How to rule out cold dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

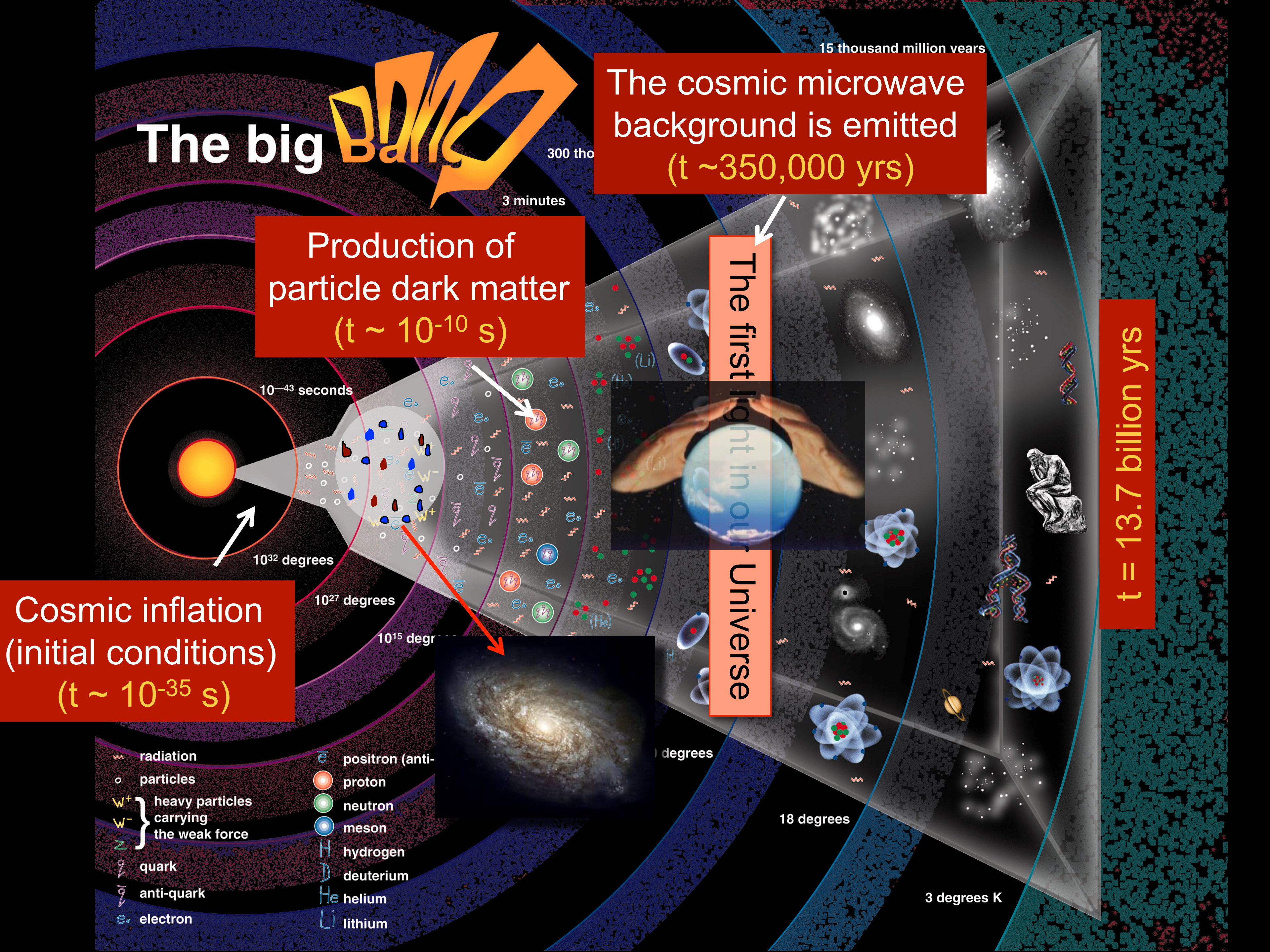
... or other viable dark matter models

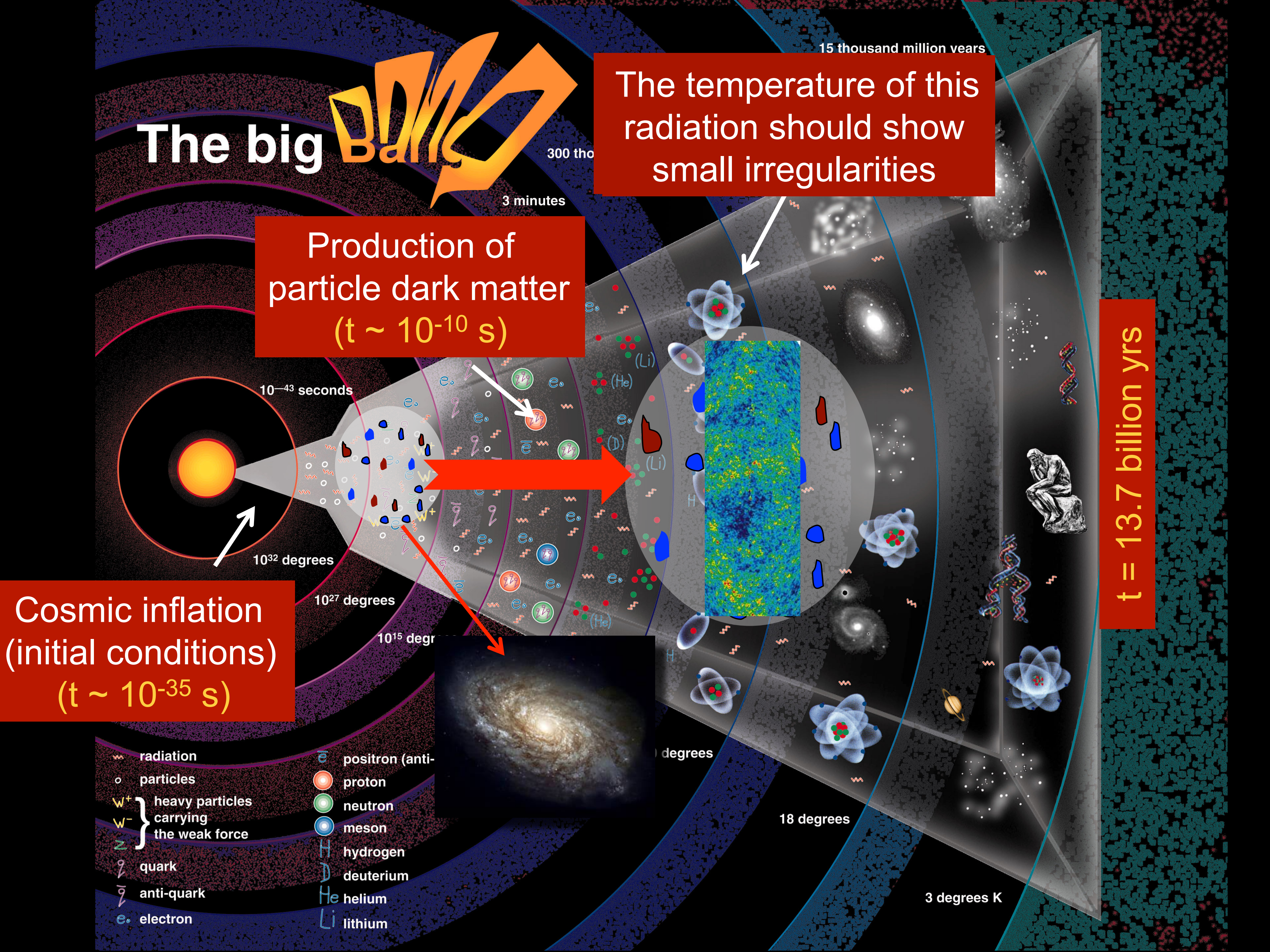
The new Ogden
Centre at Durham

The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter


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)
The first light in our Universe
t = 13.7 billion yrs
10^{-43} seconds
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


The big Bang
The temperature of this radiation should show small irregularities
15 thousand million years
300 tho
3 minutes
Production of particle dark matter (t ~ 10^-10 s)
10^-43 seconds
10^32 degrees
10^27 degrees
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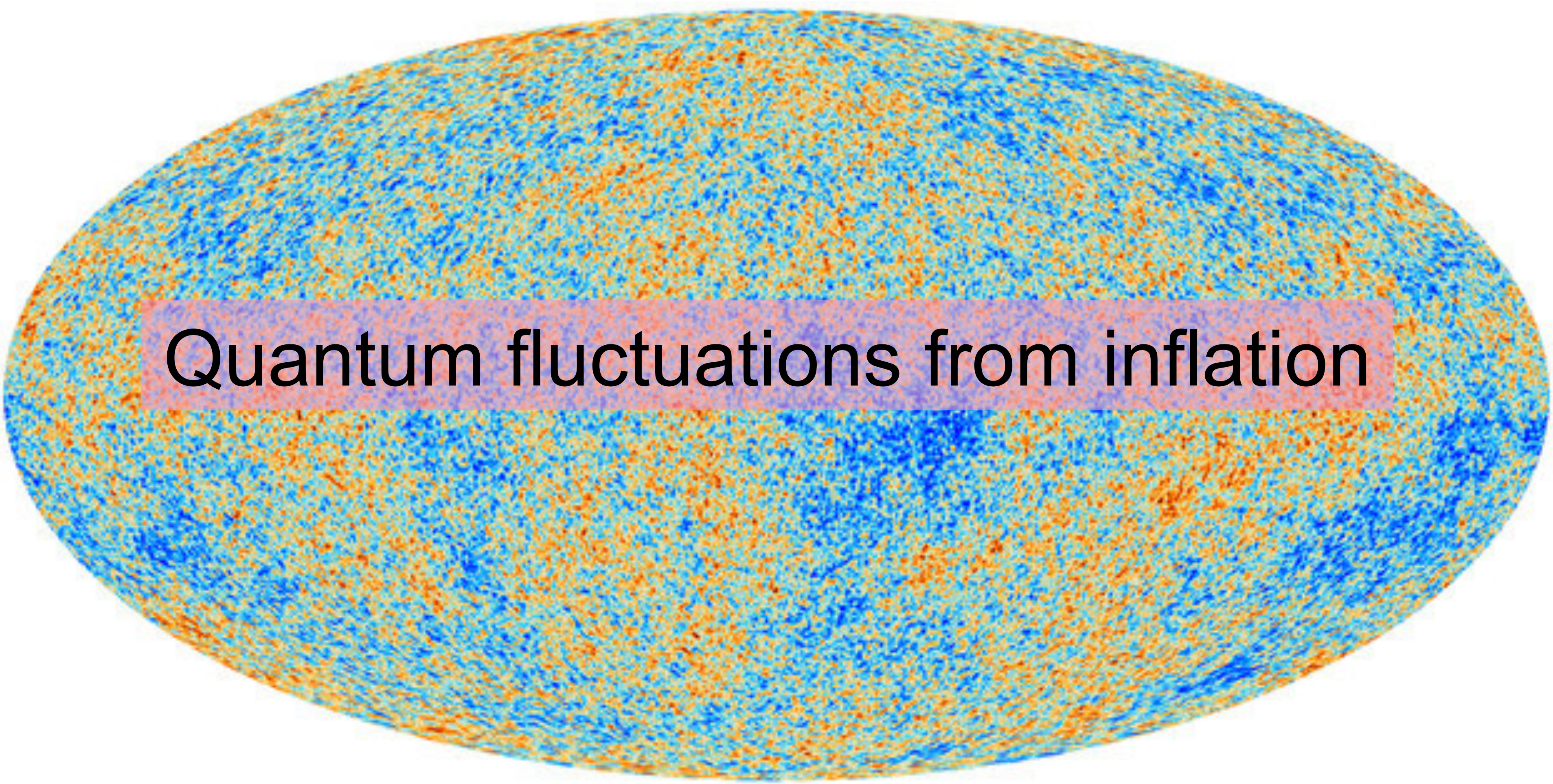
The initial conditions for galaxy formation



The six parameters of minimal ΛCDM model

Univer

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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Non-baryonic dark matter candidates

From the 1980s:

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

The dark matter power spectrum

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Free streaming →

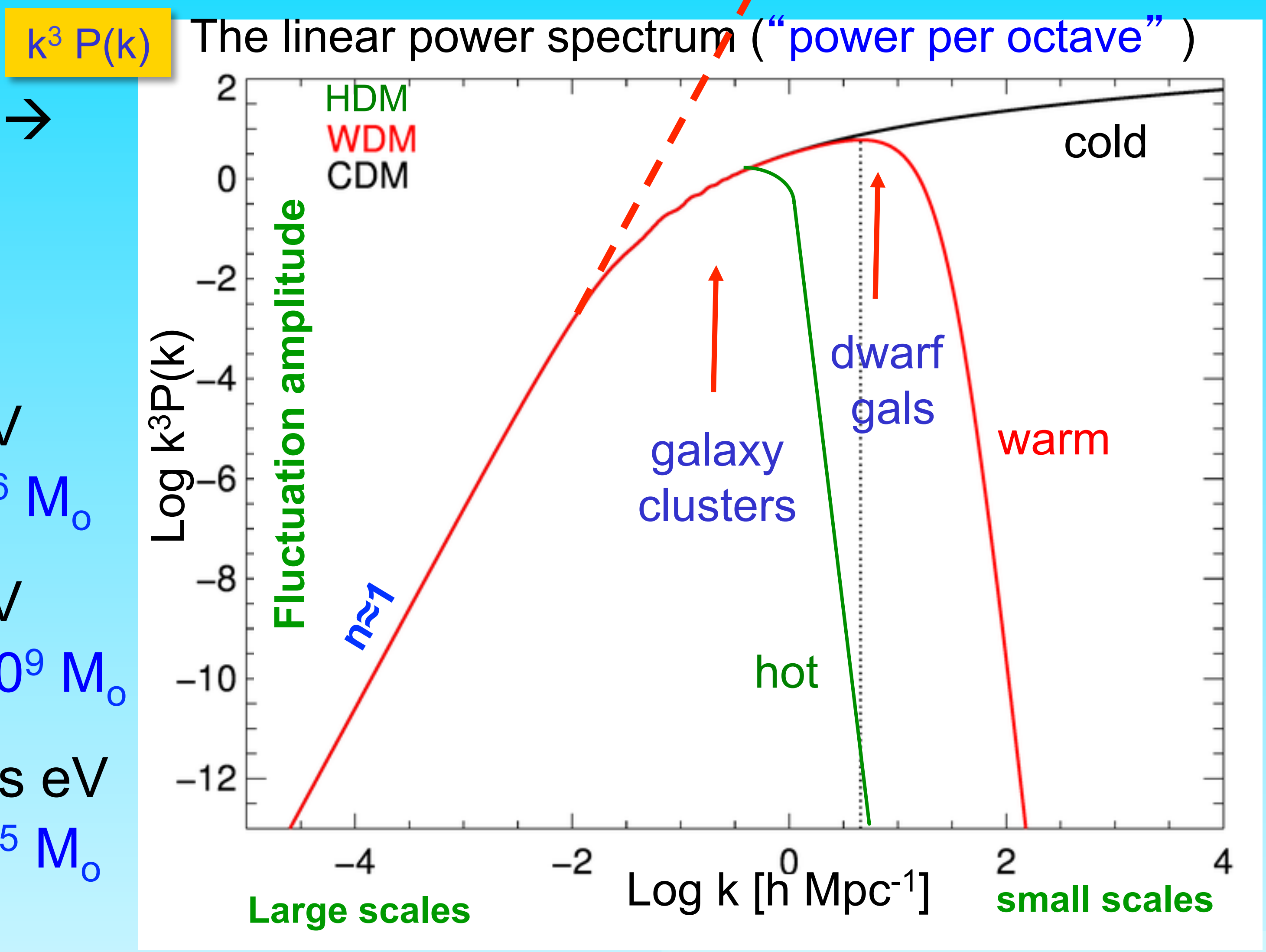
$\lambda_{cut}\ \alpha\ m_x^{-1}$

for thermal relic

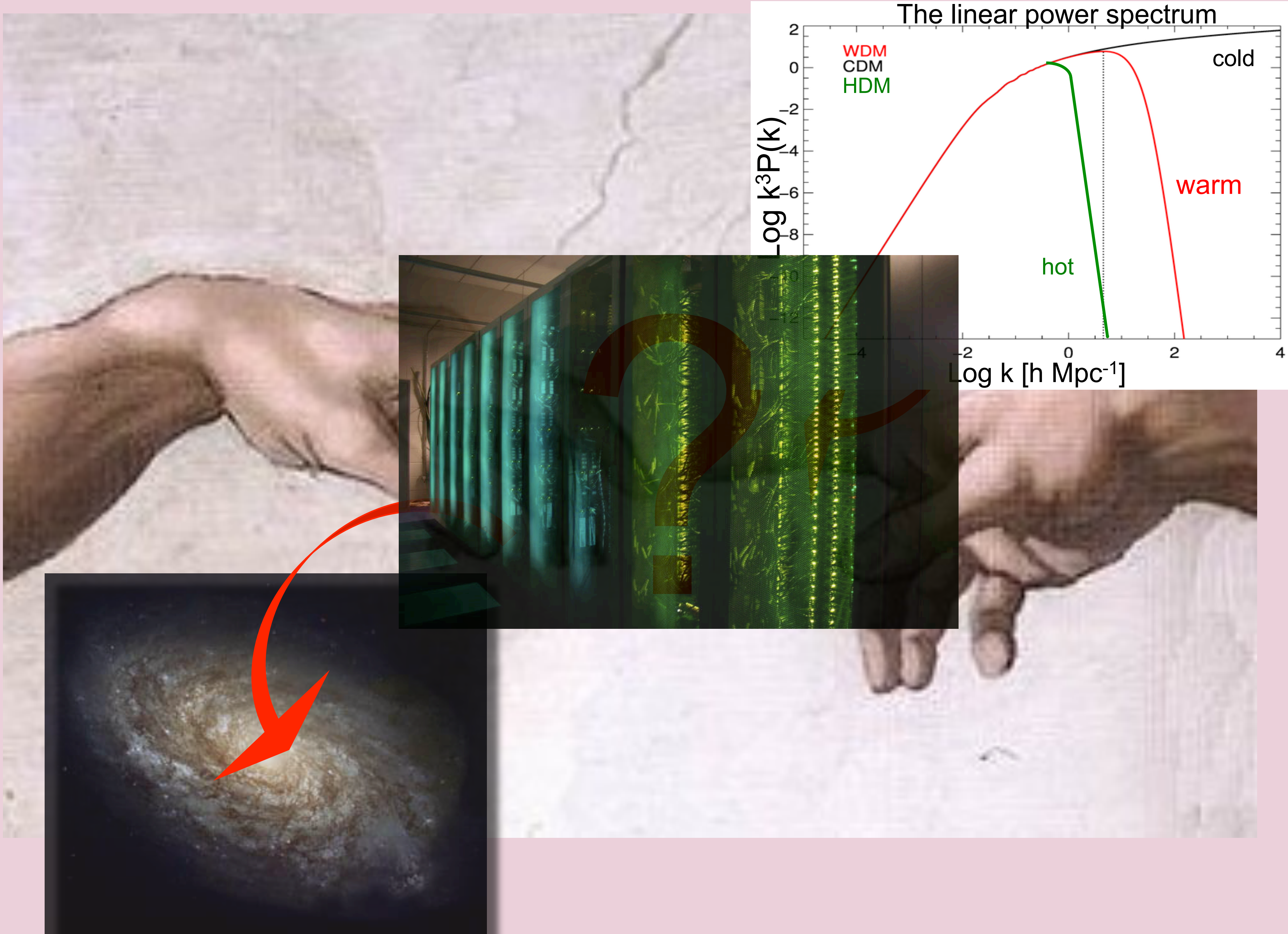
m_{CDM} ~ 100GeV
susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV
sterile ν; M_{cut}~10^9 M_o

