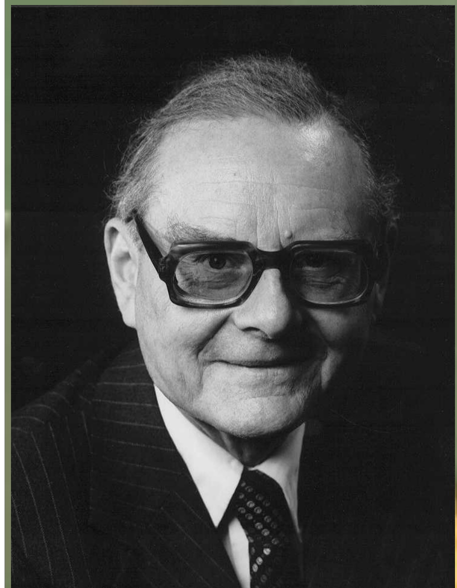
Ludwig Franz Benedict Biermann

(1907 – 1986)

Founding director Max Planck Institute for Astrophysics (1958)

The vicissitudes of the cold dark matter model of cosmogony



Carlos S. Frenk
Institute for Computational Cosmology, Durham

II. The large-scale structure of the Universe

Carlos S. Frenk

Institute for Computational Cosmology, Durham

cold dark matter

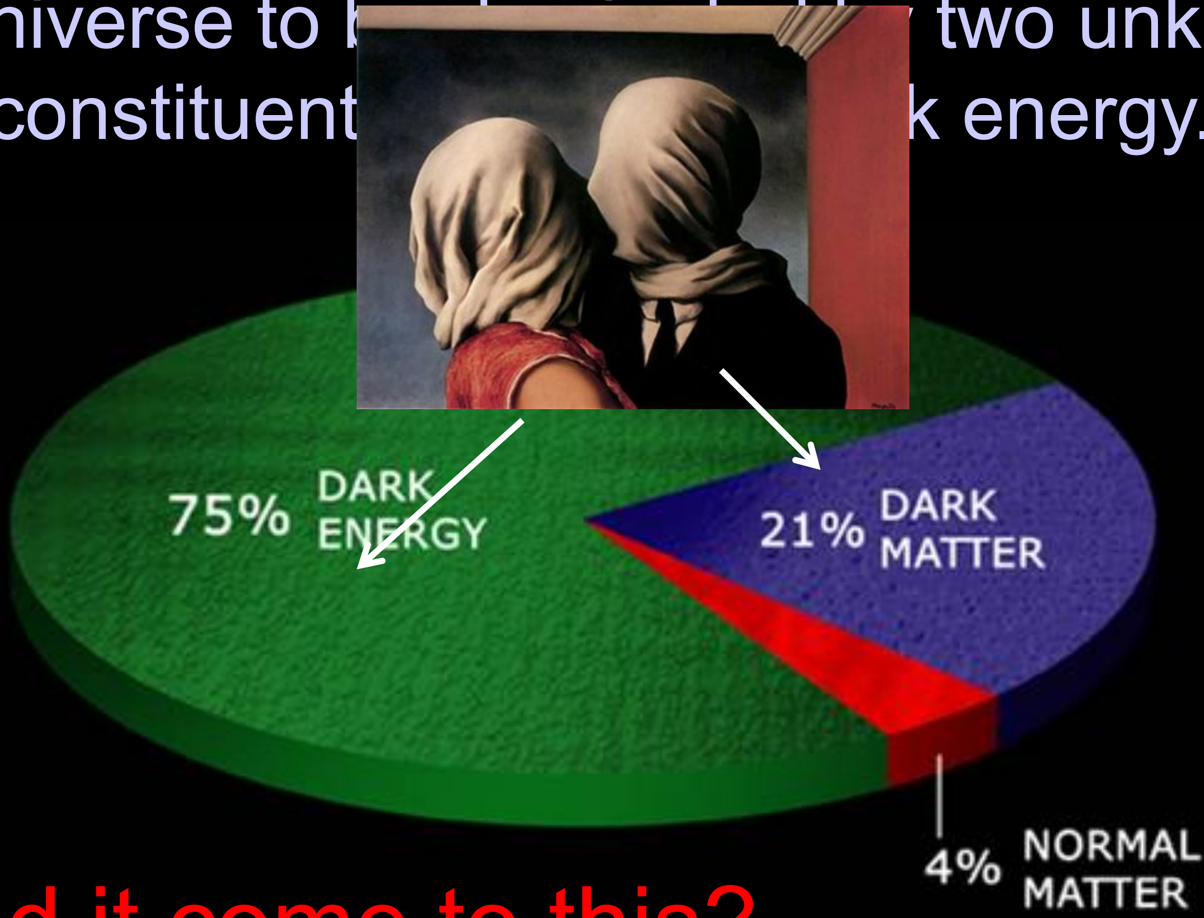
ΛCDM: the standard model of cosmology

cosmological constant

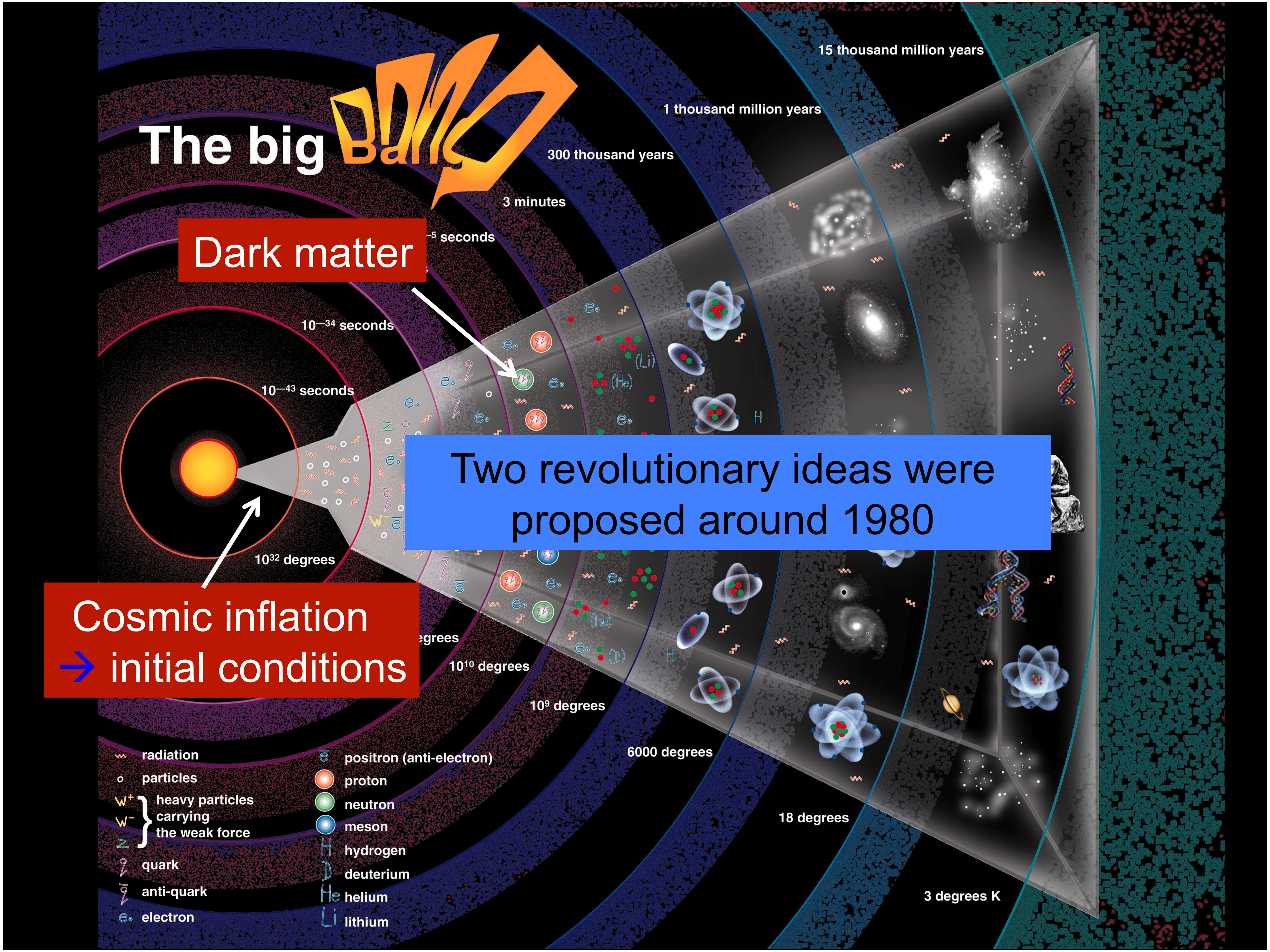
Why is this the standard model; why it is incomplete and what next?

