A conclusive test of cold dark matter

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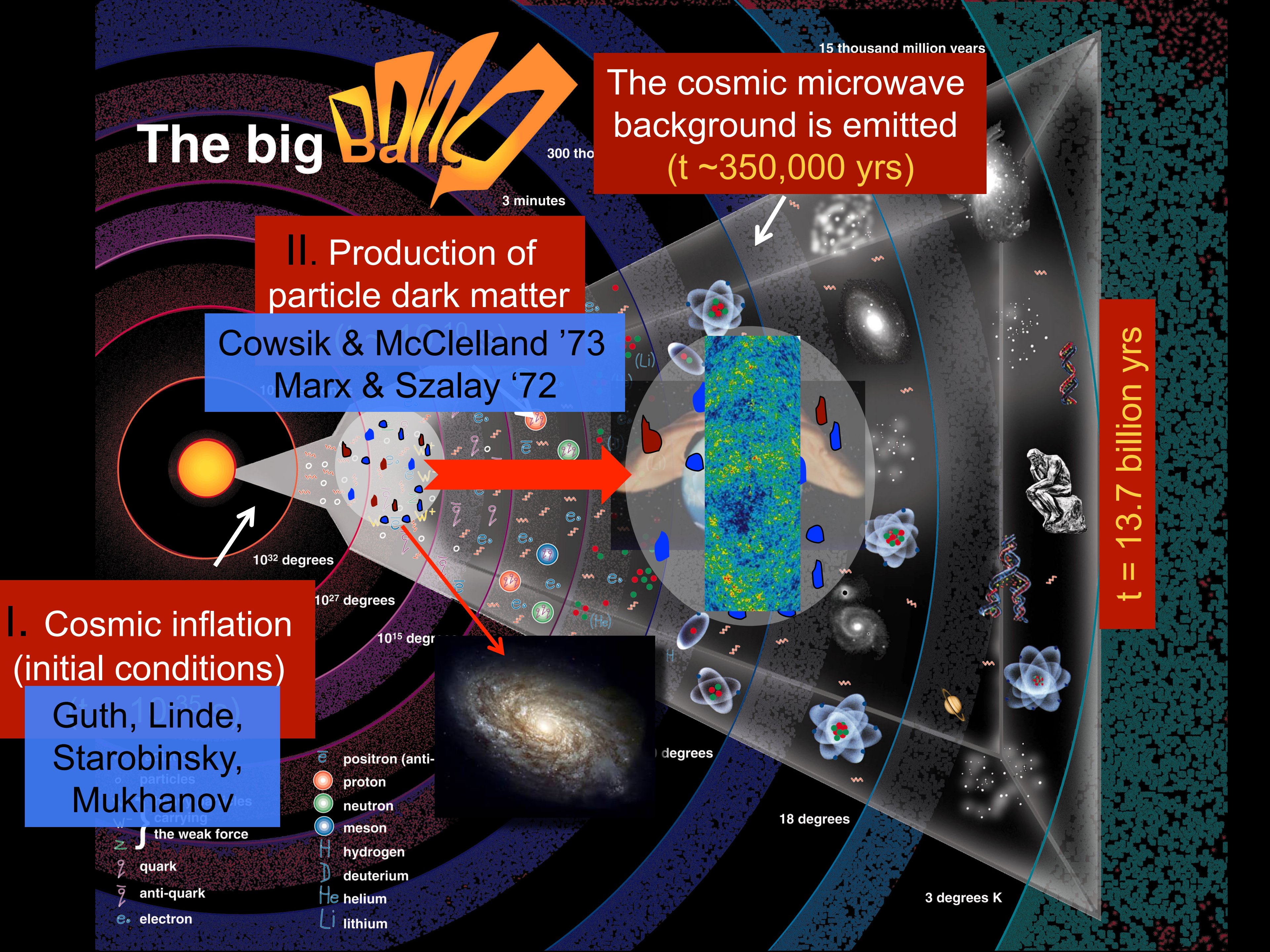
University of Durham

Modern cosmology emerged from two revolutionary ideas c.a.1980

The new Ogden Centre at Durham



The big Bang
15 thousand million years
The cosmic microwave background is emitted (t ~350,000 yrs)
300 tho
3 minutes
II. Production of particle dark matter
Cowsik & McClelland '73
Marx & Szalay '72
10^{32} degrees
10^{27} degrees
10^{15} degr
I. Cosmic inflation (initial conditions)
Guth, Linde, Starobinsky, Mukhanov
degrees
18 degrees
3 degrees K
t = 13.7 billion yrs
the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Non-baryonic dark matter candidates

From the early 1980s (Bond & Szalay '83):

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 →

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

for thermal relic

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

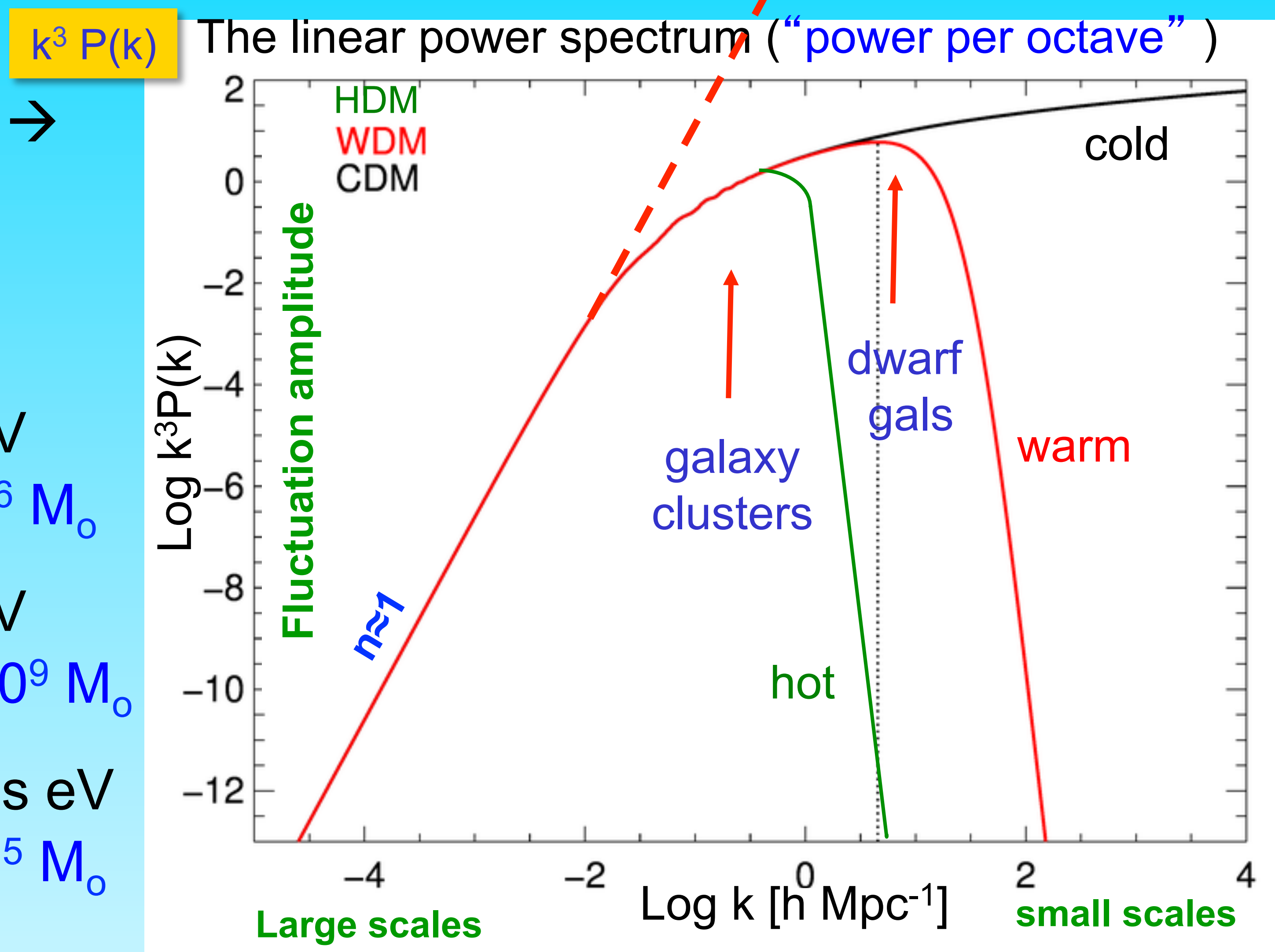
susy; $M_{cut} \sim 10^{-6} M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9} M_o$

$m_{HDM} \sim$ few tens eV

light ν; $M_{cut} \sim 10^{15} M_o$



Inflationary non-baryonic dark matter cosmogonies

- *Ab initio*, fully specified models of cosmic evolution and the formation of cosmic structure
- Have strong predictive power than can be tested by astronomical observations (esp CMB and large-scale structure)

Linear theory (CMB) — Non-linear (large-scale structure)

Temperature anisotropies in CMB

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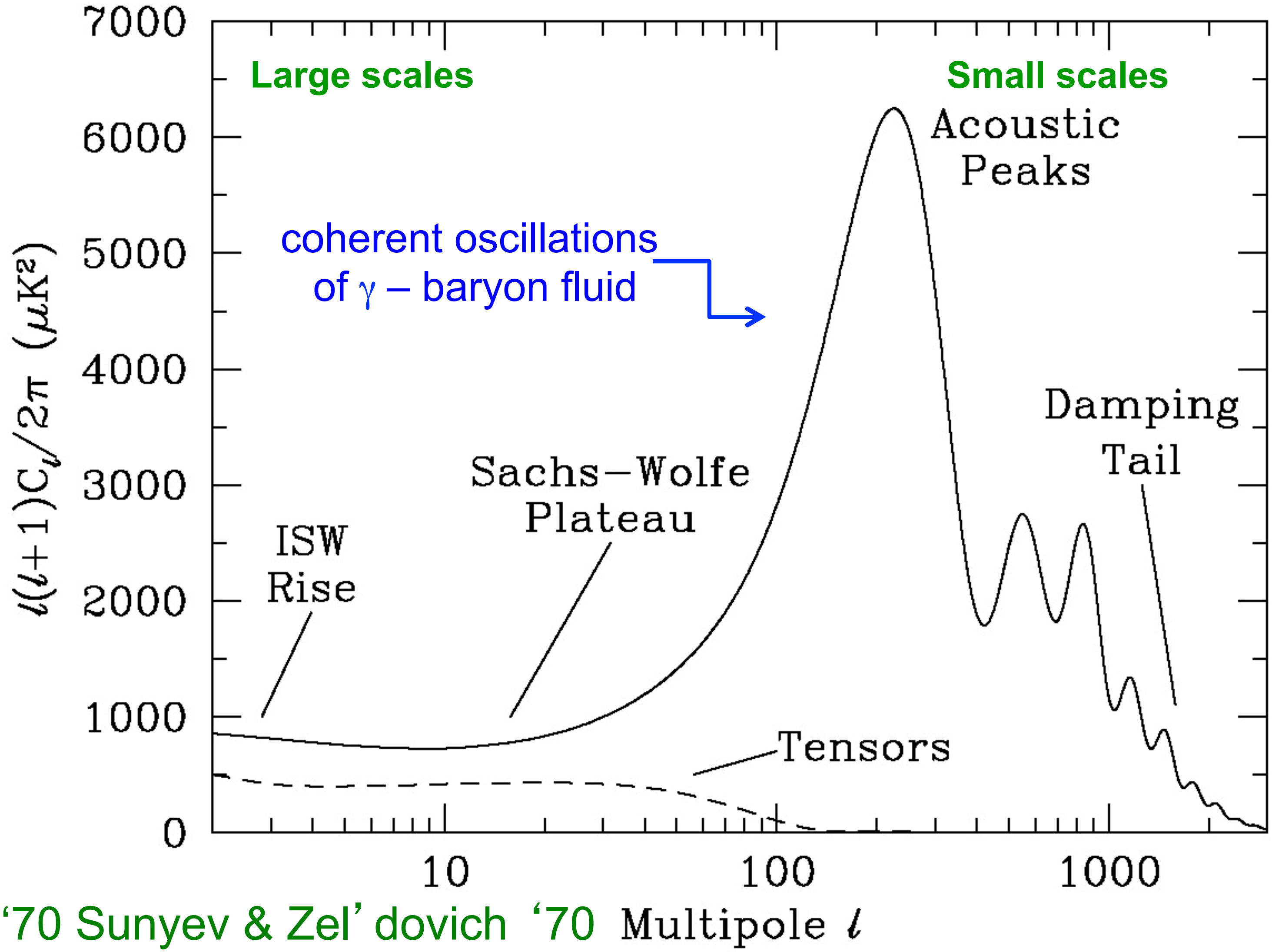
2D power spectrum



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

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

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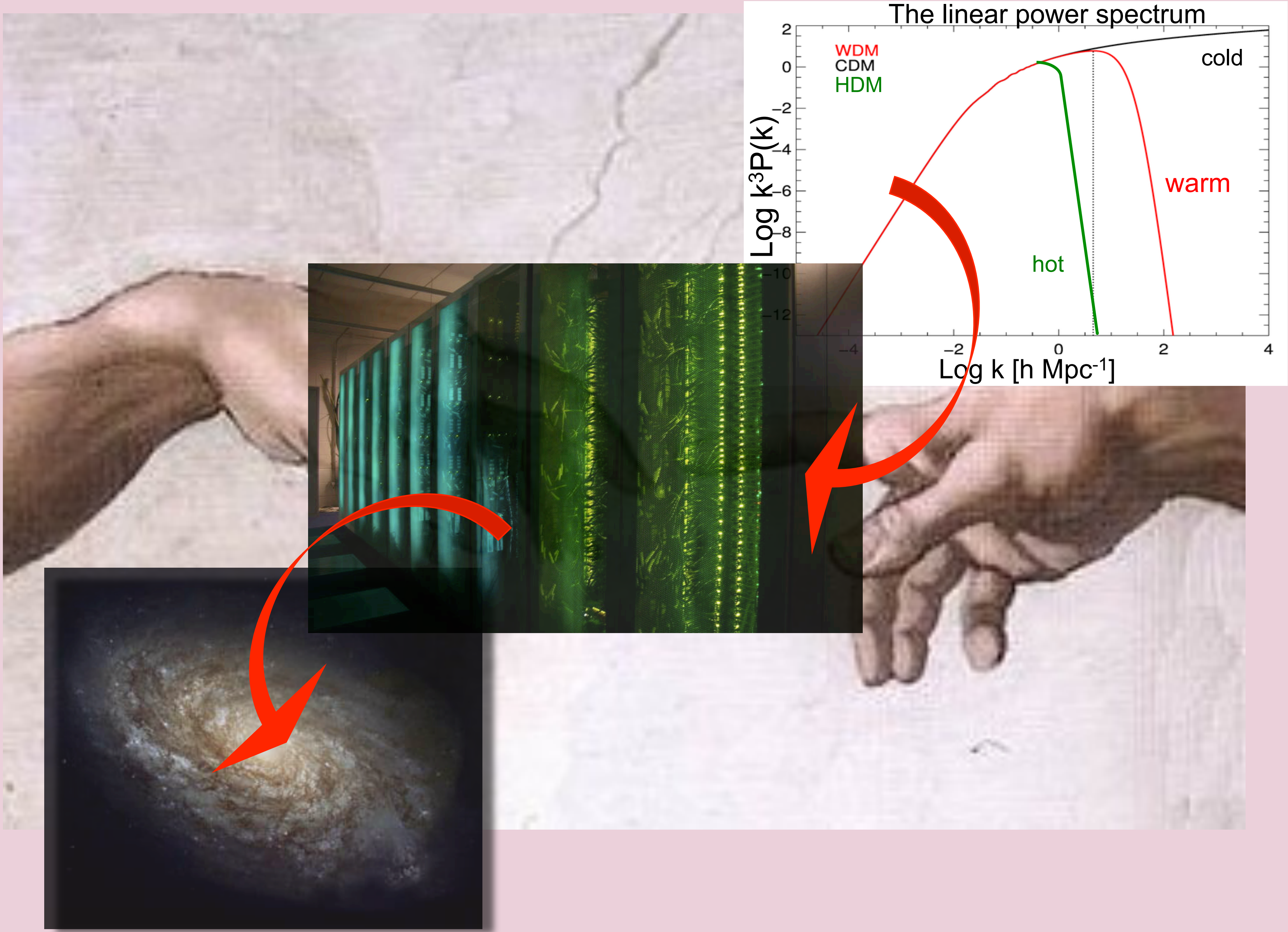
Non-linear evolution



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Non-linear evolution: simulations

Inflation + material content of Universe → Initial conditions

Relevant equations:

Collisionless Boltzmann,
Poisson, Friedmann eqn,
Radiative hydrodynamics
Astrophysics (subgrid)

How to make a virtual universe

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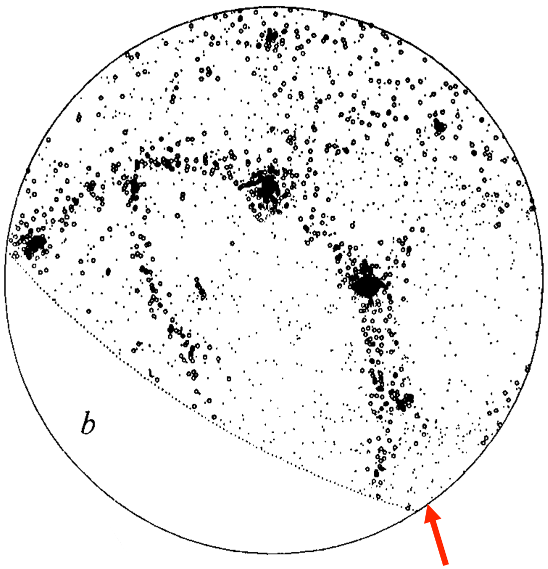
Non-baryonic dark matter cosmologies



Neutrinos
$\Omega=1$

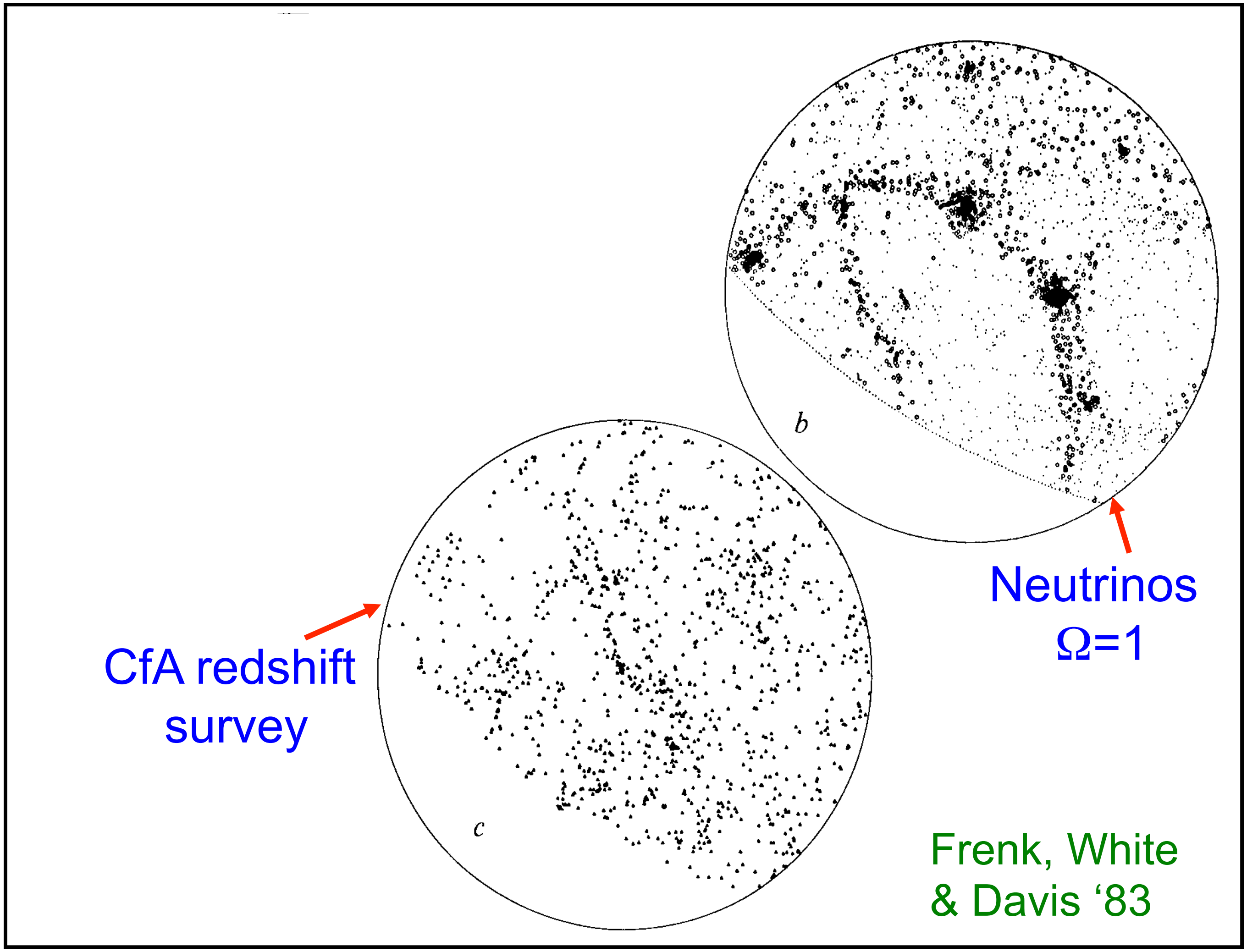
Frenk, White & Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu \ll 30$ ev



