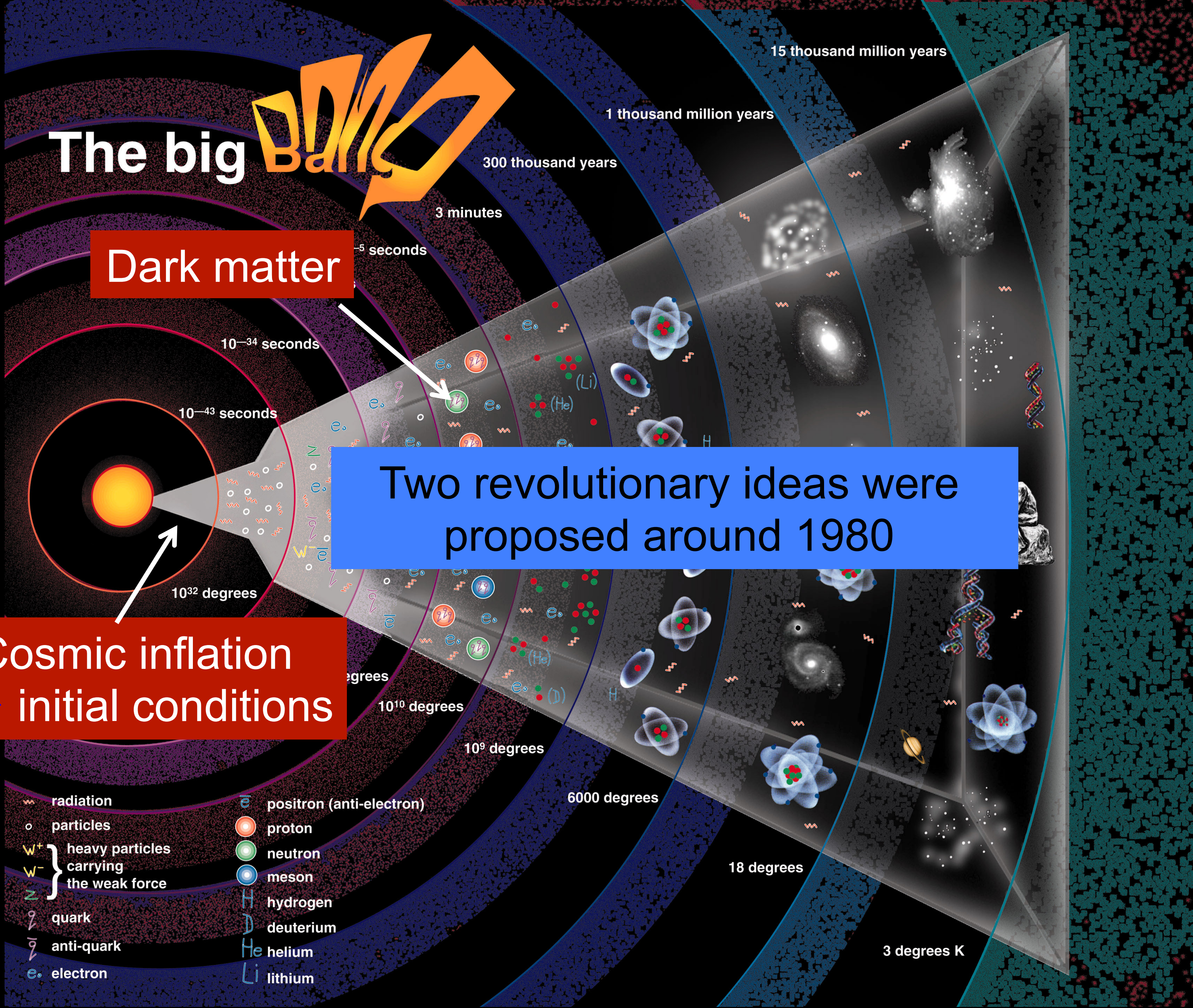
Cold dark matter *vs* warm dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham



Dark matter

Two revolutionary ideas were proposed around 1980

Cosmic inflation
→ initial conditions

University of Durham

Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm	sterile ν majoron; KeVin	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

University of Durham

The dark matter power spectrum

Free streaming →

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

for thermal relic

$m_{CDM} \sim 100GeV$

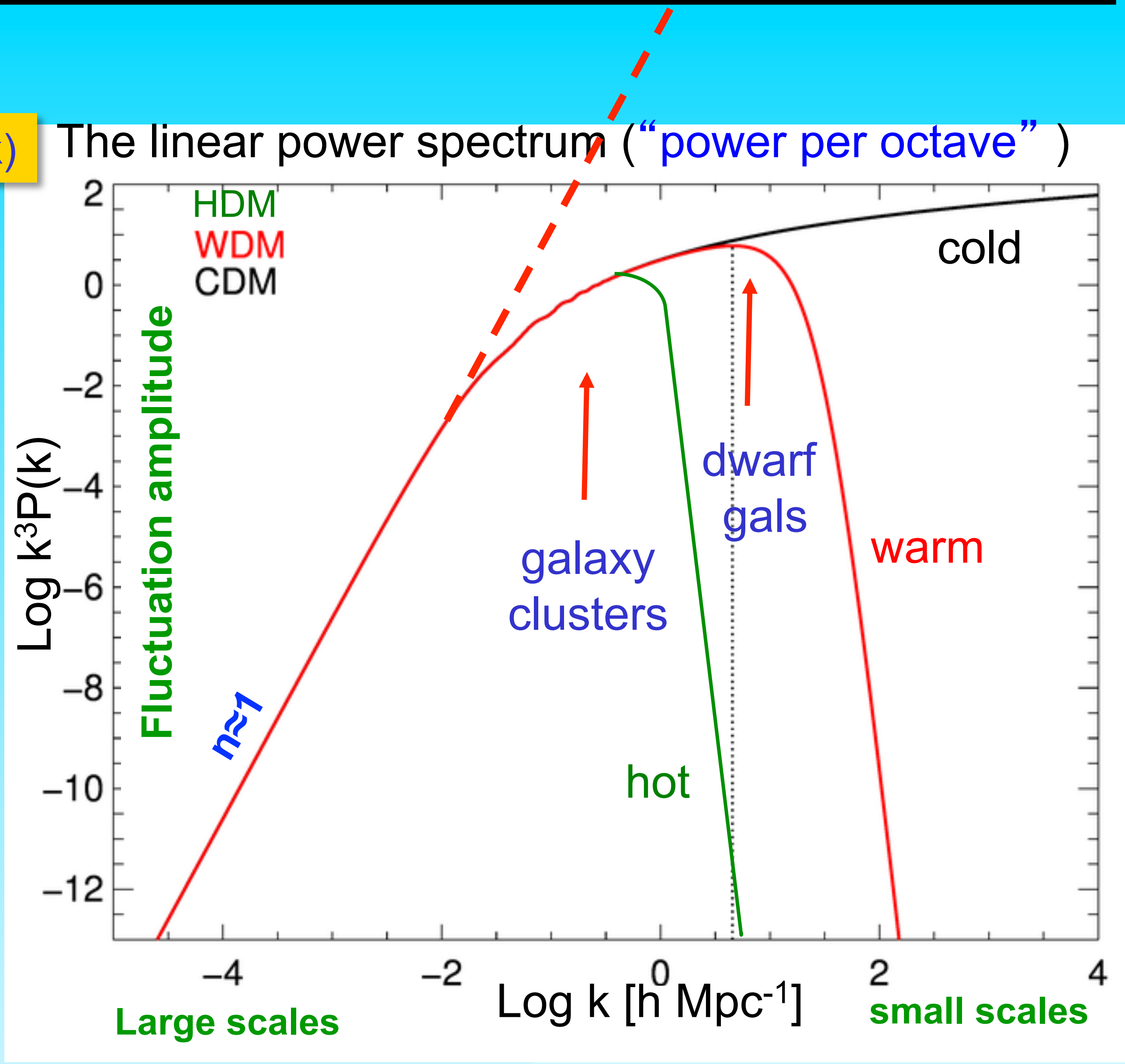
susy; $M_{cut} \sim 10^{-6} M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$

$m_{HDM} \sim$ few tens eV

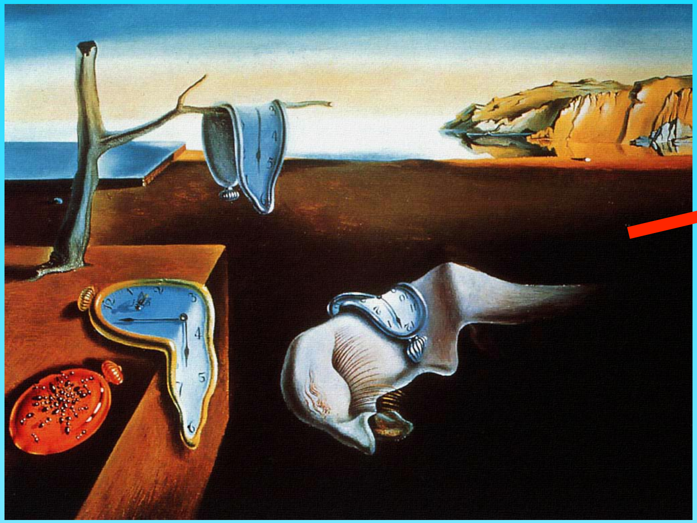
light ν; $M_{cut} \sim 10^{15} M_o$

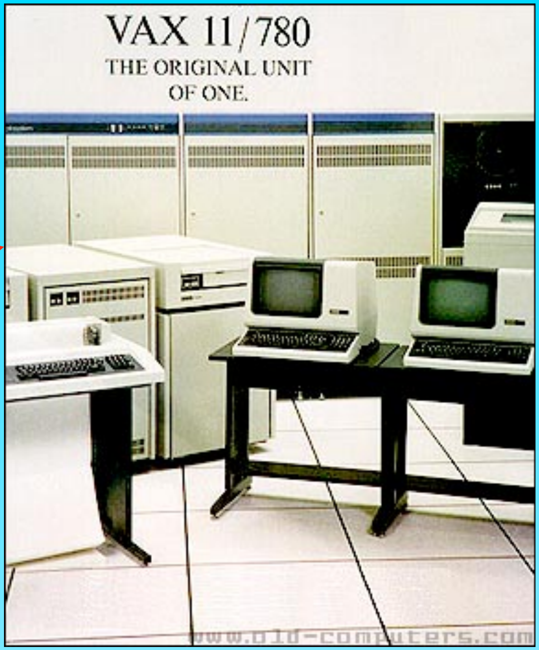


The formation of cosmic structure

University of Durham

$t=10^{-35}$ seconds





t=380,000 yrs

$\delta\rho/\rho \sim 10^{-5}$

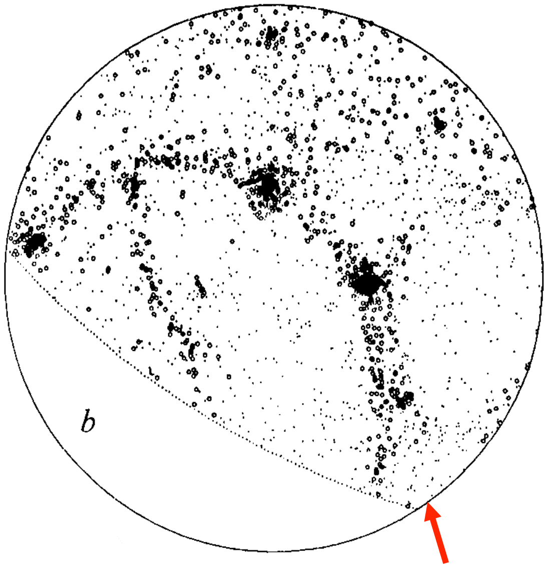
Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

t=13.8 billion yrs

$\delta\rho/\rho \sim 1-10^{6}$

University of Durham

Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis ‘83

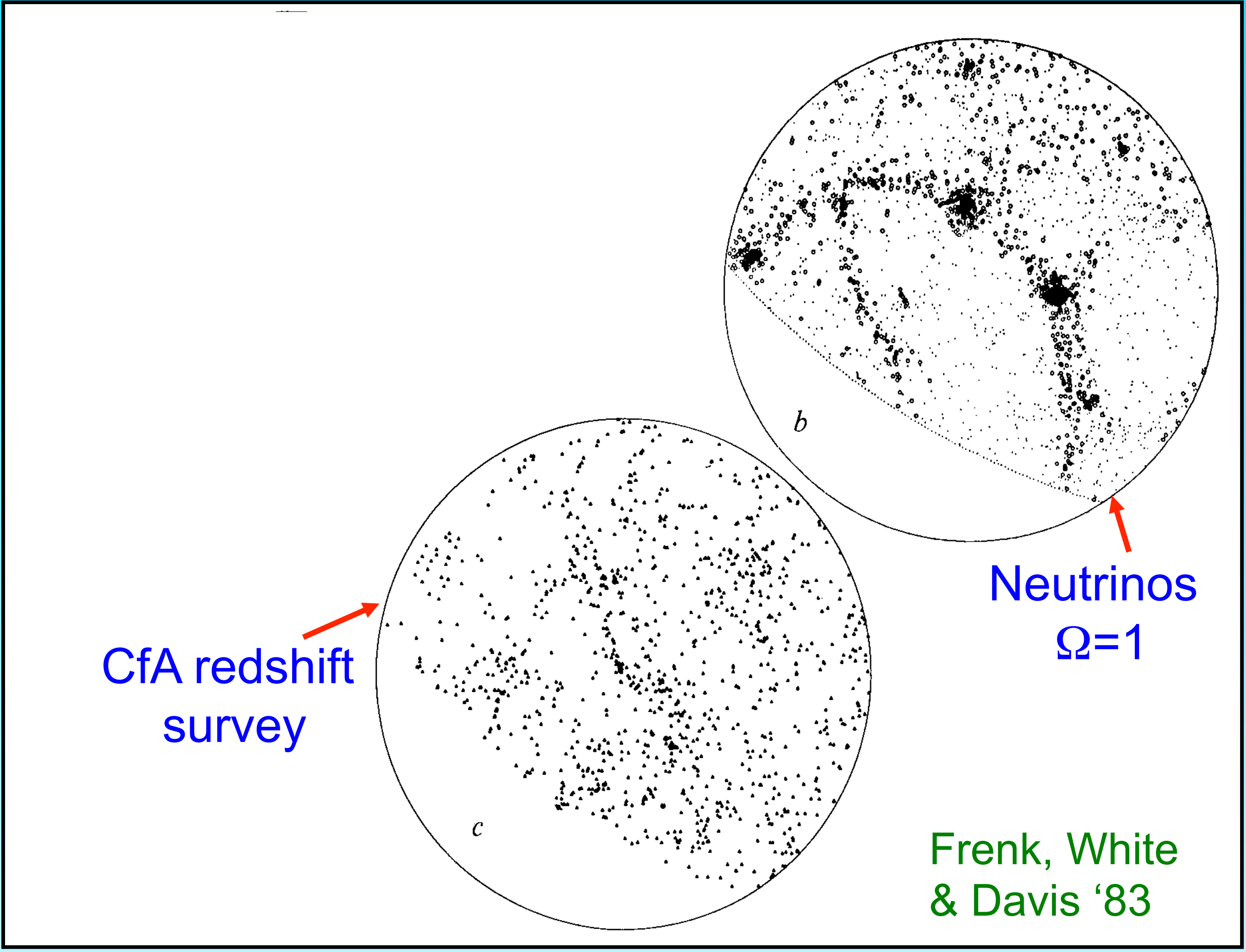
Non-baryonic dark matter cosmologies

University of Durham

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν << 30 ev



University of Durham

Non-baryonic dark matter cosmologies

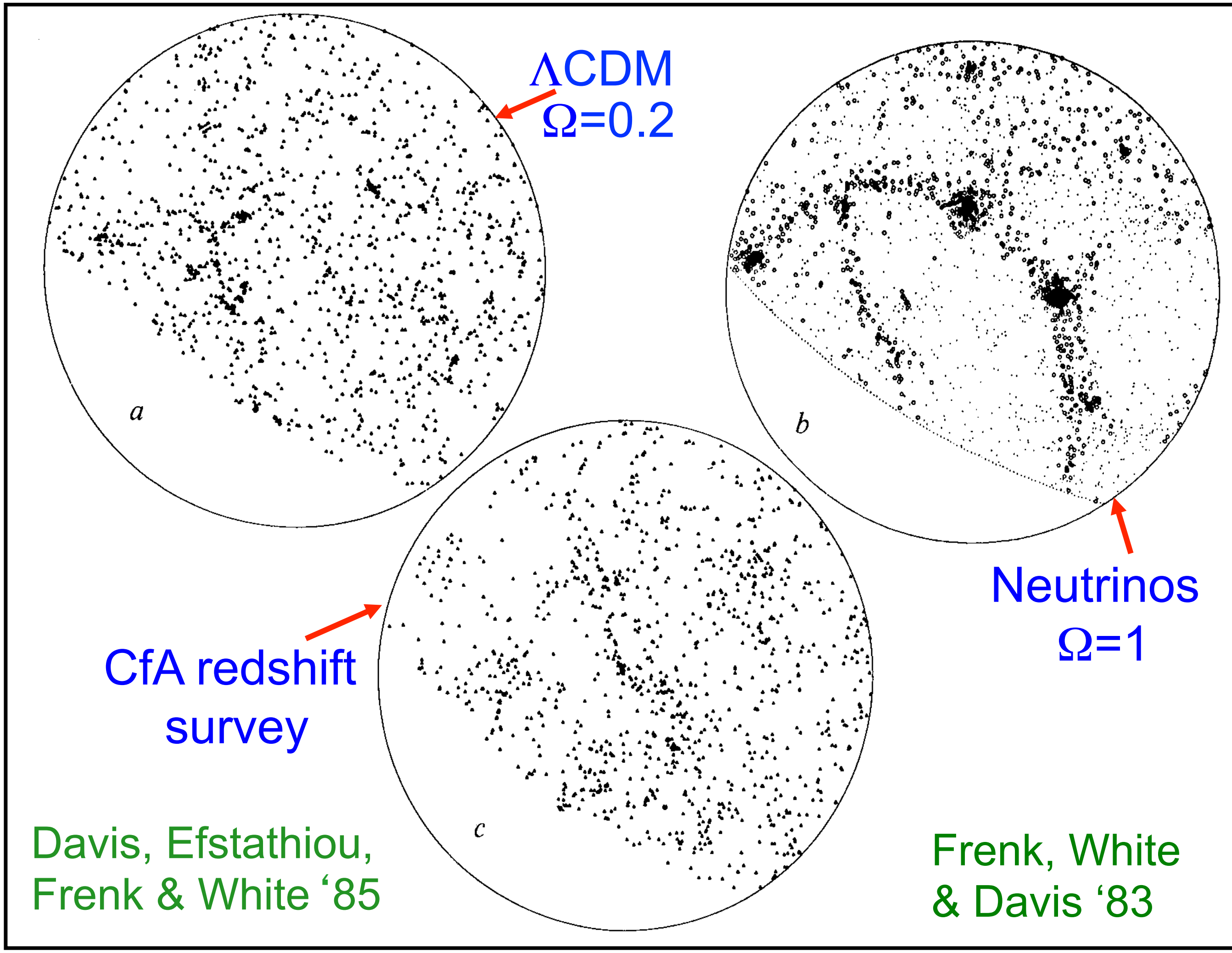
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



University of Durham

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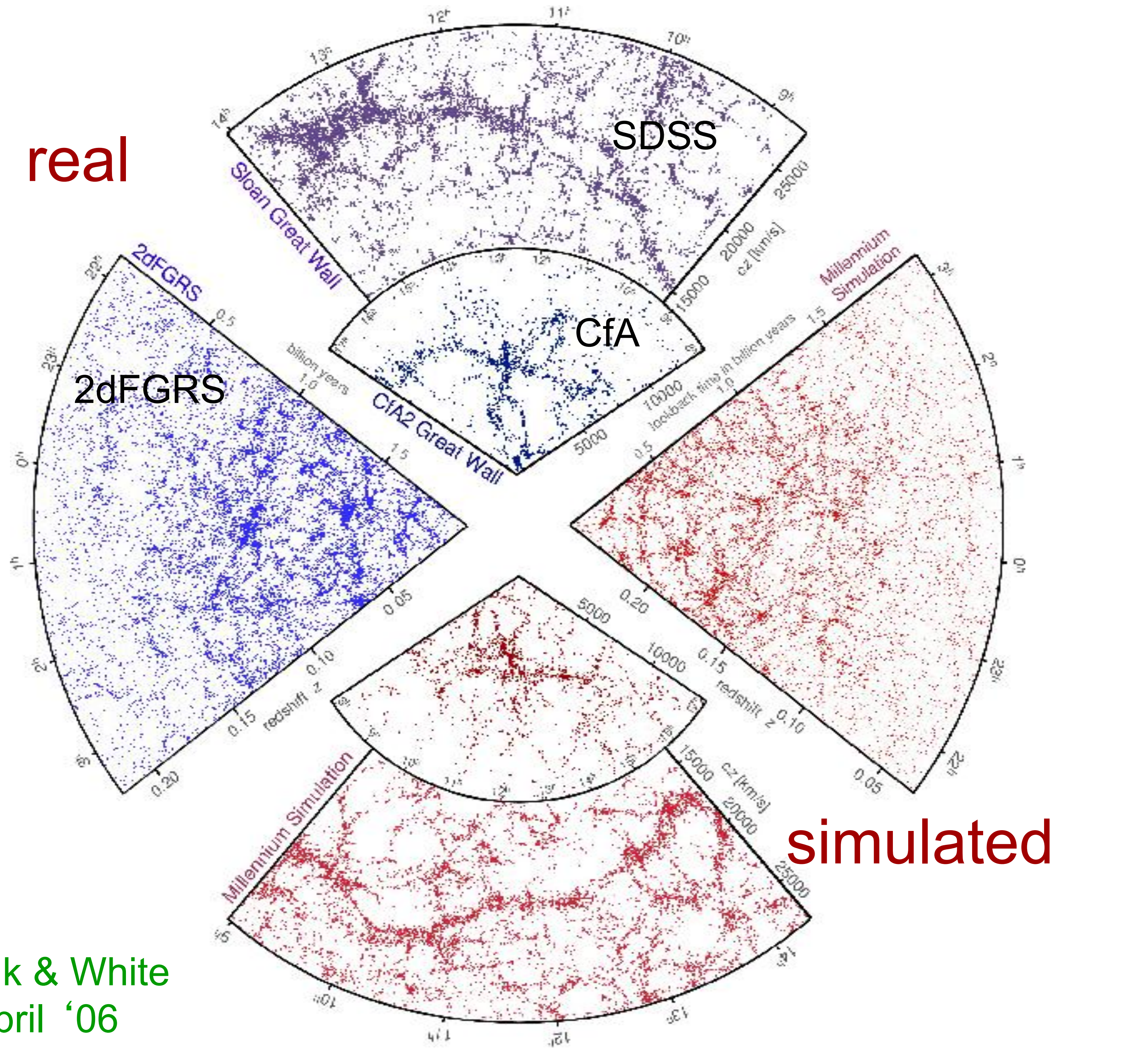
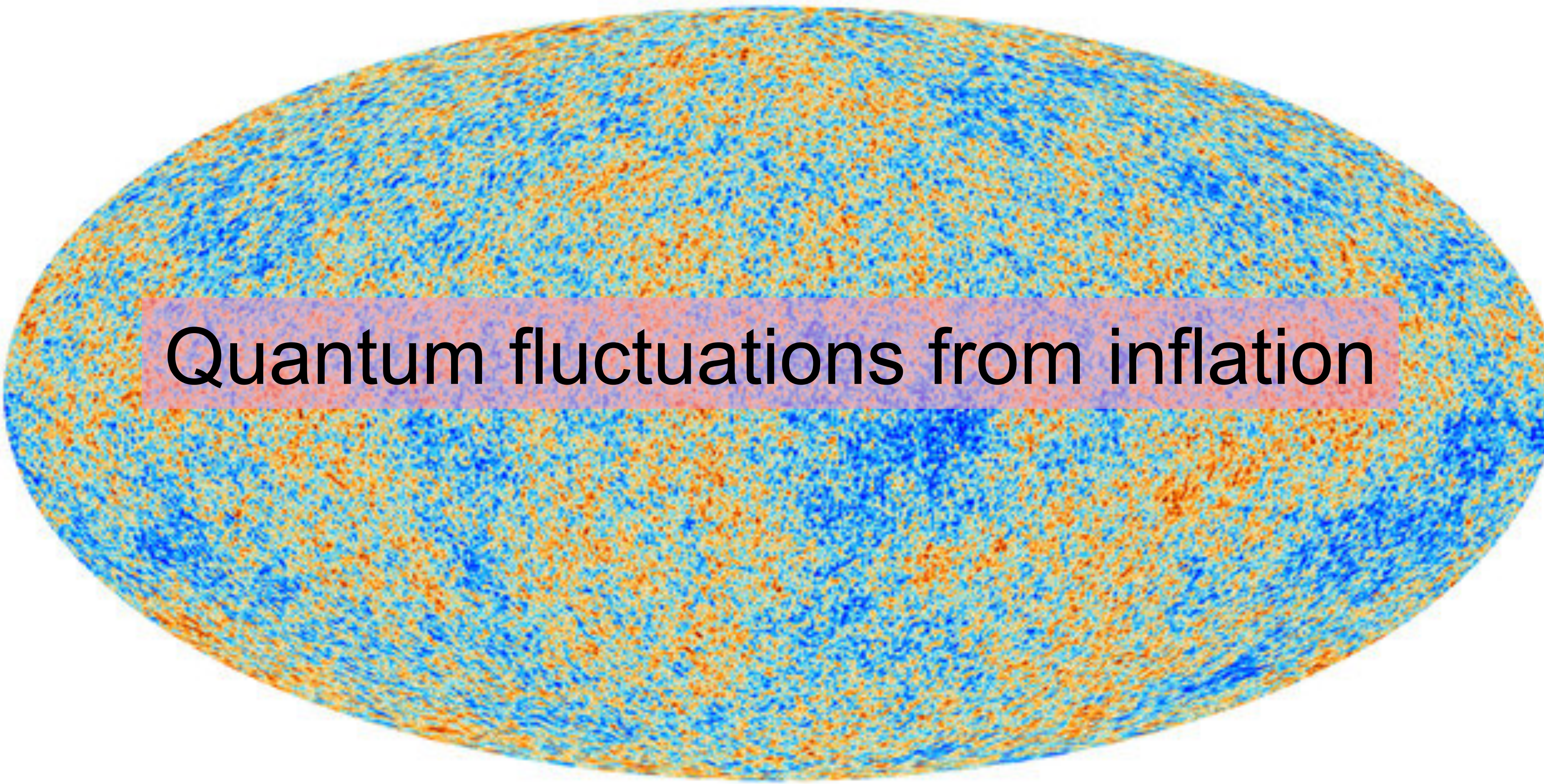
Institute for Computational Cosmology



Springel, Frenk & White
Nature, April ‘06

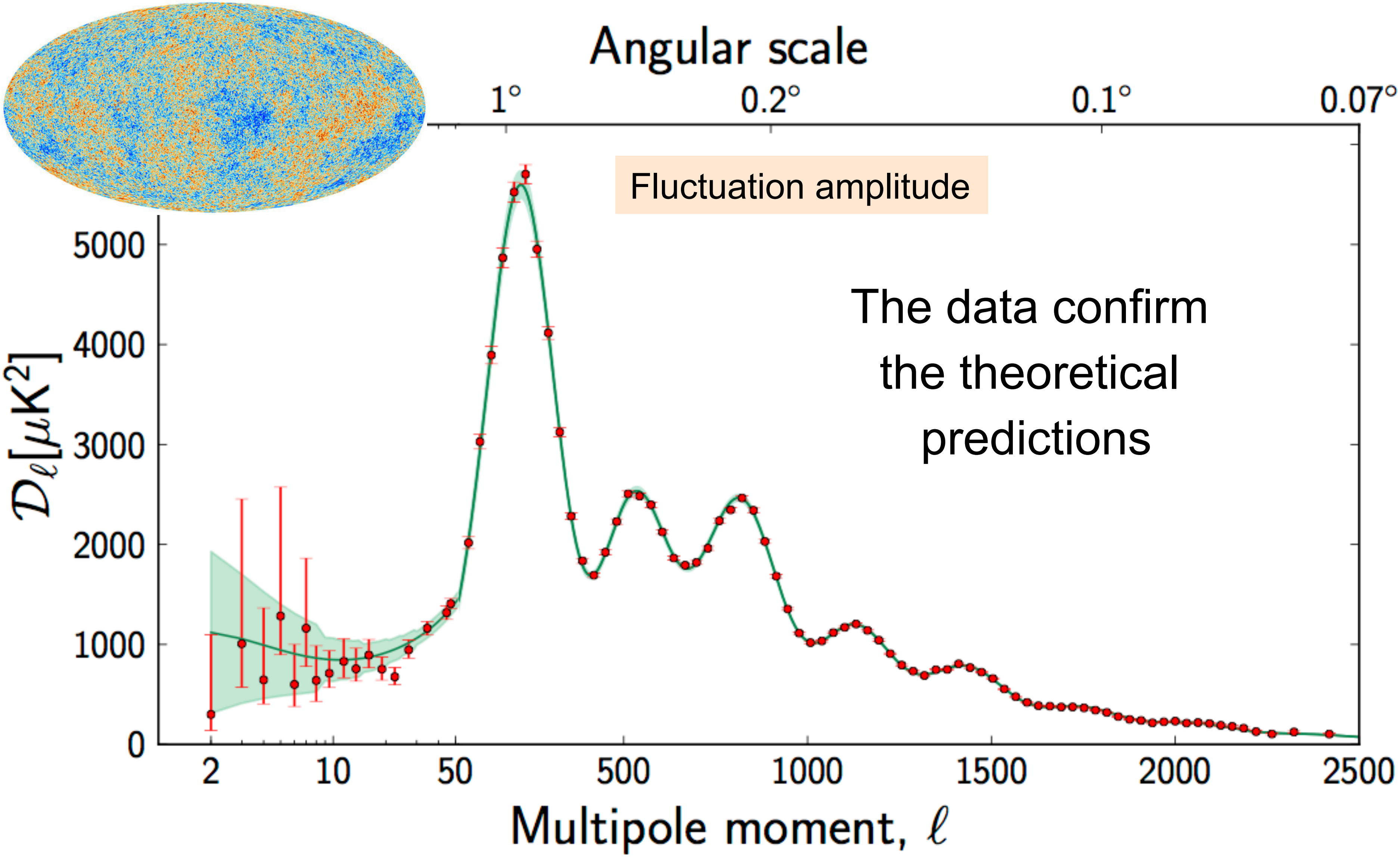
University of Durham

The initial conditions for galaxy formation



Planck: CMB temperature anisotropies

University of Durham



Planck coll. 2015

Univer

The six parameters of minimal ΛCDM model

6 mdoel parameters

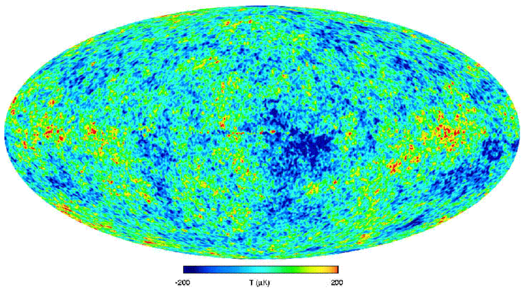
Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

A 40σ detection of non-baryonic dark matter using only z=1000 data!

