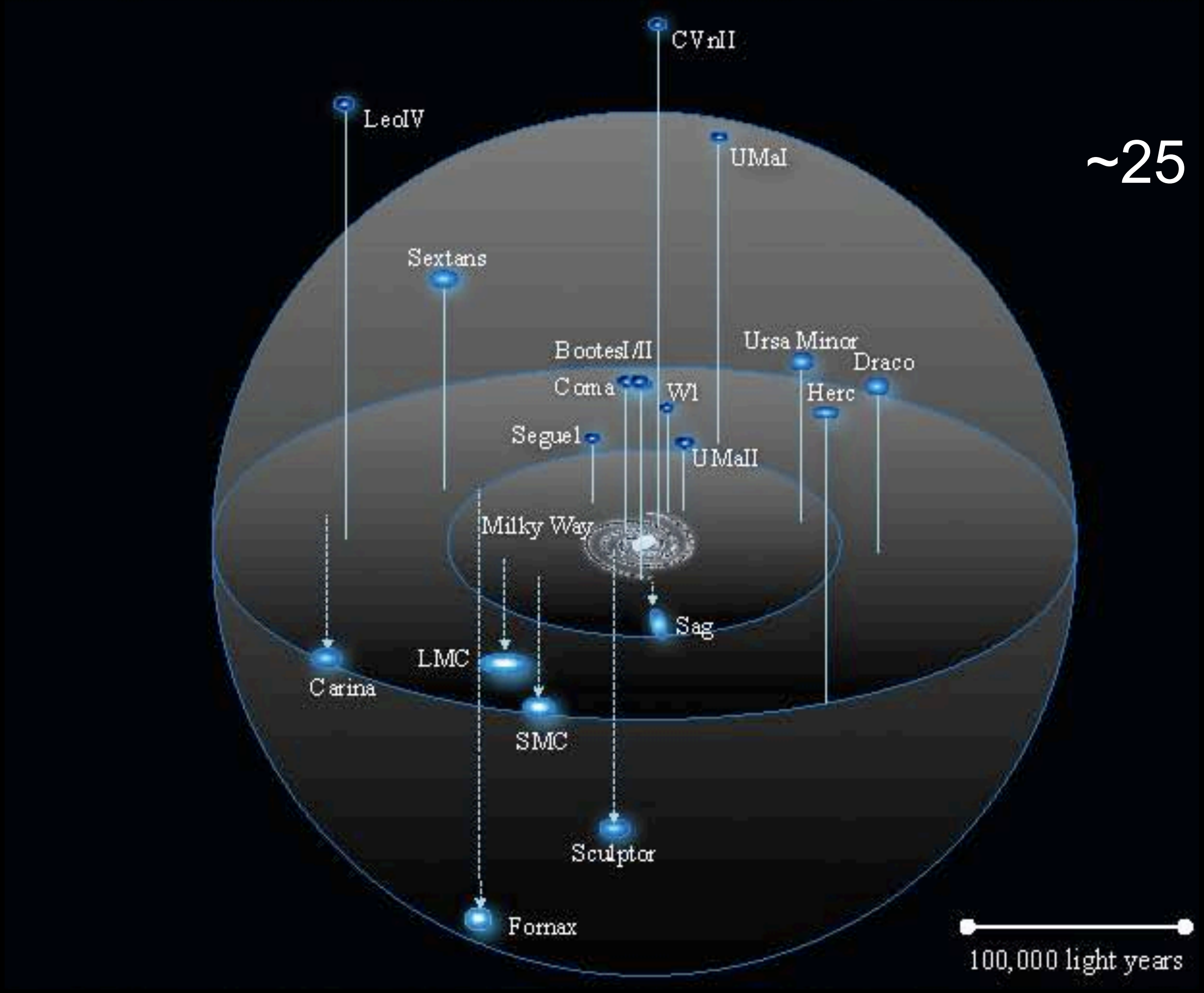
cold dark matter



warm dark matter

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

The satellites of the Milky Way



~25 satellites known in the MW

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cold dark matter

warm dark matter

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

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Making a galaxy in a small halo is hard because:

Reionization heats gas in small halos above T_{vir}, preventing it from cooling and forming stars

Supernovae feedback expels gas

Most subhalos never make a galaxy!

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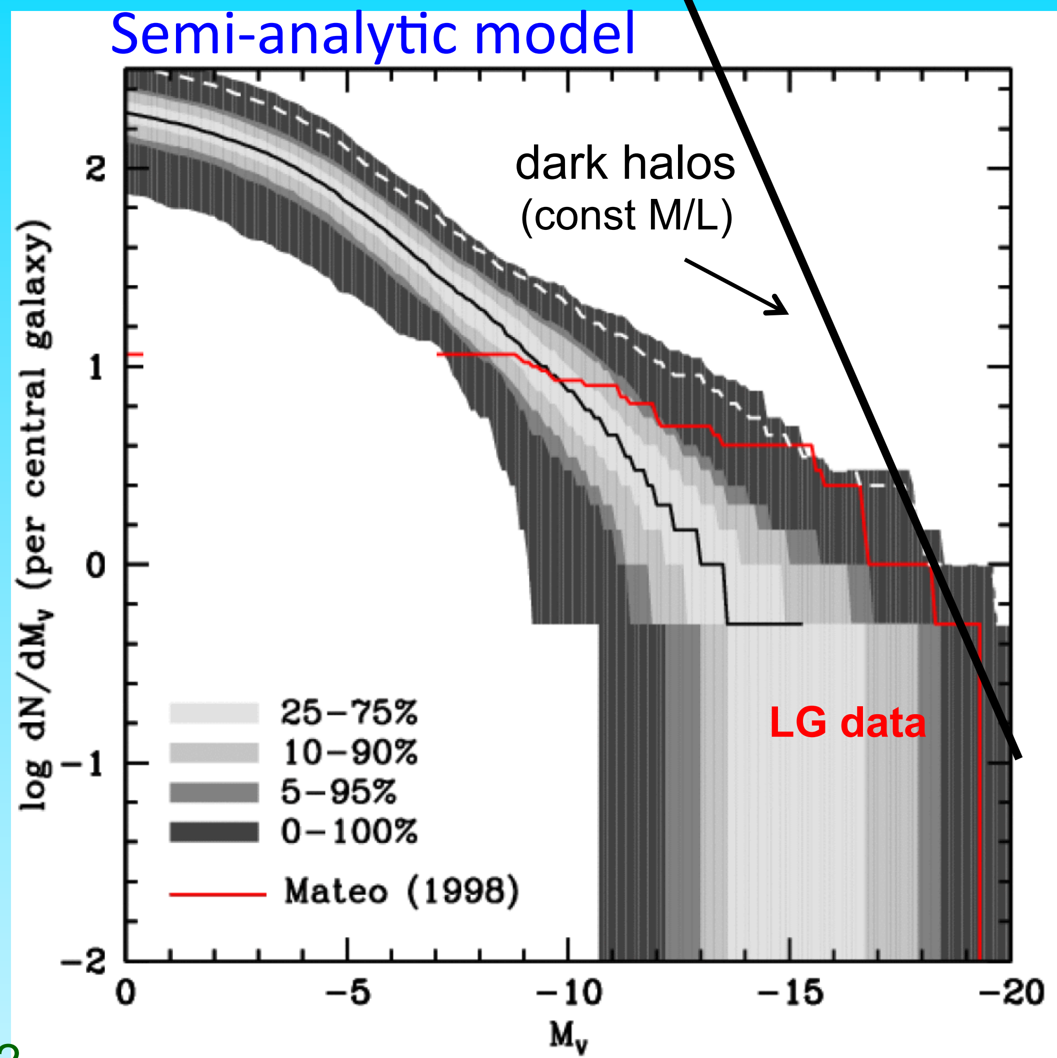
Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M_V=-9 and V_{max} > 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 etal ’93, Bullock etal ’01)

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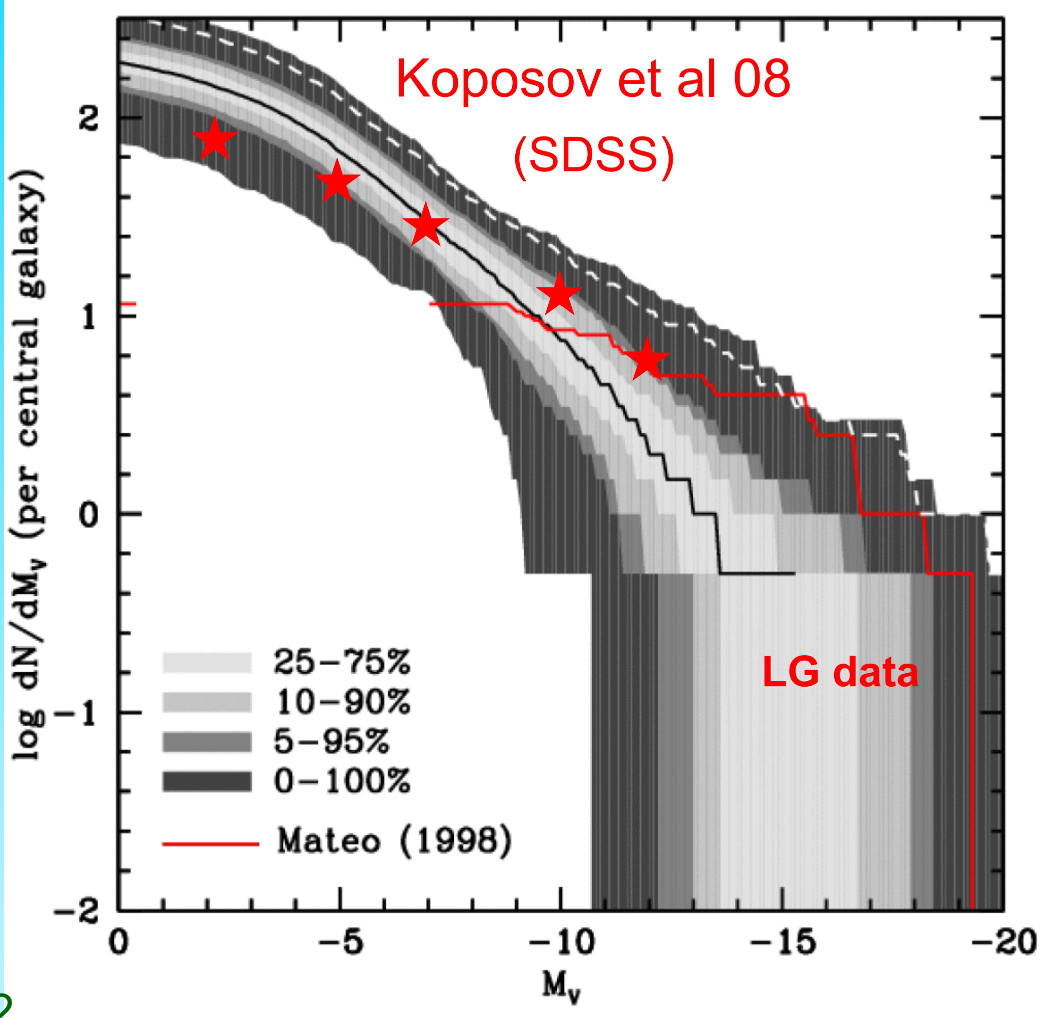

