Astrophysical tests of the identity of the dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

Non-baryonic dark matter candidates

From the 1980s:

Type	example	mass
hot	neutrino	few tens of eV
warm	sterile ν	keV-MeV
cold	axion neutralino	10^{-5}eV - 100 GeV

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The dark matter power spectrum

Free streaming →

λ_{cut} α m_x^{-1}

for thermal relic

m_{CDM} ~ 100GeV

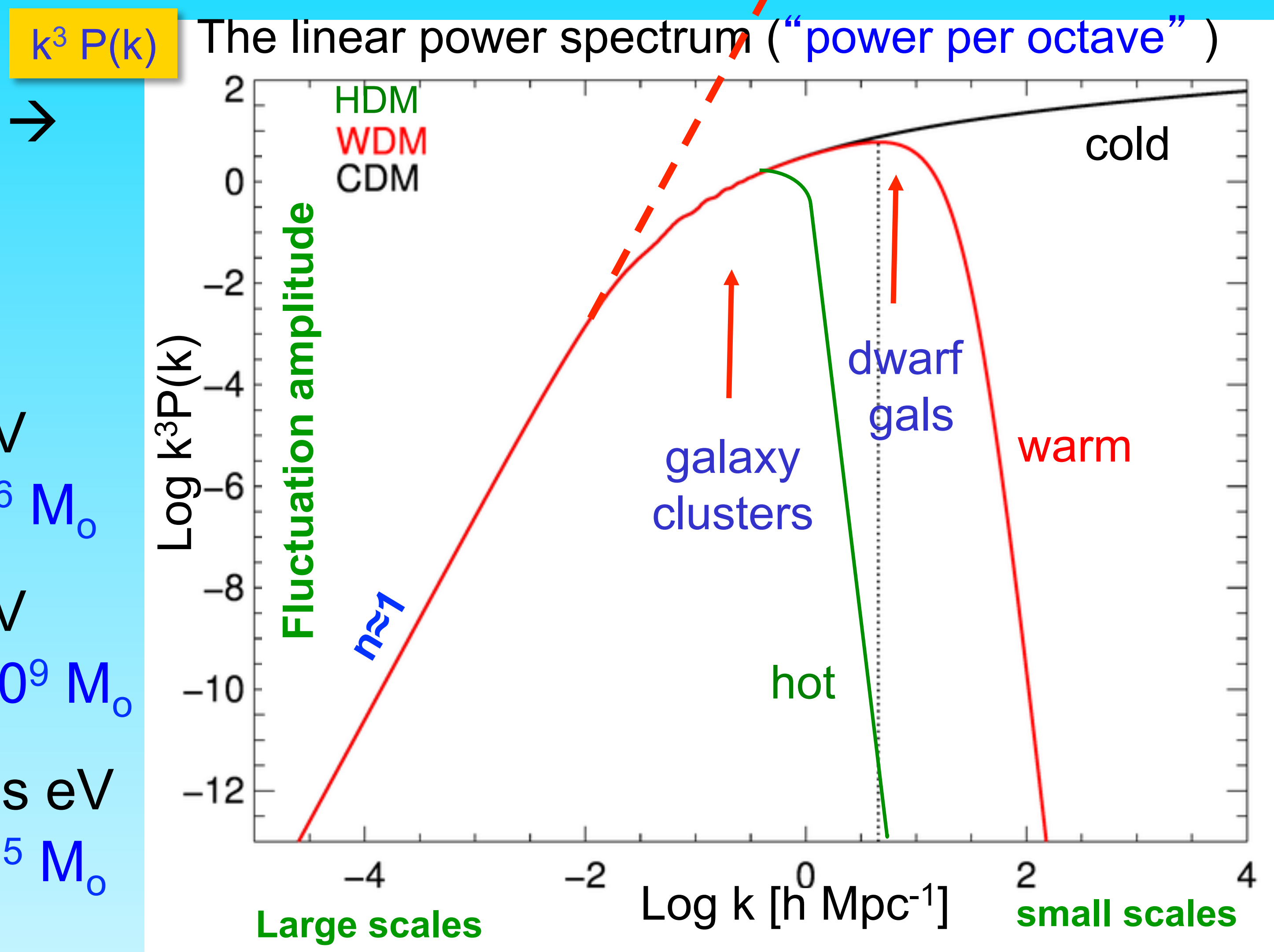
susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV

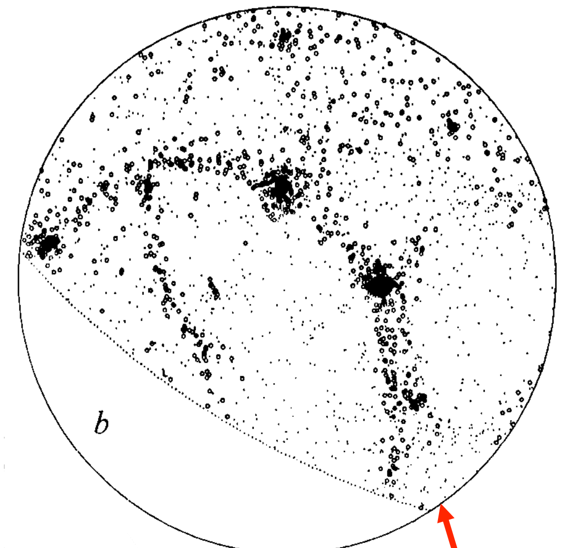
sterile ν; M_{cut}~10^9 M_o

m_{HDM} ~ few tens eV

light ν; M_{cut}~10^{15} M_o



Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

Non-baryonic dark matter cosmologies

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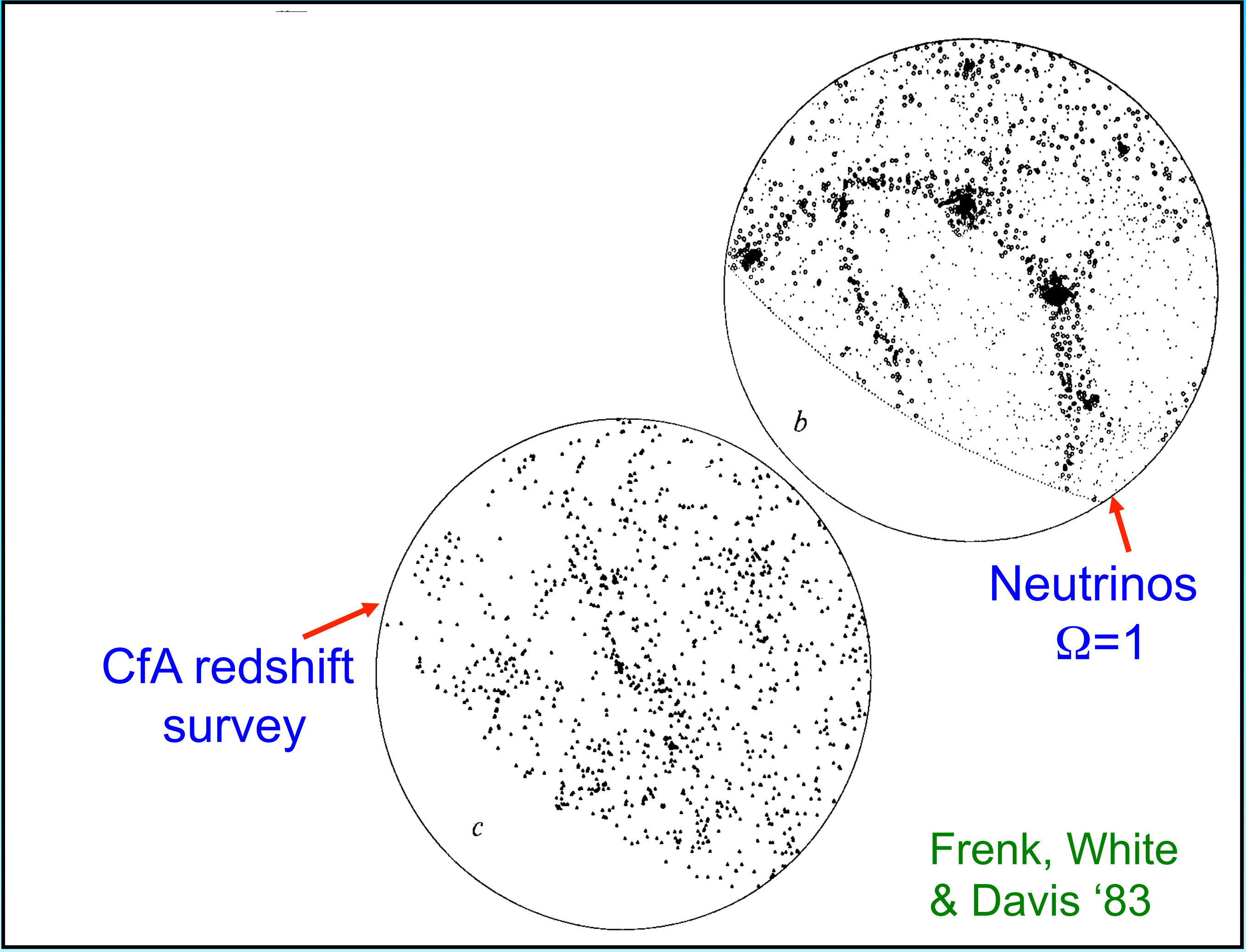
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν << 30 ev



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Non-baryonic dark matter cosmologies

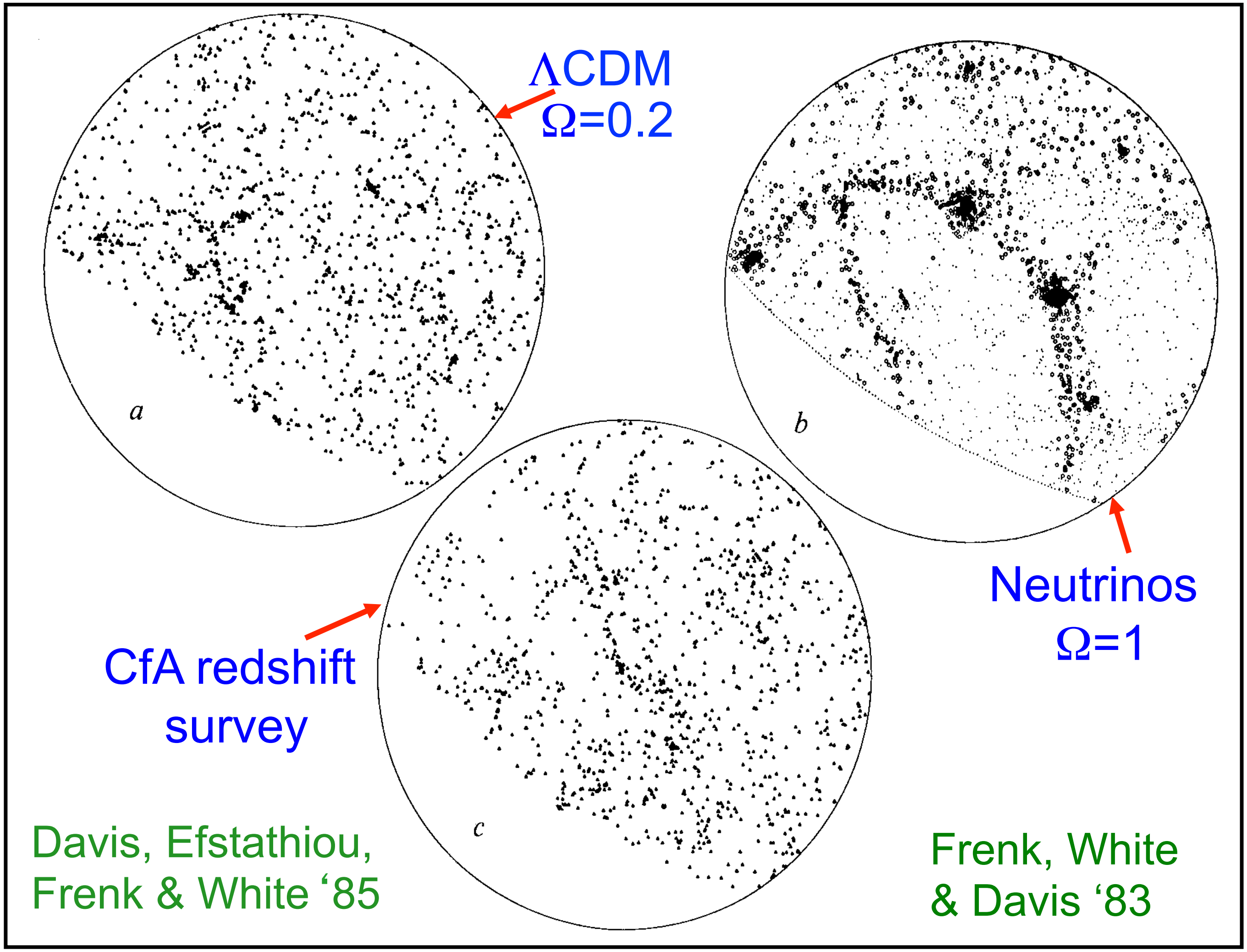
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

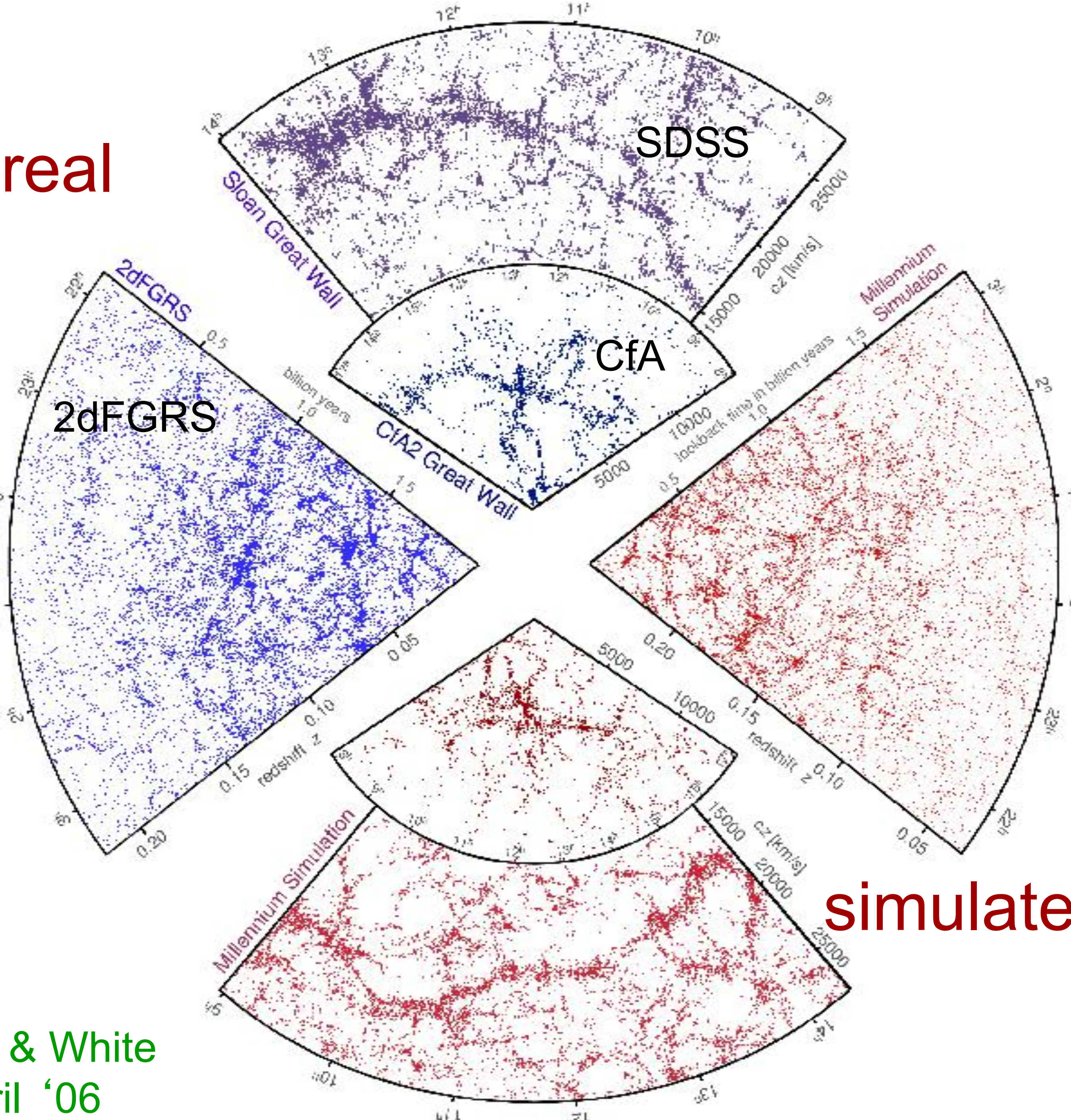
→ m_ν<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



