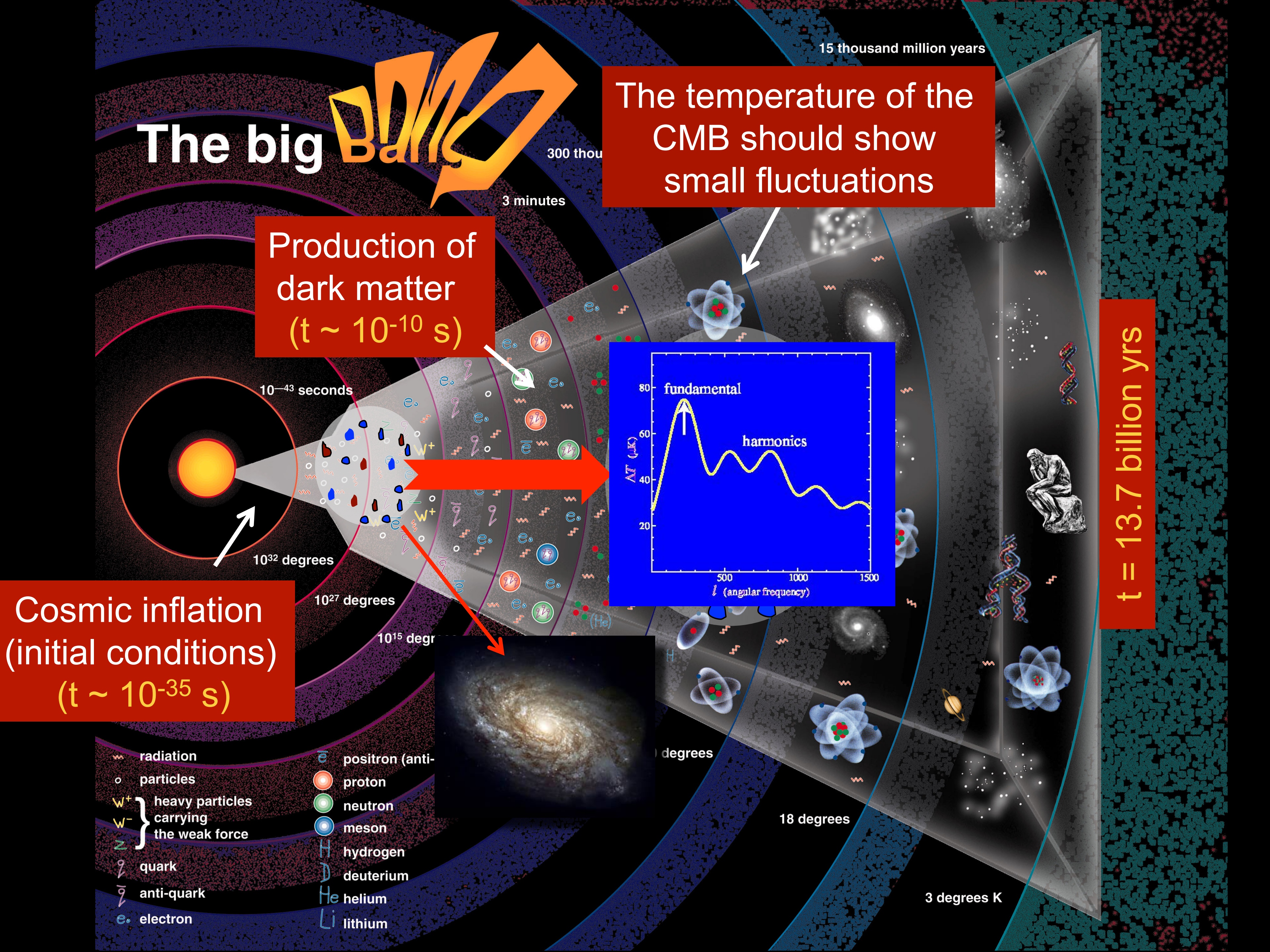
# Inferring the identity of the dark matter from the halo of the Milky Way

*Carlos S. Frenk*
*Institute for Computational Cosmology, Durham*

# Or how to rule out the cold dark matter model

*Carlos S. Frenk*
*Institute for Computational Cosmology, Durham*

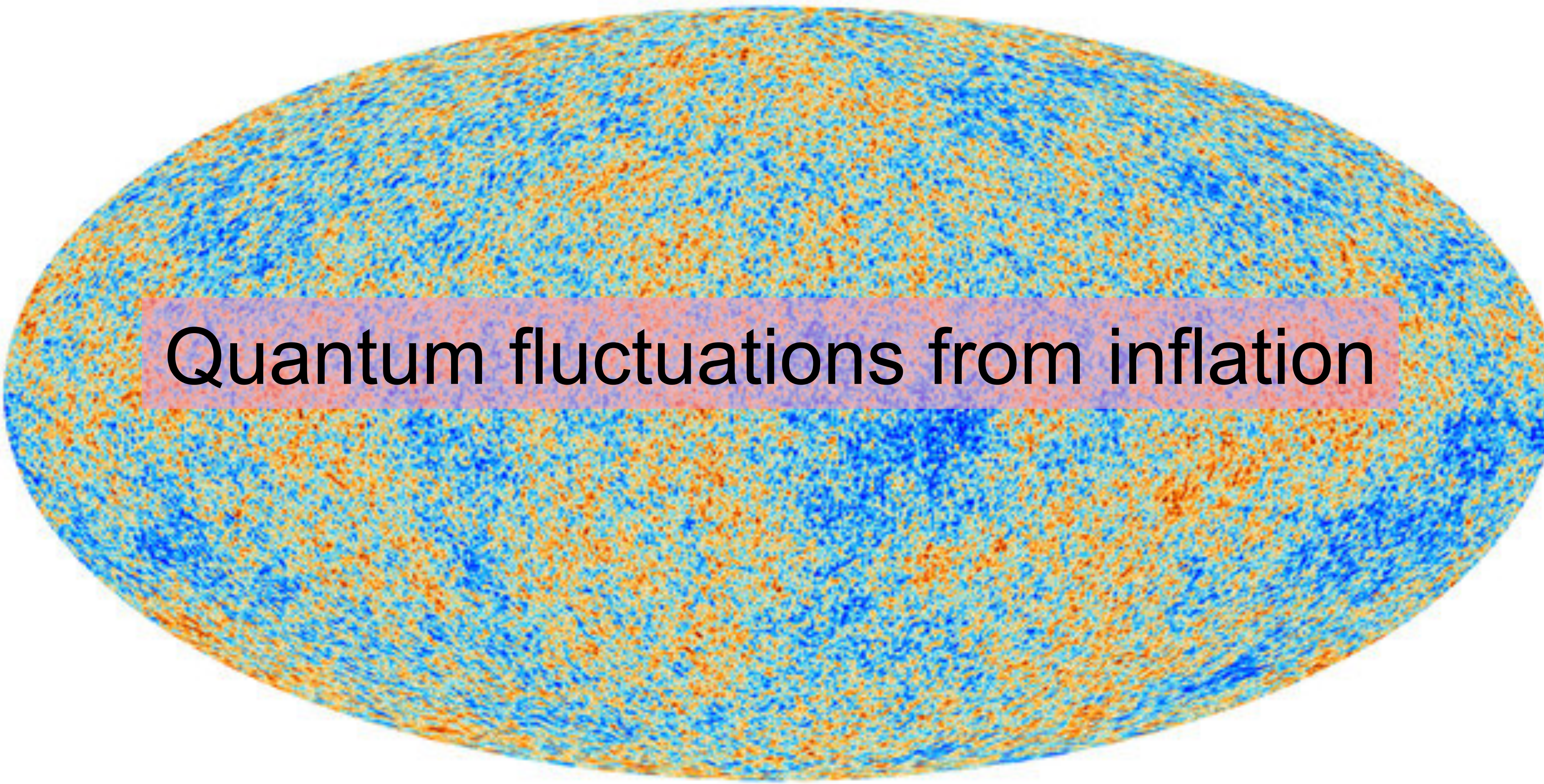
# The ΛCDM model of cosmogony



The big Bang
15 thousand million years
300 thou
3 minutes
The temperature of the CMB should show small fluctuations
Production of dark matter (t ~ $10^{-10}$ s)
$10^{-43}$ seconds
$10^{32}$ degrees
$10^{27}$ degrees
$10^{15}$ degr
fundamental
harmonics
$\Delta T$ (μK)
80
60
40
20
500
1000
1500
$l$ (angular frequency)
t = 13.7 billion yrs
Cosmic inflation (initial conditions) (t ~ $10^{-35}$ s)
degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium

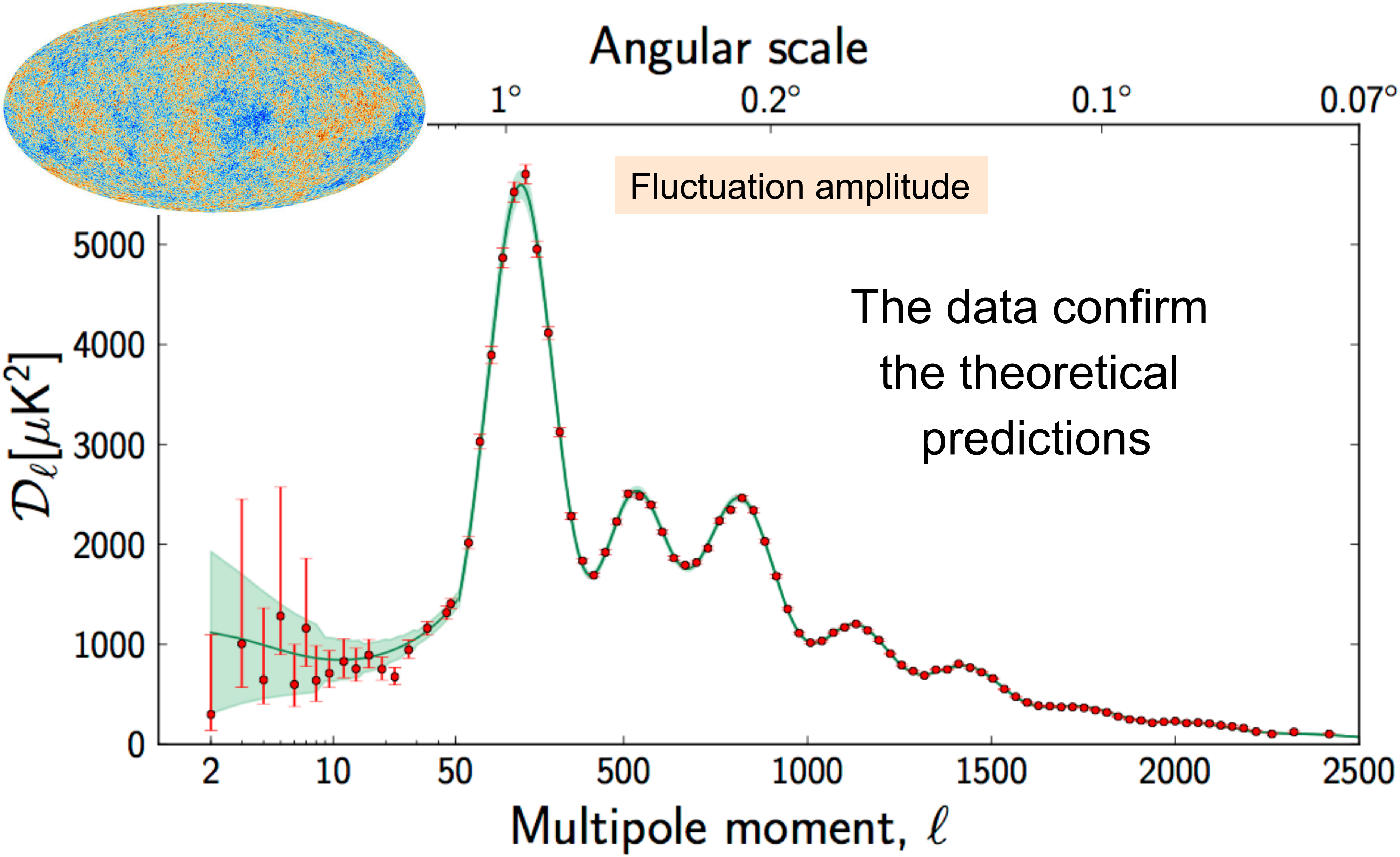
University of Durham

# The initial conditions for galaxy formation



University of Durham

# Planck: CMB temperature anisotropies




Planck coll. 2015

# The six parameters of minimal $\Lambda$CDM model

Univer

6 mdoel parameters

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

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

Planck collaboration '13

Institute for Computational Cosmology

University of Durham

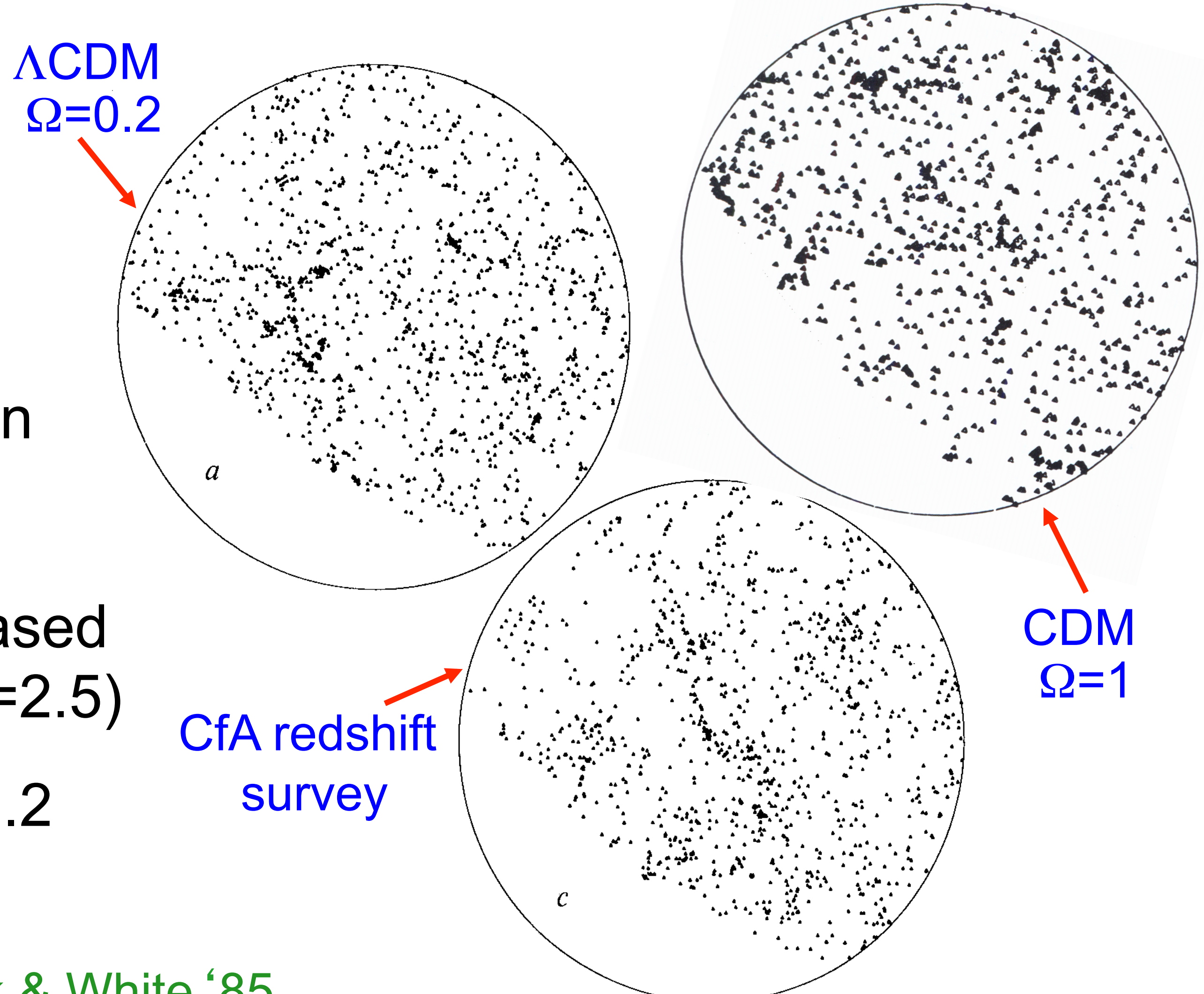
# Non-baryonic dark matter cosmologies

Early CDM N-body simulations gave promising results

Observed galaxy clustering pattern can be reproduced by:

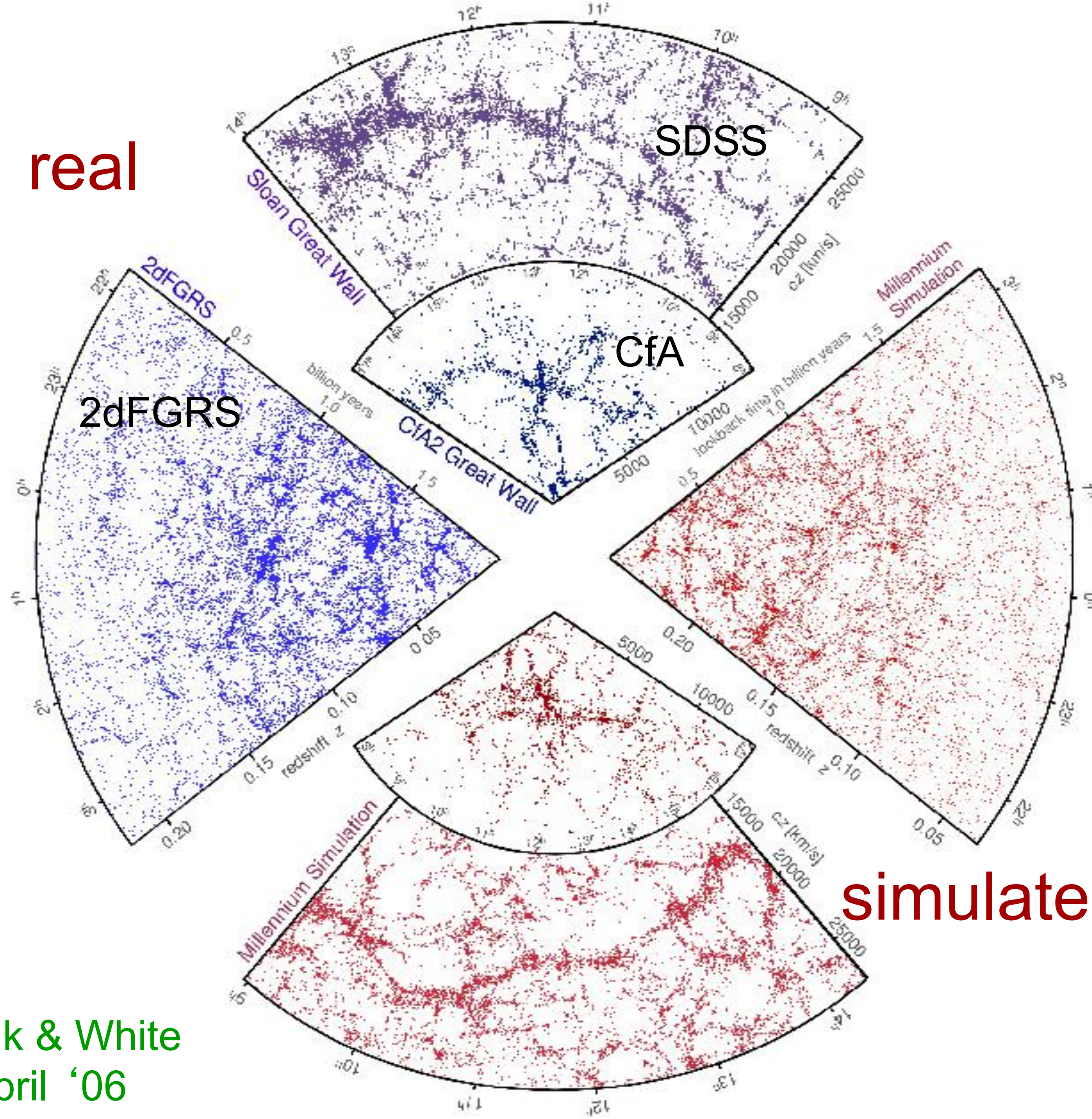
i) $\Omega$=1 CDM with biased galaxy formation (b=2.5)

ii) $\Lambda$CDM with $\Omega_m$=0.2




Davis, Efstathiou, Frenk & White '85

real

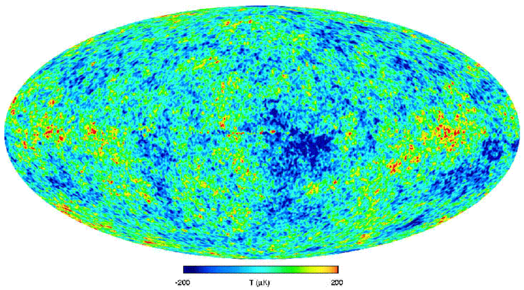



simulated

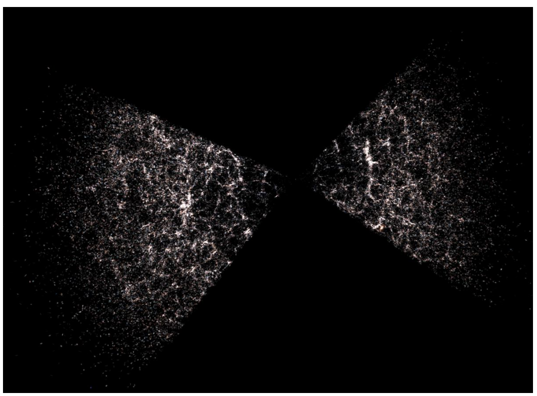
Springel, Frenk & White
Nature, April ‘06