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(see also Kauffman etal '93, Bullock etal '01)

VIRGO

The "Evolution and assembly of galaxies and their environment" (EAGLE) simulation project

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

+ Virgo Consortium

NAM 2014

DiRAC

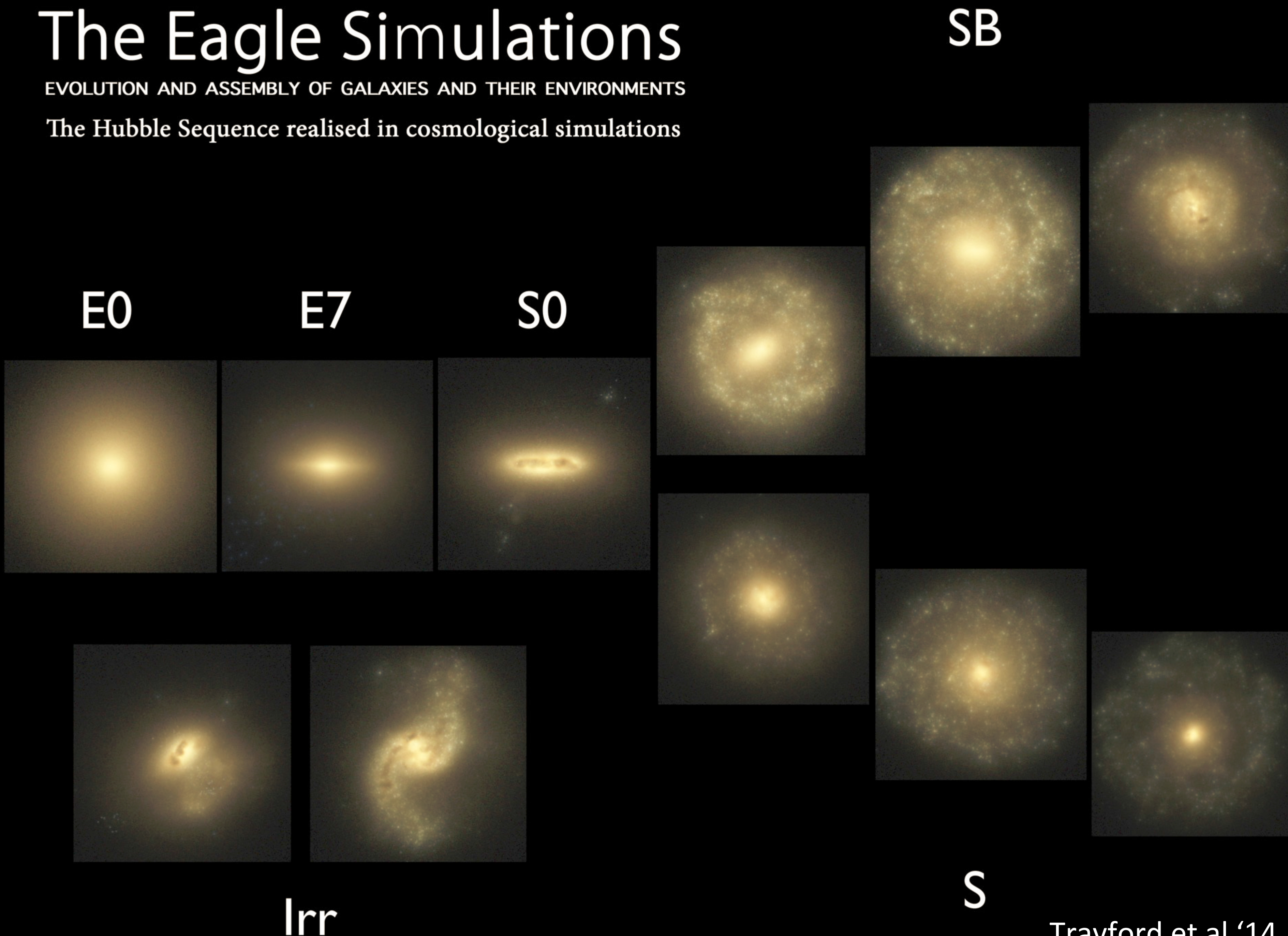
ICC Institute for Computational Cosmology

PRACE

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



Trayford et al '14

VIRGO

EAGLE full hydro simulations

Local Group

Sawala et al ‘14

VIRGO

The ‘’satellite problem’’ in CDM is a myth!

EAGLE full hydro simulations

Local Group

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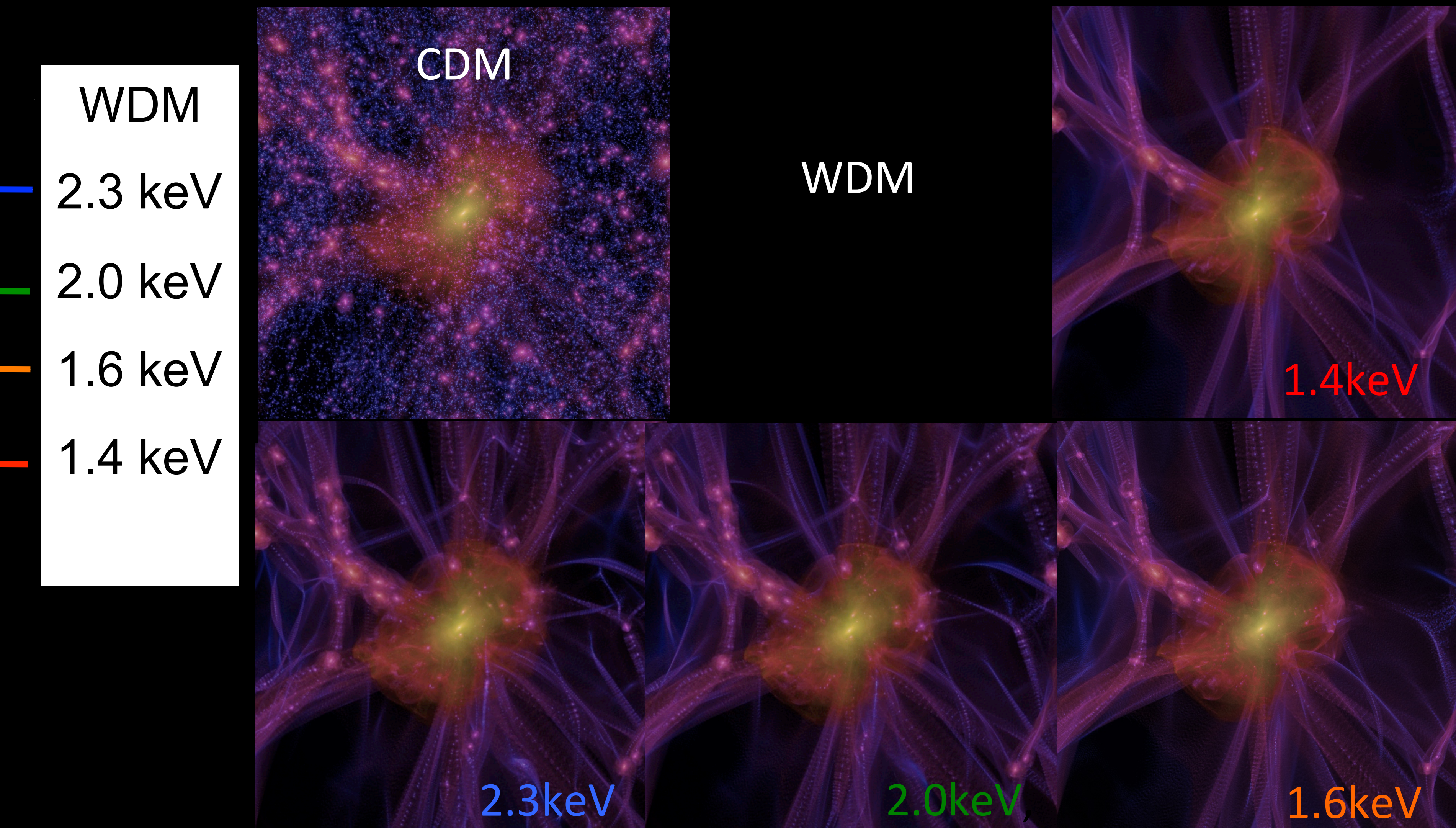
Warm DM: different ν mass

z=3



Luminosity Function of Local Group Satellites in WDM

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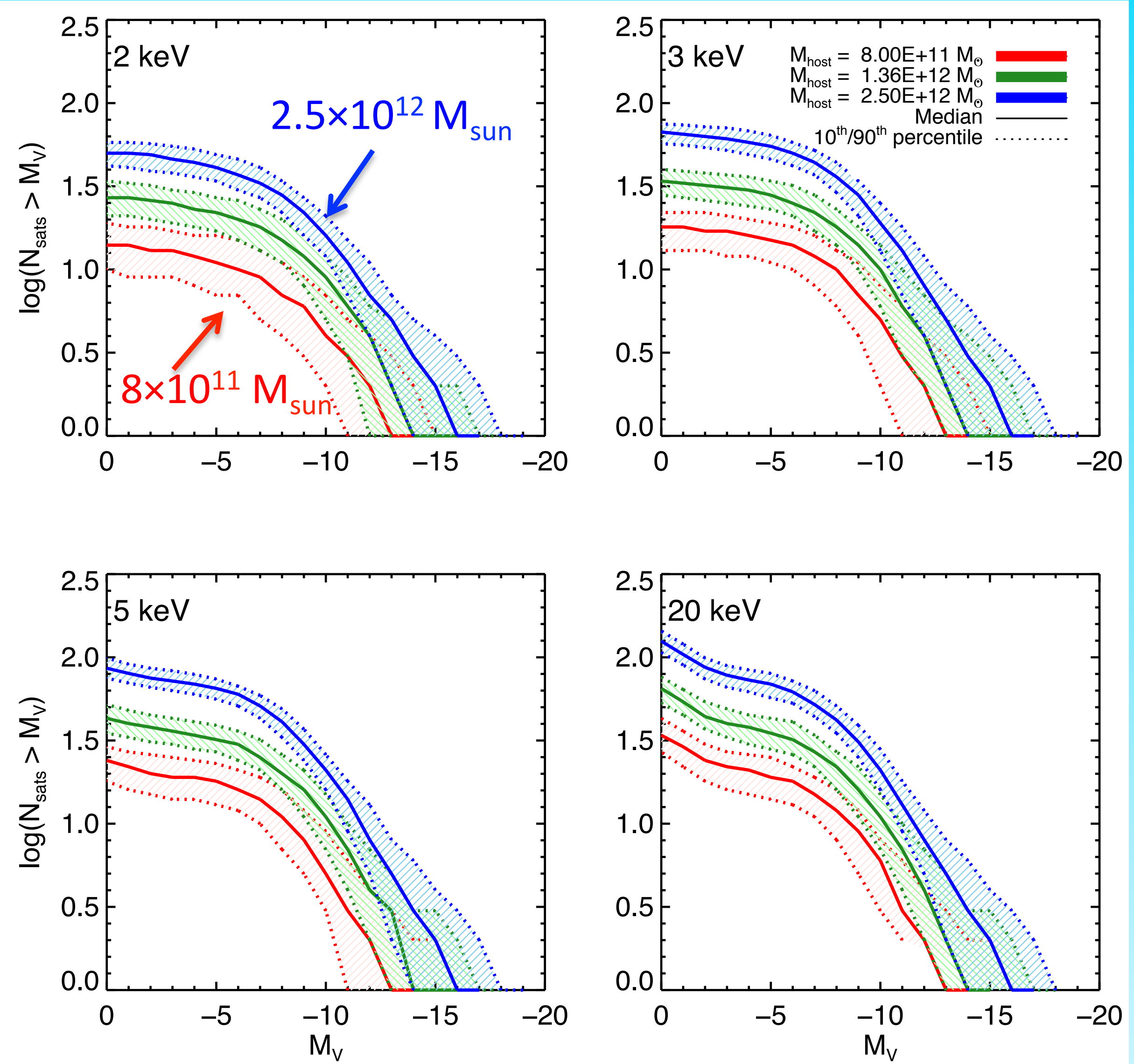
No of sats ↗ with:

- host halo mass
- WDM particle mass



Kennedy, Cole & Frenk '13

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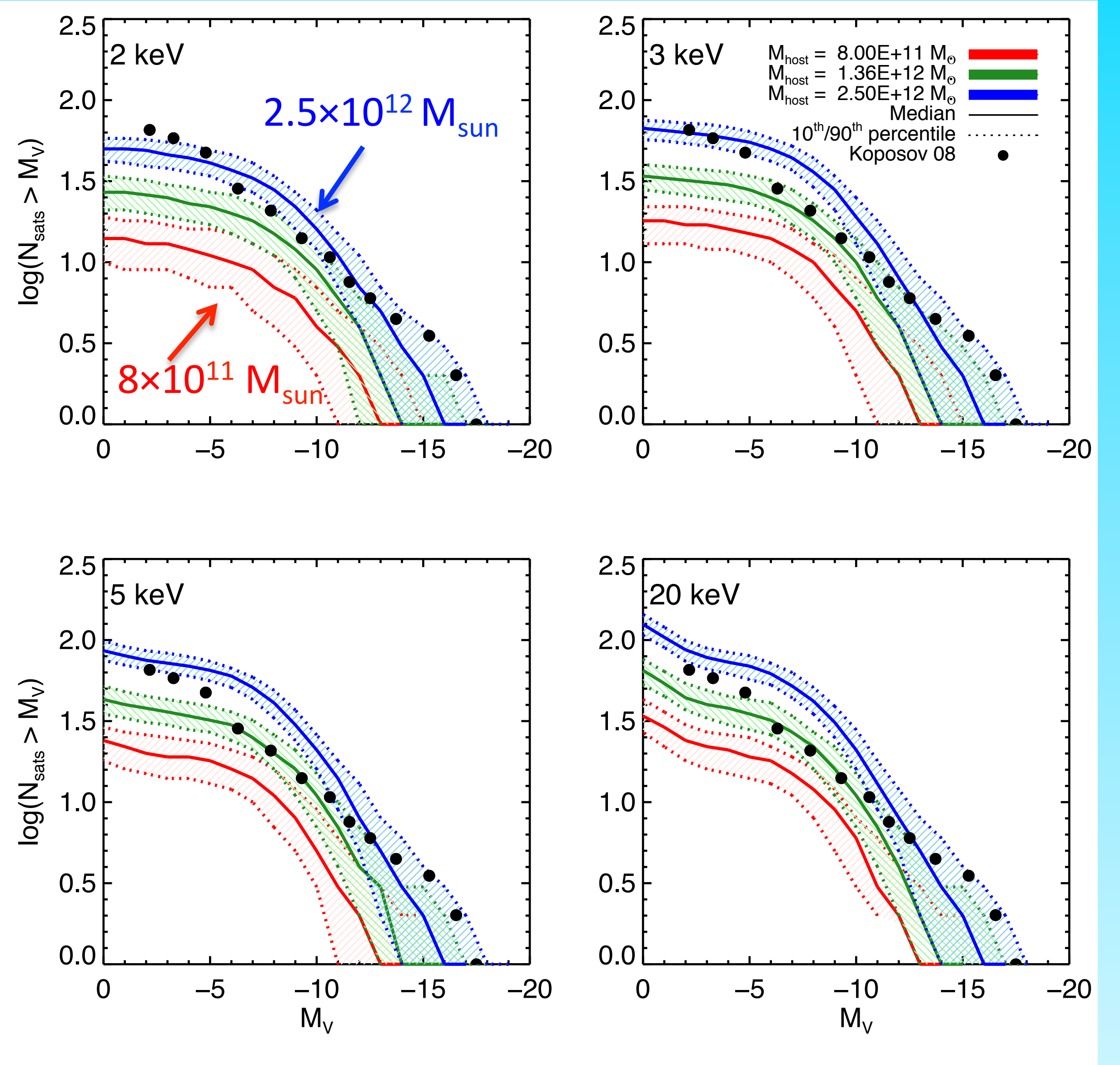

Kennedy, Cole & Frenk '13

Limits on WDM particle mass

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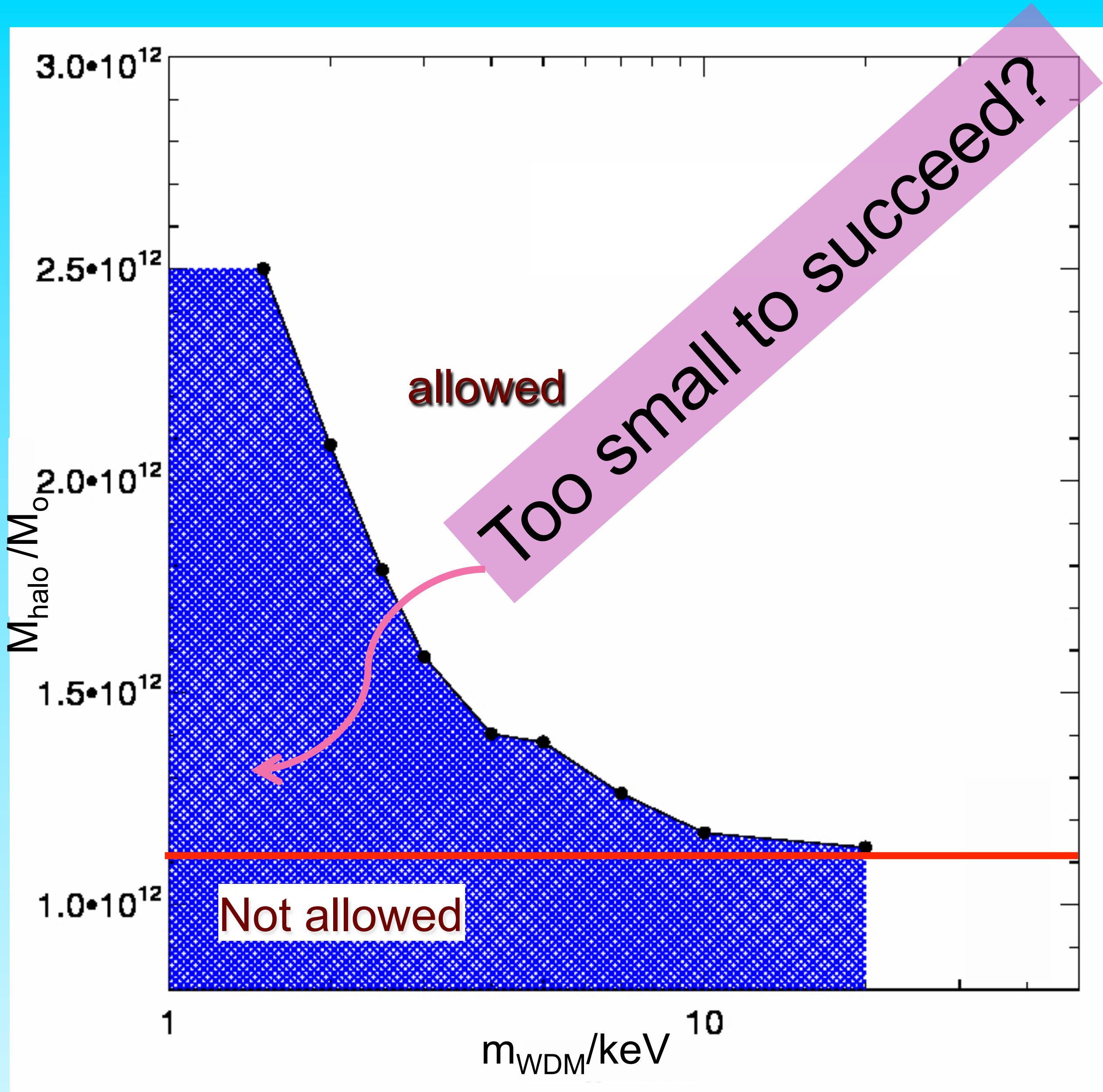
Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

