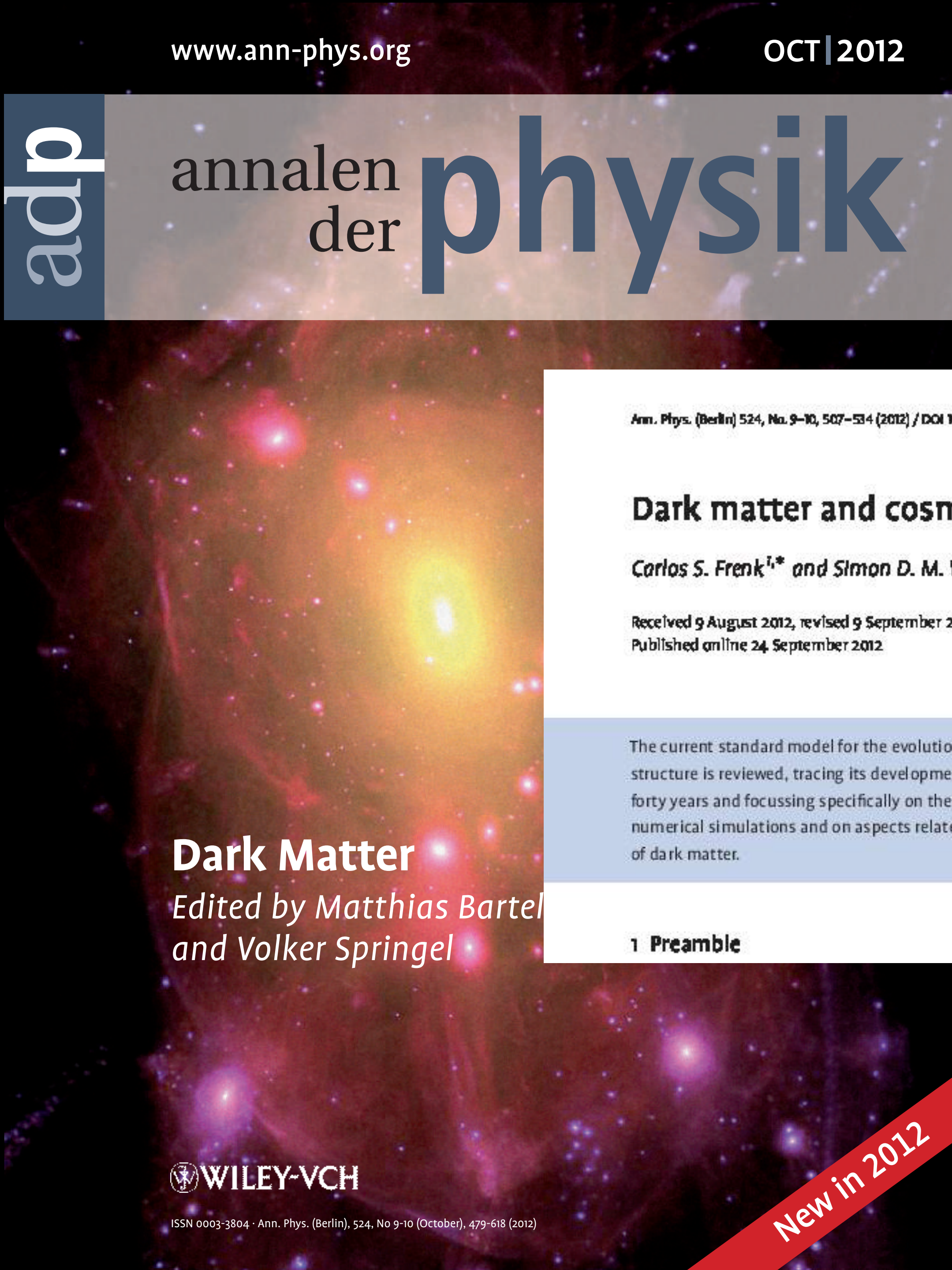
Yakob Zel'dovich (1914 – 1987)

Simulations of the cosmic web

Carlos S. Frenk
Institute for Computational Cosmology,
Durham



Ann. Phys. (Berlin) 524, No. 9–10, 507–534 (2012) / DOI 10.1002/andp.201200212

annalen der physik

Review Article

Dark matter and cosmic structure

Carlos S. Frenk[1,*] *and Simon D. M. White*[2]

Received 9 August 2012, revised 9 September 2012, accepted 13 September 2012
Published online 24 September 2012

The current standard model for the evolution of cosmic structure is reviewed, tracing its development over the last forty years and focussing specifically on the role played by numerical simulations and on aspects related to the nature of dark matter.

1 Preamble

tention is to provide an account of the main ideas and advances that have shaped the subject. We begin by presenting in Table 1 a chronological listing of the landmark developments that have driven this remarkable story.

2 Prehistory

In 1933 Zwicky published unambiguous evidence for dark matter in the Coma galaxy cluster [1]; in 1939 Bab-

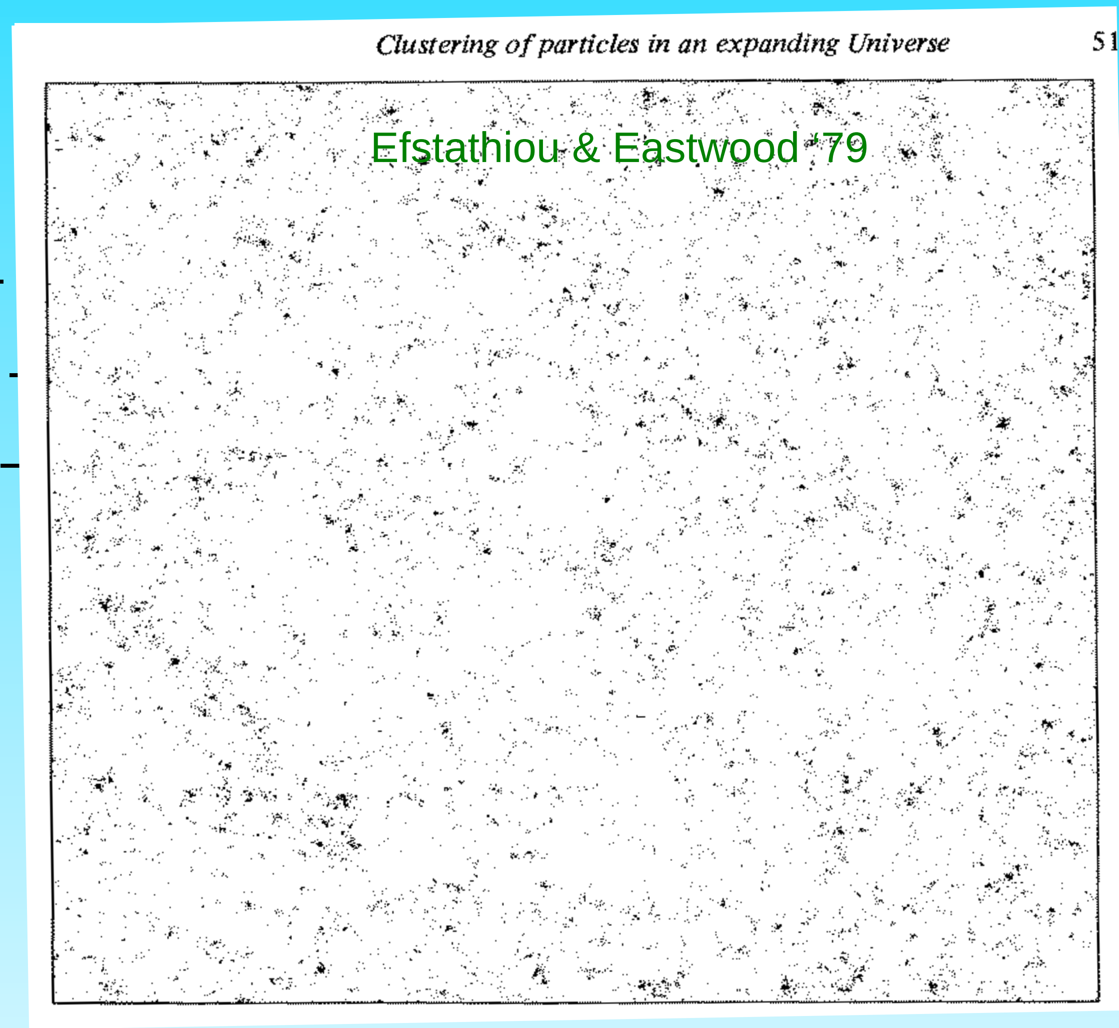
Institute for Computational Cosmology

Cosmological simulations: prehistory

University of Durham

$$|\delta_k|^2 \propto k^n \qquad \Omega = 1$$

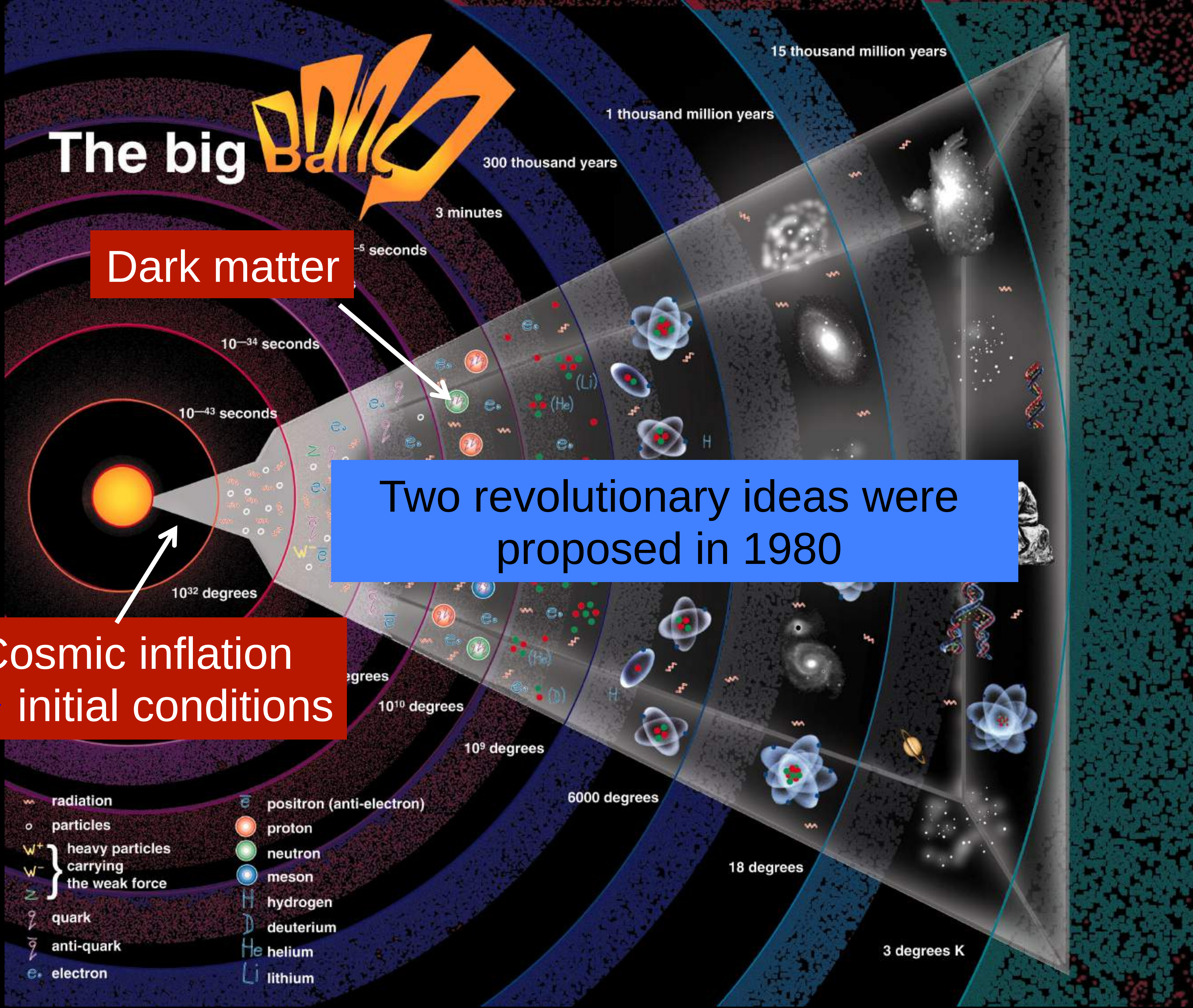
- Press & Schechter 1974 –
- Peebles & Groth 1976 –
- White 1976 – Coma cluster –
- Aarseth, Gott & Turner 1979 –
- Efstathiou & Eastwood 1979 –



Two revolutionary ideas were proposed in 1980

Dark matter

Cosmic inflation
→ initial conditions



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

The dark matter power spectrum

University of Durham

Free streaming →

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

for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

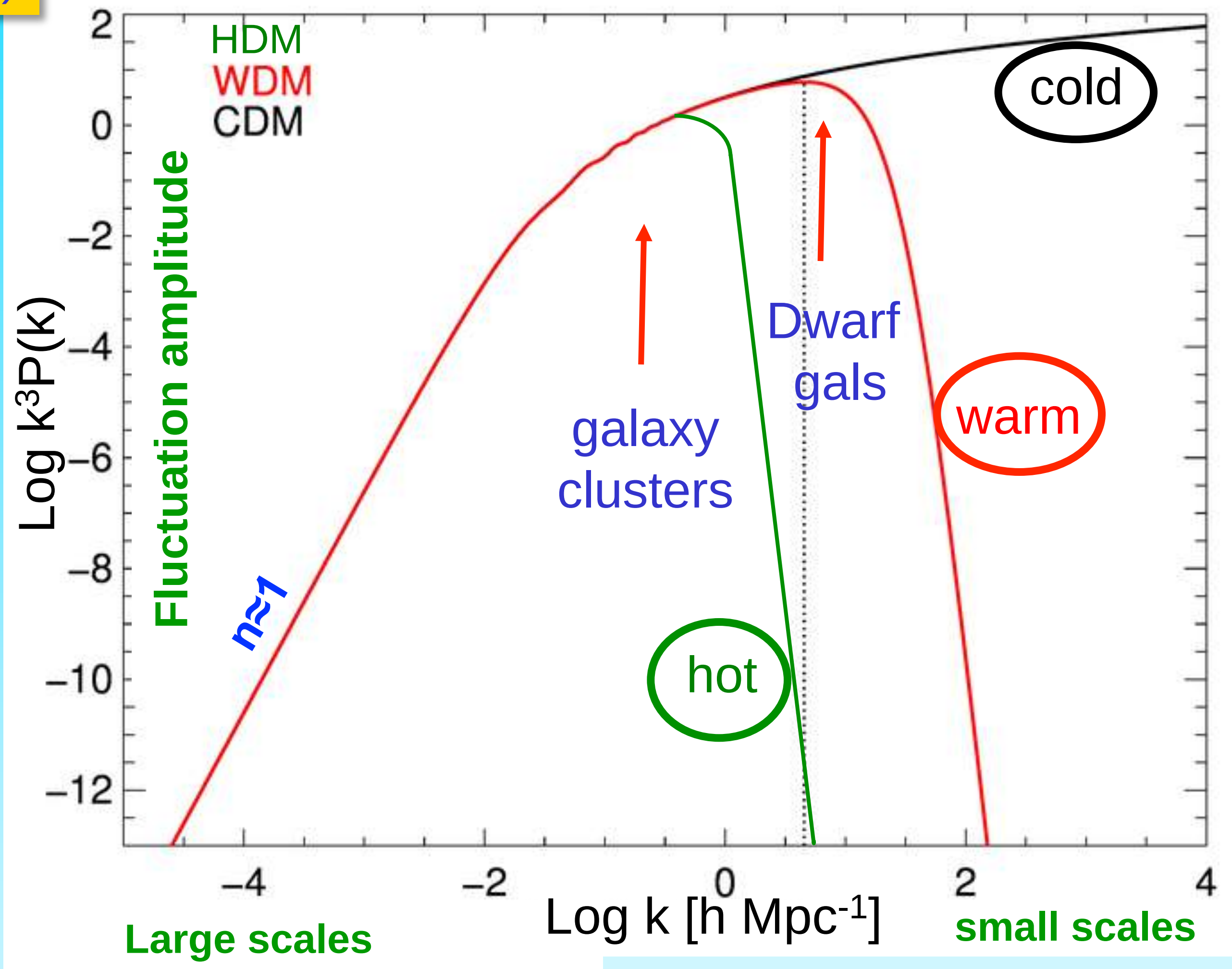
sterile ν; $M_{cut} \sim 10^9 M_o$

$m_{HDM} \sim$ few eV

light ν; $M_{cut} \sim 10^{15} M_o$

$k^3 P(k)$

The linear power spectrum ("power per octave")



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 ($E_{3\ max} \approx$ 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 $S = (E-E_o)^2$. The Kurie plot is then a straight line with the only kinematic parameter being $E_k = E_o$ (total β-transition energy). If $M_\nu \neq 0$, then $S = (E_o-E)\sqrt{(E_o-E)^2-M_\nu^2}$. The Kurie plot is then distorted, especially near the endpoint.

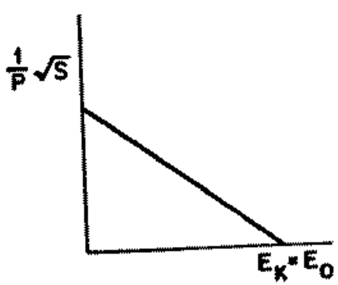


Fig. 1. Kurie plot for $M_\nu = 0$.

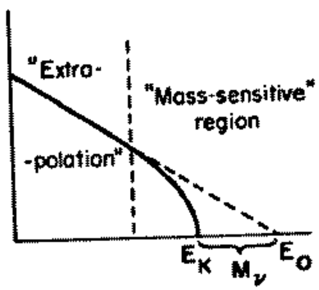
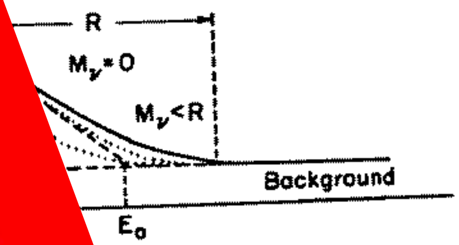


Fig. 2. Kurie plot for $M_\nu \neq 0$.

The method for the neutrino mass measurement is to obtain E_o from the extrapolation and obtain E_k from the spectrum intercept. Then $M_\nu = E_o - E_k$. 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 [...]ass and the influence of R are indistinguishable. For M_ν [...]ermination the knowledge of R is compulsory. The background determines the statistical accuracy near the endpoint, i.e., in the region of the highest sensitivity to the ν mass. So: 1) R should be $\sim M_\nu$, 2) the smaller M_ν is, the smaller the background ($\sim M_\nu^2$) must be and the higher the statistics ($\sim M_\nu^{-3}$) must be. For example, suppose that for $M_\nu = 100$ eV we need resolution R, background Q, and statistics N. If $M_\nu = 30$ eV, to achieve the same ΔM/M they should be R/3, Q/10, and N × 30, respectively.

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

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

Early cosmological simulations

Mon. Not. R. astr. Soc. (1983) **204**, 891–907

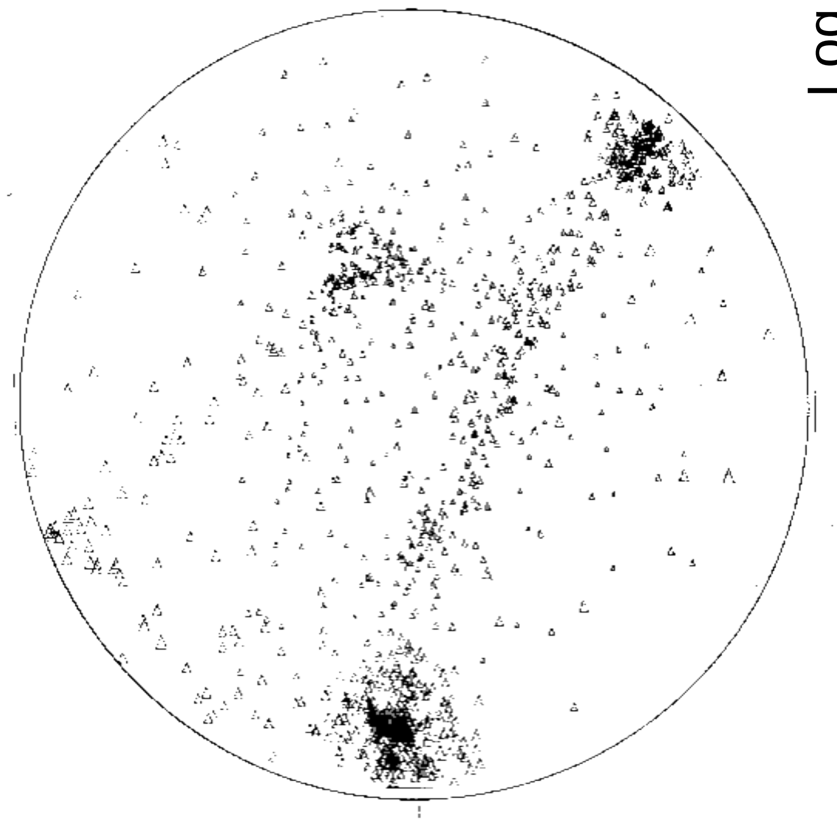
Three-dimensional numerical model of the formation of large-scale structure in the Universe

A. A. Klypin and S. F. Shandarin *The Keldysh Institute of Applied Mathematics, Academy of Sciences of USSR, Miusskaja Sq. 4, Moscow 125047, USSR*

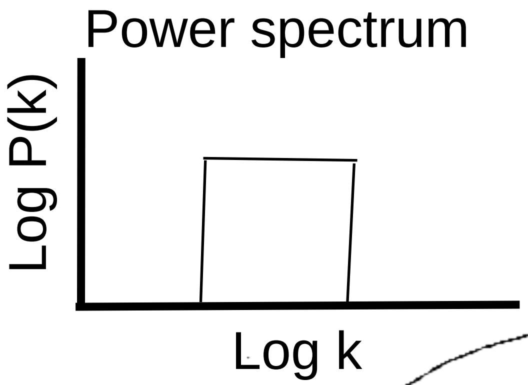
Received 1982 November 15; in original form 1982 April 28

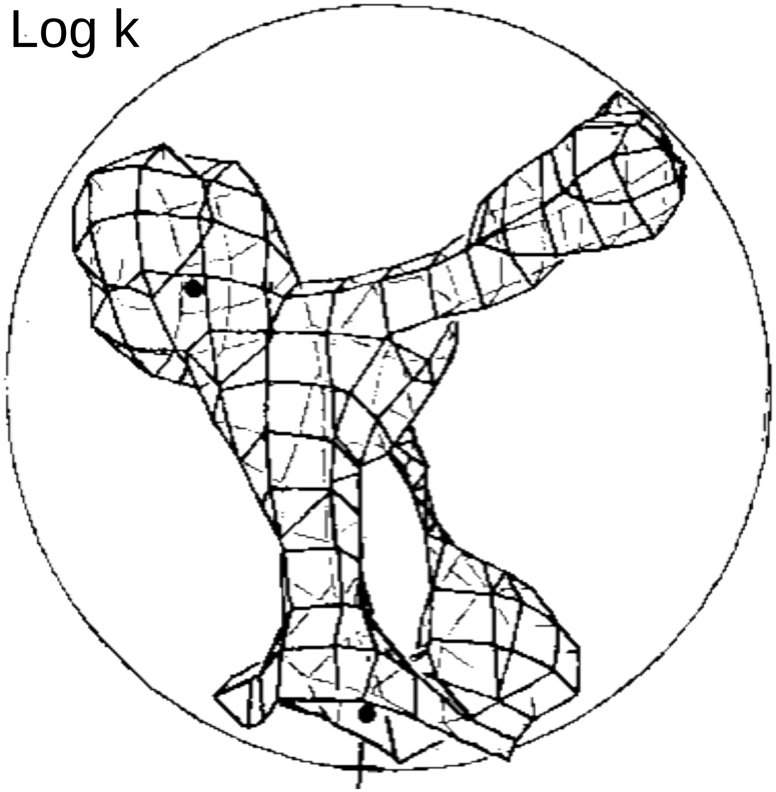
Early cosmological simulations

“Pancake” model



Klypin & Shandarin 1983





University of Durham

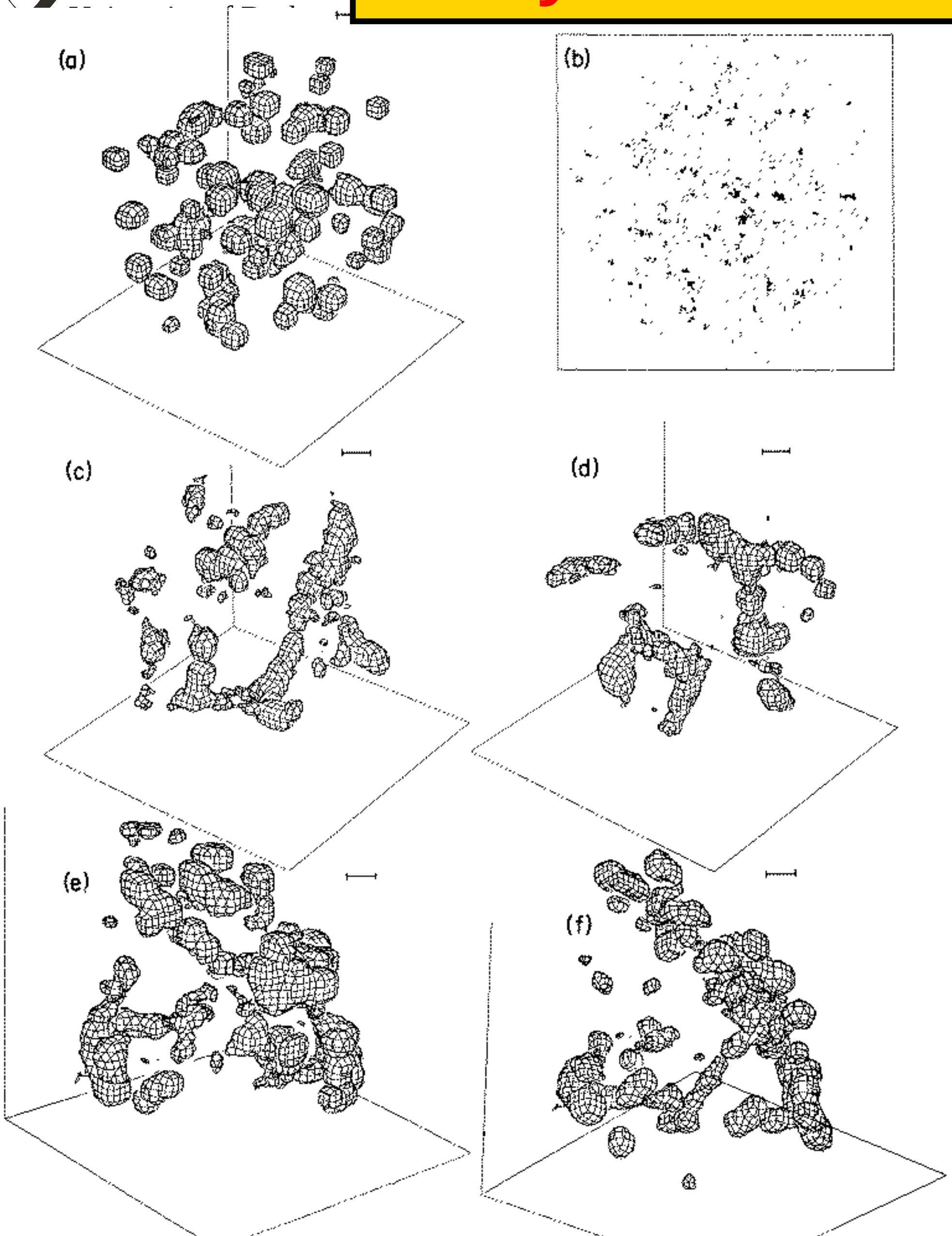
Early cosmological simulations

THE ASTROPHYSICAL JOURNAL, **271**:417–430, 1983 August 15

NONLINEAR EVOLUTION OF LARGE-SCALE STRUCTURE IN THE UNIVERSE

CARLOS S. FRENK,[1] SIMON D. M. WHITE,[1,2] AND MARC DAVIS[1,3]
University of California, Berkeley
Received 1982 November 4; accepted 1983 January 27

Early cosmological simulations



"Poisson" models (n=0)

"Pancake" models (neutrinos)

