A conclusive test of the cold dark matter model

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

The standard model of cosmology

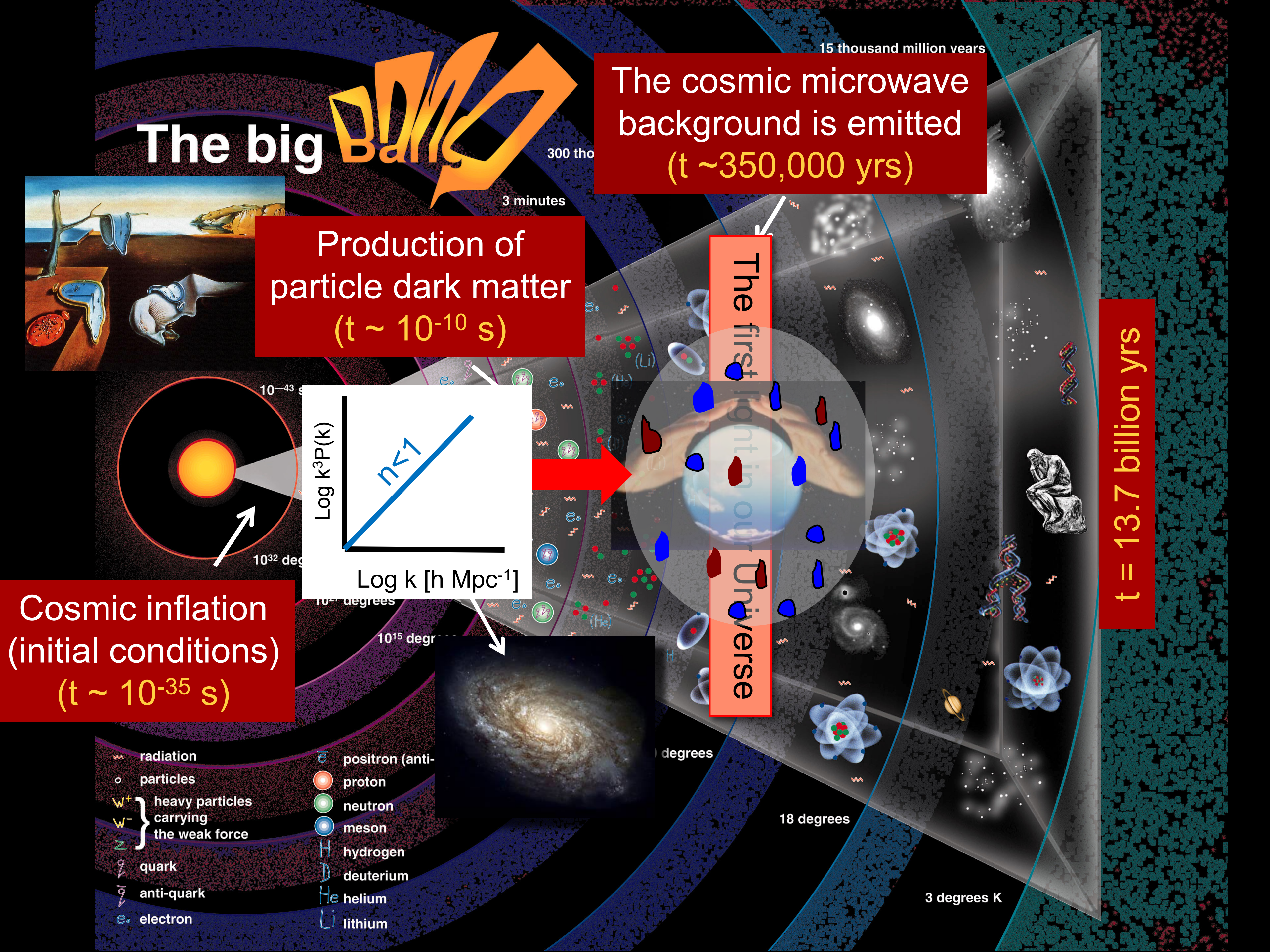
The new Ogden Centre at Durham

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


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} s
Log k^{3}P(k)
n<1
Log k [h Mpc^{-1}]
10^{32} deg
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

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

University of Durham

The dark matter power spectrum

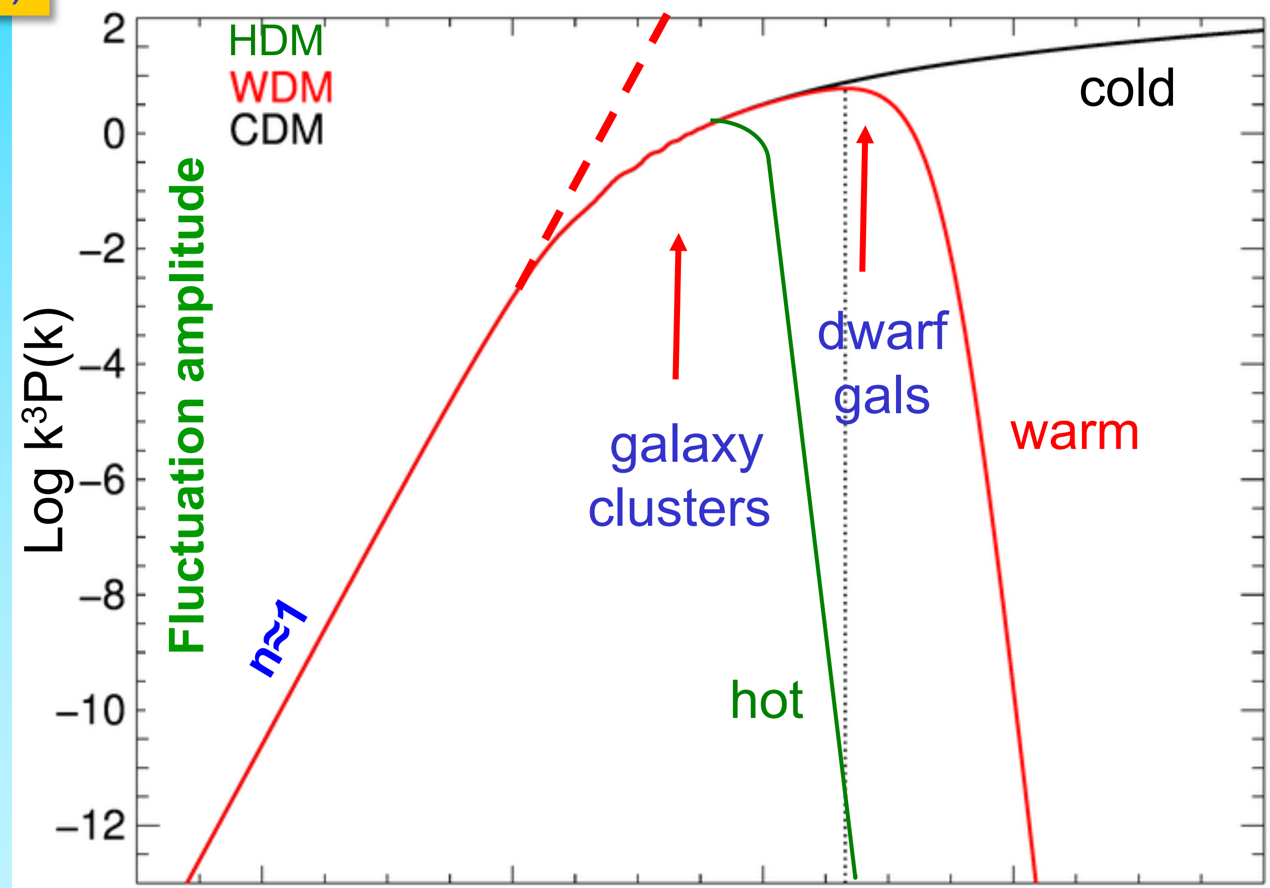
$k^3 P(k)$

Free streaming →

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

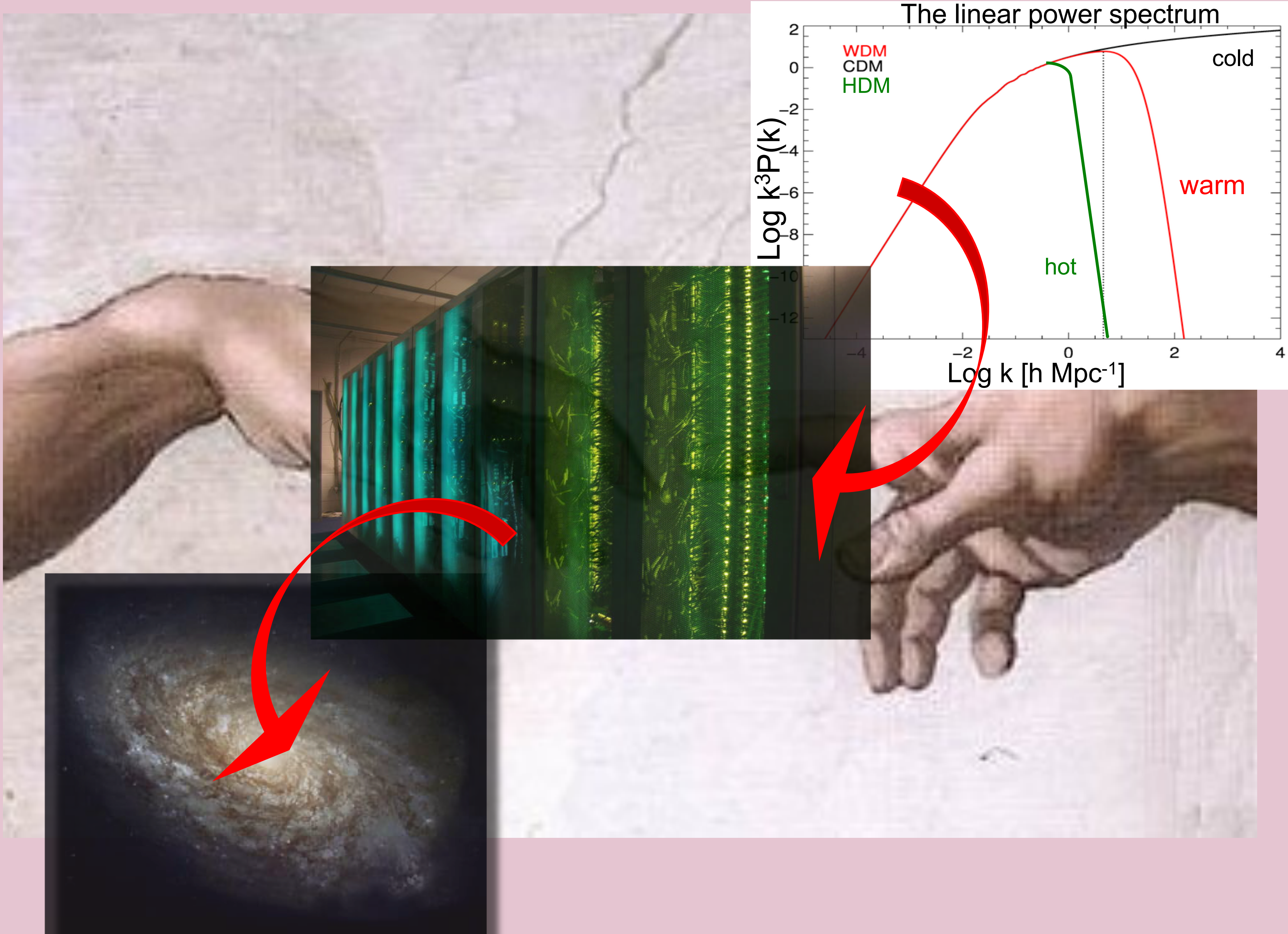
for a thermal relic

The linear power spectrum ("power per octave")



These possibilites can be tested with astrophysics

Non-linear evolution



University of Durham

Non-linear evolution: simulations

Assumption about content of Universe → Initial conditions

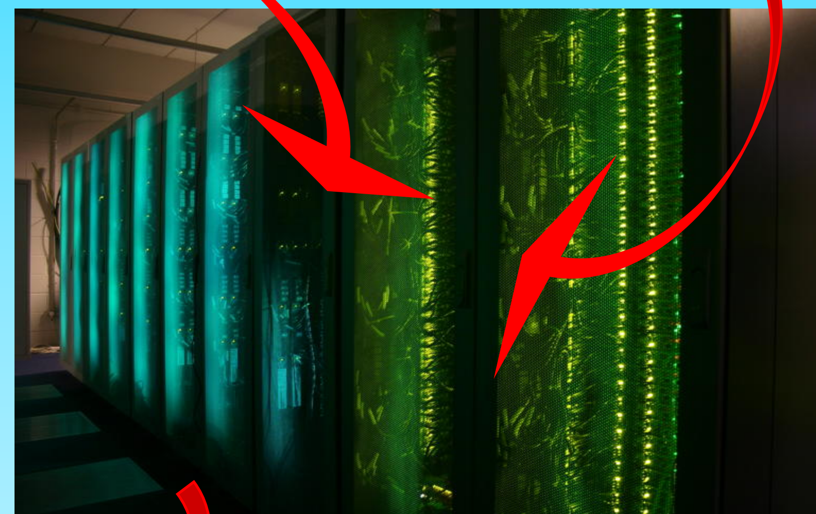
Relevant equations:

Collisionless Boltzmann;

Poisson; Friedmann eqns;

Radiative hydrodynamics

Subgrid astrophysics



How to make a virtual universe

Hot dark matter

$m_\nu = 30$ ev $\rightarrow$ $\Omega_m = 1$

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.

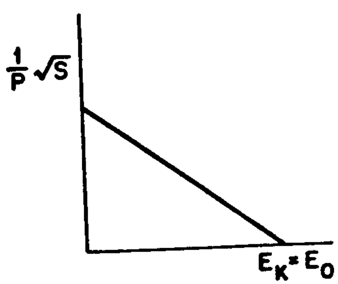


Fig. 1. Kurie plot for $M_\nu = 0$.

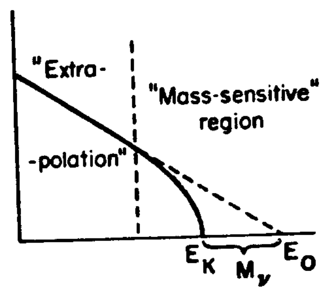
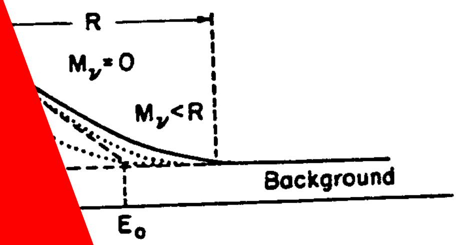


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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-... ...rongly affects the spectrum endpoint and rather ...e spectrum slope.



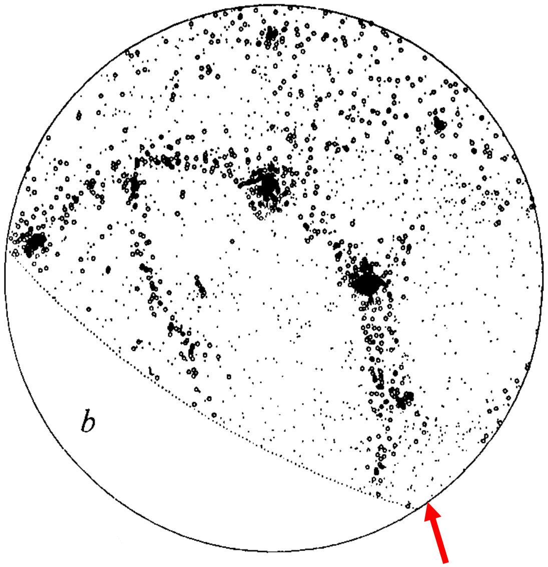
...ealistic Kurie plot.

... 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 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 $R \sim \Delta p/p$ = 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 reso-lution 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 toroi-dal magnetic field (E. Tretyakov, 1973). The principle of the tor-oidal 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.

Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White
& Davis '83

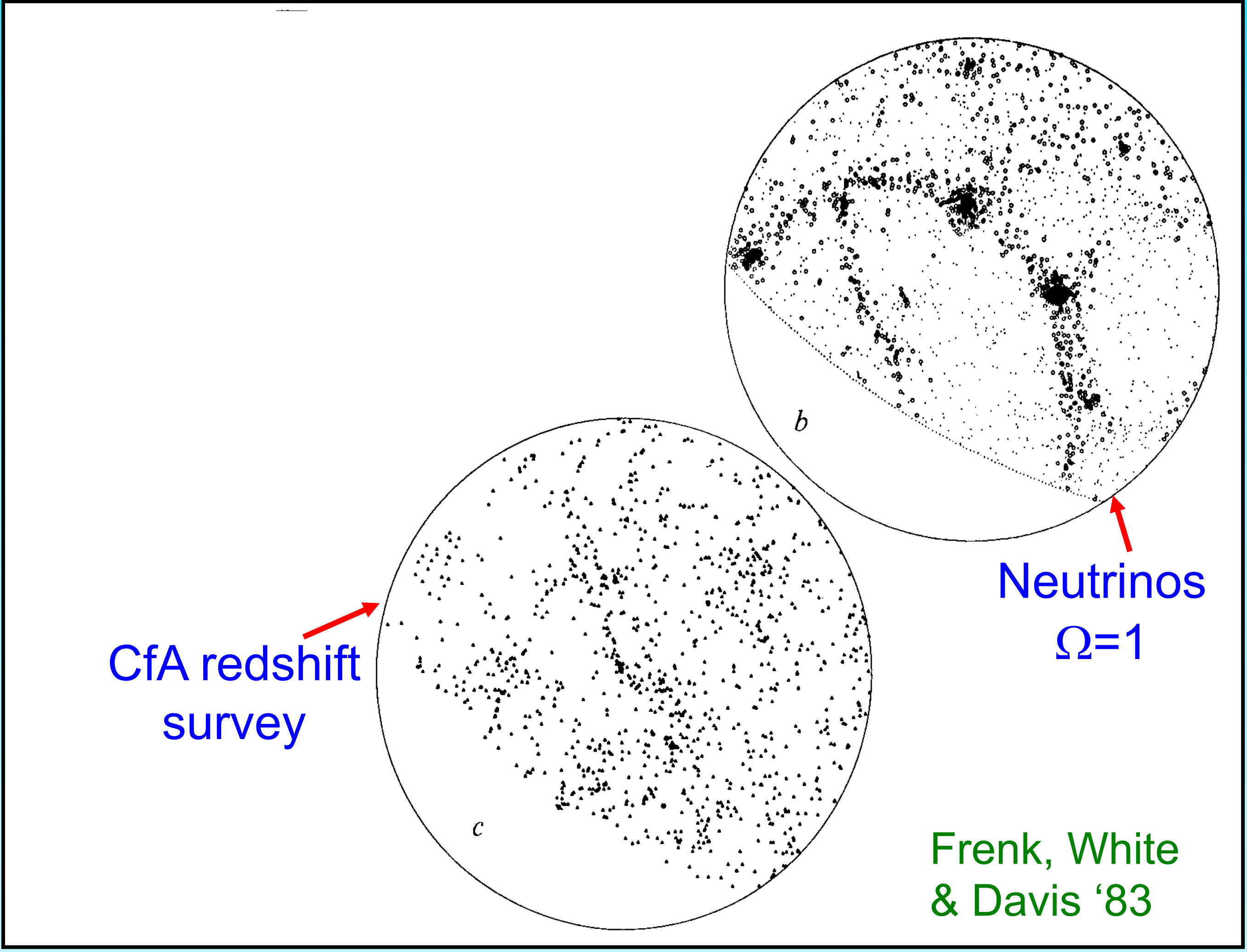
ICC
University of Durham

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev



Non-baryonic dark matter cosmologies

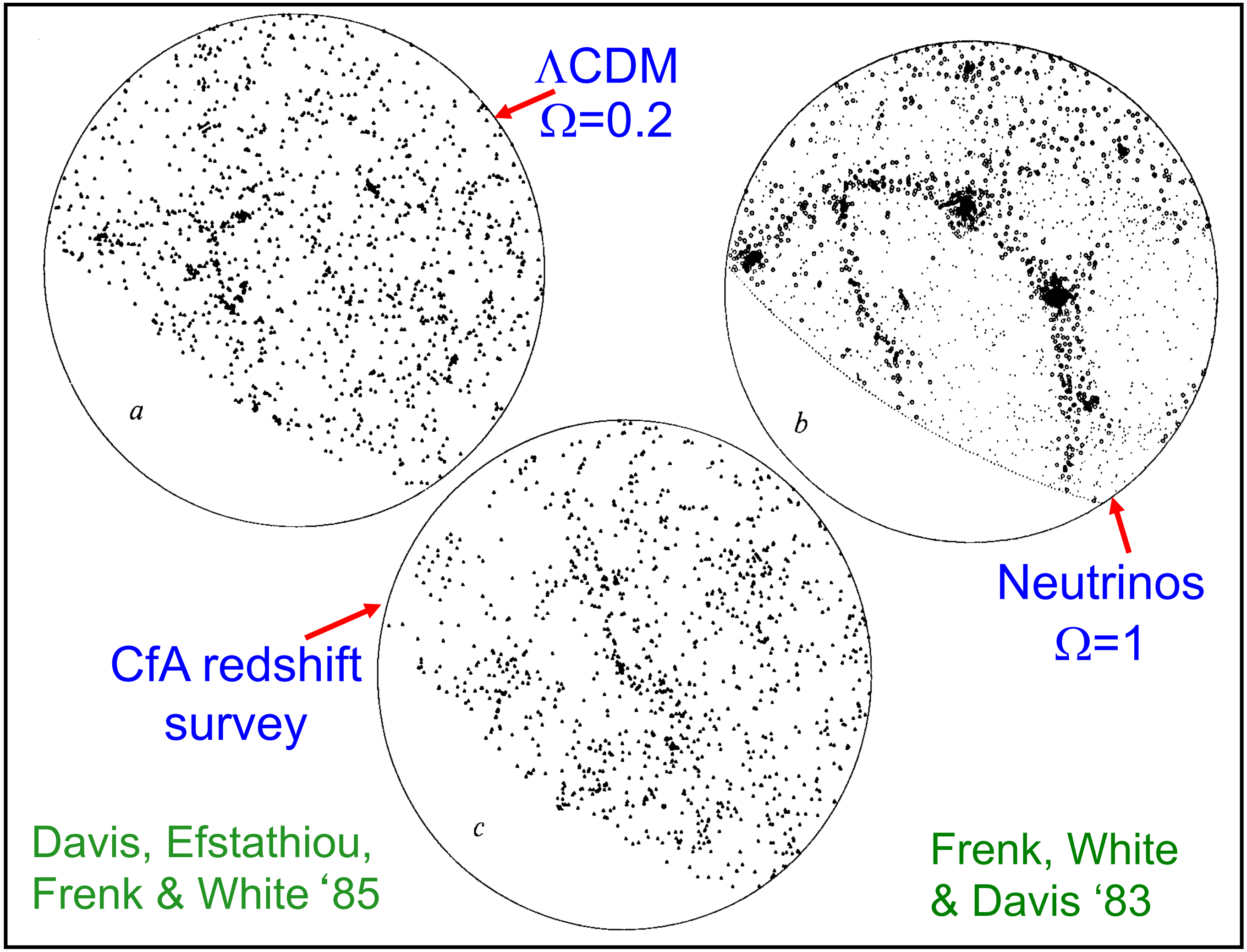
Neutrino DM → wrong clustering

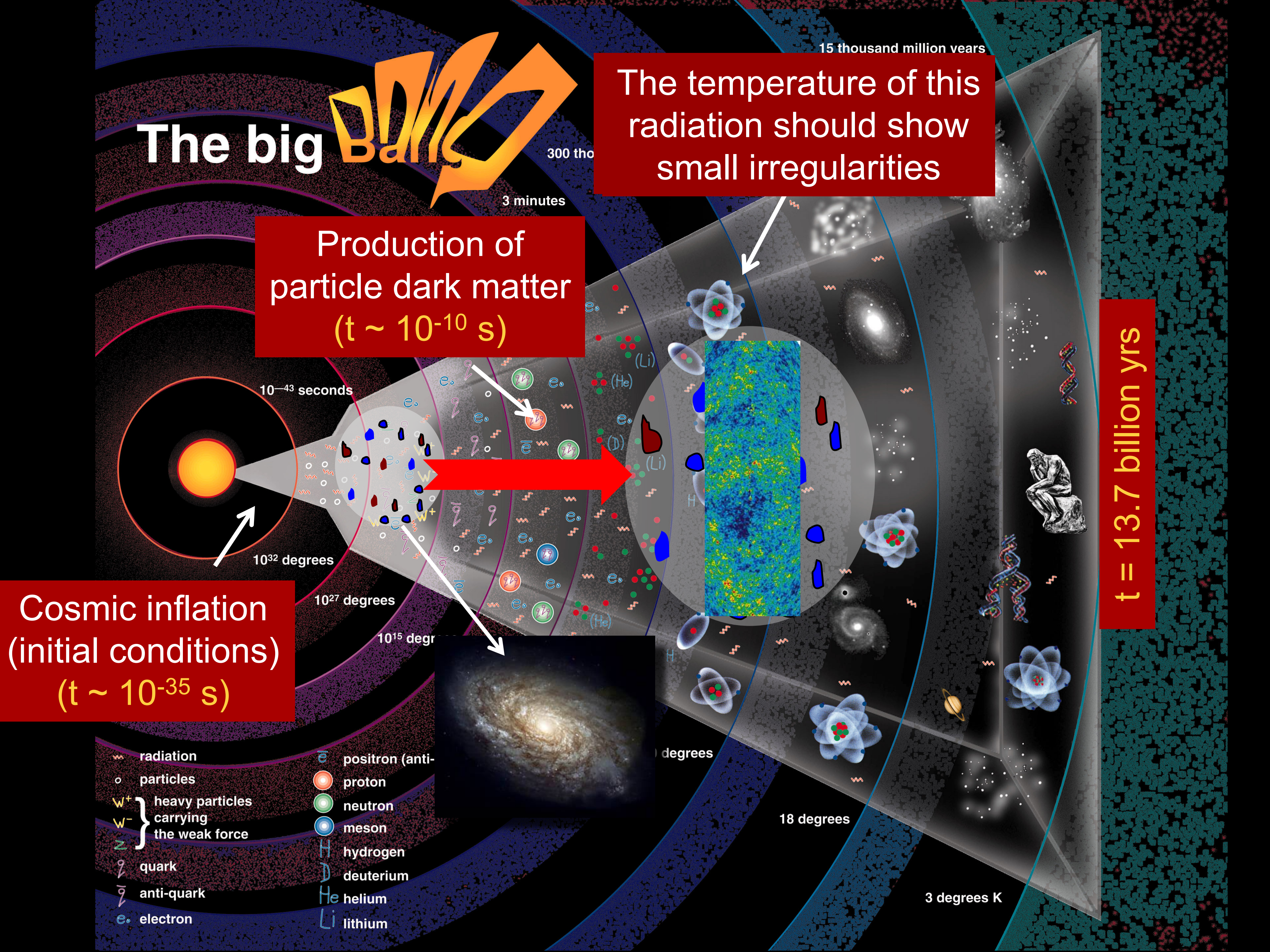
Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



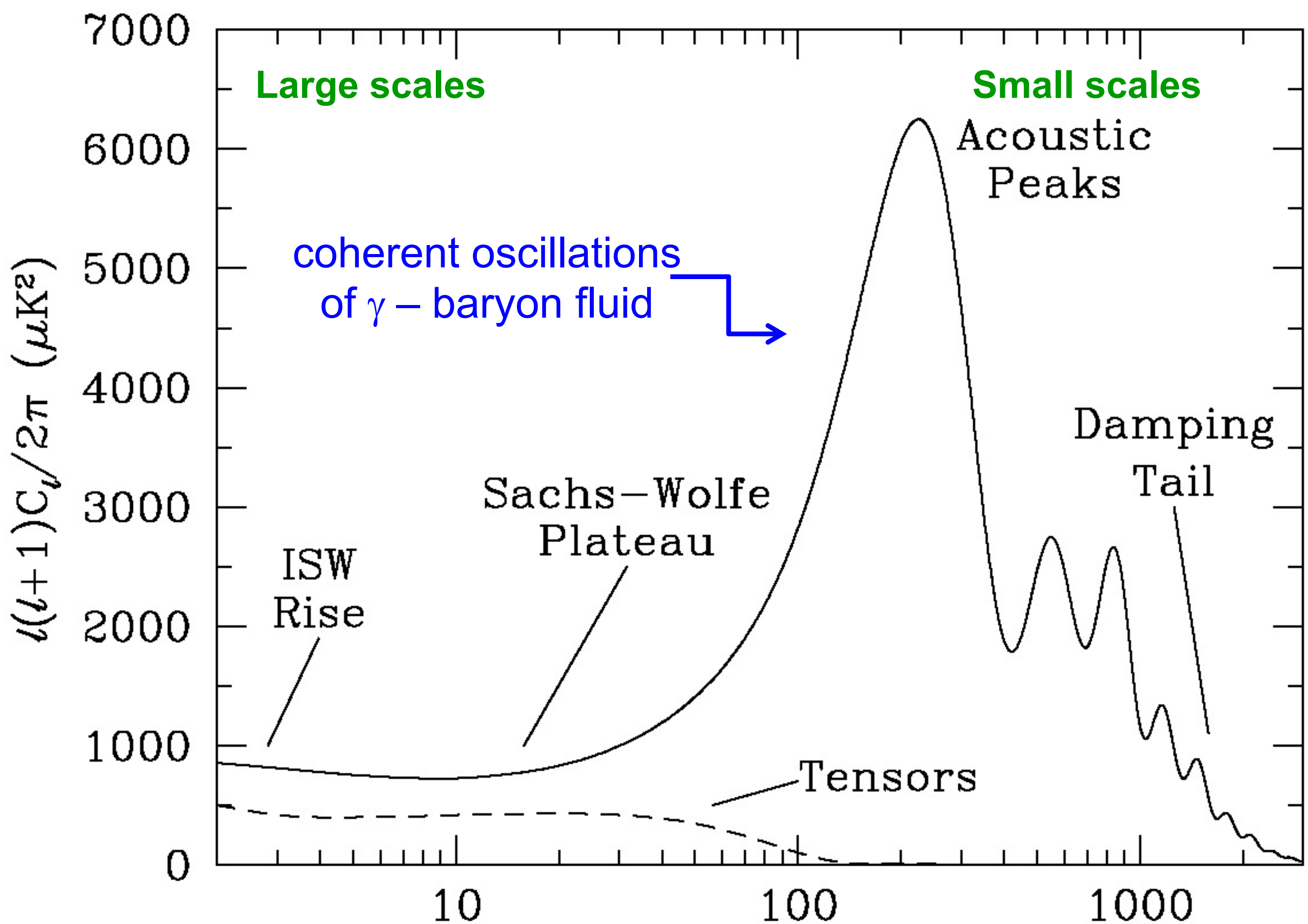


The big Bang
15 thousand million years
300 tho
3 minutes
The temperature of this radiation should show small irregularities
Production of particle dark matter
(t ~ 10^{-10} s)
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degr
Cosmic inflation (initial conditions)
(t ~ 10^{-35} s)
degrees
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