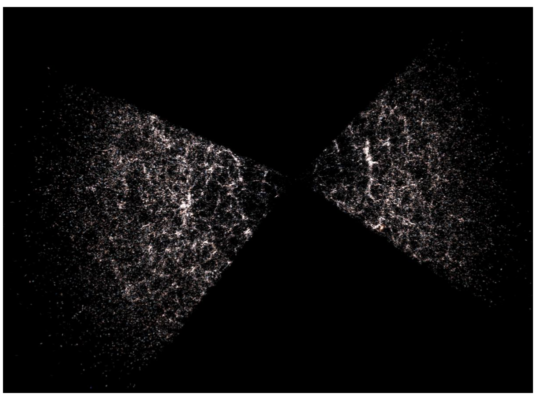
Planck collaboration '13

University of Durham

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

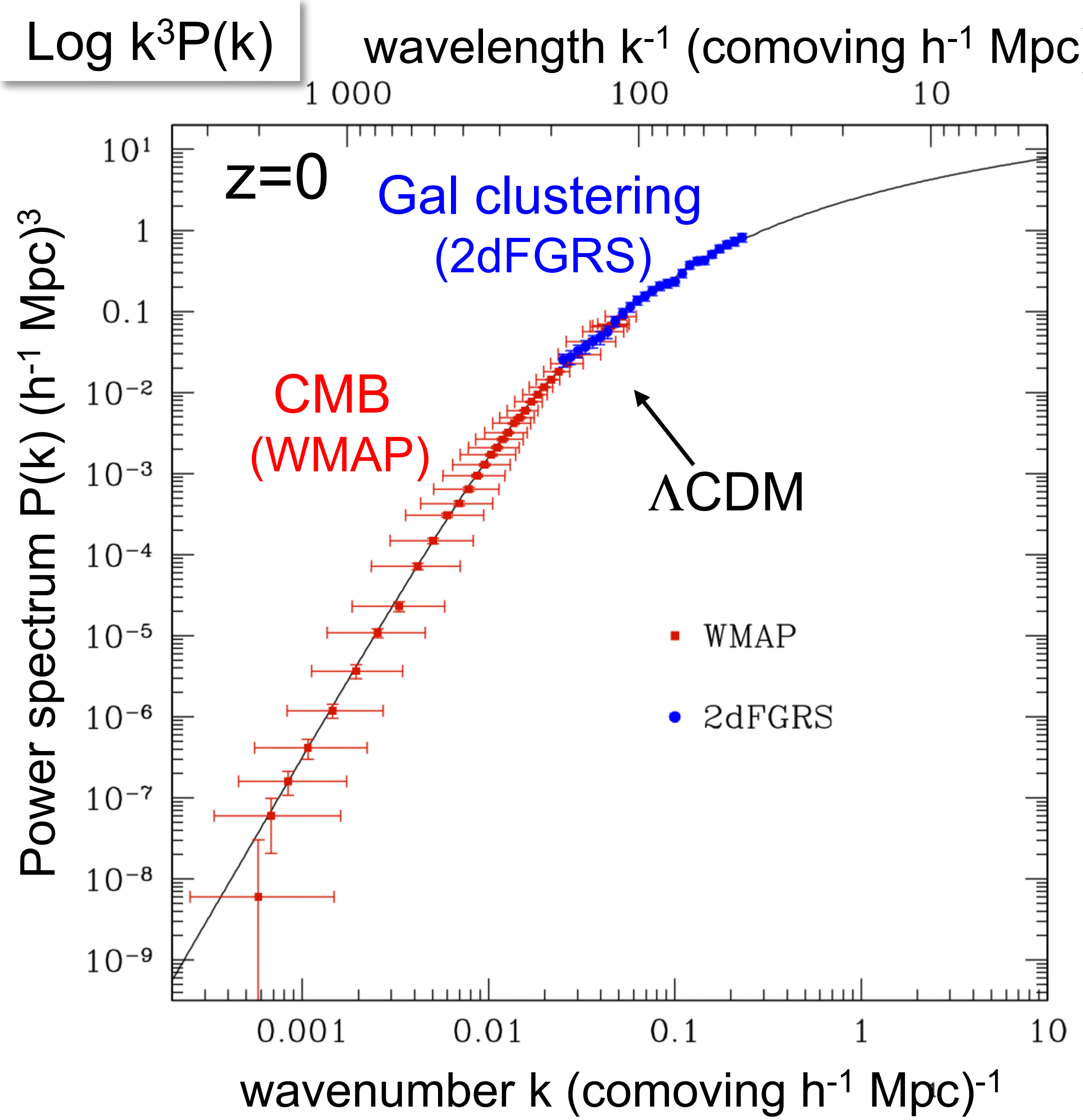


z~1000



z~0

Log $k^3P(k)$



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

Sanchez et al 06

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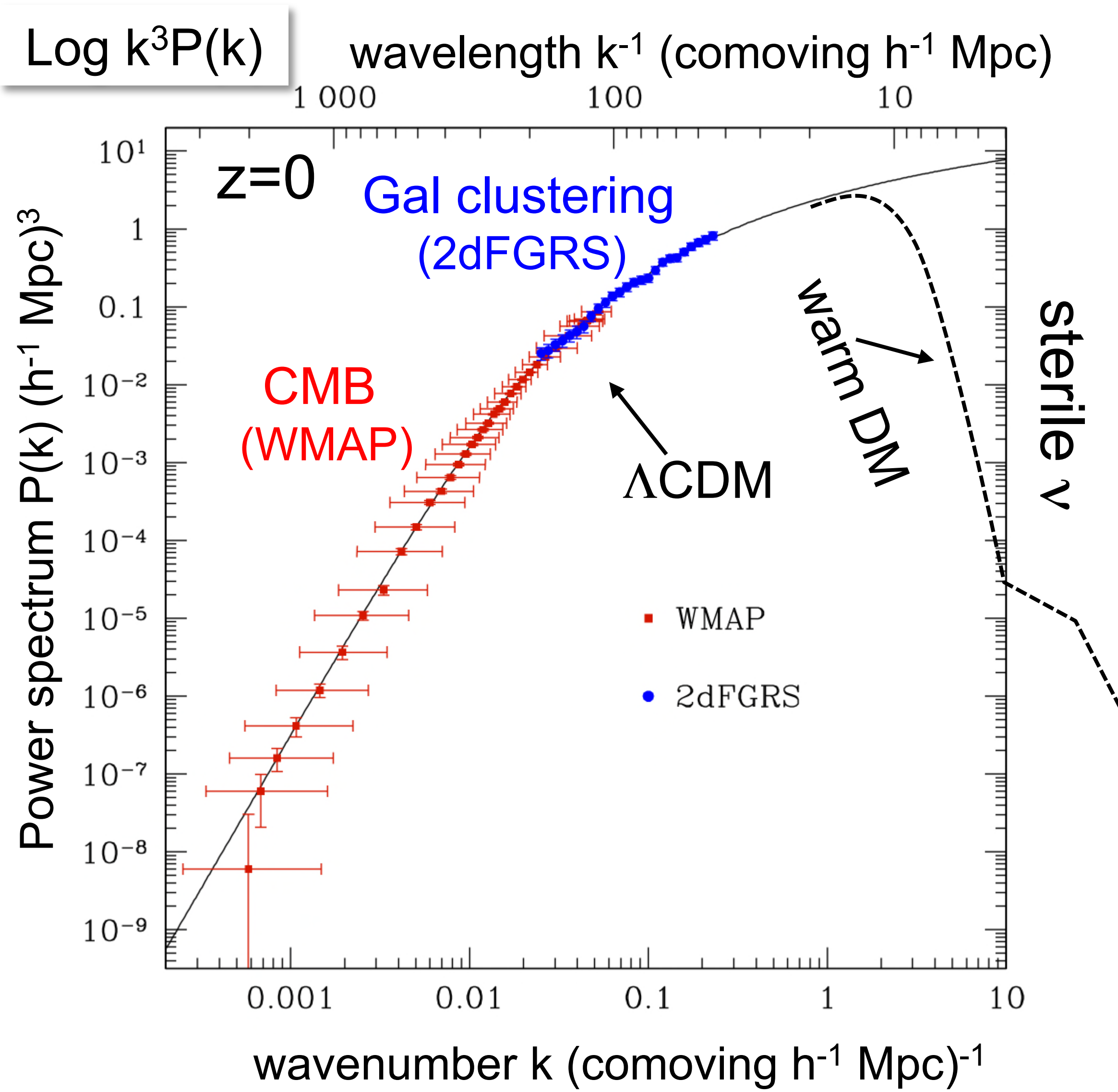


University of Durham

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

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

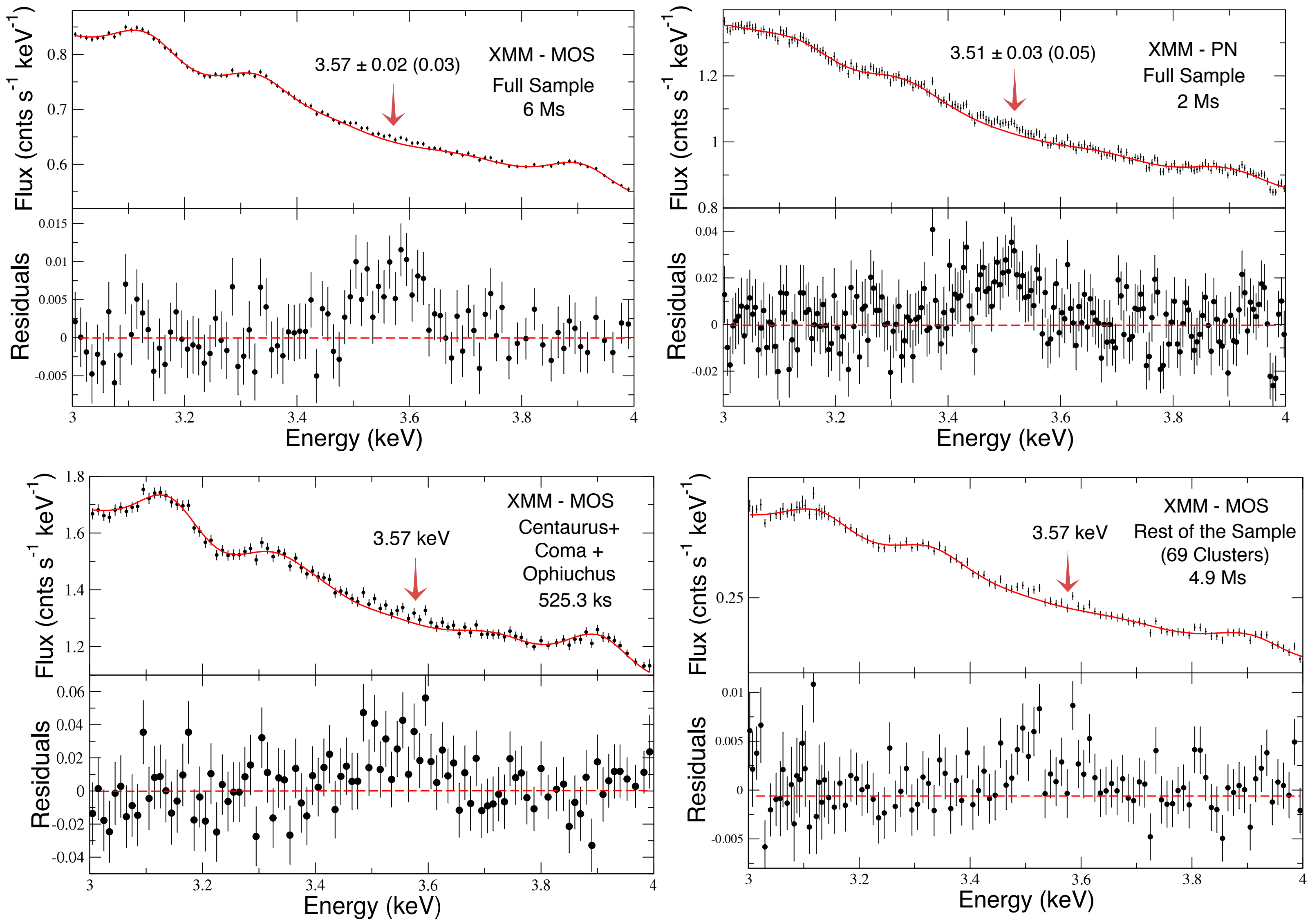
We detect a wea
spectrum of 73 g
independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra 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

WDM decay line in 69 stacked clusters?

University of Durham

E=3.57 keV

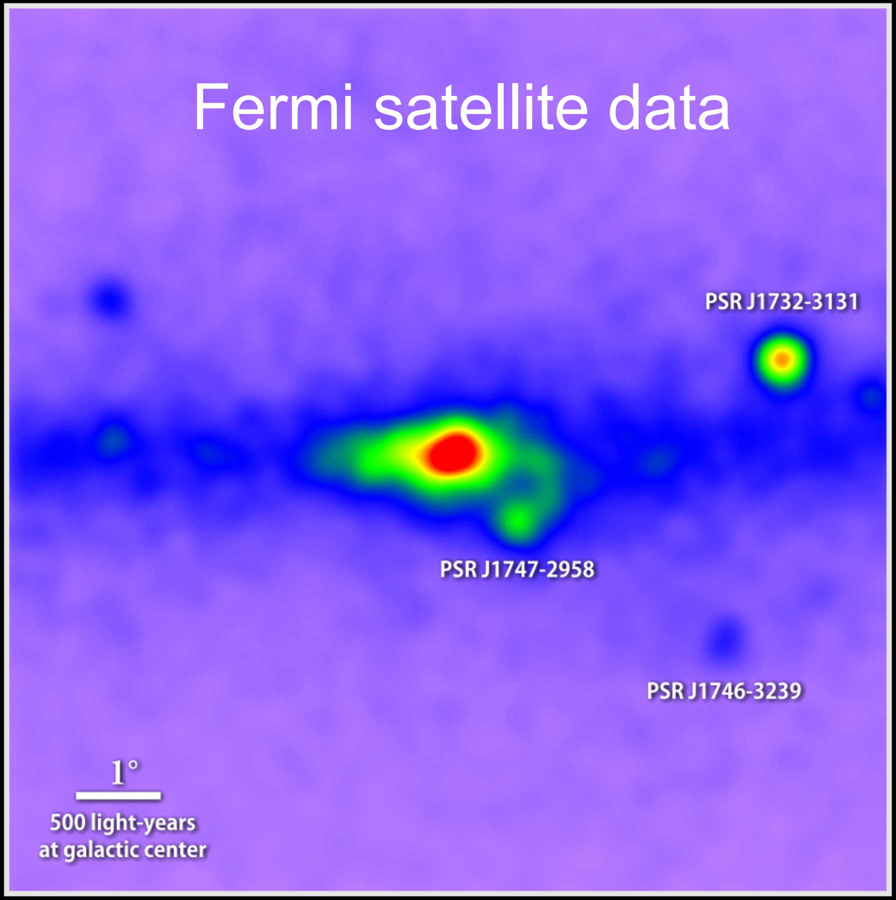
Bulbul et al. '14



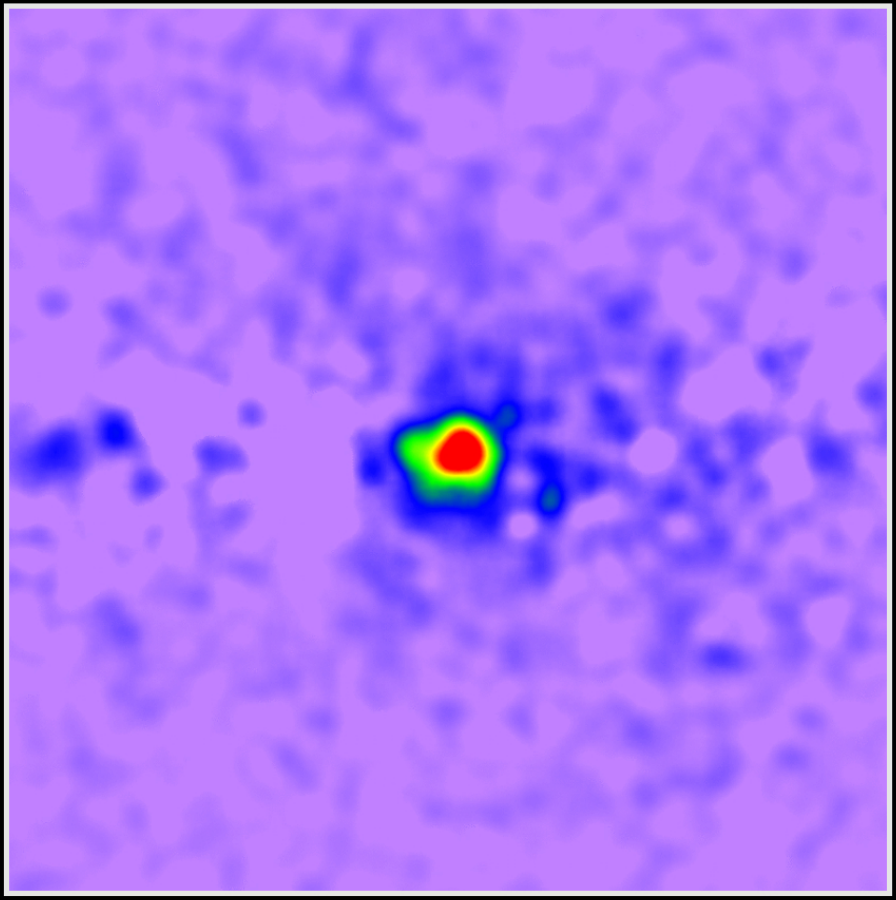
The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

Uncovering a gamma-ray excess at the galactic center

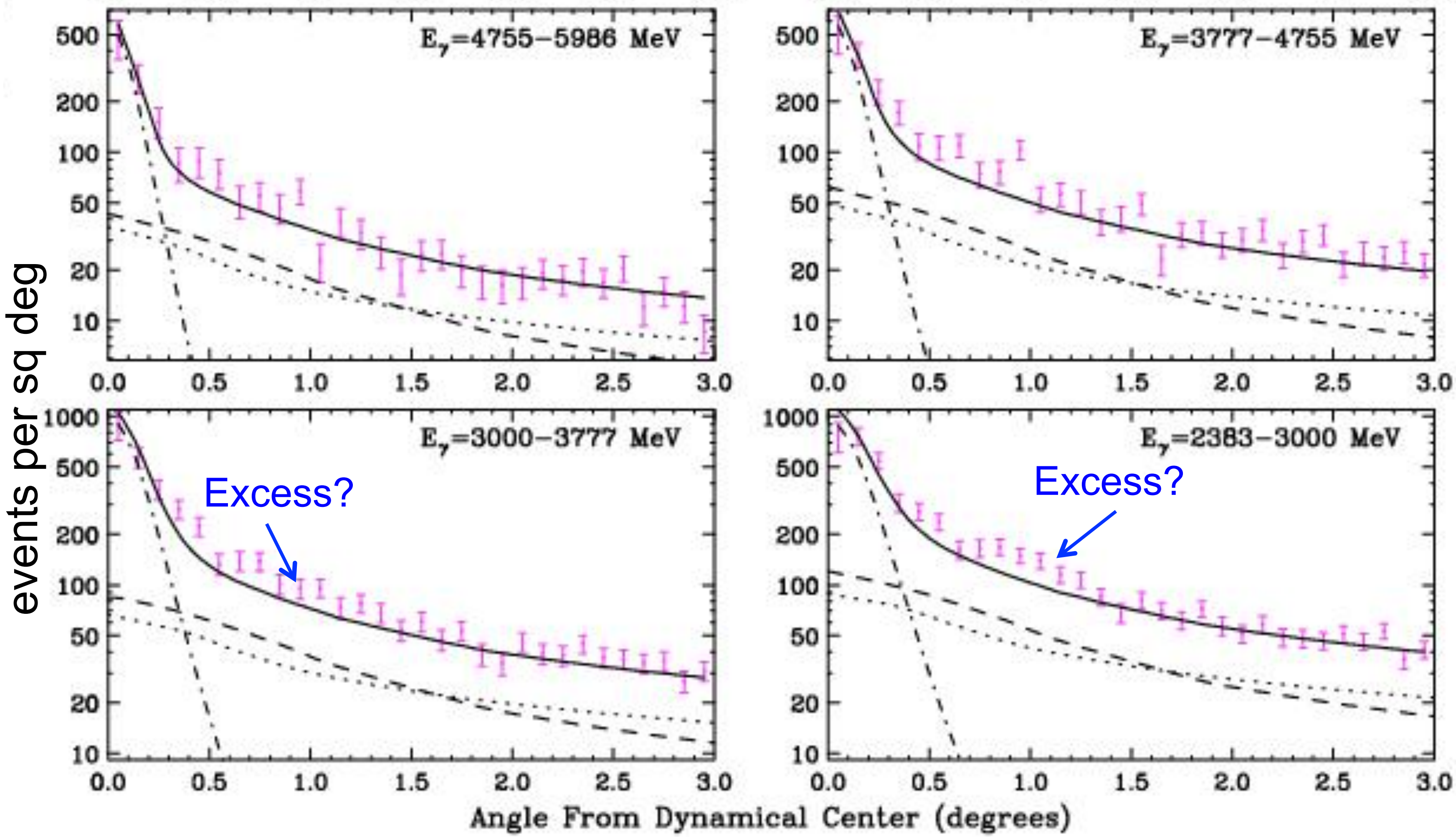


Unprocessed map of 1.0 to 3.16 GeV gamma rays



Known sources removed

Annihilation radiation from the Galactic Centre?



Hooper & Goodenough '11

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

Free streaming →

λ_{cut} α m_x^{-1}

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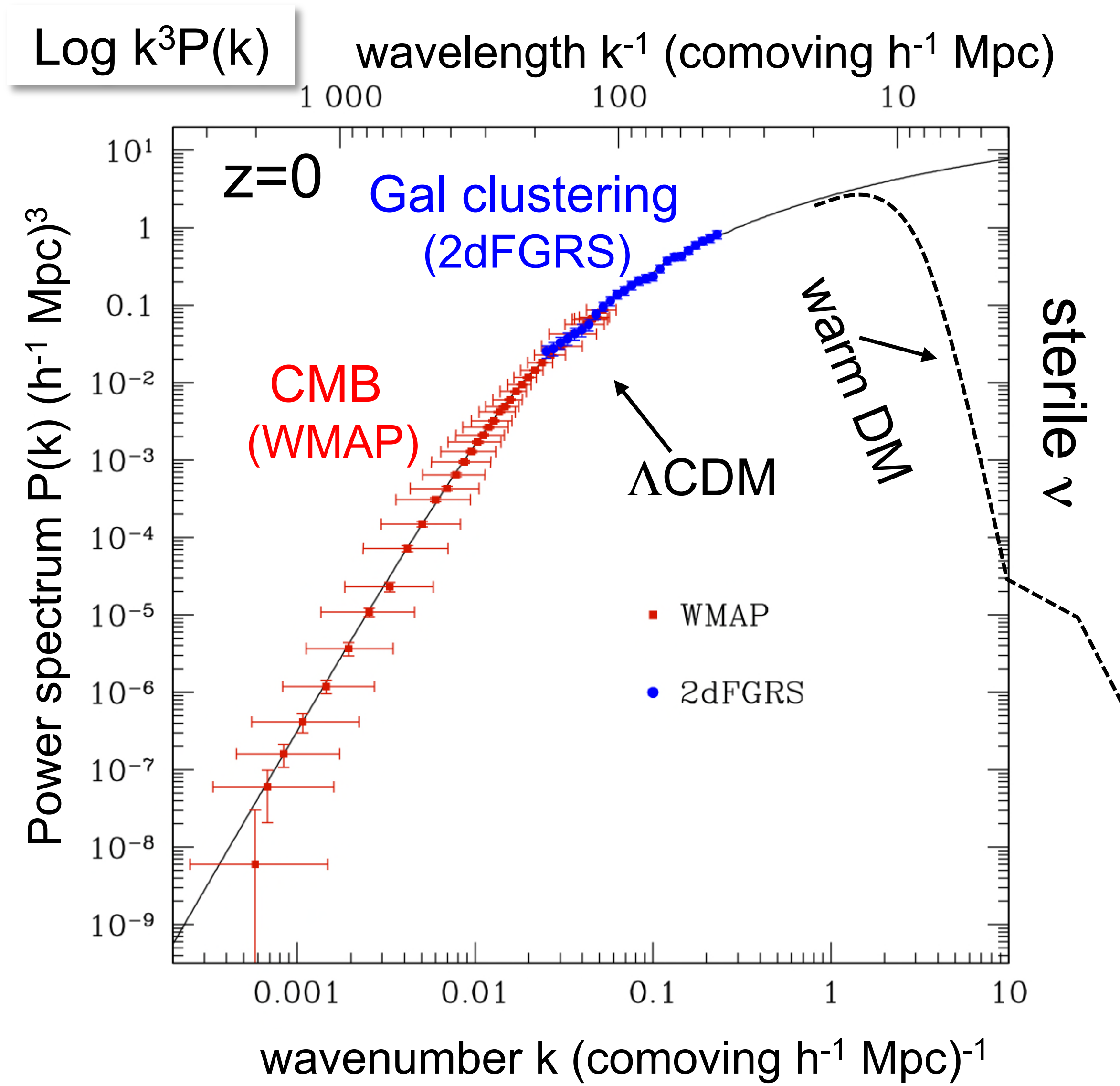
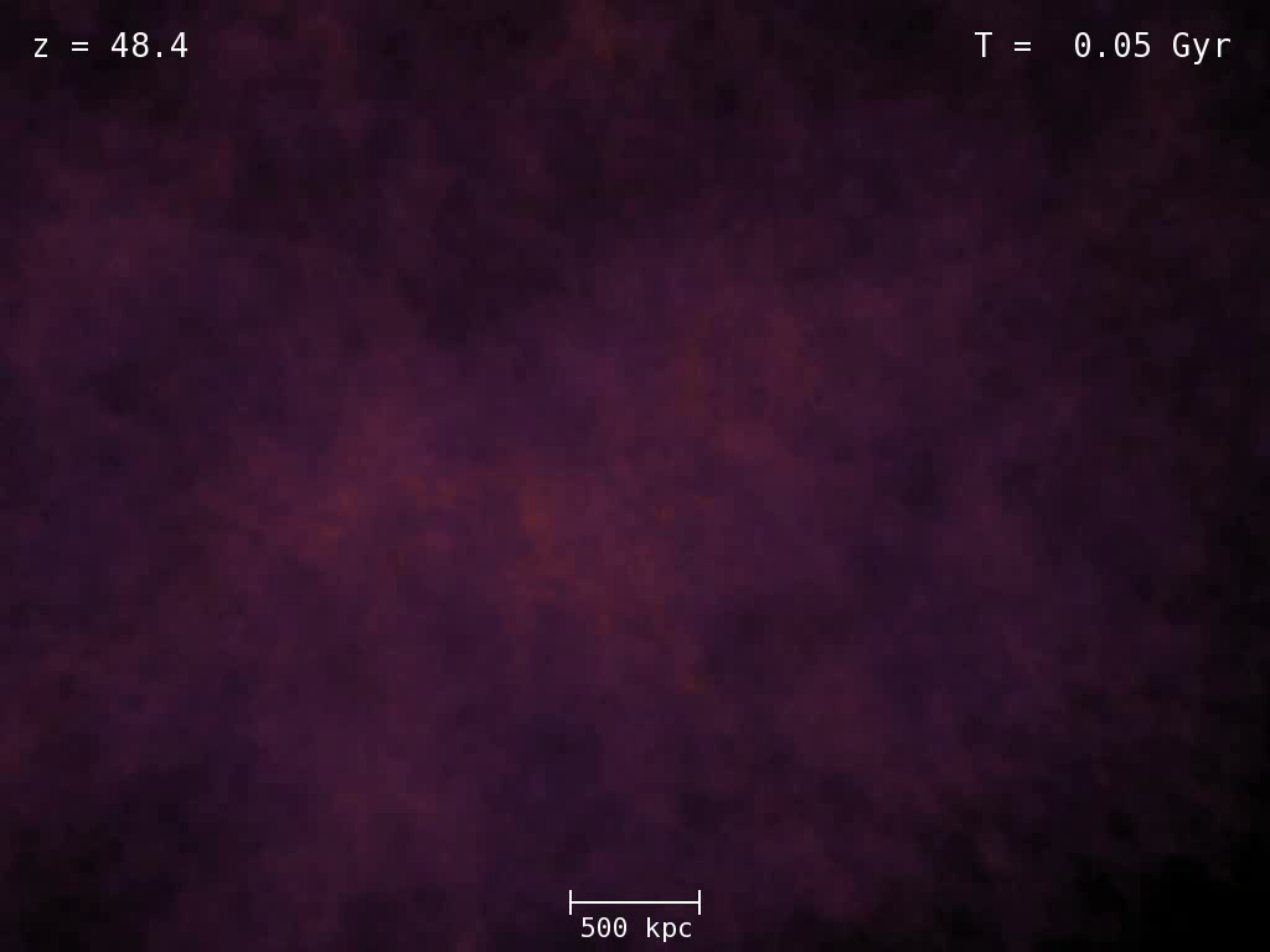


Astrophysical key to identity of dark matter:

→Subgalactic scales

(strongly non-linear)


z = 48.4
T = 0.05 Gyr
500 kpc

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

Four problems on small scales

Traditionally ascribed to CDM:

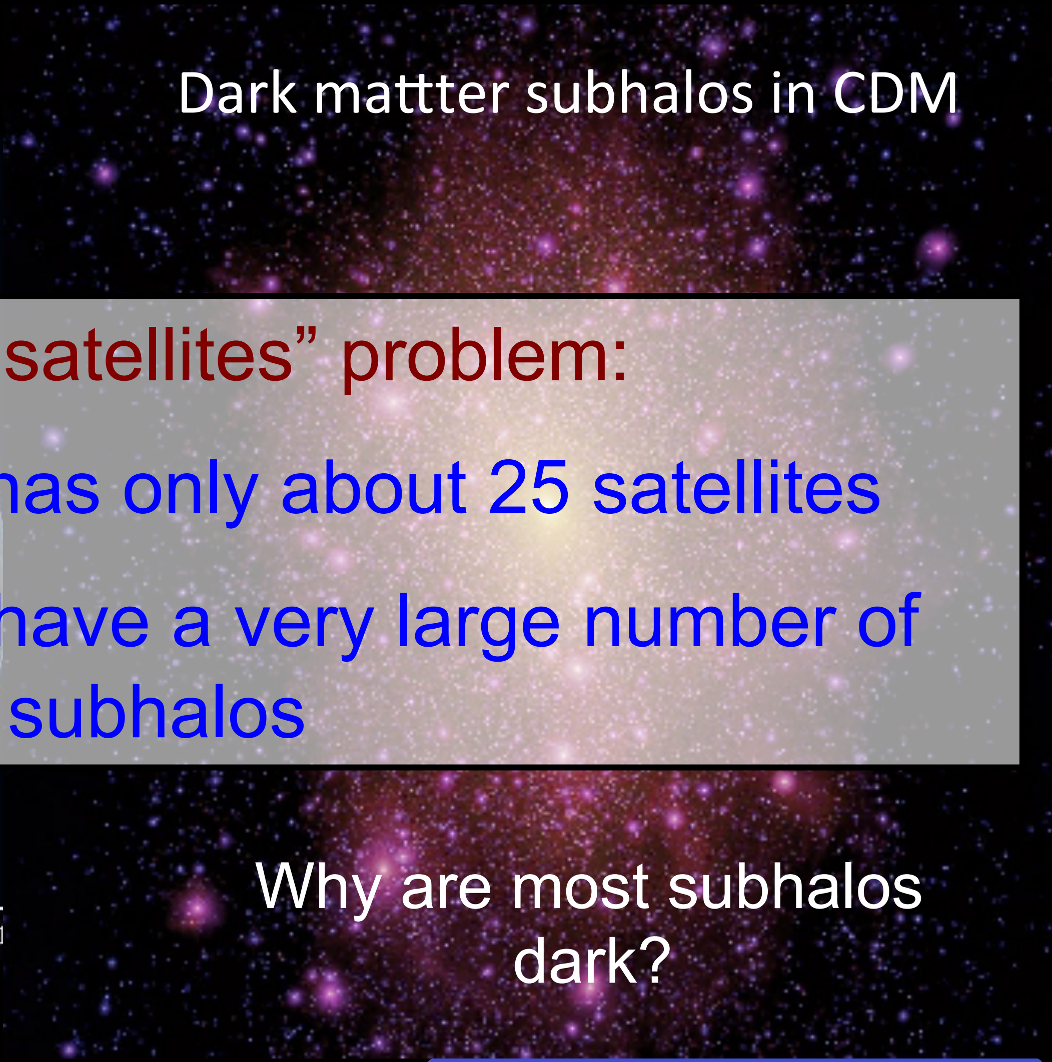
1. The “missing satellites” problem
2. The “too-big-to-fail” problem
3. The “core-cusp” problem
4. The “satellite disk” problem

Can these help distinguish between CDM & WDM?