CfA redshift survey

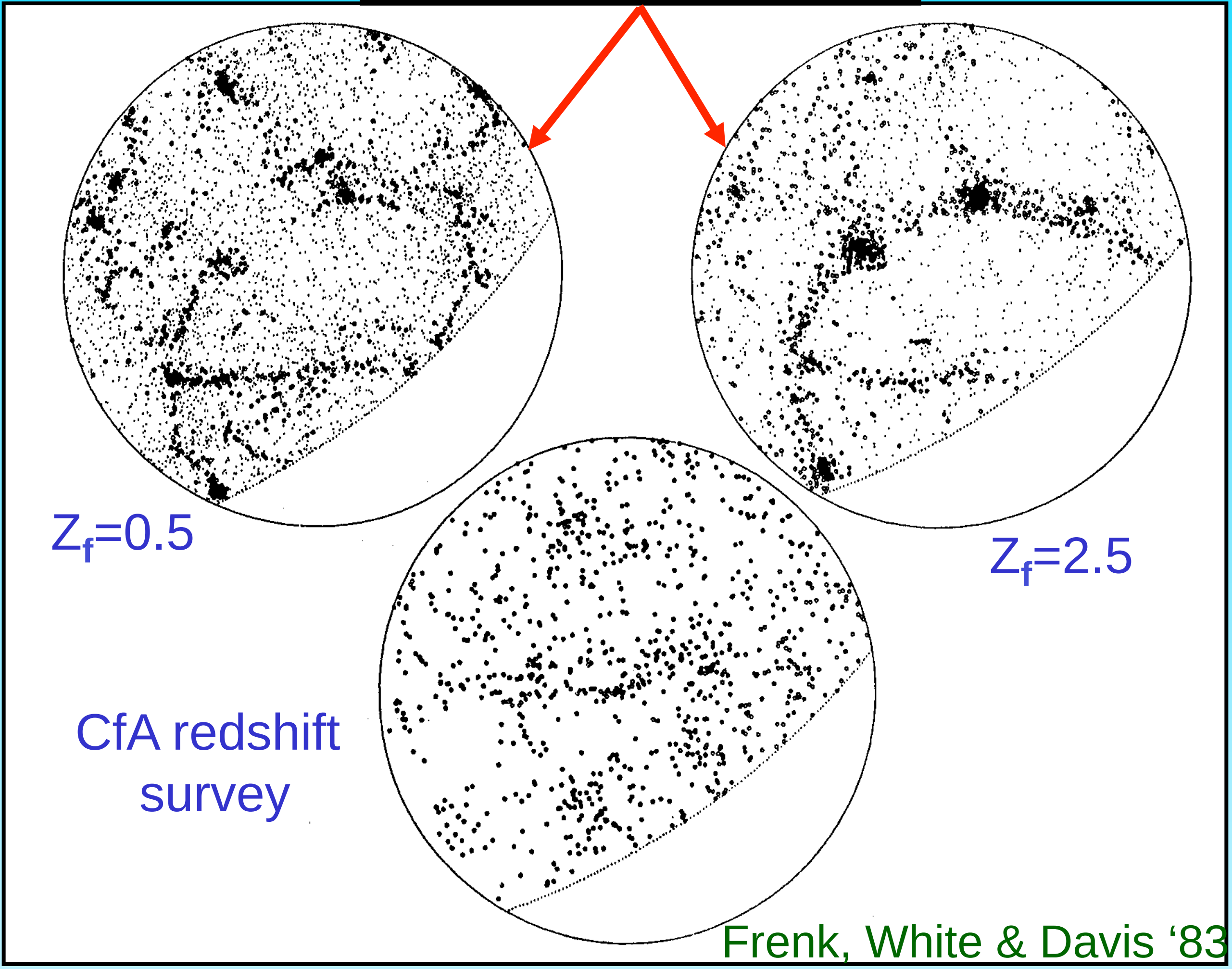
Neutrino (hot) dark matter

$\Omega_\nu = 1$ (m_ν = 30 ev)

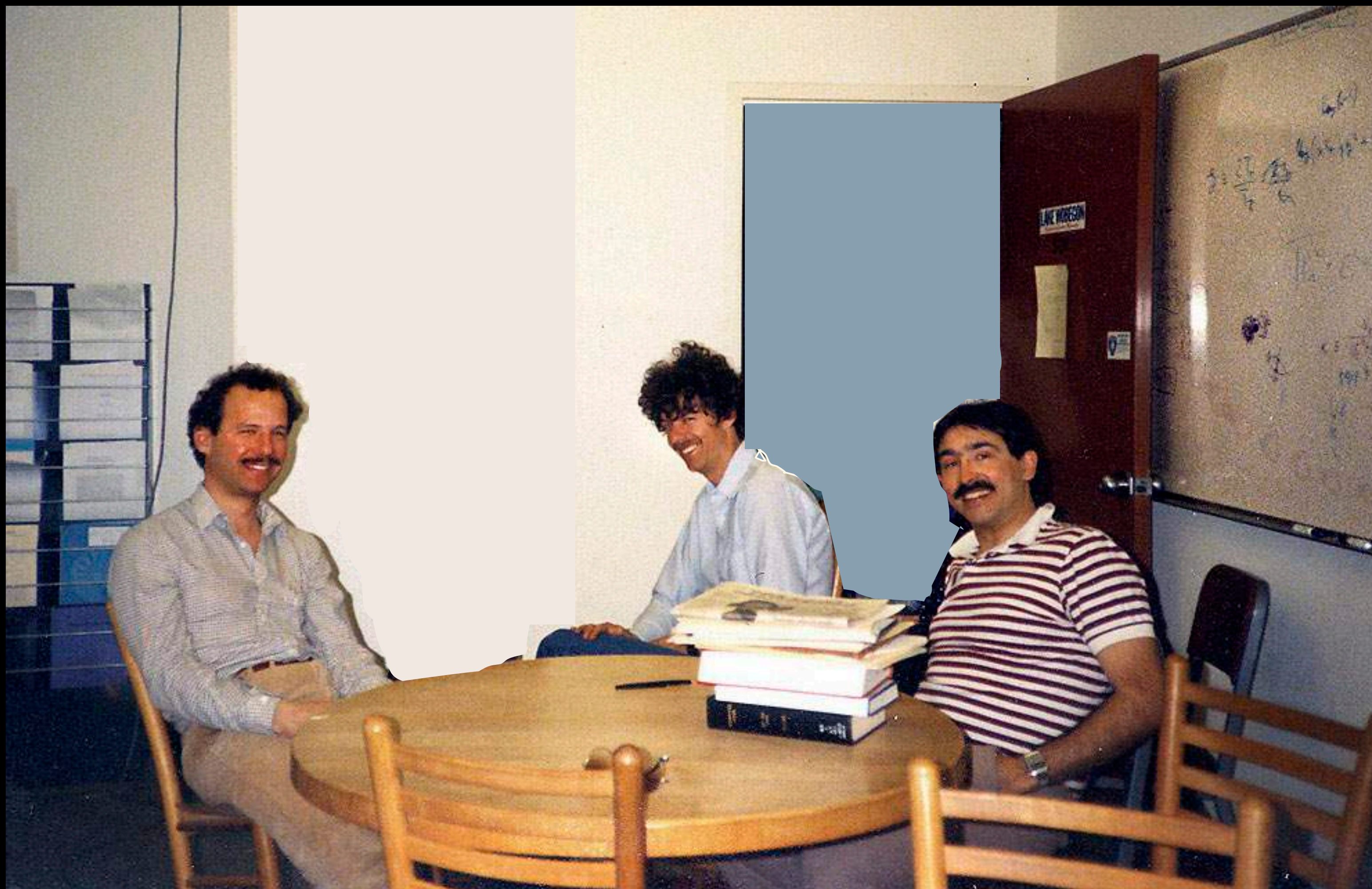
Free-streaming length so large that superclusters form first and galaxies are too young

⇨

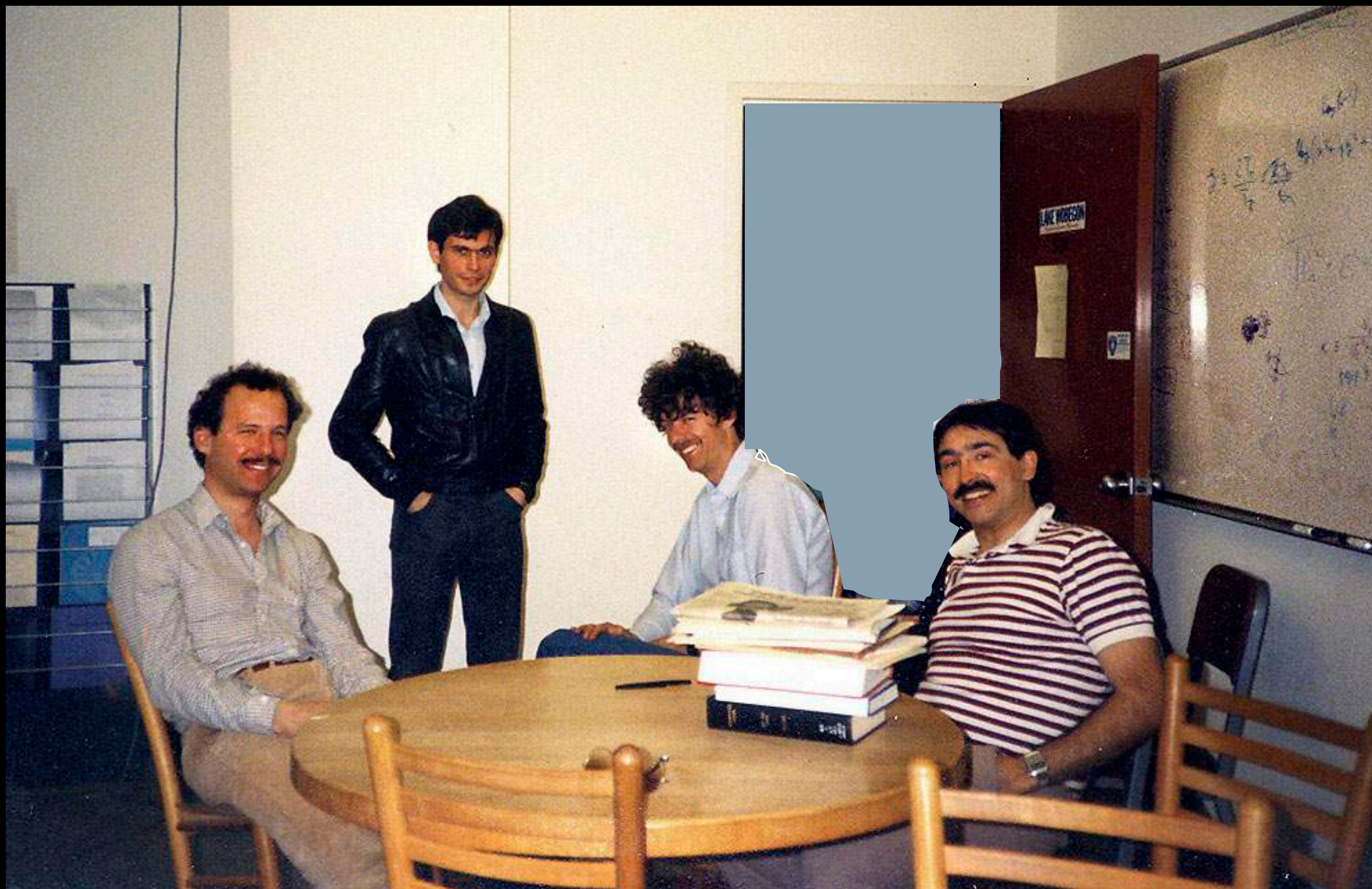
Neutrinos cannot make an appreciable contribution to Ω and $m_\nu \ll 10$ ev



ICC



The `Gang of Four' - 1983



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Non-baryonic dark matter cosmologies

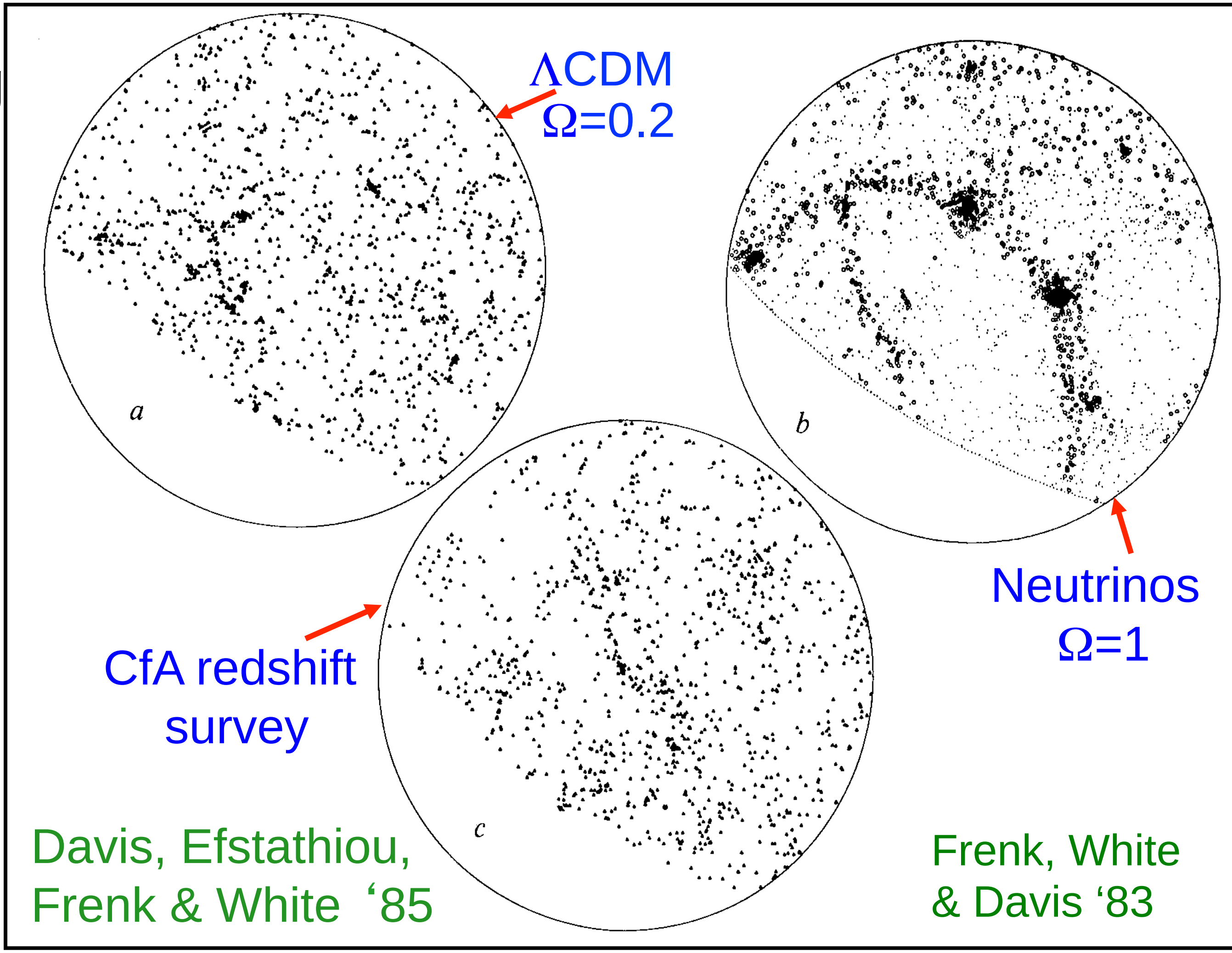
Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 10$ ev

Early CDM N-body simulations gave promising results

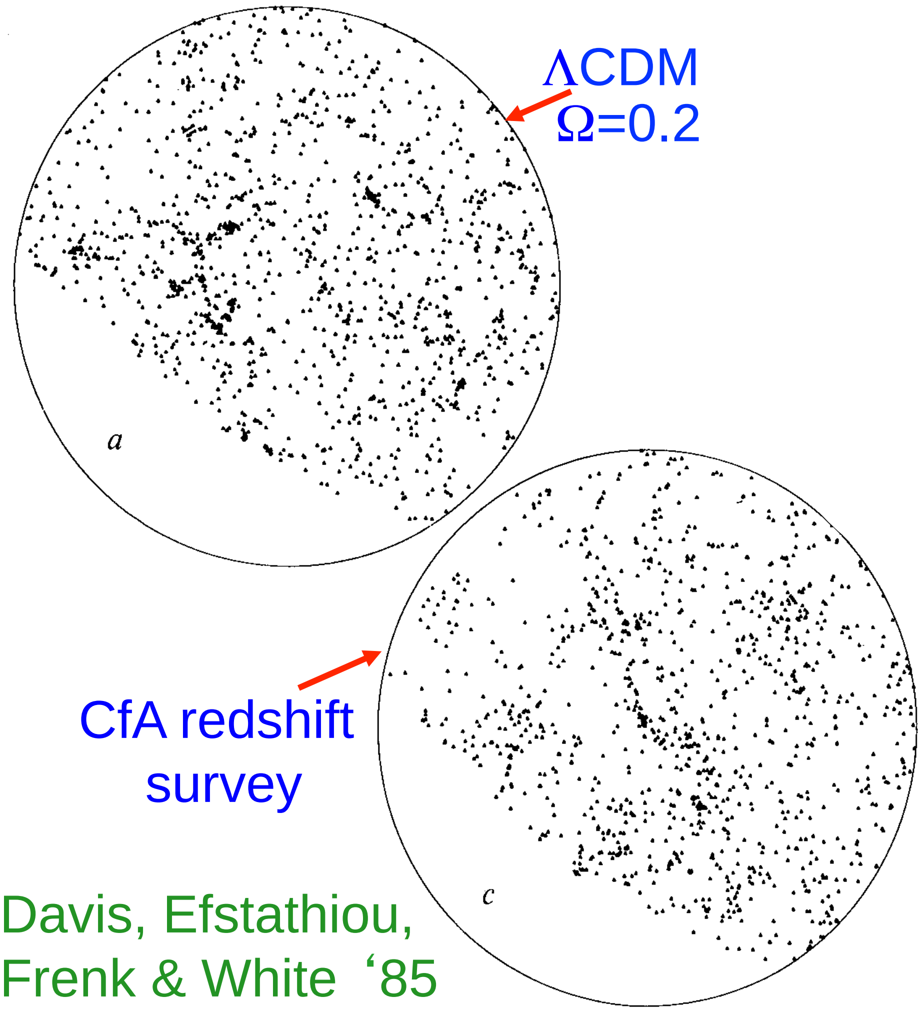
In CDM structure forms hierarchically



Non-baryonic dark matter cosmologies

Λ was inconceivable in 1985

How can we make Ω=1 give acceptable clustering?



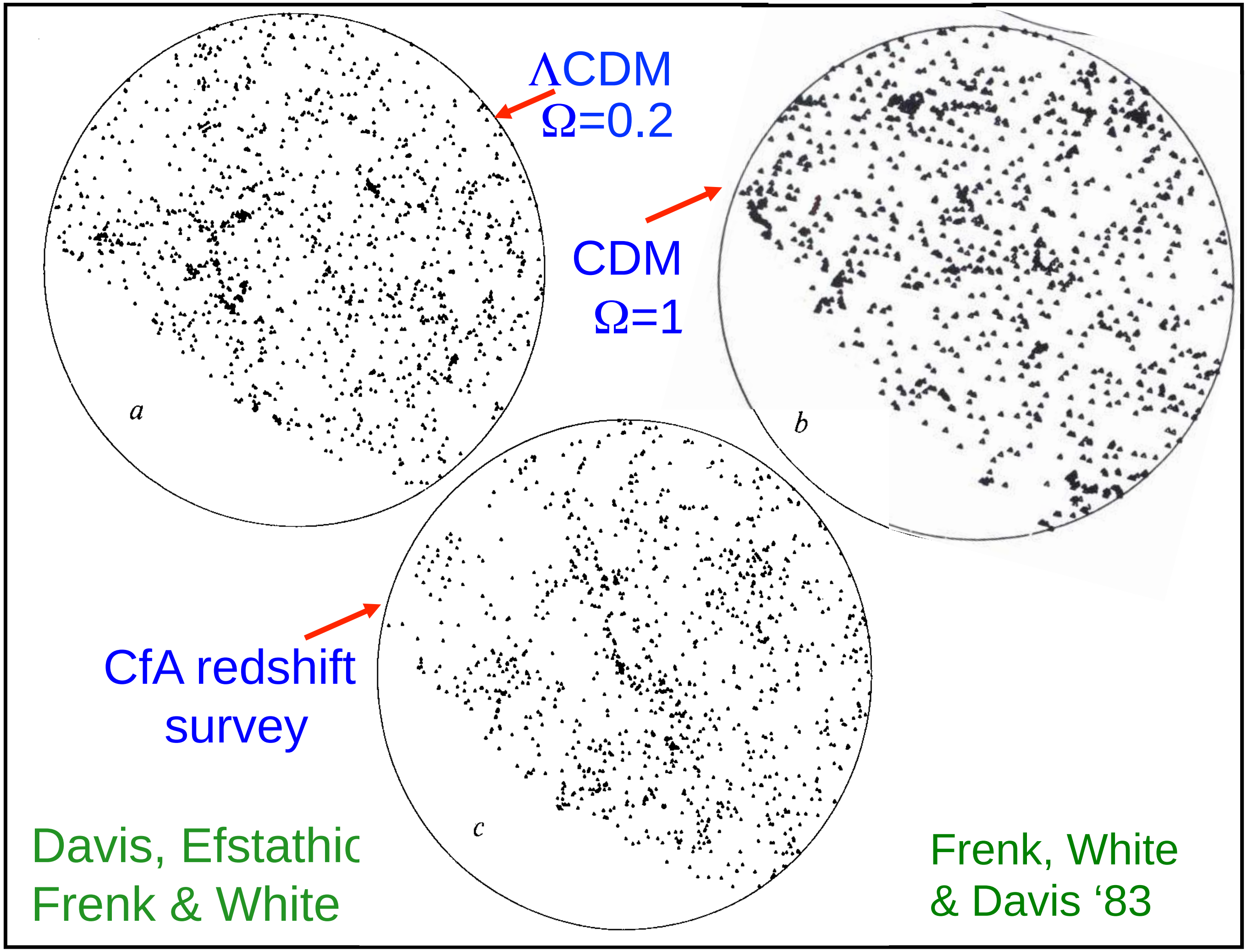
Davis, Efstathiou, Frenk & White ‘85

Frenk, White & Davis ‘83

Non-baryonic dark matter cosmologies

Λ was inconceivable in 1985

How can we make Ω=1 give acceptable clustering?



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$\Omega = 1$ CDM

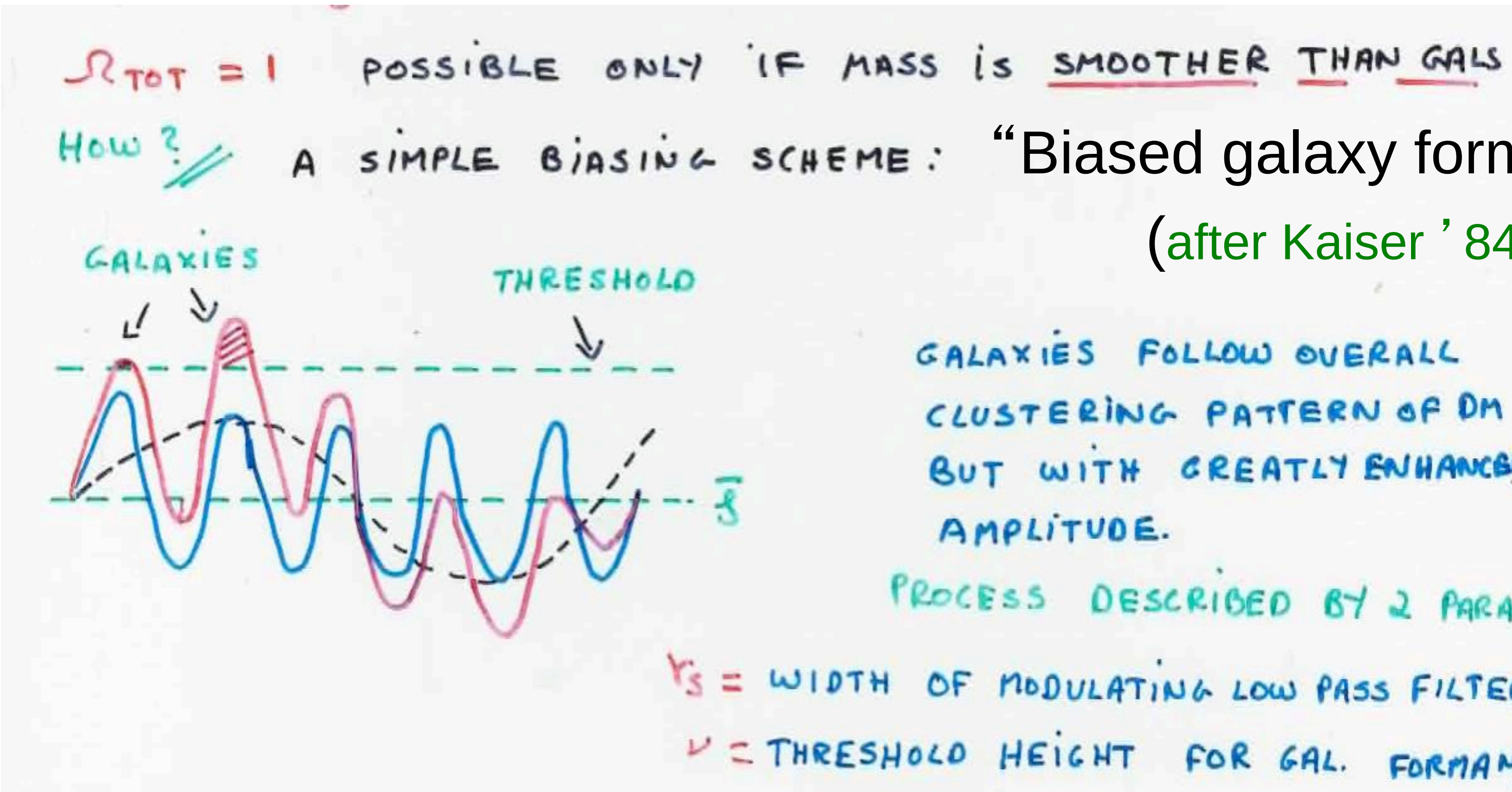
DEFW '85

If galaxies trace mass, right clustering → too large pec. velocities!