Temperature anisotropies in CMB

University of Durham

2D power spectrum



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

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

Institute for Computational Cosmology

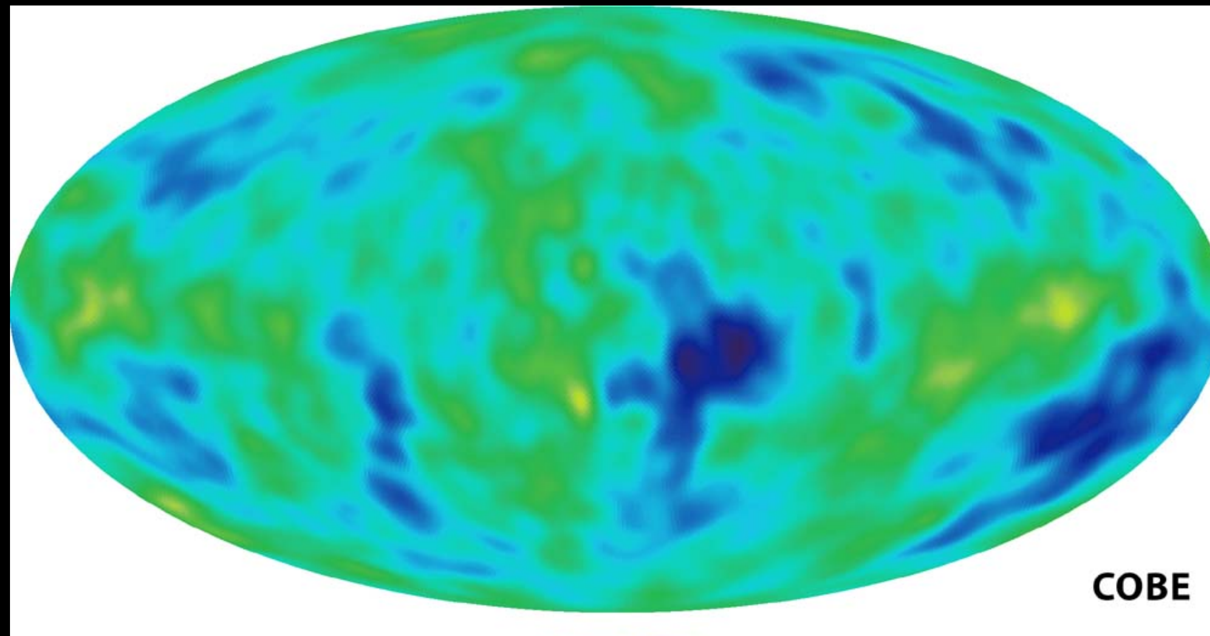
University of Durham

Jim Peebles

Nobel prize 2019

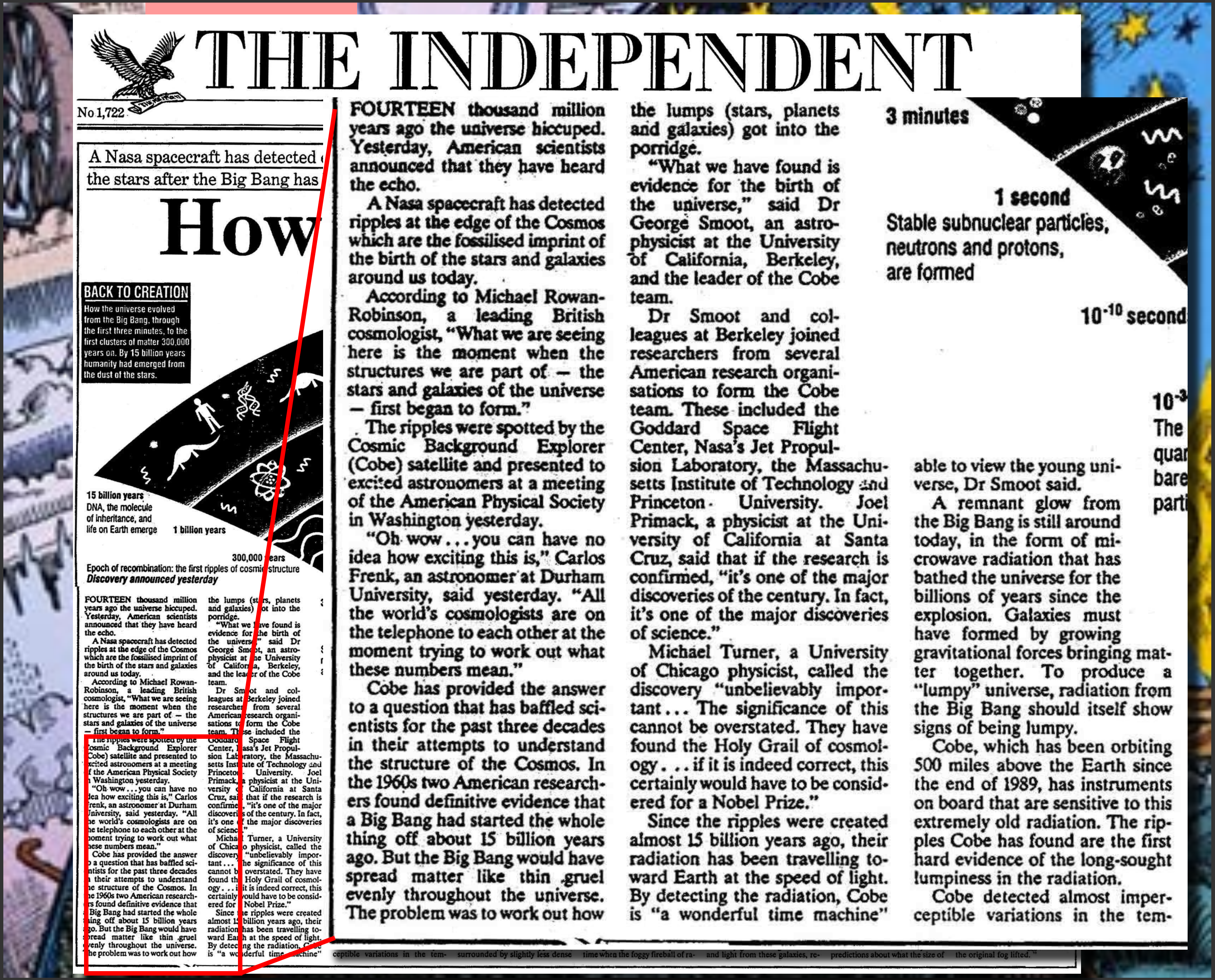
The CMB

1992



The cosmic microwave background radiation (CMB) provides a window to the universe at t~3x10^5 yrs

In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions



THE INDEPENDENT

No 1,722

A Nasa spacecraft has detected
the stars after the Big Bang has

How

BACK TO CREATION

How the universe evolved from the Big Bang, through the first three minutes, to the first clusters of matter 300,000 years on. By 15 billion years humanity had emerged from the dust of the stars.

15 billion years
DNA, the molecule of inheritance, and life on Earth emerge

1 billion years

300,000 years
Epoch of recombination: the first ripples of cosmic structure
Discovery announced yesterday

3 minutes

1 second
Stable subnuclear particles, neutrons and protons, are formed

10^{-10} second

FOURTEEN thousand million years ago the universe hiccuped. Yesterday, American scientists announced that they have heard the echo.

A Nasa spacecraft has detected ripples at the edge of the Cosmos which are the fossilised imprint of the birth of the stars and galaxies around us today.

According to Michael Rowan-Robinson, a leading British cosmologist, "What we are seeing here is the moment when the structures we are part of — the stars and galaxies of the universe — first began to form."

The ripples were spotted by the Cosmic Background Explorer (Cobe) satellite and presented to excited astronomers at a meeting of the American Physical Society in Washington yesterday.

"Oh wow . . . you can have no idea how exciting this is," Carlos Frenk, an astronomer at Durham University, said yesterday. "All the world's cosmologists are on the telephone to each other at the moment trying to work out what these numbers mean."

Cobe has provided the answer to a question that has baffled scientists for the past three decades in their attempts to understand the structure of the Cosmos. In the 1960s two American researchers found definitive evidence that a Big Bang had started the whole thing off about 15 billion years ago. But the Big Bang would have spread matter like thin gruel evenly throughout the universe. The problem was to work out how the lumps (stars, planets and galaxies) got into the porridge.

"What we have found is evidence for the birth of the universe," said Dr George Smoot, an astrophysicist at the University of California, Berkeley, and the leader of the Cobe team.

Dr Smoot and colleagues at Berkeley joined researchers from several American research organisations to form the Cobe team. These included the Goddard Space Flight Center, Nasa's Jet Propulsion Laboratory, the Massachusetts Institute of Technology and Princeton University. Joel Primack, a physicist at the University of California at Santa Cruz, said that if the research is confirmed, "it's one of the major discoveries of the century. In fact, it's one of the major discoveries of science."

Michael Turner, a University of Chicago physicist, called the discovery "unbelievably important . . . The significance of this cannot be overstated. They have found the Holy Grail of cosmology . . . if it is indeed correct, this certainly would have to be considered for a Nobel Prize."

Since the ripples were created almost 15 billion years ago, their radiation has been travelling toward Earth at the speed of light. By detecting the radiation, Cobe is "a wonderful time machine" able to view the young universe, Dr Smoot said.

A remnant glow from the Big Bang is still around today, in the form of microwave radiation that has bathed the universe for the billions of years since the explosion. Galaxies must have formed by growing gravitational forces bringing matter together. To produce a "lumpy" universe, radiation from the Big Bang should itself show signs of being lumpy.

Cobe, which has been orbiting 500 miles above the Earth since the end of 1989, has instruments on board that are sensitive to this extremely old radiation. The ripples Cobe has found are the first hard evidence of the long-sought lumpiness in the radiation.

Cobe detected almost imperceptible variations in the tem-

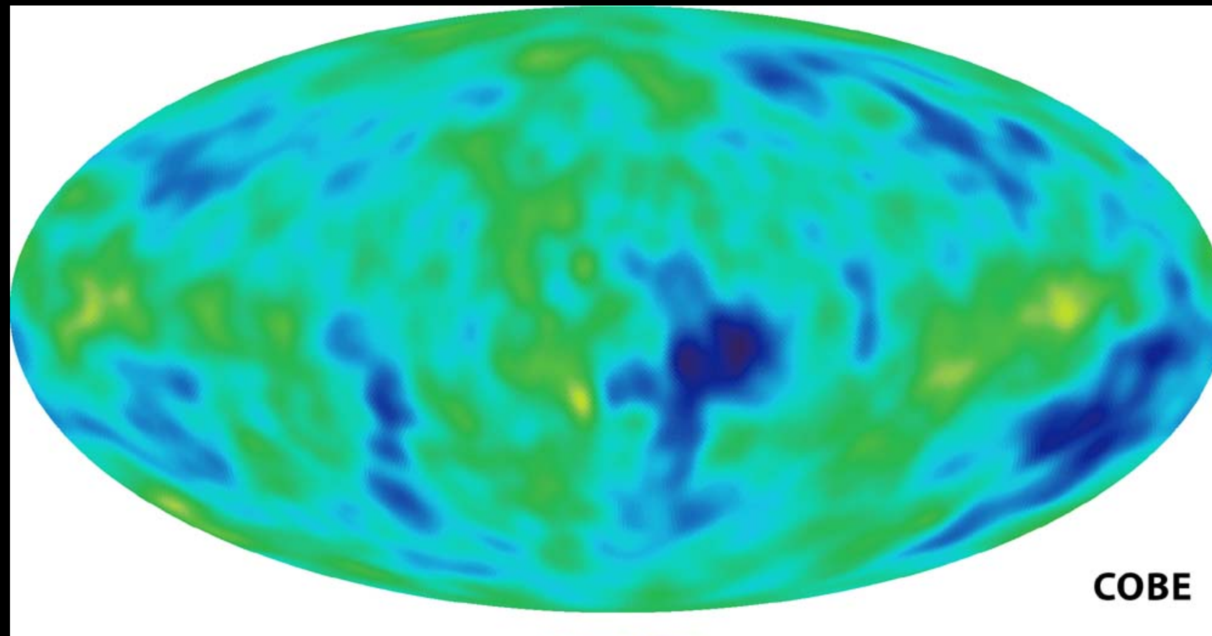
ceptible variations in the tem- … surrounded by slightly less dense … time when the foggy fireball of ra- … and light from these galaxies, re- … predictions about what the size of … the original fog lifted."

Flammarion 1888: tete des etoiles

ICC

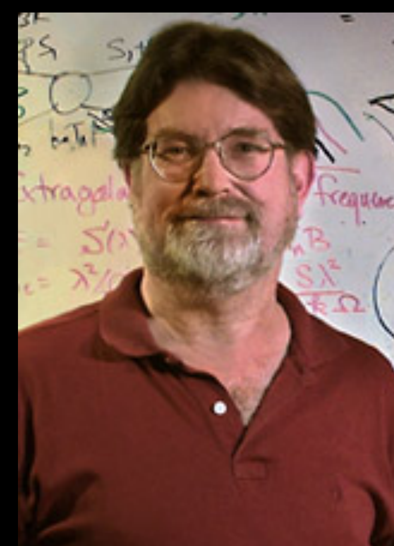
The CMB

1992



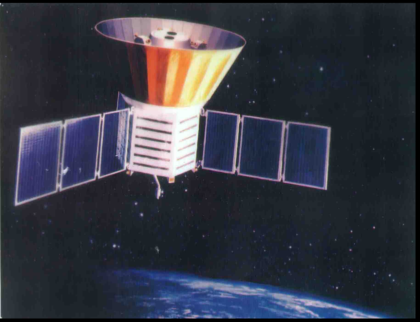
George Smoot - Nobel Prize 2006

KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

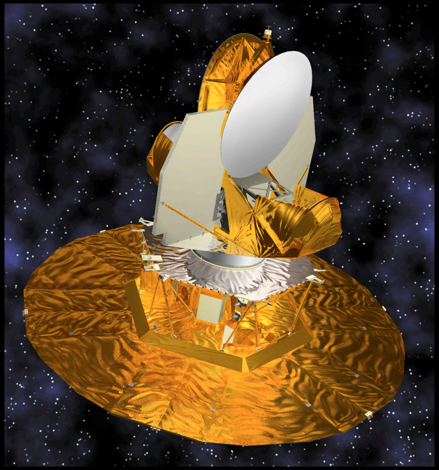


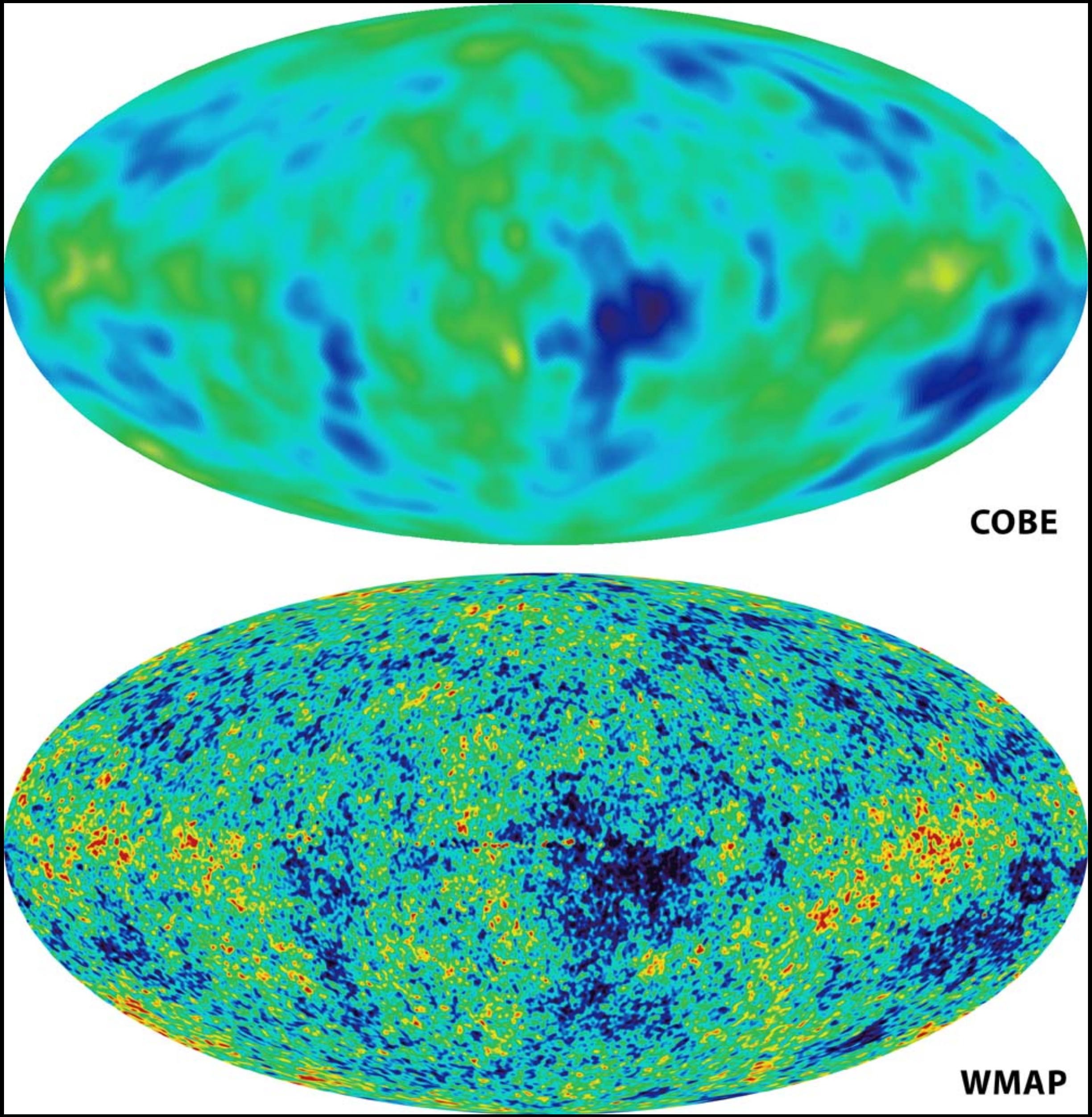
The CMB

1992



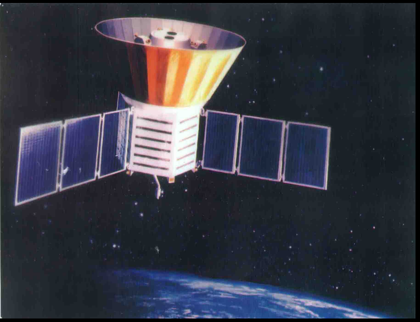
2003



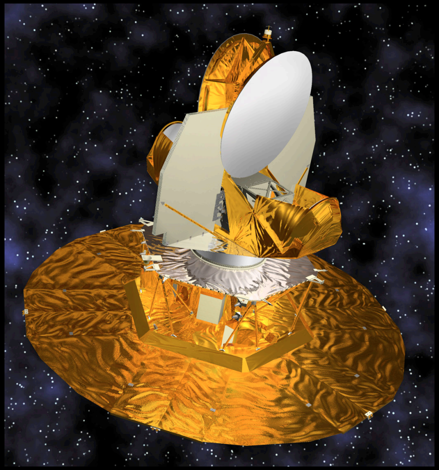


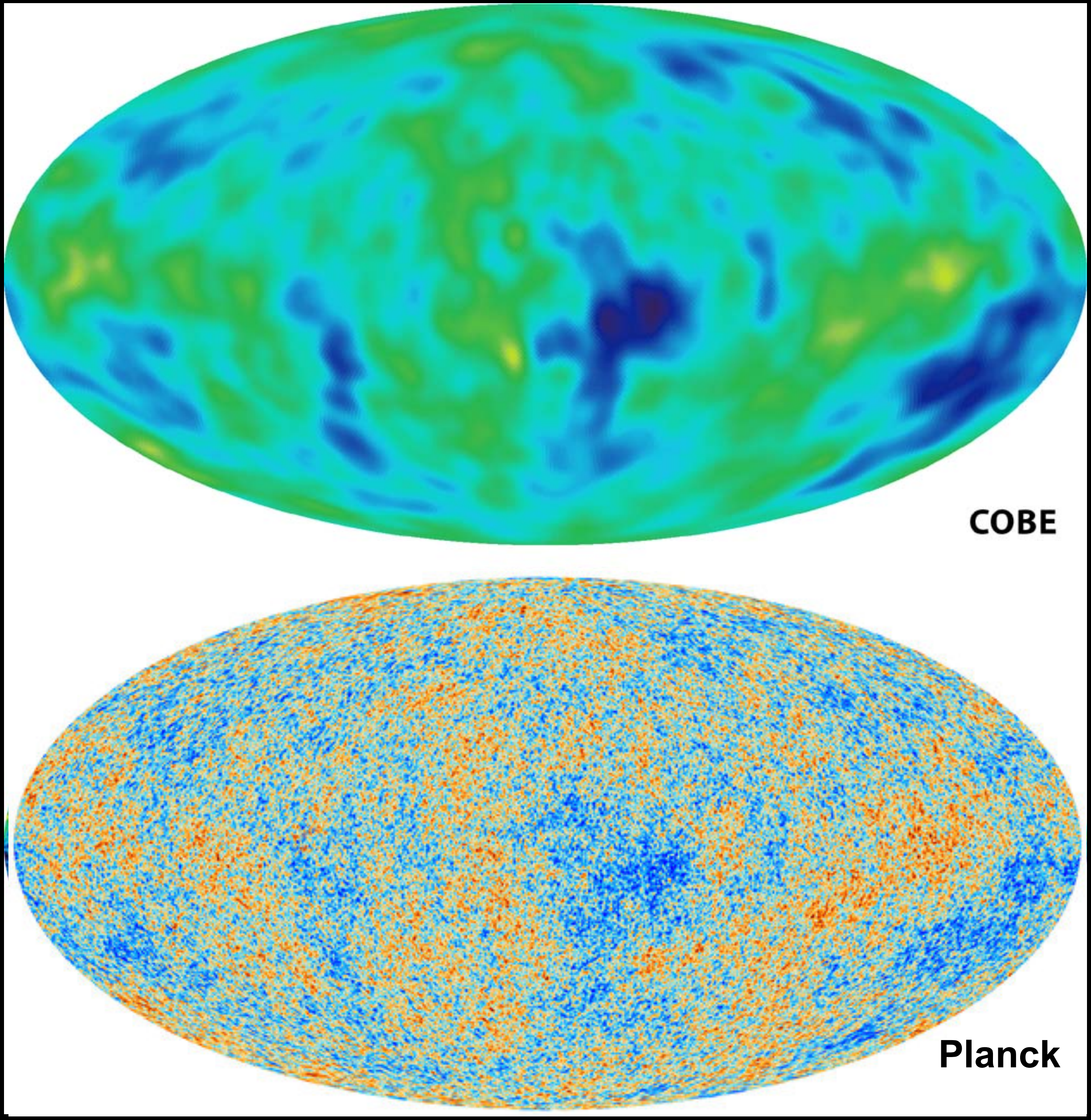
The CMB

1992



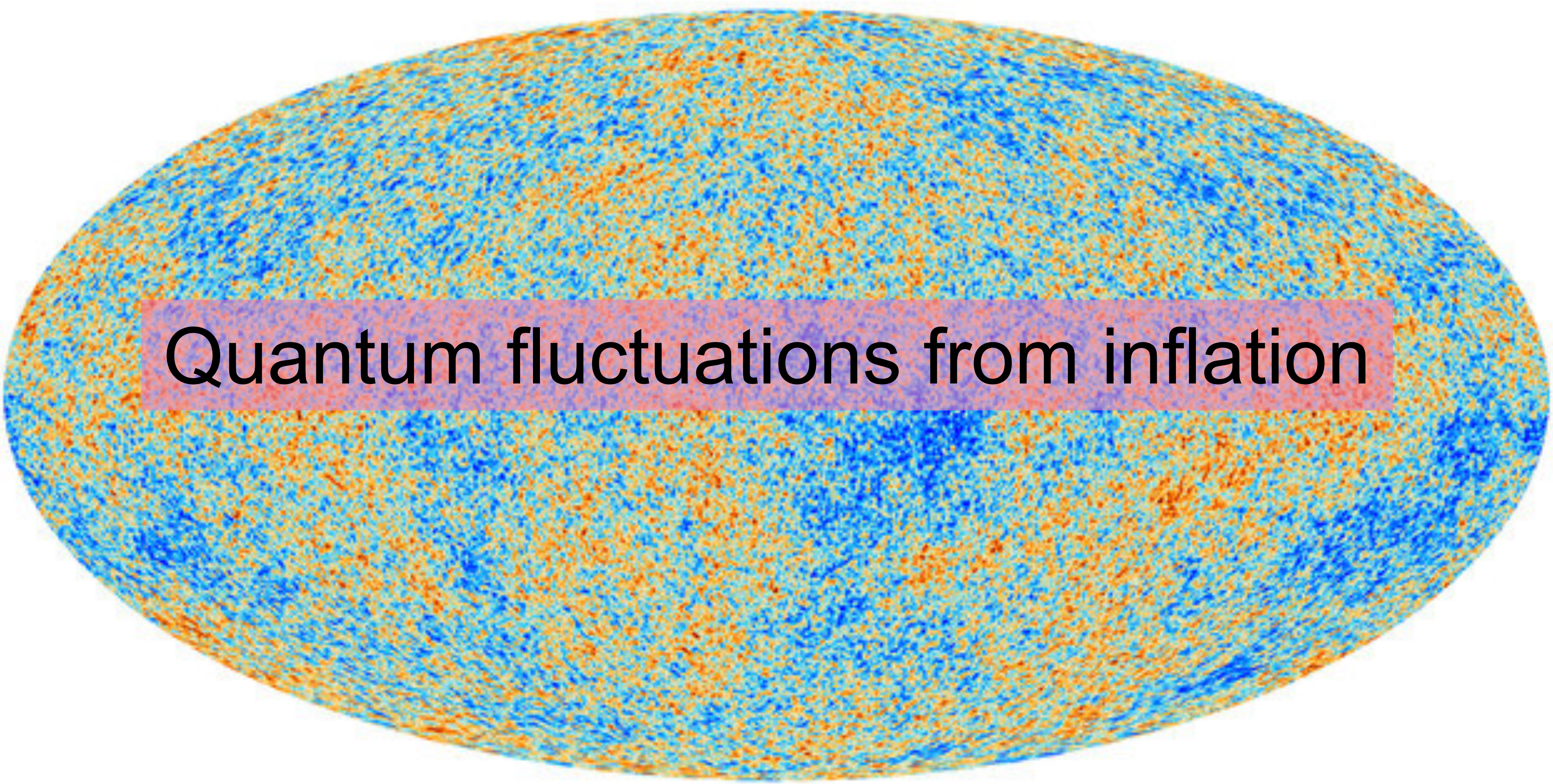
2012





University of Durham

The initial conditions for galaxy formation

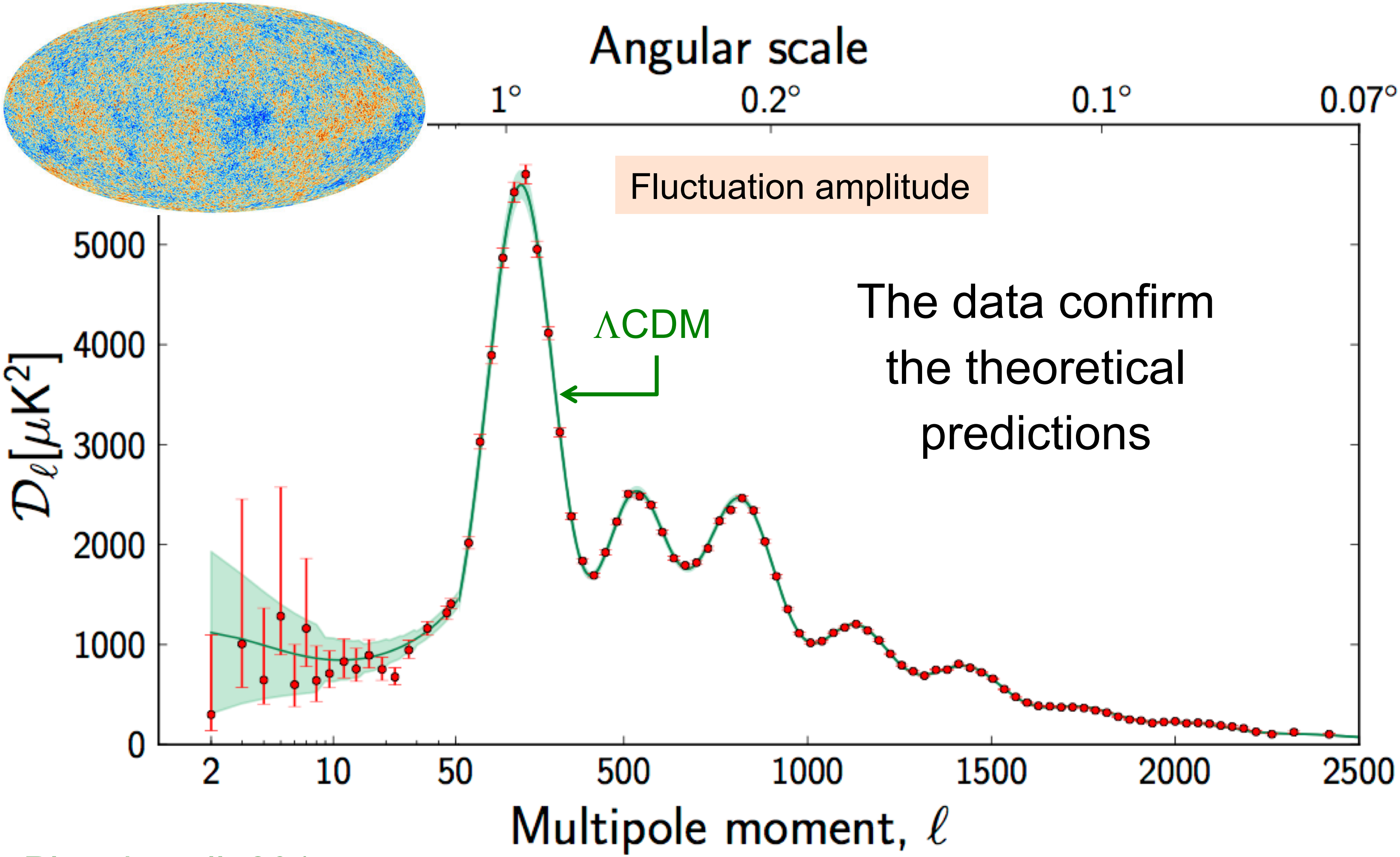


Planck collaboration ‘13

Institute for Computational Cosmology

Planck: CMB temperature anisotropies

University of Durham



Planck coll. 2015

The six parameters of minimal ΛCDM model

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!

