The small-scale stucture of the Universe

Carlos S. Frenk
Institute for Computational Cosmology, Durham

as a conclusive test of CDM

The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter

Proposed in the early 1980s

A priori implausible

- *Ab initio,* fully specified model of cosmic evolution and the formation of cosmic structure
- Has strong predictive power and can, in principle, be ruled out
- Has made a number of predictions that were subsequently verified empirically (e.g. CMB, LSS, galaxy formation)

Non-baryonic dark matter candidates

From the early 1980s:

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

The dark matter power spectrum

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Free streaming →

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

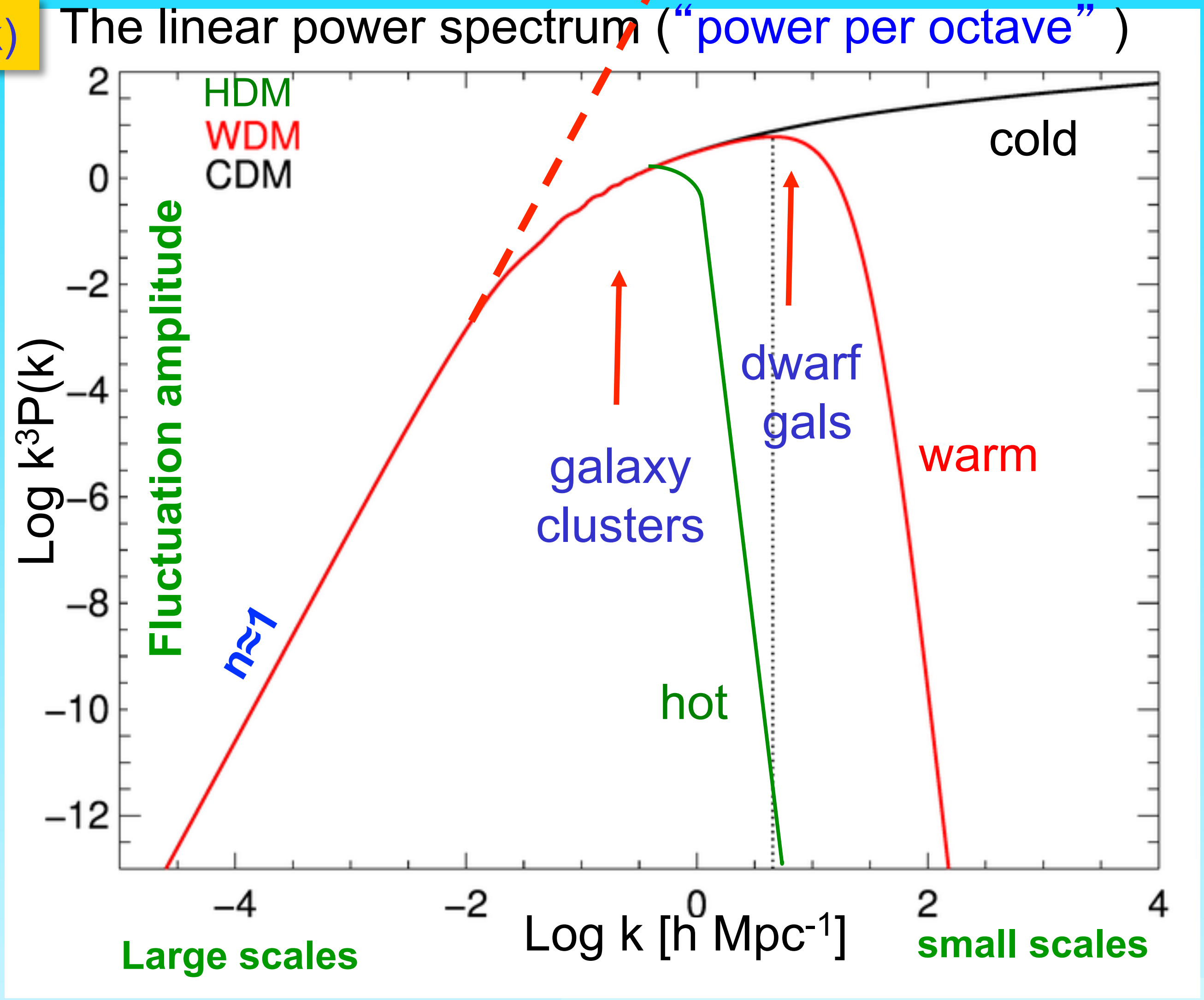
for thermal relic

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

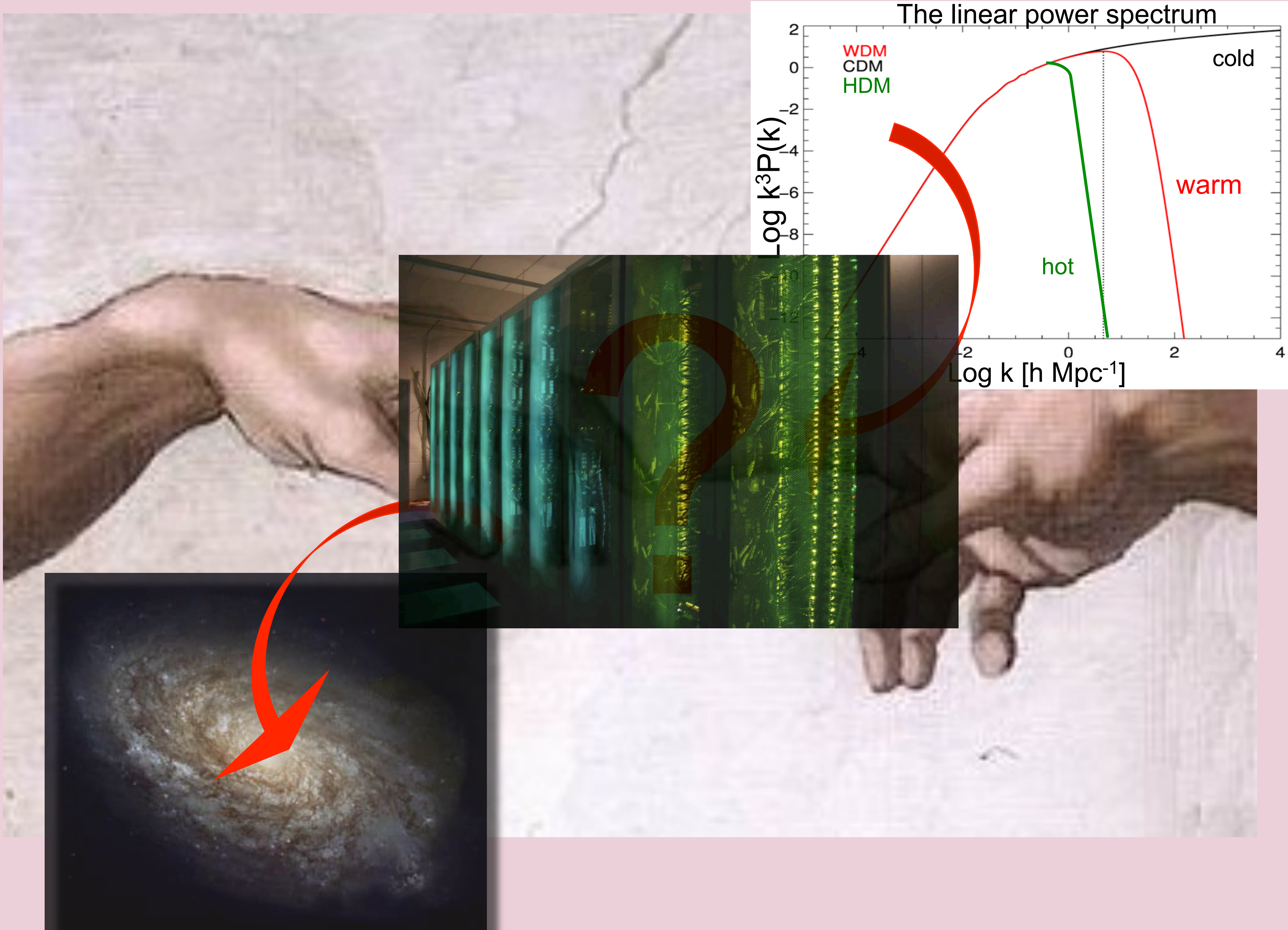
$m_{WDM} \sim$ few keV
sterile ν; $M_{cut} \sim 10^9 M_o$

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

$k^3 P(k)$



Non-linear evolution



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Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

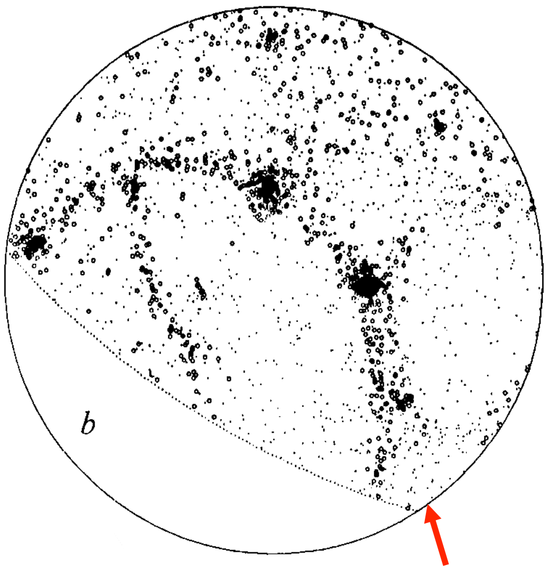
Relevant equations:

Collisionless Boltzmann,
Poisson, Friedmann eqn,
Radiative hydrodynamics
Subgrid astrophysics

How to make a virtual universe

Allows particle candidates to be tested directly against astronomical observations

Non-baryonic dark matter cosmologies



Frenk, White & Davis '83

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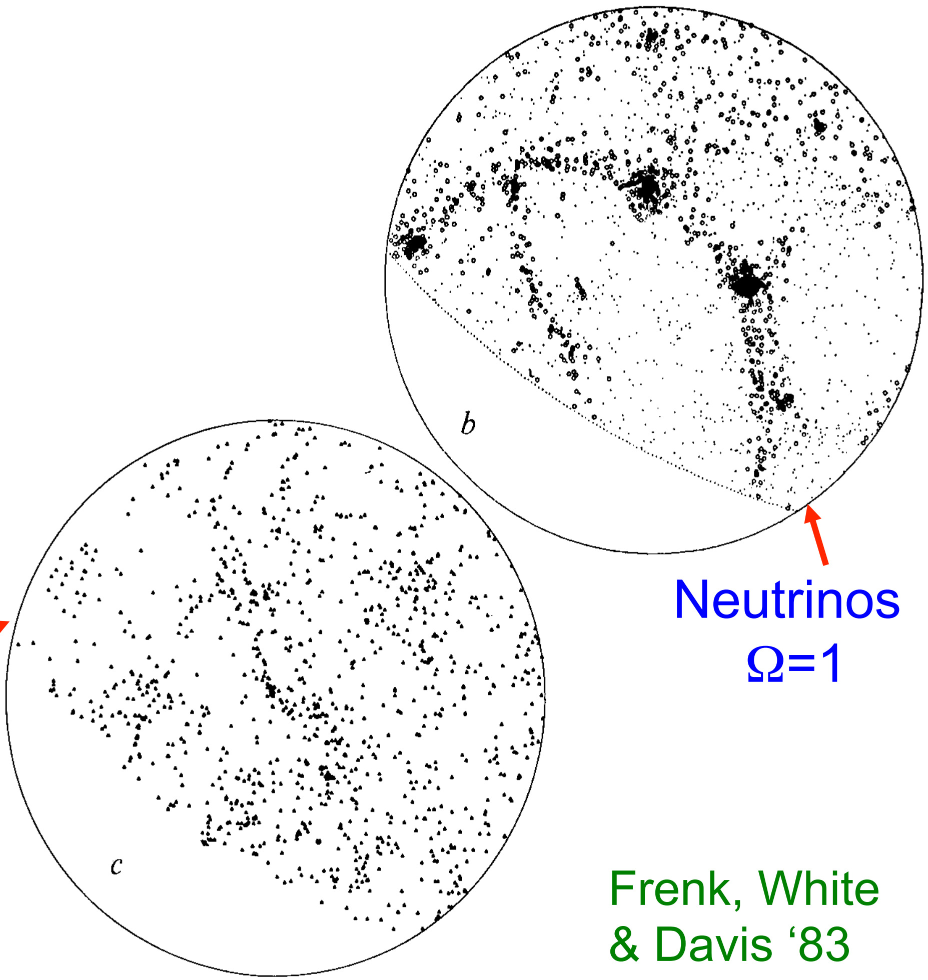
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev



Frenk, White & Davis '83

University of Durham

Non-baryonic dark matter cosmologies

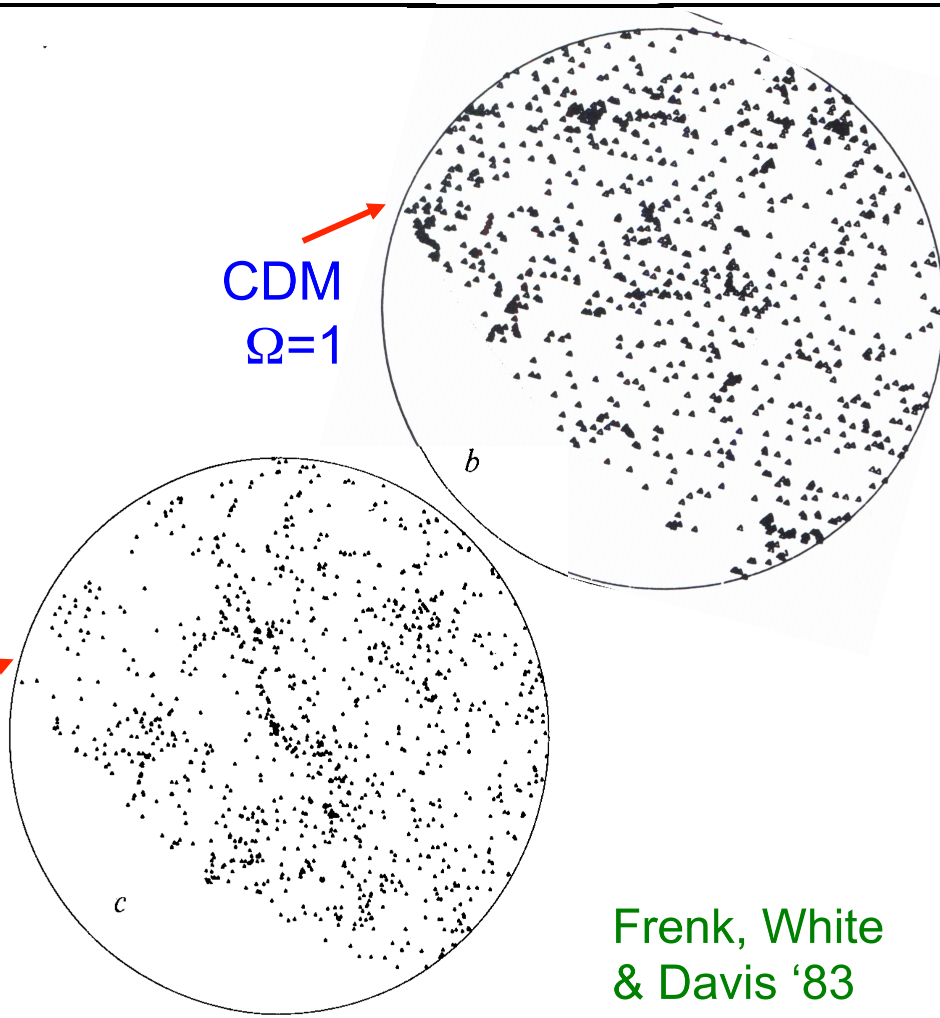
Ω=1 was the obvious choice

But with Ω=1, the dark matter is too clustered

Idea of "biasing" was introduced to have acceptable clustering and Ω=1

CDM
Ω=1

CfA redshift survey



Davis, Efstathi
Frenk & White

Frenk, White & Davis '83

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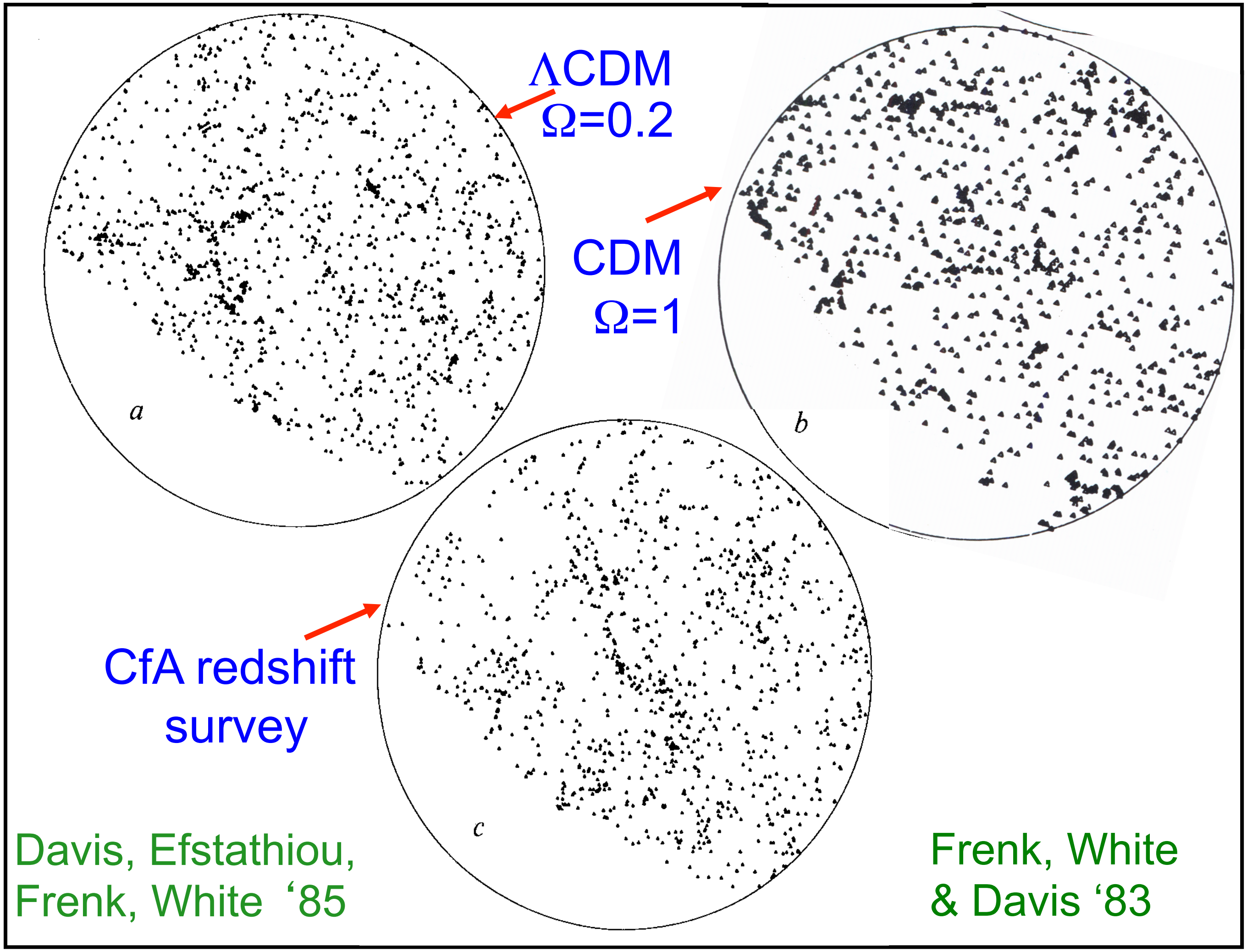
Non-baryonic dark matter cosmologies

A much less elegant solution was Λ



Λ CDM was clearly very promising, but Λ???

The end of standard (Ω_{matter} =1) CDM … or why Ω_{matter} cannot be 1

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Ω from the baryon fraction in clusters

baryon fraction in clusters ≈ baryon fraction of universe

$$f_b = \frac{M_b}{M_{tot}} = \gamma \frac{\Omega_b}{\Omega_m}$$

White, Navarro, Evrard & Frenk Nature 1993

where $\gamma=1$ if f_b has the universal value

simulations → $\gamma = 0.9 \pm 10\%$

X-rays+lensing → $f_b = (0.060h^{-3/2} + 0.009) \pm 10\%$

BBNS, CMB → $\Omega_b h^2 = 0.019 \pm 20\%$

HST → $h = 0.7 \pm 10\%$

→ $$\Omega_m = \frac{\Omega_b \gamma}{f_b} = 0.31 \pm 0.12$$

Allen etal ‘04

Evidence for Λ from high-z supernovae

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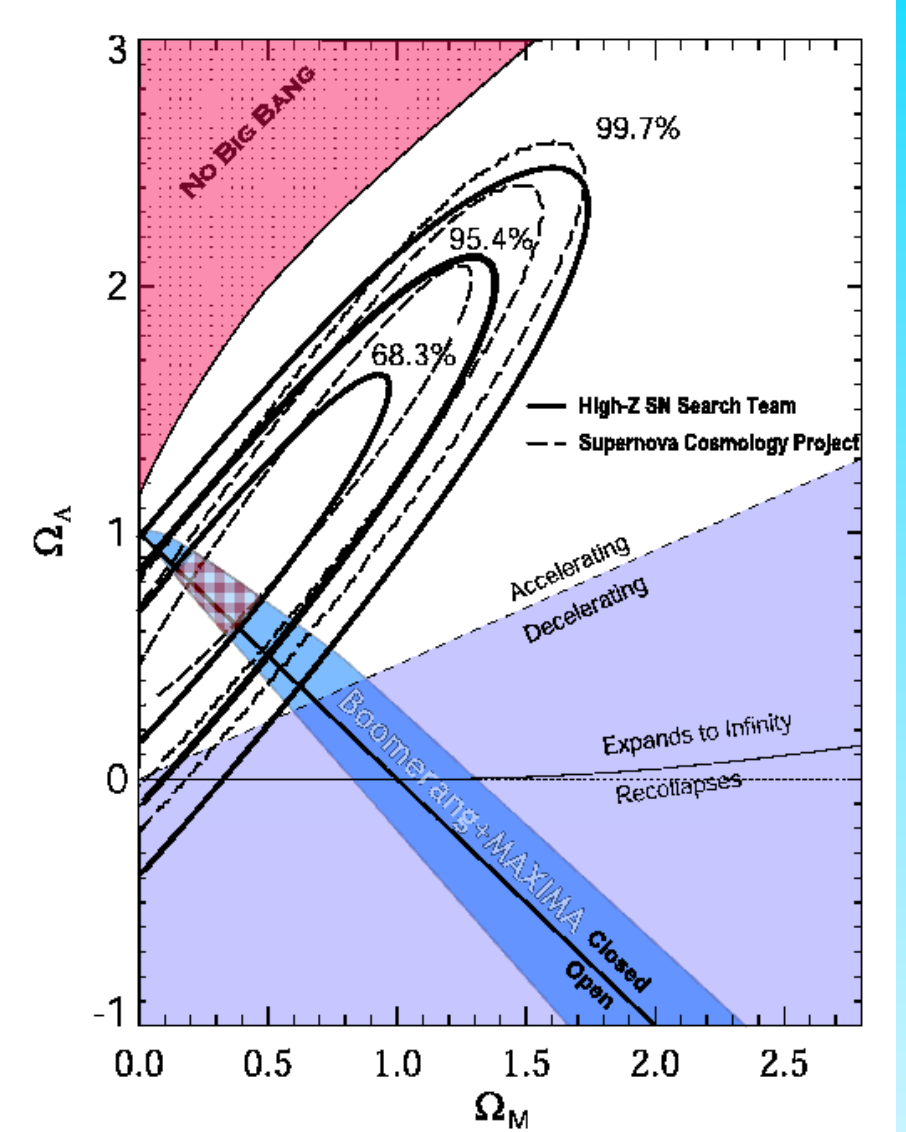
SN type Ia (standard candles) at z~0.5 are fainter than expected even if the Universe were empty

