Searching for the identity of the dark matter in the Local Group

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Collaborators

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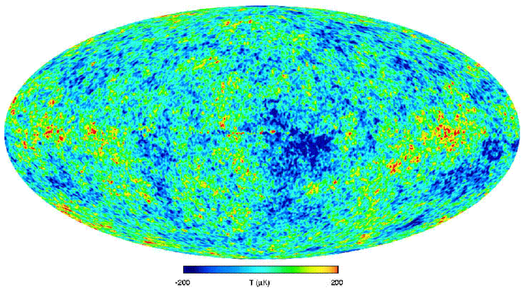
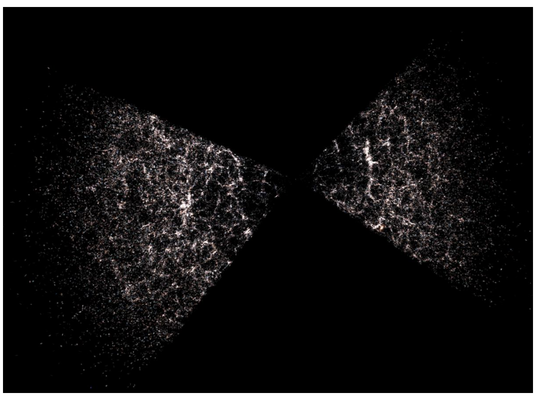
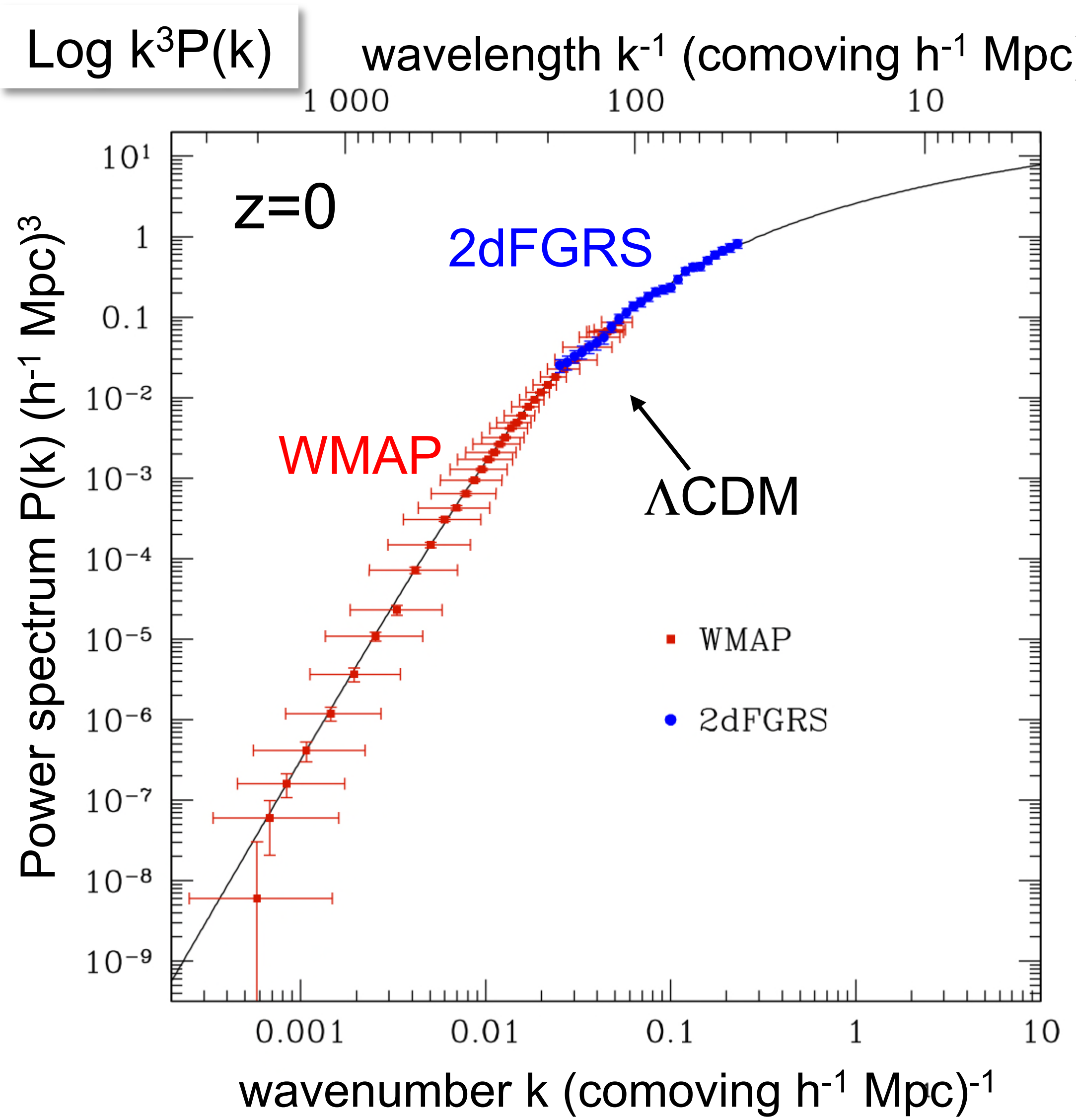
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



⇒ ΛCDM 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

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Free streaming →

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

for thermal relic

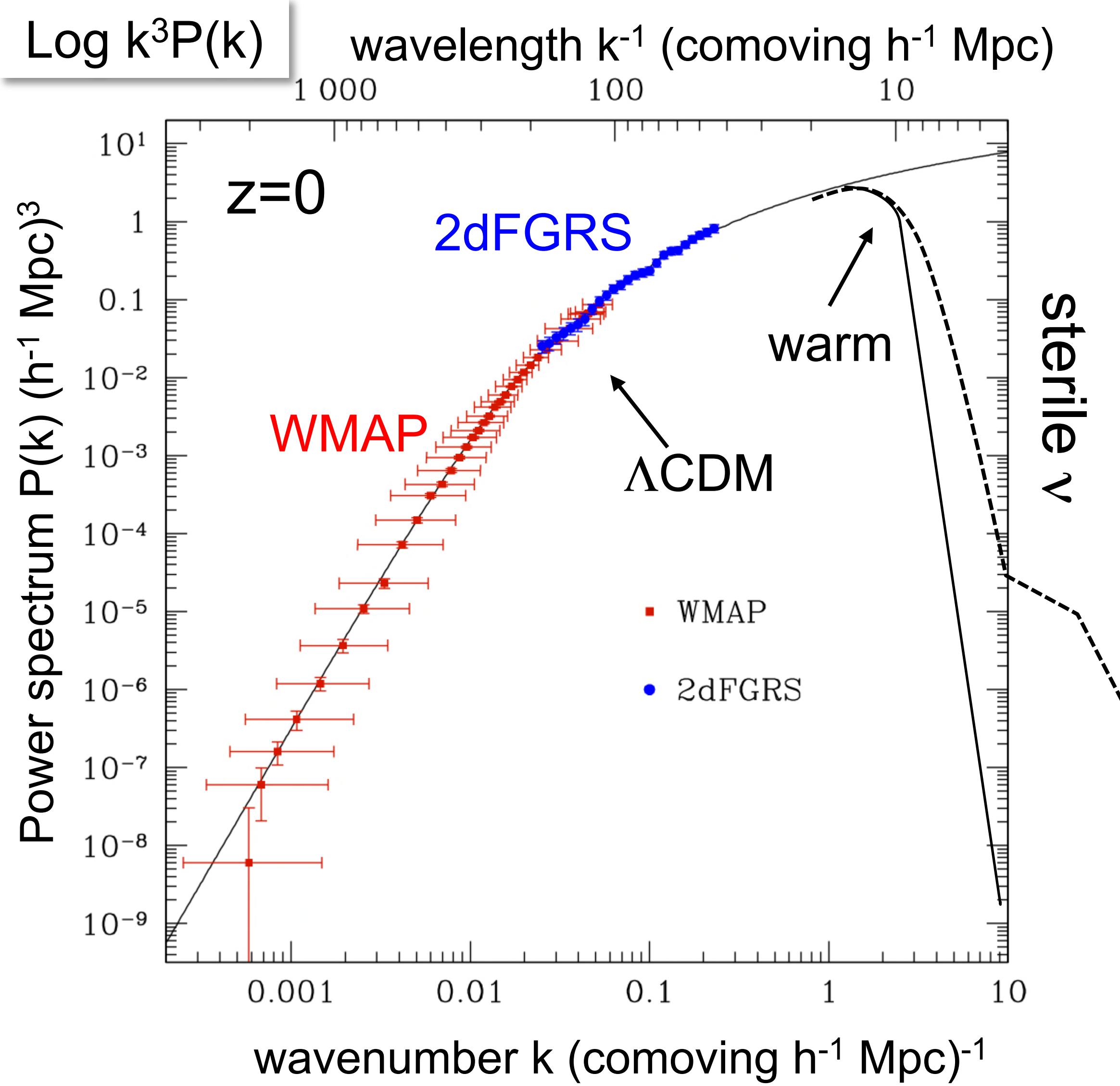
$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$

Log $k^3P(k)$



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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]

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

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

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 F
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

Institute for Computational Cosmology

cold dark matter

warm dark matter

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

University of Durham

Evidence for warm dark matter!

THE ASTROPHYSICAL JOURNAL, 663:948–959, 2007 July 10

THE OBSERVED PROPERTIES OF DARK MATTER ON SMALL SPATIAL SCALES

GERARD GILMORE,[1] MARK I. WILKINSON,[1,2] ROSEMARY F. G. WYSE,[3] JAN T. KLEYNA,[4] ANDREAS KOCH,[5,6] N. WYN EVANS,[1] AND EVA K. GREBEL[6,7]

Received 2006 December 21; accepted 2007 March 5

ABSTRACT

We present a synthesis of recent photometric and kinematic data for several of the most dark matter dominated galaxies, the dwarf spheroidal Galactic satellites, and compare them to star clusters. There is a bimodal distribution in half-light radii, with stable star clusters always being smaller than ∼30 pc, while stable galaxies are always larger than ∼120 pc. We extend the previously known observational relationships and interpret them in terms of a more fundamental pair of intrinsic properties of dark matter itself: dark matter forms cored mass distributions, with a core scale length of greater than about 100 pc, and always has a maximum central mass density within a narrow range. The dark matter in dSph galaxies appears to be clustered such that there is a mean volume mass density within the stellar distribution which has the very low value of less than about 0.1 $M_\odot$ pc^{-3} (about 5 GeV/c^2 cm^{-3}). All dSph's have velocity dispersions at the edge of their light distributions equivalent to circular velocities of ∼15 km s^{-1}. The maximum central dark matter density derived is model dependent but is likely to have a characteristic value (averaged over a volume of radius 10 pc) of ∼0.1 $M_\odot$ pc^{-3} for the favored cored dark mass distributions (where it is similar to the mean value), or ∼60 $M_\odot$ pc^{-3} (about 2 TeV/c^2 cm^{-3}) if the dark matter density distribution is cusped. Galaxies are embedded in dark matter halos with these properties; smaller systems containing dark matter are not observed. These values provide new information about the nature of the dominant form of dark matter.

Evidence for warm dark matter?

University of Durham

THE ASTROPHYSICAL JOURNAL, 663:948–959, 2007 July 10

THE OBSERVED PROPERTIES OF DARK MATTER ON SMALL SPATIAL SCALES

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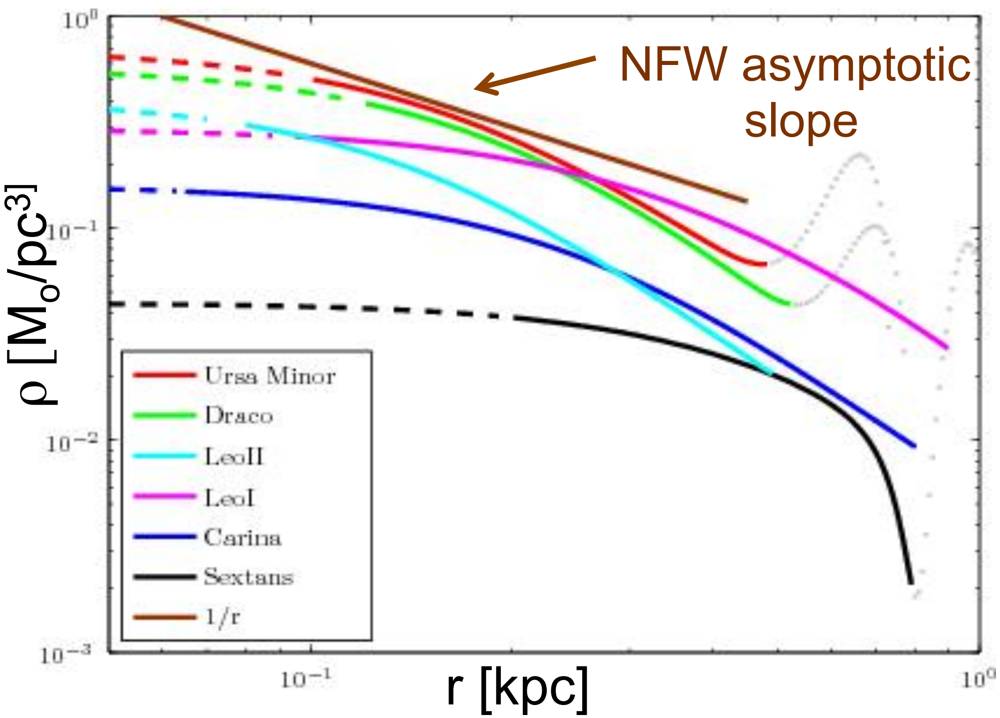

Inferred density profiles for 6 dwarf spheroidals

"…dark matter forms cored mass distributions, with a core scale length of greater than about 100pc, and always has a maximum central density in a narrow range…"

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

1. Such large cores are NOT expected in WDM

2. There is NO evidence for "cores" in dwarf spheroidals

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Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound in fine-grained space density:

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Shao, Gao, Theuns, Frenk ' 13