Planck collaboration '13

$\Omega_{tot} = 1$

Institute for Computational Cosmology

The curvature of the Universe

The Planck power spectra (temperature and polarization) (positions of acoustic peaks) → the Universe is spatially flat

Combined with LSS data, Planck → $\Omega_\kappa = 0.0004 \pm 0.0018$

→ $\Omega_{tot} = \Omega_m + \Omega_\Lambda + \Omega_k = 1$

Since $\Omega_{matter} = 0.28 \pm 0.005$ ➡ "dark energy", e.g. $\Omega_\Lambda = 0.72$

Λ anticipated from galaxy distribution in 1991;

inferred from accelerated expansion → 2011 Nobel prize

University of Durham

Observational tests of ΛCDM

Fundamental prediction of ΛCDM

→ Primordial PS of density perturbations + random phases

Can test this in two regimes:

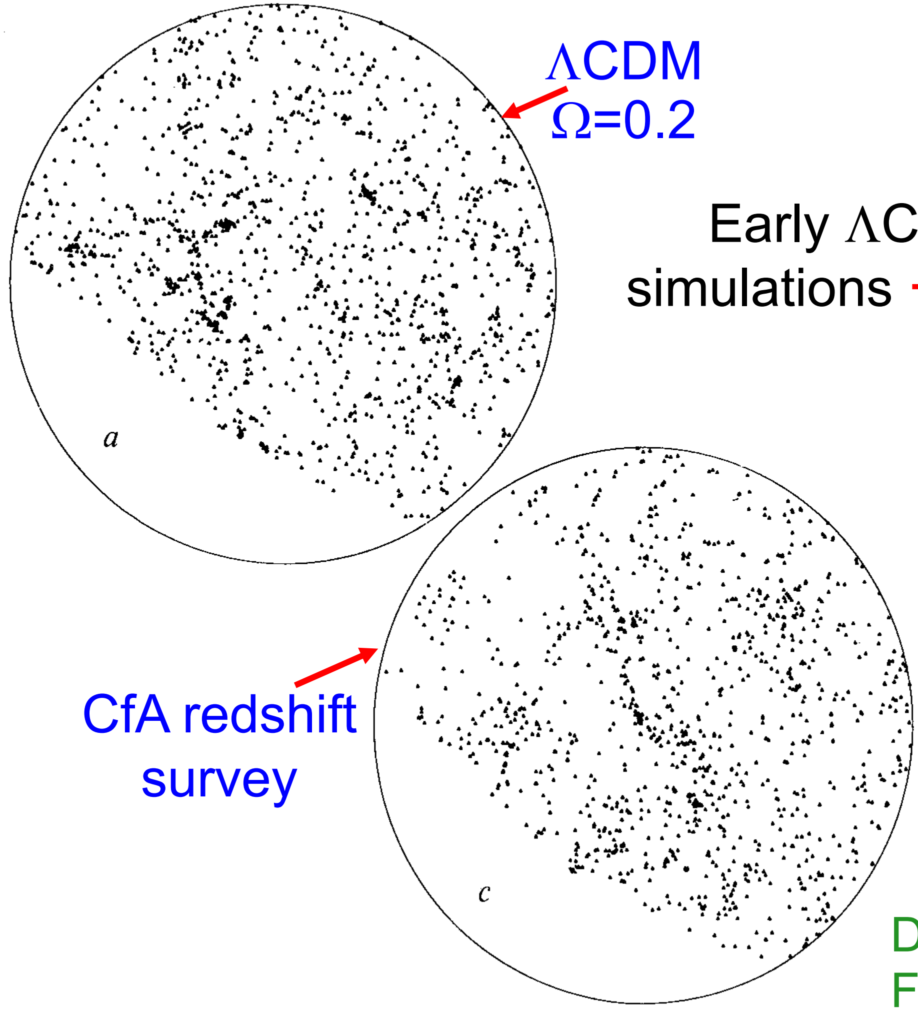
Linear regime: cosmic microwave background ✔

large-scale structure

Evolved non-linear regime: dark matter halos →

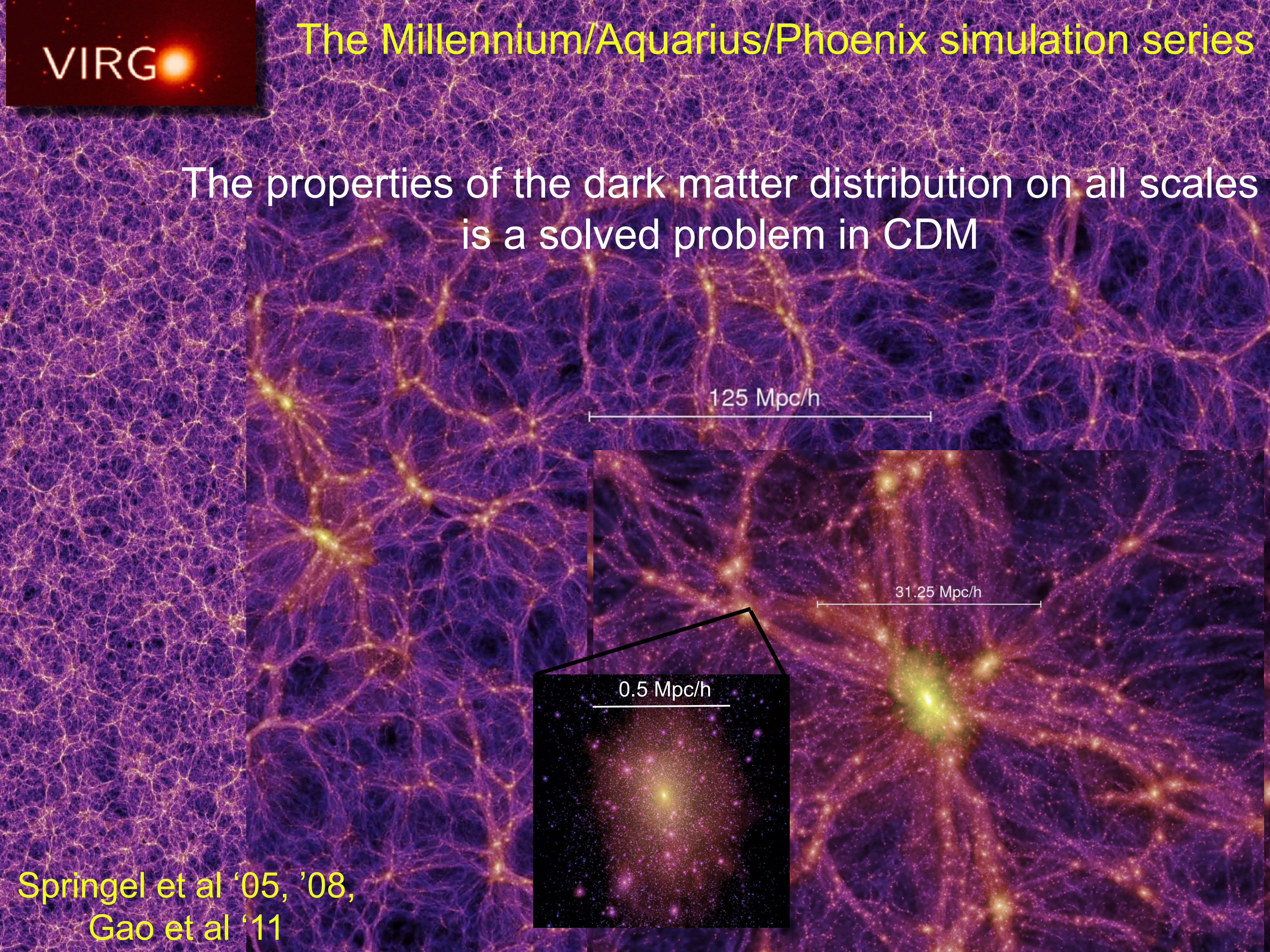
- abundance
- structure
- clustering

The ΛCDM cosmology



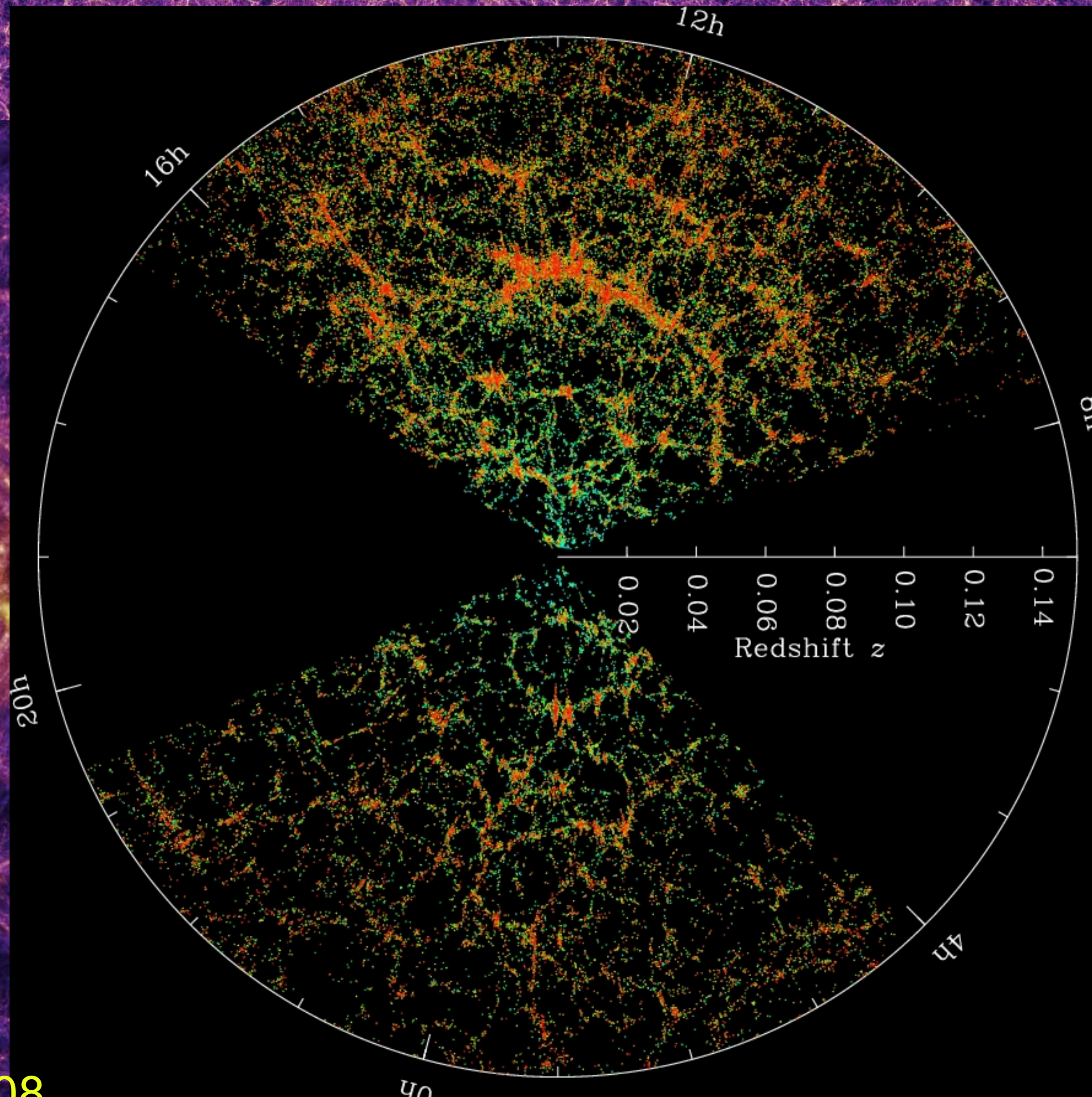
Early ΛCDM N-body simulations → realistic LSS

Davis, Efstathiou, Frenk & White ‘85


VIRGO
The Millennium/Aquarius/Phoenix simulation series
The properties of the dark matter distribution on all scales
is a solved problem in CDM
125 Mpc/h
31.25 Mpc/h
0.5 Mpc/h
Springel et al ‘05, ’08,
Gao et al ‘11

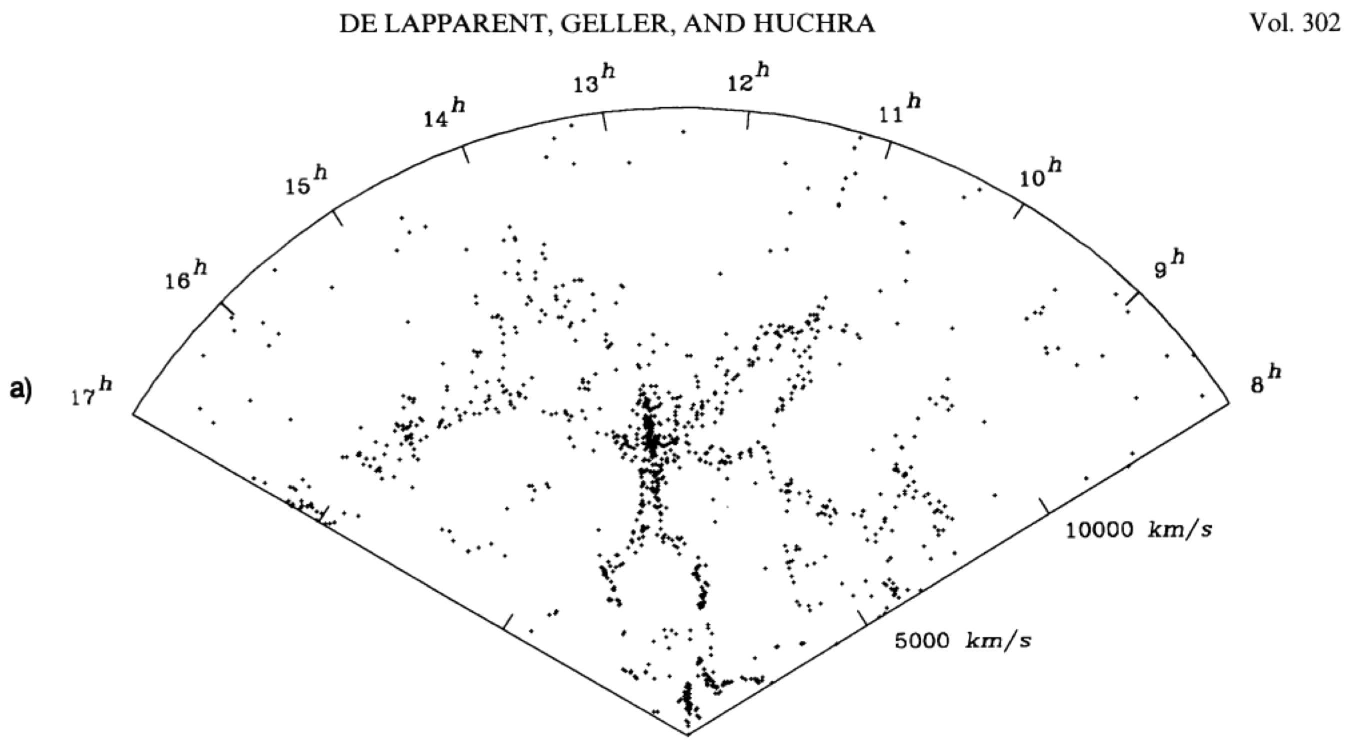
VIRGO

The Millennium/Aquarius/Phoenix simulation series



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

1980s



The CfA redshift survey

2020s

Galaxy distribution encodes info about dark matter and dark energy

DESI already has > 10 million spectra

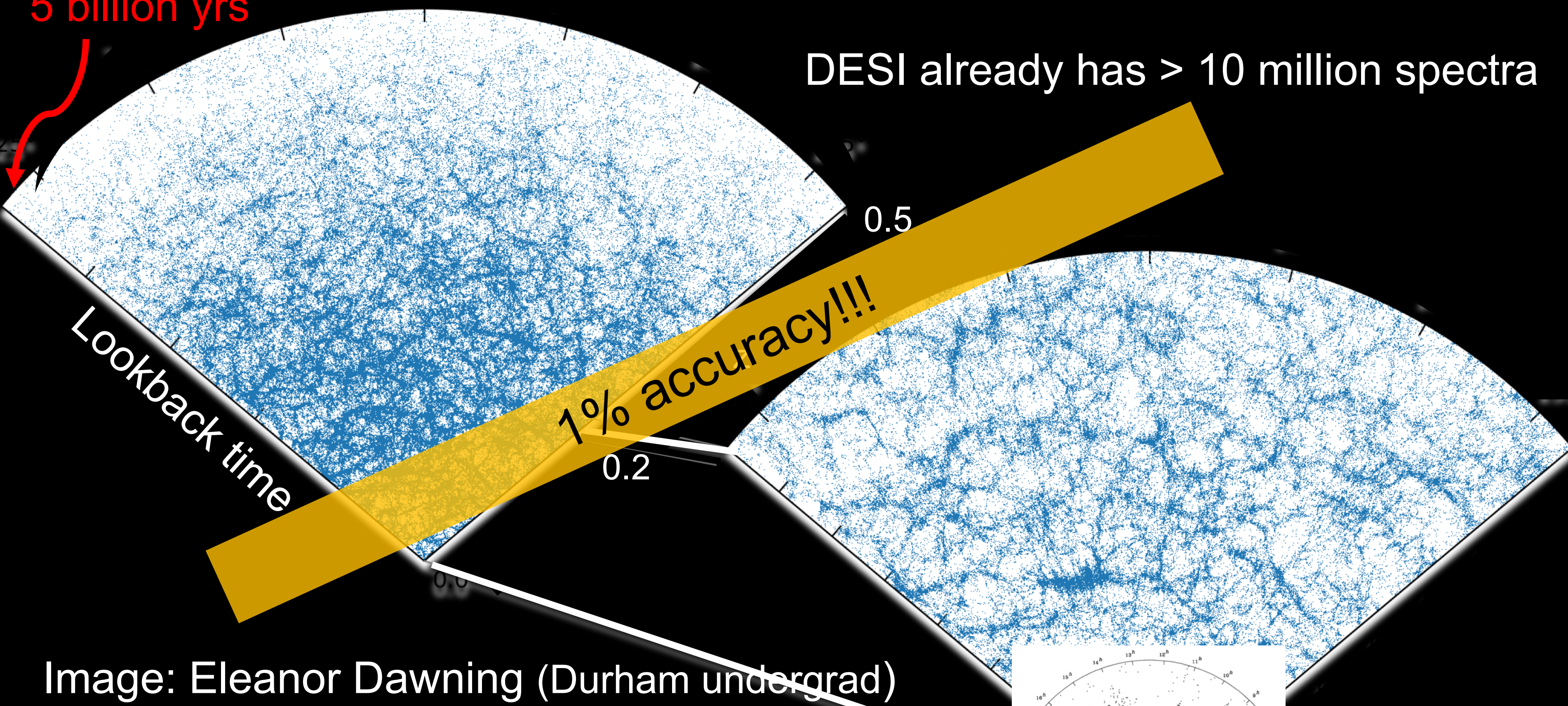
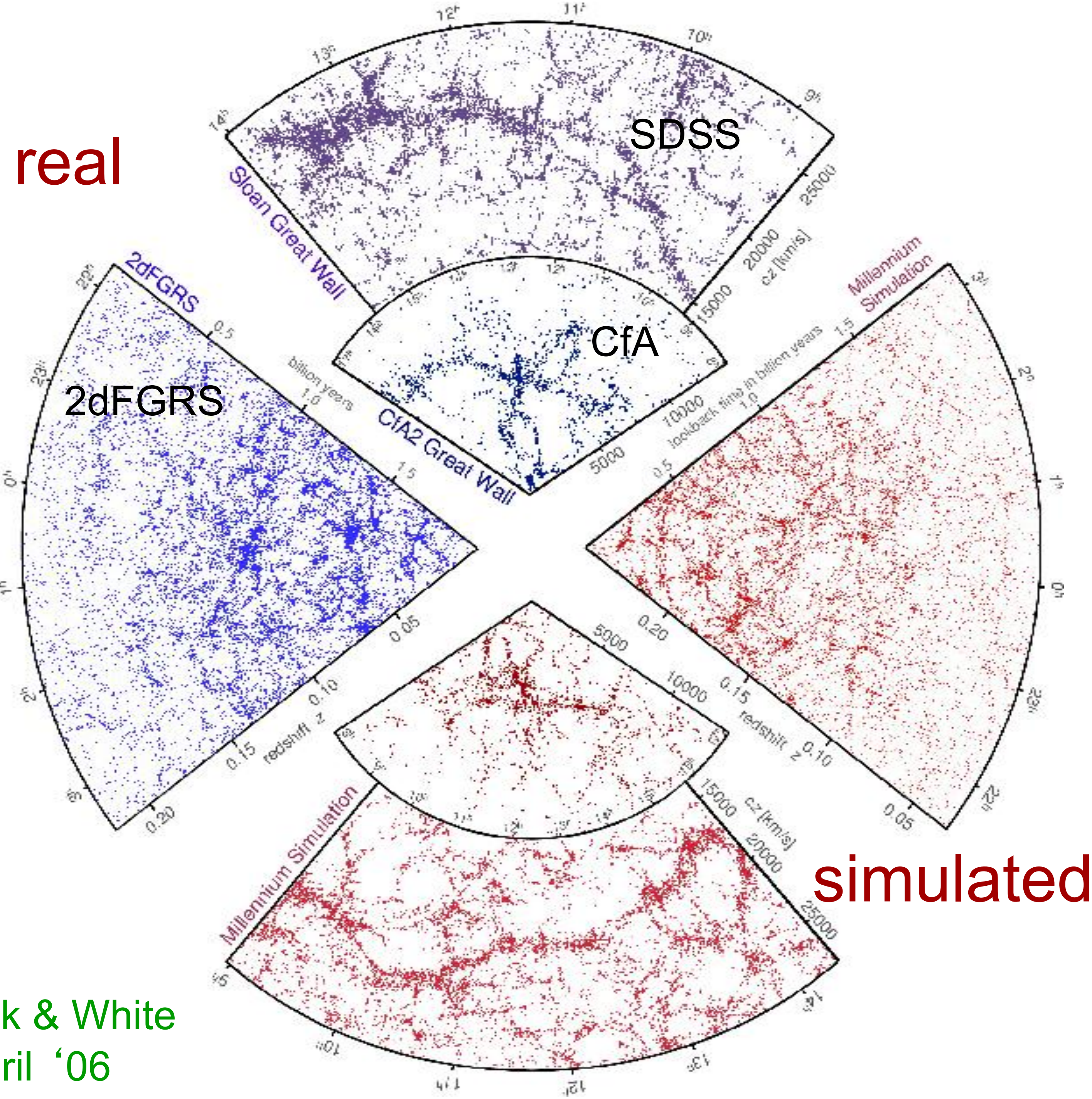


Image: Eleanor Dawning (Durham undergrad)

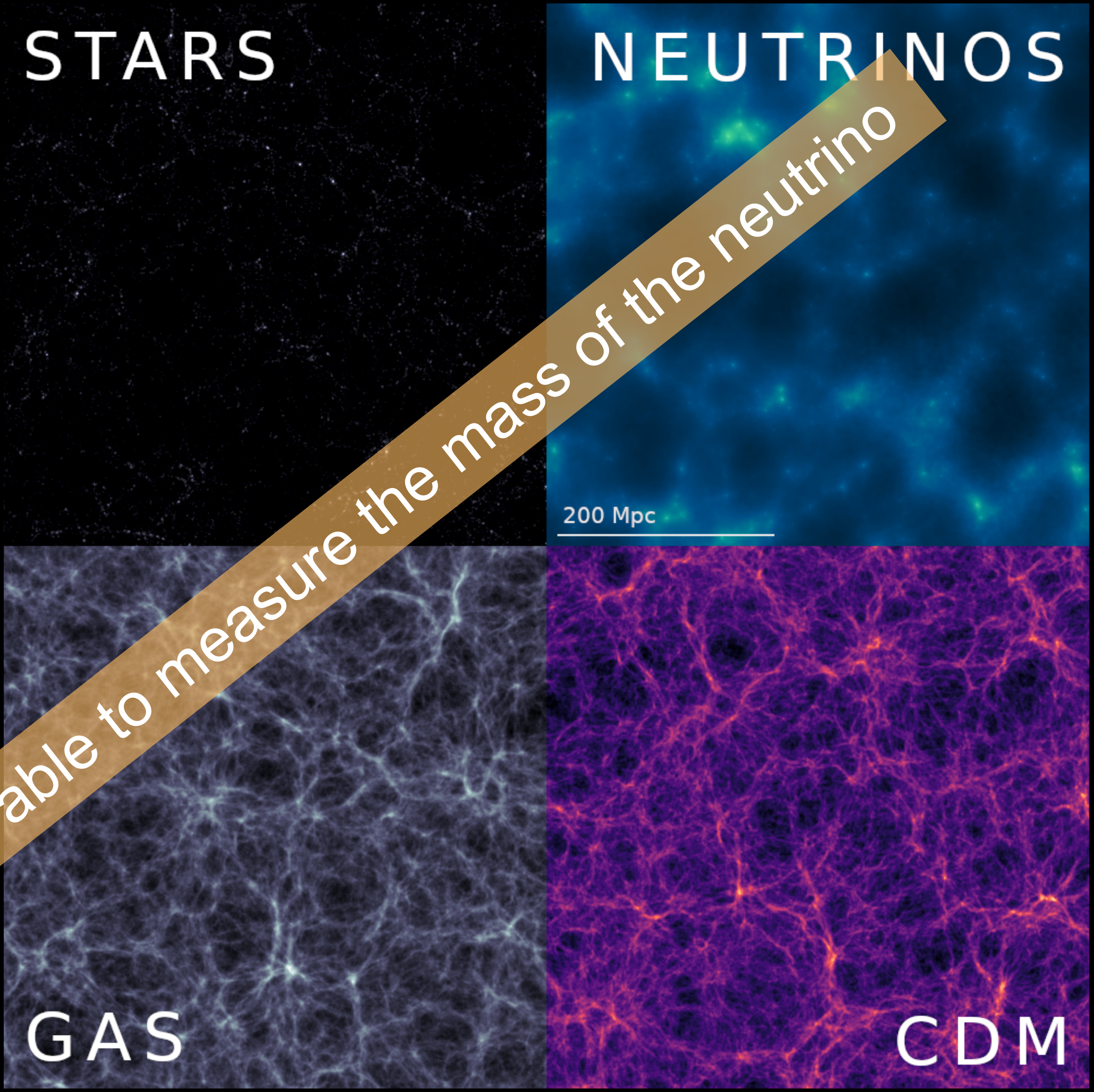


Springel, Frenk & White
Nature, April '06

ICC

Neutrinos make up < 1% of total dark matter

Can simulate their distribution with 1% accuracy



DESI may be able to measure the mass of the neutrino

Elbers, Frenk, Jenkins, Li, Pascoli '23

Institute for Computational Cosmology

ΛCDM

Basic ideas proposed in 1980s

→ Cosmic structure forms from primordial quantum fluctuations from inflation amplified by gravity of dark matter (DM)

→ N-body simulations compared to large-scale structure data

→ neutrinos are not bulk of DM

→ CDM promising

→ $\delta T/T$-fluctuations in CMB (→ DM, Flatness → Λ) → ΛCDM

→ Impressive agreement: modern simulations & galaxy surveys

→ Λ first appeared in '90s for CDM to agree galaxy distribution

→ Era of 1% accuracy is here: test ΛCDM + measure ν mass

University of Durham

Observational tests of ΛCDM

Fundamental prediction of ΛCDM

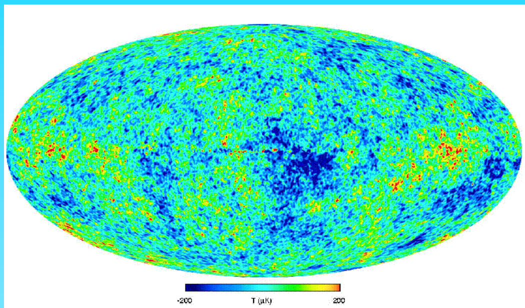
→ Primordial PS of density perturbations + random phases

Linear regime: cosmic microwave background ✔

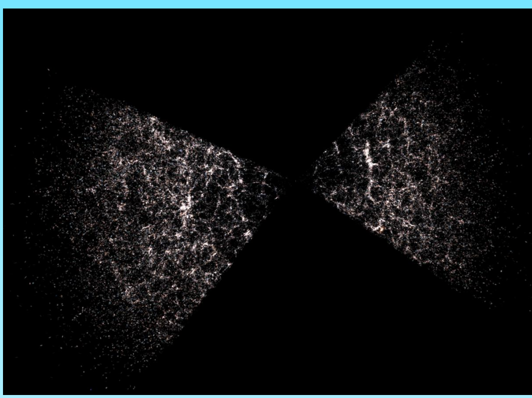
large-scale structure ✔

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

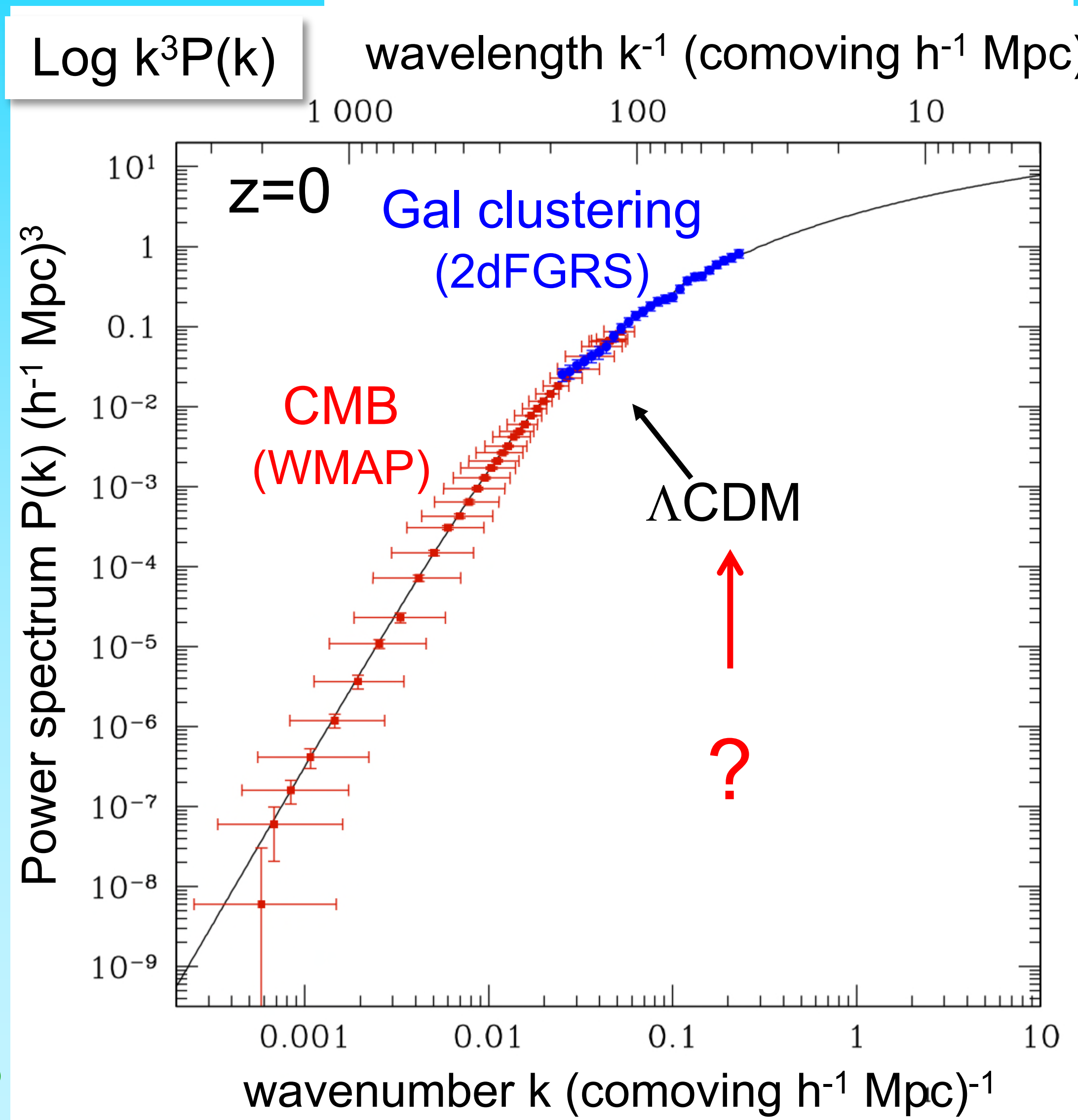
University of Durham



z~1000



z~0



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

Sanchez et al 06

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

University of Durham

Free streaming →

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

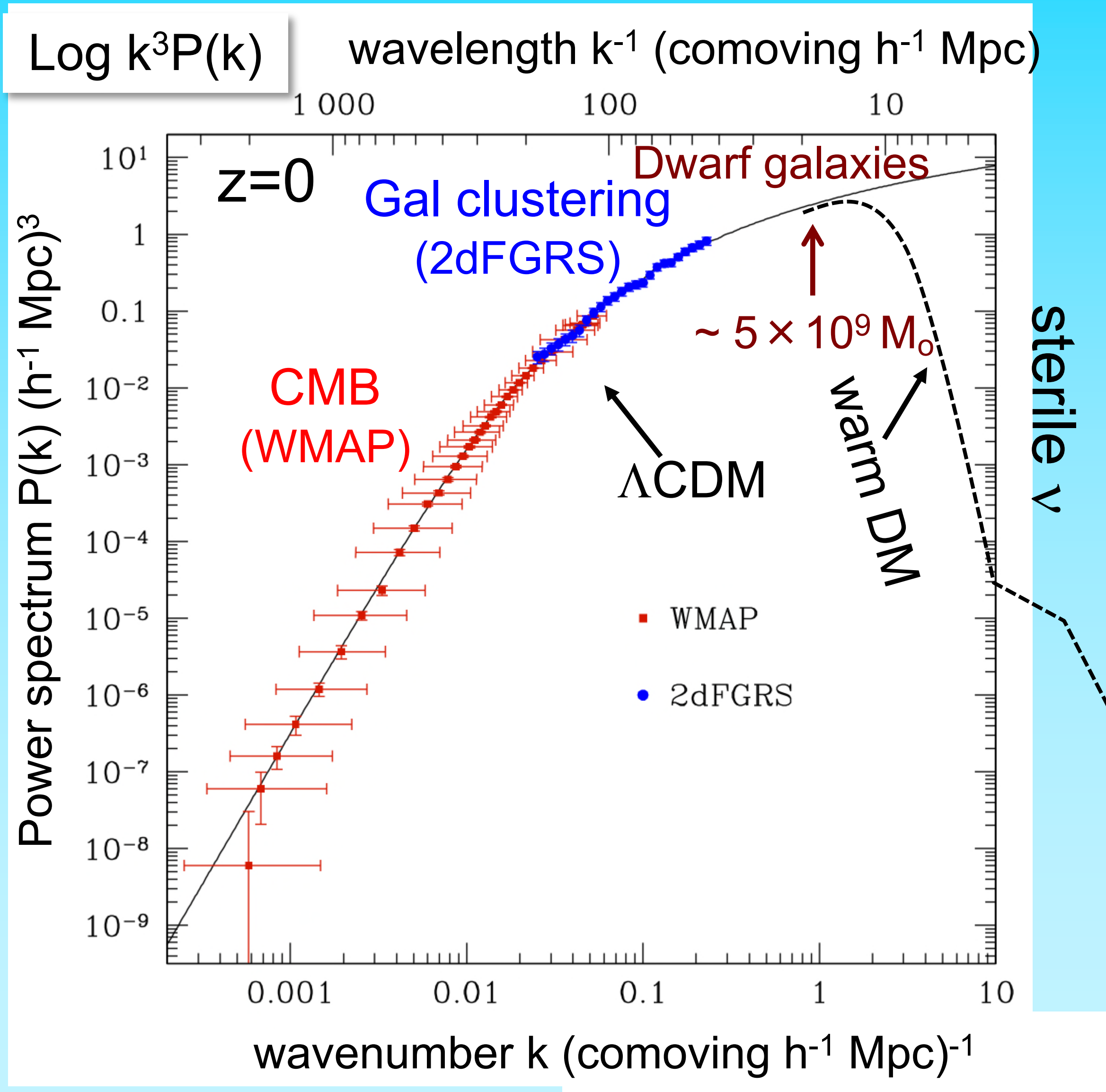
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$



