A conclusive test of the cold dark matter model

Carlos S. Frenk
Institute for Computational Cosmology, Durham

... or how to rule out CDM – or alternative models

The new Ogden Centre at Durham

University of Durham

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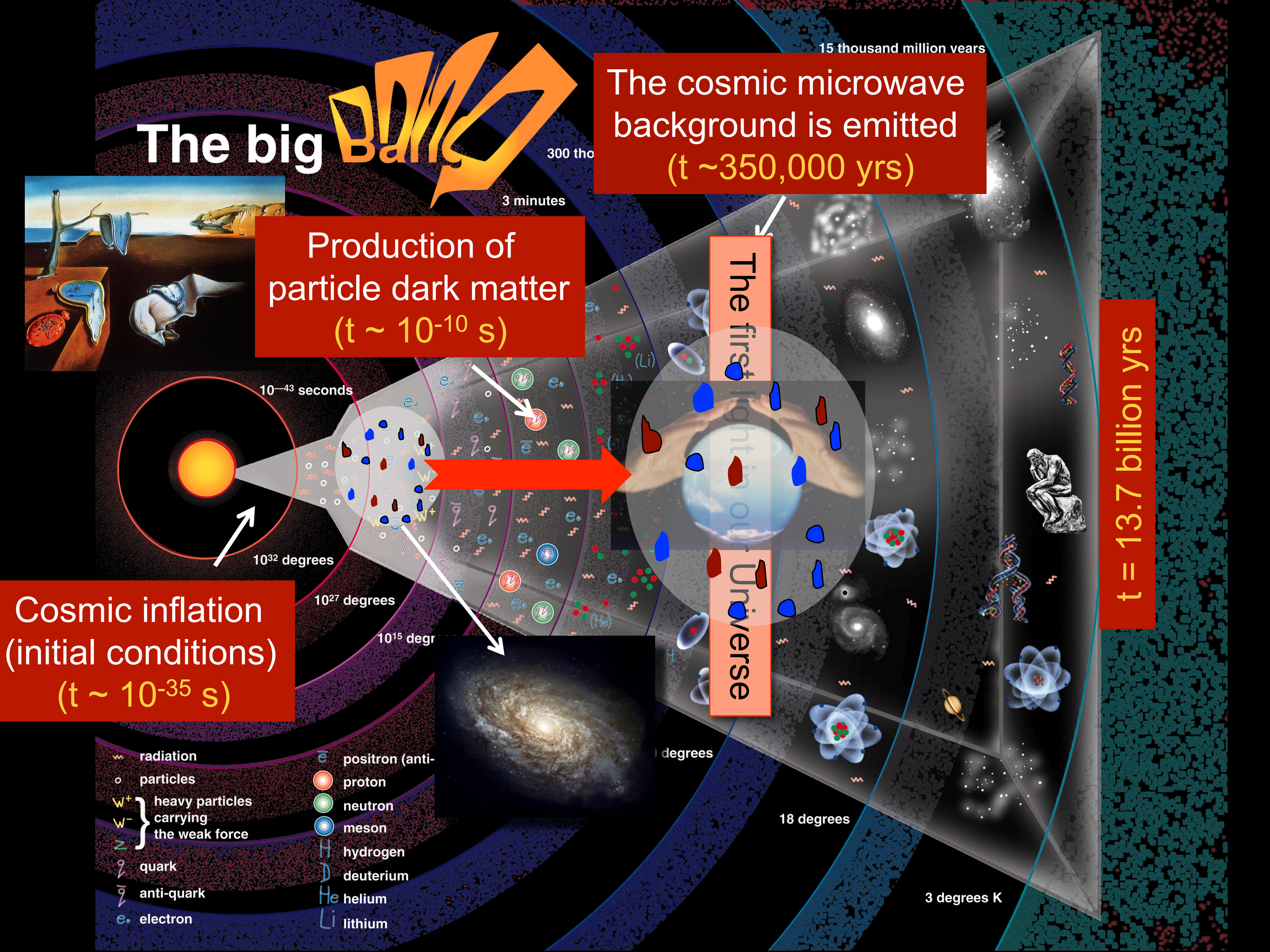
The ΛCDM model of cosmogony

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 Bang
The cosmic microwave background is emitted
(t ~350,000 yrs)
Production of particle dark matter
(t ~ 10-10 s)
Cosmic inflation (initial conditions)
(t ~ 10-35 s)
The first light in our Universe
t = 13.7 billion yrs
15 thousand million years
3 minutes
10—43 seconds
1032 degrees
1027 degrees
1015 degr
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

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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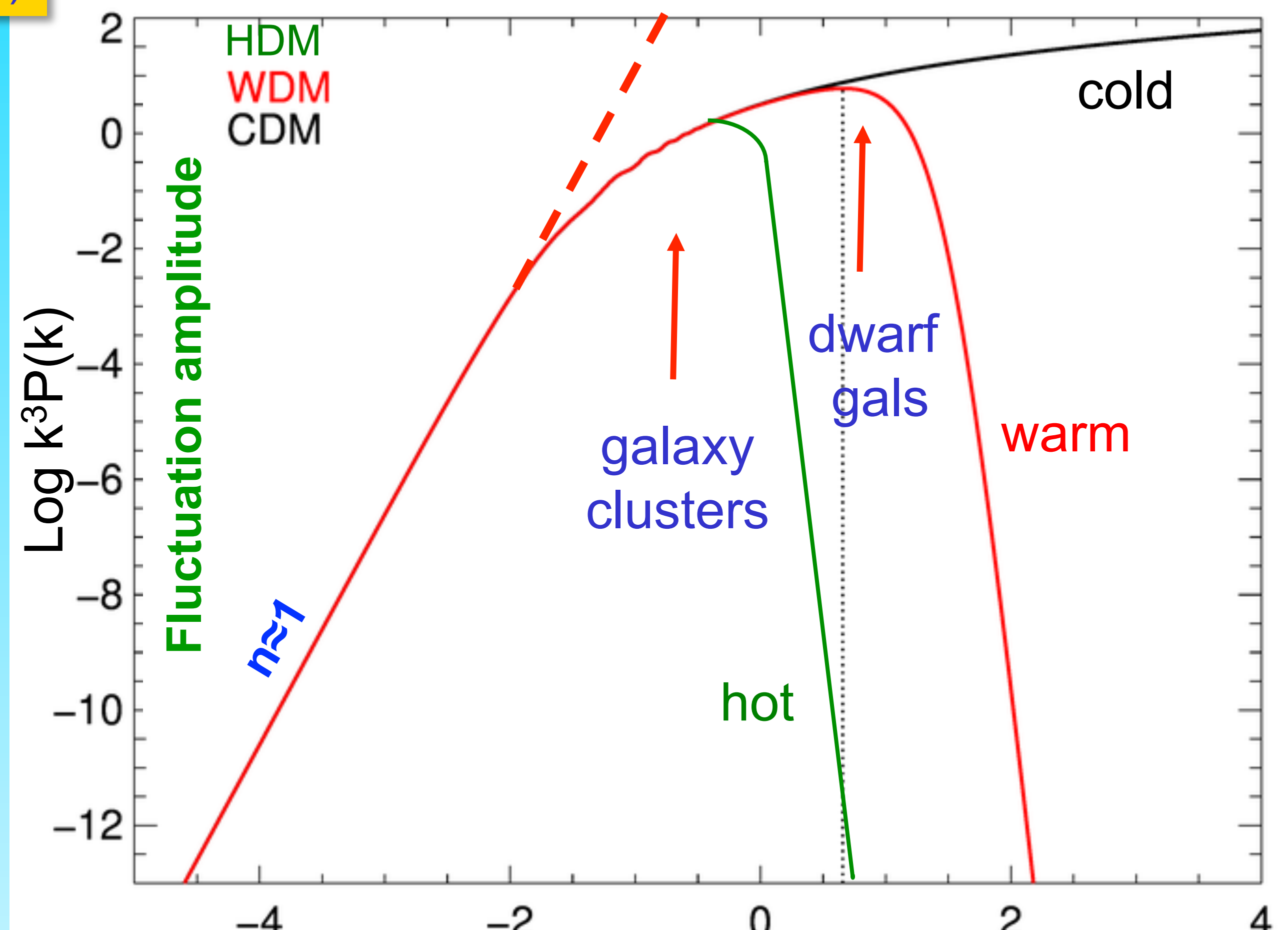
The dark matter power spectrum

Free streaming →

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

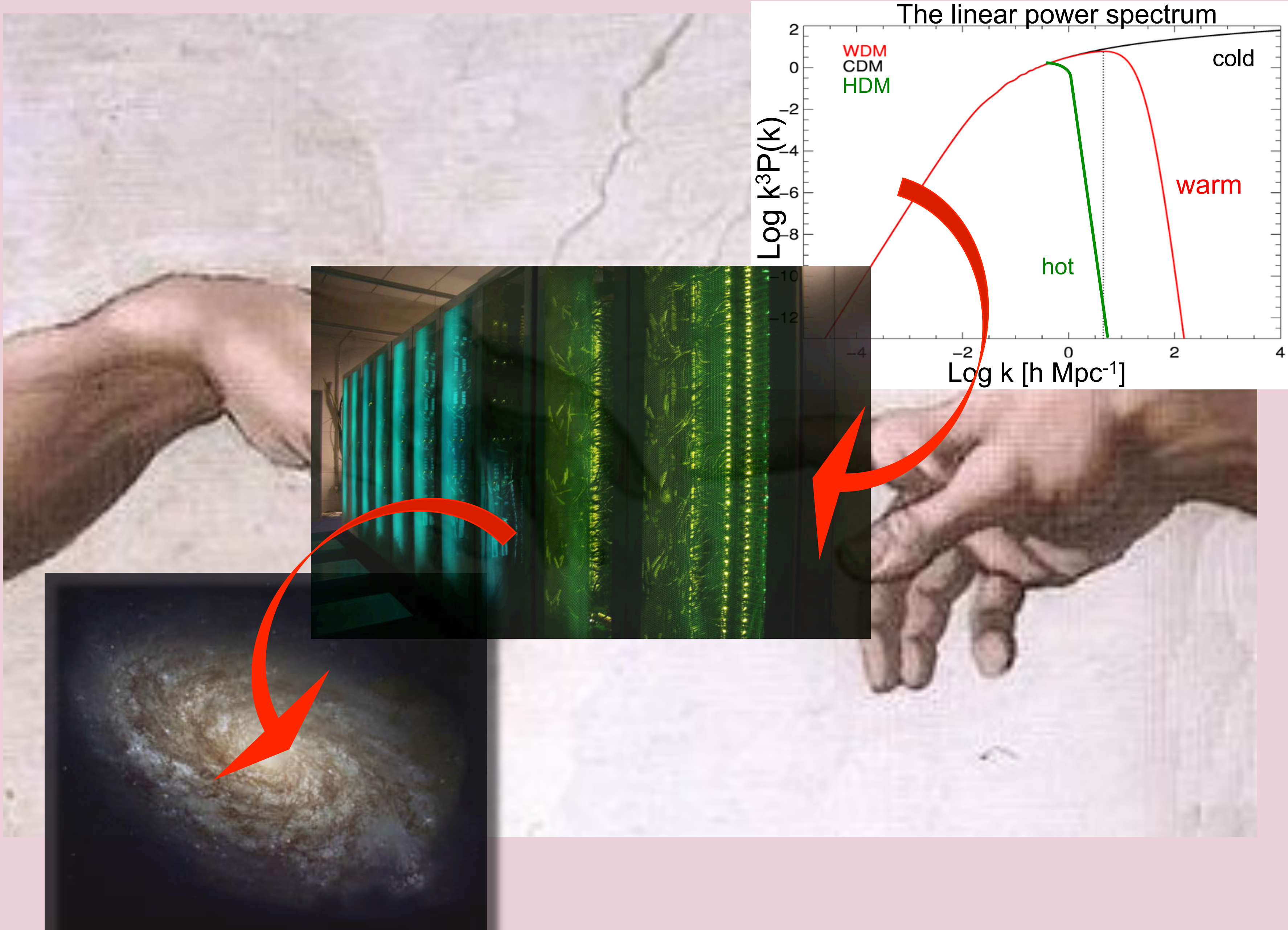
for a thermal relic

$k^3 P(k)$ 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_ν = 30 ev → Ω_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_ν = 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.

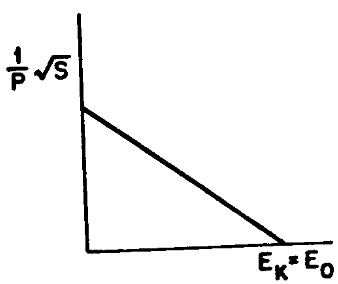


Fig. 1. Kurie plot for M_ν = 0.

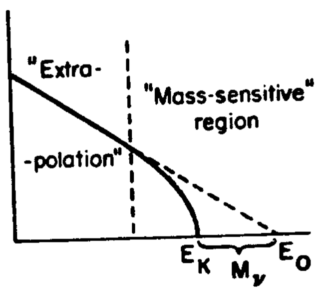
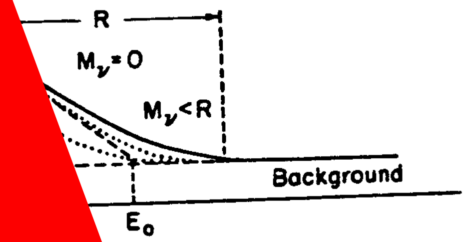


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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 $M_\nu \le R$, the changes due to ... mass and the influence of R are indistinguishable. For M_ν ...termination 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 ∿ M_ν, 2) the smaller M_ν is, the smaller the background (∿ M_ν^2) must be and the higher the statistics (∿ M_ν^{-3}) must be. For example, suppose that for M_ν = 100 eV we need resolution R, background Q, and statistics N. If M_ν = 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 ^{3}H 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 ^{3}H were by S. Curran et al. (1948) and G. Hanna, B. Pontecorvo (1949). Using ^{3}H gas in a proportional counter, they obtained $M_\nu \le$ 1 keV. Further progress required magnetic spectrometer development. This allowed the resolution to be improved considerably, and L. Langer and R. Moffat (1952) obtained $M_\nu \le$ 250 eV. The best value was obtained by K. Bergkvist (1972): R ∿ 50 eV and $M_\nu \le$ 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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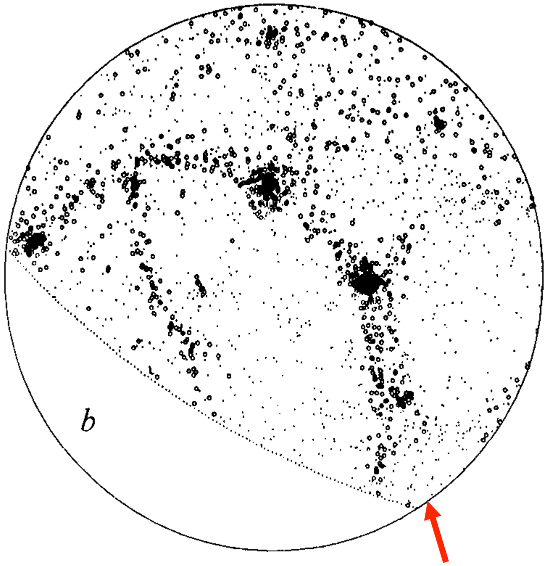
Non-baryonic dark matter cosmologies



Neutrinos
$\Omega=1$

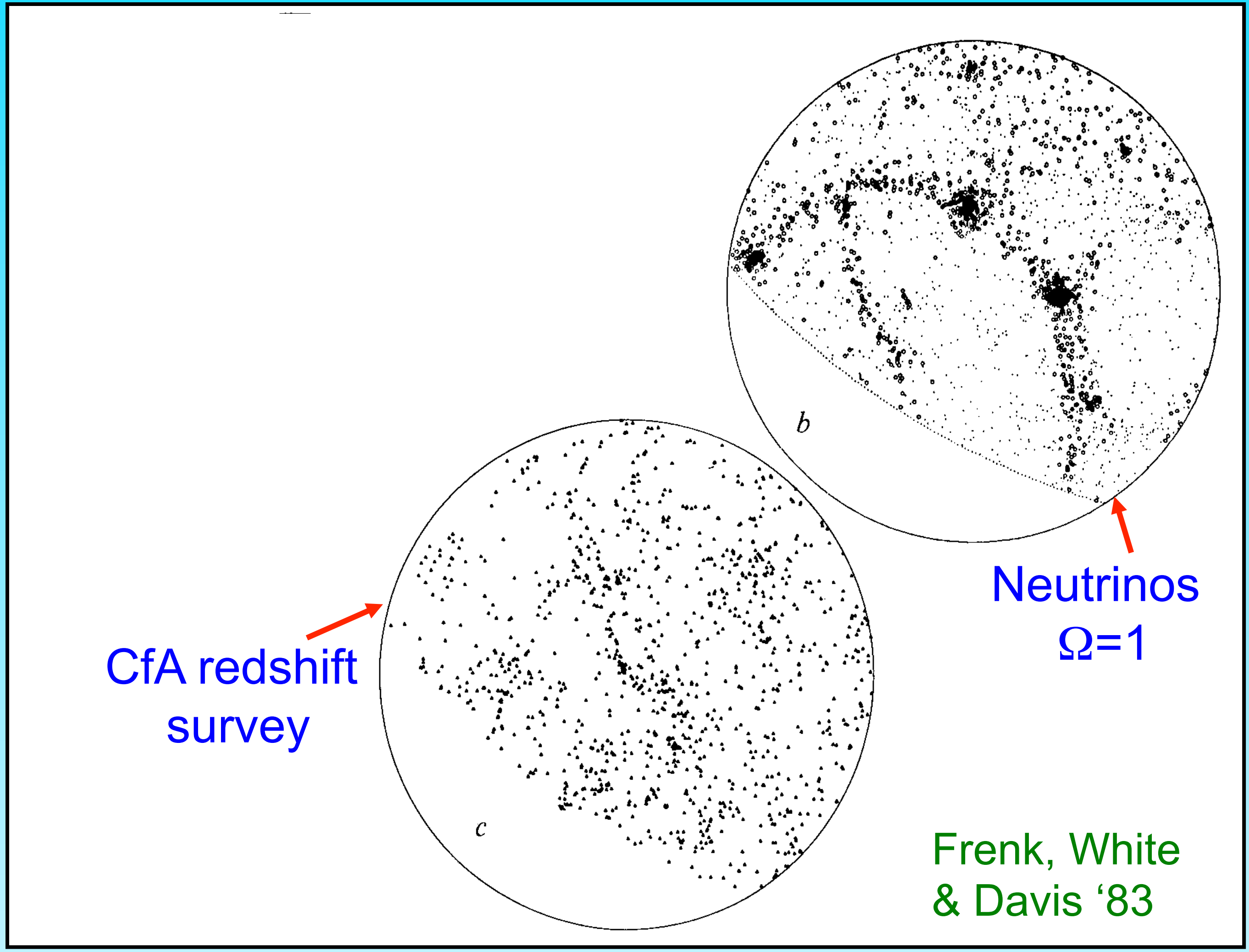
Frenk, White & Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 30 ev



Non-baryonic dark matter cosmologies

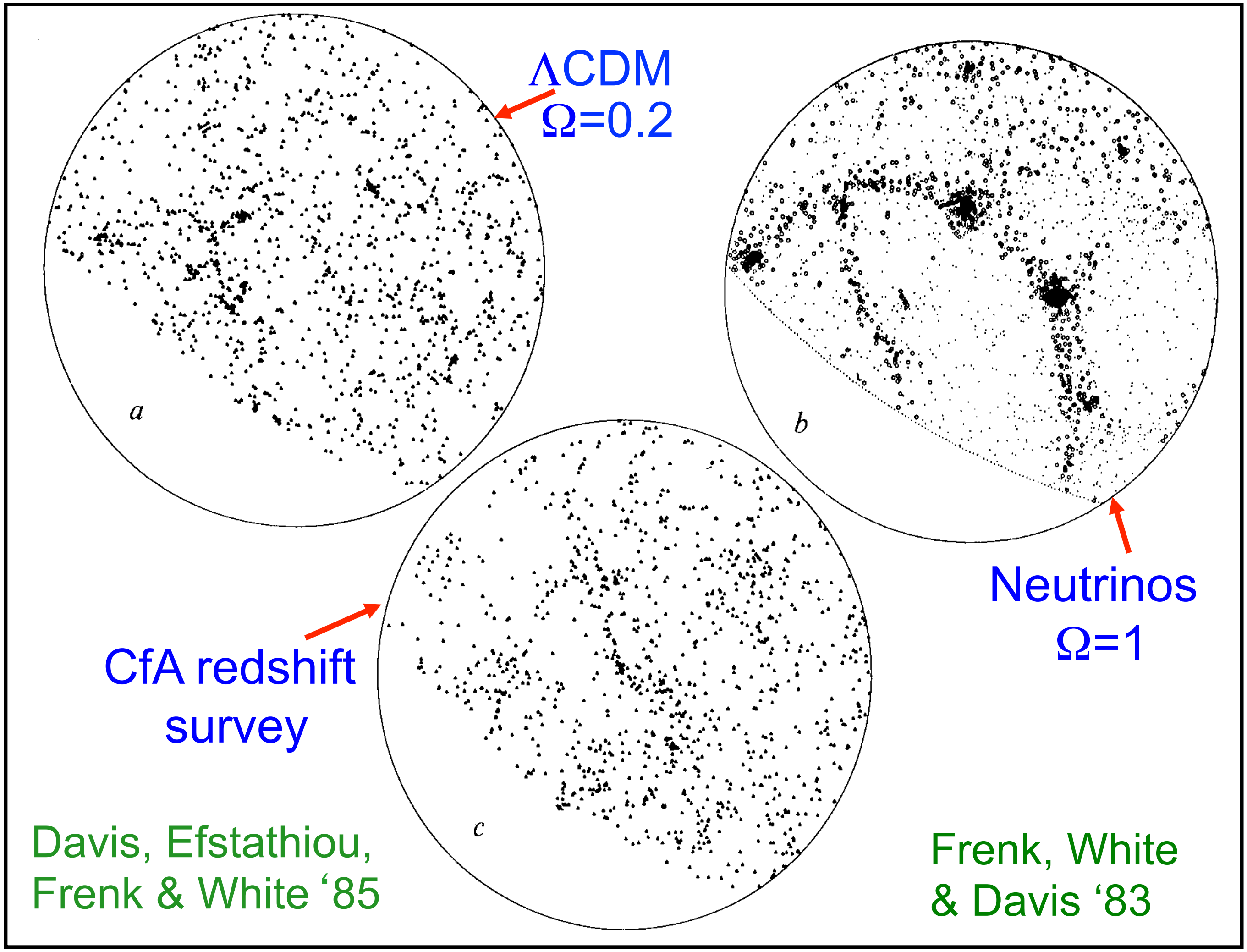
Neutrino DM → wrong clustering

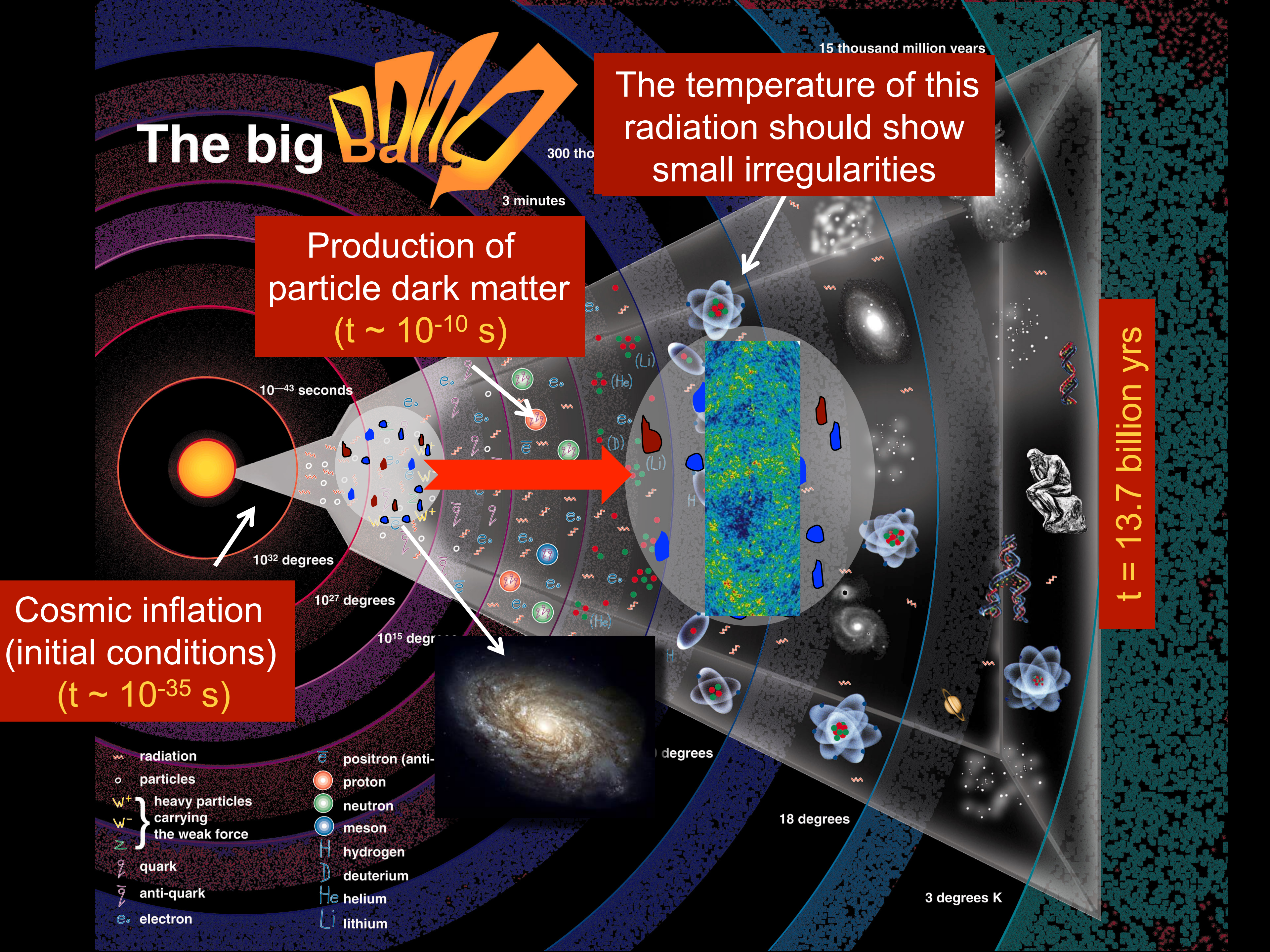
Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

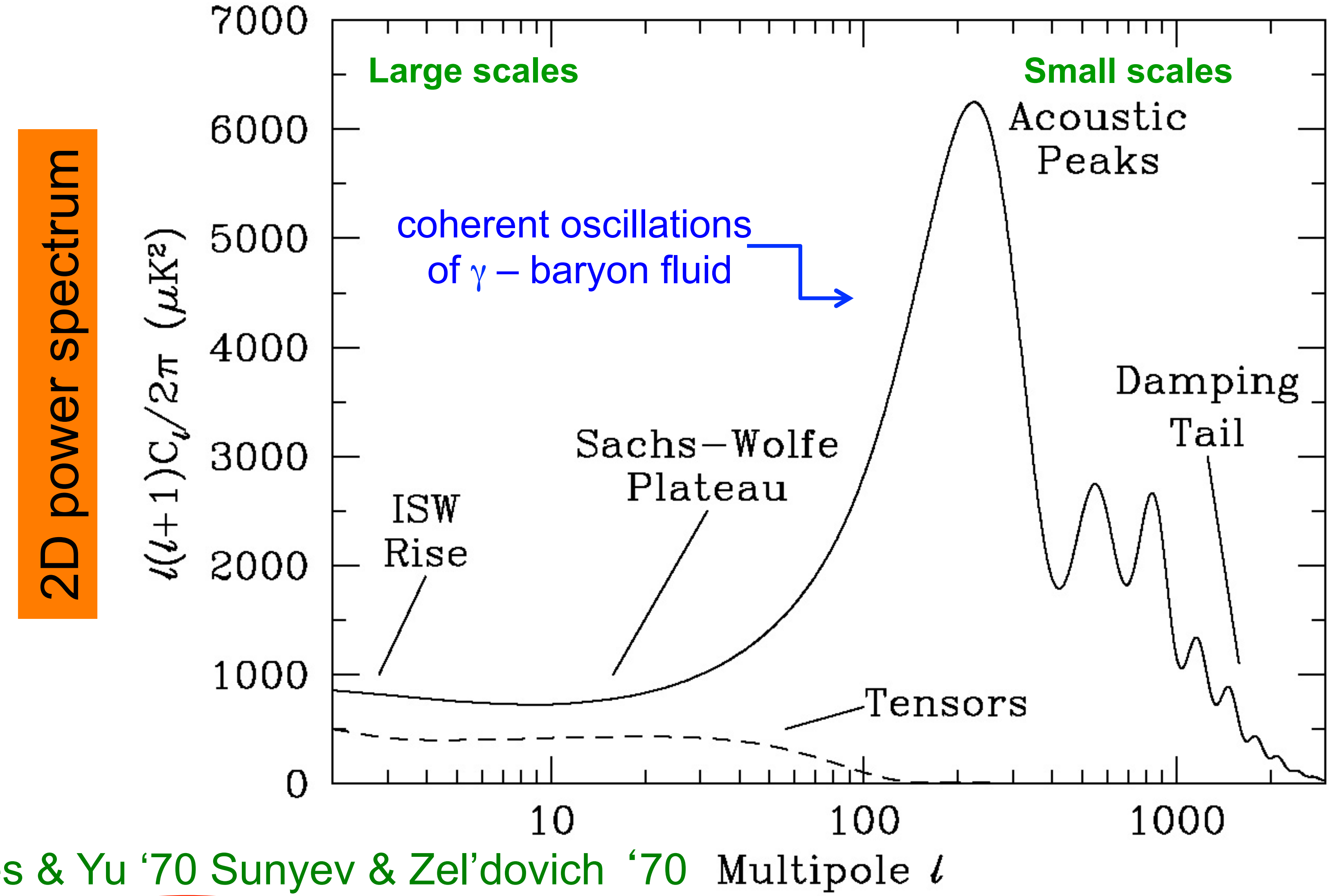
In CDM structure forms hierarchically





The big Bang
The temperature of this radiation should show small irregularities
Production of particle dark matter
(t ~ 10^-10 s)
Cosmic inflation (initial conditions)
(t ~ 10^-35 s)
t = 13.7 billion yrs
15 thousand million years
300 tho
3 minutes
10—43 seconds
1032 degrees
1027 degrees
1015 degr
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

Temperature anisotropies in CMB



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

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

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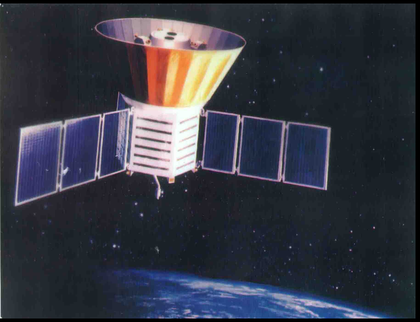
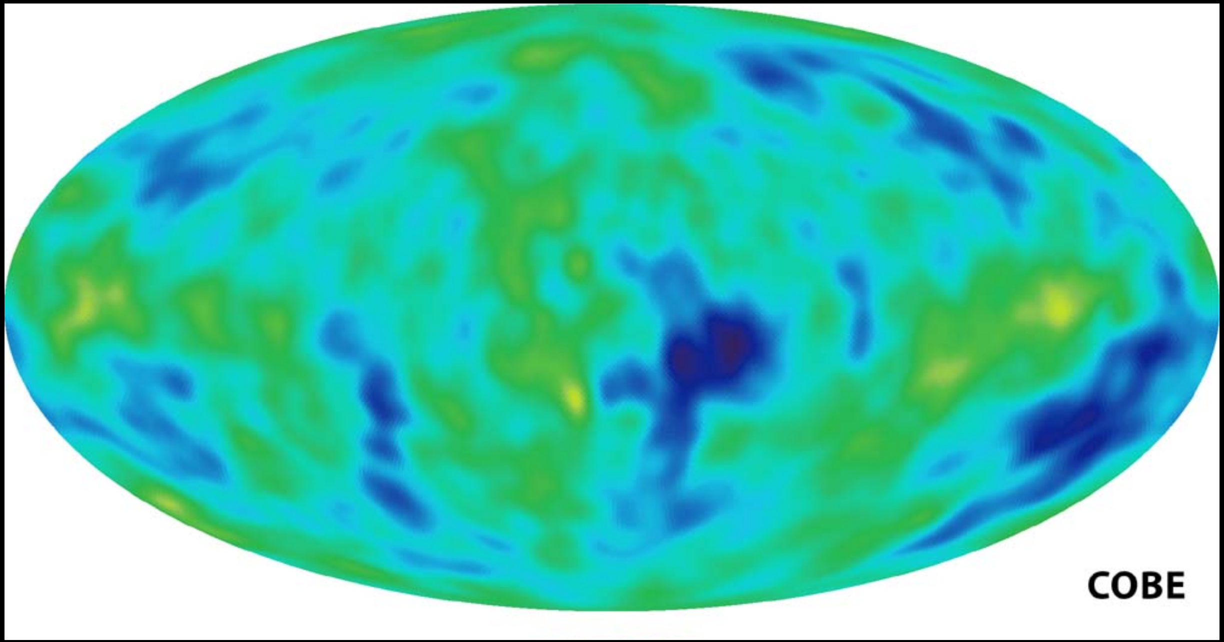
Jim Peebles

Nobel prize 2019

The CMB

1992





George Smoot - Nobel Prize 2006

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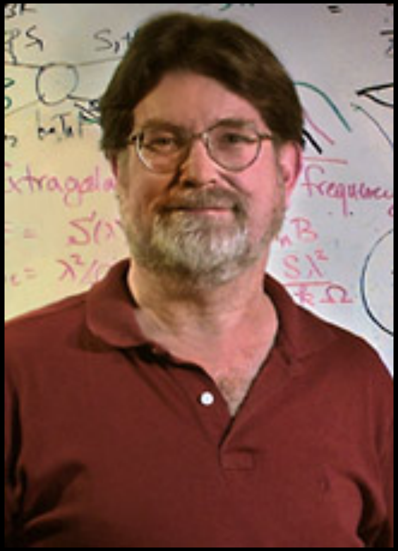
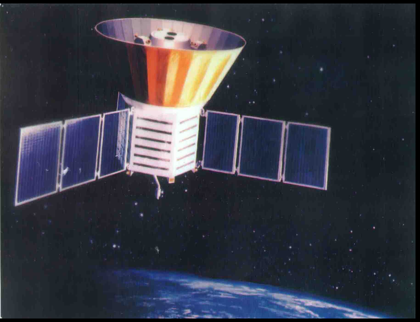
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

