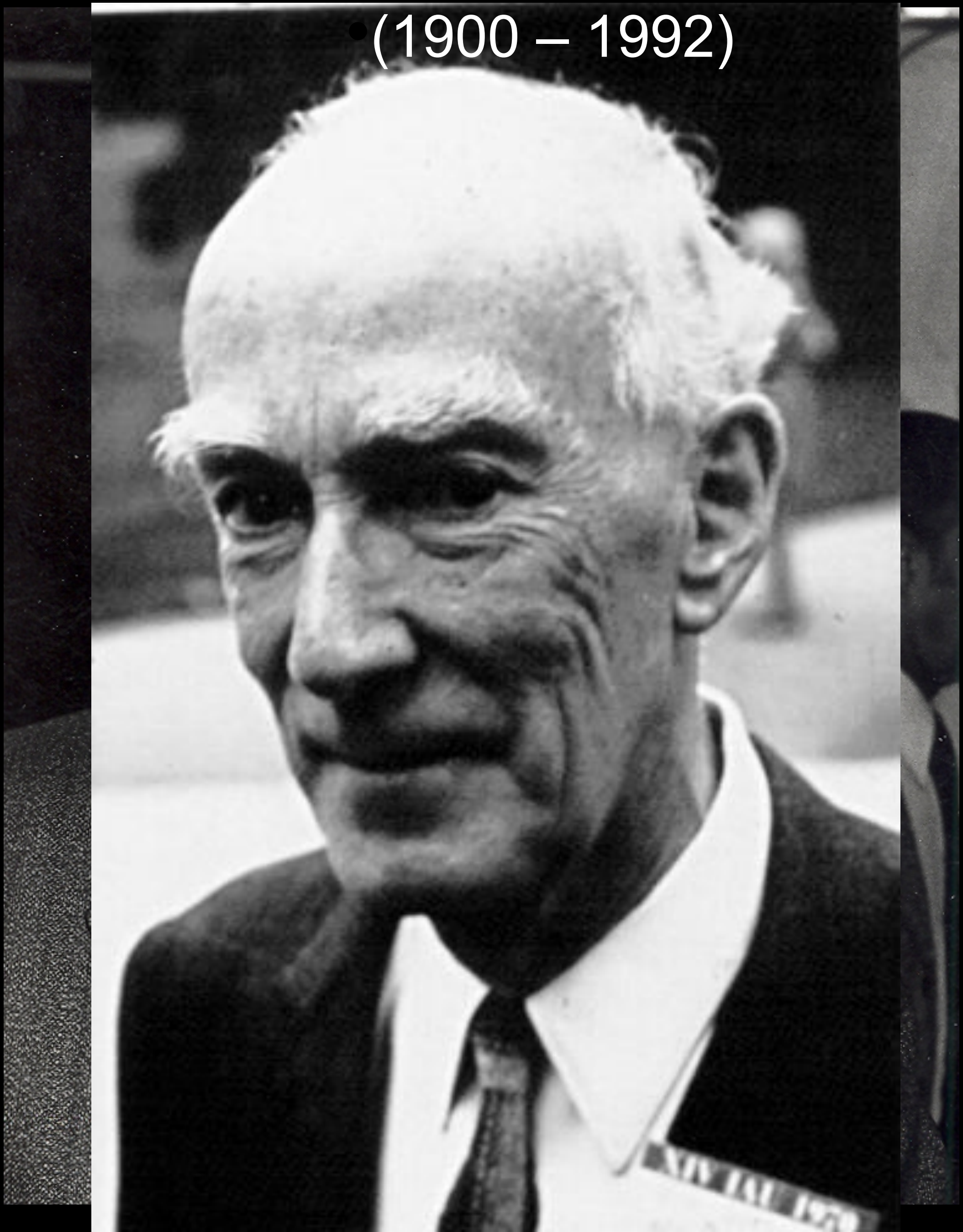
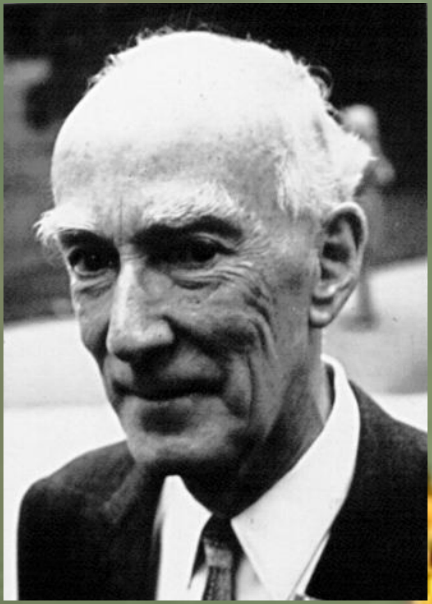
Jan Oort

- (1900 – 1992)



The vicissitudes of the cold dark matter model of cosmogony

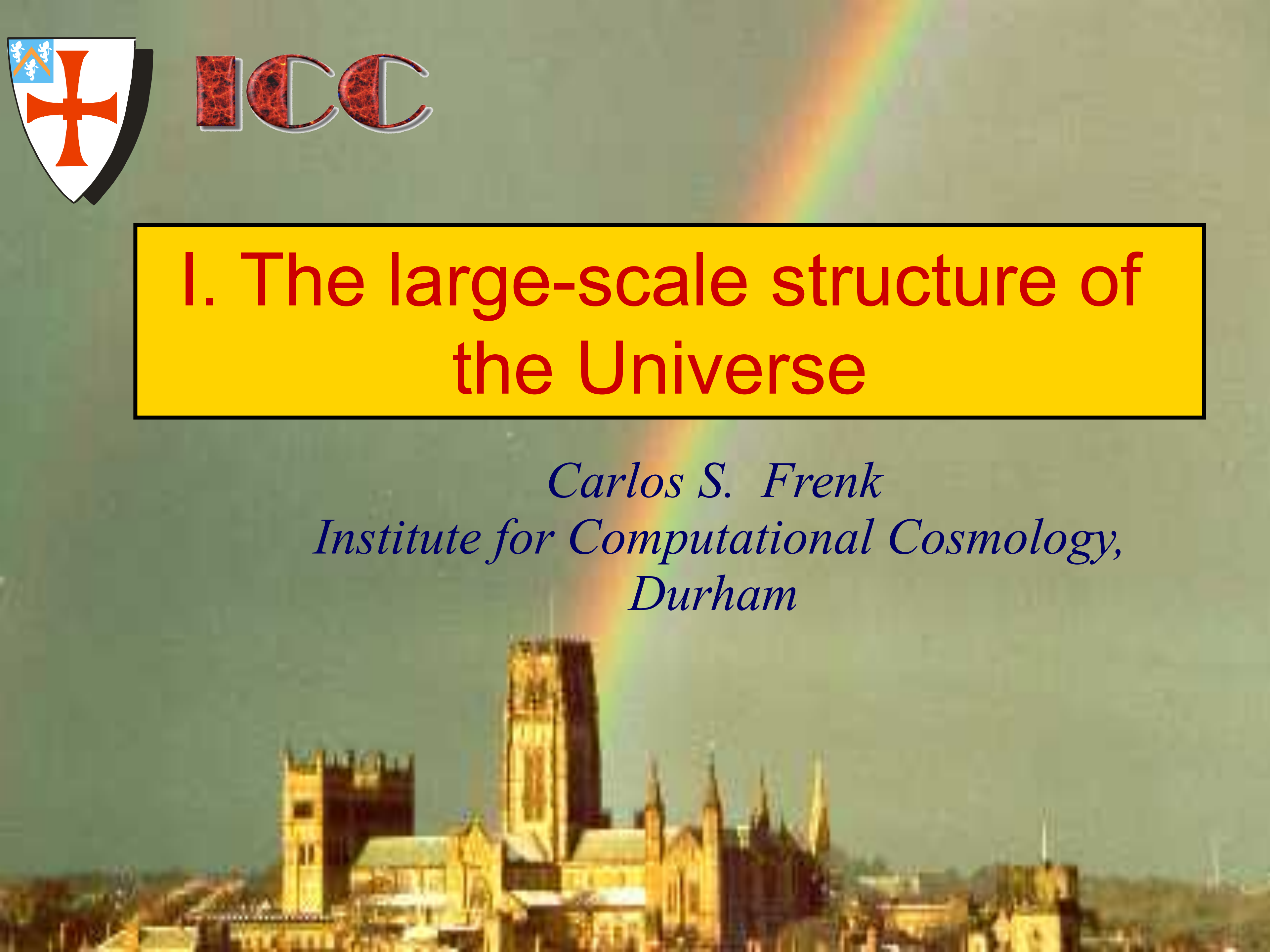


Carlos S. Frenk
Institute for Computational Cosmology,
Durham

I. The large-scale structure of the Universe

Carlos S. Frenk

Institute for Computational Cosmology,
Durham



cold dark matter

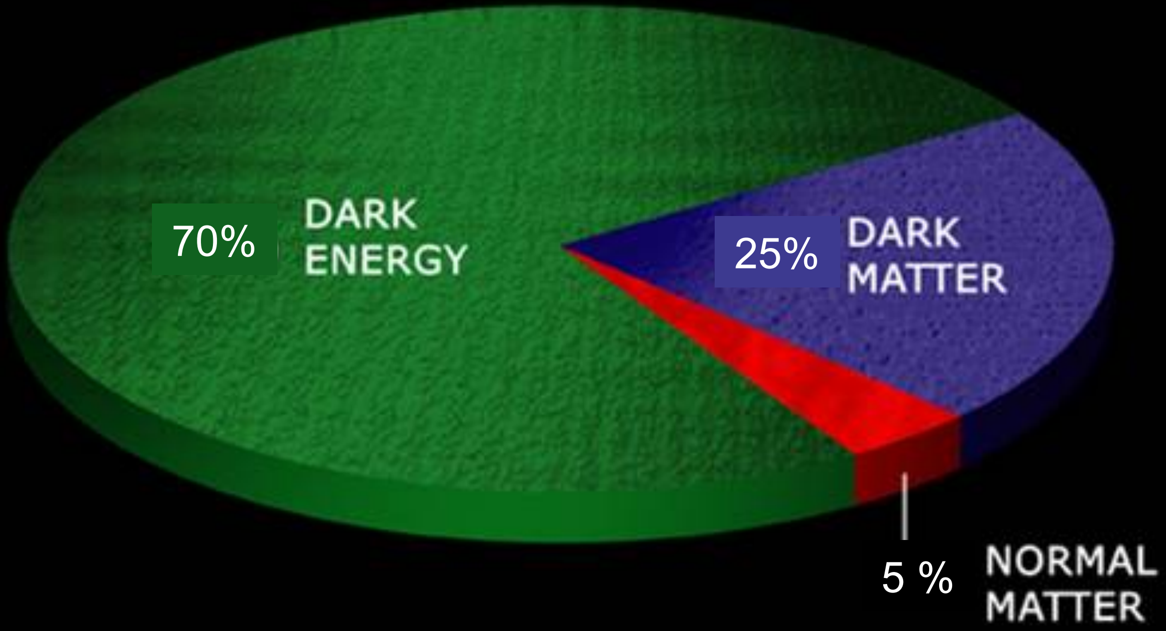
ΛCDM: the standard model of cosmology

cosmological constant

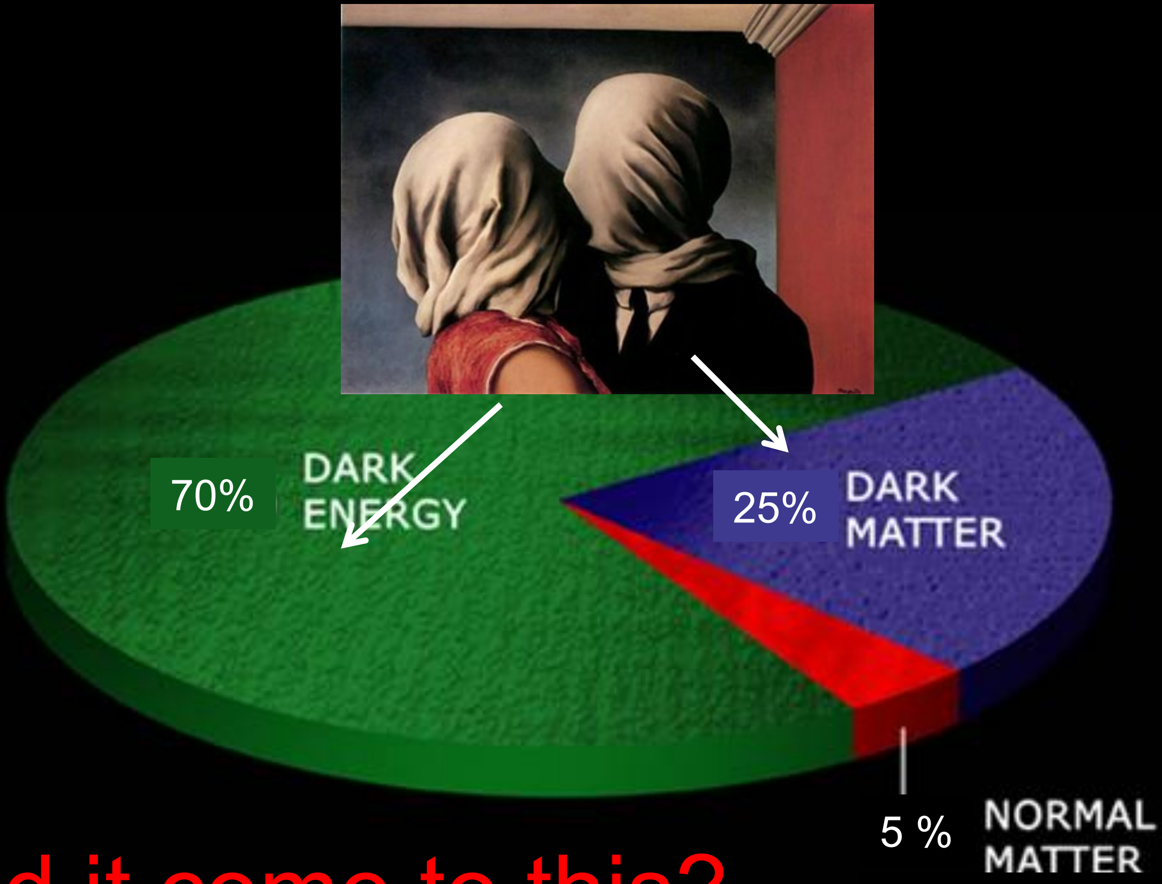
Why is this the standard model; why it is incomplete and what next?

The cold dark matter cosmogony

The CDM model is intrinsically implausible: it requires the universe to be dominated by two unknown constituents: CDM and dark energy.

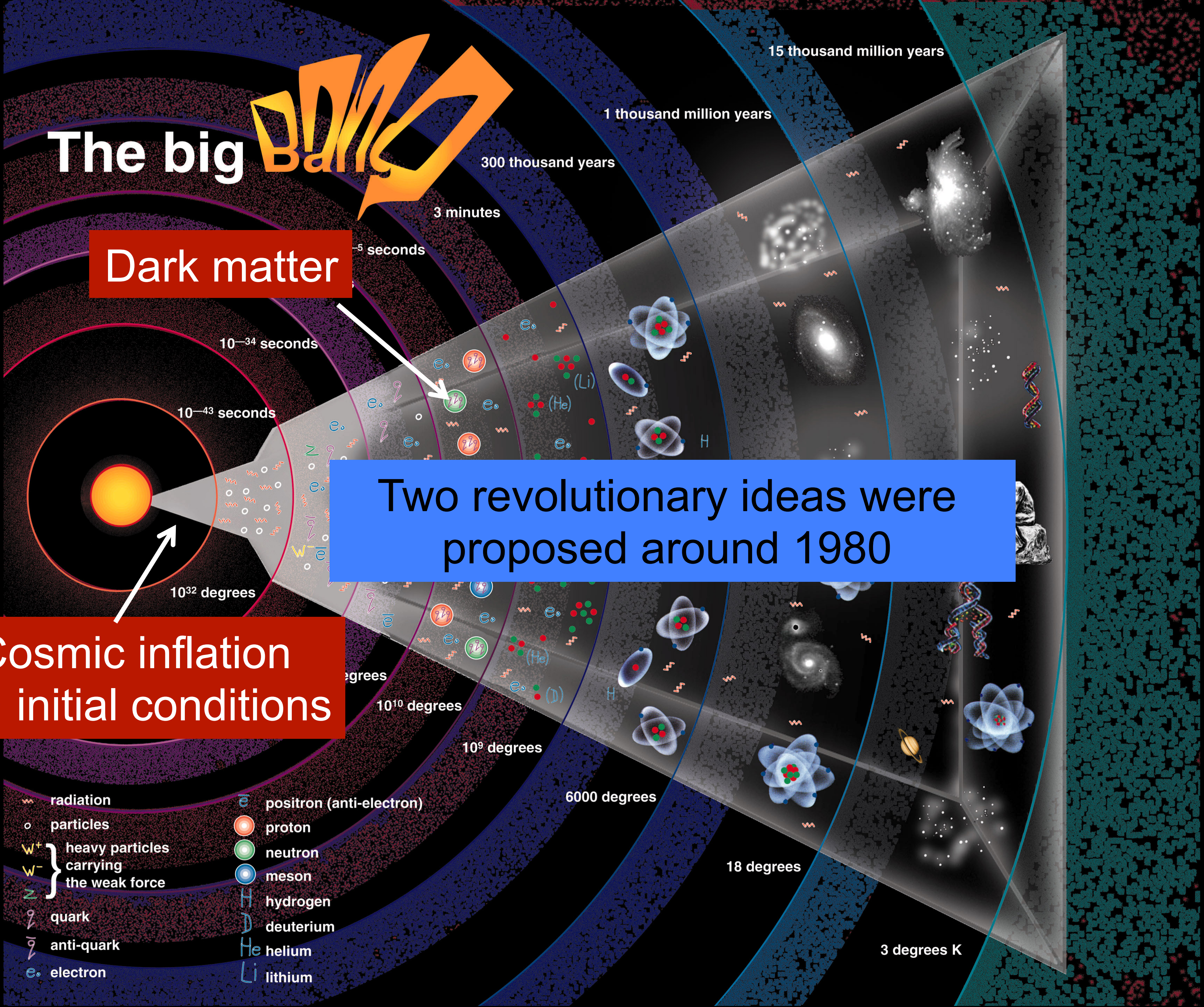


The cold dark matter cosmogony



How did it come to this?

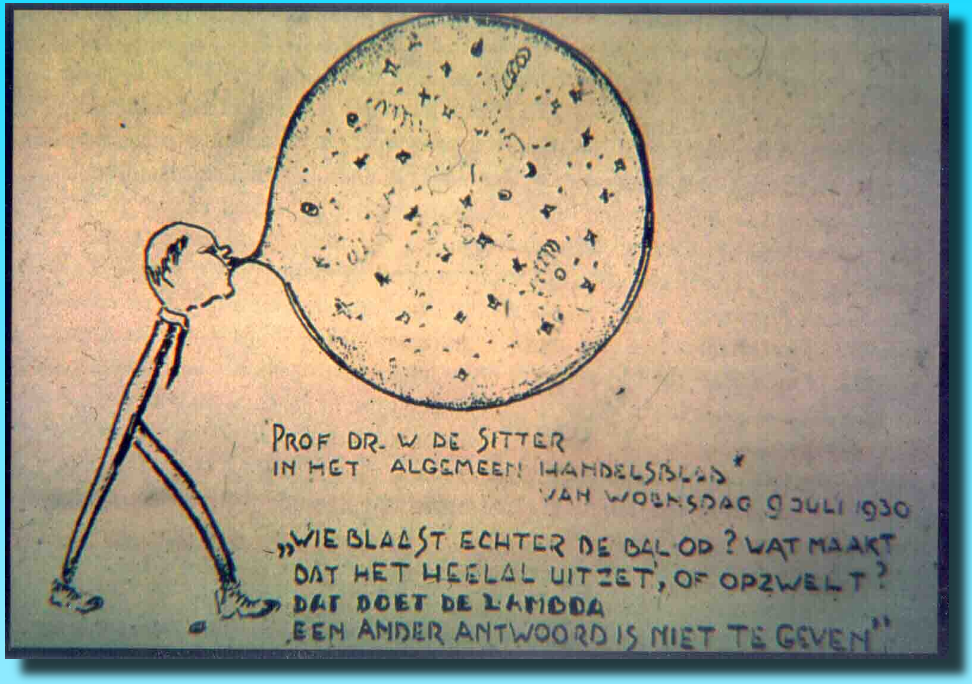
Two revolutionary ideas were proposed around 1980



Dark matter

Cosmic inflation
→ initial conditions

The ΛCDM model

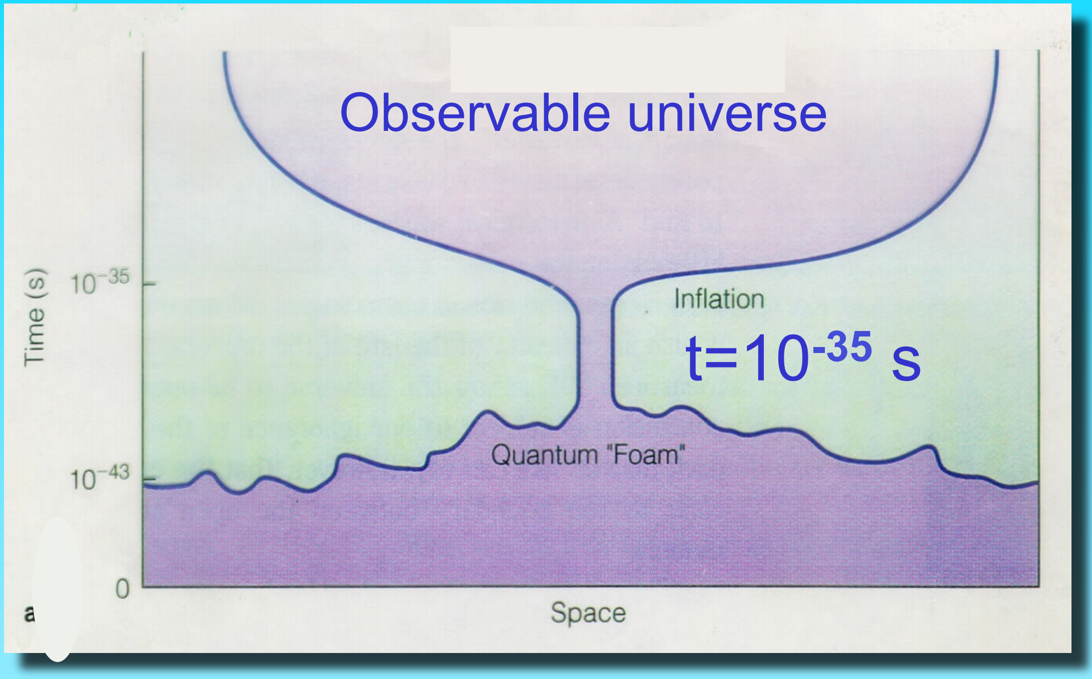


Cosmic inflation: universe started off in unstable state (constant vacuum energy) → expands exponentially fast for a short time

$\Longrightarrow$ Flat geometry: $\Omega = 1$

$$\Omega = \frac{\rho}{\rho_{crit}} \qquad \rho = \rho_{mass} + \rho_{rel} + \rho_{vac}$$

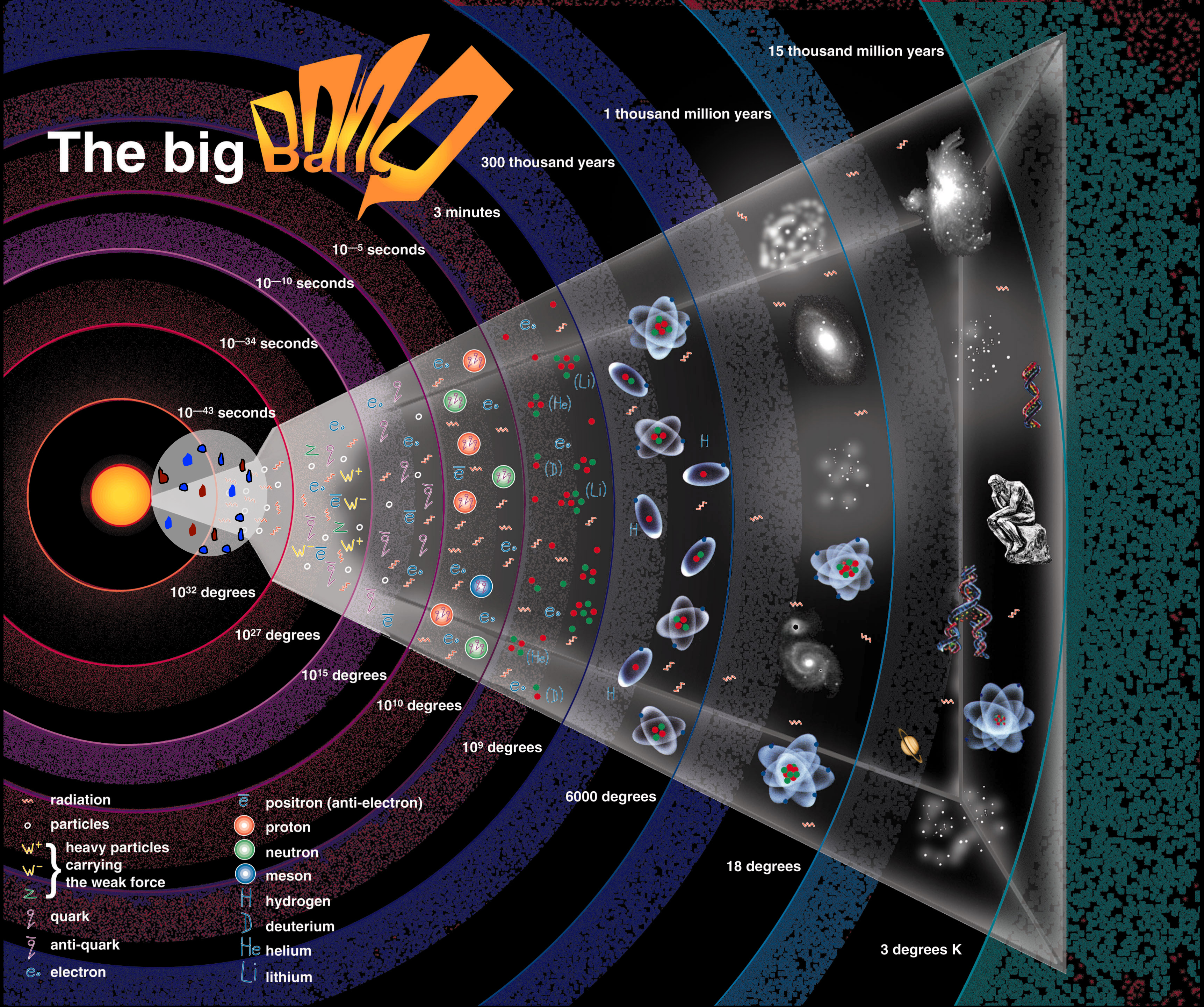
The ΛCDM model



Inflation theory predicts: early universe seeded by tiny fluctuations in mass distribution due to quantum fluctuations

$|\delta_k|^2 \propto k$; Gaussian amplitudes

The big Bang

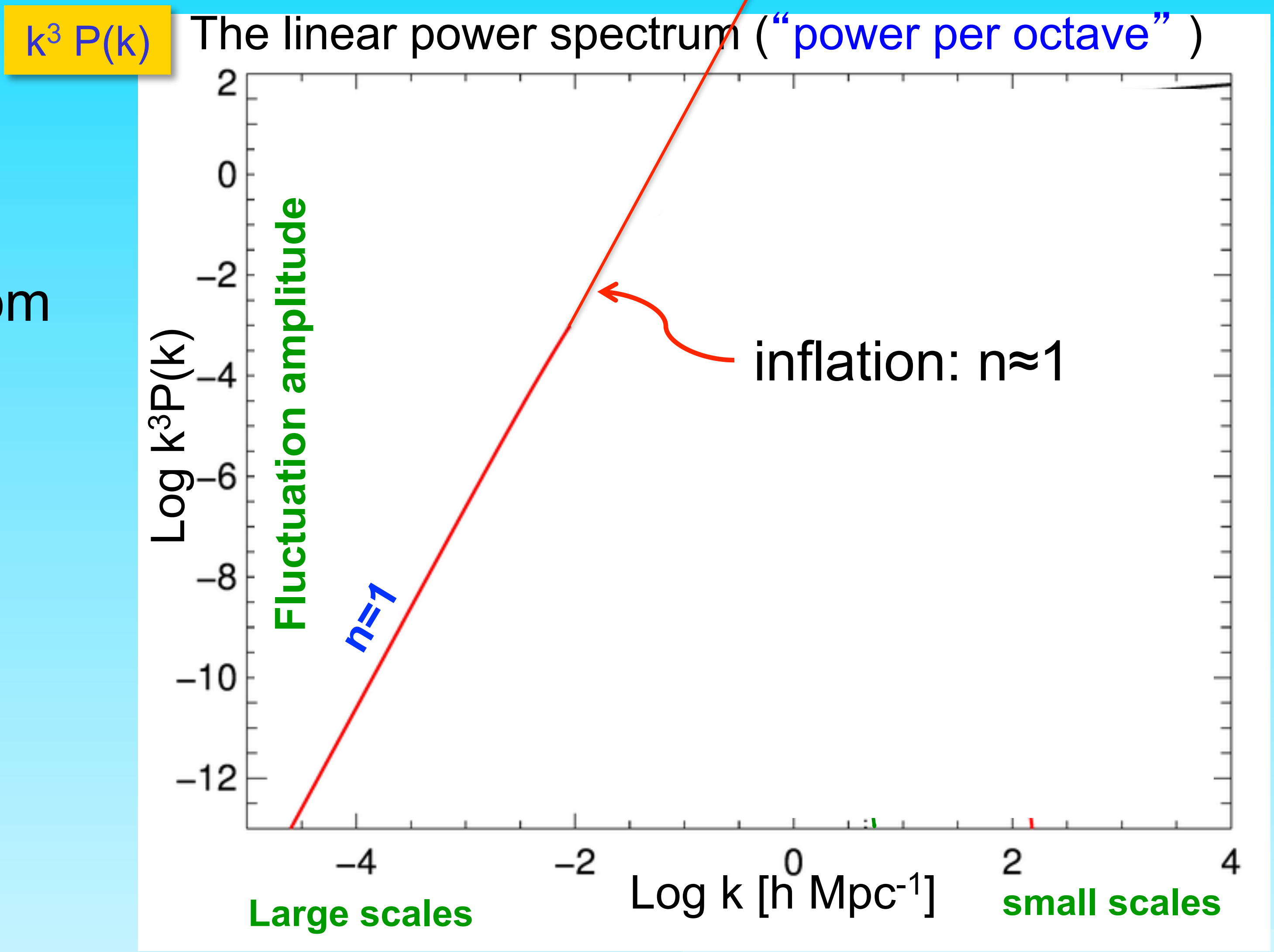


- 〰 radiation
- ○ particles
- W+ W- Z } heavy particles carrying the weak force
- q quark
- q̄ anti-quark
- e electron
- ē positron (anti-electron)
- ● proton
- ● neutron
- ● meson
- H hydrogen
- D deuterium
- He helium
- Li lithium

University of Durham

The dark matter power spectrum

Prediction from inflation



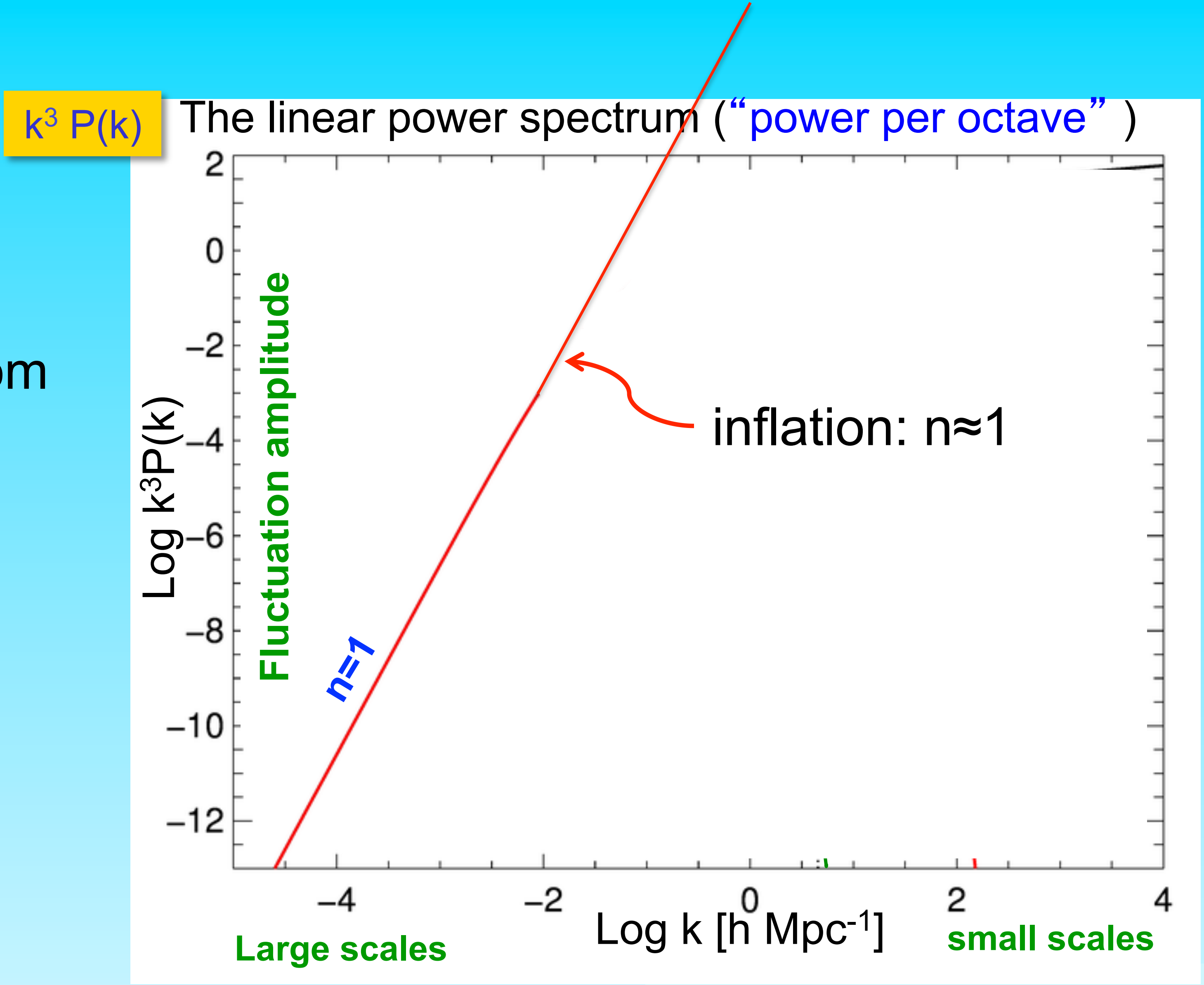
Non-baryonic dark matter candidates

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

University of Durham

The dark matter power spectrum

Prediction from inflation



University of Durham

The dark matter power spectrum

Free streaming →

λ_{cut} α m_x^{-1}

for thermal relic

m_{CDM} ~ 100GeV

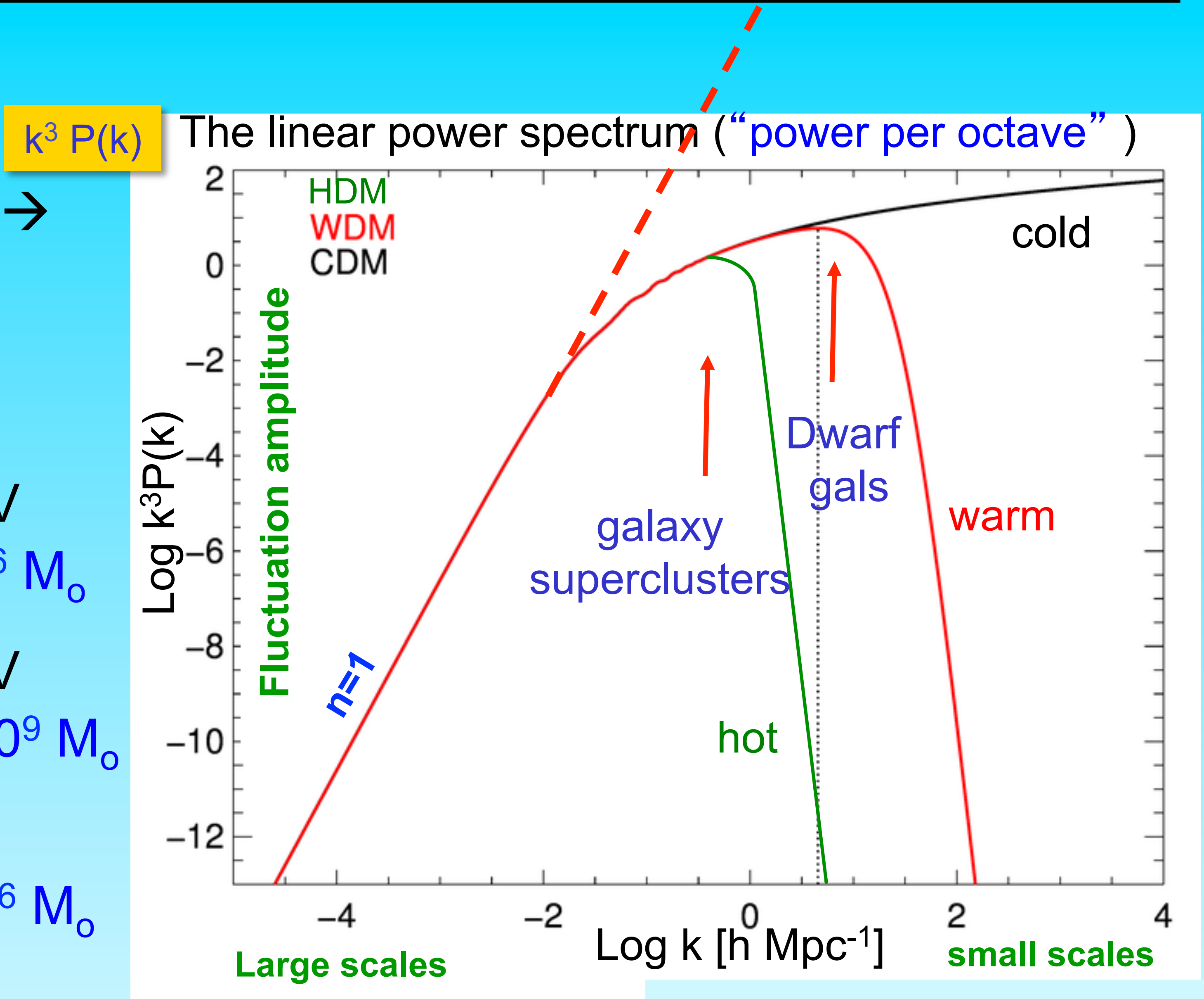
susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV

sterile ν; M_{cut}~10^9 M_o

m_{HDM} ~ few eV

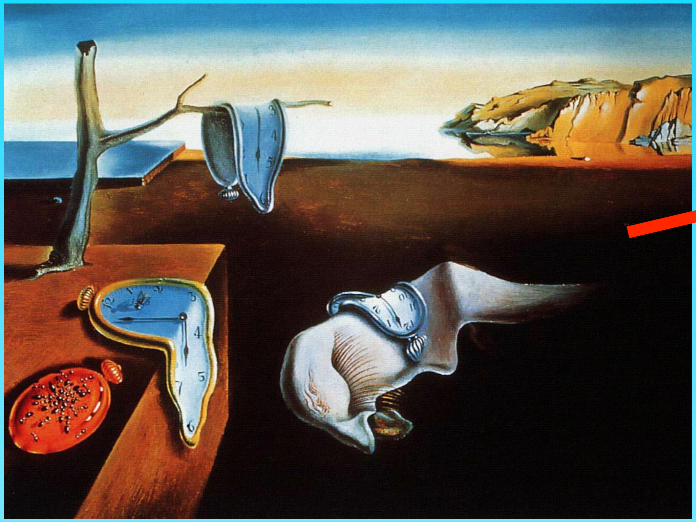
light ν; M_{cut}~10^{16} M_o



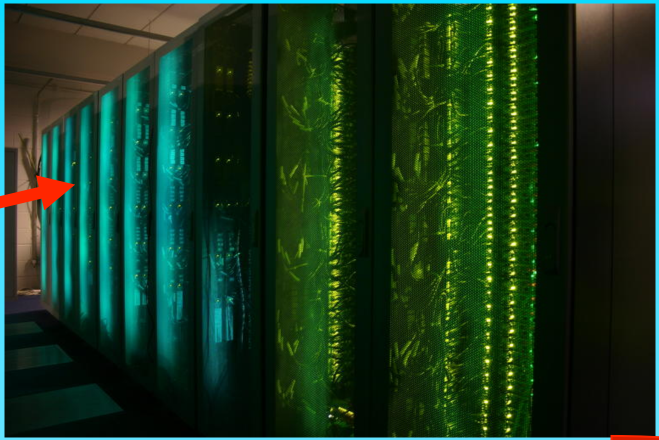
For the first time in Cosmology → a well-defined theory of the initial conditions for the formation of cosmic structure

The formation of cosmic structure

t=10^{-35} seconds



"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

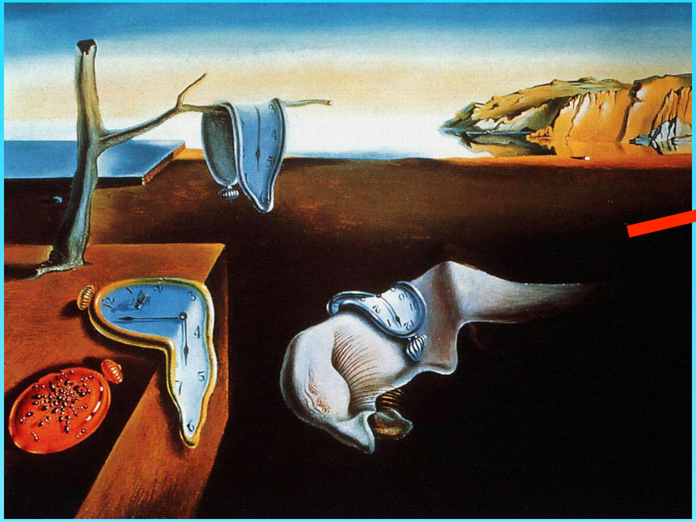
t=13.8 billion yrs

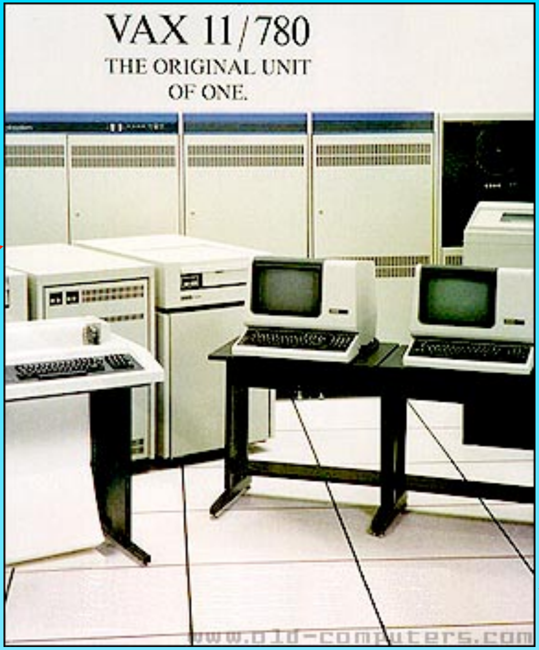
$\delta\rho/\rho \sim 1-10^{6}$

University of Durham

The formation of cosmic structure

$t=10^{-35}$ seconds





$t=380{,}000$ yrs

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

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

$t=13.8$ billion yrs

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

Institute for Computational Cosmology

Non-baryonic dark matter candidates

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

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[illegible] molecule was measured with high precision by a toroidal β-spect[illegible] meter. The results give evidence for a non-zero electron anti- [illegible] 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.

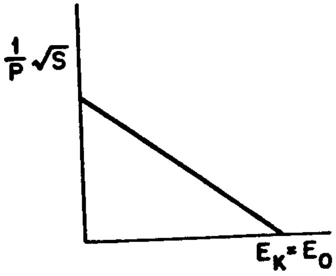


Fig. 1. Kurie plot for $M_\nu = 0$.

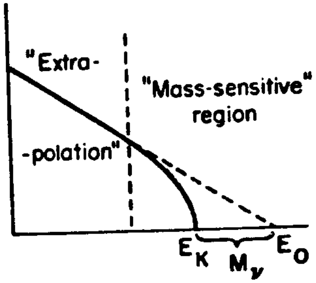
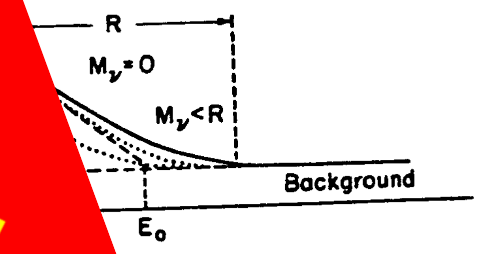


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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.

I[illegible] things are more complicated. The apparatus reso- [illegible]rongly affects the spectrum endpoint and rather [illegible]e spectrum slope.



[illegible]ealistic Kurie plot.

[illegible] extrapolation. However, we are unable [illegible], then once again the lack of counts near the [illegible] indicate that $M_\nu \neq 0$. If $M_\nu \leq R$, the changes due to [illegible]mass and the influence of R are indistinguishable. For M_ν [illegible]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 ∿ M_ν, 2) the smaller M_ν is, the smaller the background (∿ M_ν^2) must be and the higher the statistics (∿ M_ν^{-3}) must be. For example, suppose that for M_ν = 100 eV we need resolution R, background Q, and statistics N. If M_ν = 30 eV, to achieve the same ΔM/M they should be R/3, Q/10, and N × 30, respectively.