The “missing satellites” problem in CDM

The satellites of the MW

Dark mattter subhalos in CDM



“Missing satellites” problem:

The Milky Way has only about 25 satellites

BUT: CDM halos have a very large number of subhalos

Why are most subhalos dark?

The "too-big-to-fail" problem

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

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

The satellites of the MW

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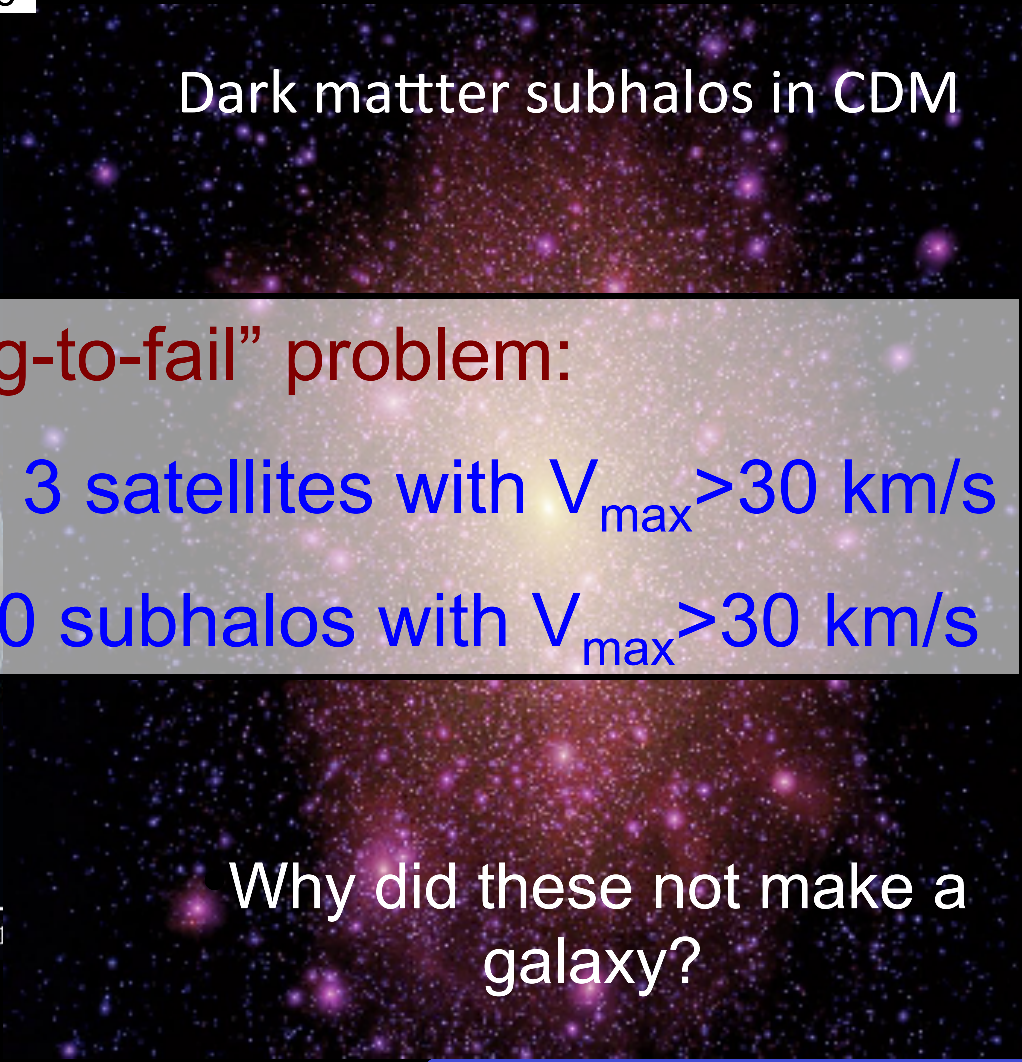


"Too-big-to-fail" problem:

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

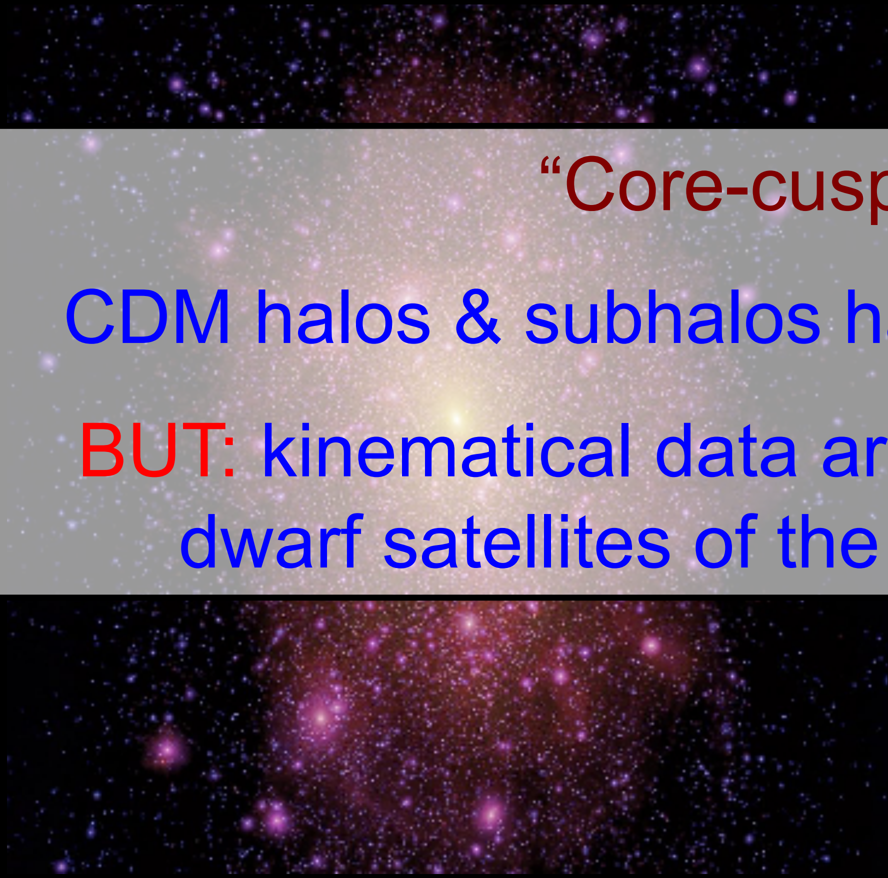
BUT: CDM has ~10 subhalos with V_{max}>30 km/s

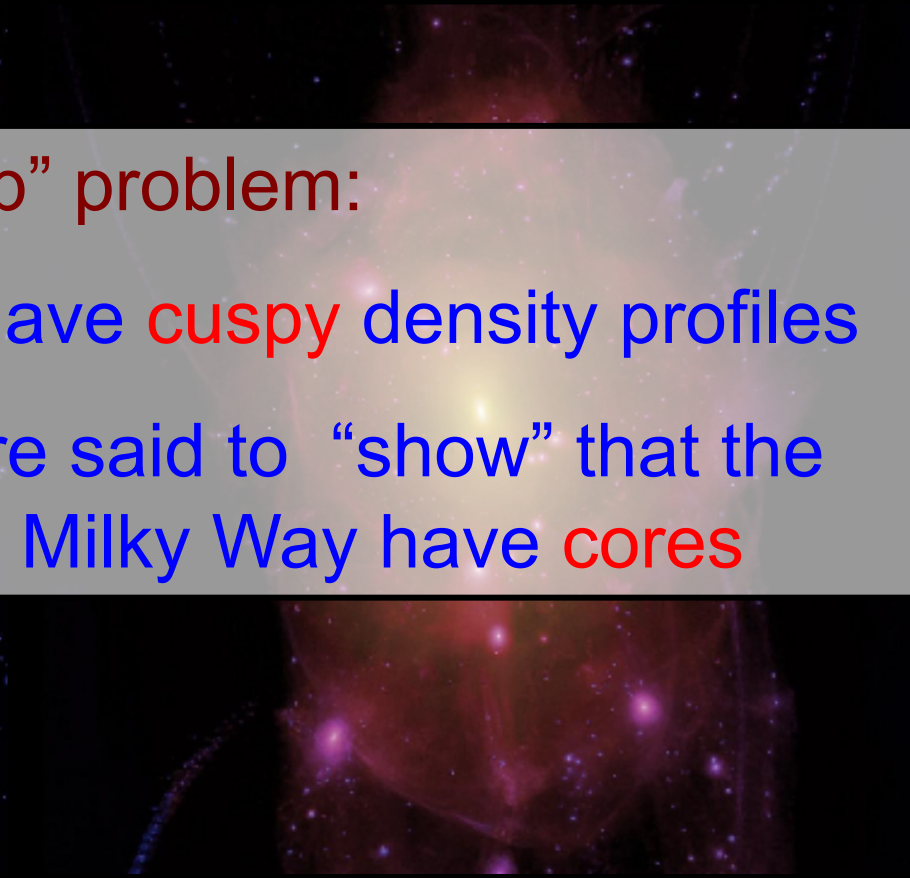
Why did these not make a galaxy?

The core-cusp problem

cold dark matter

warm dark matter





"Core-cusp" problem:

CDM halos & subhalos have cuspy density profiles

BUT: kinematical data are said to "show" that the dwarf satellites of the Milky Way have cores

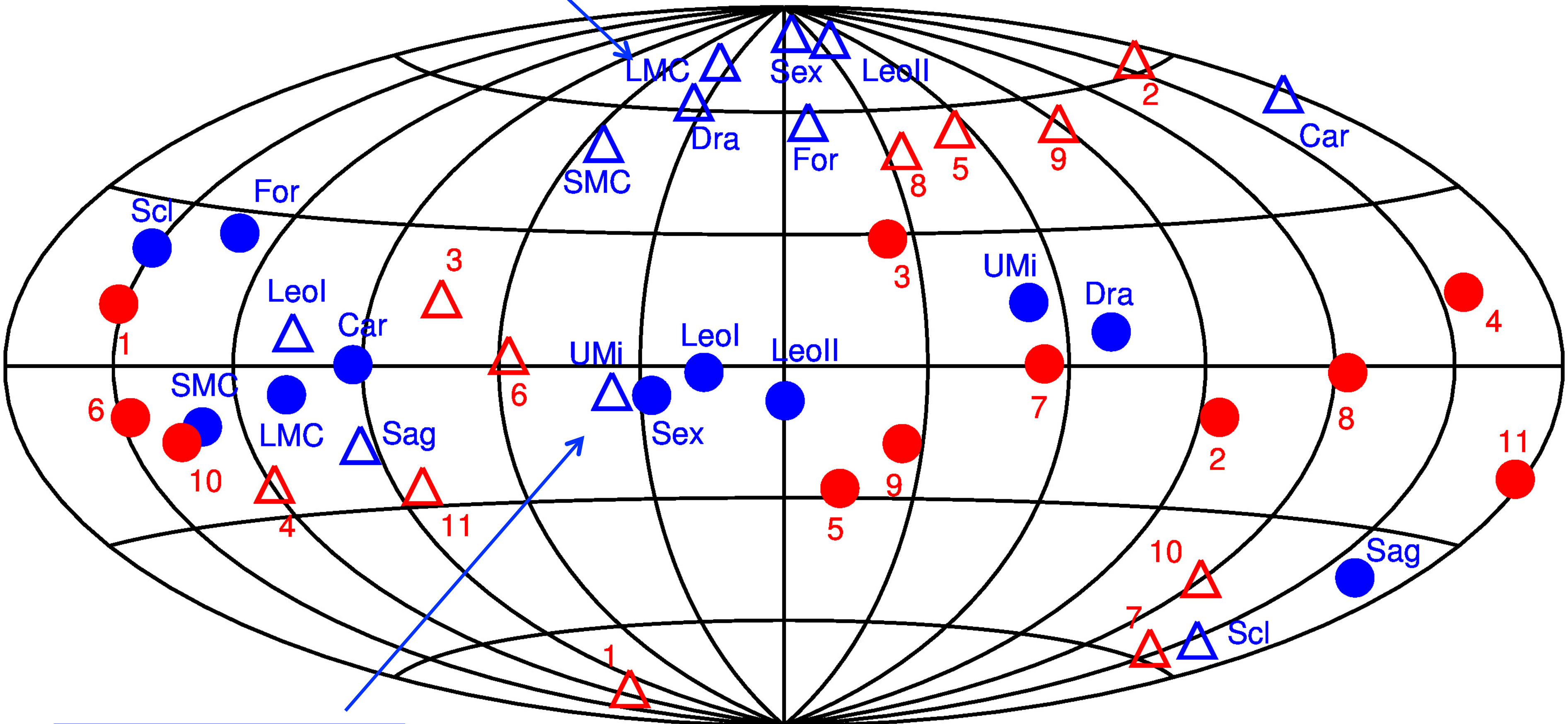
Lovell, Eke, Frenk, Gao, Jenkins, Theuns '12

University of Durham

The “satellite disk” problem

Direction of ang. mom.

Milky Way



MW satellites

Lynden-Bell ‘76

Institute for Computational Cosmology

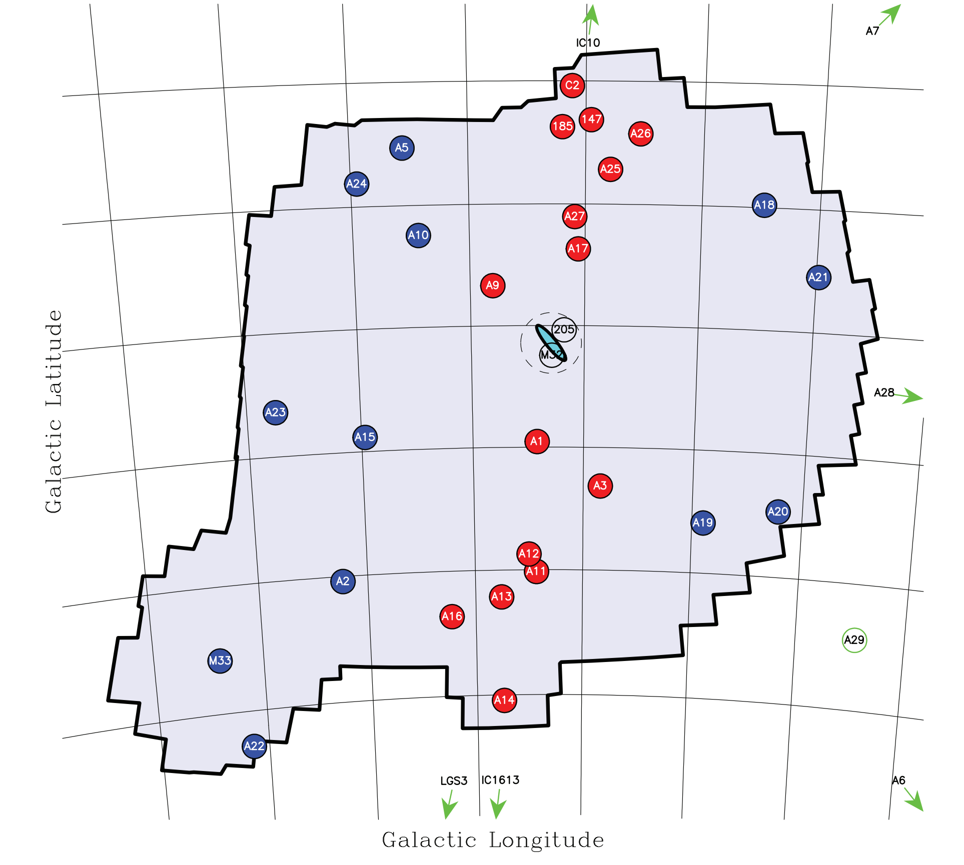
The curious case of a thin, "rotating" plane of sats in M31

University of Durham

Ibata et al '13 found a plane of 15 satellites in Andromeda (out of 27) of which 13 have the same sense of rotation

They claim a 4.3σ detection

"We find that 0.04% of host galaxies [in Millennium II] display satellite alignments that are at least as extreme as the observations, when we consider their extent, thickness, and number of members rotating in the same sense."



Ibata et al '13

Institute for Computational Cosmology

Does warm dark matter also suffer from these four “problems”?

University of Durham

Four problems on small scales

Traditionally ascribed to CDM:

Different in WDM:
1. The "missing satellites" problem
2. The "too-big-to-fail" problem

The same in WDM:
3. The "core-cusp" problem
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Can these help distinguish between CDM & WDM?

University of Durham

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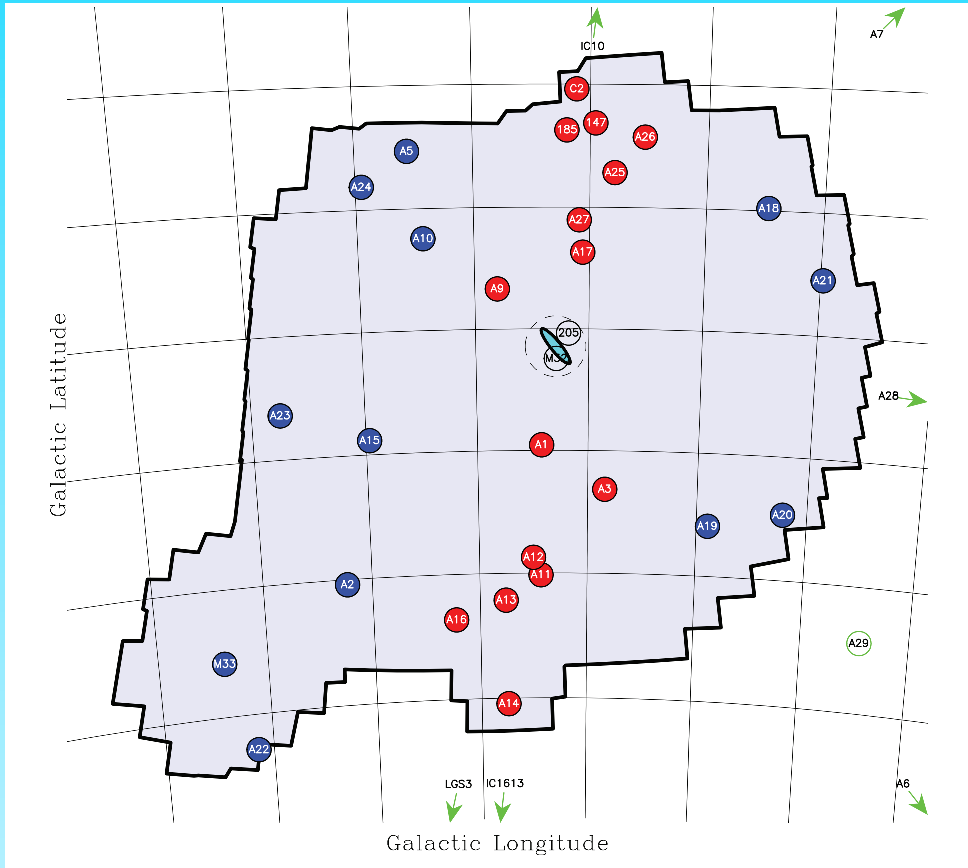


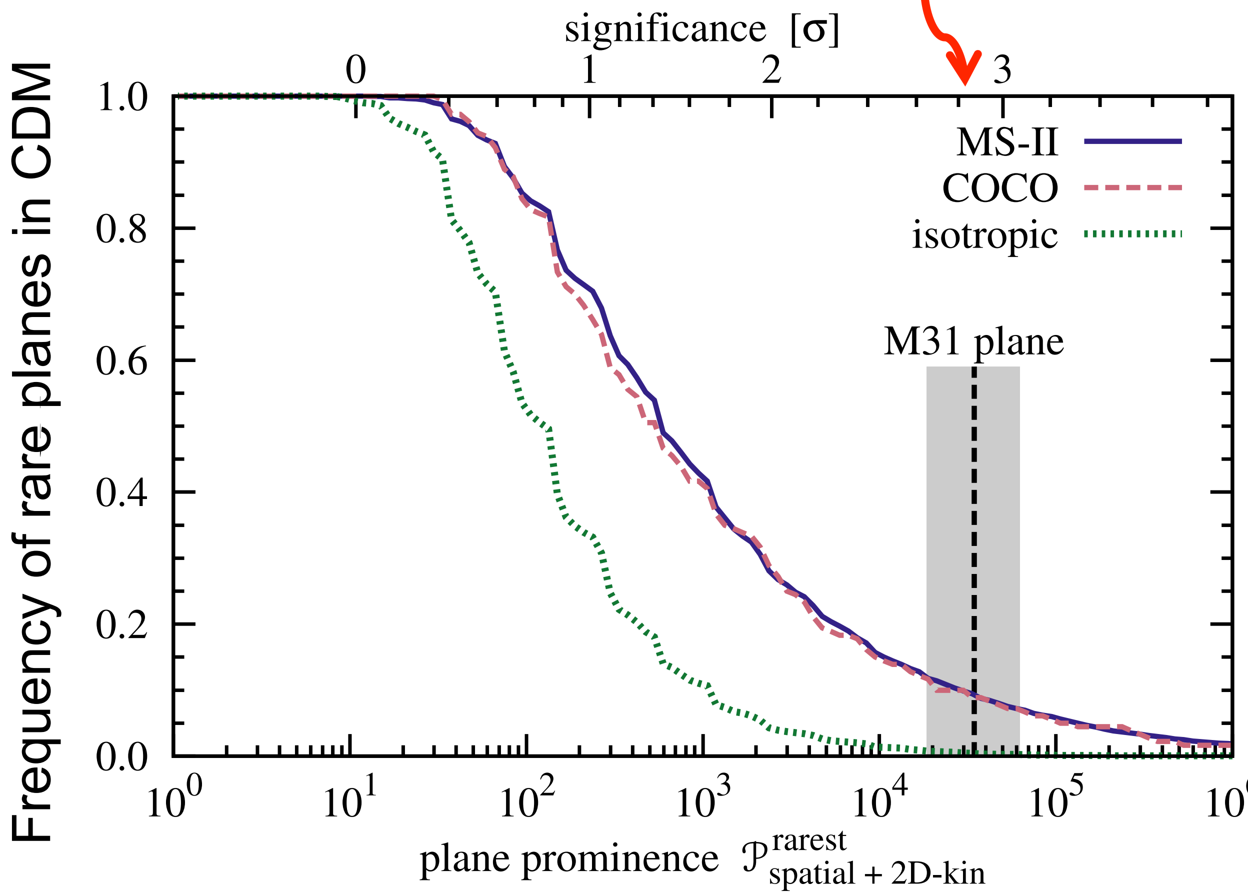
Ibata et al ‘13

University of Durham
Institute for Computational Cosmology

The significance of Ibata's plane

University of Durham

Including "trials factor"



- Significance of Ibata's plane is reduced by x100 when trials factor is included
- 8.8% of halos in ΛCDM simulation have even more prominent disks than Ibata's

In random distribution, 1 in 30,000 chance of finding a plane of 15 sats (out of 27) as thin found by Ibata et al., with at least 13 having same sense of rotation

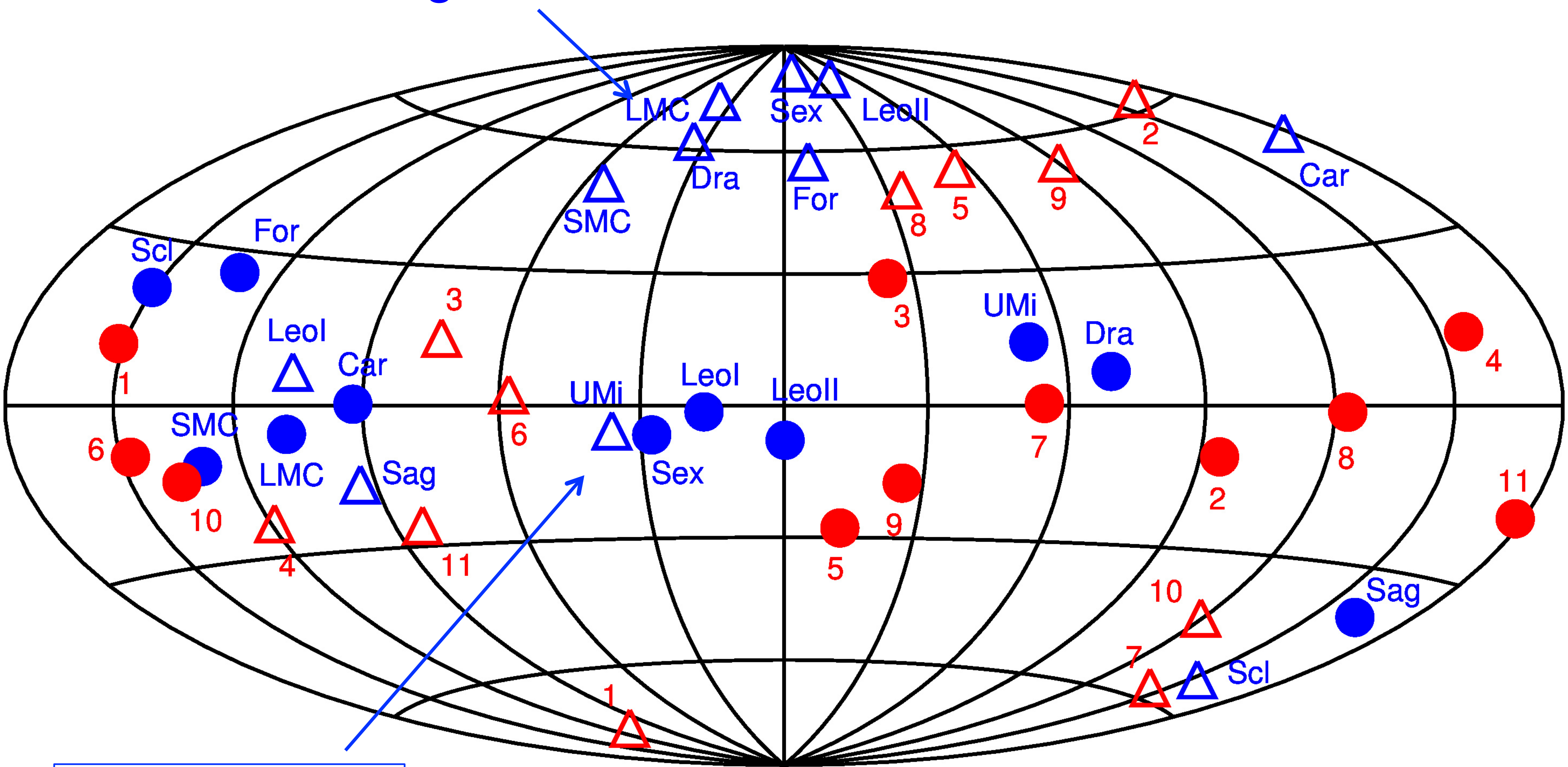
Cautun et al '15

University of Durham

The “satellite disk” problem

Direction of ang. mom.

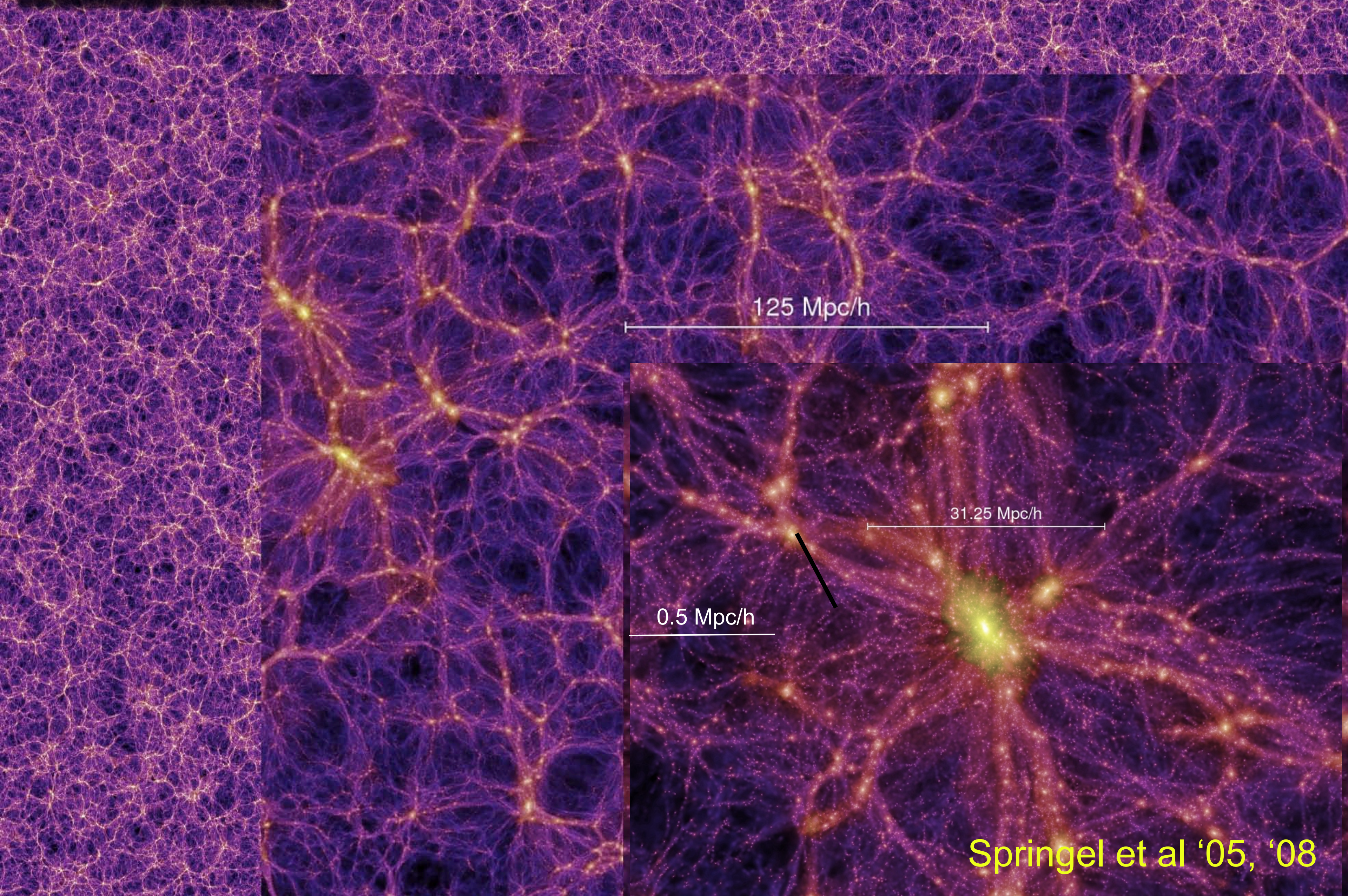
Milky Way



MW satellites

Lynden-Bell ‘76

The Millennium/Aquarius simulation series



Springel et al ‘05, ‘08

University of Durham

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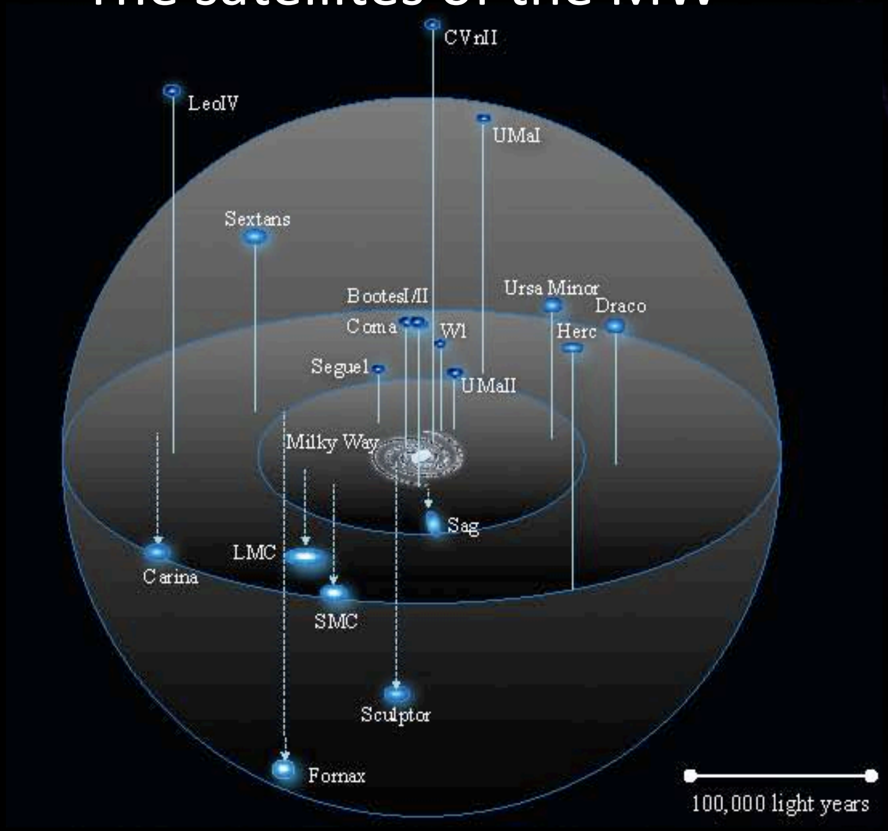
The “missing satellites” problem