The cold dark matter cosmogony

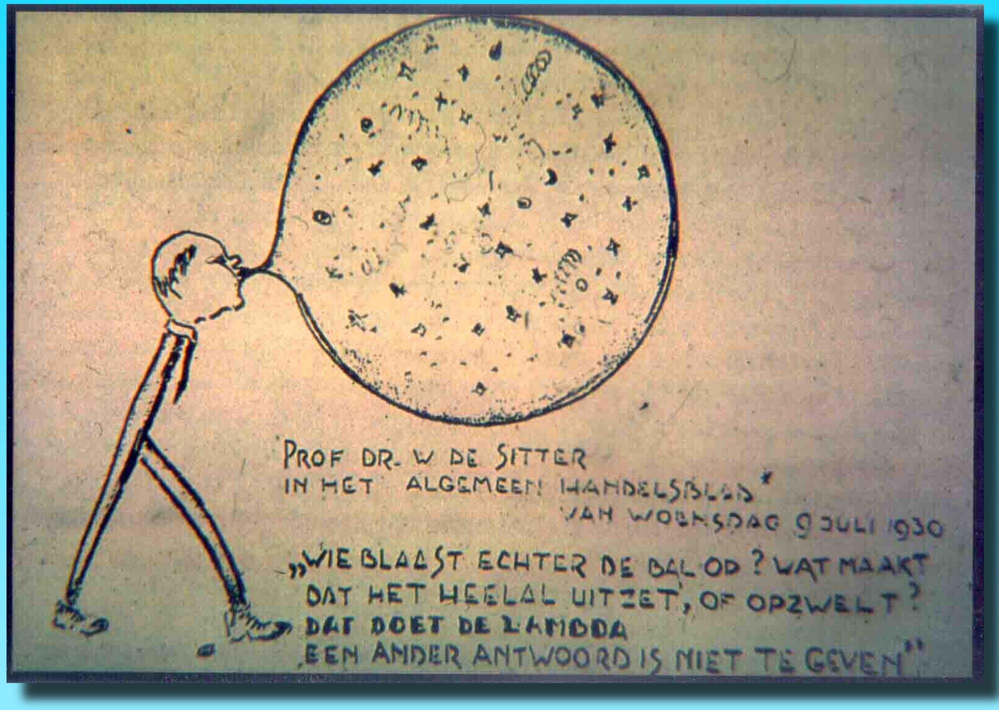
The CDM model is intrinsically implausible: it requires
the universe to b
two unknown
constituent
k energy.



How did it come to this?


The big Bang
Two revolutionary ideas were proposed around 1980
Dark matter
Cosmic inflation
→ initial conditions
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

The ΛCDM model

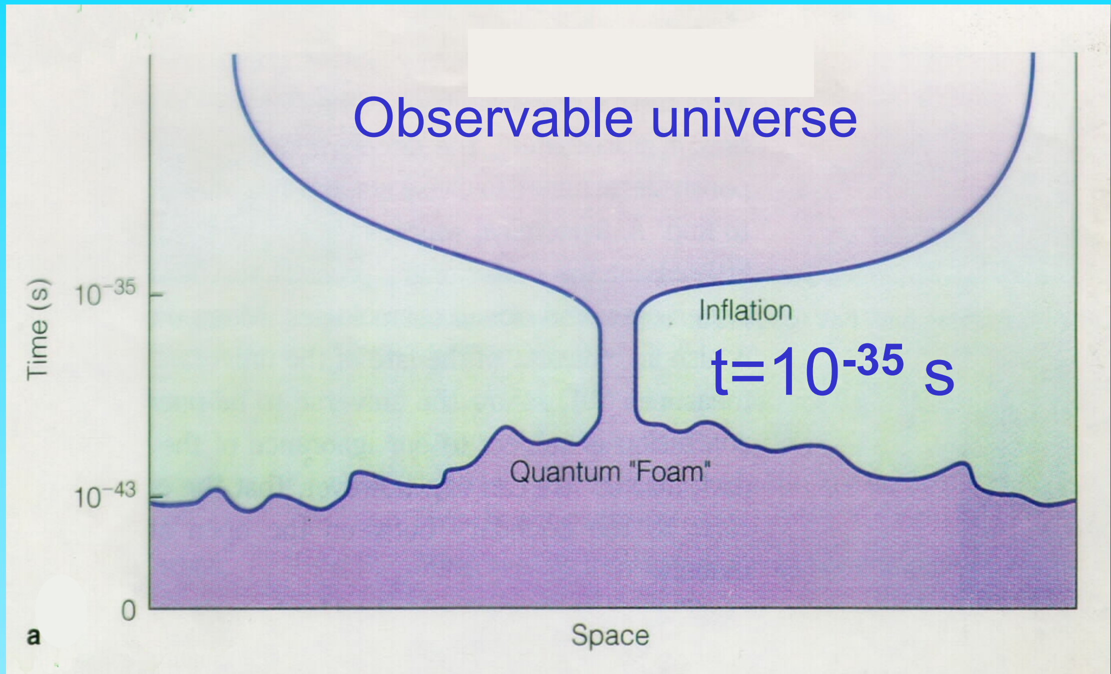


Cosmic inflation: universe started off in unstable state (vacuum energy) → expands very fast in short period of time

⟹ 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

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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

The dark matter power spectrum

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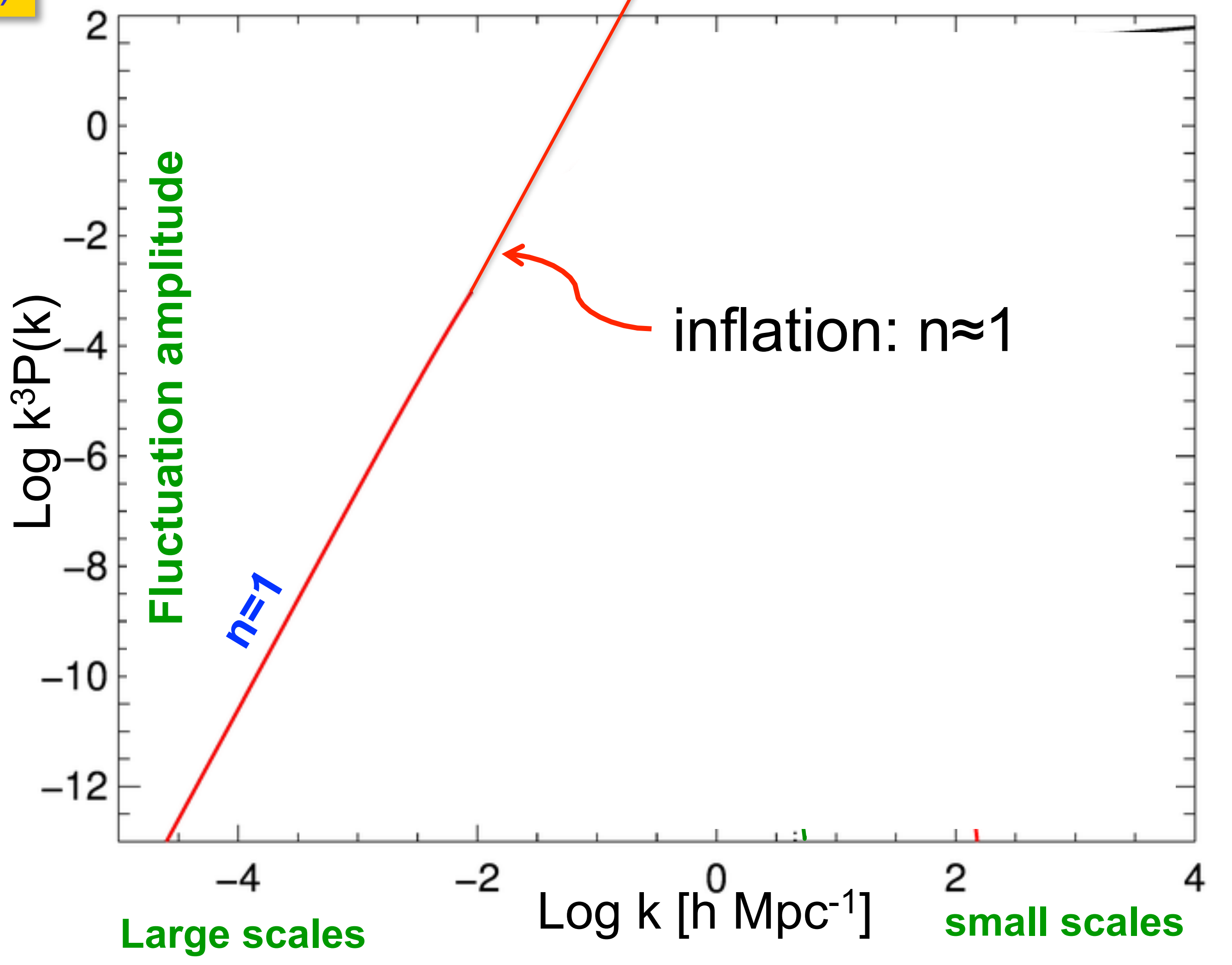
Prediction from inflation

k³ P(k)