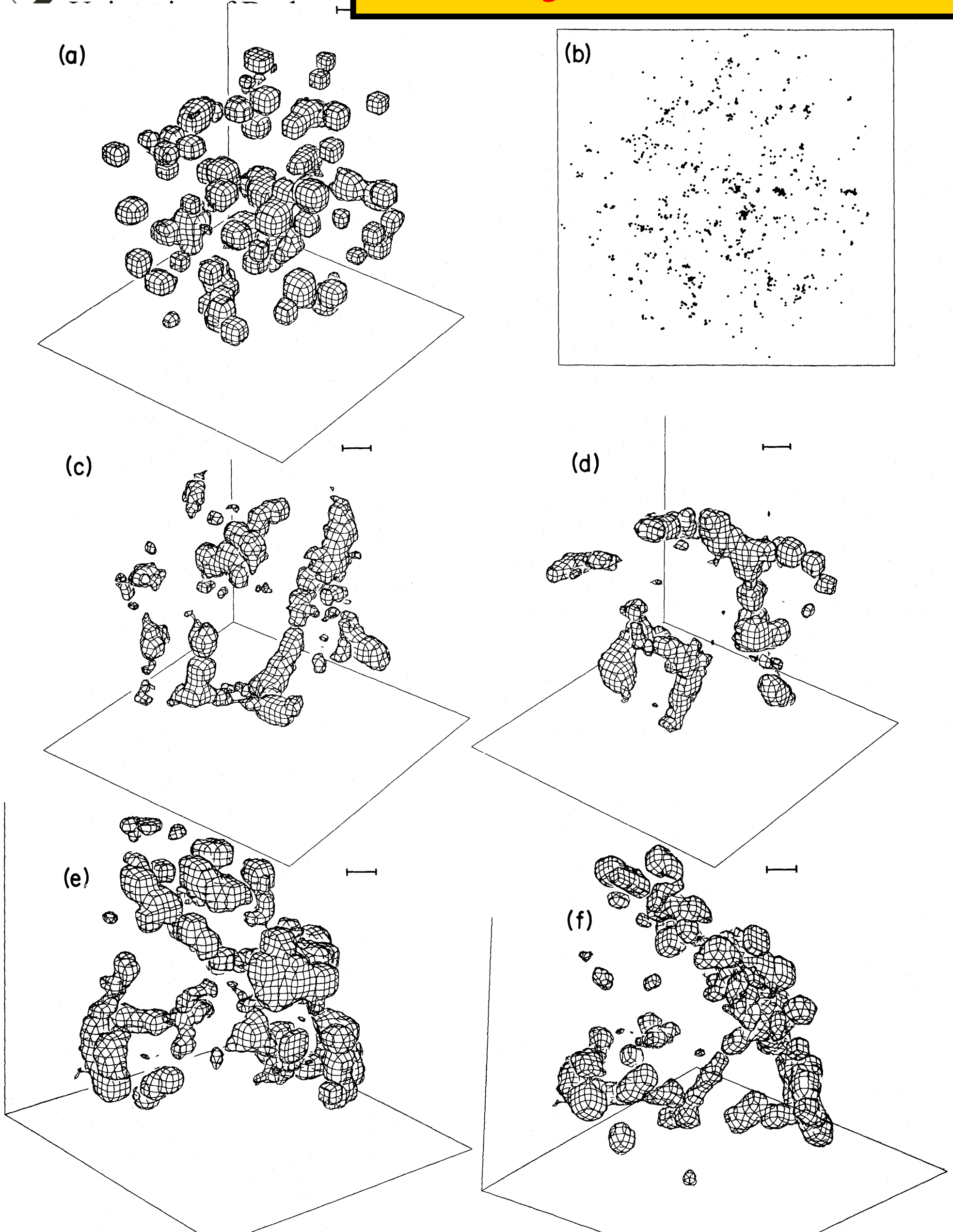
The shorter the β-spectrum, the less it is spread due to R (as R ∿ Δp/p = const.). A classical example is ^3H β-decay, which has 1) the smallest E_0 ∿ 18.6 keV, 2) an allowed β-transition, simple nucleus, and simple theoretical interpretation, 3) highly reduced radioactivity. The first experiments with ^3H were by S. Curran et al. (1948) and G. Hanna, B. Pontecorvo (1949). Using ^3H gas in a proportional counter, they obtained $M_\nu \leq$ 1 keV. Further progress required magnetic spectrometer development. This allowed the 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 ∿ 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.

---

*Paper presented by Oleg Egorov.

Early cosmological simulations



“Poisson” models (n=0)

“Pancake” models (neutrinos)

CfA redshift survey

Ann. Rev. Astron. Astrophys. 1983. 21: 373–428

SUPERCLUSTERS

J. H. Oort

Sterrewacht Leiden, Leiden, The Netherlands

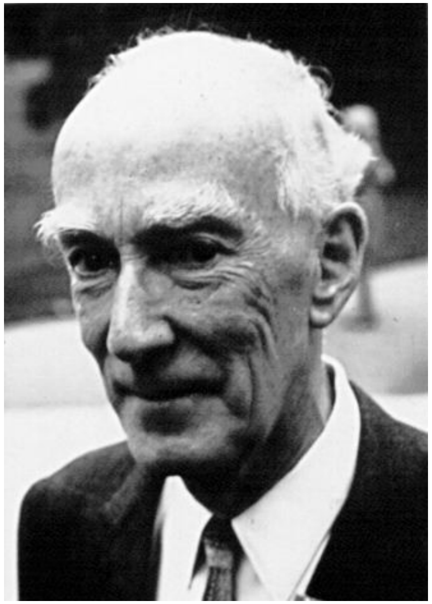
1. INTRODUCTION

The distribution of galaxies is clumpy on all scales, ranging from binaries, triples, and multiples, through groups containing between a few and a hundred galaxies, to rich clusters with thousands of members, masses up to $10^{15\pm1} M_{\odot}$, and diameters of the order of 10 Mpc. The latter have been discussed by Neta A. Bahcall (5) in a preceding volume of this series. The clusters are at the end of the scale of the more or less regular structures in the Universe.

10. ORIGIN

10.1 *Introduction; Adiabatic vs Isothermal Fluctuations*

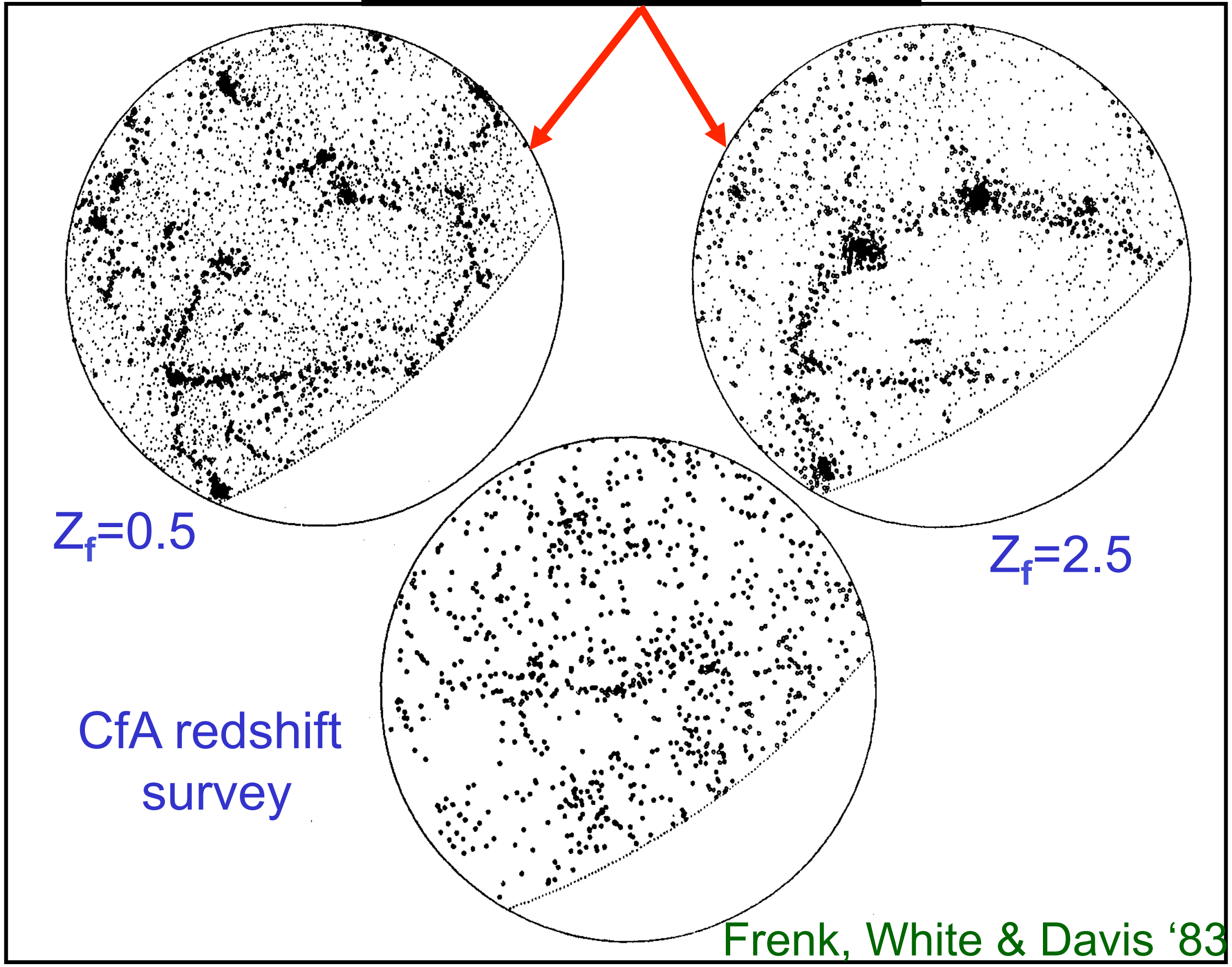
The central problem is the nature of the primeval density perturbations that formed the galaxies, clusters, and superclusters. Were they fluctuations in space curvature, in which radiation and matter were perturbed together (called "adiabatic"), or was only the matter density perturbed, the radiation remaining nearly homogeneous (therefore "isothermal")? The adiabatic model is favored by theoreticians, but in the present state of knowledge



An interesting experiment was carried out by Frenk et al. (36). They made multiparticle simulations with large cutoff lengths for the initial perturbations, mimicking the adiabatic ("pancake") theory. By choosing an appropriate cutoff length, they obtained final distributions that closely resemble observed supercluster structures. For details, see the original article.

Neutrino (hot) dark matter

Ω_ν=1 (m_ν = 30 ev)



Frenk, White & Davis '83

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

⇨

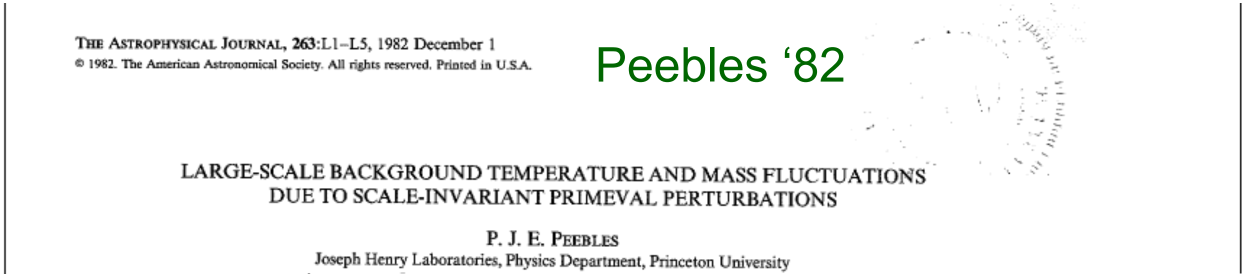
Neutrinos cannot make an appreciable contribution to Ω and m_ν<< 10 ev

Non-baryonic dark matter candidates

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

The cold dark matter cosmogony

Peebles '82



THE ASTROPHYSICAL JOURNAL, 263:L1–L5, 1982 December 1
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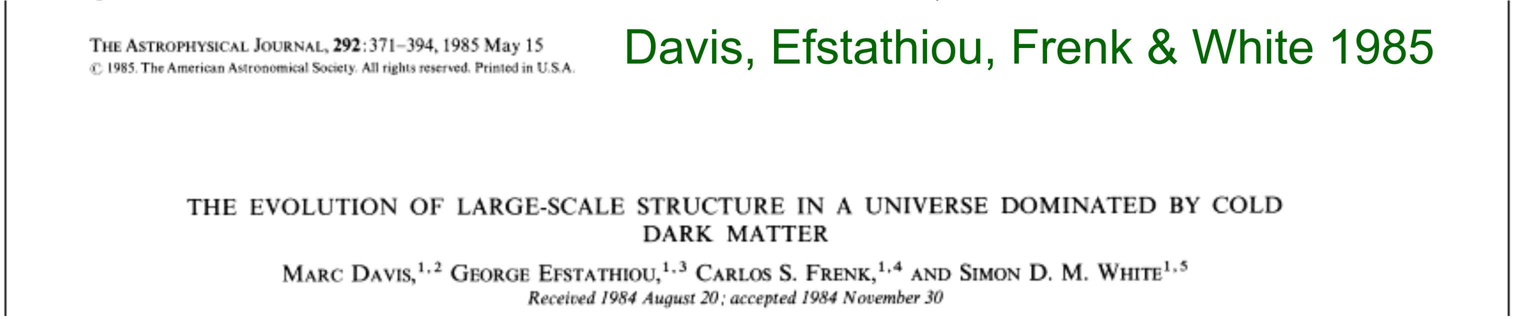
LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University

Davis, Efstathiou, Frenk & White 1985



THE ASTROPHYSICAL JOURNAL, 292:371–394, 1985 May 15
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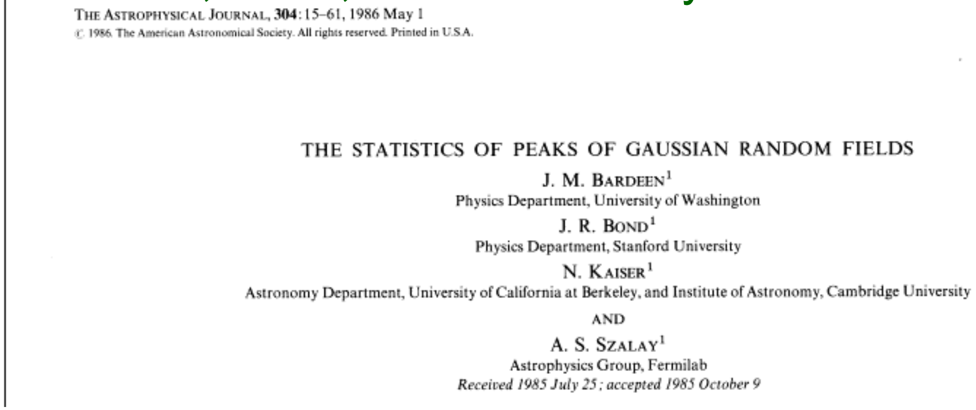
THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

MARC DAVIS,[1,2] GEORGE EFSTATHIOU,[1,3] CARLOS S. FRENK,[1,4] AND SIMON D. M. WHITE[1,5]
Received 1984 August 20; accepted 1984 November 30

Bardeen, Bond, Kaiser & Szalay 1986



THE ASTROPHYSICAL JOURNAL, 304:15–61, 1986 May 1
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THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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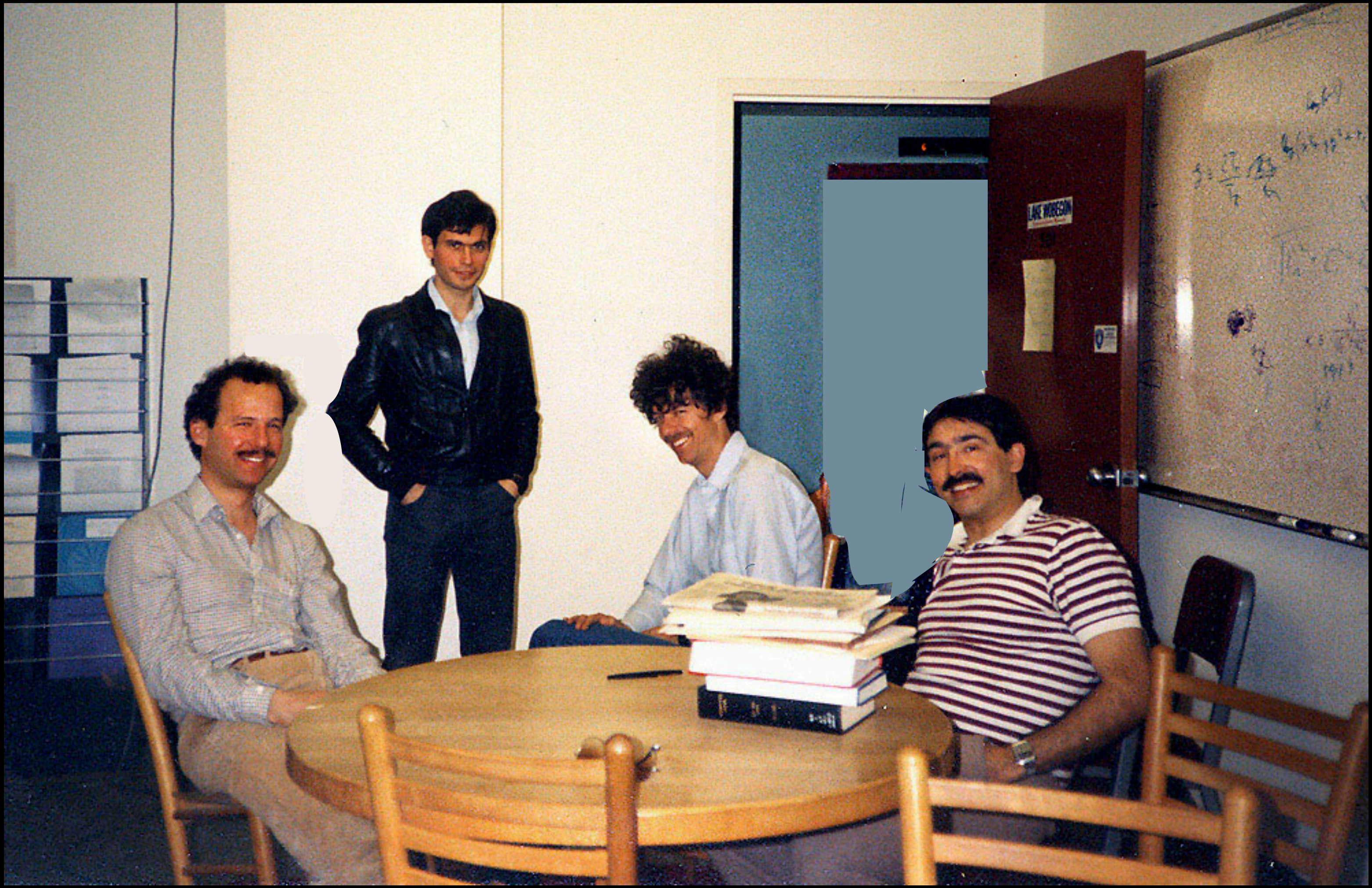
Physics Department, University of Washington
J. R. BOND[1]
Physics Department, Stanford University
N. KAISER[1]
Astronomy Department, University of California at Berkeley, and Institute of Astronomy, Cambridge University
AND
A. S. SZALAY[1]
Astrophysics Group, Fermilab
Received 1985 July 25; accepted 1985 October 9

The `Gang of Four' - 1983



University of Durham

Non-baryonic dark matter cosmologies

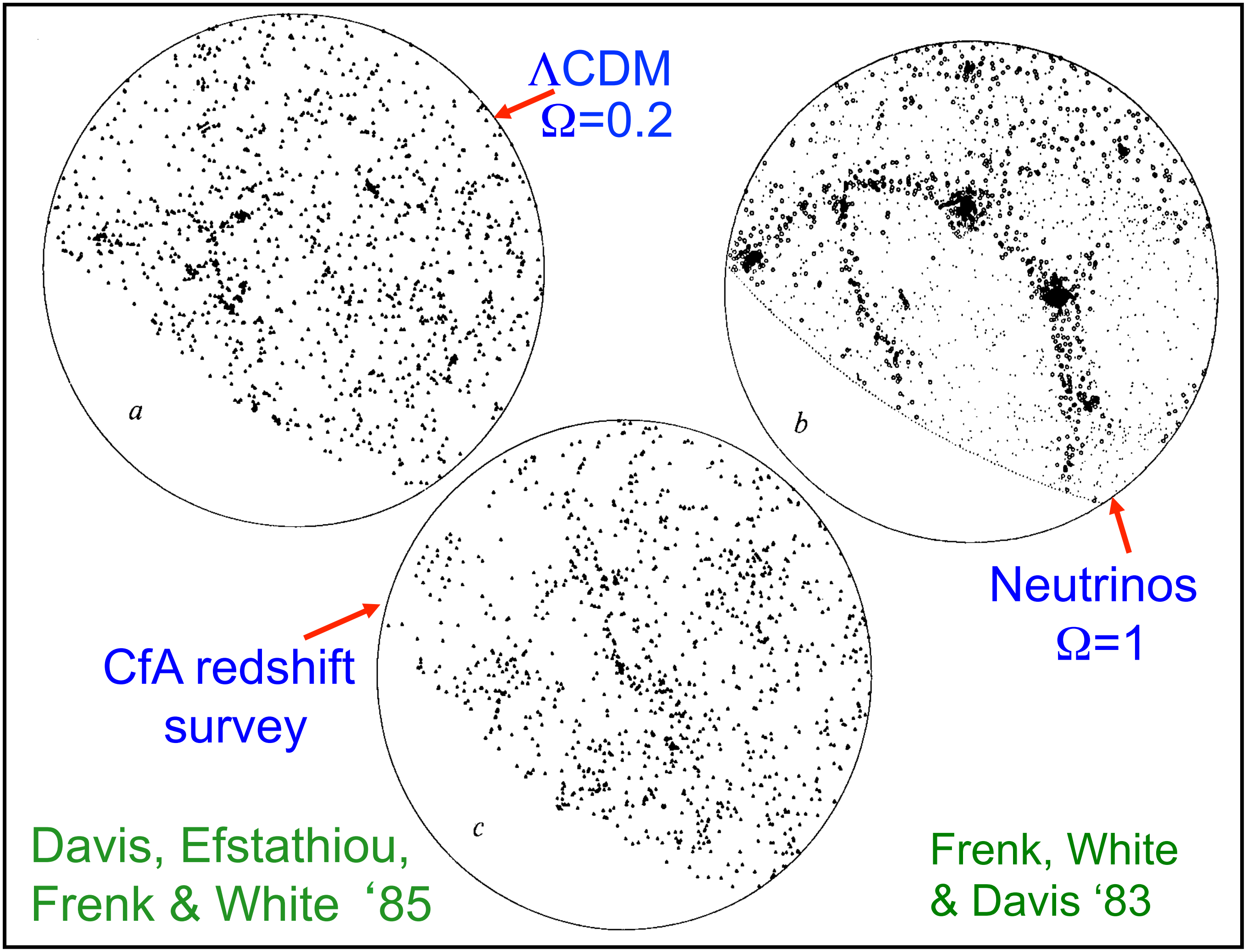
Neutrino DM → unrealistic clust’ ing

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 10 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



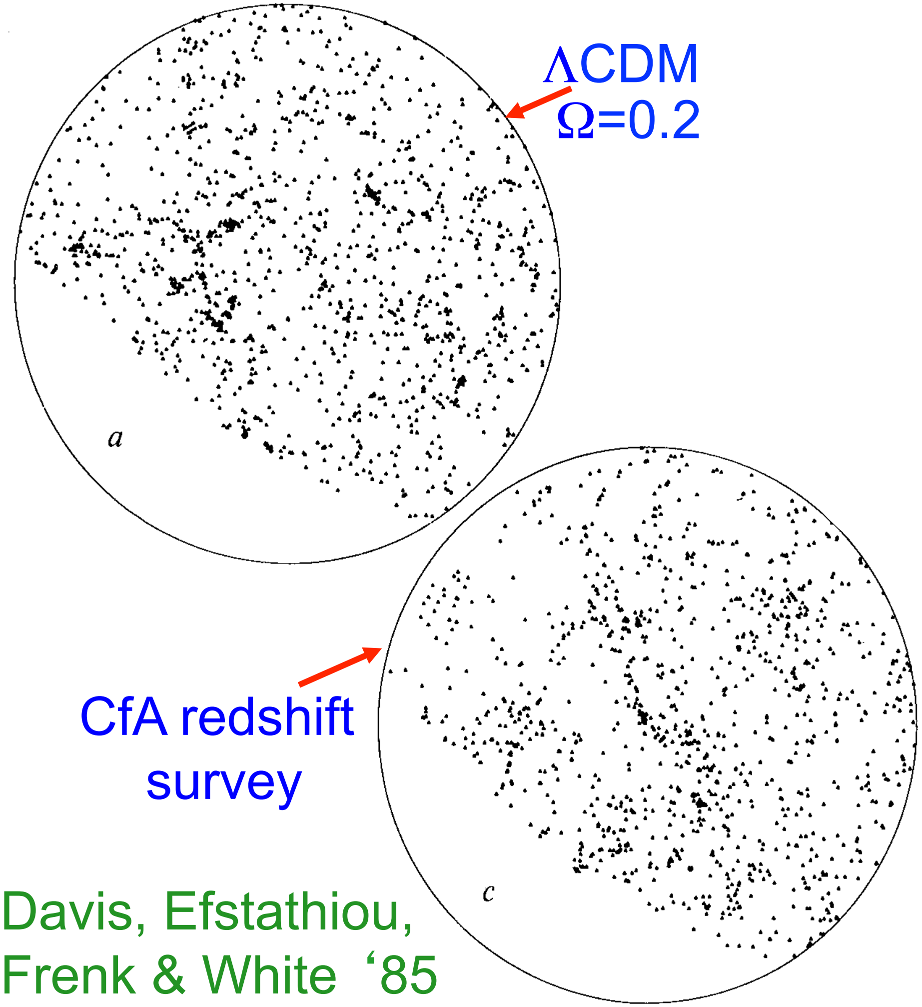
Davis, Efstathiou, Frenk & White ‘85

Frenk, White & Davis ‘83

Institute for Computational Cosmology

Non-baryonic dark matter cosmologies

Λ was inconceivable in 1985



ΛCDM
Ω=0.2

CfA redshift survey

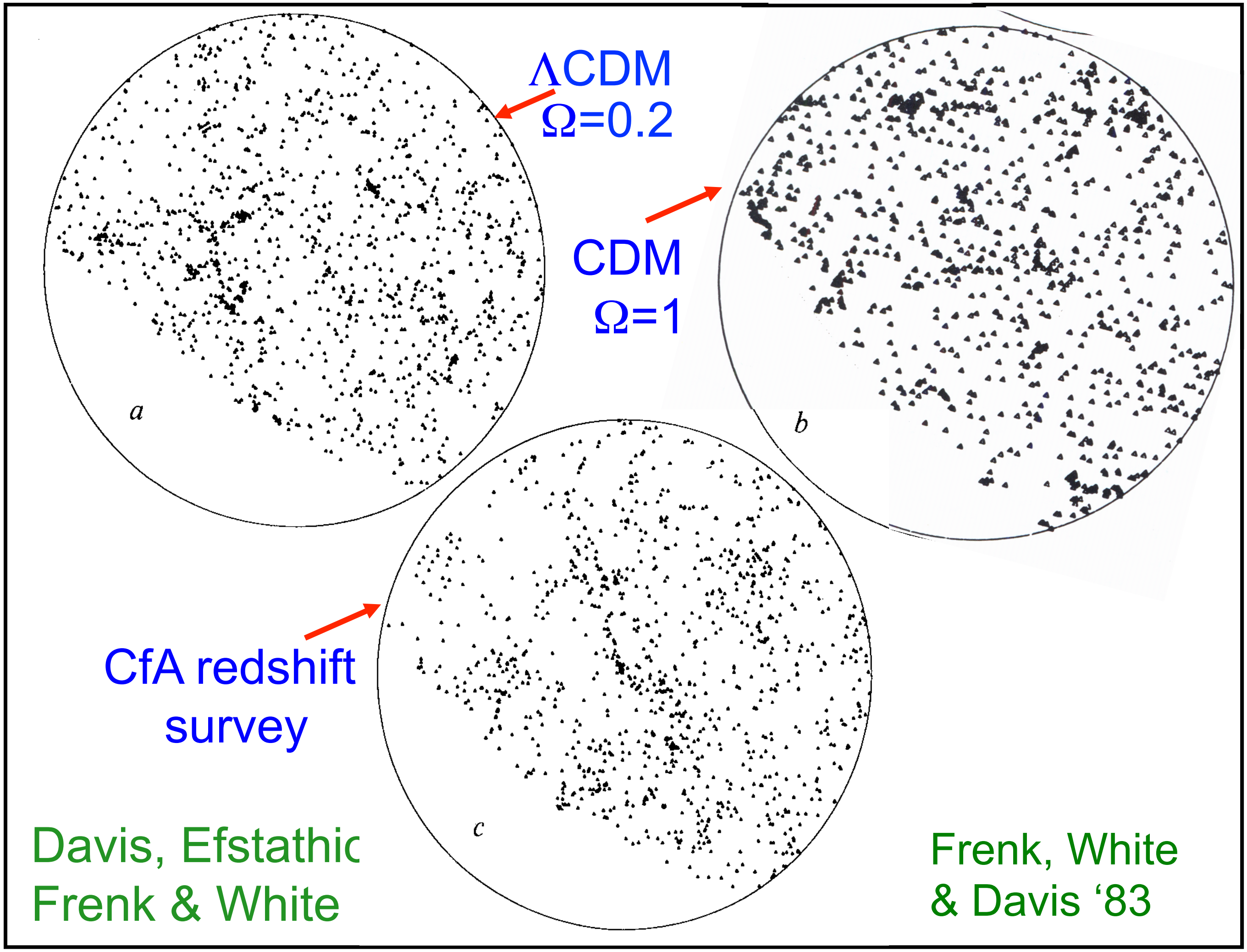
Davis, Efstathiou, Frenk & White ‘85

Frenk, White & Davis ‘83

Non-baryonic dark matter cosmologies

Λ was inconceivable in 1985

How can we make Ω=1 give acceptable clustering?



ΛCDM
Ω=0.2

CDM
Ω=1

CfA redshift survey

Davis, Efstathic
Frenk & White

Frenk, White
& Davis ‘83

Ω = 1 CDM

DEFW '85

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

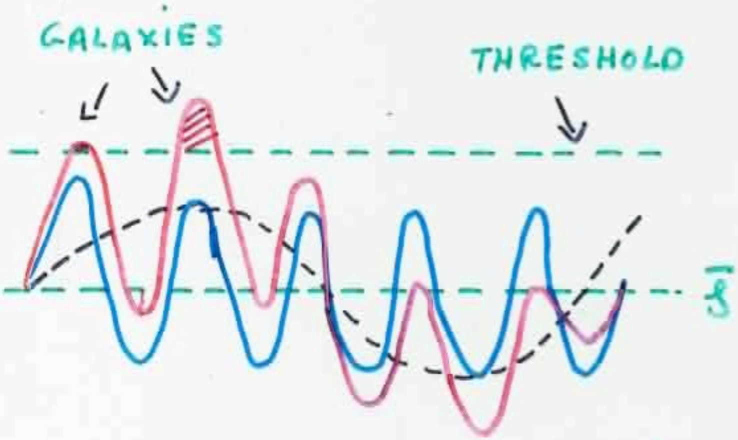
Dark matter

$\Omega_{TOT} = 1$ POSSIBLE ONLY IF MASS IS SMOOTHER THAN GALS

HOW? A SIMPLE BIASING SCHEME:

"Biased galaxy formation"

(after Kaiser '84)



GALAXIES FOLLOW OVERALL CLUSTERING PATTERN OF DM BUT WITH GREATLY ENHANCED AMPLITUDE.

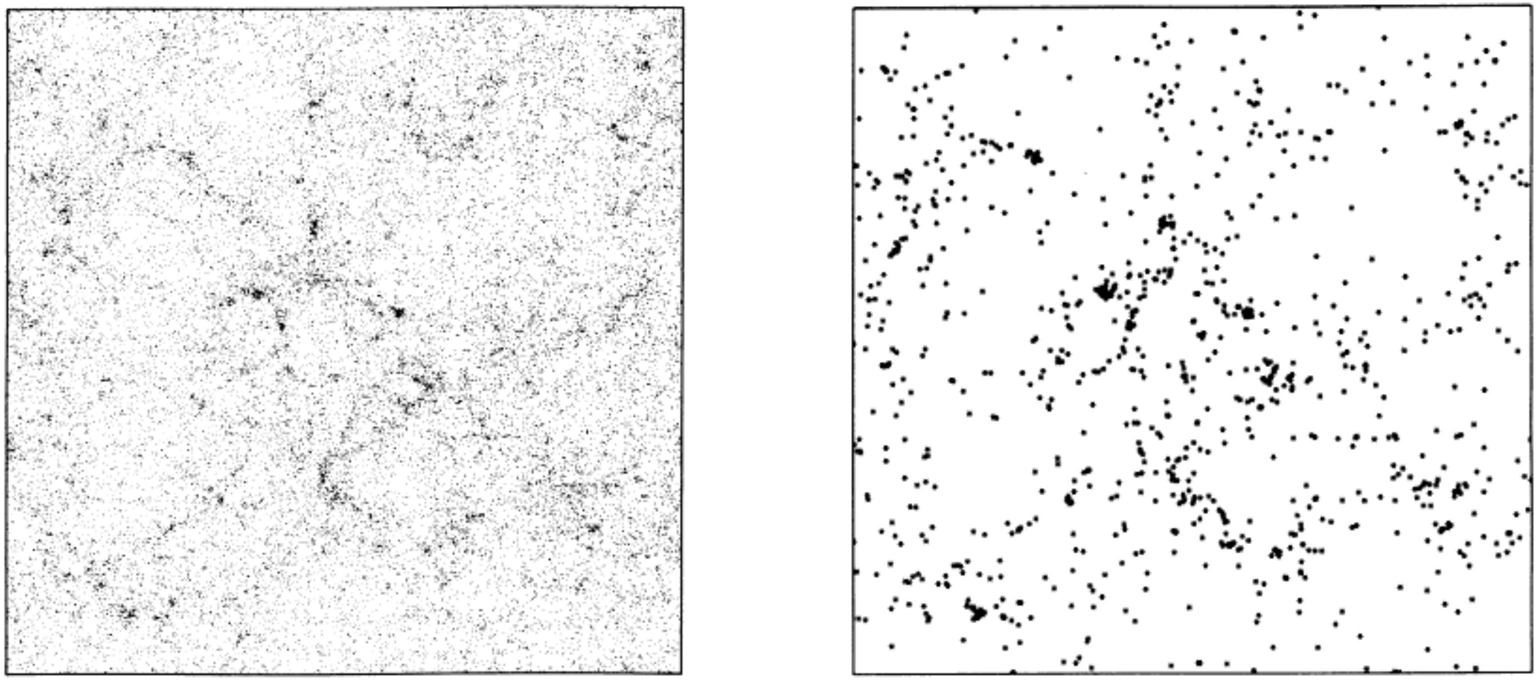
PROCESS DESCRIBED BY 2 PARA

r_s = WIDTH OF MODULATING LOW PASS FILTER

ν = THRESHOLD HEIGHT FOR GAL. FORMAN.

Biased galaxy formation

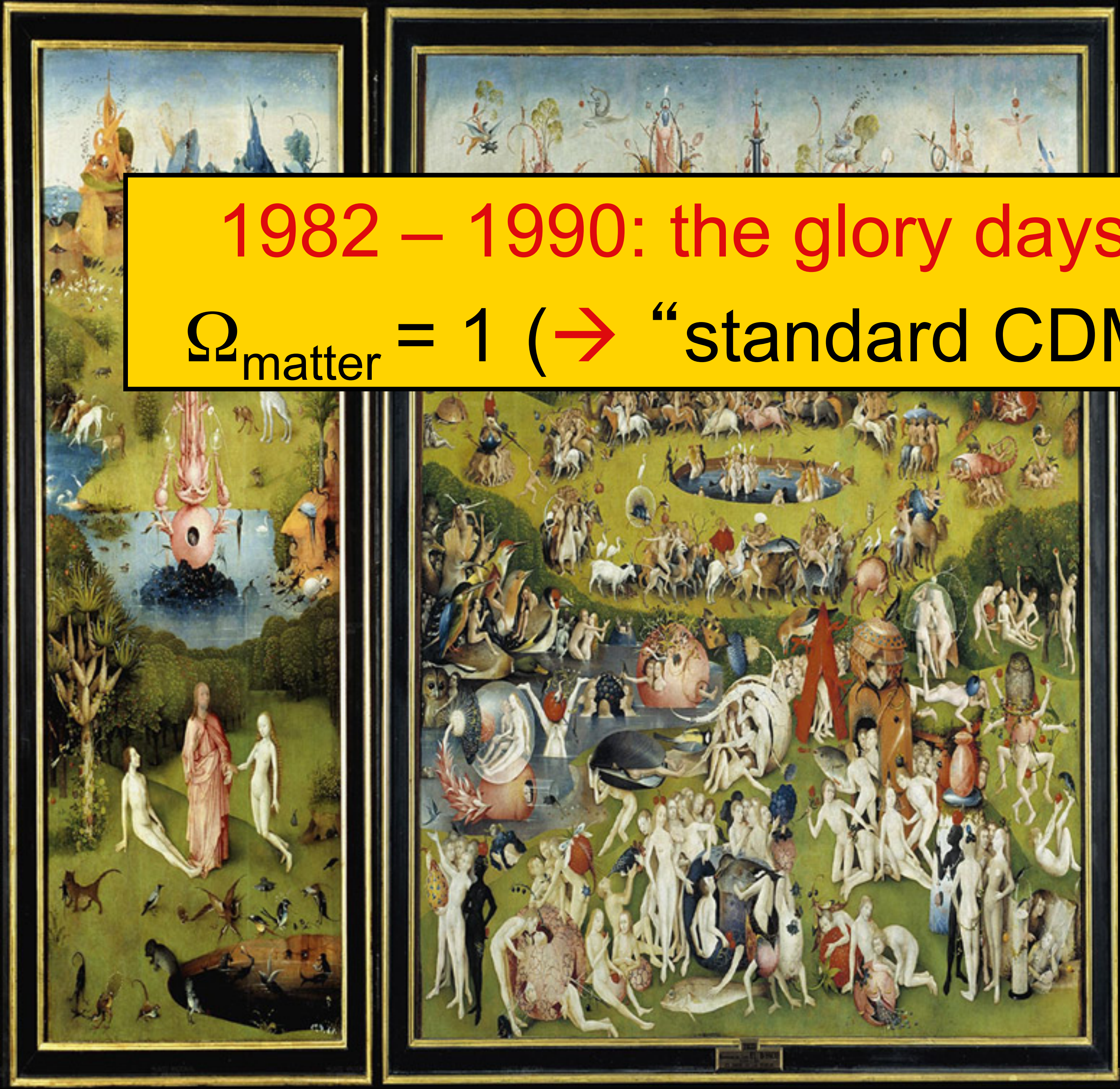
… or how to rescue $\Omega=1$! DEFW '85



Gals→ peaks of density field

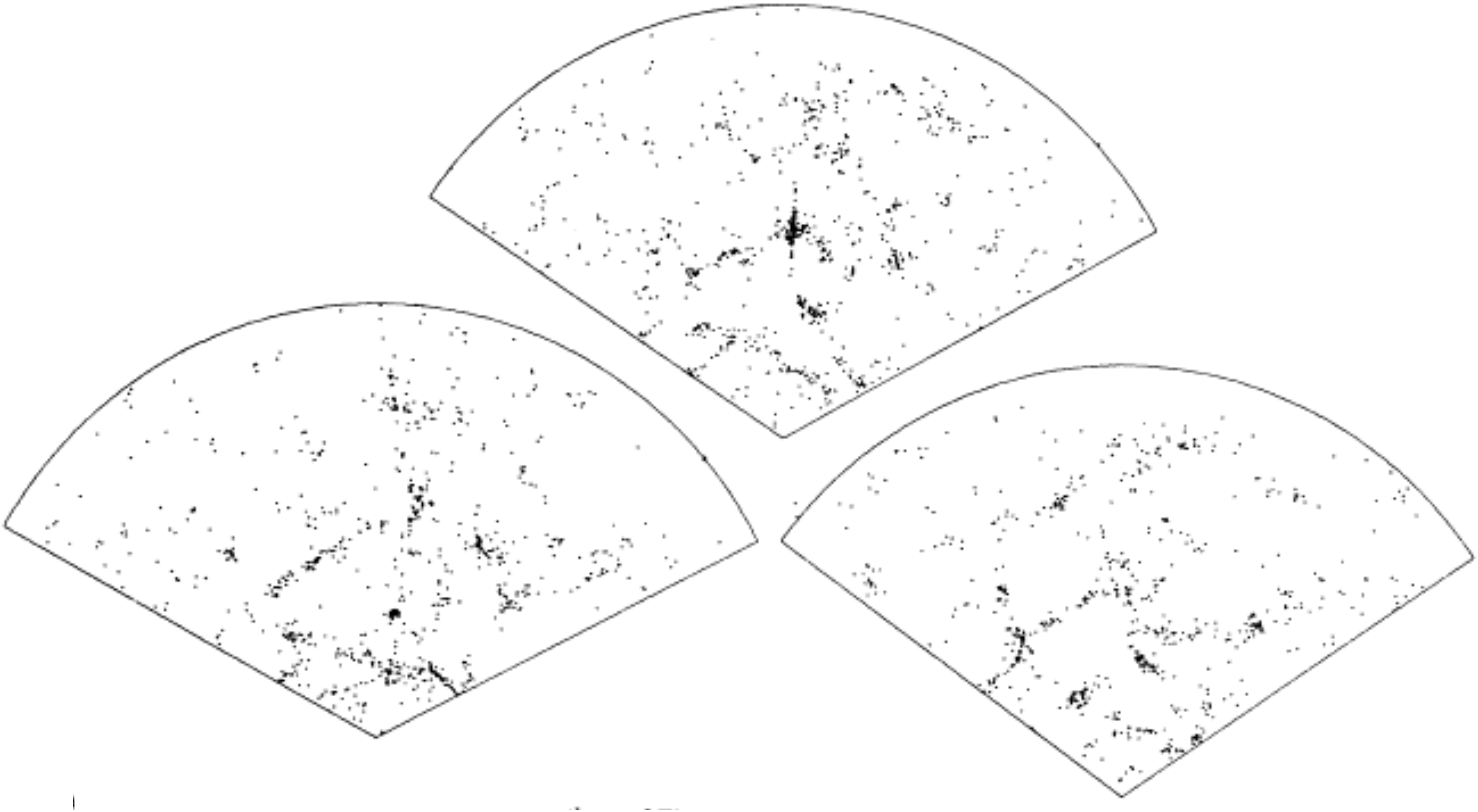
FIG. 16.—The projected distribution of all particles (*left*) and of the "galaxies" (*right*) in EdS1 at $a = 1.4$. The side of the box is $32.5h^{-1}$ Mpc. "Galaxies" are assumed to form only at the 2.5 σ peaks of the linear density distribution.

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



art-wallpaper.org

SCDM compared to CfA-2 z-survey



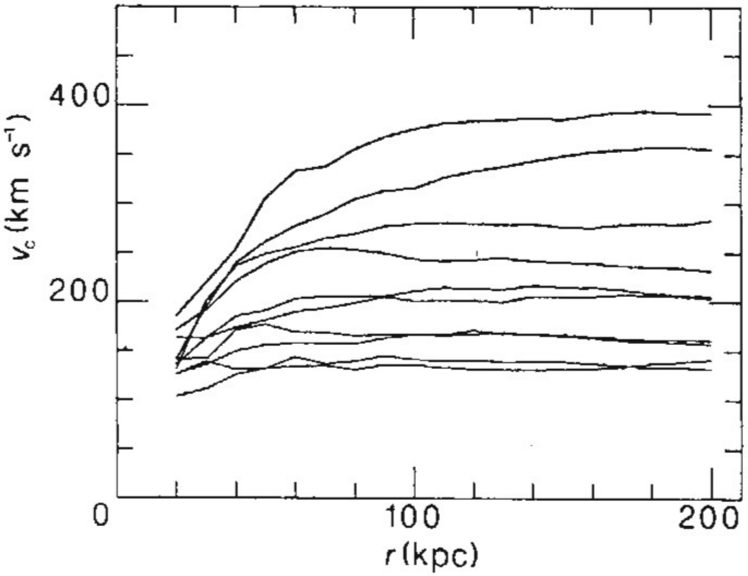
White, Frenk, Davis, Efstathiou ‘87

NATURE VOL. 317 17 OCTOBER 1985 — LETTERS TO NATURE

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.