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

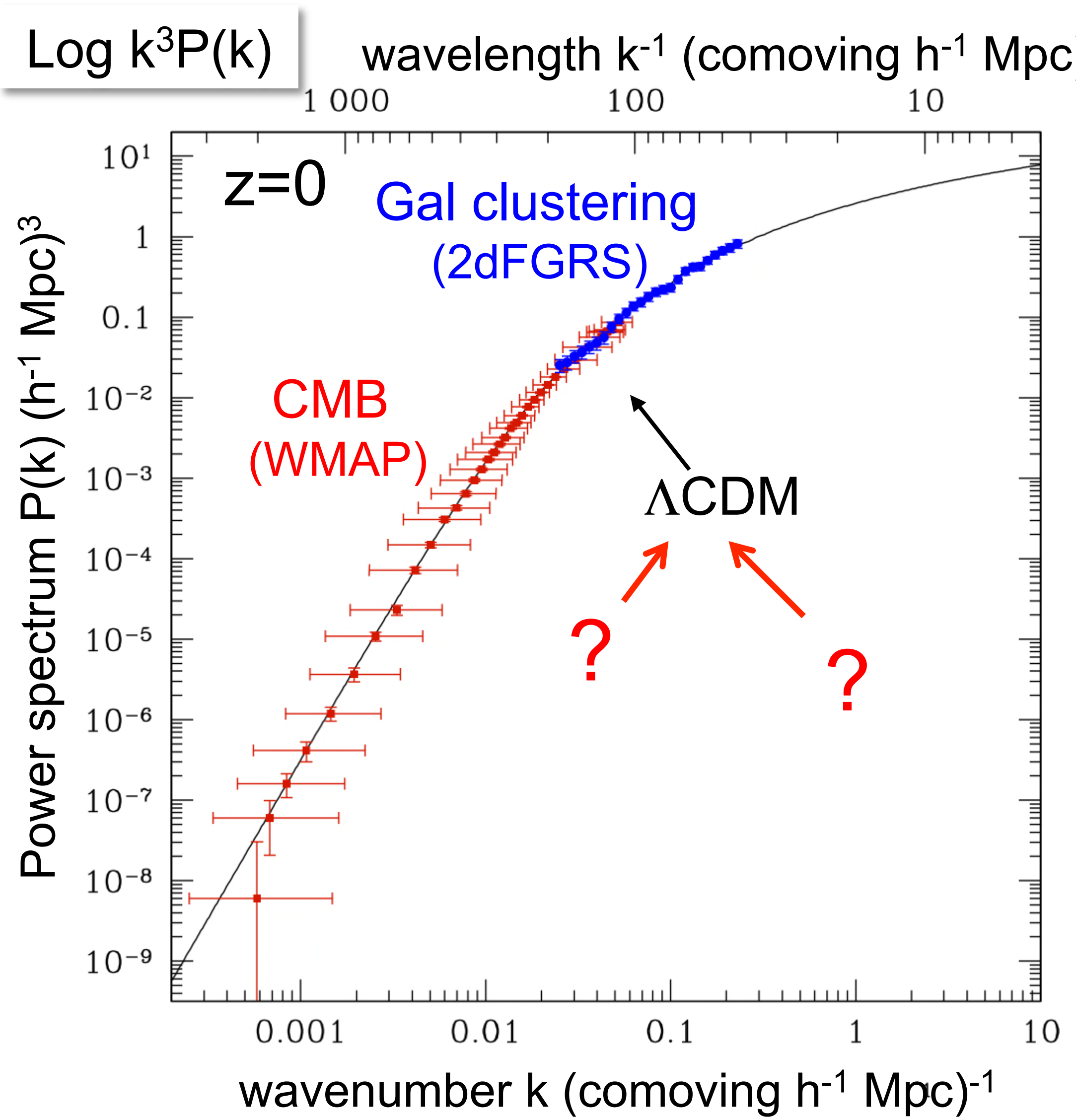
University of Durham




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

Free streaming →

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

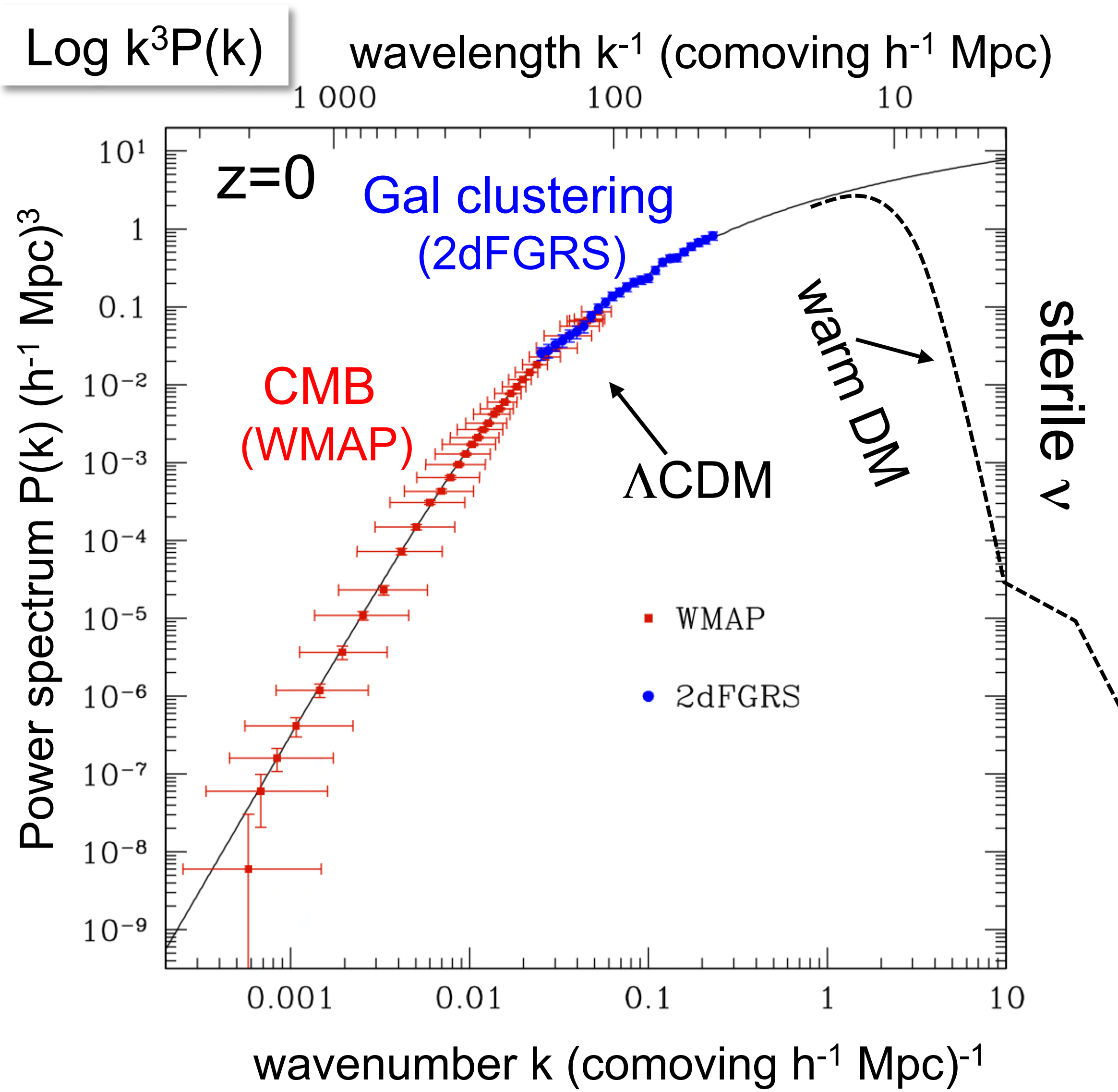
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

- CDM: $\gamma$-ray excess from Galactic Center
- WDM (sterile $\nu$): 3.5 X-ray keV line in galaxies and clusters

Very unlikely that both are right!

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

University of Durham

Free streaming →

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

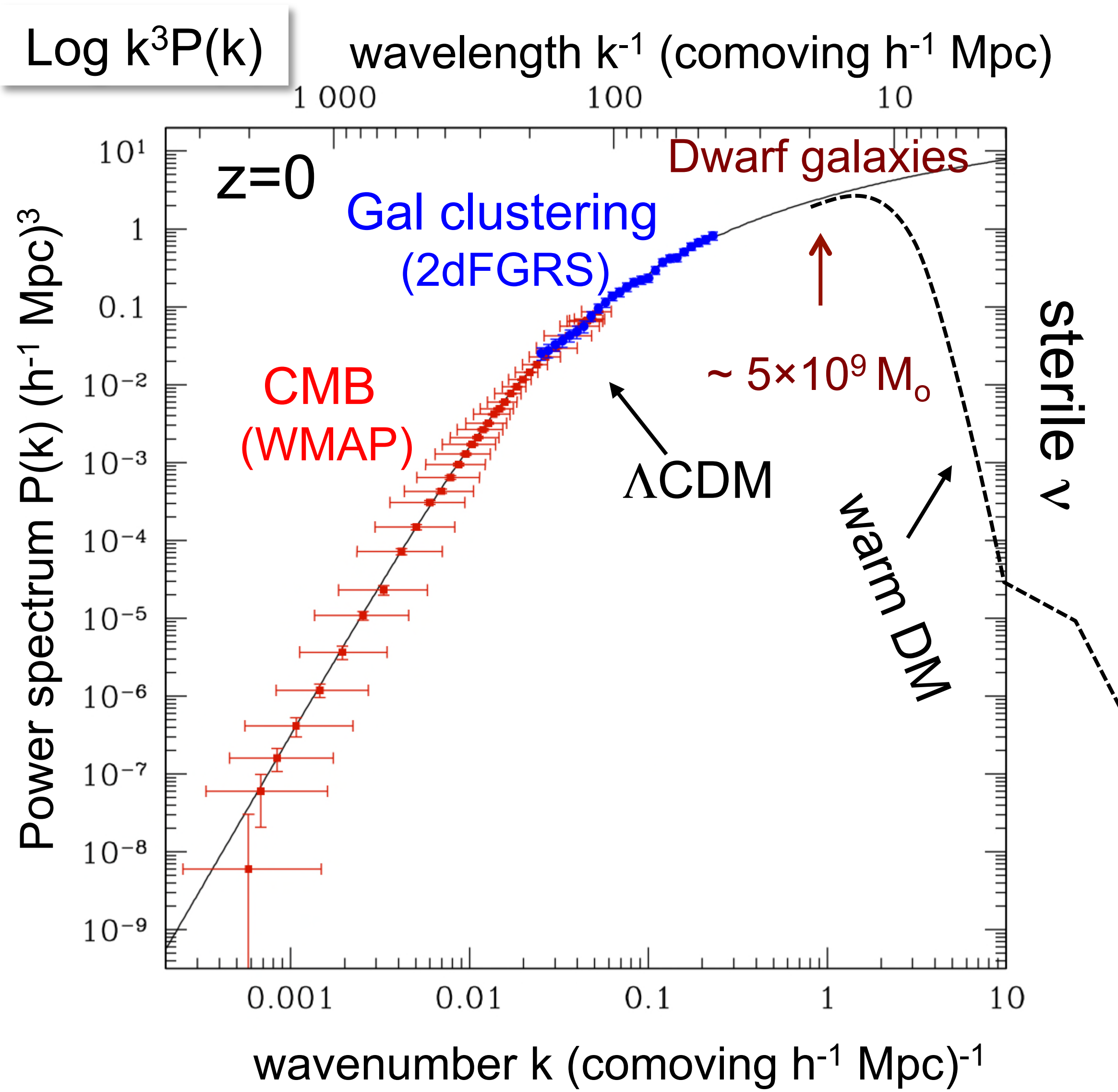
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$



The identity of the dark matter is encoded in dwarf galaxies in the halo of the MW

(strongly non-linear regime)

ICC

Cold Dark Matter

Warm Dark Matter

13.4 billion years ago

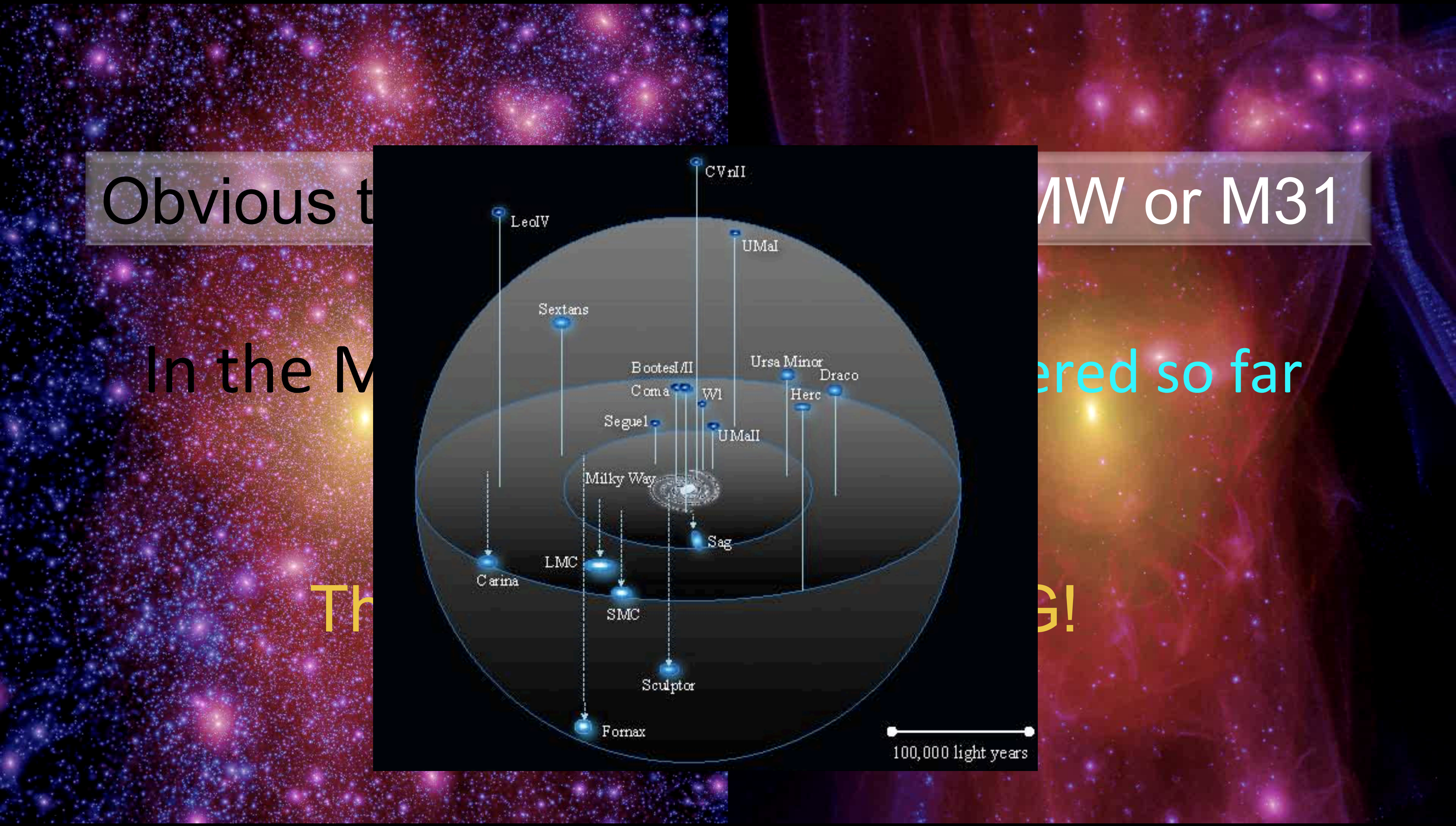
Institute for Computational Cosmology

cold dark matter　　　　warm dark matter


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

cold dark matter

warm dark matter




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

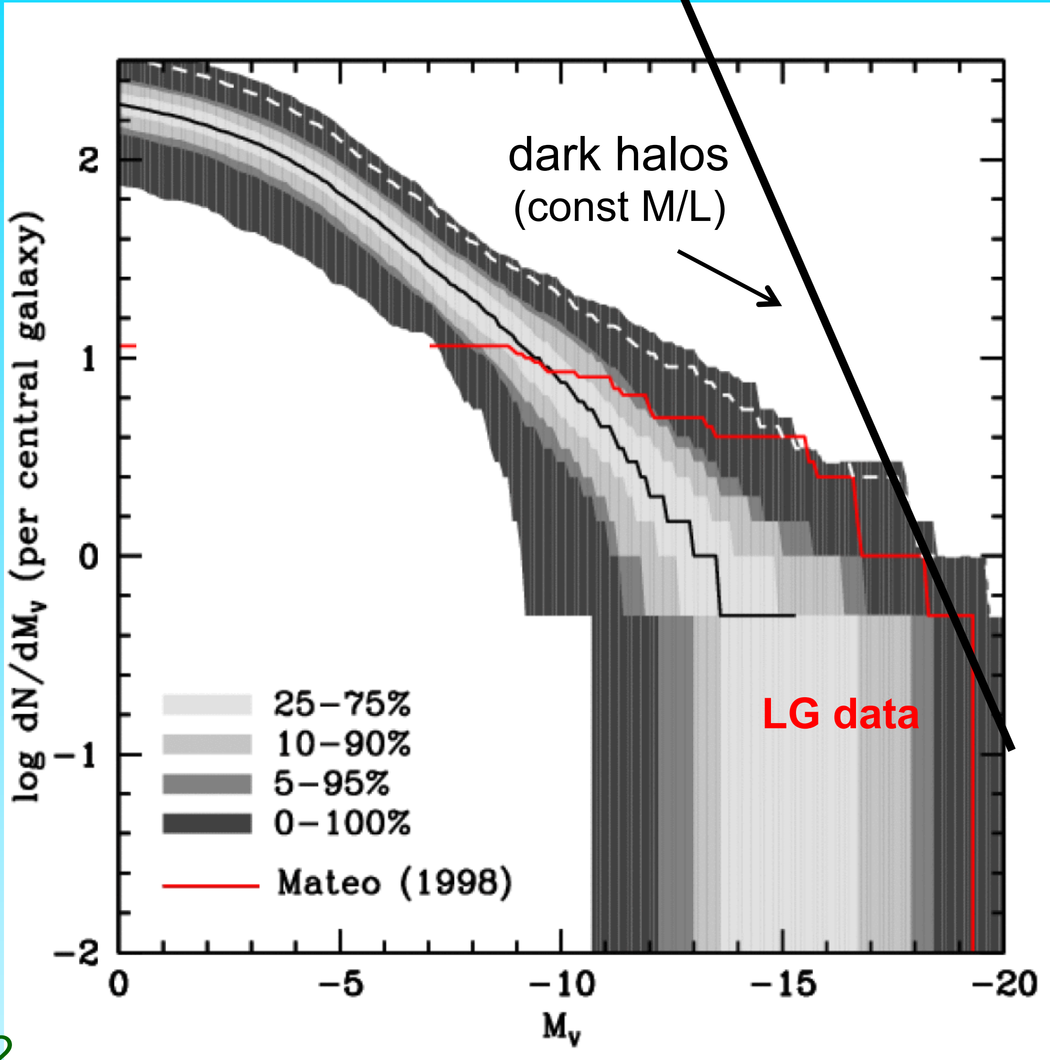
## Most subhalos never make a galaxy!

Because:

- Reionization heats gas to $10^4$K, preventing it from cooling and forming stars in small halos ($T_{vir} < 10^4$K)
- Supernovae feedback expels residual gas in slightly larger halos

# 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 (~10% of cases)

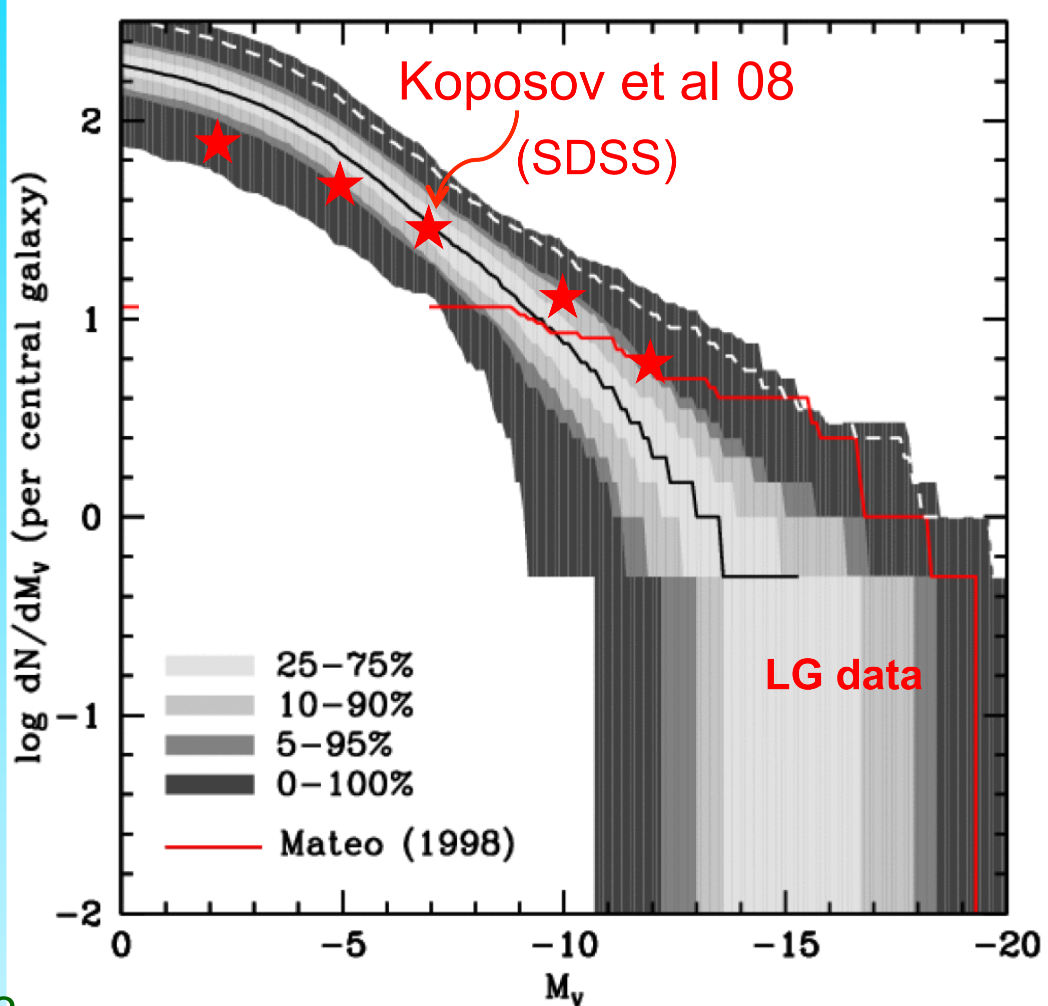



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '00)

University of Durham

# 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 (~10% of cases)




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.