Maccio et al.'12

Core radii in WDM halos

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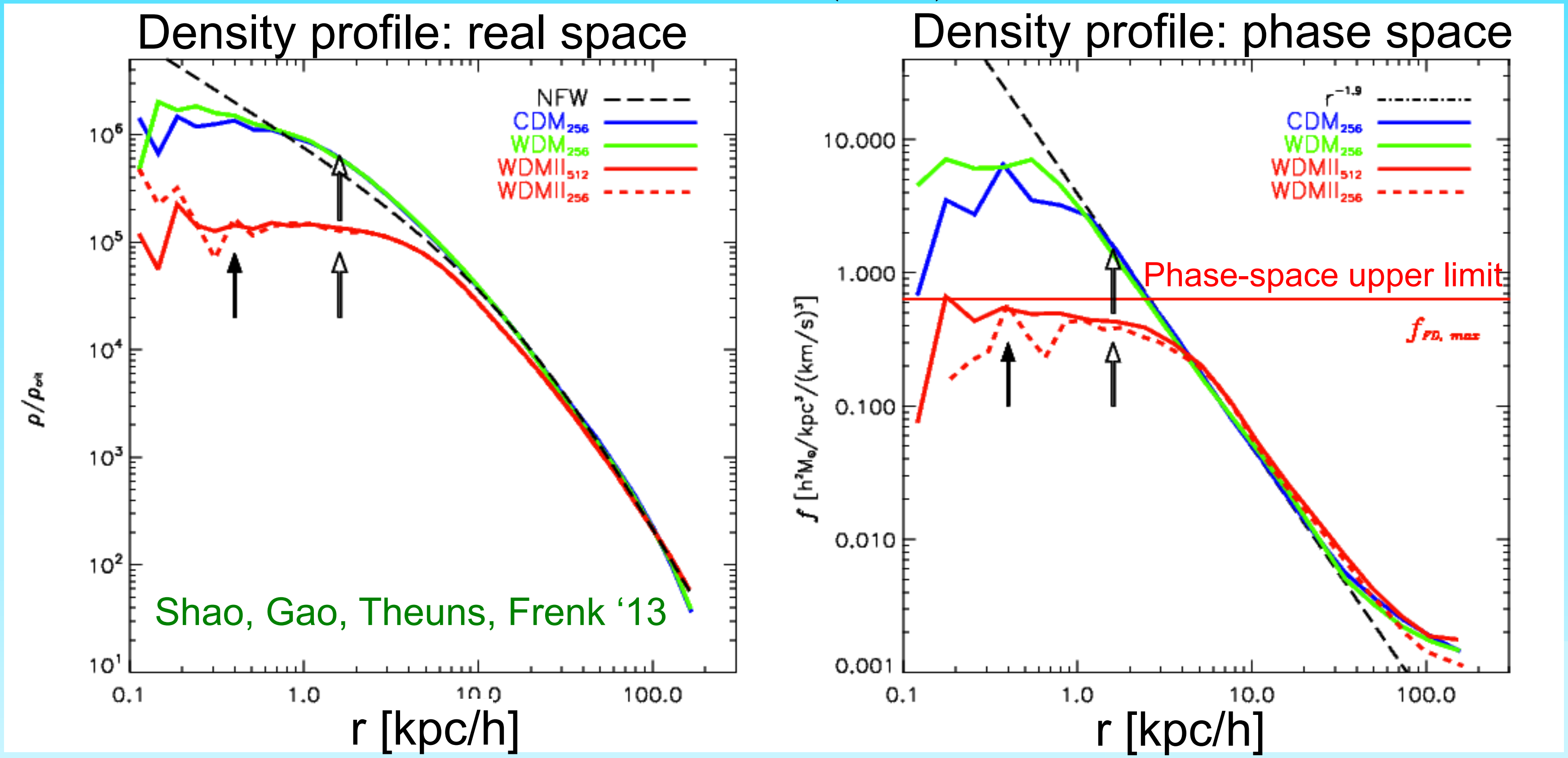

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Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

By requiring $f = f_{FD}$

$$m_x^4 = \frac{6(2\pi\hbar)^3}{(2\pi)^{5/2} g G \sigma r_h^2}$$

Shao, Gao, Theuns, Frenk '13

Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Phase space arguments →

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

core radius

For m_{WDM} > 1.5 keV, the core radii in WDM models are of 10 times smaller than the values inferred by Gilmore et al. !

→ core radii in dwarfs NOT relevant in WDM models

Shao, Gao, Theuns, Frenk '13
see also Maccio et al '12

Dwarf galaxies around the Milky Way

But do dwarf spheroidals really have cores?

Dwarf galaxies around the Milky Way

But do dwarf spheroidals really have cores?

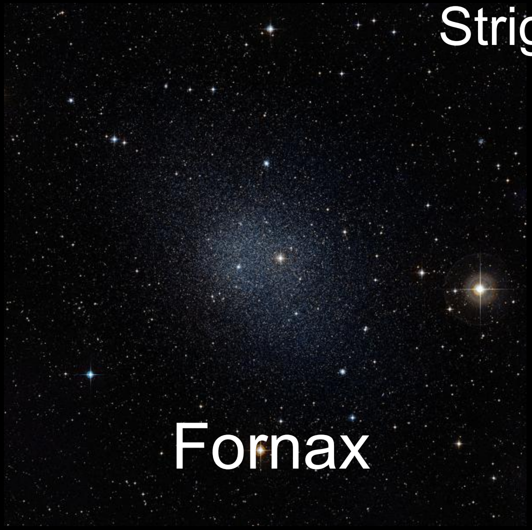
Sextans

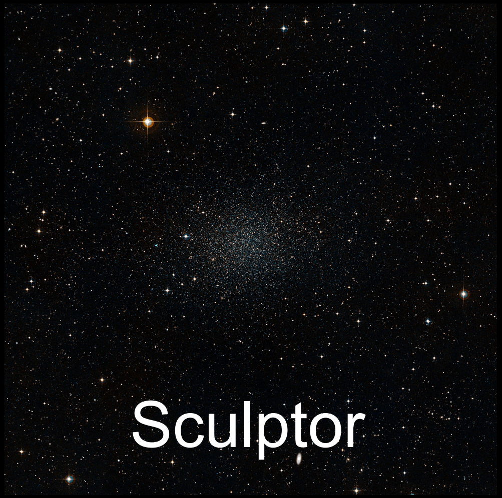
Carina

Sagittarius

Dwarf galaxies around the Milky Way

Strigari, Frenk & White '10





Sextans

Carina

Sagittarius

ICC
University of Durham

Dwarf sphs: cores or cusps?

Fits assuming NFW →

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

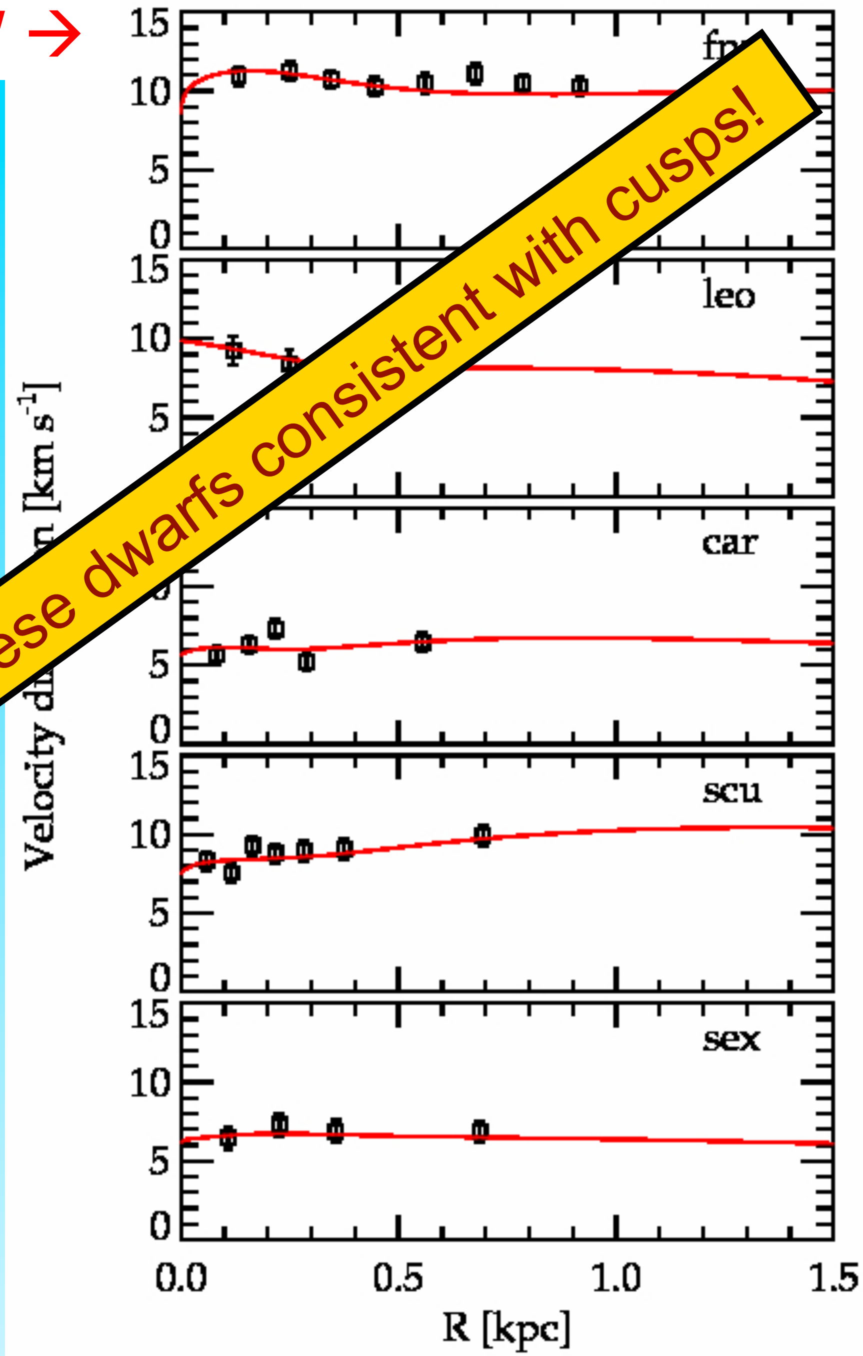
Cuspy!

vel. an… py

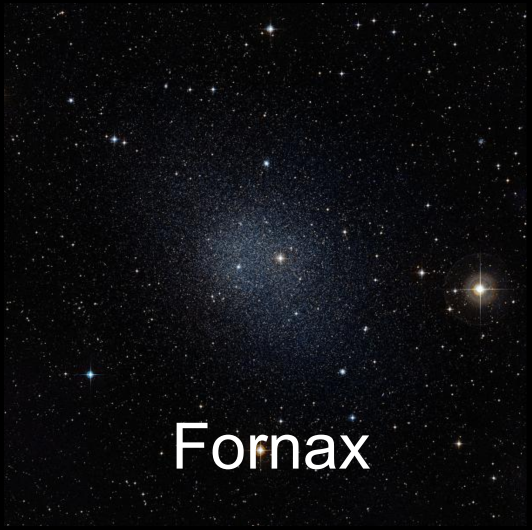
- Assume isotropi… ts
- Solve for σ…
- Com… with observed σ_r (r)
- … best fit” subhalo

Strigari, Frenk & White ‘10

Photometric and kinematical data for these dwarfs consistent with cusps!



Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

The DM halo of the Sculptor dwarf

University of Durham

Sculptor has two stellar pops:

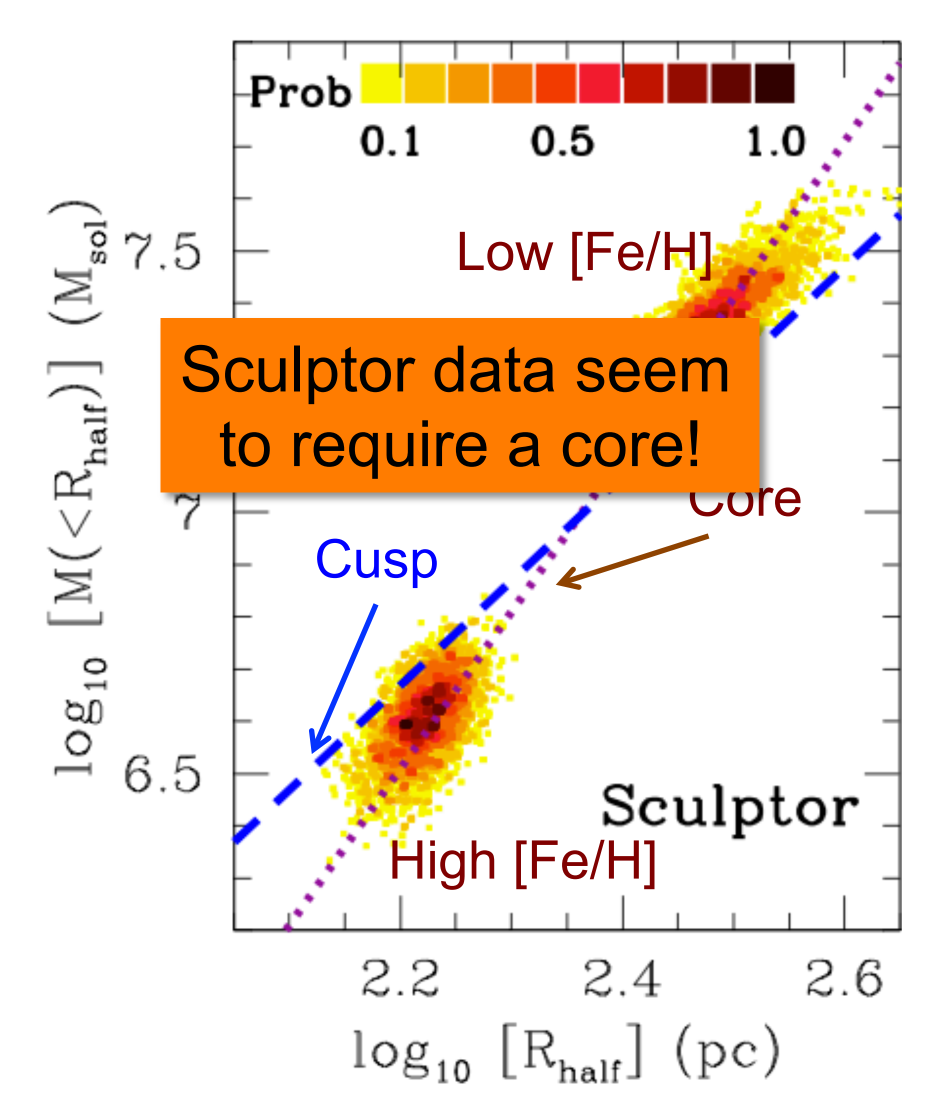
(i) centrally concentrated, high [Fe/H]

(ii) extended, low [Fe/H]

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

Walker '10; Wolf et al '10→

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



Walker & Peñarrubia '11

The DM halo of the Sculptor dwarf

Strigari, Frenk & White '14

Distribution function analysis of 2 metallicity pop. data of Battaglia et al.

