Putting cosmology to the test with computer simulations

Carlos S. Frenk
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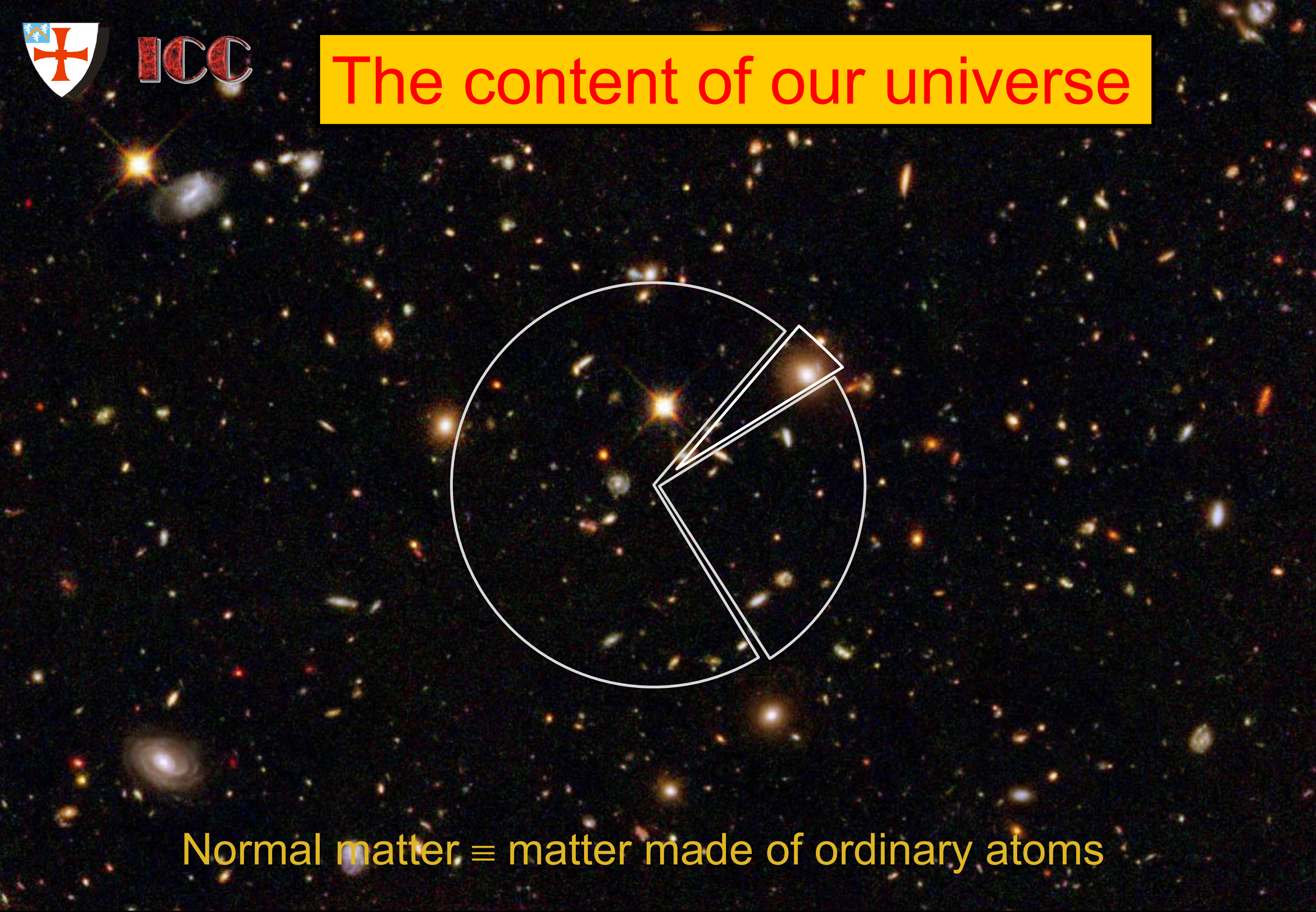
THE KEY QUESTIONS OF COSMOLOGY

- How did the Universe begin?
- What is it made of ?
- How did it evolve to its present state?
- What does the future hold?

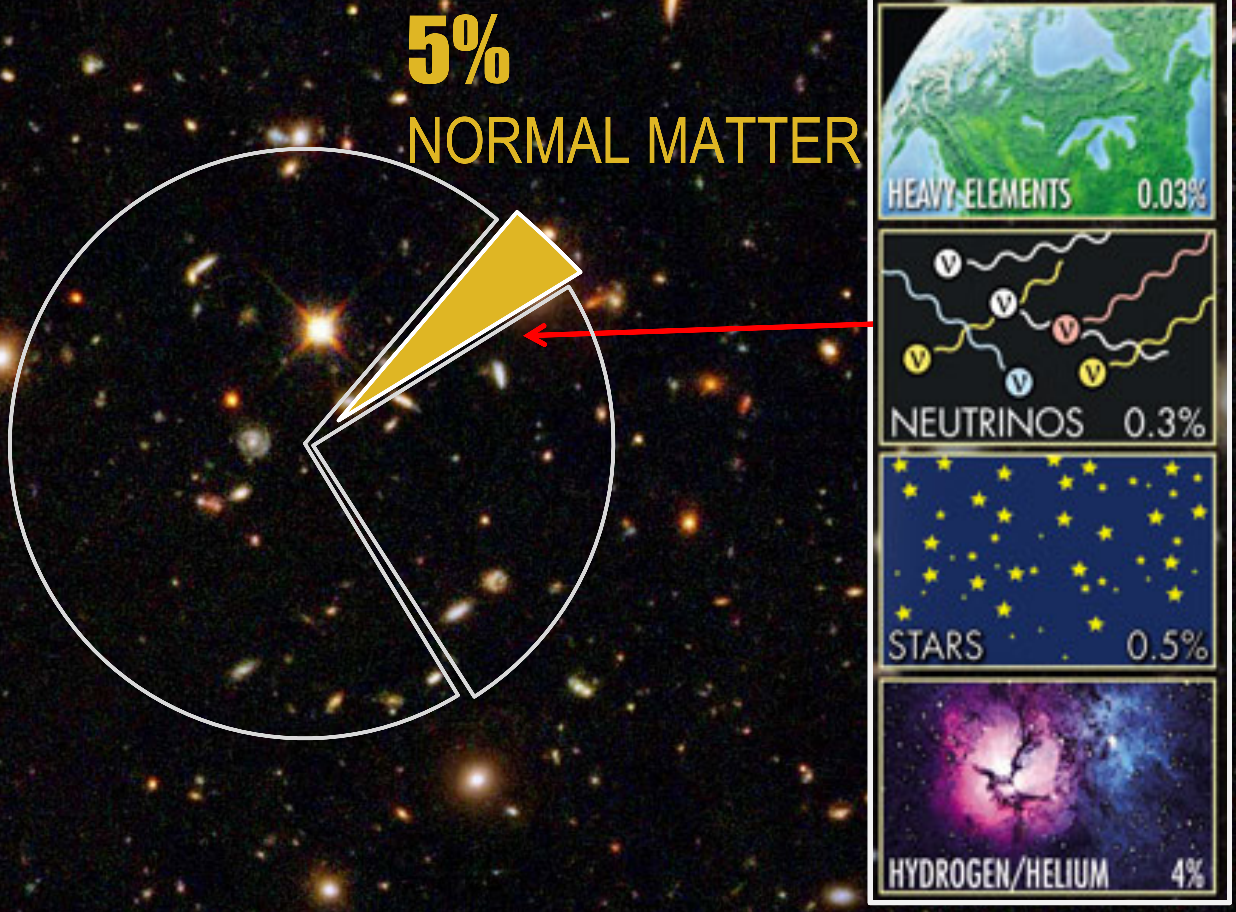
Flammarion 1888: tete des etoiles

What is the Universe made of?

The (bizarre) contents of our Universe

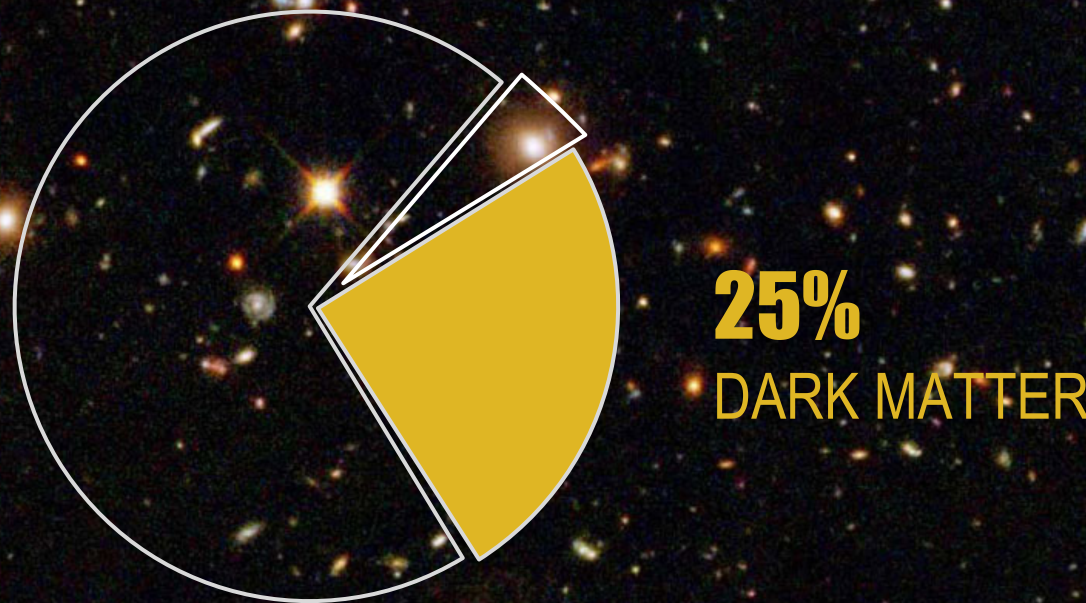

The content of our universe
Normal matter ≡ matter made of ordinary atoms

The content of our universe



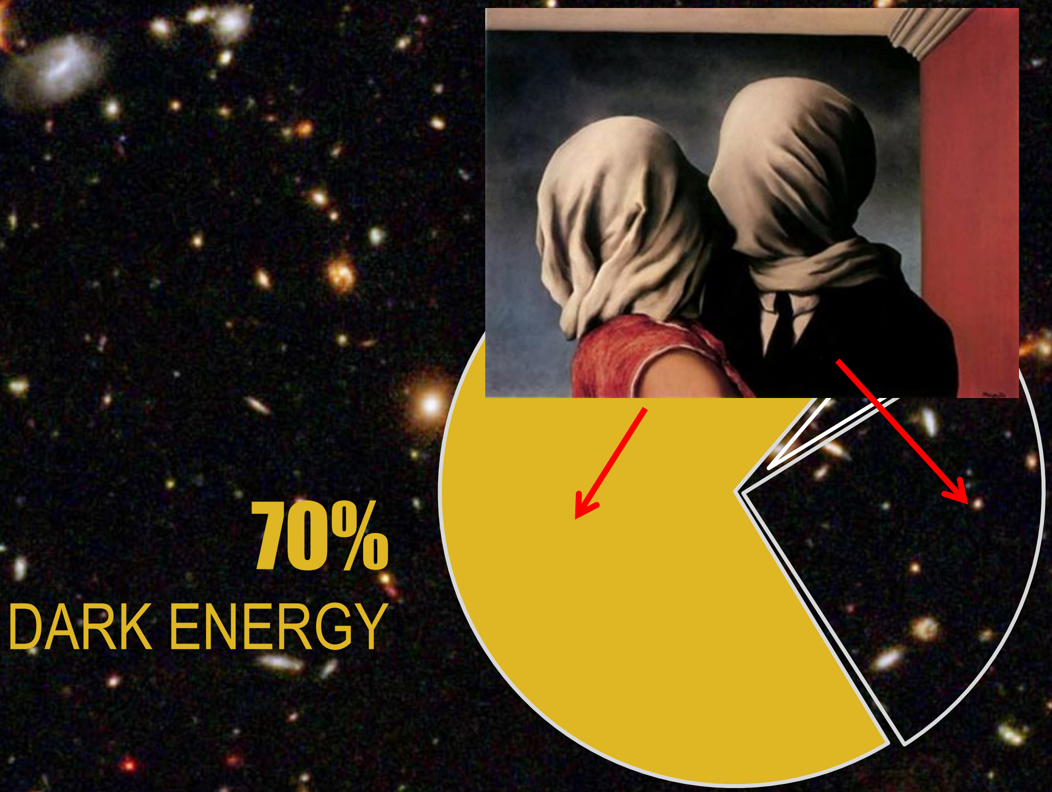
Normal matter ≡ matter made of ordinary atoms

The content of our universe



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

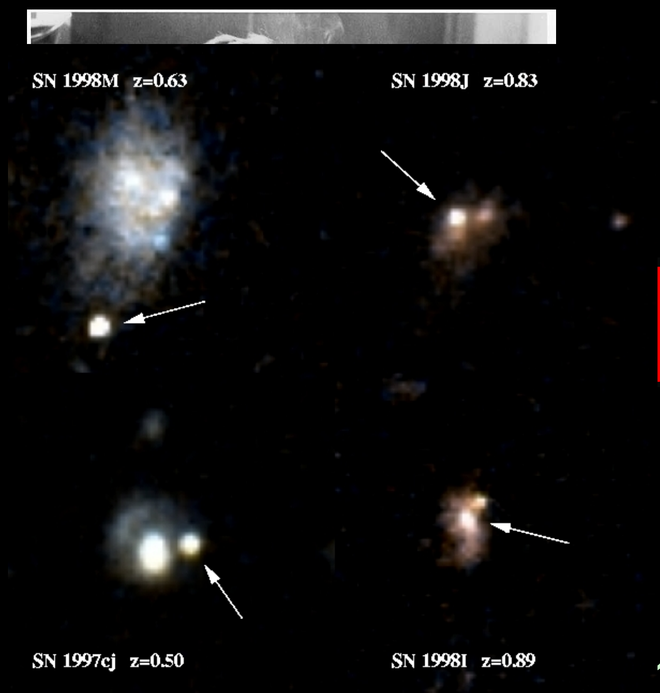
The content of our universe

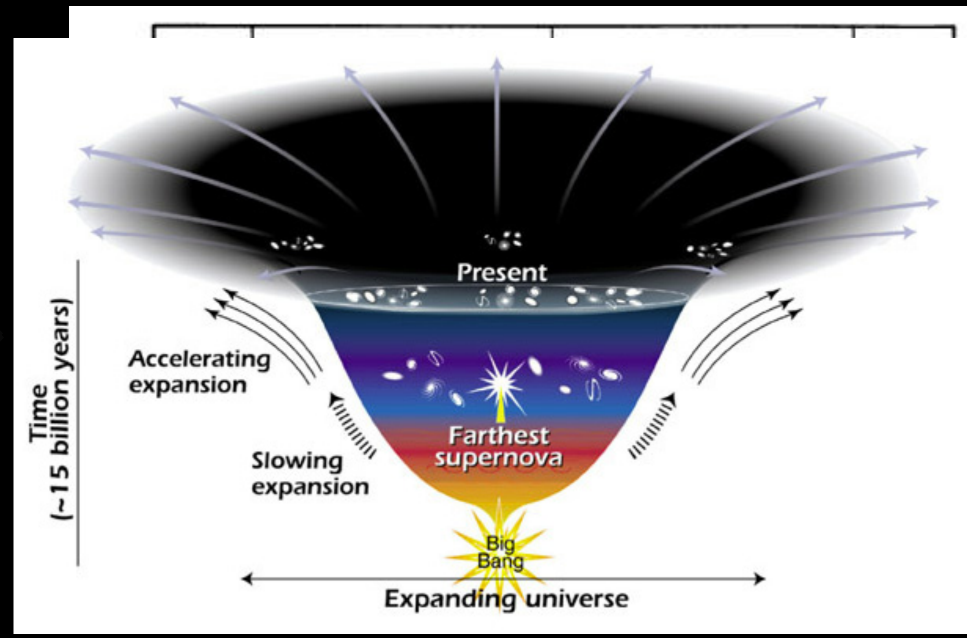


Dark energy ≡ mysterious form of energy which opposes gravity and is causing the cosmic expansion to accelerate

The cosmic expansion

1998





ıbble 1929: $v = H_0 d$

Expansion is
lerating

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

The gravitational constant

The simplest form of vacuum energy is the gravitational constant Λ introduced by Einstein (for the wrong reasons)

There is no physical explanation for the measured value of Λ

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Flammarion 1888: tete des etoiles

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The standard model of cosmology

The new Ogden Centre at Durham

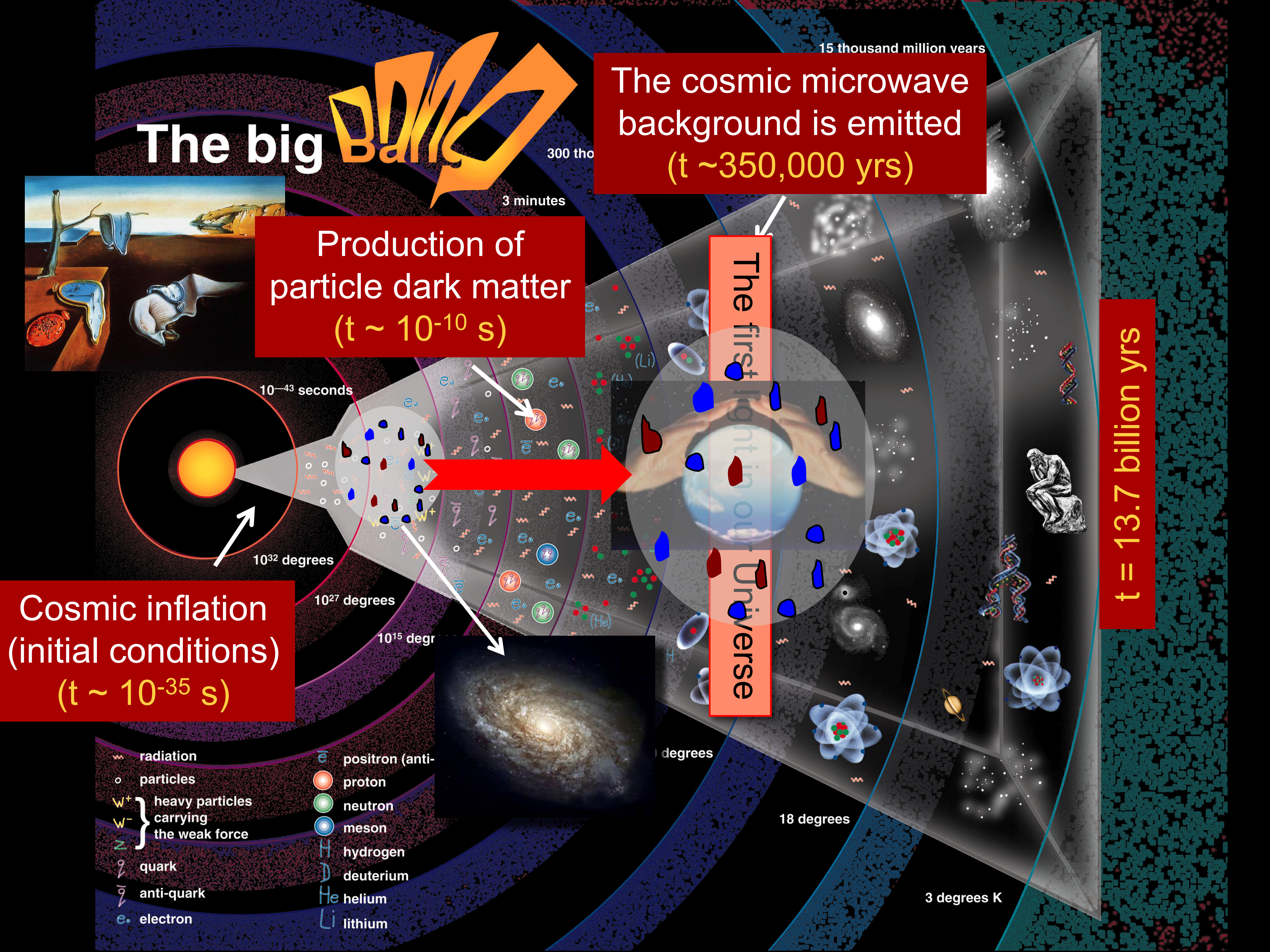
The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter

- Proposed in 1980s, it is an *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)

Three Nobel Prizes in Physics since 2006, including 2019



The big
15 thousand million years
300 tho
3 minutes
The cosmic microwave background is emitted
(t ~350,000 yrs)
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
degrees
18 degrees
3 degrees K
Cosmic inflation
(initial conditions)
(t ~ 10^{-35} s)
radiation
particles
W^+
W^-
Z
heavy particles carrying 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:

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

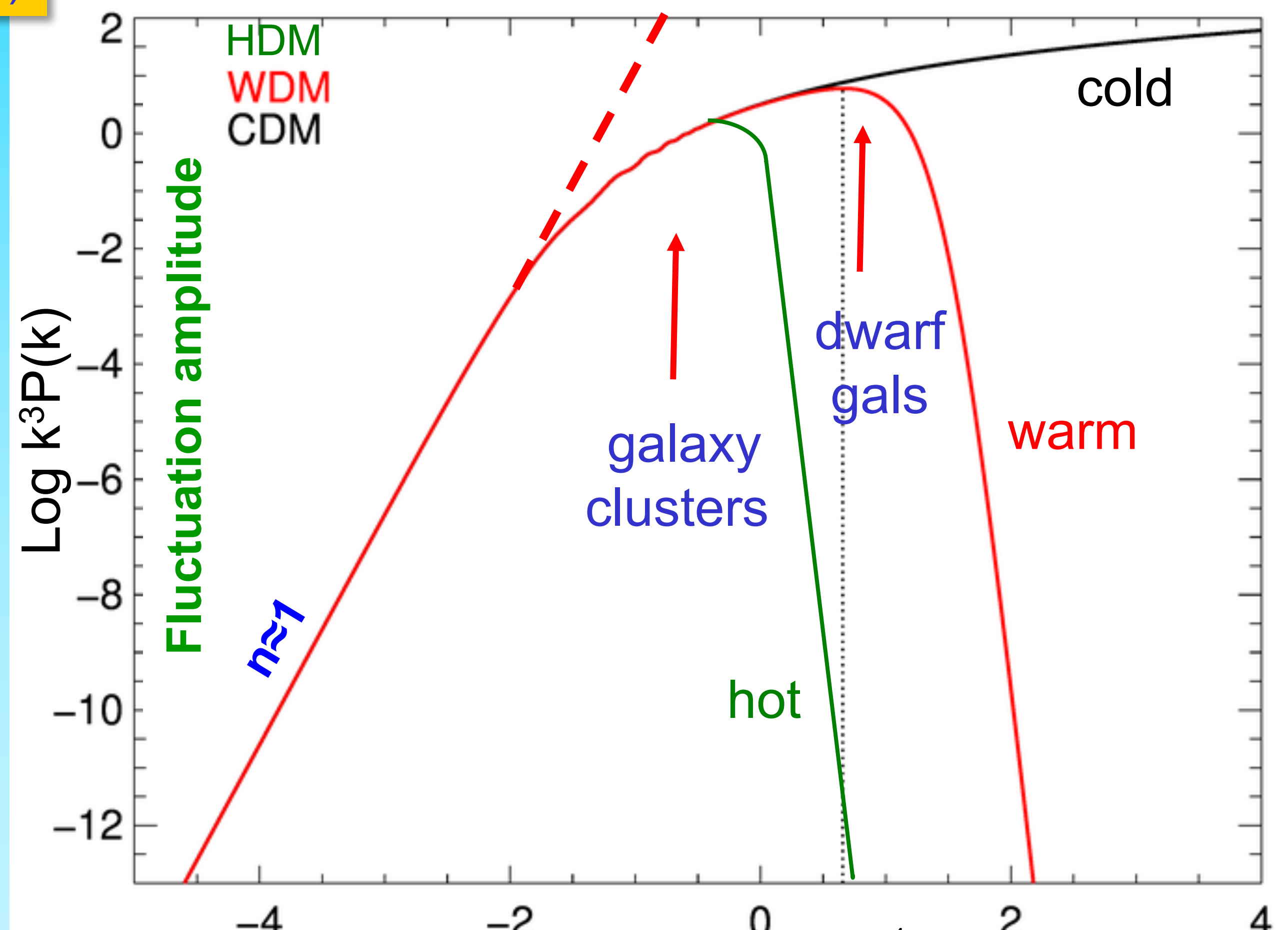
Free streaming →

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

for a thermal relic

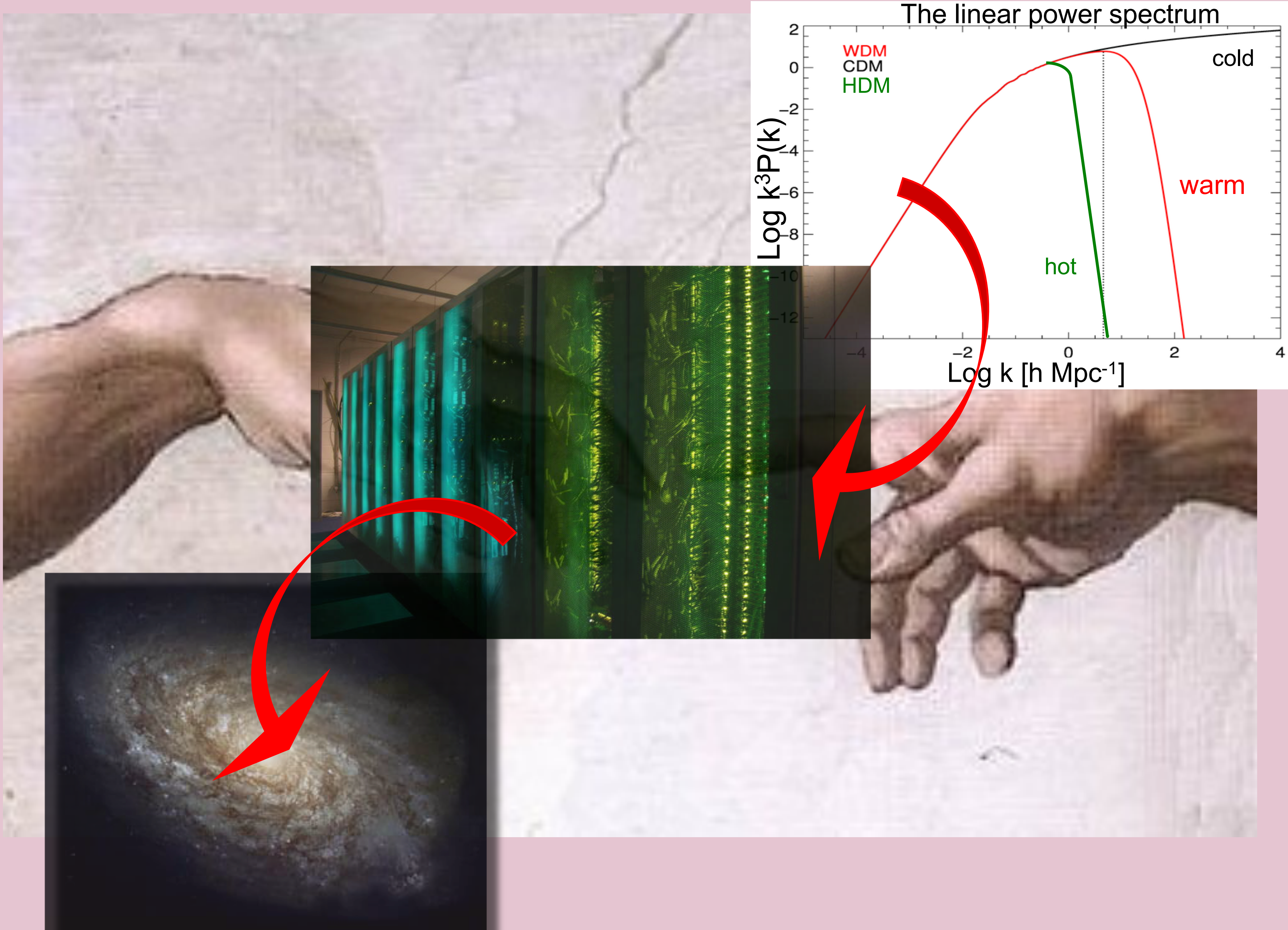
k^3 P(k)

The linear power spectrum ("power per octave")



These possibilites can be tested with astrophysics

Non-linear evolution



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Non-linear evolution: simulations

Assumption about content of Universe → Initial conditions

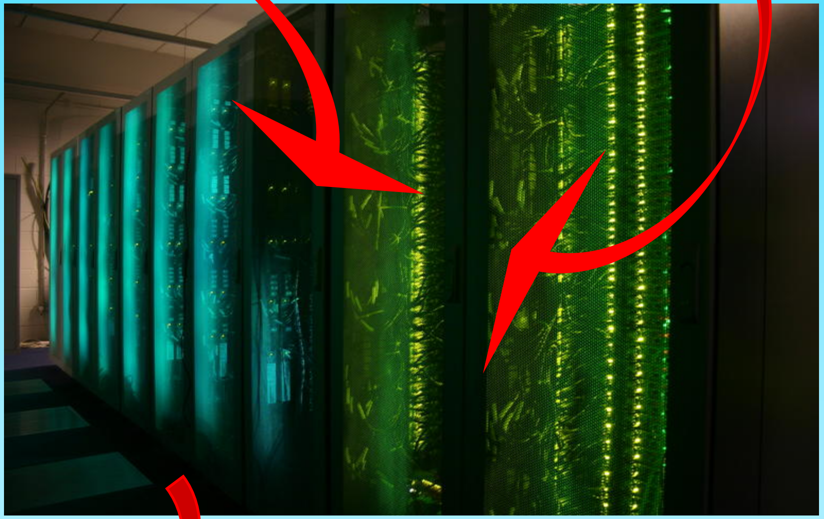
Relevant equations:

Collisionless Boltzmann;

Poisson; Friedmann eqns;

Radiative hydrodynamics

Subgrid astrophysics



How to make a virtual universe

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Hot dark matter

$m_\nu = 30$ ev → $\Omega_m = 1$

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 ($E_{3\,max}$ ≅ 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.

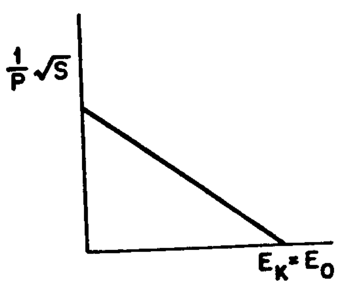


Fig. 1. Kurie plot for $M_\nu = 0$.

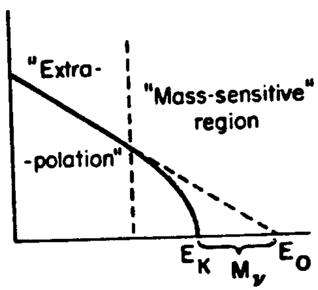
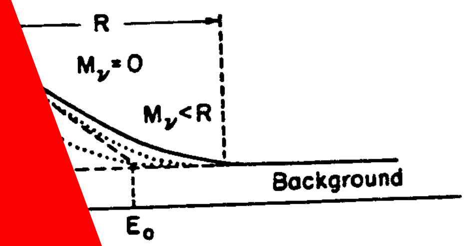


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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-... ...ongly 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 ...ass and the influence of R are indistinguishable. For M_ν ...ermination the knowledge of R is compulsory. The background de-termines 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 ∼ Δp/p = const.). A classical example is ^3H β-decay, which has 1) the smallest E_0 ∼ 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 ∼ 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.