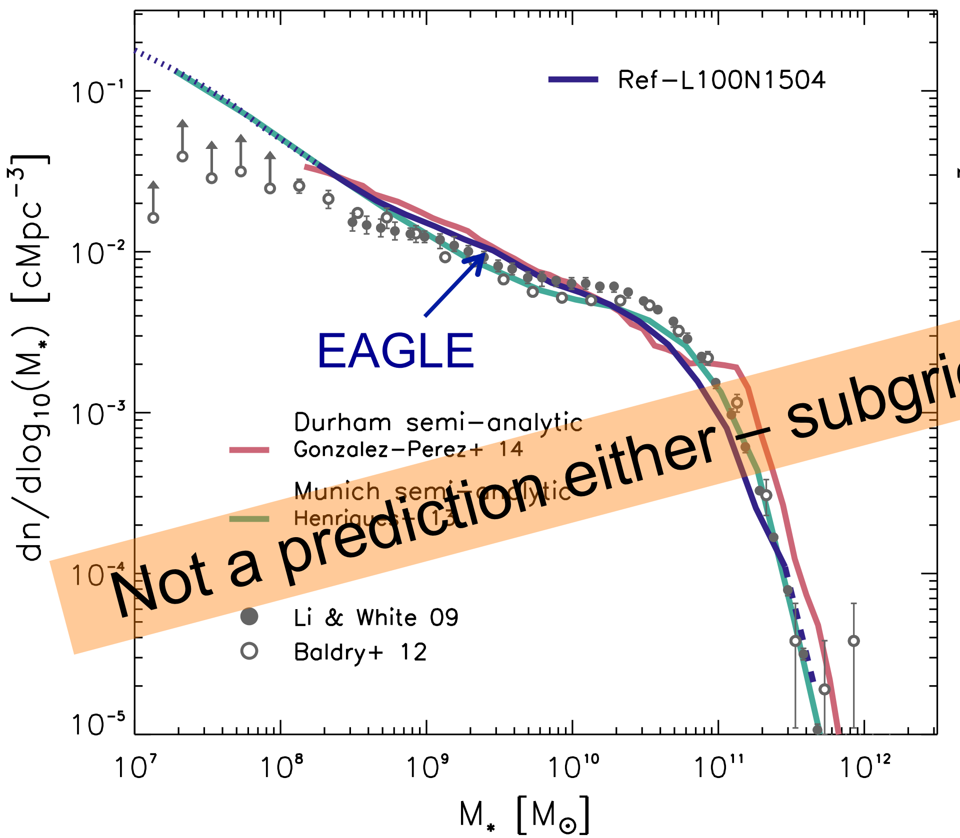
Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

Durham University VIRGO ICC DiRAC PRACE

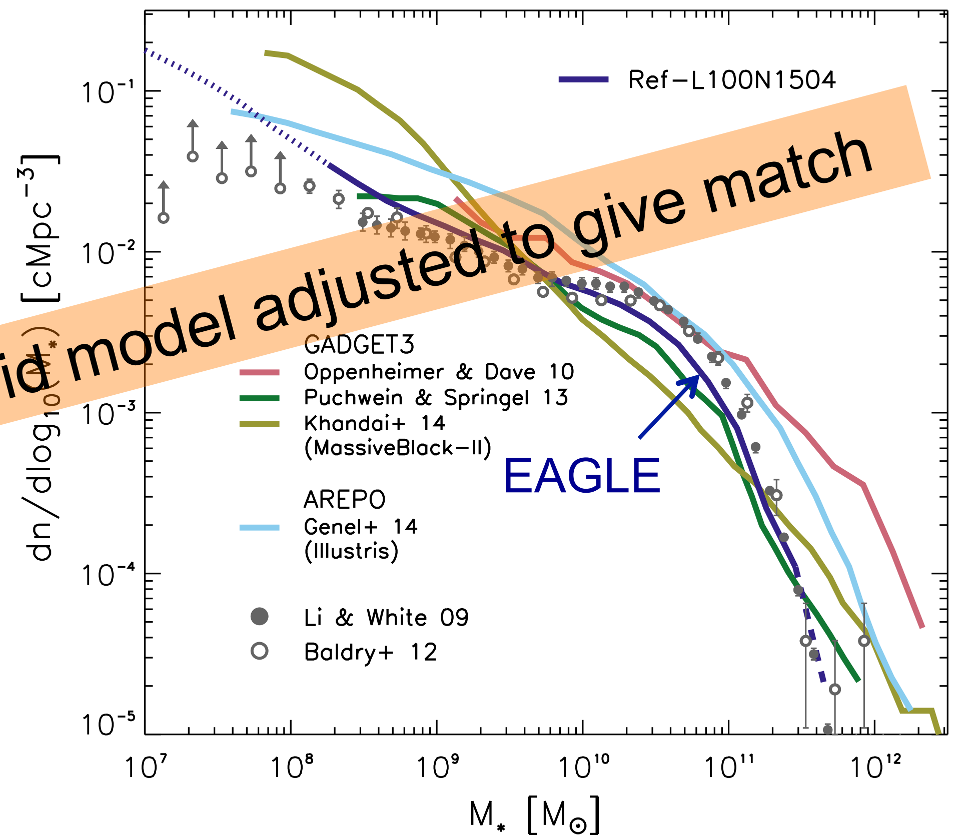
The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

# Galaxy stellar mass function

Comparison to semi-analytic models




Comparison to other Hydro simulations




Not a prediction either – subgrid model adjusted to give match

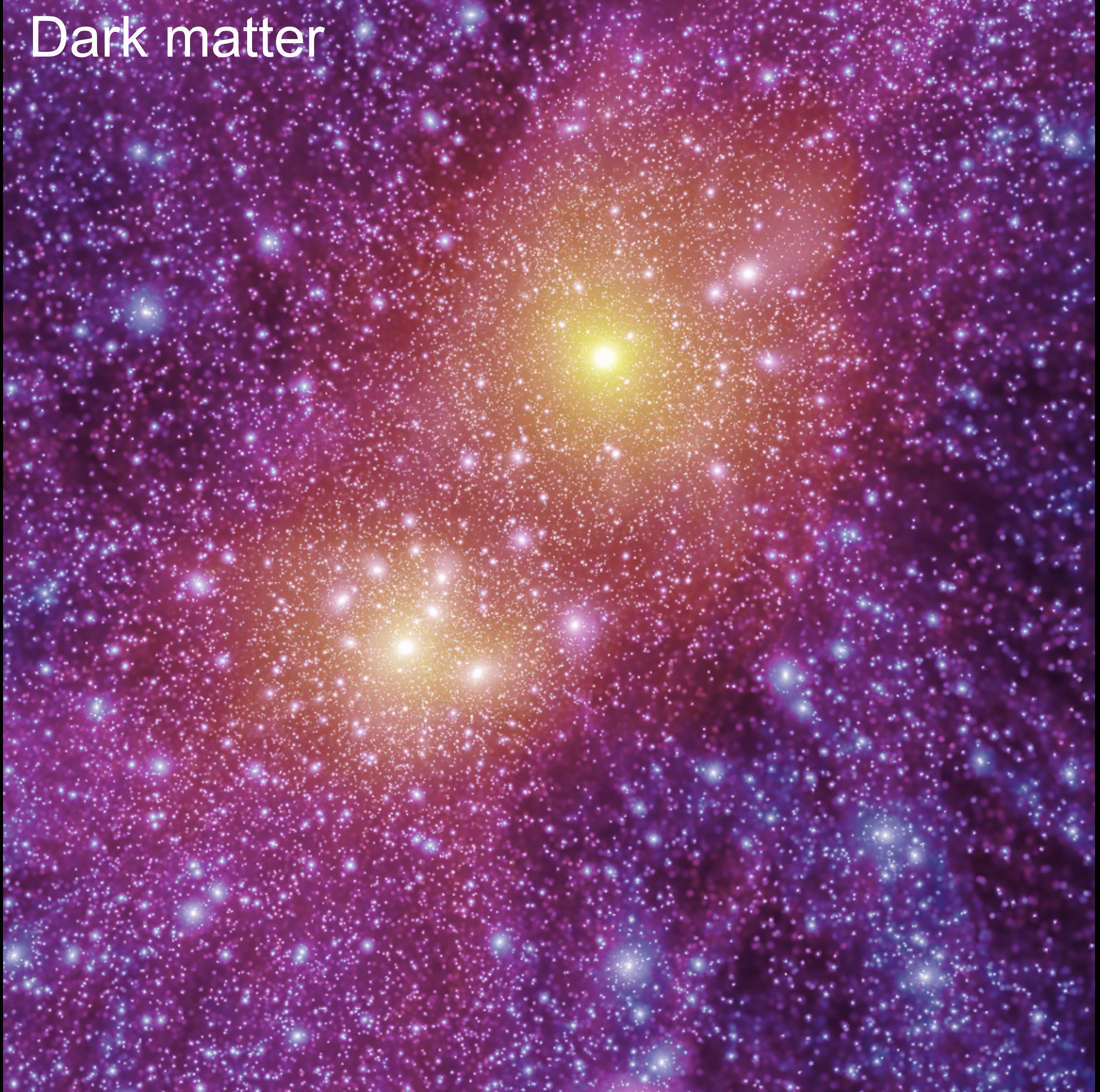
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16



Stars

APOSTLE
EAGLE full
hydro
simulations

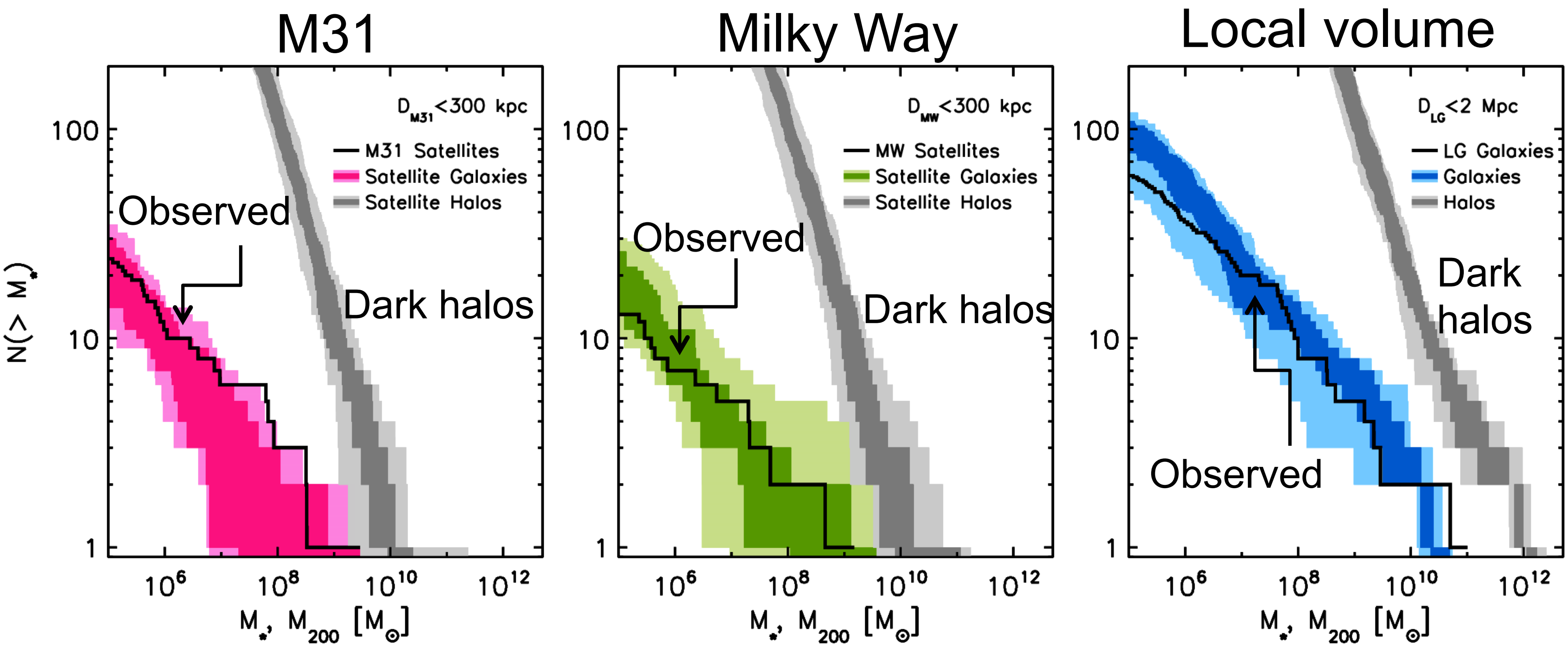
Local Group

Stars

Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

# EAGLE Local Group simulation



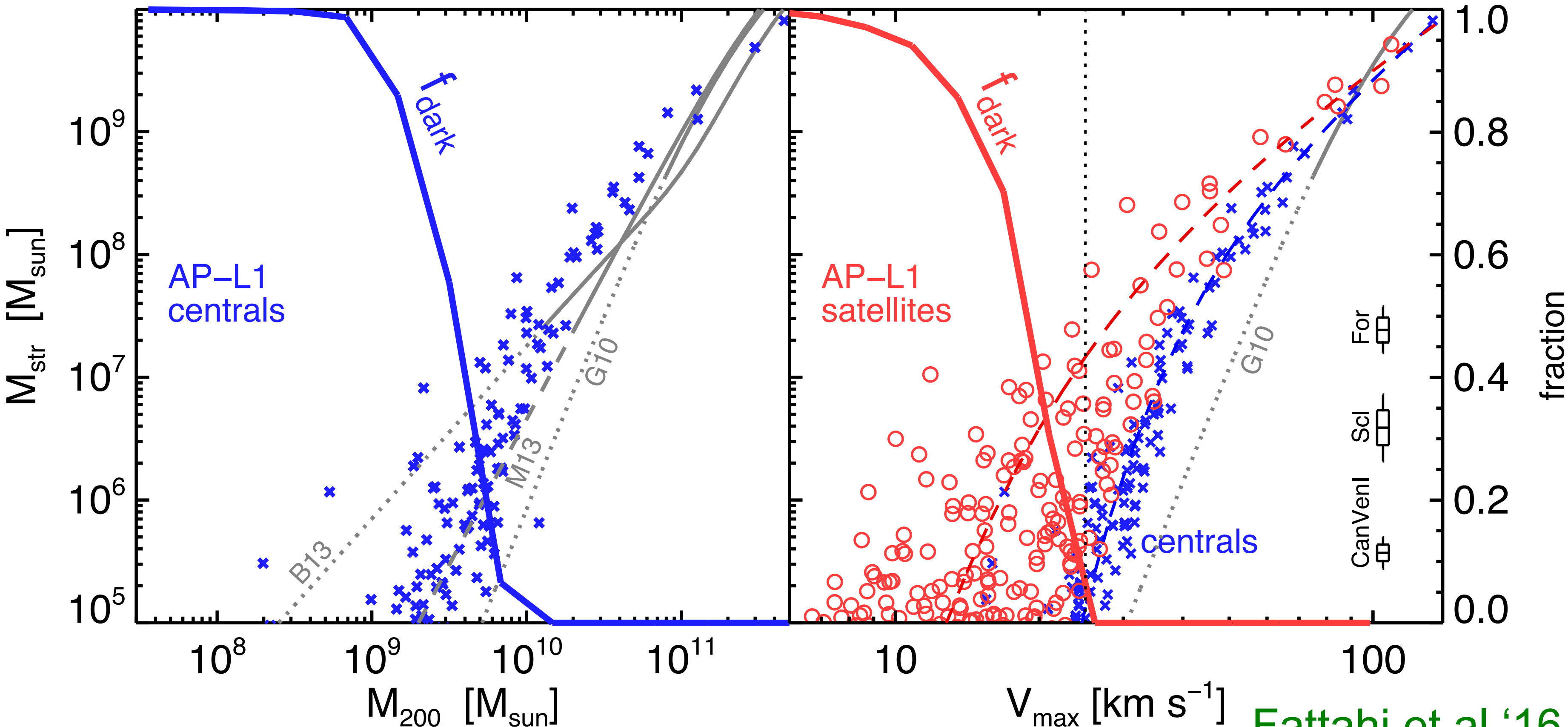

Sawala et al '16

Institute for Computational Cosmology

University of Durham

# Fraction of dark subhalos

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




Fattahi et al '16

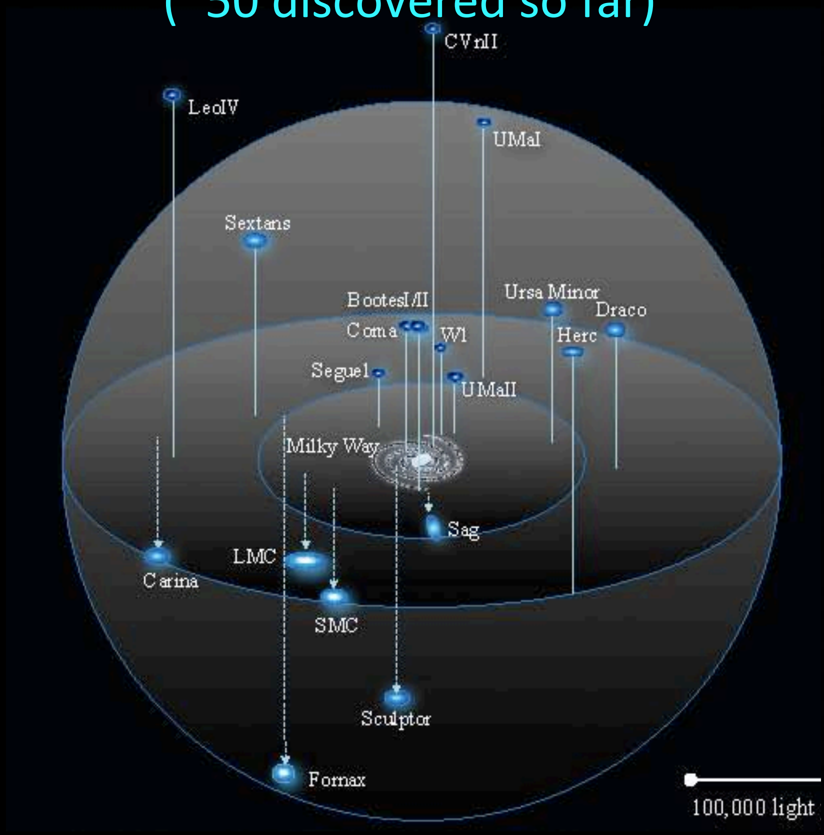
All halos of mass < $5\times10^8 M_o$ or $V_{max}$ < 7 km/s are dark

Institute for Computational Cosmology

# How about in WDM?

The satellites of the MW

(~50 discovered so far)




Dark mattter subhalos in WDM

(a few tens)

# Warm DM: different $\nu$ mass

z=3

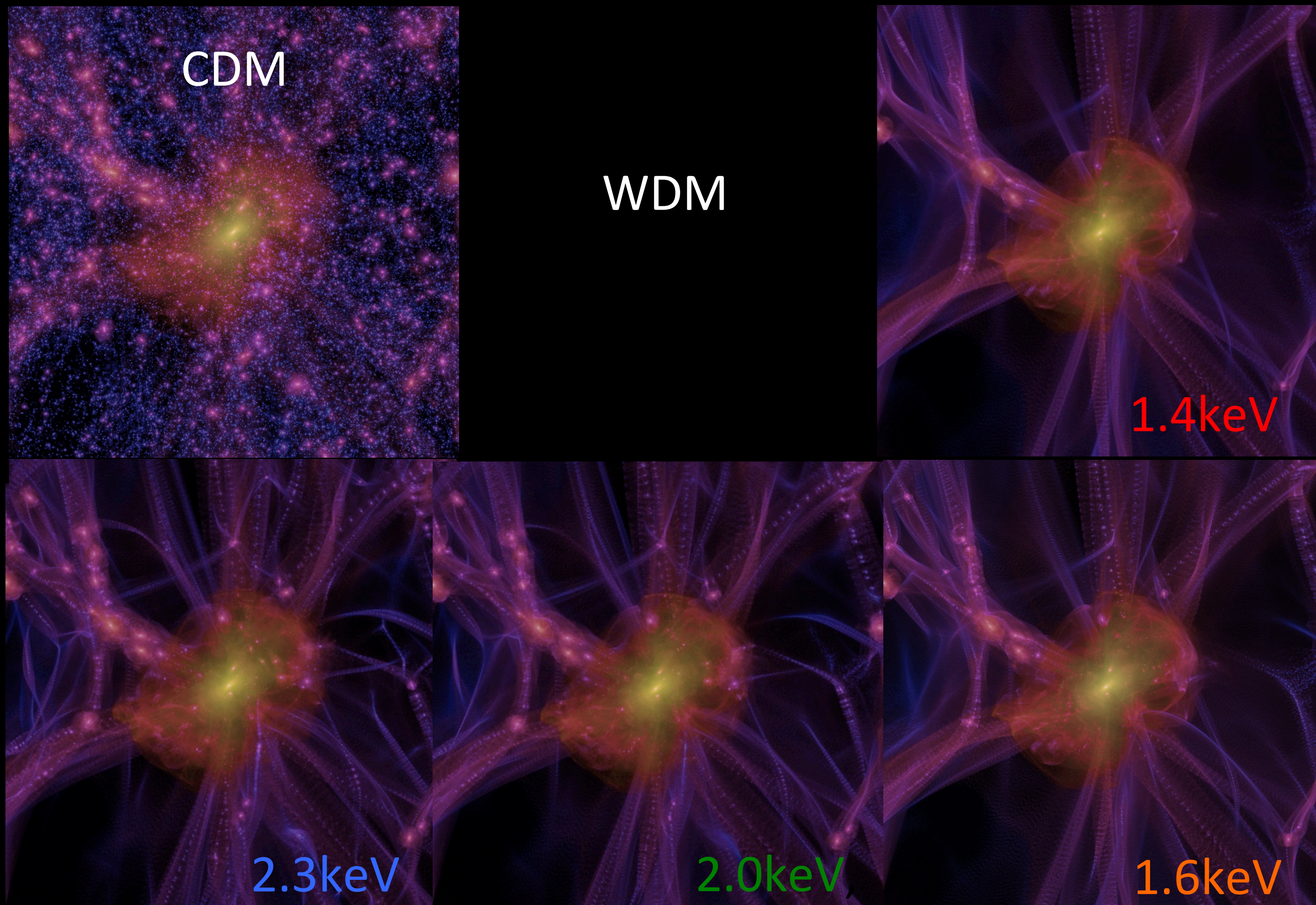
WDM

2.3 keV

2.0 keV

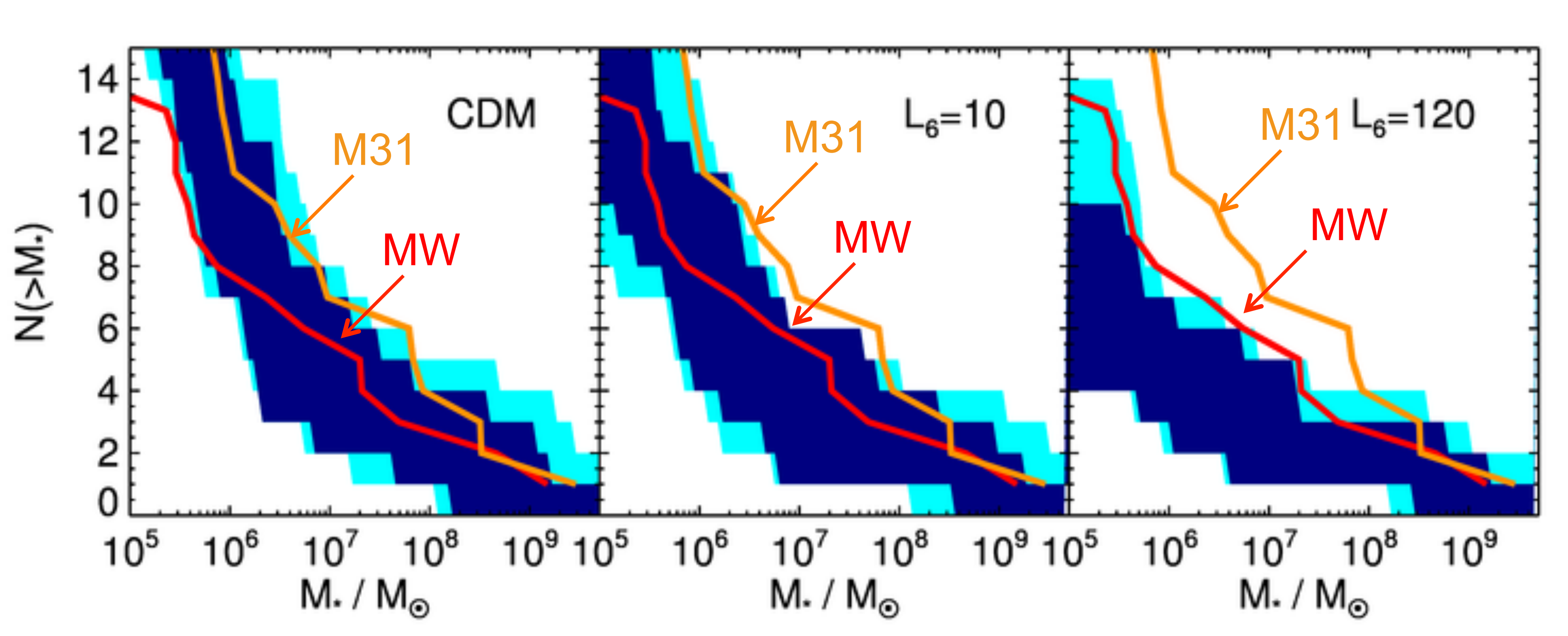
1.6 keV

1.4 keV



# Luminosity Function of Local Group Satellites in WDM

From "Warm Apostle:" 7keV sterile ν $M_h \sim 10^{12} M_o$




Lovell et al. '16

When "baryon effects" are taken into account

→

Observed abundance of satellites is compatible with CDM but rules out some WDM models

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

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

“Too-big-to-fail” problem in CDM:

N-body CDM sims produce too many massive subhalos (e.g. >10 with $V_{max}$>30 km/s)

BUT: Milky Way has only 3 sats with $V_{max}$>30 km/s

Why did the big subhalos not make a galaxy?