➔ Cosmic expansion must have been accelerating since the light was emitted



Perlmutter et al '98; Reiss et al '98
Schmidt et al '98

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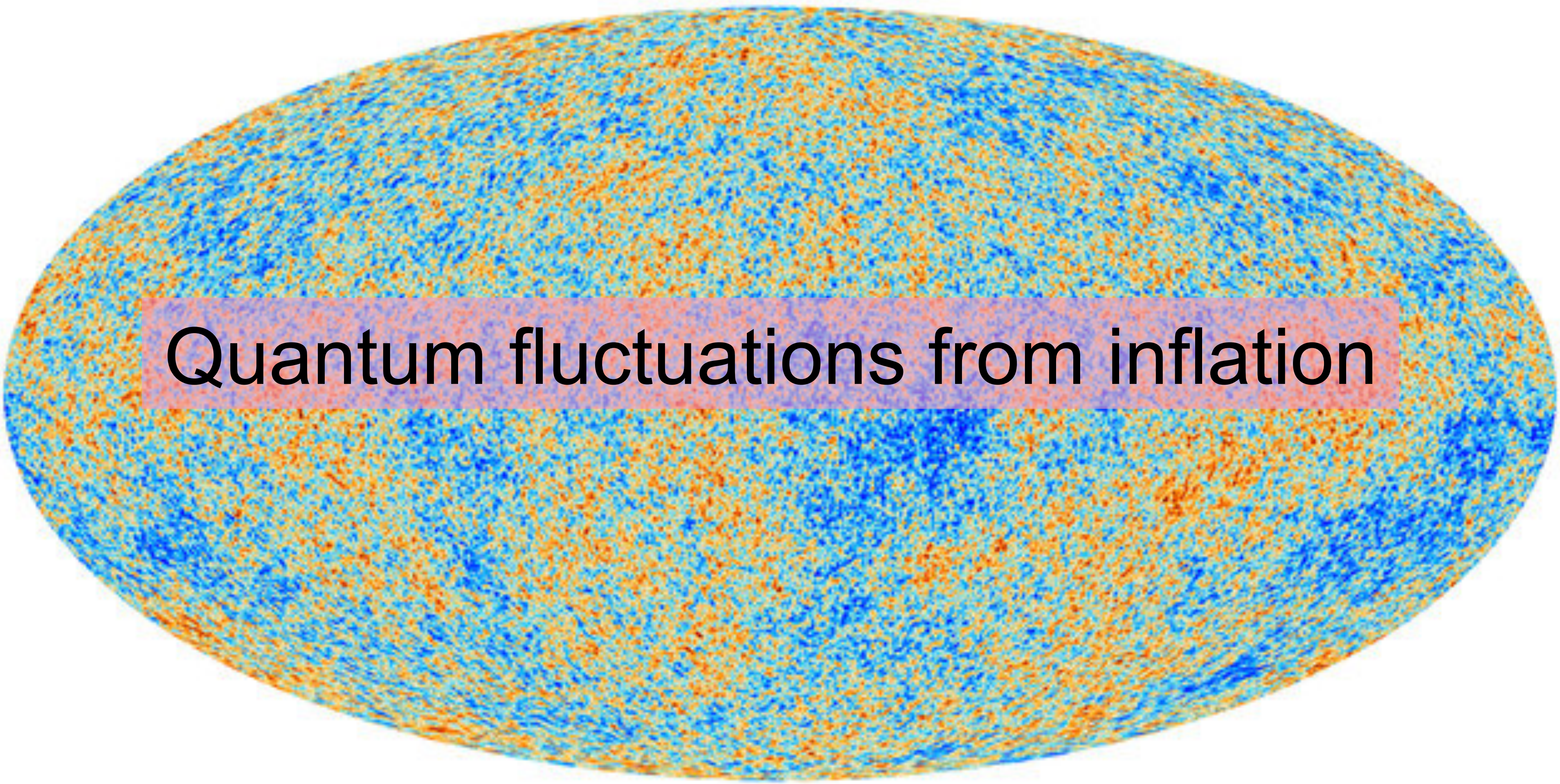
The initial conditions for galaxy formation



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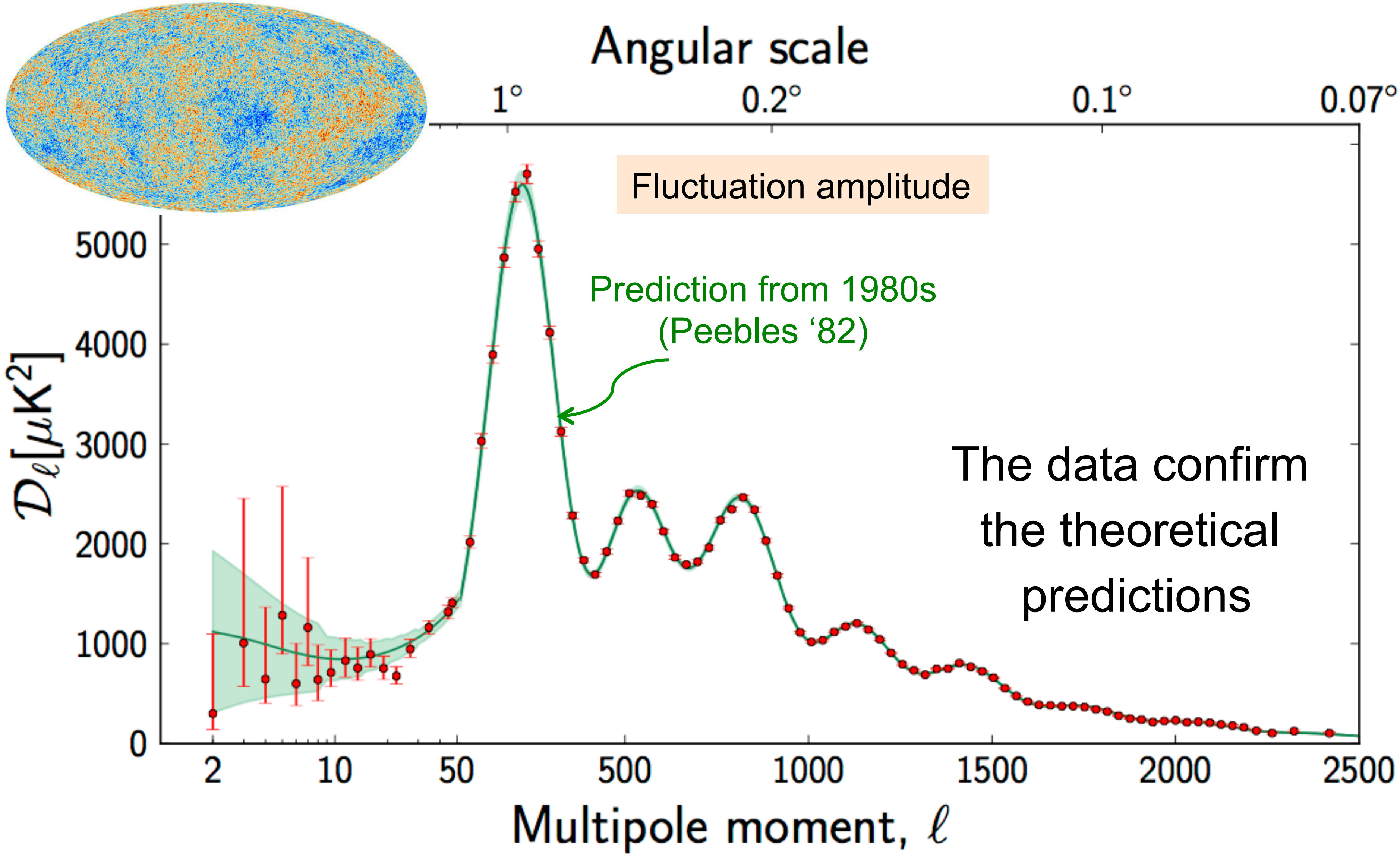
Planck: CMB temperature anisotropies



Planck coll. 2015

Univer

The six parameters of minimal ΛCDM model

6 mdoel parameters

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$ (Baryon density)	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$ (Dark matter density)	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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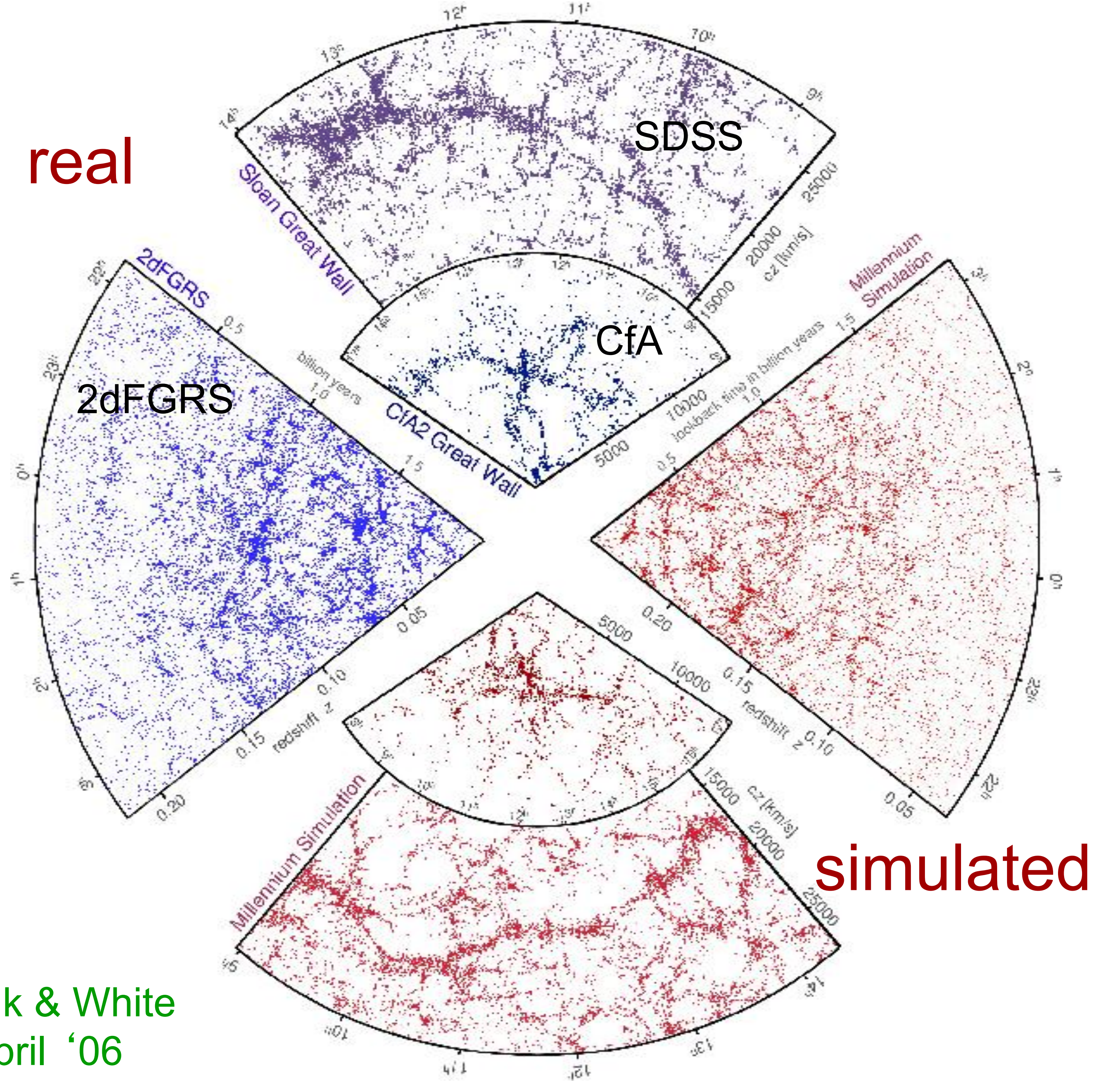

Springel, Frenk & White
Nature, April ‘06

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

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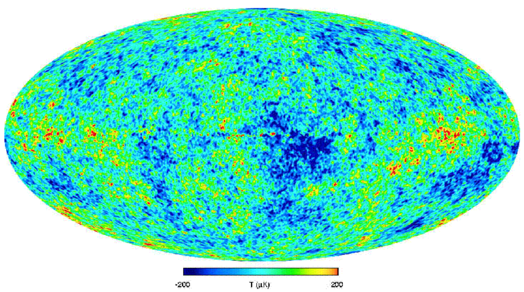
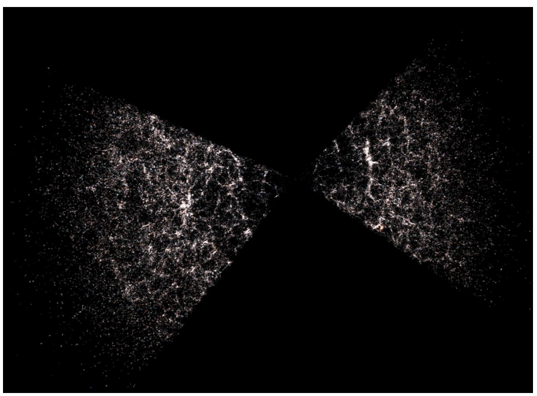
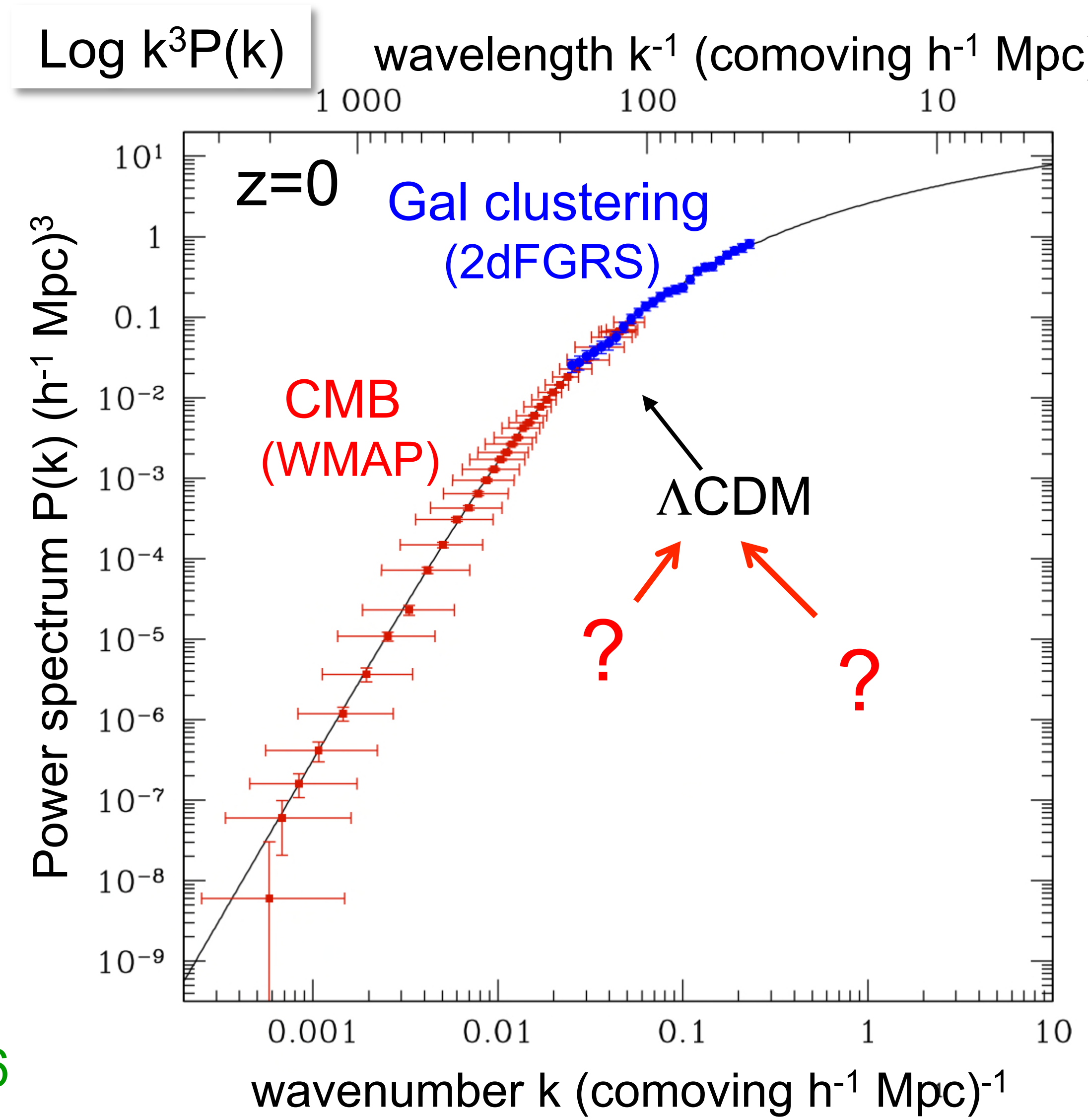


z~1000



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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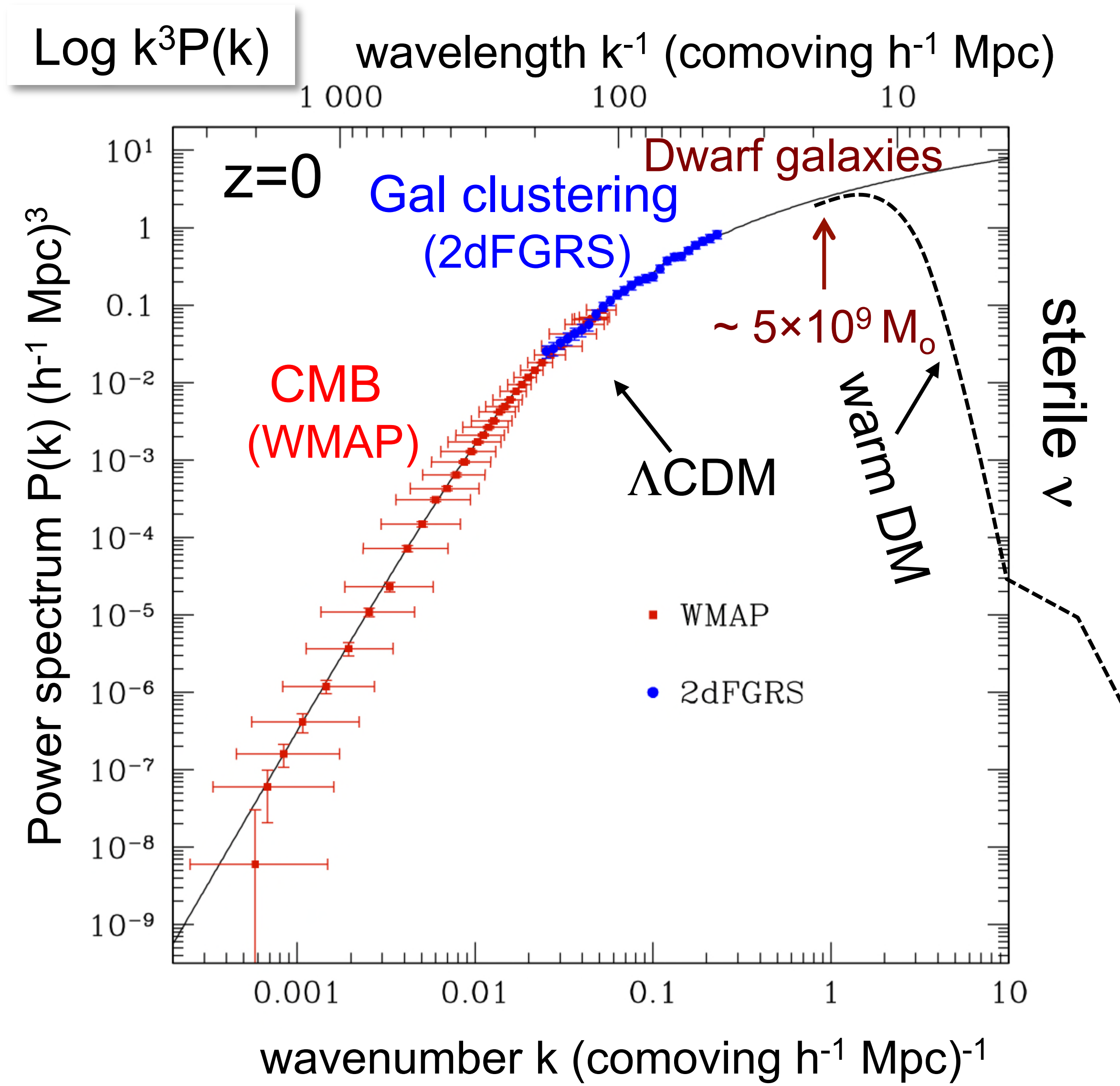

Sterile neutrinos

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-ray decay

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!

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

(strongly non-linear regime)

Cold Dark Matter Warm Dark Matter

13.4 billion years ago

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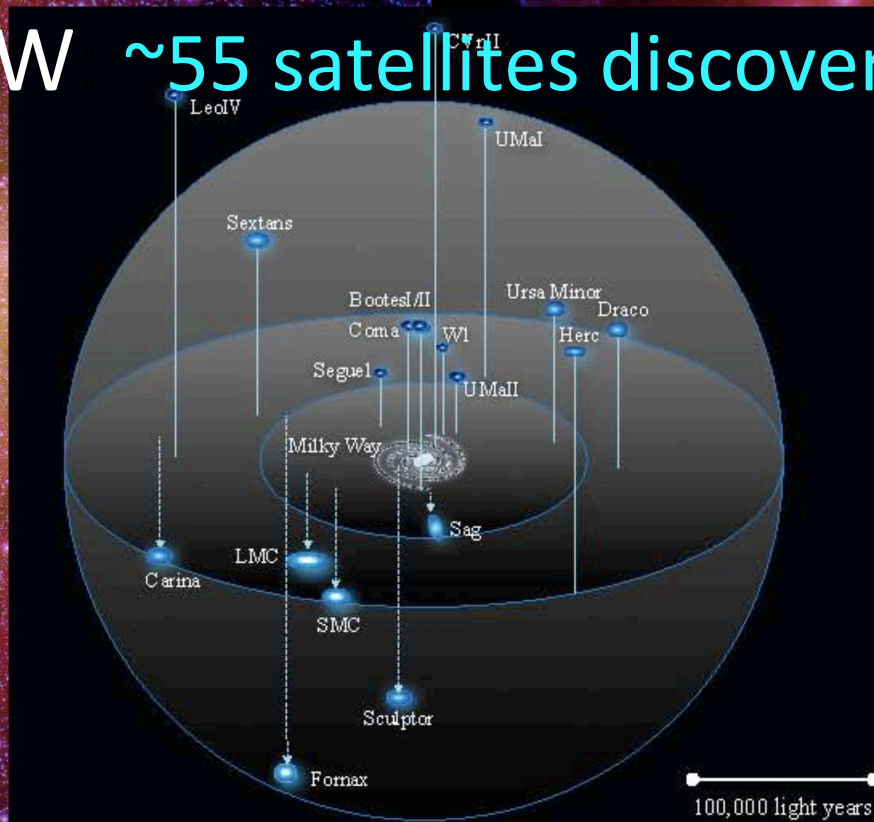
cold dark matter