Dark matter

"Biased galaxy formation"

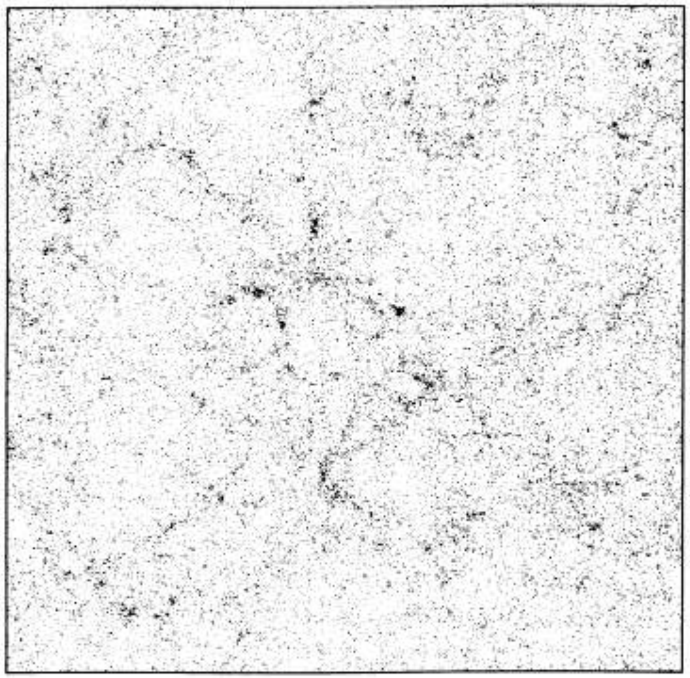
(after Kaiser ' 84)

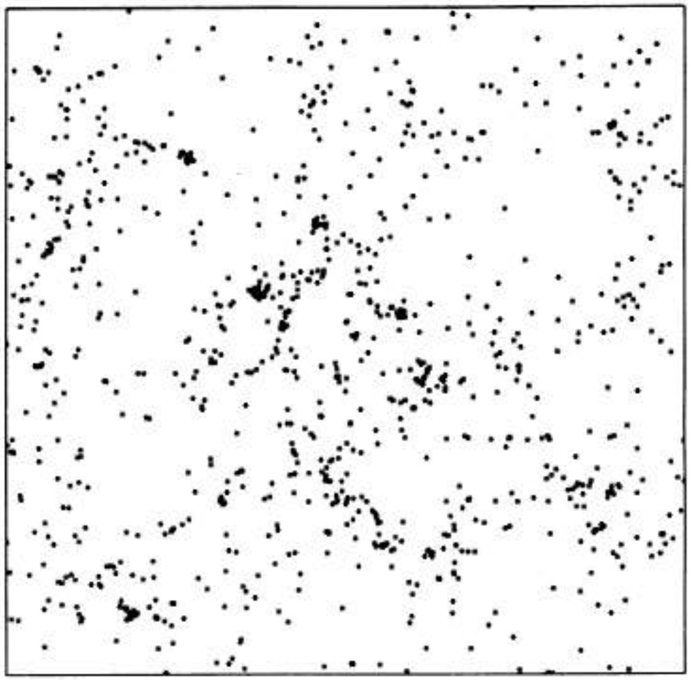


Biased galaxy formation

… or how to rescue Ω=1 !   DEFW '85

Dark matter   Galaxies

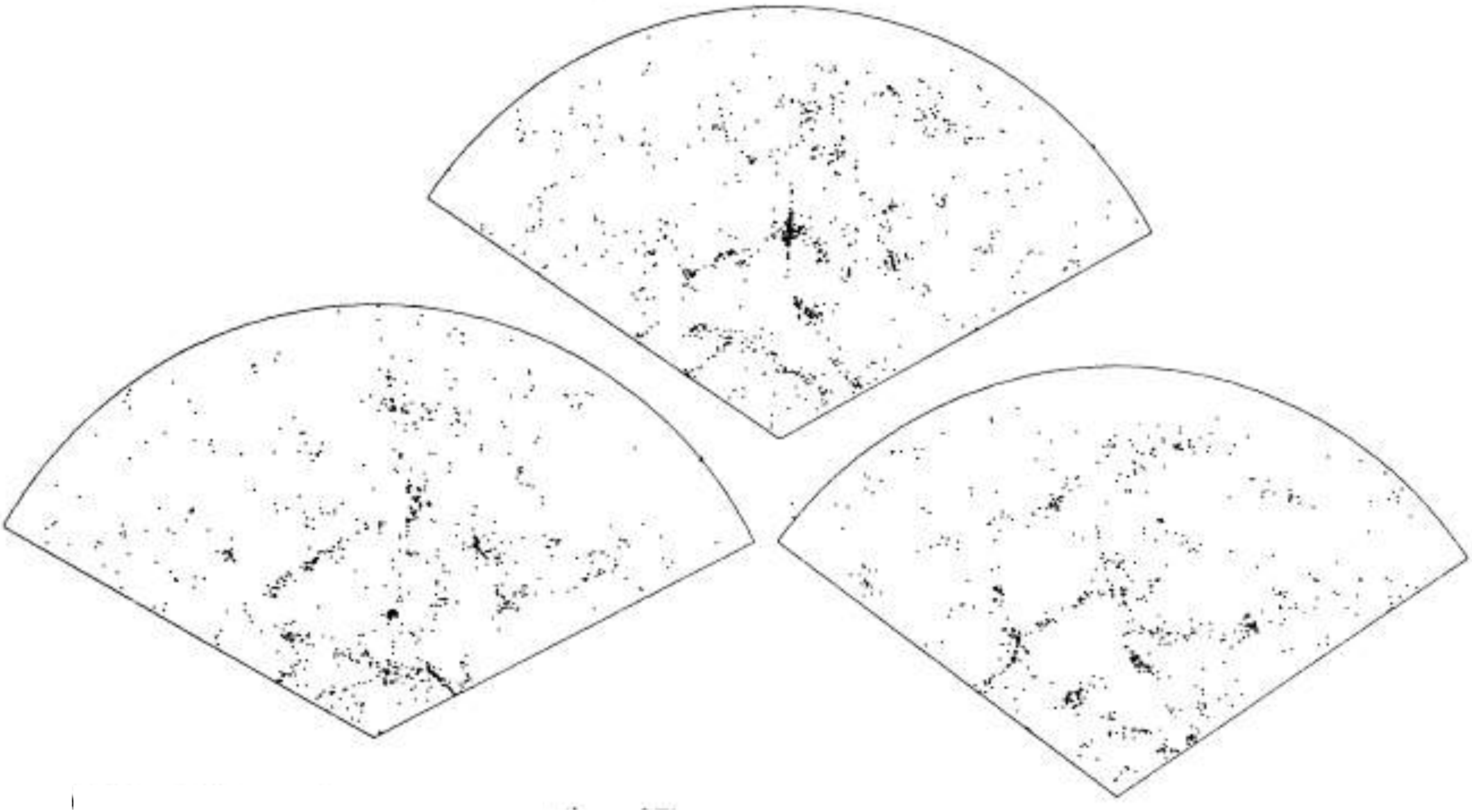




Gals→ peaks of density field

FIG. 16.—The projected distribution of all particles (*left*) and of the "galaxies" (*right*) in EdS1 at $a = 1.4$. The side of the box is $32.5h^{-1}$ Mpc. "Galaxies" are assumed to form only at the 2.5 σ peaks of the linear density distribution.

SCDM compared to CfA-2 z-survey

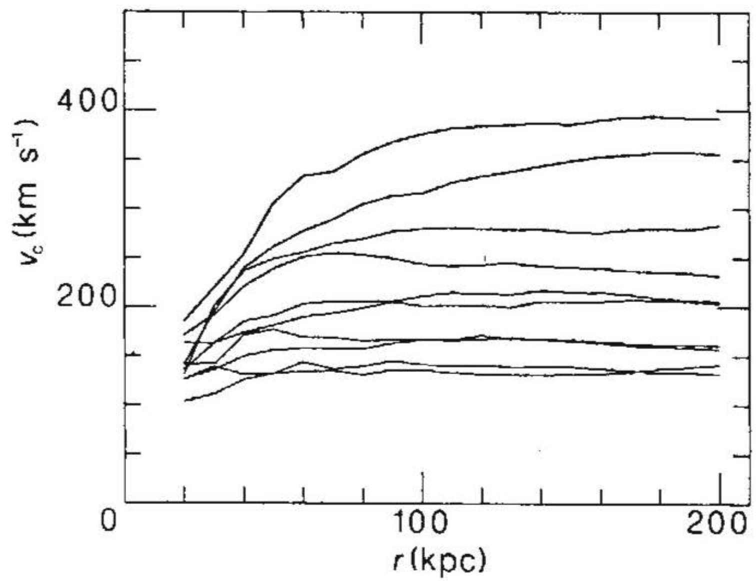


White, Frenk, Davis, Efstathiou ‘87

Cold dark matter, the structure of galactic haloes and the origin of the Hubble sequence

Carlos S. Frenk*, Simon D. M. White†, George Efstathiou‡ & Marc Davis§

A popular theory for galaxy formation holds that the Universe is dominated by exotic particles such as axions, photinos or gravitinos (collectively known as cold dark matter, CDM)[1–3]. This hypothesis can reconcile the aesthetically pleasing idea of a flat universe with the standard theory of primordial nucleosynthesis and with upper limits on anisotropies in the cosmic microwave background[4–6]. The resulting model is consistent with the observed dynamics of galaxy clustering only if galaxy formation is biased towards high-density regions[7,8]. We have shown that such a biased model successfully matches the distribution of galaxies on megaparsec (Mpc) scales[9]. If it is to be viable, it must also account for the structure of individual galaxies and their haloes. Here we describe a simulation of a flat CDM universe which can resolve structures of comparable scale to the luminous parts of galaxies. We find that such a universe produces objects with the abundance and characteristic properties inferred for galaxy haloes. Our results imply that merging plays an important part in galaxy formation and suggest a possible explanation for the Hubble sequence.



Balatonfured: East meets West

Yakob Zel’dovich (1914 – 1987)

University of Durham

(15-19) /June/1987

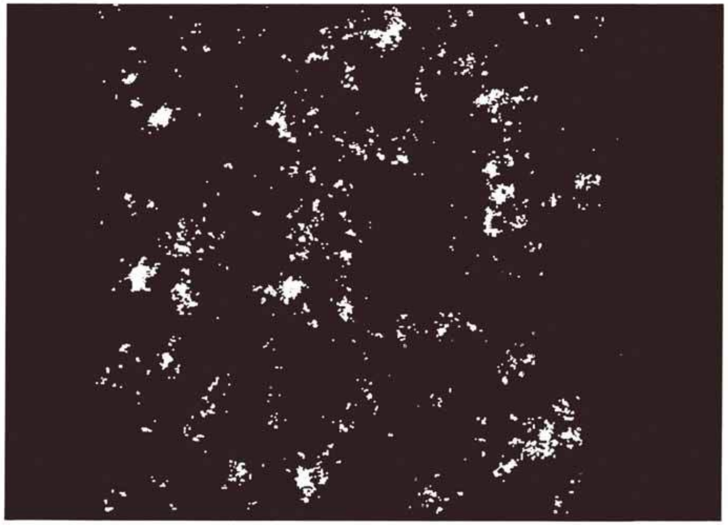
INTERNATIONAL ASTRONOMICAL UNION

SYMPOSIUM No. 130

LARGE SCALE STRUCTURES OF THE UNIVERSE

Edited by

JEAN AUDOUZE, MARIE-CHRISTINE PELLETAN and ALEX SZALAY



INTERNATIONAL ASTRONOMICAL UNION

KLUWER ACADEMIC PUBLISHERS

TABLE OF CONTENTS

† deceased on 12/2/87

APPENDIX 2 : THE BALATONFÜRED ALPHABET OF COSMOLOGY

by Vera Rich

Firstly, Aaronson let us recall,
For his death was a blow to us all,
But his papers, J. Mould,
His colleague of old,
Will present in due time, in the Hall.

With B, let us contemplate Bubbles,
Which have brought to our theory some troubles ;
Distance now must be counted,
So turn we, undaunted,
To red shift, and that constant of Hubble's.

Contrariwise, we've C for
Where galaxies closely do
Both richly and poorly,
Observing them, surely,
Will bring the keen schola

In the microwave, Dipoles
Which we plot, ΔT upon
Then, to keep the score le
Kofman draws us the Dev
And a haloed, hirsute Dei

With E, Einstein comes ir
Whose theories once brou
Now we think, with respe..,
He was not quite correct ;
But who, out of hundreds, is right ?

With F, we pursue the Fifth Force,
Of many a question the source ;
Profound explanations
Of its implications
Fujii will report in due course.

G for Galaxies, spiral, elliptic,
Or lens-shaped, of origin cryptic ;
And what is this factor
Called the Great Attractor,
Sited southerly from the ecliptic ?

H, of course, our Hungarian Hosts ;
To Sandor and György drink we toasts,
And to the SZOT hotel some !
They made us so welcome,
Down here on Lake Balaton's coasts,

Inflation and the Infrared
Are topics where much may be said,
The data from IRAS
Are sure to inspire us,
I will argue no more on that head !

May prove a delusion
And lead to confusion
And provoke us to anger irrational

Here at M let controversists chatter,
Looking far where the galaxies scatter :
"In this vast universe
Is a substance perverse :
Is it cold ? Is it Dark ? Does it Matter ?"

N-bodied is Frenk's simulation
Presentig dark halo formation,
But he gave it so fast
We were quite lost at last,
Though we noted his good correlation !

N-bodied is Frenk's simulation
Presentig dark halo formation,
But he gave it so fast
We were quite lost at last,
Though we noted his good correlation !

The picture builds up over days.

W — and arrived at this junction,
The brain shows a marked lack of gumption :
But to counter a void,
What else should be deployed
But its complement, viz : the Wall function ?

And now X—ray background (alas !)
Does it emanate from dispersed gas
Abundant in heat ?
Or from sources discrete
Of baryons, heavy in mass ?

[wh]Y is the questioning particle,
A most indispensible article !
For, did they not ask,
sk
speaking, unstartable !

t ! So, ere I go (which
let you know which
the best :
em with zest :
Audouze to Zel'dovich !

J. Audouze et al. (eds.), Large Scale Structures of the Universe, 605–608.

Cosmology

University of Durham

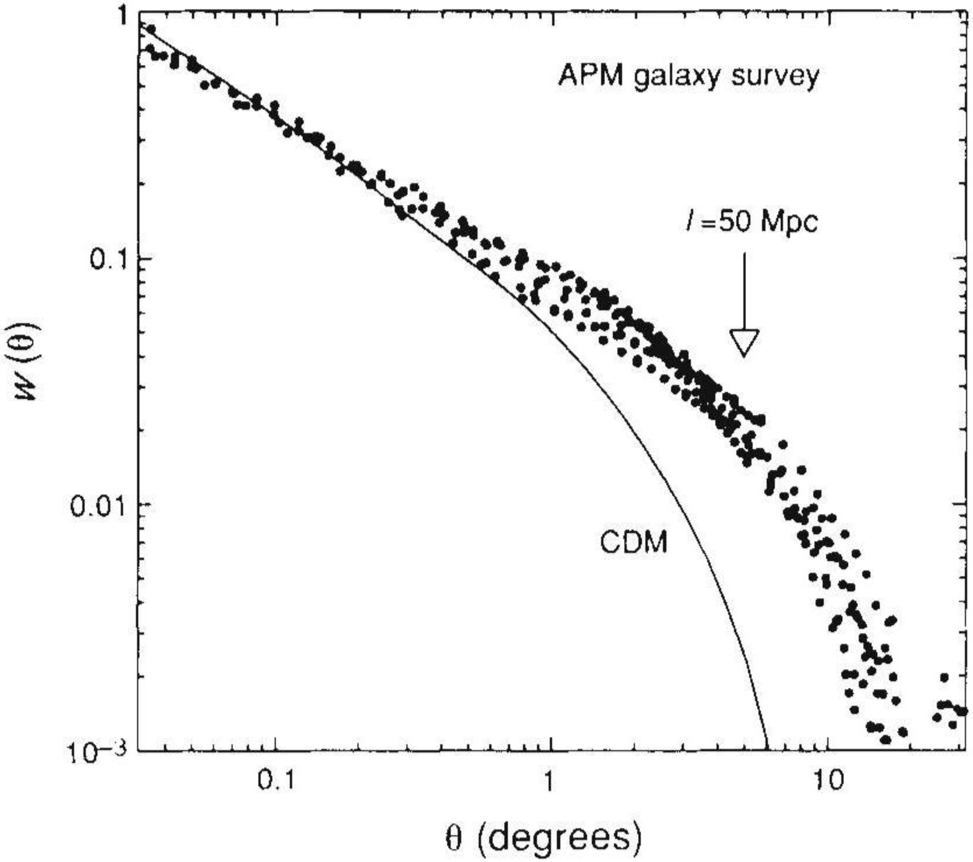
CDM rules

1987

University of Durham

Ω = 1 CDM under strain

Angular 2-pt correlation function



Maddox, Efstathiou, Sutherland & Loveday ‘90

DEFW '92

Nature 1992

REVIEW ARTICLE

The end of cold dark matter?

M. Davis, G. Efstathiou, C. S. Frenk & S. D. M. White

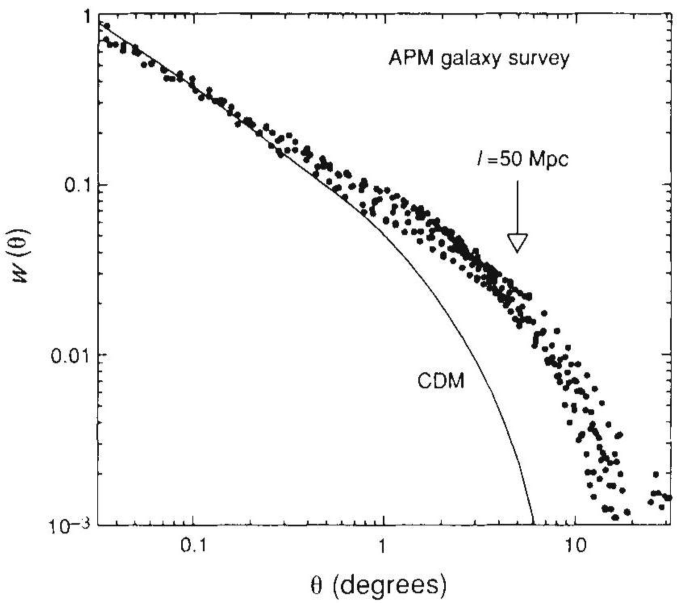
The successful cold dark matter (CDM) theory for the formation of structure in the Universe has suffered recent setbacks from observational evidence suggesting that there is more large-scale structure than it can explain. This may force a fundamental revision or even abandonment of the theory, or may simply reflect a modulation of the galaxy distribution by processes associated with galaxy formation. Better understanding of galaxy formation is needed before the demise of CDM is declared.

HOW did structure in the Universe form? This question has puzzled mankind for centuries, but in the past decade some cosmologists have felt that they were close to providing an answer. What has become known as the cold dark matter (CDM) theory is an elegant construct which links many aspects of the structure we see today to physical processes which took place when the Universe was only 10^{-35} s old. Recently, observations have been reported that seem to conflict with this model (see. tion could have originated from quantum fluctuations that were inflated to macroscopic scale. Except in circumstances that appear contrived, the fluctuations would indeed contain no characteristic scales; in technical terms, irregularities in the spatial curvature are predicted to be a gaussian random field with a scale-invariant spectrum[9-12]. For the first time cosmologists had a set of initial conditions stemming directly from fundamental, even if speculative, physics.

University of Durham

DEFW '92

Angular 2-pt correlation function



REVIEW ARTICLE

end of the range allowed by observation[55], lowering the Hubble constant still further seems an implausible way of obtaining more large-scale structure. Lowering Ω is another possibility, but without an additional ingredient such models are inconsistent both with a spatially flat universe and with present upper limits on fluctuations in the microwave background[56,57]. These problems can be avoided by appealing to a cosmological constant, because a low-density universe is spatially flat if the cosmological constant takes the value[58] $\Lambda = 3H_0^2(1-\Omega)$. With such carefully chosen parameters it is possible to construct a CDM universe that explains large-scale structure[59], is compatible with inflation and with microwave-background experiments, and is old enough to contain the oldest observed star clusters even for a present expansion rate as high as $H_0 = 80\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, the value preferred by some recent measurements[60,61]. From the point of view of a particle physicist, the value of Λ needed to work these miracles is extraordinarily small, 10^{120} times smaller than its 'natural' value[62]. Such fine tuning seems sufficiently unattractive that most cosmologists regard this solution as a long shot, preferring to think that some unknown symmetry principle requires the cosmological constant to be exactly zero.

Other possible fixes for the CDM model involve decaying particles or departures from the scale-invariant seed fluctuations predicted by simple inflationary models. For example, the pre-

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

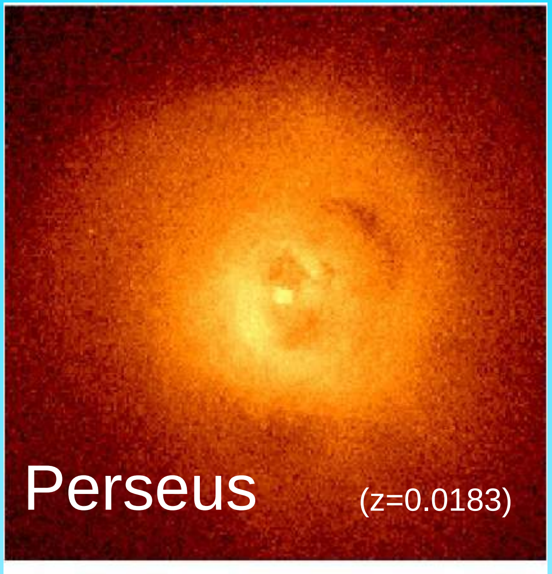
… or why Ω_{matter} cannot be 1

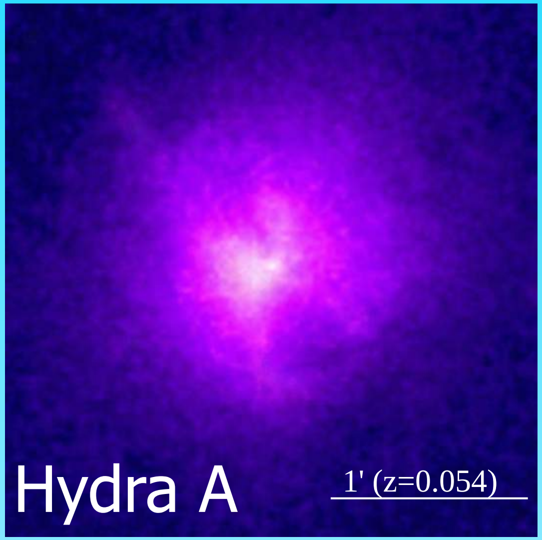
University of Durham

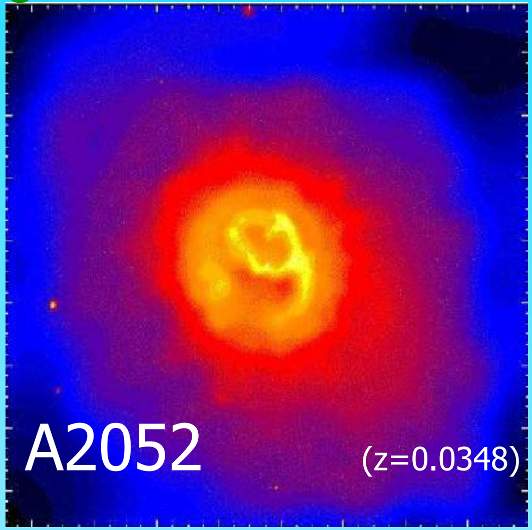
Galaxy clusters

X-ray emission from hot plasma in clusters

Images from David Buote







About 90% of baryons in clusters are in hot gas

X-rays ⇒ gas mass

Photometry ⇒ stellar mass

Gas in hydrostatic equilibrium so X-rays (or lensing) ⇒ total gravitating mass

} ⇒ Baryon fraction, f_b

Institute for Computational Cosmology

University of Durham

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 γ=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 → $h = 0.7 \pm 10\%$

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

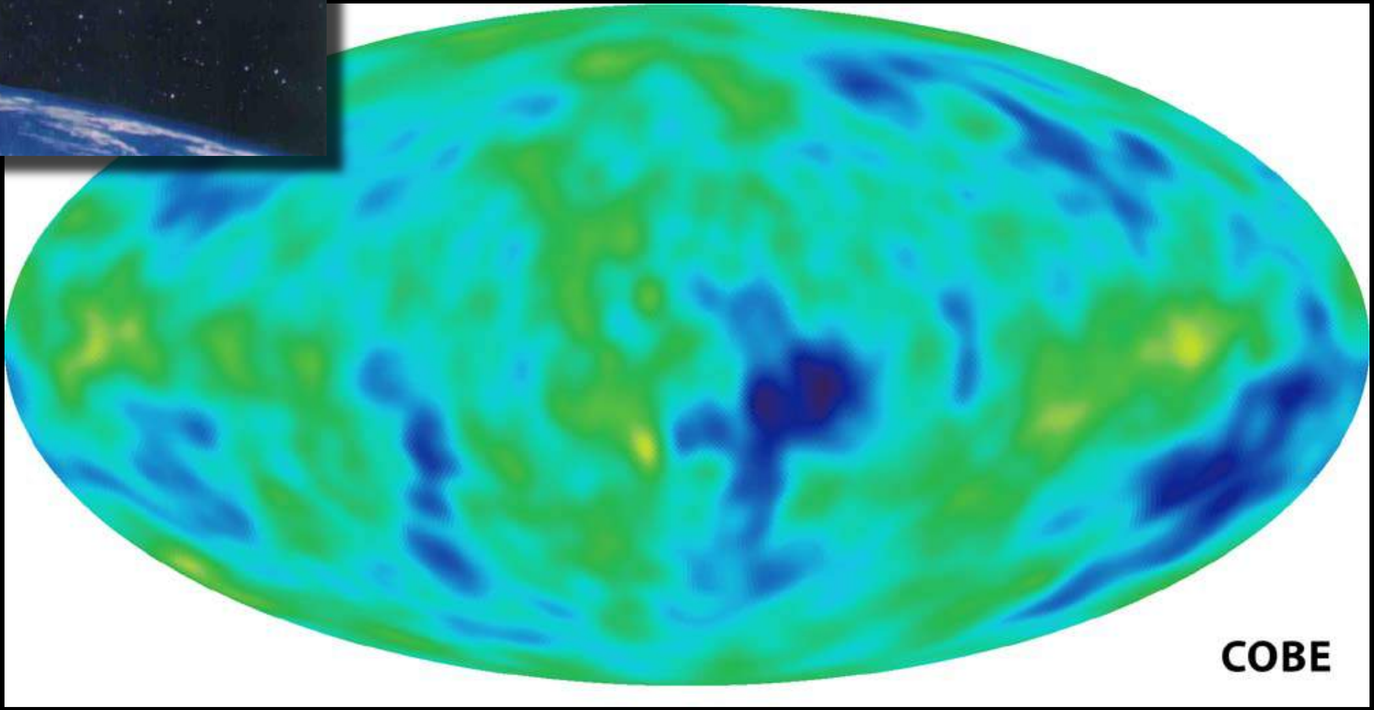
White, Navarro, Evrard & Frenk '93
Allen et al '04

