Cosmology in our backyard

Carlos S. Frenk
Institute for Computational Cosmology, Durham

cold dark matter

ΛCDM: the standard model of cosmology

cosmological constant

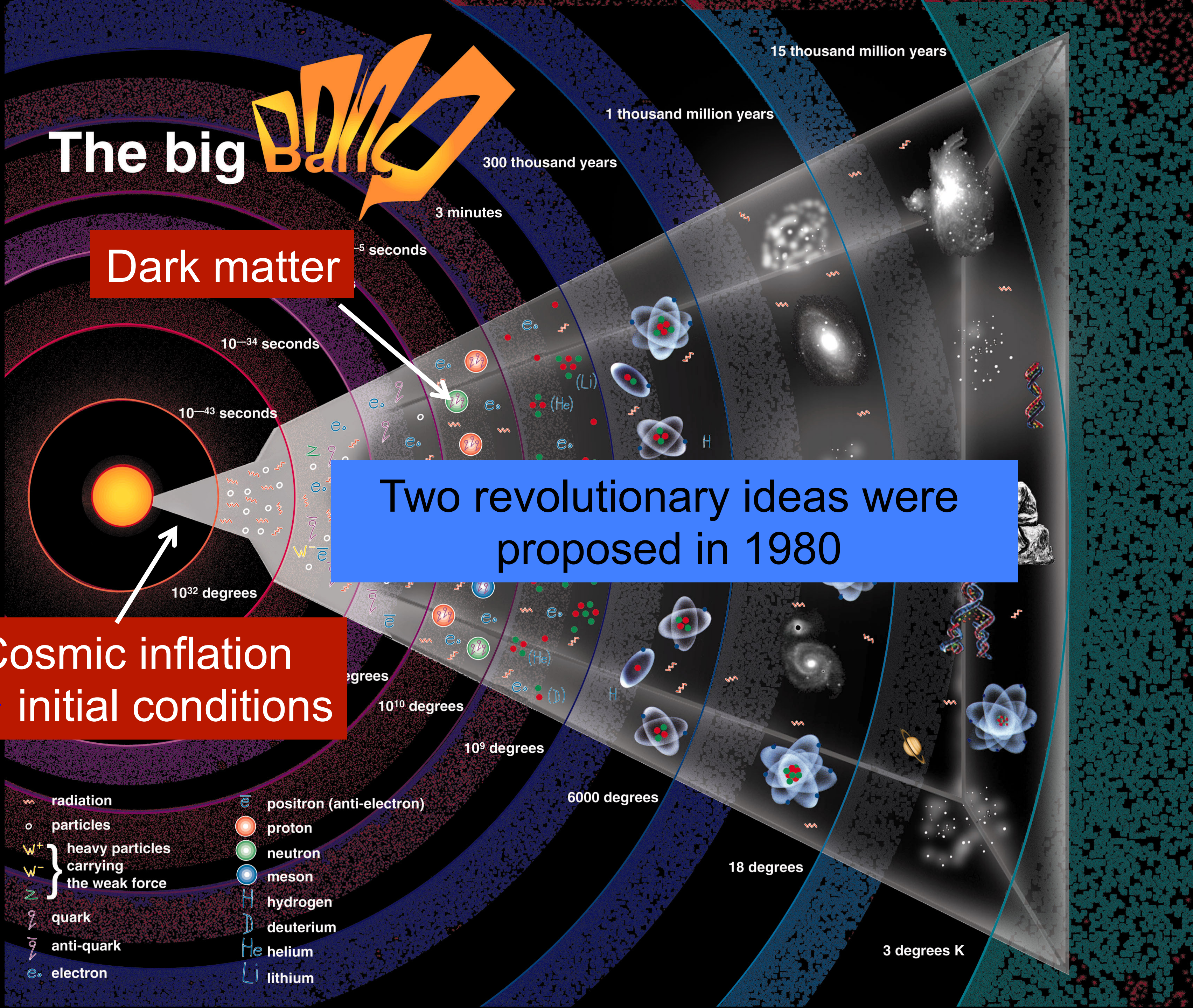
Why is this the standard model?

New tests and possible problems

Two revolutionary ideas were proposed in 1980

Dark matter

Cosmic inflation → initial conditions



Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm		keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

University of Durham

The dark matter power spectrum

Free streaming →

λ_{cut} α m_x^{-1}

for thermal relic

m_{CDM} ~ 100GeV

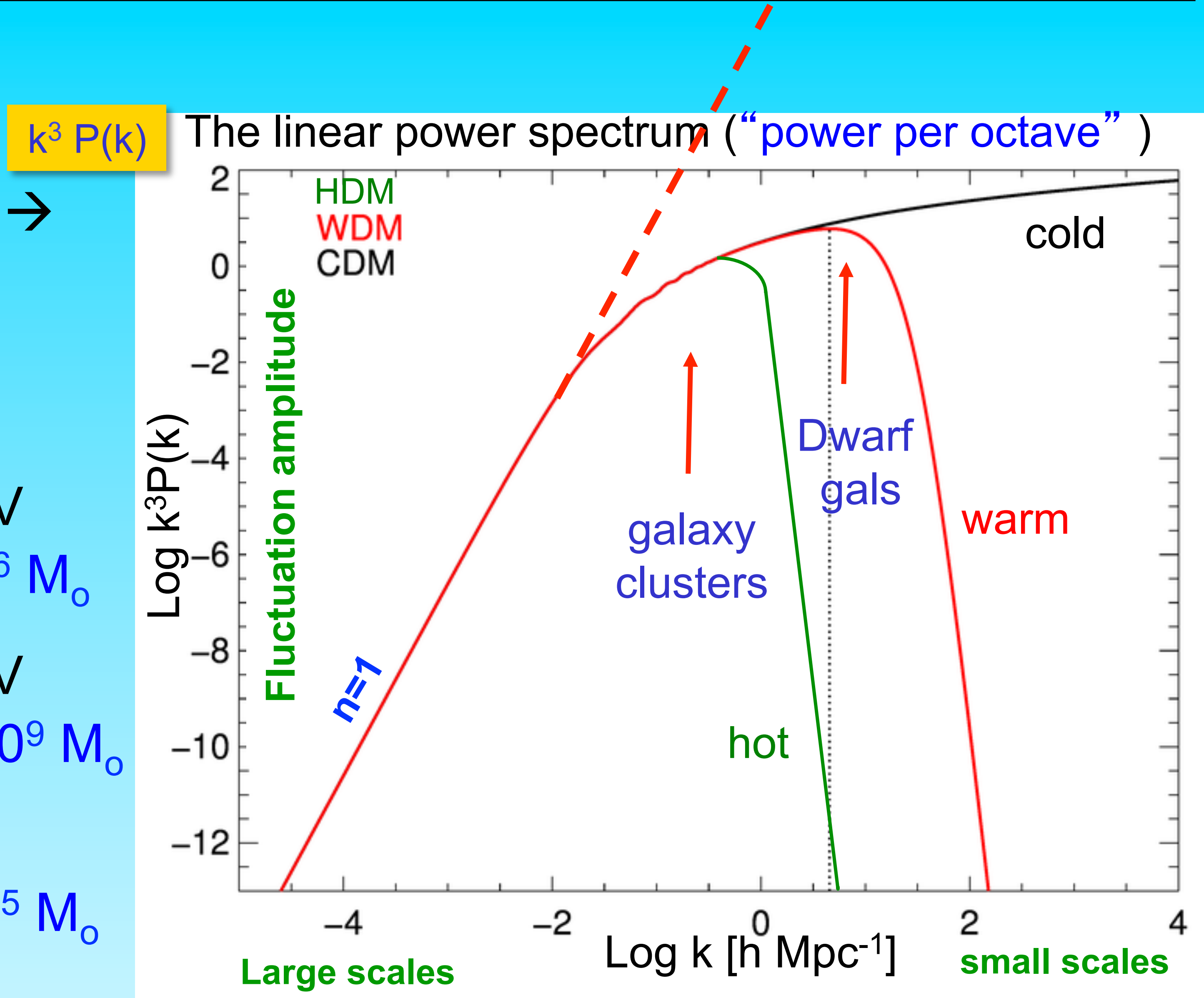
susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV

sterile ν; M_{cut}~10^9 M_o

m_{HDM} ~ few eV

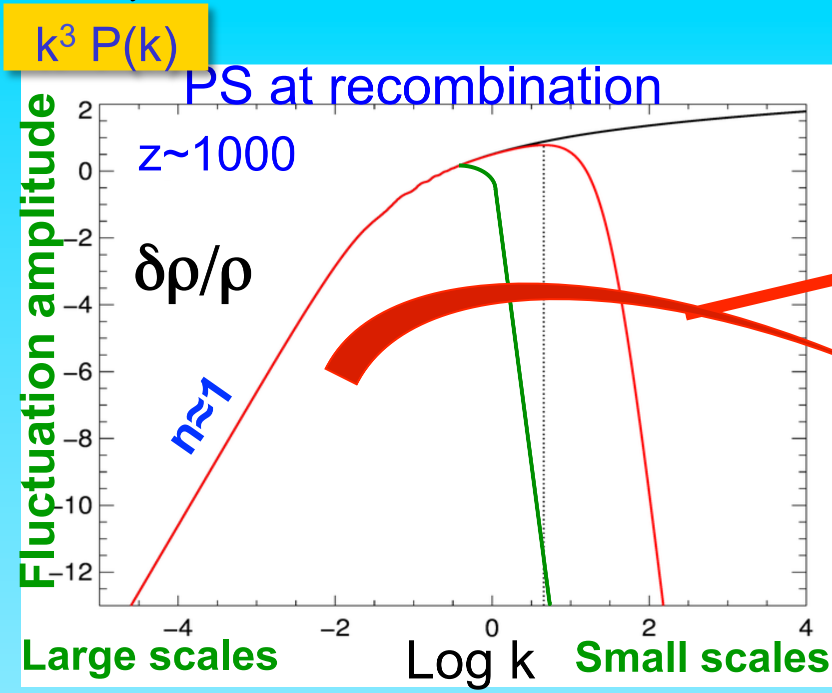
light ν; M_{cut}~10^{15} M_o

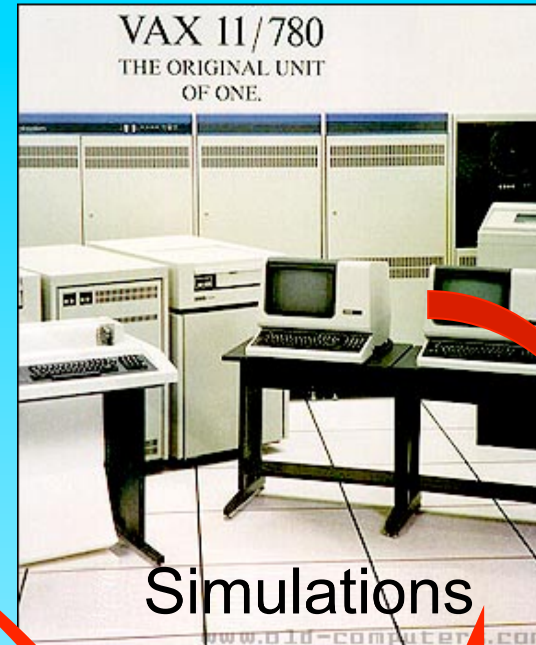


For the first time in Cosmology → a well-defined theory of the initial conditions for the formation of cosmic structure

The formation of cosmic structure

University of Durham





t=380,000 yrs

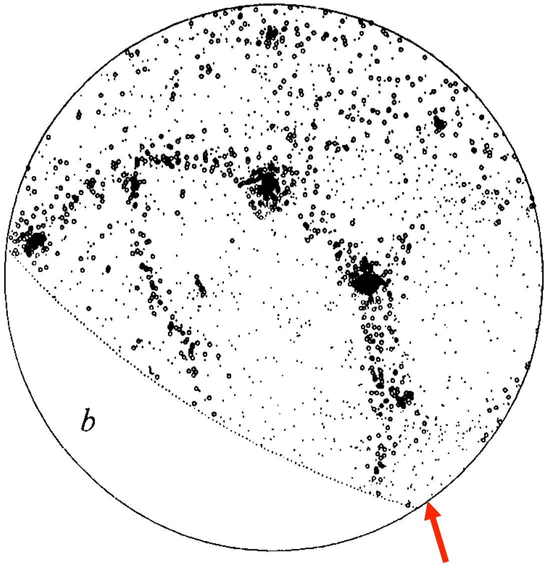
$\delta\rho/\rho \sim 10^{-5}$

Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

t=14.1billion yrs

$\delta\rho/\rho \sim 1-10^{6}$

Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

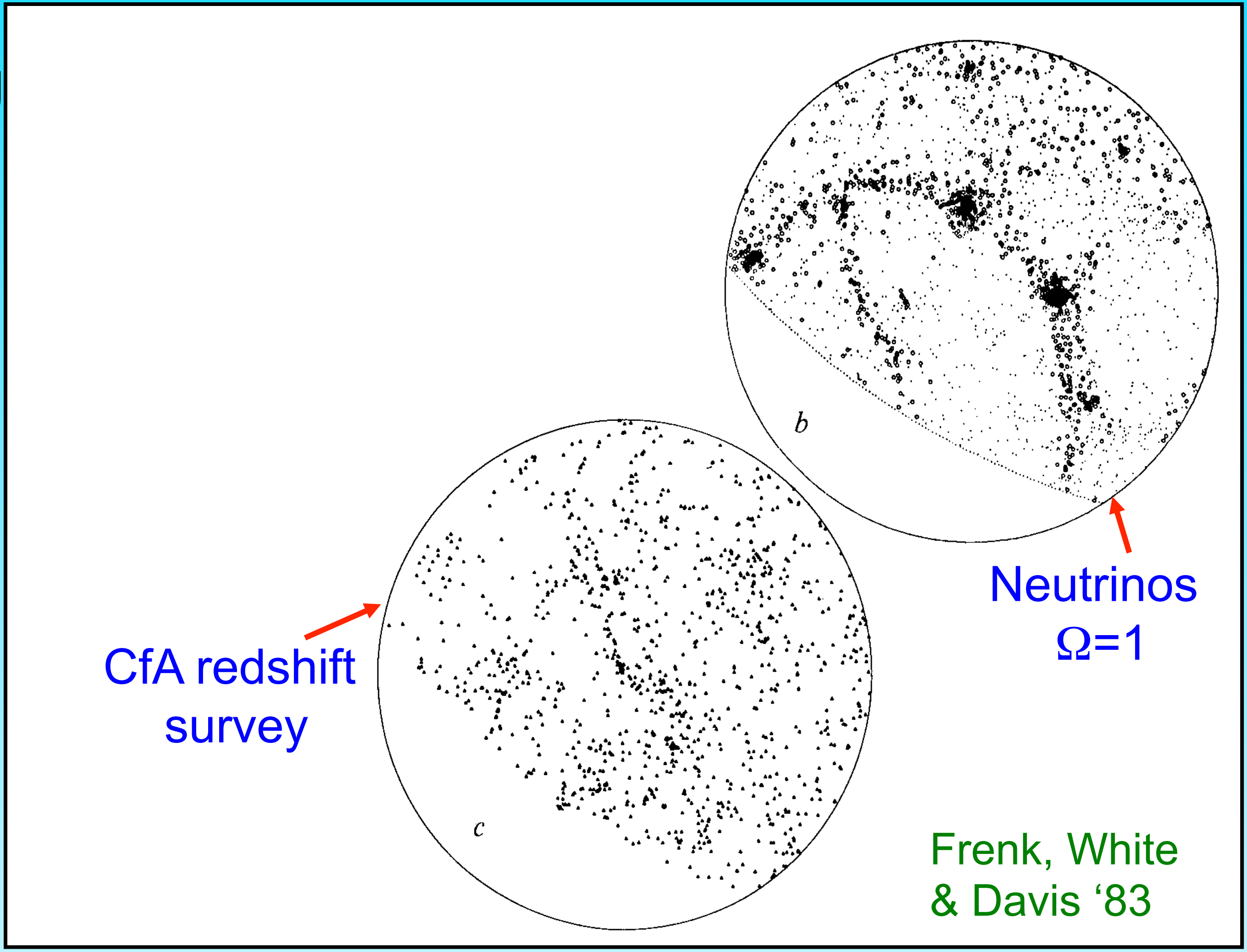
'85

Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust' ing

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 10 ev



University of Durham

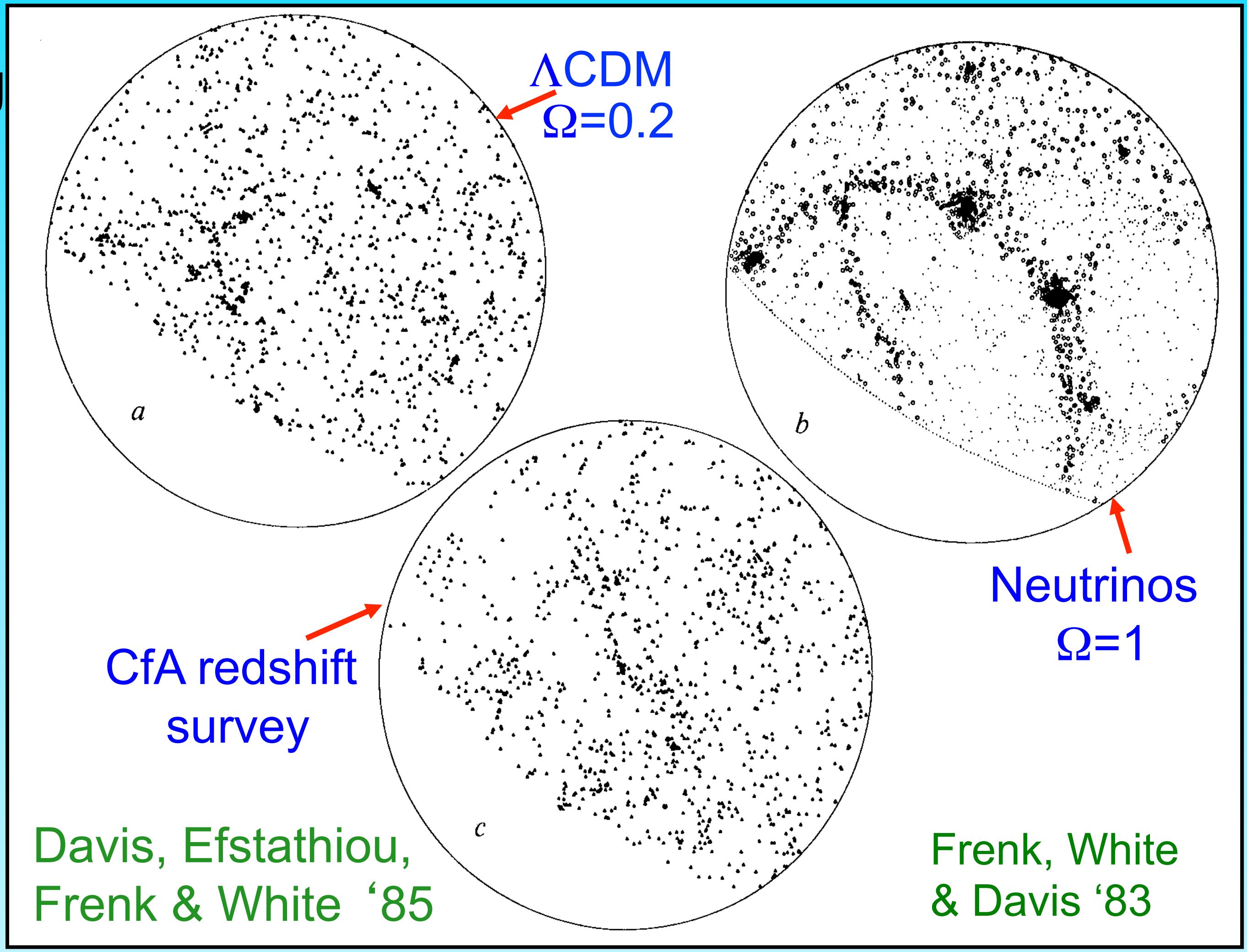
Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust’ing

Neutrinos cannot make appreciable contribution to Ω → m_ν << 10 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



Non-baryonic dark matter candidates

University of Durham

Type	example	mass
~~hot~~	~~neutrino~~	~~a few eV~~
warm		keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

University of Durham

Non-baryonic dark matter candidates

Type	example	mass
~~hot~~	~~neutrino~~	~~a few eV~~
warm	sterile neutrino majoron; KeVino	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

Institute for Computational Cosmology

1982 – 1990: the glory days of $\Omega_{matter} = 1$ (→ "standard CDM")

$$\Omega_{tot} = \frac{\text{density}}{\text{critical density}}$$

$$\rho = \rho_{mass} + \rho_{rel} + \rho_{vac}$$

ρ_{rel} → radiation, ν's

ρ_{vac} → e.g. cosmological constant, Λ

Inflation → $\Omega_{tot} = 1$

The end of standard ($\Omega_{matter}=1$) CDM

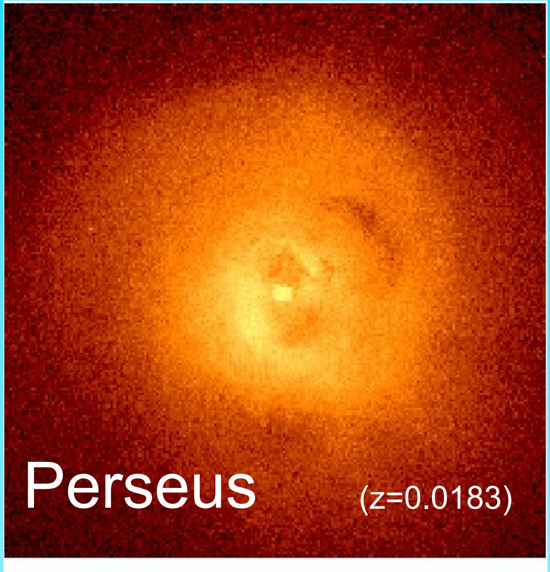
… or why Ω_{matter} cannot be 1

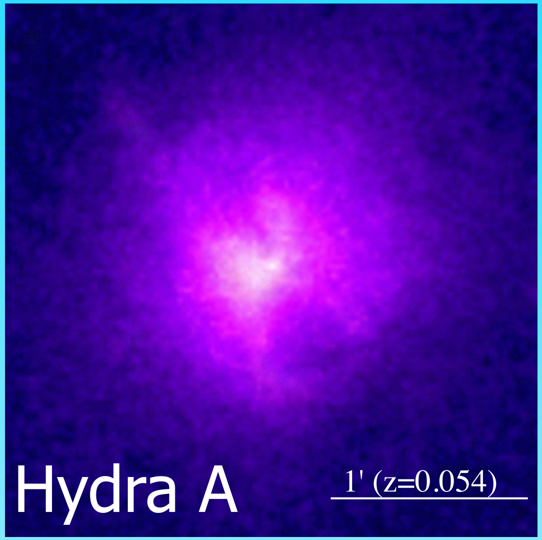
University of Durham

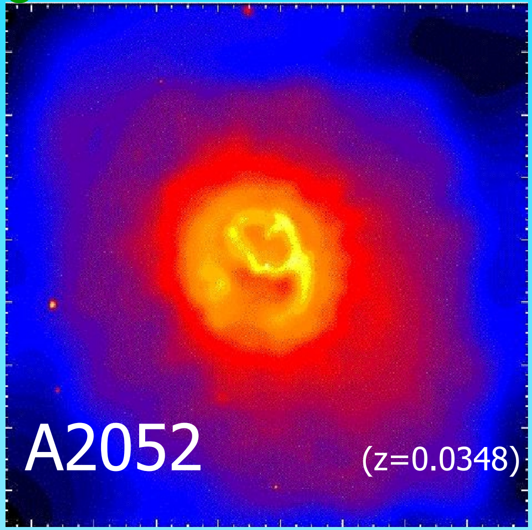
Galaxy clusters

X-ray emission from hot plasma in clusters

Images from David Buote







About 90% of baryons in clusters are in hot gas

X-rays $\Rightarrow$ gas mass

Photometry $\Rightarrow$ stellar mass

Gas in hydrostatic equilibrium so X-rays (or lensing) $\Rightarrow$ total gravitating mass

