The cold dark matter model

University of Durham

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Institute for Computational Cosmology,
Durham University

The new Ogden Centre at Durham

The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter

- *Ab initio,* fully specified model of cosmic evolution and the formation of cosmic structure
- Based on known laws of Physics (GR) which were formulated and tested independently of the ΛCDM model
- Has strong predictive power
- Has made a number of **pre**dictions that were subsequently verified empirically (e.g. CMB, LSS, galaxy formation)

Non-baryonic dark matter cosmologies

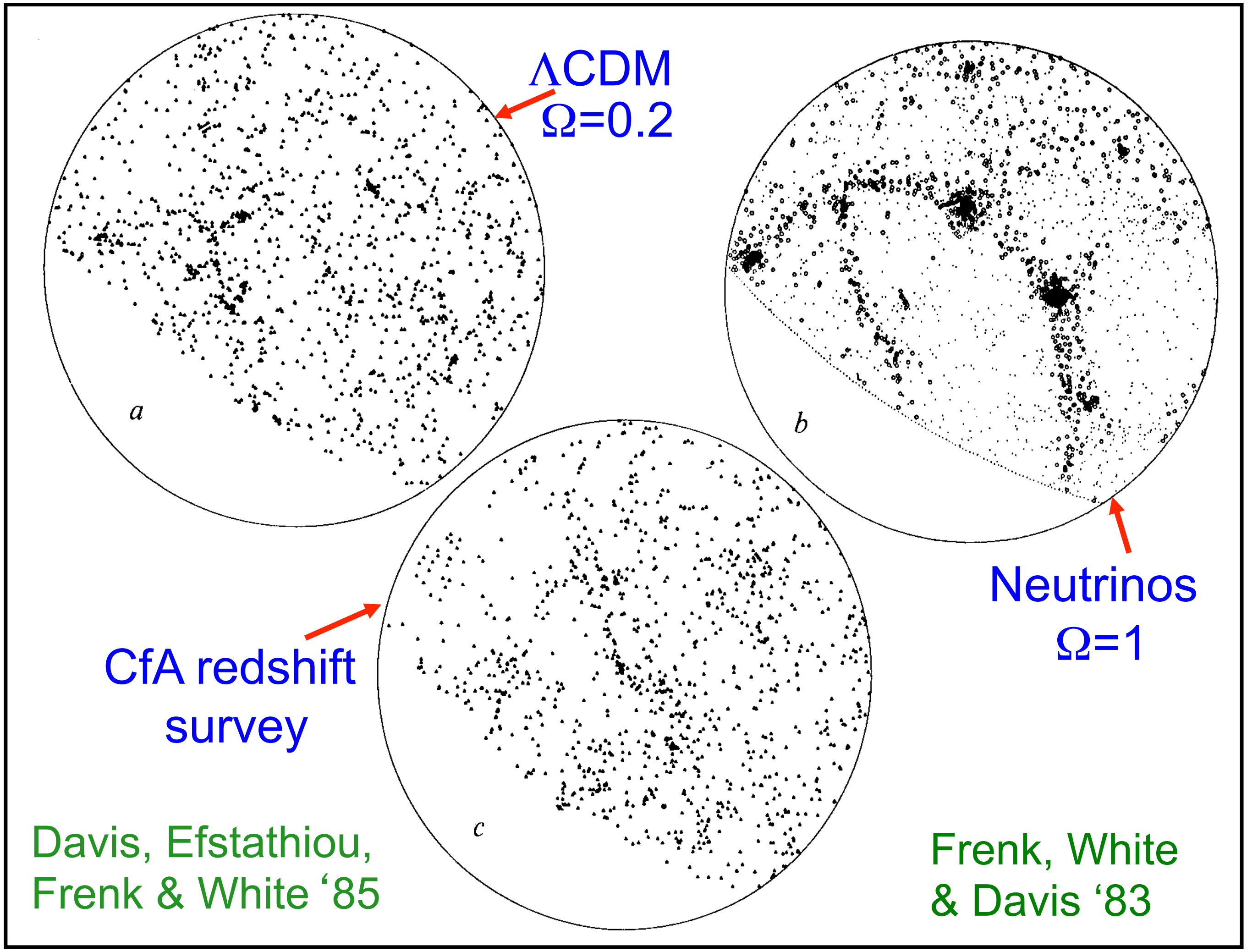
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

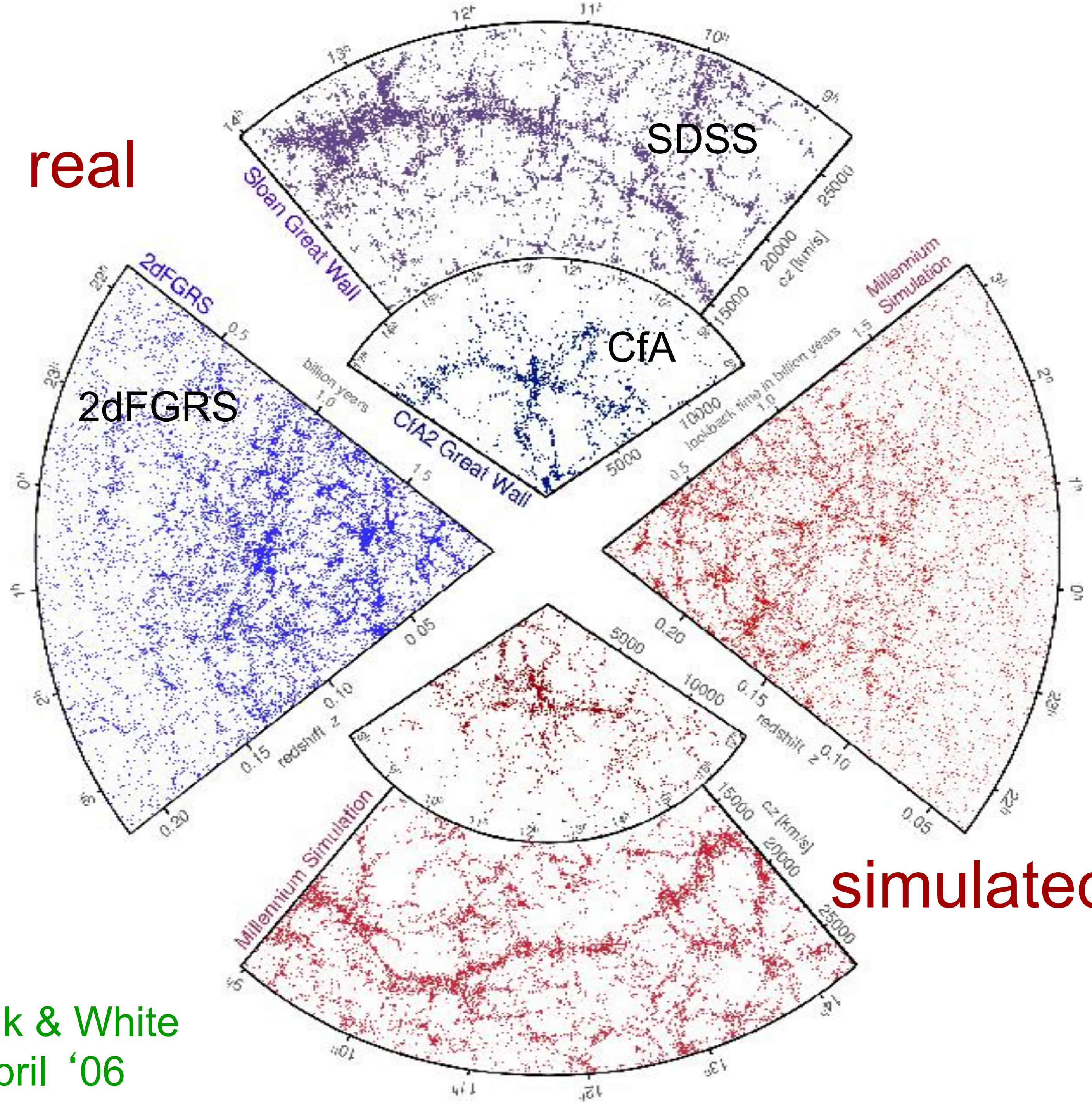
→ m_ν<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically

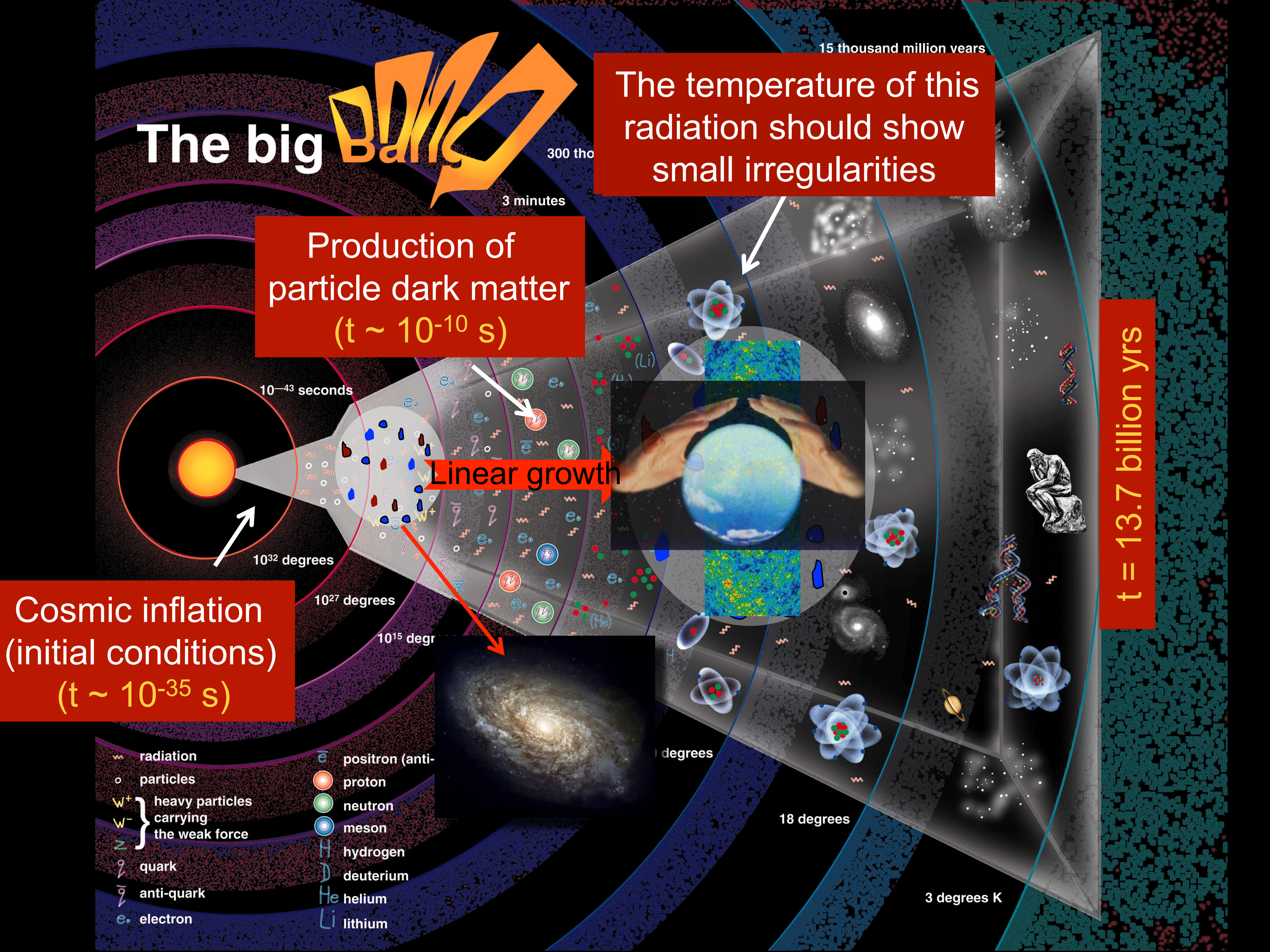


real



simulated

Springel, Frenk & White
Nature, April ‘06



The big Bang
15 thousand million years
The temperature of this radiation should show small irregularities
300 tho
3 minutes
Production of particle dark matter (t ~ 10^-10 s)
10^-43 seconds
Linear growth
t = 13.7 billion yrs
10^32 degrees
10^27 degrees
10^15 degr
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

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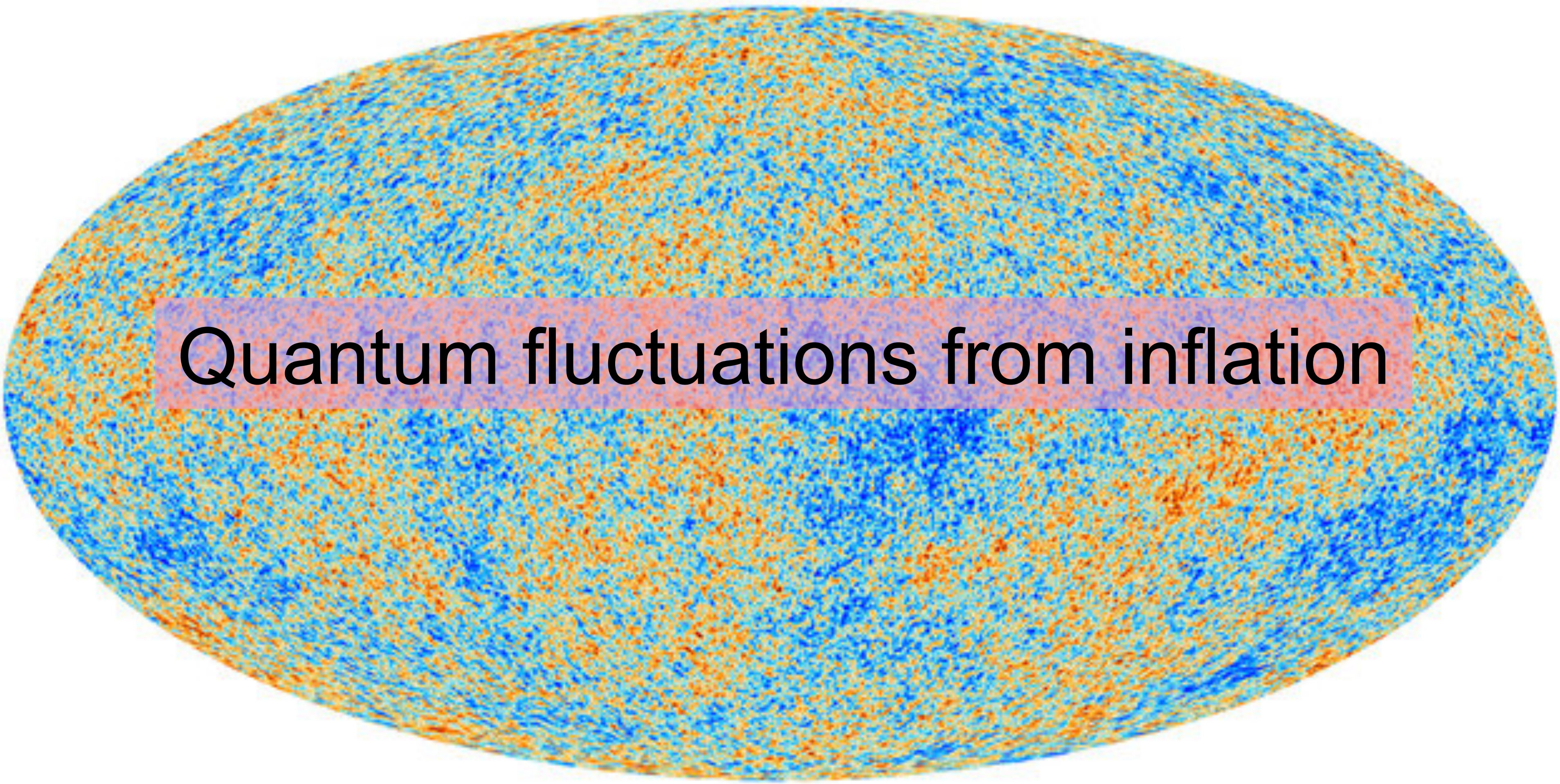
The initial conditions for galaxy formation



Planck collaboration '13

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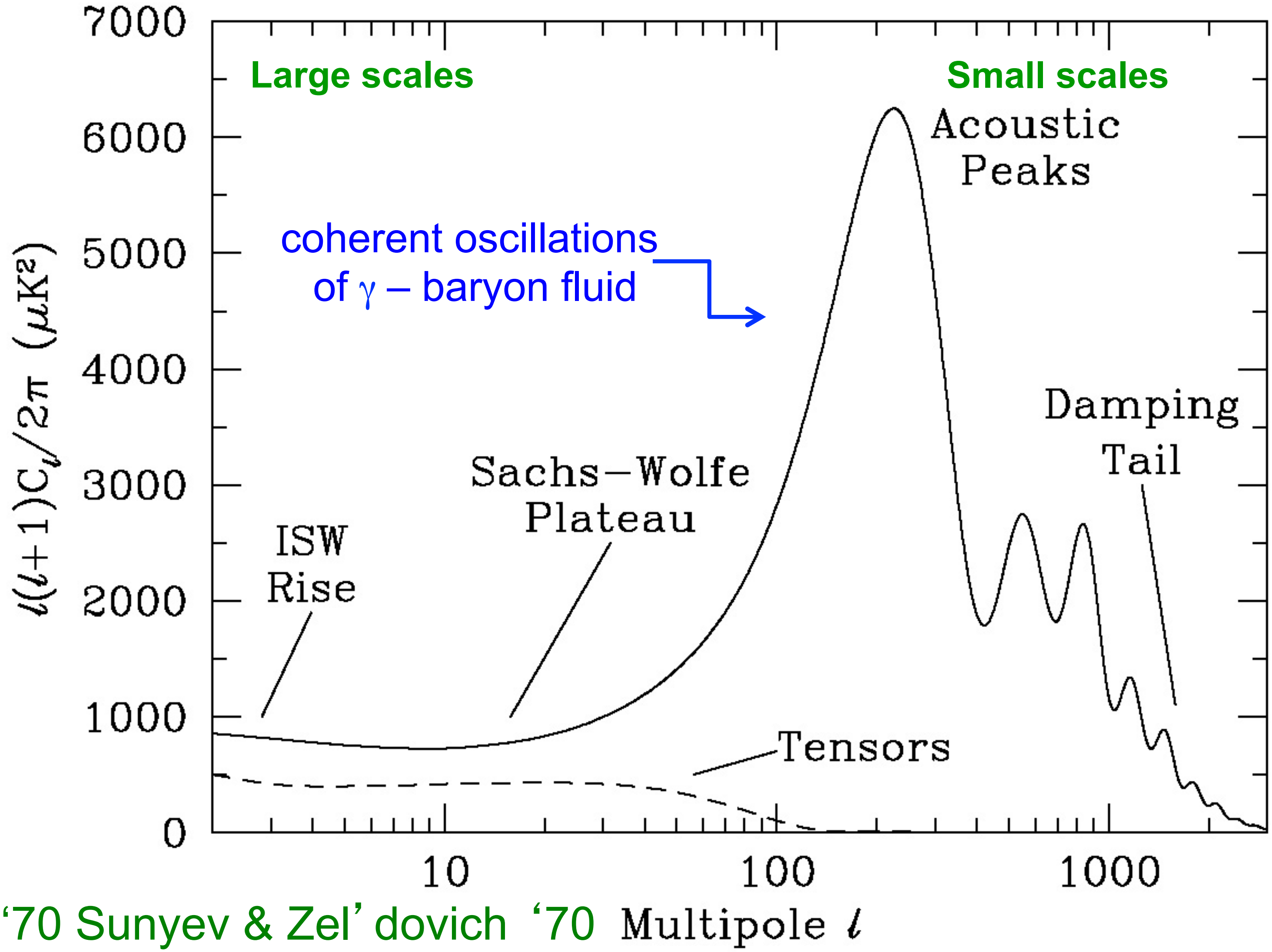
Temperature anisotropies in CMB