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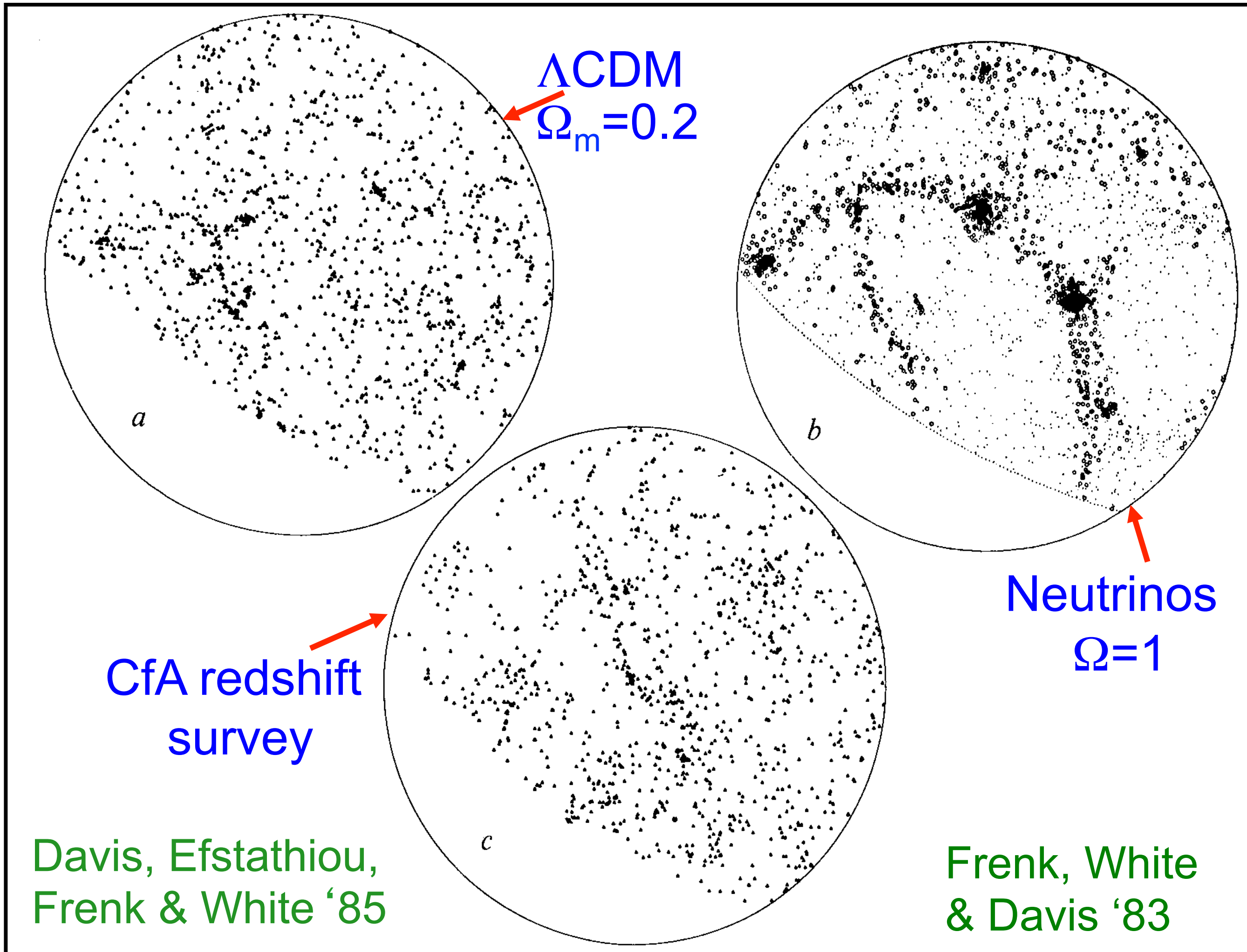
Non-baryonic dark matter cosmologies

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



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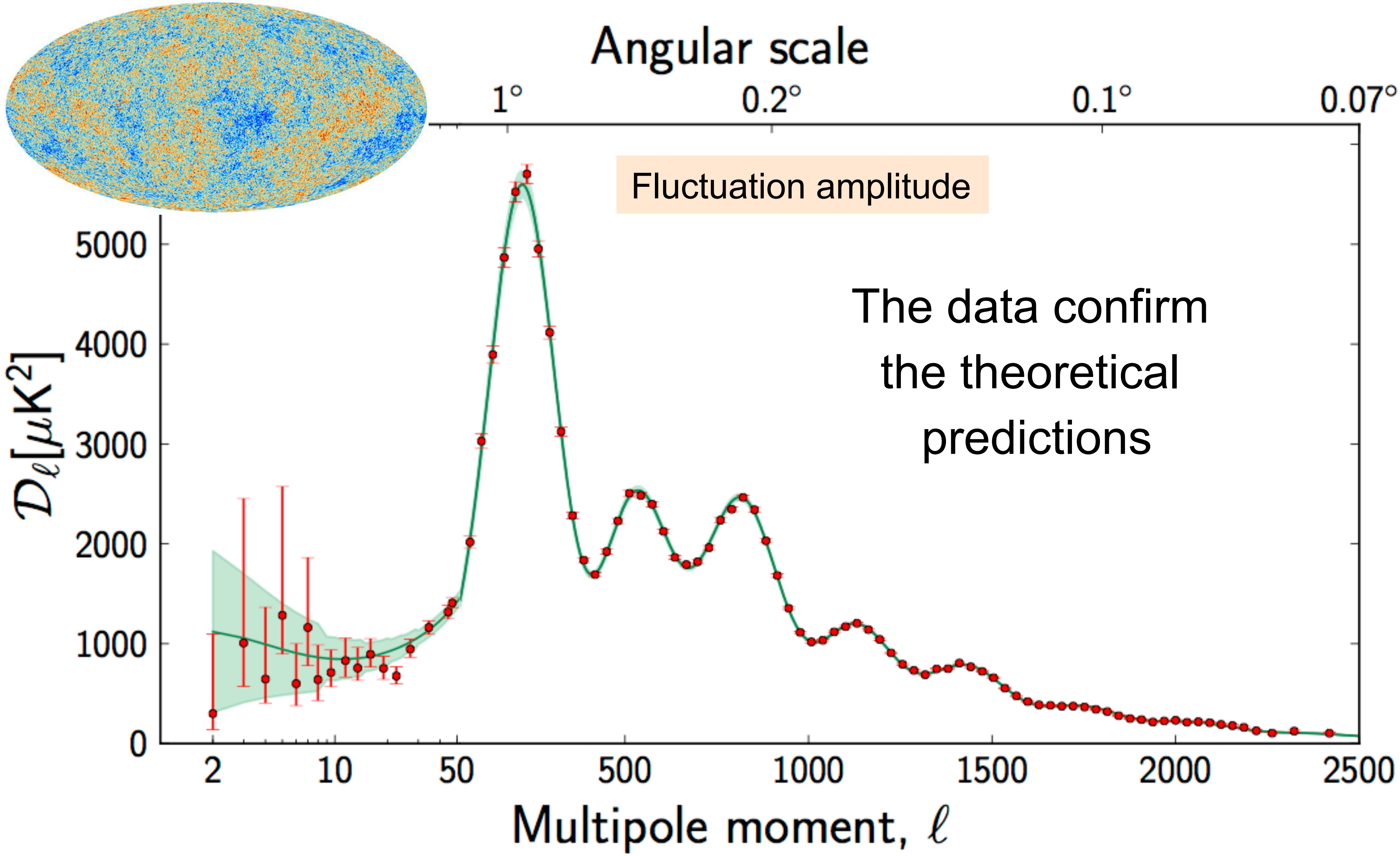
Planck: CMB temperature anisotropies



Planck coll. 2015

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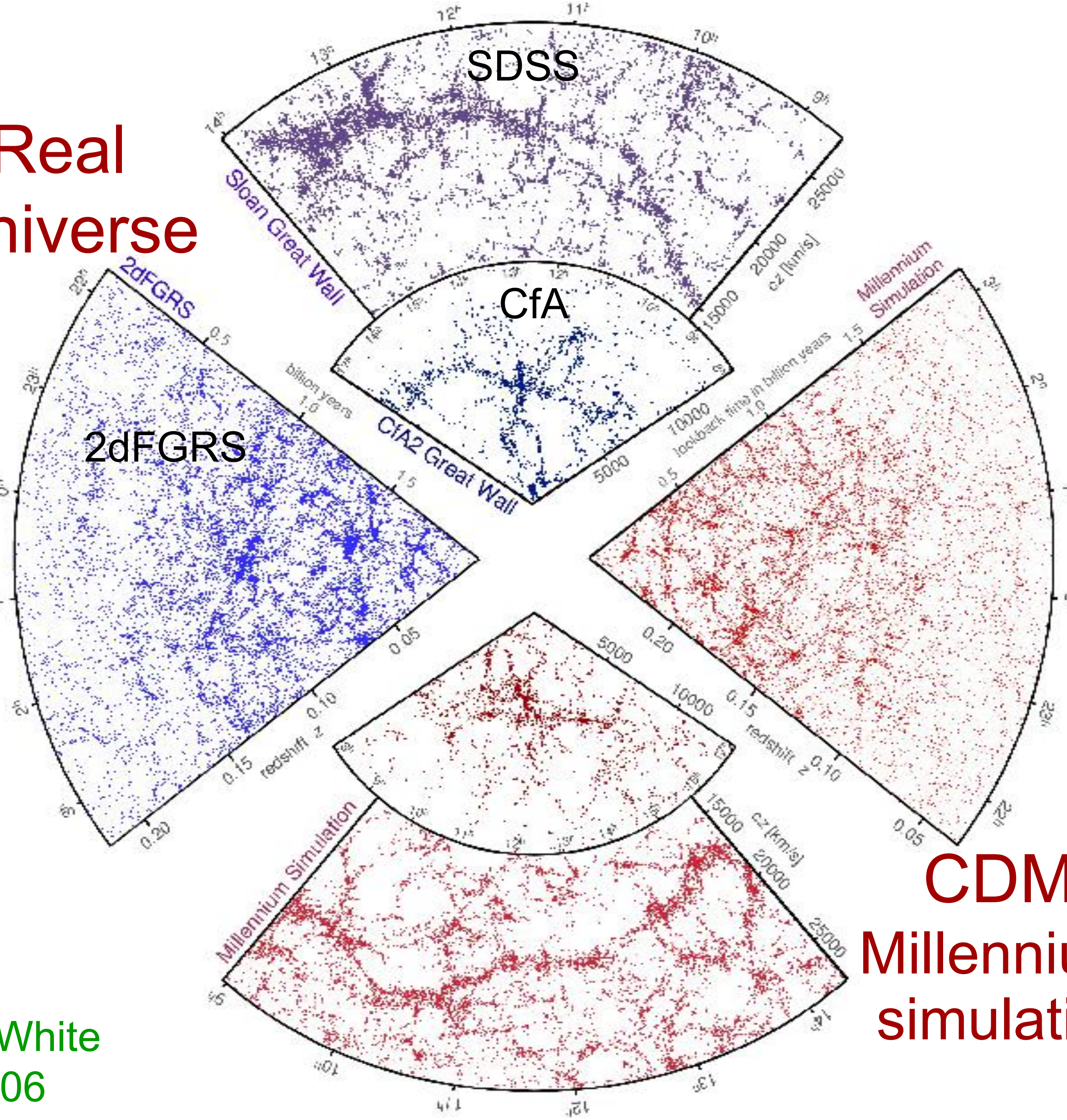
Real Universe



CDM Millennium simulation

Springel, Frenk & White
Nature, April ‘06

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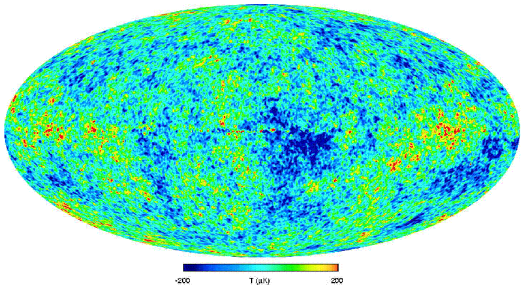
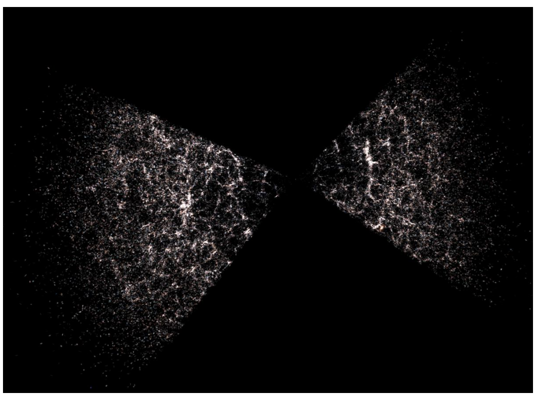
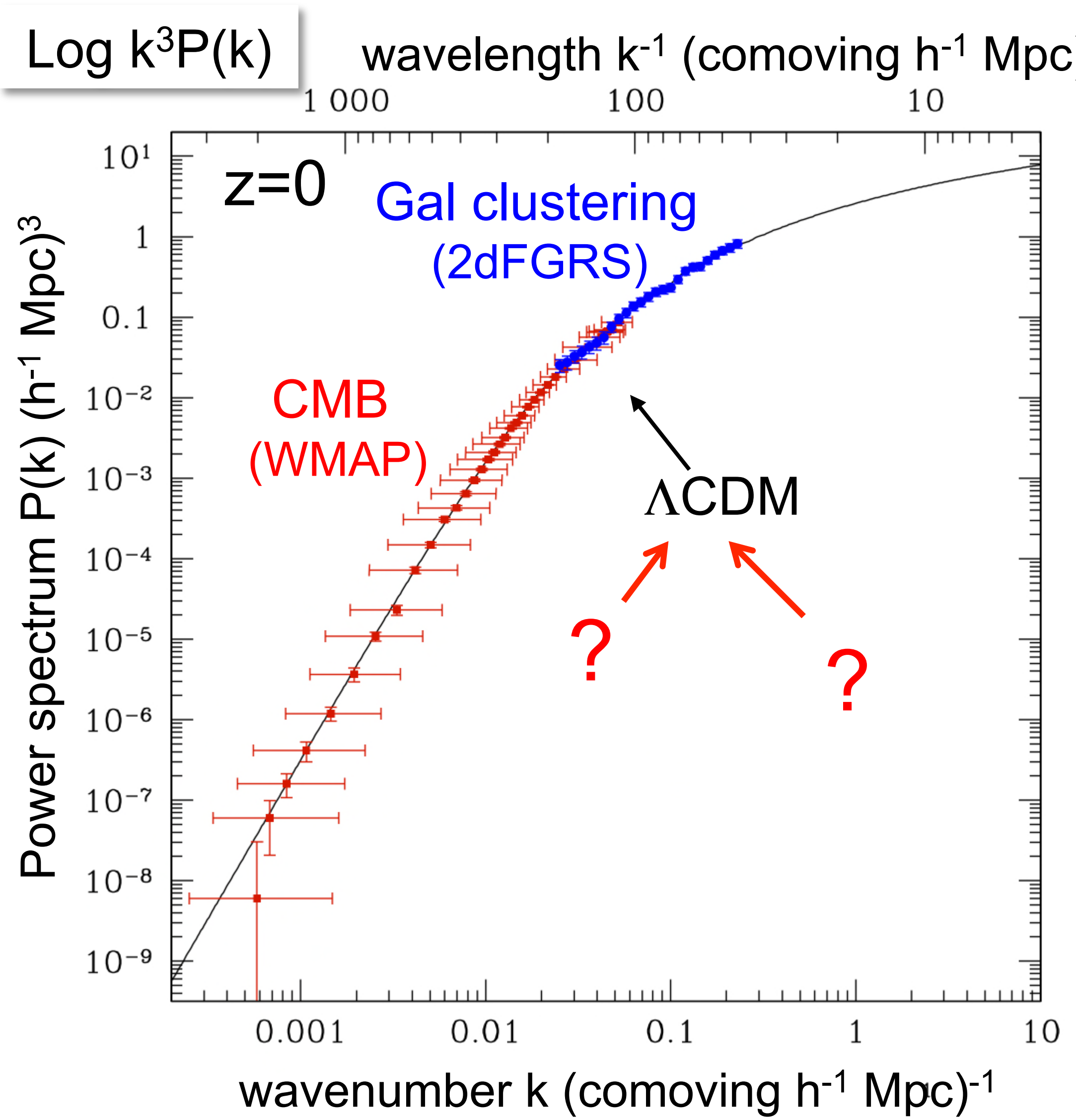
The cosmic power spectrum: from the CMB to the 2dFGRS



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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for thermal relic

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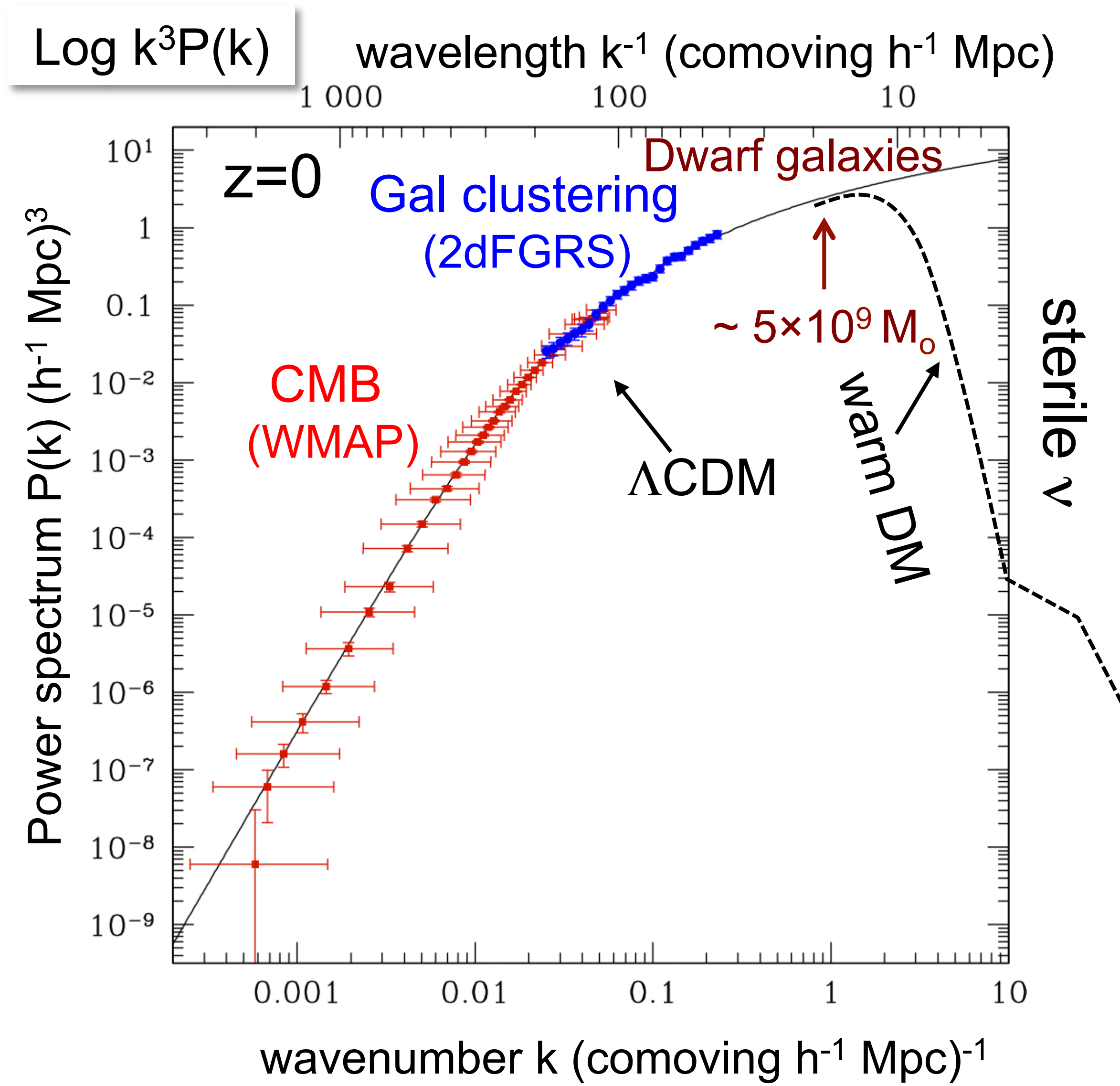


Cold Dark Matter

Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

cold dark matter

warm dark matter

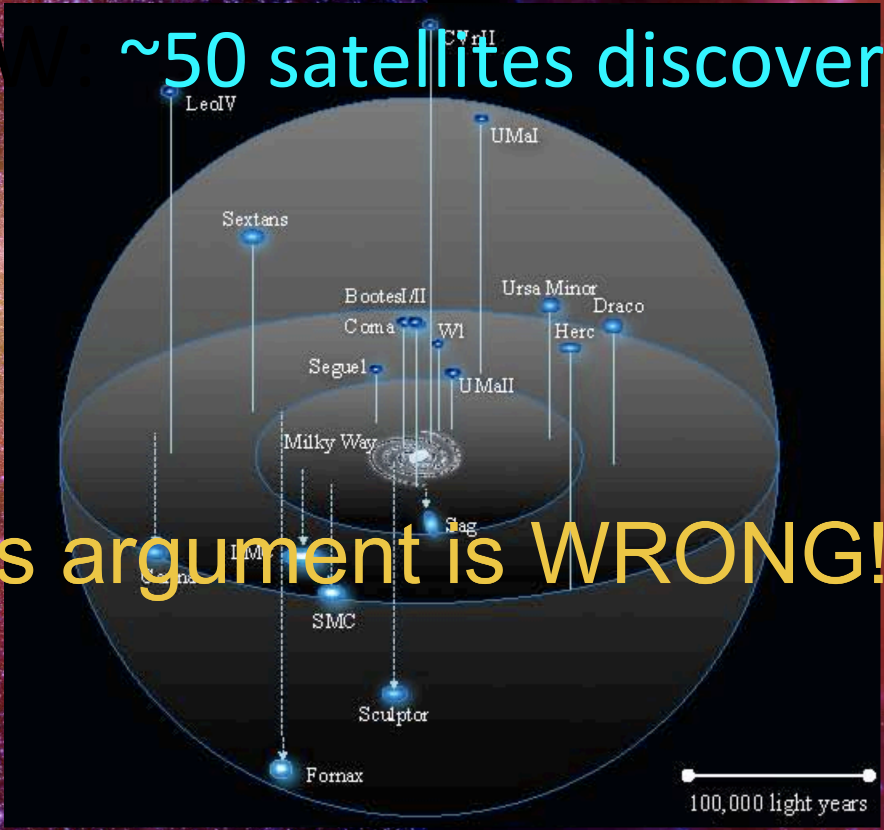
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy ‘12

cold dark matter

warm dark matter

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

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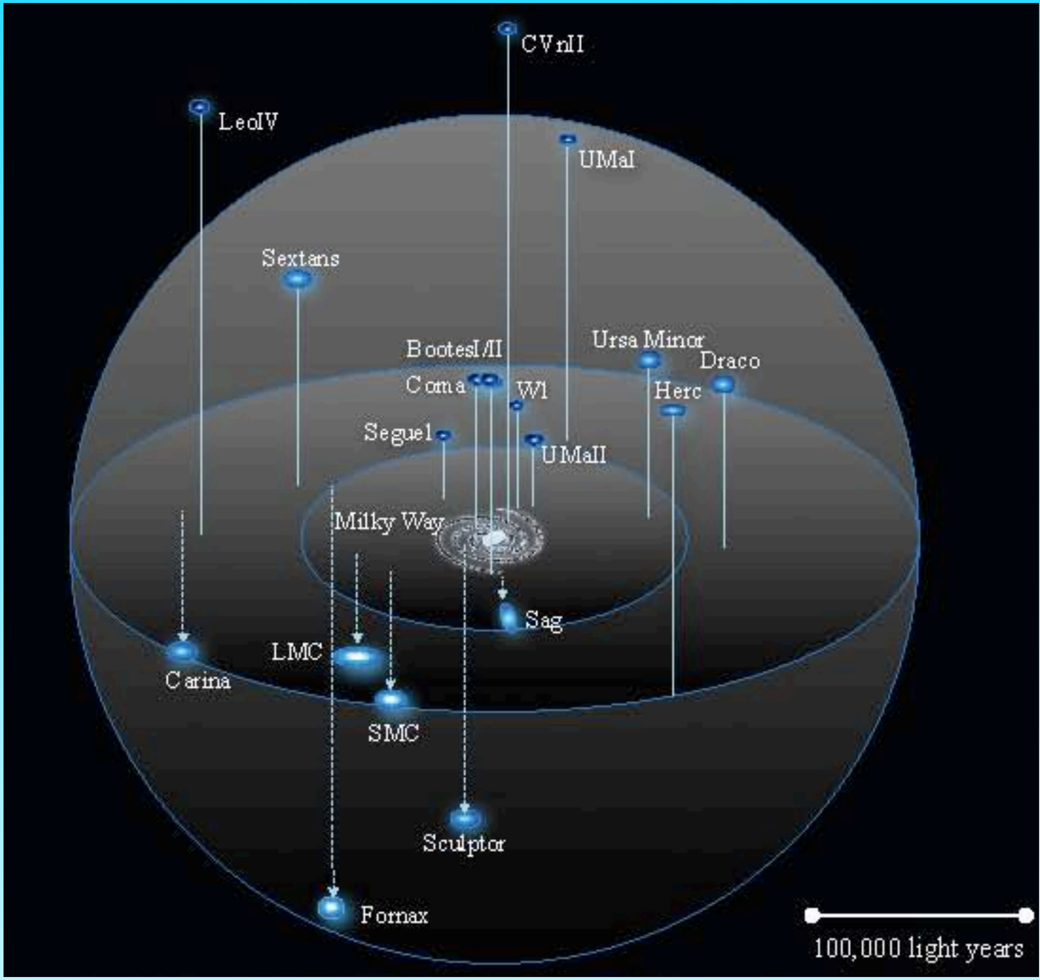
The MW satellite luminosity function

How many satellites are there in the MW?