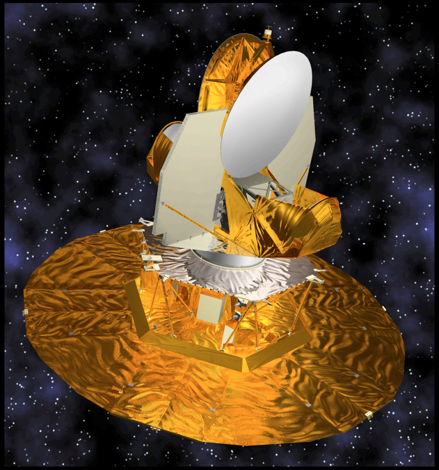


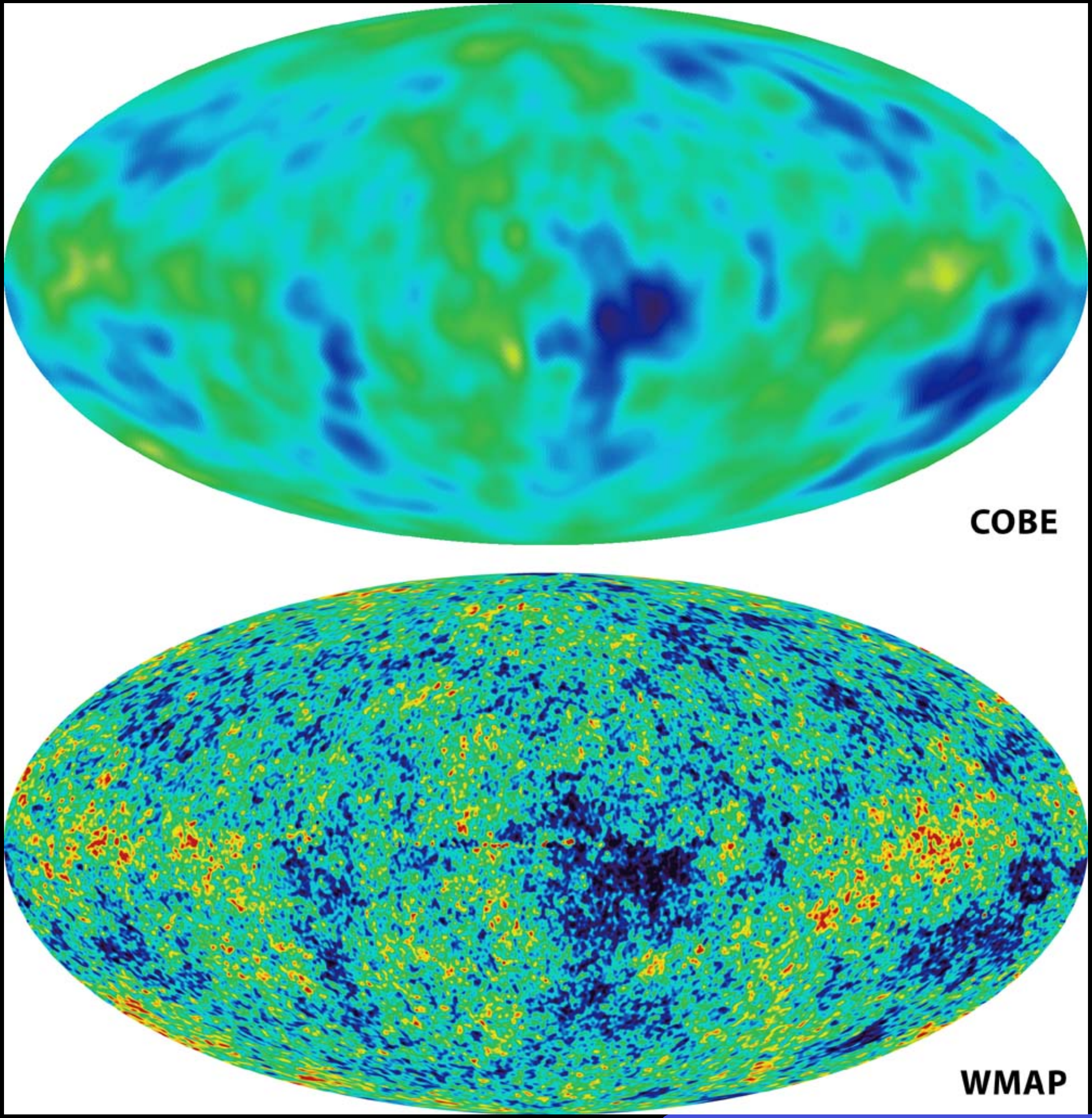
The CMB

1992



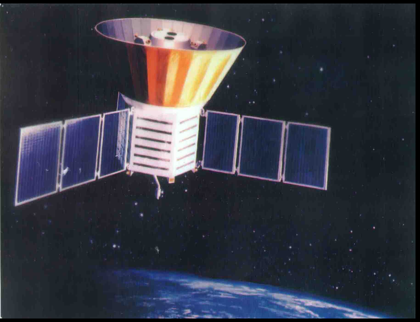
2003



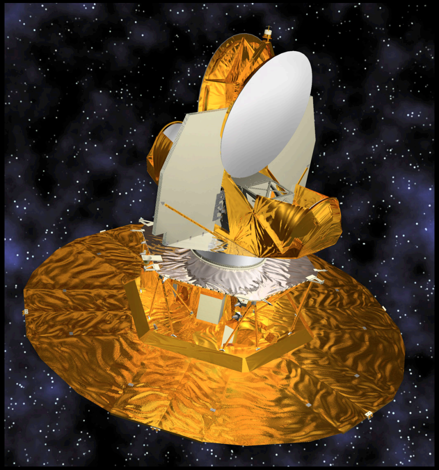


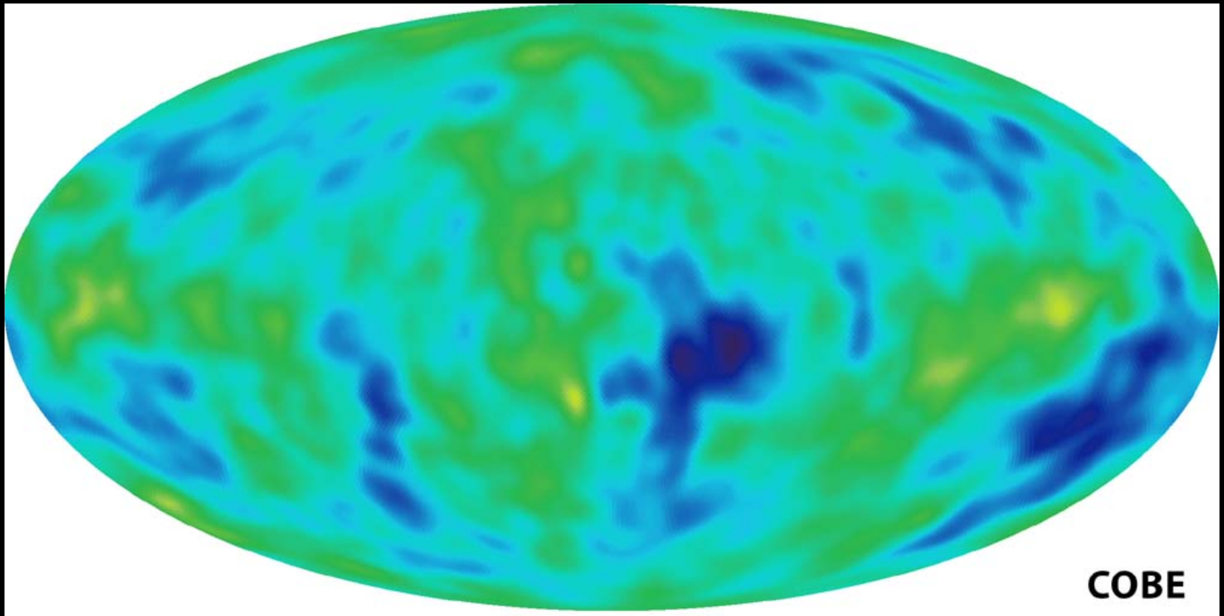
The CMB

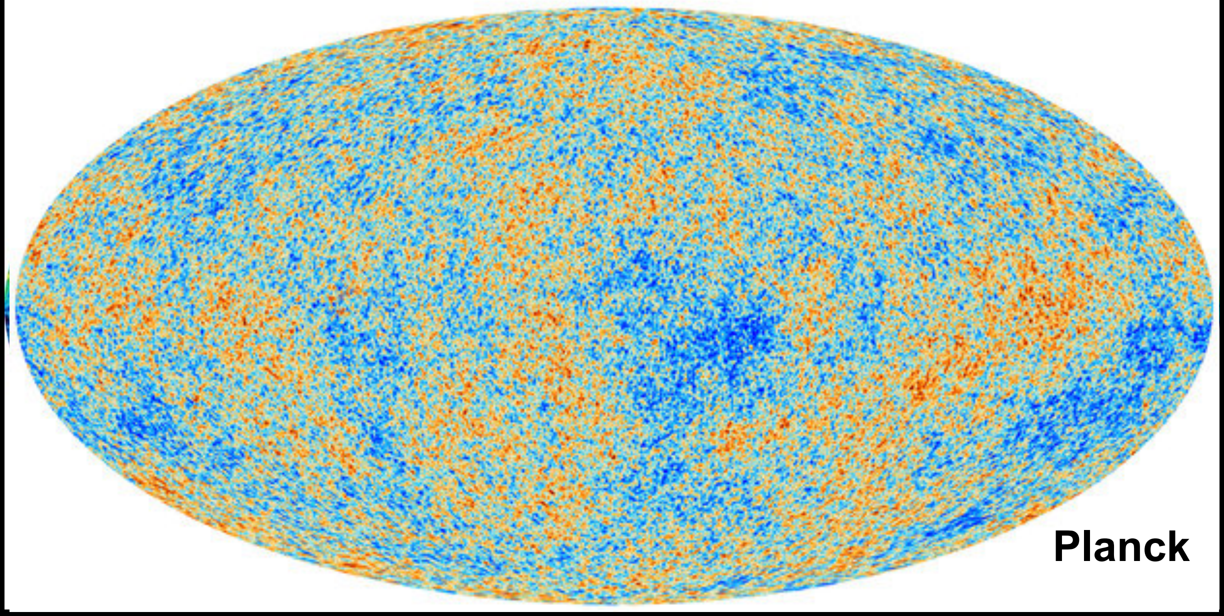
1992



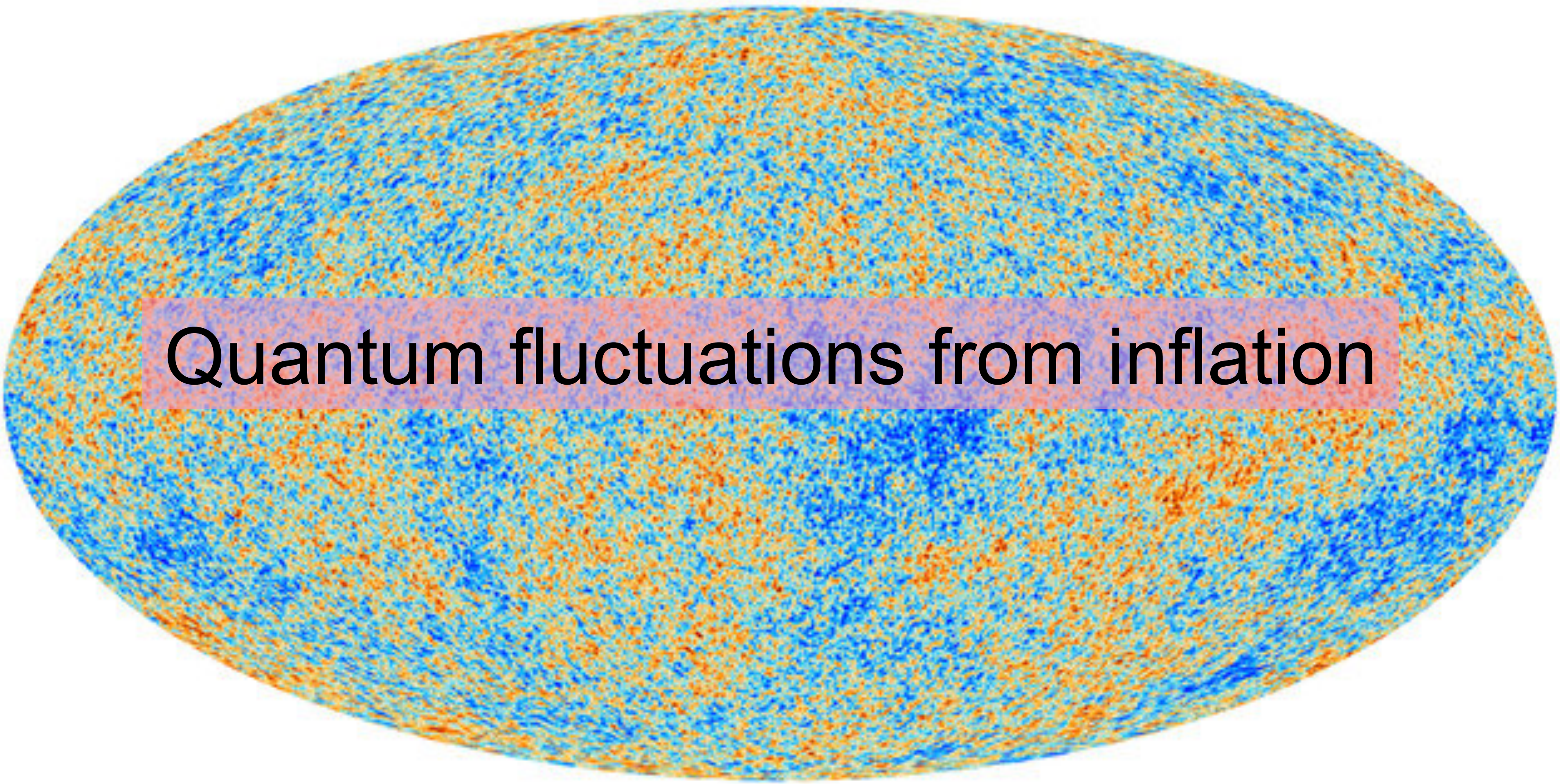
2012







The initial conditions for galaxy formation



Planck collaboration ‘13

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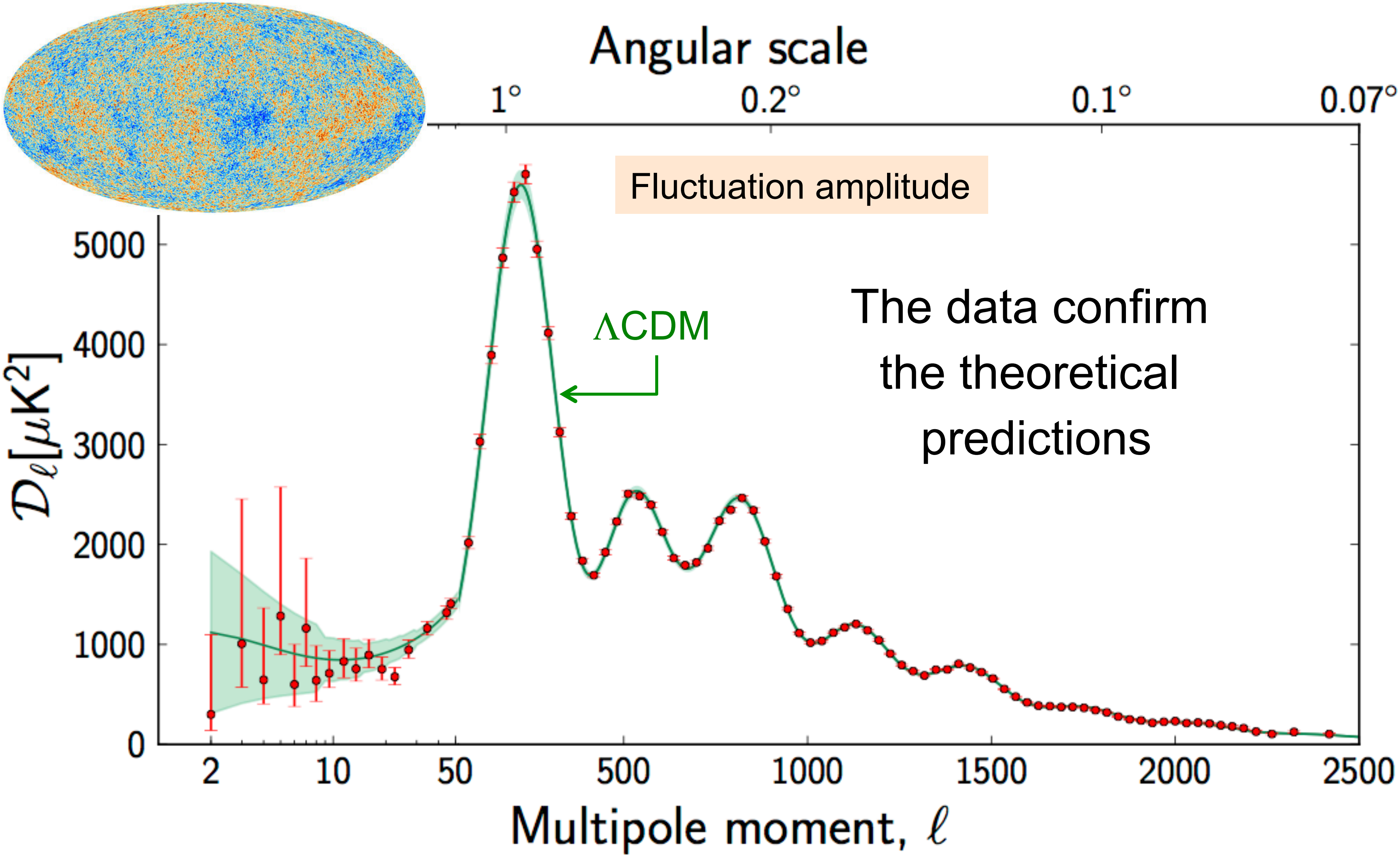
Planck: CMB temperature anisotropies



Planck coll. 2015

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The six parameters of minimal ΛCDM model

ICC

Univer

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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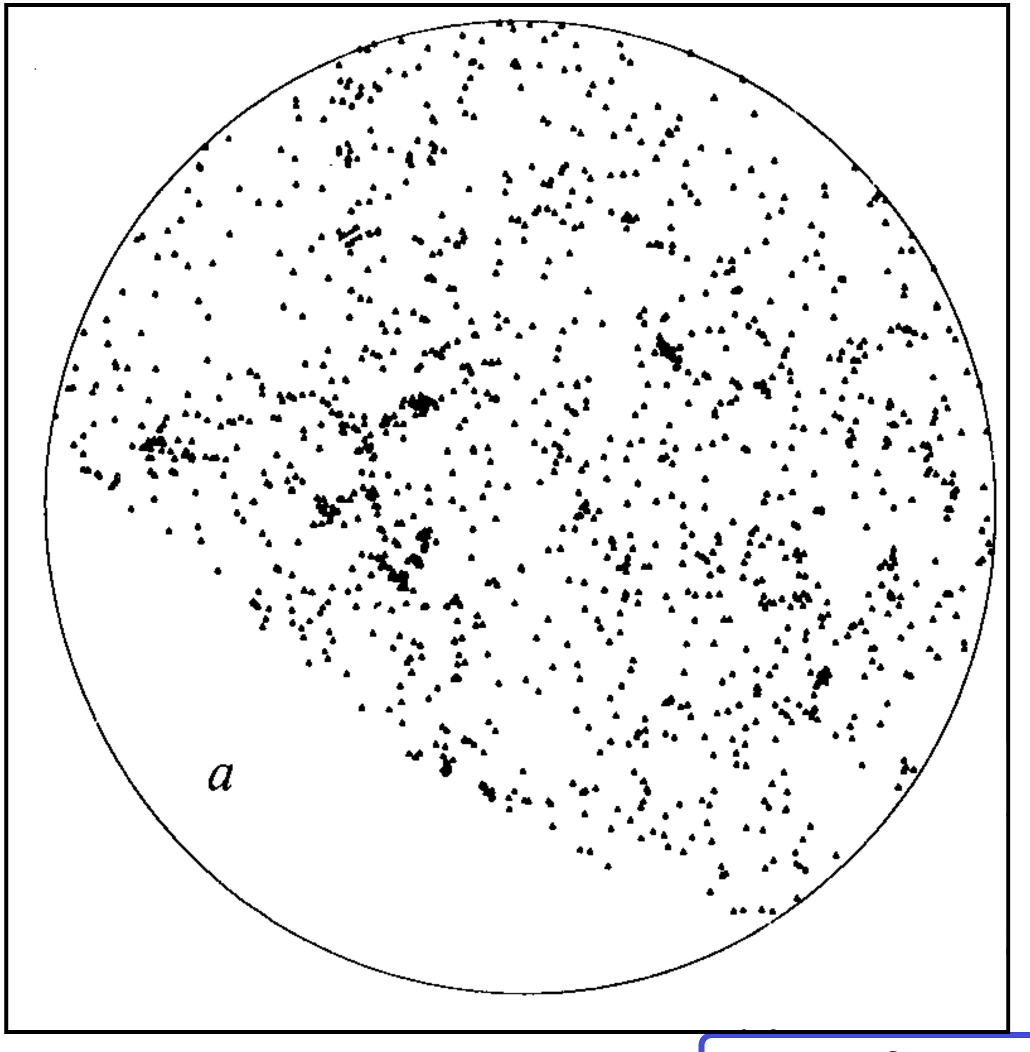
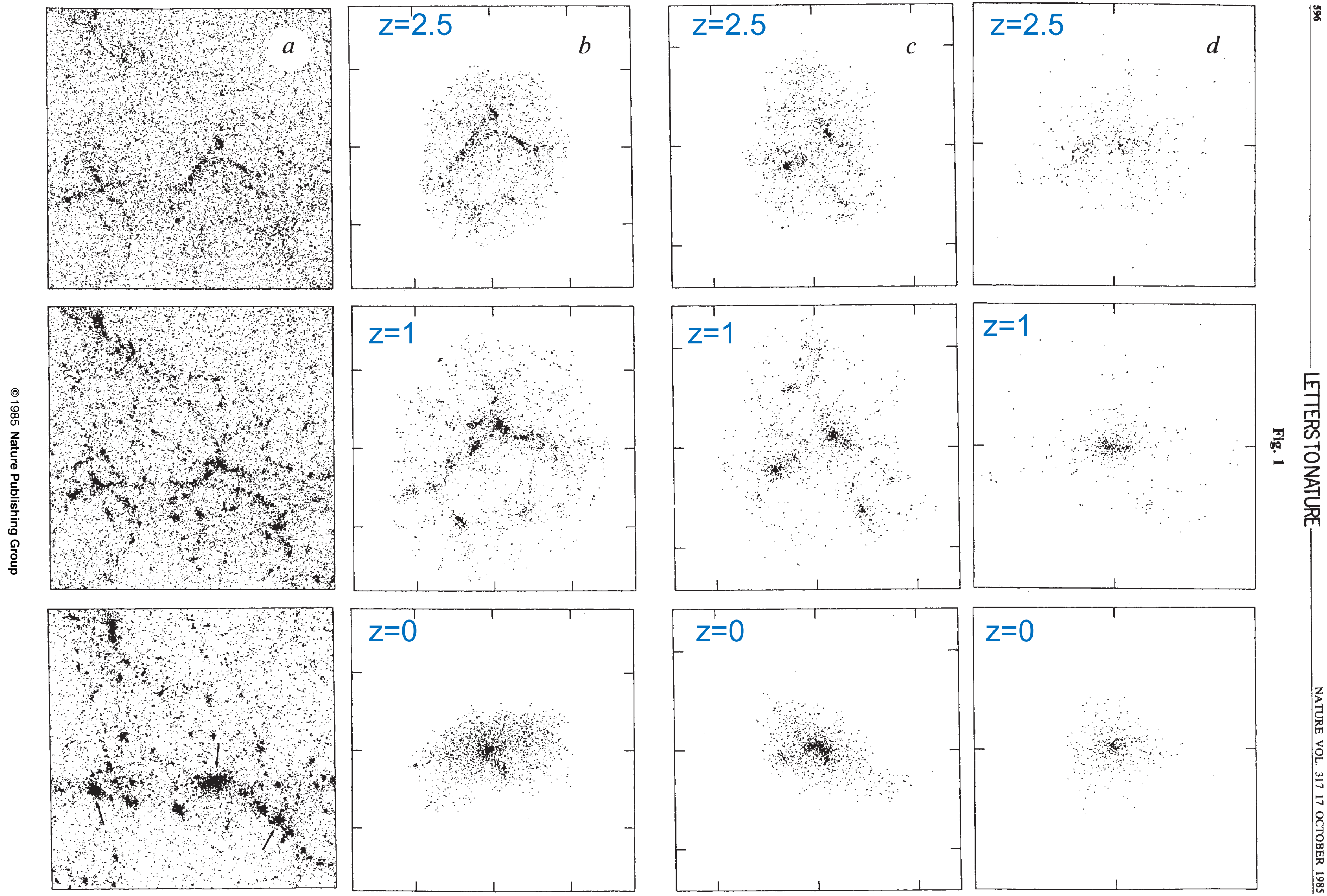
N-body simulations of large-scale structure in ΛCDM

Davis, Efstathiou, Frenk & White '85

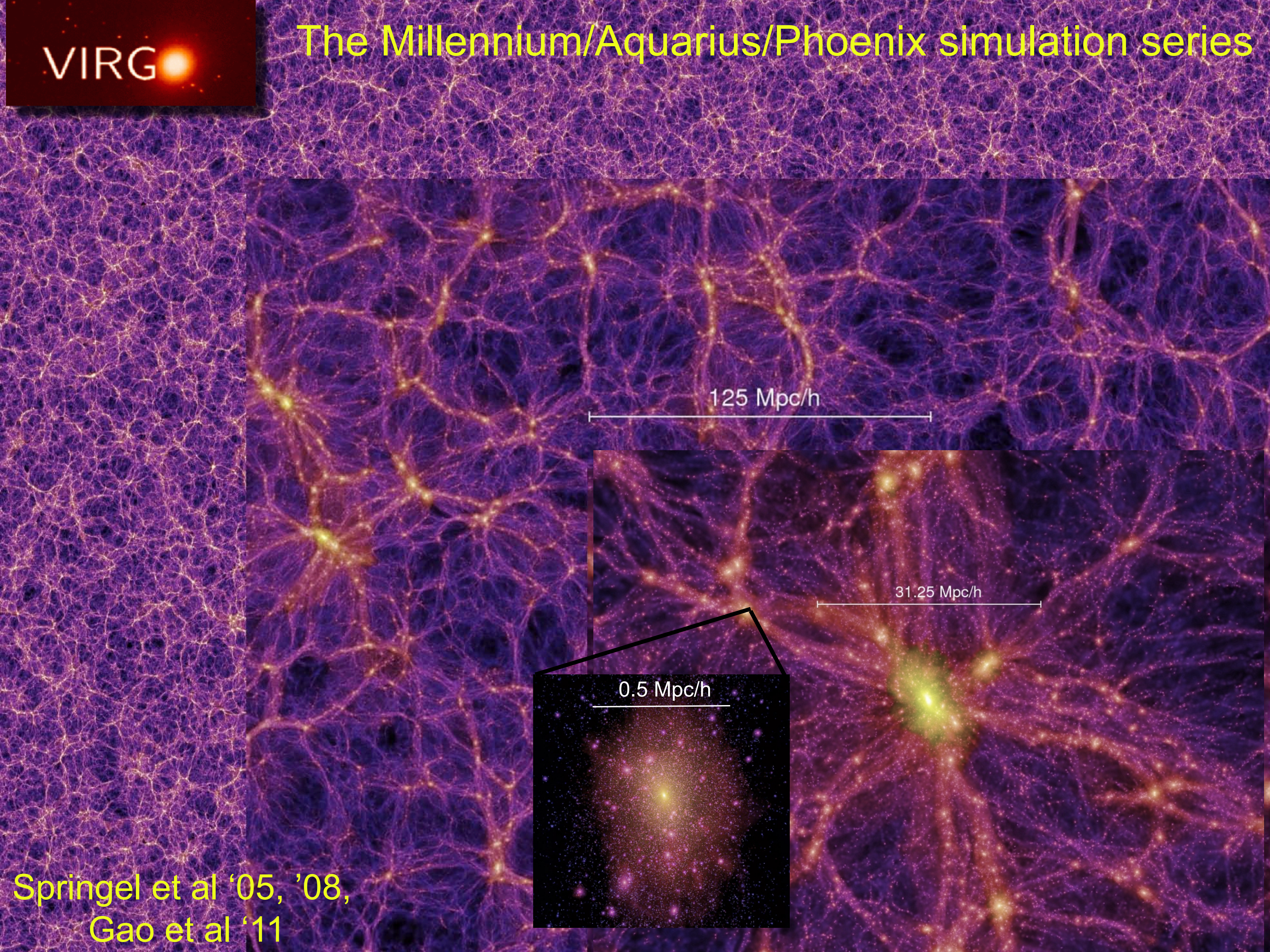


Formation of CDM halos



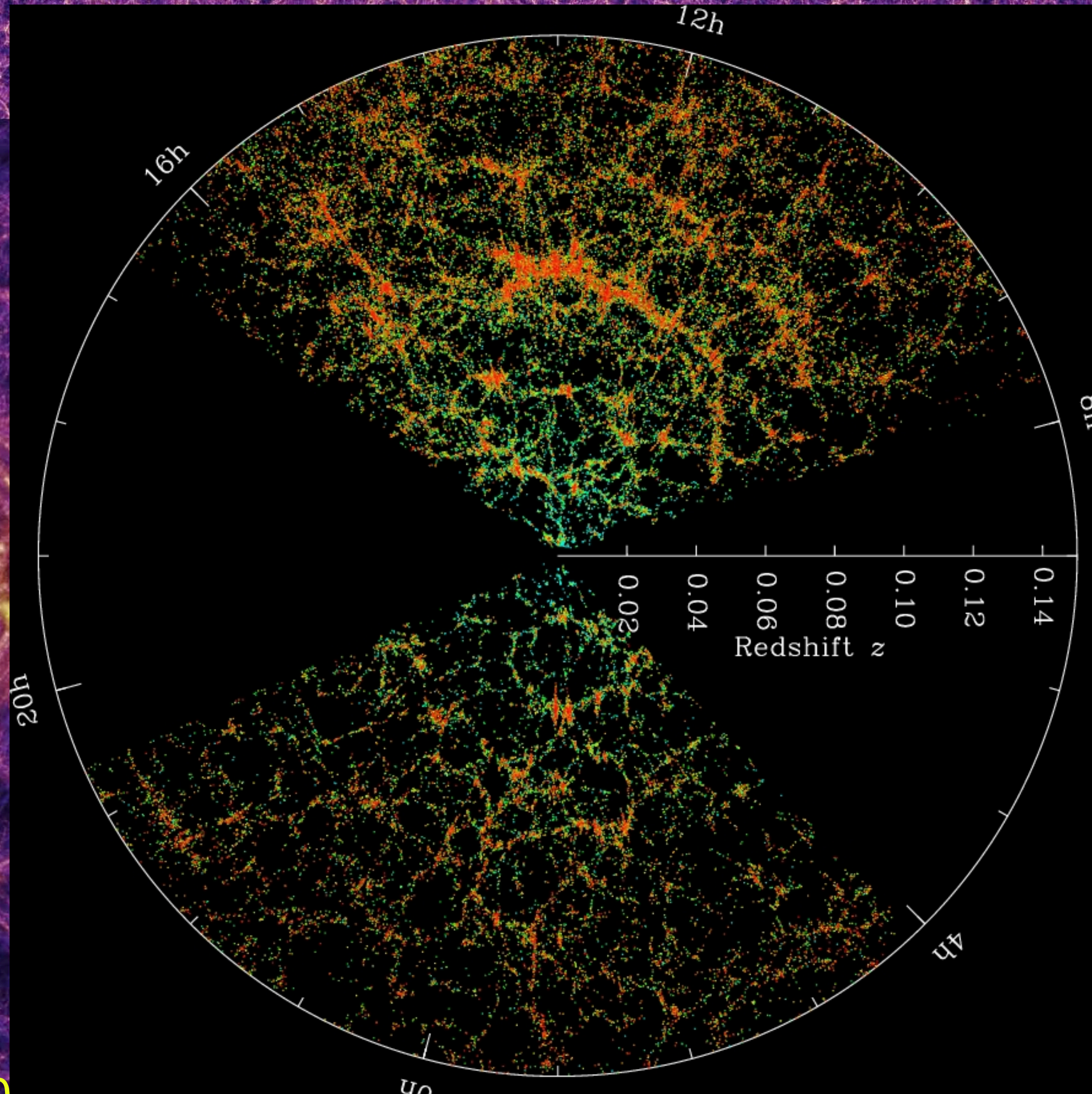
Frenk et al 1985

The Millennium/Aquarius/Phoenix simulation series

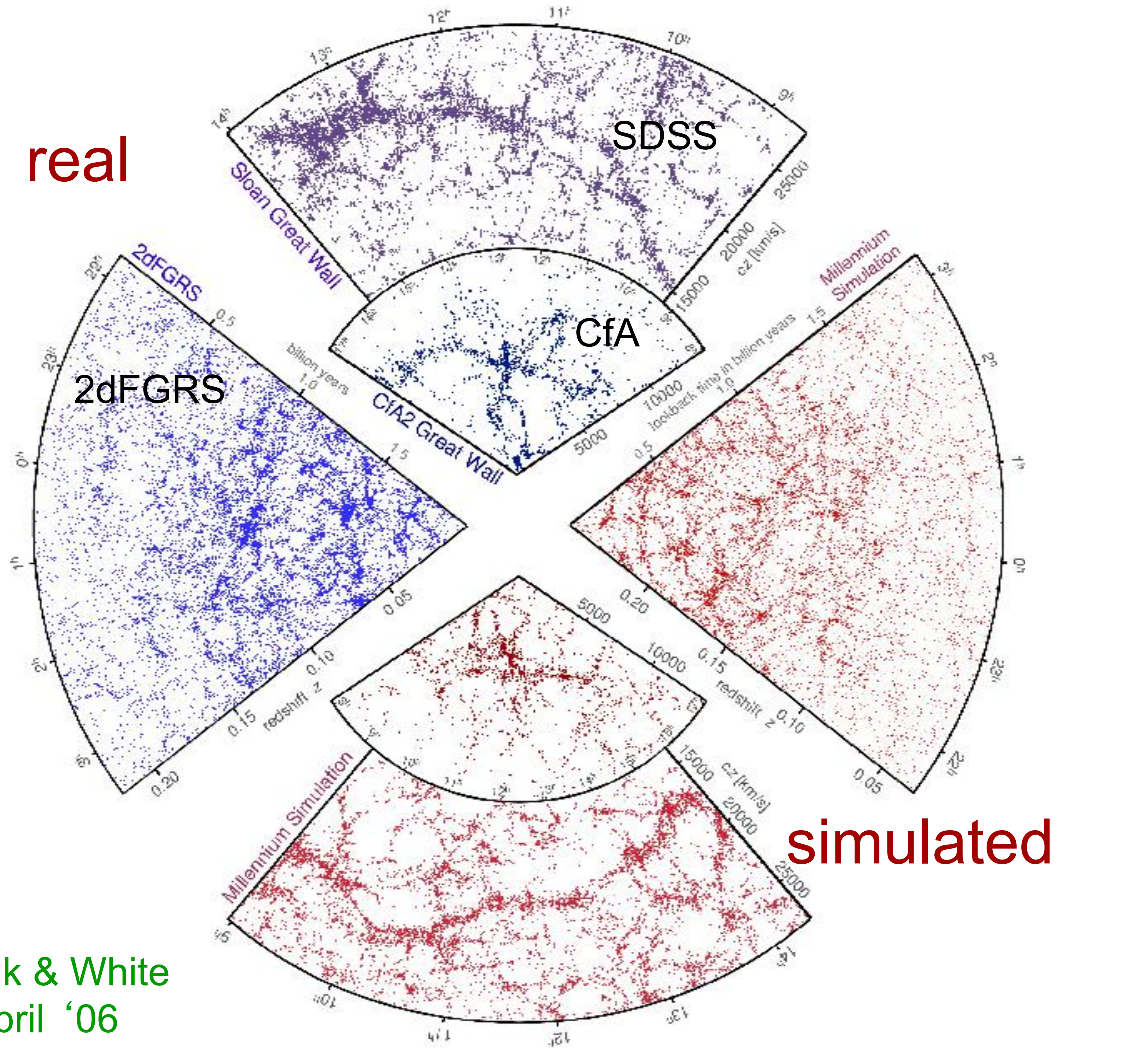


Springel et al ‘05, ’08,
Gao et al ‘11

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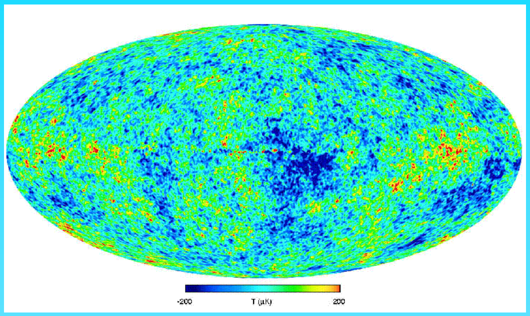
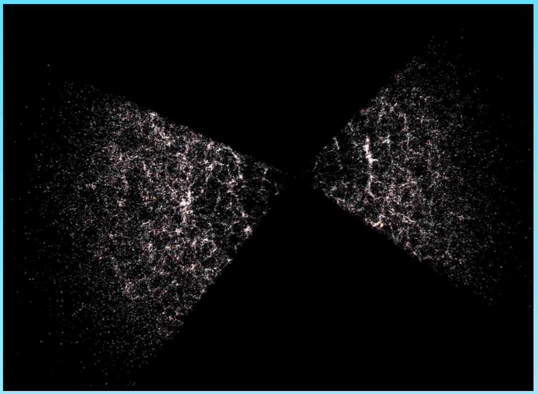
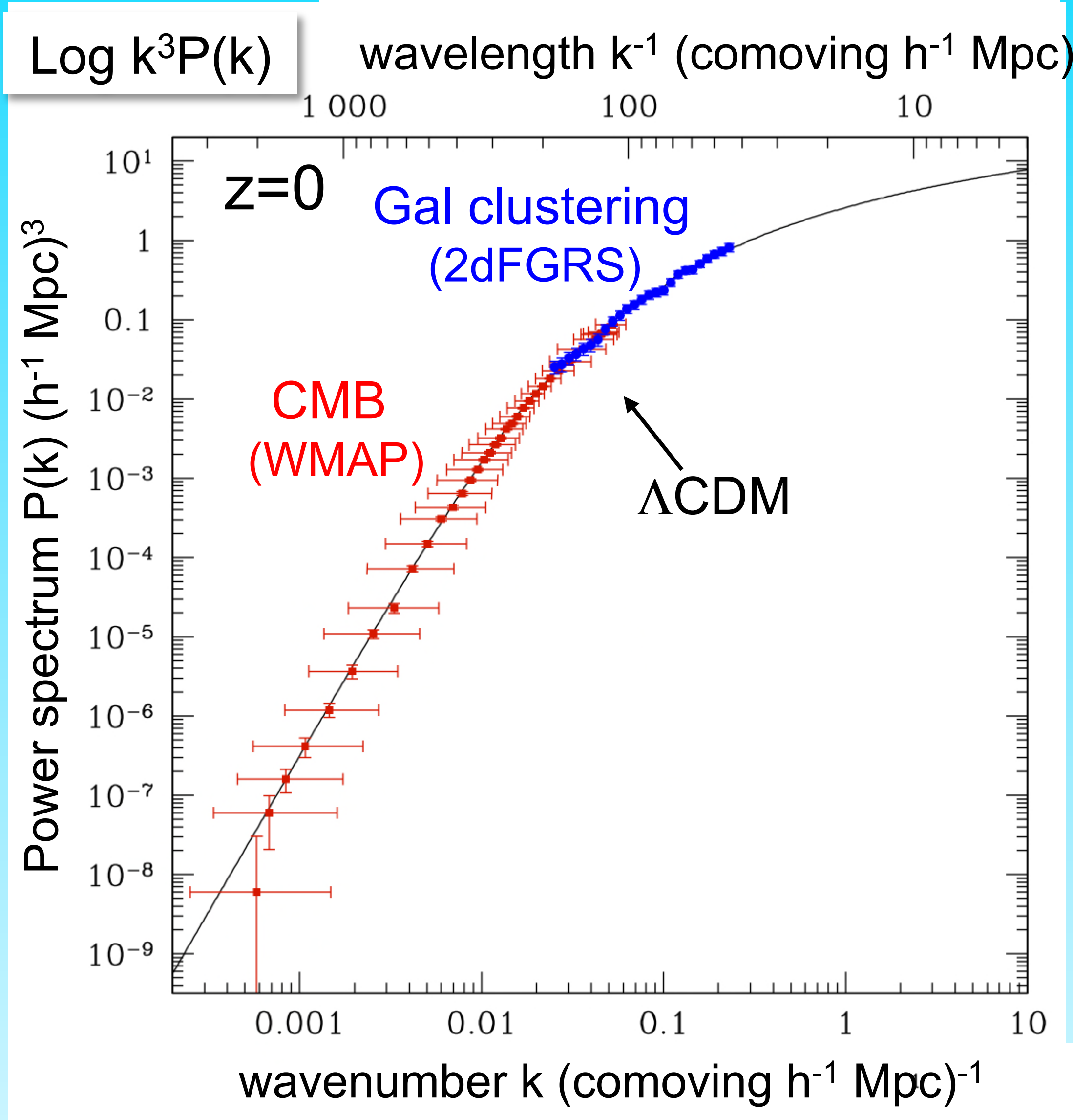
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