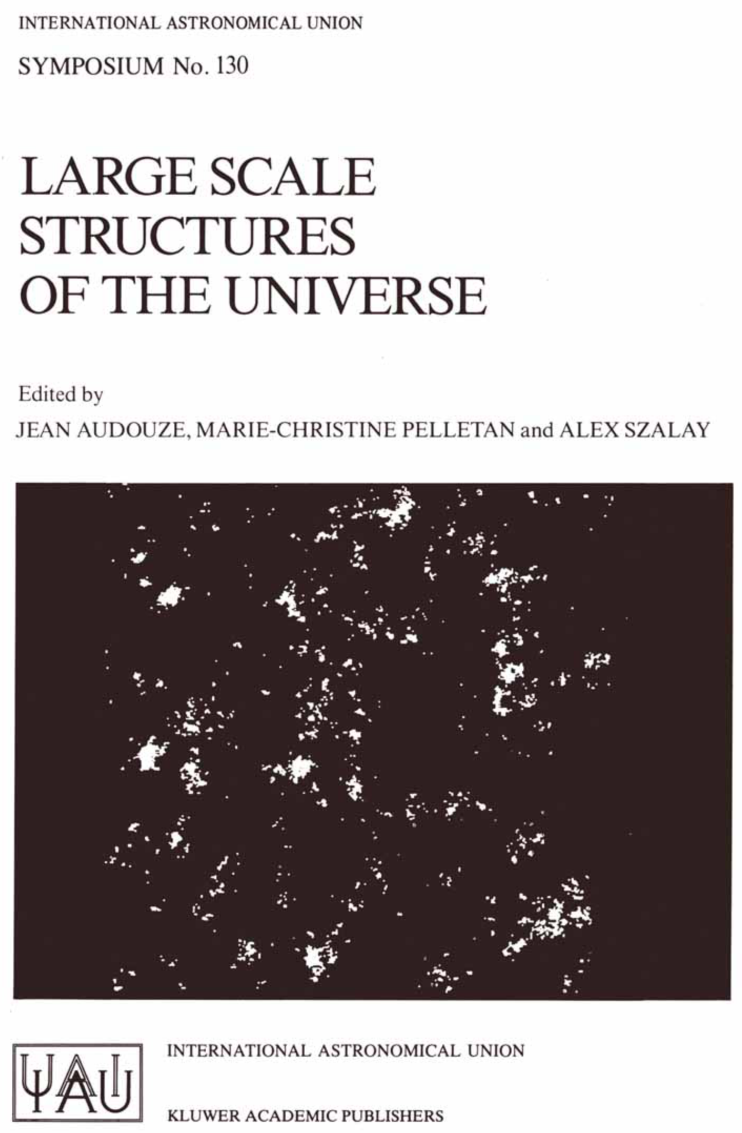


Balatonfured: East meets West

Yakob Zel’dovich (1914 – 1987)

ICC
University of Durham

(15-19) /June/1987



INTERNATIONAL ASTRONOMICAL UNION

SYMPOSIUM No. 130

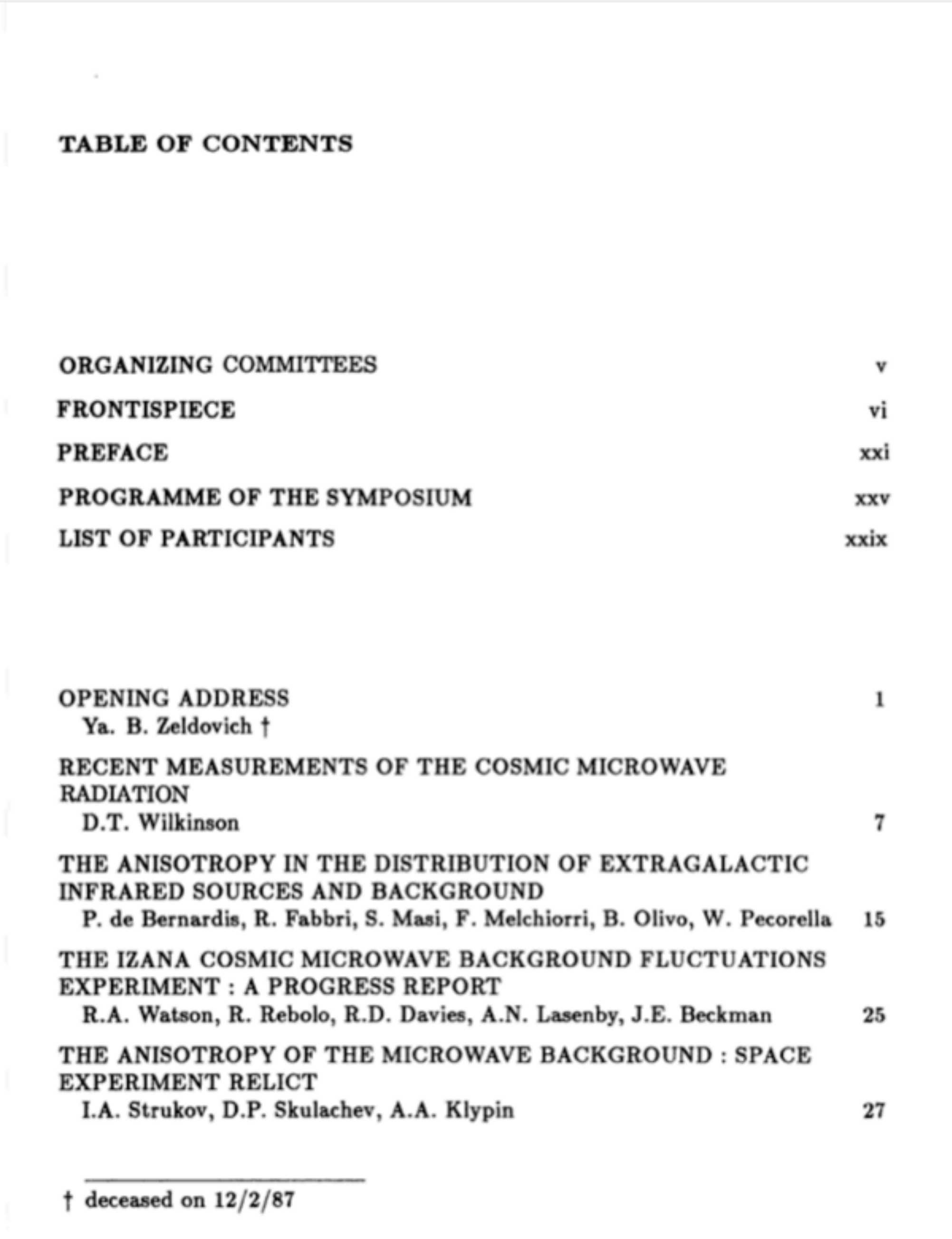
LARGE SCALE STRUCTURES OF THE UNIVERSE

Edited by

JEAN AUDOUZE, MARIE-CHRISTINE PELLETAN and ALEX SZALAY

IAU INTERNATIONAL ASTRONOMICAL UNION

KLUWER ACADEMIC PUBLISHERS



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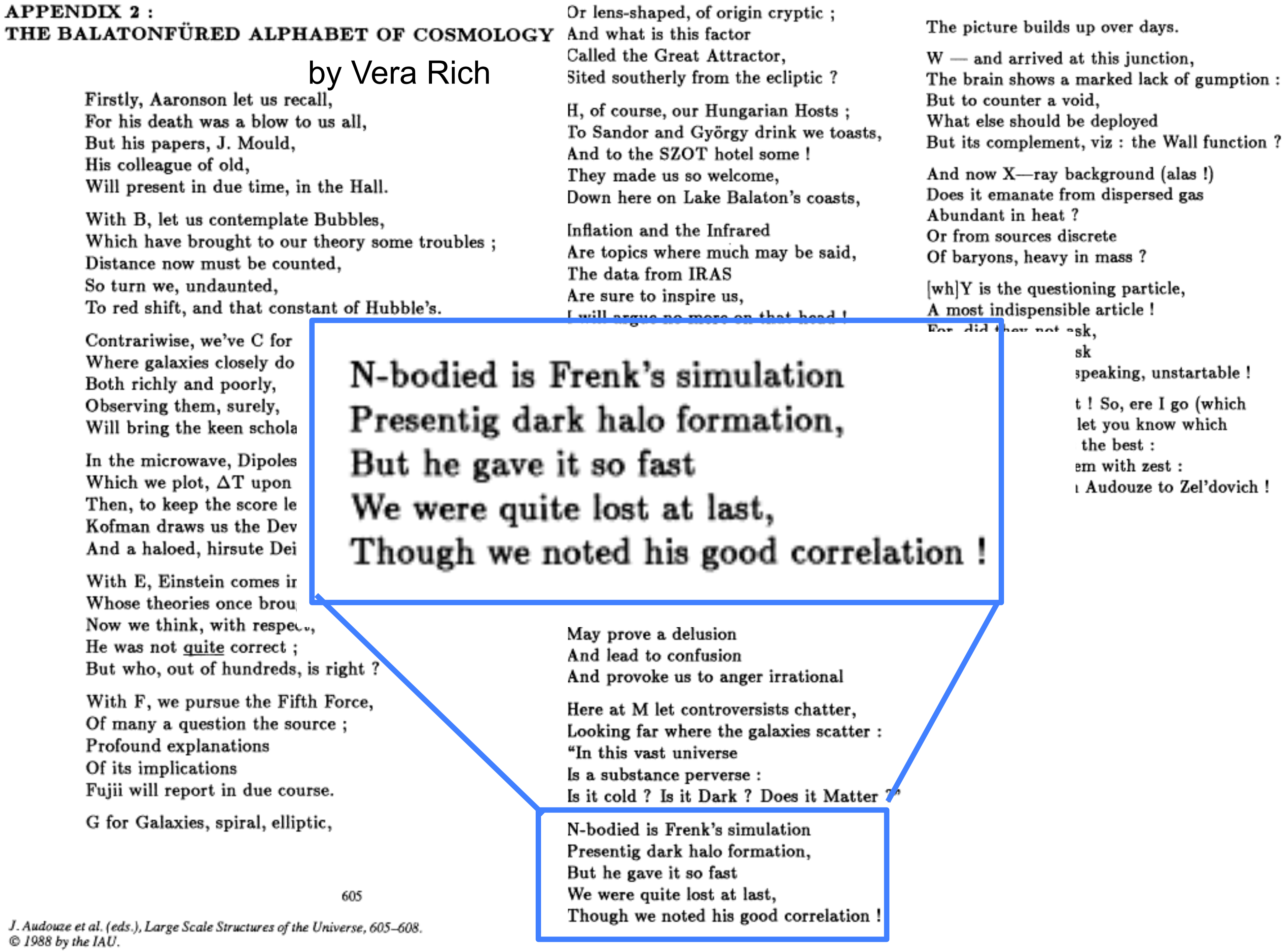
† deceased on 12/2/87



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 !

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 !

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 !

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.

ICC
University of Durham

CDM rules

1987

Institute for Computational Cosmology

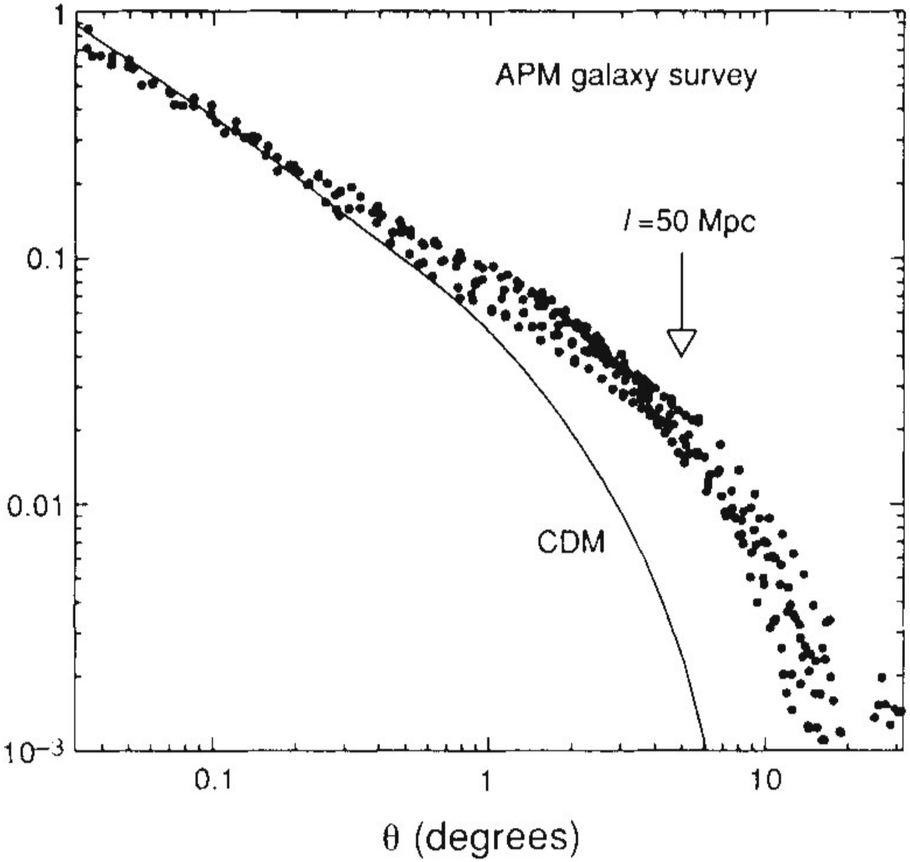
University of Durham

1990: Ω = 1 CDM under strain

Angular 2-pt correlation function

Maddox, Efstathiou, Sutherland & Loveday '90

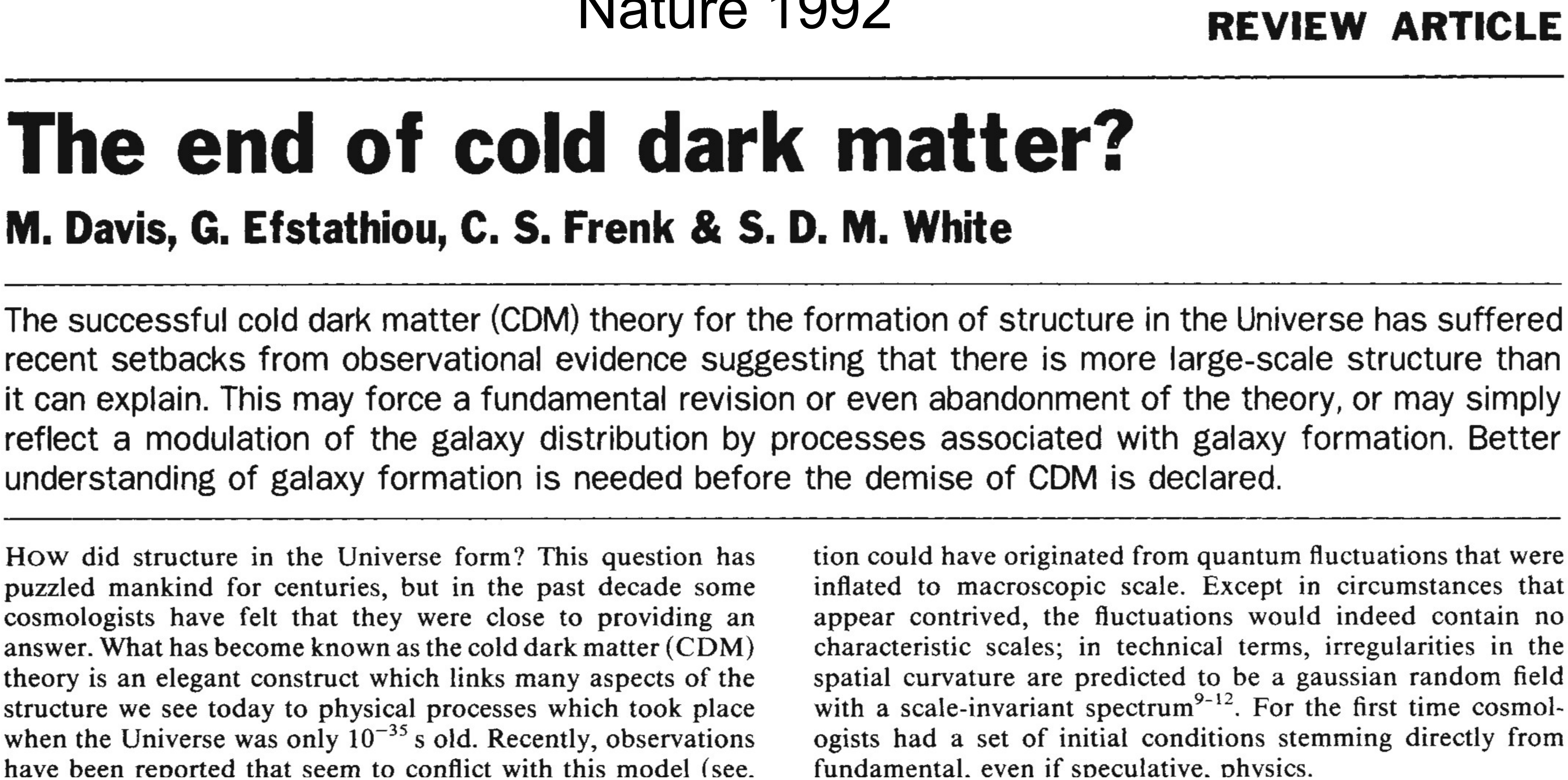
Too much "power on large scales"



Possible solution: lower Ω_{matter} and add Λ to CDM (to have Ω_{tot} =1, as required by inflation (Efstathiou et al '91)

DEFW ‘92

Nature 1992



REVIEW ARTICLE

The end of cold dark matter?

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

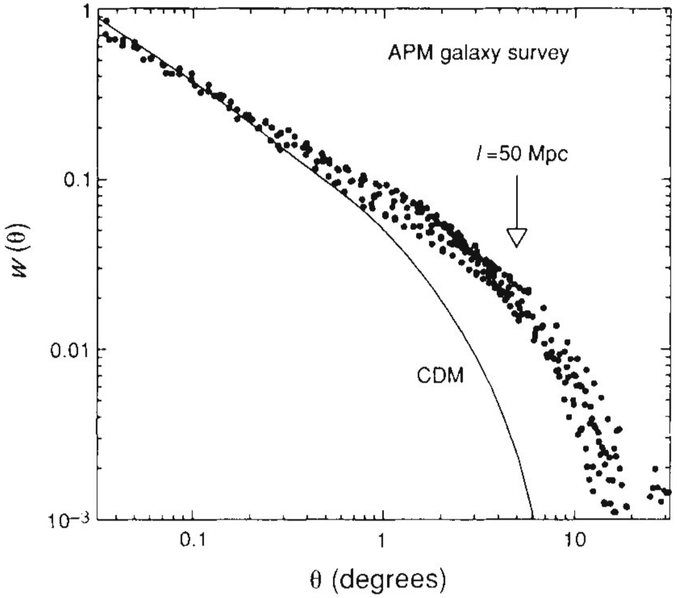
The successful cold dark matter (CDM) theory for the formation of structure in the Universe has suffered recent setbacks from observational evidence suggesting that there is more large-scale structure than it can explain. This may force a fundamental revision or even abandonment of the theory, or may 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.

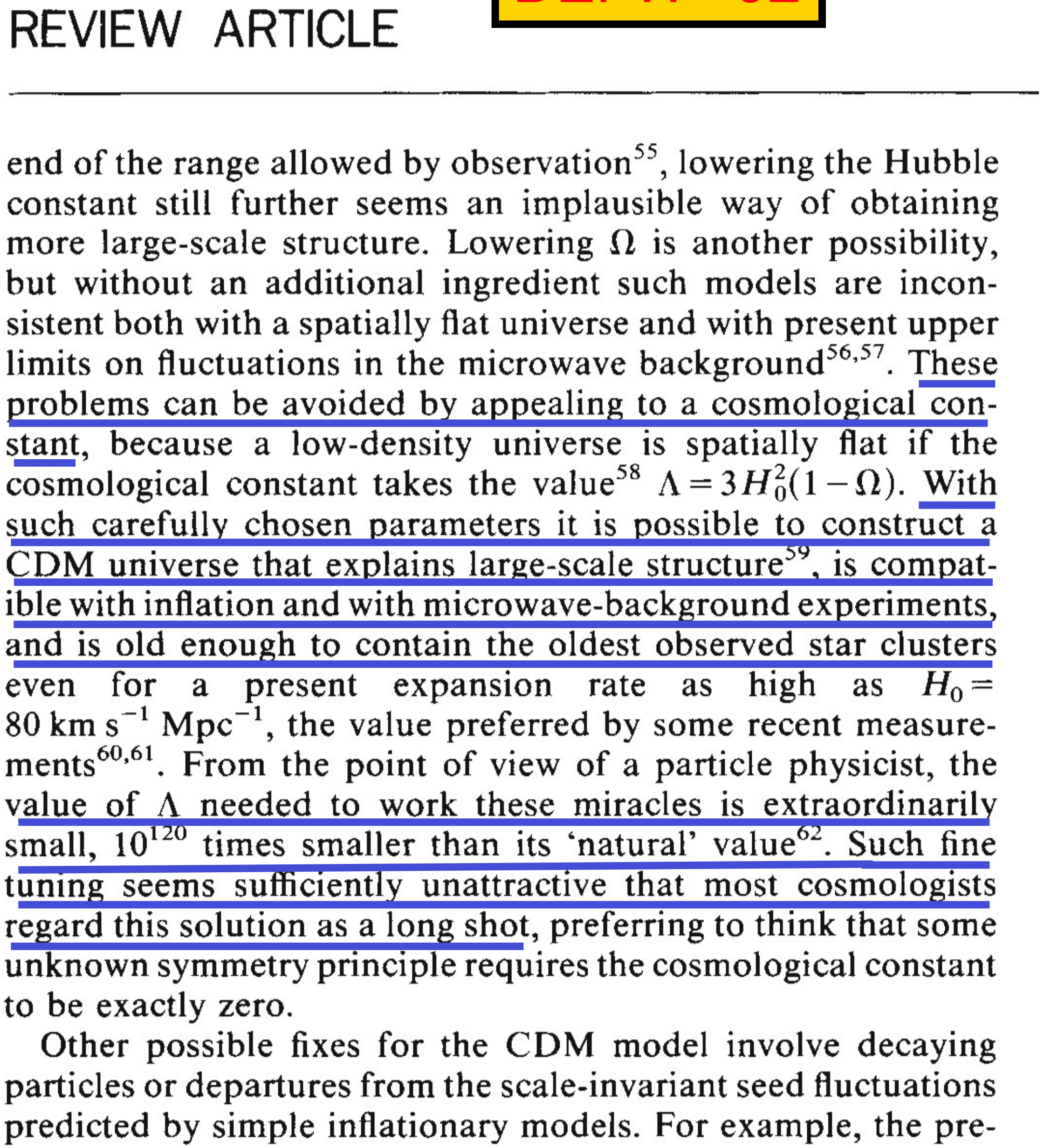
HOW did structure in the Universe form? This question has puzzled mankind for centuries, but in the past decade some cosmologists have felt that they were close to providing an answer. What has become known as the cold dark matter (CDM) theory is an elegant construct which links many aspects of the structure 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.

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 $H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$, 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 (Ω_{matter} =1) CDM … or why Ω_{matter} cannot be 1

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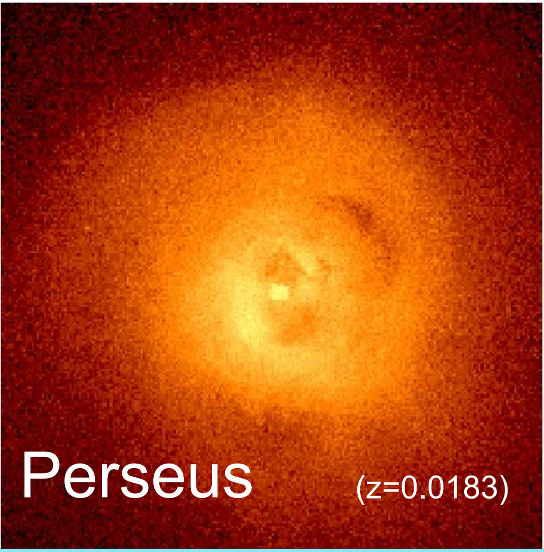
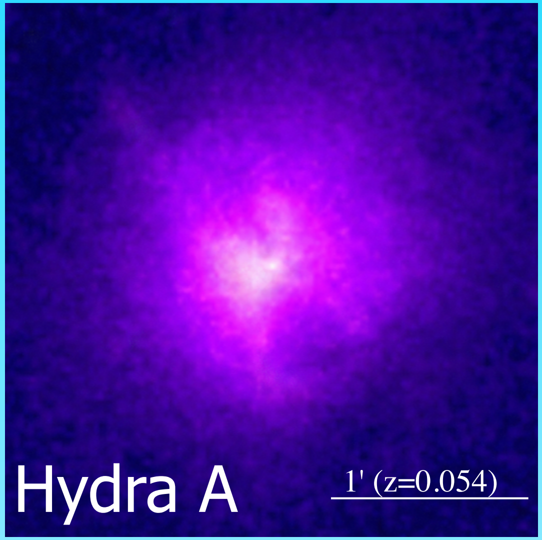
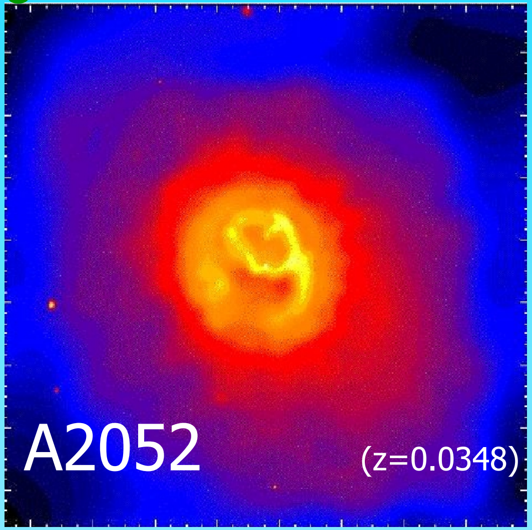
Galaxy clusters

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

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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 → $h = 0.7 \pm 10\%$

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

Allen etal ‘04

(Some) evidence for dark energy

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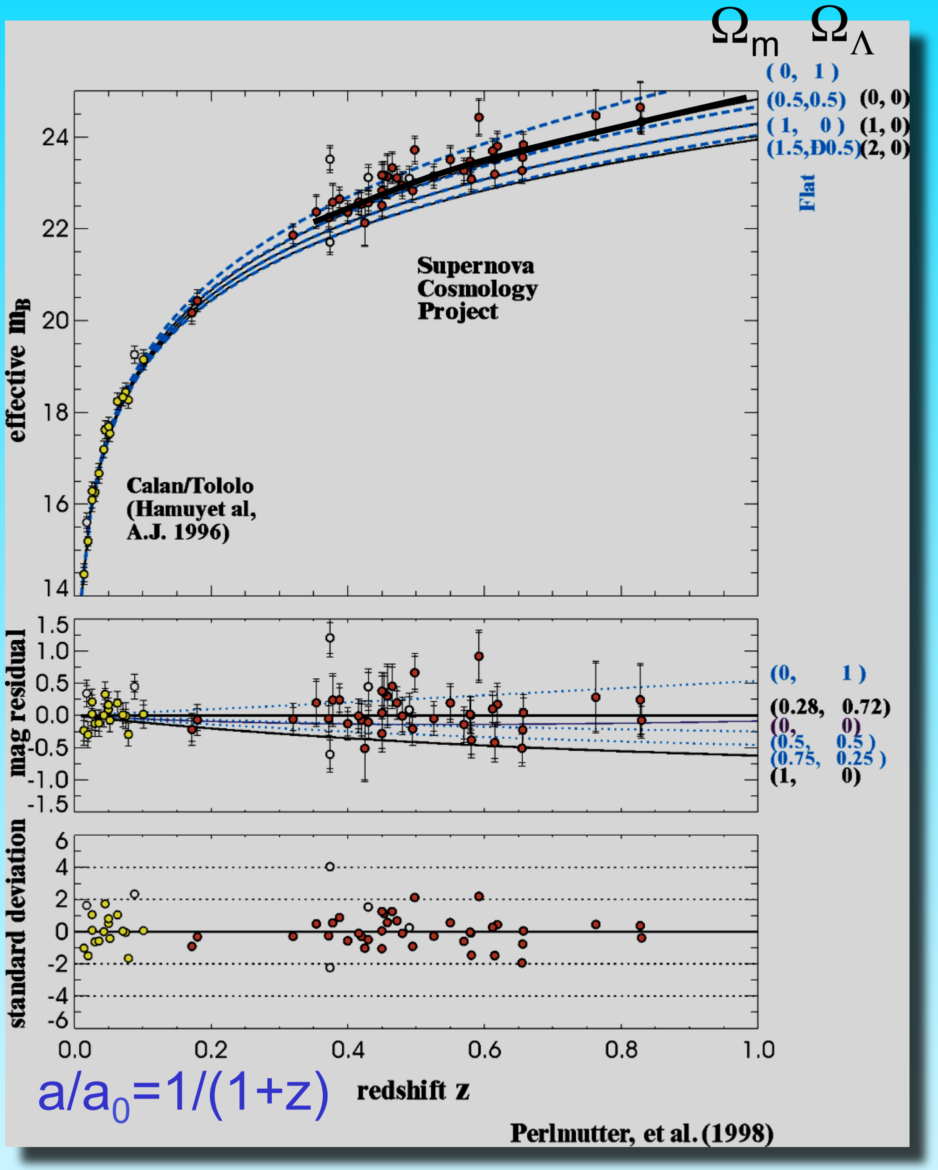
Evidence for Λ from high-z supernovae

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

flux



$a/a_0=1/(1+z)$

➔ Cosmic expansion must have been accelerating since the light was emitted

Perlmutter et al ’98; Reiss et al ‘98
Schmidt et al ‘98

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

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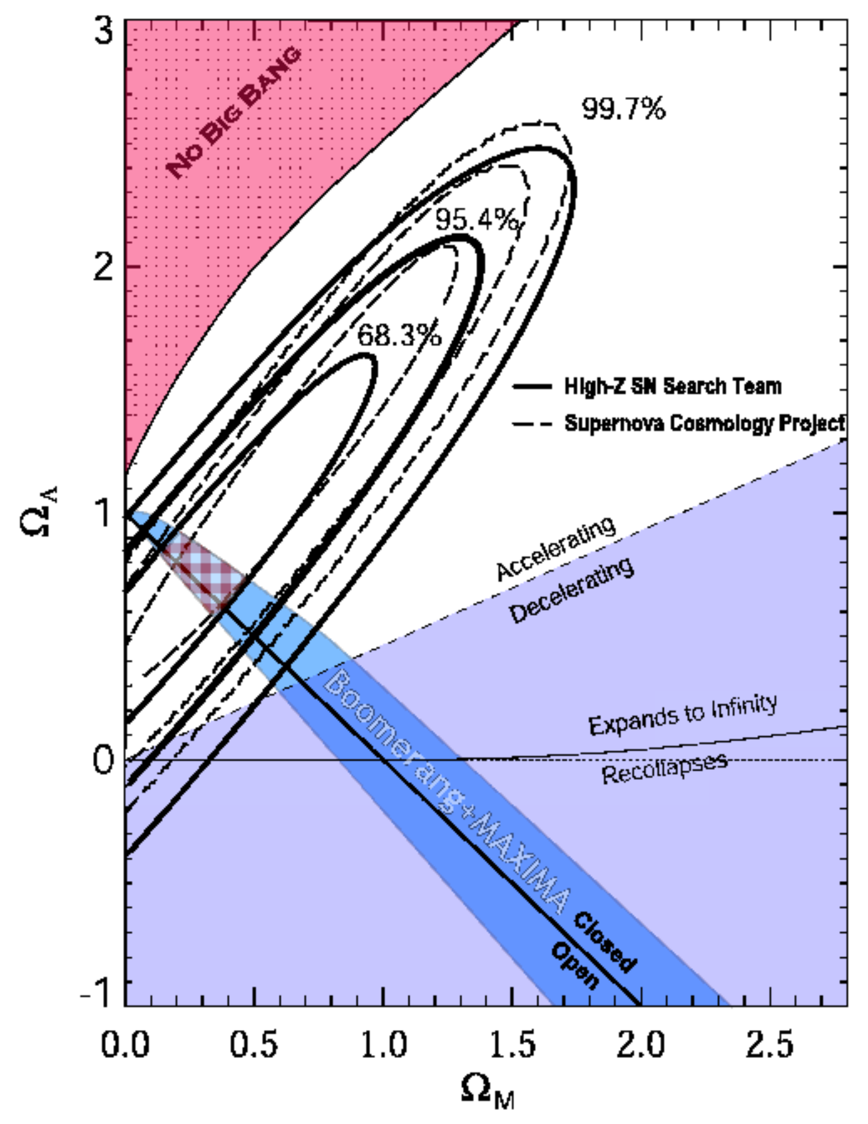

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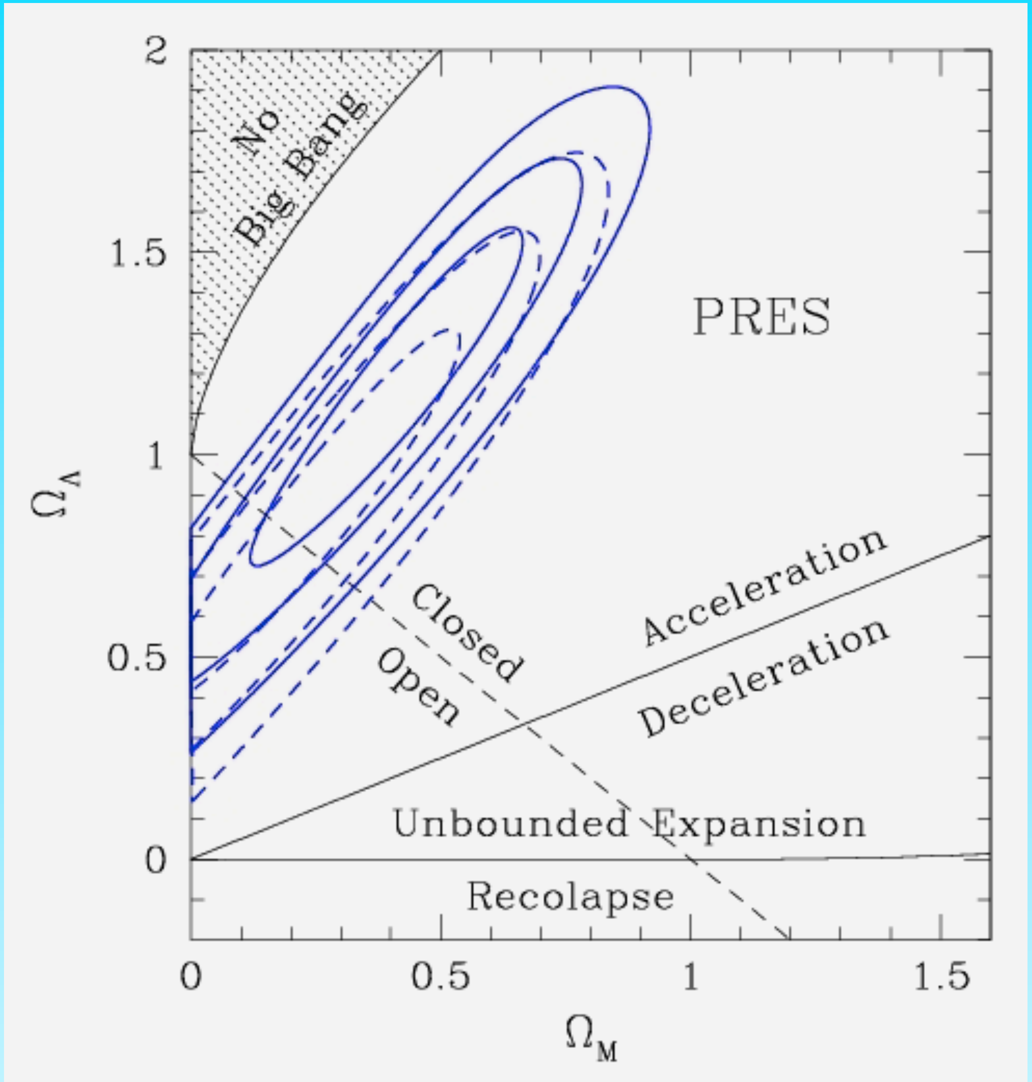
Evidence for Λ from high-z supernovae

Later data ruled out $\Omega_\Lambda = 0$.



Clocchiatti et al ‘06

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Friedmann equations

$$\ddot{a} = -\frac{4\pi}{3} G\rho a(3w+1)$$

$$c^2 a \frac{d\rho}{da} = -3(p + \rho c^2)$$

$$\rho_{tot} = \underbrace{\rho_{mass}}_{a^{-3}} + \underbrace{\rho_{rel}}_{a^{-4}} + \underbrace{\rho_{vac}}_{\text{const?}}$$

where $p = w\rho c^2$

expansion accelerates $\Rightarrow \ddot{a} > 0 \quad \Rightarrow \quad 3w + 1 < 0 \quad \Rightarrow \quad w < -\frac{1}{3}$

If $\rho = \rho_{vac} = \text{const}$, $\frac{d\rho}{da} = 0 \Rightarrow p = -\rho c^2 \Rightarrow w = -1$

cosmological constant

$[\rho_{vac} = \rho_{vac}(x,z)]$ $\Rightarrow$ dark energy

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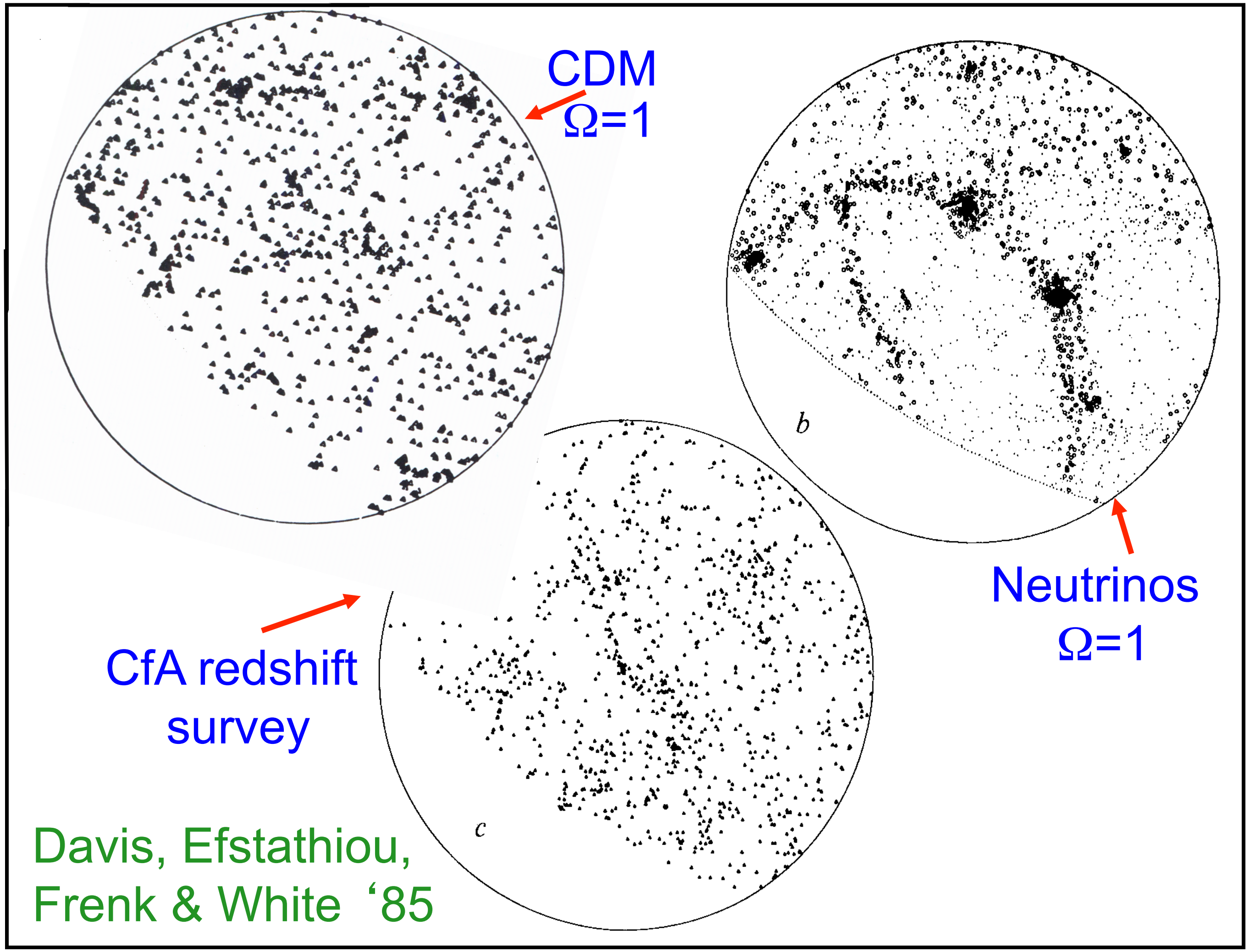
Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



CDM
Ω=1

Neutrinos
Ω=1

CfA redshift survey

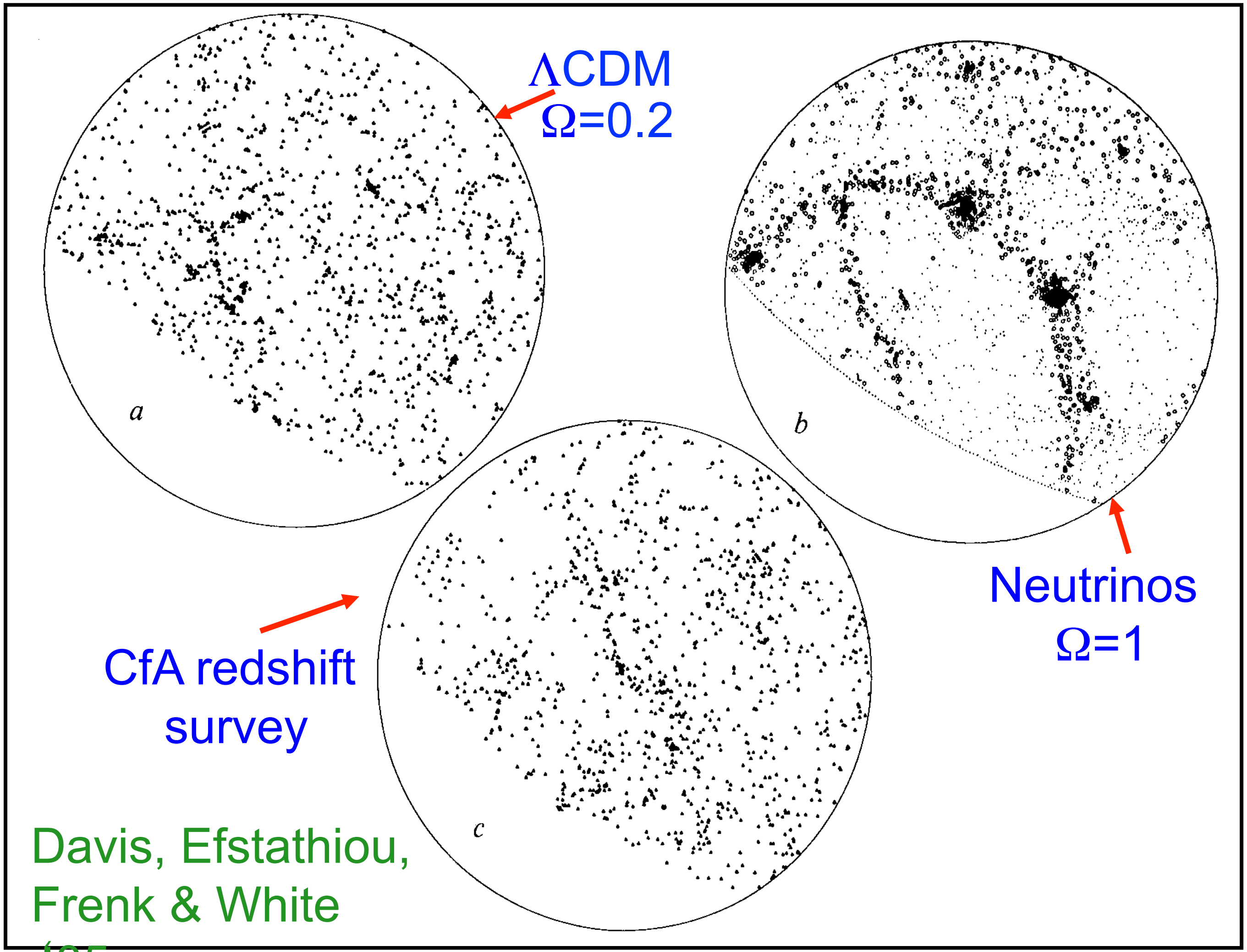
Davis, Efstathiou, Frenk & White ‘85

Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



ΛCDM
Ω=0.2

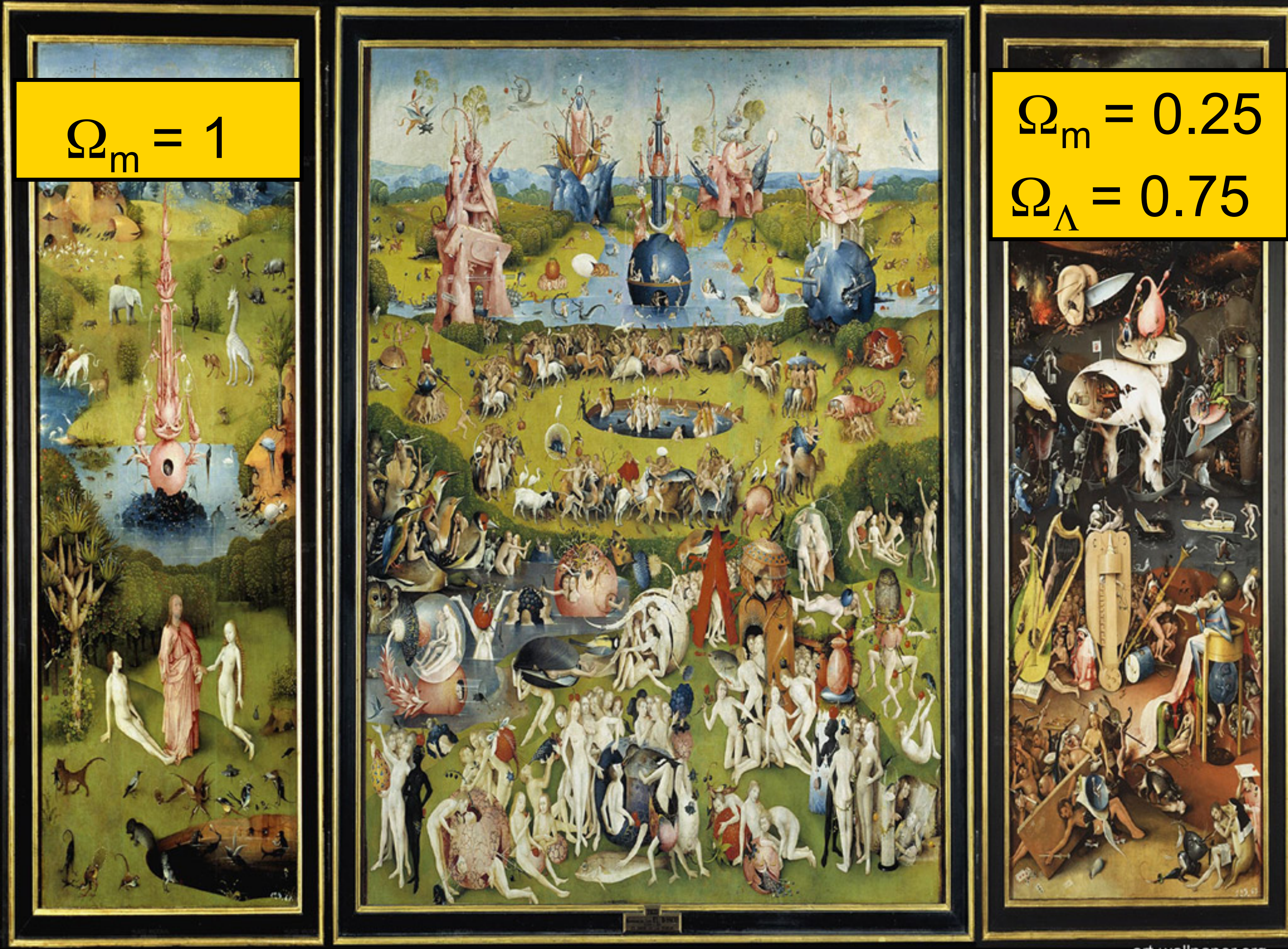
Neutrinos
Ω=1

CfA redshift survey

Davis, Efstathiou, Frenk & White
‘85

‘85

$\Omega_m = 1$



$\Omega_m = 1$

$\Omega_m = 0.25$

$\Omega_\Lambda = 0.75$

The cosmic dark energy

Current physics predicts a "natural" value for the cosmological constant (Planck value)