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



Non-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

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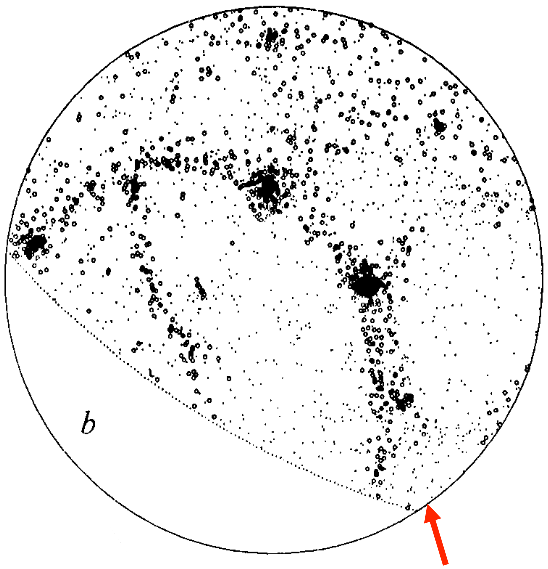
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

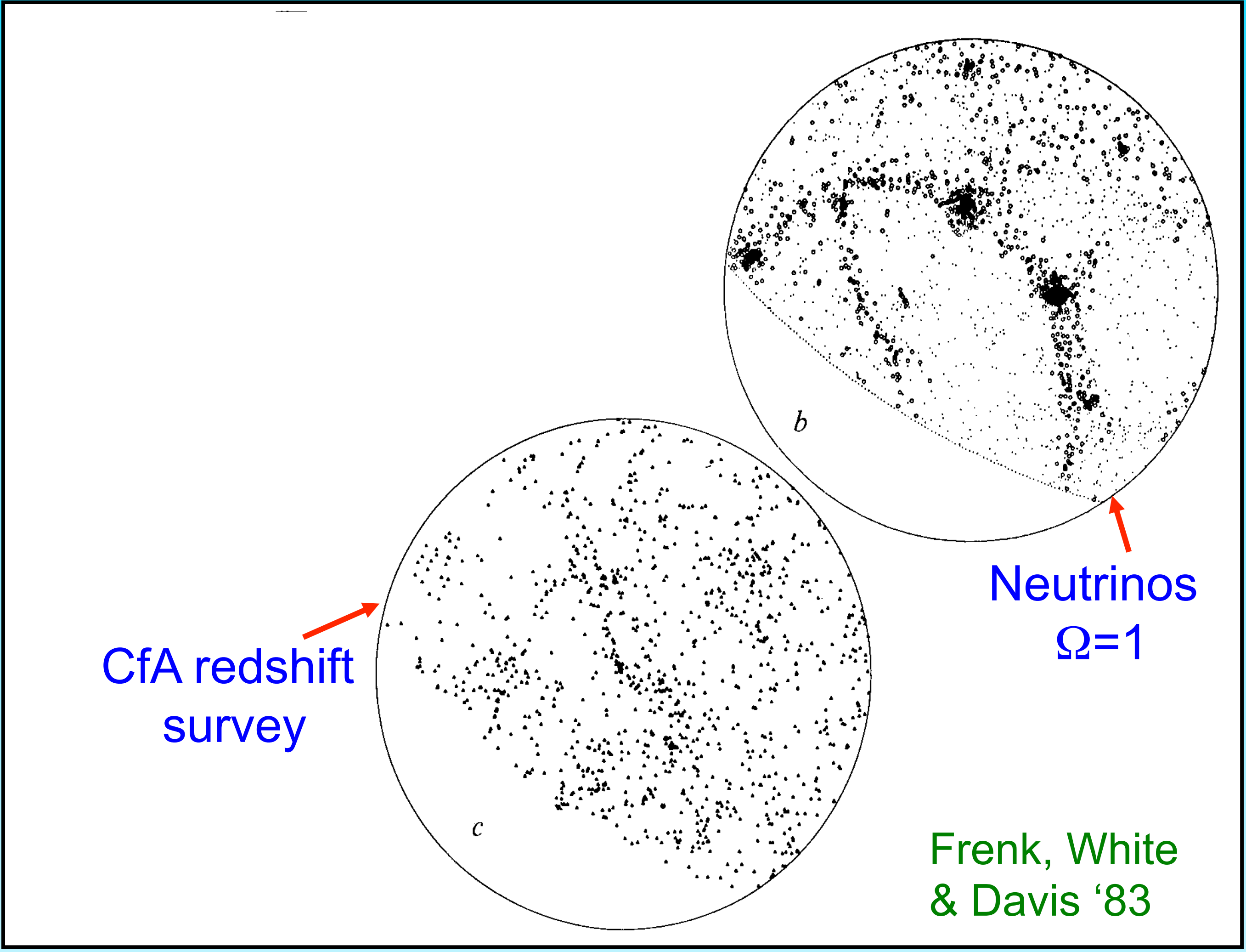
Frenk, White
& Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν << 30 ev



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Non-baryonic dark matter cosmologies

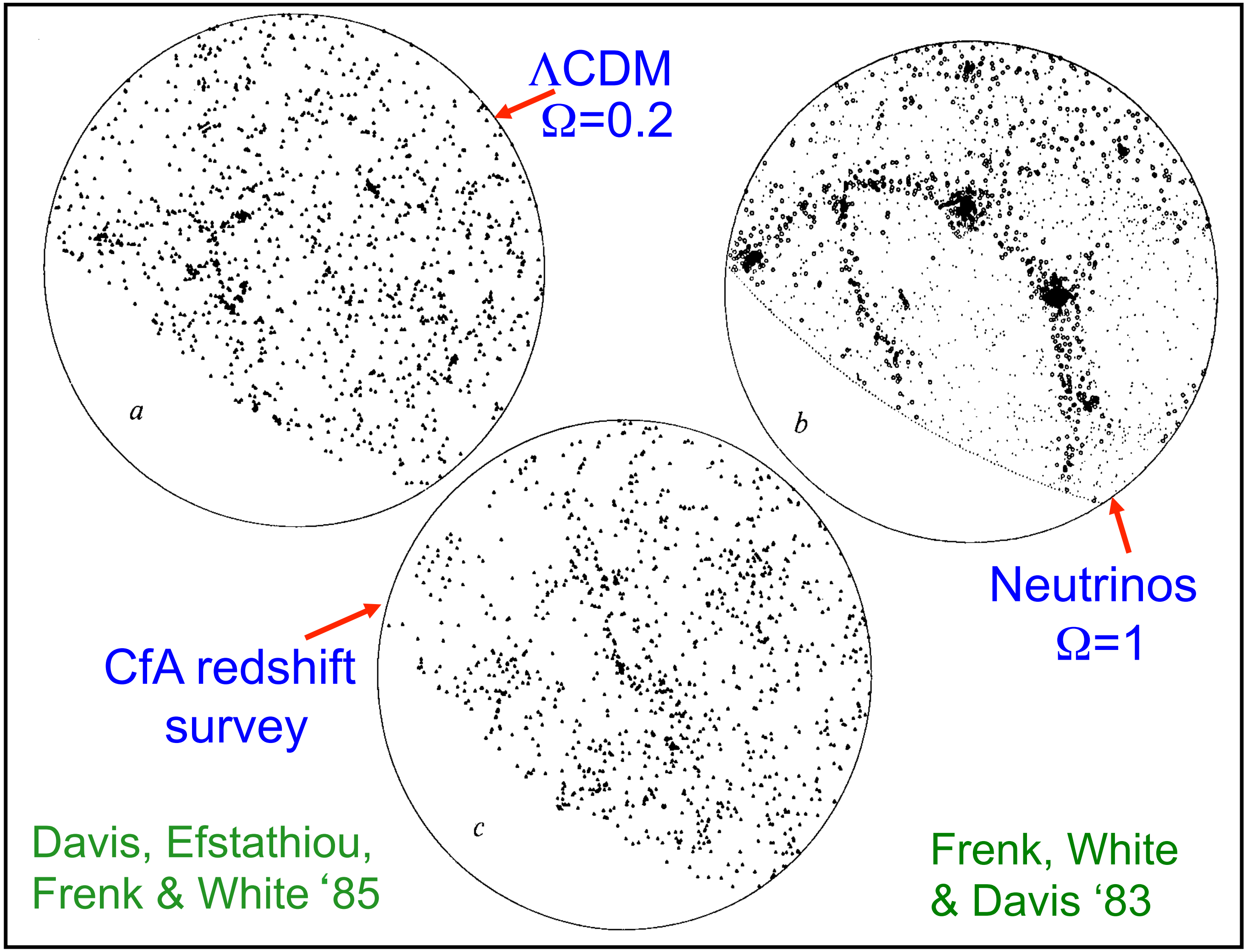
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



The ΛCDM model of cosmogony

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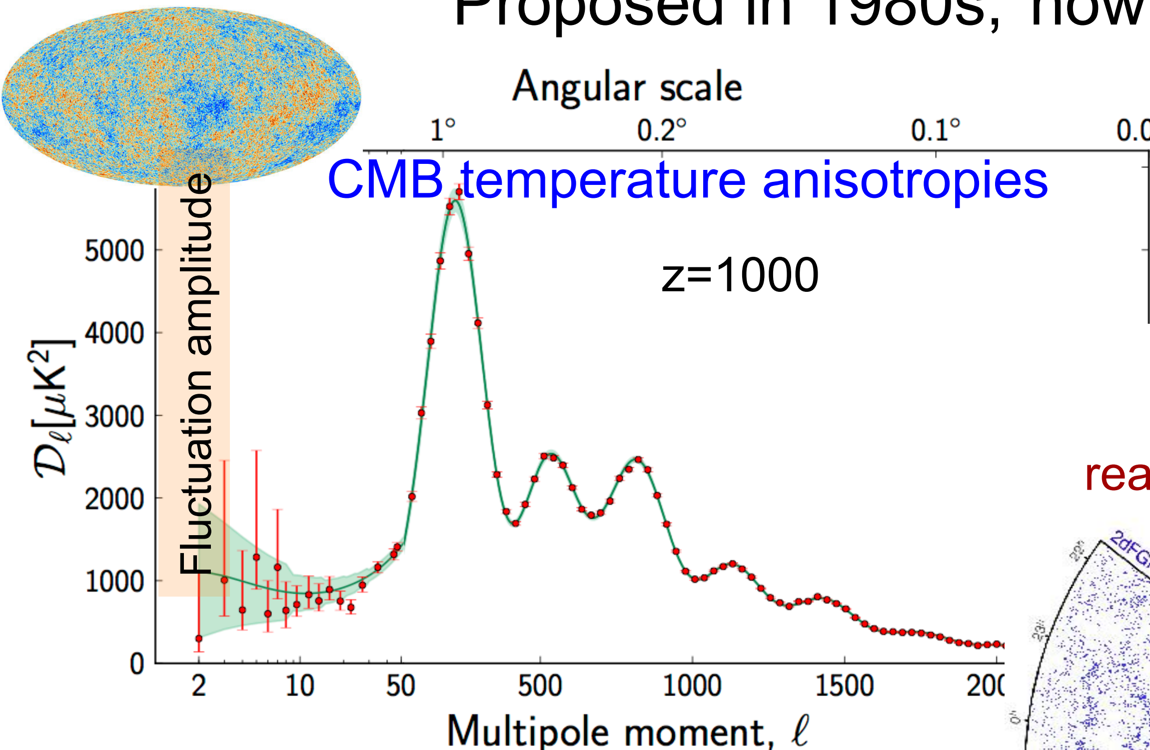
Proposed in 1980s; now empirically supported by:



CMB temperature anisotropies

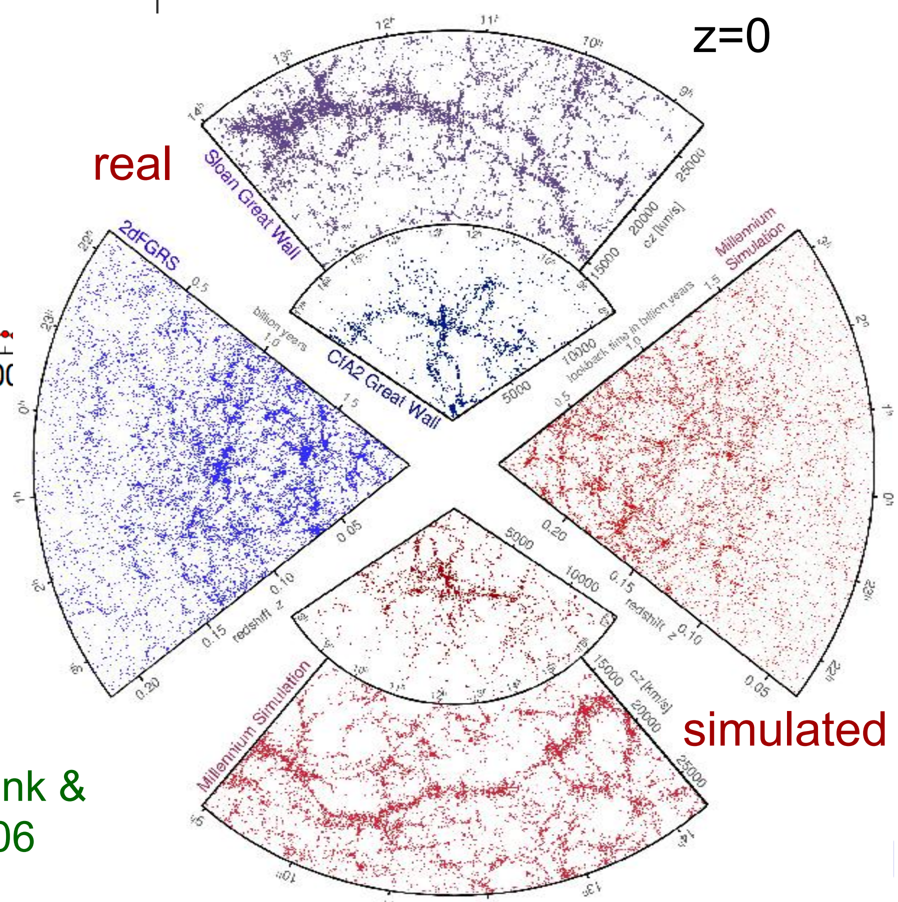
z=1000

Planck coll. 2015

Galaxy clustering

z=0

real



simulated

Springel, Frenk & White 2006

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

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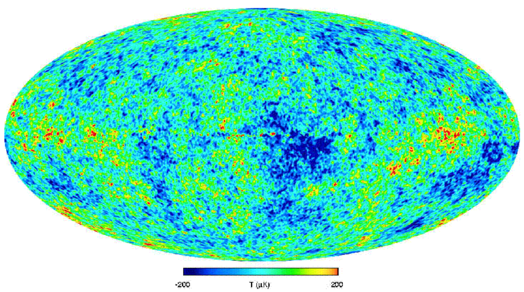
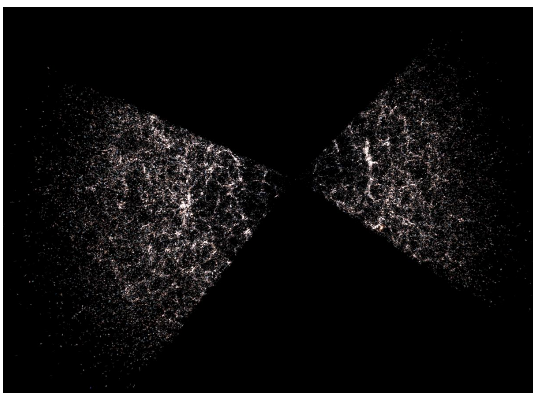
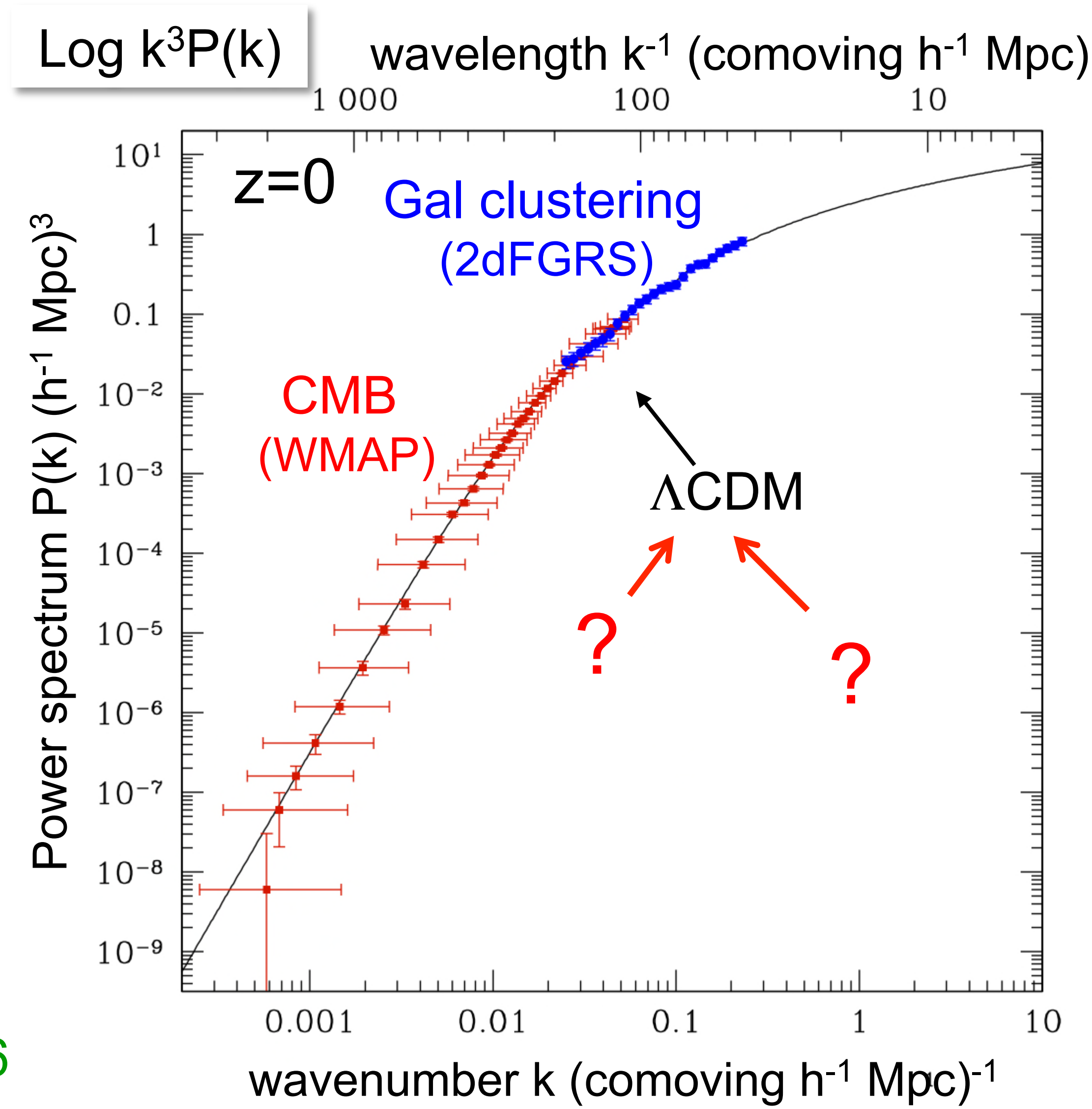


z~1000



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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Free streaming →