real

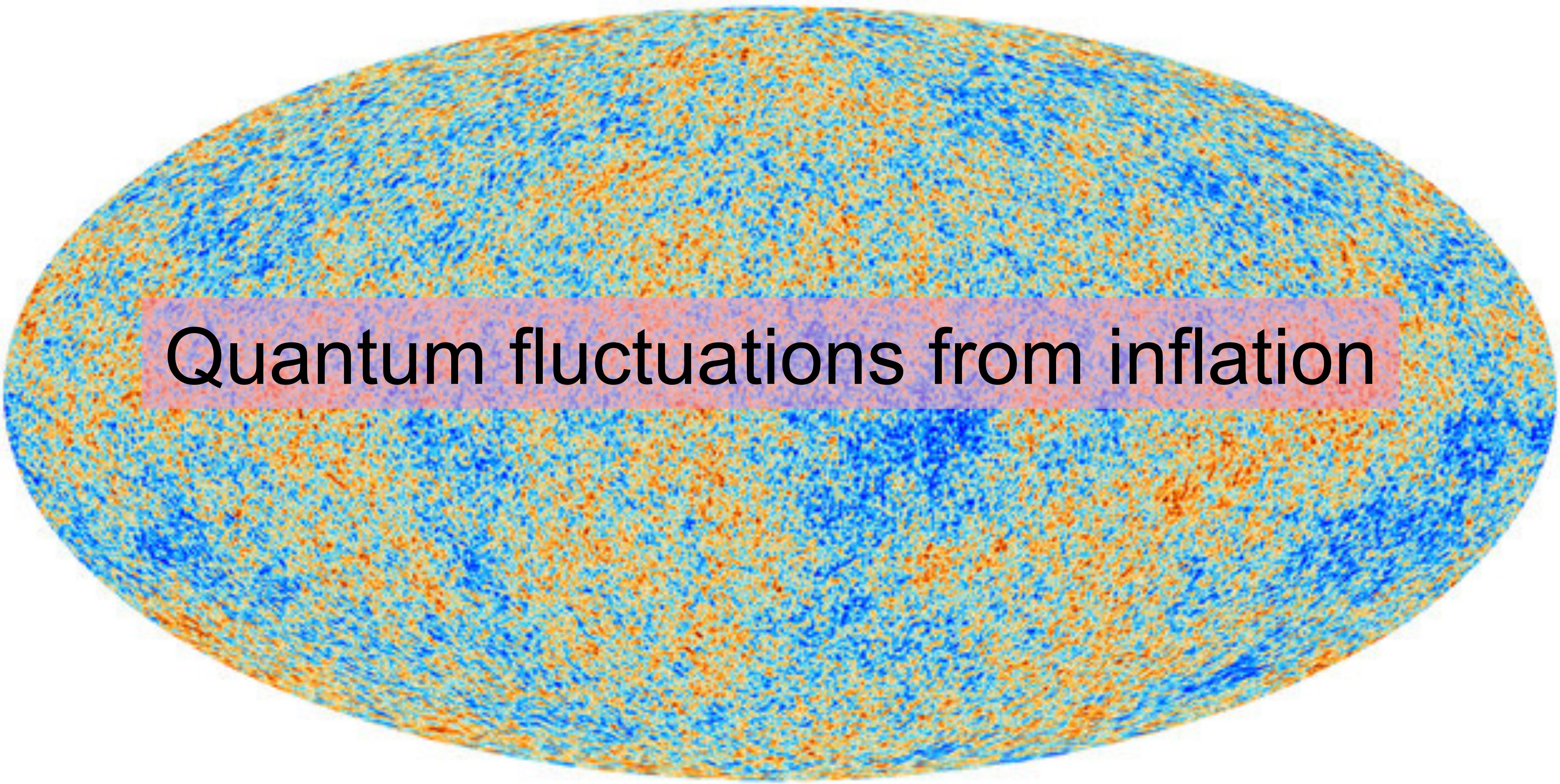


simulated

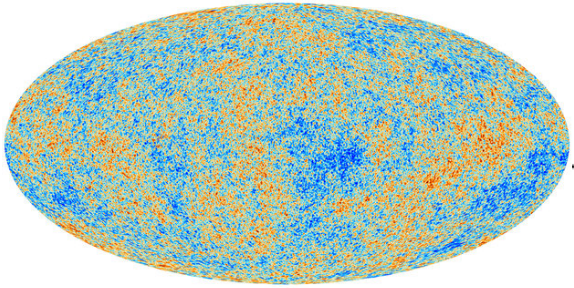
Springel, Frenk & White
Nature, April '06

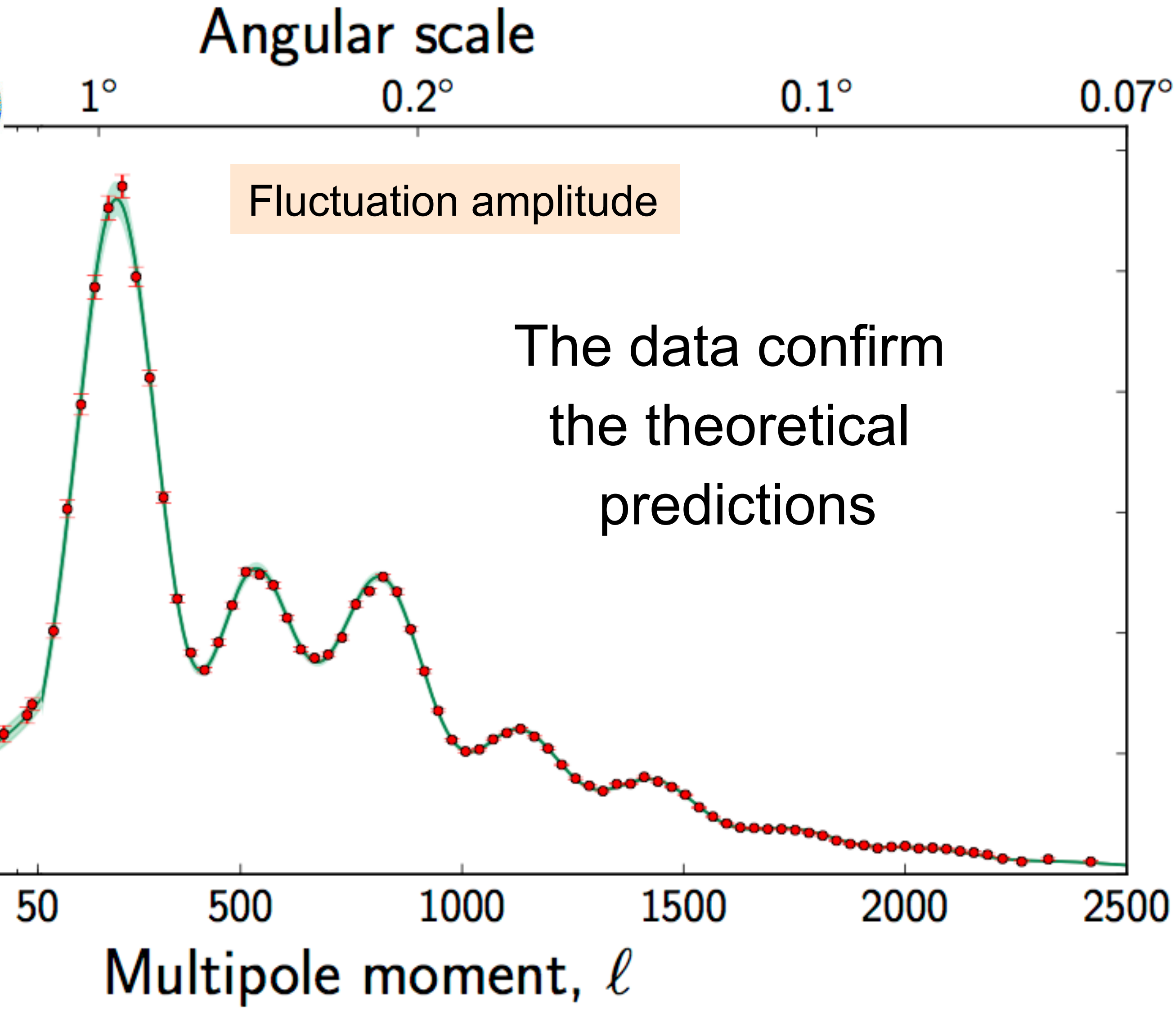
University of Durham ICC

The initial conditions for galaxy formation



Planck: CMB temperature anisotropies





Planck coll. 2015

Univer

The six parameters of minimal ΛCDM model

6 mdoel parameters

	Planck+WP	
Parameter	Best fit	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

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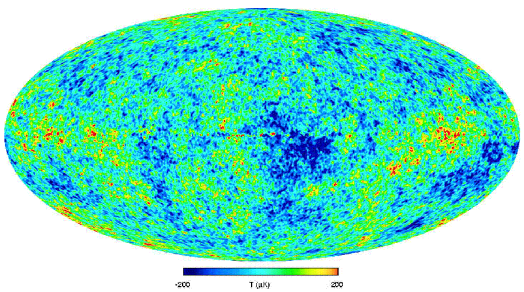
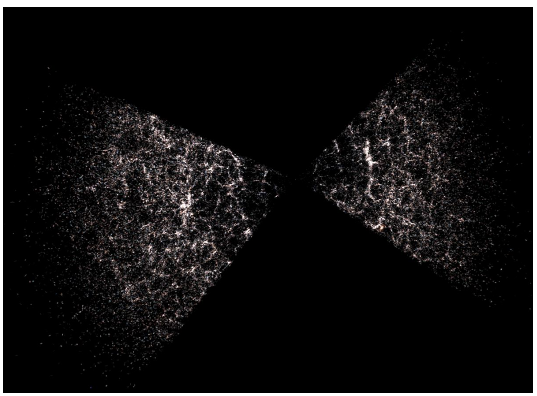
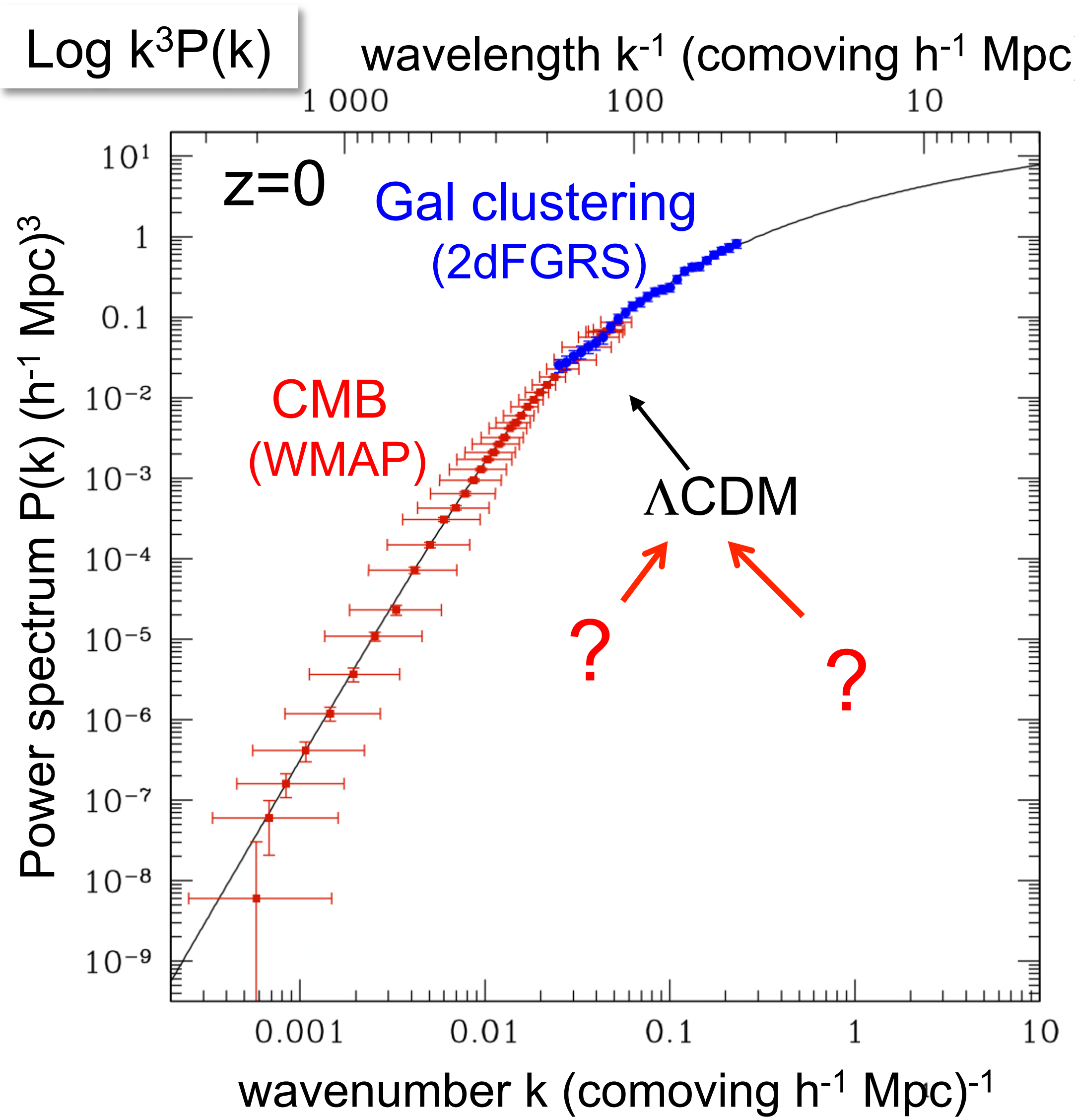
The cosmic power spectrum: from the CMB to the 2dFGRS



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

$m_{CDM} \sim 100GeV$

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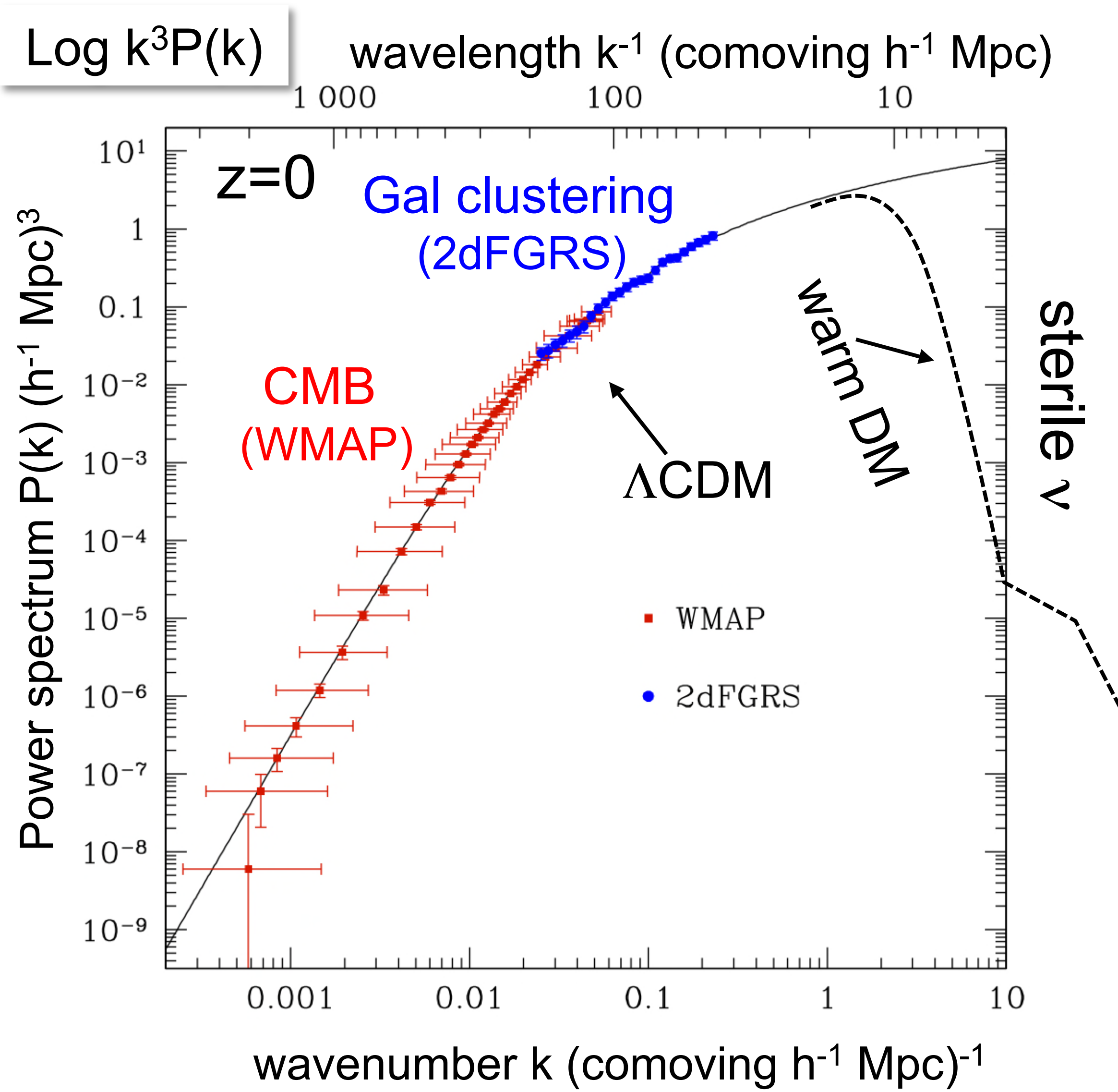

Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

- CDM: γ-ray excess from Galactic Center
- WDM (sterile ν): 3.5 X-ray keV line in galaxies and clusters

Very unlikely that both are right!