Assume pops in equil. in NFW halo: $\rho(r) = \frac{\rho_s}{x(1+x)^2}$

For each population: $f(E,J) = g(J)h(E),$

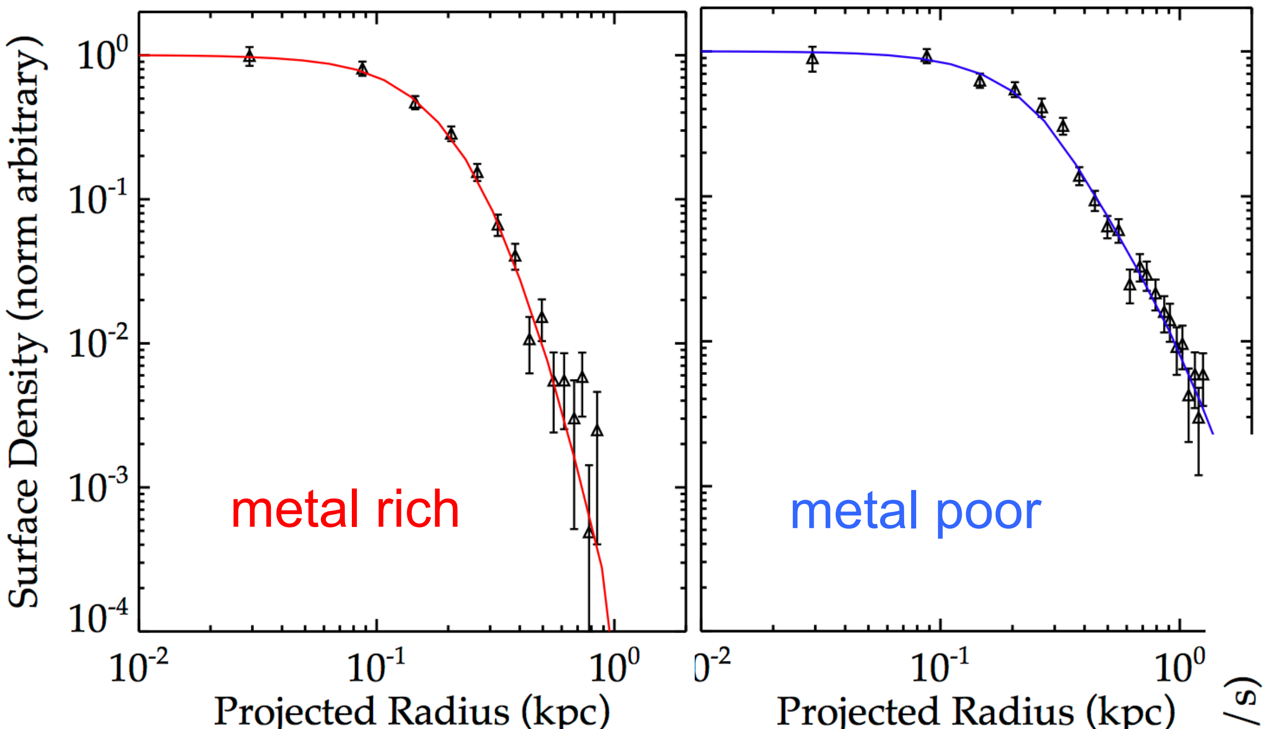
Parametrize: $g(J) = \left[\left(\frac{J}{J_\beta}\right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta}\right)^{\frac{b_1}{\alpha}}\right]^{\alpha}$

$$h(E) = \begin{cases} NE^a(E^q + E_c^q)^{d/q}(\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for} E \geq \Phi_{lim}, \end{cases}$$

Find best-fit parameters using MCMC

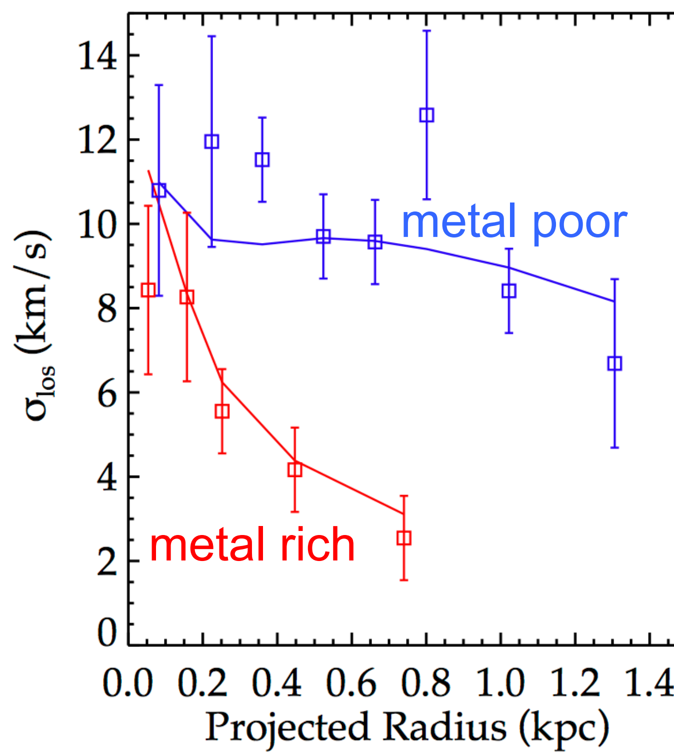
The DM halo of the Sculptor dwarf

University of Durham



Surface density

Velocity dispersion



Data consistent with two populations in equilibrium in NFW halo

Strigari, Frenk & White '14

The DM halo of the Sculptor dwarf

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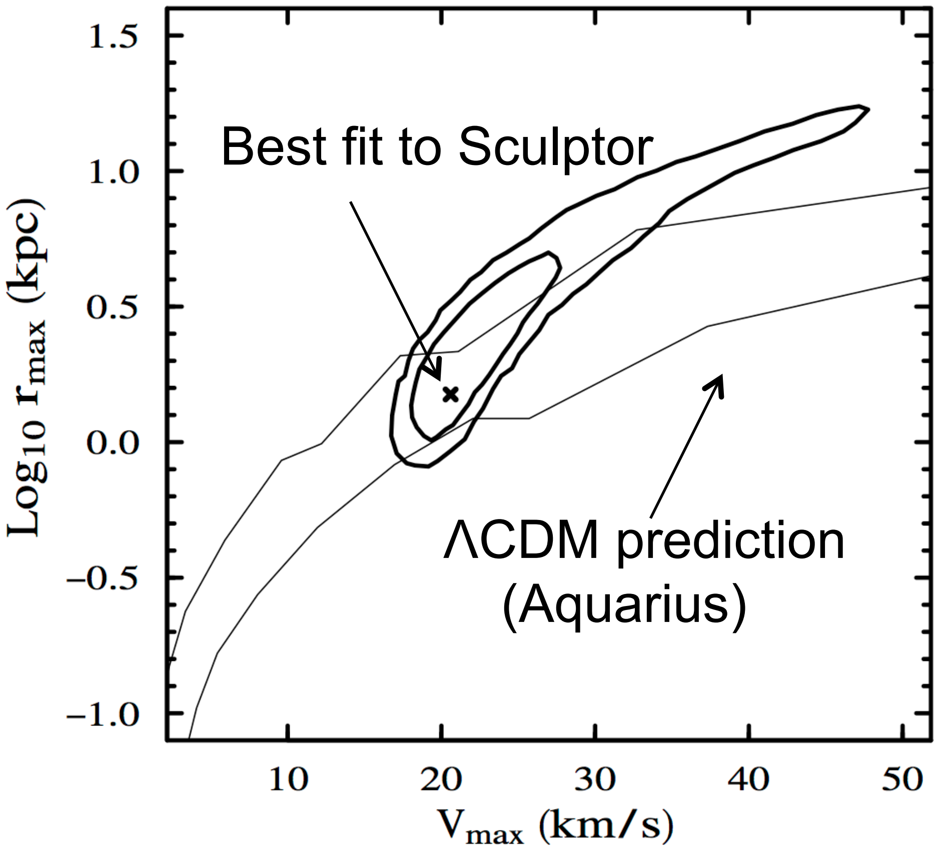
NFW best-fit parameters as expected in ΛCDM



Strigari, Frenk & White ‘14

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The DM halo of the Sculptor dwarf

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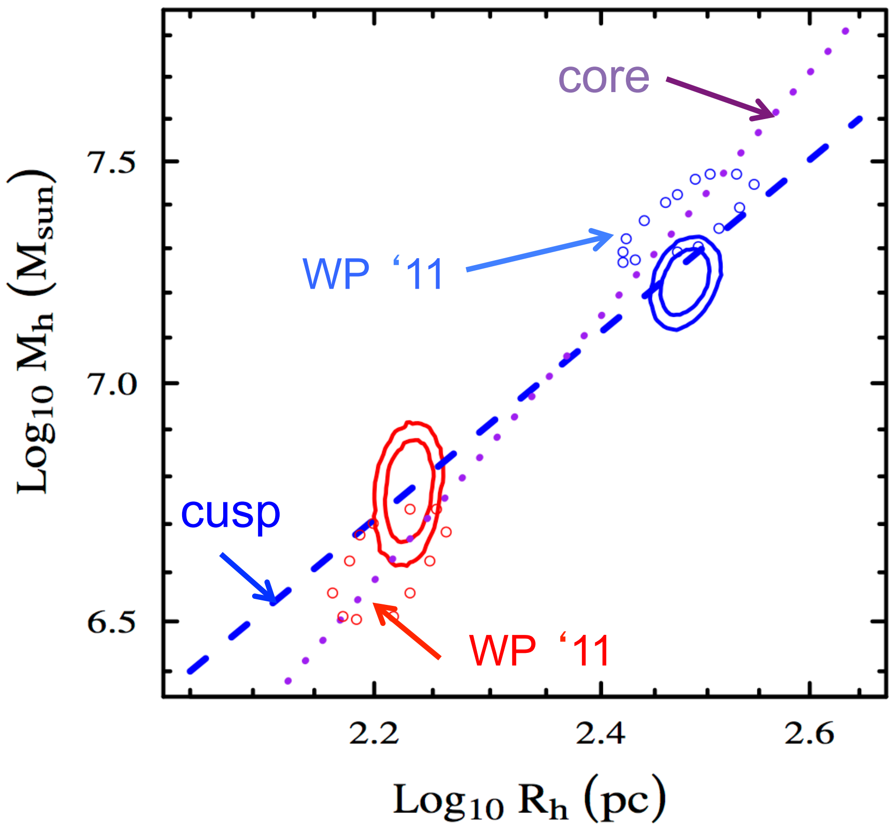
Comparison with Walker & Penarrubia '11



Strigari, Frenk & White '14

WP '11 use:

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

and assume μ = 2.5 for both populations

(Walker et al '10, Wolfe et al '10)

For our best-fit model however:

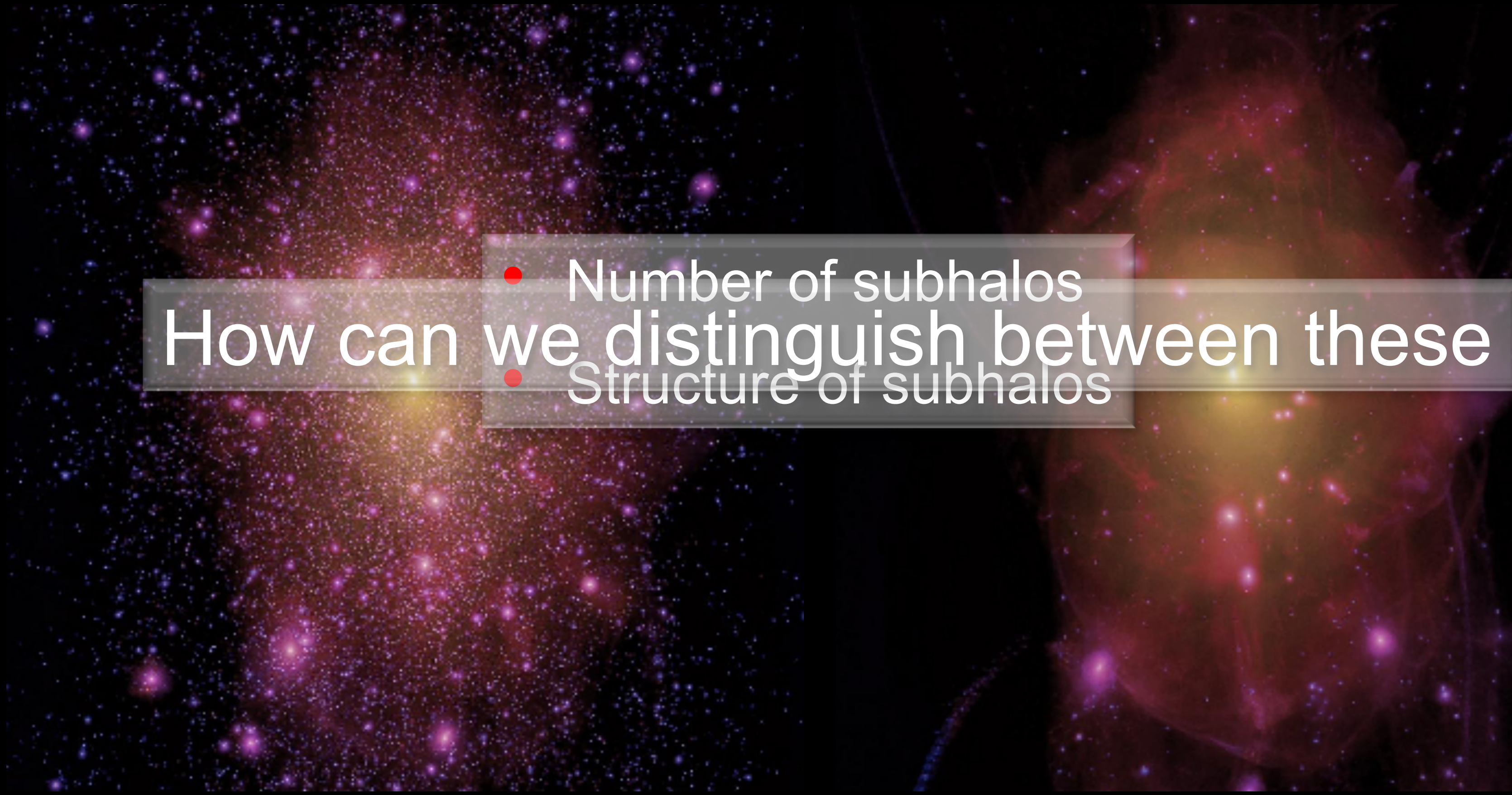
μ = { 2.6 for metal poor; 2.9 for metal rich }