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

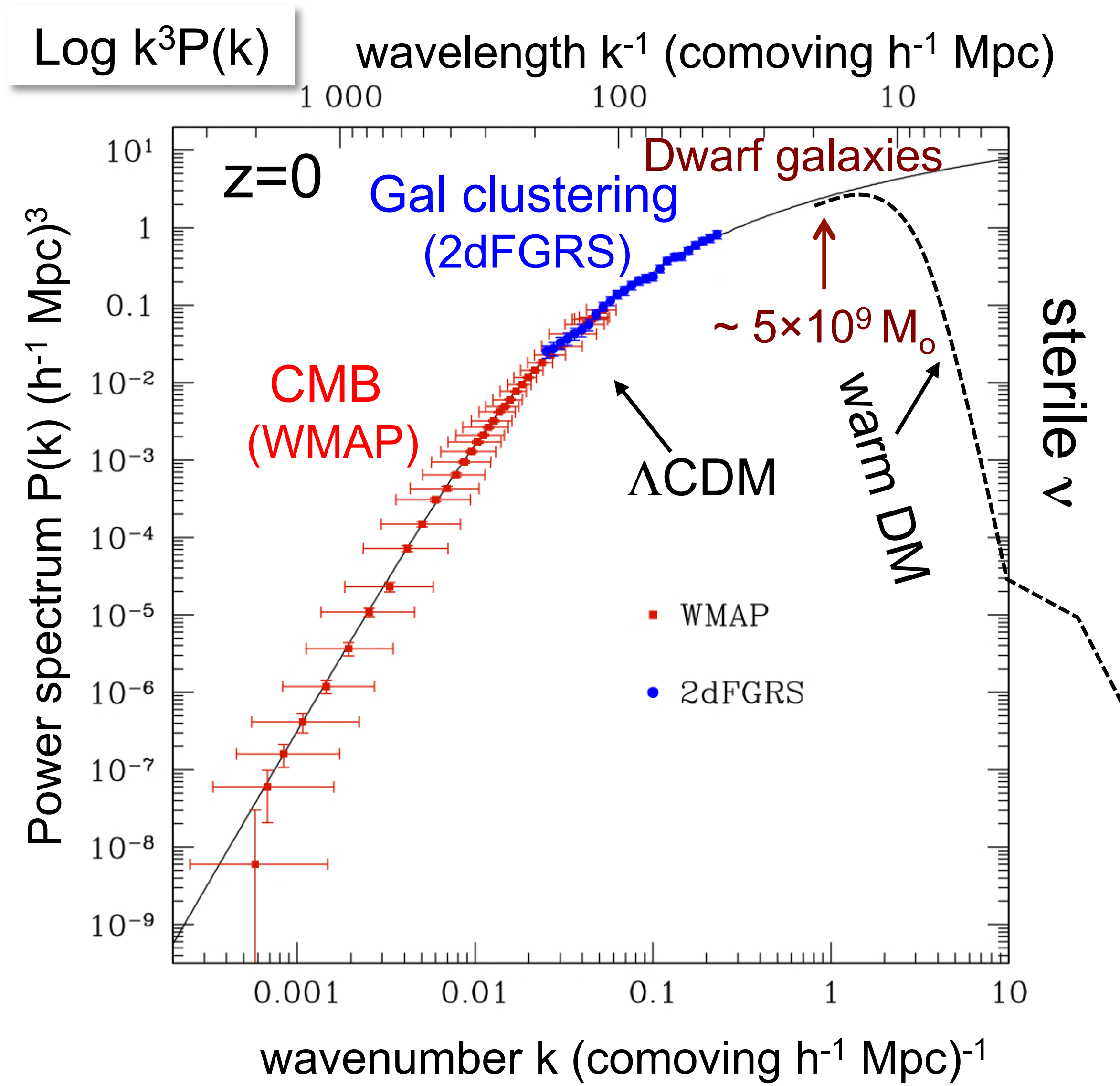
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

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

Very unlikely that both are right!

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Sterile neutrinos

Explain:

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

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

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

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

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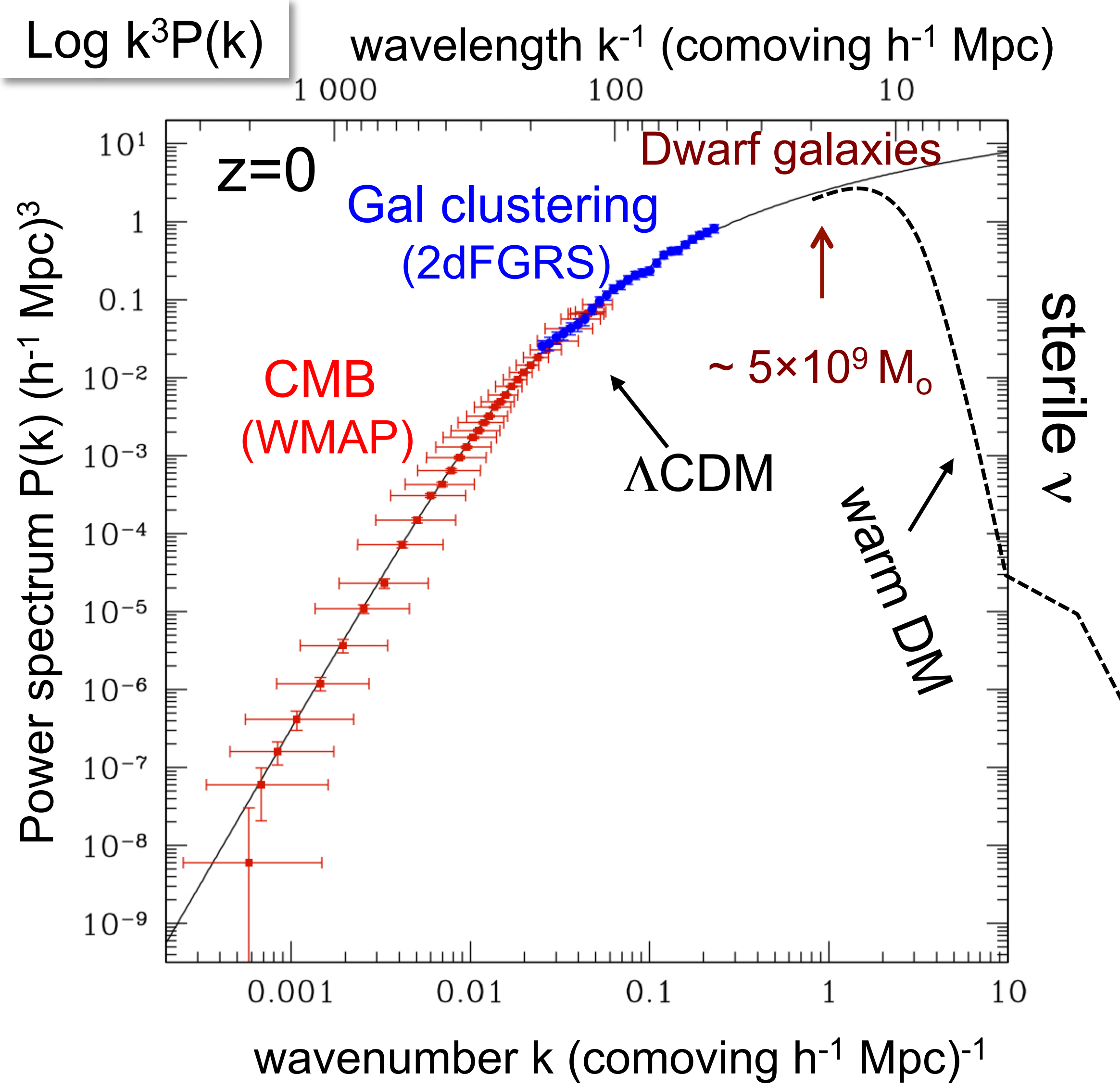
Log $k^3P(k)$



Cold Dark Matter | Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

cold dark matter

warm dark matter

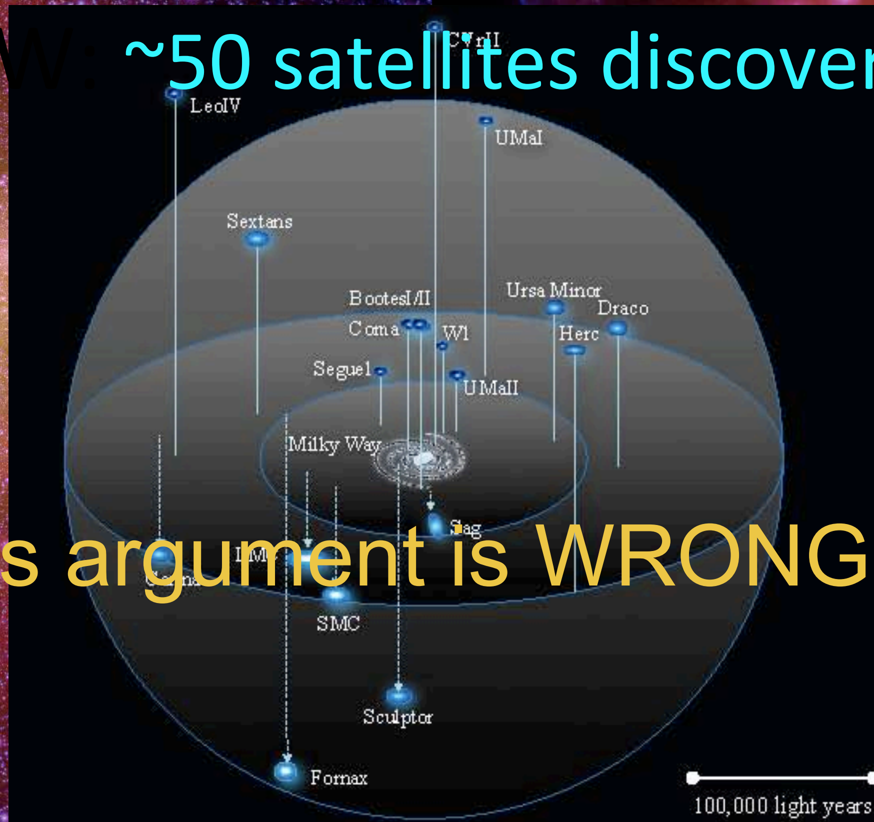
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

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

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

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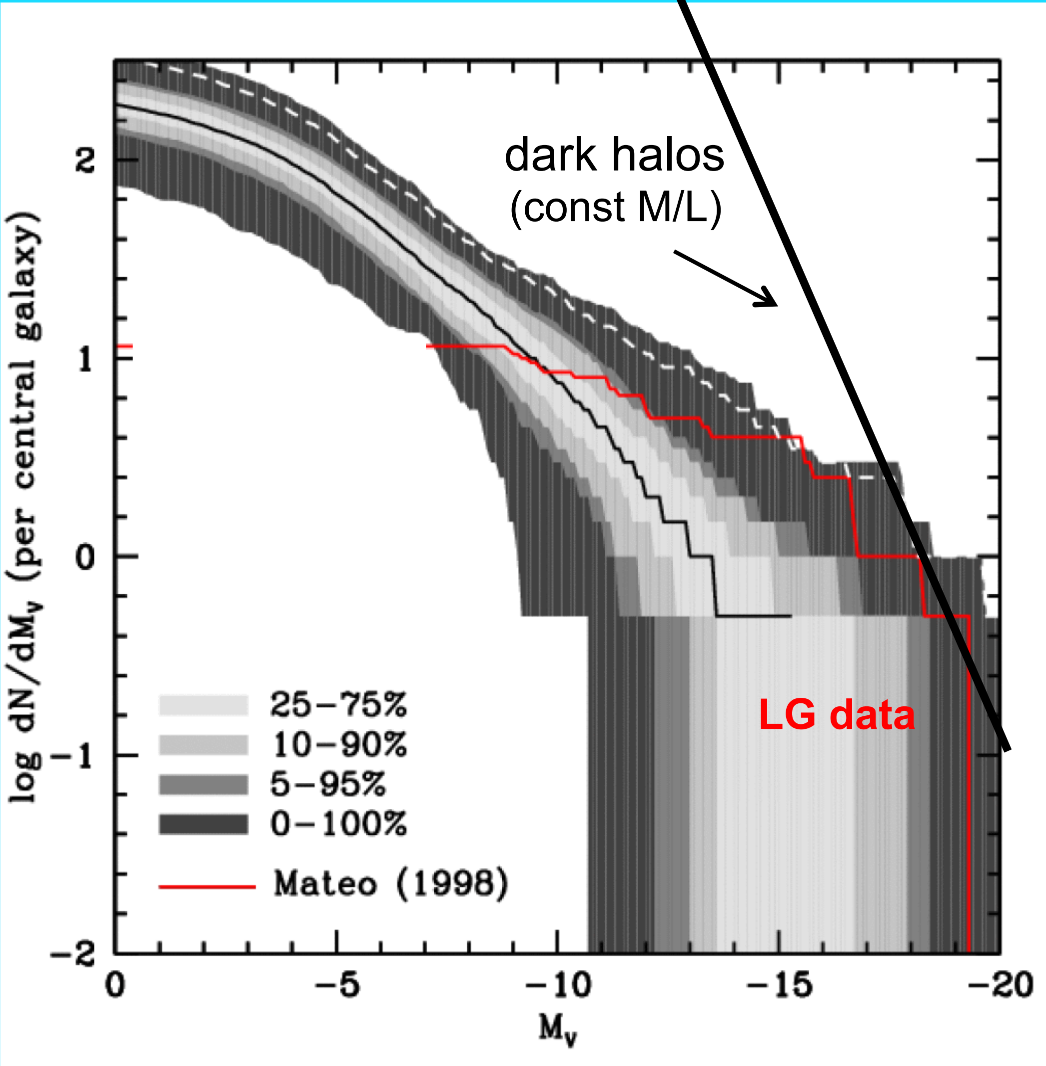
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~10% of cases)



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

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Luminosity Function of Local Group Satellites

University of Durham

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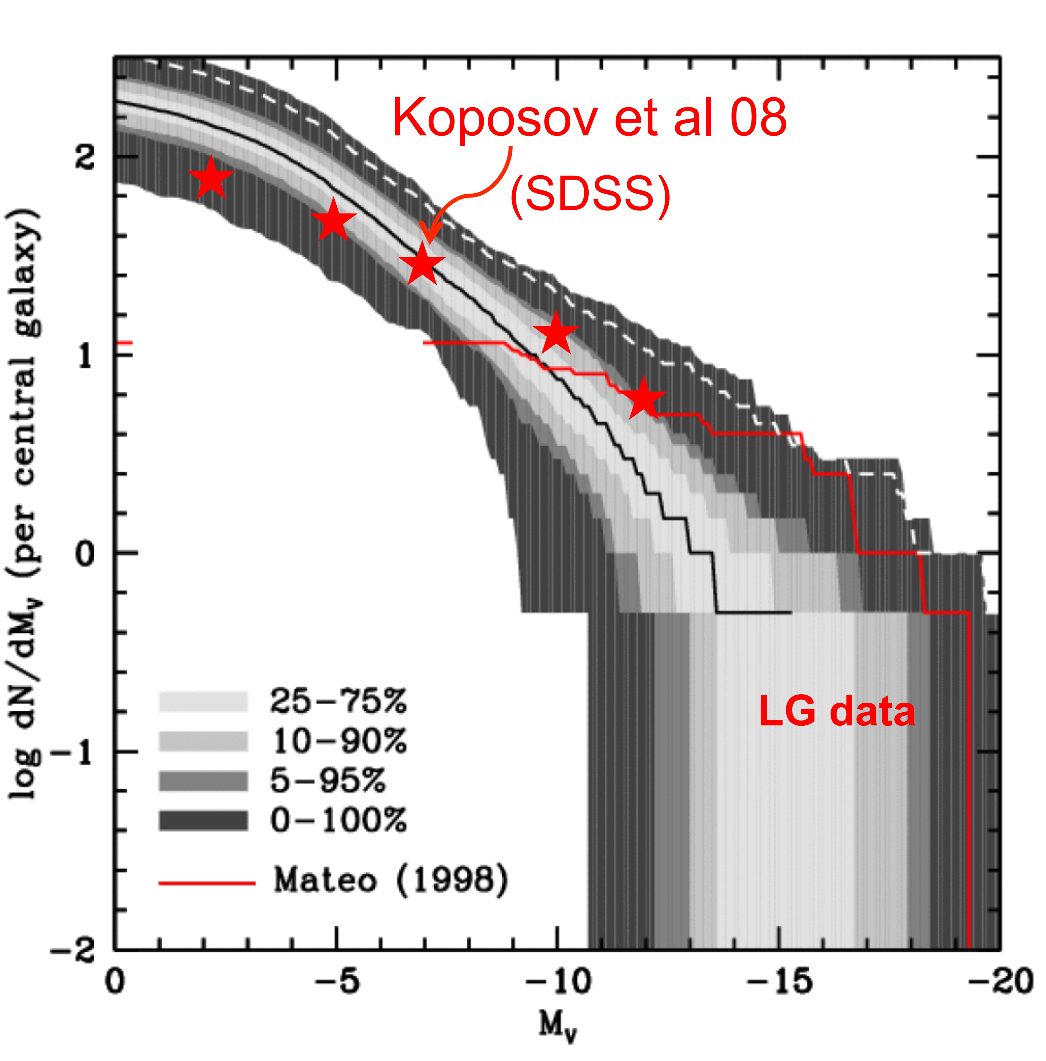