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Sterile neutrinos

Explain:

- Neutrino oscillations and masses
- Baryogenesis
- Absence of right-handed neutrinos in standard model
- Dark matter

Sterile neutrino minimal standard model (νMSM; Boyarski+ 09):

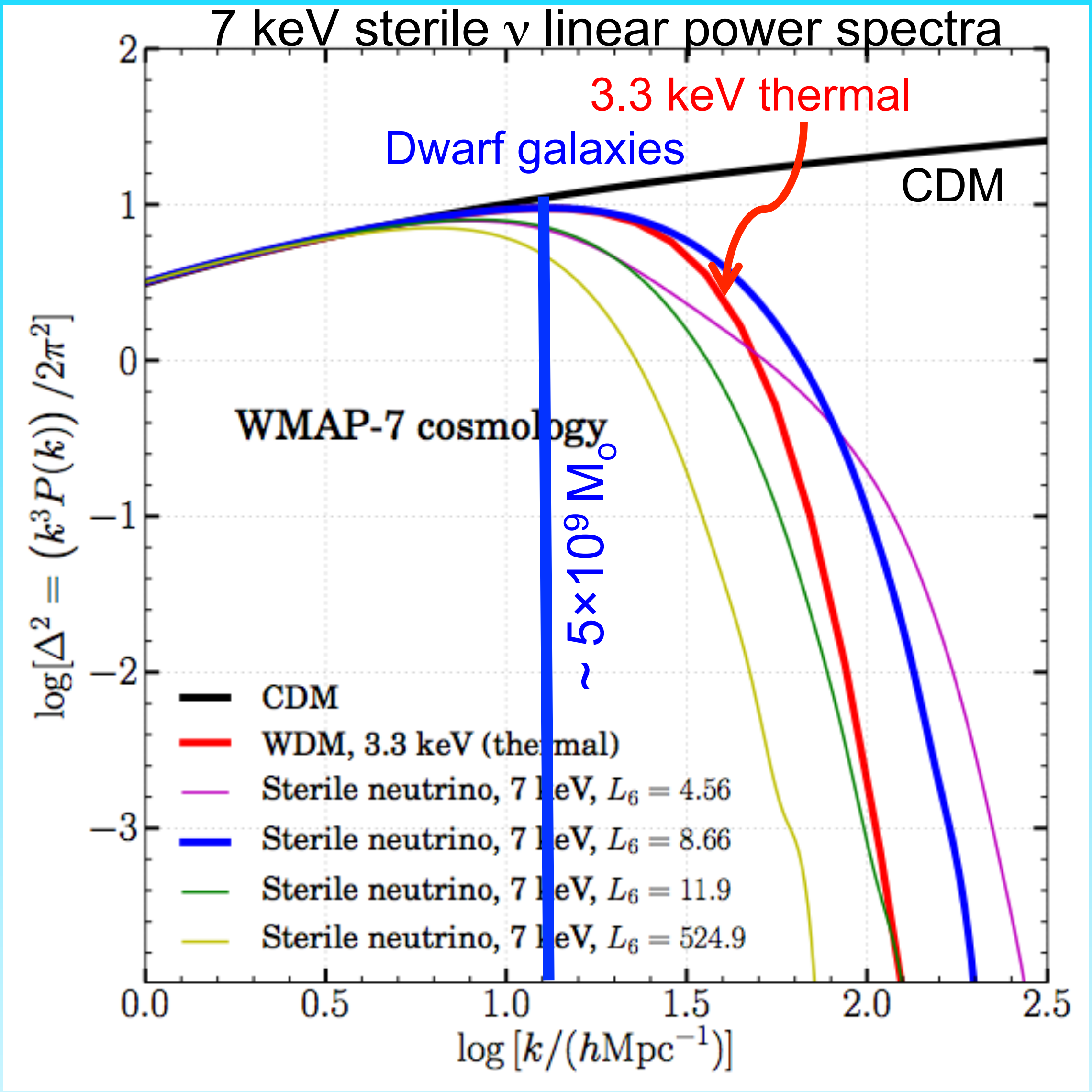
- Extension of SM w. 3 sterile neutrinos: 2 of GeV; 1 of keV mass
- If $\Omega_N=\Omega_{DM}$, 2 parameters: mass, lepton asymmetry/mixing angle
- GeV particles may be detected at CERN (SHiP)
- Dark matter candidate can be detected by X-rays decay

Primordial P(k) for 7 keV sterile neutrino models

- Thermal and resonant production mechanisms
- Resonant production depends on baryon asymmetry parameter, L_6
- Linear PS varies non-monothonically with L_6

Ly-α forest rules out thermal masses, mν<3.3 keV (Viel + '13)

Lovell, Bose, CSF et al. 16



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Cold Dark Matter | Warm Dark Matter

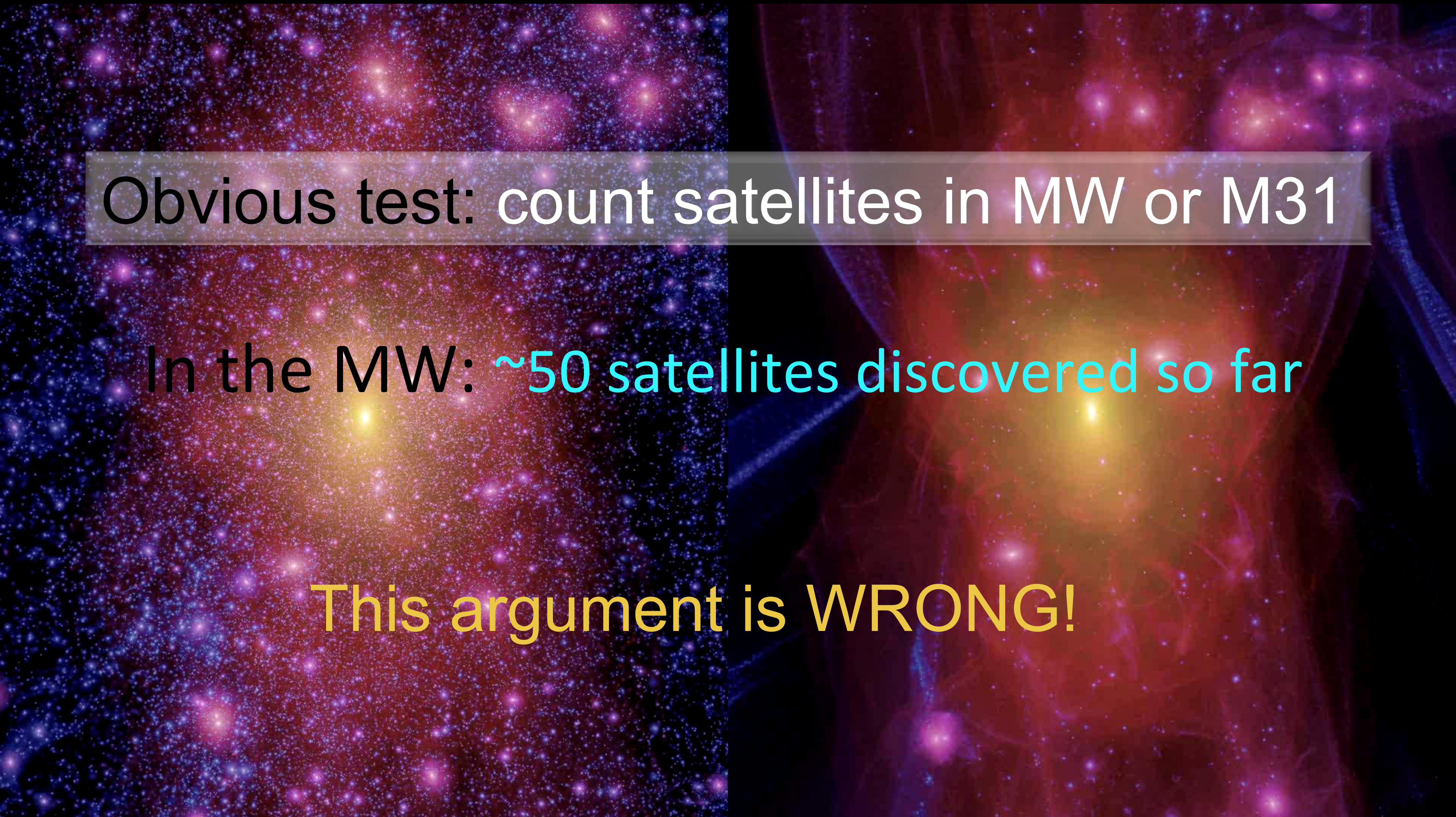
13.4 billion years ago

cold dark matter

warm dark matter

How can we distinguish between these?

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12 cold dark matter | warm dark matter



Obvious test: count satellites in MW or M31

In the MW: ~50 satellites discovered so far

This argument is WRONG!

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

Luminosity Function of Local Group Satellites

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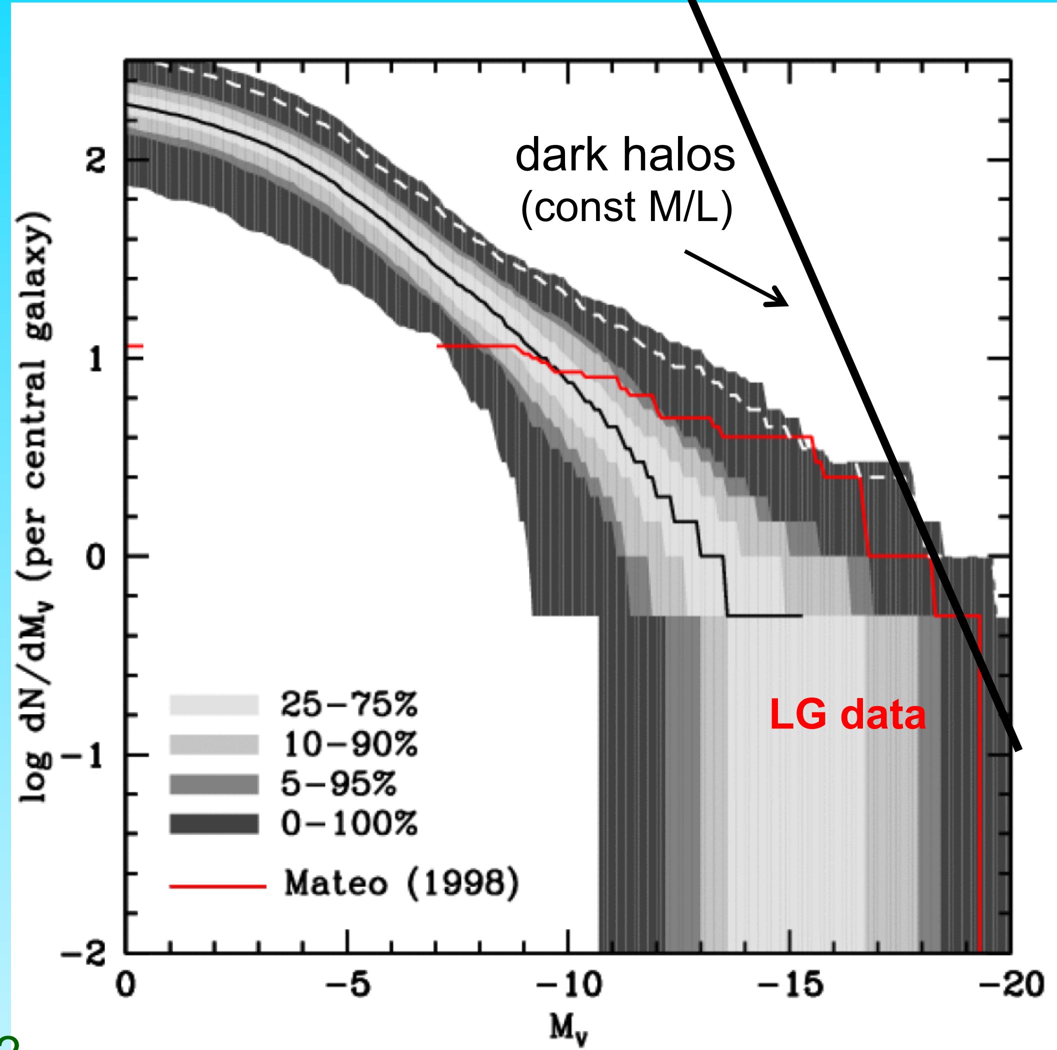
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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

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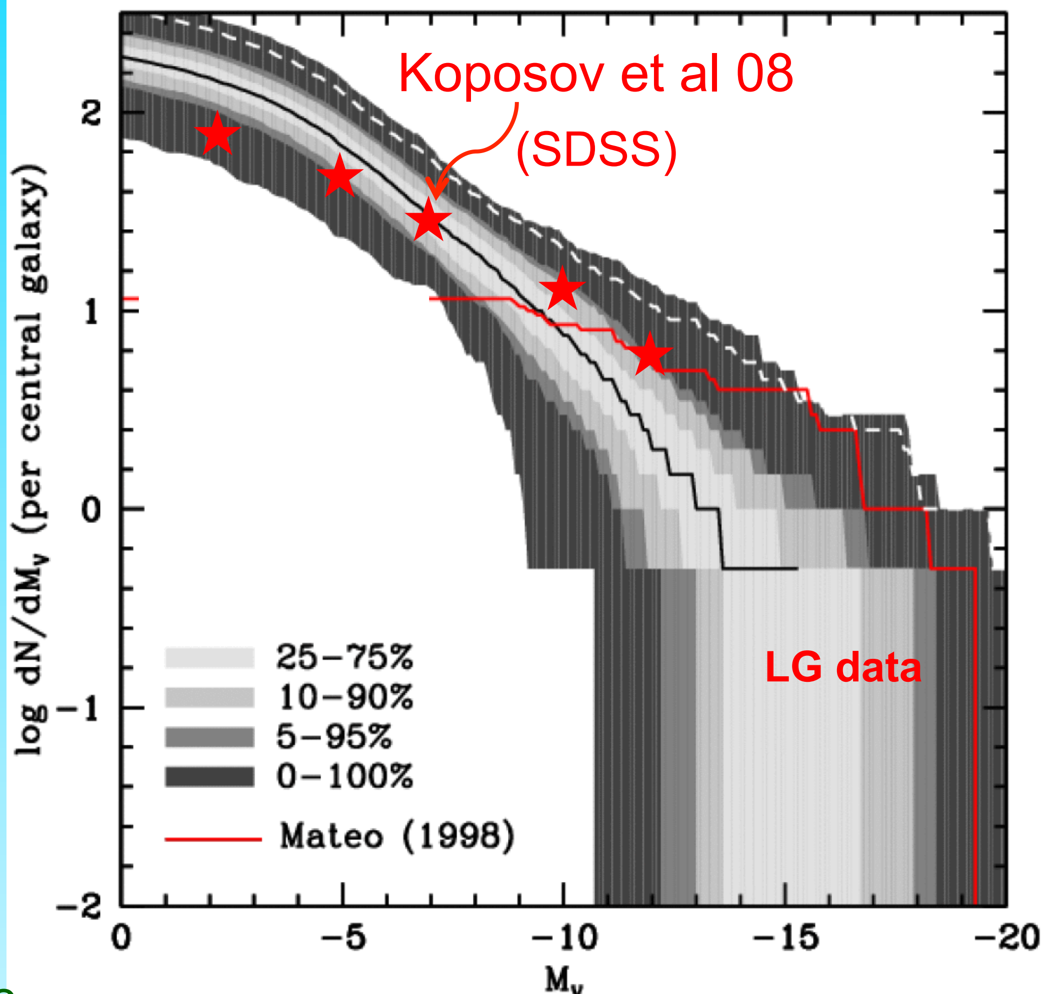

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(see also Kauffman etal '93, Bullock etal '01)

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

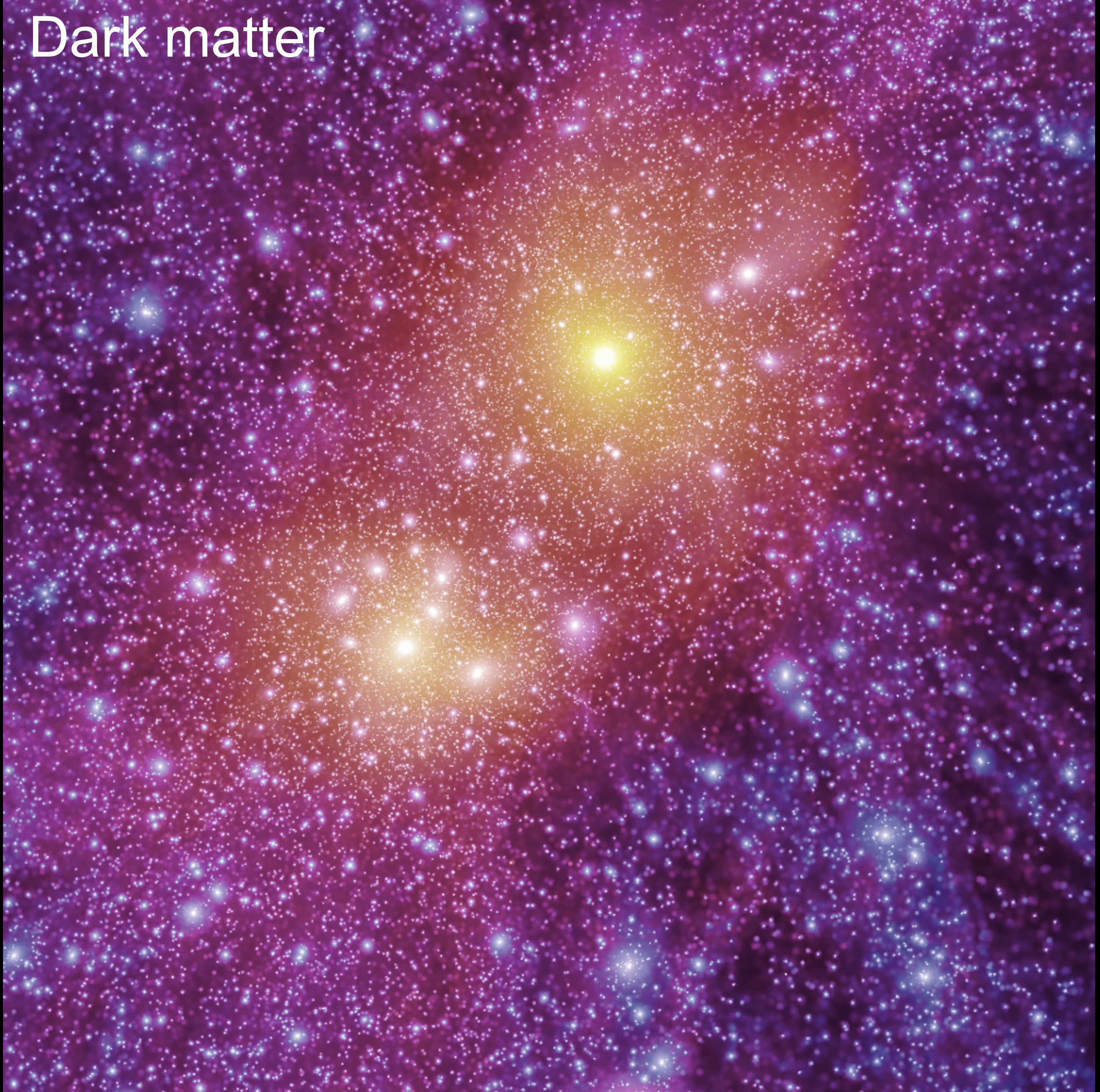
The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

