Johannes Hans Daniel Jensen (1907–1973)

Shell model of atomic nucleus

The standard model of cosmology

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

... and how to rule it out

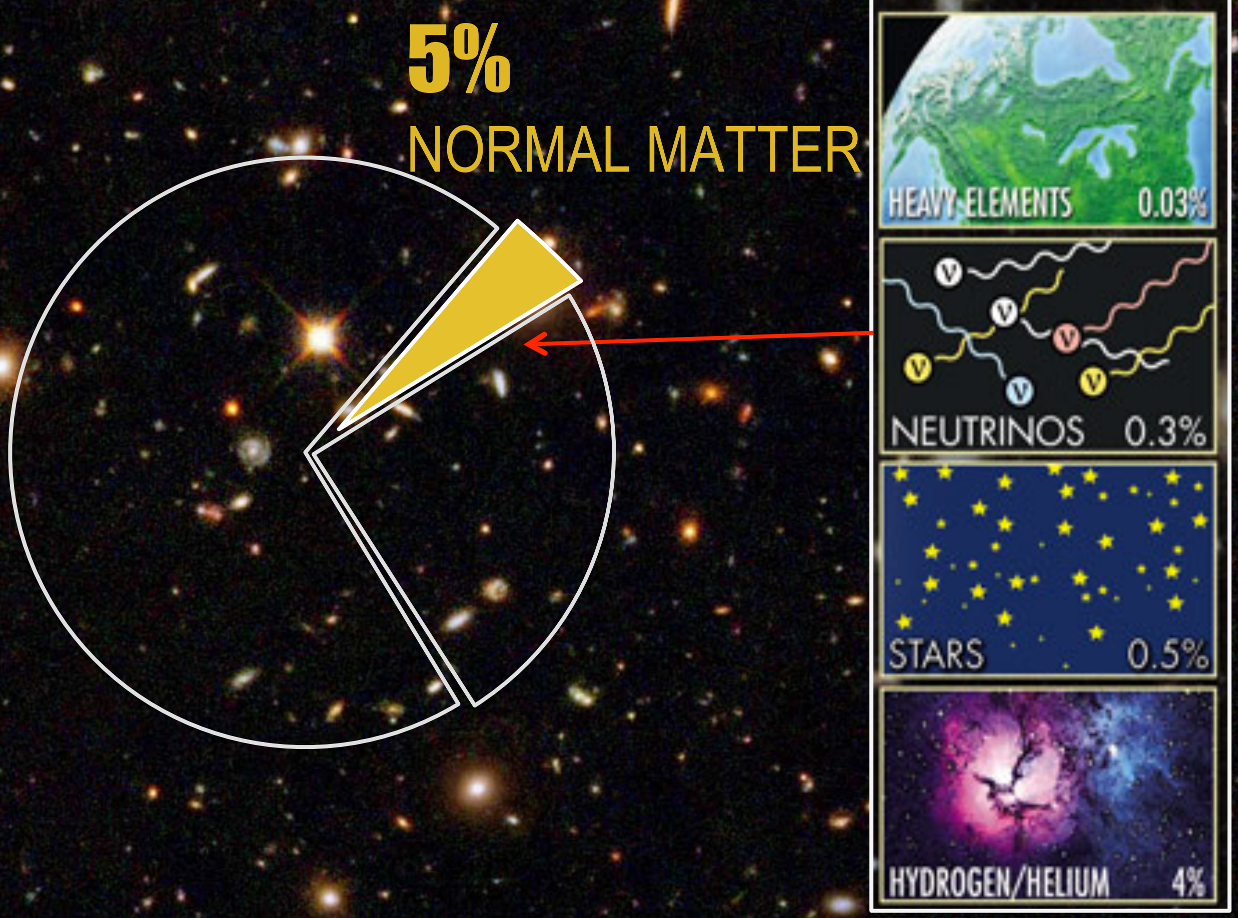
The ΛCDM model of cosmogony

Cosmological constant → Λ

Cold dark matter → CDM

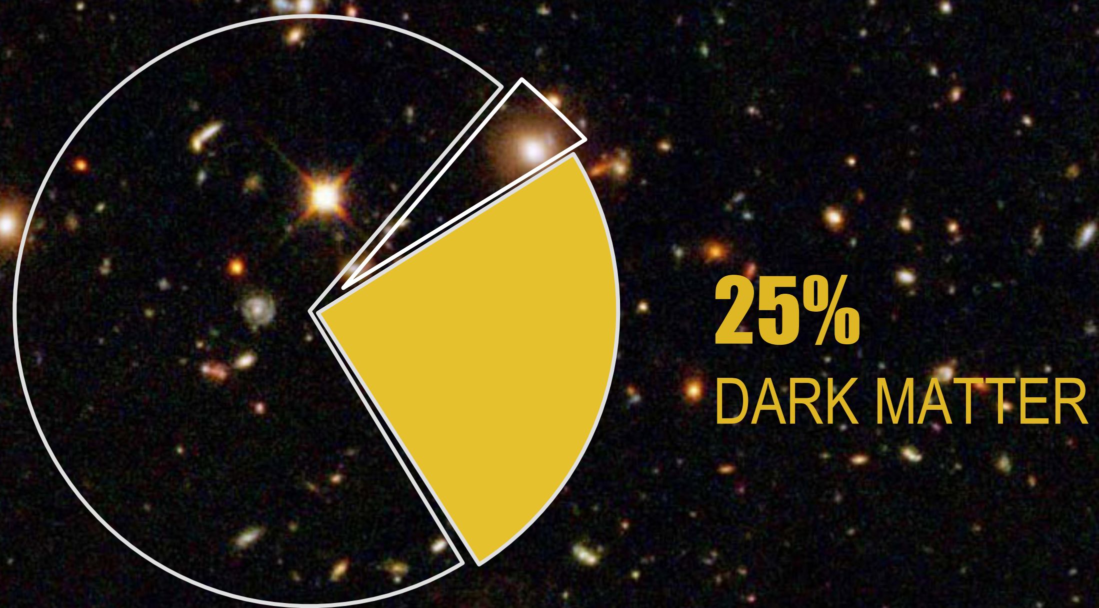
- *Ab initio,* fully specified model of cosmic evolution and the formation of cosmic structure
- Has strong predictive power and can, in principle, be ruled out
- Has made a number of predictions that were subsequently verified empirically (e.g. CMB, LSS, galaxy formation)

The content of our universe



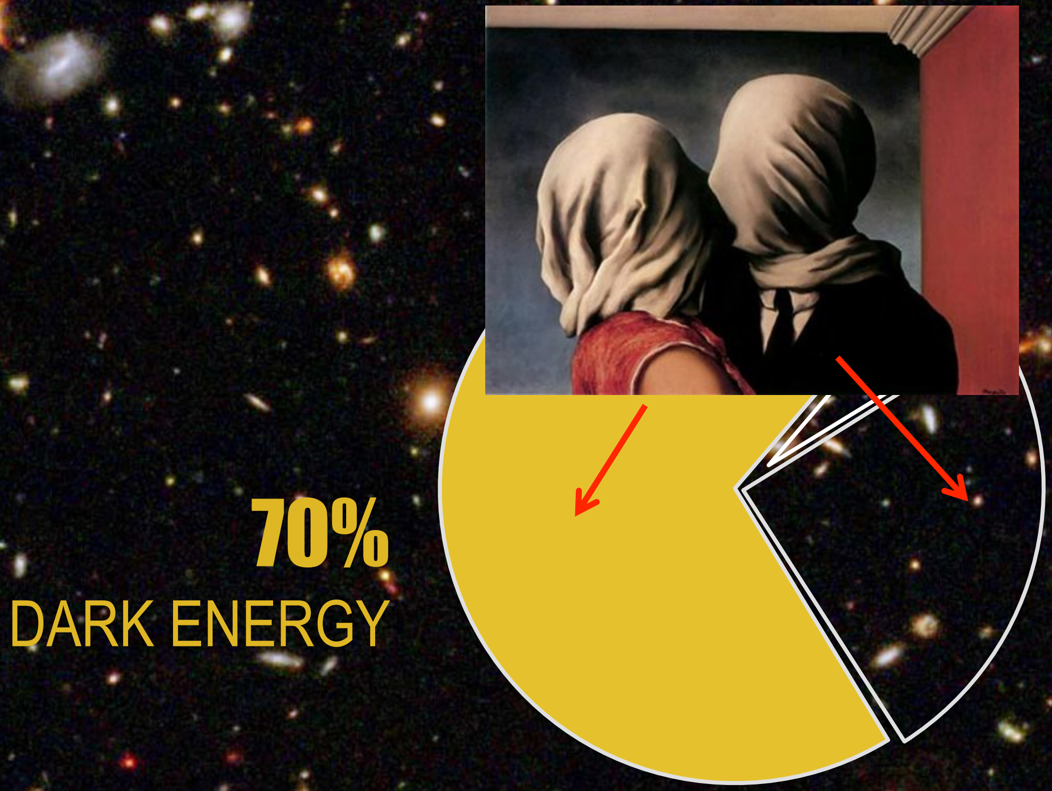
Normal matter ≡ matter made of ordinary atoms

The content of our universe



Dark matter ≡ matter that does not emit light at any wavelength

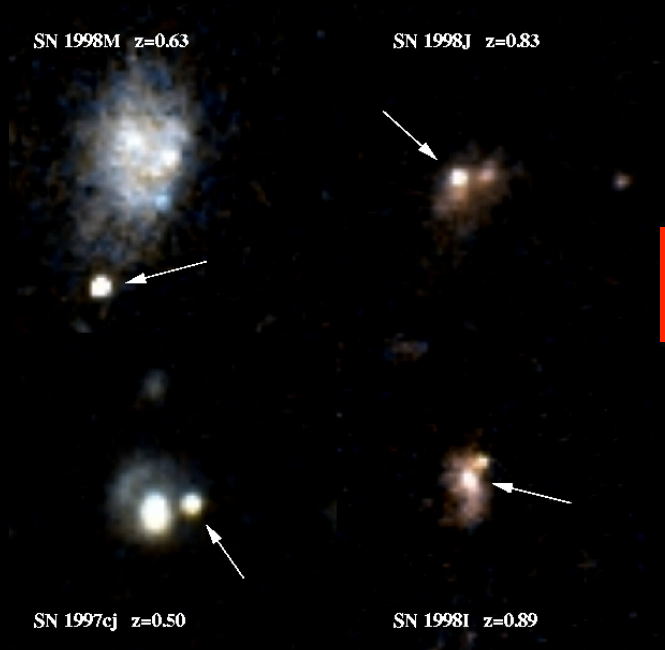
The content of our universe

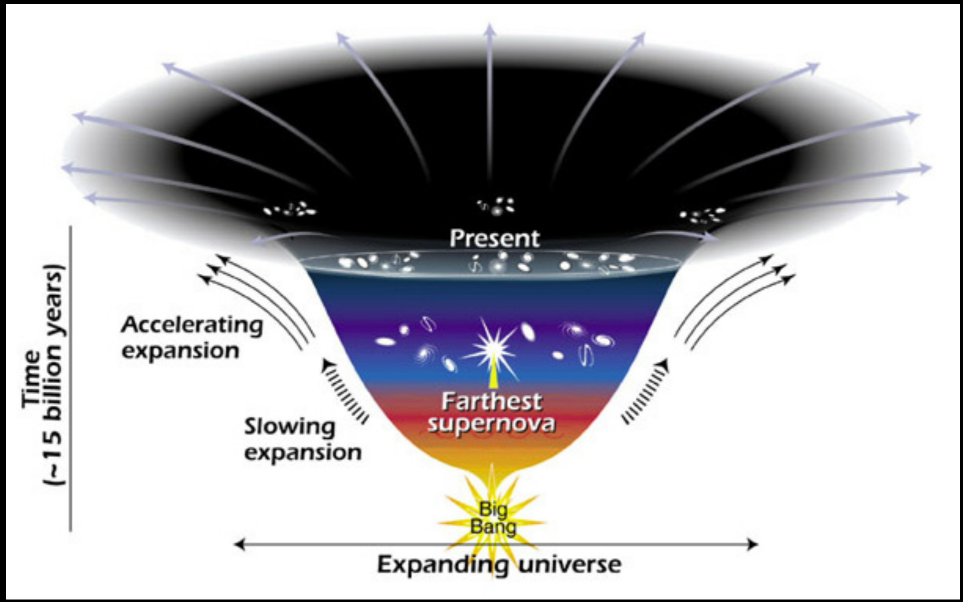


Dark energy ≡ mysterious form of energy which opposes gravity and is causing the cosmic expansion to accelerate

The cosmic expansion

1998





Expansion is
rating

2011 Nobel prize in physics!

➔Universe full of dark energy

What is the cosmic dark energy?

A form of energy that produces a repulsive force, causing the universal expansion to accelerate

It is likely to be energy associated with empty space – the vacuum

Simplest possibility – Einstein's cosmological constant, Λ

University of Durham ICC

The cosmic dark energy

Current physics predicts a "natural" value for the cosmological constant (Planck value)

$$\rho_{\Lambda}^{PL} \sim M_{PL}^{4} \sim (8\pi G)^{-2} \sim (10^{18} GeV)^{4} \sim 2\times 10^{130} erg / cm^{3}$$

$$\rho_{\Lambda}^{obs} \sim (10^{-12} GeV)^{4} \sim 2\times 10^{10} erg / cm^{3}$$

10^{120} larger than observed !!!

- Most inaccurate prediction in physics ever
- Requires new physics!
- But Λ consistent will everything we know

The contents of the Universe

University of Durham

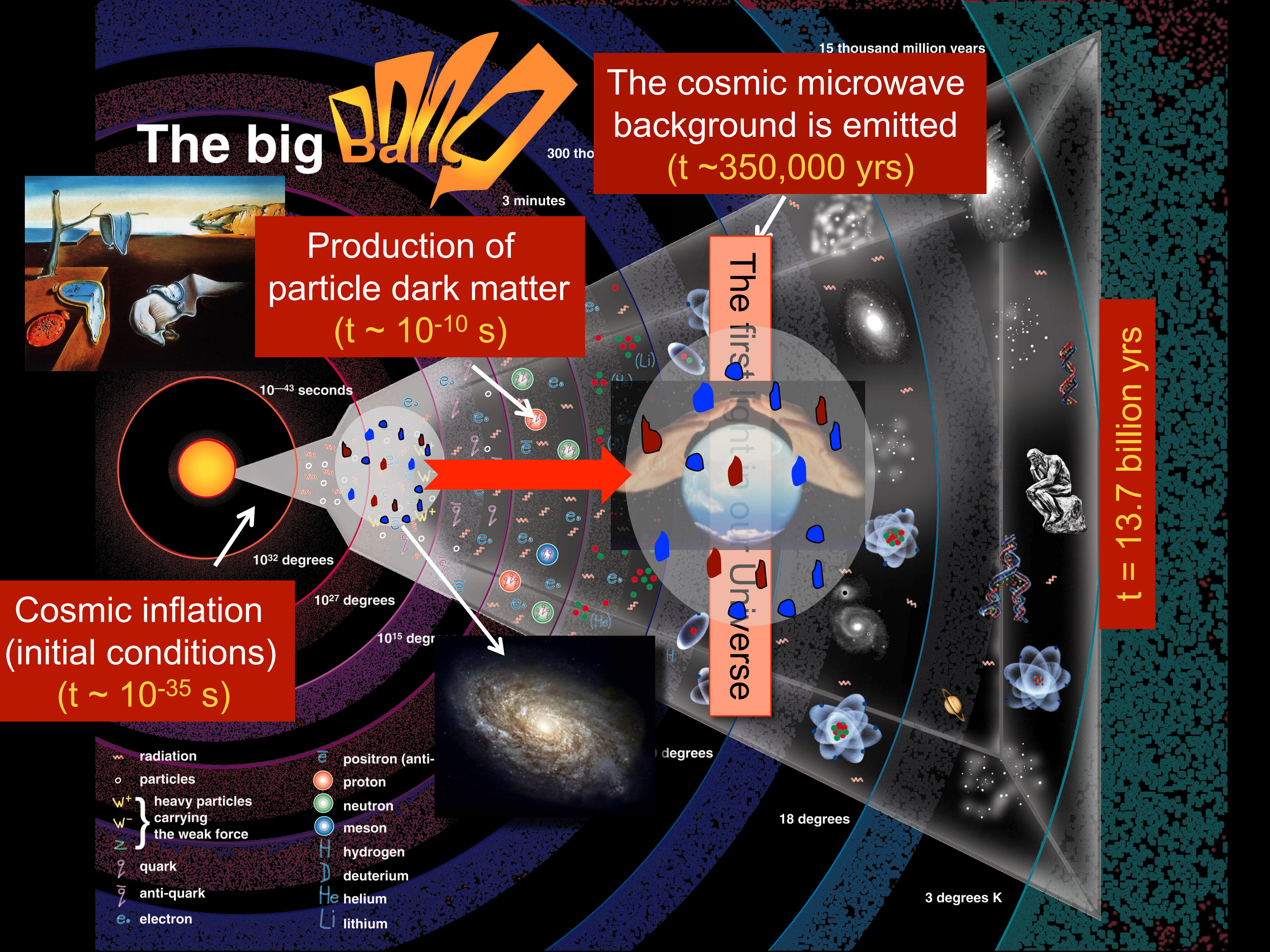
a = cosmic expansion factor

$$\rho_{tot} = \underbrace{\rho_{mass}}_{a^{-3}} + \underbrace{\rho_{rel}}_{a^{-4}} + \underbrace{\rho_{vac}}_{const?}$$

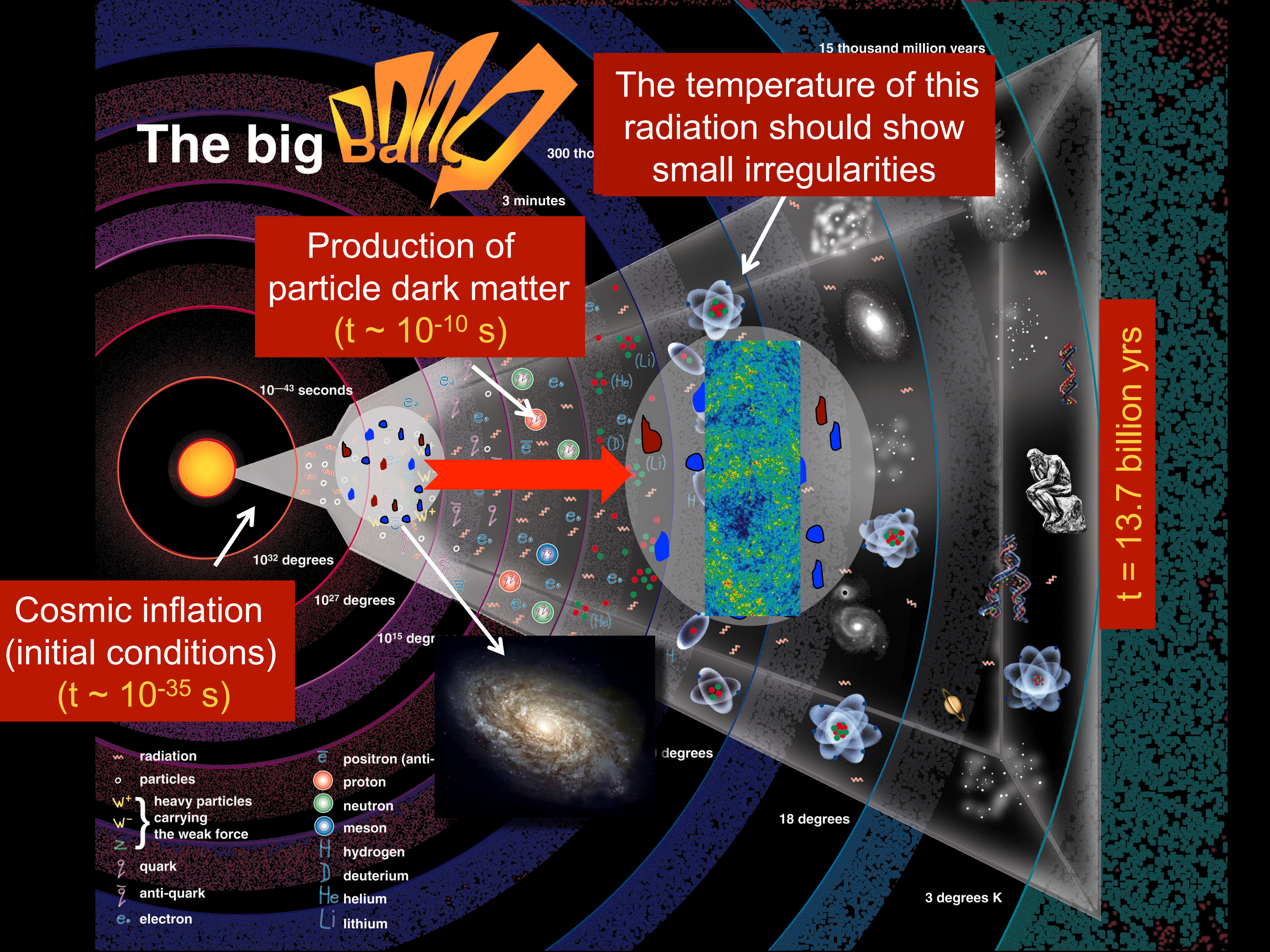
ρ_{vac} only became dominant about 4 billion years ago ($z=1.5$)

Universe dominated by matter in period when most structure forms

→ Cosmological constant not important for structure formation



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

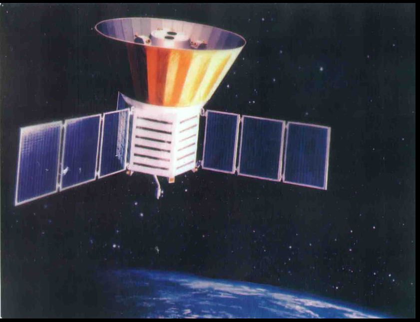


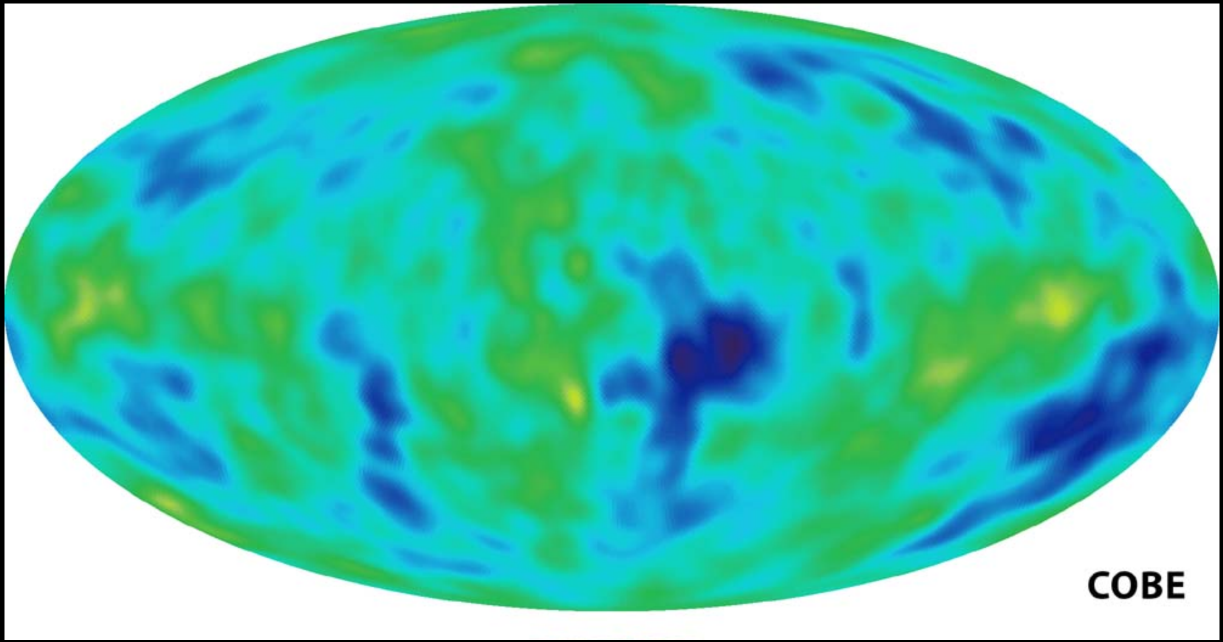
The big Bang
15 thousand million years
300 tho
3 minutes
The temperature of this radiation should show small irregularities
Production of particle dark matter
(t ~ 10^{-10} s)
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degr
Cosmic inflation (initial conditions)
(t ~ 10^{-35} s)
degrees
18 degrees
3 degrees K
t = 13.7 billion yrs
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium