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

Kennedy, Cole & Frenk '14



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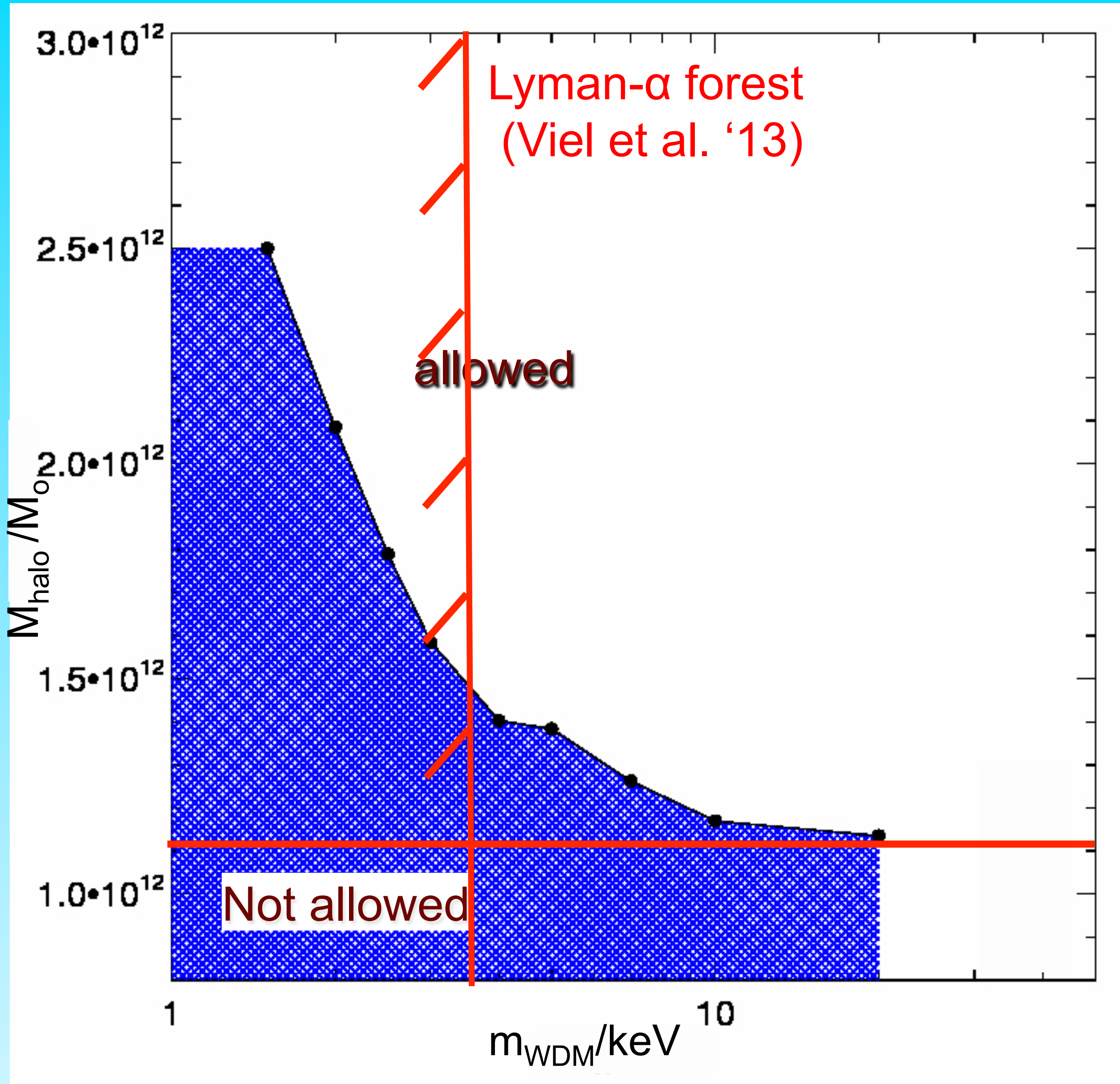
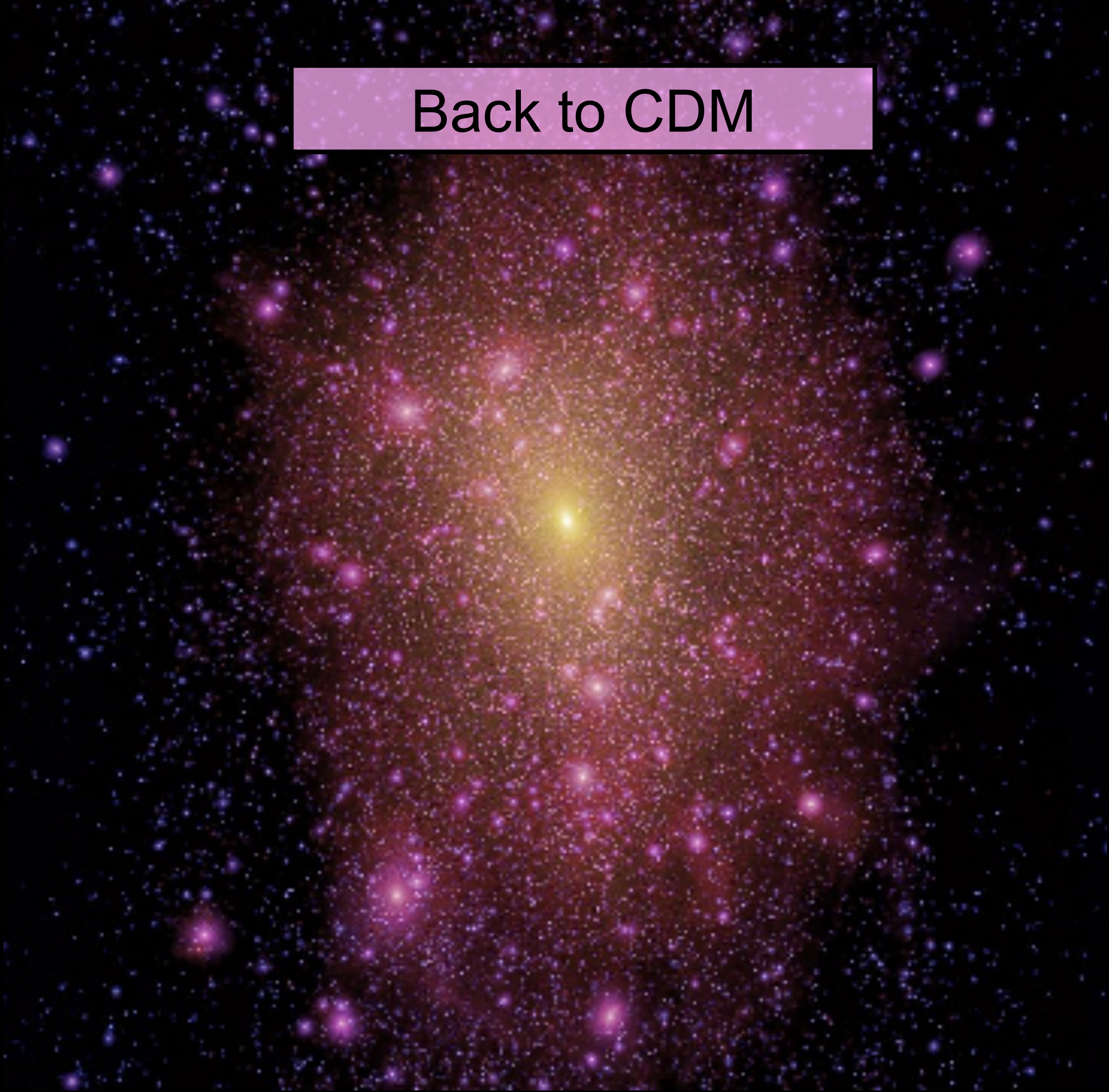
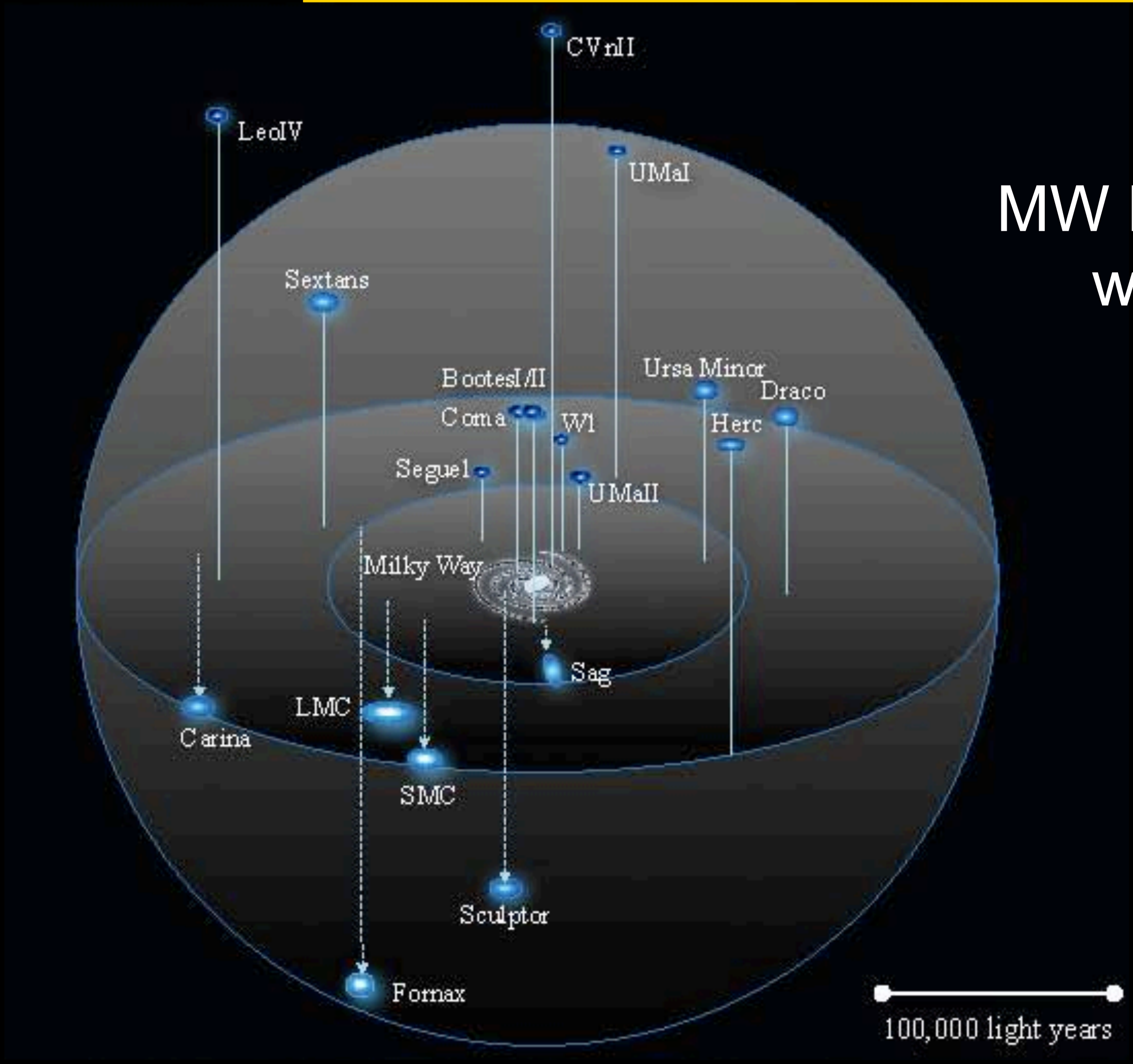