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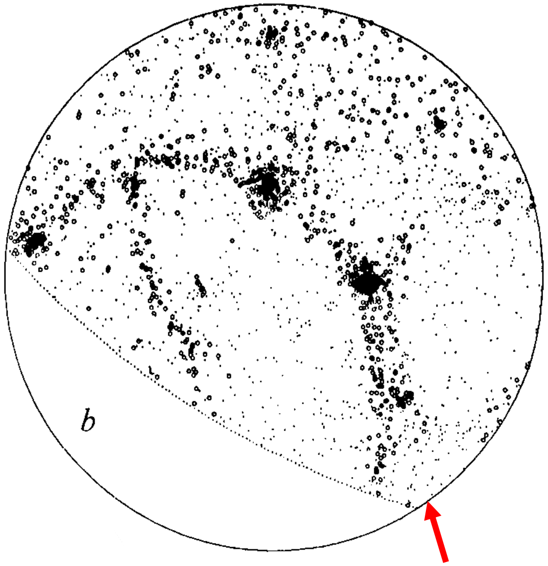
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

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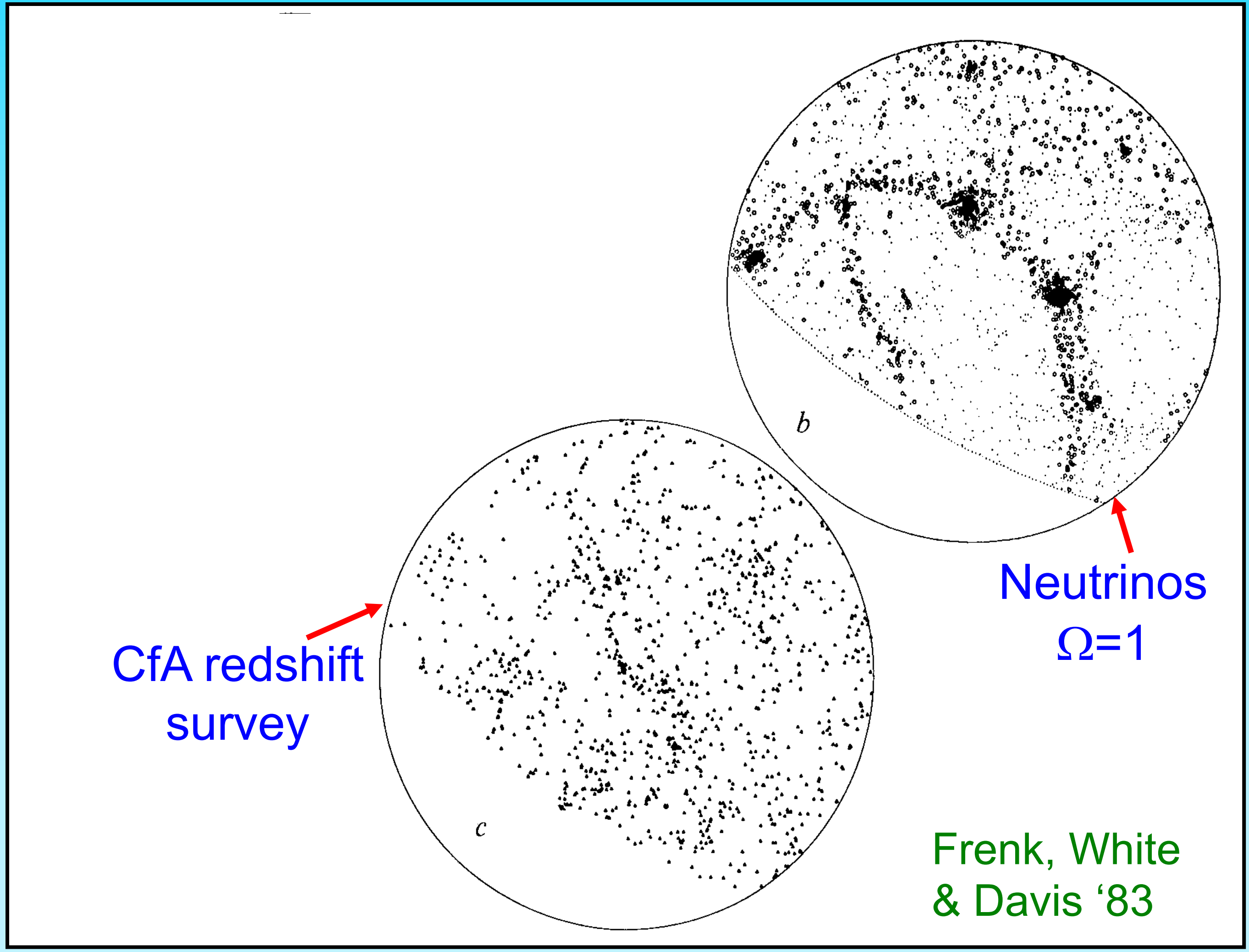
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω → m_ν<< 30 ev



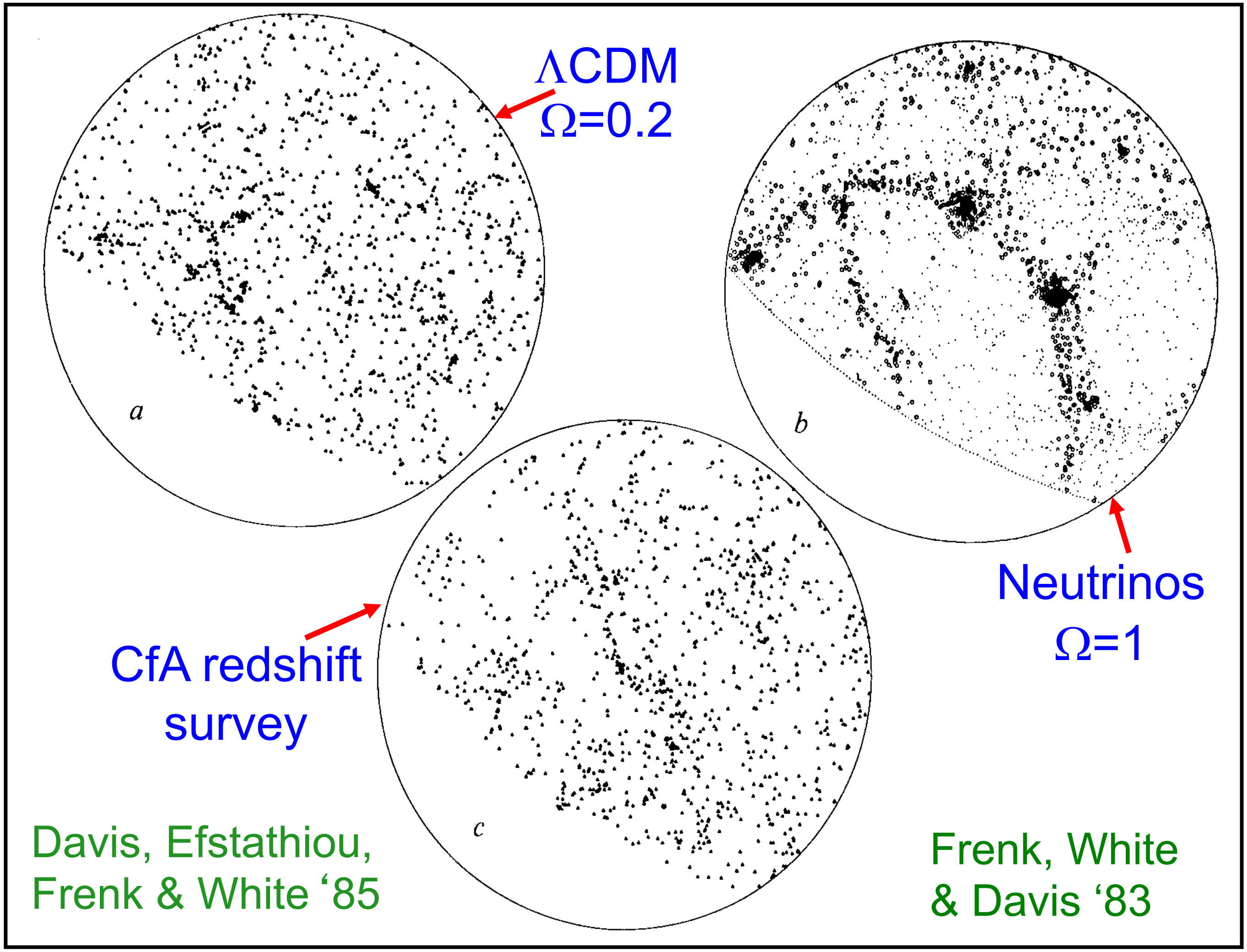
Non-baryonic dark matter cosmologies

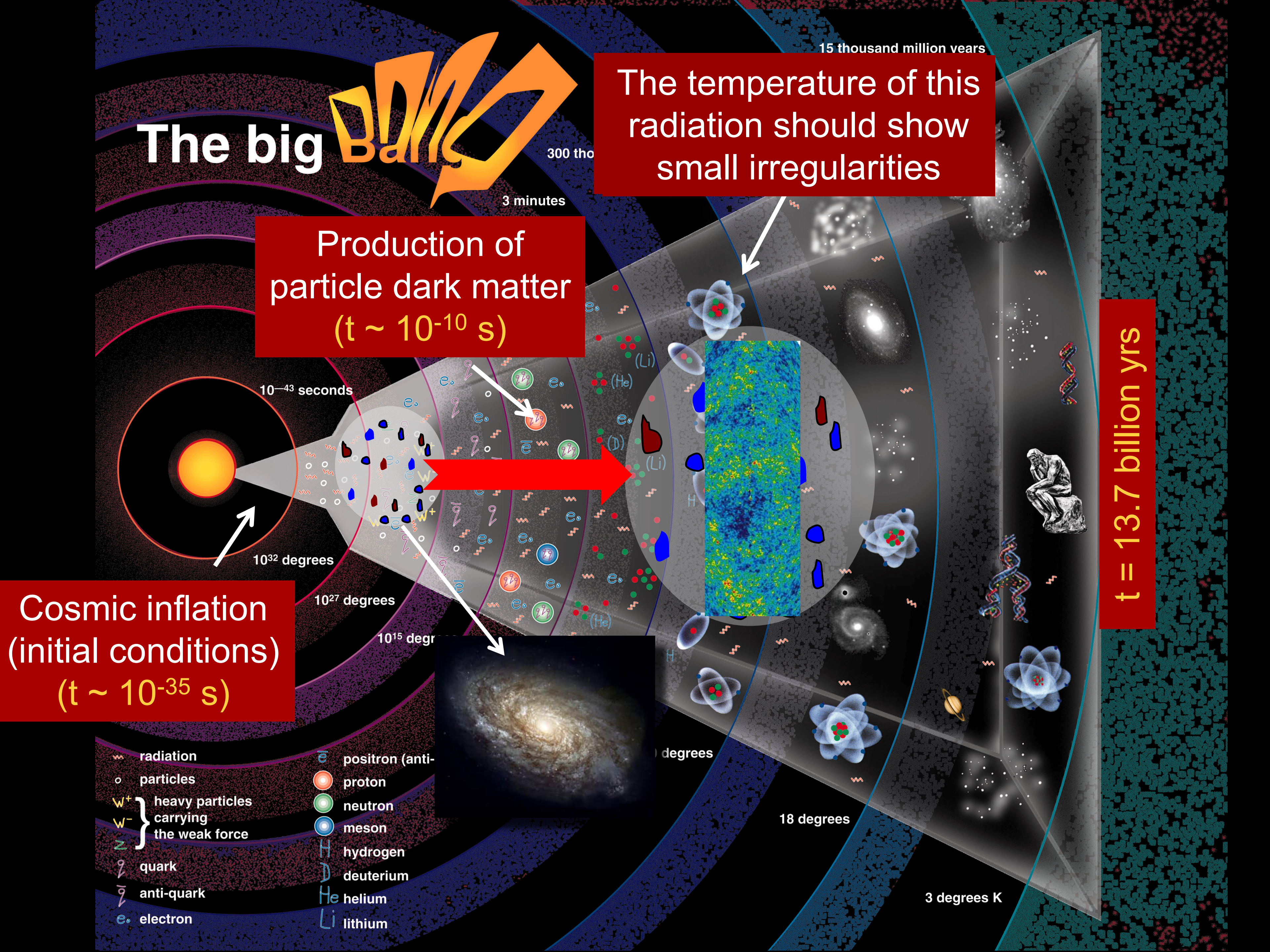
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω → m_ν<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically





The big Bang
15 thousand million years
The temperature of this radiation should show small irregularities
300 tho
3 minutes
Production of particle dark matter
(t ~ 10^{-10} s)
10^{-43} seconds
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

Temperature anisotropies in CMB

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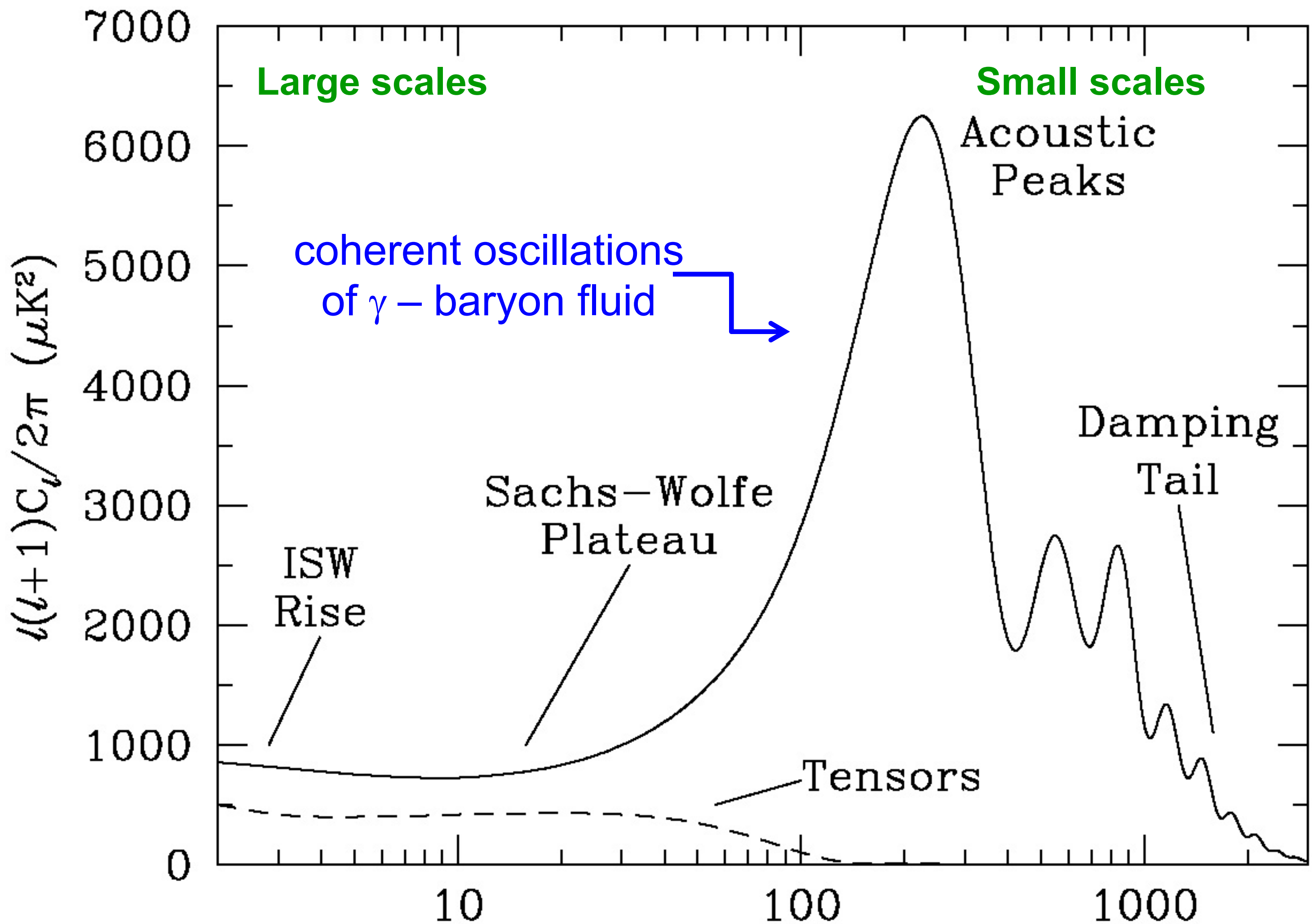
2D power spectrum



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

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

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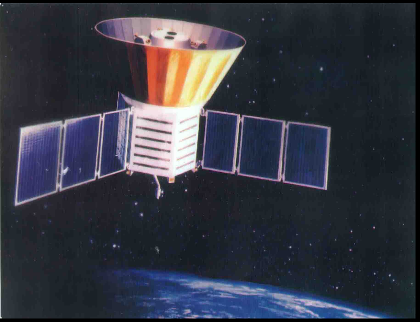
Jim Peebles

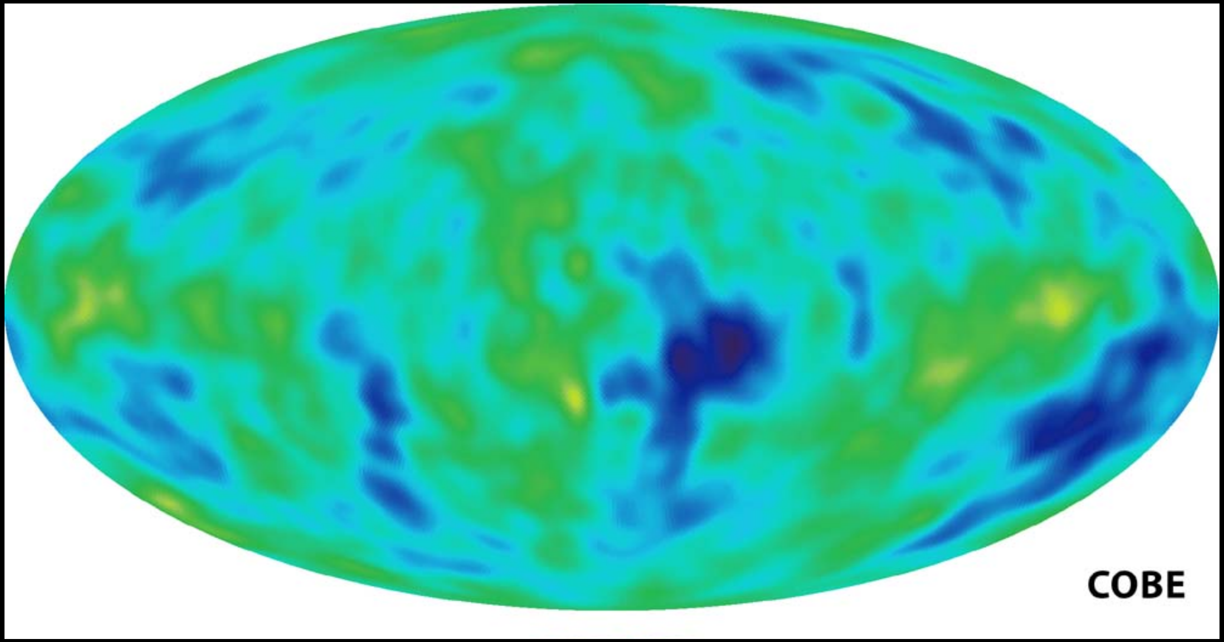
Nobel prize 2019

ICC

The CMB

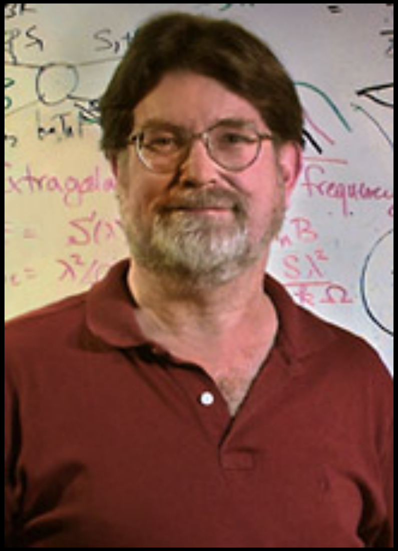
1992





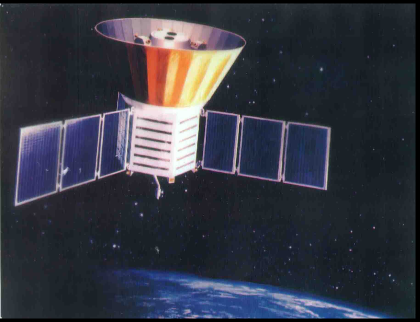
George Smoot - Nobel Prize 2006

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

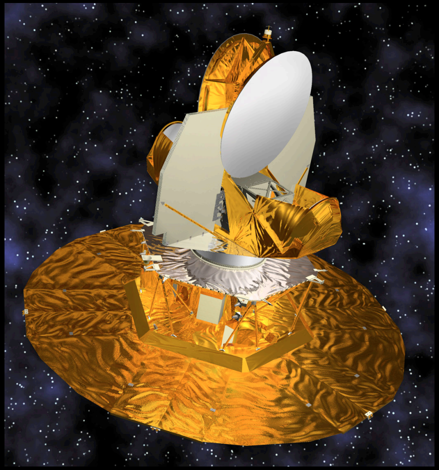


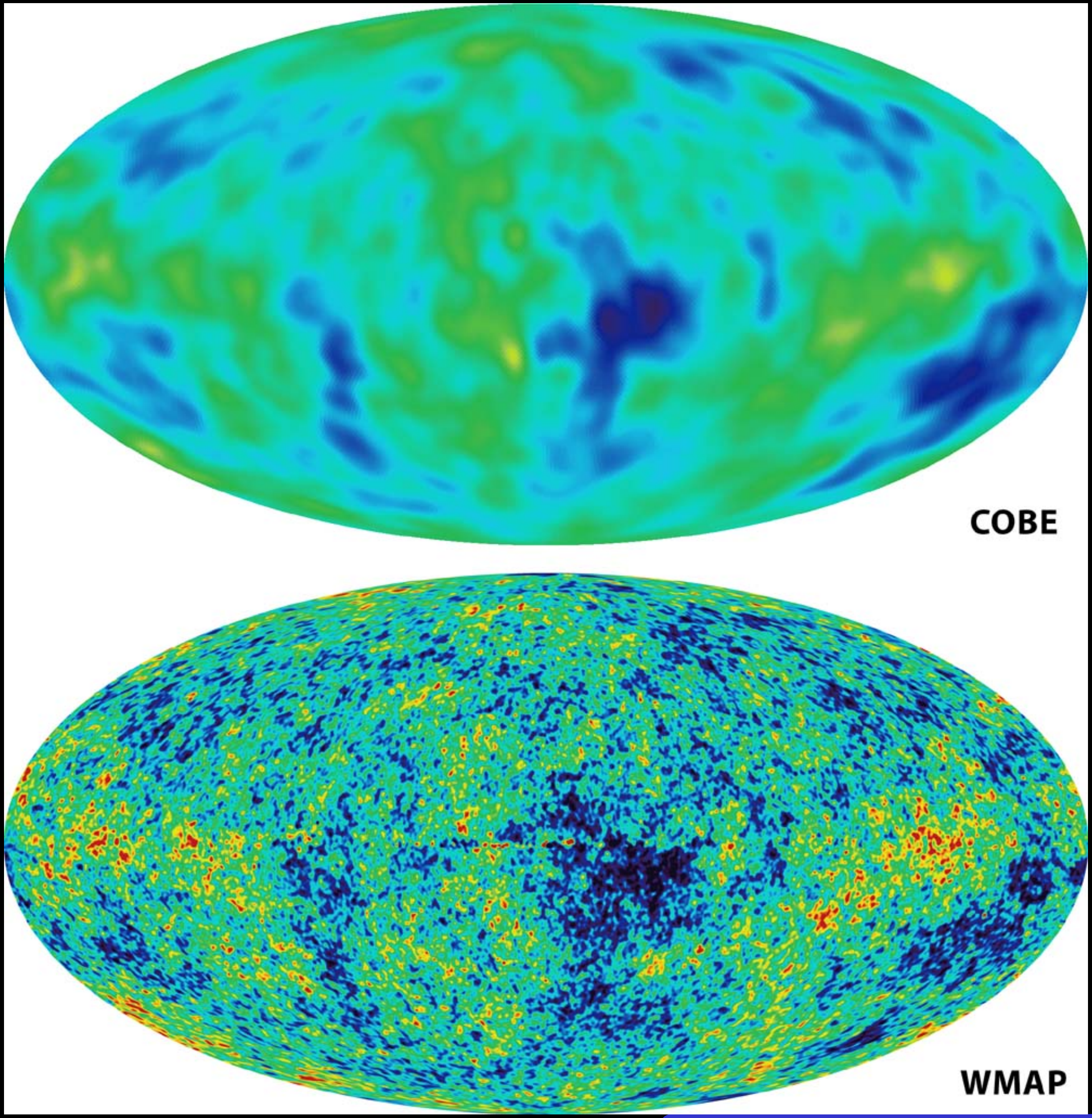
The CMB

1992



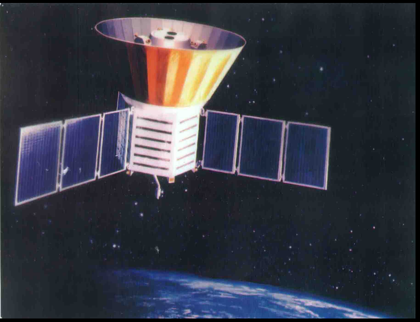
2003



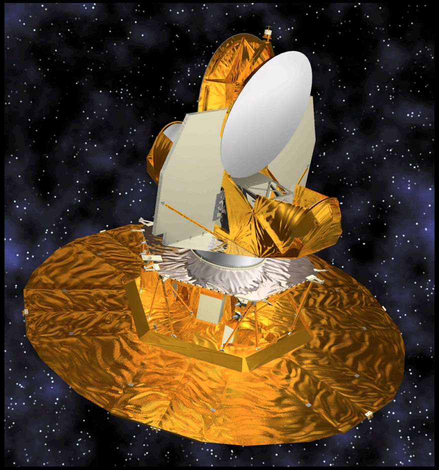


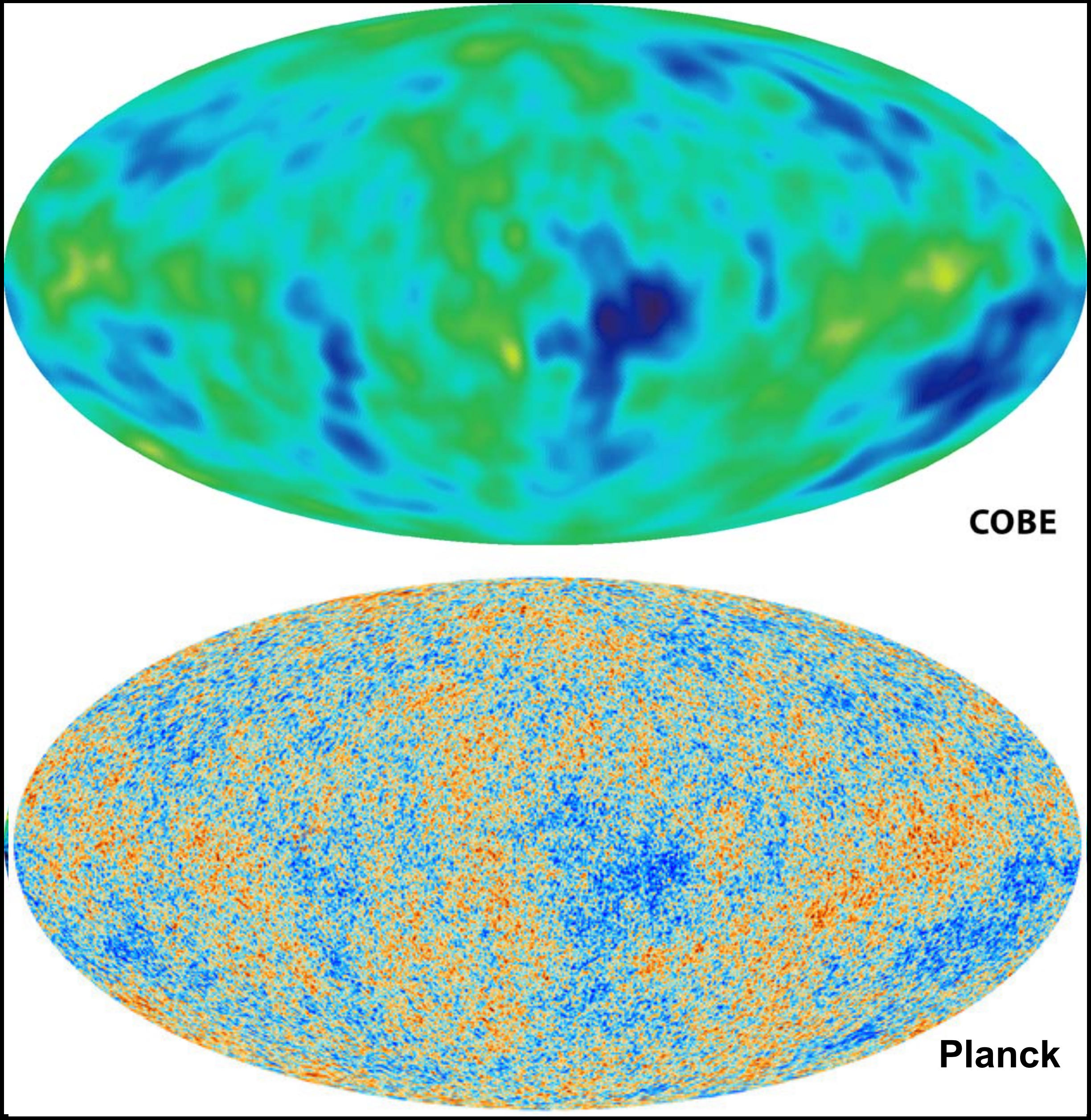
The CMB

1992



2012





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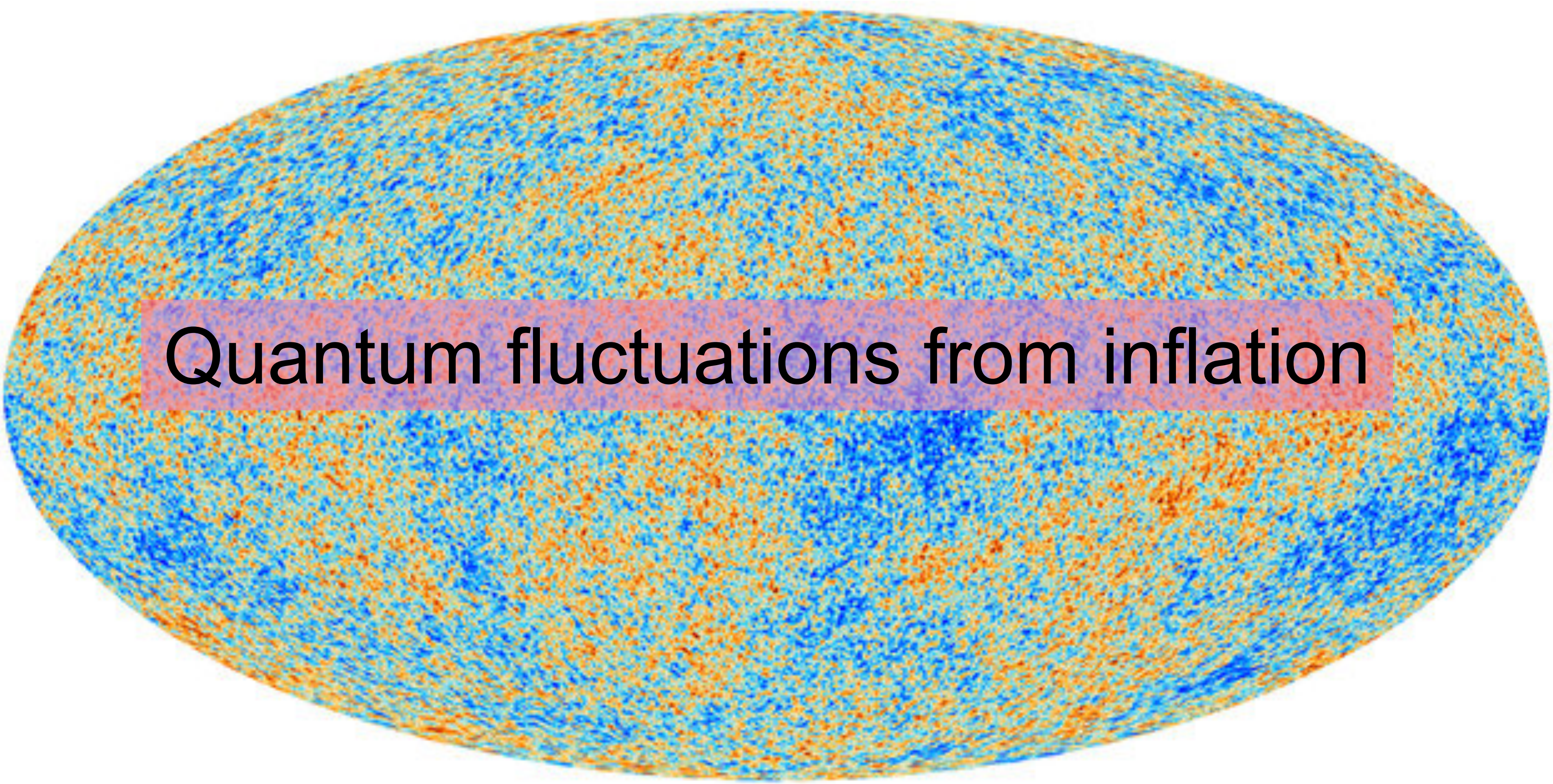
The initial conditions for galaxy formation



Planck collaboration ‘13

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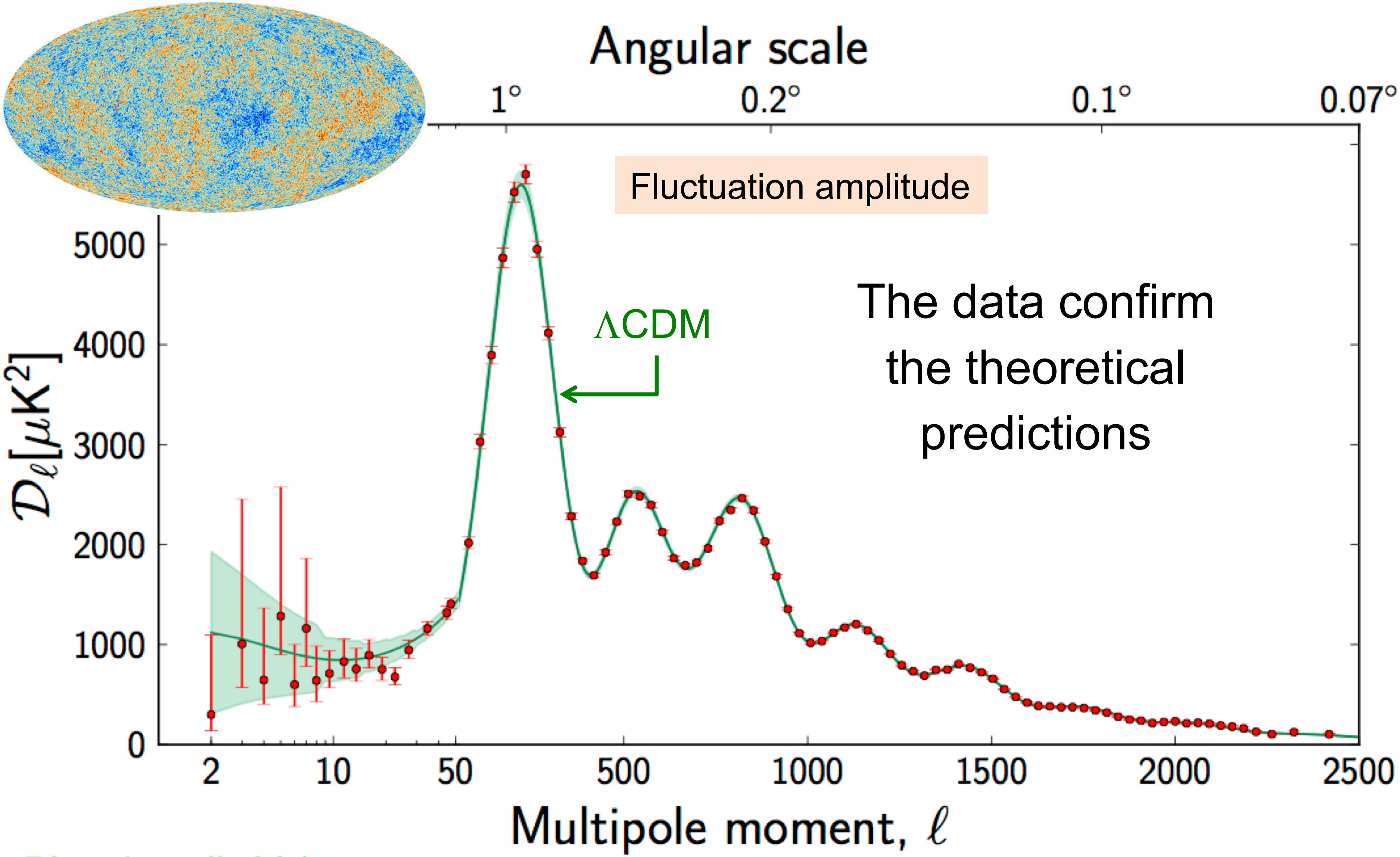
Planck: CMB temperature anisotropies



Planck coll. 2015

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Univer

The six parameters of minimal ΛCDM model

6 model parameters

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$ . . . . density of baryons	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$ . . . . density of CDM	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!

