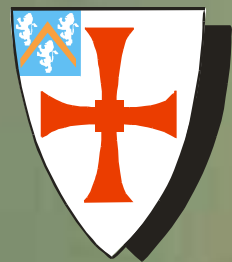


Observational tests of Λ CDM

Carlos S. Frenk
Institute for Computational Cosmology,
Durham



Observational tests of CDM

and how to rule it (or other models) out

Carlos S. Frenk
Institute for Computational Cosmology,
Durham



Non-baryonic dark matter candidates

From the 1980s:

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

The dark matter power spectrum

$k^3 P(k)$

The linear power spectrum (“power per octave”)

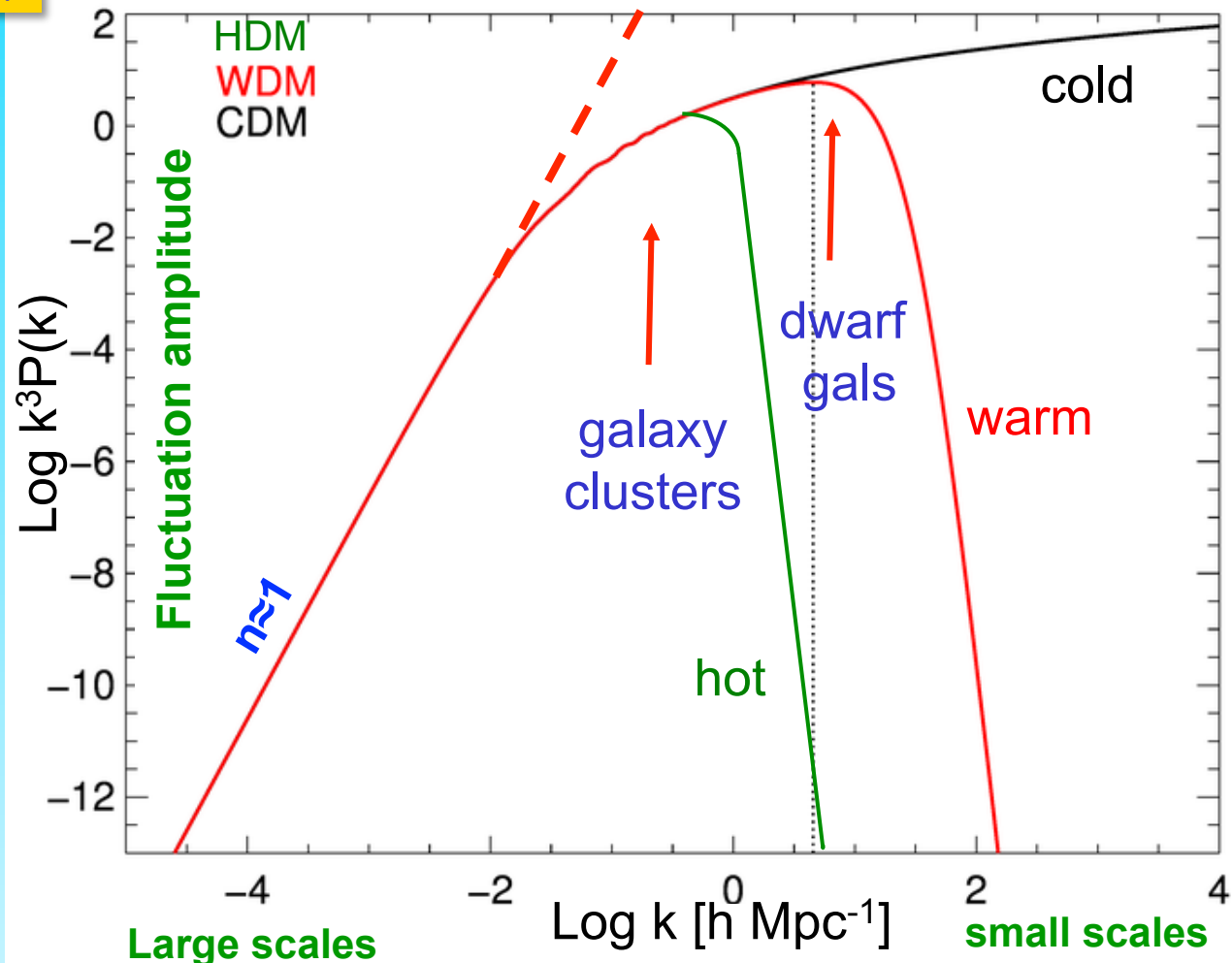
Free streaming $\rightarrow$

$\lambda_{\text{cut}} \propto m_x^{-1}$
for thermal relic

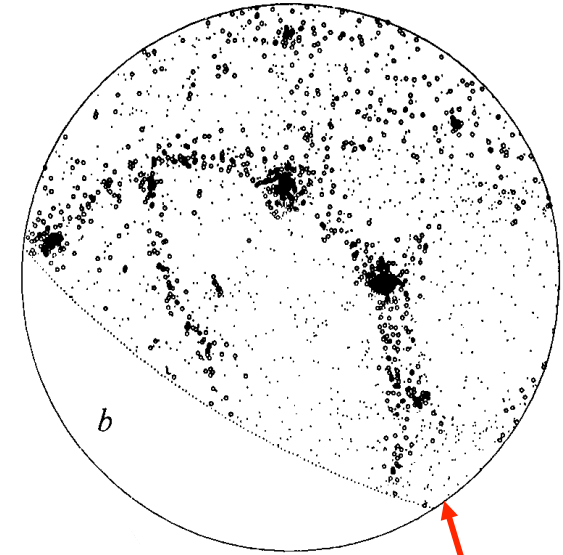
$m_{\text{CDM}} \sim 100 \text{ GeV}$
susy; $M_{\text{cut}} \sim 10^{-6} M_{\odot}$

$m_{\text{WDM}} \sim \text{few keV}$
sterile ν ; $M_{\text{cut}} \sim 10^9 M_{\odot}$

$m_{\text{HDM}} \sim \text{few tens eV}$
light ν ; $M_{\text{cut}} \sim 10^{15} M_{\odot}$



Non-baryonic dark matter cosmologies



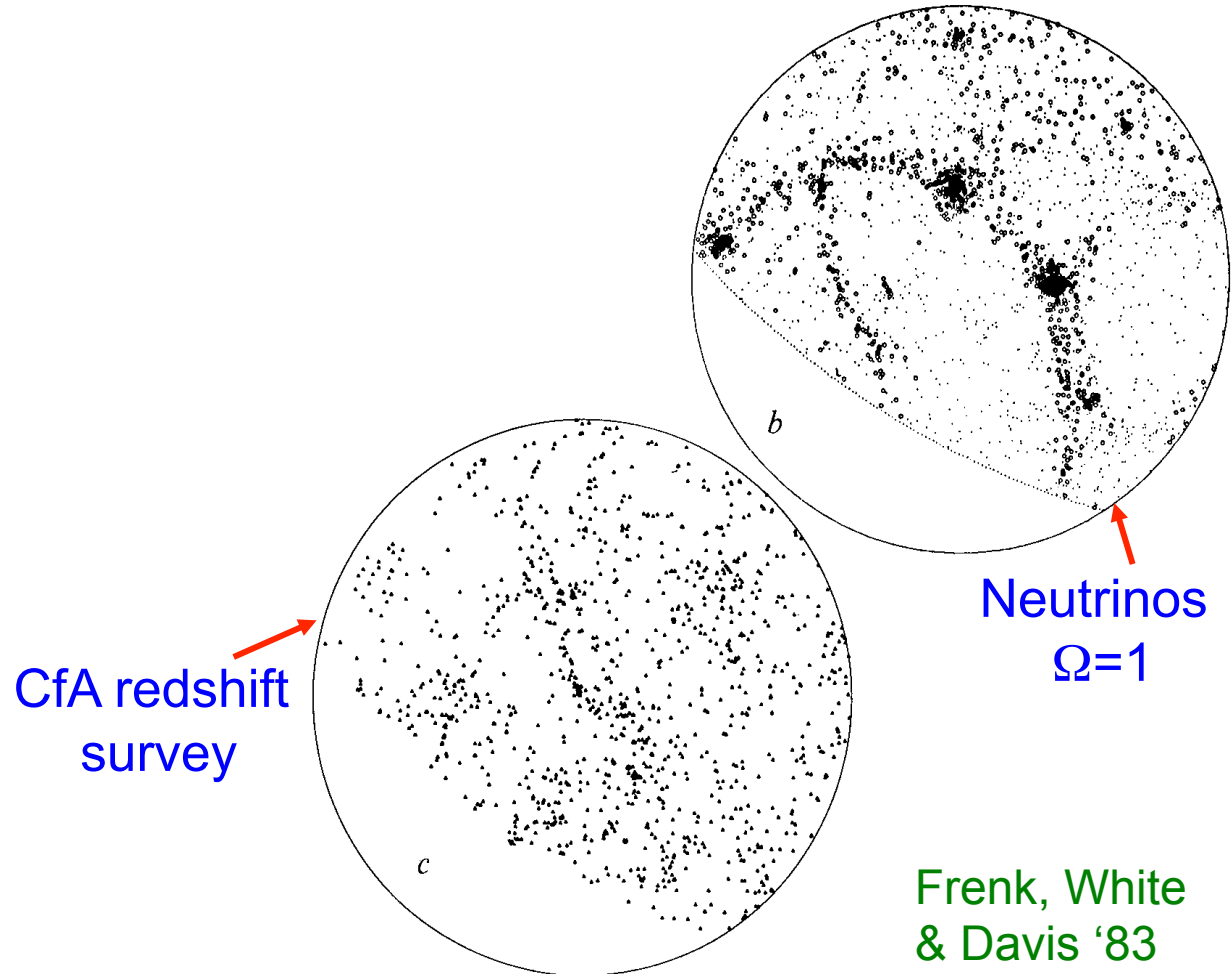
Neutrinos
 $\Omega=1$

Frenk, White
& Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM →
wrong clustering

Neutrinos cannot
make appreciable
contribution to Ω
→ $m_\nu \ll 30$ eV



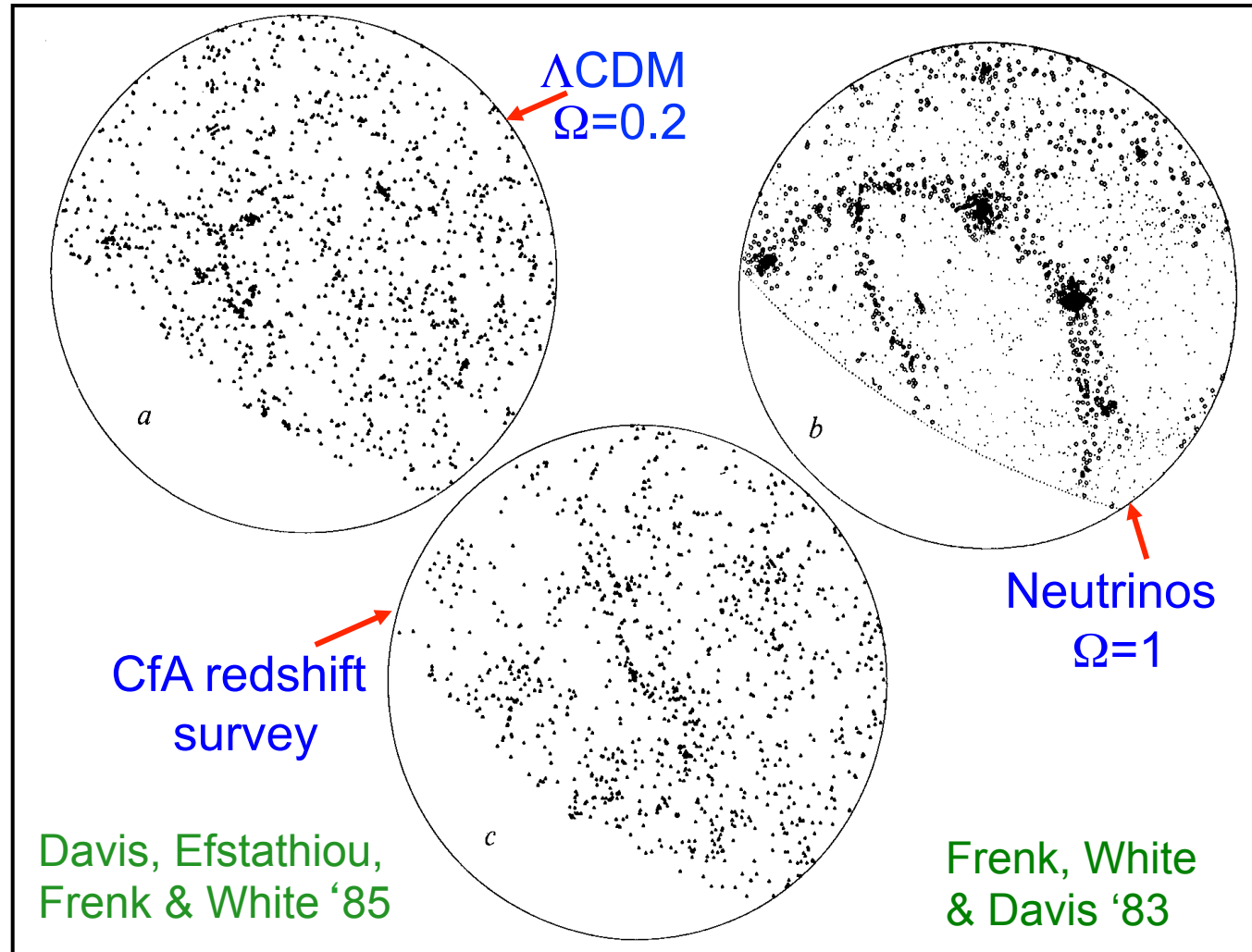
Non-baryonic dark matter cosmologies

Neutrino DM →
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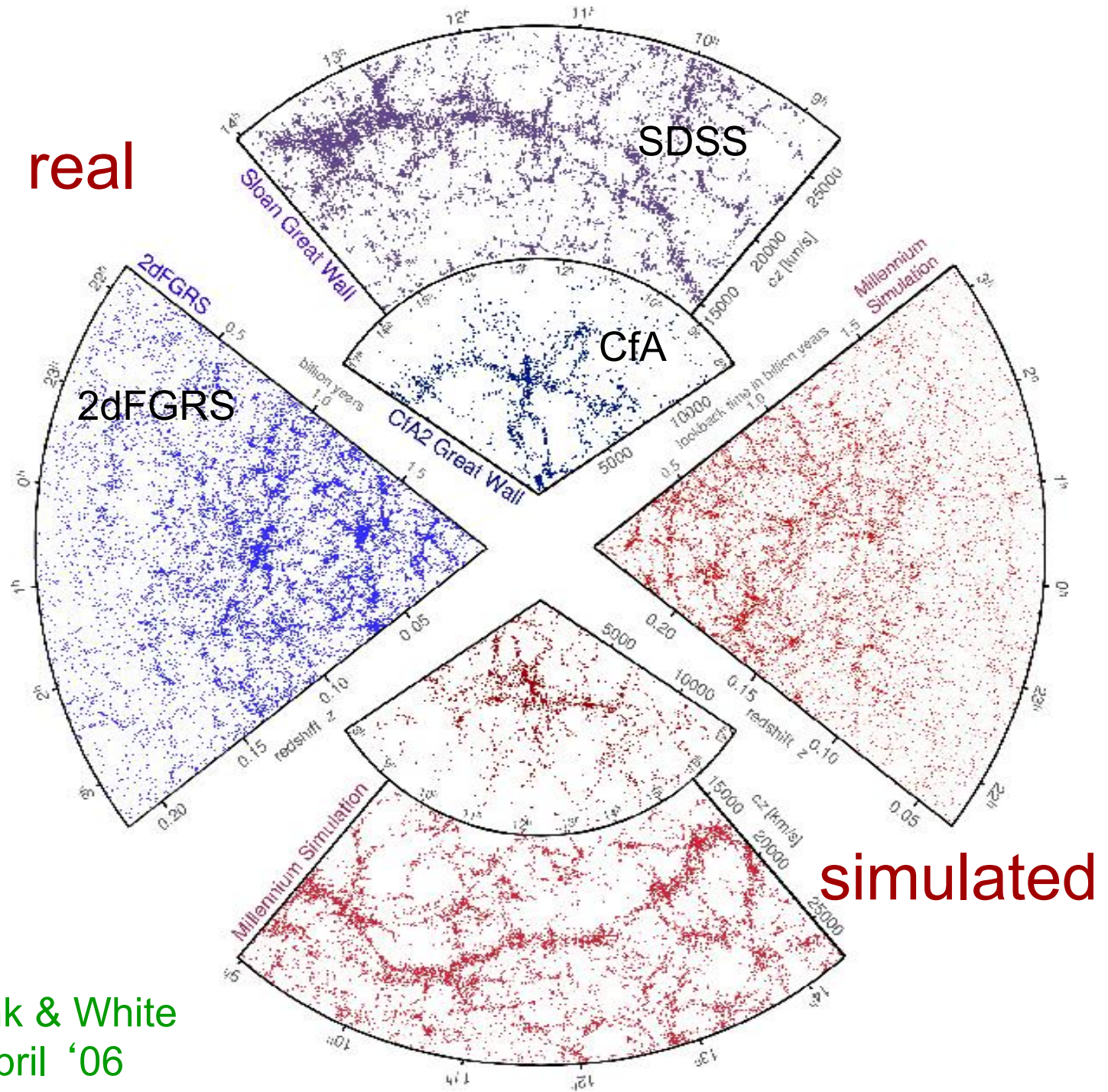
Neutrinos cannot
make appreciable
contribution to Ω
→ $m_\nu \ll 30$ eV