About 55 satellites known in the MW so far from partial surveys (e.g. SDSS, Pan-STARRS, DES)

Can infer total population from survey selection function, assuming a radial distribution (from simulations)

(Newton+18, Koposov+08, Tollerud+08, Hargis+14)



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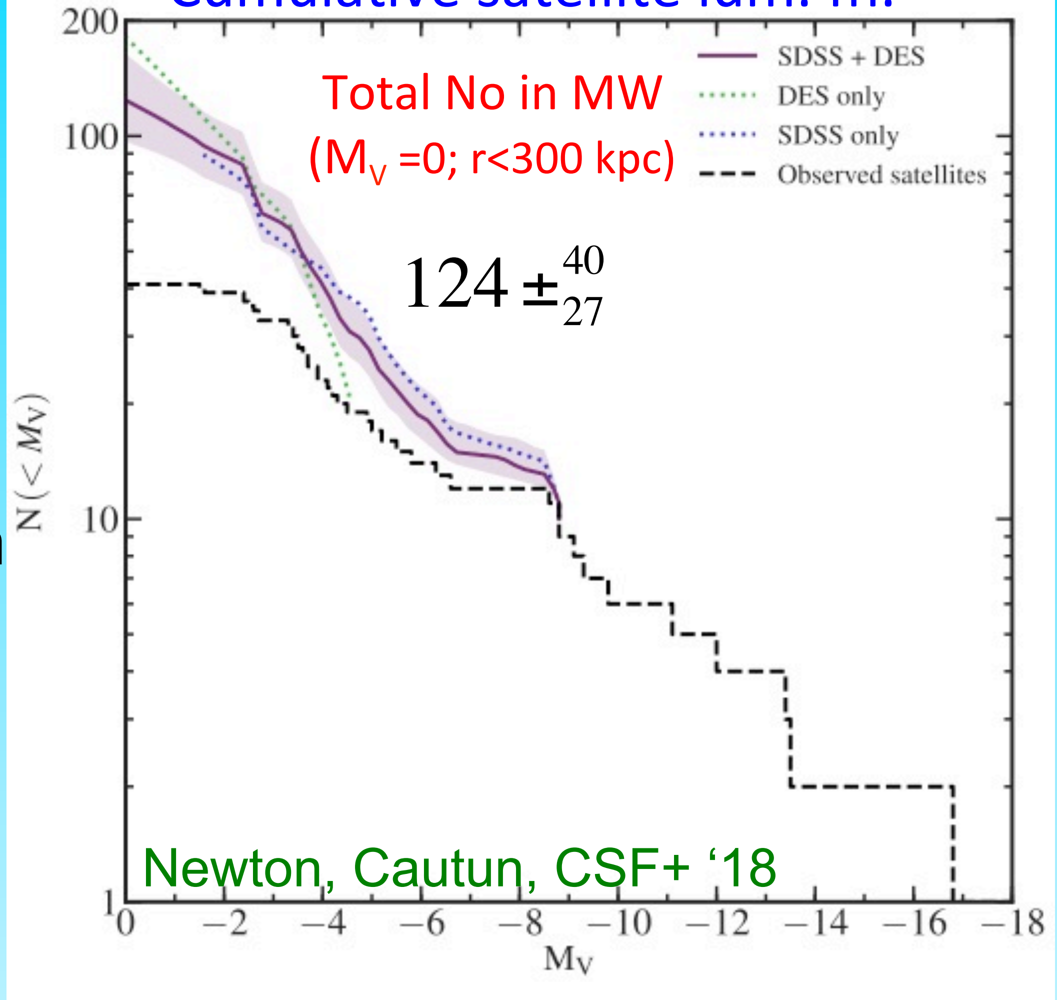
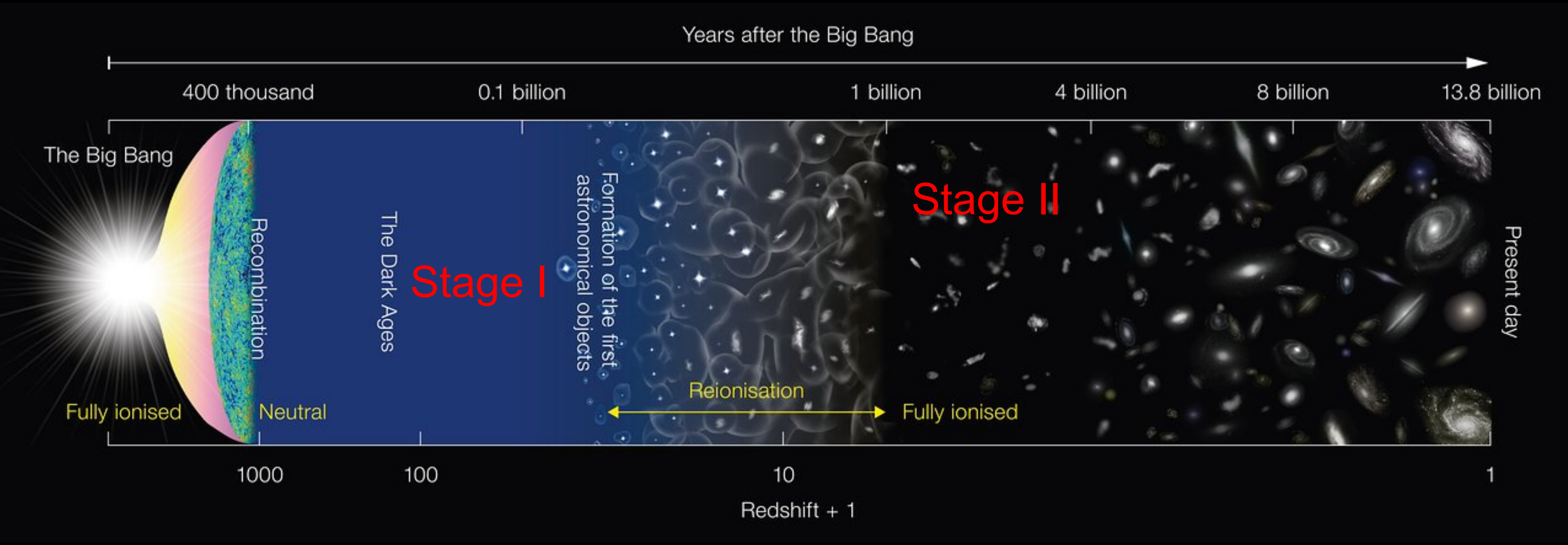
Cumulative satellite lum. fn.




Most subhalos never make a galaxy!

The two stages of galaxy formation



Stage I: Galaxies begin to form during the "dark ages"

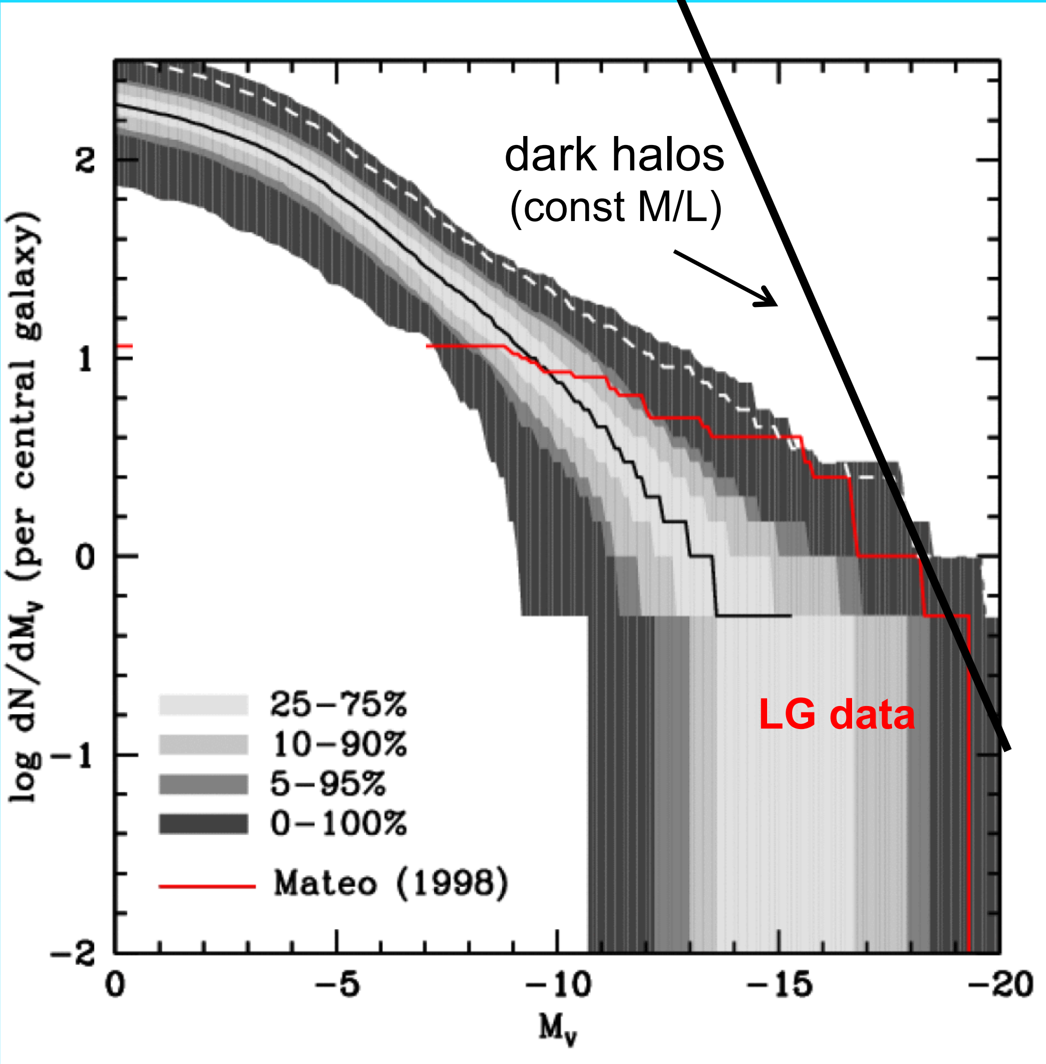
First stars reionize H and heat it up to 10^4K → prevents gas from cooling in halos of "T_{vir}" < 10^4K – galaxy formation is interrupted

Stage II: Halos with "T_{vir}" > 10^4K form → galaxy formation resumes

Luminosity Function of Local Group Satellites

University of Durham

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

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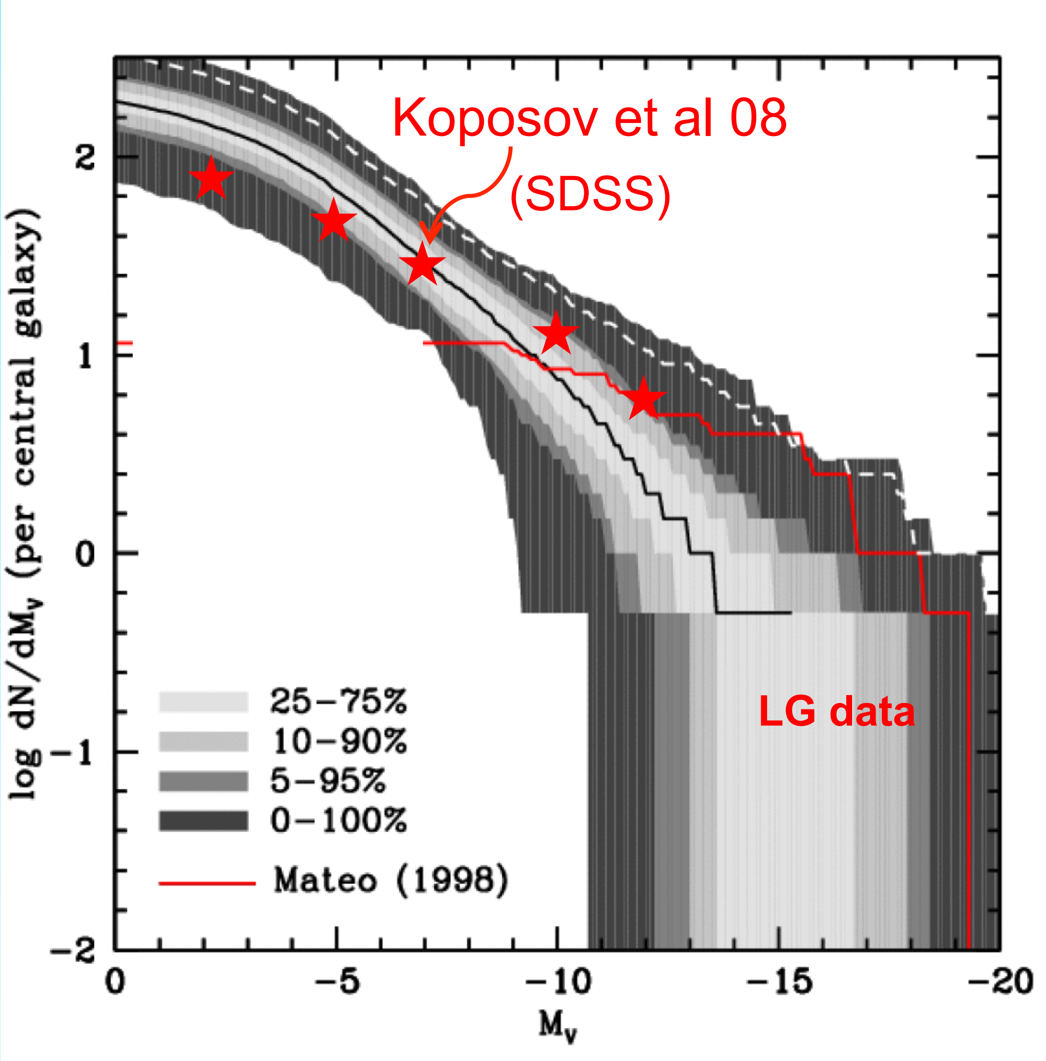

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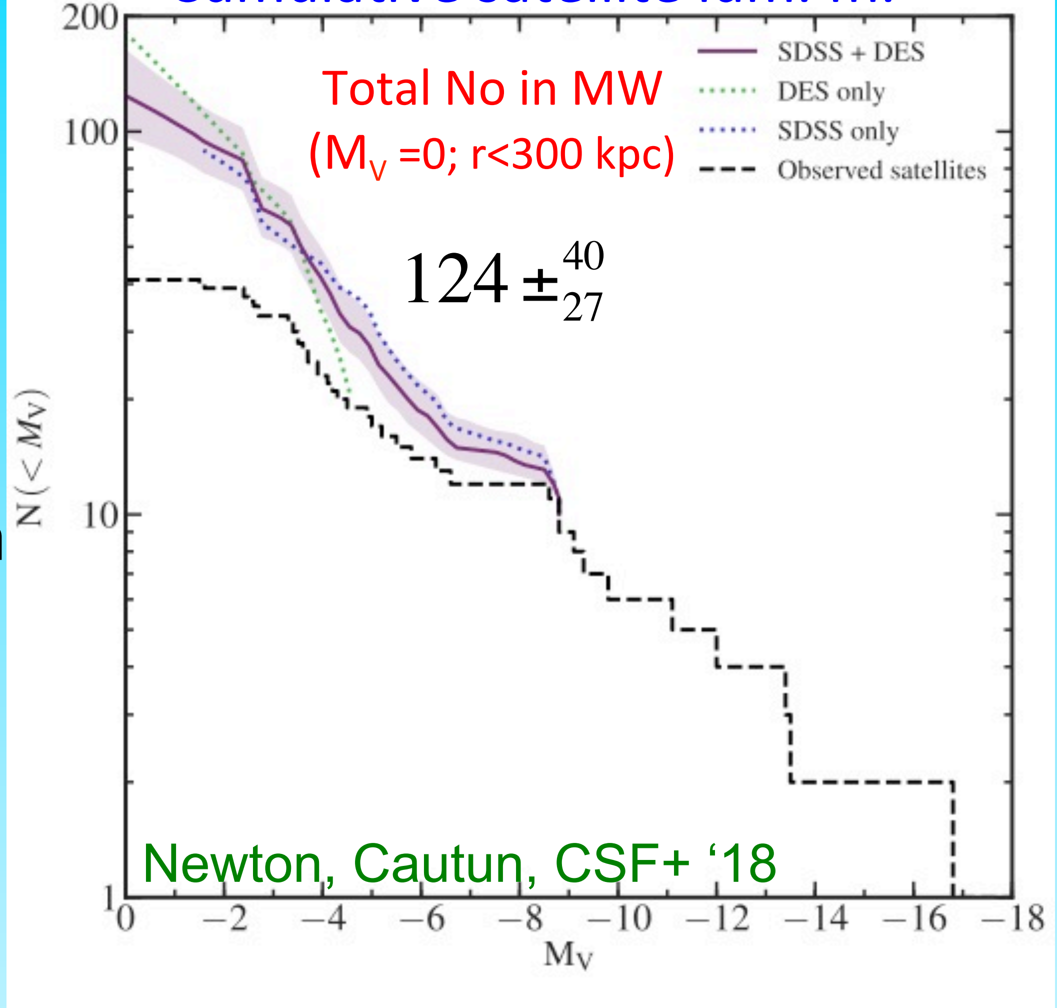

The MW/M31 sat. luminosity function

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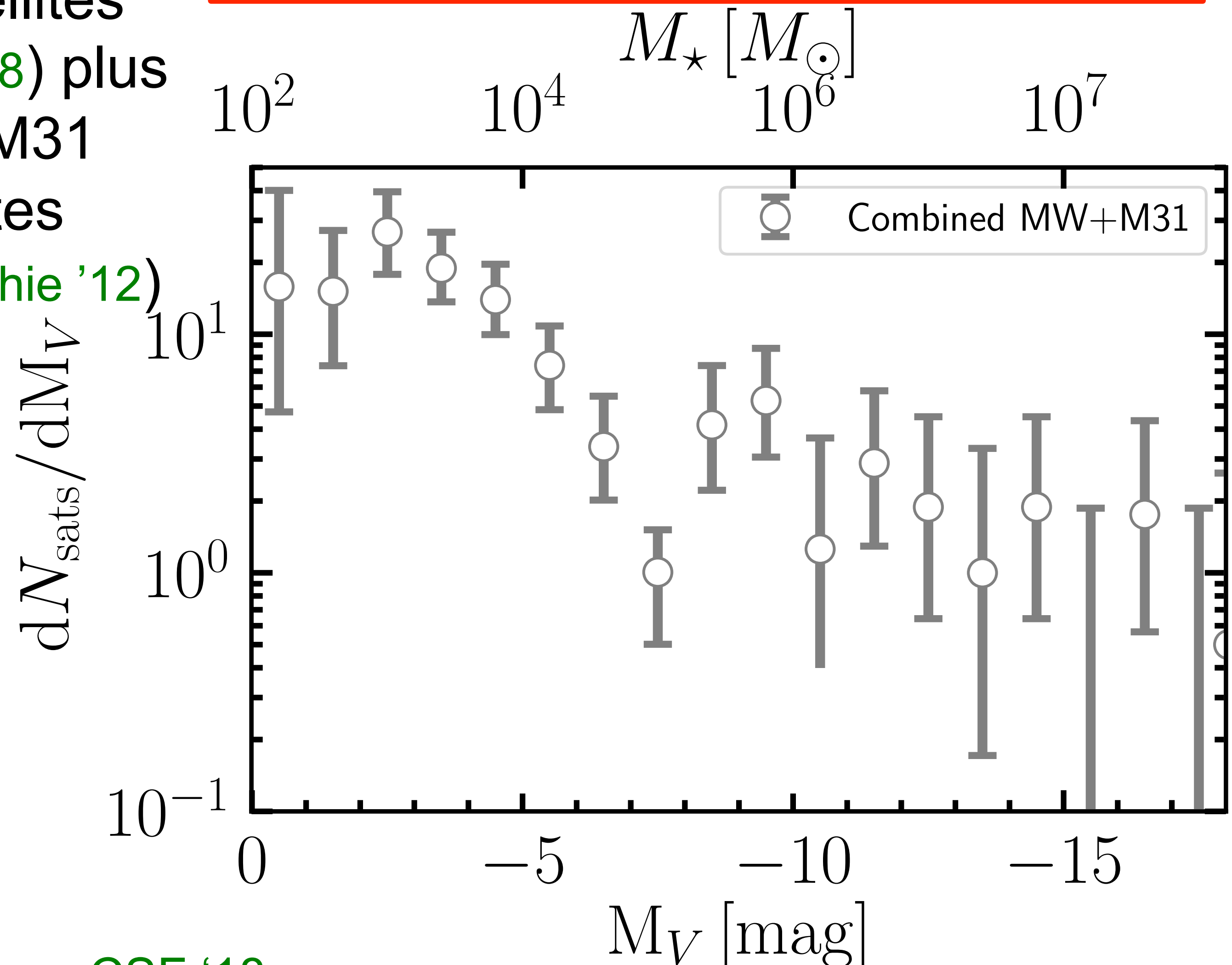
Differential satellite luminosity function