$\Omega = 1$

Planck collaboration '13

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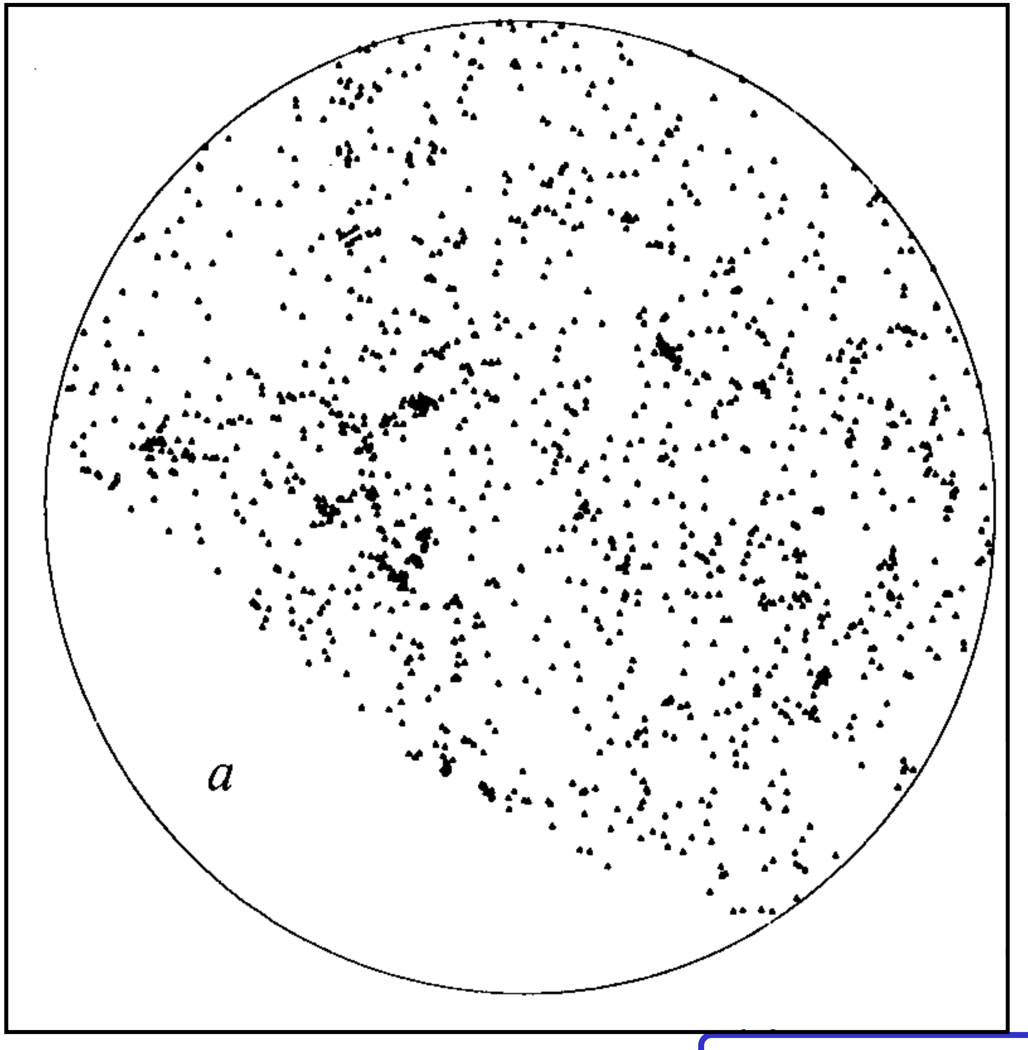
N-body simulations of large-scale structure in ΛCDM

Davis, Efstathiou, Frenk & White '85



Formation of CDM halos

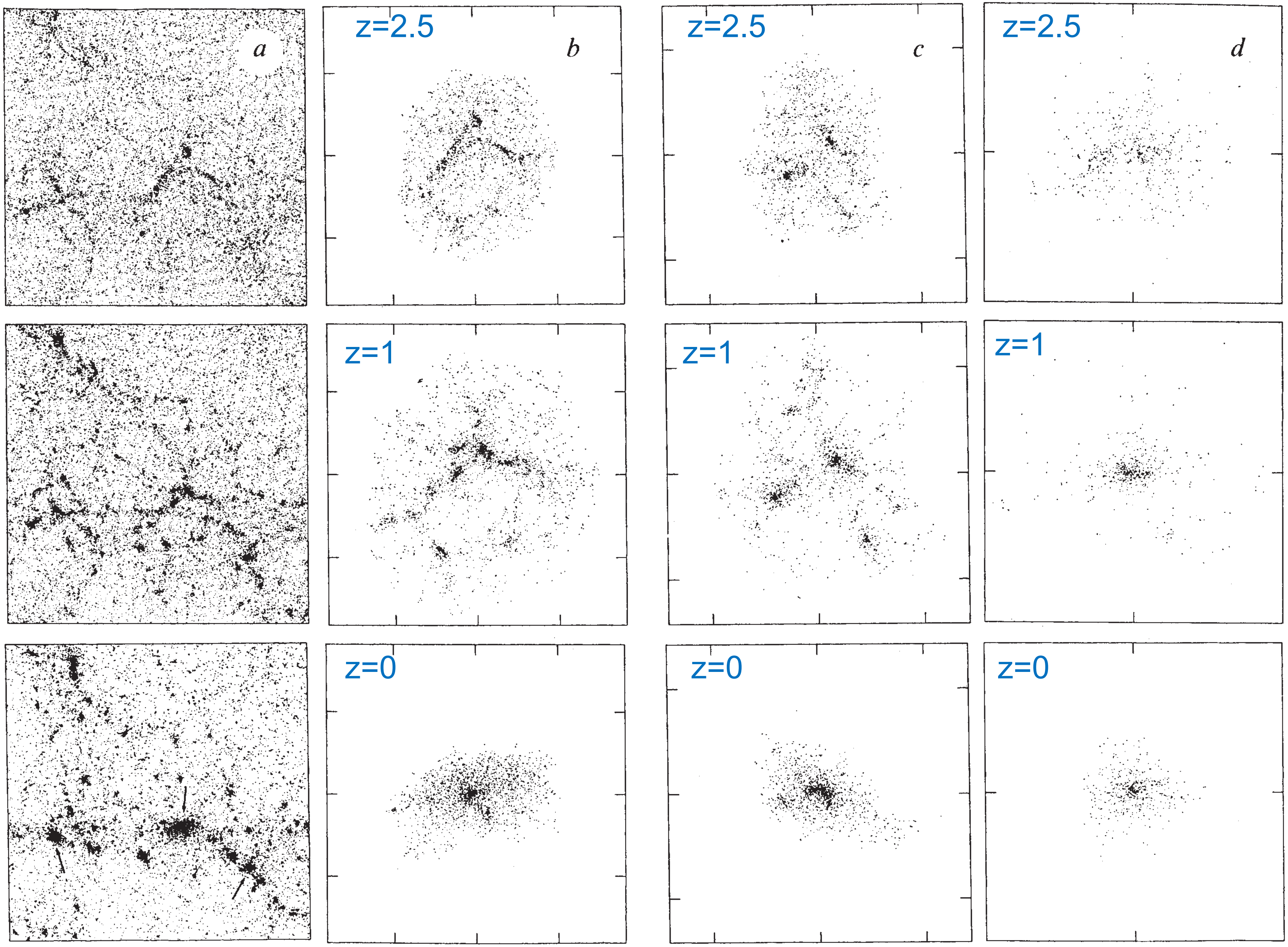
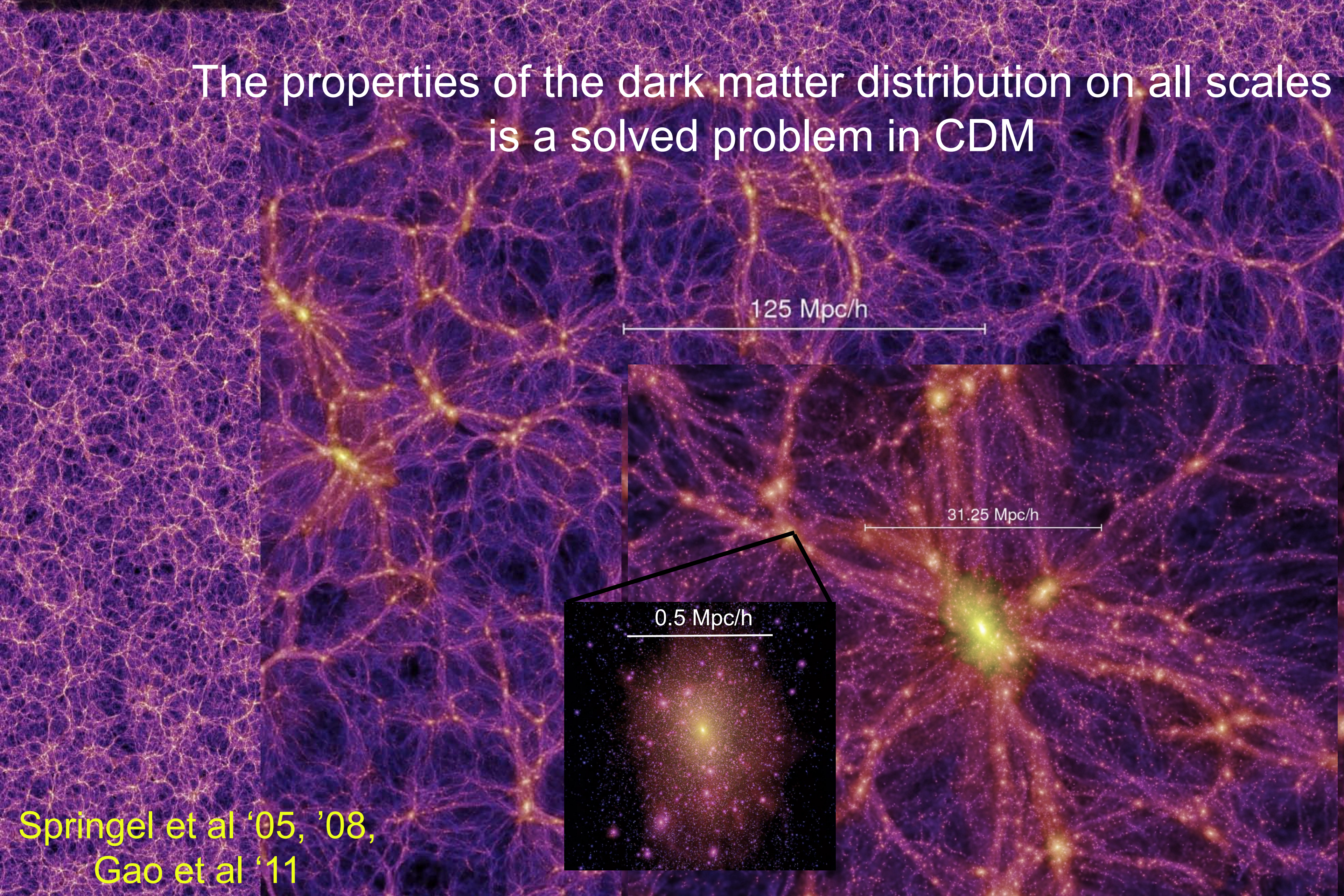


Fig. 1

Frenk et al 1985

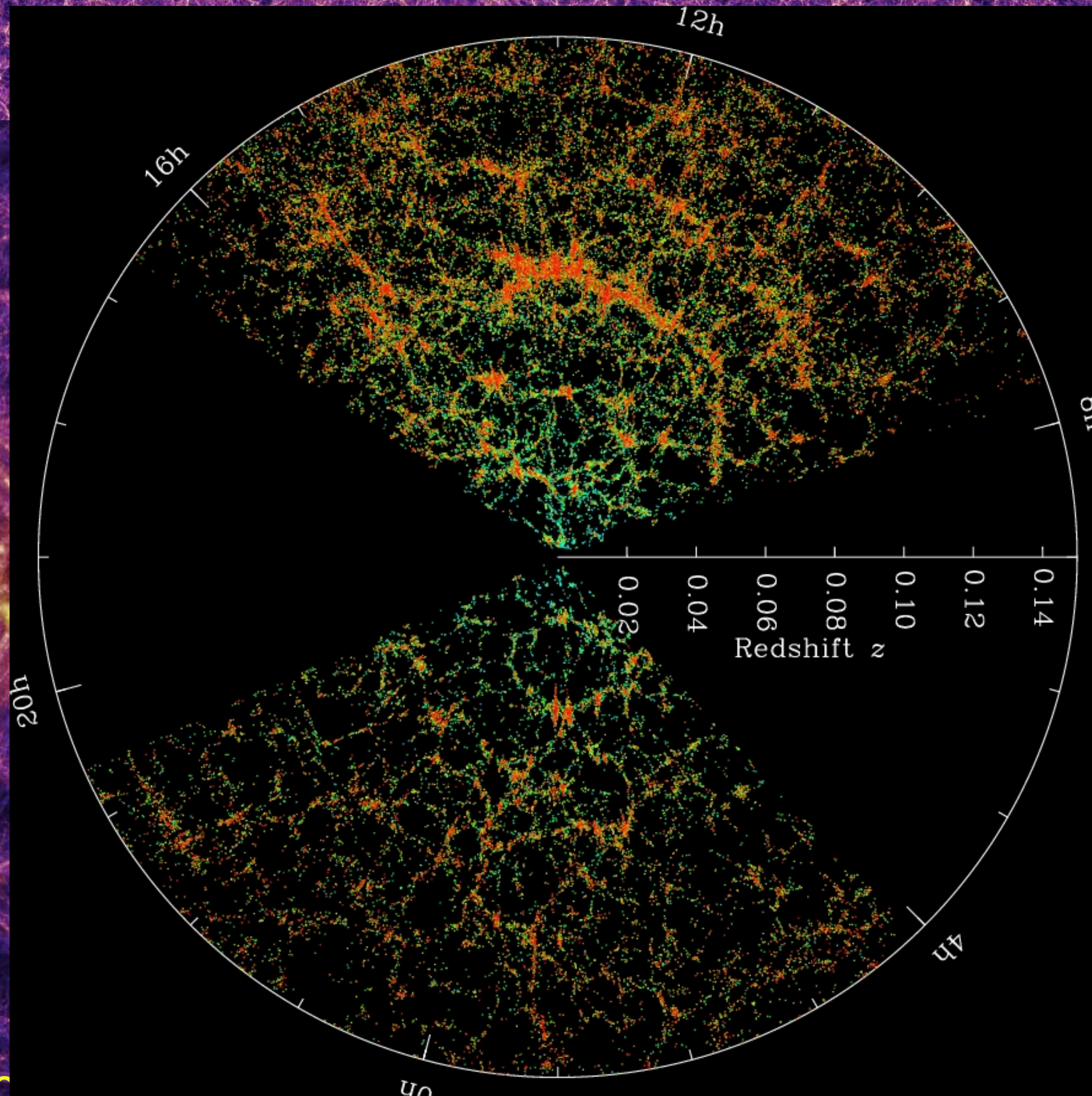
The Millennium/Aquarius/Phoenix simulation series

The properties of the dark matter distribution on all scales is a solved problem in CDM



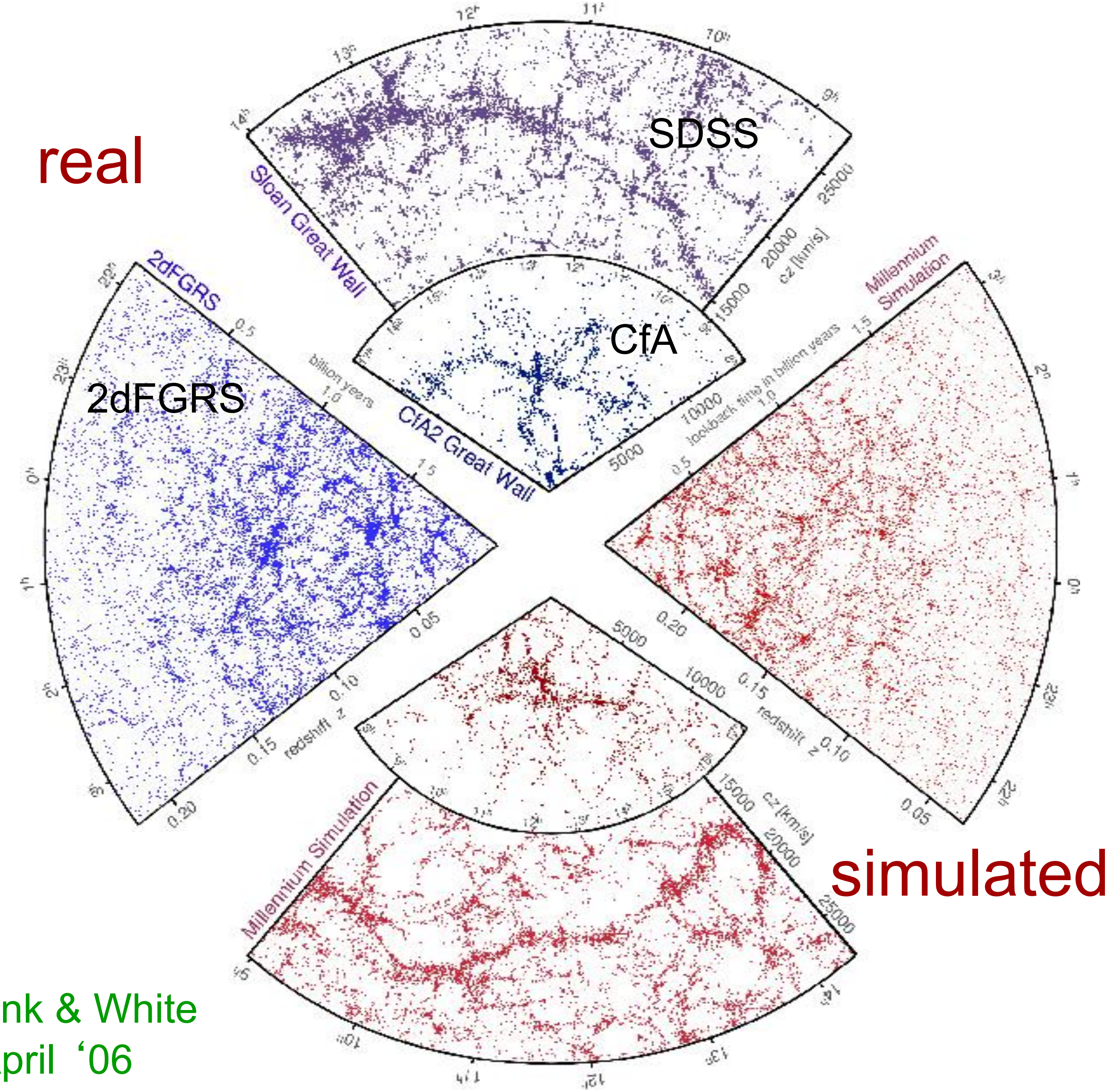
Springel et al ‘05, ’08, Gao et al ‘11

The Millennium/Aquarius/Phoenix simulation series



Springel et al ‘05, ’0

Gao et al ‘11



Springel, Frenk & White
Nature, April ‘06

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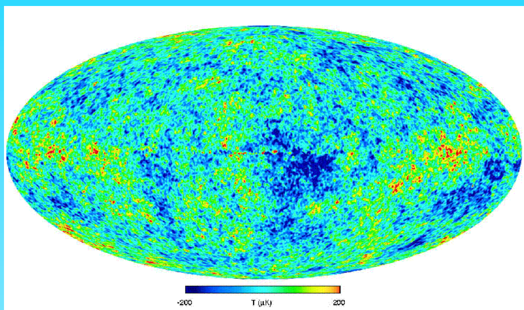
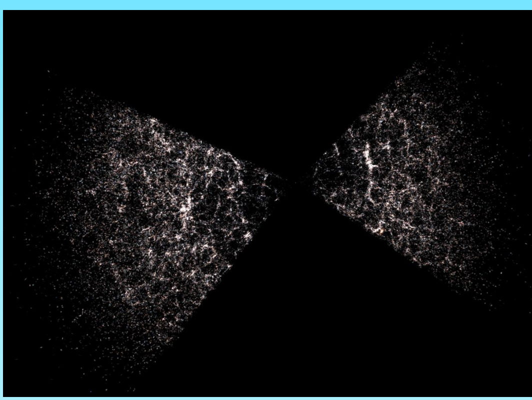
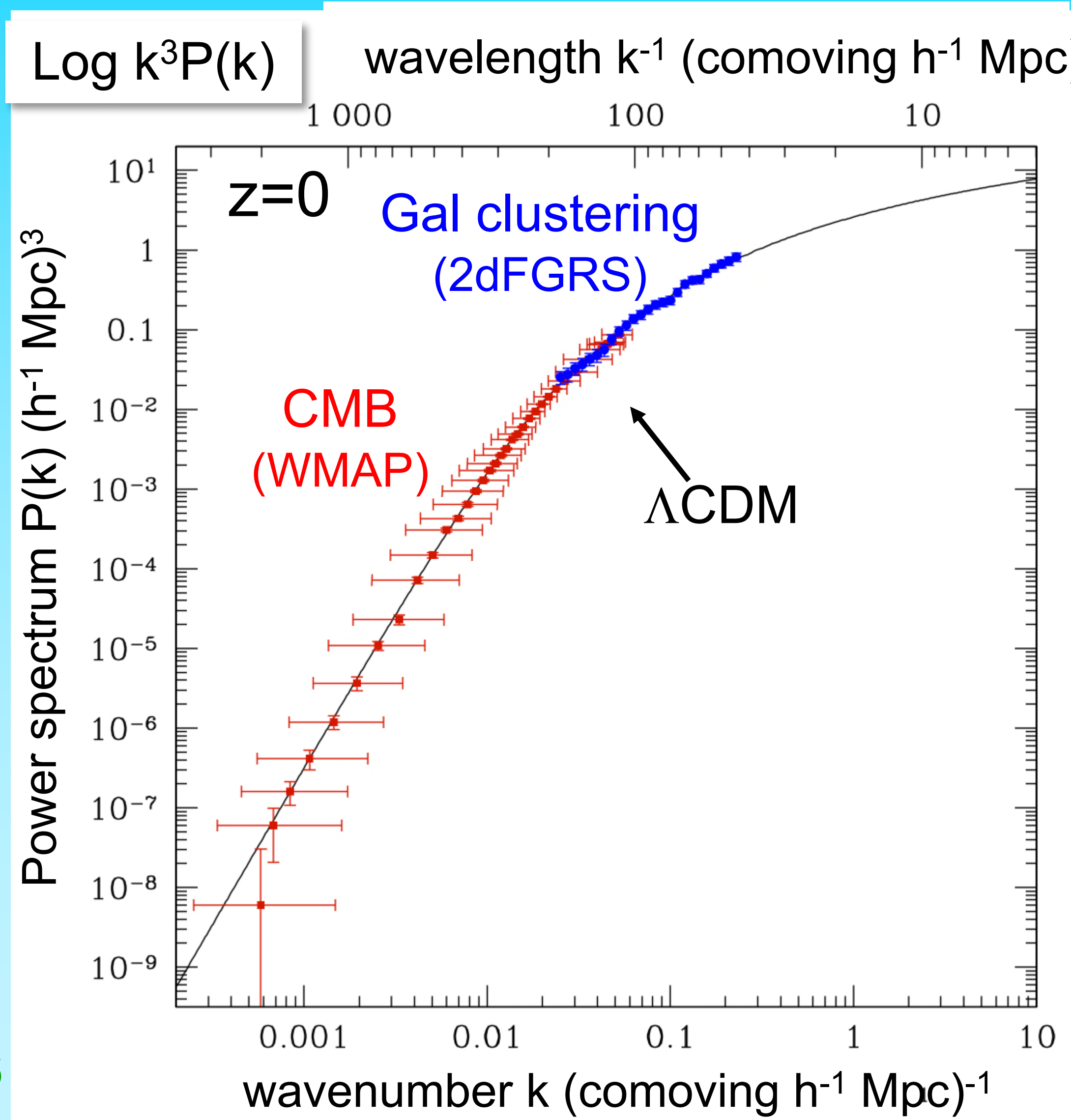
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

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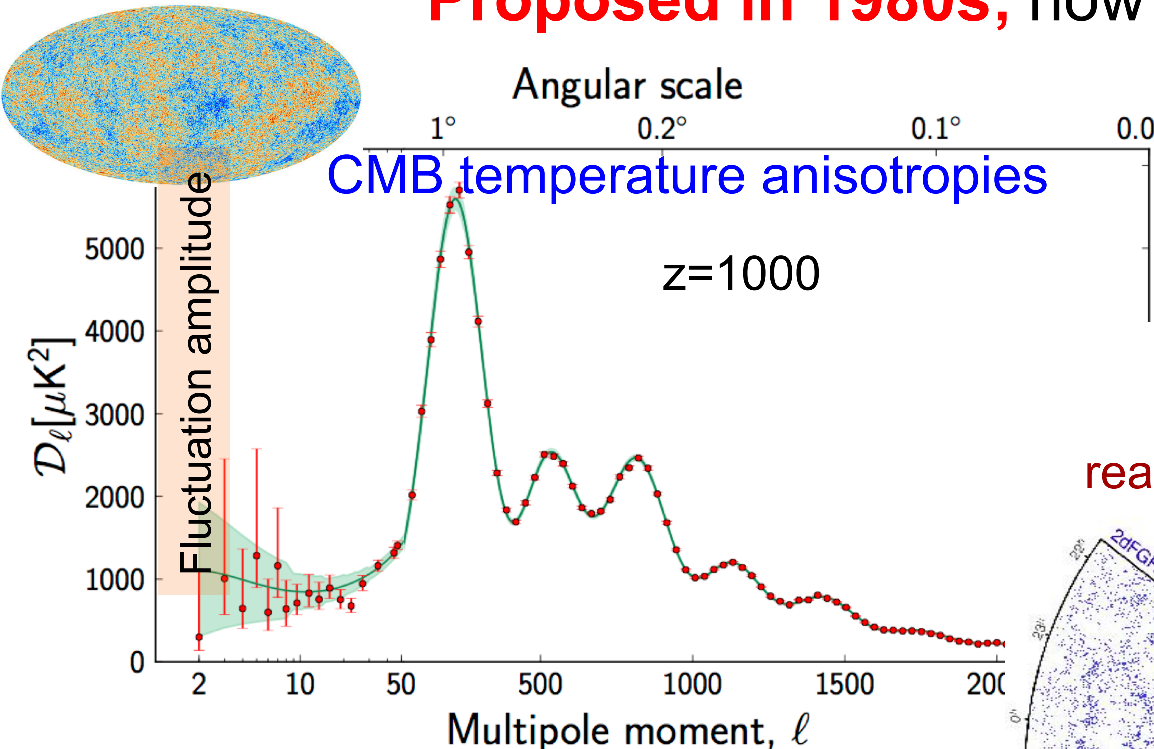
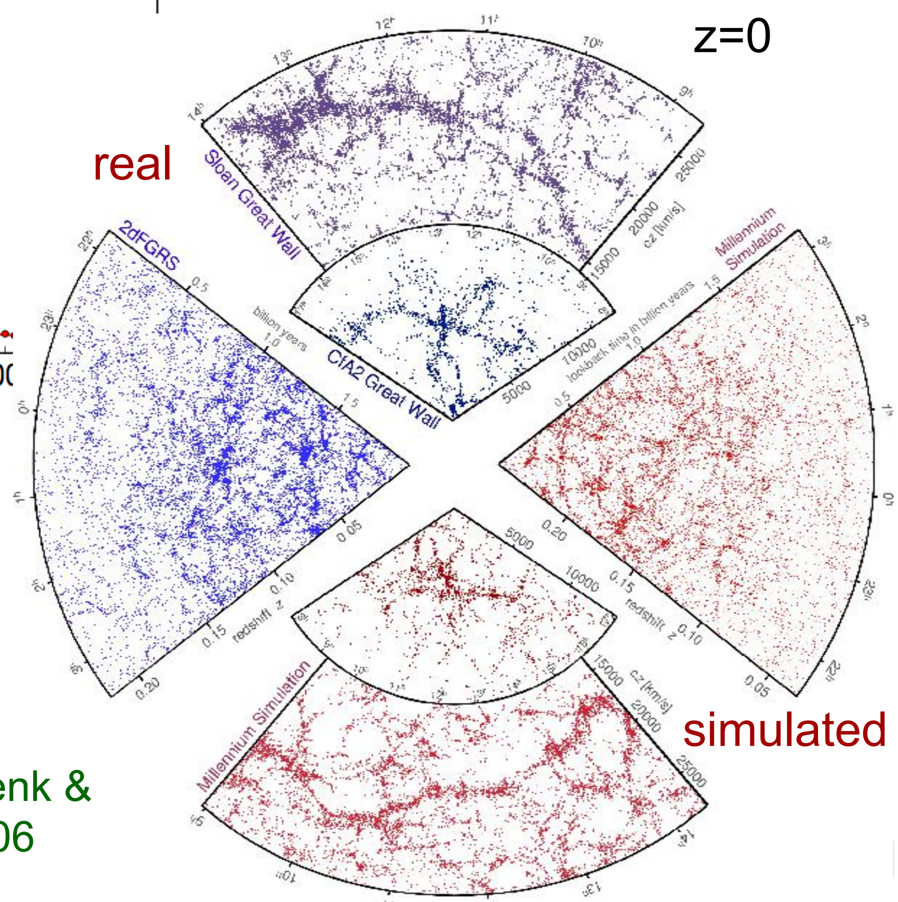
The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:



Planck coll. 2015



Springel, Frenk & White 2006

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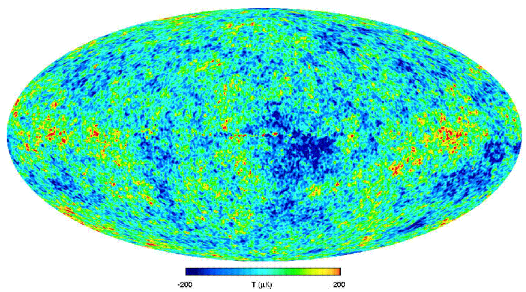
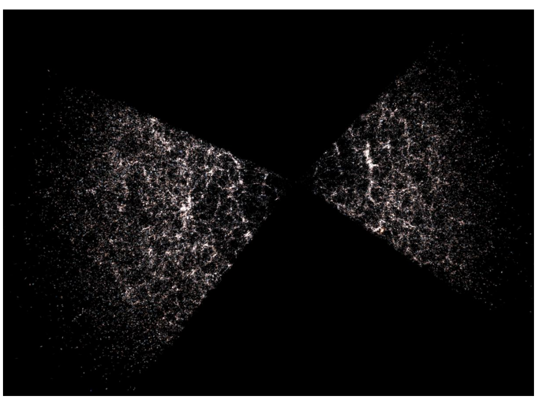
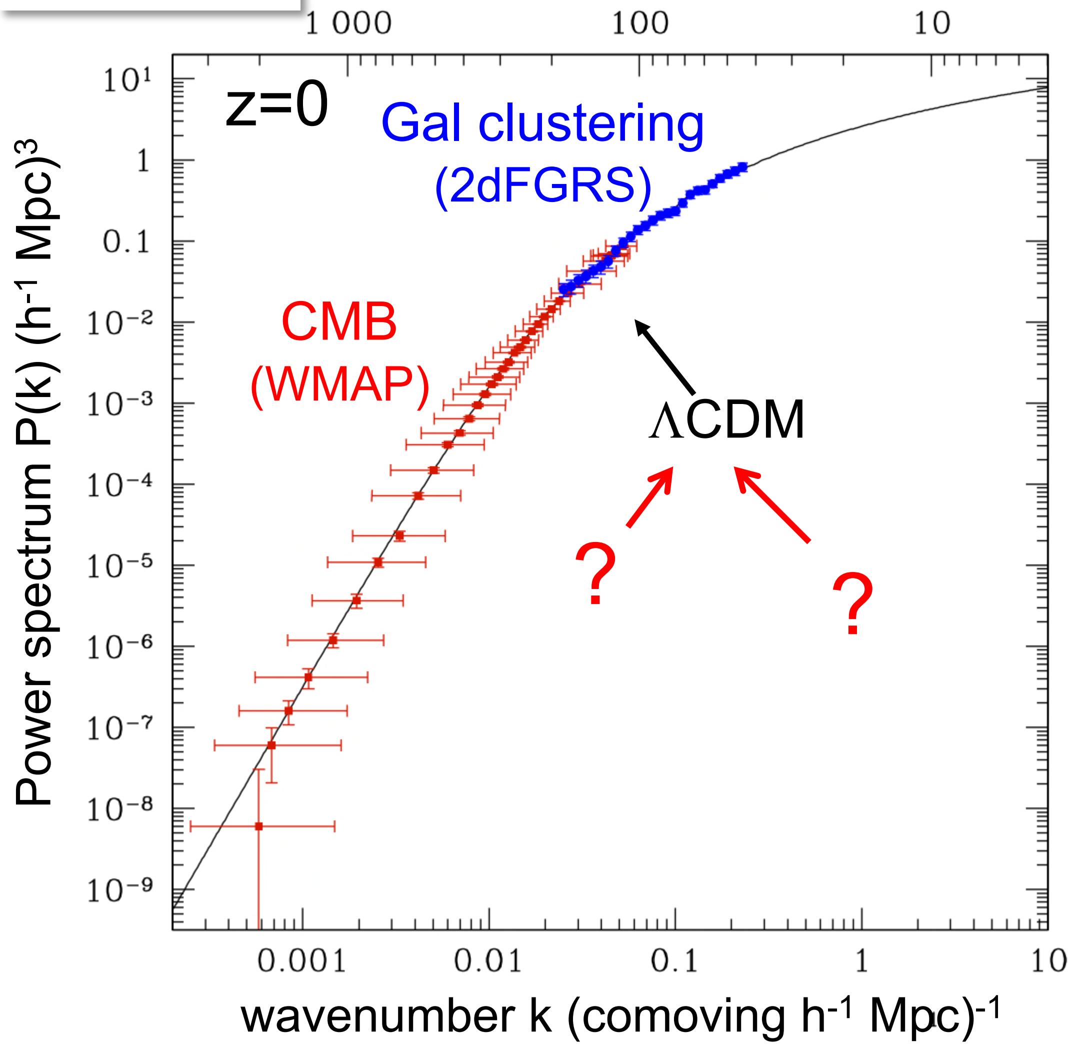
The cosmic power spectrum: from the CMB to the 2dFGRS



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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Free streaming →

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

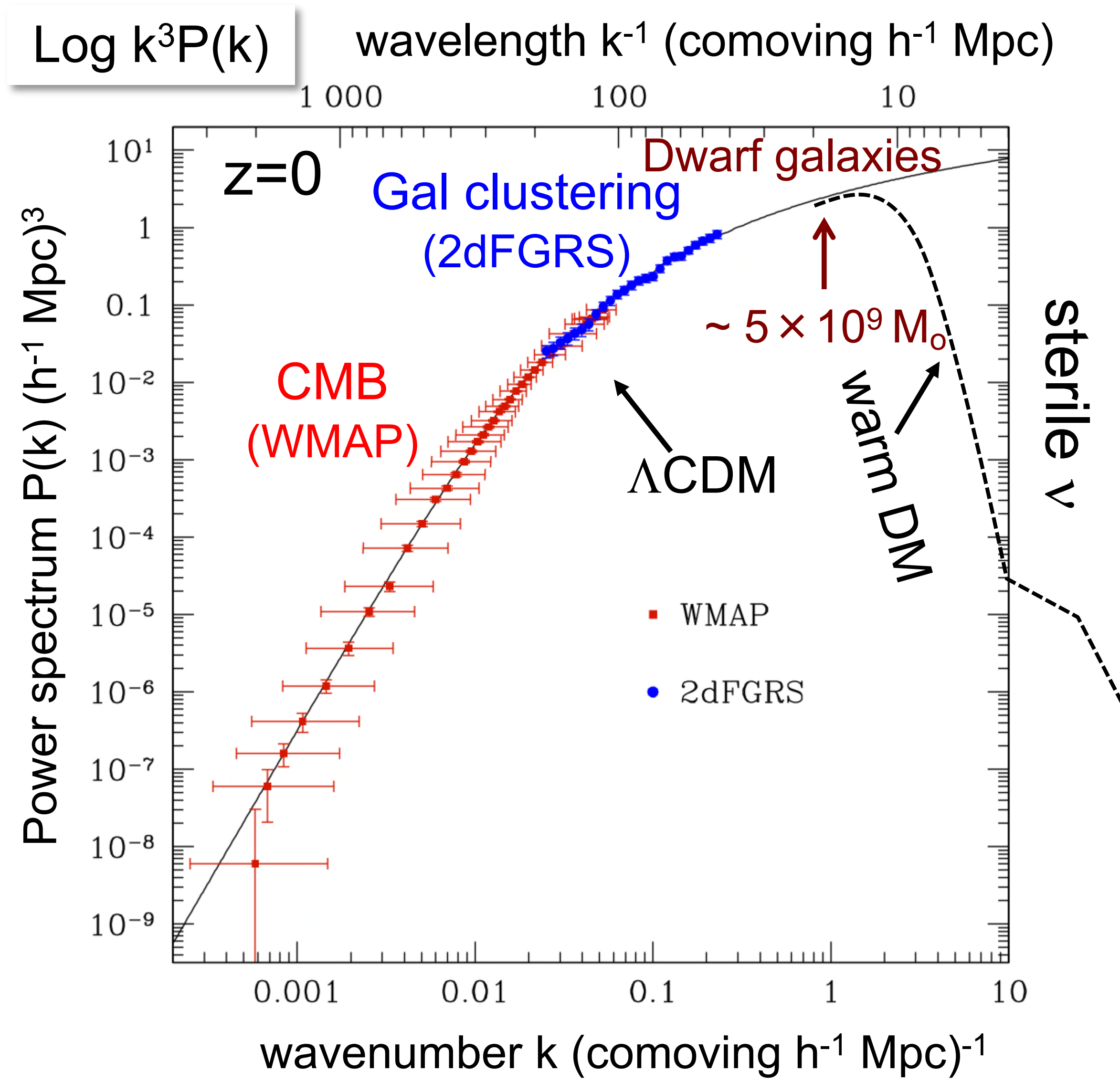
for thermal relic

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

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\,M_o$



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

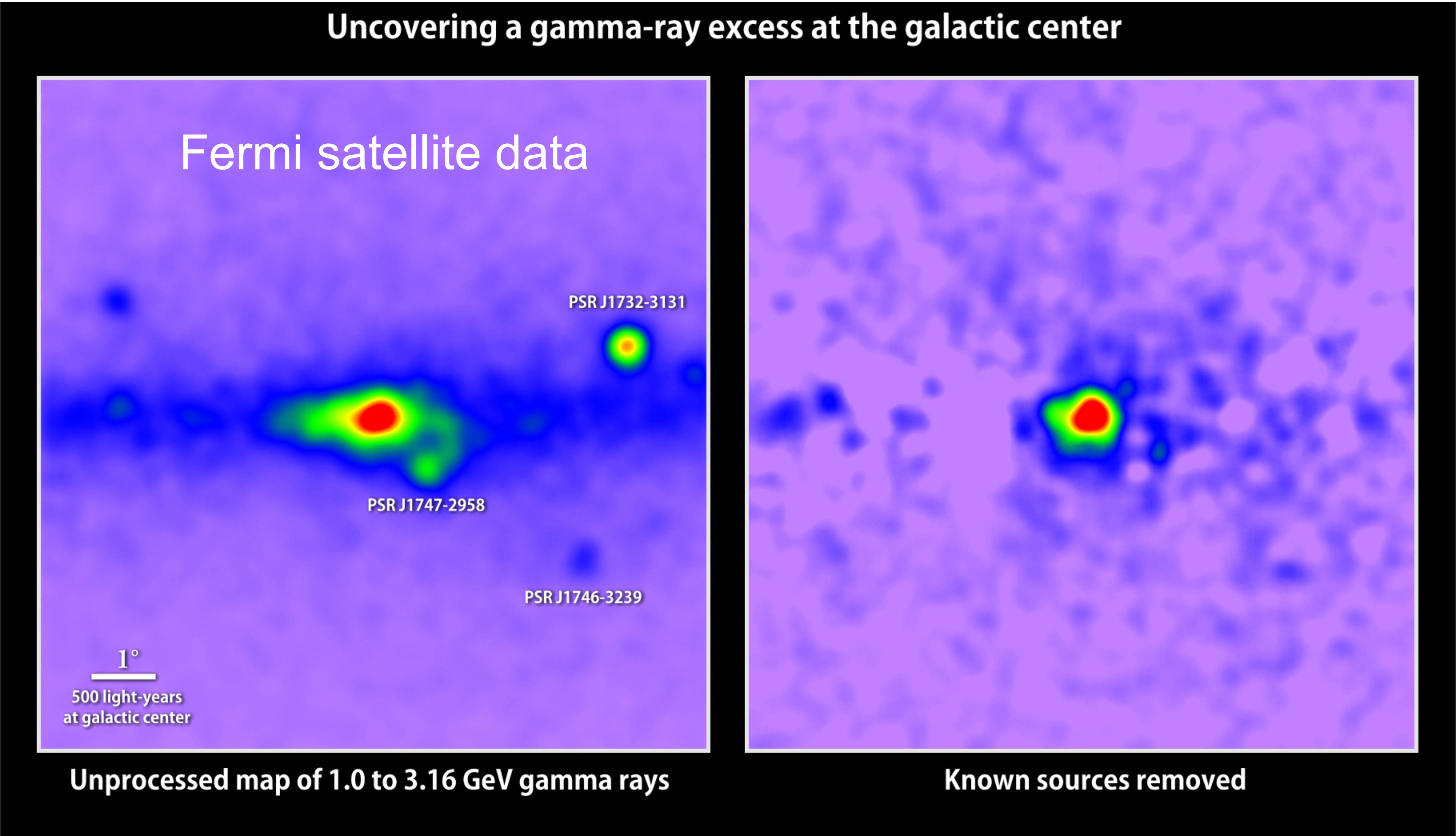
Cold dark matter

Annihilation radiation from the Galactic Centre?