University of Durham

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

University of Durham

Observational tests of ΛCDM

Fundamental prediction of ΛCDM

→ Primordial PS of density perturbations + random phases

Can test this in two regimes:

Linear regime: cosmic microwave background ✔

large-scale structure ✔

Evolved non-linear regime: dark matter halos →

- abundance
- structure
- clustering

Formation of CDM halos

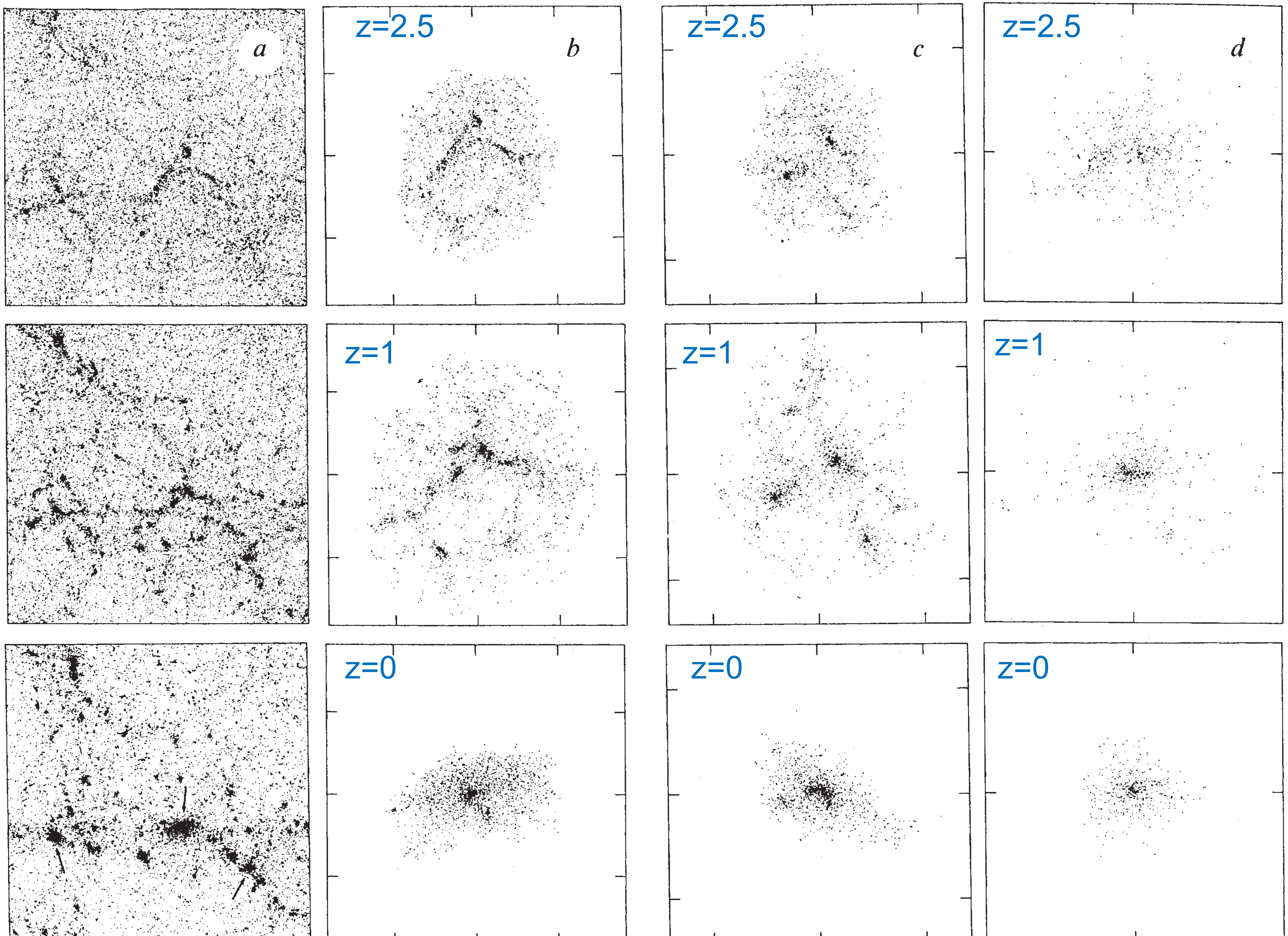
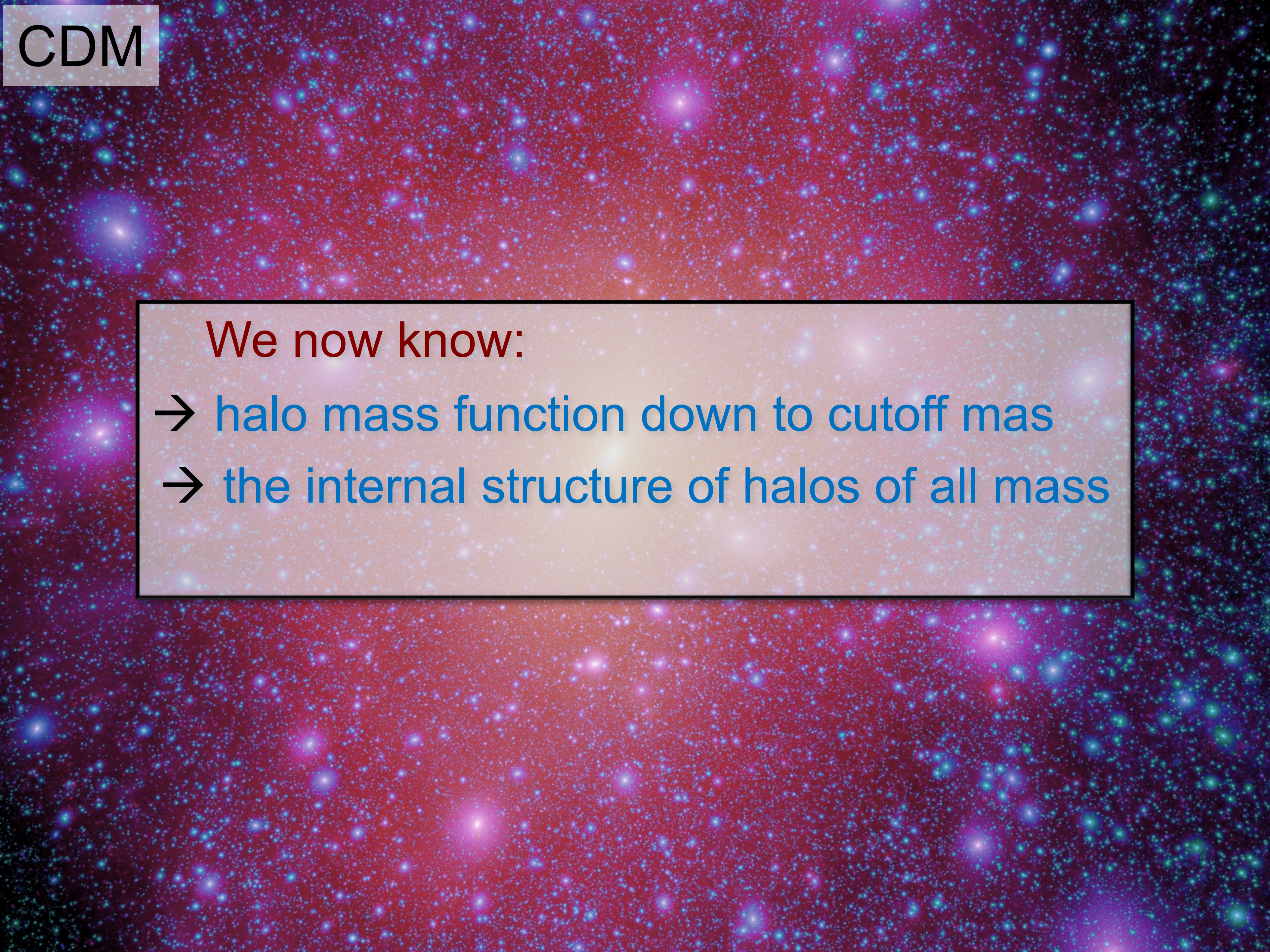


Fig. 1

Frenk et al 1985



CDM

We now know:

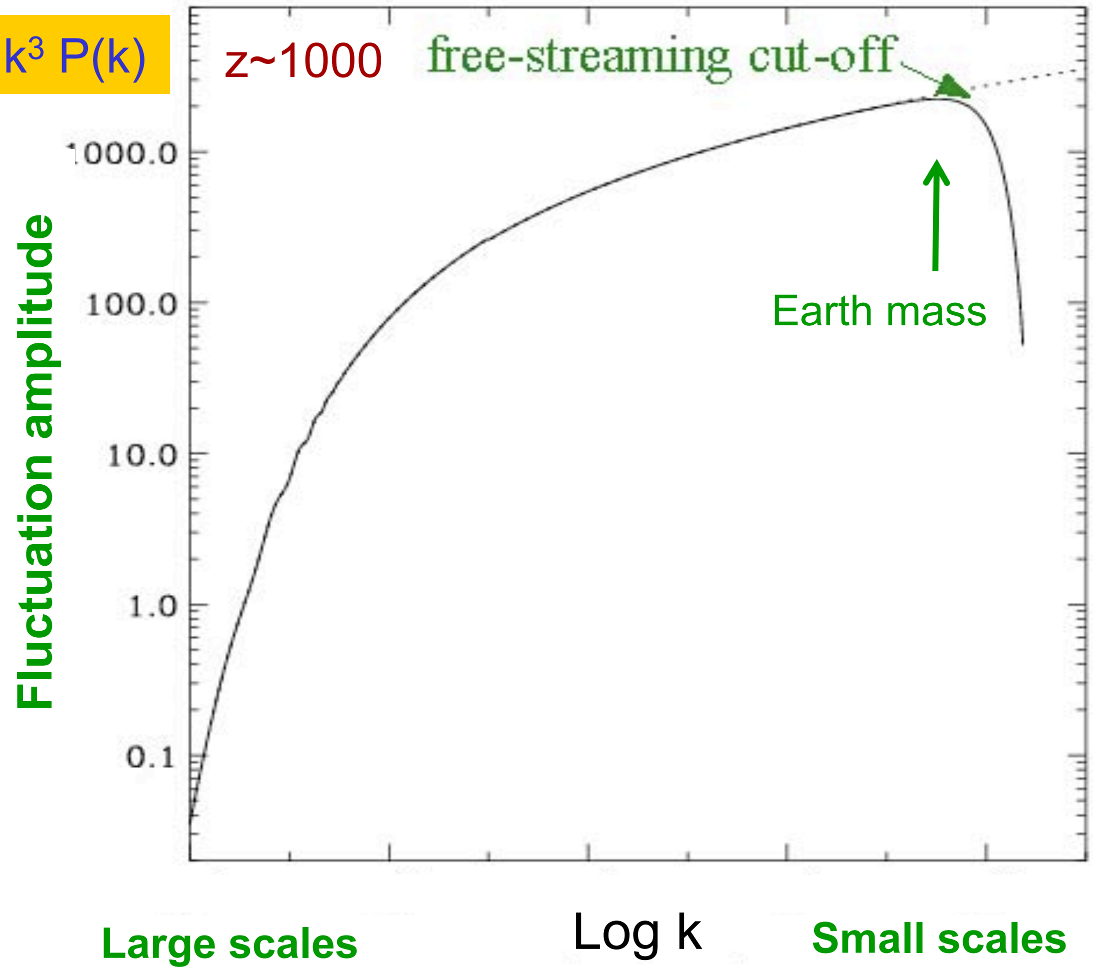
→ halo mass function down to cutoff mas

→ the internal structure of halos of all mass

The cold dark matter power spectrum

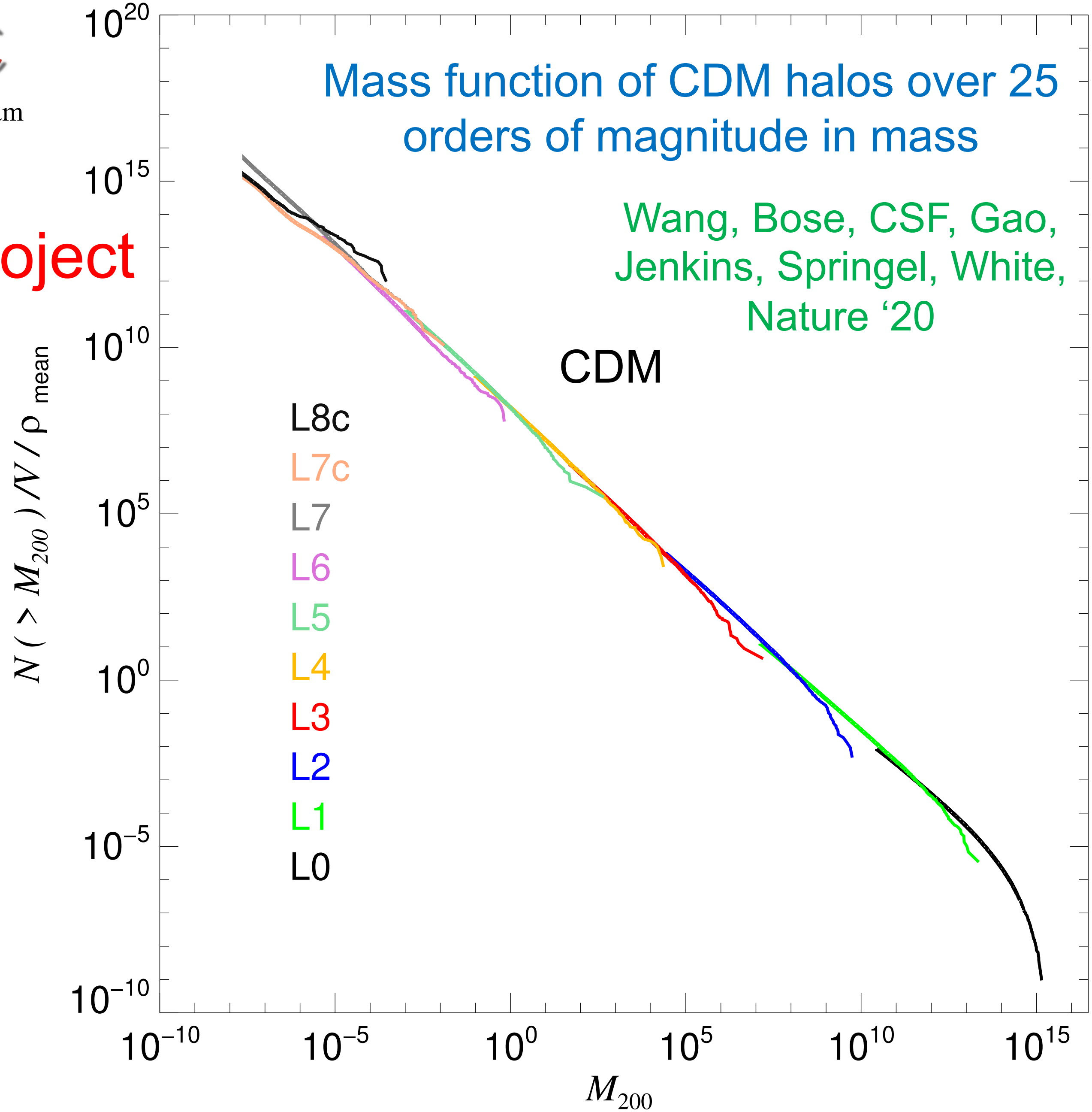
The linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04



Institute for Computational Cosmology

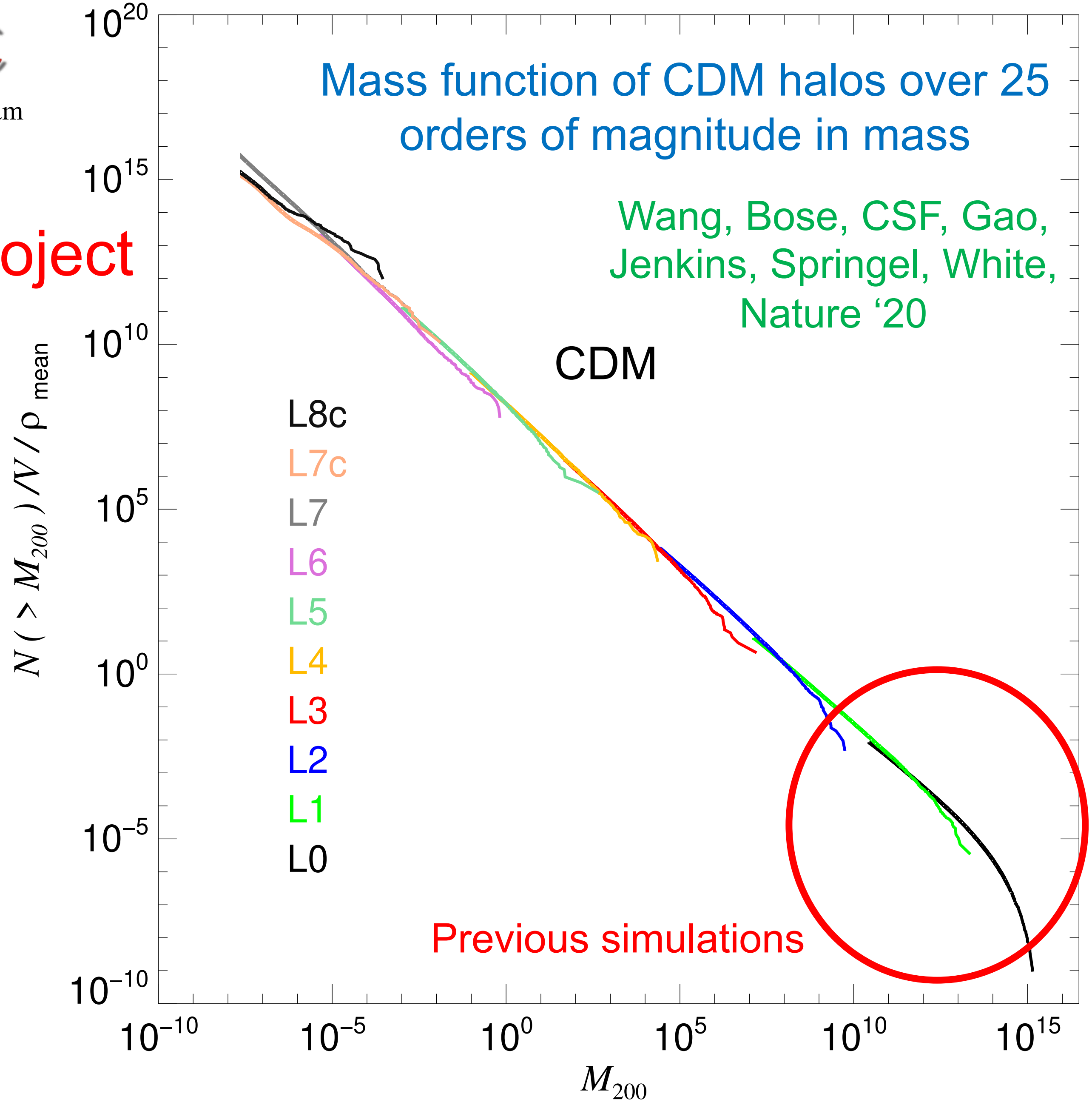
The VVV project

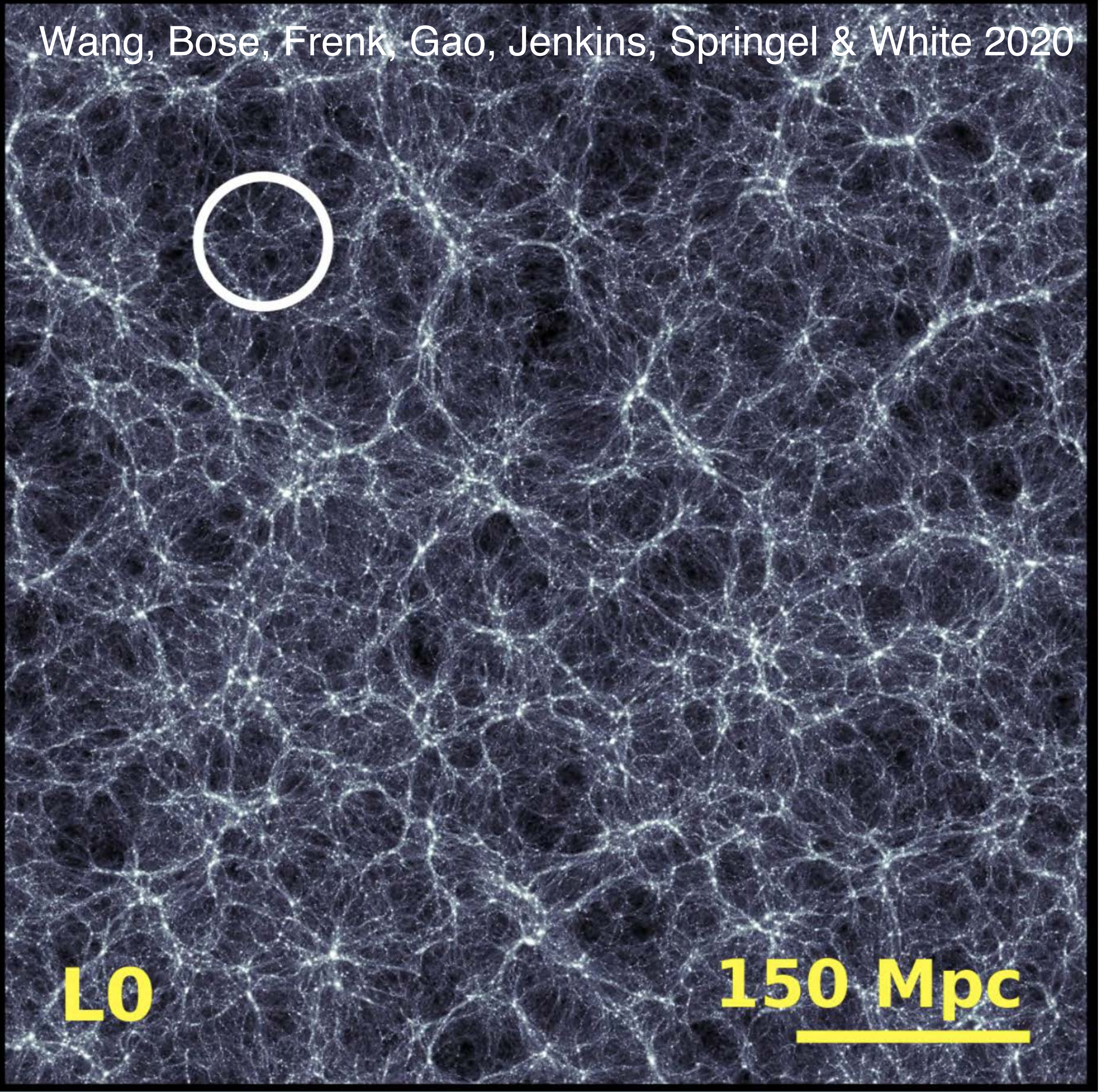


University of Durham

Institute for Computational Cosmology

The VVV project





The VVV simulation

Planck cosmology

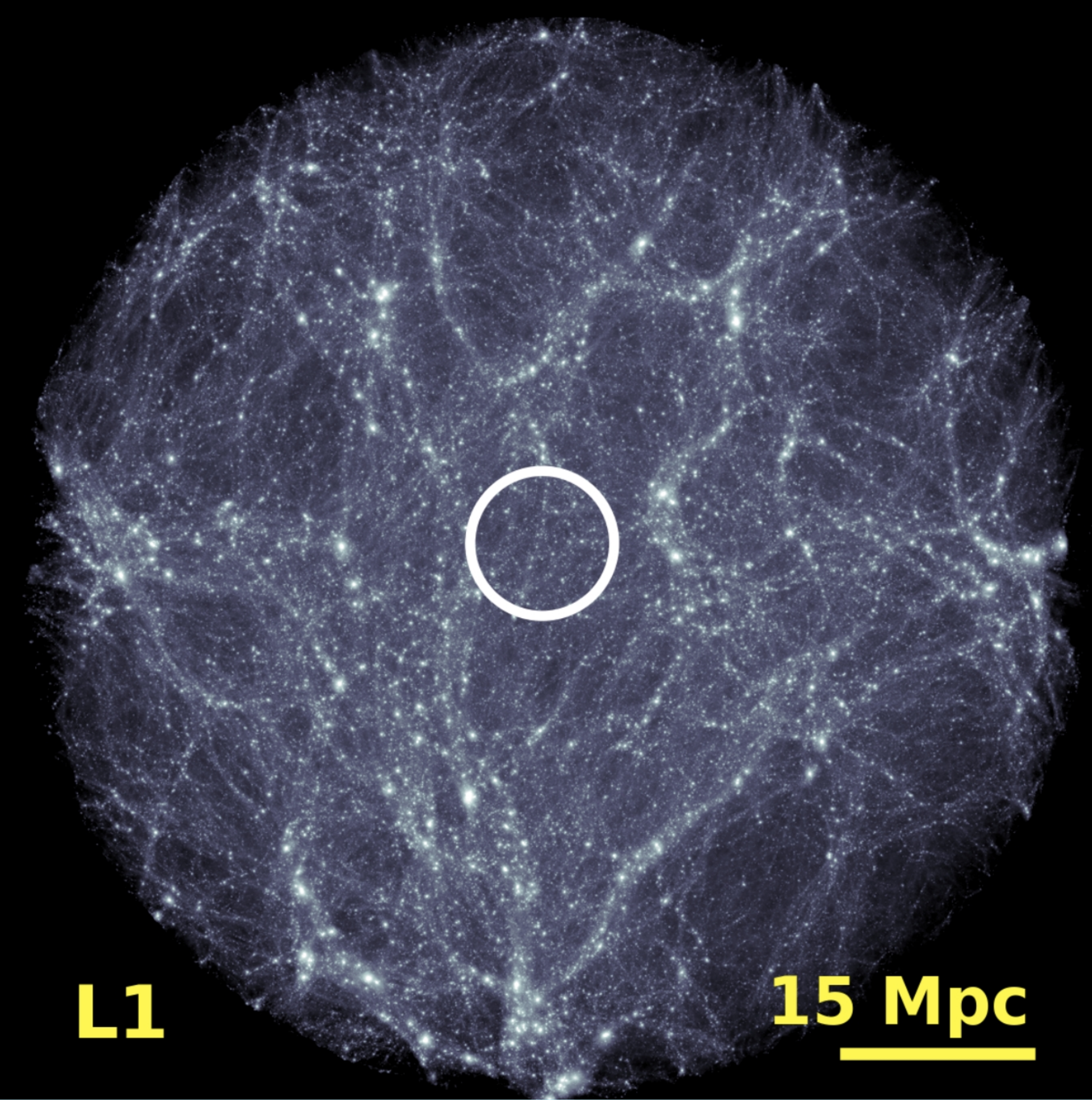
Dark matter only

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

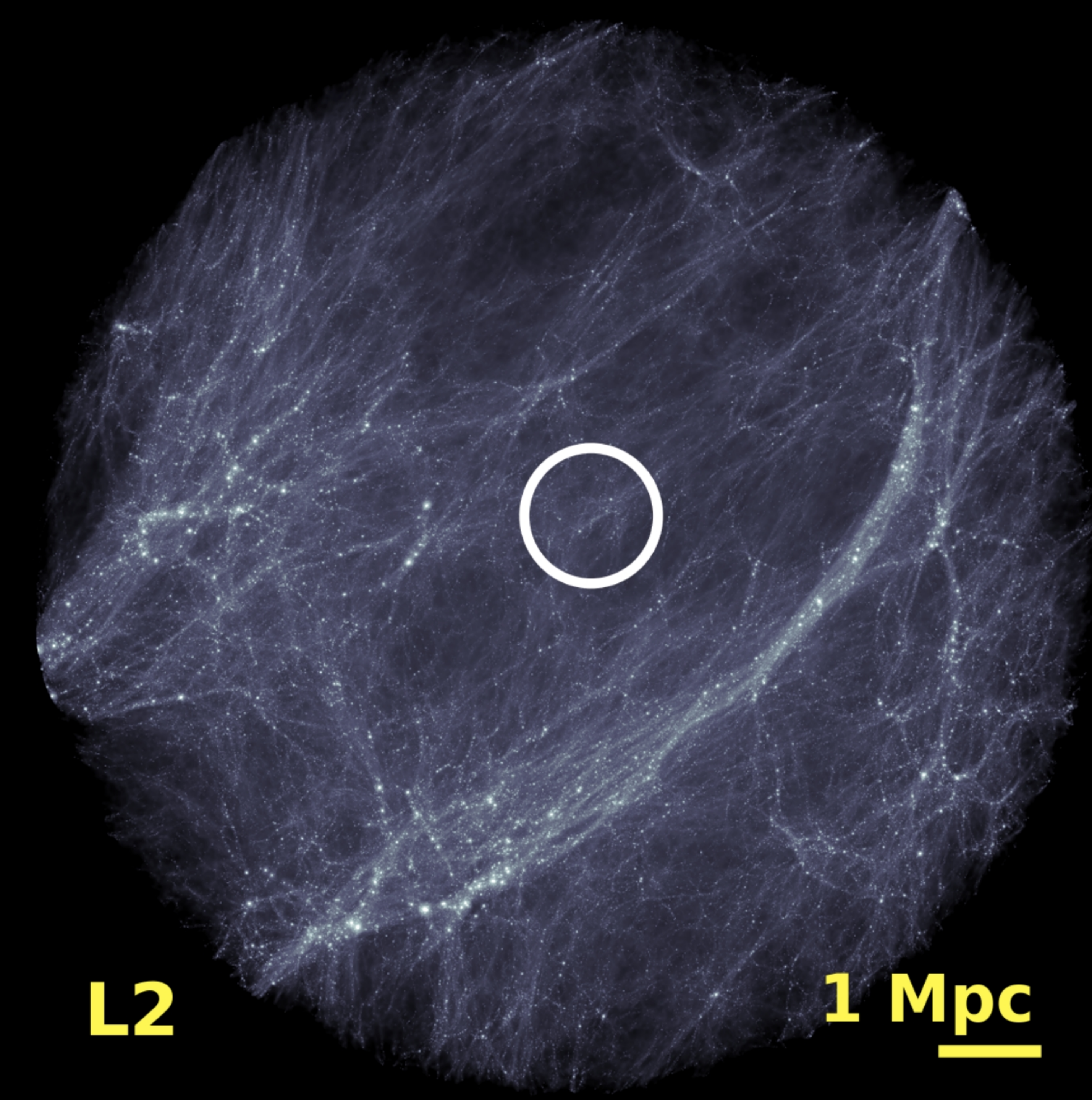
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 1