} $\Rightarrow$ Baryon fraction, f_b

Ω from the baryon fraction in clusters

baryon fraction in clusters ≈ baryon fraction of universe

$$f_b = \frac{M_b}{M_{tot}} = \gamma \frac{\Omega_b}{\Omega_m}$$

White, Navarro, Evrard & Frenk Nature 1993

where $\gamma=1$ if f_b has the universal value

simulations → $\gamma = 0.9 \pm 10\%$

X-rays+lensing → $f_b = (0.060h^{-3/2} + 0.009) \pm 10\%$

BBNS, CMB → $\Omega_b h^2 = 0.019 \pm 20\%$

HST → $h = 0.7 \pm 10\%$

→ $$\Omega_m = \frac{\Omega_b \gamma}{f_b} = 0.31 \pm 0.12$$

White, Navarro, Evrard & Frenk '93

Allen et al '04

→ Flat geometry (inflation) requires $\Lambda=0.7$

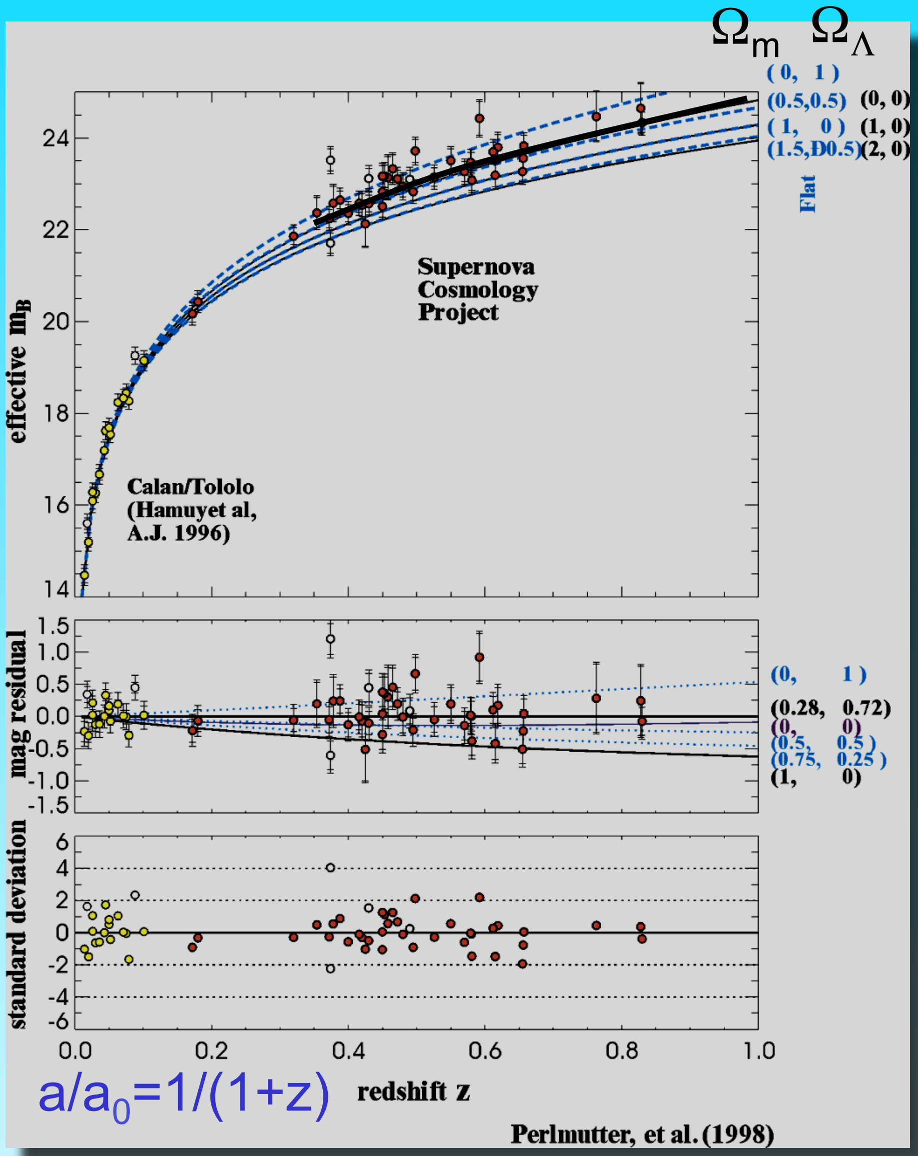
(Some) evidence for dark energy

Evidence for Λ from high-z supernovae

University of Durham

SN type Ia (standard candles) at z~0.5 are fainter than expected even if the Universe were empty

flux



➔ The cosmic expansion must have been accelerating since the light was emitted

Perlmutter et al ’98; Reiss et al ‘98

Schmidt et al ‘98

University of Durham

Evidence for Λ from high-z supernovae

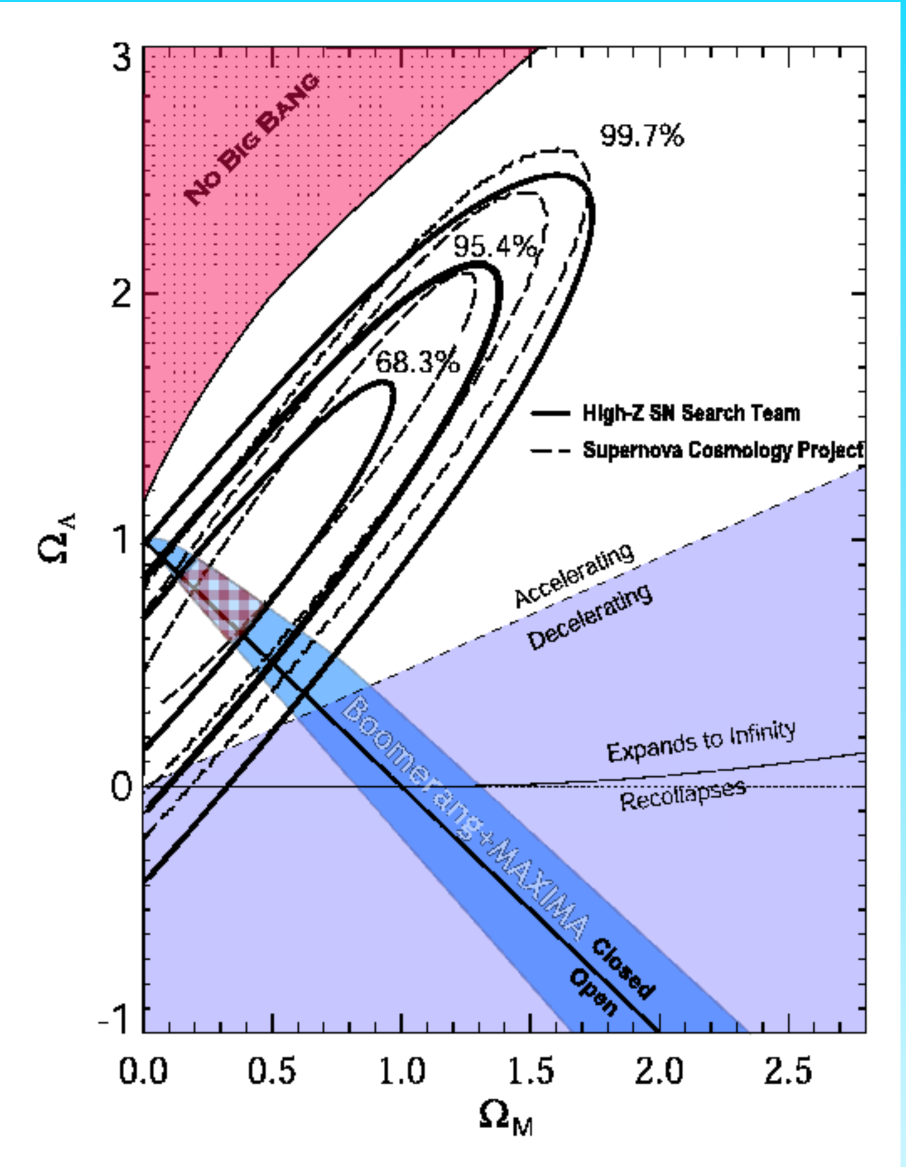
SN type Ia (standard candles) at z~0.5 are fainter than expected even if the Universe were empty

➔ The cosmic expansion must have been accelerating since the light was emitted

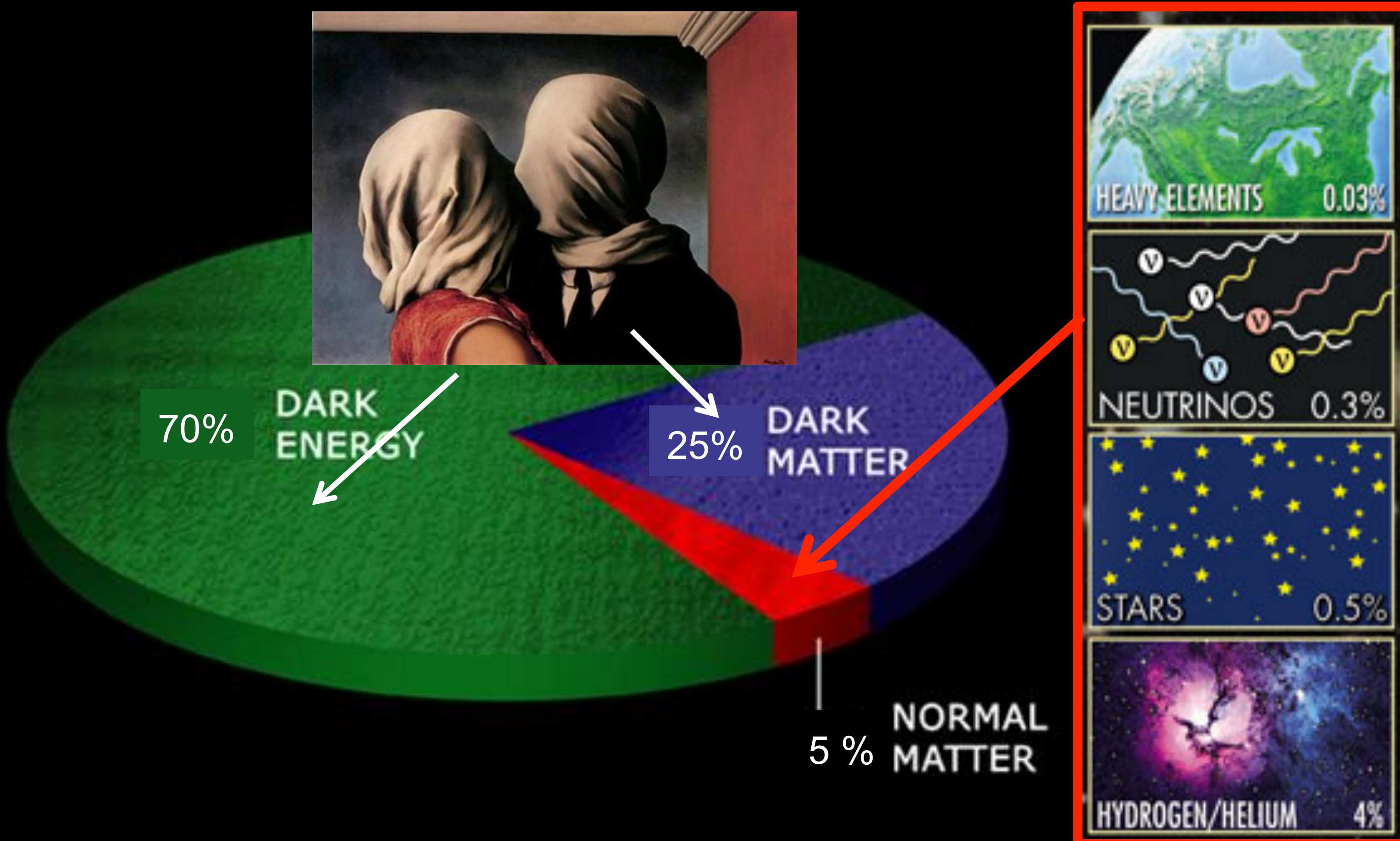
$$\Omega = \frac{\text{density}}{\text{critical density}}$$

$$\rho = \rho_{mass} + \rho_{rel} + \rho_{vac}$$

Perlmutter et al '98; Reiss et al '98
Schmidt et al '98



The content of our universe



Dark energy ≡ mysterious form of energy which opposes gravity

ΛCDM model is an *a priori* implausible model!

… but makes definite predictions and is therefore testable

The cold dark matter cosmogony

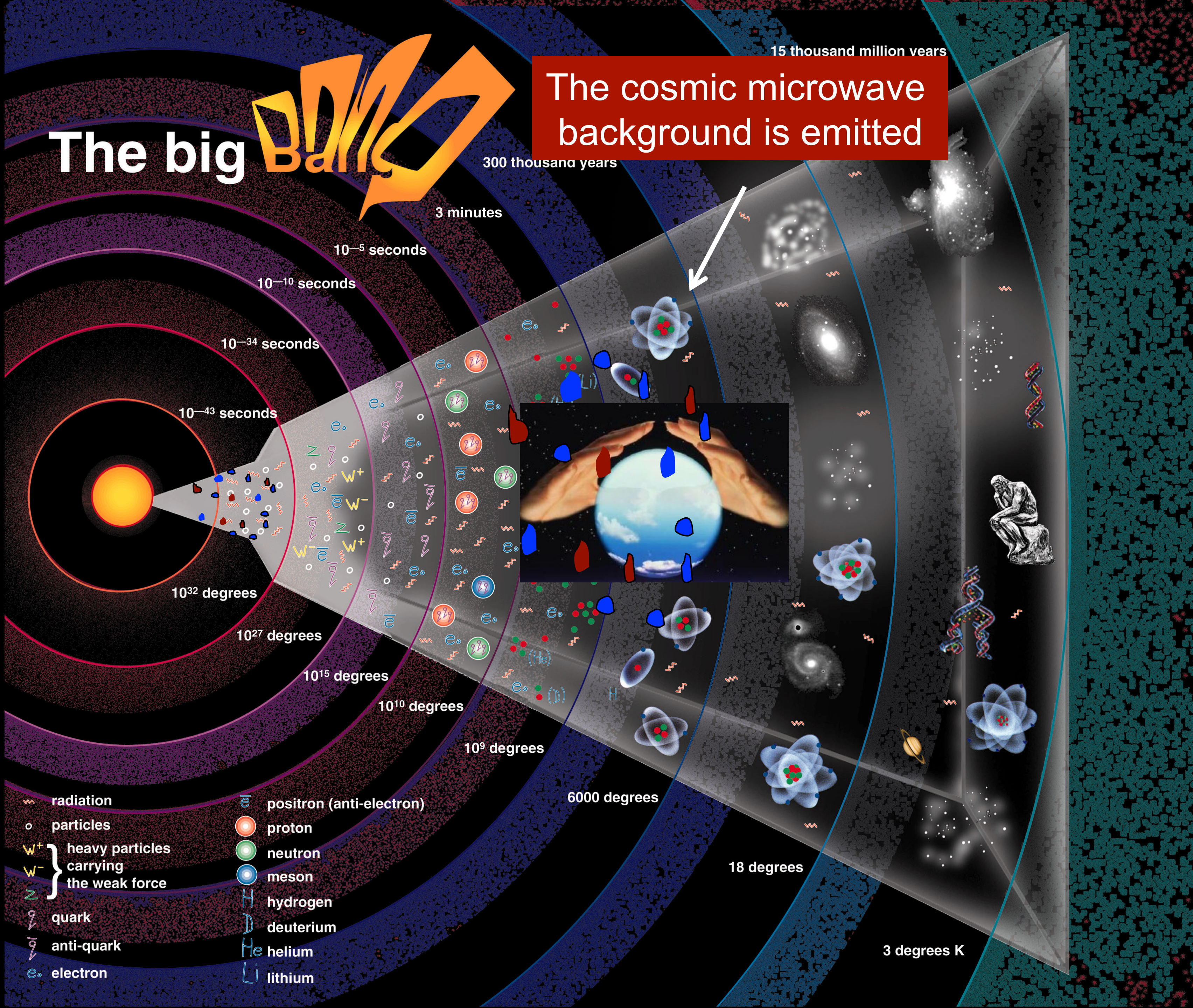
Main successes of the CDM cosmogony:

1. CMB temp. anisotropies: predicted 1981; discovered 1993
2. Galaxy formation and evolution (modelled early 90s; 1991 -)
3. Galaxy clustering (predicted early 80s; measured 1990- QDOT, APM, 2dFGRS, SDSS)

The cold dark matter cosmogony

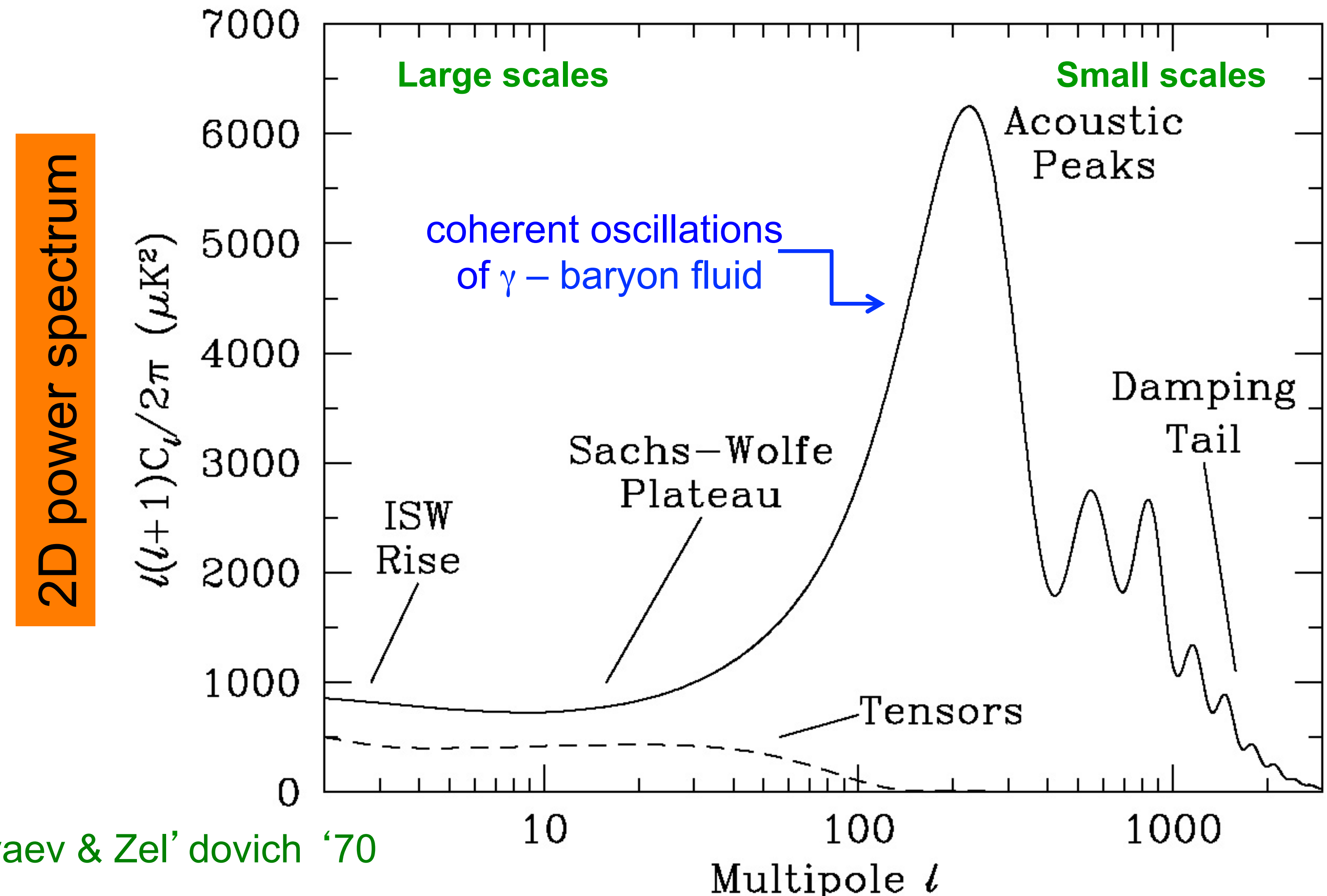
Main successes of the CDM cosmogony:

1. CMB temp. anisotropies: predicted 1981; discovered 1993
2. Galaxy formation and evolution (modelled early 90s; 1991 -)
3. Galaxy clustering (predicted early 80s; measured 1990- QDOT, APM, 2dFGRS, SDSS)


The big Bang
The cosmic microwave background is emitted
15 thousand million years
300 thousand years
3 minutes
10—5 seconds
10—10 seconds
10—34 seconds
10—43 seconds
1032 degrees
1027 degrees
1015 degrees
1010 degrees
109 degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Temperature anisotropies in CMB