Back to CDM



The satellites of the Milky Way



MW has only 3 satellites with V_{max}>30 km/s

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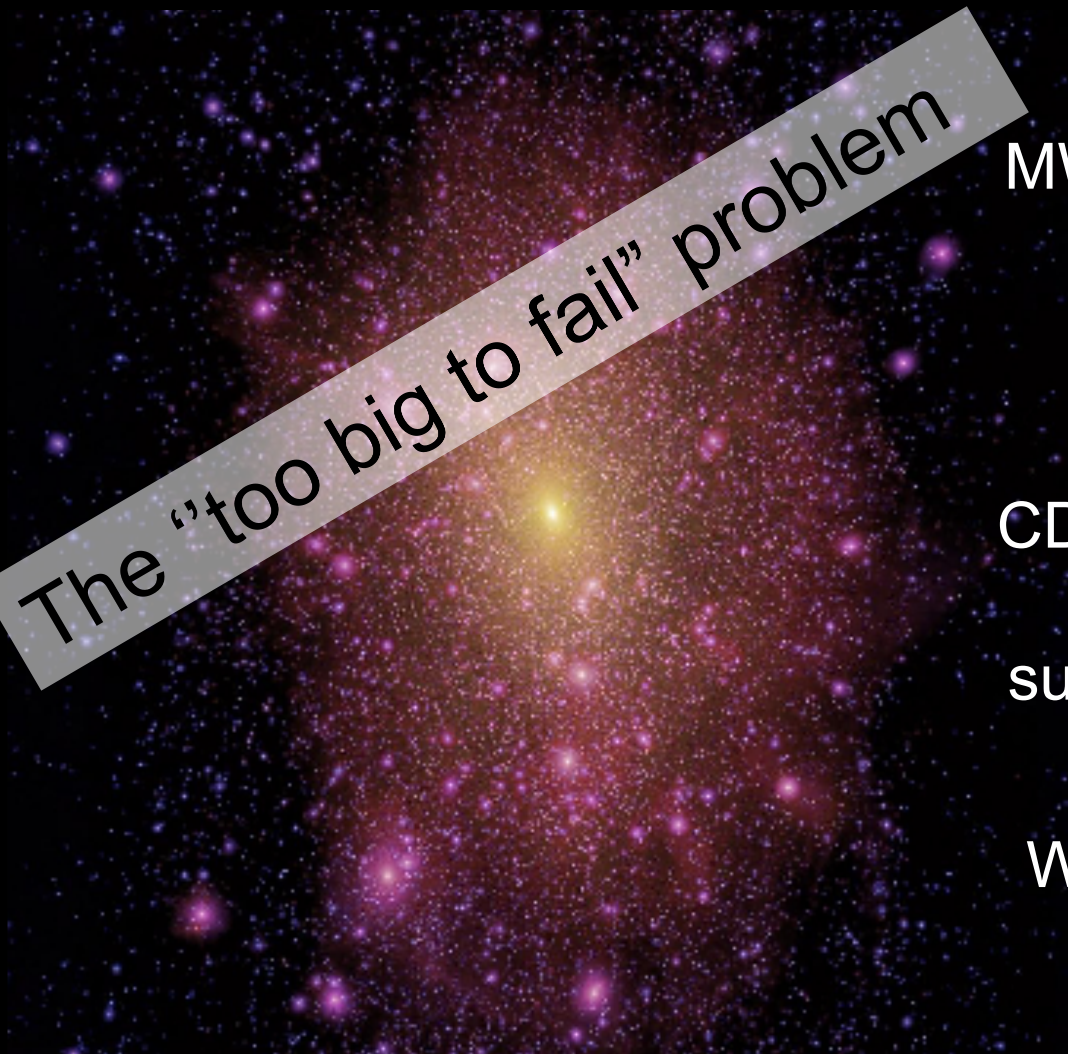


MW has only 3 satellites with V_{max}>30 km/s

CDM simulations of halos of $M \sim 2 \times 10^{12}\ M_o$ have ~10 subhalos with V_{max}>30 km/s

Why did these not make a galaxy?

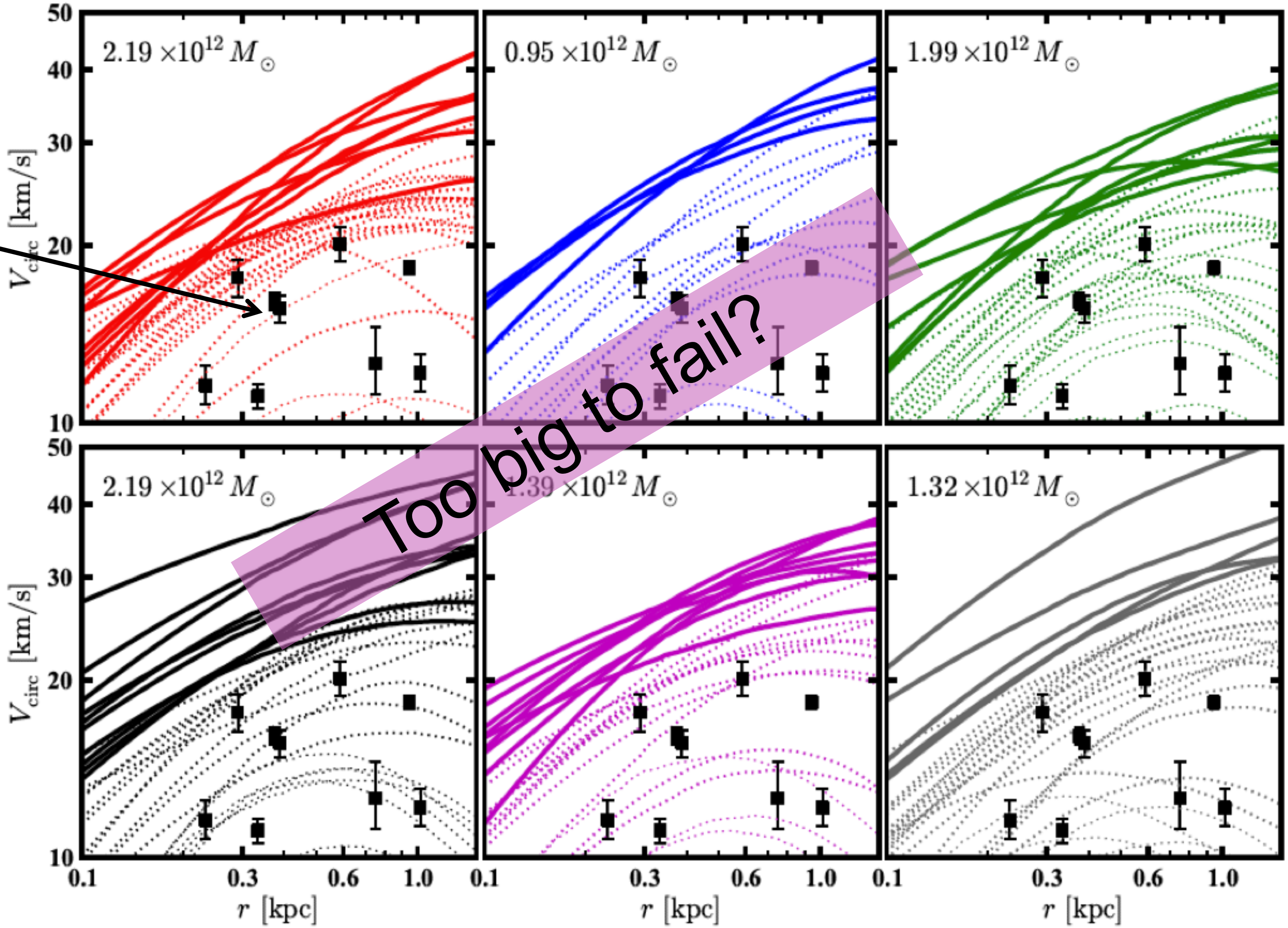
Rotation curves of Aquarius subhalos

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



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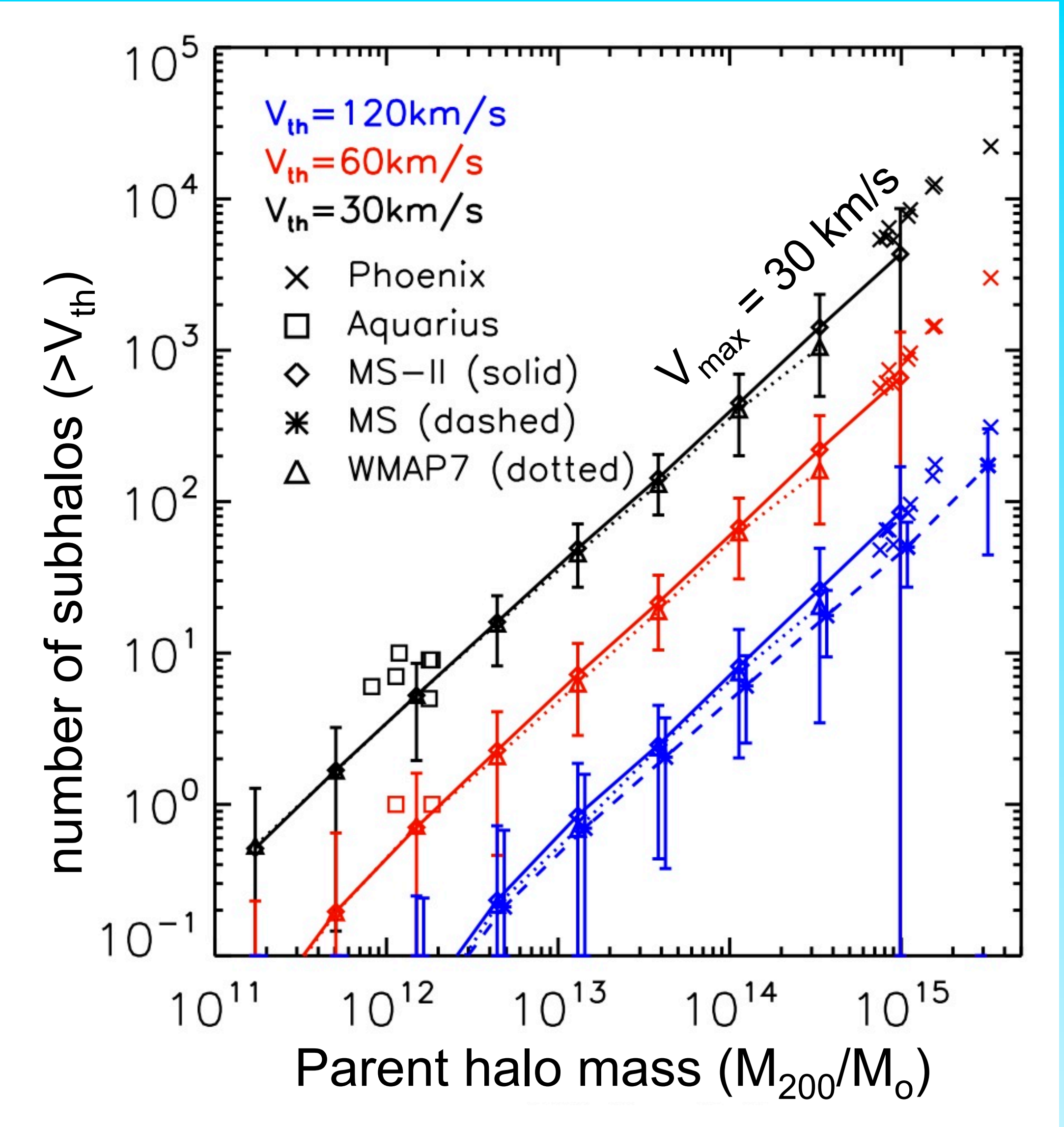