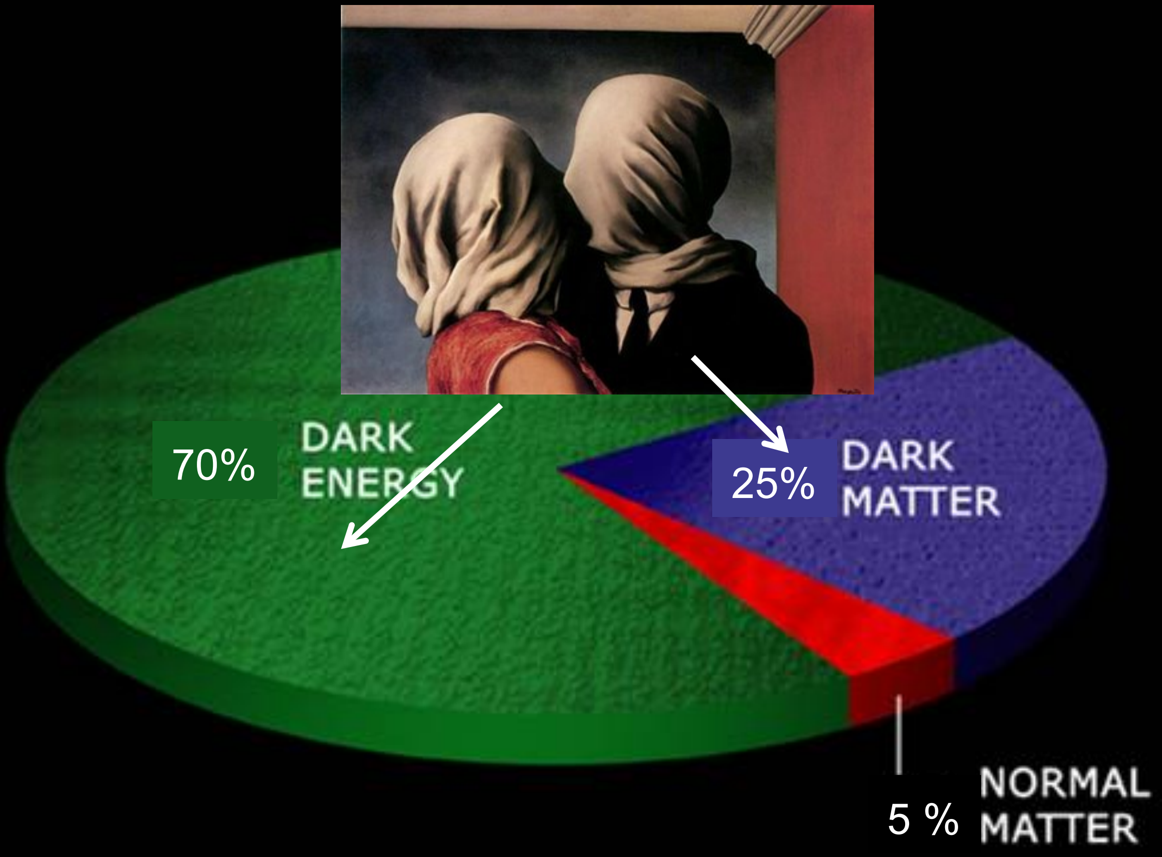
$$\rho_\Lambda^{PL} \sim M_{PL}^4 \sim (8\pi G)^{-2} \sim (10^{18} GeV)^4 \sim 2\times 10^{130} erg/cm^3$$

$$\rho_\Lambda^{obs} \sim (10^{-12} GeV)^4 \sim 2\times 10^{10} erg/cm^3$$

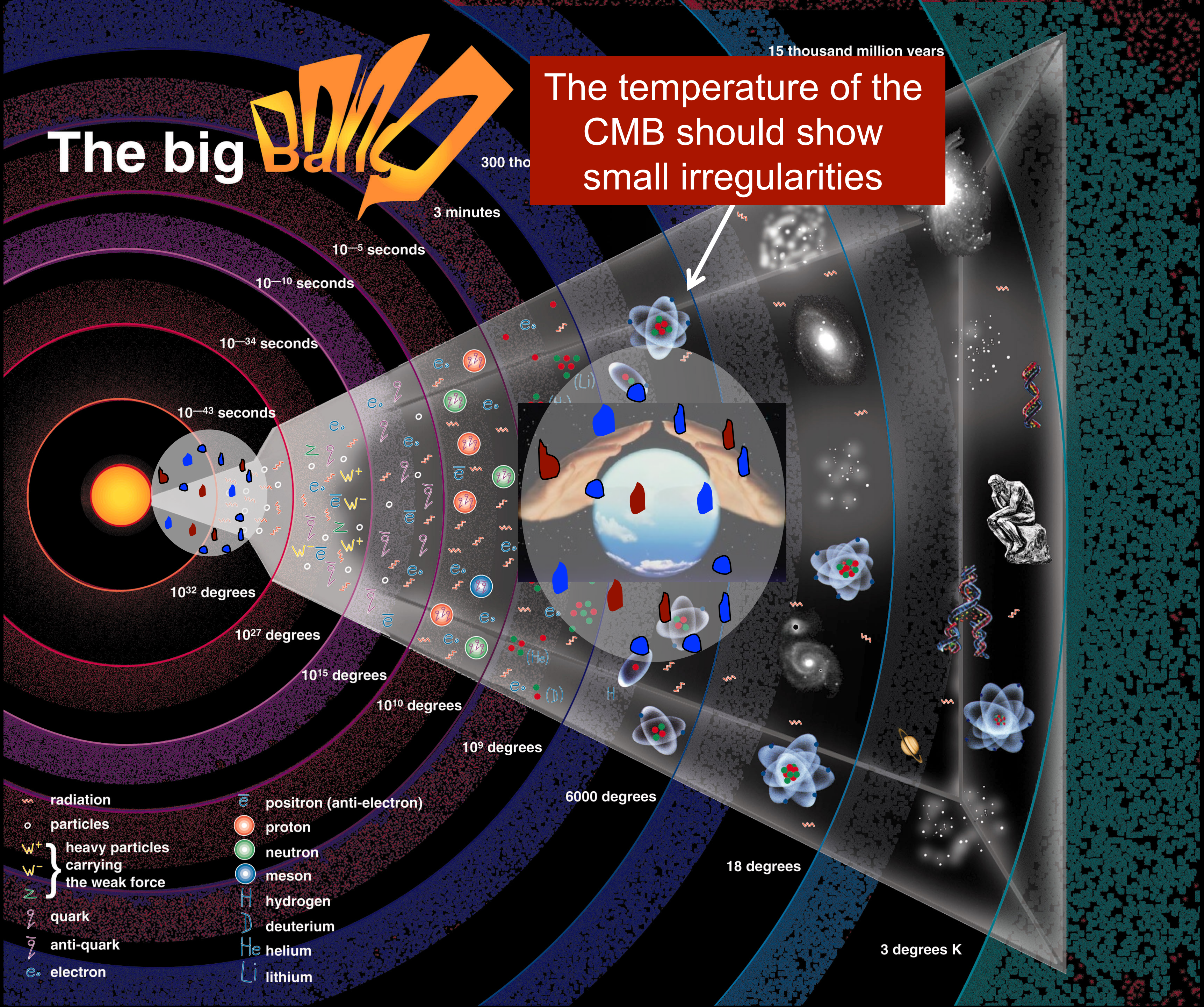
10^{120} larger than observed !!!

- Most inaccurate prediction in physics ever
- Requires new physics!

ΛCDM is an *a priori* implausible model



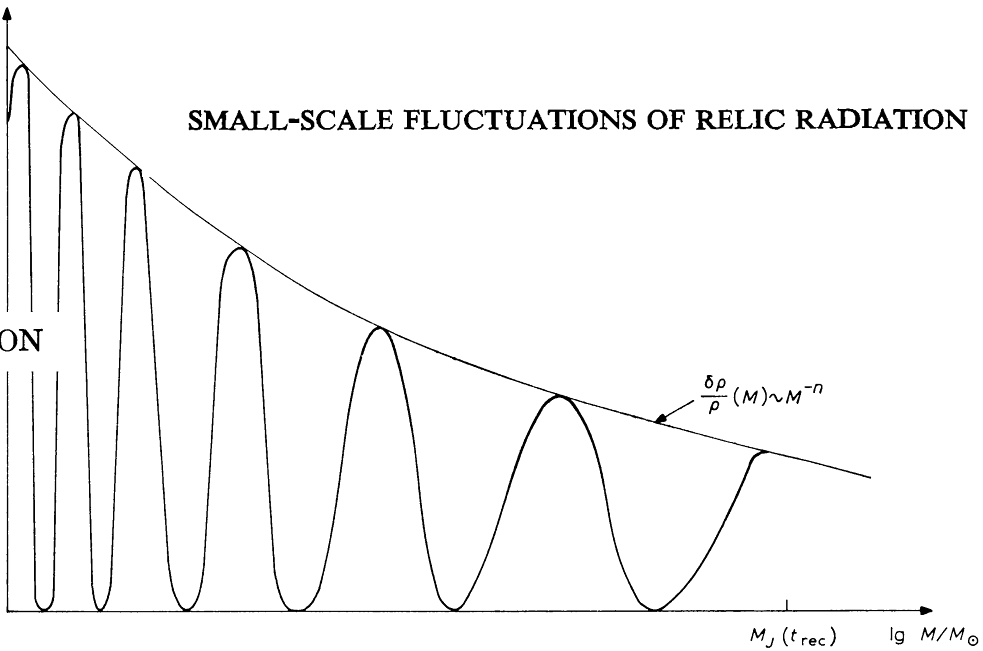
… but makes definite predictions and is therefore testable



The temperature of the CMB should show small irregularities

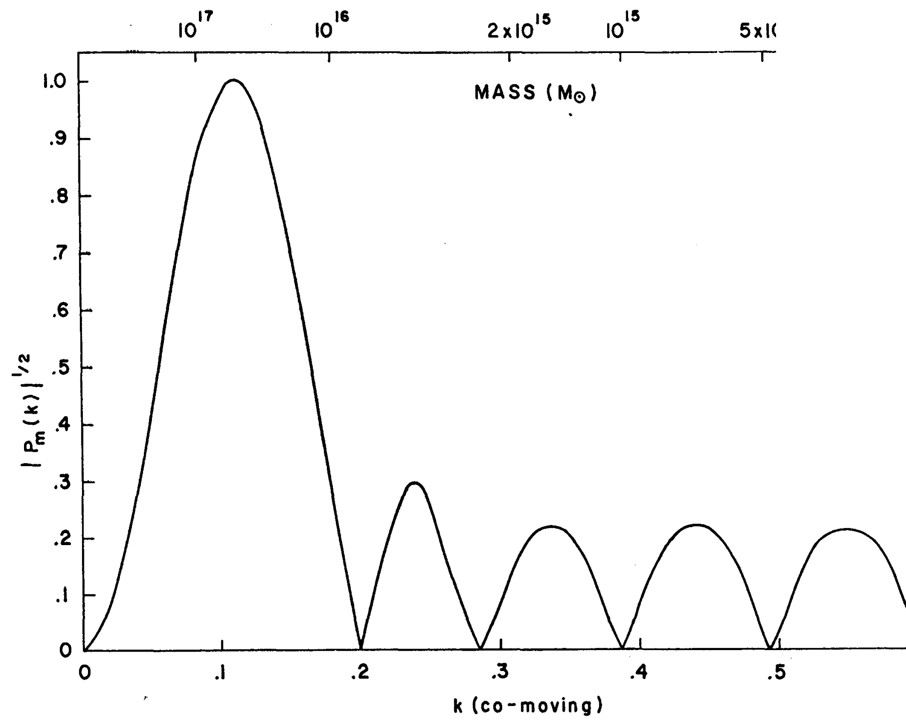
Temperature anisotropies in CMB

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION



Sunyaev & Zel’dovich ‘70

No. 3, 1970 PRIMEVAL ADIABATIC PERTURBATION

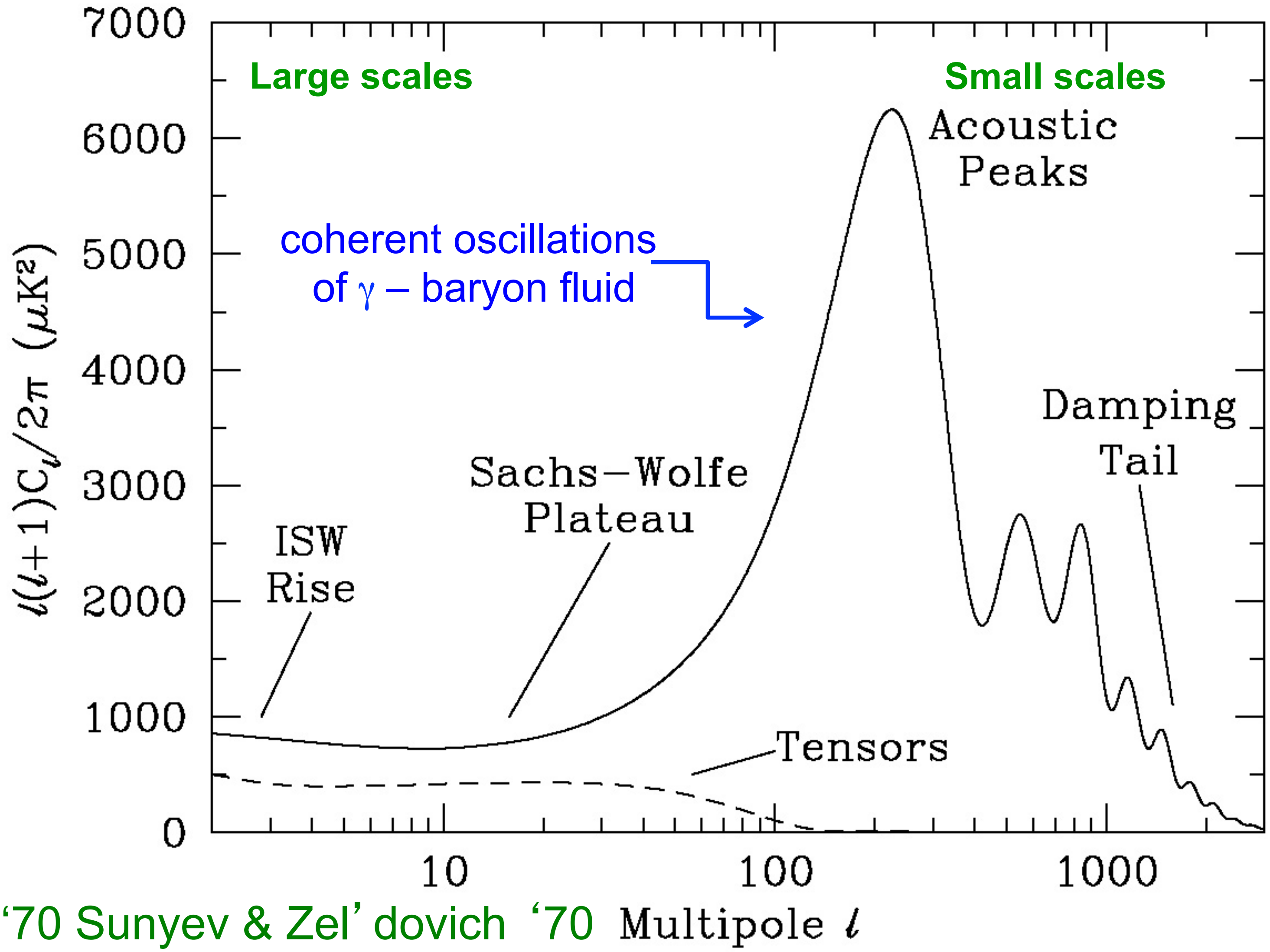


Peebles & Yu ‘70

University of Durham

Temperature anisotropies in CMB

2D power spectrum



Peebles & Yu ‘70 Sunyev & Zel’dovich ‘70

For CDM: Peebles ’82; Bond &Efstathiou ‘84

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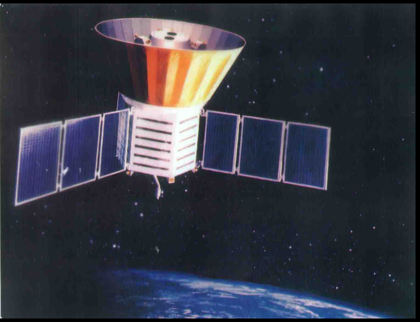
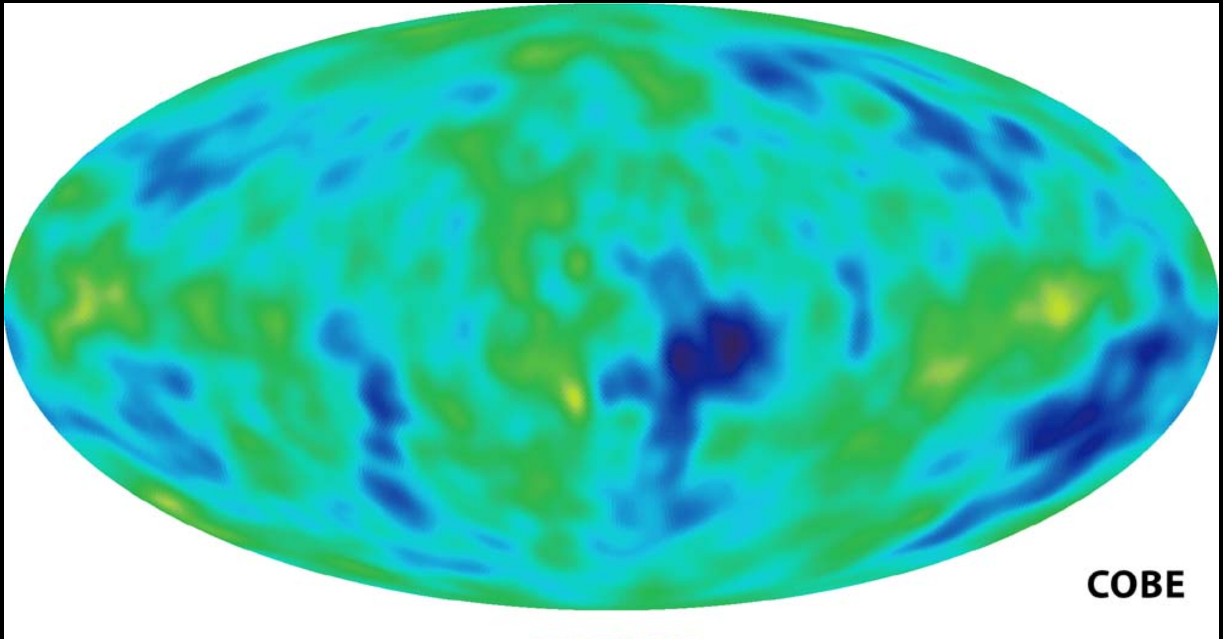
The CMB

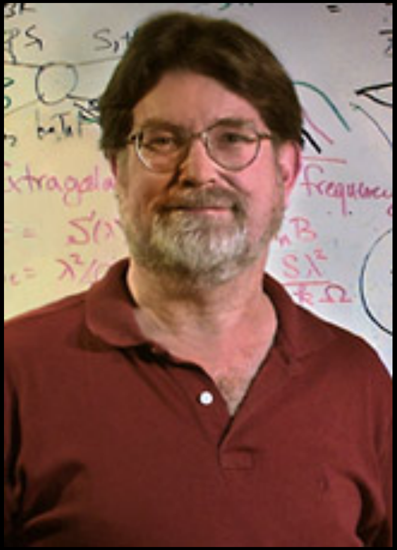
1992





George Smoot - Nobel Prize 2006

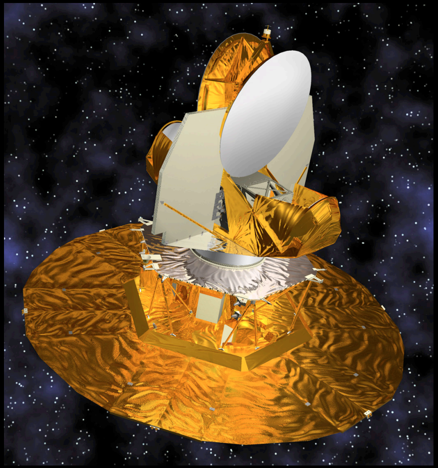
KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

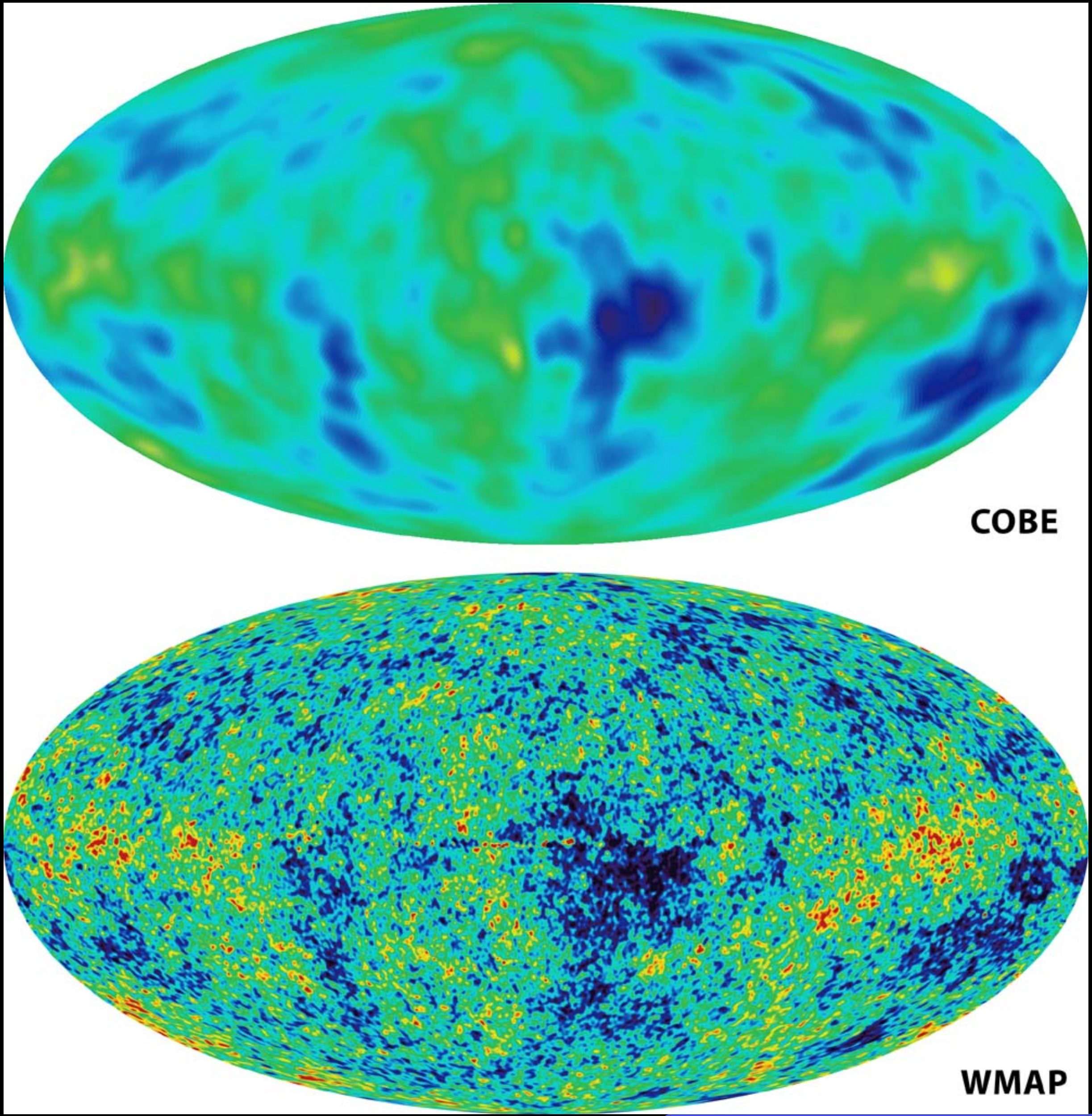


The CMB

1992

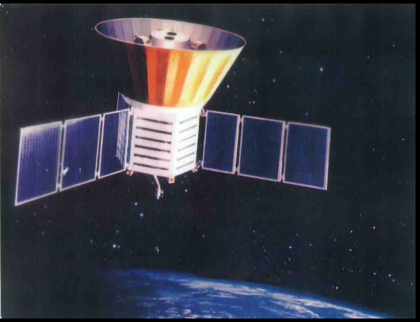
2003



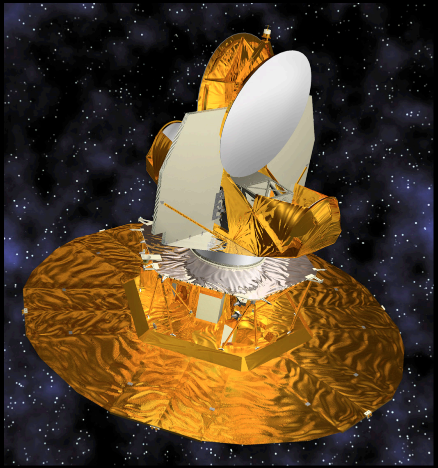


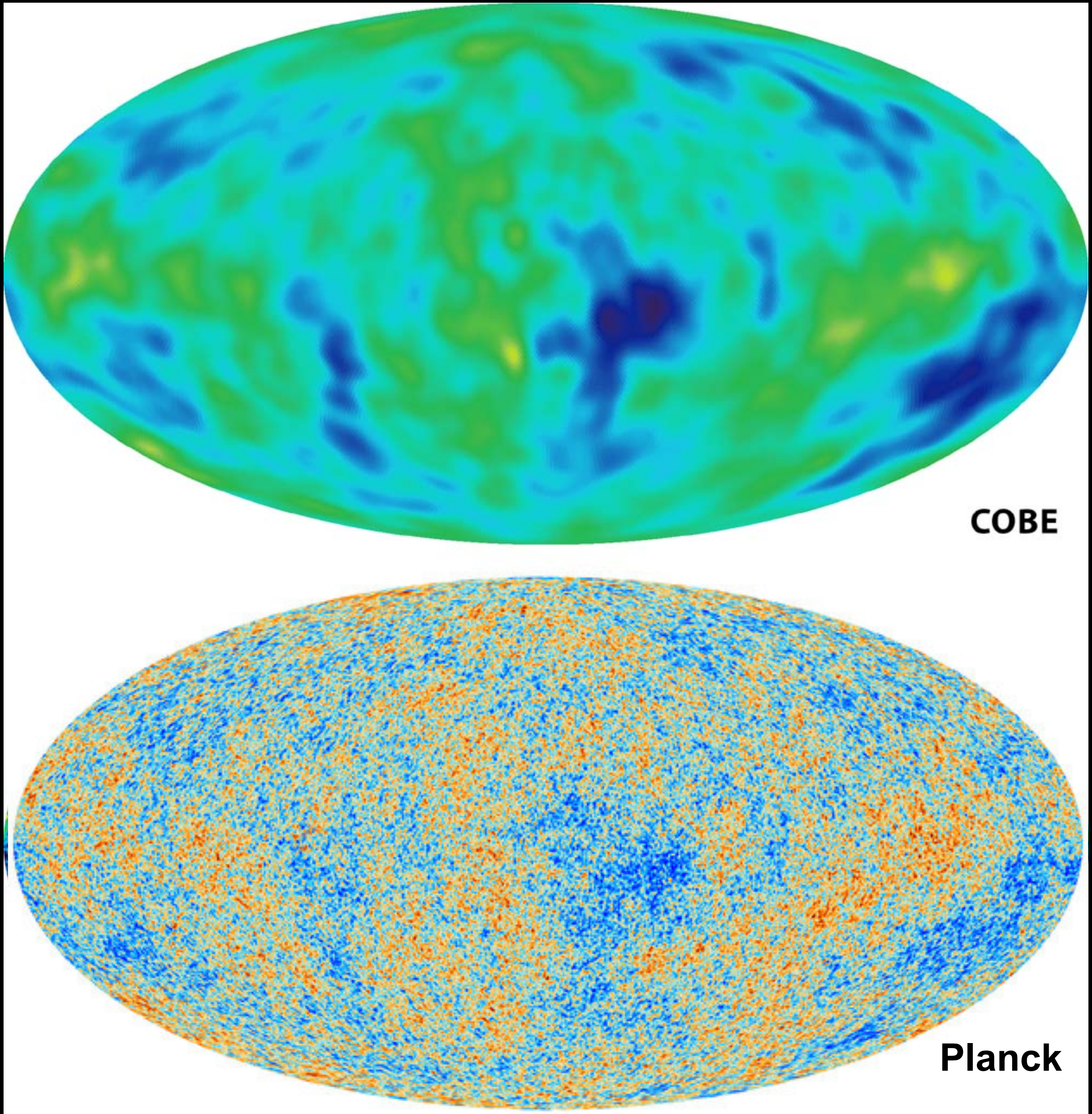
The CMB

1992



2012





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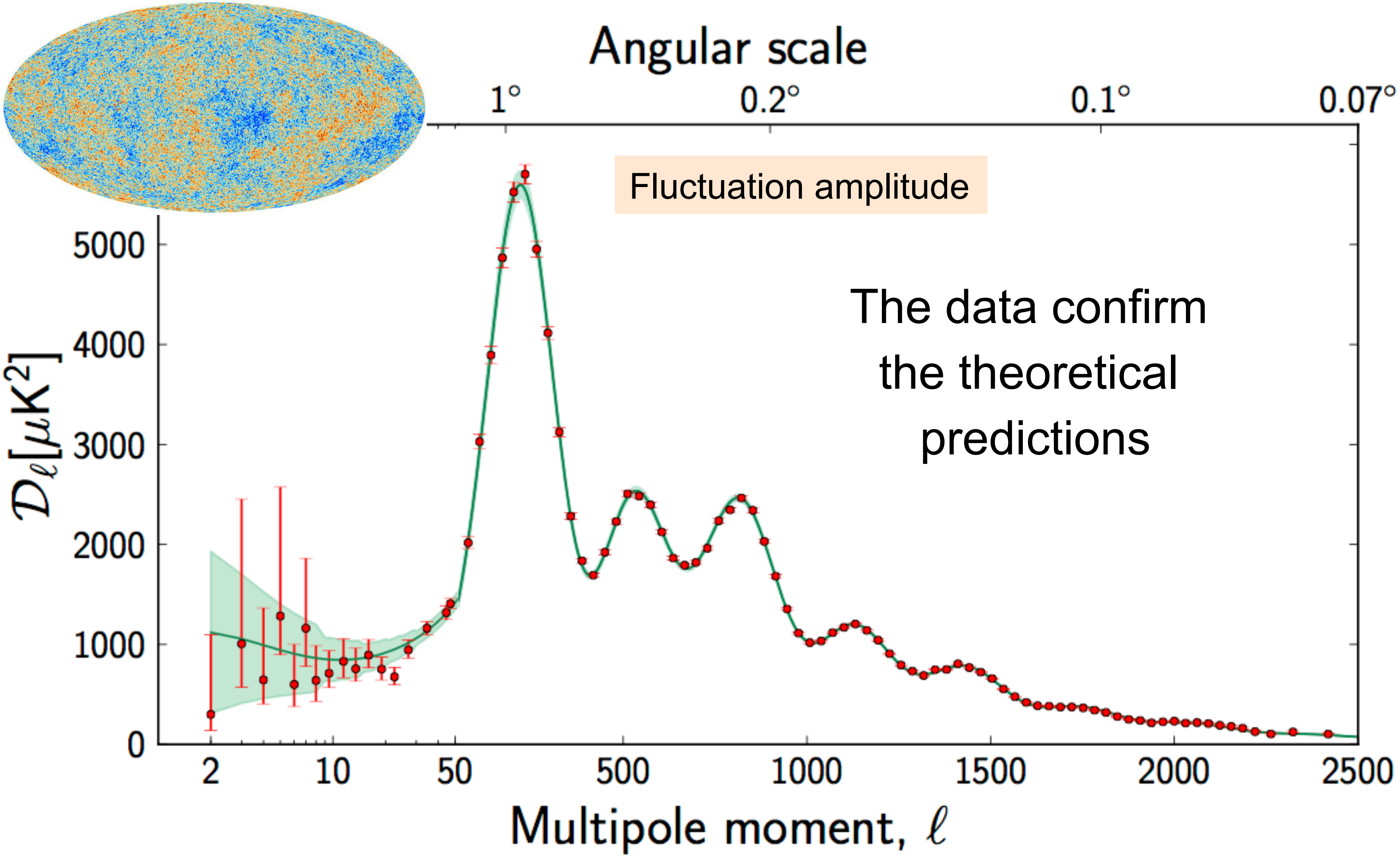
Planck: CMB temperature anisotropies

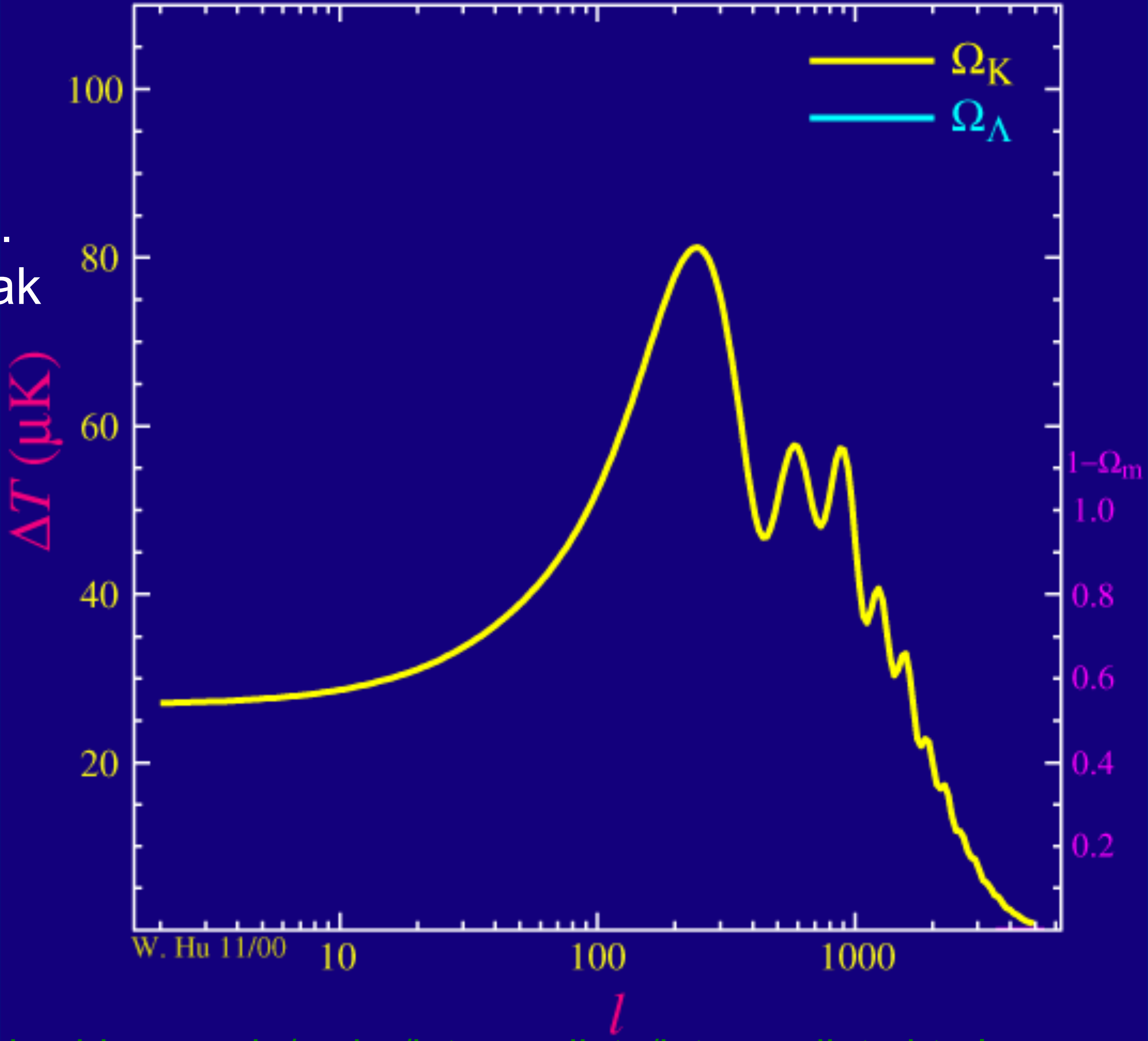


Fluctuation amplitude

The data confirm
the theoretical
predictions

Planck coll. 2015

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



Wayne Hu

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

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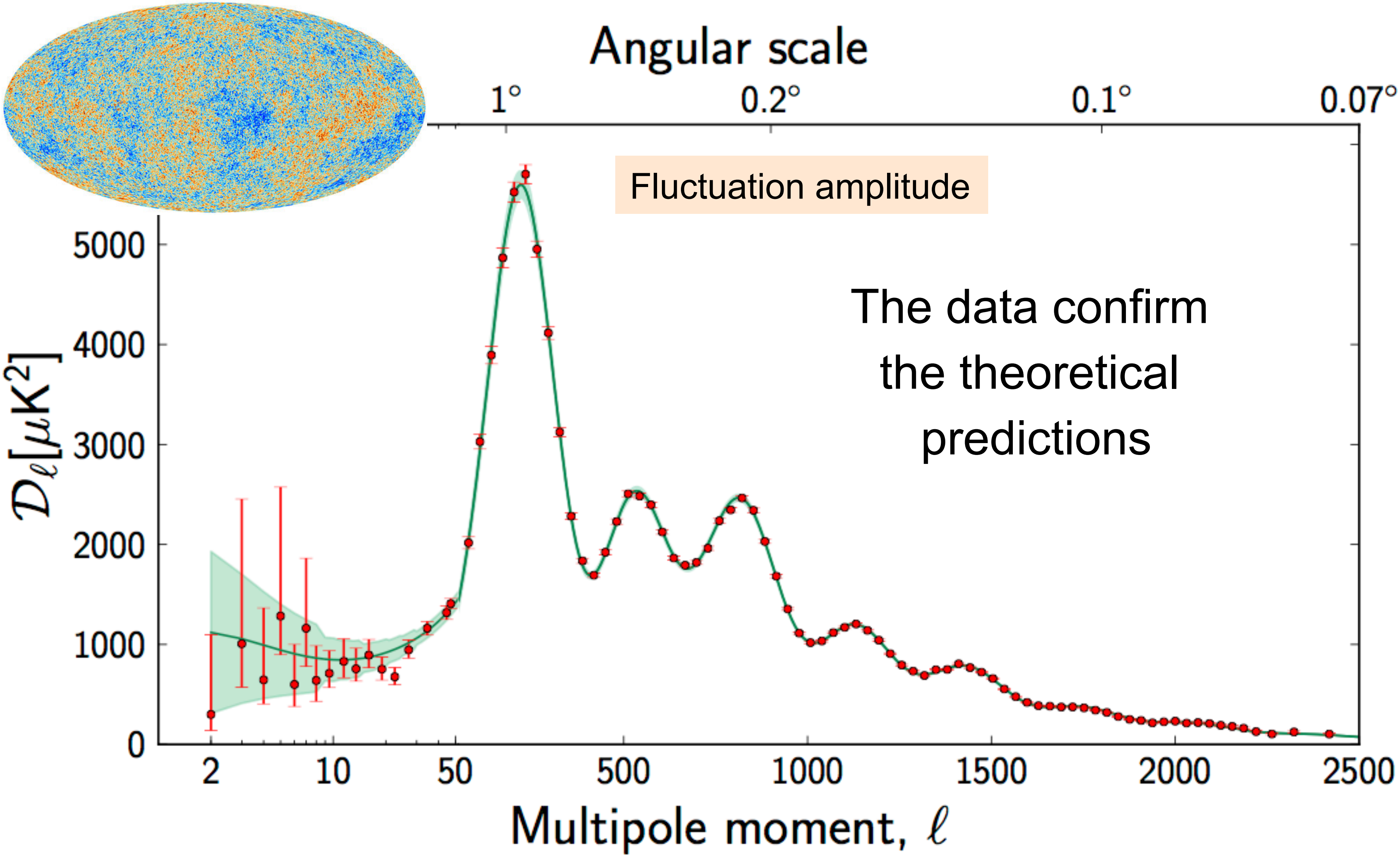
Planck: CMB temperature anisotropies



Fluctuation amplitude

The data confirm
the theoretical
predictions

Planck coll. 2015

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Cosmological parameters from CMB data

		Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL	
	Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
6 mdoel parameters	$\Omega_b h^2$	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
derived parameters	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

Institute for Computational Cosmology

The six parameters of minimal ΛCDM model

6 mdoel parameters

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	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 using only z=1000 data!