The ΛCDM model of cosmogony

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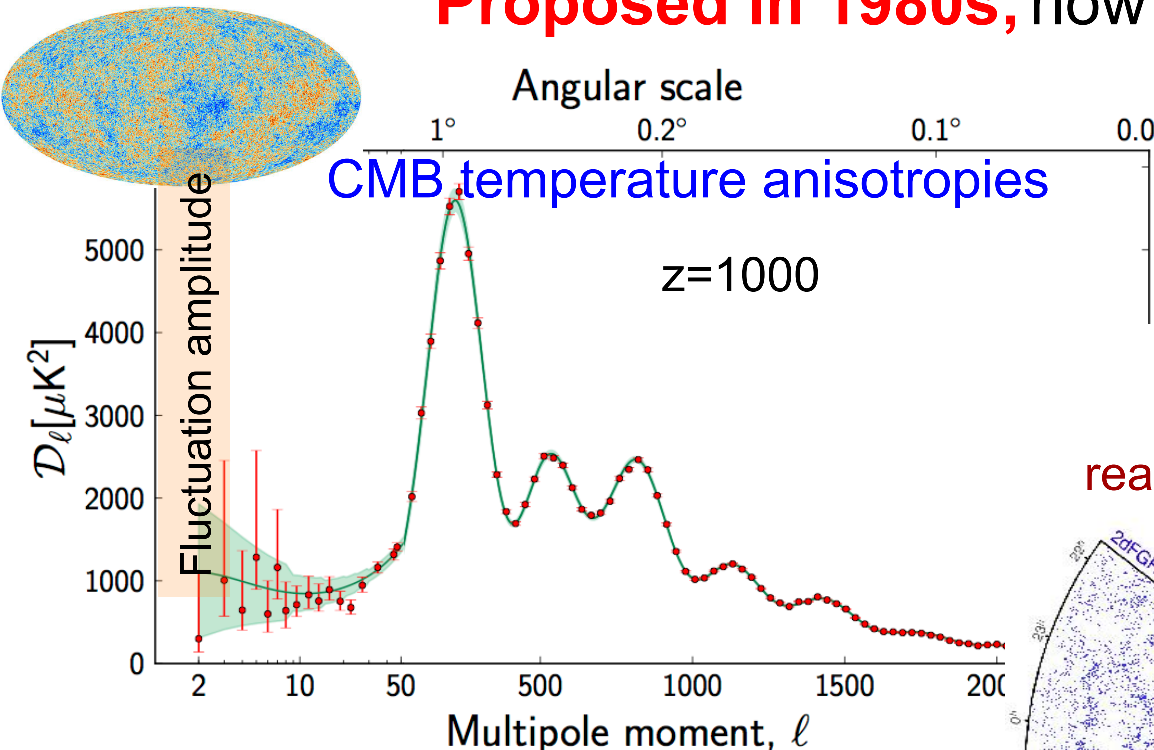
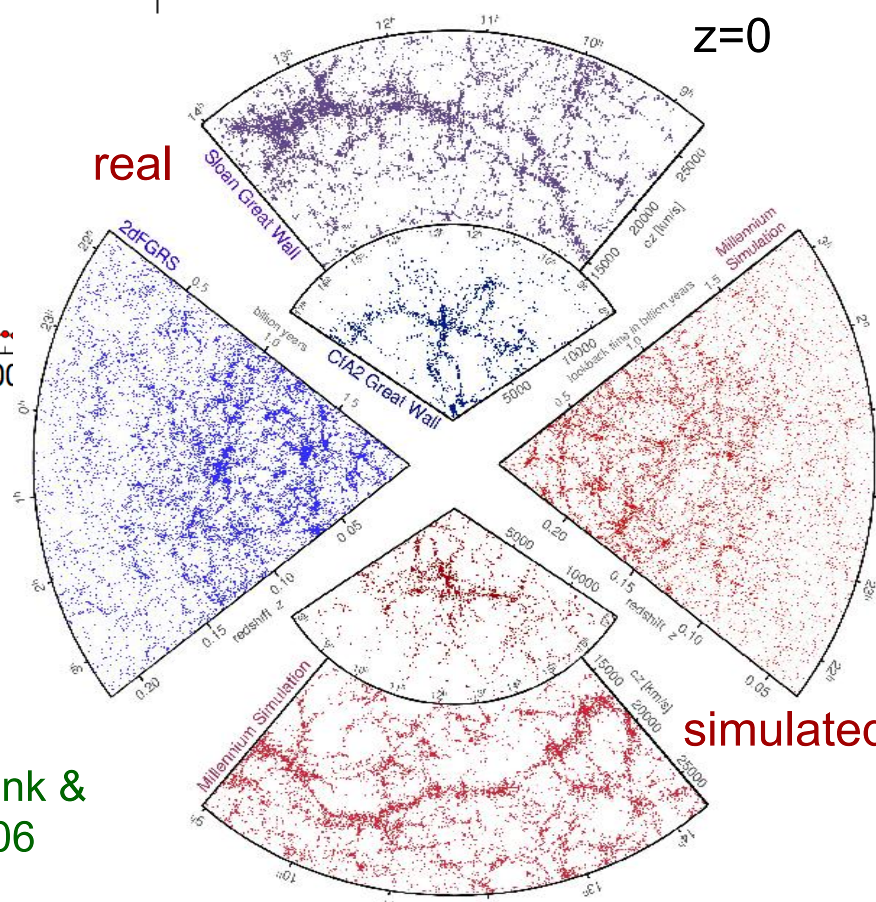
Proposed in 1980s; now empirically supported by:



Planck coll. 2015

Galaxy clustering



Springel, Frenk & White 2006

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

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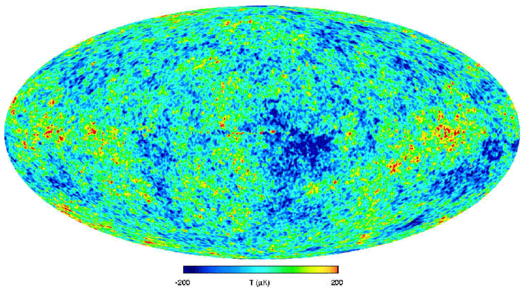
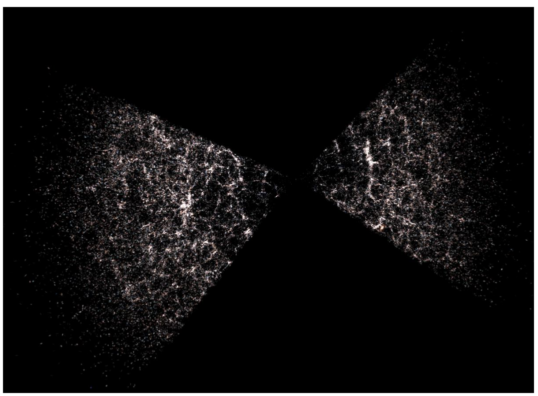
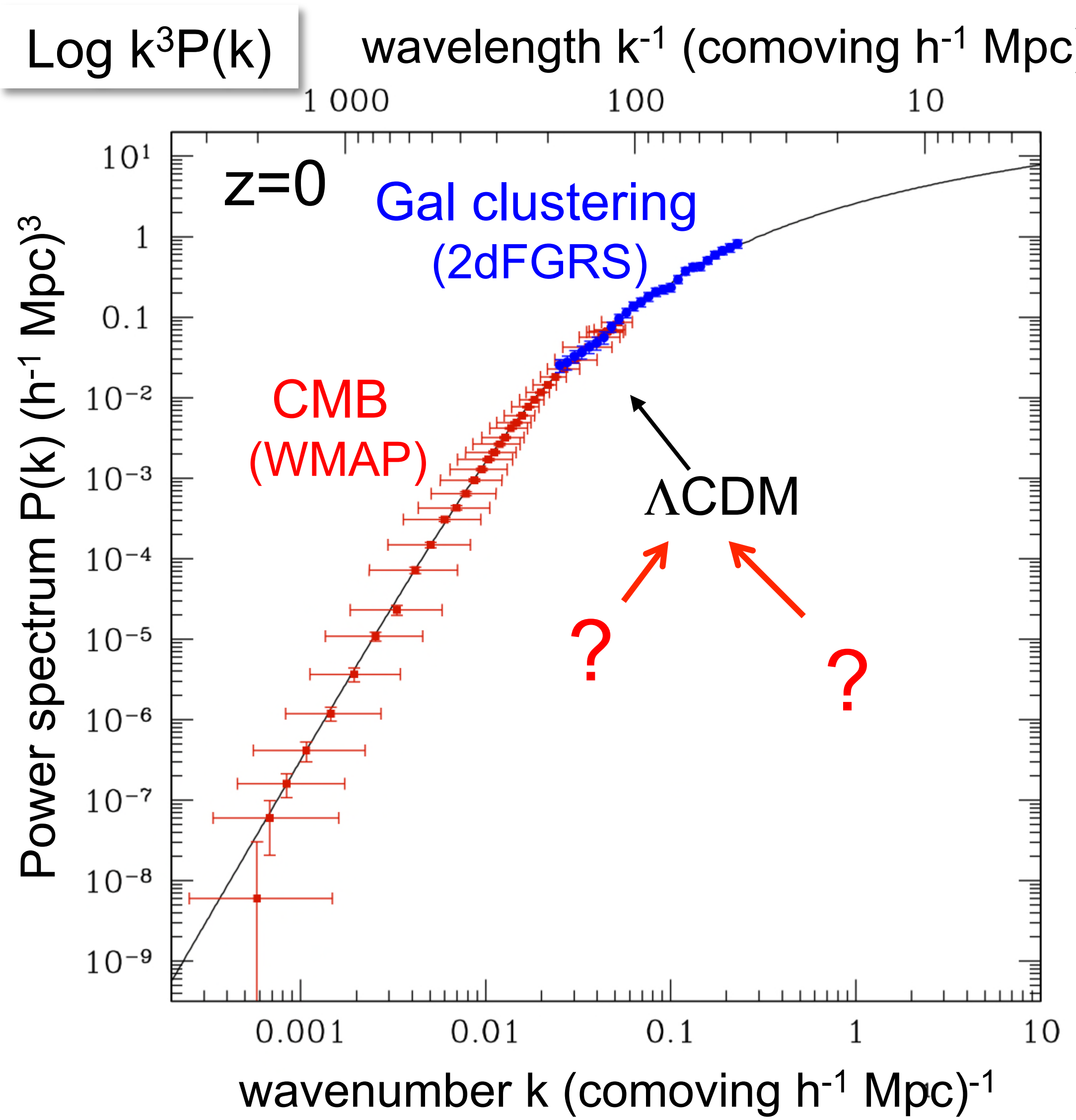


z~1000



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

Free streaming →

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

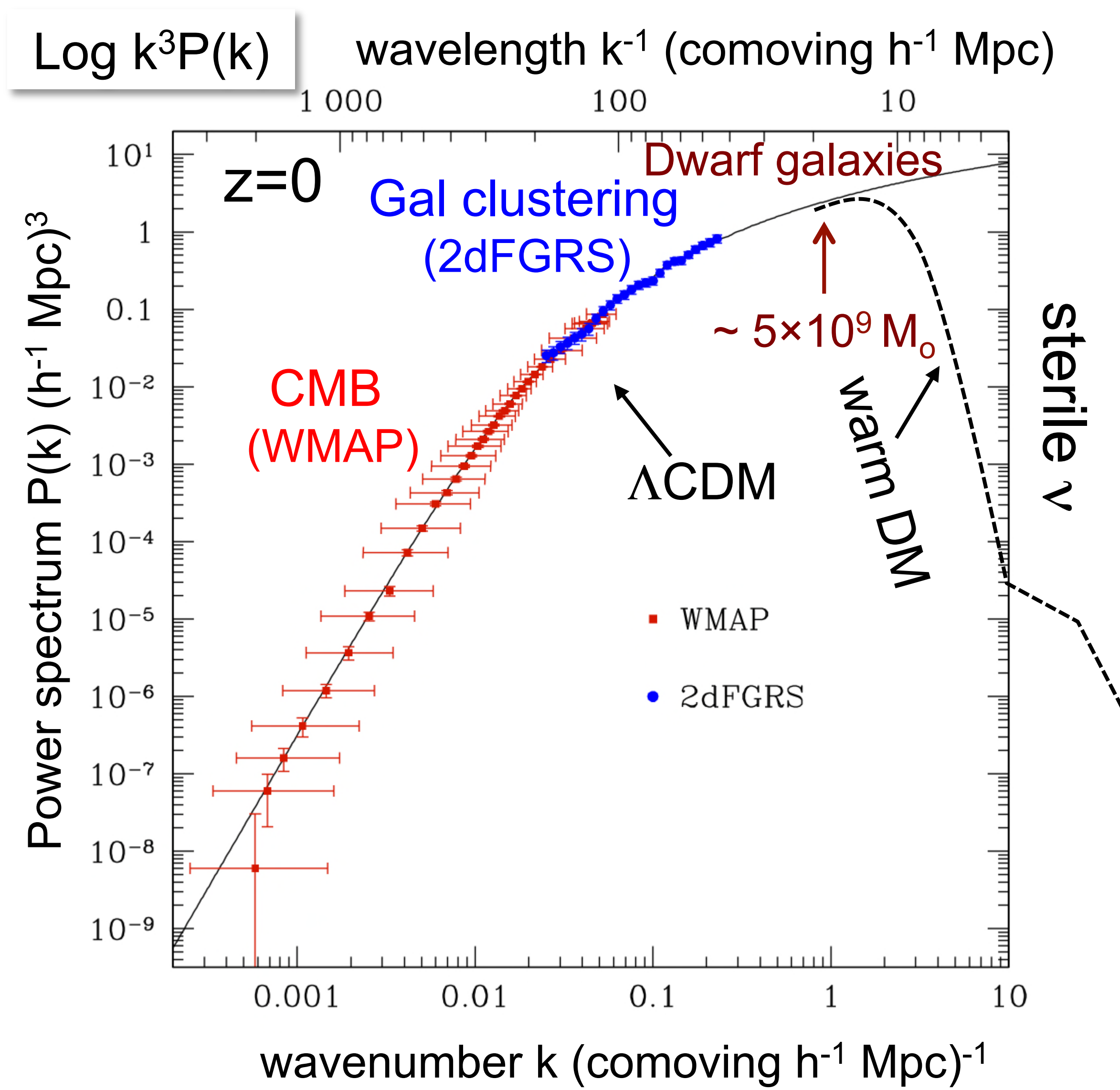
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$



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Sterile neutrinos

Explain:

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

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

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

Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

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

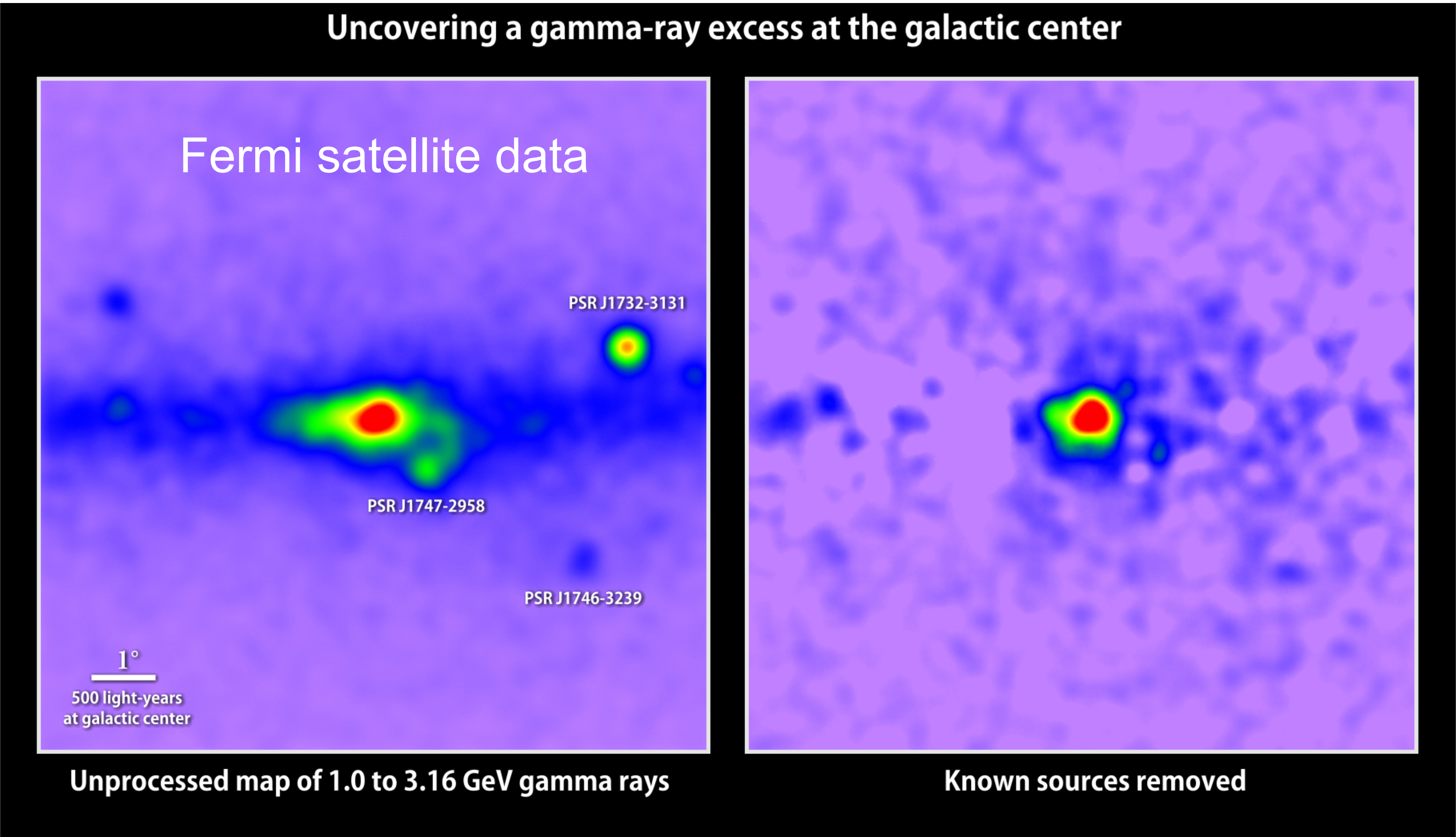
Cold dark matter

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]



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Warm dark matter

Decay line at 3.51 keV in galaxies and clusters

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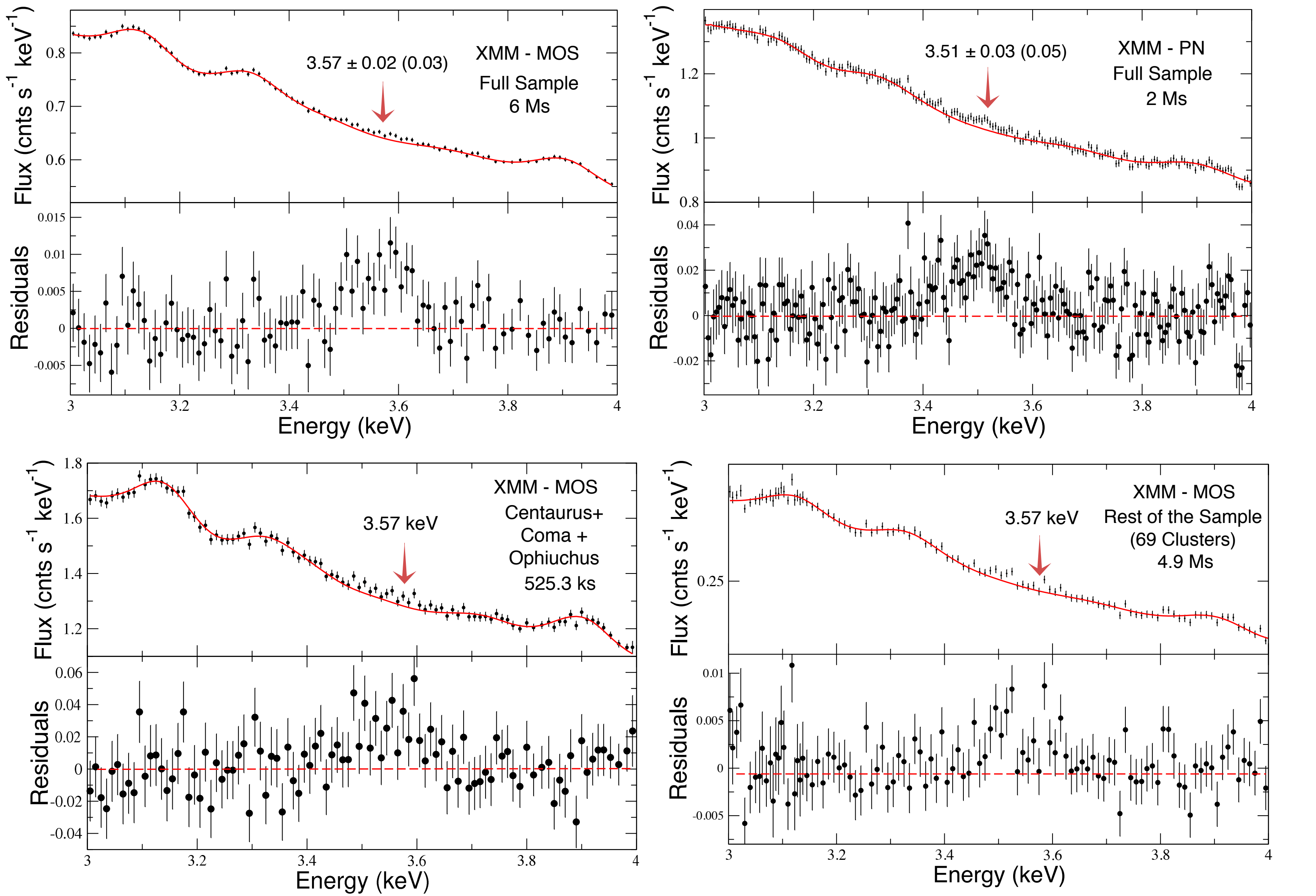
Warm dark matter
WDM decay line in 69 stacked clusters?

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

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cold dark matter | warm dark matter

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

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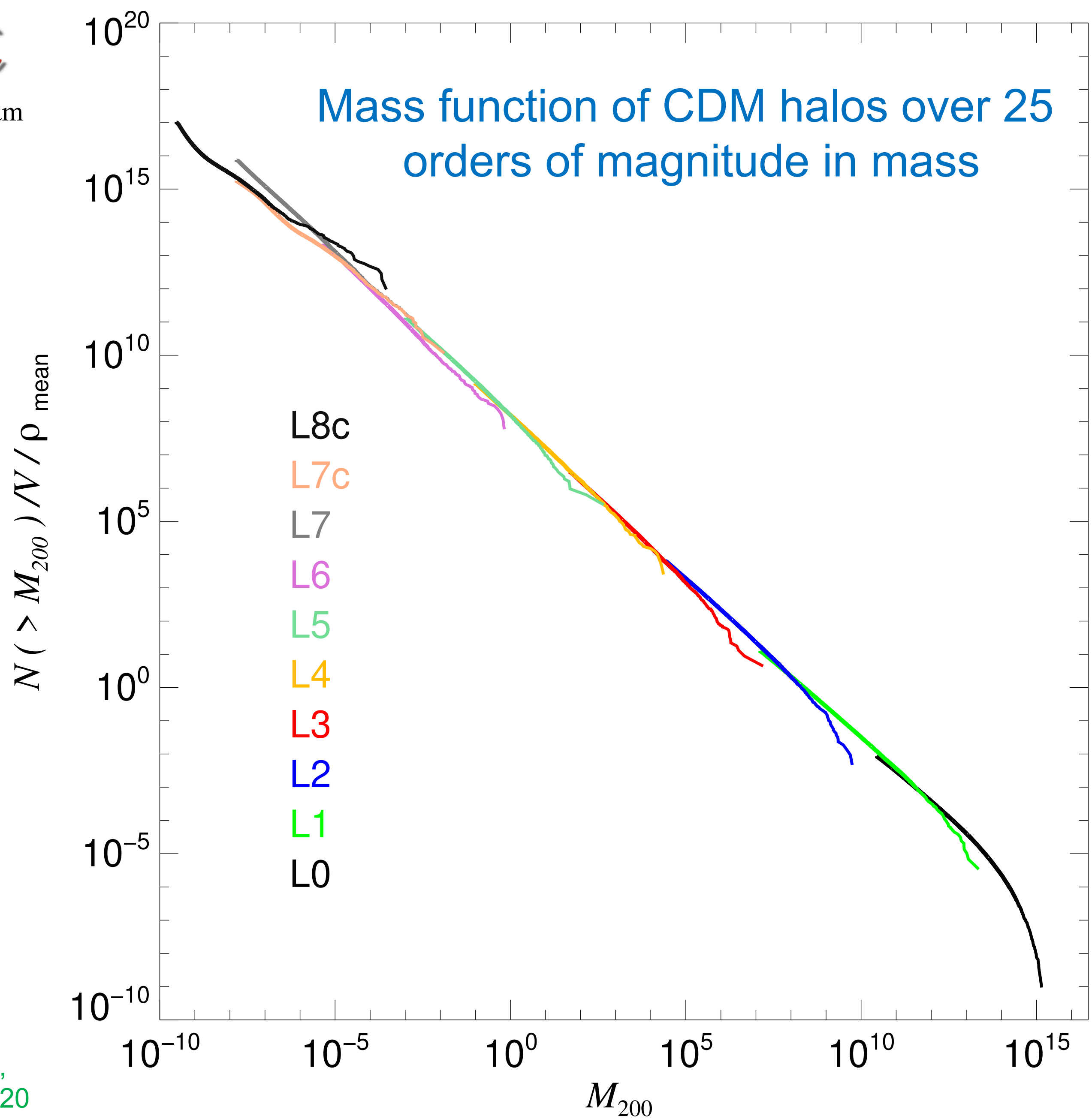

Wang, Bose, CSF, Gao, Jenkins, Springel, White '20

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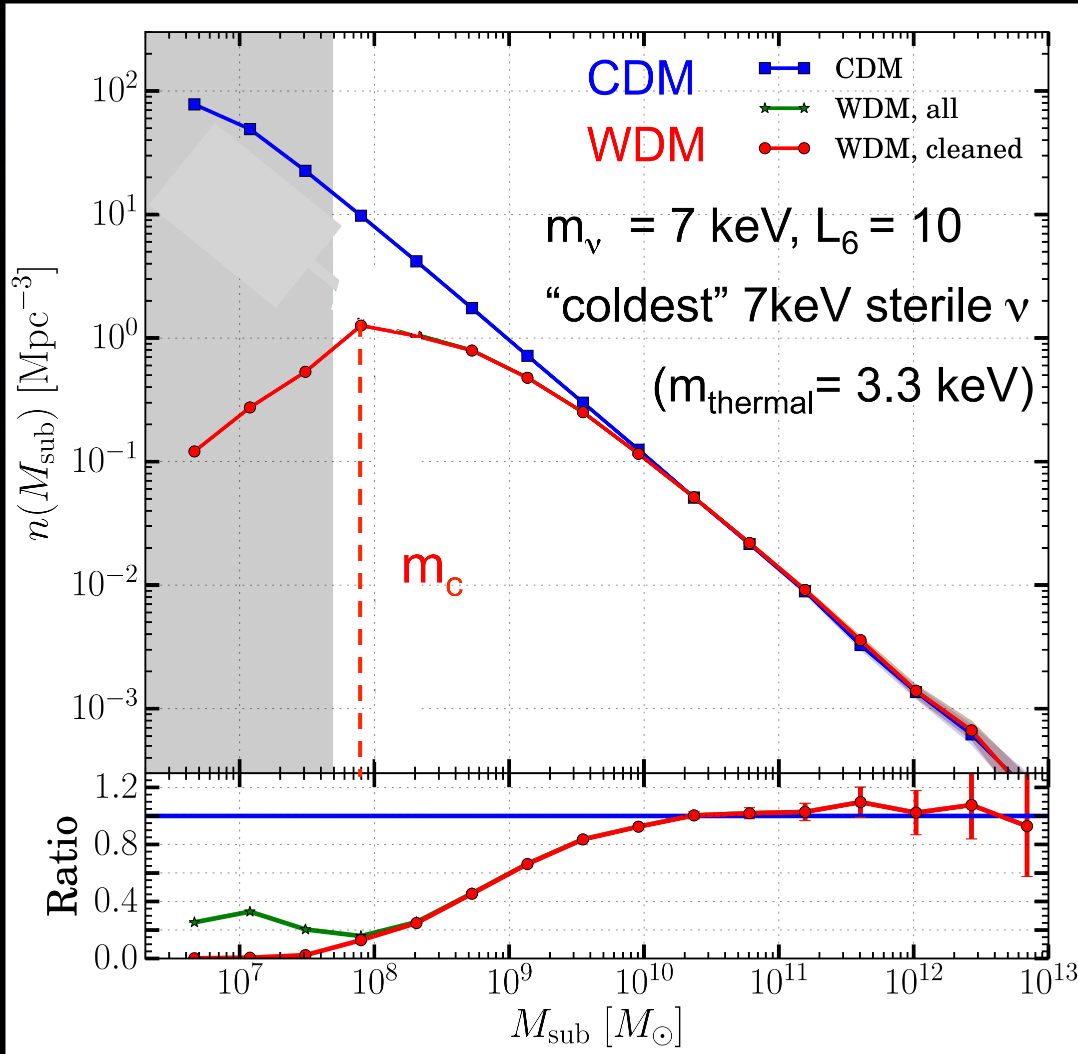
The subhalo mass function

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

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.)