The satellites of the MW



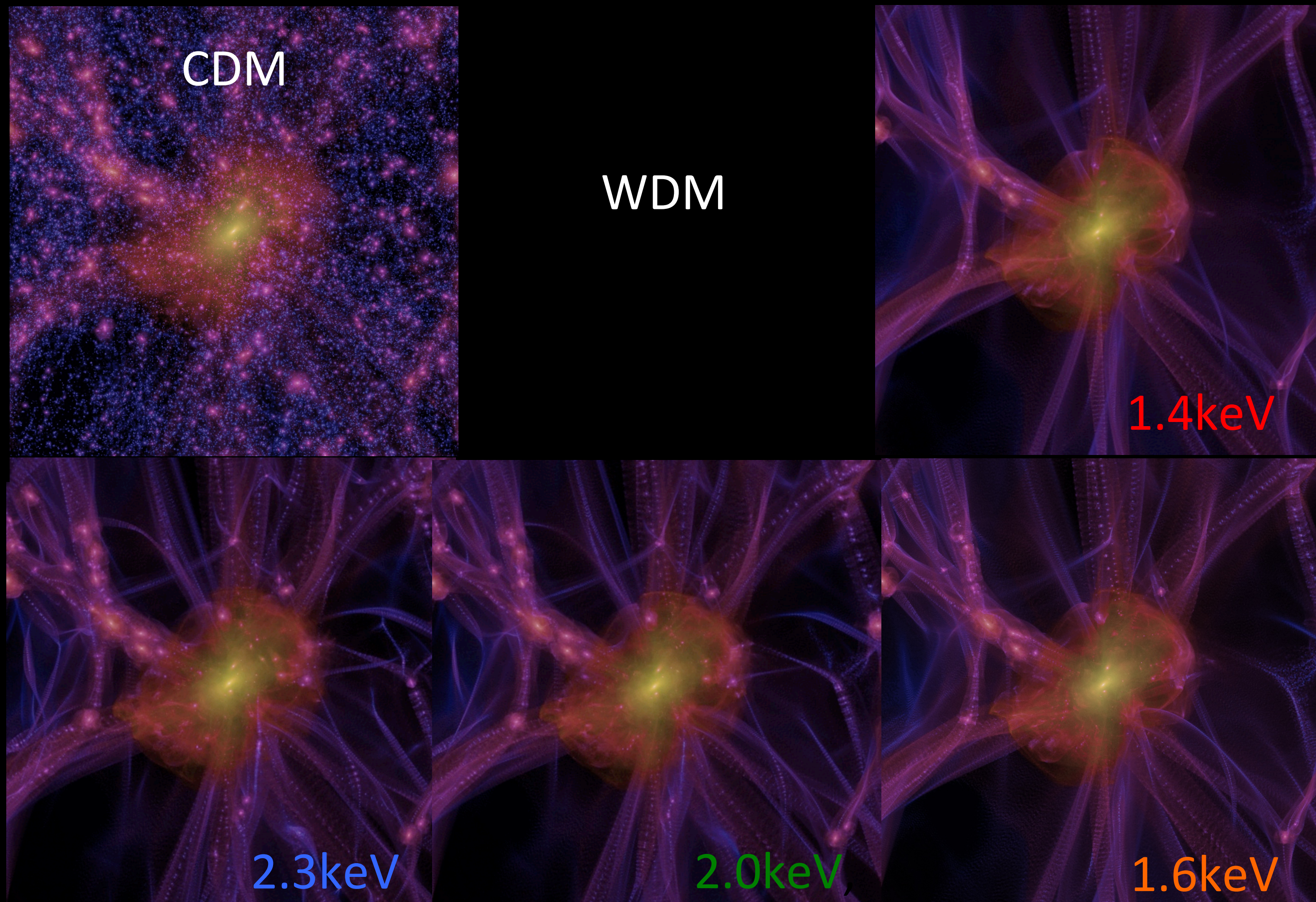
warm dark matter

No missing satellite problem in WDM!

Warm DM: different ν mass

z=3

WDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV



Tests of the nature of the DM

warm dark matter

If the halo mass is too small and/or the WDM particle mass is too small, there will not be enough subhalos to account for the observed satellites!

Kennedy, Cole & Frenk '14

Limits on WDM particle mass

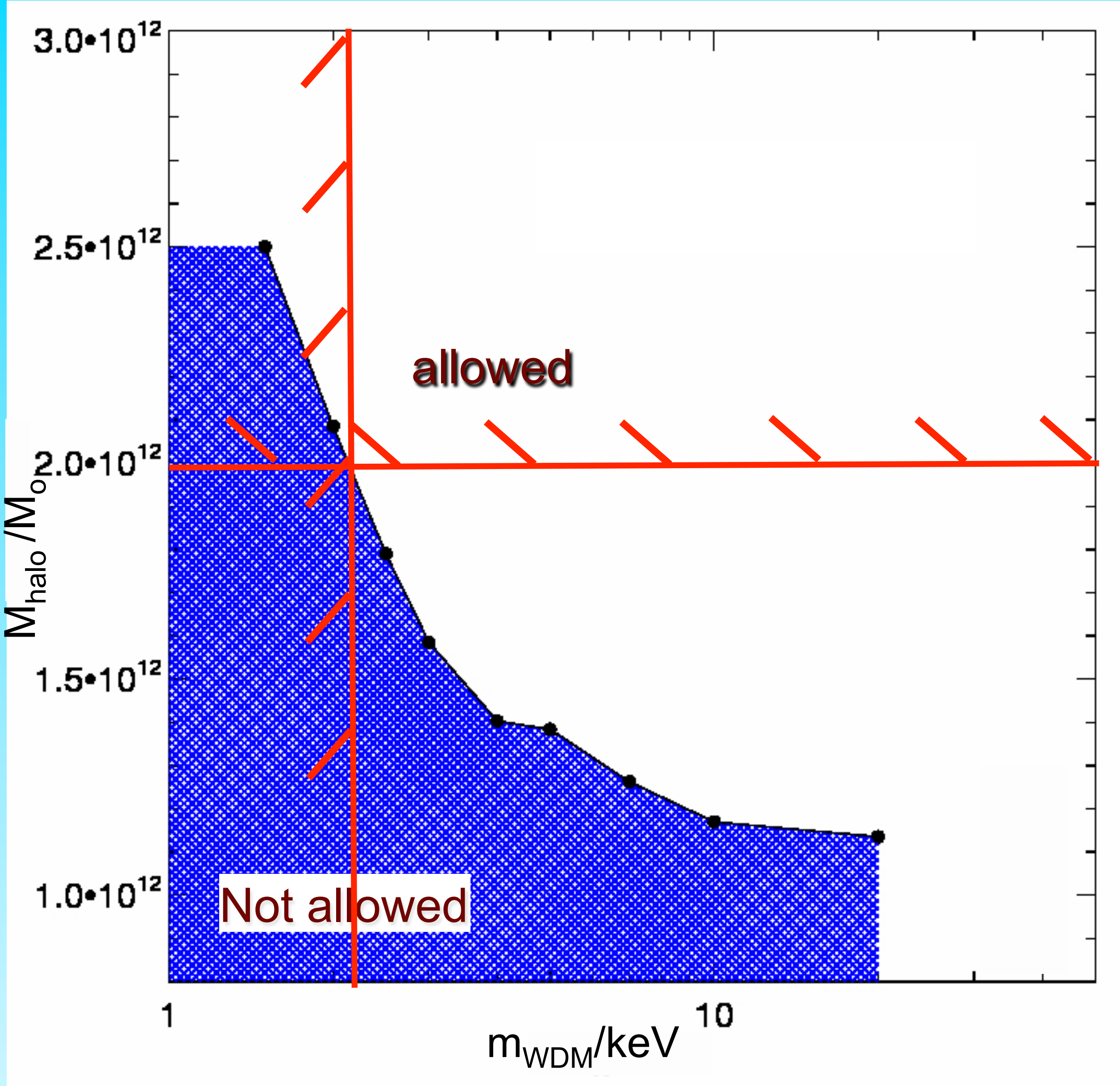
University of Durham

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

For standard galaxy formation model, if

$M_{halo} < 2 \times 10^{12}\ M_o$

→ $m_{WDM} > 2.2$ keV



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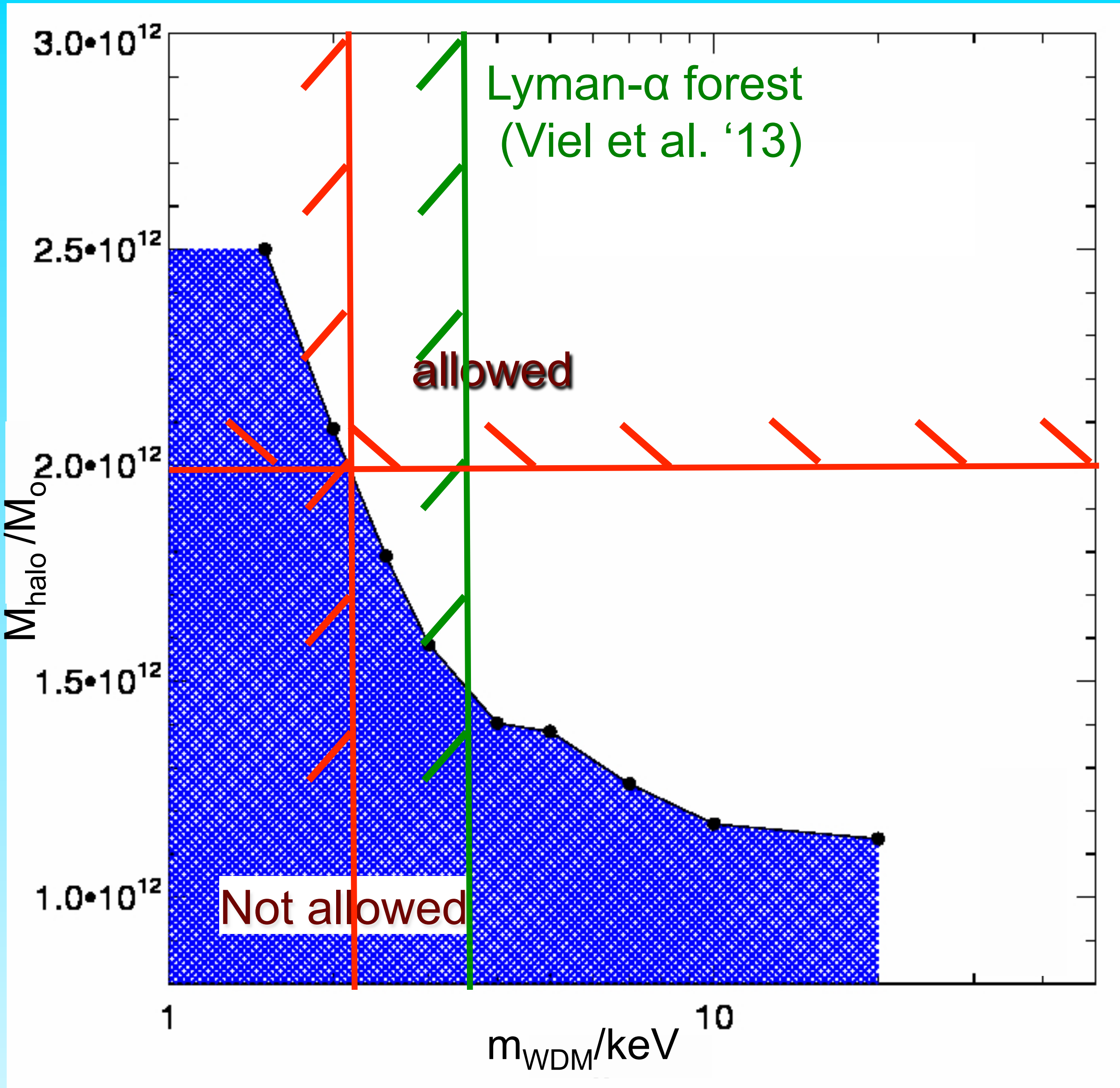

University of Durham

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The "too-big-to-fail" problem

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

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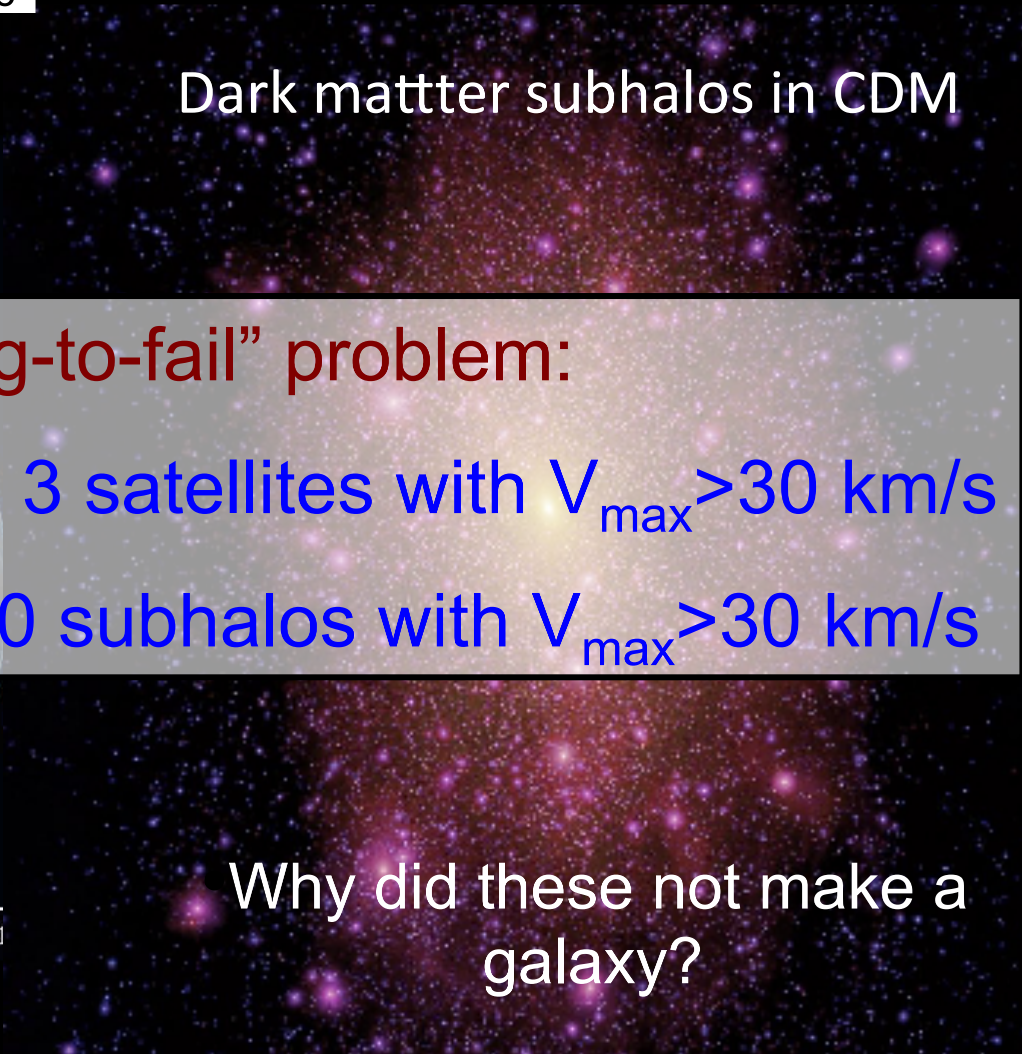
The satellites of the MW

Dark mattter subhalos in CDM



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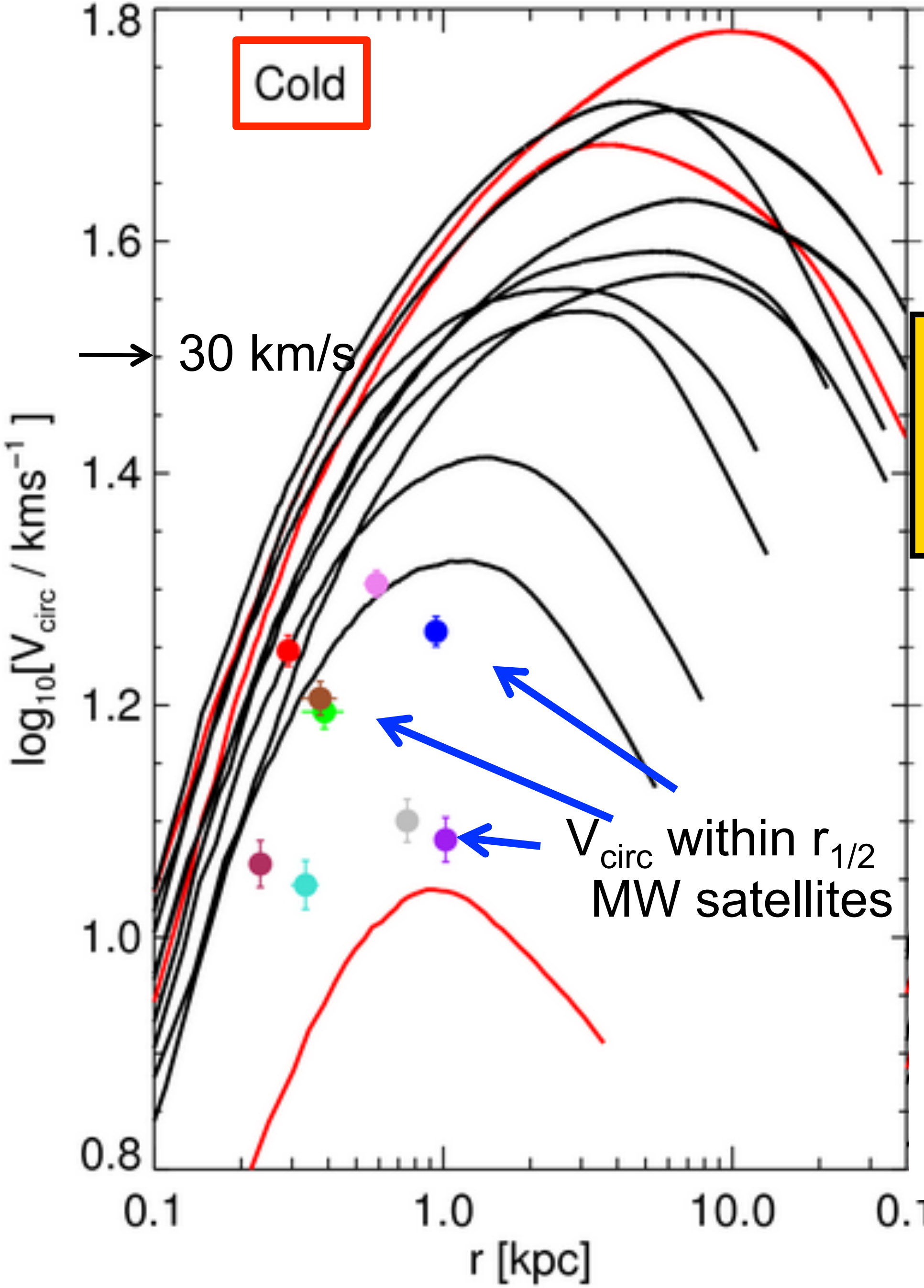
BUT: CDM has ~10 subhalos with V_{max}>30 km/s

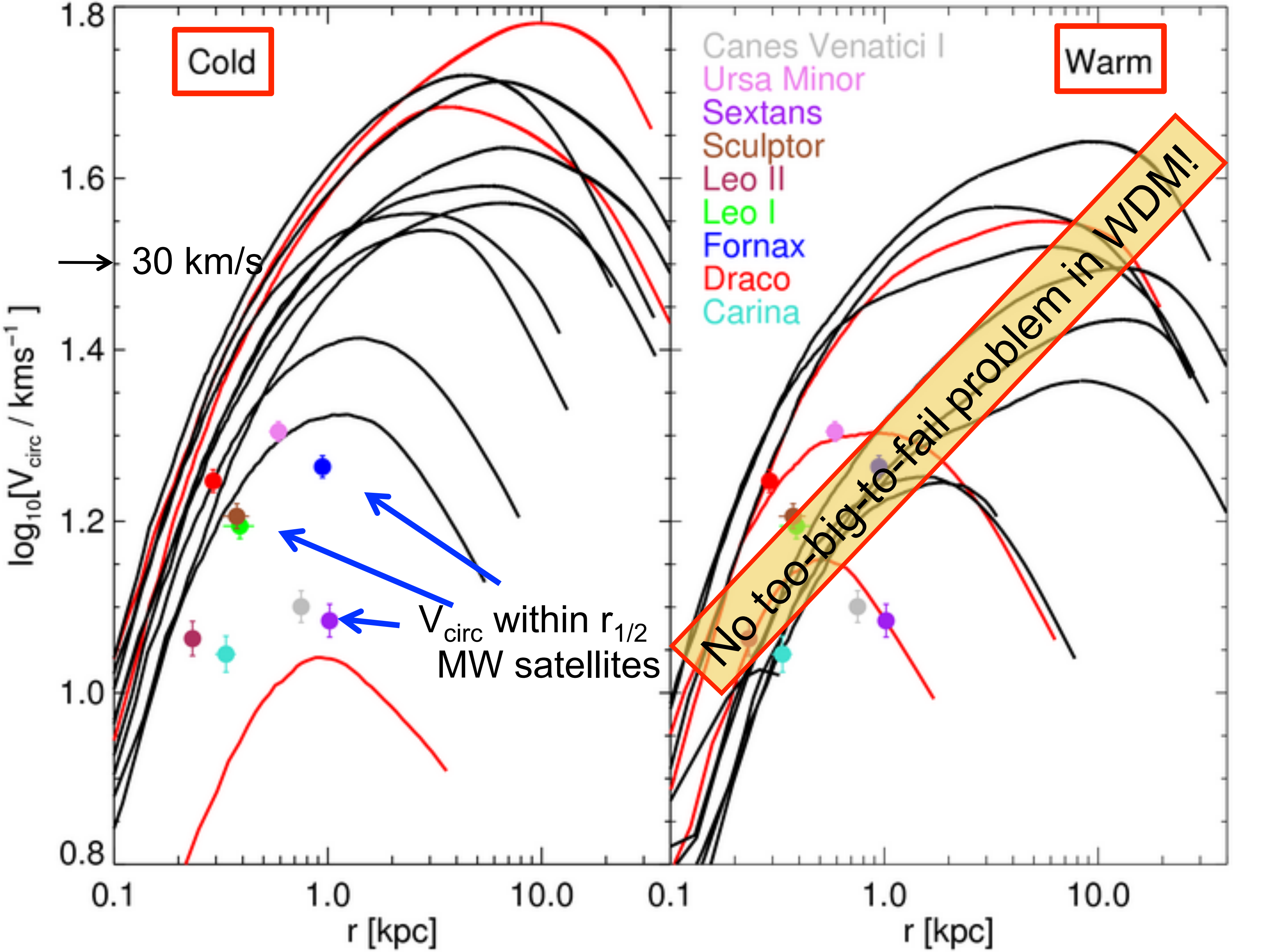
Why did these not make a galaxy?



$$V(r)_c = \sqrt{\frac{GM(r)}{r}}$$

The "too-big-to-fail" problem

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



Cold
Warm
30 km/s
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
No too-big-to-fail problem in WDM!
V_{circ} within $r_{1/2}$
MW satellites
$\log_{10}[V_{circ} / kms^{-1}]$
r [kpc]
1.8
1.6
1.4
1.2
1.0
0.8
0.1
1.0
10.0

No "satellite" or "too-big-to-fail" problems in WDM (provided m_{WDM} is large enough)

How about in CDM?

These problems have all been identified in N-body simulations that follow only dark matter

Need to consider “baryon effects”

Four problems on small scales

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Can these help distinguish between CDM & WDM?

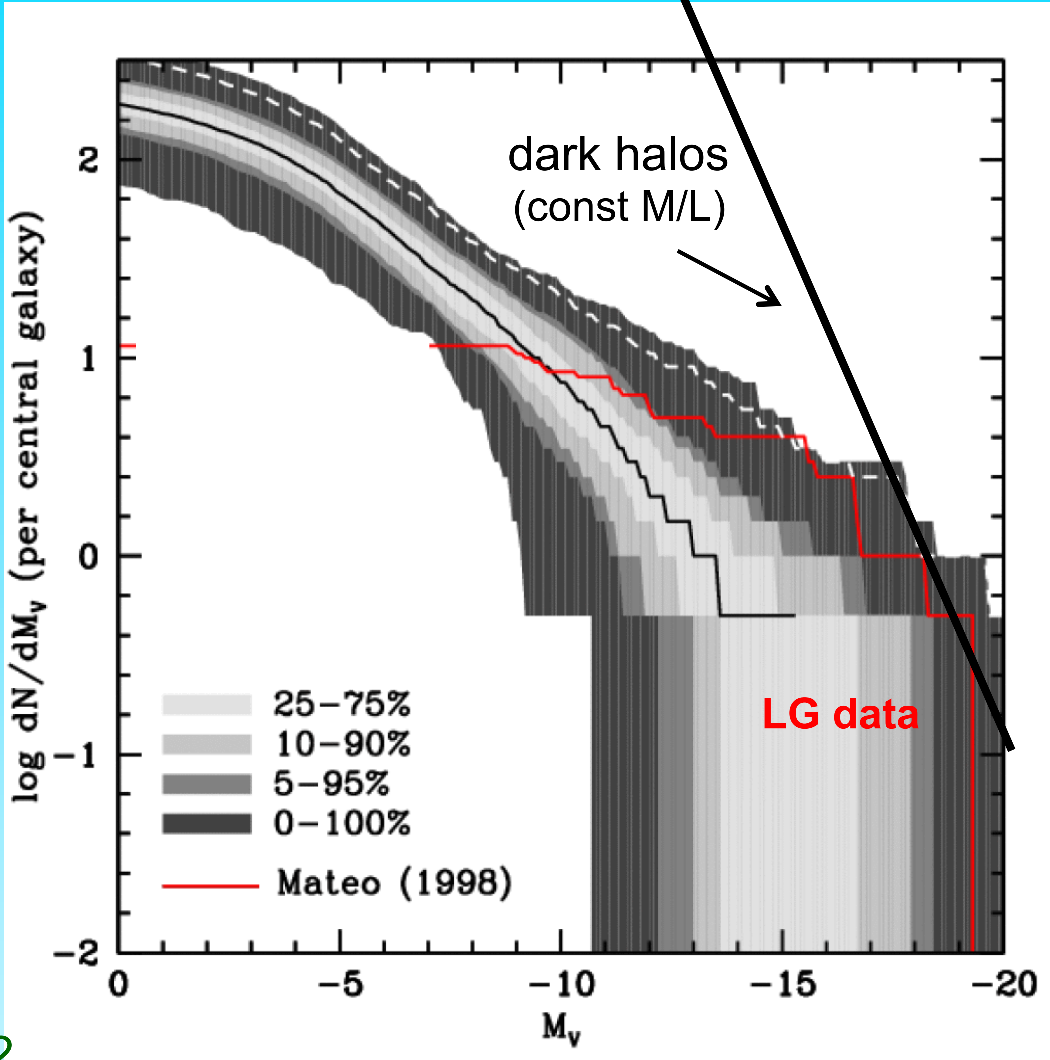
Making a galaxy in a small halo is hard because:

- Reionization heats gas above T_{vir}, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels residual 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_{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 etal '93, Bullock etal '01)

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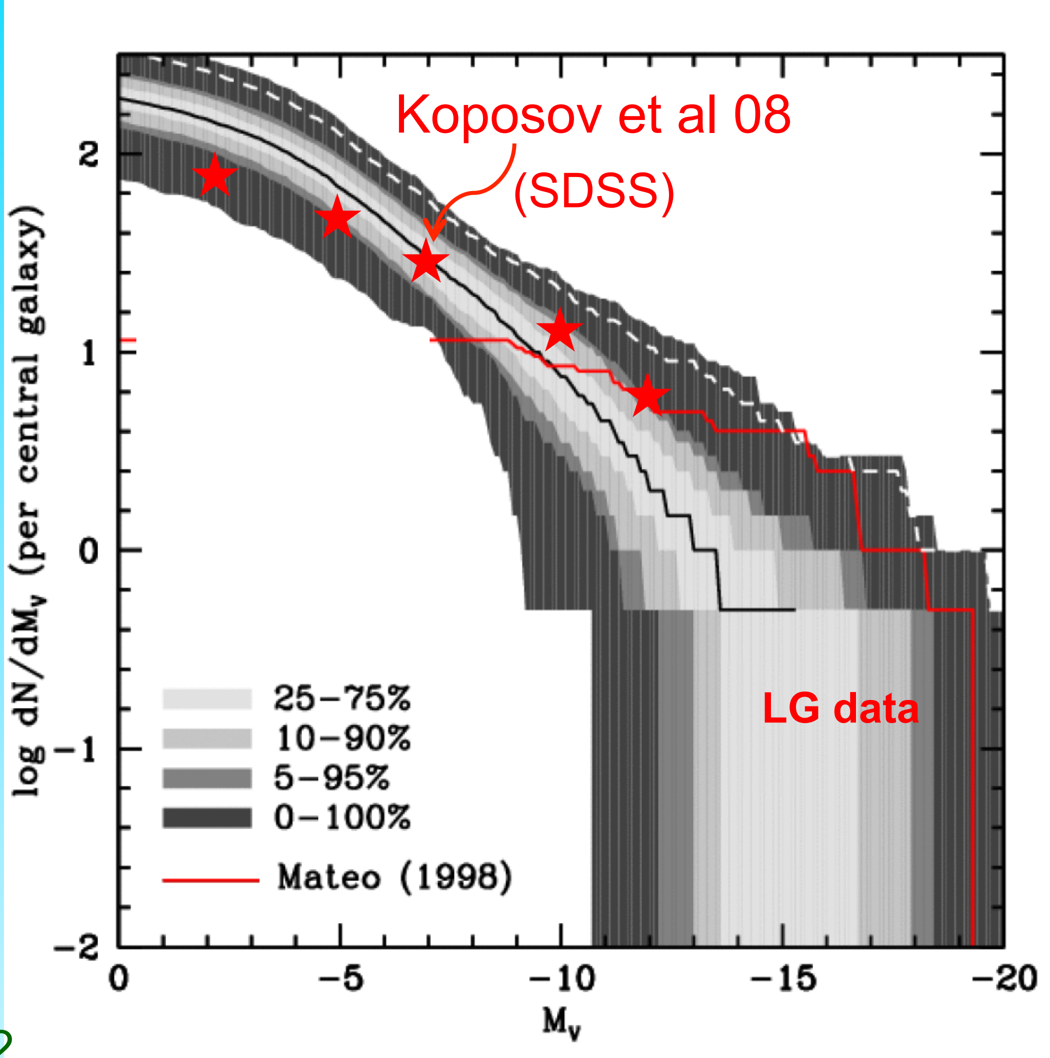