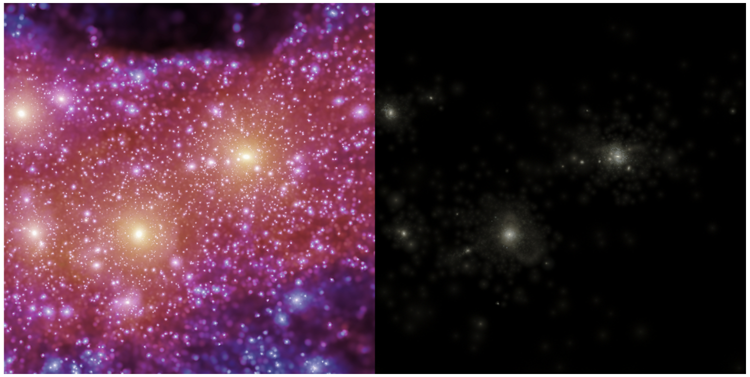
# To-big-to-fail in CDM: baryon effects

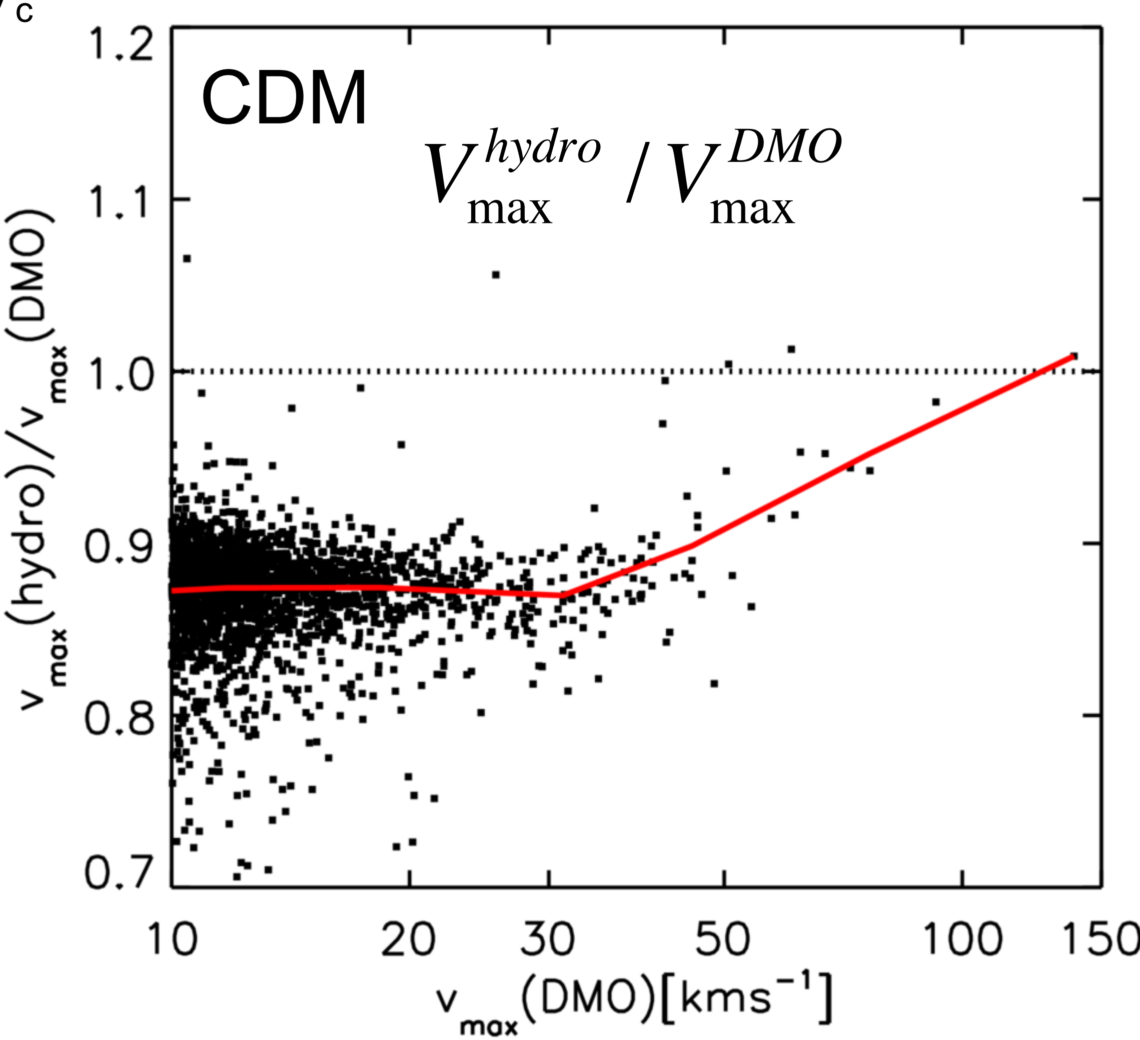
University of Durham

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

Reduction in $V_{max}$ due to SN feedback:

→ Lowers halo mass & thus halo growth rate



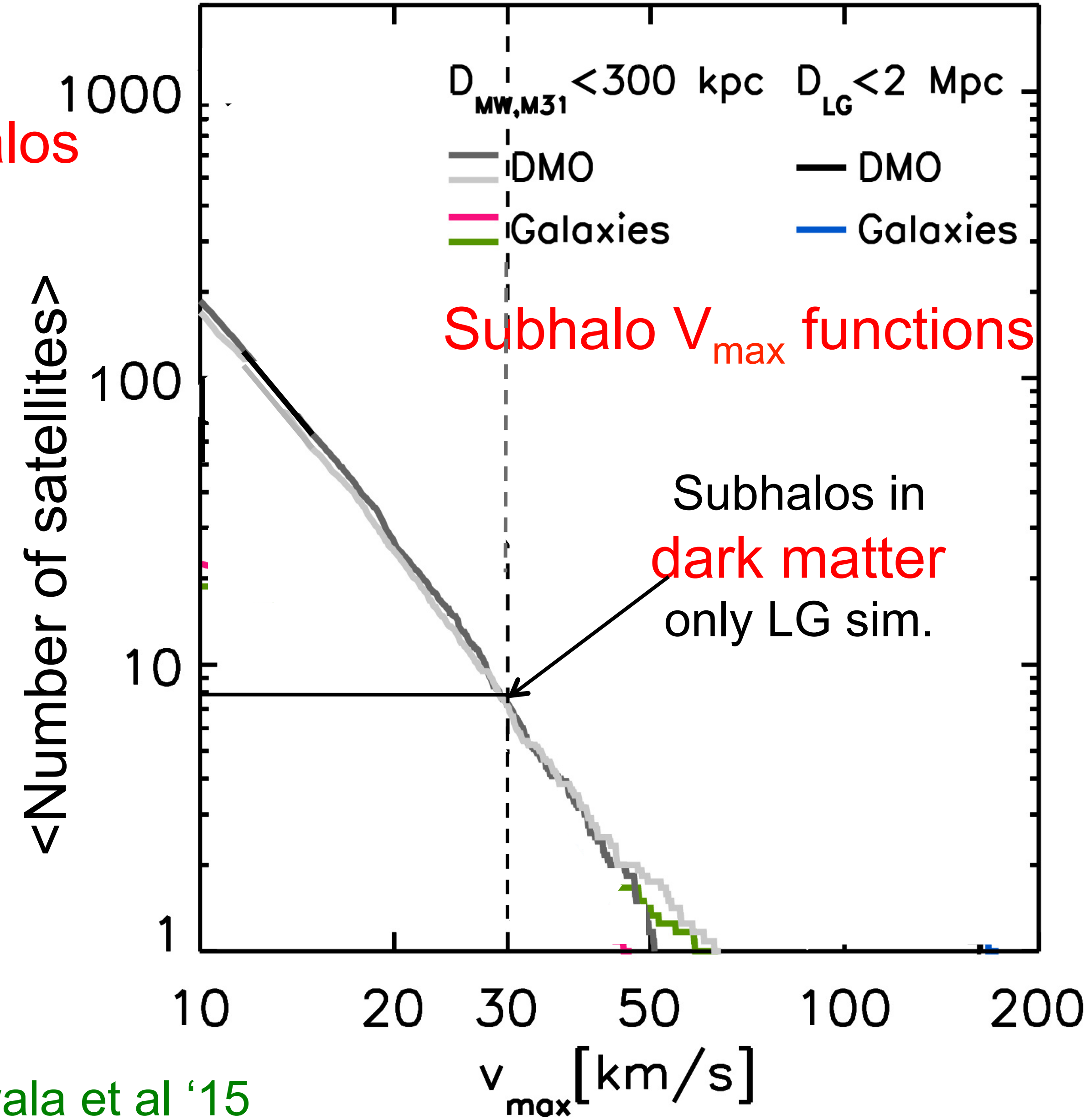



Sawala et al. ‘13, ‘15

University of Durham

# Too-big-to-fail: the baryon bailout

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



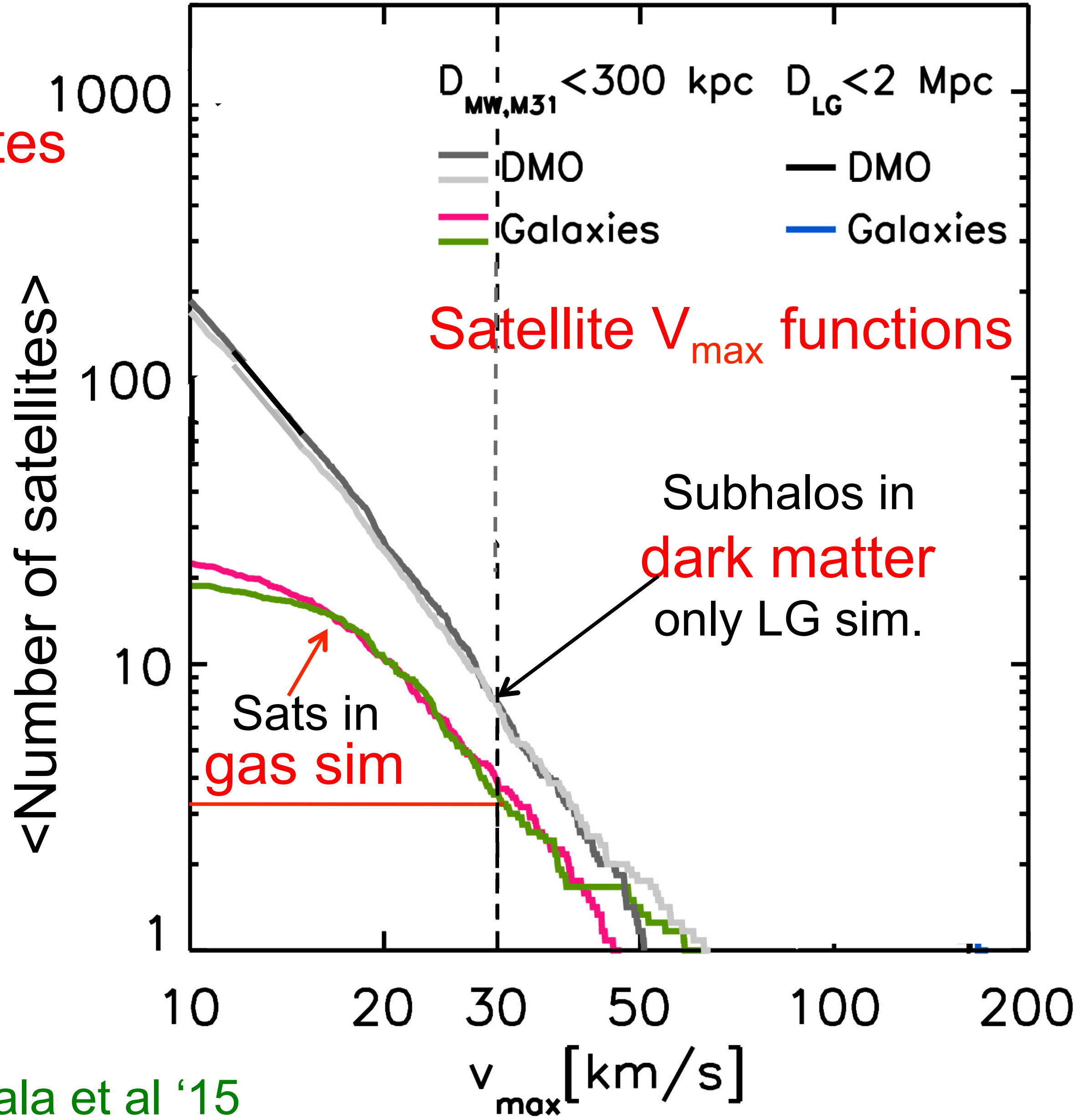

Sawala et al '15

# Too-big-to-fail: the baryon bailout

ICC

University of Durham

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

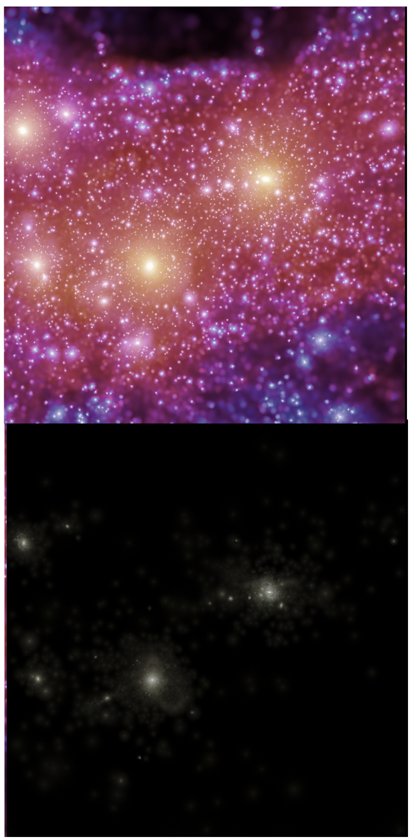


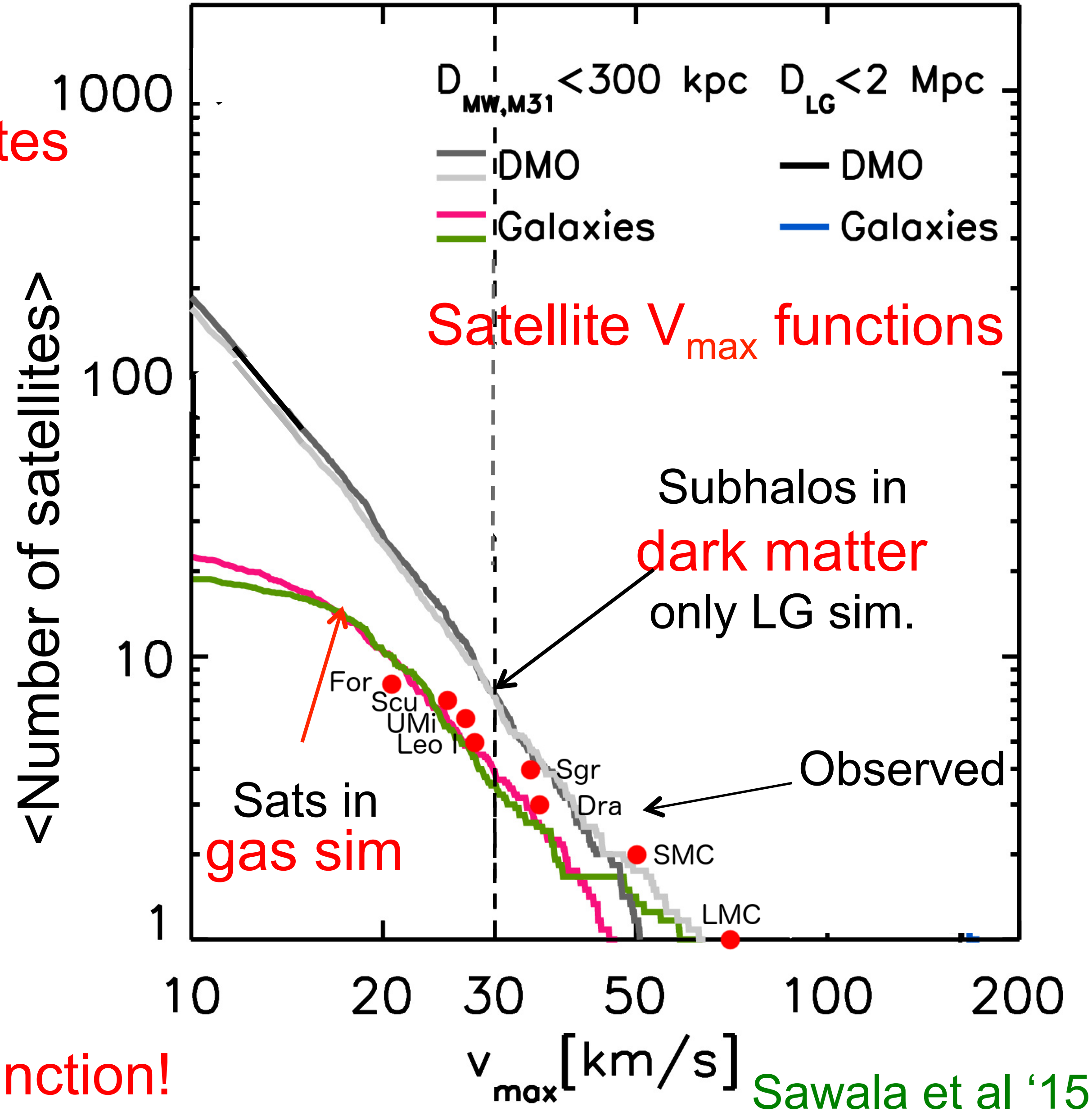

Sawala et al '15

University of Durham

# Too-big-to-fail: the baryon bailout

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






. and with correct $V_{max}$ function!