The linear power spectrum ("power per octave")



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The dark matter power spectrum

Free streaming →

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

for thermal relic

$m_{CDM} \sim$ 100GeV

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

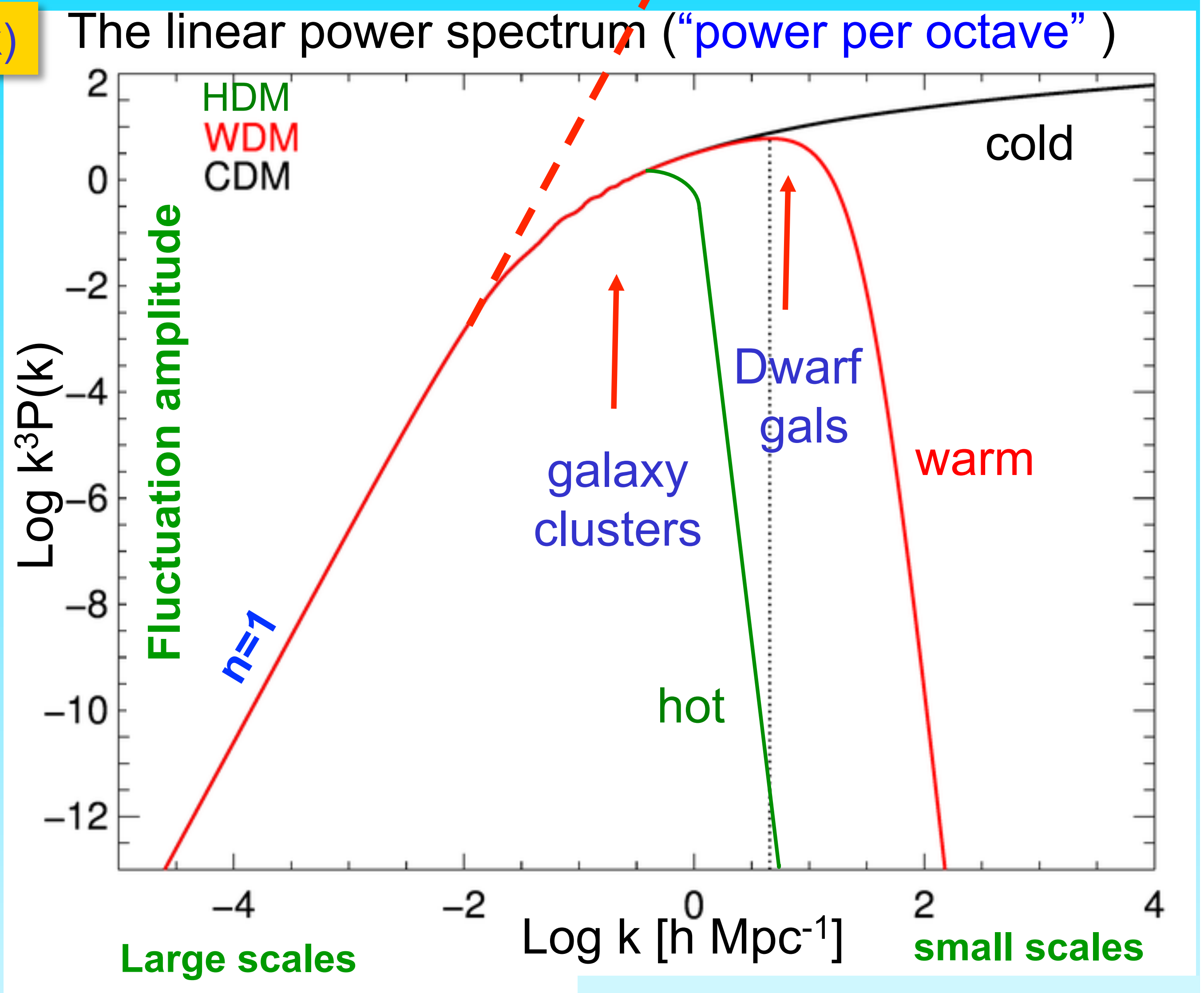
$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$

$m_{HDM} \sim$ few eV

light ν; $M_{cut} \sim 10^{15}\ M_o$

k^3 P(k)



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

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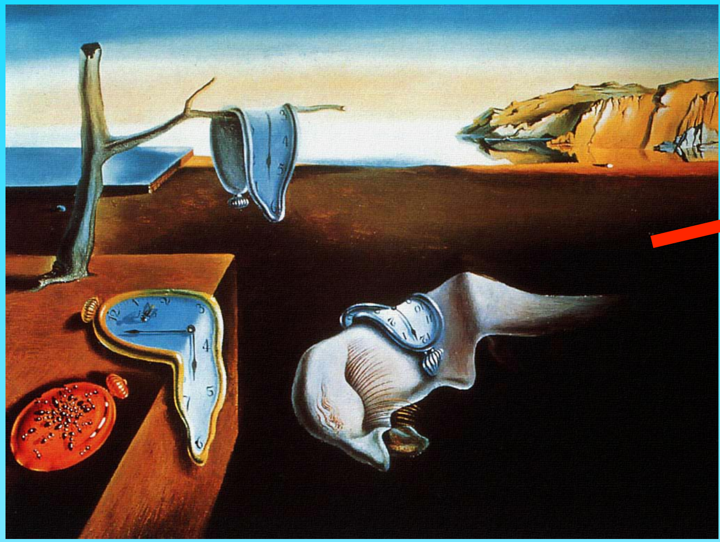
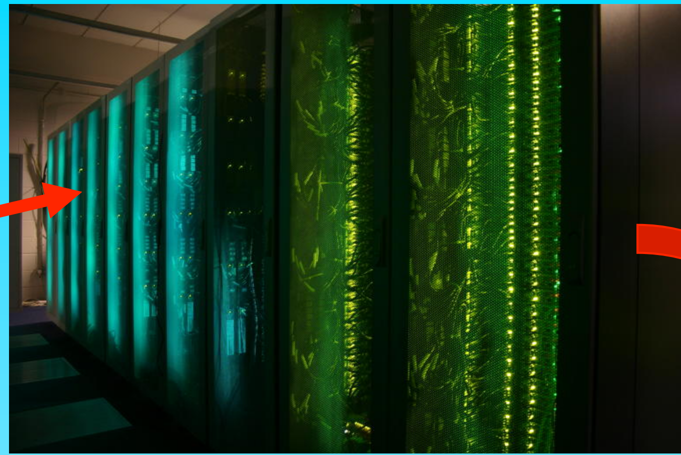
The formation of cosmic structure