Planck collaboration ‘13

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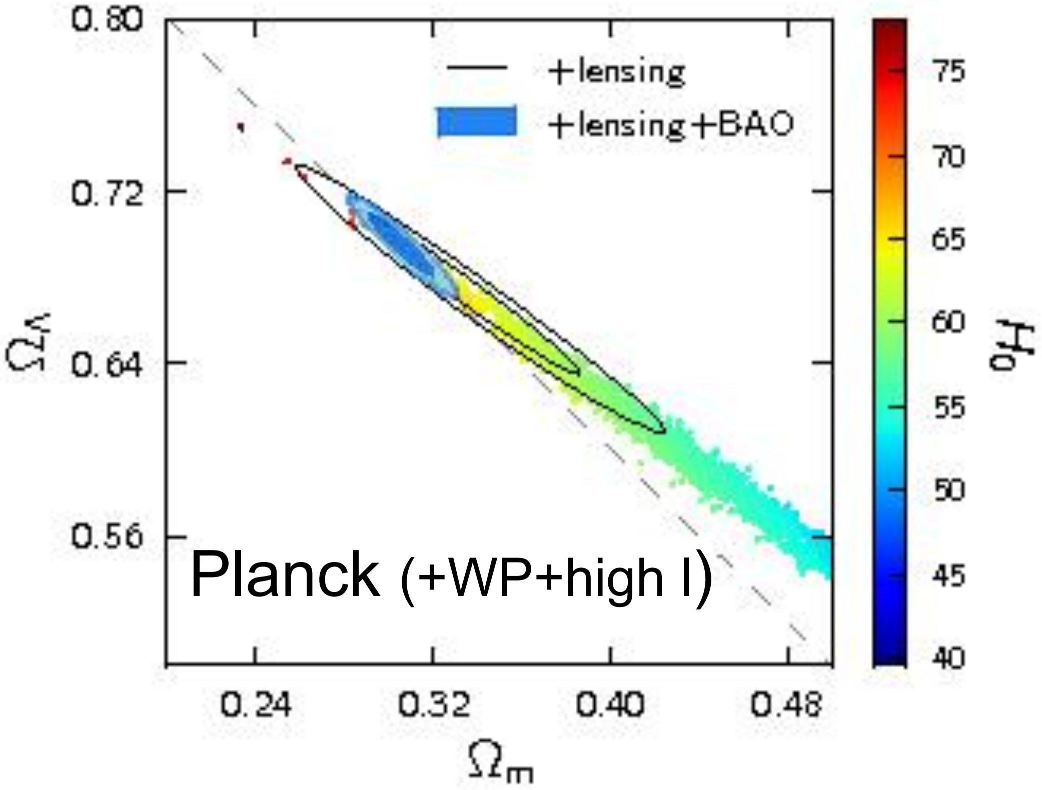
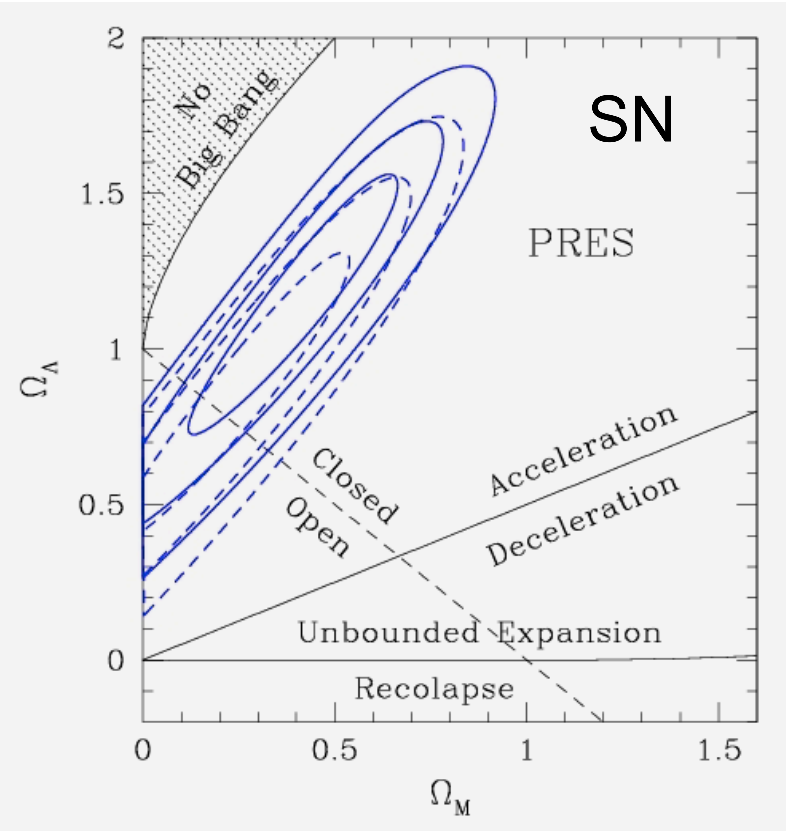
Breaking $\Omega_{matter} - \Omega_{\Lambda}$ degeneracy

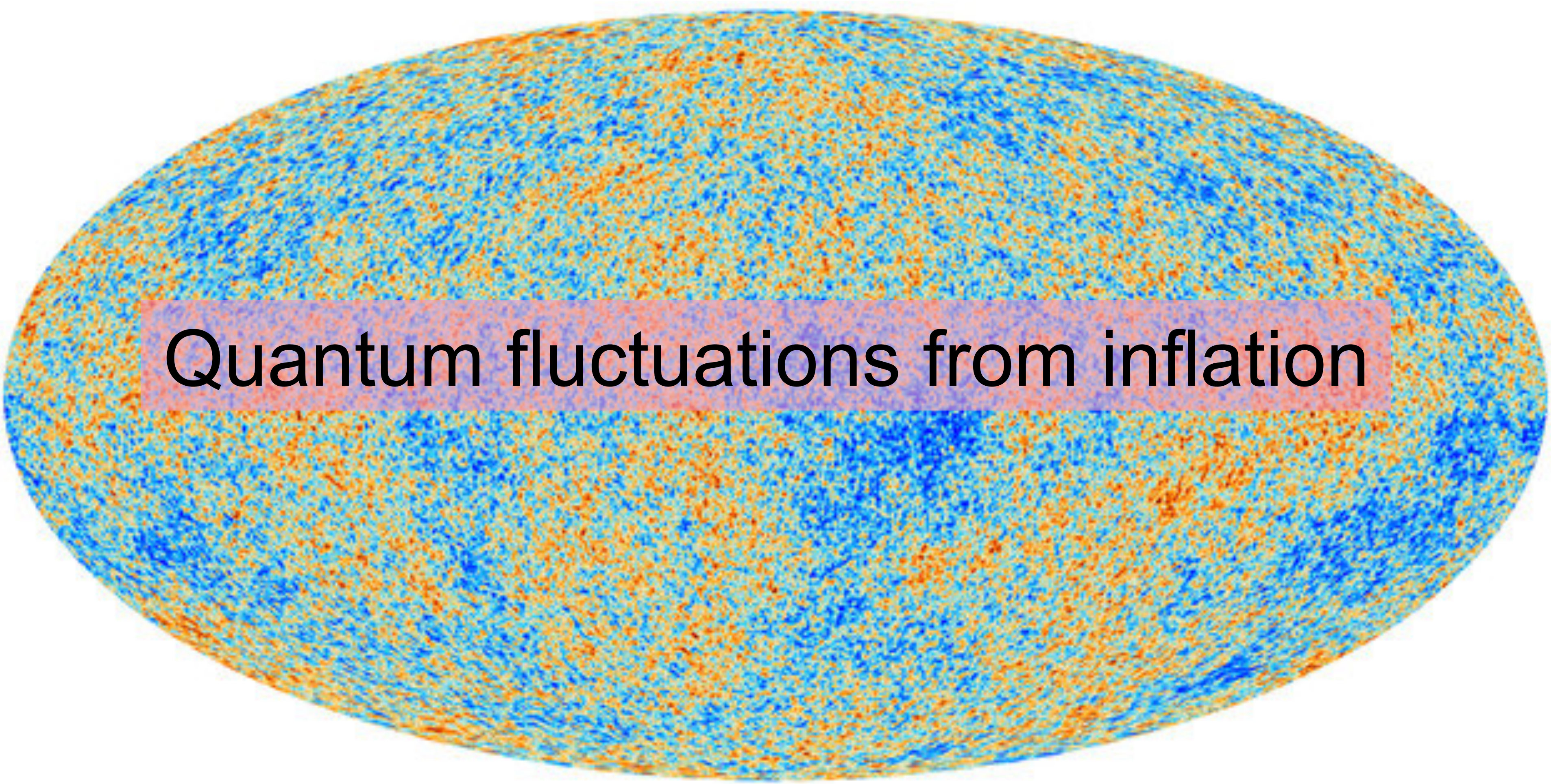
Planck breaks the geometric degeneracy between Ω_{matter} and Ω_{Λ}

→ flat geometry



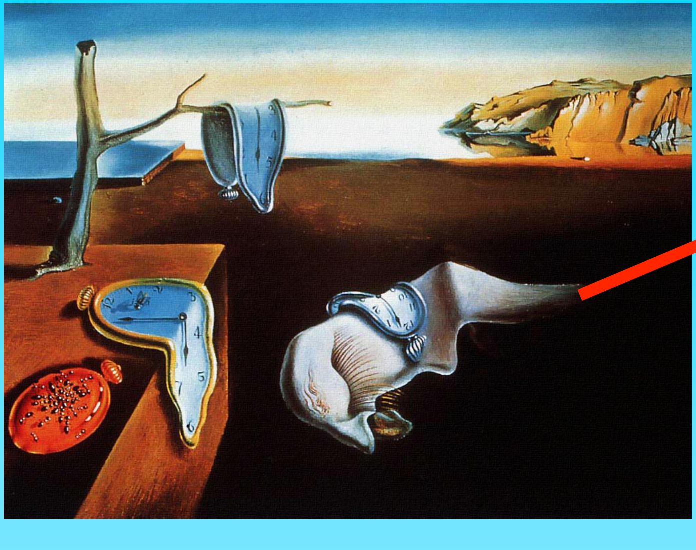


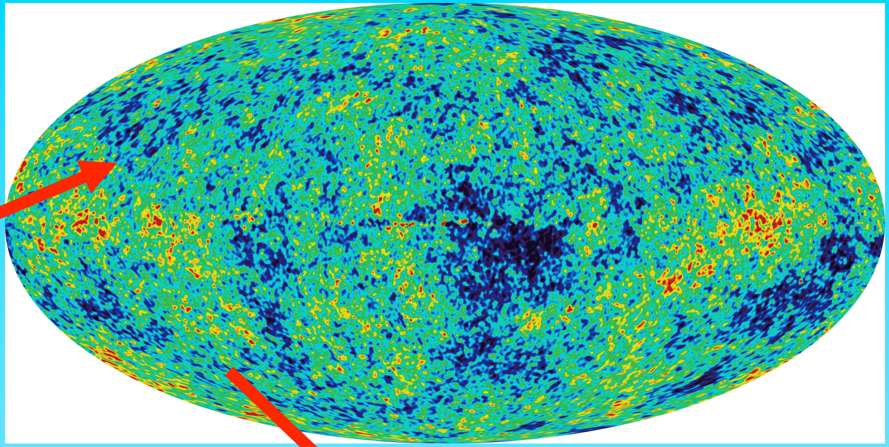
The initial conditions for galaxy formation



Quantum fluctuations from inflation

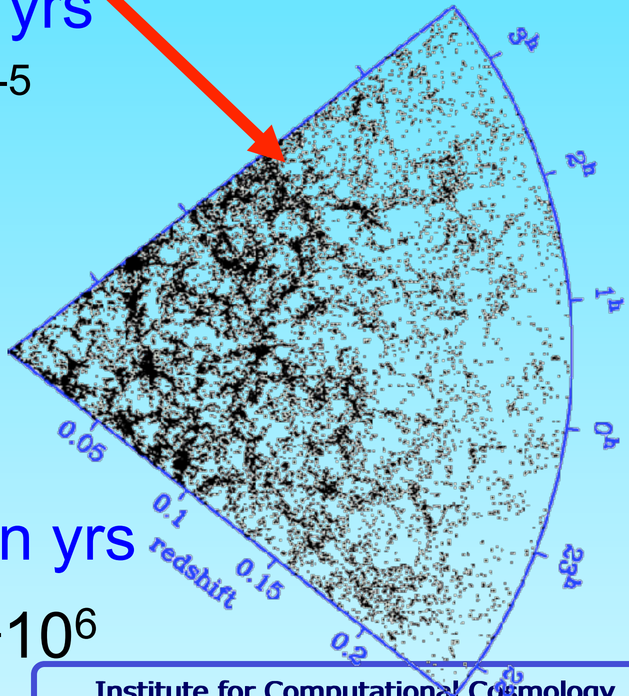
The growth of cosmic structure





t=380,000 yrs

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



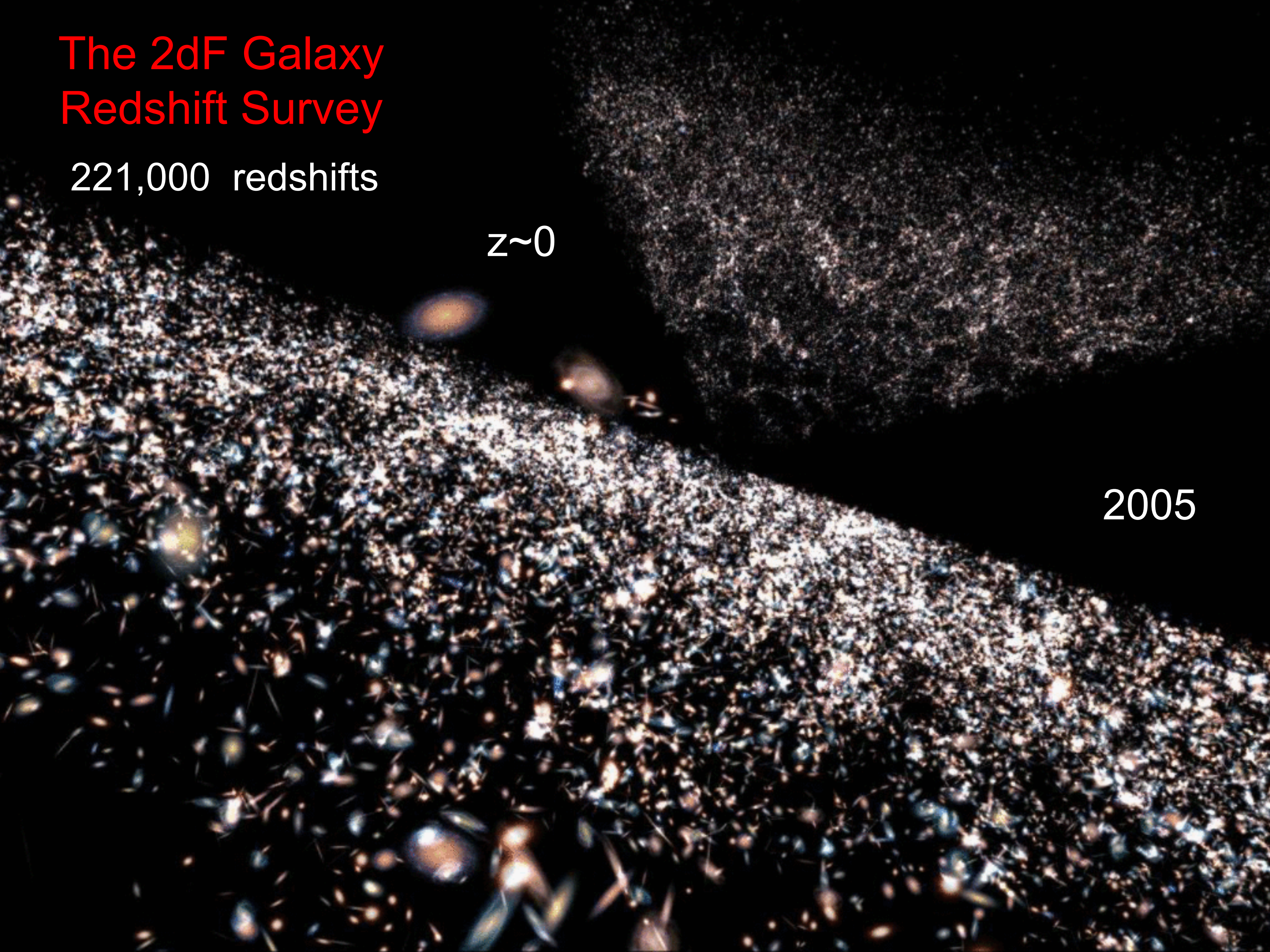
Supercomputer simulations use the laws of physics to calculate how small primordial perturbations grow into galaxies today

t=13.8 billion yrs

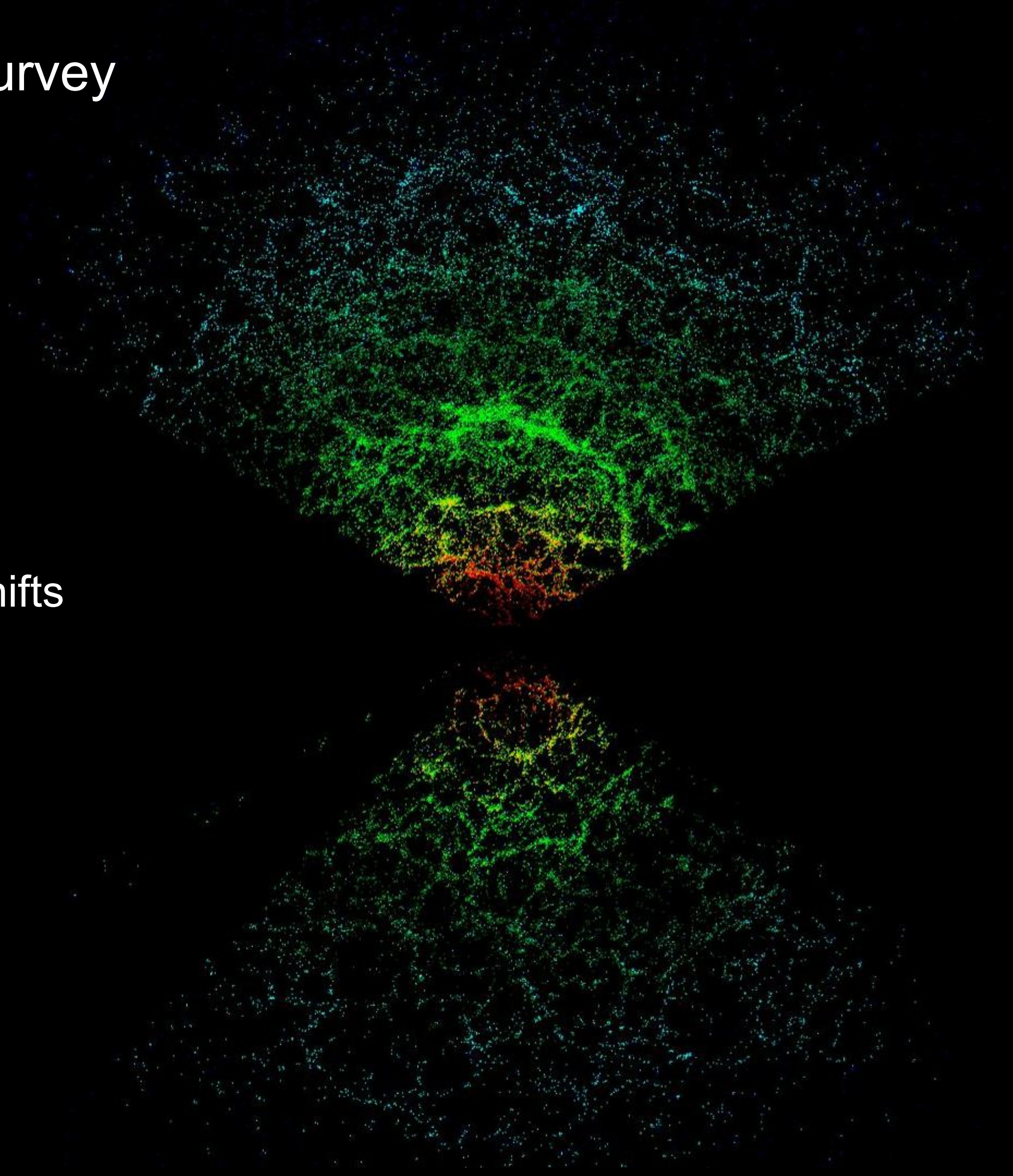
$\delta\rho/\rho \sim 1-10^6$

The 2dF Galaxy Redshift Survey

221,000 redshifts



Sloan Digital Sky Survey



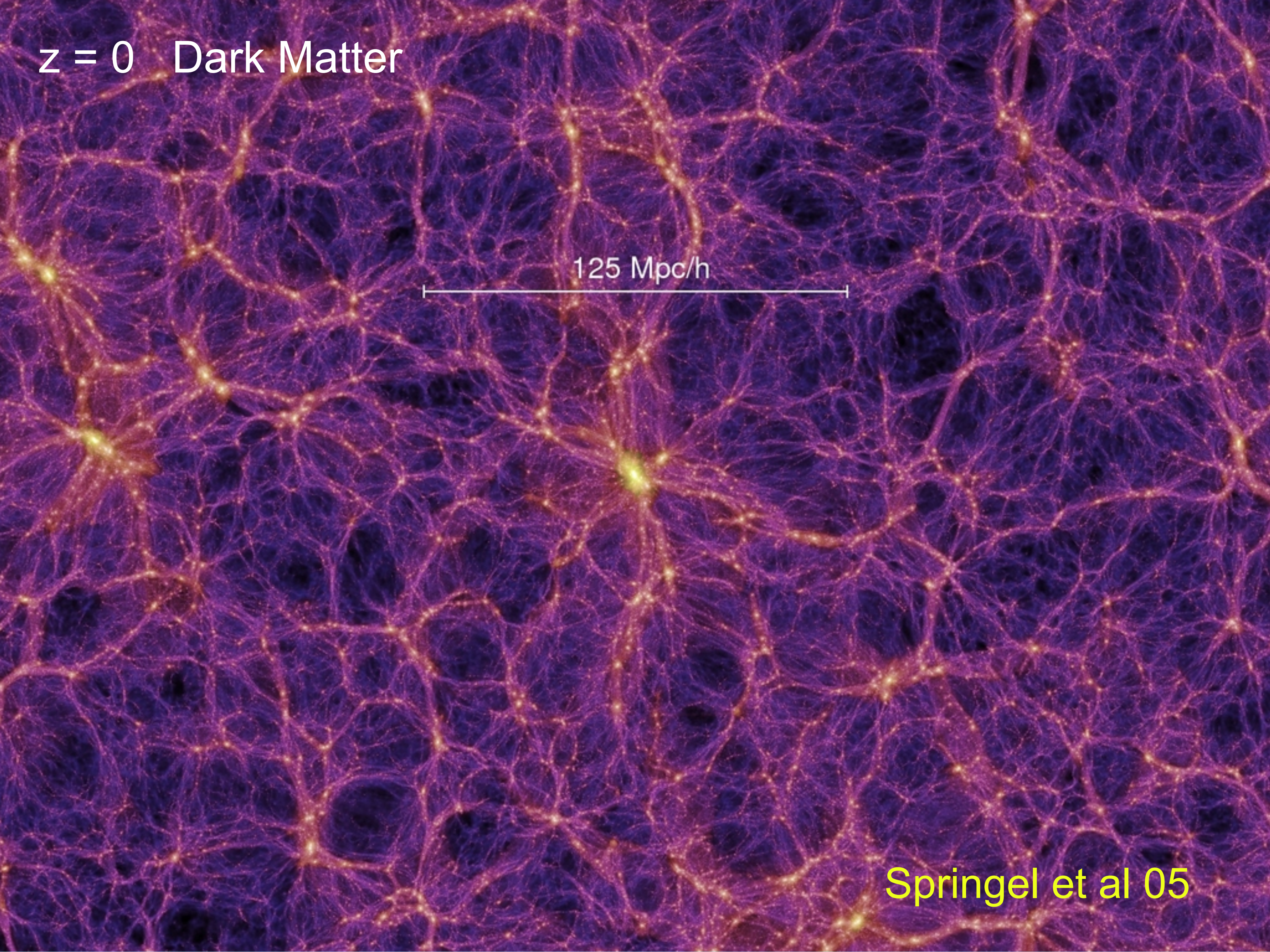
~500,000 galaxy redshifts

The 2dF Galaxy Redshift Survey

221,000 redshifts

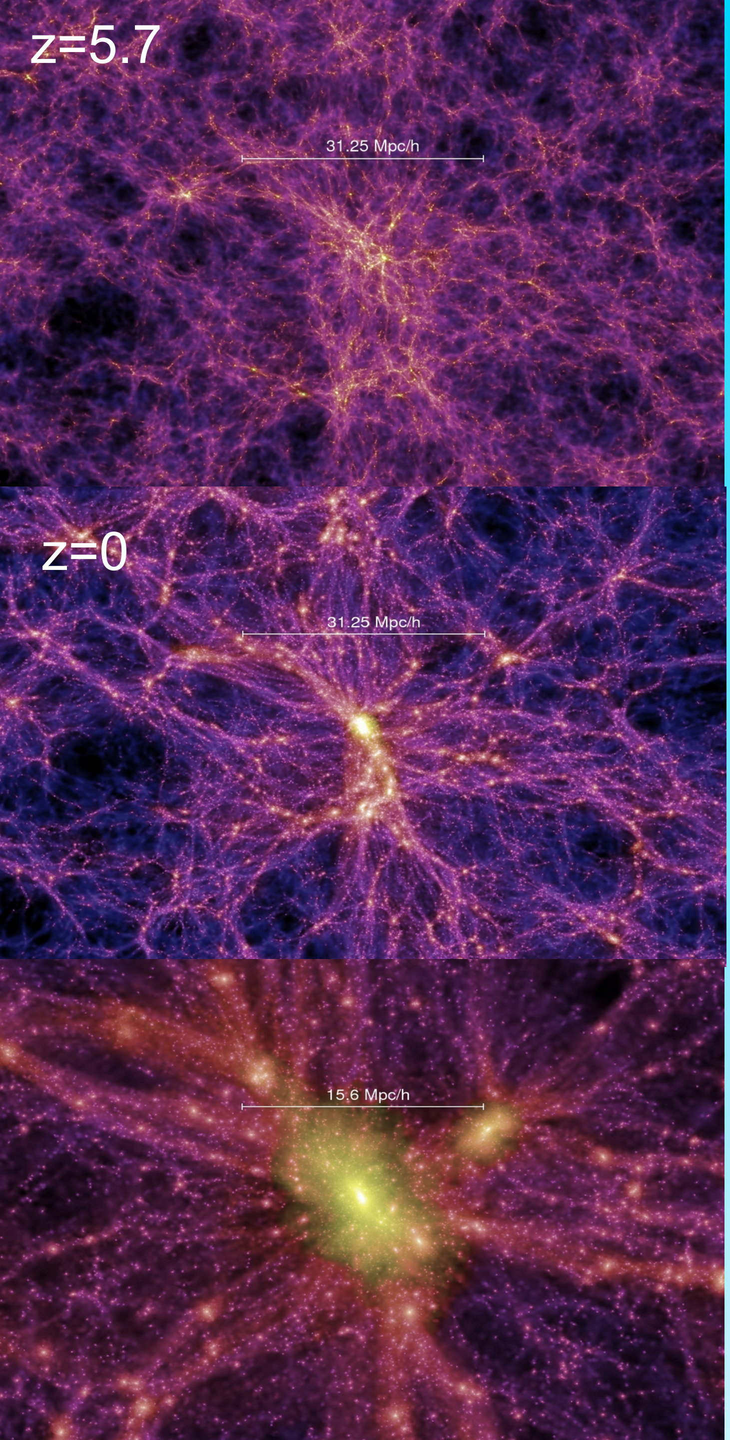
$z \sim 0$

2005



z = 0 Dark Matter

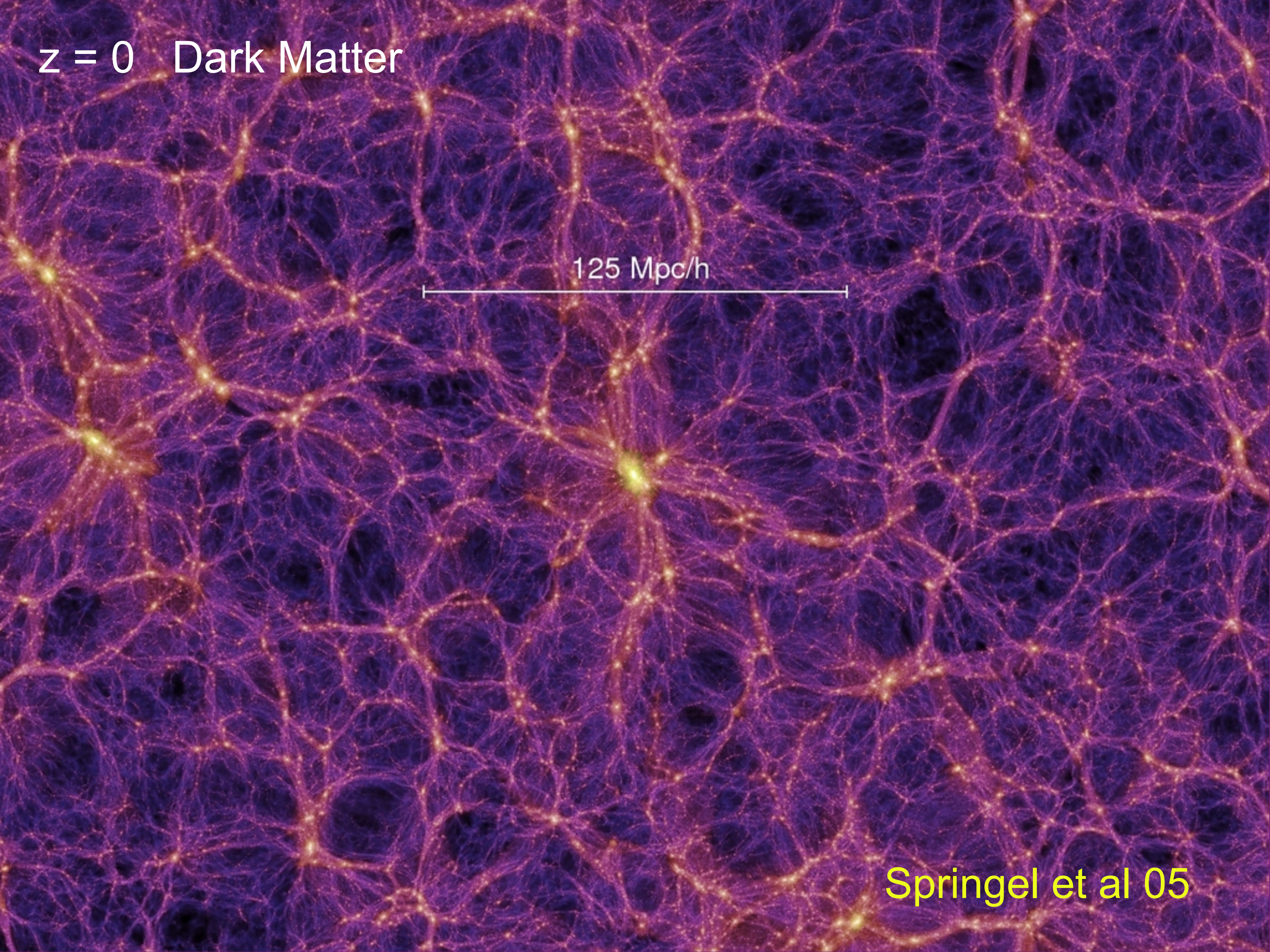
Springel et al 05



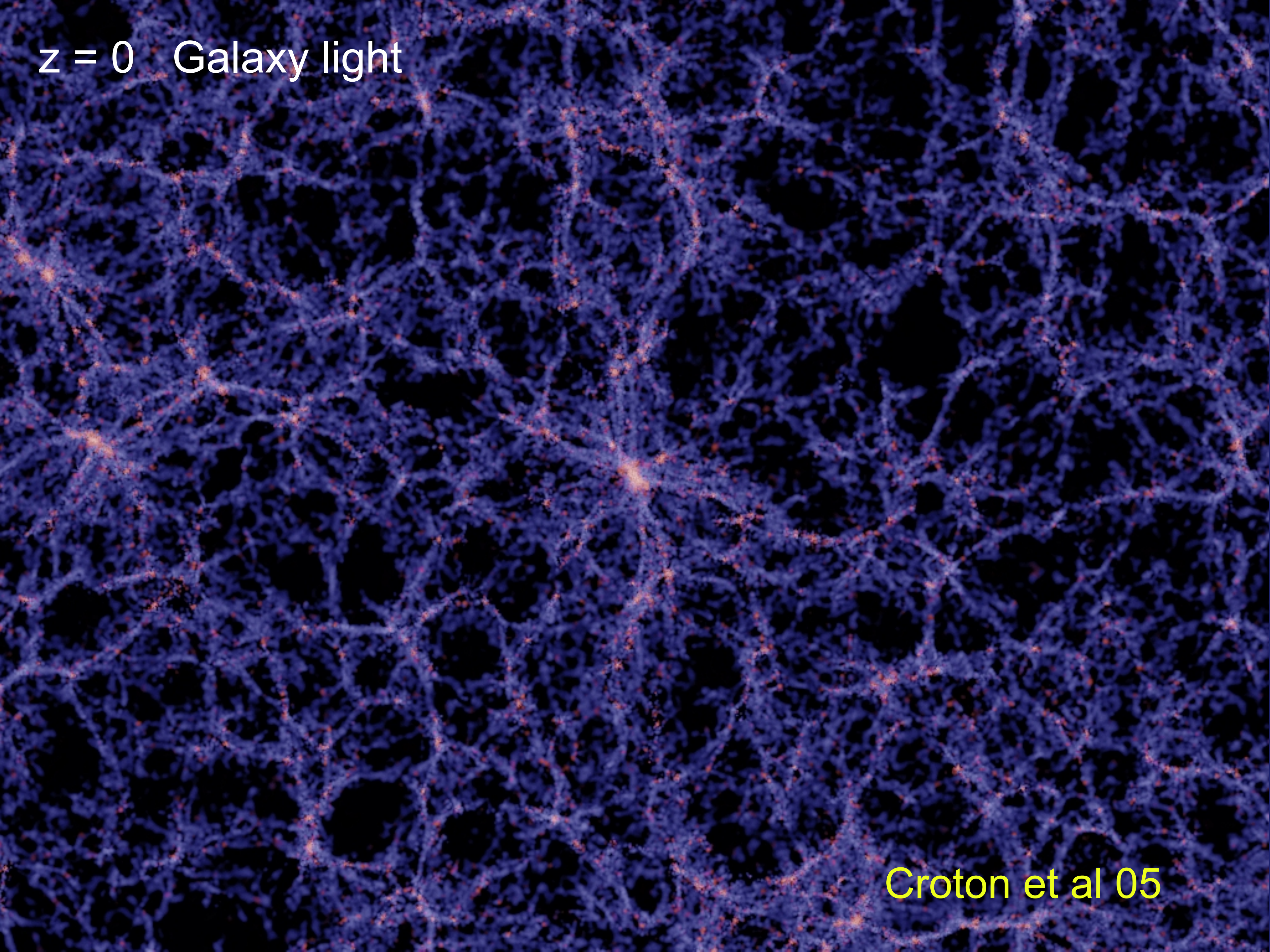
Galaxy formation theory

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

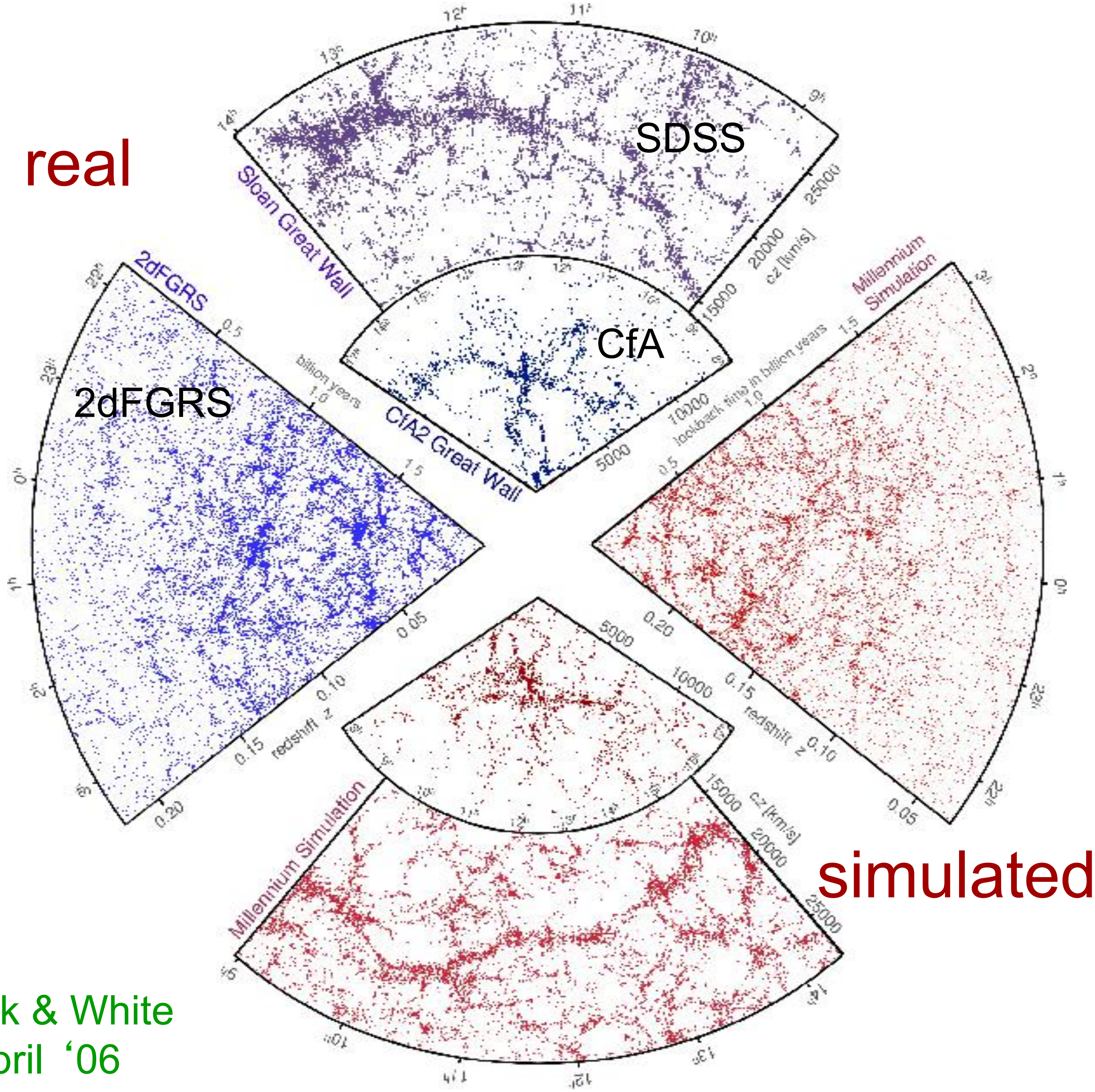


Springel et al 05



z = 0 Galaxy light

Croton et al 05



real

SDSS

CfA

2dFGRS

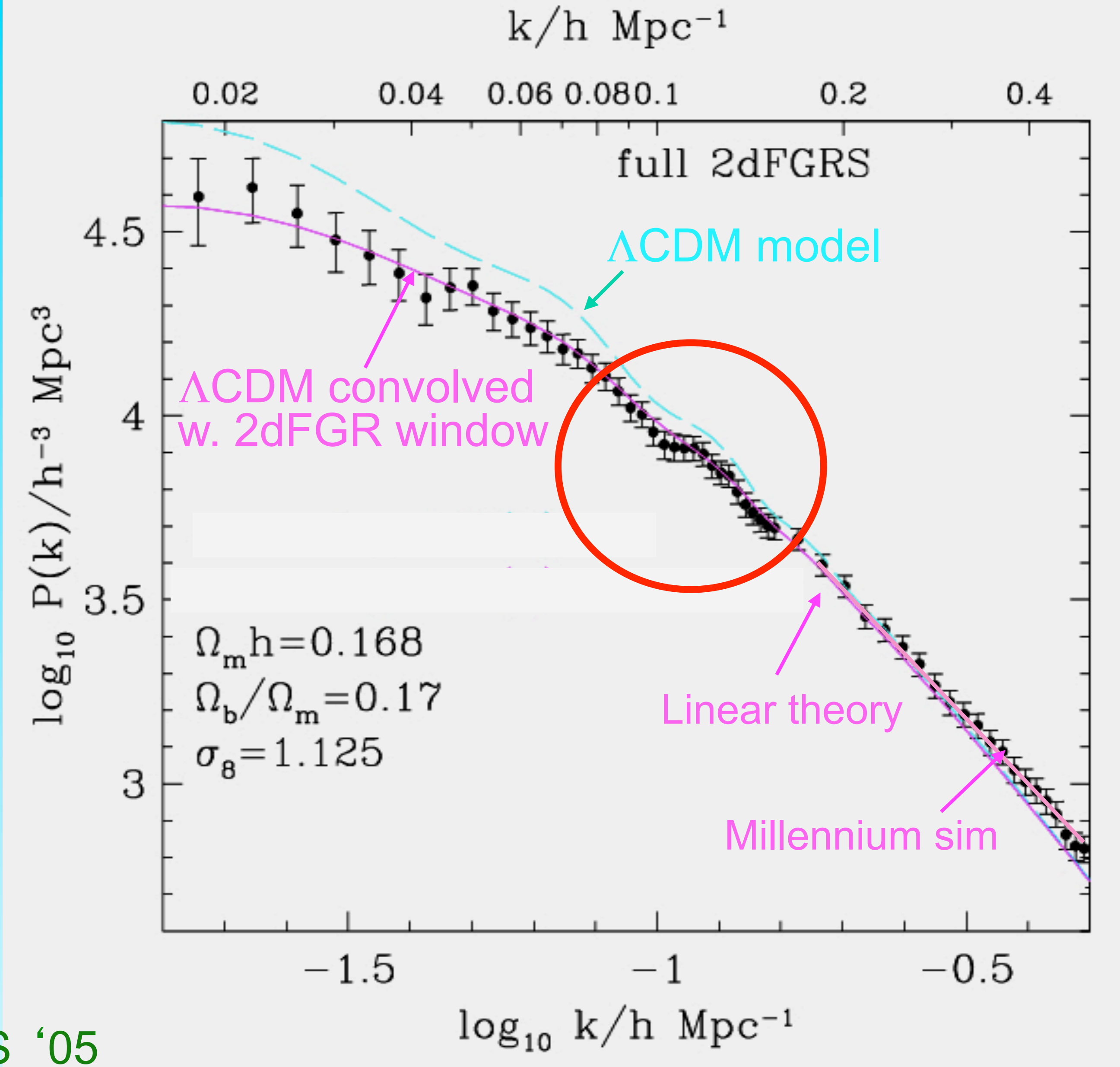
simulated

Springel, Frenk & White
Nature, April ‘06

University of Durham

The final 2dFGRS power spectrum

2dFGRS P(k) well fit by ΛCDM model convolved with window function

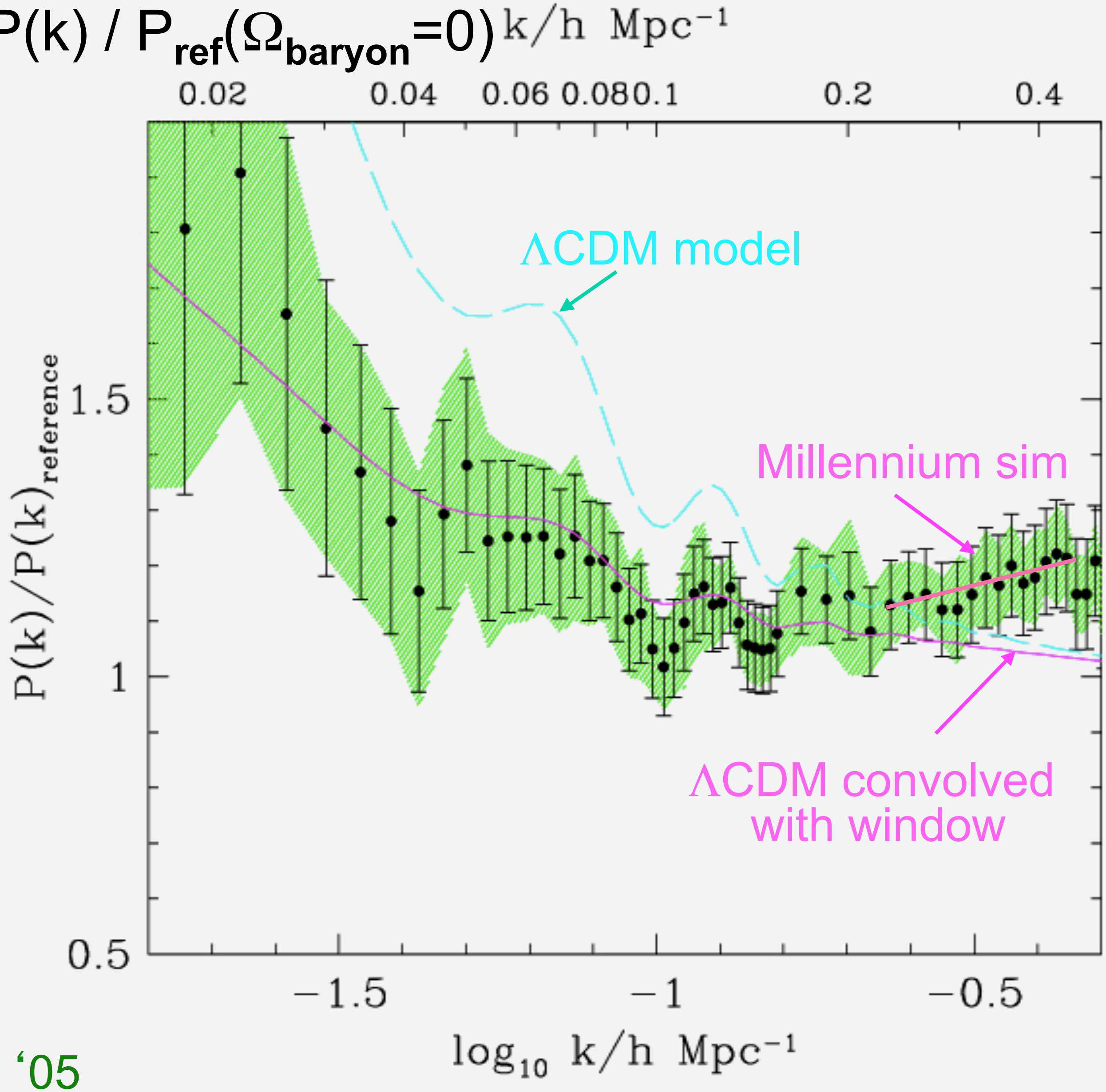


Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS ‘05

Baryon acoustic oscillations in 2dFGRS

220,000 redshifts

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



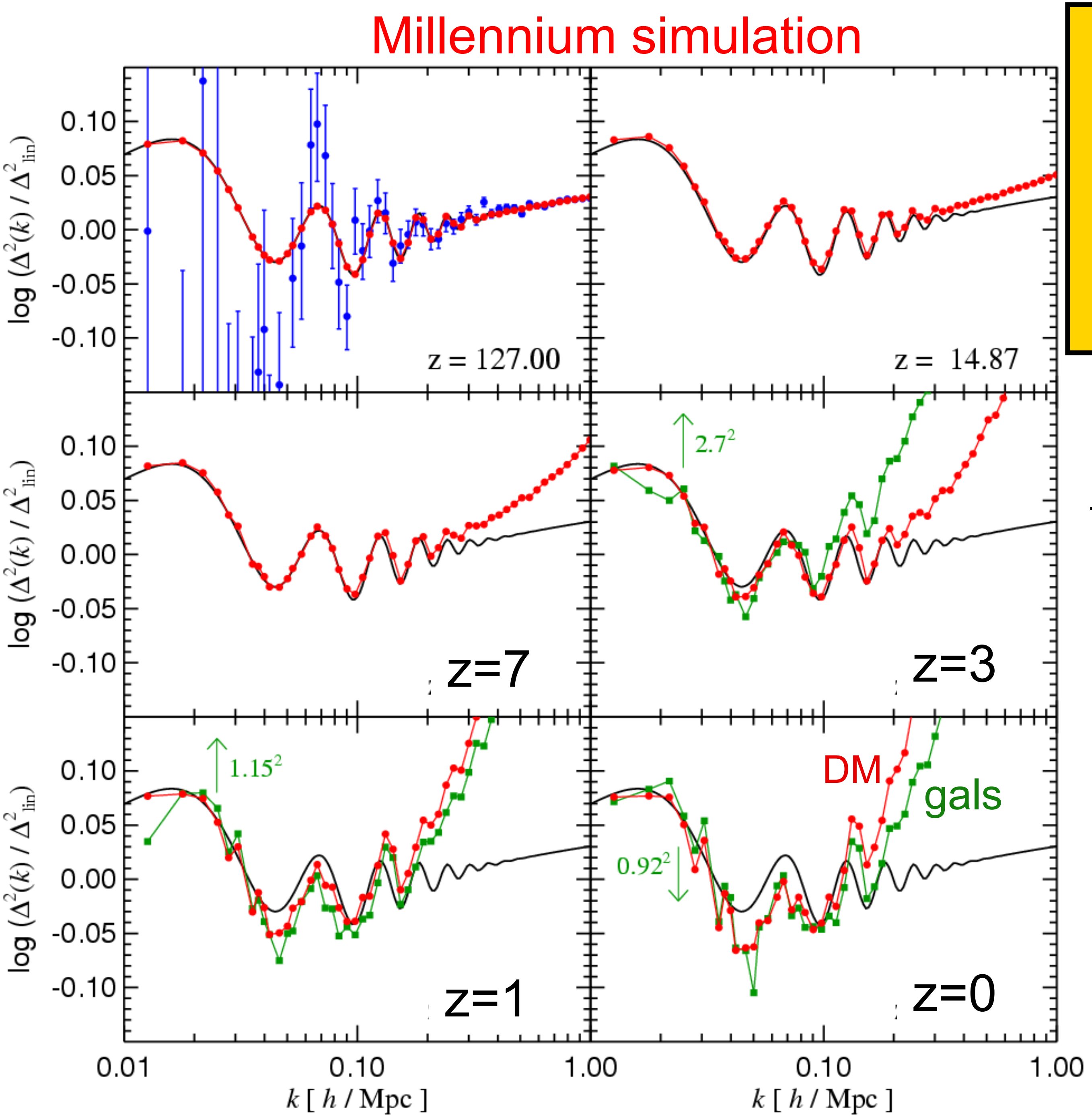
ΛCDM model

Millennium sim

ΛCDM convolved with window

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

Baryon wiggles in the galaxy distribution



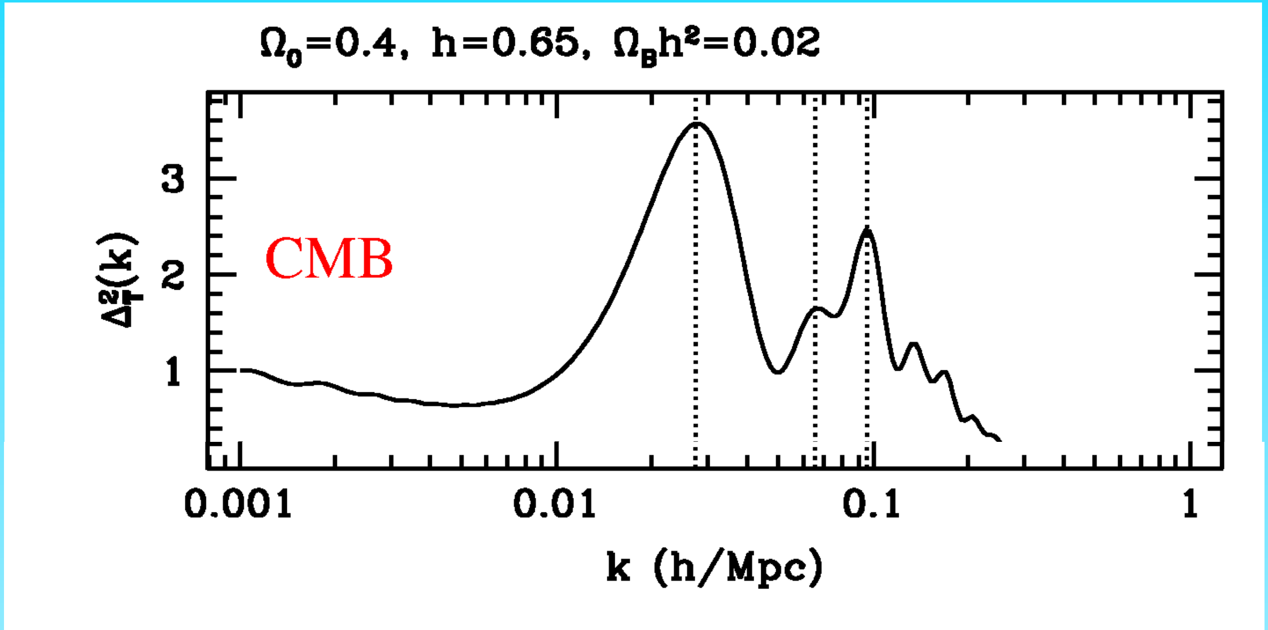
Power spectrum from MS divided by a baryon-free ΛCDM spectrum