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

ICC VIRGO

cold dark matter | warm dark matter

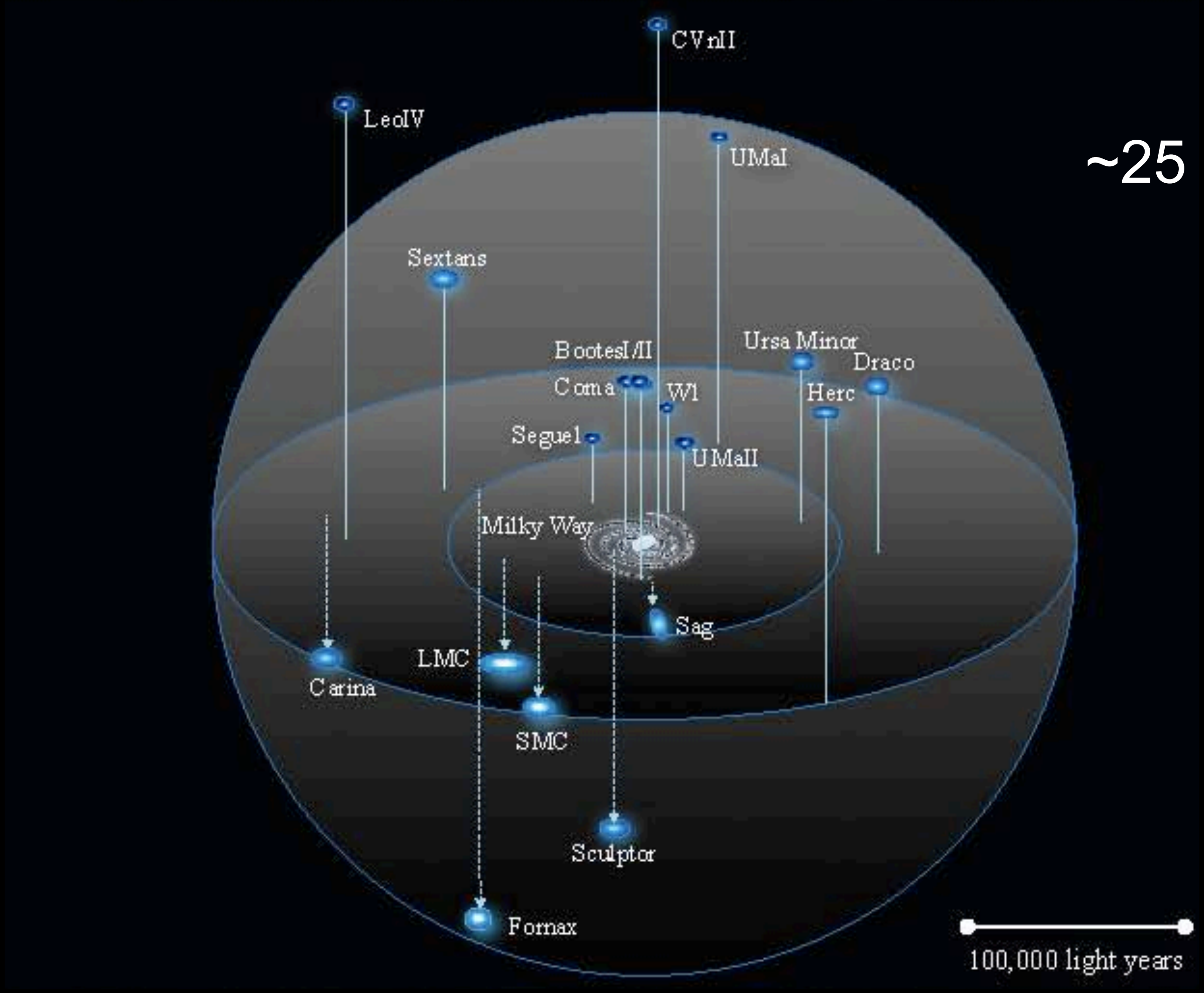


How can we distinguish between these

- Number of subhalos
- Structure of subhalos

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

The satellites of the Milky Way



~25 satellites known in the MW

cold dark matter

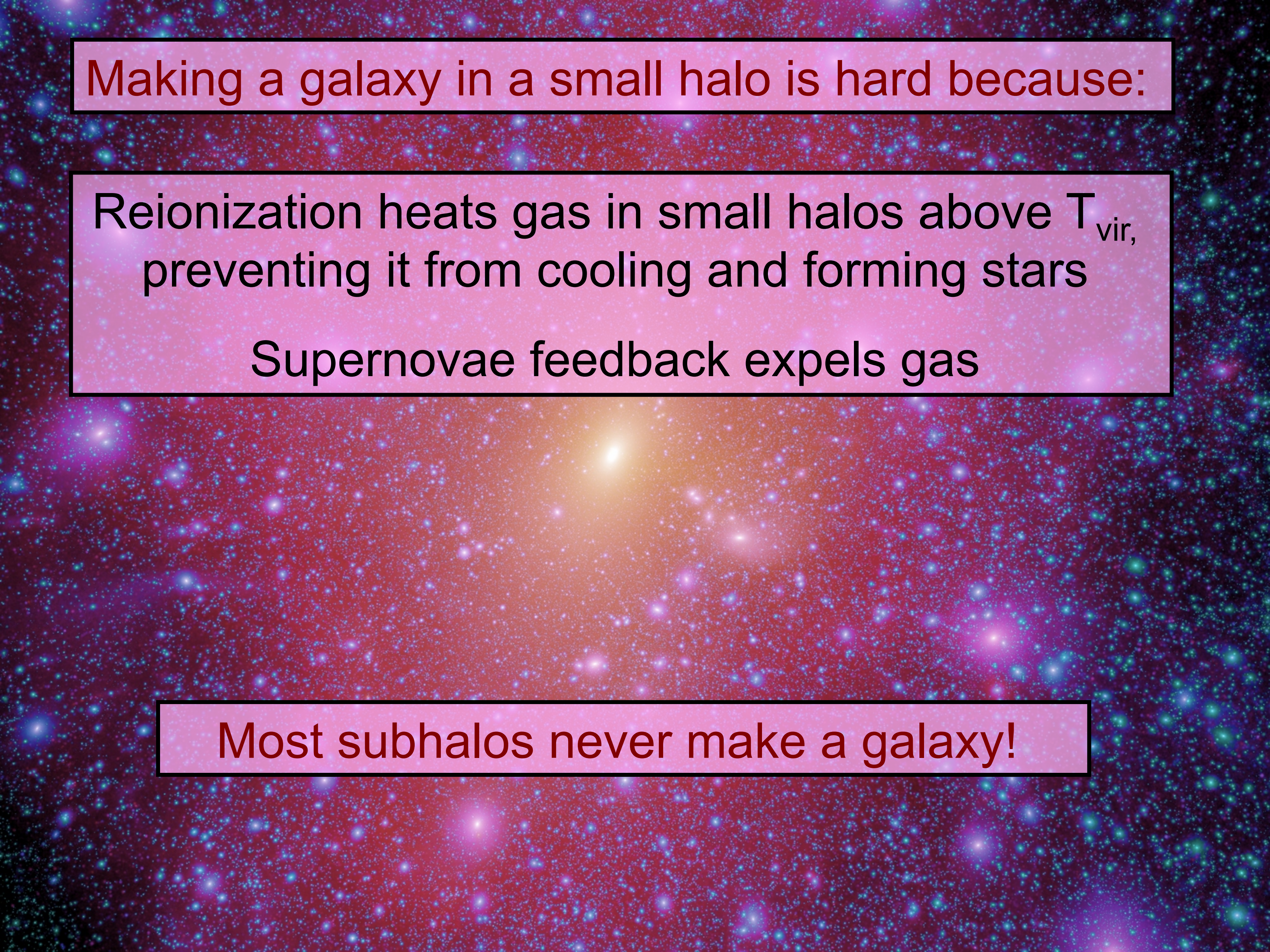
warm dark matter

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

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

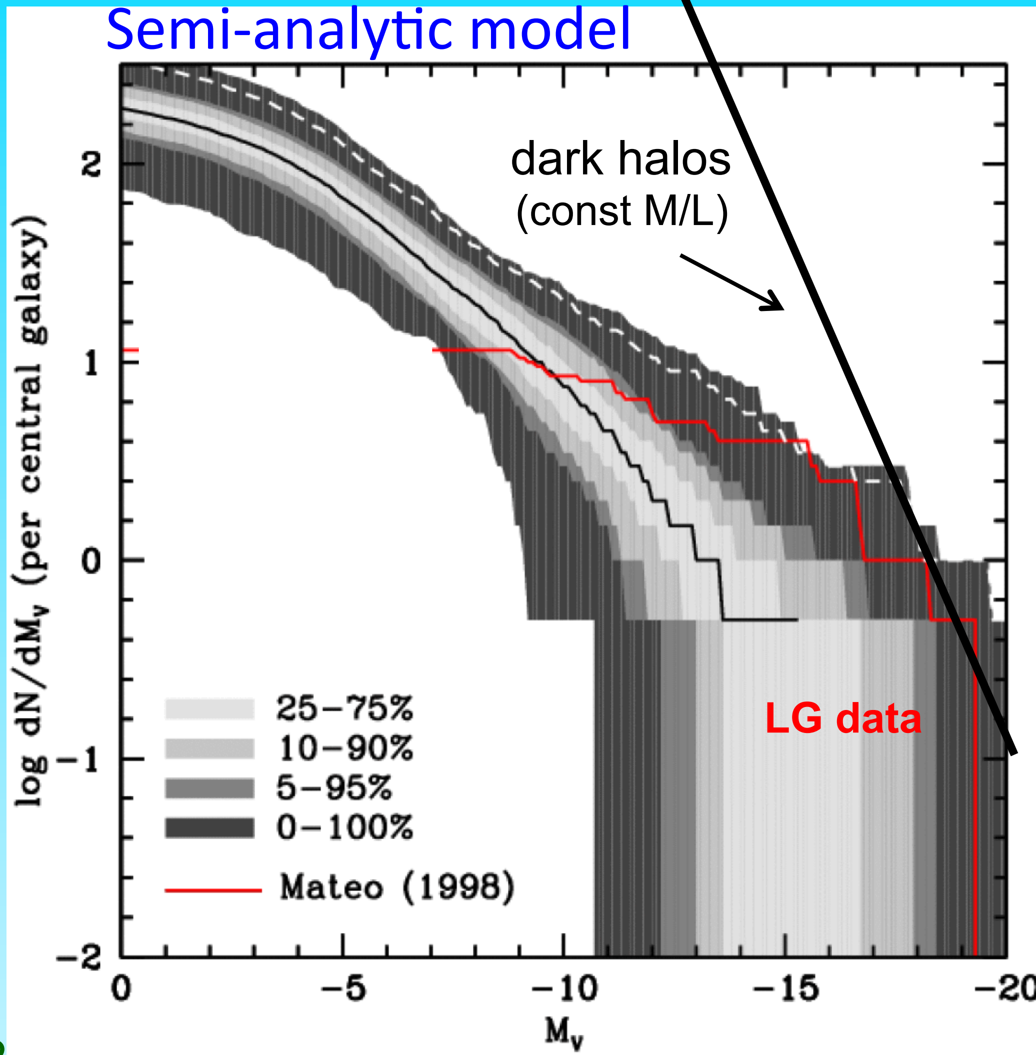
Supernovae feedback expels gas



Most subhalos never make a galaxy!

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 et al '00)

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Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
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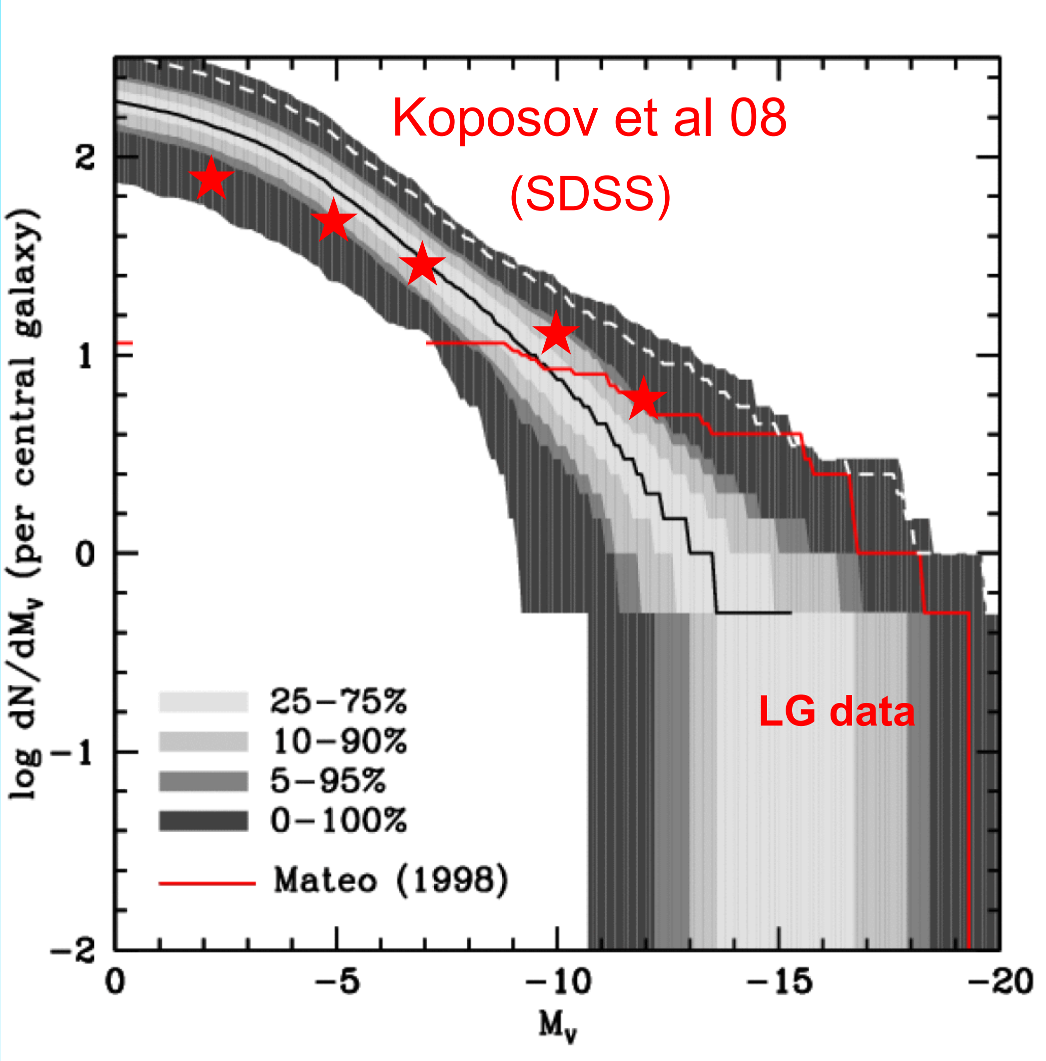