MW satellites (Newton+ '18) plus M_V<-8 M31 satellites (Mcconnachie '12)



Bose, Deason, CSF '18

The 2 populations of galactic satellites

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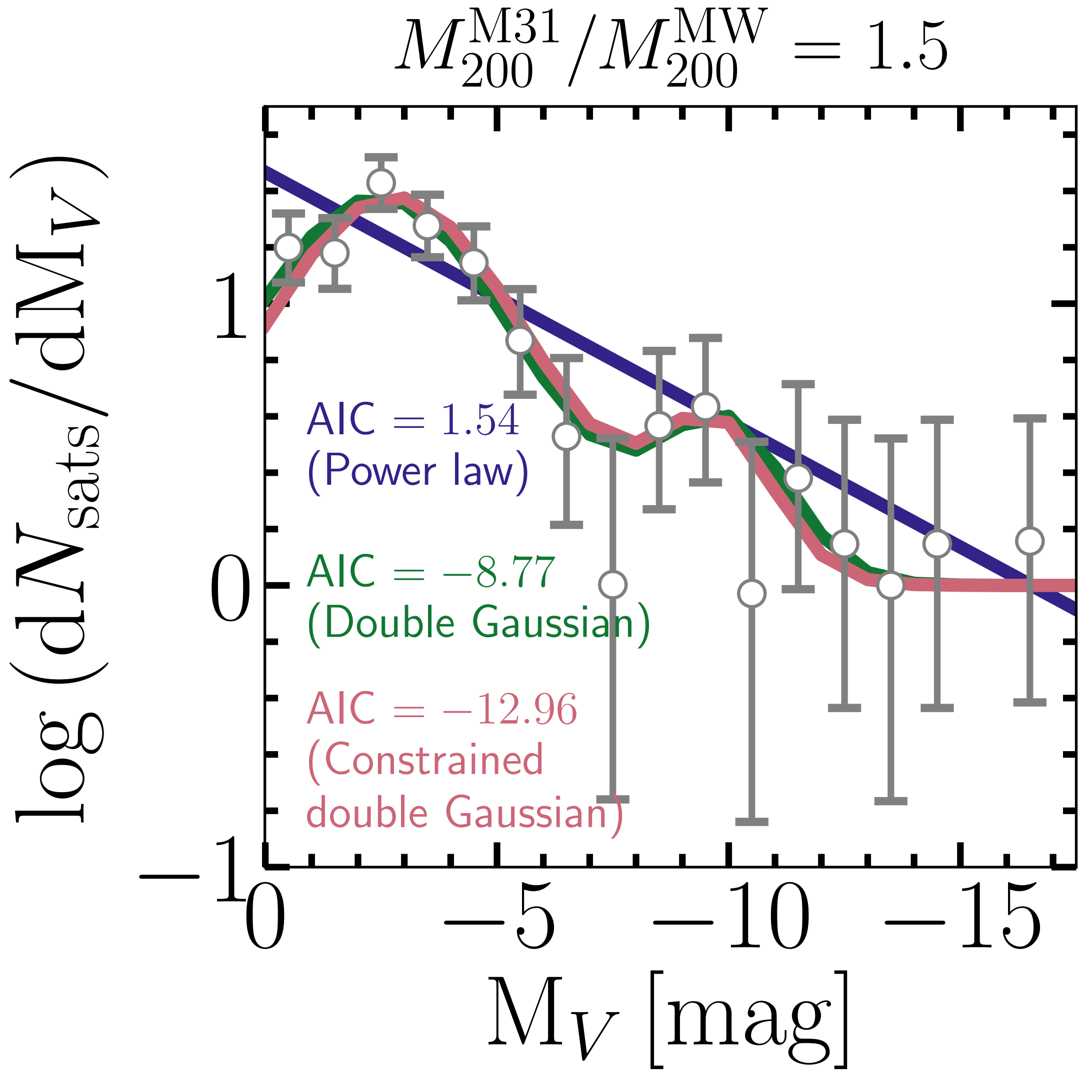
Fit 3 models and compare using Akaike Information Criterion (AIC)

Model	AIC
Power law	-1.5
Double Gaussian	-8.8
Constrained DG*	-13.0

*Assumes V_{cut}=30 km/s

Bose, Deason, CSF '18



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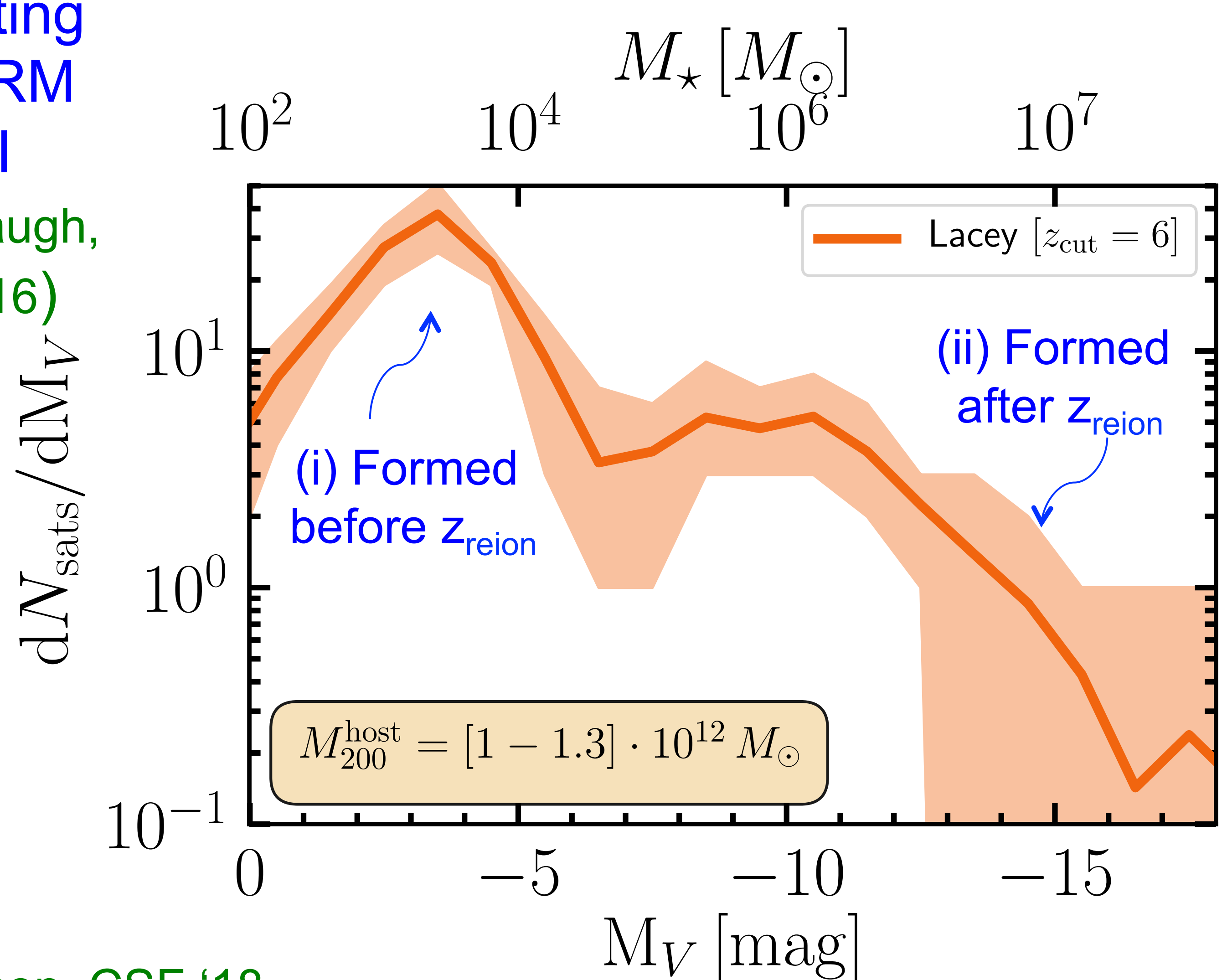
Theory vs data

Pre-existing GALFORM model

(Lacey, Baugh, CSF + '16)



Bose, Deason, CSF '18

Theory *vs* data

Pre-existing GALFORM model

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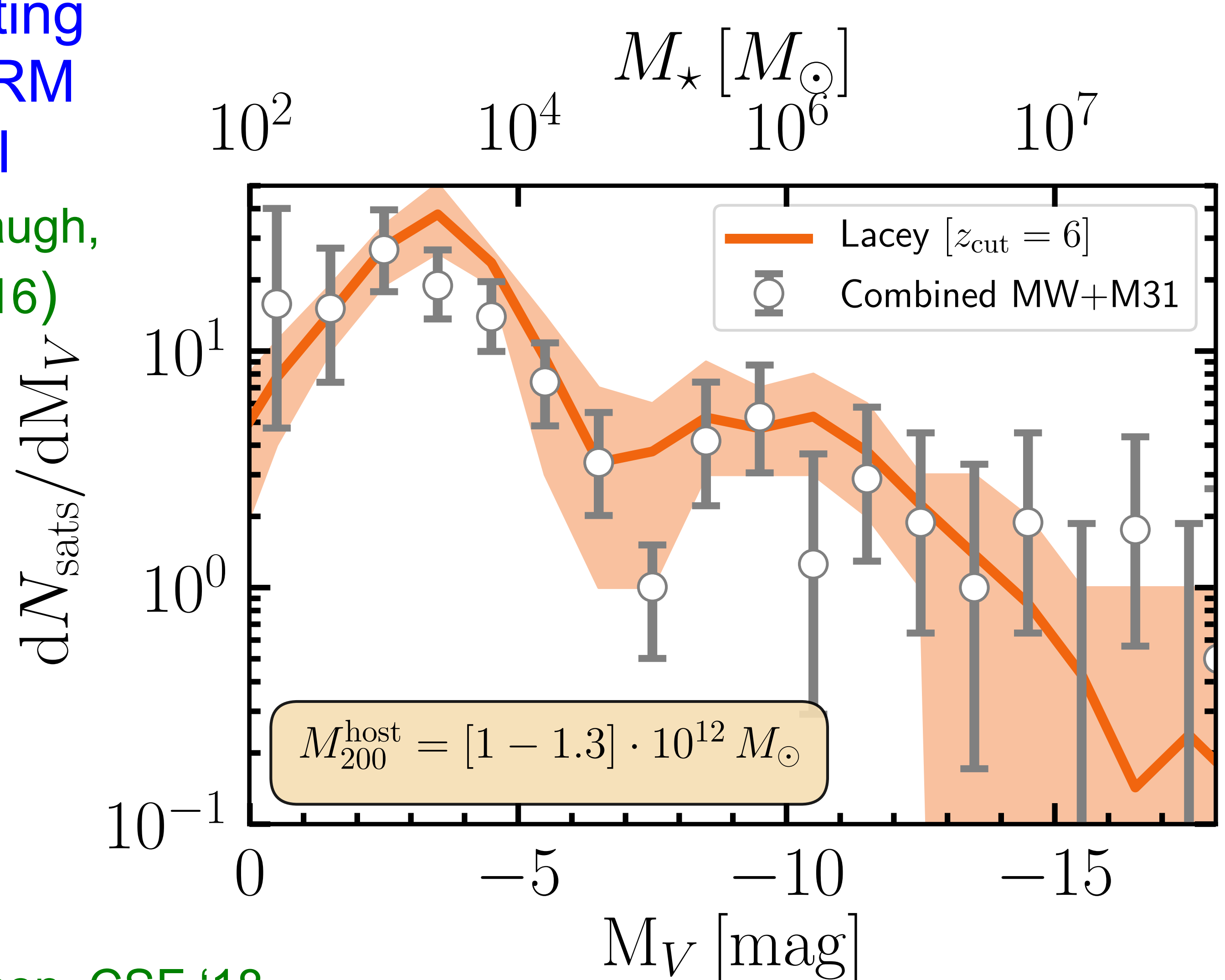

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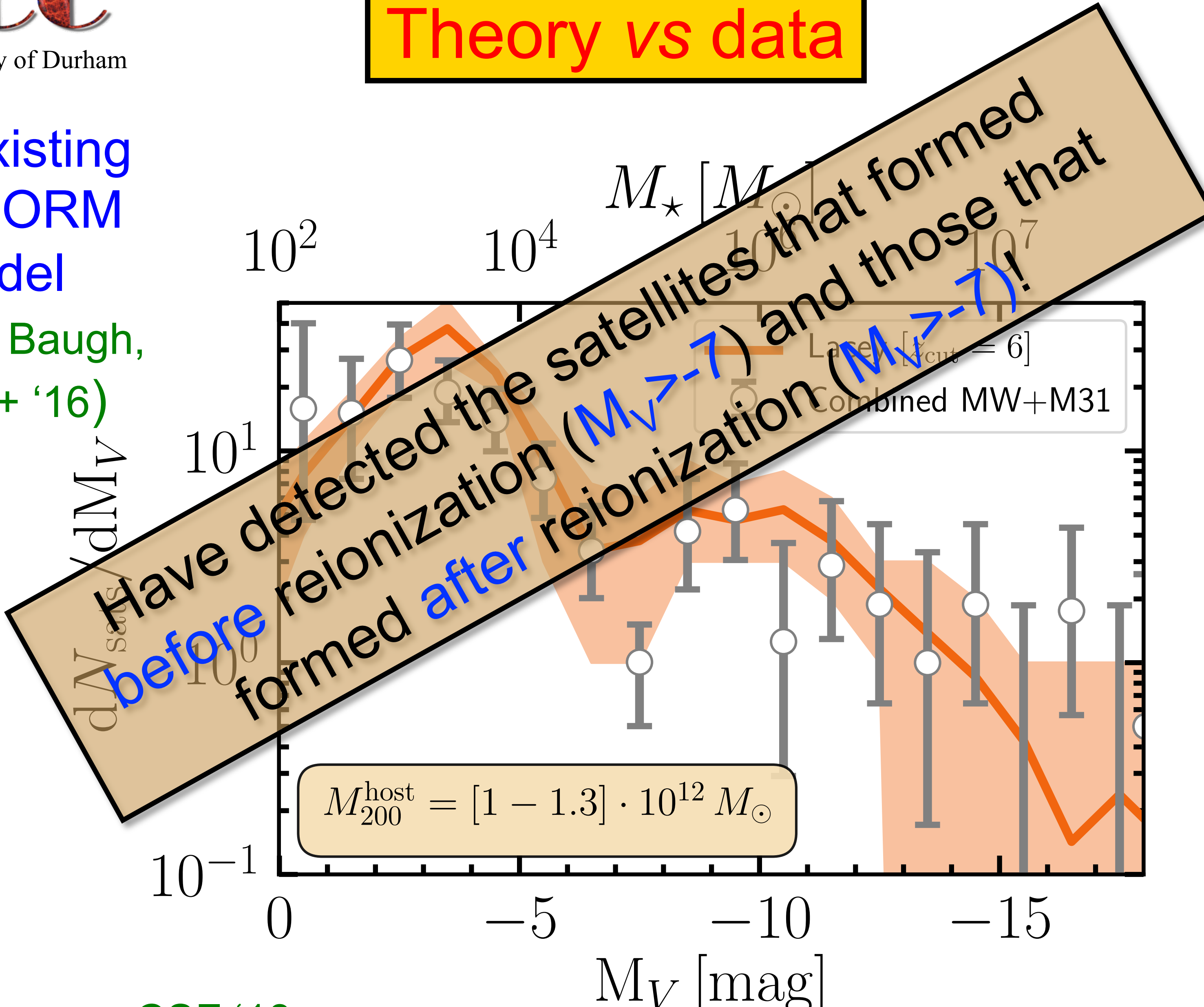

Bose, Deason, CSF '18

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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…

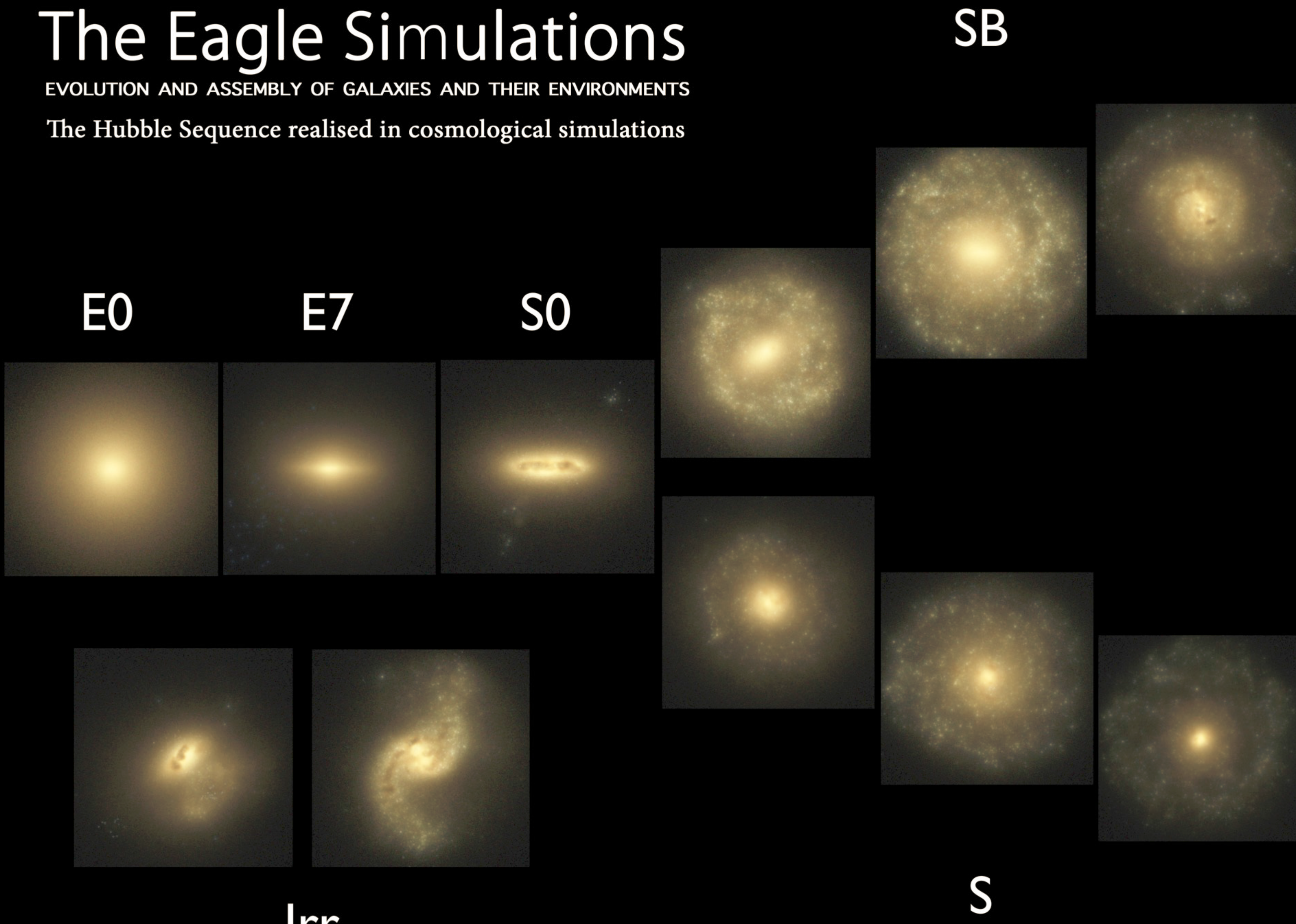
Durham University VIRGO ICC DiRAC PRACE

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

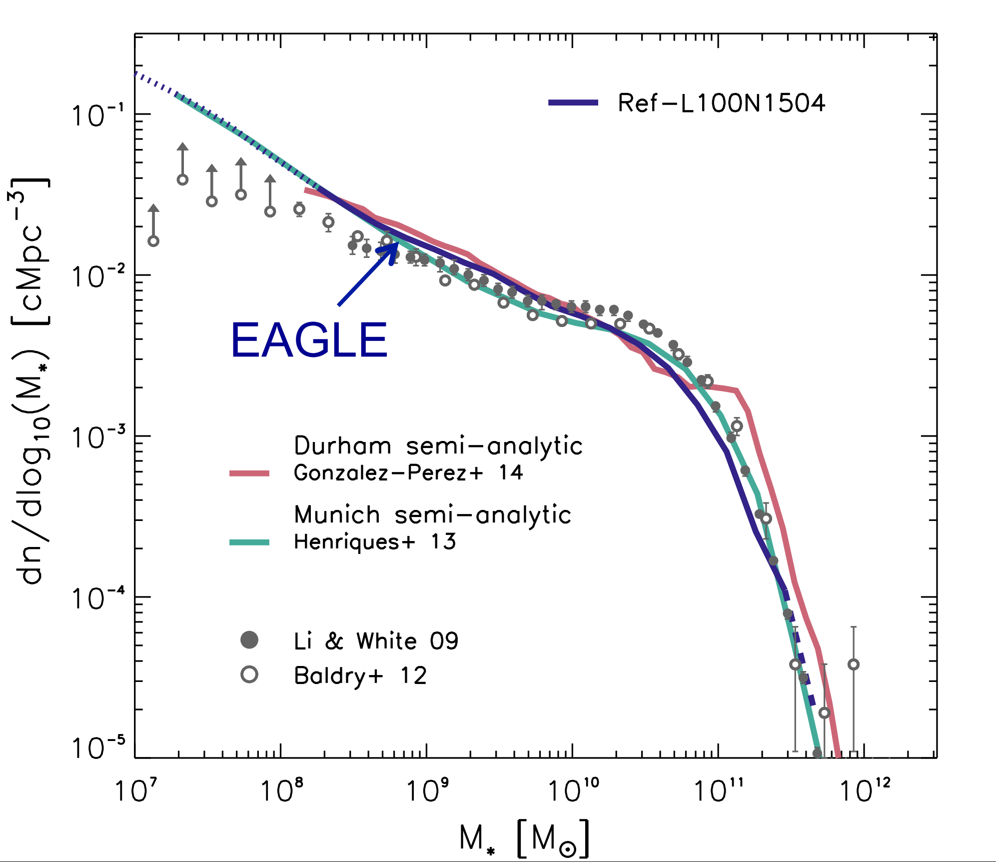
The Hubble Sequence realised in cosmological simulations