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

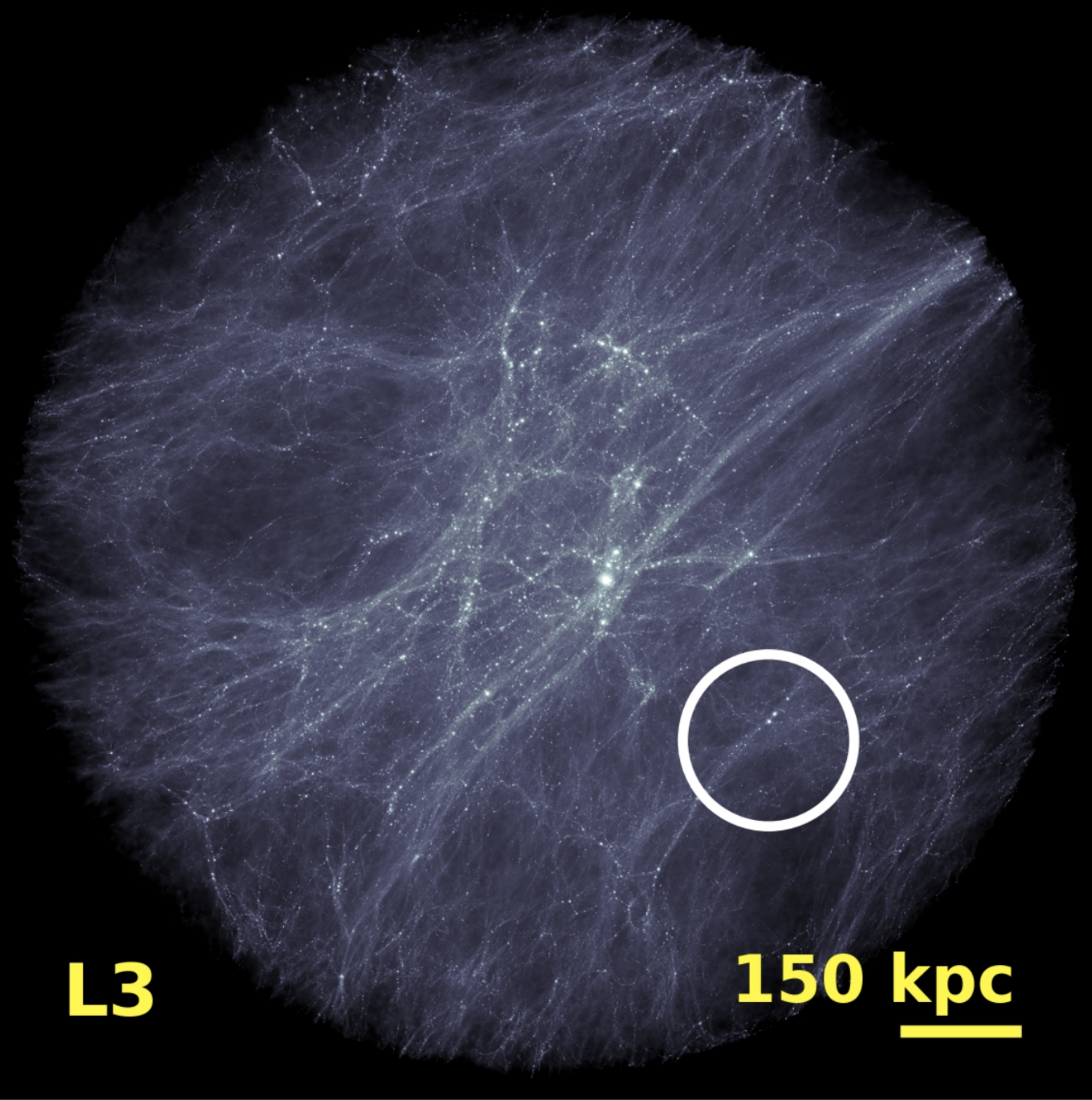
Dark matter only

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

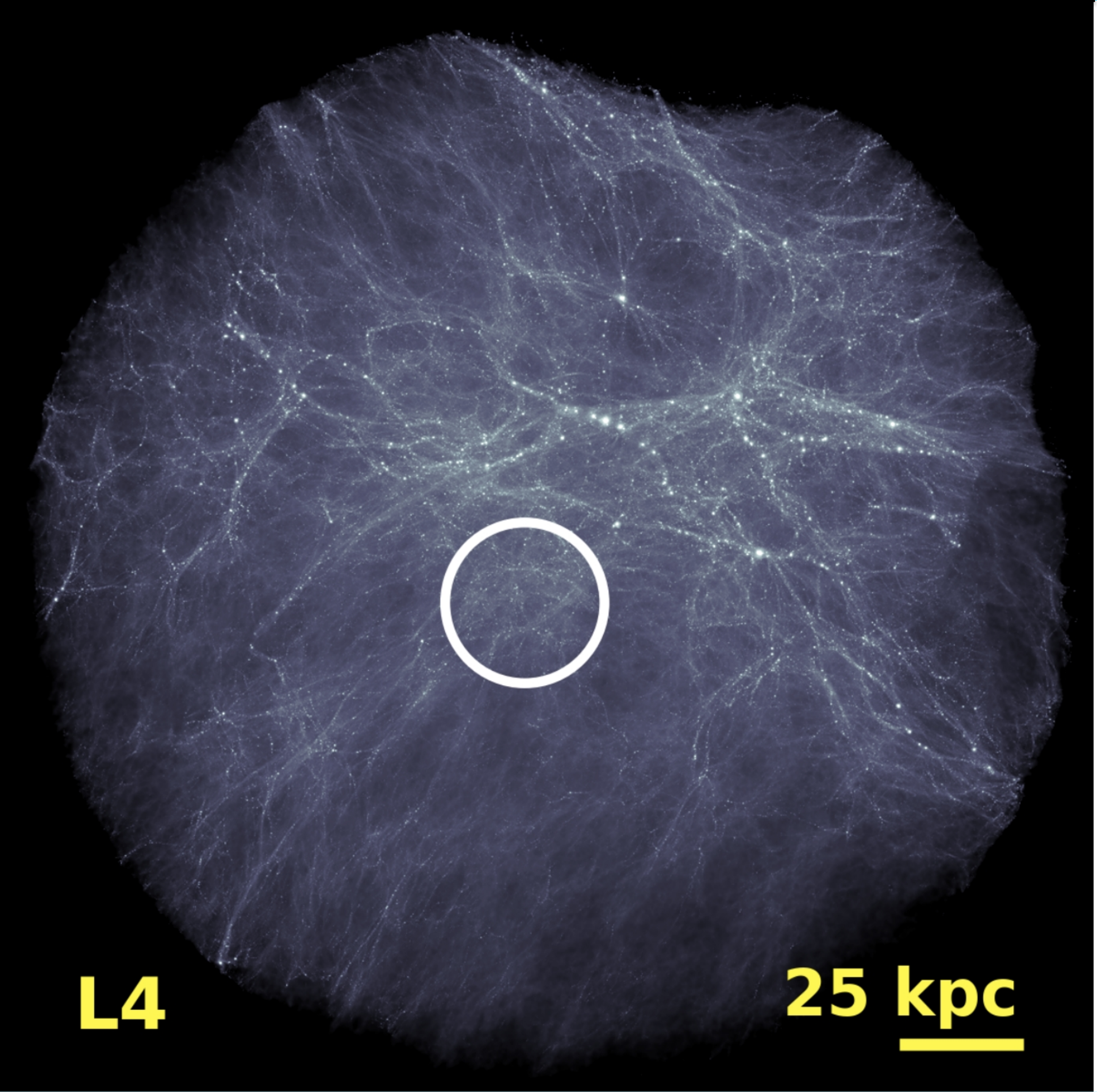
Dark matter only

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

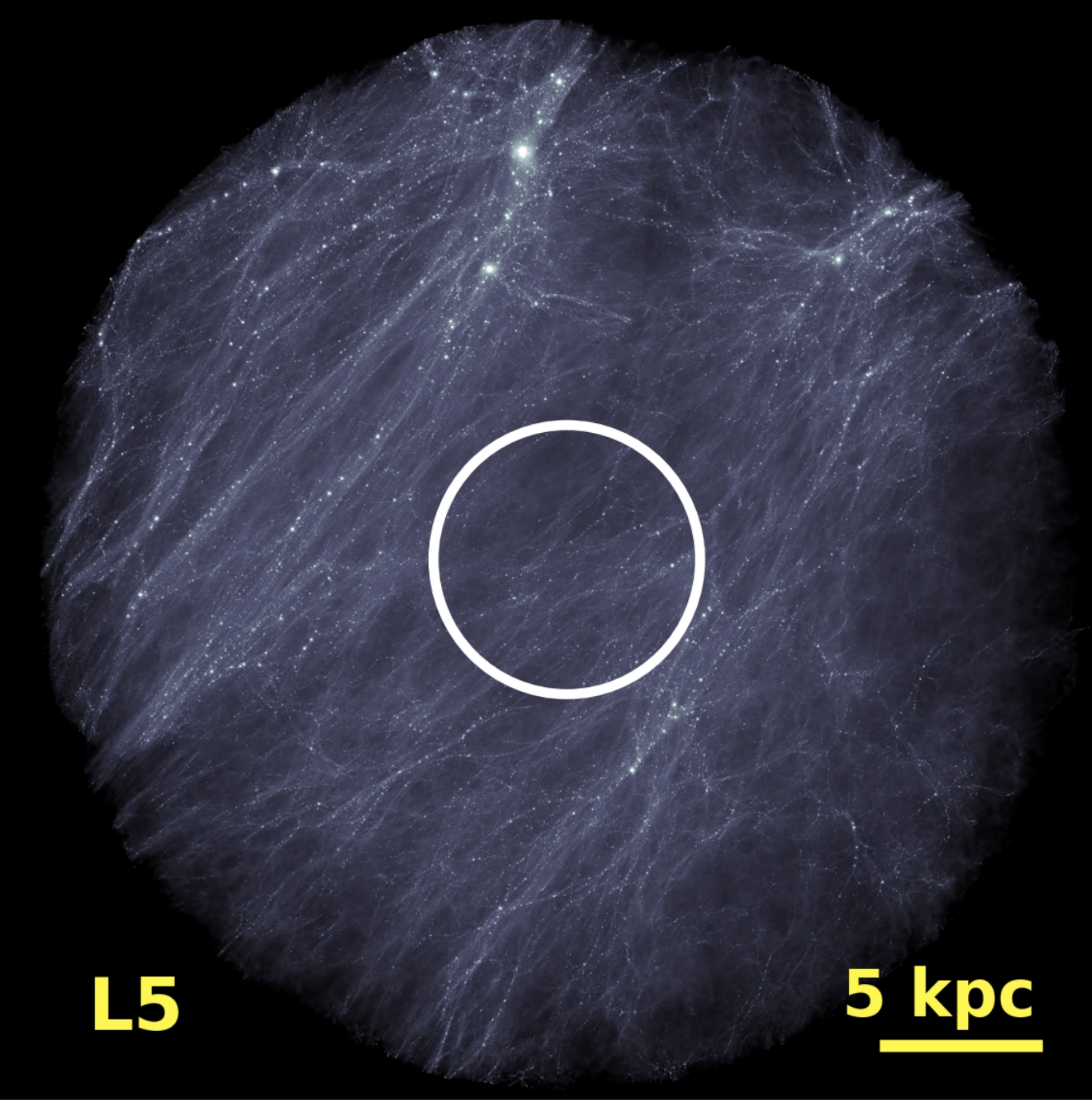
Dark matter only

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

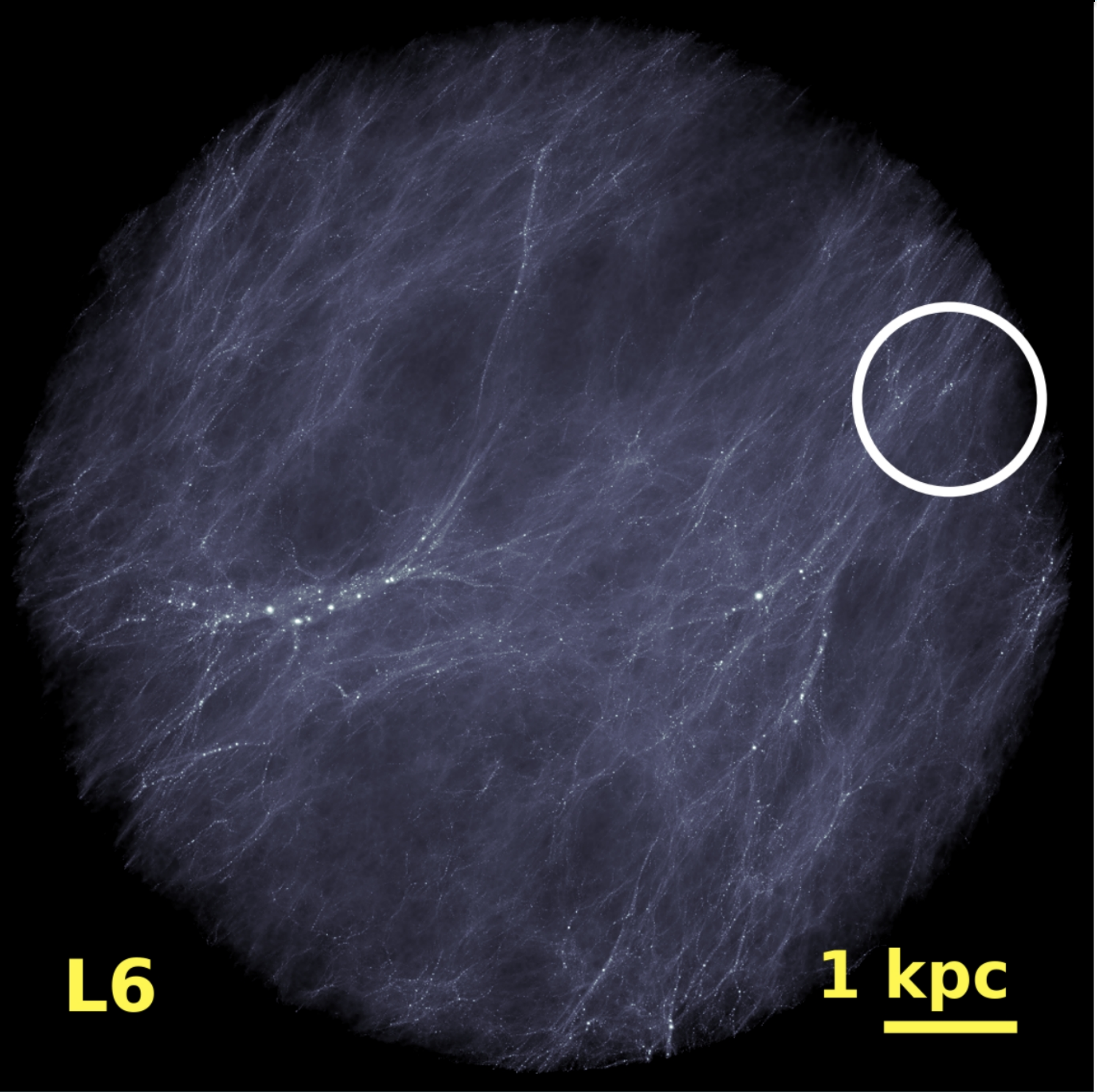
Dark matter only

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

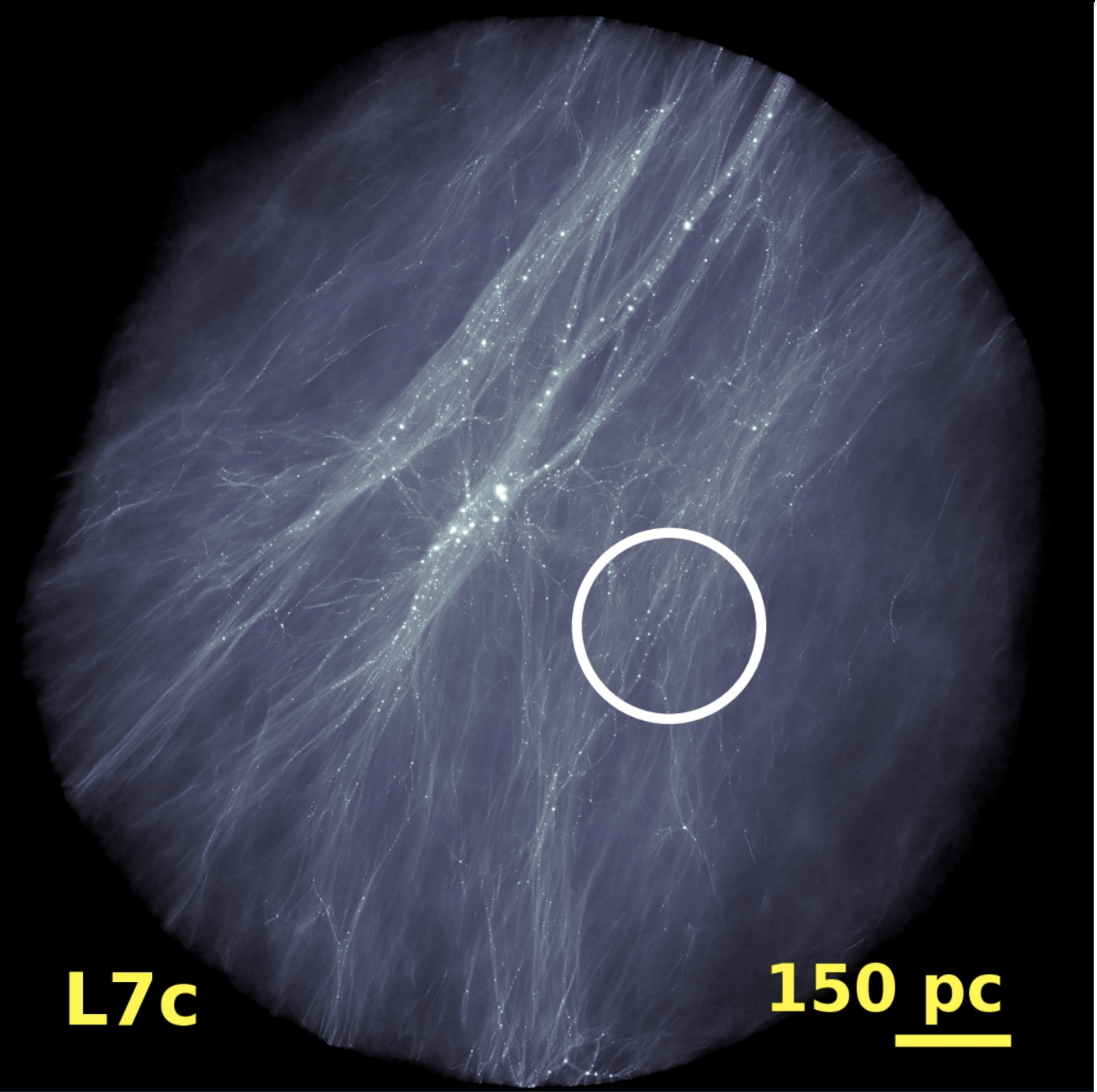
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 6

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

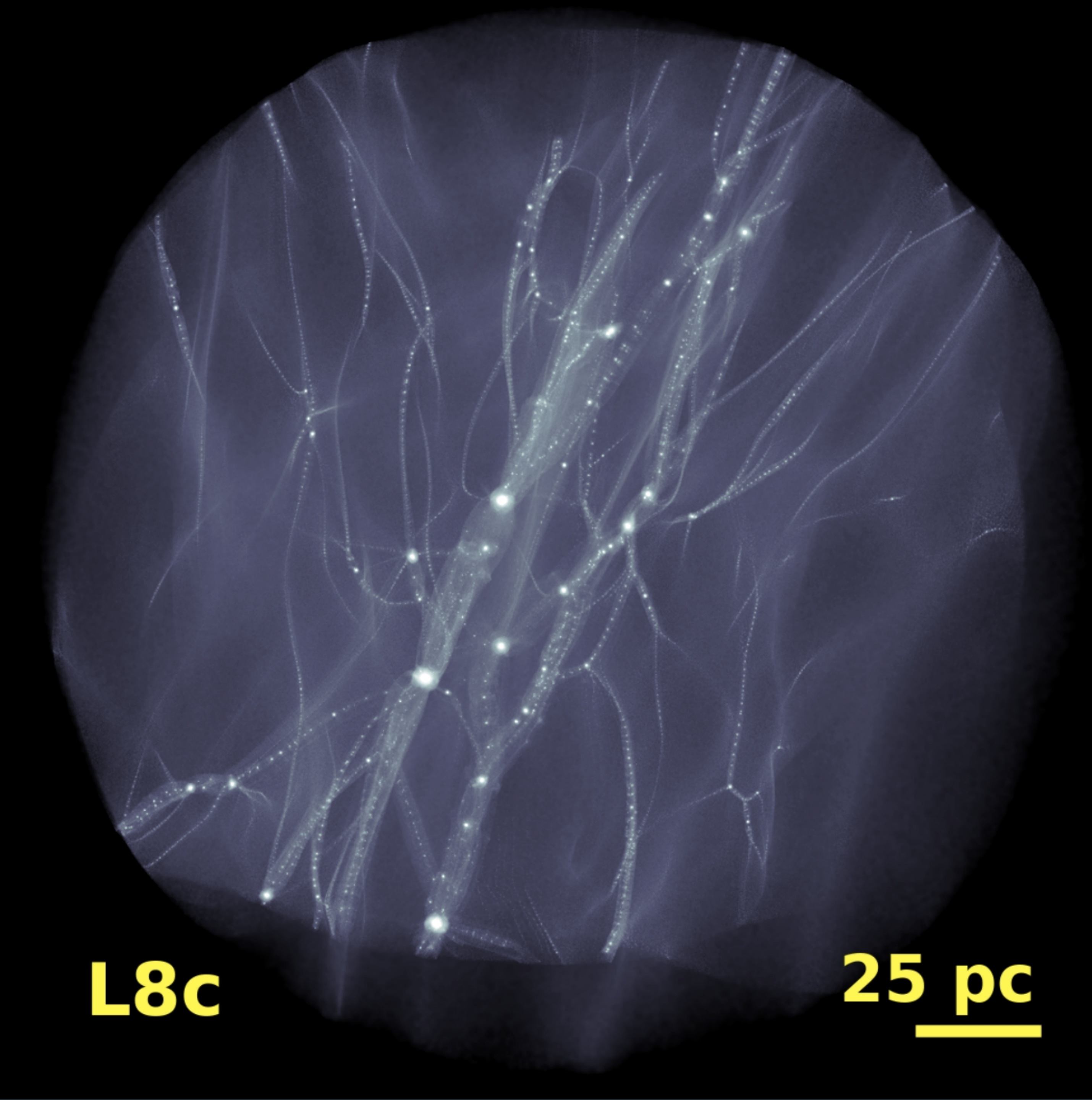
Dark matter only

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

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

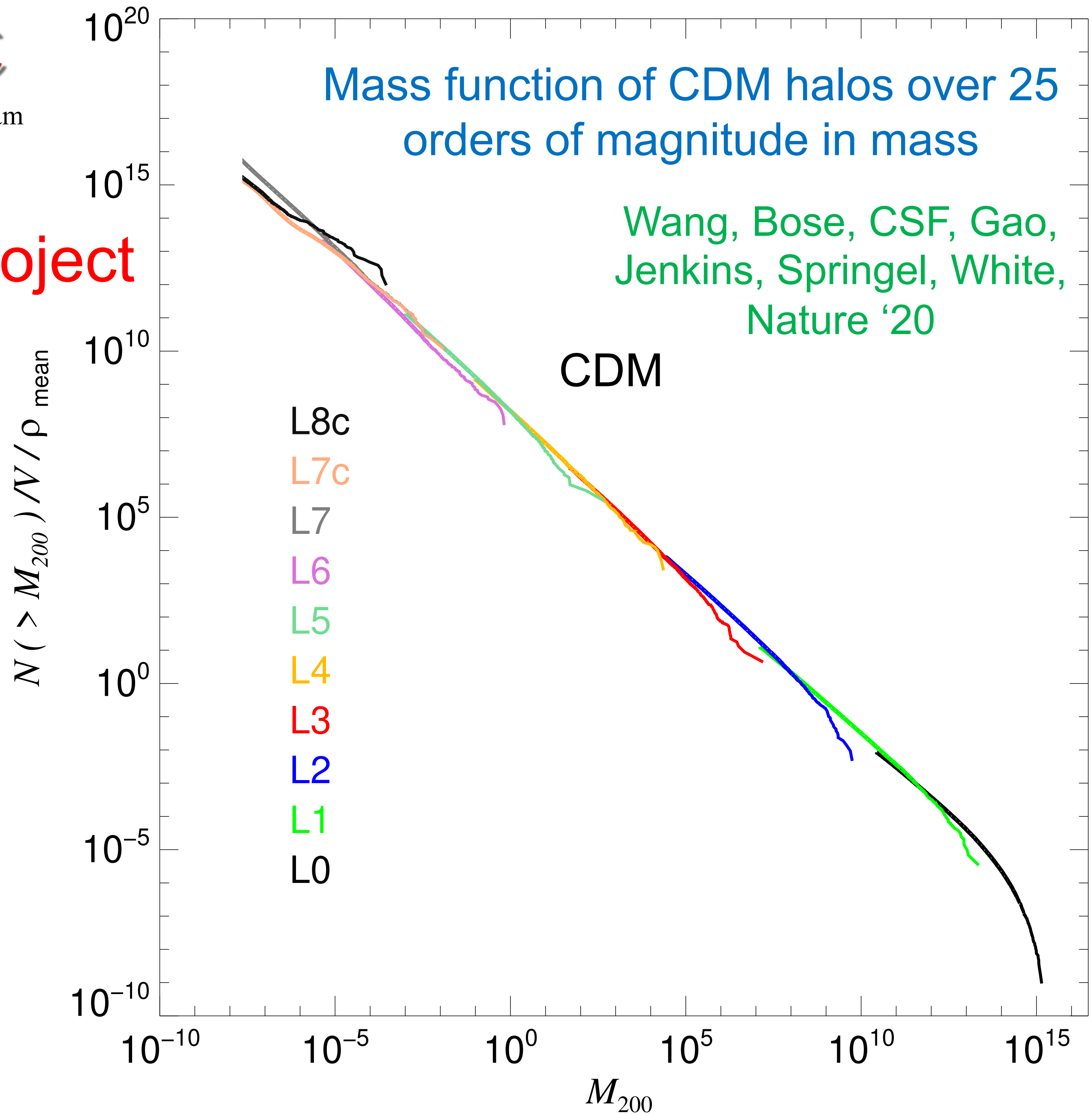
Zoom Level 8

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

Wang, Bose et al 2020

University of Durham

The VVV project



Institute for Computational Cosmology

The density profile of cold dark matter halos

Shape of halo profiles
~independent of halo mass &
rameters

re “cuspy” -
e centre

formula:

$$\frac{\delta_c}{\ldots 1 + r/r_s)^2}$$

White ’97)

halos and
earlier have
higher densities (bigger δ)