When "baryon effects" are taken into account

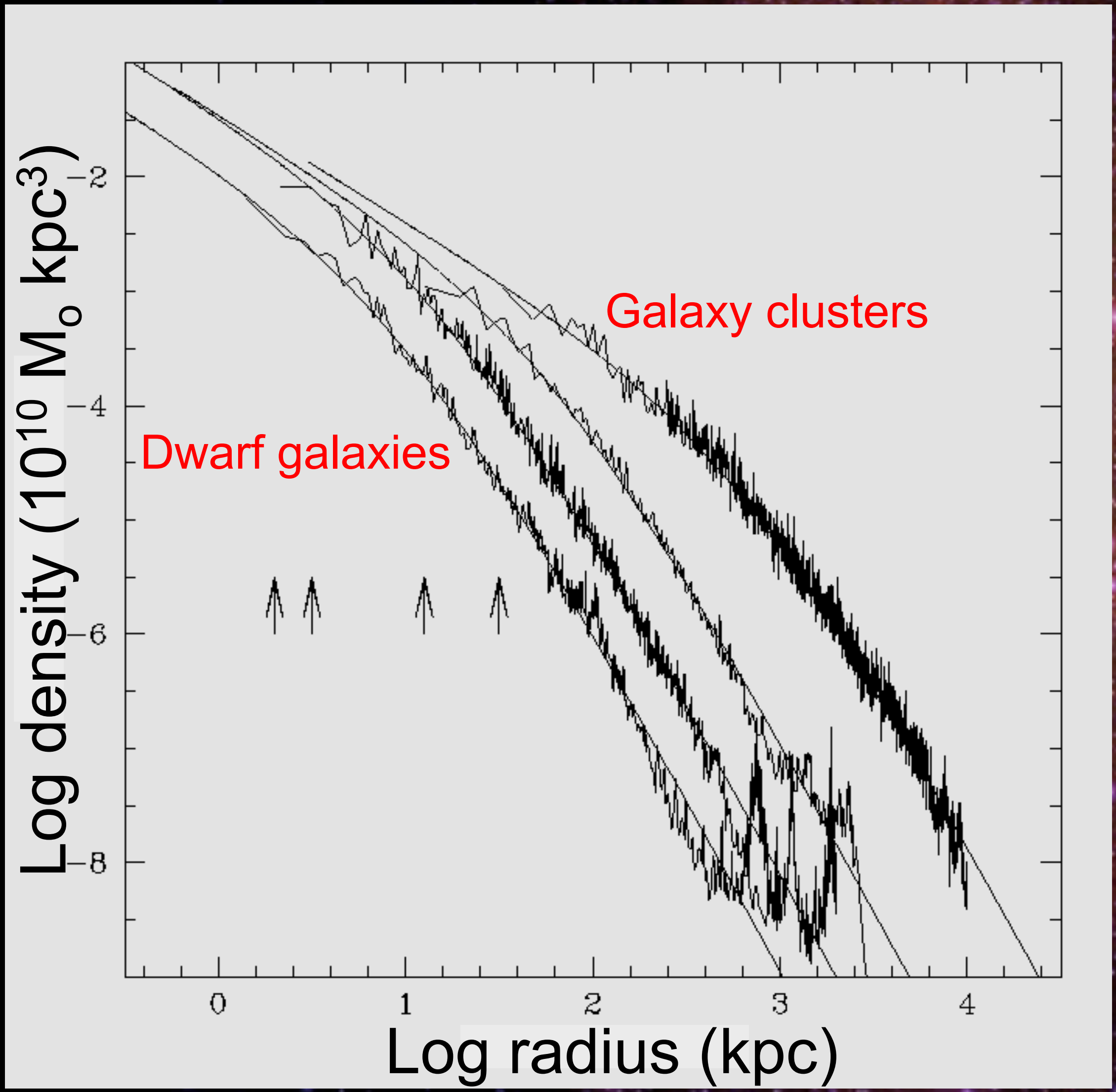
→

No too-big-to-fail problem in CDM
similar result for WDM

All we have achieved by counting satellite galaxies is to rule out a few WDM models!

Does the inner structure of satellites help?

# 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:

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

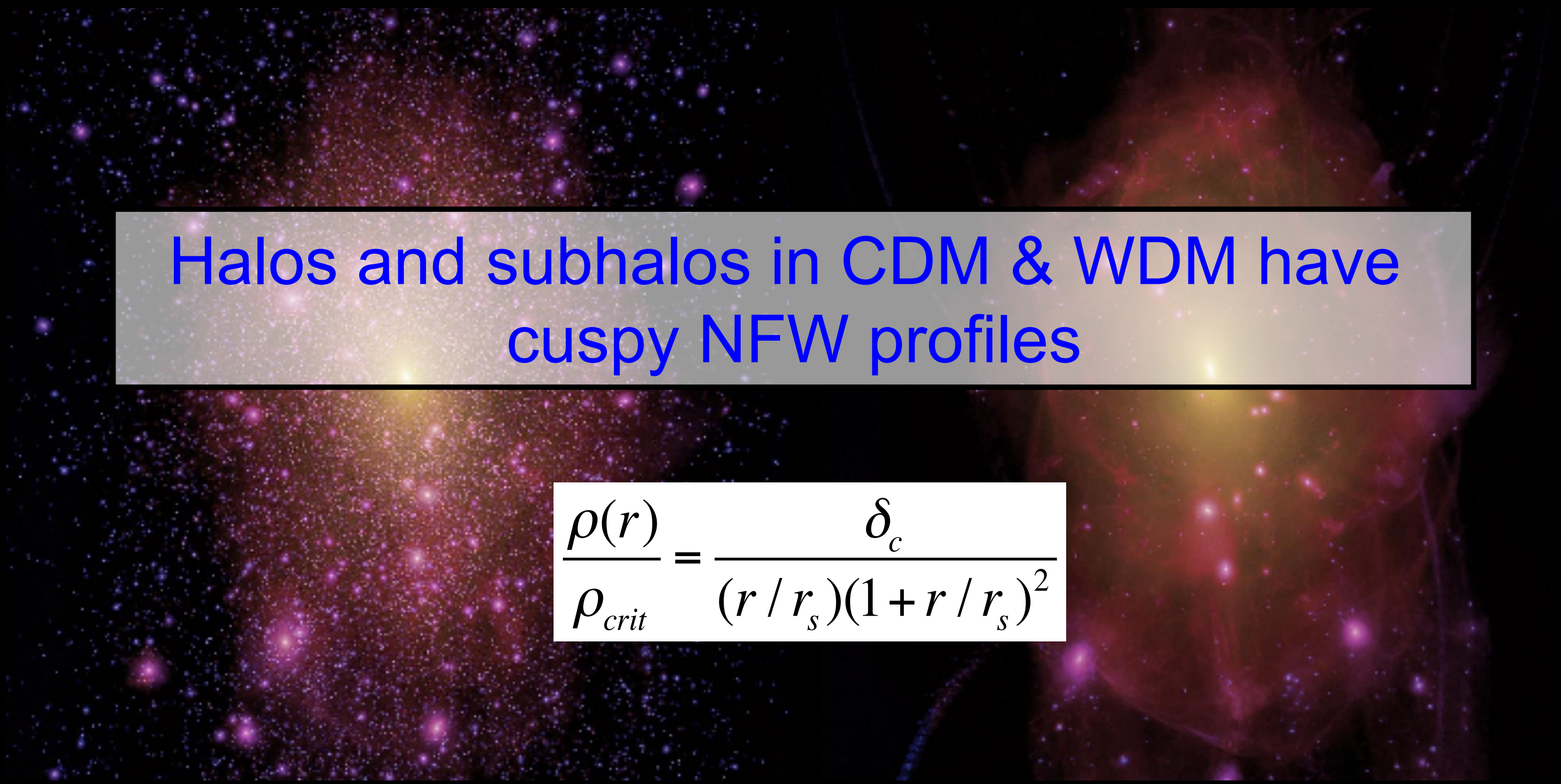
(Navarro, Frenk & White ’97)

More massive halos and halos that form earlier have higher densities (bigger $\delta$)

# The core-cusp problem

cold dark matter

warm dark matter

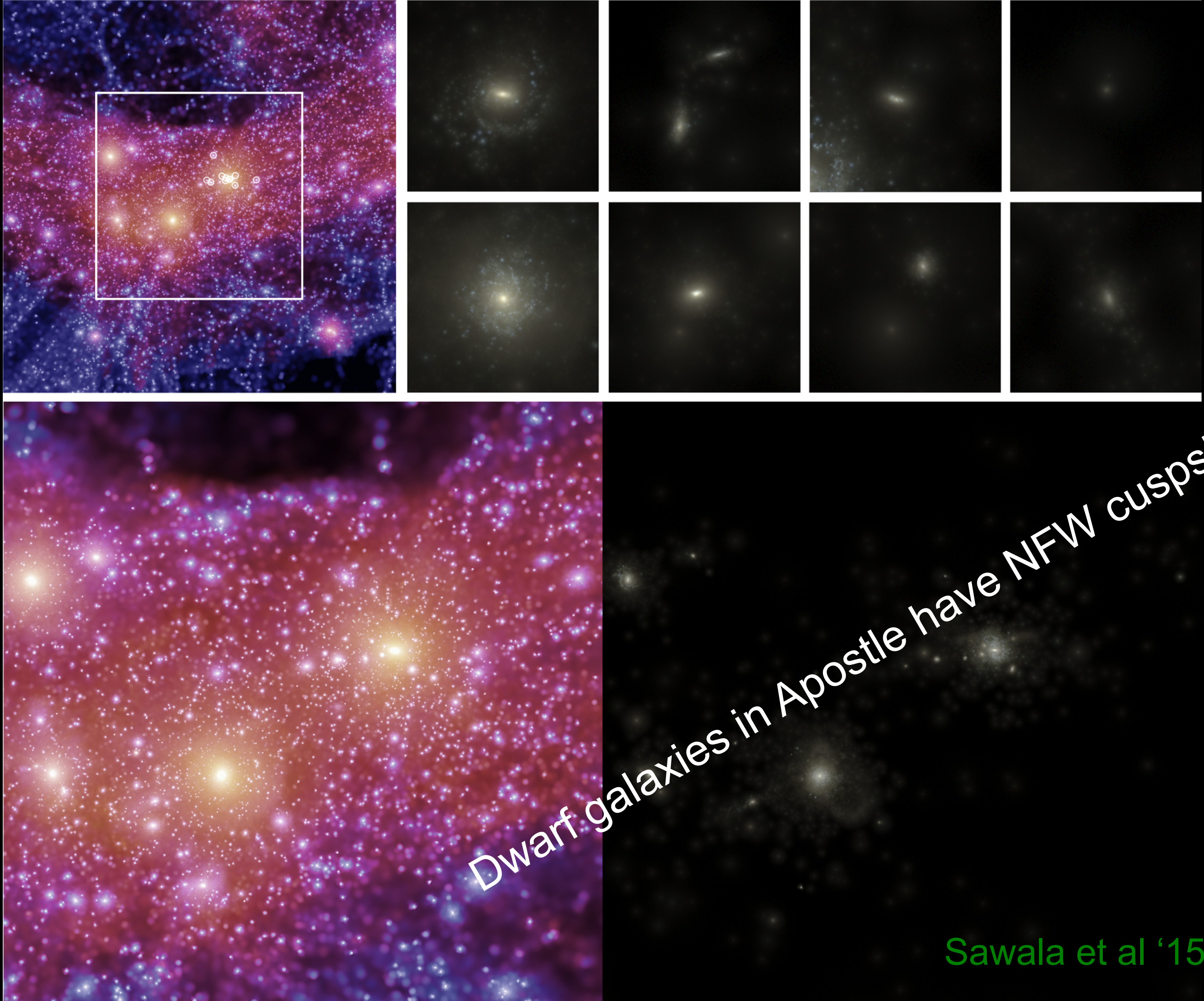


Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

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

ICC



Dwarf galaxies in Apostle have NFW cusps!

Sawala et al ‘15

Does Nature have them?
Sawala et al ‘15

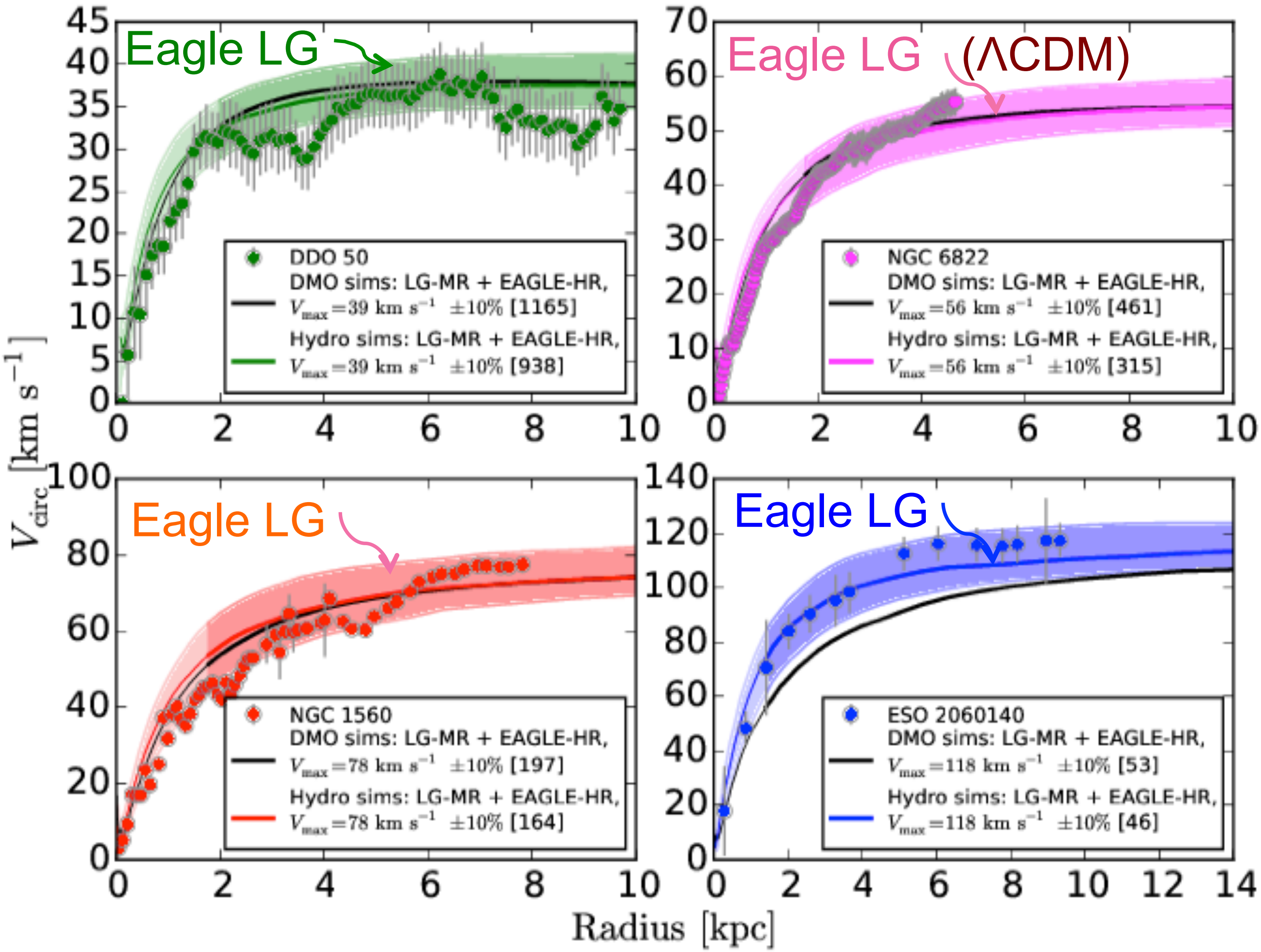
University of Durham

# The diversity of gal rotation curves

$$V_{circ} = \sqrt{\frac{GM}{r}}$$

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L*)




Oman, Navarro, Frenk et al. '15

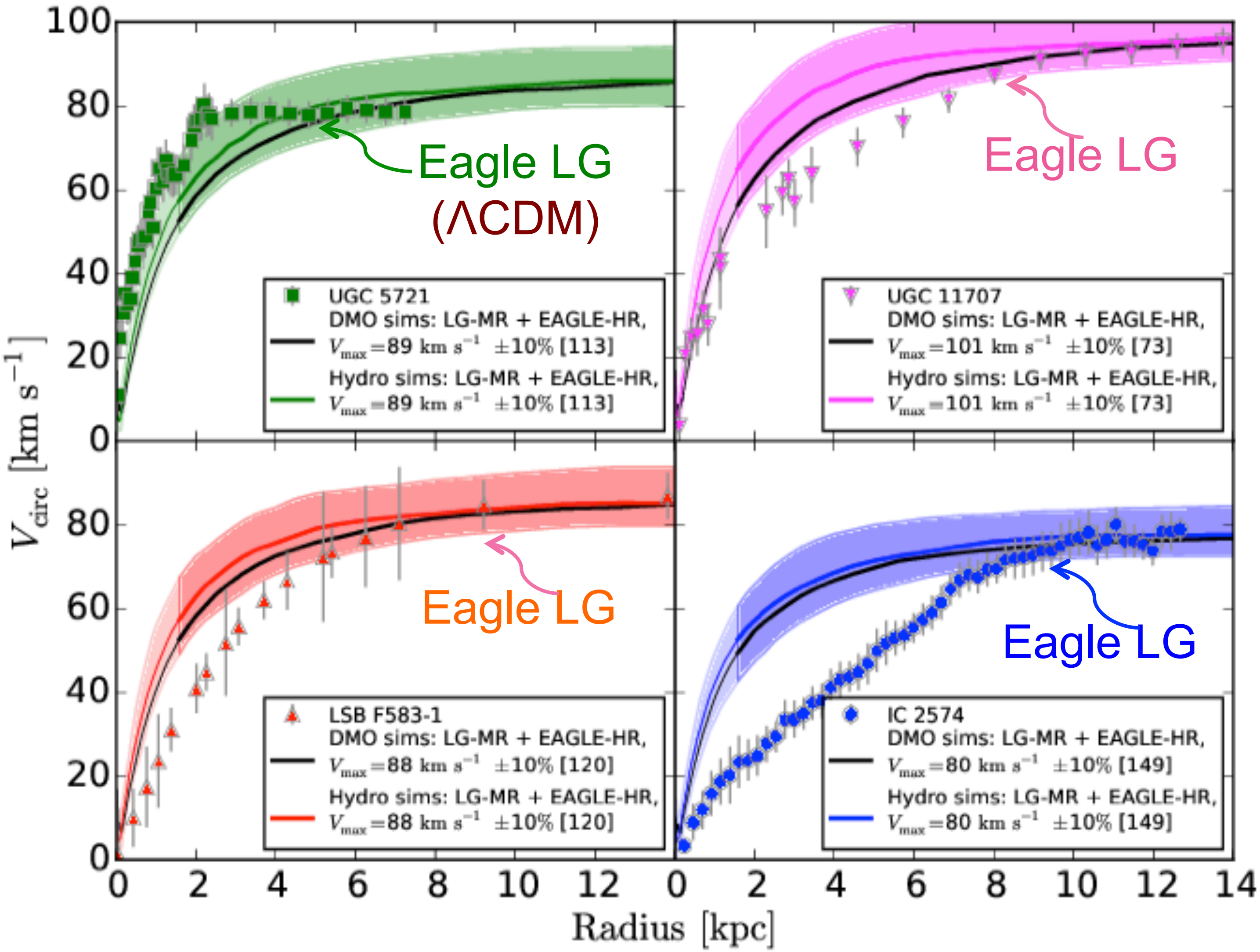
University of Durham

# The diversity of gal rotation curves

$$V_{circ} = \sqrt{\frac{GM}{r}}$$

Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~$L_*$)




Oman, Navarro, Frenk et al. ‘15

Does IC2574 rule out CDM (and WDM)?