Galaxy samples matched to plausible large observational surveys at given z

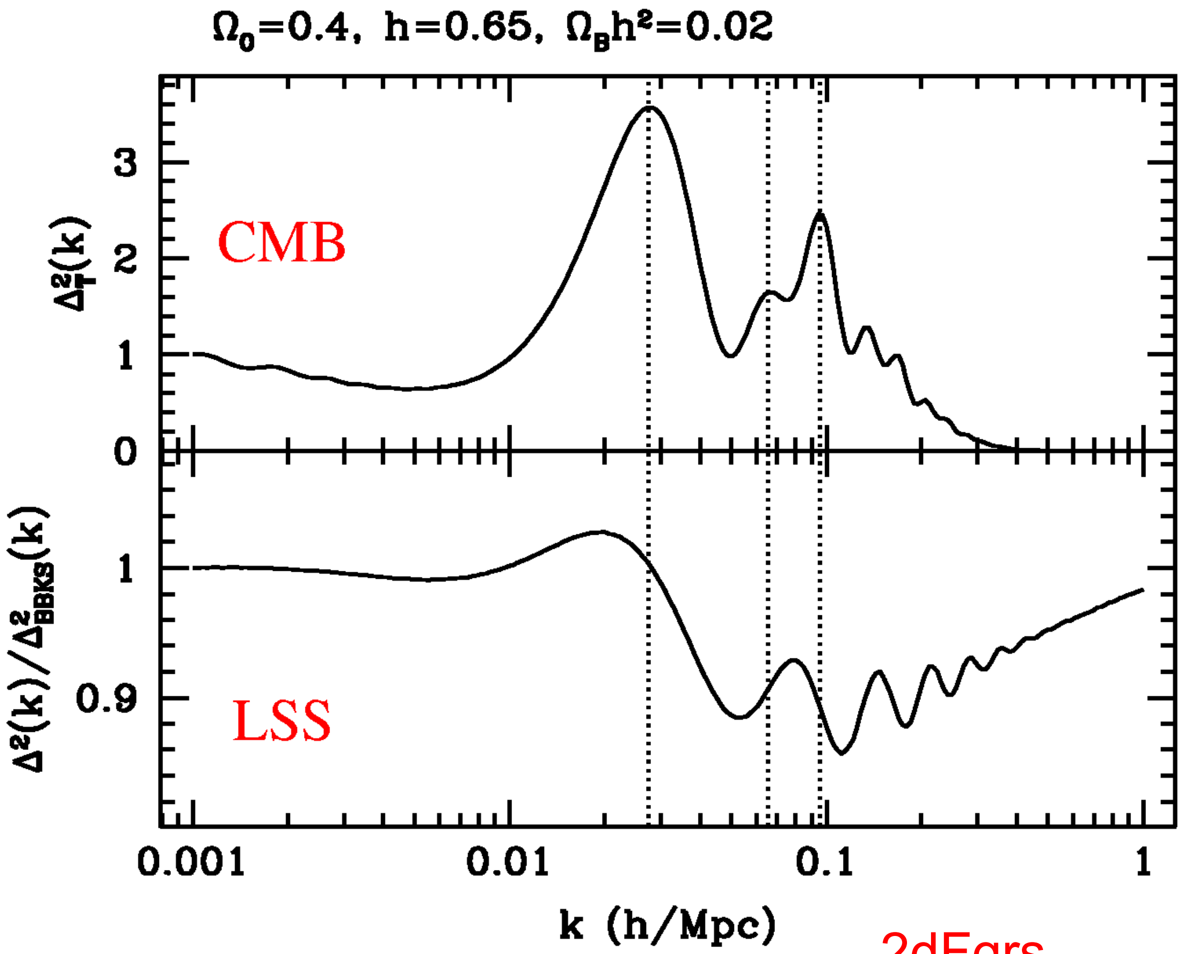
Springel et al 2005

University of Durham

CMB anisotropies and large-scale structure



CMB anistropies and large-scale structure



2dFgrs

CMB and LSS out of phase:

'velocity overshoot'

LSS amplitude smaller than CMB

Meiksin etal 99

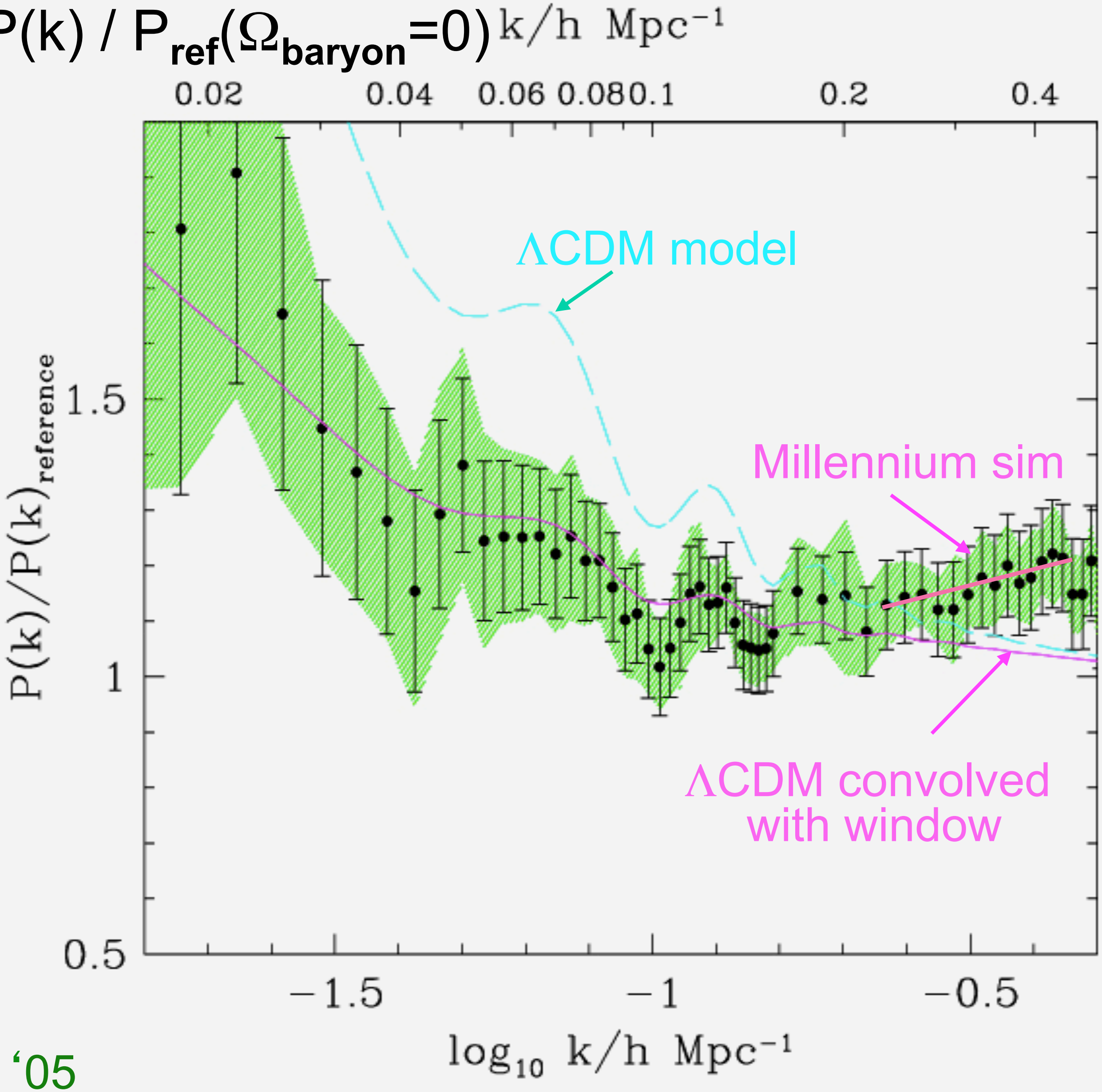
University of Durham

Baryon acoustic oscillations in 2dFGRS

220,000 redshifts

Baryon oscillations conclusively detected in 2dFGRS!!!

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



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

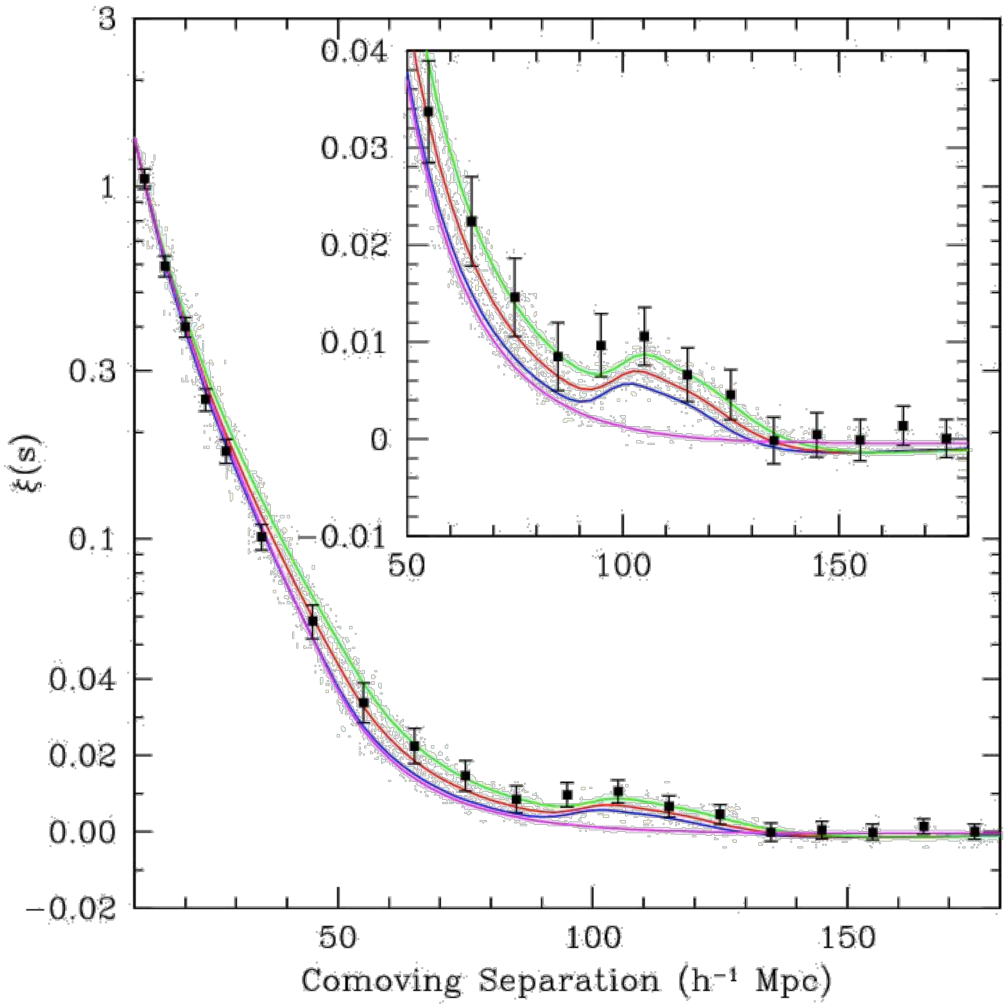
Baryon acoustic oscillations in SDSS

- 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

University of Durham

Baryon acoustic oscillations in 2dFGRS

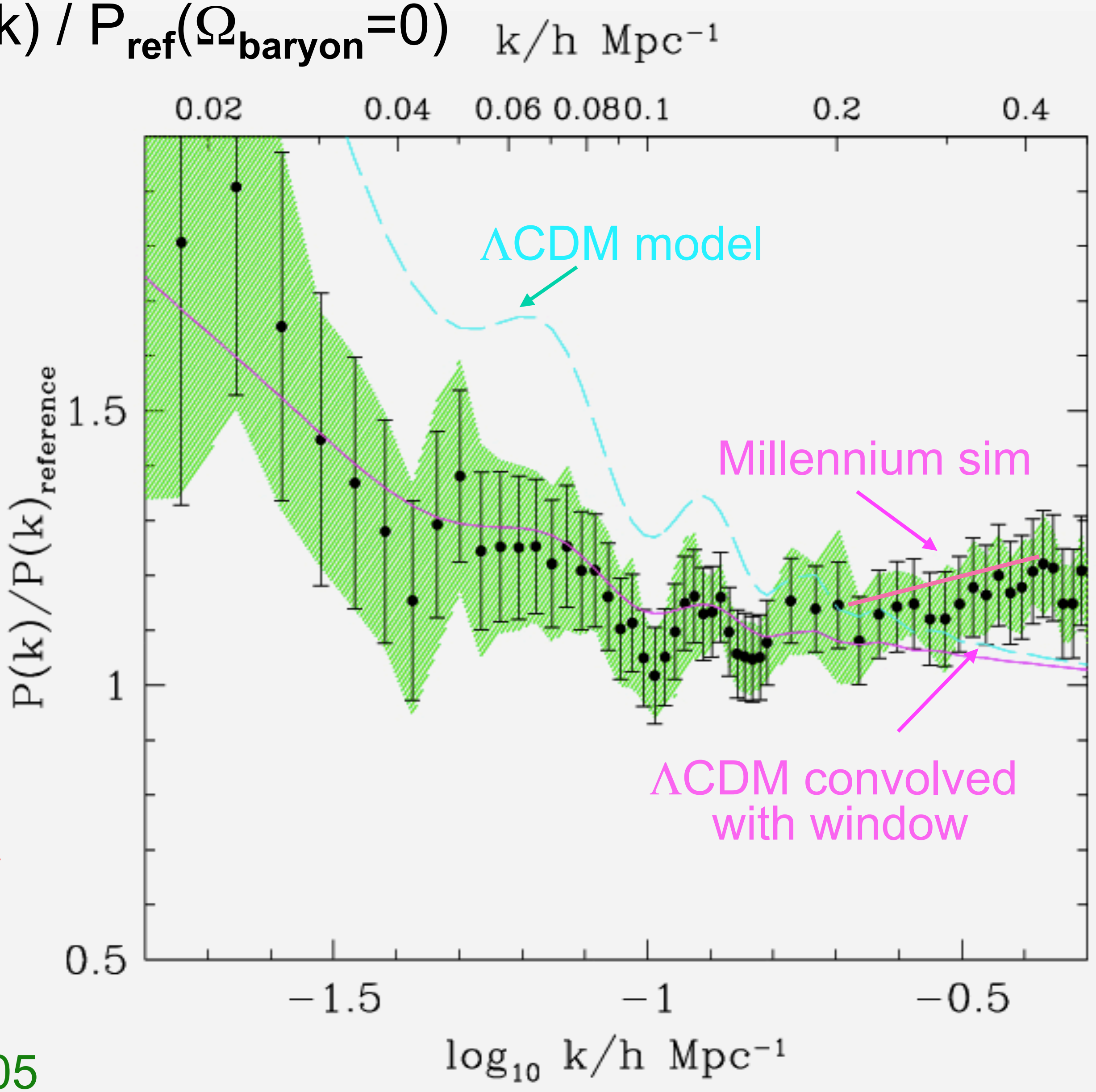
Baryon oscillations in 2dFGRS ➔

- 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

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



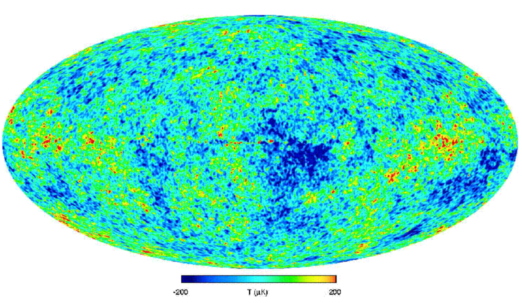
ΛCDM model

Millennium sim

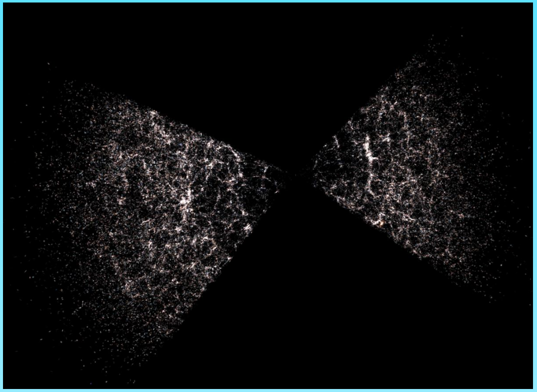
ΛCDM convolved with window

University of Durham

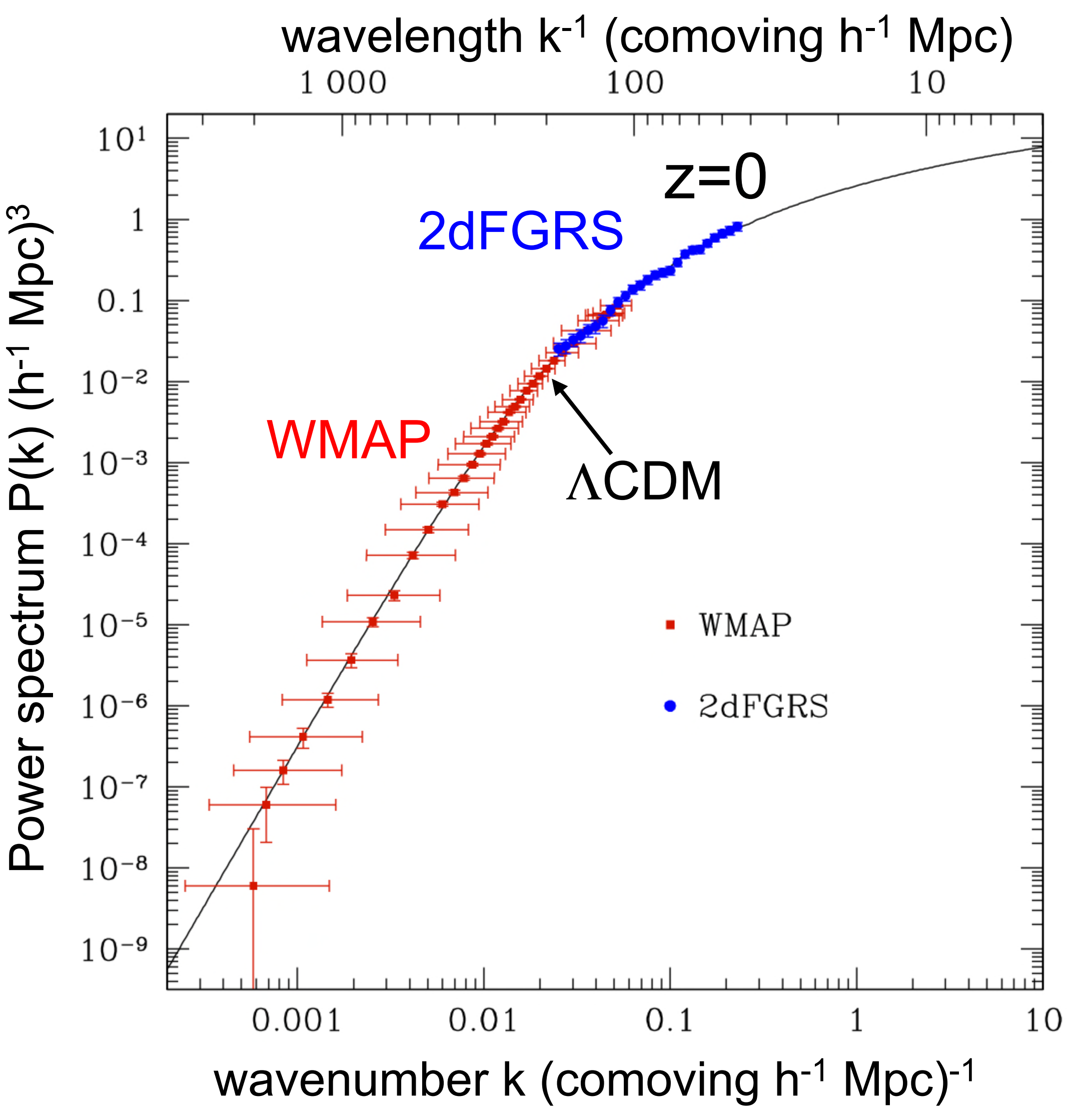
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



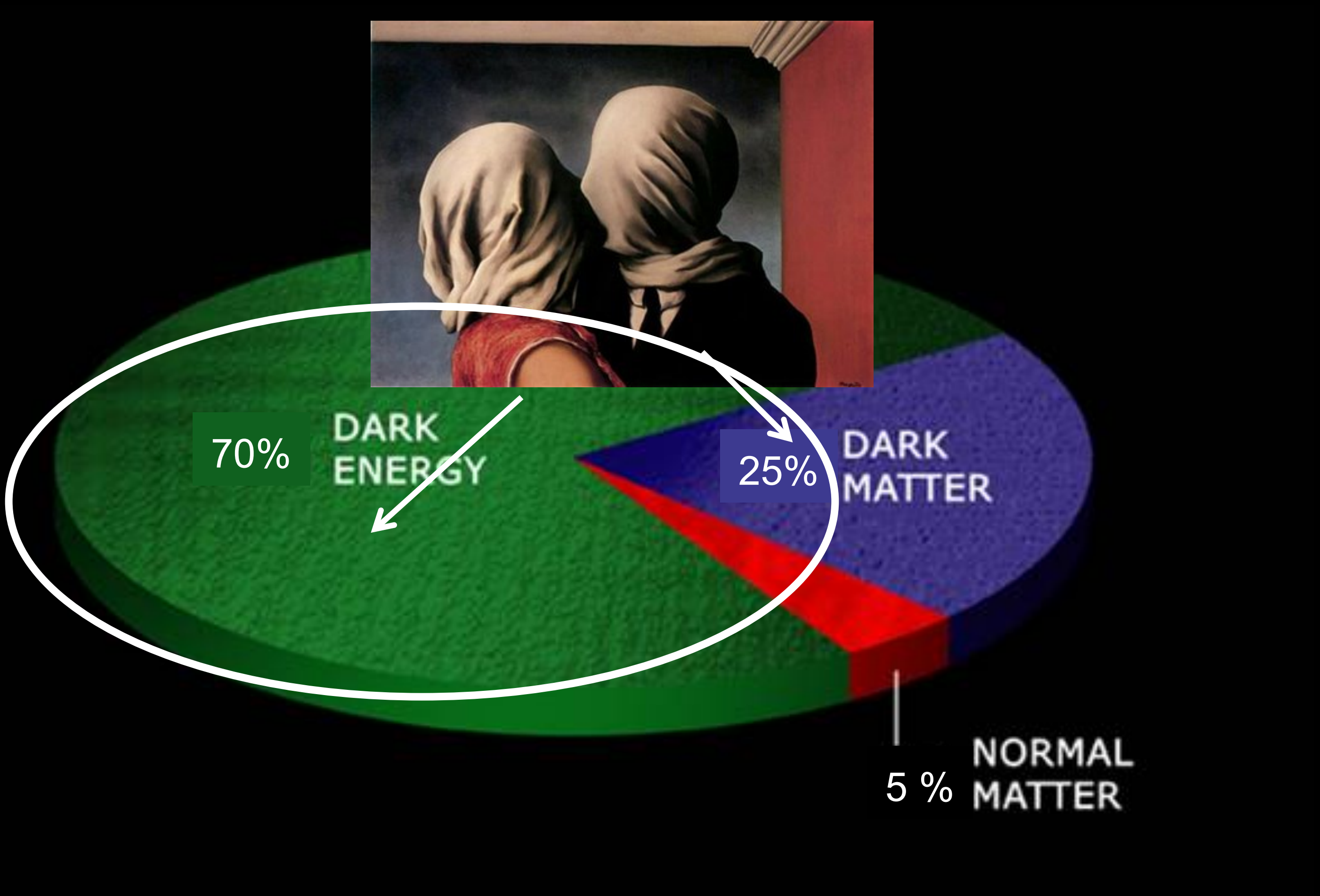
z~0



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

Sanchez et al 06

What next in studies of LSS?



What next?

Understanding the accelerated expansion

At present 3 possibilities :

- Einstein's cosm. const. Λ – constant (vacuum?) energy density
- Quintessence – a variable (in time and space) form of Λ
- Modifications of General Relativity – e.g. f(R)

What next?

Understanding the dark energy

Two approaches:

- Theoretical: string theory?
- Astronomical tests: constrain dark energy “models”
  - Geometrical (e.g. Ia SNe, BAO)
  - Dynamical (z-space distortions, cluster counts, lensing …)

Geometric tests

Within General Relativity:

Friedmann eqn (const w):

$$H^2(a) = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_K a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

matter

radiation

curvature

dark energy

D

(easy to extend to variable w(a))

Eqn of state: $w = \frac{P}{\rho}$

$$w(a) = w_0 + w_a(1-a)$$

Just need to measure H(a) → dist to source at z: D(z)=f(H(a))

- Standard candle – Type Ia SNe
- Standard ruler – BAO

$$D_A(z) \propto \int_0^z \frac{dz'}{H(z')}$$

Dynamical tests

Dark energy changes growth rate of structure

Relevant quantities are: δ_m, Ψ, Φ

$$d^2 s = -(1+2\Psi)dt^2 + (1-2\Phi)a^2 d\mathbf{x}^2$$

μ and γ encode theoretical information on dark energy or modified gravity in linear regime, with μ = γ = 1 for the standard LCDM paradigm

$$\ddot{\delta}_m + 2H(a)\dot{\delta}_m - 4\pi\mu(a,k)G\bar{\rho}_m(a)\delta_m = 0$$
$$\Phi = \gamma(a,k)\Psi$$

H(a) can be reconstructed from geometric observables, such as supernova luminosity distance and baryon acoustic oscillation

in principle, ψ+ϕ is measured by weak lensing and integrated Sachs Wolfe effect; ψ may be inferred from galaxy velocity measurements e.g., redshift space distortions; δ may be obtained from galaxy clustering and cluster counts; etc.

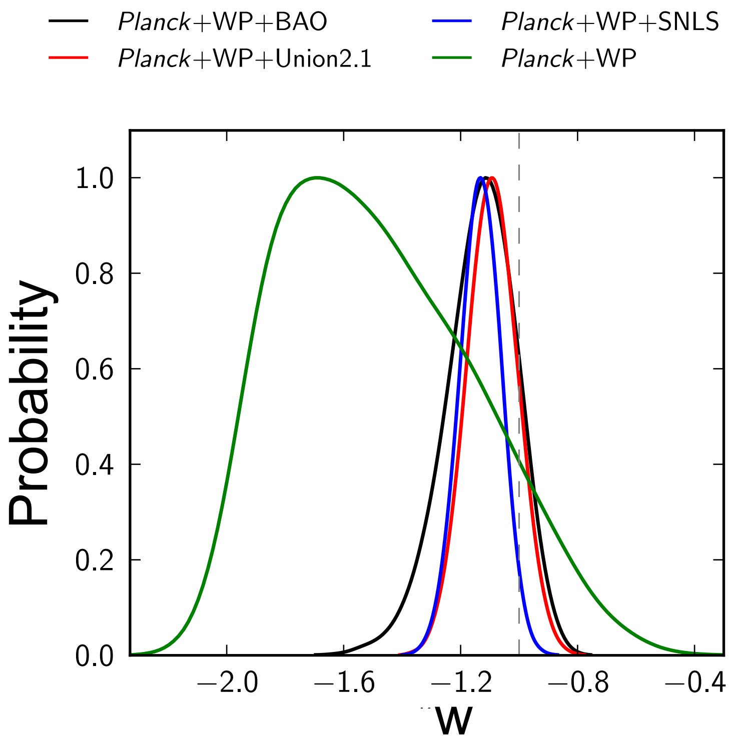
From Baojiu Li

What do we know already and how well do we need to do to go further?

University of Durham

Dark energy with different w
Constraints from Planck + other data

Constant w

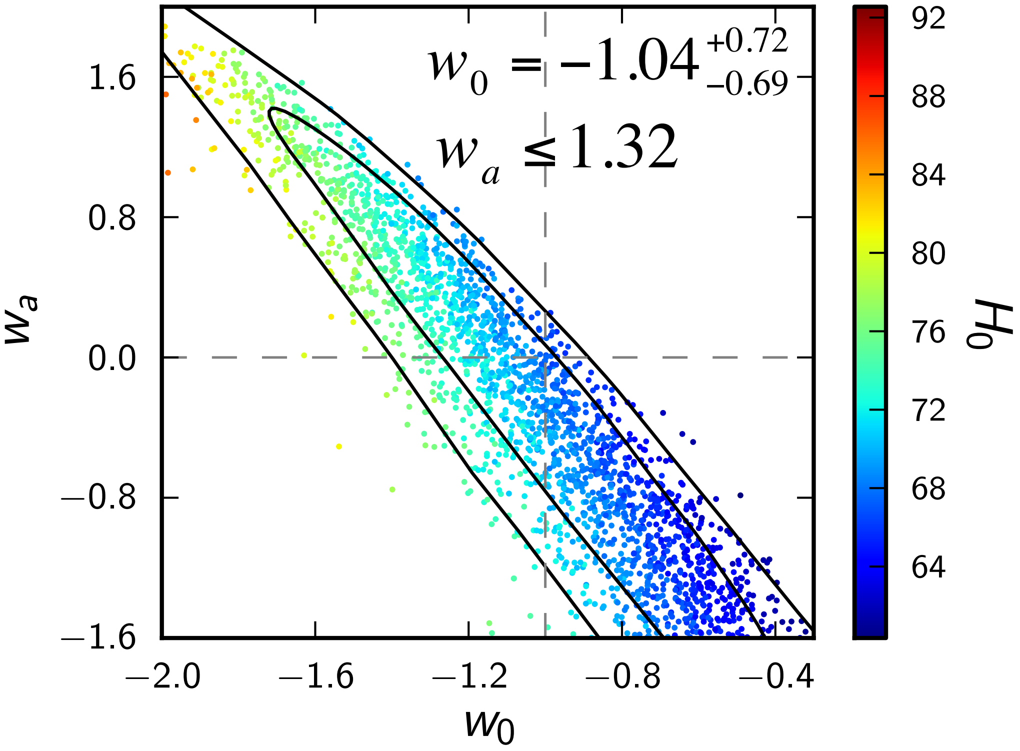


$$w = -1.13^{+0.13}_{-0.14}$$

(95% Planck+WP+SNLS)

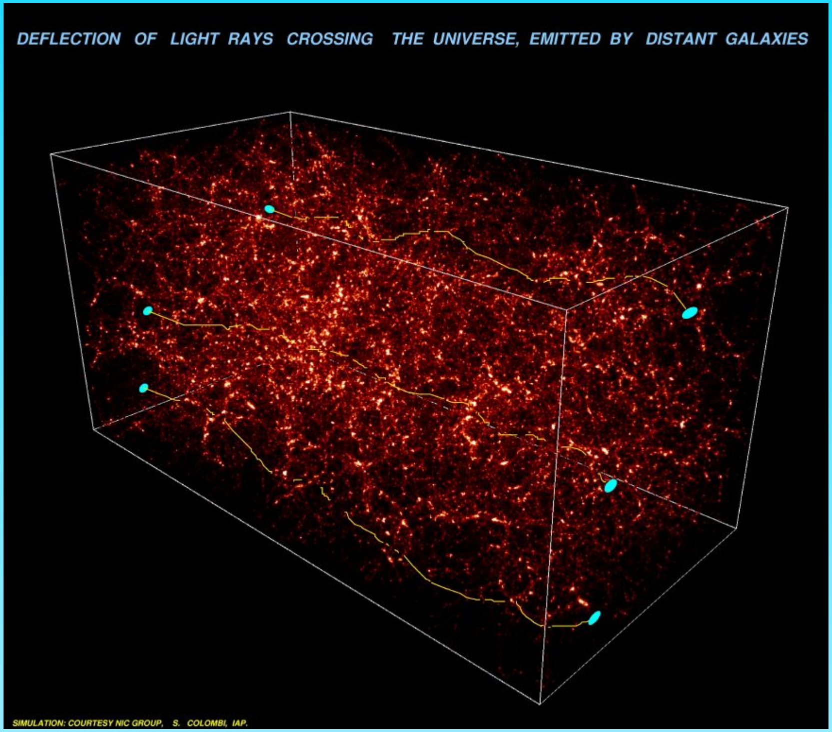
Quintessence (variable w(a))

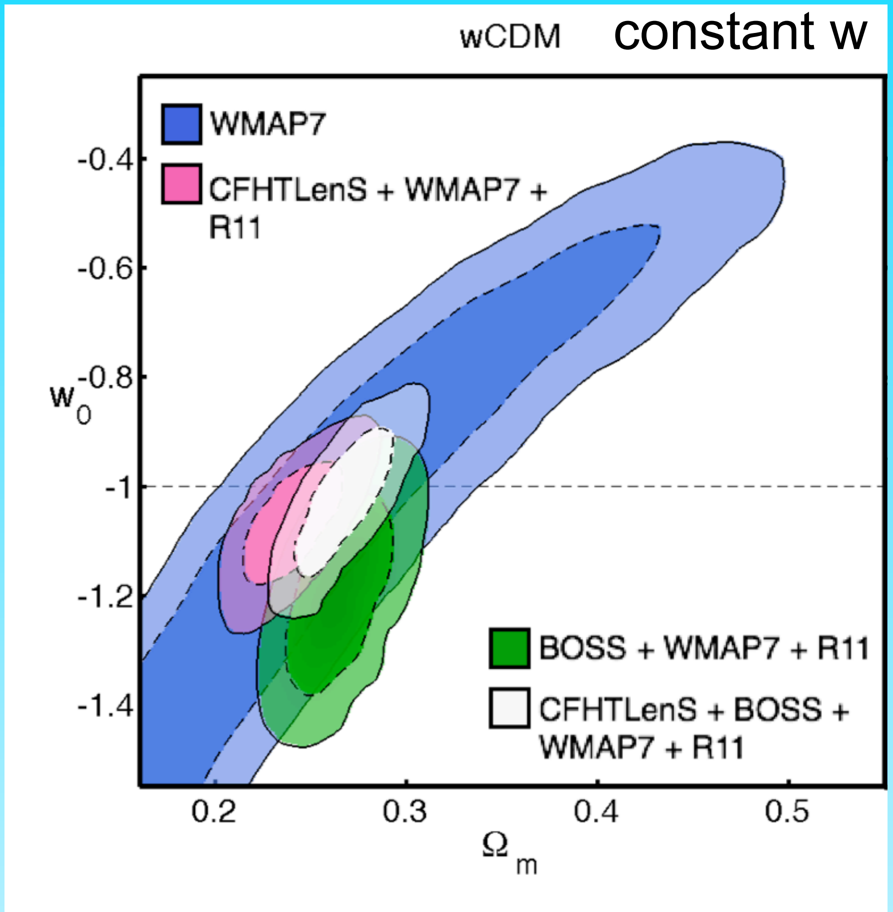
$$w(a) = \frac{P(a)}{\rho(a)} \qquad w(a) = w_0 + w_a(1 - a)$$



(95% Planck+WP+BAO)

Dark energy with different w
Constraints from lensing + other data





Gravitational lensing (shear) → amplitude of density fluctns

Tomography → growth rate of fluctns

w=-1.02 ± 0.9

Heynmans etal ‘13

University of Durham

How accurately do we need to measure the BAO scale?

$$p = w\rho c^2$$

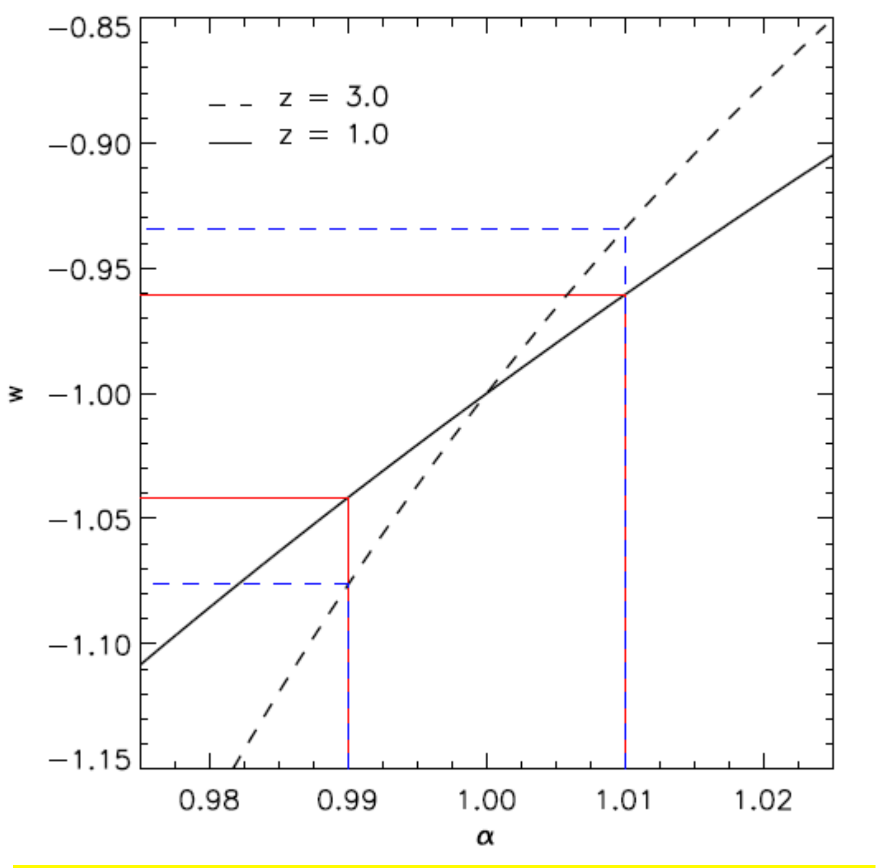
Hold other cosmological parameters fixed

- Δw ~ 7 Δs (z=3)
- Δw ~ 4 Δs (z=1)

k= 2π/s

α= k_{app}/k_{true}

Angulo et al . 2008



Dark energy equation of state

distance scale measurement

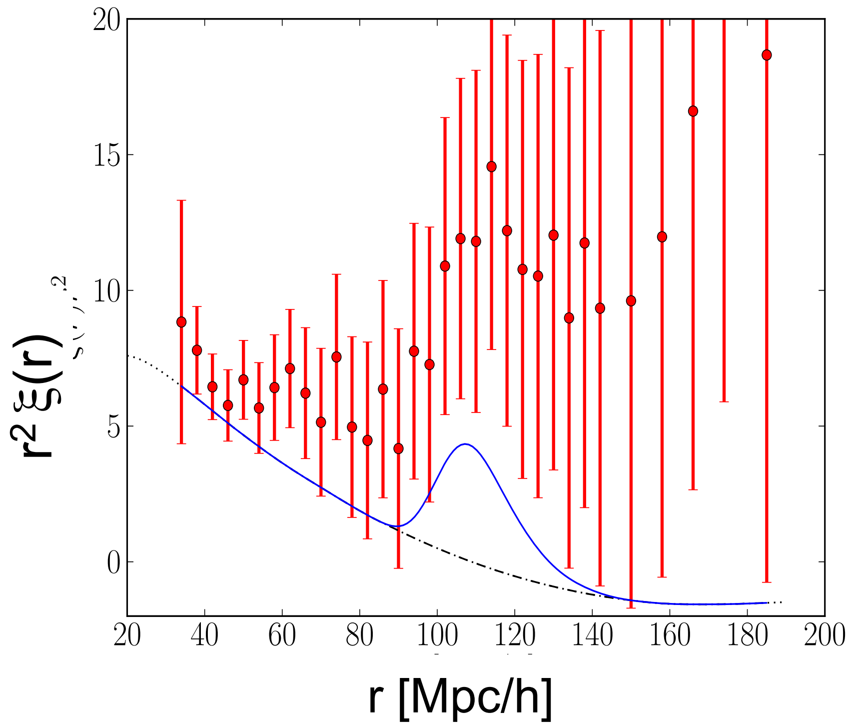
Detection of BAO in Lyman-α forest

BOSS survey: detection of BAO in Ly-α forest at z=2.4

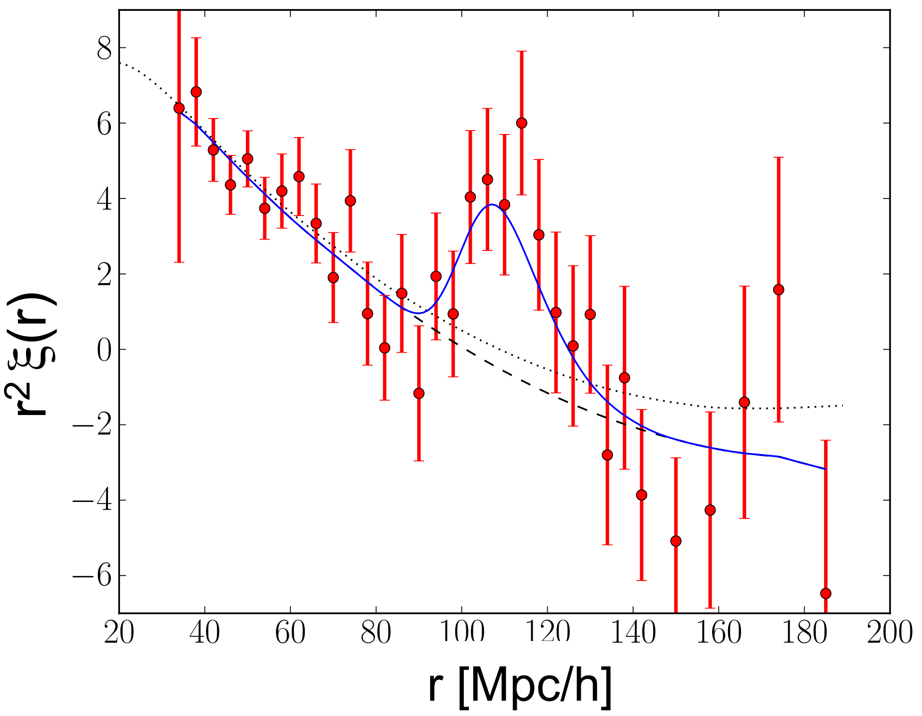
→ ideal for measuring w(a)