APOSTLE
EAGLE full hydro simulations

Local Group

CDM

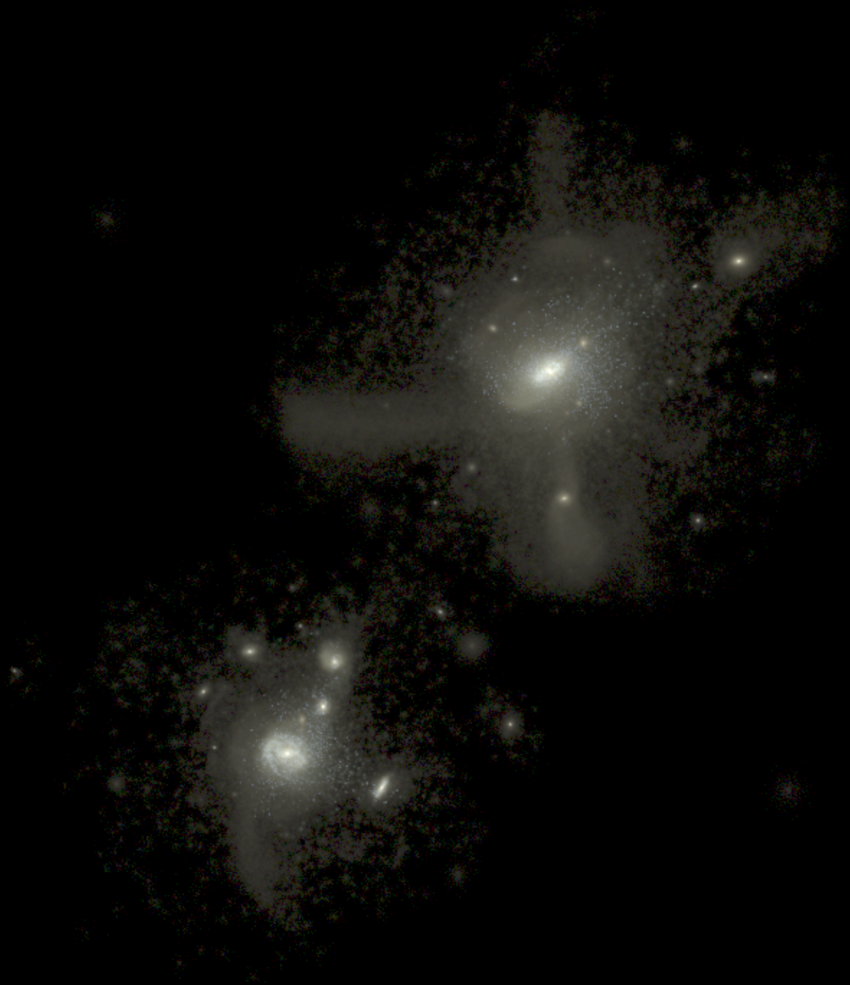
Sawala et al ‘15



Stars

APOSTLE
EAGLE full
hydro
simulations

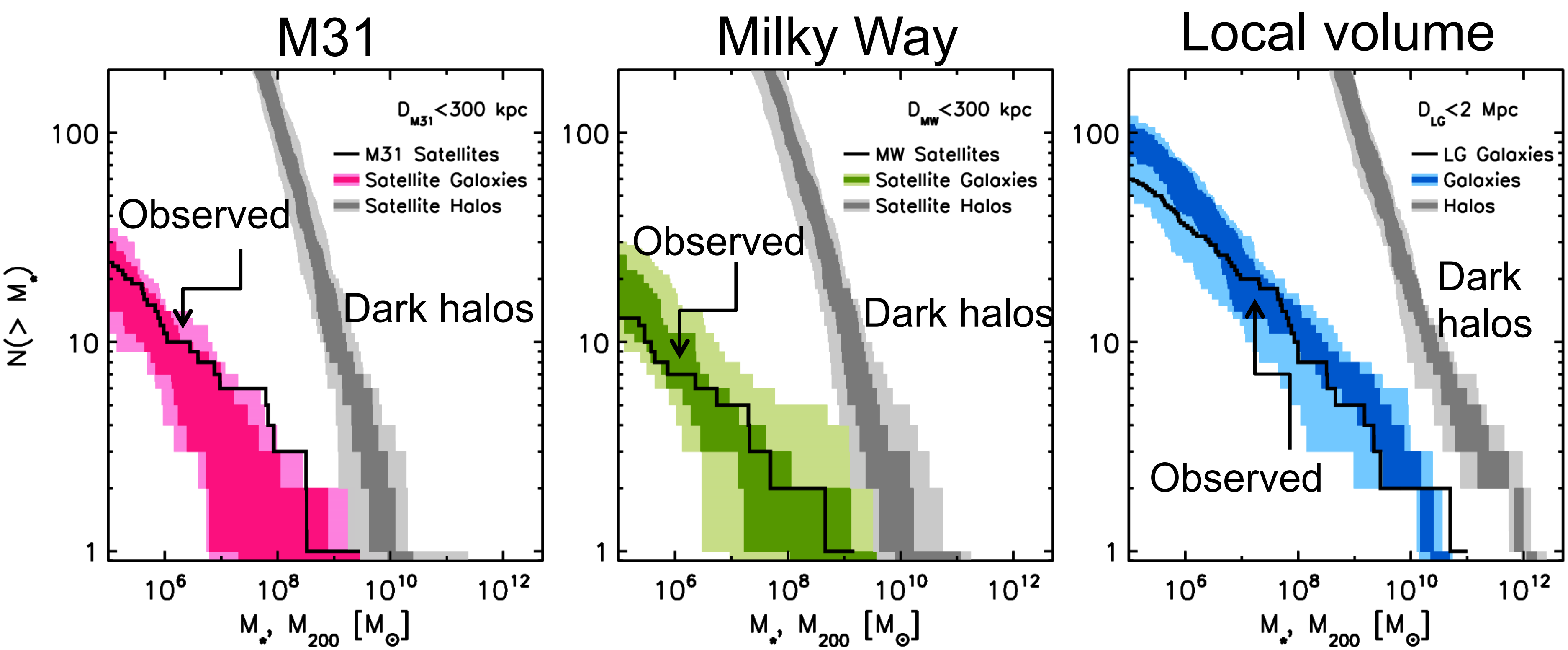
Local Group



Far fewer satellite galaxies than CDM halos

Sawala et al ‘15

EAGLE Local Group simulation



Sawala et al '15

Fraction of dark subhalos

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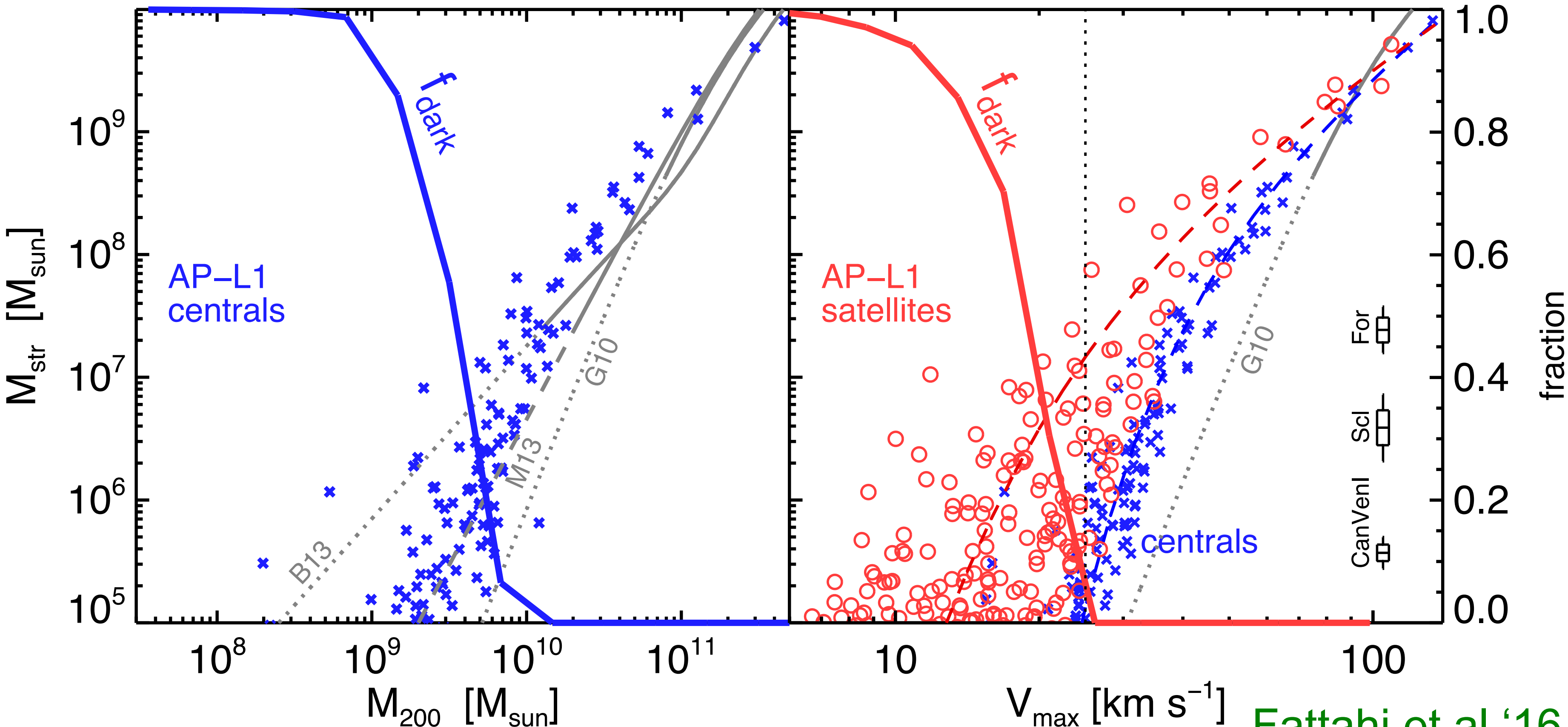
$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$



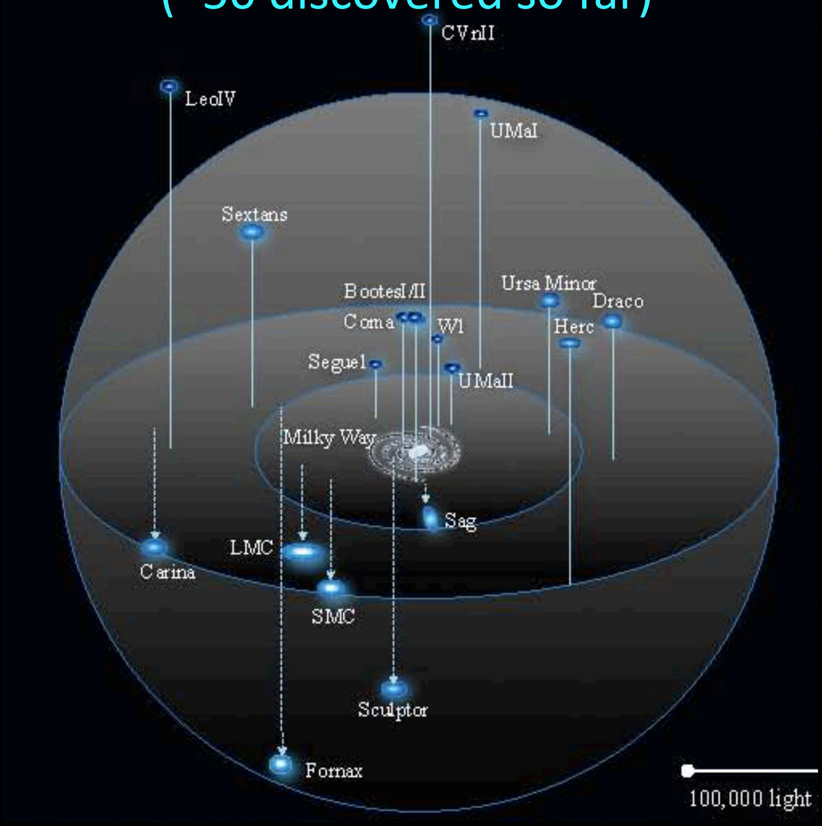
Fattahi et al '16

All halos of mass < $10^9 M_o$ or V_{max} < 7 km/s are dark

How about in WDM?

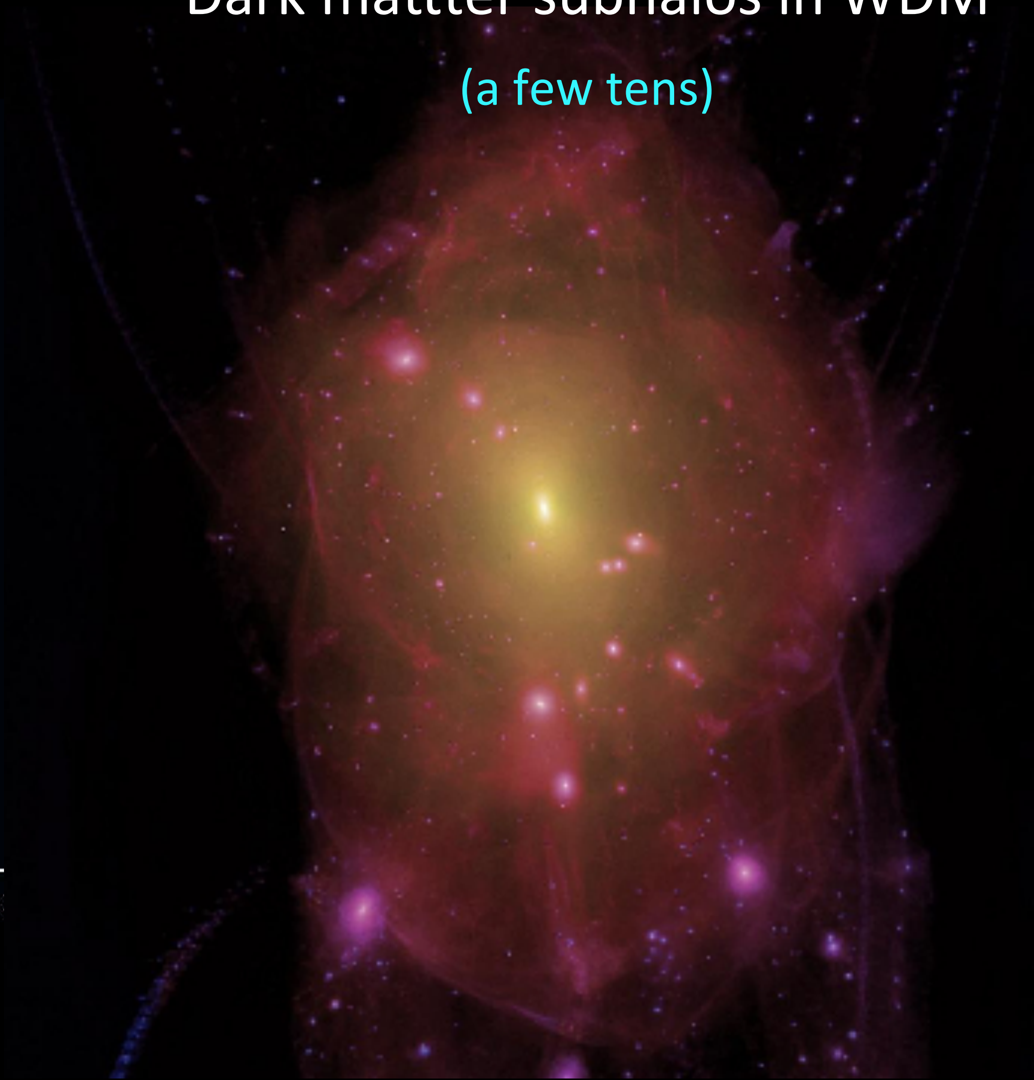
The satellites of the MW

(~50 discovered so far)



Dark matter subhalos in WDM

(a few tens)