Or are there 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



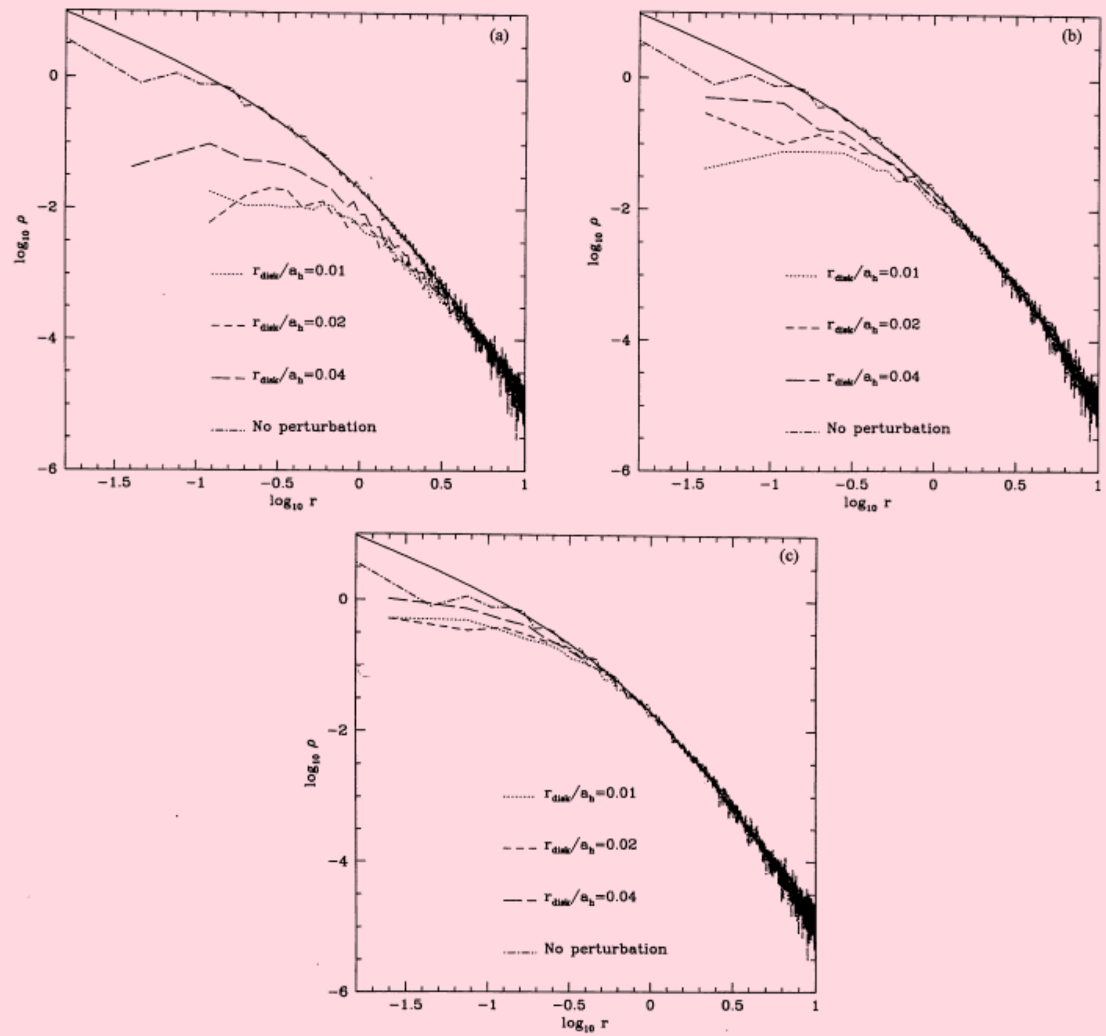



**Figure 3.** Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

Institute for Computational Cosmology

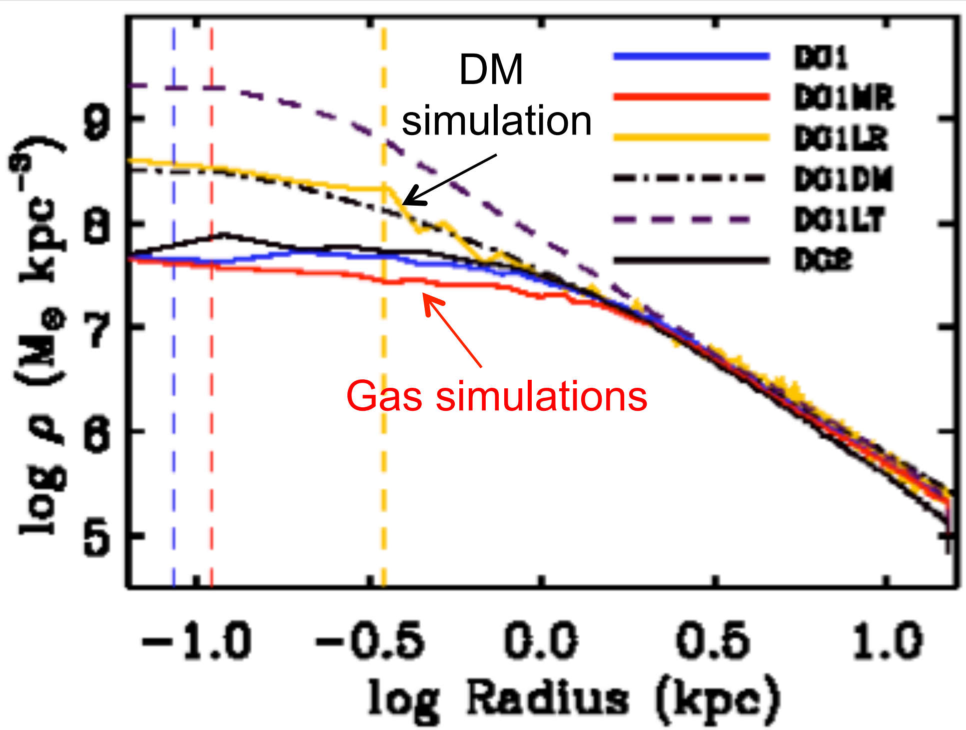
# Cores in dwarf galaxy simulations

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

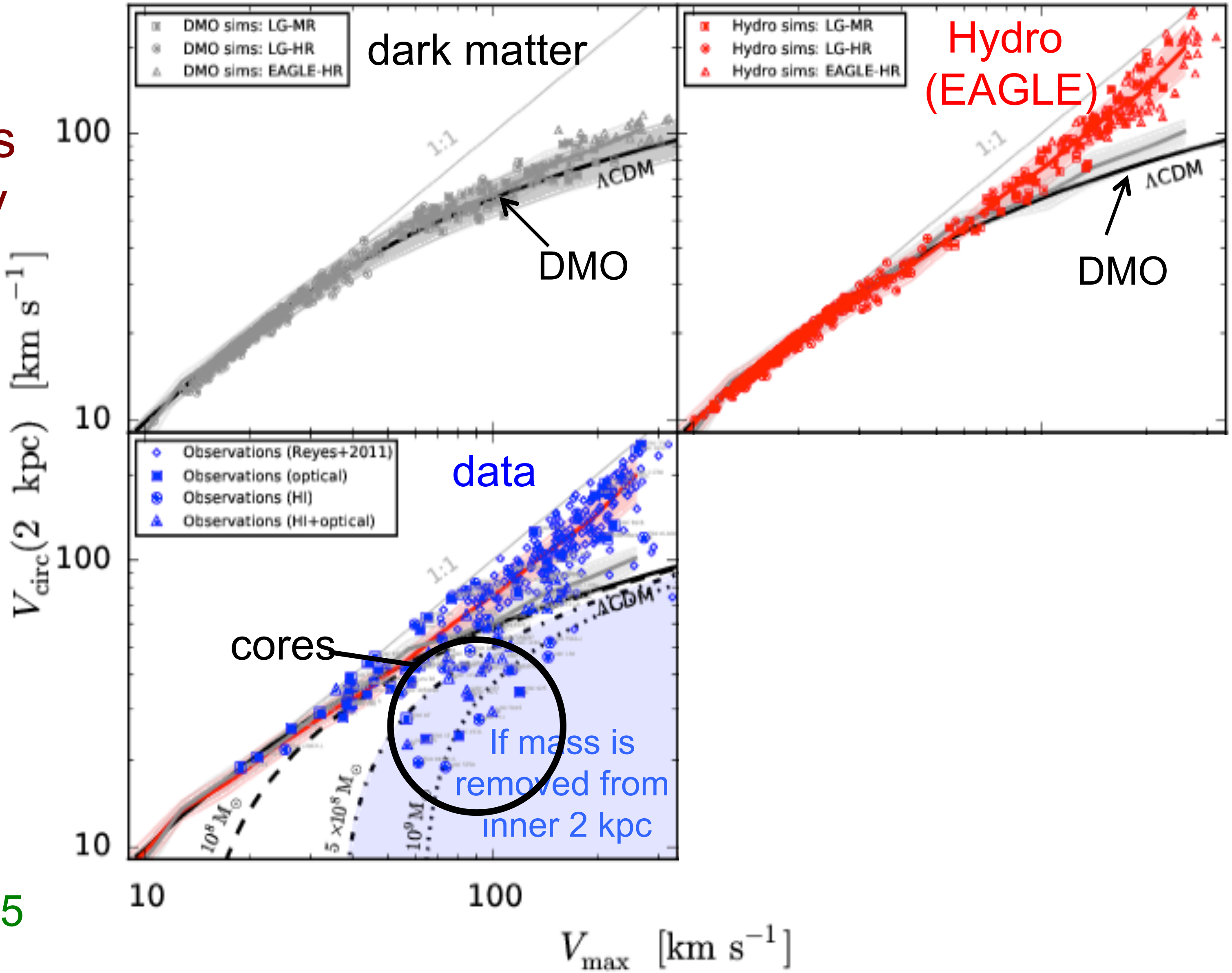



Governato et al. '10
Pontzen et al. '11

# The diversity of gal rotation curves

University of Durham

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

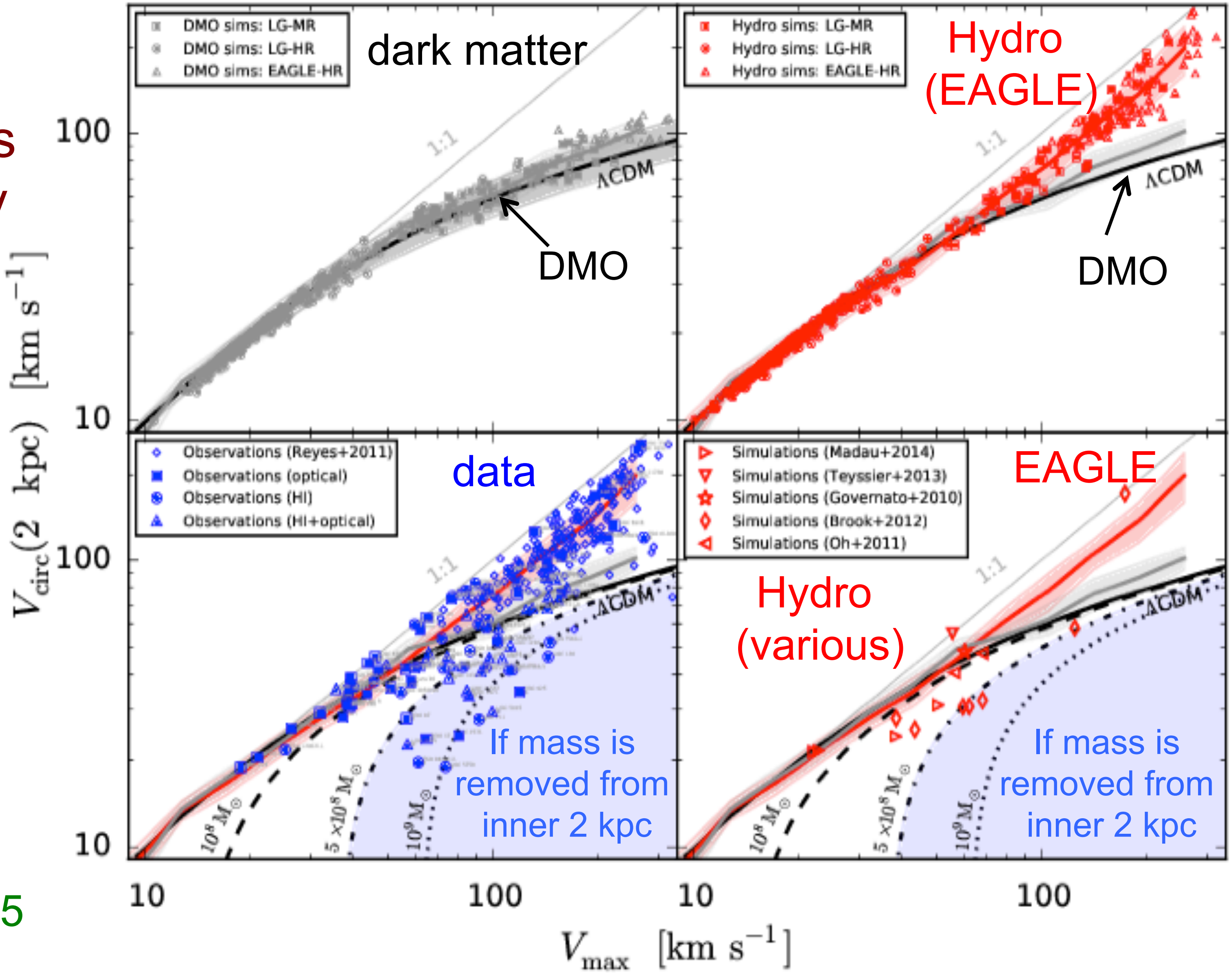



Oman et al. '15

# The diversity of gal rotation curves

University of Durham

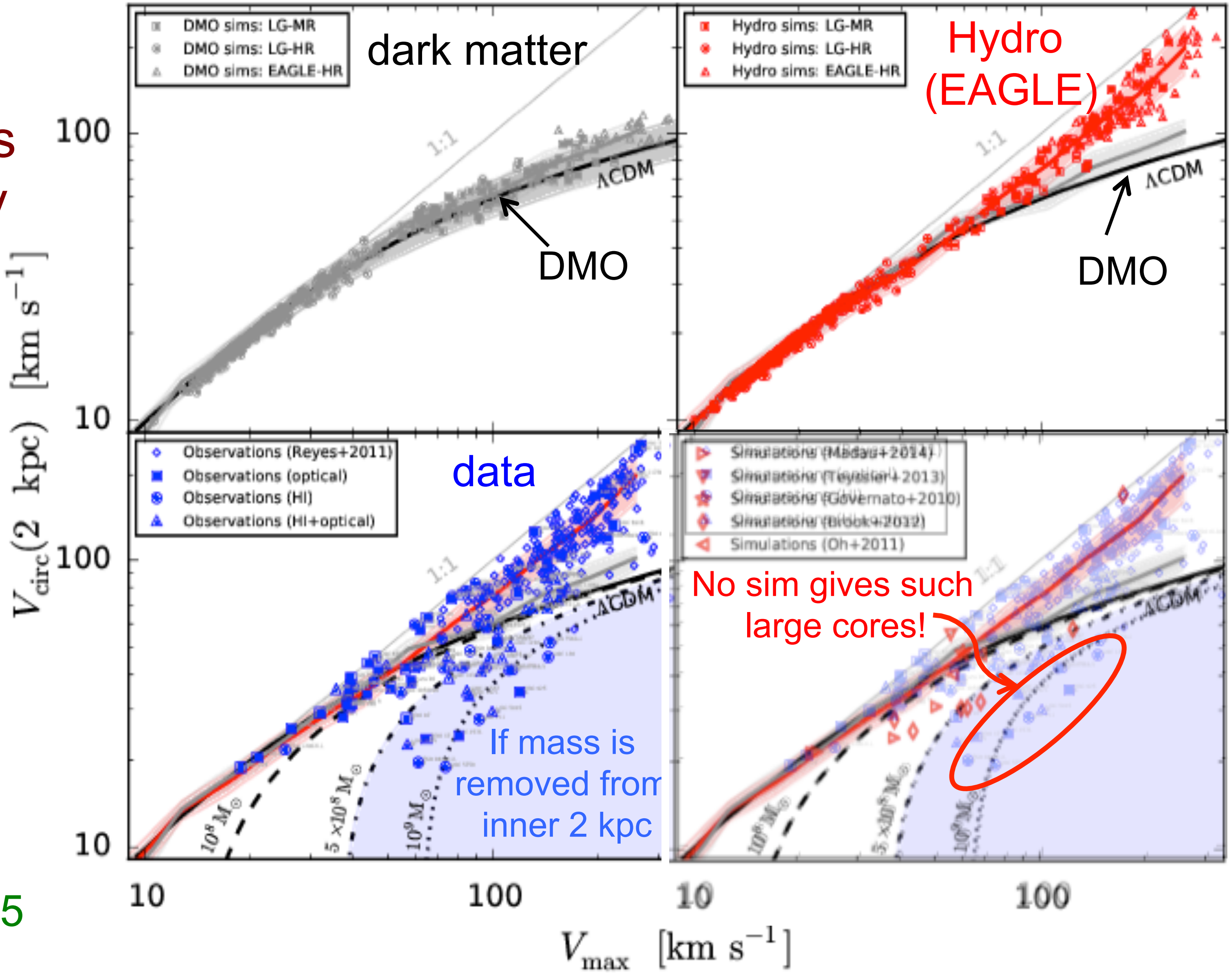
Most galaxies are well fit by EAGLE; others not fit by any simulation




Oman et al. '15

# The diversity of gal rotation curves

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




Oman et al. '15

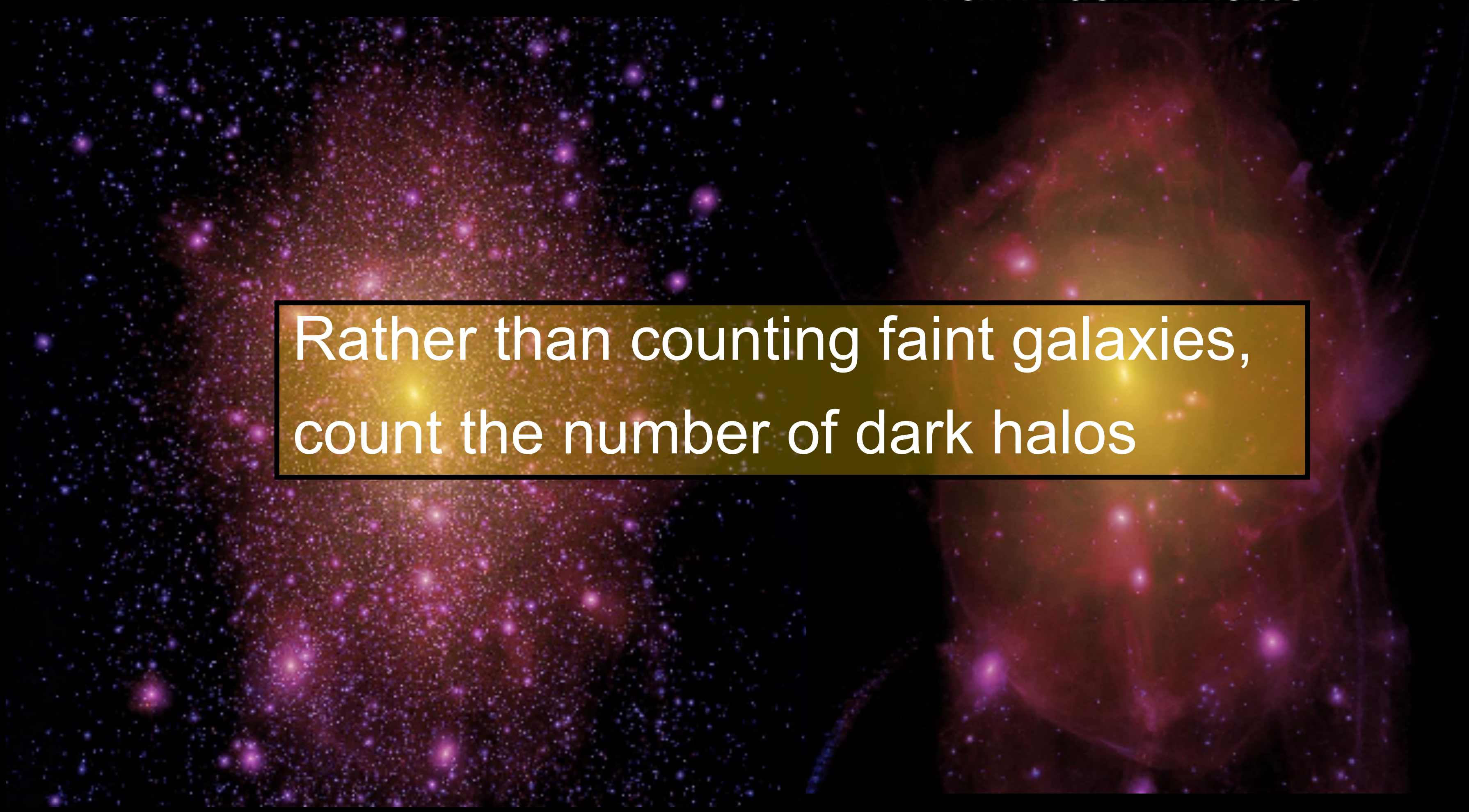
All we achieved by counting satellite galaxies was to rule out a few WDM models

The inner structure of satellites doesn't help to distinguish either

Anything else?