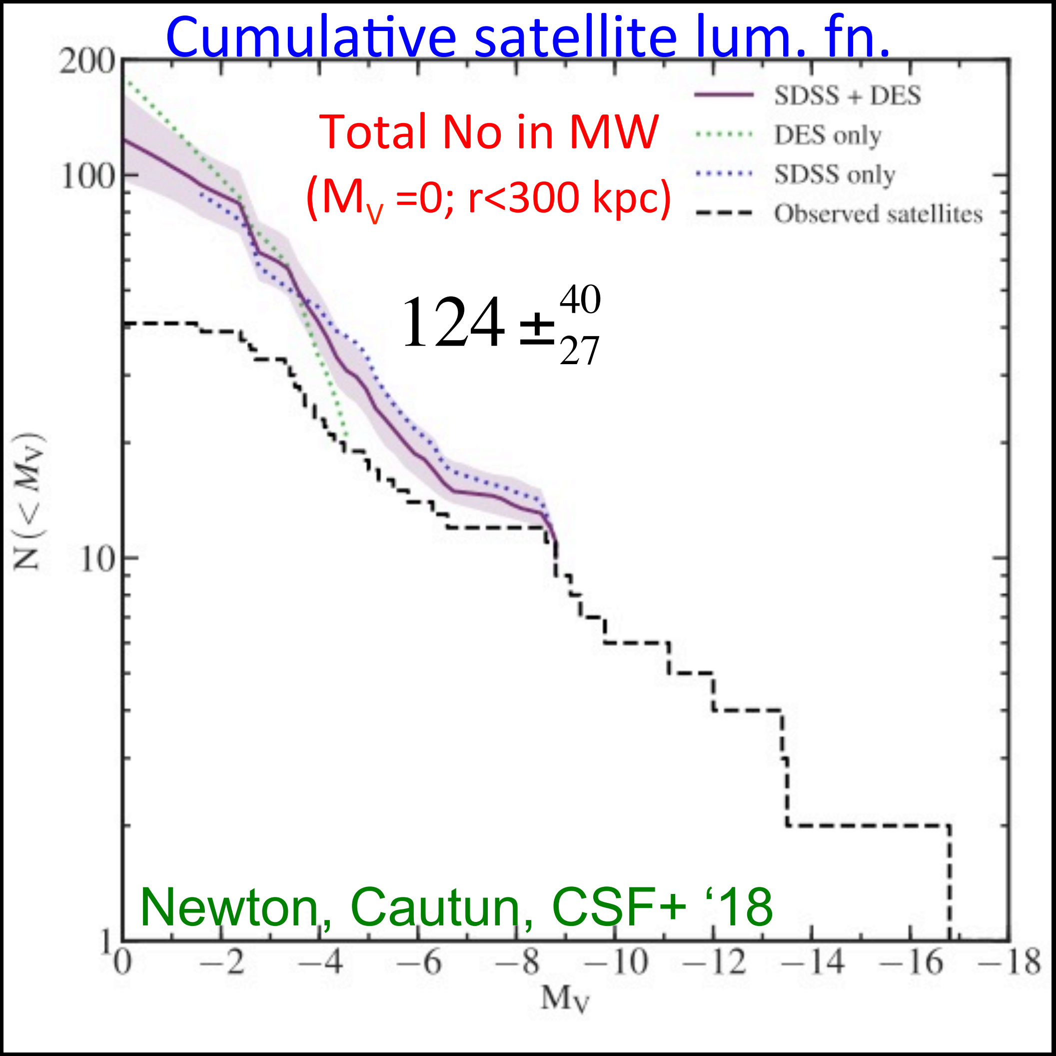
(the ``missing satellites problem)

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



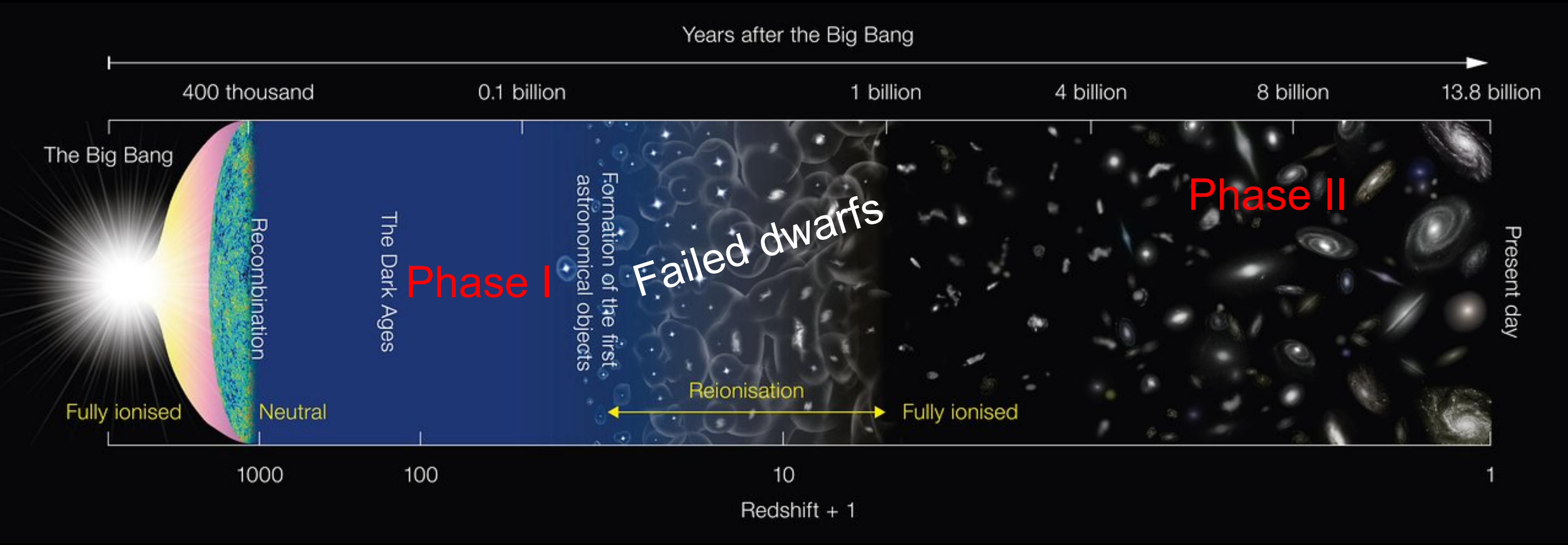
CDM

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

University of Durham

1. Before reionization, stars can only form if gas can cool for which

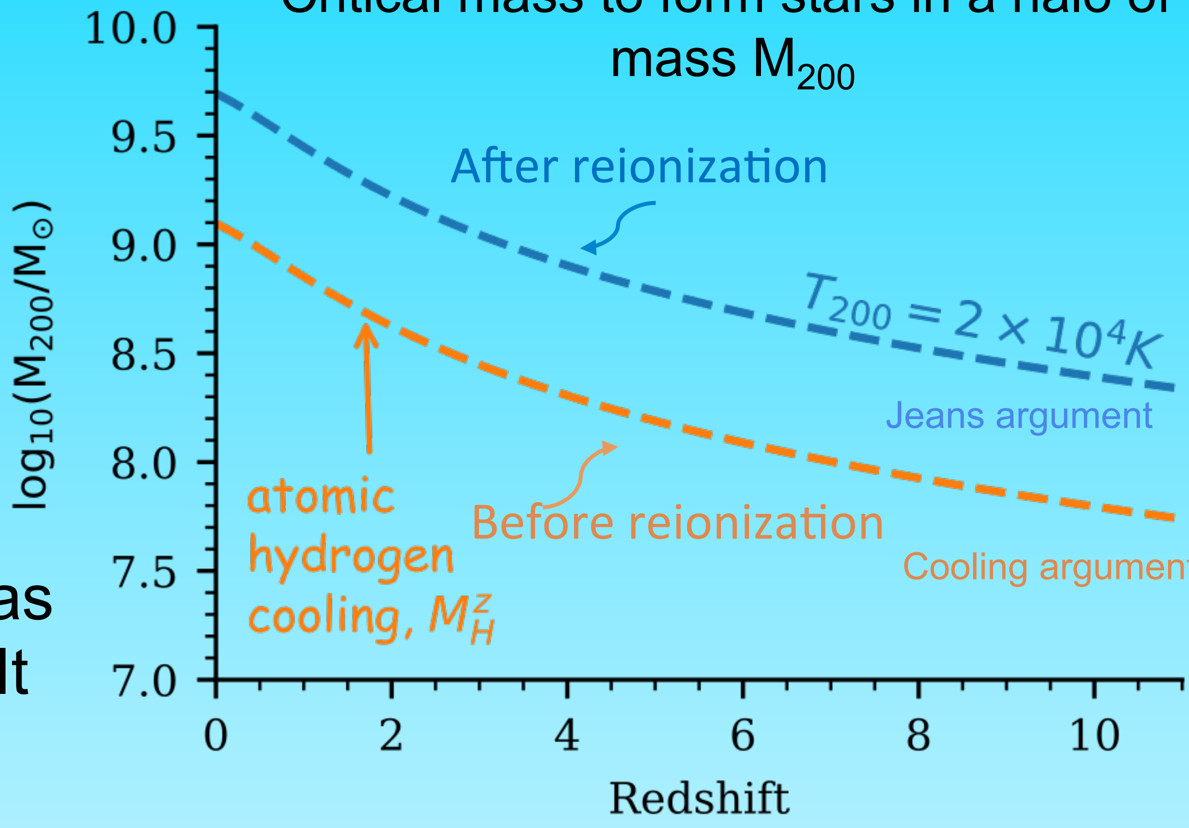
→ T>7000 K

$$M_H^z \sim (4 \times 10^7 \ M_\odot) \left(\frac{1+z}{11} \right)^{-3/2}$$

2. After H reionization, gas is heated to $T=2\text{x}10^4$ K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2\text{x}10^4$ K

Critical mass to form stars in a halo of mass M_{200}



Benitez-Llambay & CSF '20

Institute for Computational Cosmology

University of Durham

A galaxy formation primer

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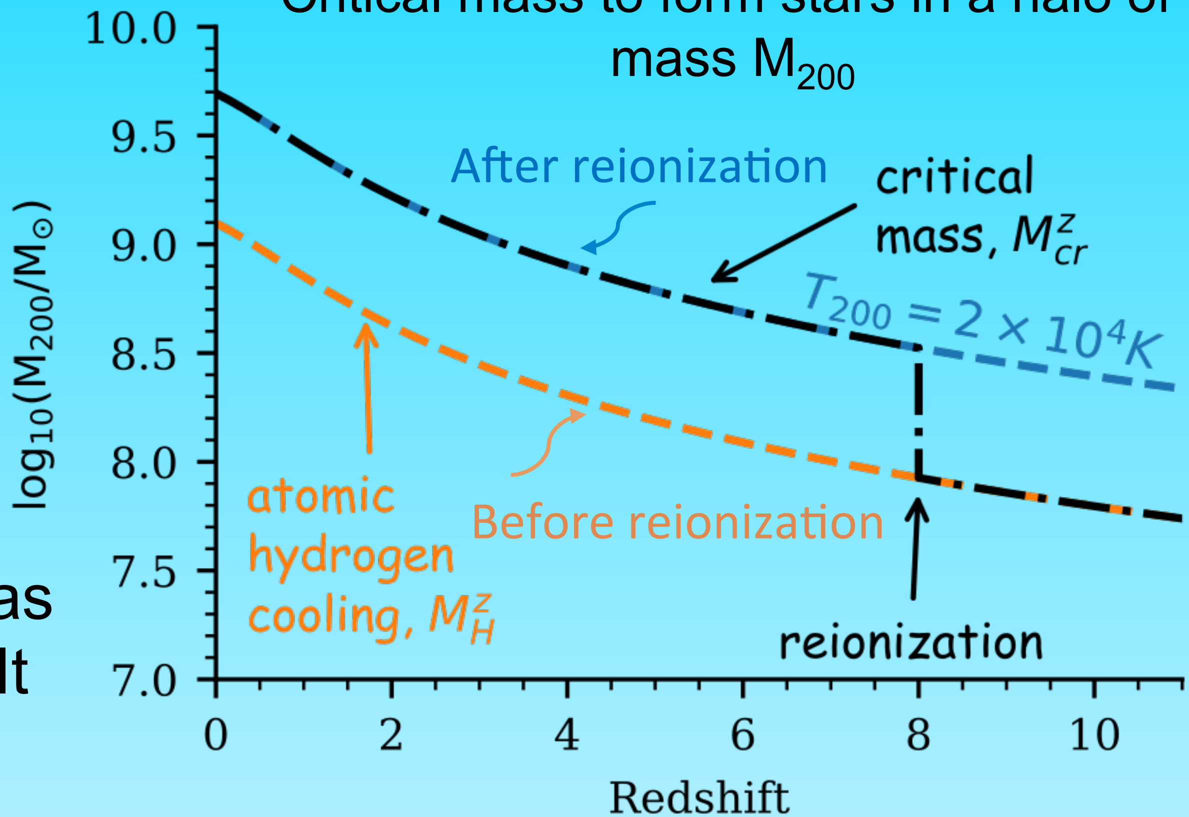

Benitez-Llambay & CSF '20

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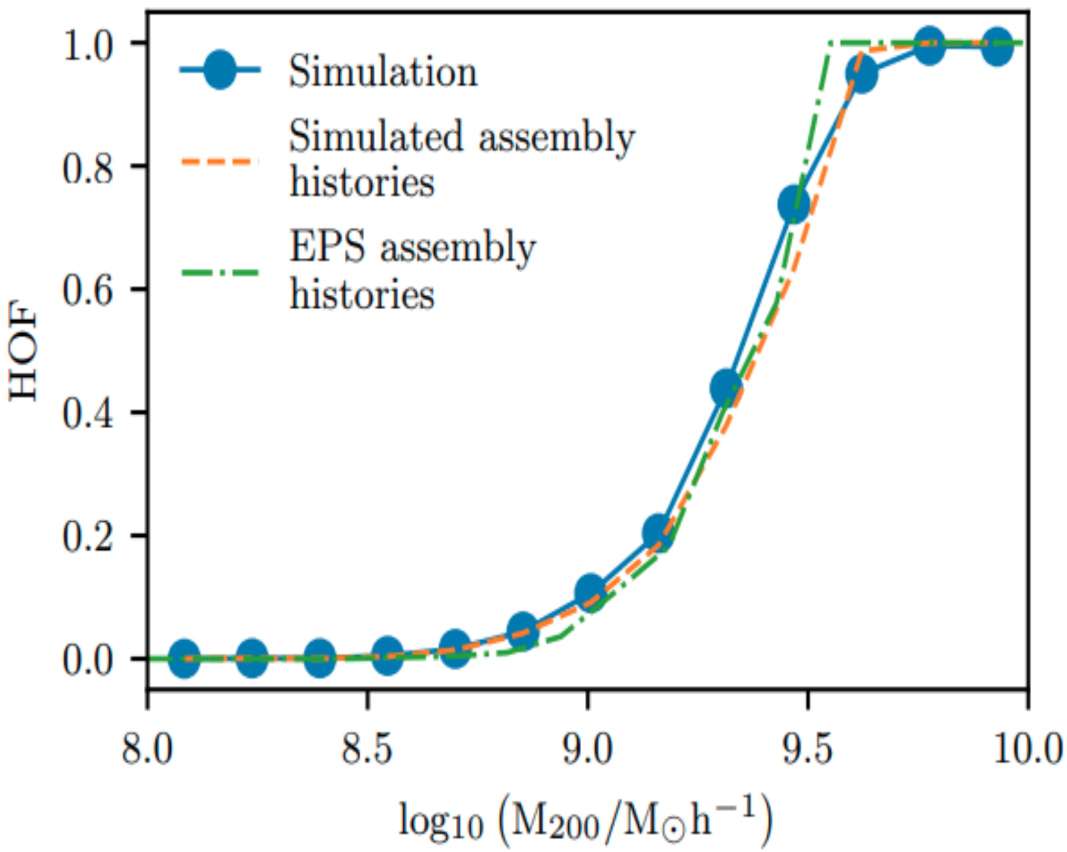
A galaxy formation primer

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

fraction of halos that host a galaxy



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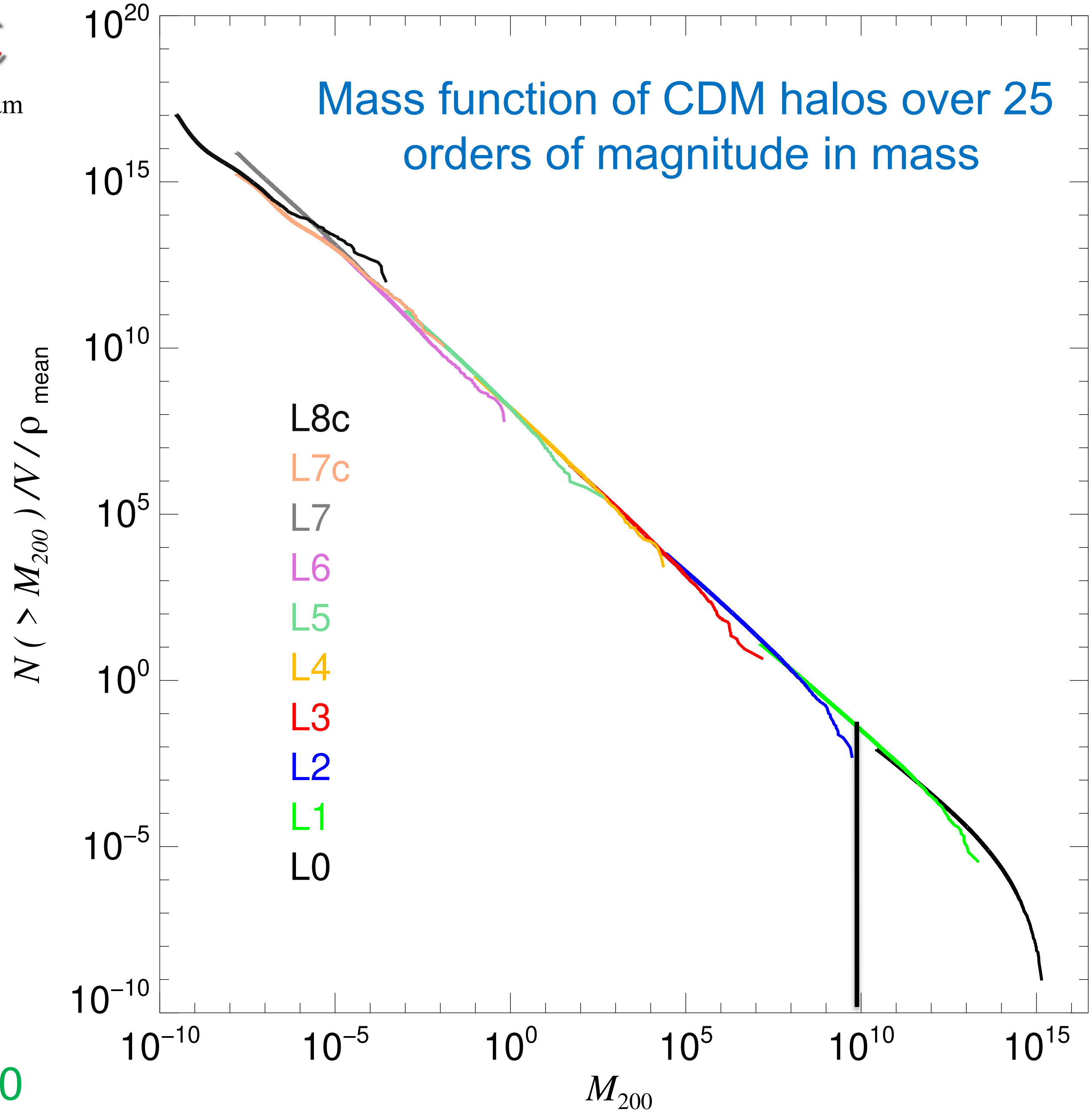


Wang et al '20

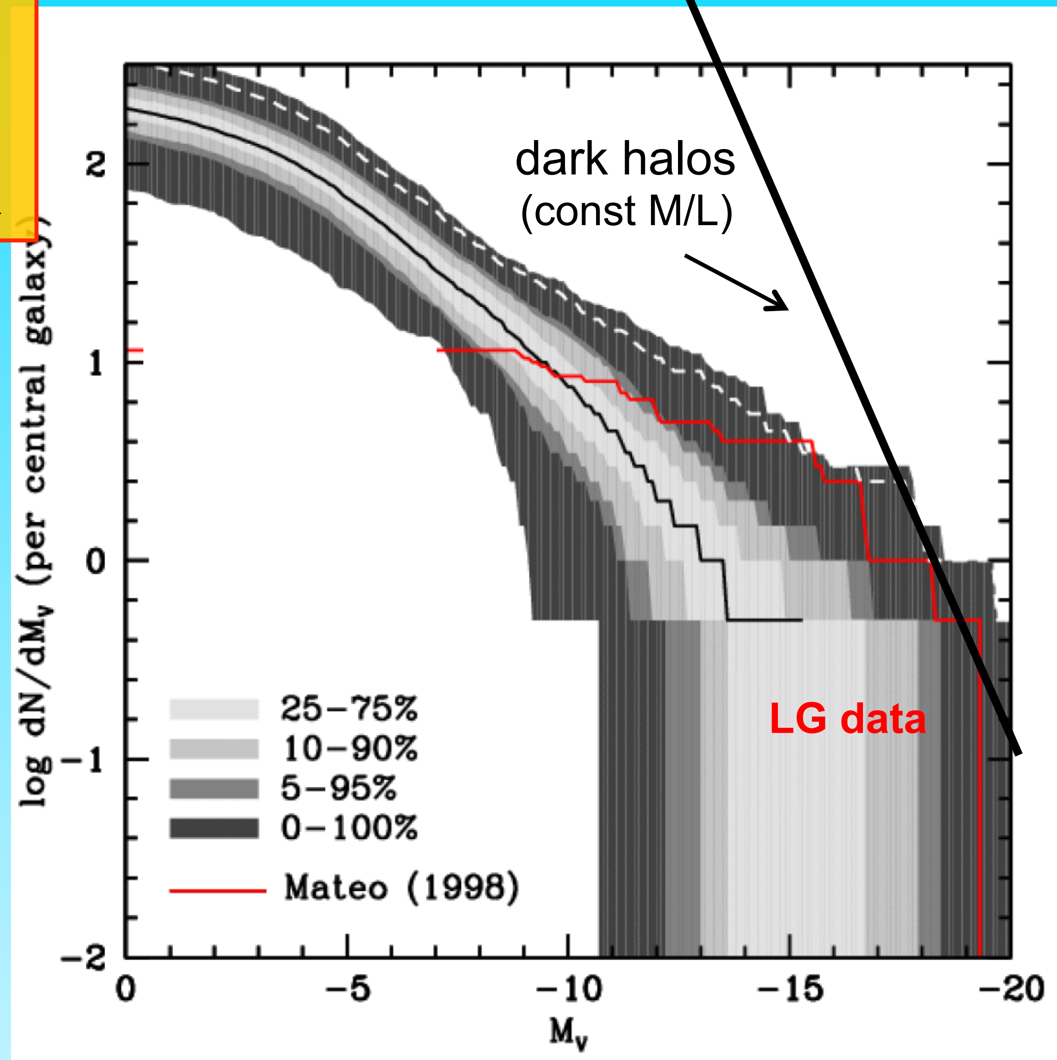
Institute for Computational Cosmology

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)

Luminosity Function of Local Group Satellites

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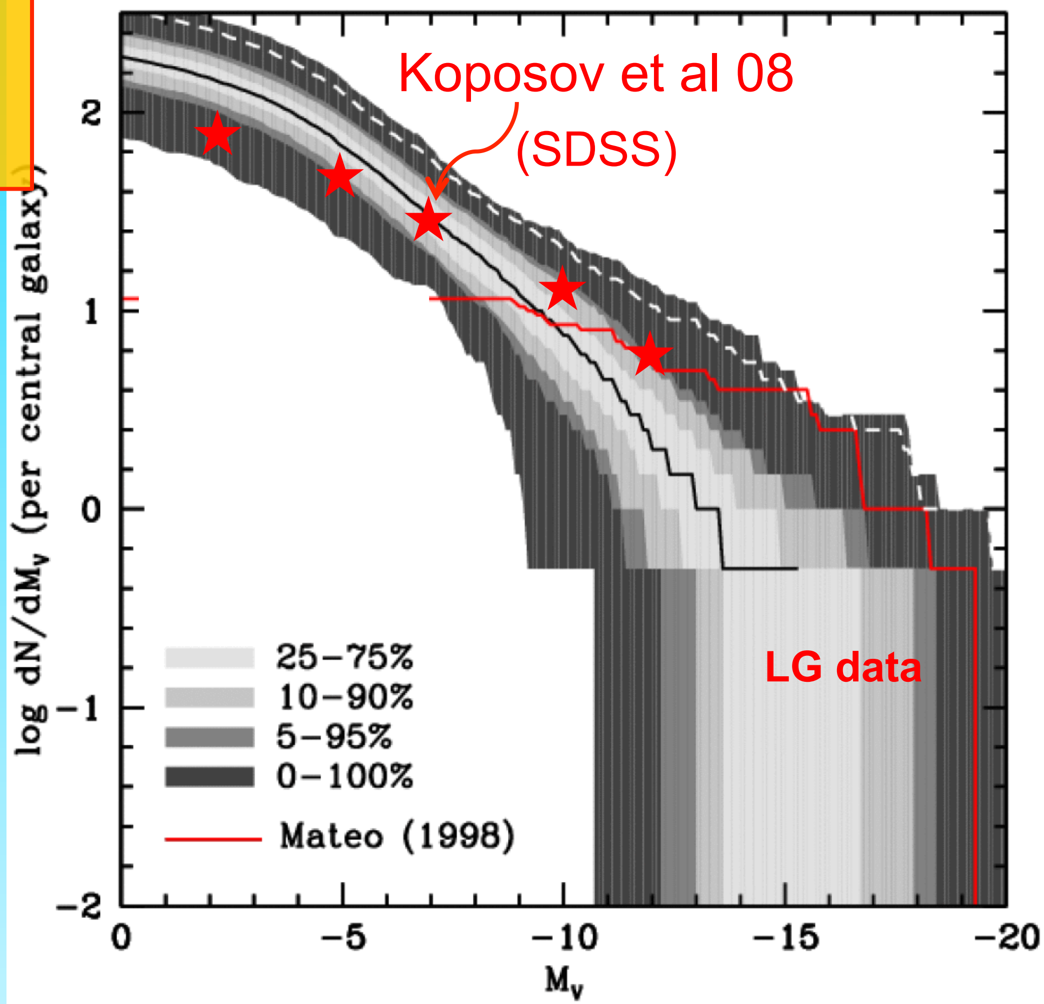


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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…

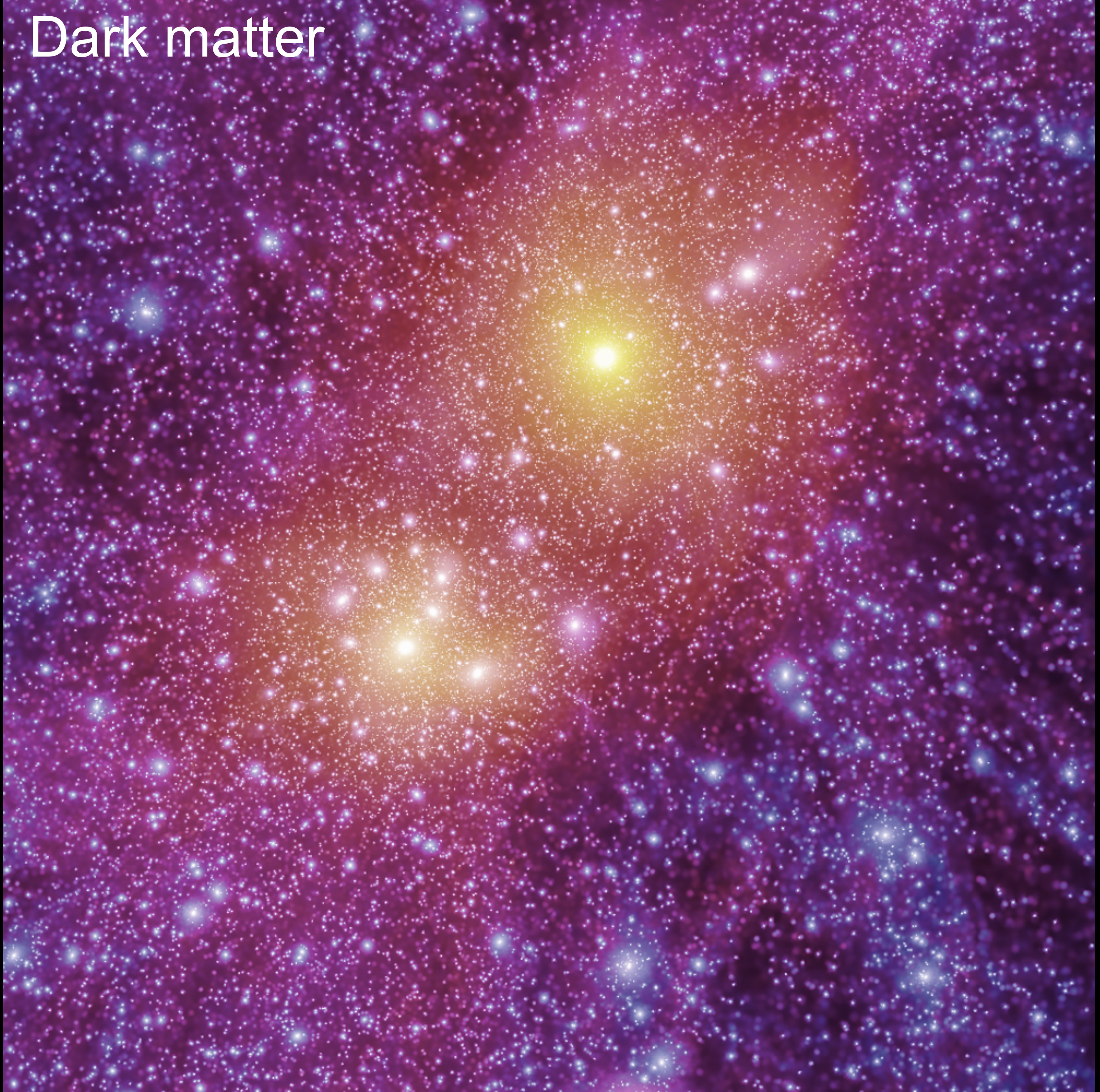
Durham University VIRGO ICC DiRAC PRACE

The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM



Sawala, CSF
et al ‘16

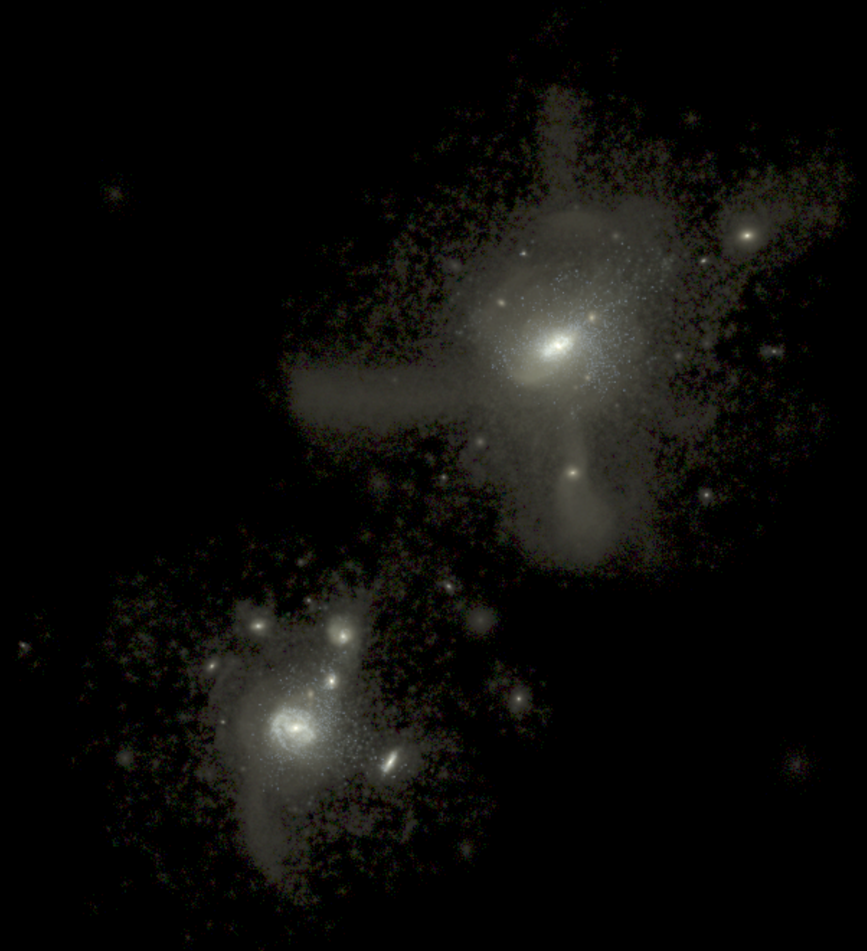
VIRGO

Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group

Stars

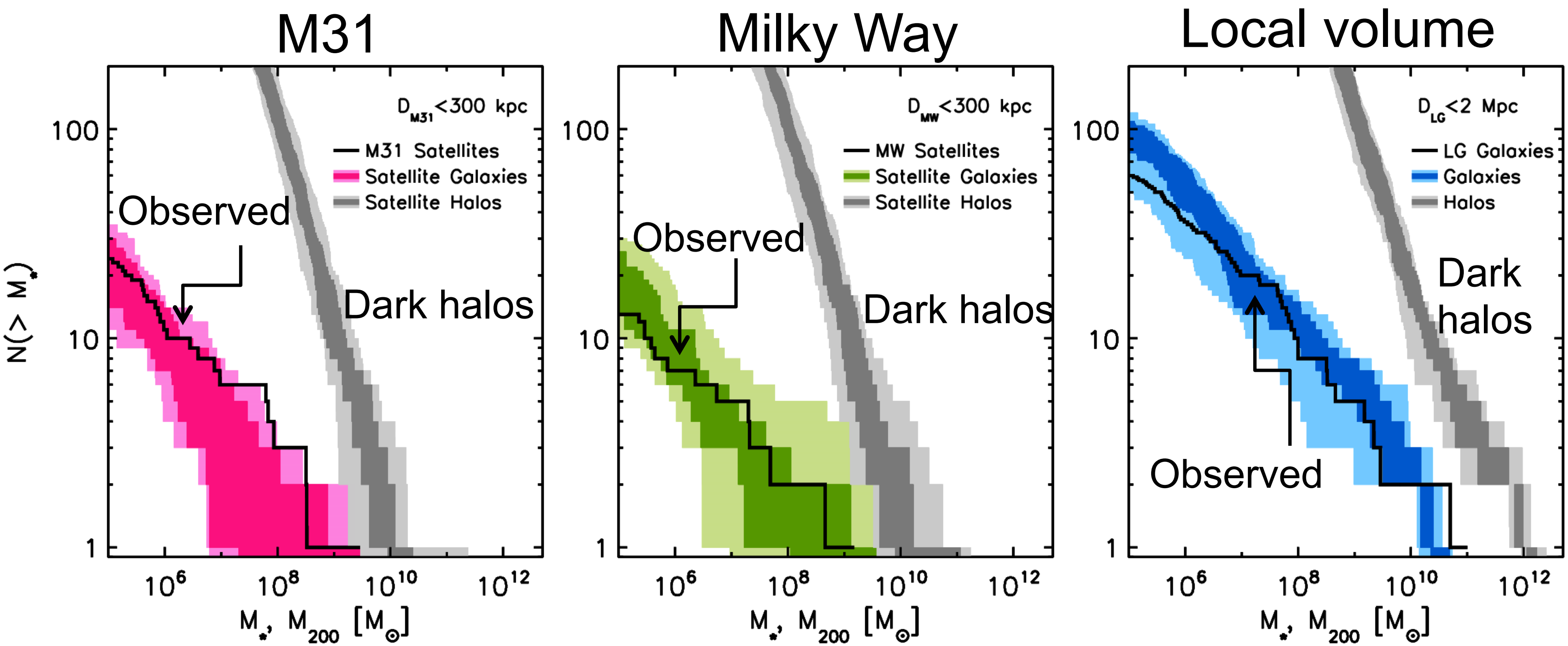


Far fewer satellite galaxies than CDM halos

Sawala, CSF et al ‘16

EAGLE Local Group simulation

University of Durham



Sawala, CSF et al '16

Institute for Computational Cosmology

ICC

When galaxy formation is taken into account

→

CDM predicts the observed abundance of satellites

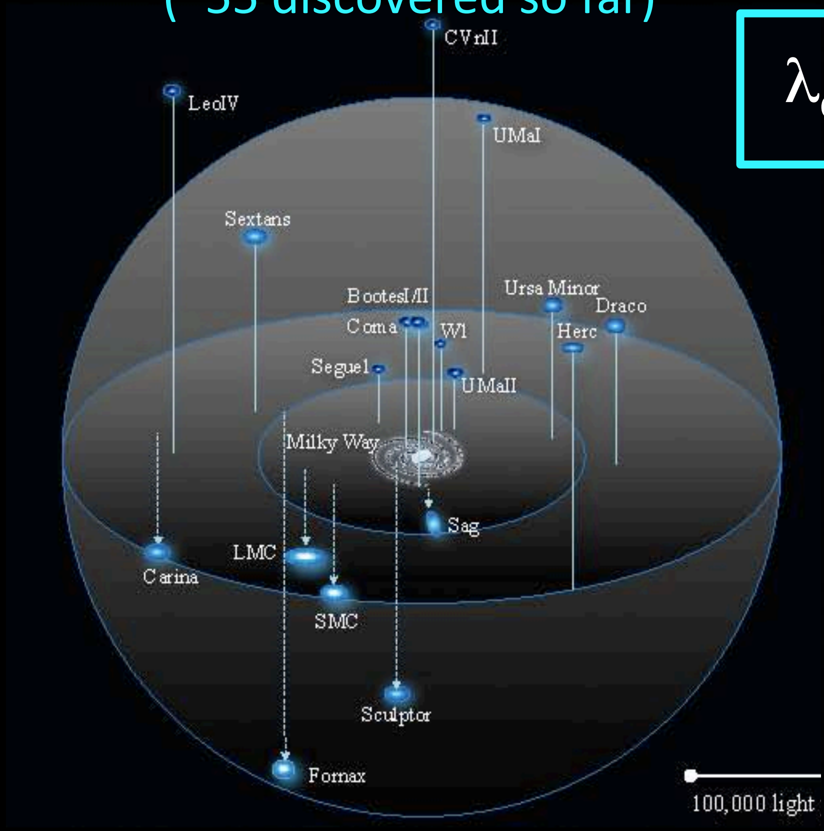
→

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

How about in WDM?