Trayford et al '15

Galaxy stellar mass function

Comparison to semi-analytic models



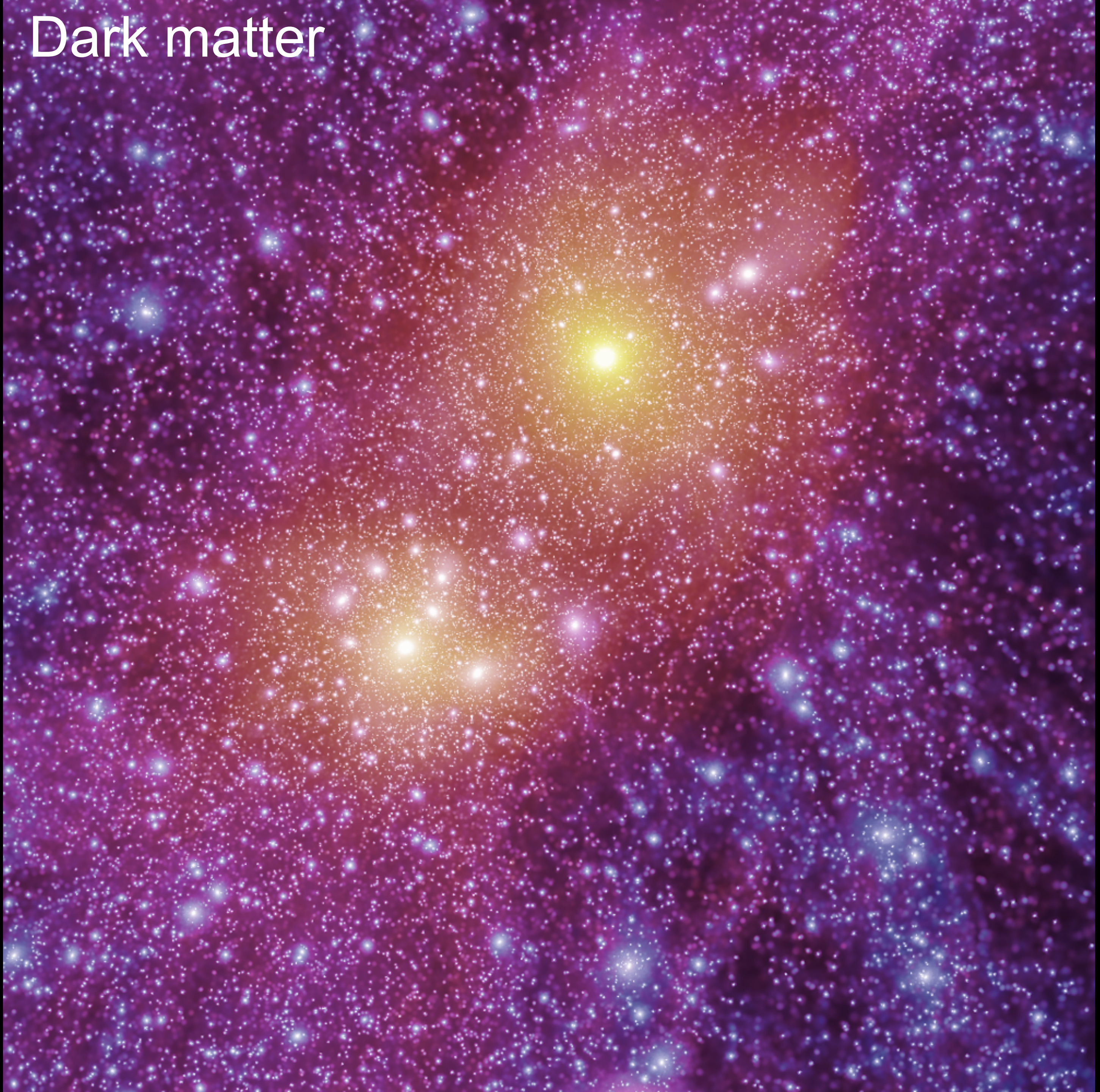
Schaye et al ‘15

APOSTLE
EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16



Stars

APOSTLE
EAGLE full
hydro
simulations

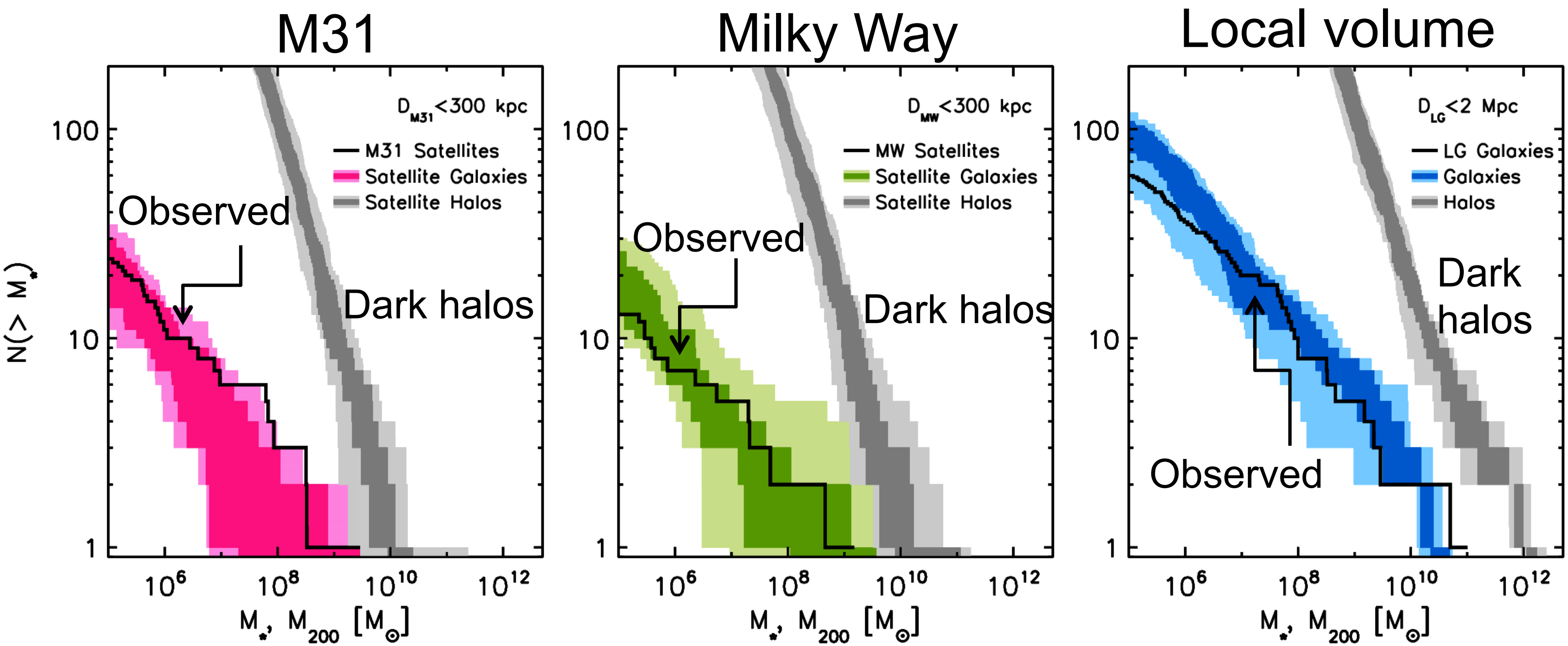
Local Group

Stars

Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

EAGLE Local Group simulation



Sawala, CSF et al '16

Fraction of dark subhalos

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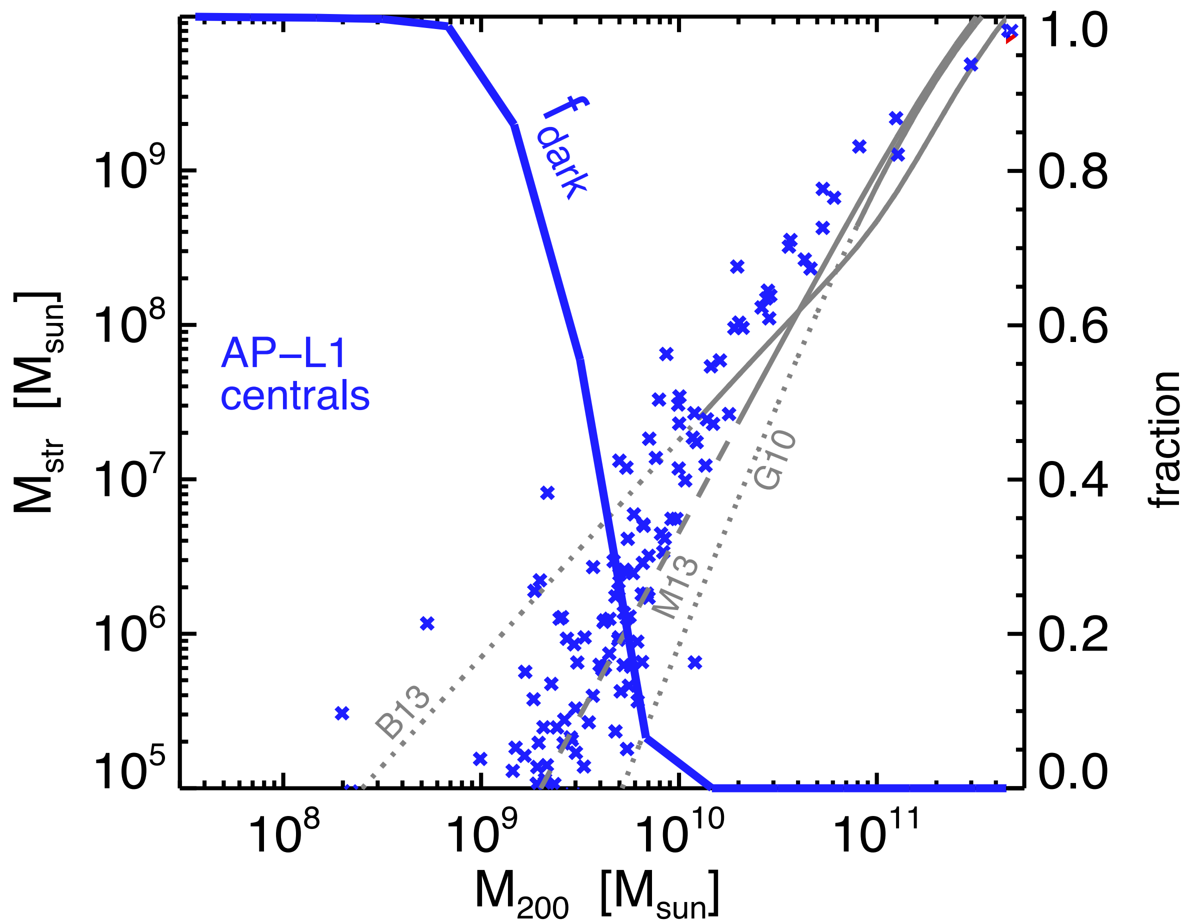
$$V_c = \sqrt{\frac{GM}{r}}$$

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



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

CDM theory predicts 2 populations of gal. satellites, formed (i) before and (ii) after reionization

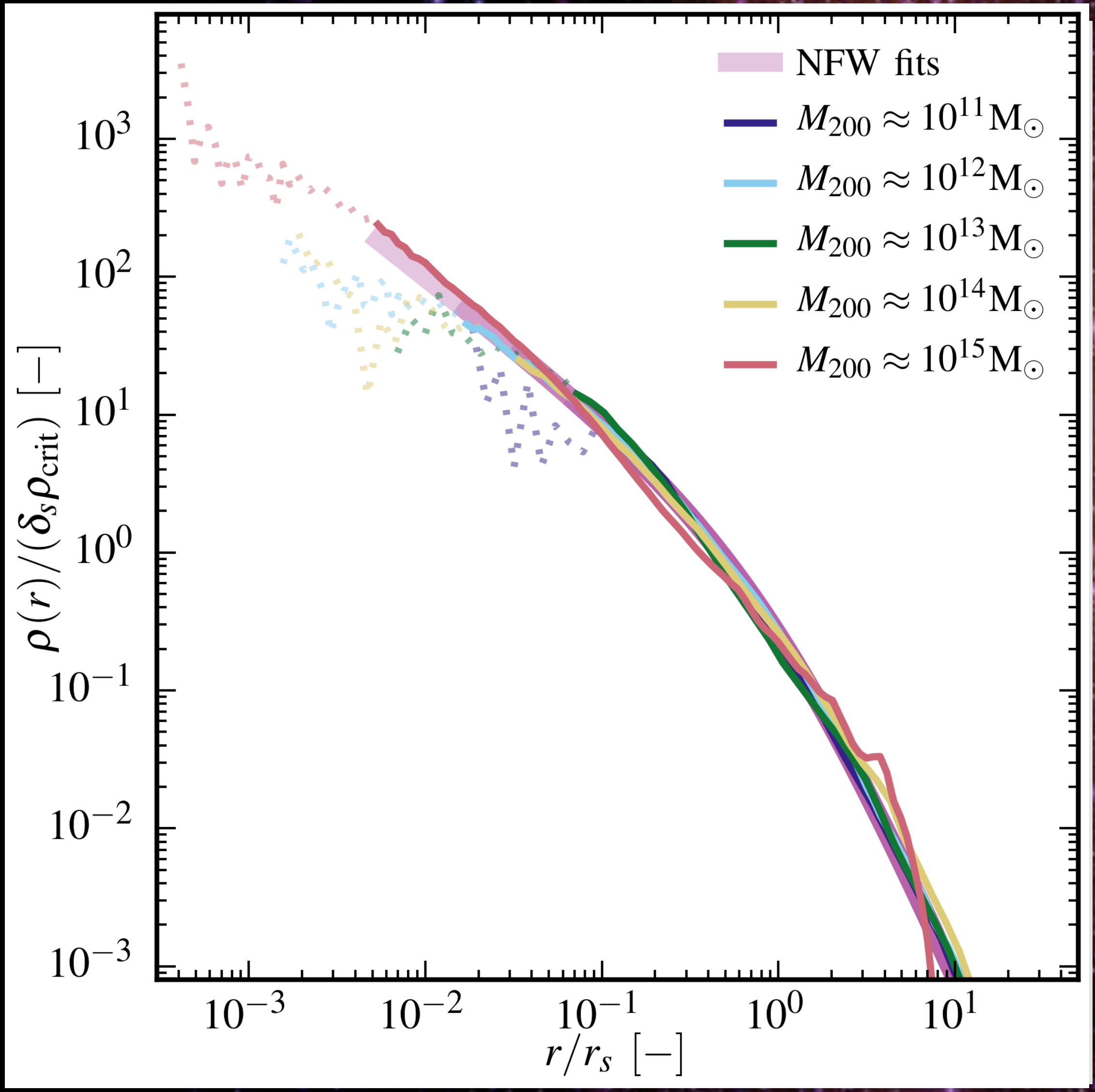
→

Seem to be present in the data

The MW satellite lum fn is compatible with CDM

Can the inner structure of satellites provide a test?

The Density Profile of Cold Dark Matter Halos



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

Density profiles are “cuspy” - no `core’ near the centre

Fitted by simple formula:

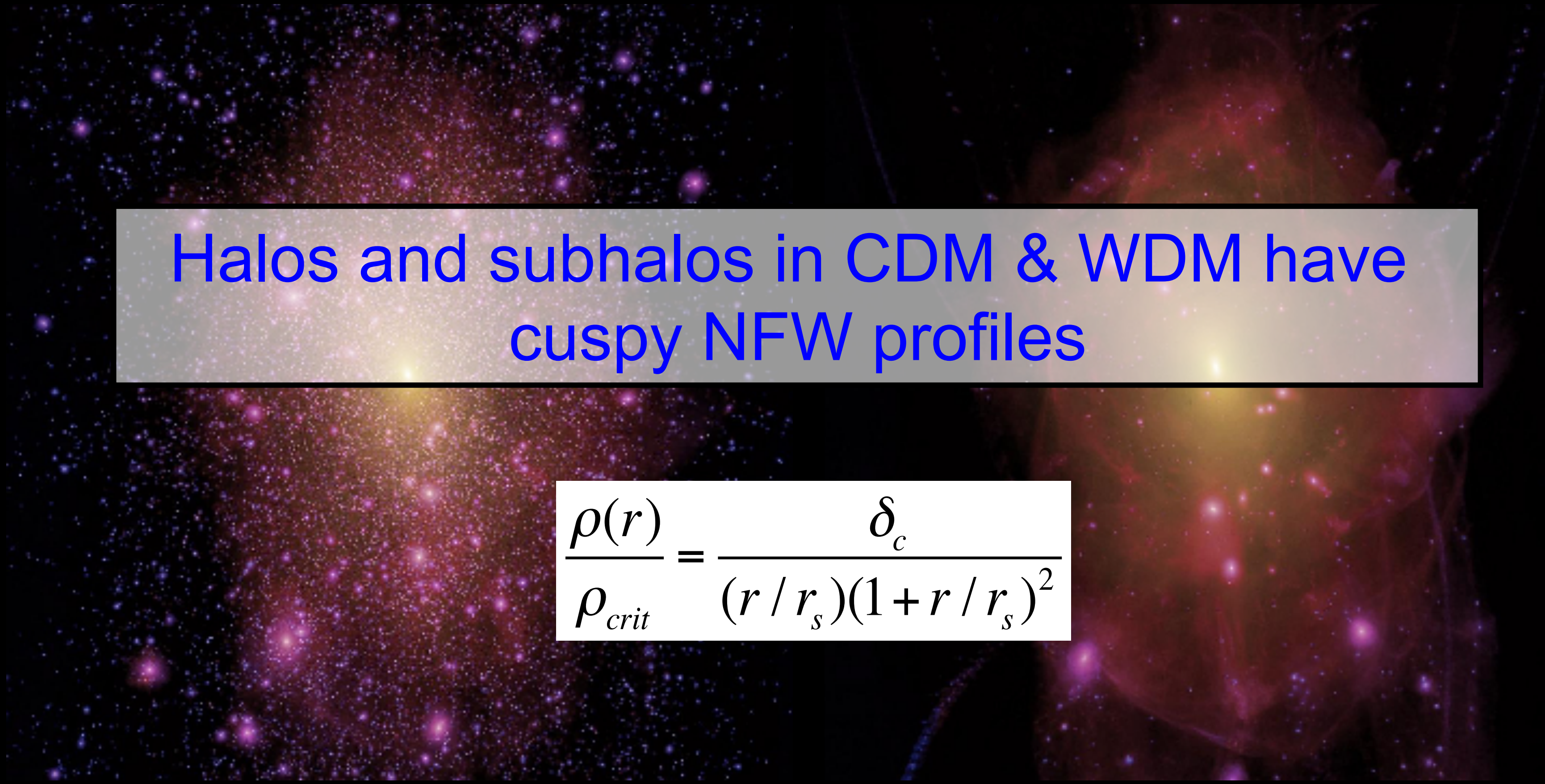
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White ’97)