→ Flat geometry (inflation) requires Λ=0.7

Institute for Computational Cosmology

The CMB

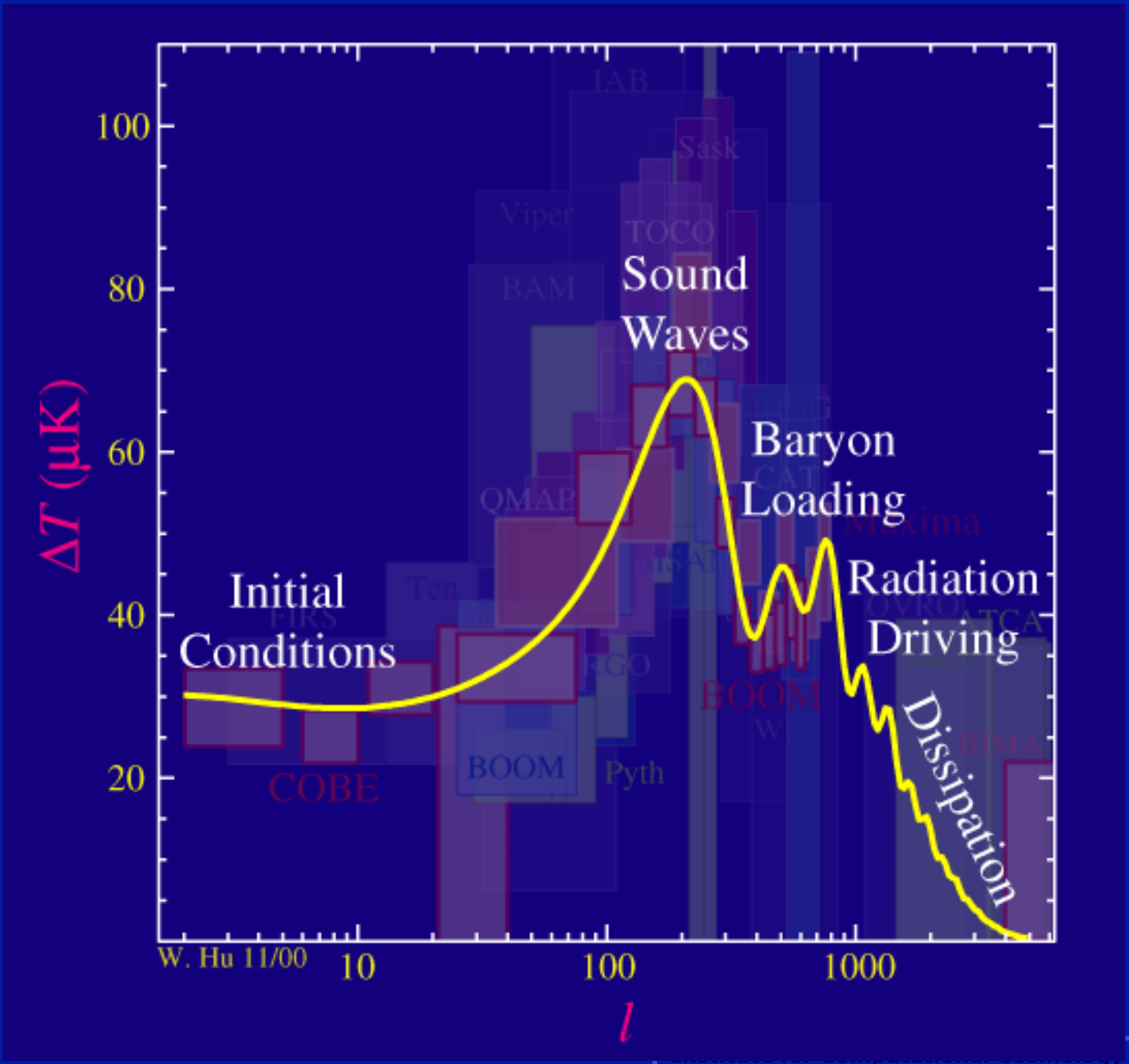
1992



Evidence for a flat universe

University of Durham

1993

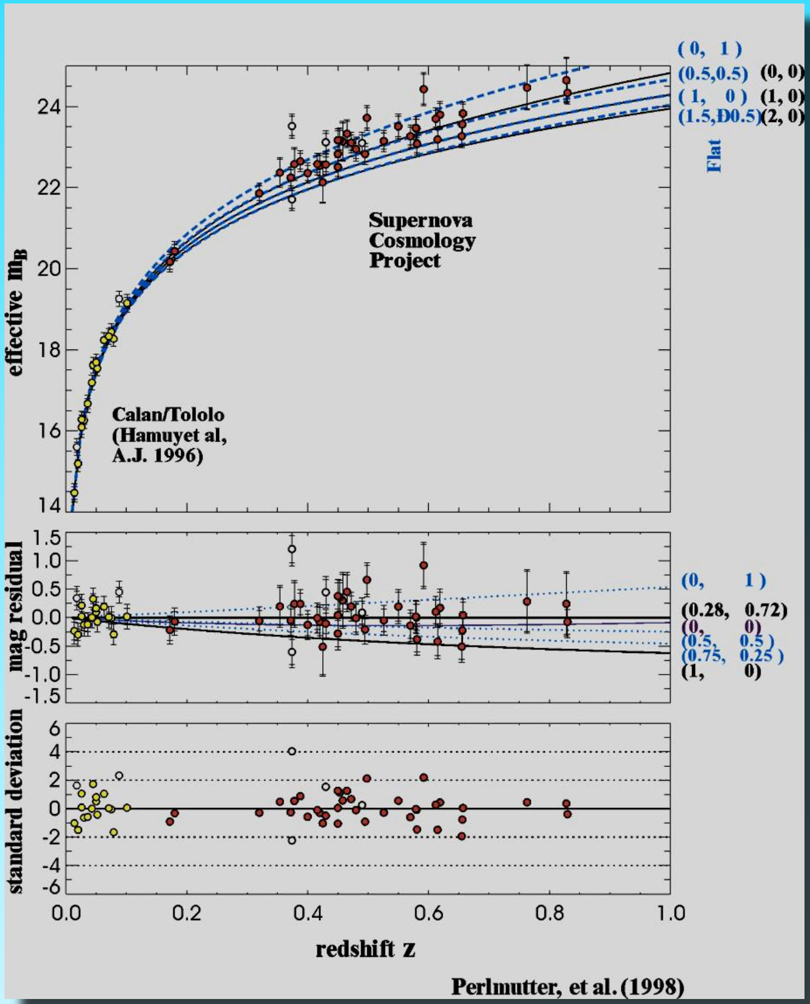


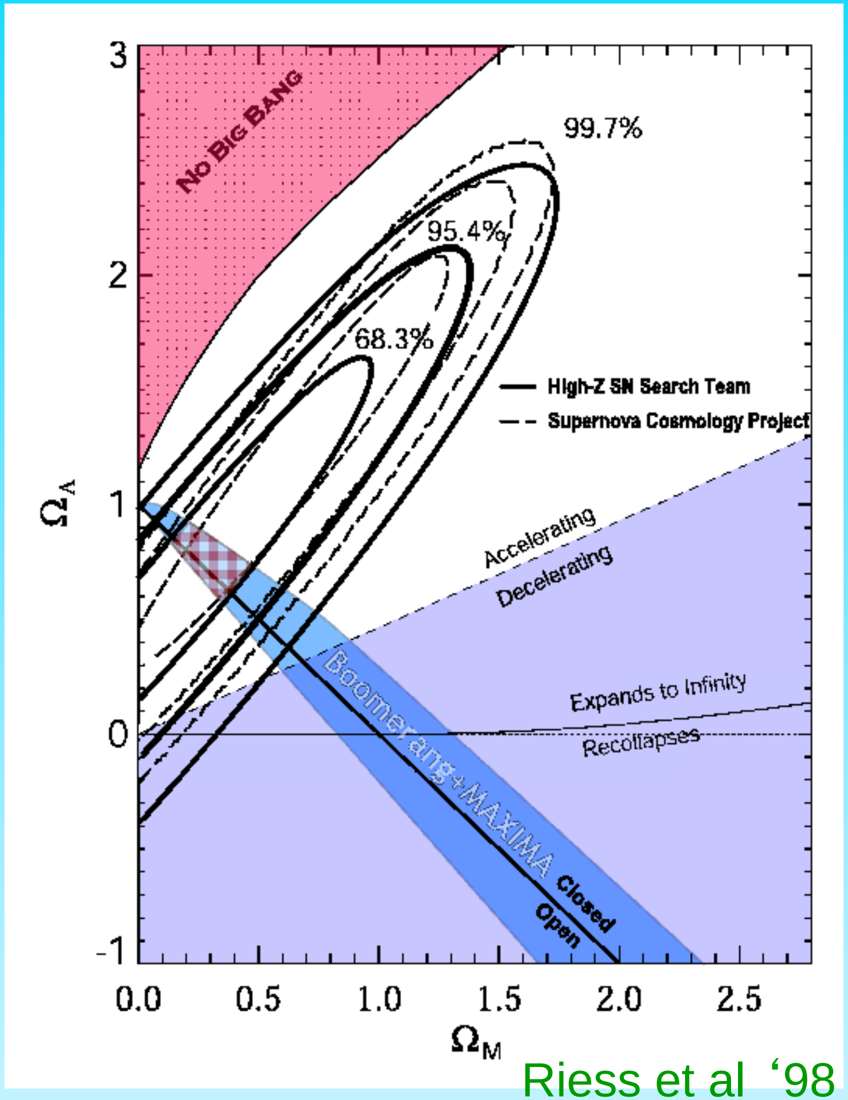
(Some) evidence for dark energy

University of Durham

Evidence for Λ from high-z supernovae

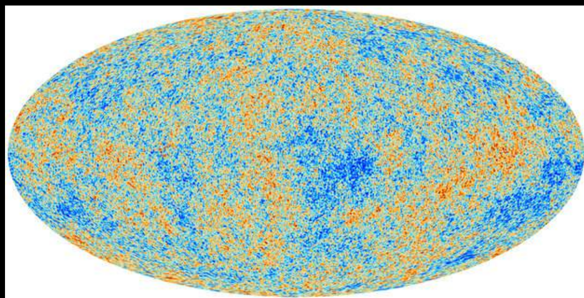
Distant SN are fainter than expected if expansion were decelerating



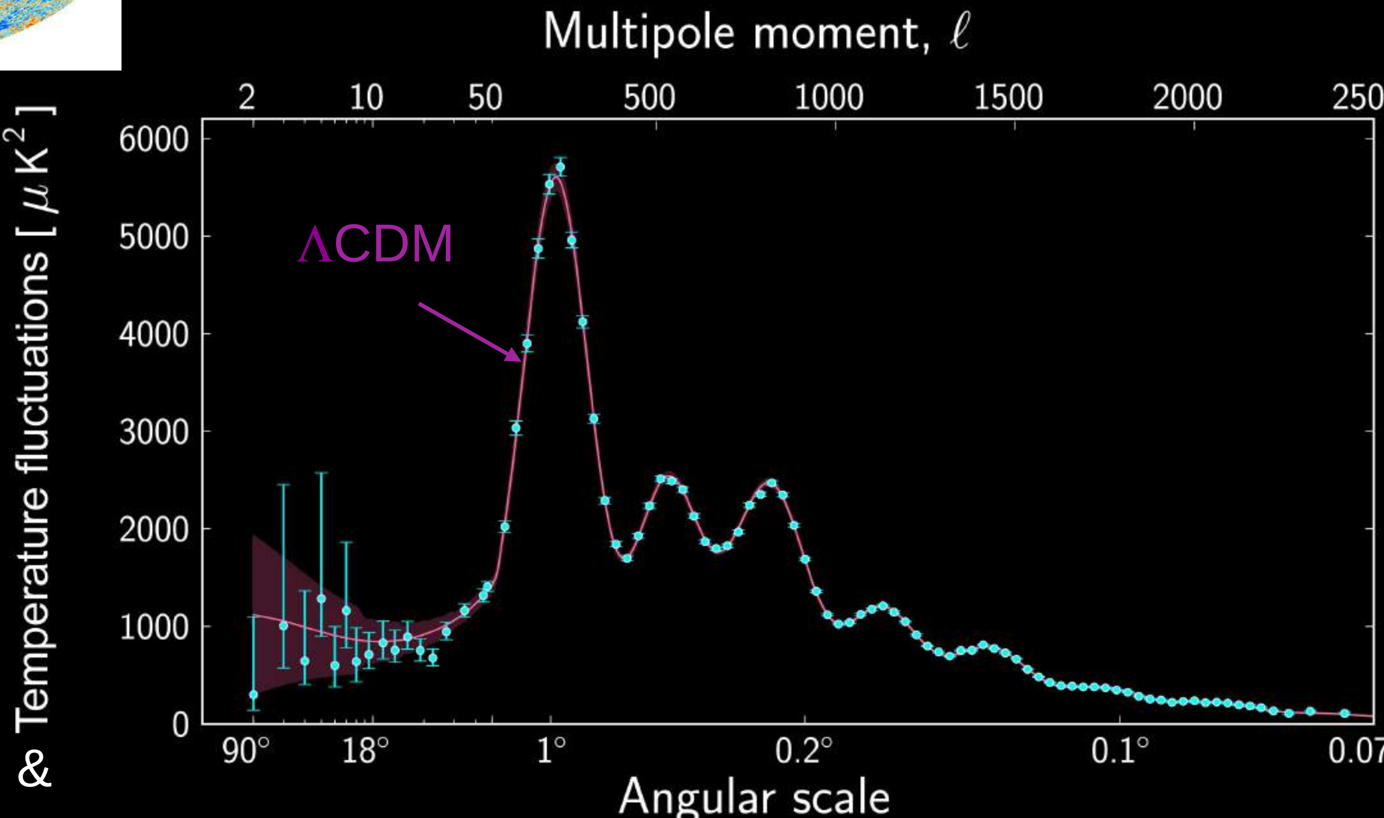


Riess et al '98

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

University of Durham

Cosmological parameters from CMB data

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 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

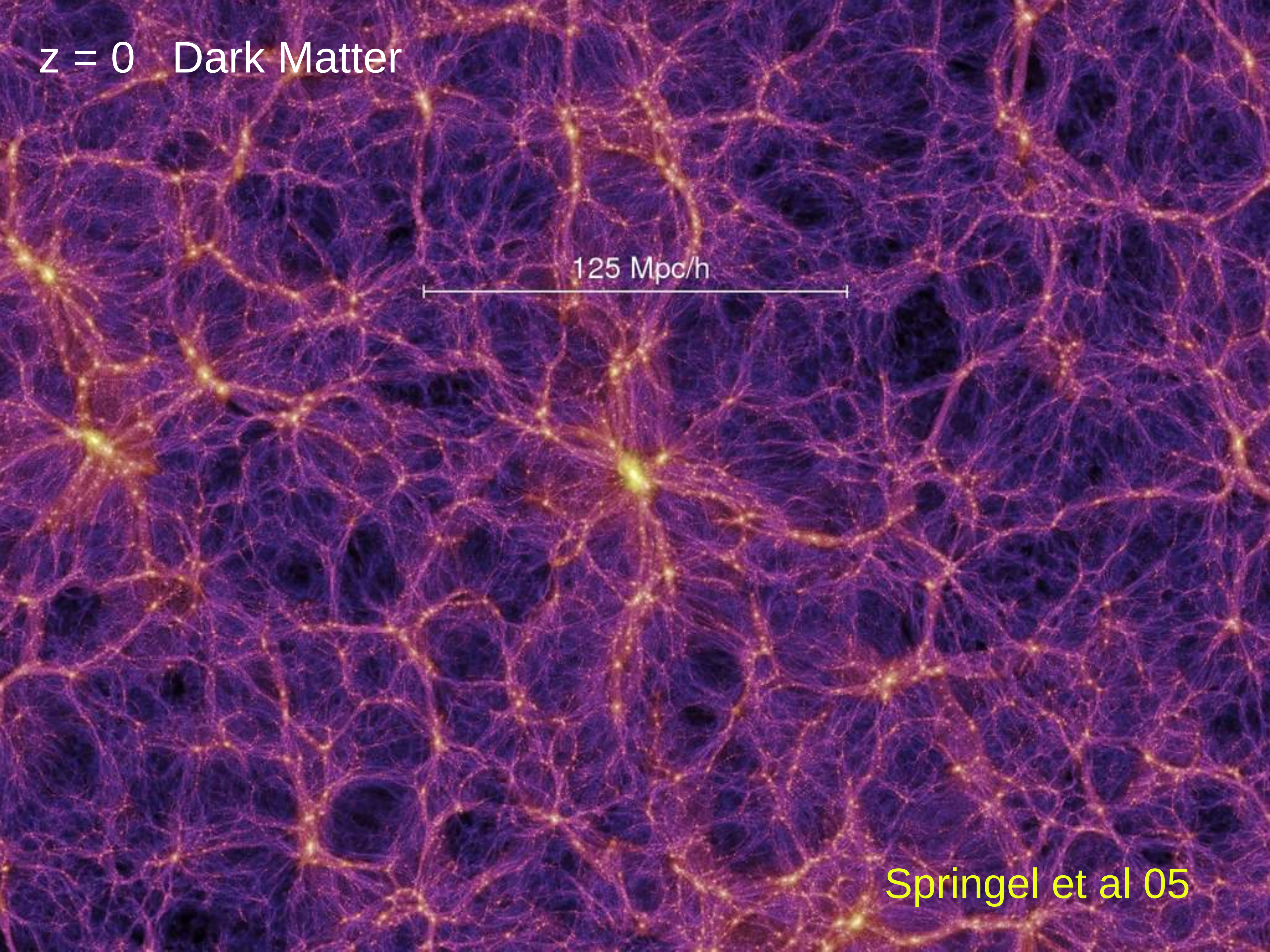
Planck collaboration '13

The 2dF Galaxy Redshift Survey

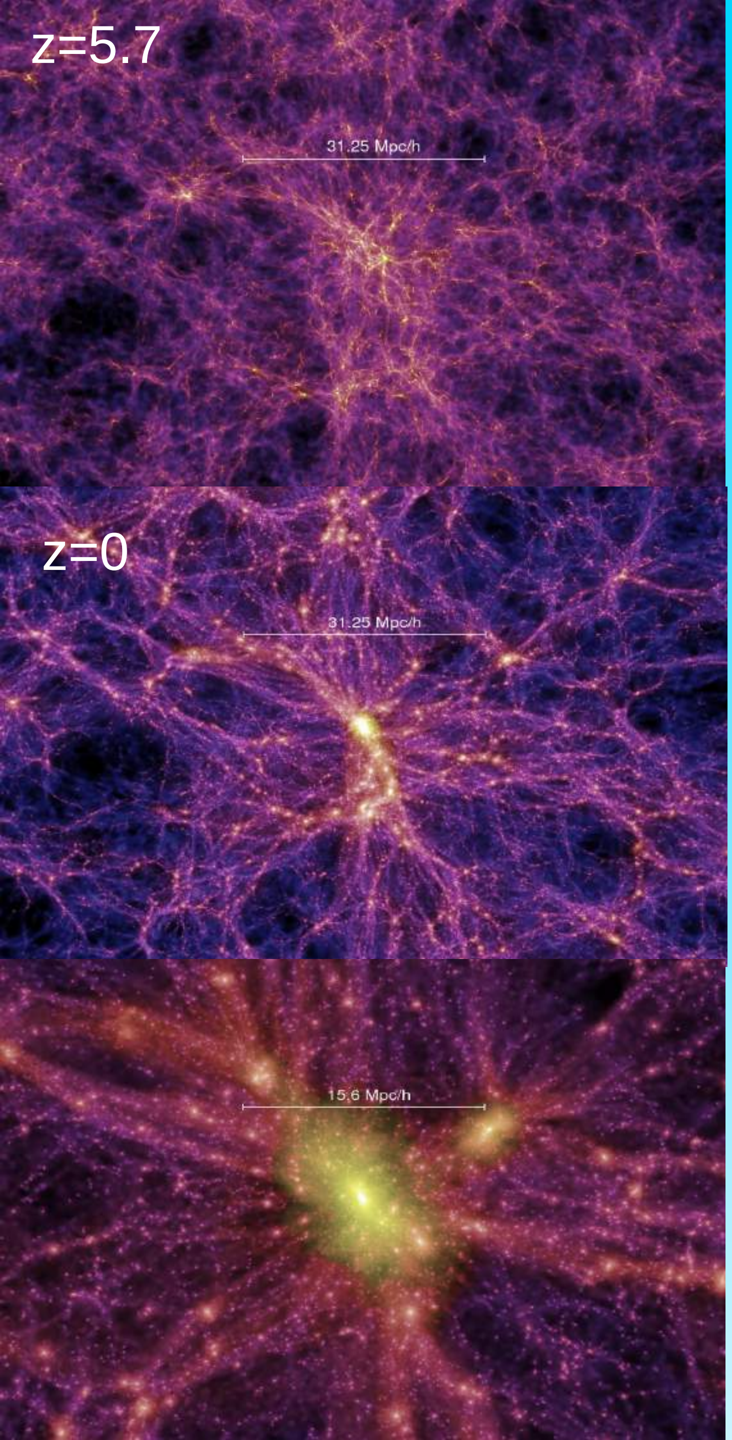
221,000 redshifts

z~0

2005


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

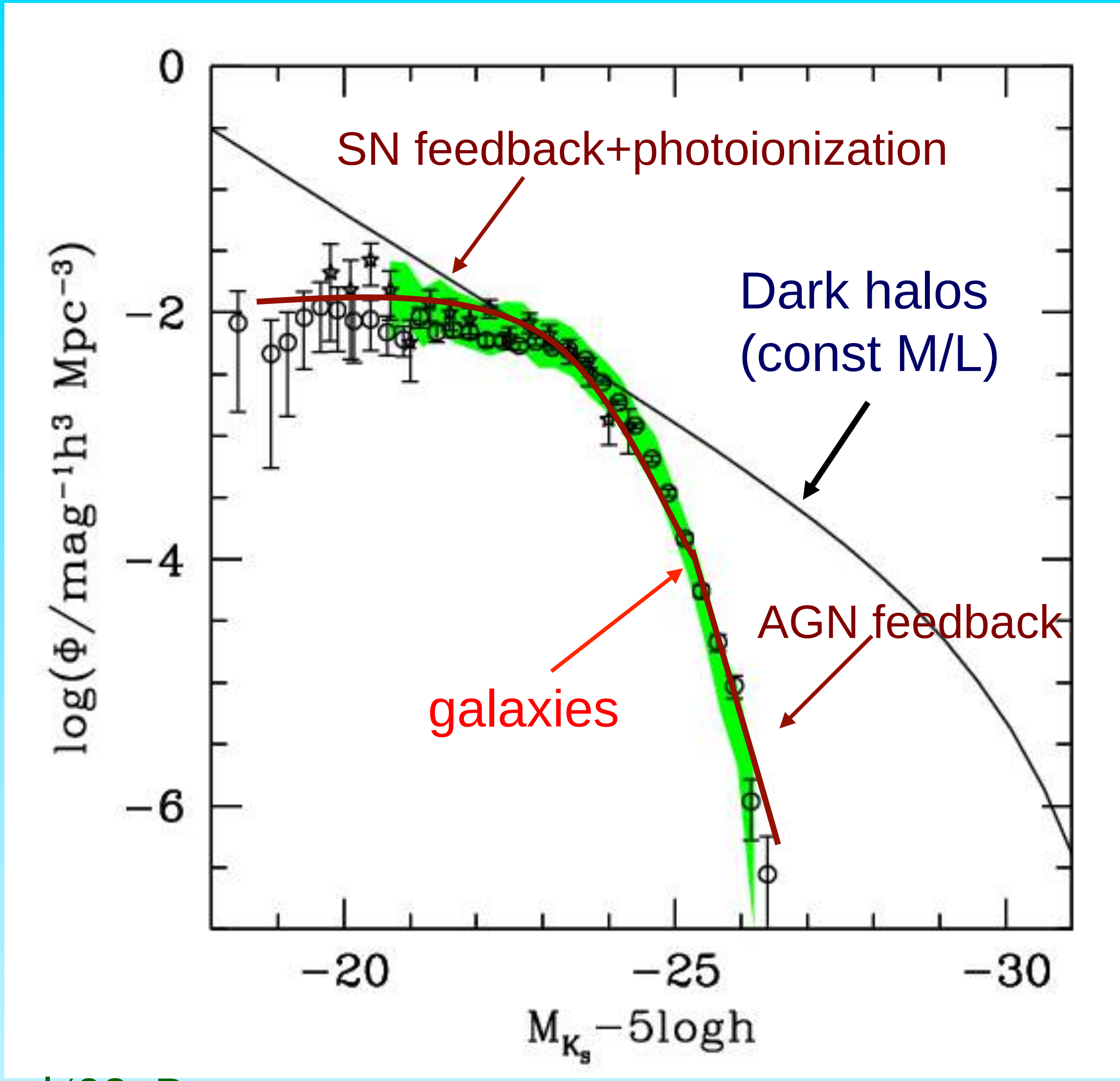
The galaxy luminosity function

University of Durham

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

⇨

Complicated variation of M/L with halo mass

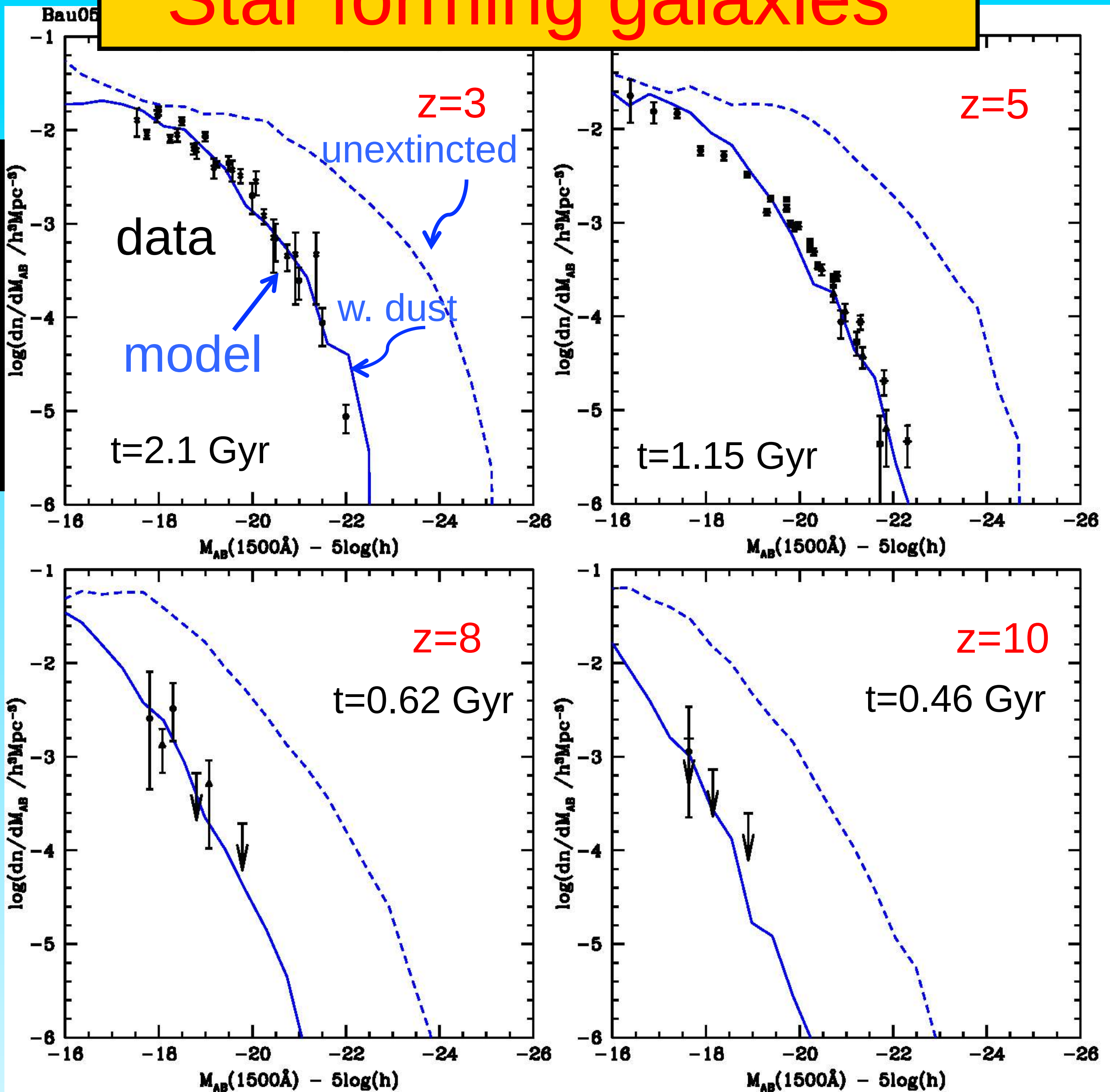


White & Frenk ‘91; Kauffmann et al ‘93; Benson et al ’03; Croton et al ‘05; Bower et al. ’06