Wang, Frenk, Navarro, Gao '12

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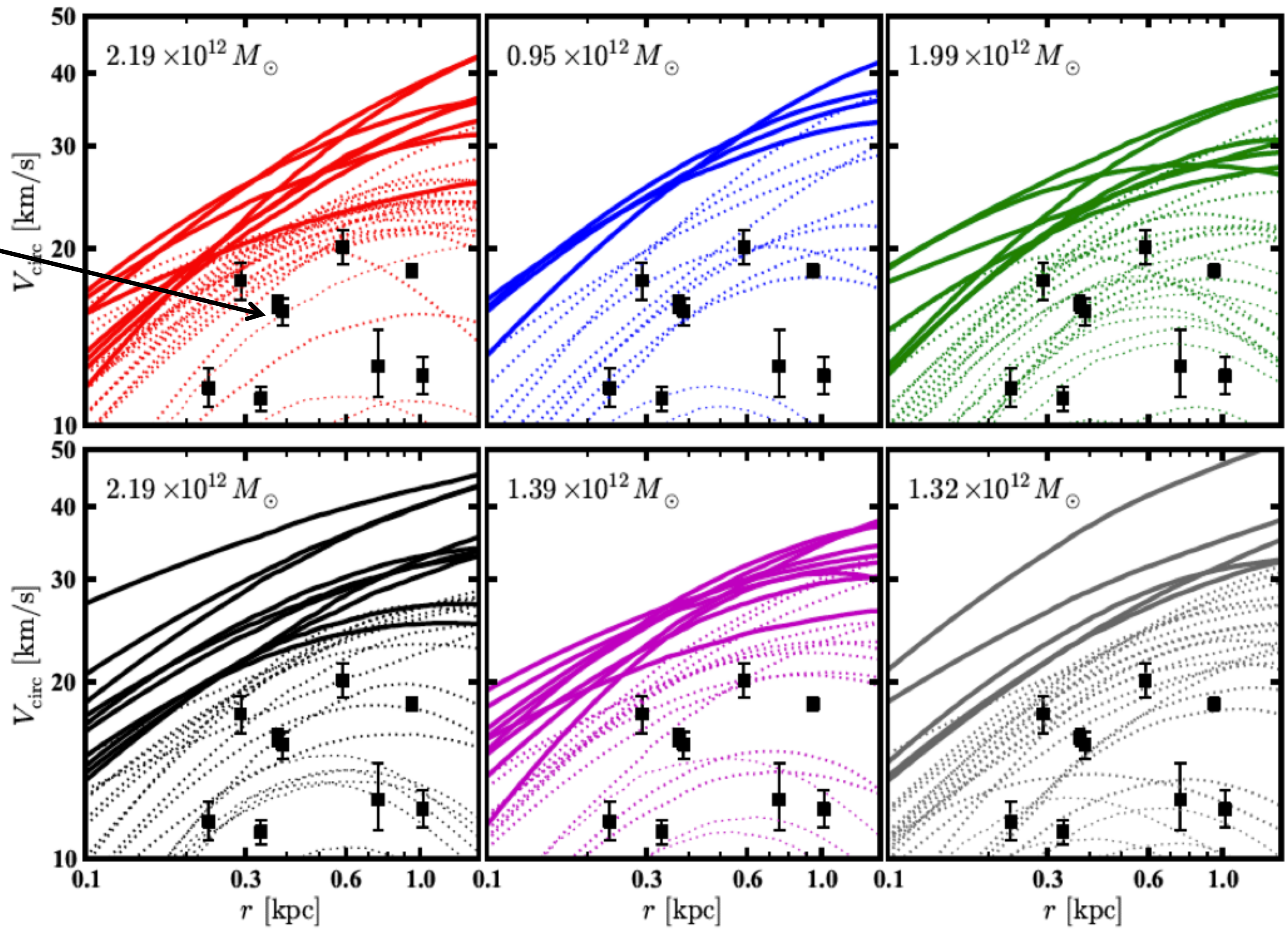

Probability of massive subhalos

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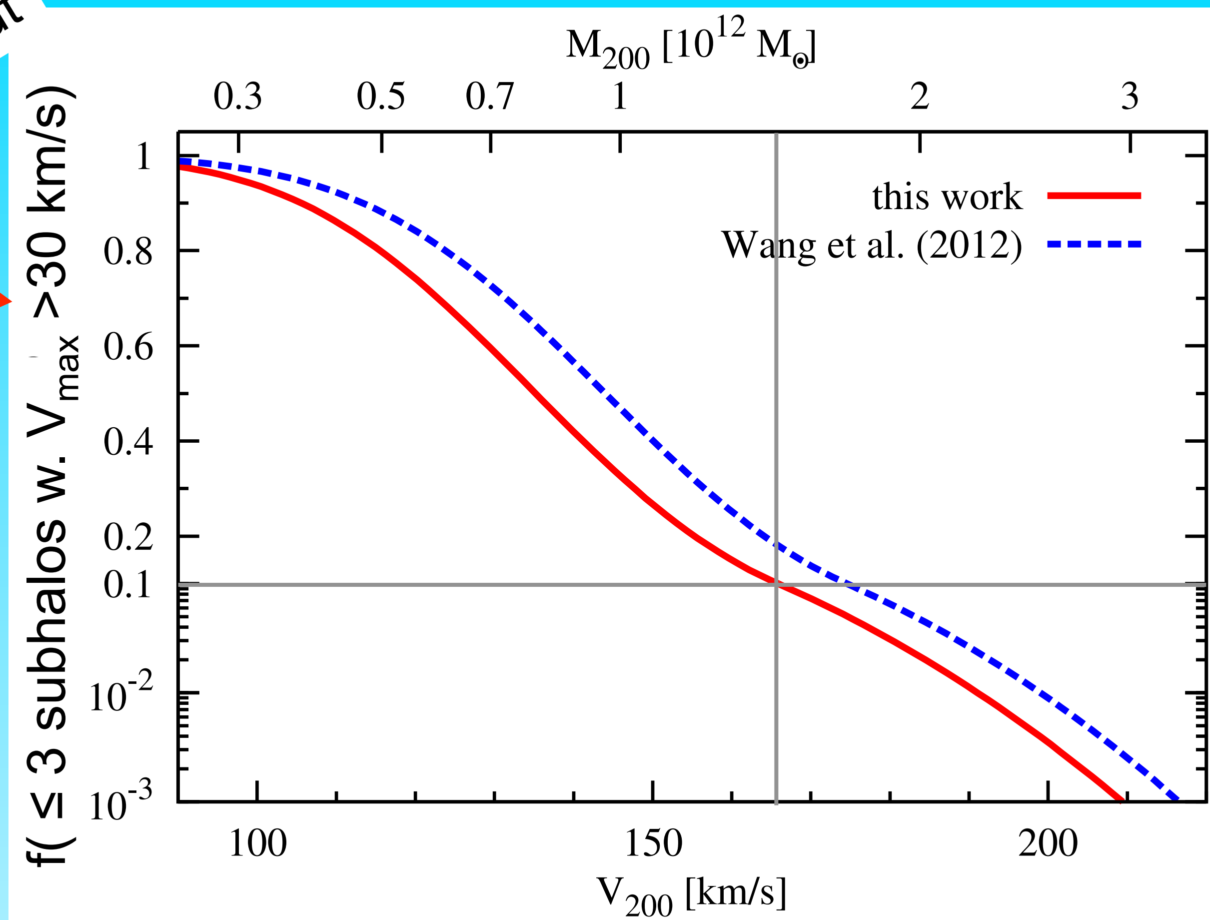
Probability of having at … subha… with V… 30 km/s

1 – prob. that ΛCDM is ruled out



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

CDM requires

$M_{halo} < 1.5 \times 10^{12} M_o$

(90% confidence)