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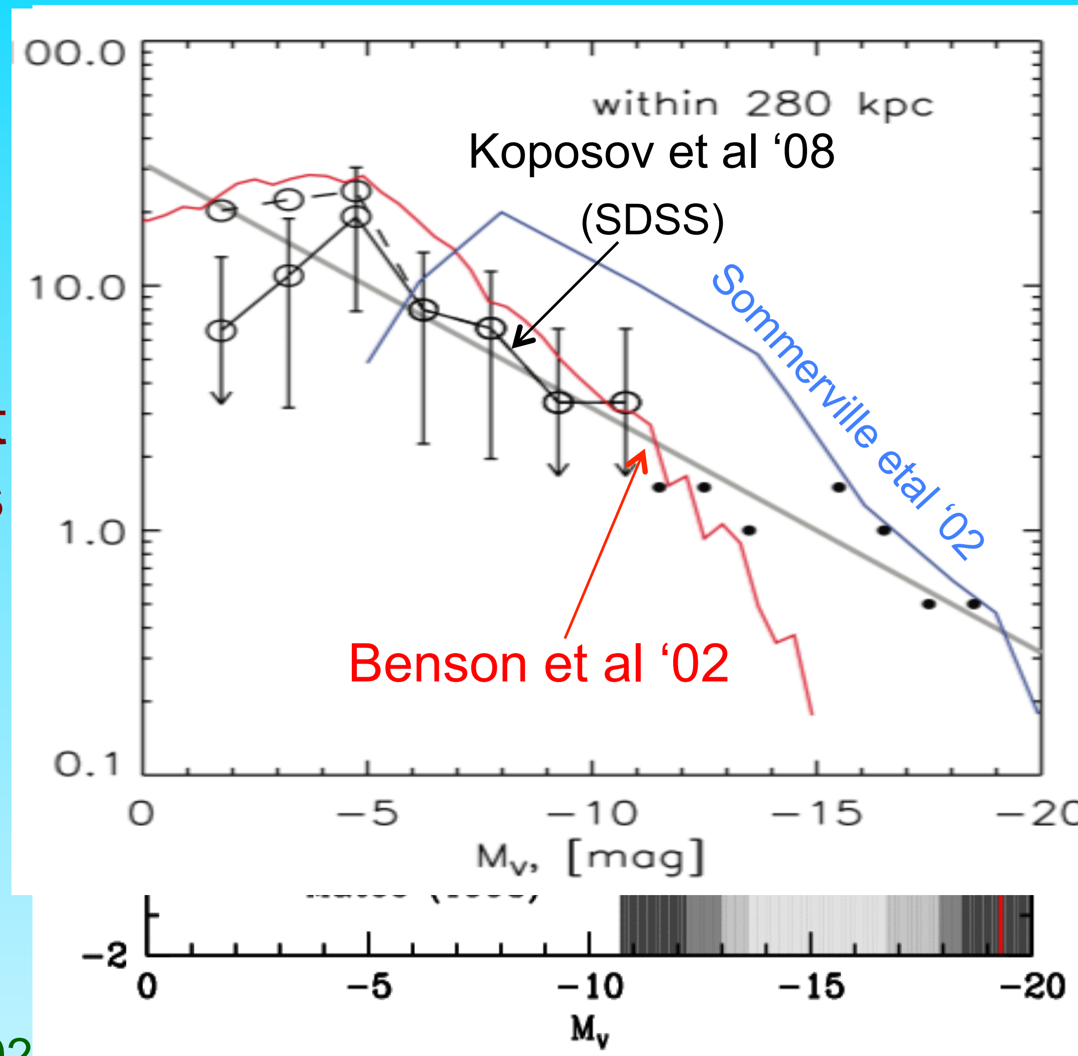


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

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…

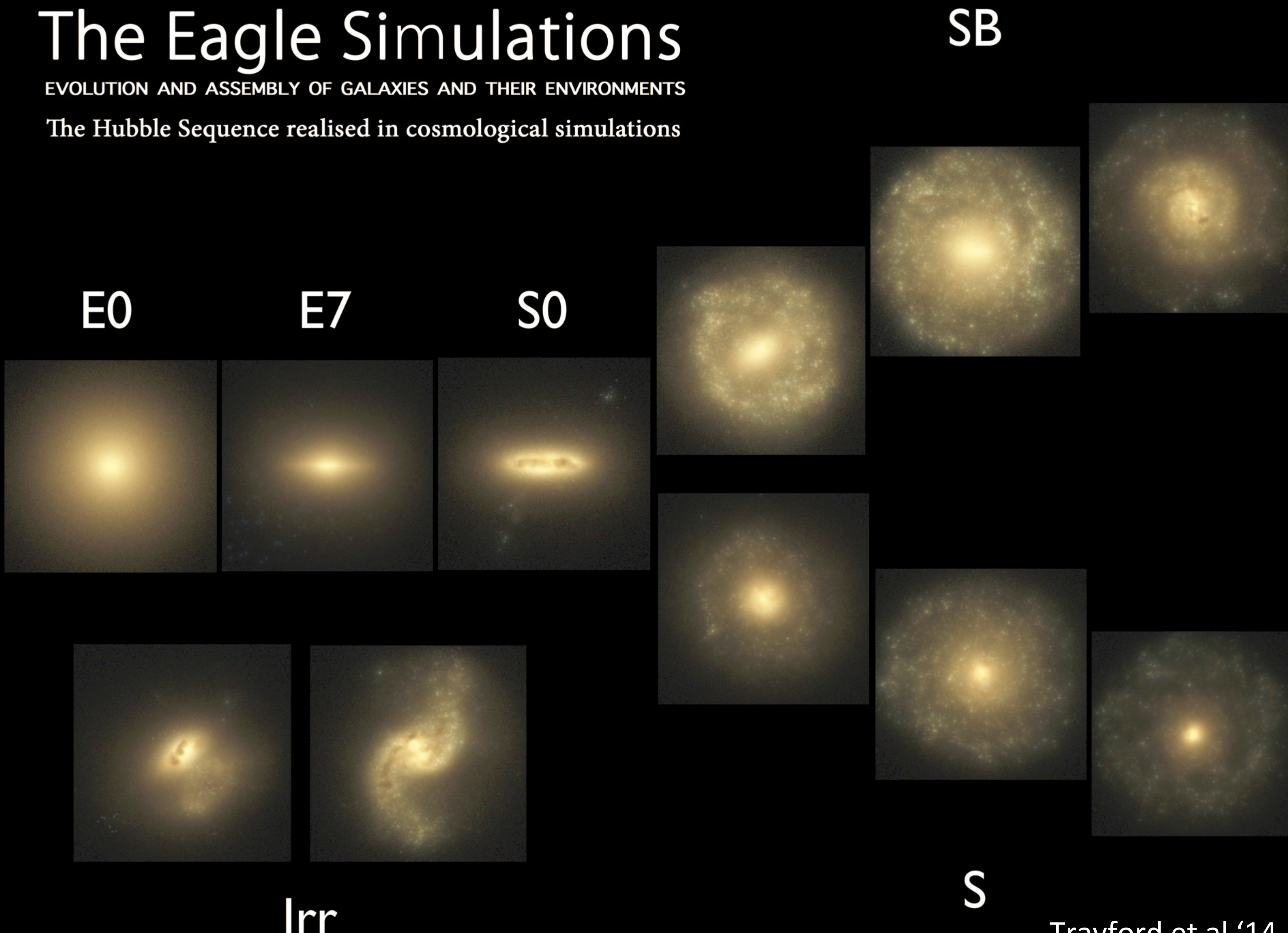
+ Virgo Consortium

NAM 2014

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations

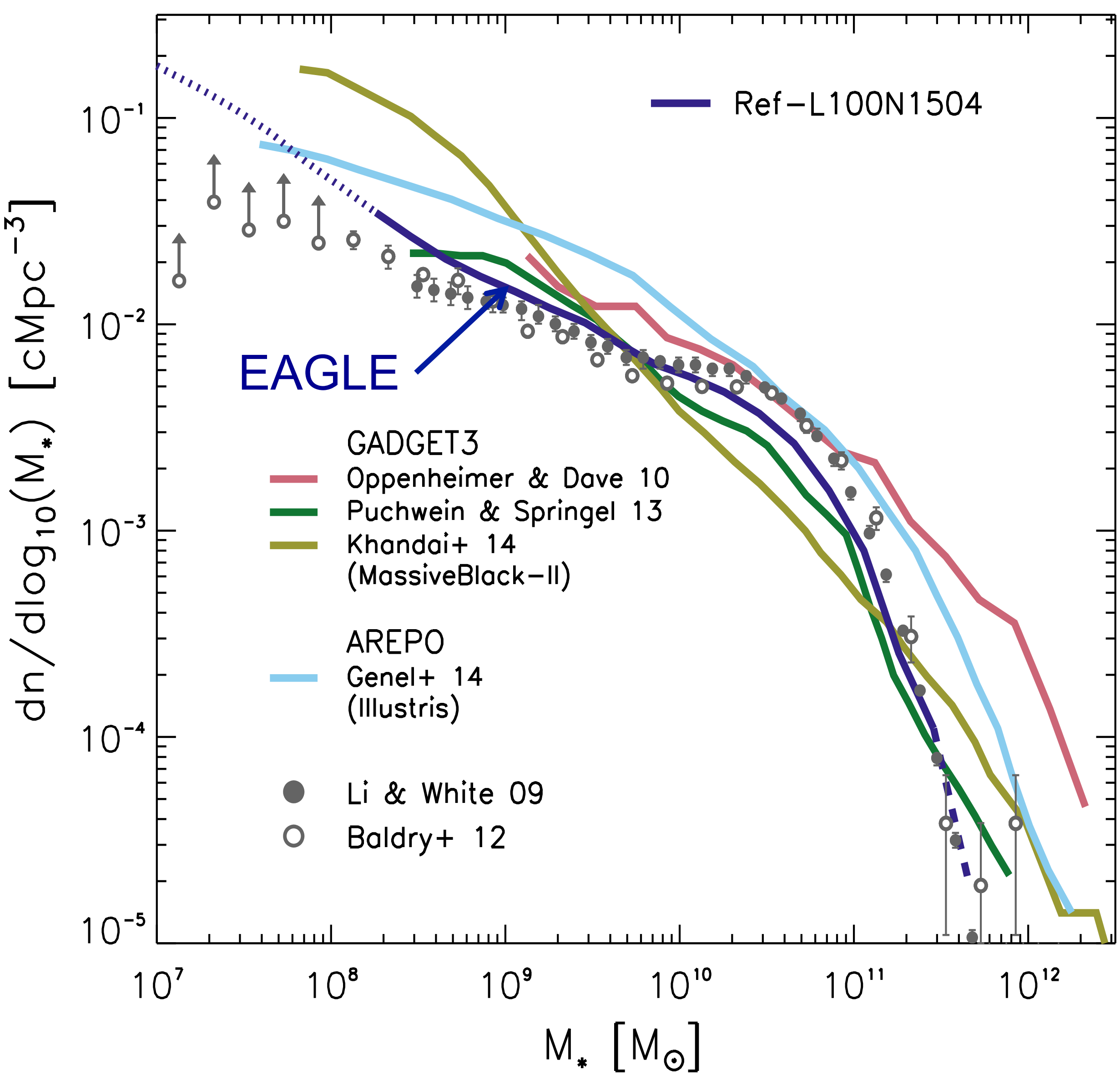


Trayford et al '14

Galaxy stellar mass function

EAGLE:

Feedback parameters calibrated to provide acceptable match to galaxy stellar mass function over range $2\text{x}10^8 – 3\text{x}10^{11}$ M_o