University of Durham

Universal halo density profiles

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

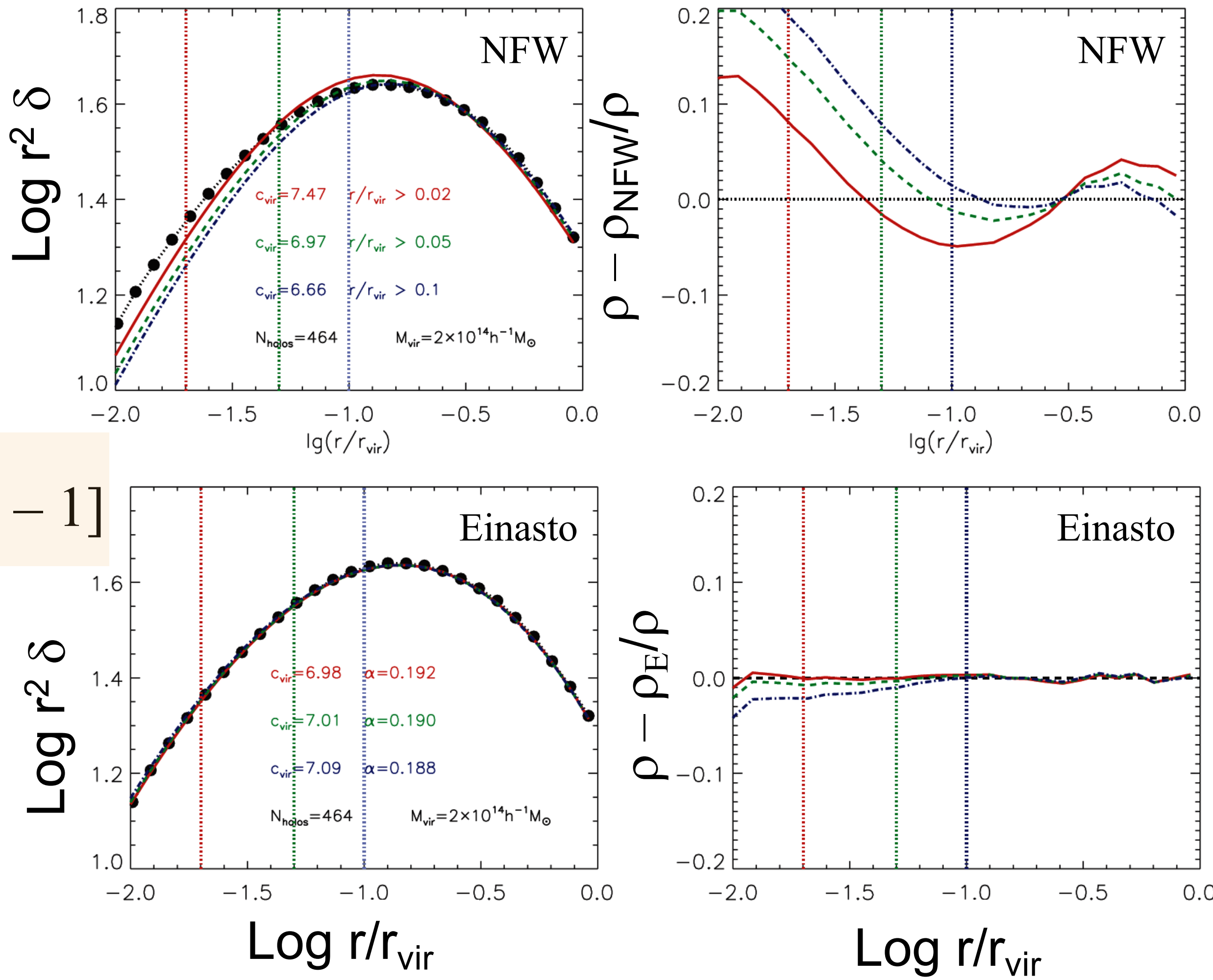
The "Einasto" formula

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

Fits mean profiles even better

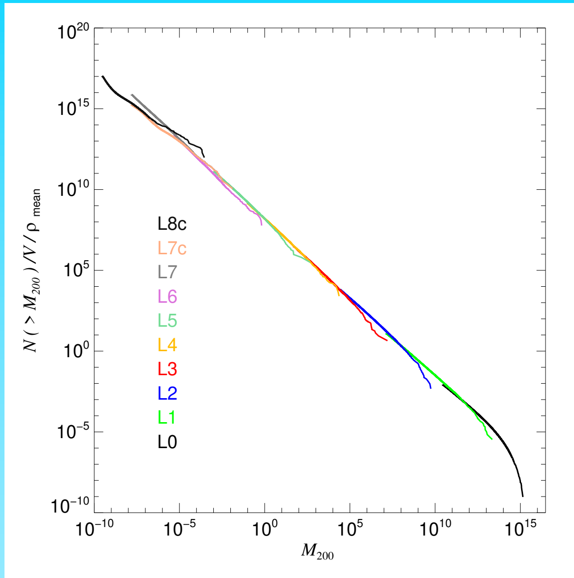
Gao, N, F, W + 2008

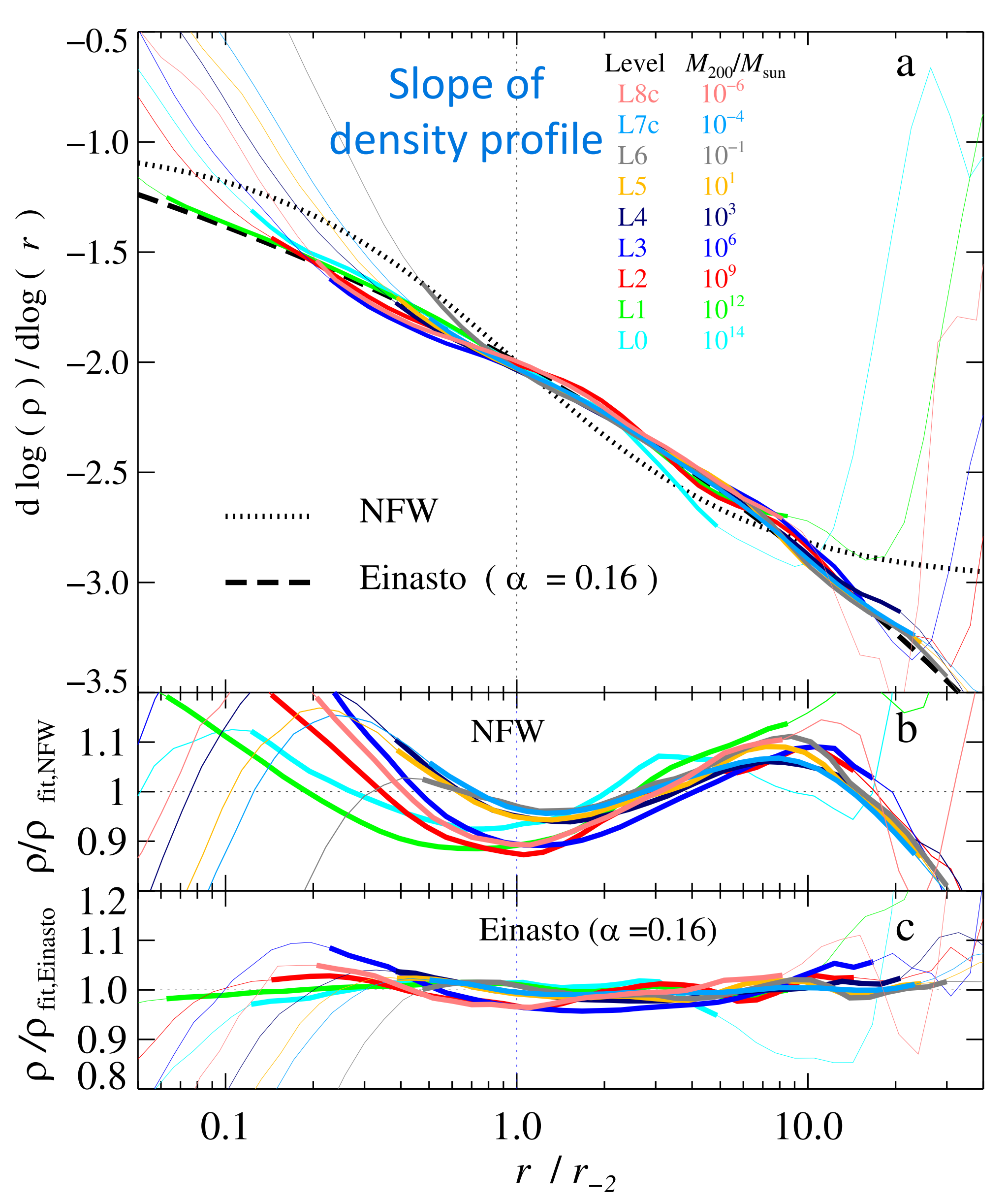
Averaged cluster mass halos fit with NFW and Einasto



Density profiles of ALL halos

University of Durham





Over 20 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

University of Durham ICC

Observational tests of ΛCDM

Fundamental prediction of ΛCDM

→ Primordial PS of density perturbations + random phases

Can test this in two regimes:

Linear regime: cosmic microwave background
large-scale structure

Evolved non-linear regime: dark matter halos →

- abundance
- structure
- clustering

Institute for Computational Cosmology

A galaxy formation primer

In which halos do galaxy form?

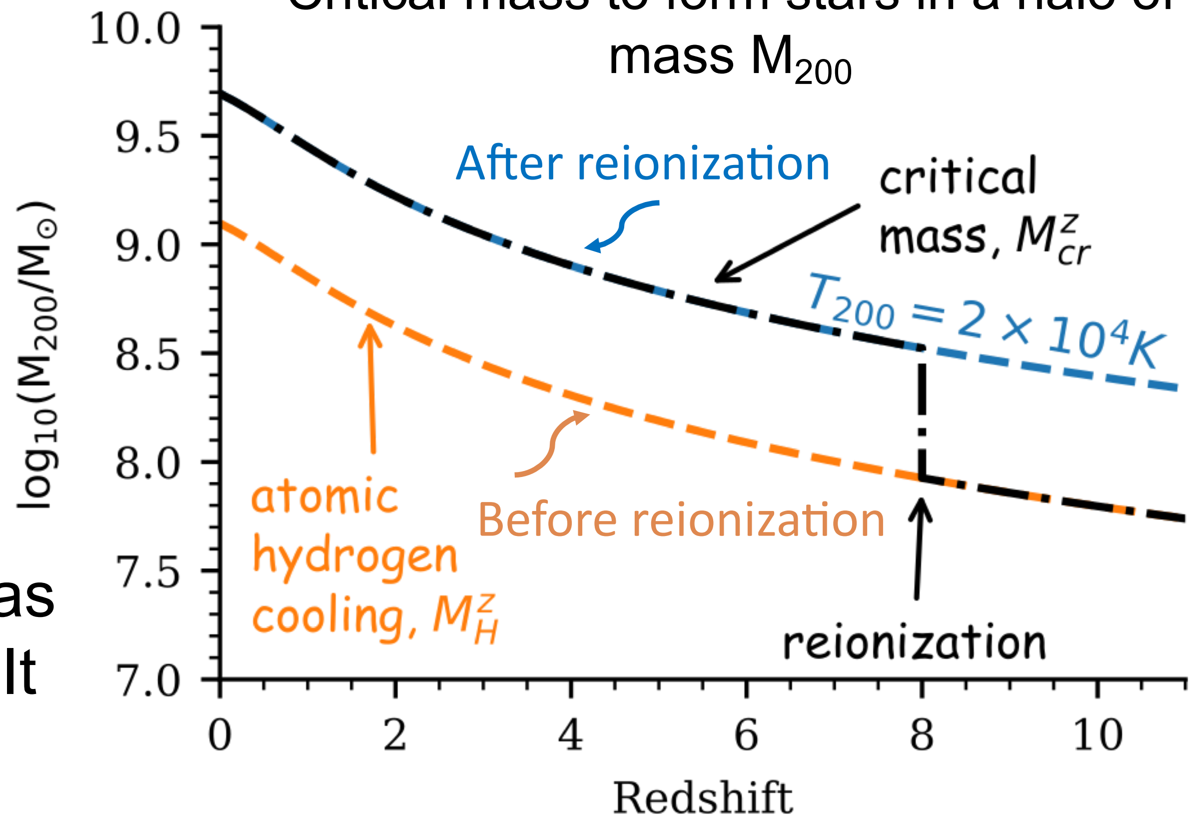
1. Before reionization, stars can only form if atomic H cooling is effective: → T>7000 K

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

2. After H reionization, gas is heated to T=2x10^4 K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2x10^4$ K

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



Benitez-Llambay & CSF '20

A galaxy formation primer

University of Durham

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

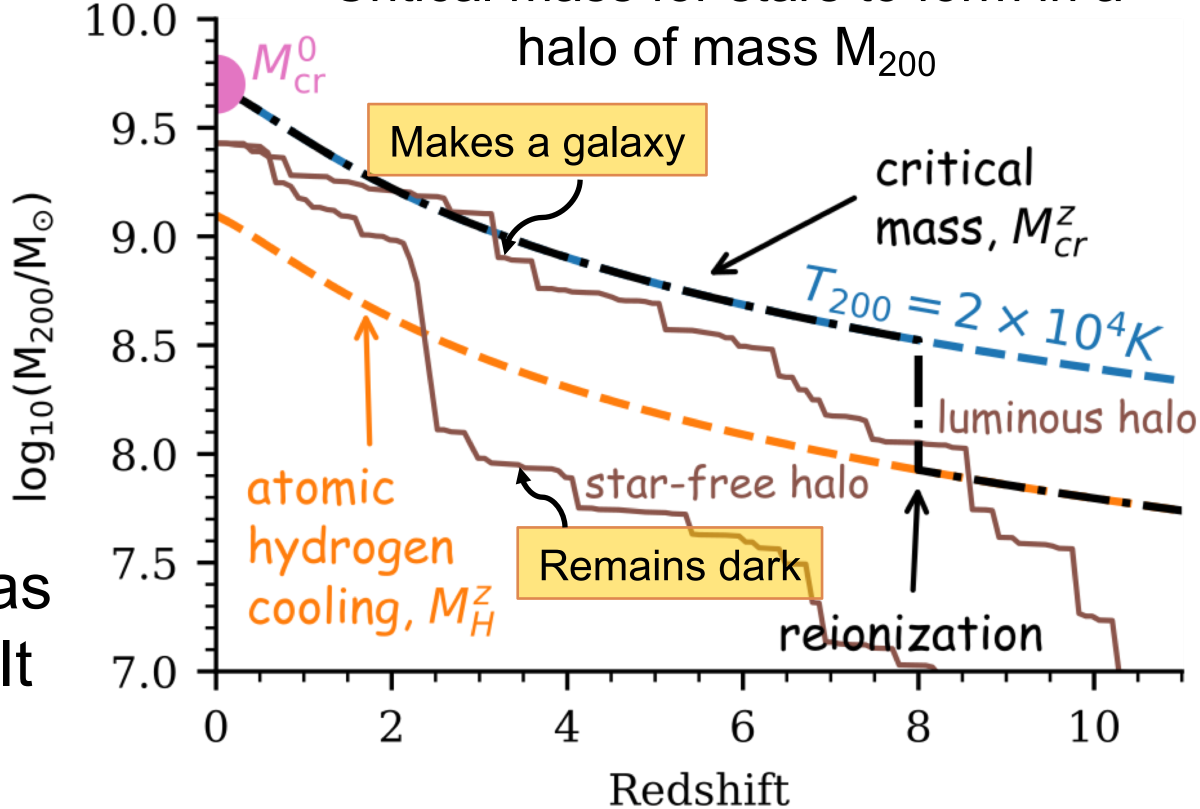
→ T>7000 K

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

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

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

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



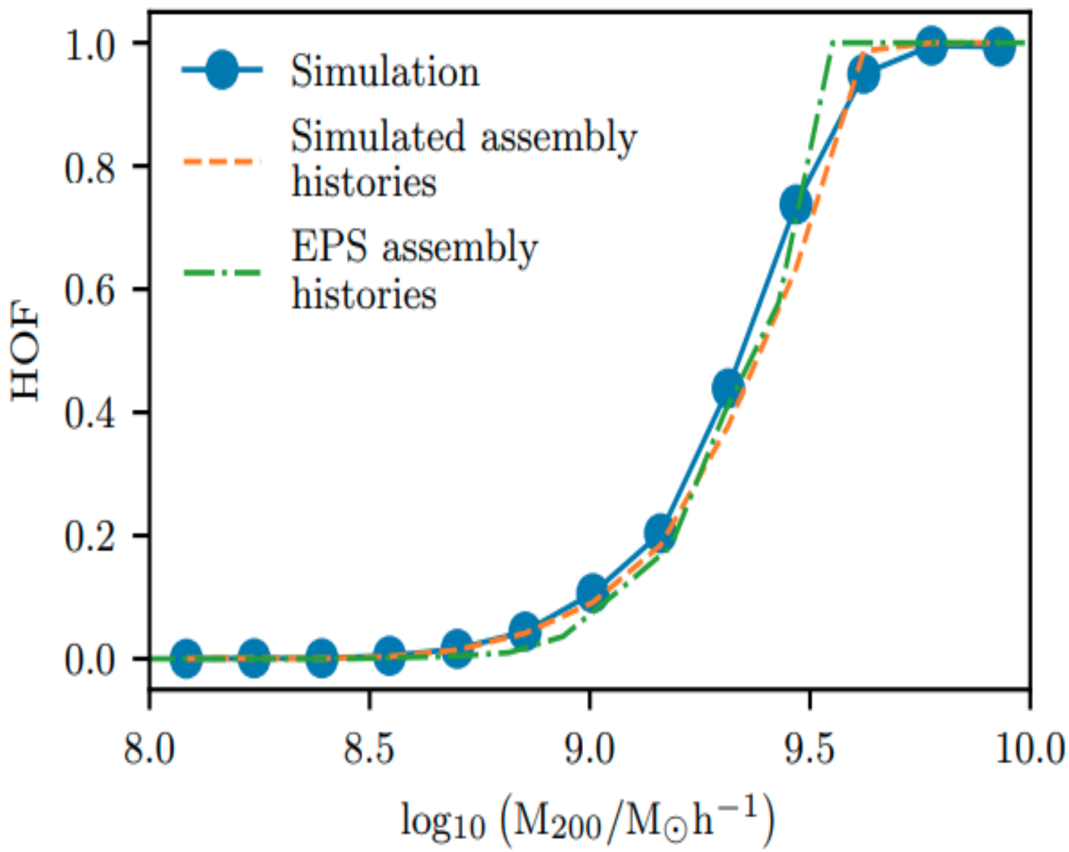
Benitez-Llambay & CSF '20

A galaxy formation primer

University of Durham

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

fraction of halos that host a galaxy

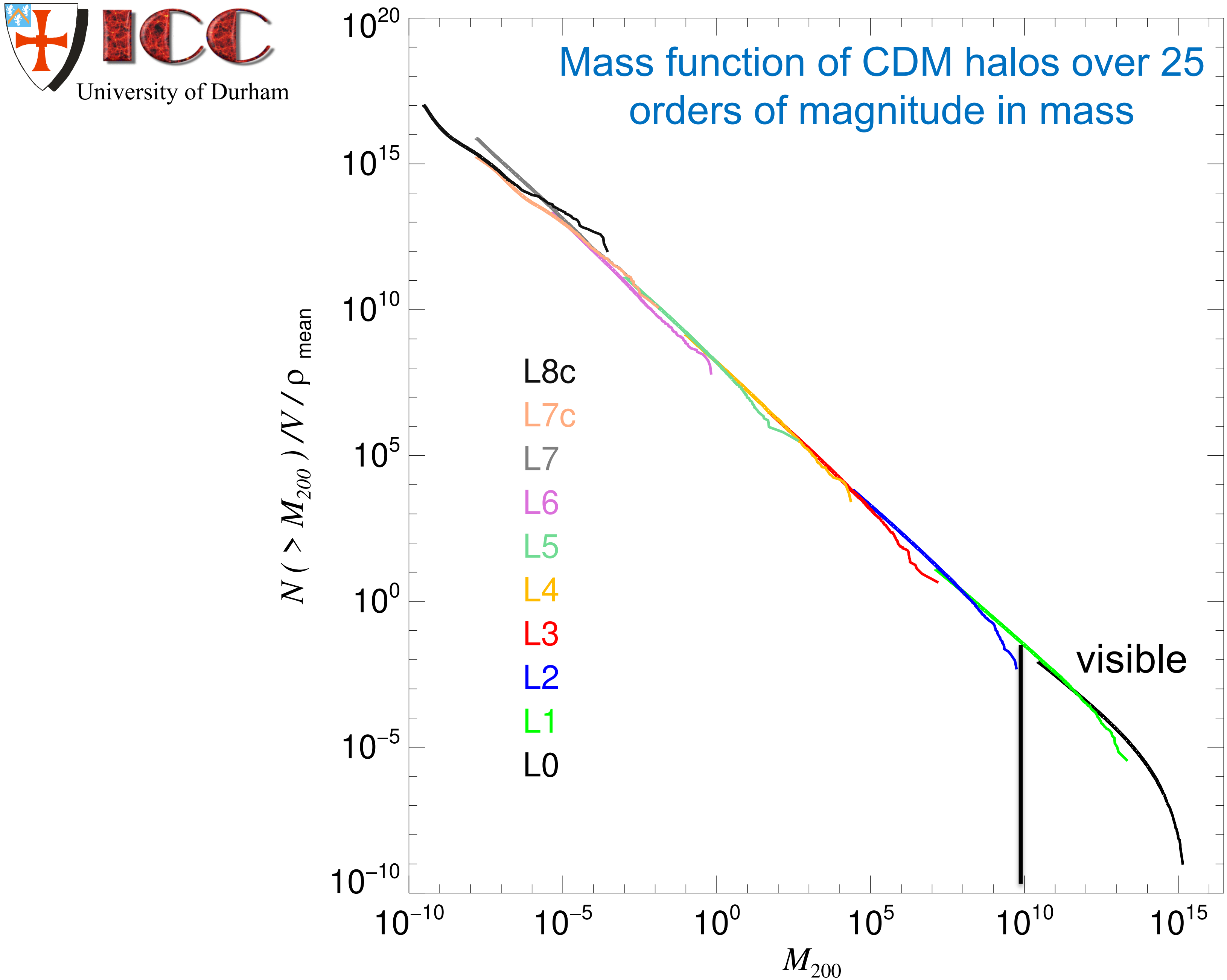


$M<3\times10^8 M_o$ → dark

$M>3\times10^9 M_o$ → visible

Benitez-Llambay & CSF '20

Institute for Computational Cosmology



Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

The small-scale "crisis": four problems

	"Solved" in:	
1. "Missing satellites"	2002	Baryon effects
2. "Too-big-to-fail"	2015	Baryon effects
3. "Core-cusp"	1996	Baryon effects
4. "Plane of satellites"	2023	

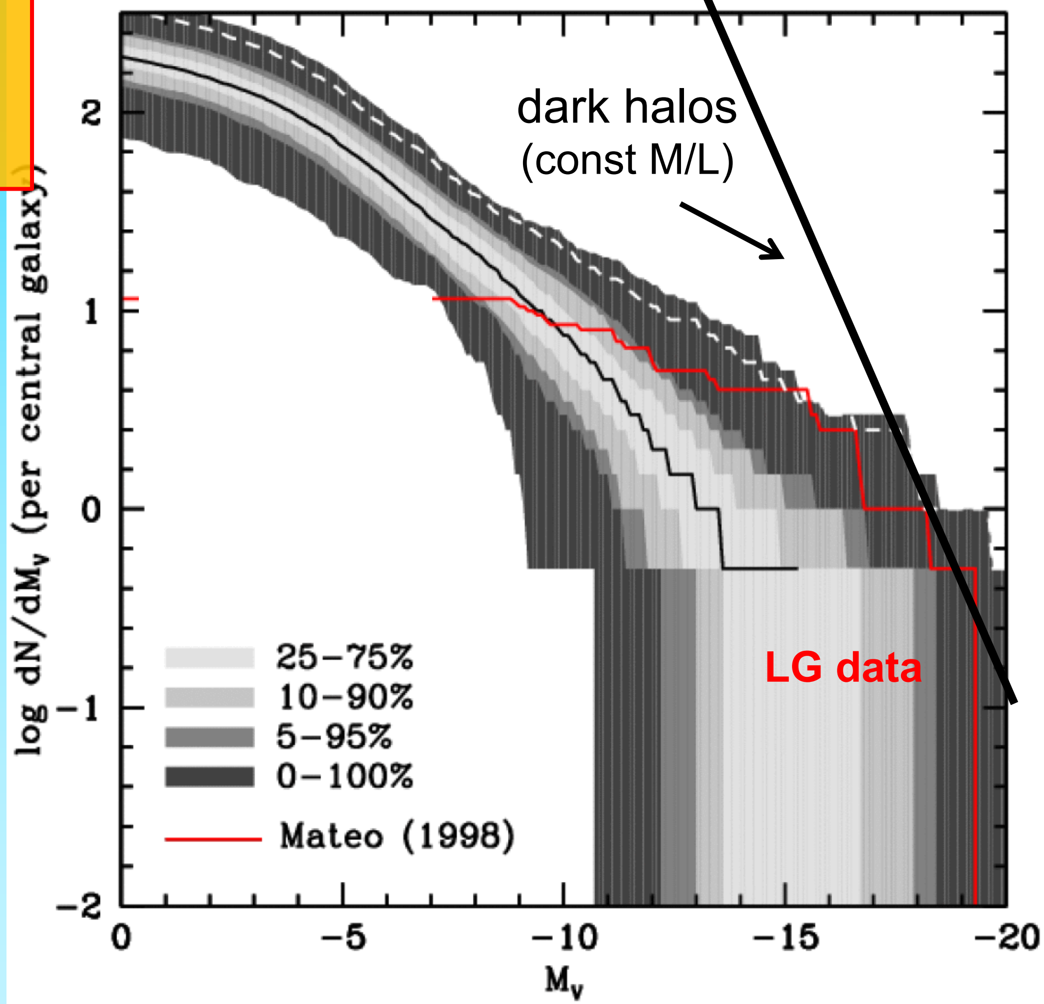

CDM
DM-only CDM simulations predict many more subhalos in the Milky Way than there are observed satellites
“Missing satellites” problem
Most subhalos never make a galaxy!

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

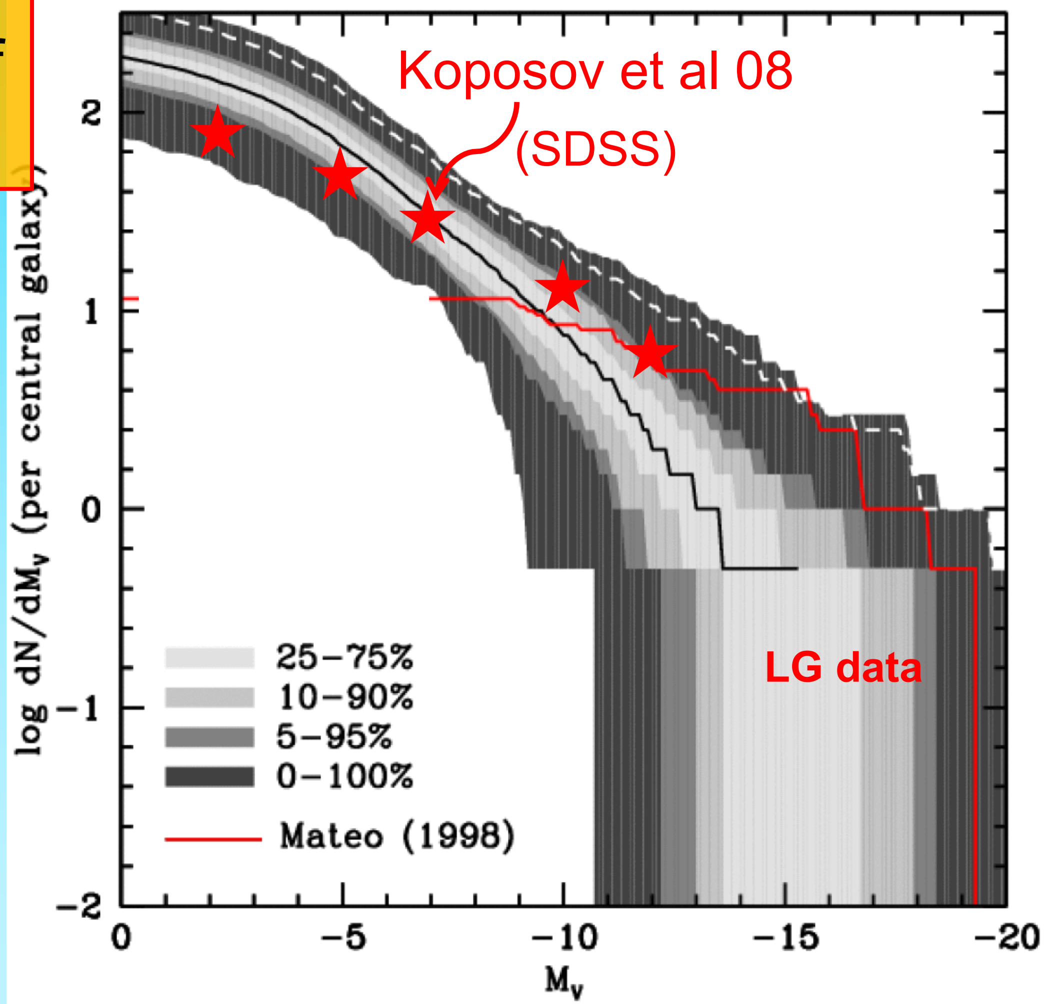
Luminosity Function of Local Group Satellites

University of Durham

Semi-analytic model of galaxy formation iqncluding 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)

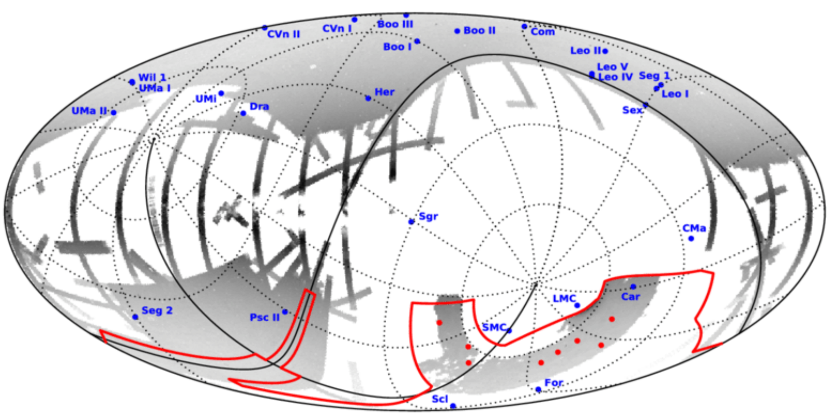
University of Durham

The plane of satellites in the MW

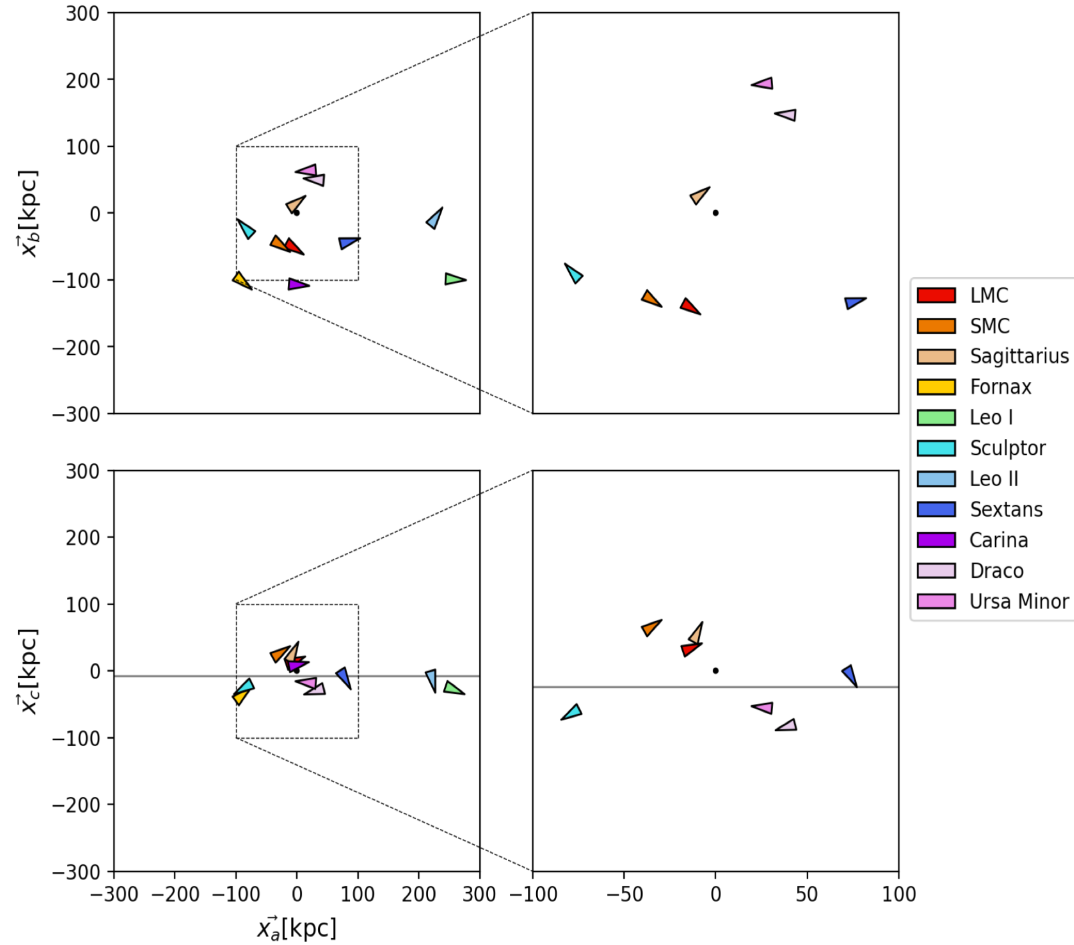
The plane of satellites in the MW

University of Durham

Problem: the 11 “classical” Milky Way satellites are in a thin, possibly rotating plane (Lynden-Bell 1976)