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

Decay line at 3.51 keV in galaxies and clusters

Warm dark matter
WDM decay line in 69 stacked clusters?

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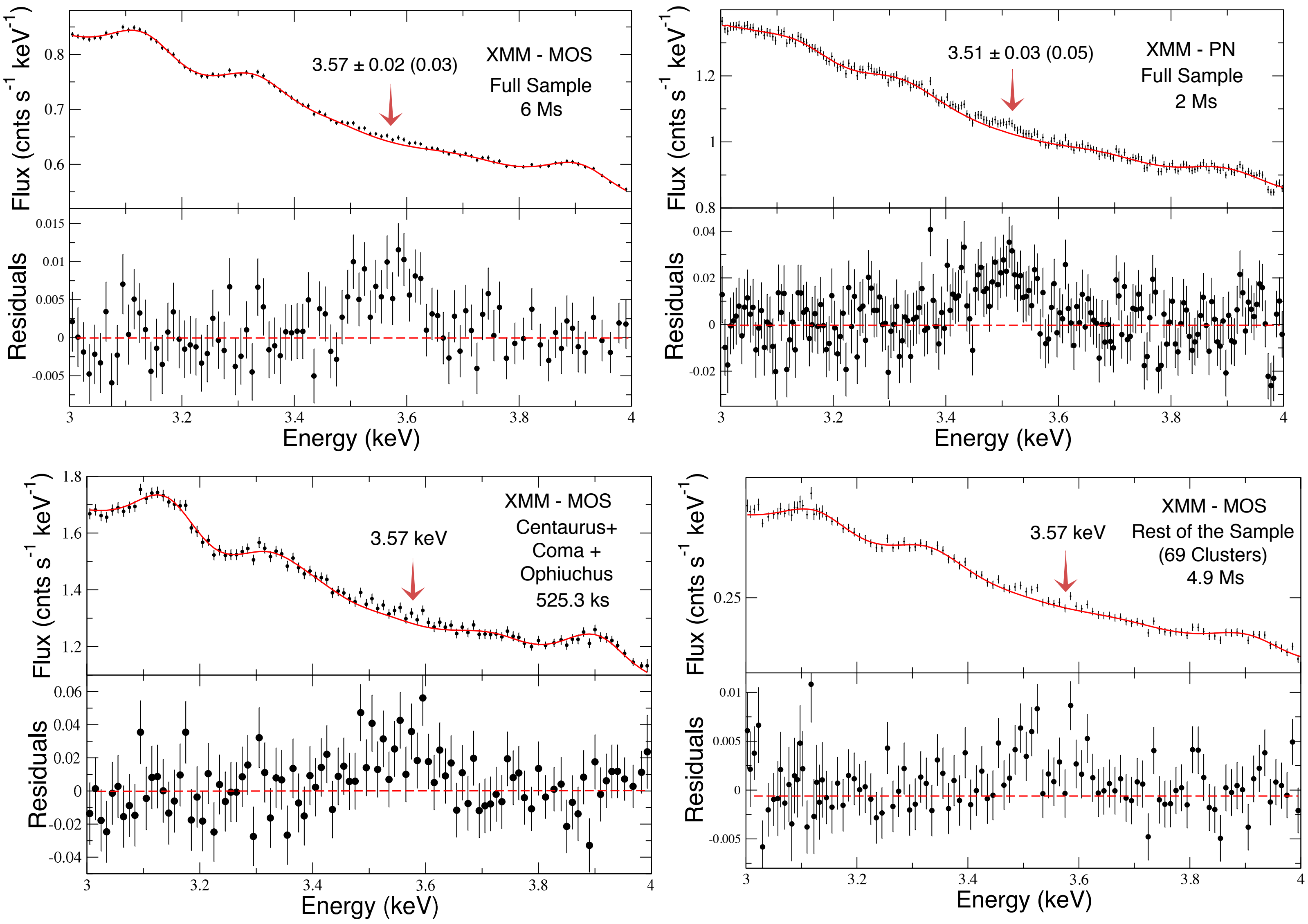
E=3.57 keV   Bulbul et al. ‘14   See also Boyarsky et al. ‘14



Both CDM & WDM compatible with CMB & galaxy clustering

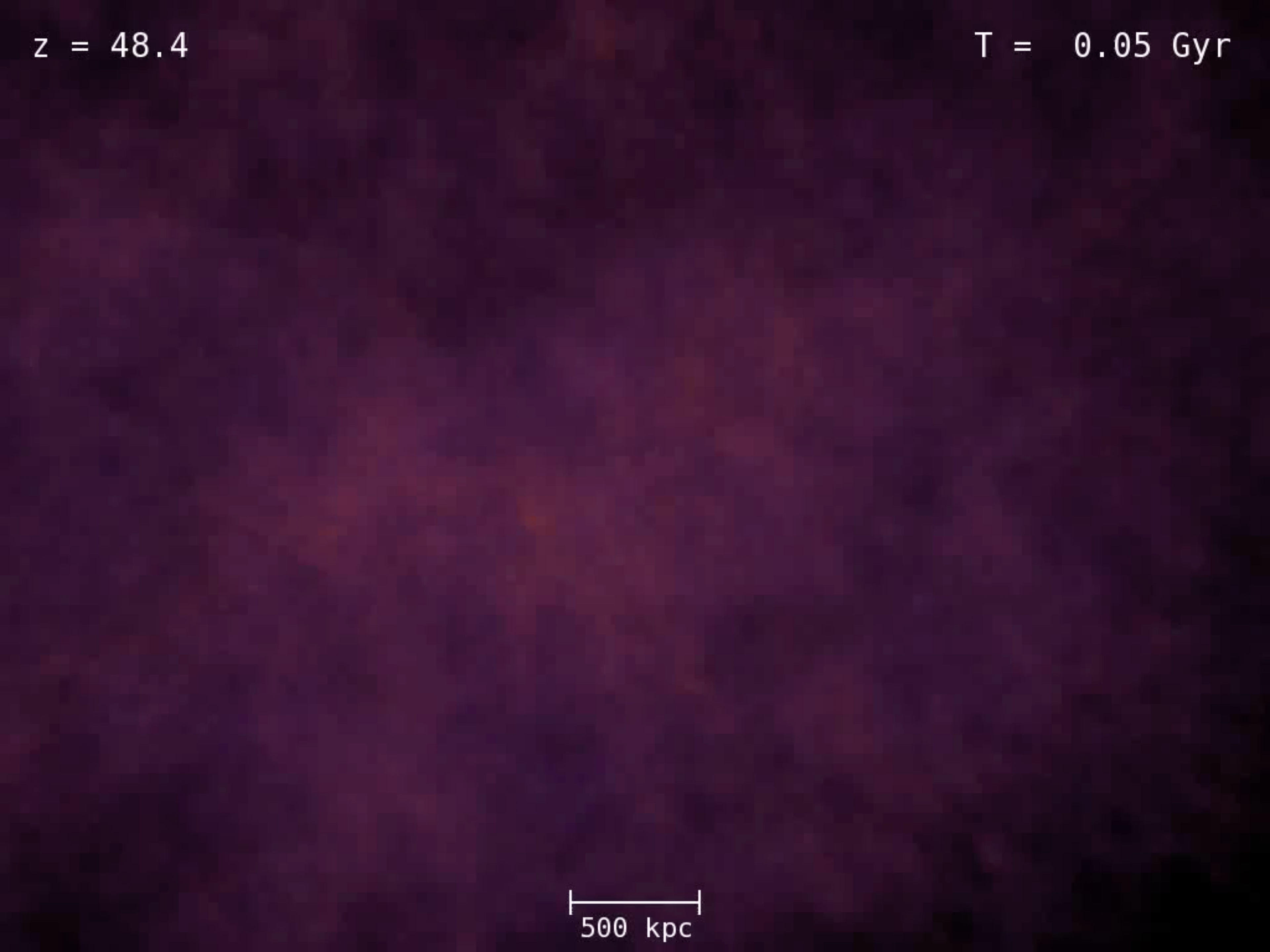
Claims that both types of DM have been discovered:

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

(strongly non-linear regime)


z = 48.4
T = 0.05 Gyr
500 kpc

Cold Dark Matter | Warm Dark Matter

13.4 billion years ago

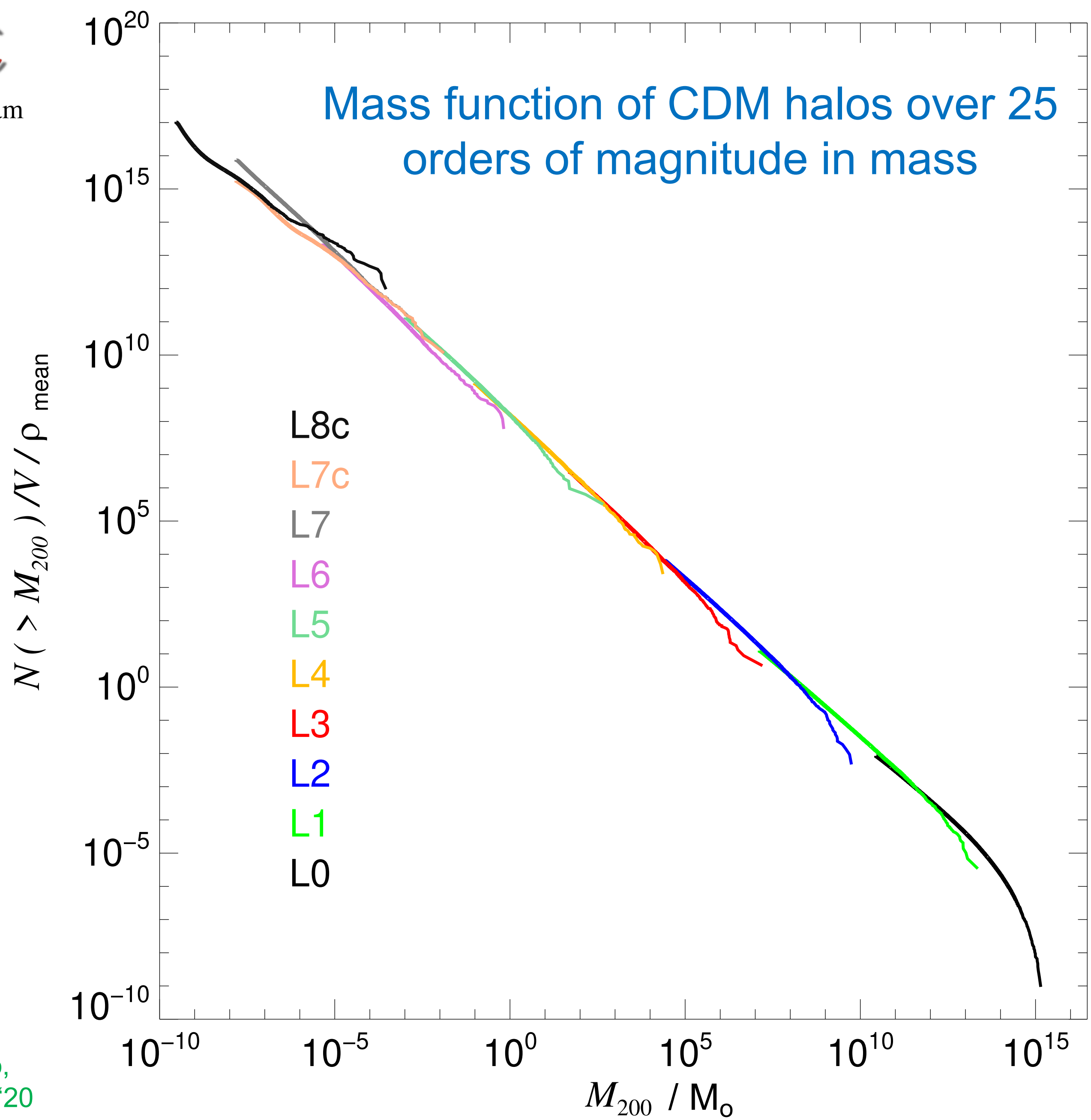
Institute for Computational Cosmology

cold dark matter

warm dark matter

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

University of Durham

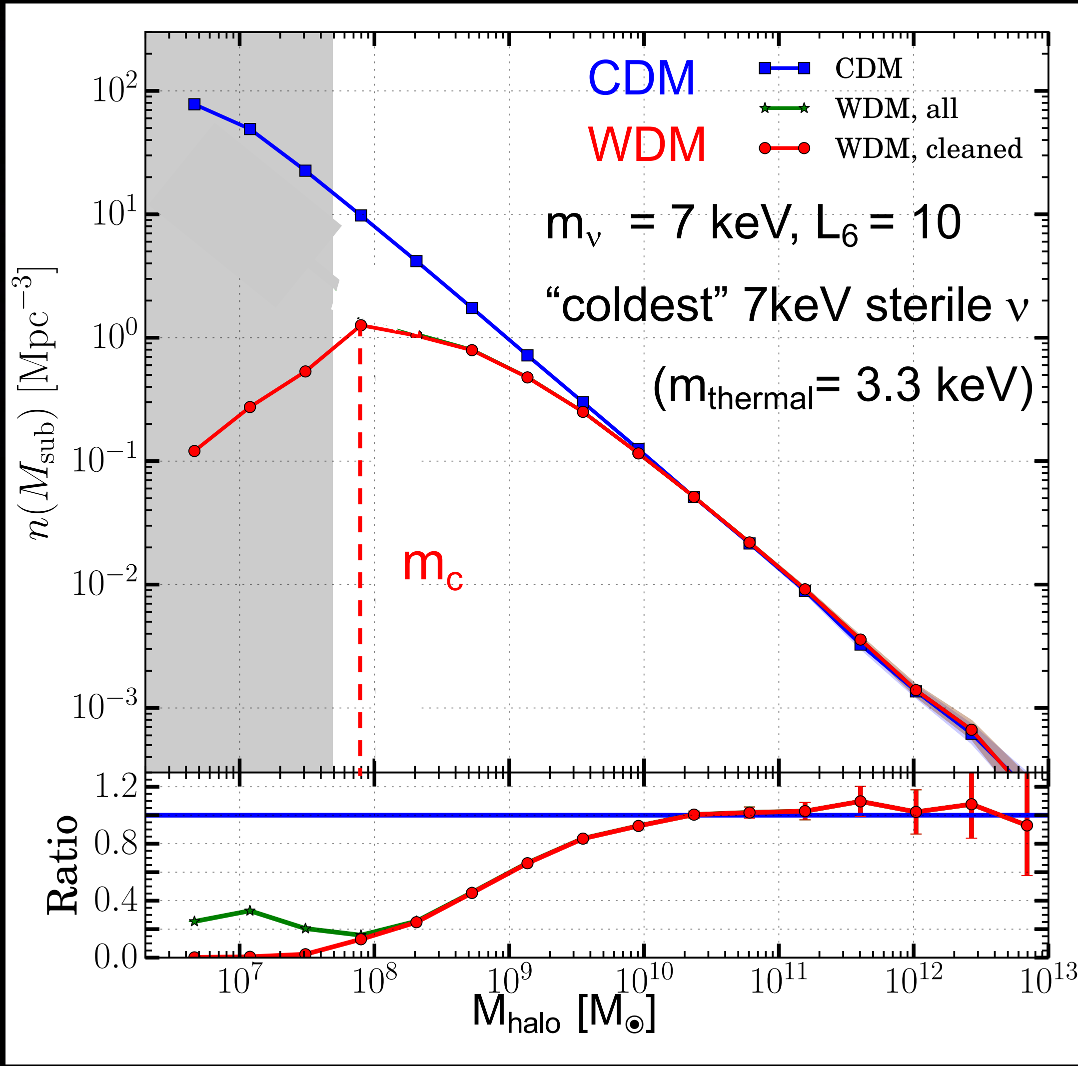


Wang, Bose, CSF, Gao, Jenkins, Springel, White '20

Institute for Computational Cosmology

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

Institute for Computational Cosmology

University of Durham

How can we distinguish the two?

Astrophysical tests of dark matter

Count the number of small-mass halos

1. Number of dark matter halos (the halos mass fn.)

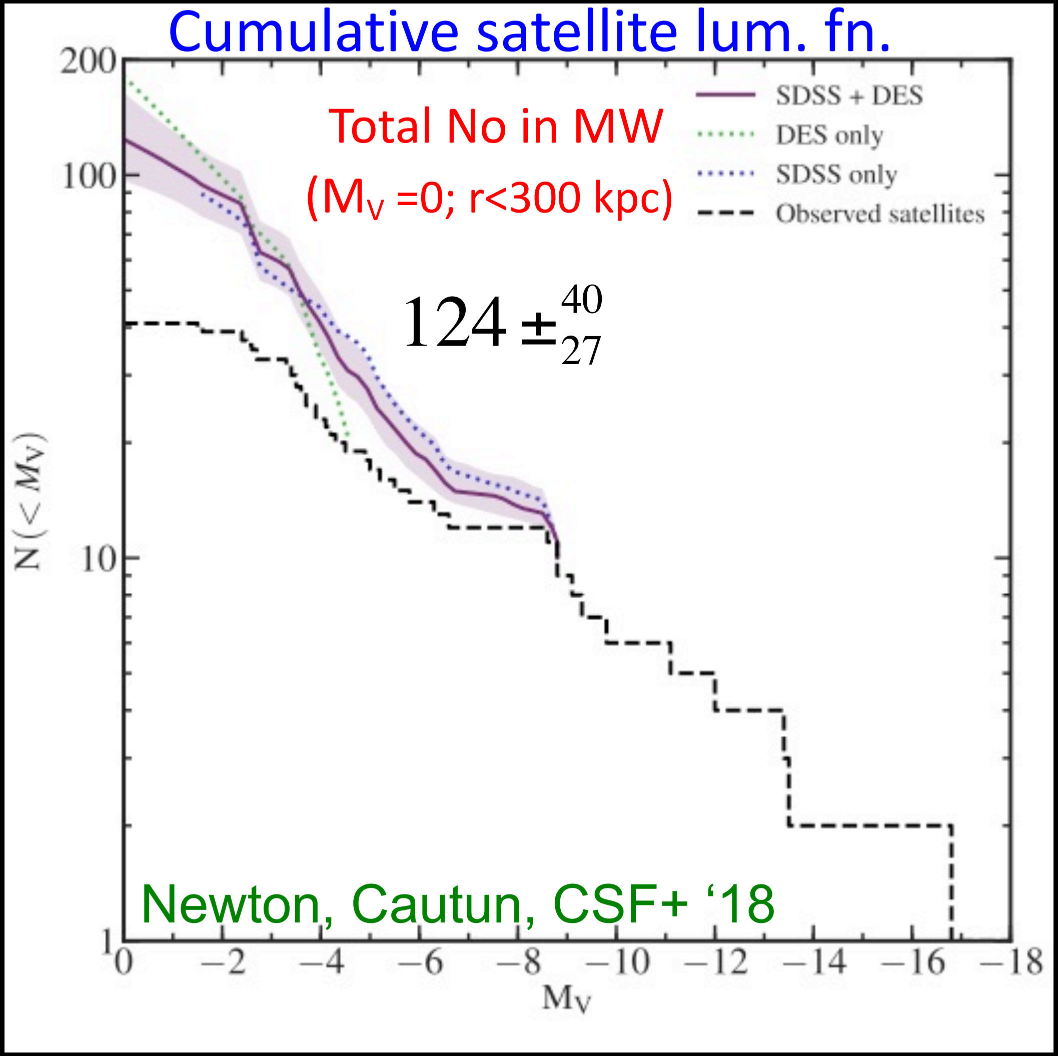
(the ``missing satellites problem)

2. Annihilation/decay radiation

Let's begin by counting what we can see

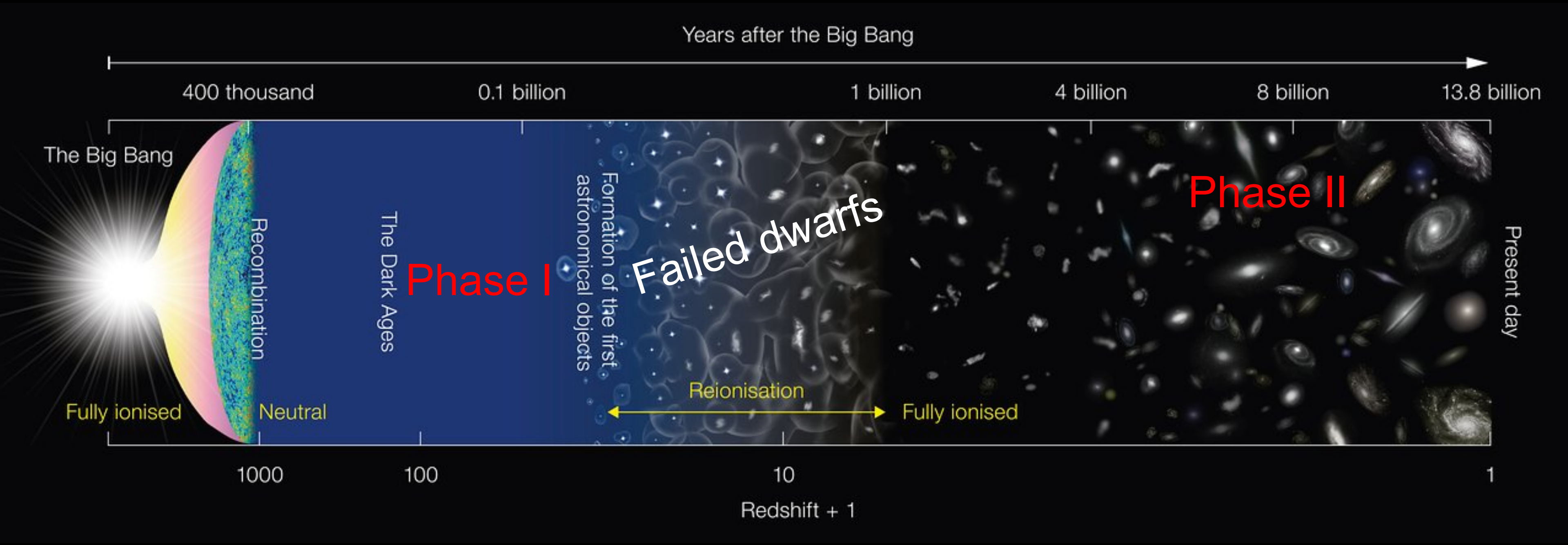
The satellites of the Milky Way

In the MW: ~55 satellites discovered so far




CDM
Most subhalos never make a galaxy!
“Missing satellites” problem:
CDM predicts many more subhalos in the Milky Way than there are observed satellites

The two phases of galaxy formation



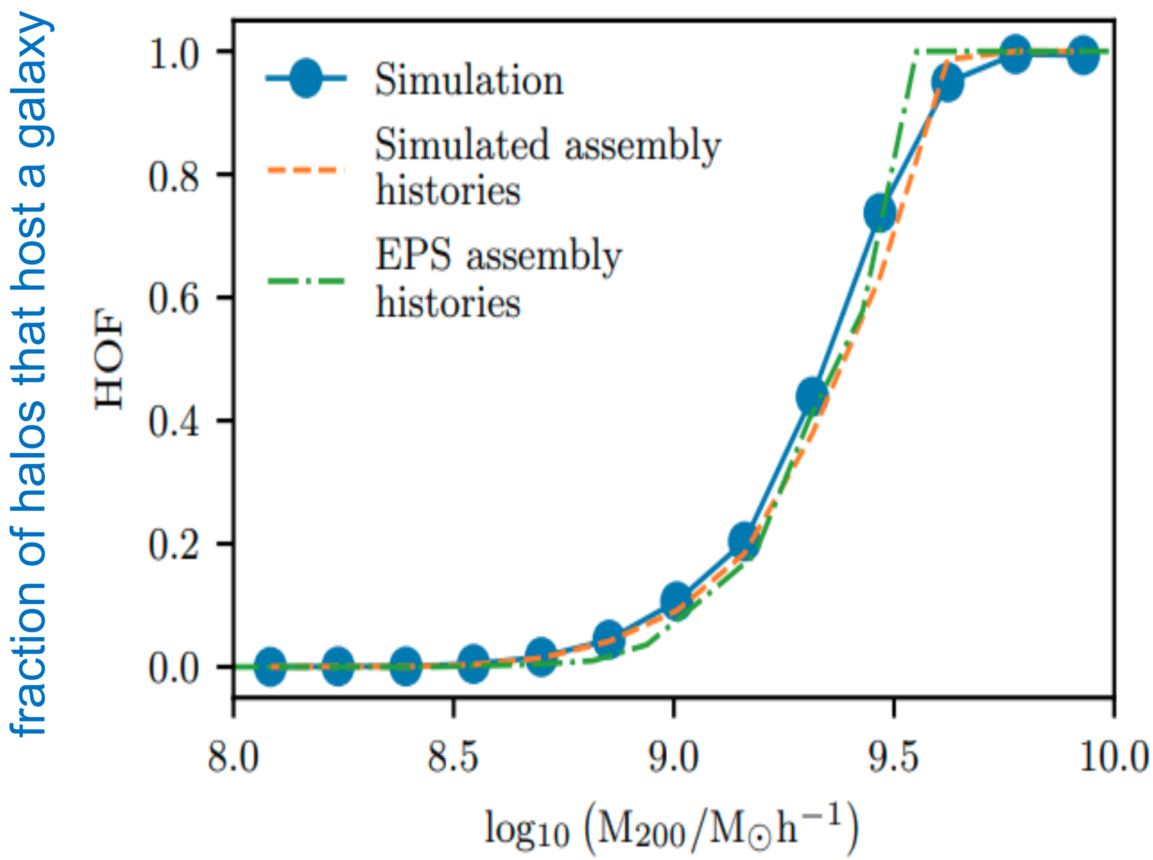
Phase I: During the "dark ages" H gas is neutral

First stars reionize H and heat it up to 10^4K

Phase II: H Gas is ionized ("T_{vir}" > 10^4K form)

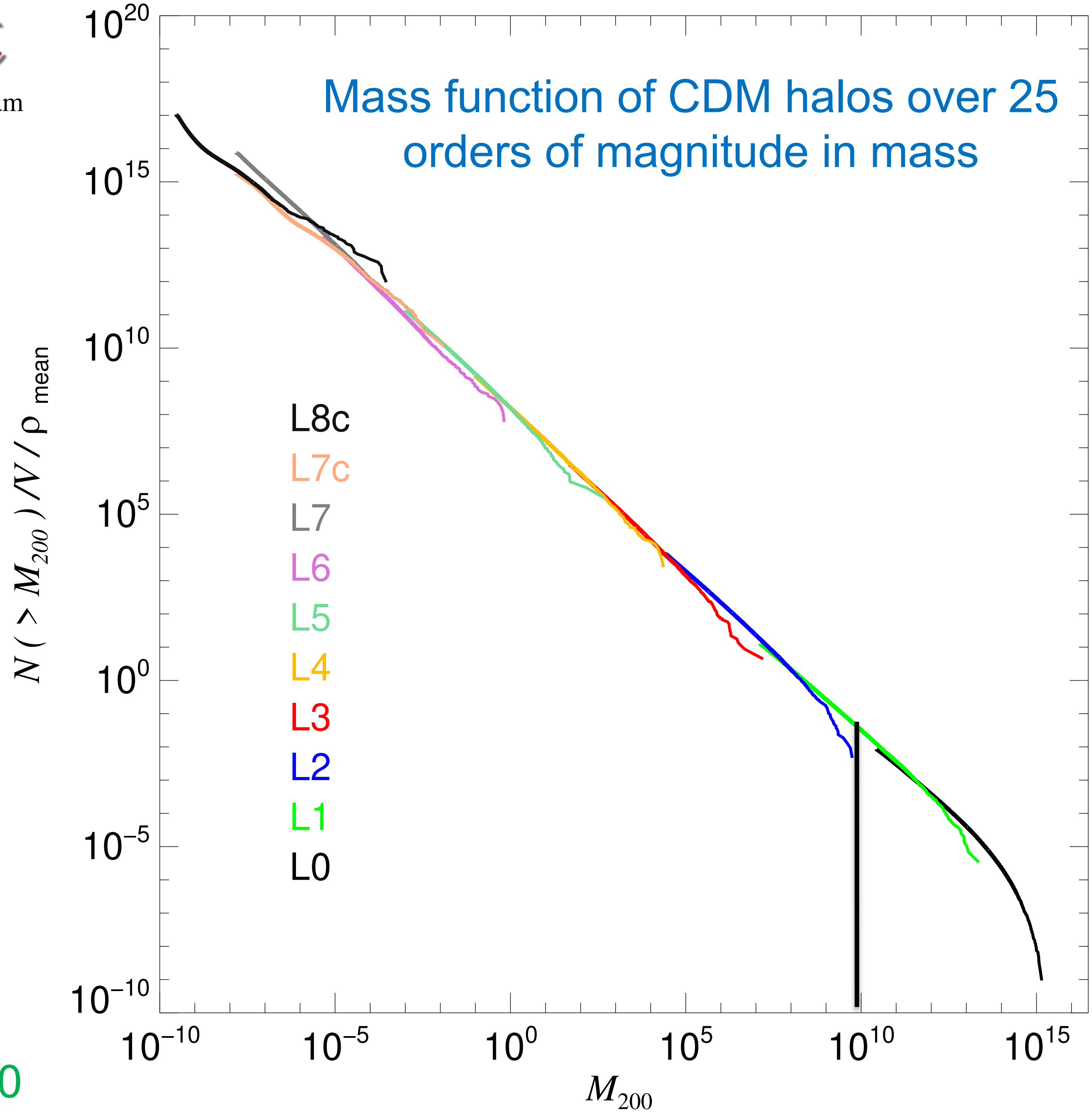
A galaxy formation primer

Halo Occupation Fraction (HOF): fraction of halos of a given mass that host a galaxy



Benitez-Llambay & CSF '20

University of Durham



Wang et al '20

Institute for Computational Cosmology

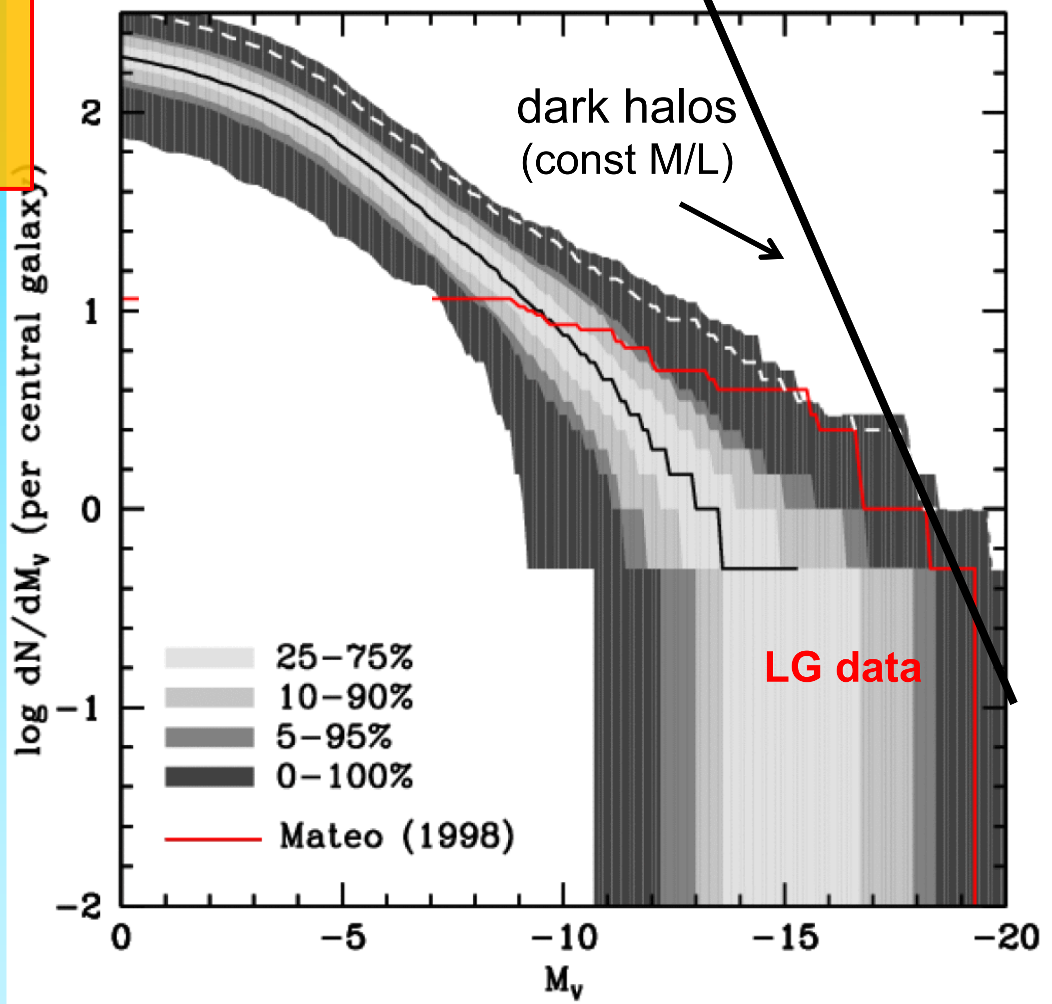
Luminosity Function of Local Group Satellites