Slosar et al '13

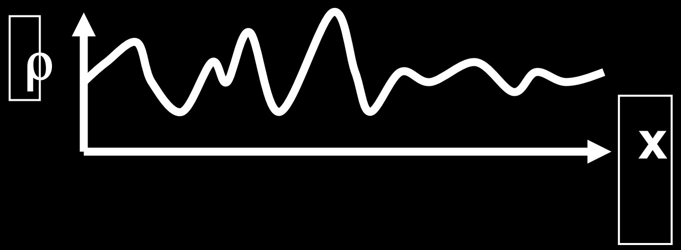
… in principle



… after some massaging

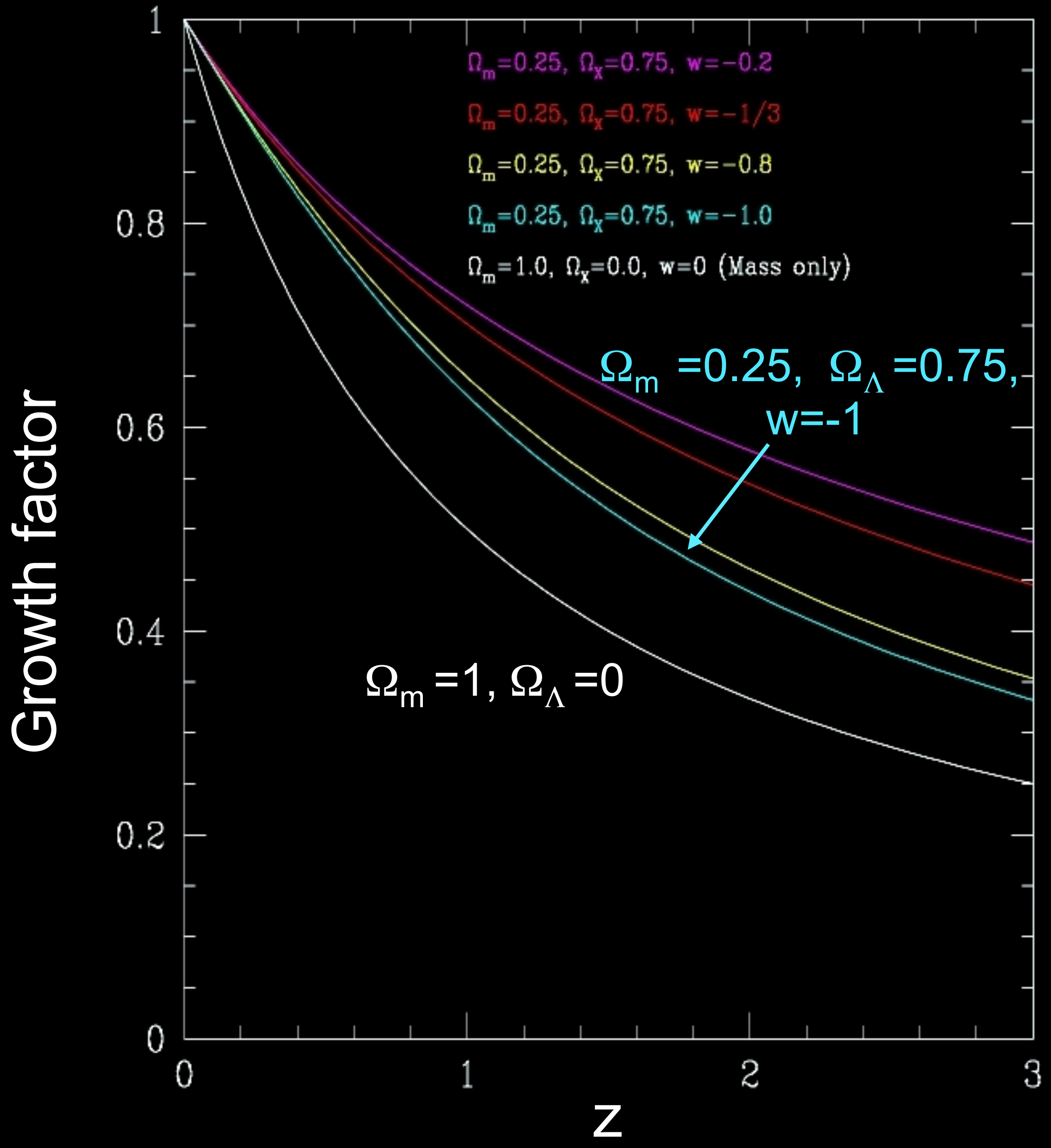


Linear theory: fluctuation growth rate



The growth rate of density fluctuations depends on Ω_m , Ω_Λ and w

(At high-z, the growth rate always approaches the Ω_m =1 case)

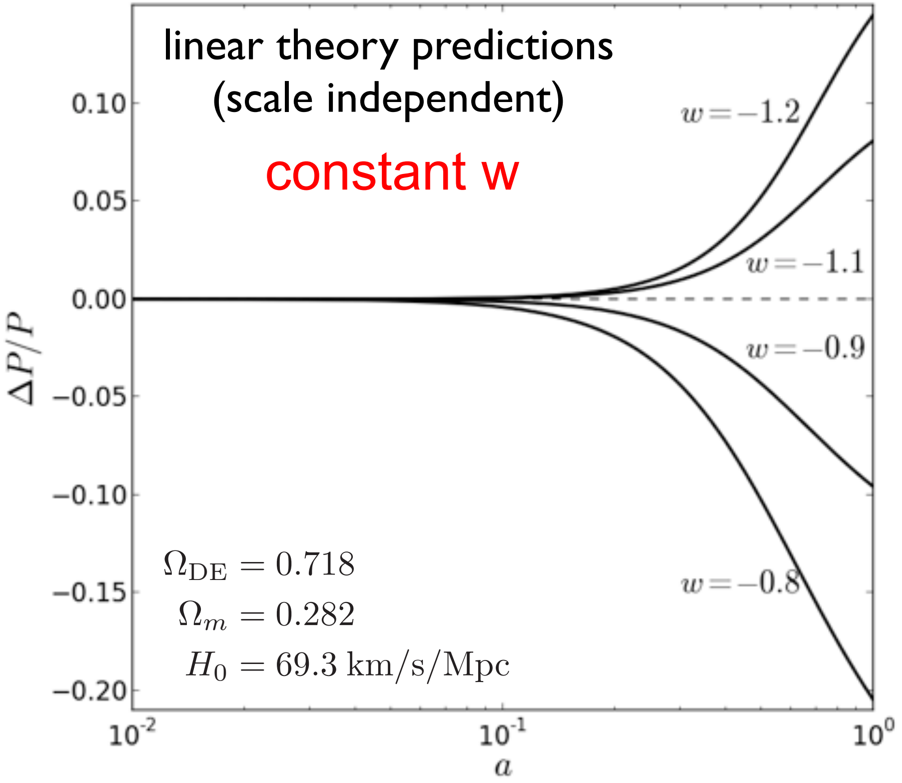


Dark energy with different w

$$\ddot{\delta}_m + 2H(a)\dot{\delta}_m - 4\pi G\left[\bar{\rho}_m(a)\delta_m + \bar{\rho}_{\rm DE}(a)\delta_{\rm DE}\right] = 0$$

expansion history is modified

negligible, as dark energy clusters very weakly



linear theory predictions (scale independent)

constant w

relative difference from LCDM spectrum

cosmic scale factor

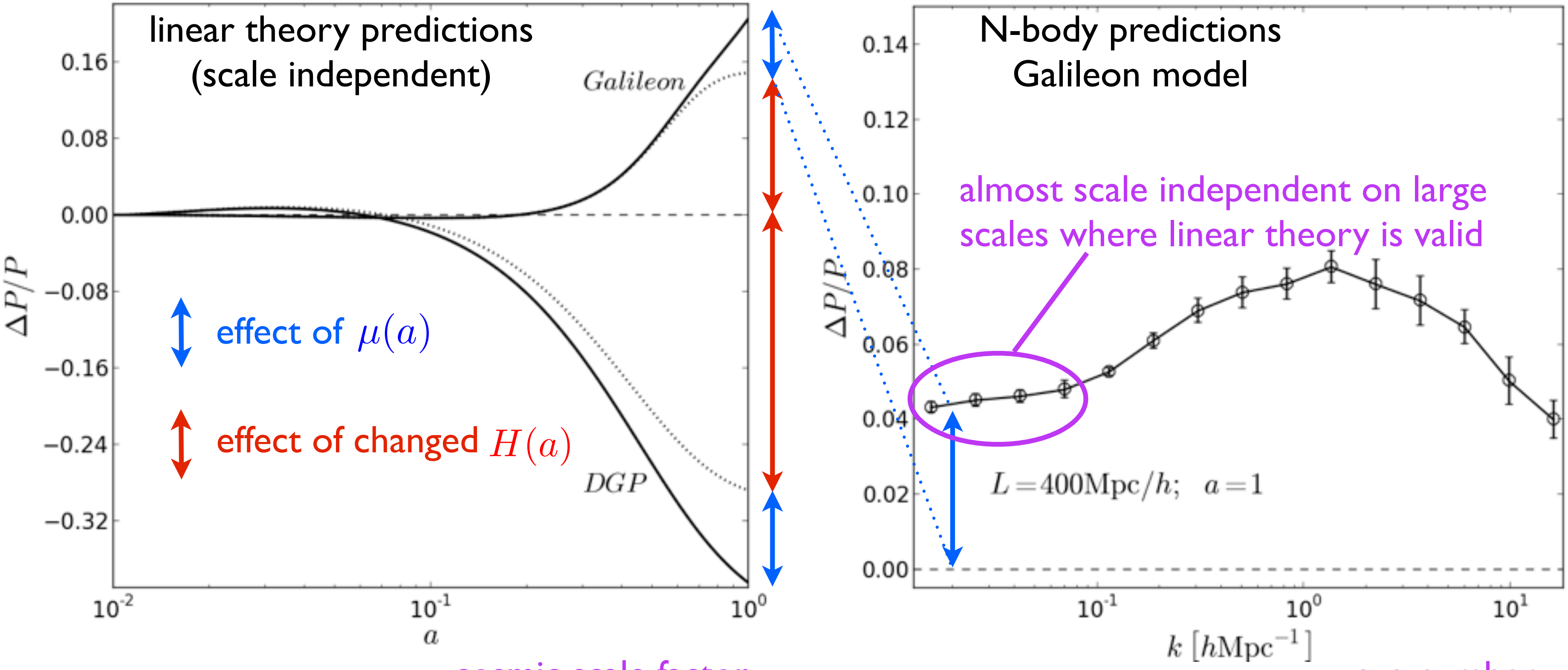
Differences from ΛCDM of only a few %

Modified gravity: DGP and Galileon

$$\ddot{\delta}_m + 2H(a)\dot{\delta}_m - 4\pi\mu(a)G\bar{\rho}_m(a)\delta_m = 0$$

expansion history is modified

strength of gravity varies with time but is scale-independent



linear theory predictions
(scale independent)

effect of $\mu(a)$

effect of changed $H(a)$

N-body predictions
Galileon model

almost scale independent on large scales where linear theory is valid

relative difference from GR spectrum

cosmic scale factor

wave number

From Baojiu Li

University of Durham

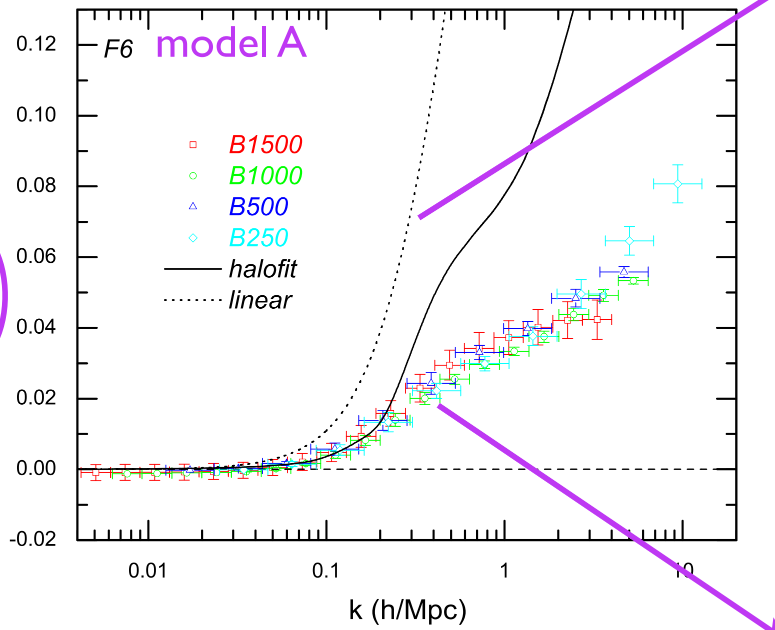
Modified gravity: f(R) gravity

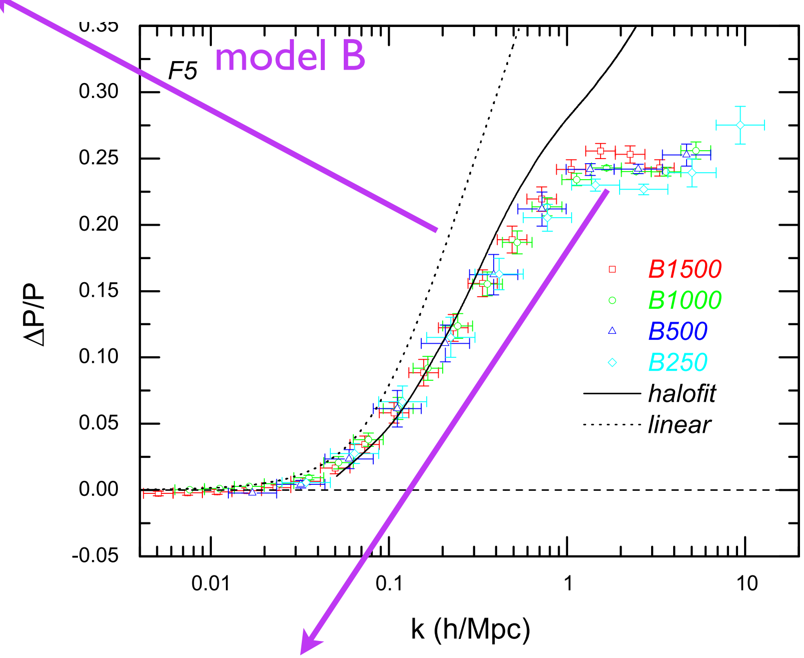
$$\ddot{\delta}_m + 2H(a)\dot{\delta}_m - 4\pi\mu(a,k)G\bar{\rho}_m(a)\delta_m = 0$$

expansion history mimics LCDM

strength of gravity varies with both time and scale

scale-dependent difference in linear theory



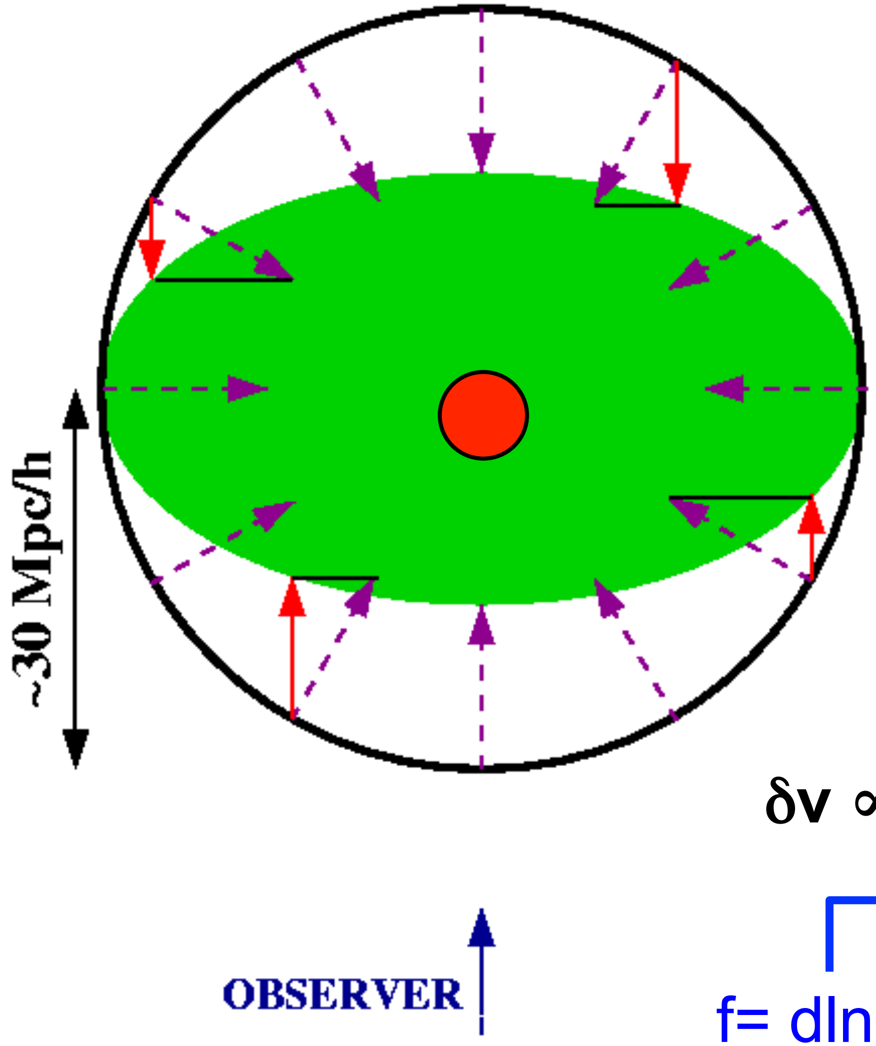


relative difference from
LCDM power spectrum

nonlinearity suppresses the
difference in full simulations

From Baojiu Li

Redshift space distortions



Large Scale Flattening Due To Coherent Cluster Infall

$$v_{obs} = v_{true} + \delta v$$

$$\delta v \propto f \, \delta\rho/\rho = f \, b^{-1} \, \delta n/n$$

f= dlnD/dlna

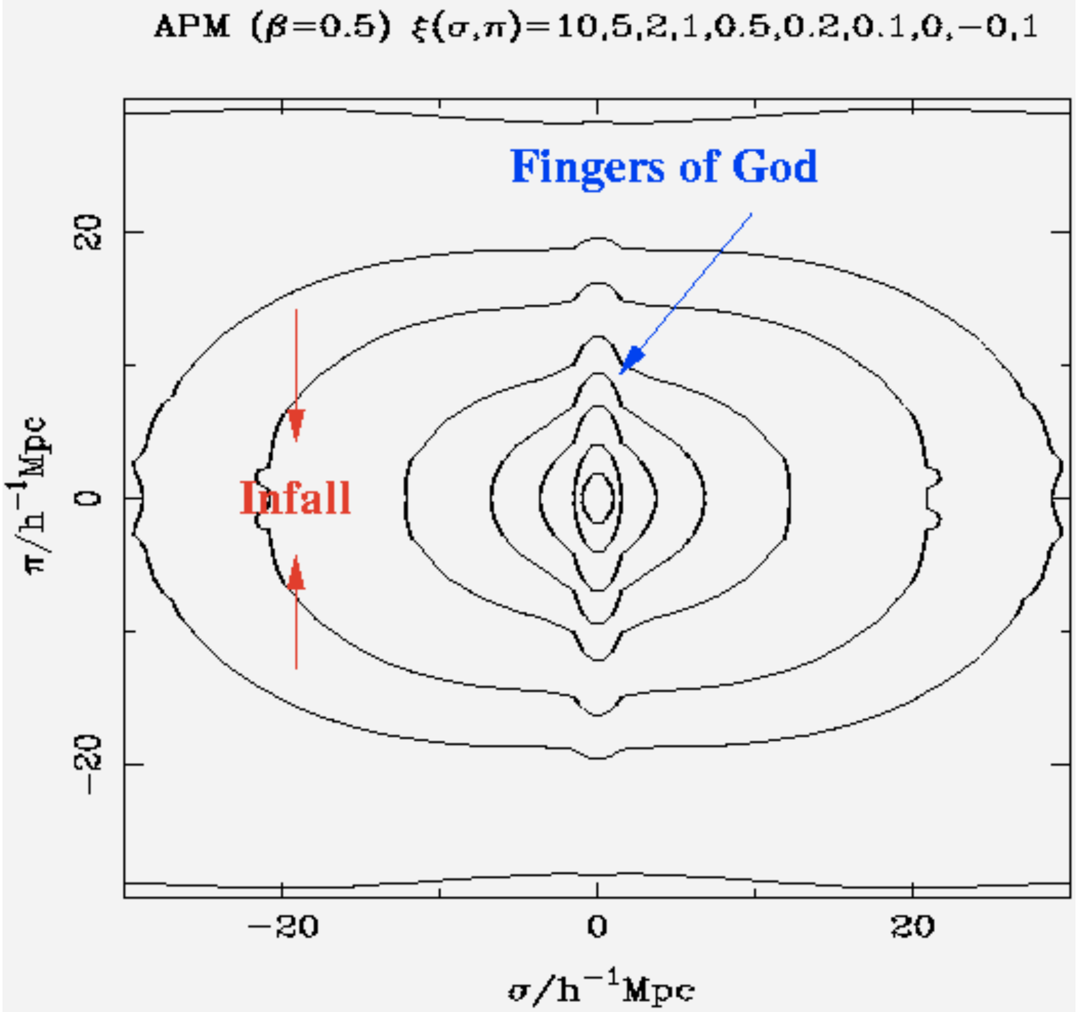
"bias" parameter

Kaiser 1987

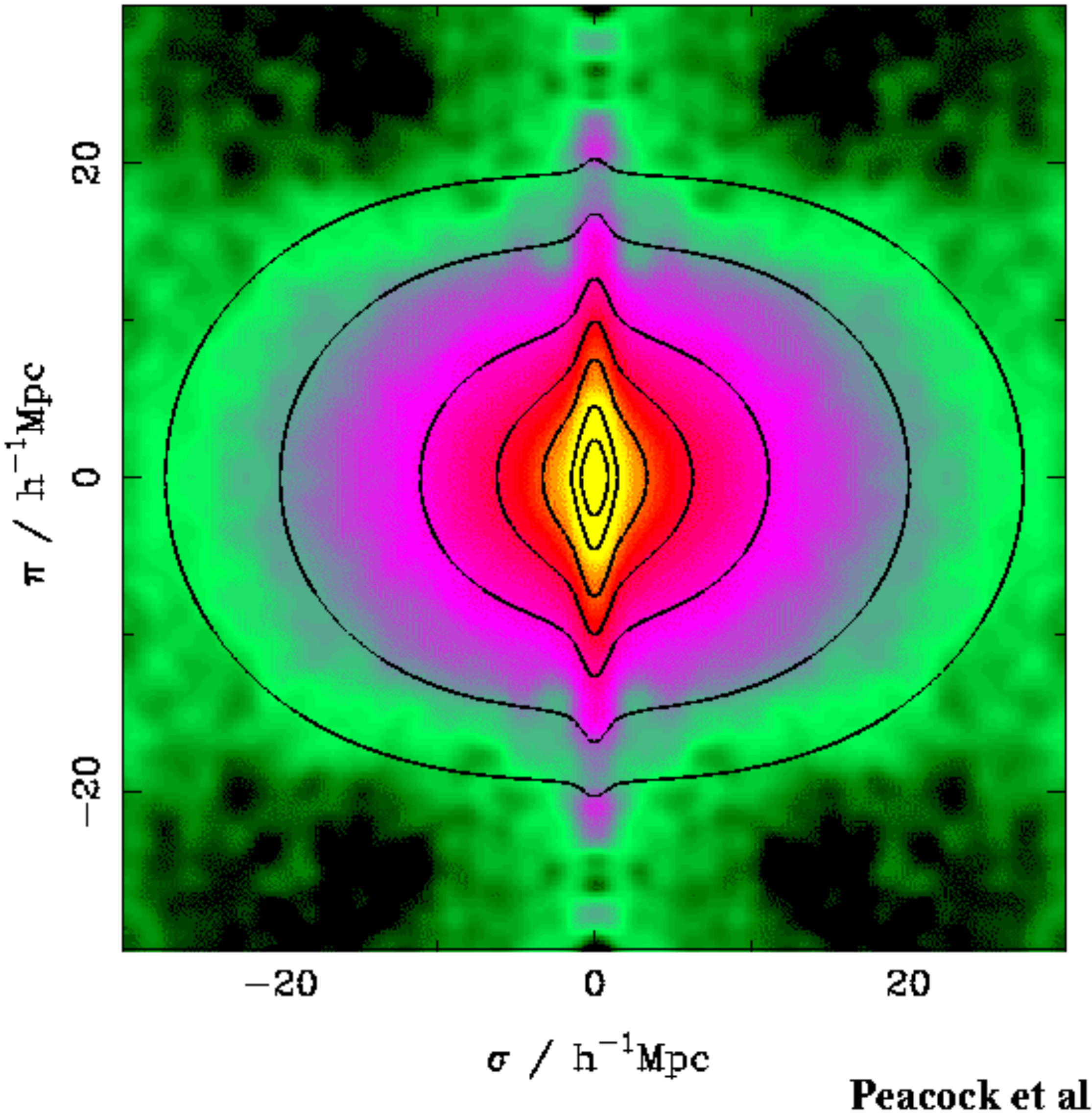
D(a) = linear growth factor

Flattening depends on $\beta=\Omega^{0.6}/b$

$\delta_{gal} = b\delta_{mass}$ $\quad$ 2dF $\longrightarrow$ β



2dF galaxy redshift survey



Large Scale Flattening Due To Coherent Cluster Infall measured via Redshift Space Galaxy Clustering

=> $\beta = \Omega^{0.6} / b$

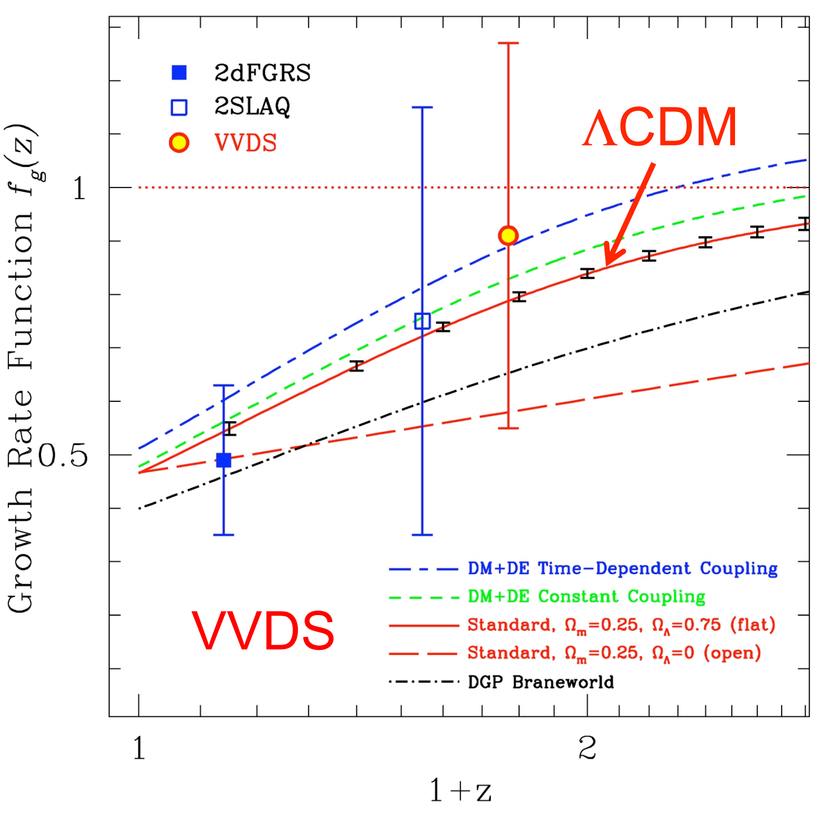
$= 0.43 \pm 0.07$

Peacock et al. , 2001, Nature, 410, 169

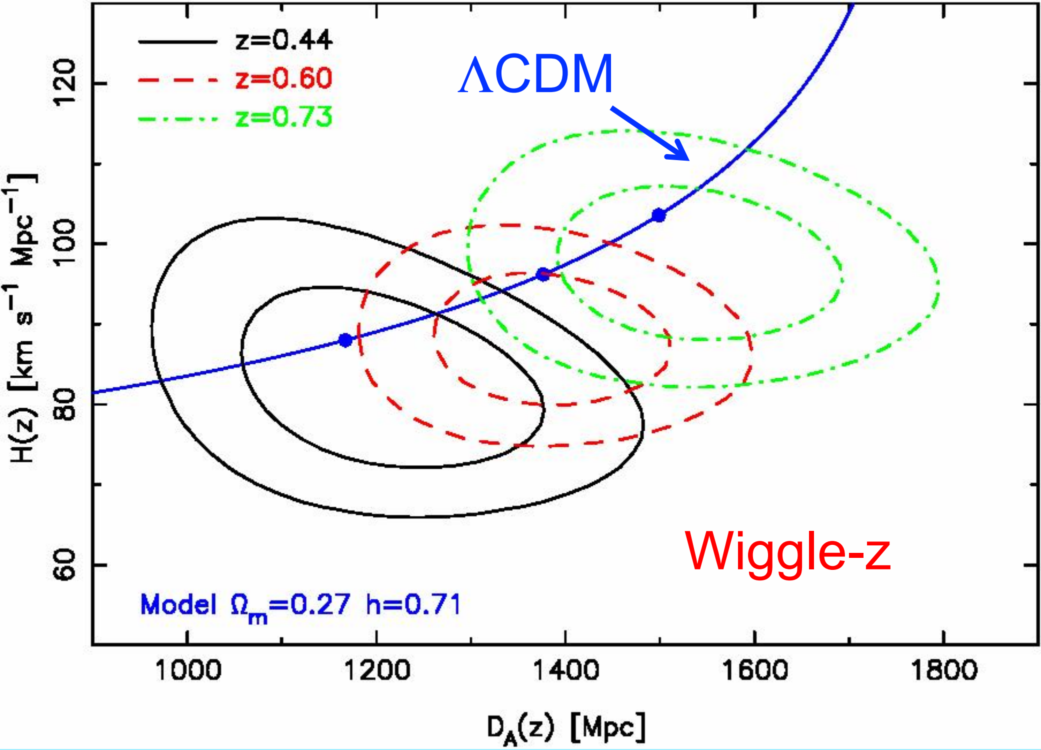
University of Durham

Redshift space distortions

Detected out to z~0.7



Guzzo et al ‘08



Blake et al ‘12

Institute for Computational Cosmology

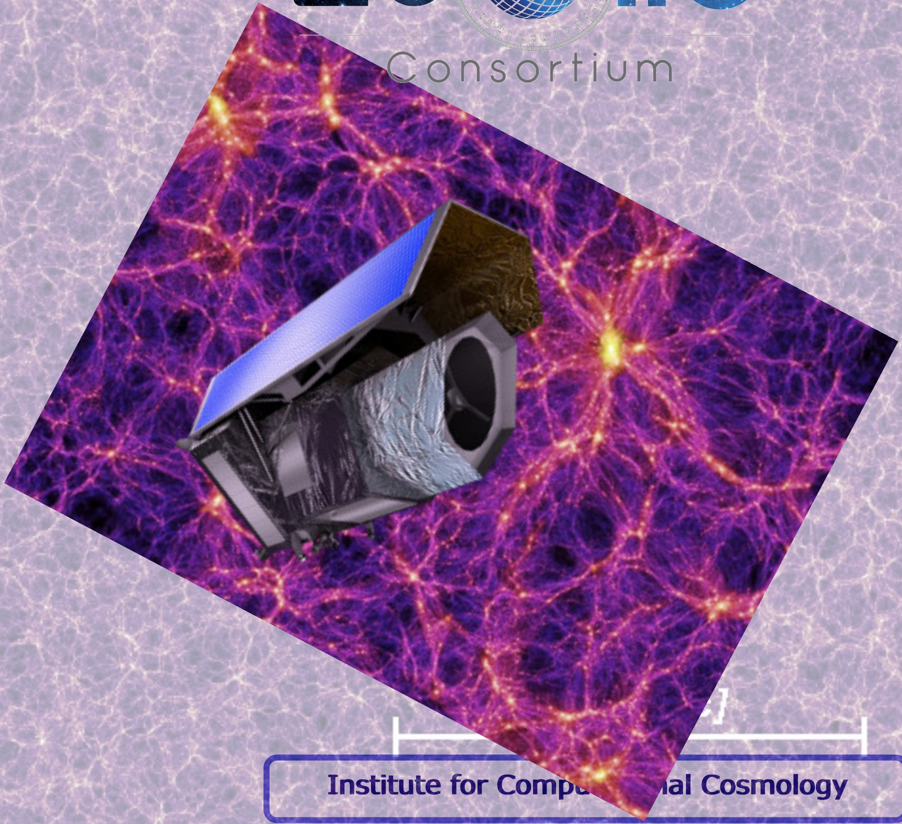
ICC
University of Durham

LSST
Large Synoptic Survey Telescope

MS-DESI

Euclid
Consortium

DES



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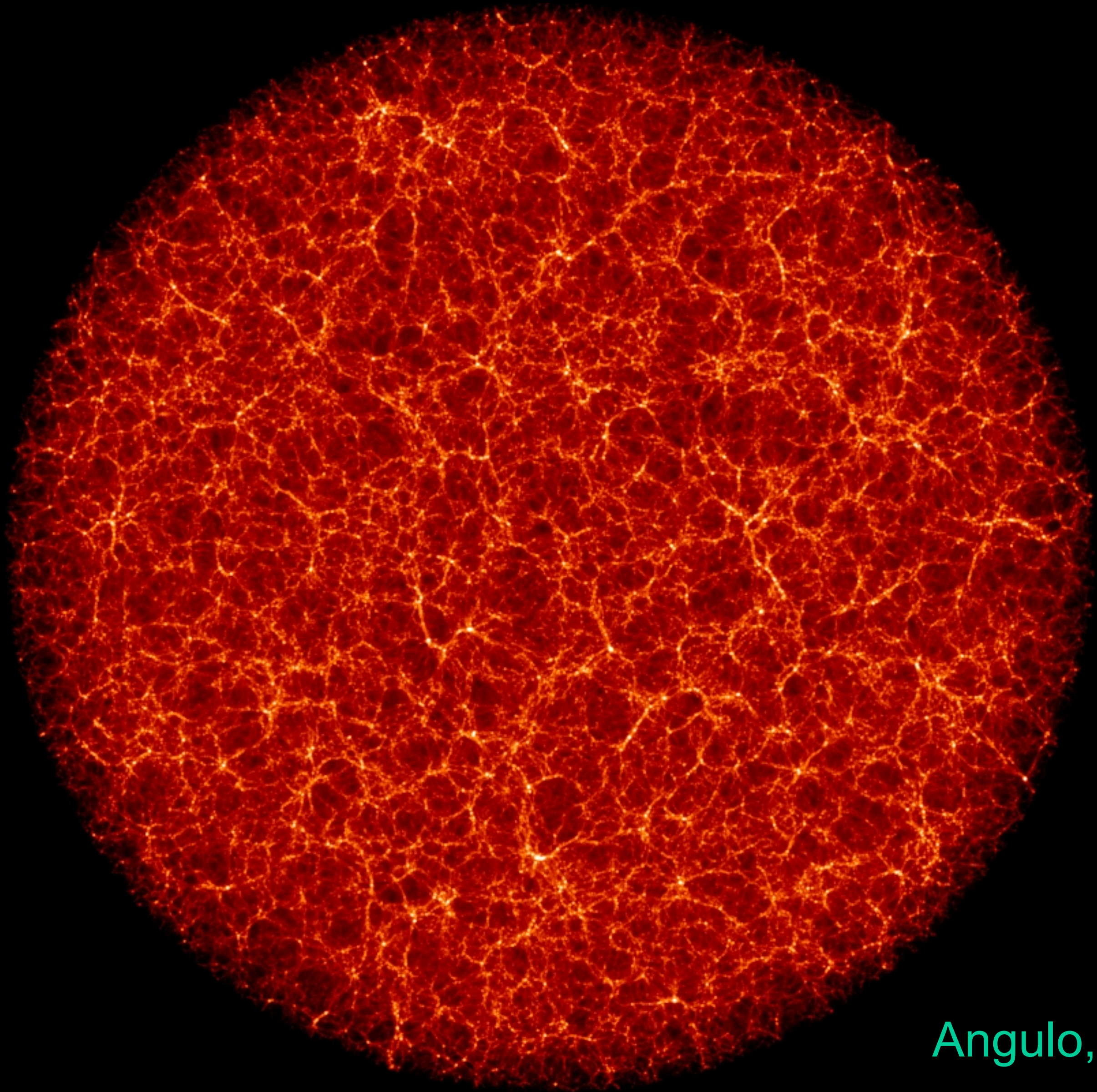
Theoretical challenges for precision cosmology

Obstacles in way of extracting cosmological info from surveys:

- Systematic effects in the interpretation of the data
- Cosmic variance

  - Focus on BAO in galaxies
  - Similar considerations apply to RSD, Ly-α forest

N-body simulations of large cosmological volumes



BASICC

L=1340/h Mpc

N=3,036,027,392

20 times the Millennium volume

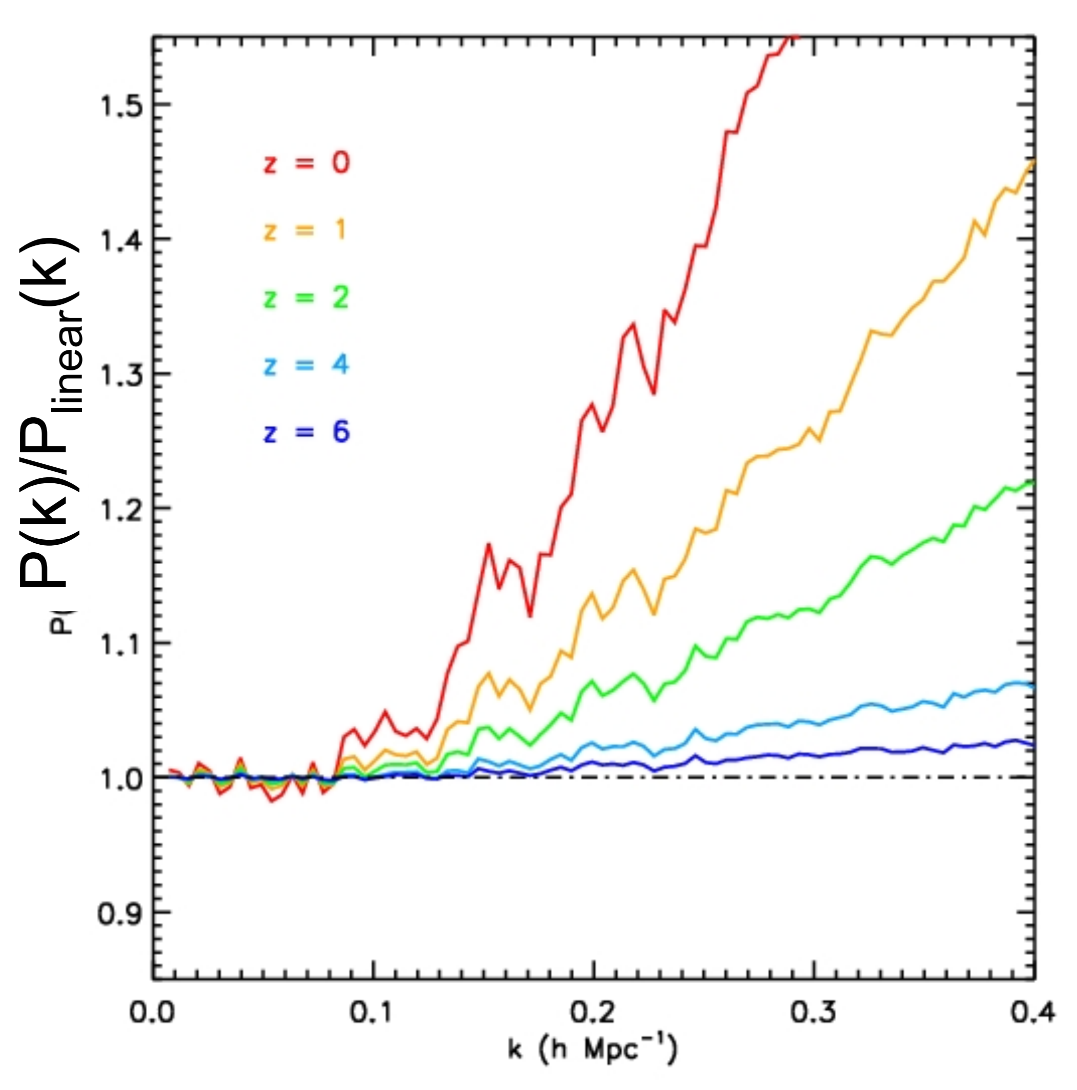
Halo resolution:
(10 particle limit)
5.5 e+11/h Mpc

130,000 cpu hours on the Cosmology Machine

Angulo, Baugh, Frenk & Lacey ‘08

University of Durham

Non-linear evolution of matter fluctuations



BASICC simulation dark matter real space

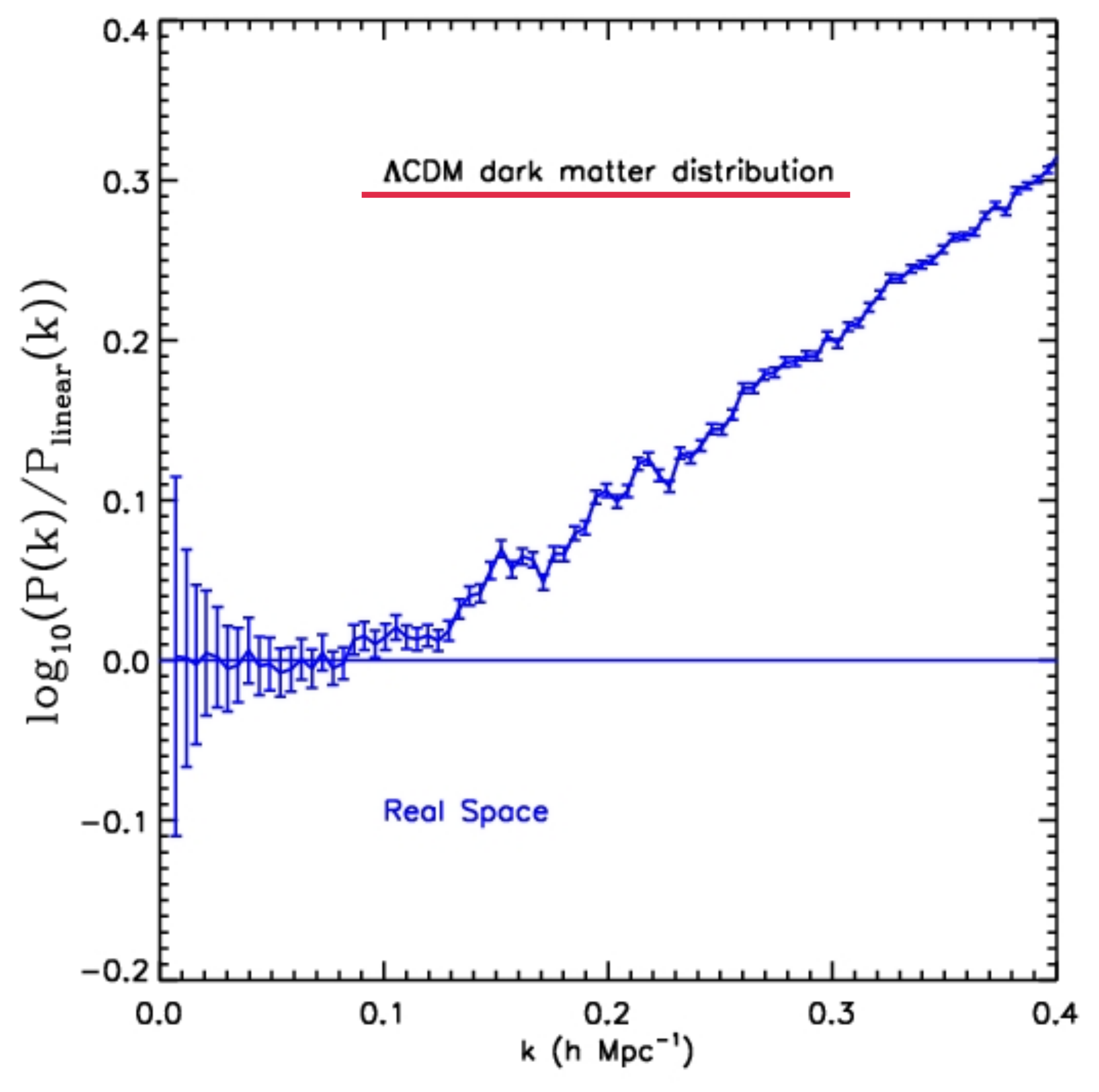
P(k) divided
by linear theory P(k),
scaling out growth factor

Angulo, Baugh, Frenk &
Lacey '08

Institute for Computational Cosmology

University of Durham

Non-linear evolution of matter fluctuations



Log $(P(k)/P_{linear}(k))$
at z=1

Angulo, Baugh, Frenk & Lacey ‘08

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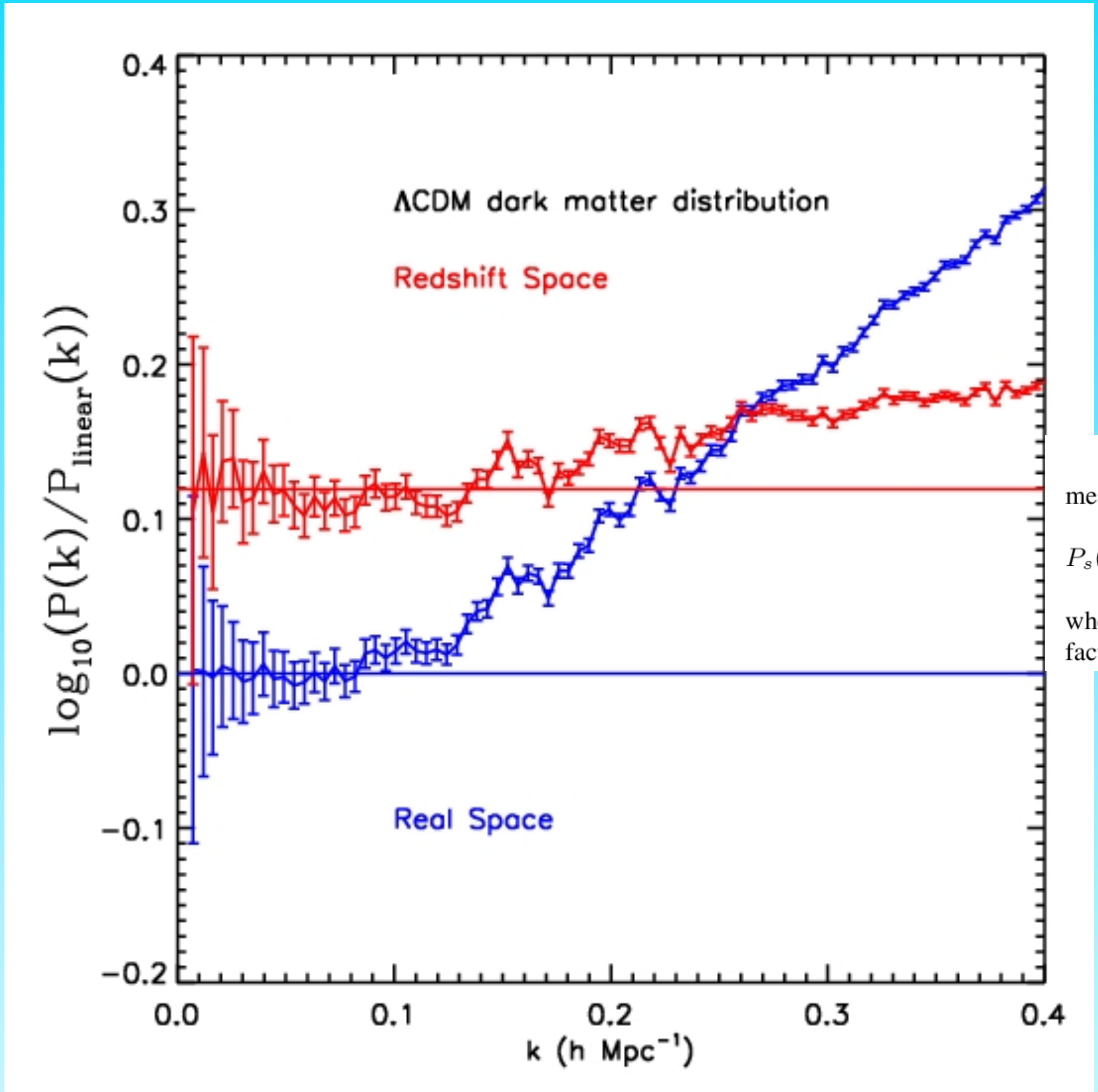
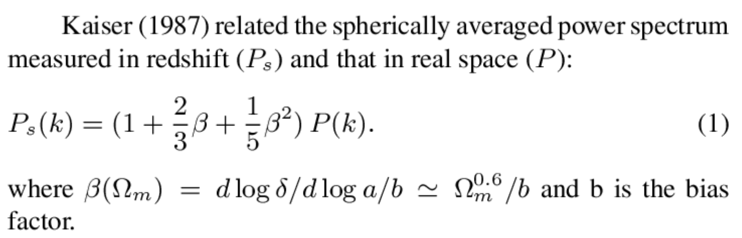
Redshift space distortions



Peculiar motions distort clustering pattern

Coherent bulk flows boost large scale power (Kaiser 1987)



Kaiser (1987) related the spherically averaged power spectrum measured in redshift (P_s) and that in real space (P):

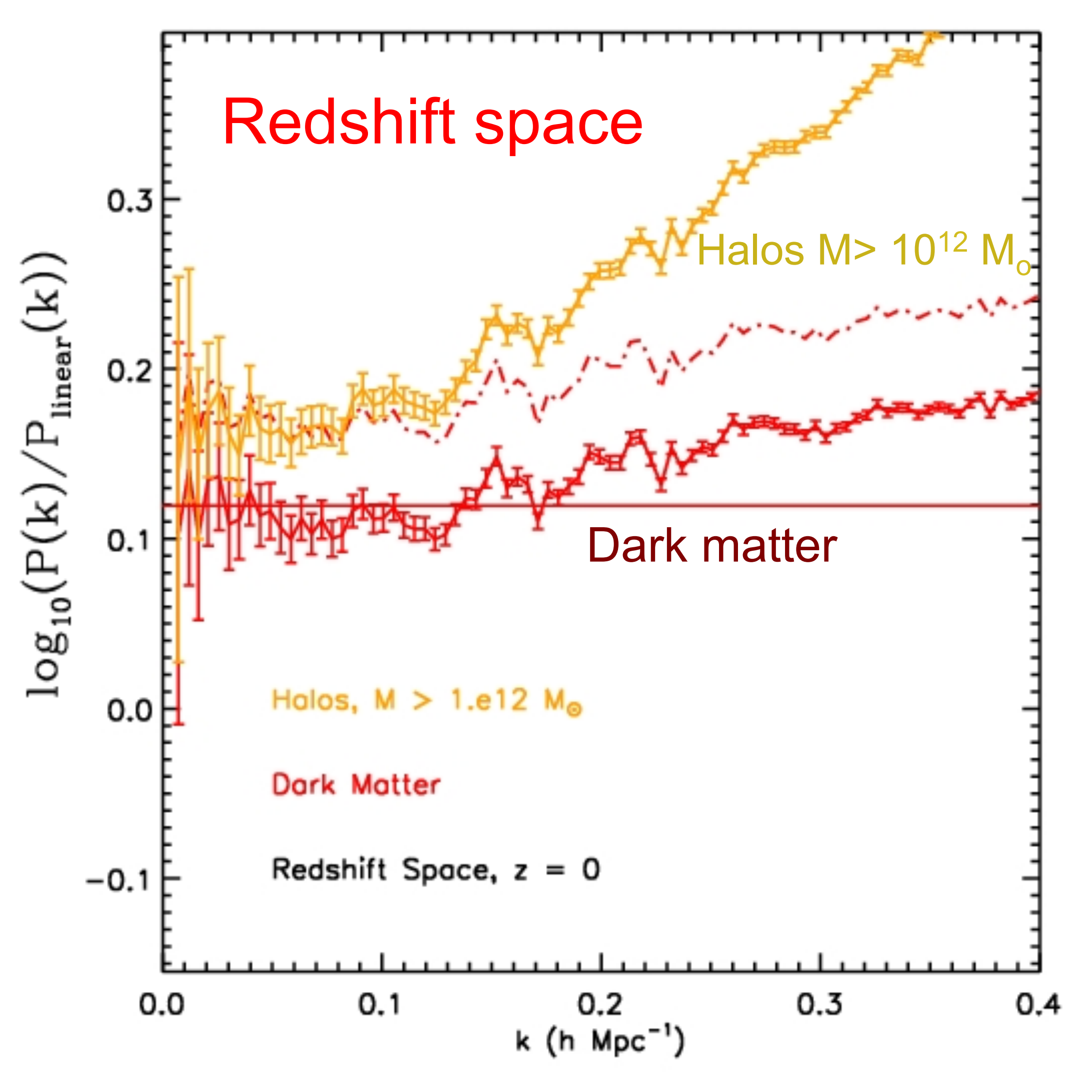
$$P_s(k) = (1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2)\, P(k). \qquad (1)$$

where $\beta(\Omega_m) = d\log\delta/d\log a/b \simeq \Omega_m^{0.6}/b$ and b is the bias factor.