EAGLE full hydro simulations

Local Group

Sawala et al ‘14

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

EAGLE full hydro simulations

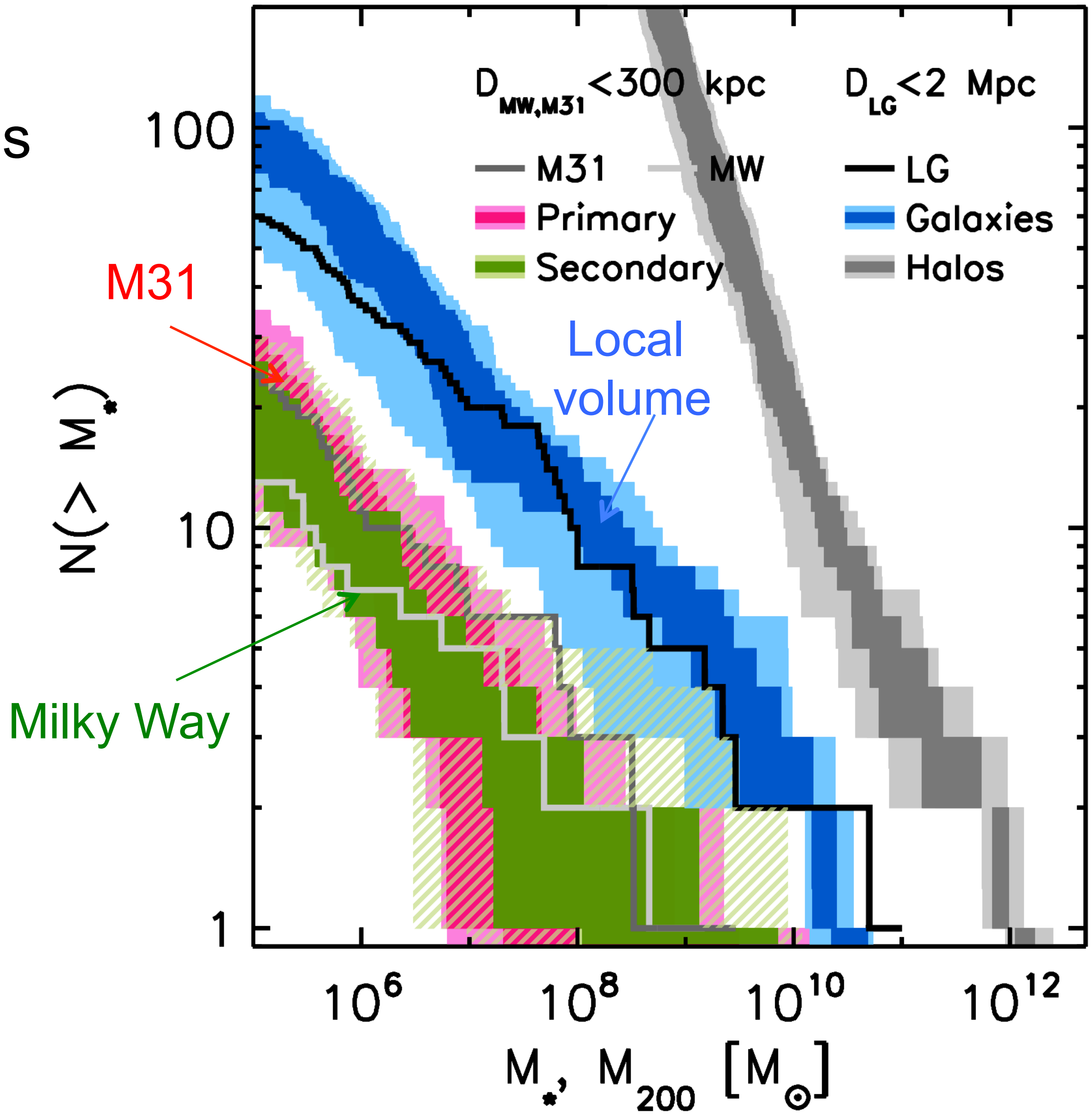
Local Group

Sawala et al ‘14

EAGLE Local Group simulation

University of Durham

Stellar mass functions



Sawala et al ‘14

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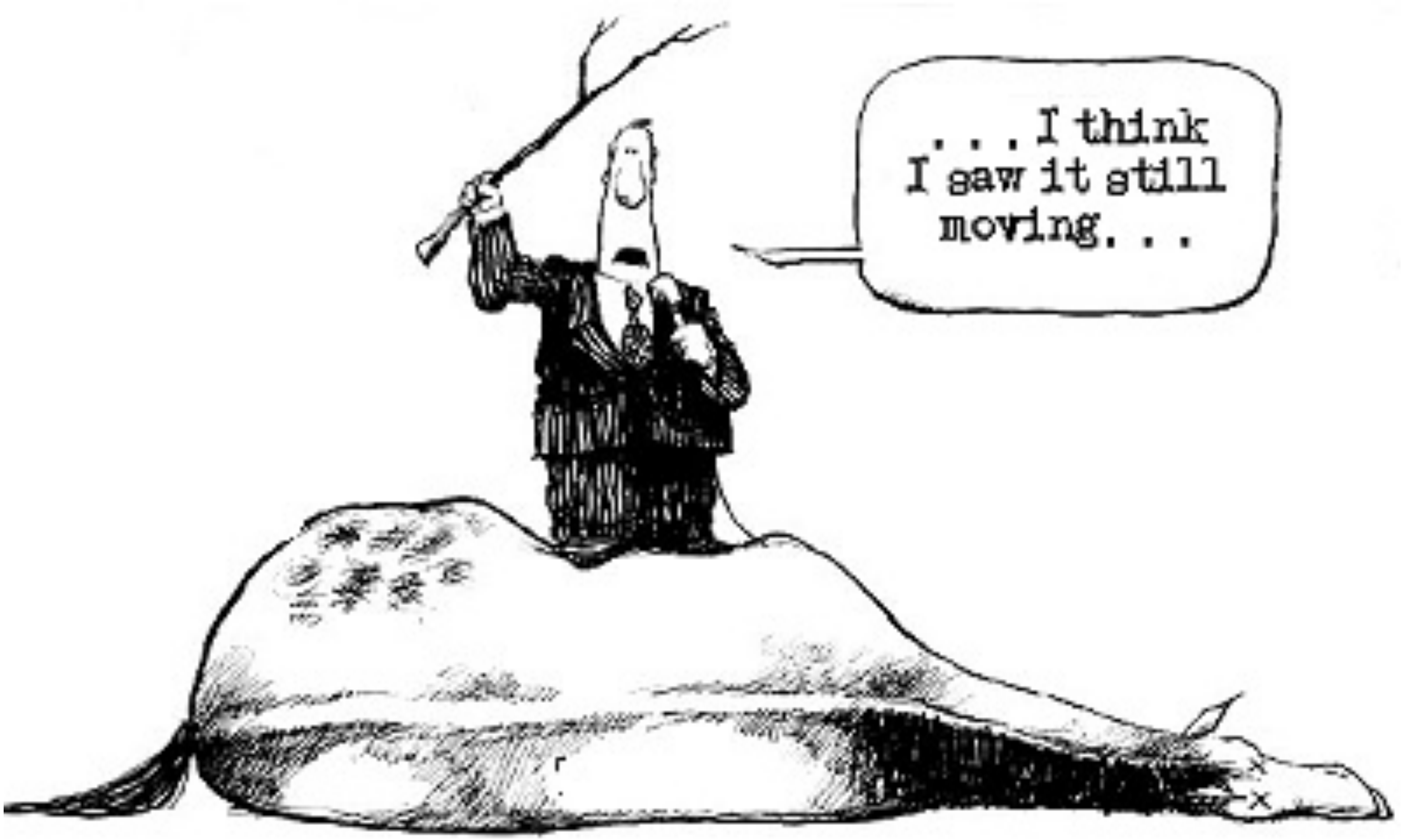
The “missing satellite problem”



Warm DM: different ν mass

z=3

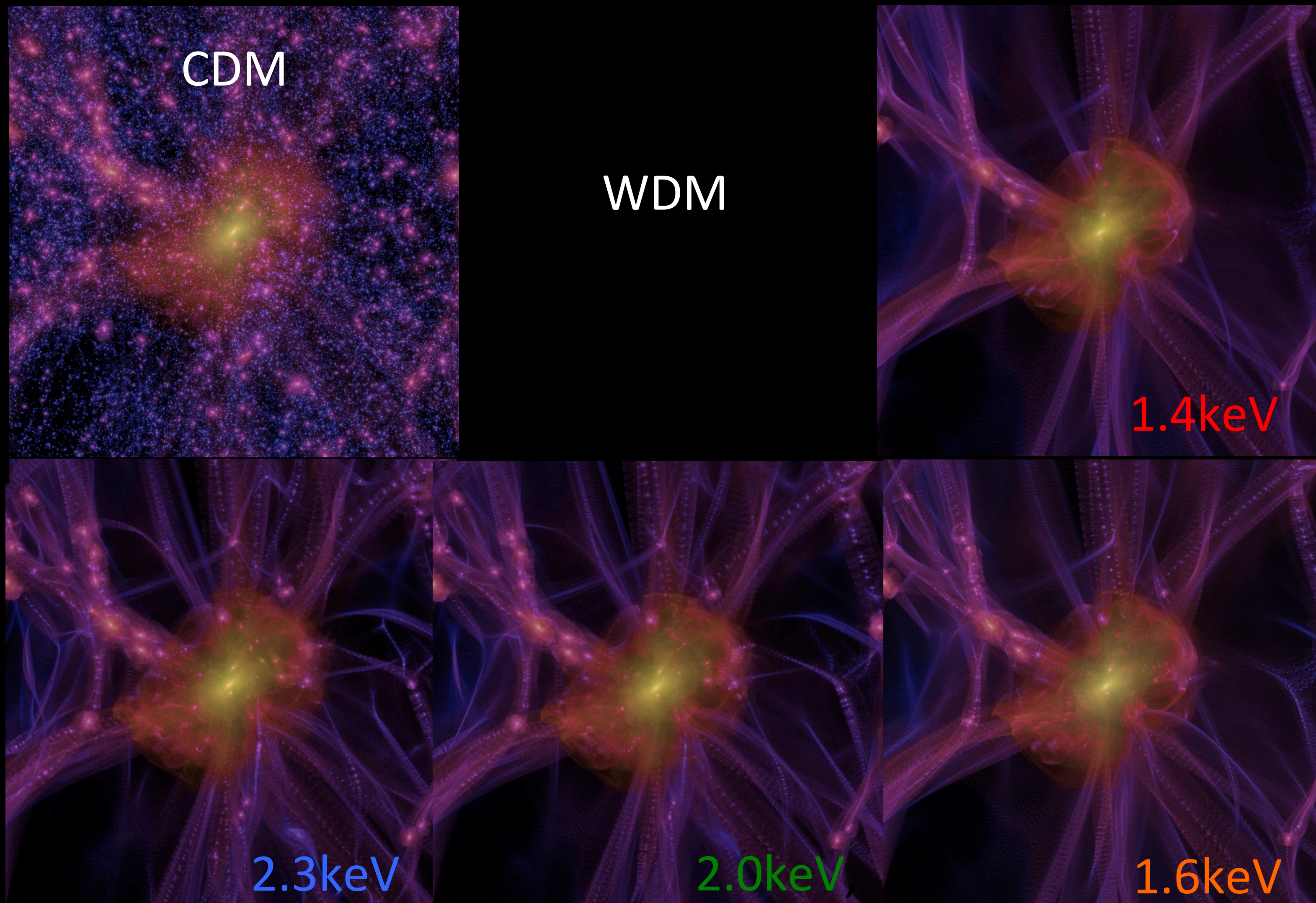
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



Luminosity Function of Local Group Satellites in WDM

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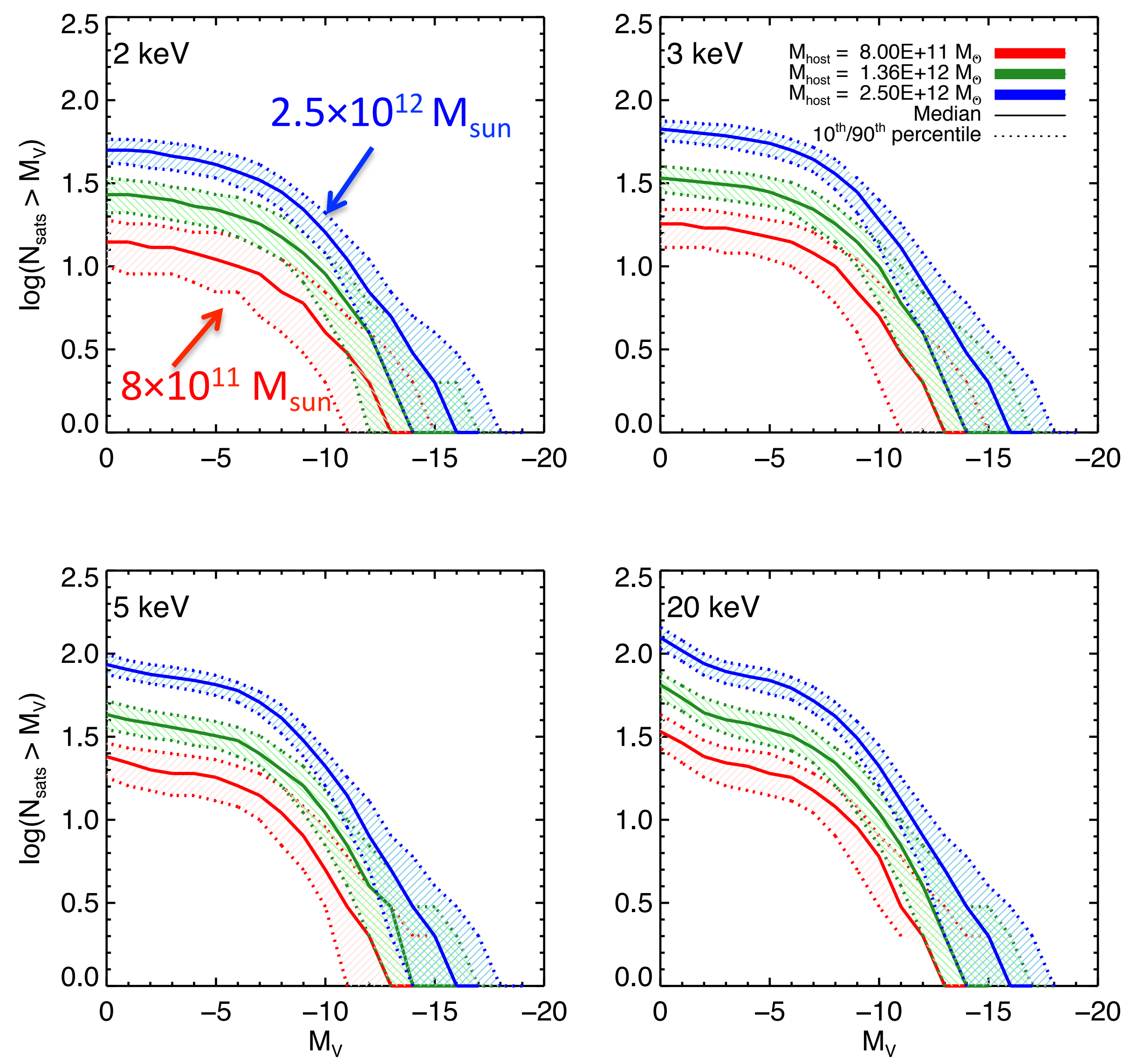
No of sats ↗ with:

- host halo mass
- WDM particle mass



Kennedy, Cole & Frenk '13

Luminosity Function of Local Group Satellites in WDM

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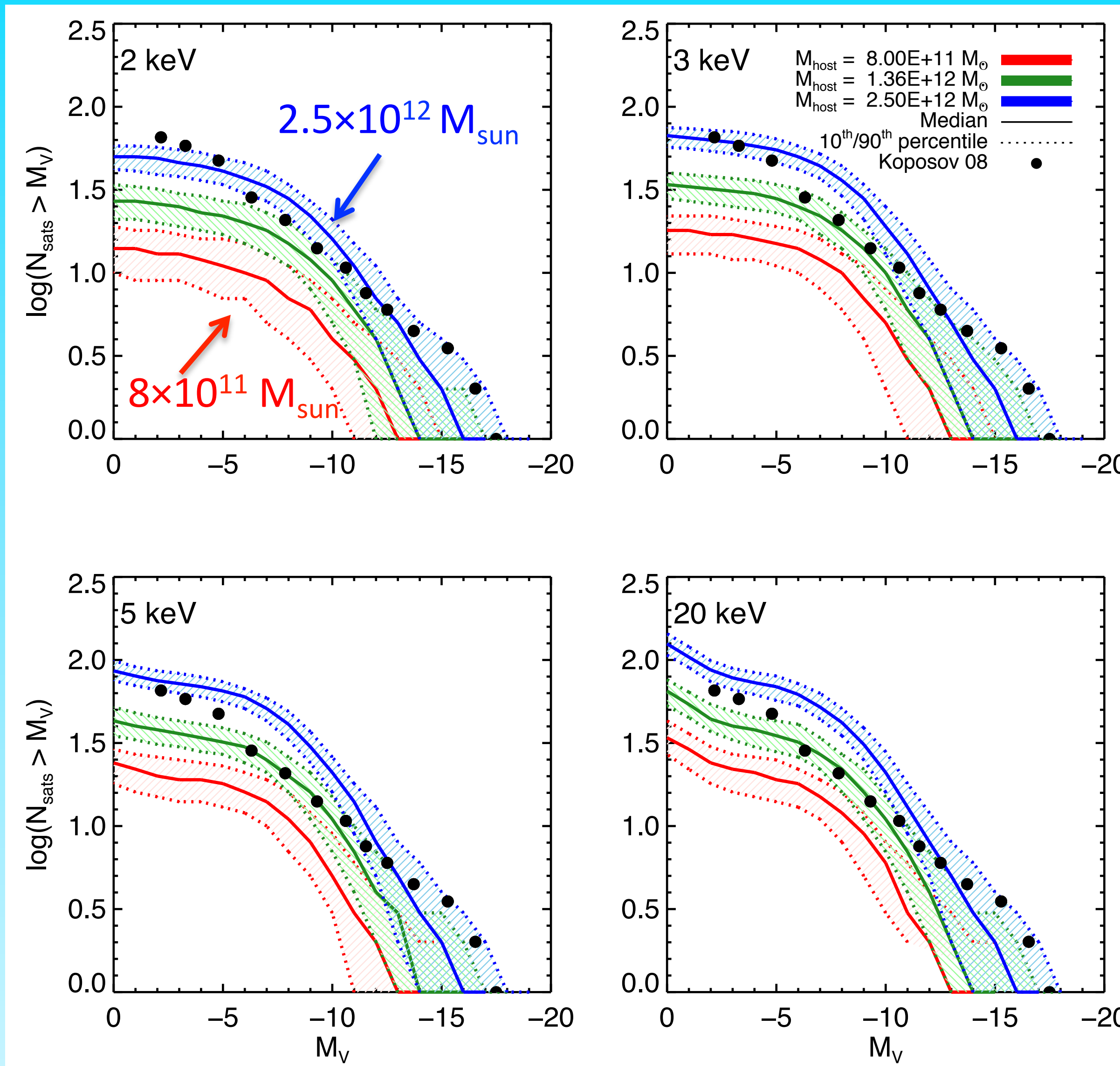