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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…

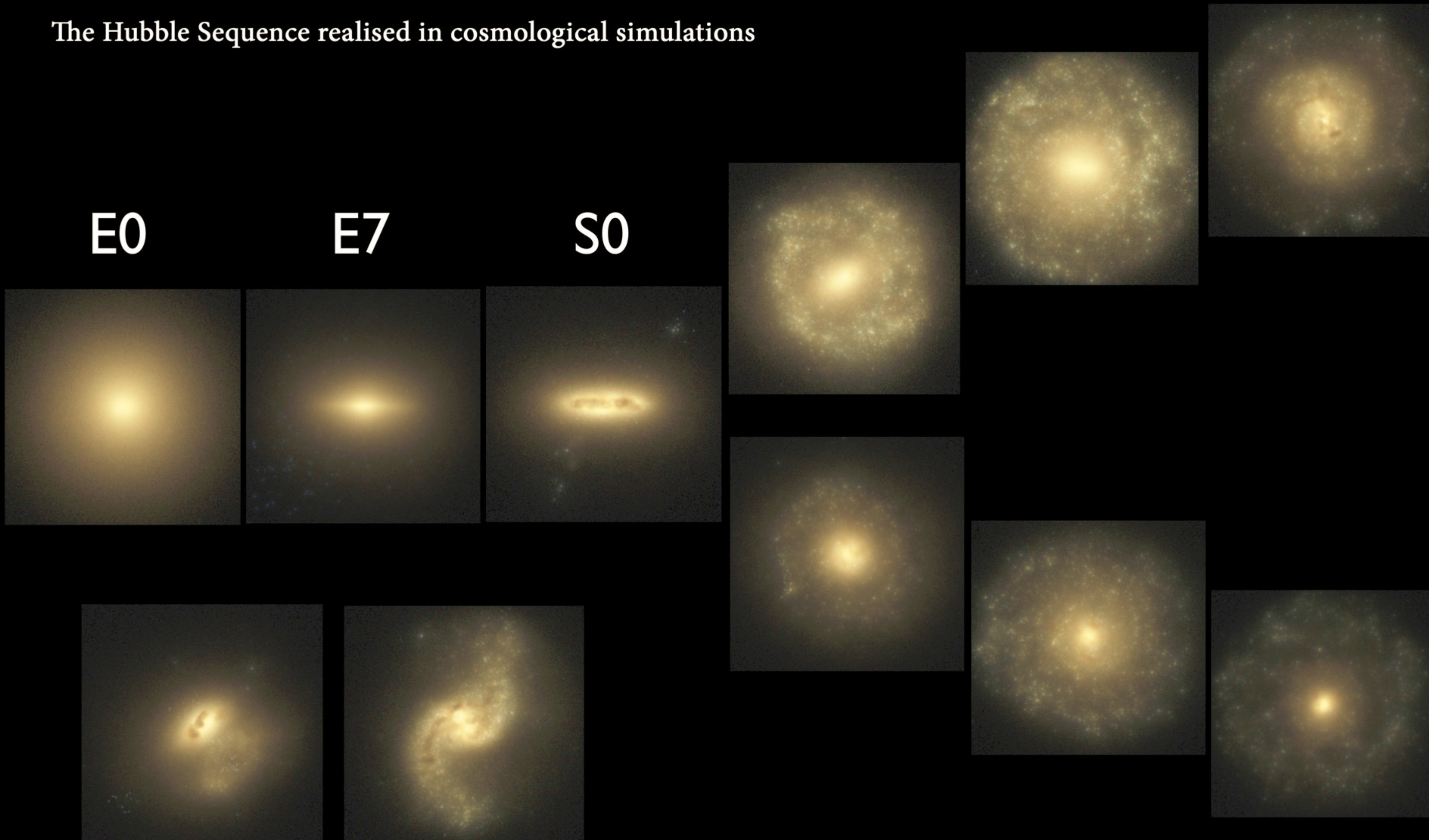
Durham University VIRGO ICC DiRAC PRACE

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

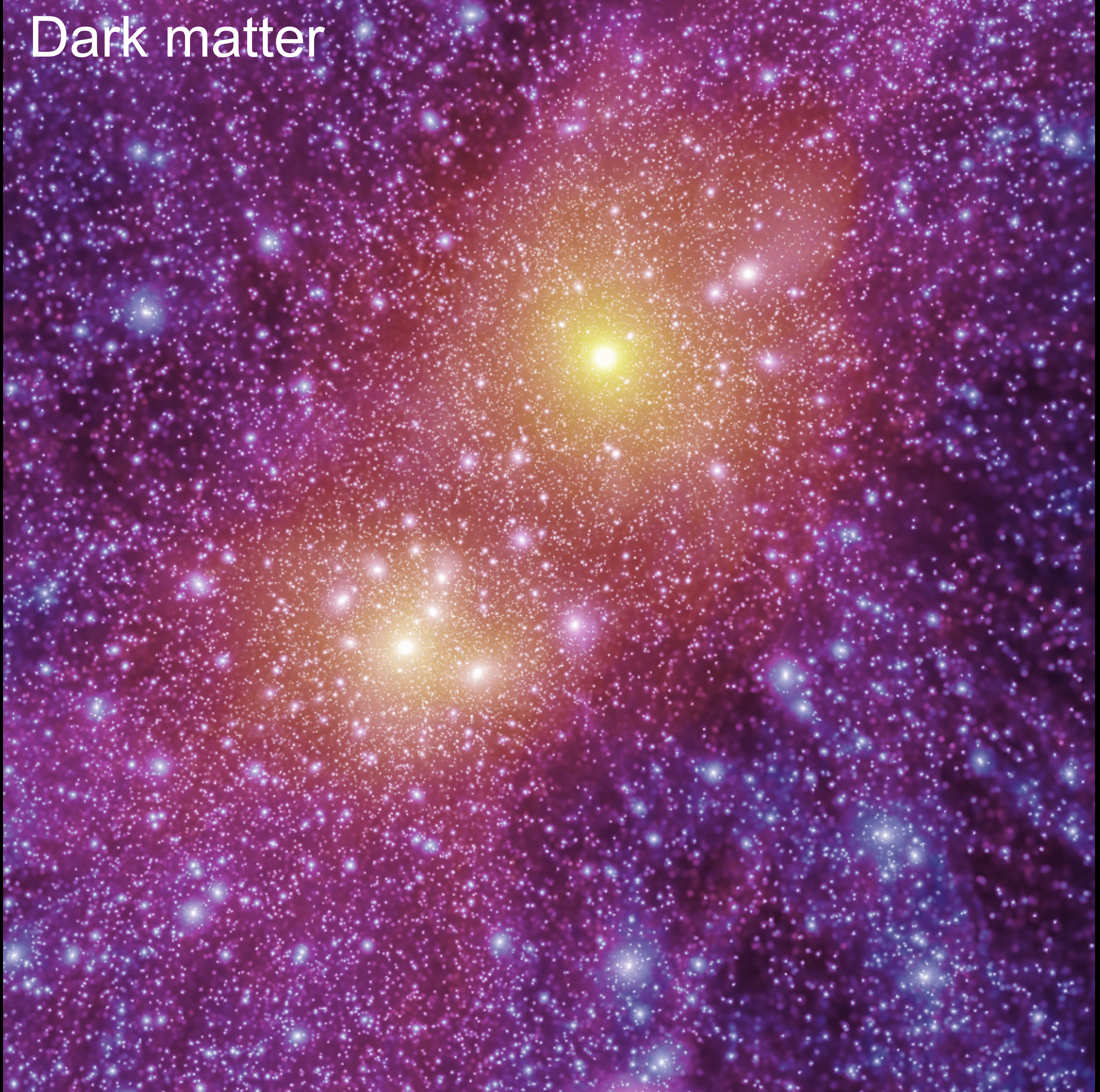
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16



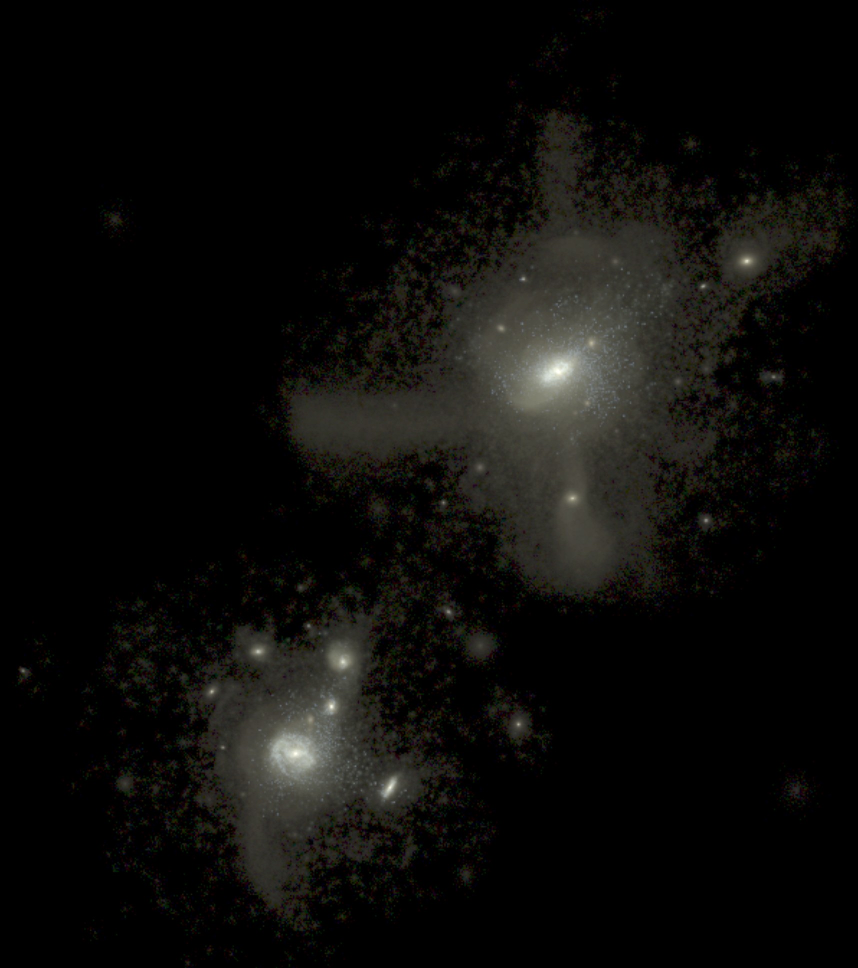
VIRGO

Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group

Stars



Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

Fraction of dark subhalos

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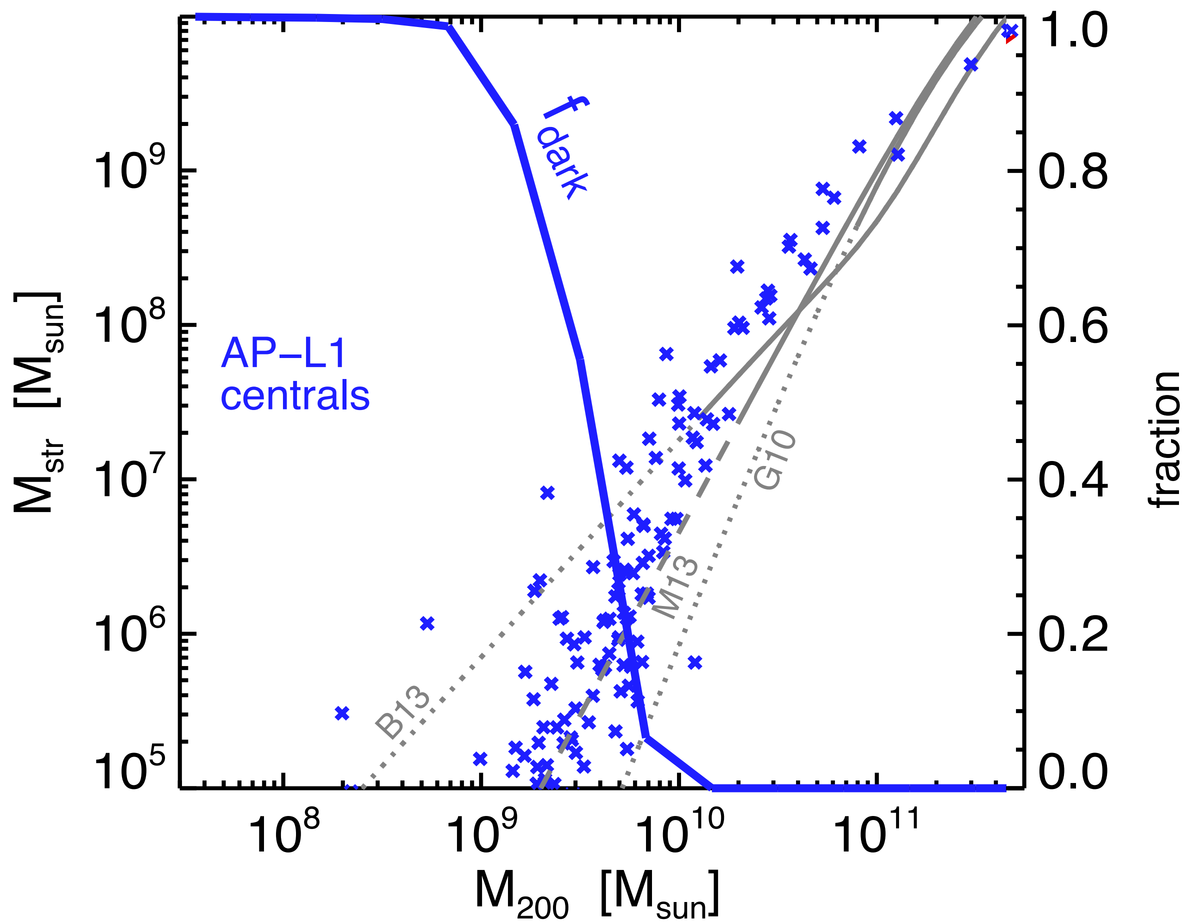
$$V_c = \sqrt{\frac{GM}{r}}$$

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



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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EAGLE Local Group simulation

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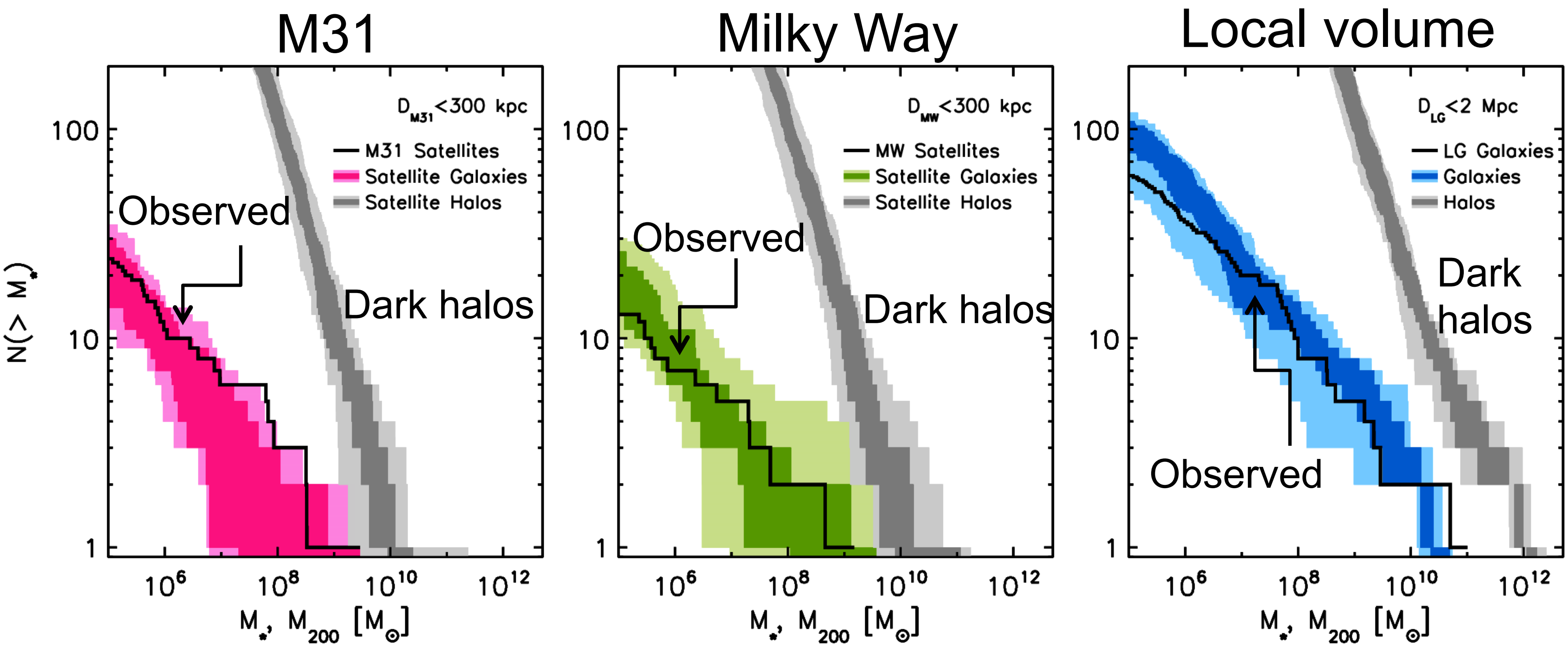

Sawala, CSF et al '16

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When “baryon effects” are taken into account

→

Observed abundance of satellites is compatible with CDM

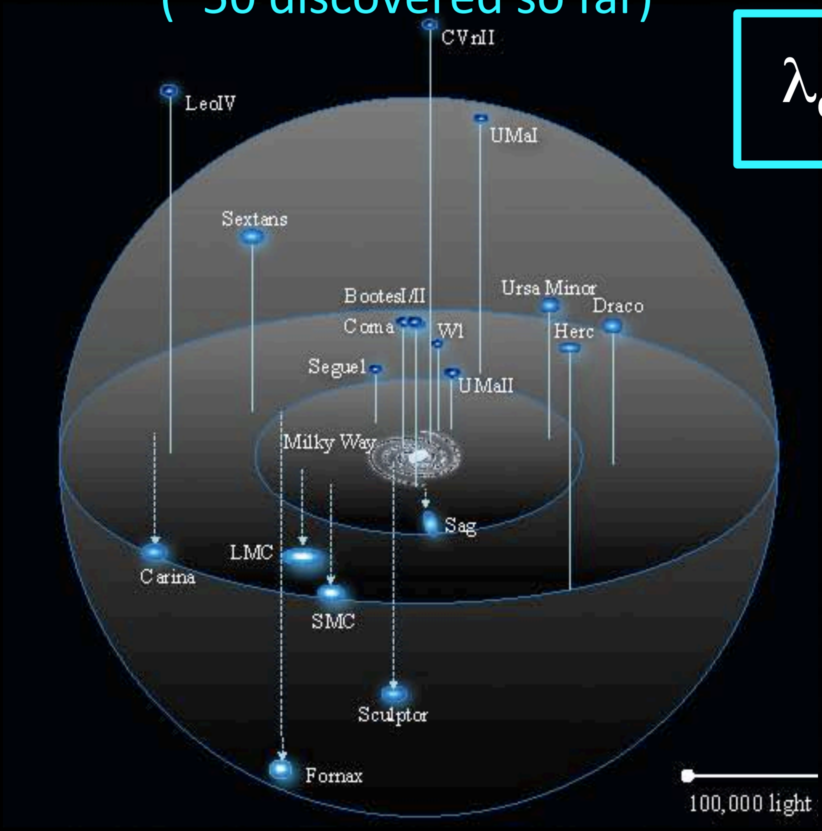
→

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

How about in WDM?