Early CDM N-body
simulations gave
promising results

In CDM structure
forms hierarchically

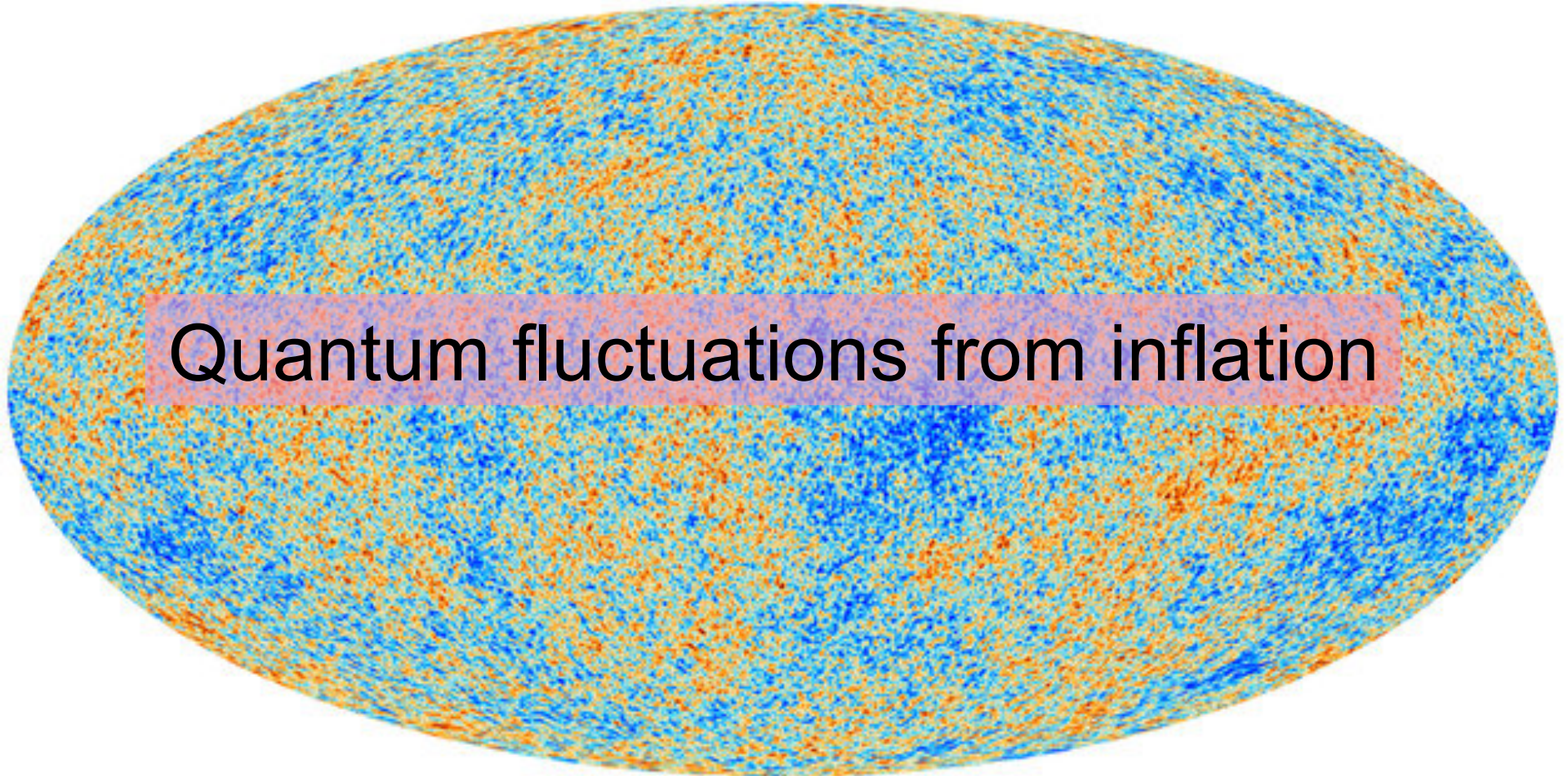


real



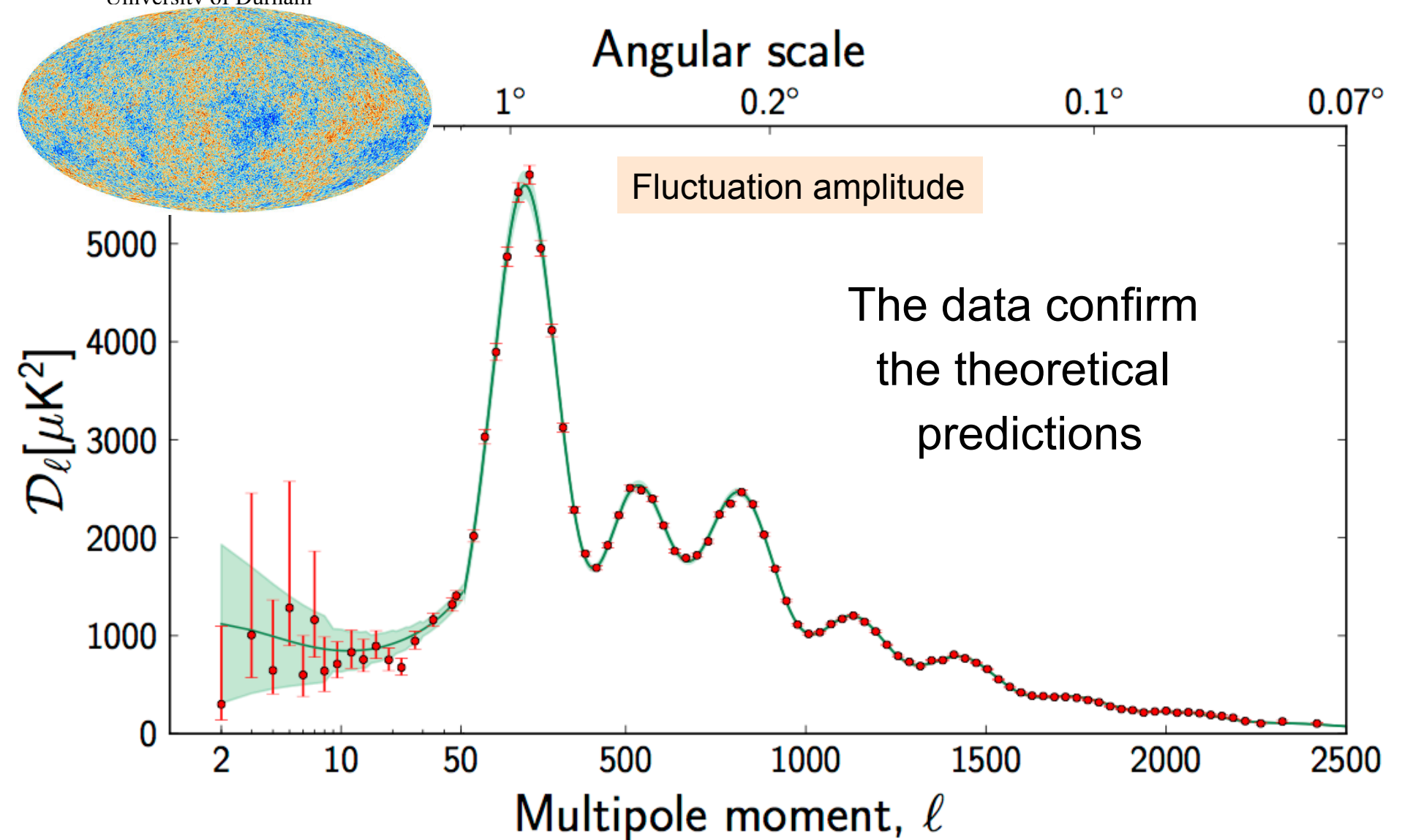
simulated

The initial conditions for galaxy formation



Quantum fluctuations from inflation

Planck: CMB temperature anisotropies

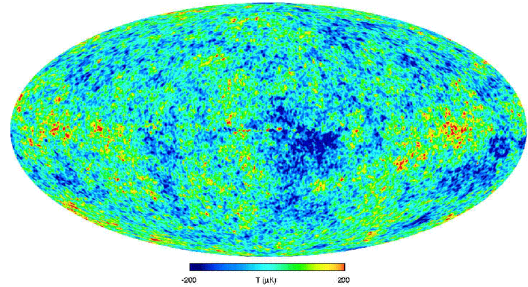


The six parameters of minimal Λ CDM model

		<i>Planck</i> +WP	
Parameter		Best fit	68% limits
6 model parameters	$\Omega_b h^2$	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!

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

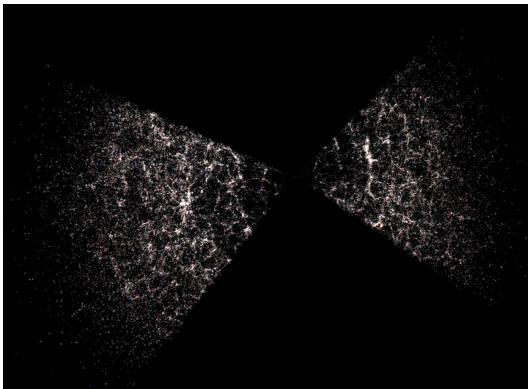


$z \sim 1000$

$\text{Log } k^3 P(k)$

wavelength k^{-1} (comoving h^{-1} Mpc)

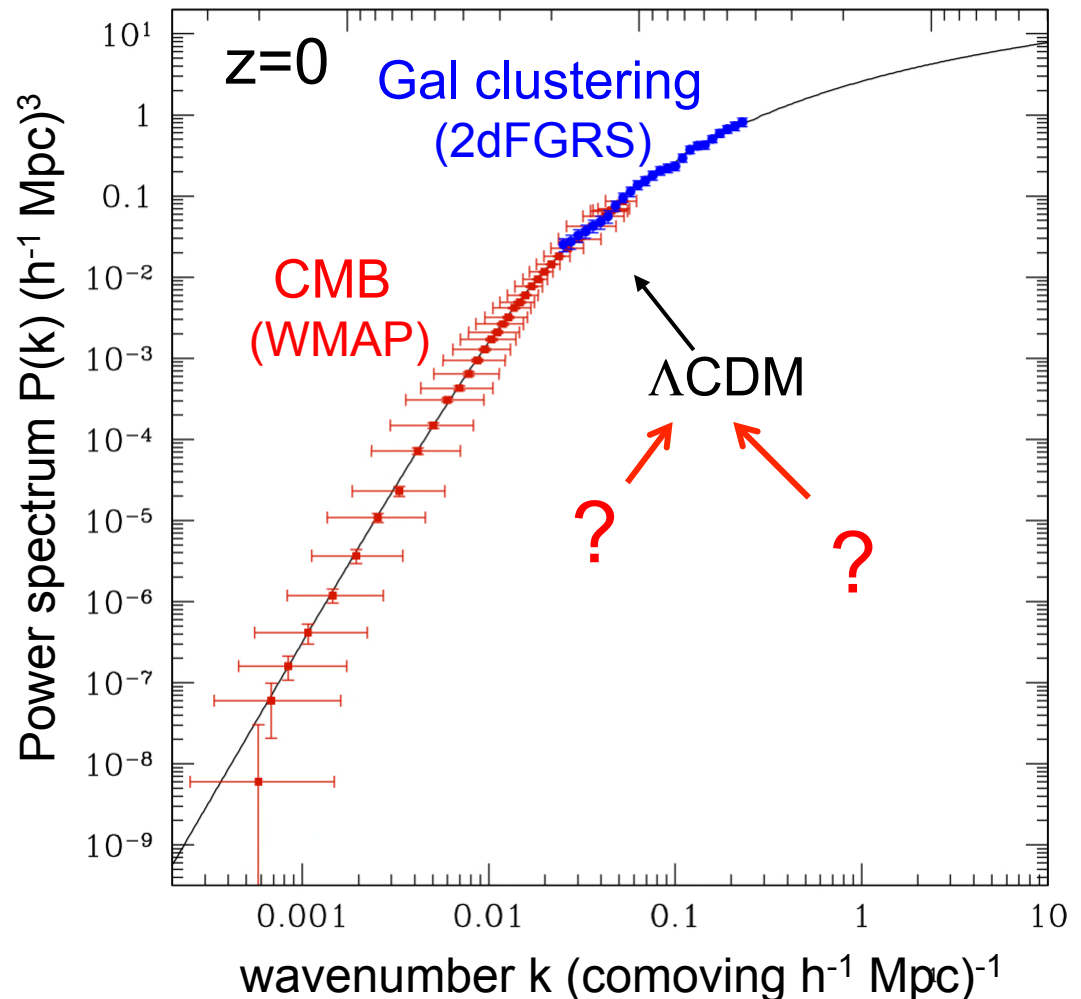
1 000 100 10



$z \sim 0$

⇒ Λ CDM 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 →

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

for thermal relic

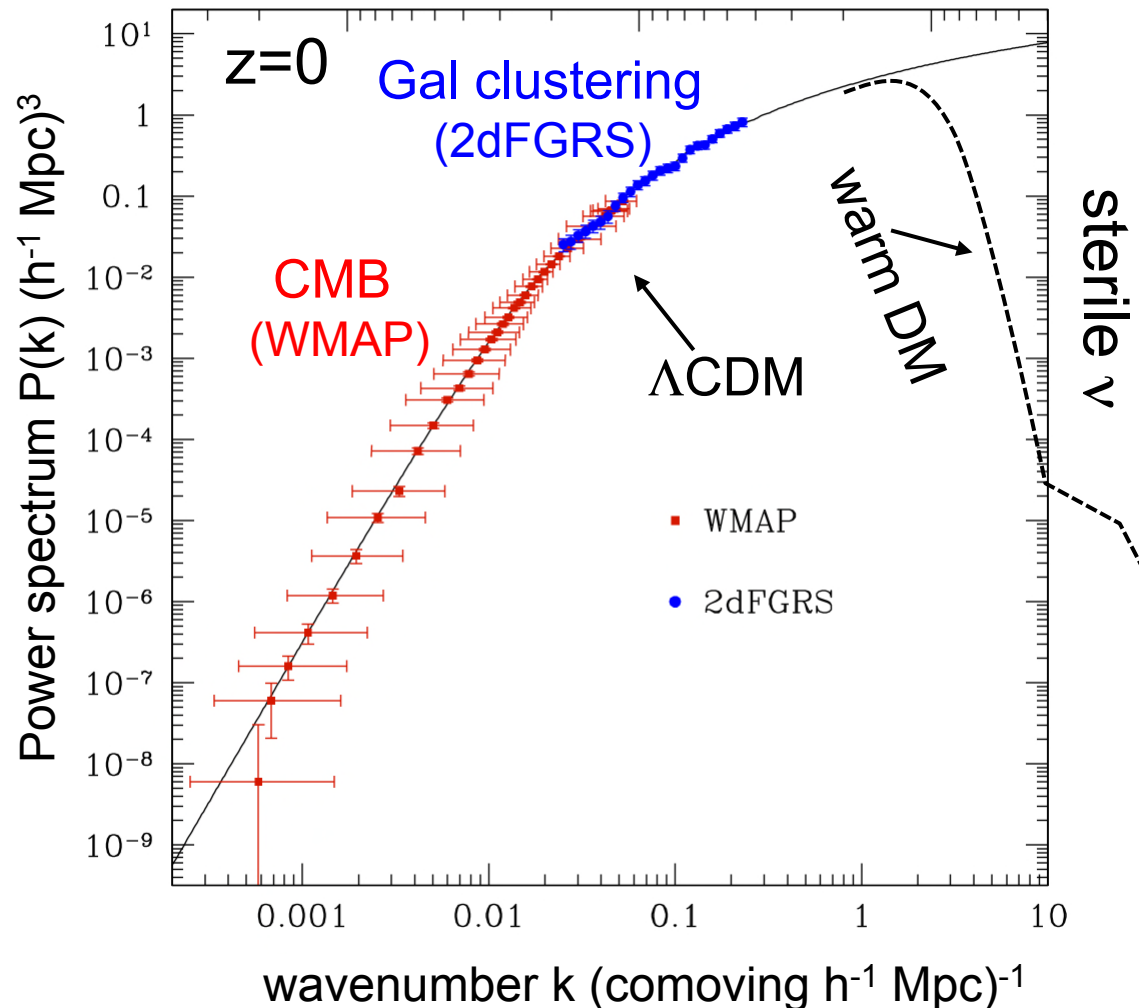
$$m_{\text{CDM}} \sim 100 \text{ GeV}$$

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

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$$\text{sterile } \nu; M_{\text{cut}} \sim 10^9 M_{\odot}$$

Log $k^3 P(k)$ wavelength k^{-1} (comoving $h^{-1} \text{ Mpc}$)



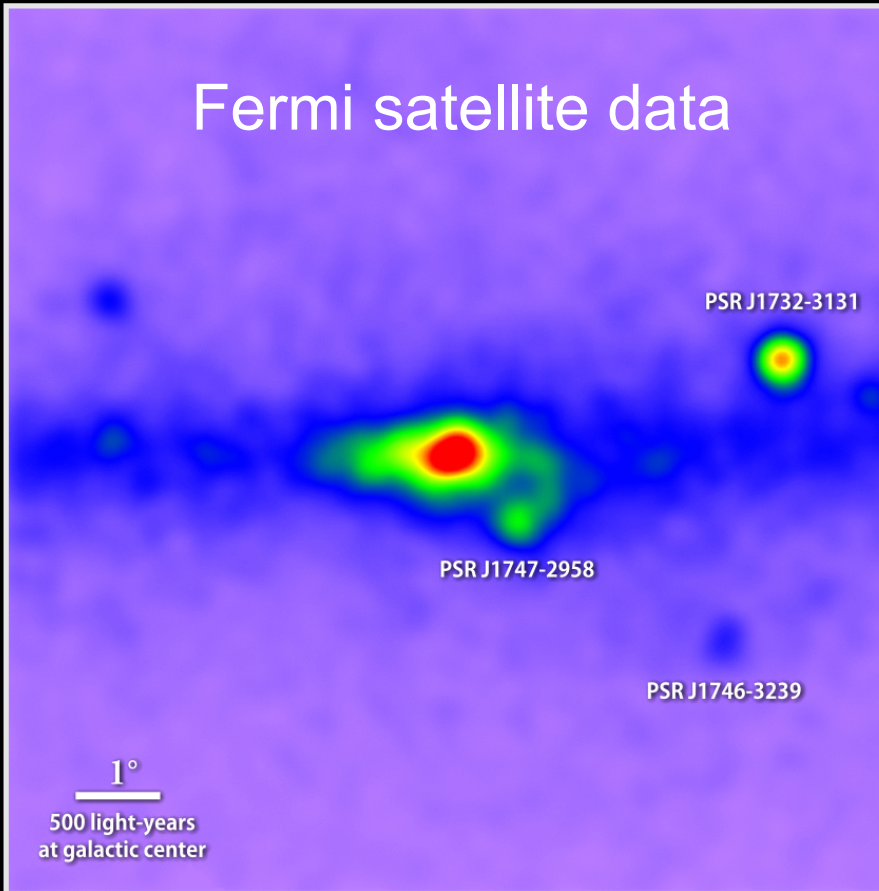
Cold dark matter

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

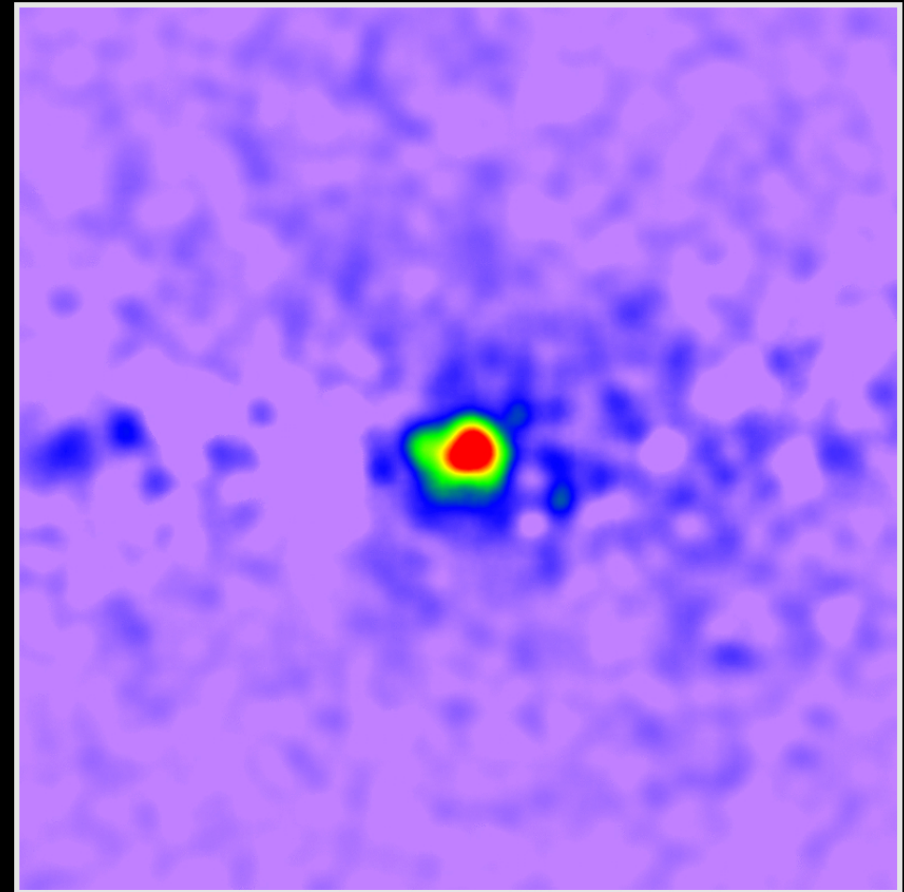
Tansu Daylan,¹ Douglas P. Finkbeiner,^{1,2} Dan Hooper,^{3,4} Tim Linden,⁵
Stephen K. N. Portillo,² Nicholas L. Rodd,⁶ and Tracy R. Slatyer^{6,7}