warm dark matter

Obvious test: count satellites in MW or M31

In the MW ~55 satellites discovered so far

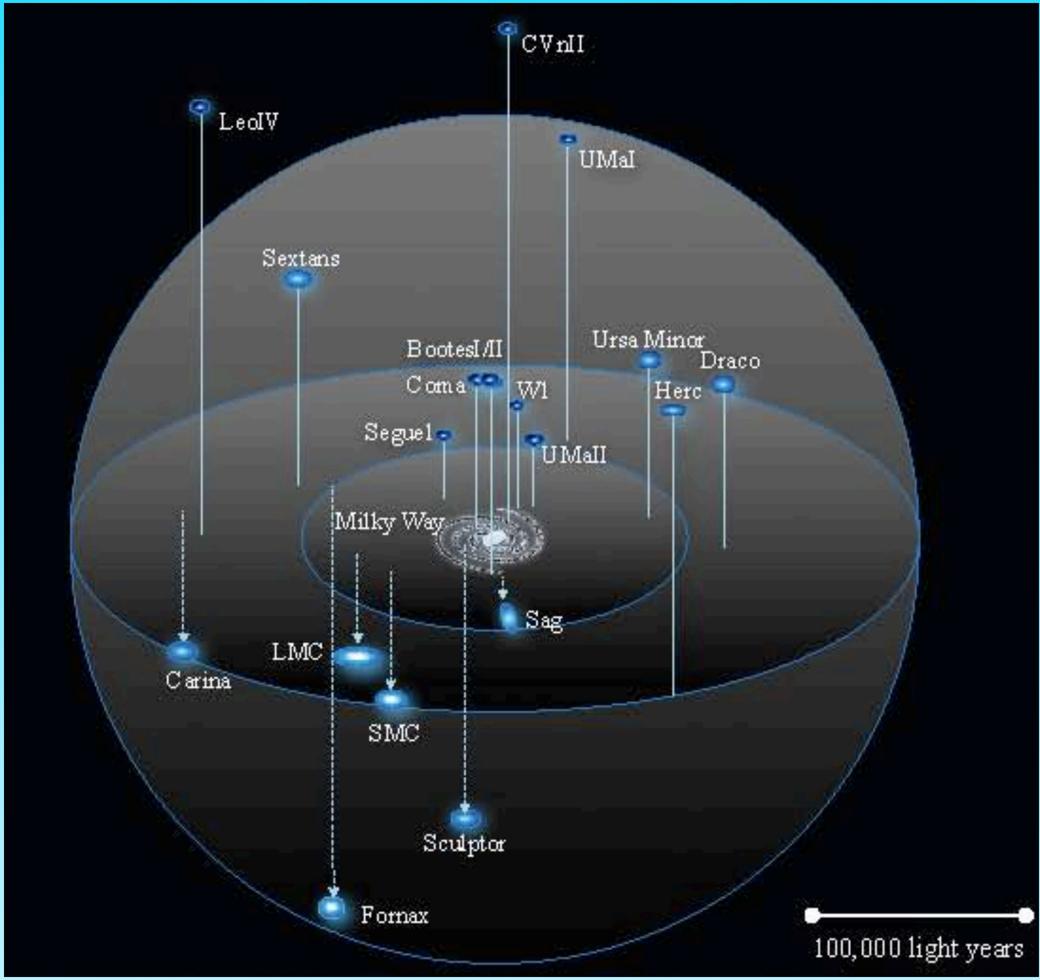


Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '12

The MW satellite luminosity function

University of Durham

~55 satellites discovered so far in 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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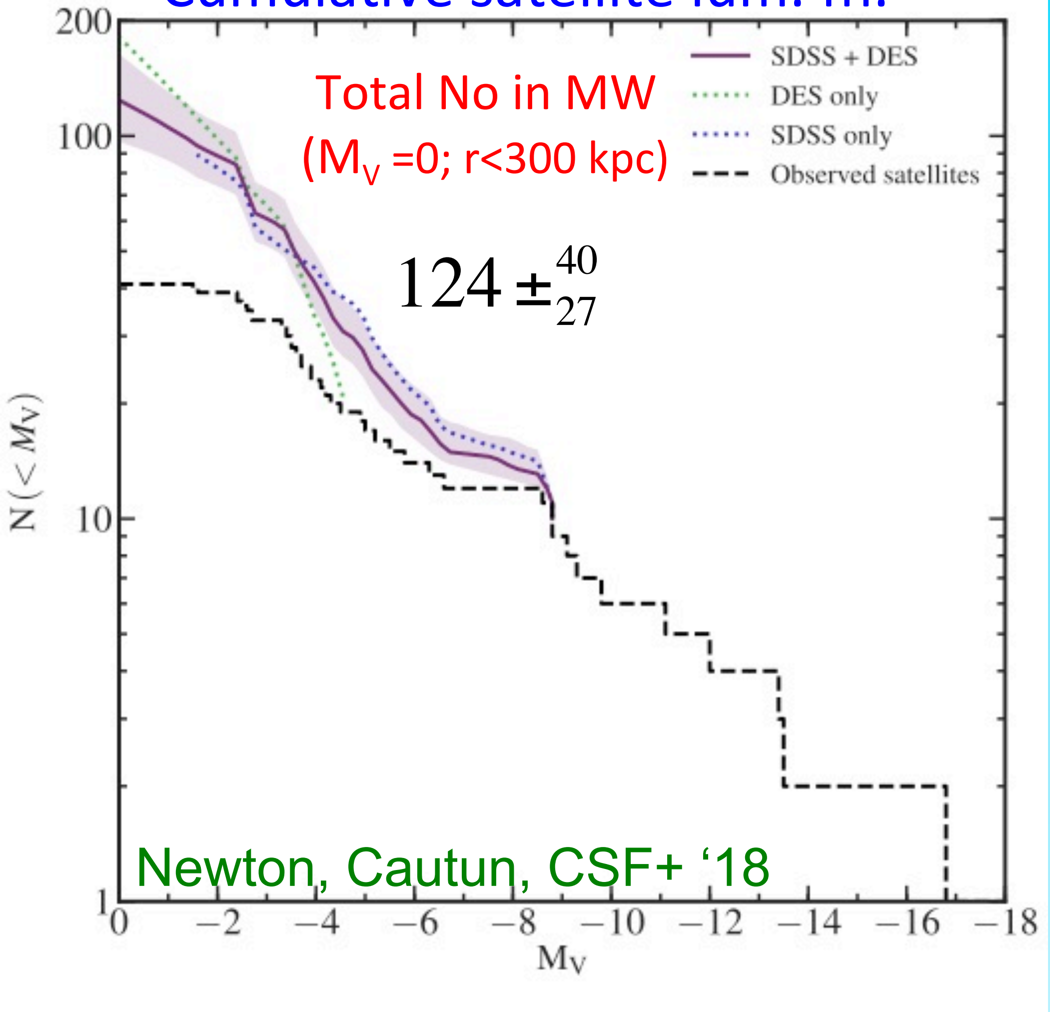
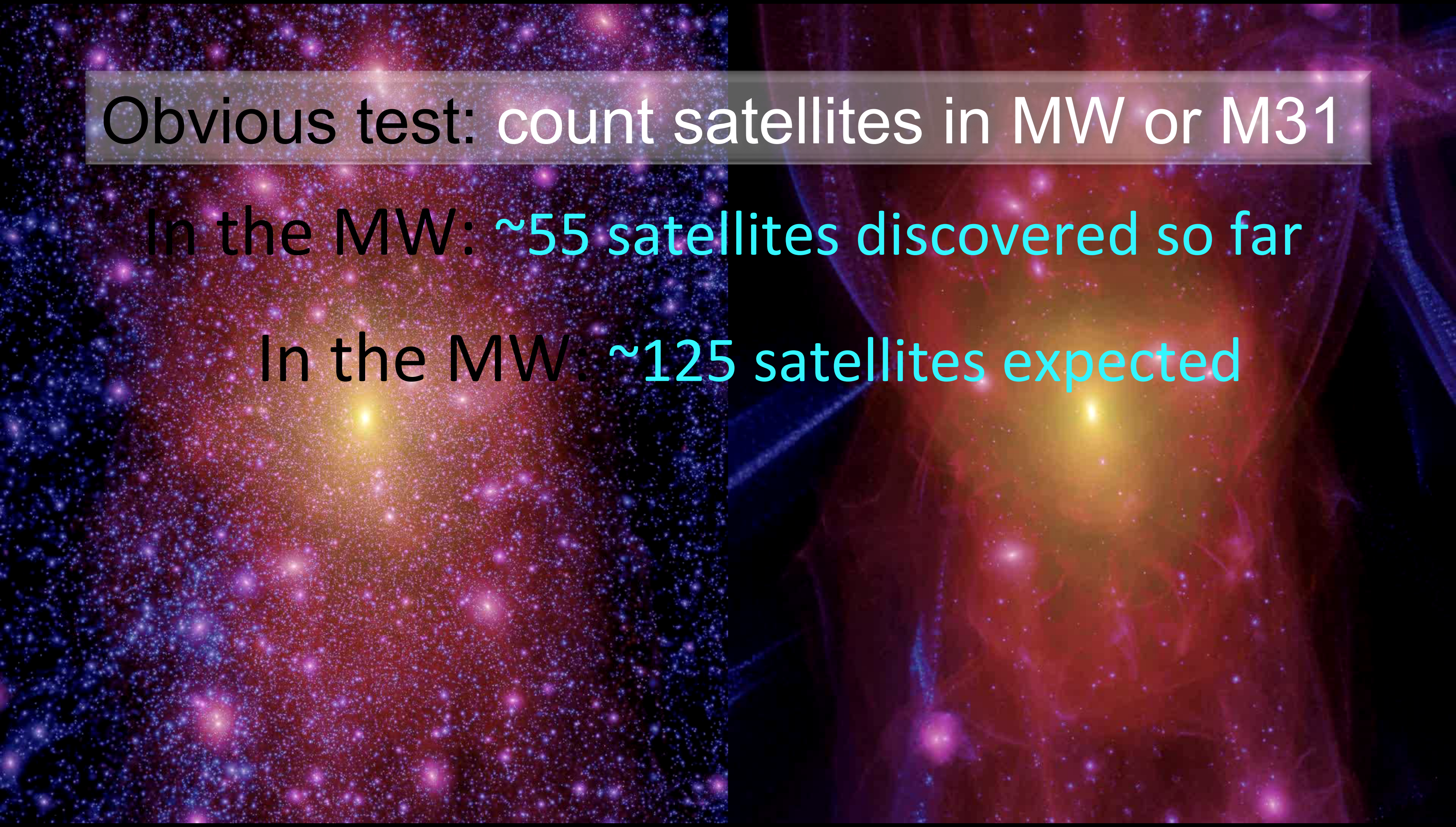
Cumulative satellite lum. fn.



cold dark matter

warm dark matter



Obvious test: count satellites in MW or M31

In the MW: ~55 satellites discovered so far

In the MW: ~125 satellites expected

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

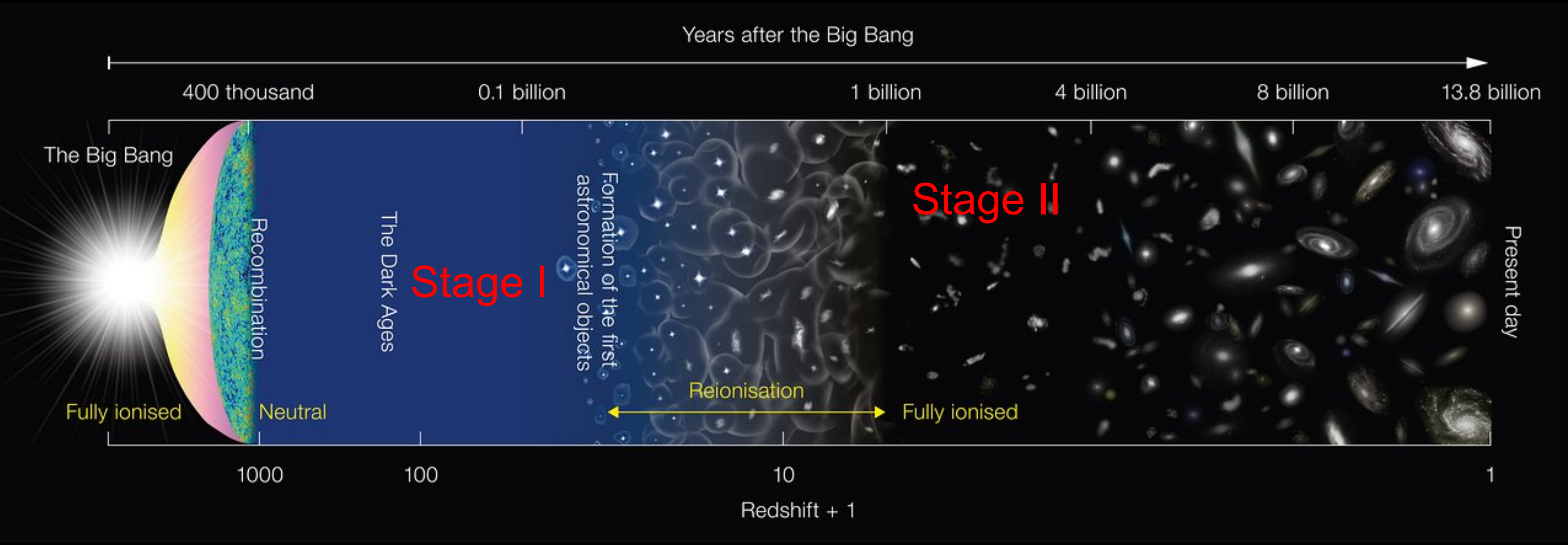
Obvious test: count satellites in MW or M31

This argument is WRONG!

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


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

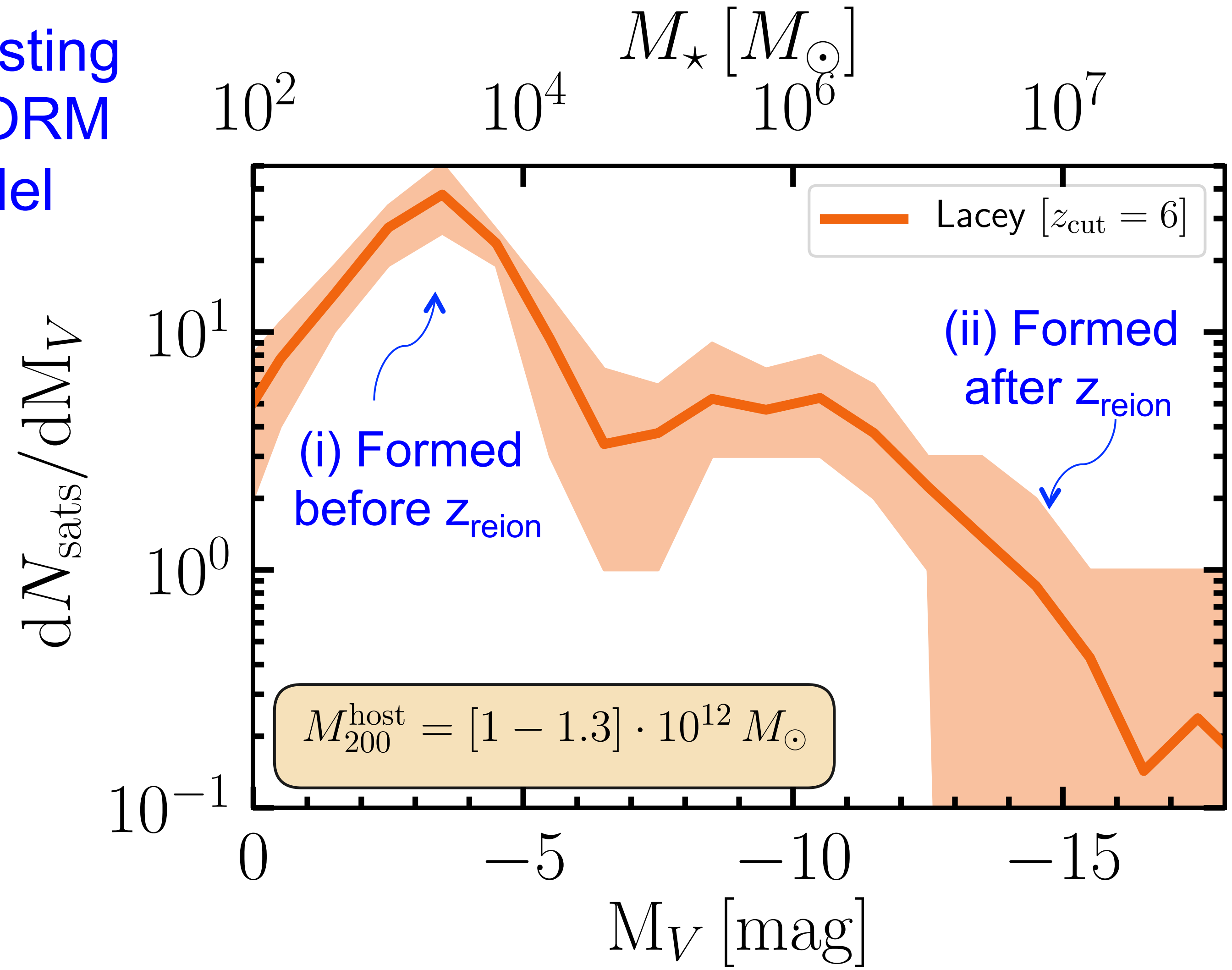
Stage II: Halos with “T_{vir}” > 10^4K form → galaxy formation resumes

The satellite luminosity function

University of Durham

Two populations of sats formed: (i) before and (ii) after reionization

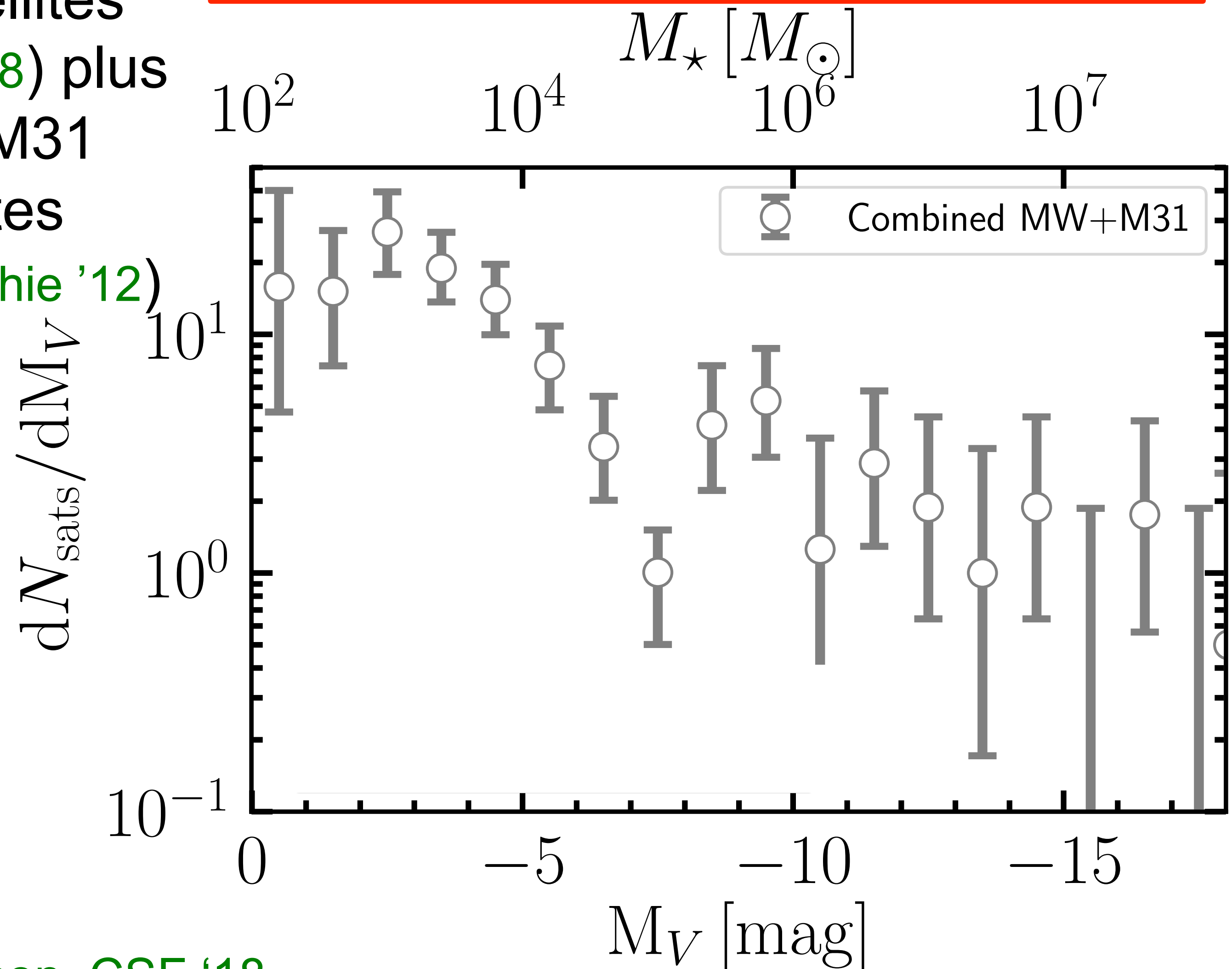
Pre-existing GALFORM model



The MW/M31 sat. luminosity function

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

Differential satellite luminosity function



Bose, Deason, CSF '18

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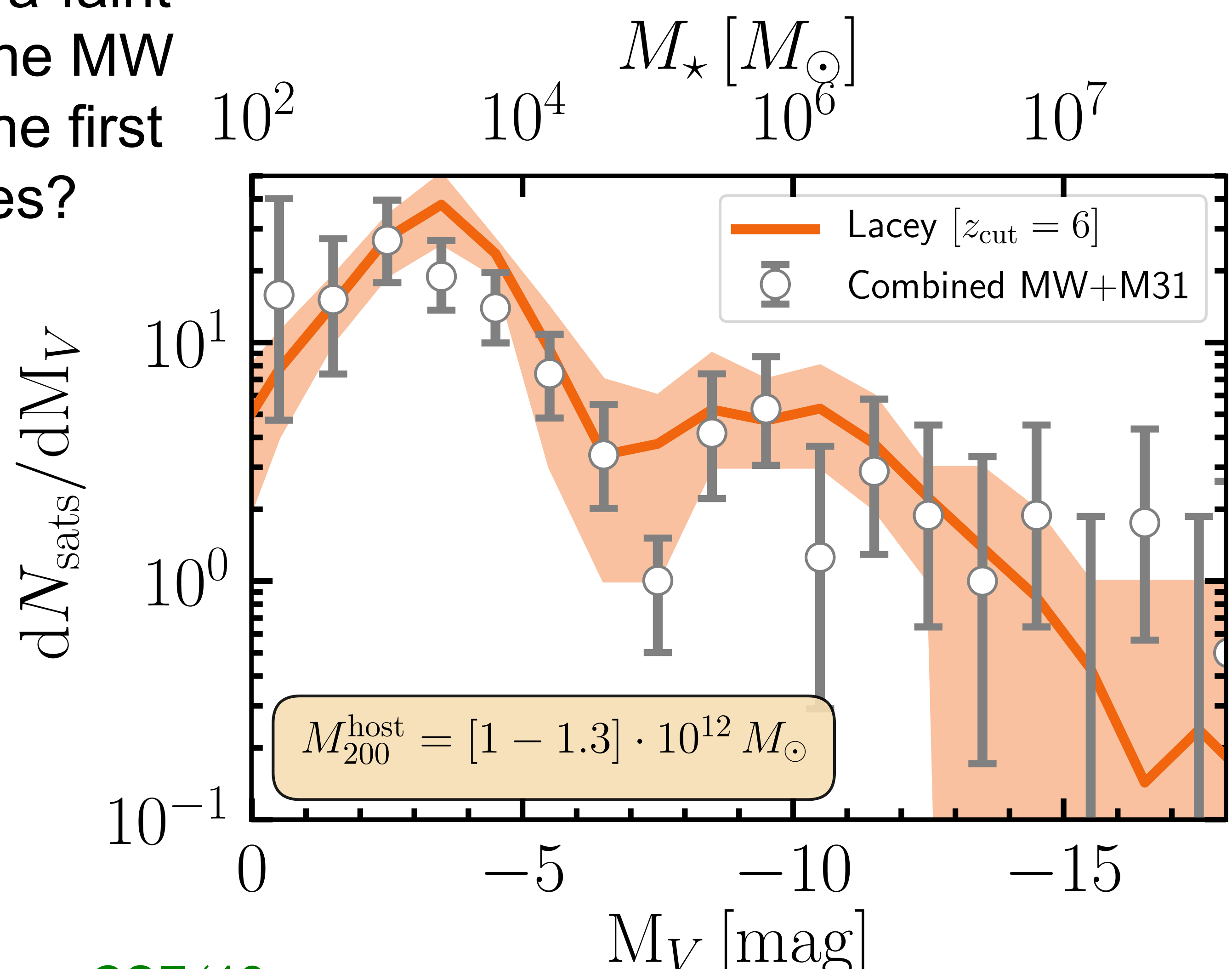
Theory vs data

Are the ultra-faint dwarfs of the MW amongst the first galaxies?



Bose, Deason, CSF ‘18

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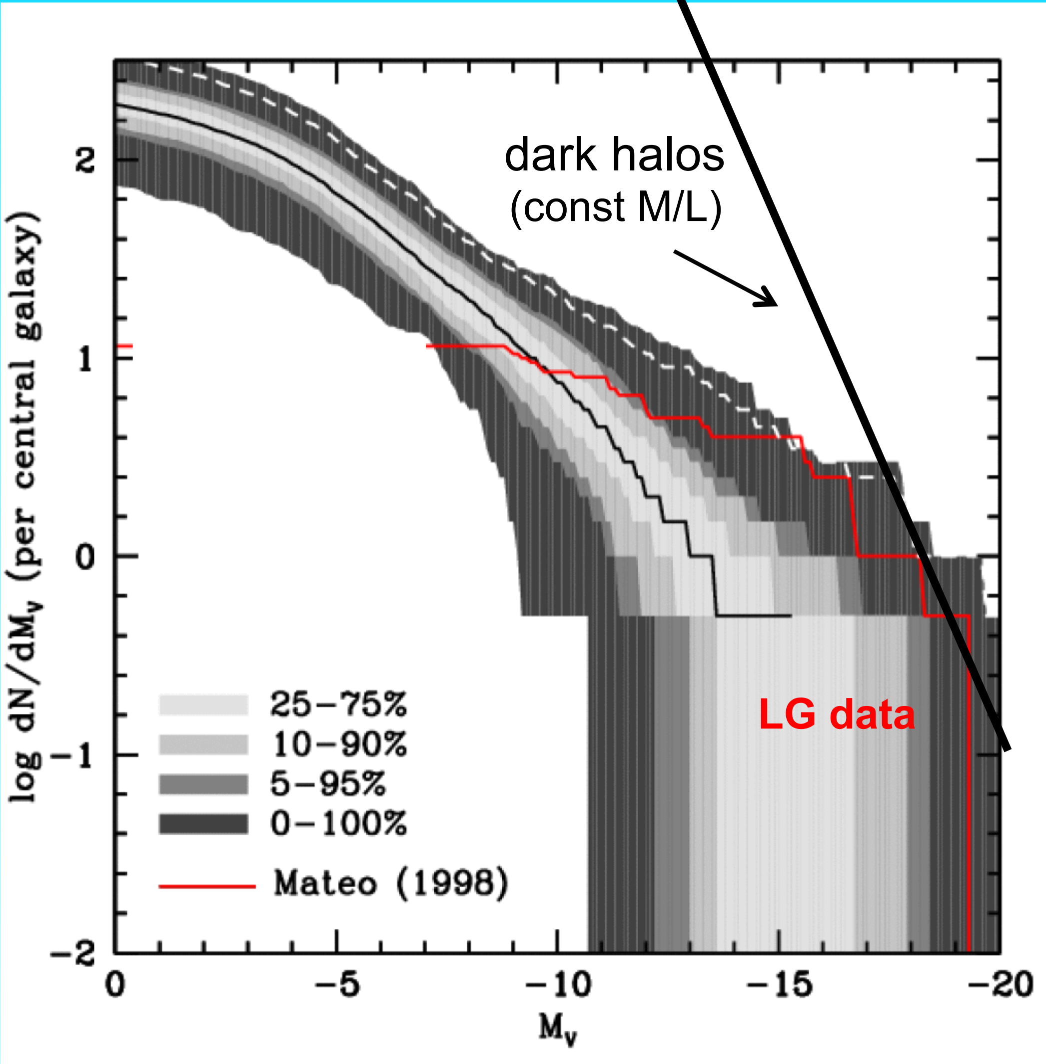
Luminosity Function of Local Group Satellites

- 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)

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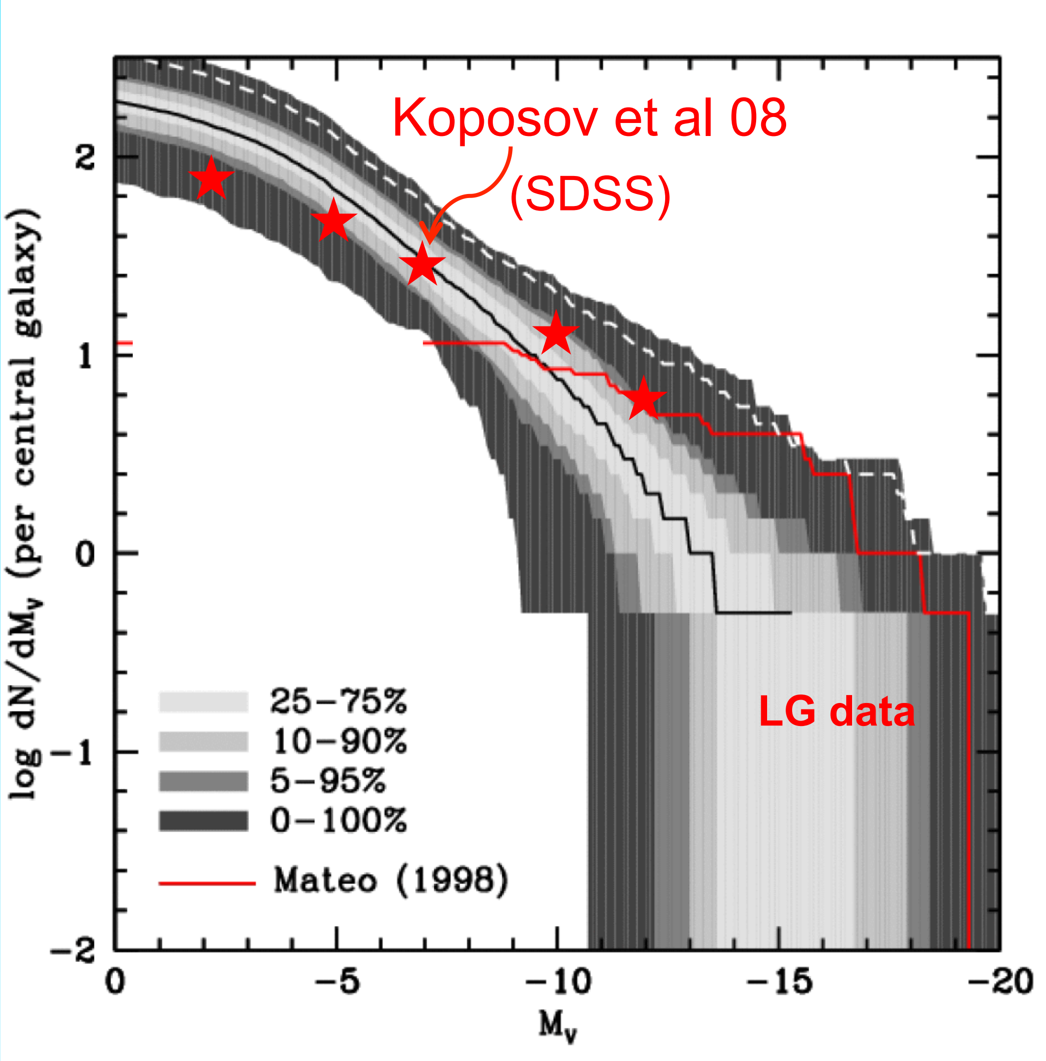