University of Durham

Semi-analytic model of galaxy formation including effects of reionization and SN feedback

- Median model → correct abundance of sats brighter than M_V=-9 (V_{cir} > 12 km/s)

- Model predicts many, as yet undiscovered, faint satellites



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

Institute for Computational Cosmology

Luminosity Function of Local Group Satellites

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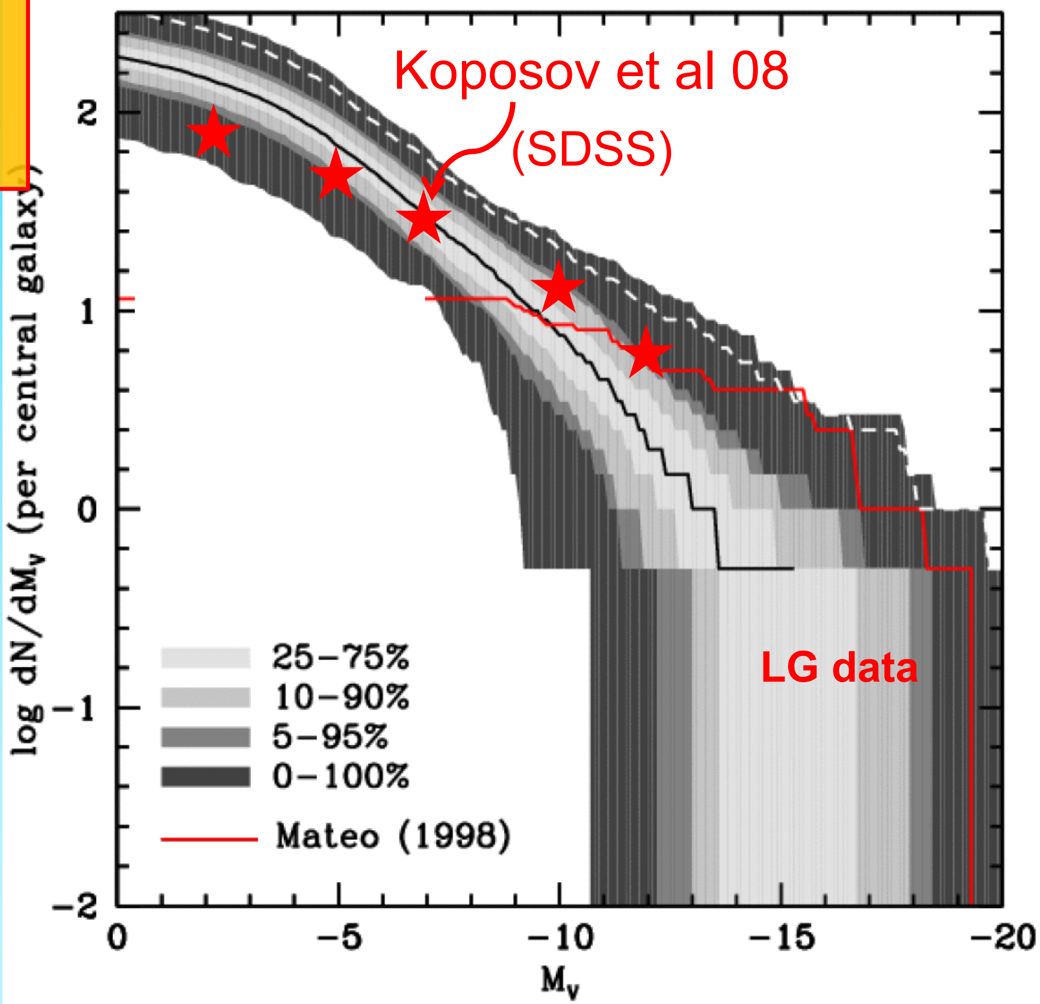


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

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…

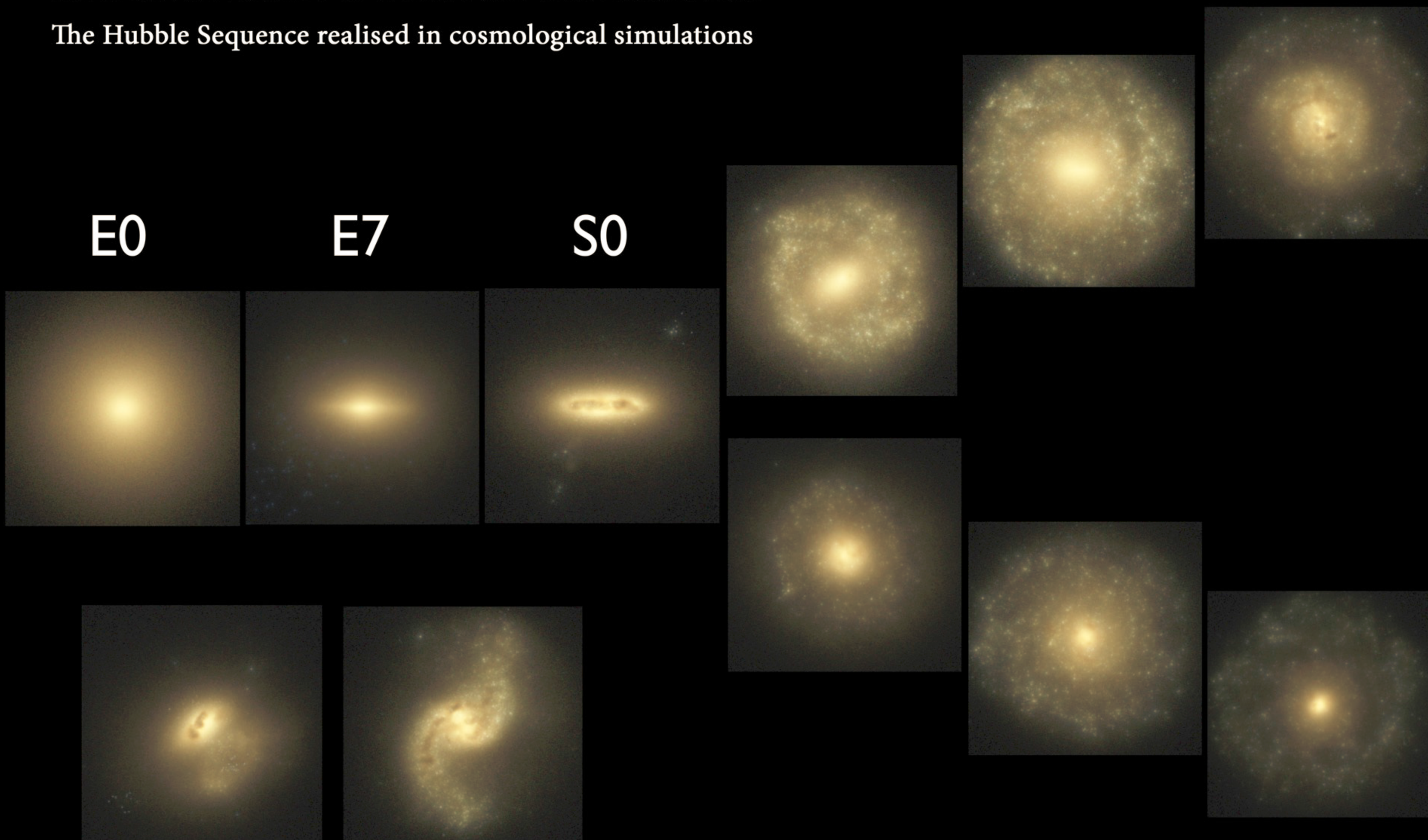
Durham University VIRGO ICC DiRAC PRACE

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

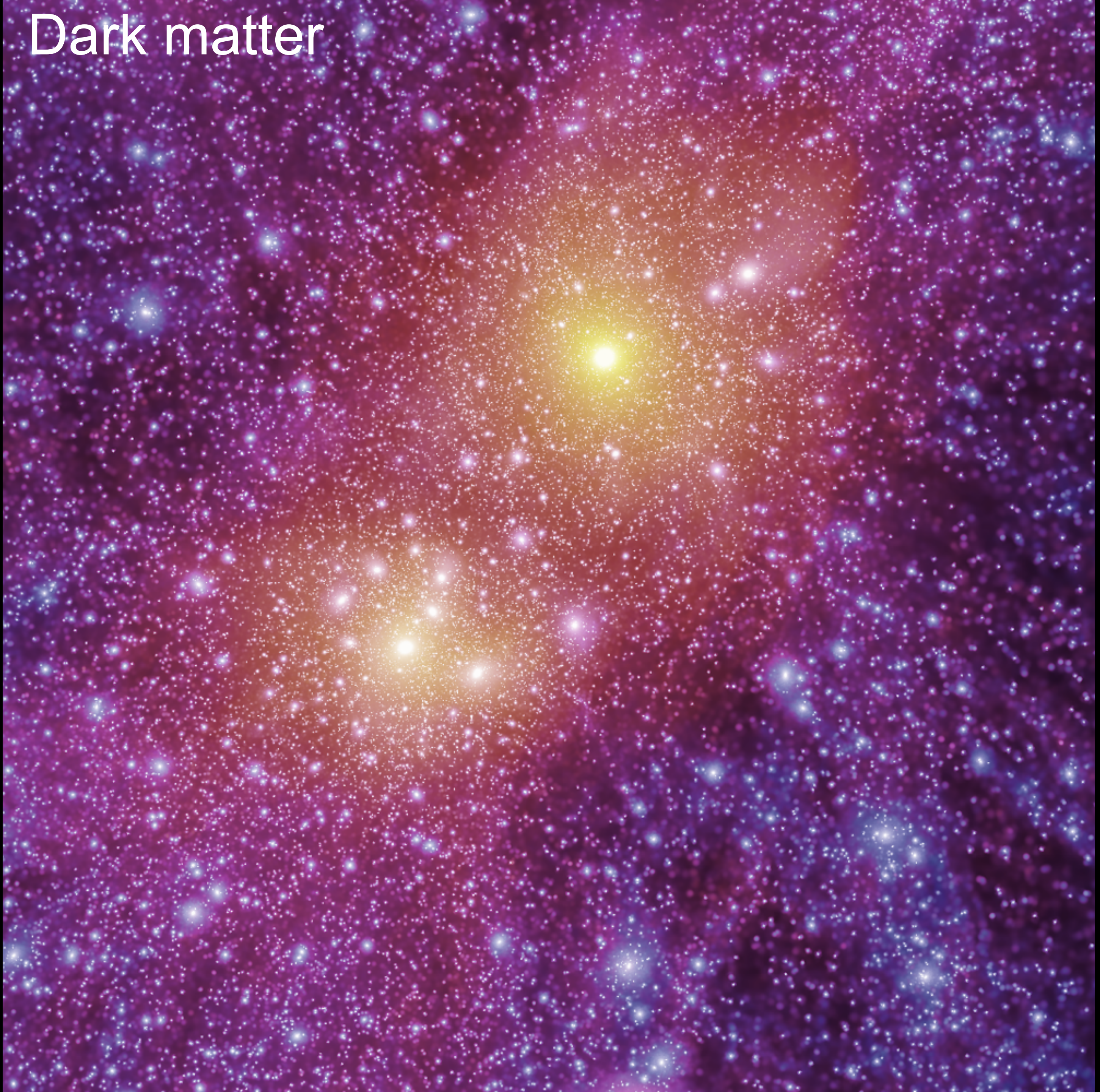
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala, CSF et al ‘16



Stars

APOSTLE EAGLE full hydro simulations

Local Group

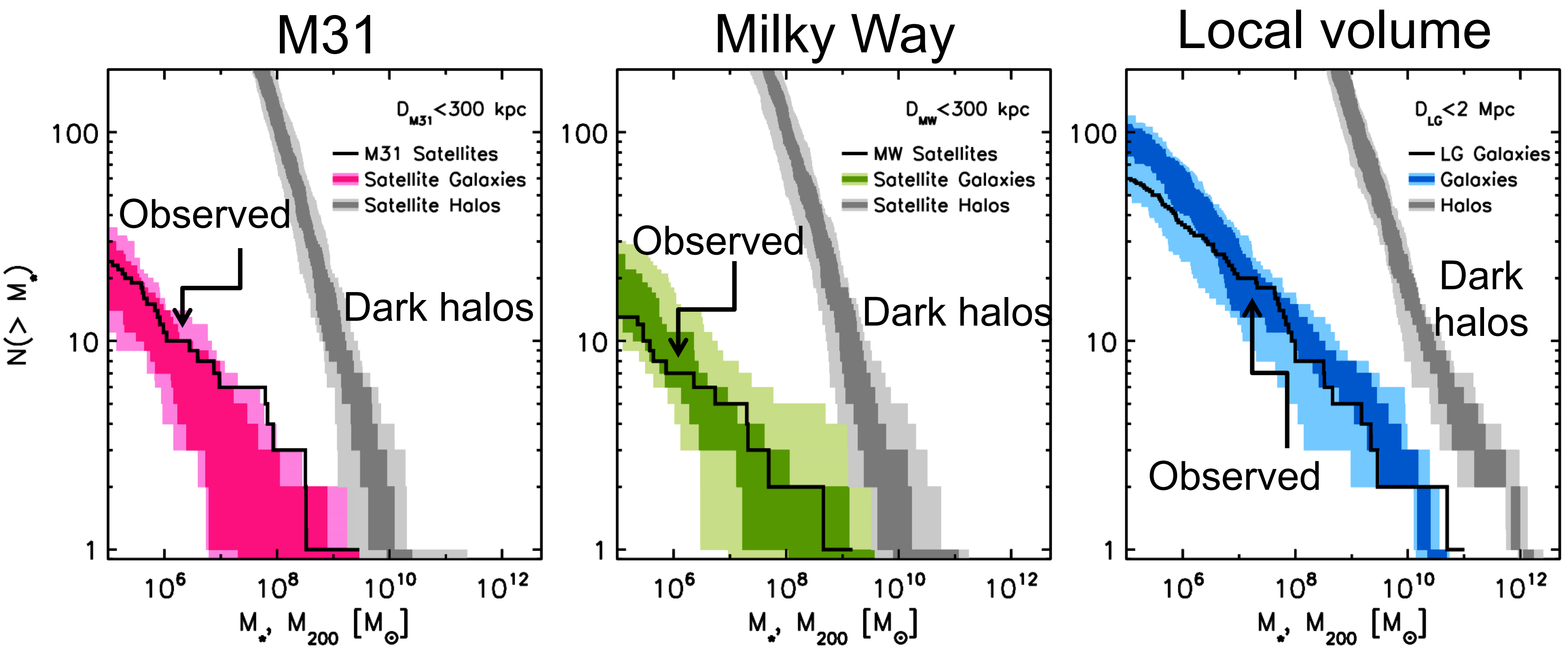
Stars

Far fewer satellite galaxies than CDM halos

Sawala, CSF et al ‘16

EAGLE Local Group simulation

University of Durham



Sawala, CSF et al ‘16

When galaxy formation is taken into account

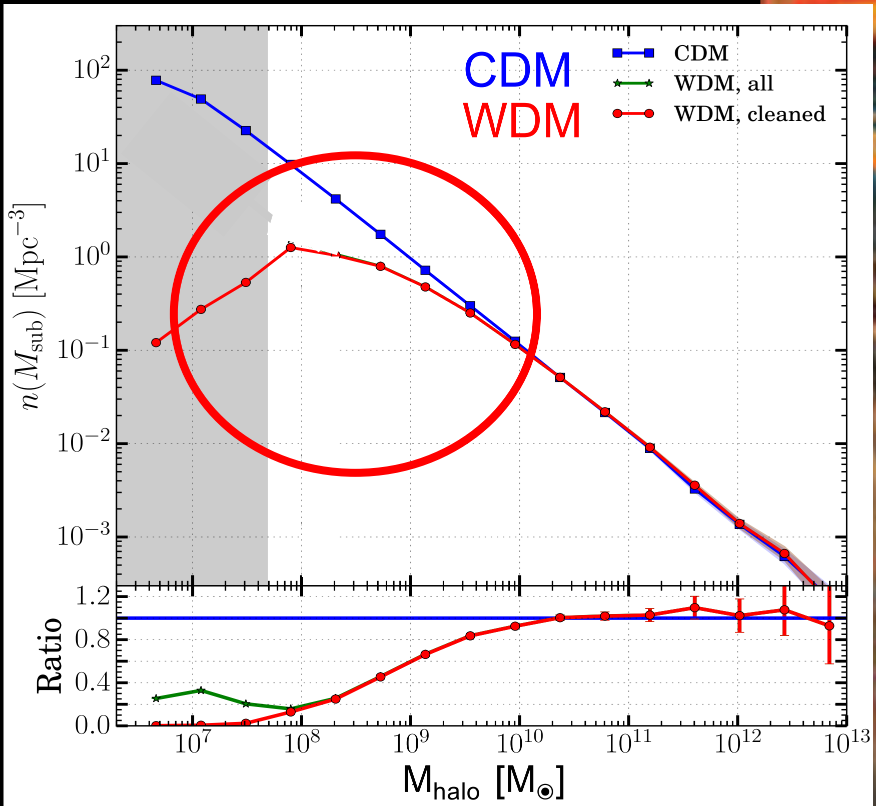
→

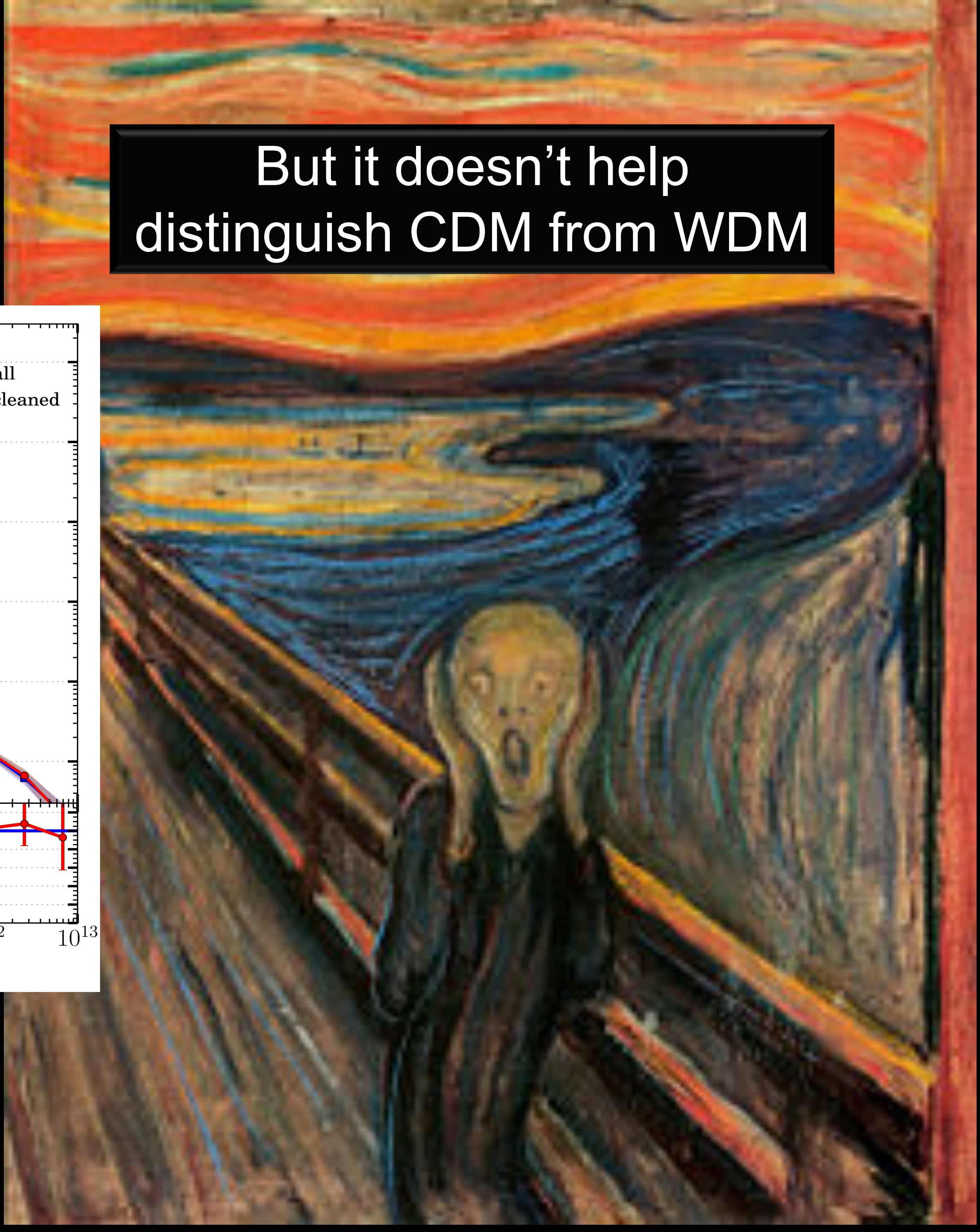
CDM predicts the observed abundance of satellites

→

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

But it doesn't help distinguish CDM from WDM

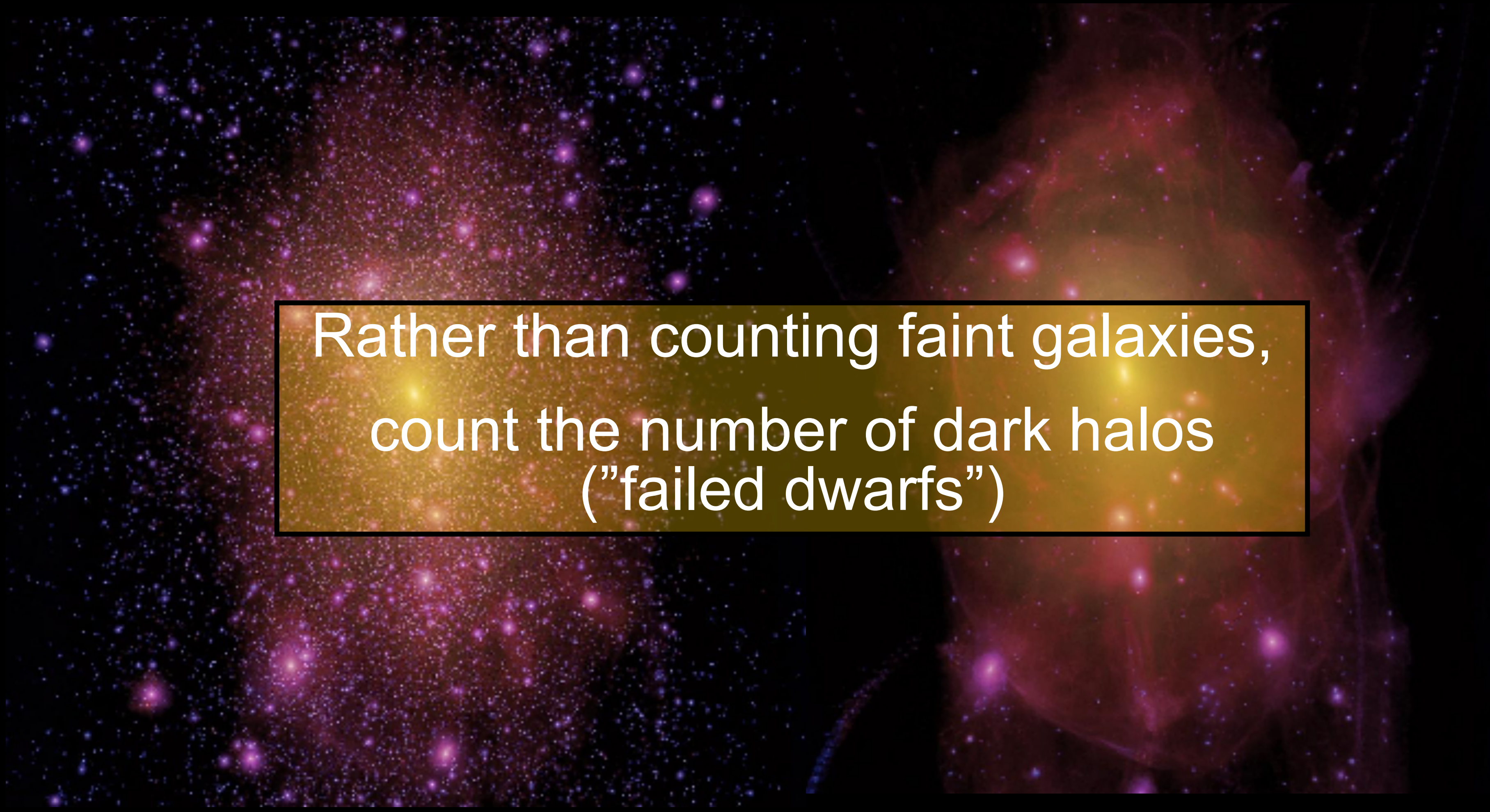




Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

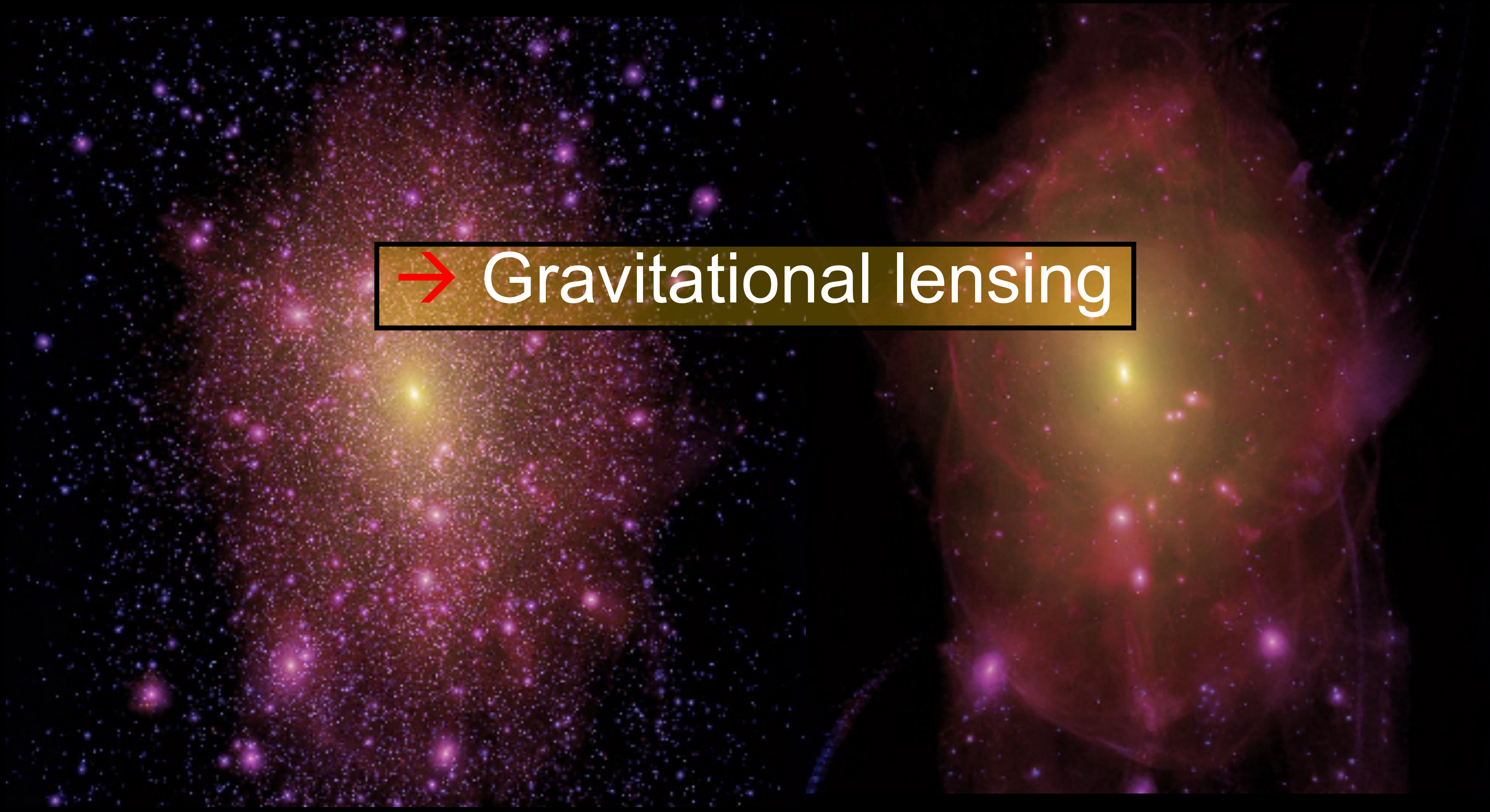


Rather than counting faint galaxies,

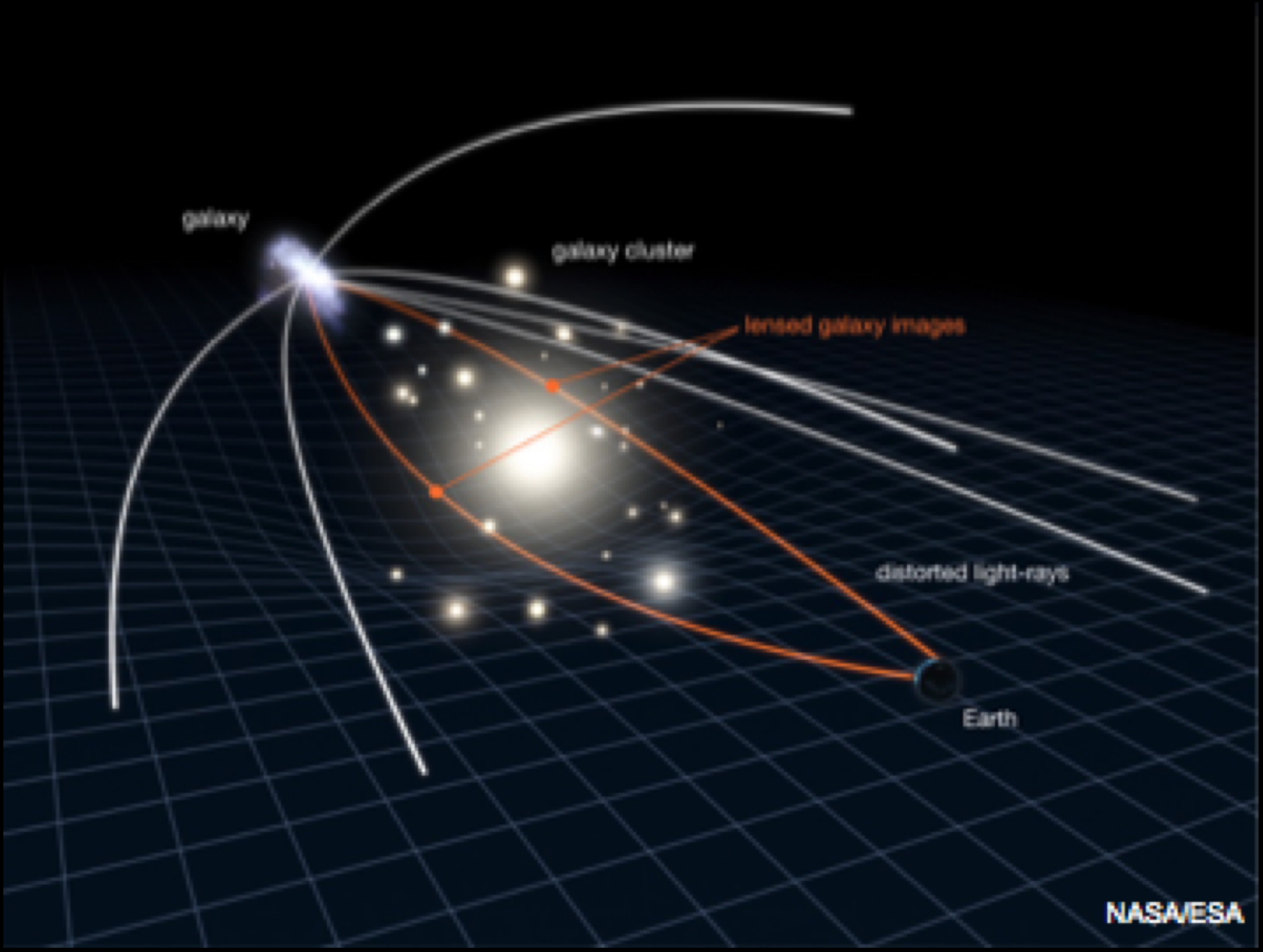
count the number of dark halos ("failed dwarfs")

Can we count dark haloes?