Uncovering a gamma-ray excess at the galactic center

Fermi satellite data



Unprocessed map of 1.0 to 3.16 GeV gamma rays

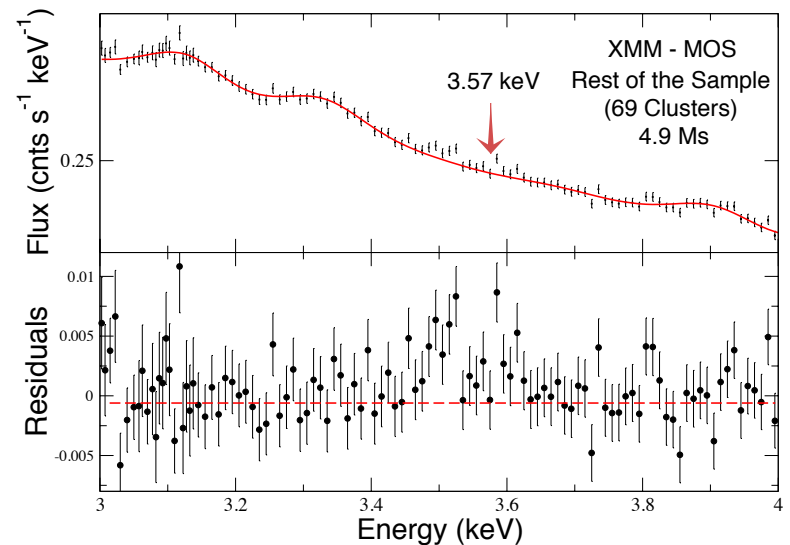
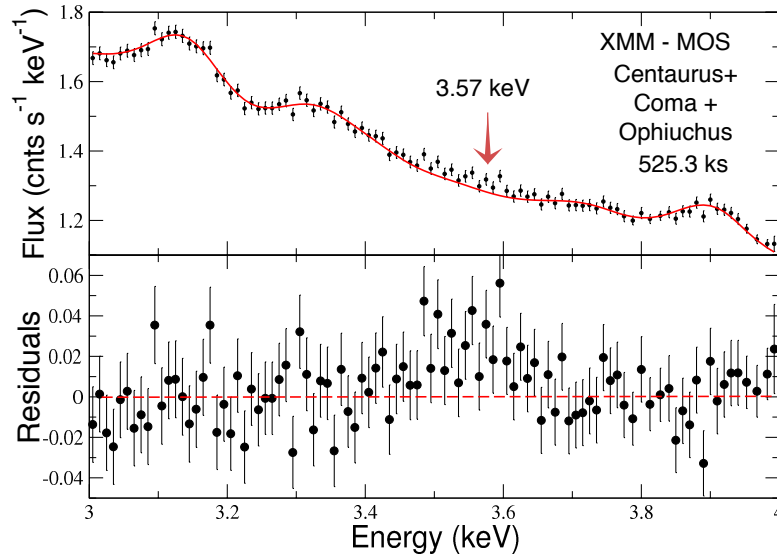
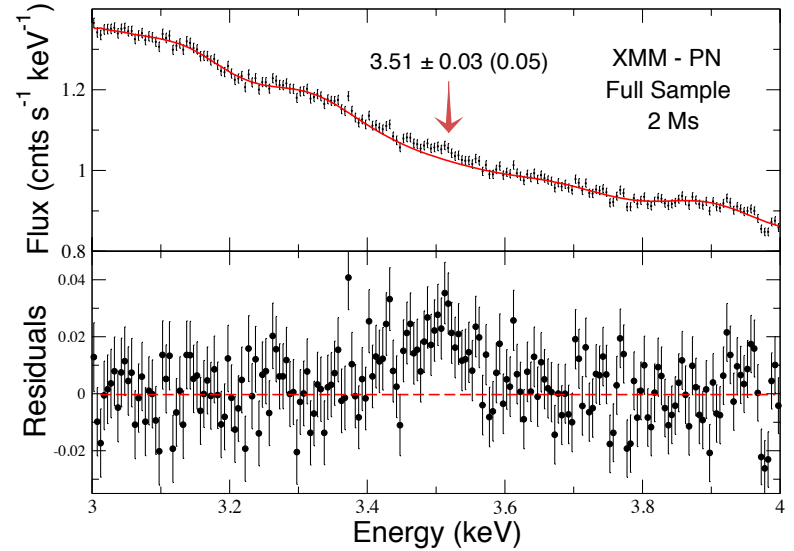
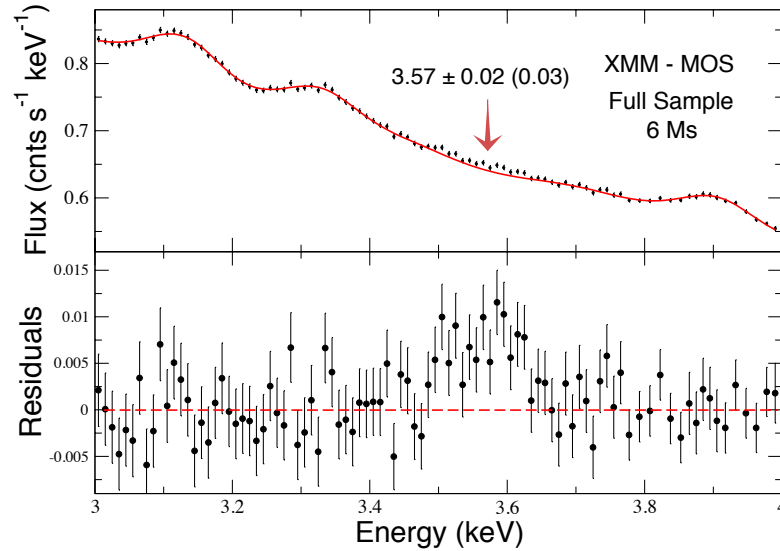


Known sources removed

Warm dark matter WDM decay line in 69 stacked clusters?

$E=3.57$ keV

Bulbul et al. '14 See also Boyarsky et al. '14





Very unlikely that both are right!

Sterile neutrinos

Explain:

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

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

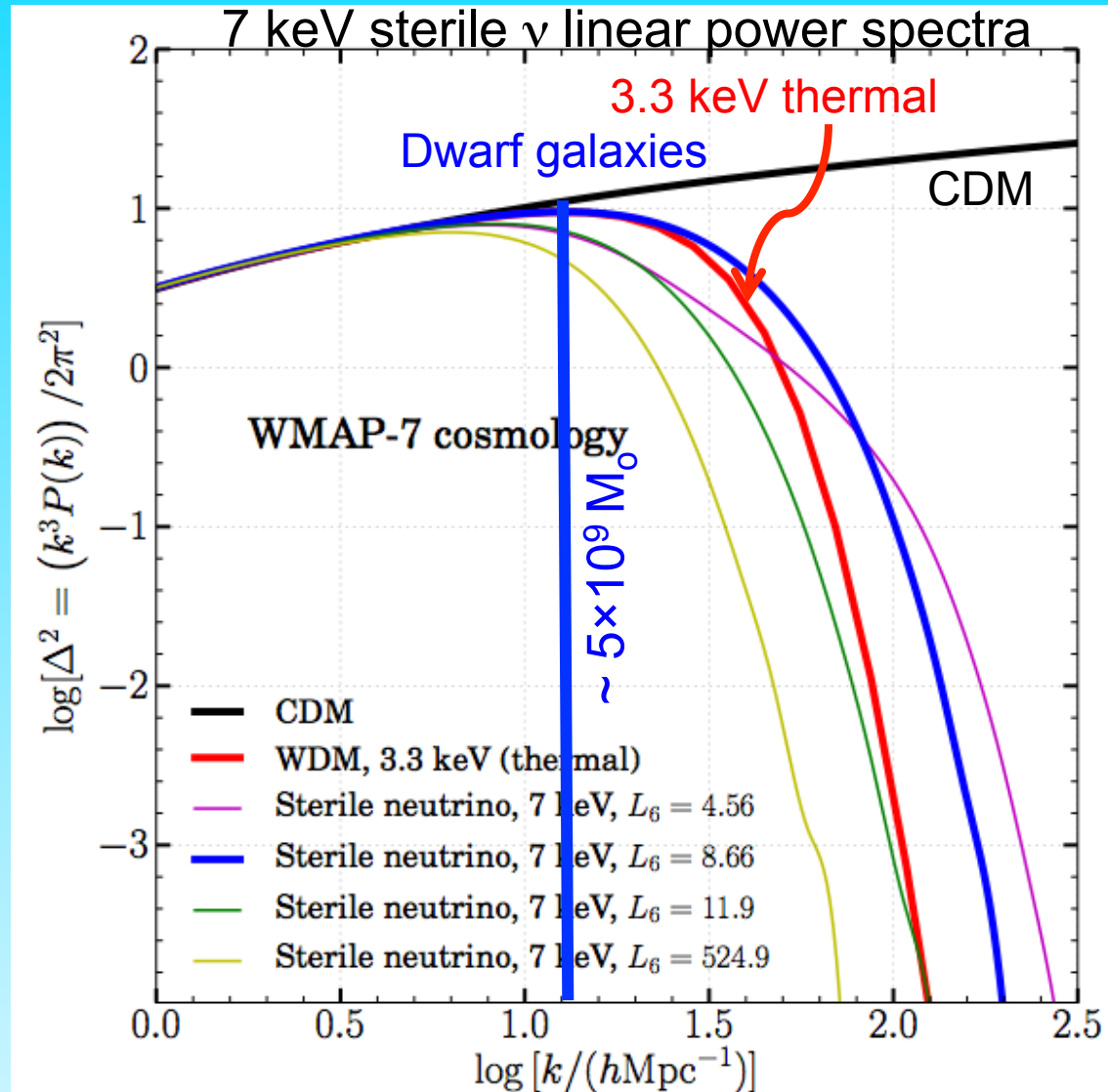
- Extension of SM w. 3 sterile neutrinos: 2 of GeV; 1 of keV mass
- If $\Omega_N = \Omega_{DM}$, 2 parameters: mass, lepton asymmetry/mixing angle
- GeV particles may be detected at CERN (SHiP)
- Dark matter candidate can be detected by X-rays decay

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-monotonically** with L_6

Ly- α forest rules out thermal masses, $m_\nu < 3.3$ keV (Viel + '13)

Lovell, Bose, CSF et al. 16





Astrophysical key to identity of dark matter:

→ Subgalactic scales
(strongly non-linear)



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

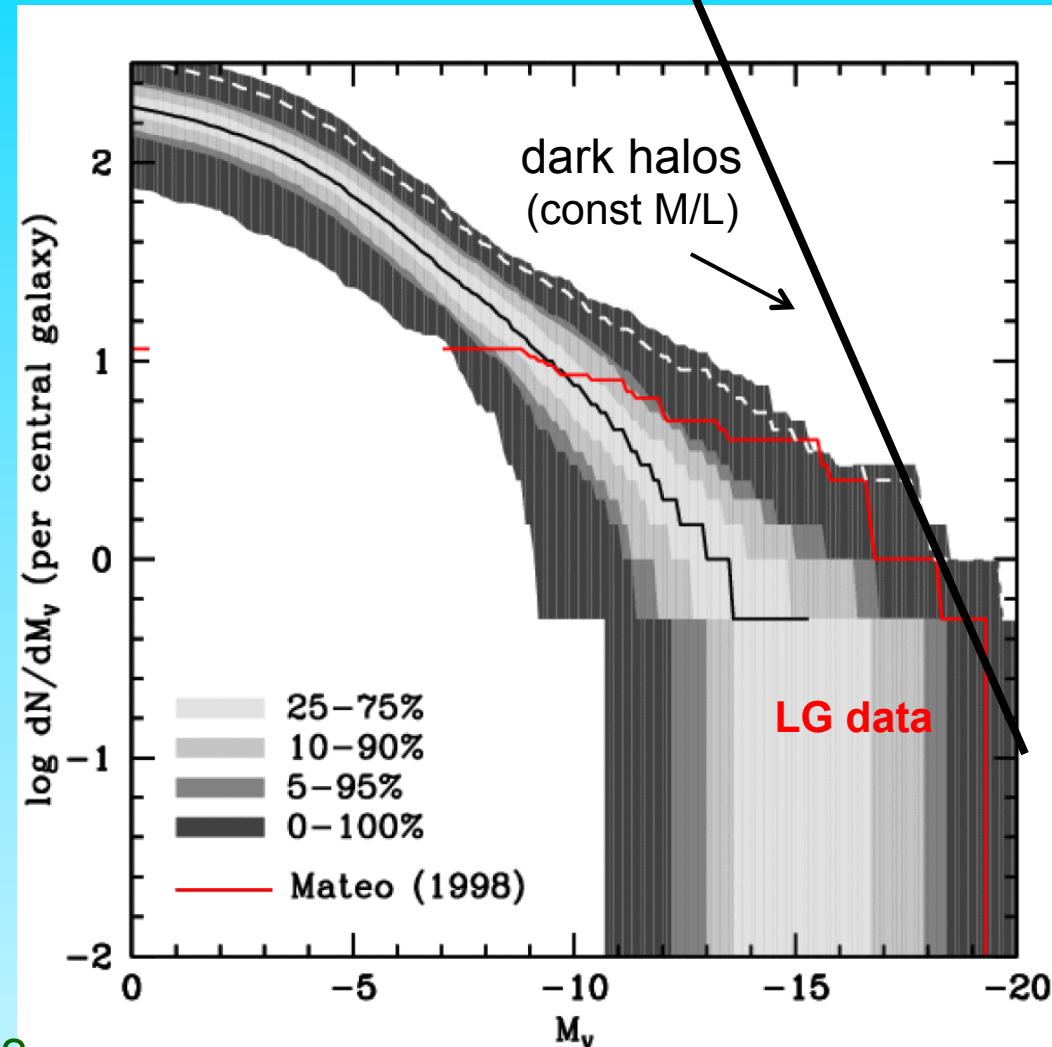
Most subhalos never make a galaxy!