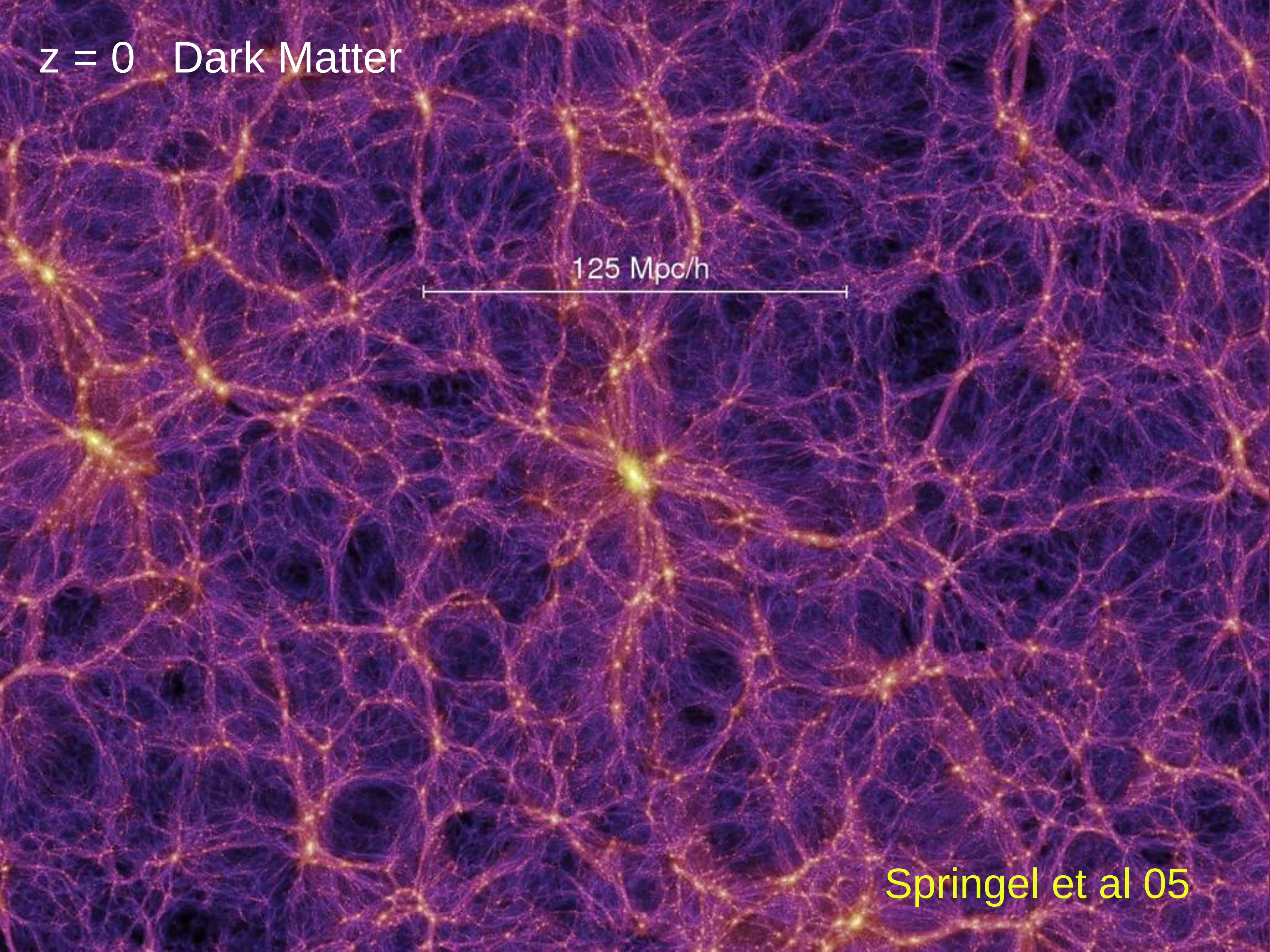
University of Durham

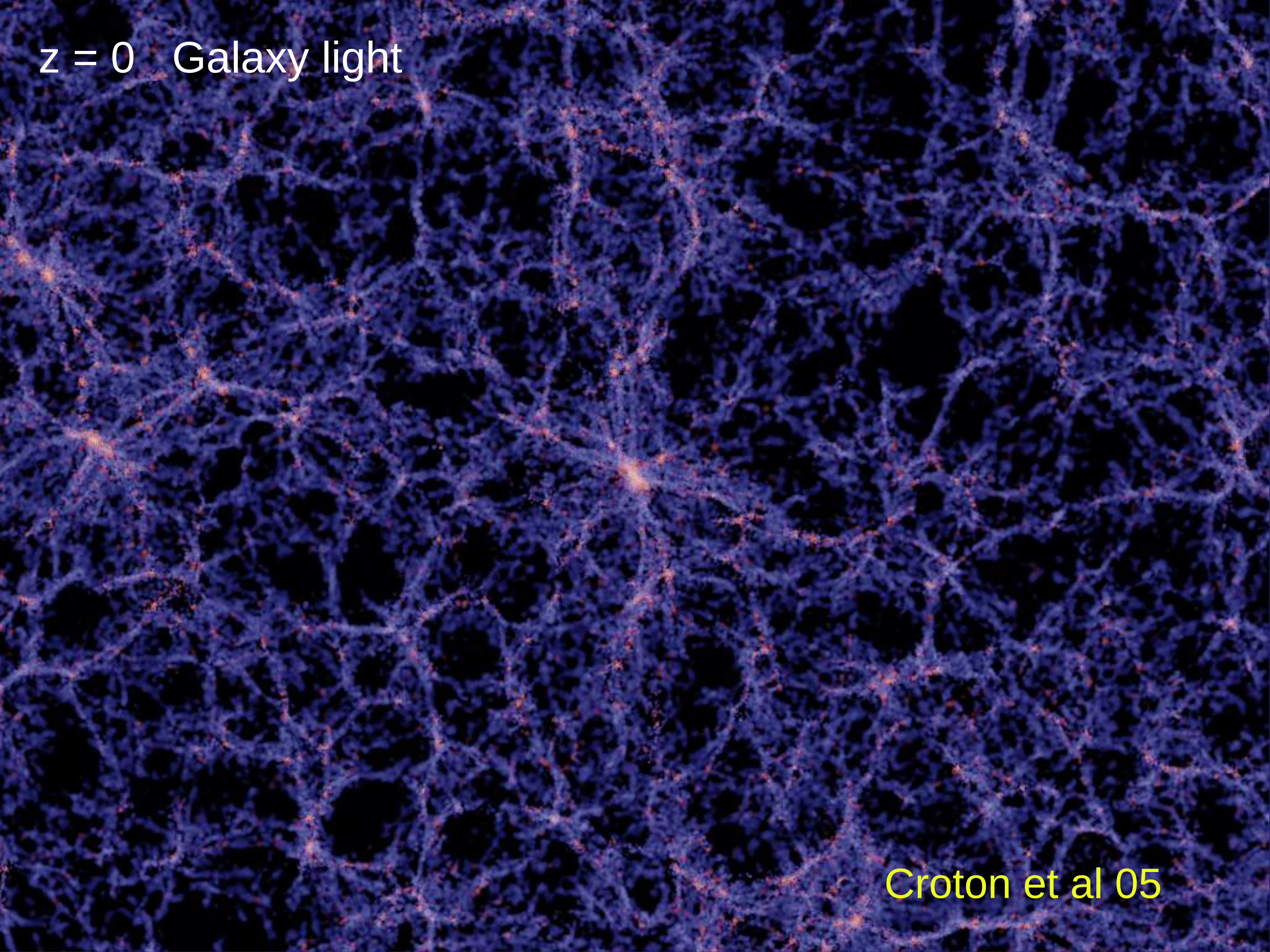
Star forming galaxies

Evolution of Lyman-break galaxy lum. function

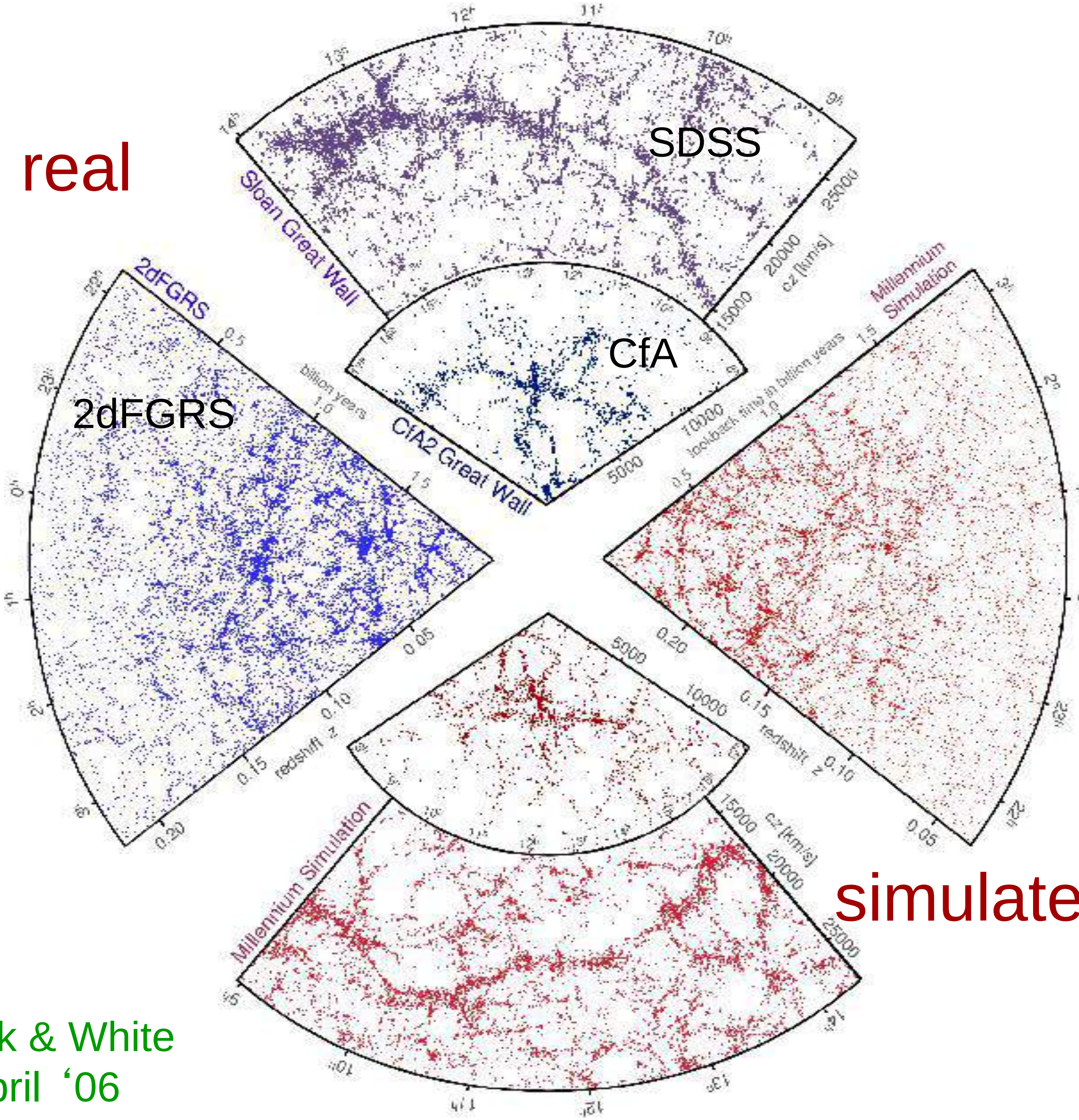


Lacey, Baugh, Frenk, Benson ‘12


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


z = 0 Galaxy light
Croton et al 05

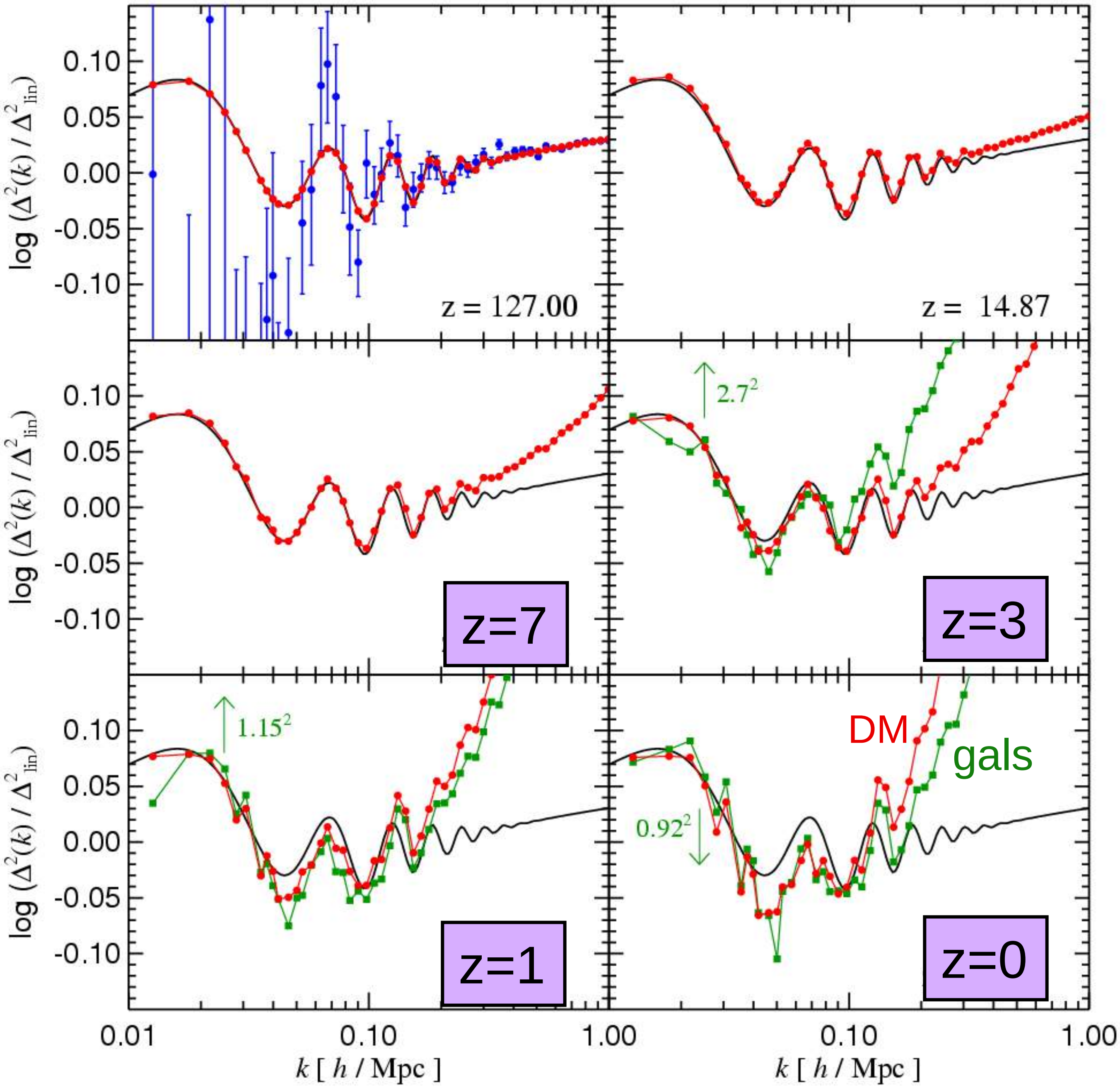
real



simulated

Springel, Frenk & White
Nature, April '06

Millennium simulation



Baryon wiggles in the *galaxy* distribution

Power spectrum from MS divided by a baryon-free ΛCDM spectrum

Galaxy samples matched to plausible large observational surveys at given z

Springel et al 2005

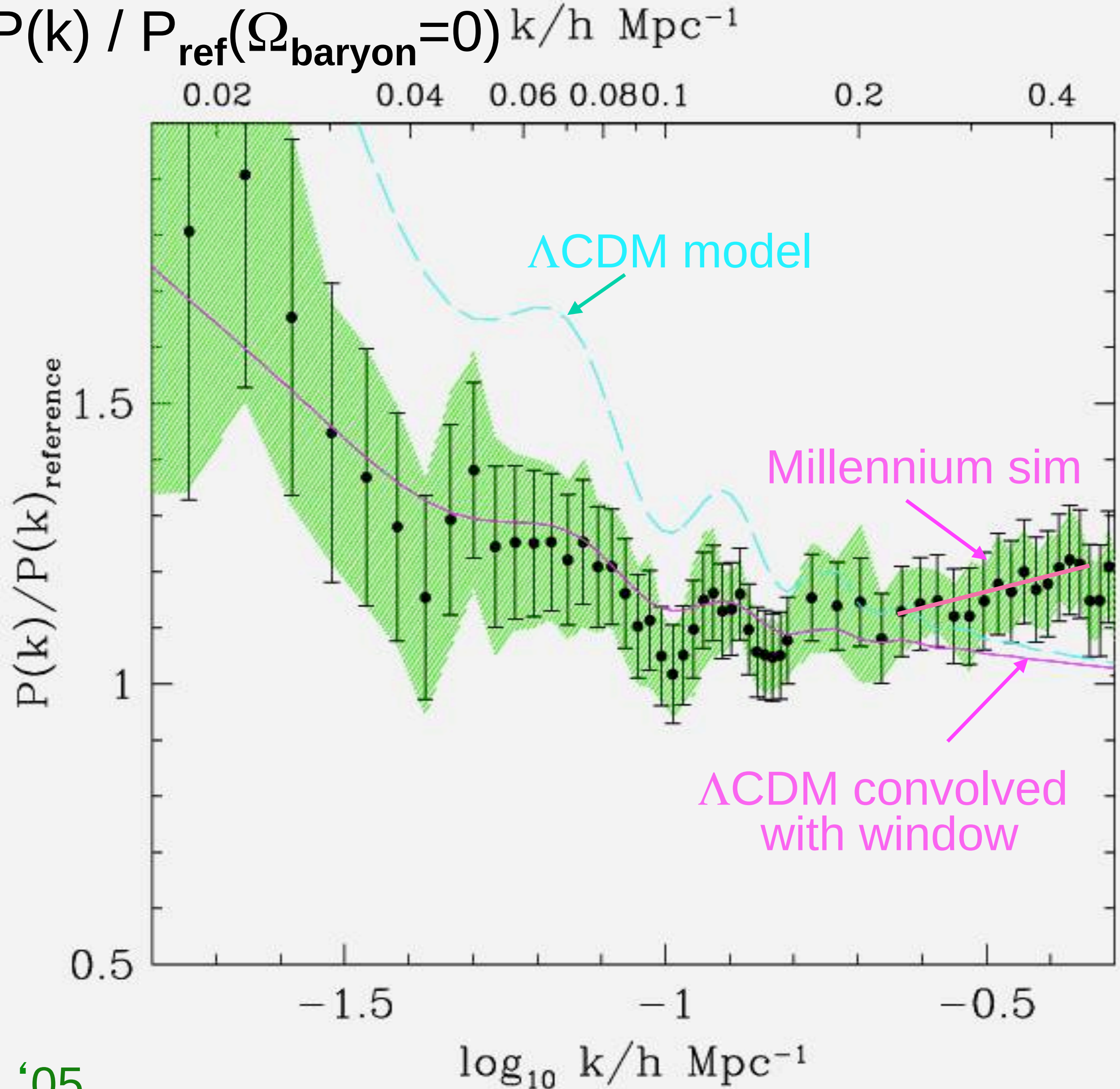
Baryon acoustic oscillations in 2dFGRS

University of Durham

220,000 redshifts

Baryon oscillations conclusively detected in 2dFGRS!!!

$P(k) / P_{ref}(\Omega_{baryon}=0)$



Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05

Baryon acoustic oscillations in SDSS

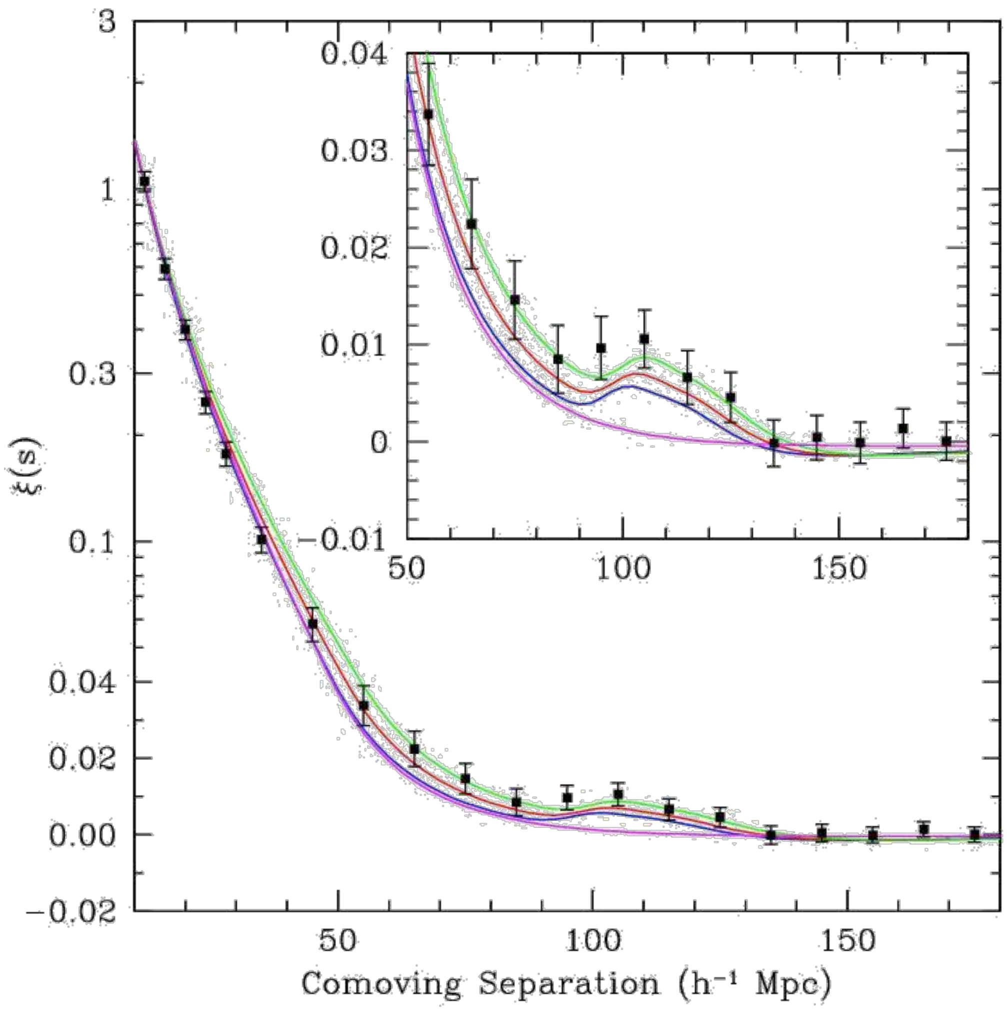
University of Durham

- 47,000 SDSS LRGs
- 0.72 cubic Gpc
- Constraint on spherically averaged BAO scale
- Constrain distance parameter:

$$D_V(z) = \left[D_M(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

Angular diameter distance

Hubble parameter



Eisenstein et al '05

Baryon acoustic oscillations in 2dFGRS

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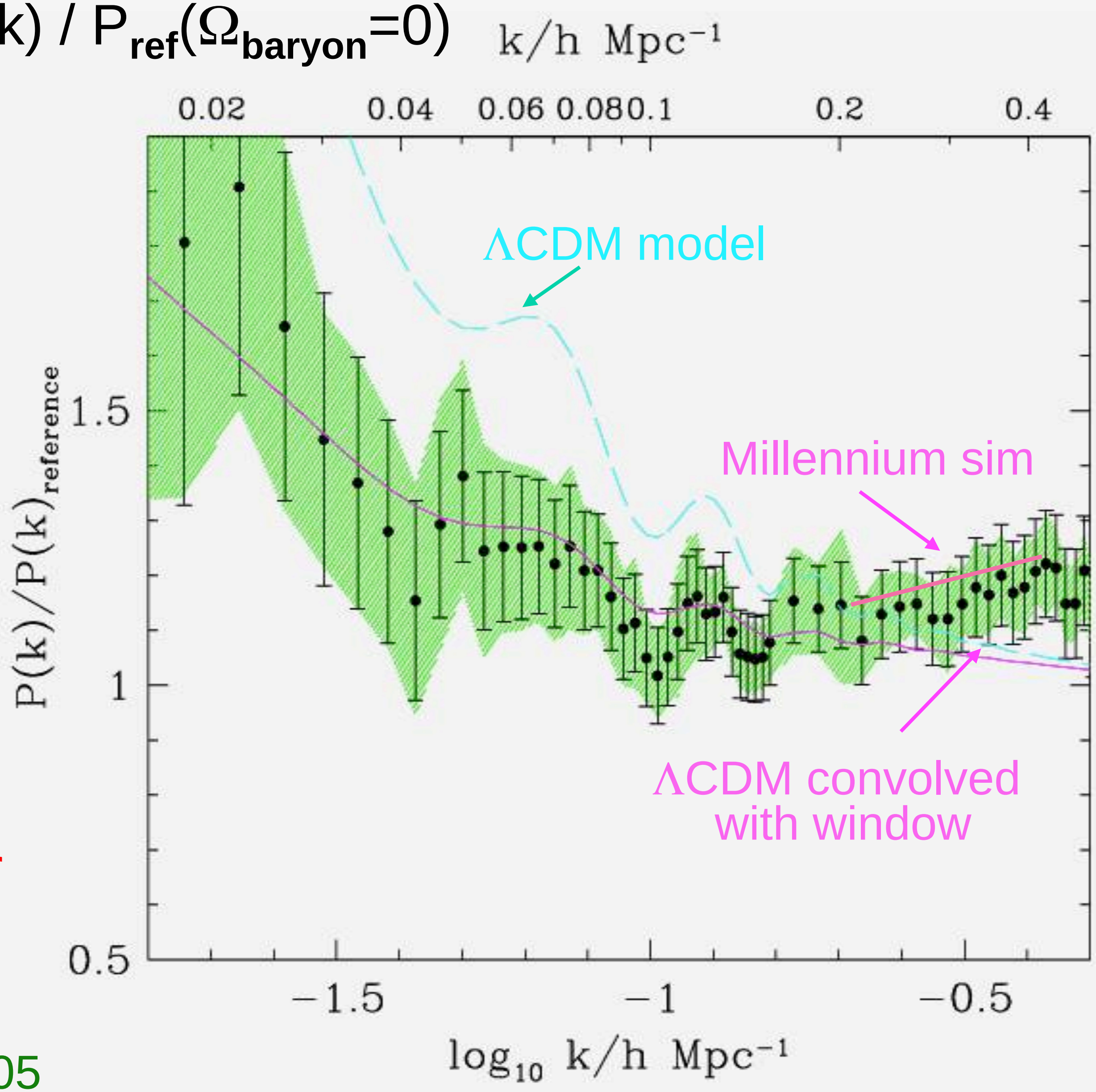
$P(k) / P_{ref}(\Omega_{baryon}=0)$

Baryon oscillations in 2dFGRS ➔

- Consistency with structure growth by gravitational instability in a ΛCDM universe