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VIRGO

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…

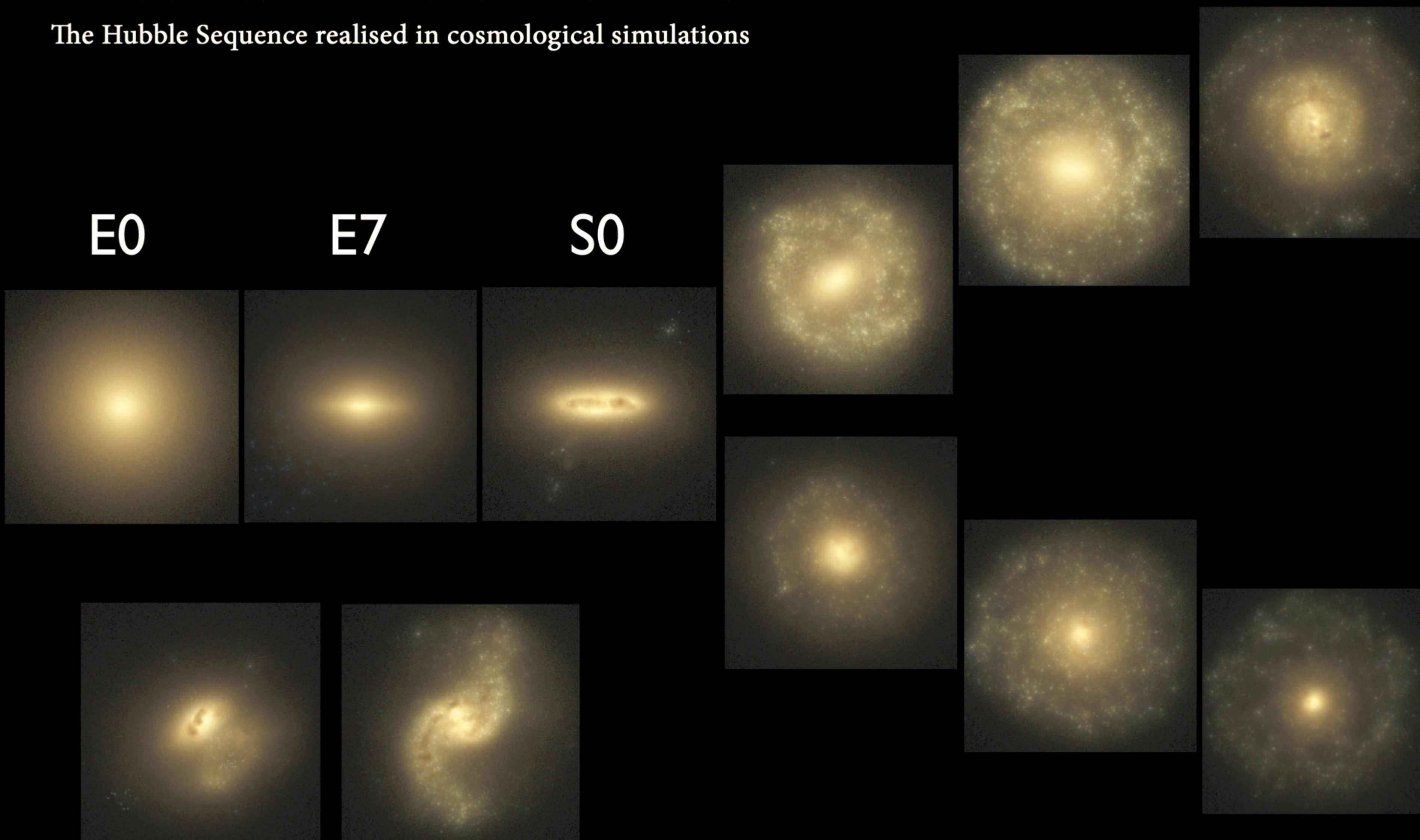
Durham University VIRGO ICC DiRAC PRACE

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

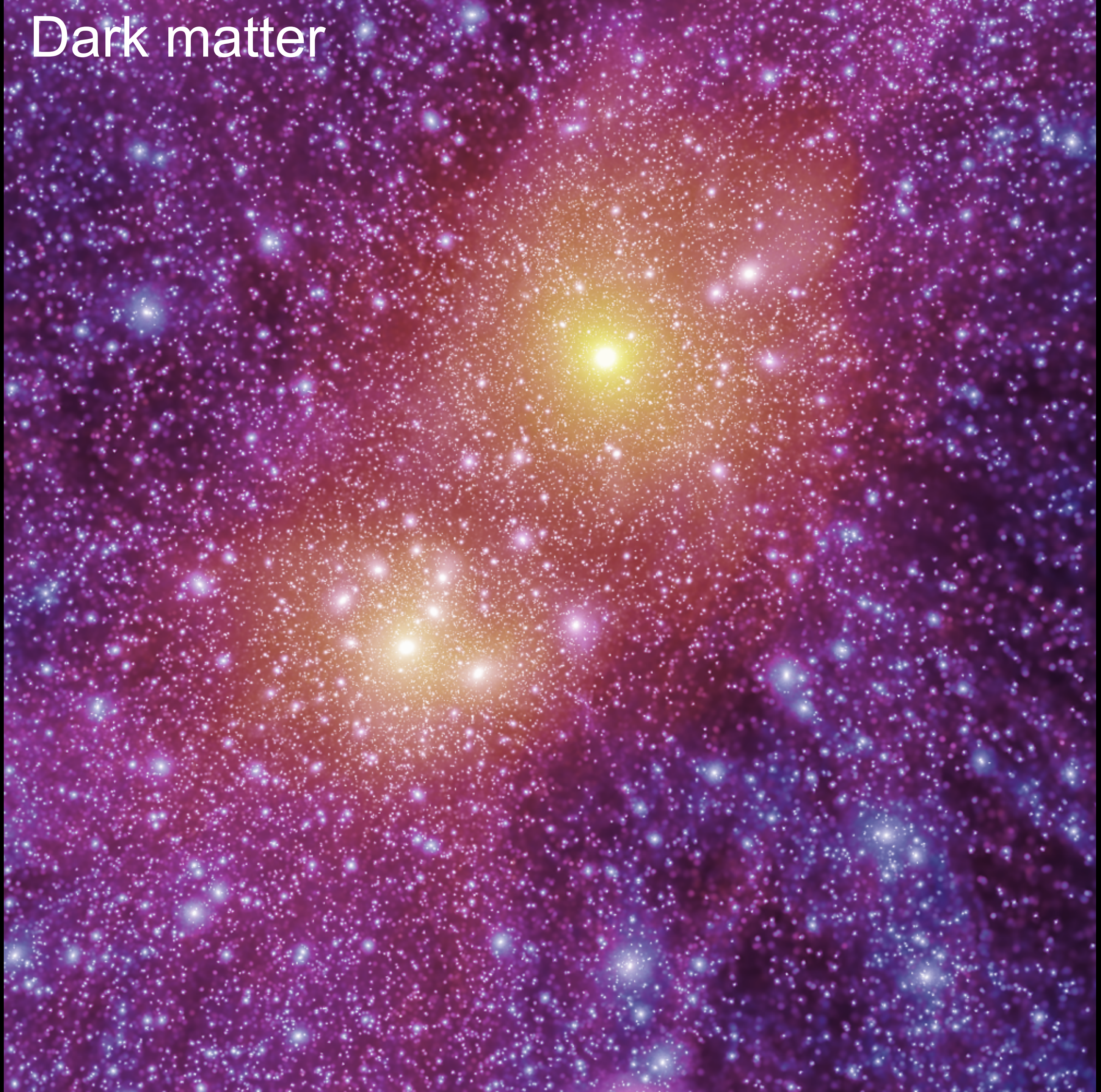
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16



Stars

APOSTLE EAGLE full hydro simulations

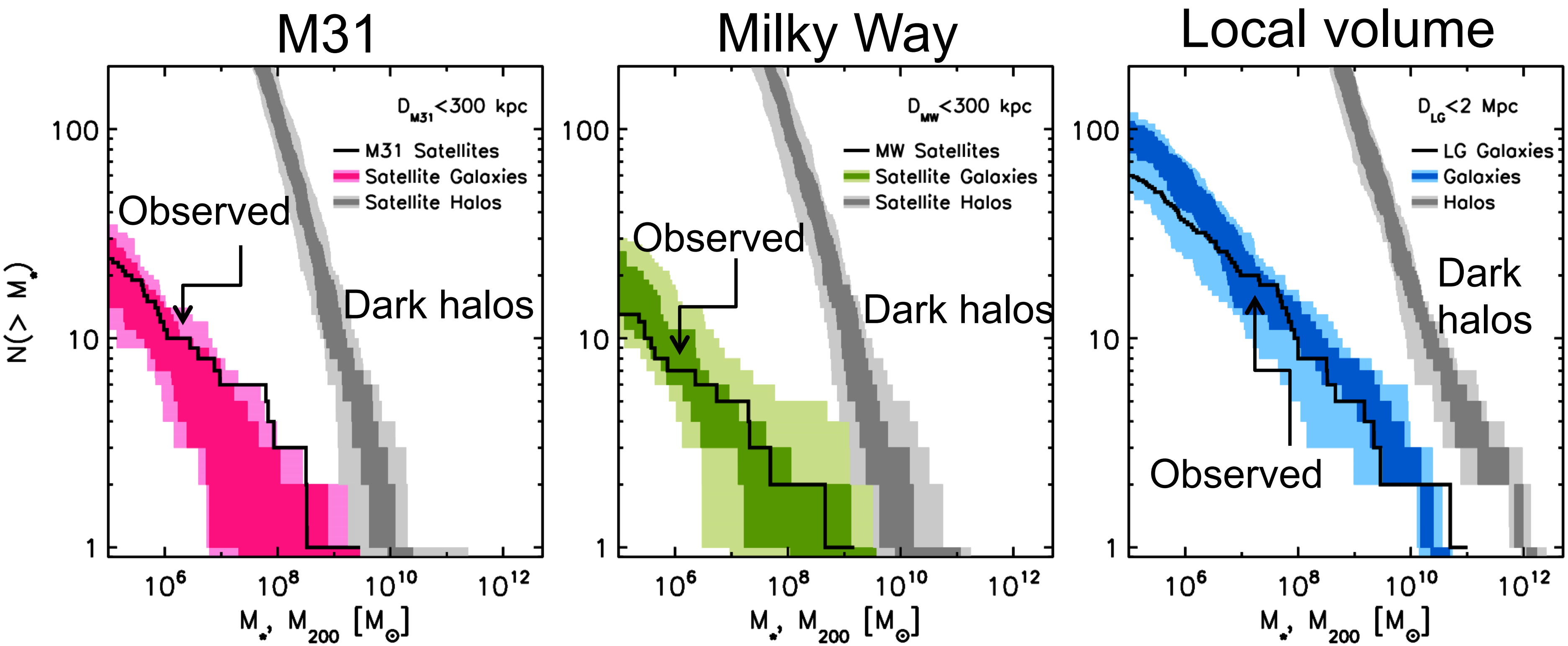
Local Group

Stars

Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

EAGLE Local Group simulation



Sawala, CSF et al '16

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When “baryon effects” are taken into account

→

Observed abundance of satellites is compatible with CDM

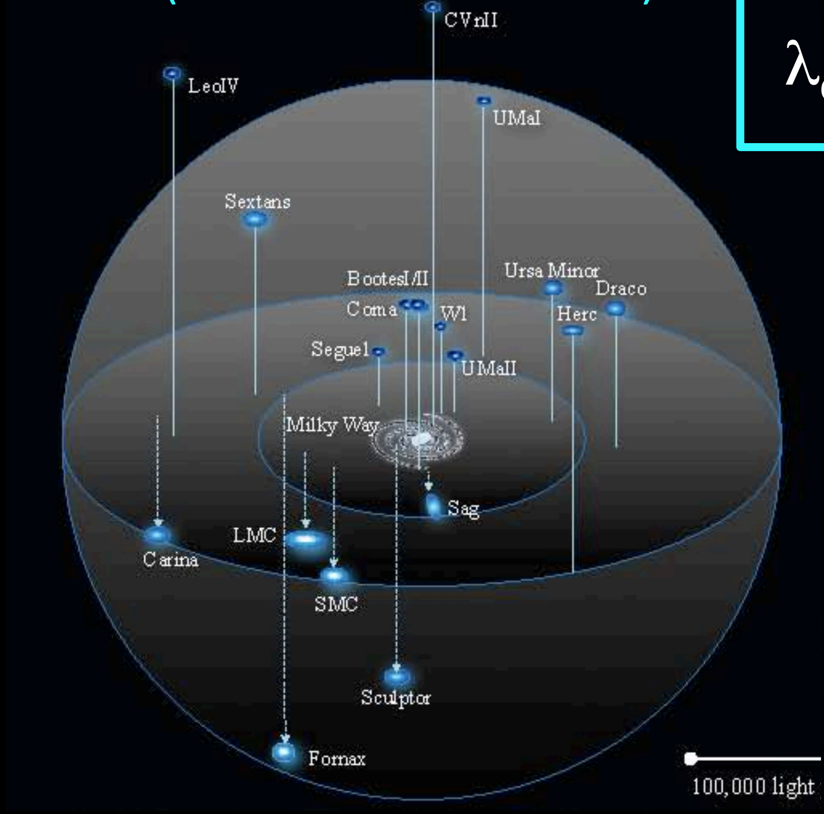
→

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

How about in WDM?

The satellites of the MW

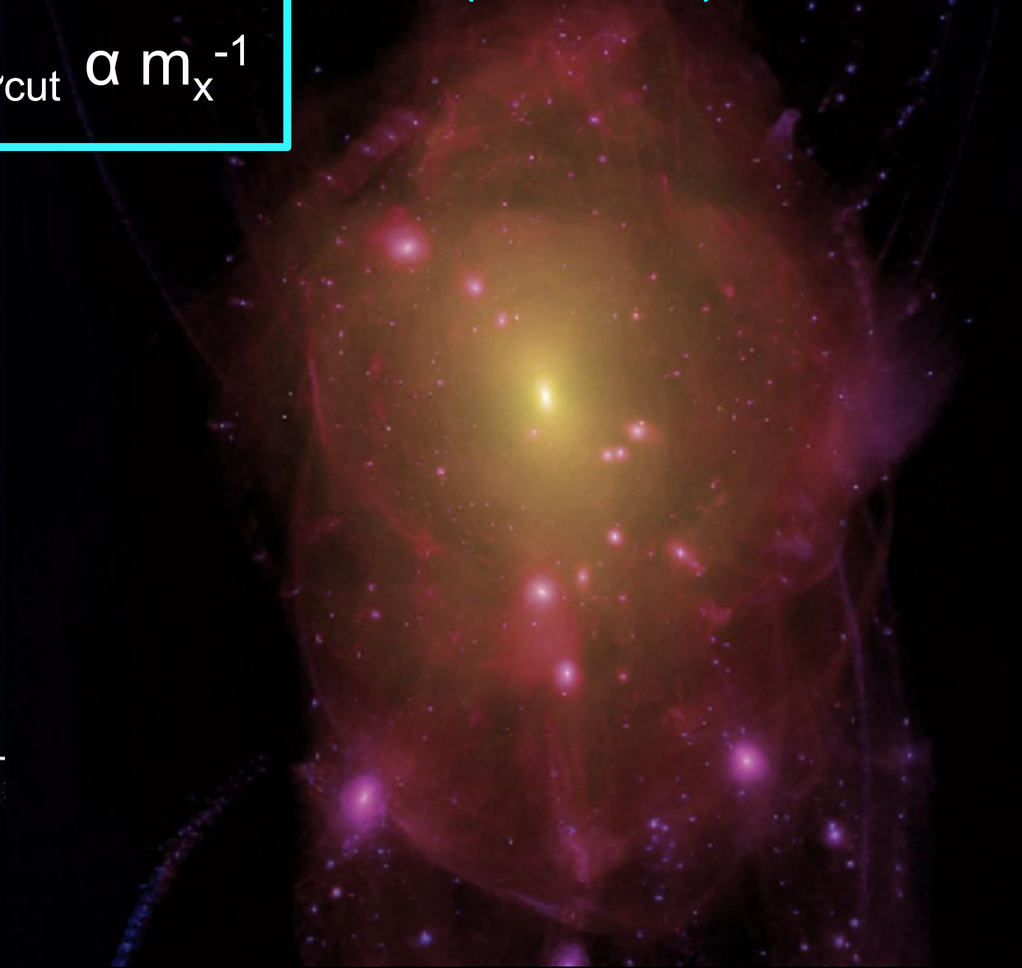
(~50 discovered so far)



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

Dark matter subhalos in WDM

(a few tens)



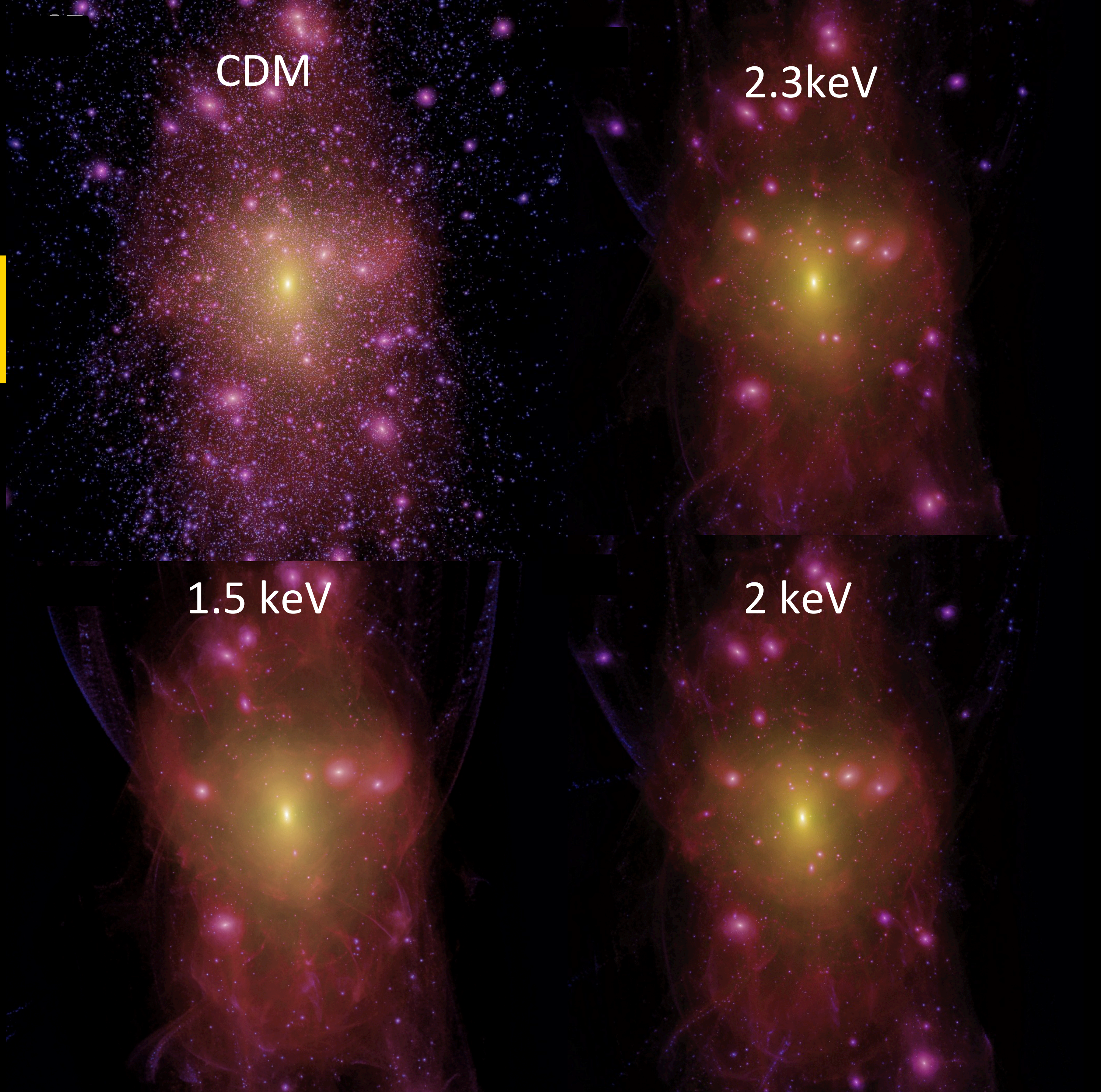
Warm DM:
different ν mass

WDM

2.3 keV

2.0 keV

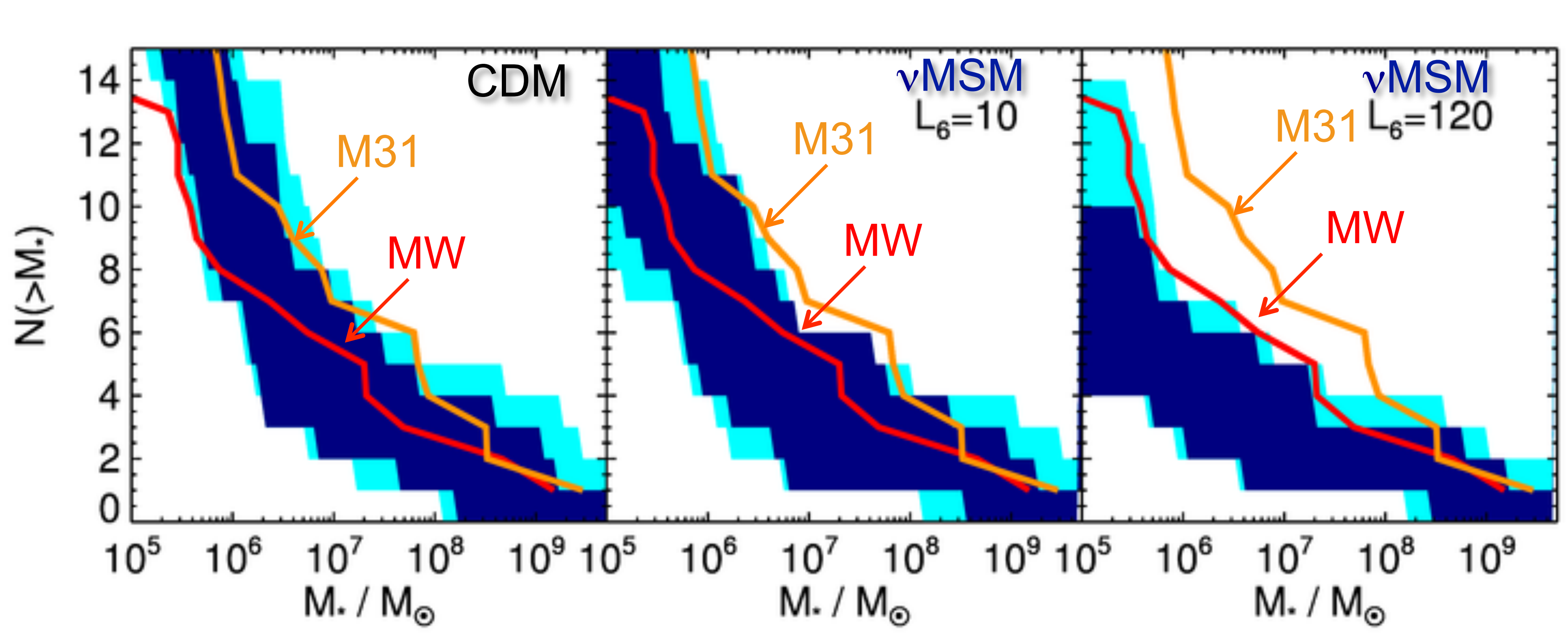
1.5 keV



Luminosity Function of Local Group Satellites in WDM

University of Durham

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

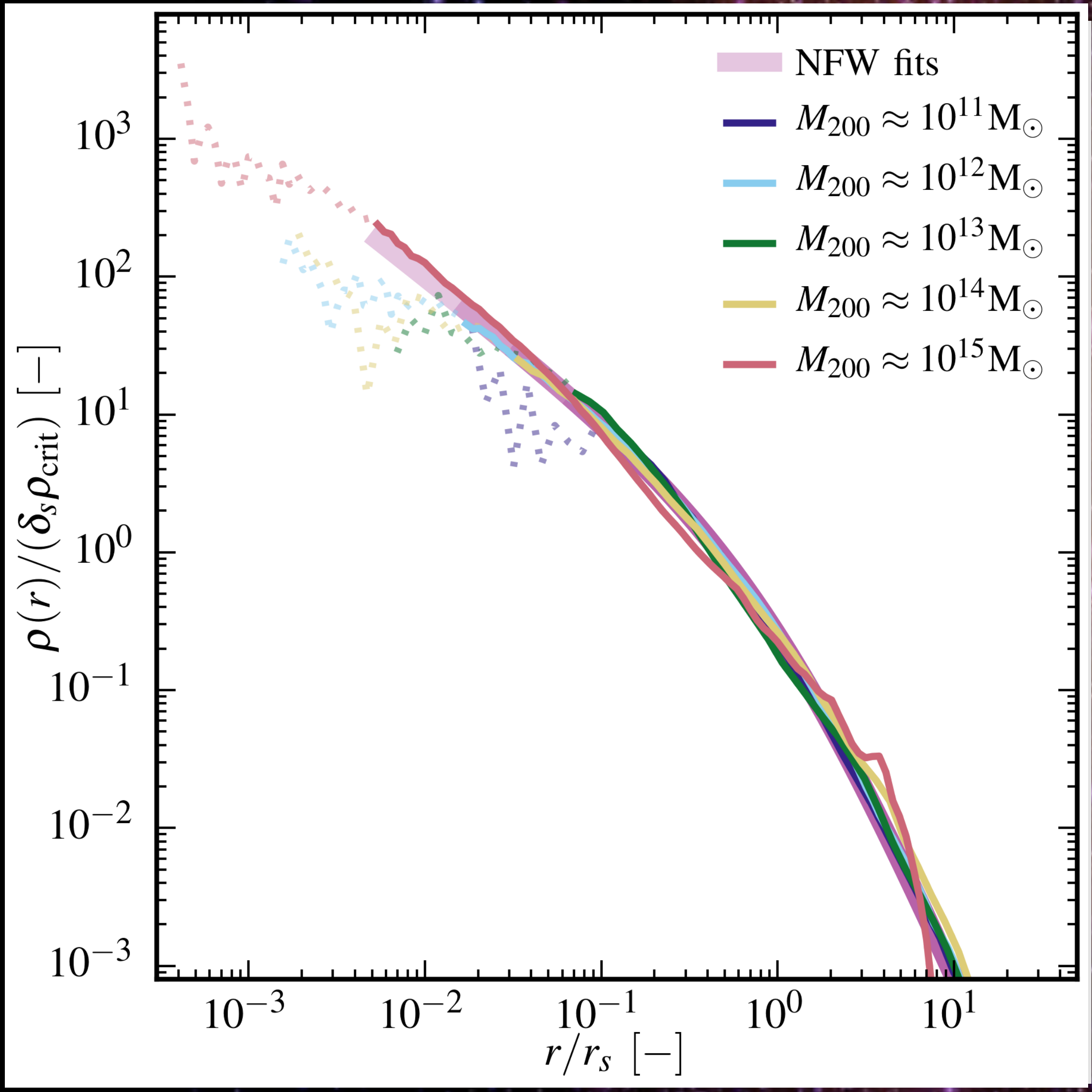


Lovell et al. '16

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

Does the inner structure of satellites help?