2D power spectrum



Peebles & Yu '70 Sunyev & Zel'dovich '70

For CDM: Peebles '82; Bond & Efstathiou '84

Planck: CMB temperature anisotropies

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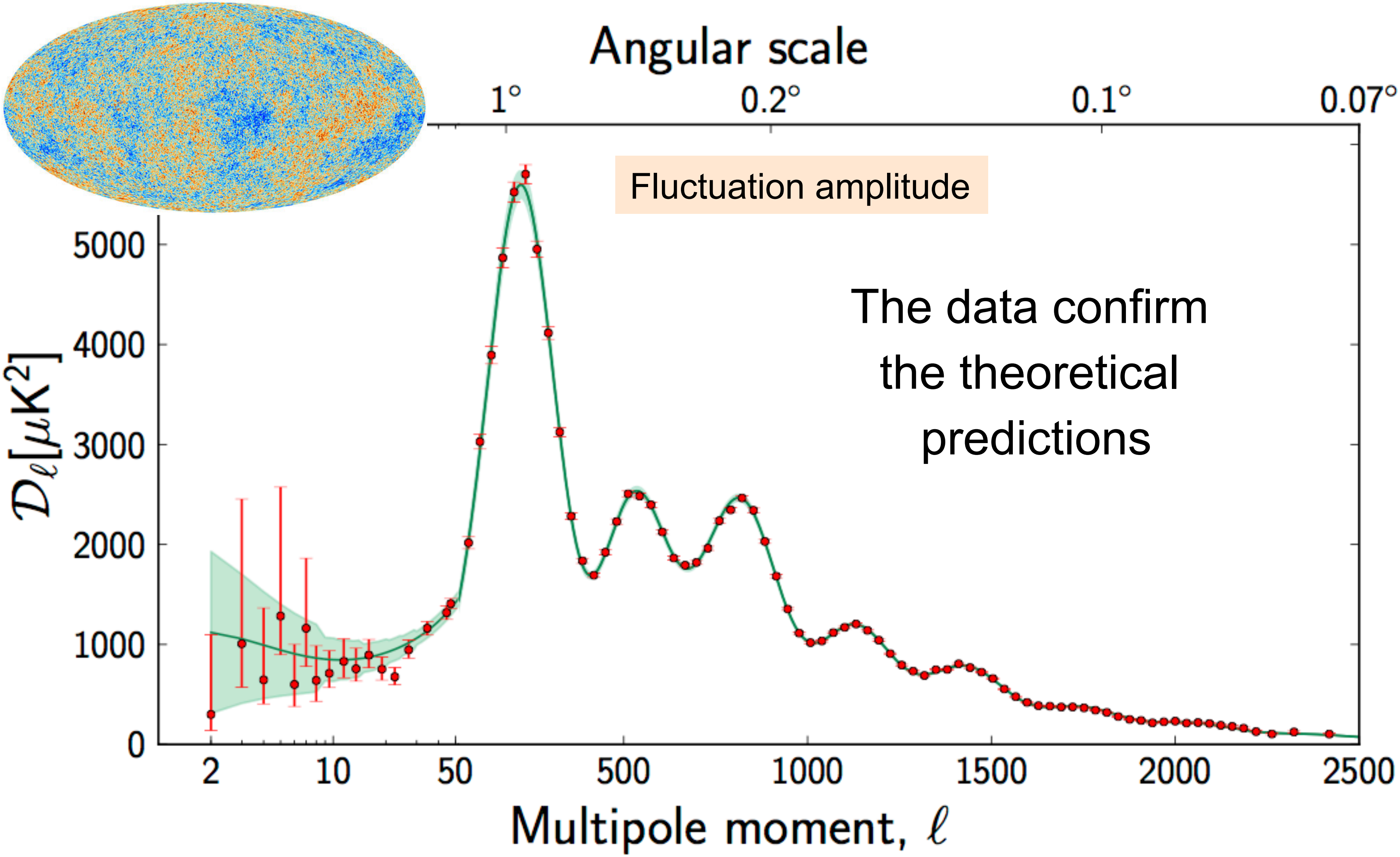

Planck coll. 2015

Institute for Computational Cosmology

Univer

The six parameters of minimal ΛCDM model

6 model 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

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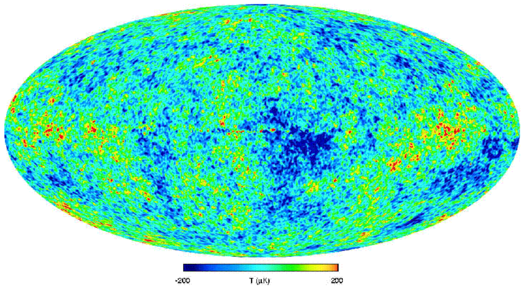
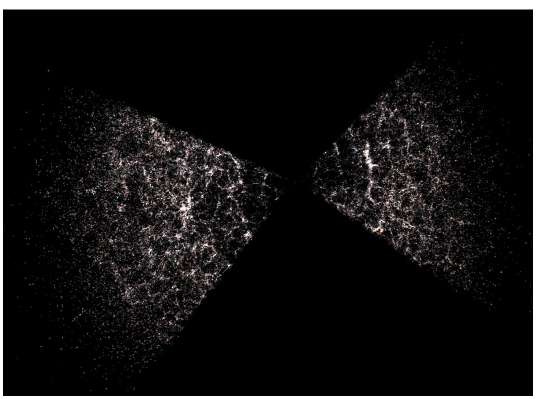
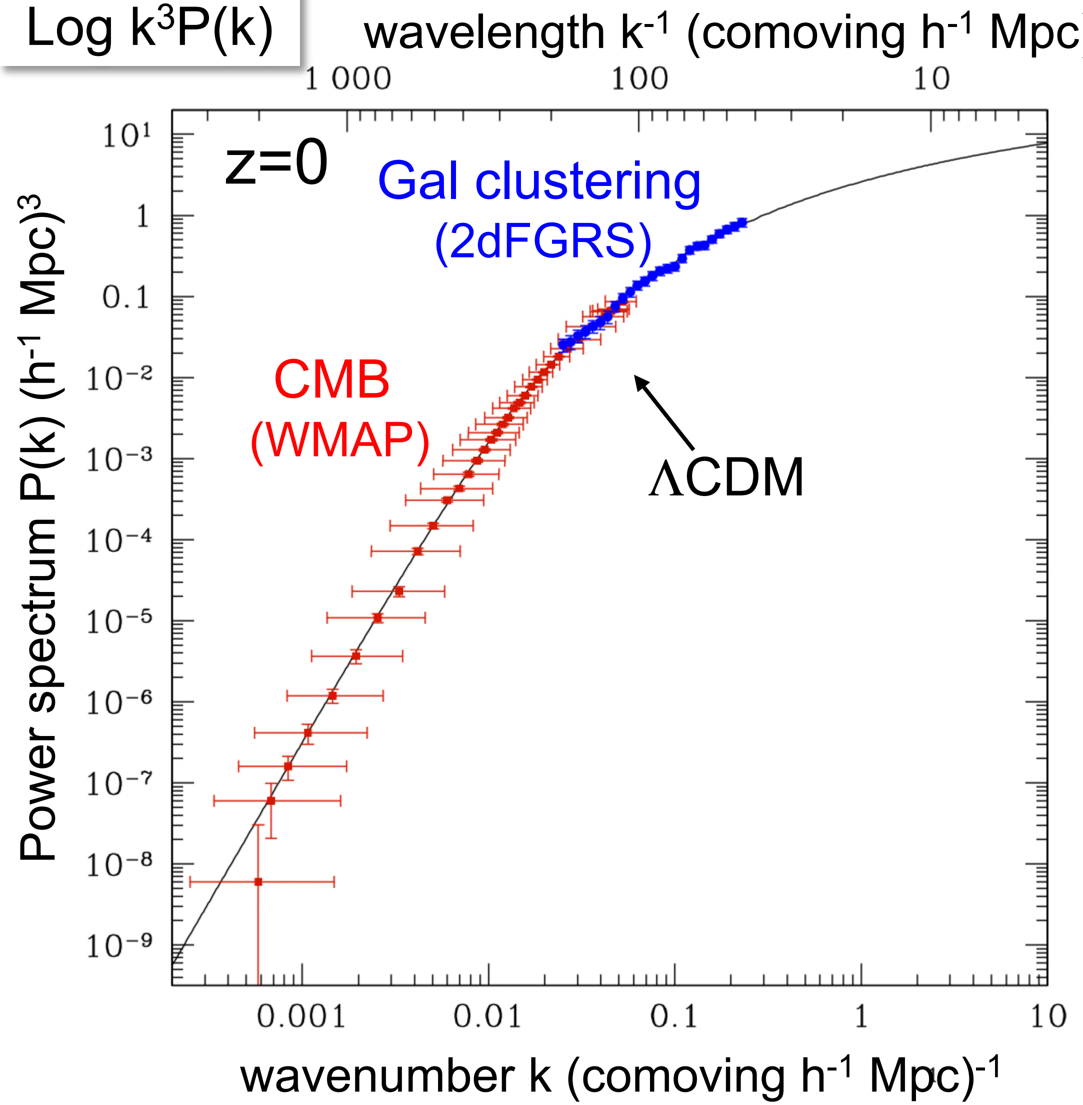


z~1000



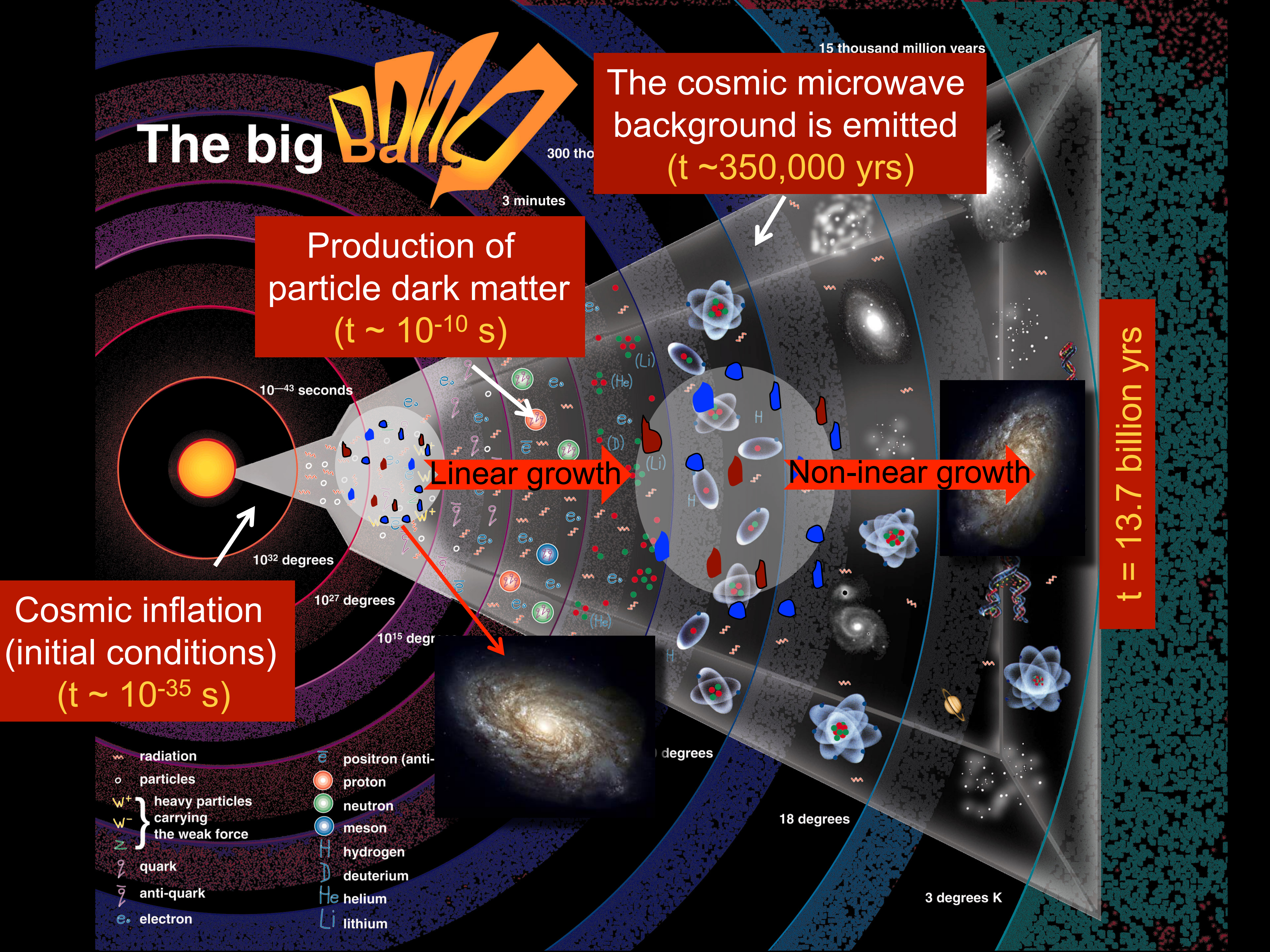
z~0

Log $k^3P(k)$



$\Rightarrow$ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06



The big Bang
15 thousand million years
The cosmic microwave background is emitted (t ~350,000 yrs)
300 tho
3 minutes
Production of particle dark matter (t ~ 10-10 s)
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Linear growth
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t = 13.7 billion yrs
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particles
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anti-quark
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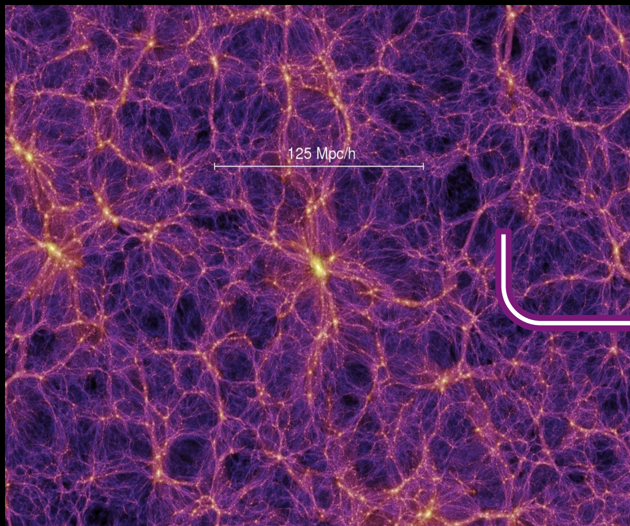
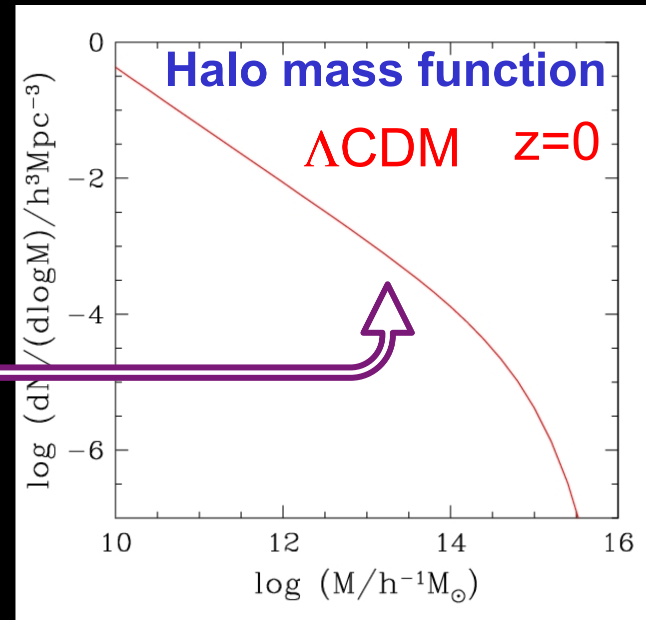
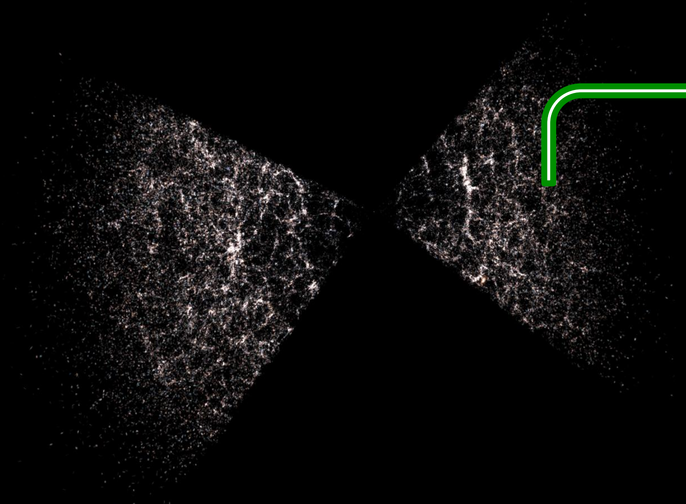
lithium