- Since size of acoustic horizon at t_{rec} known, BAO are standard ruler



Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05

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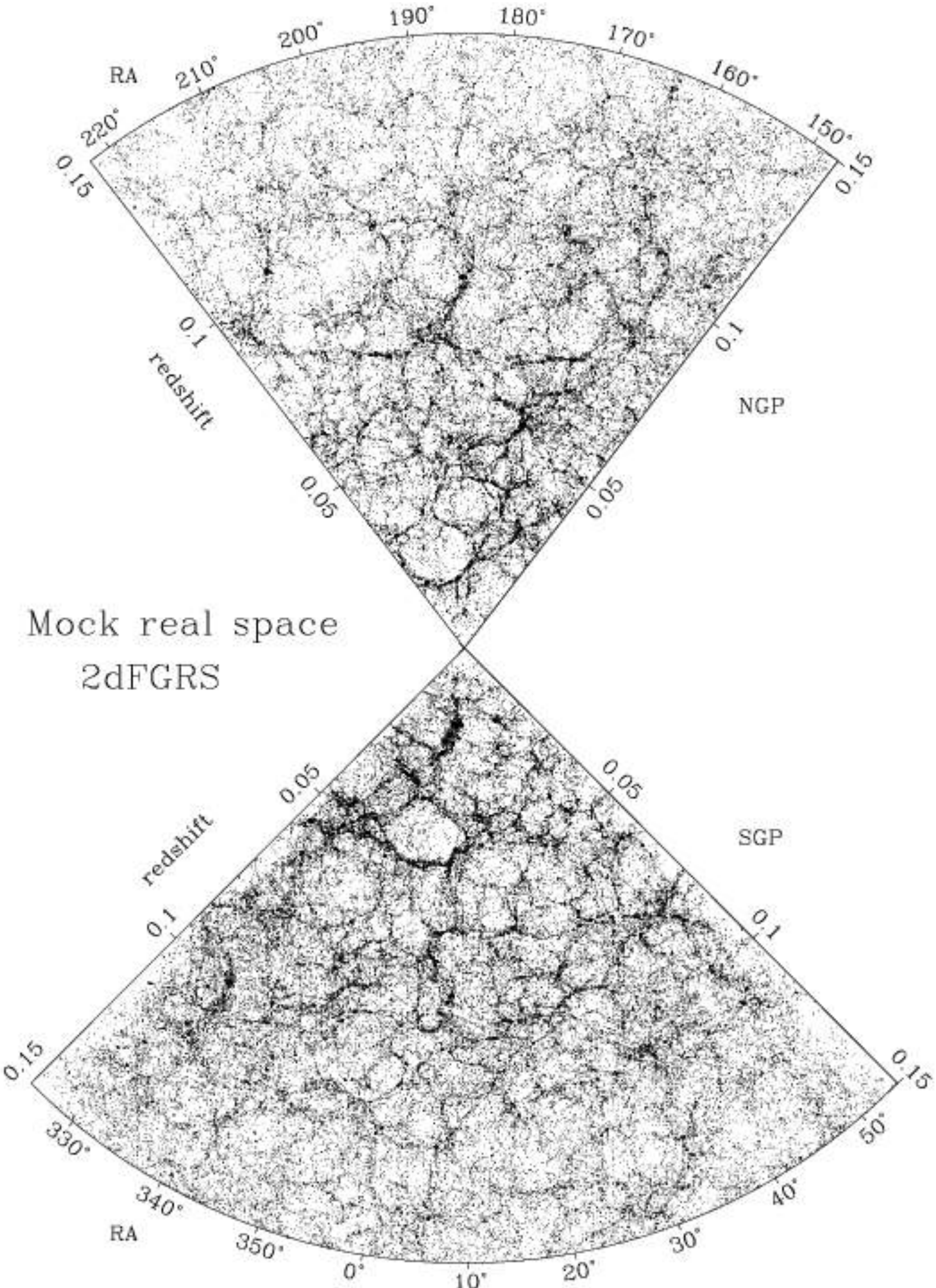
Mock 2dFGRS from Hubble vol sim

real space



Eke, Frenk, Cole, Baugh + 2dFGRS 2003

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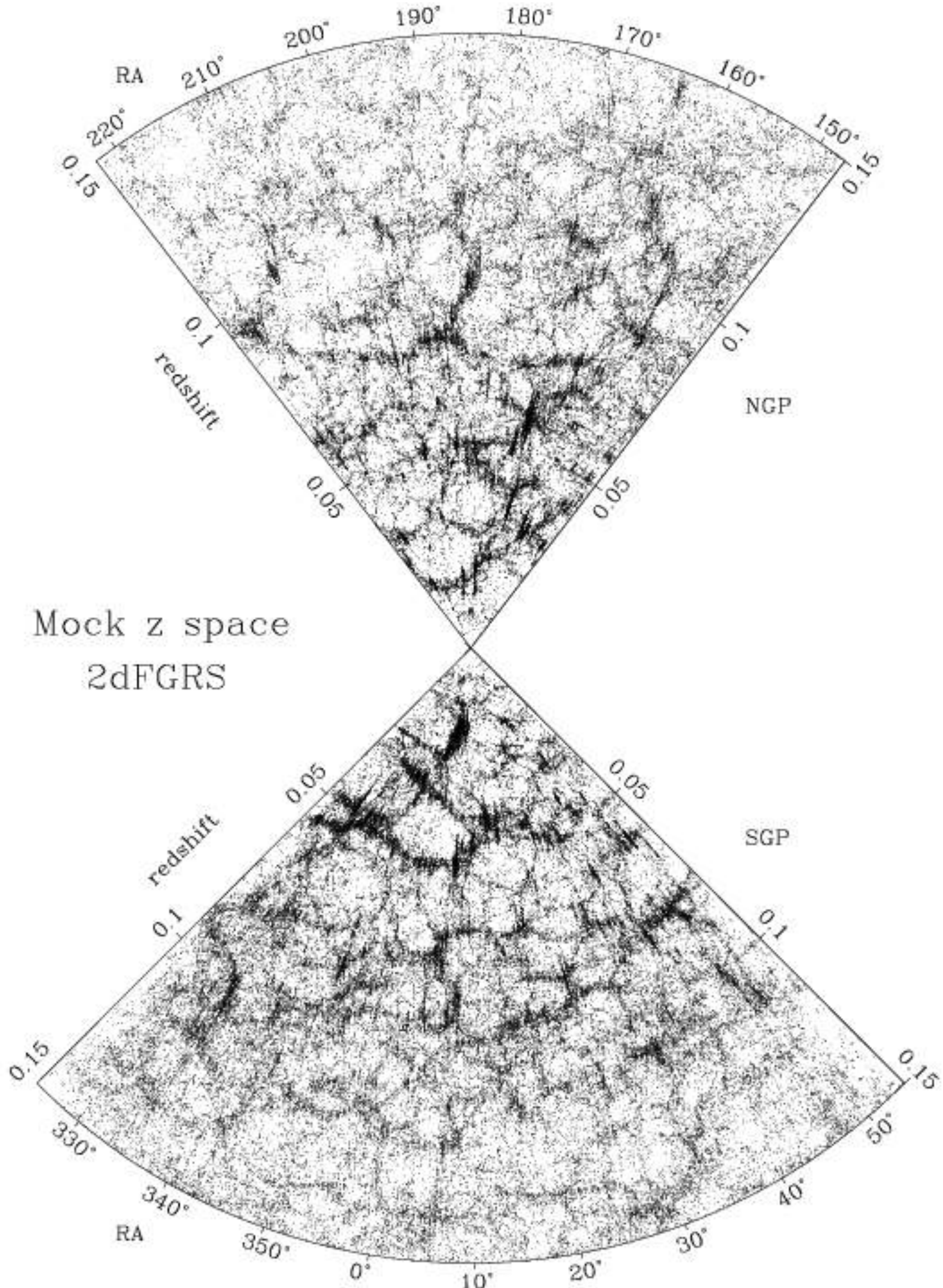
Mock 2dFGRS from Hubble vol sim

z-space

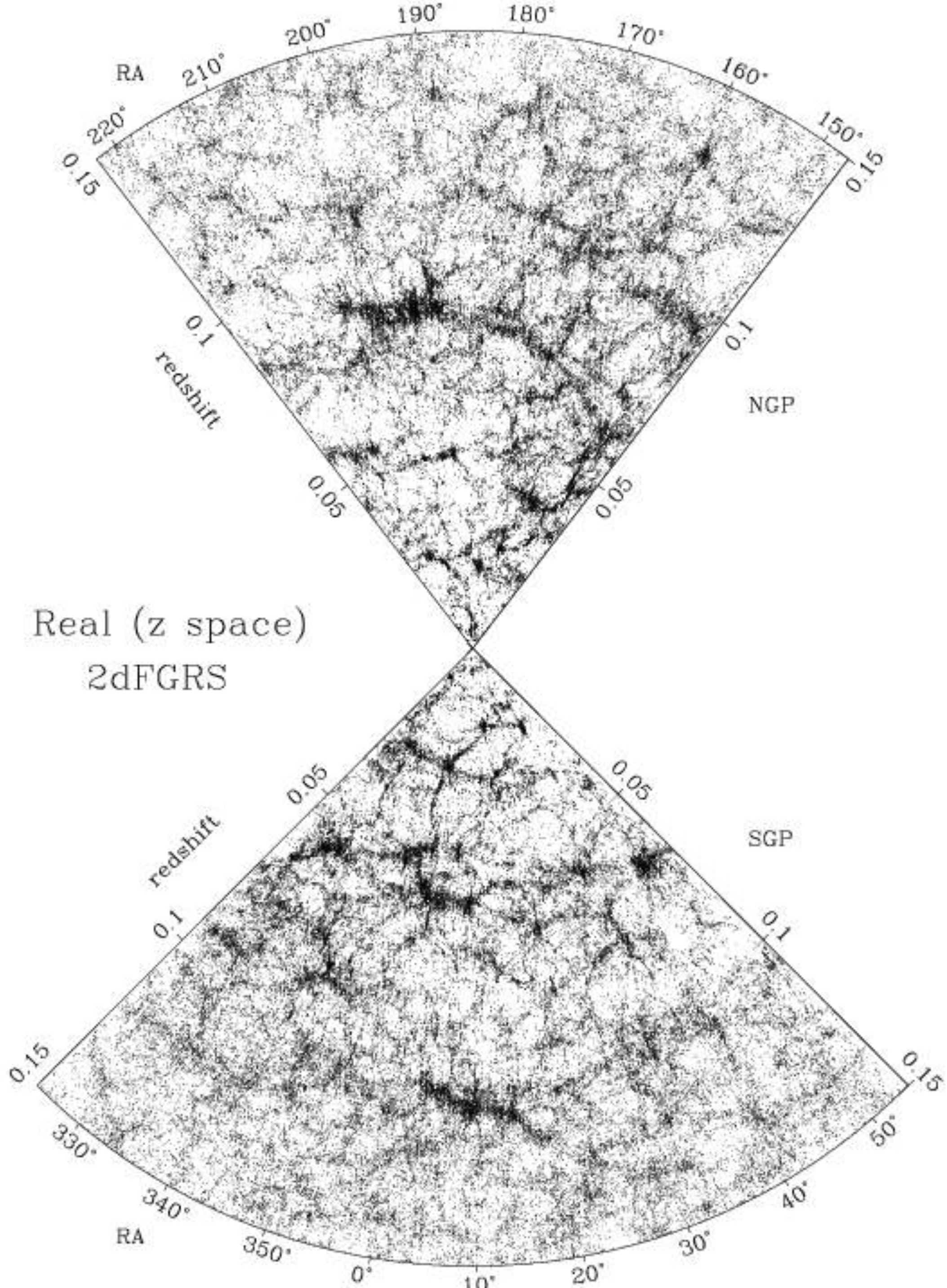


Eke, Frenk, Cole, Baugh + 2dFGRS 2003

University of Durham

Real 2dFGRS

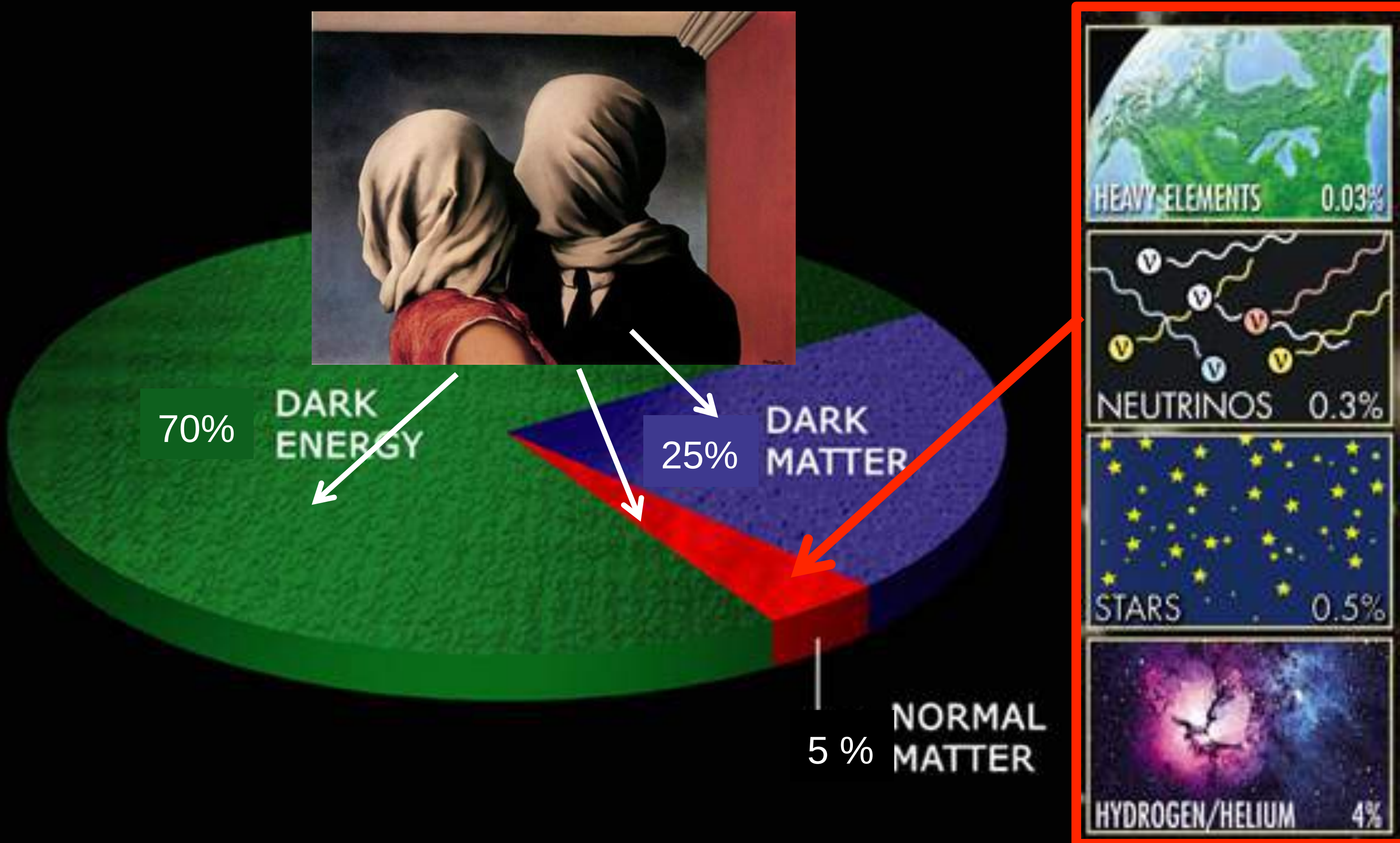
z-space



Eke, Frenk, Cole, Baugh +
2dFGRS 2003

Open problems cosmology best tackled with simulations

The content of our universe



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Open problems in cosmology

- The dark energy problem:
  - Alternatives to ΛCDM: modified gravity, quintessence, etc
- The dark matter problem
  - Warm dark matter, self-interacting dark matter
- The baryon problem
  - How do galaxies form and how do baryons affect the evolution of DM?

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

Free streaming →

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

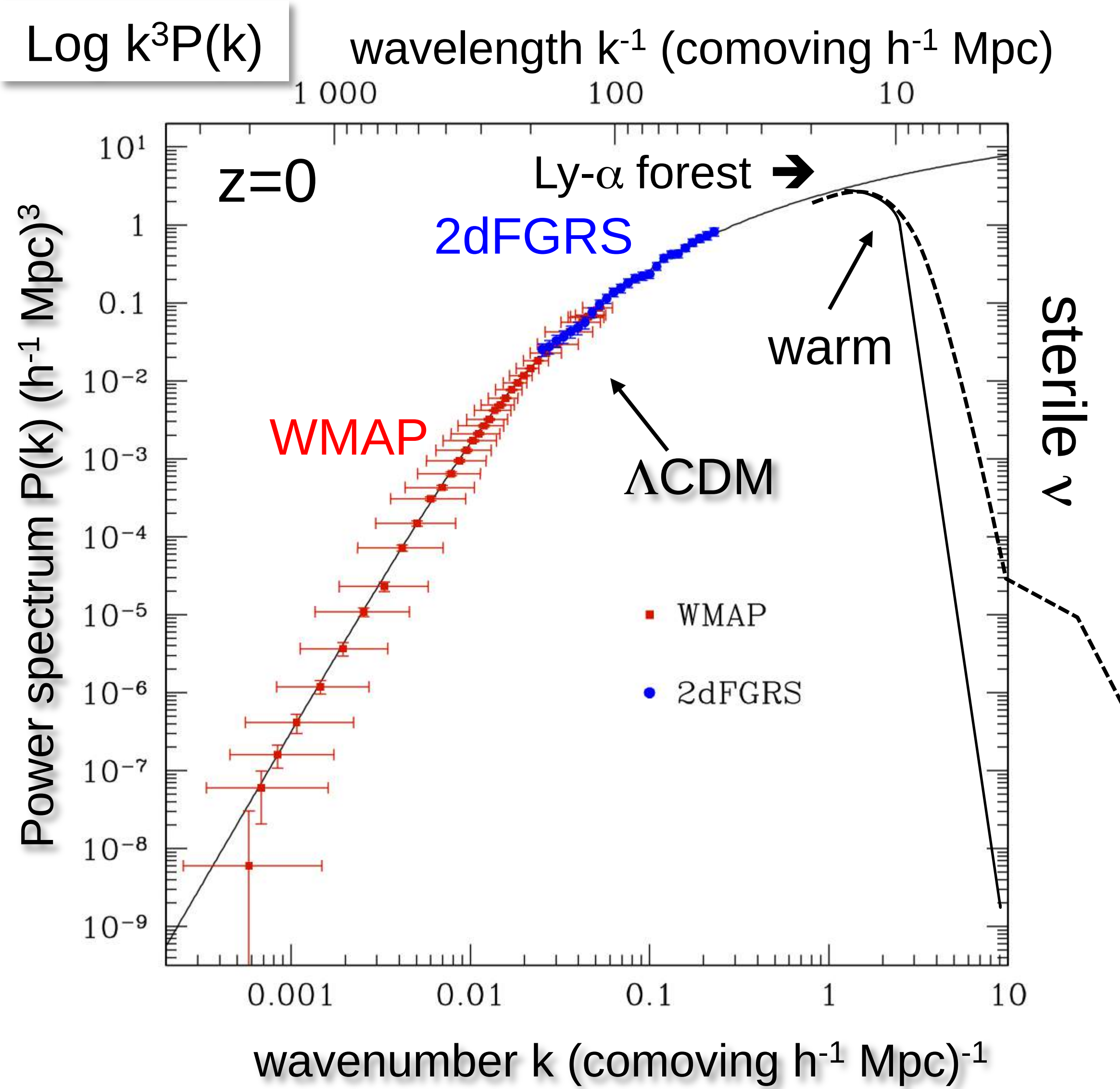
for thermal relic

$m_{CDM} \sim 100$GeV

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$

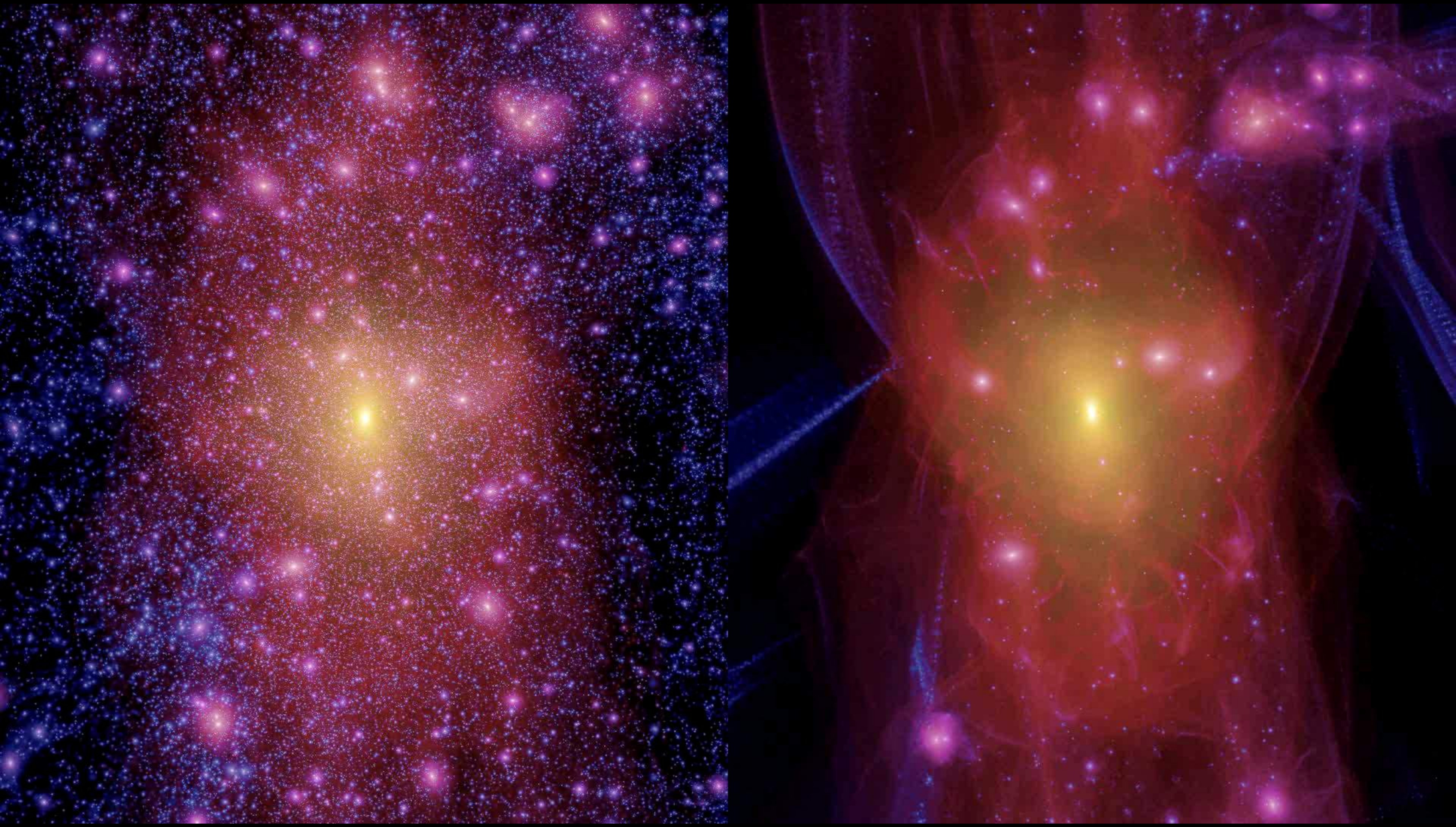


Cold Dark Matter | Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

cold dark matter | warm dark matter

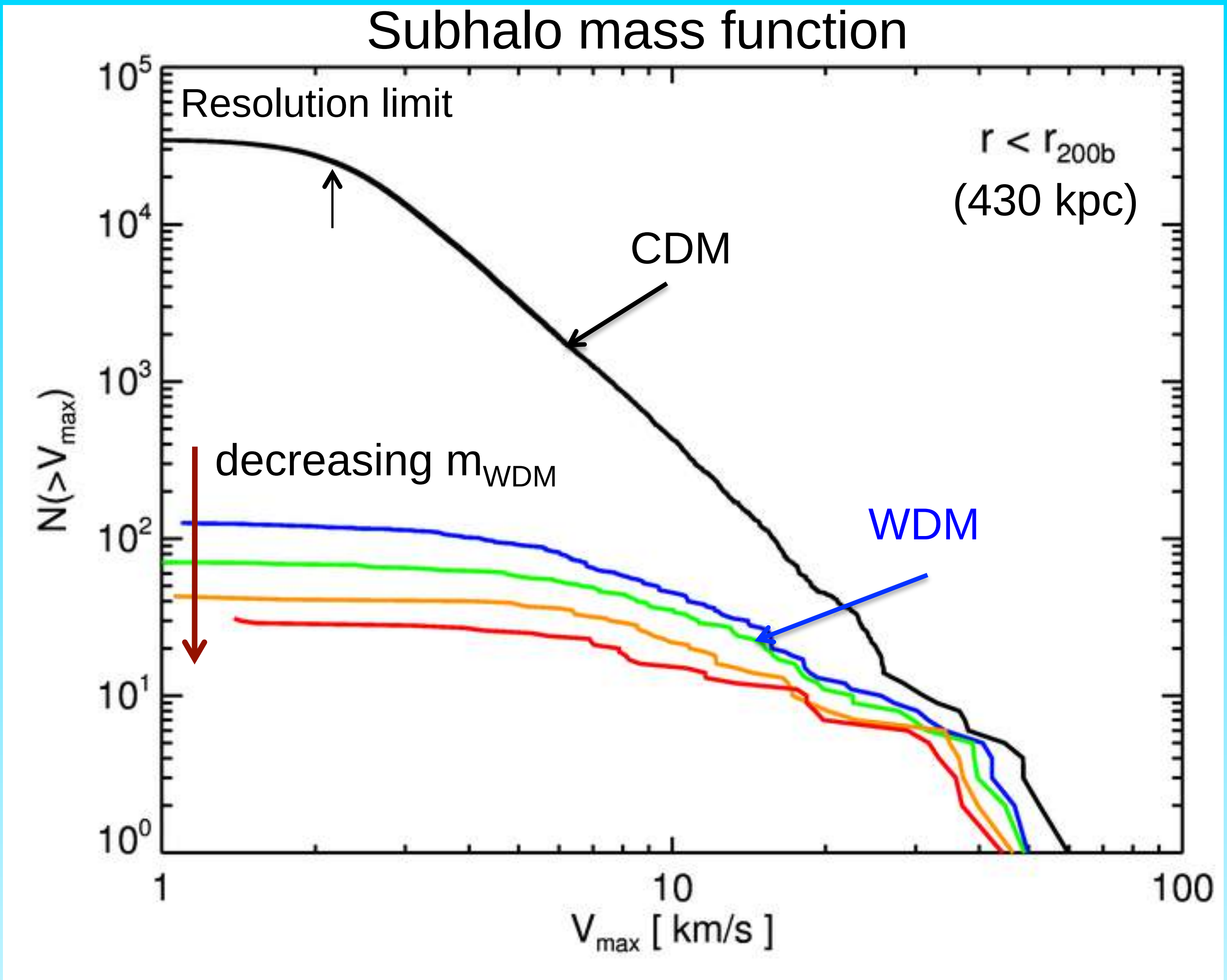


Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘13

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 abundance

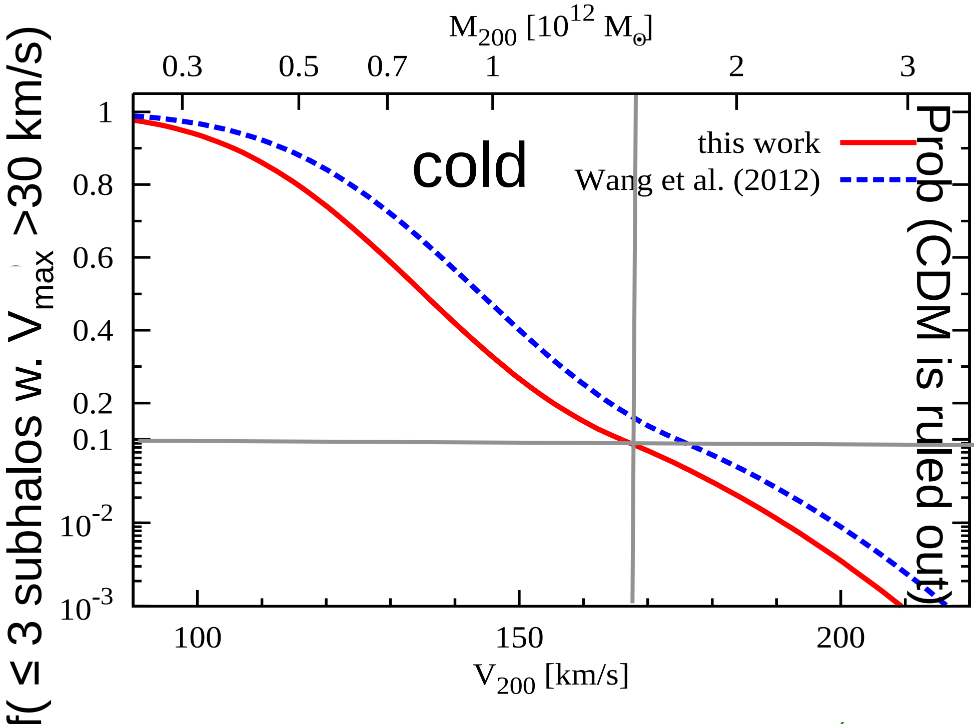
cold dark matter

warm dark matter

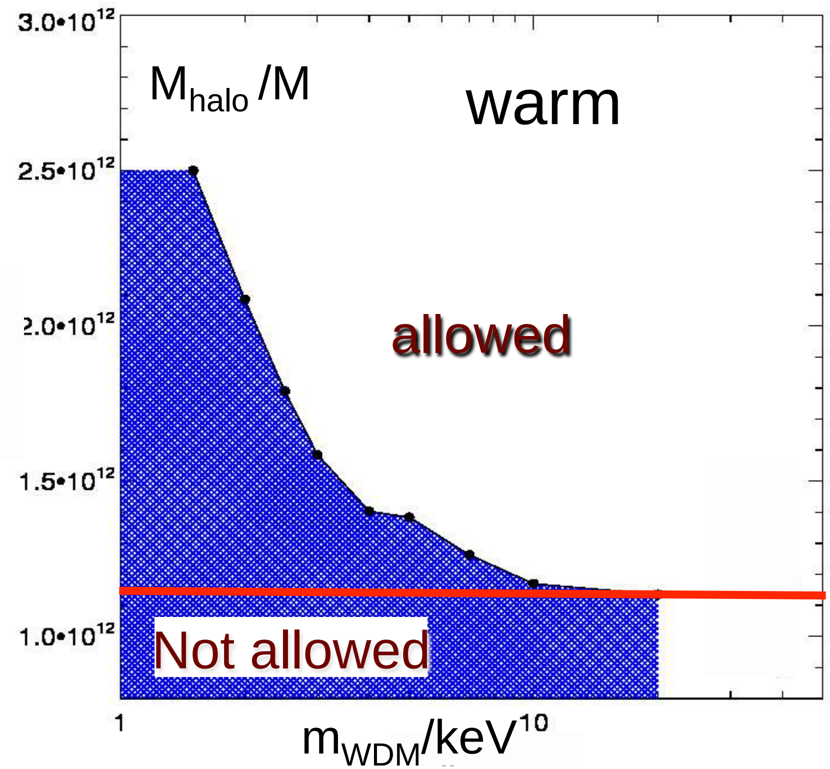
Lovell, Frenk, Eke, Gao, Jenkins, Theuns ’12, ‘13

The nature of the DM and M_{halo}

University of Durham



Wang, Frenk, Navarro, Gao '12
Cautun, Frenk, van den Weygaert, Hellwing '14



Kennedy, Cole Frenk, '14

CDM requires

$M_{halo} < 1.5\times10^{12} M_o$

(95% confidence)

WDM requires

$M_{halo} > 1.1\times10^{12}$ M_o

(95% confidence)