ICC

The CMB

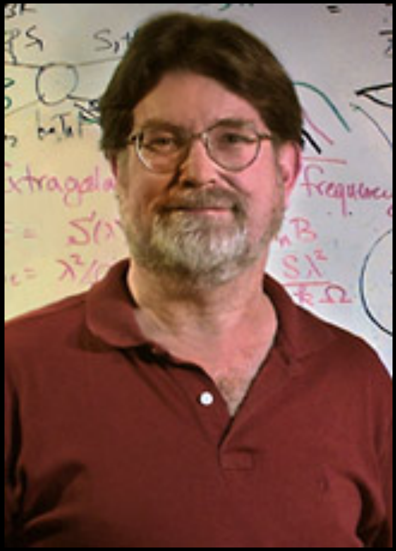
1992





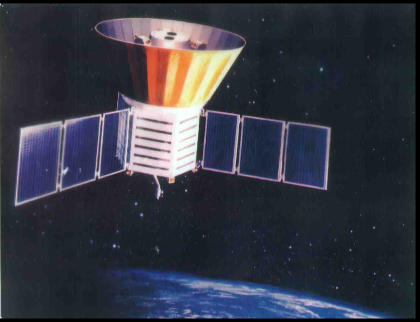
George Smoot - Nobel Prize 2006

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

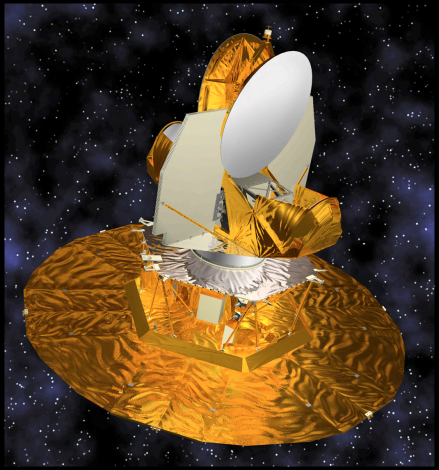


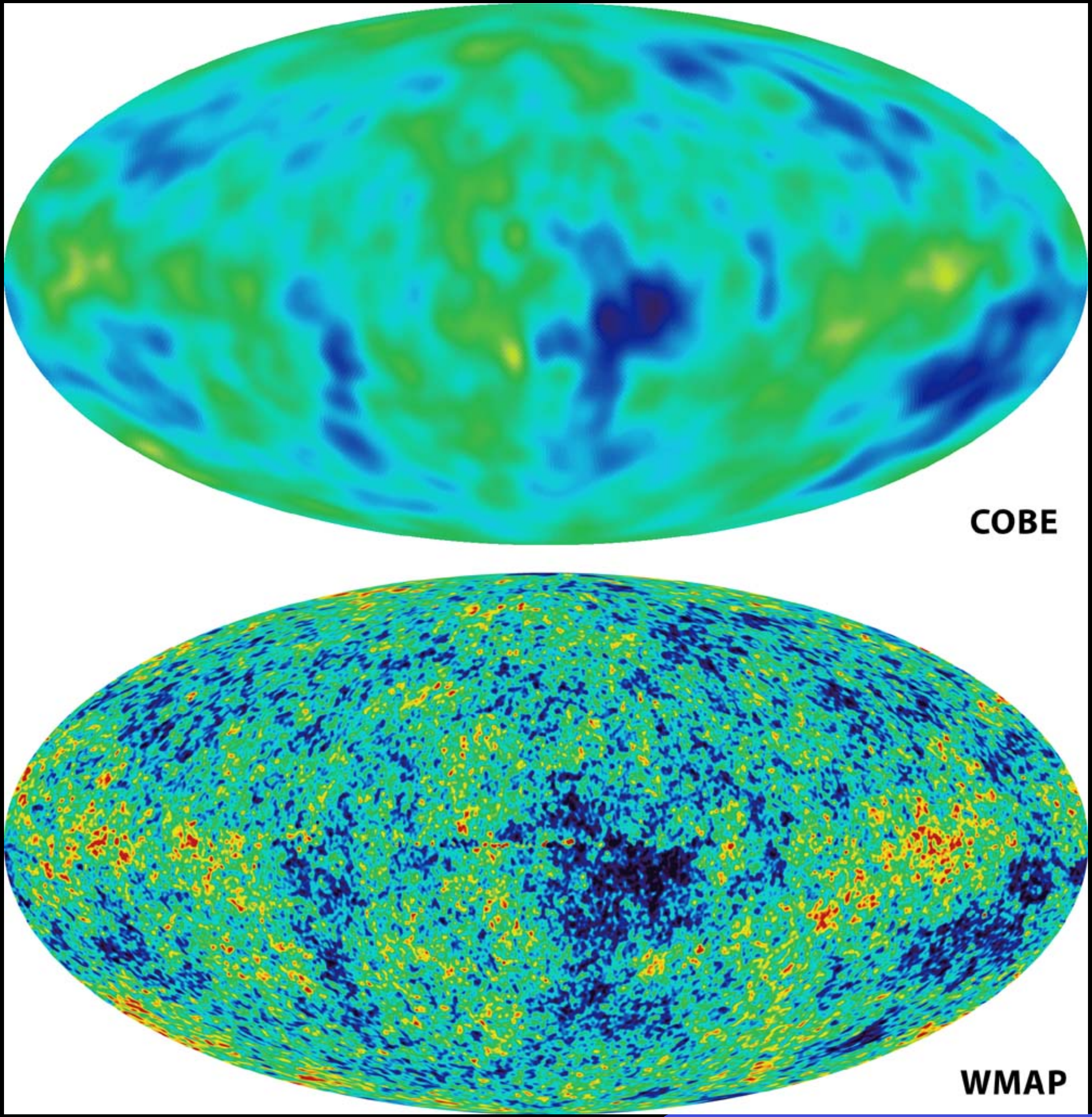
The CMB

1992



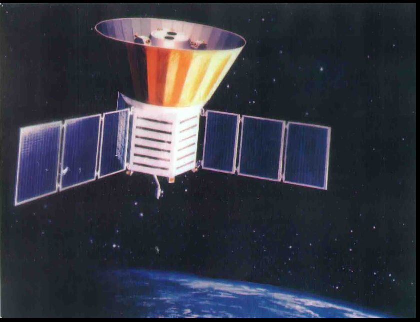
2003



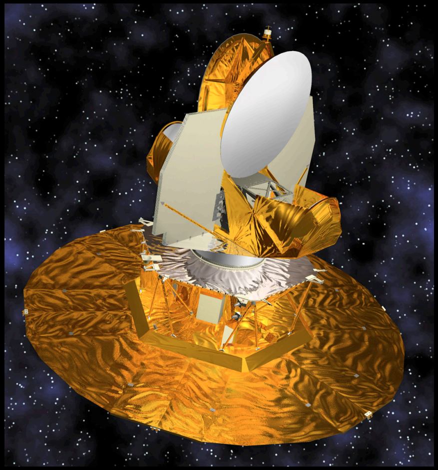


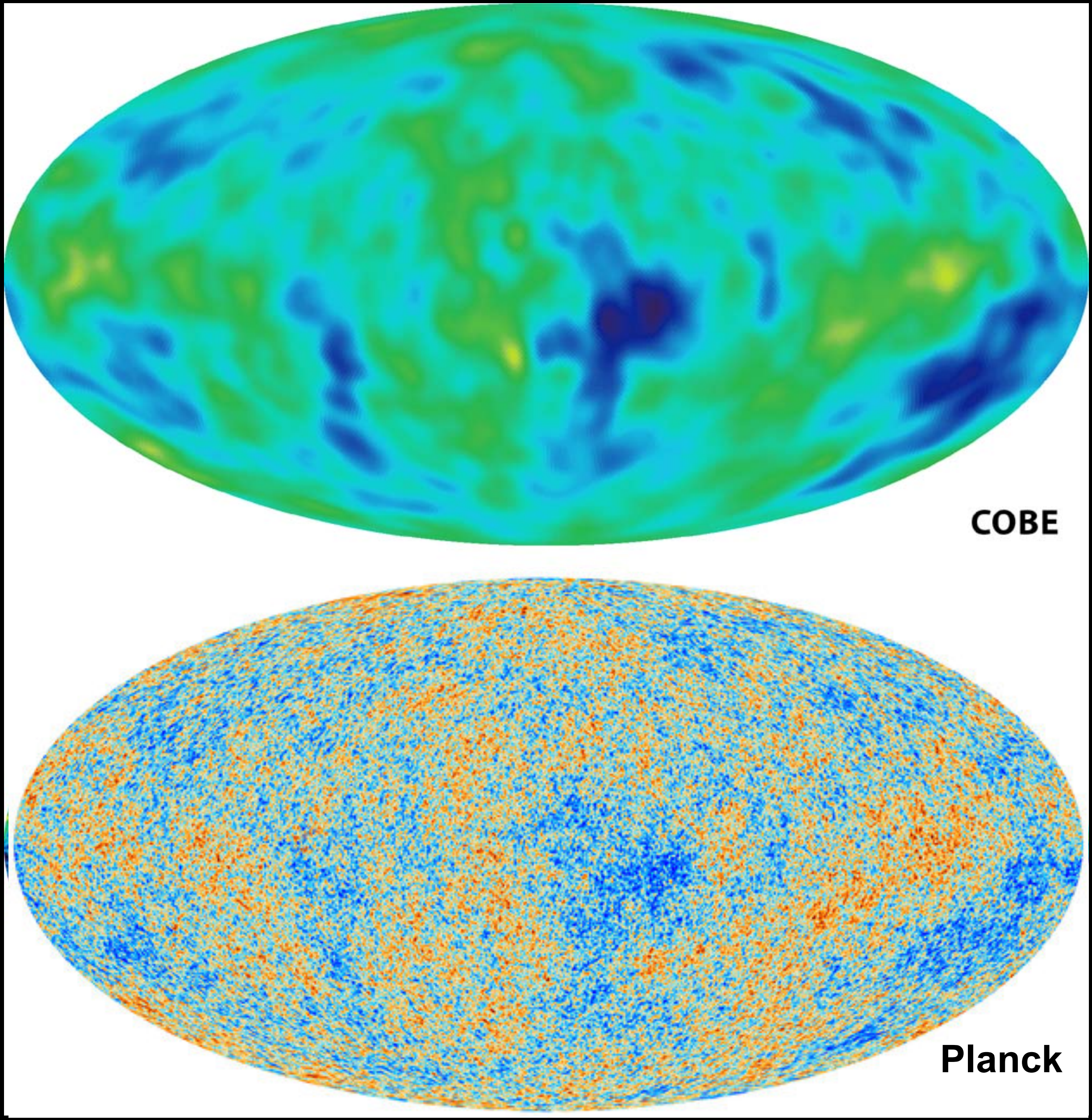
The CMB

1992



2012





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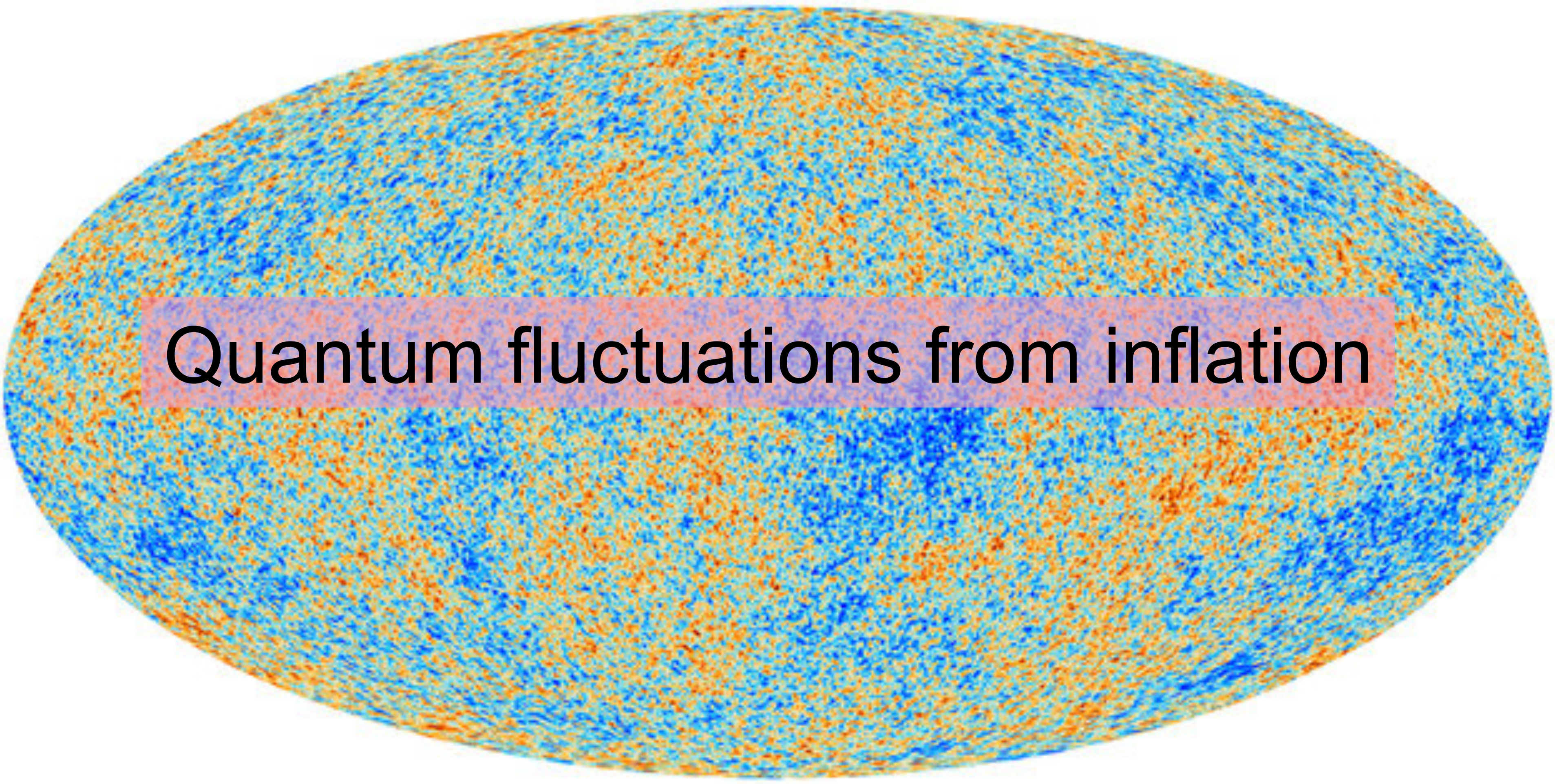
The initial conditions for galaxy formation

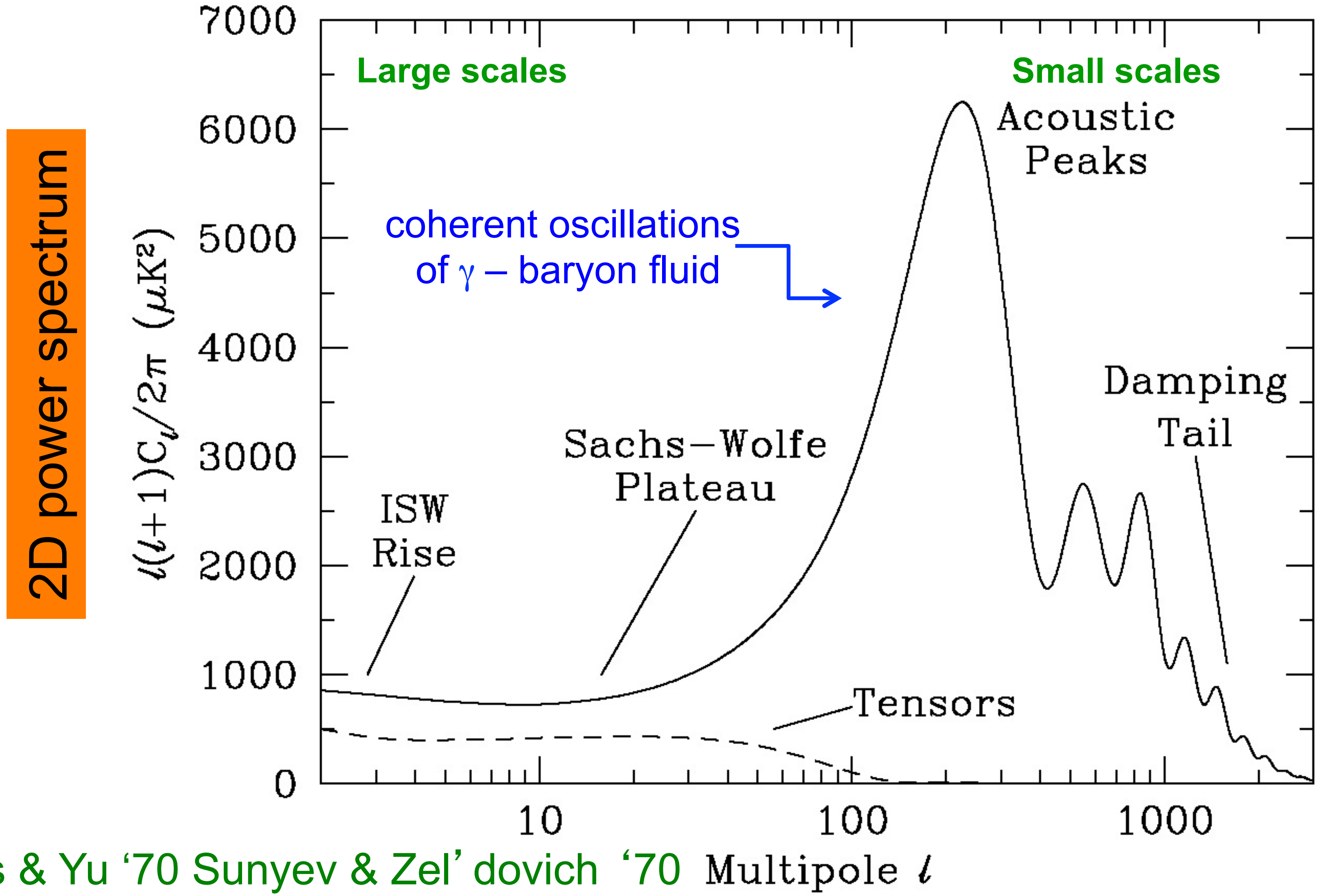


Planck collaboration ‘13

Institute for Computational Cosmology

Temperature anisotropies in CMB

University of Durham



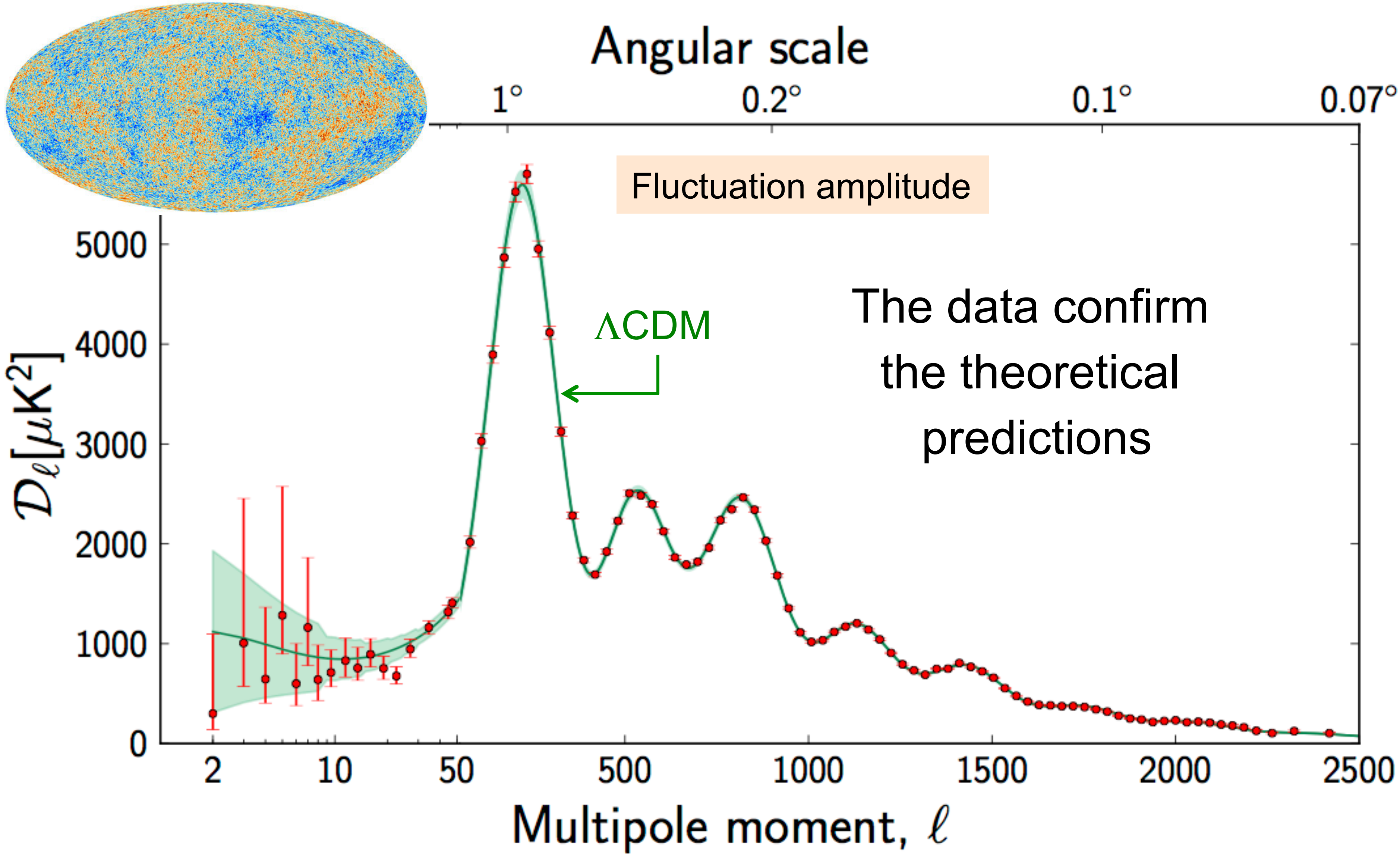
Peebles & Yu '70 Sunyev & Zel'dovich '70

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

Institute for Computational Cosmology

Planck: CMB temperature anisotropies

University of Durham



Planck coll. 2015

Univer

The six parameters of minimal ΛCDM model

6 model parameters

Parameter	*Planck*+WP Best fit	*Planck*+WP 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

Institute for Computational Cosmology

University of Durham

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

Hot dark matter

$m_\nu = 30$ ev → $\Omega = 1$

1981

HAS THE NEUTRINO A NON-ZERO REST MASS?*
(Tritium β-Spectrum Measurement)

V. Lubimov, E. Novikov, V. Nozik, E. Tretyakov
Institute for Theoretical and Experimental Physics, Moscow, U.S.S.R.

V. Kosik
Institute of Molecular Genetics, Moscow, U.S.S.R.

ABSTRACT

The high energy part of the β-spectrum of tritium in the v... molecule was measured with high precision by a toroidal β-spect... meter. The results give evidence for a non-zero electron anti-neutrino mass.

Fifty years ago Pauli introduced the neutrino to explain the β-spectrum shape. Pauli made the first estimate of the neutrino mass ($E_{3\,max} \cong$ nuclei mass defect): it should be very small or maybe zero. Up to now the study of the β-spectrum shape is the most sensitive, direct method of neutrino mass measurement.

For allowed β-transitions, if $M_\nu = 0$, then $S \simeq (E-E_0)^2$. The Kurie plot is then a straight line with the only kinematic parameter being $E_k = E_0$ (total β-transition energy). If $M_\nu \neq 0$, then $S \simeq (E_0-E)\sqrt{(E_0-E)^2-M_\nu^2}$. The Kurie plot is then distorted, especially near the endpoint.

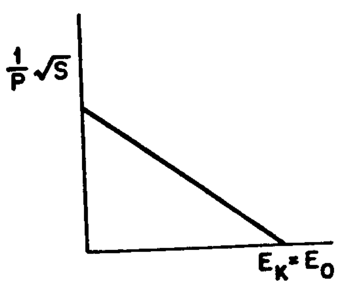


Fig. 1. Kurie plot for $M_\nu = 0$.

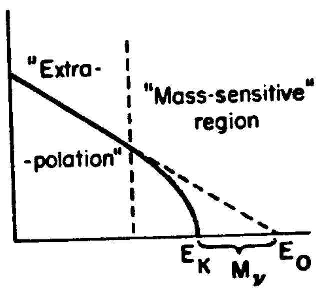
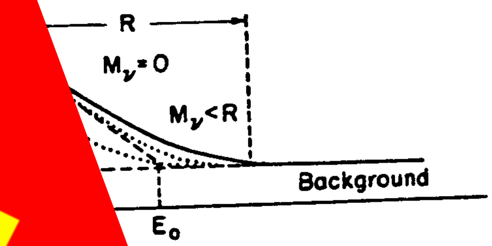


Fig. 2. Kurie plot for $M_\nu \neq 0$.

The method for the neutrino mass measurement is to obtain E_0 from the extrapolation and obtain E_k from the spectrum intercept. Then $M_\nu = E_0 - E_k$. Qualitatively, $M_\nu \neq 0$ if the β-spectrum near the end-point runs below the extrapolated curve.

*Paper presented by Oleg Egorov.

... things are more complicated. The apparatus reso-... ...rongly affects the spectrum endpoint and rather ...e spectrum slope.



...ealistic Kurie plot.

...extrapolation. However, we are unable ..., then once again the lack of counts near the ...indicate that $M_\nu \neq 0$. If $M_\nu \leq R$, the changes due to ...mass and the influence of R are indistinguishable. For M_ν ...ermination the knowledge of R is compulsory. The background determines the statistical accuracy near the endpoint, i.e., in the region of the highest sensitivity to the ν mass. So: 1) R should be $\sim M_\nu$, 2) the smaller M_ν is, the smaller the background ($\sim M_\nu^2$) must be and the higher the statistics ($\sim M_\nu^{-3}$) must be. For example, suppose that for $M_\nu = 100$ eV we need resolution R, background Q, and statistics N. If $M_\nu = 30$ eV, to achieve the same ΔM/M they should be R/3, Q/10, and N × 30, respectively.

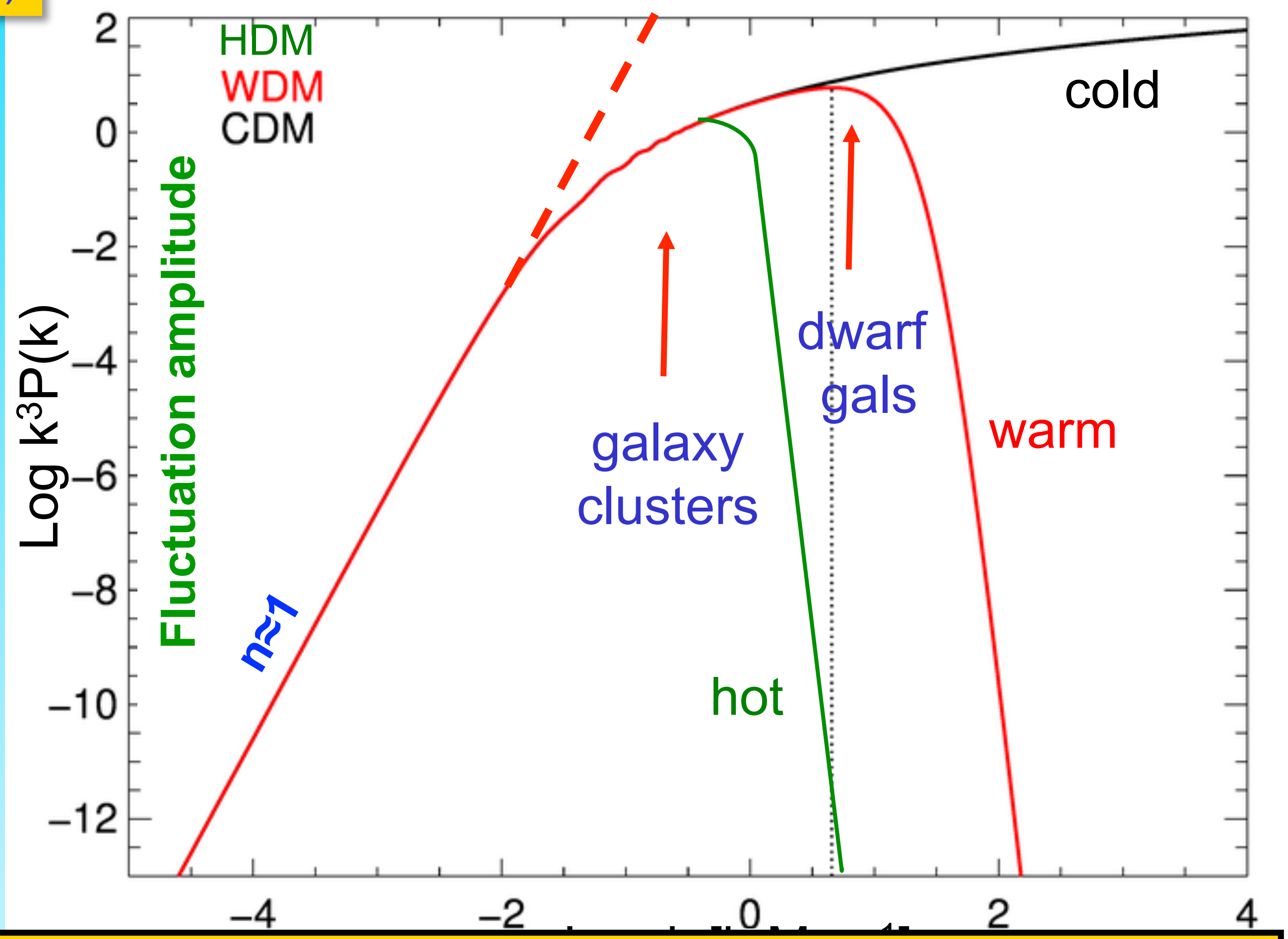
The shorter the β-spectrum, the less it is spread due to R (as $R \sim \Delta p/p$ = const.). A classical example is ^3H β-decay, which has 1) the smallest $E_0 \sim 18.6$ keV, 2) an allowed β-transition, simple nucleus, and simple theoretical interpretation, 3) highly reduced radioactivity. The first experiments with ^3H were by S. Curran et al. (1948) and G. Hanna, B. Pontecorvo (1949). Using ^3H gas in a proportional counter, they obtained $M_\nu \leq 1$ keV. Further progress required magnetic spectrometer development. This allowed the resolution to be improved considerably, and L. Langer and R. Moffat (1952) obtained $M_\nu \leq 250$ eV. The best value was obtained by K. Bergkvist (1972): $R \sim 50$ eV and $M_\nu \leq 55$ eV.

The ITEP spectrometer is of a new type: ironless, with toroidal magnetic field (E. Tretyakov, 1973). The principle of the toroidal magnetic field focusing systems was proposed by V. Vladimirsky et al. (An example is a "Horn" of ν-beams.) It turns out that a rectilinear conductor (current) has a focusing ability for particles emitted perpendicular to the rotation axis. This system has infinite periodical focusing structure. The ITEP spectrometer is based on this principle.

The dark matter power spectrum

University of Durham

k³ P(k) The linear power spectrum ("power per octave")



Free streaming →

λ_{cut} α m_x^{-1}

for thermal relic

m_{CDM} ~ 100GeV

susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV

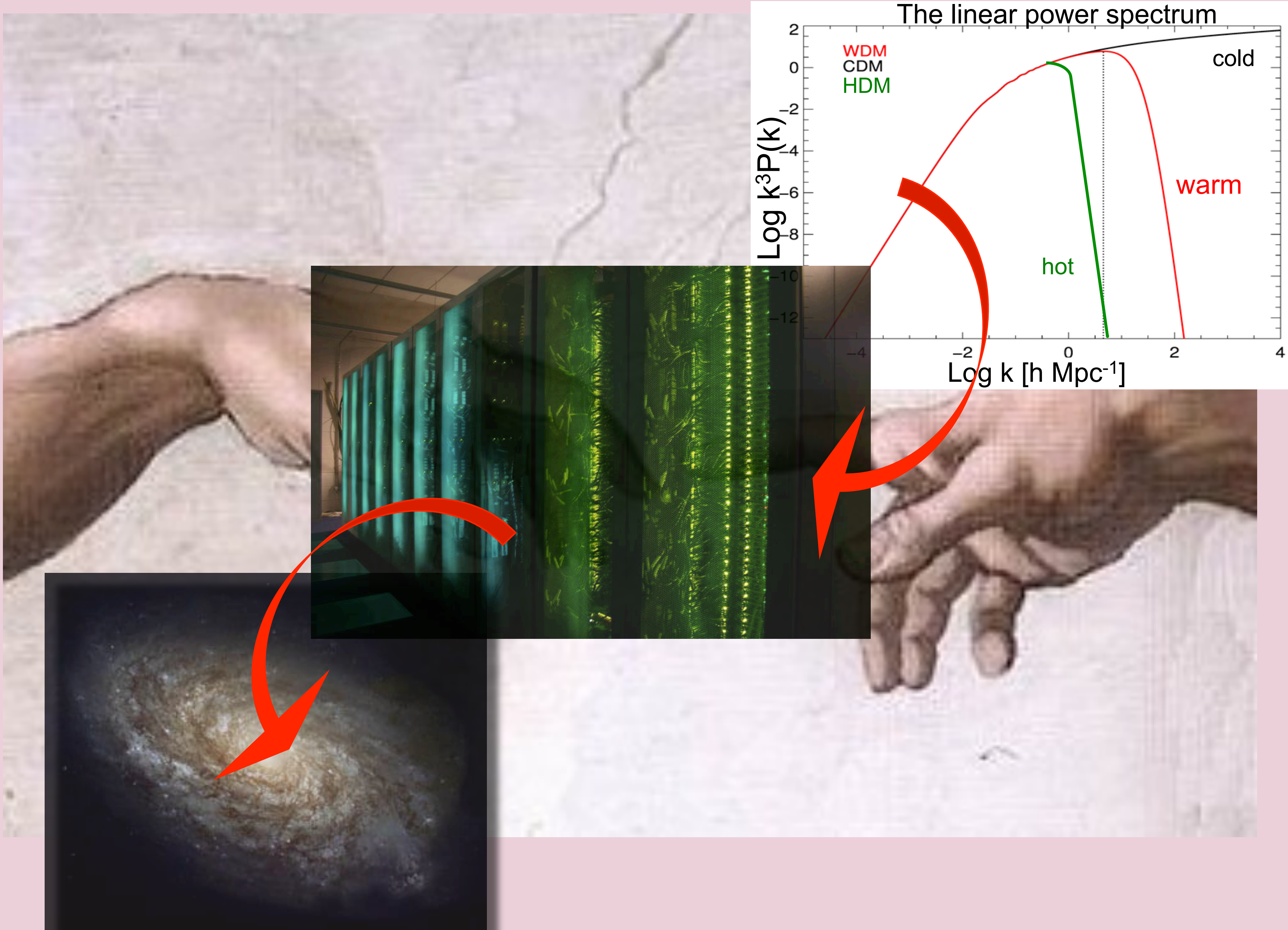
sterile ν; M_{cut}~10^9 M_o

m_{HDM} ~ few tens eV

light ν; M_{cut}~10^{15} M_o

These possibilites can be tested with astrophysics

Non-linear evolution



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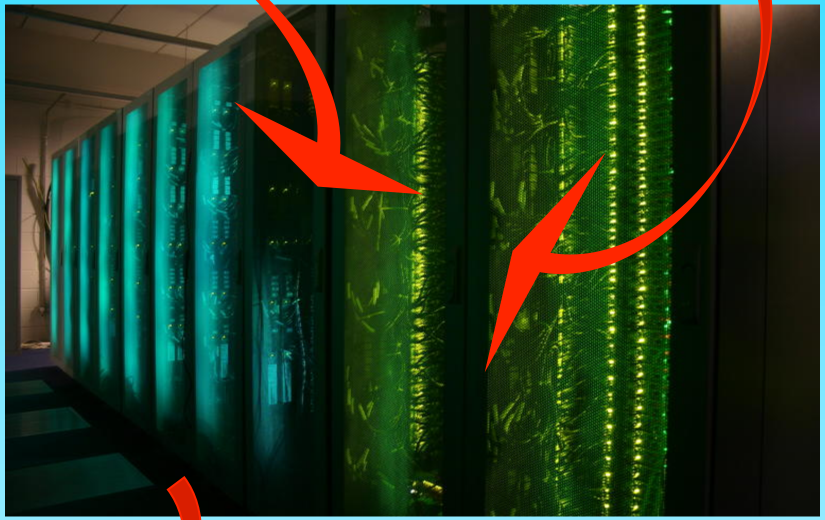
University of Durham

Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

Relevant equations:

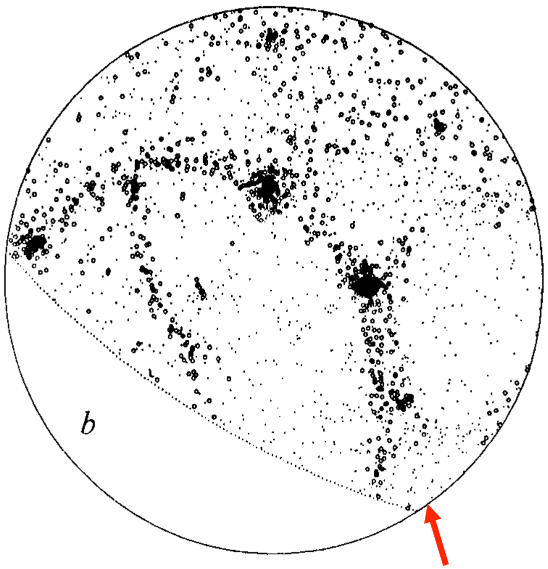
Collisionless Boltzmann,
Poisson, Friedmann eqn,
Radiative hydrodynamics
Astrophysics (subgrid)



How to make a virtual universe

Non-baryonic dark matter cosmologies

University of Durham



Neutrinos
Ω=1

Frenk, White & Davis '83

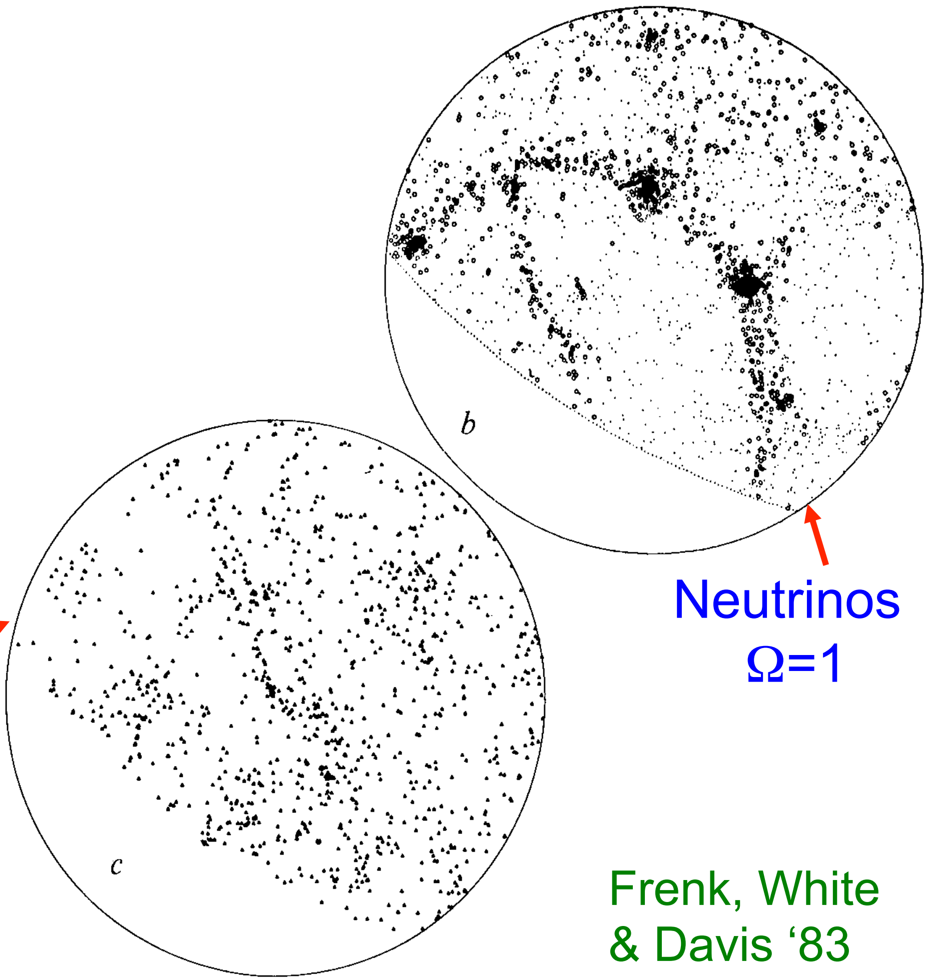
Non-baryonic dark matter cosmologies

University of Durham

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 30 ev



CfA redshift survey

Neutrinos
Ω=1

Frenk, White & Davis '83

Non-baryonic dark matter cosmologies

University of Durham

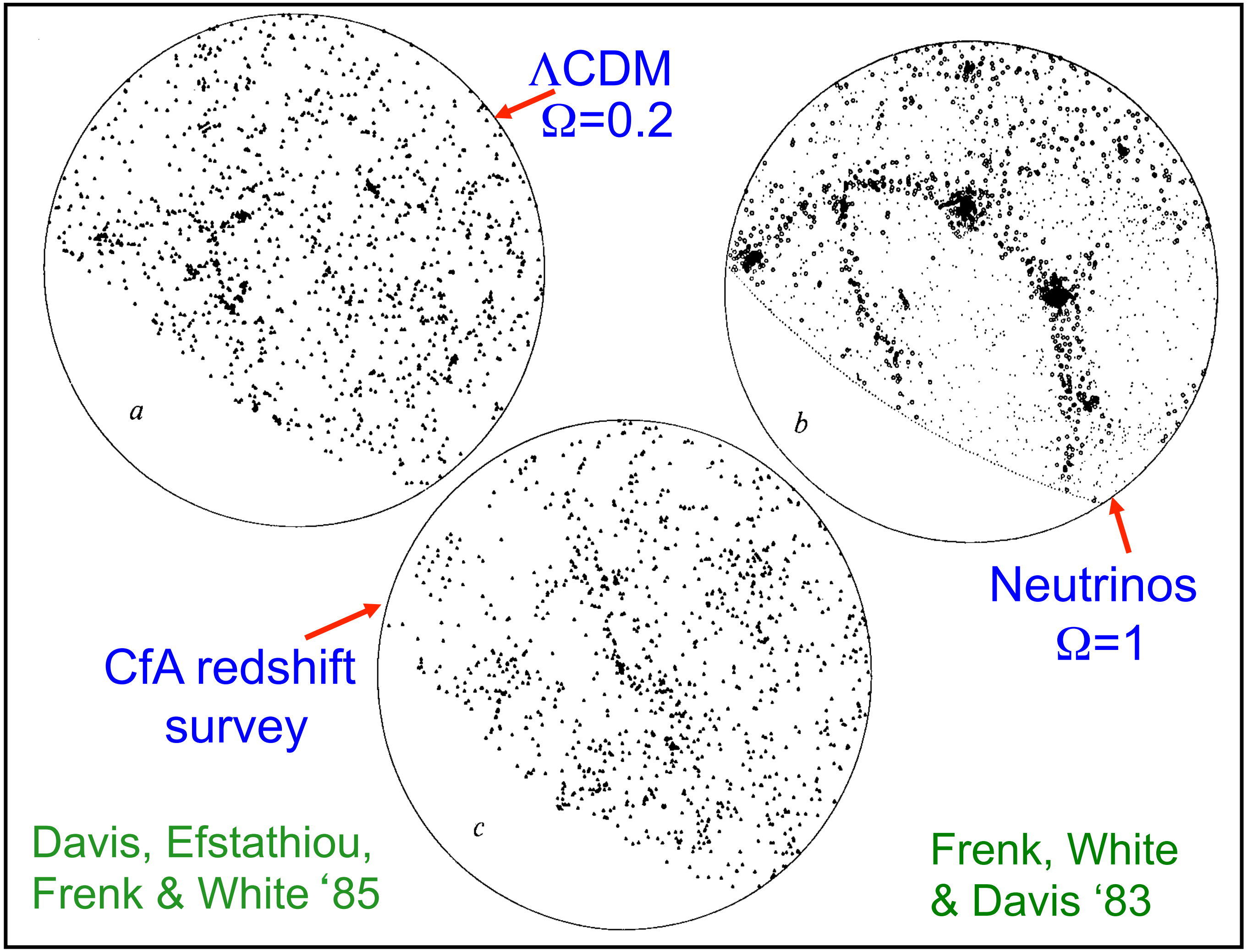
Neutrino DM → wrong clustering

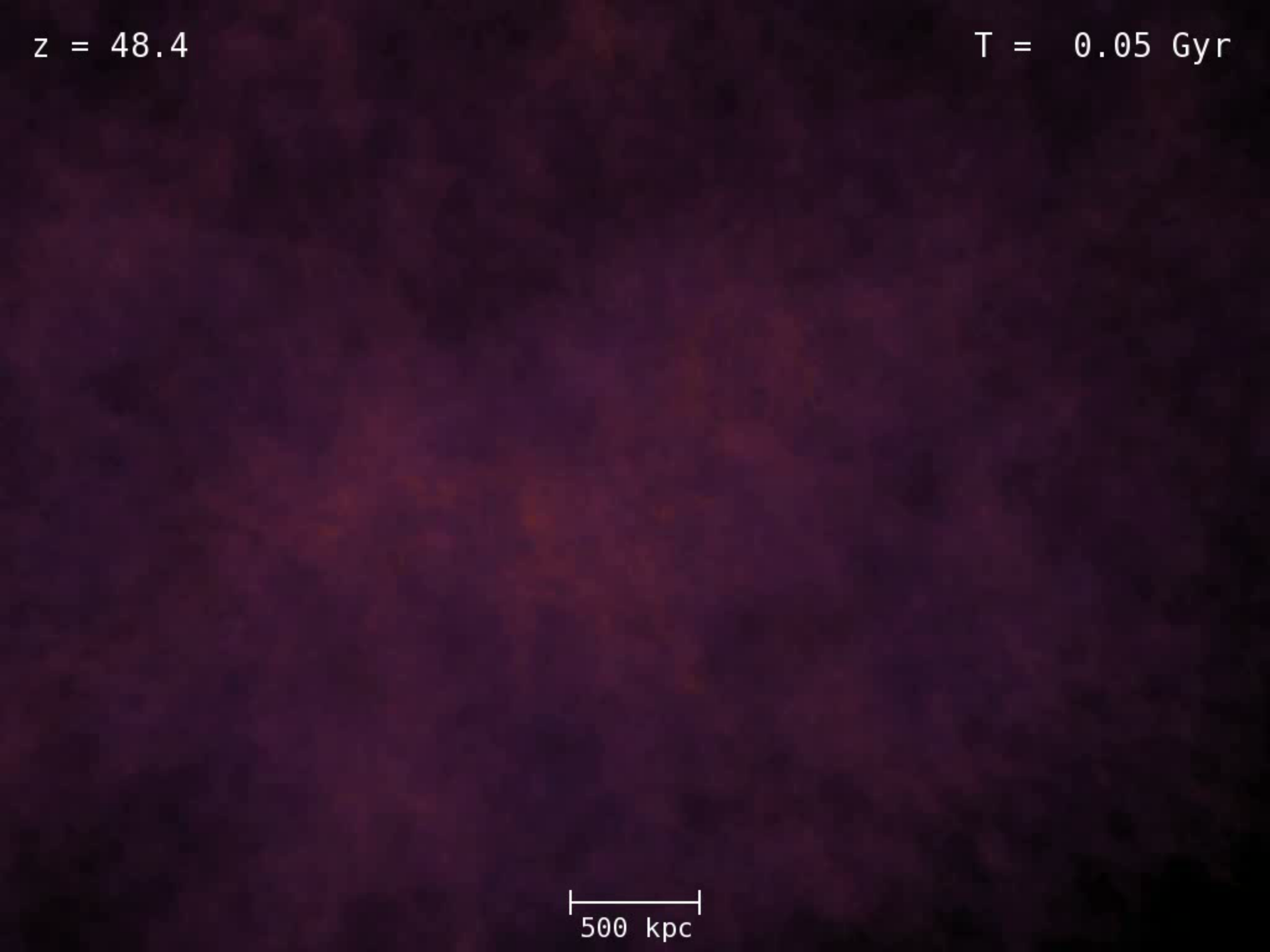
Neutrinos cannot make appreciable contribution to Ω

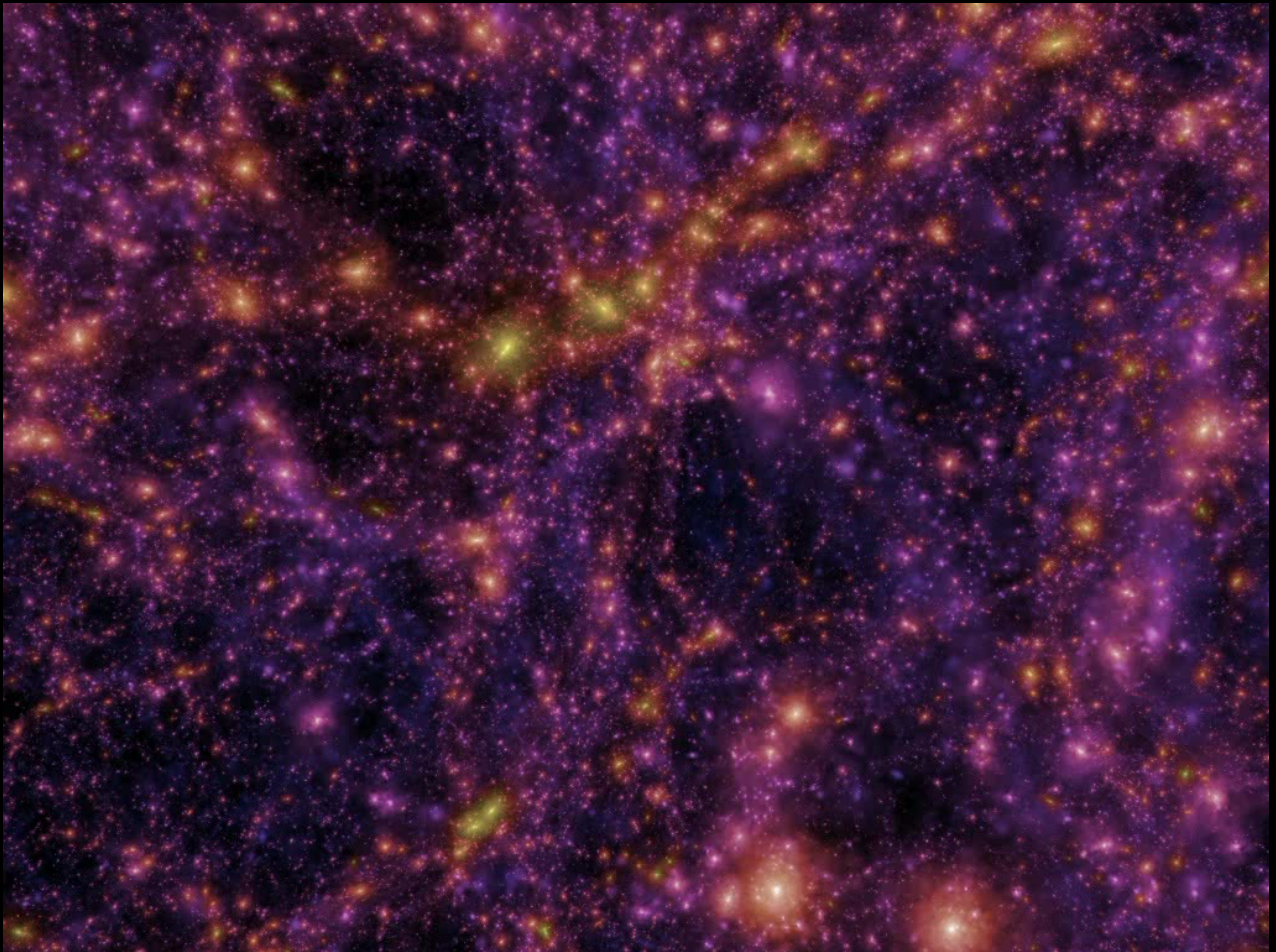
→ $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

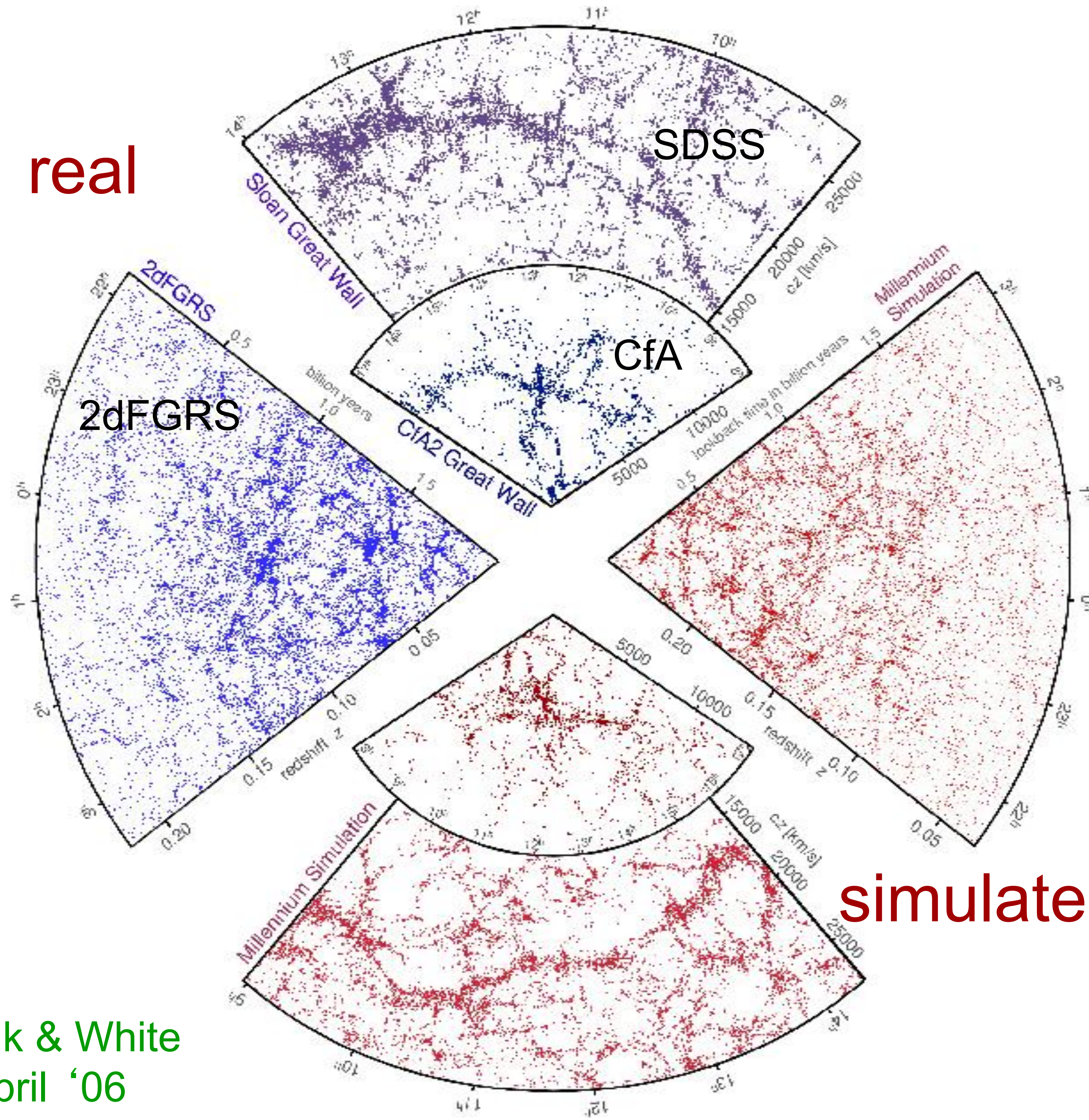
In CDM structure forms hierarchically




z = 48.4
T = 0.05 Gyr
500 kpc



real



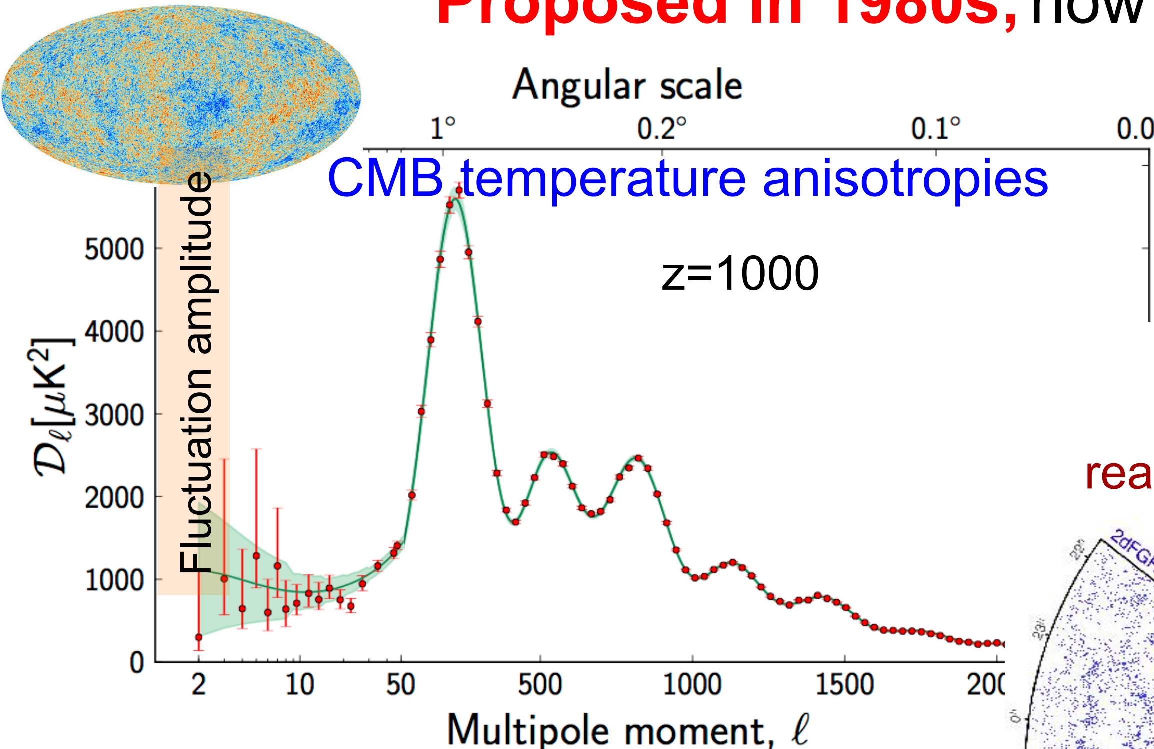
simulated

Springel, Frenk & White
Nature, April ‘06

University of Durham

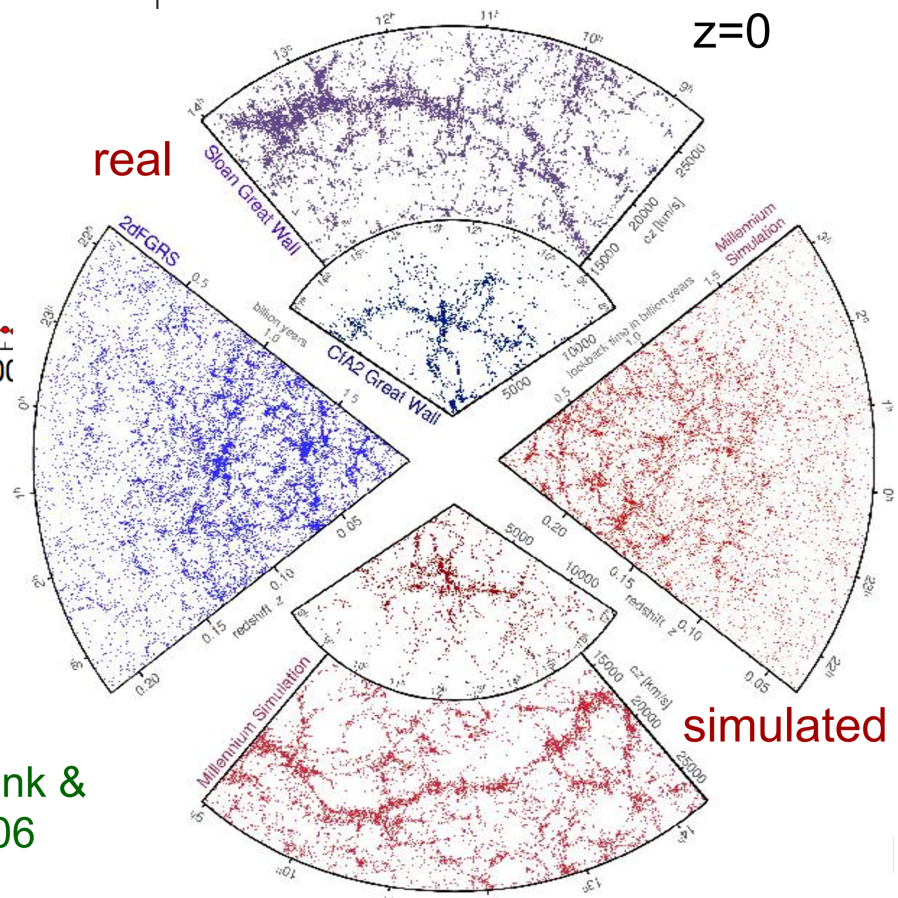
The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:



Planck coll. 2015

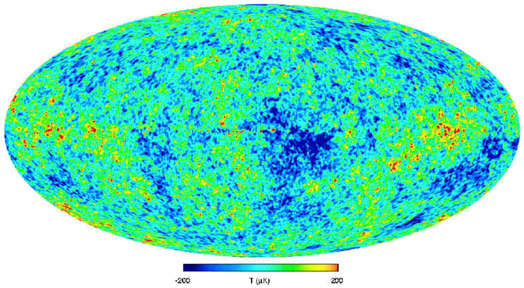
Galaxy clustering



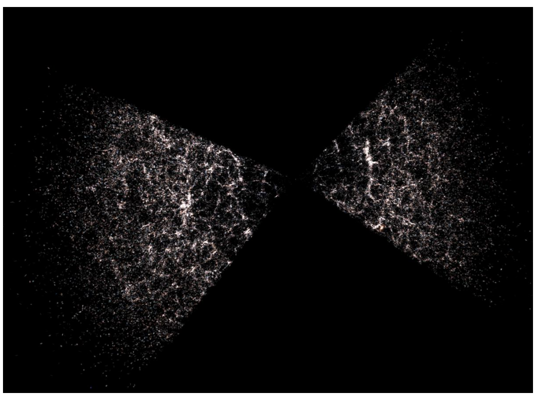
Springel, Frenk & White 2006

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

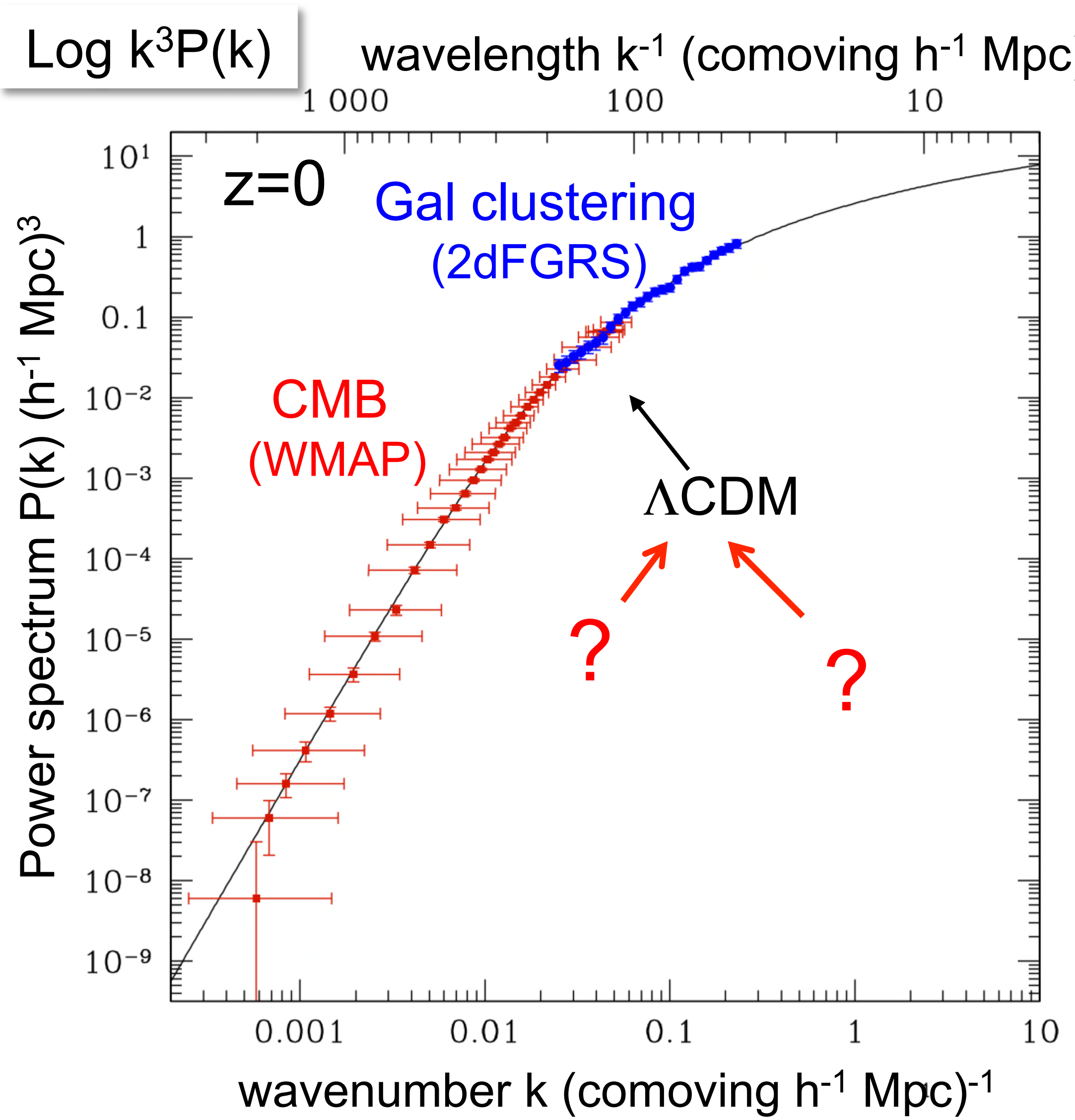
University of Durham



z~1000



z~0



⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

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University of Durham

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

Free streaming →

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

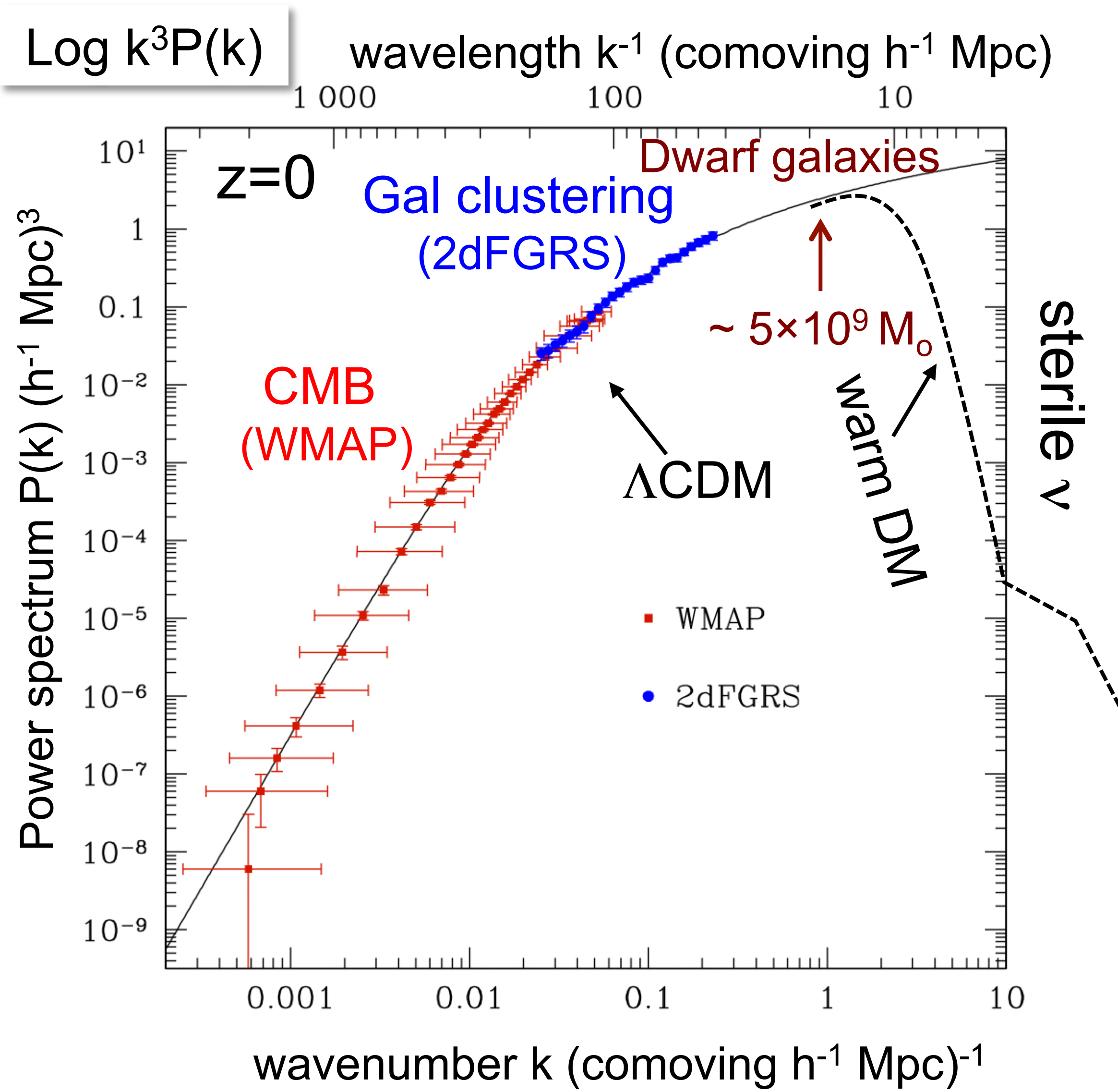
for thermal relic

$m_{CDM} \sim 100$GeV

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$



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

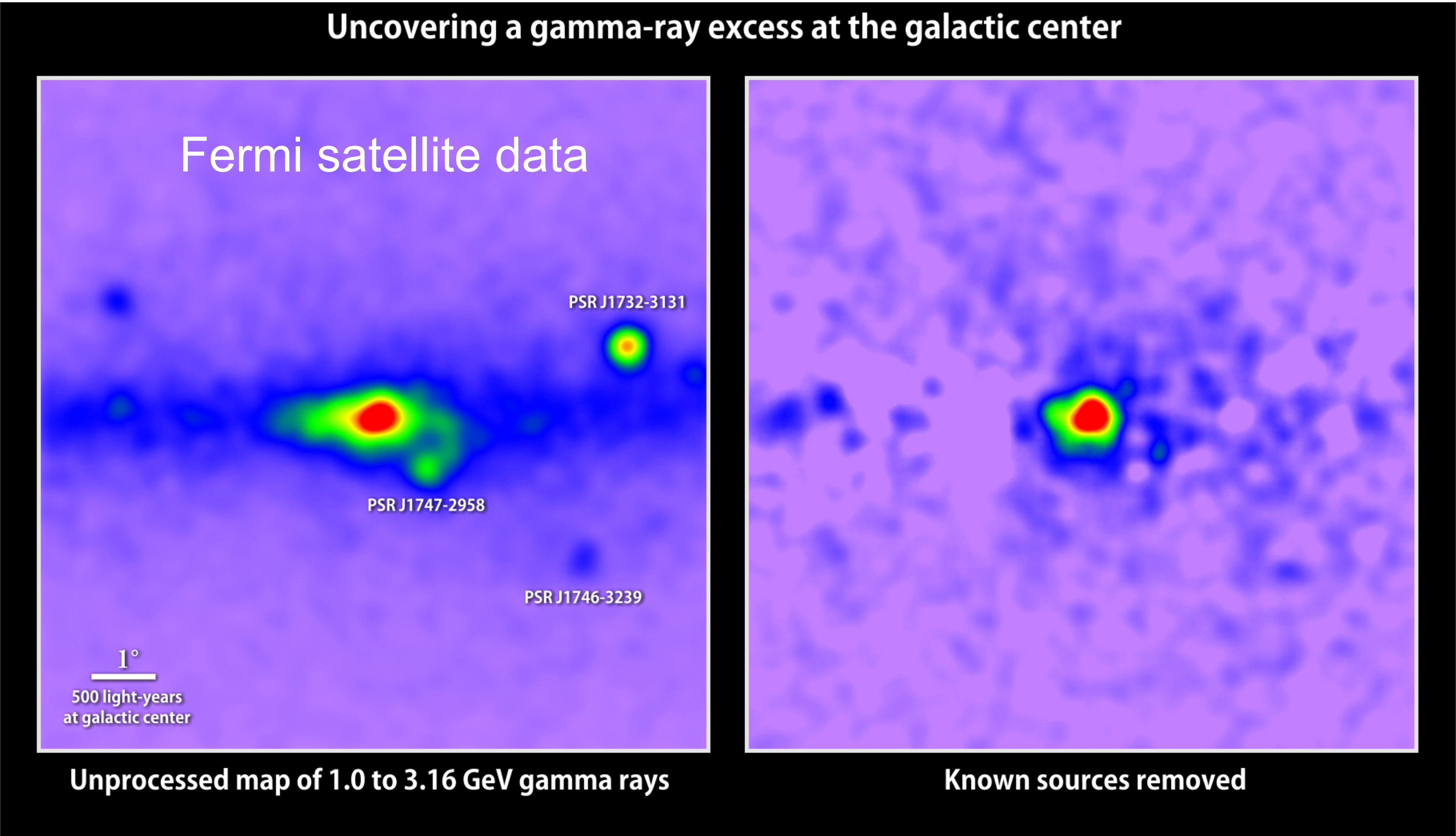
Claims that both types of DM have been discovered:

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

Cold dark matter

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

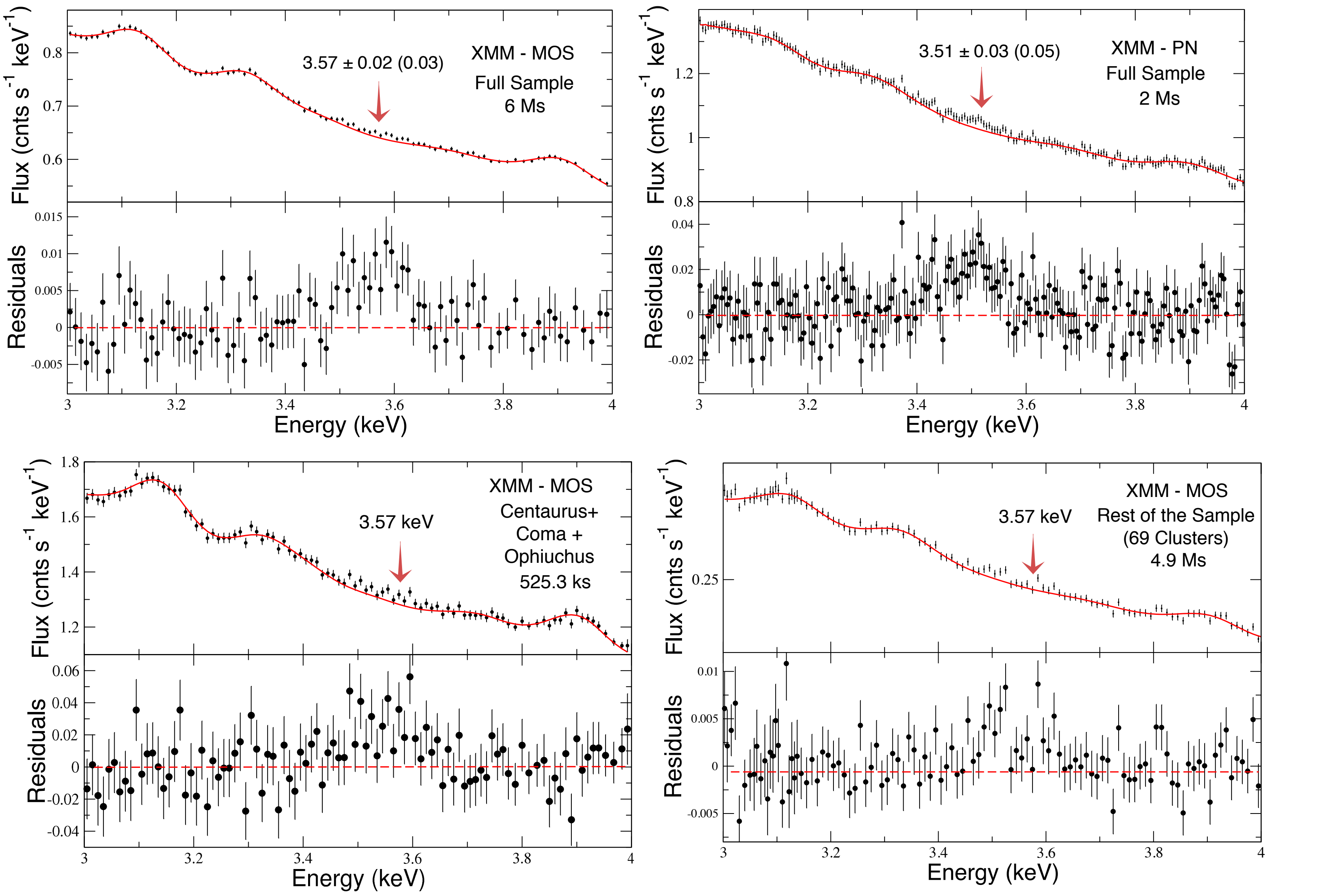
Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]



Warm dark matter
WDM decay line in 69 stacked clusters?

University of Durham

E=3.57 keV   Bulbul et al. '14   See also Boyarsky et al. '14



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 search for dark matter

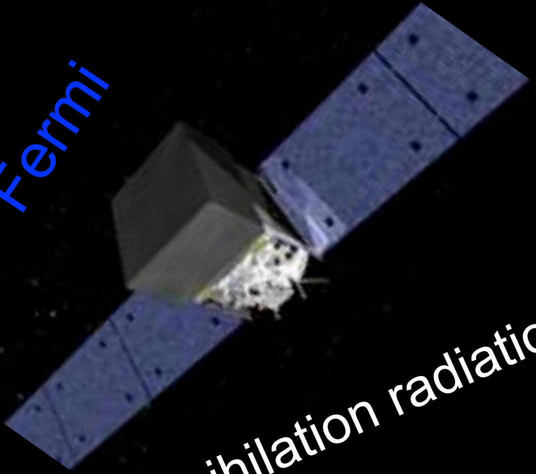
Dark matter discovery possible in several ways

Direct detection

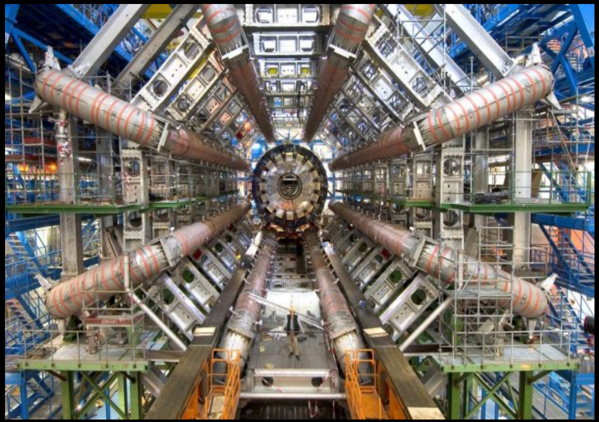
UK DM search
(Boulby mine)

CDM

Fermi



Annihilation radiation



Evidence for SUSY

Institute for Computational Cosmology

The search for dark matter

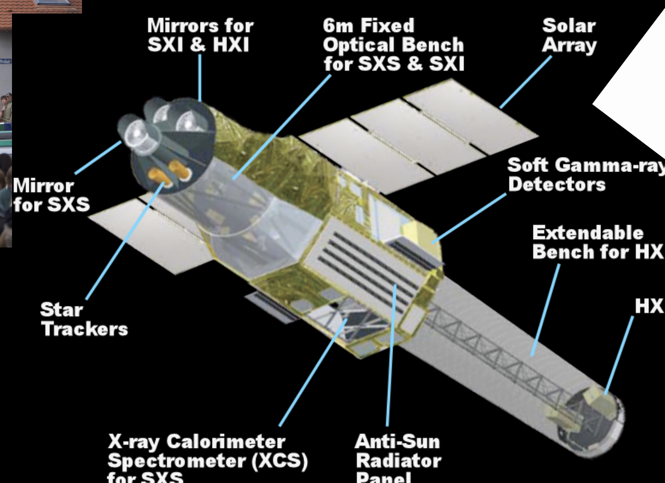
Dark matter discovery possible in several ways

WDM (sterile neutrino)

Measure the sterile ν mass

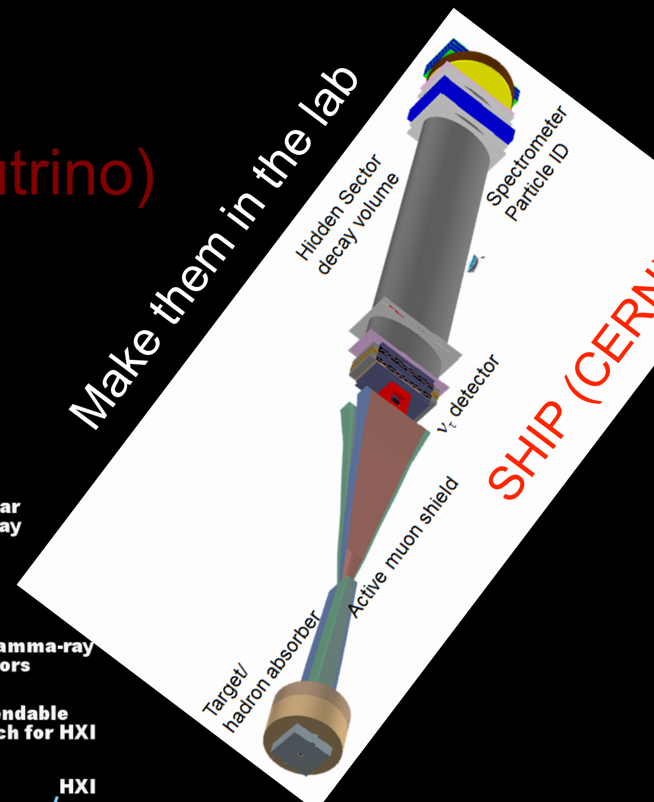
Katrina

X-ray decay line



XARM

Make them in the lab



SHIP (CERN)

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

(strongly non-linear regime)

Cold Dark Matter

Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

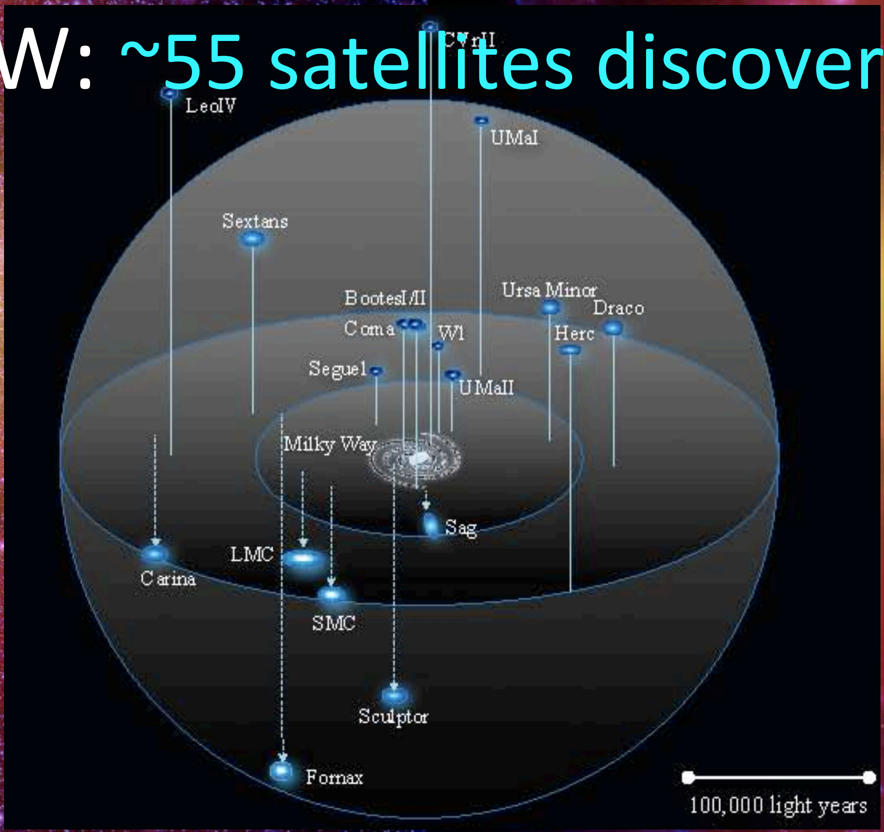
cold dark matter | warm dark matter

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

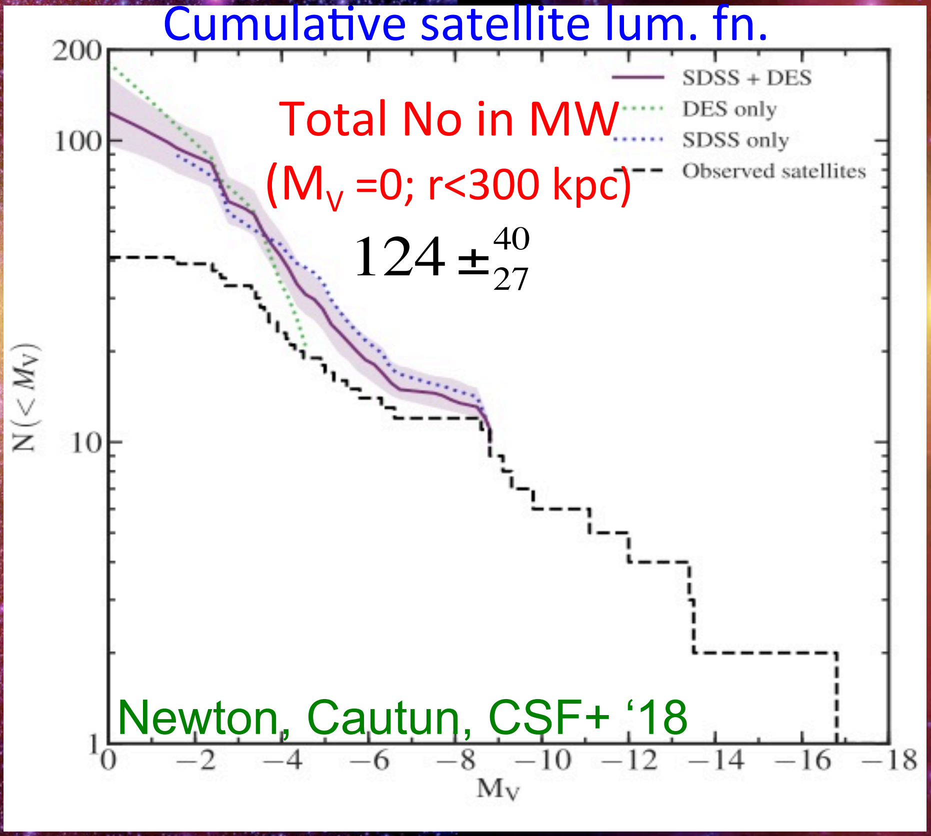
In the MW: ~55 satellites discovered so far



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



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

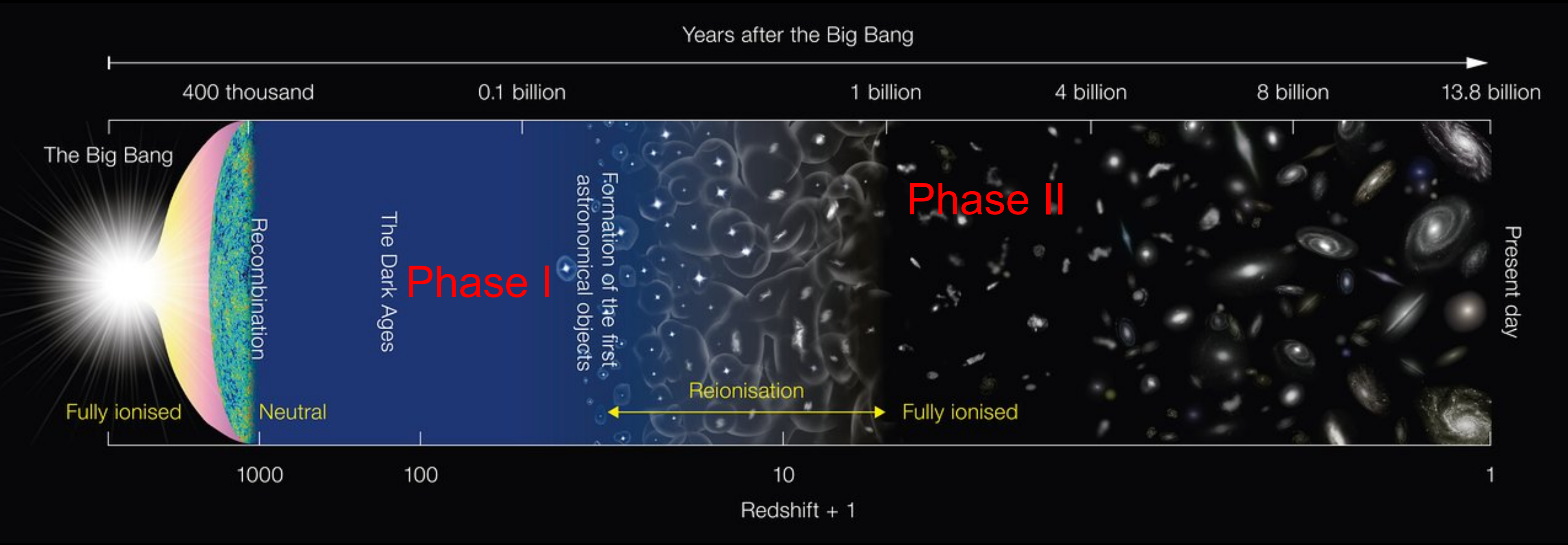
Obvious test: count satellites in MW or M31

This argument is WRONG!

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


Most subhalos never make a galaxy!

The two phases of galaxy formation



Phase 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

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

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Evolution of baryons

ICC University of Durham

Basic differential equations of Durham SA model:

Mass conservation

$$
\begin{aligned}
\dot{M}_{\star} &= (1-R)\psi \\
\dot{M}_{\rm hot} &= -\dot{M}_{\rm cool} + \beta\psi \\
\dot{M}_{\rm cold} &= \dot{M}_{\rm cool} - (1-R+\beta)\psi
\end{aligned}
$$

Conservation of metals

$$
\begin{aligned}
\dot{M}^{Z}_{\star} &= (1-R)Z_{\rm cold}\psi \\
\dot{M}^{Z}_{\rm hot} &= -\dot{M}_{\rm cool}Z_{\rm hot} + (pe + \beta Z_{\rm cold})\psi \\
\dot{M}^{Z}_{\rm cold} &= \dot{M}_{\rm cool}Z_{\rm hot} \\
&+ (p(1-e) - (1+\beta-R)Z_{\rm cold})\psi,
\end{aligned}
$$

R = recycled fraction

ψ = star formation rate

β = SN feedback parameter

p = metal yield

e = fraction of metals ejected

White & Frenk '91

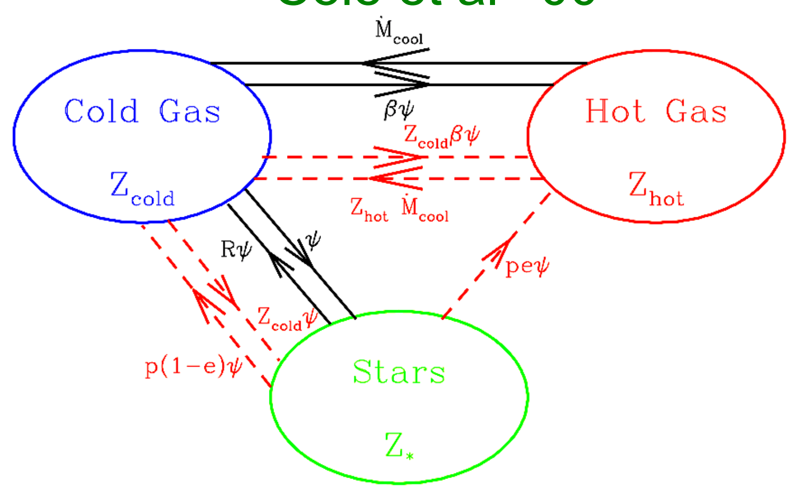
Cole et al '00

SFR & mass ejection

SFR $$\psi = \frac{M_{\rm cold}}{\tau_{\star}(r_{\rm disk}, V_{\rm disk})}$$

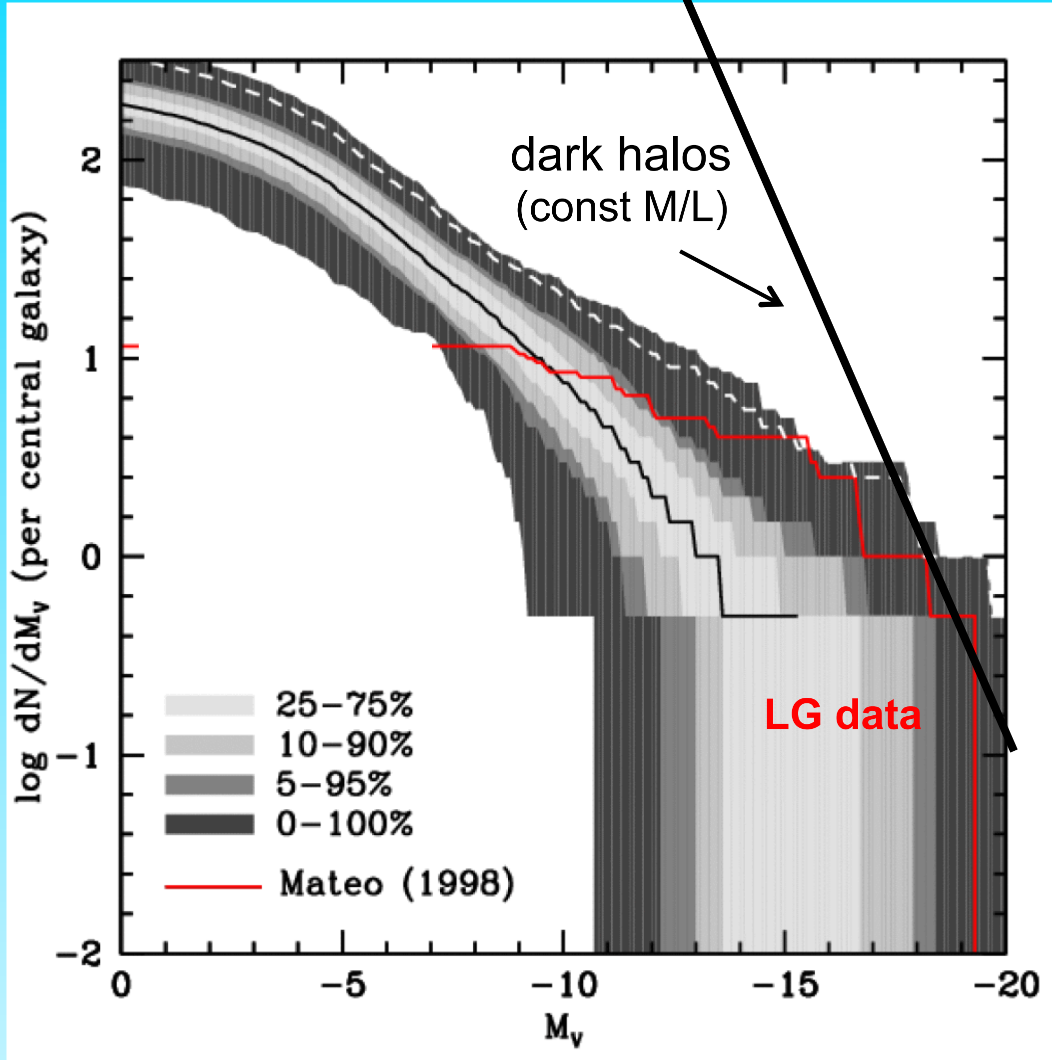
SN feedback $$\dot{M}_{\rm eject} = \beta(V_{\rm disk})\,\psi$$