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

VIRGO

icc.dur.ac.uk/Eagle

"Evolution and assembly of galaxies and their environment"

THE EAGLE PROJECT

Virgo Consortium

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…

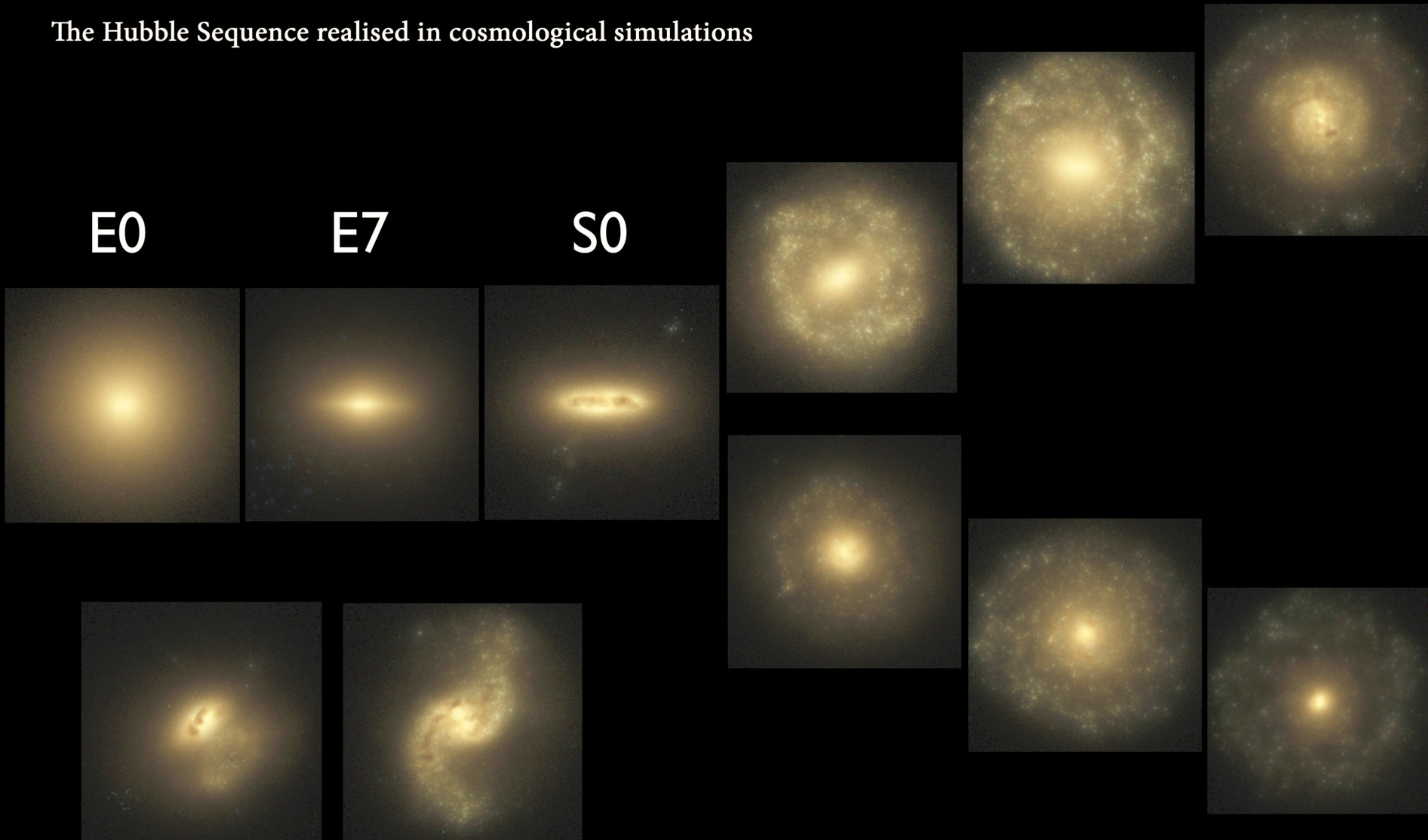
Durham University VIRGO ICC DiRAC PRACE

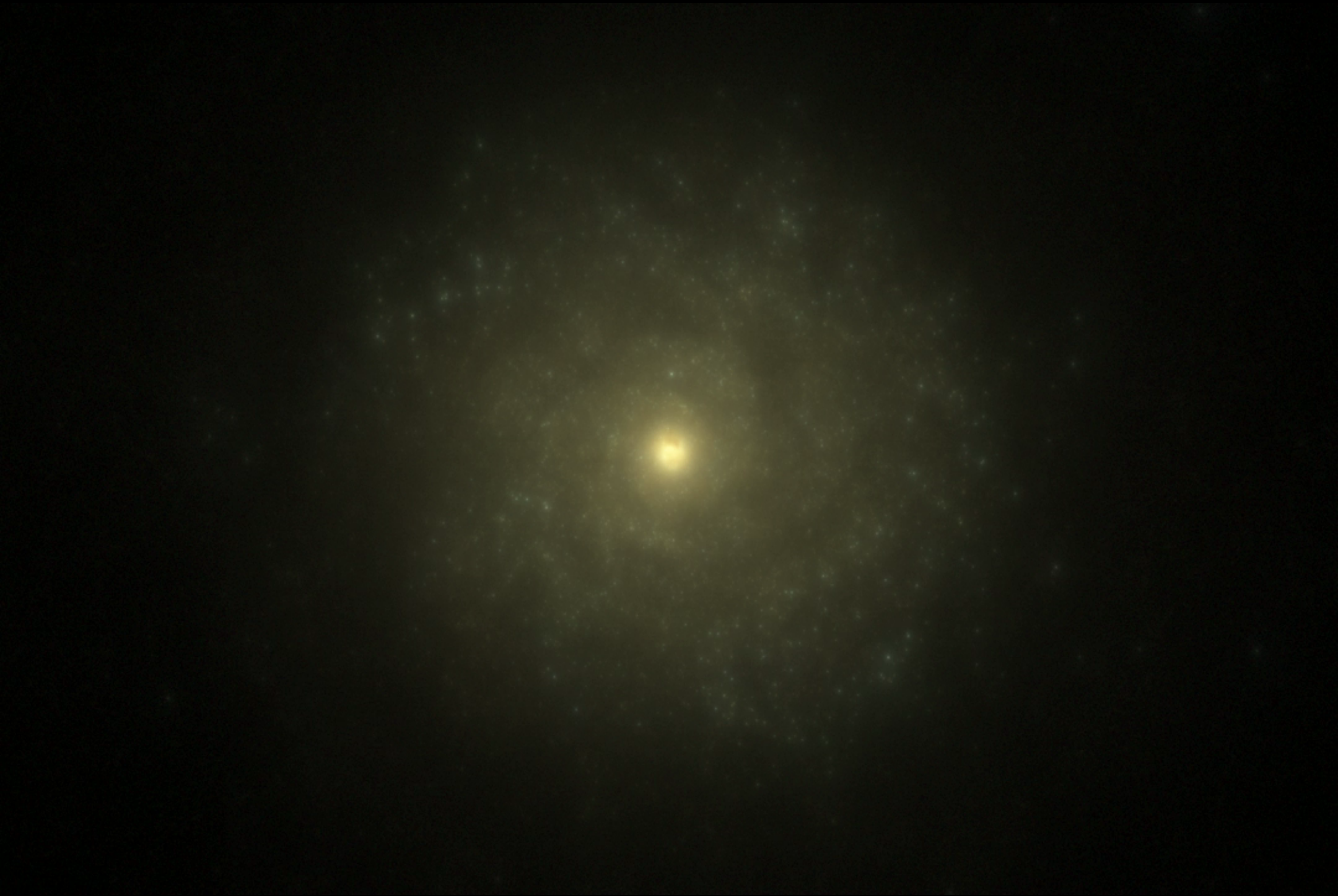
The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



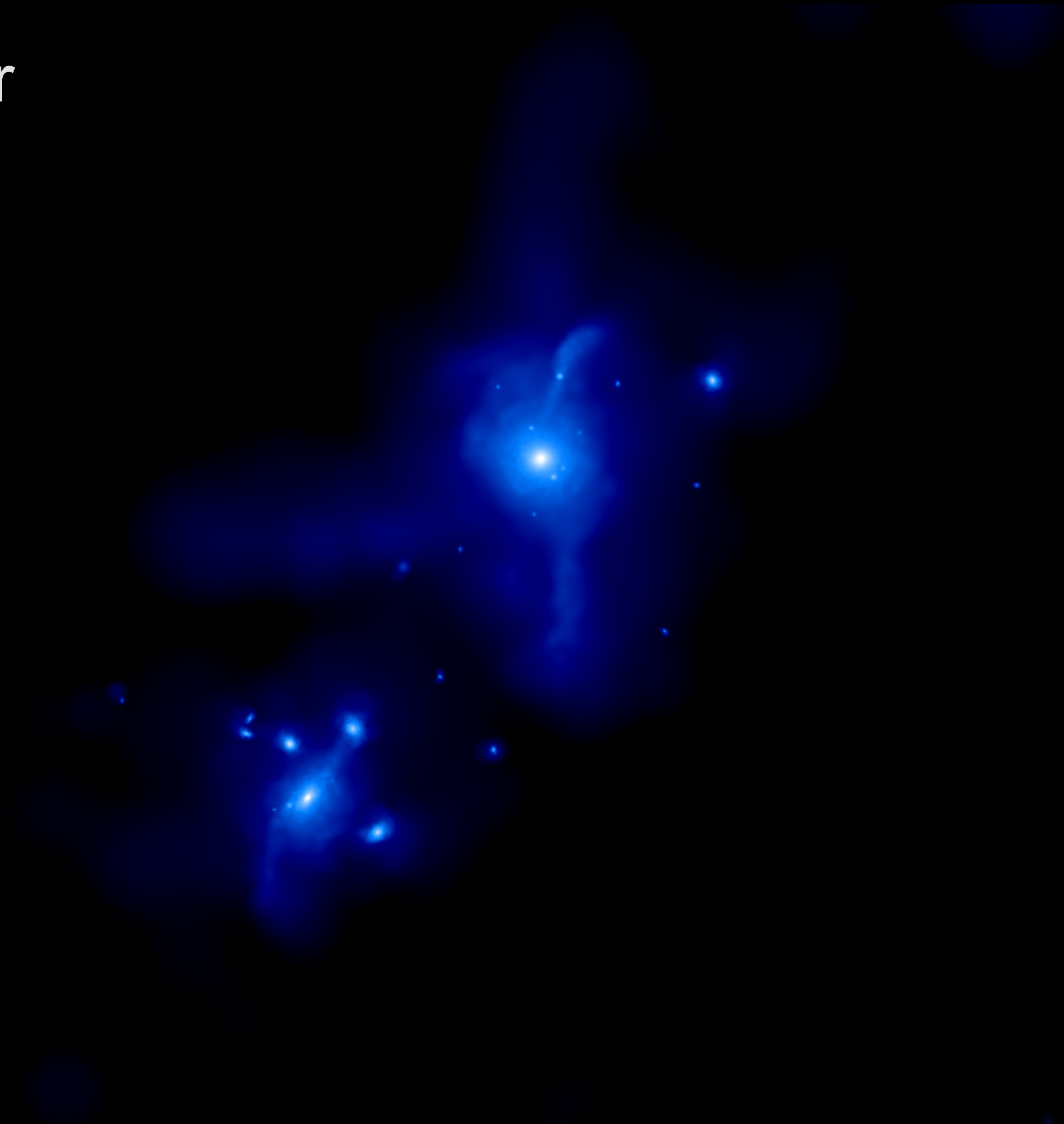


APOSTLE: EAGLE Local Group simulations

Dark Matter

Gas

Stars



Four problems on small scales

Traditionally ascribed to CDM:

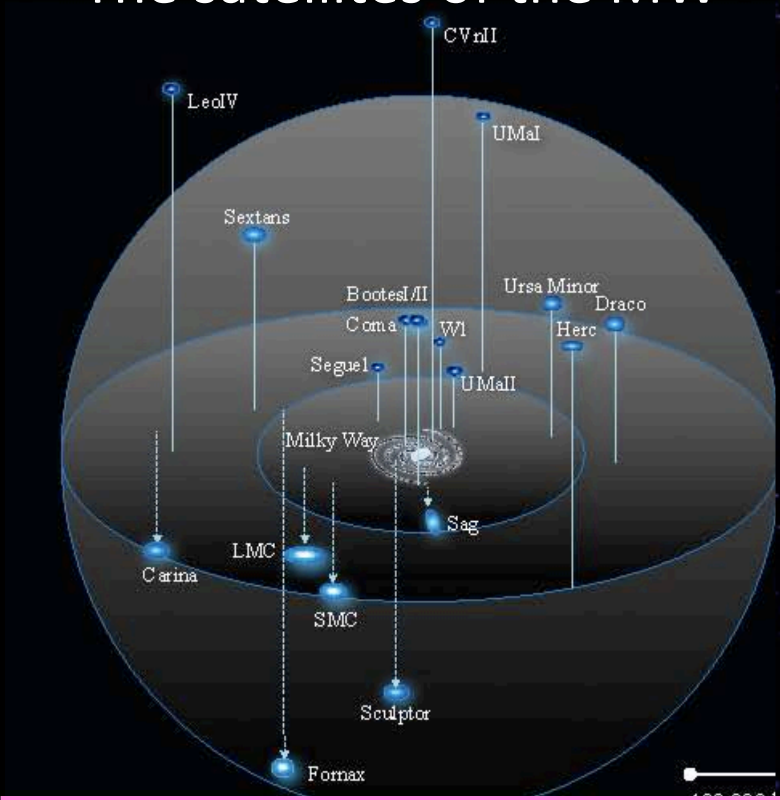
Different in WDM
1. The “missing satellites” problem
2. The “too-big-to-fail” problem

The same in WDM
3. The “core-cusp” problem
4. The “satellite disk” problem

Can these help distinguish between CDM & WDM?

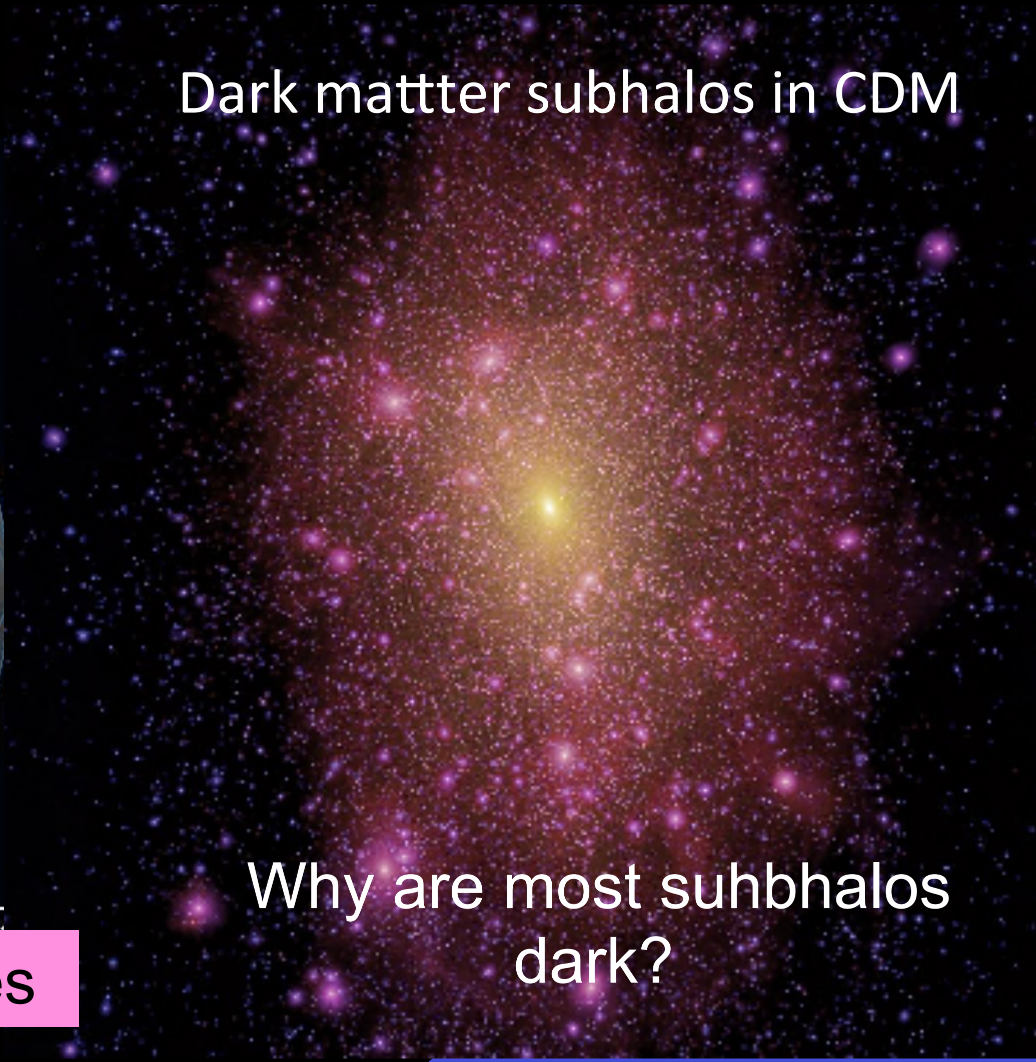
The "missing satellites" problem

The satellites of the MW



MW has only ~25 satellites

Dark matter subhalos in CDM

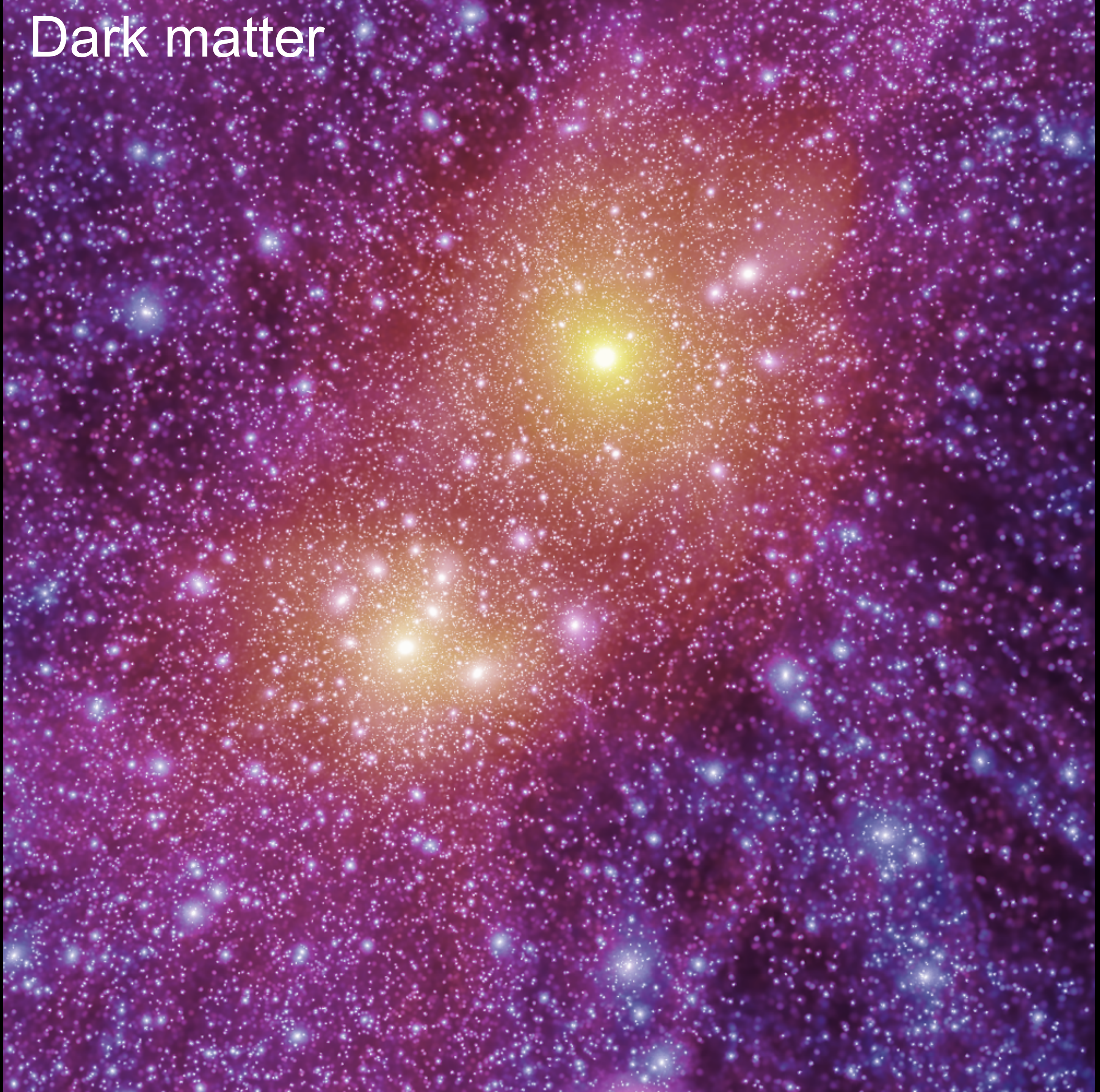


Why are most suhbhalos dark?

VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group



Sawala et al ‘15

Stars

APOSTLE
EAGLE full
hydro
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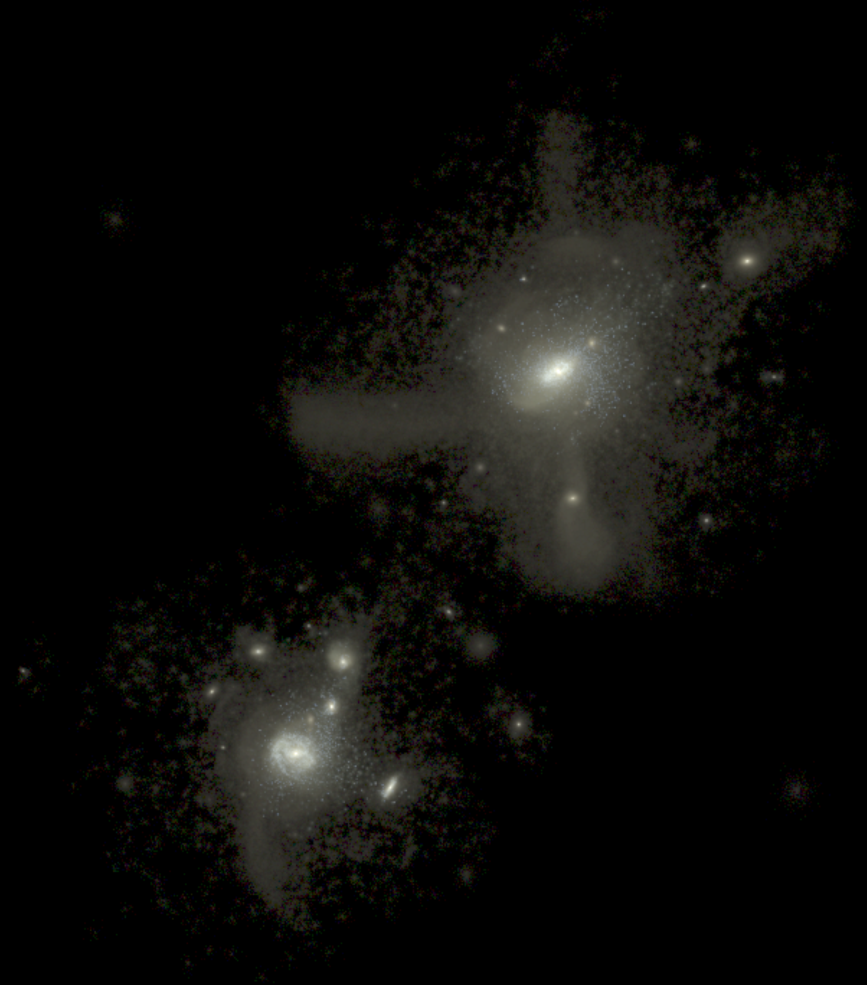
Local Group



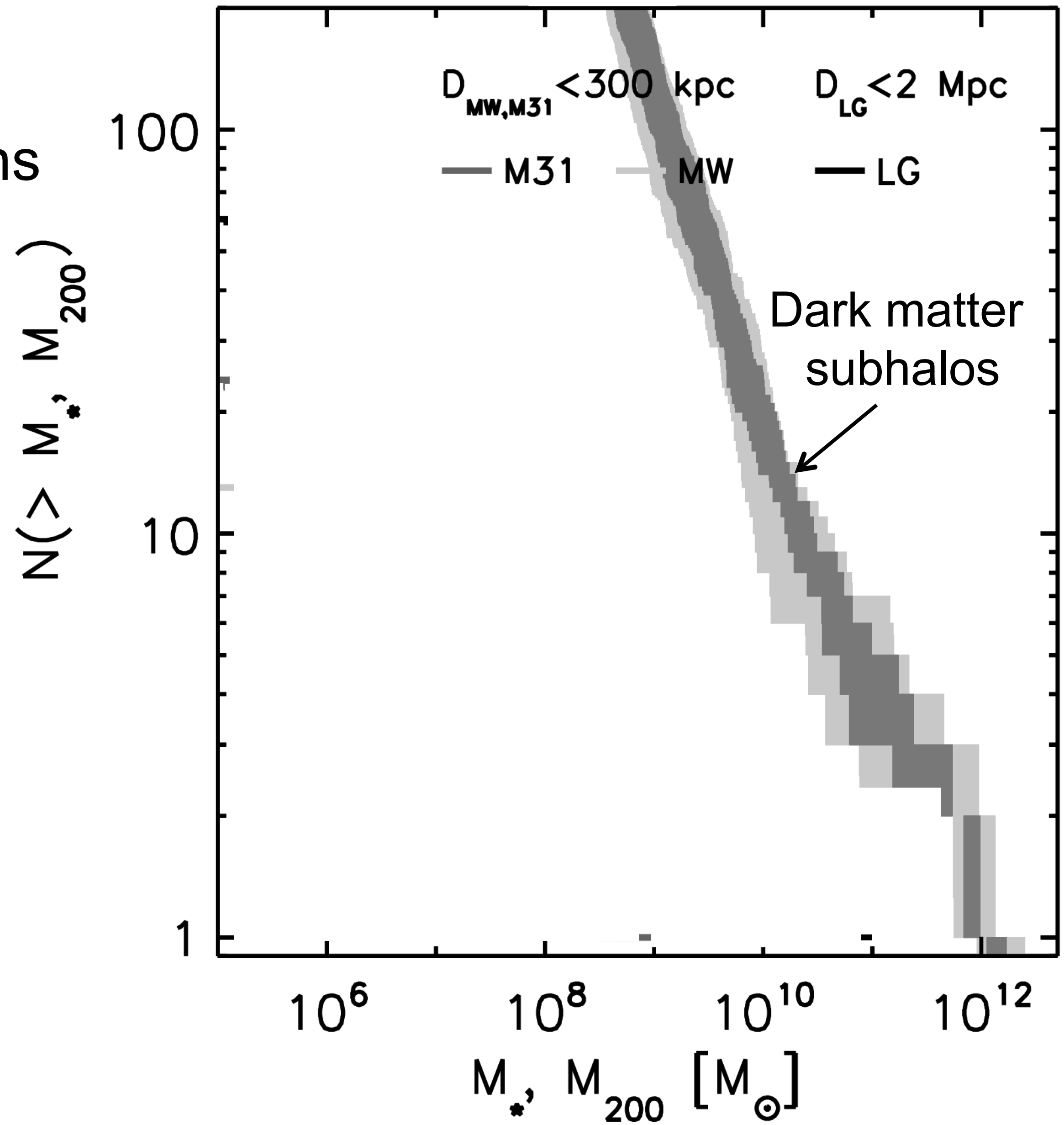
Far fewer satellite galaxies than CDM halos