$t=10^{-35}$ 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

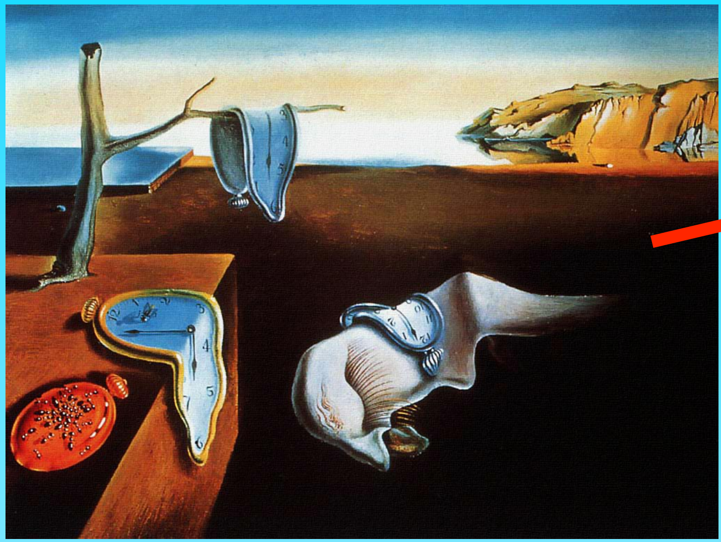
$\delta\rho/\rho \sim 1-10^{6}$

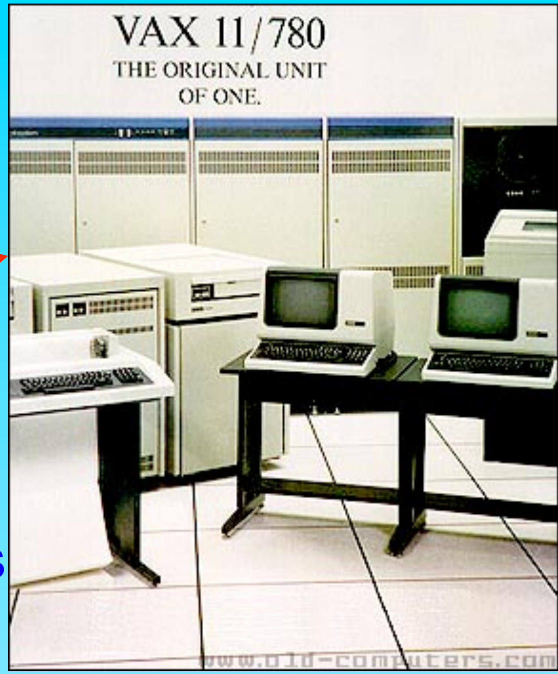
Institute for Computational Cosmology

The formation of cosmic structure

University of Durham

t=10^{-35} seconds





t=380,000 yrs

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

t=13.8 billion yrs

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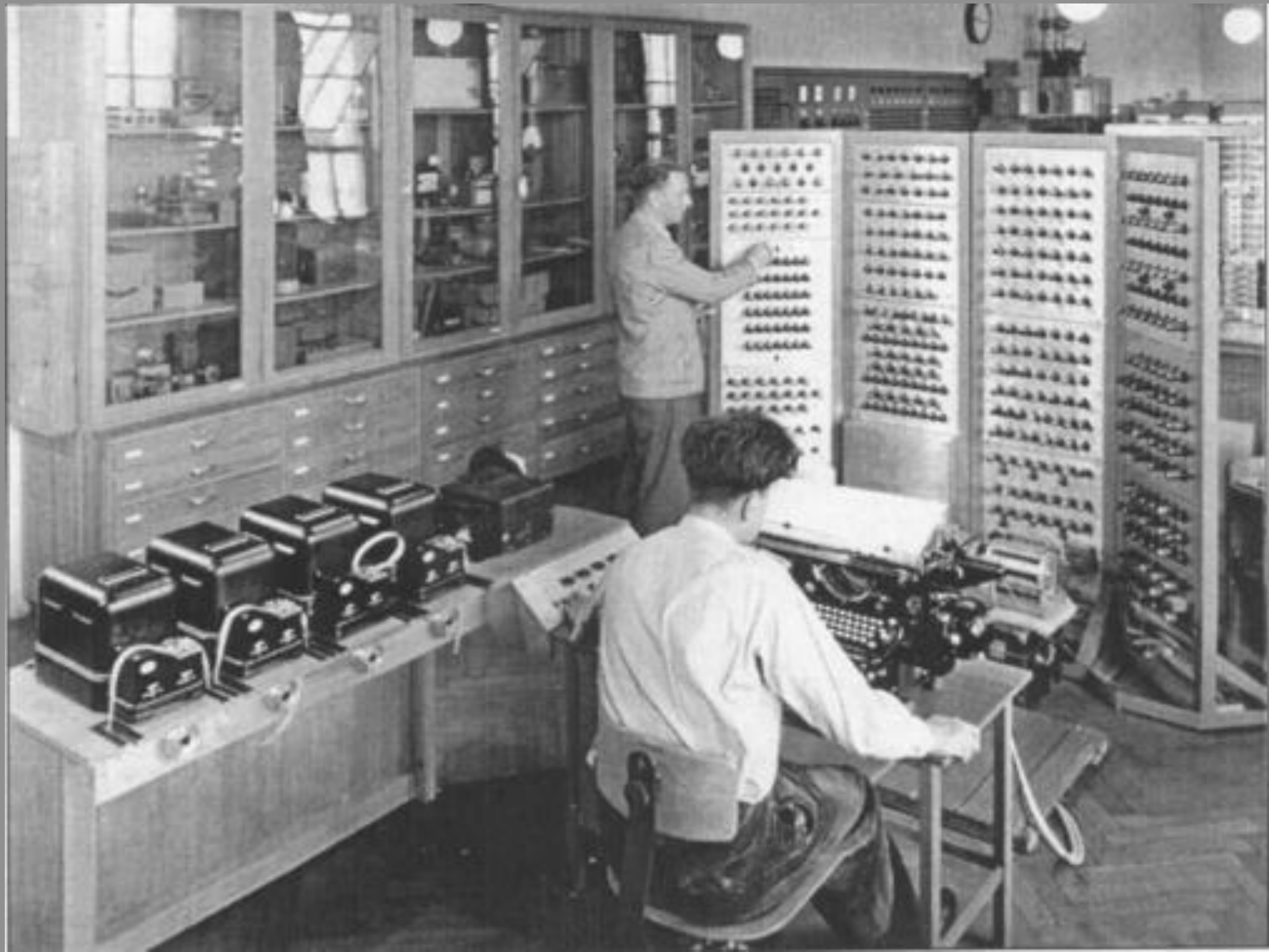
Ludwig Biermann's "G1" computer



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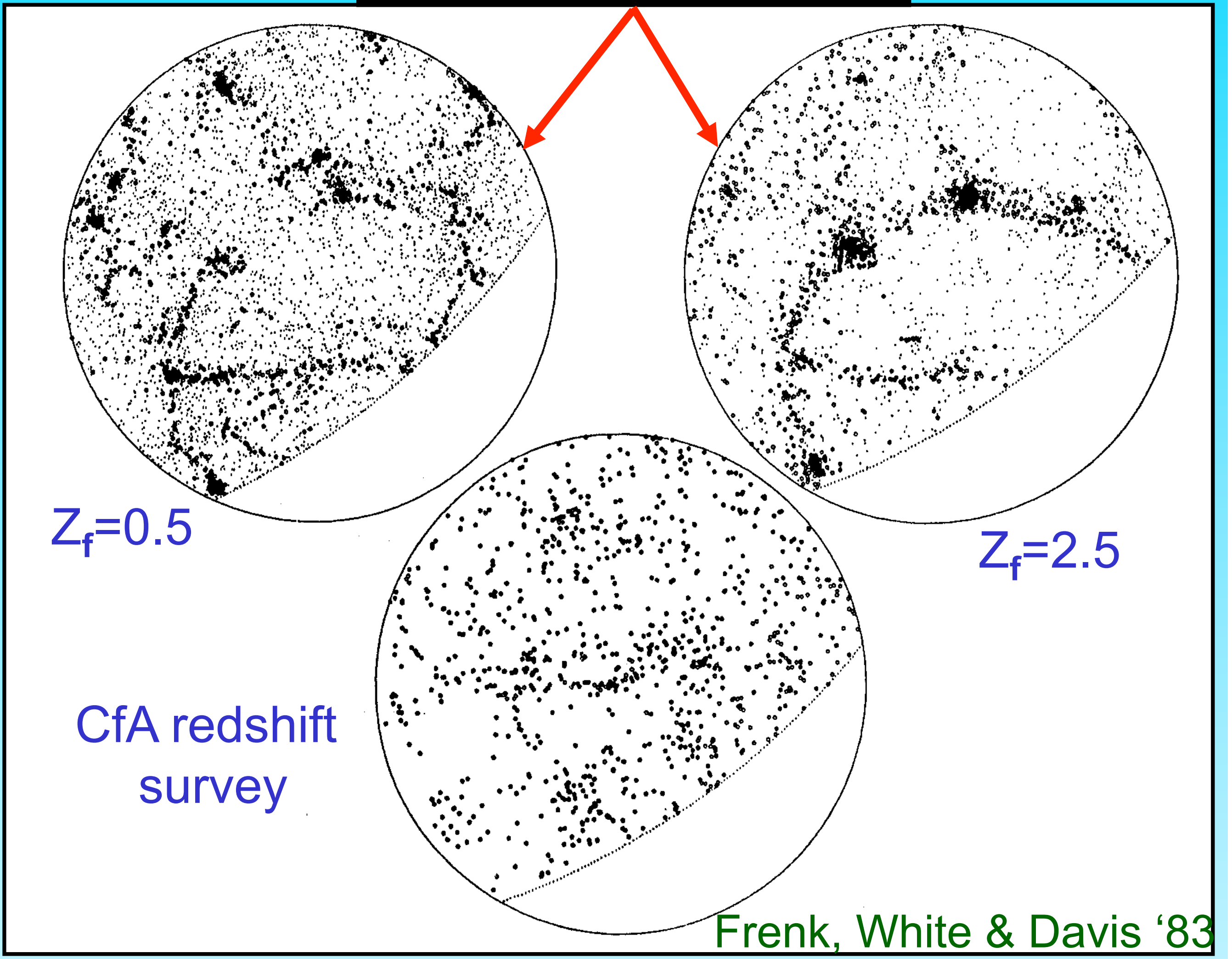
Non-baryonic dark matter candidates