Warm DM: different ν mass

z=3

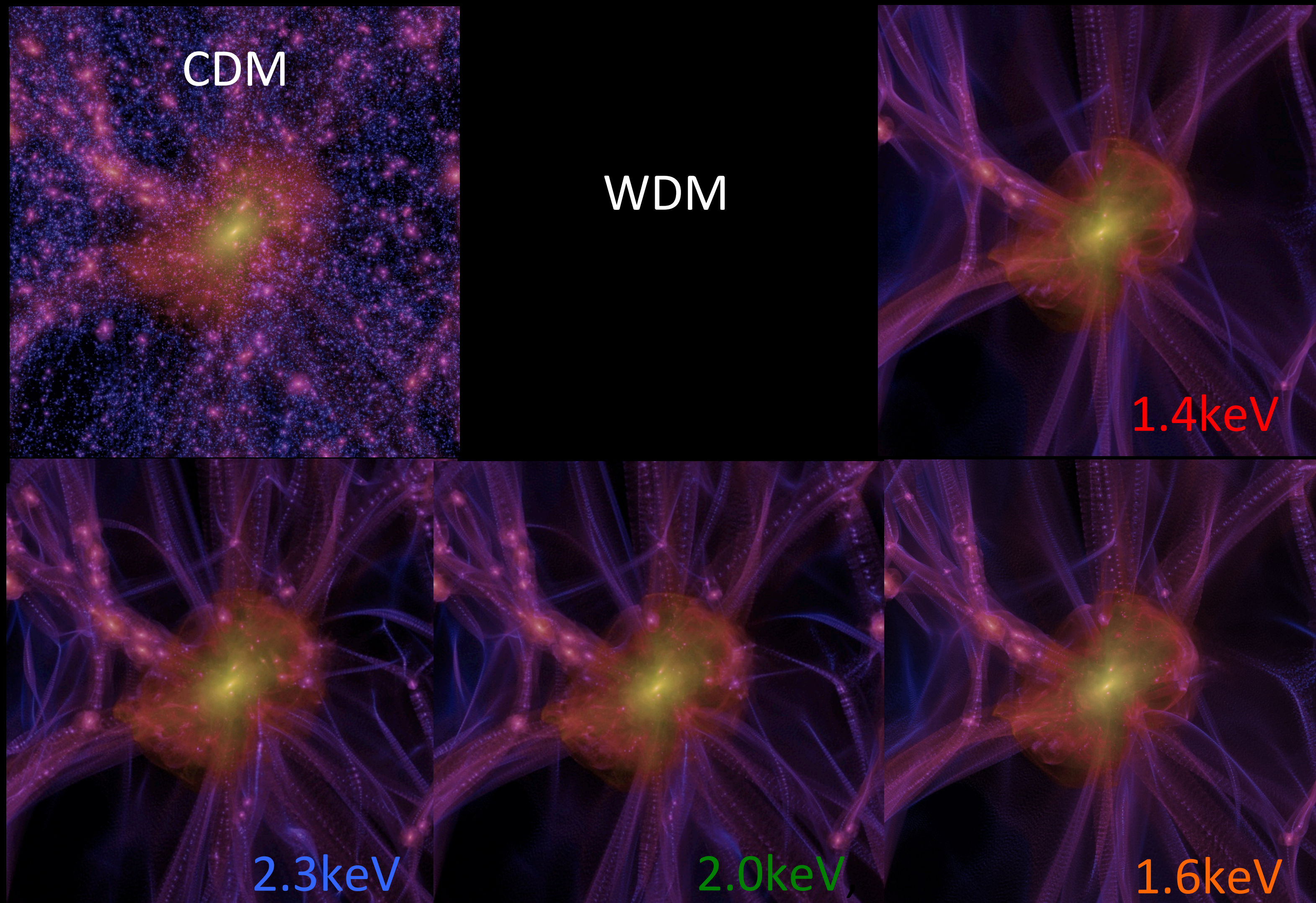
WDM

2.3 keV

2.0 keV

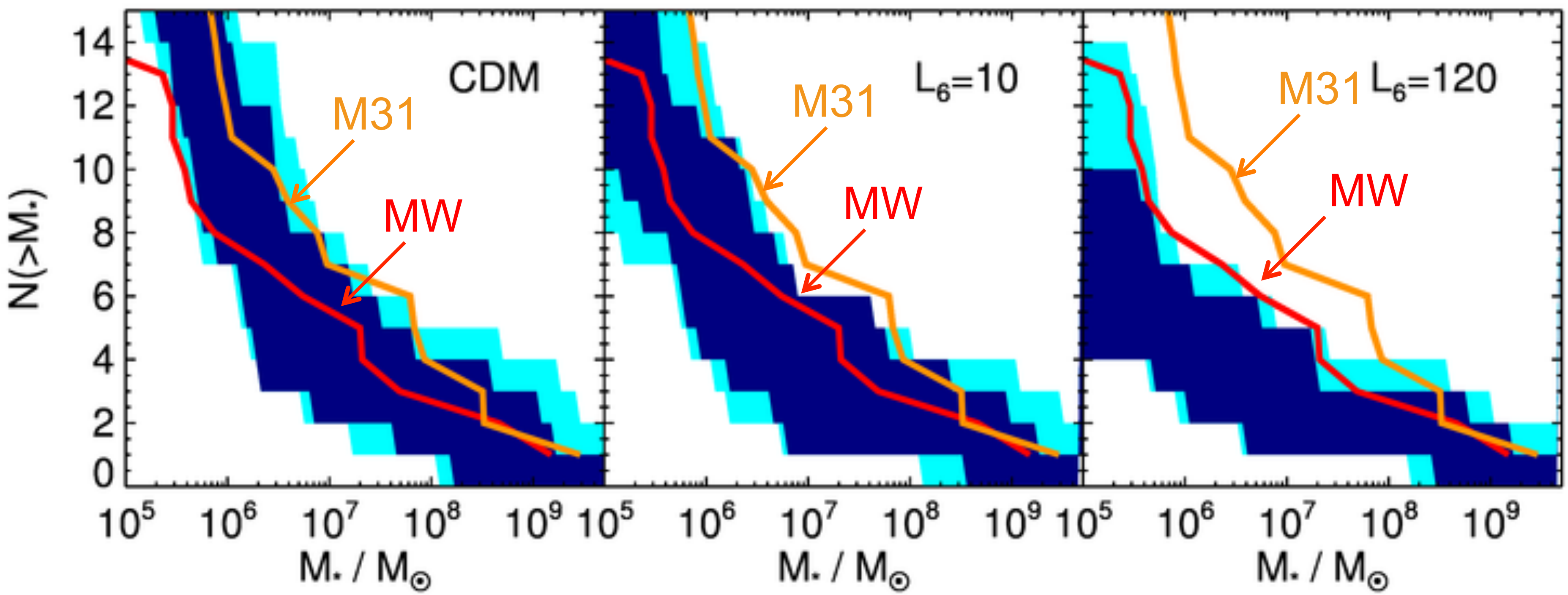
1.6 keV

1.4 keV



Luminosity Function of Local Group Satellites in WDM

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



Lovell et al. '16

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

$V_{max} = \max V_c$

"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

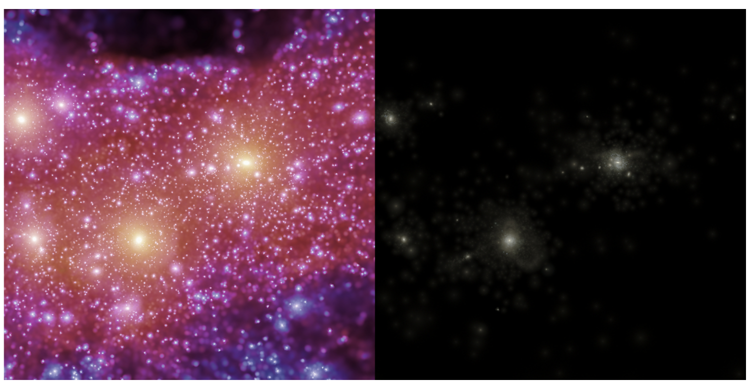
Why did the big subhalos not make a galaxy?

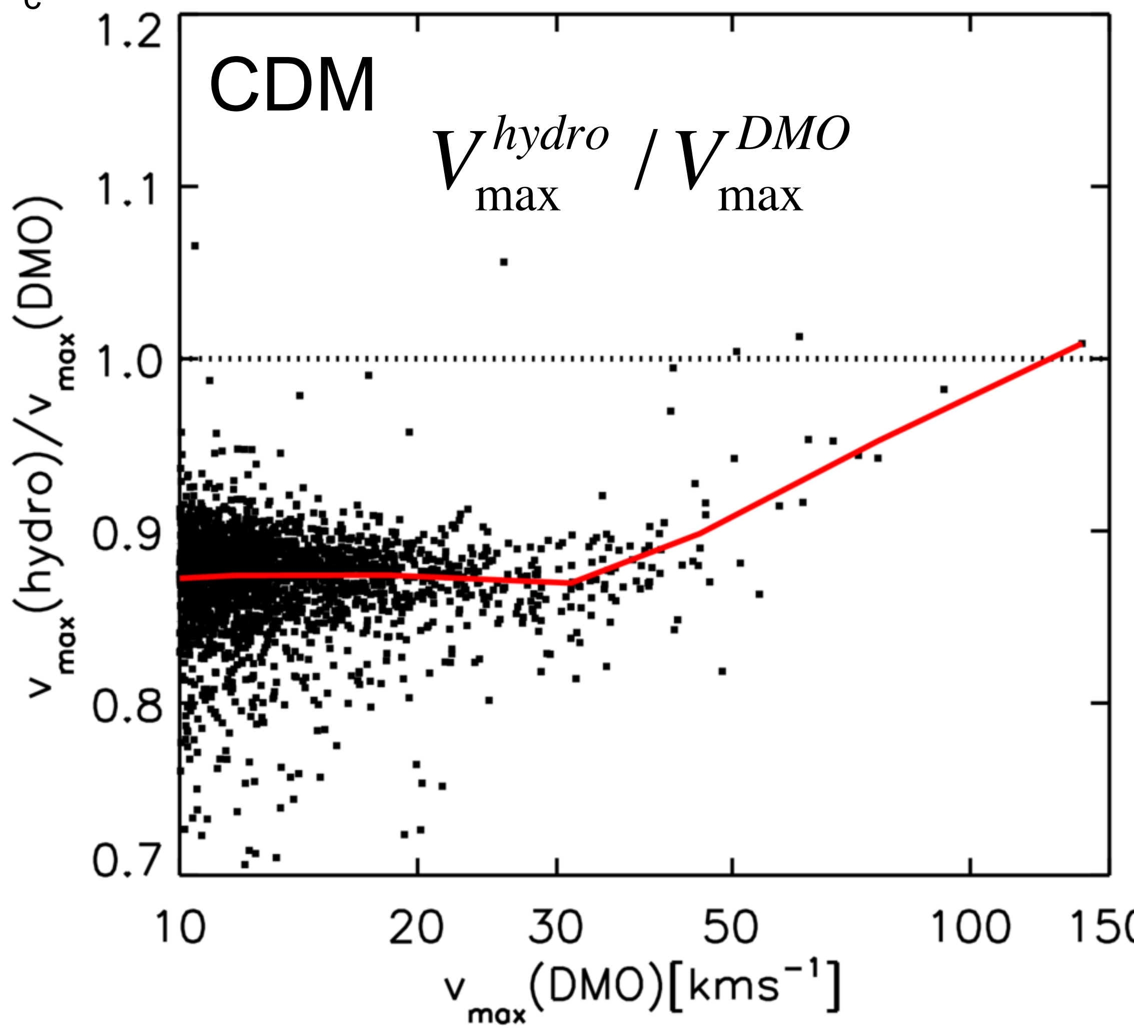
To-big-to-fail in CDM: baryon effects

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

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate



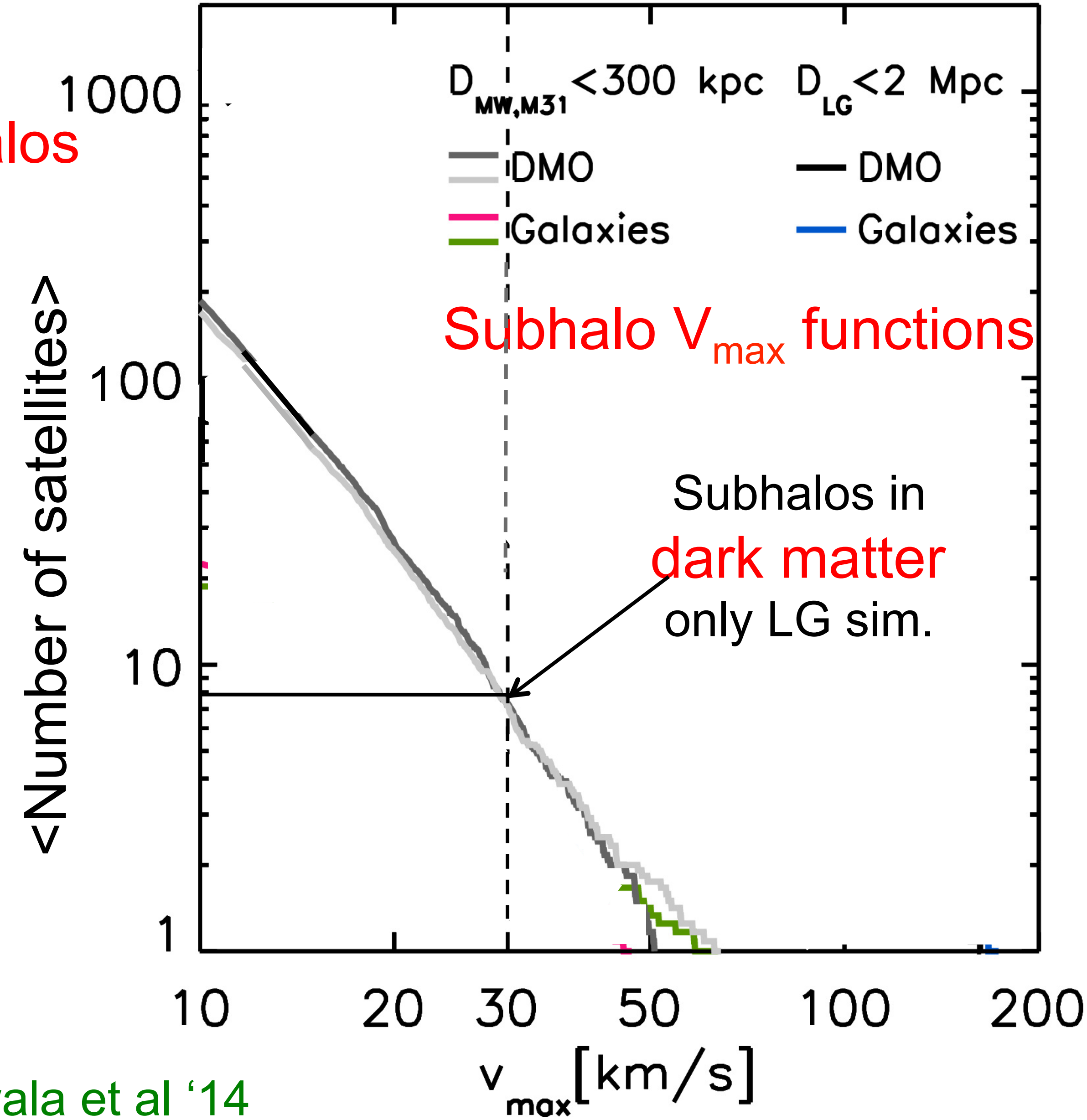


Sawala et al. '13, '15

Too-big-to-fail: the baryon bailout

University of Durham

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

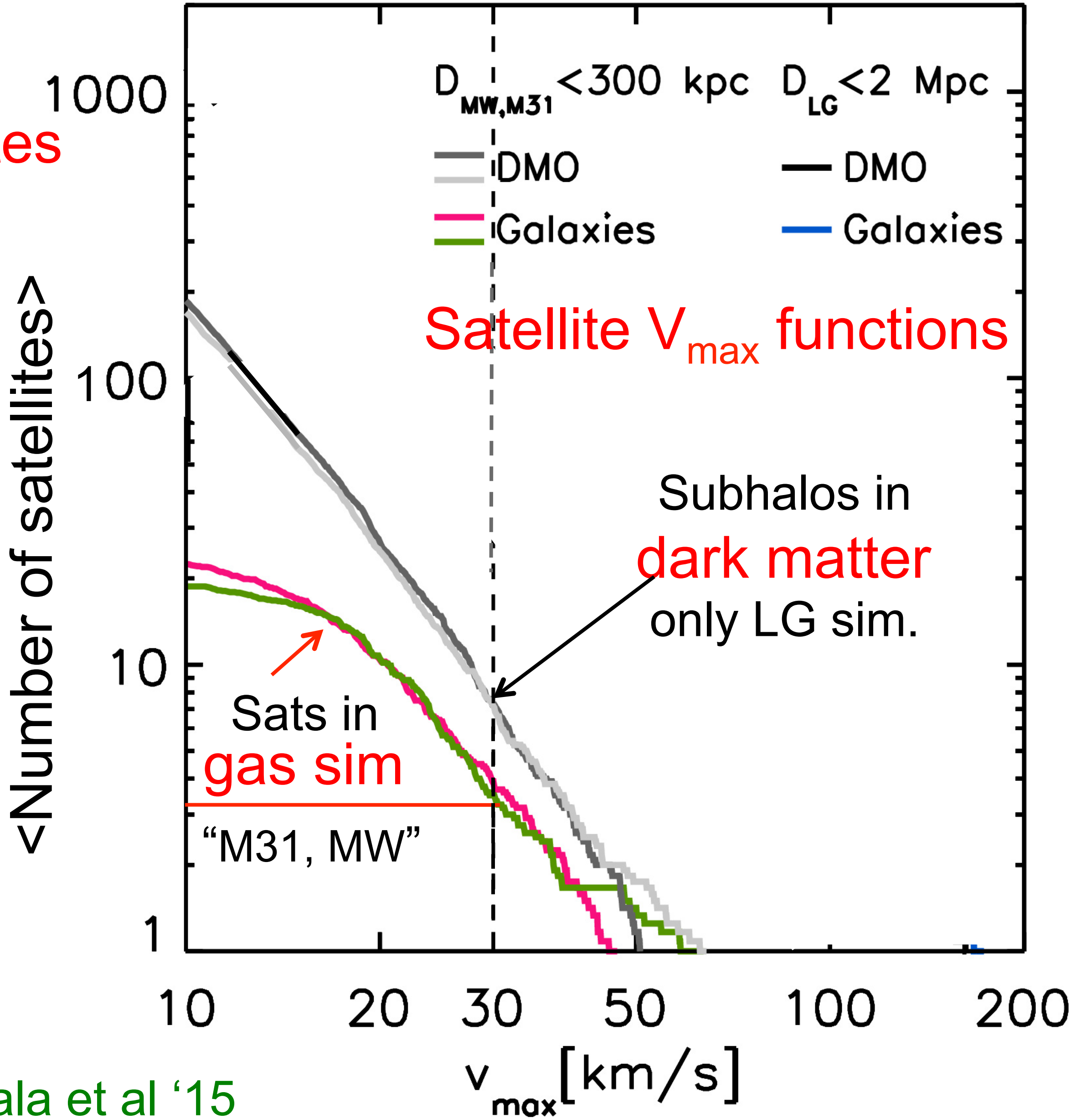


Sawala et al '14

Too-big-to-fail: the baryon bailout

University of Durham

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

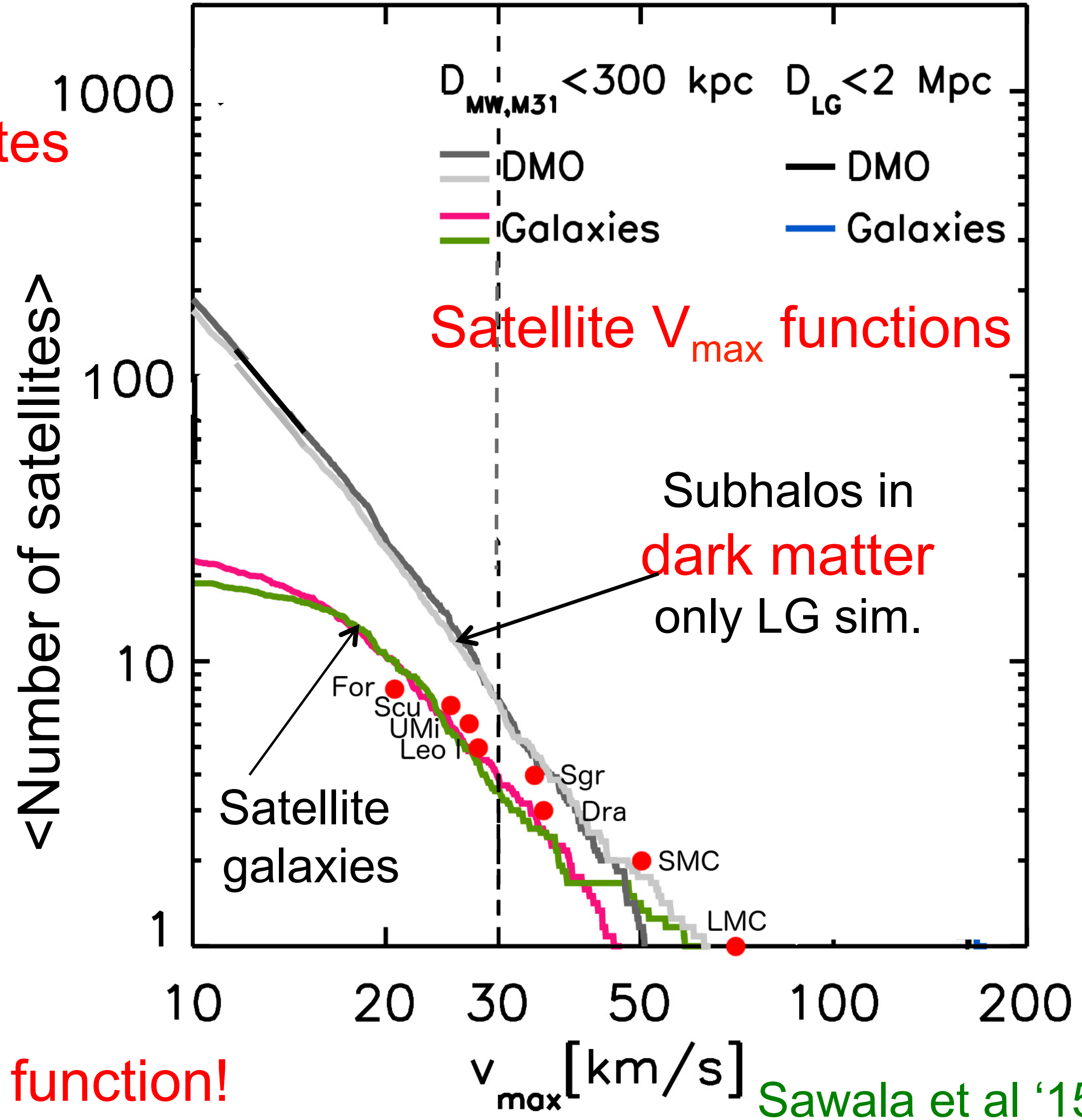


Sawala et al '15

Too-big-to-fail: the baryon bailout

University of Durham

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



… and with correct V_{max} function!