The Density Profile of Cold Dark Matter Halos



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

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

Fitted by simple formula:

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

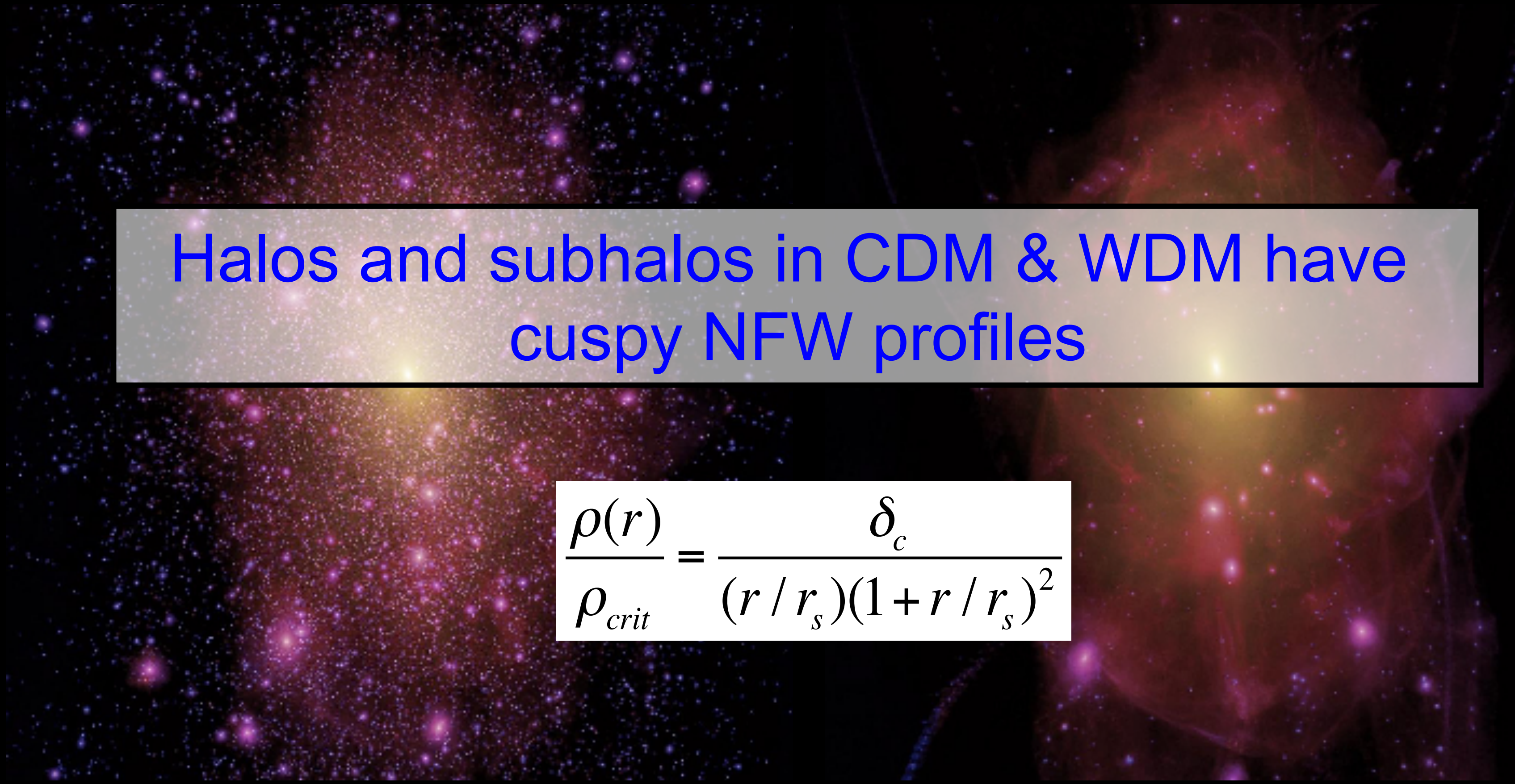
(Navarro, Frenk & White ’97)

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

Dark matter halos: cores or cusps?

A myth

The DM halos of dwarf galaxies have central cores

A challenge for CDM (and WDM)?

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)

Many nearby galaxies now have hi-res 2D HI velocity fields → ideal for infering potential

Assume: gas is in centrifugal equilibrium on approximately circular orbits

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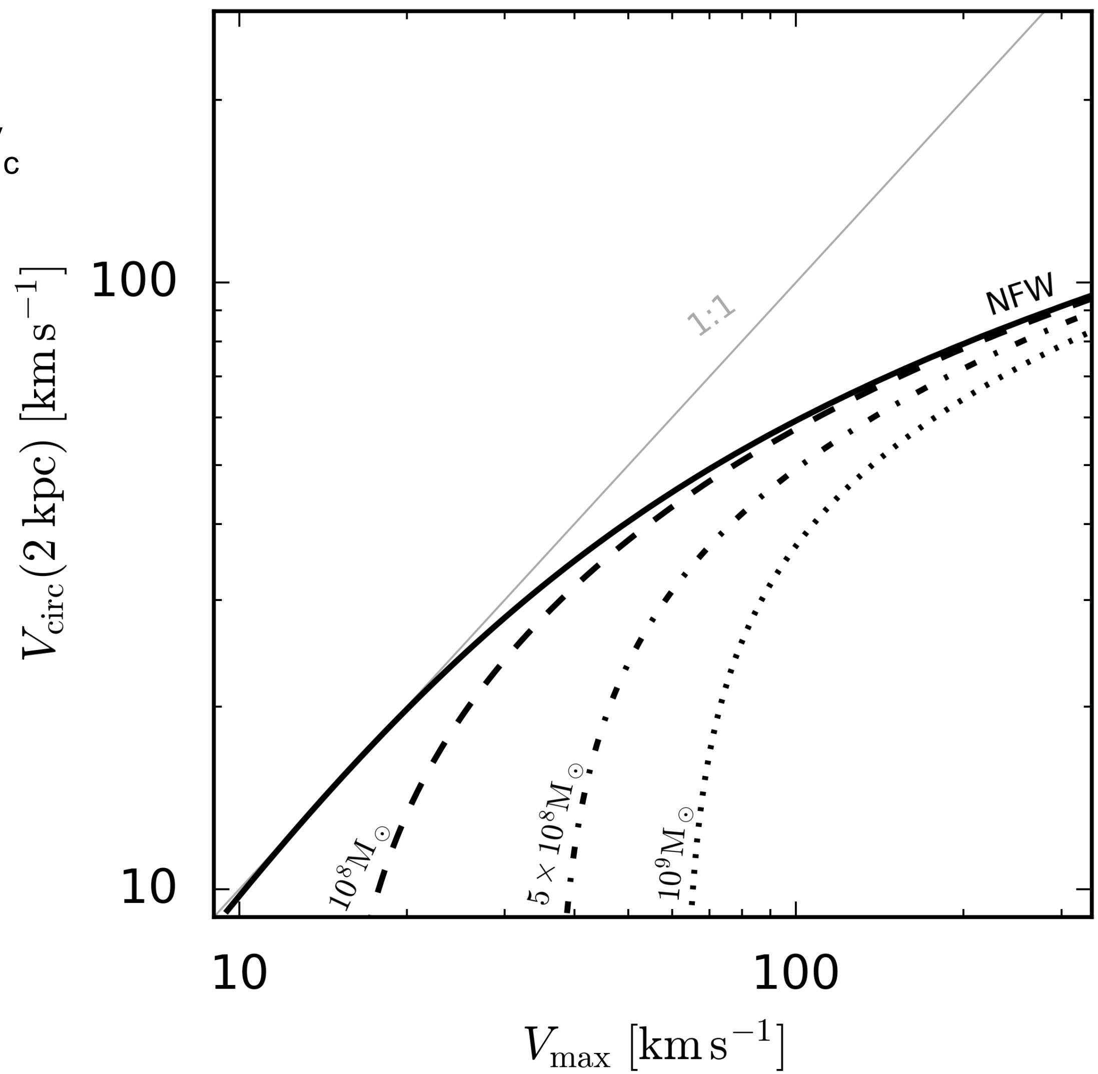
The diversity of rotation curves

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

$V_{max} = \max V_c$



Oman+ '17

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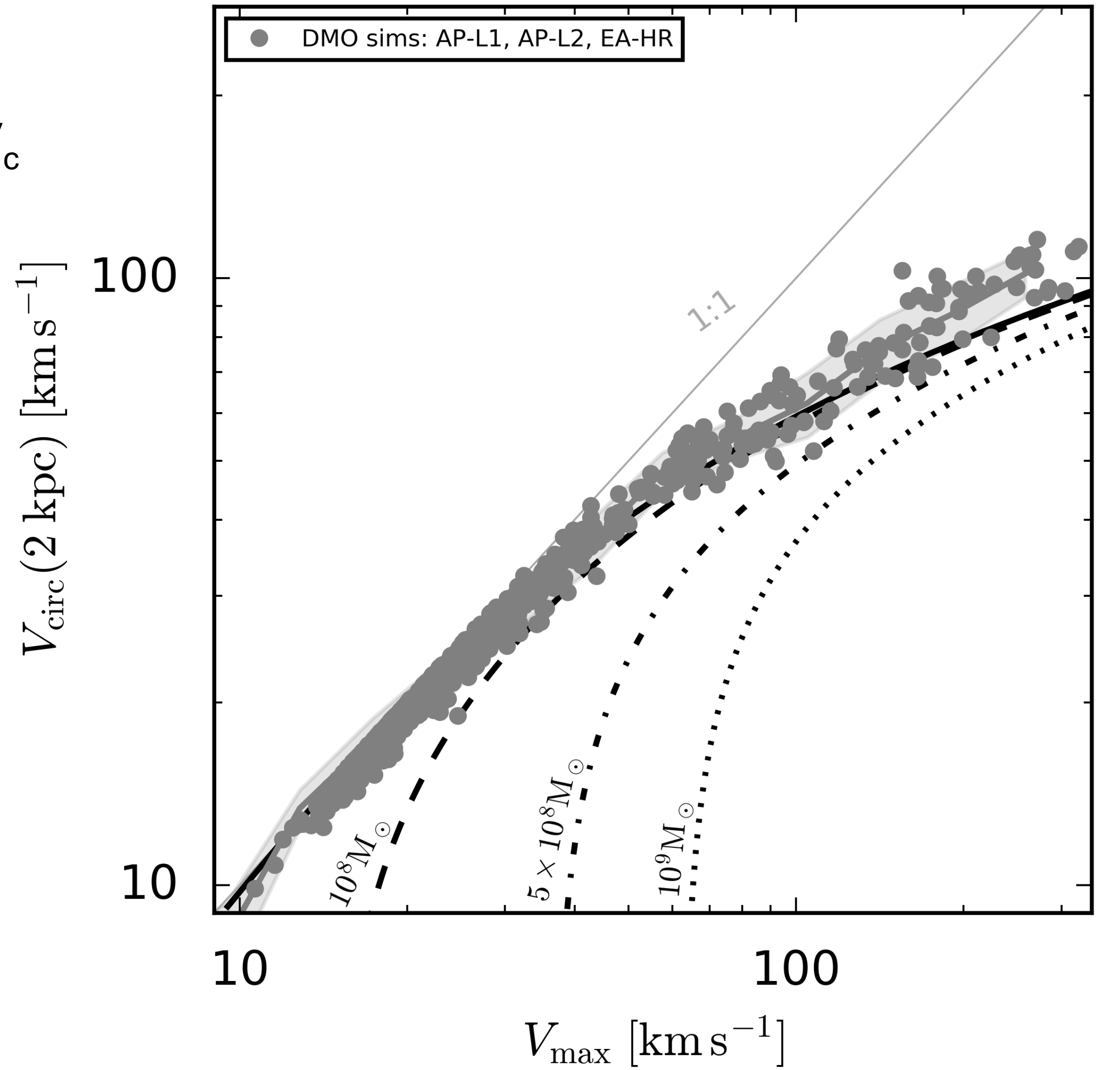

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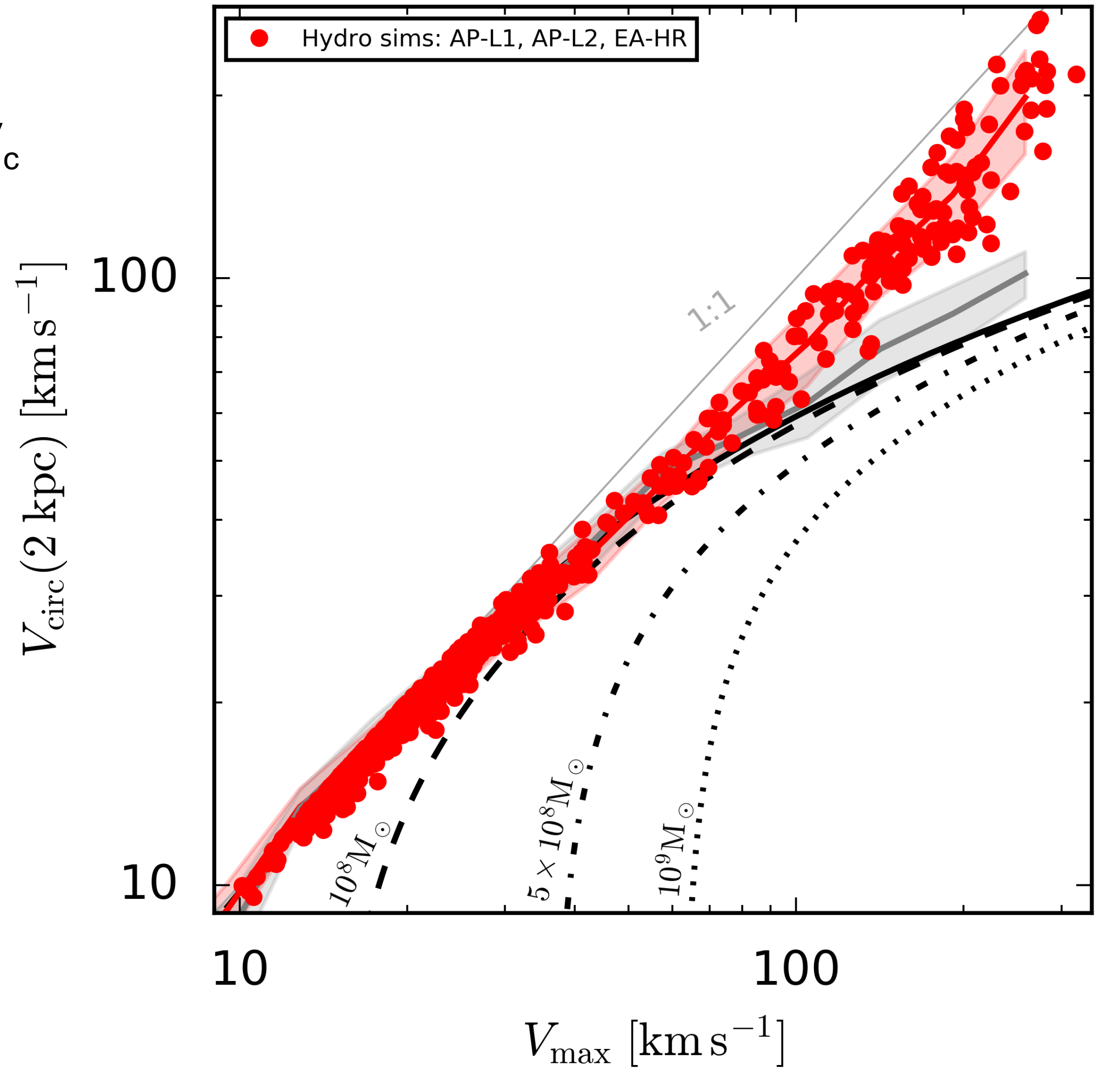

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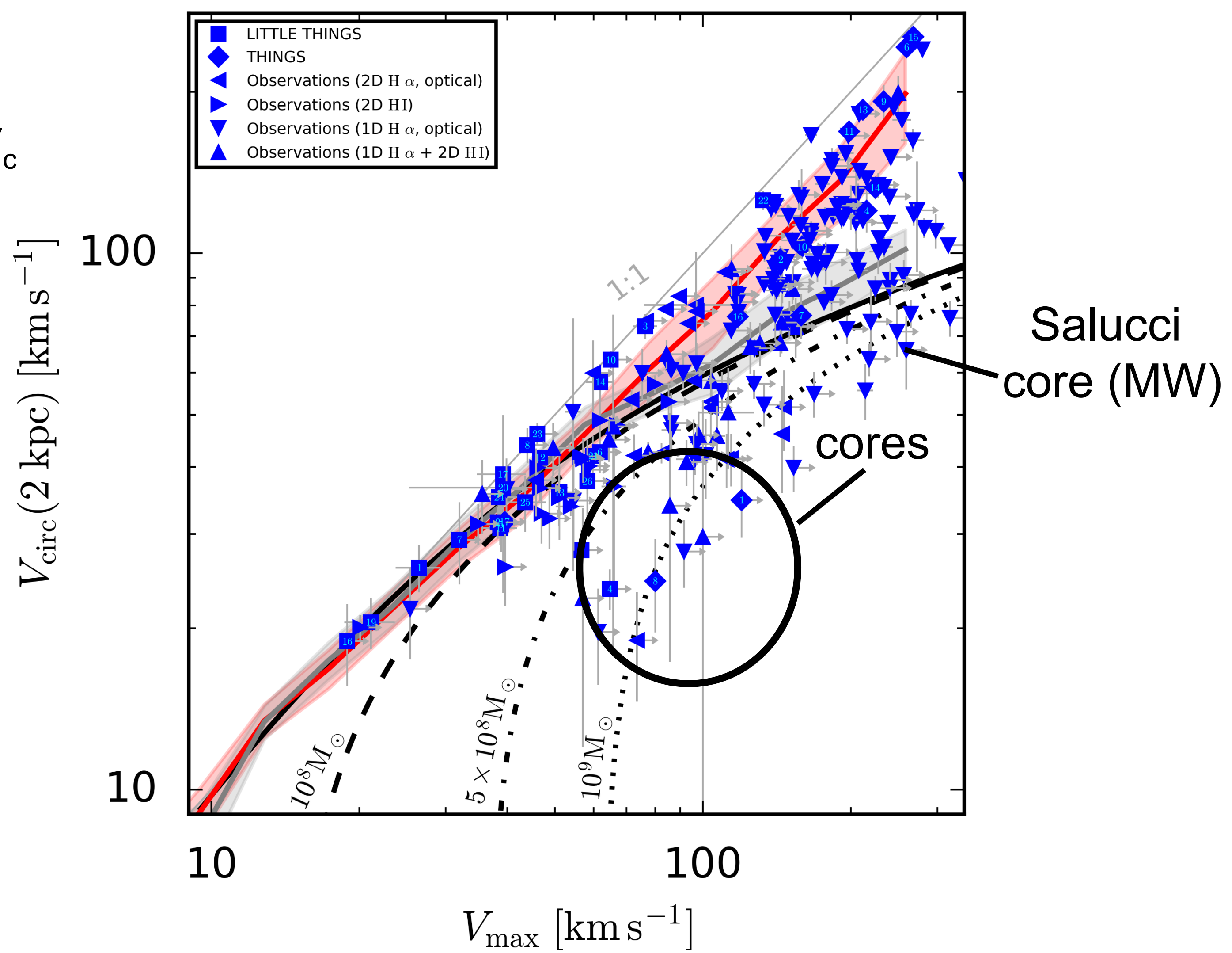

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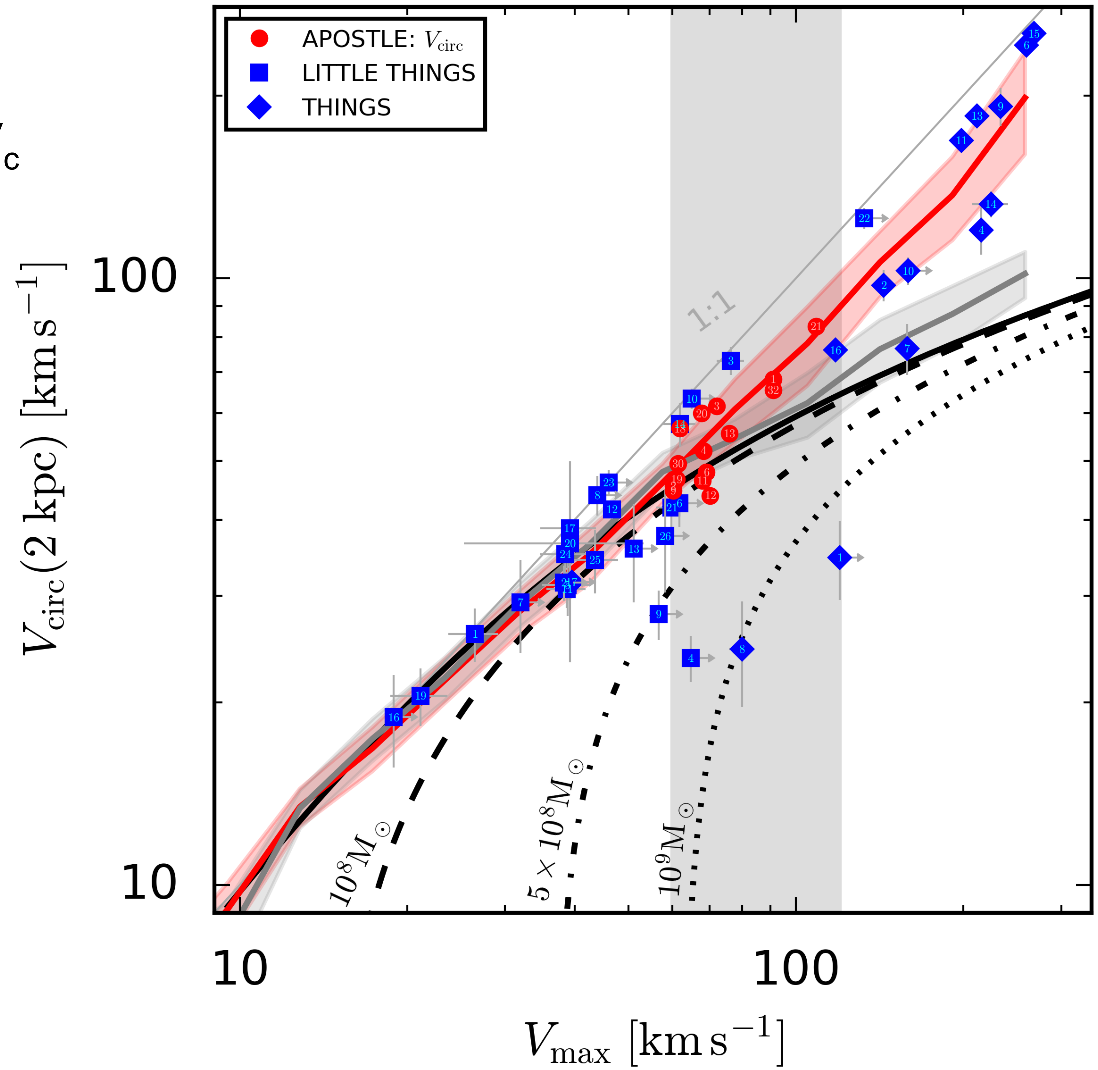