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

Neutrino (hot) dark matter

Ω_ν=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_ν<< 10 ev

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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

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The cold dark matter cosmogony

Peebles '82

THE ASTROPHYSICAL JOURNAL, 263:L1–L5, 1982 December 1

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

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

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

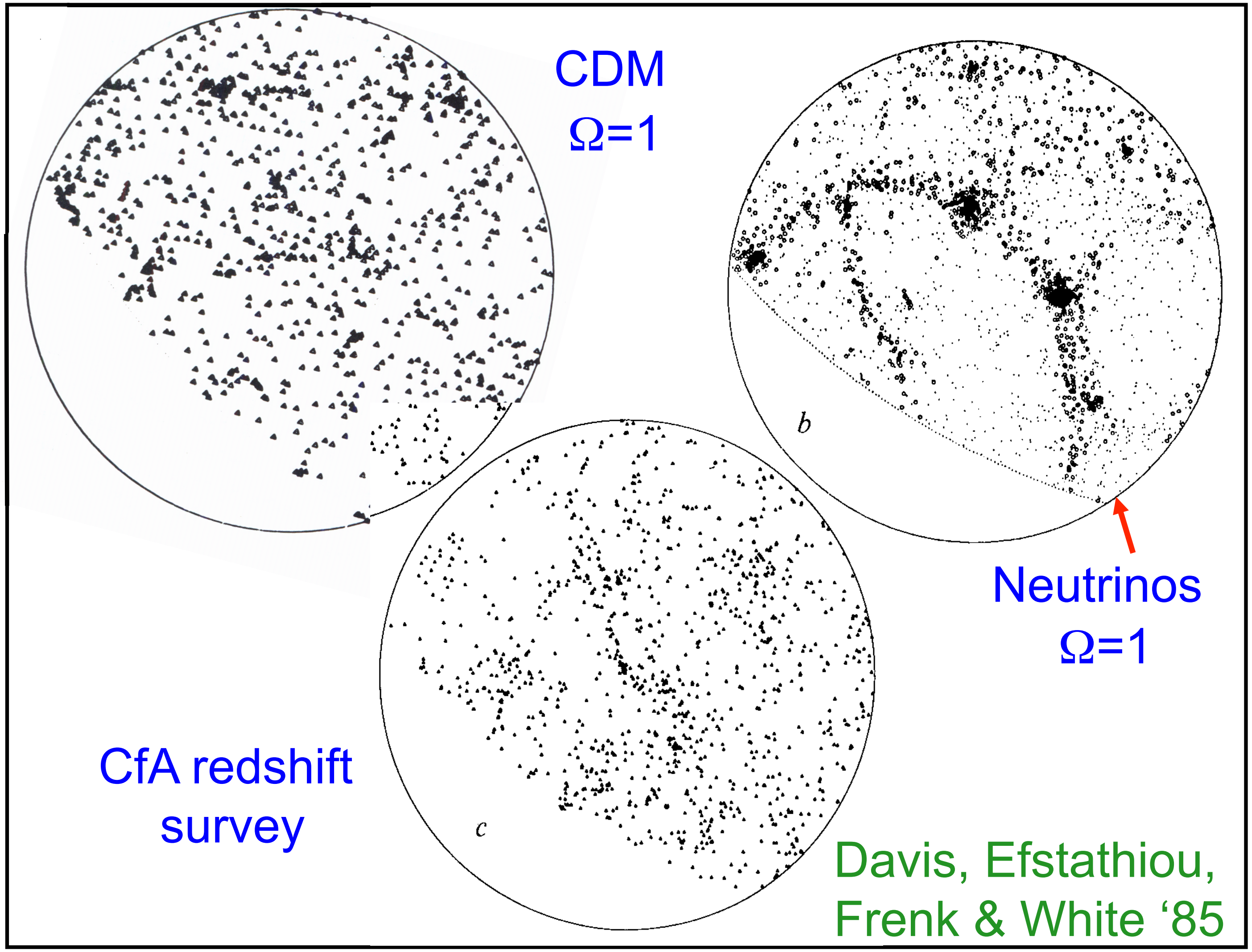
The `Gang of Four' - 1983

Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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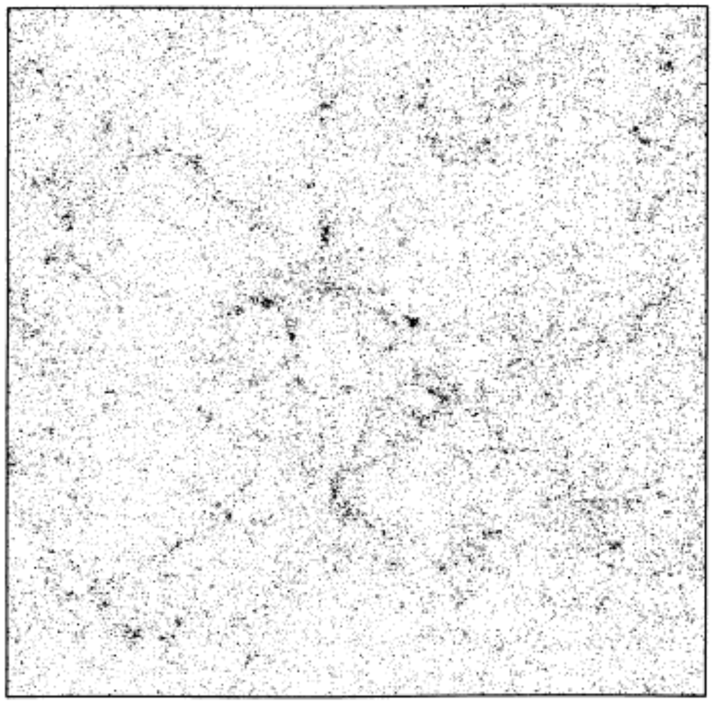
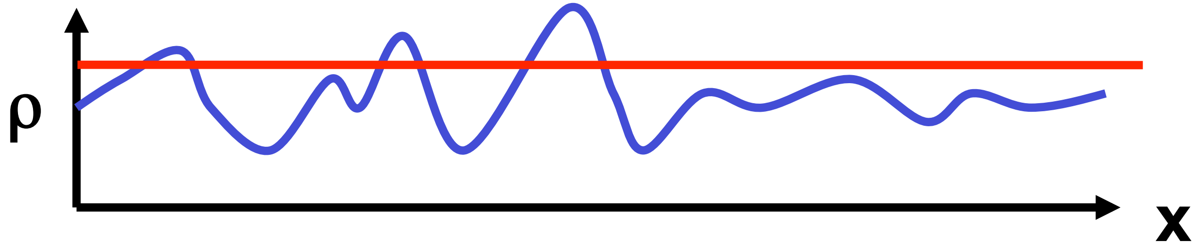
Ω = 1 CDM

DEFW '85

Galaxies trace mass { pec vels too large / wrong clustering }

Dark matter





"Biased galaxy formation"

(after Kaiser '84)