Bechtol+ 2015



Sawala, Cautun, CSF et al Nature Astr ‘23

Institute for Computational Cosmology

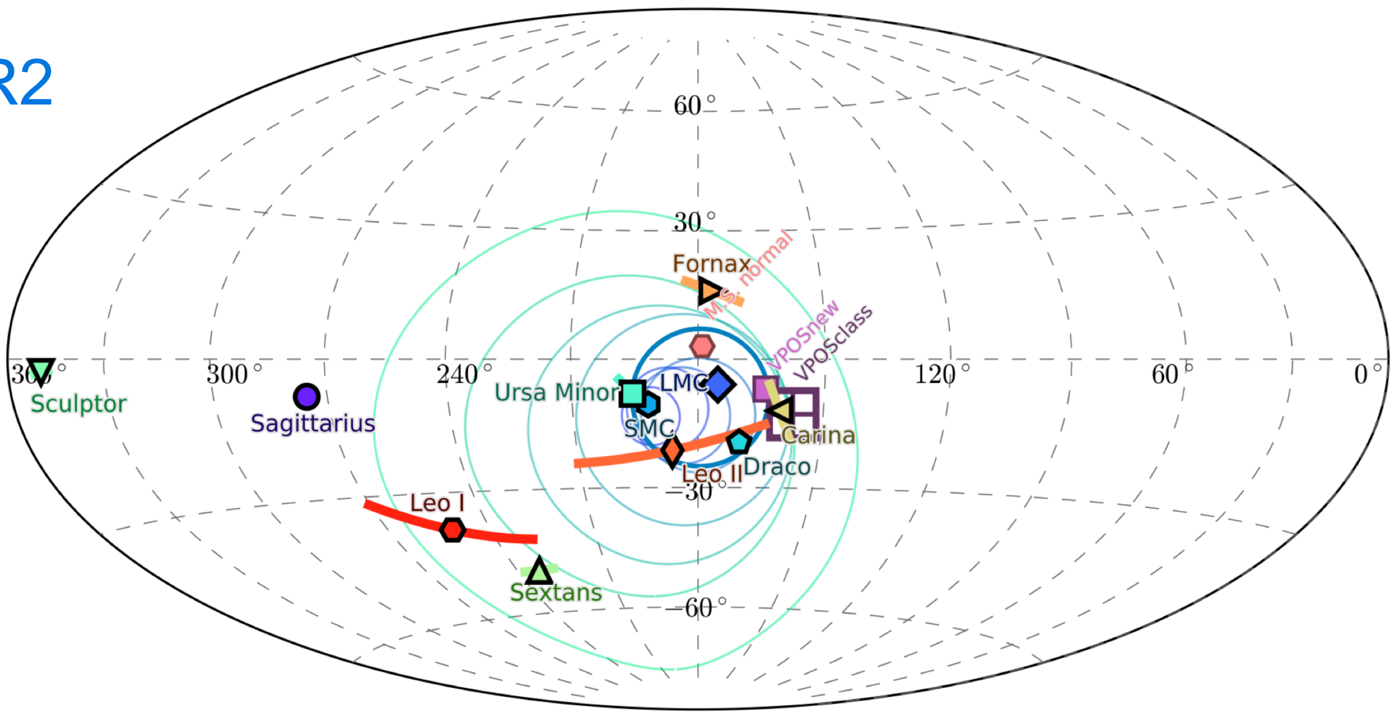
The plane of satellites in the MW

University of Durham

The plane could be a spinning disk

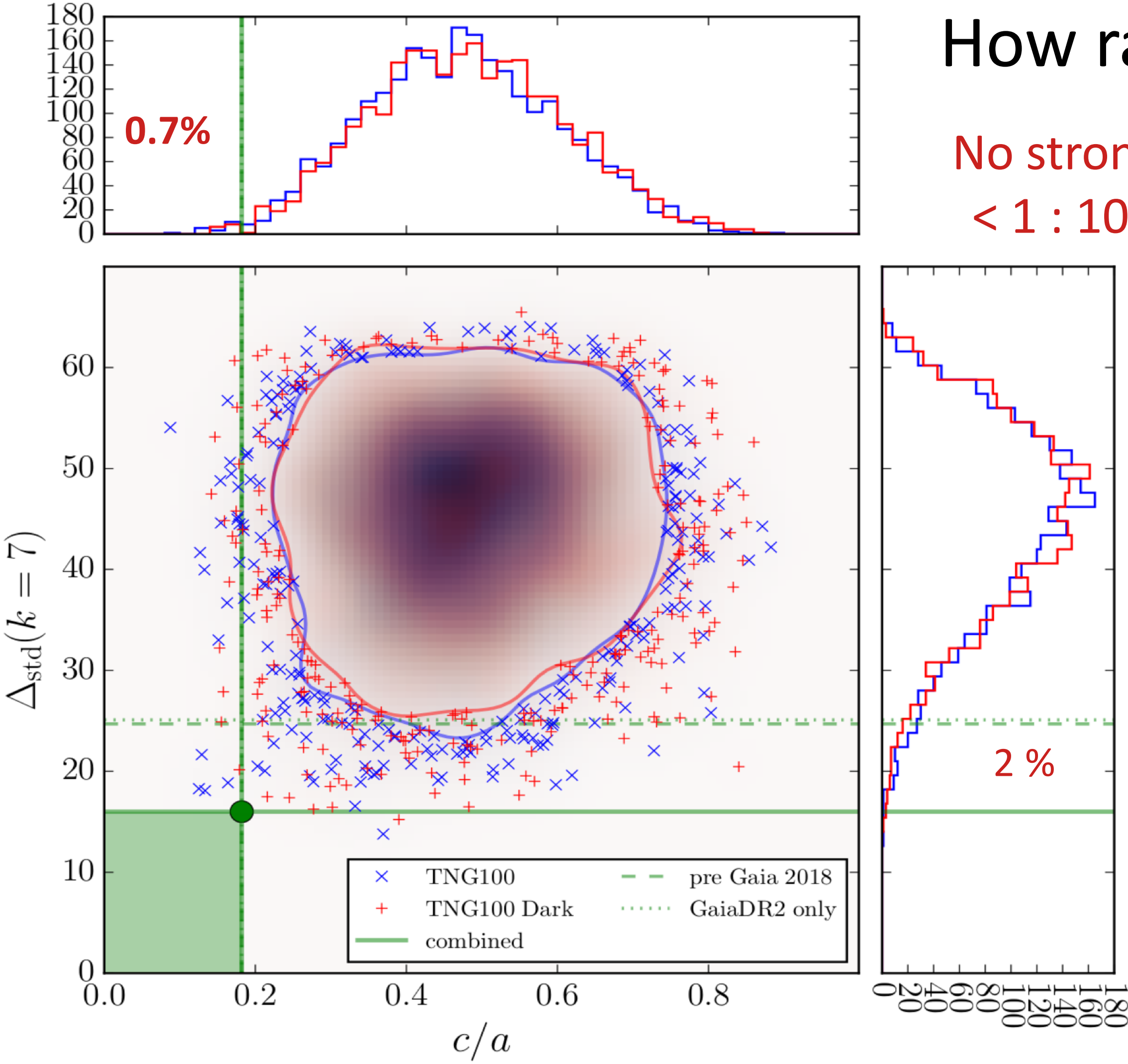
The orbital poles of 7 of the 11 satellites are clustered

GAIA DR2



Pawlowski & Kroupa (2020)

The plane of satellites in the MW



How rare is it?

No strong correlation –
< 1 : 100,000 chance?

Eigenvalues of inertia tensor

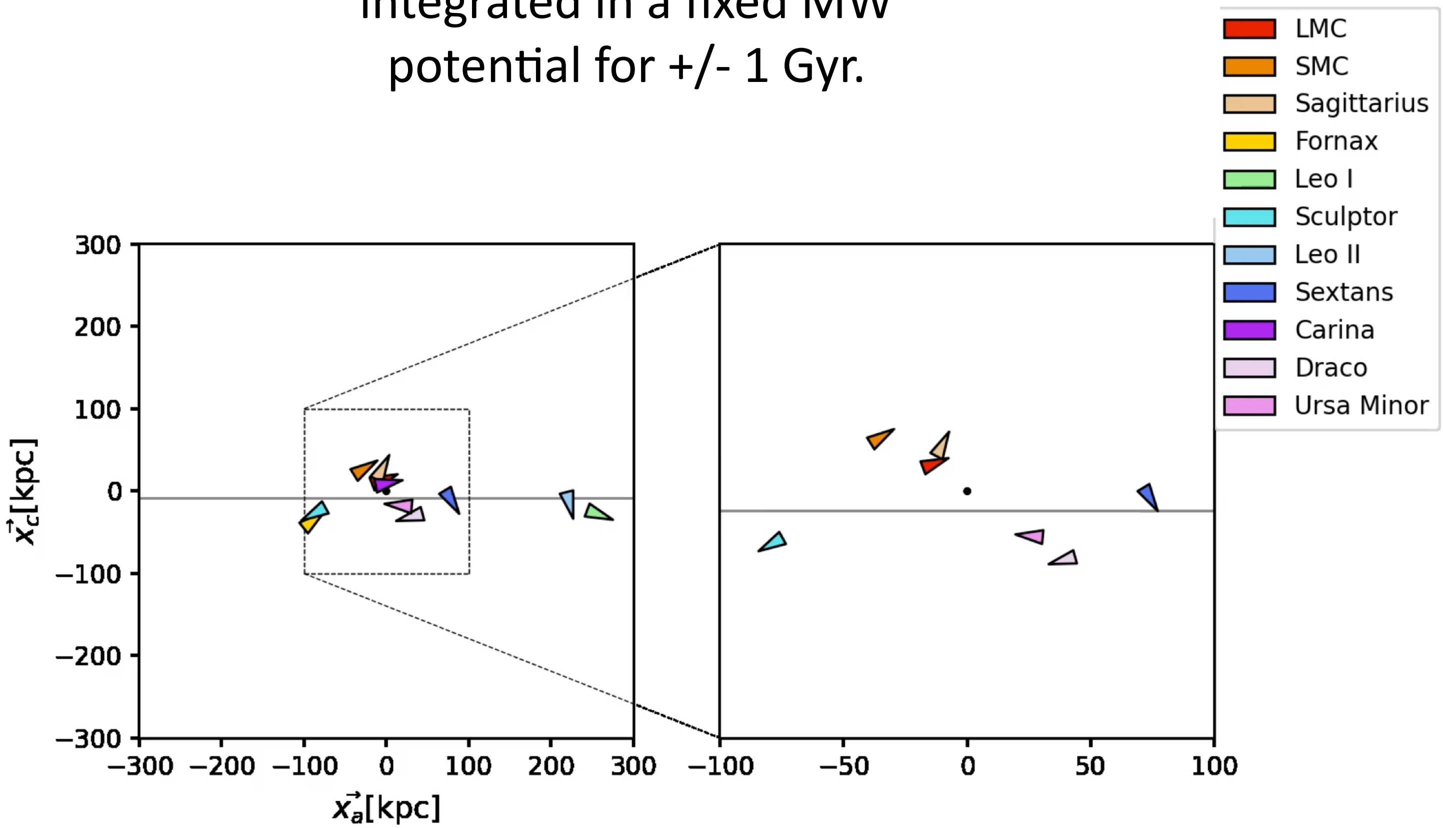
a>b>c

Pawlowski & Kroupa (2020)

University of Durham

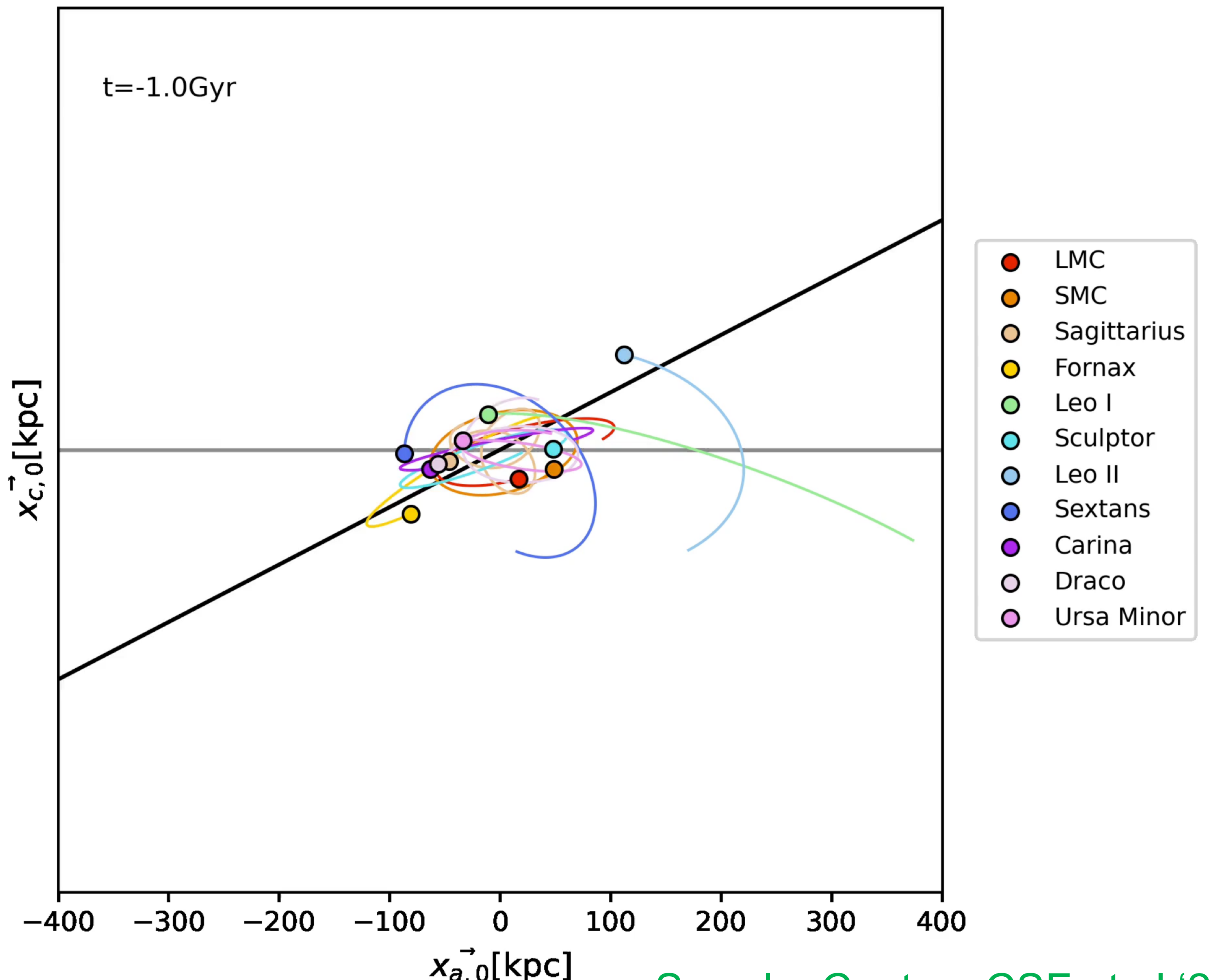
Institute for Computational Cosmology

Gaia EDR3 proper motions, integrated in a fixed MW potential for +/- 1 Gyr.



Sawala, Cautun, CSF et al '23

The MW plane of satellites is transient



Sawala, Cautun, CSF et al ‘23

University of Durham

The rotating plane of satellites

200 ΛCDM N-body simulations of Local Group analogues: $m_p=1x10^6 M_o$

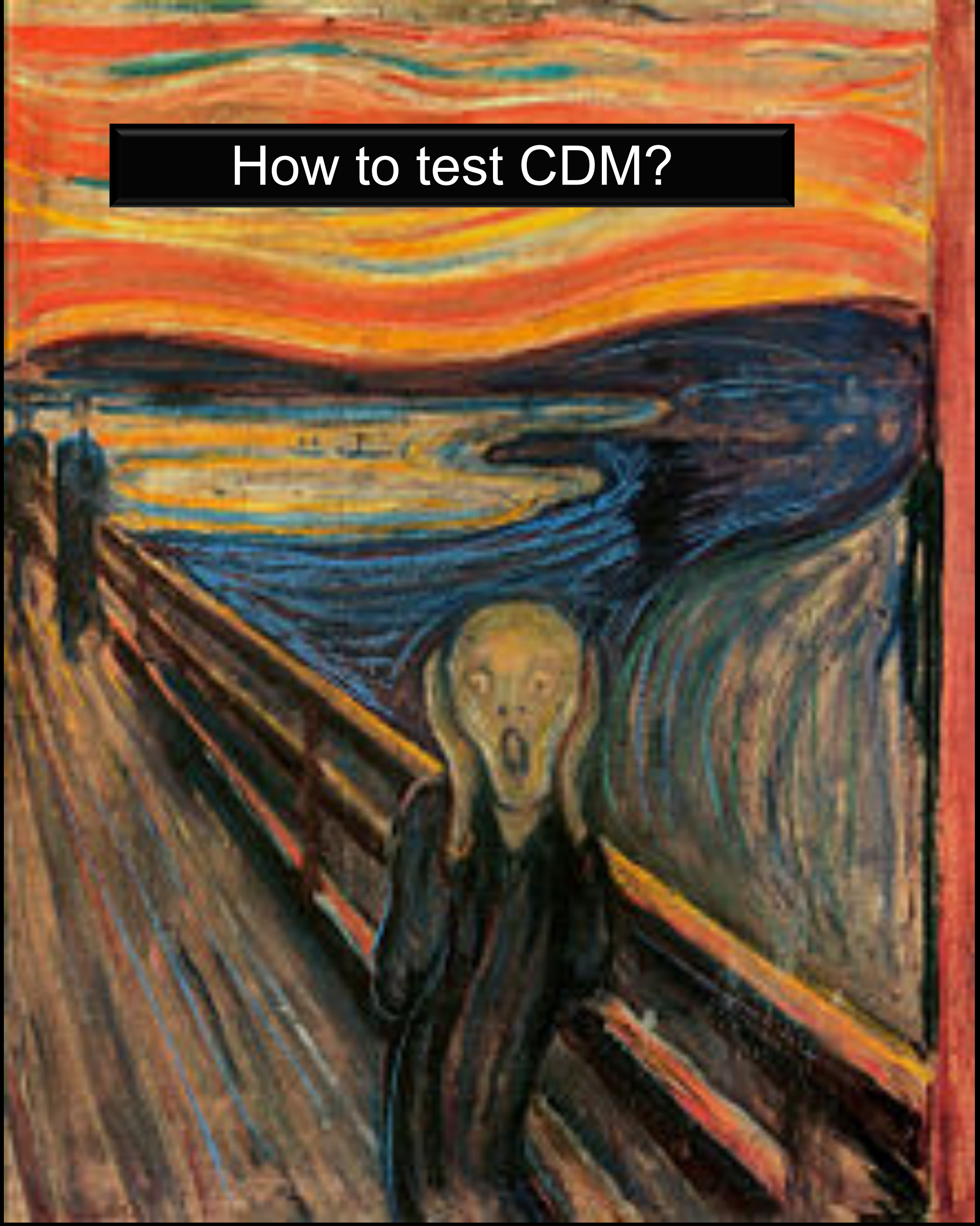
We have 5/200 (2.5%) more clustered than the MW (compared to 0.04%)

Still rare, but not *astronomically* unlikely

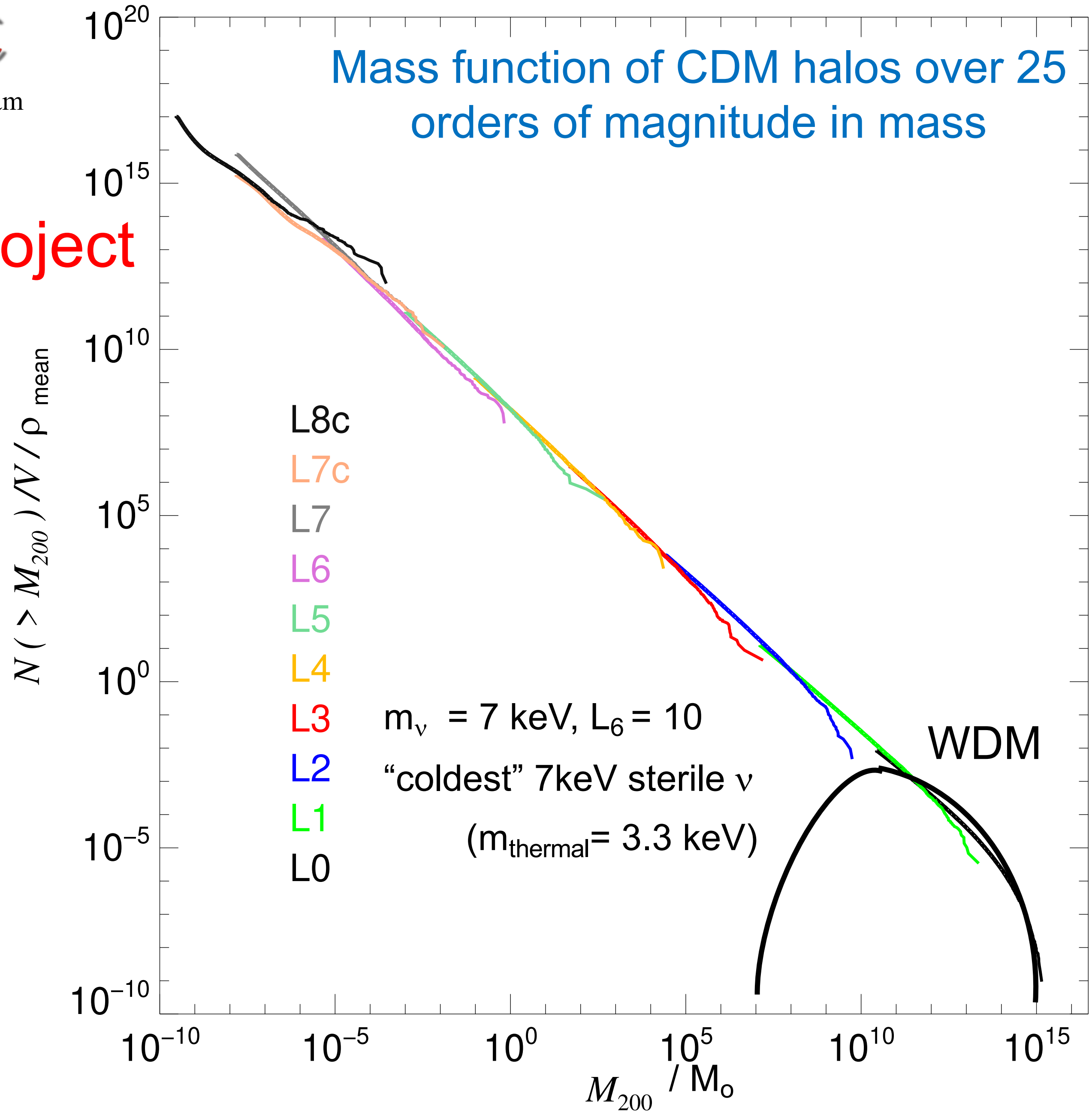
Sawala, Cautun, CSF+ Nat Astr '22

Institute for Computational Cosmology

How to test CDM?



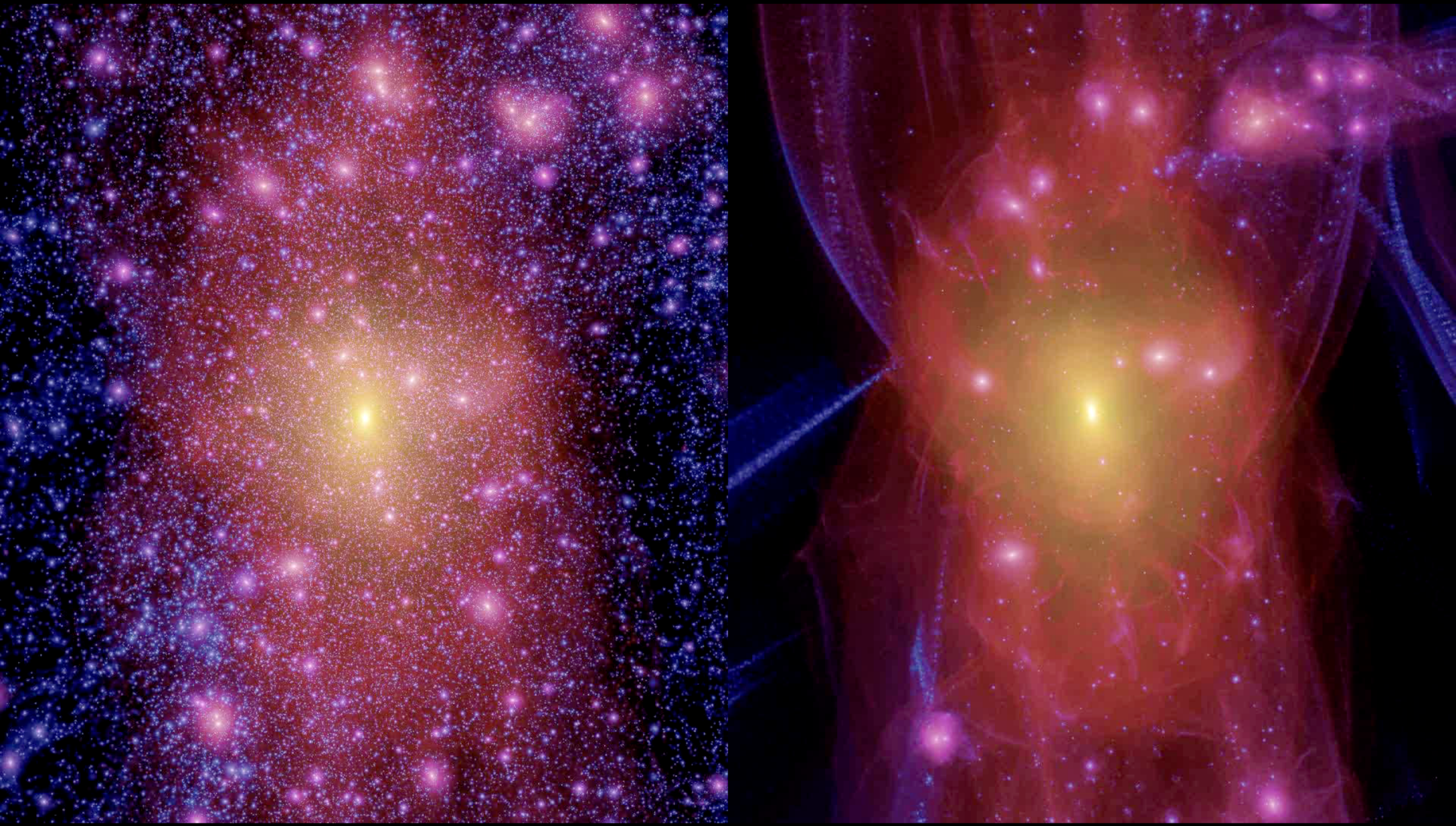
The VVV project



Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

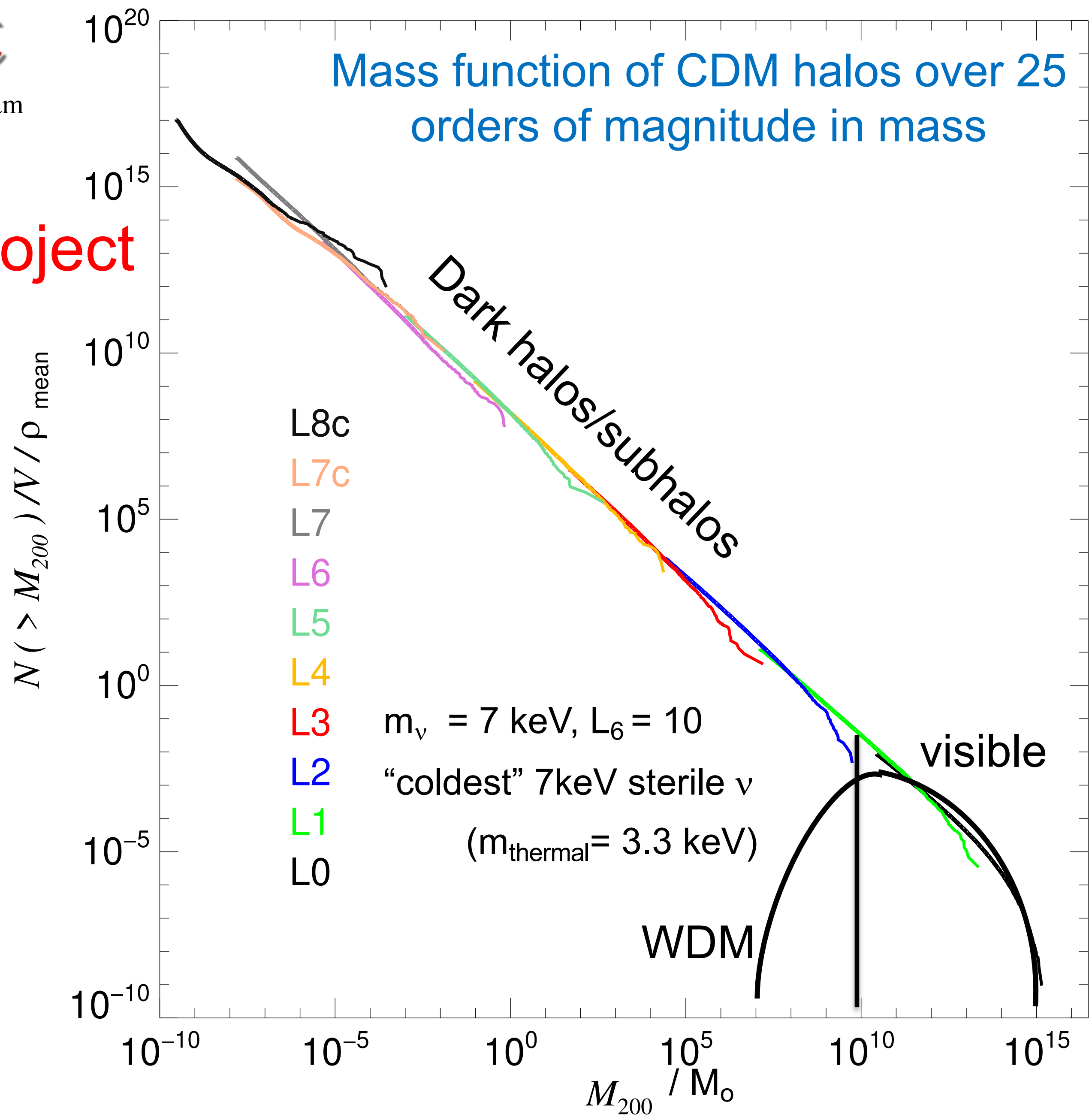
cold dark matter

warm dark matter



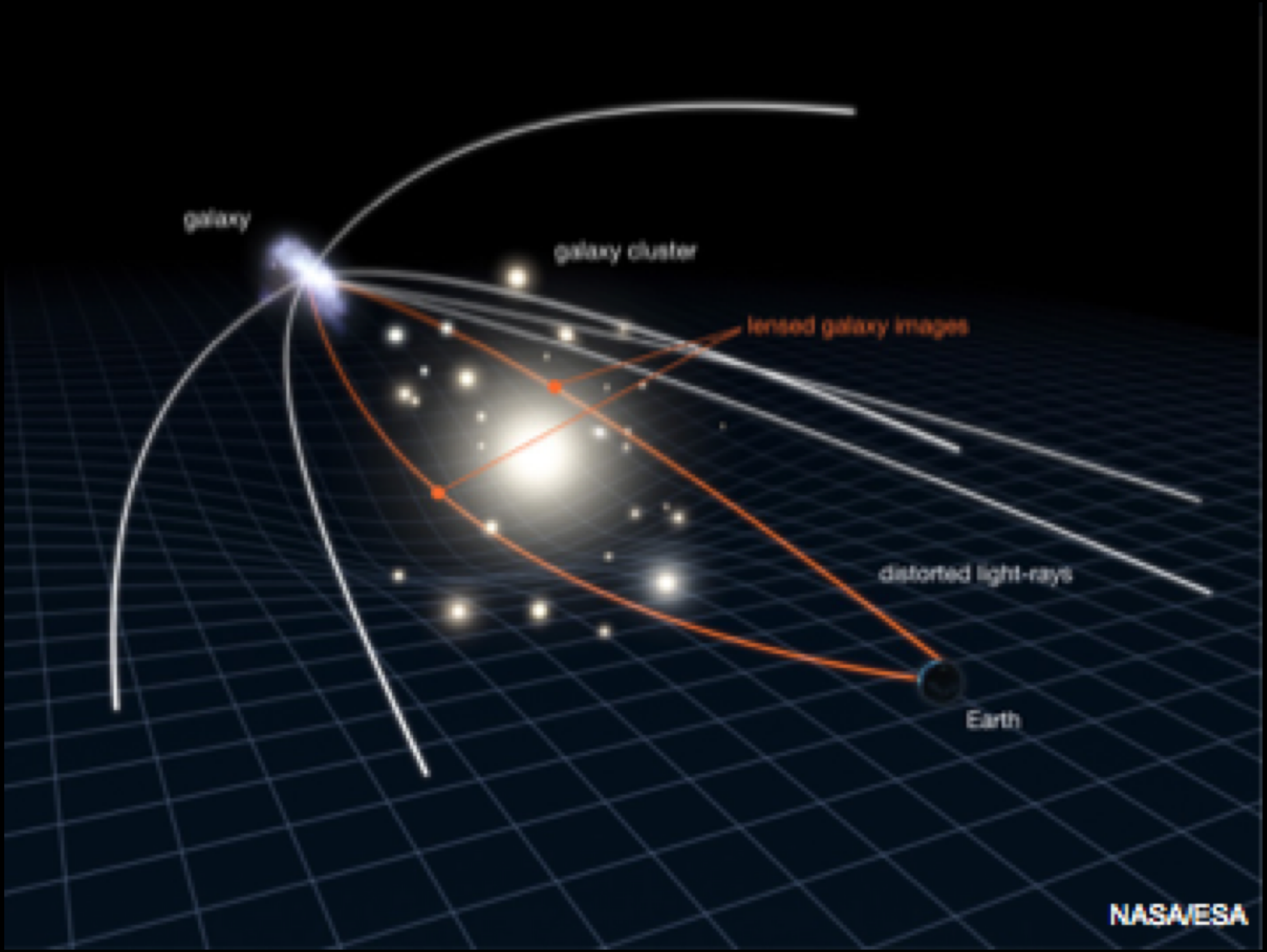
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