Wang, Frenk, Navarro, Gao '12

Cautun, Frenk, van den Weygaert, Hellwing '14

VIRGO

EAGLE full hydro simulations

Local Group

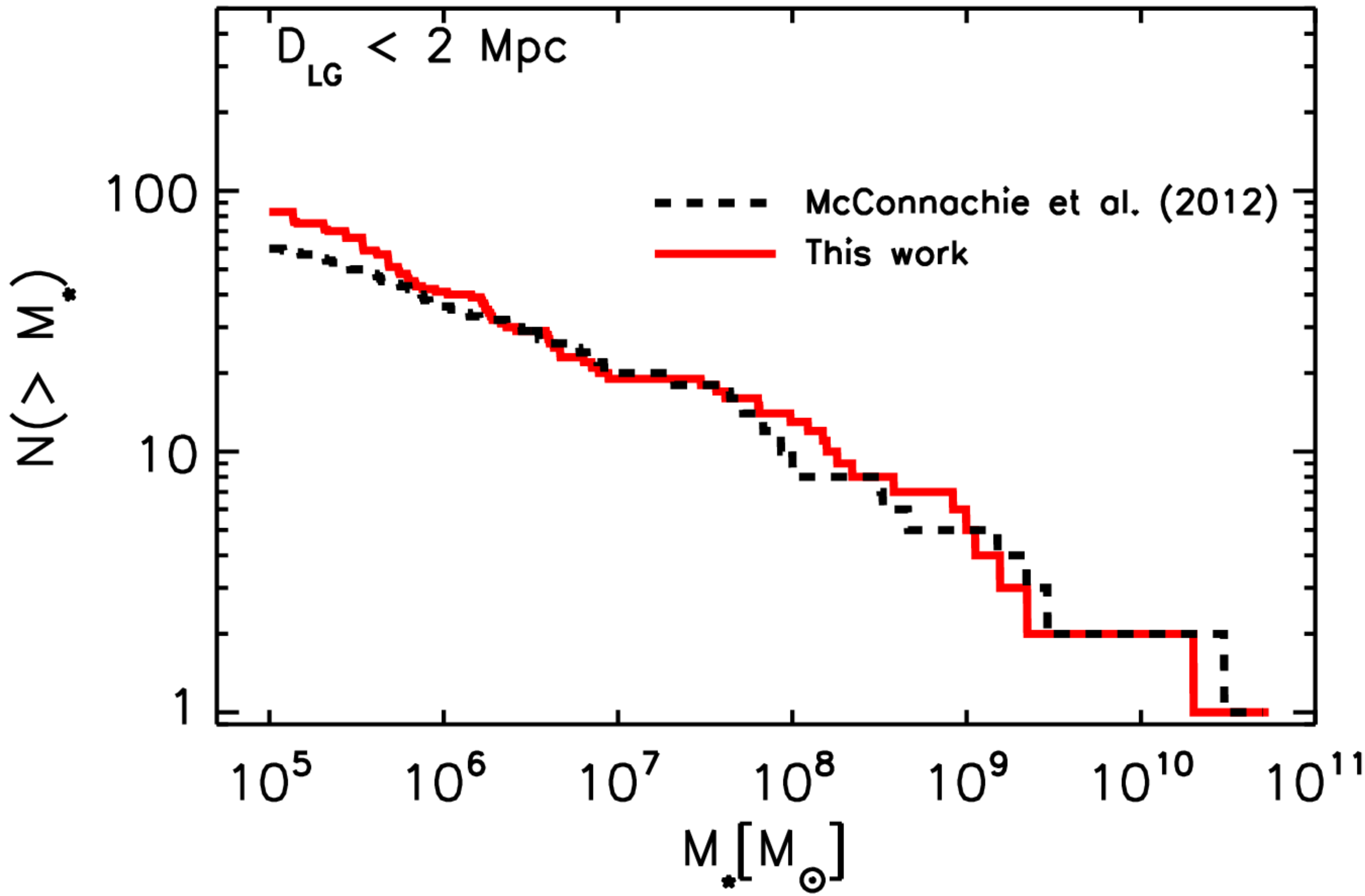
VIRGO

EAGLE full hydro simulations

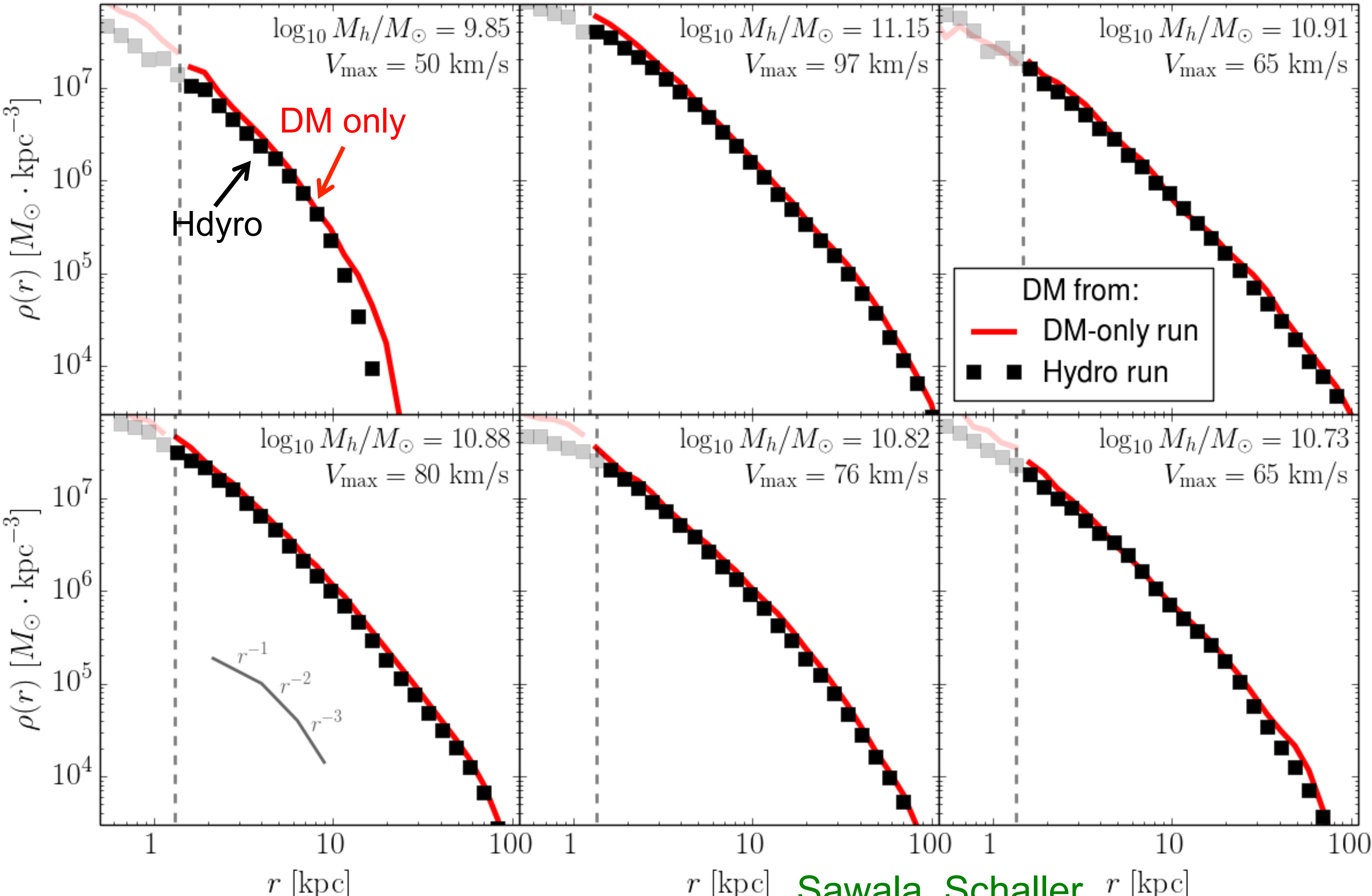
Local Group

Sawala et al ‘14

The stellar mass fn in the Local Group



The effect of baryons on the DM halo



Sawala, Schaller

The MW halo mass: baryon effects

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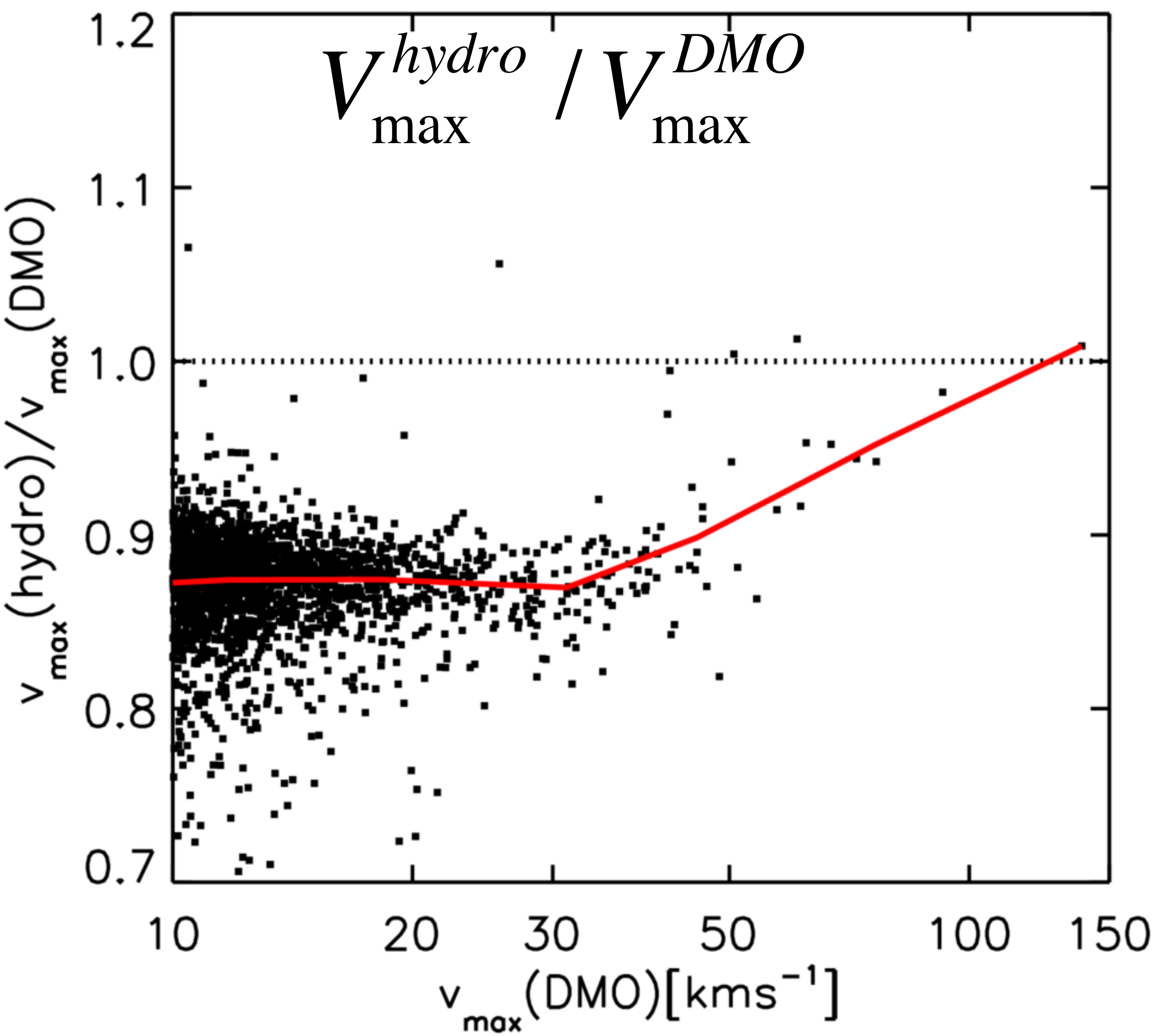
Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate



Sawala et al. '14

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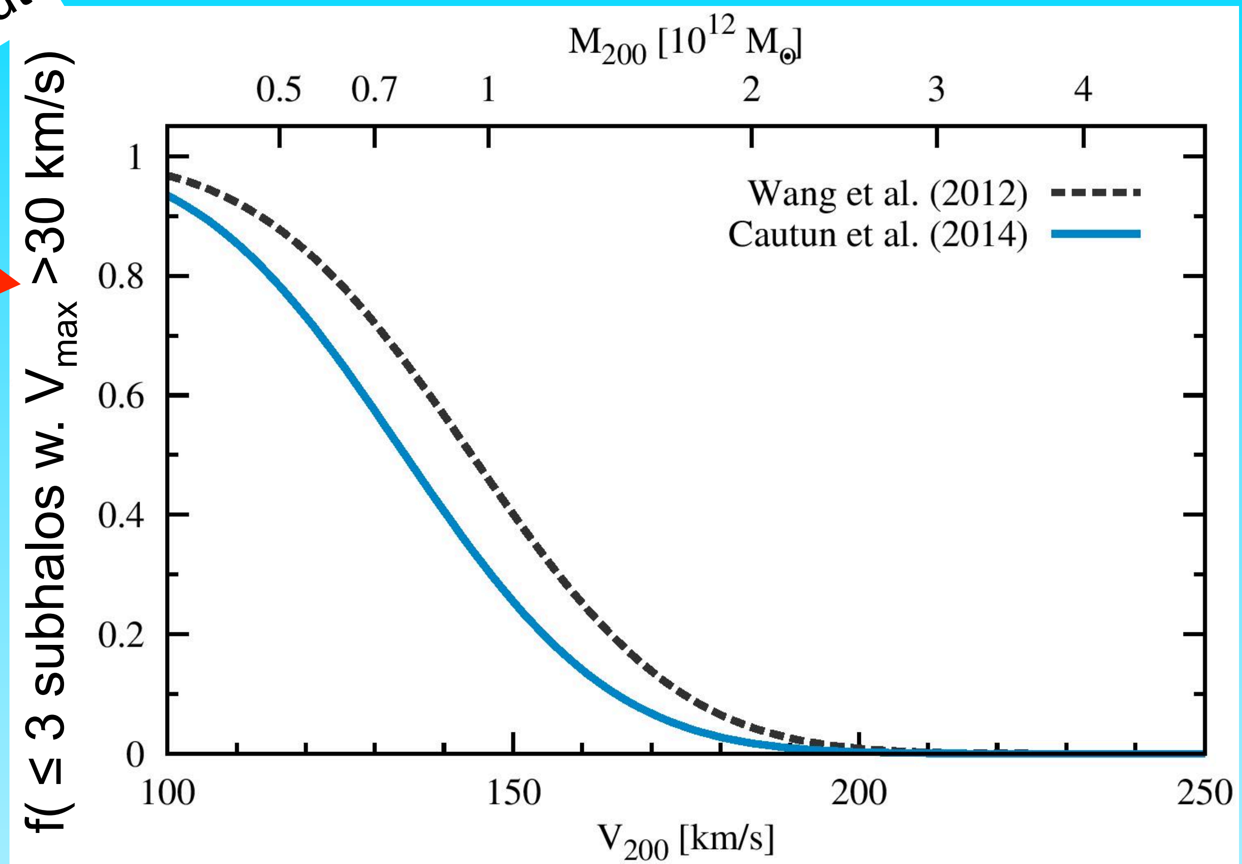