cold dark matter | warm dark matter

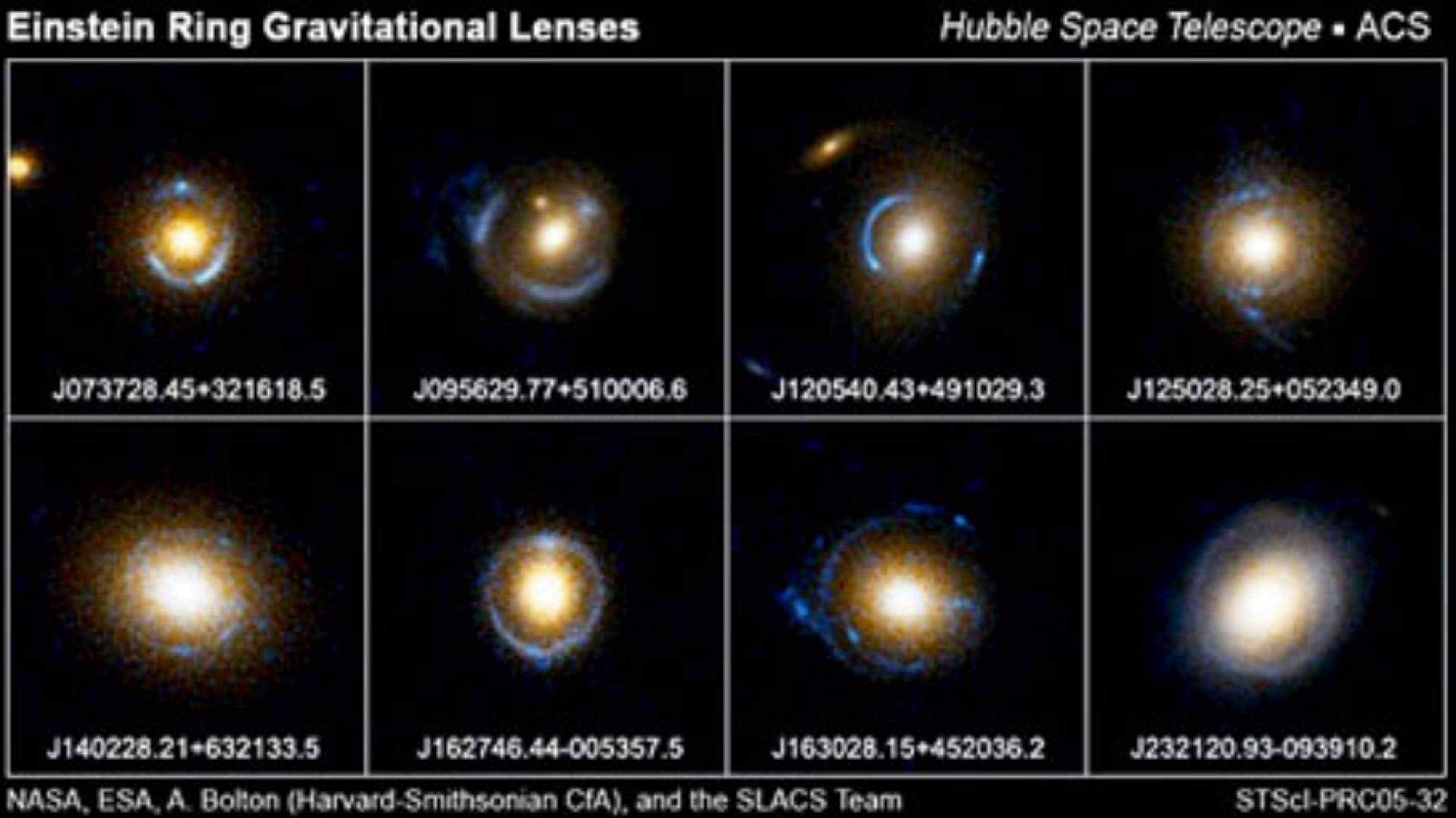


Gravitational lensing: Einstein rings

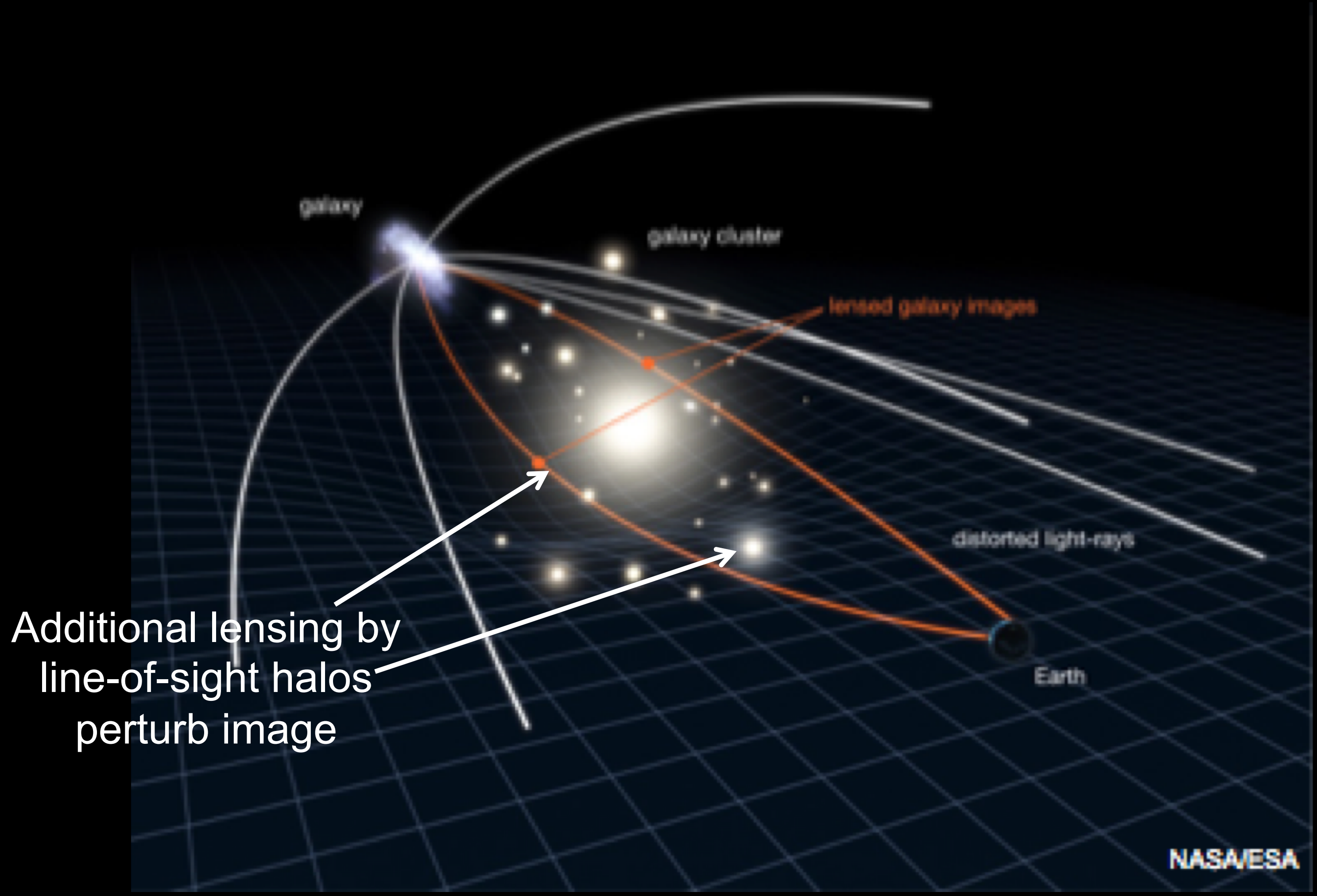


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



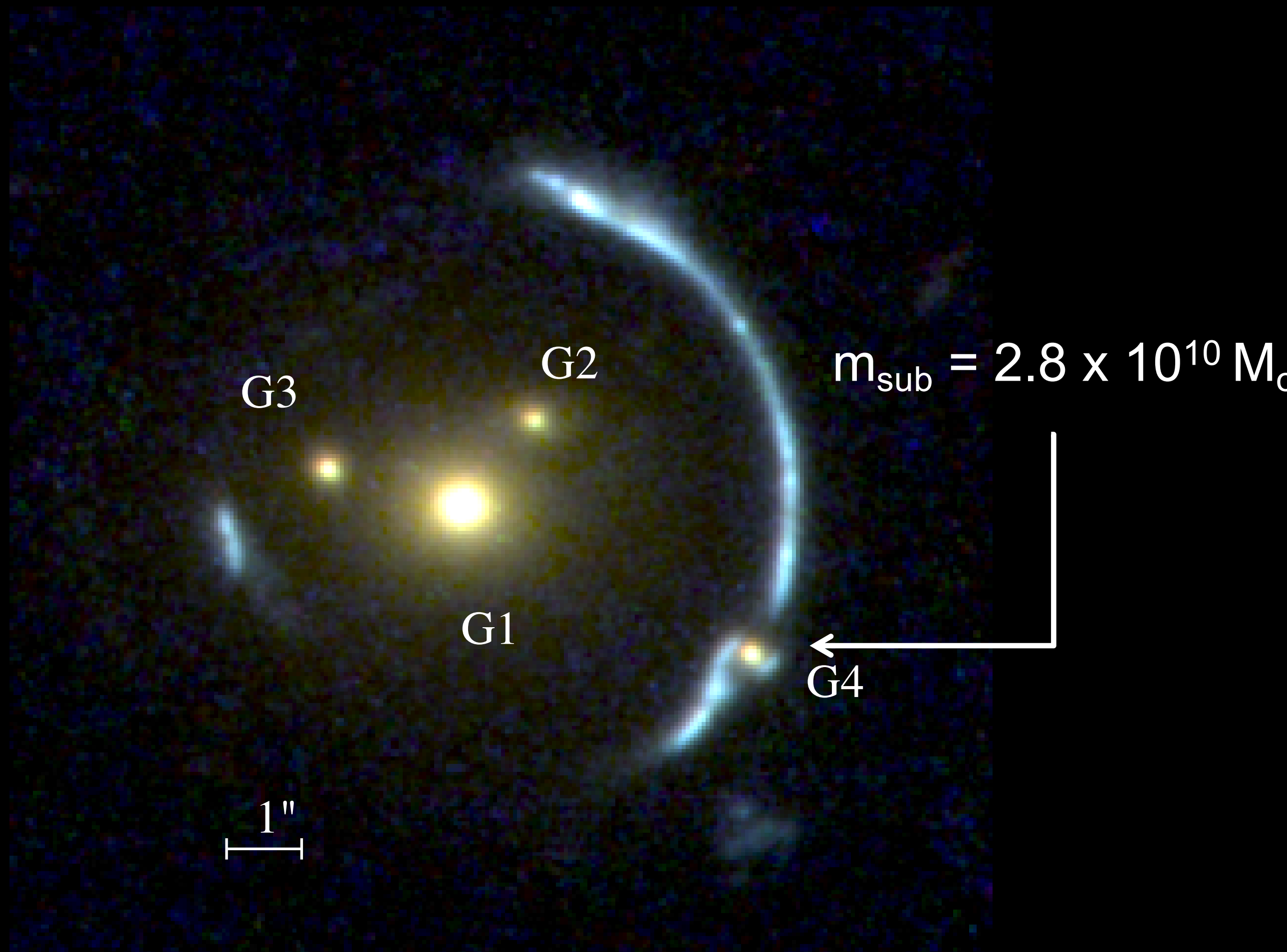
Gravitational lensing: Einstein rings



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



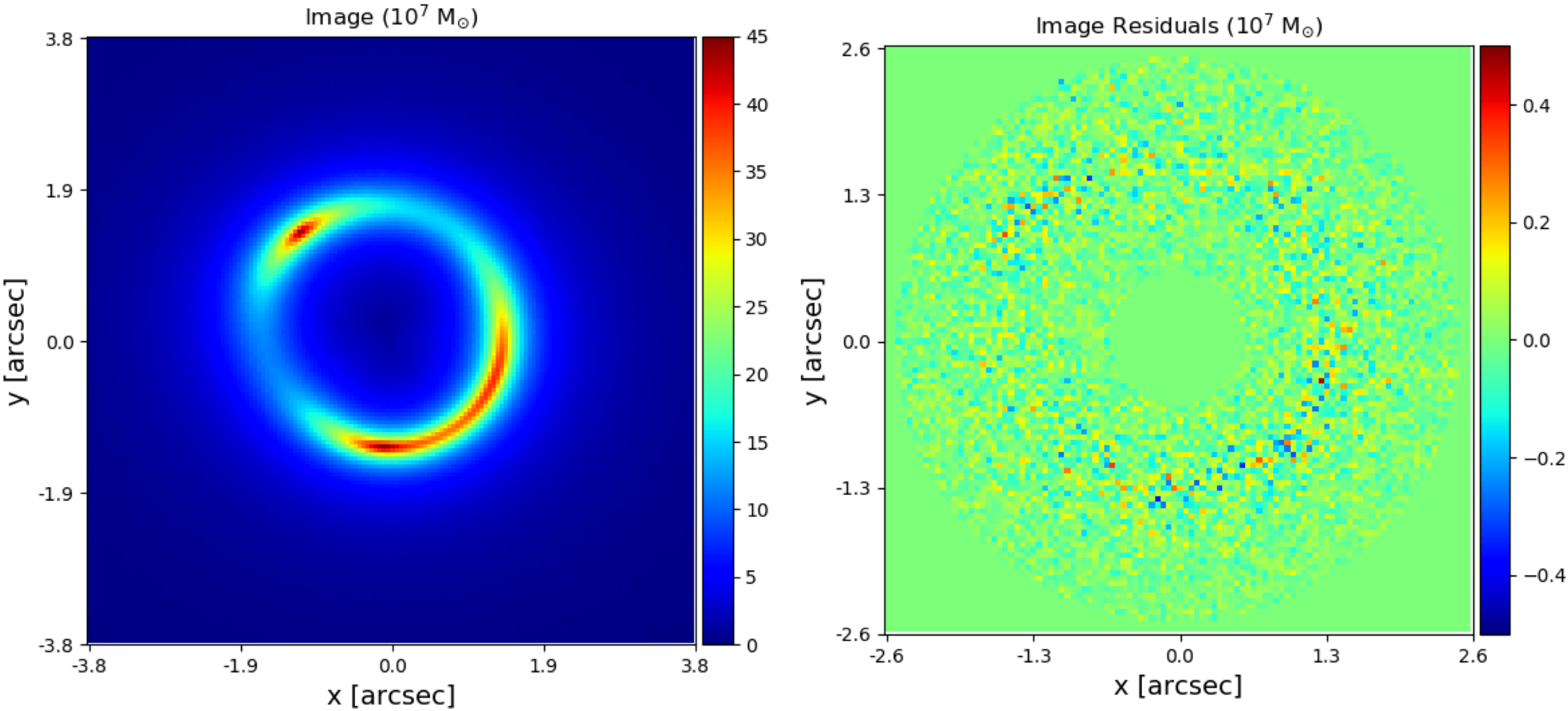
Vegetti et al '10

Strong lensing: detecting small halos

HST "data": $z_{source}=1$; $z_{lens}=0.2$ 10^7 M_o halo – NOT so easy to spot

Image

Residuals (image – smooth model)

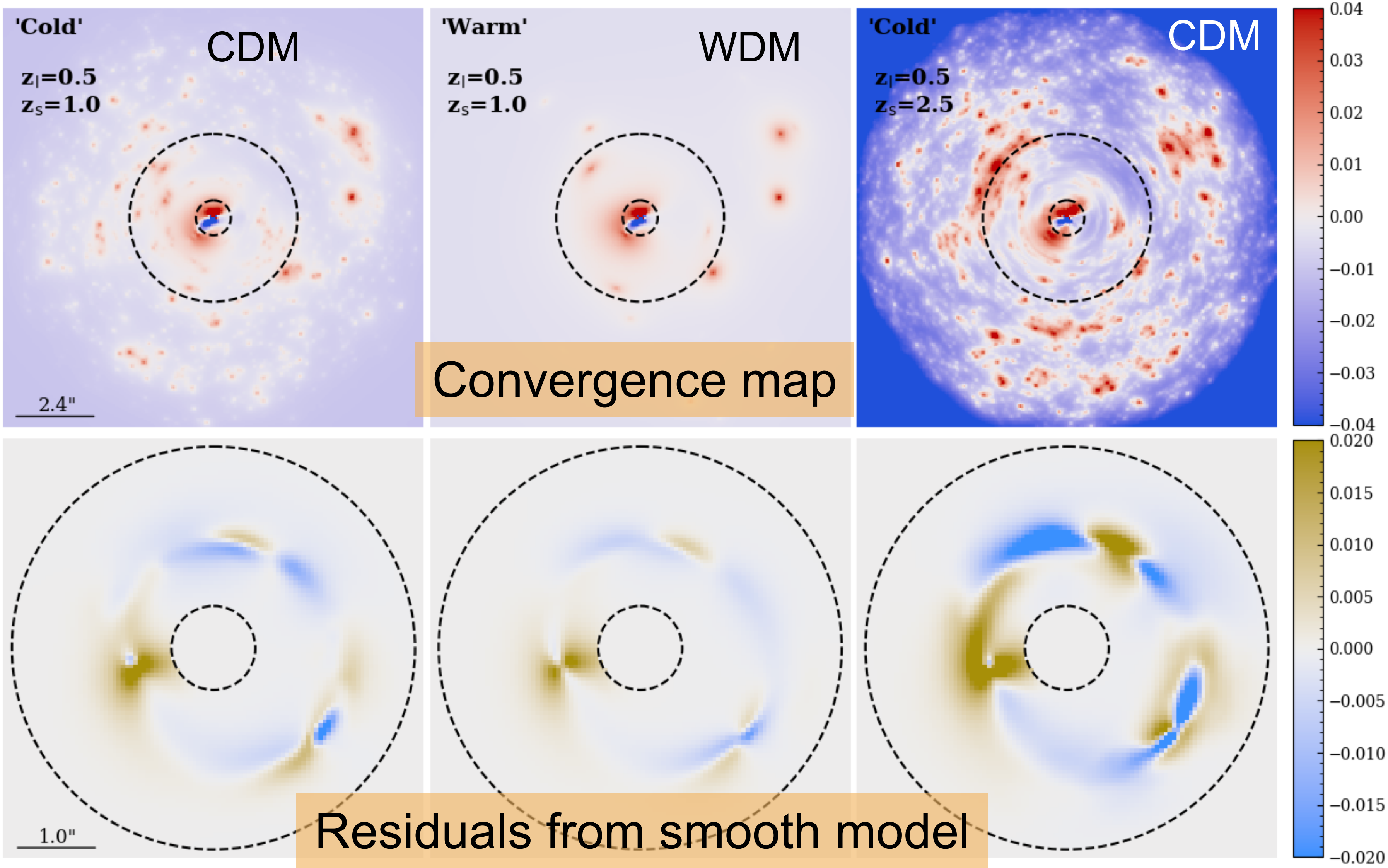


He, Li, CSF et al '19

Institute for Computational Cosmology

University of Durham

Strong lensing: detecting small halos



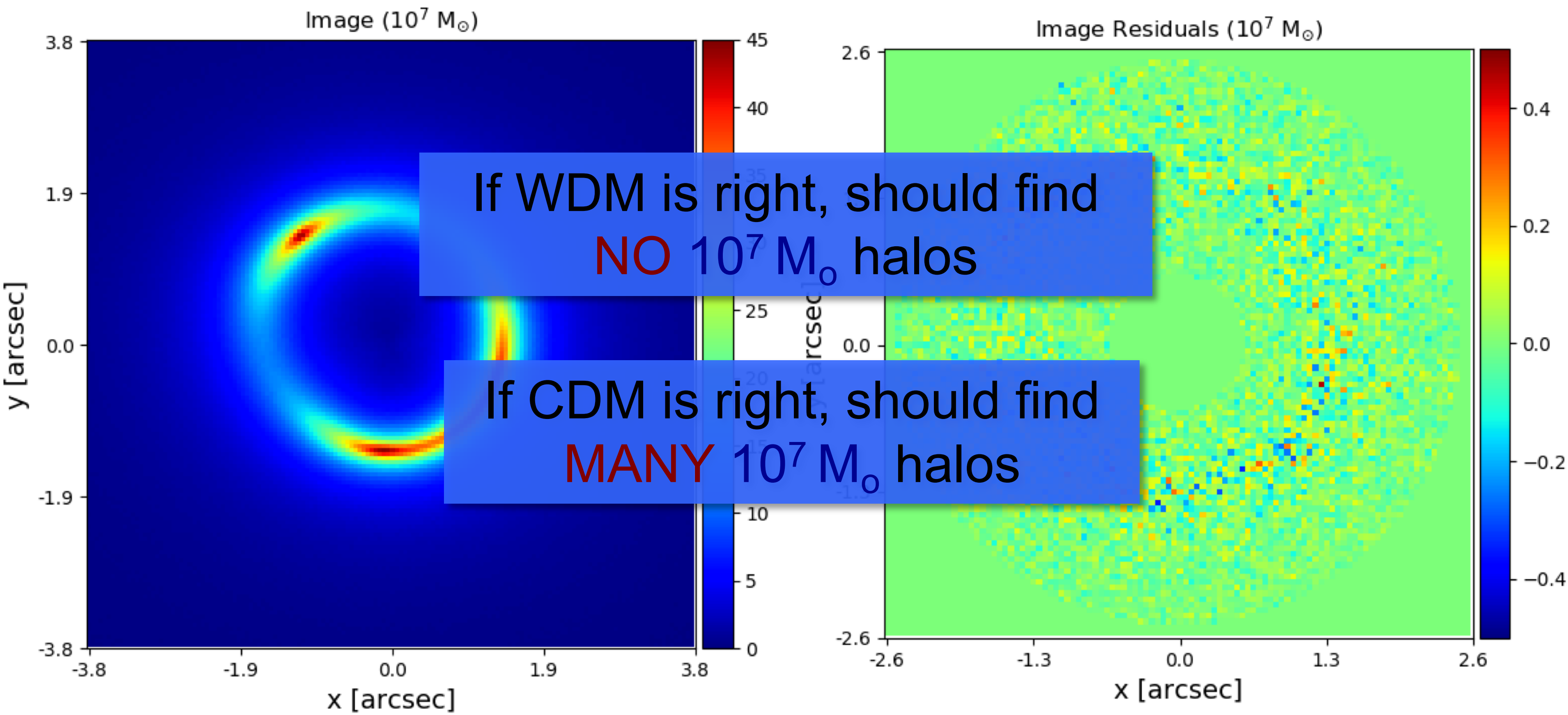
He et al. '20

Institute for Computational Cosmology

University of Durham

Detecting halos w. strong lensing

Can detect halos 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

He, Li, CSF et al '19

Institute for Computational Cosmology

Detecting substructures with strong lensing

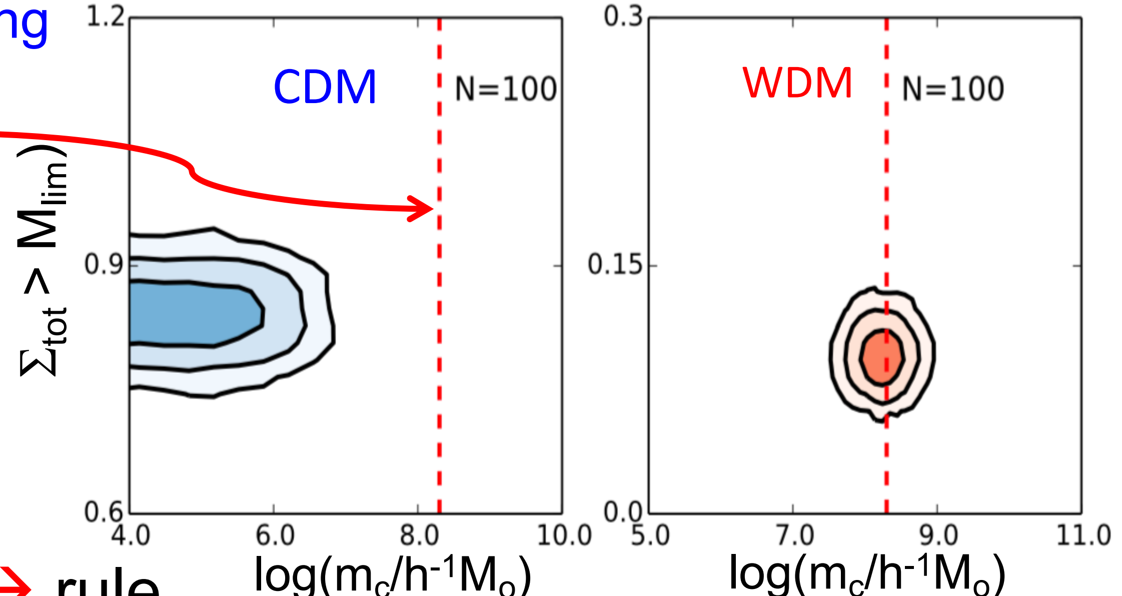
University of Durham

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

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

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

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



m_c= halo cutoff mass

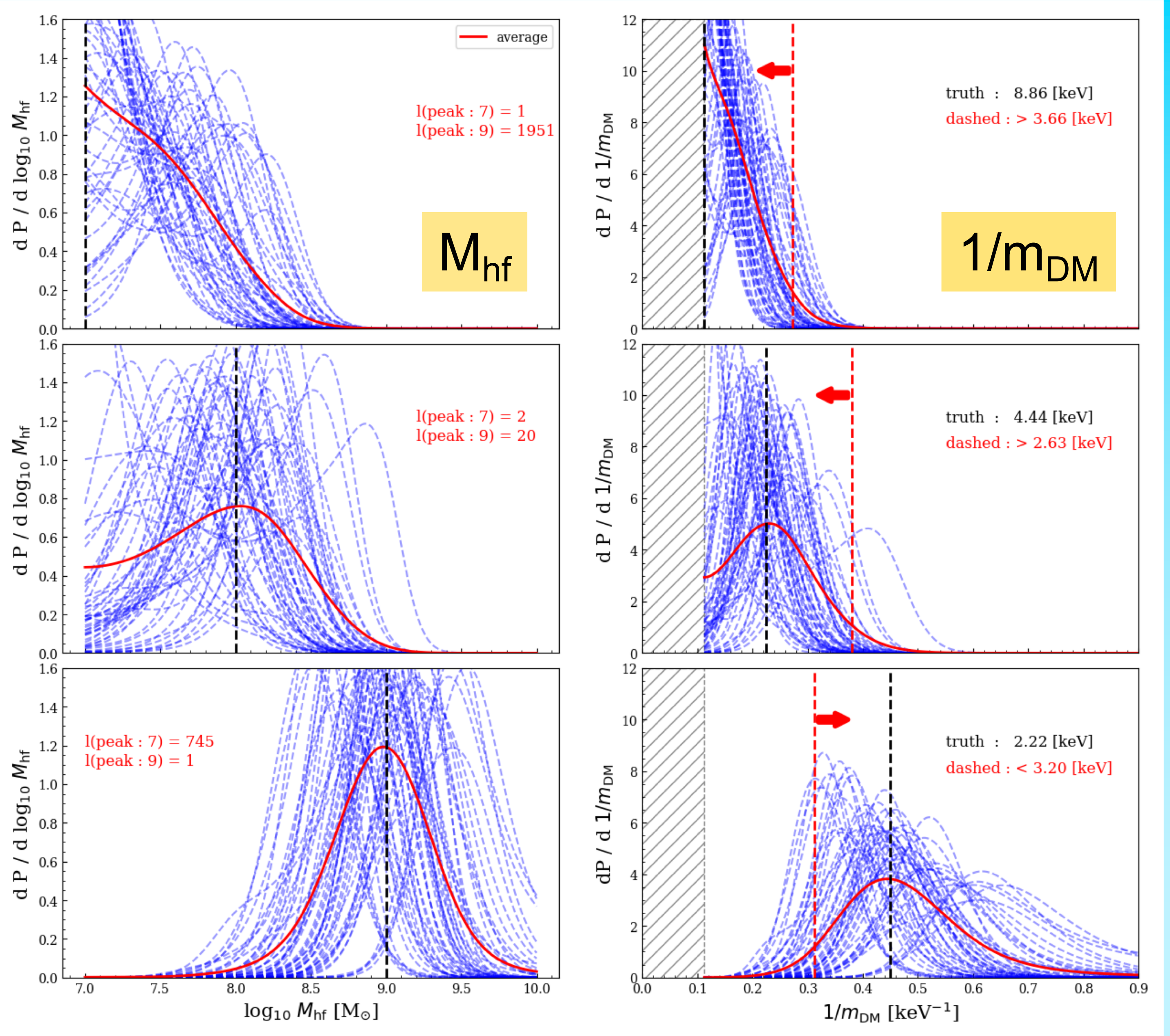
- If DM is 7 keV sterile ν → rule out CDM at >3σ!
- If DM is CDM → rule out 7 keV sterile ν at many σ

Li, CSF et al '16

Institute for Computational Cosmology

Strong lensing: statistical detection

Power spectrum of residuals map

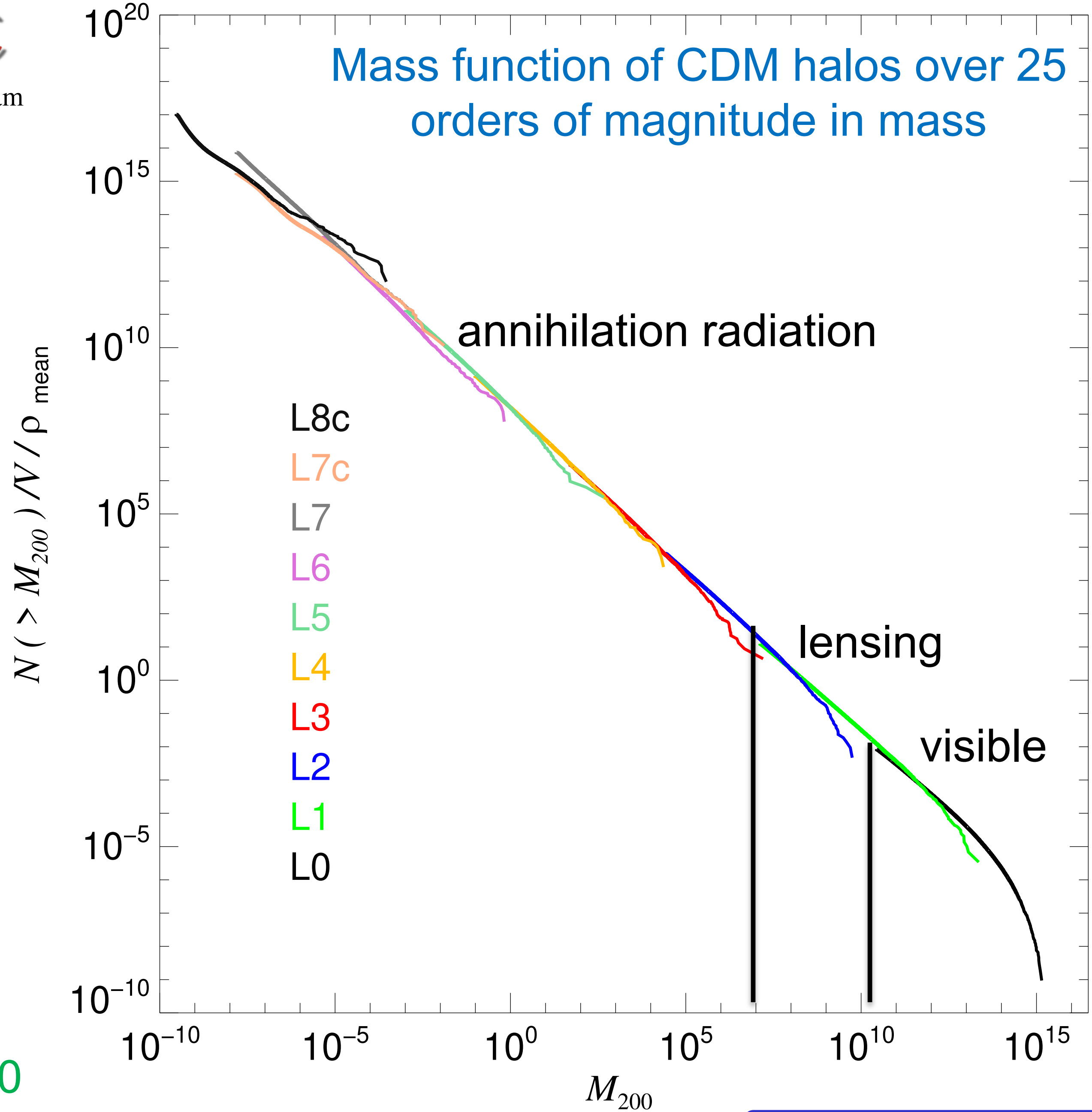


Posterior distributions (mock observations) for power spectrum of residuals

Constraints from forward modelling of 50 systems

He et al. '20

University of Durham



Wang et al '20

Indirect CDM detection through annihilation radiation

University of Durham

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)

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

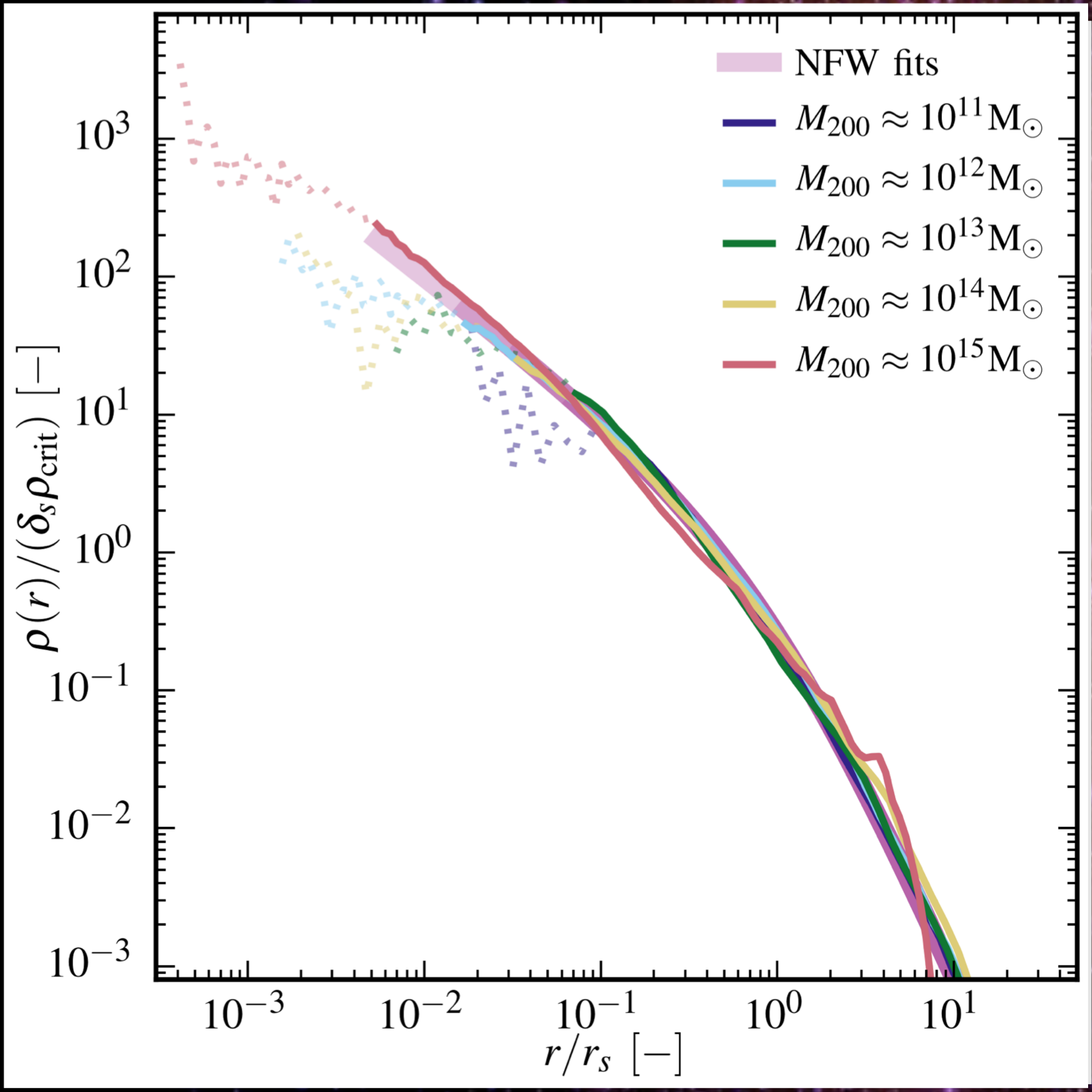
cross-section (particle physics)

$\langle\sigma v\rangle = 3\times10^{-26} cm^3 s^{-1}$ → 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

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)

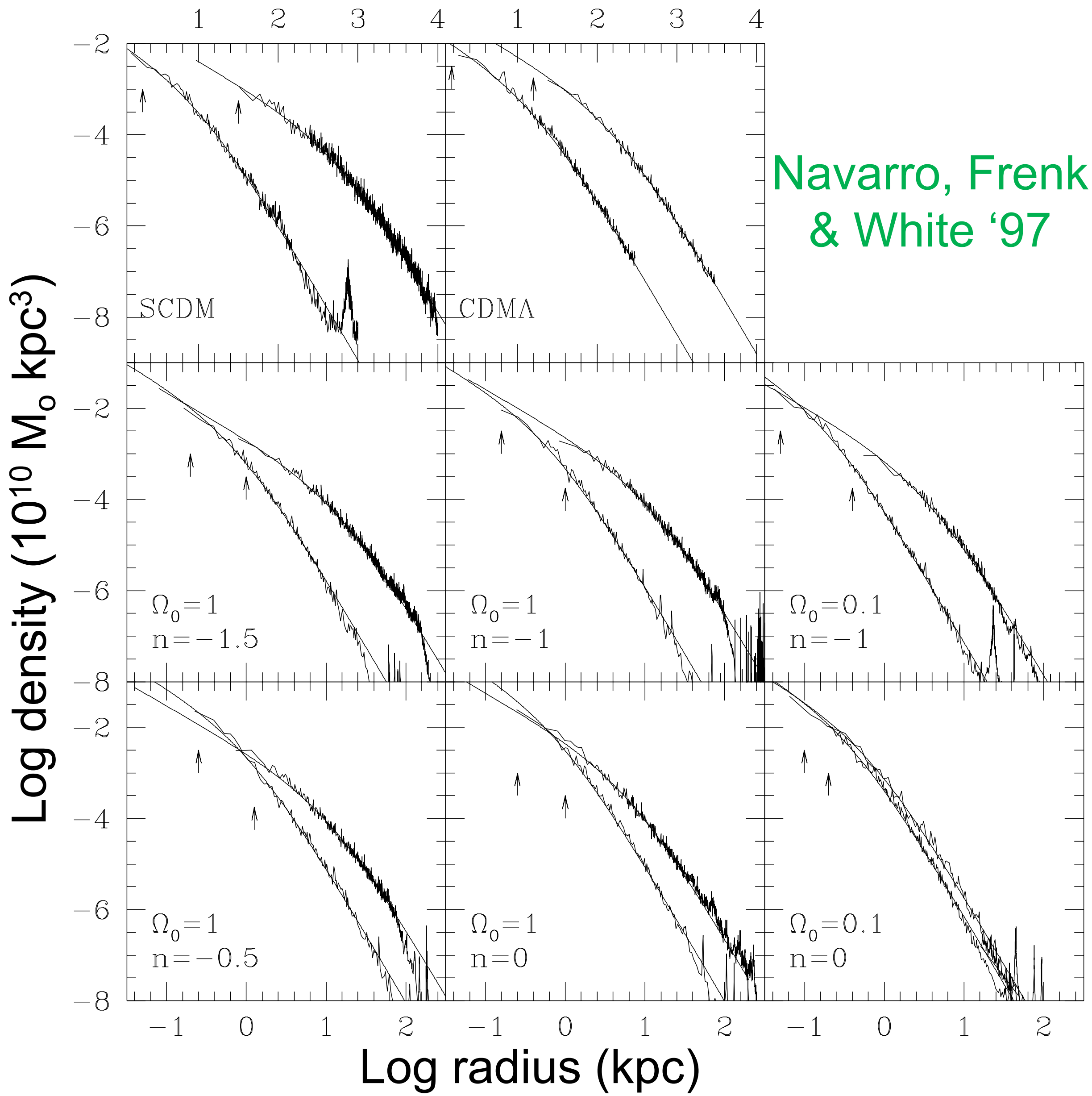
Universal halo density profiles

University of Durham

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

Fits the spherically averaged density profiles of halos over a wide mass range.