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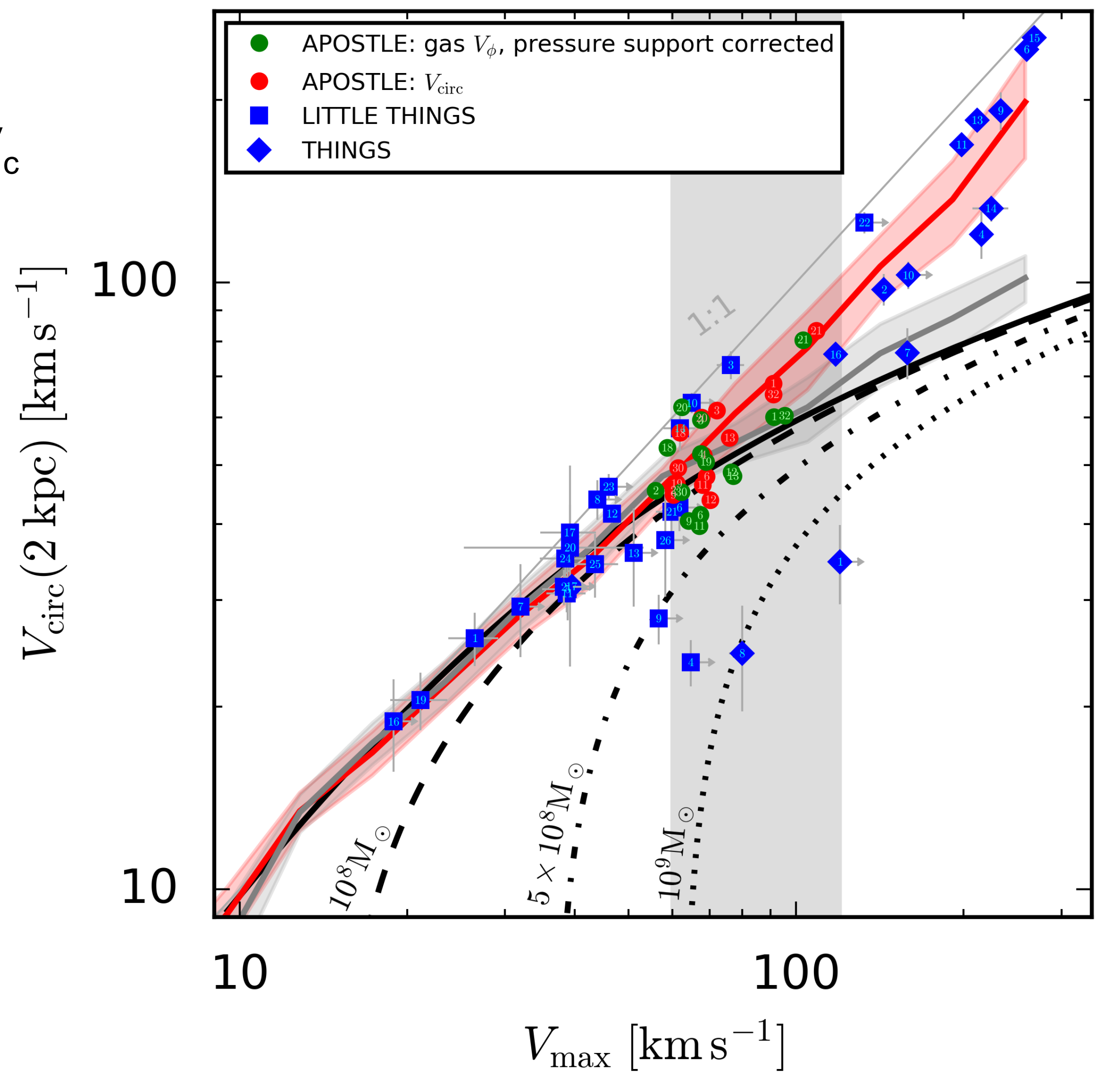

Oman+ ‘17

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Analysis of 2D velocity fields

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{r}}$

Tilted-ring model corrected for asymmetric drift

^{3D}BAROLO fit

Analysis of 2D velocity fields

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Tilted-ring model corrected for asymmetric drift

● ^{3D}BAROLO fit

Let's apply this to APOSTLE galaxies by making a mock 2D velocity field data cube and analysing it just as the real data

Rotation curves of 2 APOSTLE dwarfs

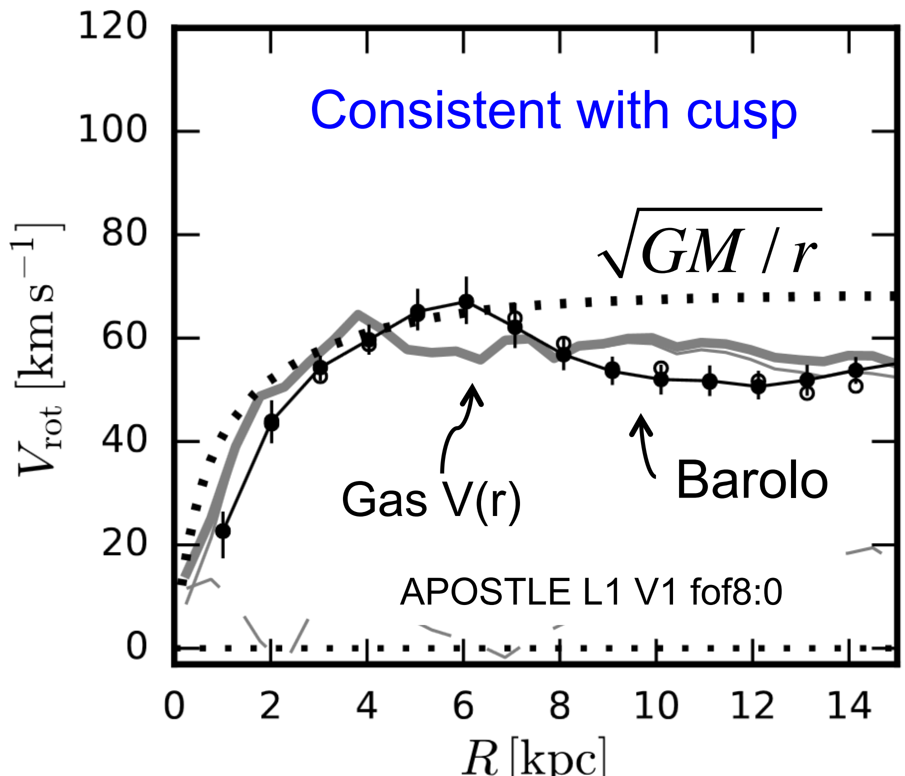
University of Durham

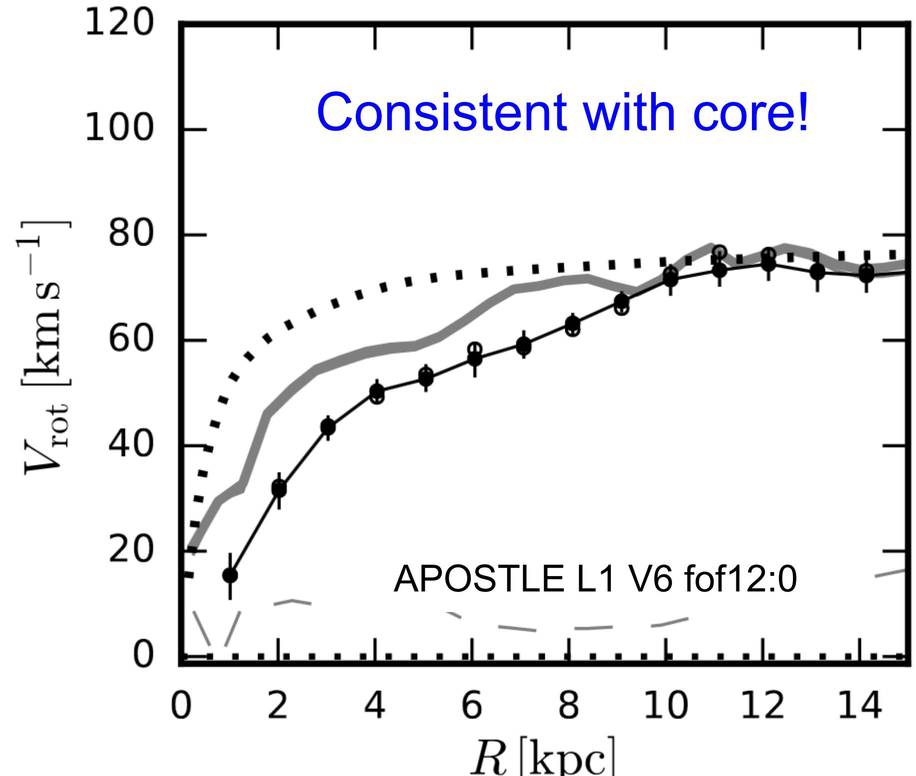
APOSTLE galaxies all have NFW cusps

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{r}}$

Tilted-ring model corrected for asymmetric drift

^{3D}BAROLO fit





Oman et al '18; Marasco et al '18

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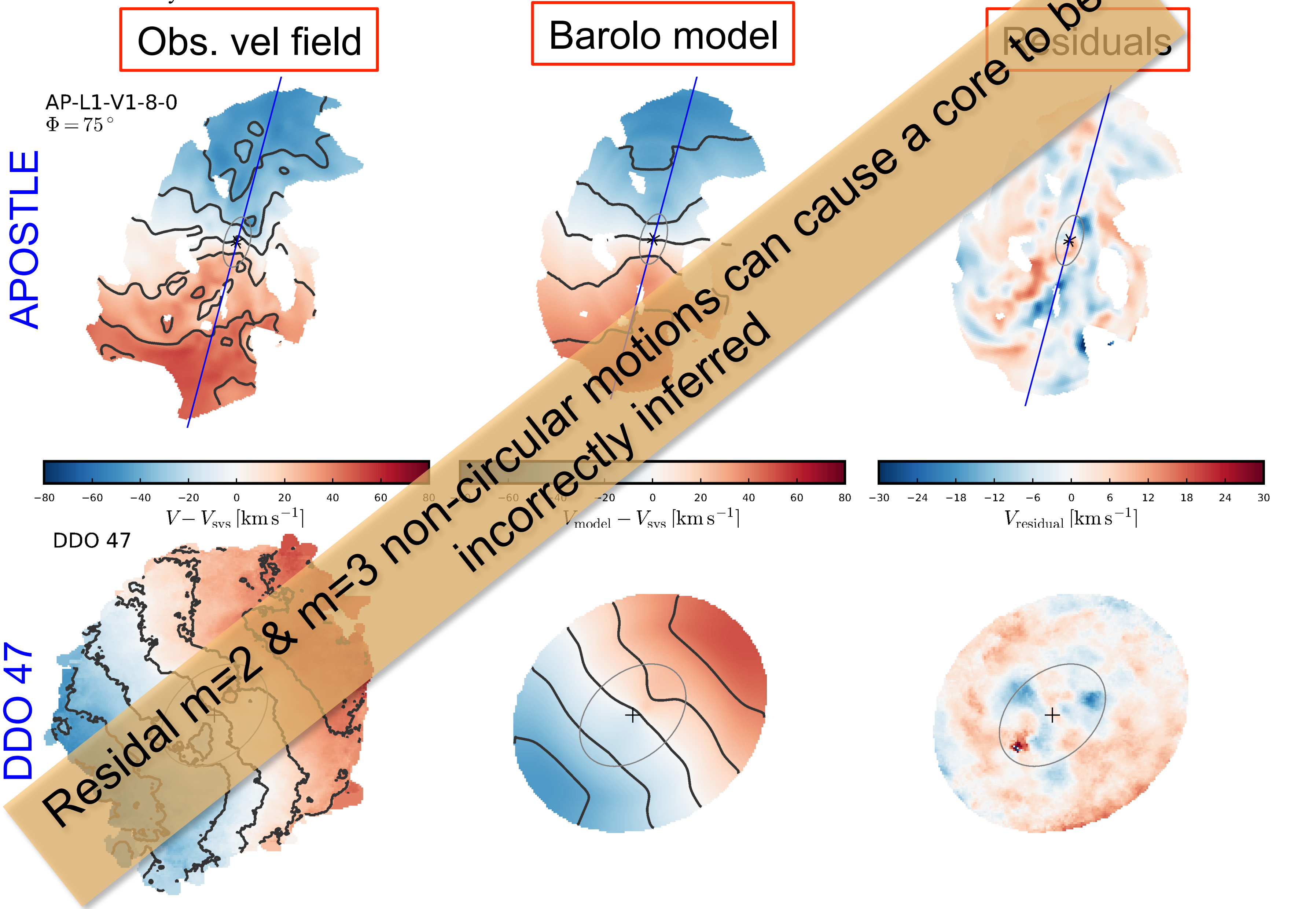
Non-circular motions



Residal m=2 & m=3 non-circular motions can cause a core to be incorrectly inferred

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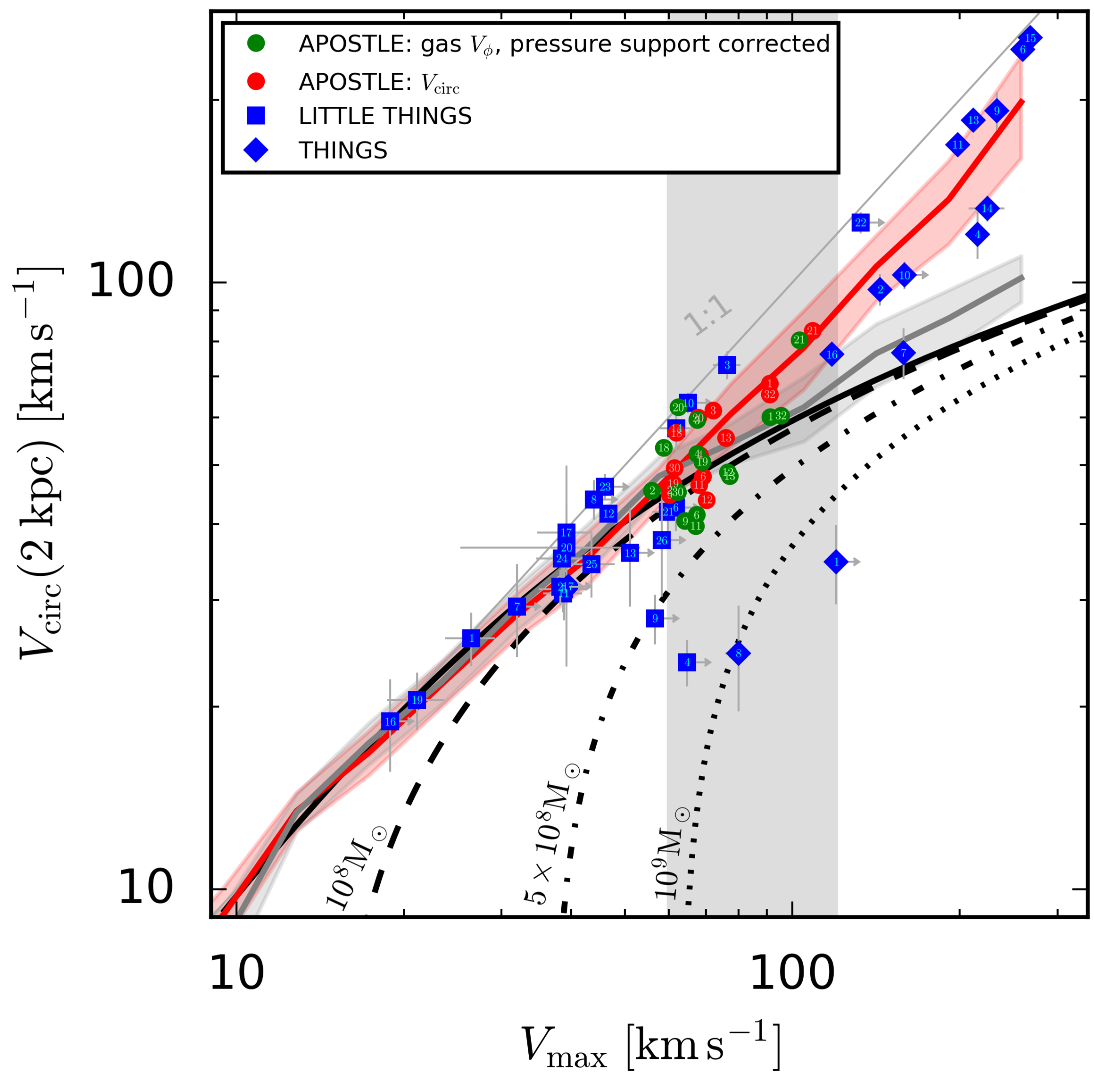
The diversity of rotation curves



Oman+ '17

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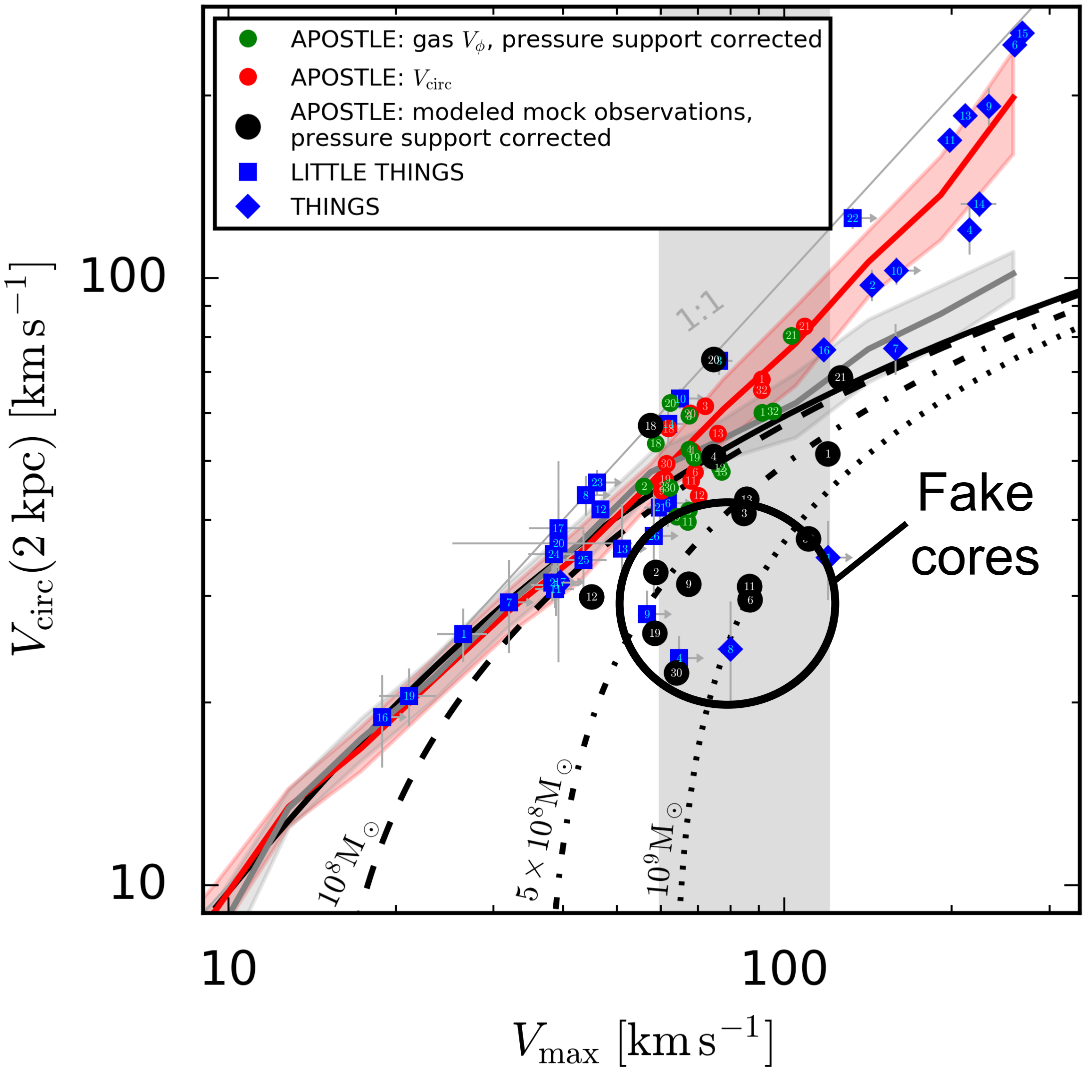
The diversity of rotation curves



Oman+ '17

Cores or cusps in nature?

Cores

Cusps

No convincing evidence for cores in observed galaxies

But if cores were found in galaxies would that rule out CDM and WDM?

How about baryon effects?

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

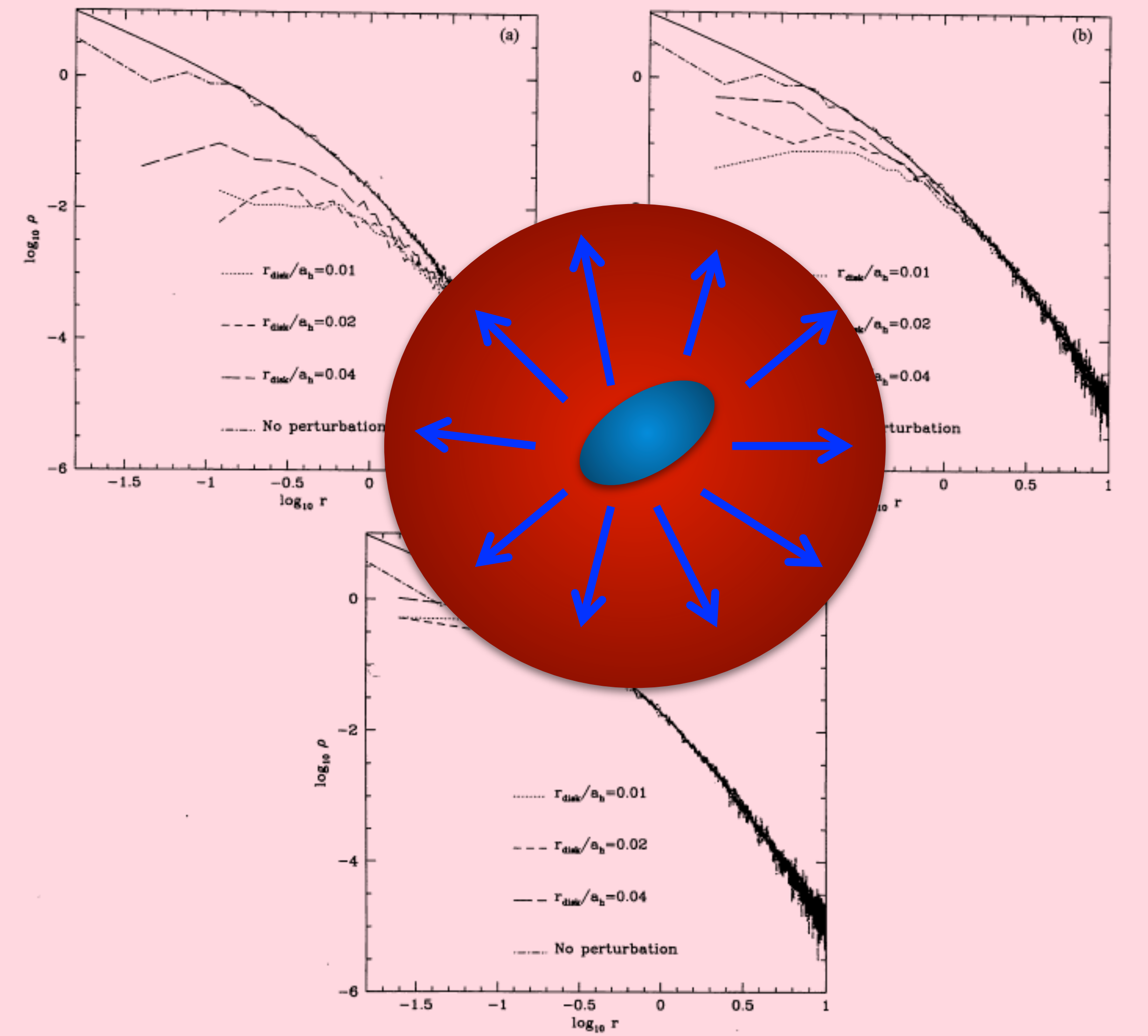
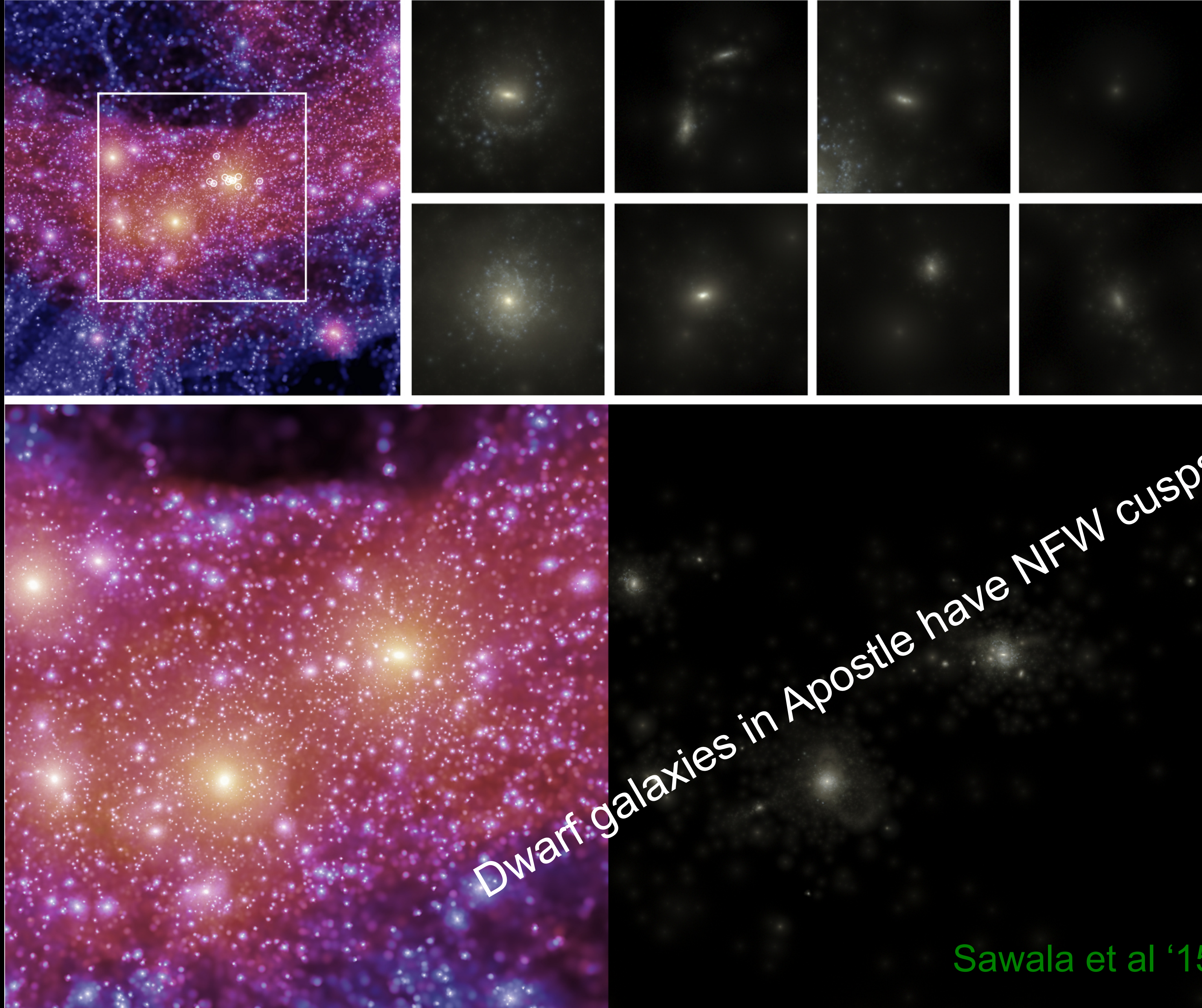


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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



Dwarf galaxies in Apostle have NFW cusps!