Abundance of gals & dark halos

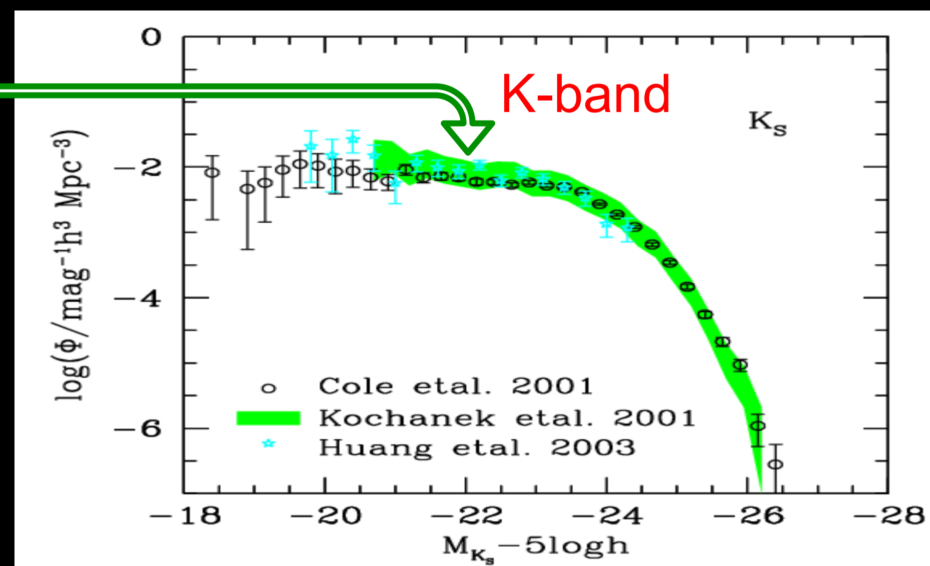


Millennium simulation





2dFGRS



The galaxy luminosity function

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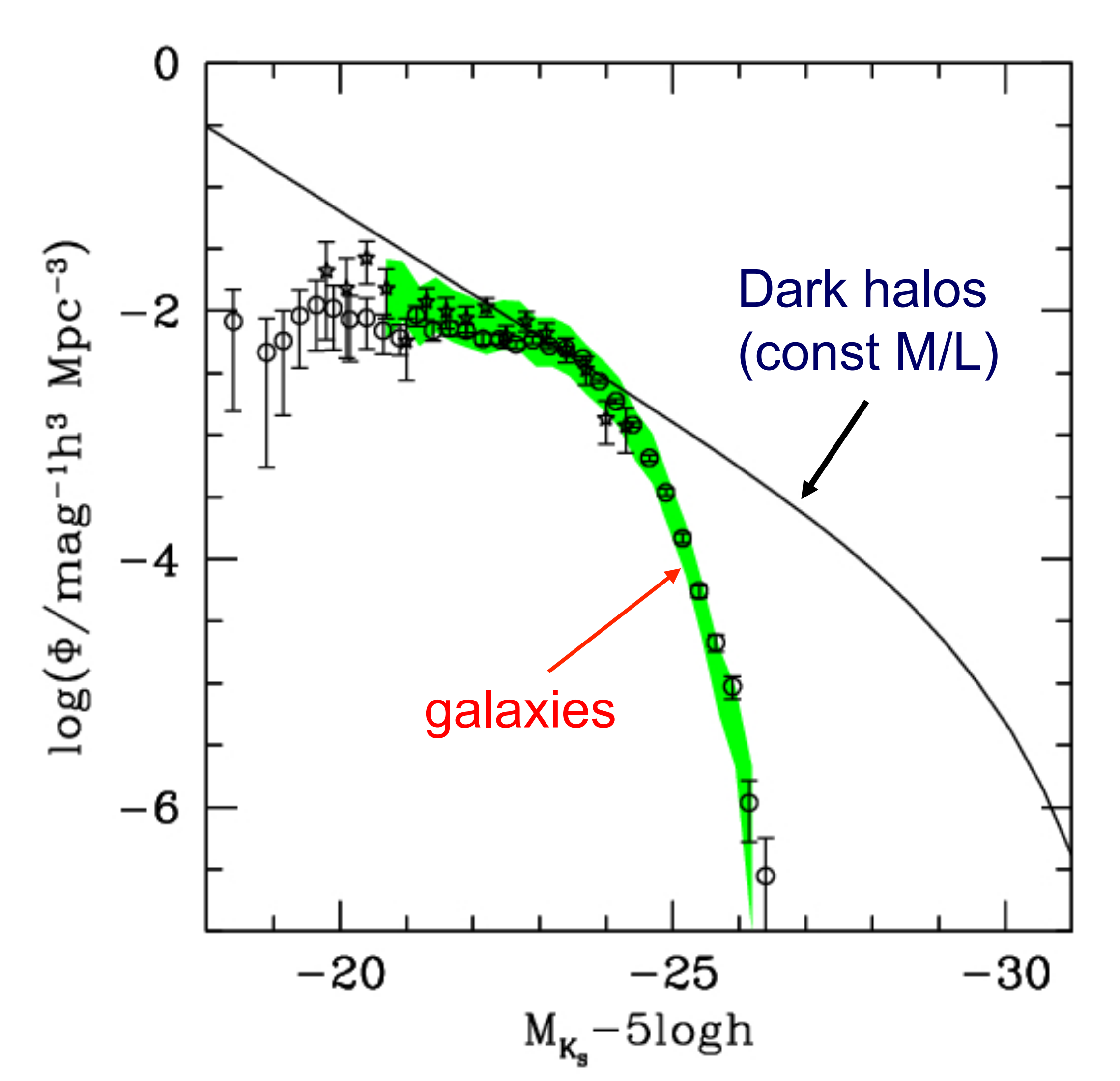
The halo mass function and the galaxy luminosity function have different shapes

⇨

Complicated variation of M/L with halo mass



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

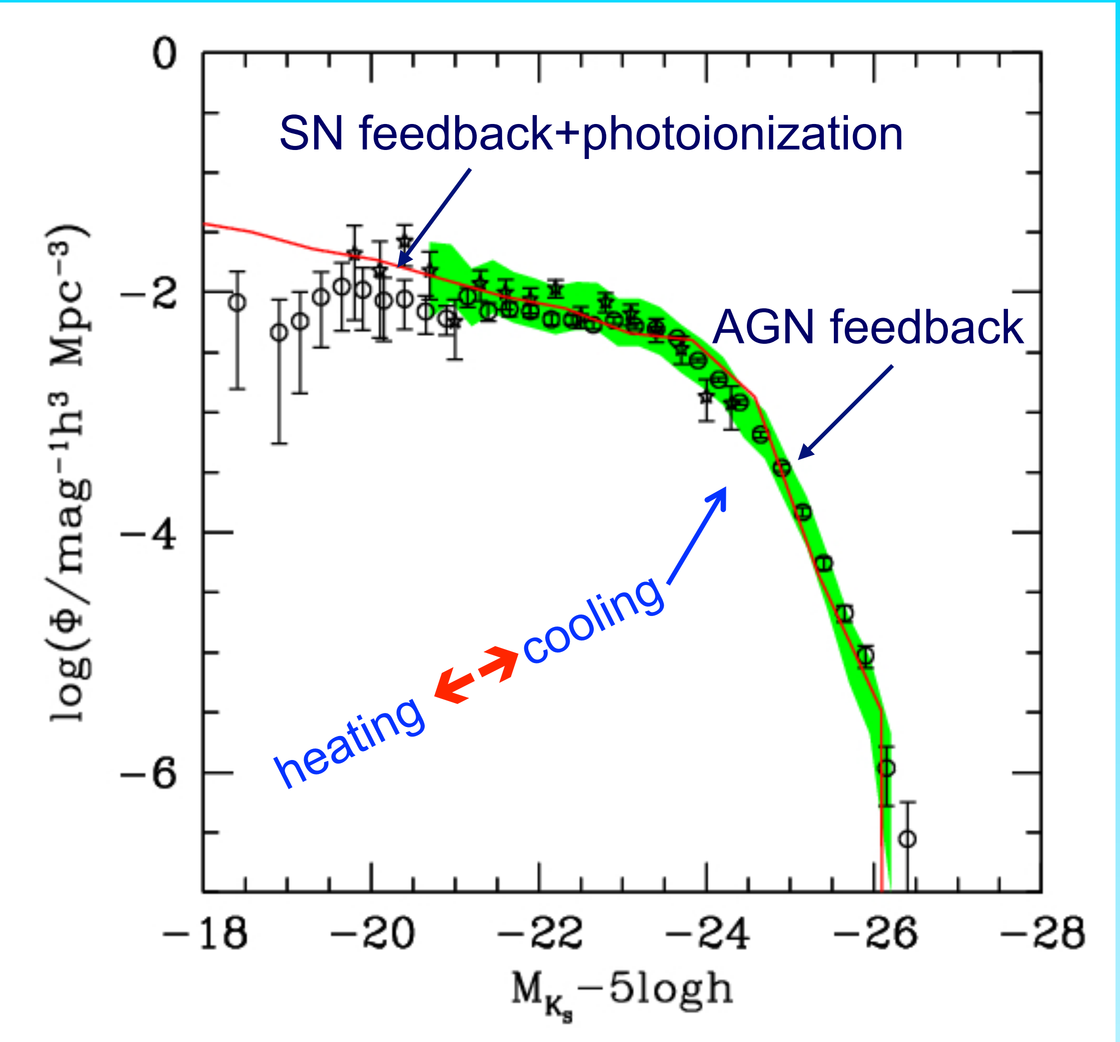
Deconstructing the galaxy LF

Faint end:

Photoionization + reheating of cold disk gas by SN

Bright end:

AGN feedback: energy transported by bubbles



Croton et al '06, Bower et al '06

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…

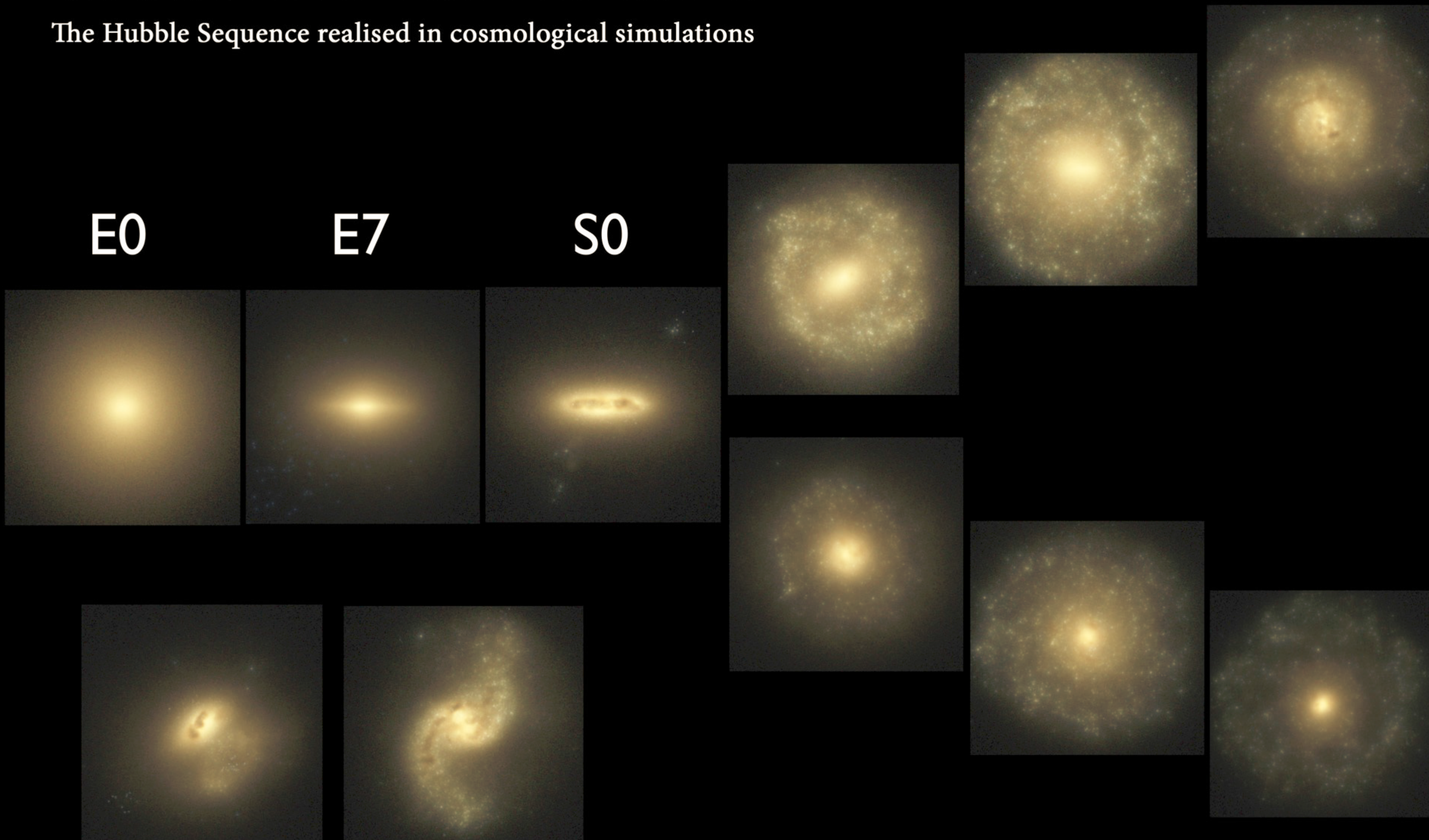
Durham University VIRGO ICC DiRAC PRACE

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

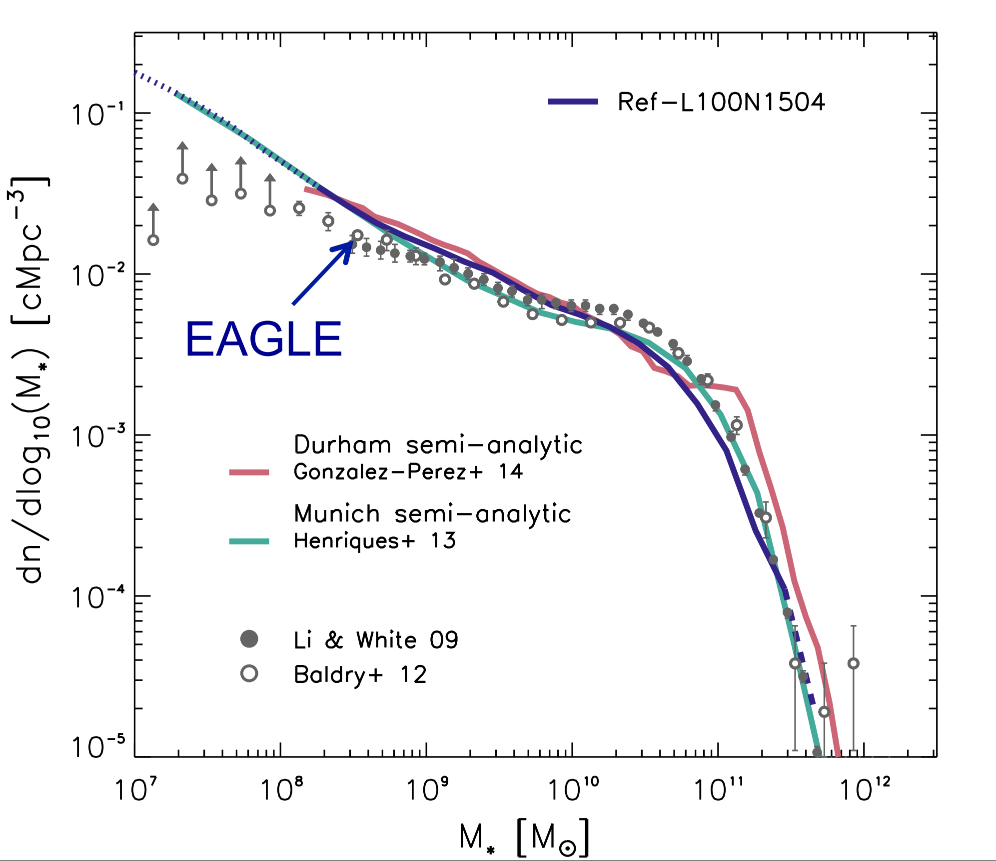


Trayford et al ‘15

Galaxy stellar mass function

ΛCDM gives an excellent match to the galaxy stellar mass function

Comparison to semi-analytic models



Schaye et al ‘15

The CDM small-scale “crisis”

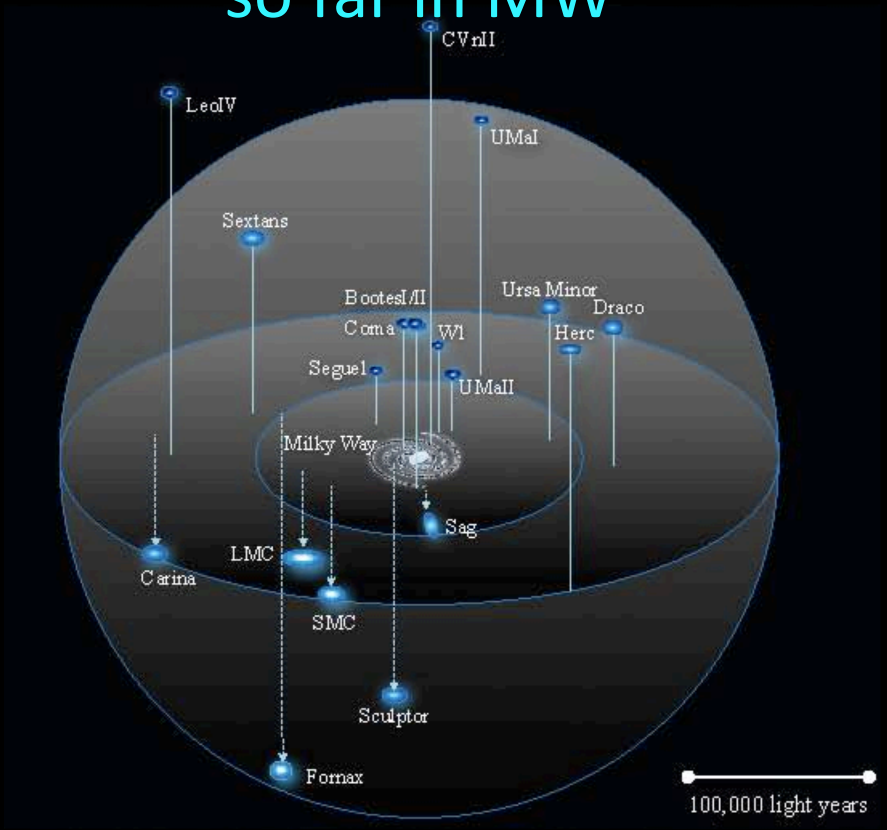
Three “problems:”

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

The satellites of the Milky Way

cold dark matter

~50 satellites discovered so far in MW



Most subhalos never make a galaxy!