AGN feedback $$\dot{M}_{BH} = f_{BH}\psi_{burst} + \frac{L_{cool}}{c^2\varepsilon_{SMBH}}$$



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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Luminosity Function of Local Group Satellites

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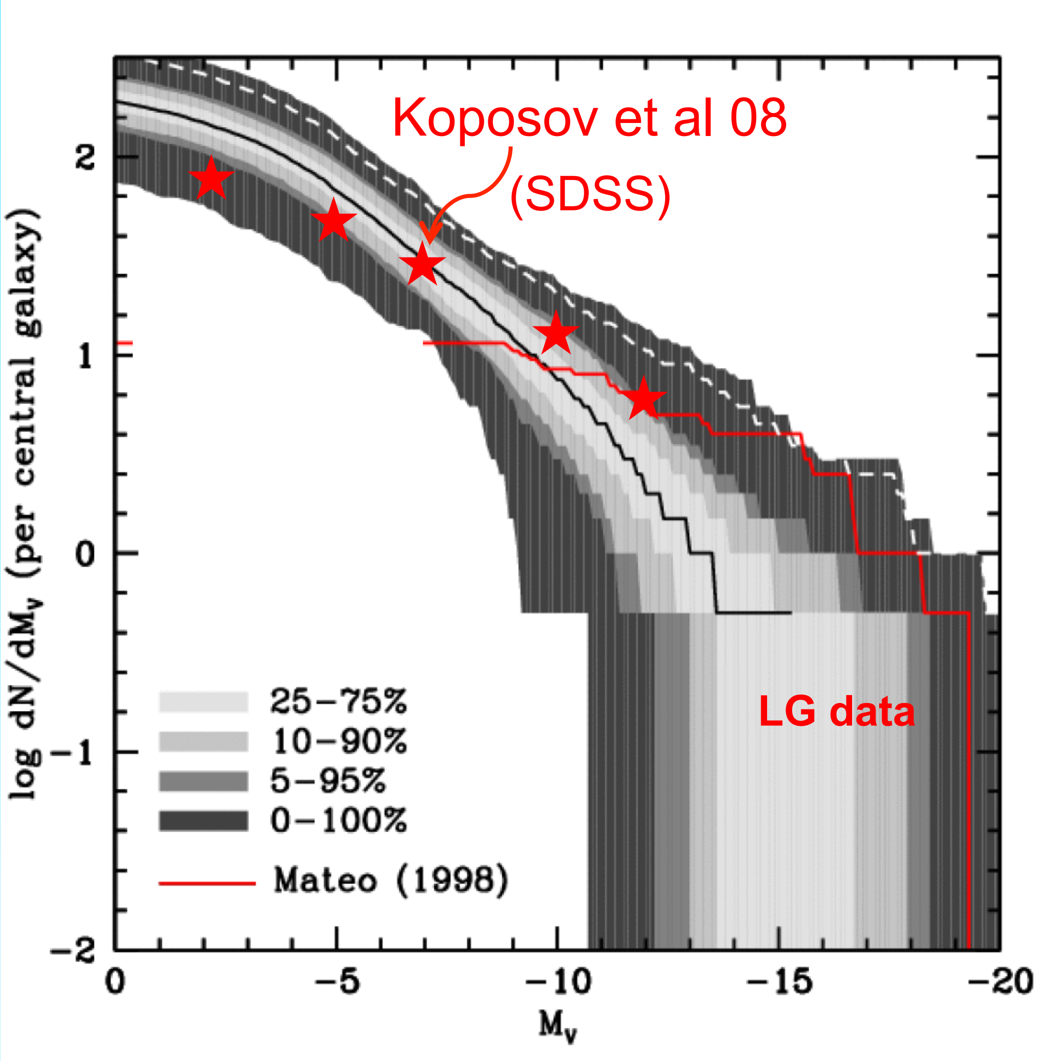


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

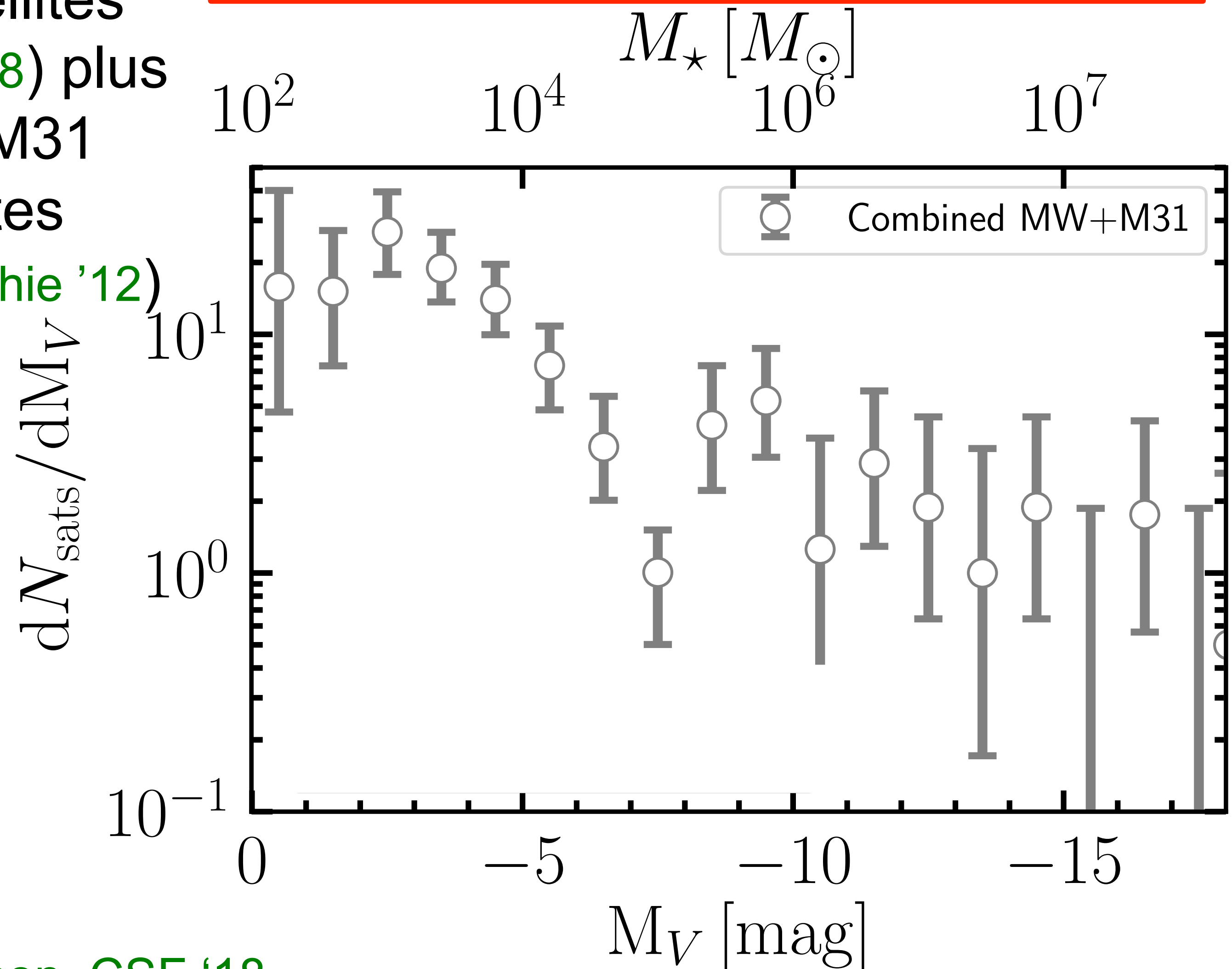
An aside: have the first galaxies been discovered?

The MW/M31 sat. luminosity function

University of Durham

Differential satellite luminosity function

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



Bose, Deason, CSF '18

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The satellite luminosity function

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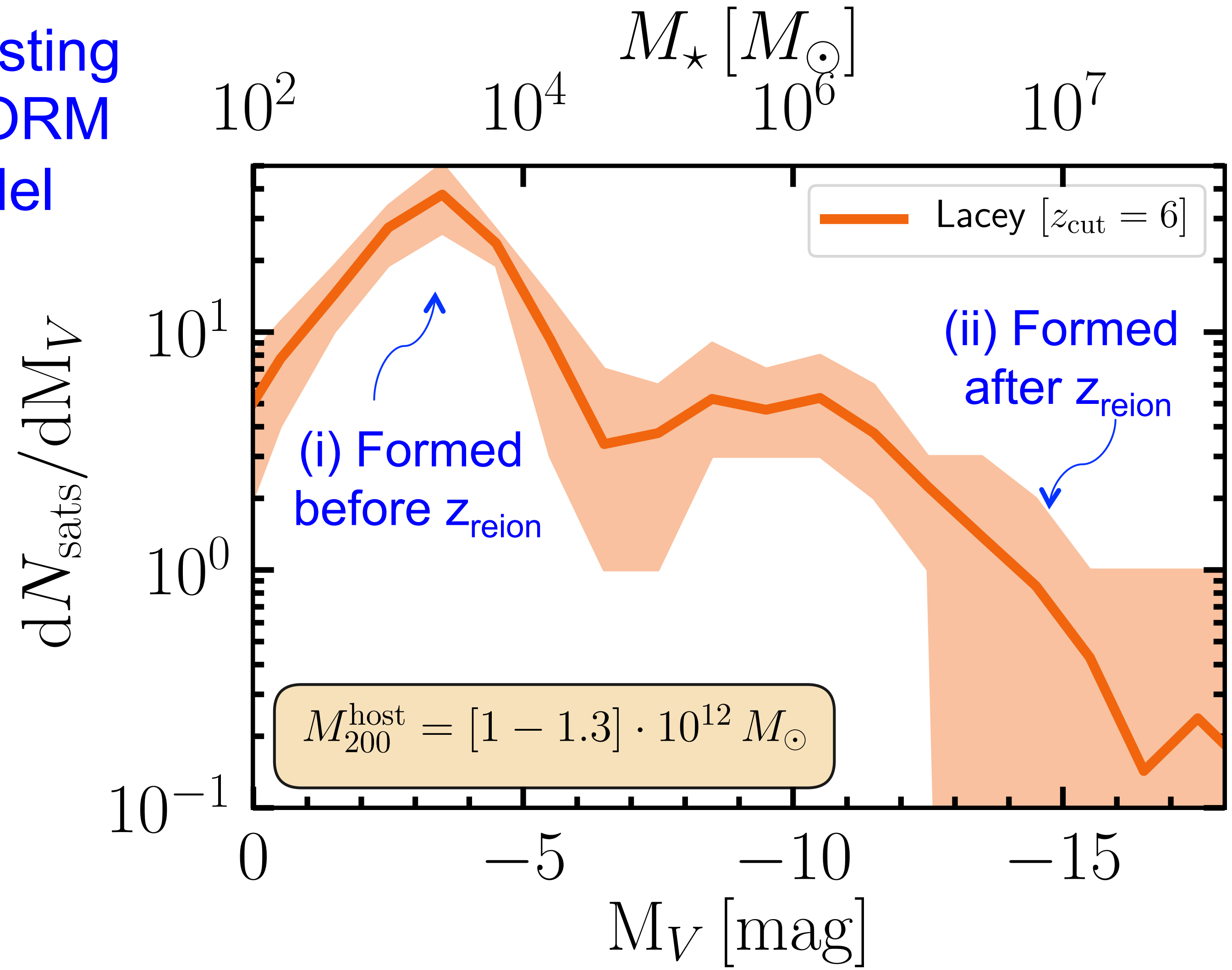
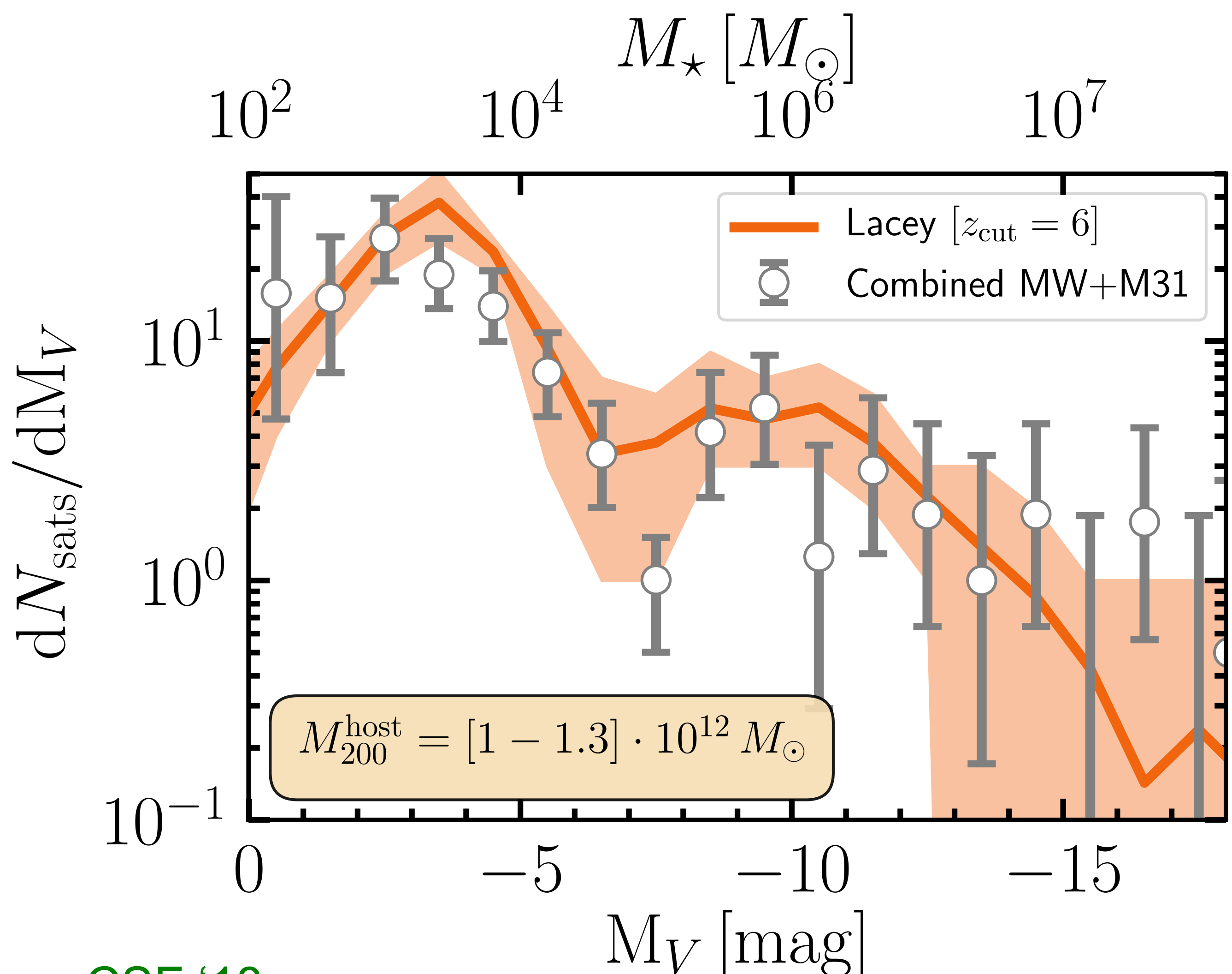
Two populations of sats formed: (i) before and (ii) after reionization

Pre-existing GALFORM model



Theory *vs* data



Bose, Deason, CSF '18

VIRGO

icc.dur.ac.uk/Eagle

"Evolution and assembly of galaxies and their environment"

THE EAGLE PROJECT

Virgo Consortium

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

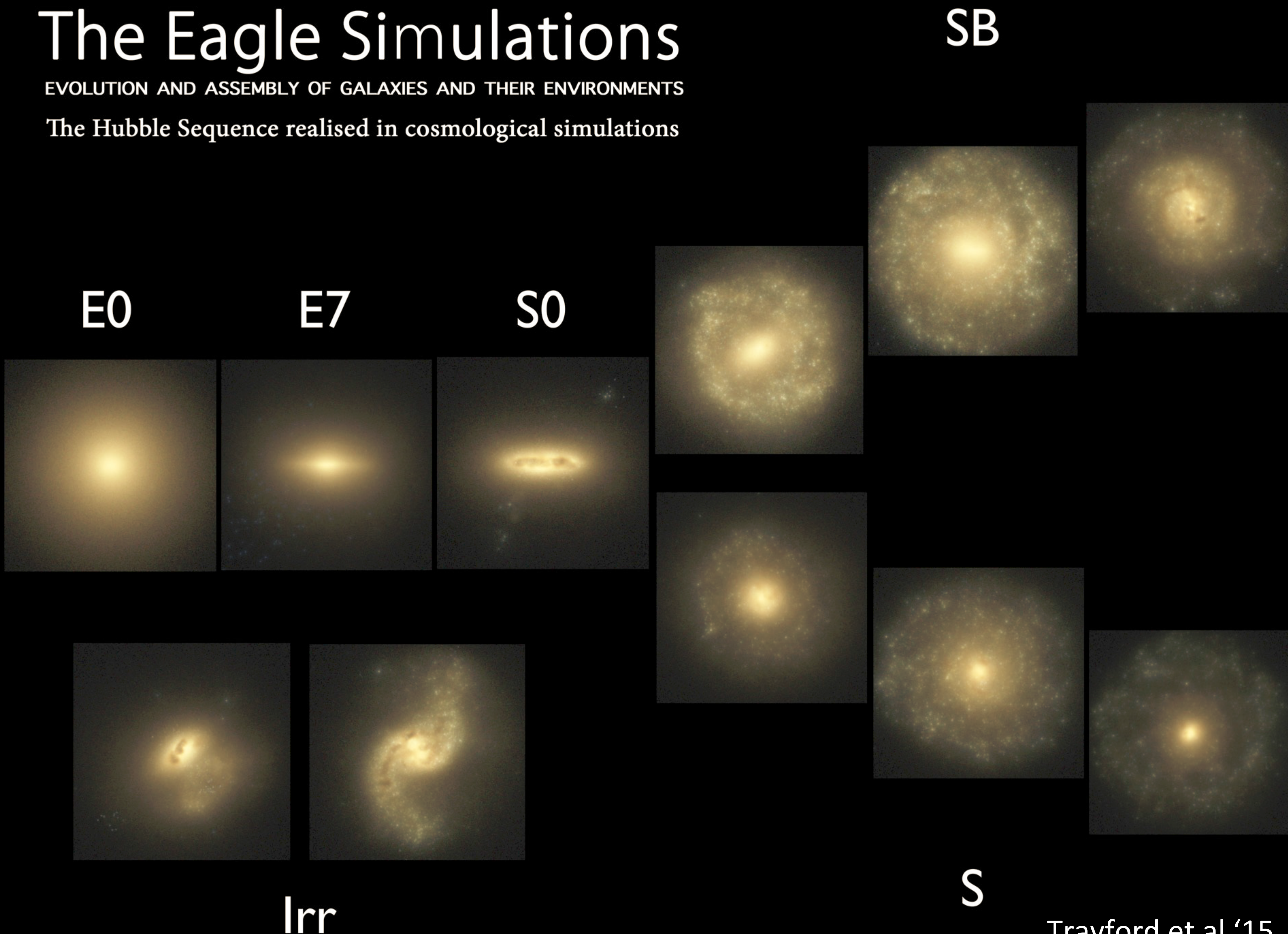
Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

The EAGLE 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



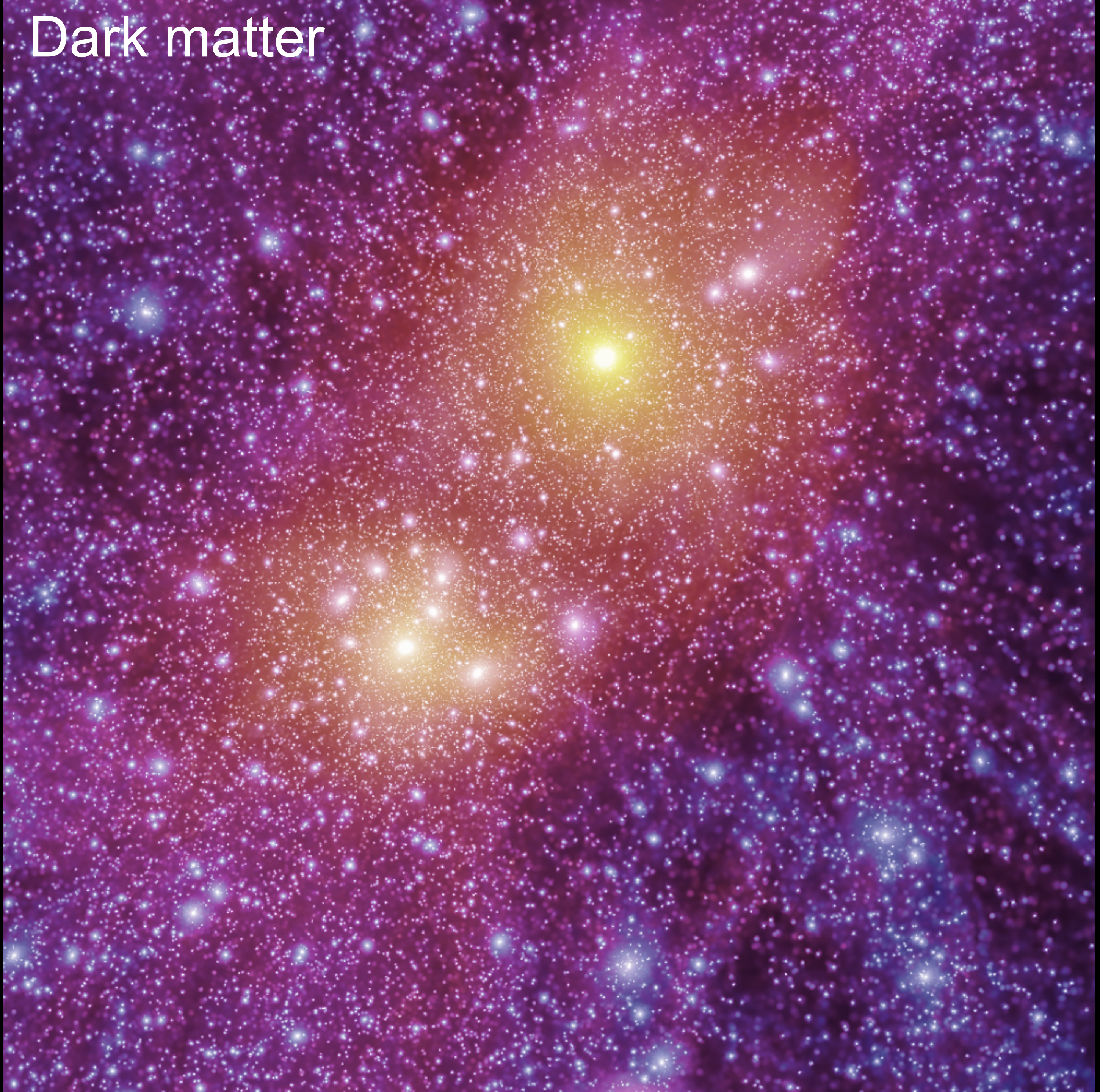
Trayford et al ‘15

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16

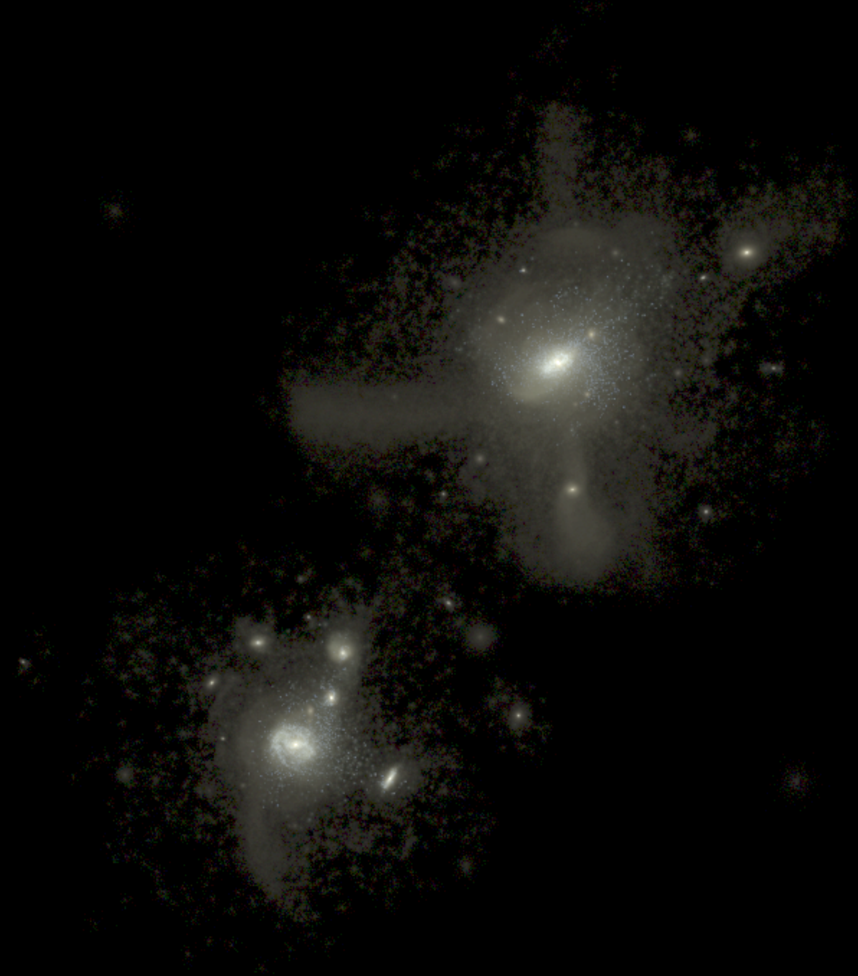


Stars

APOSTLE
EAGLE full hydro simulations

Local Group

Stars

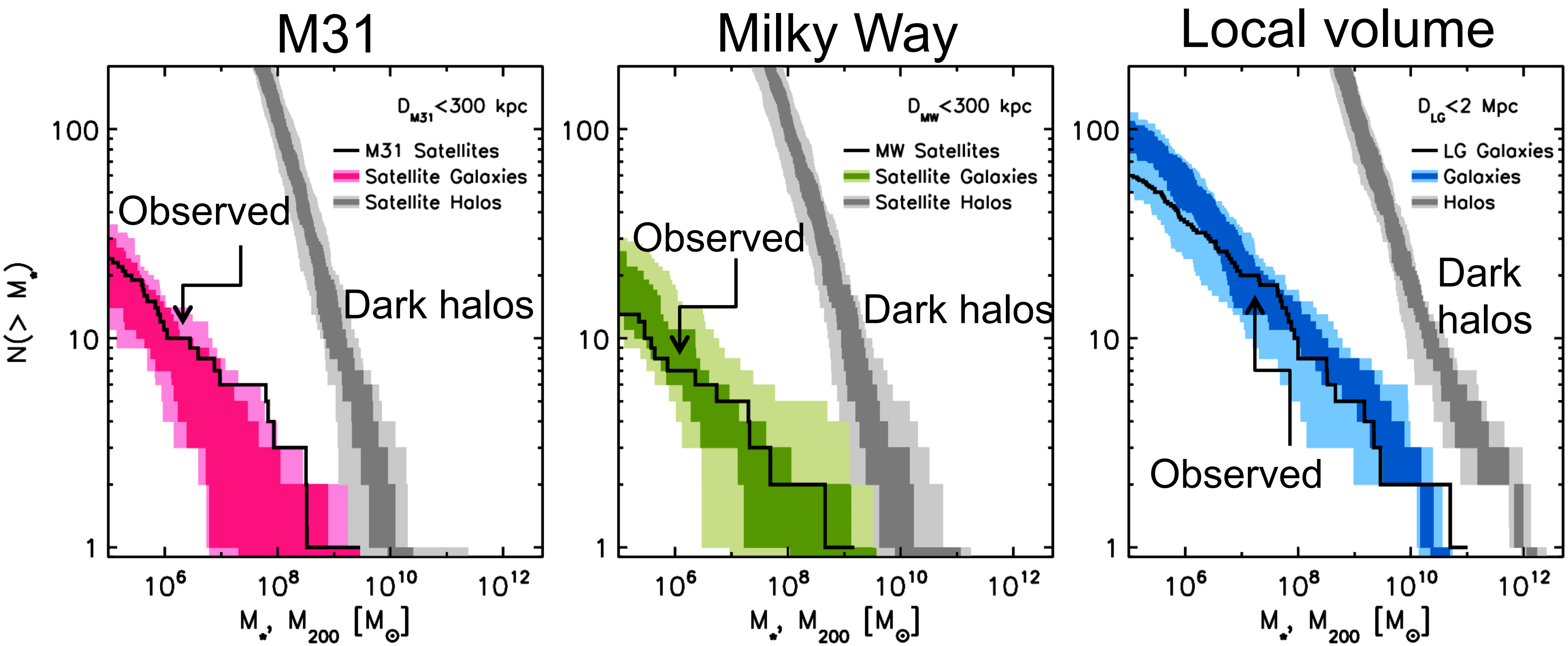


Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

EAGLE Local Group simulation

University of Durham



Sawala, CSF et al ‘16

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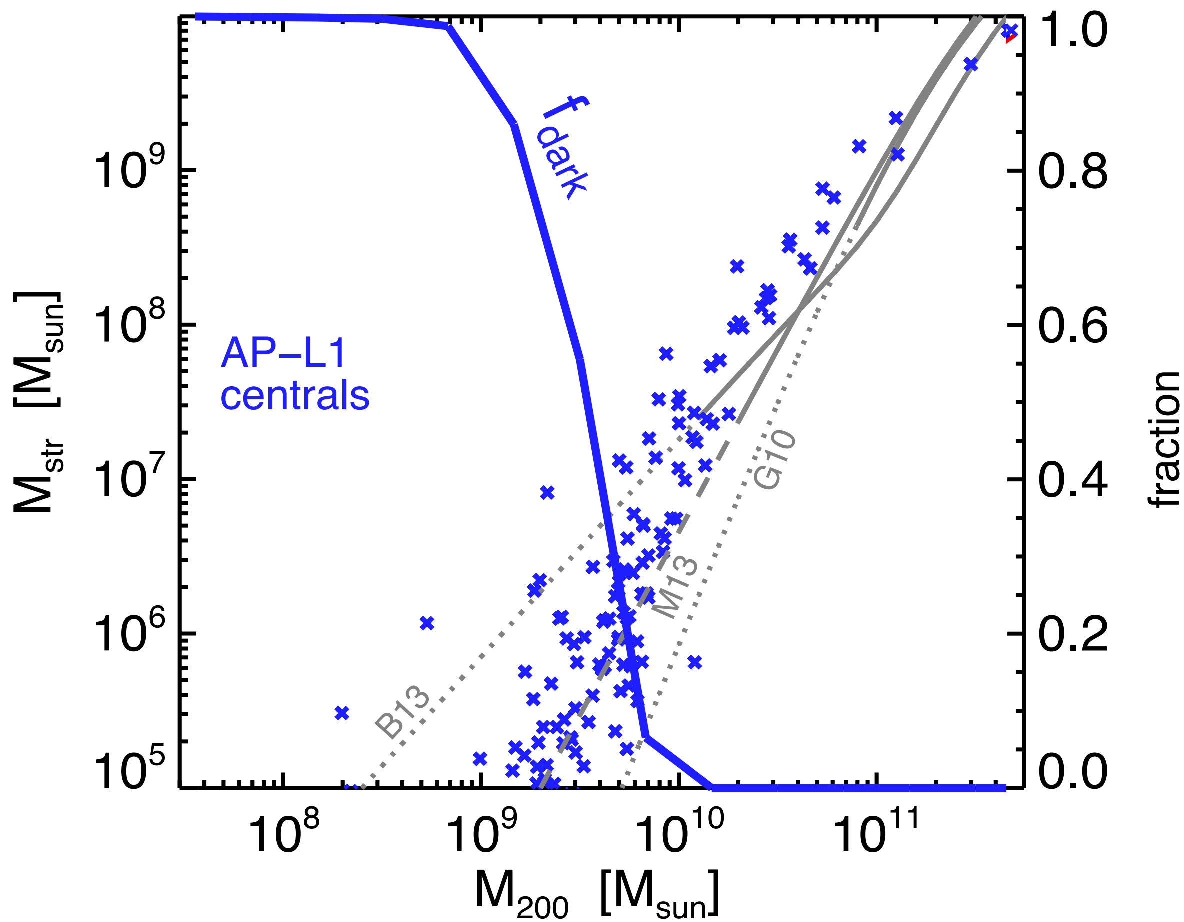
Fraction of dark subhalos