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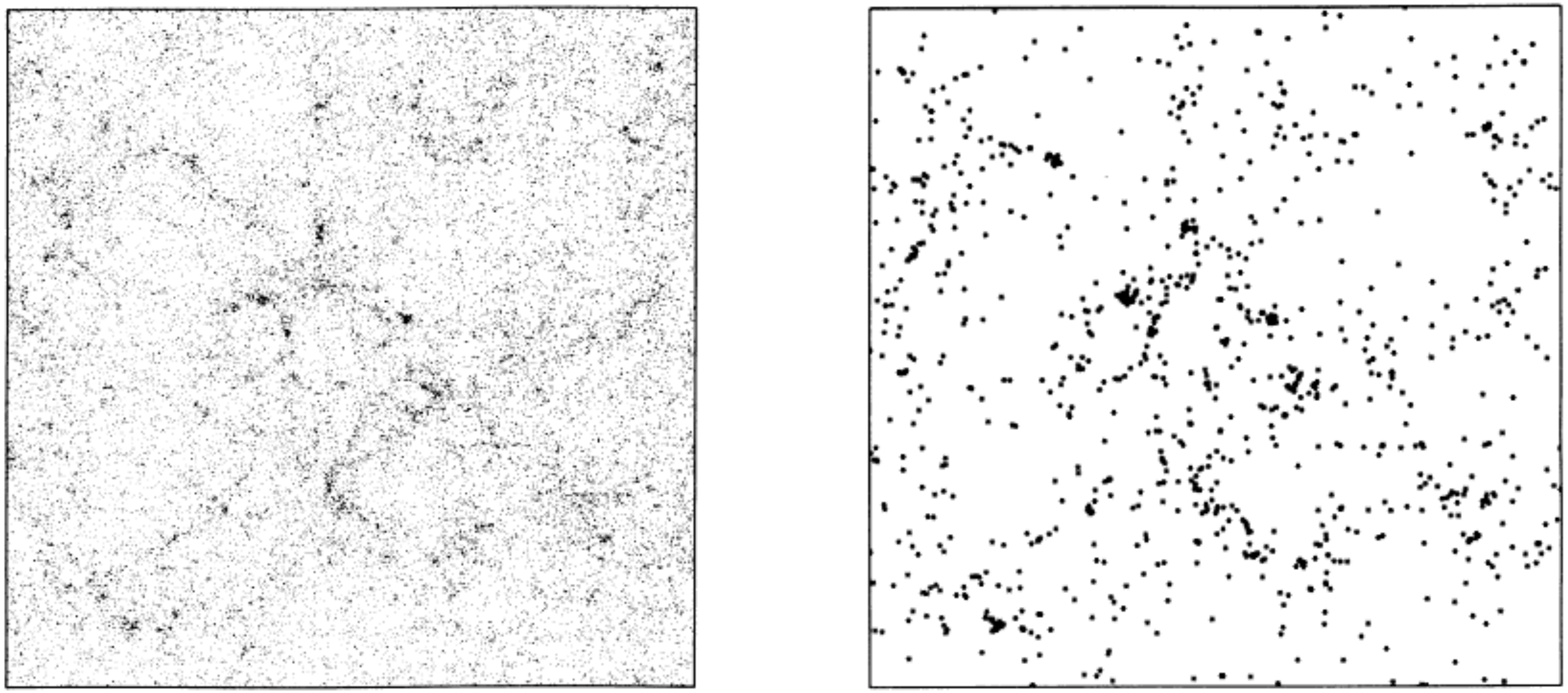
Biased galaxy formation

… 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.

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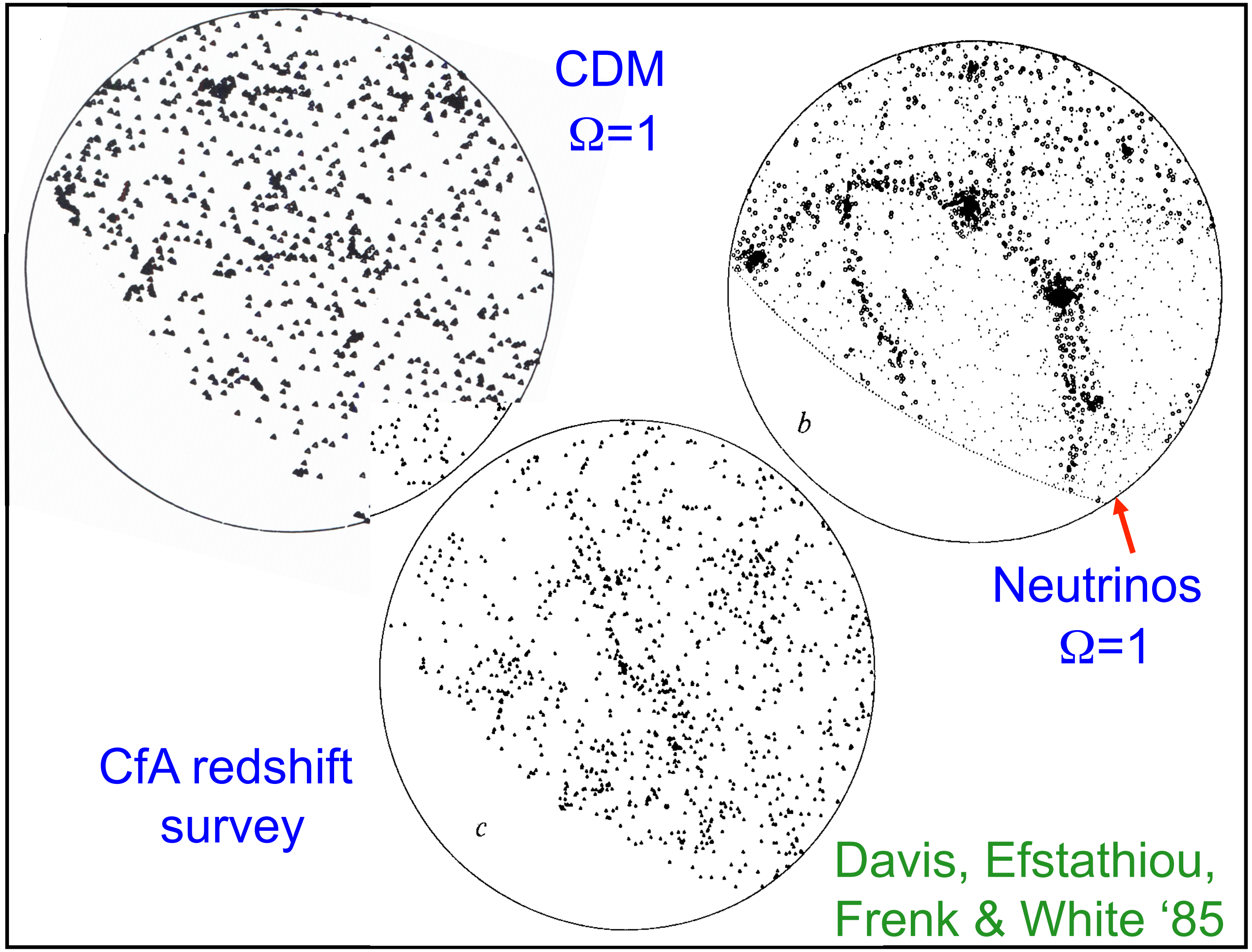
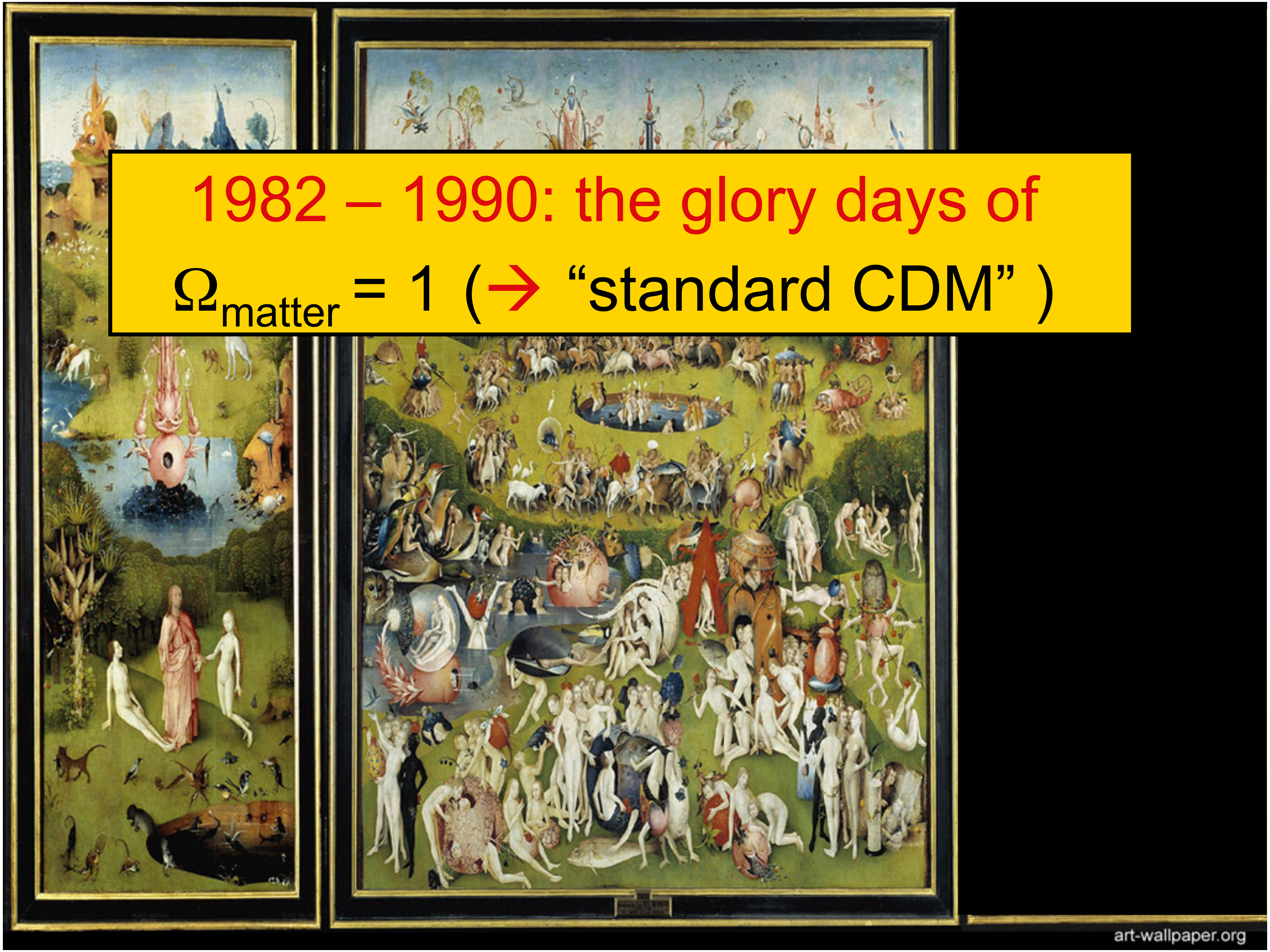