Because:

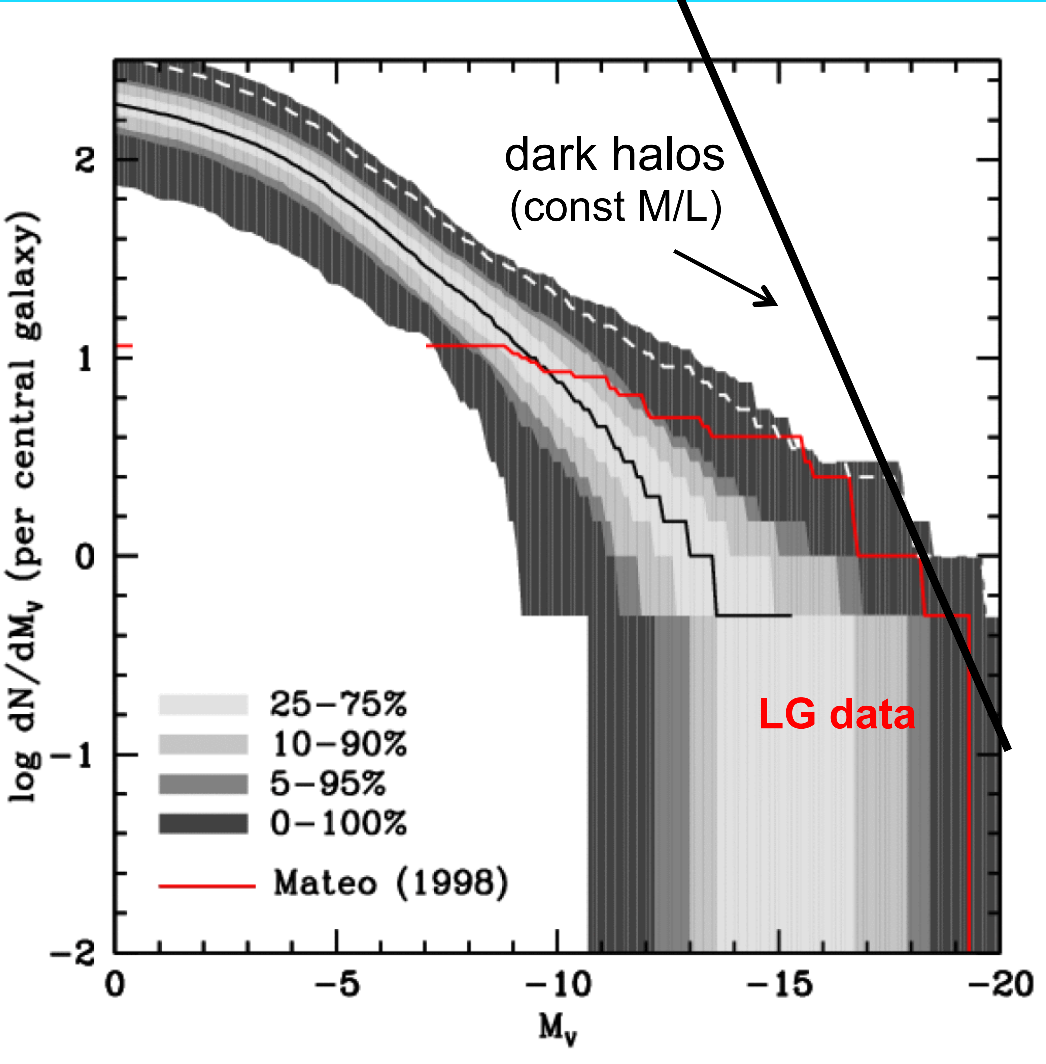
- Reionization heats gas to 10^4K, preventing it from cooling and forming stars in small halos ($T_{vir} < 10^4$K)
- Supernovae feedback expels residual gas in slightly larger halos

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+ '93, Bullock+ '00, Somerville '02)

Luminosity Function of Local Group Satellites

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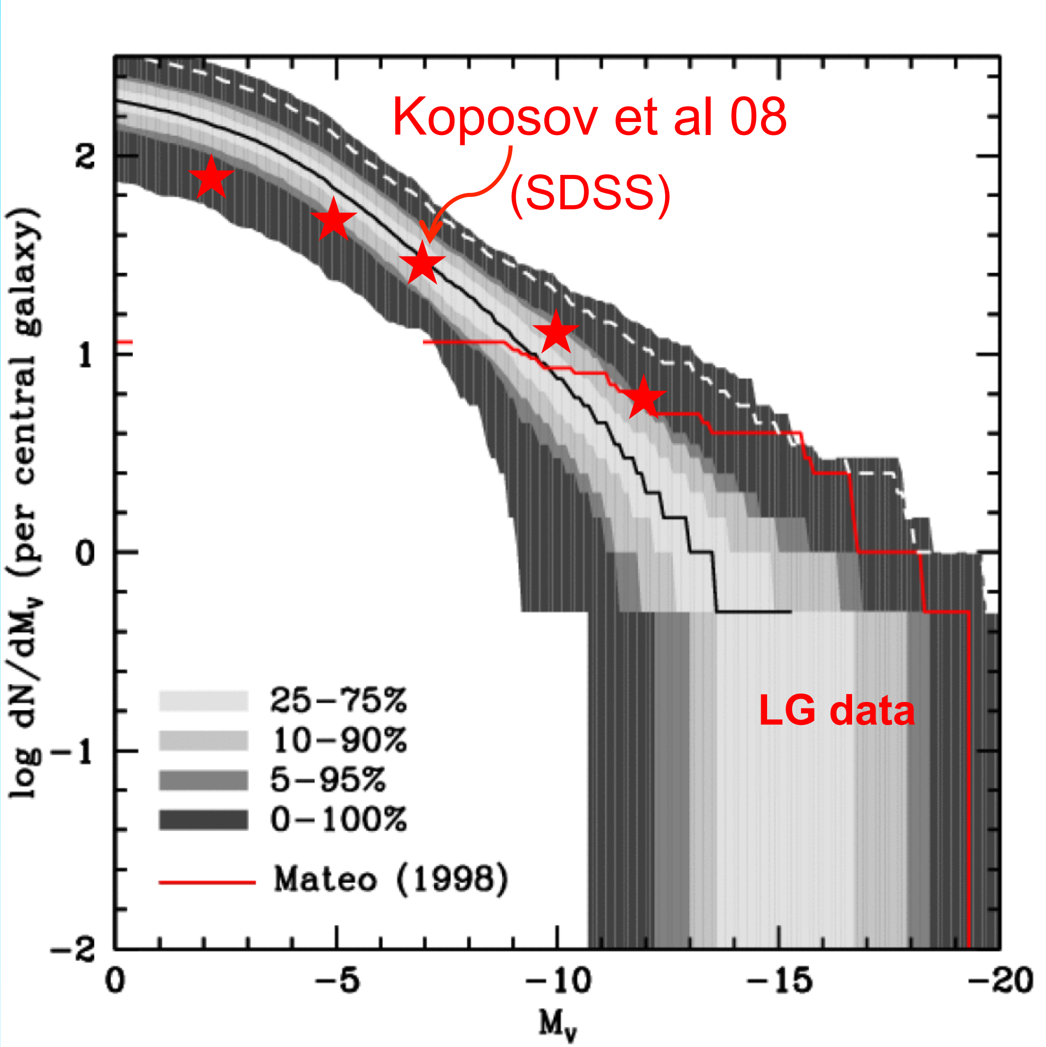

Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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THE ASTROPHYSICAL JOURNAL, 524:L19–L22, 1999 October 10

DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS

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Received 1999 April 16; accepted 1999 August 2; published 1999 September 13

ABSTRACT

We use numerical simulations to examine the substructure within galactic and cluster mass halos that form within a hierarchical universe. Clusters are easily reproduced with a steep mass spectrum of thousands of substructure clumps that closely matches the observations. However, the survival of dark matter substructure also

2131 citations

University of Durham

THE ASTROPHYSICAL JOURNAL, 539:517–521, 2000 August 20

637 citations

REIONIZATION AND THE ABUNDANCE OF GALACTIC SATELLITES

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Department of Astronomy, The Ohio State University, 140 W. 18th Avenue, Columbus, OH 43210-1173; james@astronomy.ohio-state.edu, andrey@astronomy.ohio-state.edu, dhw@astronomy.ohio-state.edu
Received 2000 February 9; accepted 2000 March 24

Mon. Not. R. Astron. Soc. **333,** 177–190 (2002)

The effects of photoionization on galaxy formation – II. Satellite galaxies in the Local Group

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[1]*California Institute of Technology, MC 105-24, Pasadena, CA 91125, USA*
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Accepted 2002 February 2. Received 2002 January 30; in original form 2001 August 13

282 citations

ABSTRACT
We use a self-consistent model of galaxy formation and the evolution of the intergalactic medium to study the effects of the reionization of the Universe at high redshift on the

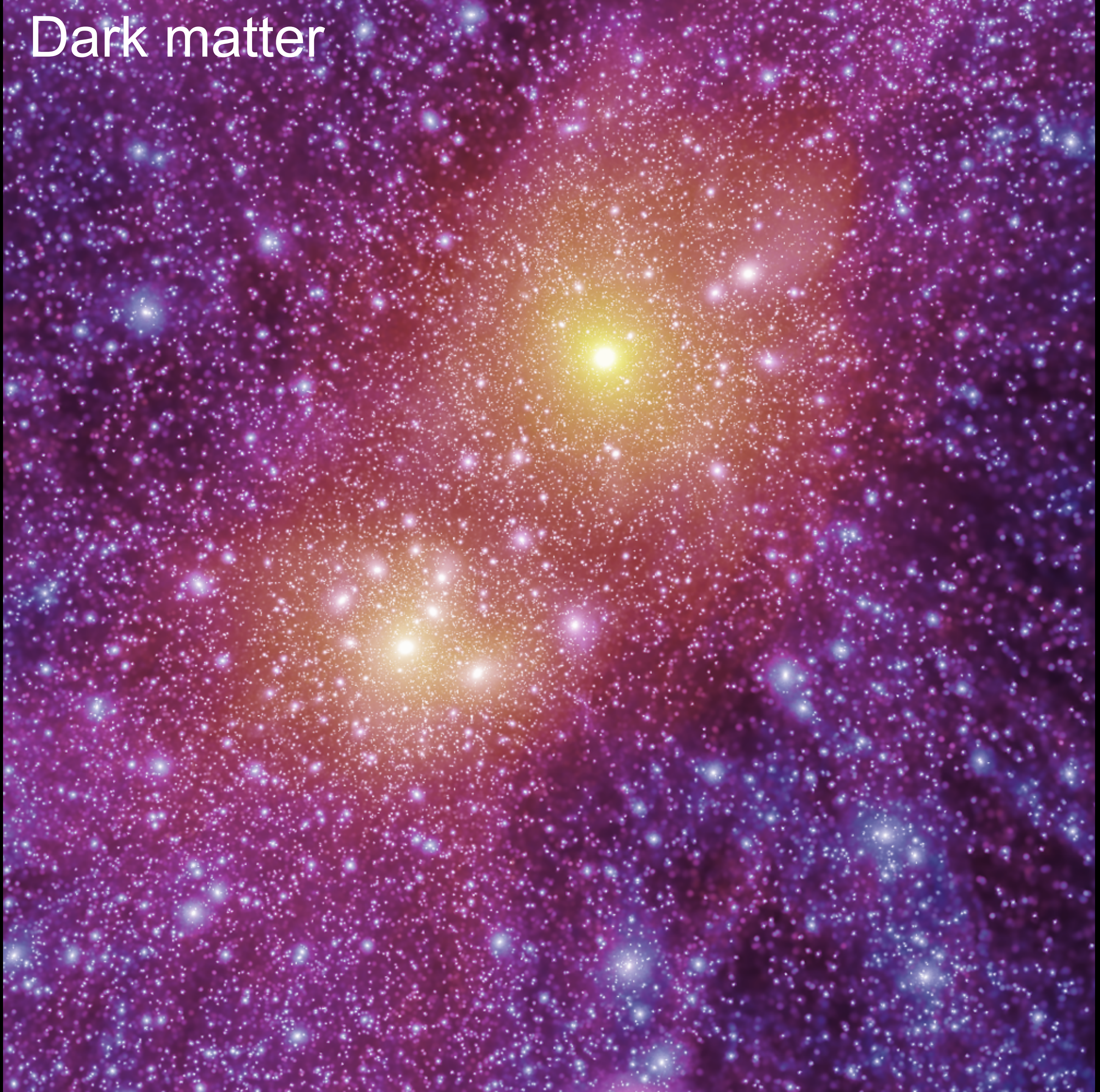
VIRGO

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

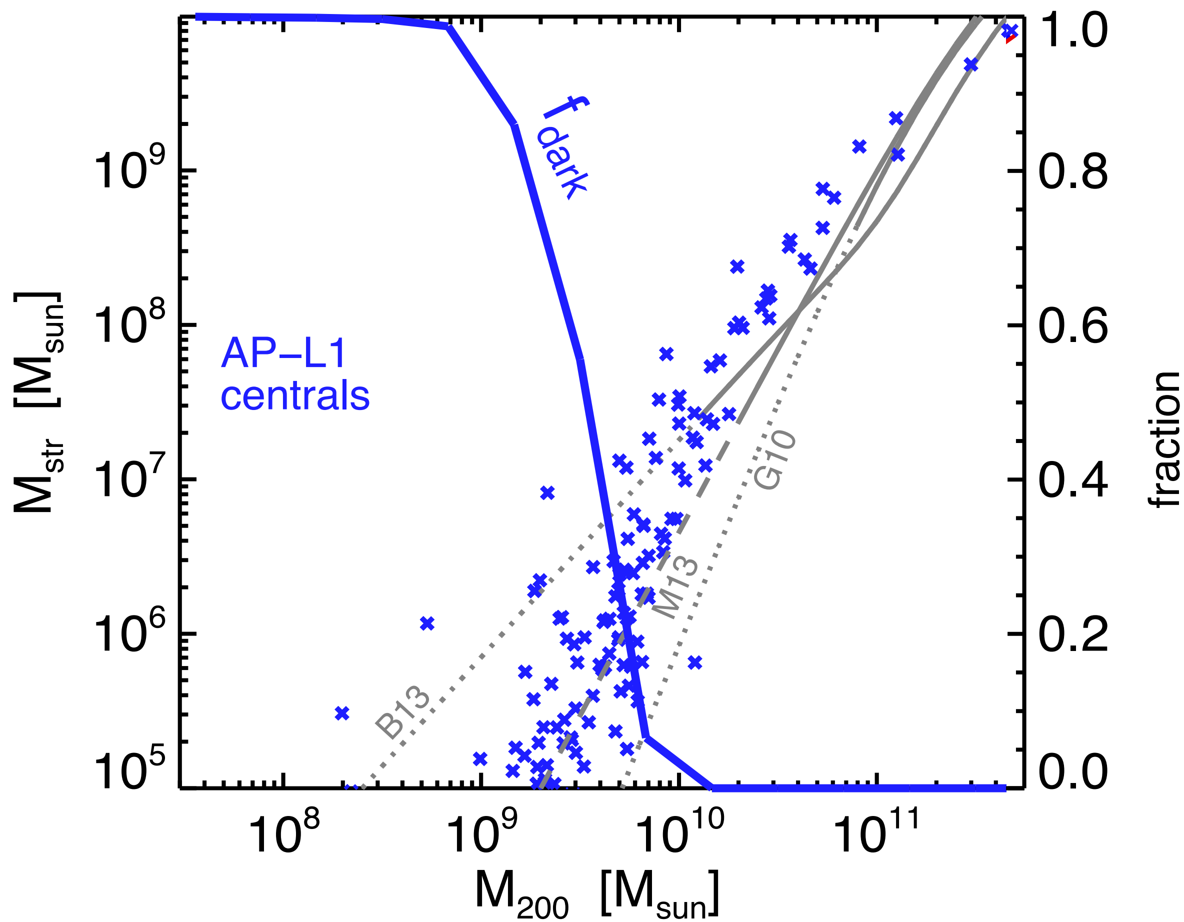
Sawala et al ‘16

University of Durham

Fraction of dark subhalos

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

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



All halos of mass < $5\times10^8 M_o$ or V_{max} < 7 km/s are dark ($m_* < 10^4 M_o$)

Fattahi et al '16

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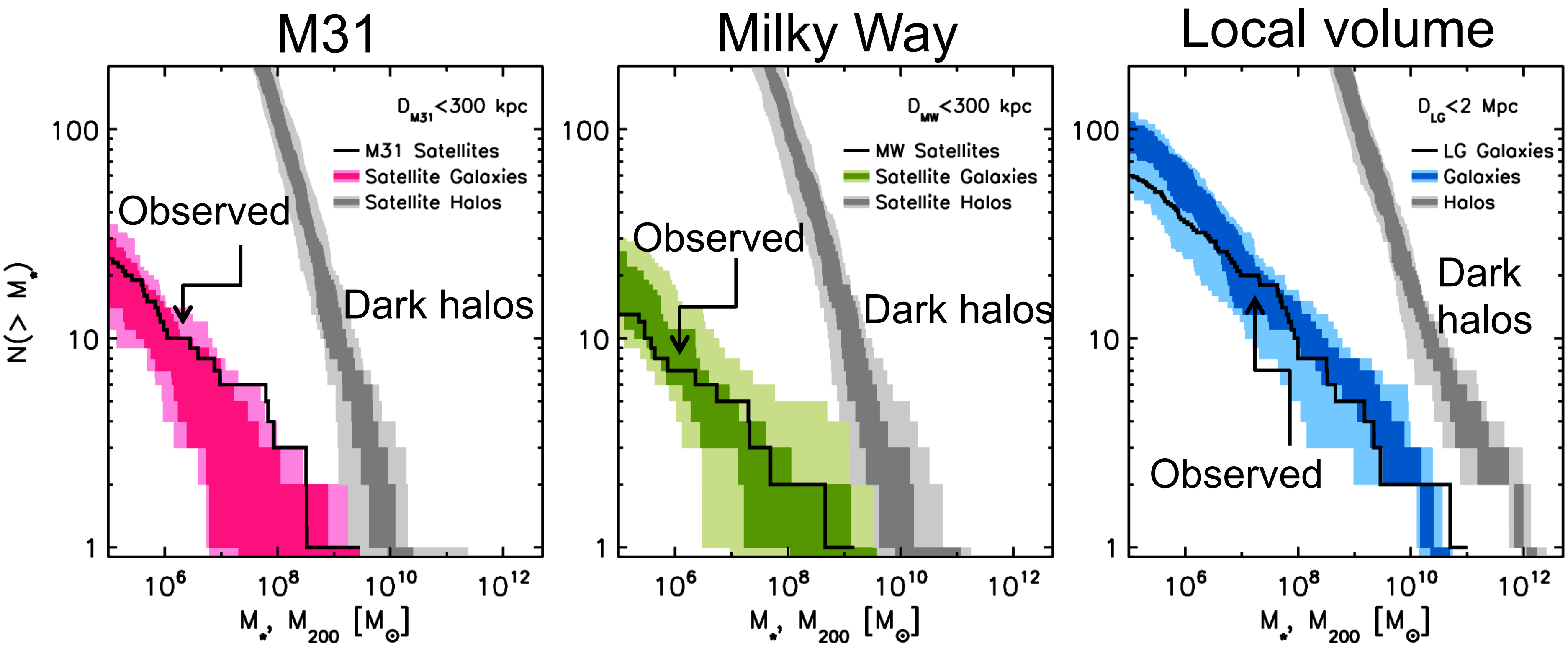
EAGLE Local Group simulation

University of Durham



Sawala, CSF et al '16

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When "baryon effects" are taken into account

→

Observed abundance of satellites is compatible with CDM

→

There is no such thing as the "satellite problem" in CDM!

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The CDM small-scale "crisis"

Three "problems:"

1. ~~The "missing satellites" problem~~
2. The "too-big-to-fail" problem
3. The "core-cusp" problem

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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?