Because:

- Reionization heats gas above T_{vir} , preventing it from cooling and forming stars in small halos
- Supernovae feedback expels any residual gas

Luminosity Function of Local Group Satellites

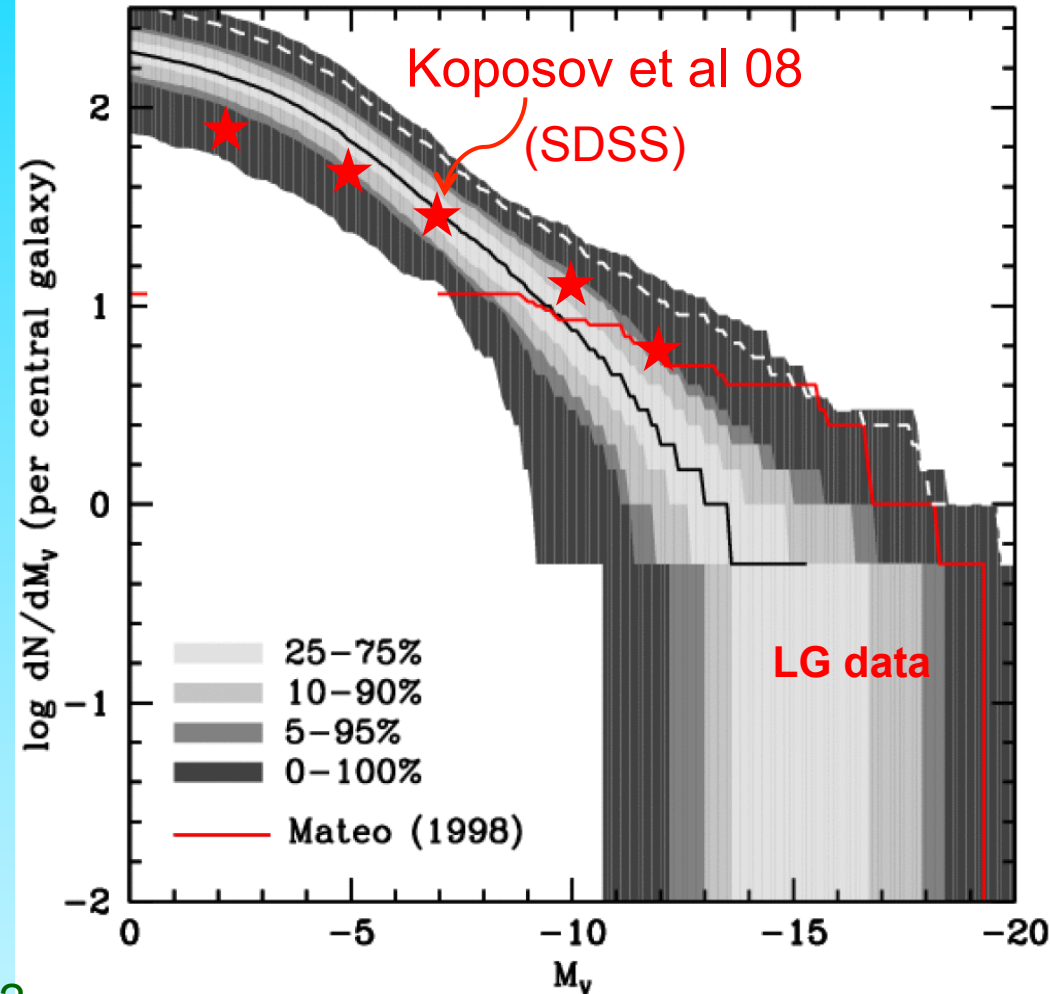
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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

Luminosity Function of Local Group Satellites

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

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

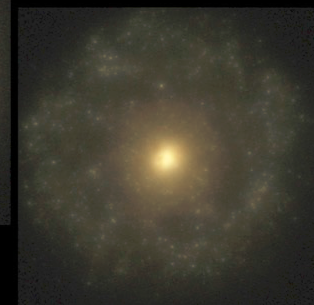
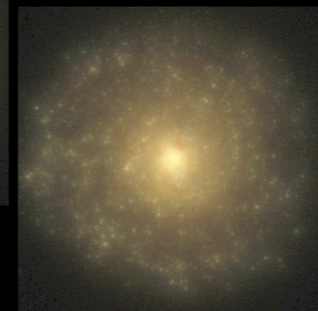
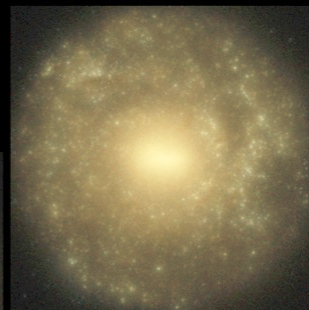
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



Irr

S

Trayford et al '15

VIRG

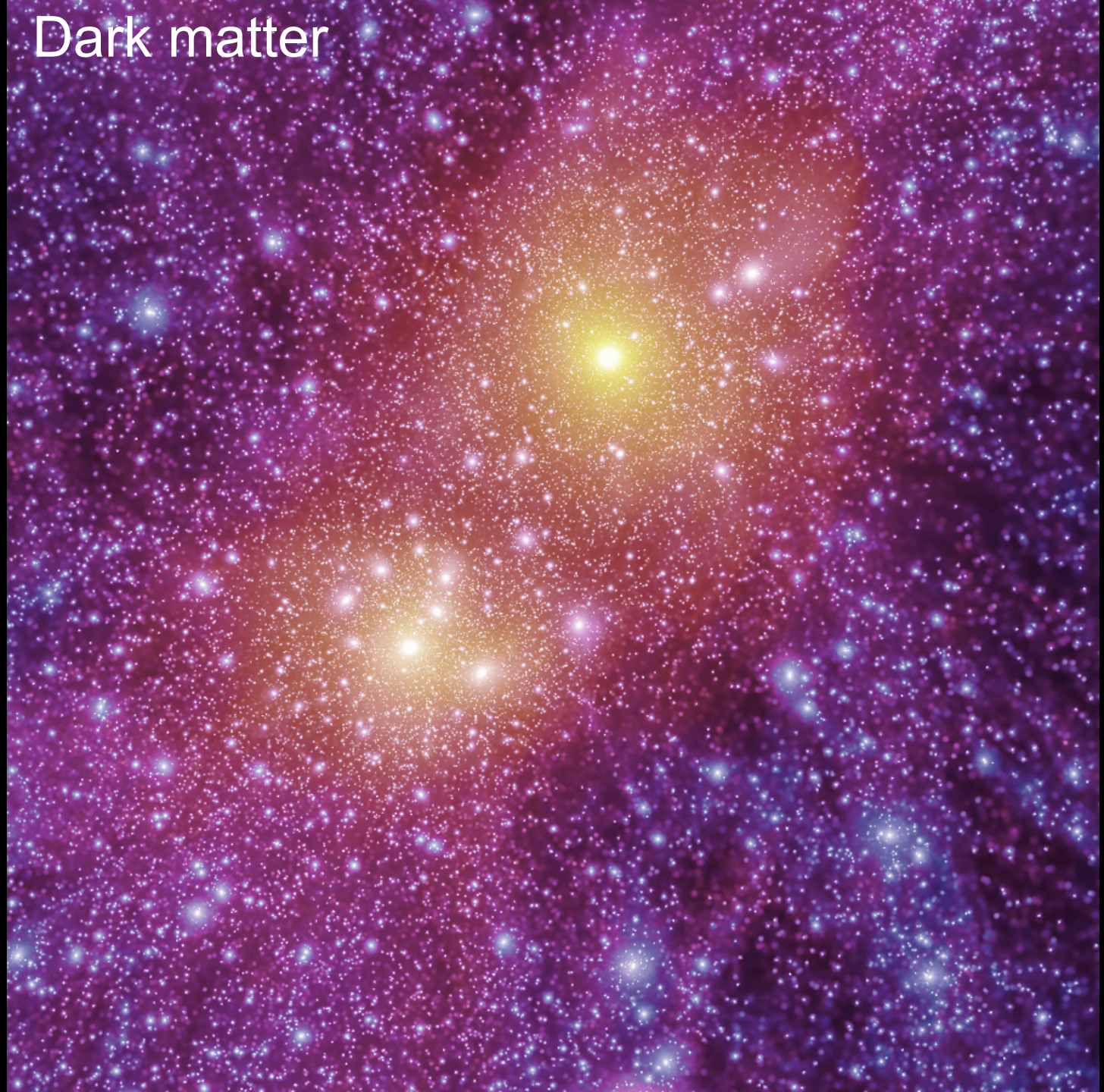
Dark matter

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al '15



Stars

VIRG

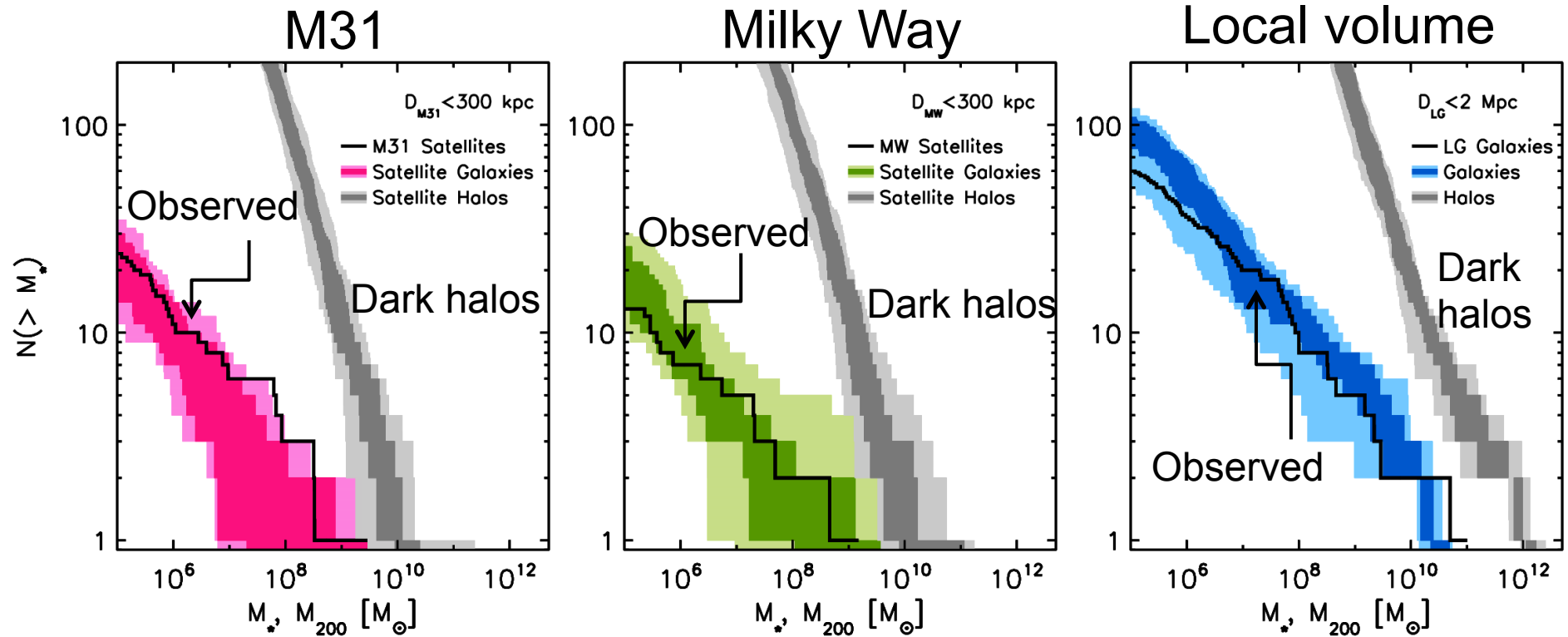
APOSTLE
EAGLE full
hydro
simulations

Local Group

Far fewer satellite galaxies than CDM halos

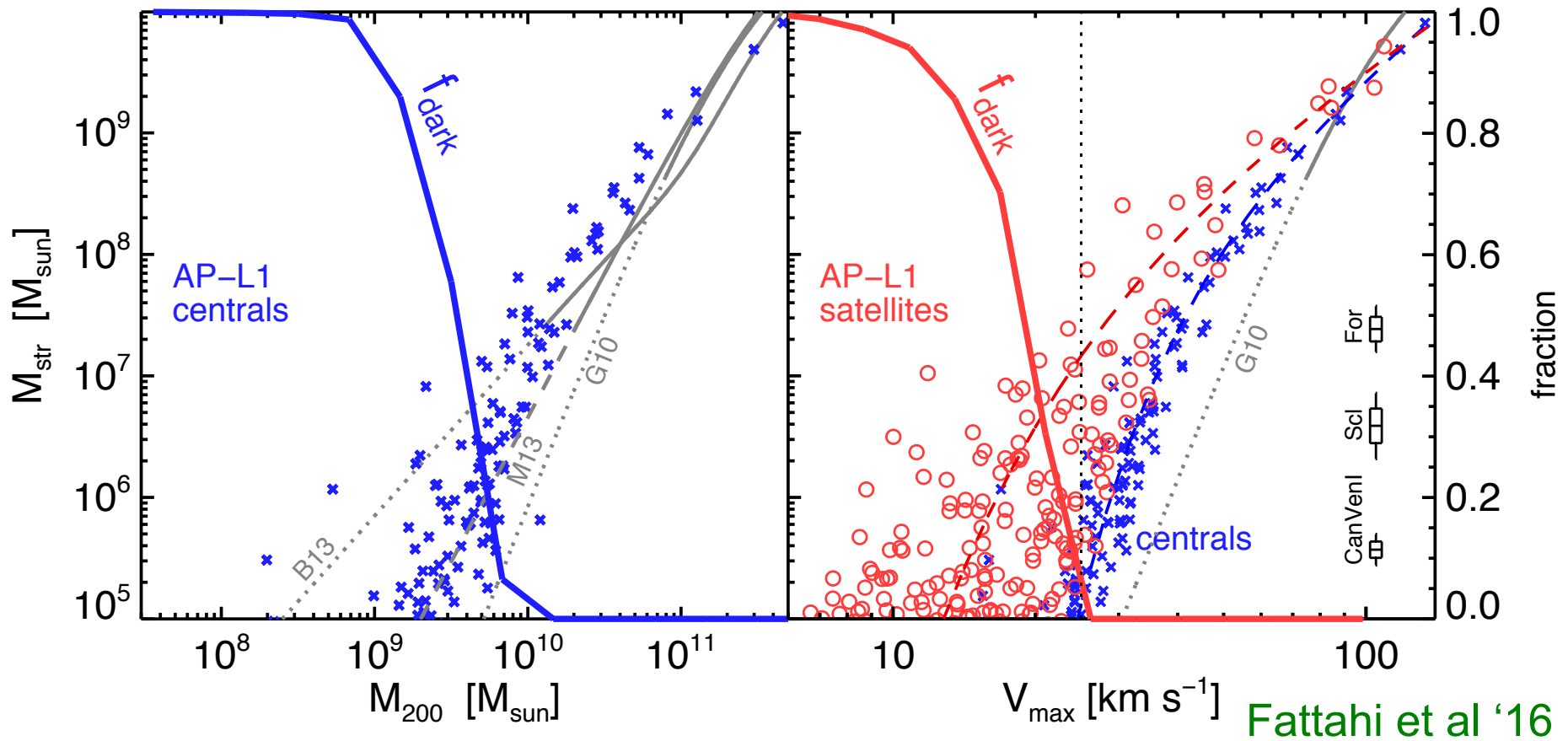
Sawala et al '15

EAGLE Local Group simulation



Fraction of dark subhalos

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



Fattahi et al '16

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



(~50 discovered so far)



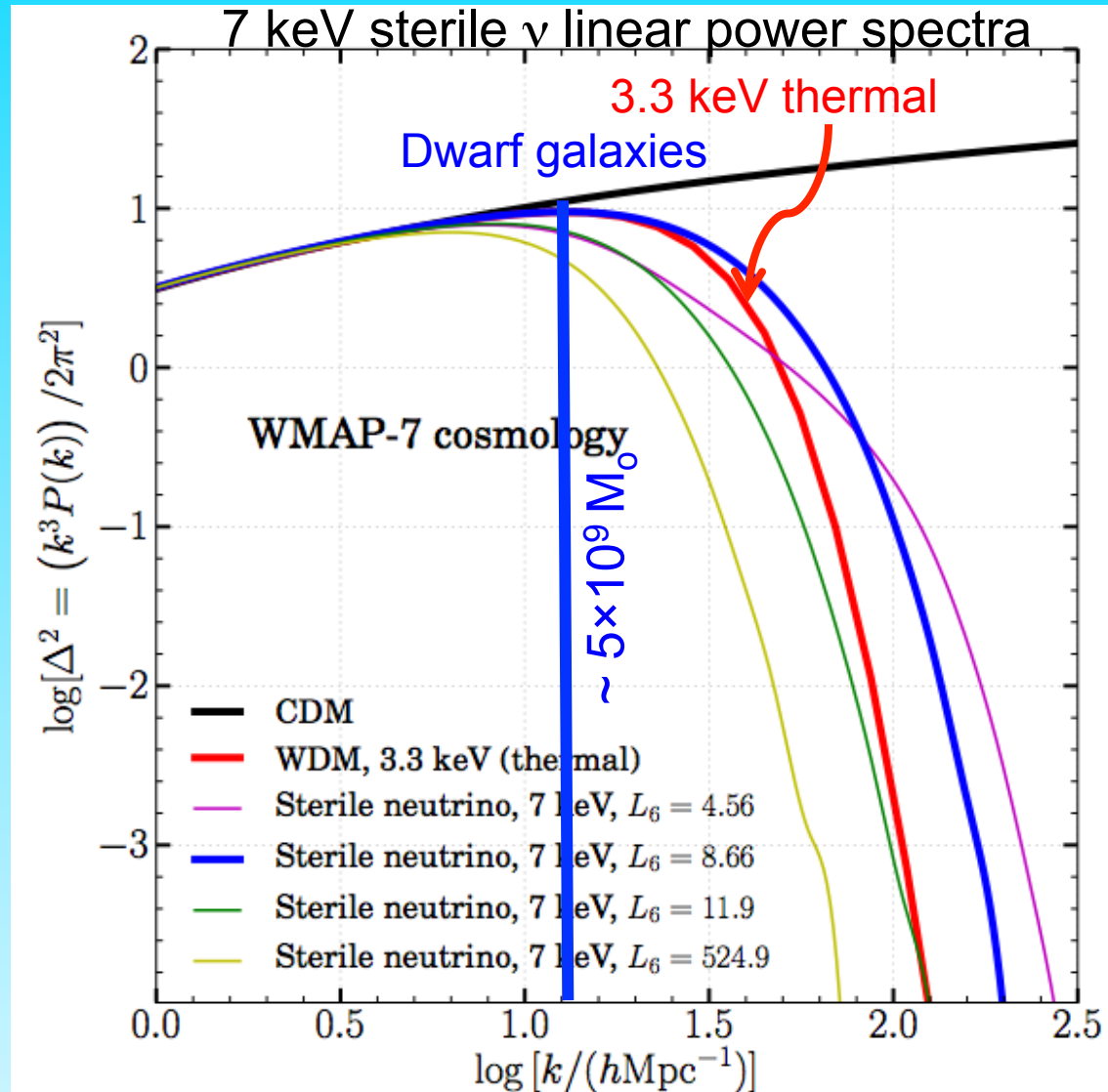
(a few tens)

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-monotonically** with L_6

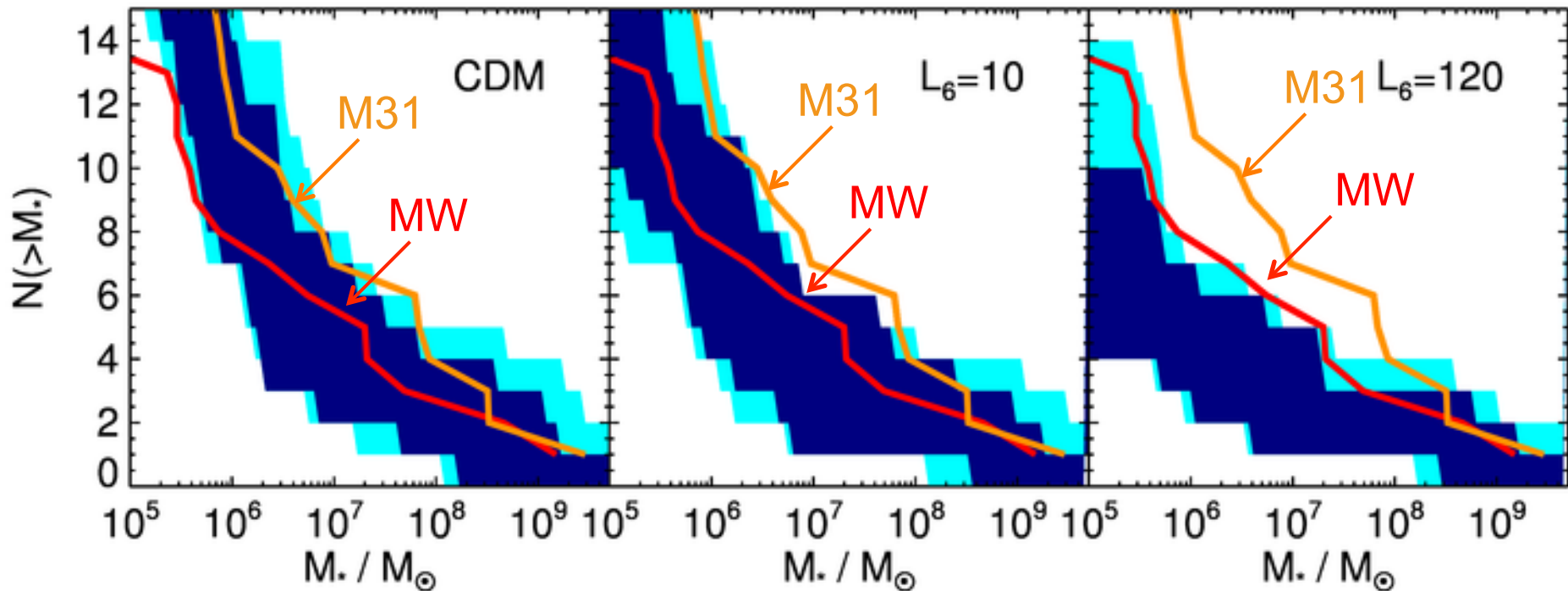
Ly- α forest rules out thermal masses, $m_\nu < 3.3$ keV (Viel + '13)