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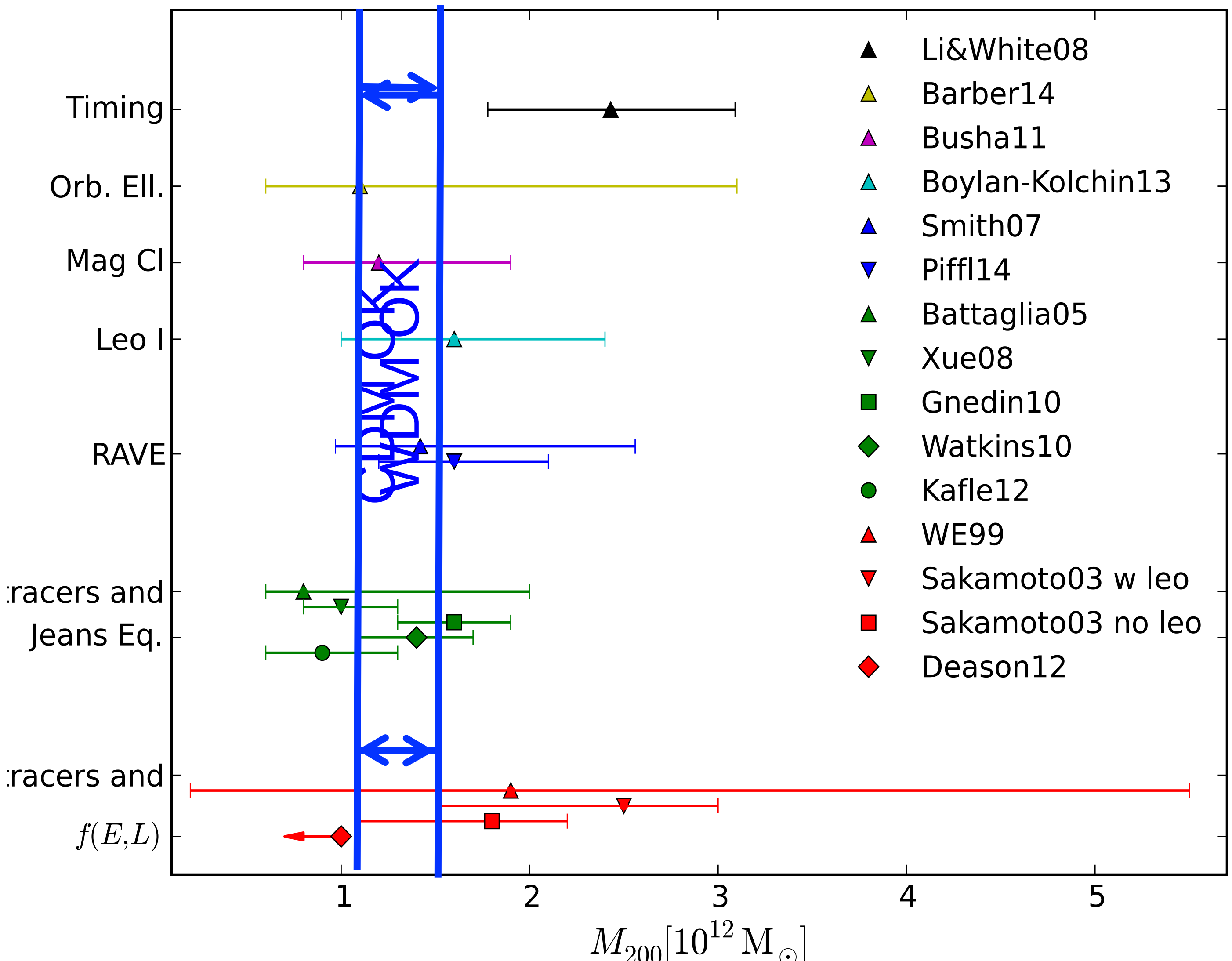
Estimates of the MW halo mass



Wenting Wang et al. ‘14

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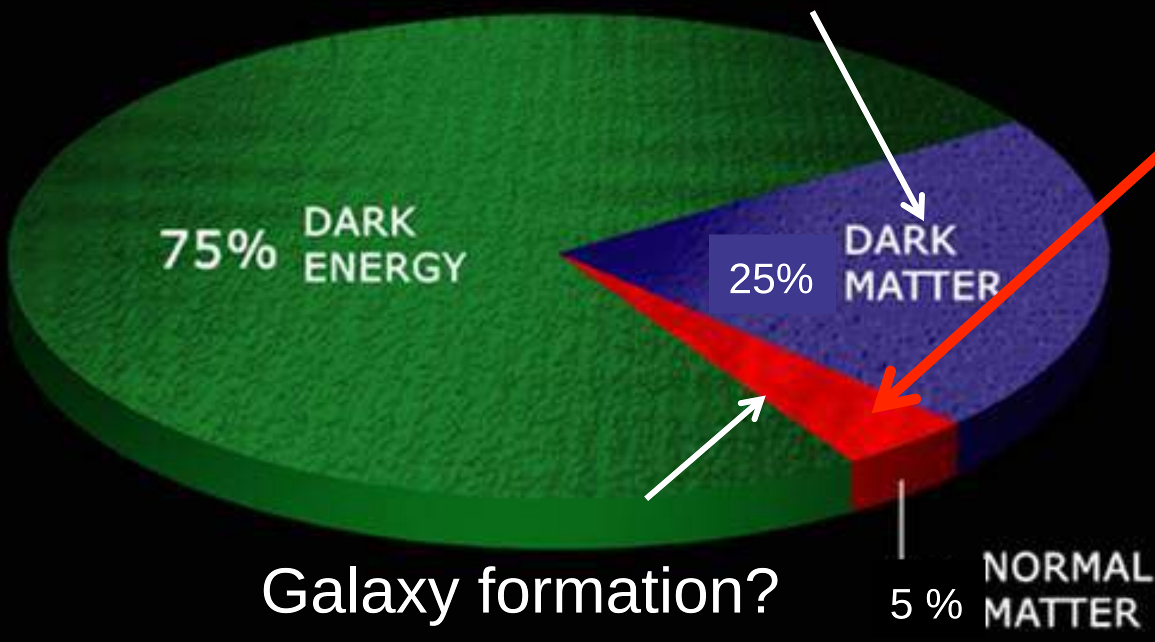
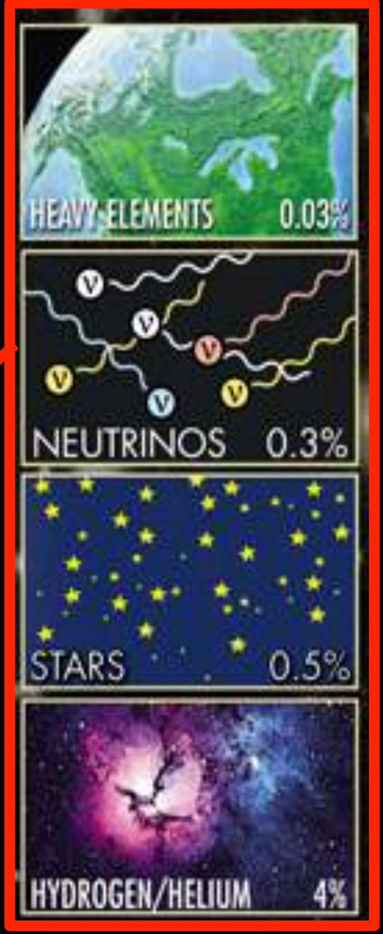
The content of our universe

Could be CDM, WDM, SIDM or xxx



Galaxy formation?



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IAU Symposium 79

The Large Scale Structure of the Universe, Tallinn, Sep 12-16,1977

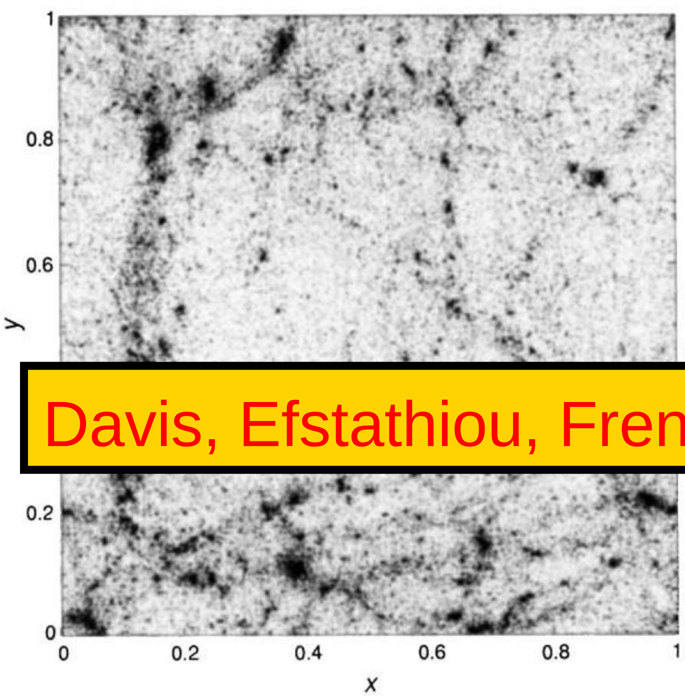
Extrapolating from Krakow through Tallinn to the next symposium somewhere in the early eighties one can be pretty sure that the question of the formation of galaxies and clusters will be solved in the next few years.

Institute for Computational Cosmology

University of Durham ICC

Nature **REVIEW ARTICLE**

z=3



5 Mpc

Davis, Efstathiou, Frenk & White '92

Many details of the CDM model, particularly those associated with galaxy formation, remain to be worked out, but the prospects seem promising. The next generation of sky surveys at optical, infrared and X-ray wavelengths, in combination with the measurement of redshifts for hundreds of thousands of galaxies, will produce a qualitative improvement in our knowledge of the large-scale galaxy distribution. If CDM is right, the 8–10-m apertures of the new generation of optical telescopes will enable us to see forming galaxies, to measure the evolution of galaxy clustering and to use absorption lines in the spectra of background quasars to study the gaseous component of protogalaxies. These observations will allow us to quantify many ... structure and to explore the evolution of ... latest 90% of its history. Together with the rapidly improving technology for searches of variations in the brightness of the microwave background, they provide our best chance of testing the essential elements of the CDM picture for structure formation.

of the candidates. The attempt to identify the substance that apparently constitutes more than 90% of the mass of the Universe is surely one of the greatest challenges in contemporary physics. There are good reasons to hope that the mystery will be solved during this decade. □

Illustris Simulation

Vogelsberger, Genel, Springel, Torrey, Sijacki, Xu, Snyder, Bird, Nelson, Hernquist

Simulating the Universe
The EAGLE simulation project

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…

+ Virgo Consortium

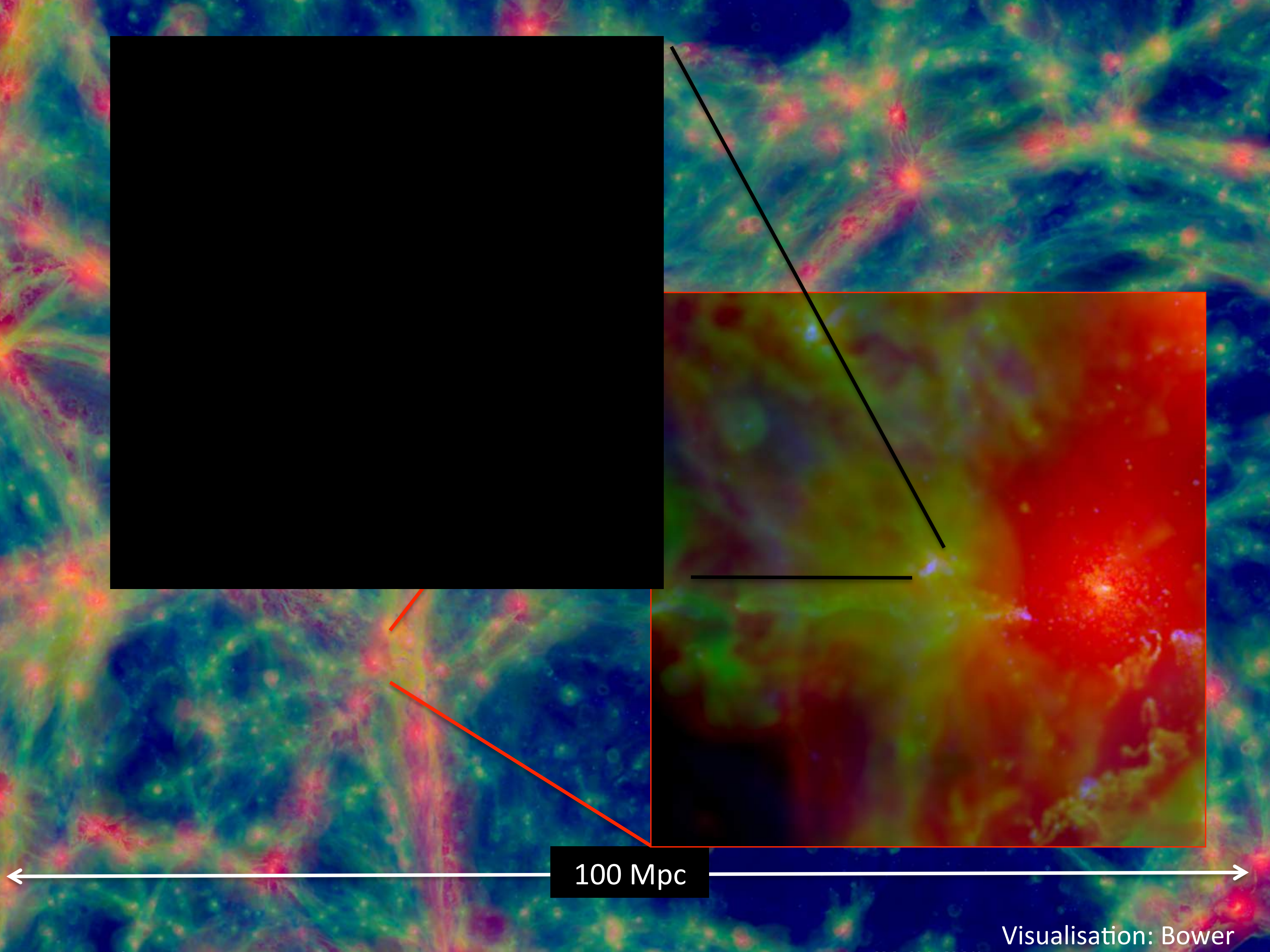
NAM 2014

EAGLE: Evolution and Assembly of GaLaxies and their Environments

- Anarchy-SPH (Gadget-3) + Planck Cosmology
- Resolution 10^6 solar masses
- 25, 50 and 100 Mpc boxes
- Subgrid physics
  - Star formation
  - Cooling
  - Chemical evolution
  - Stellar feedback -> thermal
  - AGN feedback -> ang. mom.
- Evolution to z= 0

← 20 Mpc →

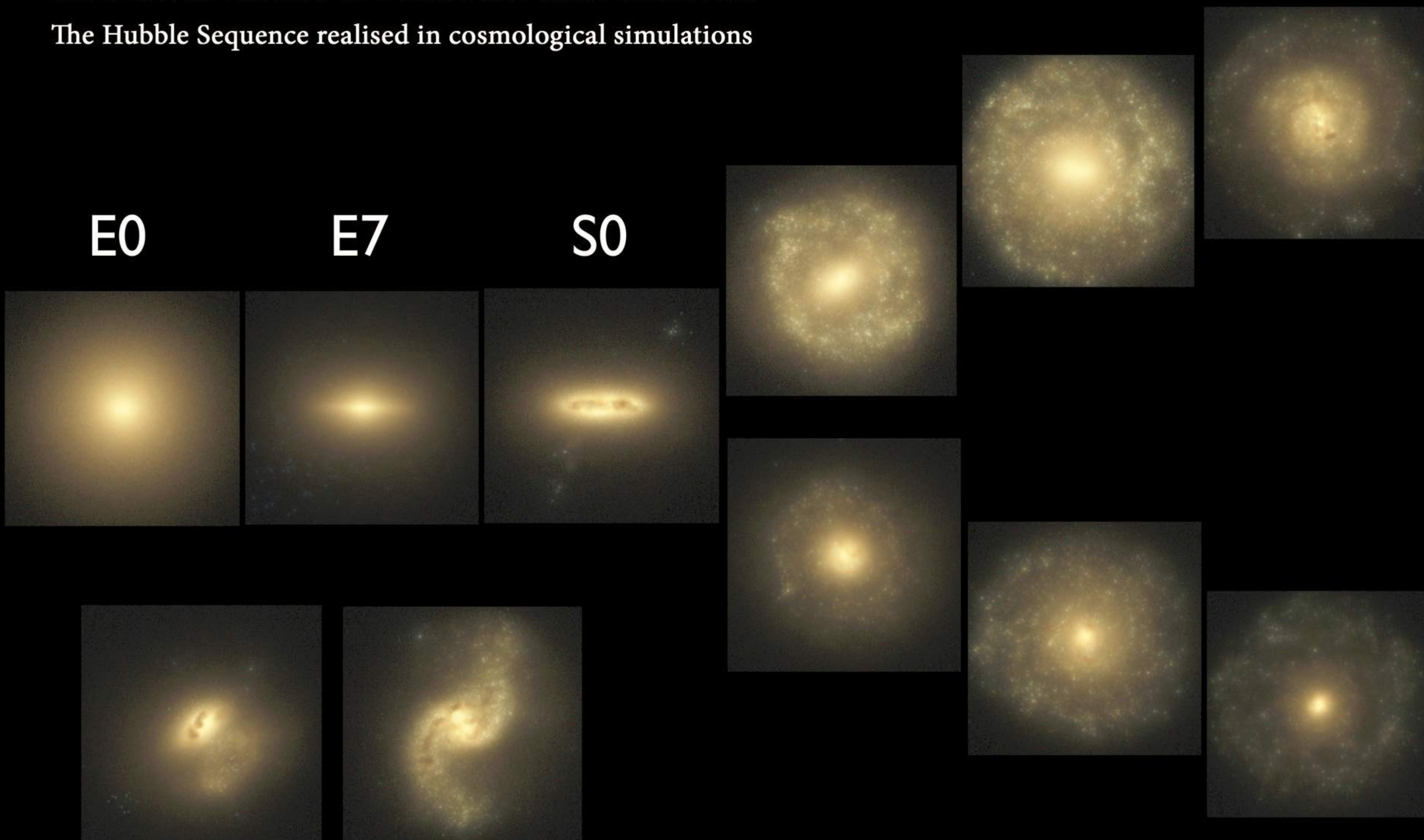
This is is only 1/8000 of the total volume


100 Mpc
Visualisation: Bower

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



Trayford/Baes

Sub-grid schemes in EAGLE

Star formation

$$\tau_* \propto P^{n_{KS}}$$

ISM turbulence

$$P_{ISM} \propto \rho^{\gamma}$$

Supernova feedback

$$p_{heat} = \frac{E_{SN}}{kT_{heat}} f(Z, \rho)$$

Metal enrichment and stellar mass loss

AGN accretion

$$\dot{m}_{BH} = \max\left(f(\rho, v_{\phi}), \dot{m}_{Edd} \right)$$

AGN feedback

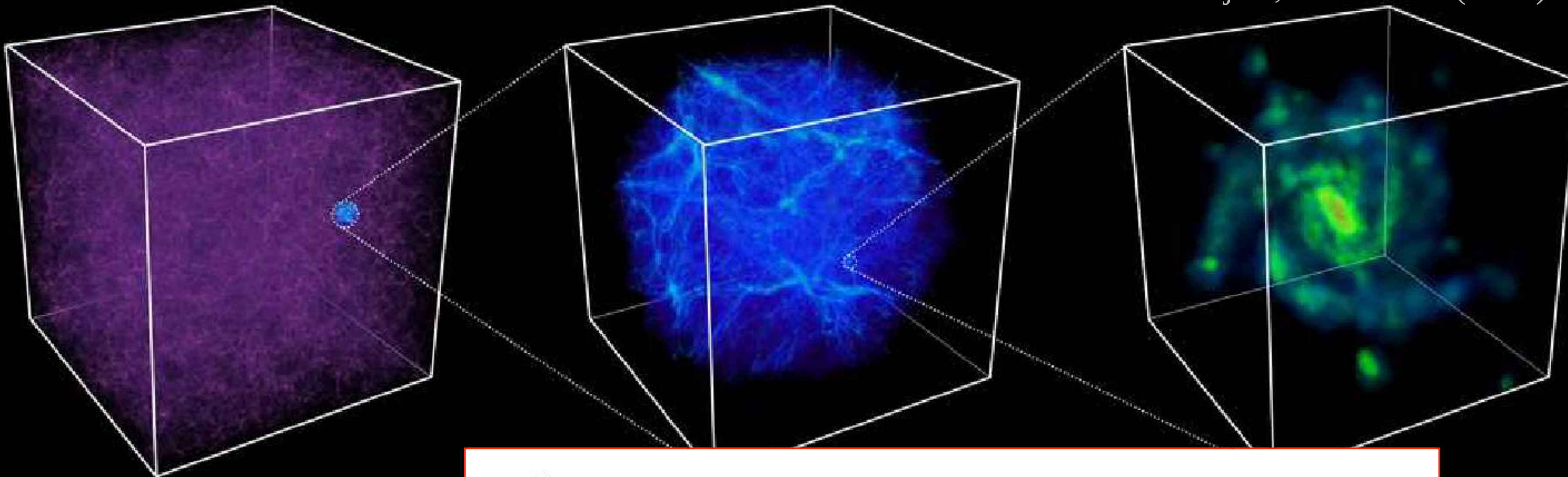
$$p_{heat} = \frac{0.01\dot{m}c^2}{kT_{heat}}$$

Cooling and photoionisation

Subgrid physics with fully coupled hydrodynamics

Dalla Vecchia & Schaye 2009, 2012; Rosas-Guevara et al 2014

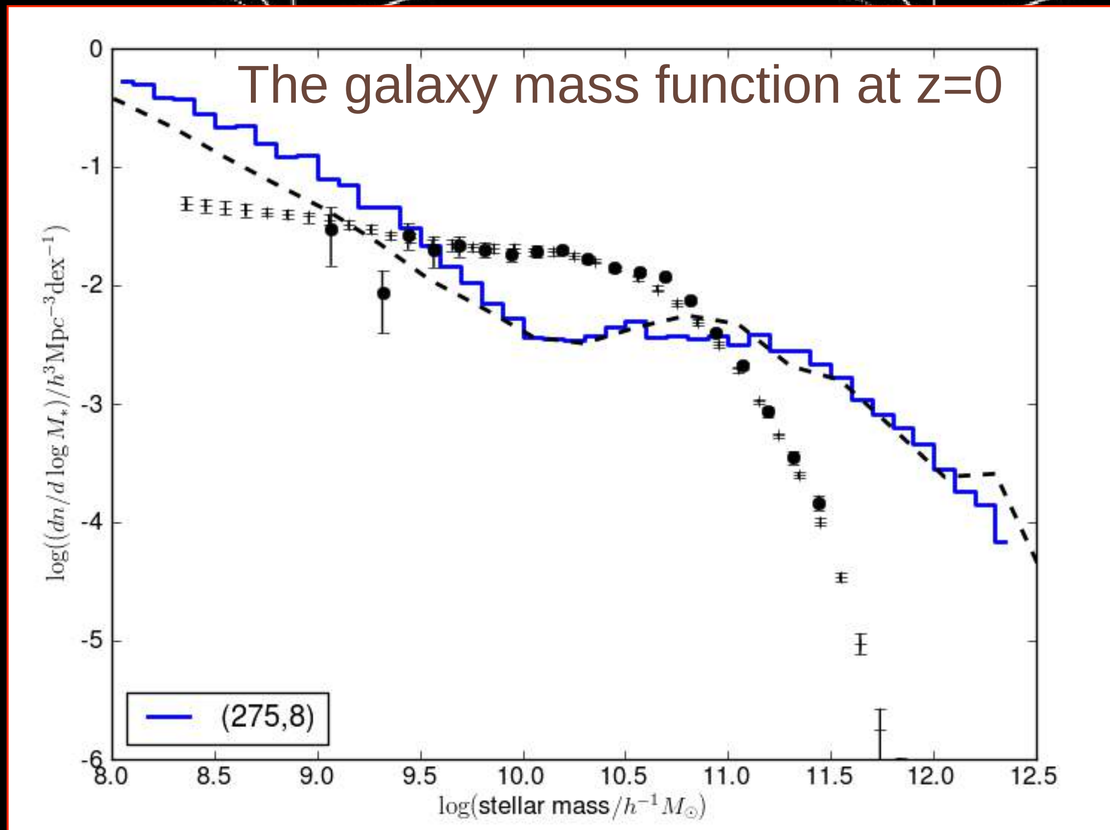
GIMIC Project, Crain et al. (2008)



GIMIC

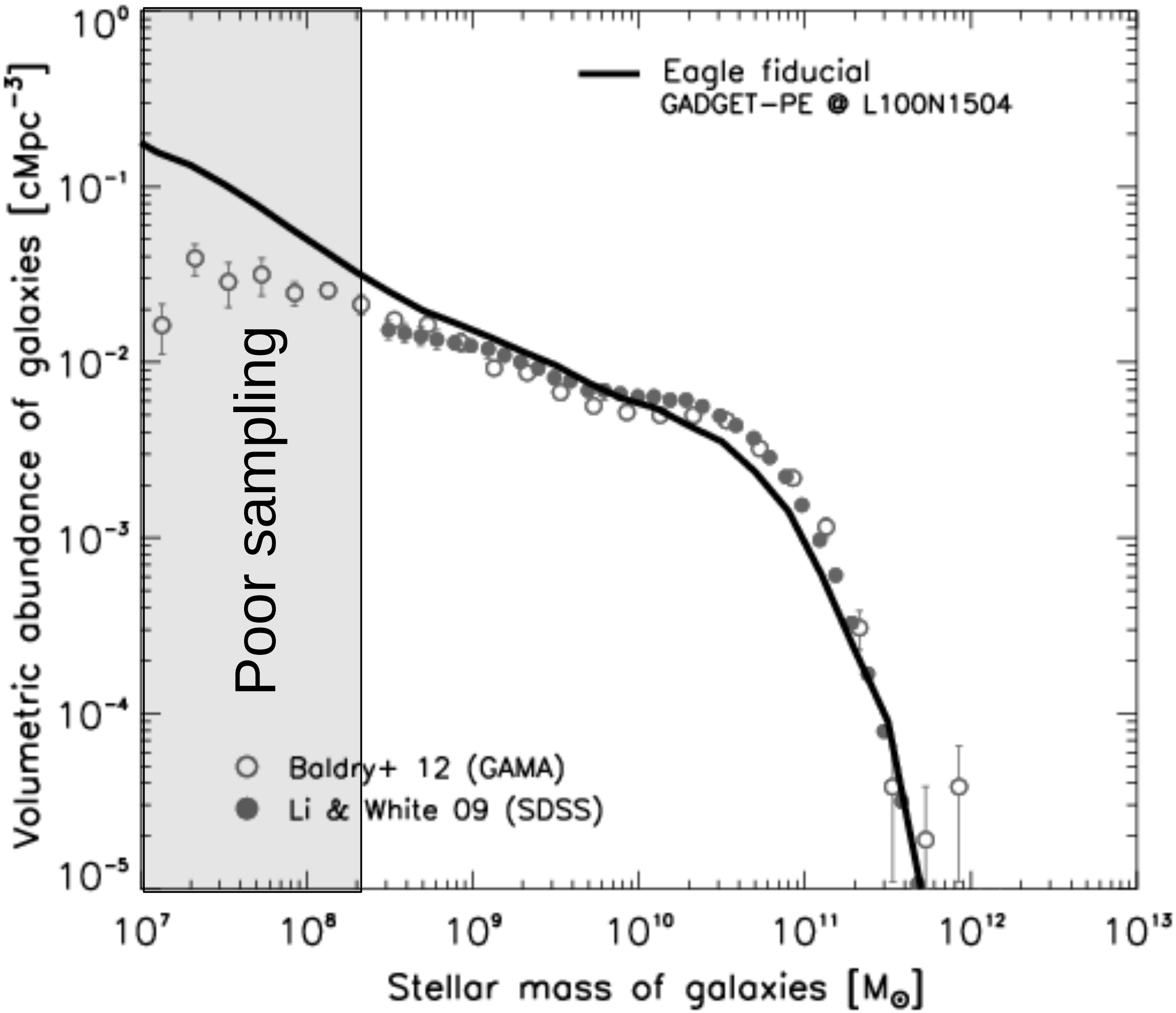
Previous generation of cosmological hydrodynamical simulations

(Crain et al ’08)