The satellites of the MW

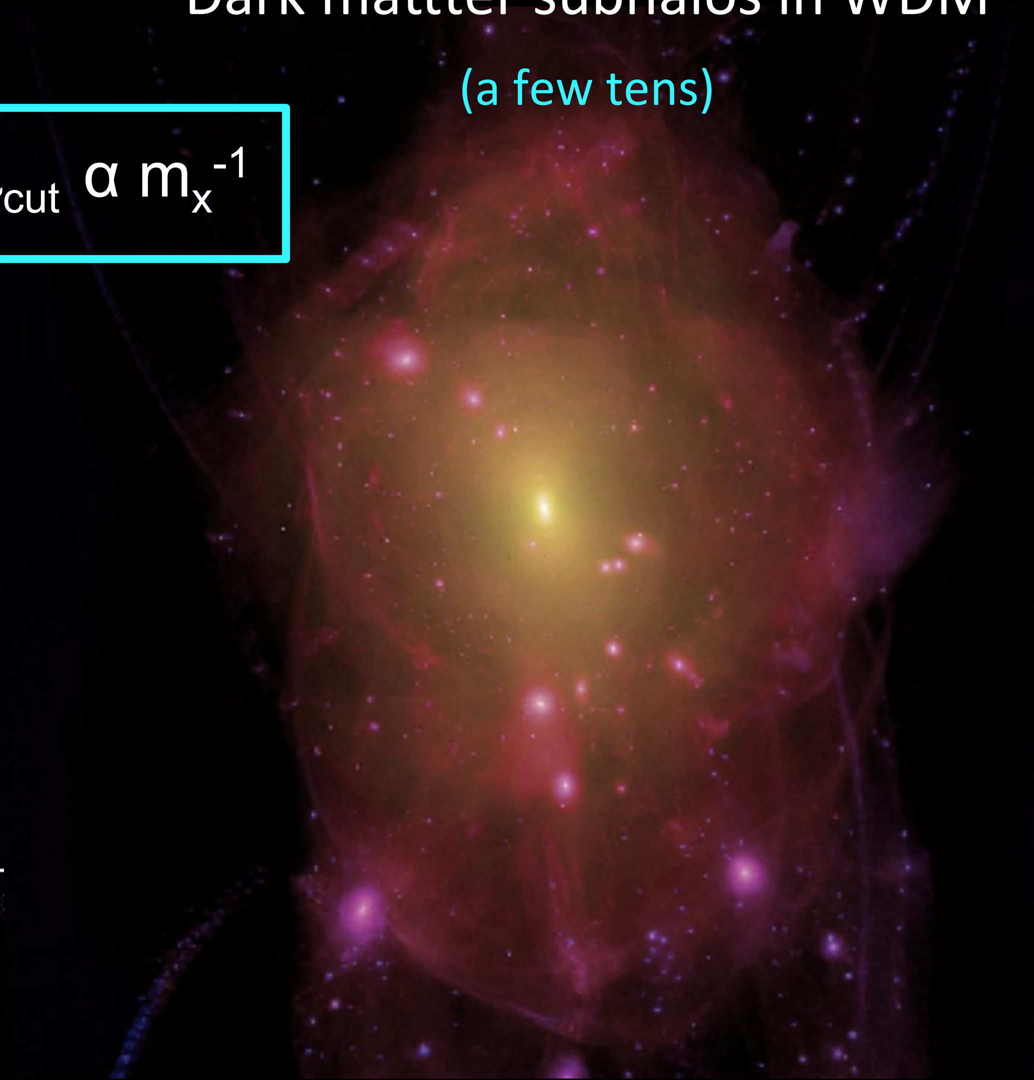
(~50 discovered so far)



λ_{cut} α m_x^{-1}

Dark matter subhalos in WDM

(a few tens)



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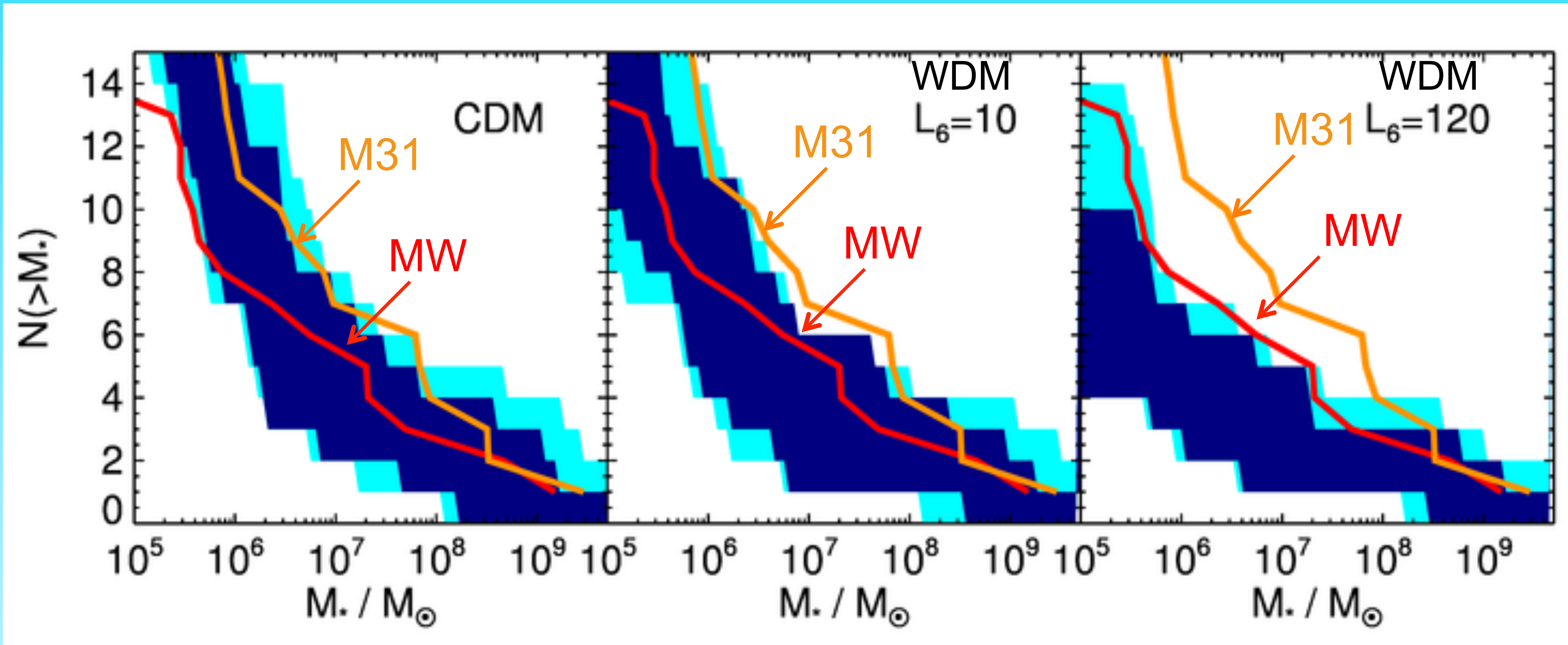
Luminosity Function of Local Group Satellites in WDM

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

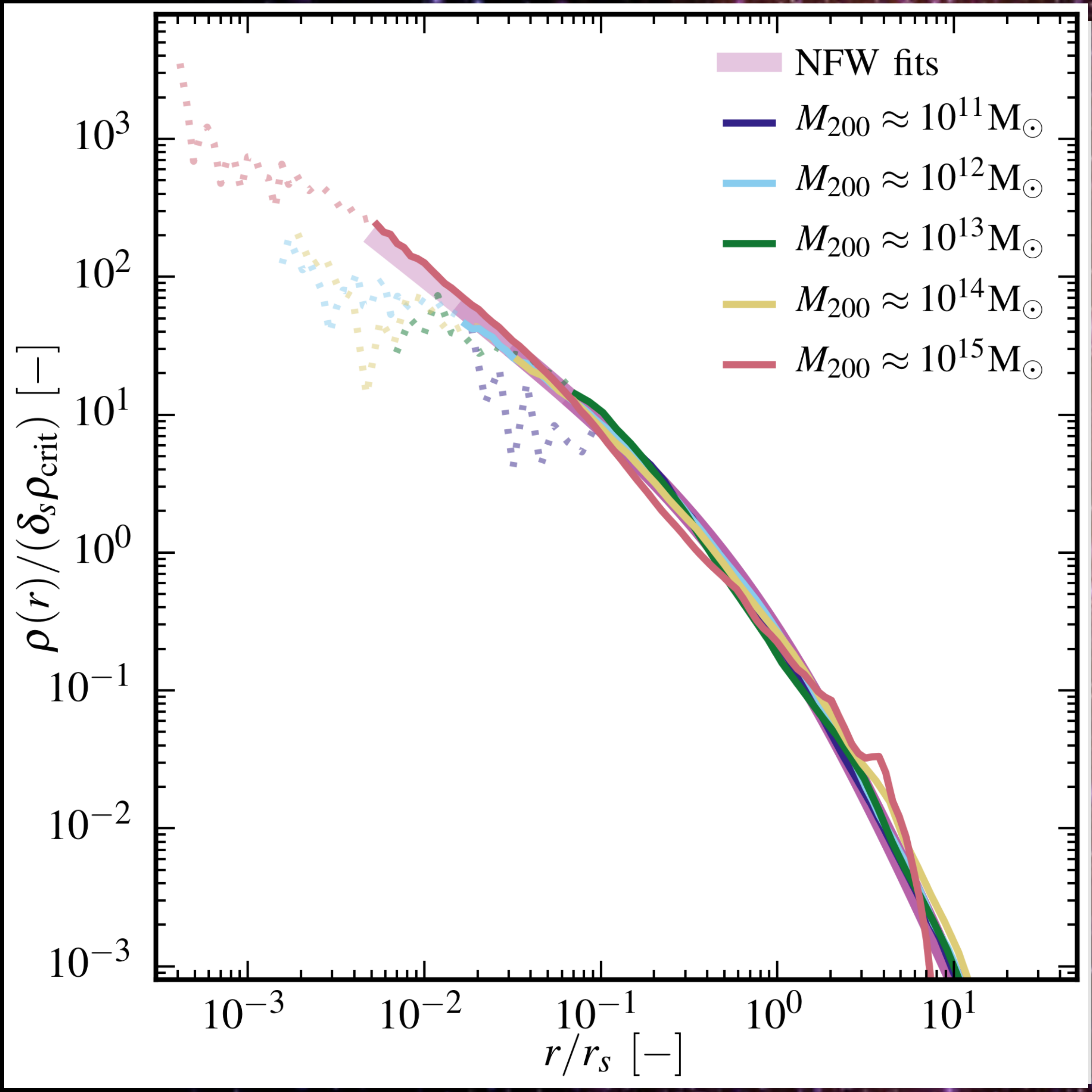


Lovell et al. '16

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:

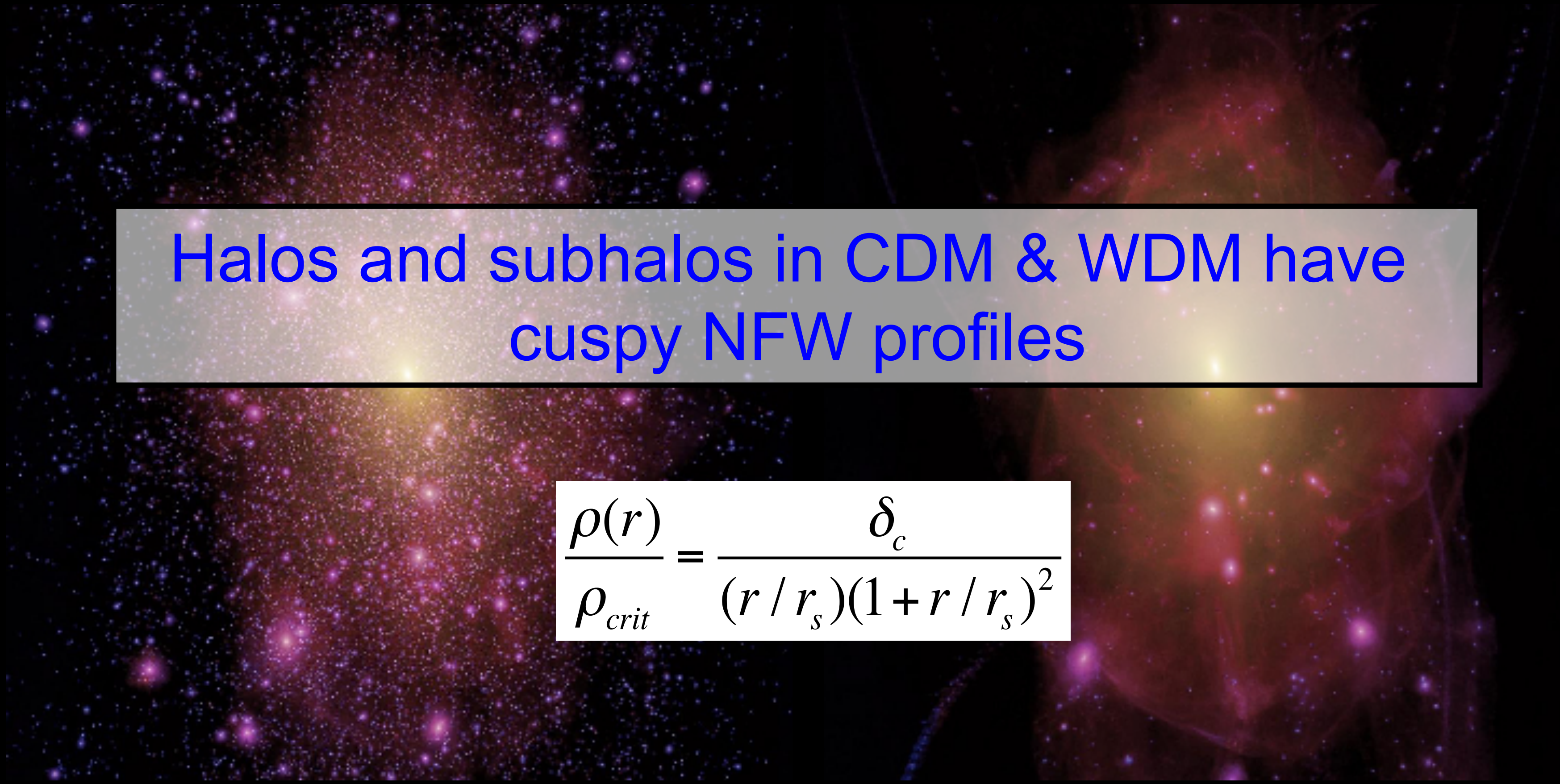
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(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

Is this it?

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

How about baryon effects?