Kennedy, Cole & Frenk '13

Mon. Not. R. Astron. Soc. 283, L72–L78 (1996)

1996

Baryon effects

The cores of dwarf galaxy haloes

Julio F. Navarro,[1,2★] Vincent R. Eke[2] and Carlos S. Frenk[2]

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

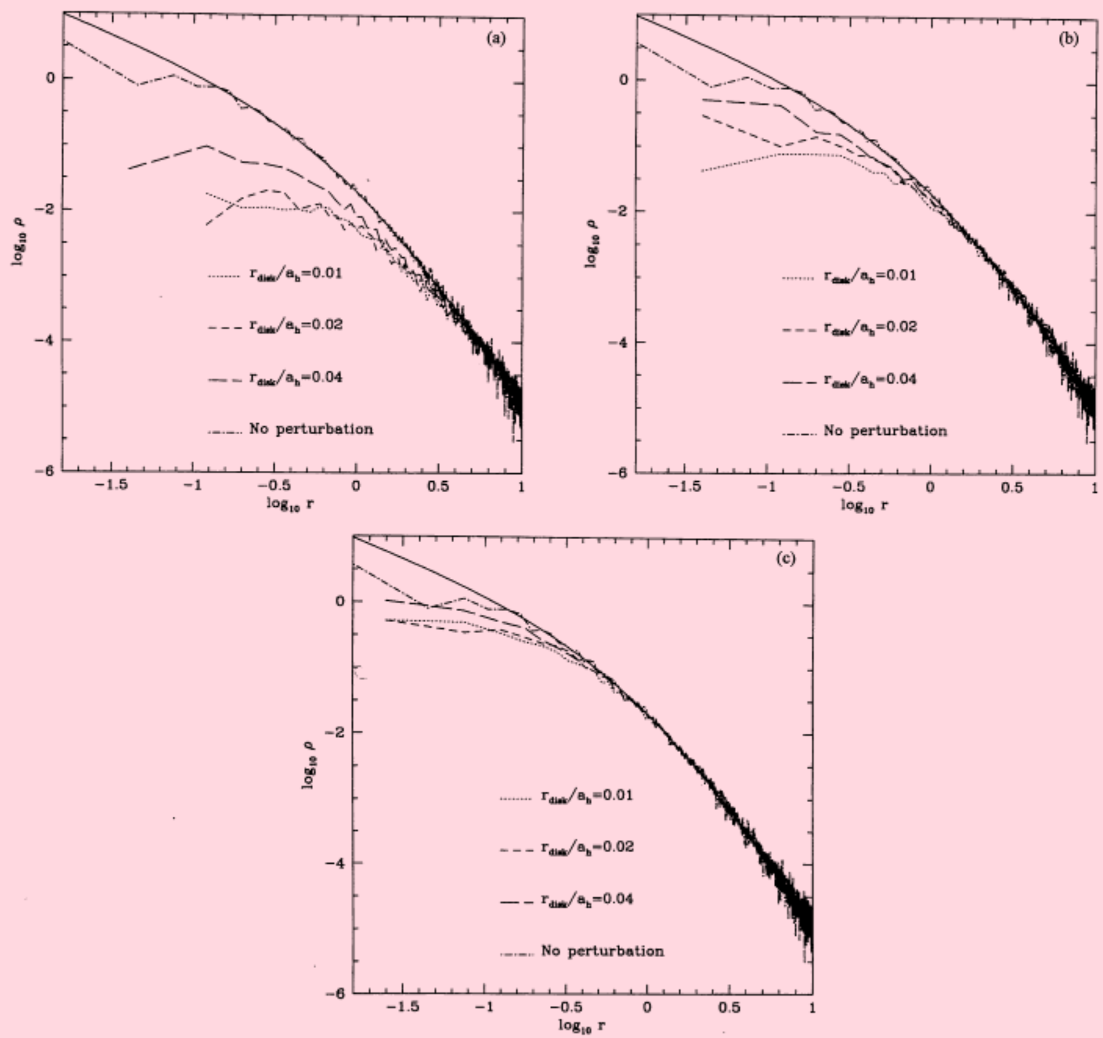
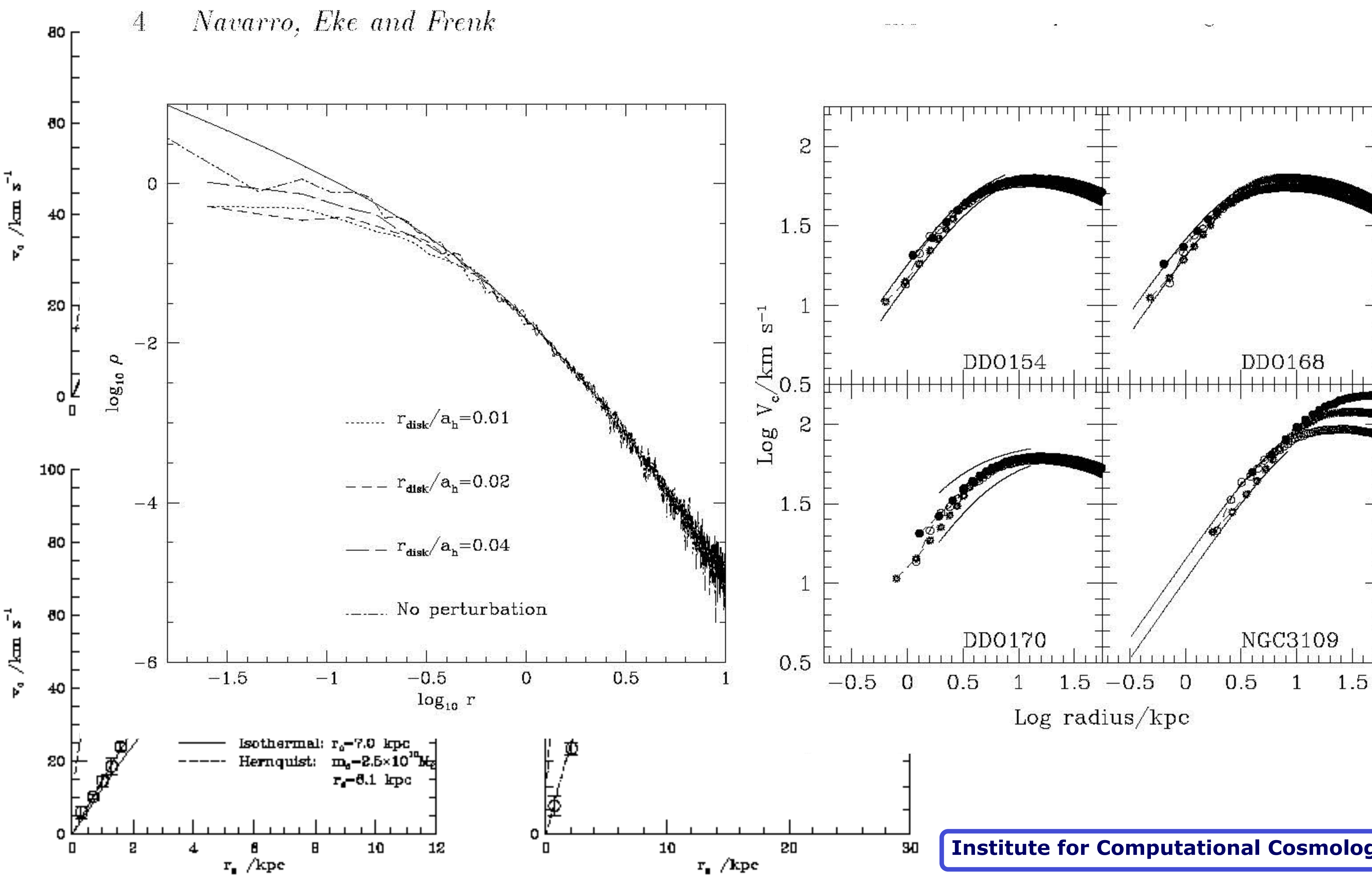


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a)

Cores in dwarf galaxies

University of Durham



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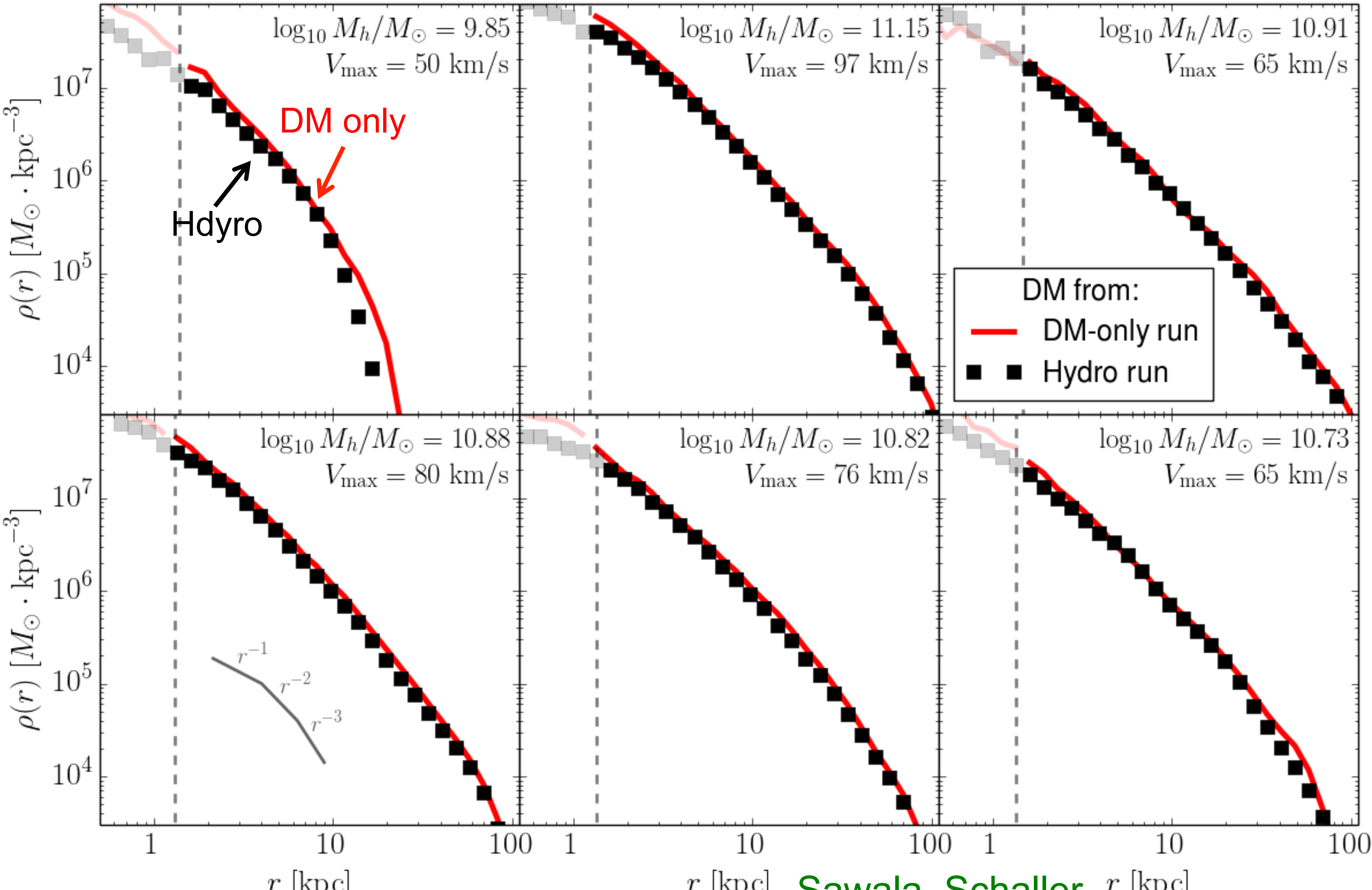
The effect of baryons on the DM halo