The satellites of the MW

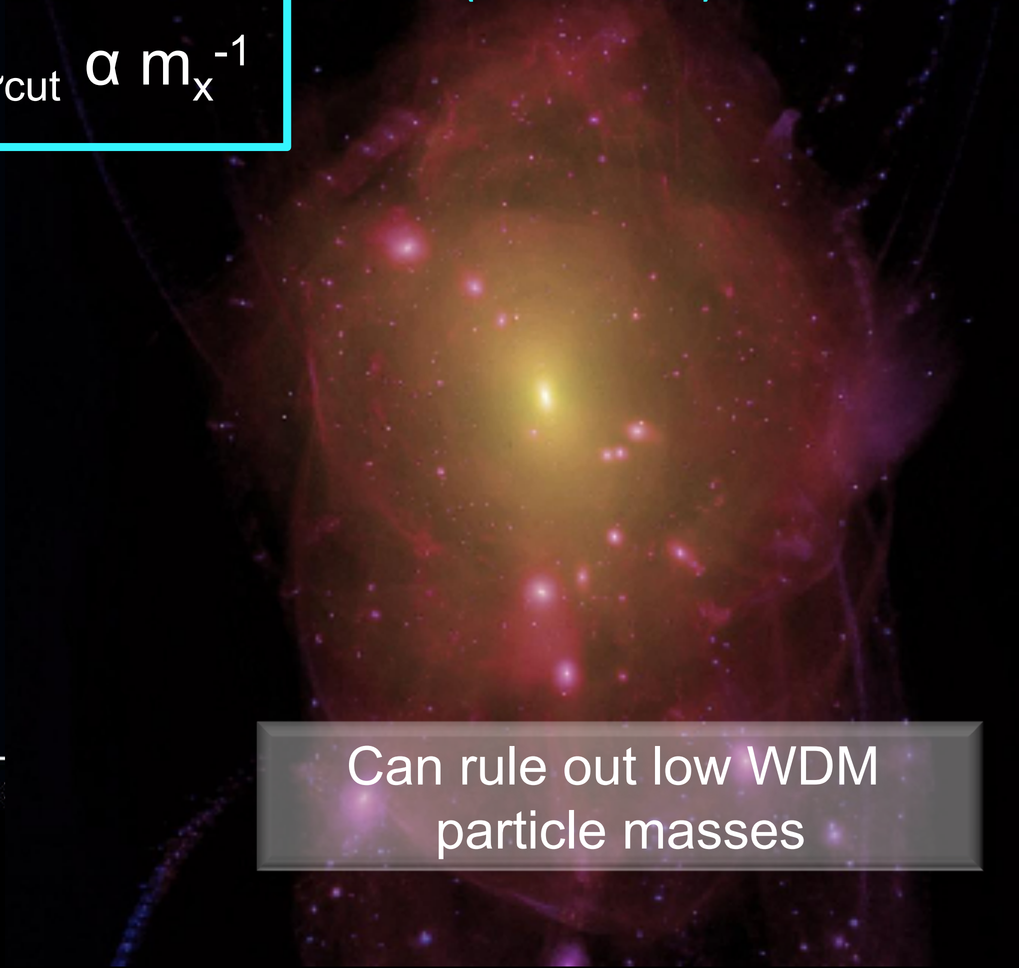
(~55 discovered so far)



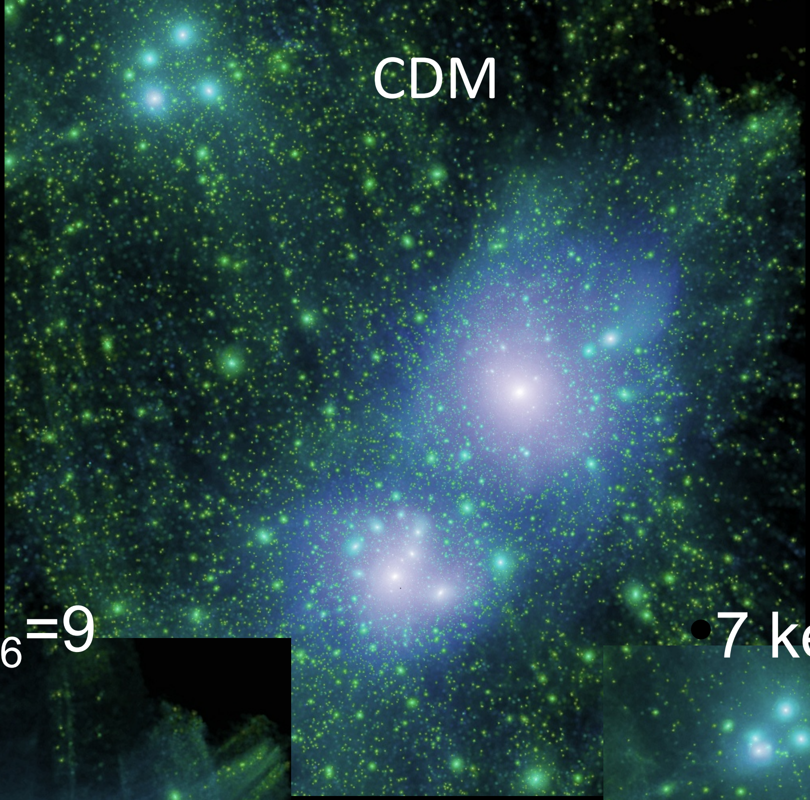
$\lambda_{cut}\ \alpha\ m_x^{-1}$

Dark matter subhalos in WDM

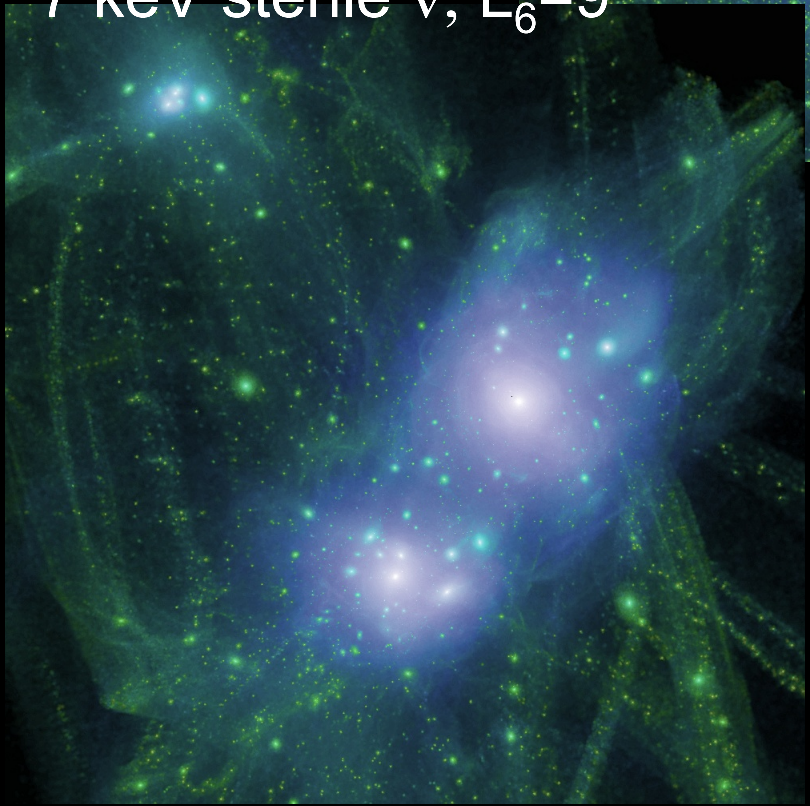
(a few tens)



Can rule out low WDM particle masses



7 keV sterile ν; L_6=9

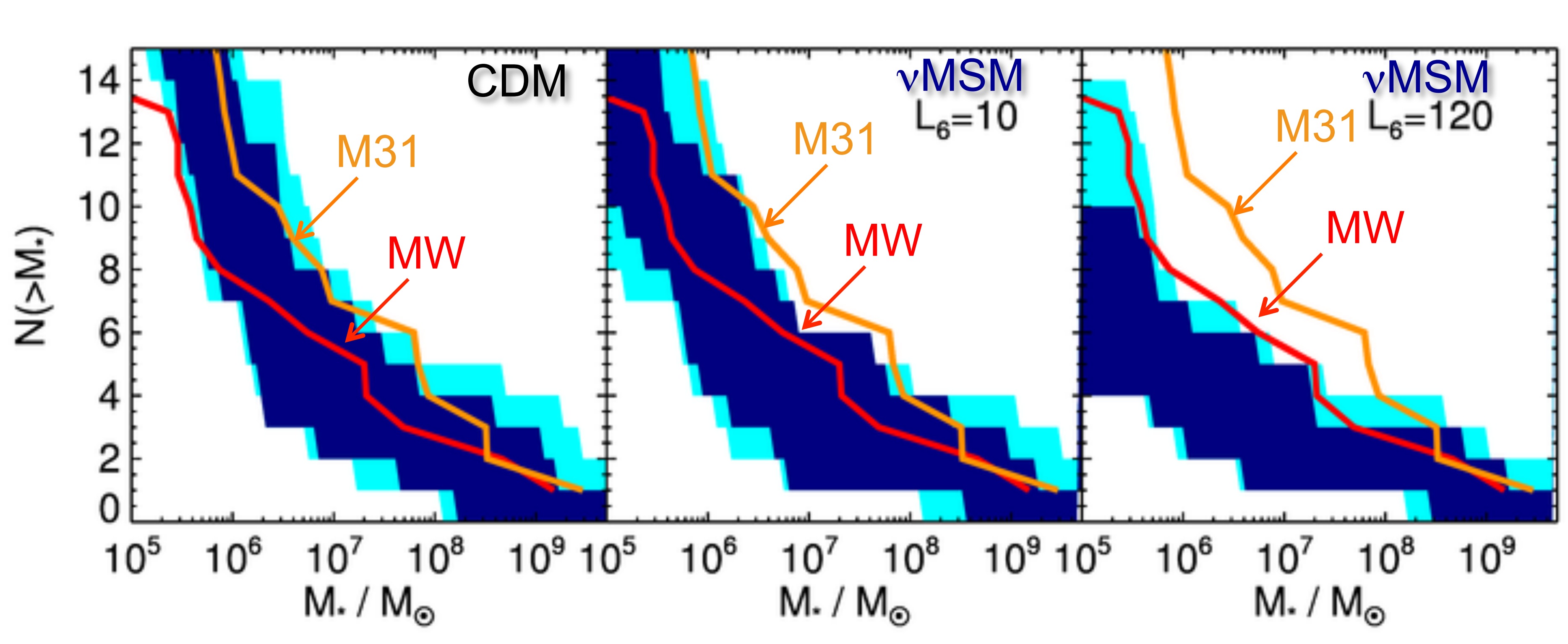


• 7 keV sterile ν; L_6=11.2

Luminosity Function of Local Group Satellites in WDM

University of Durham

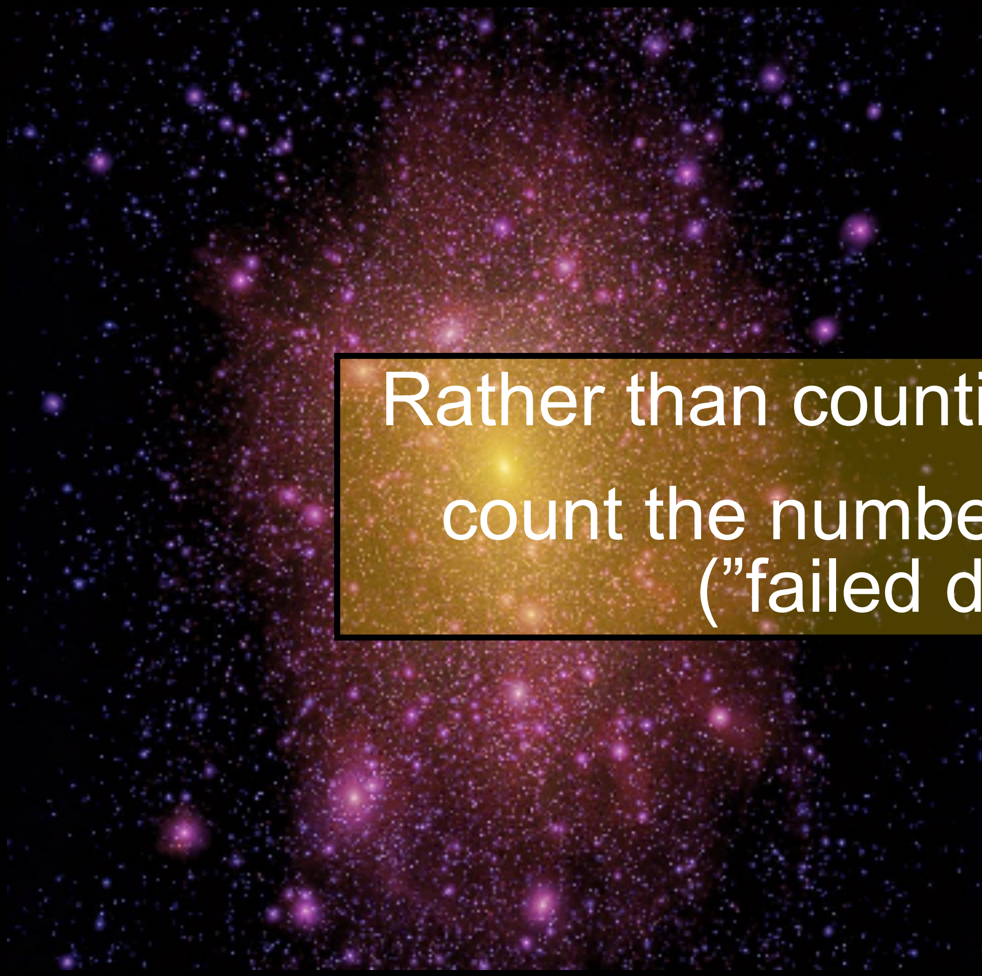
From "Warm Apostle:" 7keV sterile ν $M_h \sim 10^{12} M_o$



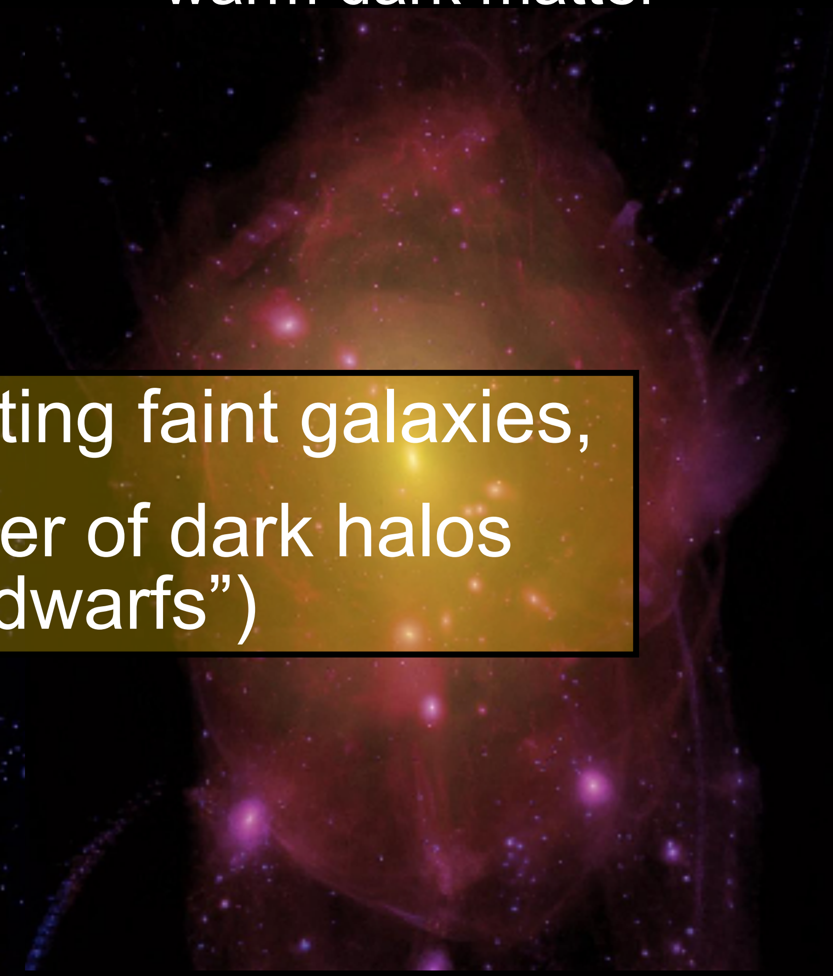
Lovell et al. '16

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

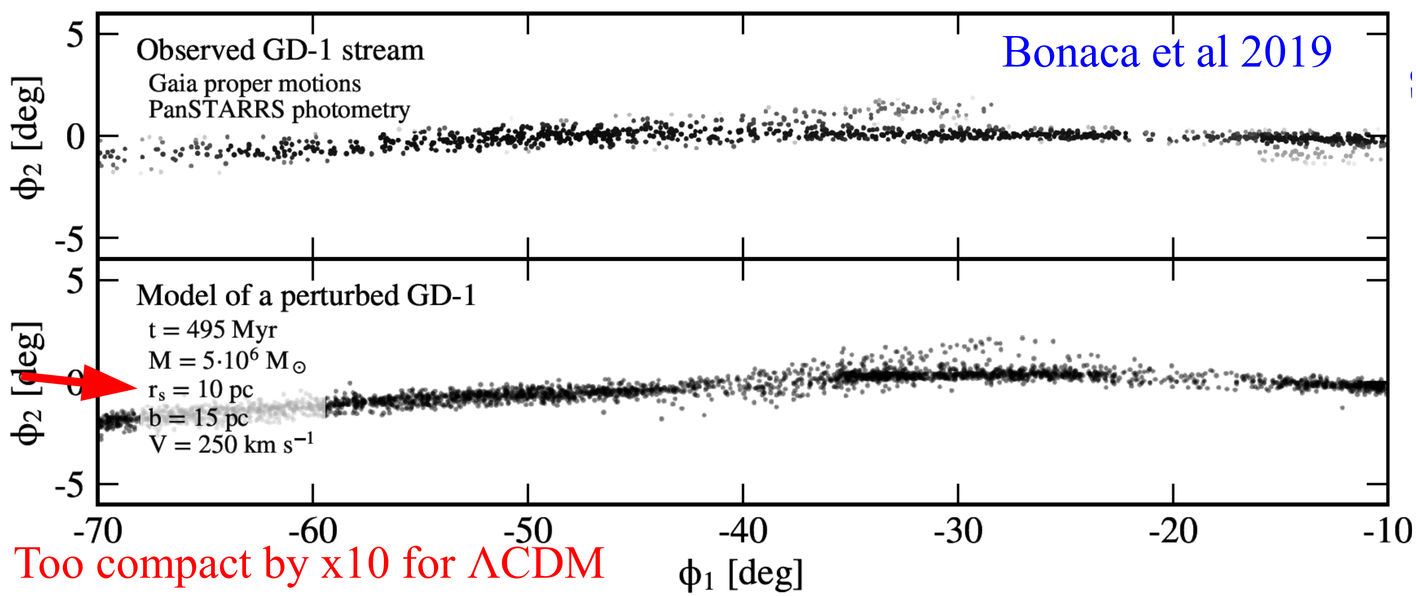
Three ways to detect small CDM halos

1. Gaps in streams
2. Gravitational lensing
3. Annihilation radiation

Gaps in tidal streams

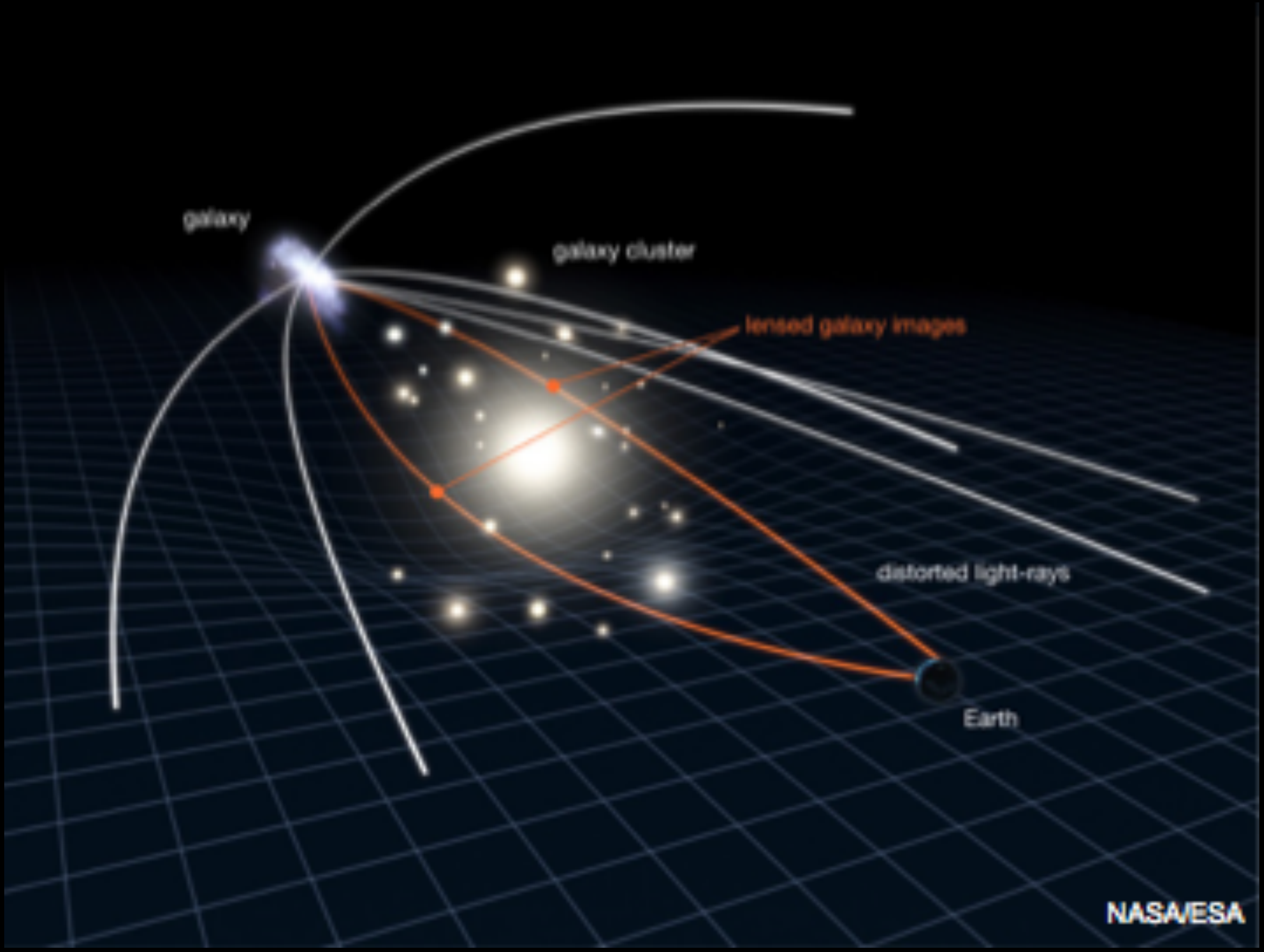
Cold tidal streams (e.g. from globular clusters) in the MW halo can be perturbed by passing subhalos

Perturbations are significant and could be created by encounter with object of mass ~$10^7 M_o$ object