University of Durham

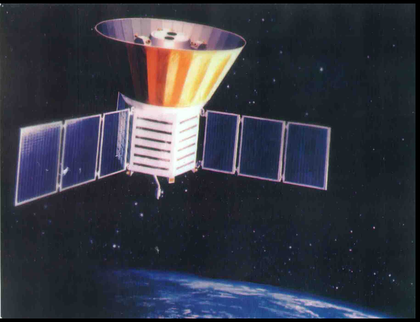


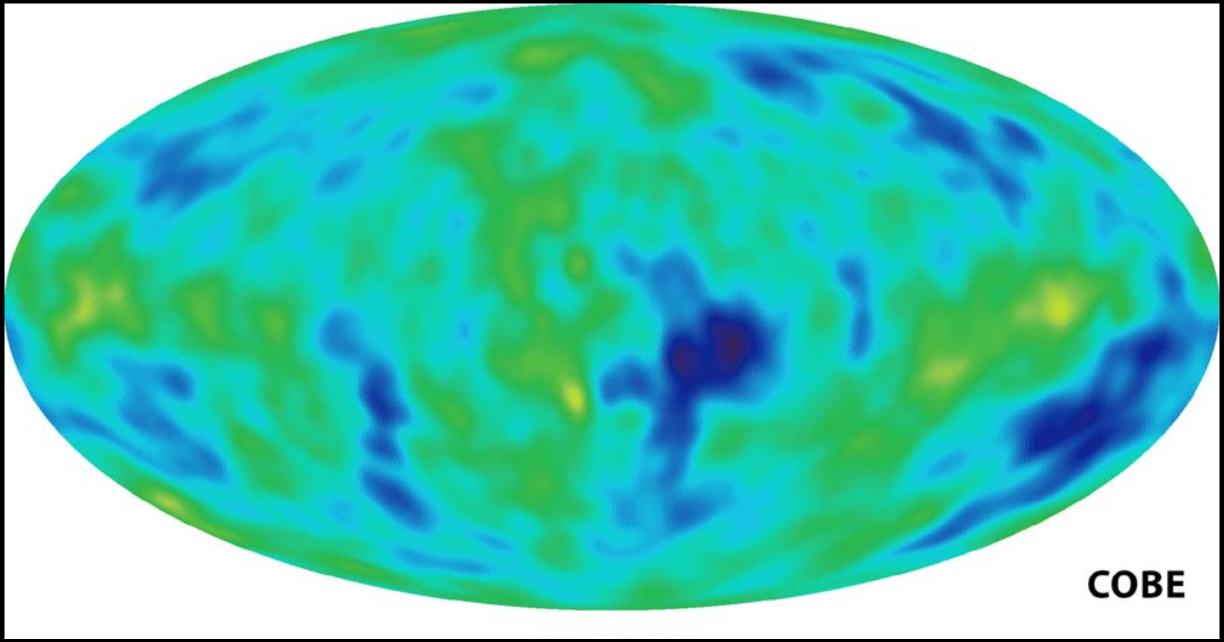
Sunyaev & Zel'dovich '70

After Peebles & Yu '70; Peebles '82

The CMB

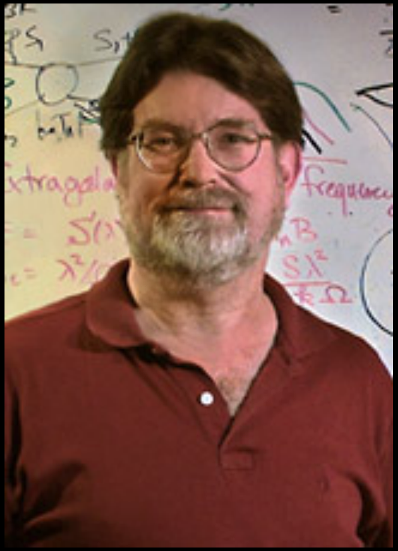
1992





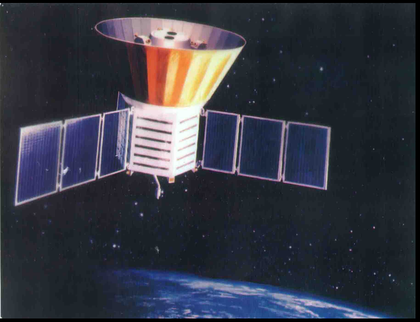
George Smoot - Nobel Prize 2006

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

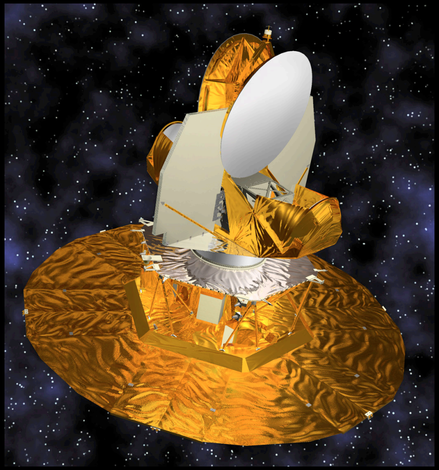


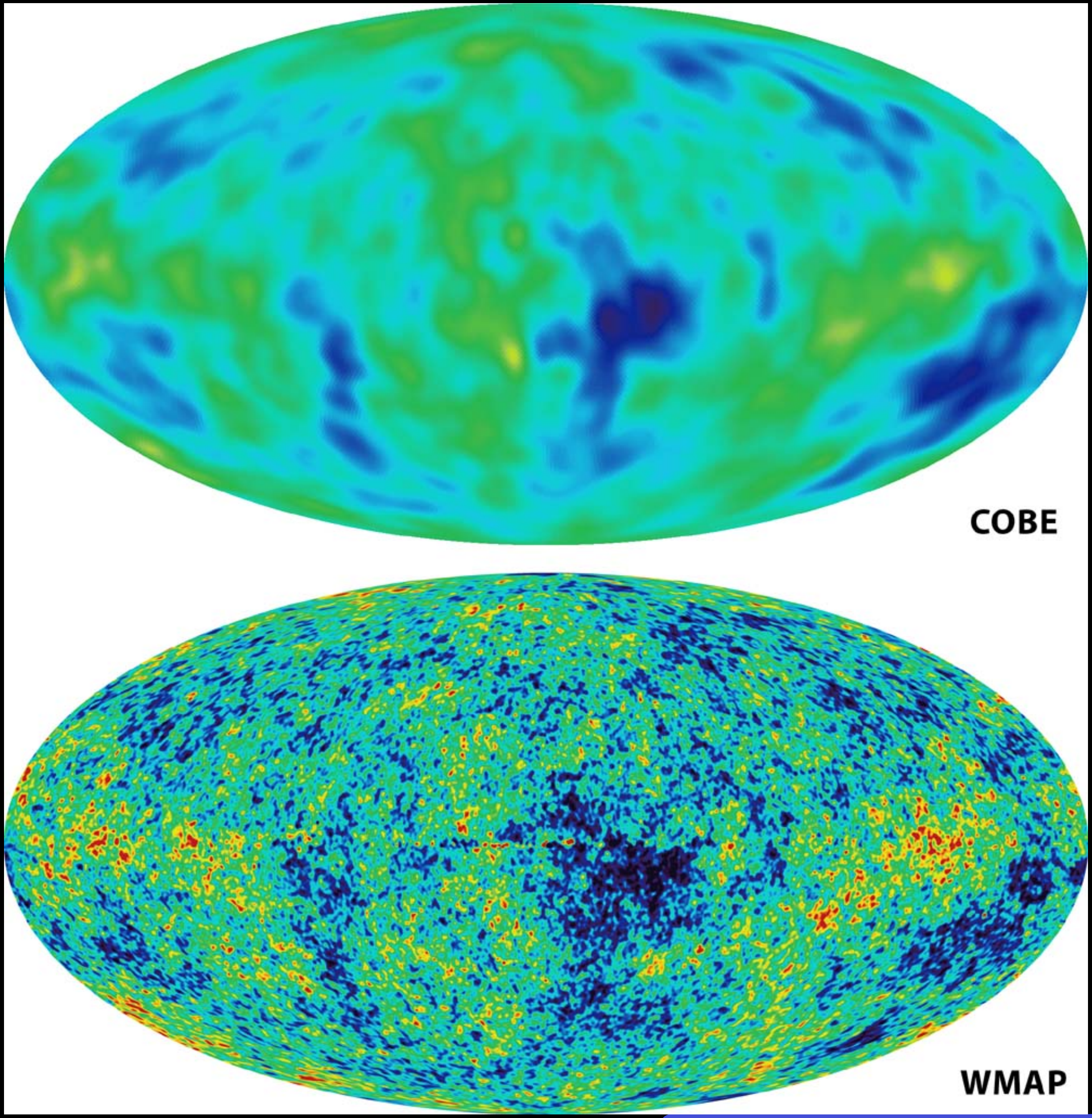
The CMB

1992



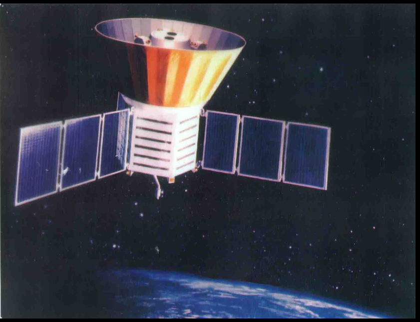
2003



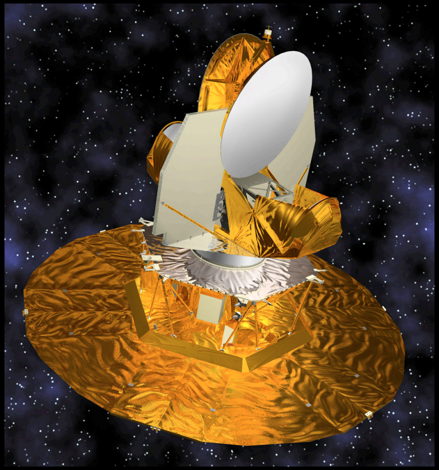


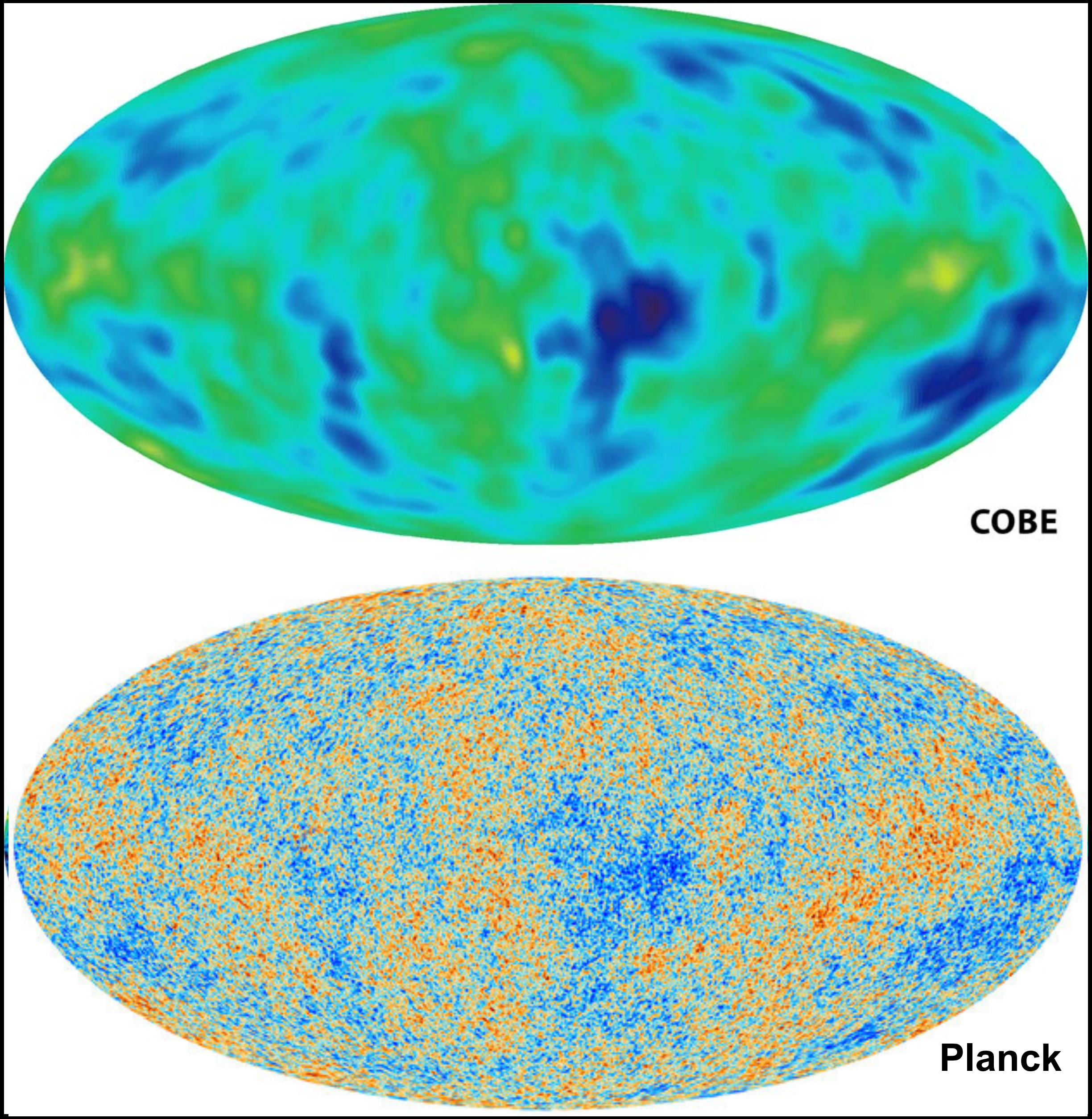
The CMB

1992

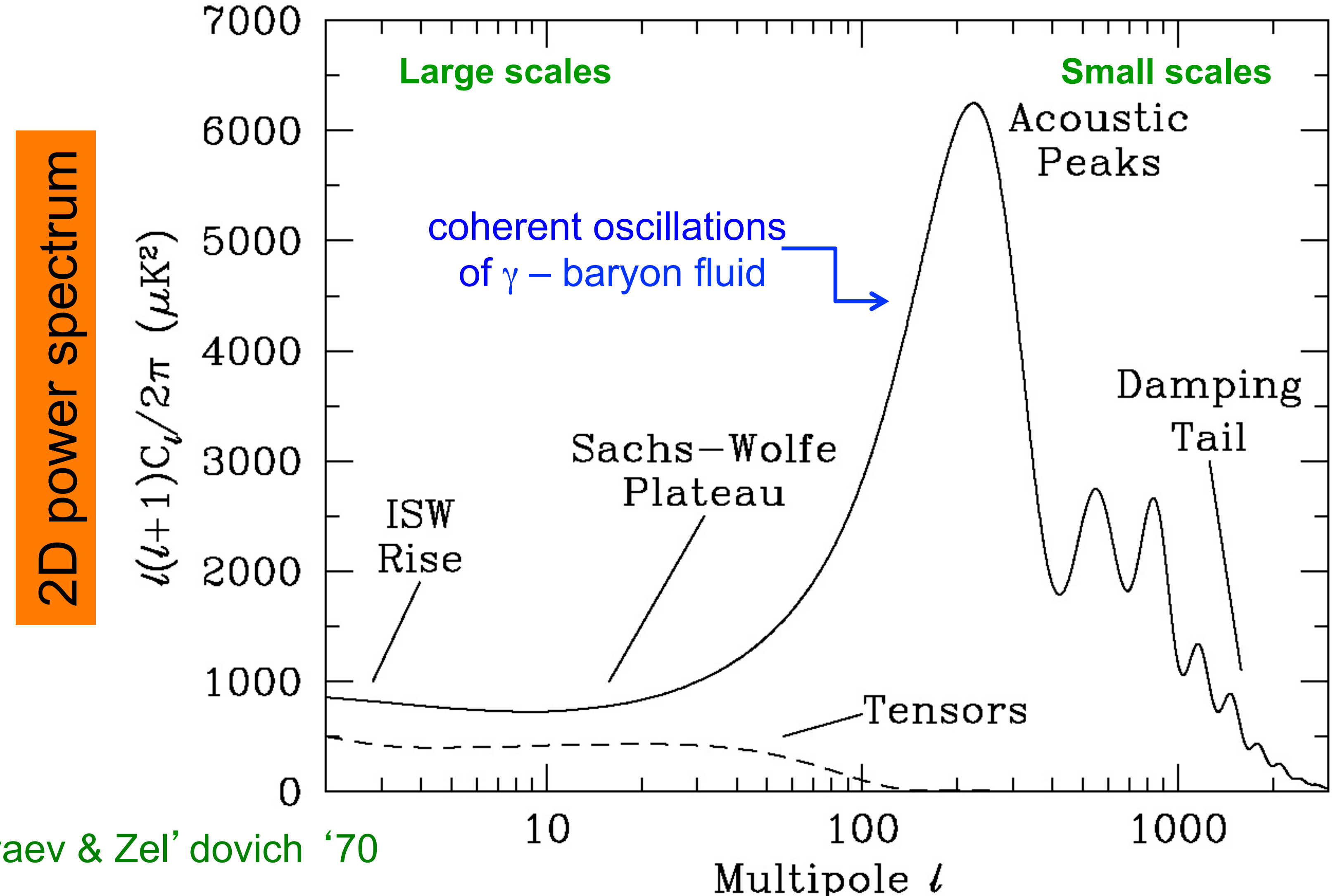


2012





Temperature anisotropies in CMB



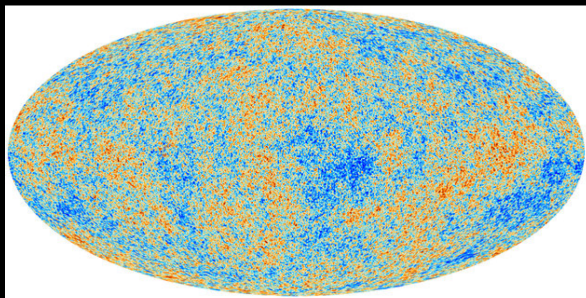
Sunyaev & Zel'dovich '70

After Peebles & Yu '70; Peebles '82

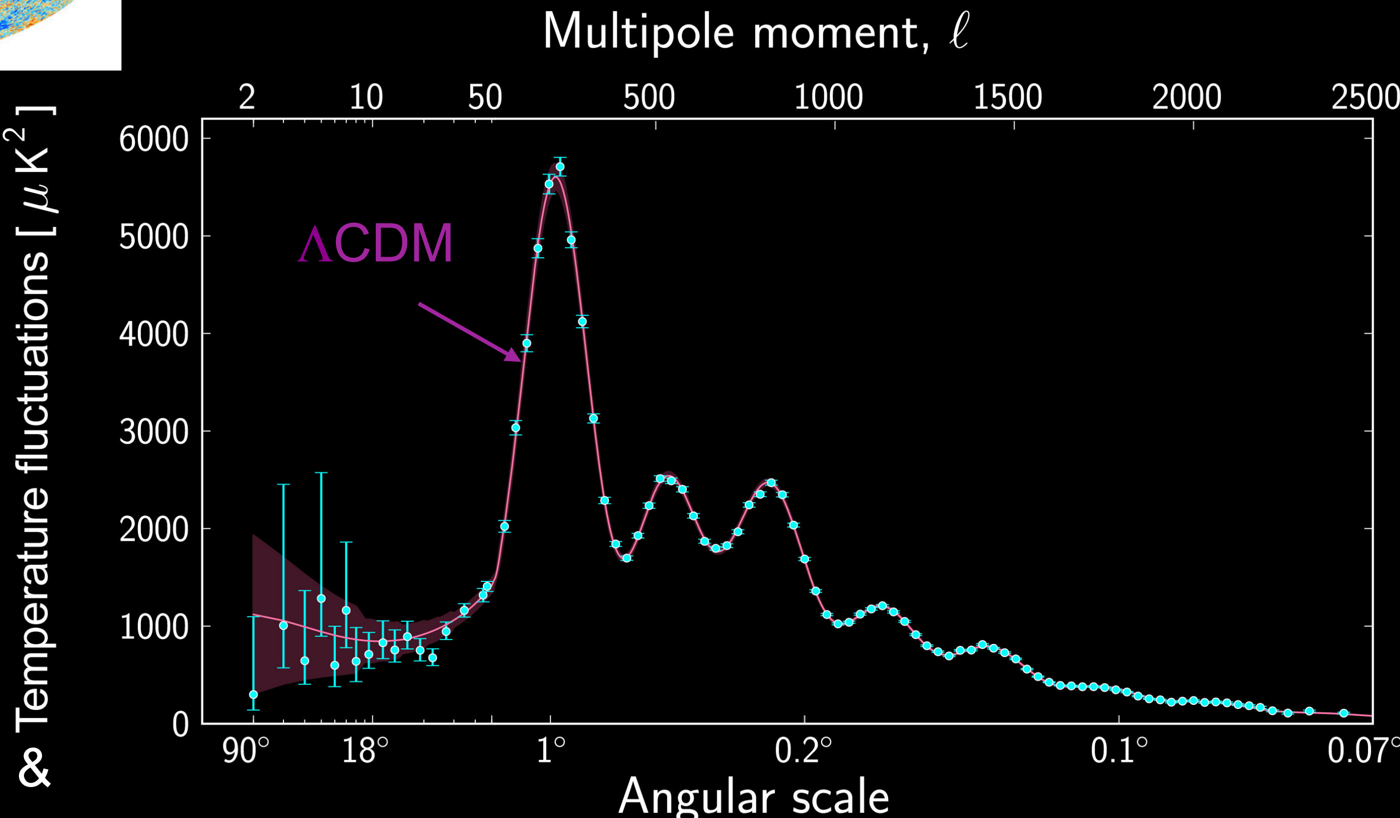
University of Durham

Institute for Computational Cosmology

Planck temp anisotropies in CMB



Amplitude of fluctuations at z~ 1000

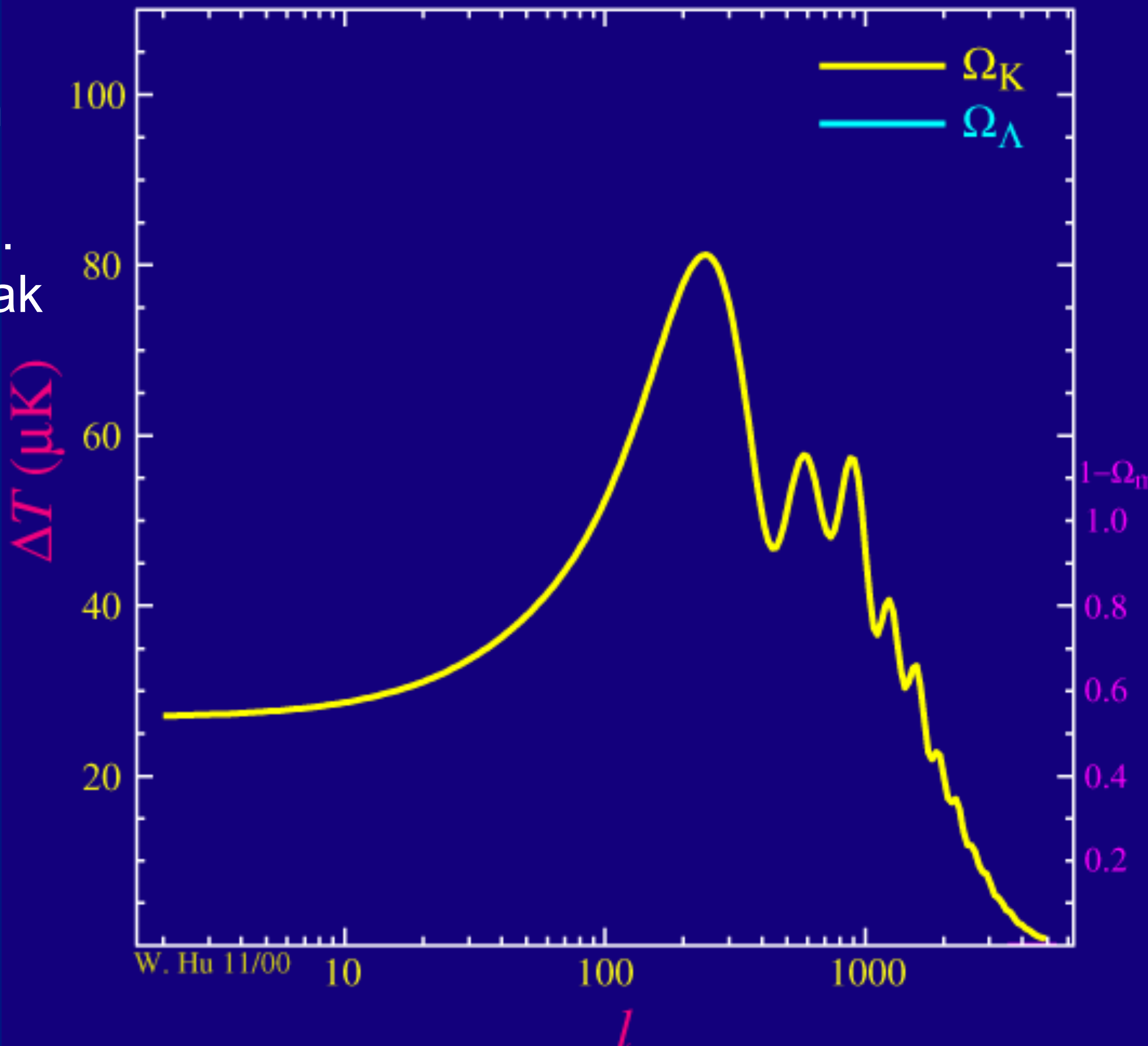


The data confirm the theoretical predictions (linear theory)

Peebles ’82; Bond & Efstathiou ‘80s

Planck collaboration ‘13

PS depends on cosmological parameters, e.g. position of 1st peak → curvature



Wayne Hu

http://background.uchicago.edu/~whu/intermediate/intermediate.html

University of Durham

Cosmological parameters from CMB data

Parameter	*Planck*+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50

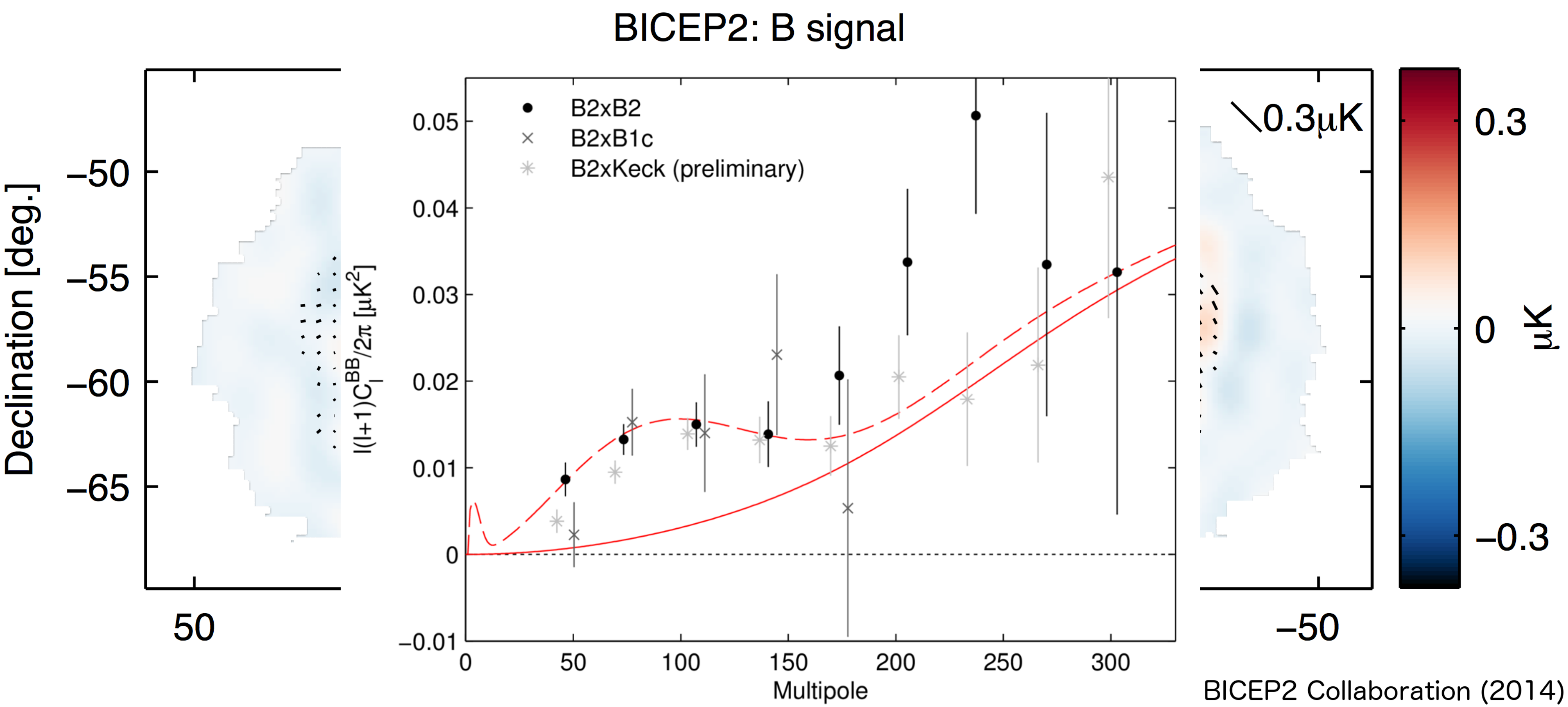
Planck collaboration '13

University of Durham

Detection of B-mode polarization?