Motions of particles inside virialised structures damp power at high k

University of Durham

Redshift space distortions



Peculiar motions distort clustering pattern

Boost in power on large scales due to coherent flows

Damping at higher k affects DM but not the halos

In z-space, halo bias is scale-dependent

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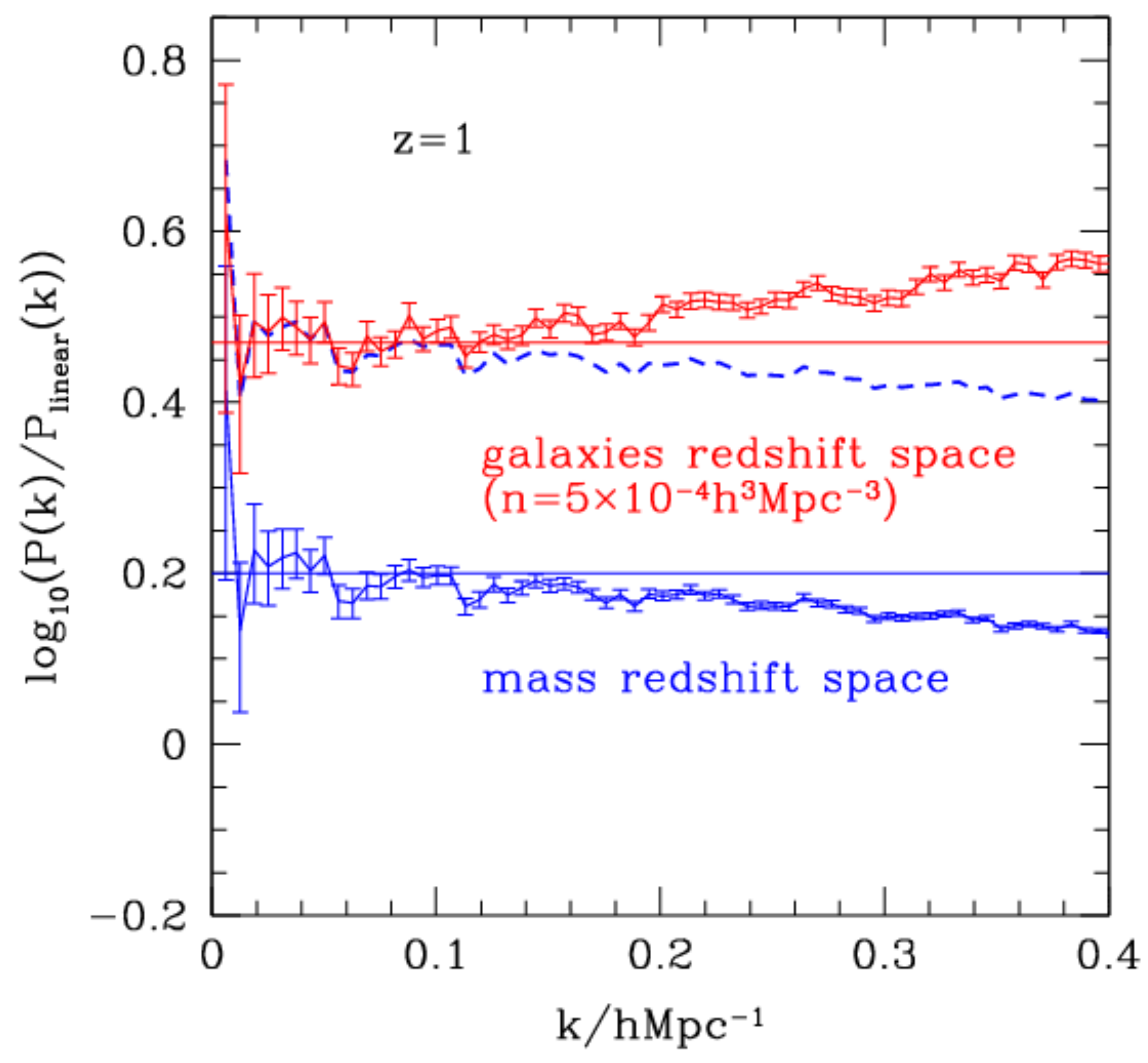
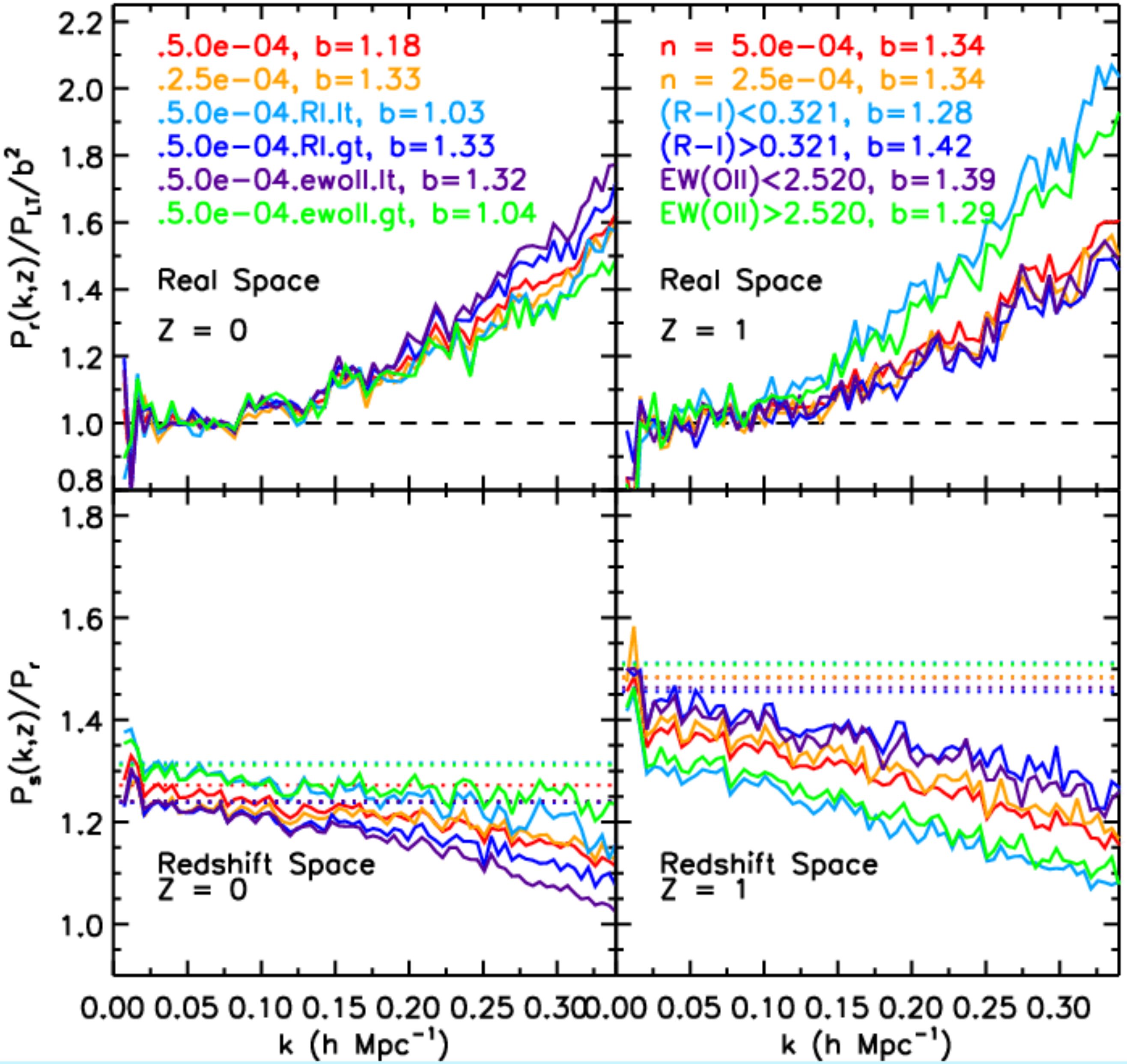
Galaxy bias in redshift space



Galaxy P(k) cannot be reproduced by multiplying mass P(k) by constant factor in redshift space.

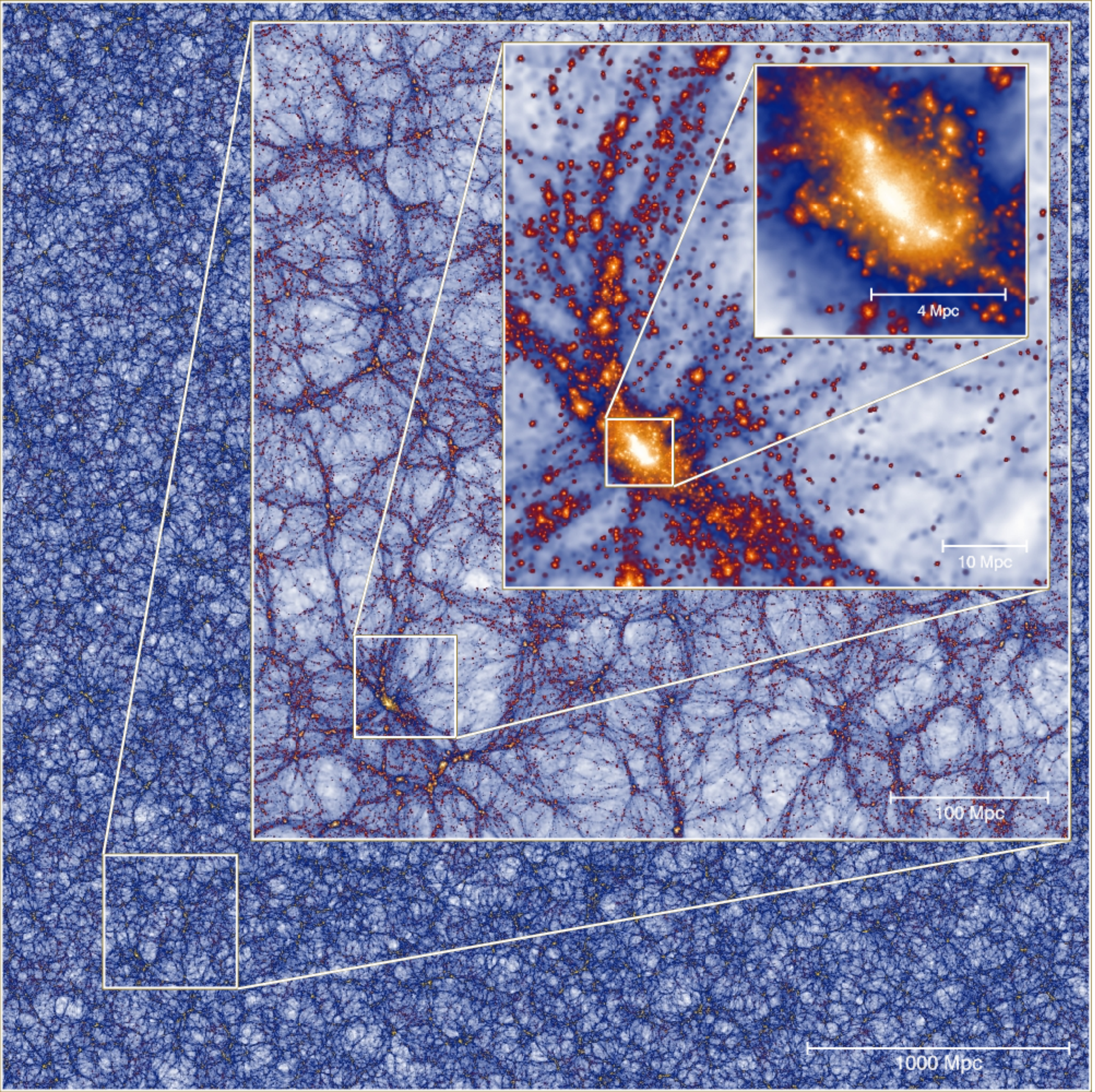
⇒ In z-space, galaxies have a scale-dependent bias out to k~0.1

Galaxy bias in redshift space



Comparison of different selections e.g. colour, emission line strength

Angulo et al ‘08



The MXXL

Angulo, Springel et al. ‘12

Bigger than the Millennium run by factors of

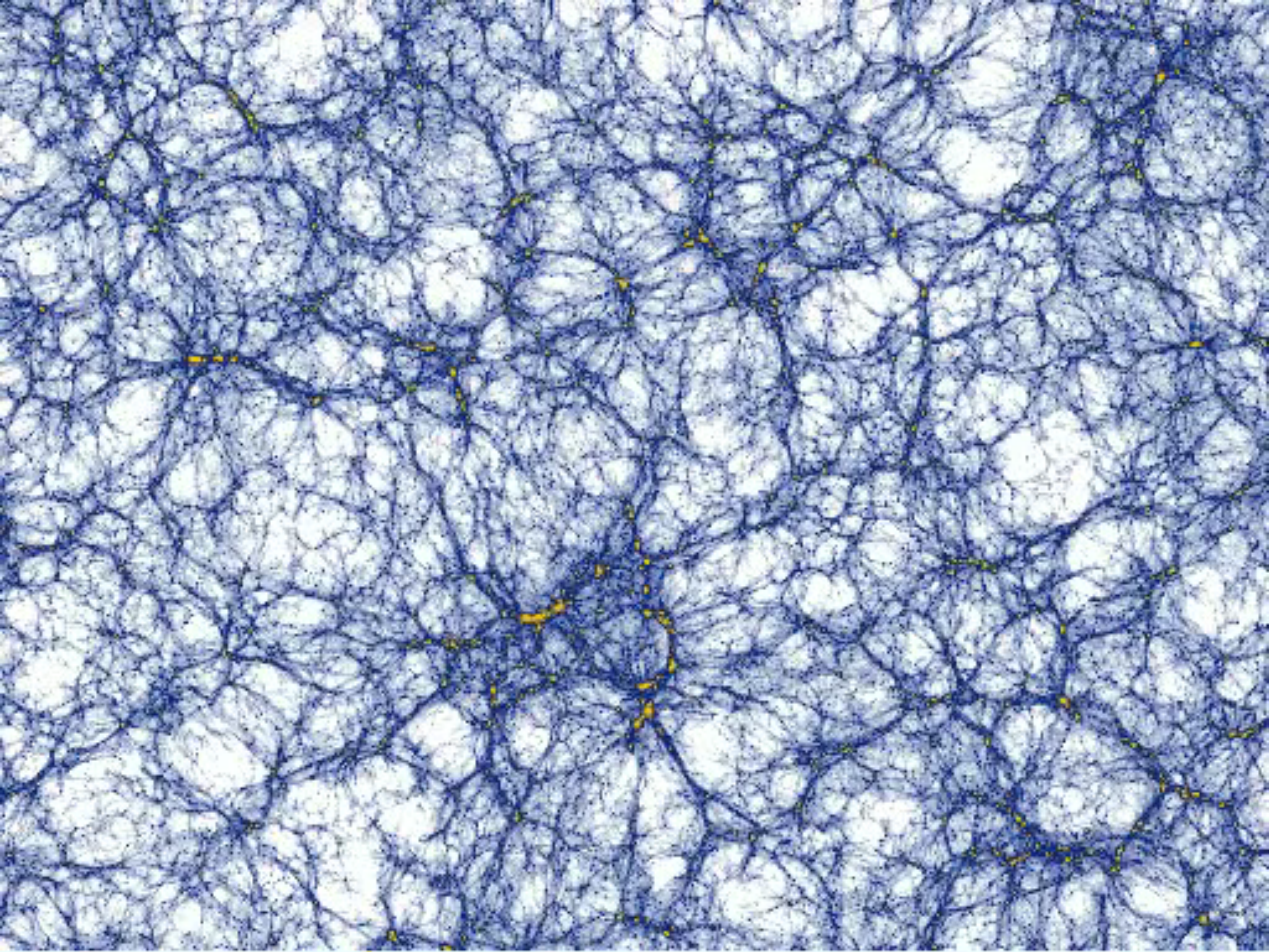
30 in $N_{particle}$

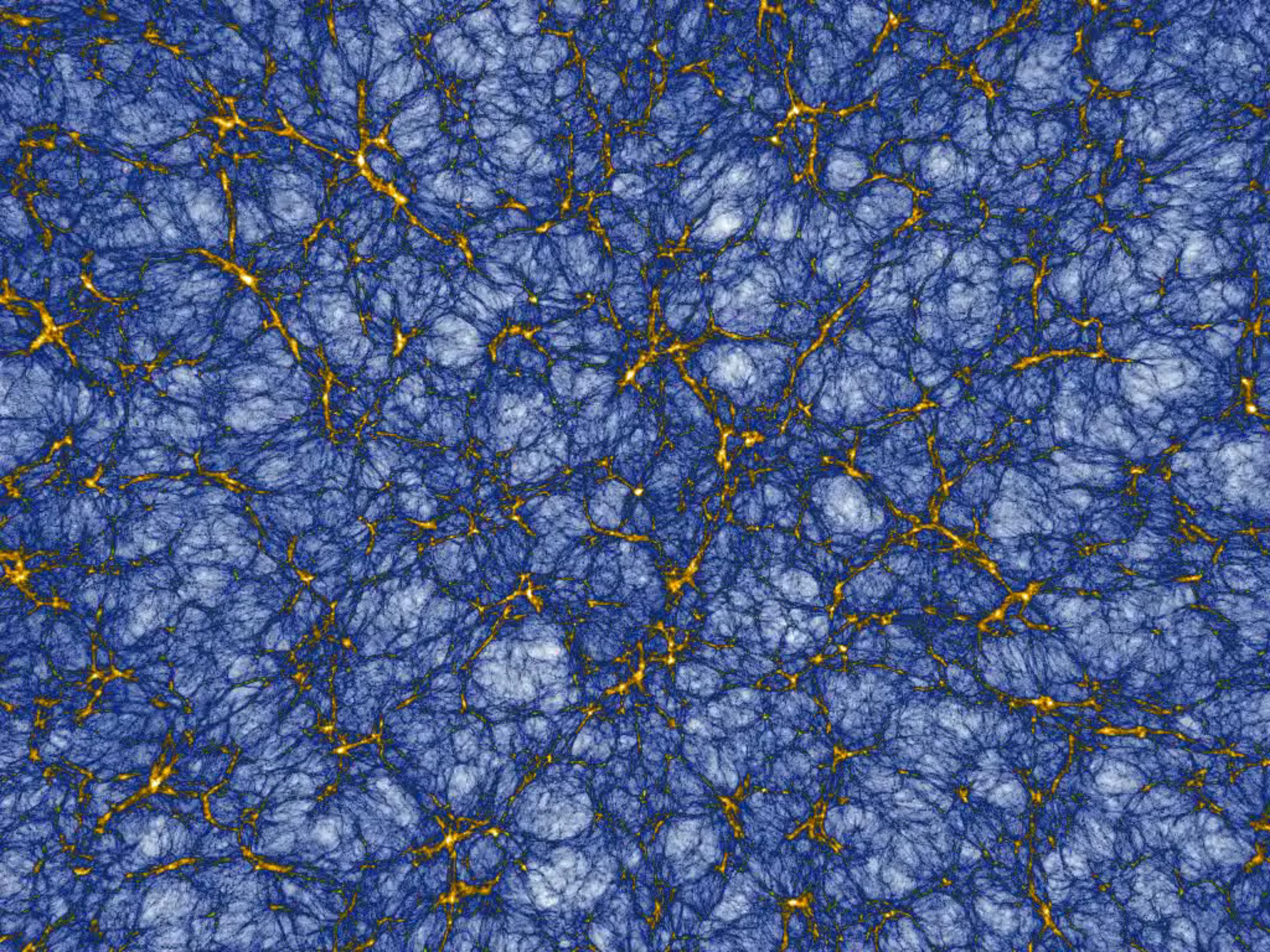
200 in volume

6 in $m_{particle}$

3×10^8 galaxies $M_* > 10^{10} M_\odot$

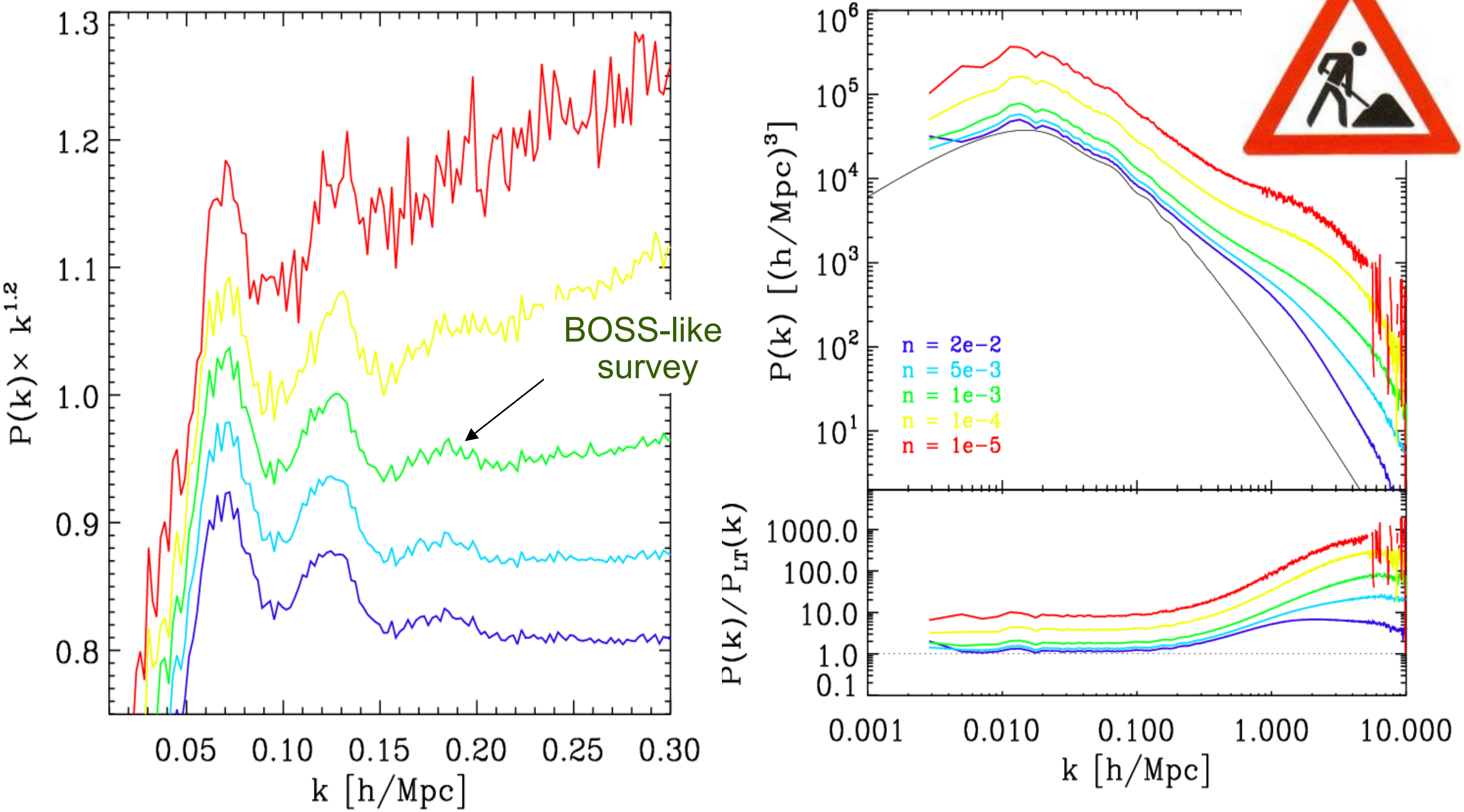
3×10^5 clusters $M_* > 10^{14} M_\odot$





Different galaxy catalogues in the MXXL simulation trace the BAO features with a mass- and scale-dependent bias

POWER SPECTRA OF THE GALAXY DISTRIBUTION AT Z=0 FOR DIFFERENT SPACE DENSITIES



Angulo et al. (2012)

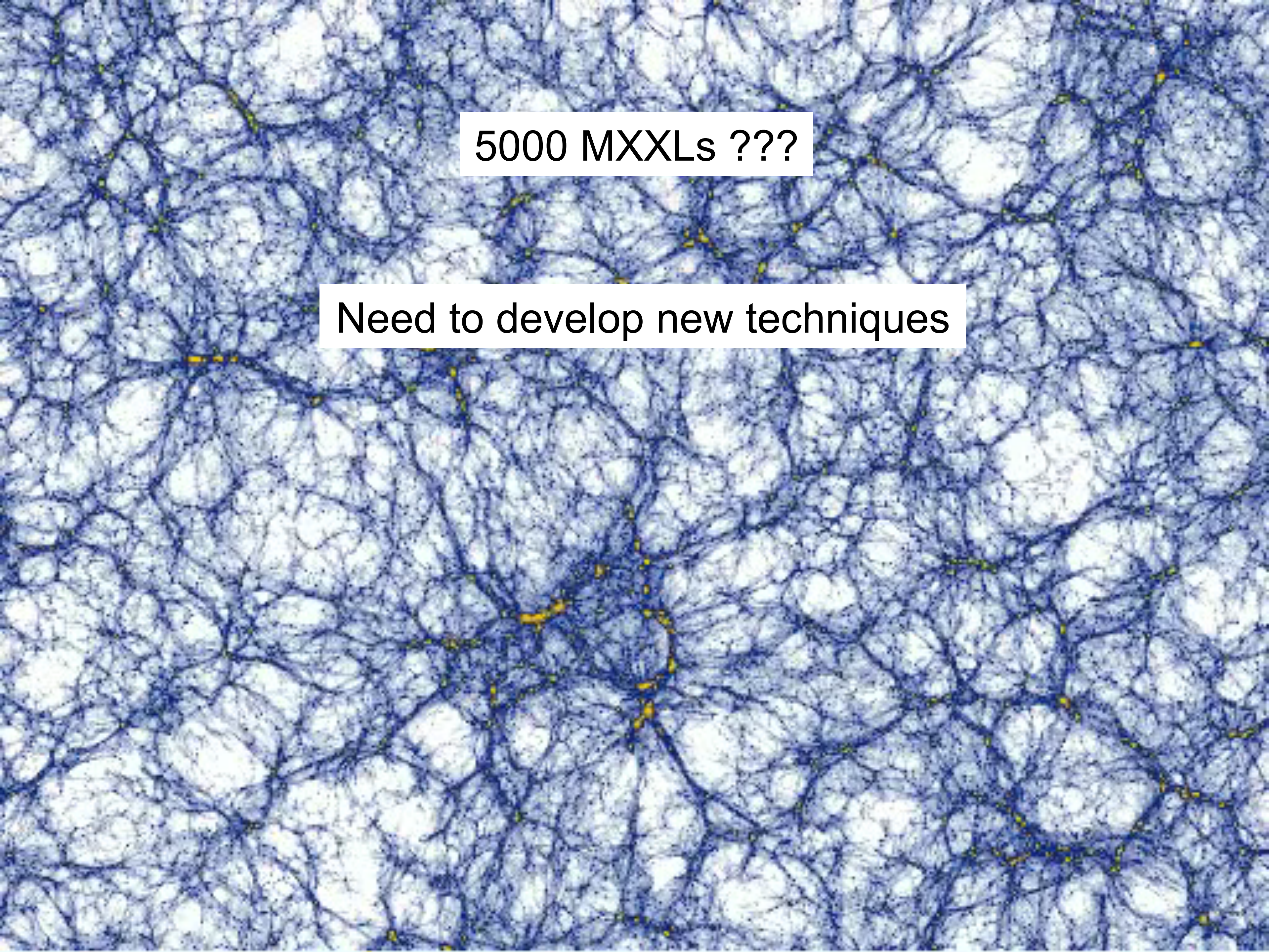
Estimating the PS covariance

Measurements of matter power spectrum → constraints on cosmological parameters

Only if mean power spectrum predicted by the cosmological model and its error distribution are known

→ Need accurate estimates of the PS covariance matrix

Takahashi et al '09 show that for a given cosmology, this can be achieved with …. 5000 large N-body simulations!!!



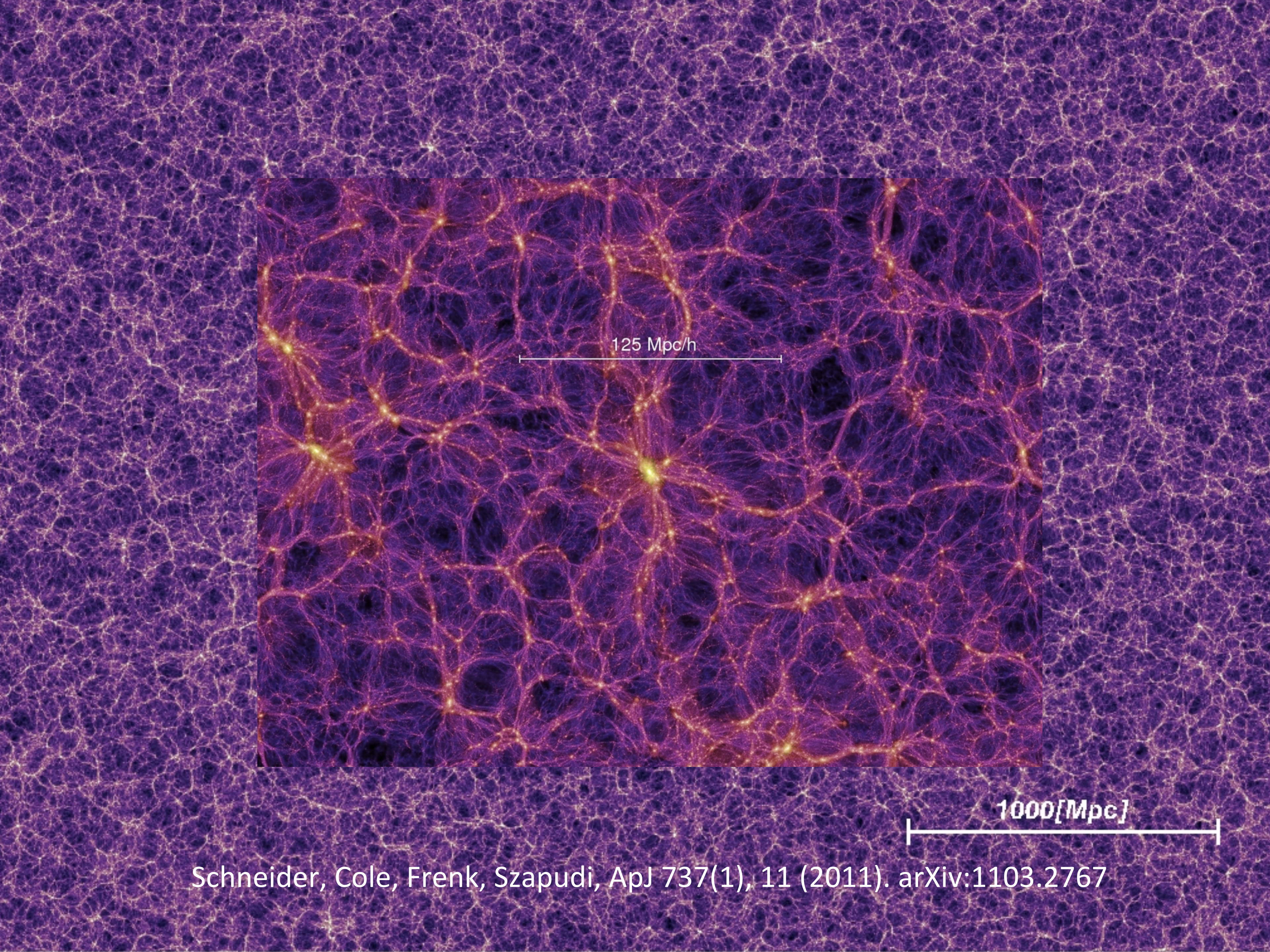
5000 MXXLs ???

Need to develop new techniques

Fast generation of ensembles of cosmological N-body simulations via mode-resampling

Schneider, Cole, Frenk, Szapudi ‘11

Schneider, Cole, Frenk, Szapudi, ApJ 737(1), 11 (2011). arXiv:1103.2767

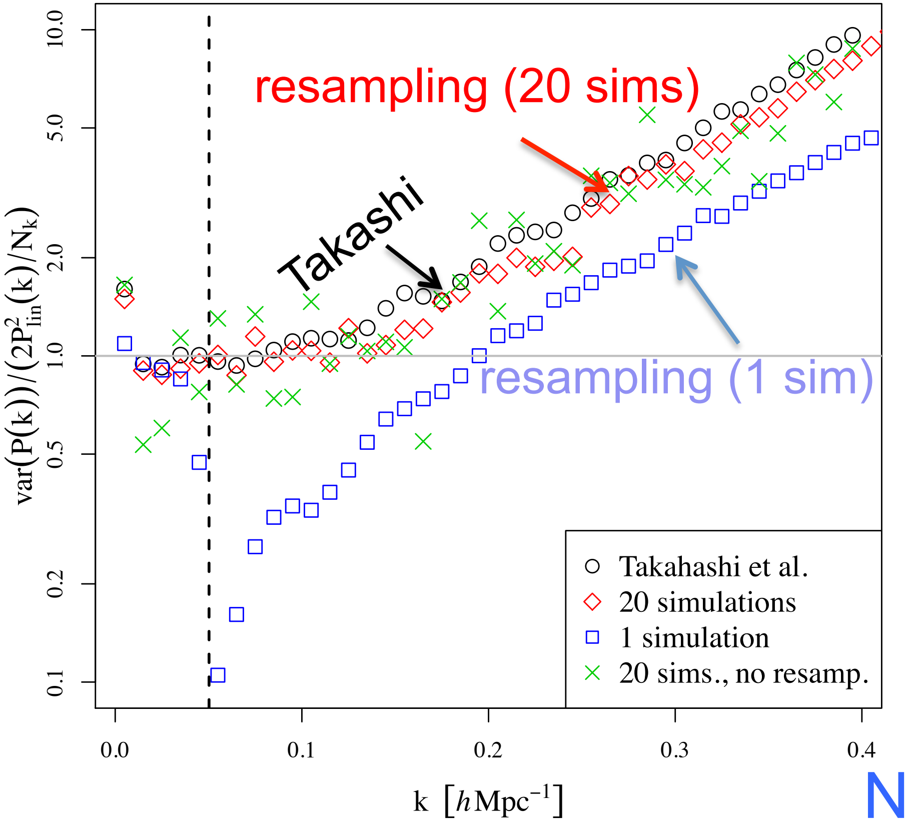


Schneider, Cole, Frenk, Szapudi, ApJ 737(1), 11 (2011). arXiv:1103.2767

Power spectrum covariance estimates

500 long-λ resamplings

P(k) variance

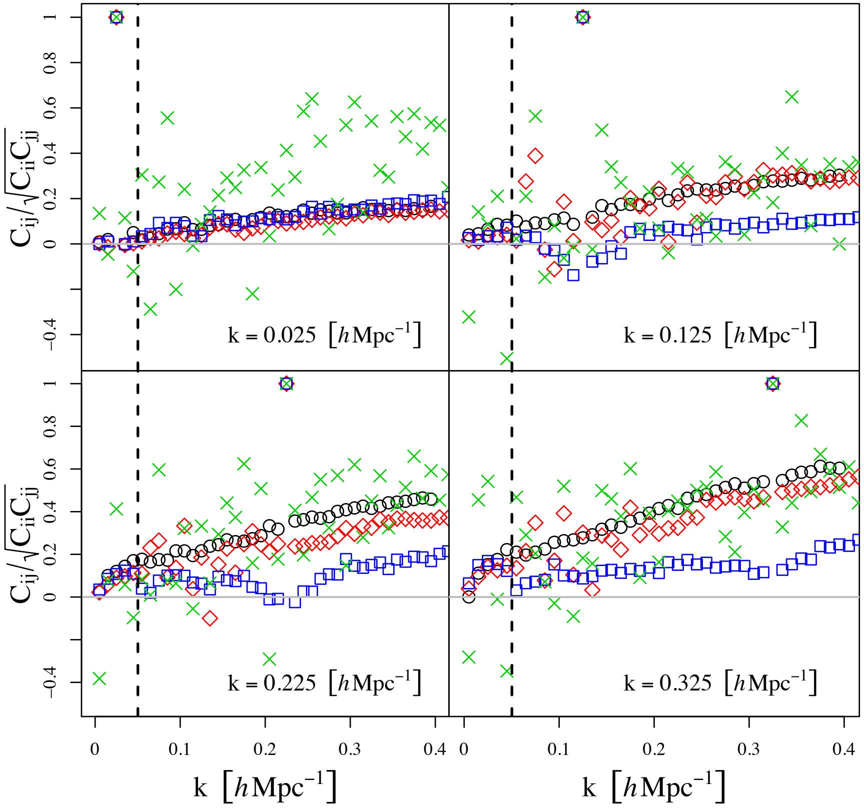


resampling (20 sims)

Takashi

resampling (1 sim)

Covariance matrix elements



Need 20 “small-mode’’ re-sampled simulations for <20% errors in covariance matrix

Schneider et al ‘11

Conclusions & challenges

Studies of large-scale structure,past 30 yrs: remarkably successful

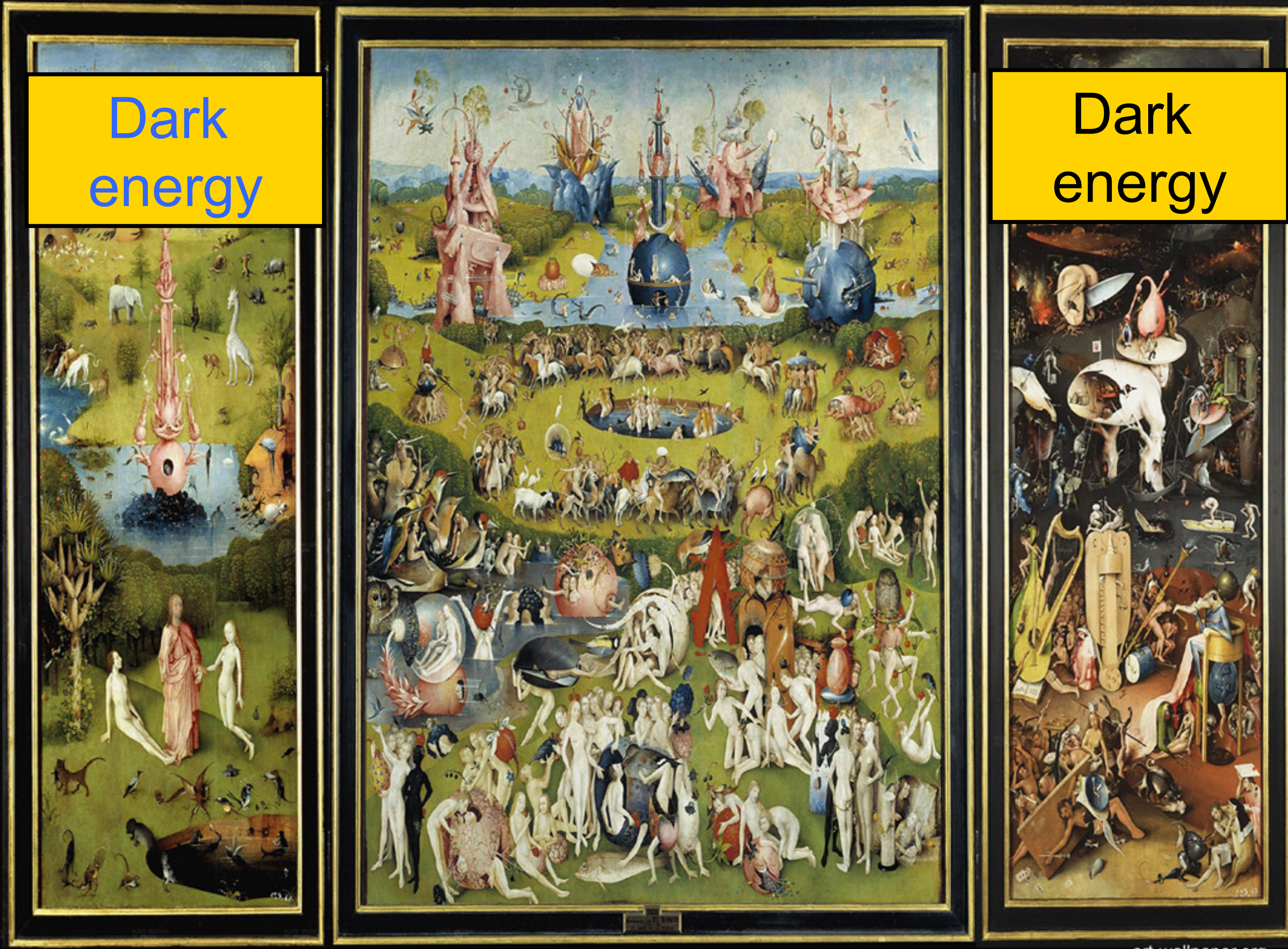
Along the way, we lost Ω_{matter}=1 … and gained dark energy

→ ΛCDM validated by CMB and LSS data from many sources

… NO idea of what DE is: Λ has no explanation in current physics

Further progress → great technological/computational challenges

- Control of systematics at sub-% level not obviously possible
- Best strategy for building mocks (HoD, Galform…) not clear yet
- Need to develop new techniques (e.g. mode resampling)
- Simulations will be vital: a large number of MXXLs?



Dark energy

Dark energy

art-wallpaper.org