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

The core-cusp problem

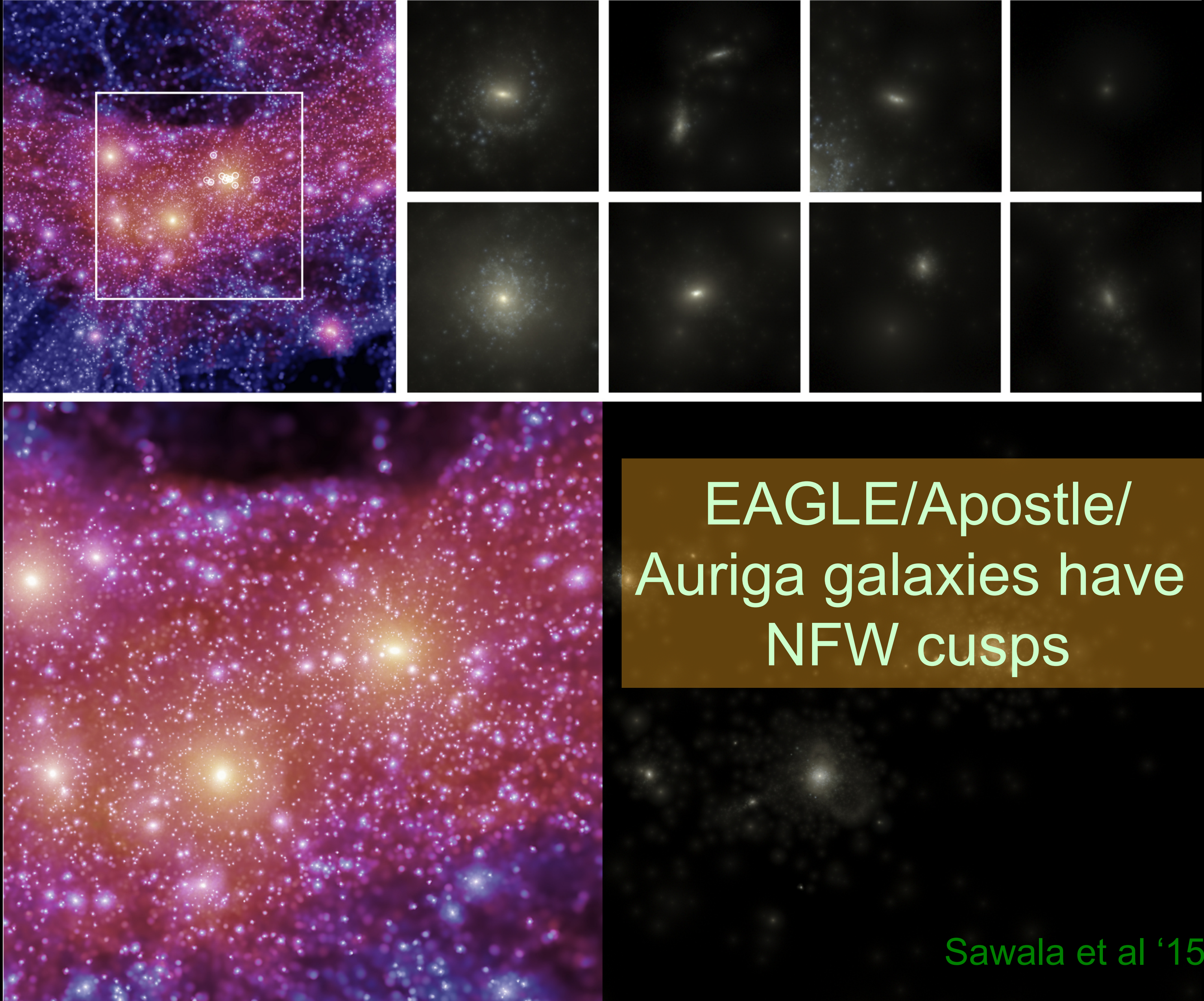
cold dark matter   warm dark matter

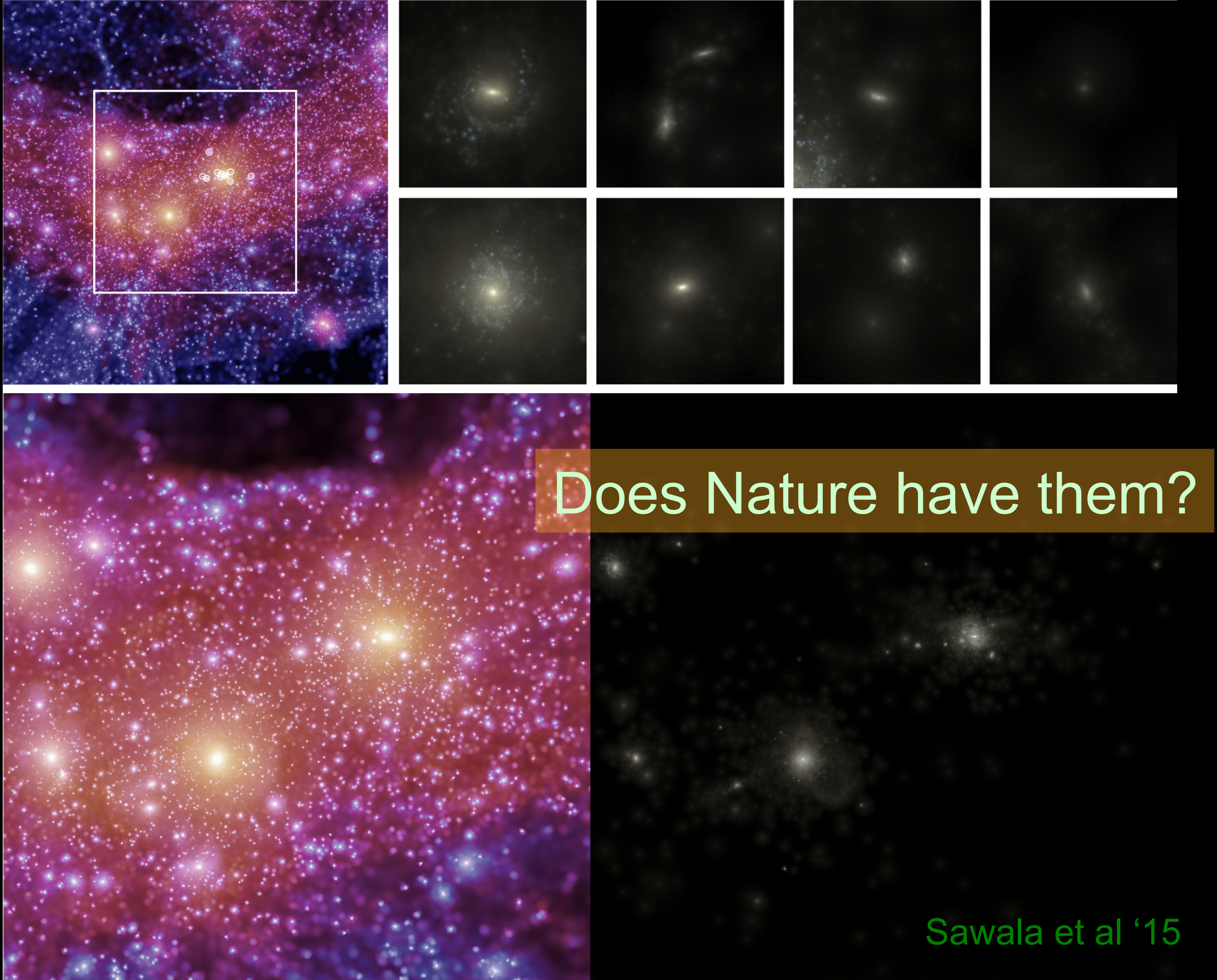


Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

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


EAGLE/Apostle/
Auriga galaxies have
NFW cusps
Sawala et al '15



Does Nature have them?
Sawala et al ‘15

There is NO evidence for cores in dwarf galaxies

(Existing data are consistent with either cusps or cores)

(e.g Strigari+ 15, Genina +18, Oman+ 18)

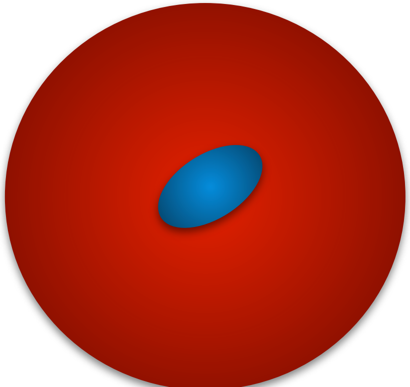
But if cores were found in halos, would this rule out CDM (and WDM)?

The physics of core formation

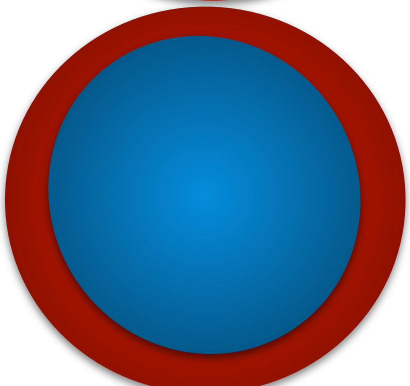
Cusps → cores

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

I.



II.



Navarro, Eke & Frenk (1996)

The cores of dwarf galaxy haloes L75

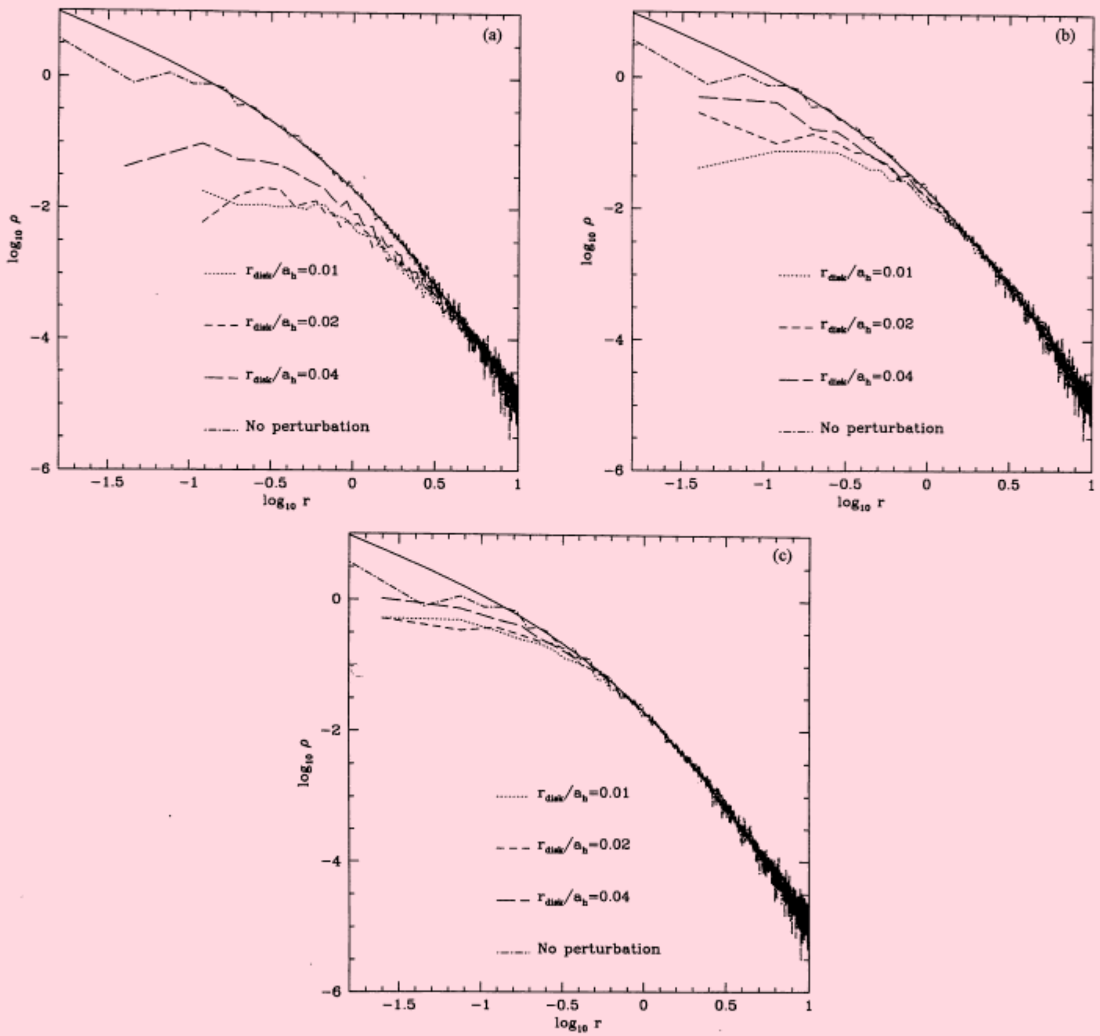


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

The physics of core formation

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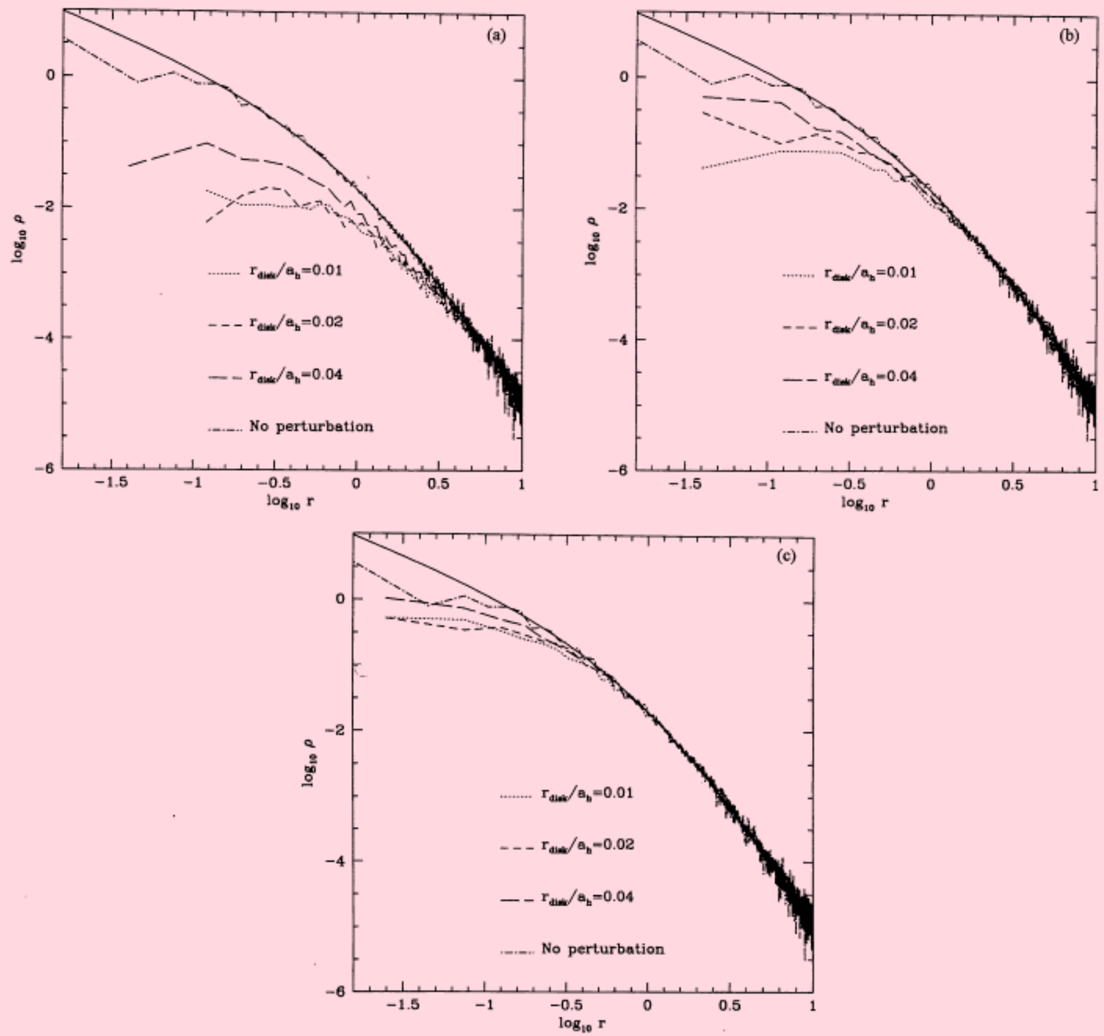
Cores may also form by repeated fluctuations in central potential (e.g. by SN explosions) (Read & Gilmore '05; Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

The cores of dwarf galaxy haloes L75



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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

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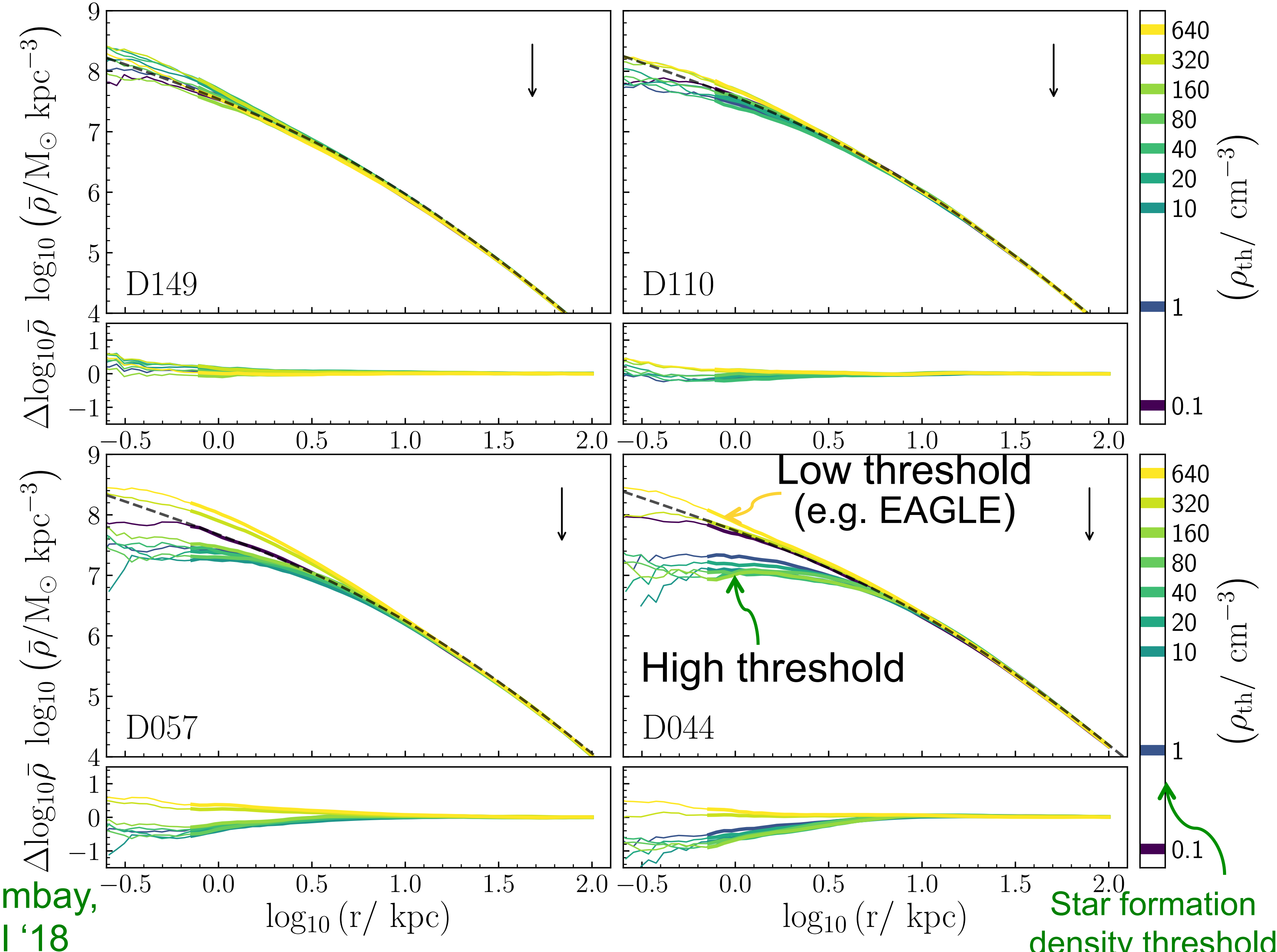
Cores or cusps in simulations?

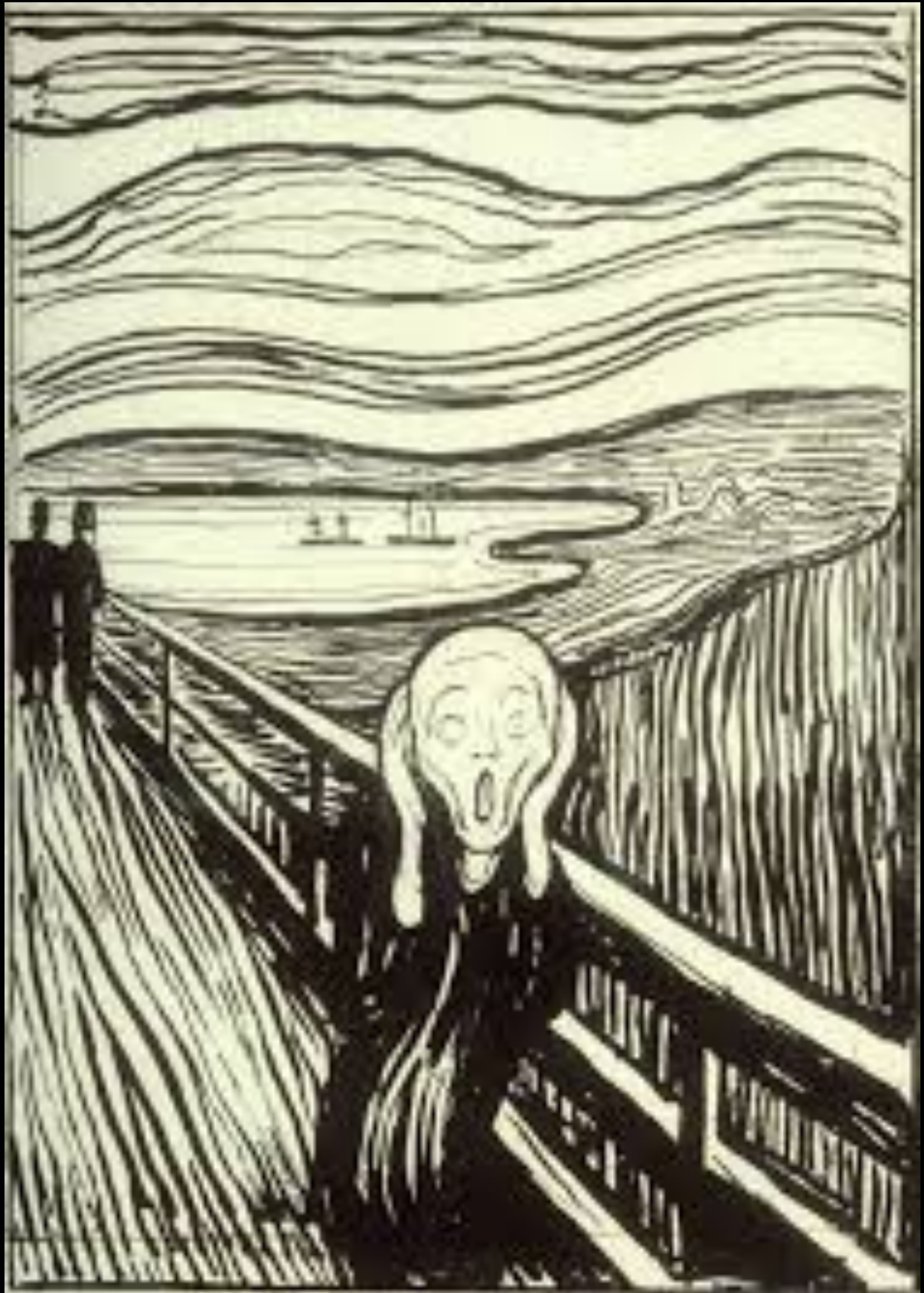


Benitez-Llambay, CSF et al '18

There is NO strong evidence for cores in dwarf galaxies

(Existing data are consistent with either cusps or cores)

But in any case cores can be easily created by baryon effects



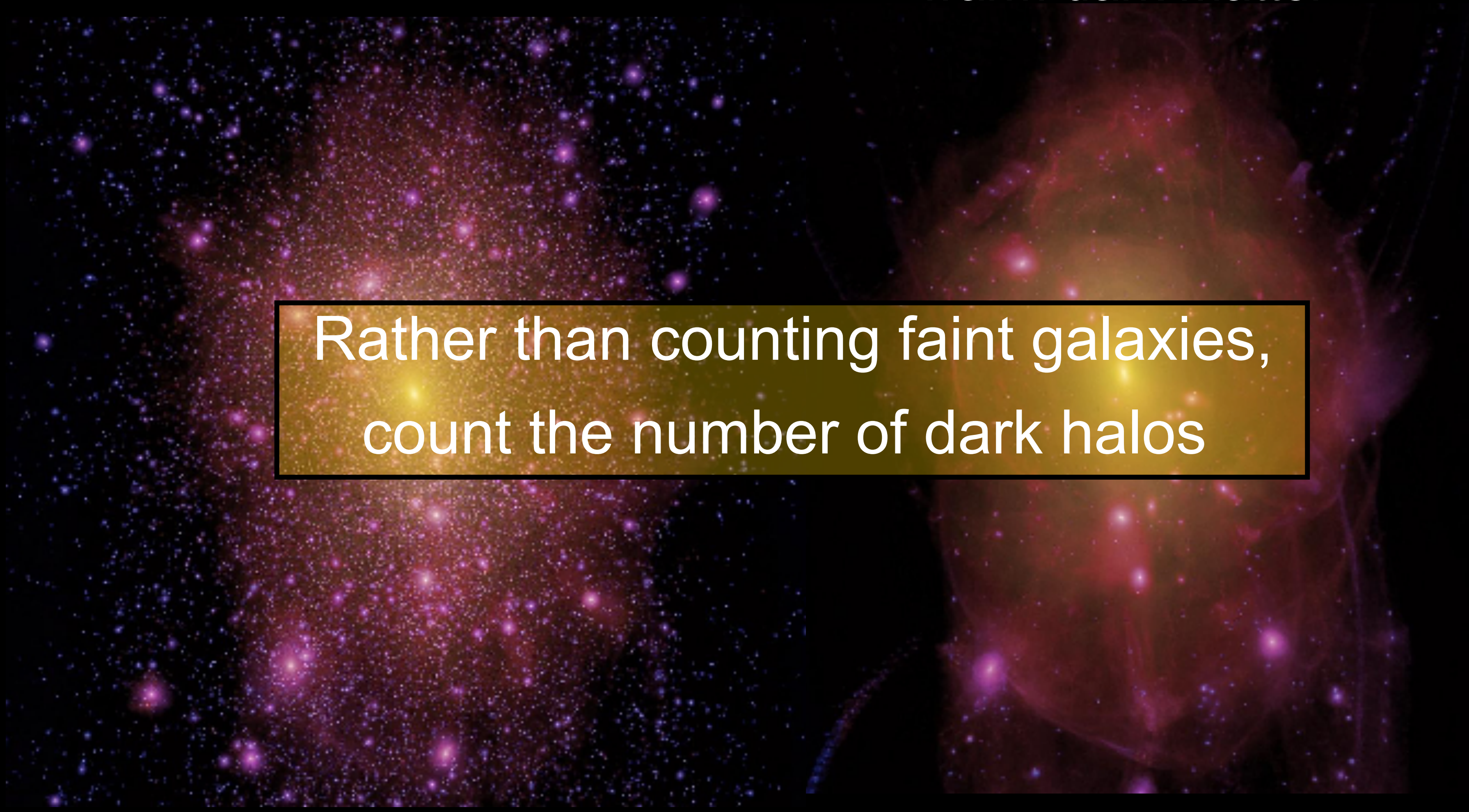
Is there any way we can distinguish CDM from WDM?