Gravitational waves are a fundamental prediction of inflation

They induce B-mode polarization in the CMB at low l



BICEP2 Collaboration (2014)

Ade et al. '14

Volume 91B, number 1 PHYSICS LETTERS 24 March 1980

A NEW TYPE OF ISOTROPIC COSMOLOGICAL MODELS WITHOUT SINGULARITY

A.A. STAROBINSKY
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England [1]
and The Landau Institute for Theoretical Physics, The Academy of Sciences, Moscow, 117334, USSR [2]

The important property of all nonsingular models with the initial superdense de Sitter state is that, as shown in ref. [8], such a large amount of relic gravitational waves is generated by one-loop processes in these models (in particular, in the range $1-10^{-5}$ Hz) that predictions of the semiclassical theory and the very existence of this state can be experimentally verified in the near future. Adopting such a model, one should also call for some mechanism of baryon-number generation because initial symmetry requires zero initial values of all charges.

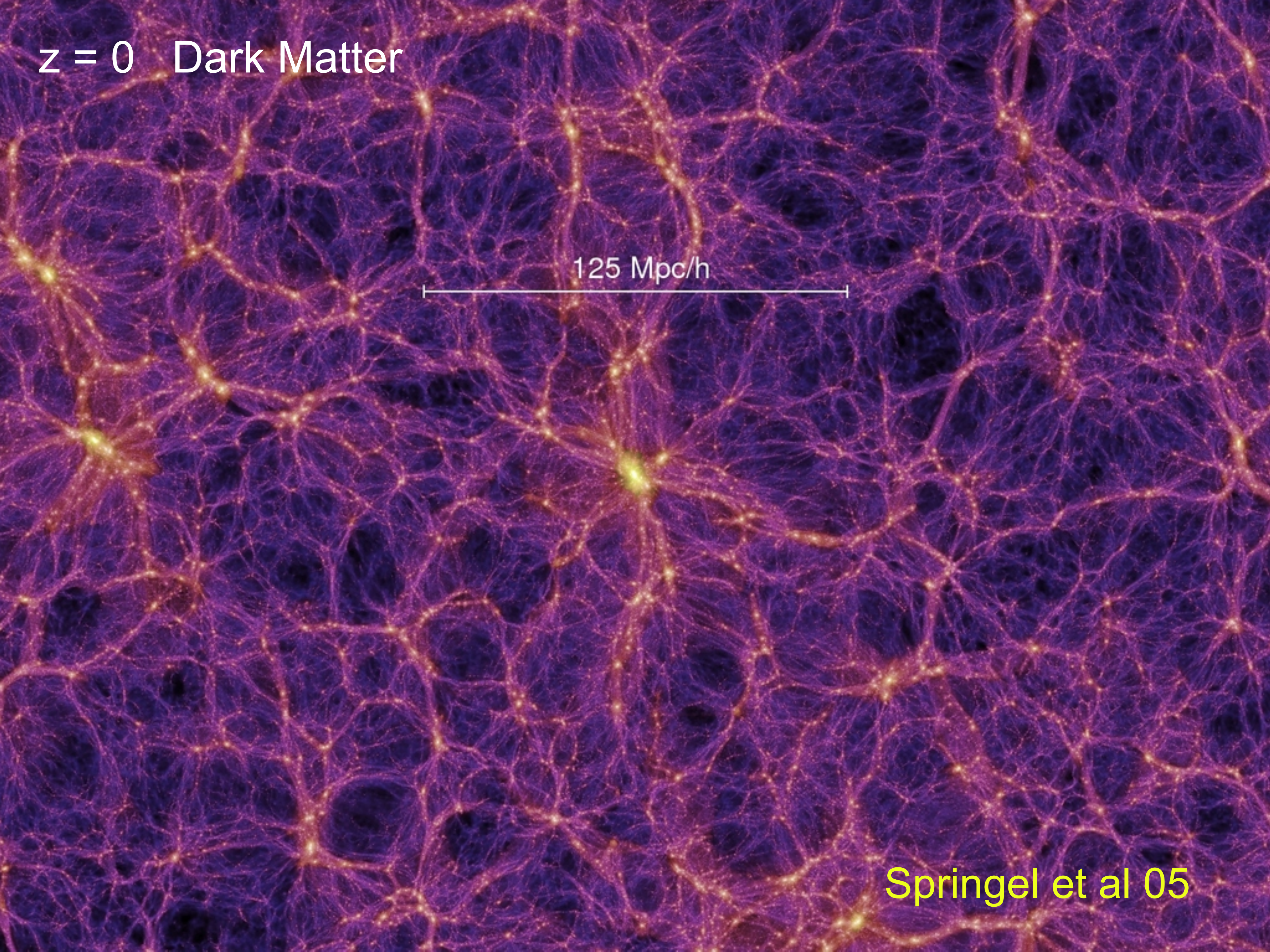
l Cosmology

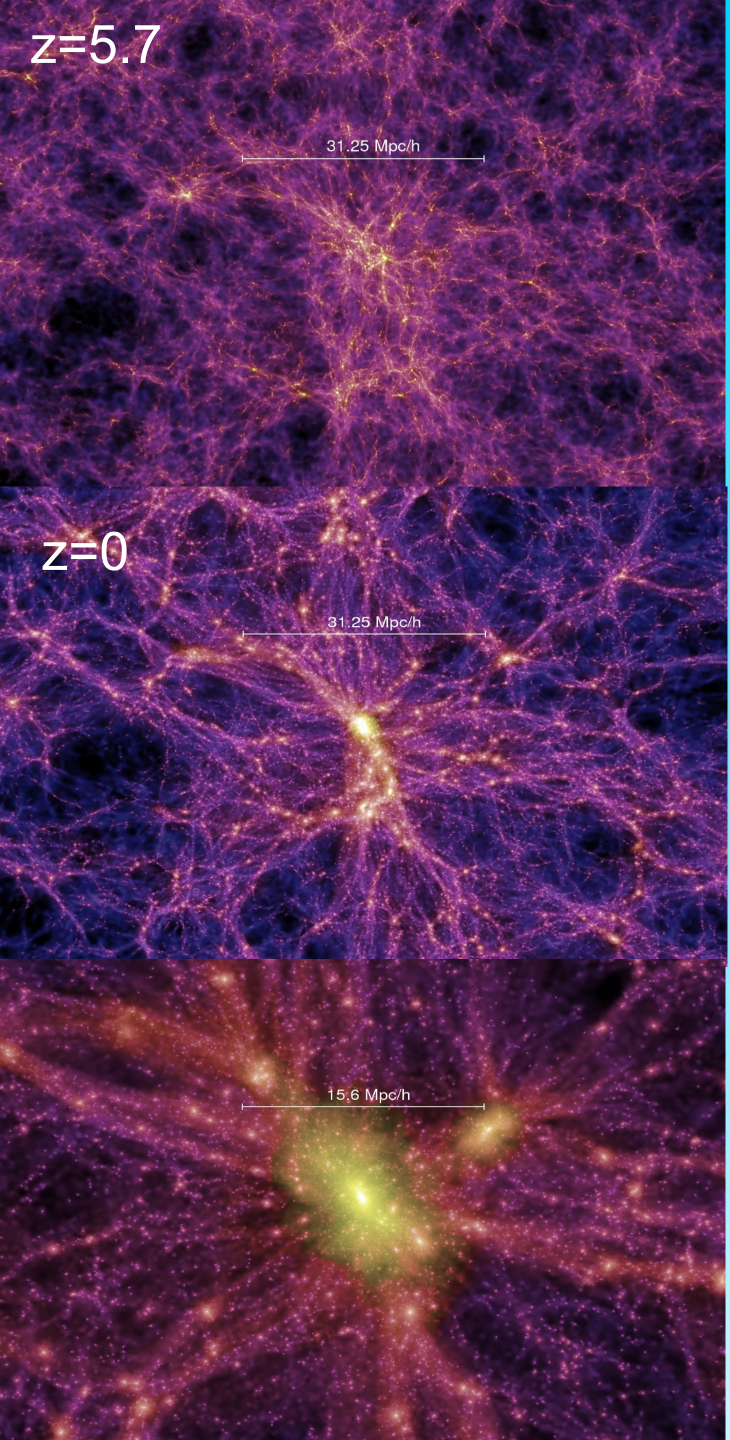
University of Durham

The cold dark matter cosmogony

Main successes of the CDM cosmogony:

1. CMB temp. anisotropies: predicted 1981; discovered 1993
2. Galaxy formation and evolution (modelled early 90s; 1991 -)
3. Galaxy clustering (predicted early 80s; measured 1990- QDOT, APM, 2dFGRS, SDSS)


z = 0 Dark Matter
125 Mpc/h
Springel et al 05



Galaxy formation theory

To compare simulations *vs* observations, need to know where the galaxies form

Galaxy formation theory:
a physics-based model for the formation and evolution of galaxies

Institute for Computational Cosmology

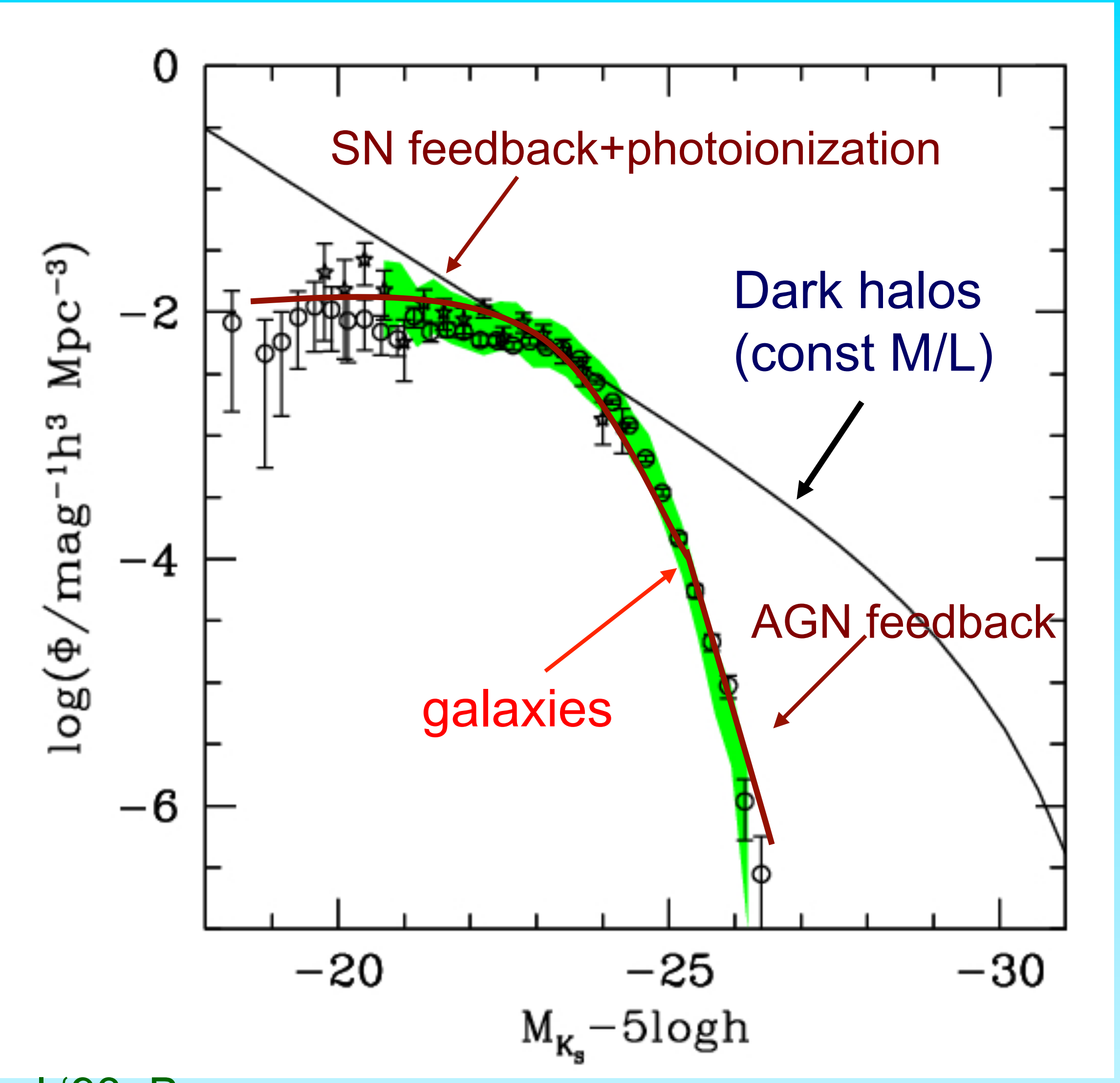
University of Durham

The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes

⇨

Complicated variation of M/L with halo mass



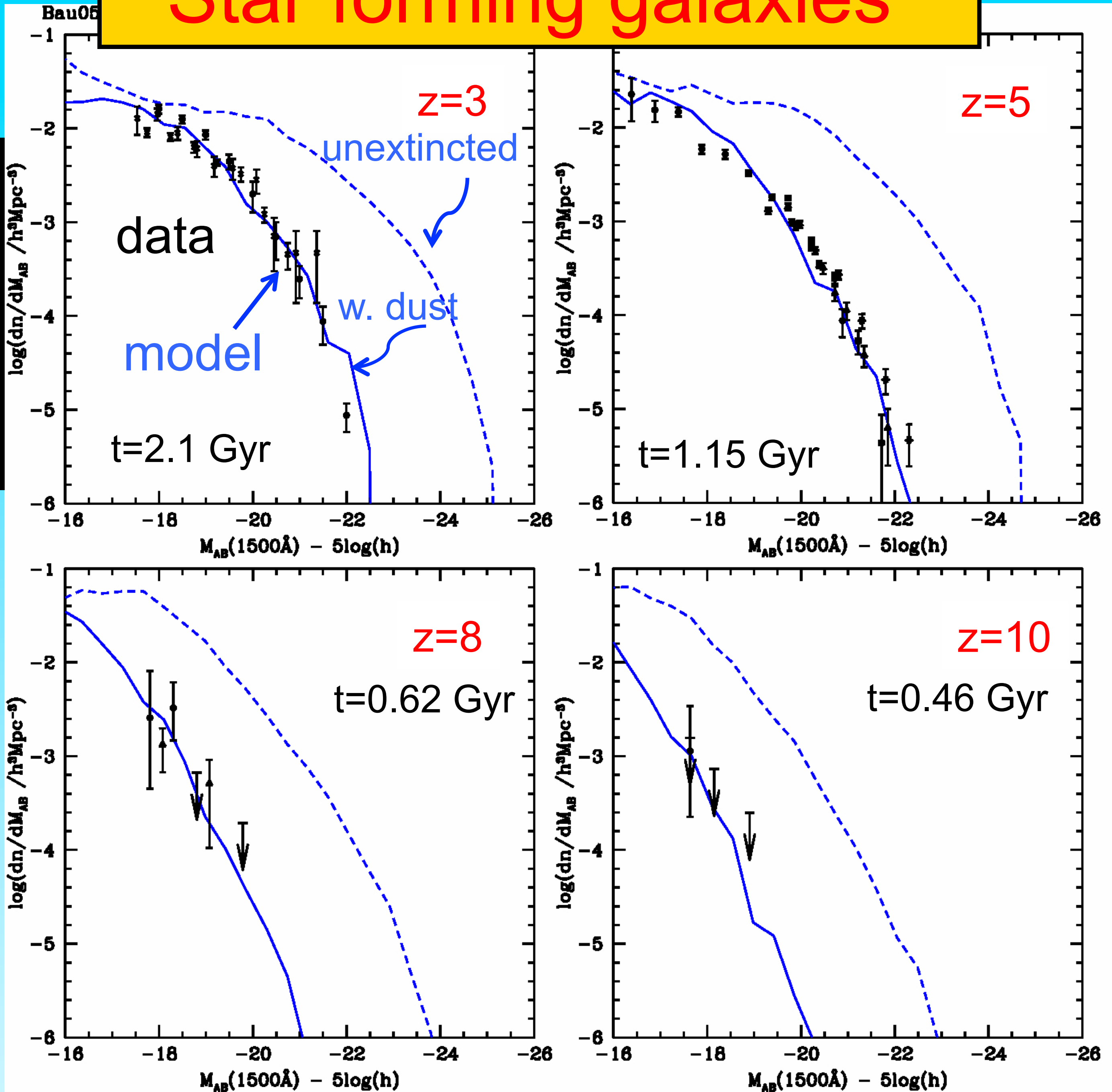
White & Frenk '91; Kauffmann et al '93; Benson et al '03; Croton et al '05; Bower et al. '06

Institute for Computational Cosmology

Star forming galaxies

University of Durham

Evolution of Lyman-break galaxy lum. function



Lacey, Baugh, Frenk, Benson '12

The cold dark matter cosmogony

Main successes of the CDM cosmogony:

1. CMB temp. anisotropies: predicted 1981; discovered 1993
2. Galaxy formation and evolution (modelled early 90s; 1991 -)
3. Galaxy clustering (predicted early 80s; measured 1990- QDOT, APM, 2dFGRS, SDSS)