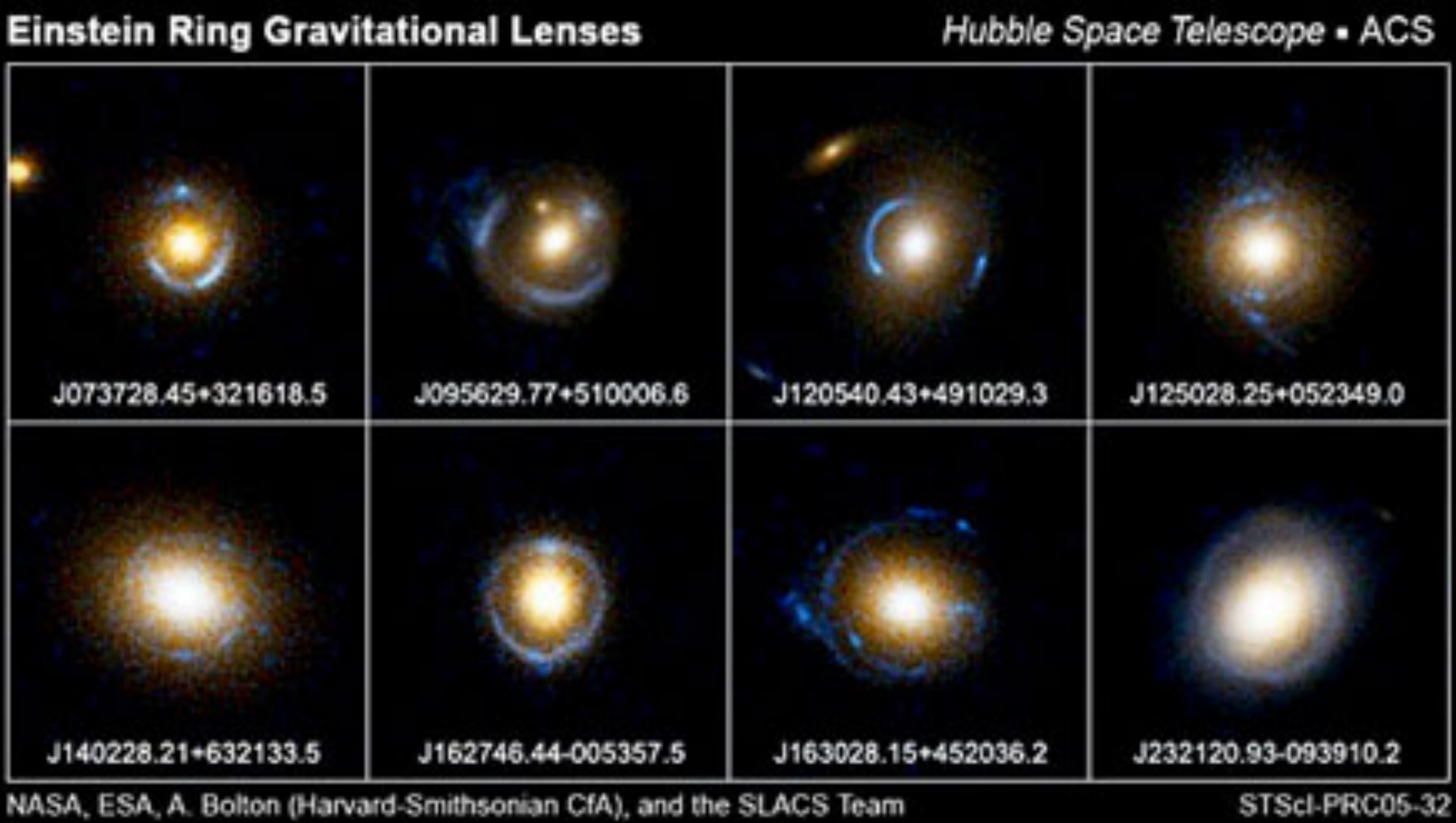
Too compact by x10 for ΛCDM

Gravitational lensing: Einstein rings

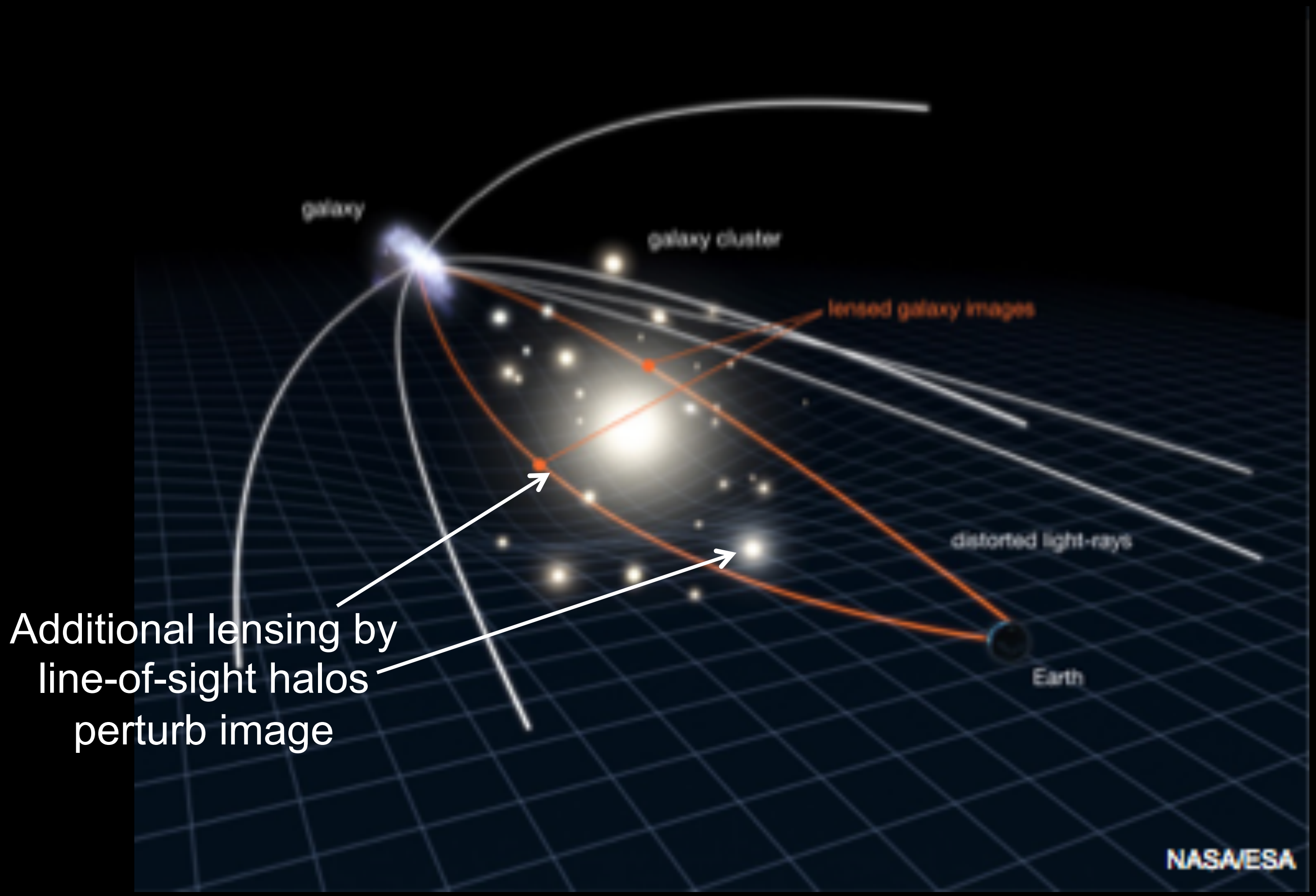


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



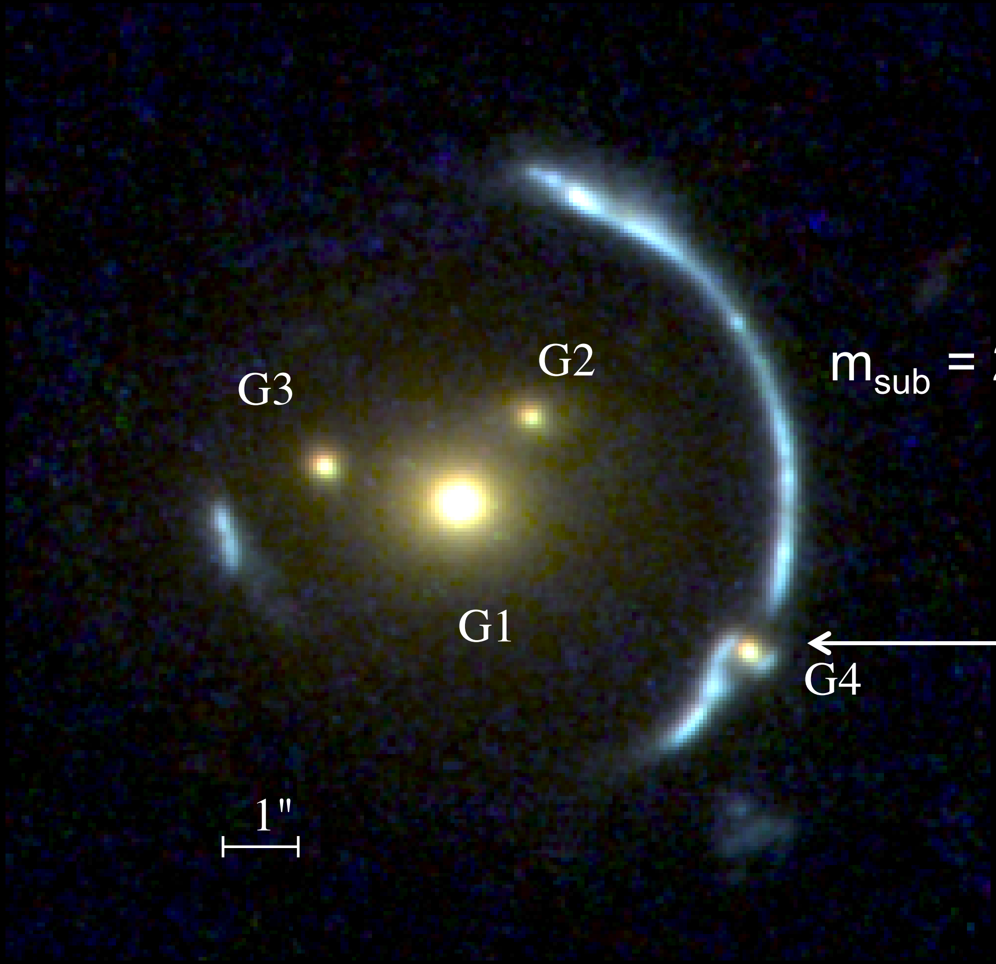
Gravitational lensing: Einstein rings



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



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

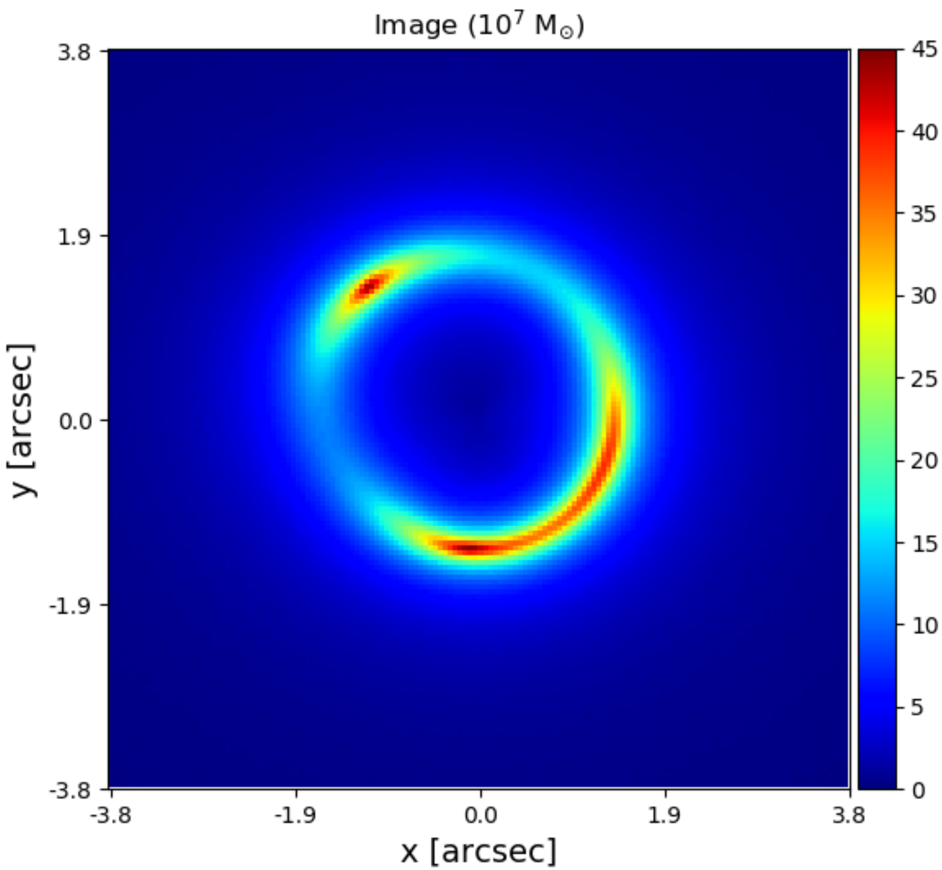
Vegetti et al '10

Strong lensing: detecting small halos

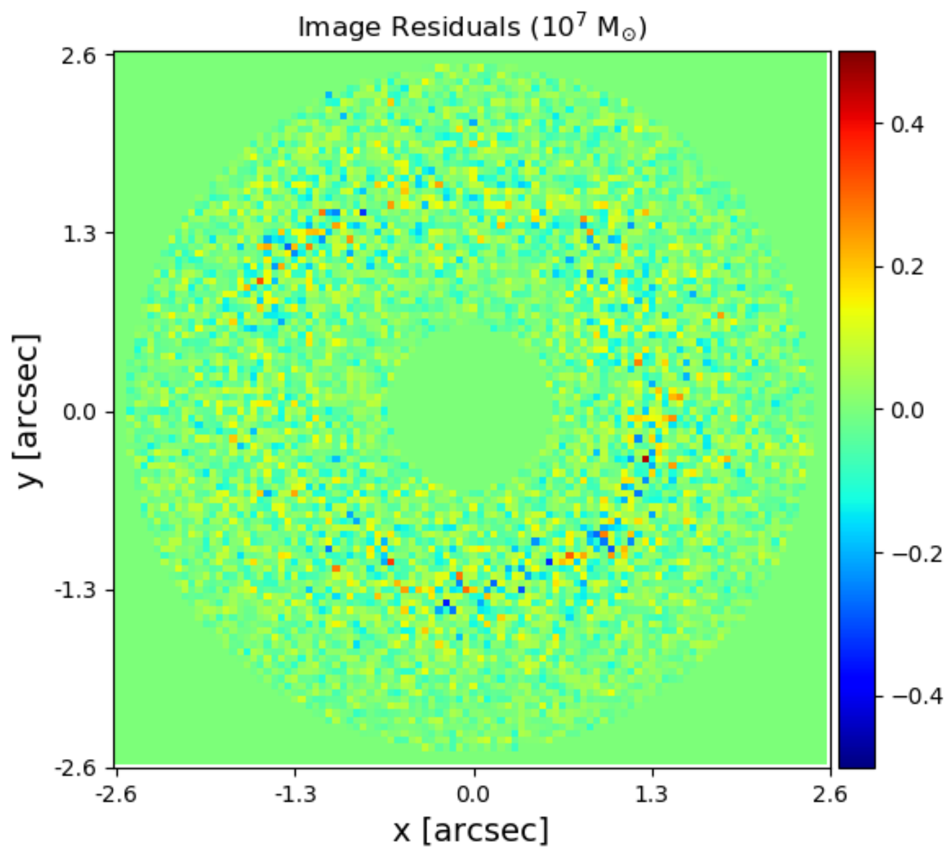
University of Durham

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

Image



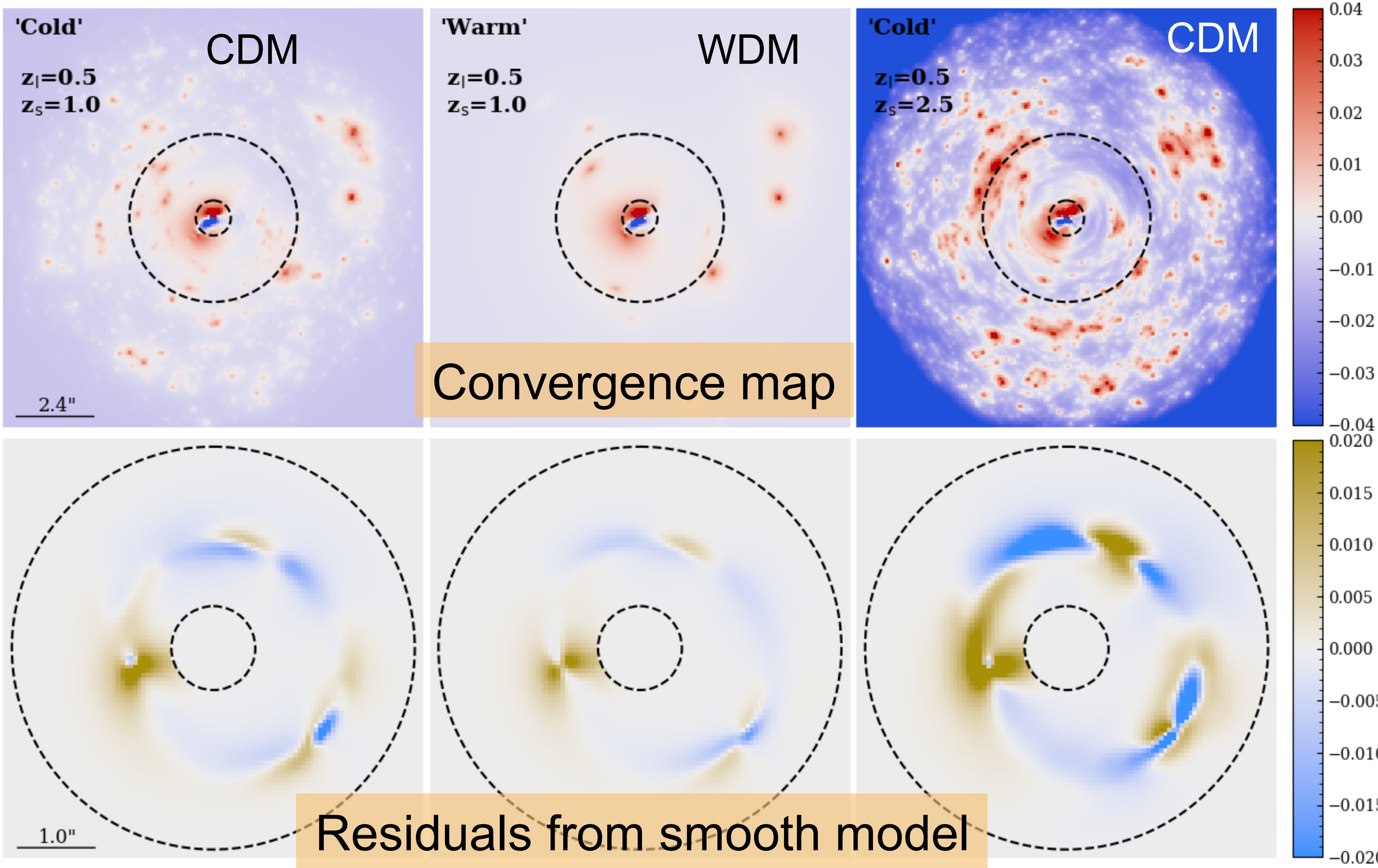
Residuals



He, Li, CSF et al '19

Institute for Computational Cosmology

Strong lensing: detecting small halos



He et al. '20

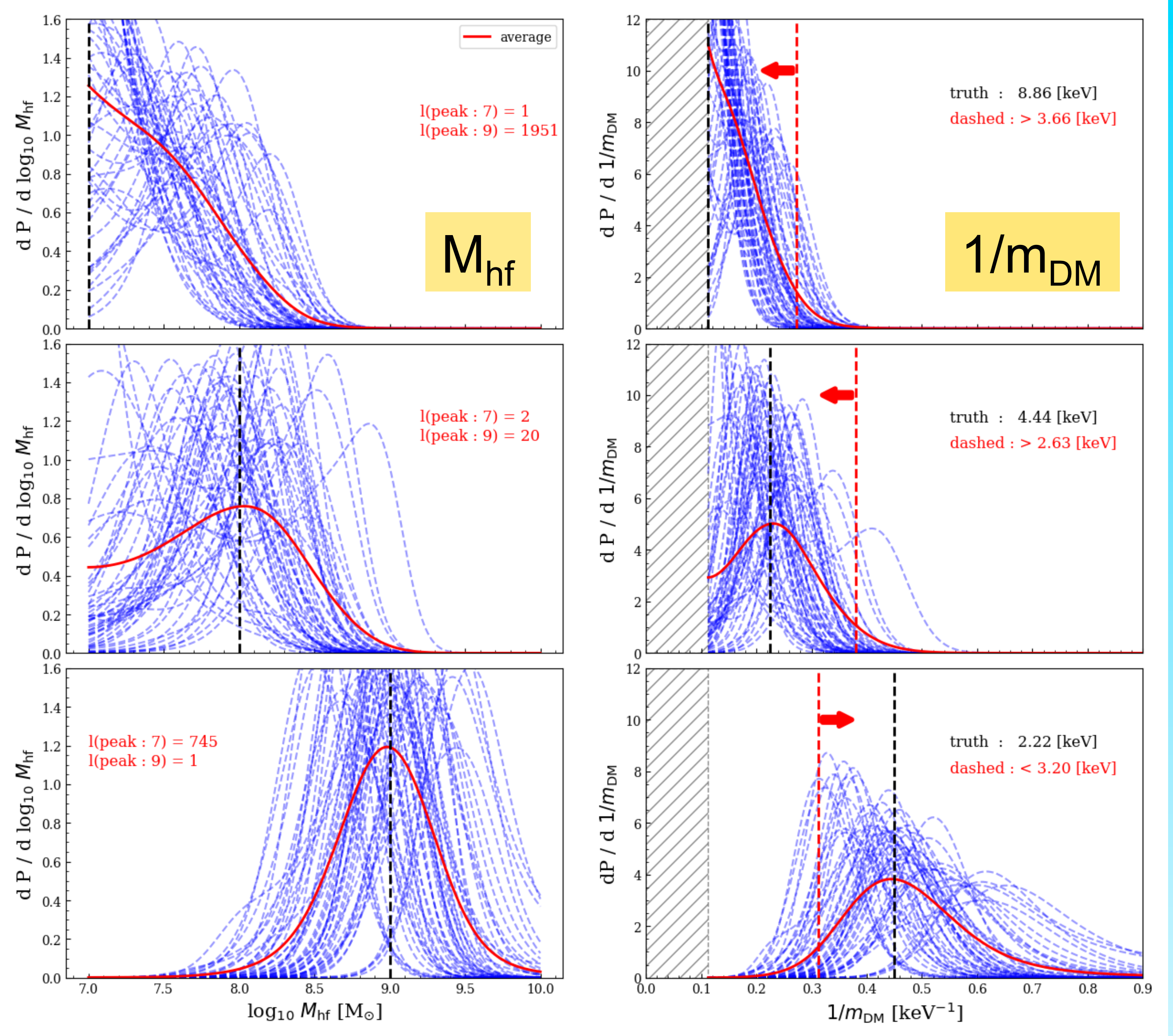
University of Durham

Institute for Computational Cosmology

Strong lensing: detecting small halos

University of Durham

Posterior distributions (mock observations) for power spectrum of residuals



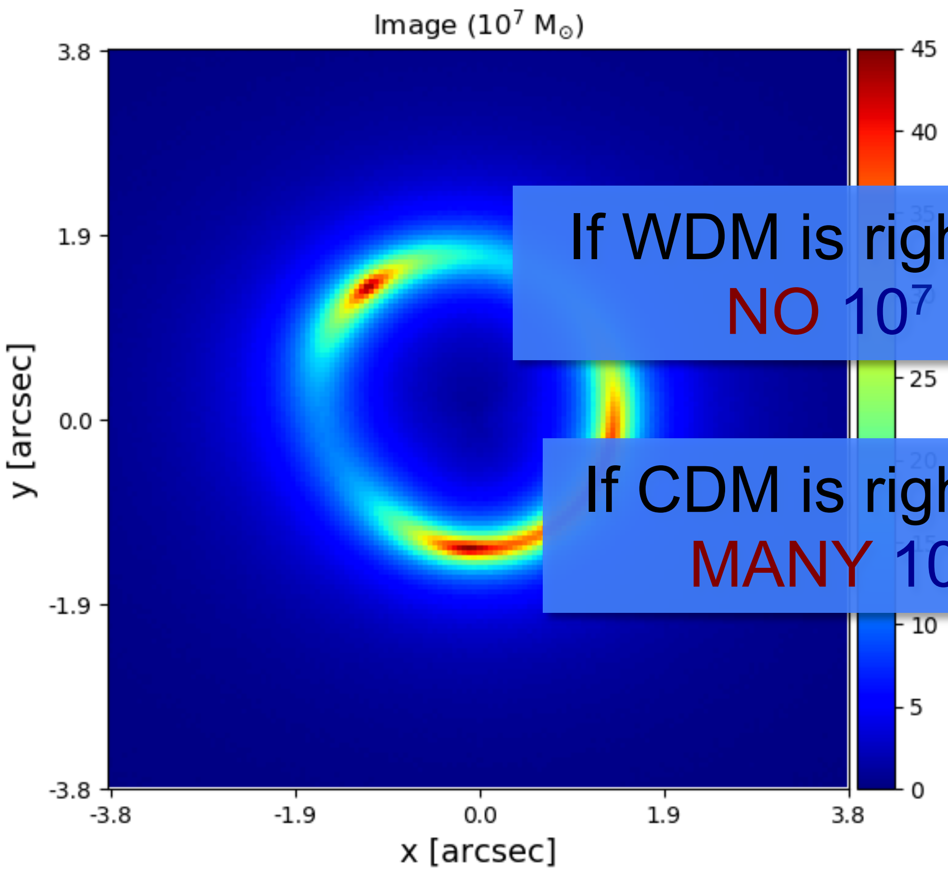
Constraints from forward modelling of 50 systems

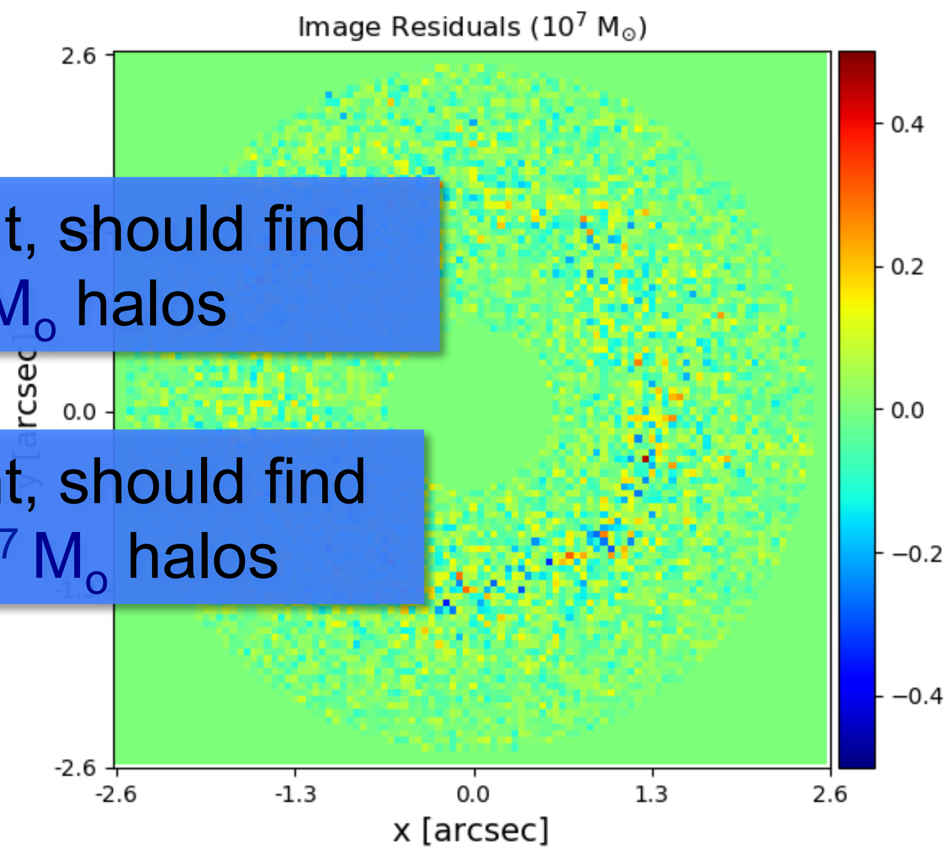
He et al. '20

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

University of Durham

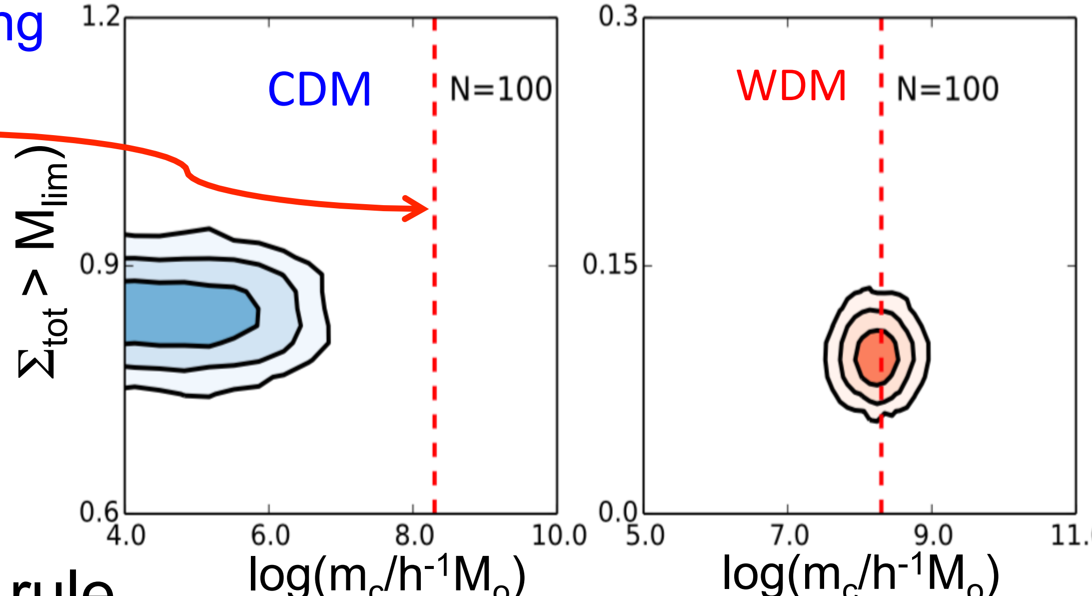
Detecting substructures with strong lensing

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: $m_{low} = 10^7\ h^{-1}M_o$



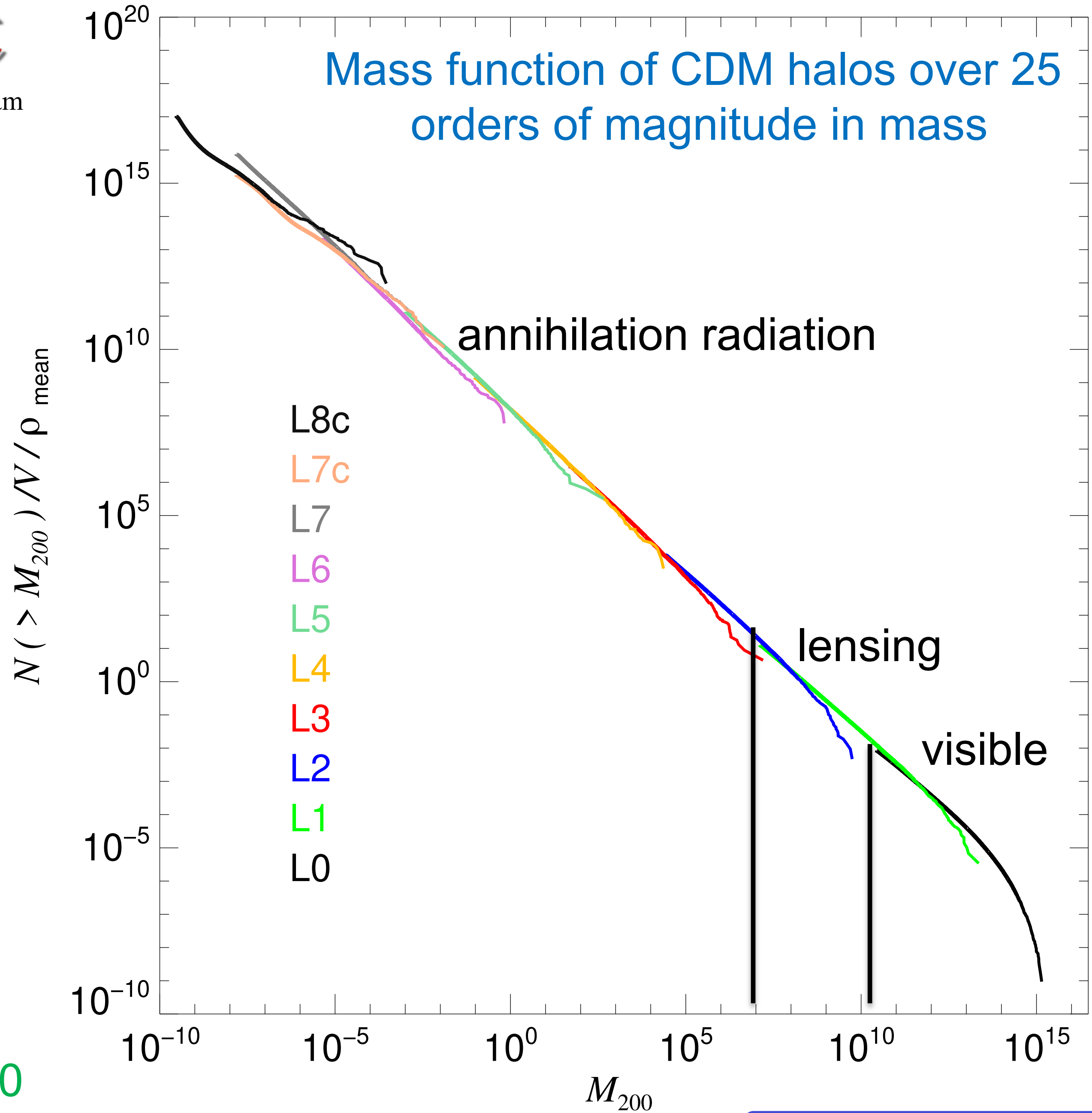
m_c= halo cutoff mass

- 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

University of Durham



Wang et al ‘20

Institute for Computational Cosmology

Can we count dark haloes?

cold dark matter

warm dark matter

Three ways to detect small CDM halos

1. Gaps in streams
2. Gravitational lensing
3. Annihilation radiation

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)

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

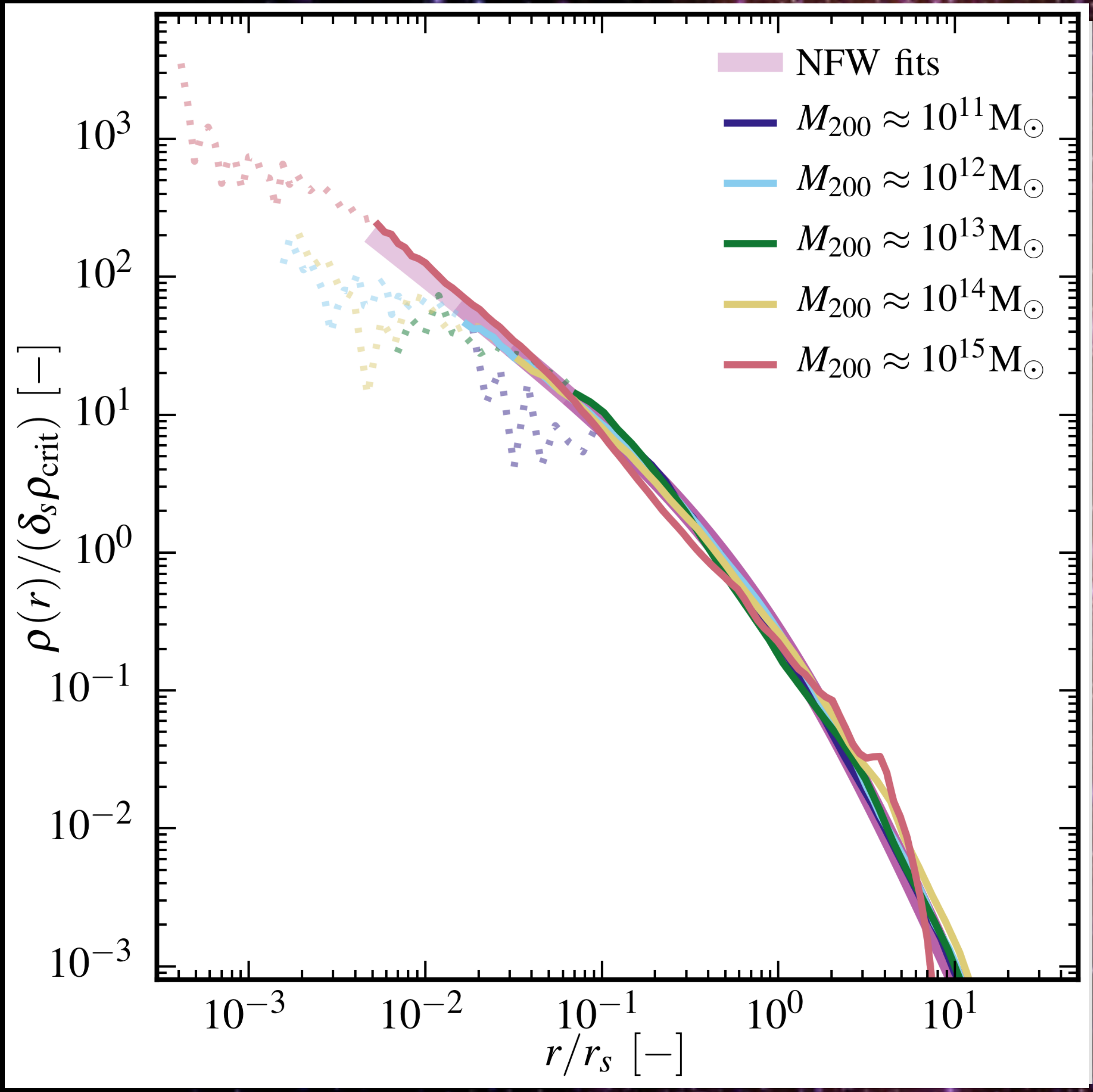
cross-section (particle physics)

$\langle\sigma v\rangle = 3\times 10^{-26} cm^3 s^{-1}$ → 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

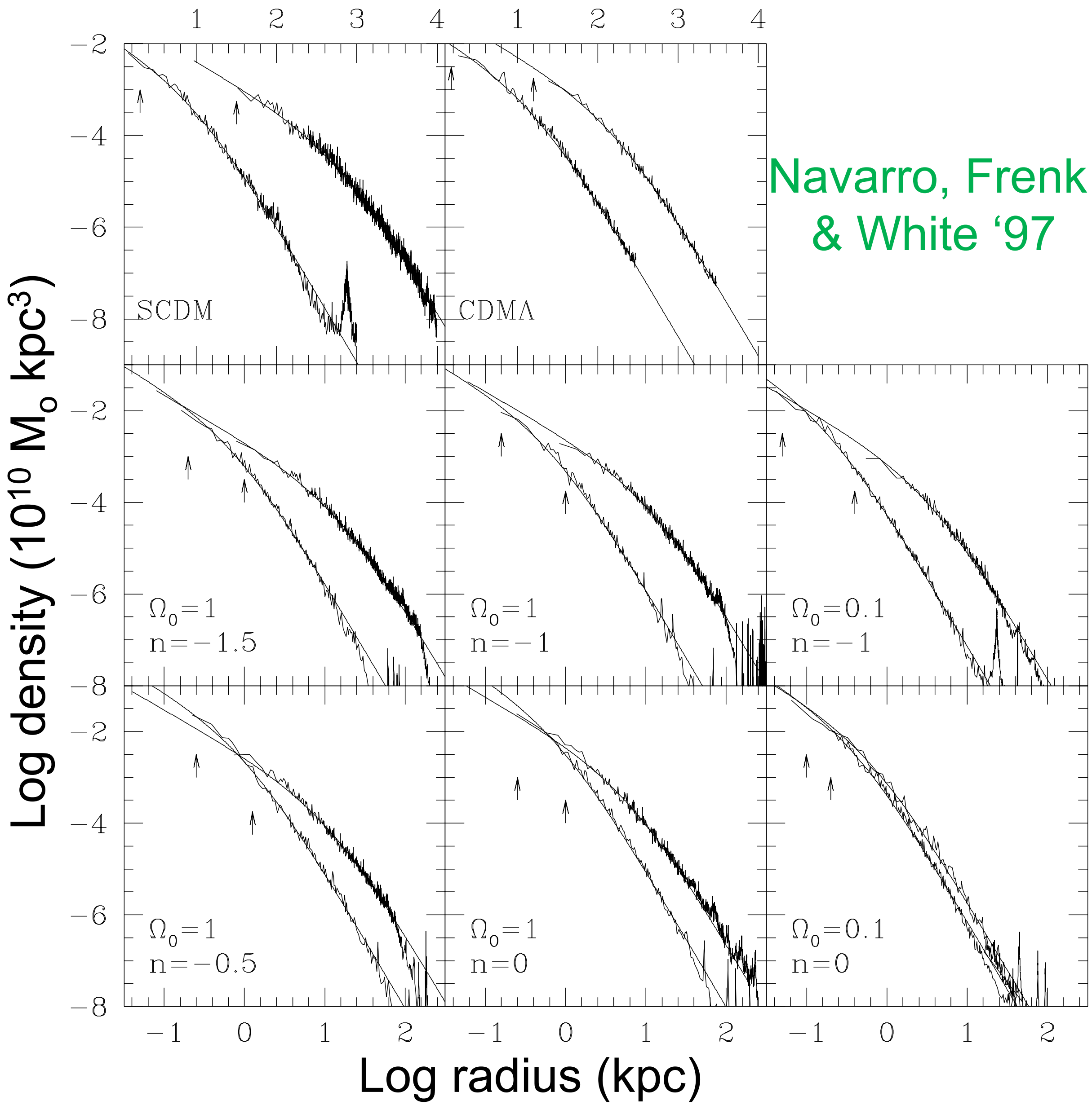
University of Durham

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

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



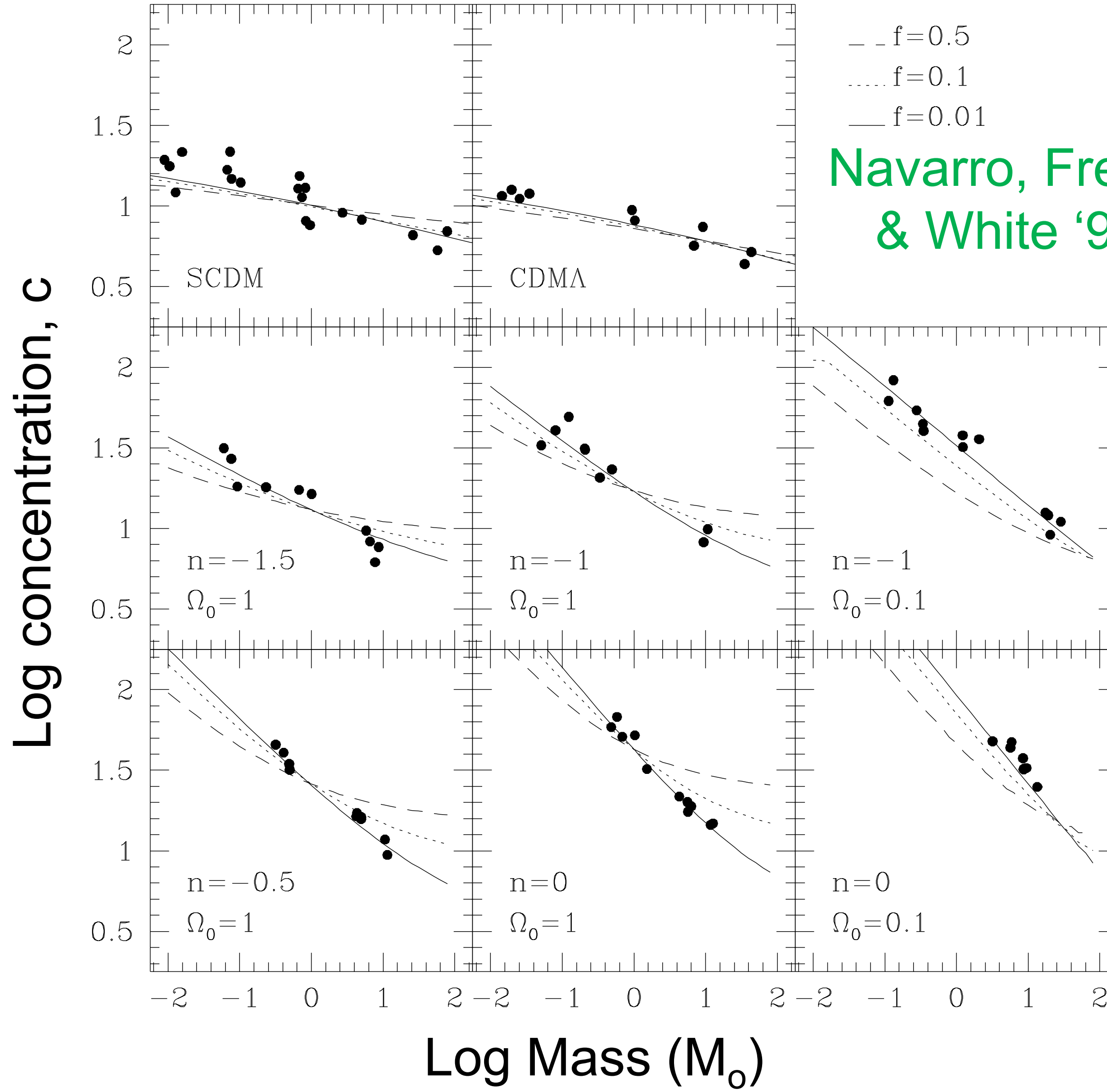
ICC University of Durham

Universal halo density profiles

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

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

Universal halo density profiles

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

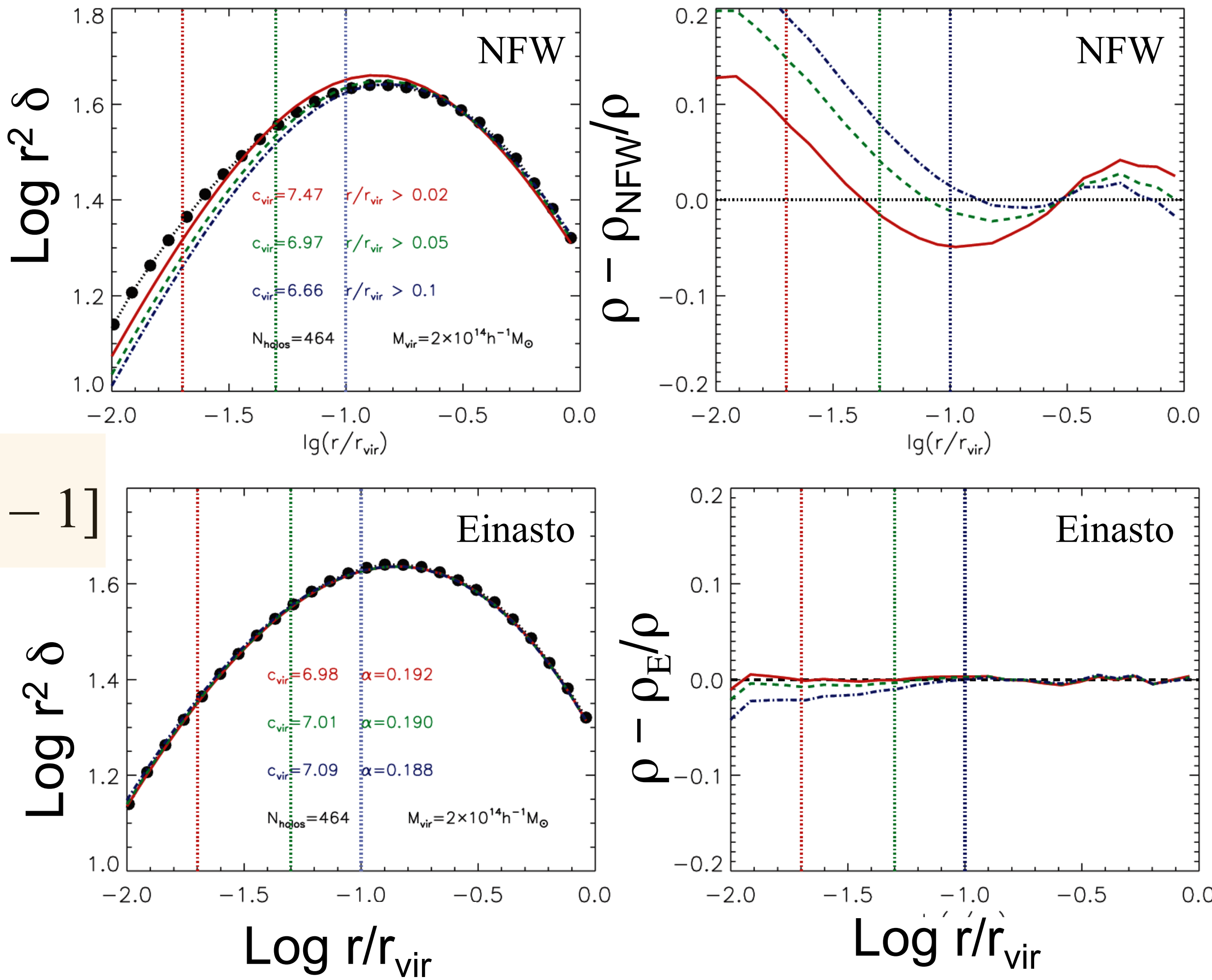
The “Einasto” formula

$$\ln(\rho(r)/\rho_{-2}) = (-2/\alpha)\,[(r/r_{-2})^{\alpha} - 1]$$

Fits mean profiles even better

Gao et al 2008

Averaged cluster mass halos fit with NFW and Einasto



Cores or cusps in nature?

Cores

Cusps

No convincing evidence for cores in observed galaxies

But, if it turns out that cores exist is this end of CDM?