University of Durham

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

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



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

Fattahi, CSF et al '19

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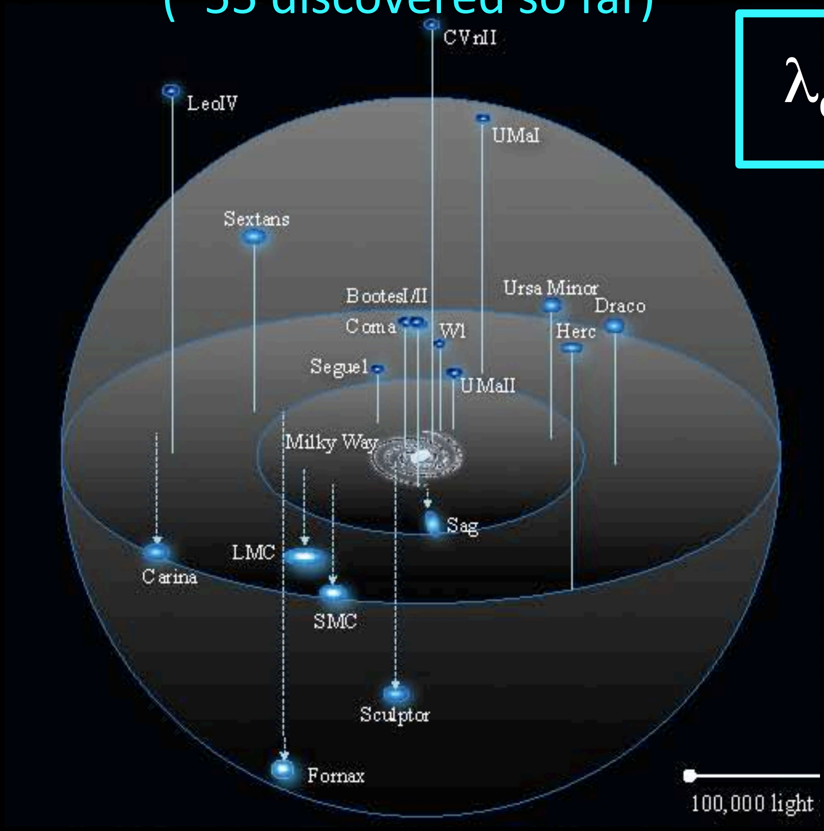
How about in WDM?

The satellites of the MW

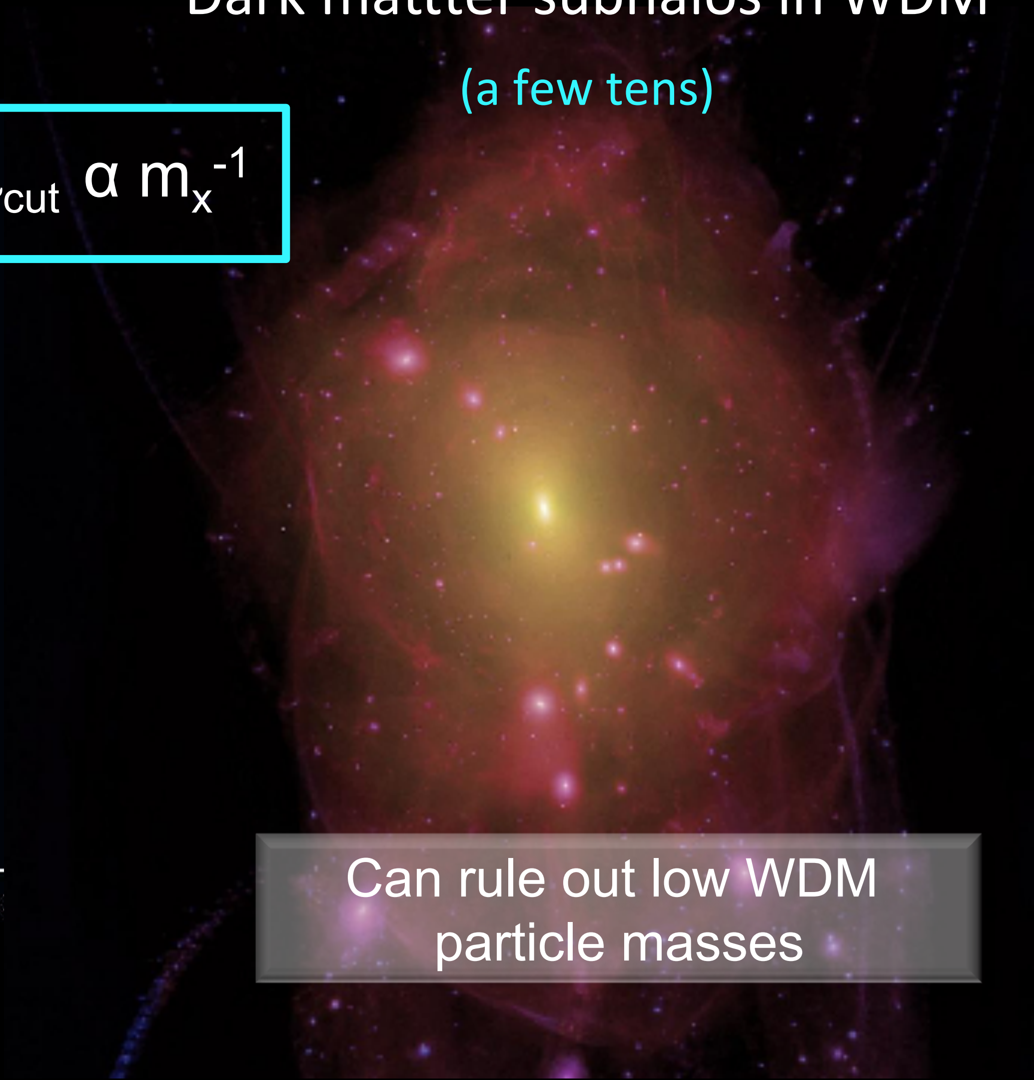
(~55 discovered so far)



λ_{cut} α m_x^{-1}

Dark matter subhalos in WDM

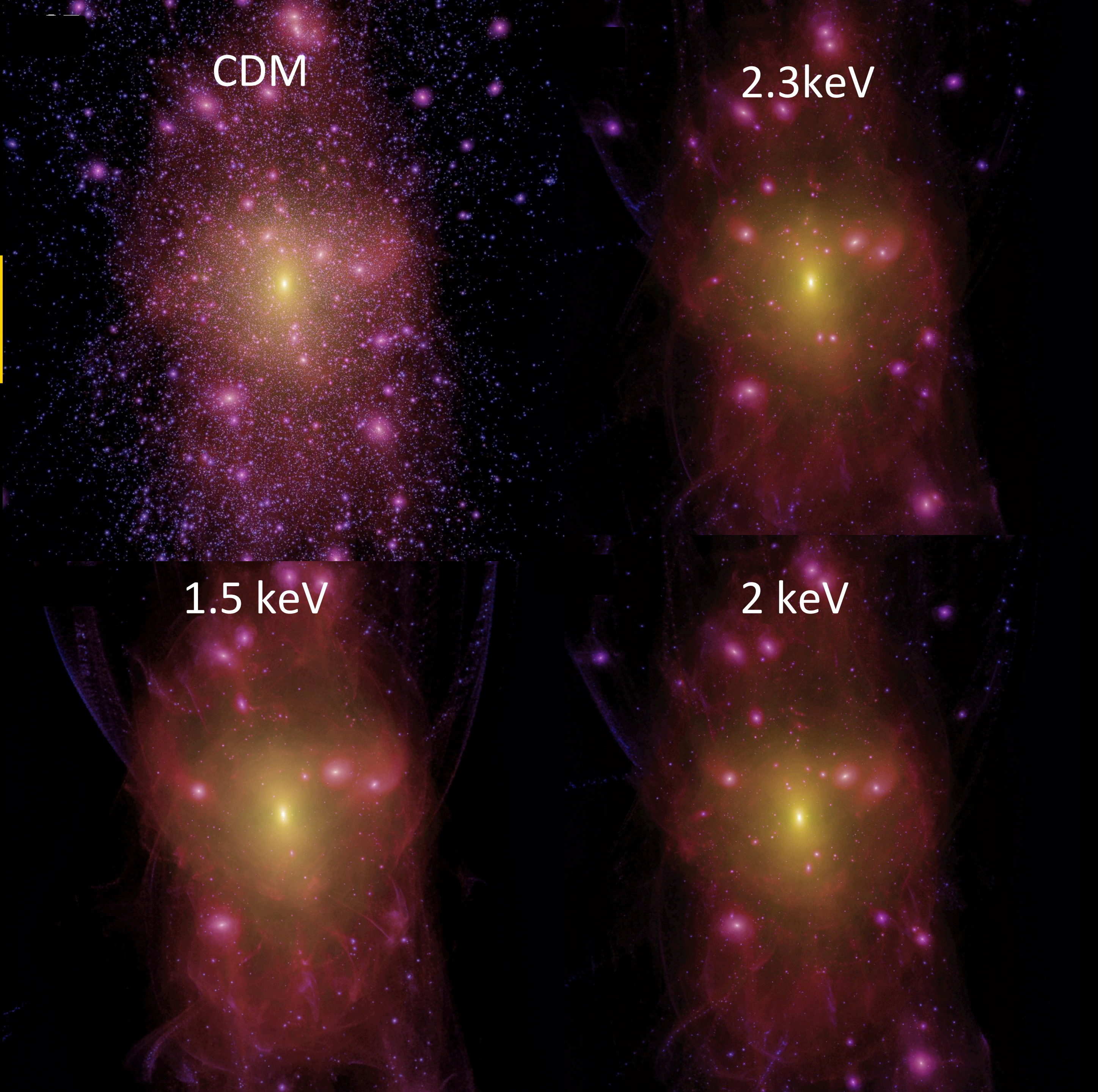
(a few tens)



Can rule out low WDM particle masses

Warm DM:
different ν mass

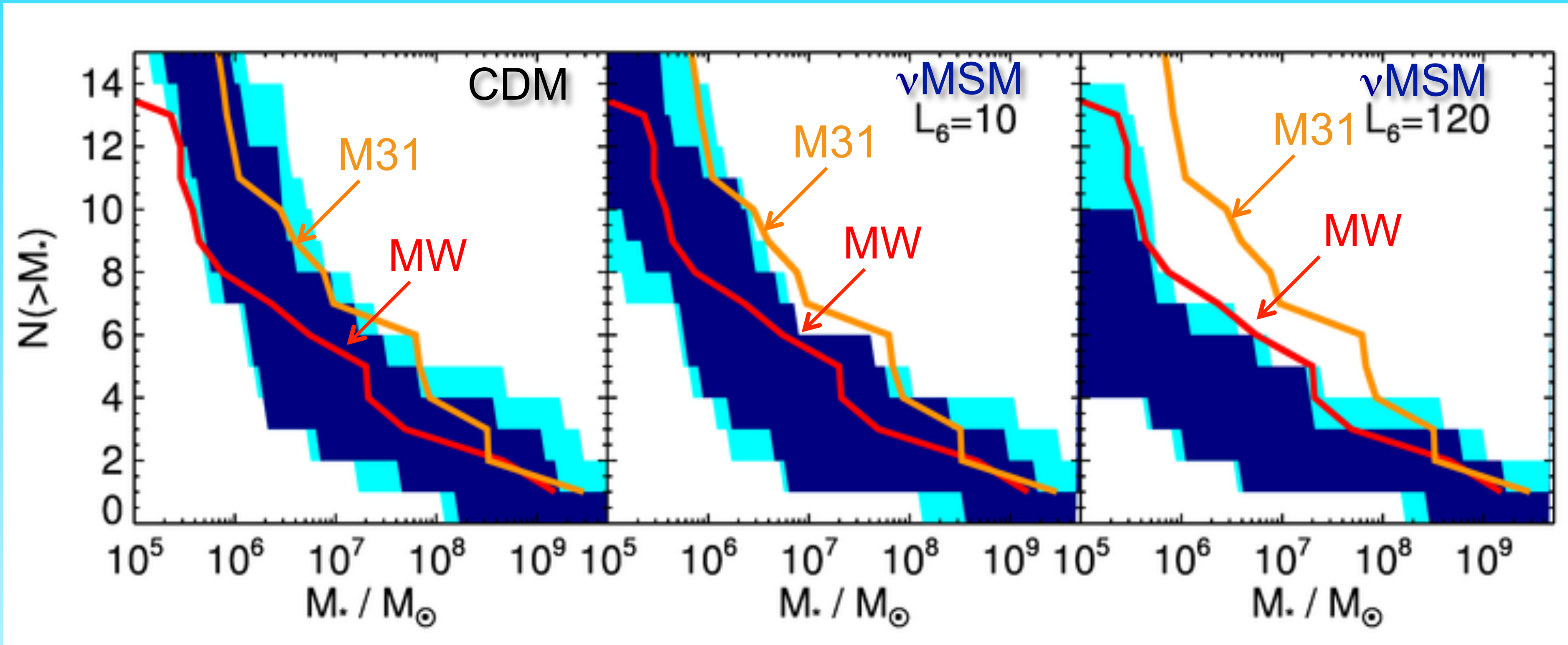
WDM
2.3 keV
2.0 keV
1.5 keV



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

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When “baryon effects” are taken into account

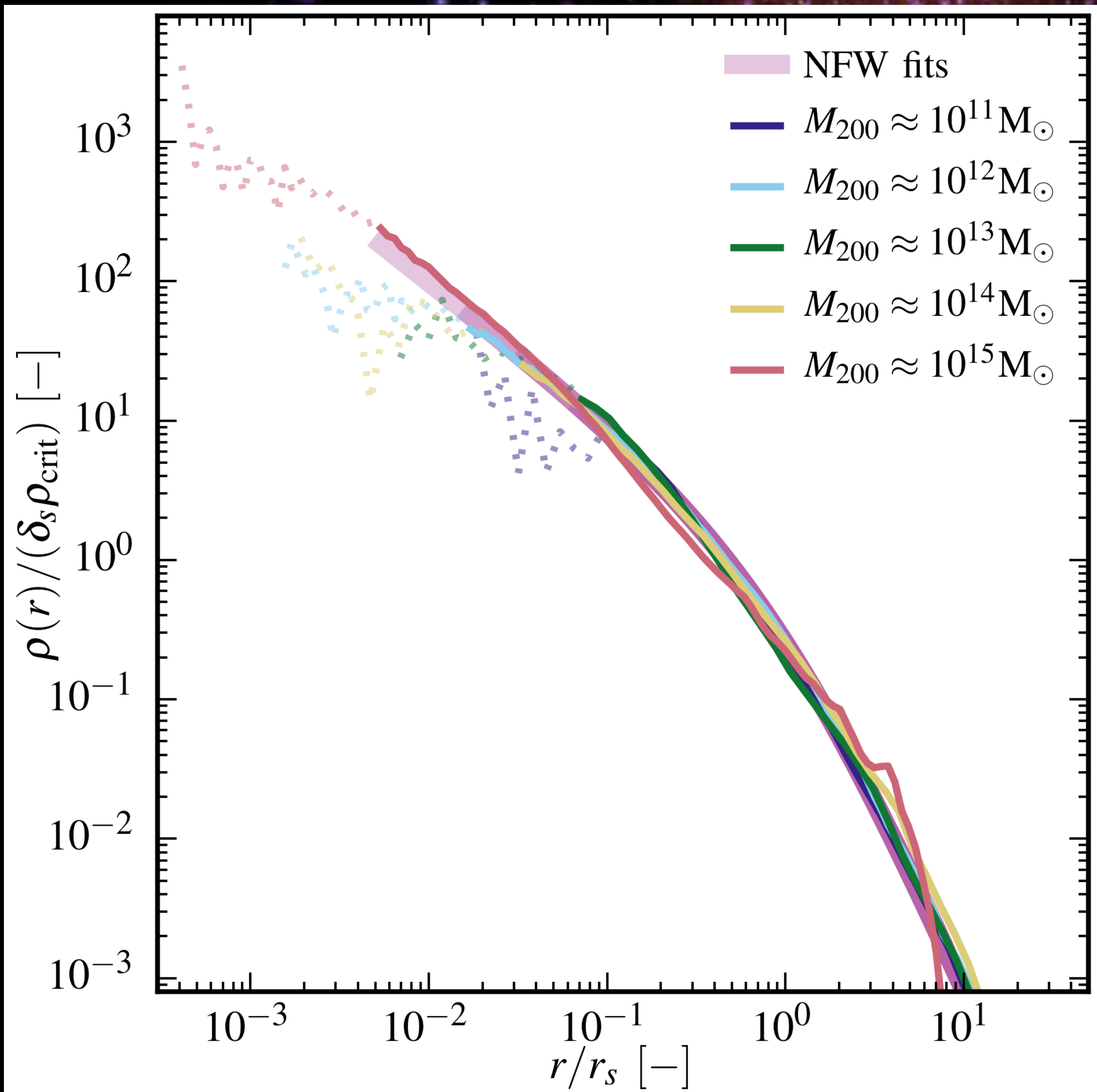
→

Observed abundance of satellites is compatible with CDM but rules out some WDM models

→

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

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:

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

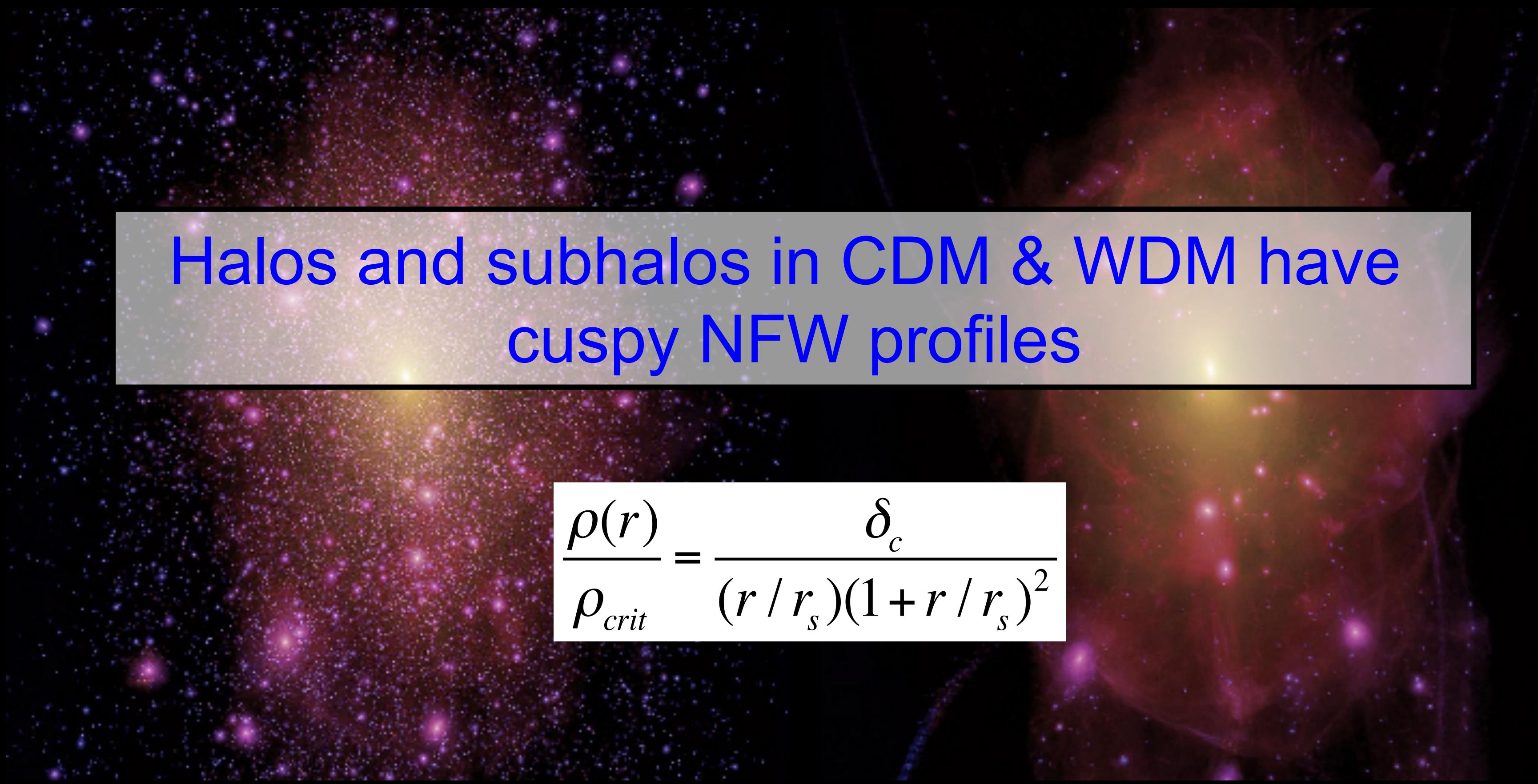
(Navarro, Frenk & White '97)

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

The core-cusp problem

cold dark matter

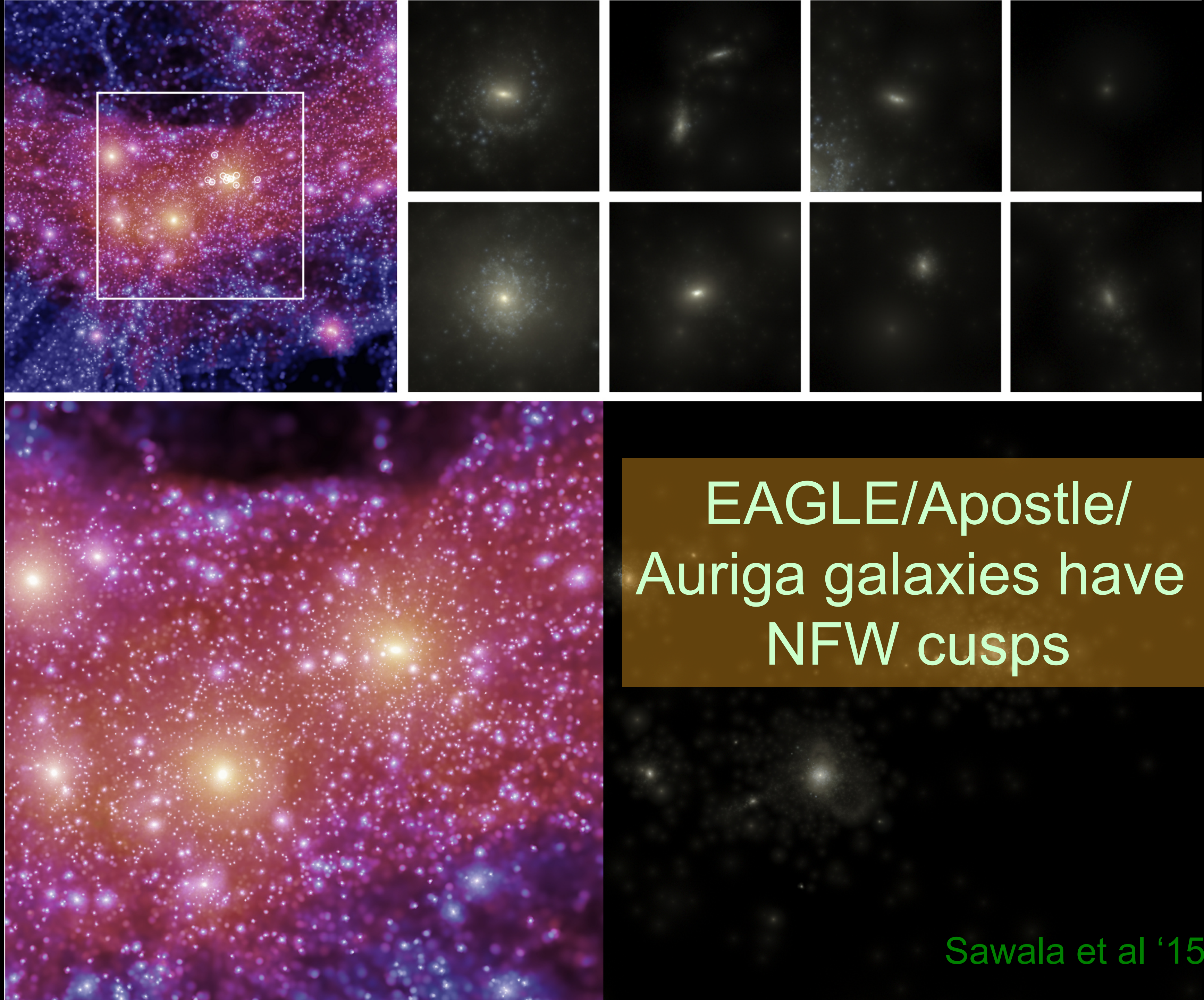
warm dark matter

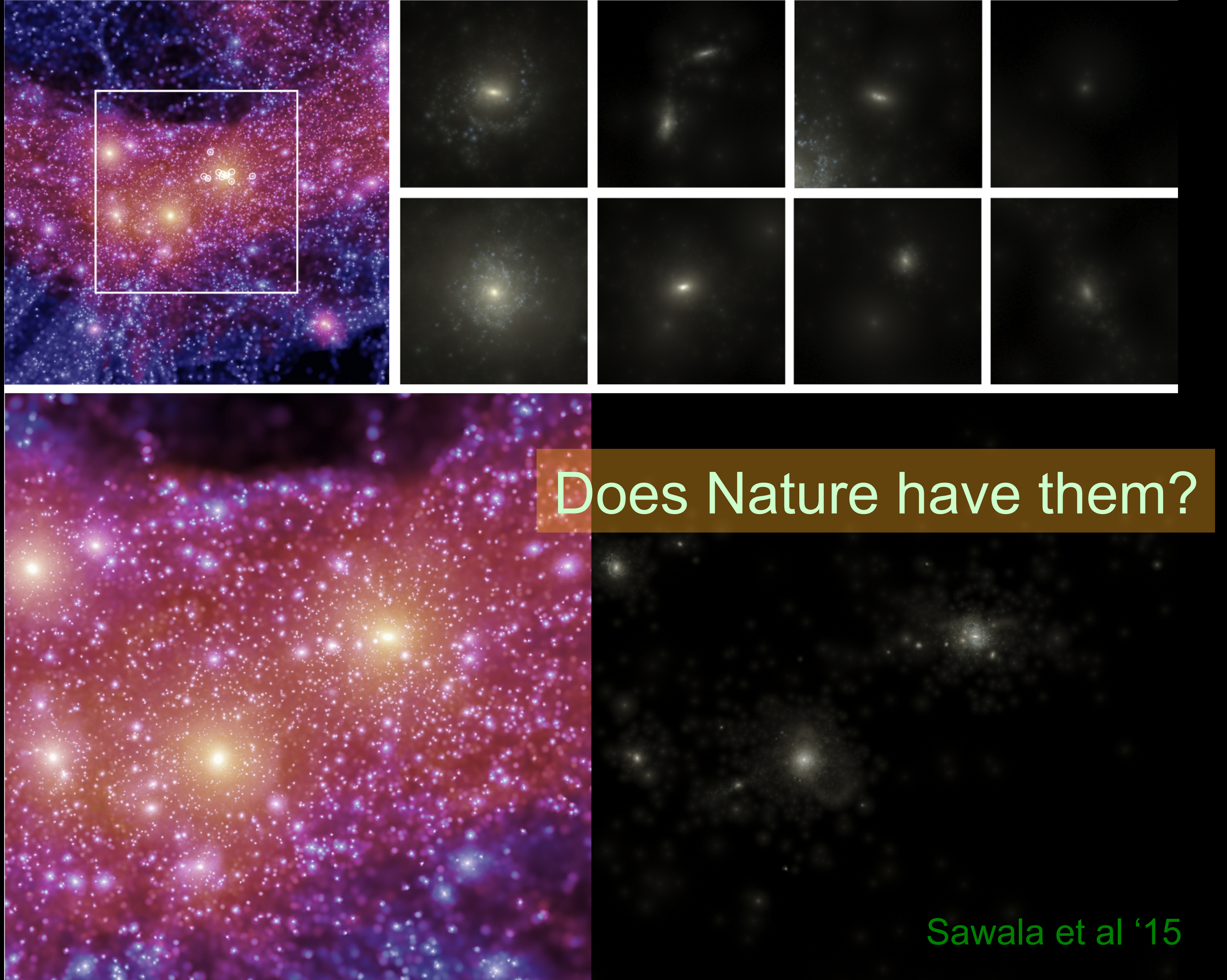


Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

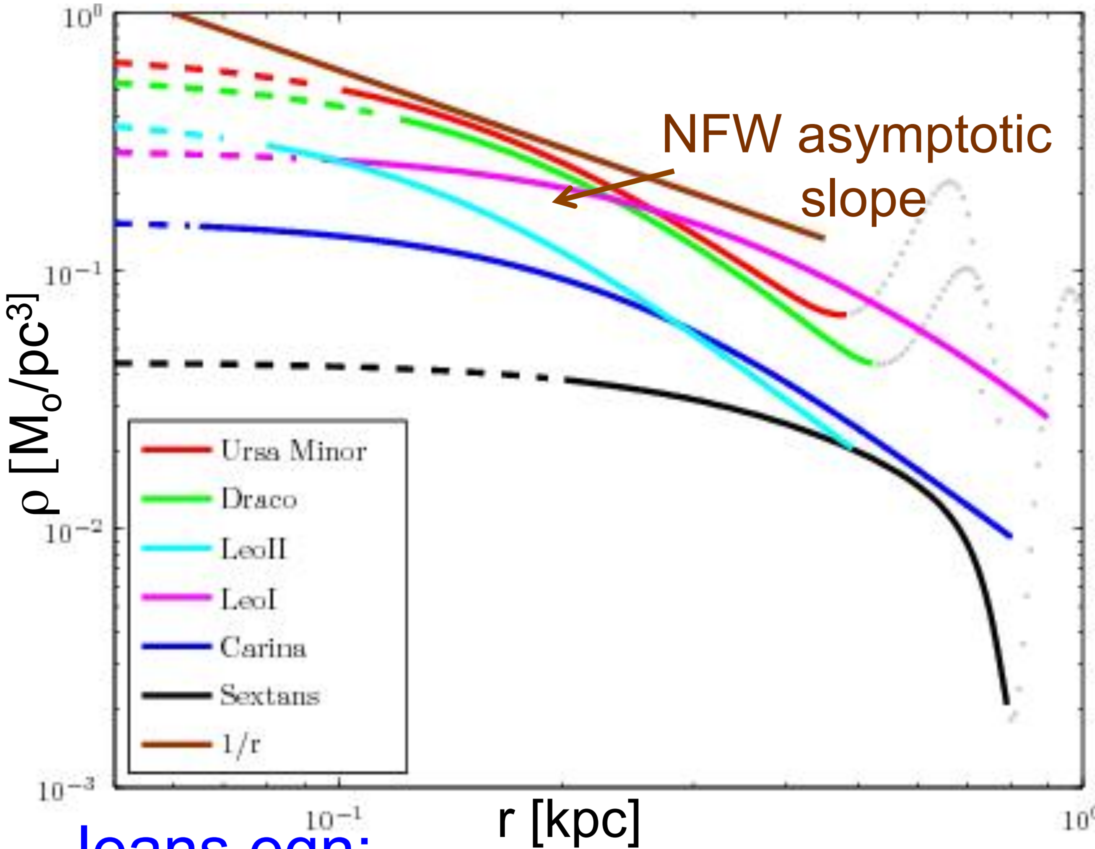
Lovell, Eke, Frenk, Gao, Jenkins, Theuns ‘12


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


Does Nature have them?
Sawala et al '15

The DM halos of dwarf spheroidals

University of Durham



Gilmore etal '07

Inferred density profiles for 6 dwarf spheroidals

"…dark matter forms cored mass distributions, with a core scale length of greater than about 100pc…"

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

vel. anisotropy

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Cores or cusps in nature?