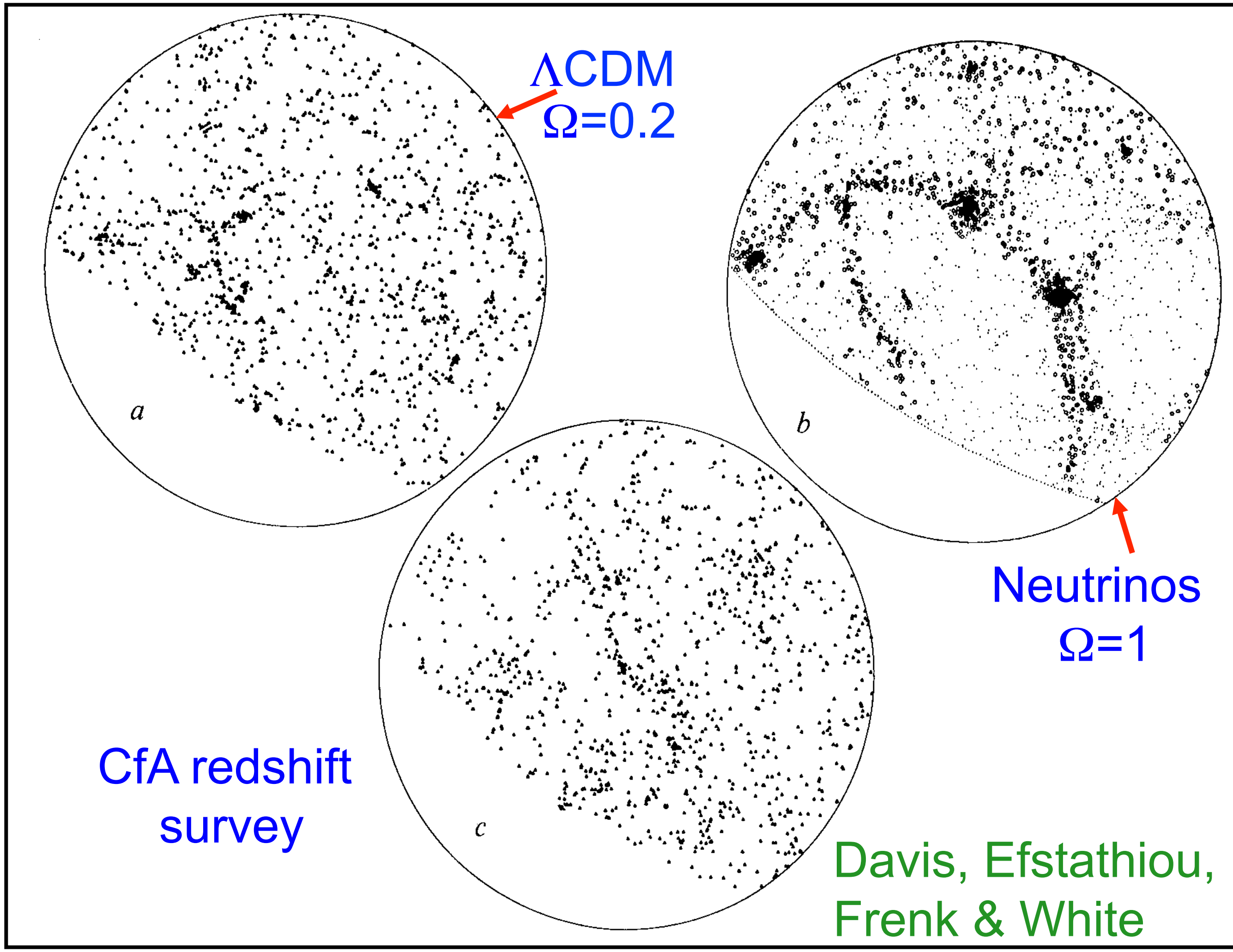
University of Durham

Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



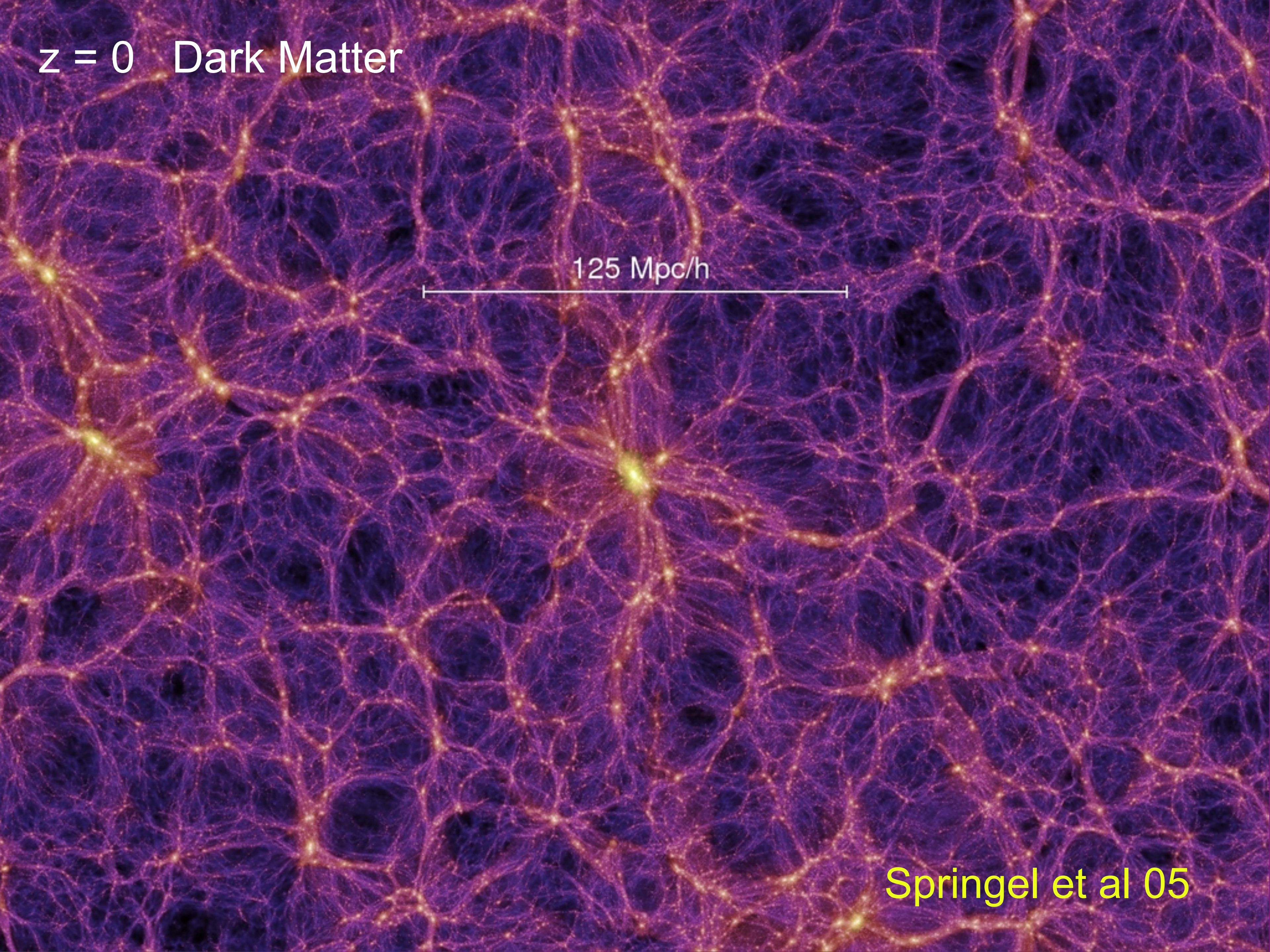
Davis, Efstathiou, Frenk & White '85

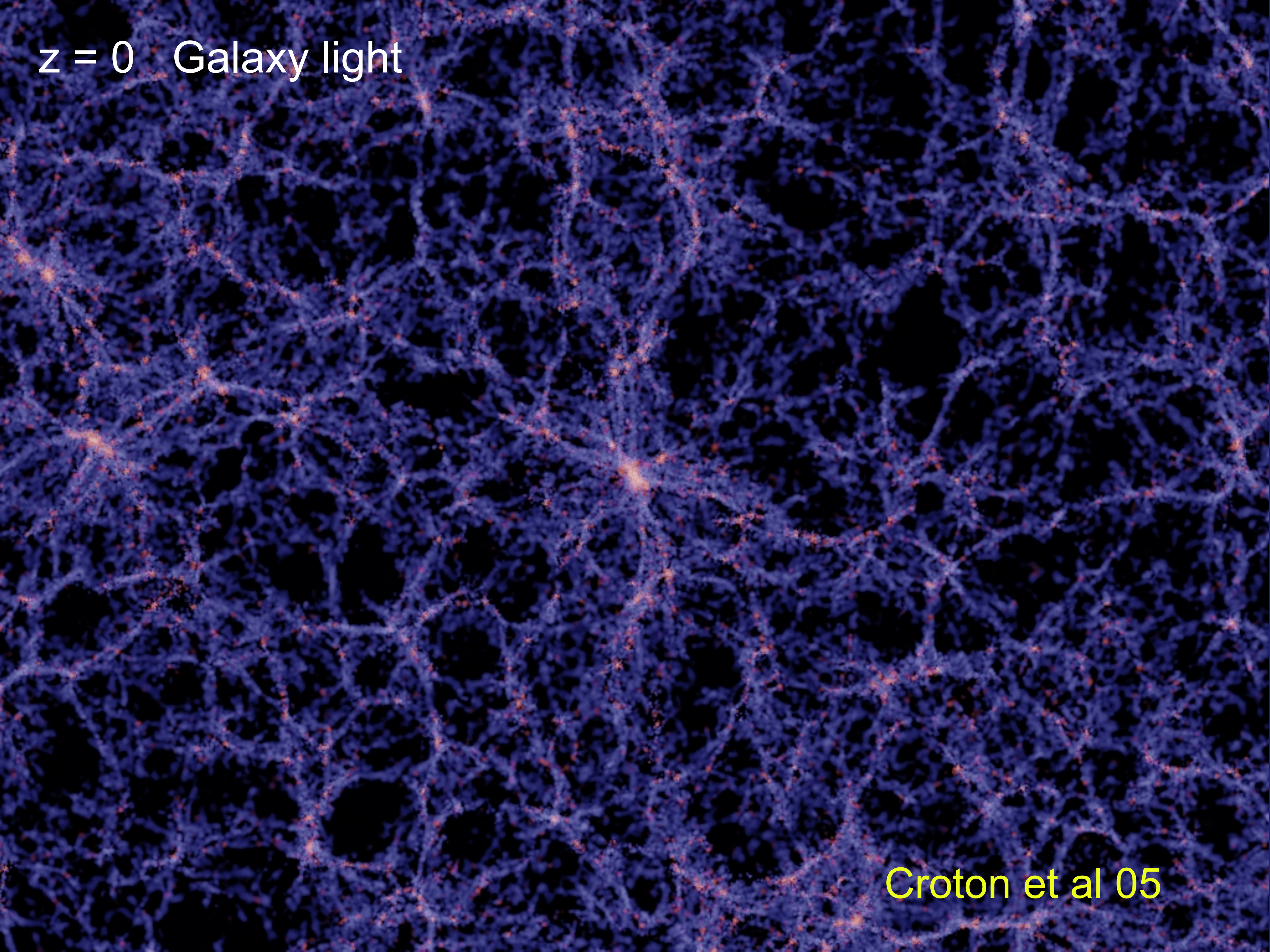
The 2dF Galaxy Redshift Survey

221,000 redshifts

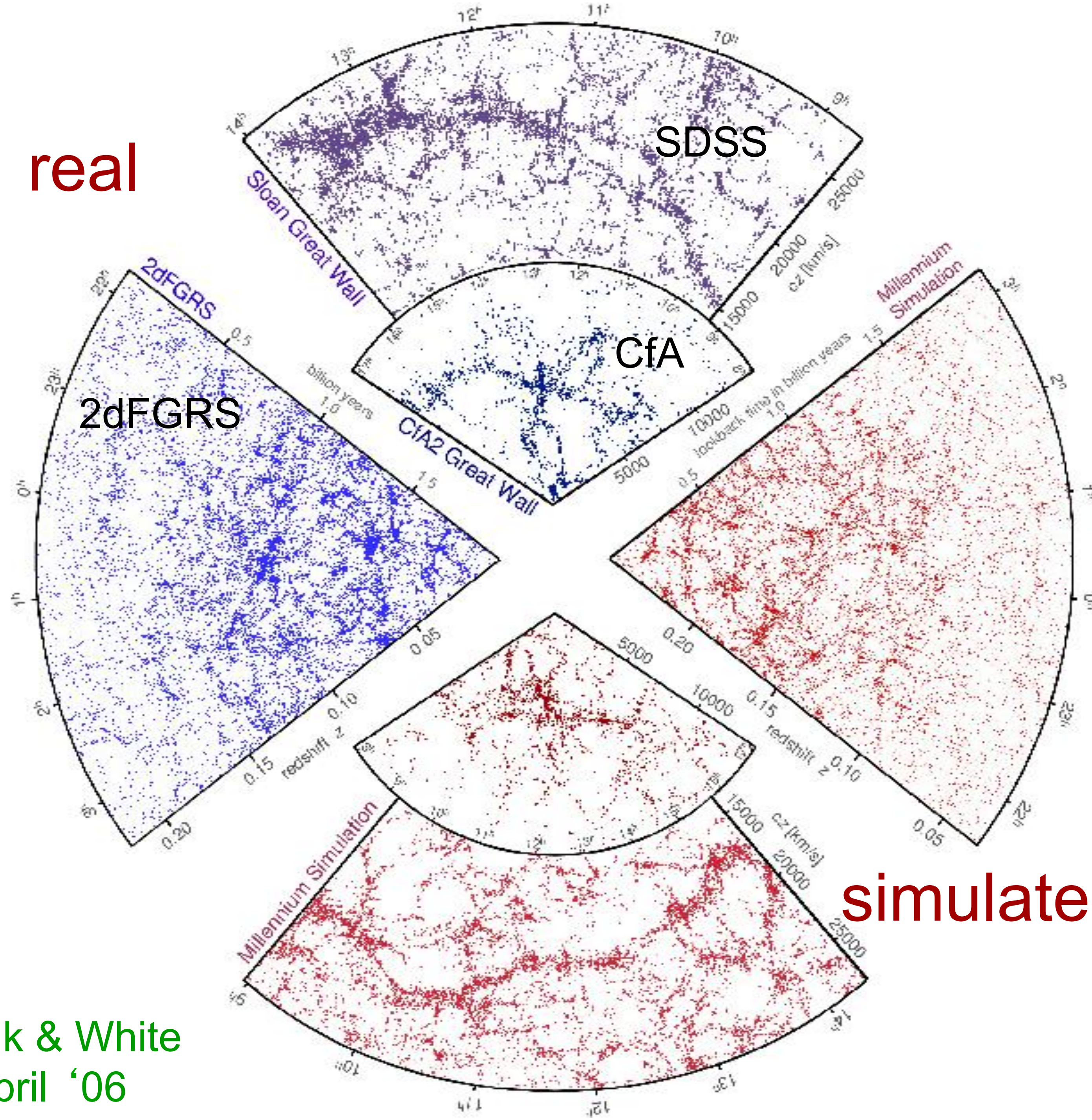
z~0

2005


z = 0 Dark Matter
125 Mpc/h
Springel et al 05


z = 0 Galaxy light
Croton et al 05

real

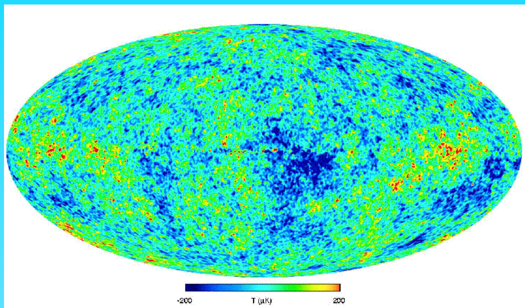


simulated

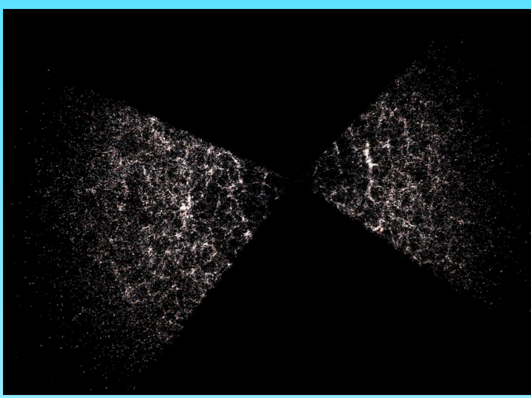
Springel, Frenk & White
Nature, April ‘06

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

University of Durham

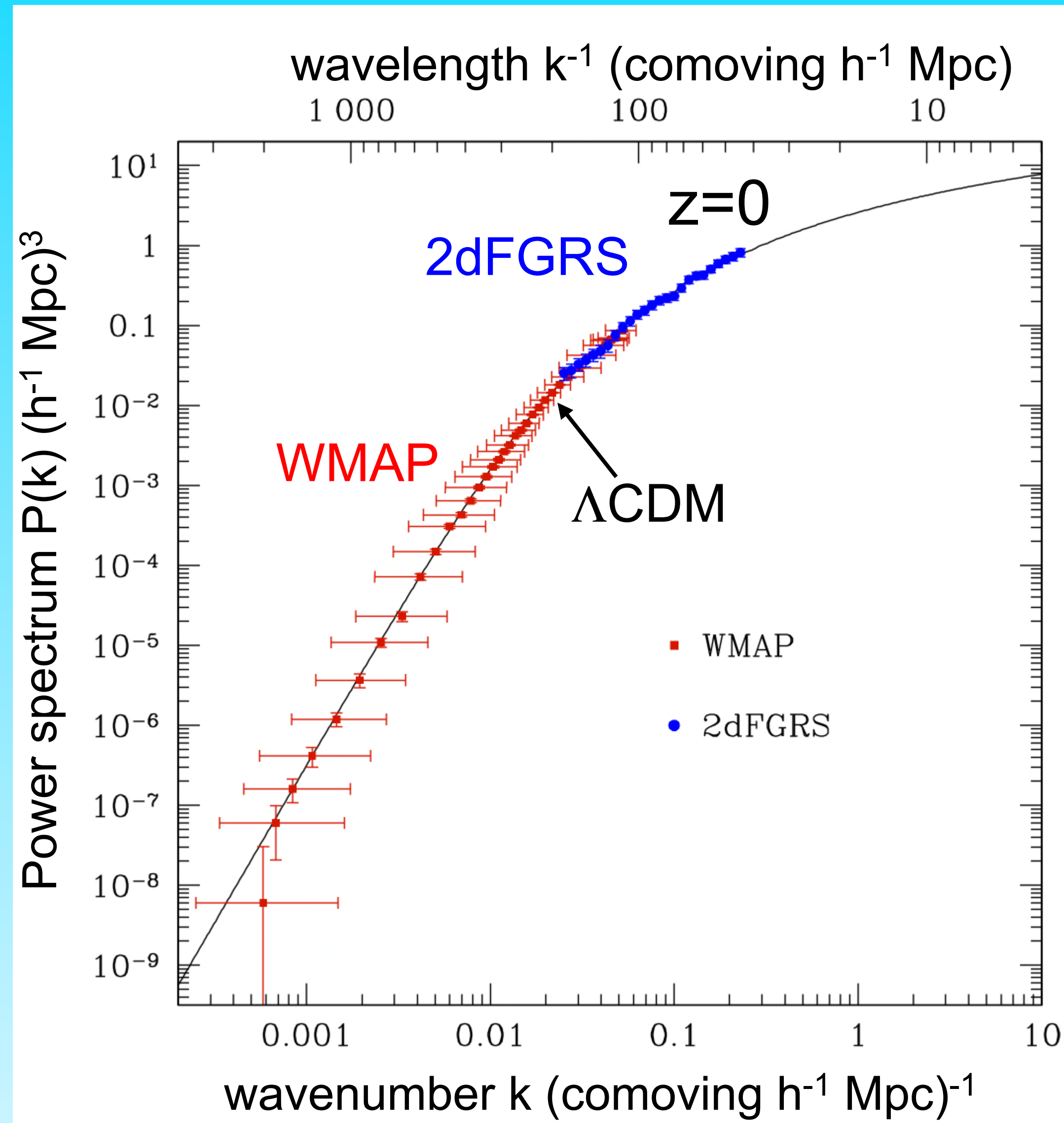


z~1000



z~0

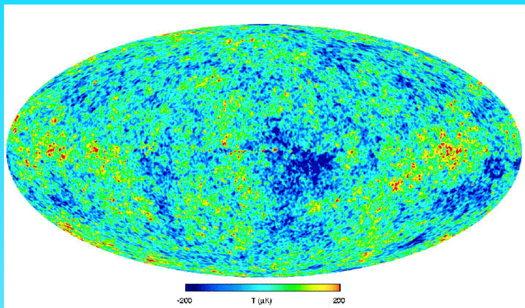
$\Rightarrow$ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc



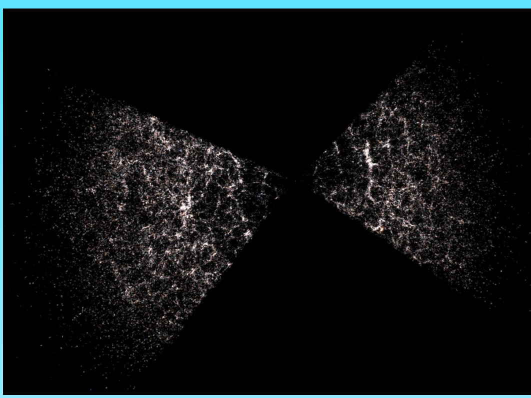
Sanchez et al 06

University of Durham

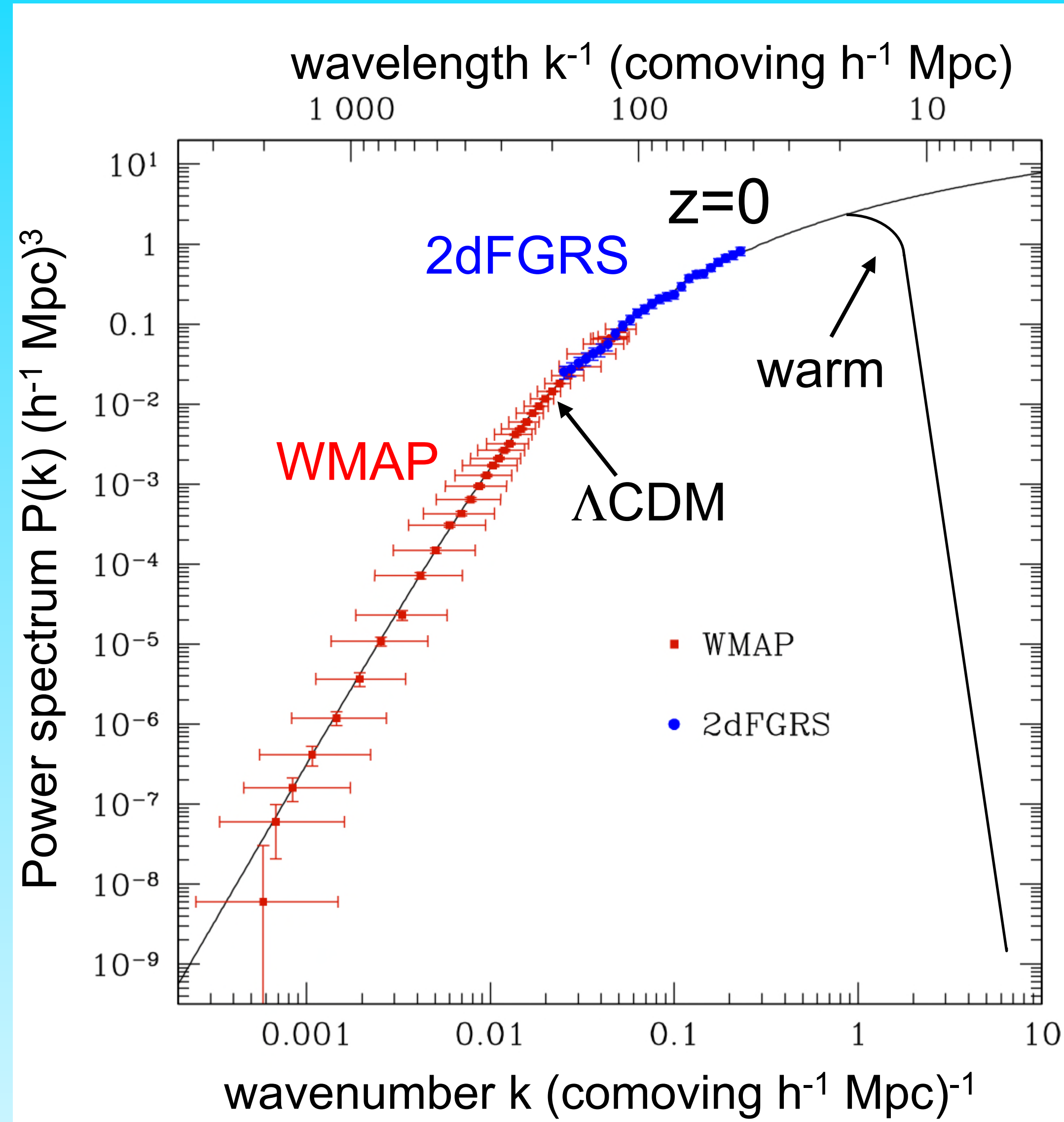
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



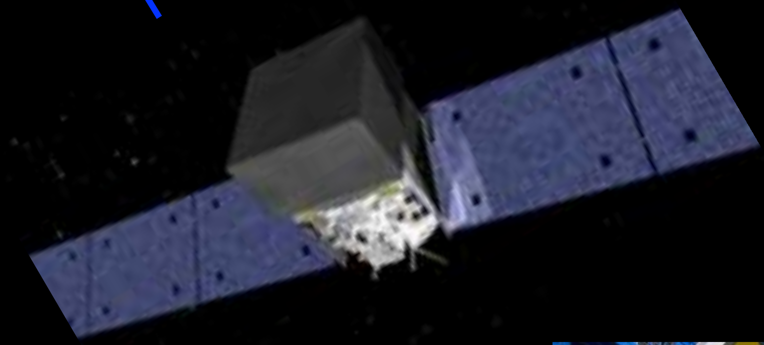
⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

SUSY cold dark matter

Dark matter discovery possible in several ways

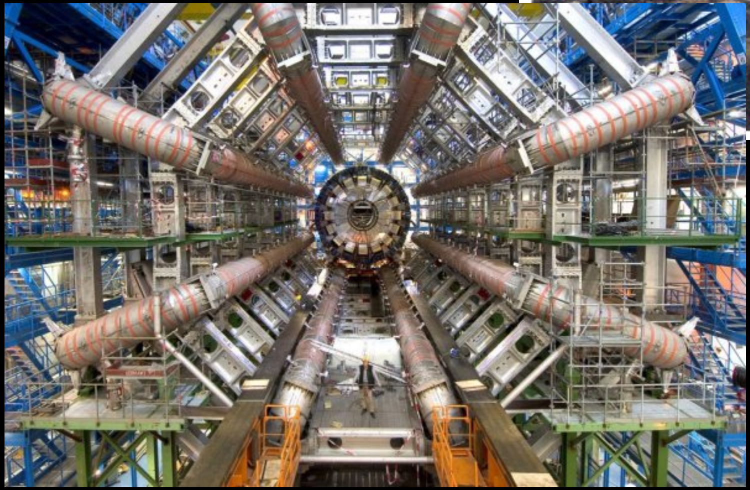
Fermi



Annihilation radiation

Direct detection

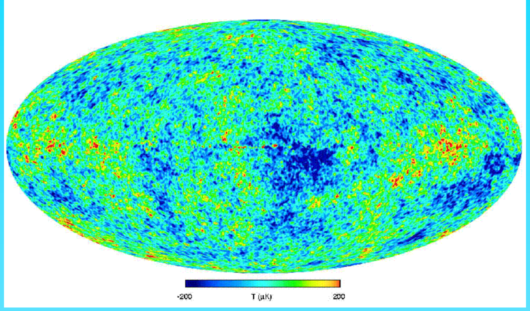
UK DM search
(Boulby mine)



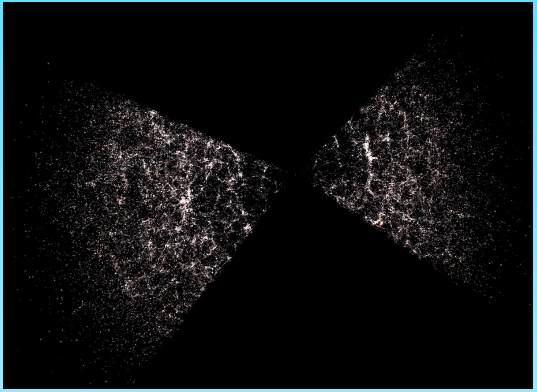
Evidence for SUSY

University of Durham

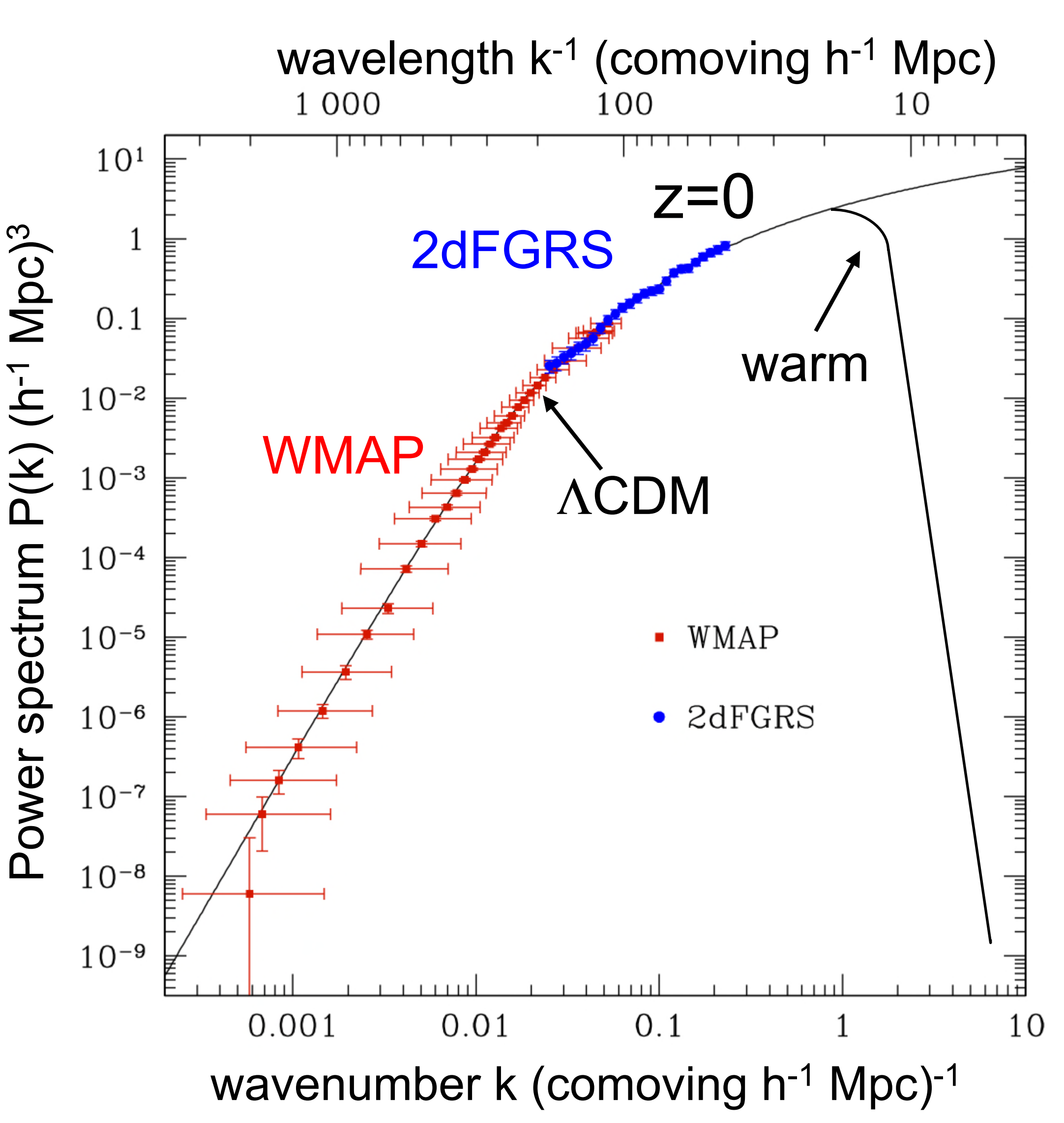
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