The galaxy mass function at z=0

University of Durham



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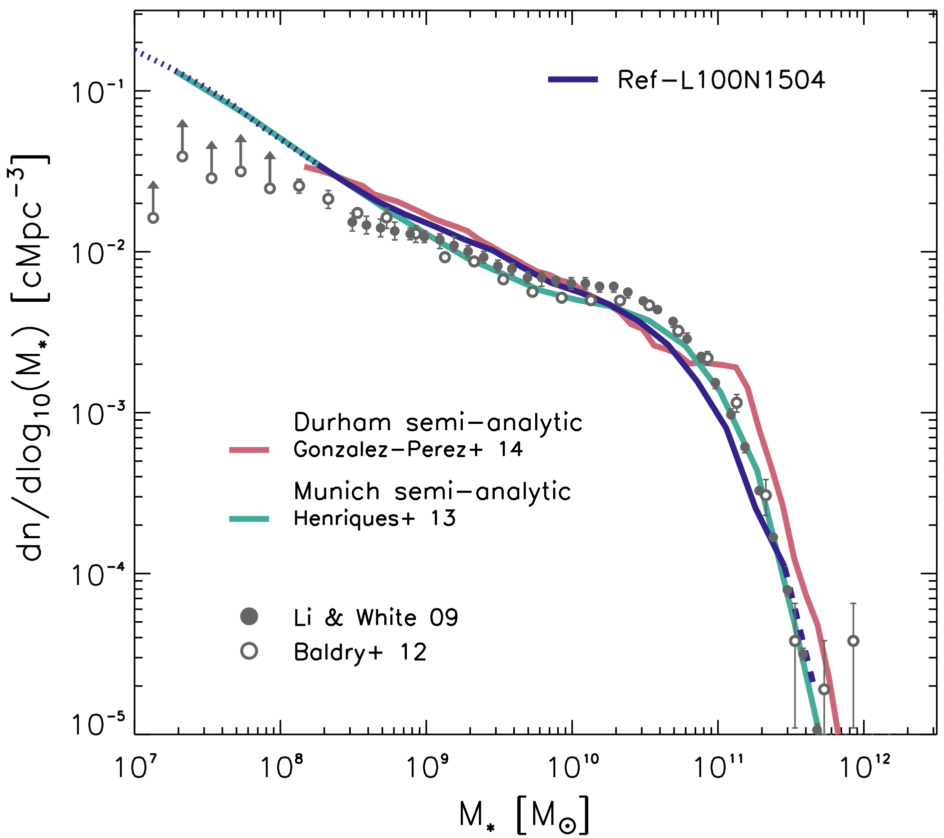
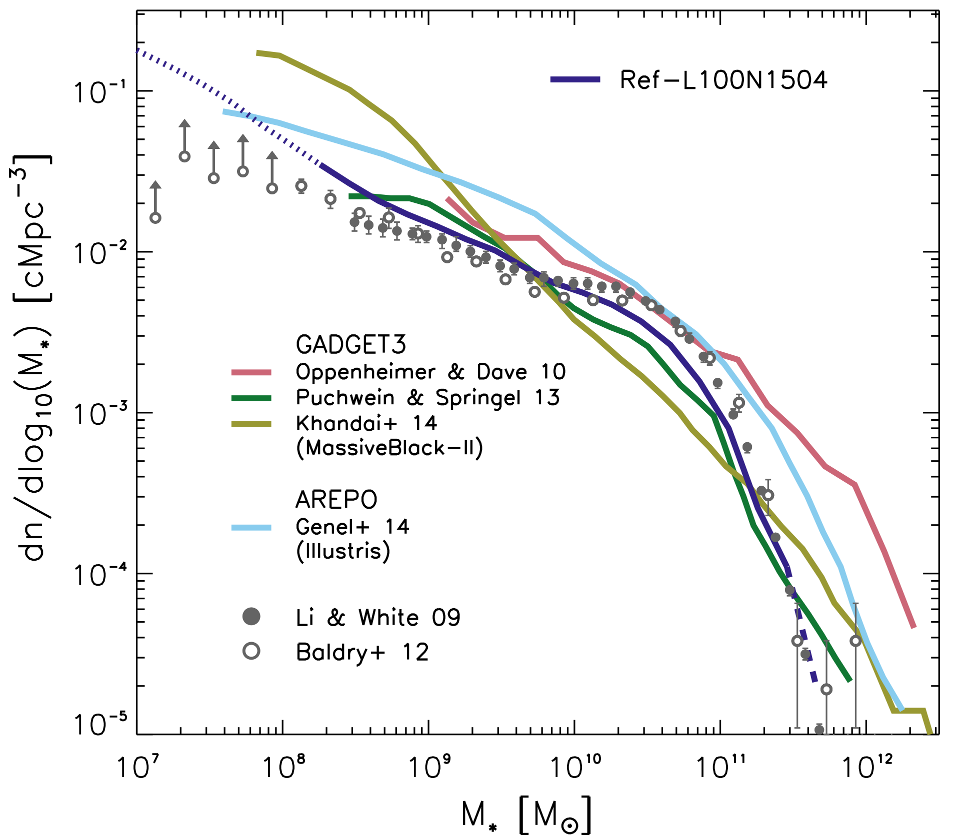
EAGLE compared to other models

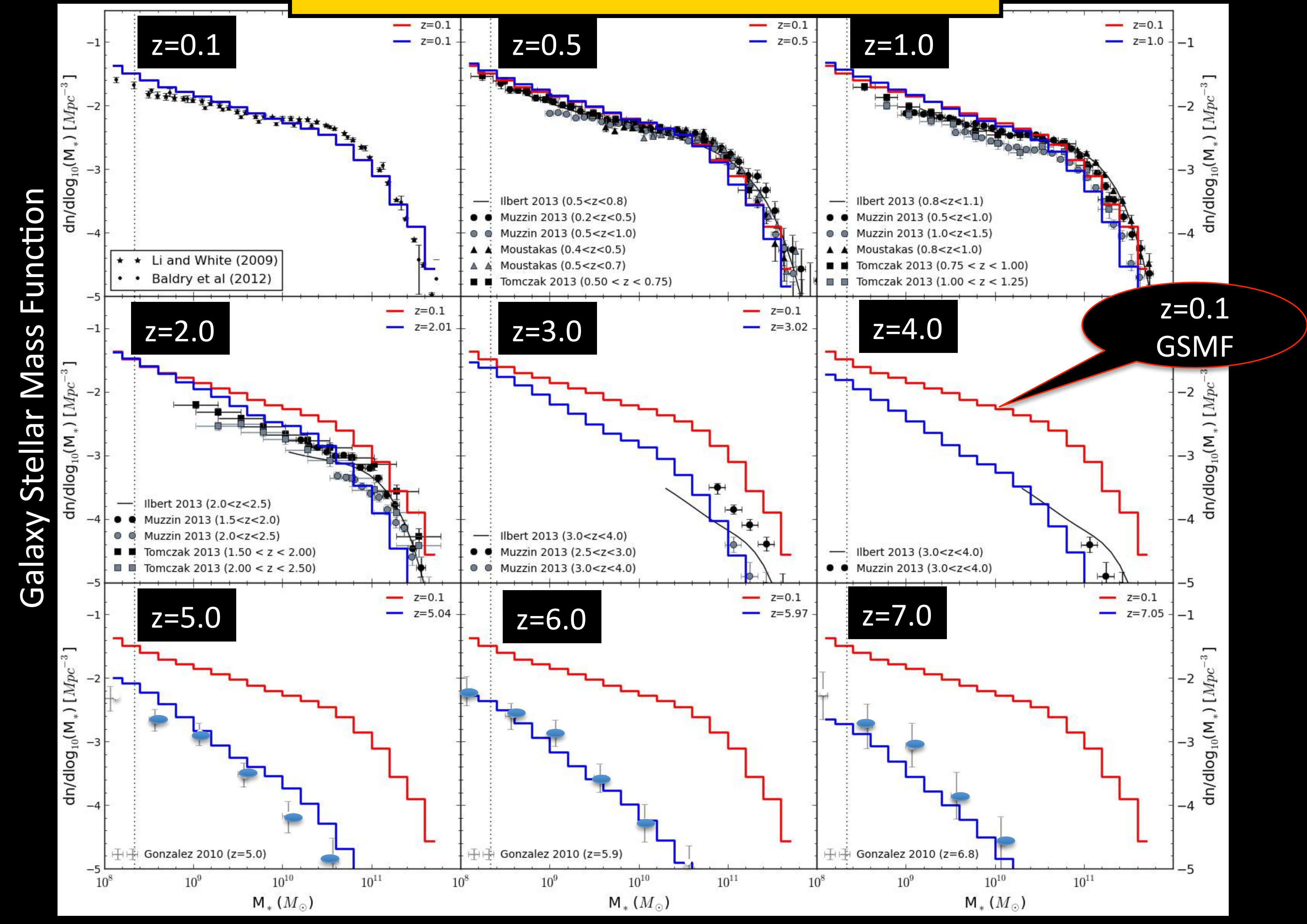




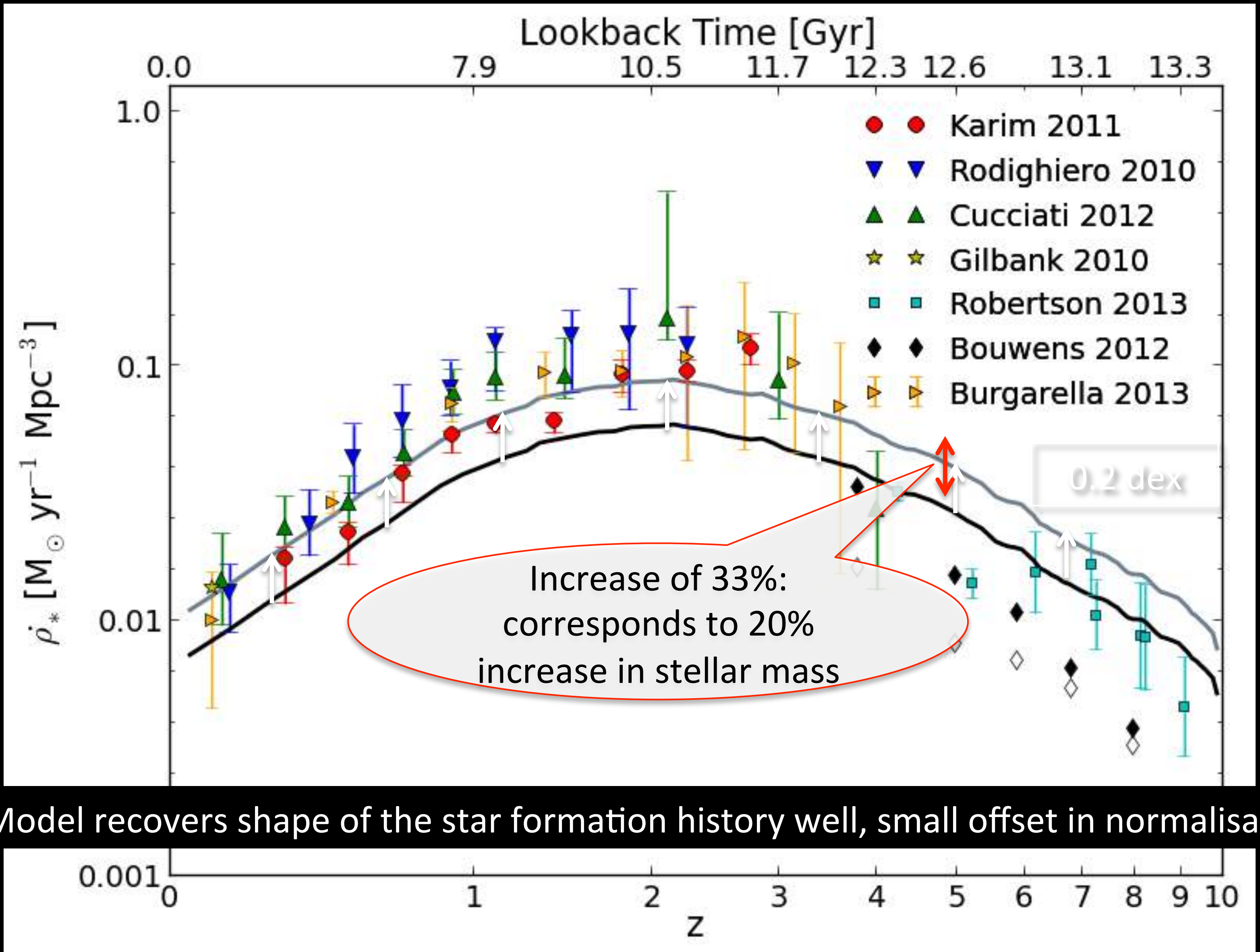
Semi-analytic models

Hydrodynamic simulations

Evolution of the mass function

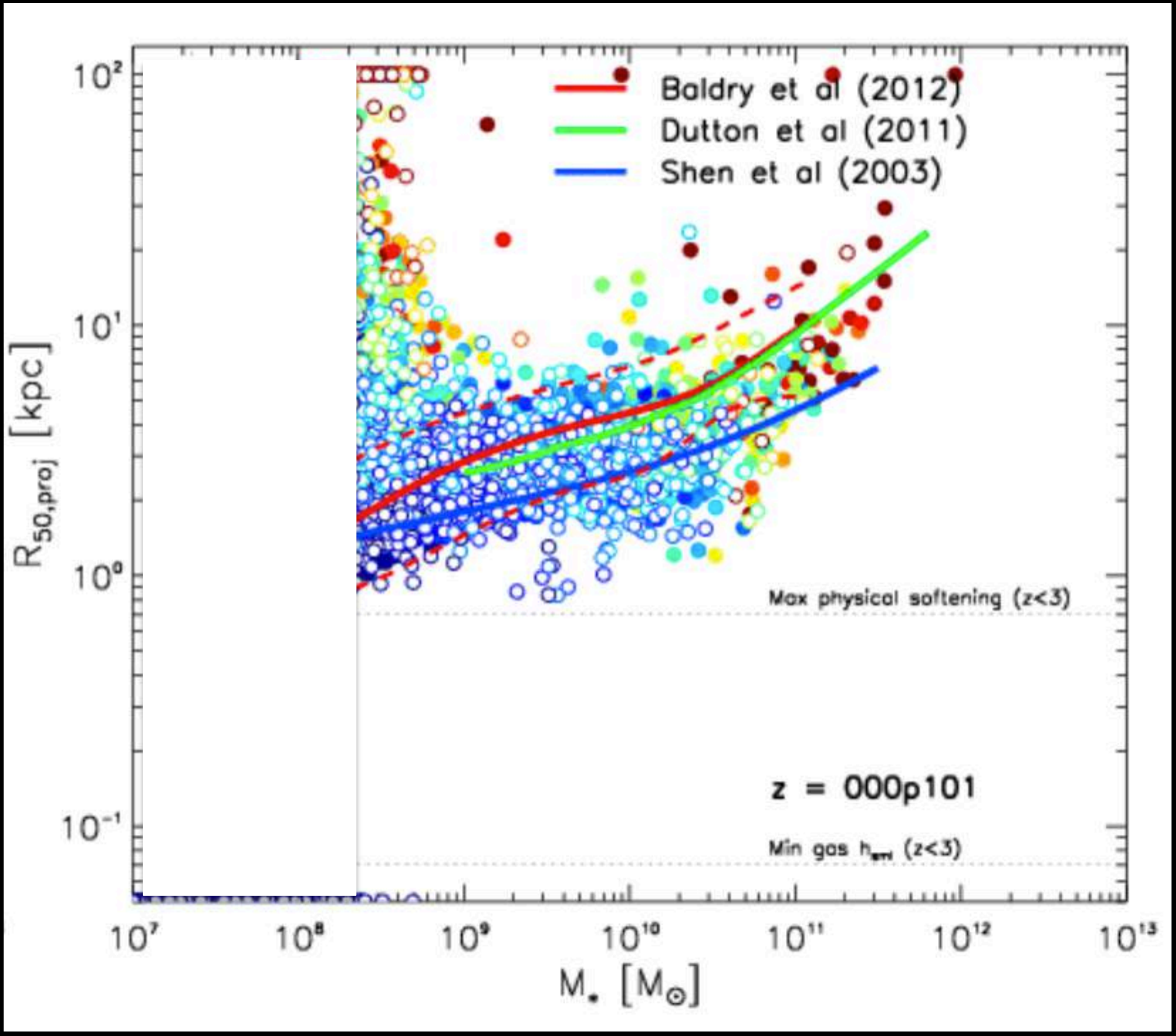


Evolution of the SFR density



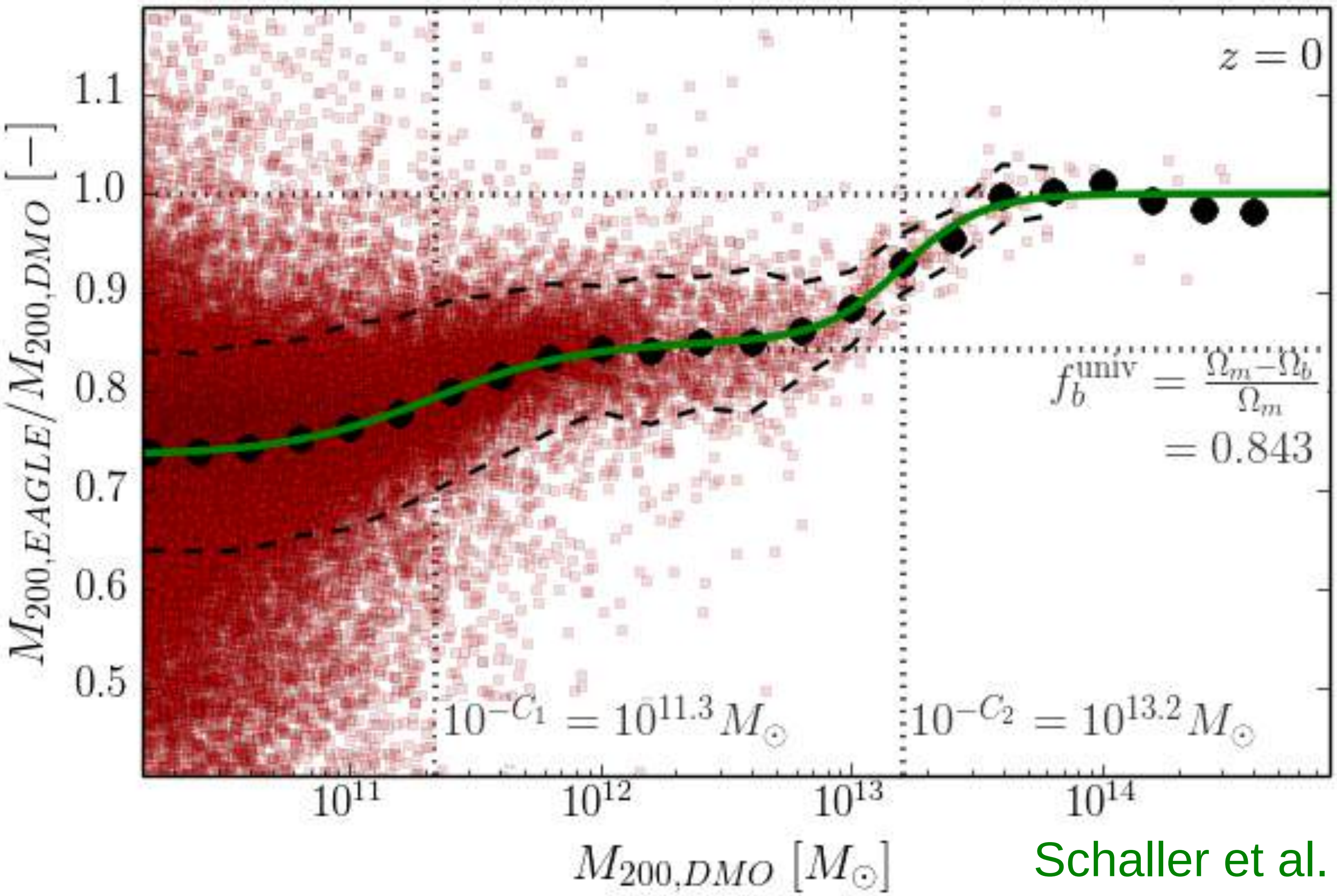
Model recovers shape of the star formation history well, small offset in normalisation

Galaxy sizes



Baryon effects: halo masses

Average modification of halo masses as a function of mass

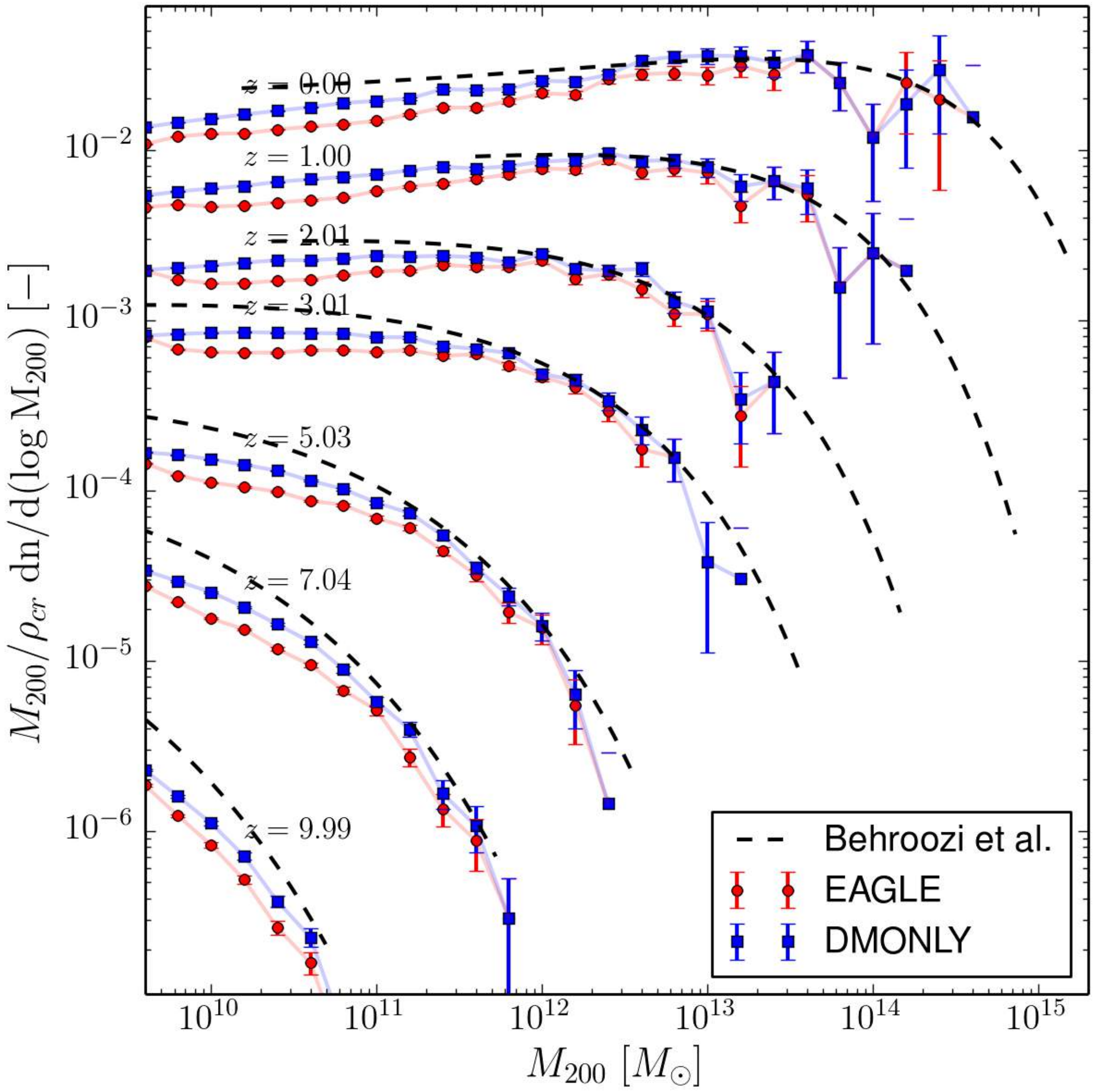


Schaller et al. ‘14

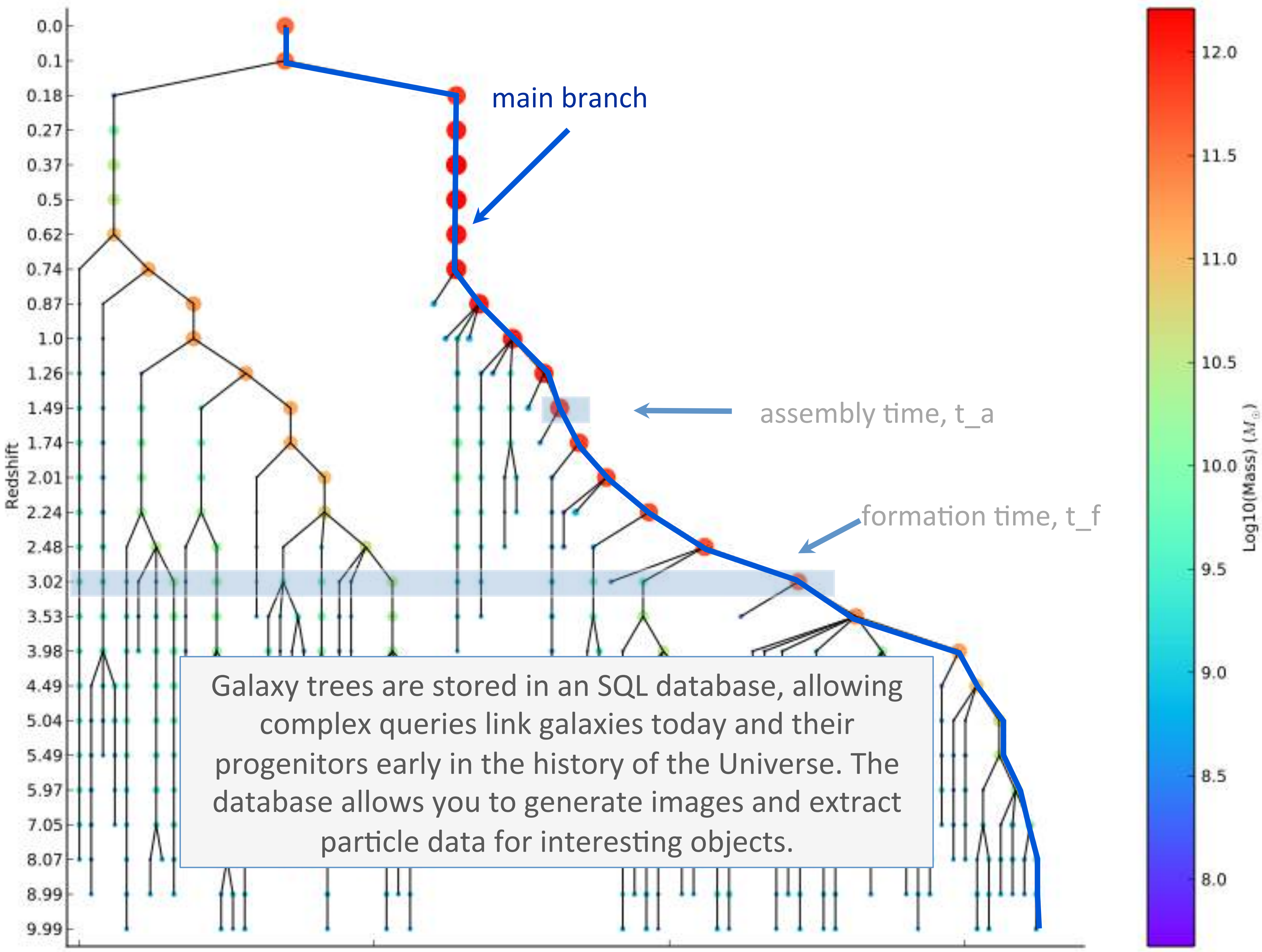
See also Sawala et al. ‘12, ‘14

Baryon effects: halo masses

Halo mass function as a function of z



Schaller et al. '14


main branch
assembly time, t_a
formation time, t_f
Redshift
0.0
0.1
0.18
0.27
0.37
0.5
0.62
0.74
0.87
1.0
1.26
1.49
1.74
2.01
2.24
2.48
3.02
3.53
3.98
4.49
5.04
5.49
5.97
7.05
8.07
8.99
9.99
Log10(Mass) ($M_{\odot}$)
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
Galaxy trees are stored in an SQL database, allowing complex queries link galaxies today and their progenitors early in the history of the Universe. The database allows you to generate images and extract particle data for interesting objects.

University of Durham

Conclusions

- Modern cosmology began in ~1980 with two theoretical proposals
  - Inflation
  - non-baryonic DM
- Simulations of the cosmic web played the key role in developing the ΛCDM model, now validated by CMB and LSS data
- We don't know if the DM is CDM, but whatever it is, it must look like CDM on super-Galactic scales
- No too-big-to fail if M_h is small; WDM requires M_h to be large
- New frontiers
  - Dark energy
  - DM on sub-Galactic scales
  - Galaxy formation + environmental effects