Sawala et al '15

Core formation

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

Key parameter: gas density threshold for star formation

Physically meaningless

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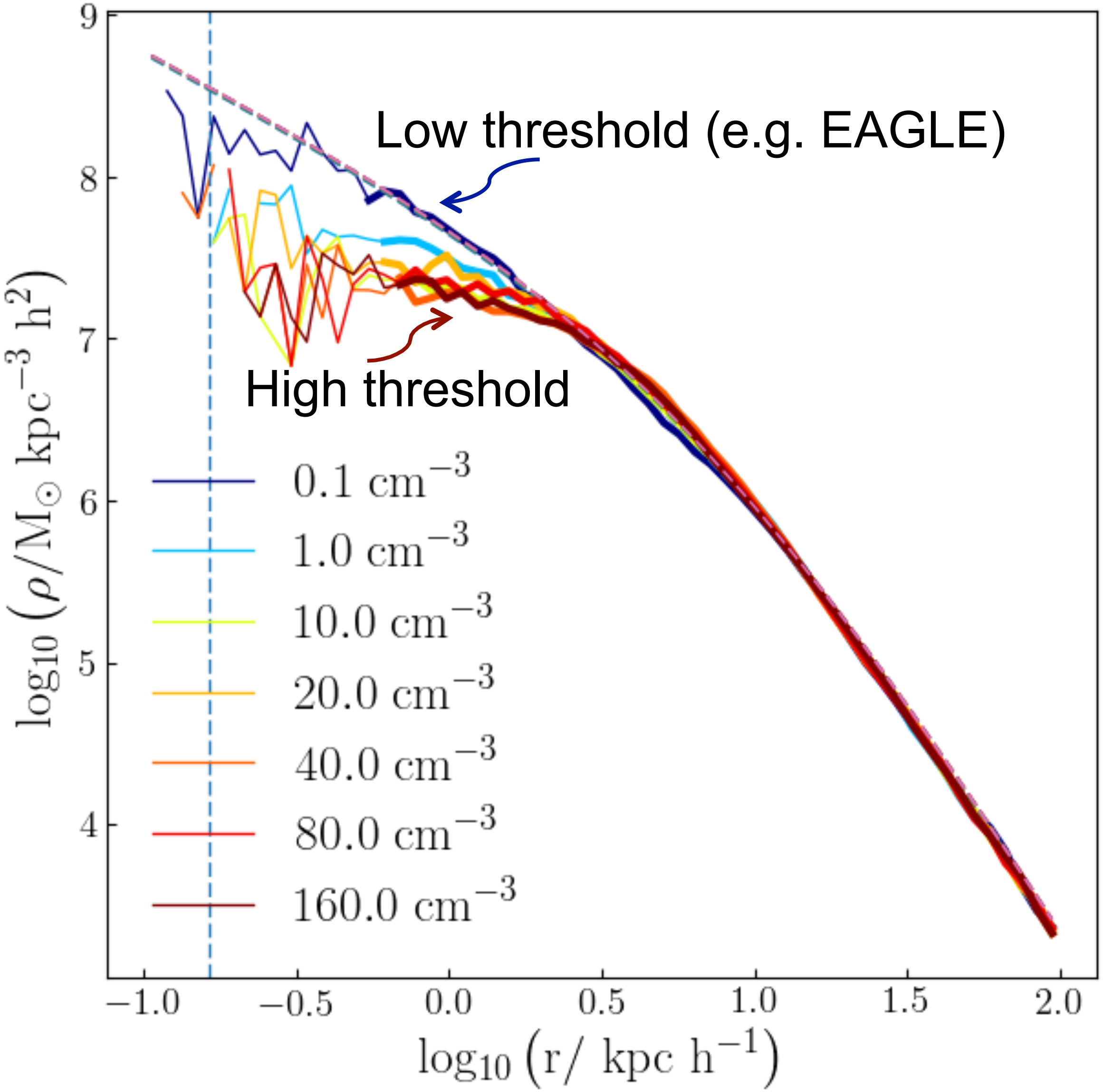
Cores or cusps in simulations?



Benitez-Llambay, CSF et al '17

There is NO 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

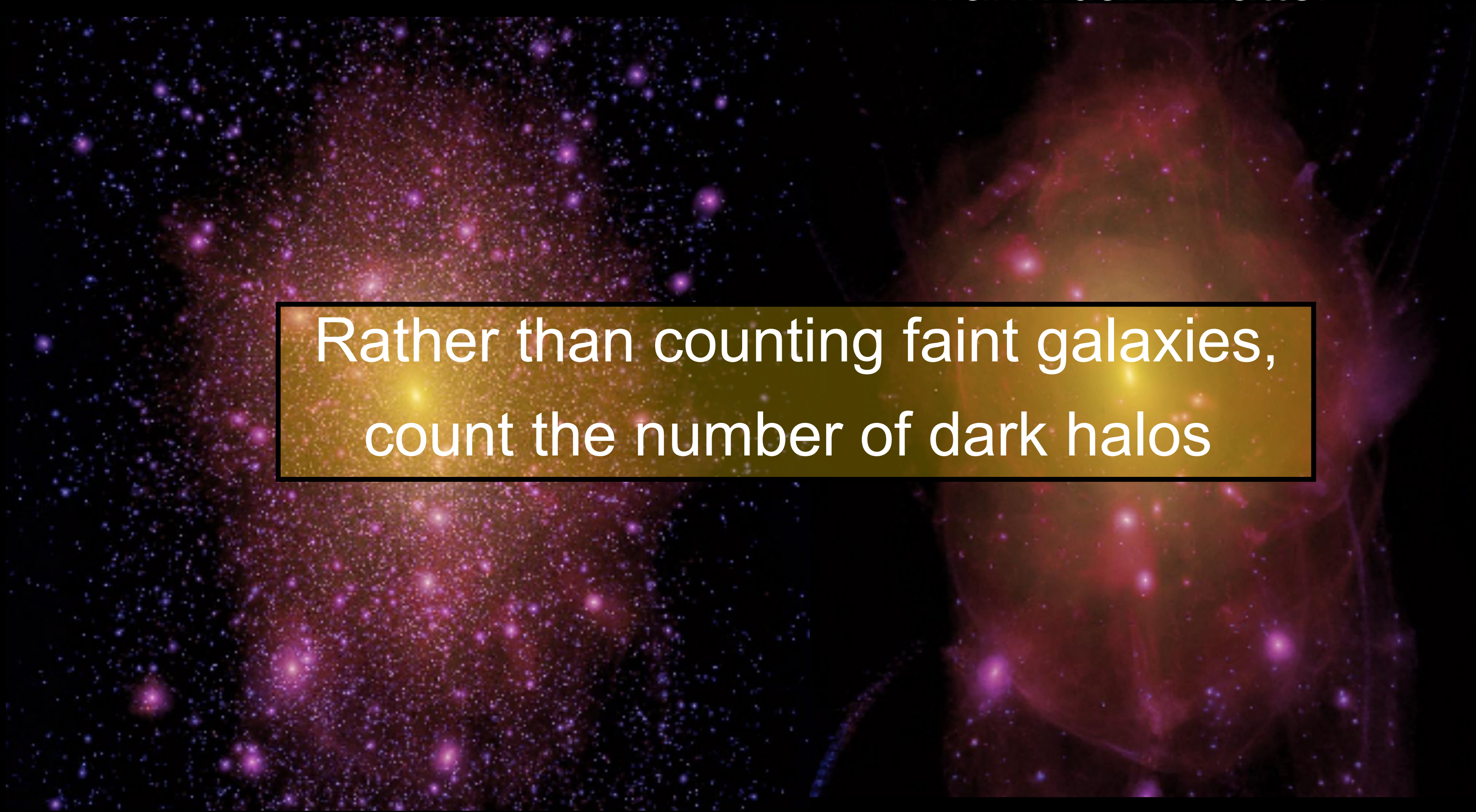
Is there any way can distinguish CDM from WDM?

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

Can we distinguish CDM/WDM?

cold dark matter

warm dark matter



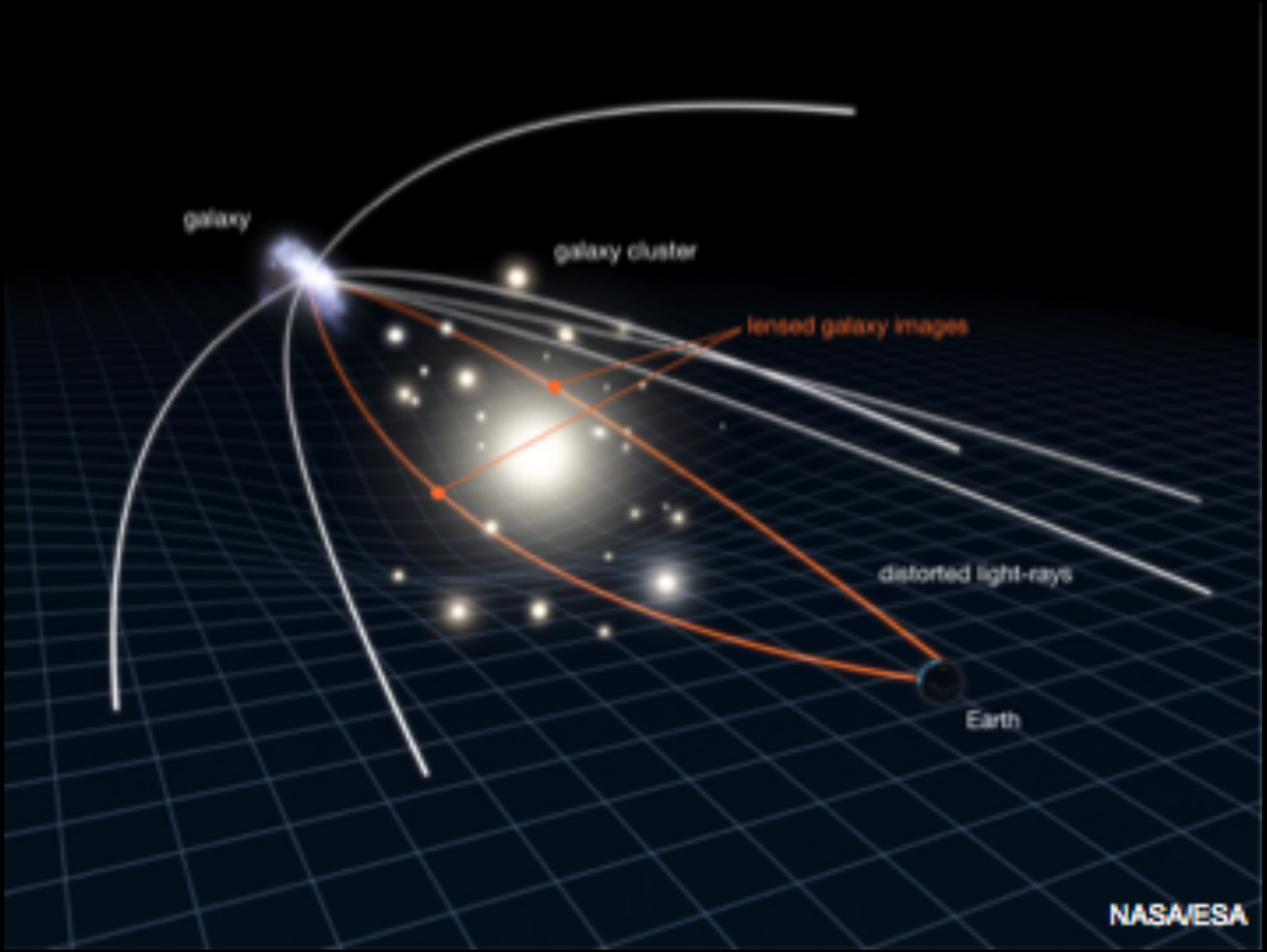
Rather than counting faint galaxies,
count the number of dark halos

Can we distinguish CDM/WDM?