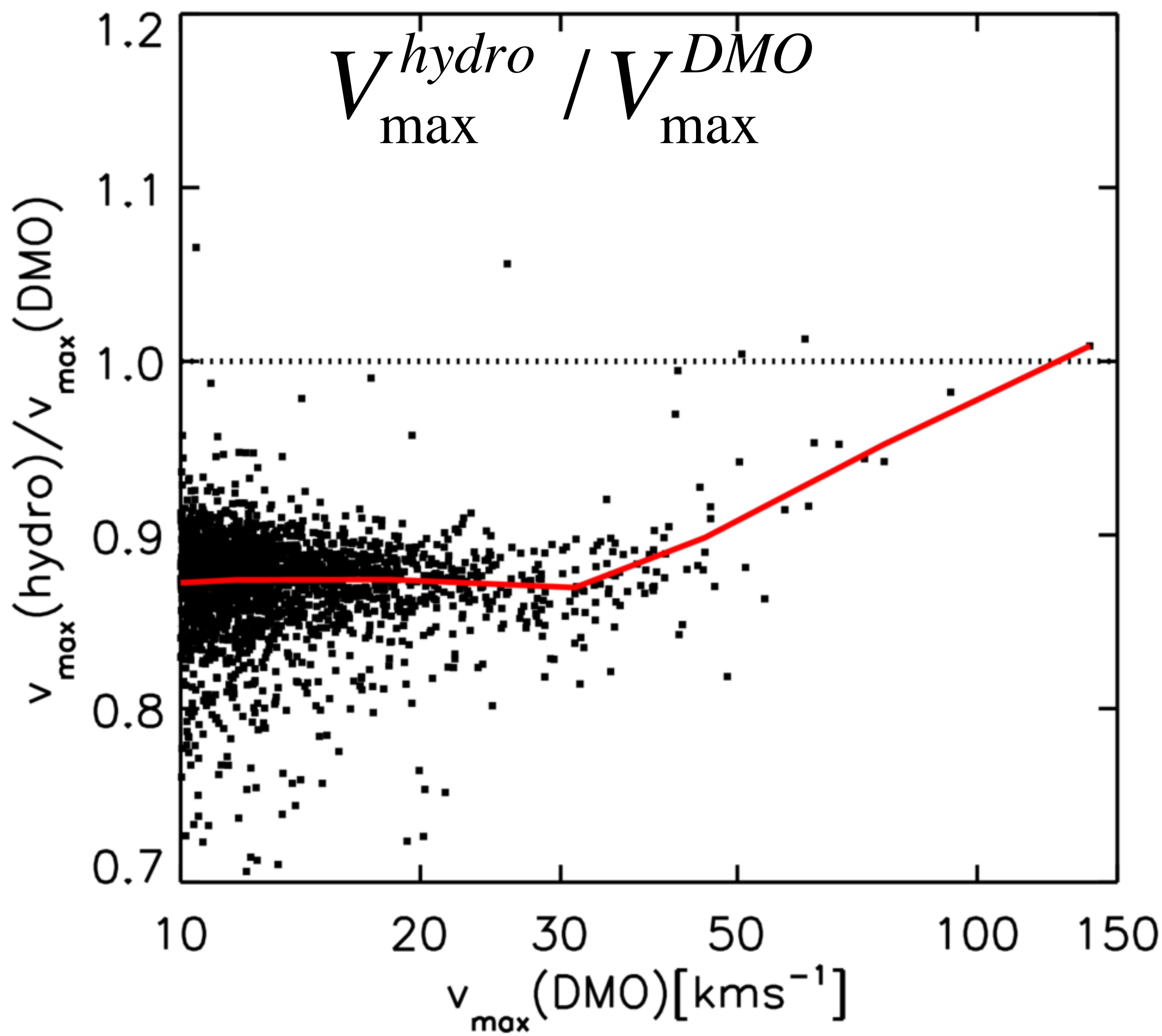
Sawala, Schaller

University of Durham

The MW halo mass: baryon effects

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate



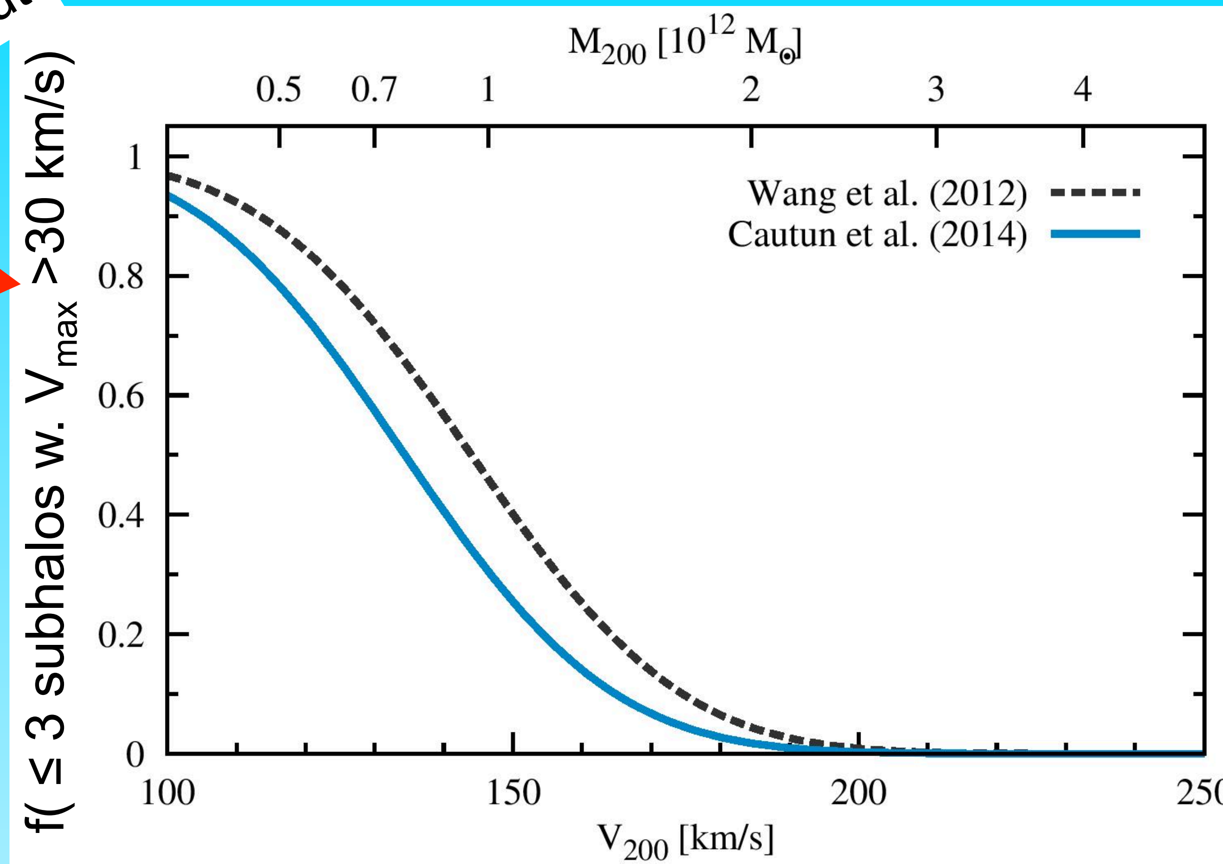
Sawala et al. '14

Probability of massive subhalos

University of Durham

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

1 – prob. that ΛCDM is ruled out



Wang, Frenk, Navarro, Gao '12

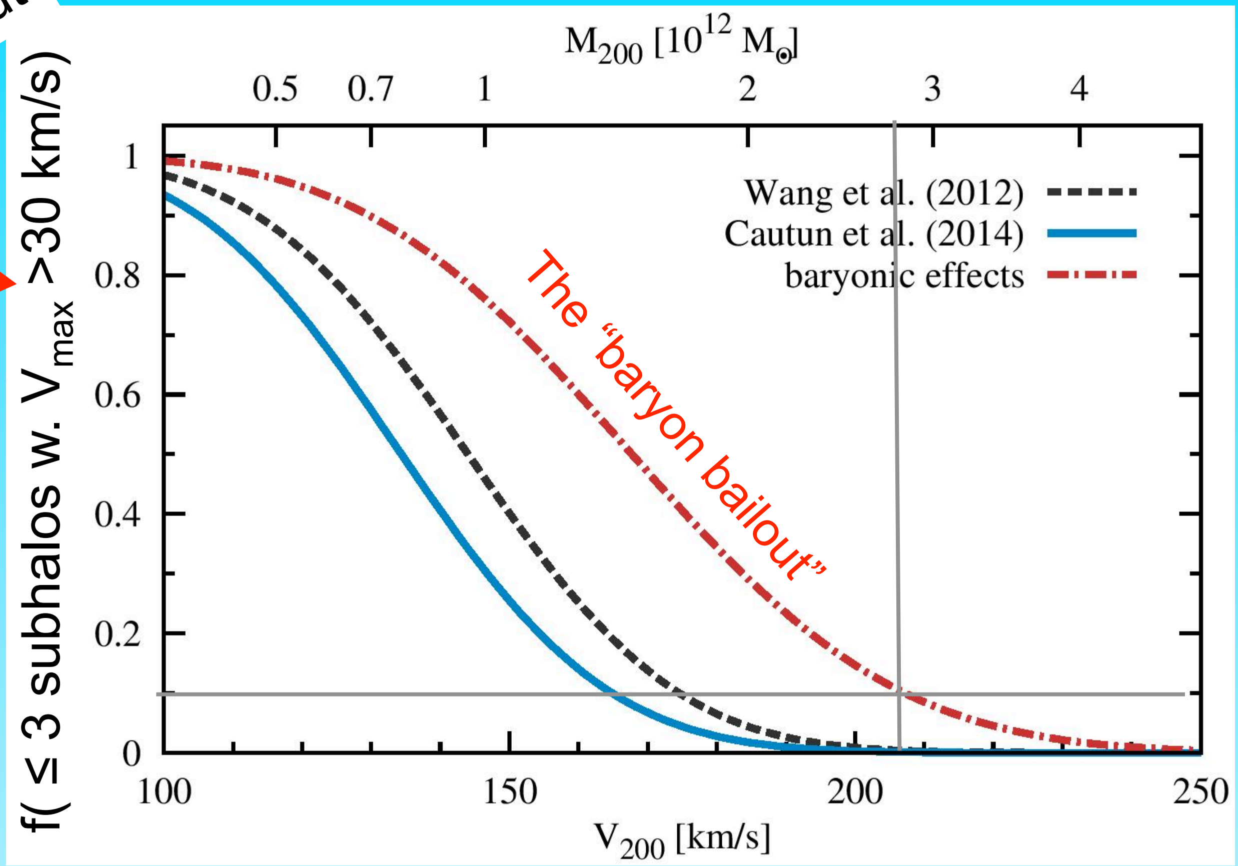
Cautun, Frenk, van den Weygaert, Hellwing '14

Probability of massive subhalos

University of Durham

Probability of having at [obscured] subha[obscured] with V[obscured] 30 km/s

1 – prob. that ΛCDM is ruled out



CDM requires

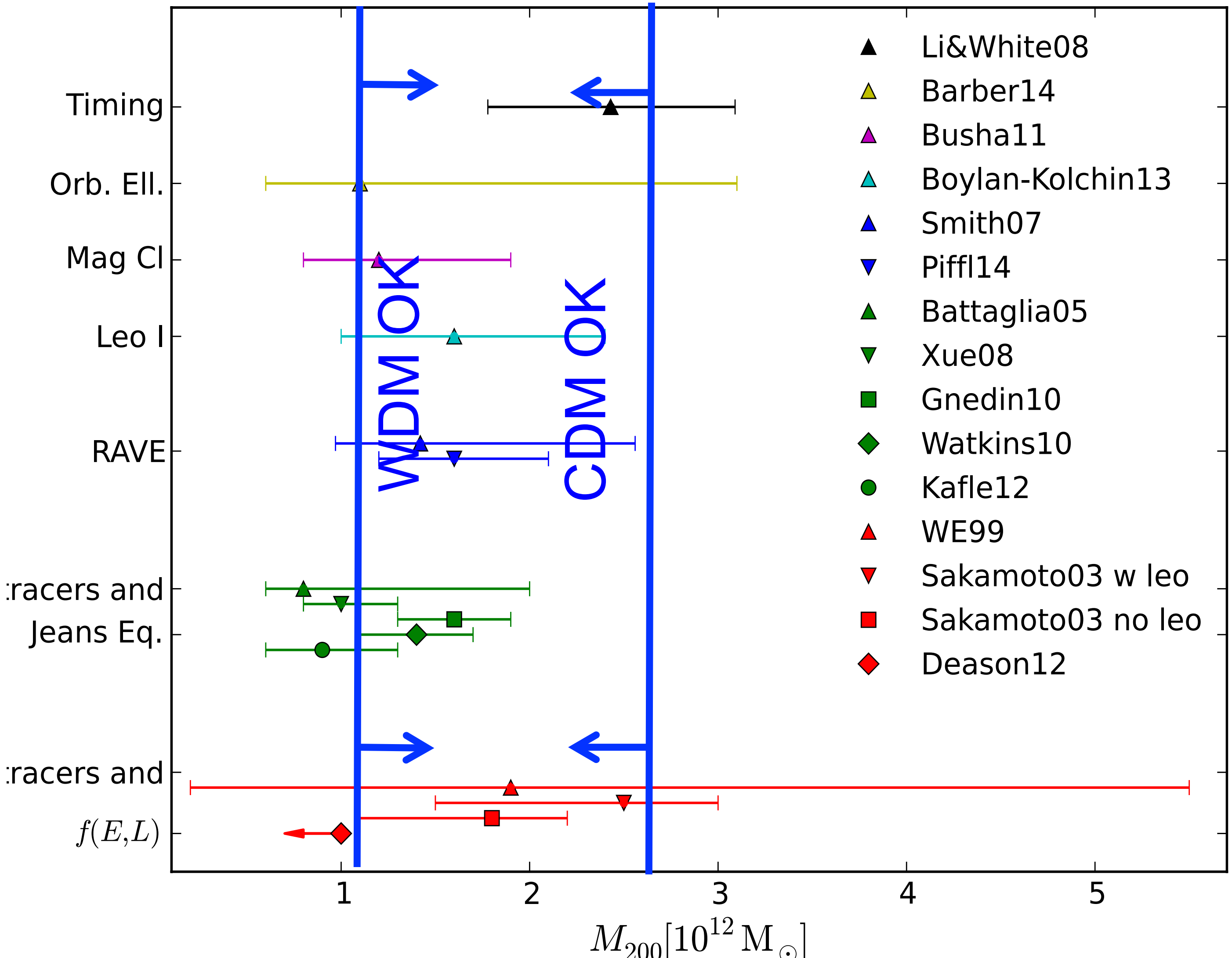
$M_{halo} < 2.6 \times 10^{12} M_o$

(90% confidence)

Wang, Frenk, Navarro, Gao '12

Cautun, Frenk, van den Weygaert, Hellwing '14

Estimates of the MW halo mass



Wenting Wang et al. ‘14

University of Durham

Conclusions

Dwarf galaxies may hold the clue to the identity of the dark matter

WDM:

- Sterile neutrino is an attractive candidate
- Phase space → no significant cores
- Satellite abundance requires $M_{MW\ halo} > 1.2 \times 10^{12}\ M_o$

CDM:

- Cusps in real sats consistent with kinematic data (even Sculptor)
- Core formation in simulations depend on detailed subgrid physics
- When gal formation taken into account NO "satellite problem"
- Baryon effects lower V_{max} → "too big to fail" avoided if $M_{MW\ halo} < 2.6 \times 10^{12}\ M_o$