University of Durham

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands

[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine

[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine

[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

Submitted to ApJ, 2014 F
Preprint typeset using LaTeX

DETECTION OF AN U

Esra Bulbul[1,2], M

[1] Har

We detect a wea spectrum of 73 g independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum. The line is also detected at the same energy in the *Chandra* ACIS-S and ACIS-I spectra of the Perseus cluster, with a flux consistent with *XMM-Newton* (however, it is not seen in the ACIS-I spectrum of Virgo). The line is present even if we allow maximum freedom for all the known thermal emission lines. However, it is very weak (with an equivalent width in the full sample of only ~ 1 eV) and located within 50–110 eV of several known faint lines; the detection is at the limit of the current instrument capabilities and subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. Assuming that all dark matter is in sterile neutrinos with $m_s = 2E = 7.1$ keV, our detection in the full sample corresponds to a neutrino decay mixing angle $\sin^2(2\theta) \approx 7 \times 10^{-11}$, below the previous upper limits. However, based

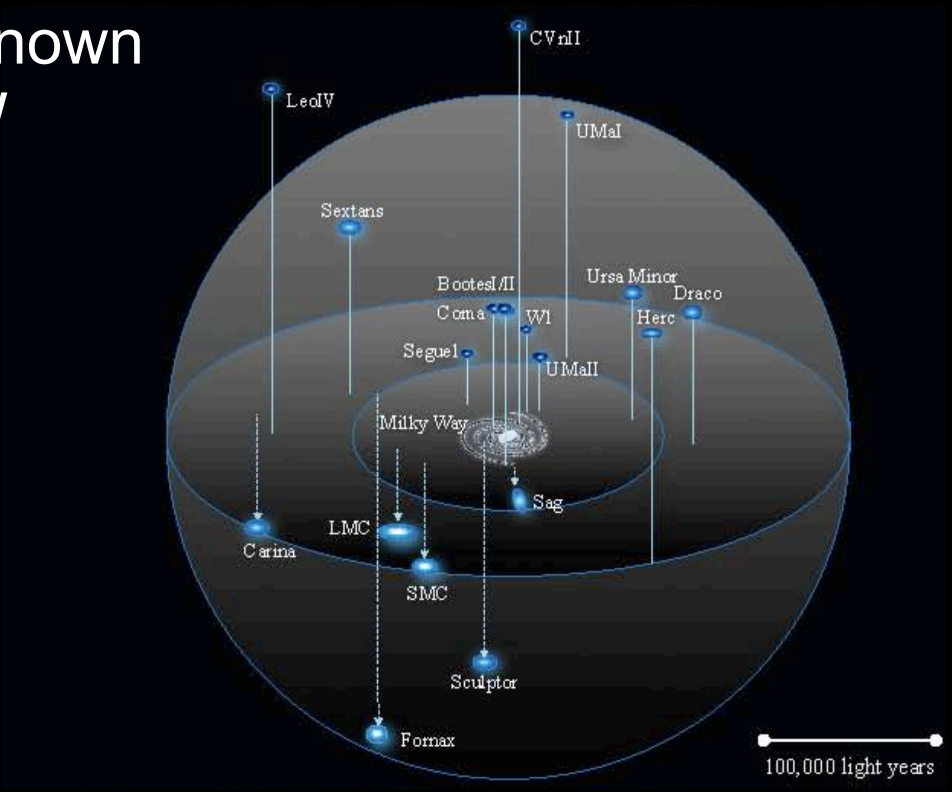
Astrophysical key to identity of dark matter:

→Subgalactic scales

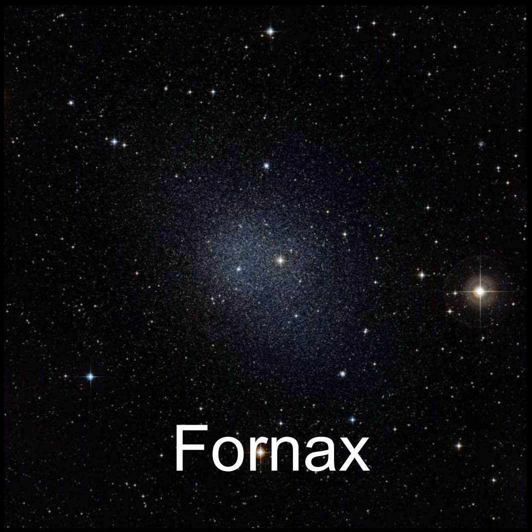
(strongly non-linear)

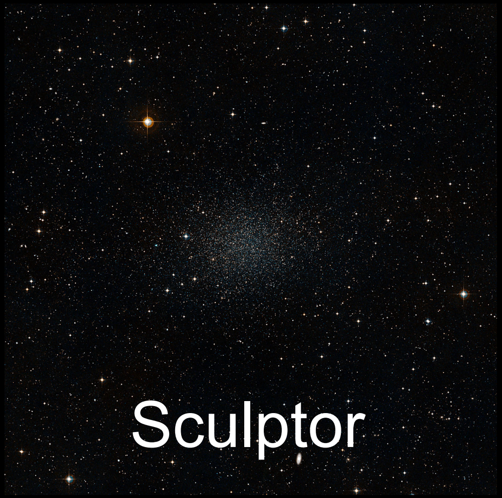
The satellites of the Milky Way

~25 satellites known
in the MW



Dwarf galaxies around the Milky Way






Sextans

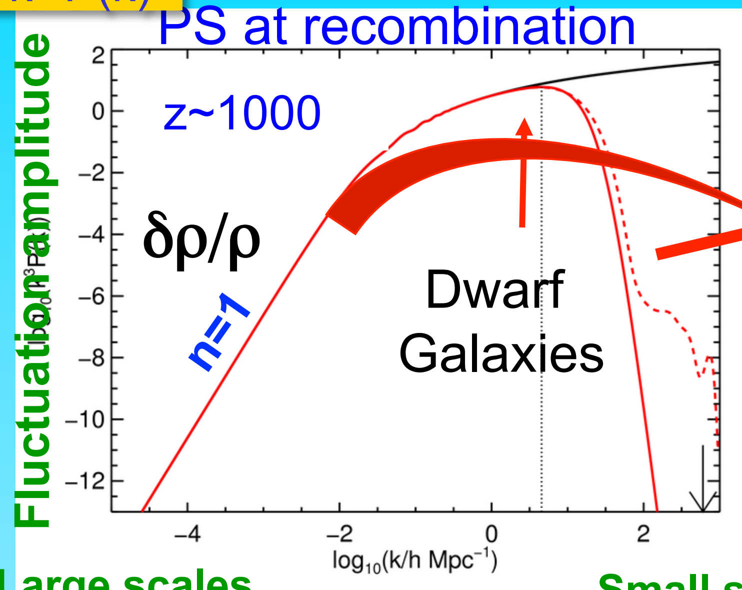
Carina


Sagittarius

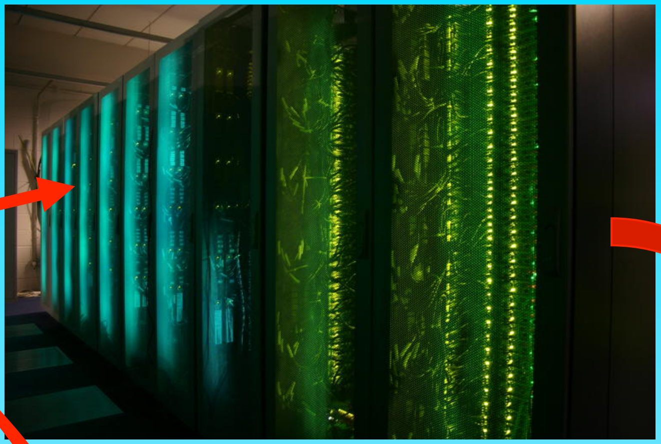
The formation of cosmic structure

University of Durham

k^3 P(k)



"Cosmology machine"



t=380,000 yrs

$\delta\rho/\rho \sim 10^{-5}$

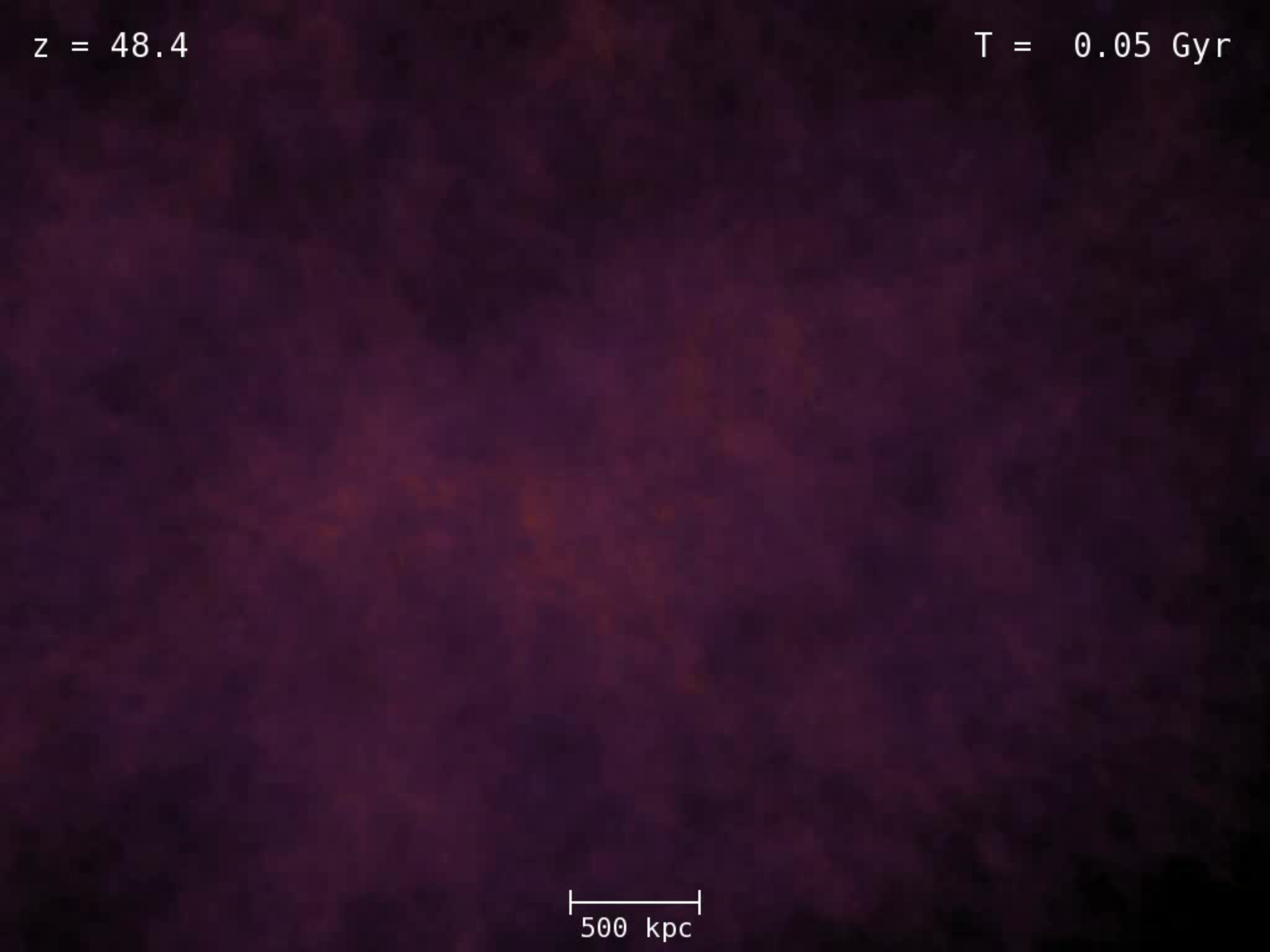
Simulations

Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

t=14.1billion yrs

$\delta\rho/\rho \sim 1-10^6$

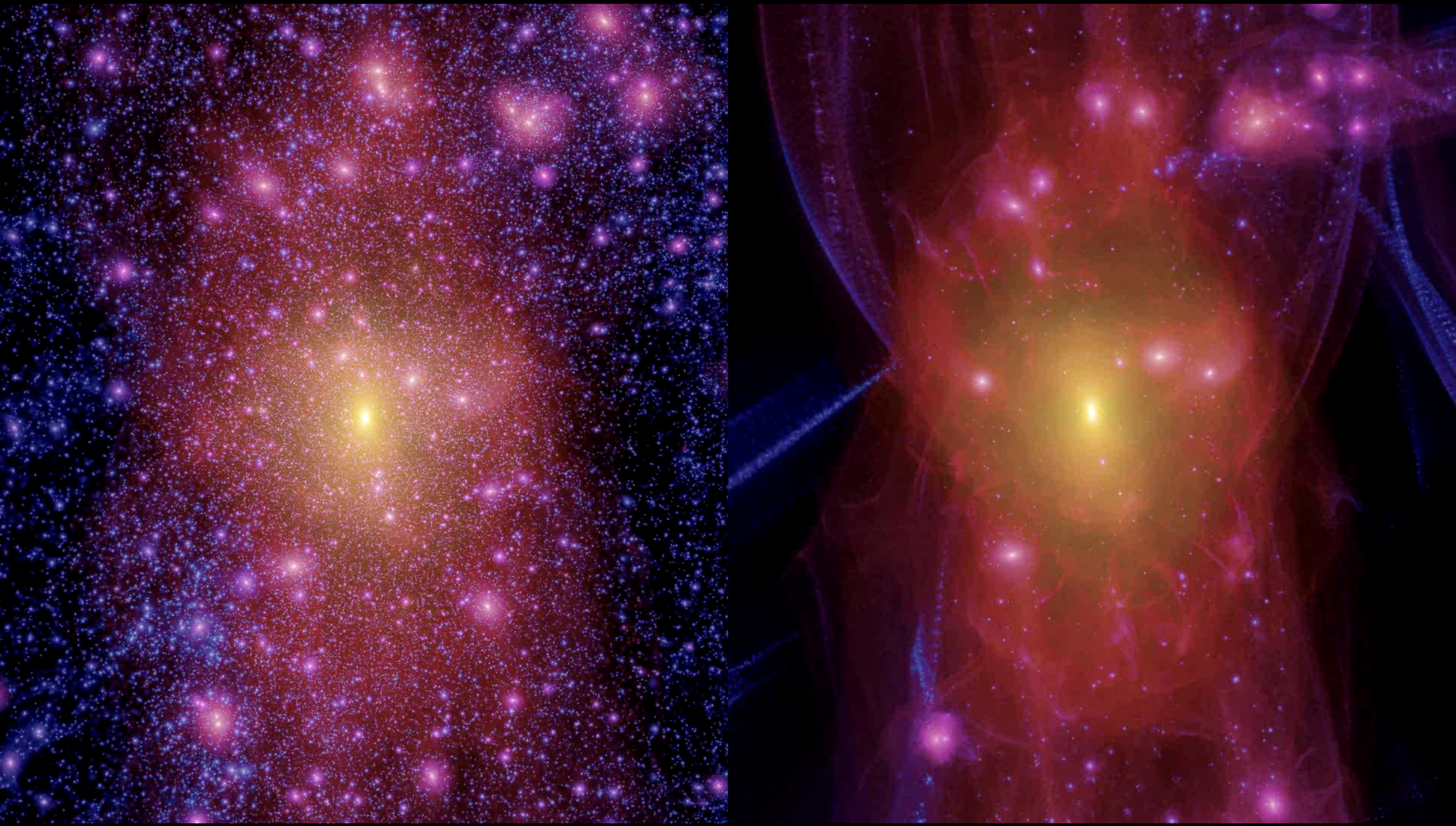
Institute for Computational Cosmology


z = 48.4
T = 0.05 Gyr
500 kpc

Cold Dark Matter Warm Dark Matter

13.4 billion years ago

cold dark matter | warm dark matter



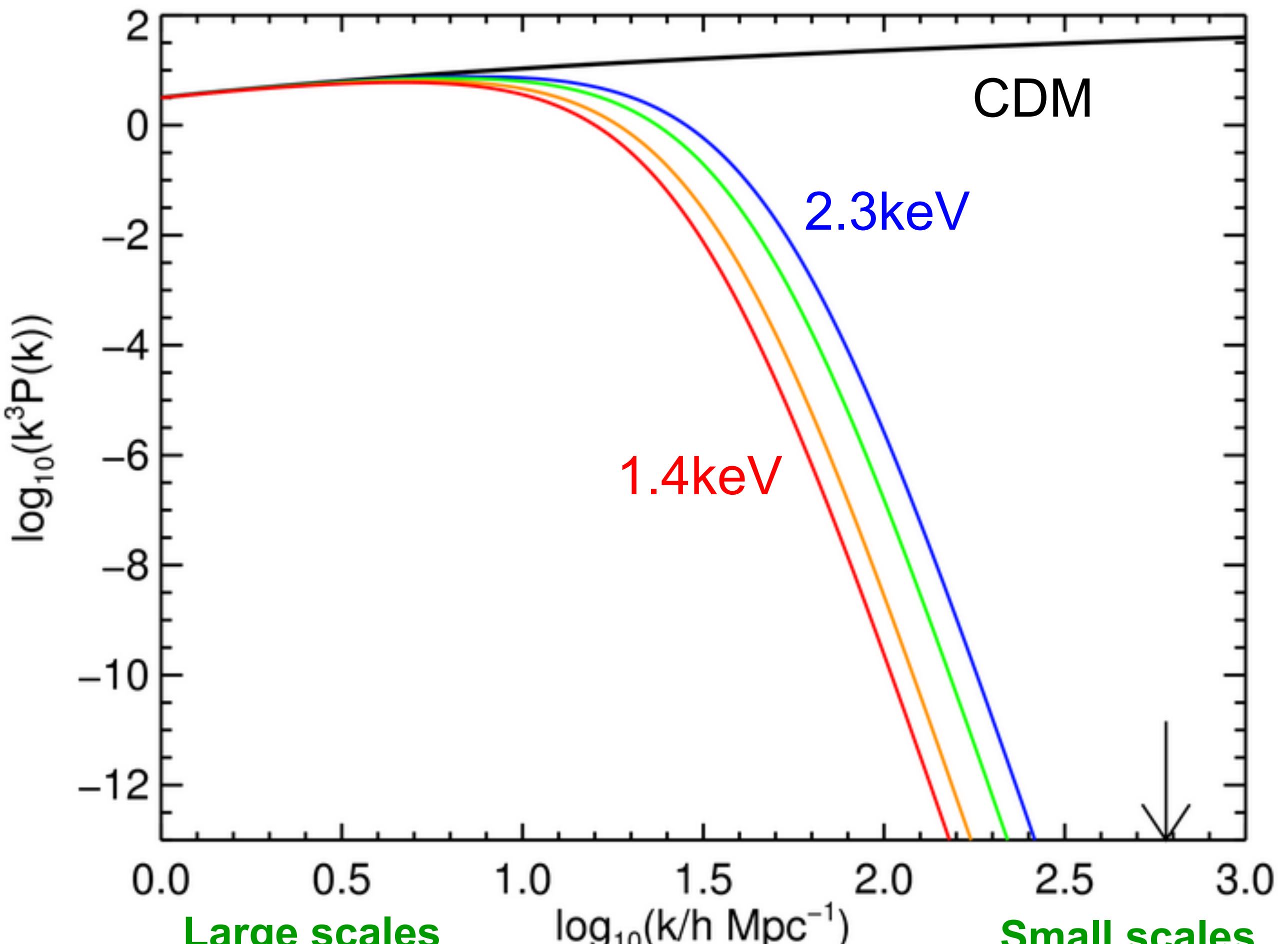
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘13

Warm DM: different ν mass

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

- WDM (black)
- 2.3 keV (blue)
- 2.0 keV (green)
- 1.6 keV (orange)
- 1.4 keV (red)

The linear power spectrum ("power per octave")



Large scales   Small scales

Lovell et al '14

Warm DM: different ν mass

z=3

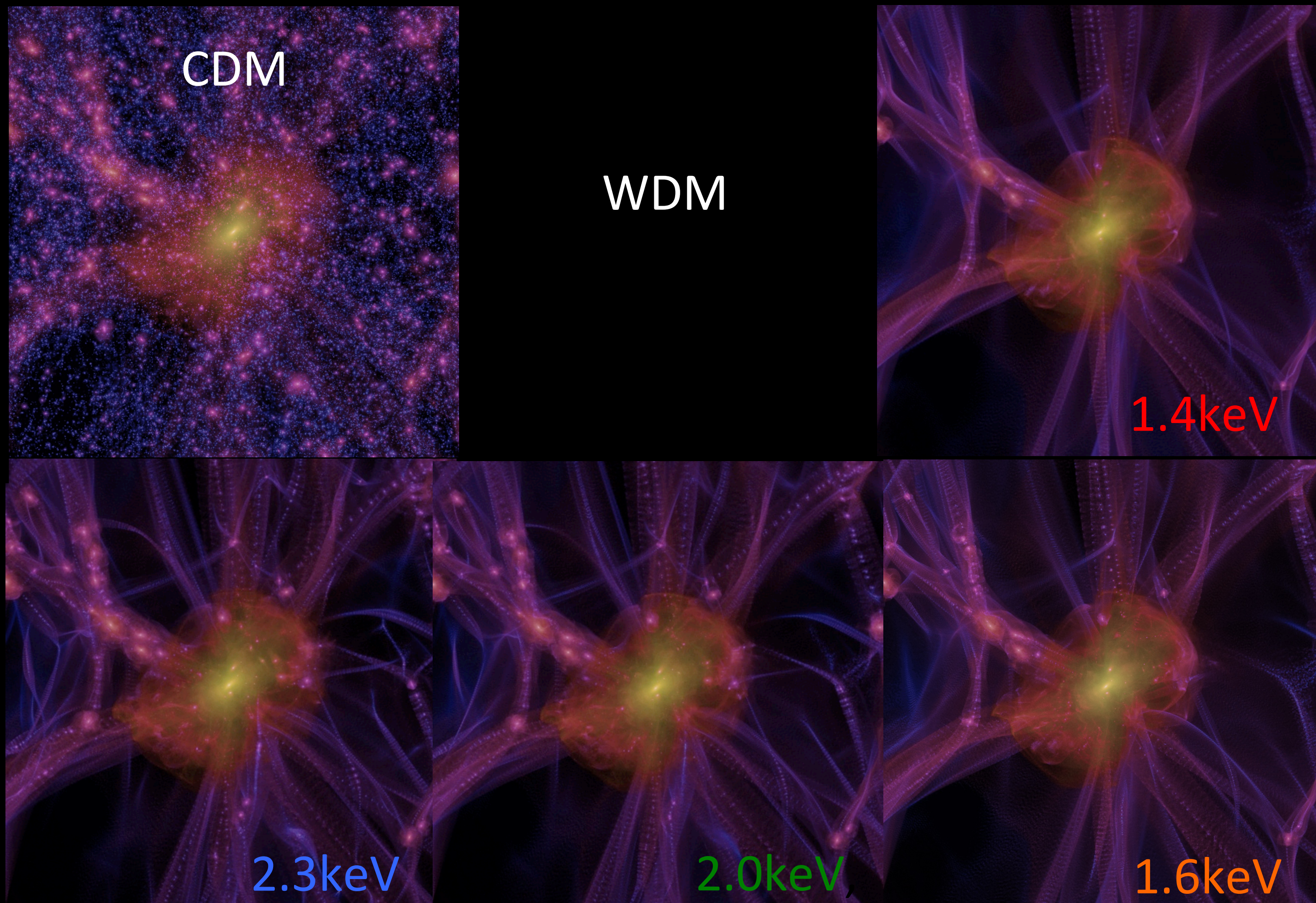
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