Baryon effects in the MW satellites

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Let gas cool and condense to the galactic centre

→ gas self-gravitating
→ star formation/burst

Rapid ejection of gas during starburst → a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

Parry, CSF et al. '11
Governato et al. '12
Pontzen & Governato '12
Brooks et al. '12

Navarro, Eke, Frenk '96

The cores of dwarf galaxy haloes L75

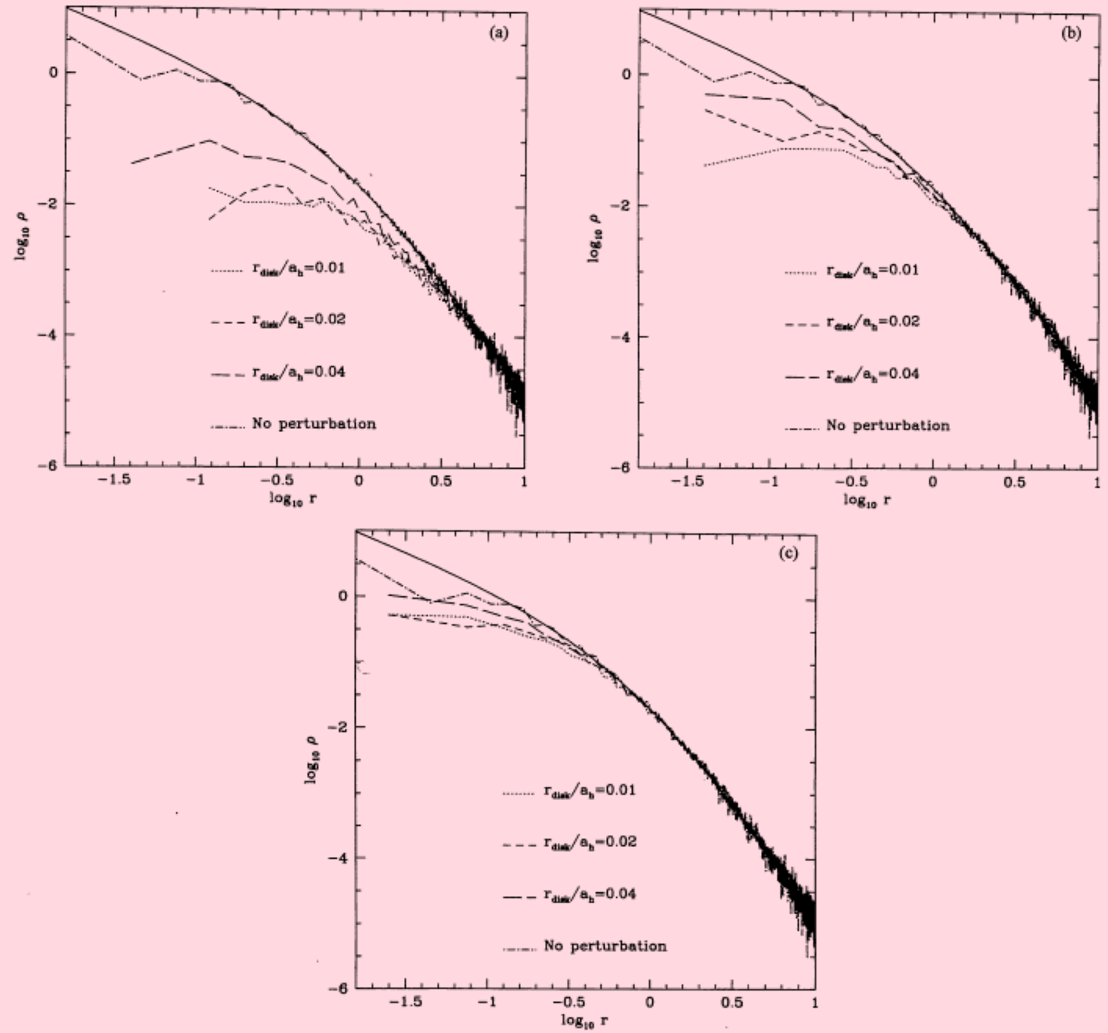

Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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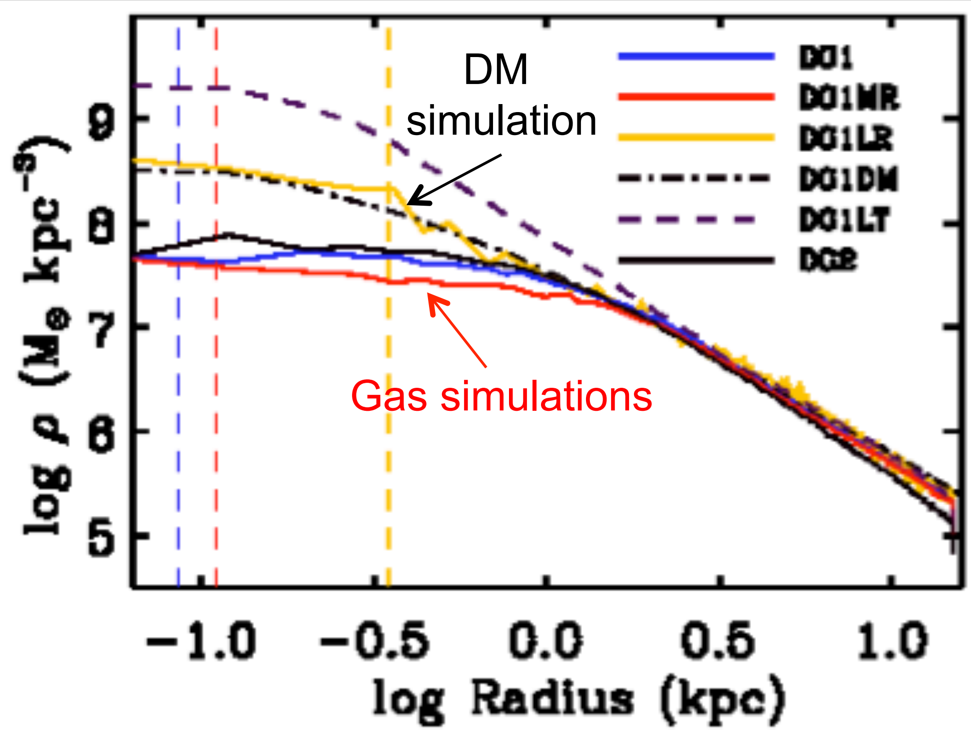
Cores in dwarf galaxy simulations

Governato et al. assume high density threshold for star formation

→ High threshold allows large gas mass to accumulate in centre

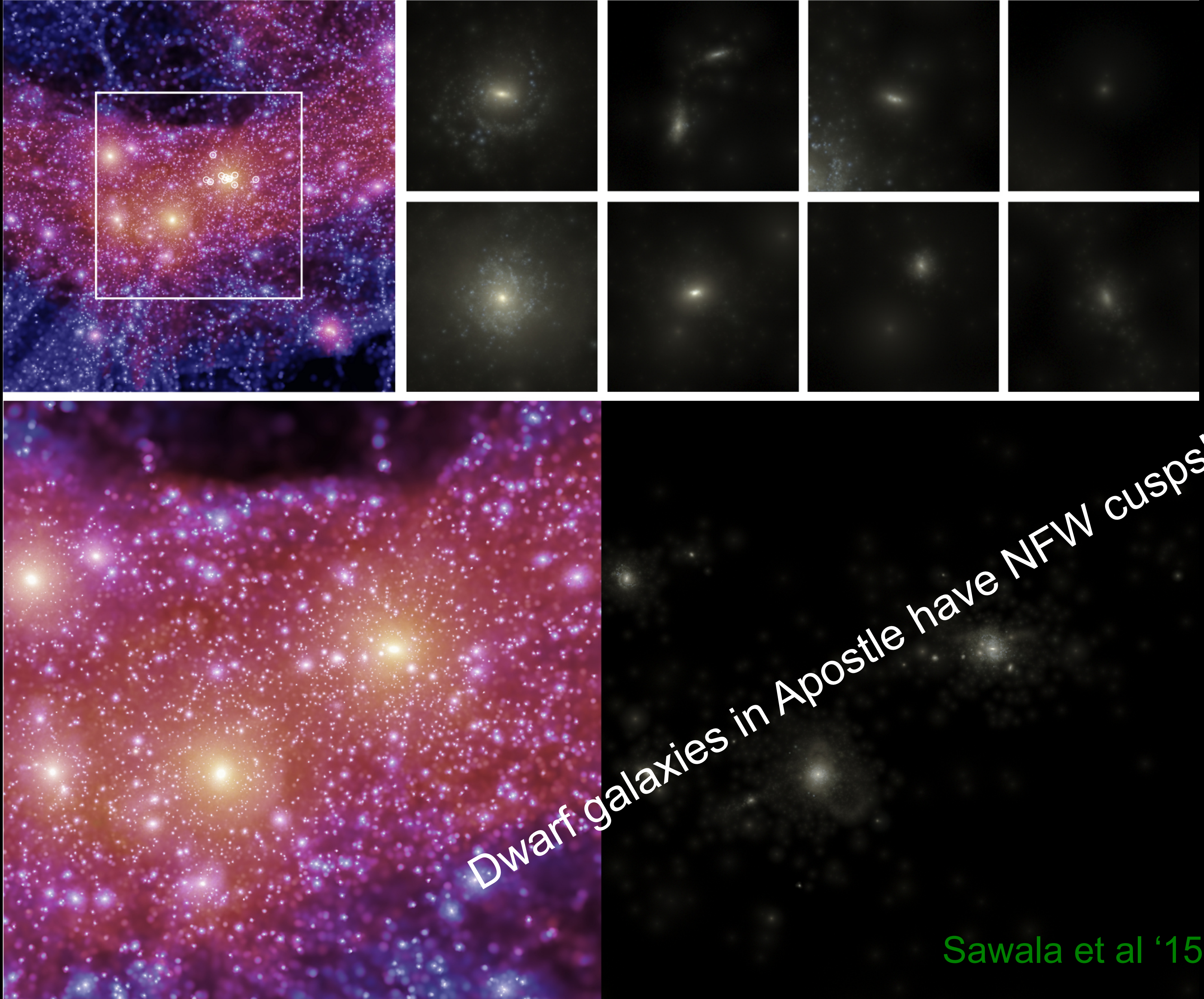
→ Sudden repeated removal of gas transfers binding energy



Governato et al. '12

Pontzen et al. '12

Institute for Computational Cosmology


Dwarf galaxies in Apostle have NFW cusps!
Sawala et al '15

Cores or cusps in simulations?

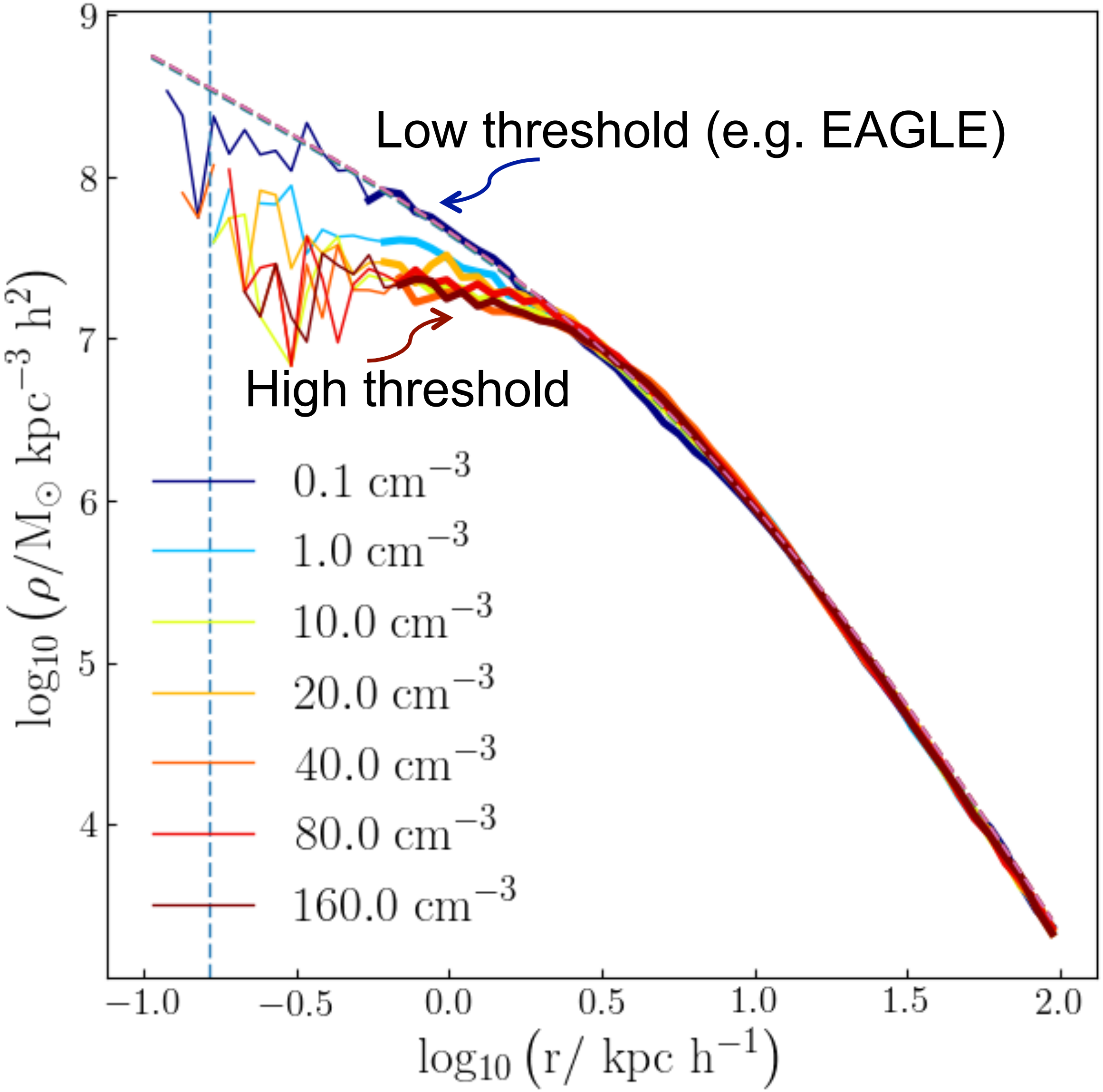
Depends on details of how star formation is modelled
(subgrid physics)

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

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Indirect CDM detection through annihilation radiation

Supersymmetric particles are Majorana particles → annihilate into Standard Model particles (including γ-rays)

Intensity of annihilation radiation at *x* is:

halo density at ***x*** (astrophysics)

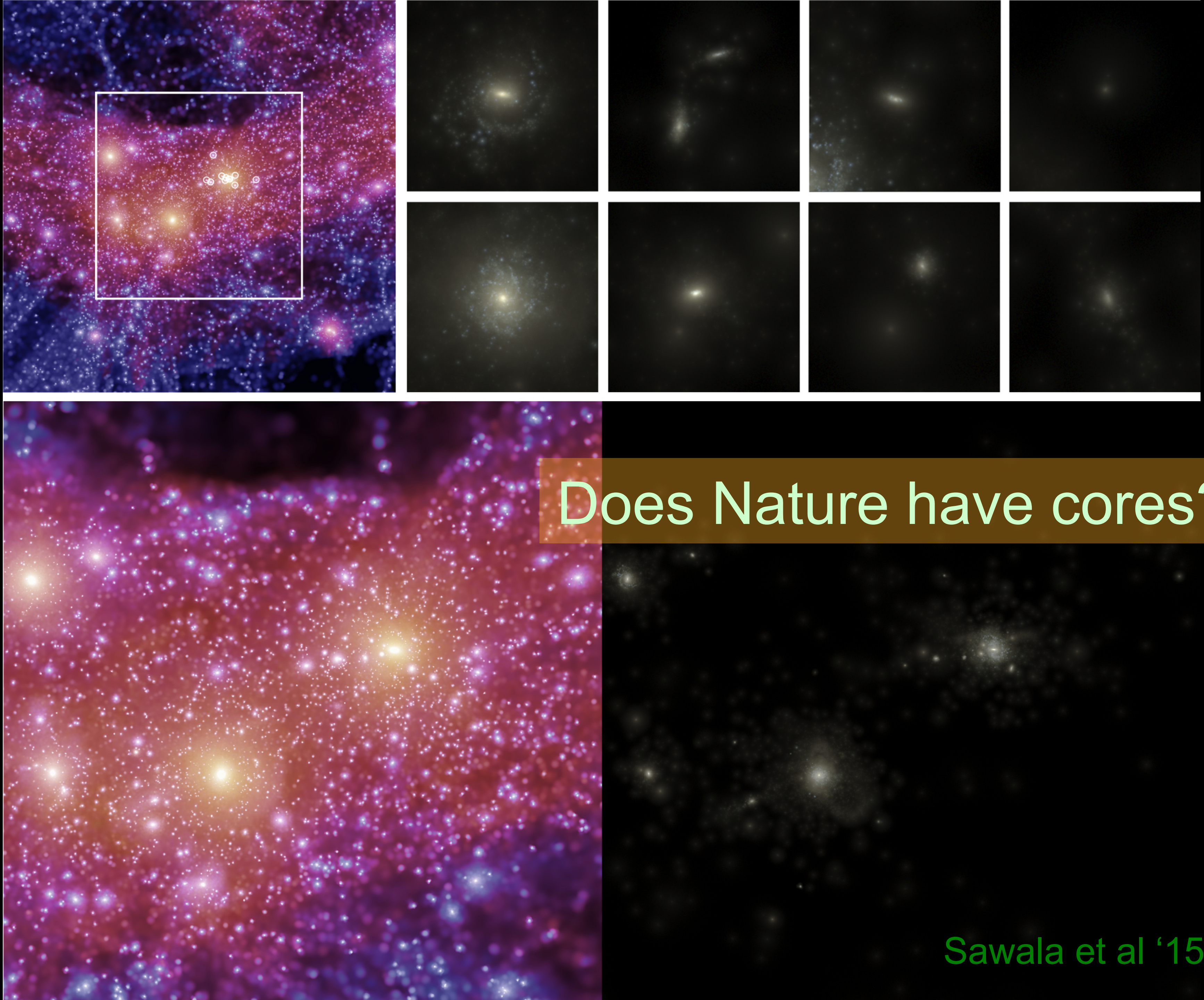
$$I(x) = \frac{1}{8\pi}\sum_f \frac{dN_f}{dE}\langle\sigma_f v\rangle\int_{los}\left(\frac{\rho_\chi}{M_\chi}\right)^2 l\,dl$$

cross-section (particle physics)

$\langle\sigma v\rangle = 3\times10^{-26}cm^3s^{-1}$ → relic abundance in simple SUSY models

⟹ Theoretical expectation requires knowing ρ(***x***)

⟹ Accurate high resolution N-body simulations of halo formation from CDM initial conditions



Does Nature have cores?