Sawala et al ‘15

EAGLE Local Group simulation

University of Durham

Subhalo mass functions

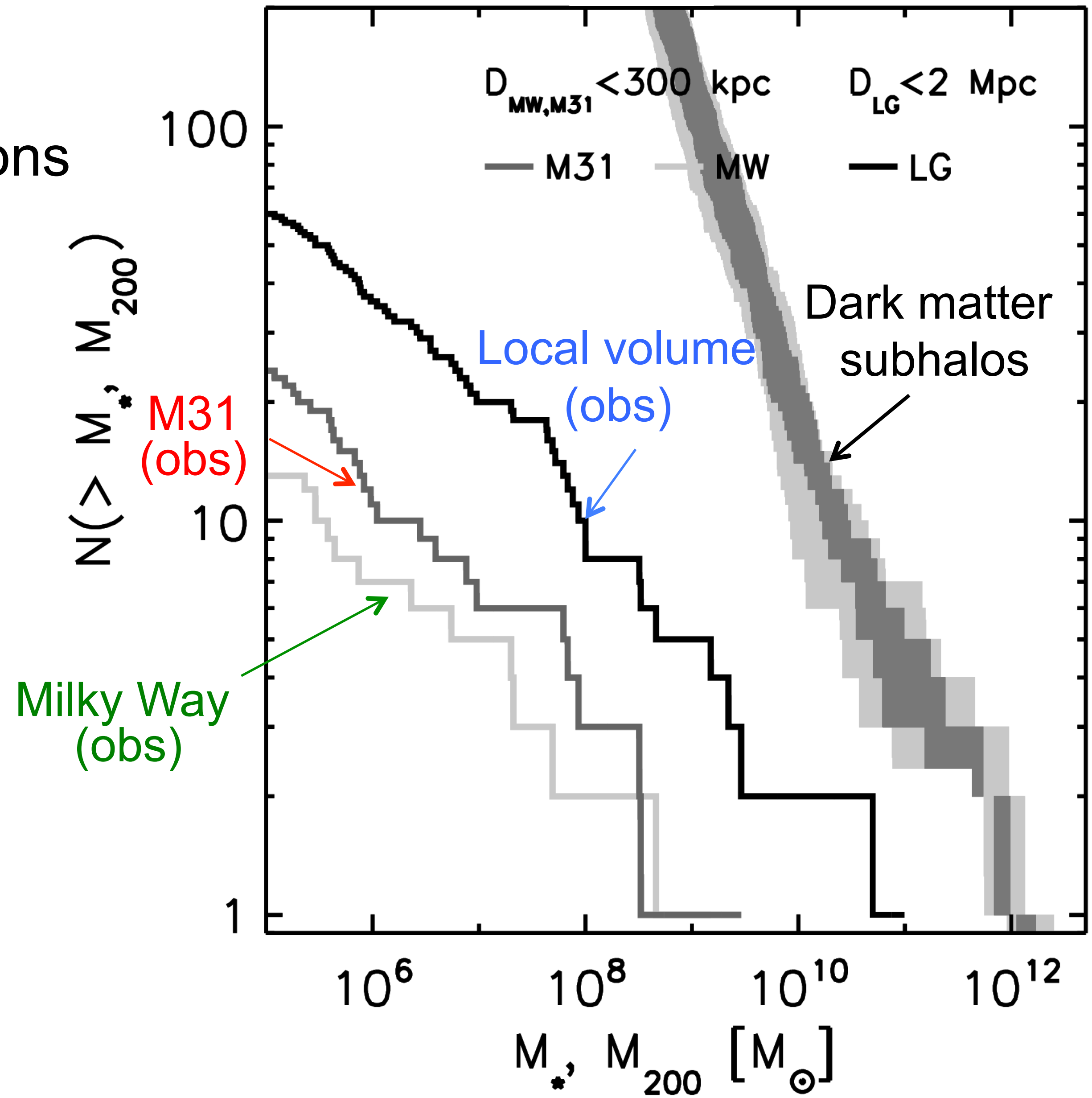


Sawala et al ‘15

EAGLE Local Group simulation

University of Durham

Stellar mass functions

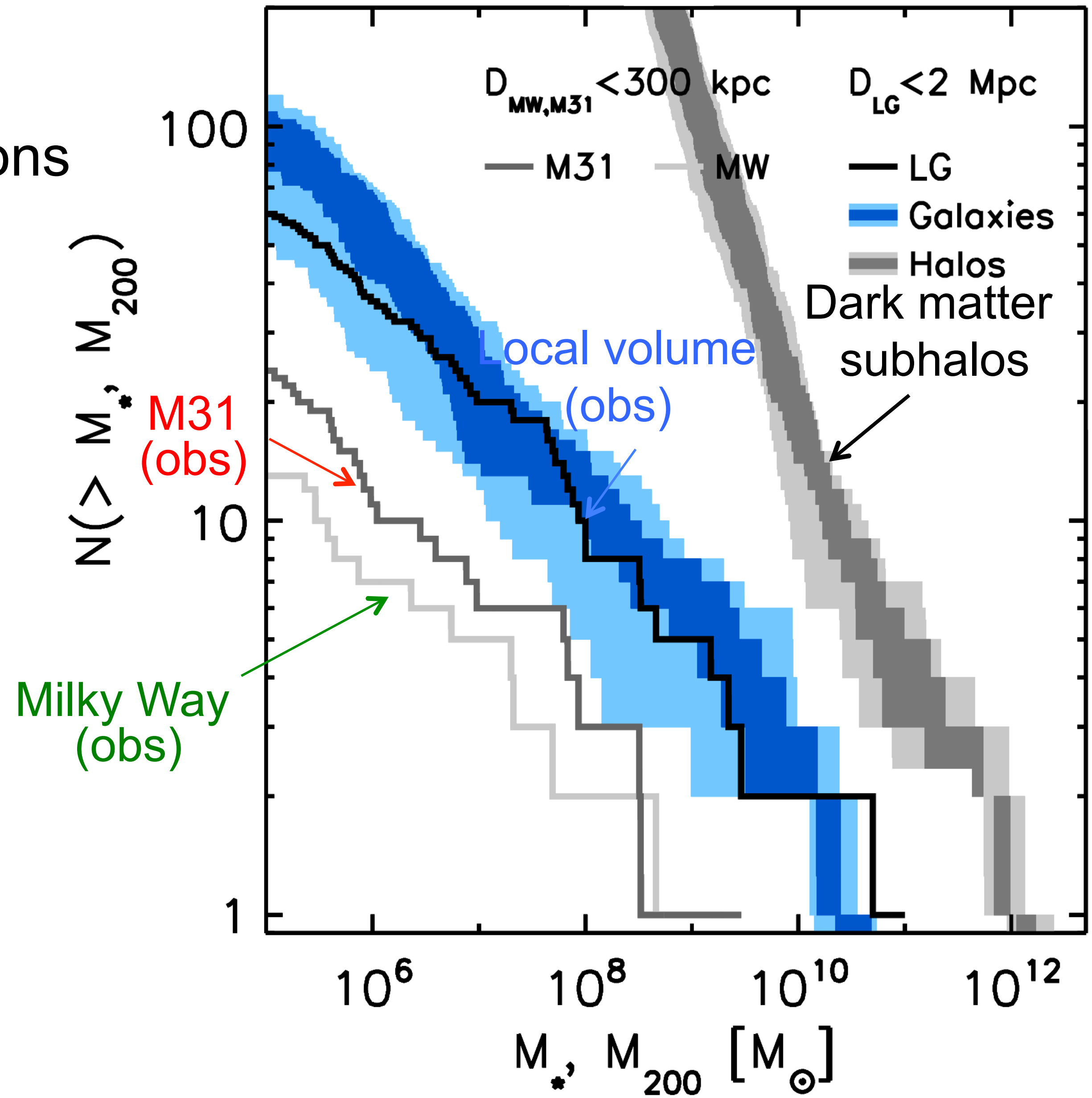


Sawala et al '15

EAGLE Local Group simulation

University of Durham

Stellar mass functions

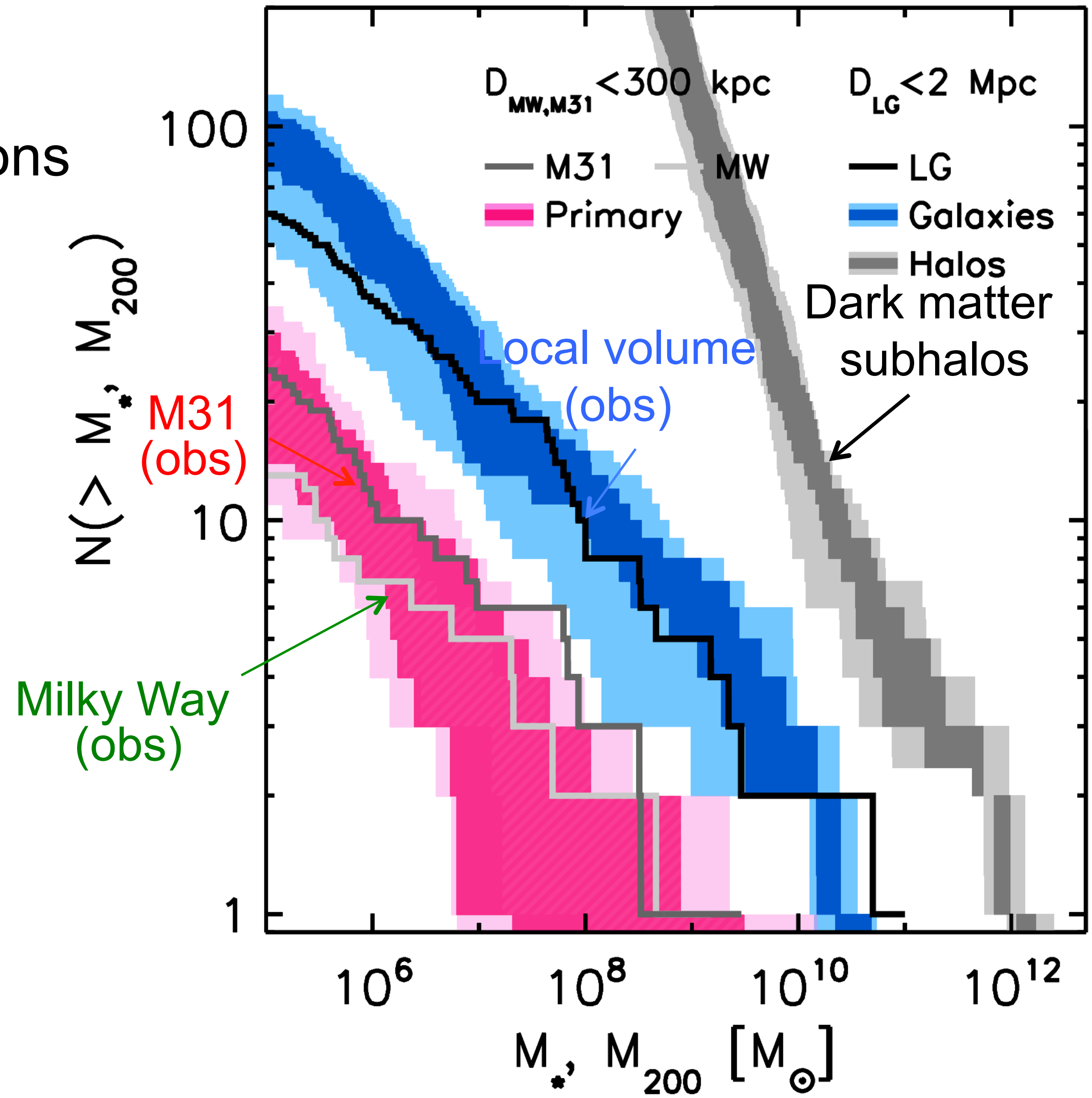


Sawala et al '15

University of Durham

EAGLE Local Group simulation

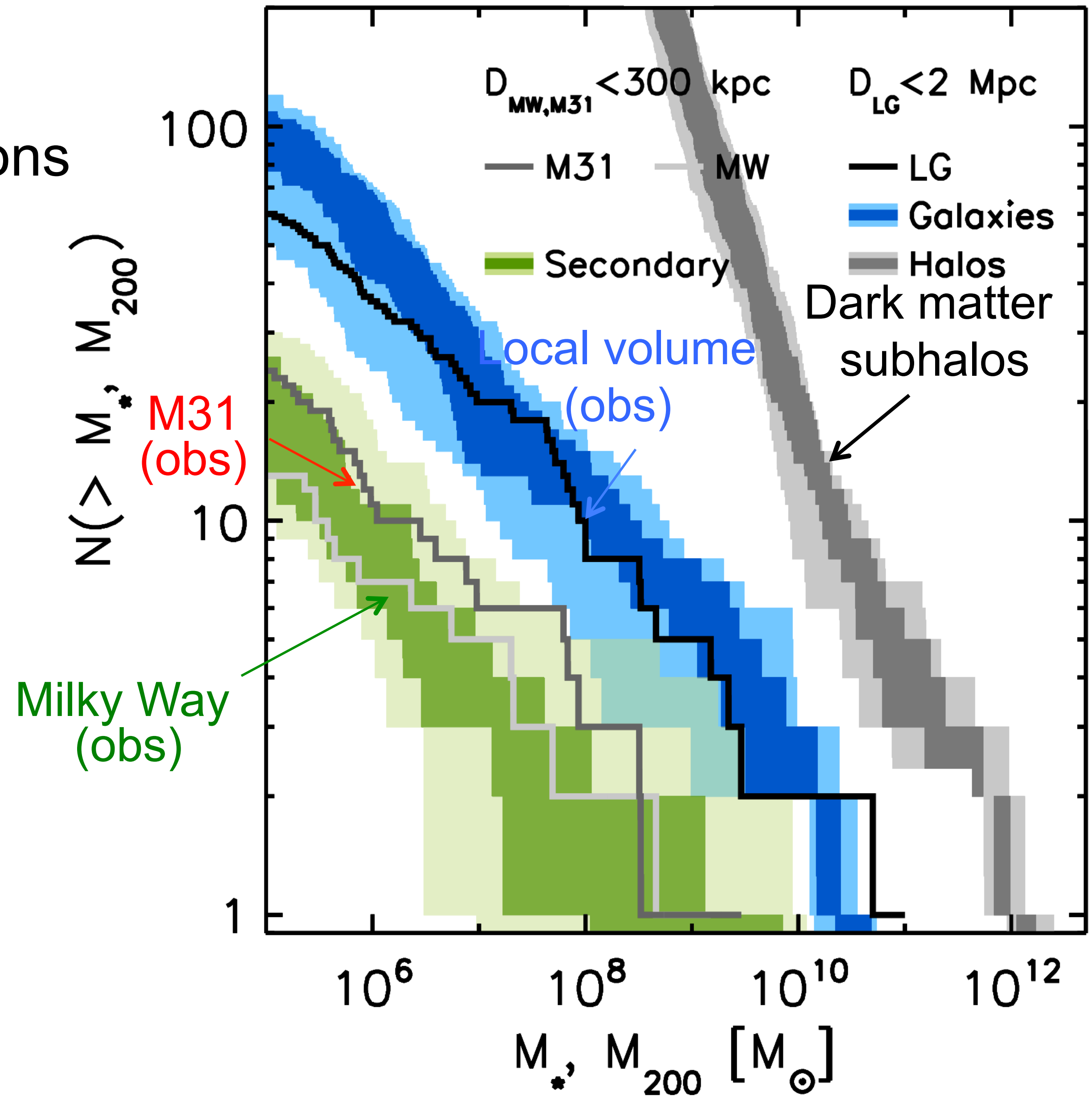
Stellar mass functions



Sawala et al ‘15

EAGLE Local Group simulation

Stellar mass functions



Sawala et al '15

Is there a “satellite problem” in CDM?

No, when galaxy formation is taken into account!

University of Durham

Four problems on small scales

Traditionally ascribed to CDM:

Different in WDM
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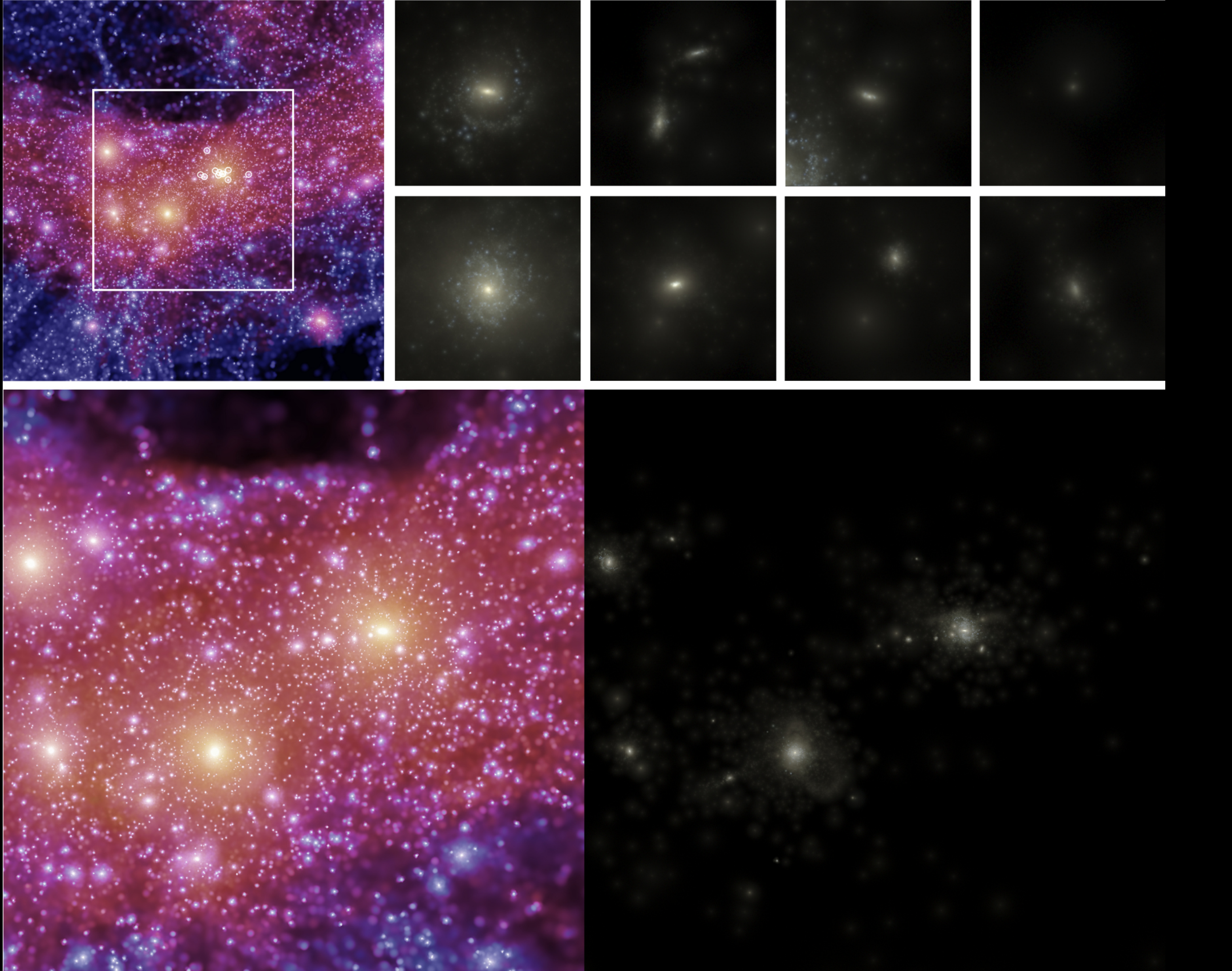


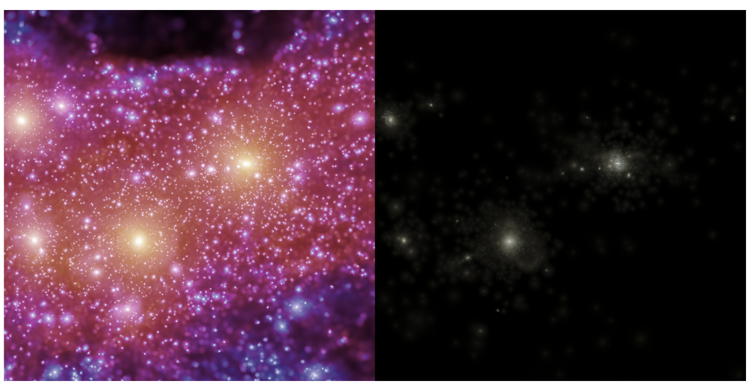
To-big-to-fail in CDM: baryon effects

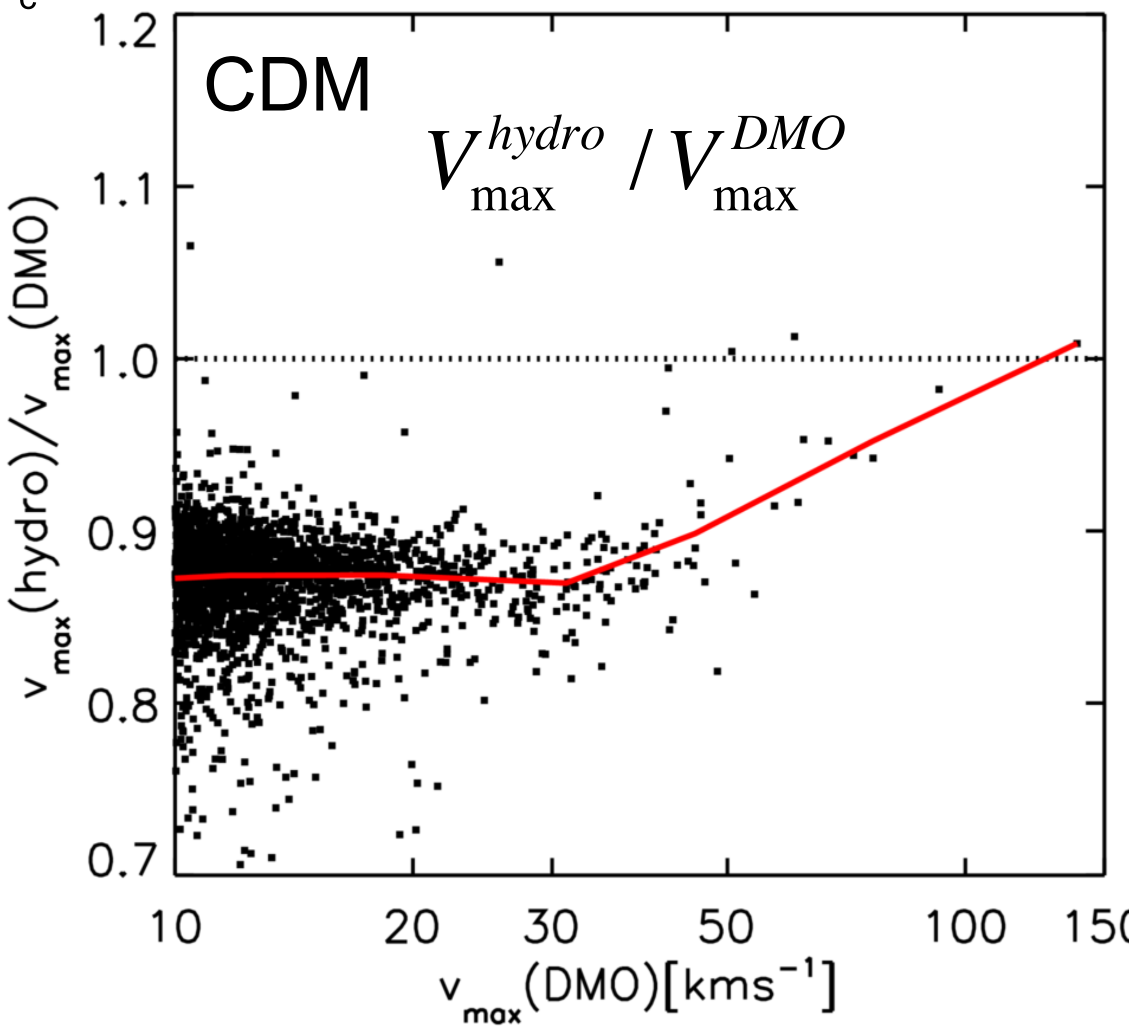
University of Durham

$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate



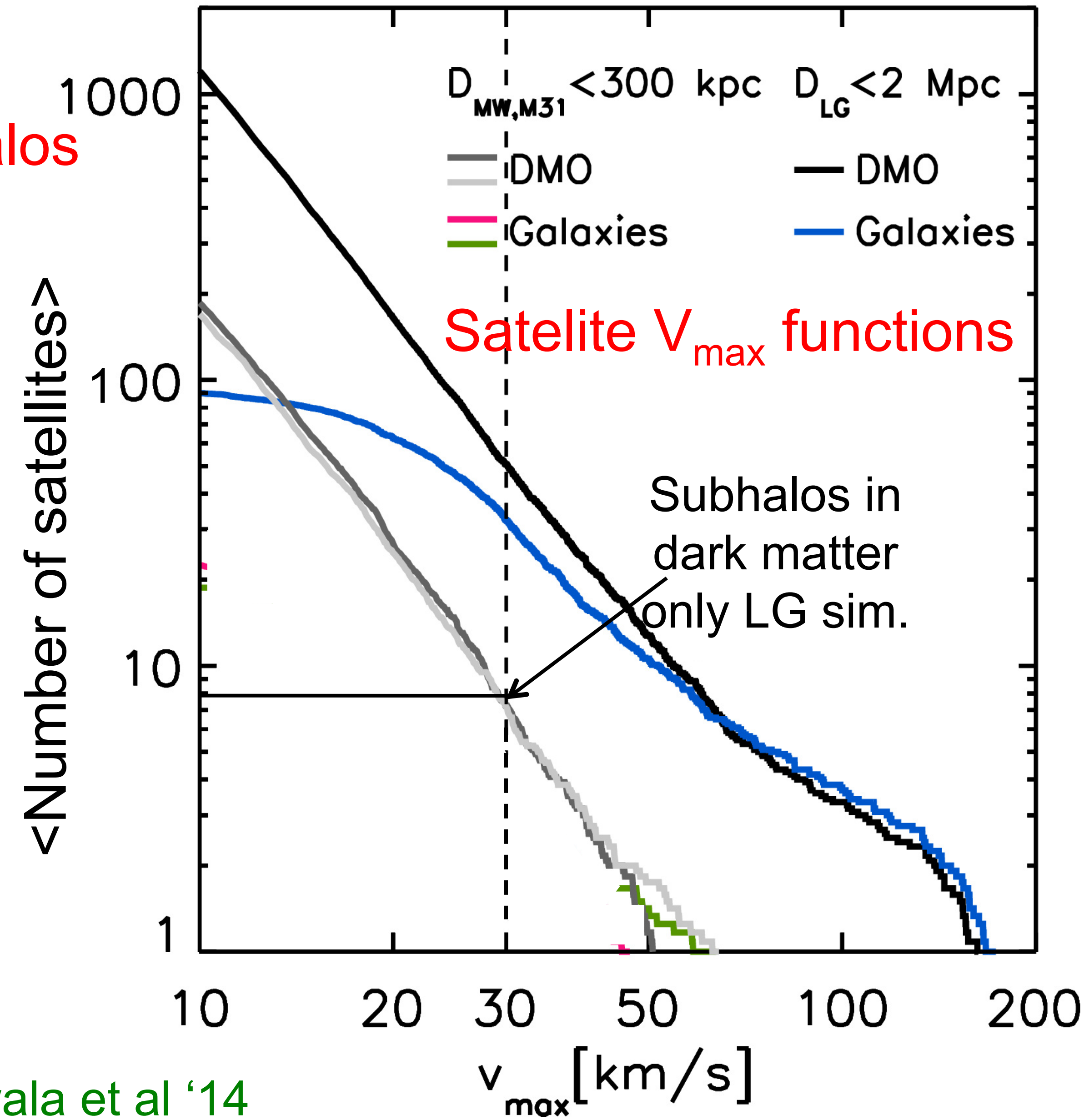


Sawala et al. ‘13, ‘15

Too-big-to-fail: the baryon bailout

University of Durham

DM only sims → ~10 halos with V_{max}> 30 km/s

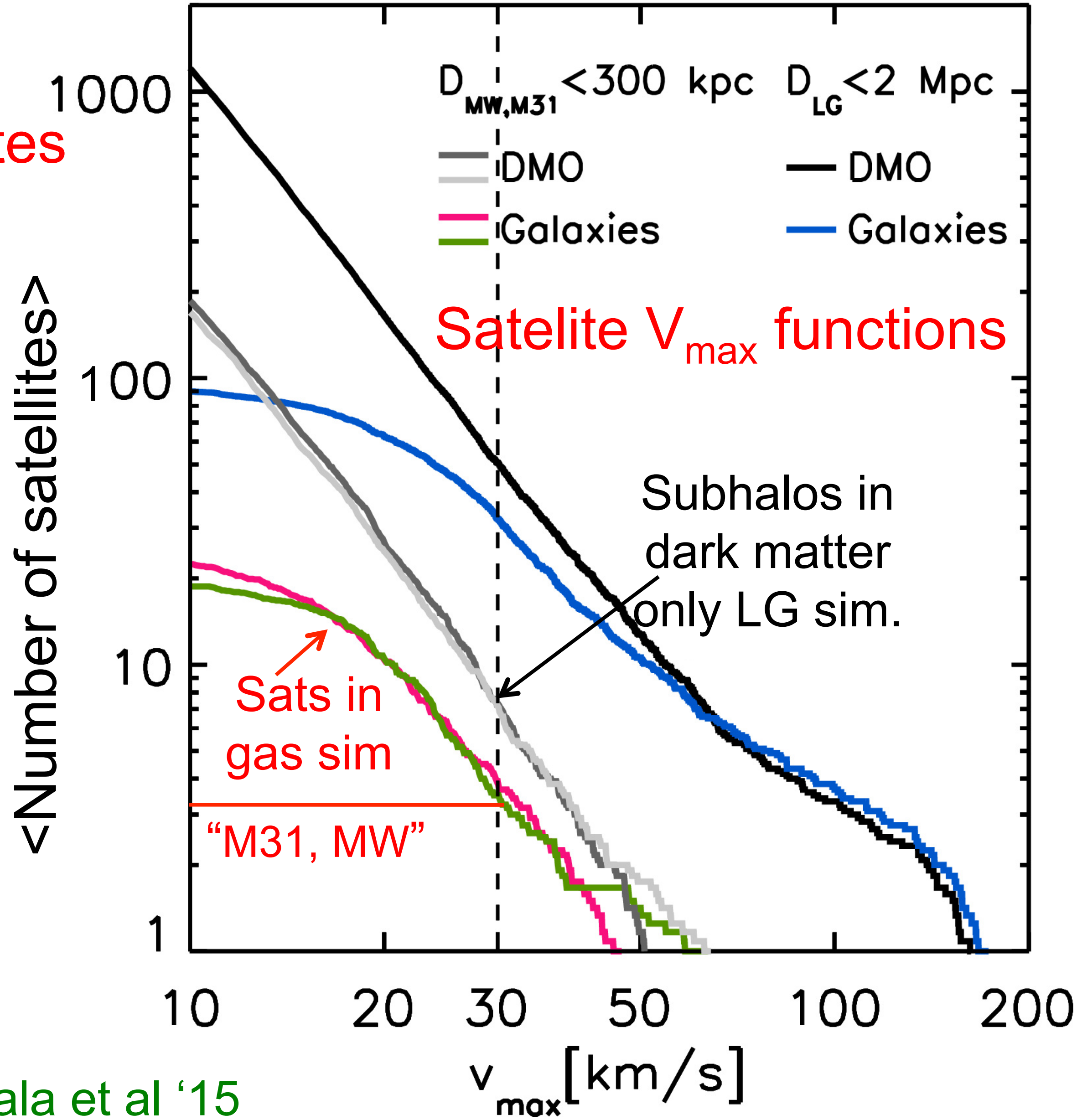


Sawala et al '14

Too-big-to-fail: the baryon bailout

University of Durham

Hydro sims → ~3 satellites with V_{max}> 30 km/s



Sawala et al '15

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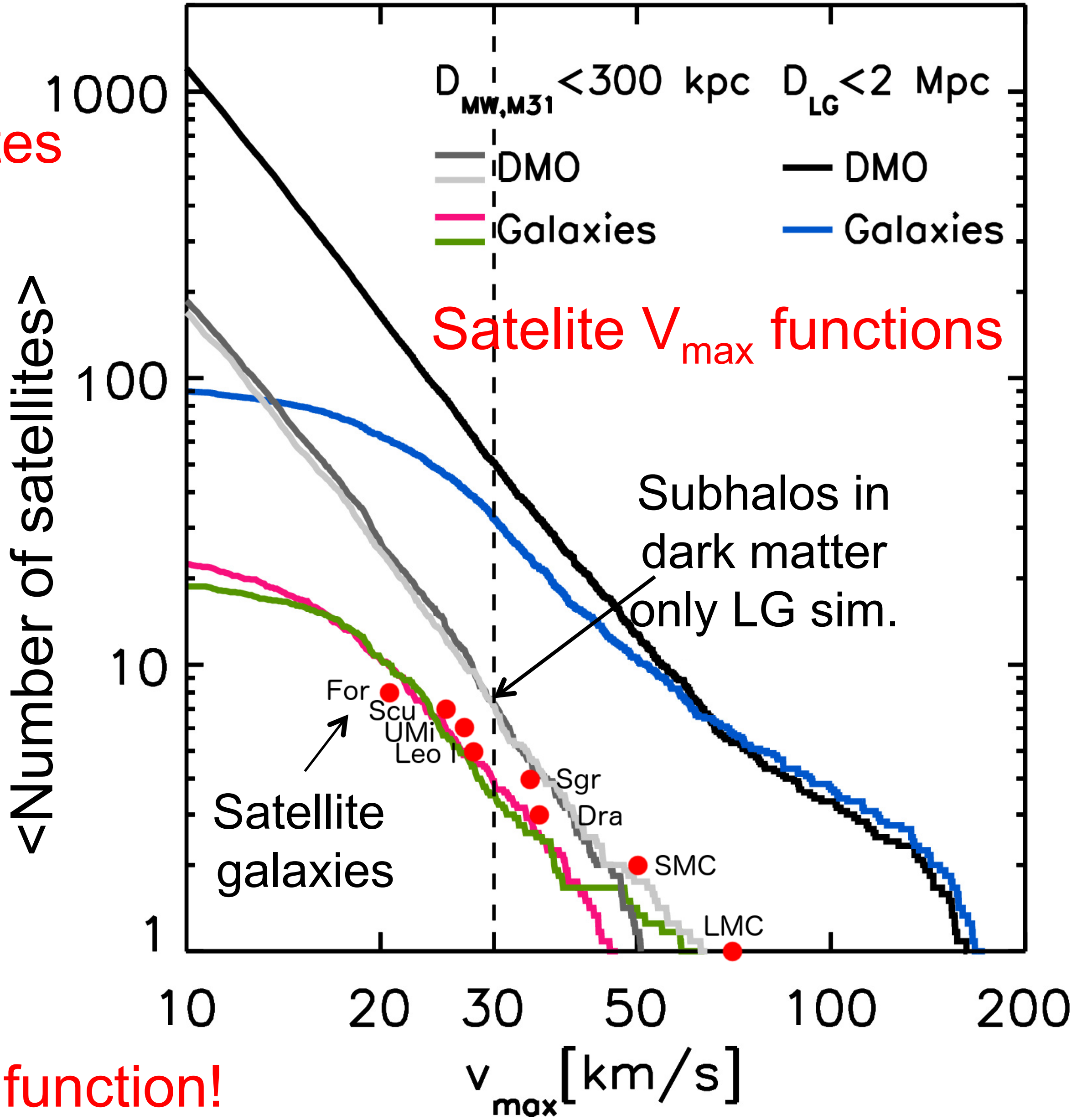

… and with correct V_{max} function!

Is there a "too-big-to-fail" problem in CDM?

No, when galaxy formation is taken into account!