2 parameters:
Characteristic density δ_C
radius: r_s



Navarro, Frenk & White '97

Universal halo density profiles

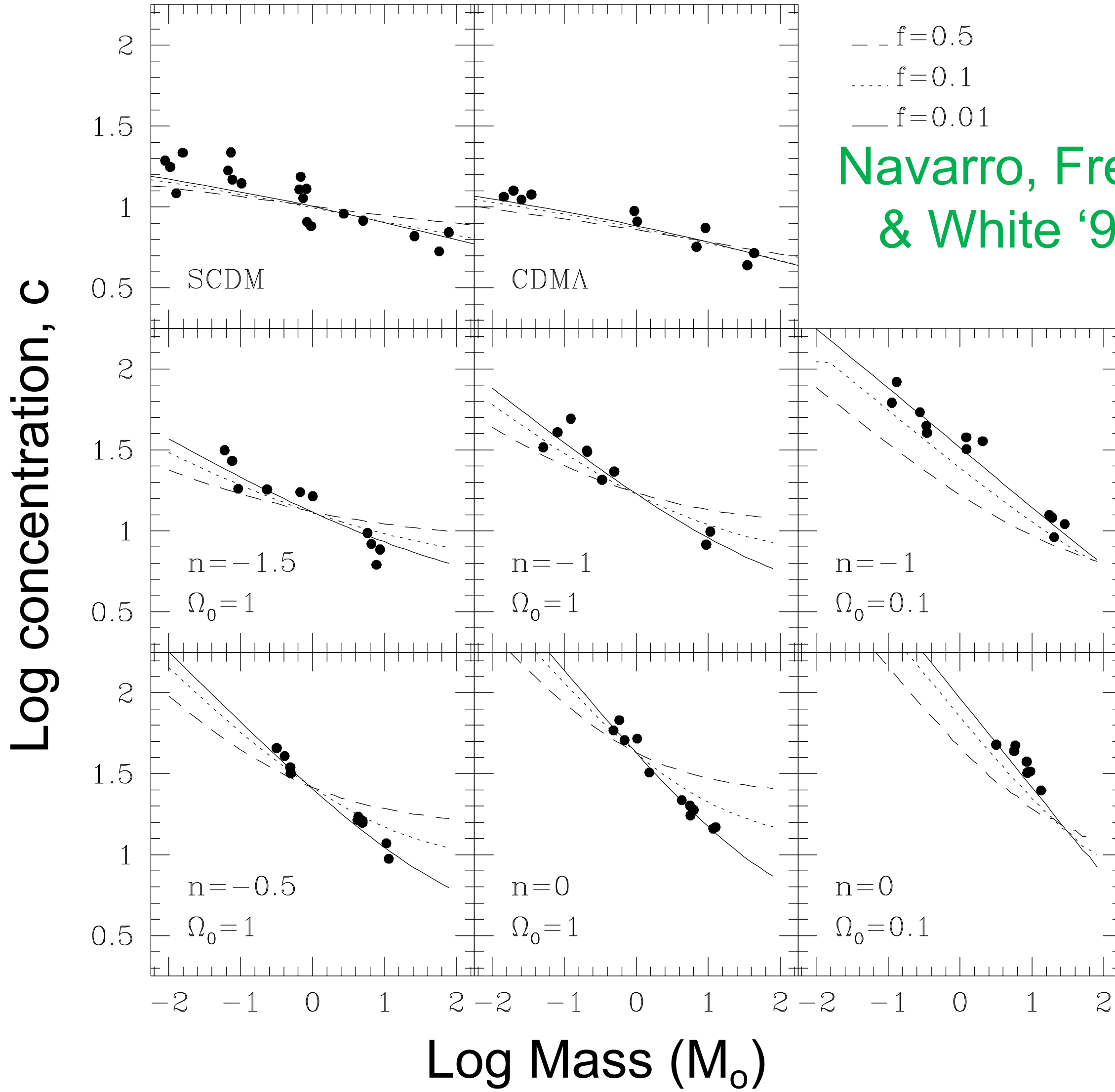
University of Durham

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

2 parameters: Characteristic density, δ_c radius, r_s

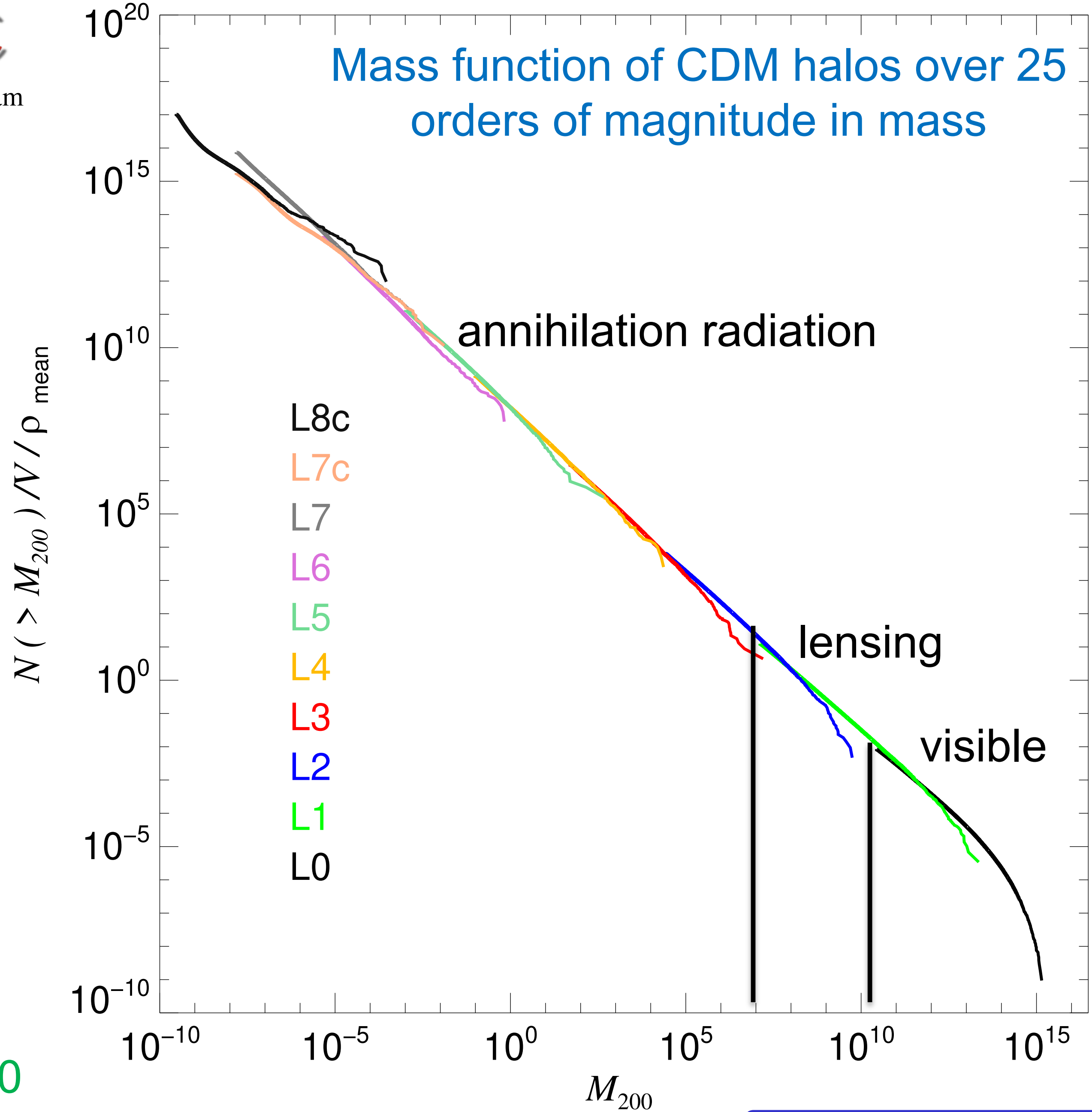
The two parameters are related to halo mass in a way that is cosmology dependent:

c ↖ as M ↘



Navarro, Frenk & White '97

University of Durham



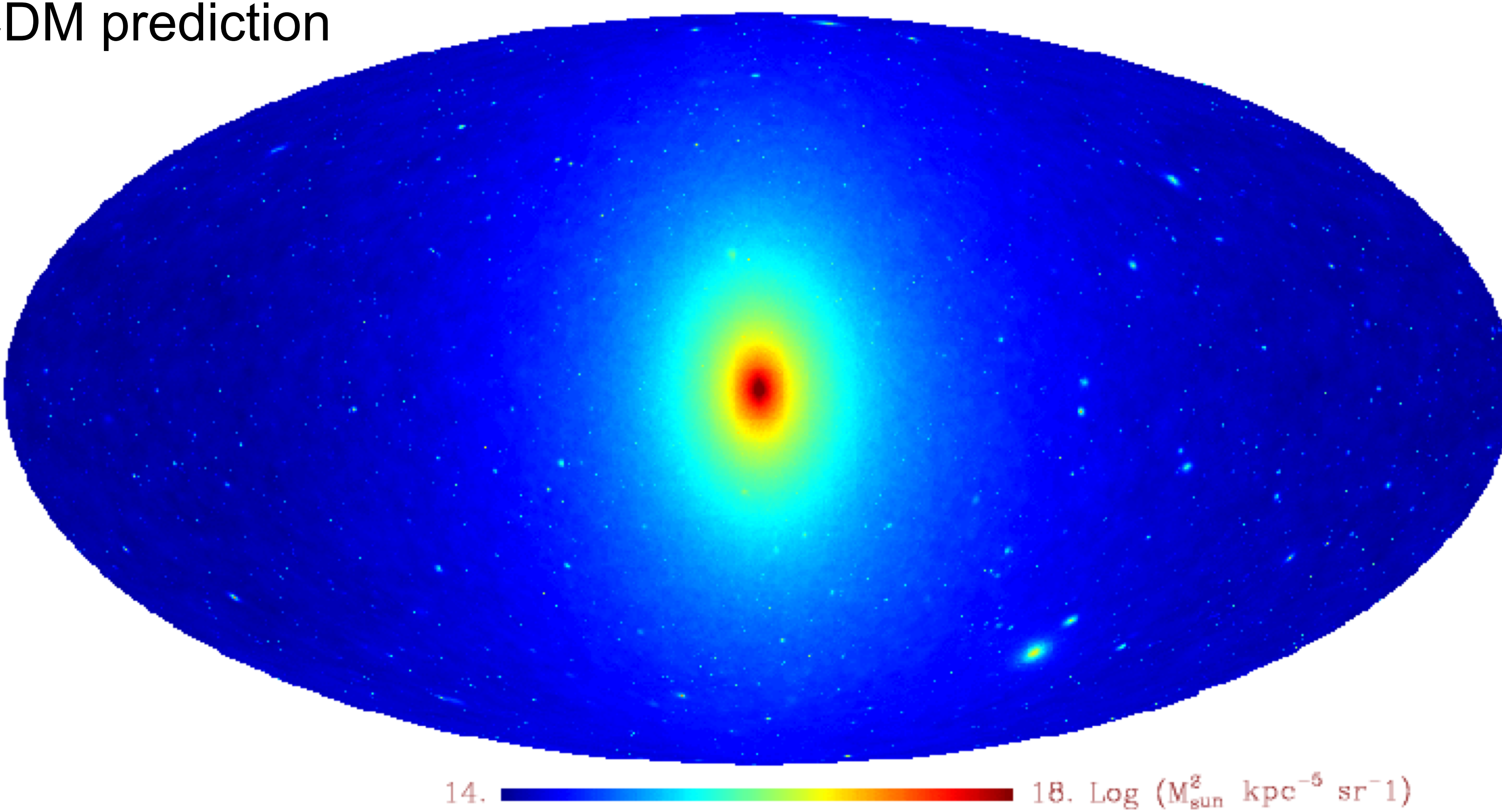
Wang et al ‘20

University of Durham

The Milky Way seen in annihilation radiation

Aquarius simulation: $N_{200} = 1.1 \times 10^9$

CDM prediction



Springel et al. ‘08

Mass resolution – 10^5 M_o

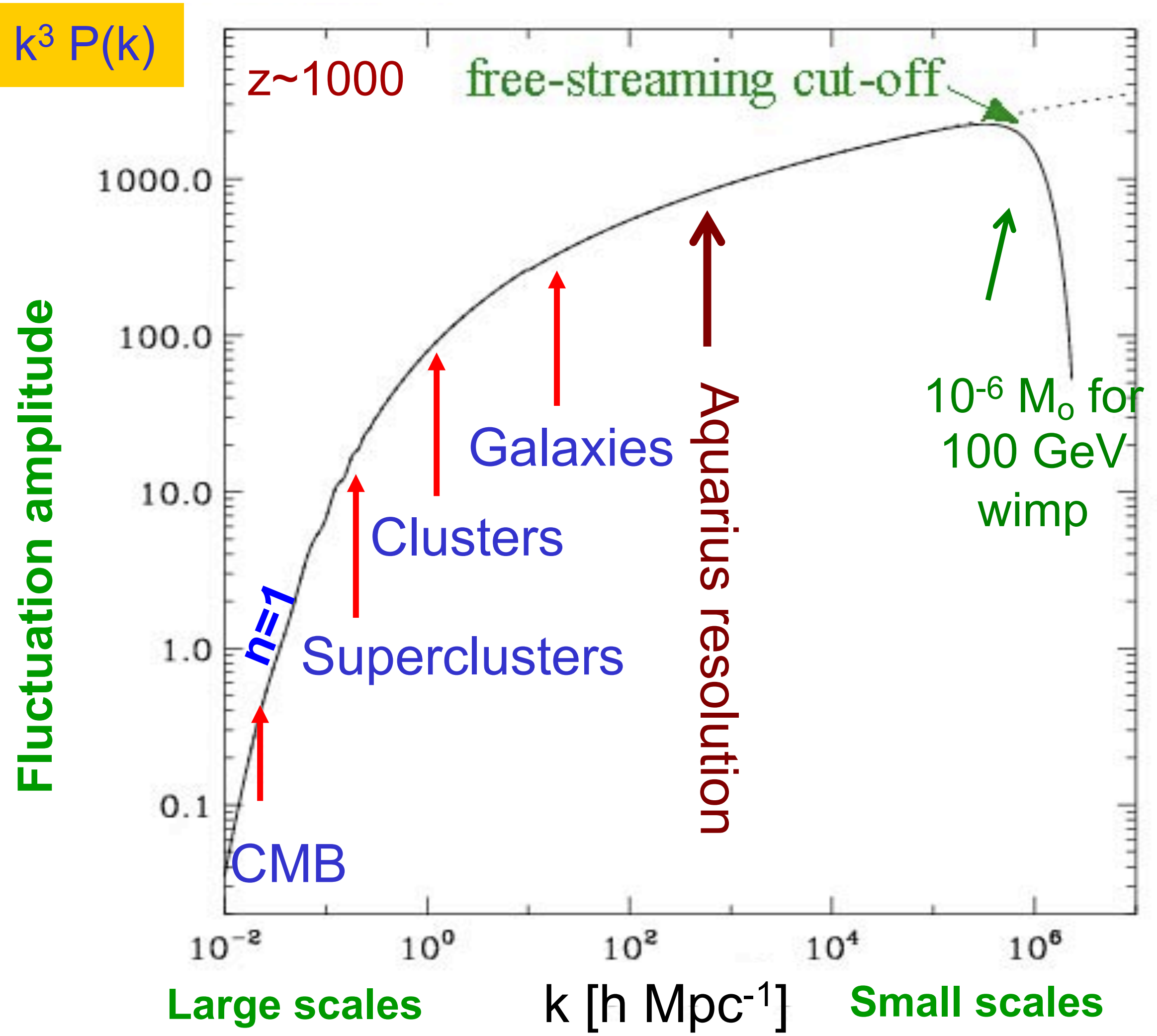
The cold dark matter linear power spectrum

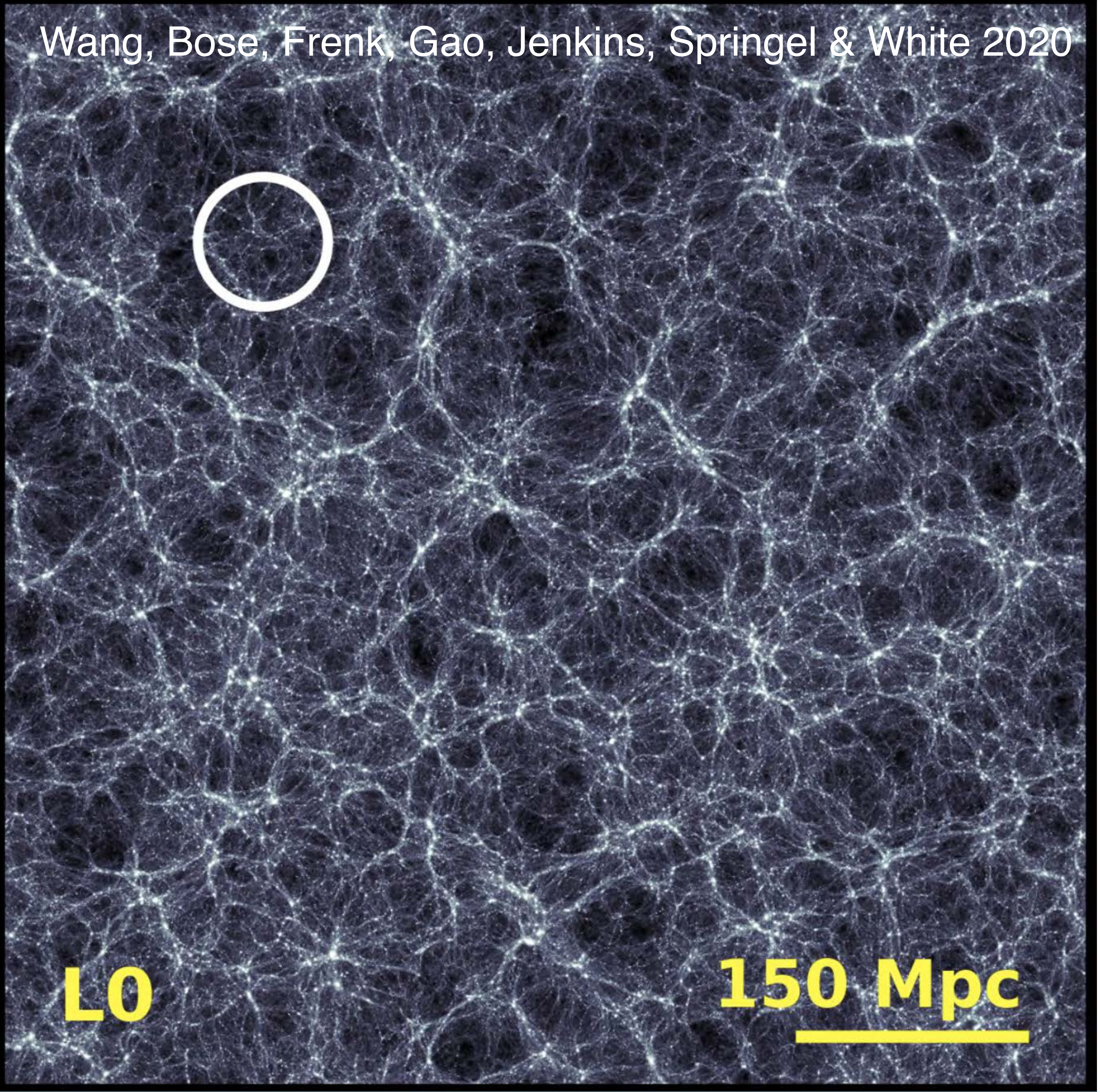
The linear power spectrum ("power per octave")

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

Assumes a 100GeV wimp

Green et al '04





The VVV simulation

Planck cosmology

Dark matter only

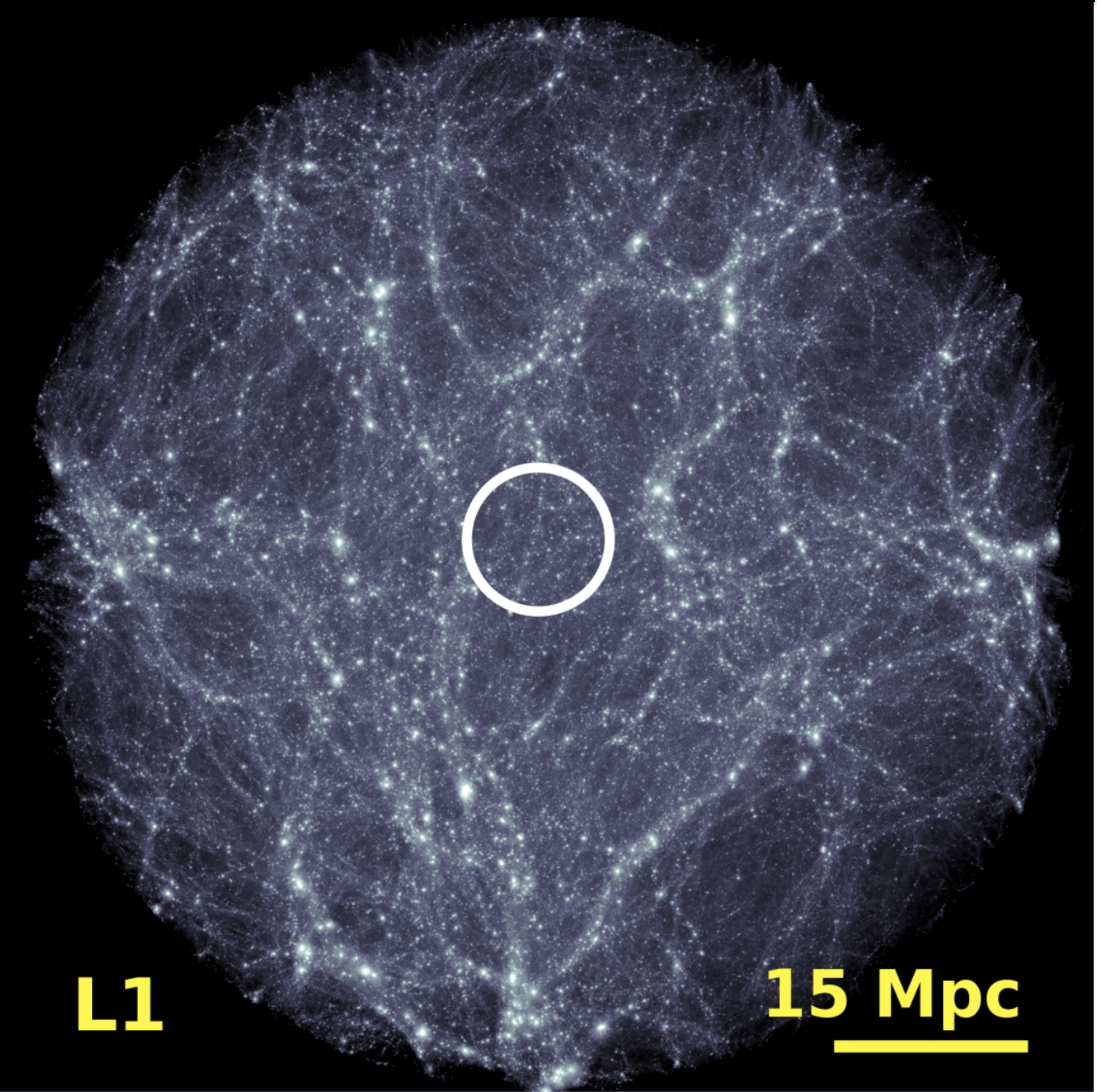
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{14} M_{\odot}$

Base Level

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

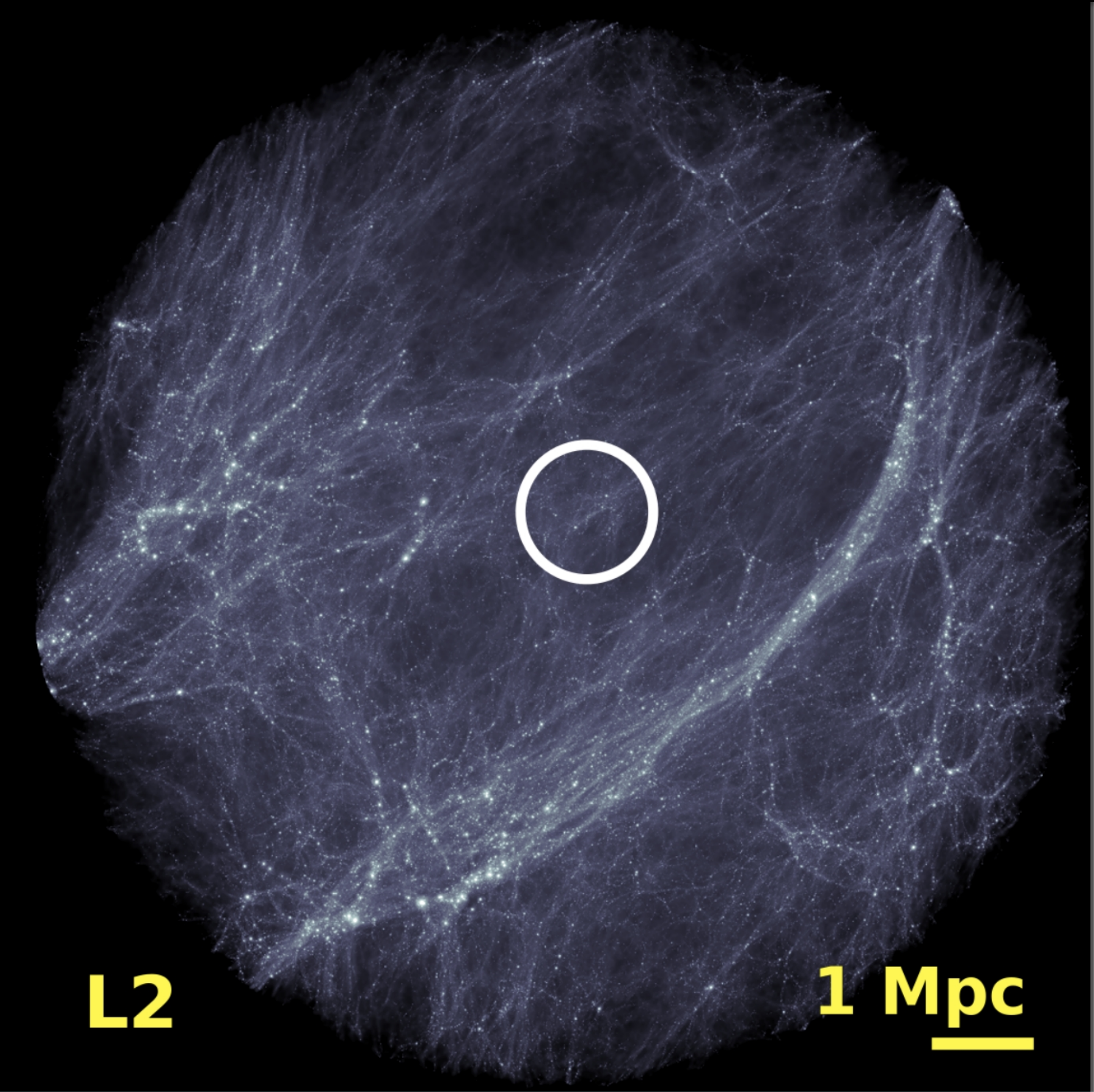
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{12}\ M_{\odot}$

Zoom Level 1

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

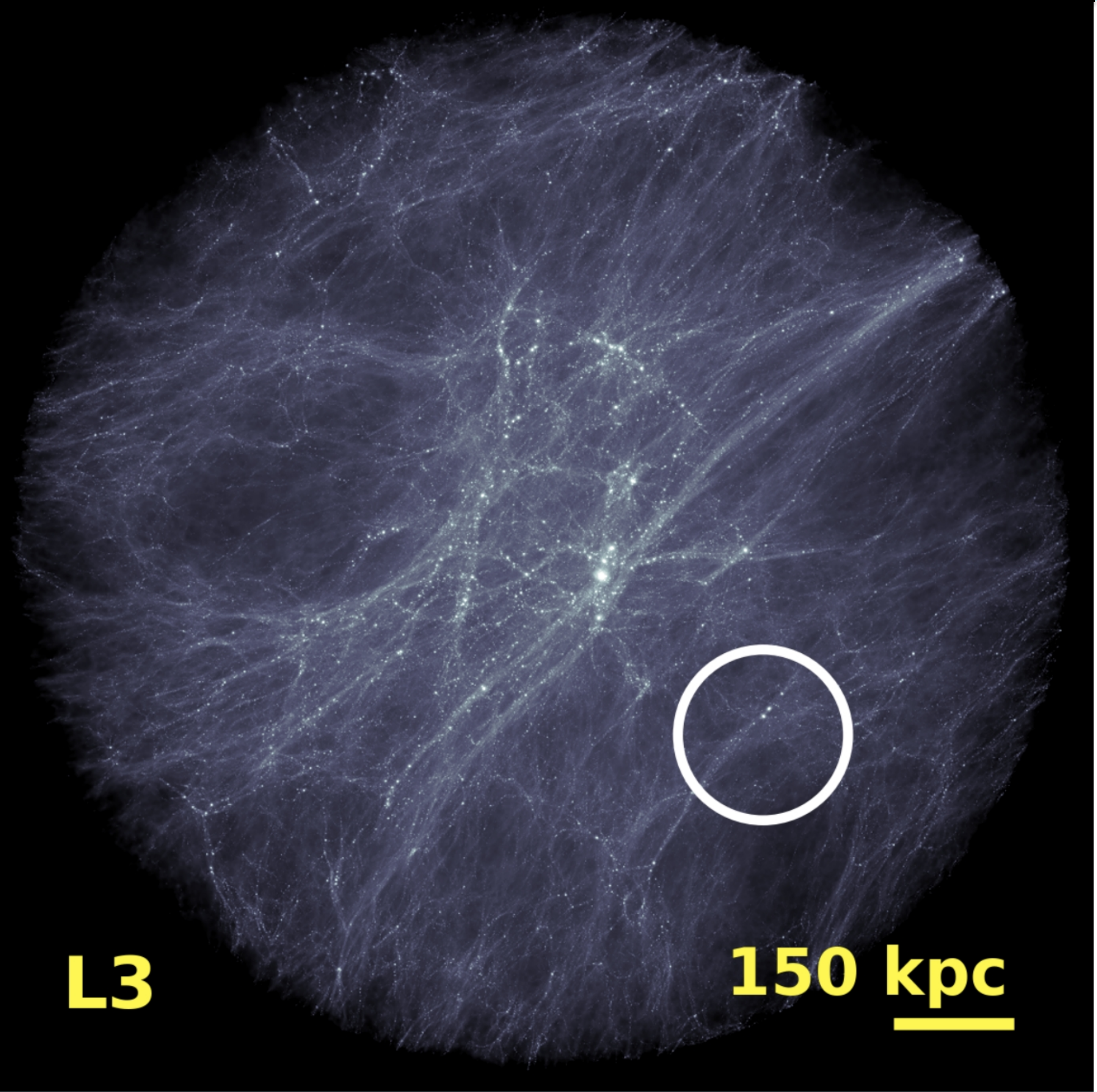
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^9 \ M_\odot$

Zoom Level 2

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

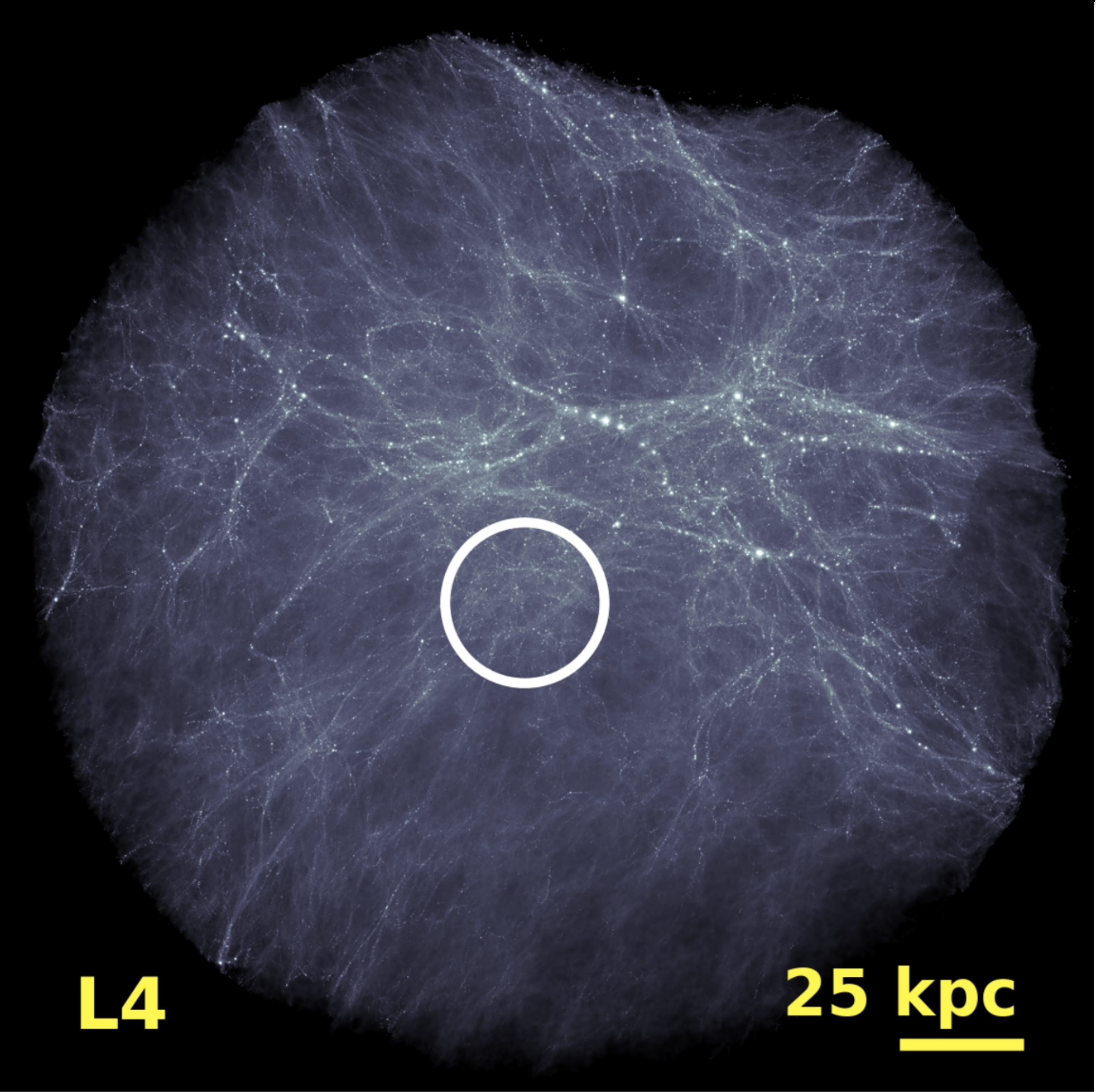
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^6 M_\odot$