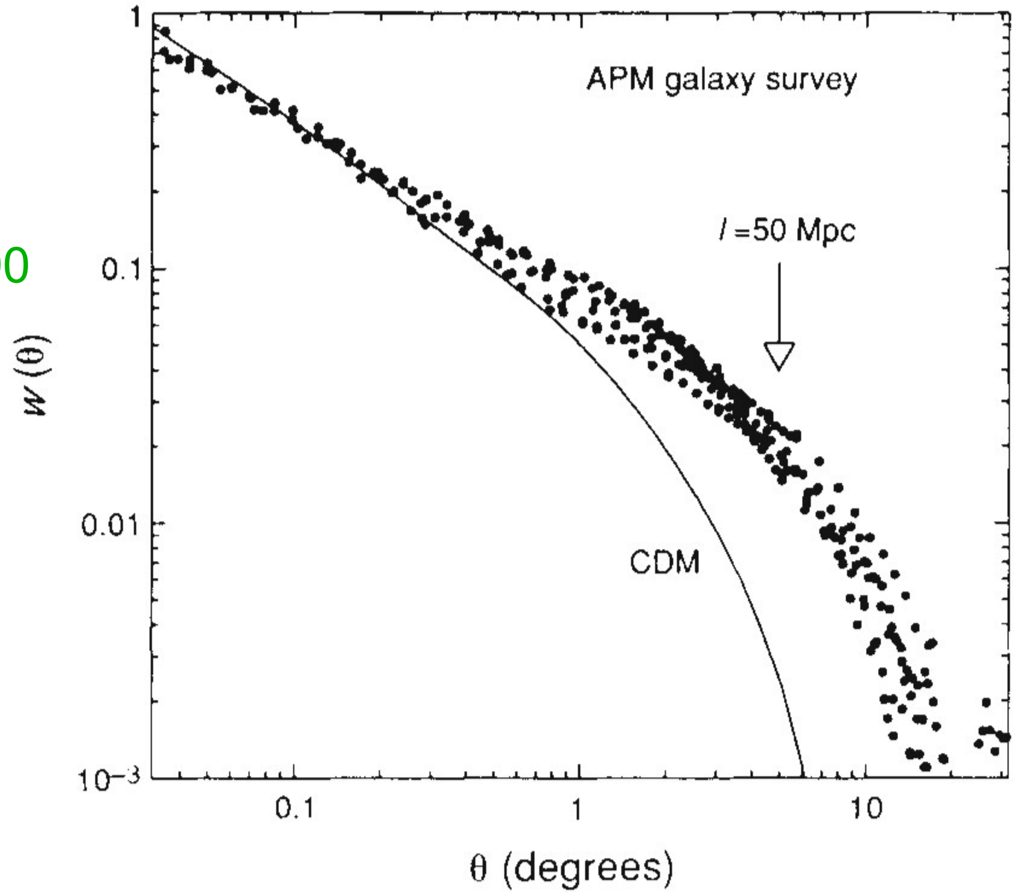
1982 – 1990: the glory days of $\Omega_{matter} = 1$ (→ “standard CDM”)



1990: Ω = 1 CDM under strain

Angular 2-pt correlation function

Maddox, Efstathiou, Sutherland & Loveday '90



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

The end of standard (Ω_{matter} =1) CDM … or why Ω_{matter} cannot be 1

ICC
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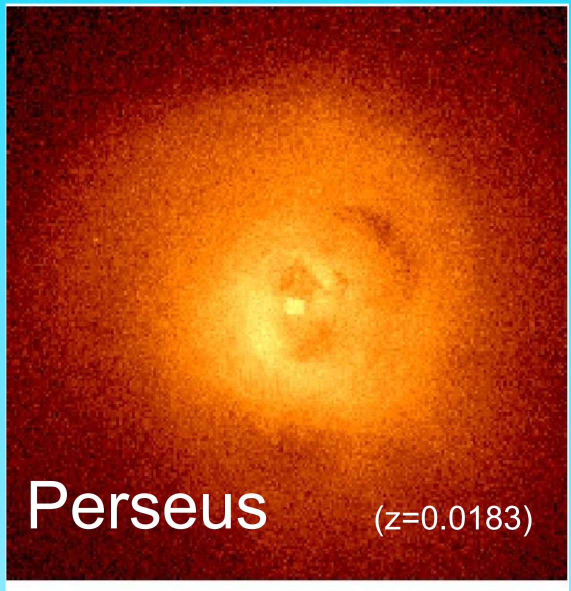
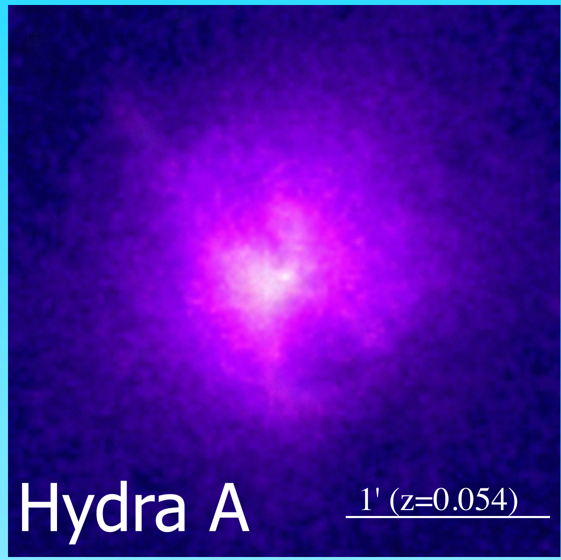
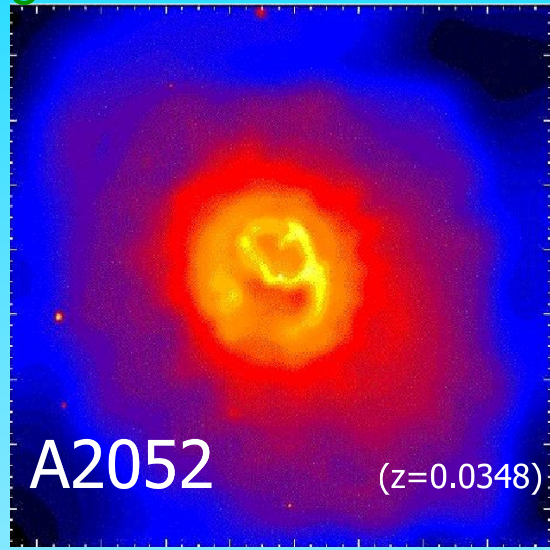
Galaxy clusters