Bose, Lovell et al. 16



Luminosity Function of Local Group Satellites in WDM

From “Warm Apostle:” 7keV sterile ν $M_h \sim 10^{12} M_\odot$



Lovell et al. '16

Limits on sterile ν mass

In WDM, no. of sats depends:

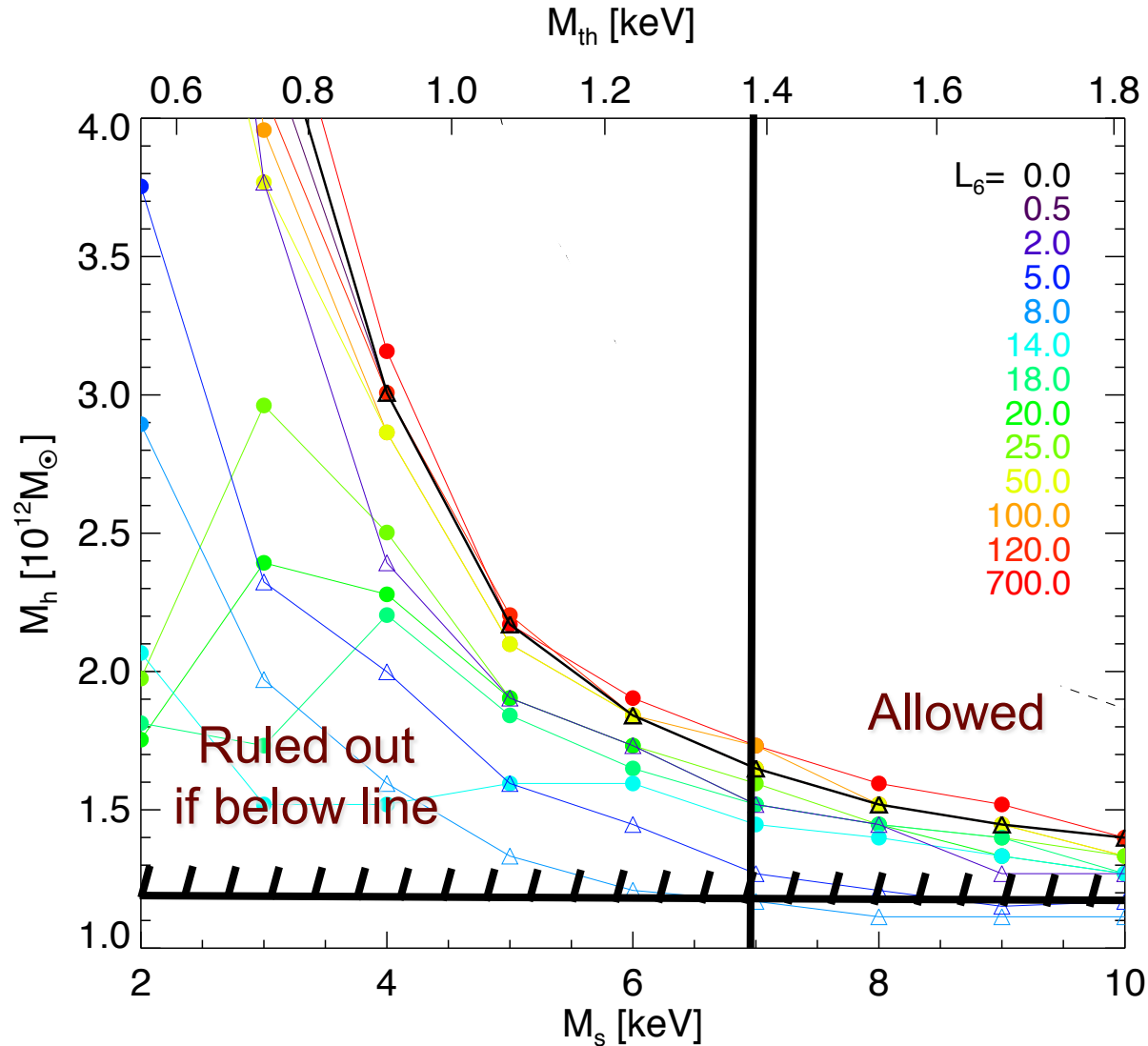
- Particle mass
- MW halo mass

If $M_{\text{halo}} < 1.2 \times 10^{12} M_{\odot}$



7keV sterile ν ruled out

Lovell et al '16



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

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

“Too-big-to-fail” problem in CDM: *Boylan-Kolchin et al ‘11*

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

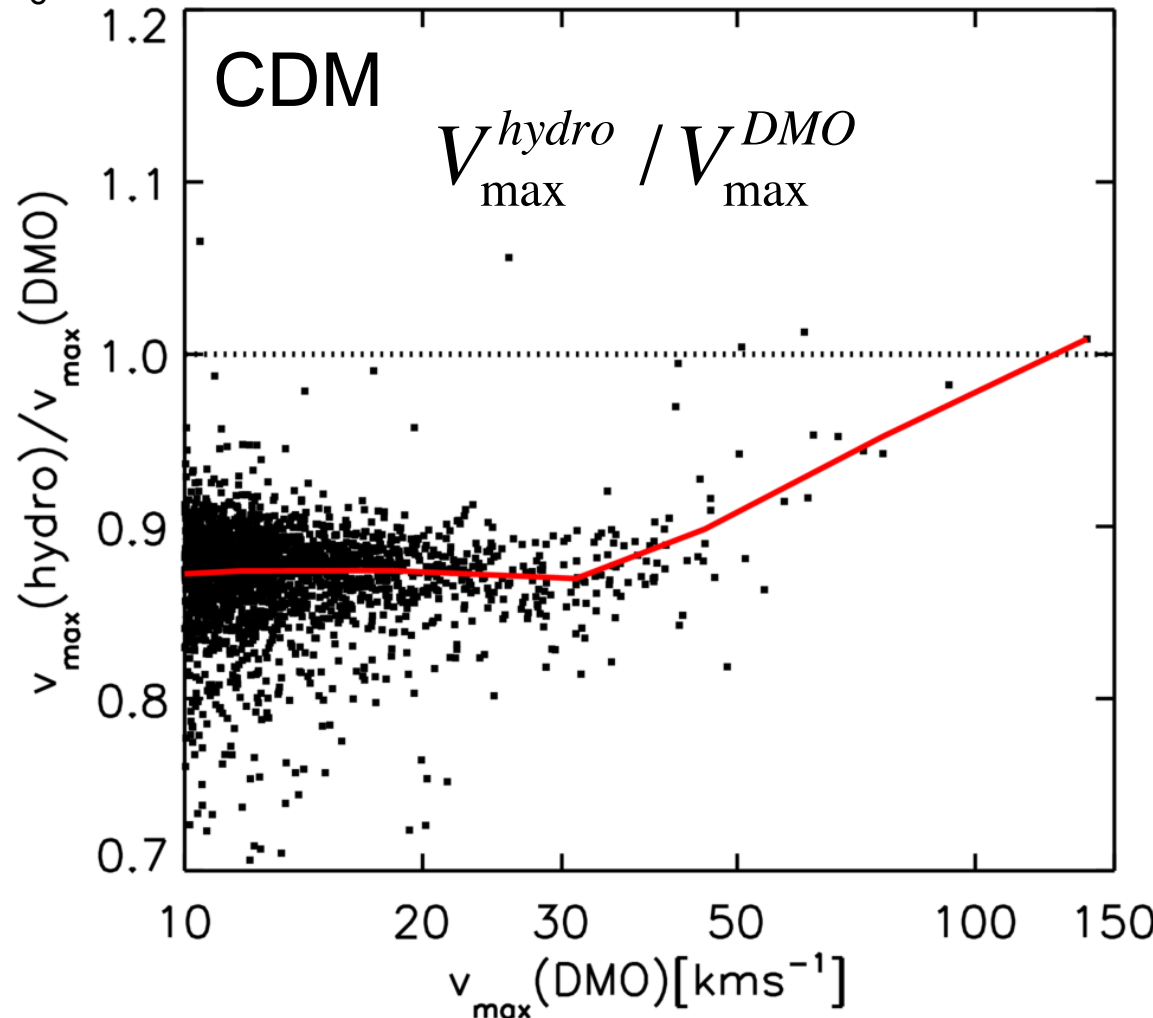
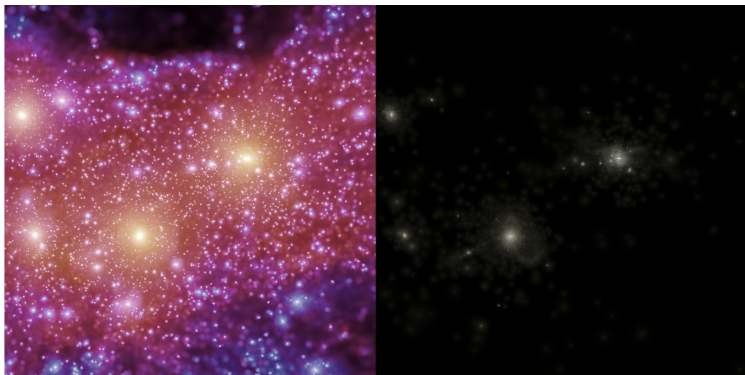
Why did the big subhalos
not make a galaxy?

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

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

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

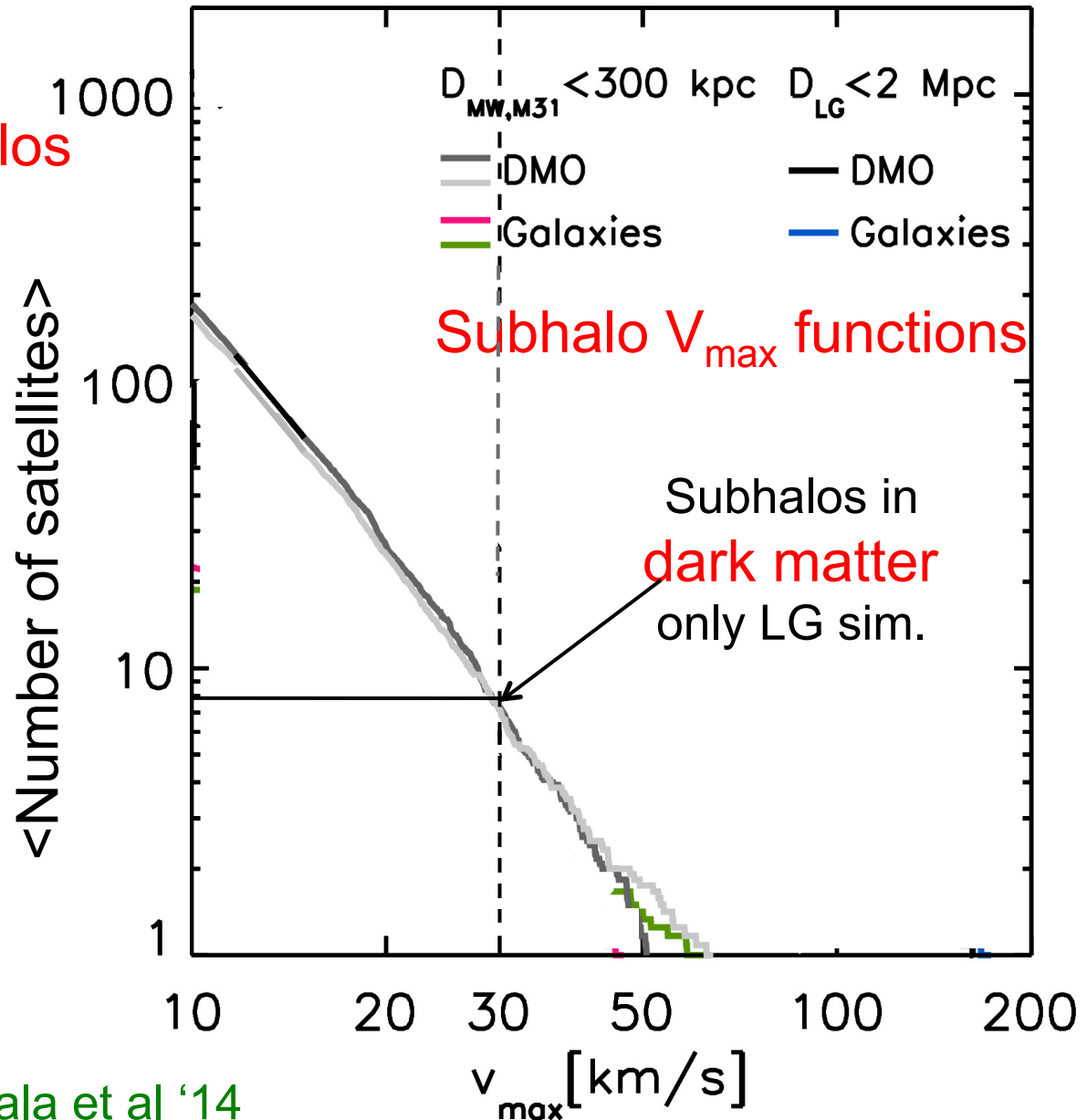
→ Lowers halo mass &
thus halo growth rate