University of Durham

N-body simulations: CDM *vs* WDM

Simulations make 2 important predictions on galactic scales:

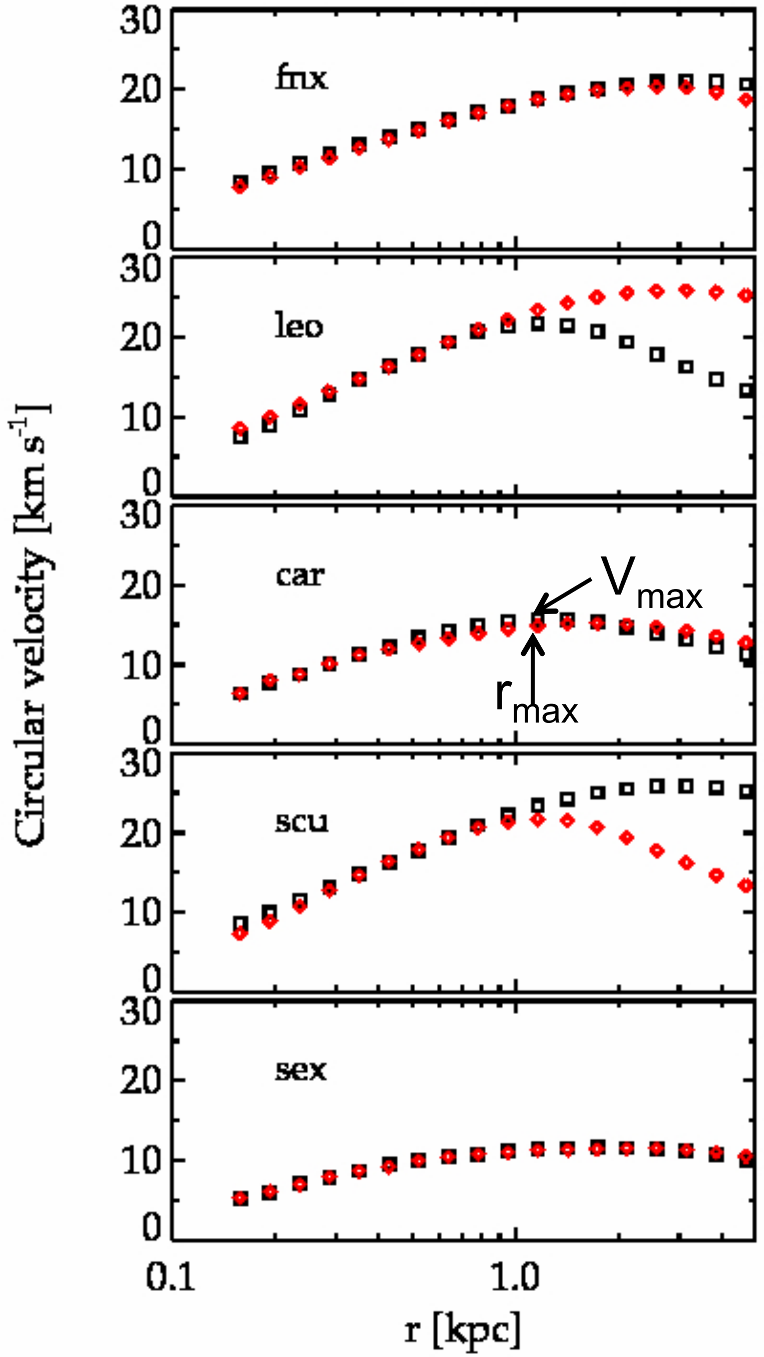
Cold dark matter

- Large number of self-bound substructures (10% of mass) survive
- The main halo and its subhalos have "cuspy" density profiles

Warm dark matter

- Far fewer self-bound substructures (5% of mass) survive
- Main halo profile identical to CDM; subhalos still "cuspy" but less concentrated than in CDM

The structure of the Milky Way satellites



$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$

Strigari, Frenk & White 2010

Subhalo abundance

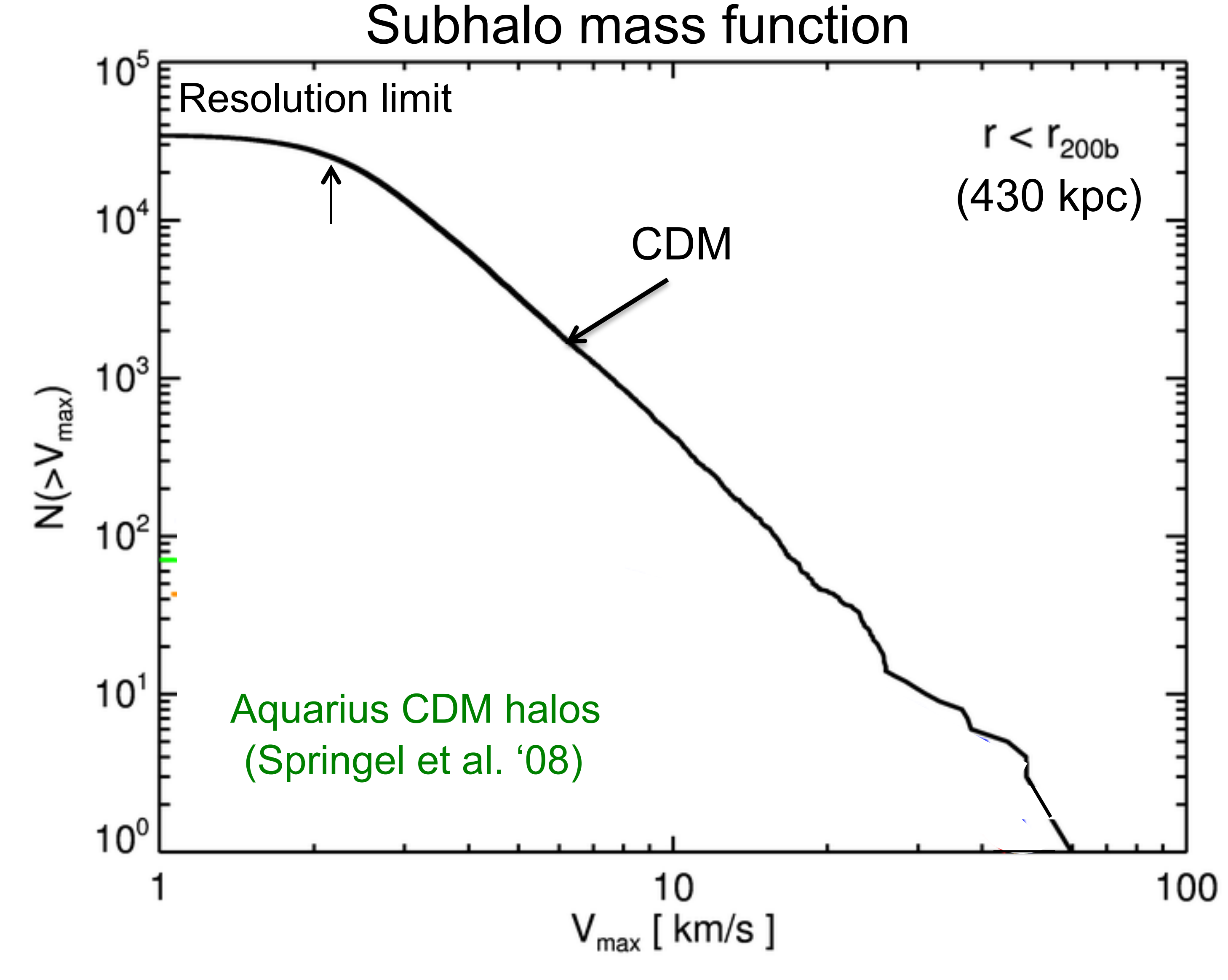
cold dark matter

warm dark matter

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

The mass function of substructures

University of Durham

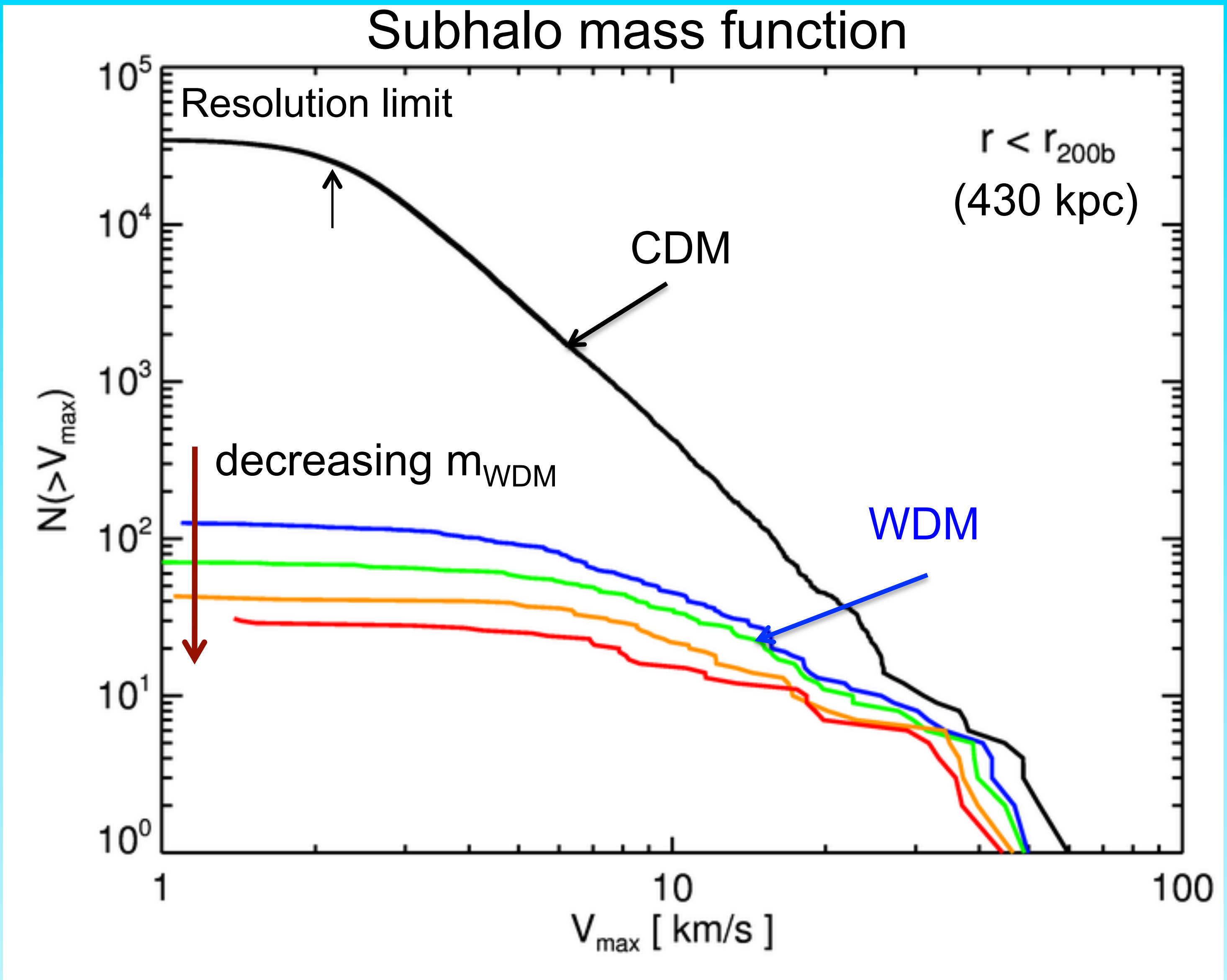


Lovell et al '14

The mass function of substructures

University of Durham

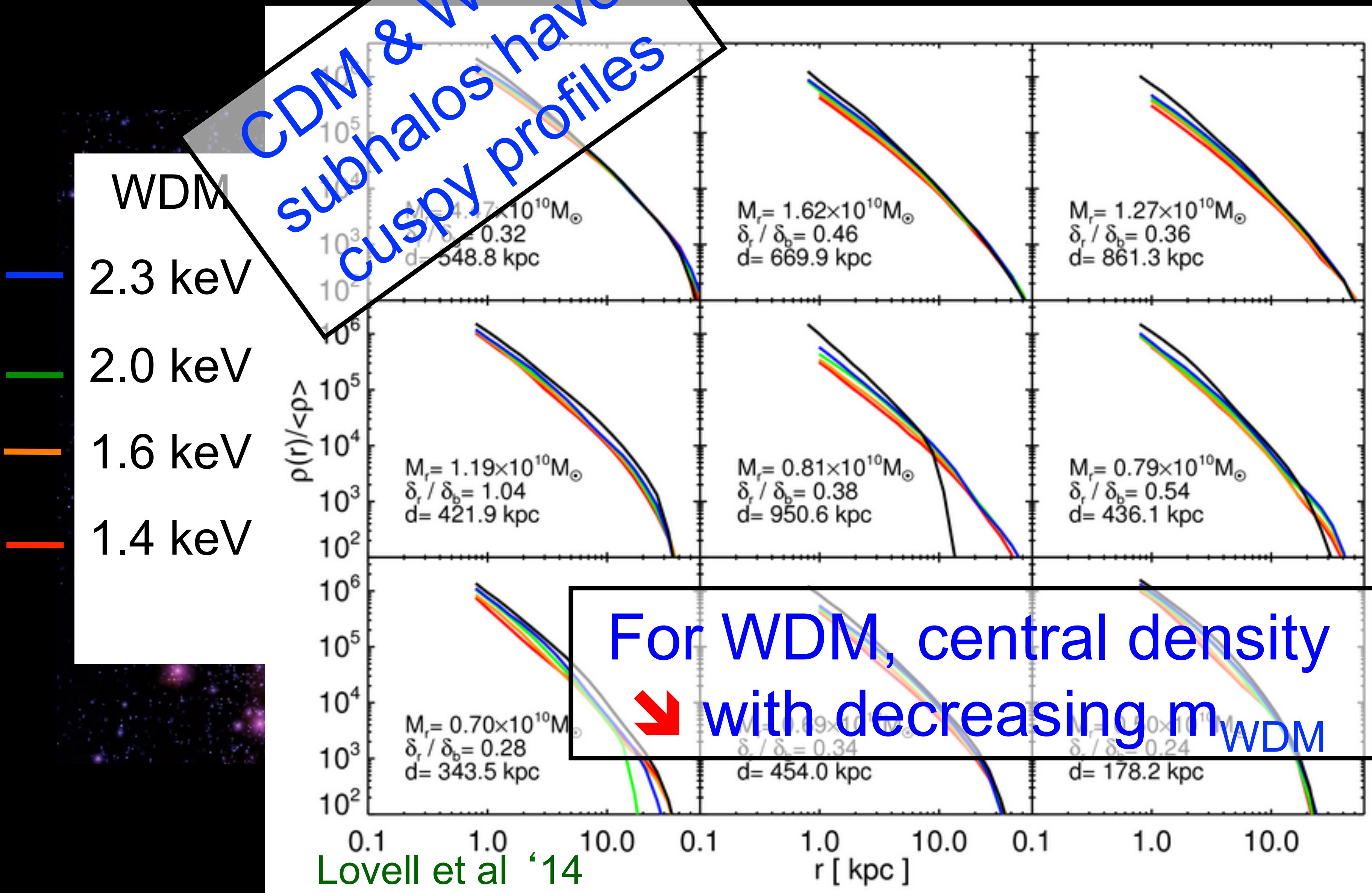
WDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV



No of suhalos ↗ with m_{WDM}

Lovell et al '14

Subhalo density profiles



Lovell et al '14

CDM & WDM subhalos have cuspy profiles

For WDM, central density ↘ with decreasing m_{WDM}

How can we distinguish between CDM & WDM ?

Subhalo abundance

cold dark matter | warm dark matt

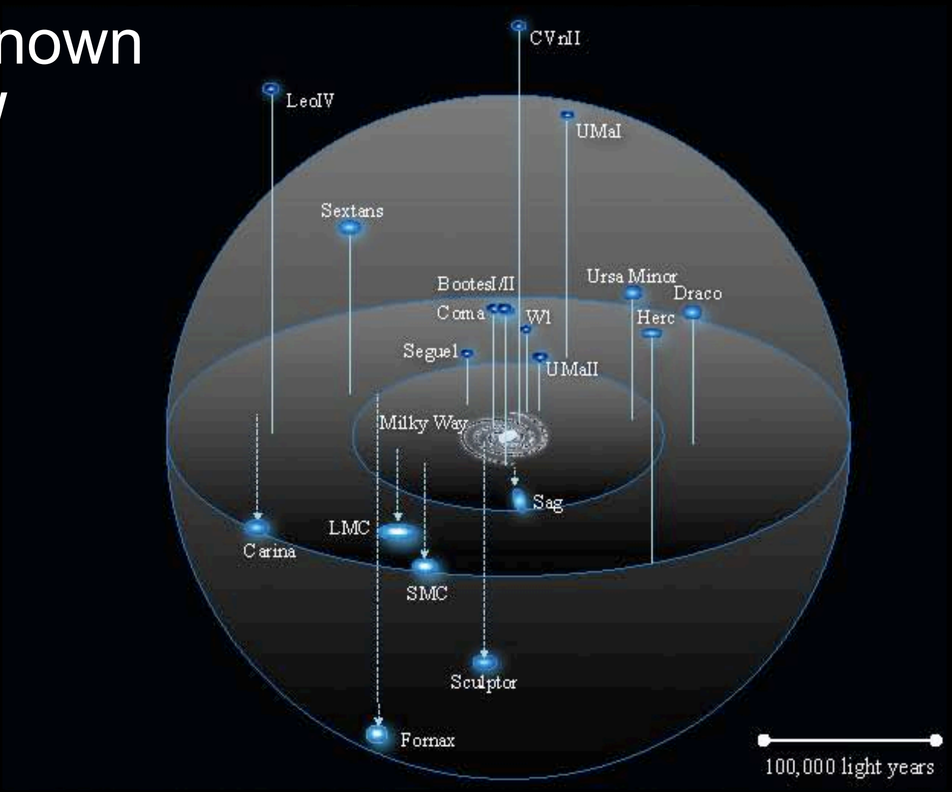
Spot the difference!

By looking at number & structure of subhalos

Lovell, Frenk, Eke, Gao, Jenkins, Theuns ’12, ‘13

The satellites of the Milky Way

~25 satellites known
in the MW



Subhalo abundance

cold dark matter | warm dark matter

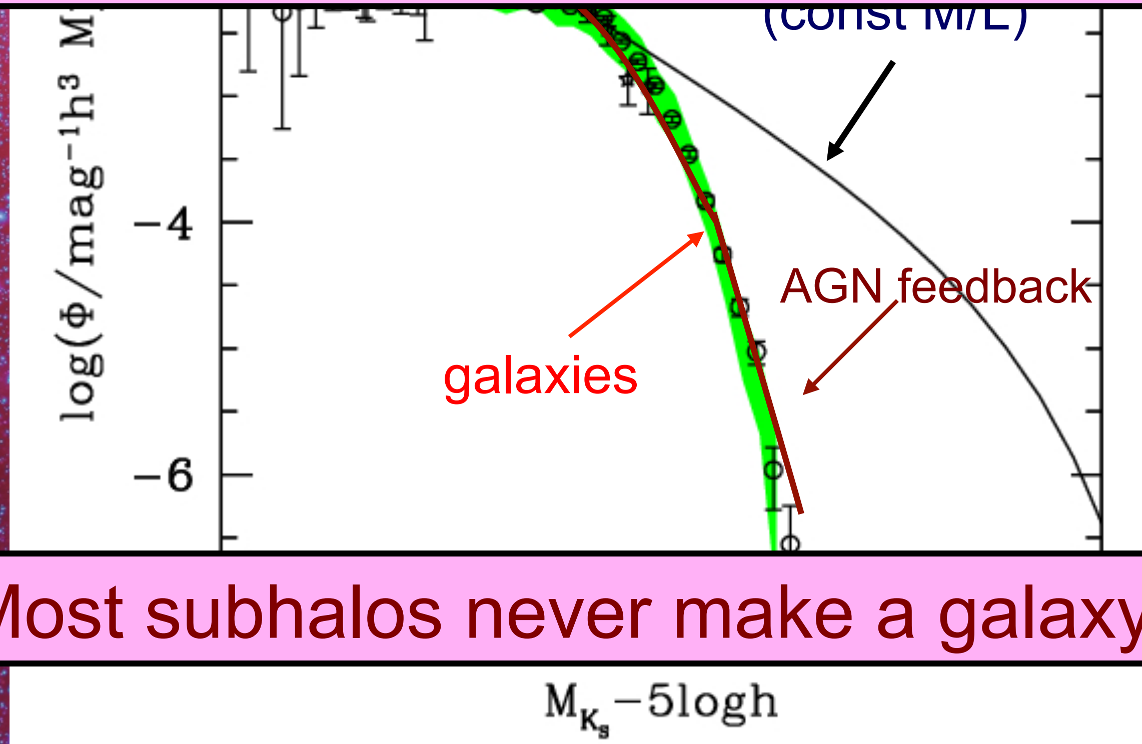
Lovell, Frenk, Eke, Gao, Jenkins, Theuns ’12, ‘14

CDM simulations produce >10^5 subhalos

Making a galaxy in a small halo is hard because:

Reionization heats gas above $T_{vir,}$ preventing it from cooling and forming stars in small halos

- Supernovae feedback expels gas



Most subhalos never make a galaxy!

Institute for Computational Cosmology

MW has only 3 very massive satellites: V_{max} > 30 km/s
(→ $M_{sat} > 0.01\ M_{MW}$) → LMC, SMC, Sagittarius

The “too big to fail” problem

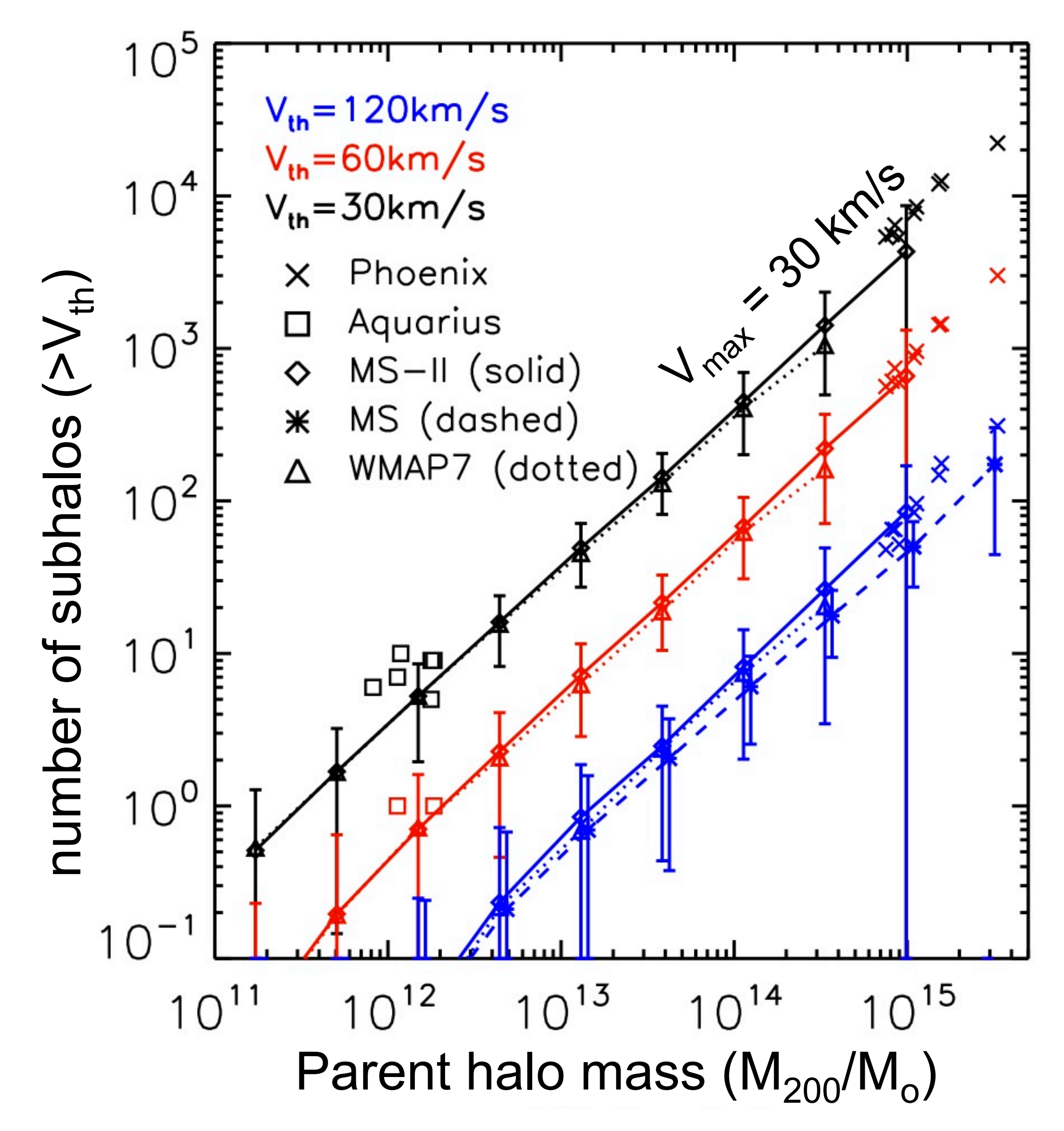
This CDM example ($M_{halo} = 2x10^{12}\ M_o$) has 10 massive satellites with V_{max} > 30 km/s

Number of massive subhalos

University of Durham

Number of massive subhalos increases rapidly with halo mass

→ Milky Way halo mass cannot be too large if CDM is right!