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

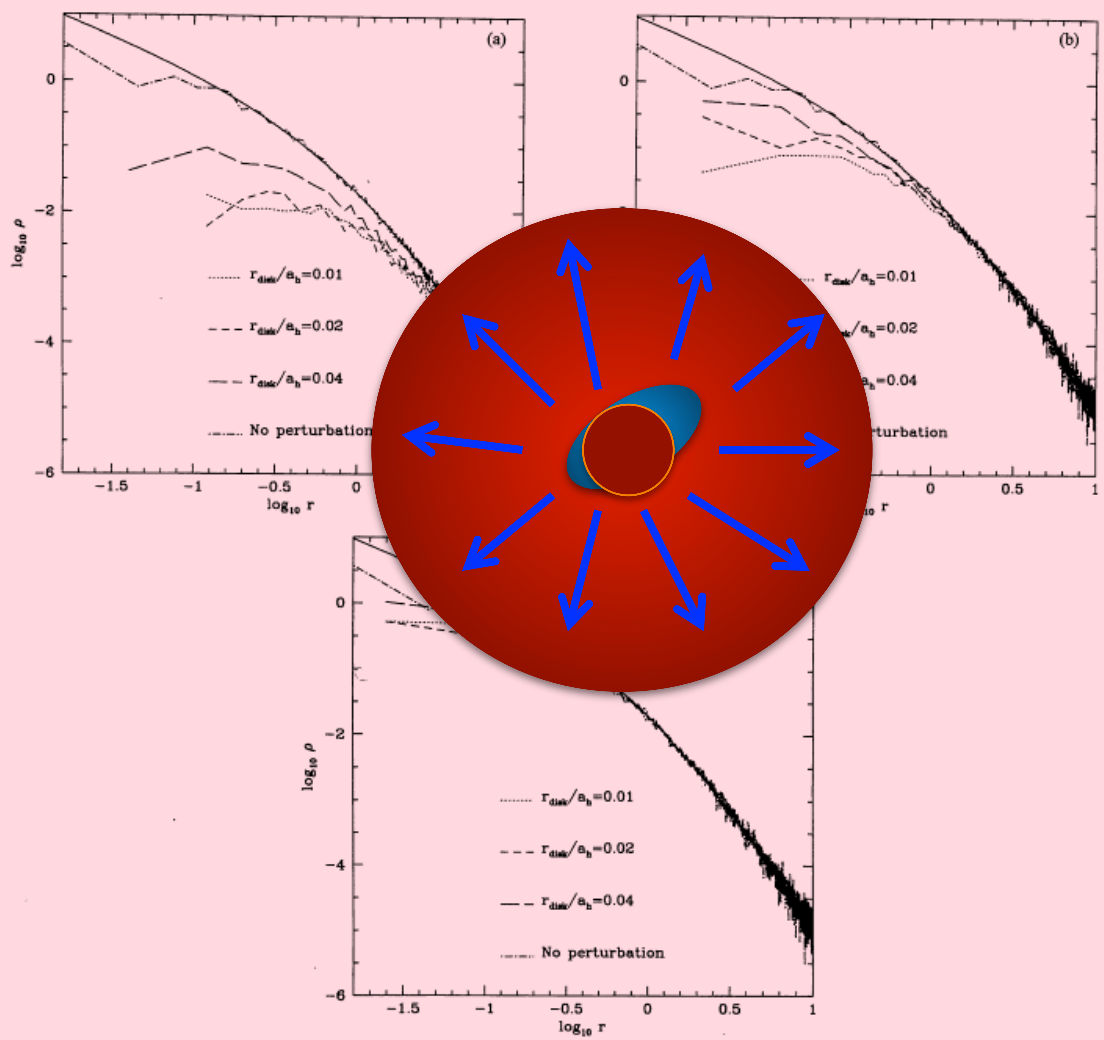
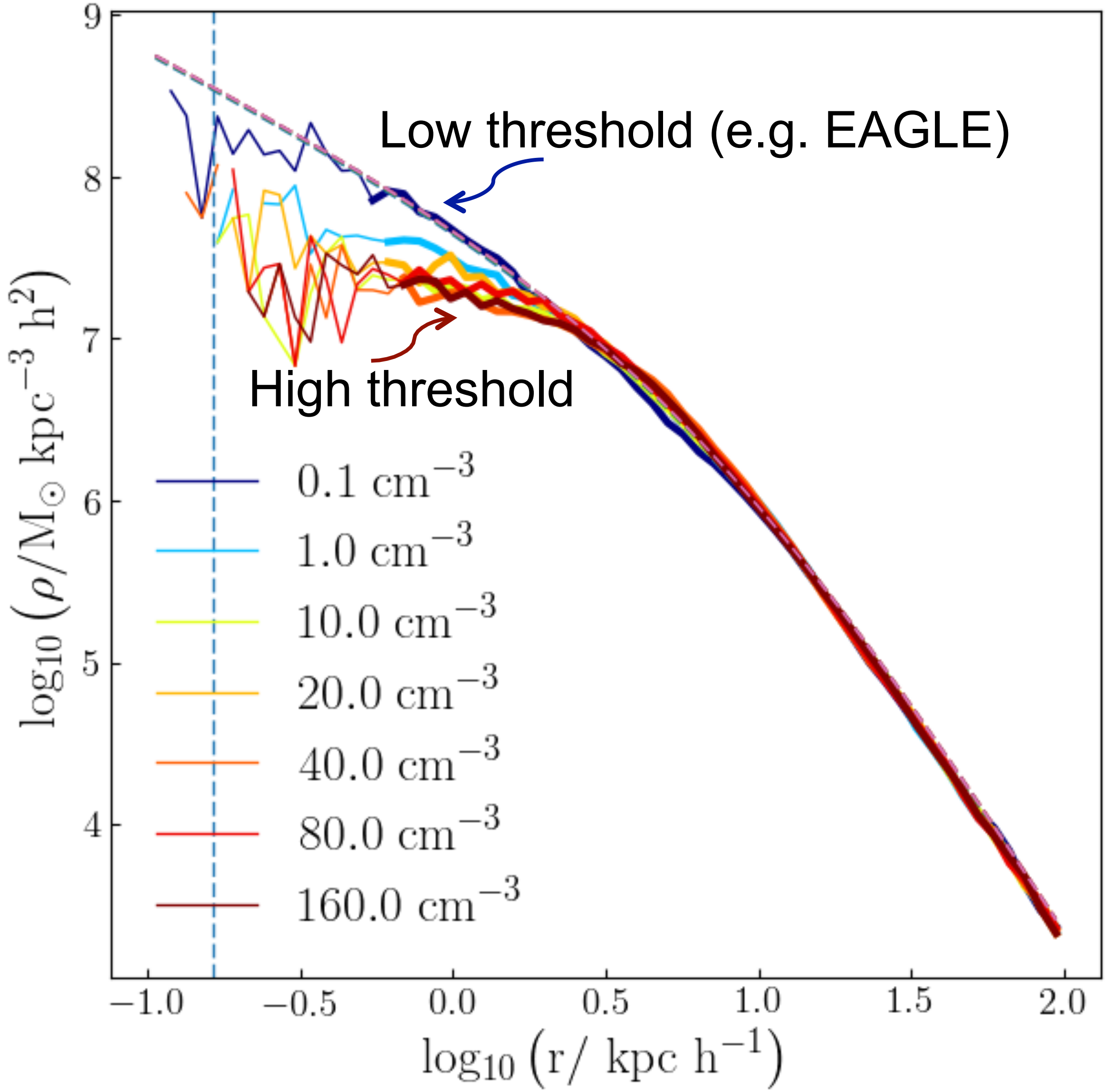
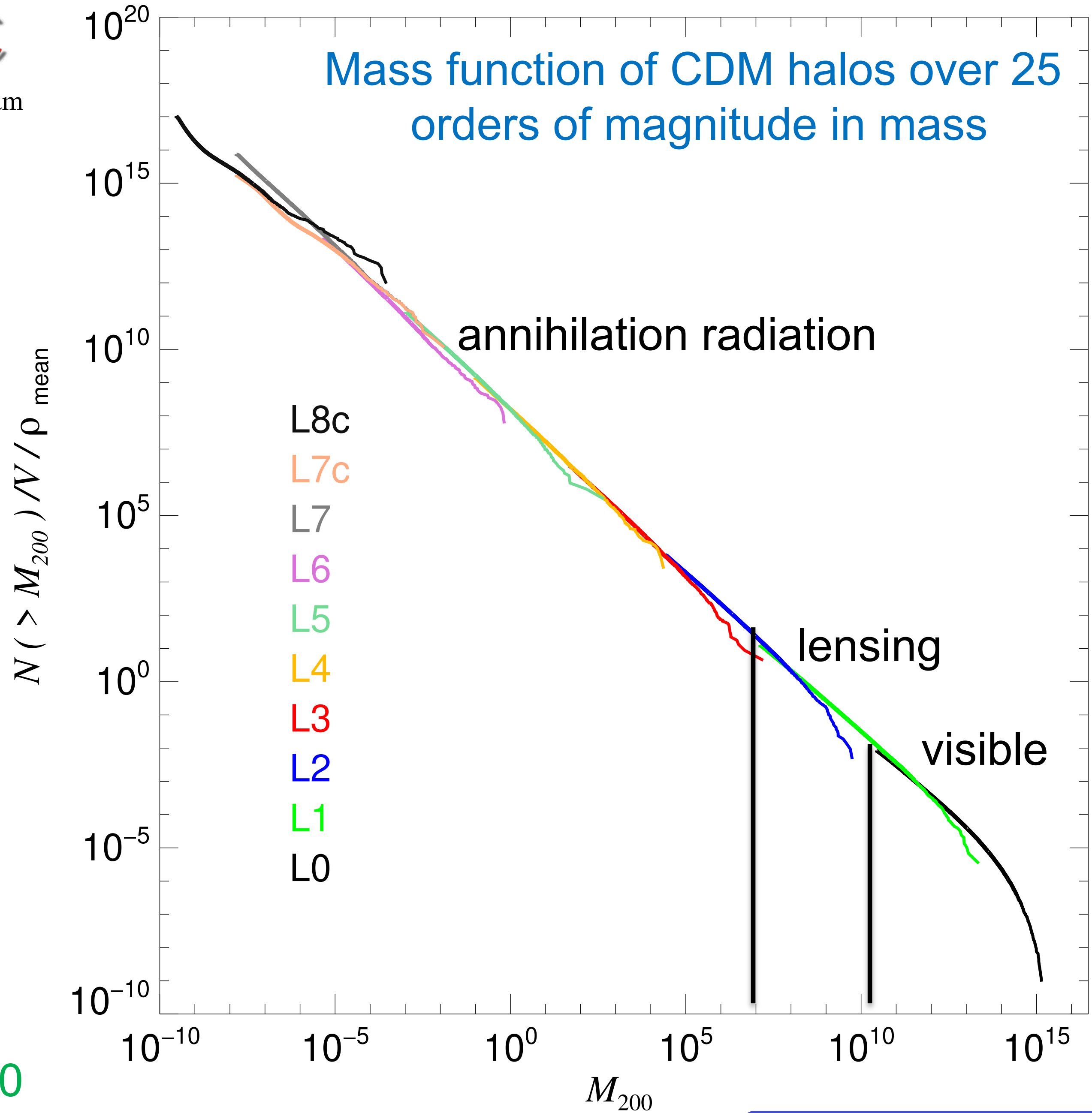


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

Cores or cusps in simulations?



Benitez-Llambay, CSF et al '17



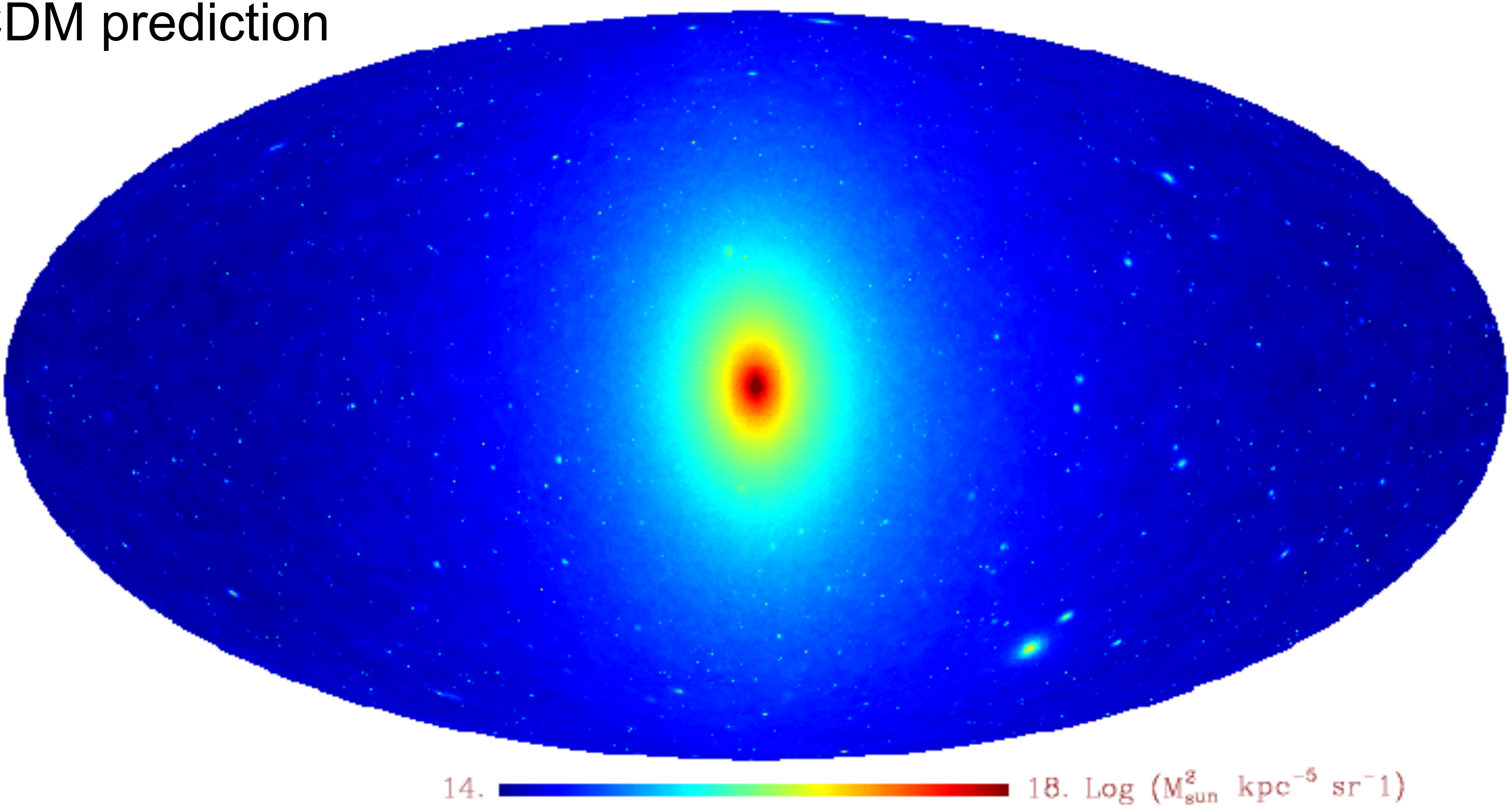
Mass function of CDM halos over 25 orders of magnitude in mass
annihilation radiation
lensing
visible
L8c
L7c
L7
L6
L5
L4
L3
L2
L1
L0
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
$N(>M_{200})/V/\rho_{mean}$
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
M_{200}

Wang et al '20

The Milky Way seen in annihilation radiation

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

CDM prediction



Springel et al. ‘08

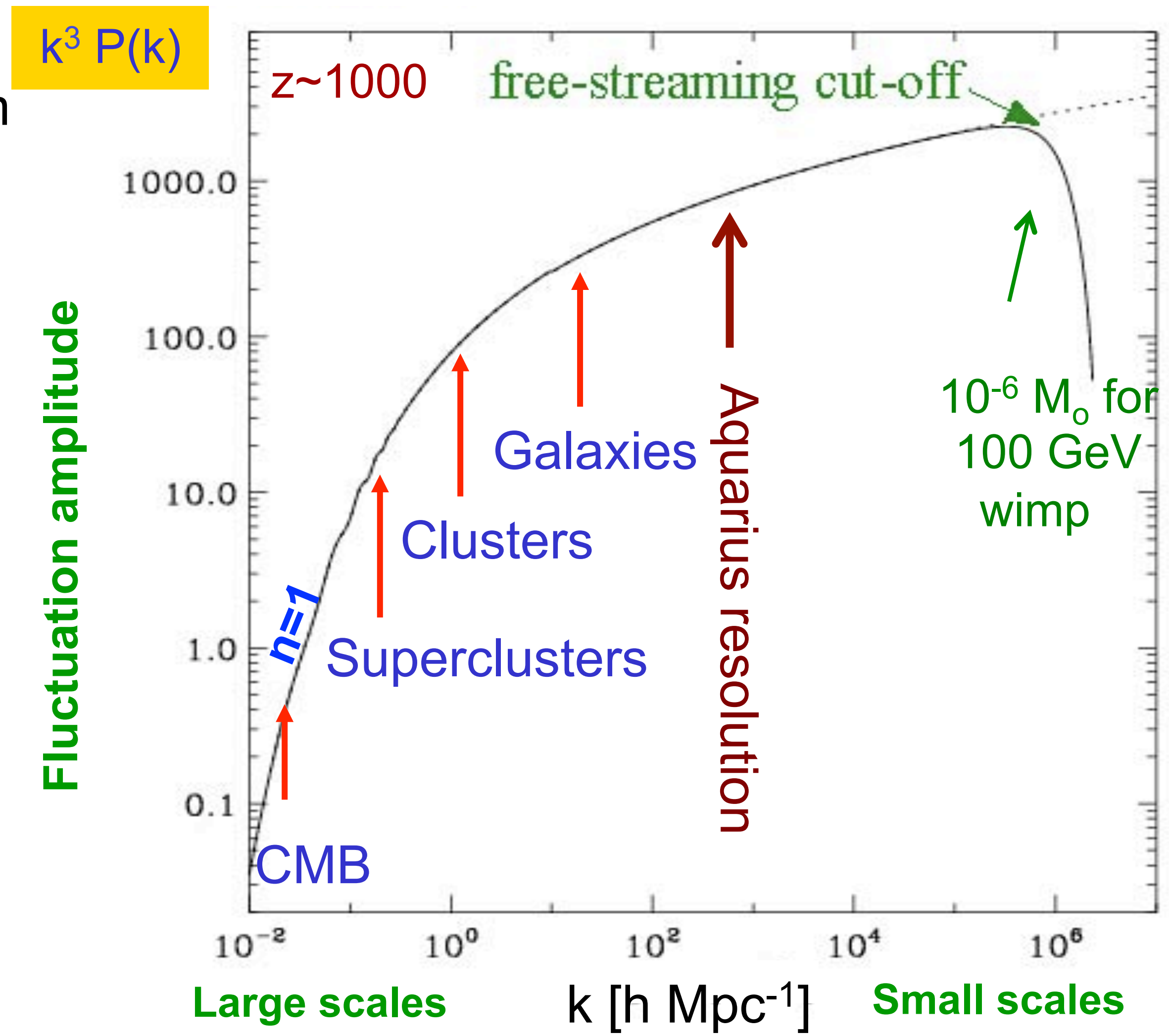
The cold dark matter linear power spectrum

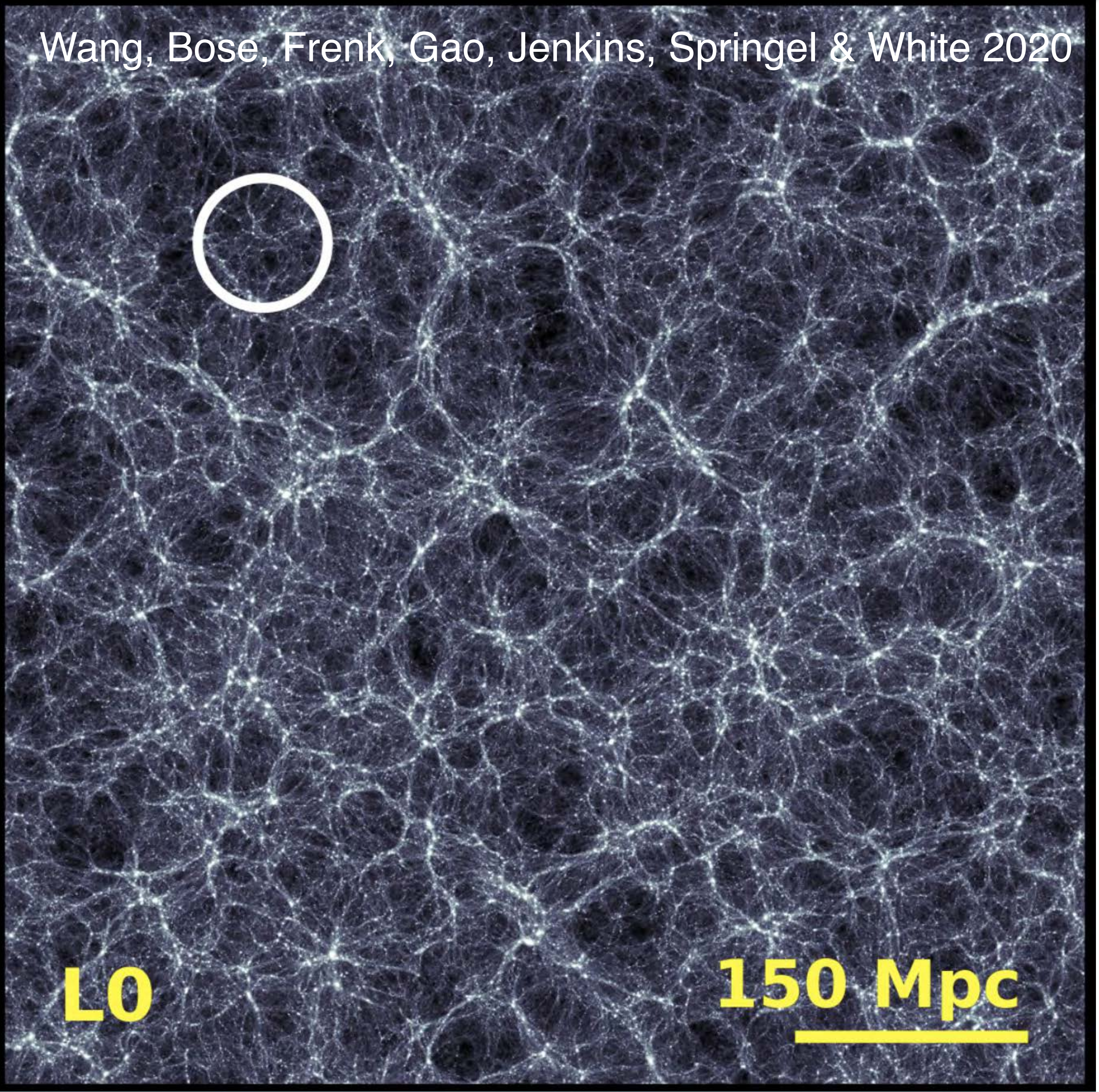
The linear power spectrum ("power per octave")