Sawala et al. '13, '15

Too-big-to-fail: the baryon bailout

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

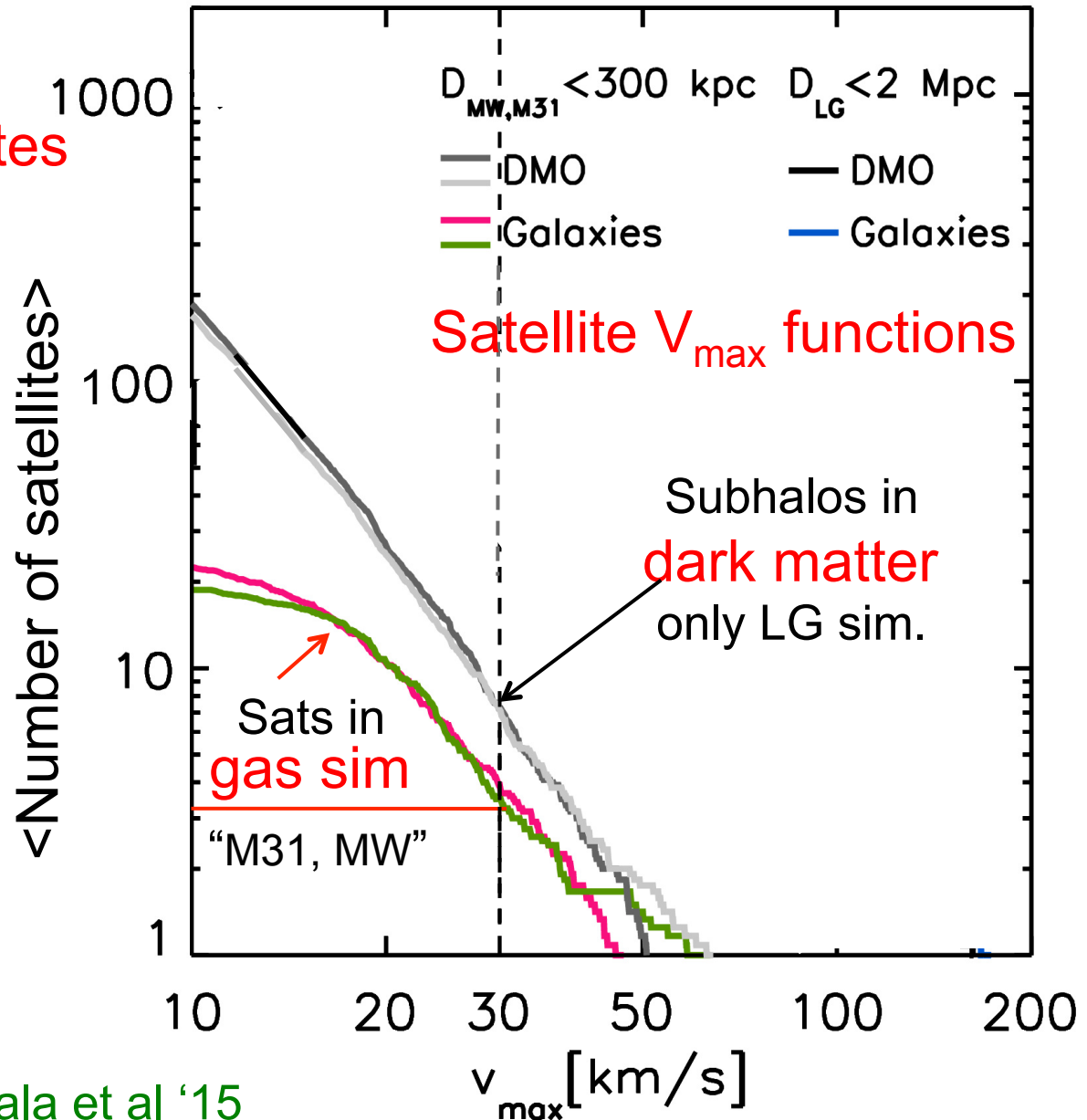


Too-big-to-fail: the baryon bailout

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

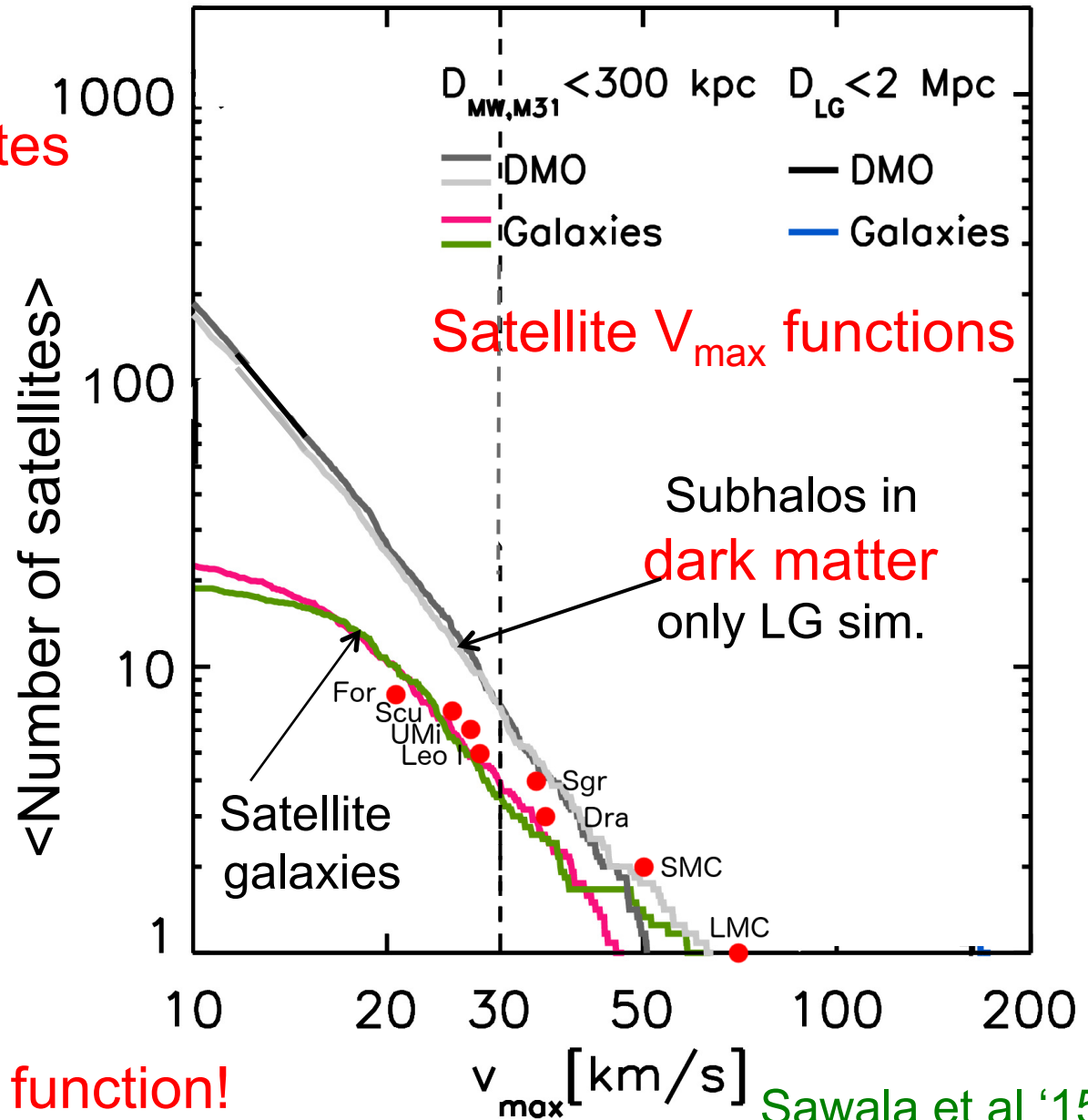


Sawala et al '15



Too-big-to-fail: the baryon bailout

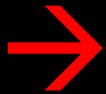
Hydro sims $\rightarrow$ **~3 satellites**
with $V_{\max} > 30$ km/s



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



No too-big-to-fail problem in CDM



When “baryon effects” are included

Too-big-to-fail in WDM

Dark matter subhalos in WDM

(a few tens)

In WDM models that match satellite LF there is **no** too-big-to-fail problem

- Halos are **less dense** than in CDM
(**later formation**)
- V_{max} **reduction** due to baryons





The core-cusp problem

cold dark matter

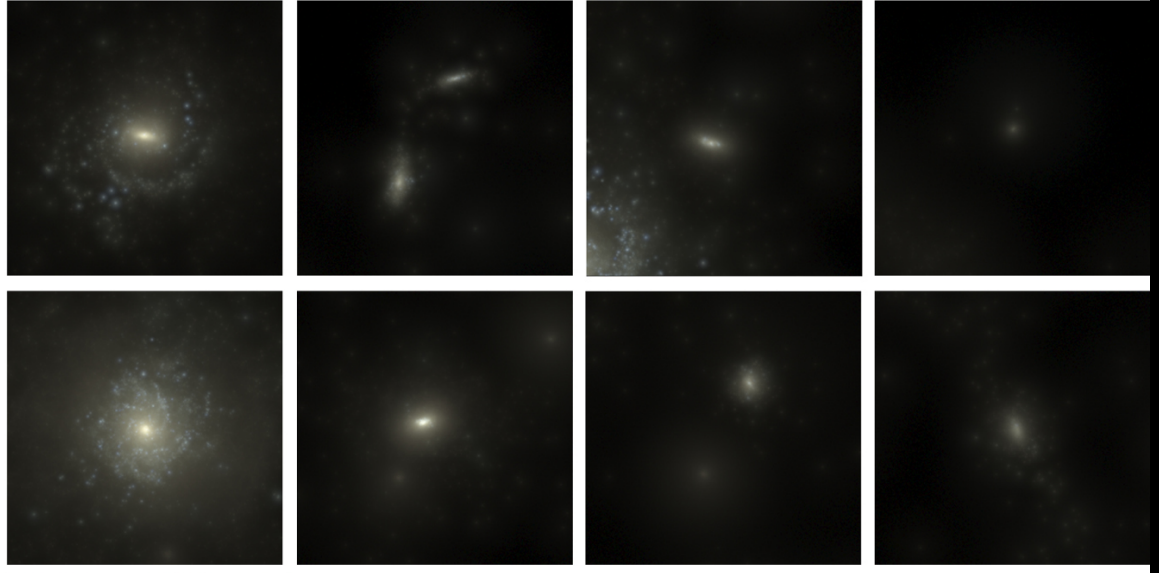
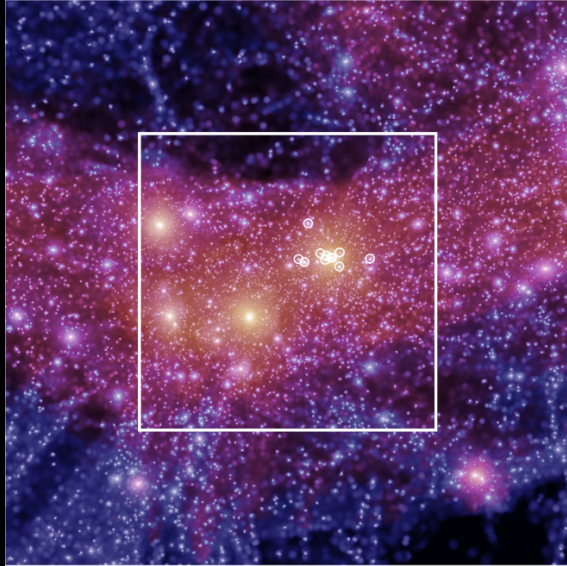
warm dark matter

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





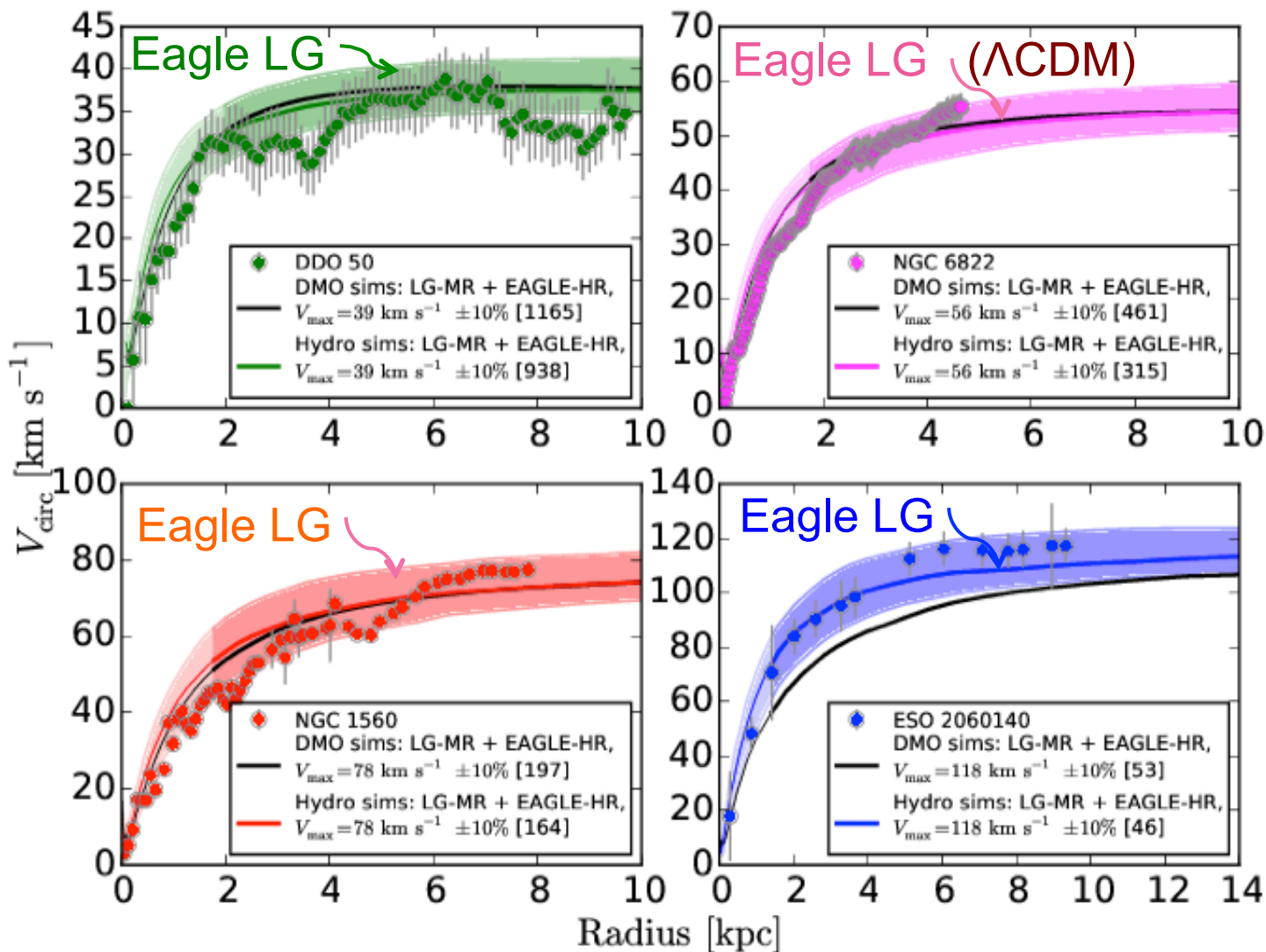
Dwarf galaxies in Apostle have NFW cusps!

Sawala et al '15

The diversity of gal rotation curves

Four rotation curves that are well fit by Λ CDM

(from dwarfs to $\sim L_*$)

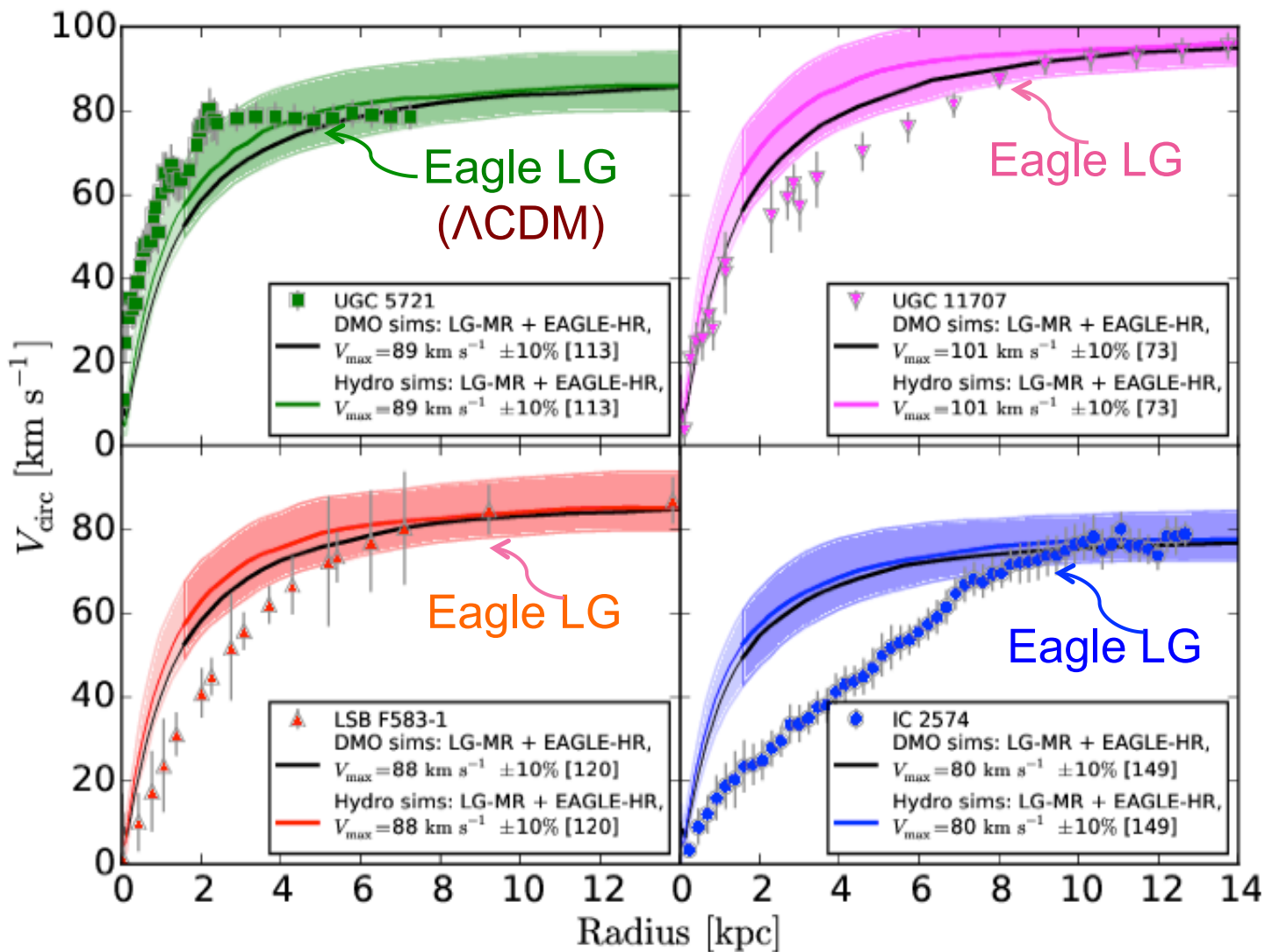


Oman, Navarro, Frenk et al. '15

The diversity of gal rotation curves

Four rotation curves that are NOT well fit by Λ CDM

(from dwarfs to $\sim L_*$)



Oman et al. '15

Cores or cusps?

Core are generally thought to exist in some galaxies

But, do they???

Cores or cusps?

Core are generally thought to exist in some galaxies

But, do they???

And if they exist, do they tell us anything about dark matter?

The cores of dwarf galaxy haloes

Julio F. Navarro,^{1,2★} Vincent R. Eke² and Carlos S. Frenk²

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.

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

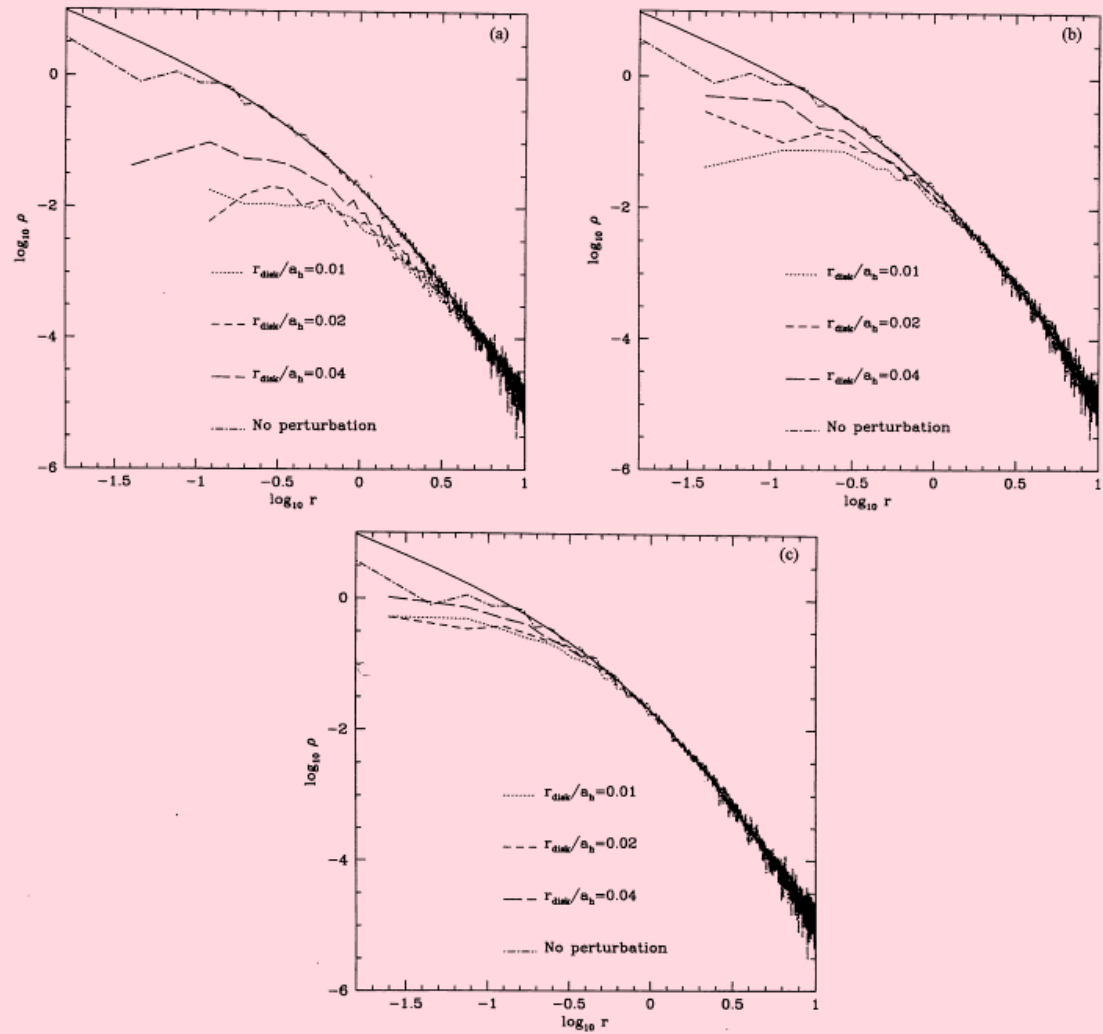


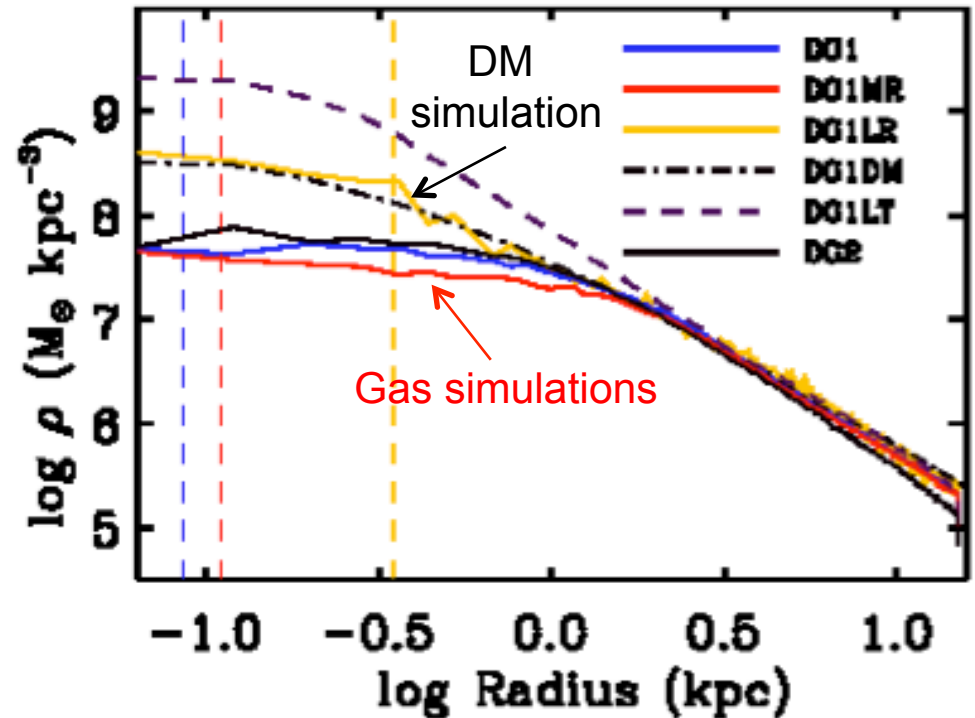
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{\text{disc}}=0.2$.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