Sawala et al '15

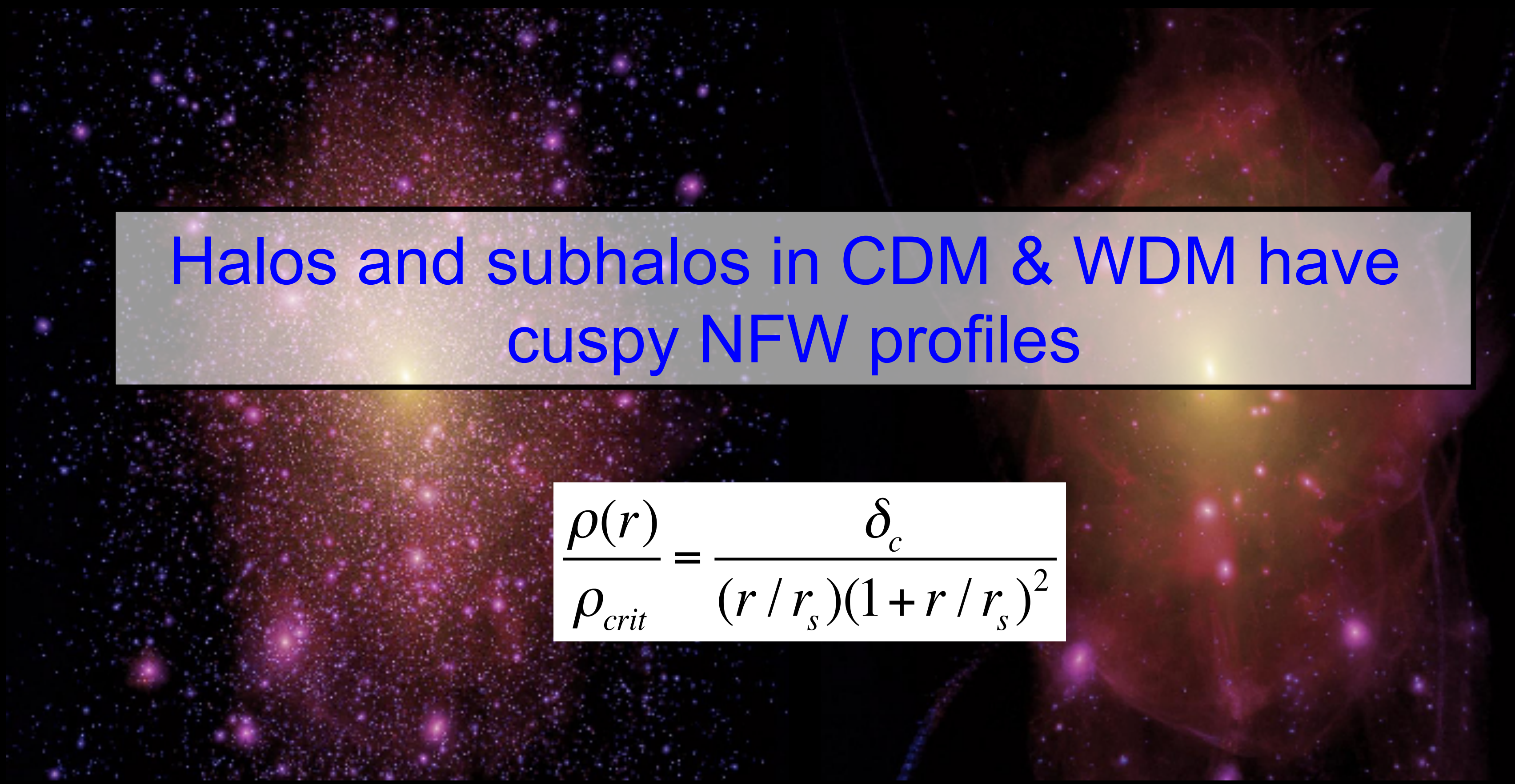
No too-big-to-fail problem in CDM

→

When “baryon effects” are included

The core-cusp problem

cold dark matter | warm dark matter



Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

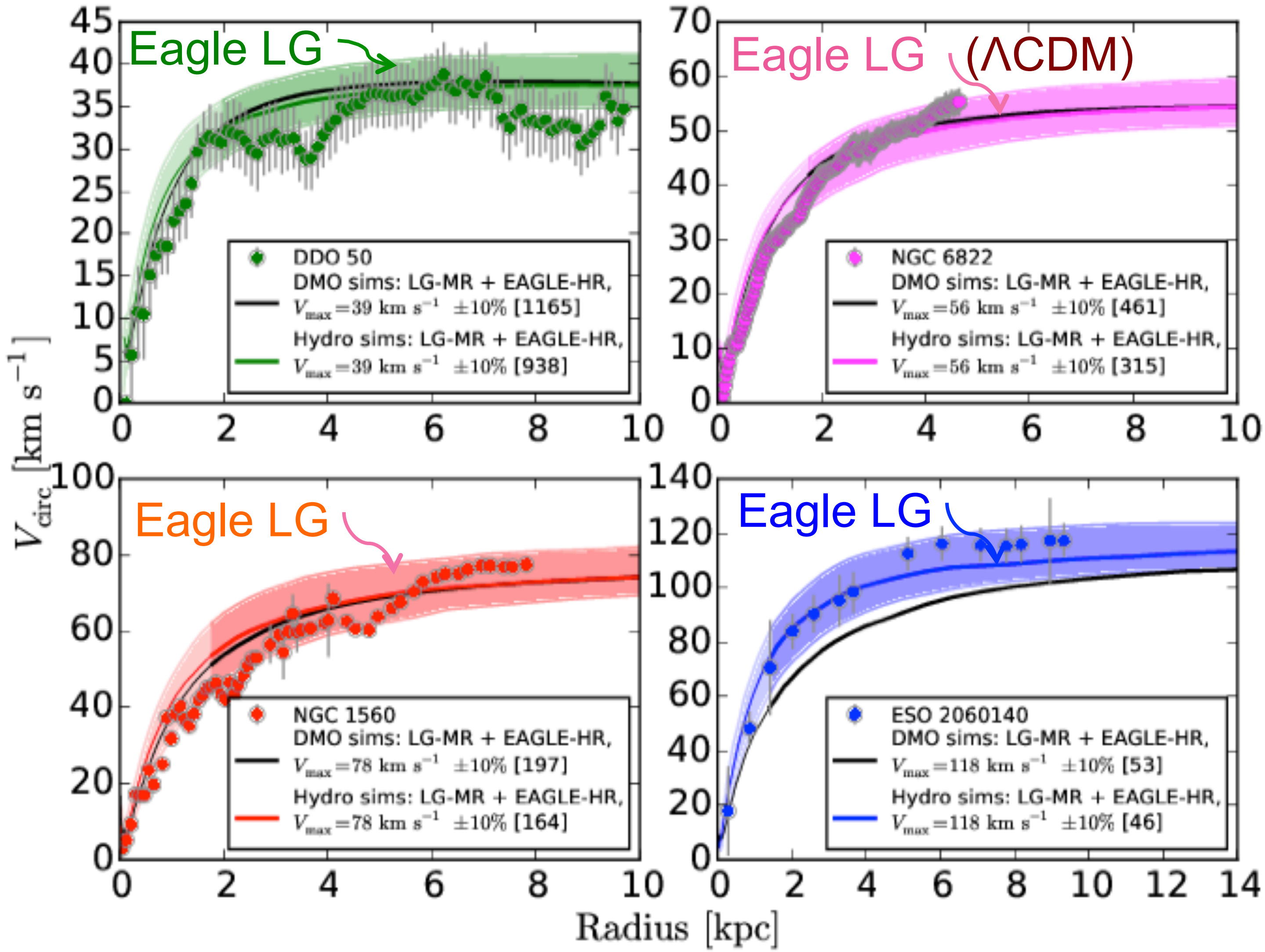
Lovell, Eke, Frenk, Gao, Jenkins, Theuns ‘12

ICC

The diversity of gal rotation curves

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L*)



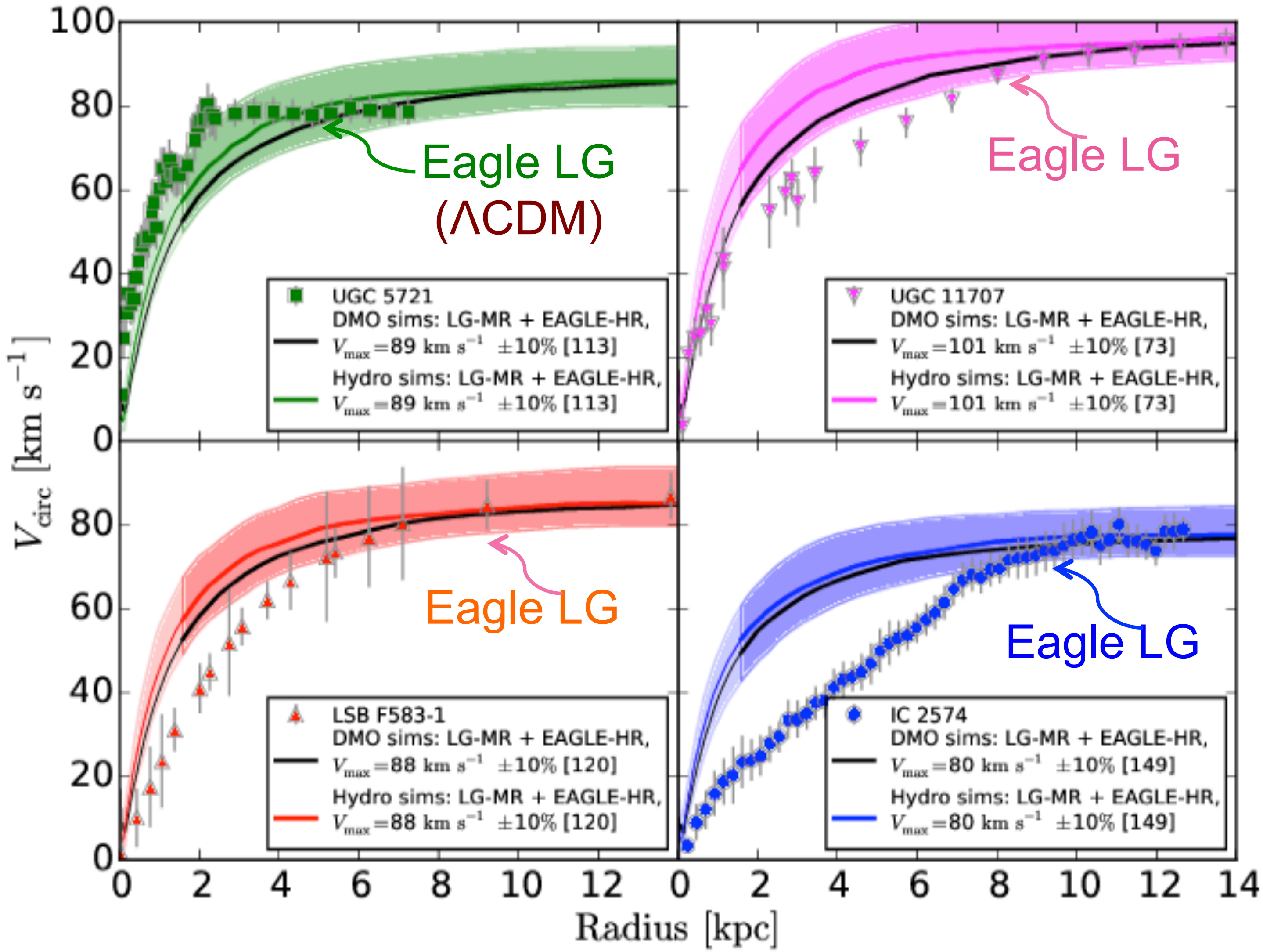
Oman, Navarro, Frenk et al. '15

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

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Cores or cusps?

Core are generally thought to exist in some galaxies

But, do they???

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]

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

ABSTRACT

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

Baryon effects in the MW satellites

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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