cold dark matter | warm dark matter

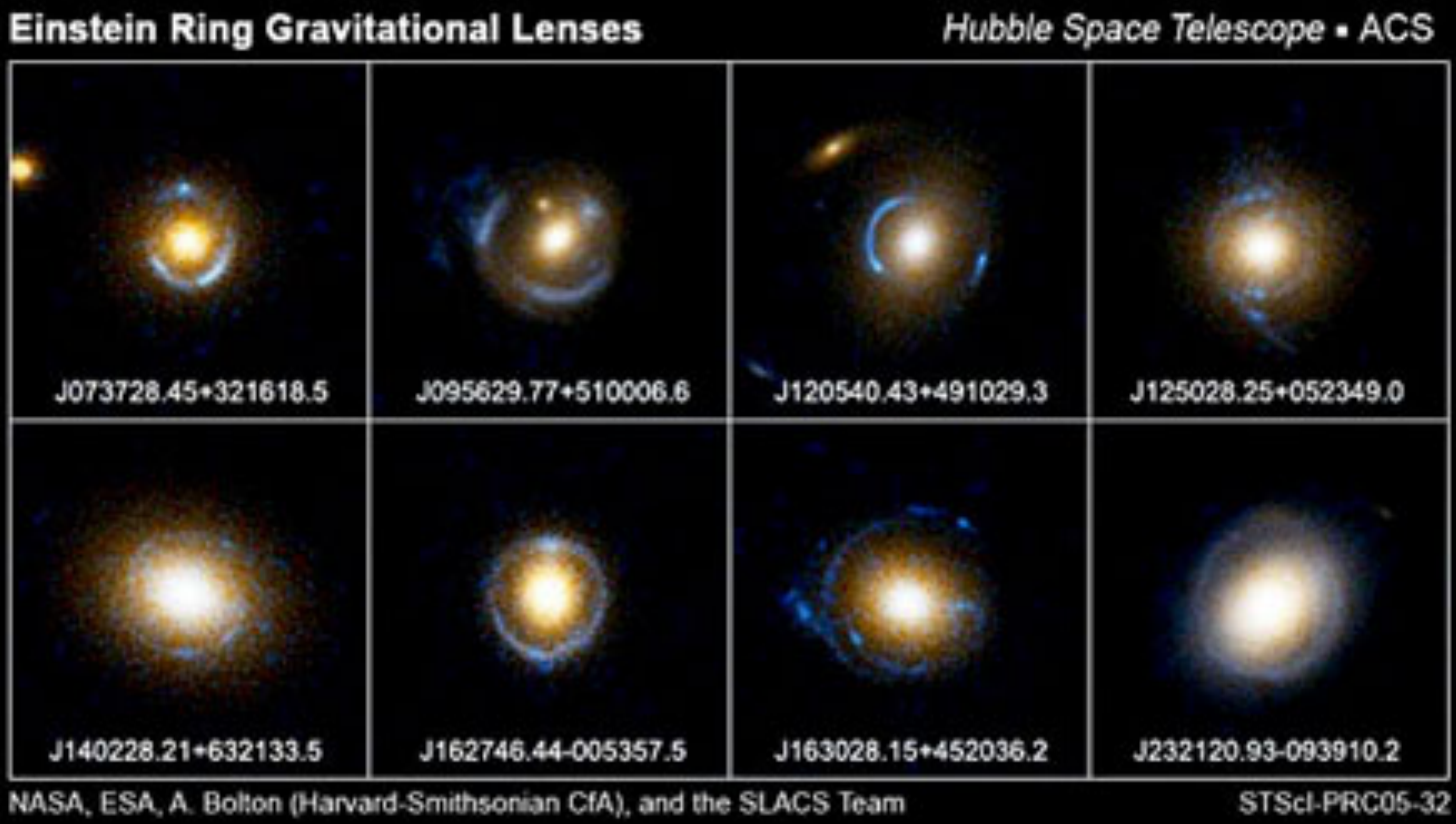
How to rule out CDM

Gravitational lensing: Einstein rings

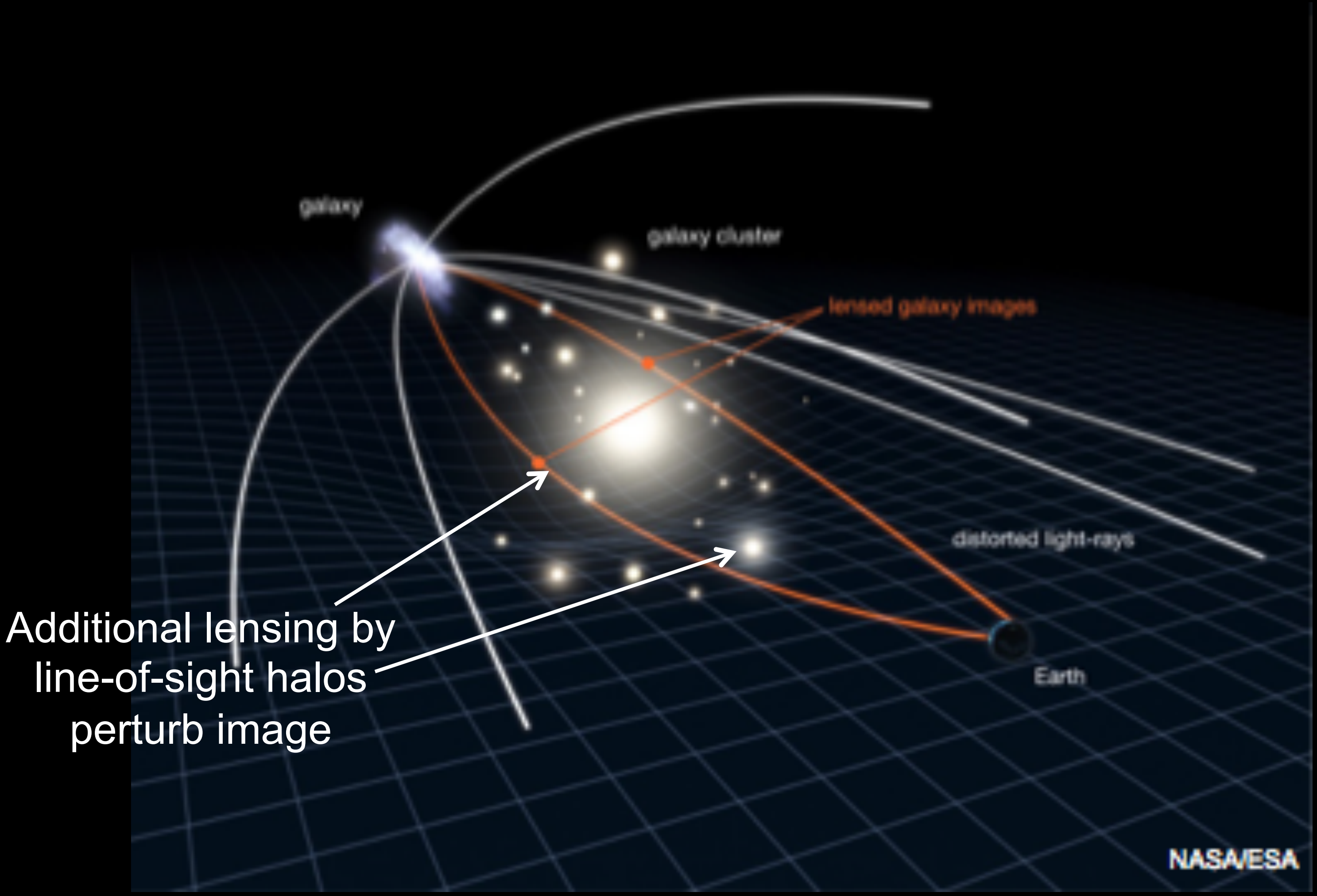


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



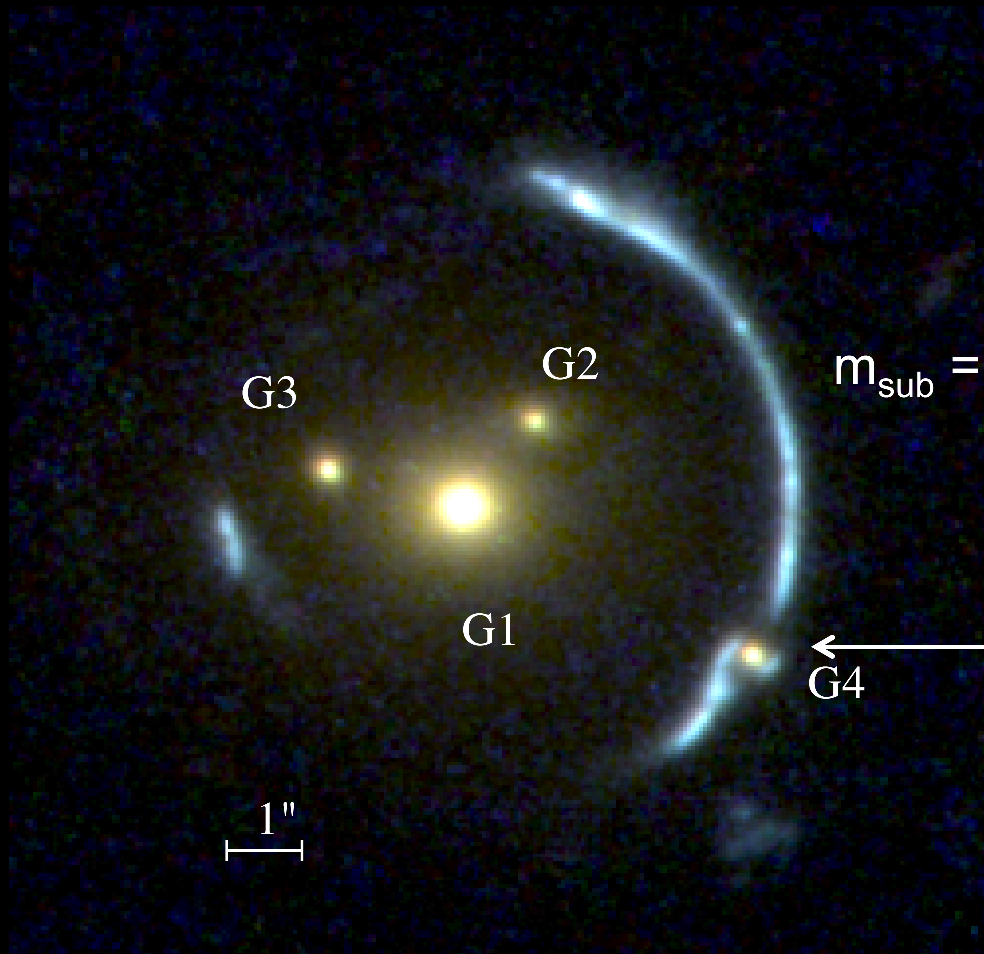
Gravitational lensing: Einstein rings



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

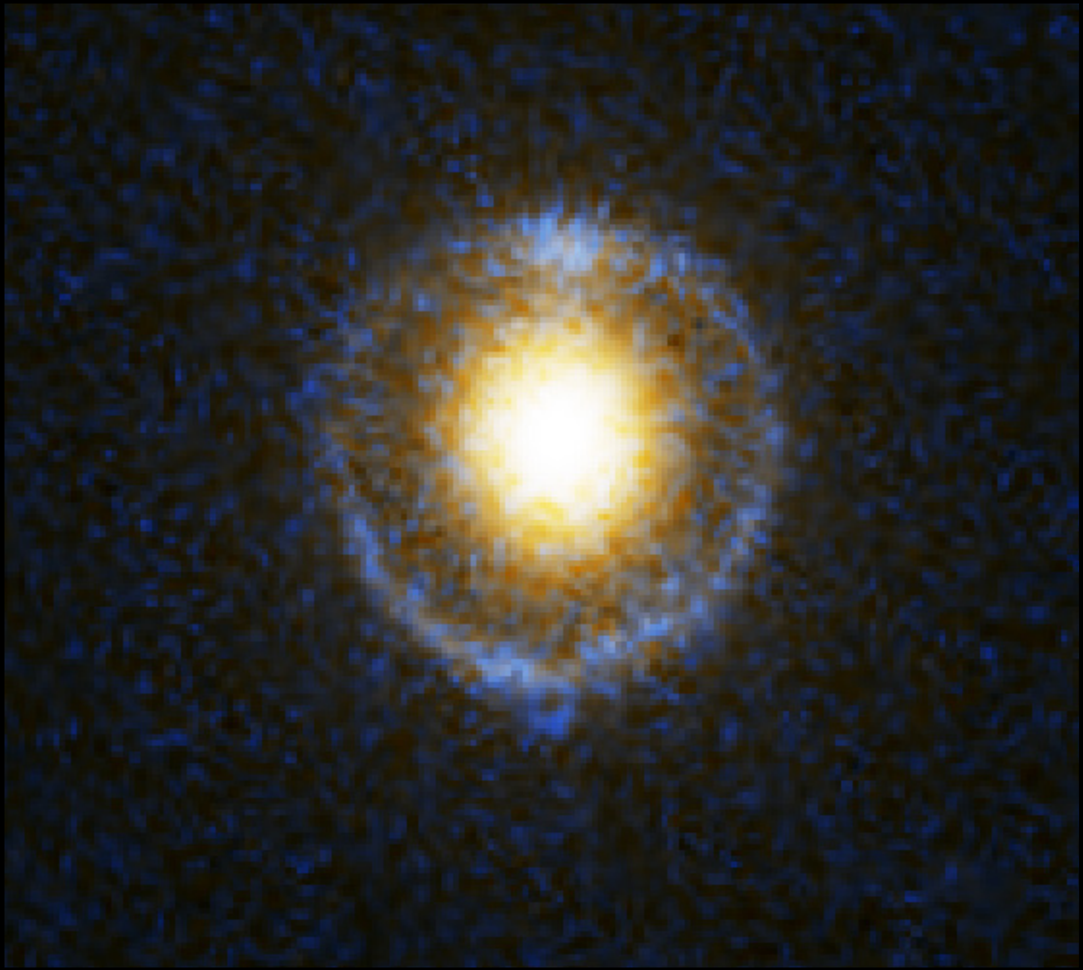


$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al '10

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



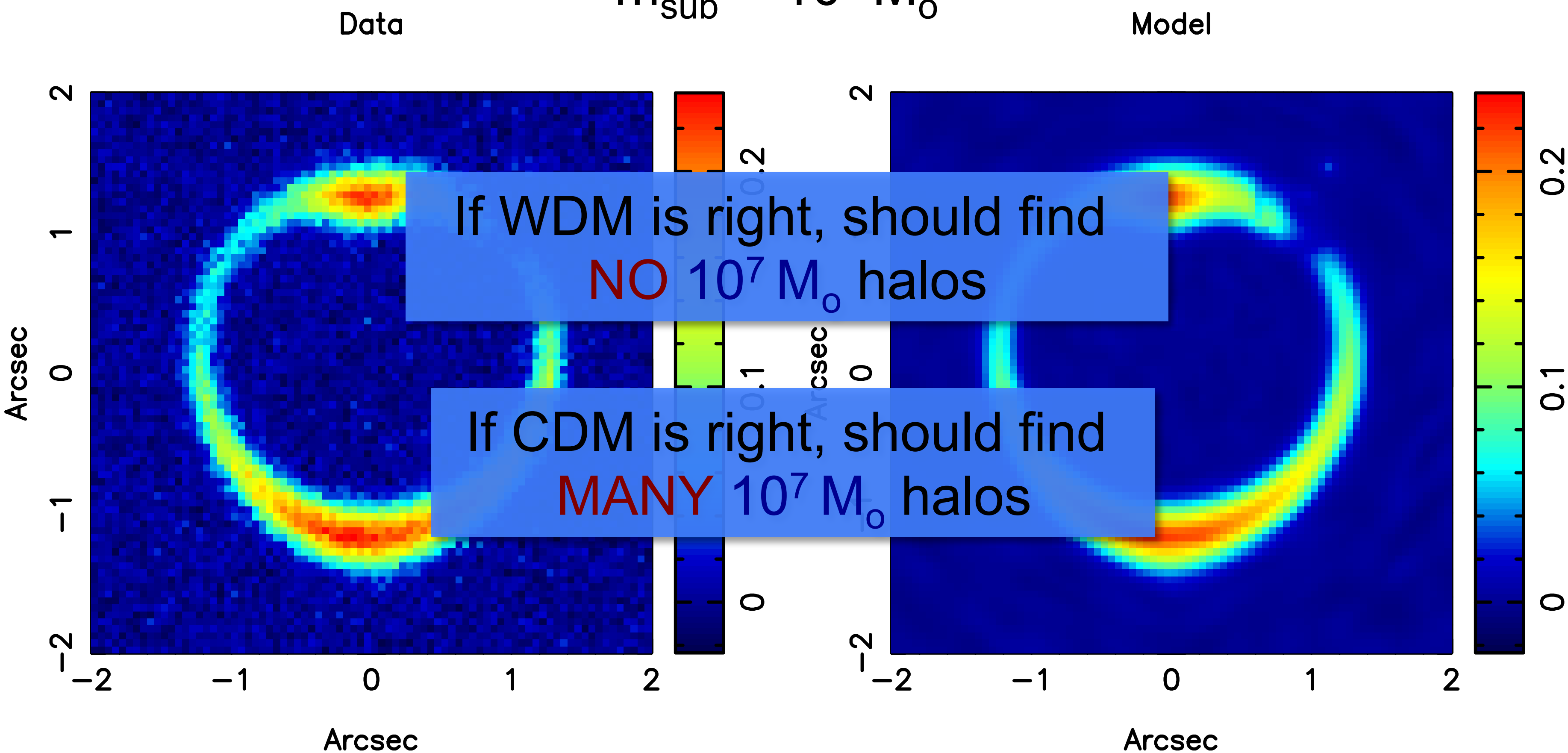
Vegetti & Koopmans '09

University of Durham

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8 M_o$



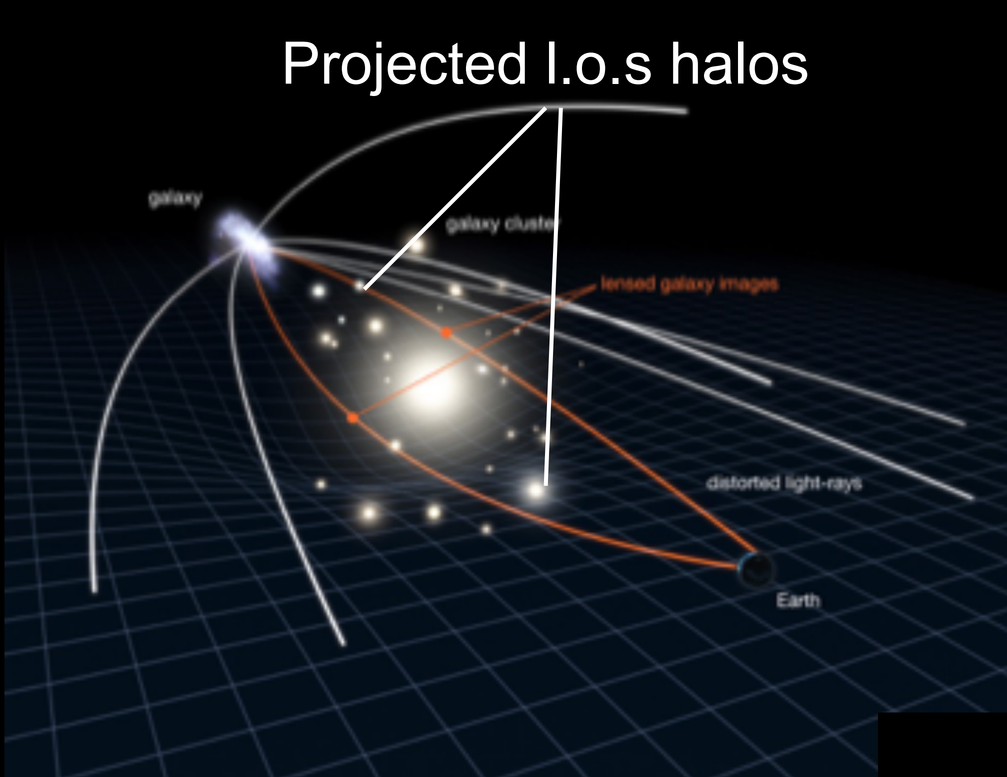
If WDM is right, should find NO $10^7 M_o$ halos

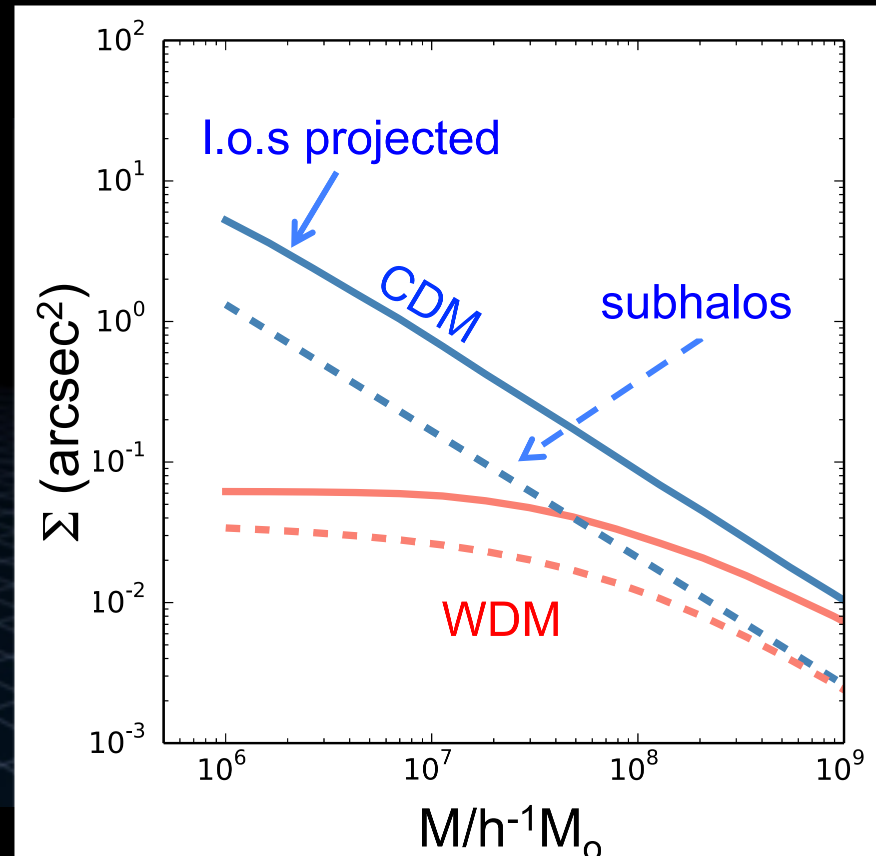
If CDM is right, should find MANY $10^7 M_o$ halos

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

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

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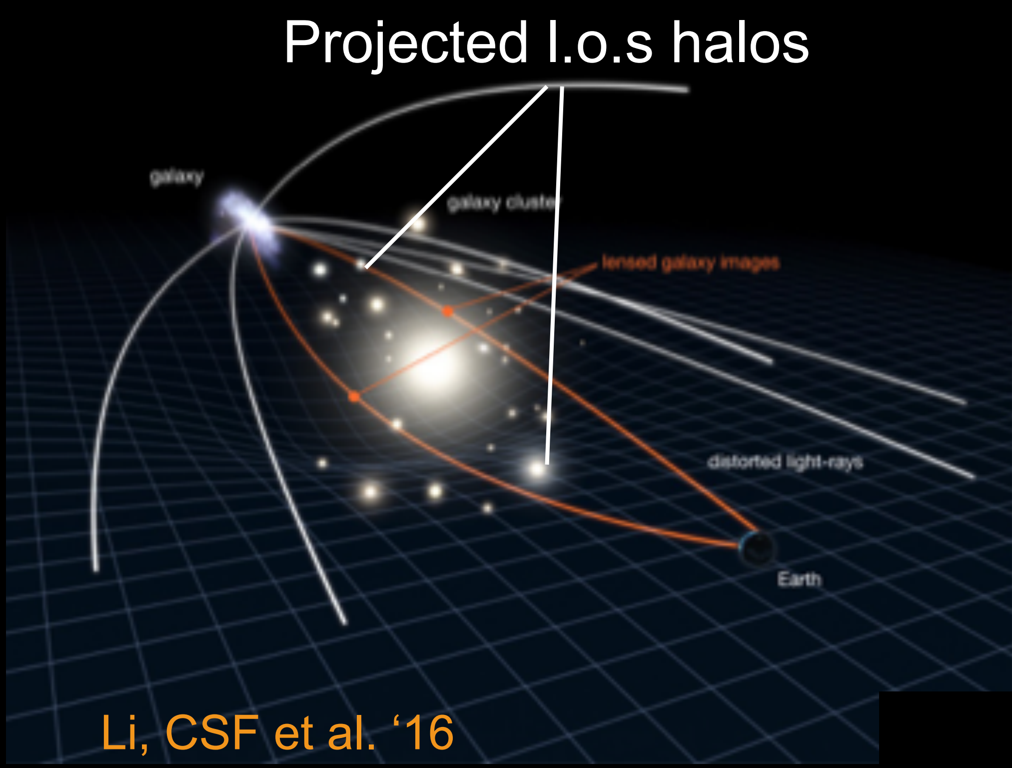
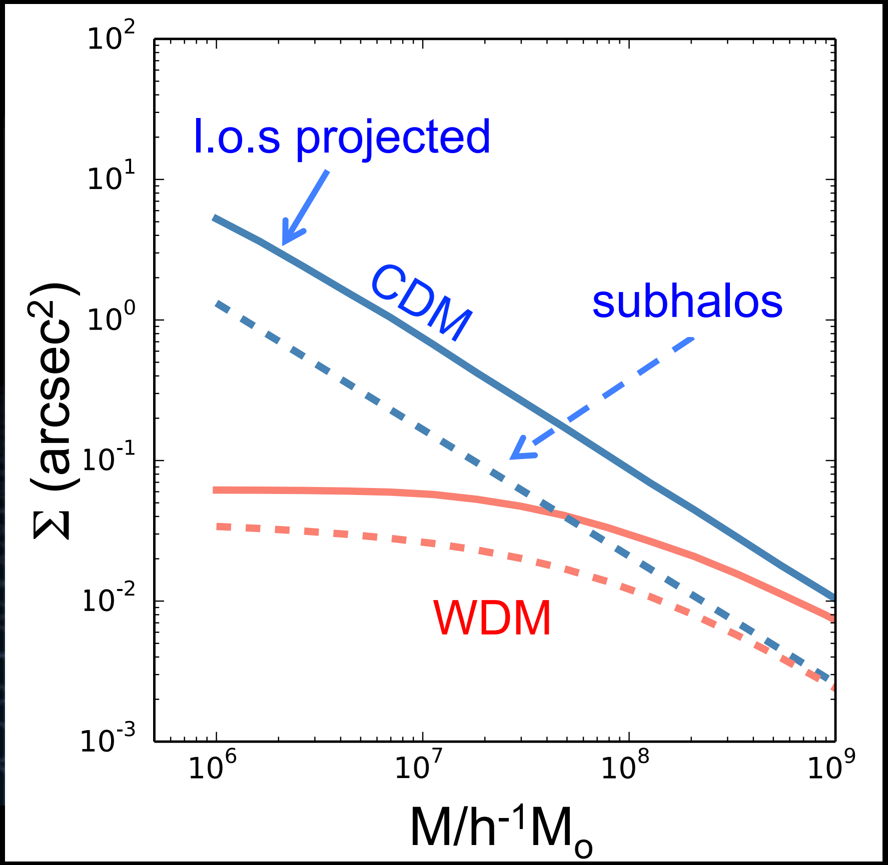
Substructures vs interlopers

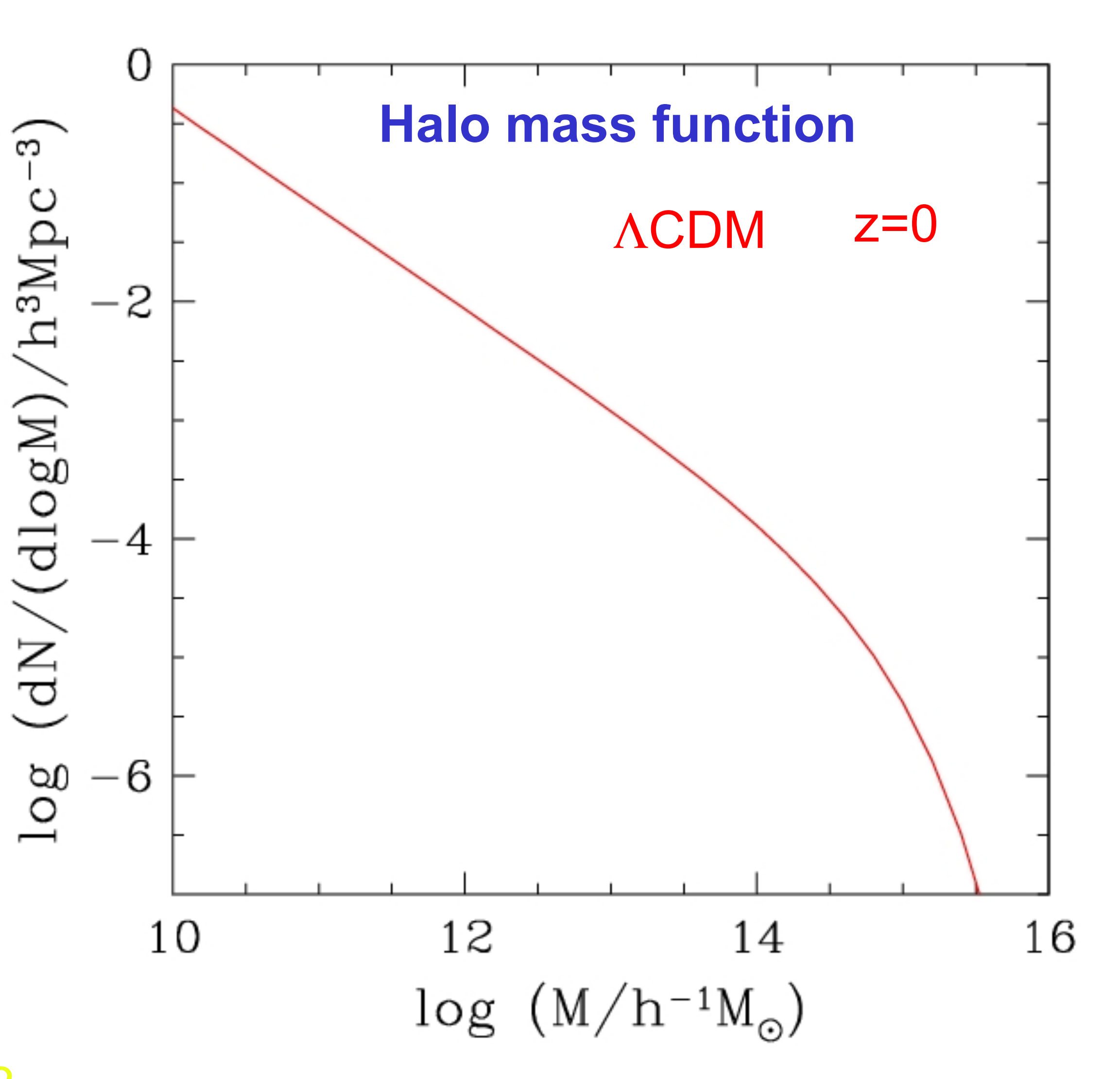
Subhalos & halos projected along the l.o.s both lens: who wins?





→ 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

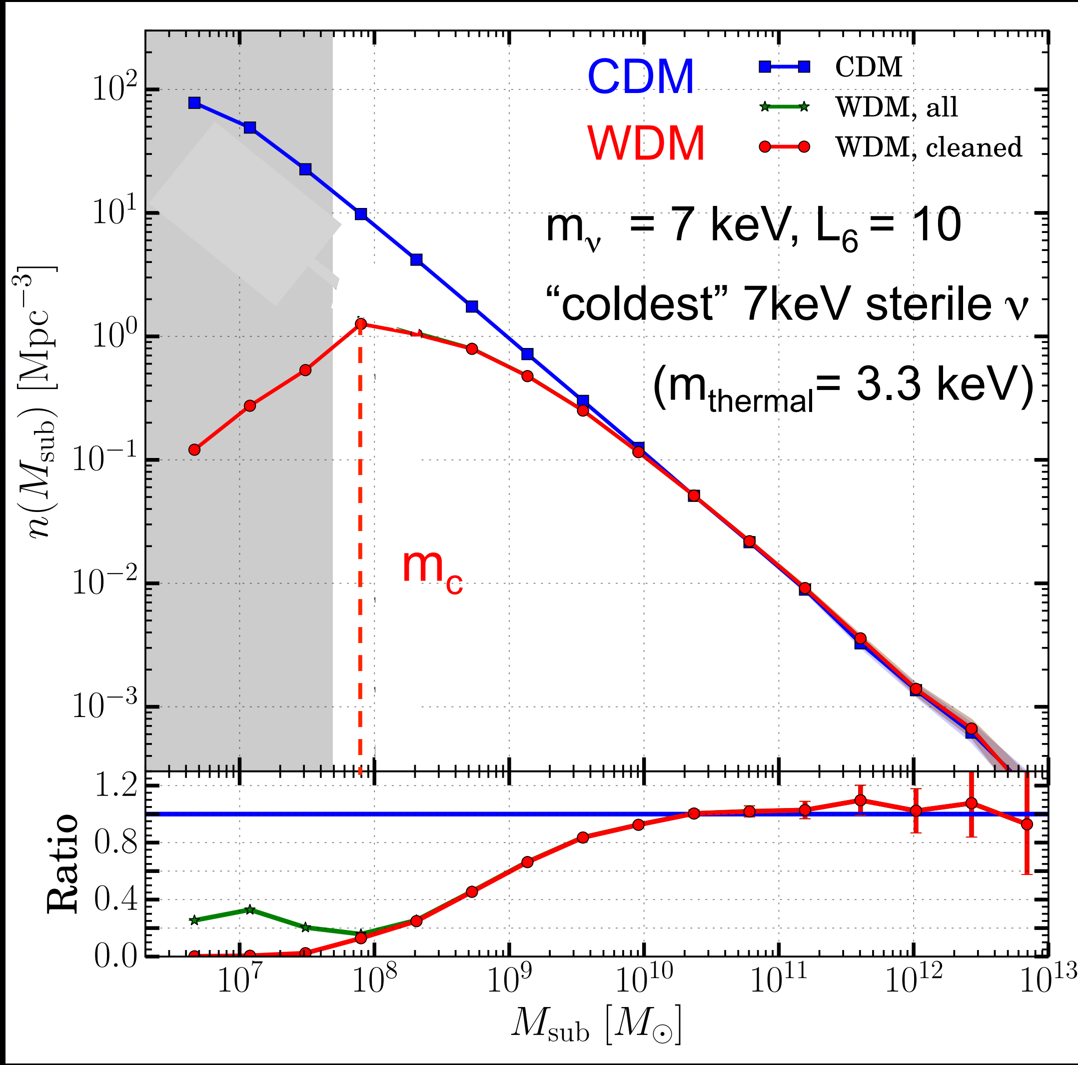
The Millennium/Aquarius/Phoenix simulation series



Springel et al ‘05, ’08,
Gao et al ‘11

The subhalo mass function

CDM WDM



3 x fewer WDM subhalos at 3×10^9 M_o

10 x fewer at 10^8 M_o

Bose, CSF et al '16

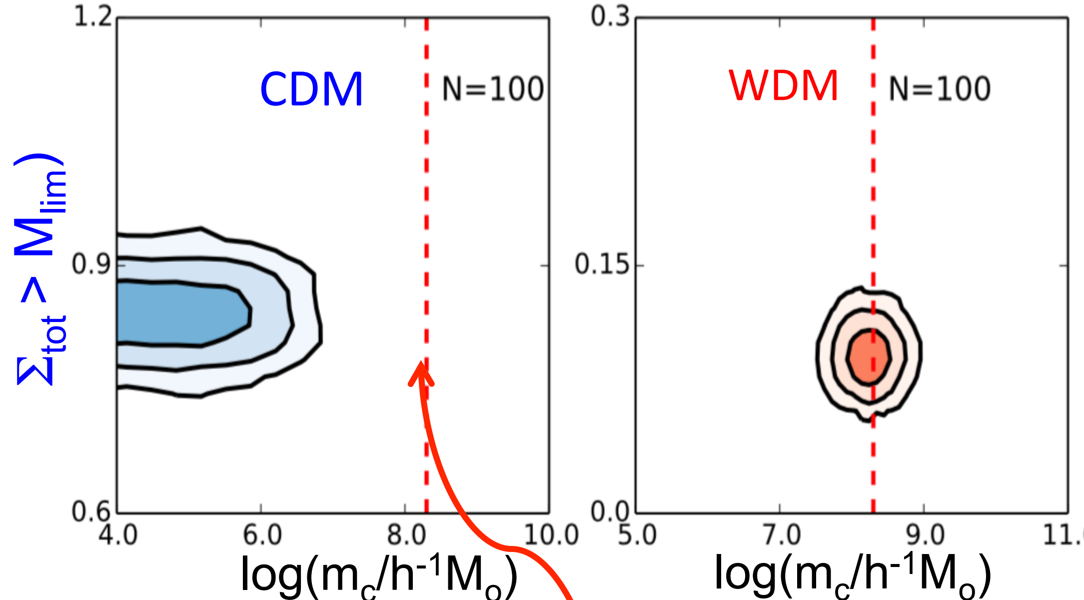
Detecting substructures with strong lensing

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

m_c= halo cutoff mass

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

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

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Conclusions

- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution
- Λ makes little difference to formation of cosmic structure
- But the identity of DM makes a big difference on small scales

1. CDM makes many small subhalos but most ($<5.10^8 M_0$) are dark → No satellite problem in CDM or WDM
2. No evidence for cores; baryon effects can make them → No "core/cusp" problem in CDM or WDM
3. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!