# Can we distinguish CDM/WDM?

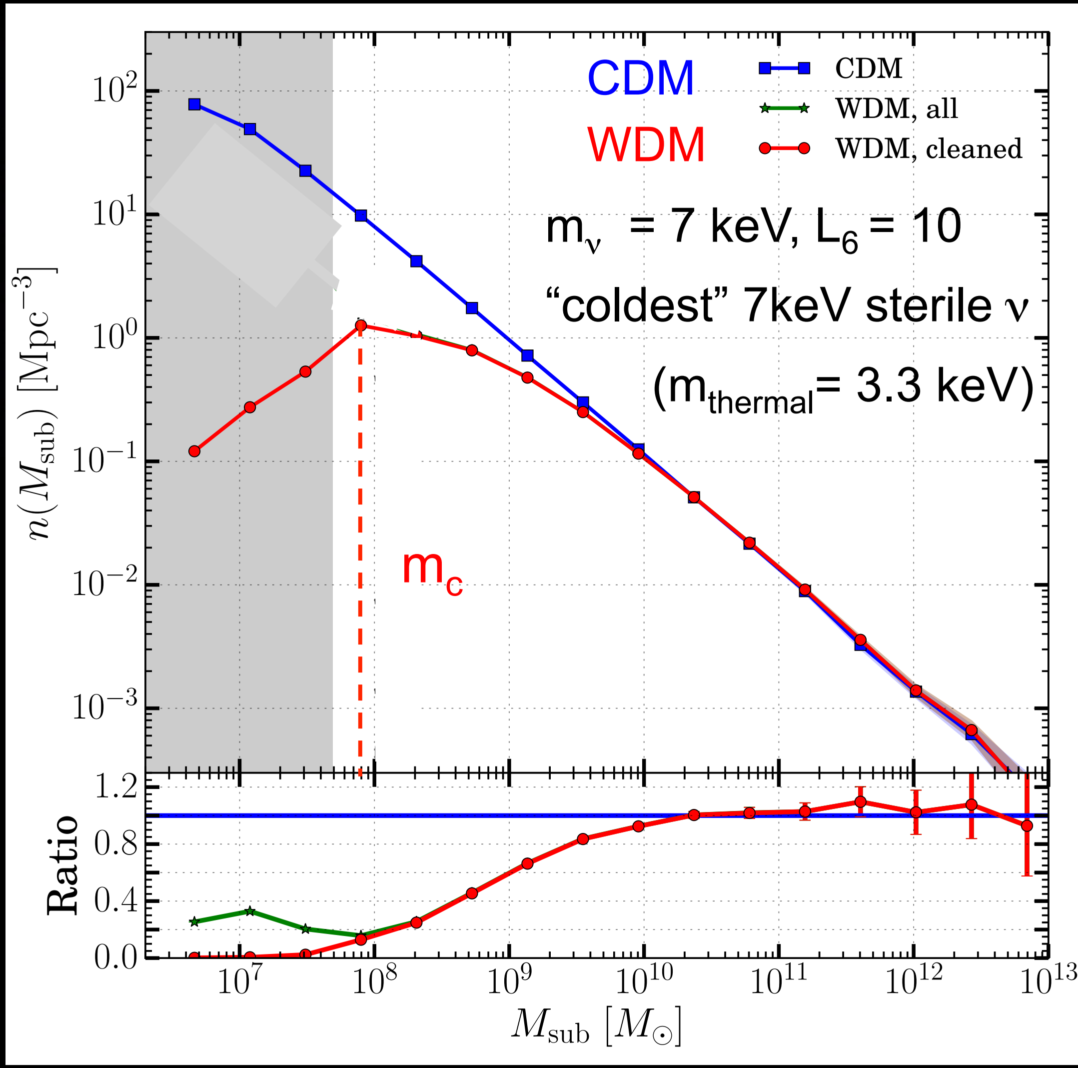
cold dark matter | warm dark matter



Rather than counting faint galaxies, count the number of dark halos

# The subhalo mass function

CDM WDM



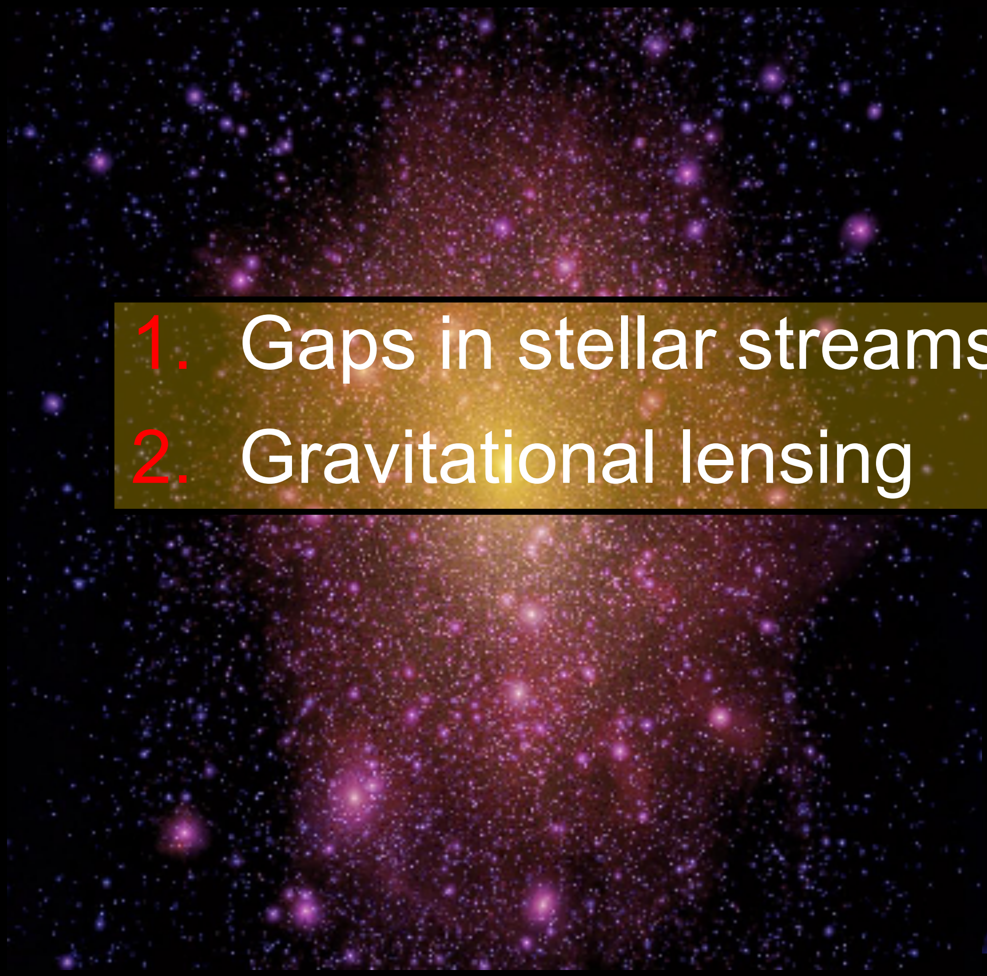

3 x fewer WDM subhalos at $3x10^9$ $M_o$

10 x fewer at $10^8$ $M_o$

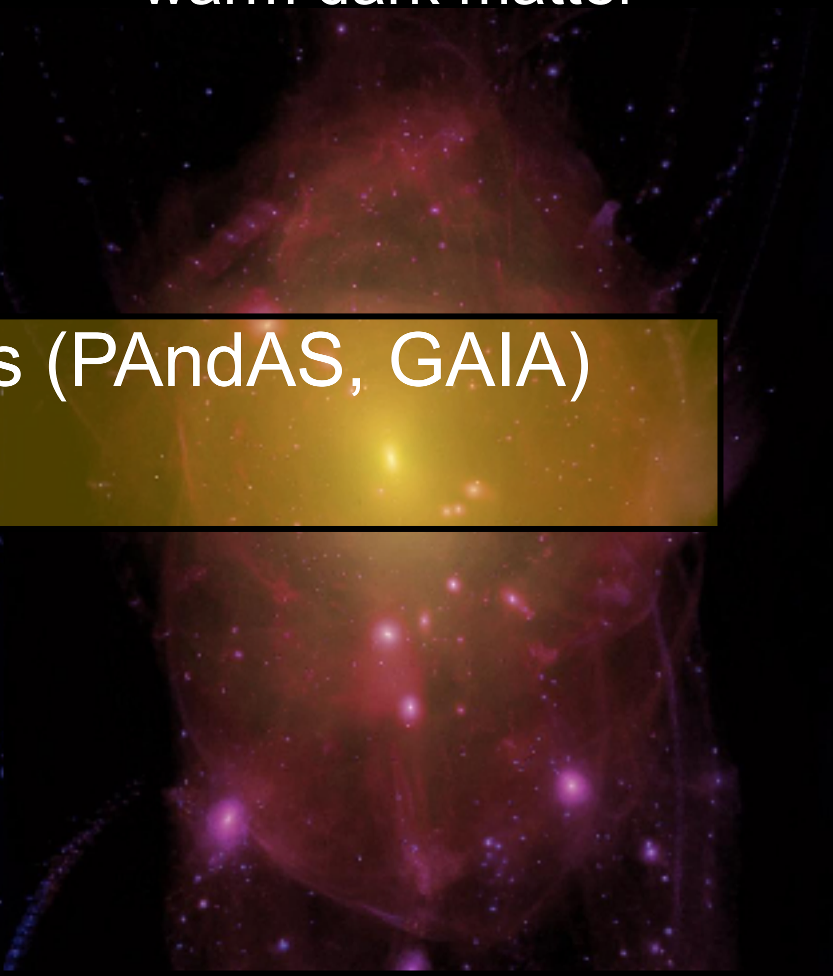
Bose, CSF et al '16

# Can we distinguish CDM/WDM?

cold dark matter



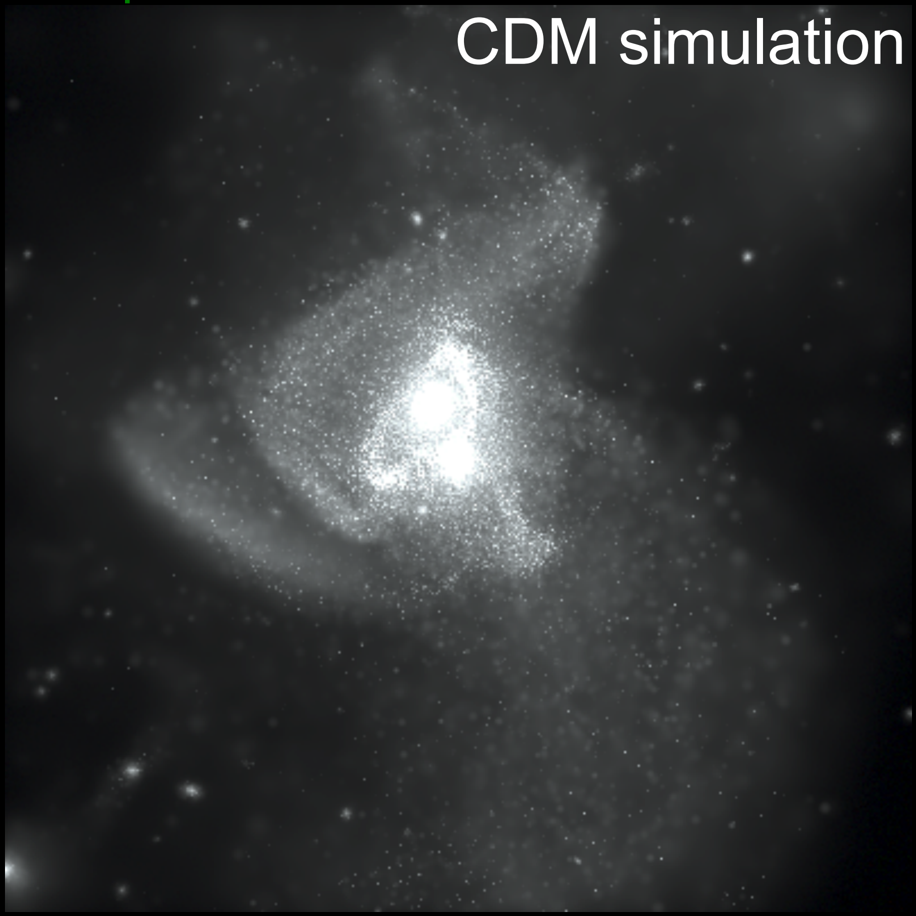
warm dark matter

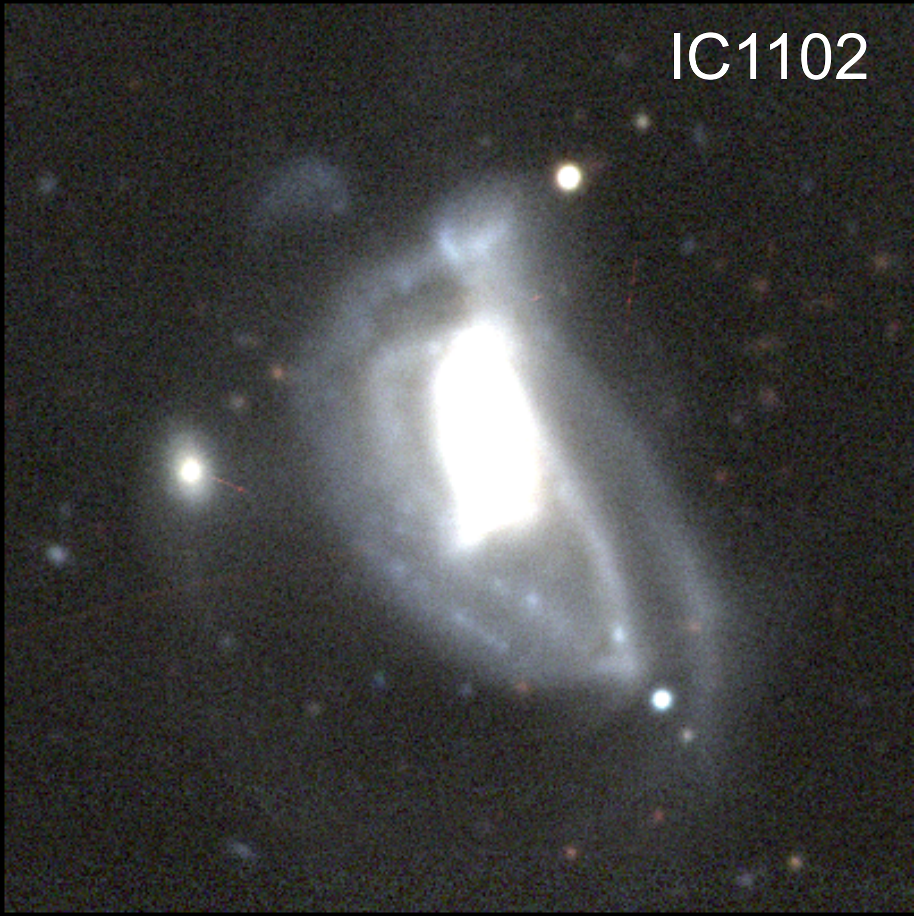


1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing

# Can we distinguish CDM/WDM?

Cooper et al ‘16



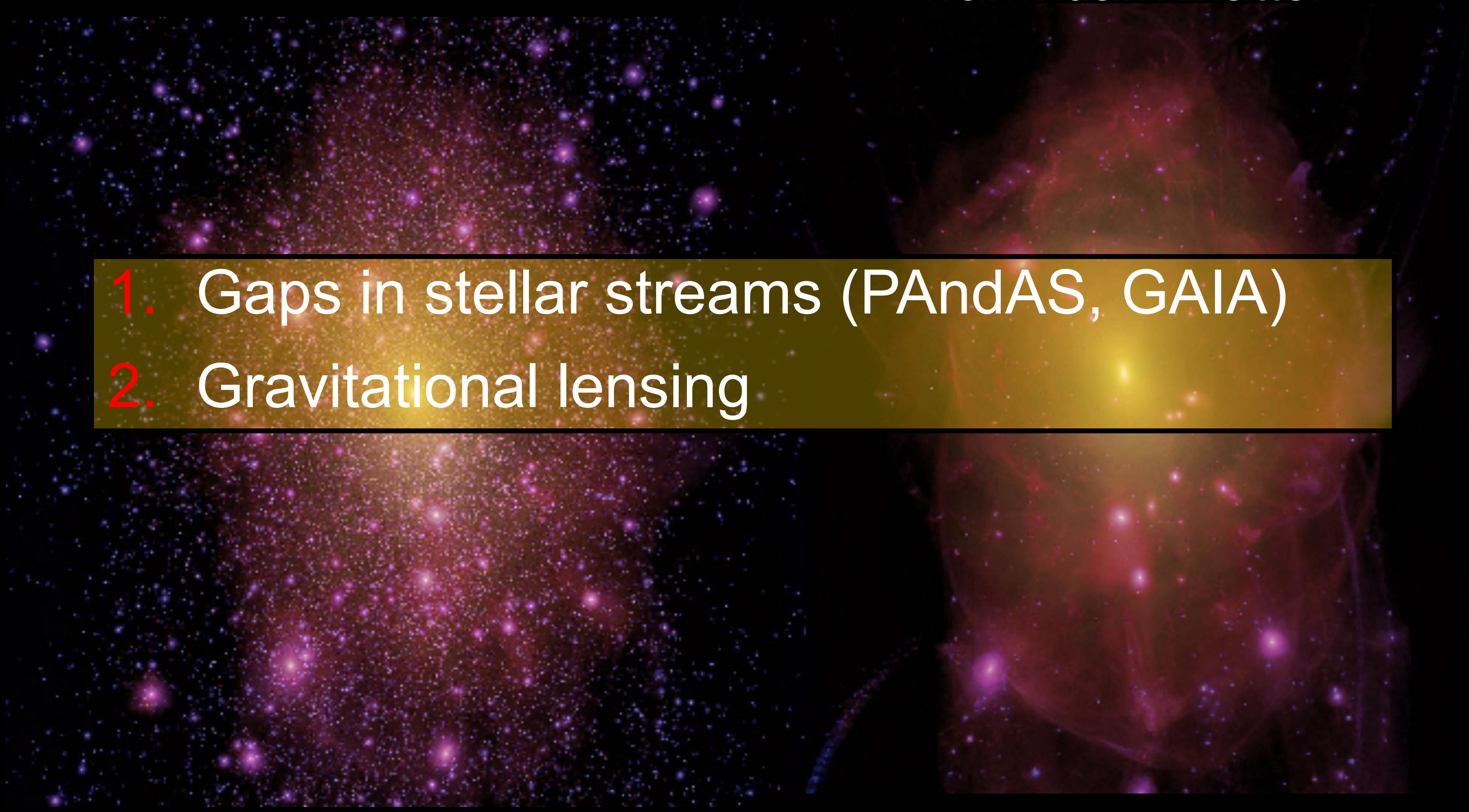




Subhalos crossing a cold tidal stream can produce a gap

Globular cluster streams (e.g. Pal 5) may be best

# Can we distinguish CDM/WDM?

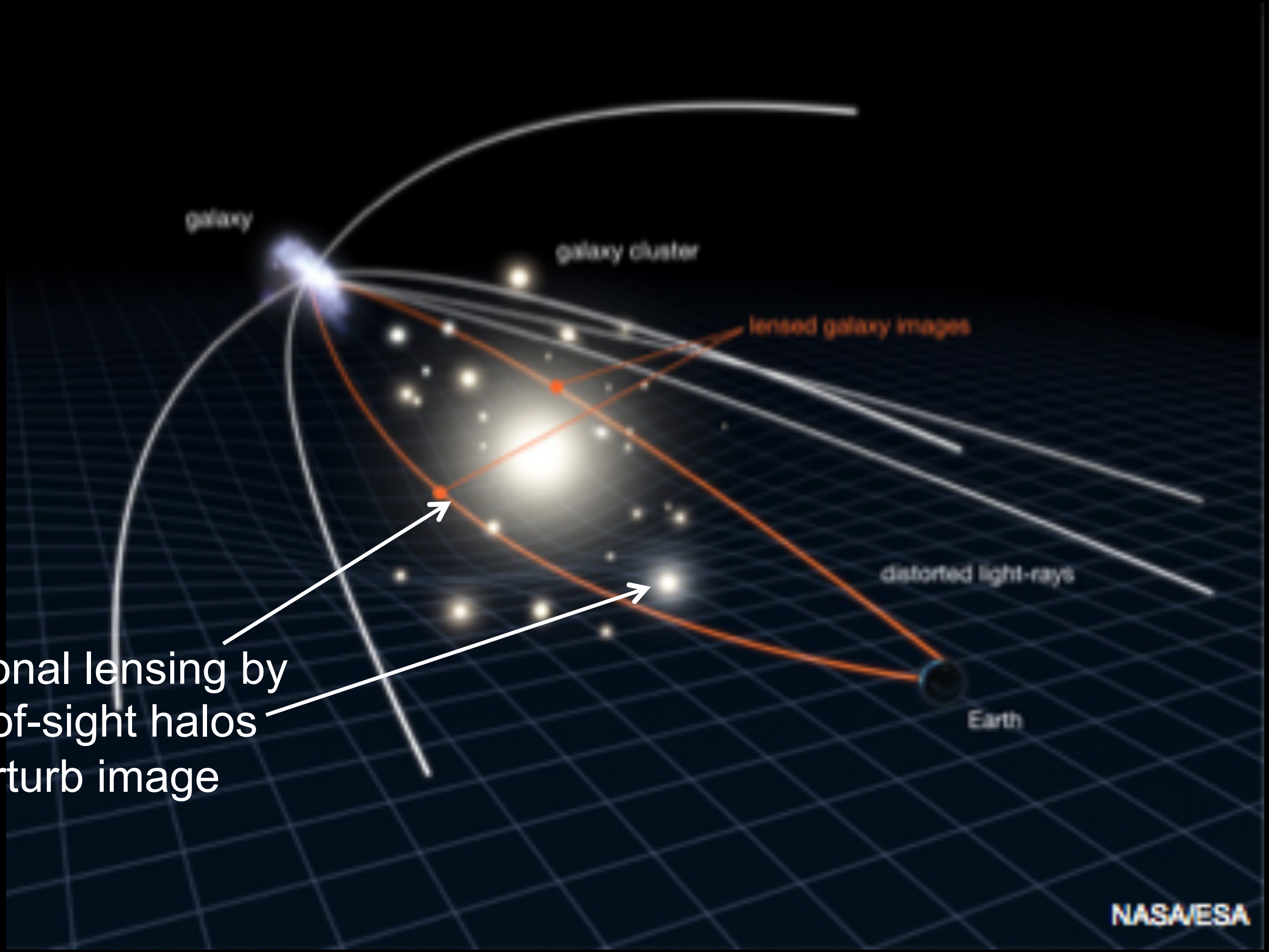
cold dark matter | warm dark matter



1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing

How to rule out CDM

# Gravitational lensing: Einstein rings

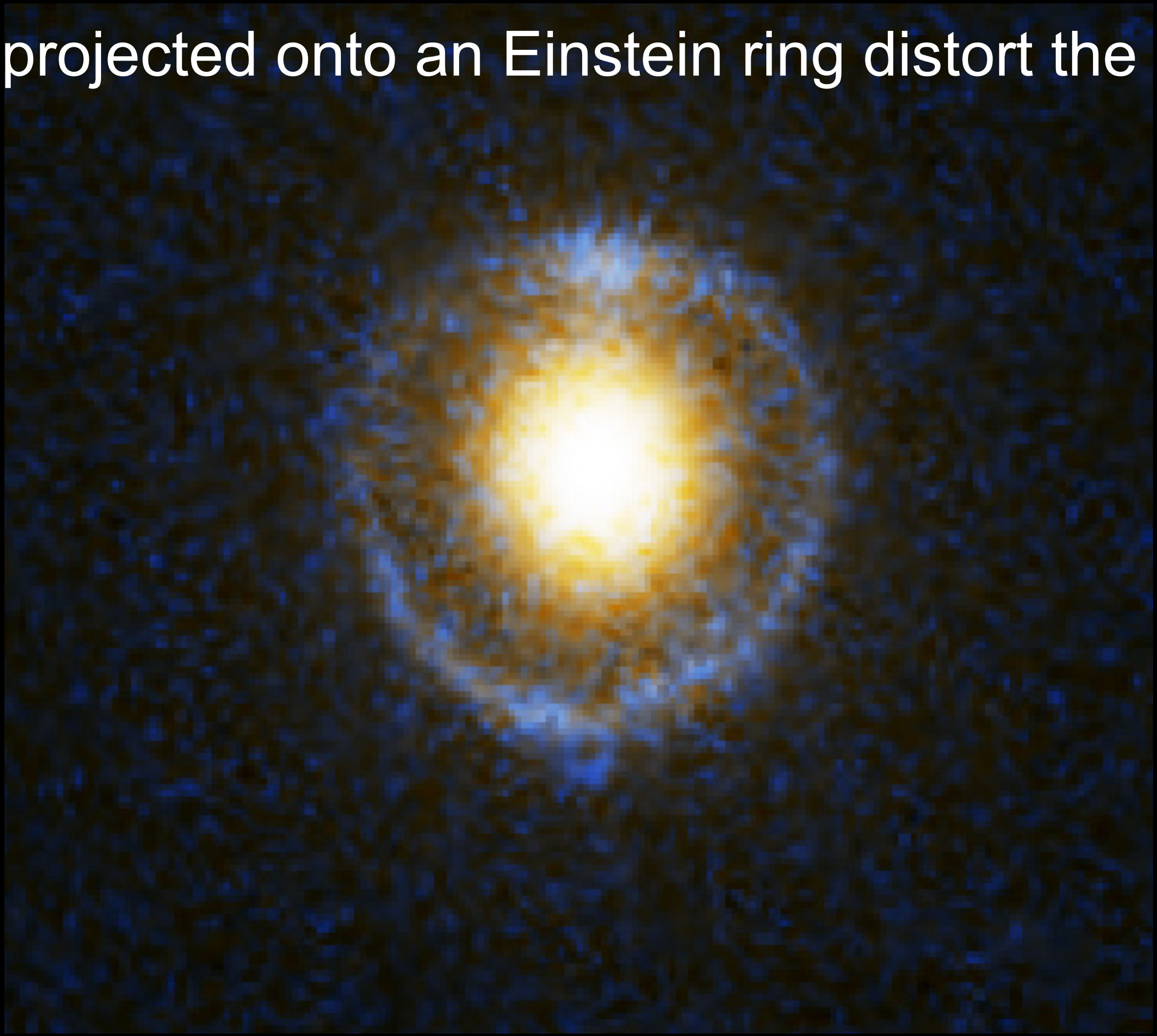



Additional lensing by line-of-sight halos perturb image

When the source and the lens are well aligned → strong arc or an Einstein ring

# Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image

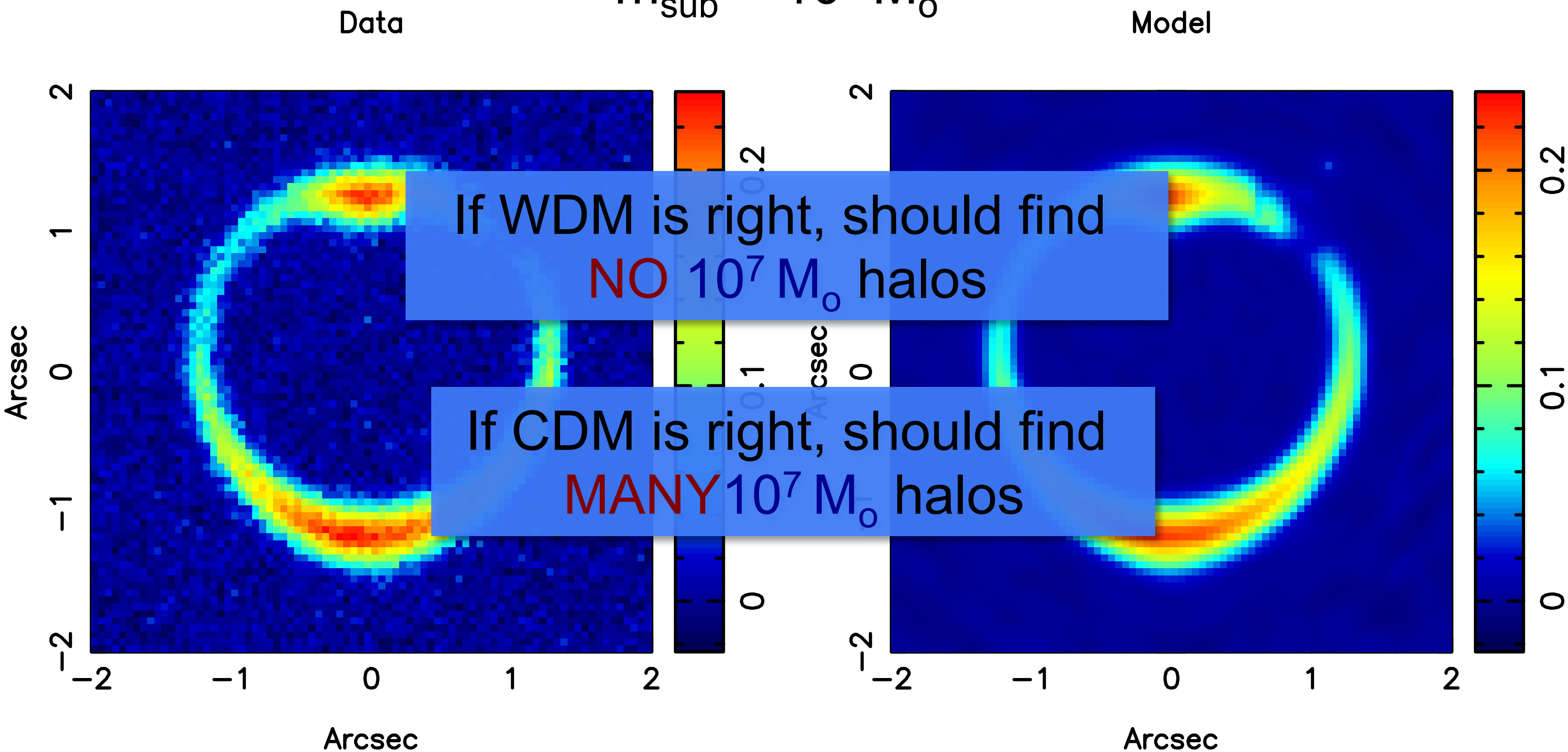


Vegetti & Koopmans '09

# Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8 \, M_o$




If WDM is right, should find NO $10^7 \, M_o$ halos

If CDM is right, should find MANY $10^7 \, M_o$ halos

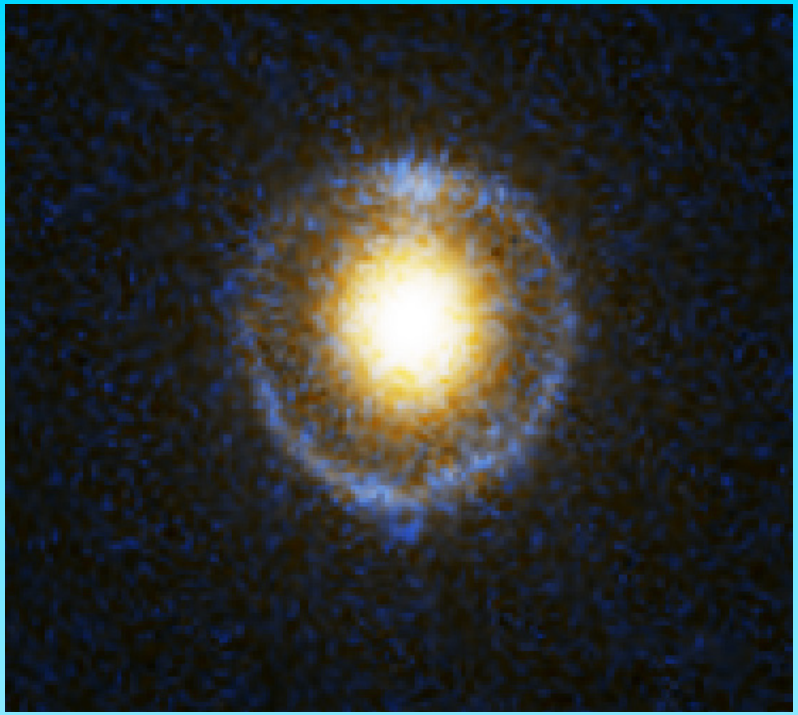
Can detect subhalos as small as $10^7 \, M_o$

University of Durham

# Gravitational lensing: Einstein rings

Two important considerations:

- The central galaxy can destroy subhalos