University of Durham

Four problems on small scales

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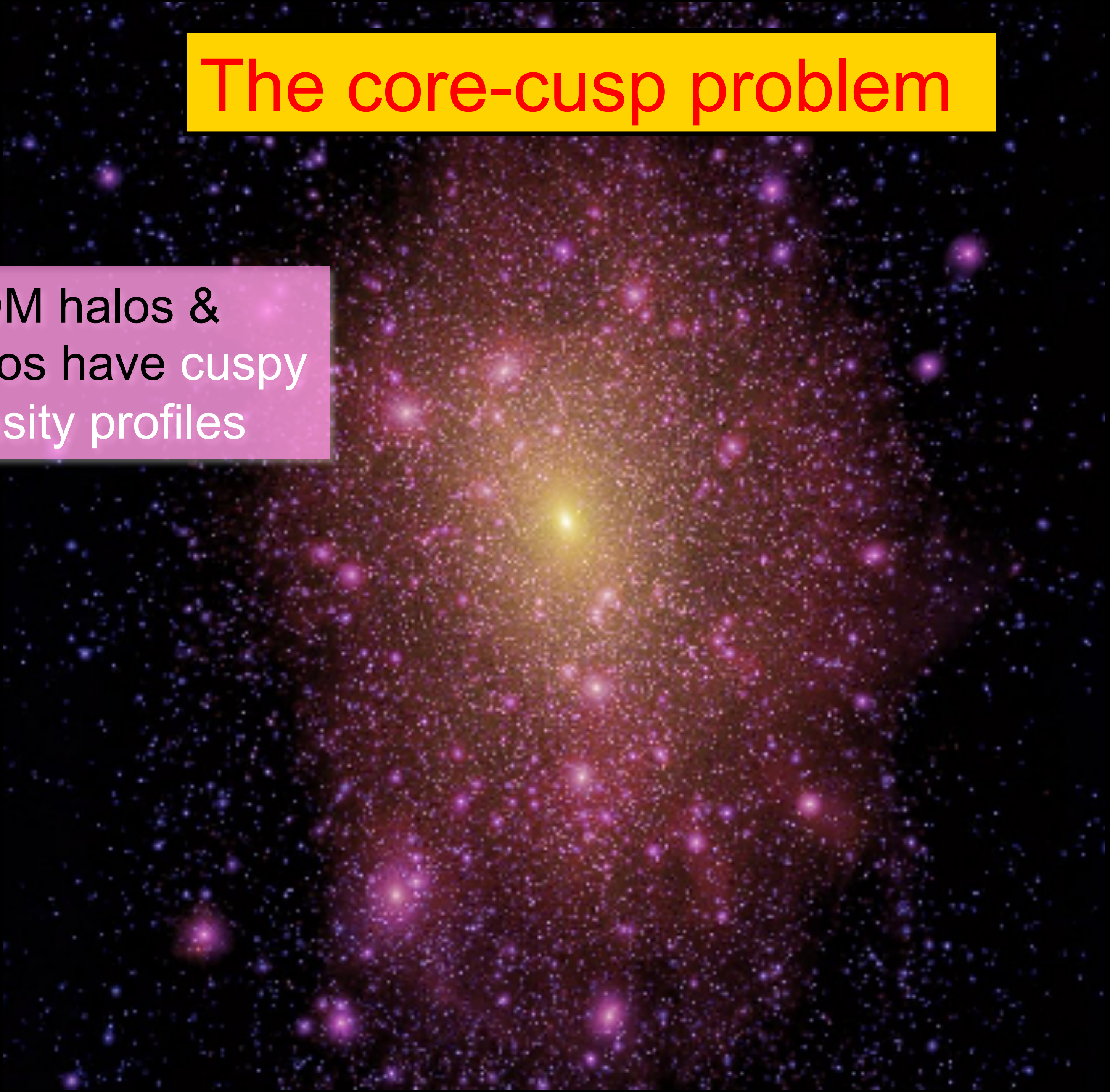
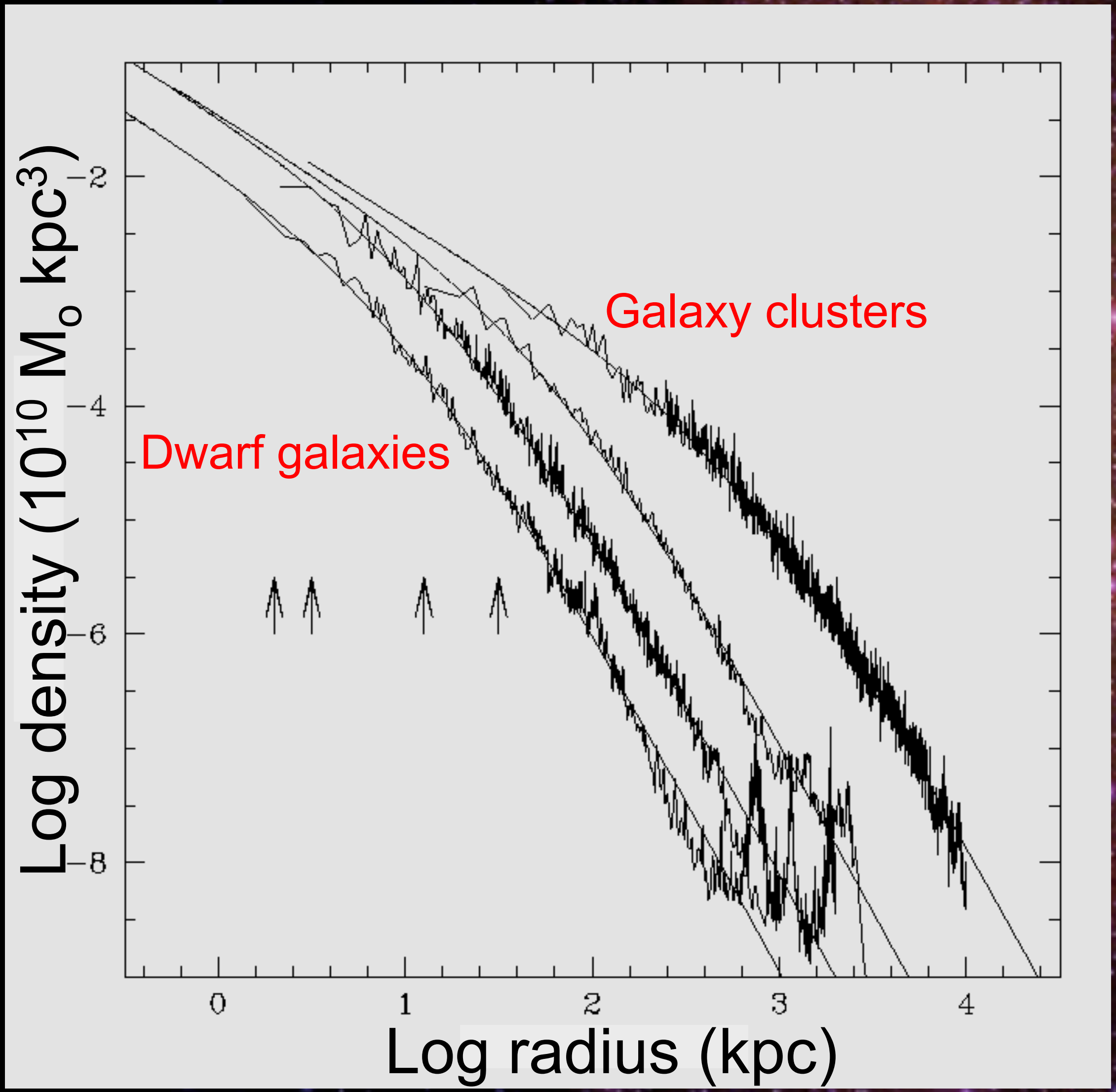
Can these help distinguish between CDM & WDM?

The core-cusp problem



CDM halos & subhalos have cuspy density profiles

The Density Profile of Cold Dark Matter Halos



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are "cuspy" - no `core' near the centre

Fitted by simple formula:

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

More massive halos and halos that form earlier have higher densities (bigger δ)

The core-cusp problem

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

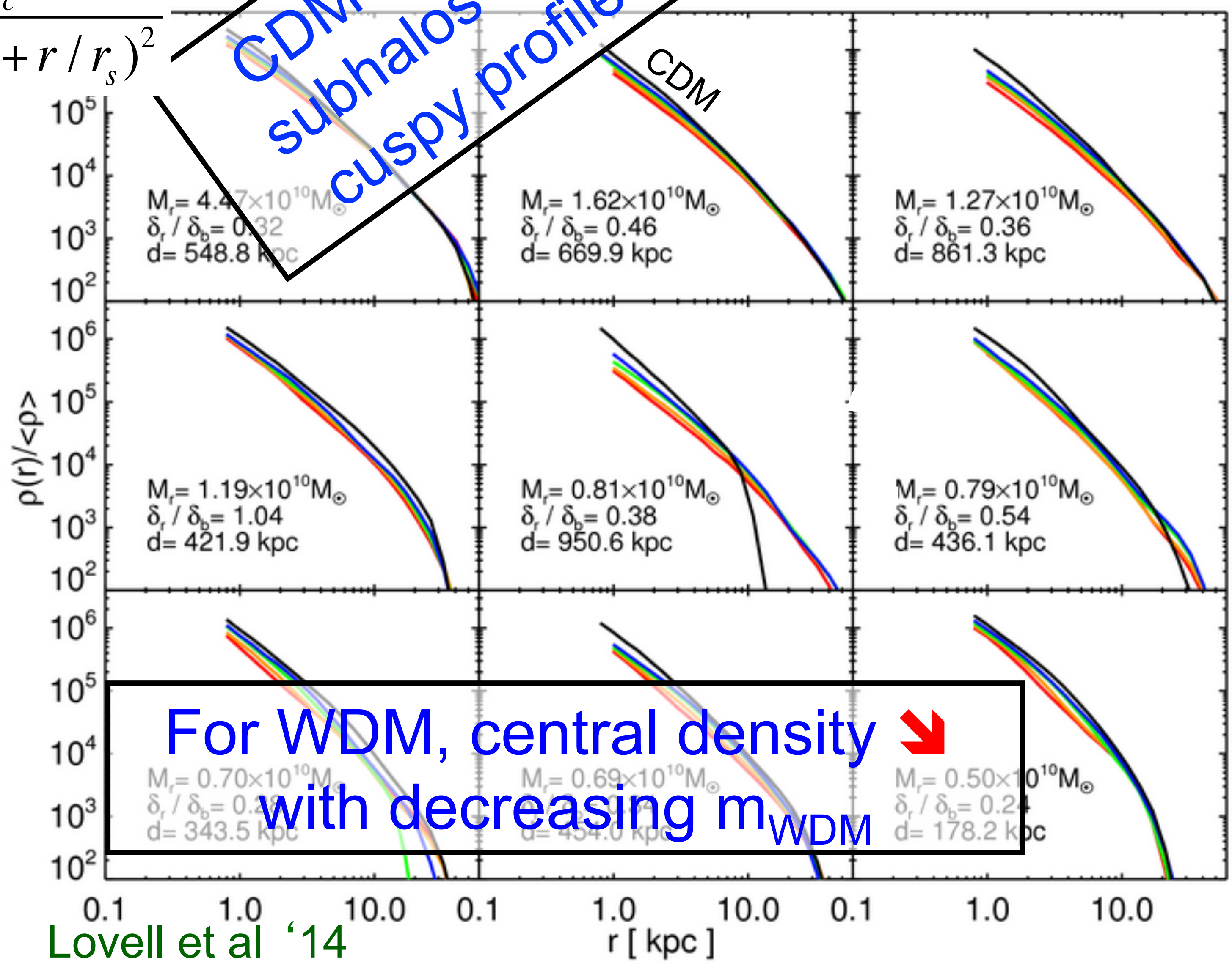
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV

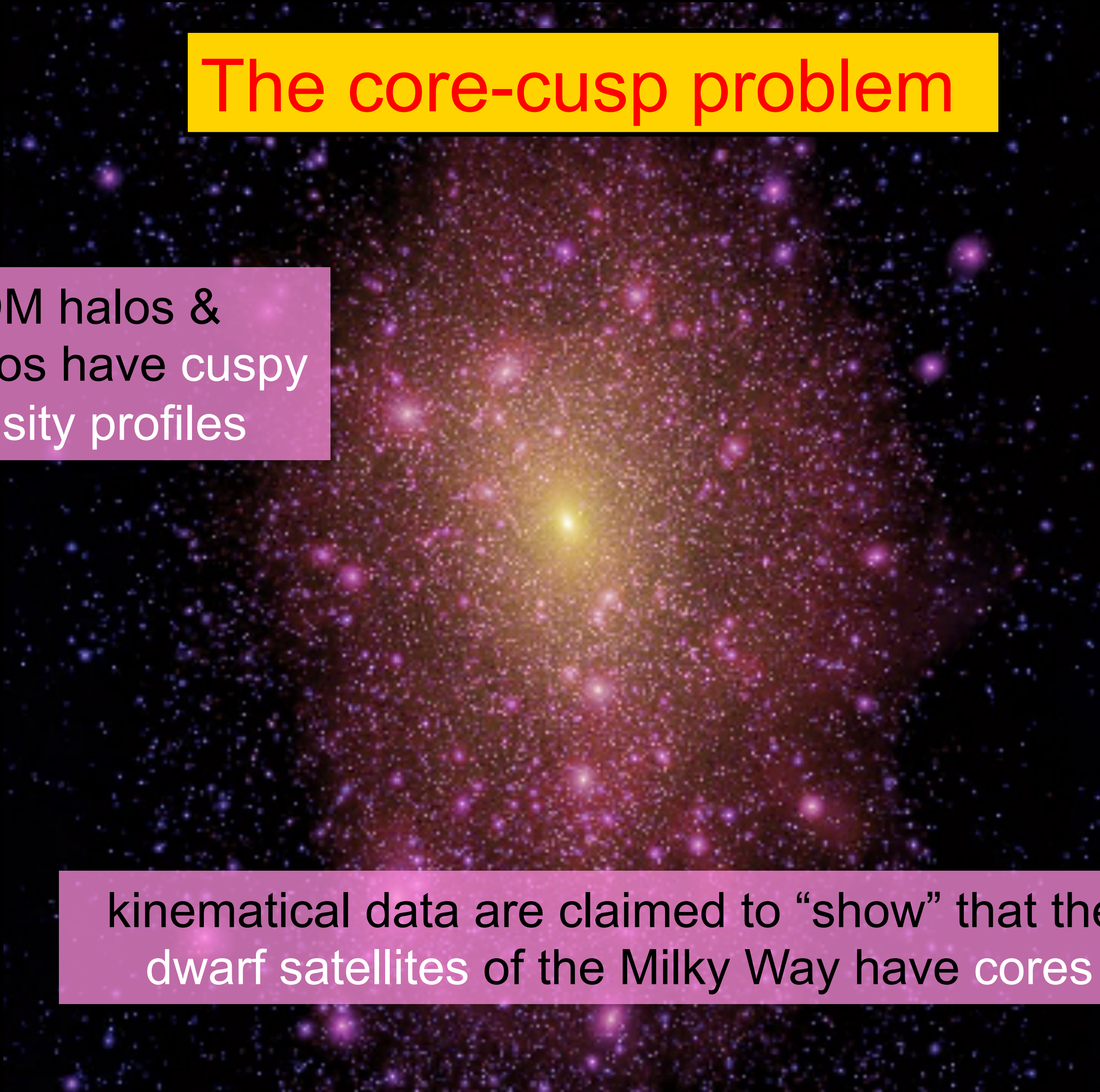


CDM & WDM subhalos have cuspy profiles

For WDM, central density ↘ with decreasing m_{WDM}

Lovell et al '14

The core-cusp problem



CDM halos & subhalos have cuspy density profiles

kinematical data are claimed to “show” that the dwarf satellites of the Milky Way have cores

Dwarf galaxies around the Milky Way

Many claims that dwarf spheroidal satellites have density cores

- e.g. Gilmore et al. ’07, Kuzio de Naray ’08 and many more

Fornax

Sculptor

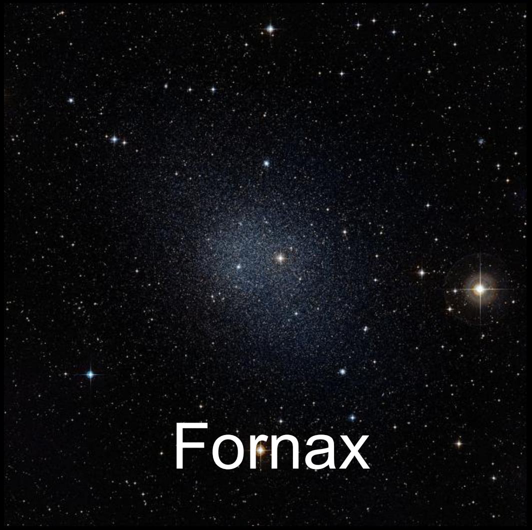
Leo I

Sextans

Carina

Sagittarius

Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

The DM halo of the Sculptor dwarf

University of Durham

Sculptor has two stellar pops:

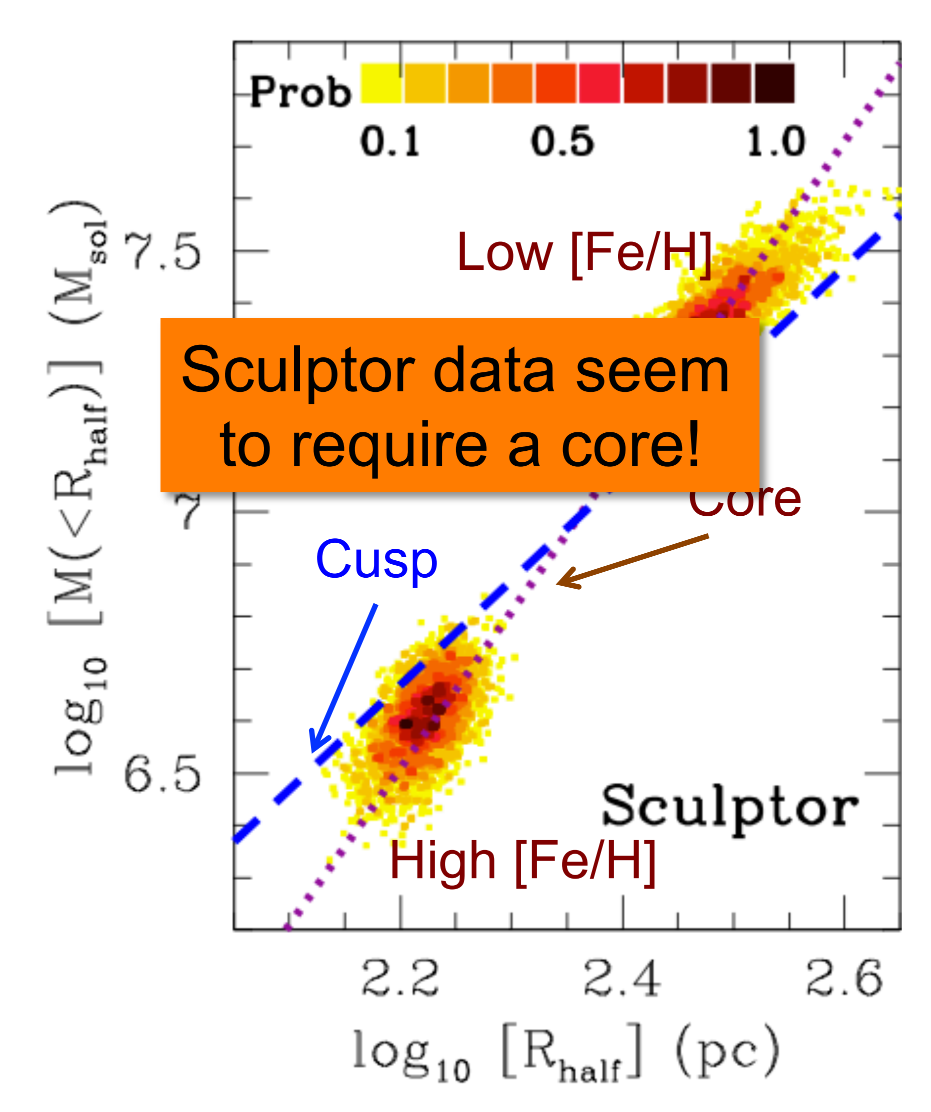
(i) centrally concentrated, high [Fe/H]

(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

University of Durham ICC

The DM halo of the Sculptor dwarf

Strigari, Frenk & White '15

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

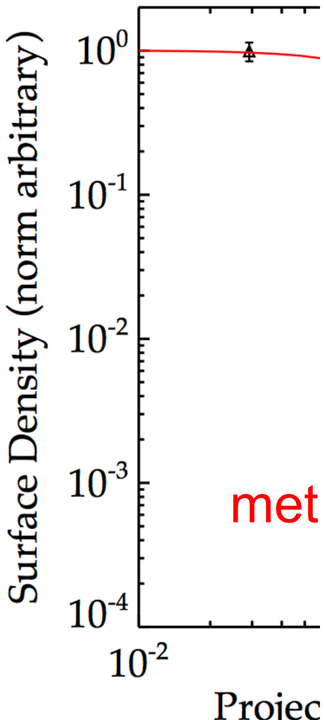
$$h(E) = \begin{cases} NE^a(E^q + E_c^q)^{d/q}(\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for} E \geq \Phi_{lim}, \end{cases}$$

Find best-fit parameters using MCMC

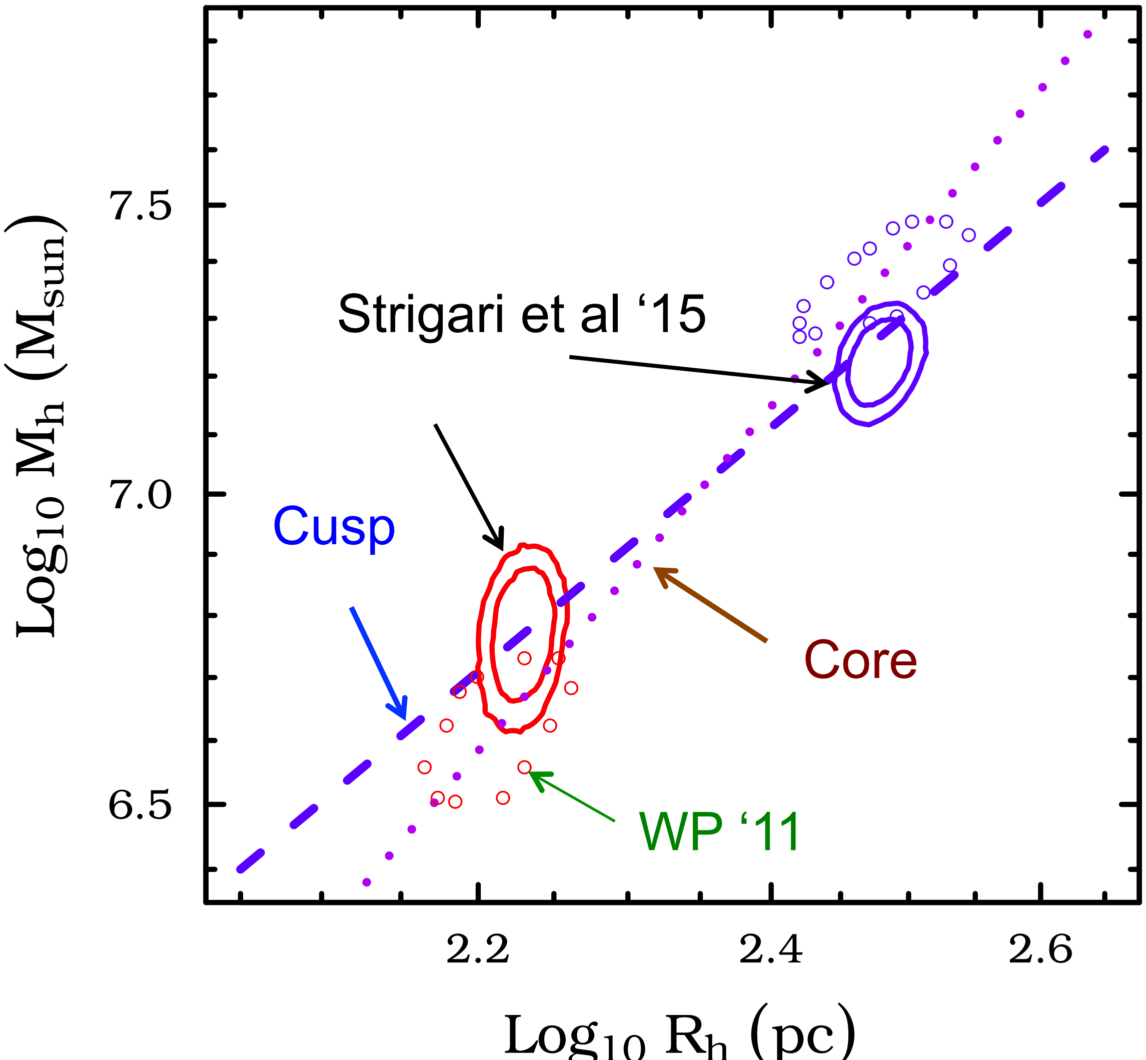
Institute for Computational Cosmology

The DM halo of the Sculptor dwarf

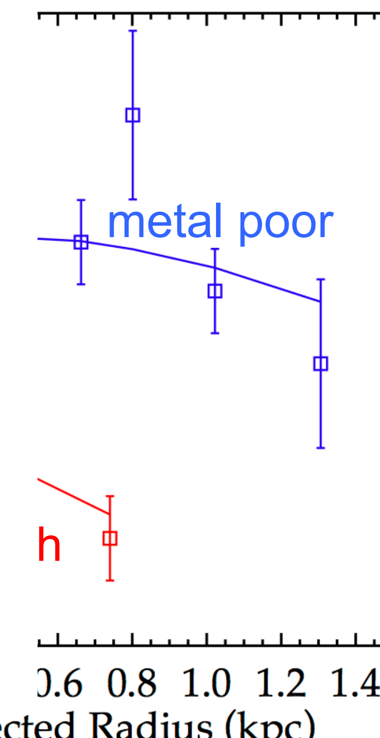
University of Durham



Distribution function analysis



y dispersion



Data cons
eq

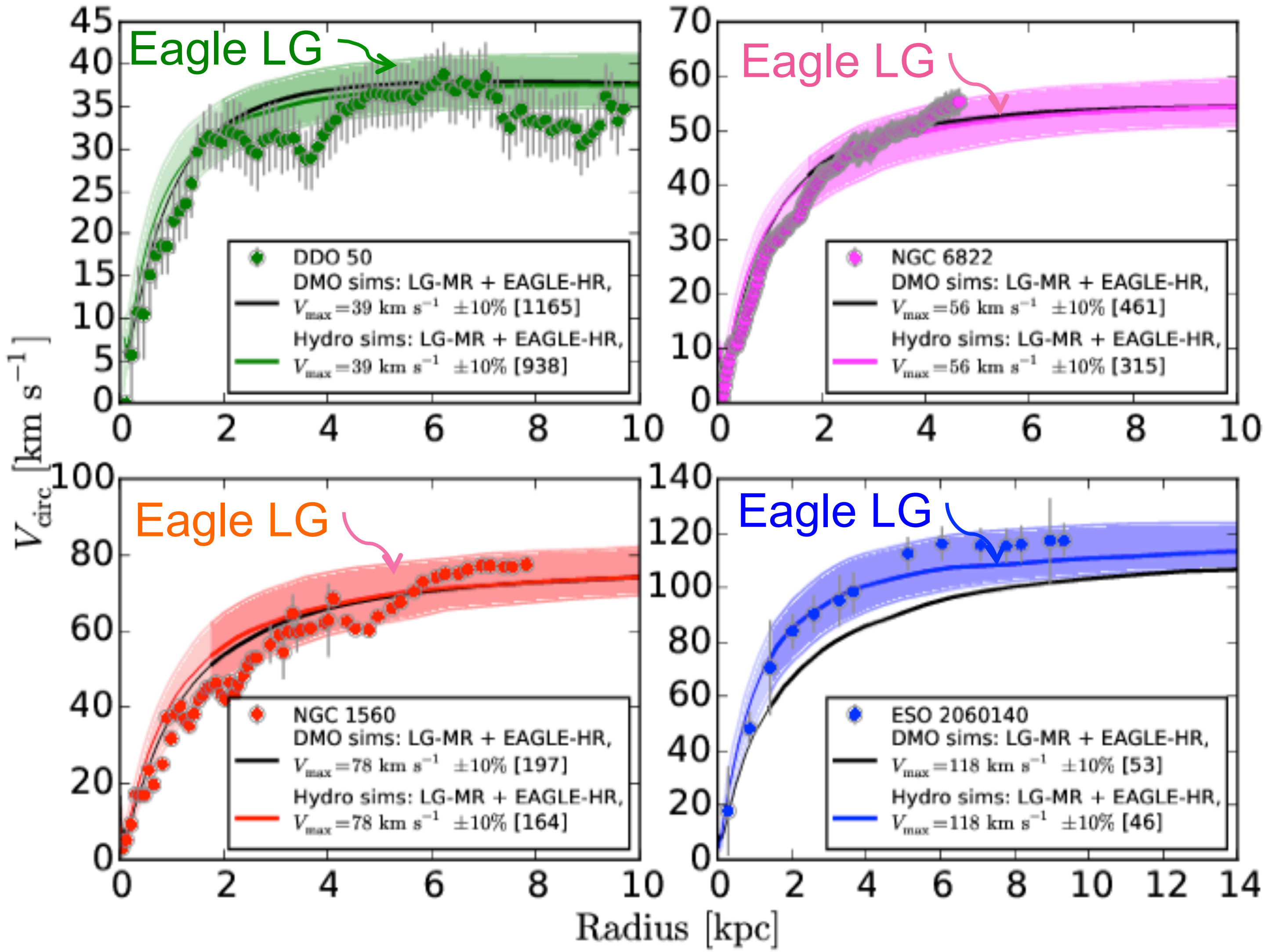
Strigari, Frenk & White '15

The diversity of gal rotation curves

University of Durham

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L*)