Sawala et al '15

There is NO evidence for cores in dwarf galaxies

Existing data are consistent with either cusps or cores

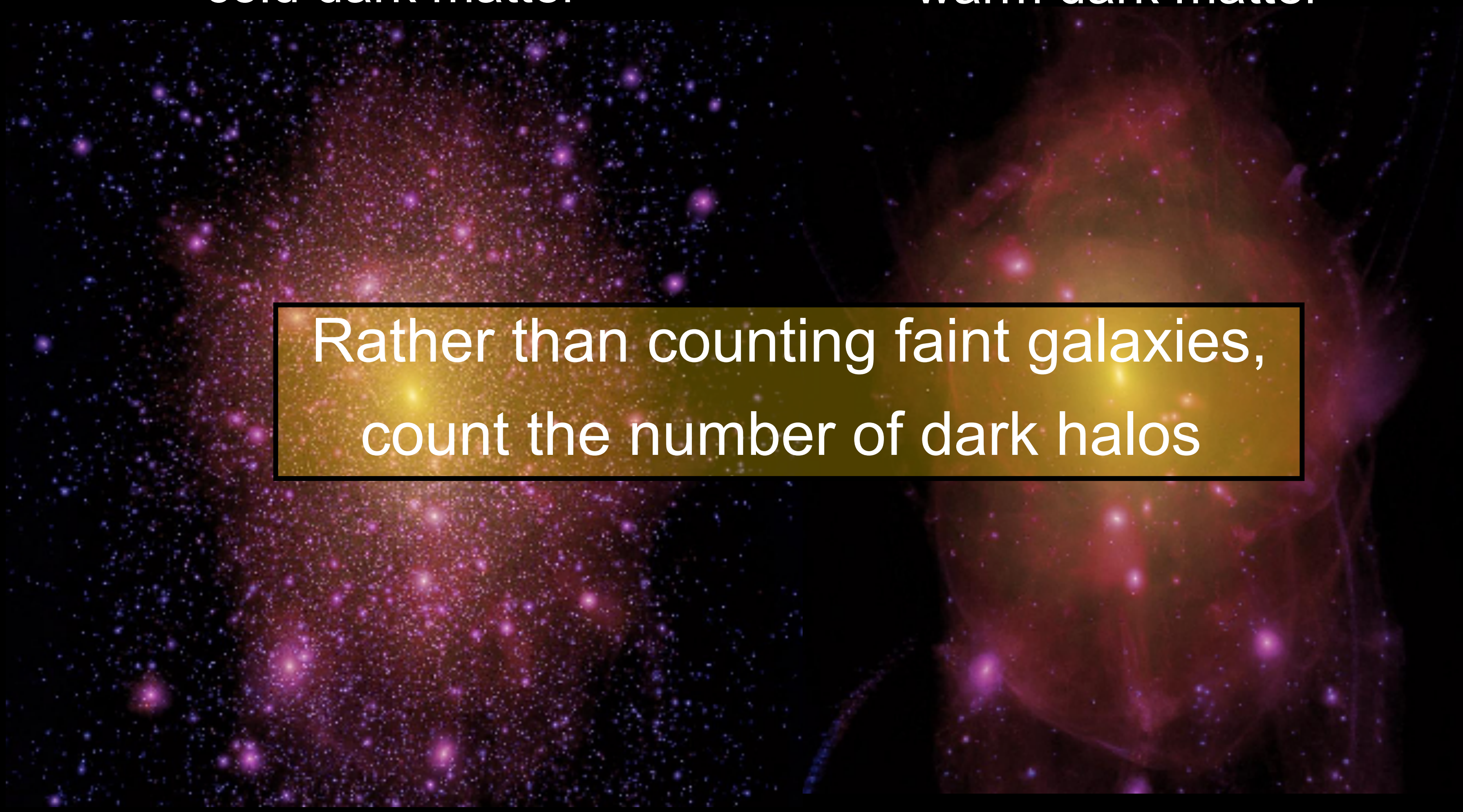
ICC

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?

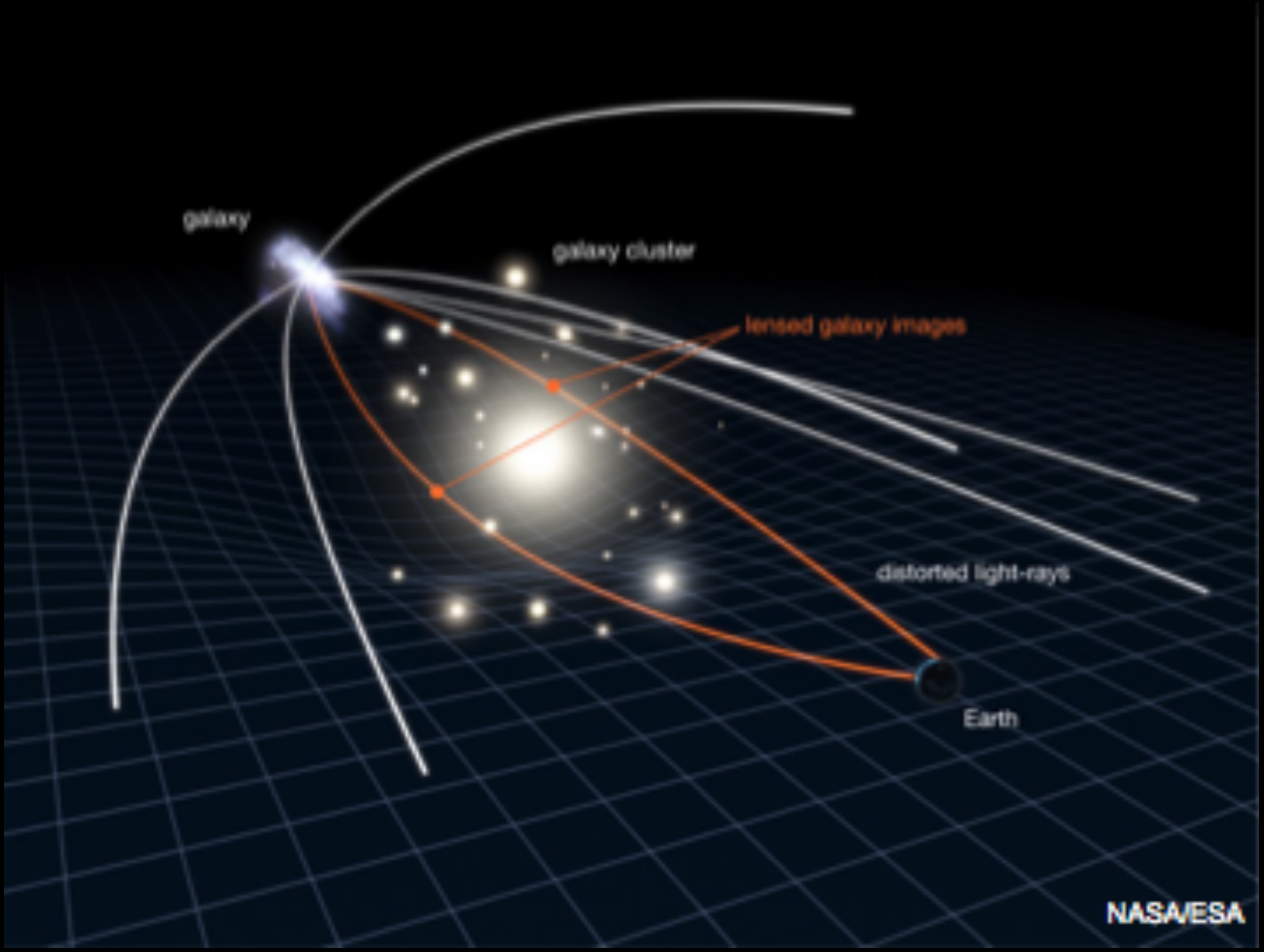
cold dark matter

warm dark matter

Dark halos can be detected through gravitational lensing

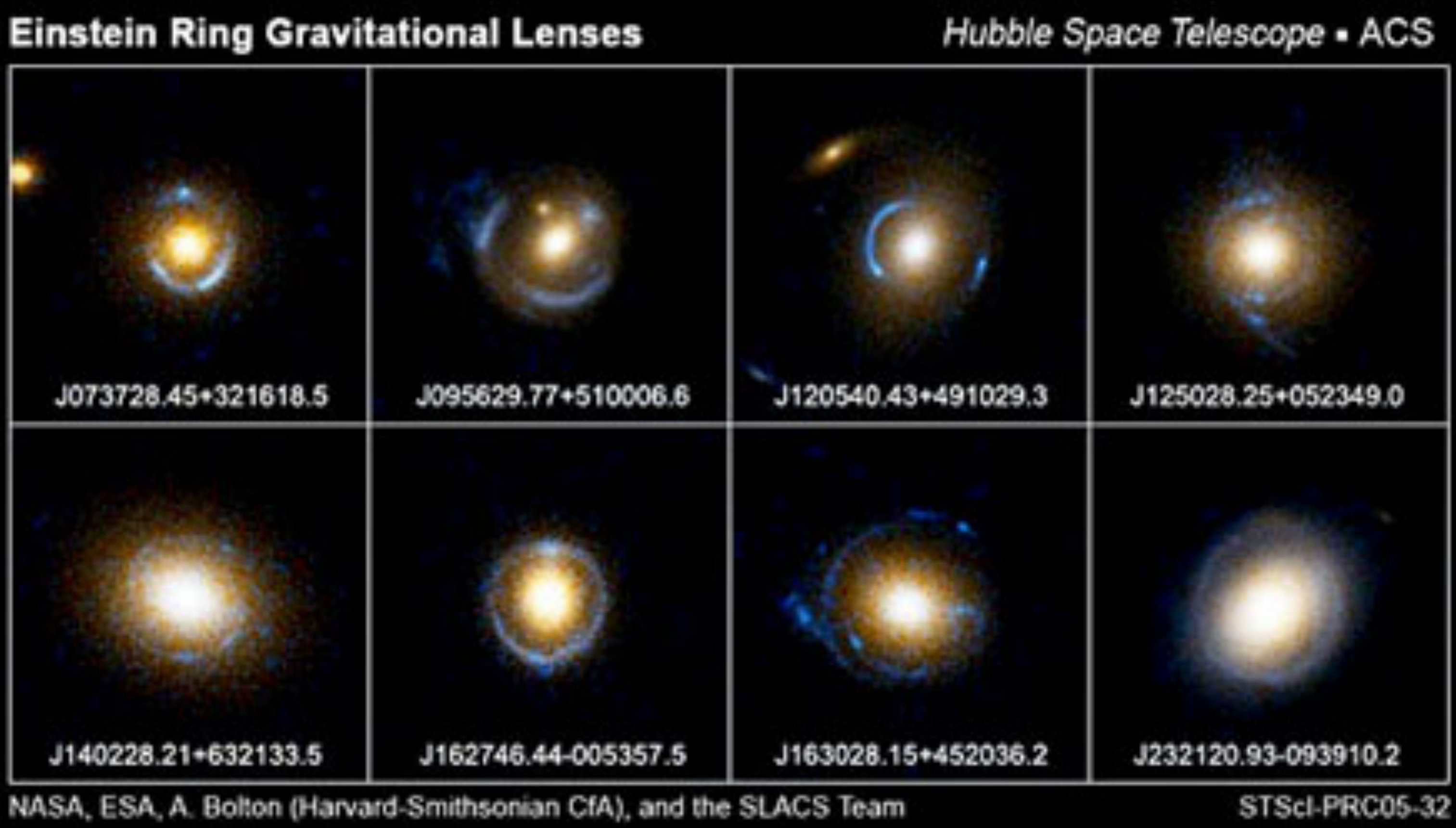
How to rule out CDM

Gravitational lensing: Einstein rings

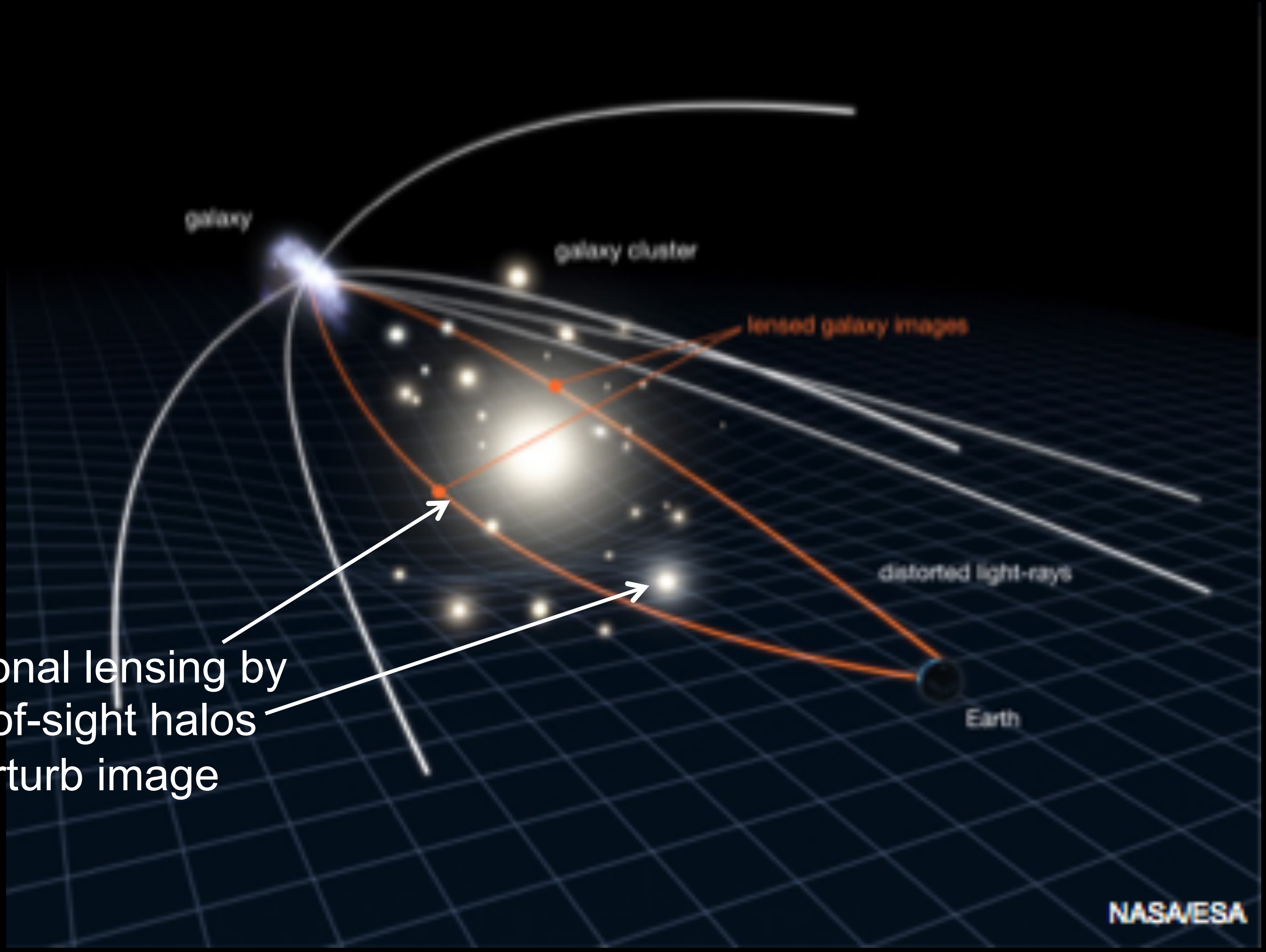


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

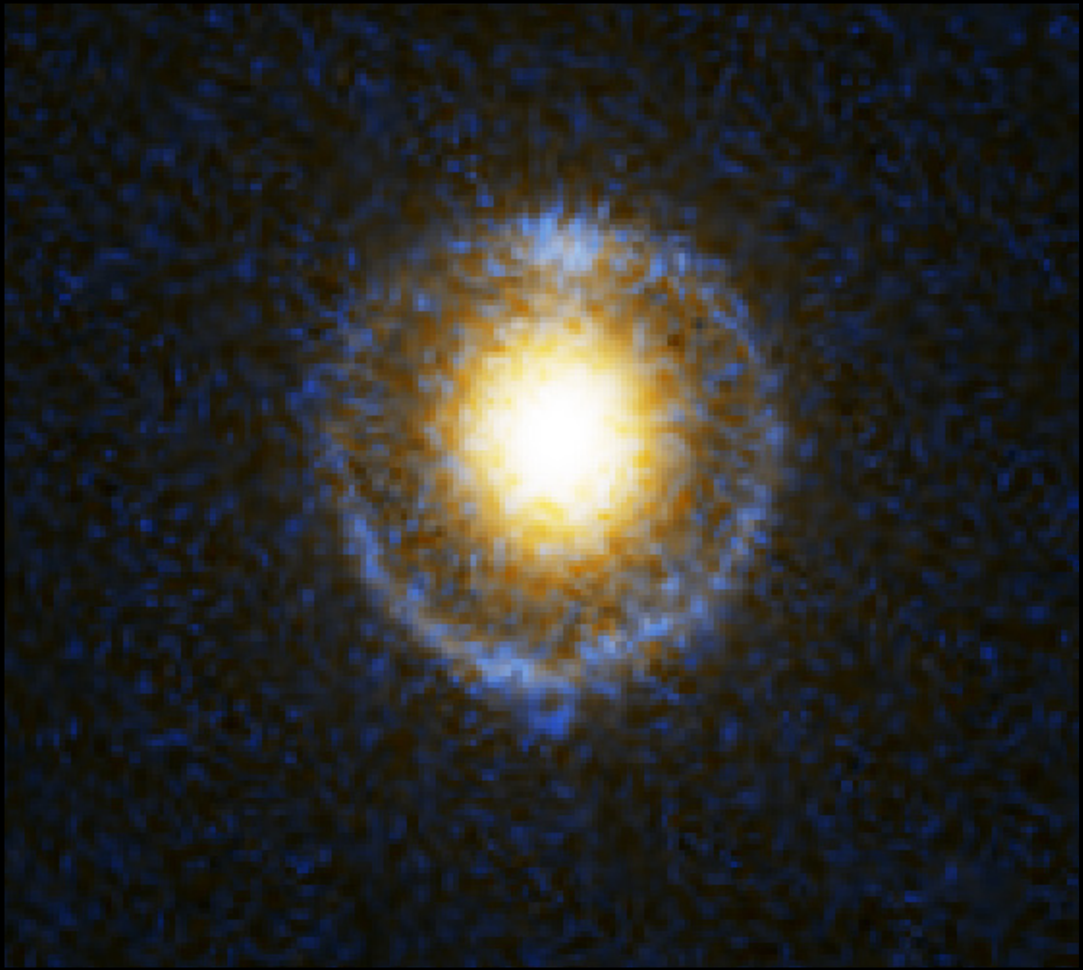


Additional lensing by line-of-sight halos perturb image

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



Vegetti & Koopmans '09

Detecting substructures with strong lensing

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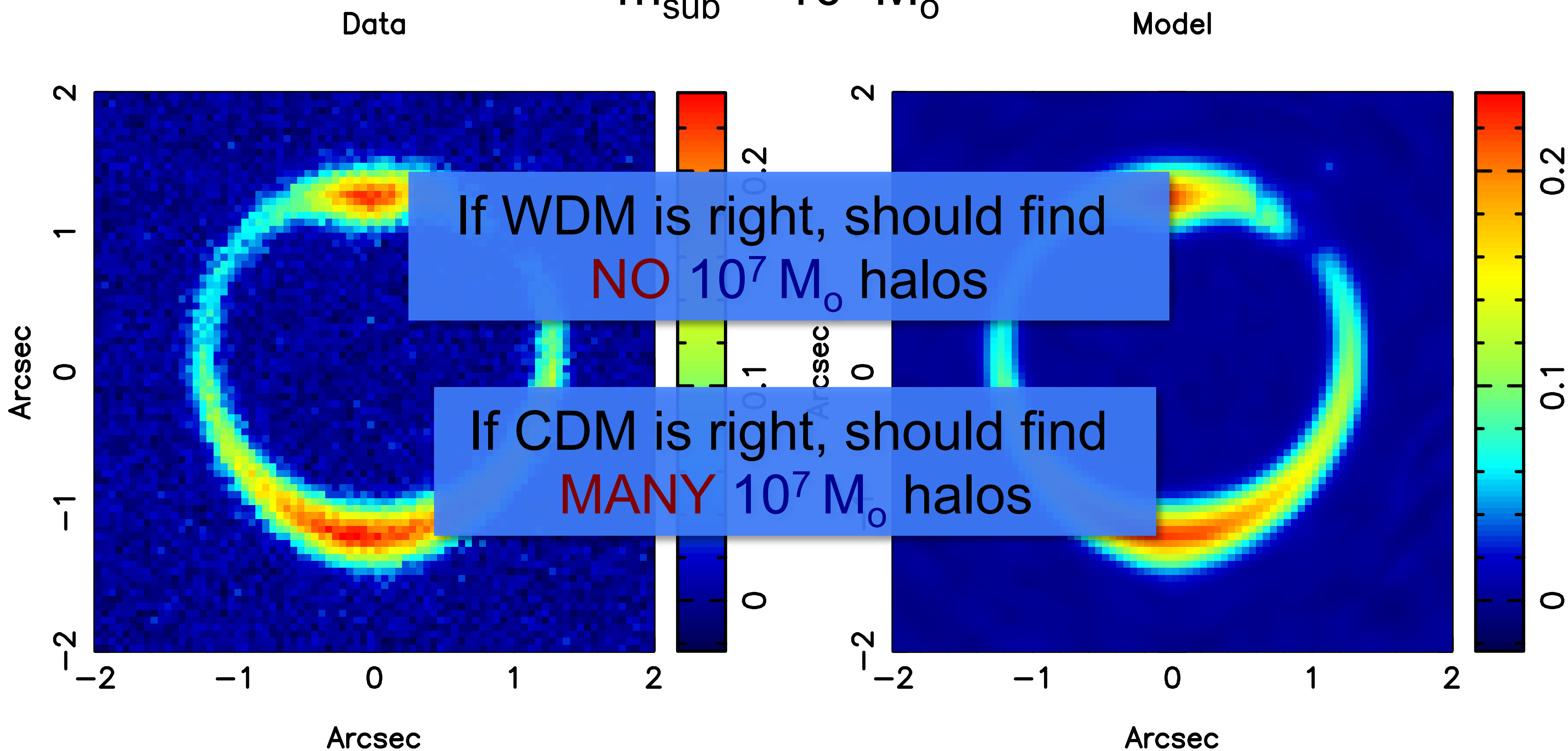
Vegetti & Koopmans '09