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

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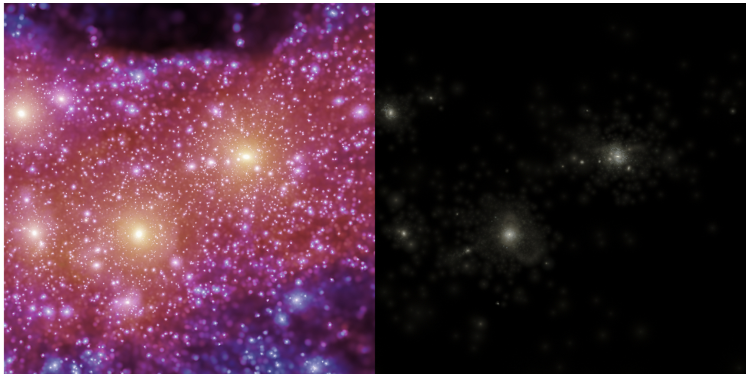
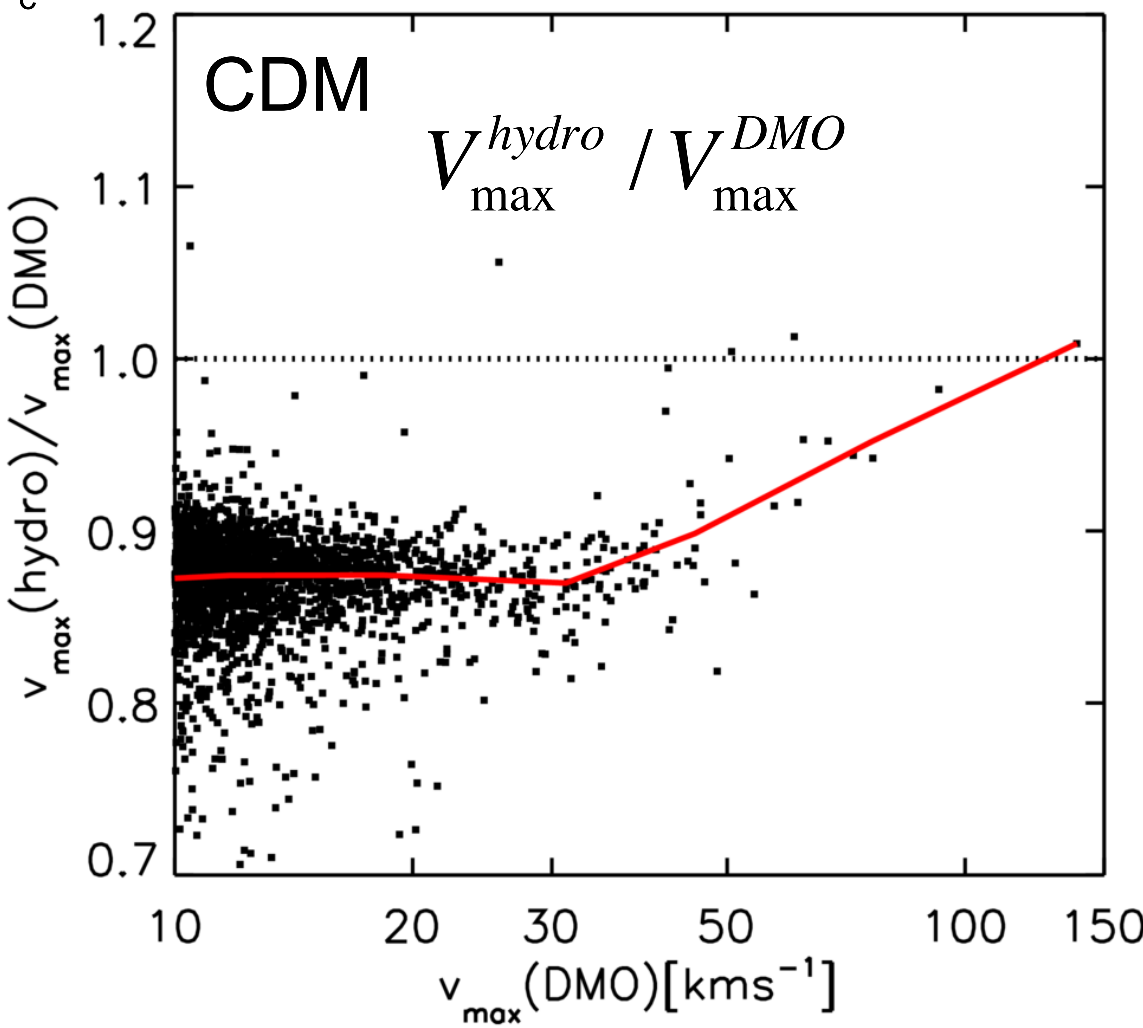
$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala et al. '13, '15

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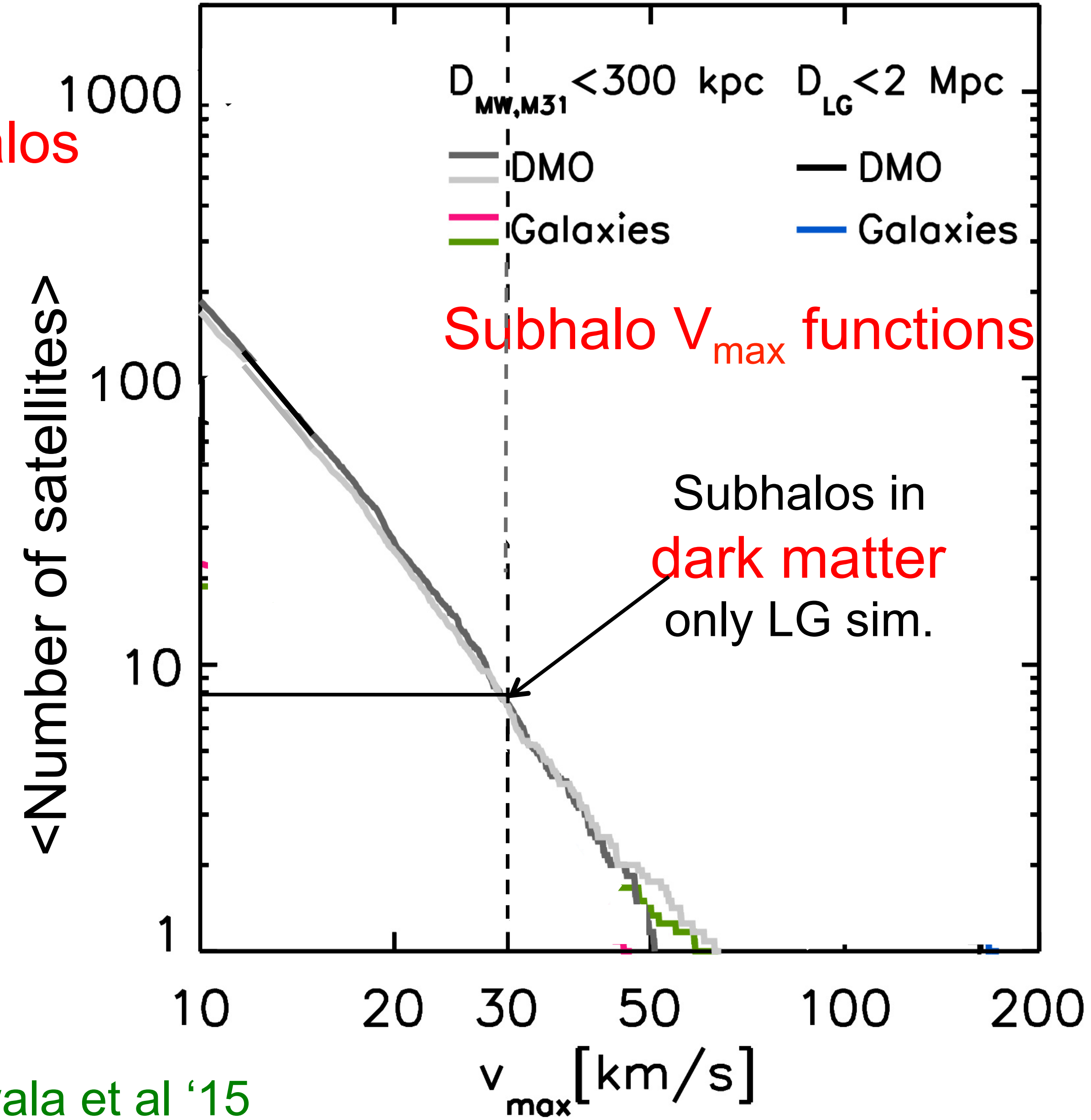
Too-big-to-fail: the baryon bailout

University of Durham

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



Sawala et al '15

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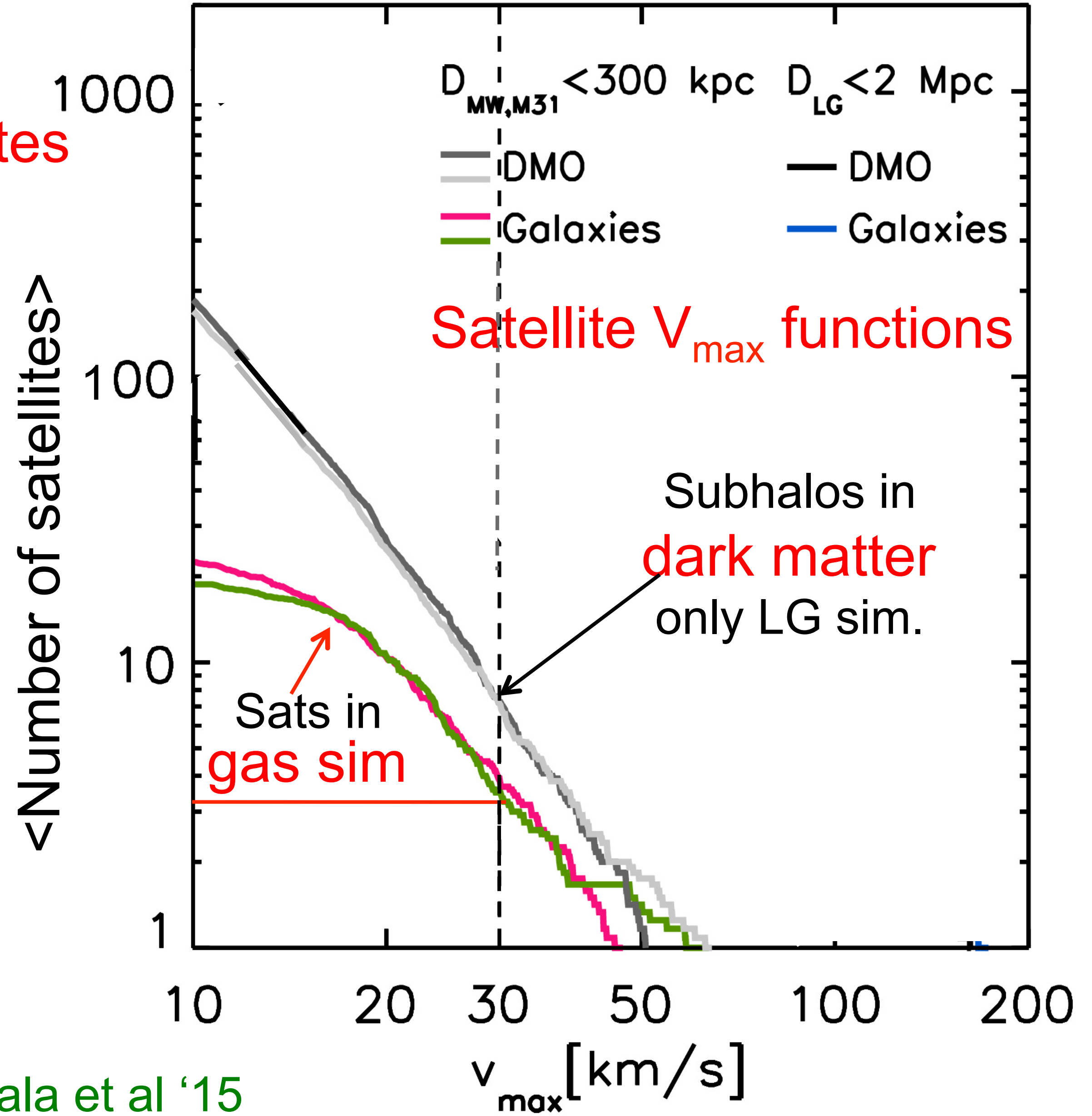
Too-big-to-fail: the baryon bailout

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



Sawala et al '15

When “baryon effects” are taken into account

→

No too-big-to-fail problem in CDM

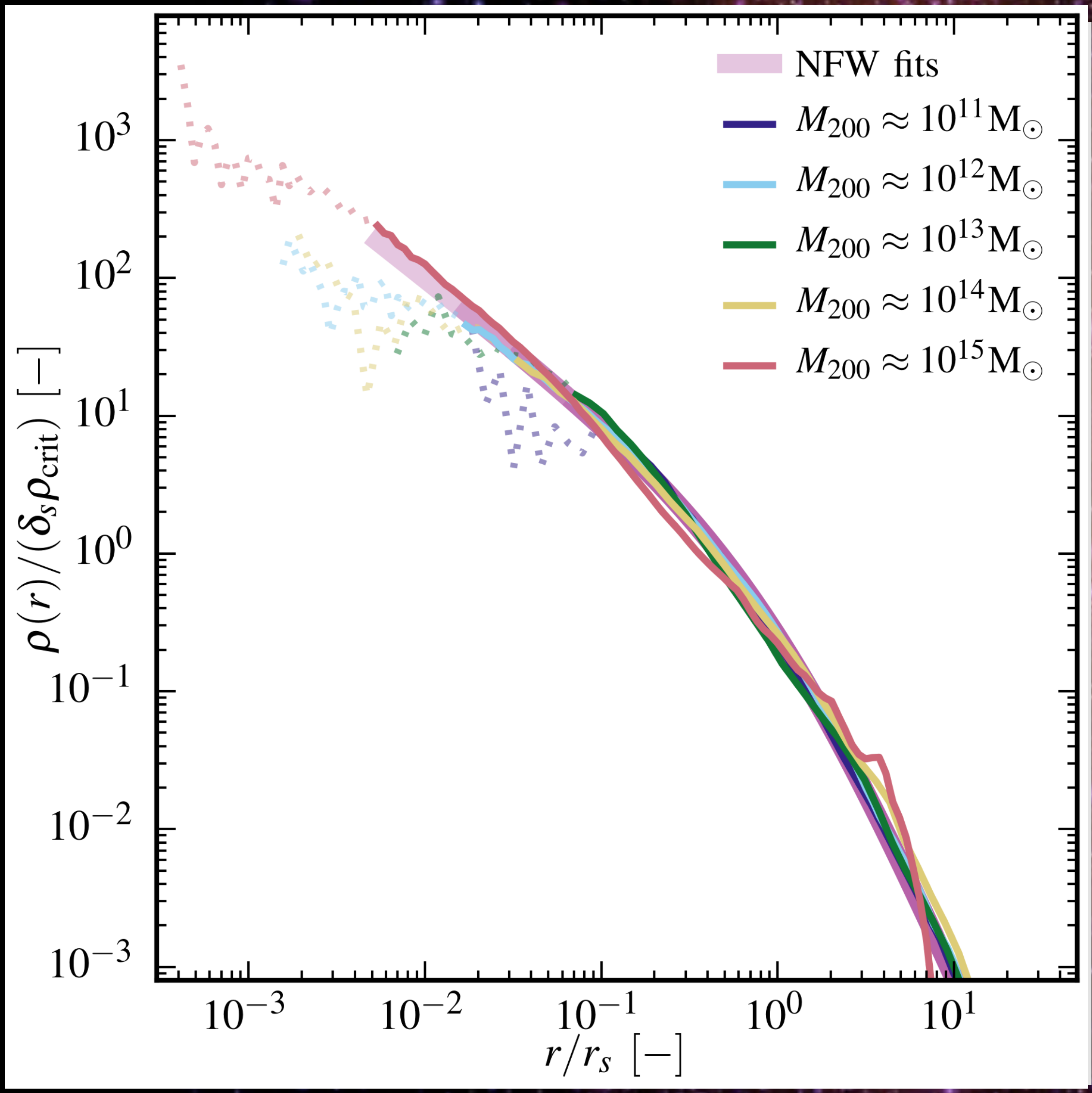
University of Durham

The CDM small-scale "crisis"

Three "problems:"

1. ~~The "missing satellites" problem~~
2. ~~The "too-big-to fail" problem~~
3. The "core-cusp" problem

The Density Profile of Cold Dark Matter Halos



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

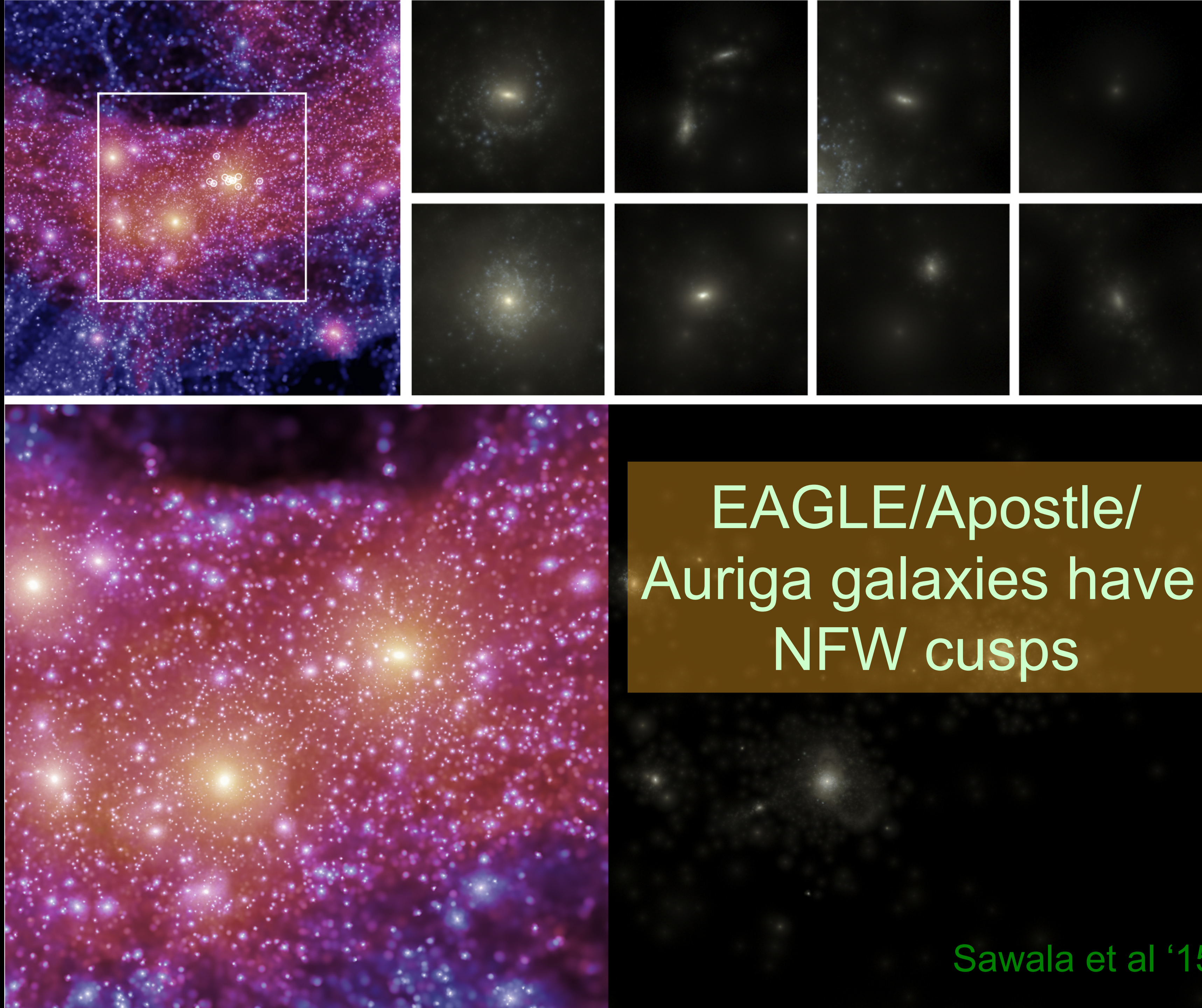
Density profiles are "cuspy" - no `core' near the centre