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



VIRGO

cold dark matter

warm dark matter

Core/cusp will not tell us anything
about the nature of the dark matter

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



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

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





Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

Rather than counting faint galaxies
count the number of dark halos



Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

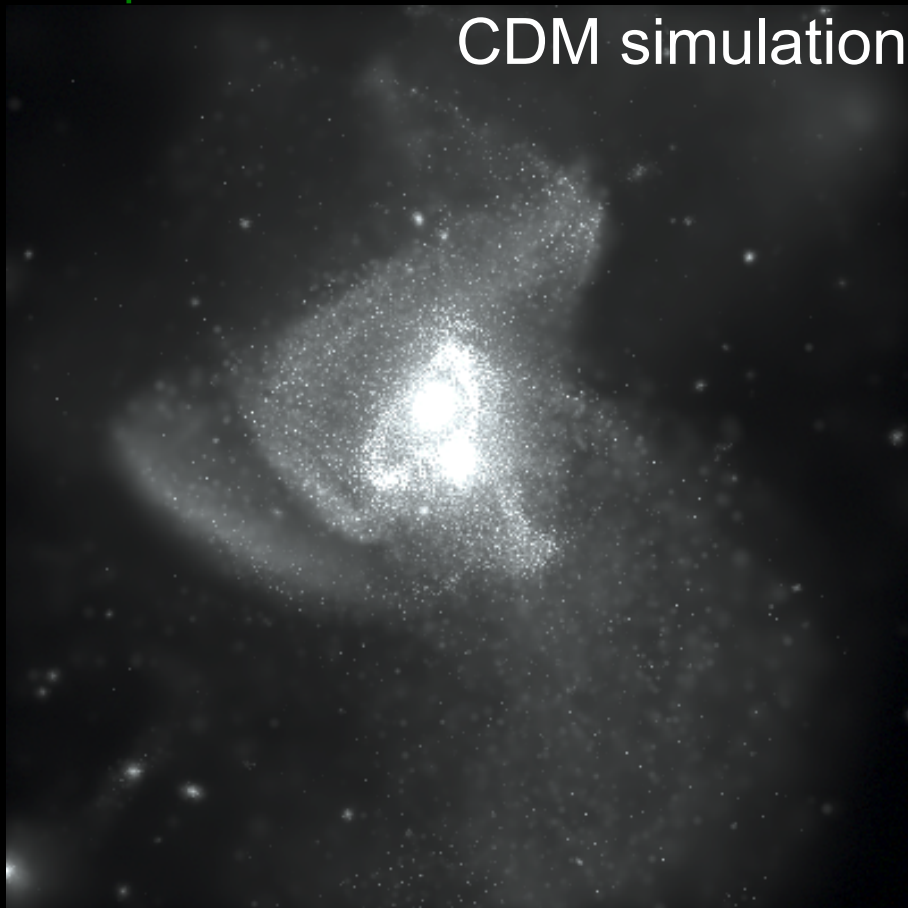
1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing



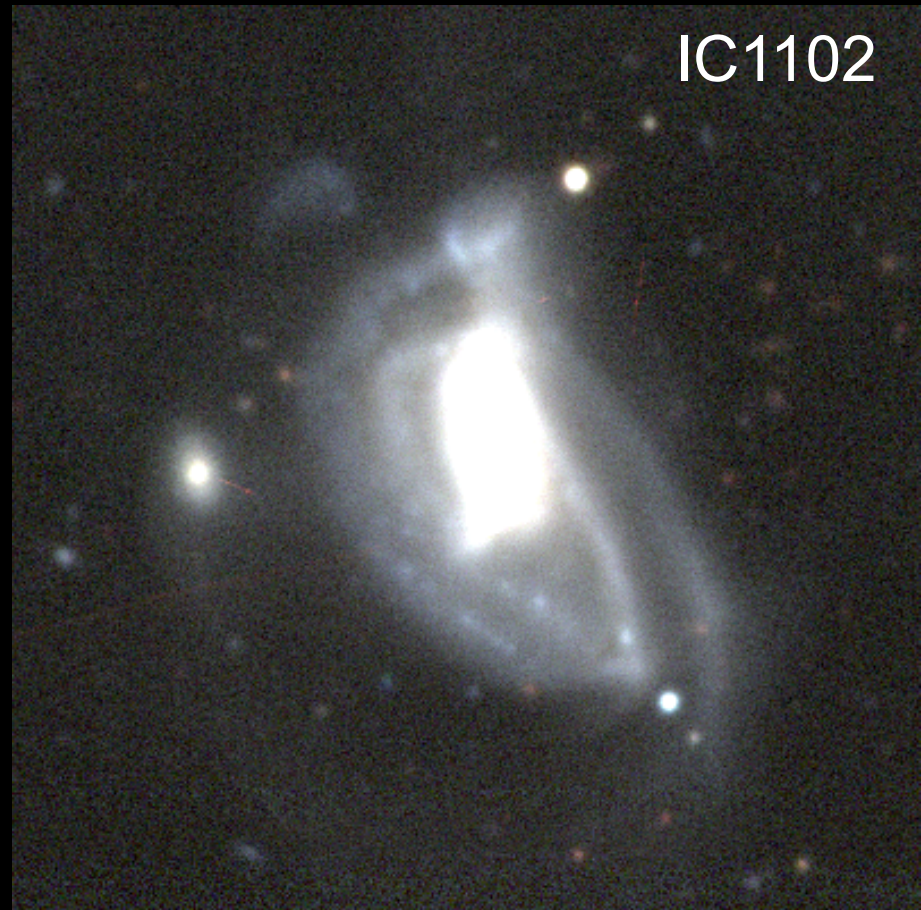
Can we distinguish CDM/WDM?

Cooper et al '16

CDM simulation



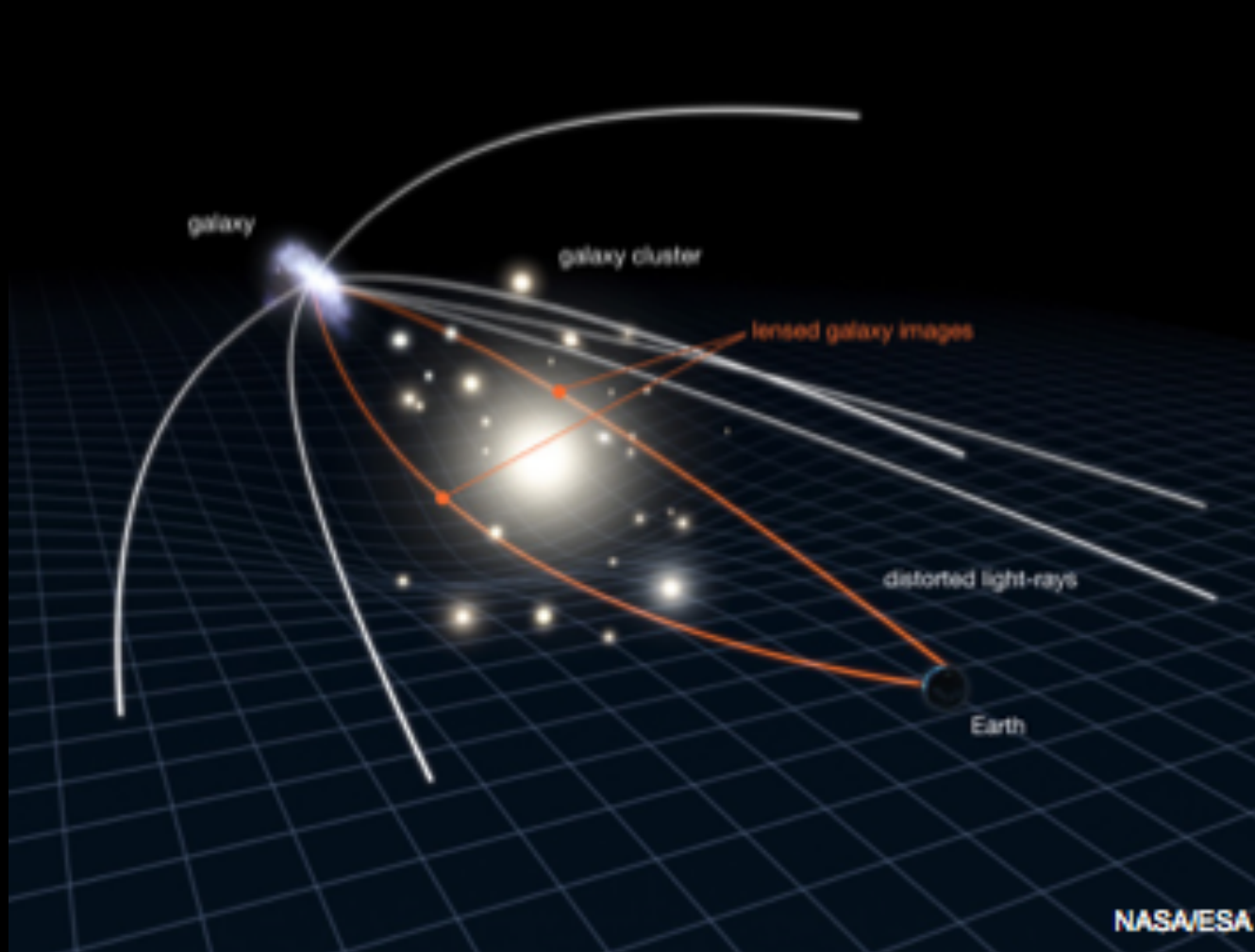
IC1102



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 or an Einstein ring



Gravitational lensing: Einstein rings

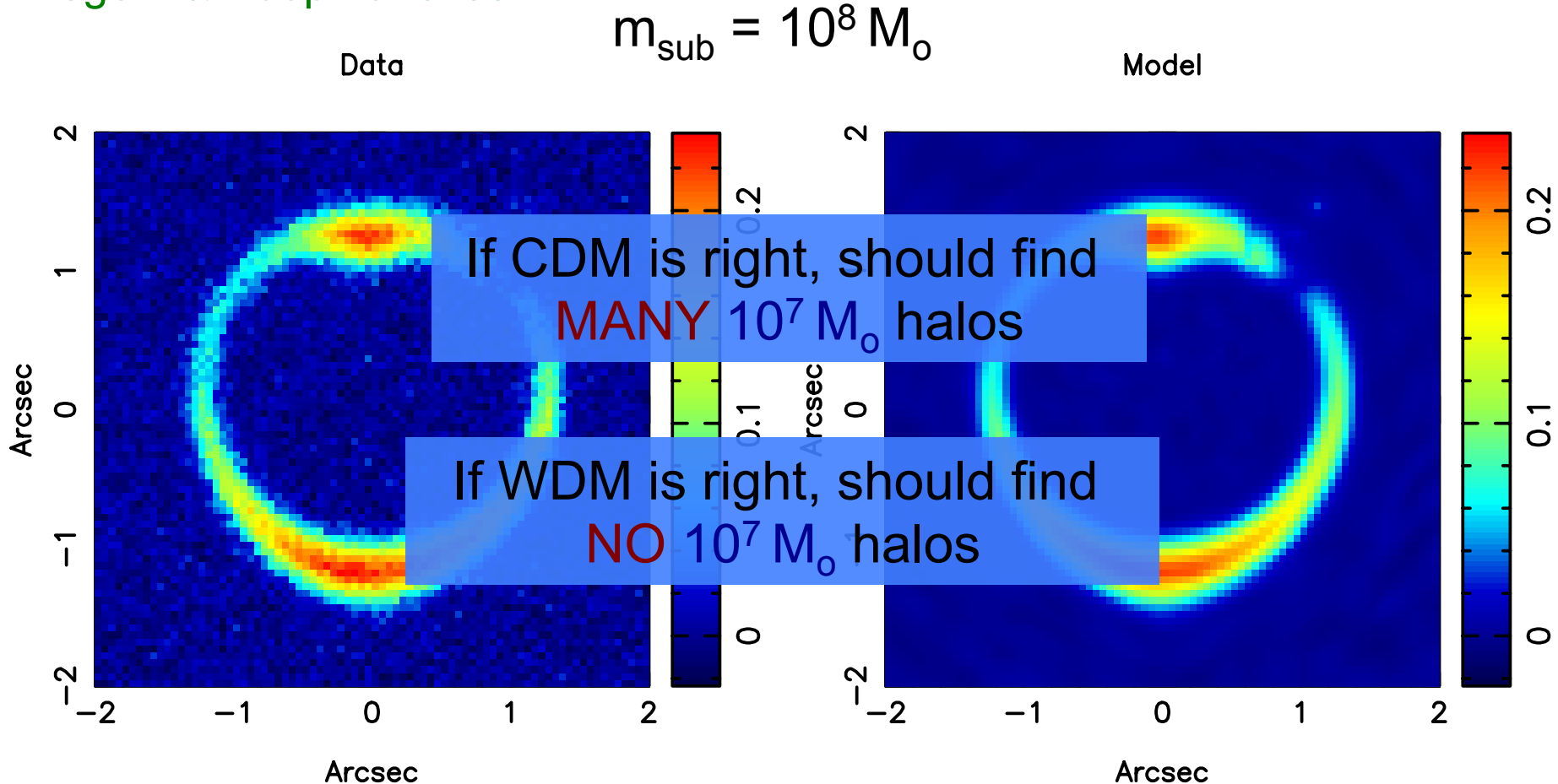
Halos projected onto an Einstein ring distort the image



Vegetti & Koopmans '09

Detecting substructures with strong lensing

Vegetti & Koopmans '09



Can detect subhalos as small as $10^7 M_{\odot}$

Gravitational lensing: Einstein rings

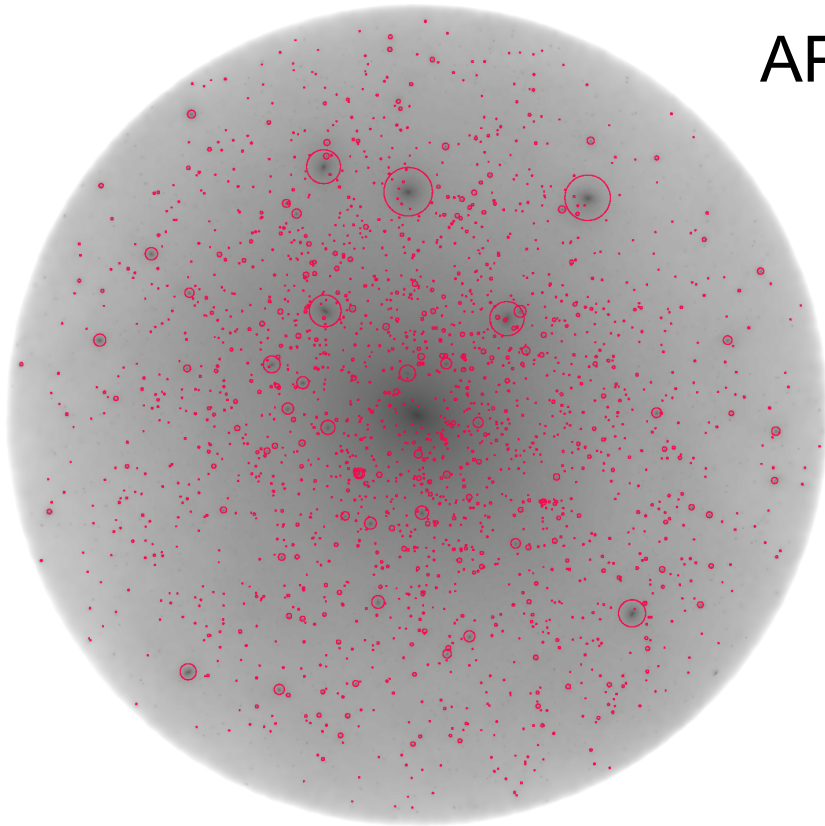
Two important considerations:

- The central galaxy can destroy subhalos
- Line-of-sight projected halos also lens