Cores

Cusps

No convincing evidence for cores in observed galaxies

But, if cores we found to exist in galaxies, would this rule out CDM (& WDM)?

No!

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

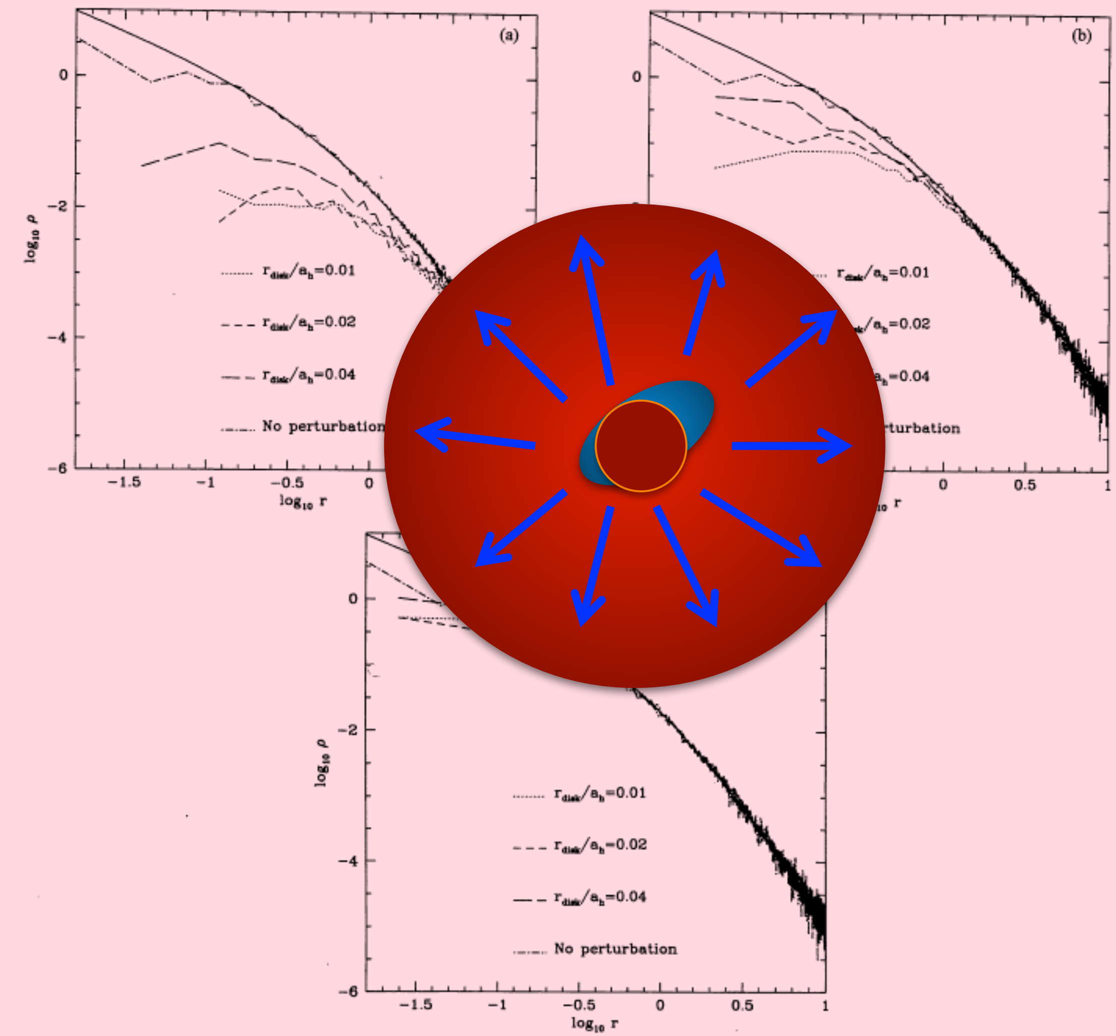

Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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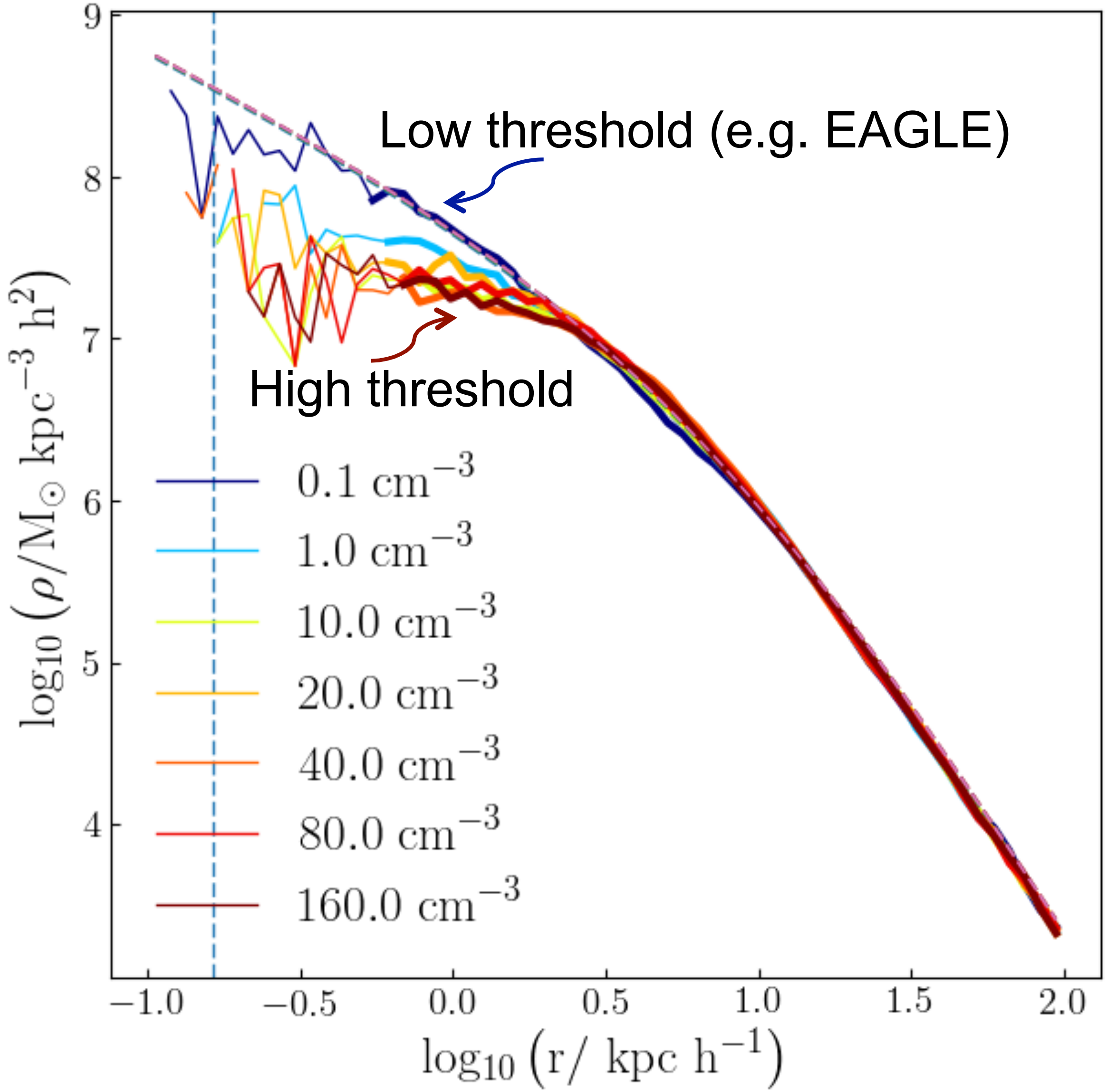
Core formation

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

Key parameter: gas density threshold for star formation

Physically meaningless

Cores or cusps in simulations?



Benitez-Llambay, CSF et al ‘17

Many halos are consistent with NFW cusps; there is no convincing evidence for cores

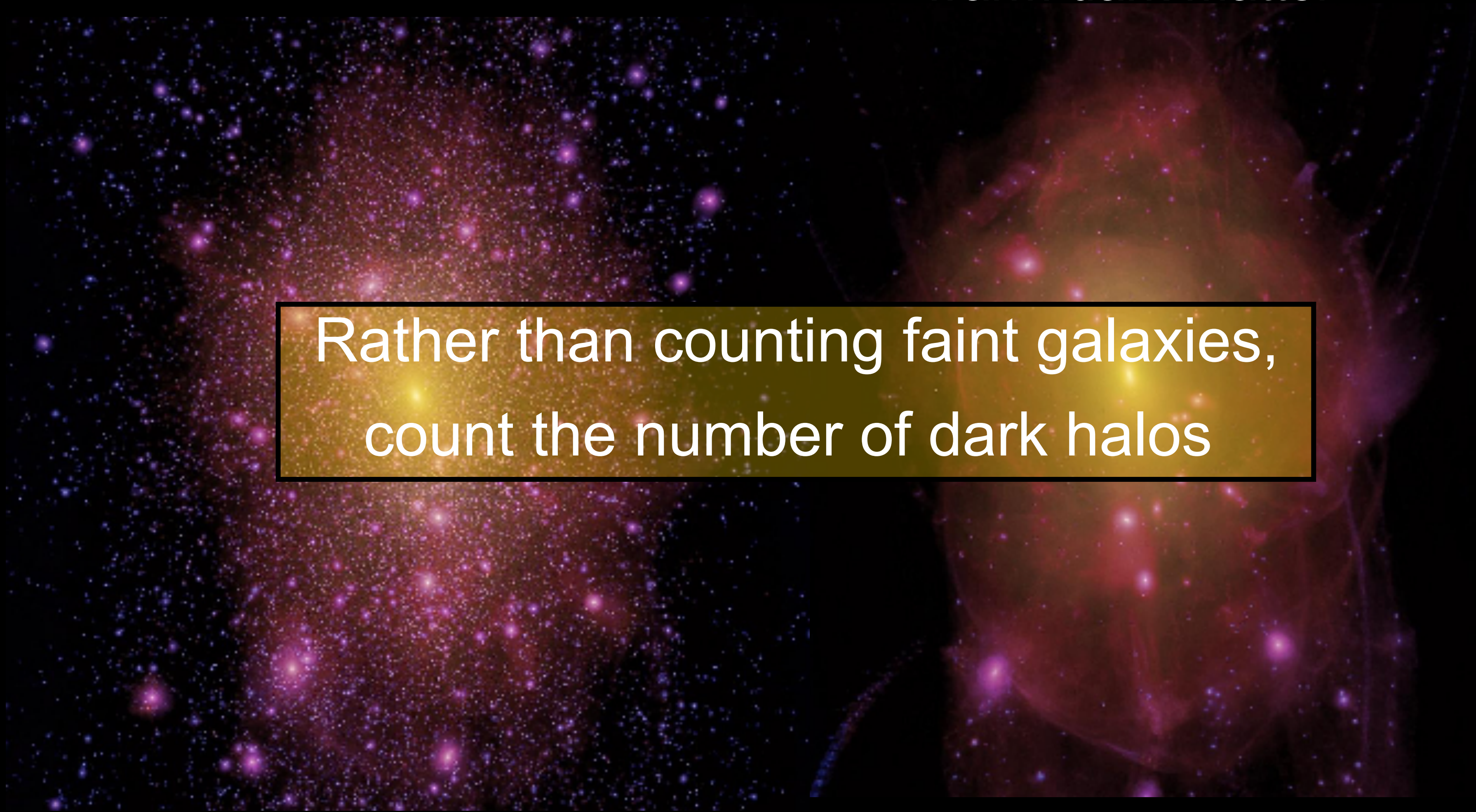
And if cores do exist, they inform us about baryon astrophysics not about the nature of the dark matter

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?

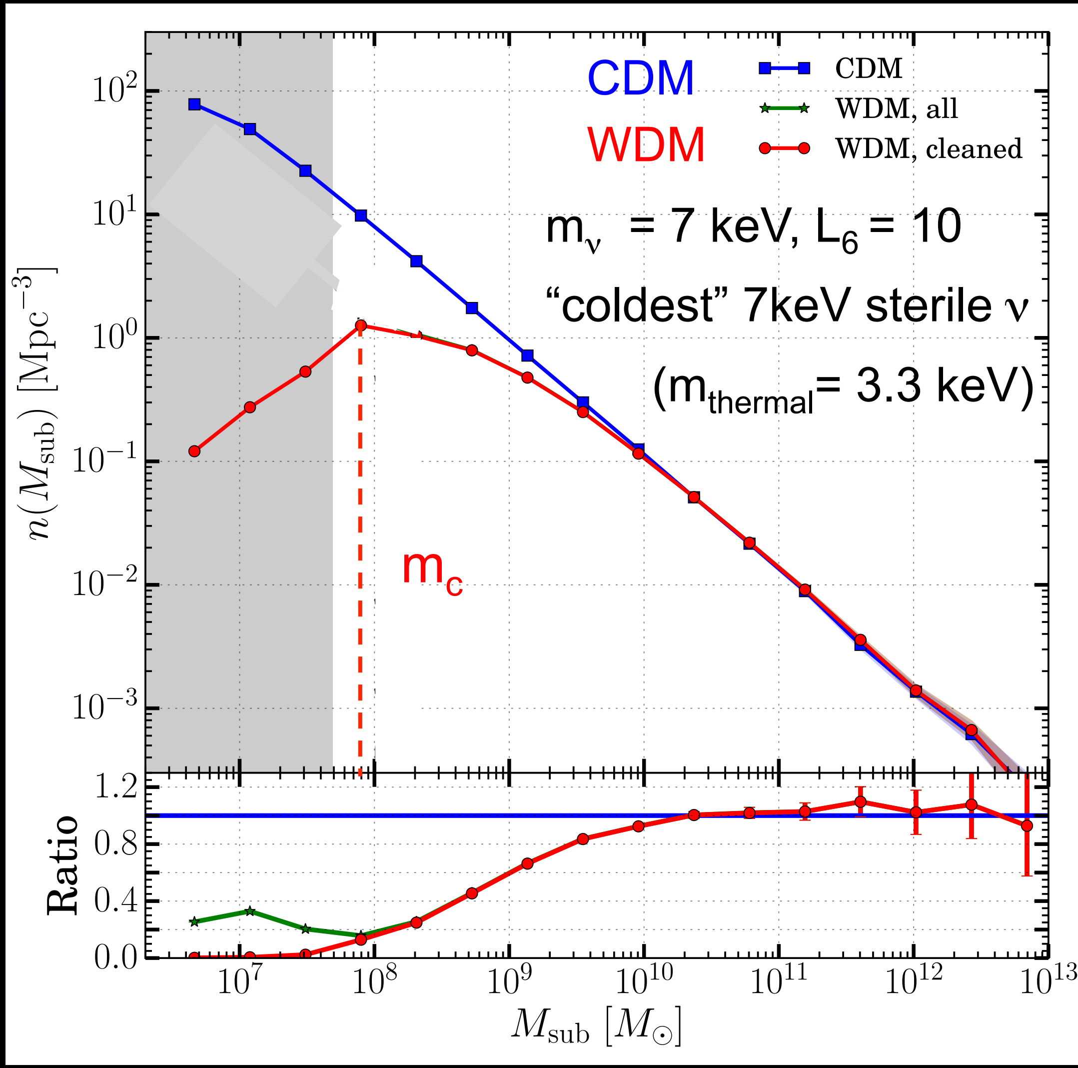
cold dark matter | warm dark matter



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

Can we distinguish CDM/WDM?