Fitted by simple formula:

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

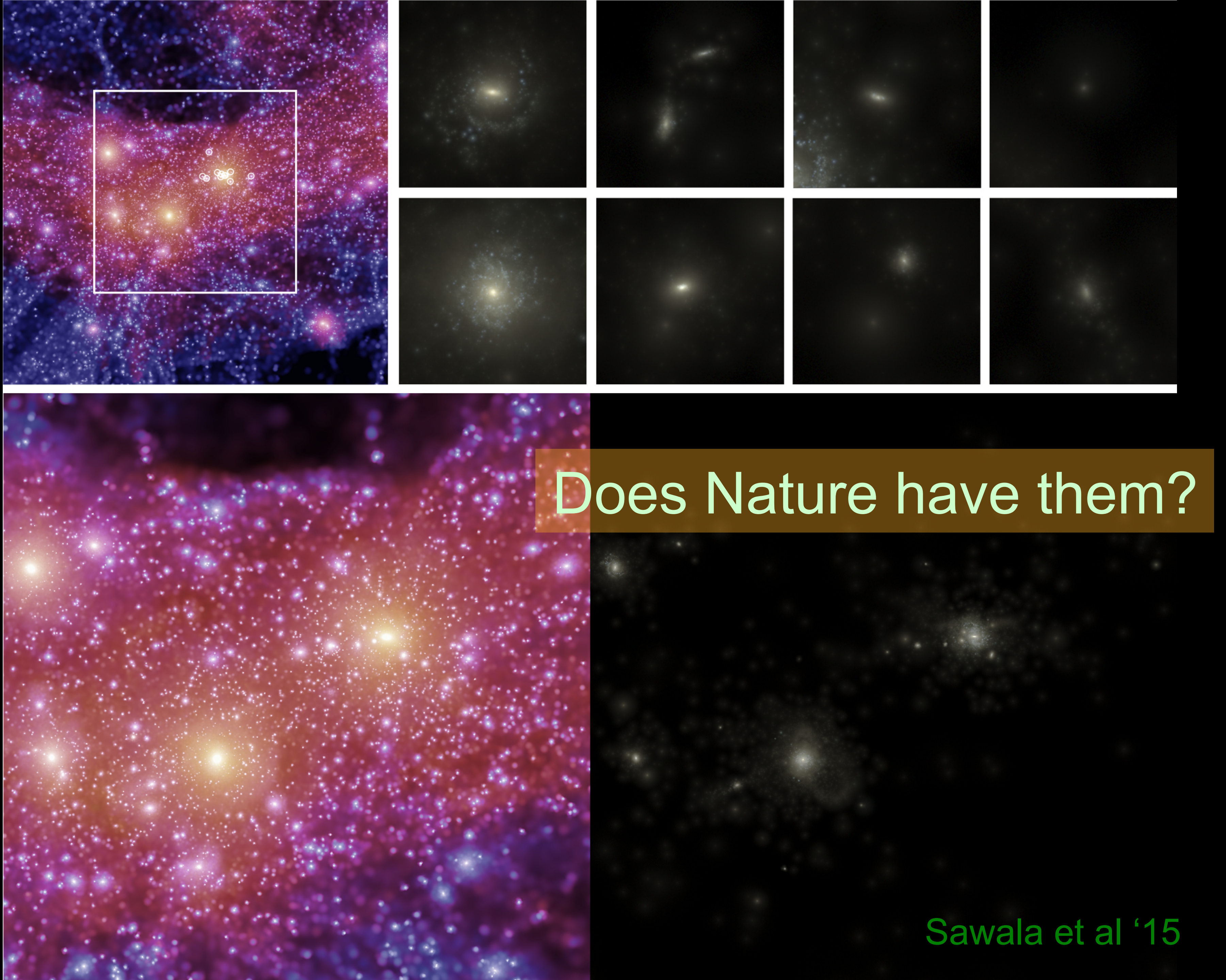
(Navarro, Frenk & White '97)

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



EAGLE/Apostle/
Auriga galaxies have
NFW cusps

Sawala et al ‘15


Does Nature have them?
Sawala et al '15

But if cores were found in halos, would this rule out CDM ?

The physics of core formation

Cusps → cores

Perturb central halo region by growing a galaxy adiabatically and removing it suddenly (Navarro, Eke & Frenk '96)

Cores may also form by repeated fluctuations in central potential (e.g. by SN explosions) (Read & Gilmore '05; Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

The cores of dwarf galaxy haloes L75

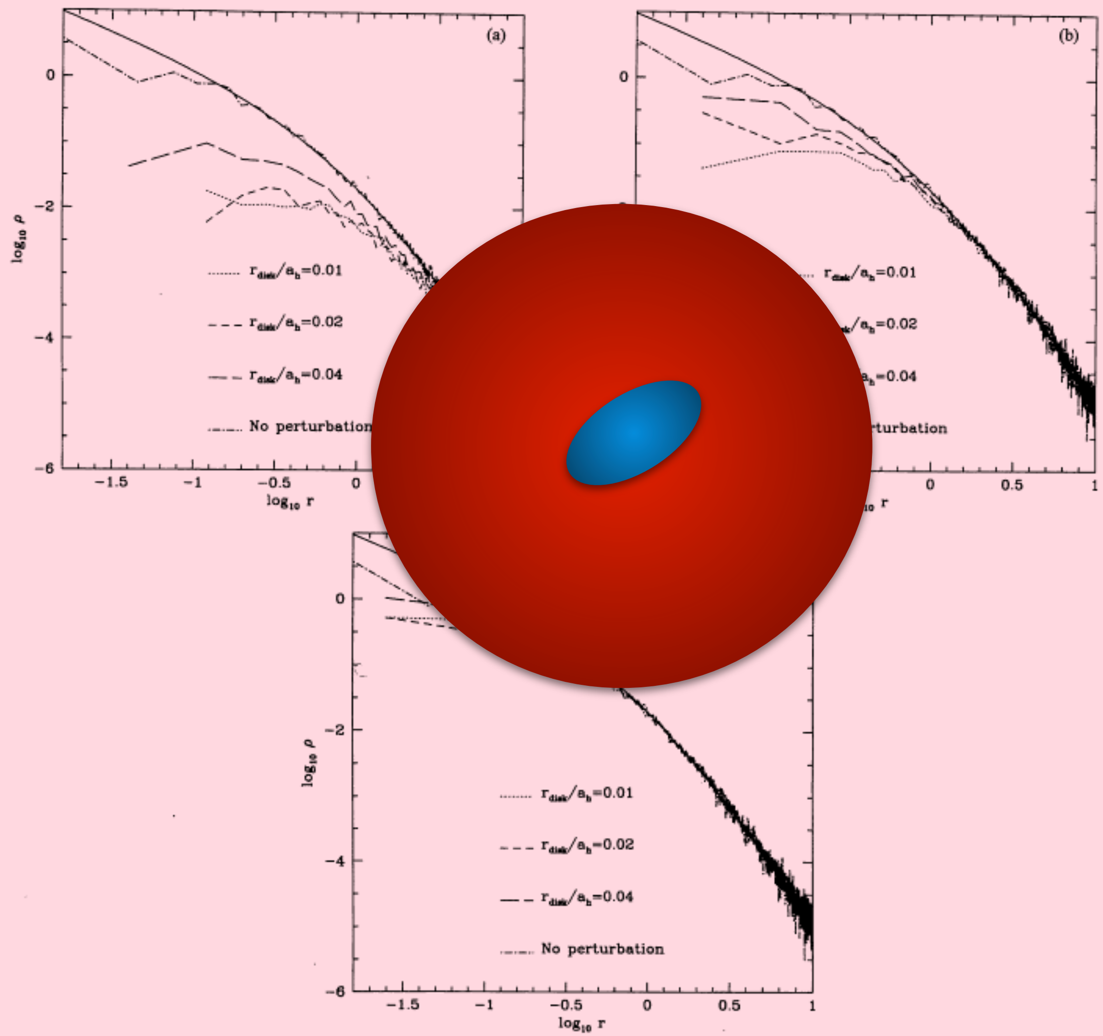


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t = 200$. (a) $M_{disc} = 0.2$.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

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Core formation

In the absence of a treatment of the (multi-phase) interstellar medium, need a “subgrid” model for star formation

In Eagle stars form from (cooling) gas that reaches a density higher than ρ_{th} (and T~10^4 K)

In Eagle ρ_{th}~0.1 cm^{-3}

For each resimulated dwarf, vary ρ_{th} from 0.1 - 10^4 cm^{-3}

Physically meaningless

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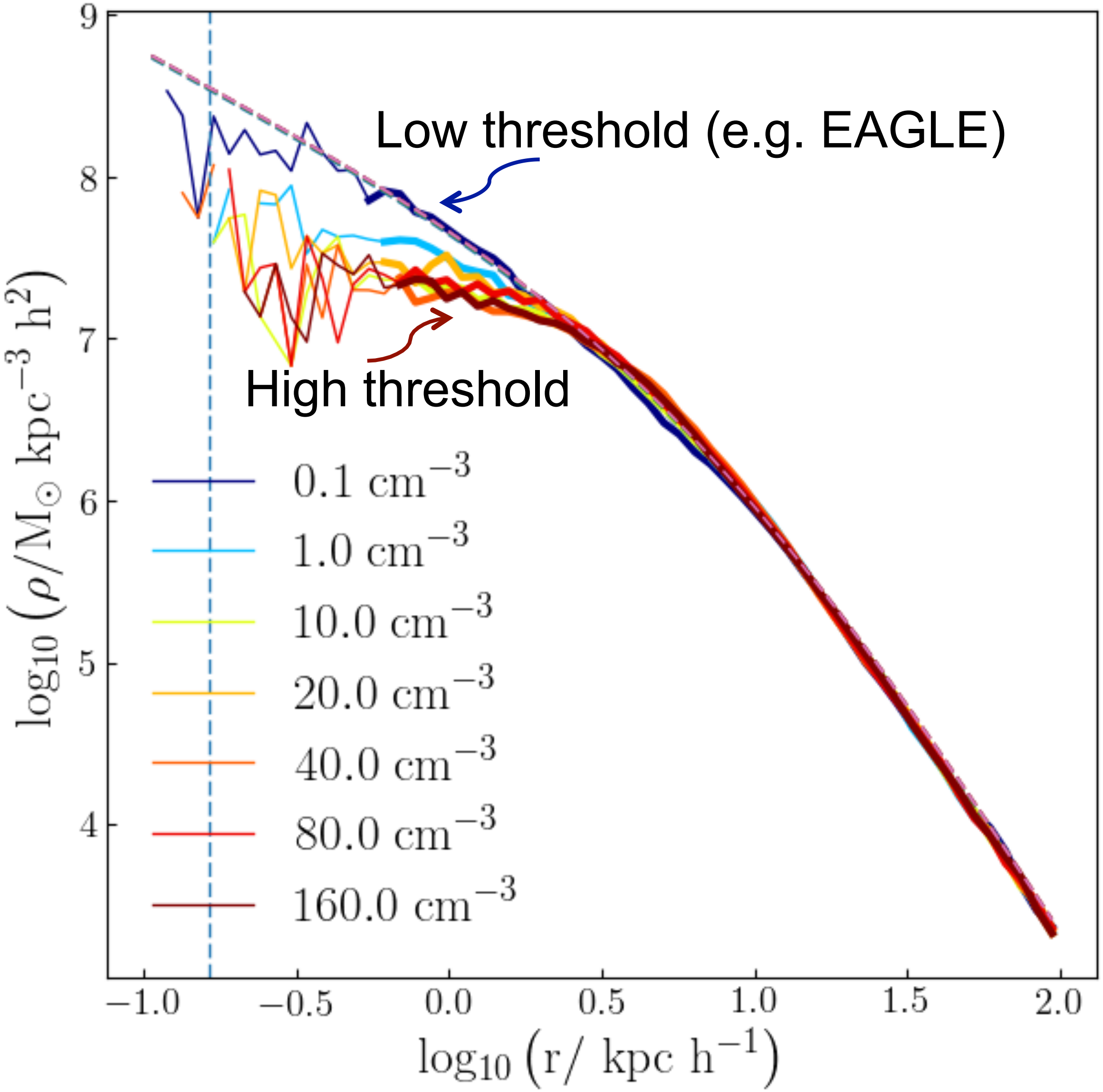
Cores or cusps in simulations?

Key parameter: gas density threshold for star formation

High density → NEF mechanism

Low density → not enough central gas density to perturb DM

Cores or cusps in simulations?



Benitez-Llambay, CSF et al '17

The CDM small-scale "crisis"

Three "problems:"

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2. ~~The "too-big-to fail" problem~~
3. ~~The "core-cusp" problem~~

The mass discrepancy-acceleration relation (MDAR)

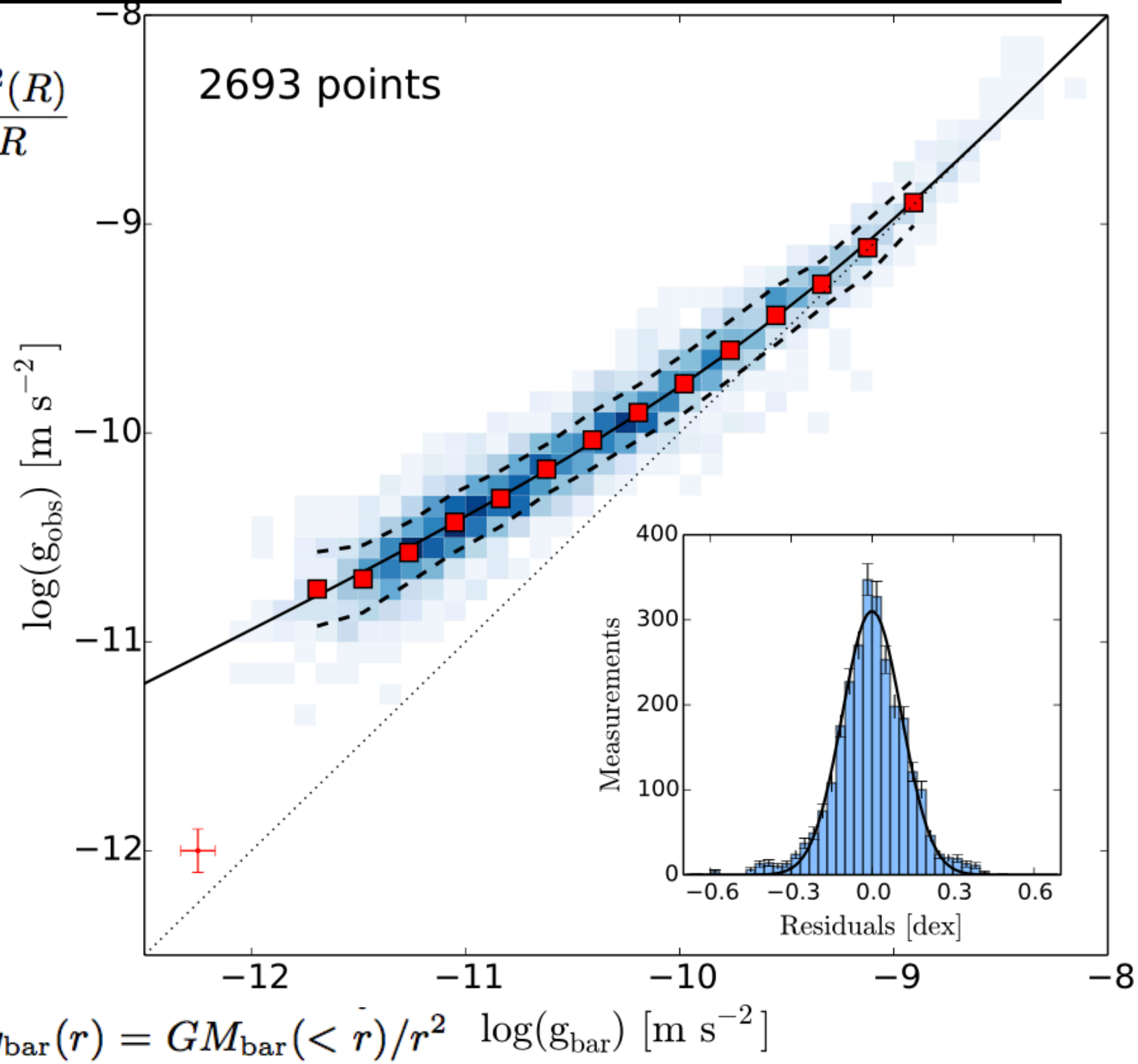
Relatively small scatter

Two characteristic accelerations:

$a_0 \sim 10^{-10}$ m/s^2: above which there is little need for dark matter, and

$a_{min} \sim 10^{-11}$ m/s^2: a "minimum" acceleration probed by galaxies

$$g_{obs} = \frac{V^2(R)}{R}$$



$$g_{bar}(r) = GM_{bar}(< r)/r^2$$

McGaugh+16

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$$g_{obs} = \frac{V^2(R)}{R}$$