$m_{sub} = 10^8\, M_o$



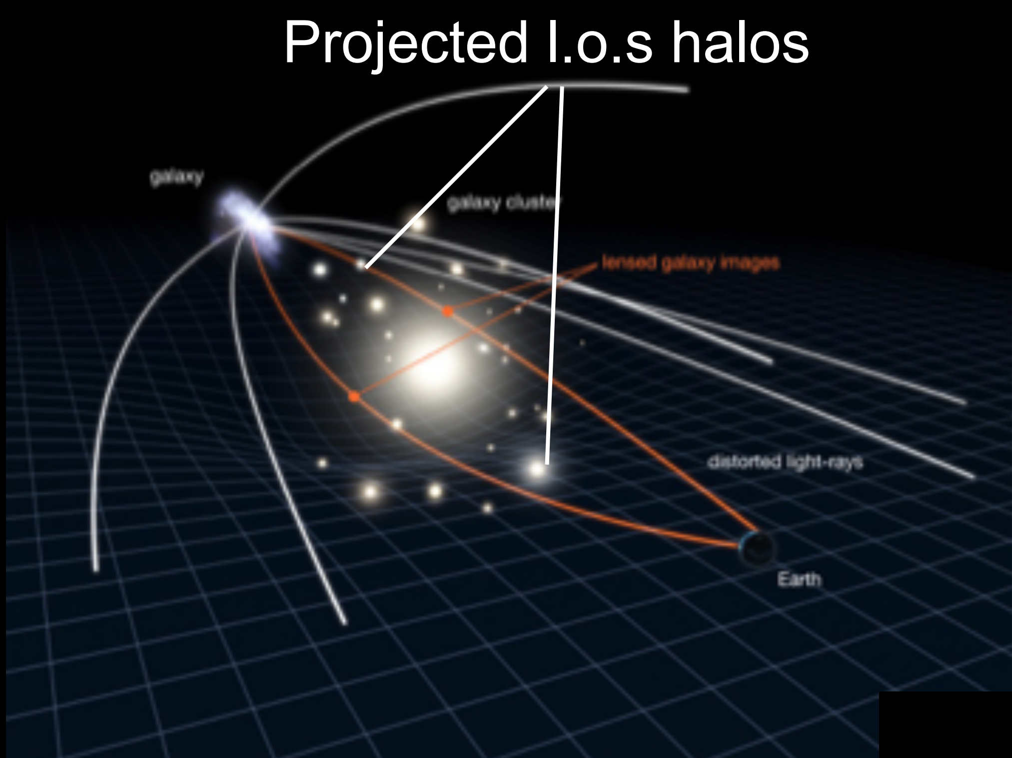
If WDM is right, should find
NO $10^7\, M_o$ halos

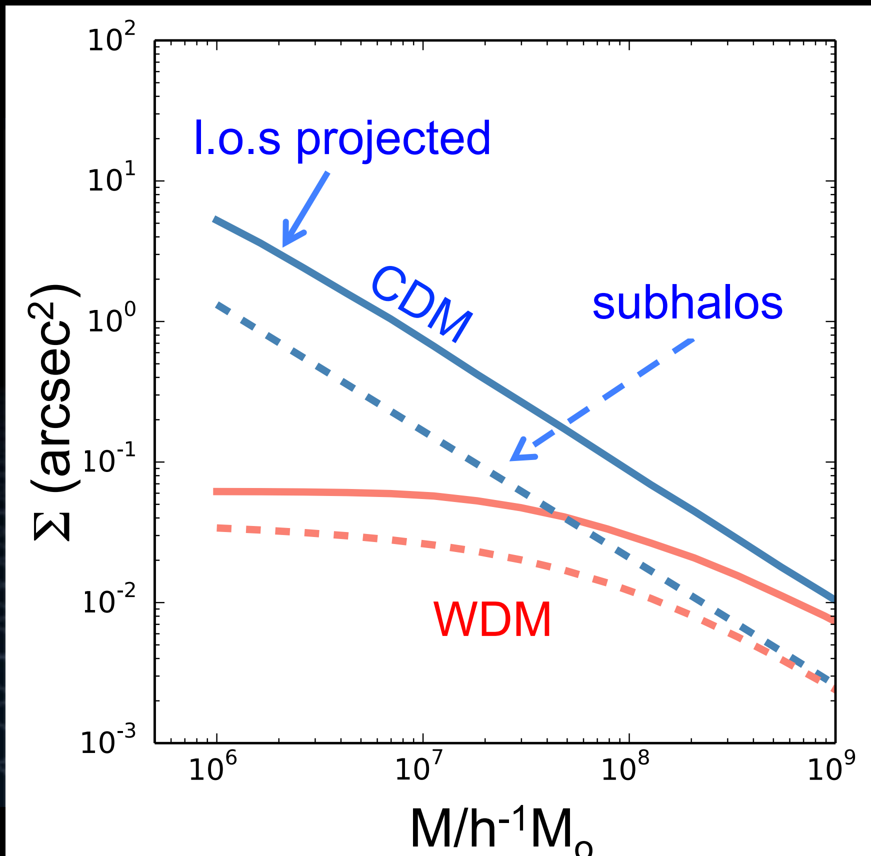
If CDM is right, should find
MANY $10^7\, M_o$ halos

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

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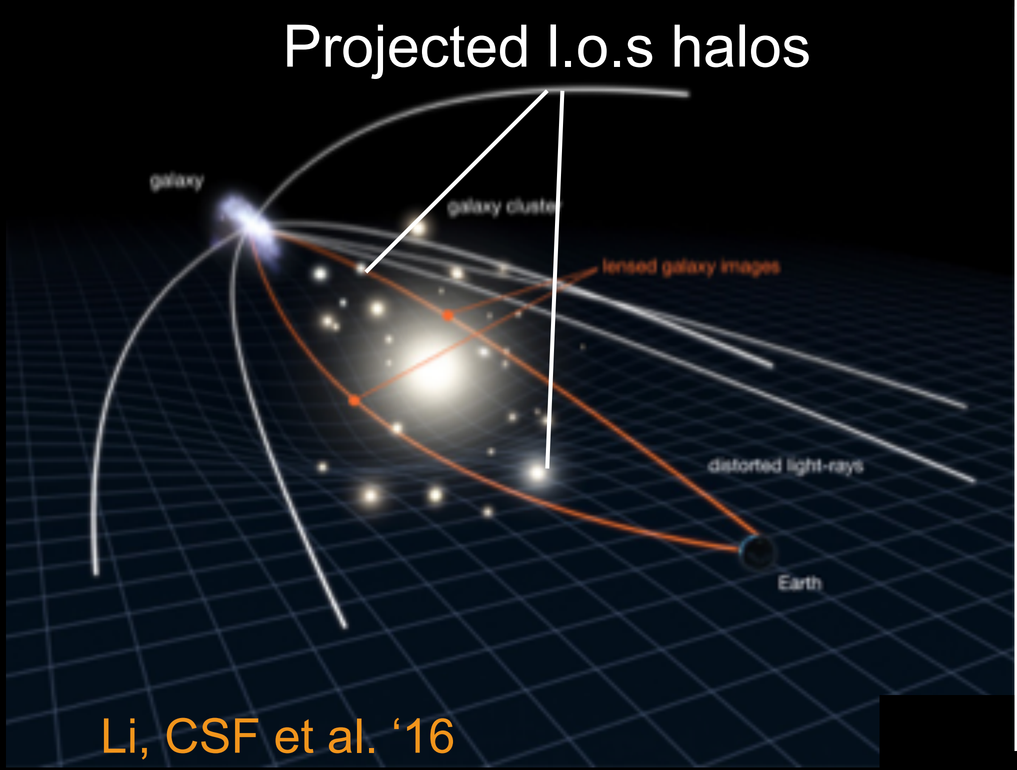
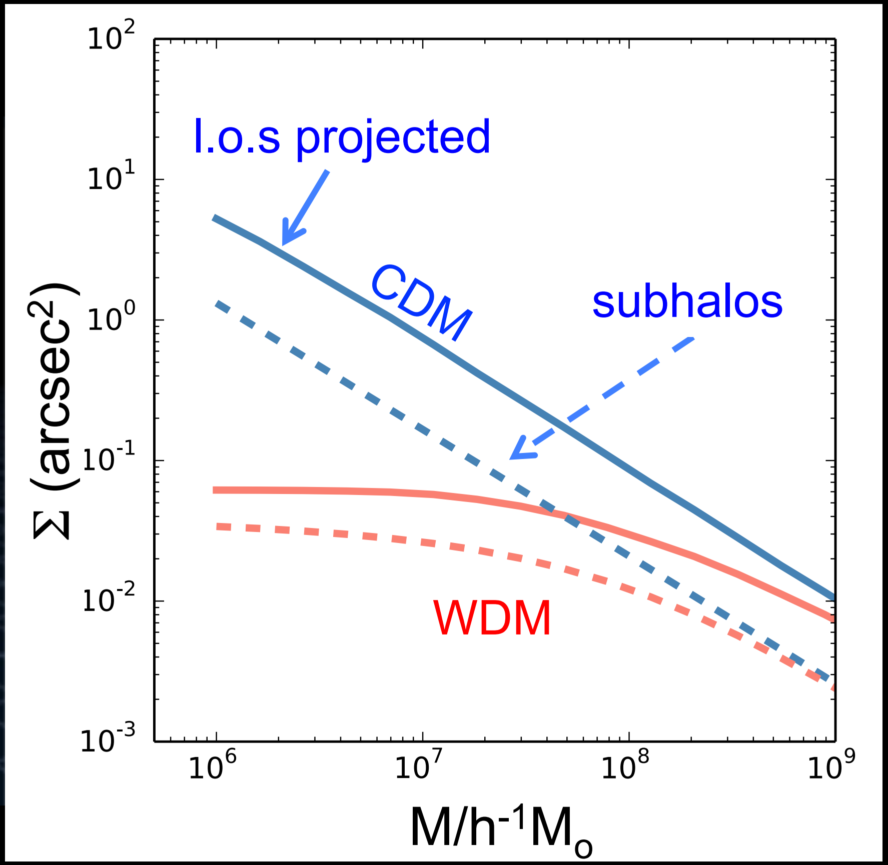


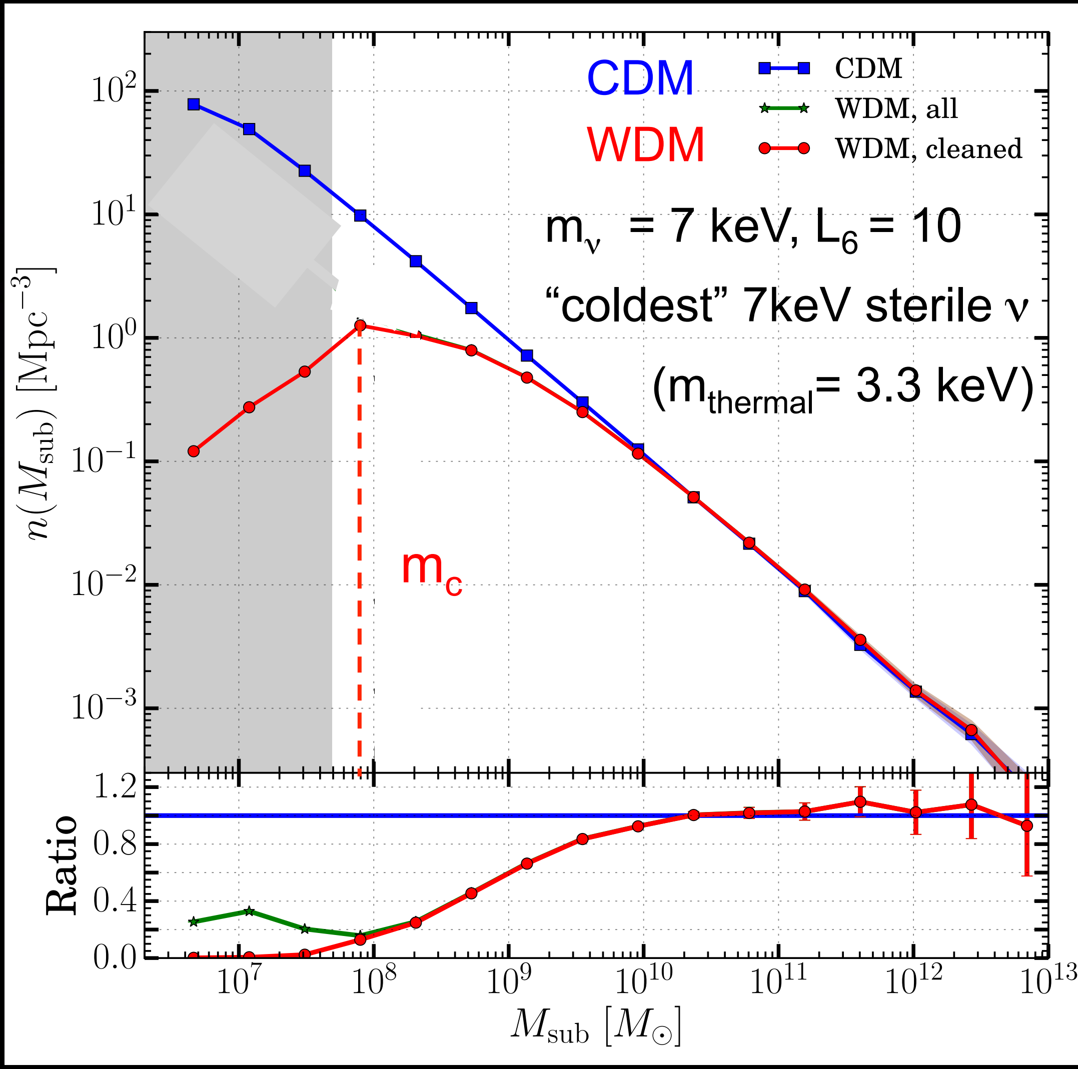


→ This is the cleanest possible test: it depends ONLY on the small-mass end of the "field" halo mass function which we know how to calculate and is unaffected by baryons

The 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

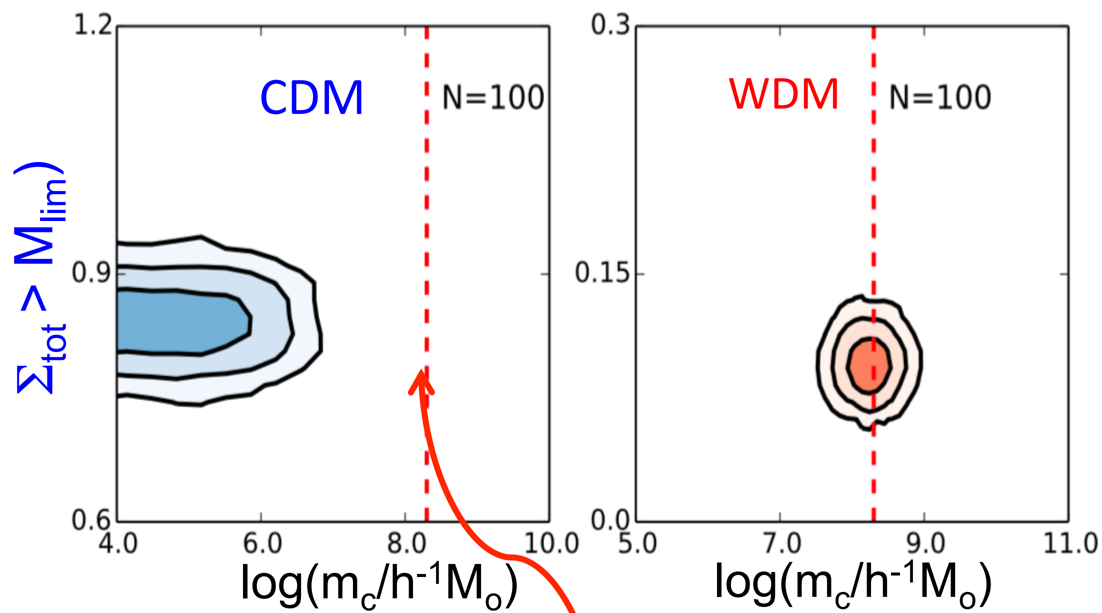
Detecting substructures with strong lensing

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
- But on these scales ΛCDM cannot be distinguished from WDM
- The identity of the DM makes a big difference on small scales

1. Counting faint galaxies cannot distinguish CDM/WDM
2. Halos < ~5.$10^8 M_0$ are dark; halos >$10^{10} M_0$ are bright (abundance matching fails for halos <$10^{10} M_0$)
3. No evidence for cores but 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!