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

Assumes a 100GeV wimp

Green et al '04





The VVV simulation

Planck cosmology

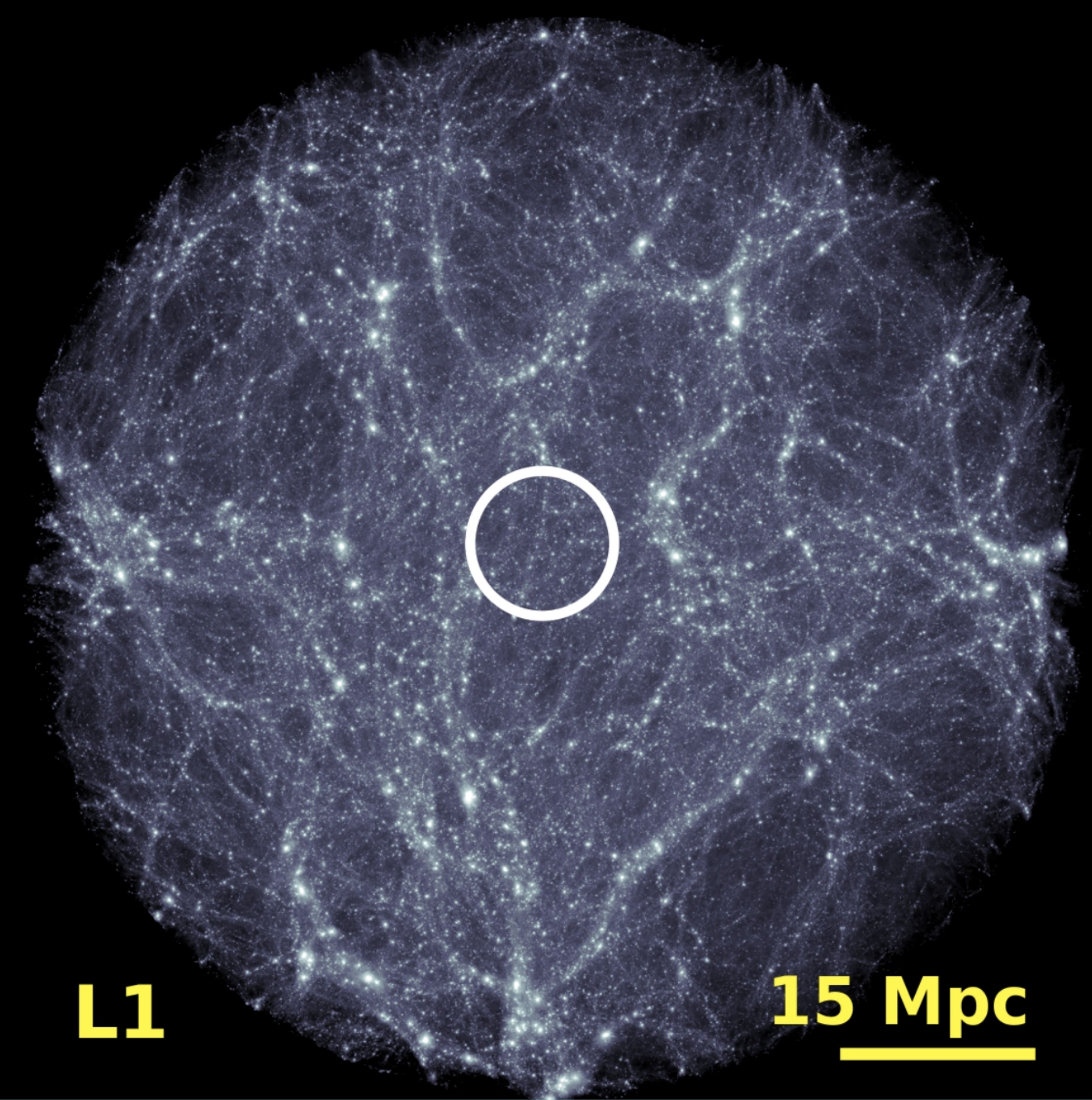
Dark matter only

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

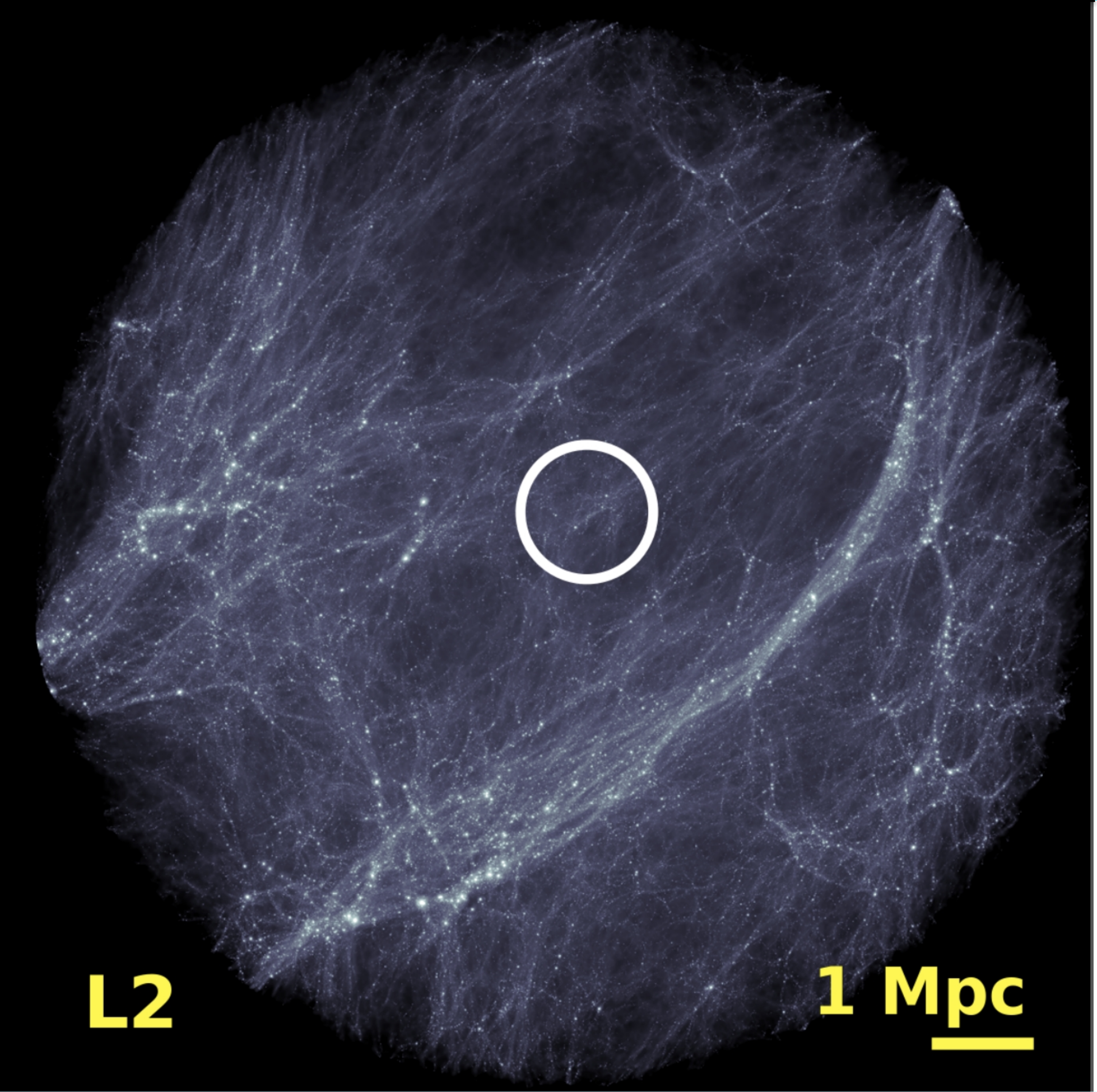
Dark matter only

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

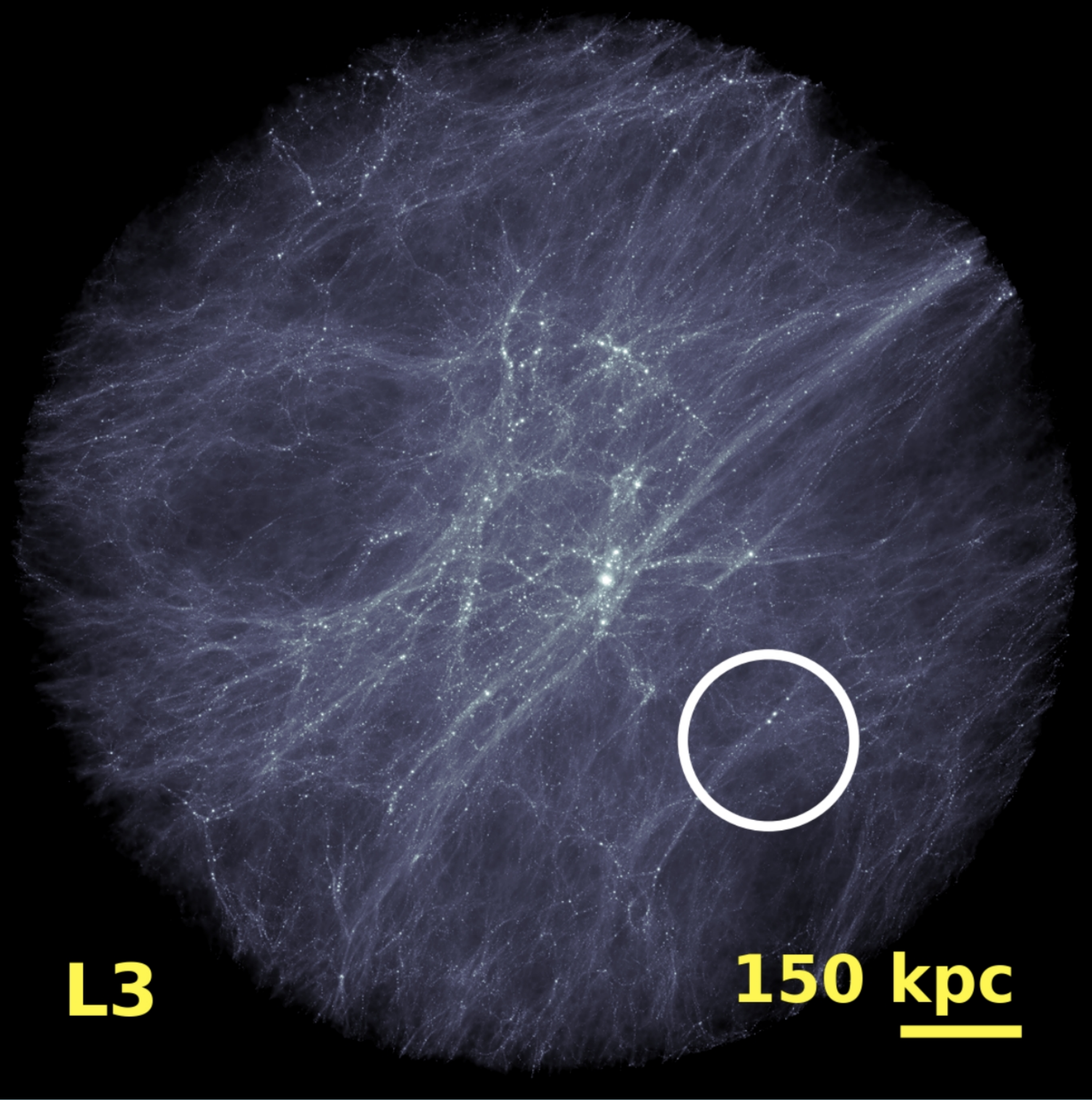
Dark matter only

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

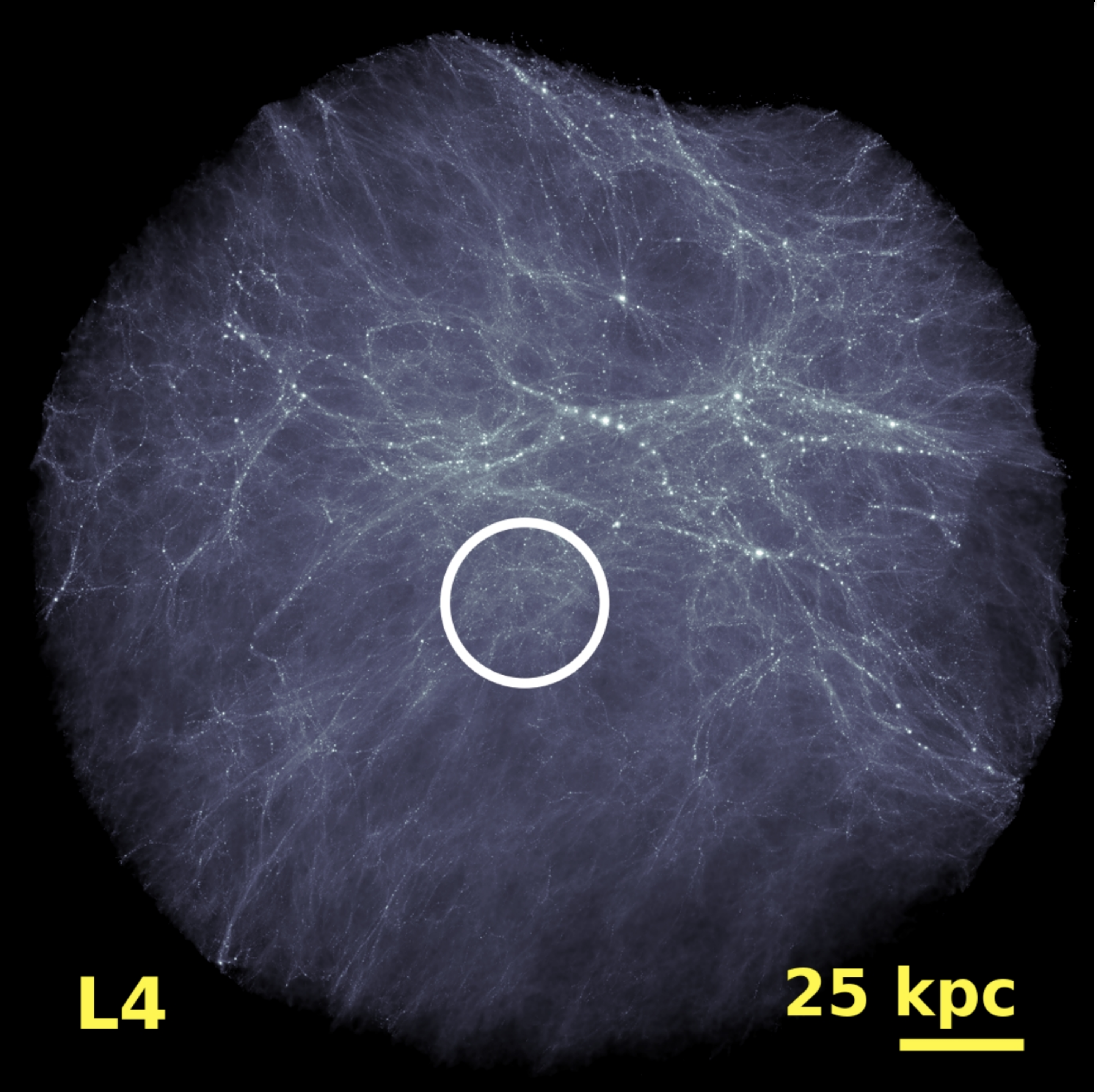
Dark matter only

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

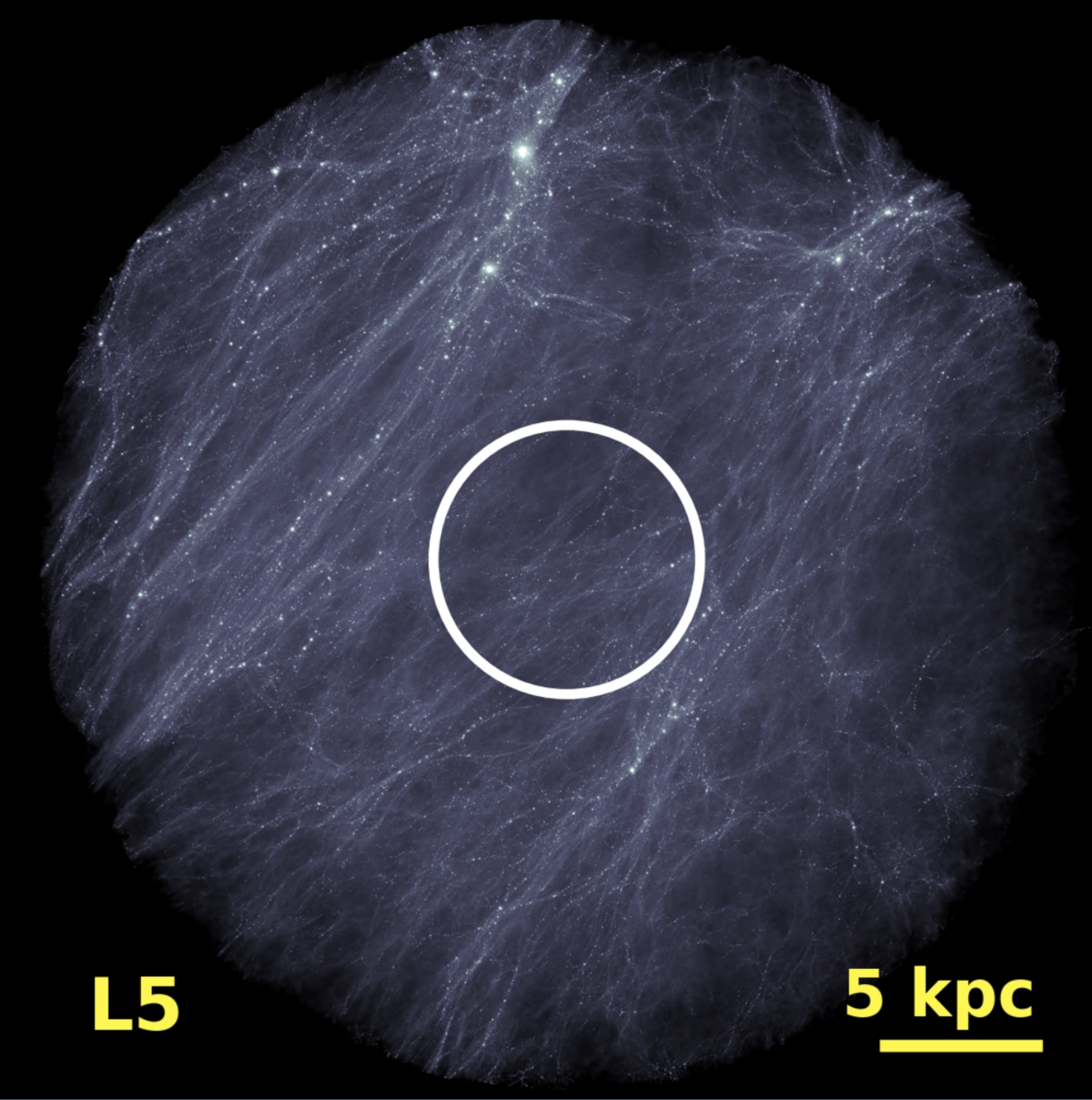
Dark matter only

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

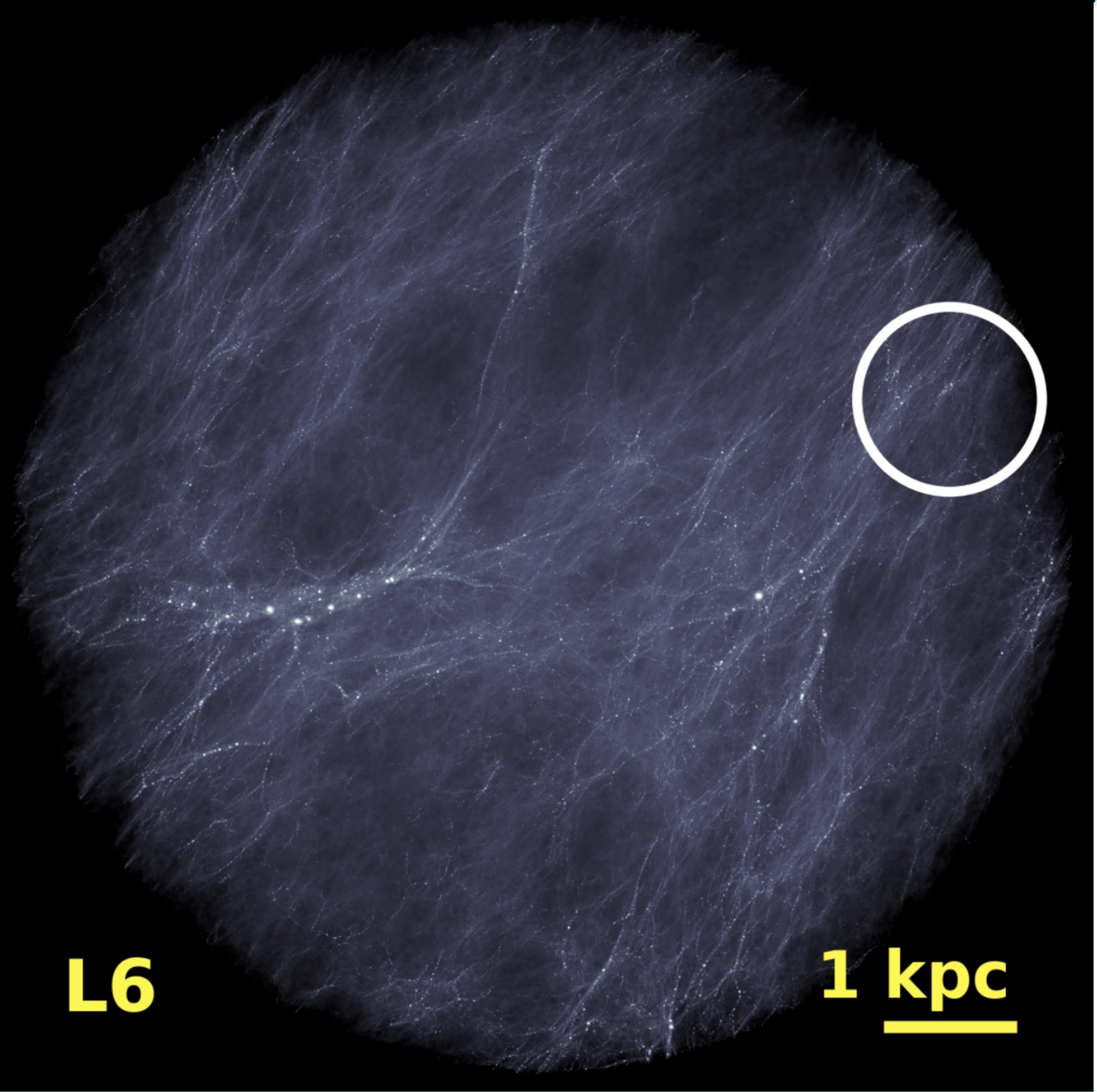
Dark matter only

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

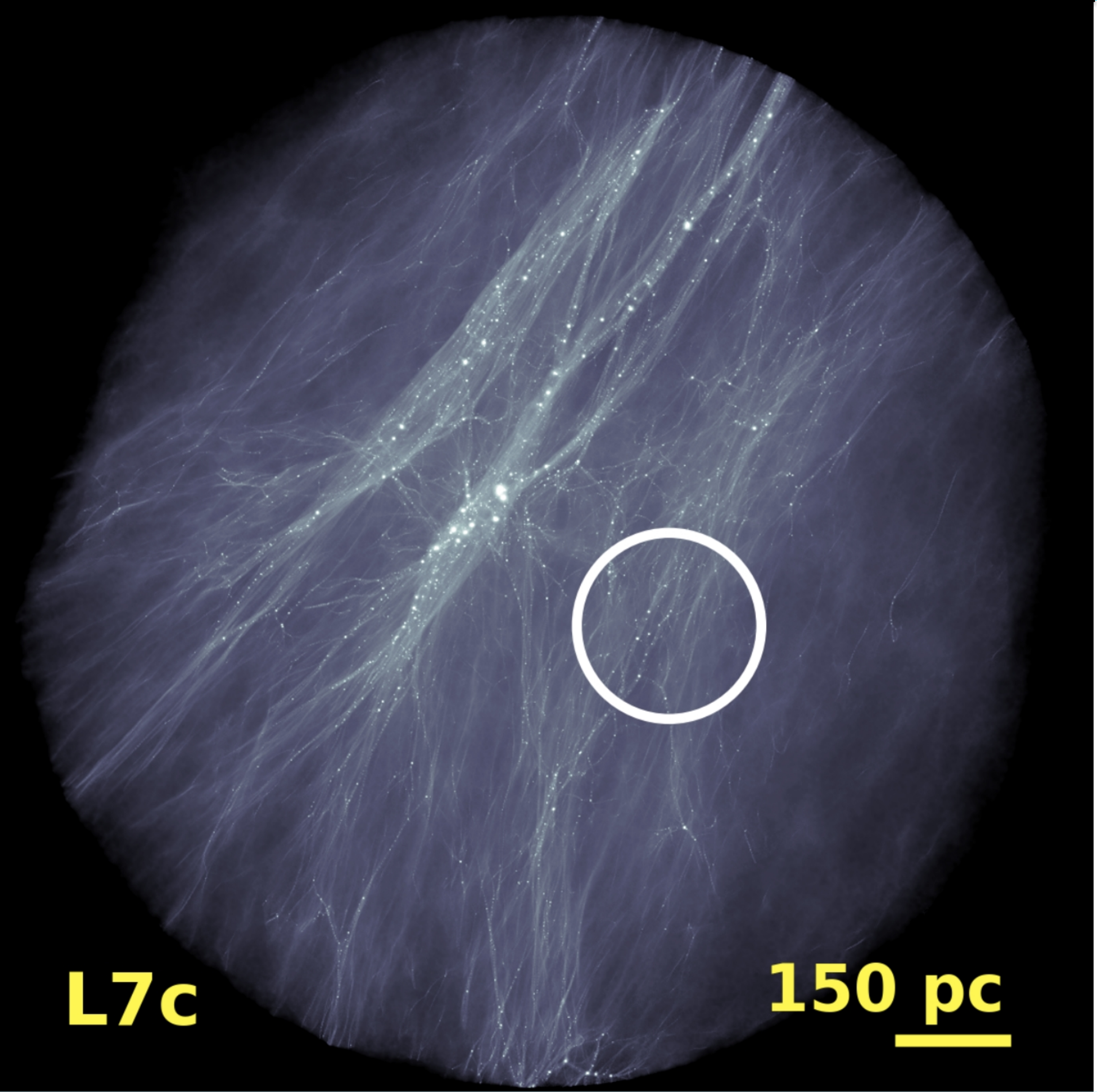
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 6

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

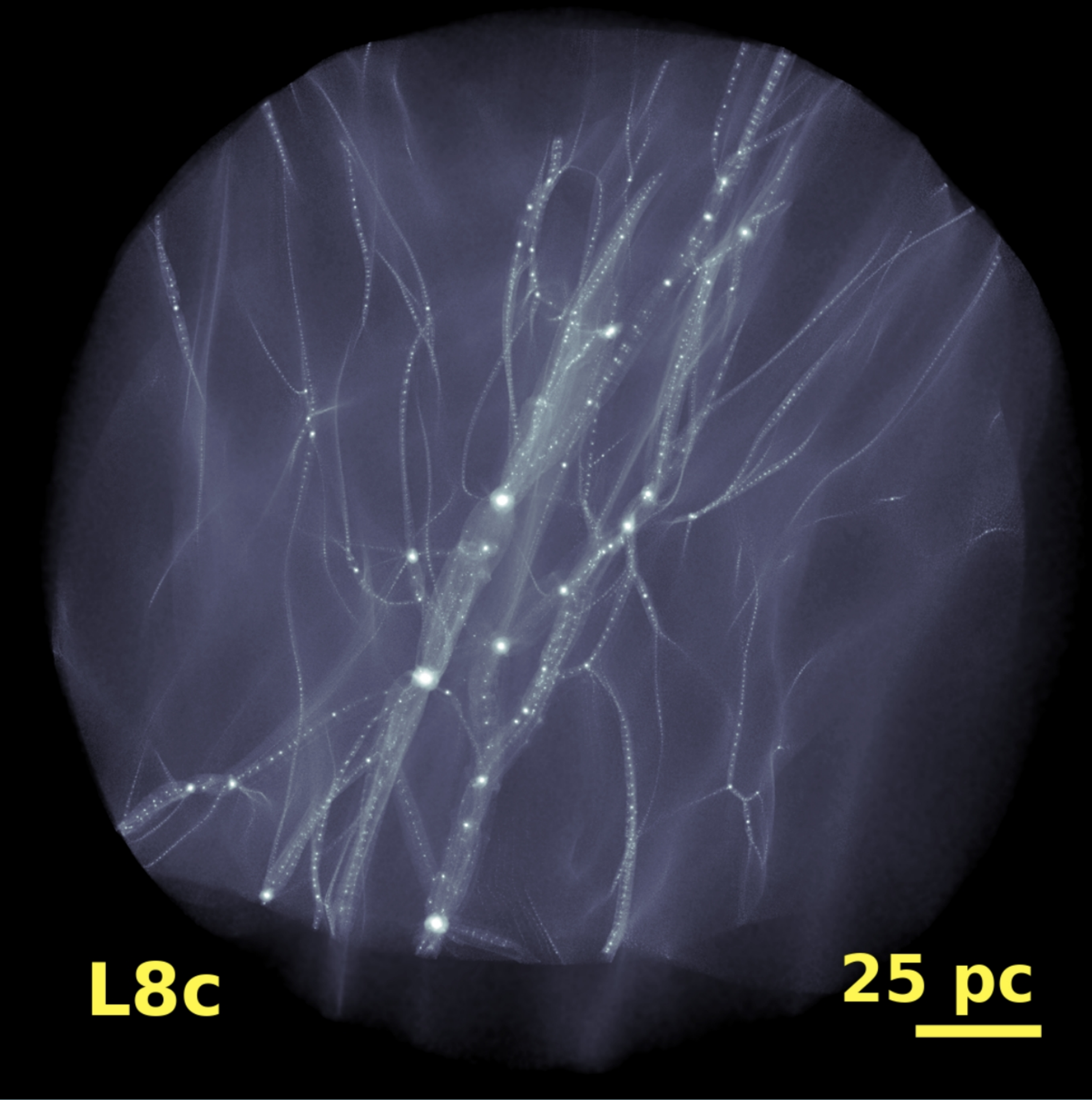
Dark matter only

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

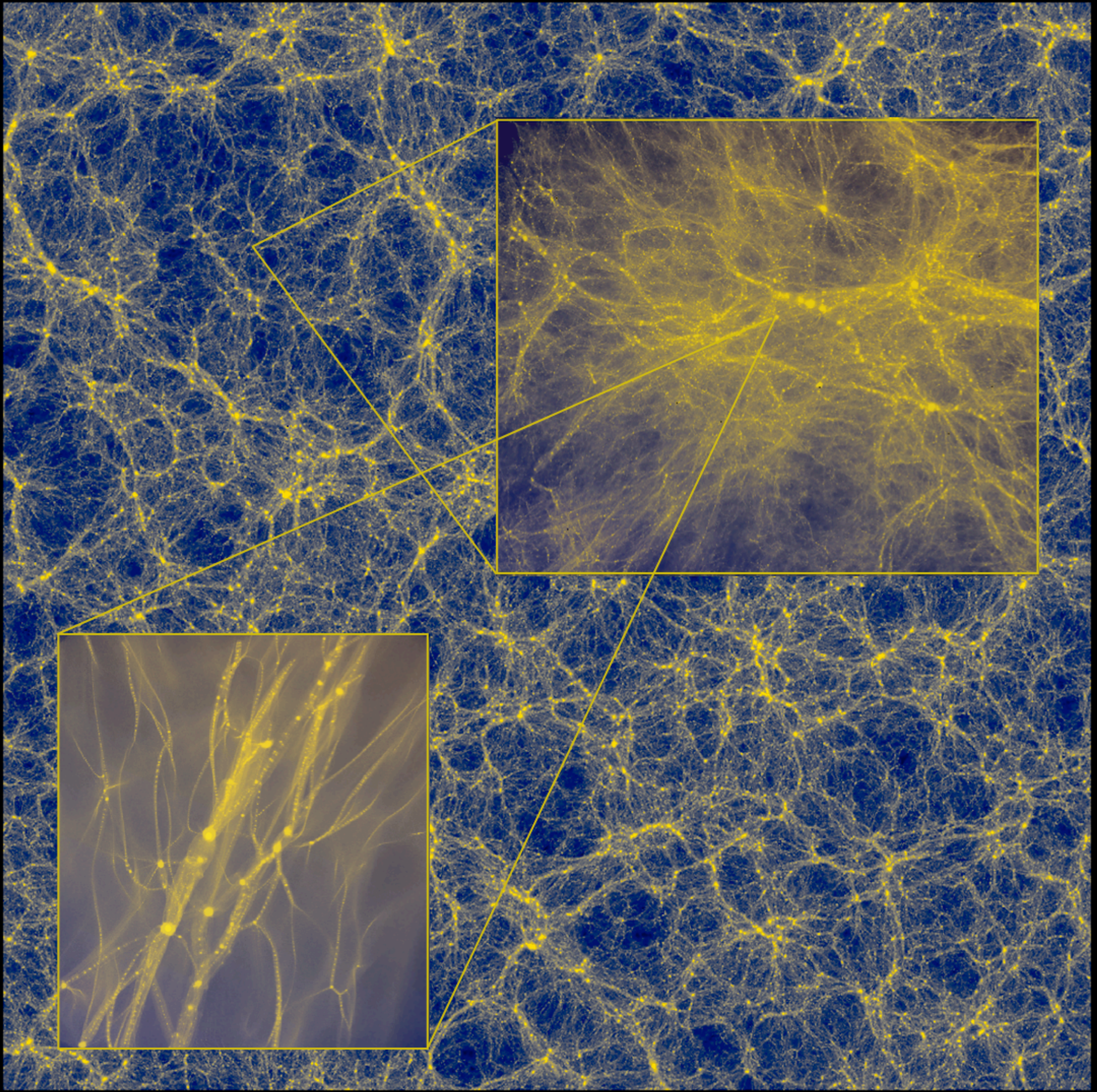
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 8

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

Wang, Bose et al 2020

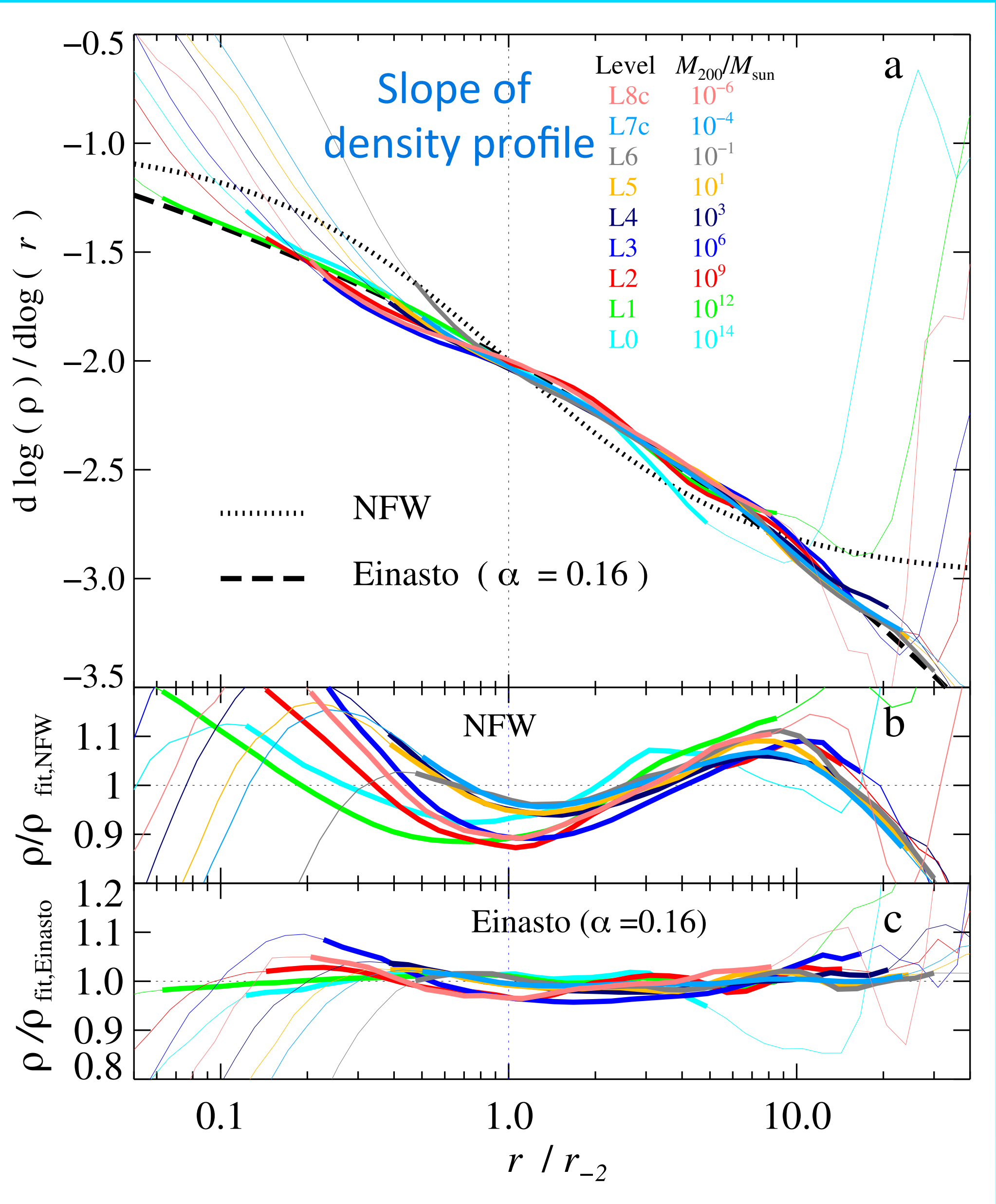


Wang et al ‘20

University of Durham

Density profile shapes

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

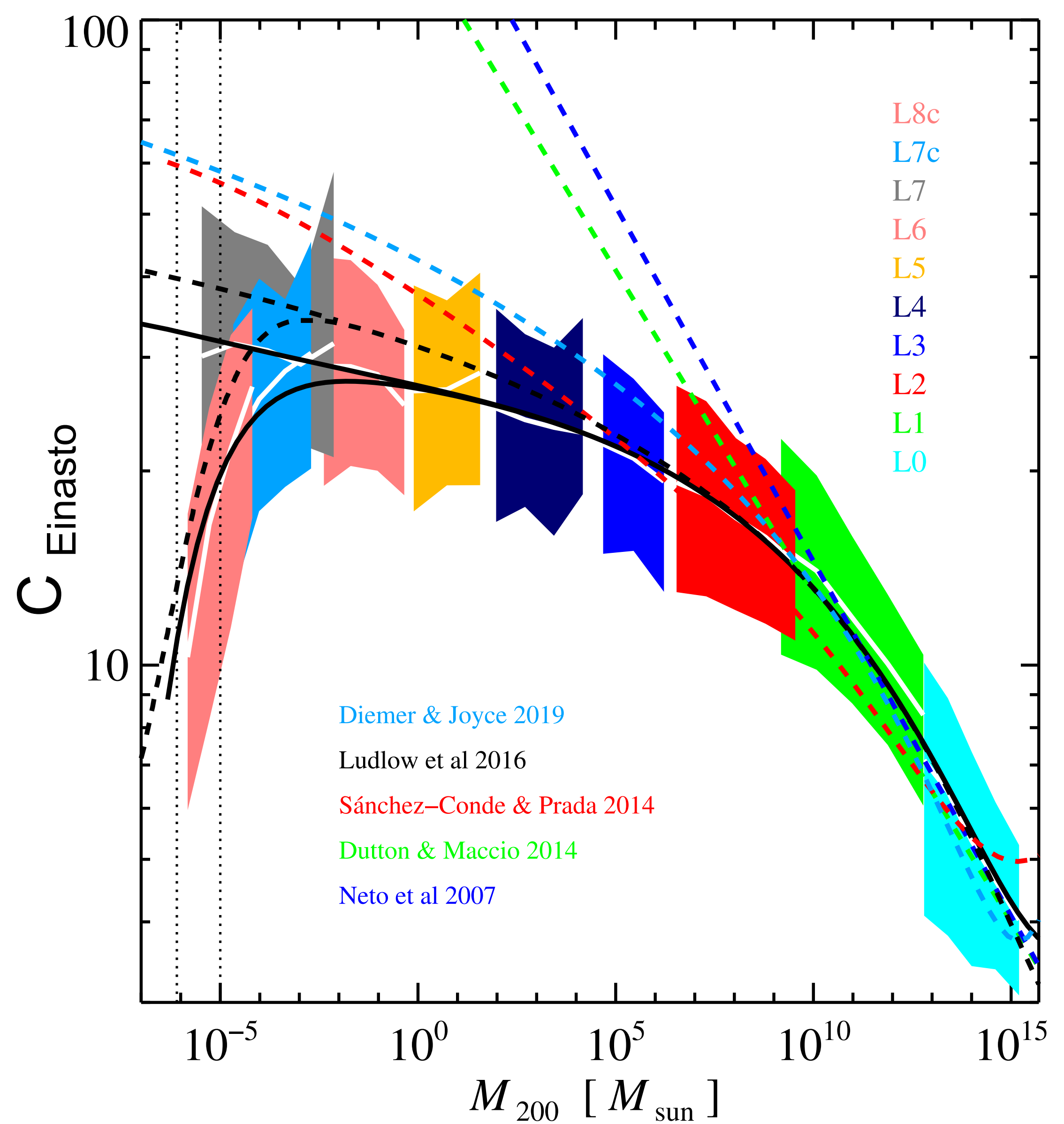
Concentration-mass relation

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



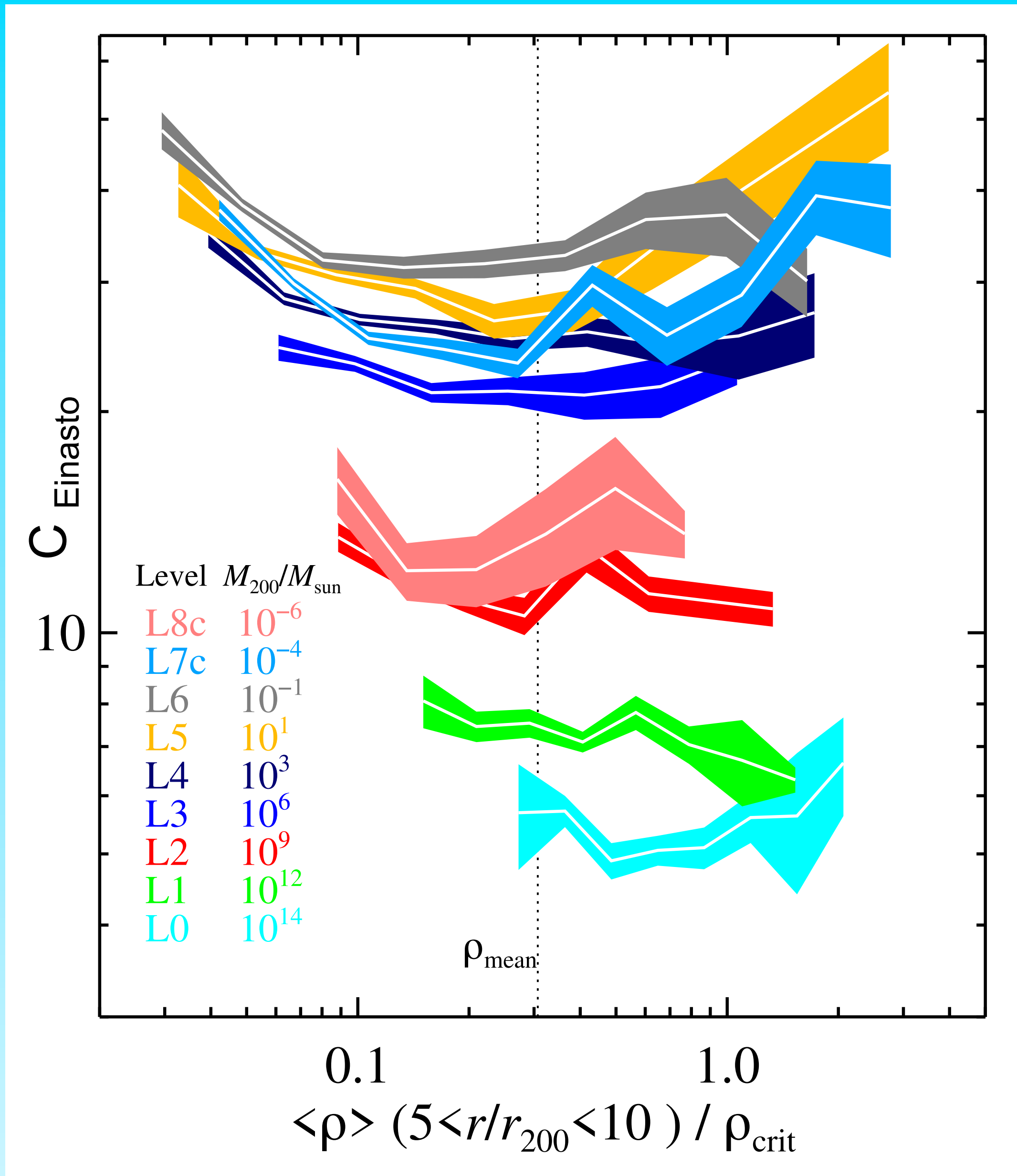
Wang, Bose, CSF + '20

Concentration-density relation

University of Durham

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

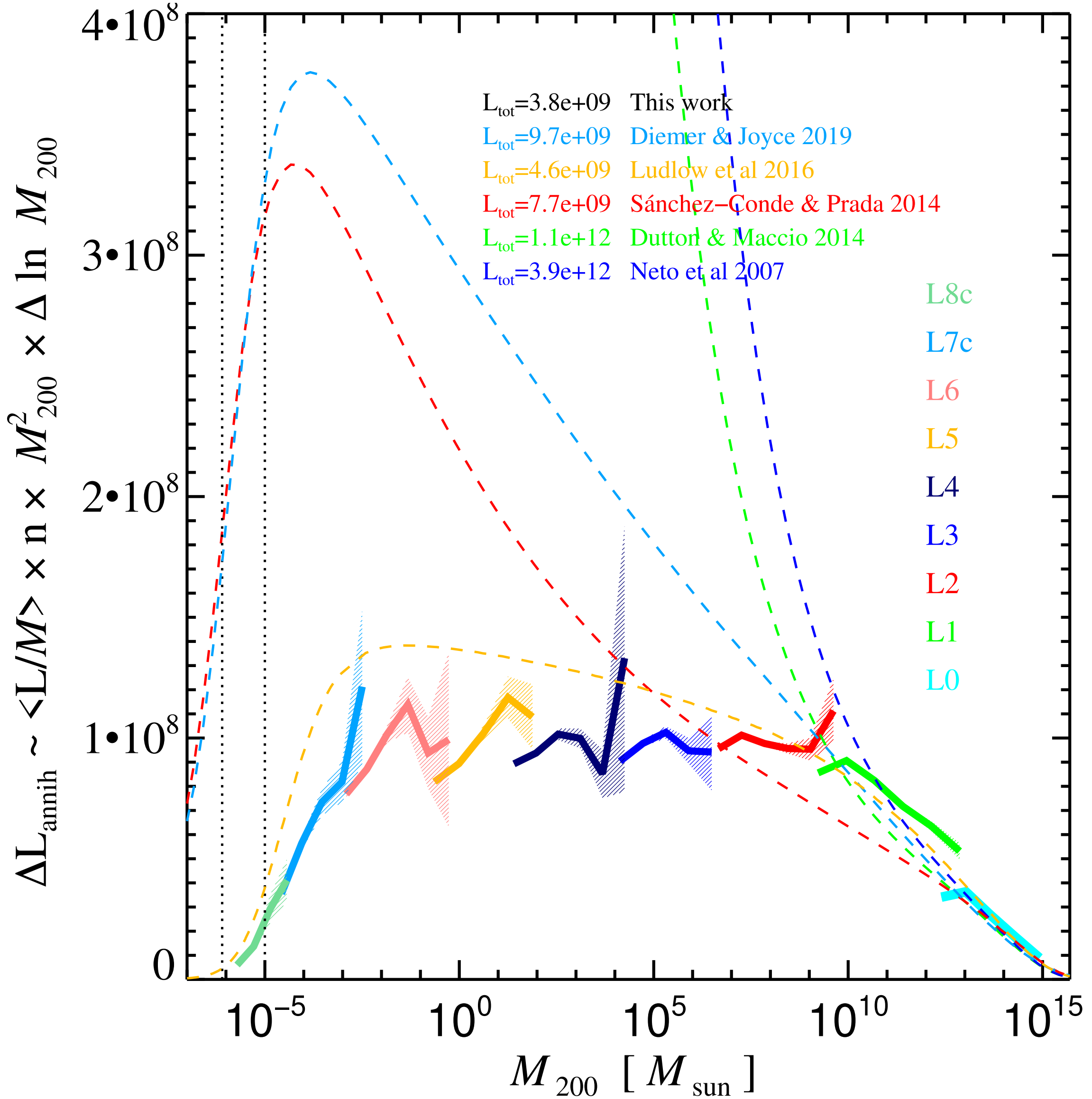
$10^{-4}\,M_\odot < M_{halo} < 10^{12}\,M_\odot$

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 ($\sim 5.10^8 M_0$) 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!
4. Halos of all masses have NFW profiles → annihiln radn

Conclusions II

- Smallest halos: in CDM → Earth mass
- Halos of collisionless dark matter have universal NFW density profiles at low redshift on all mass scales (21 orders of magnitude)
- Near the cutoff free-streaming reduces halo concentration
- Mass-concentration relation independent of local environment
- Very small (sub)halos can dominate the annihilation luminosity