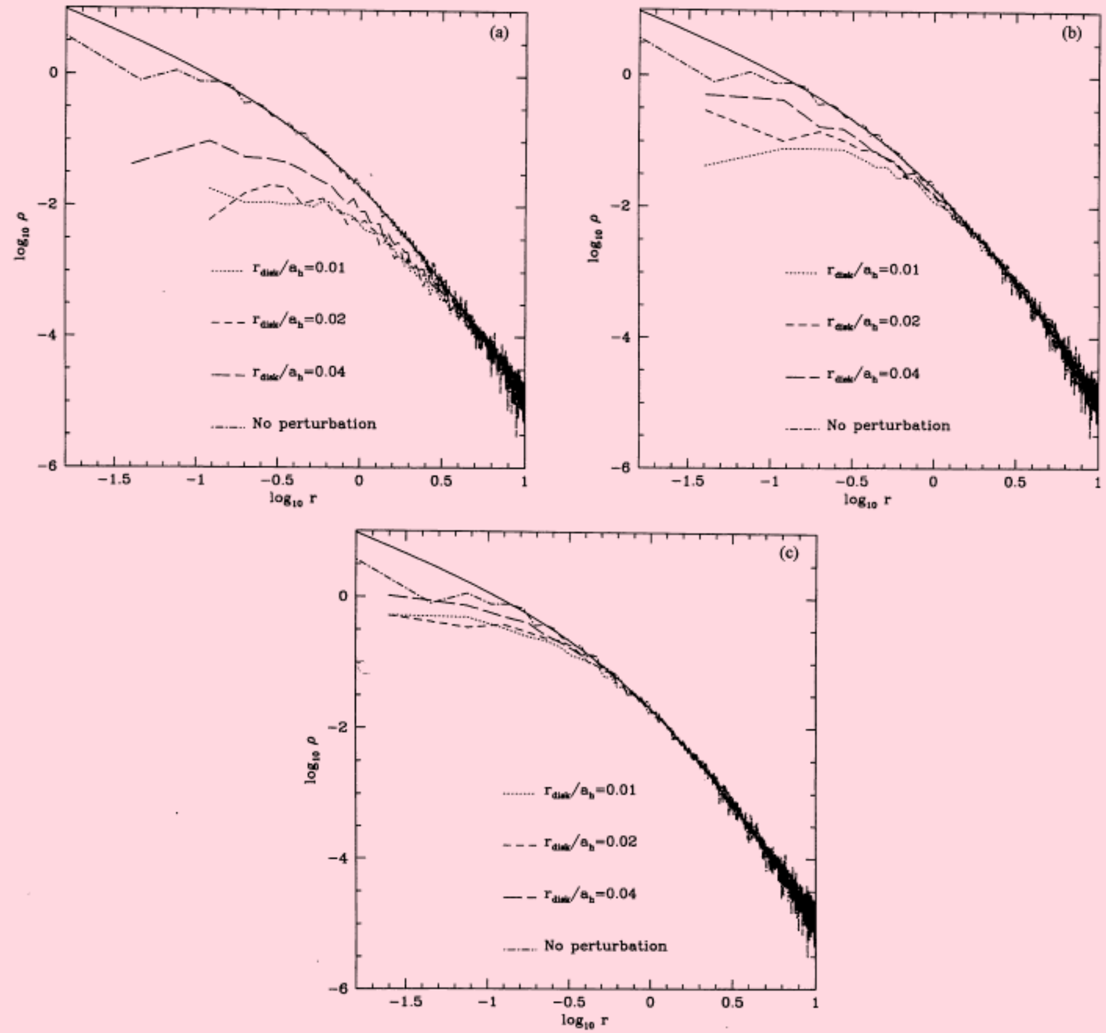


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

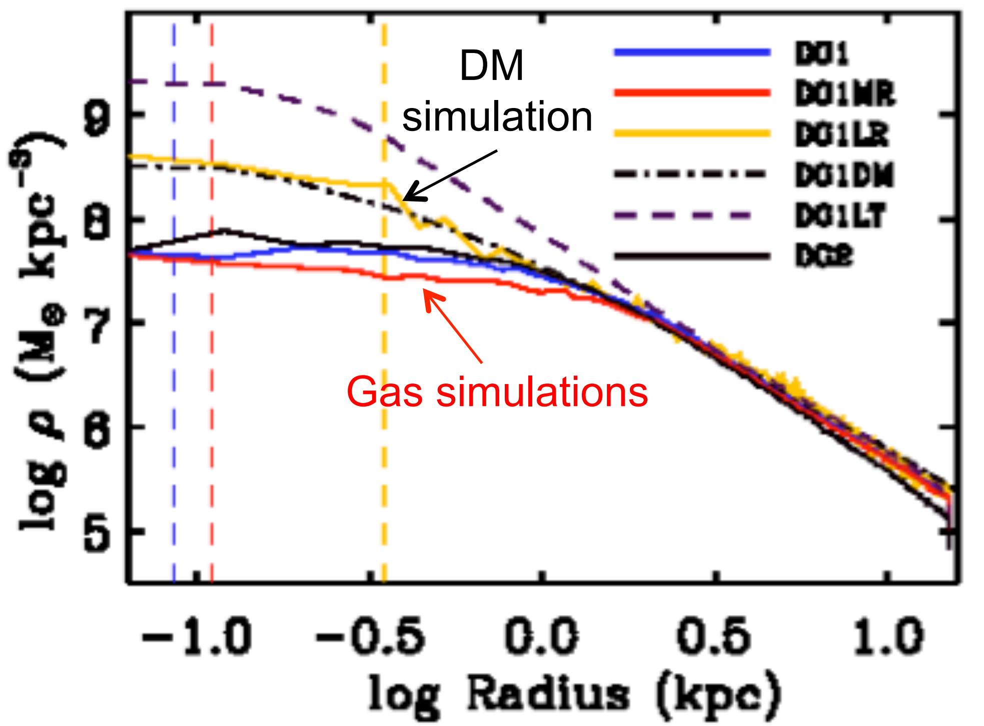
Cores in dwarf galaxy simulations

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

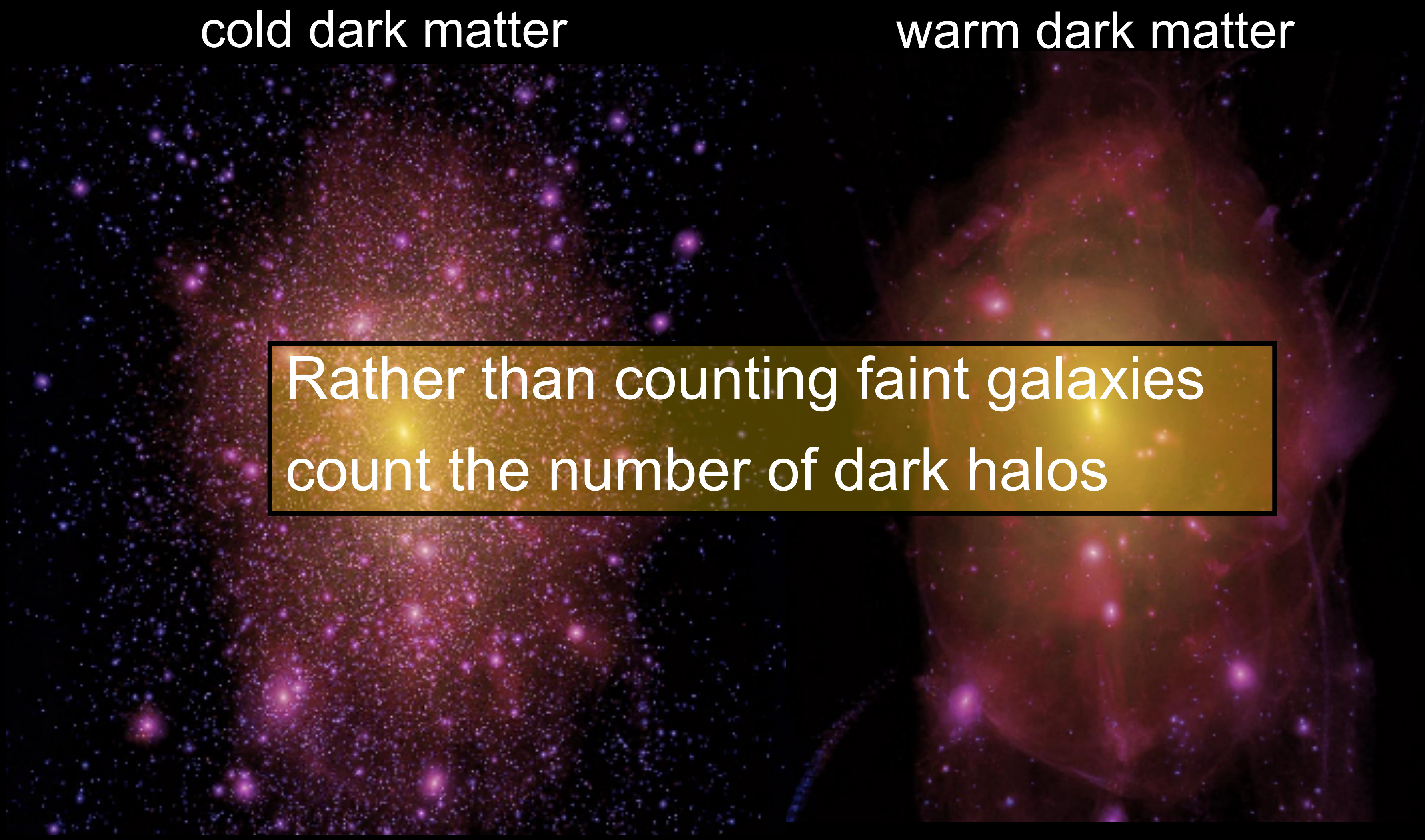


Governato et al. '10
Pontzen et al. '11

So, we can't distinguish CDM from WDM by counting satellite galaxies

There is no need for despair: there is a way to distinguish them

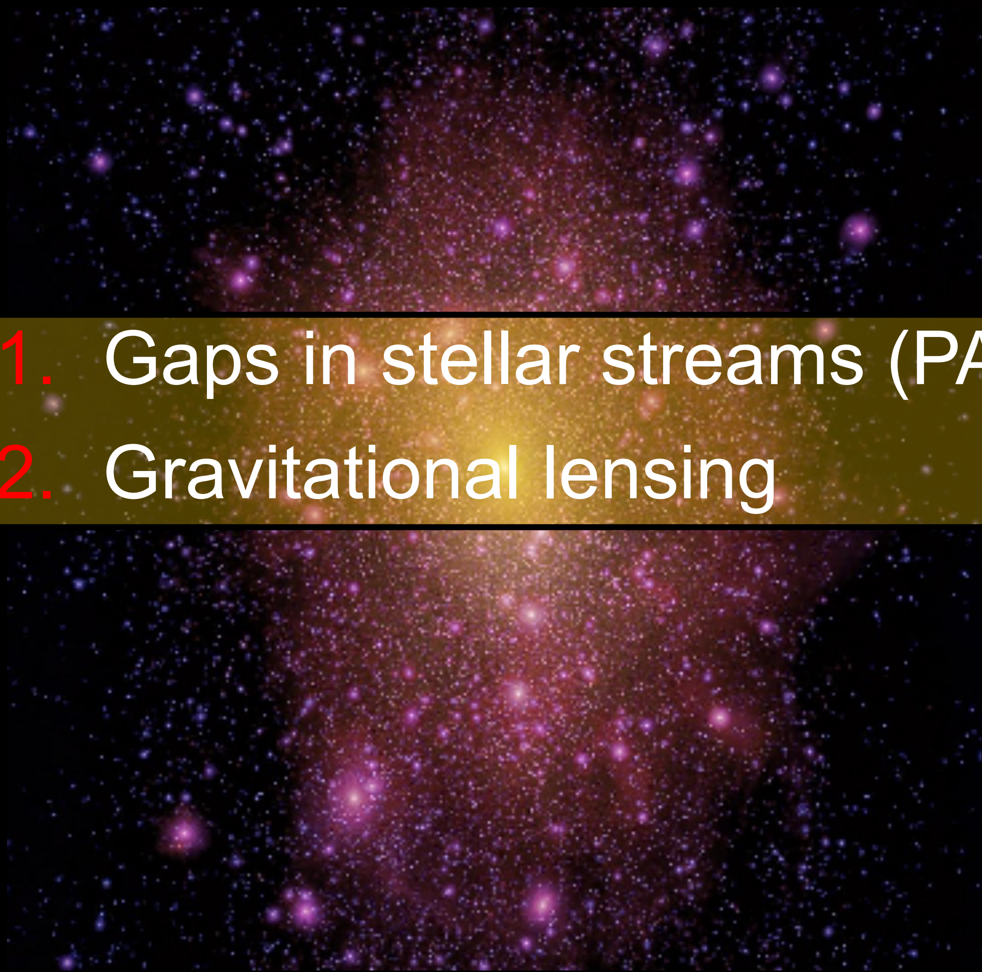
Can we distinguish CDM/WDM?



Rather than counting faint galaxies count the number of dark halos

Can we distinguish CDM/WDM?

cold dark matter

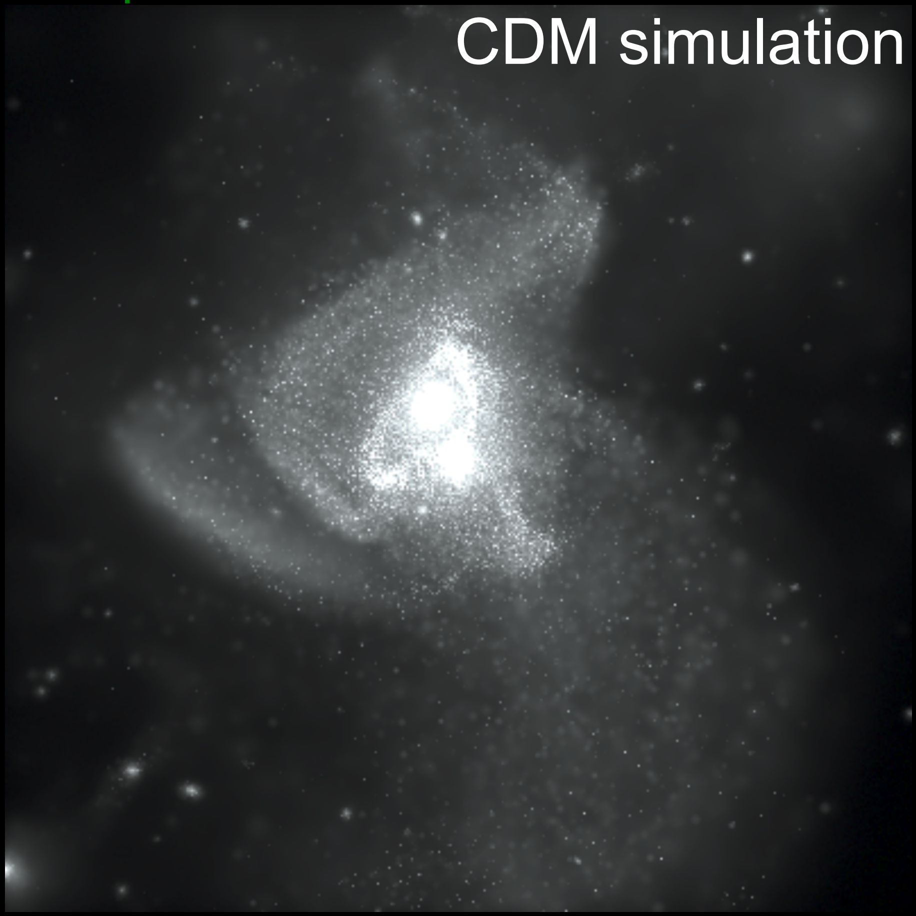


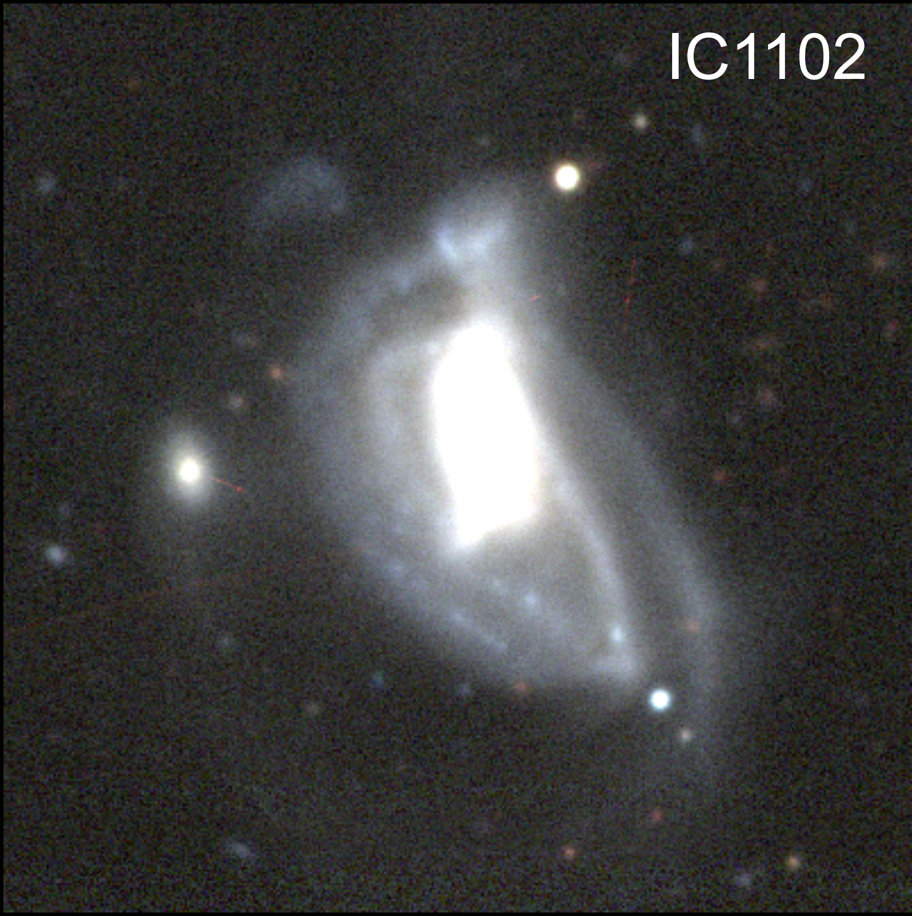
warm dark matter

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

Can we distinguish CDM/WDM?