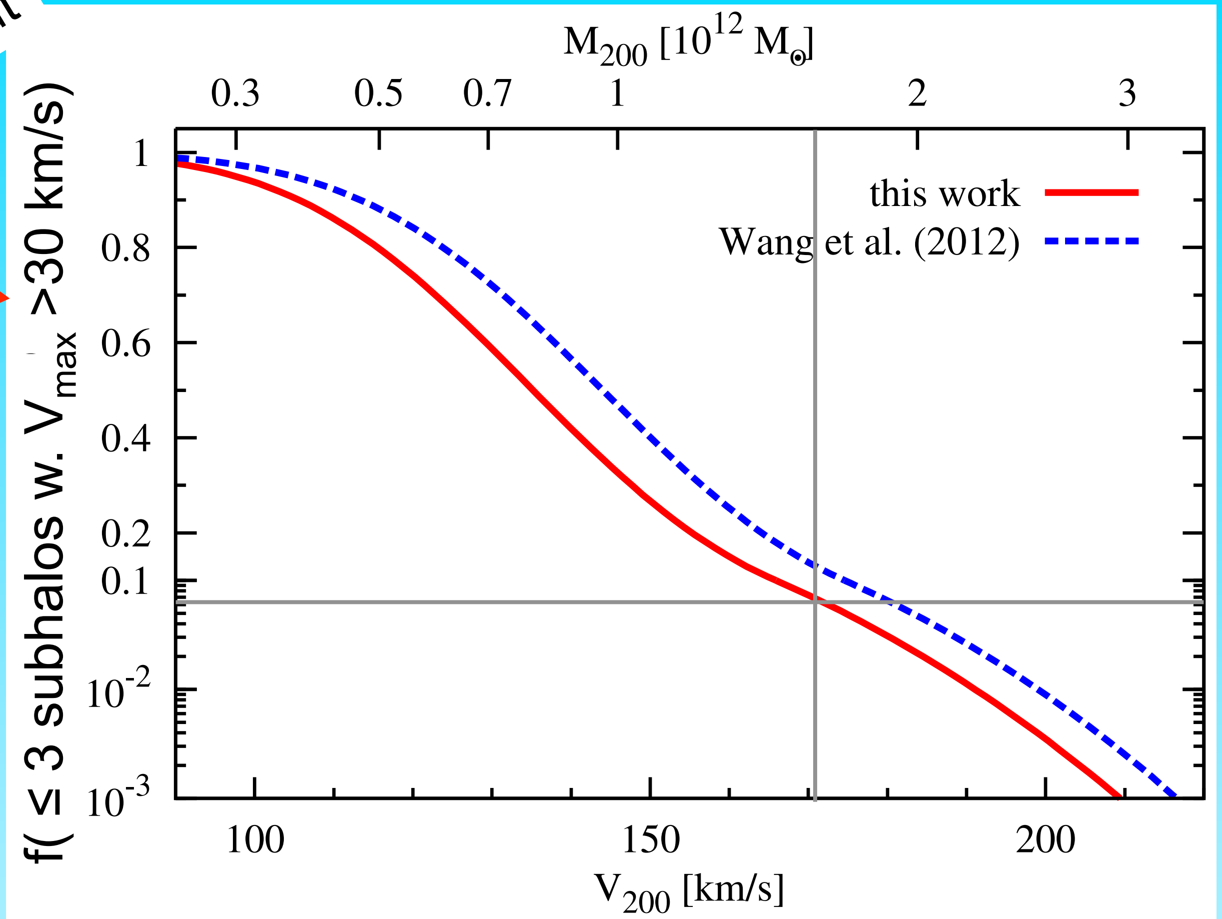
Wang, Frenk, Navarro, Gao '12

Probability of massive subhalos

University of Durham

Probability of having at … subhal… with V… 30 km/s

1 – prob. that ΛCDM is ruled out



Depends strongly on M_{200} (and V_{cut})

CDM requires

$M_{halo} < 1.5 \times 10^{12} M_o$

(95% confidence)

Wang, Frenk, Navarro, Gao '12

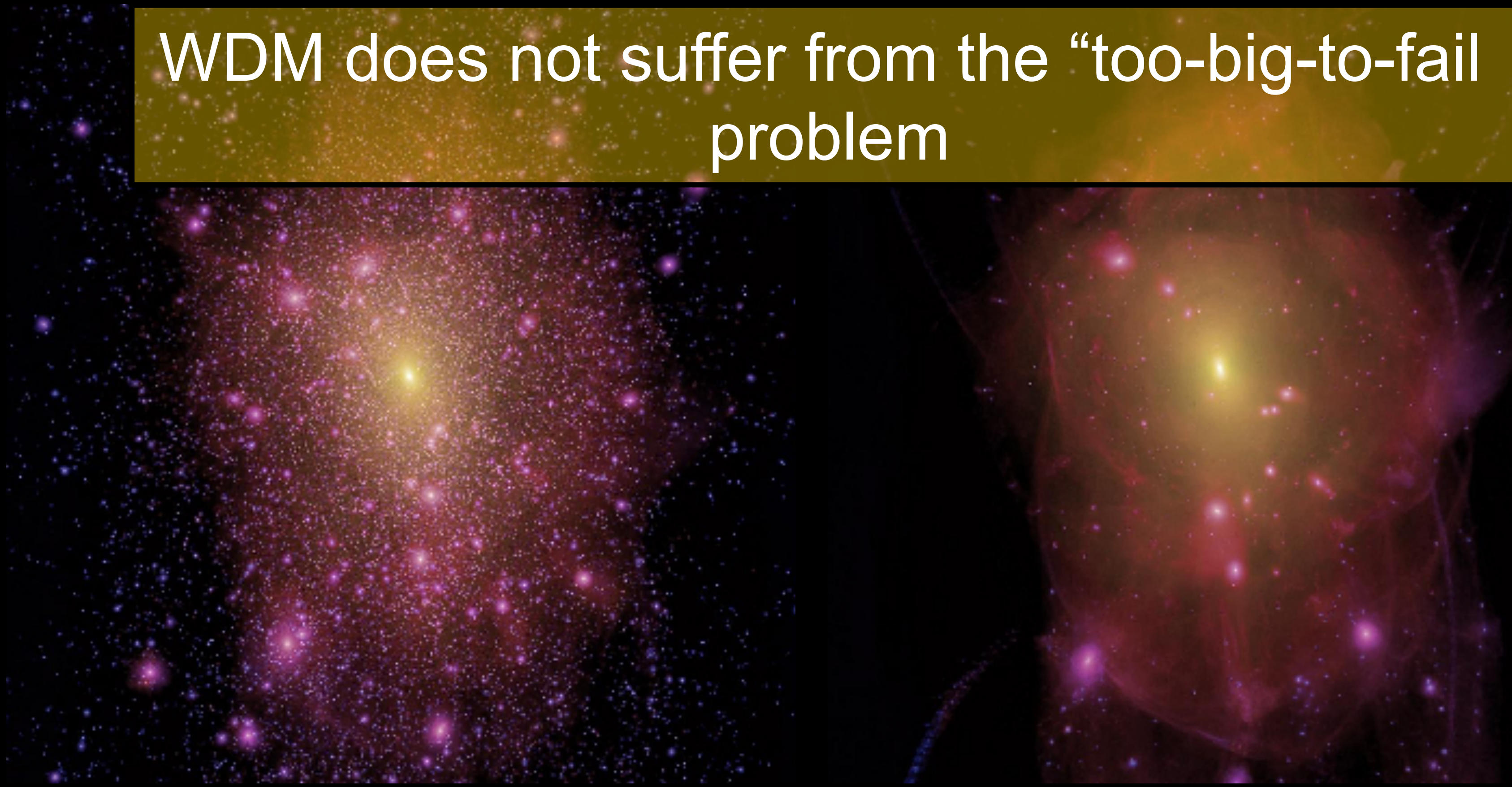
Cautun, Frenk, van den Weygaert, Hellwing '14

Institute for Computational Cosmology

Tests of the nature of the DM

cold dark matter | warm dark matter

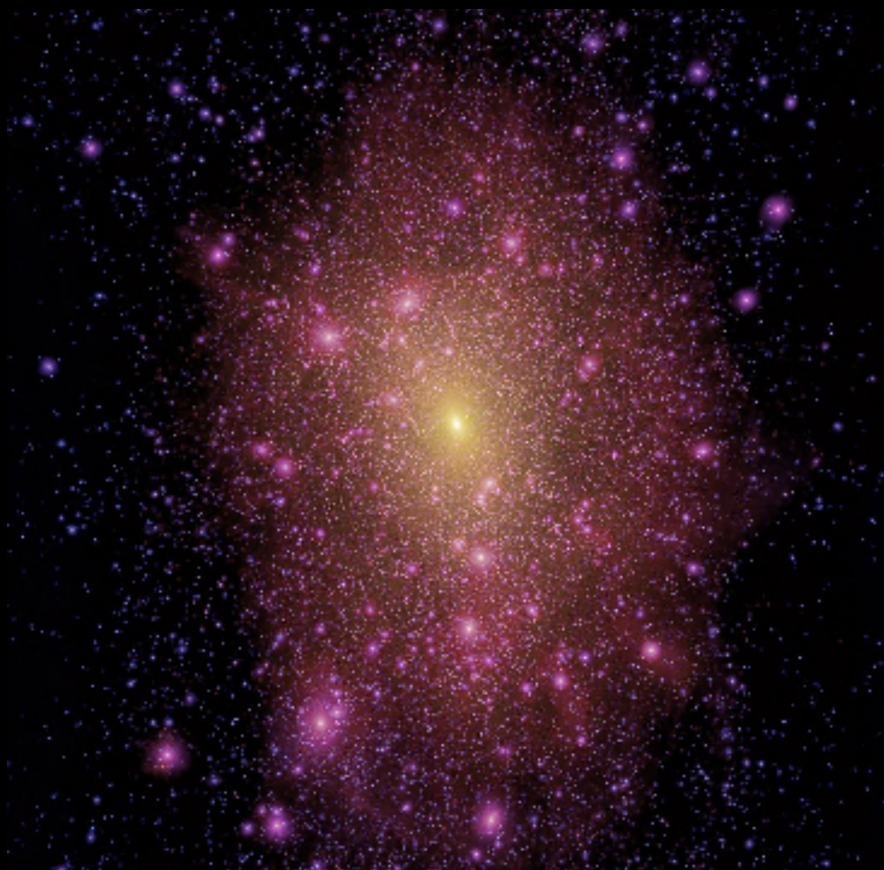
WDM does not suffer from the “too-big-to-fail problem



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

Tests of the nature of the DM

cold dark matter



warm dark matter

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

Warm DM: different ν mass

z=3

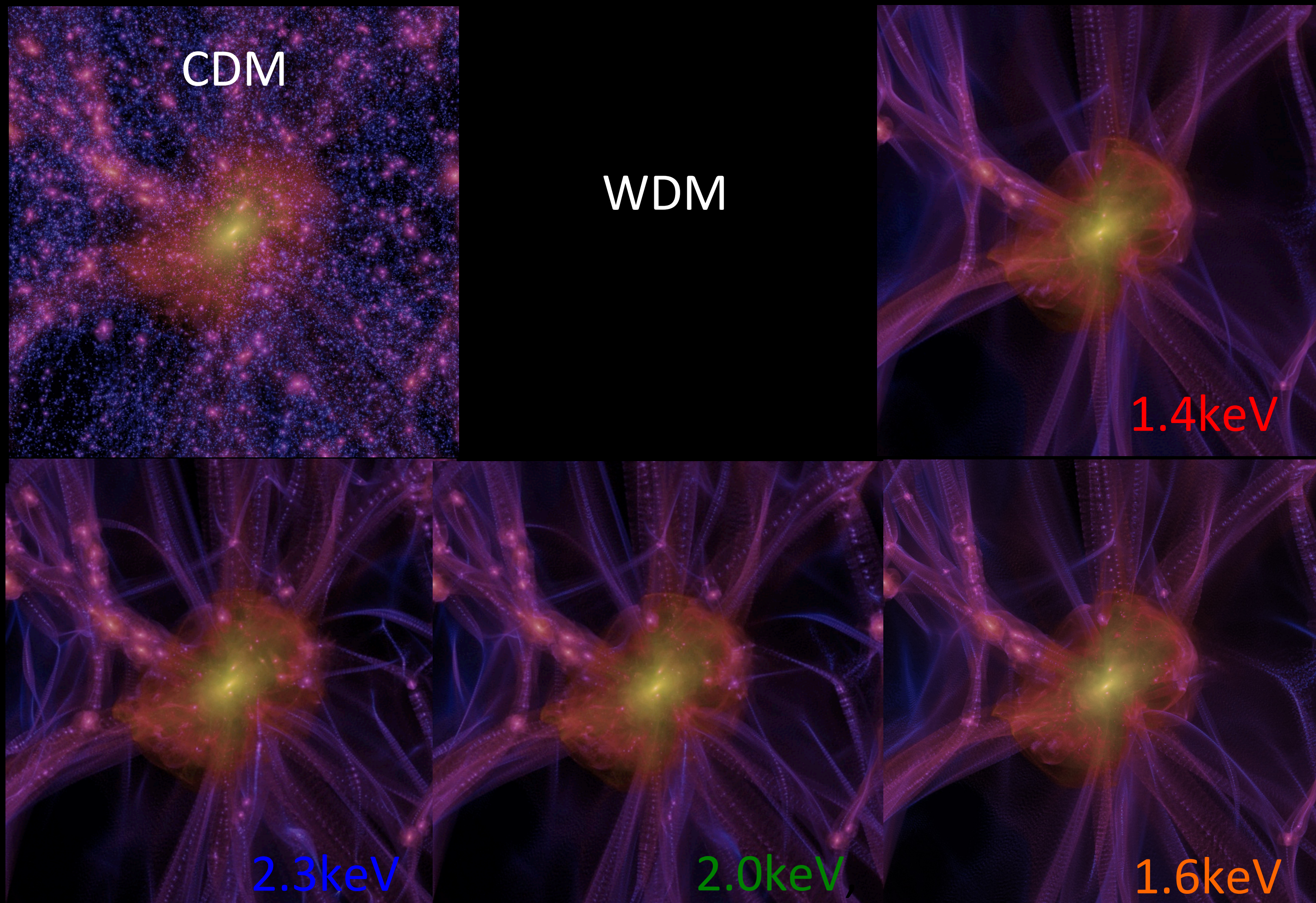
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



Tests of the nature of the DM

warm dark matter

If the halo mass is too small and/or the WDM particle mass is too small, there will not be enough subhalos to account for the observed satellites!

→ lower limit on m_{wdm}

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

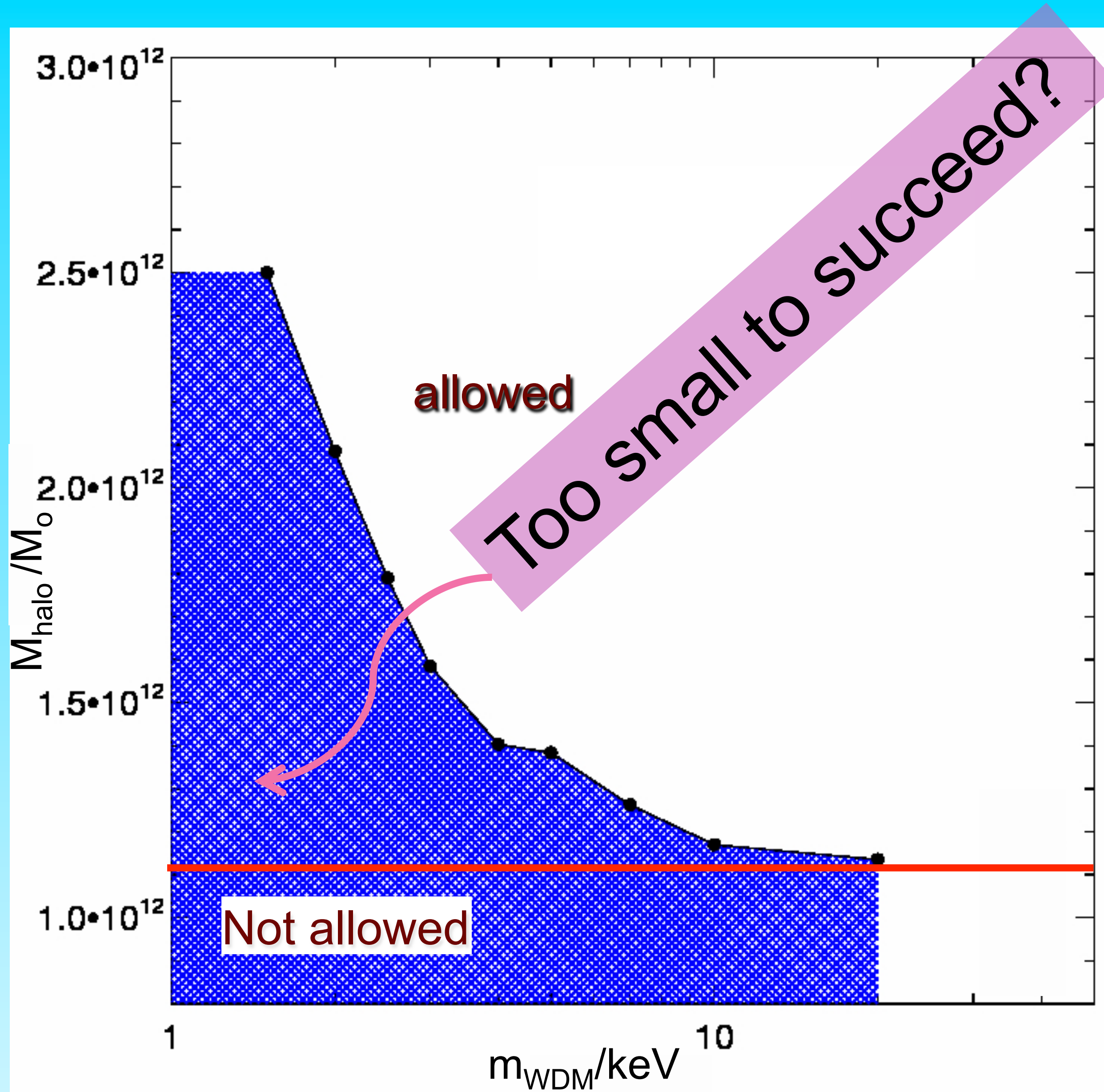
Limits on WDM particle mass

University of Durham

Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

For standard galaxy formation model, WDM ruled out if $M_{halo}<1.1x10^{12}$ M_o

Kennedy, Cole & Frenk '14



University of Durham

Constraints on CDM & WDM from the Milky Way satellites

With our standard assumptions: at 95% confidence

Cold dark matter :

Ruled out unless $M_{halo} < 1.5 \times 10^{12} M_o$

(from abundance of massive satellites)

Warm dark matter :

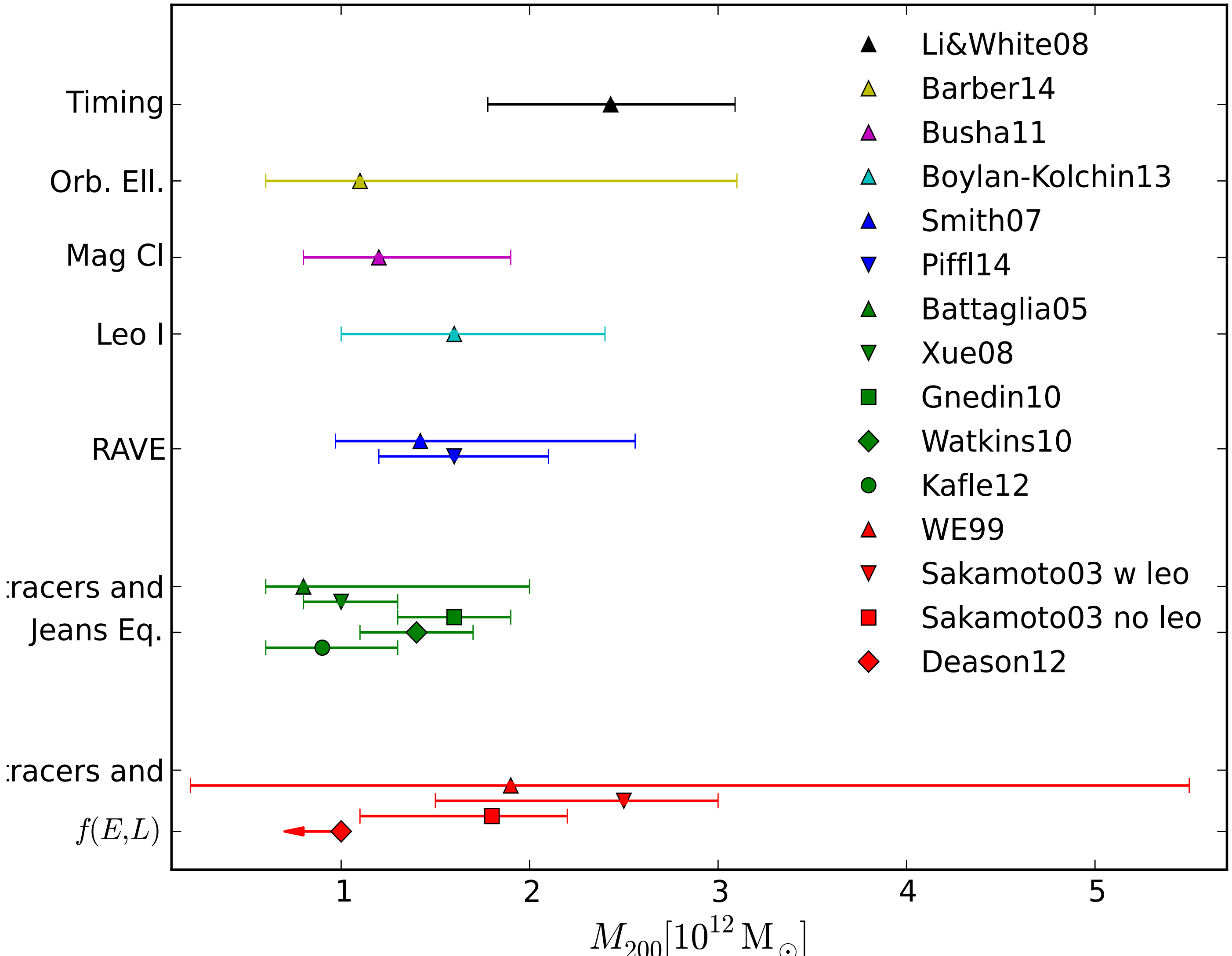
Ruled out unless $M_{halo} > 1.2 \times 10^{12} M_o$

(from abundance of small satellites)

From X-ray decay limit, for resonantly produced sterile νs

→ need $m_{WDM} < 5$keV and $M_{halo} > 1.4 \times 10^{12} M_o$

Estimates of the MW halo mass



Wenting Wang et al. '14

University of Durham

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

Abundance and kinematics of MW sats set strong constraints on nature of dark matter

IF Mass of Milky Way halo

- $> 1.5 \times 10^{12} M_o$ CDM ruled out*
- $< 1.1 \times 10^{12} M_o$ WDM ruled out

* unless exotic baryonic effects are important