Wang, Frenk, Navarro, Gao '12

Cautun, Frenk, van den Weygaert, Hellwing '14

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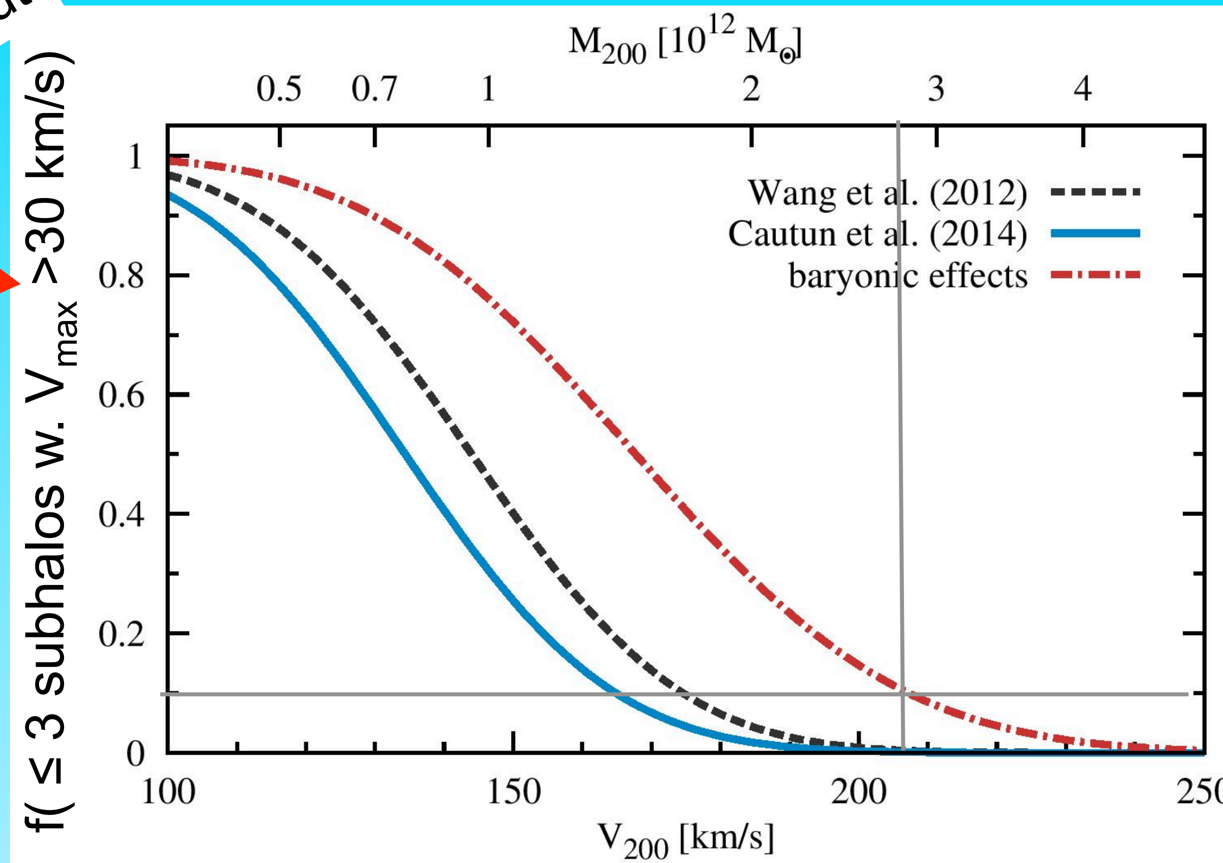

CDM requires

$M_{halo} < 2.6\times10^{12} M_o$

(90% confidence)

Wang, Frenk, Navarro, Gao ‘12

Cautun, Frenk, van den Weygaert, Hellwing ‘14

Estimates of the MW halo mass

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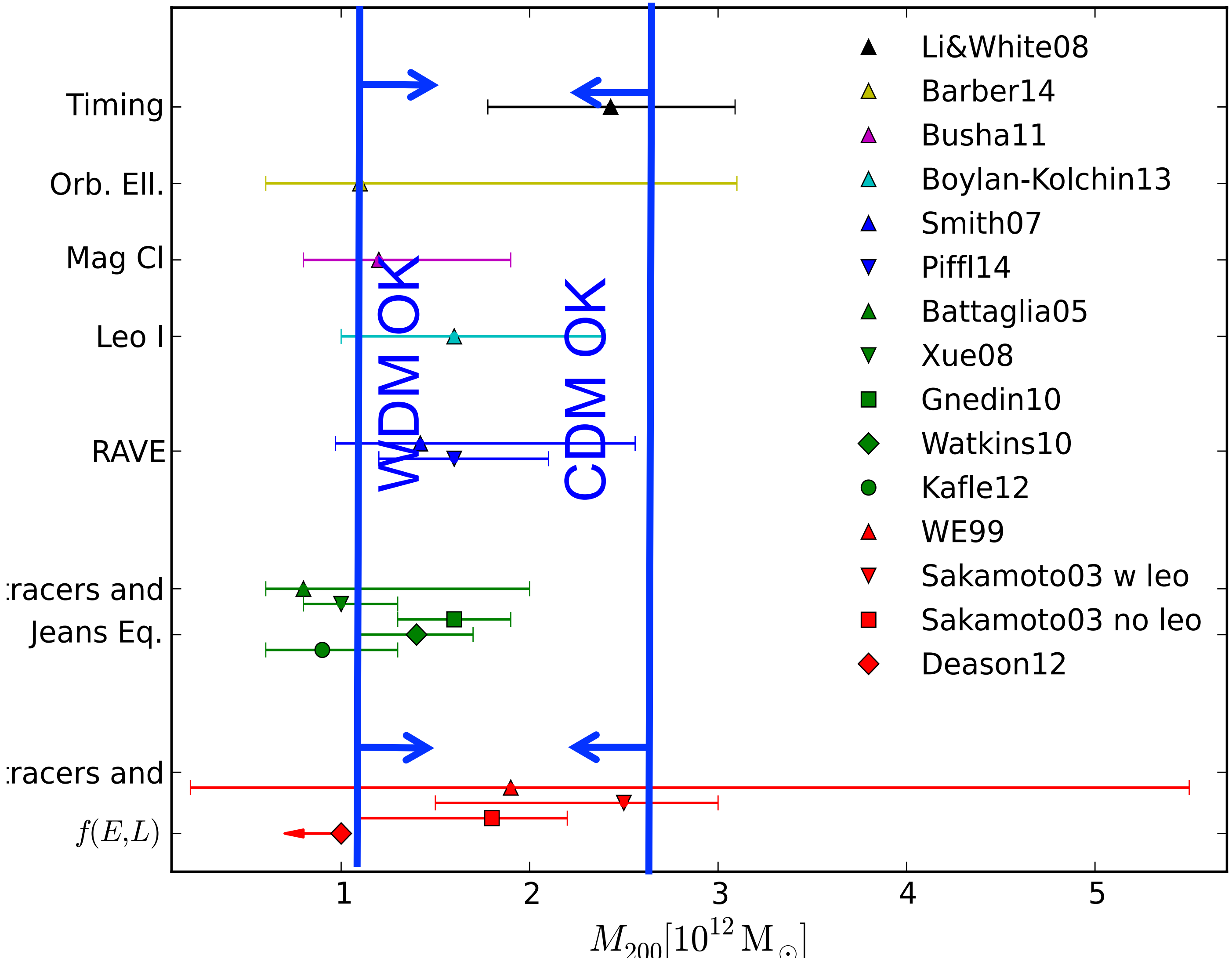

Wenting Wang et al. ‘14

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Constraints on CDM & WDM from the Milky Way satellites

With our standard assumptions: at 90% confidence

Cold dark matter :

Ruled out unless $M_{halo} < 2.6 \times 10^{12} M_o$

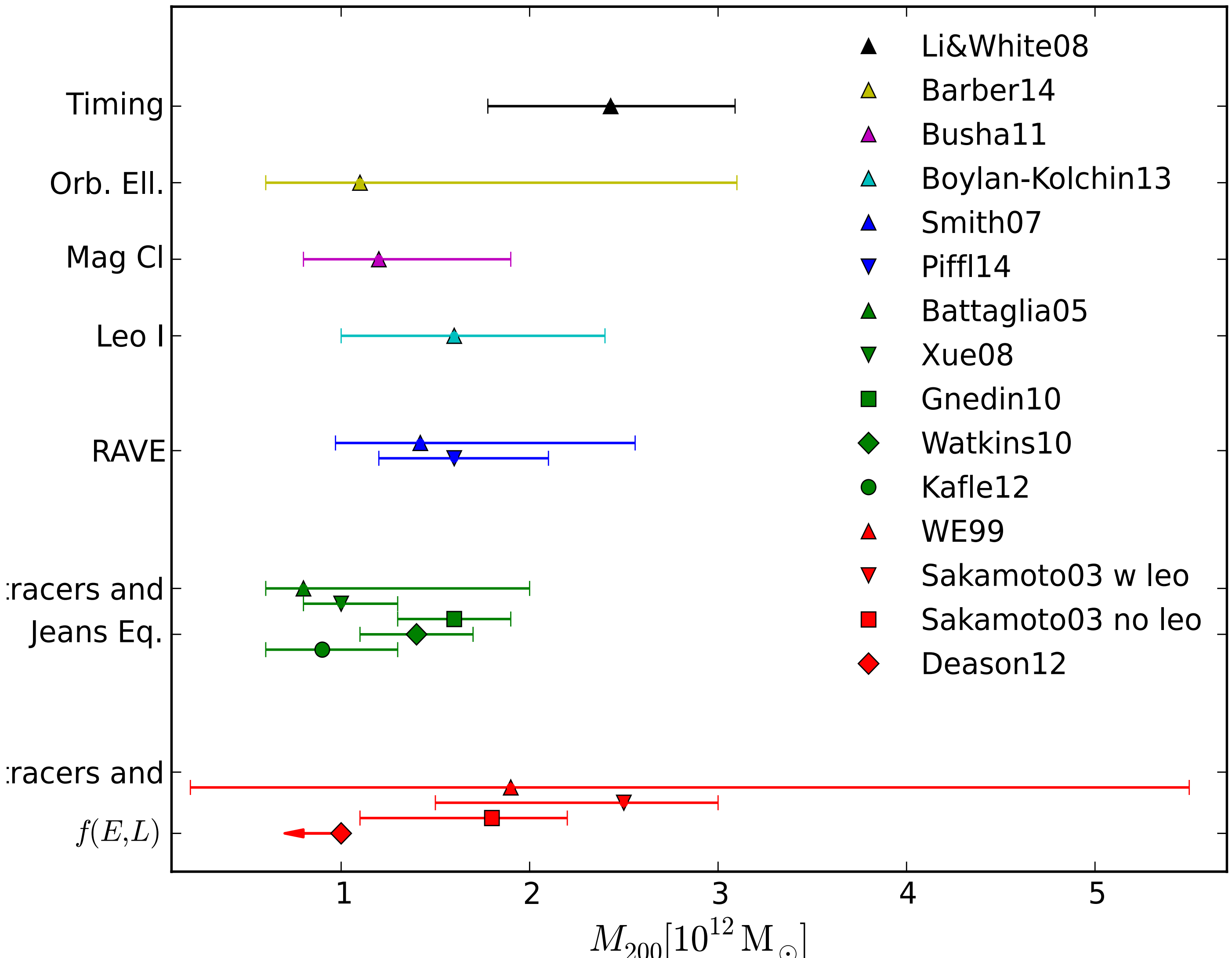
(from abundance of massive satellites)

Warm dark matter :

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

(from abundance of satellites)

Estimates of the MW halo mass



Wenting Wang et al. '14