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

Can we distinguish CDM/WDM?

cold dark matter

warm dark matter



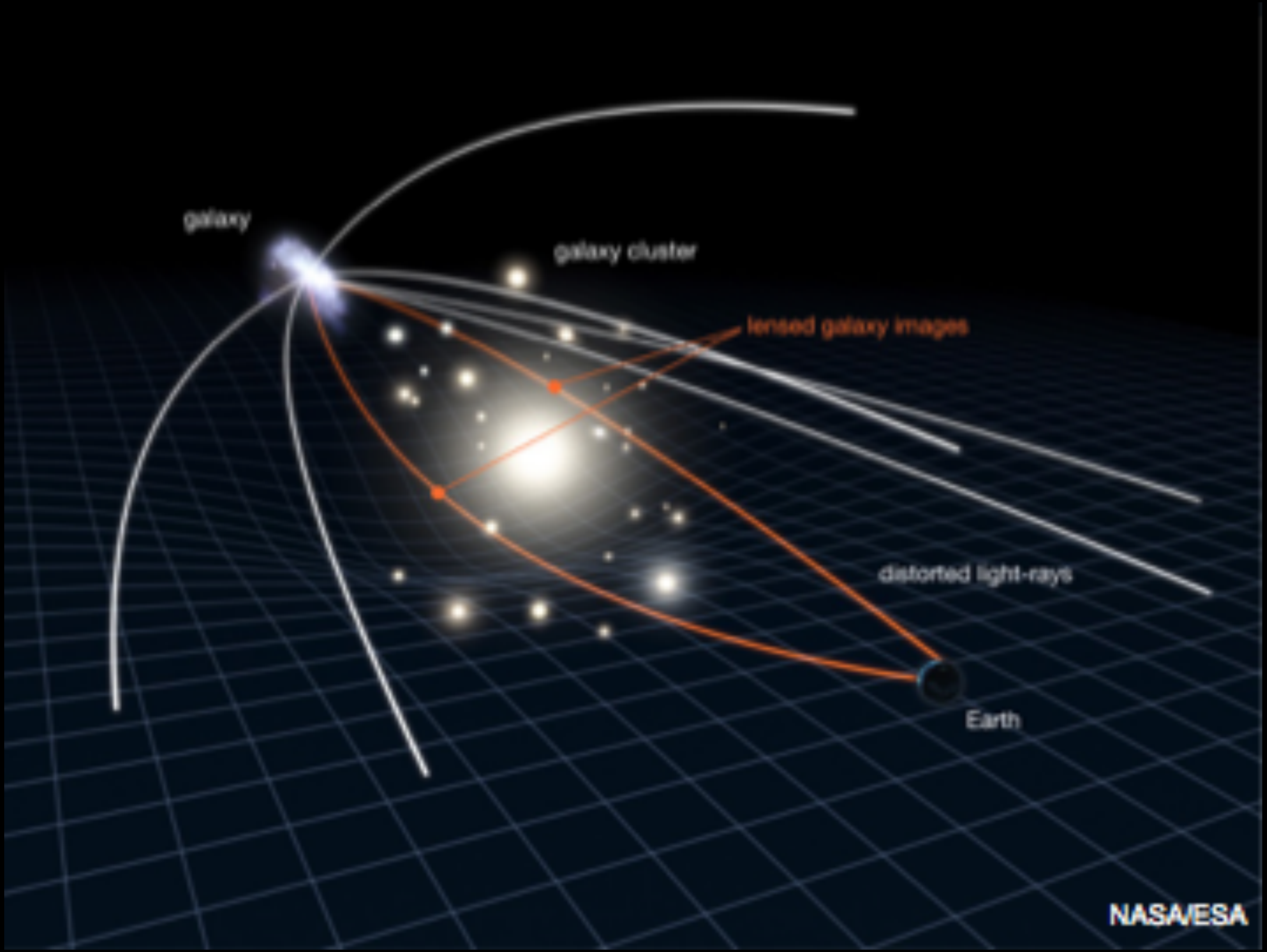
Can we distinguish CDM/WDM?