Zoom Level 3

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

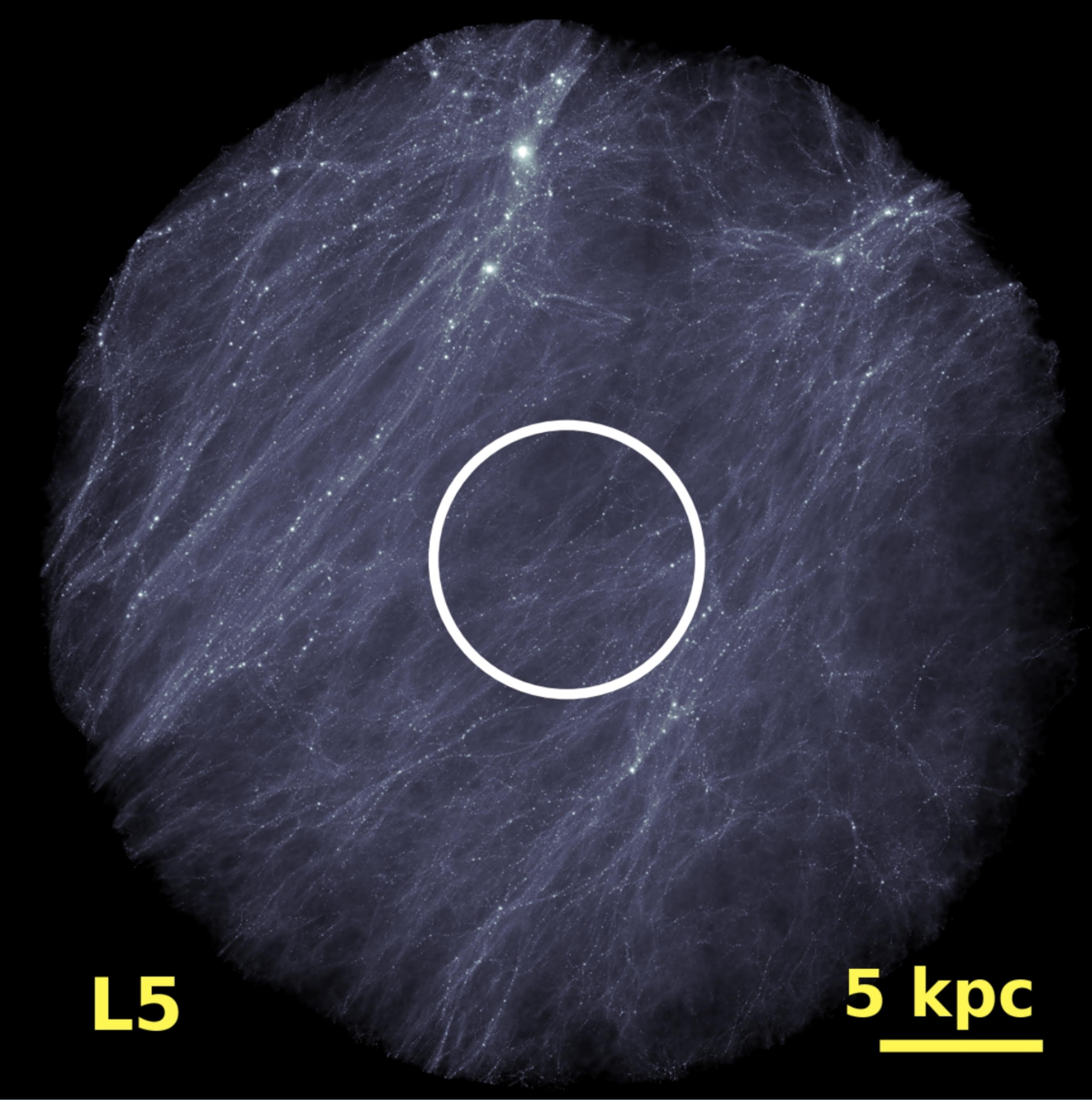
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^3 M_\odot$

Zoom Level 4

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

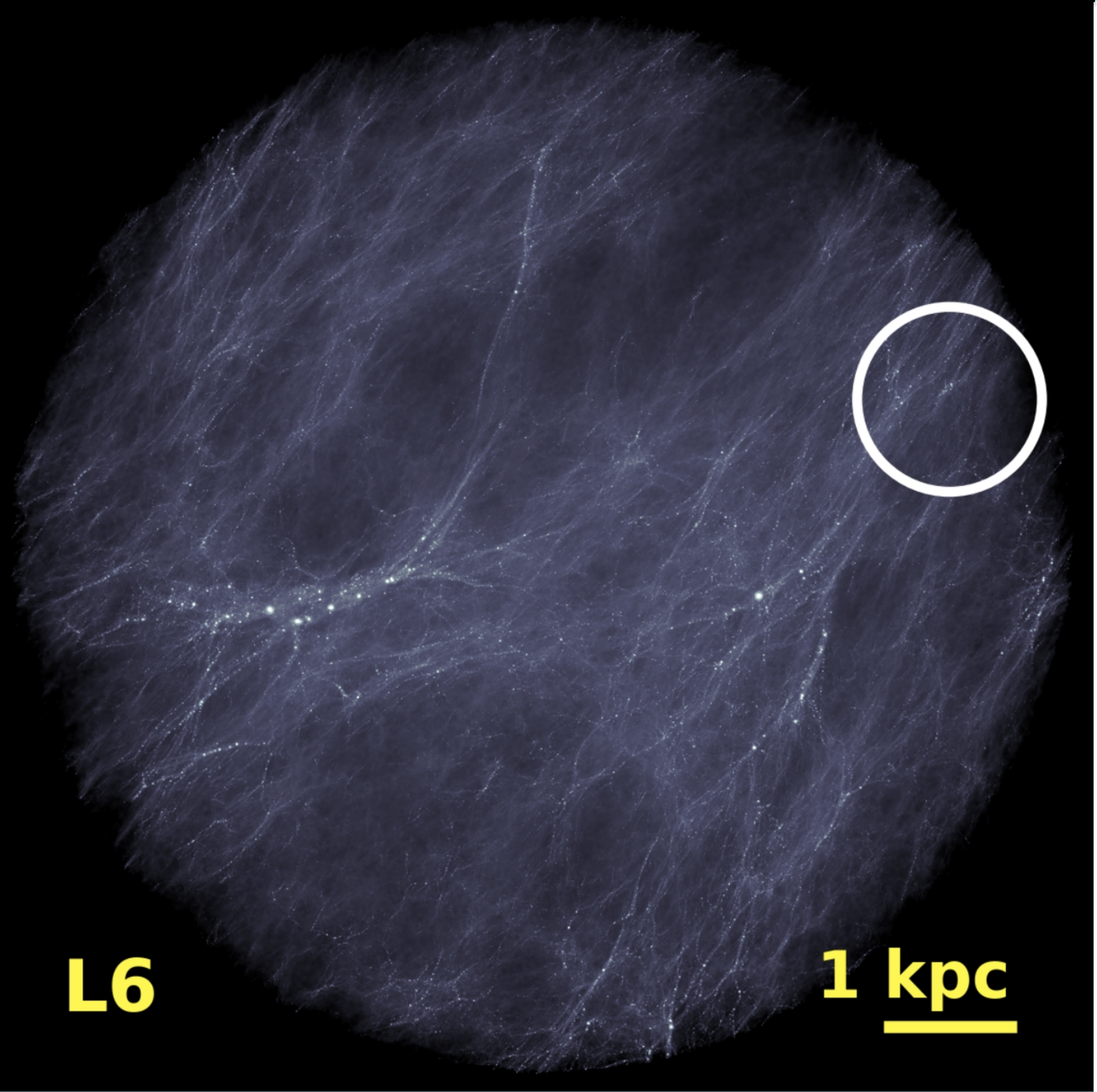
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10\ M_{\odot}$

Zoom Level 5

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

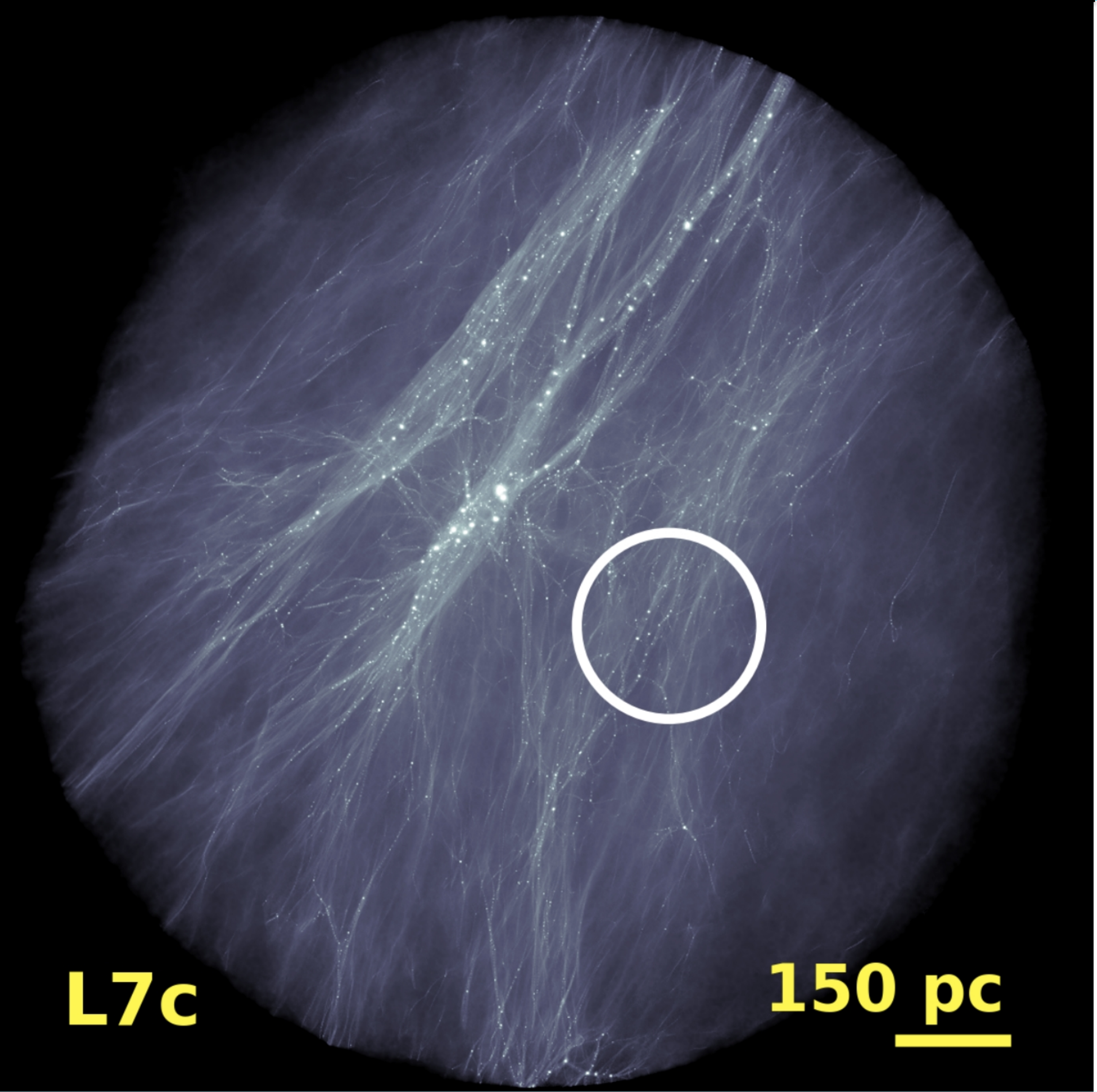
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-1}\ M_{\odot}$

Zoom Level 6

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

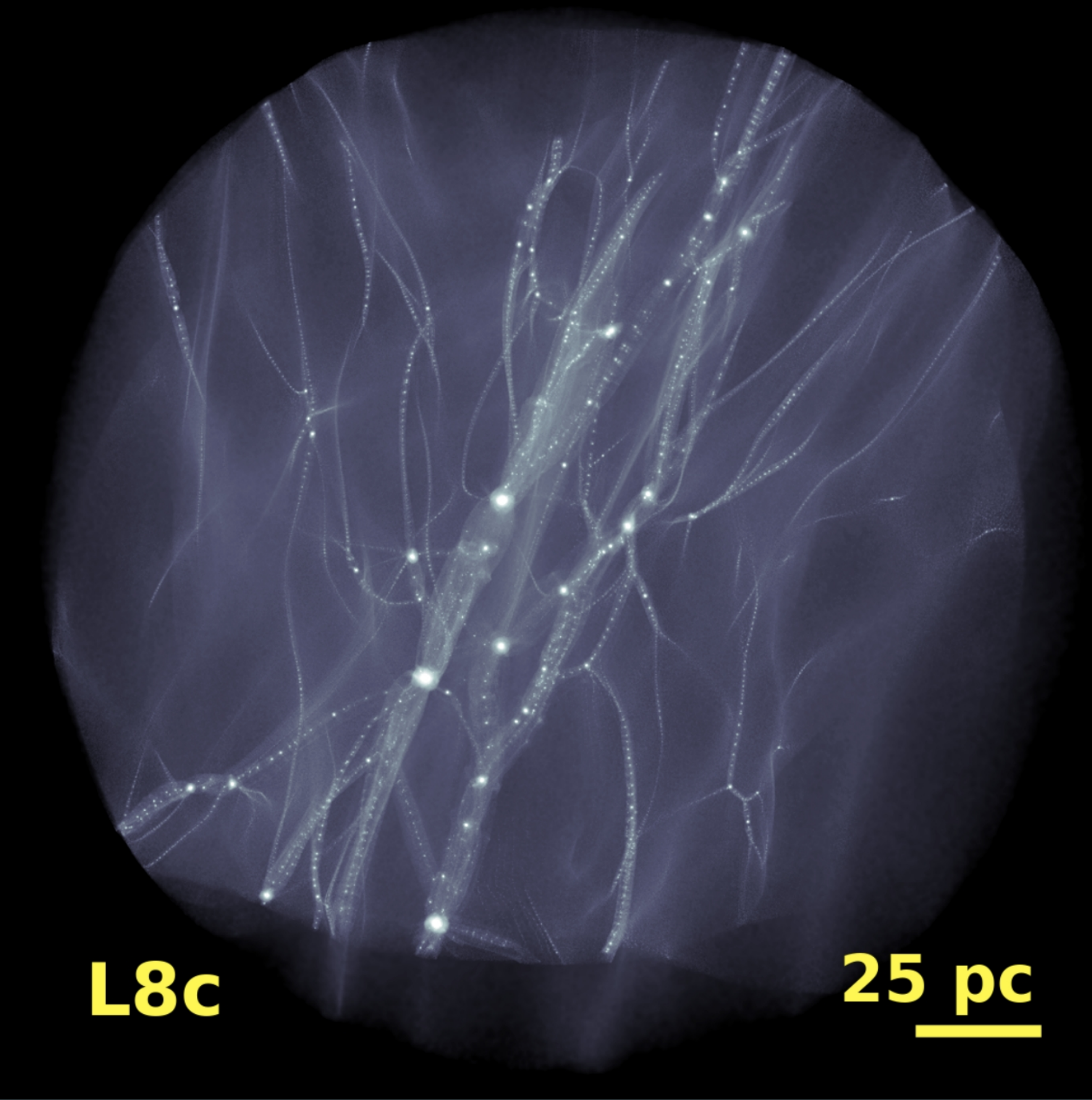
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-4}\ M_\odot$

Zoom Level 7

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

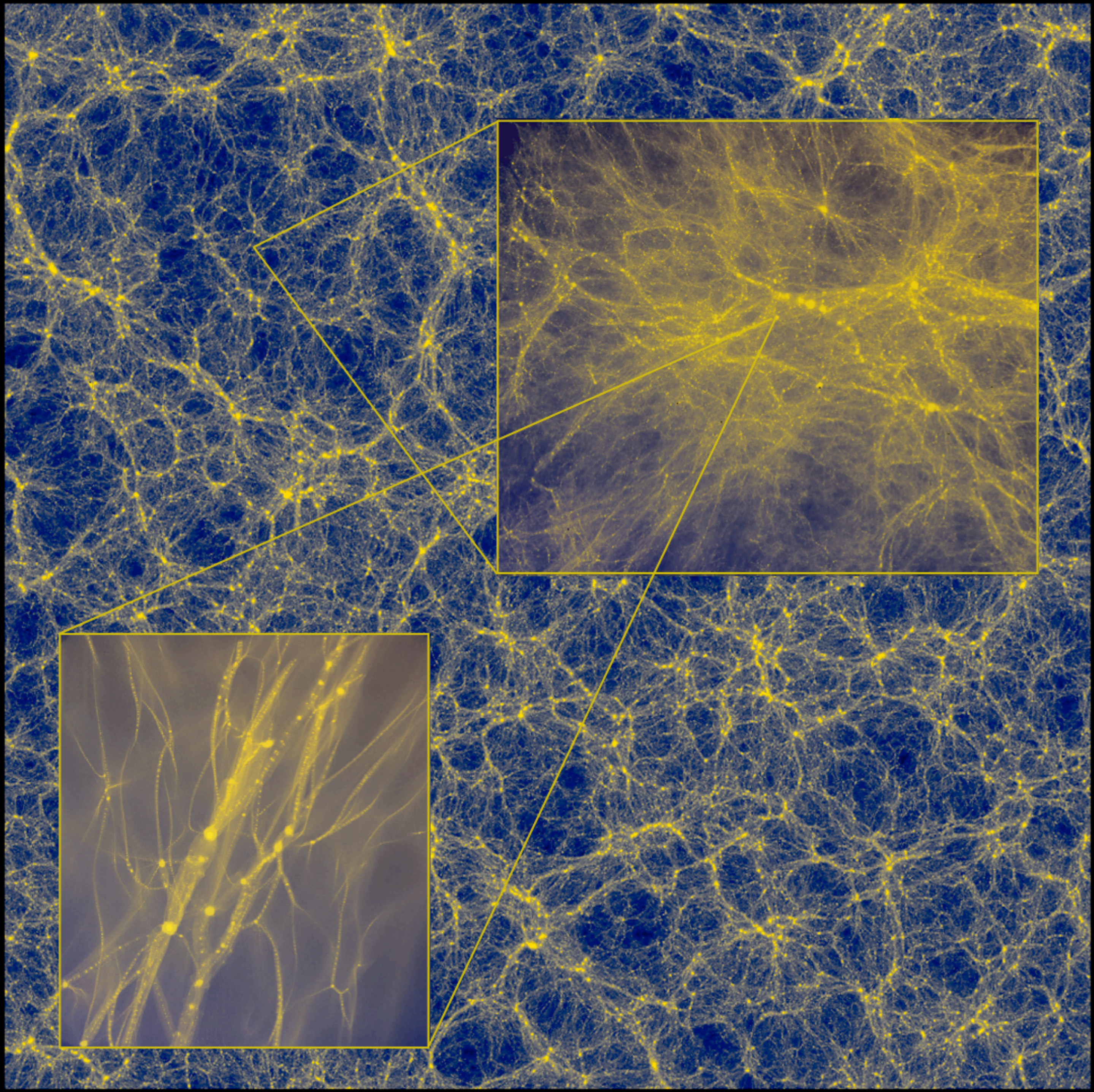
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-6}\ M_{\odot}$

Zoom Level 8

The density of this region is only ~3% of the cosmic mean

Wang, Bose et al 2020

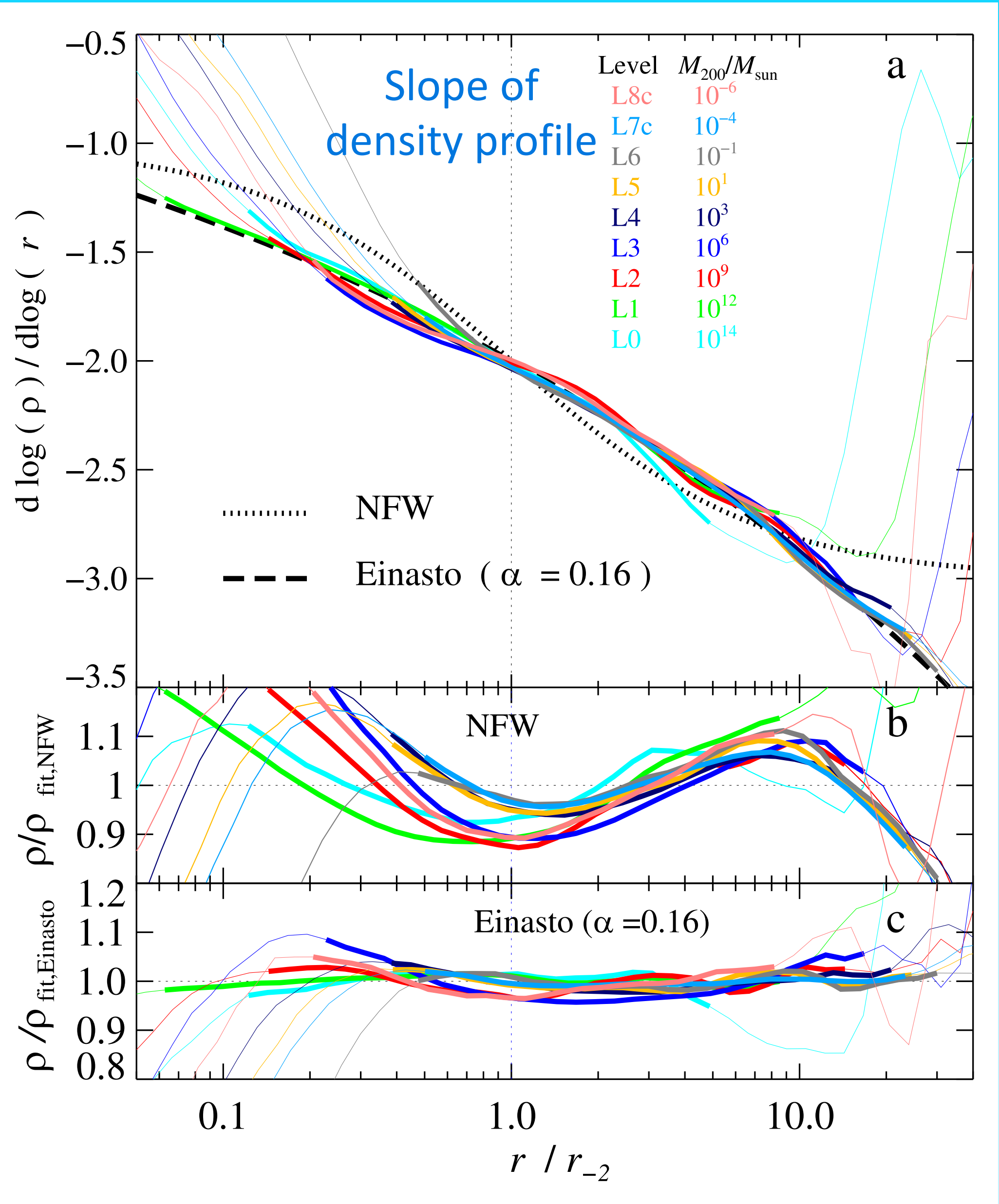


Wang et al ‘20

Density profile shapes

University of Durham

Over 19 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (α =0.16) to within 7%



Wang, Bose, CSF + '20

Concentration-mass relation

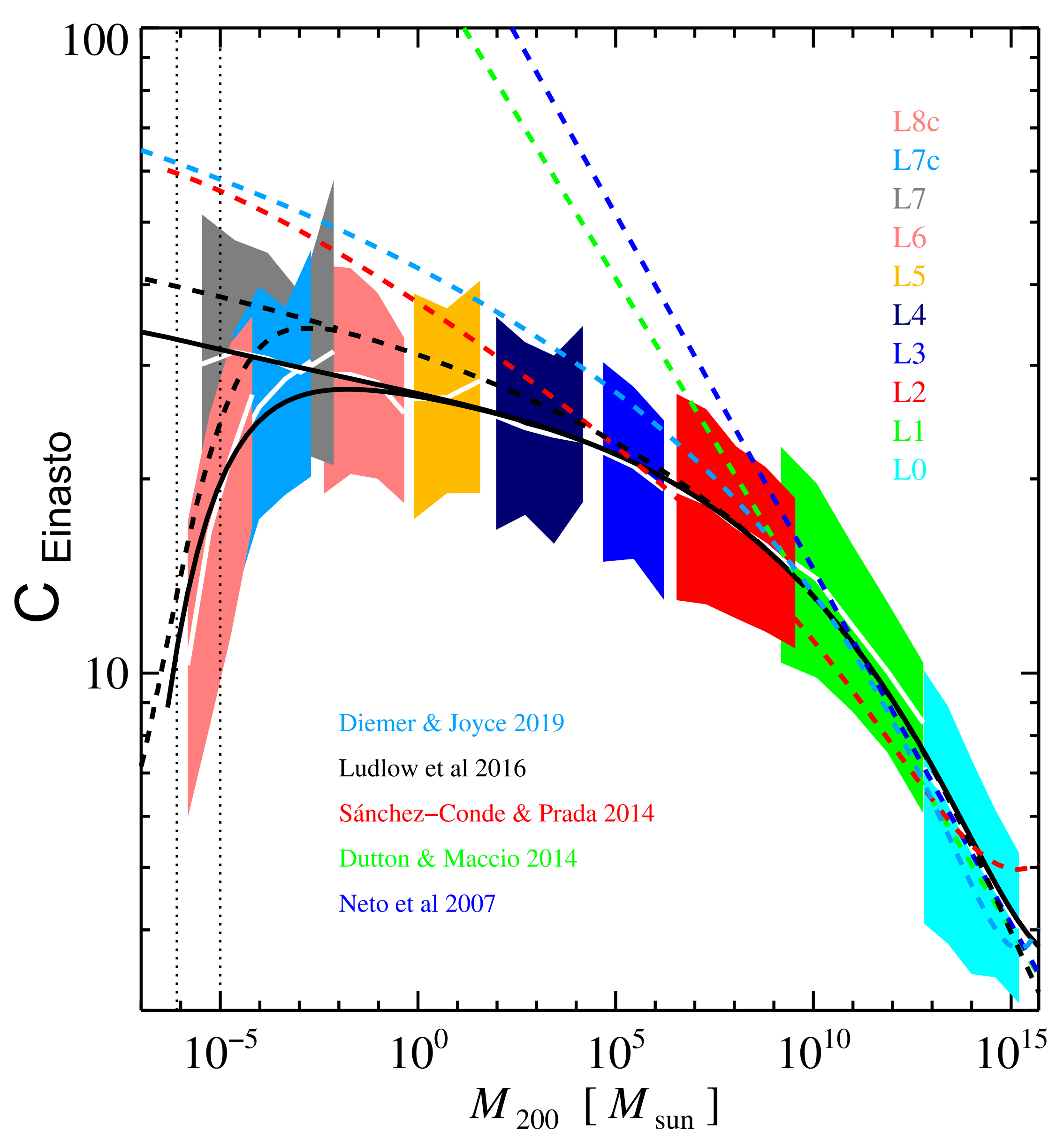
University of Durham

Concentrations at small mass are lower than all previous extrapolations by up to factors of tens.

A turndown at 10^3 Earth masses is due to the free-streaming limit.

The scatter depends only weakly on halo mass

Wang, Bose, CSF + '20

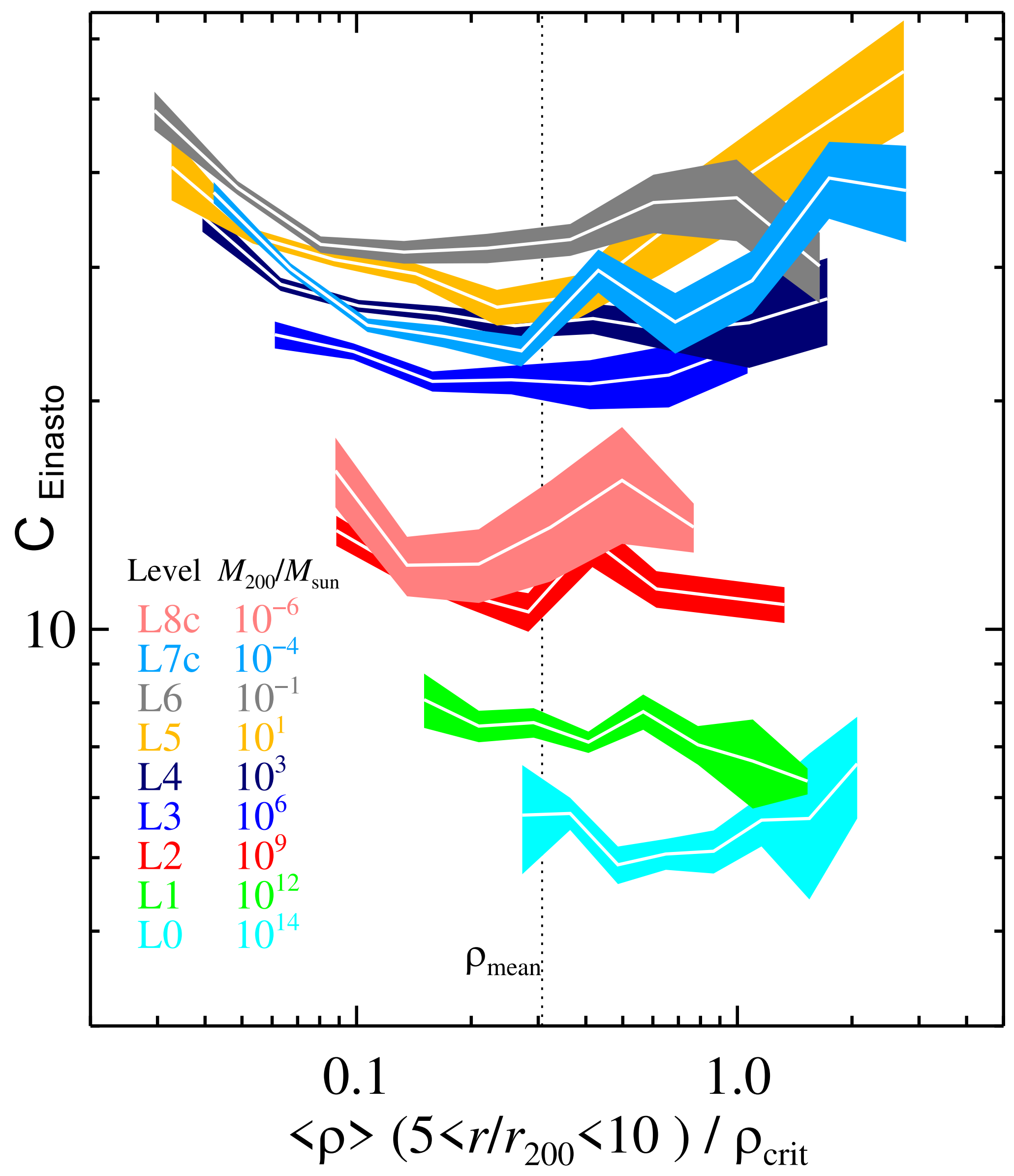


University of Durham

Concentration-density relation

At given halo mass, concentration does not depend on local environment density

The range of local environment density does not depend strongly on halo mass



Wang, Bose, CSF + ‘20

Annihilation luminosity

University of Durham

The contribution of halos to the mean z = 0 luminosity density of the Universe is almost independent of their mass over the mass range

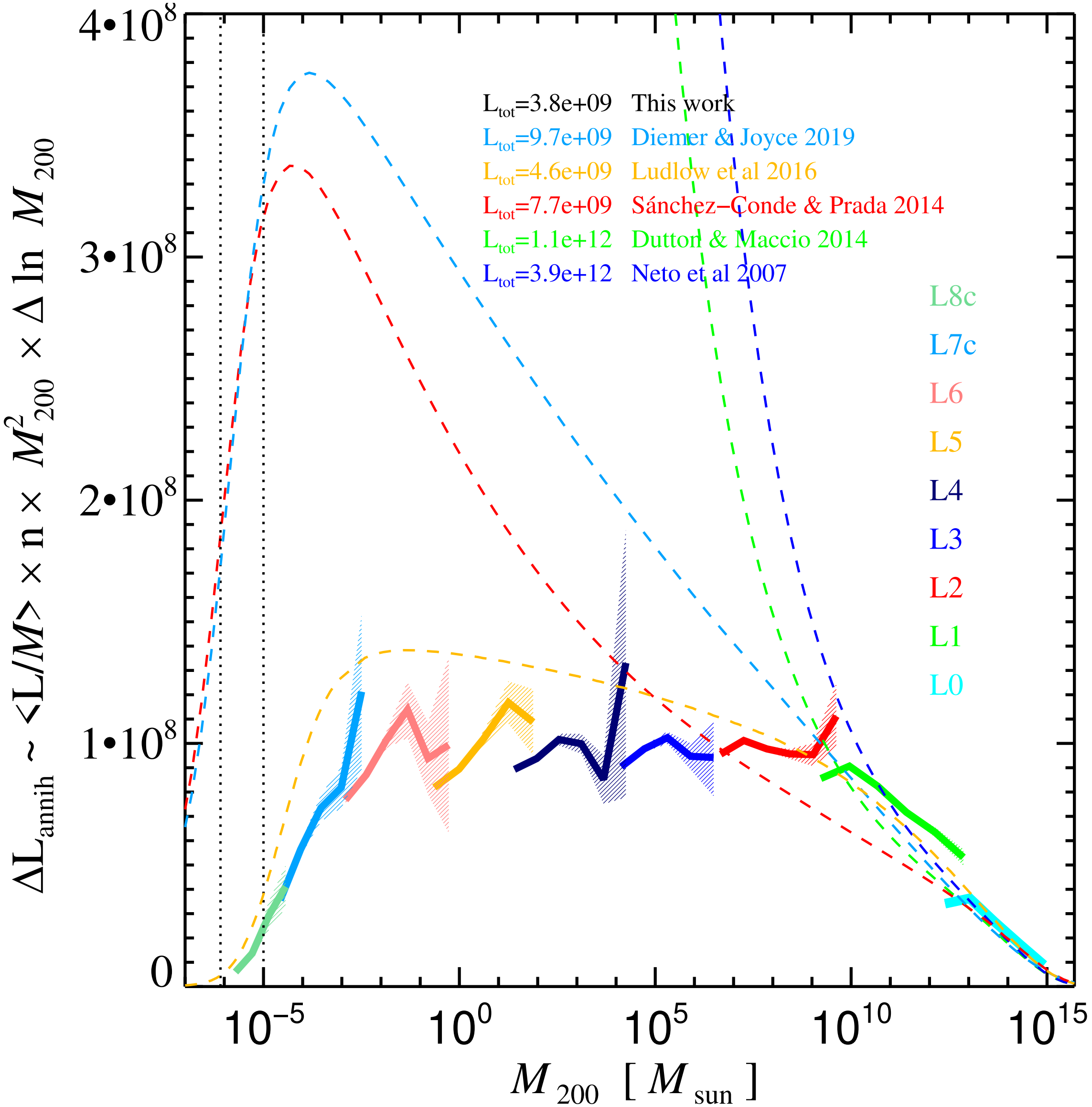
$10^{-4}\ M_\odot < M_{halo} < 10^{12}\ M_\odot$

It is lower than previously estimated by factors between 3 and 1000

This still neglects the substructure contribution to halo luminosity

Wang, Bose, CSF + '20

Annihilation luminosity per unit cosmological volume



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. CDM makes many small subhalos but most (~$5.10^8 M_0$) are dark → No satellite problem in CDM or WDM
2. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!
3. Halos of all masses (21 orders of magnitude) have NFW profiles → small haloes may dominate annihiln radn