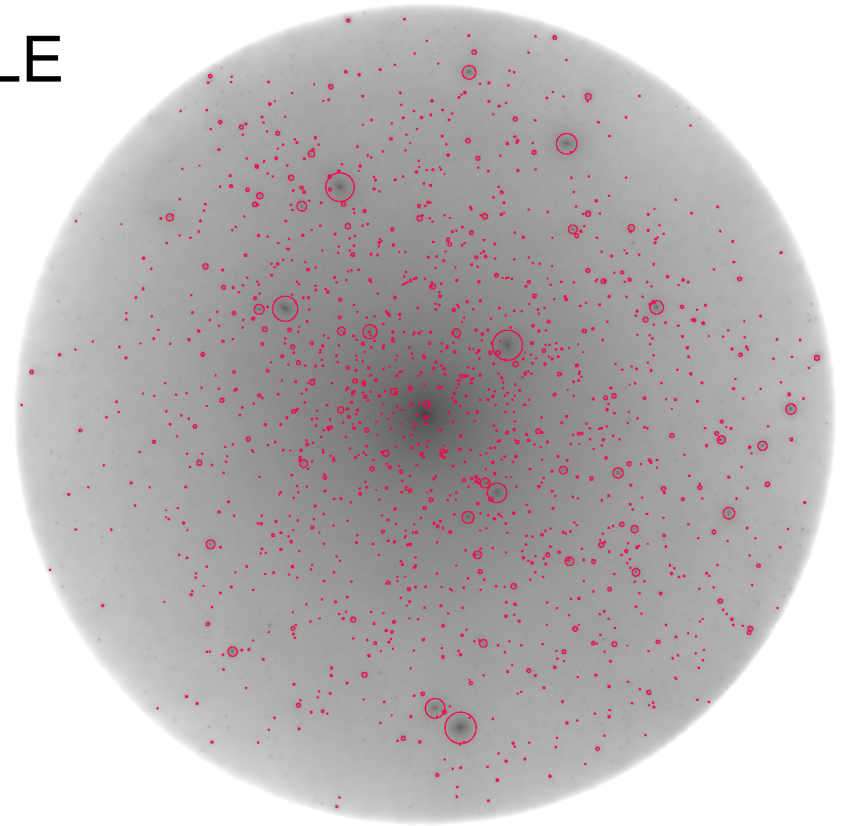


Destruction of dark substructures by galactic baryons

APOSTLE

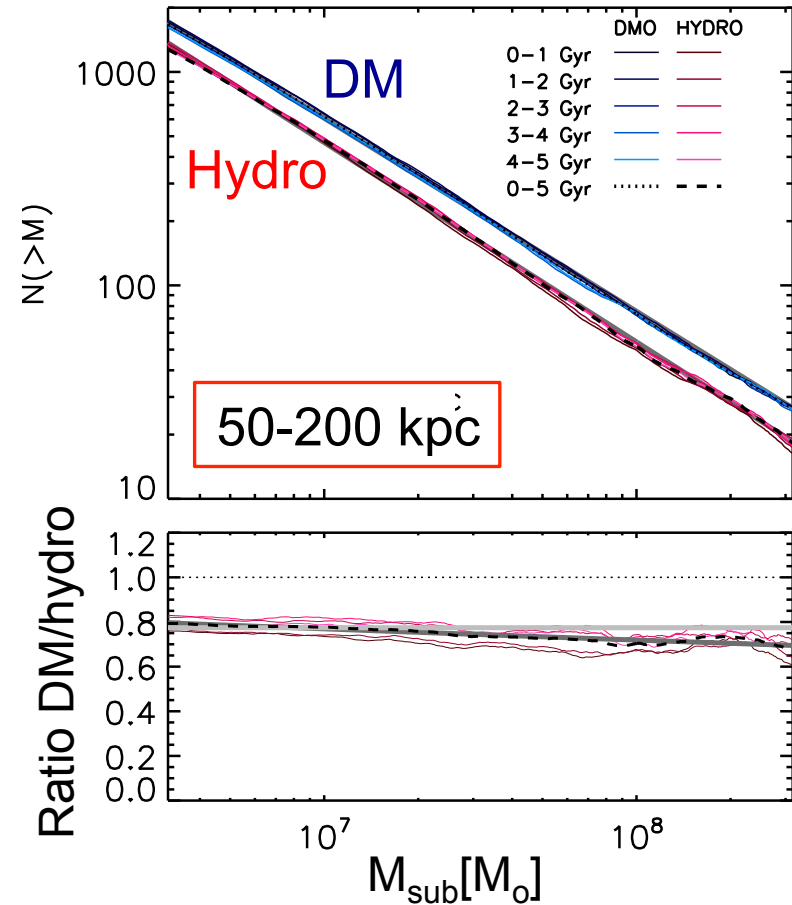
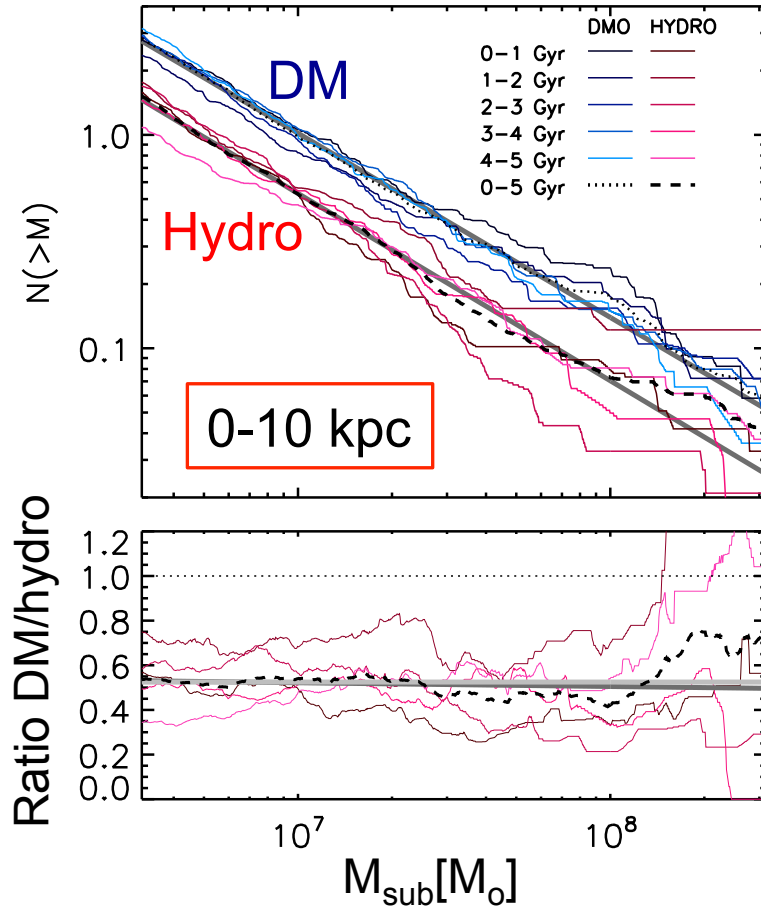


Dark matter only simulation



Hydrodynamic simulation

Destruction of dark substructures by galactic baryons

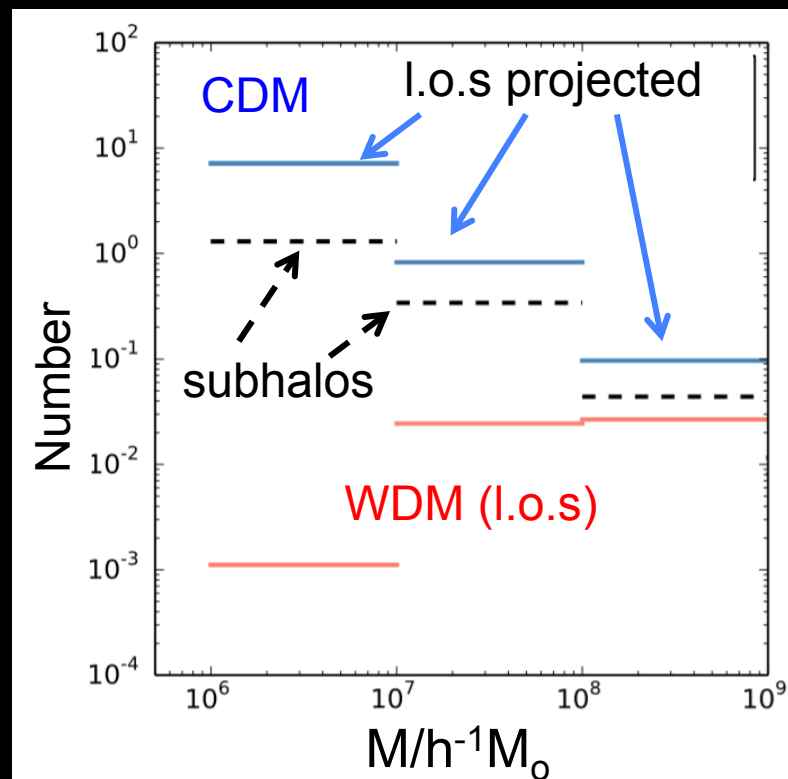
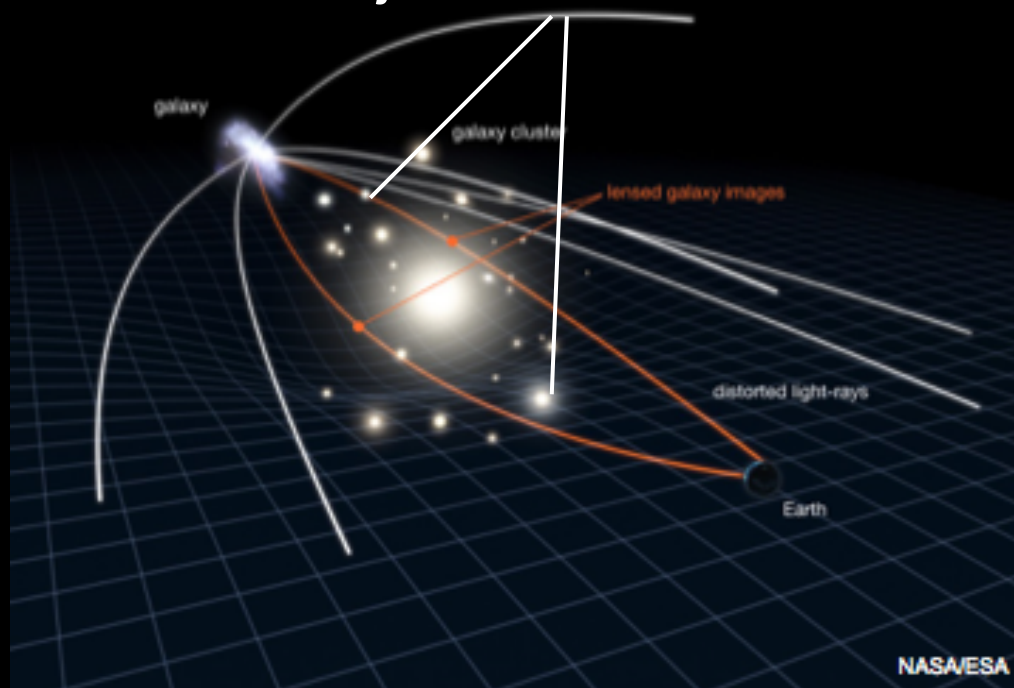


- 40% of subhalos in 0-10 kpc destroyed by interaction w. galaxy
 - 20% “ 50-200 kpc “
- Sawala et al '16

Substructures vs interlopers

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

Projected l.o.s halos



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

Two key considerations:

- The central galaxy can destroy subhalos
- Line-of-sight projected halos also lens

Answer:



- Central galaxy destroys $\sim 40\%$ of halos within Einstein ring (Sawala et al. '16)
- Projected halos **dominate** the strong lensing signal (Li et al '16)

The subhalo mass function

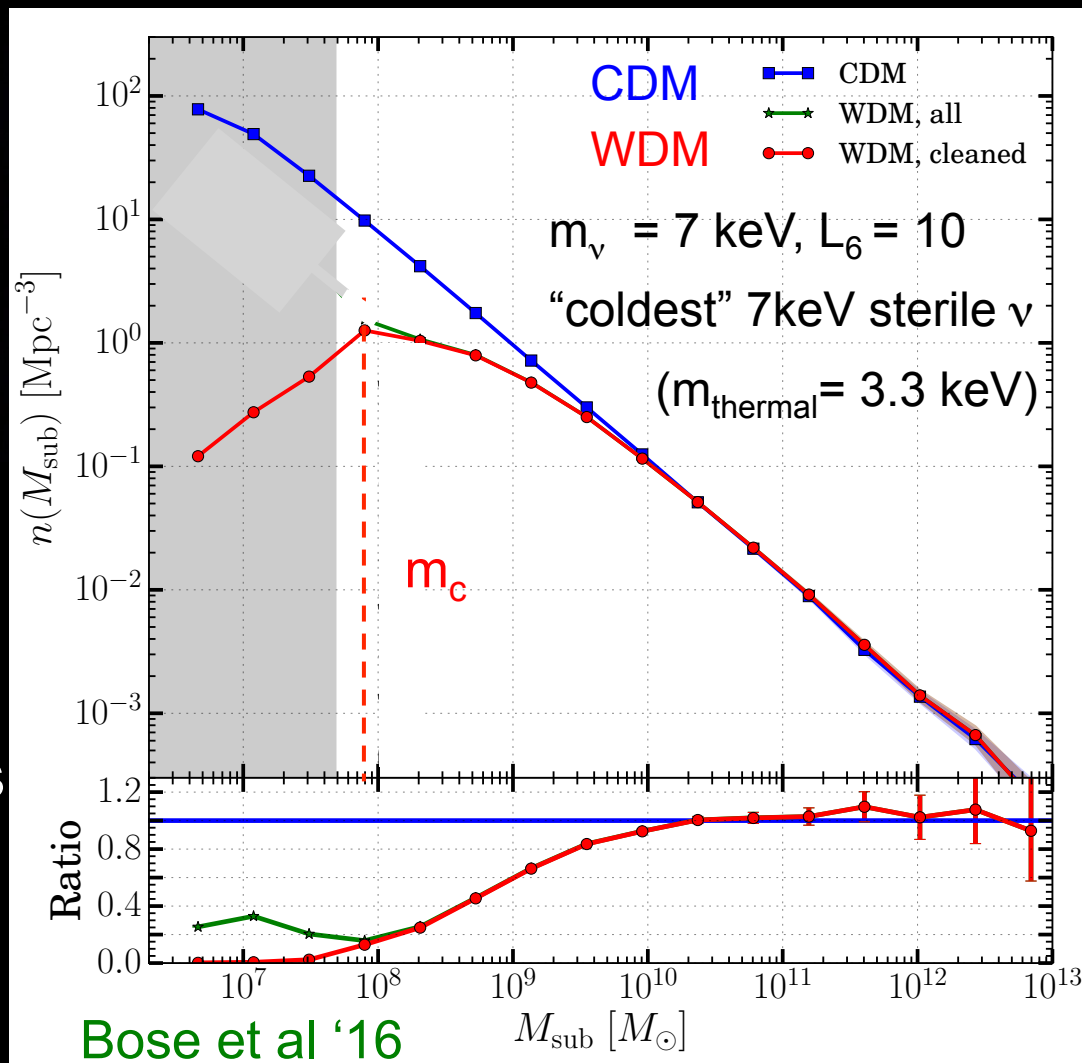


CDM

WDM

Already fewer WDM subhalos
at $3 \times 10^9 M_\odot$

10 x fewer at $10^8 M_\odot$



Detecting substructures with strong lensing

Σ_{tot} = projected halo number density within Einstein ring

m_c = halo cutoff mass

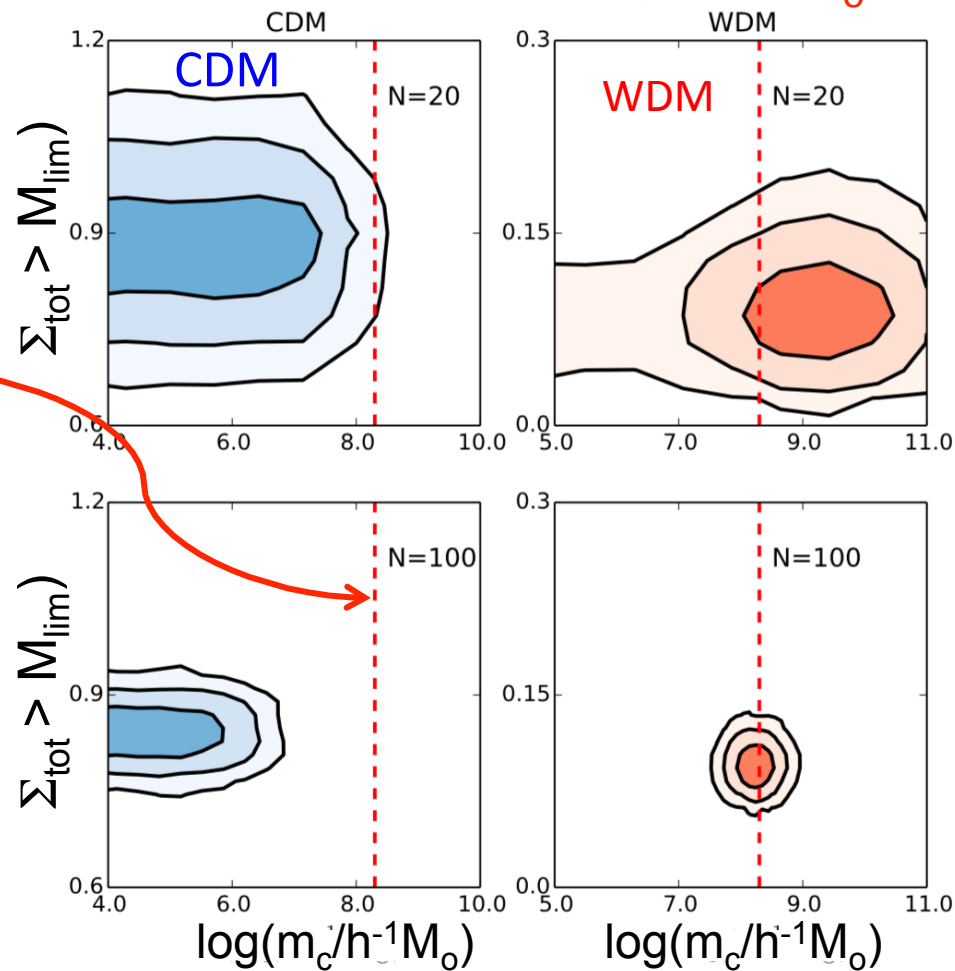
$m_c = 1.3 \times 10^8 h^{-1} M_\odot$ for coldest 7 keV sterile neutrino

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

- If DM is CDM $\rightarrow$ rule out 7 keV sterile ν at many σ
- If DM is 7 keV sterile $\nu \rightarrow$ rule out CDM at 3σ !

Li, CSF et al '16

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





Strong
gravitational
lensing could rule
out CDM within
the next few
years!!!





Conclusions

- Λ CDM: great **success** on scales $> 1\text{Mpc}$: CMB, LSS, gal evolution
- But on these scales **Λ 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. Presence of cores debatable, but irrelevant for DM
4. Strong gravitational lensing can distinguish CDM/WDM
(and could rule out CDM!)