The VVV project



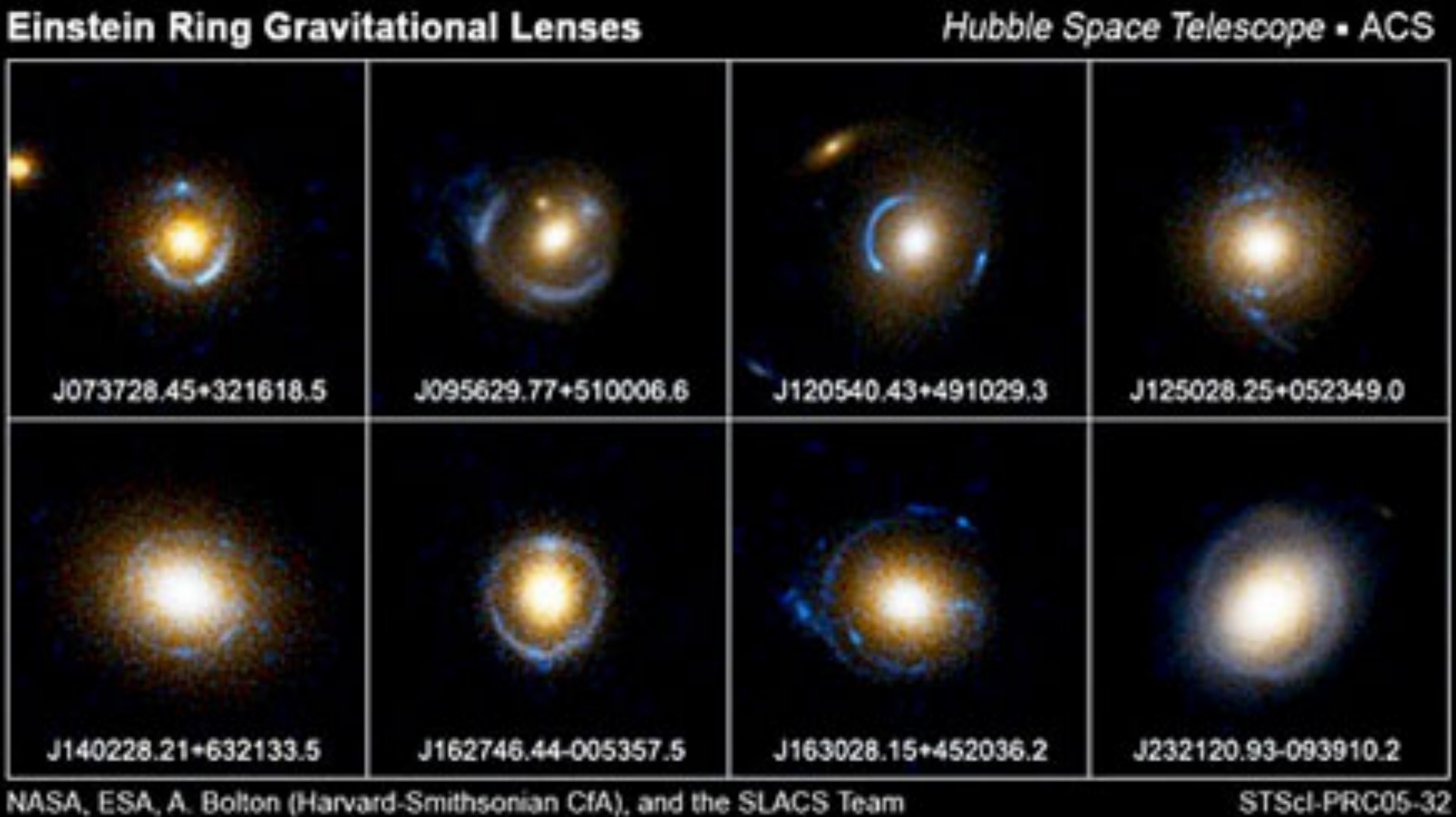
Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

Gravitational lensing: Einstein rings

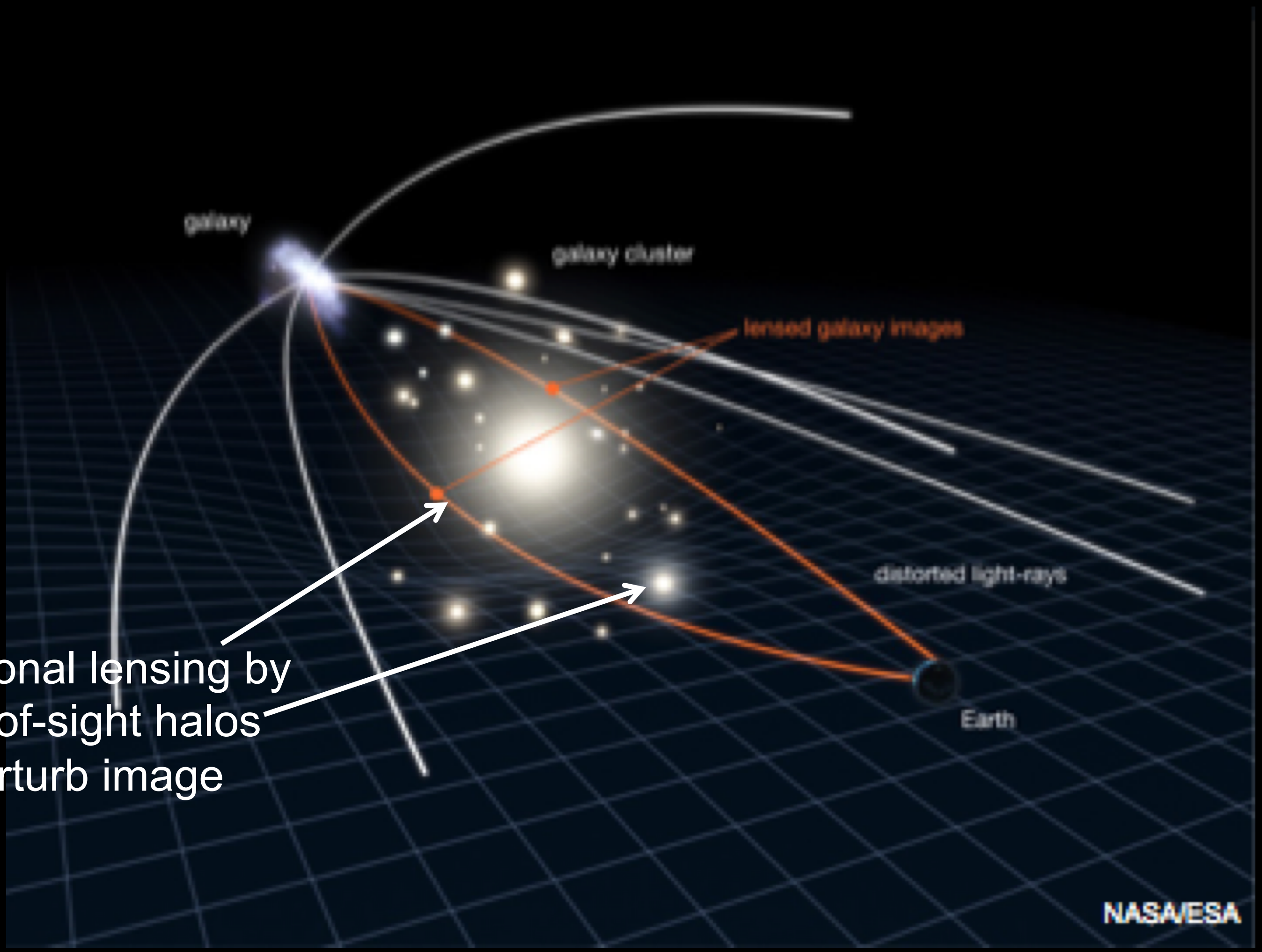


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

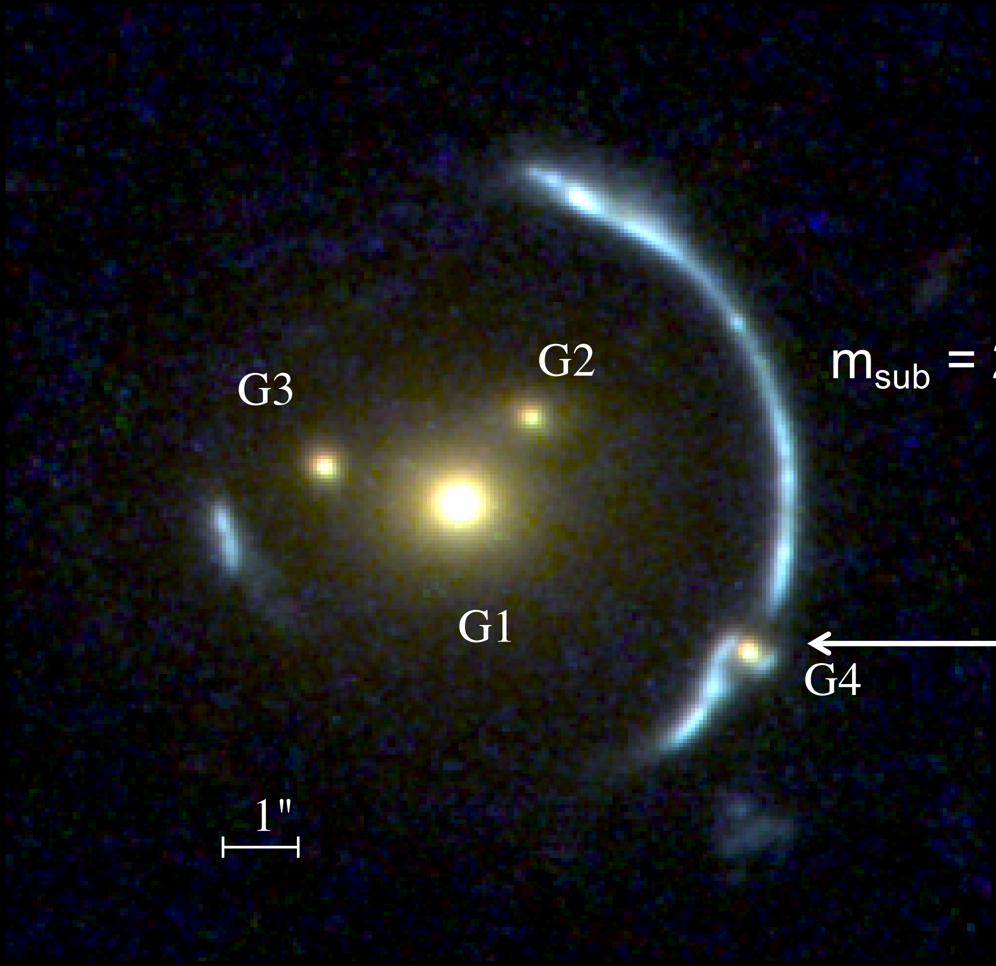


Additional lensing by line-of-sight halos perturb image

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

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



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

Vegetti et al '10

Gravitational lensing: substructures

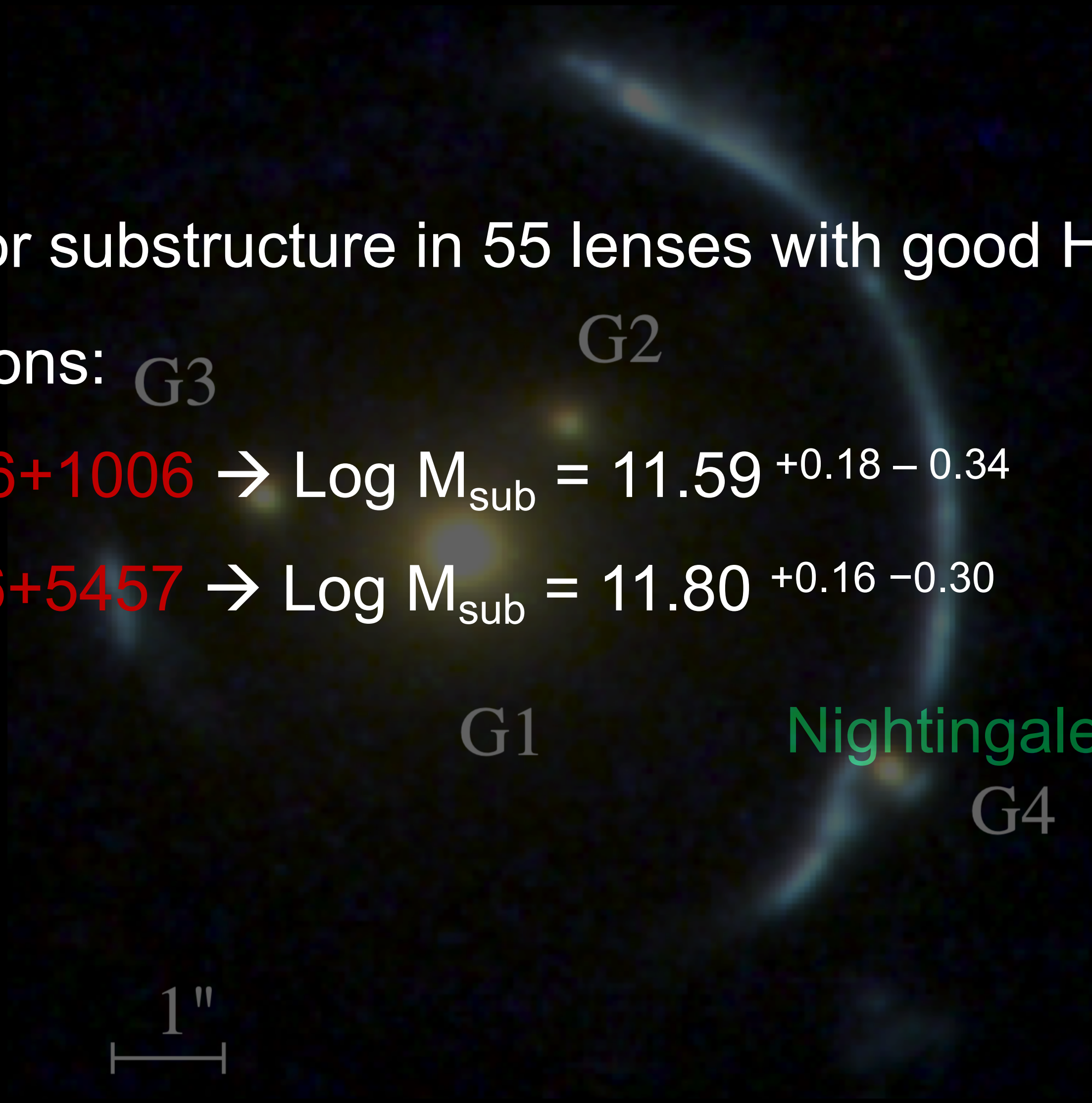
Searched for substructure in 55 lenses with good HST imaging

→ 2 detections:

SLACS0946+1006 → Log M_{sub} = 11.59 $^{+0.18\,-0.34}$

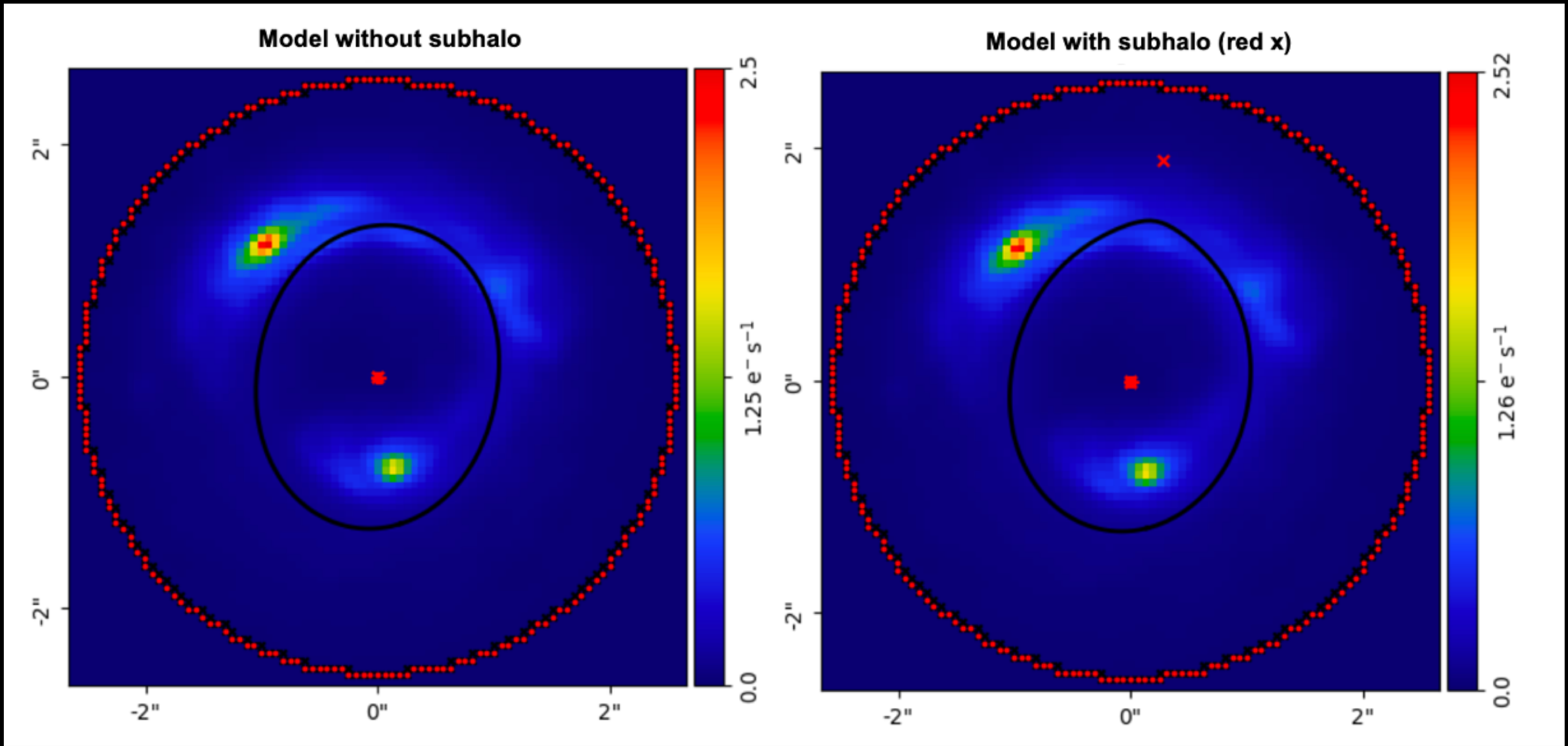
BELLS1226+5457 → Log M_{sub} = 11.80 $^{+0.16\,-0.30}$

Nightingale + ‘22



Gravitational lensing: substructures

JWST



And another one in JWST data:

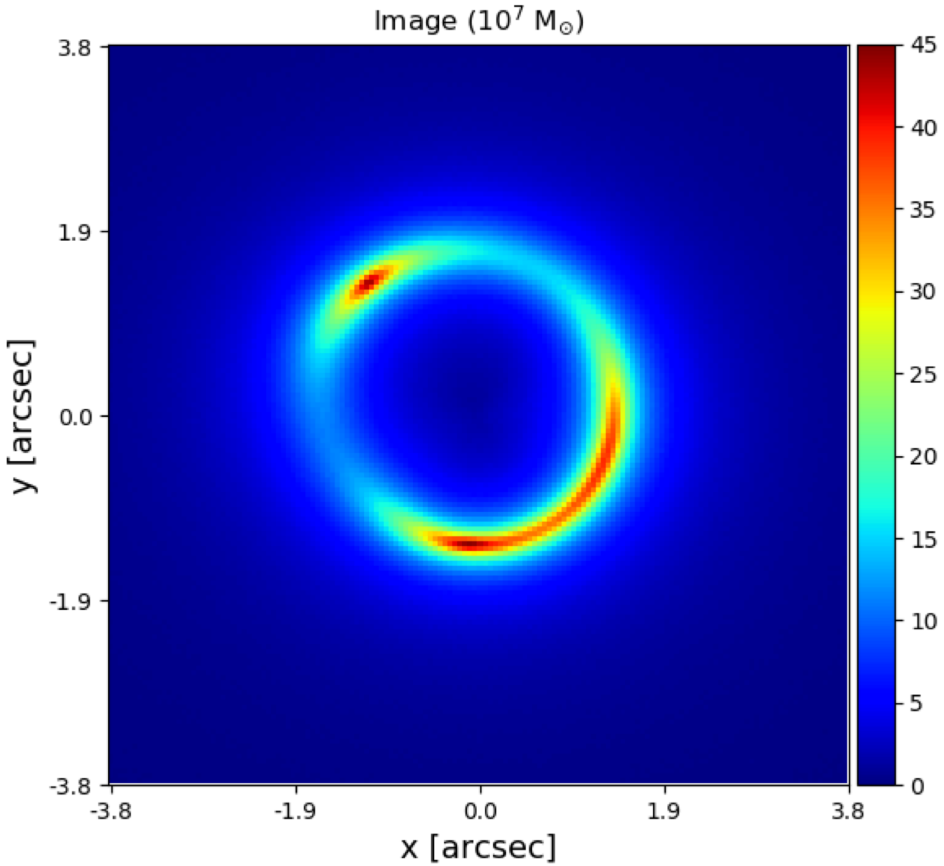
→ Log M_{sub} = 11.59 $^{+0.18\,-\,0.34}$

Lange, Nightingale, CSF+ '23

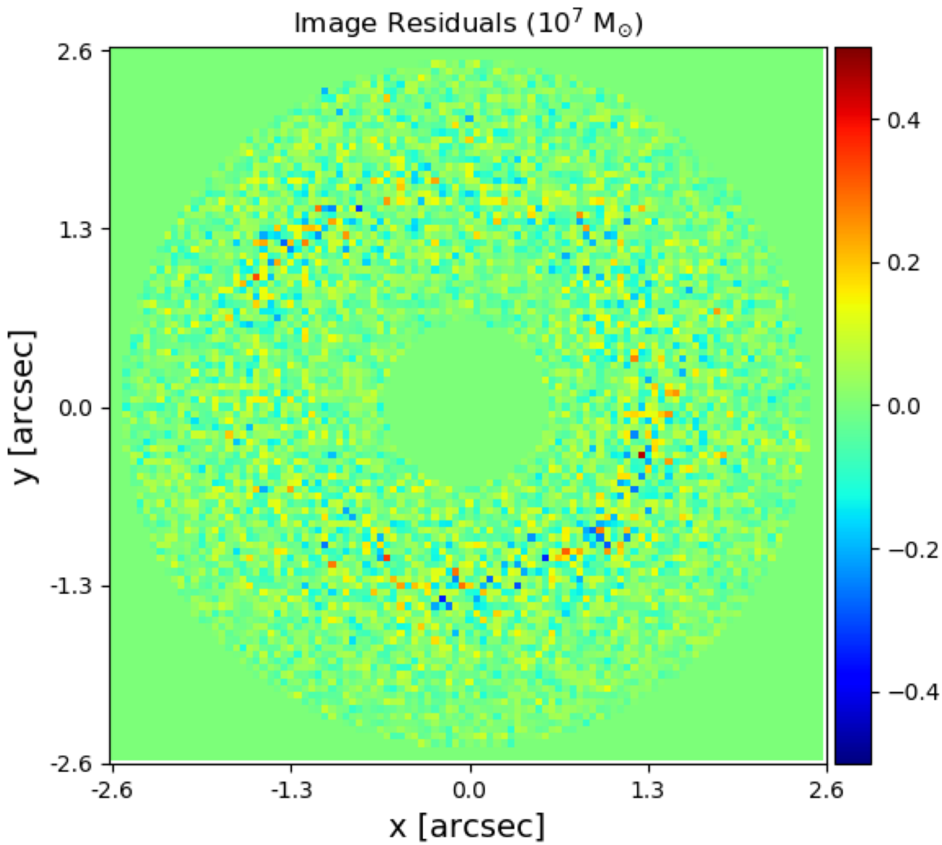
Strong lensing: detecting small halos

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

Image



Residuals (image – smooth model)



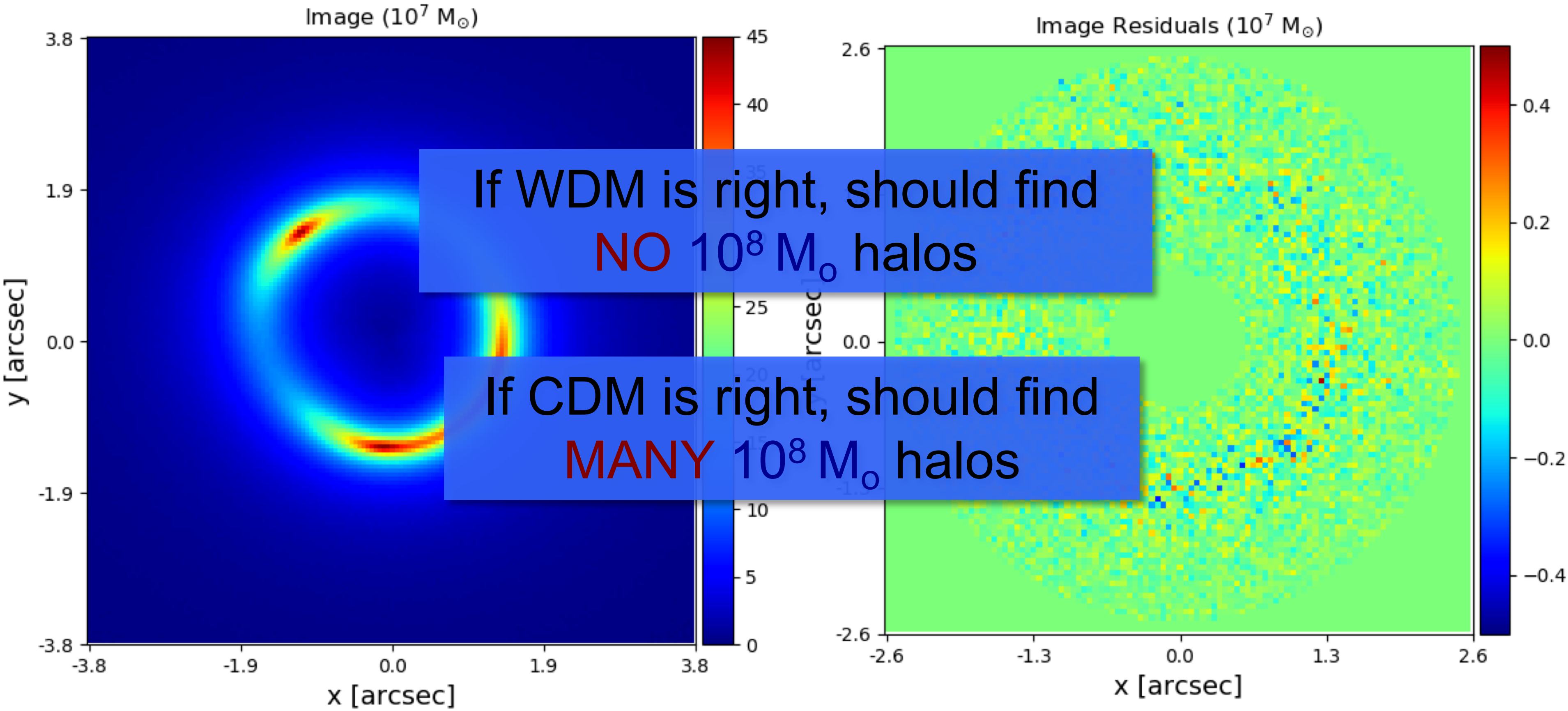
He, Li, CSF et al '19

Detecting halos w. strong lensing

University of Durham

ICC

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



If WDM is right, should find NO 10^8 M_o halos

If CDM is right, should find MANY 10^8 M_o halos

He, Li, CSF et al ‘19

Conclusions

- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution
- But on these scales ΛCDM cannot be distinguished from WDM
- Need to test ΛCDM on non-linear scales
- Non-linear DM problem solved: halo abundance, structure, distr.
- Halos of $M < 5.10^8 M_0$ are dark; halos of $> 5.10^9 M_0$ have a galaxy
- Satellite , TBTF, core/cusp "problems" in CDM → baryon effects
- Distortions of strong gravitational lenses → detect small haloes

→ offer a clean test of CDM *vs* WDM

→ can potentially rule out CDM!