Cooper et al '16

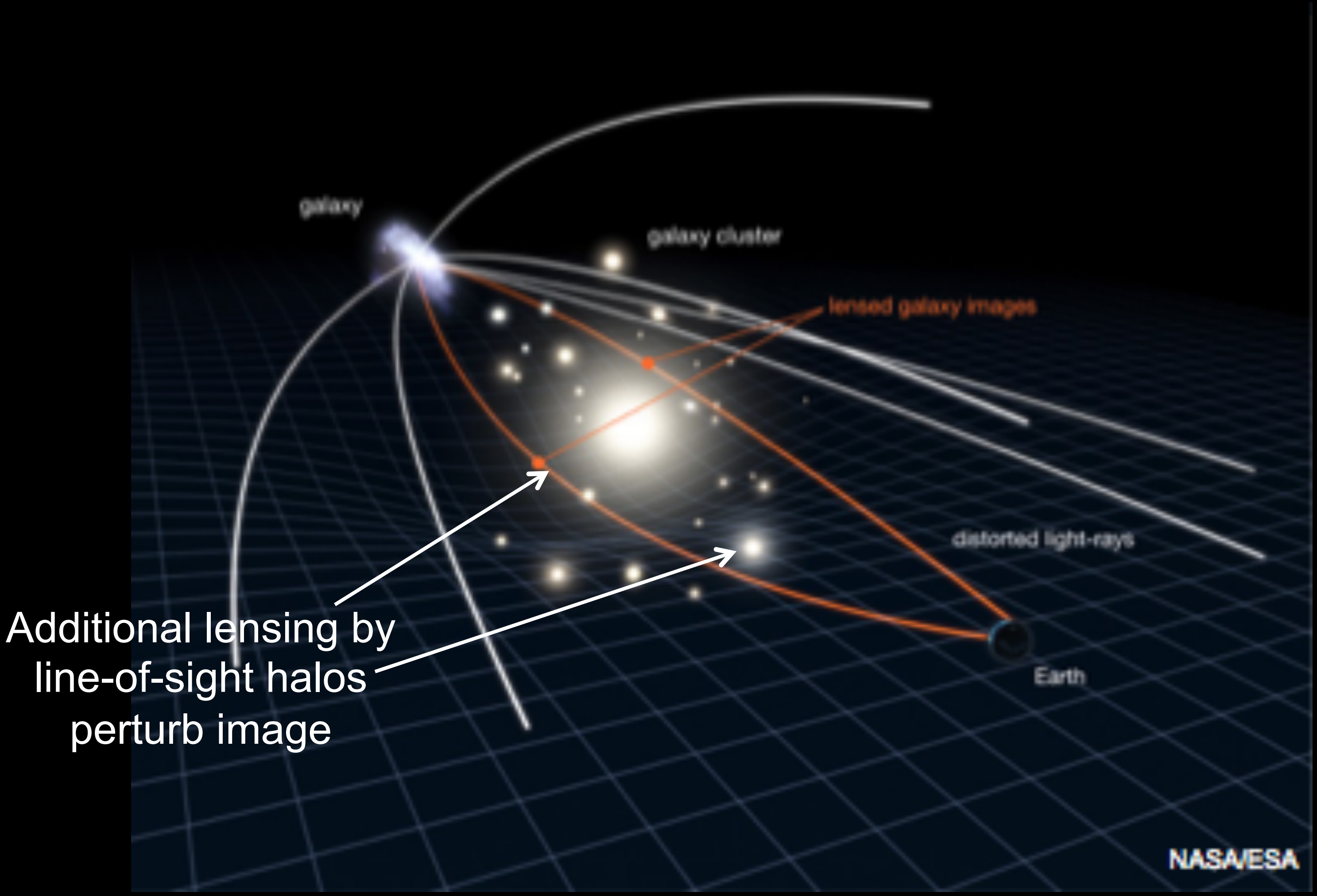




Subhalos crossing a cold tidal stream can produce a gap

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

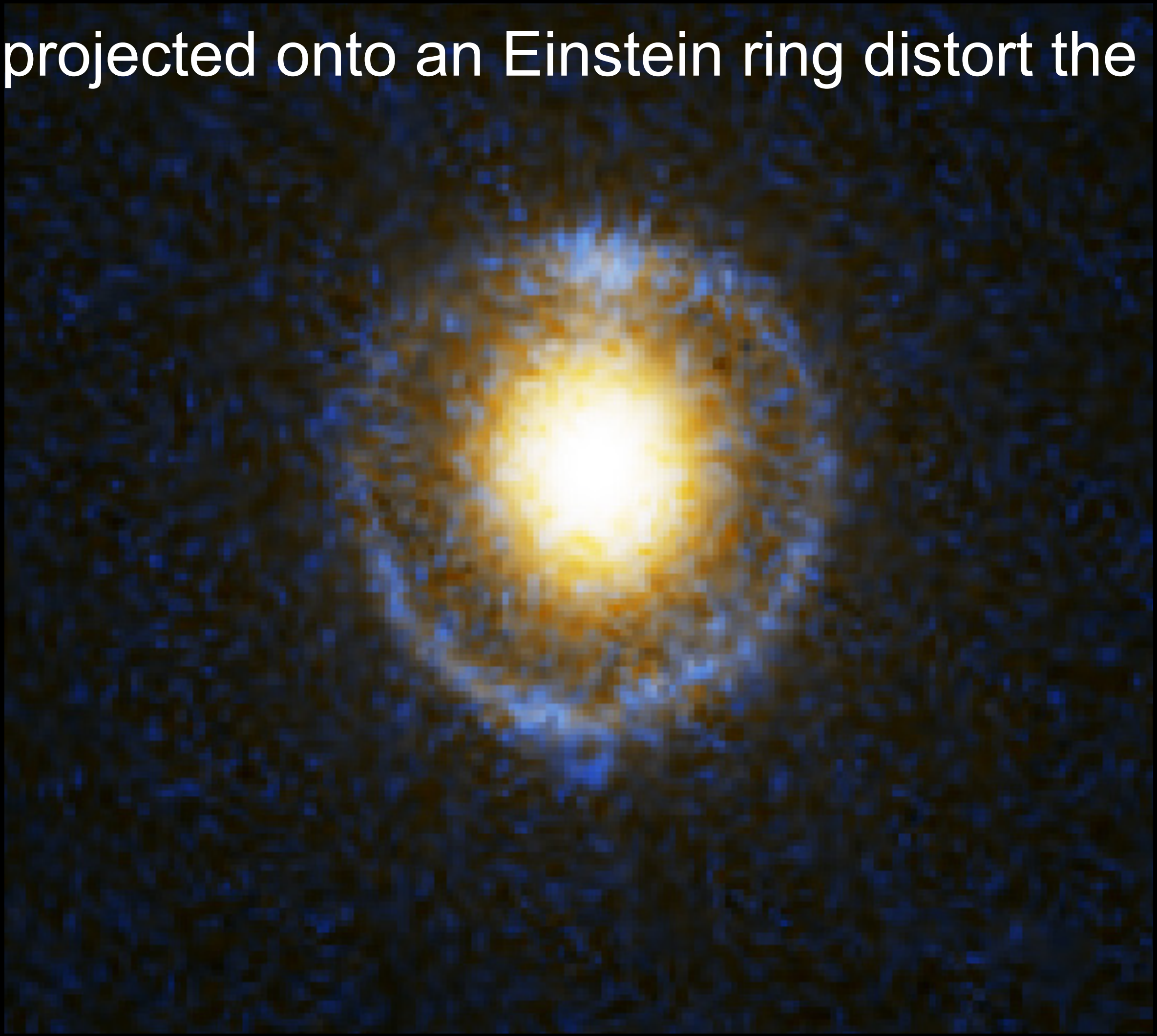
Gravitational lensing: Einstein rings



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

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



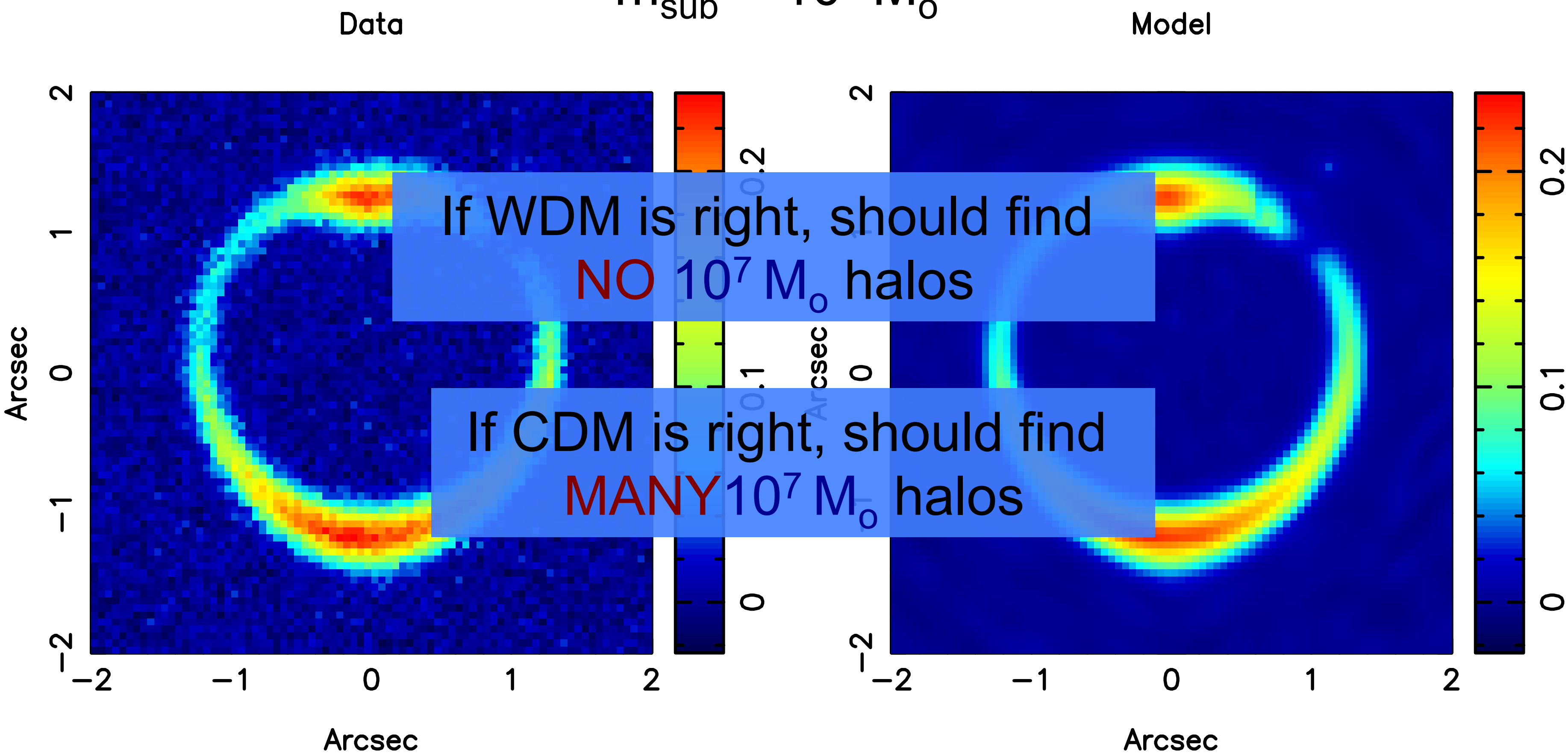
Vegetti & Koopmans '09

Detecting substructures with strong lensing

University of Durham

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 $10^7 M_o$

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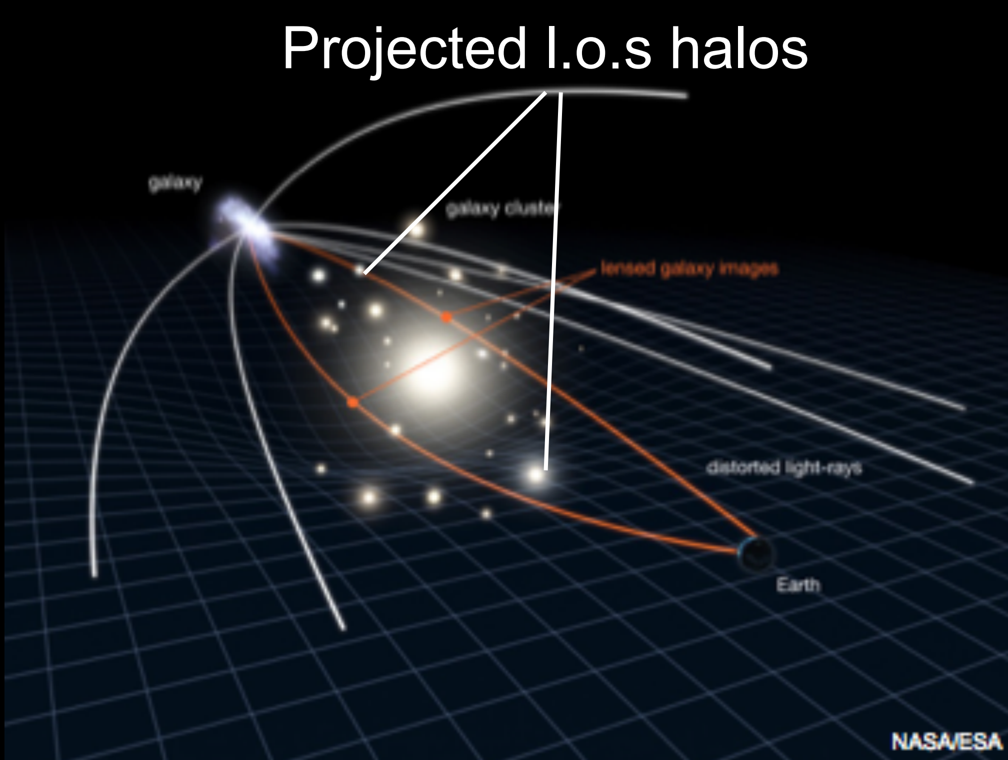
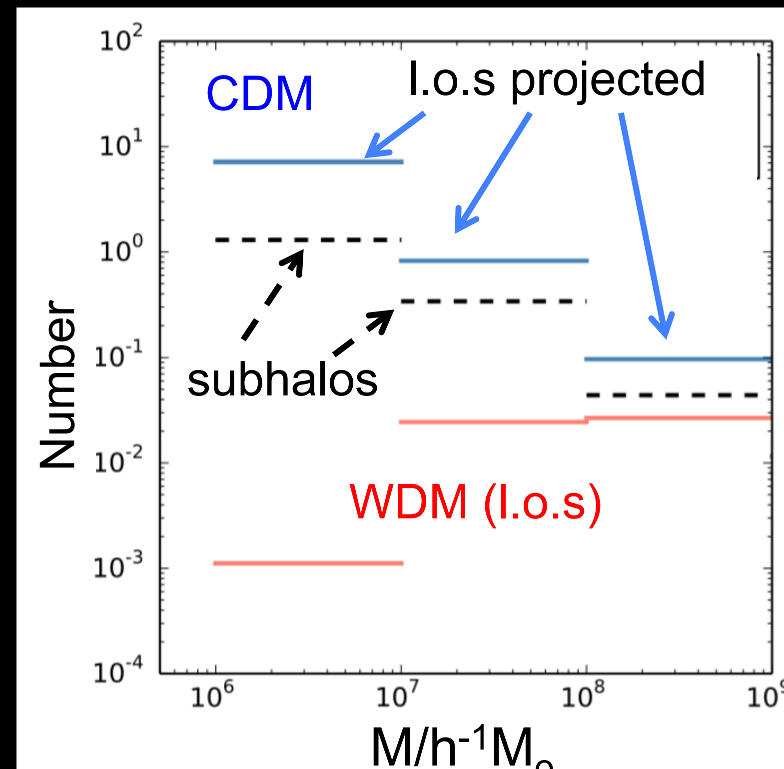
Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens





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

Li, CSF et al. '16

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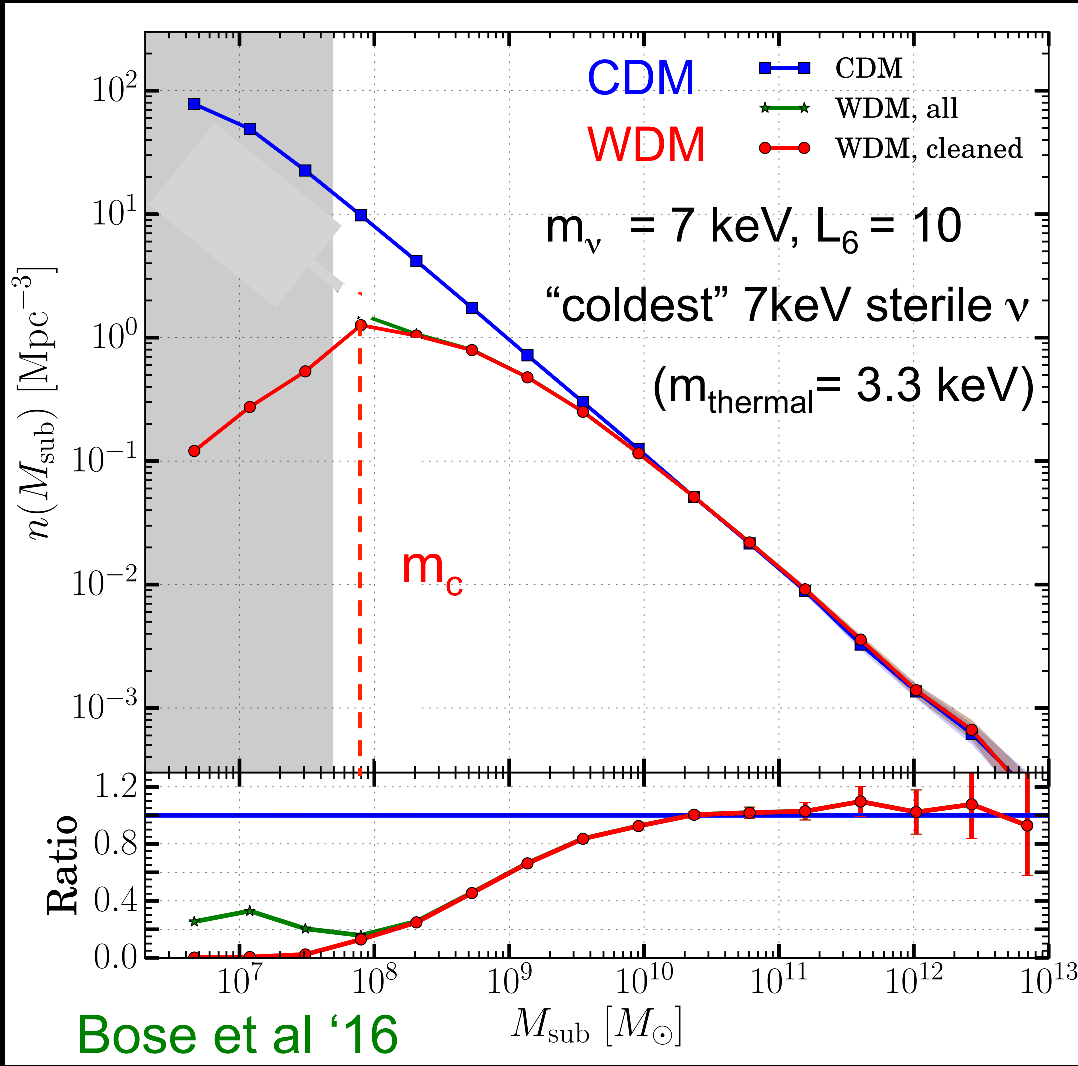
The halo mass function

CDM WDM



Already fewer WDM halos at $3\times10^9 M_o$

10 x fewer at $10^8 M_o$

University of Durham

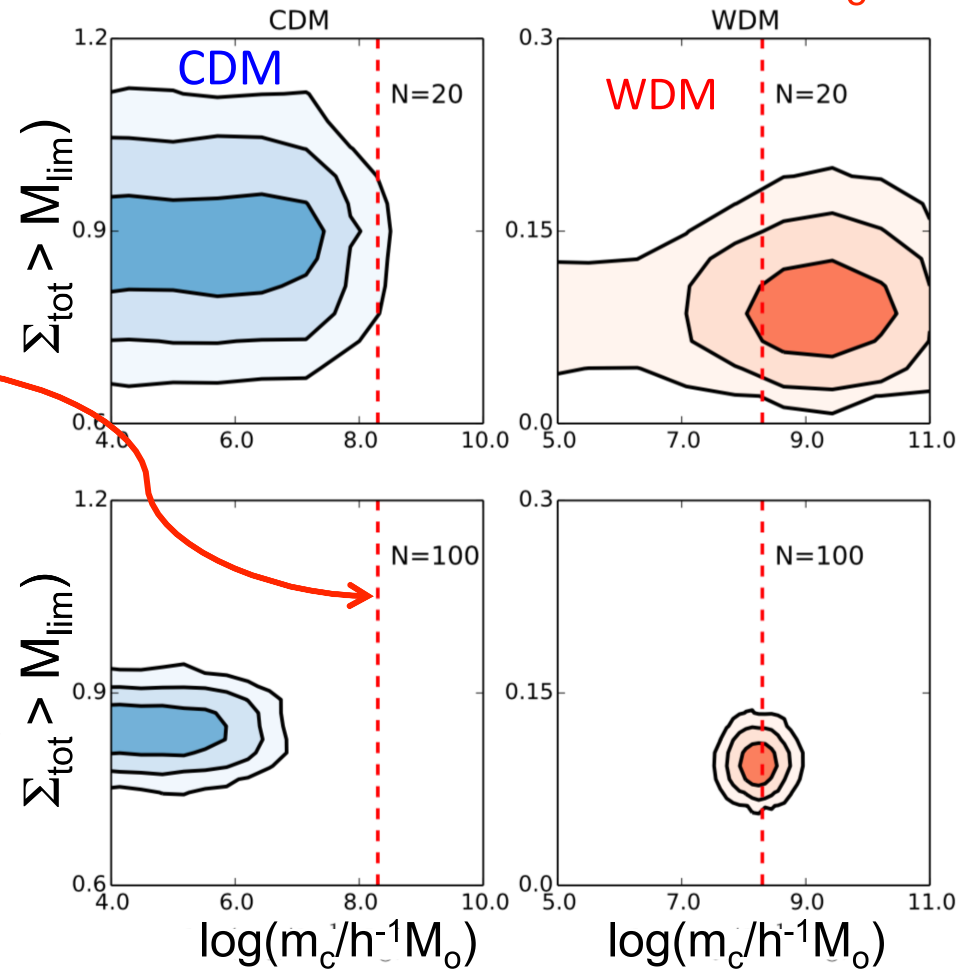
Detecting substructures with strong lensing

Σ_{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 CDM → rule out 7 keV sterile ν at many σ
- If DM is 7 keV sterile ν → rule out CDM at 3σ!

Li, CSF et al '16

Institute for Computational Cosmology

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

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!)