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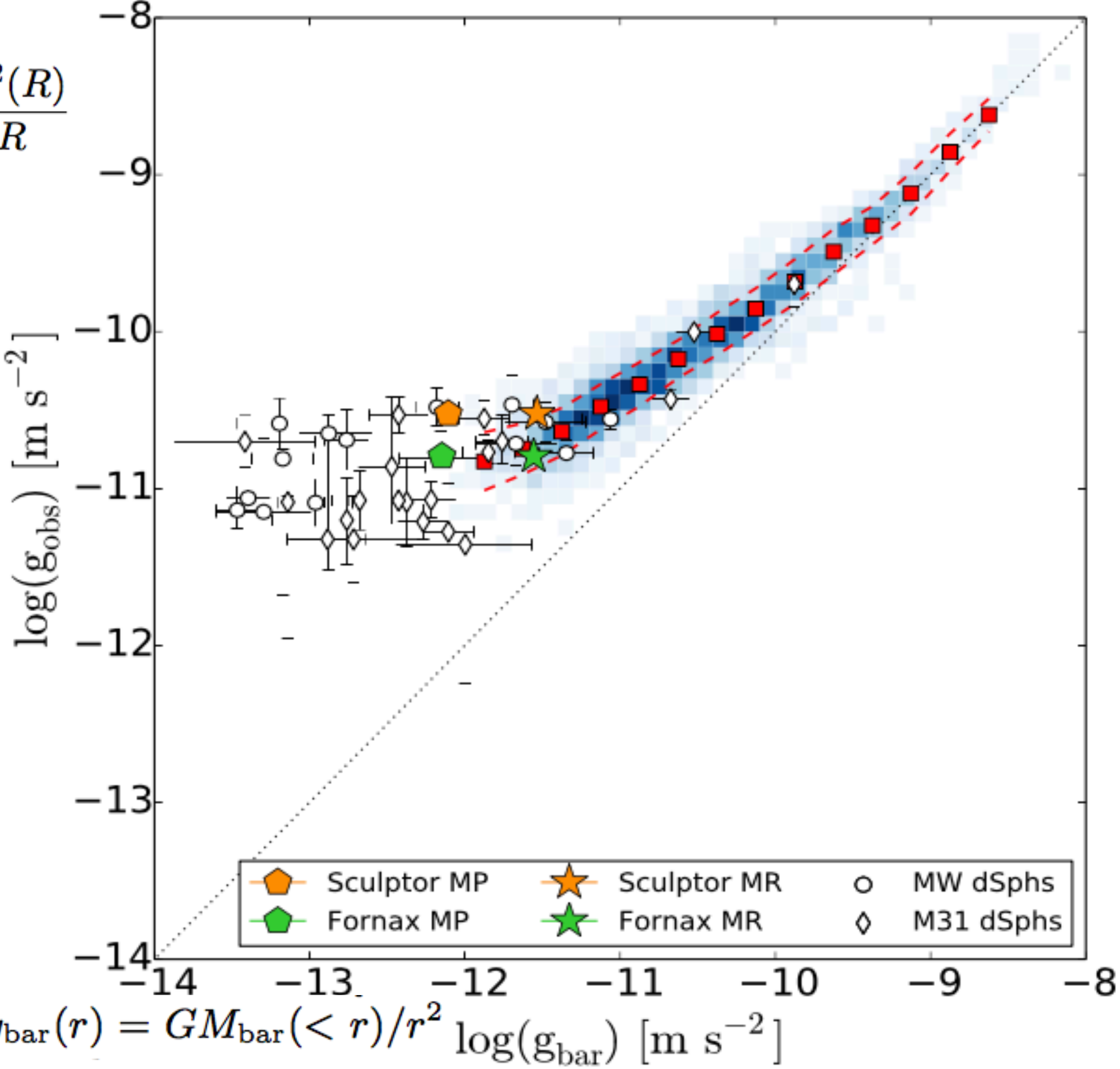
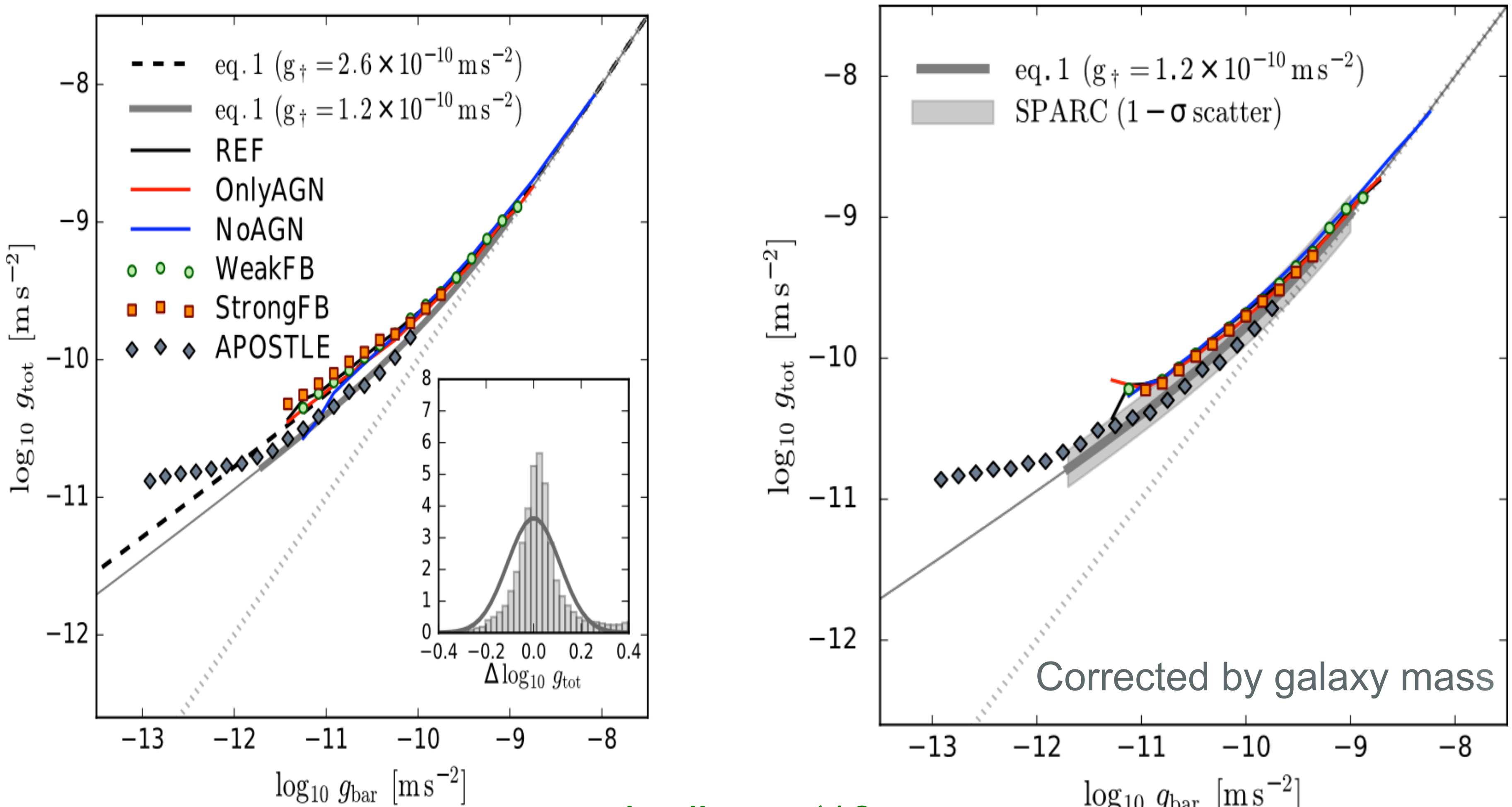


$$g_{bar}(r) = GM_{bar}(<r)/r^2$$

Lelli+17

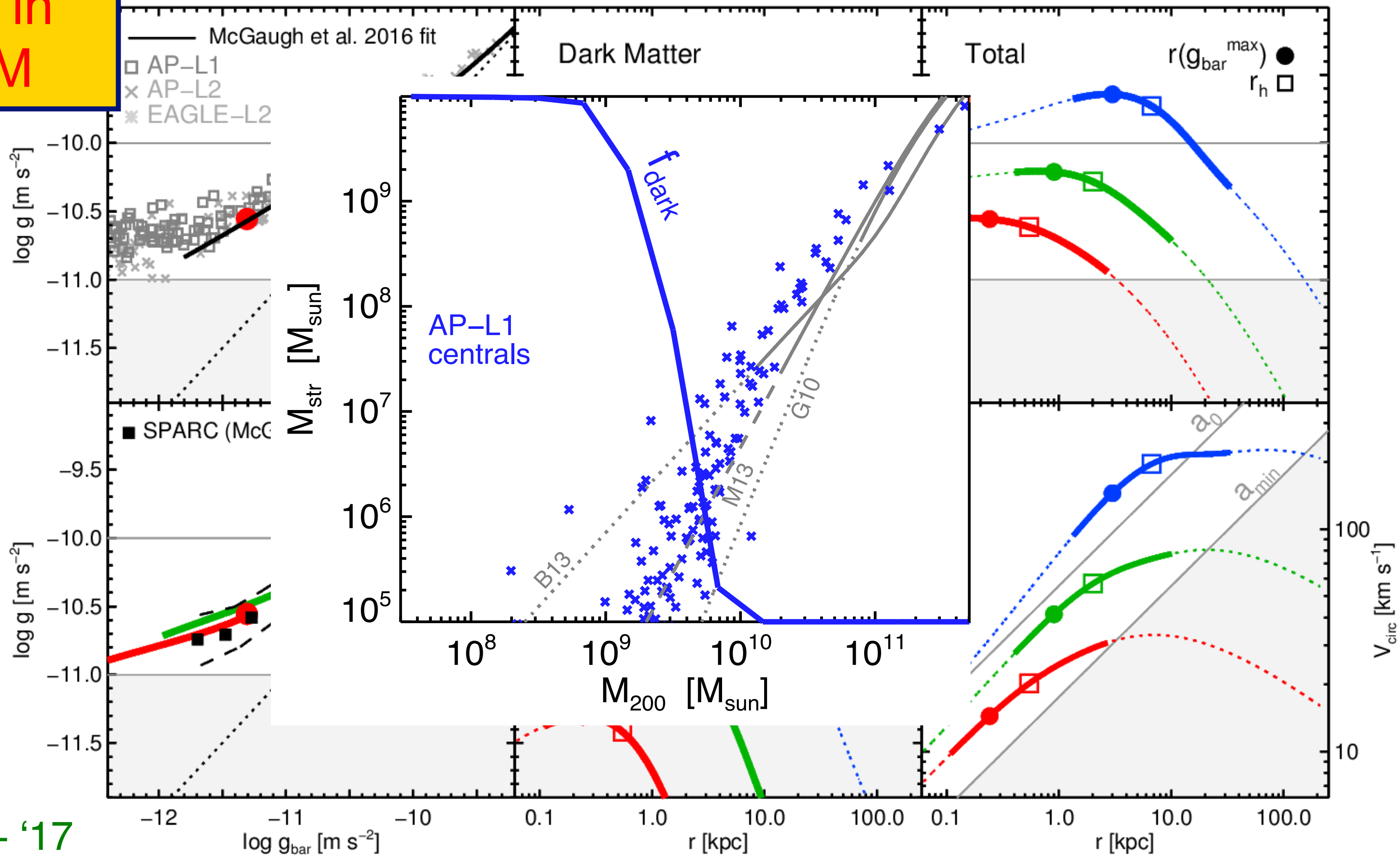
MDAR in Eagle

Different subgrid physics models: M* varies by x4 in same halo, but MDAR hardly changes



Ludlow + ‘16

MDAR in ΛCDM



Navarro + '17

ΛCDM halos have a well-defined maximum central acceleration

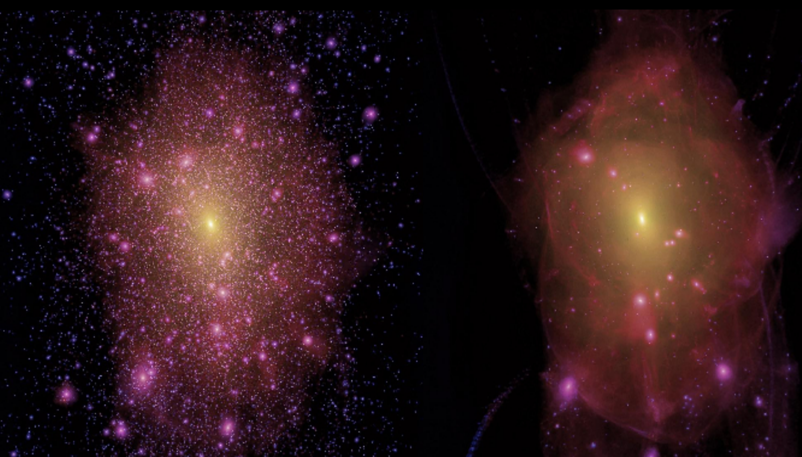
$a_0 \sim 10^{-10}$ m/s^2 is the central acceleration of the most massive halo that may host a disk galaxy ($V_{max} \sim$ 200-300 km/s)

$a_{min} \sim 10^{-11}$ m/s^2: is the acceleration of the least massive halo able to host a luminous galaxy ($V_{max} \sim$20-30 km/s)

Can CDM be ruled out?

Yes !

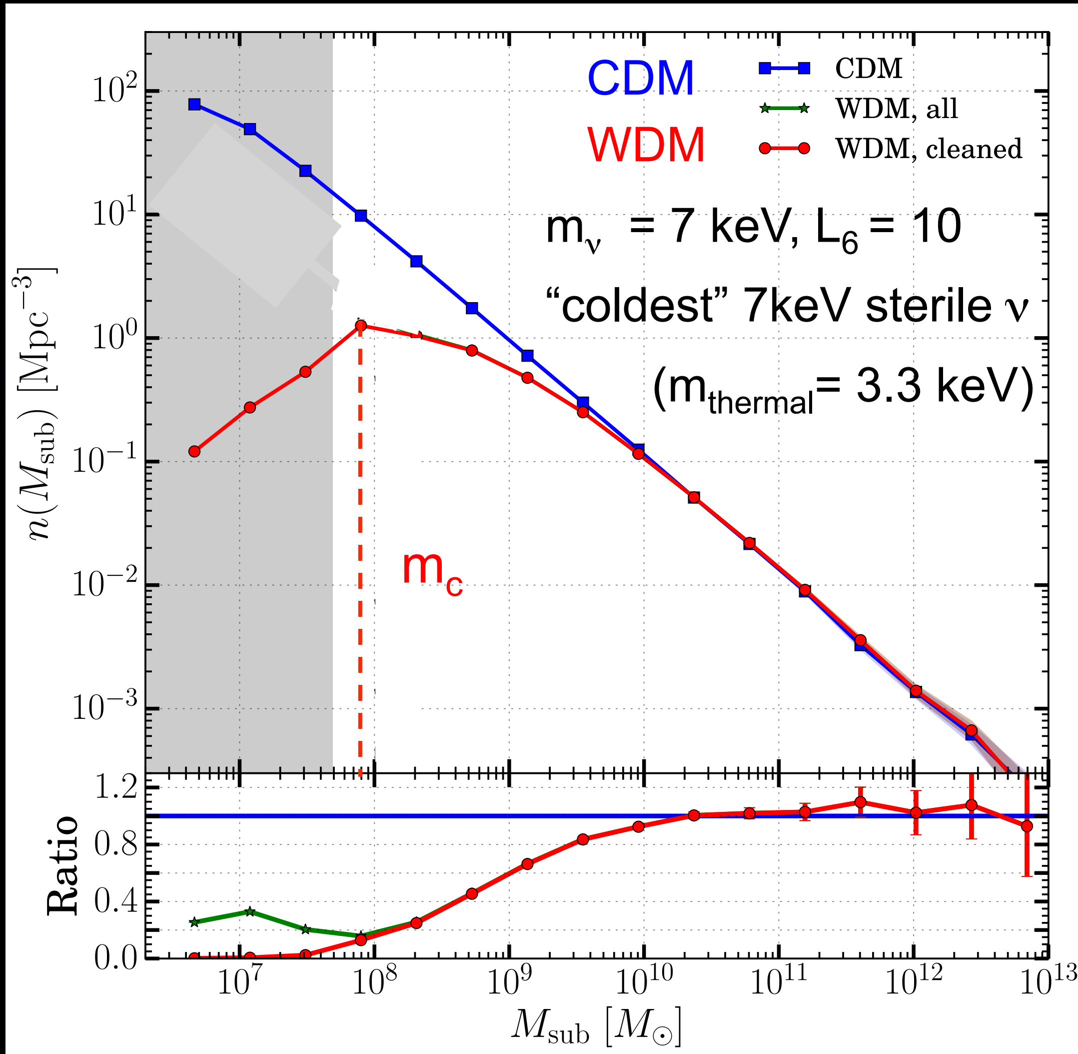
The subhalo mass function



CDM WDM

3 x fewer WDM subhalos at $3 \times 10^9\ M_o$

10 x fewer at $10^8\ M_o$

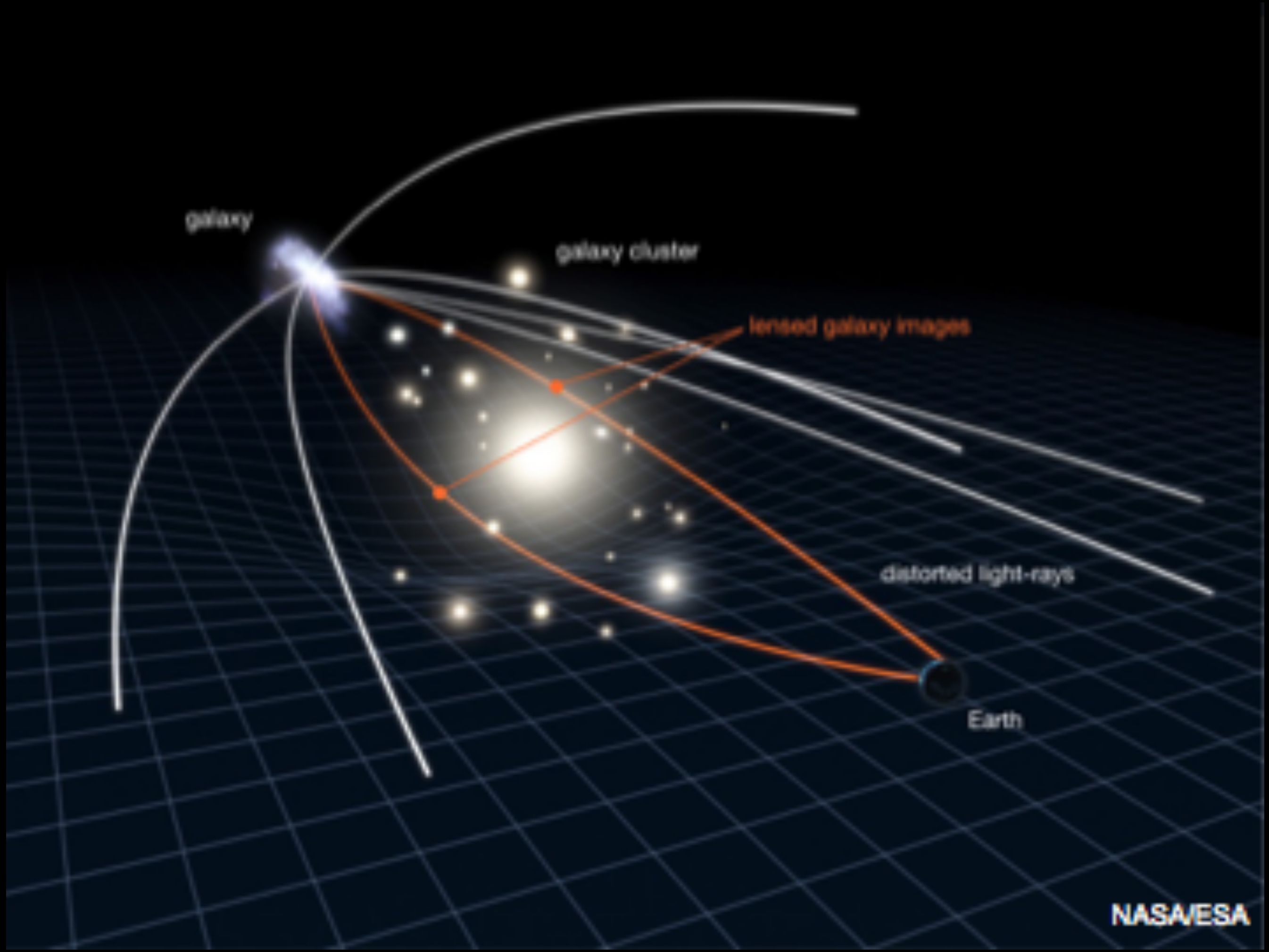


Bose, CSF et al '16

Can we distinguish CDM/WDM?