cold dark matter

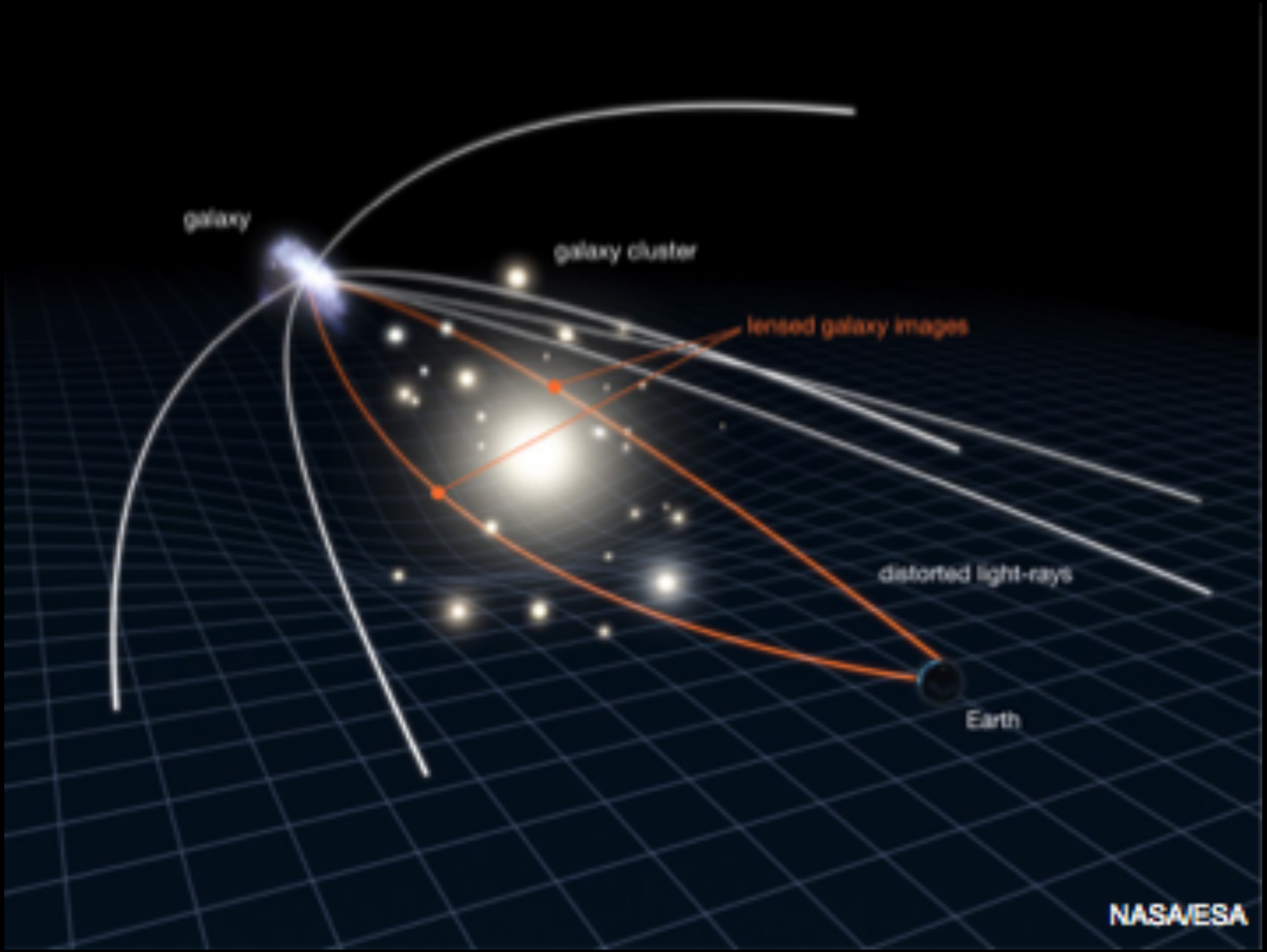
warm dark matter

Dark halos can be detected through gravitational lensing

Gravitational lensing: Einstein rings

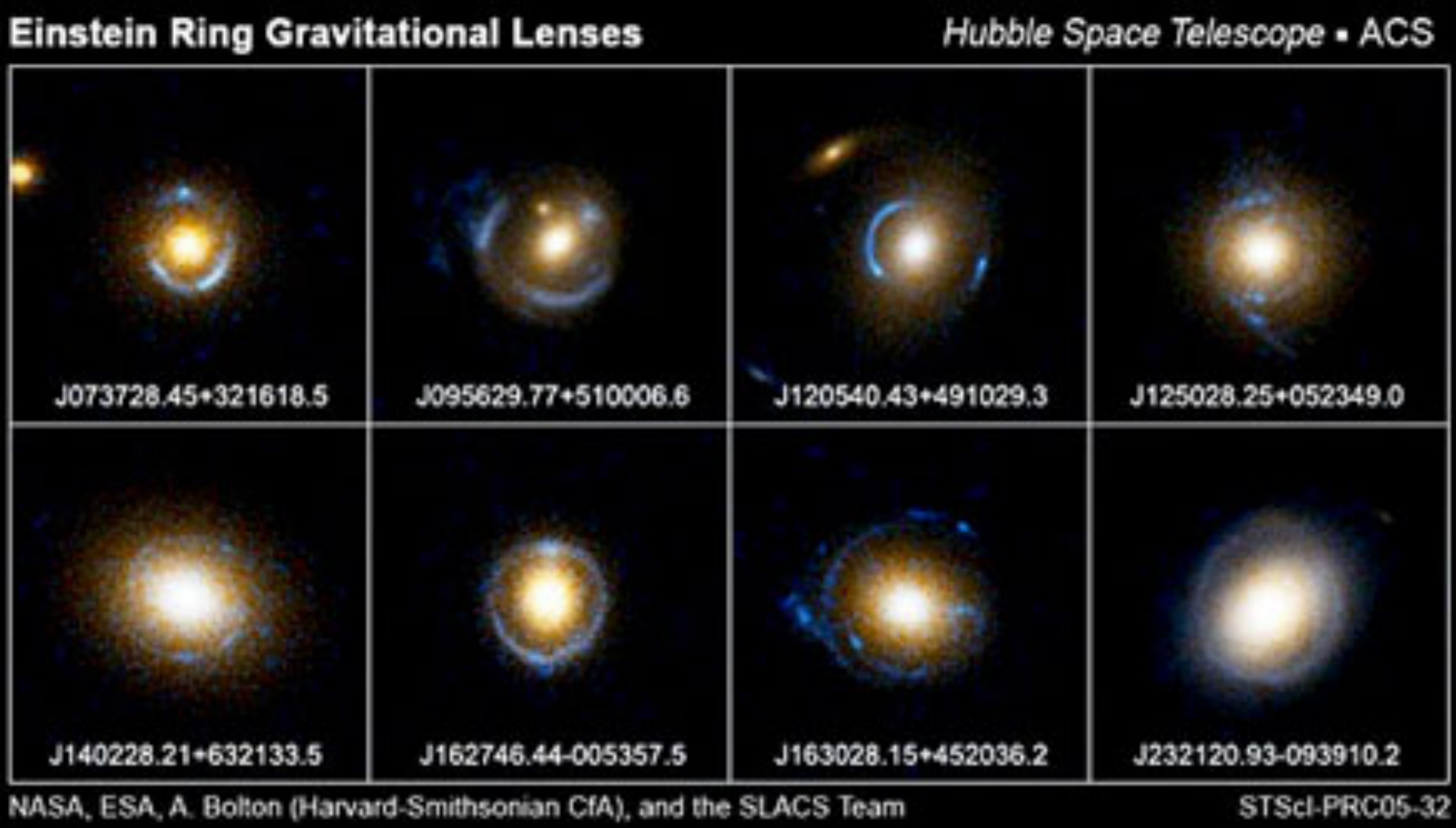
How to rule out CDM

Gravitational lensing: Einstein rings

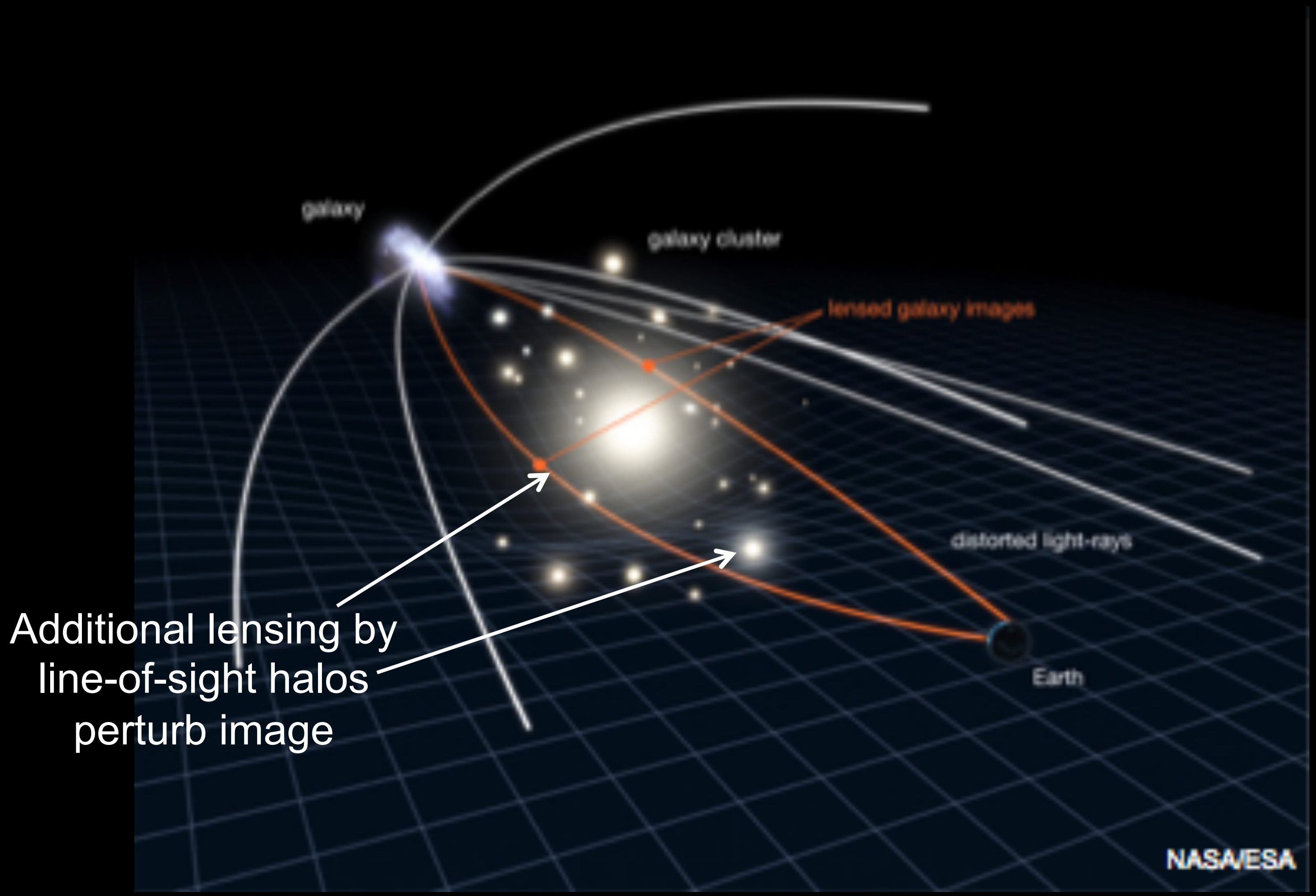


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



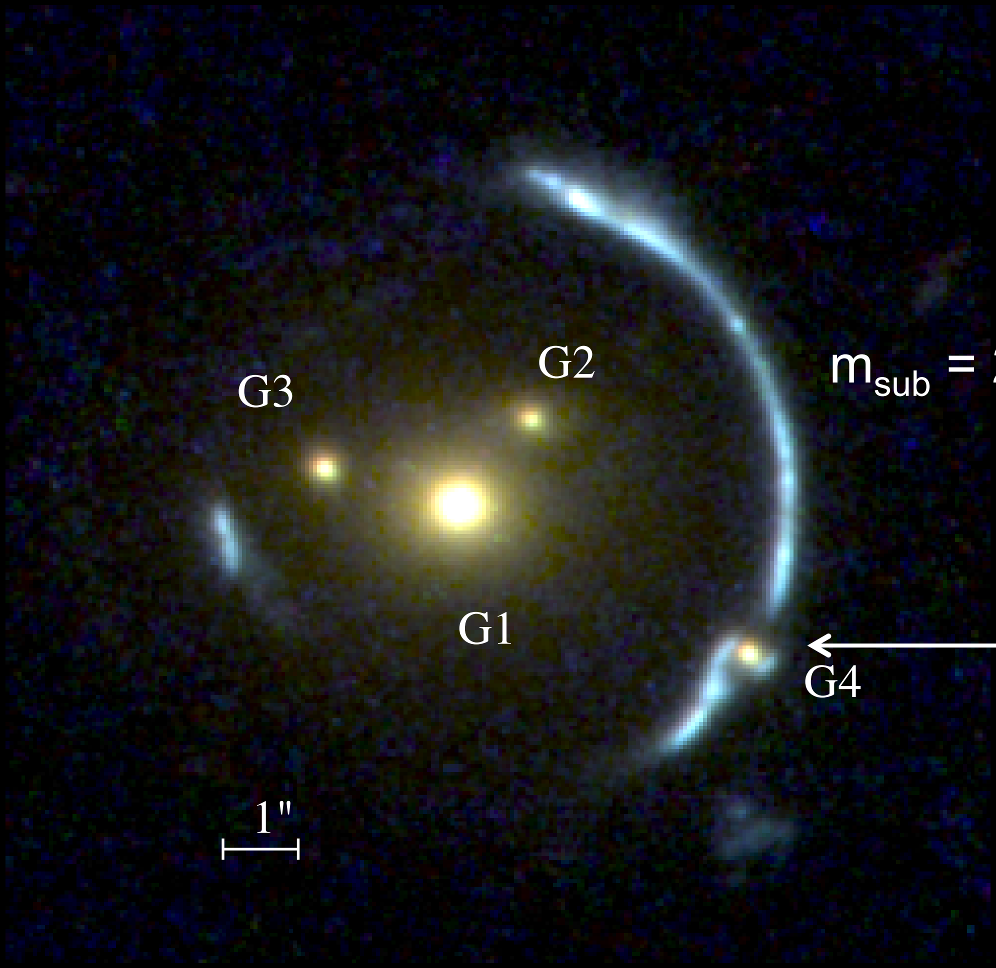
Gravitational lensing: Einstein rings



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

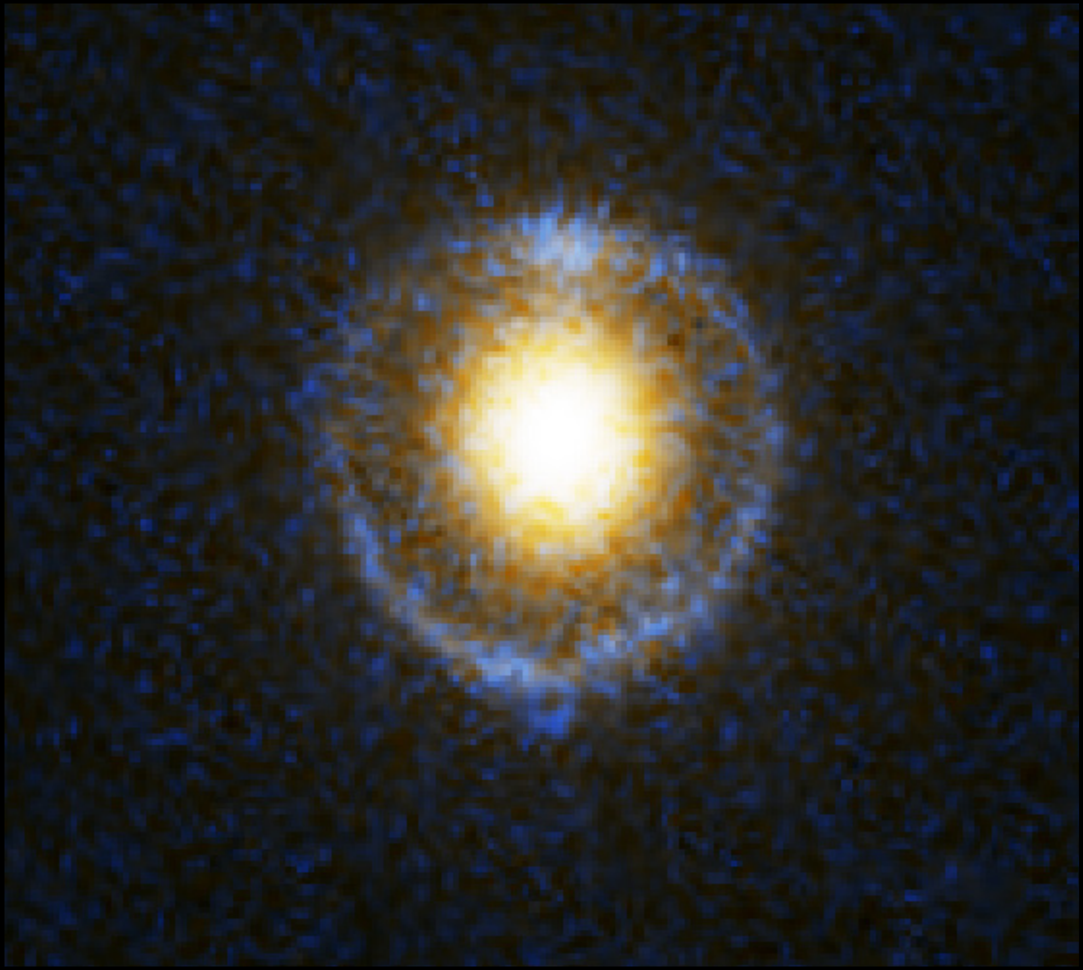


$m_{sub} = 2.8 \times 10^{10}\, M_o$

Vegetti et al '10

Gravitational lensing: Einstein rings

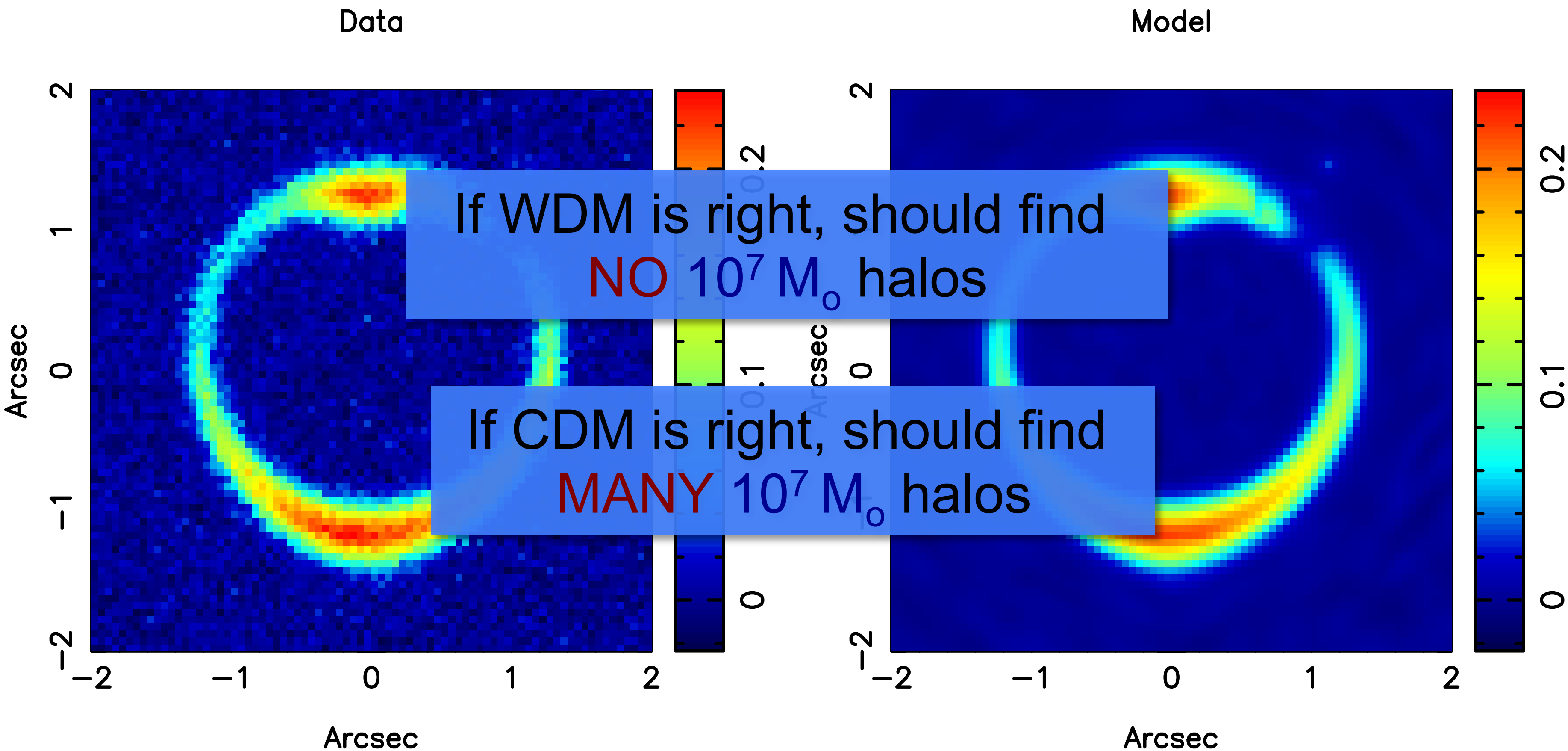
Halos projected onto an Einstein ring distort the image



Vegetti & Koopmans '09

Detecting substructures with strong lensing

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



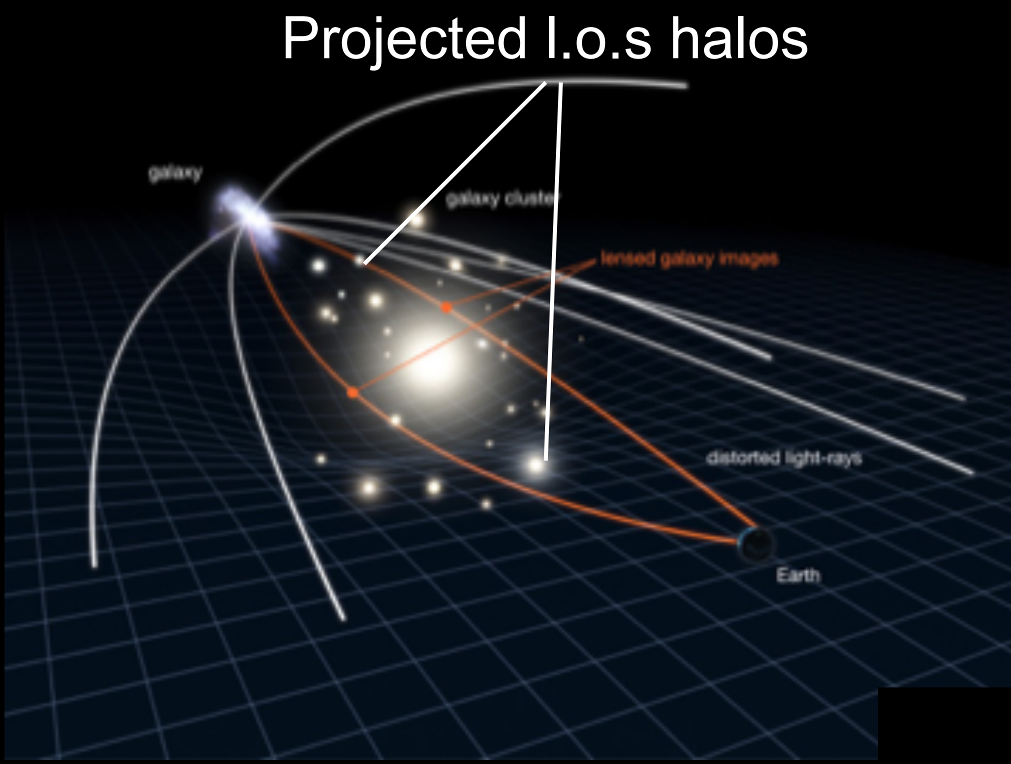
If WDM is right, should find NO $10^7\ M_o$ halos

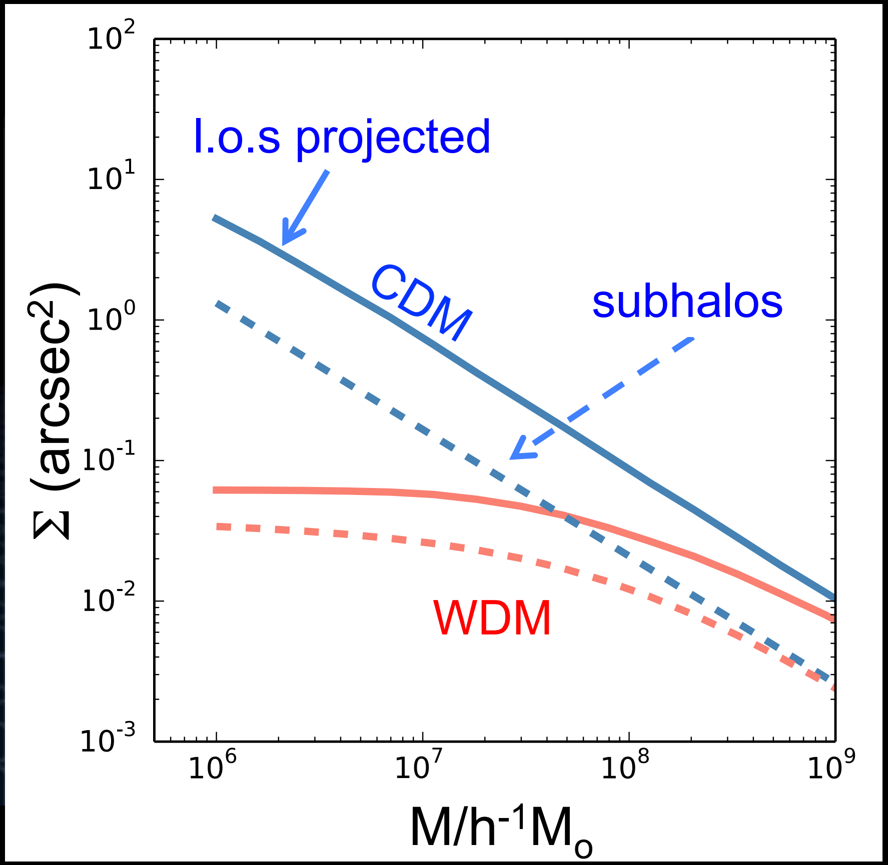
If CDM is right, should find MANY $10^7\ M_o$ halos

Vegetti & Koopmans '09

Substructures vs interlopers

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

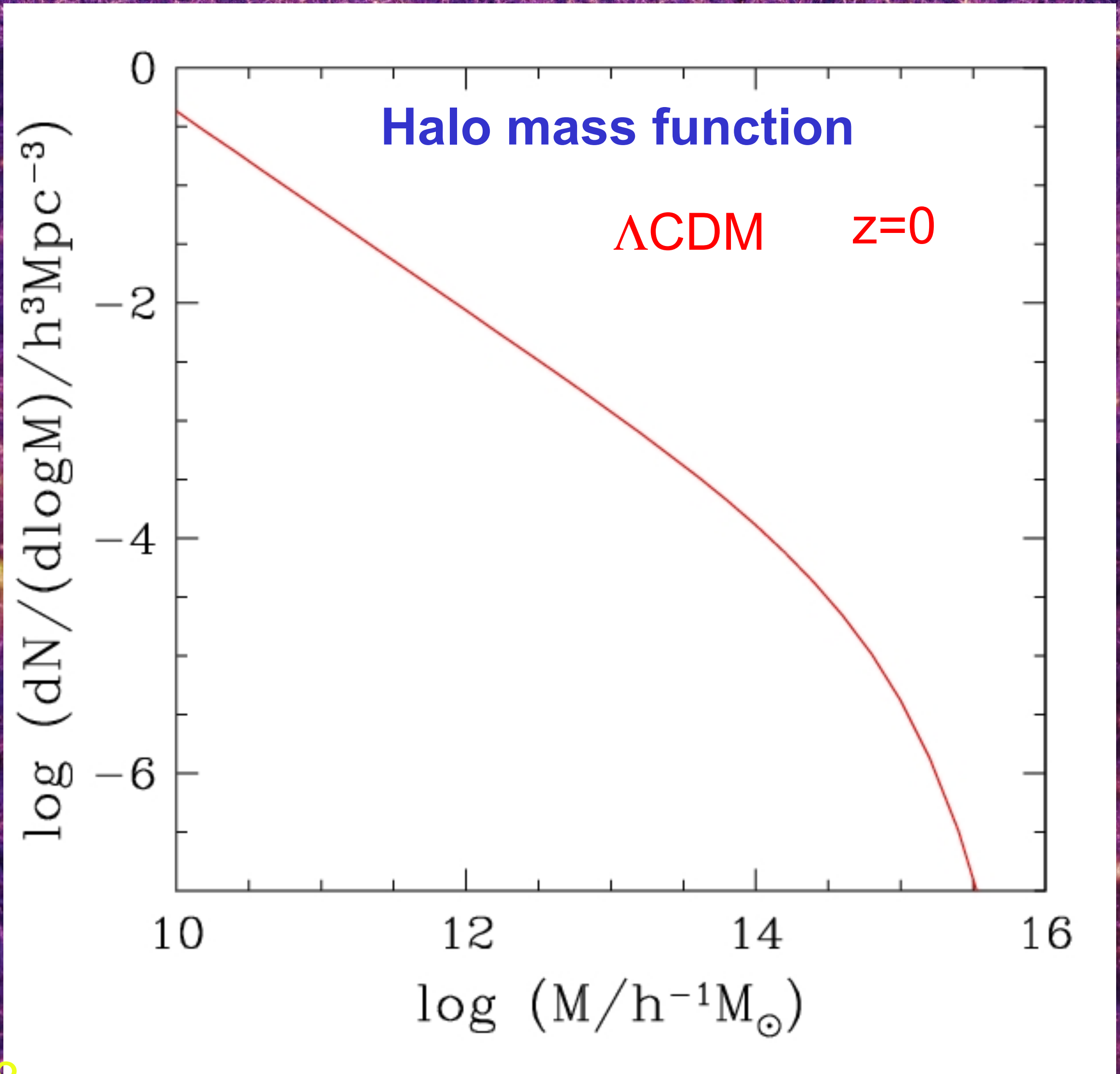




The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16

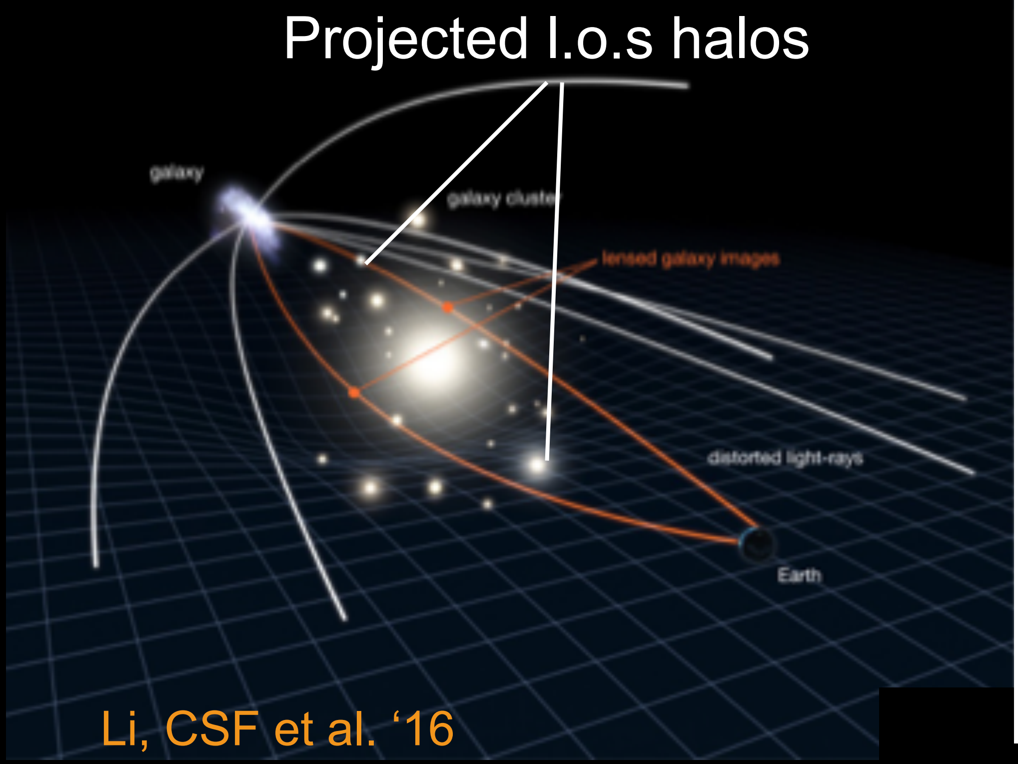
The Millennium/Aquarius/Phoenix simulation series

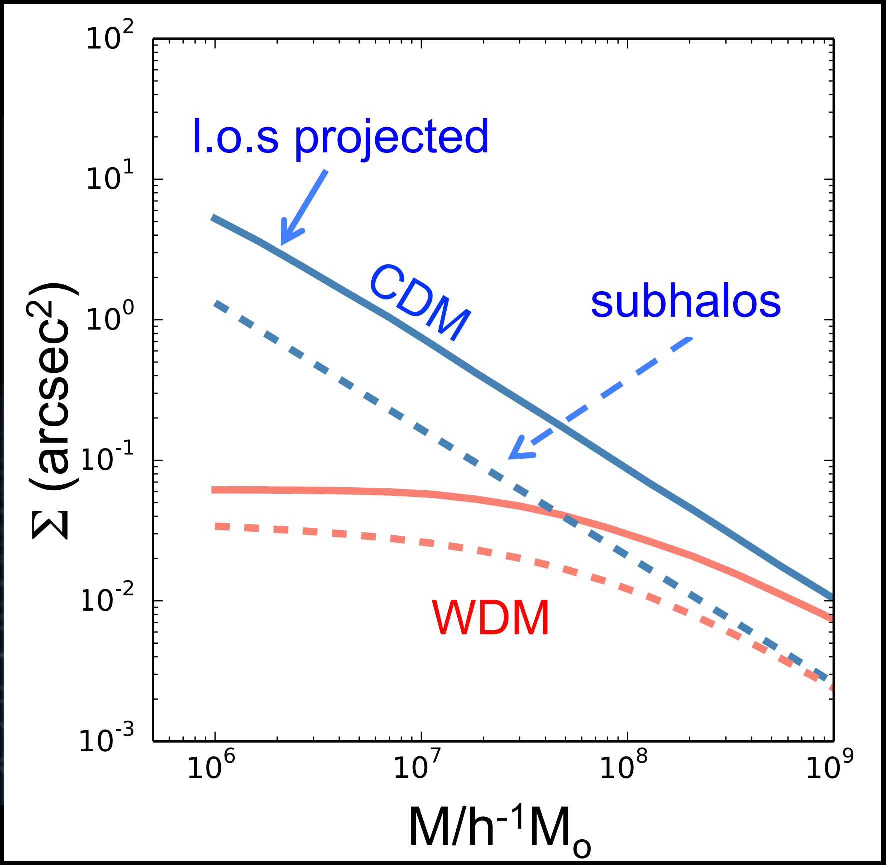


Springel et al '05, '08,
Gao et al '11

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

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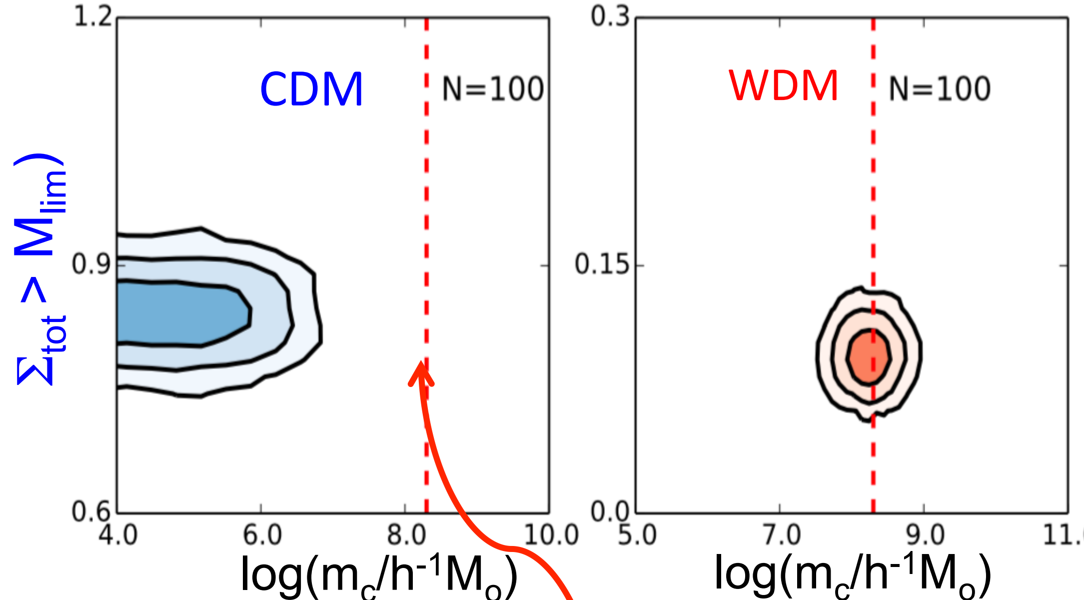
Detecting substructures with strong lensing

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

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!

Open questions

How did the universe begin?

What is the dark matter?

What is the dark energy?

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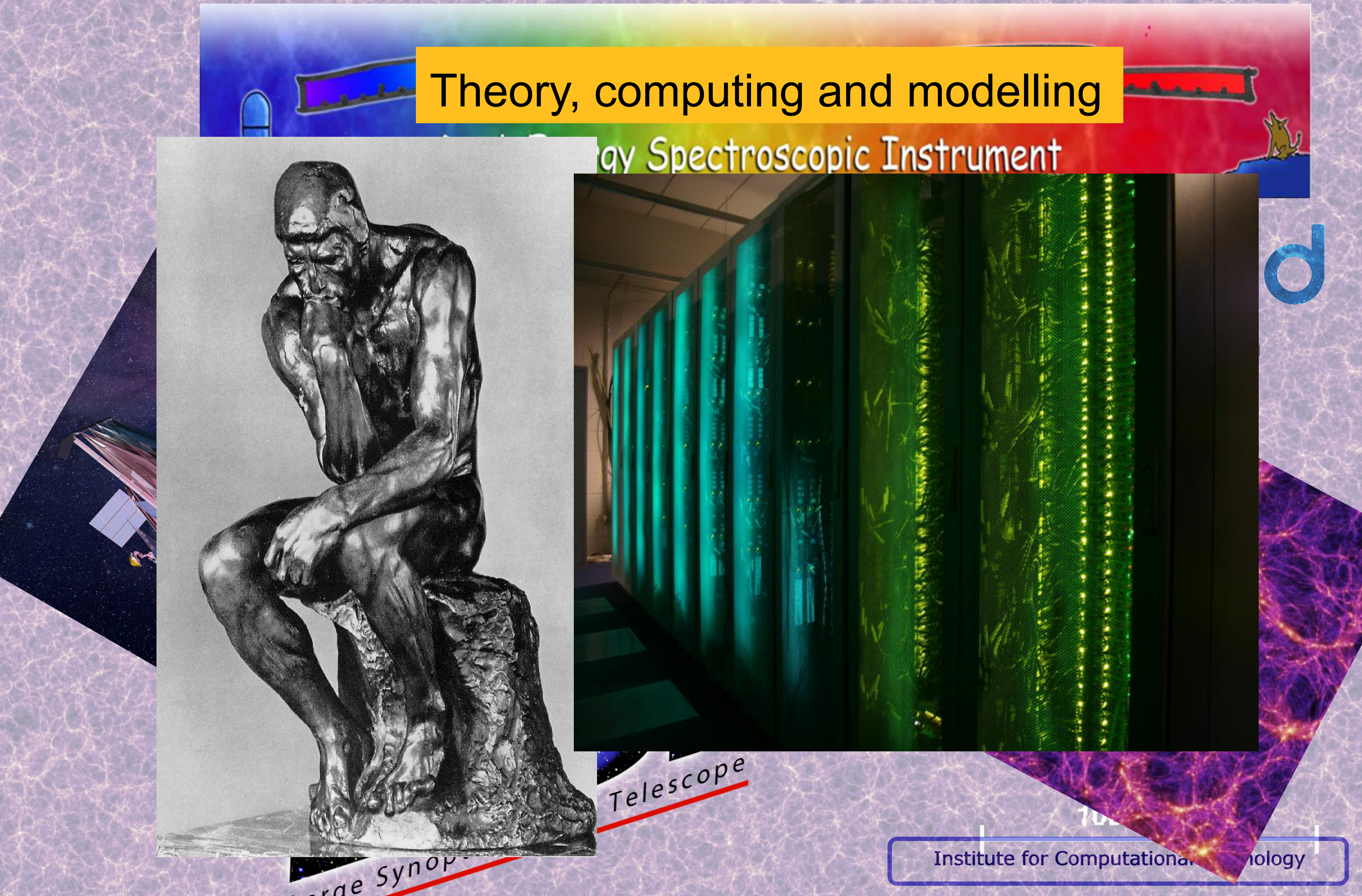
The future

Theory, computing and modelling



There has been great progress in cosmology in the past 30 years