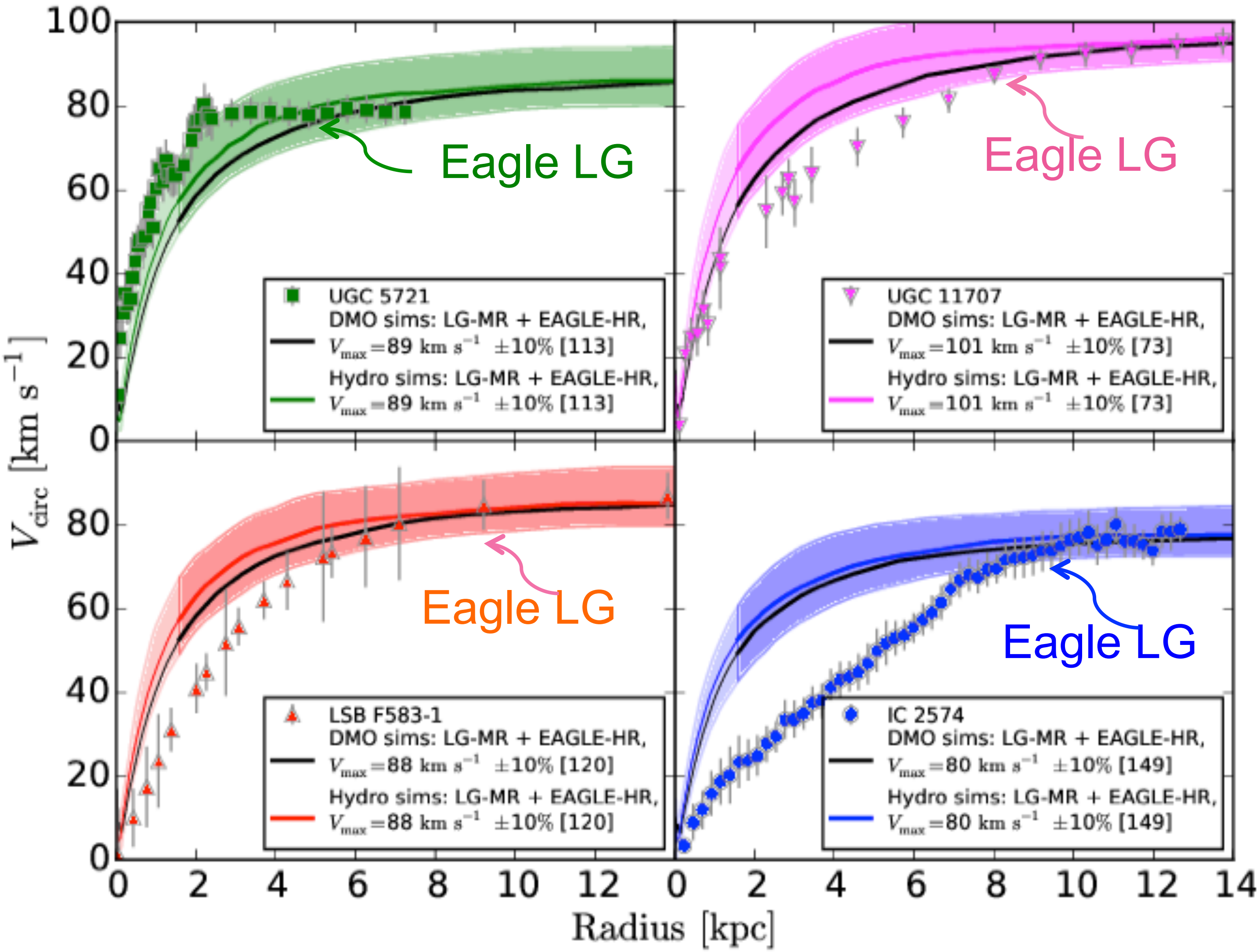
Oman, Navarro, Frenk et al. ‘15

The diversity of gal rotation curves

University of Durham

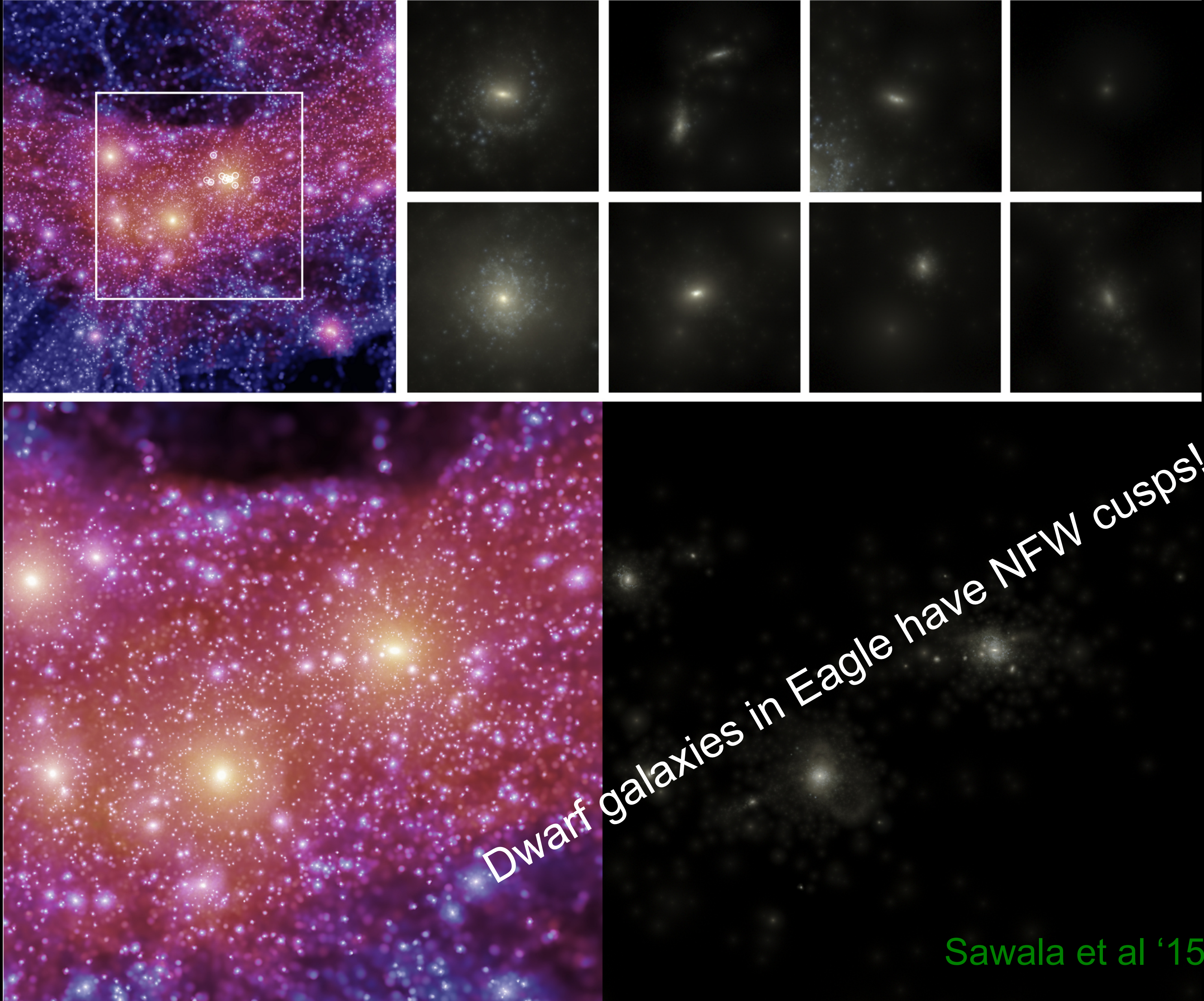
Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~L*)

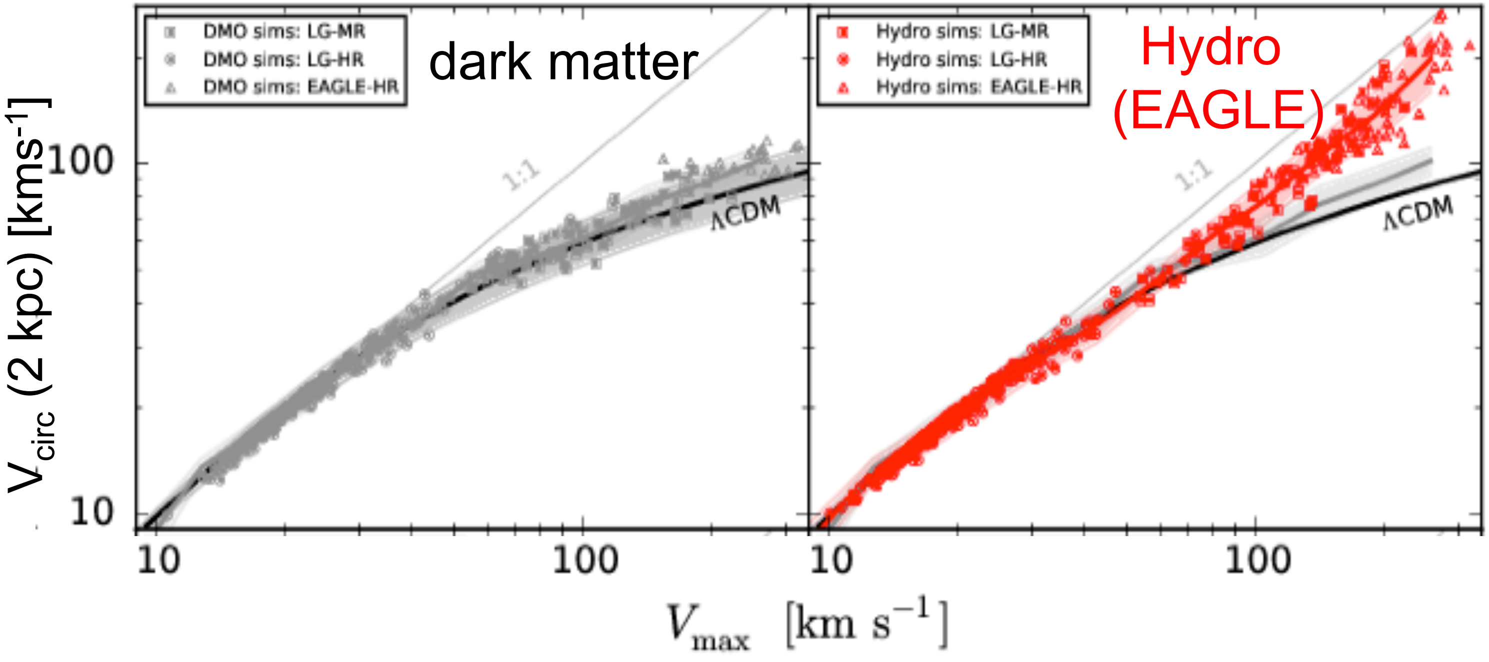


Oman et al. '15

Institute for Computational Cosmology

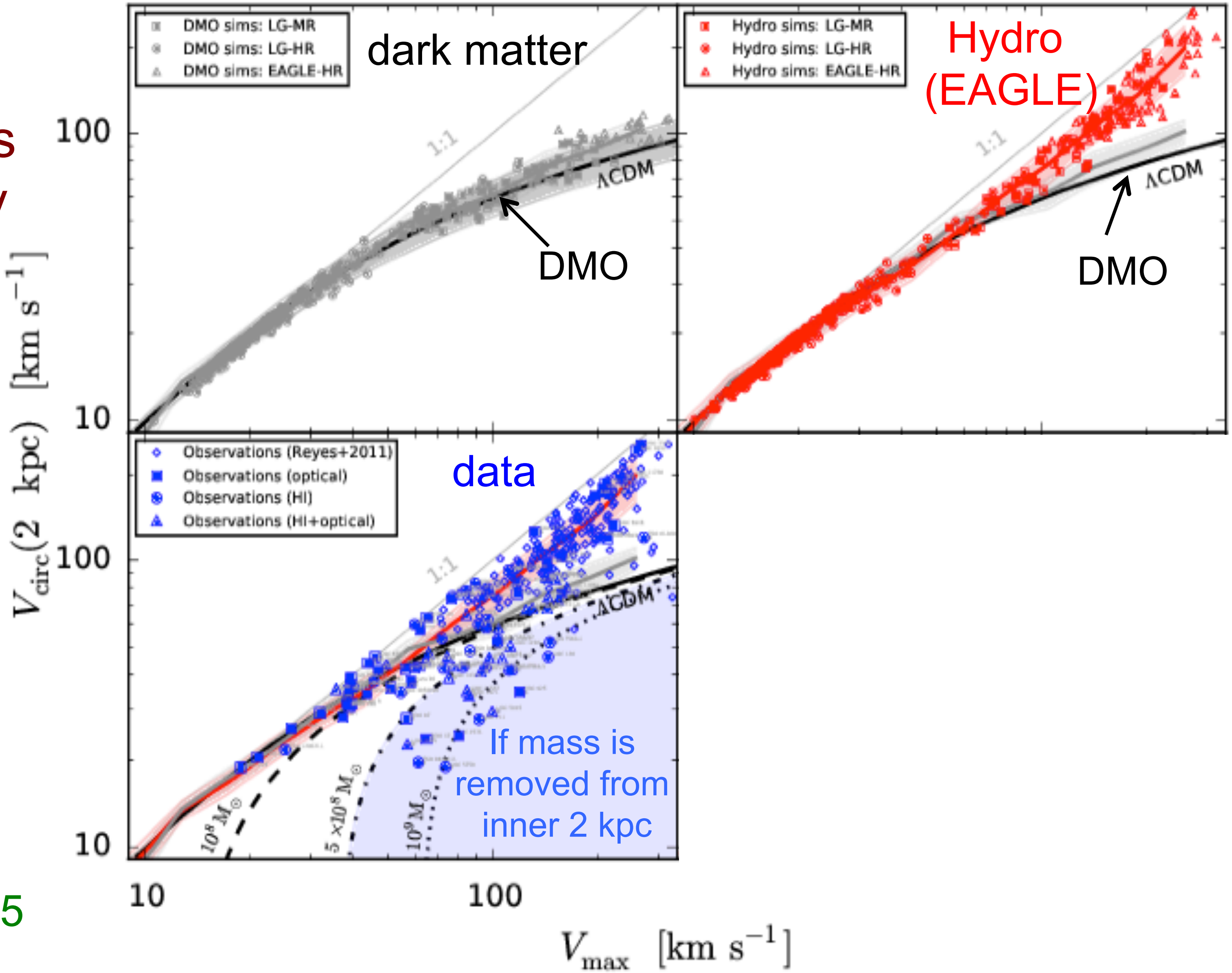

Dwarf galaxies in Eagle have NFW cusps!
Sawala et al '15

The diversity of gal rotation curves



Oman et al. '15

The diversity of gal rotation curves



Most galaxies are well fit by EAGLE; others not fit by any simulation

Oman et al. '15

Are there other baryon effects that could make cores but are not present in Eagle?

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

The cores of dwarf galaxy haloes

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

[1]*Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA*
[2]*Physics Department, University of Durham, South Road, Durham DH1 3LE*

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.

Baryon effects in the MW satellites

University of Durham

Let gas cool and condense to the galactic centre

→ gas self-gravitating
→ star formation/burst

Rapid ejection of gas during starburst → a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

Governato et al. '12
Pontzen & Governato '12
Brooks et al. '12

Navarro, Eke, Frenk '96

The cores of dwarf galaxy haloes L75

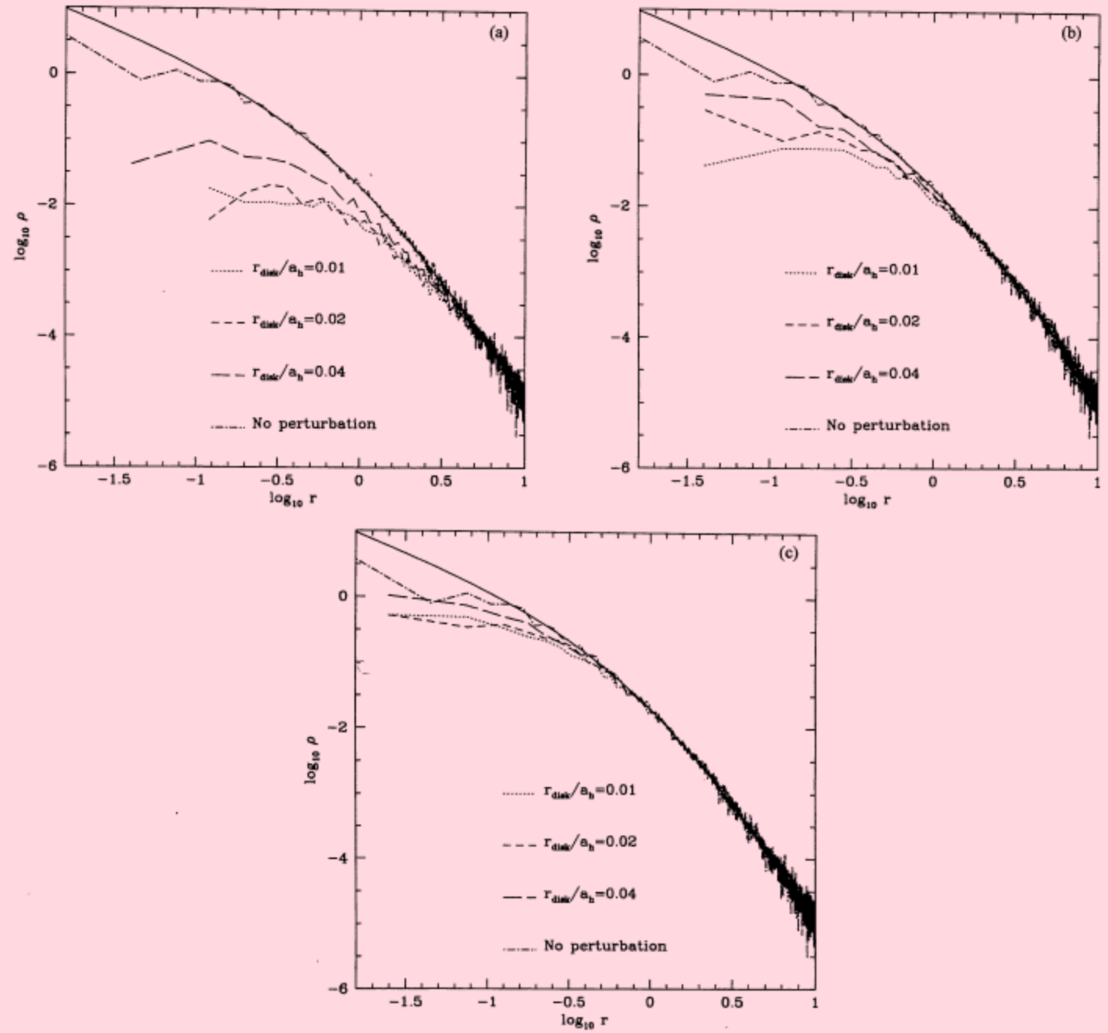


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

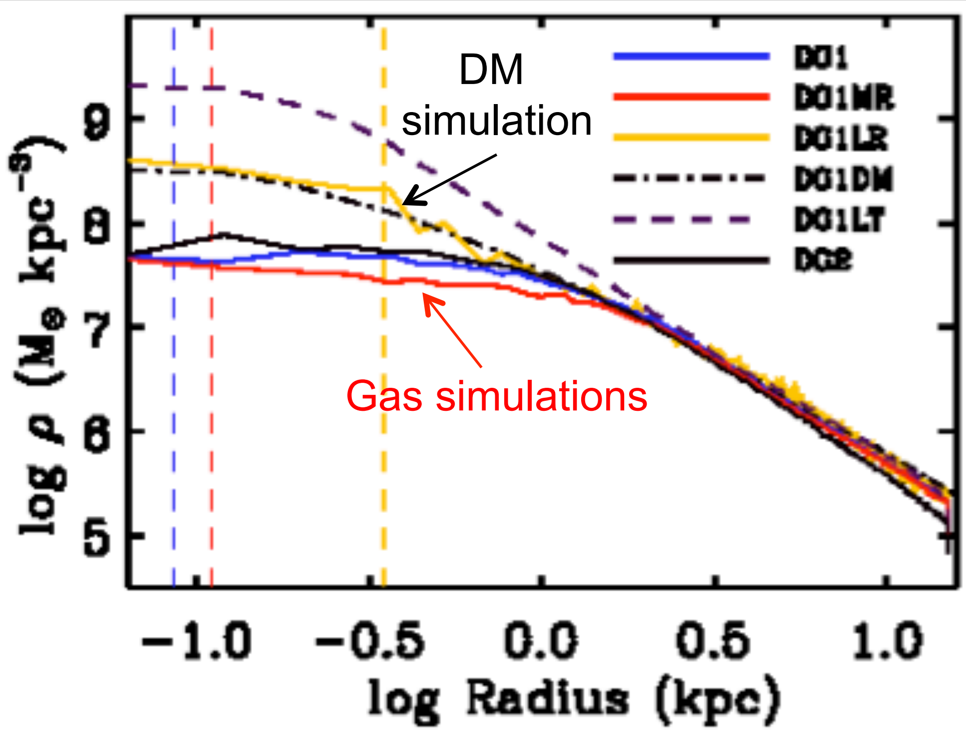
Cores in dwarf galaxy simulations

Governato et al. assume high density threshold for star formation

EAGLE does not

→ High threshold allows large gas mass to accumulate in centre

→ Sudden repeated removal of gas transfers binding energy

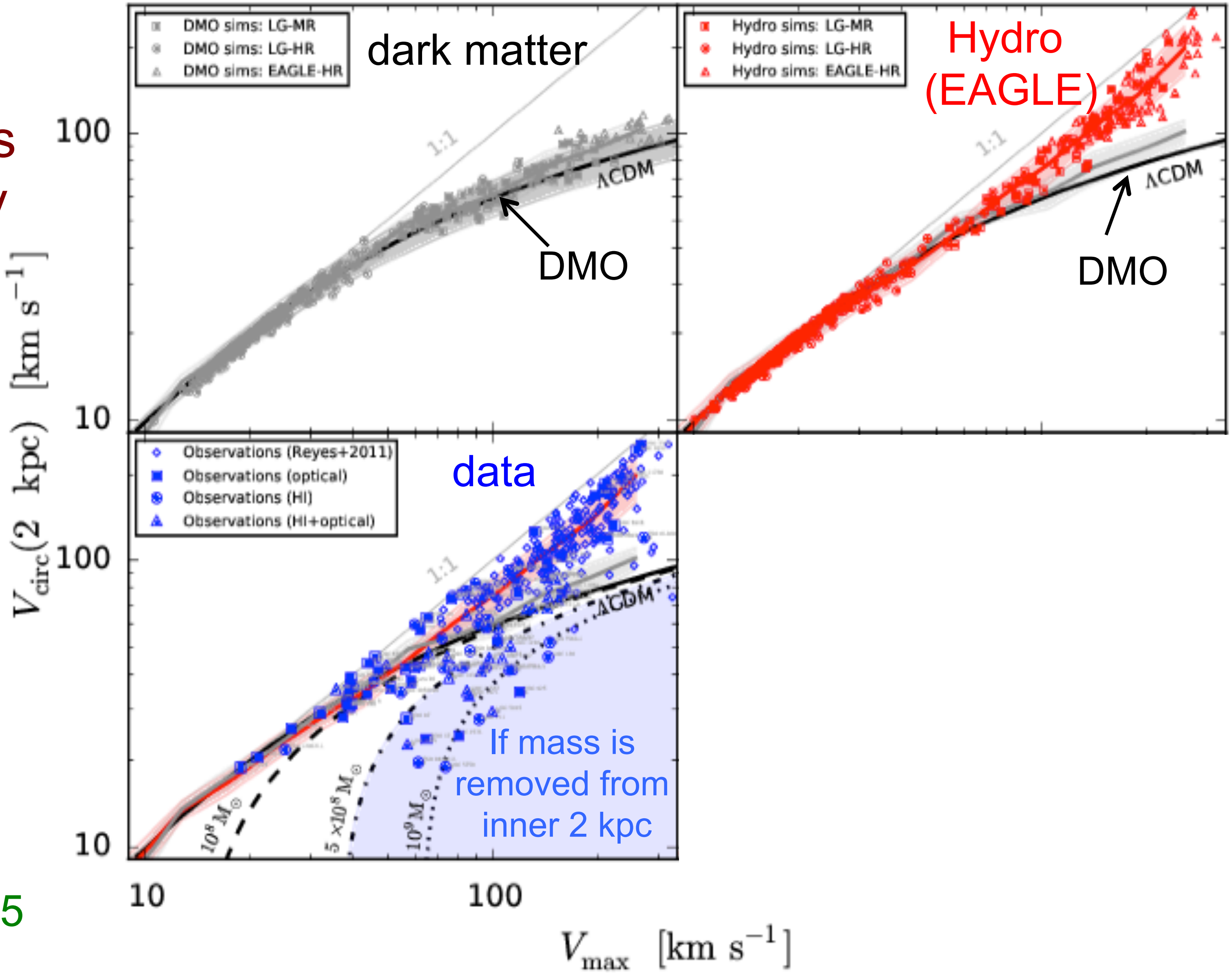


Governato et al. '10
Pontzen et al. '11

The diversity of gal rotation curves

University of Durham

Most galaxies are well fit by EAGLE; others not fit by any simulation



Oman et al. '15

University of Durham

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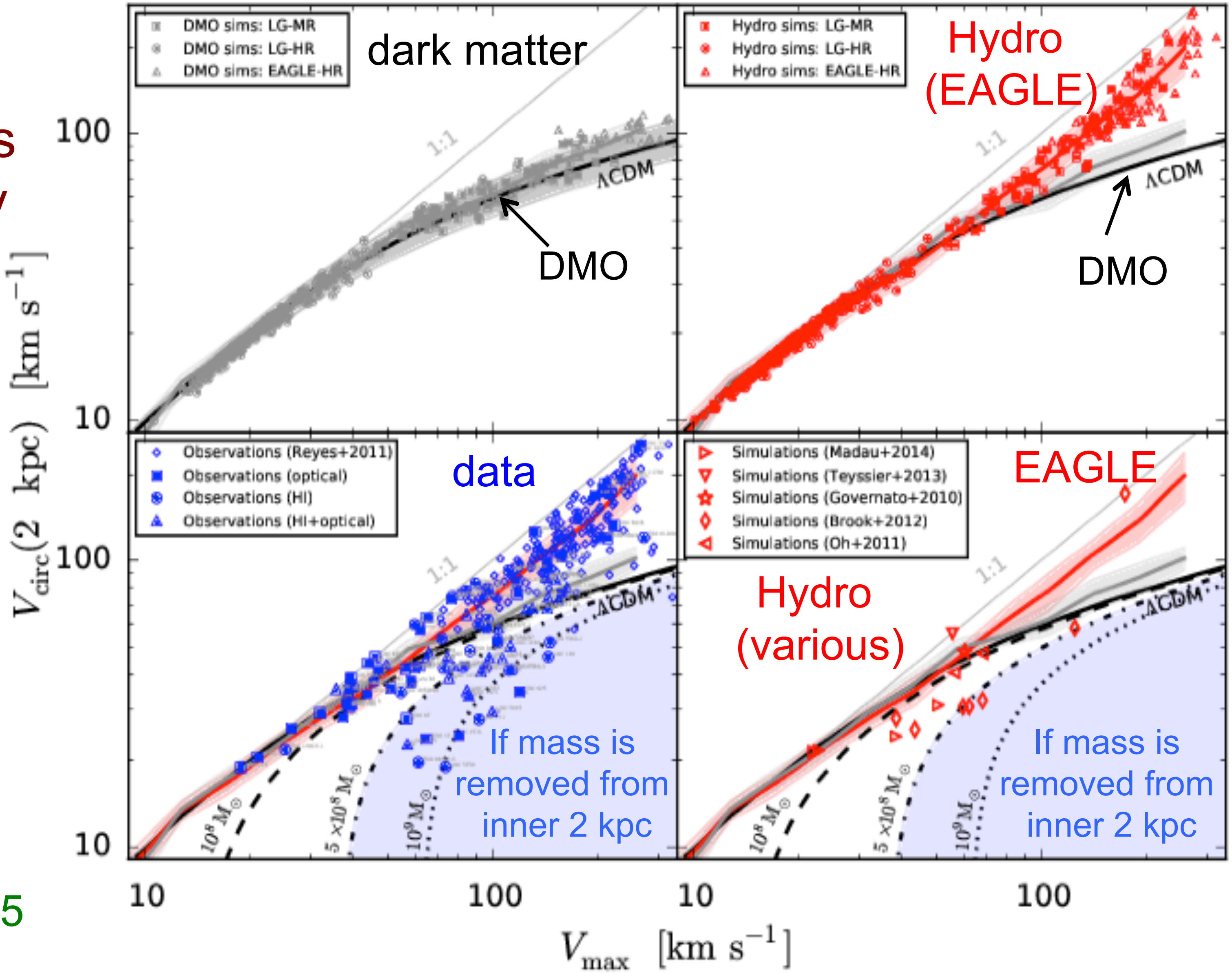


Oman et al. '15

Cores or cusps in dwarf gals?

- Some dwarfs have rotation curves that agree well with EAGLE
- Others have inner mass deficits compared to ΛCDM expectation
- In many cases, inner deficit much larger than seen in simulations that make cores

EITHER (i) dark matter more complex than in any current model

OR (ii) current simulations fail to reproduce effects of baryons on inner regions of dwarfs

AND/OR (iii) the mass profiles of "inner mass deficit" galaxies inferred from kinematic data are incorrect.

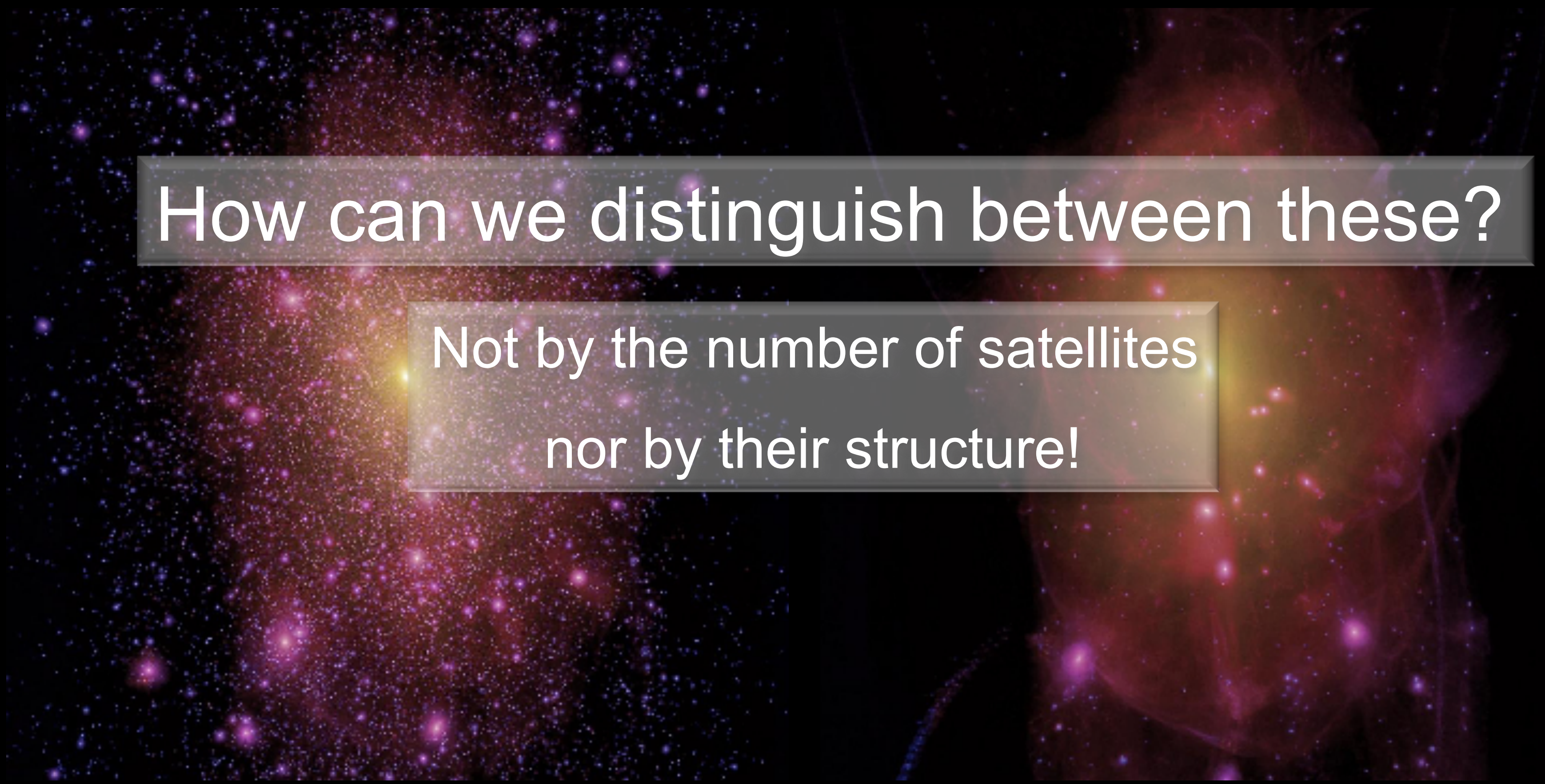
Conclusions

- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution
- But on these scales ΛCDM cannot be distinguished from WDM
- The identity of the DM makes a big difference on small scales

	CDM	WDM
1. The "missing satellites" problem	✓	✓
2. The "too-big-to-fail" problem	✓	✓
3. The "core-cusp" problem	?	?
4. The "satellite disk" problem	✓	✓

cold dark matter

warm dark matter



How can we distinguish between these?

Not by the number of satellites

nor by their structure!

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

Can we distinguish CDM/WDM?

cold dark matter | warm dark matter

1. Dark subhalos (gravitational lensing)?
2. Stellar streams (stellar surveys – PAndAS, GAIA)?