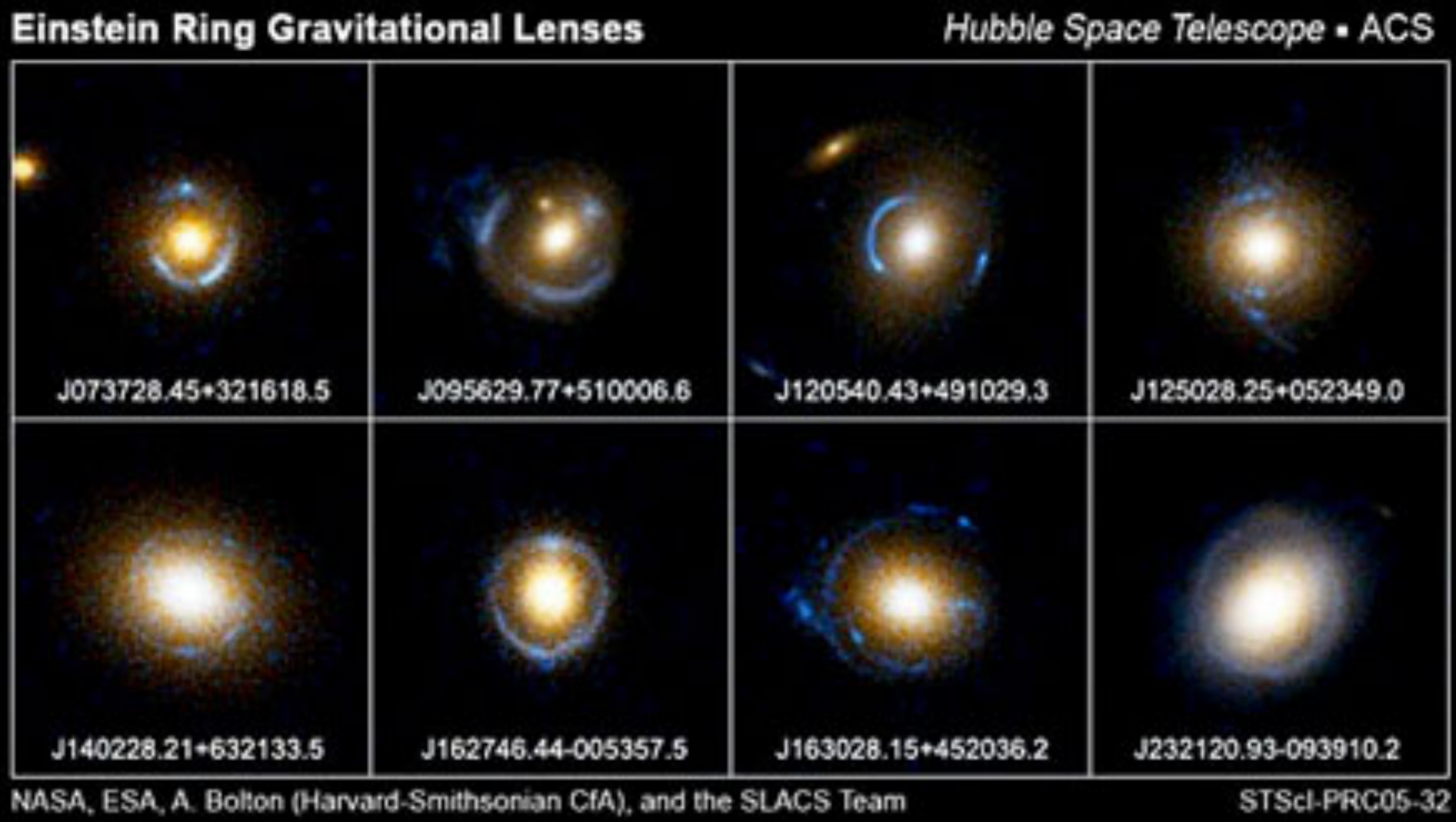
How to rule out CDM

Gravitational lensing: Einstein rings

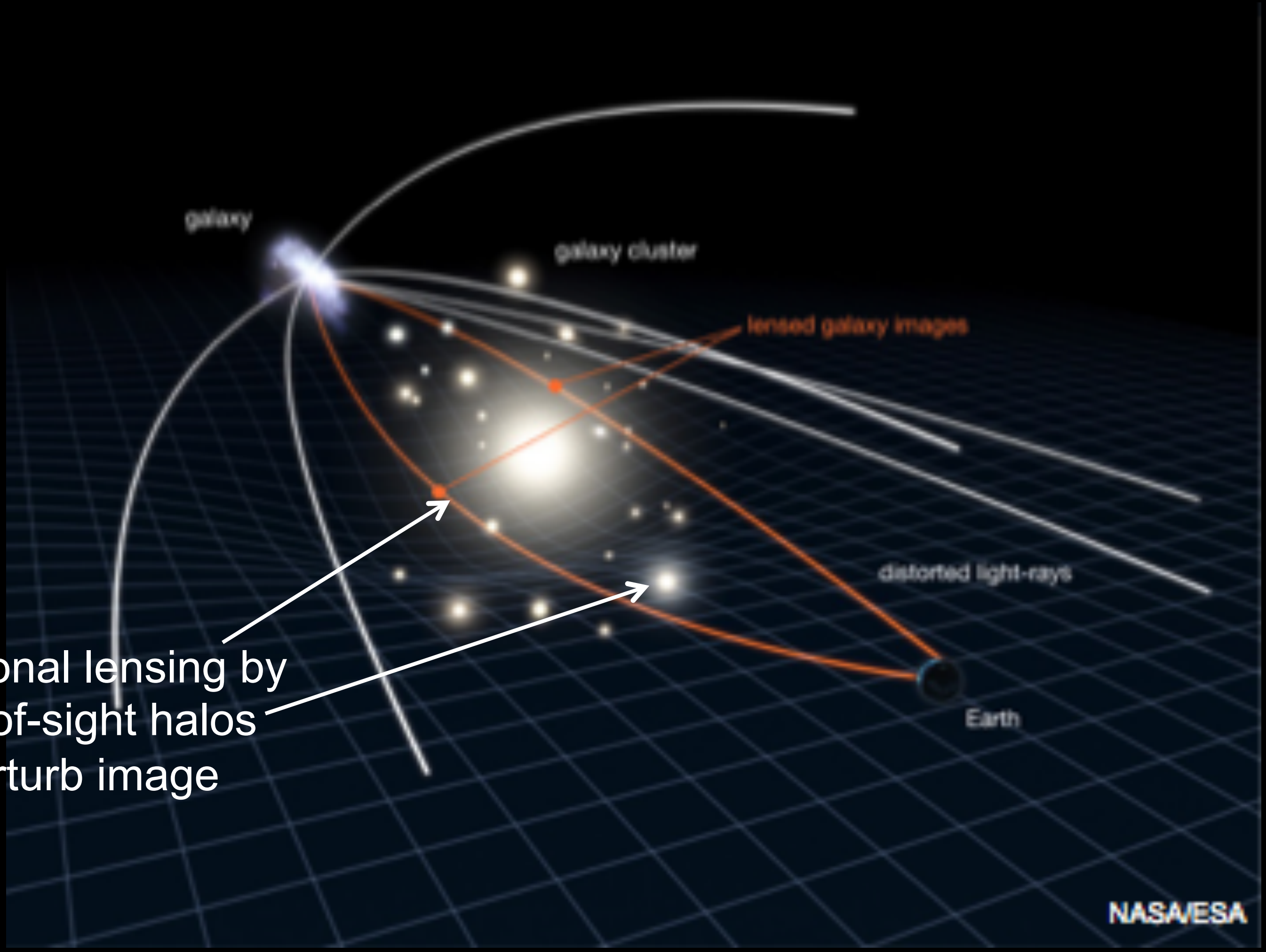


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

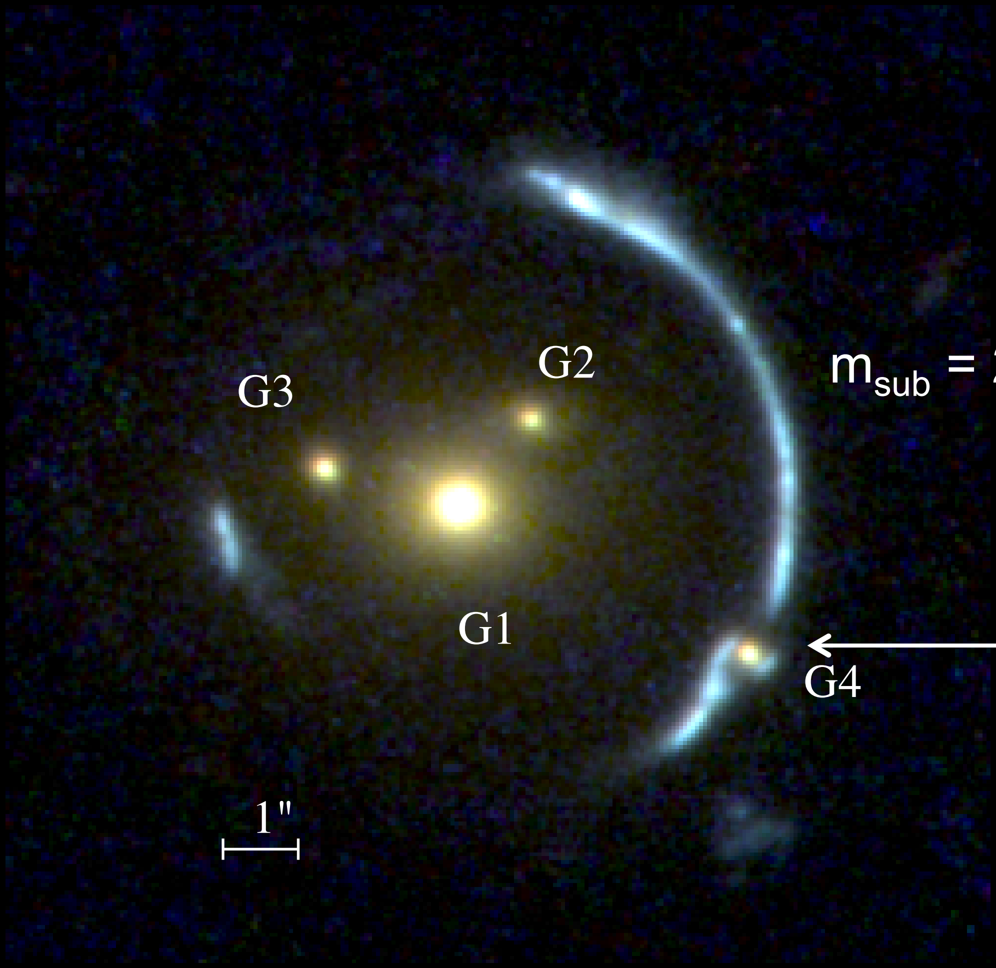


Additional lensing by line-of-sight halos perturb image

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



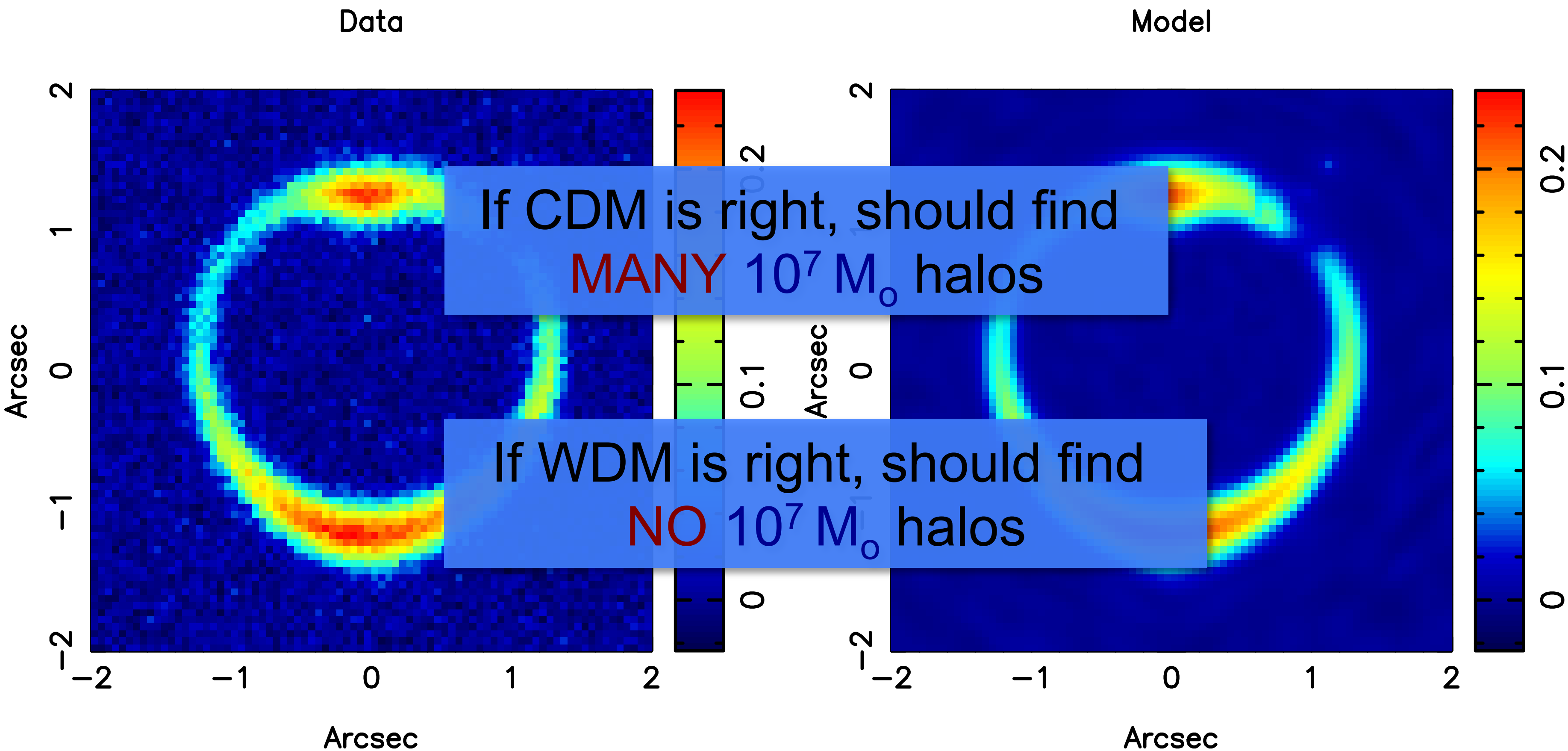
$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al '10

Detecting substructures with strong lensing

University of Durham

Can detect subhalos as small as $10^7 - 10^8 M_o$



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

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

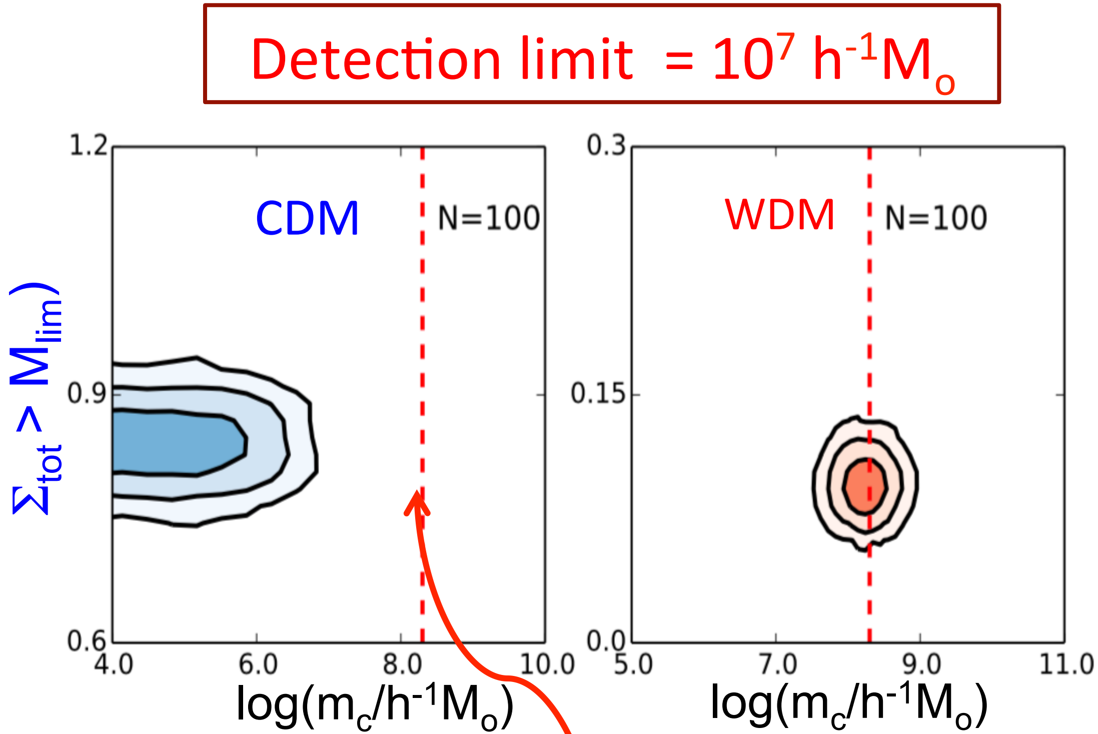
Vegetti & Koopmans '09

Detecting substructures with strong lensing

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

m_c= halo cutoff mass

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



m_c= halo cutoff mass

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

- If DM is 7 keV sterile ν → exclude CDM at >>σ!
- If DM is CDM → exclude 7 keV sterile ν at >>σ

Li, CSF et al '16

Institute for Computational Cosmology

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Conclusions

- ΛCDM:
- Fully-specified physical model with predictive power
- Important predictions (CMB, LSS, gal form) verified empirically
- One of the great successes of physics of past 30 years

CDM small-scale "crisis":

- Halos < ~$5.10^8 M_0$ are dark; halos >$10^{10} M_0$ are bright
- When baryons taken into account → No satellite, too-big-to-fail, plane of sats, core/cusp problems in CDM
- Distortions of strong gravitational lenses offer clean test of CDM

→ and can potentially rule it out!