cold dark matter | warm dark matter

Dark halos can be detected through gravitational lensing

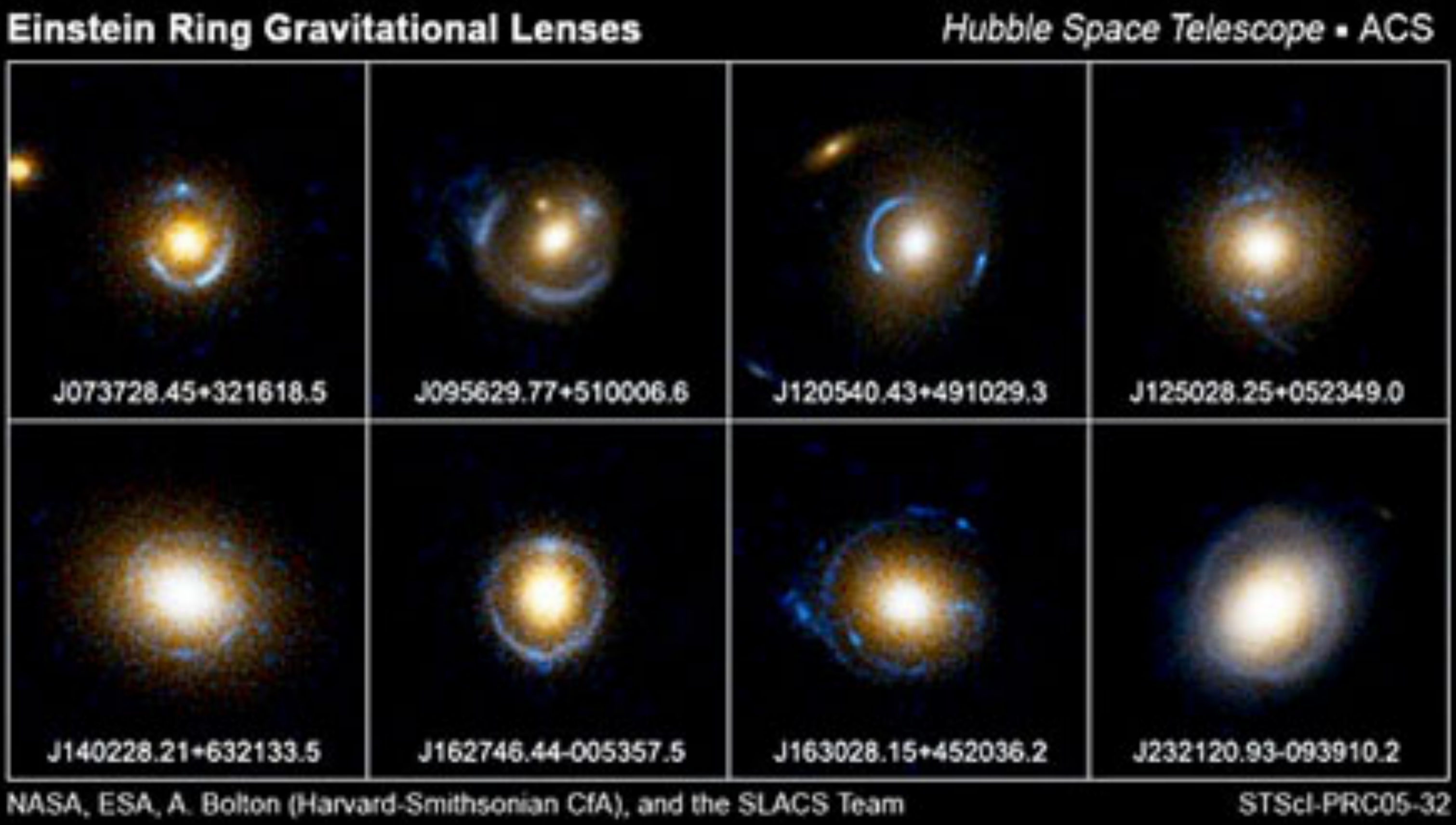
How to rule out CDM

Gravitational lensing: Einstein rings

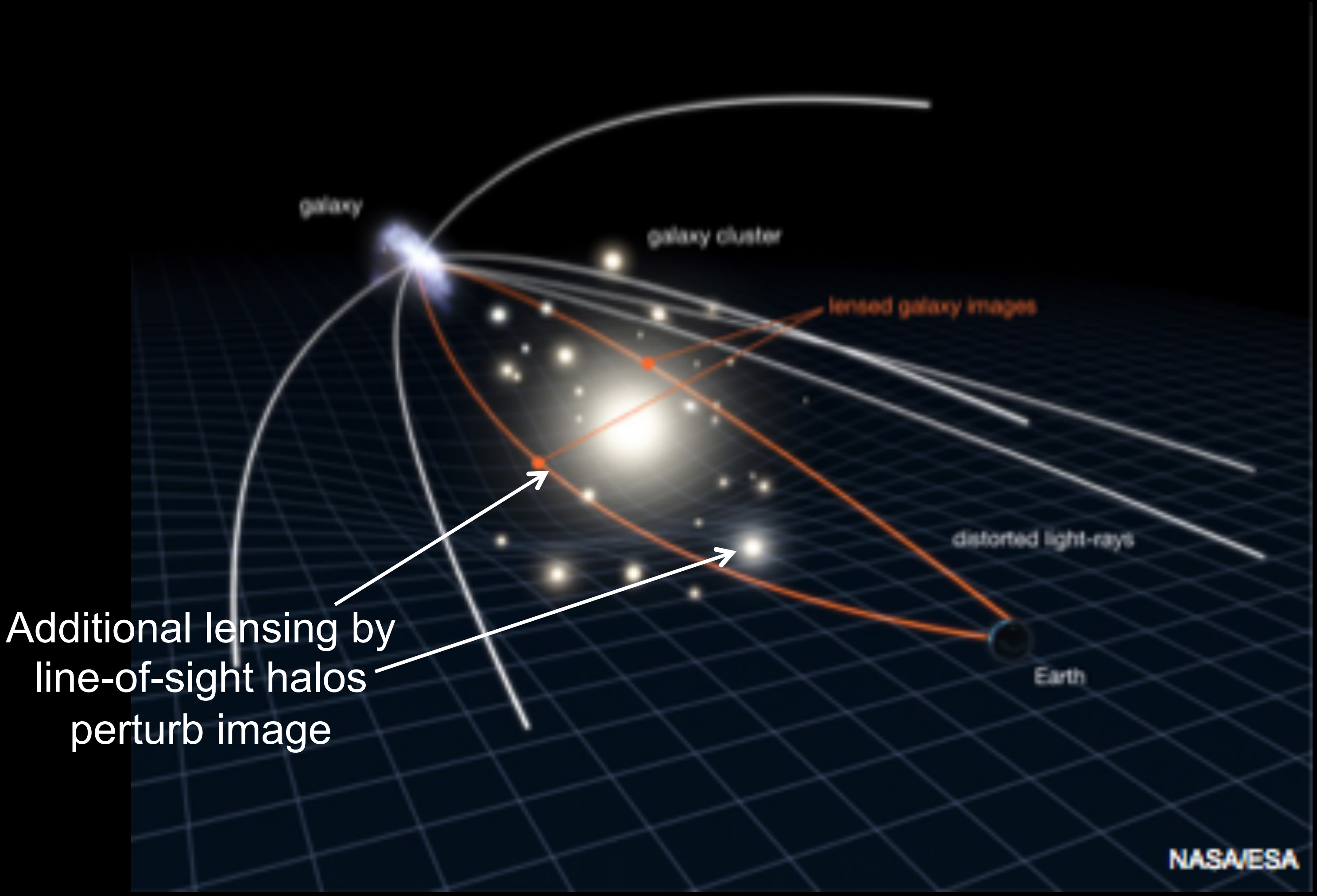


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



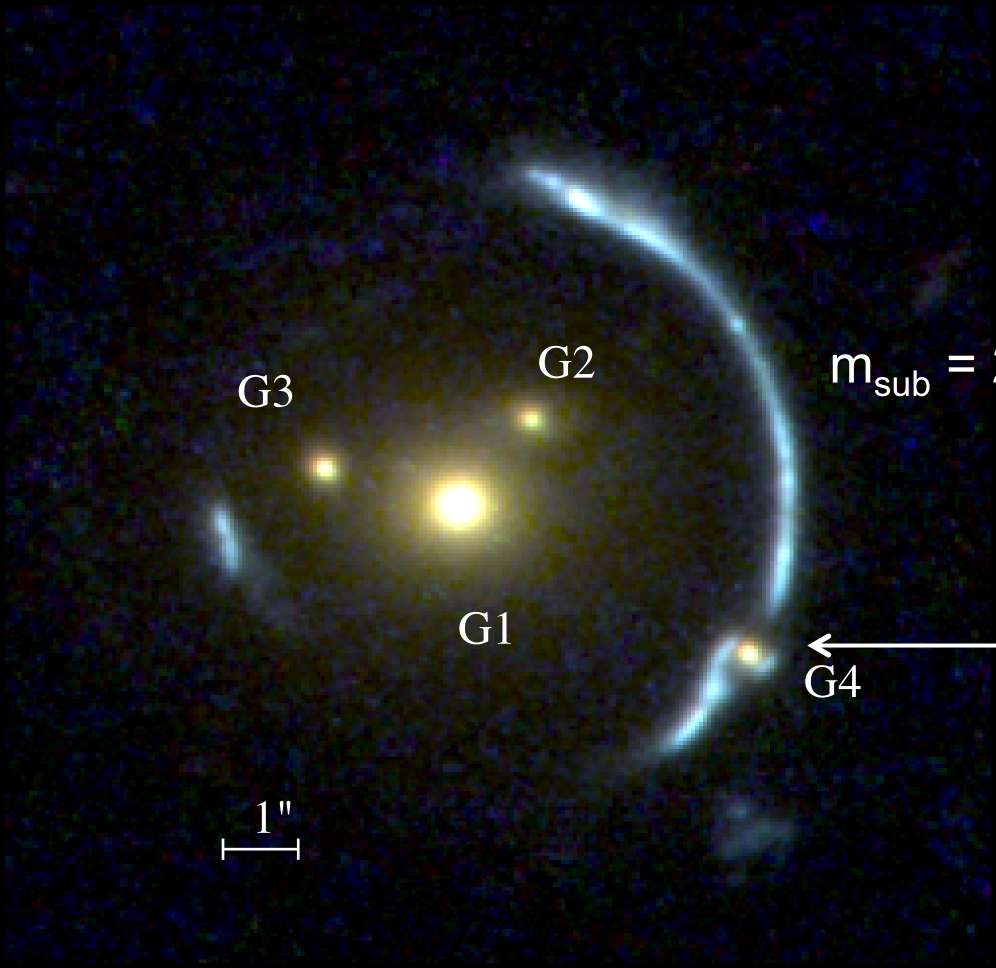
Gravitational lensing: Einstein rings



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

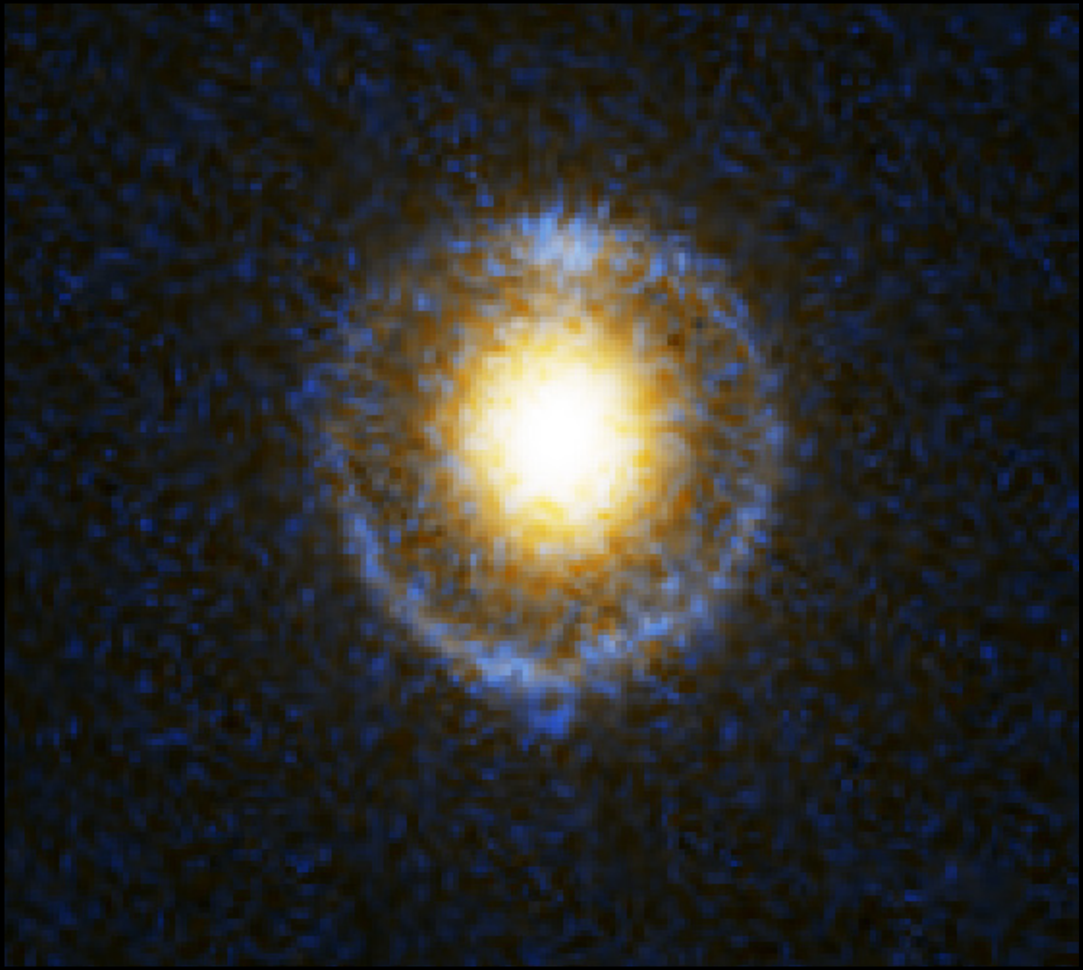


$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al '10

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image

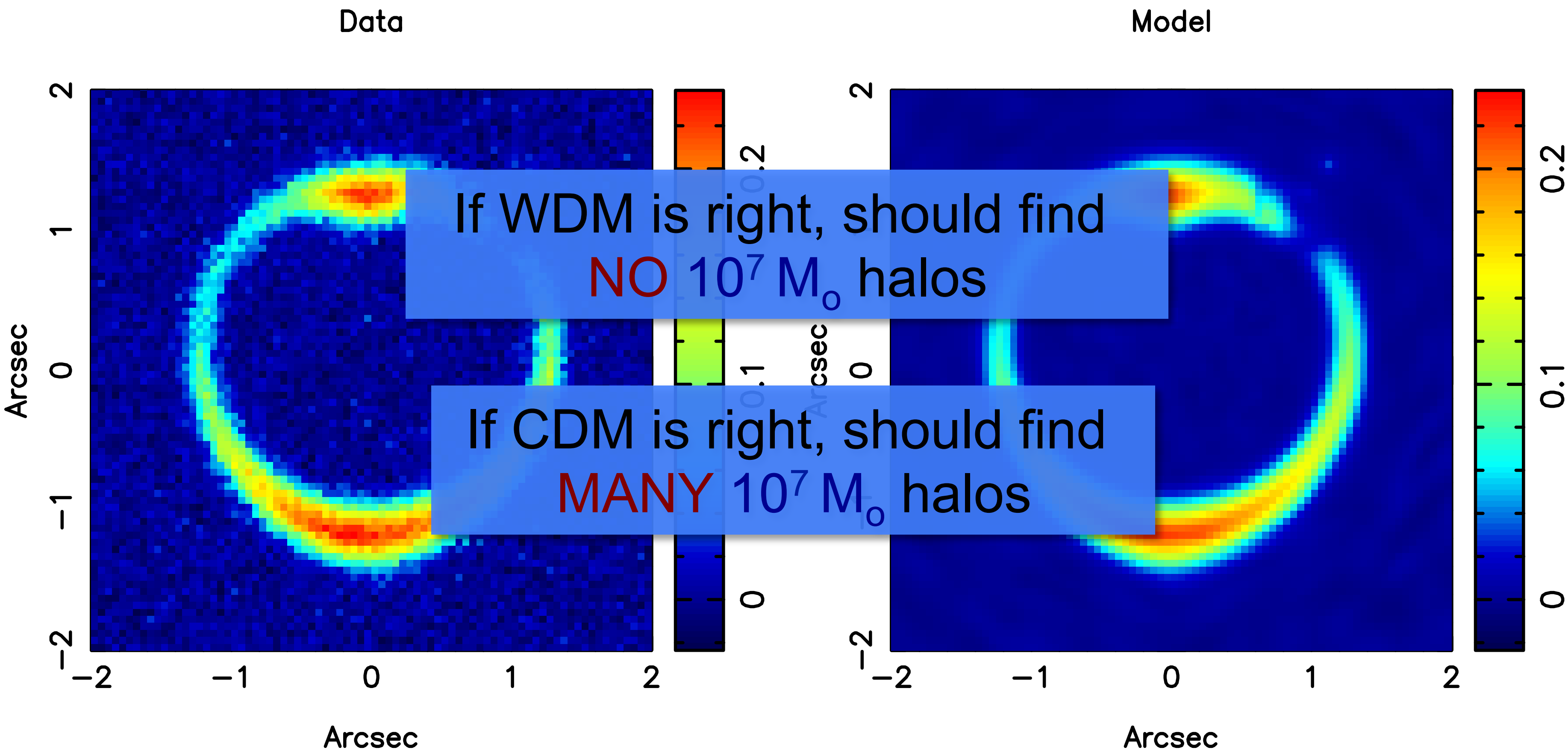


Vegetti & Koopmans ‘09

University of Durham

Detecting substructures with strong lensing

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



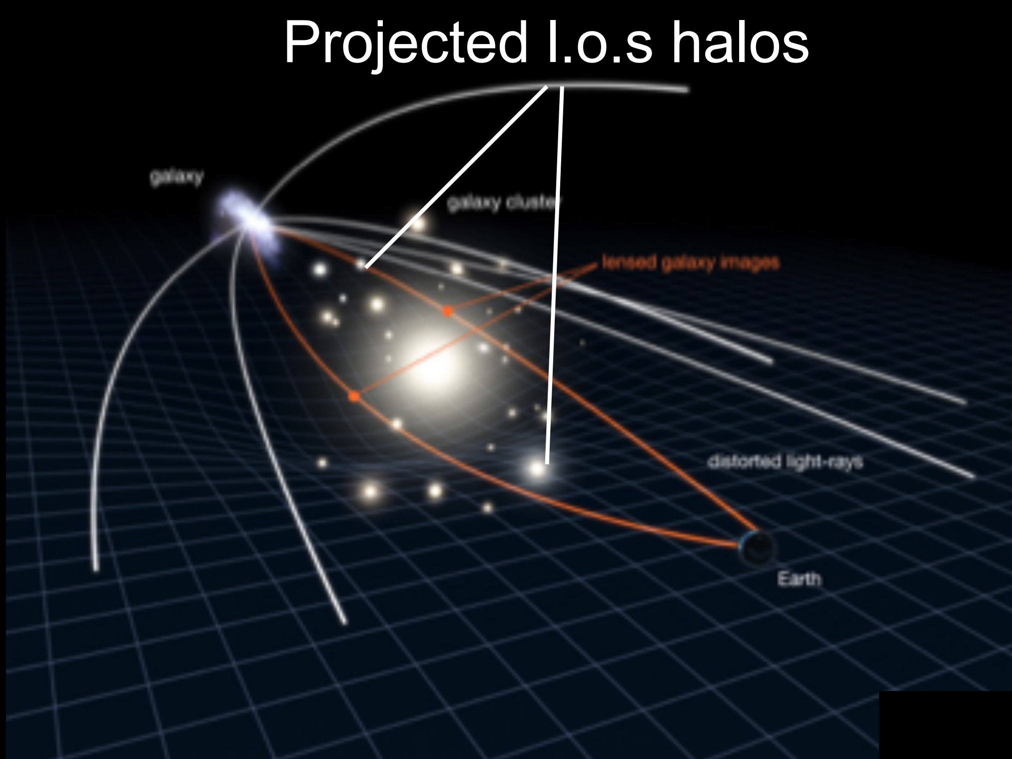
If WDM is right, should find NO 10^7 M_o halos

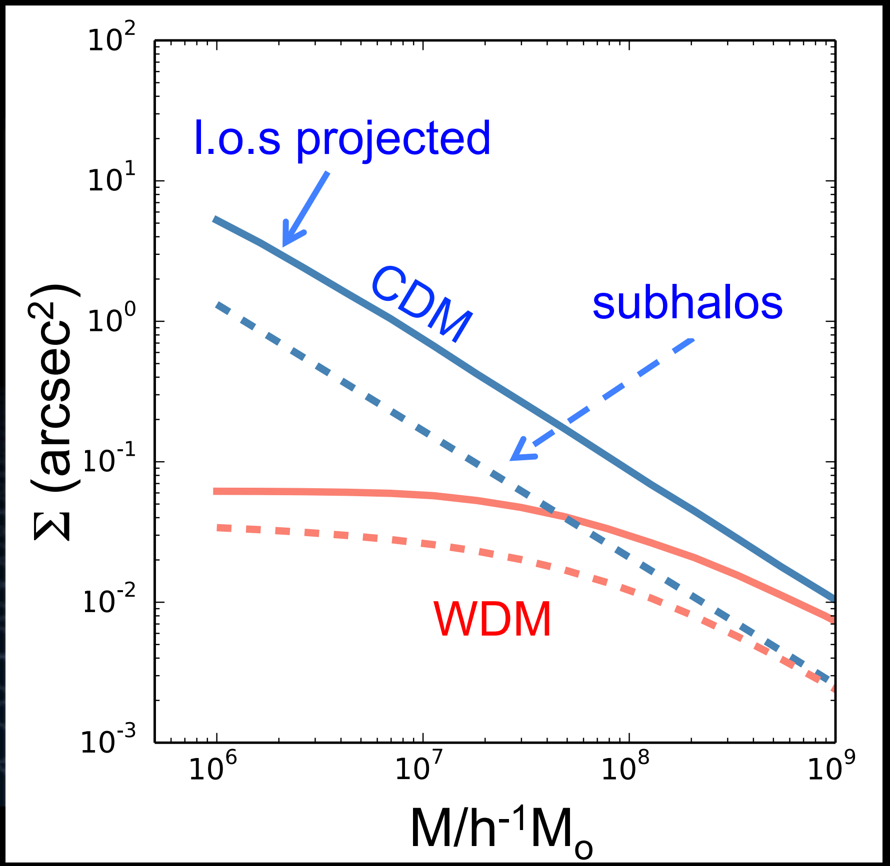
If CDM is right, should find MANY 10^7 M_o halos

Vegetti & Koopmans ‘09

Substructures vs interlopers

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



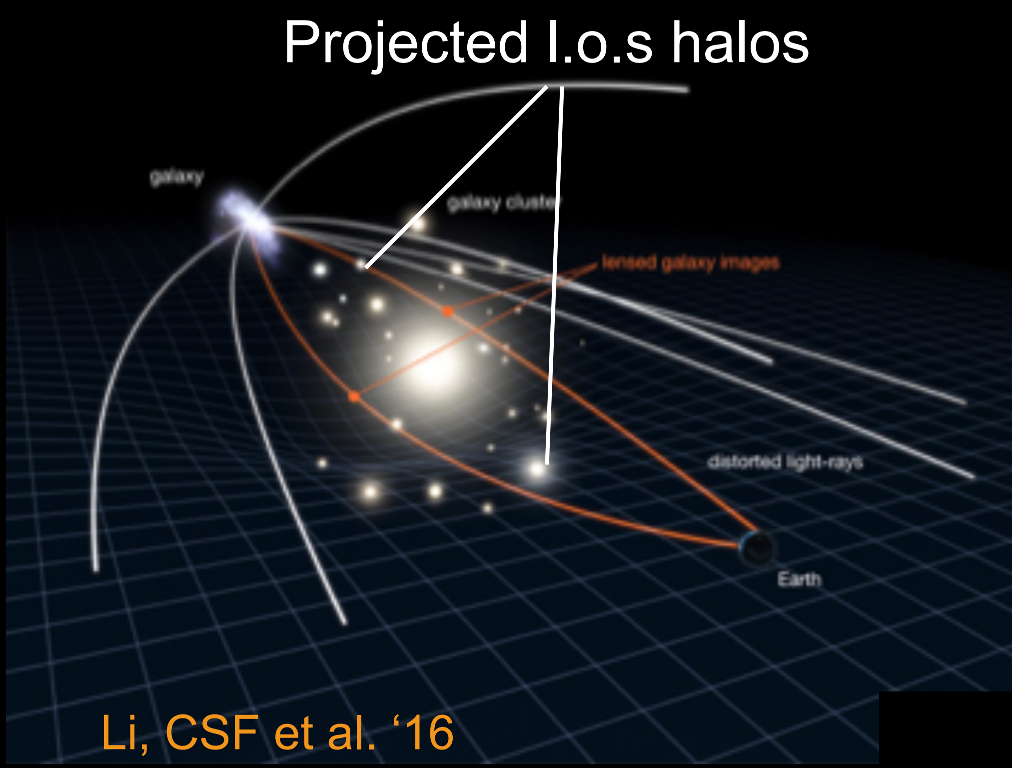


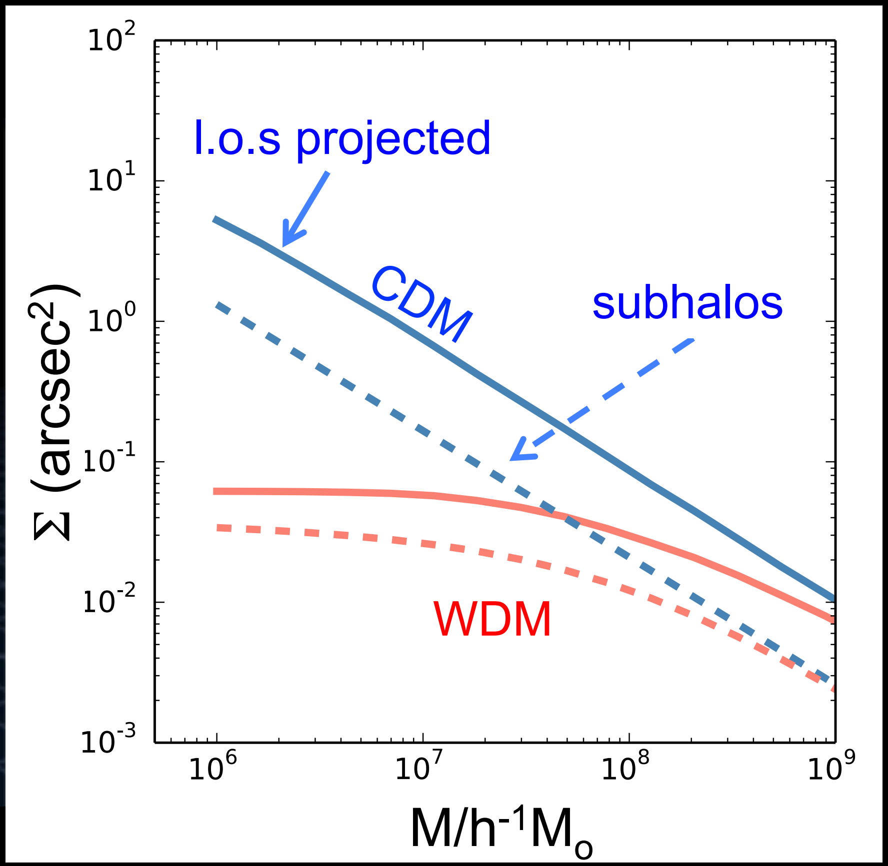
The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16; see also Despali et al.'18

Substructures vs interlopers

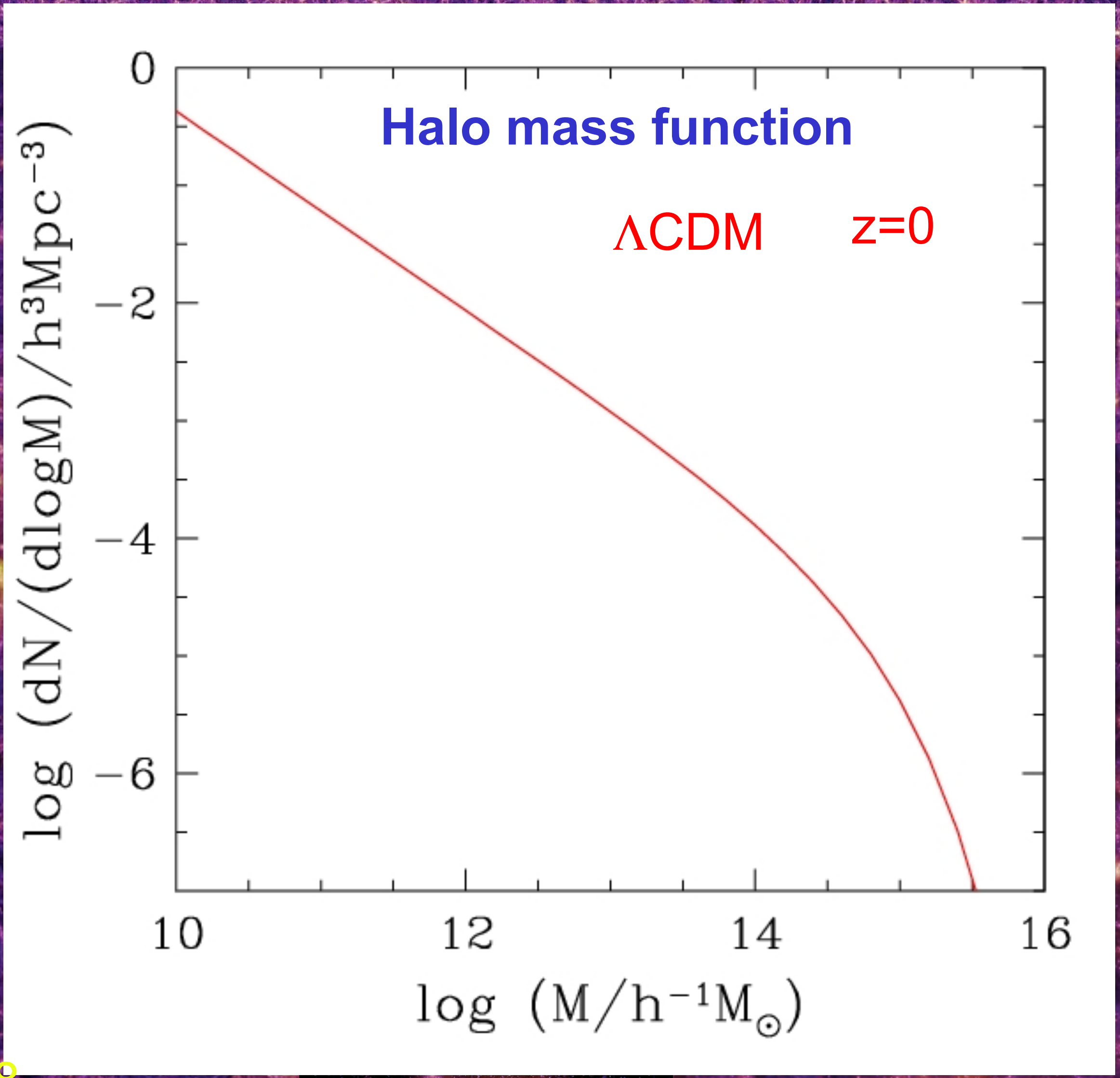
Subhalos & halos projected along the l.o.s both lens: who wins?





→ This is the cleanest possible test: it depends ONLY on the small-mass end of the "field" halo mass function which we know how to calculate and is unaffected by baryons

The Millennium/Aquarius/Phoenix simulation series

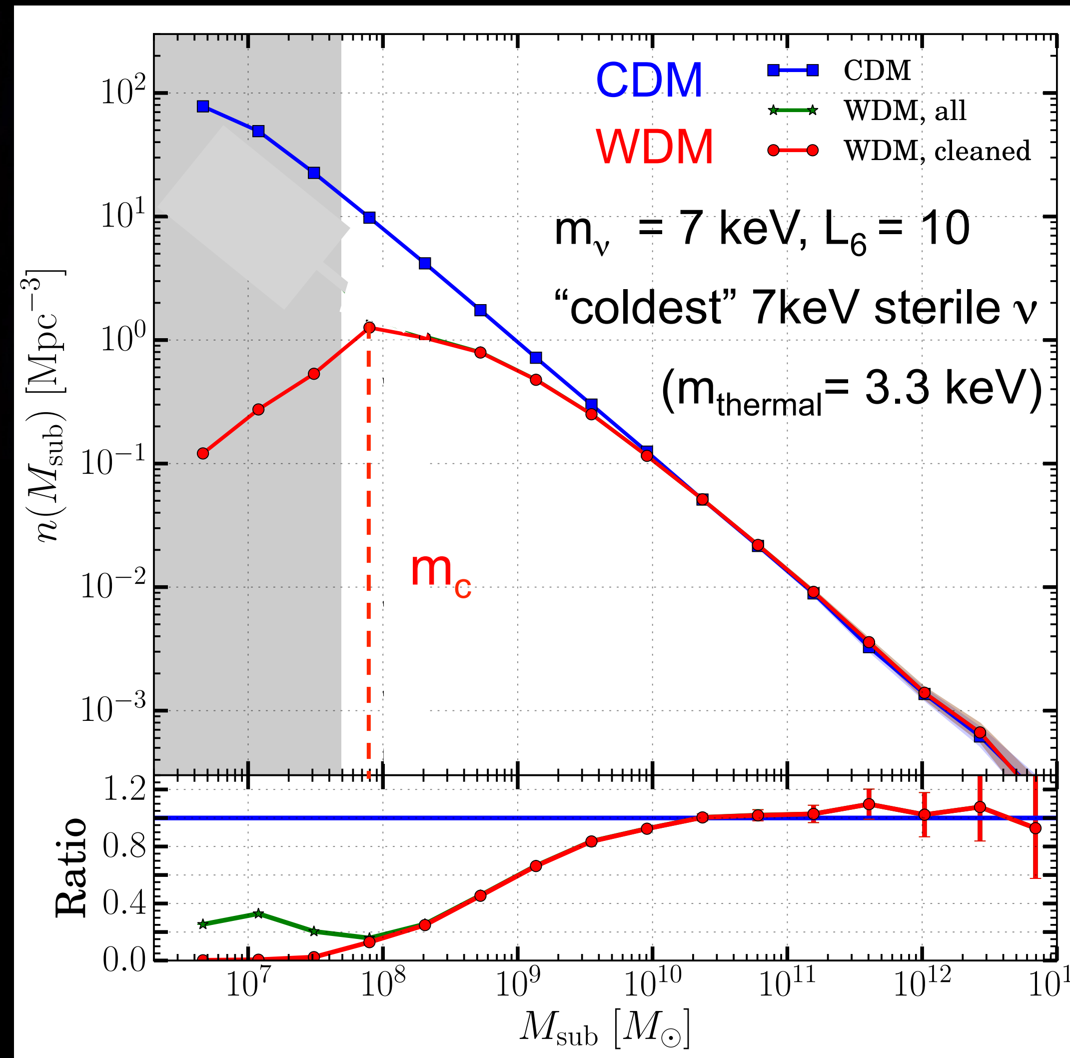


Springel et al '05, '08,
Gao et al '11

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

Detecting substructures with strong lensing

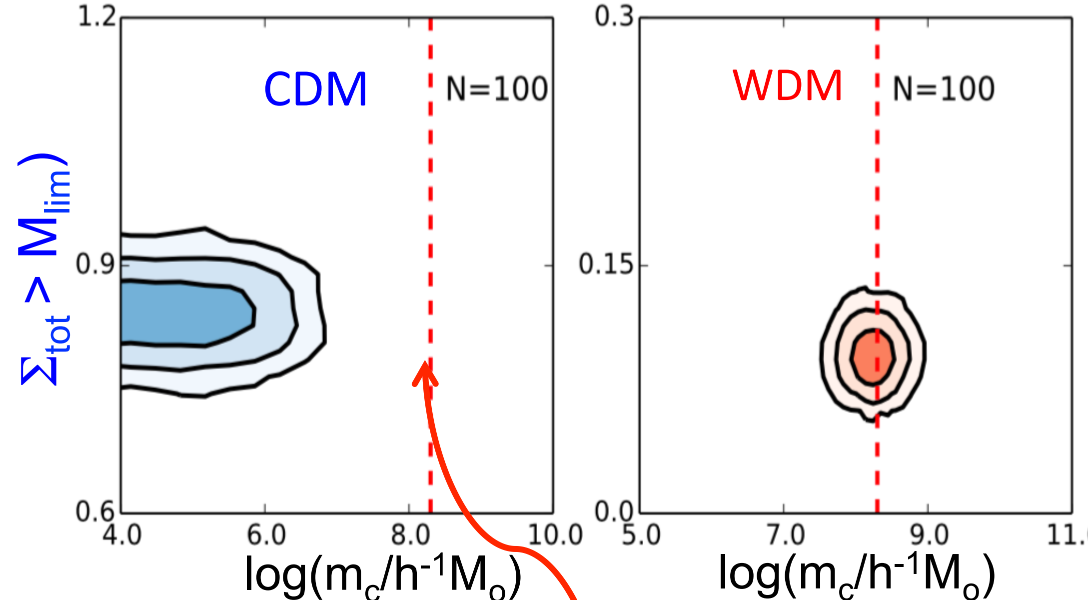
University of Durham

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

m_c= halo cutoff mass

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

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



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

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. The MW sat lum fn agrees with (pre-existing) CDM predictions → NO satellite problem in CDM. Have detected sats formed before and after recombination.
2. Halos < ~$5.10^8 M_0$ are dark; halos >$10^{10} M_0$ are bright
3. No evidence for cores; baryon effects can make them
4. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!