- Both subhalos and line-of-sight projected halos lens

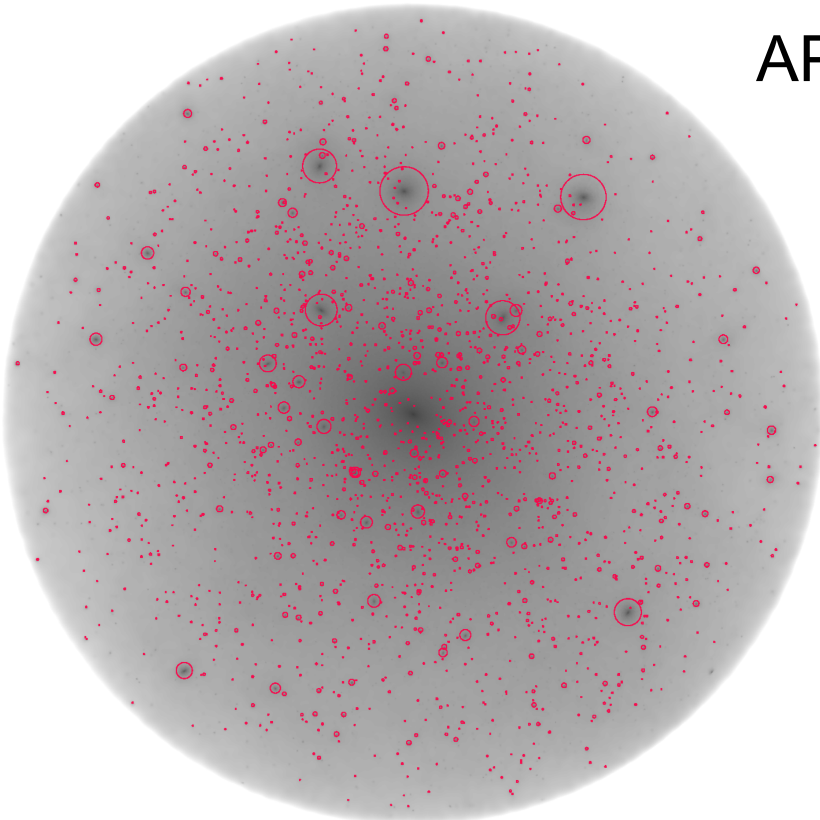


Sawala et al '16

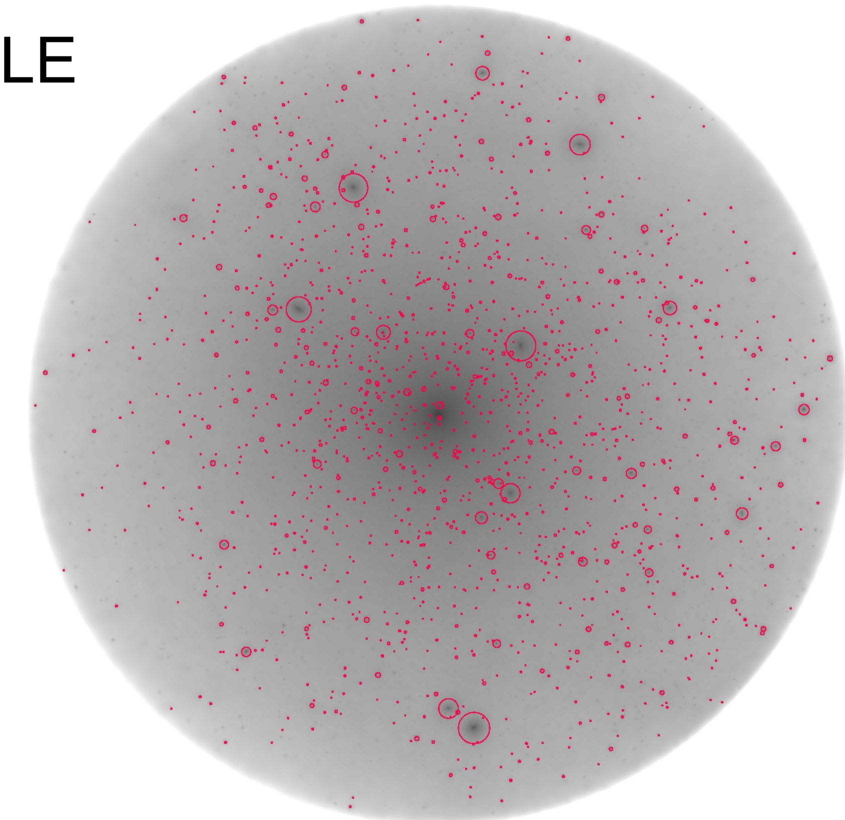
# Destruction of dark substructures by galactic baryons

University of Durham

APOSTLE



Dark matter only simulation



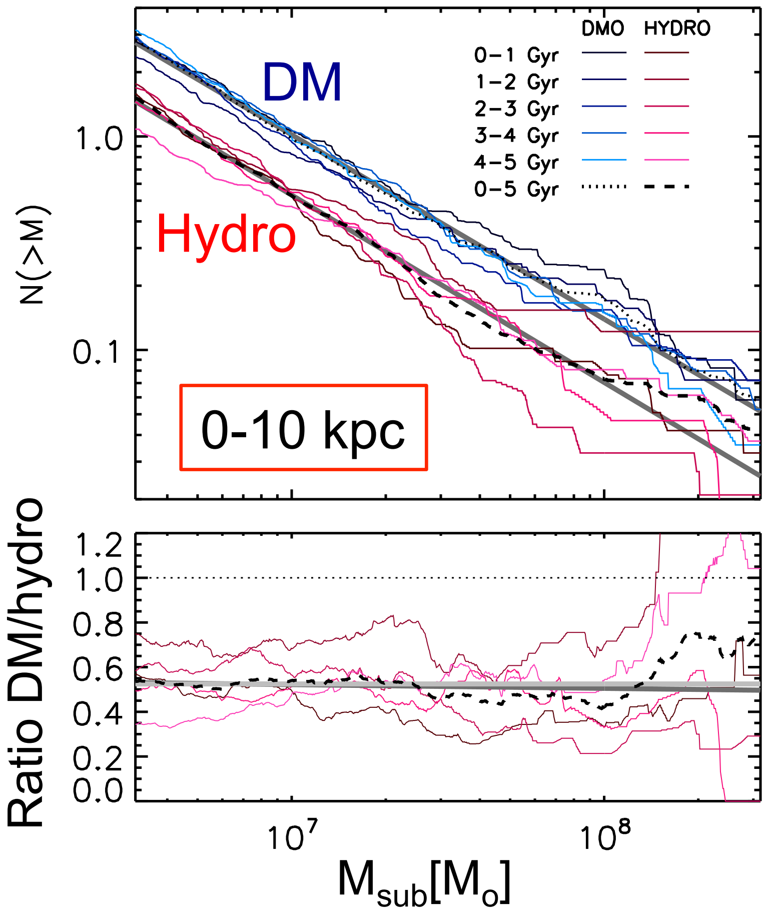
Hydrodynamic simulation

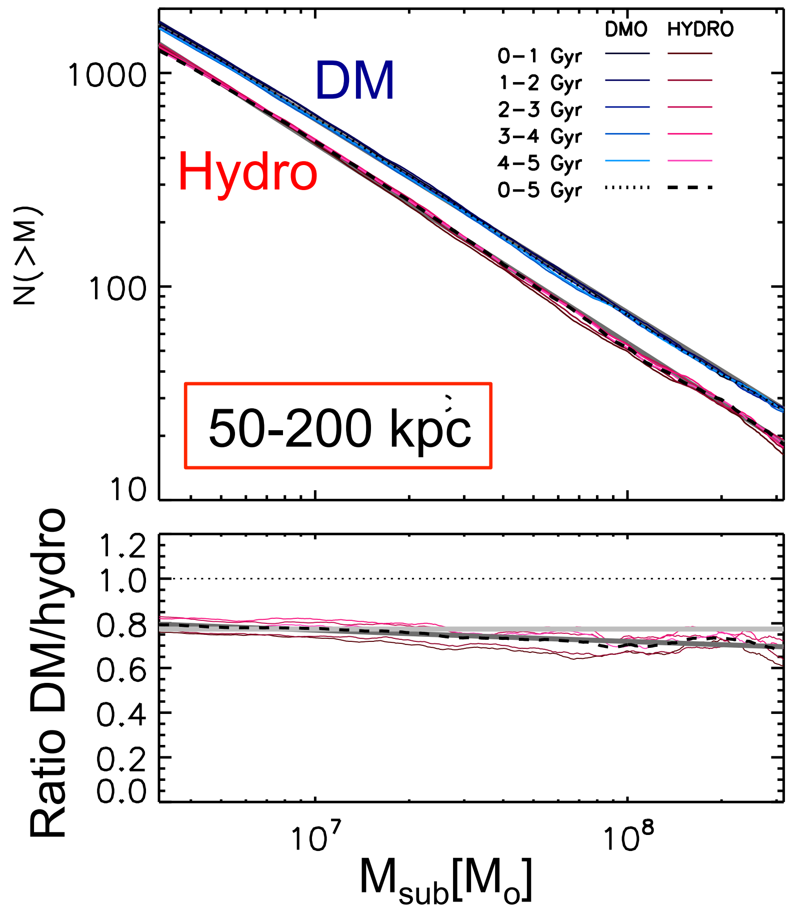
Sawala et al ‘16

Institute for Computational Cosmology

University of Durham

# Destruction of dark substructures by galactic baryons



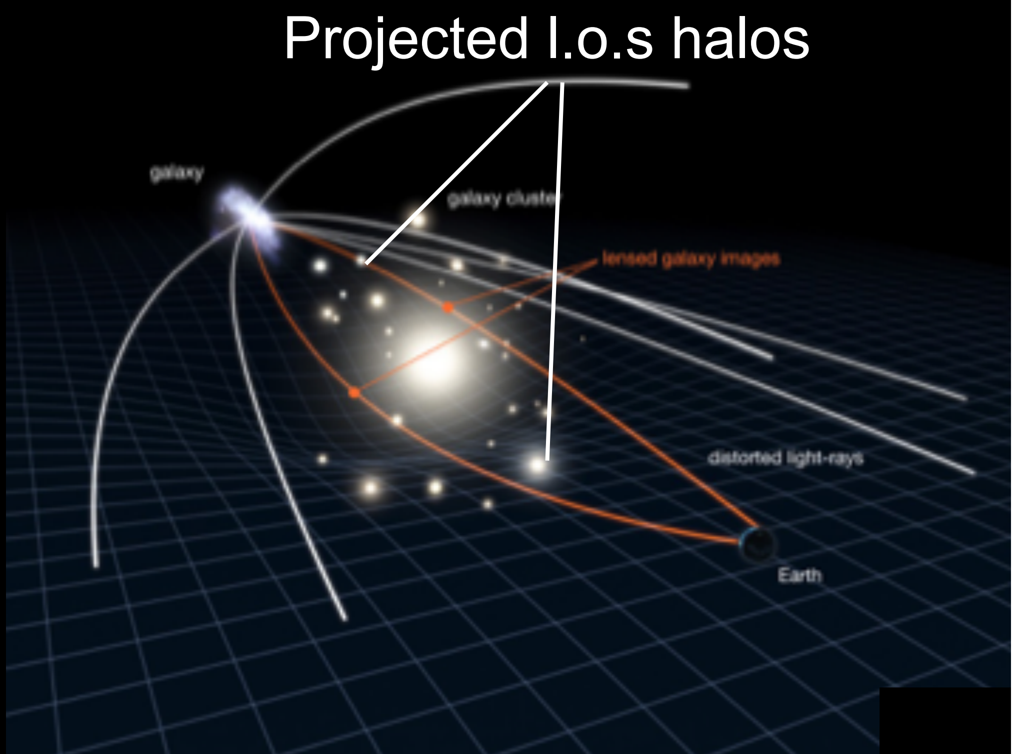



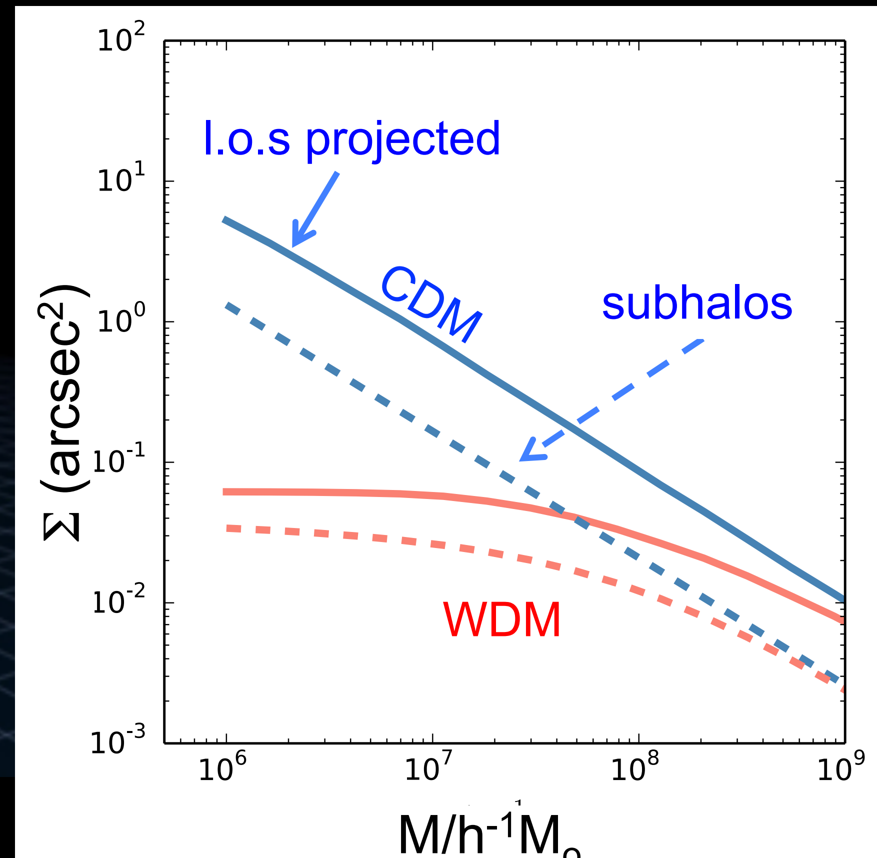

- 40% of subhalos in 0-10 kpc destroyed by interaction w. galaxy
- 20% “ 50-200 kpc “

Sawala et al ‘16

# Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens: who wins?




The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16

# Detecting substructures with strong lensing

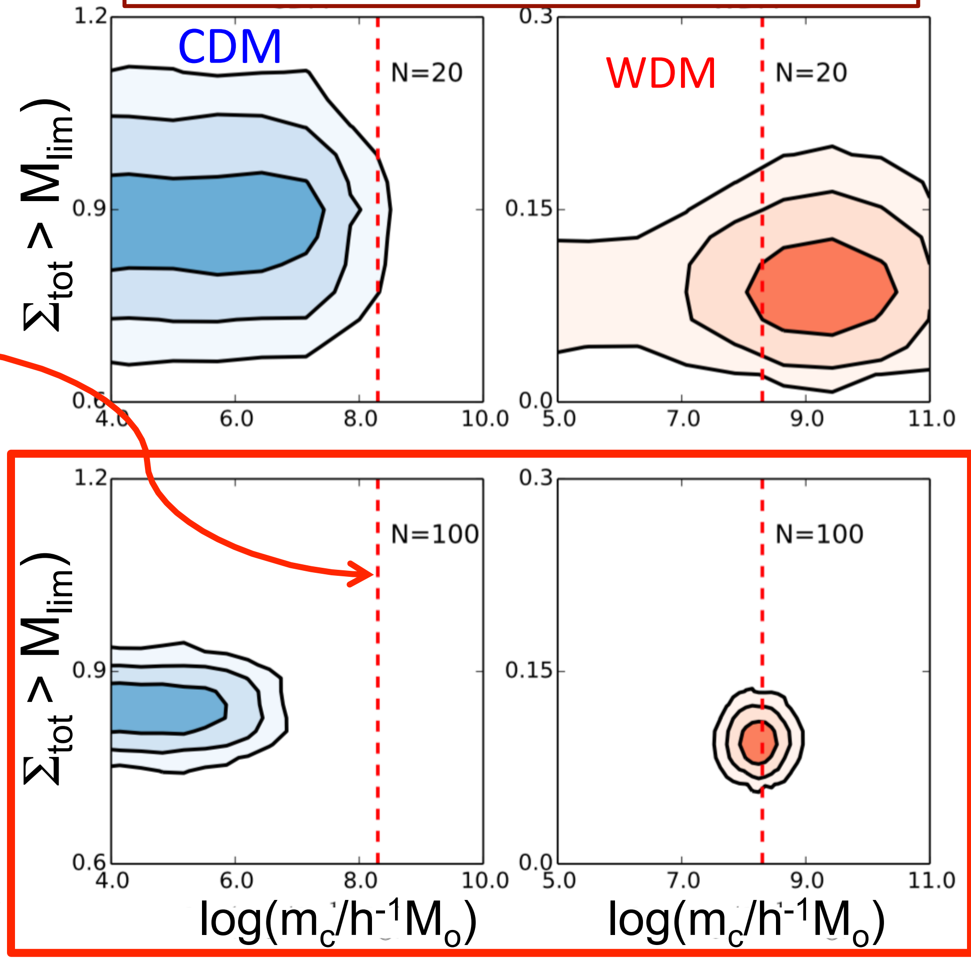
University of Durham

$\Sigma_{tot}$= projected halo number density within Einstein ring

$m_c$= halo cutoff mass

$m_c = 1.3 \times 10^8\ h^{-1}M_o$ for coldest 7 keV sterile neutrino

Detection limit = $10^7\ h^{-1}M_o$




100 Einstein ring systems and detection limit: $m_{low} = 10^7\ h^{-1}M_o$

- If DM is 7 keV sterile $\nu$ → rule out CDM at >3$\sigma$!
- If DM is CDM → rule out 7 keV sterile $\nu$ at many $\sigma$

Li, CSF et al '16

Institute for Computational Cosmology

# Conclusions

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

1. Counting faint galaxies cannot distinguish CDM/WDM
2. No too-big-to-fail when baryon effects are included
3. Cores can be easily produced by baryon effects
4. Strong gravitational lensing can distinguish CDM/WDM

   (and could rule out CDM!)