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 → $h = 0.7 \pm 10\%$

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

Allen etal '04

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(Some) evidence for dark energy

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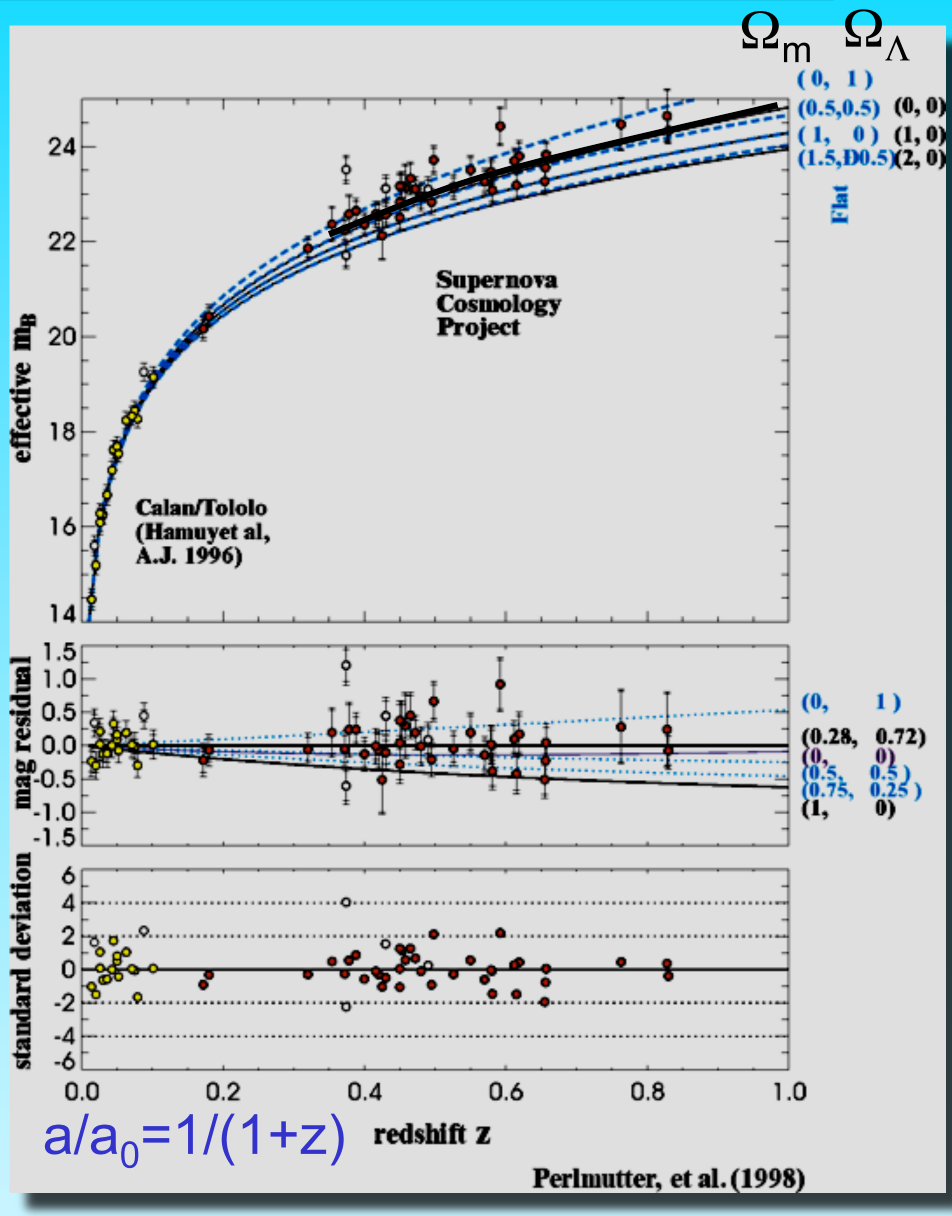
Evidence for Λ from high-z supernovae

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

flux



➔ The 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

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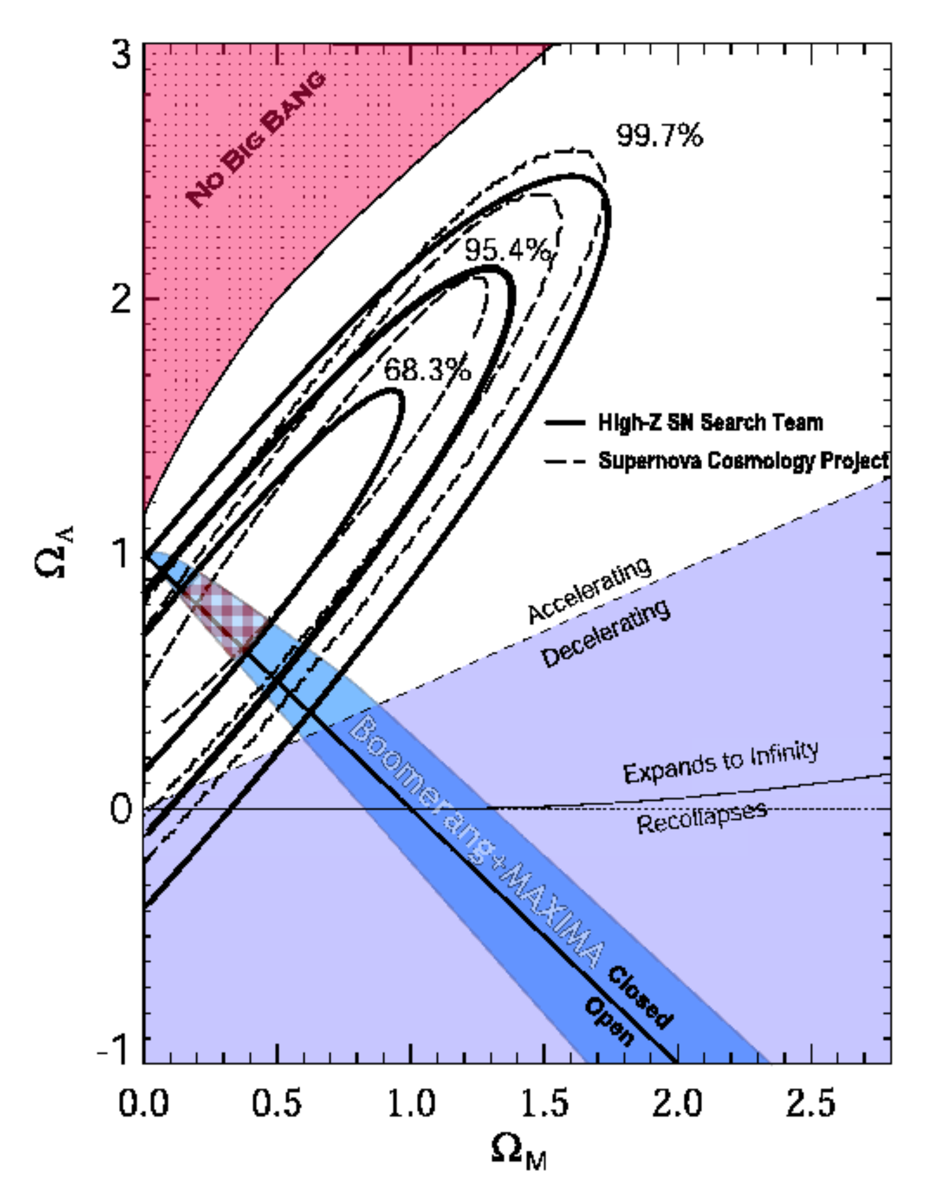
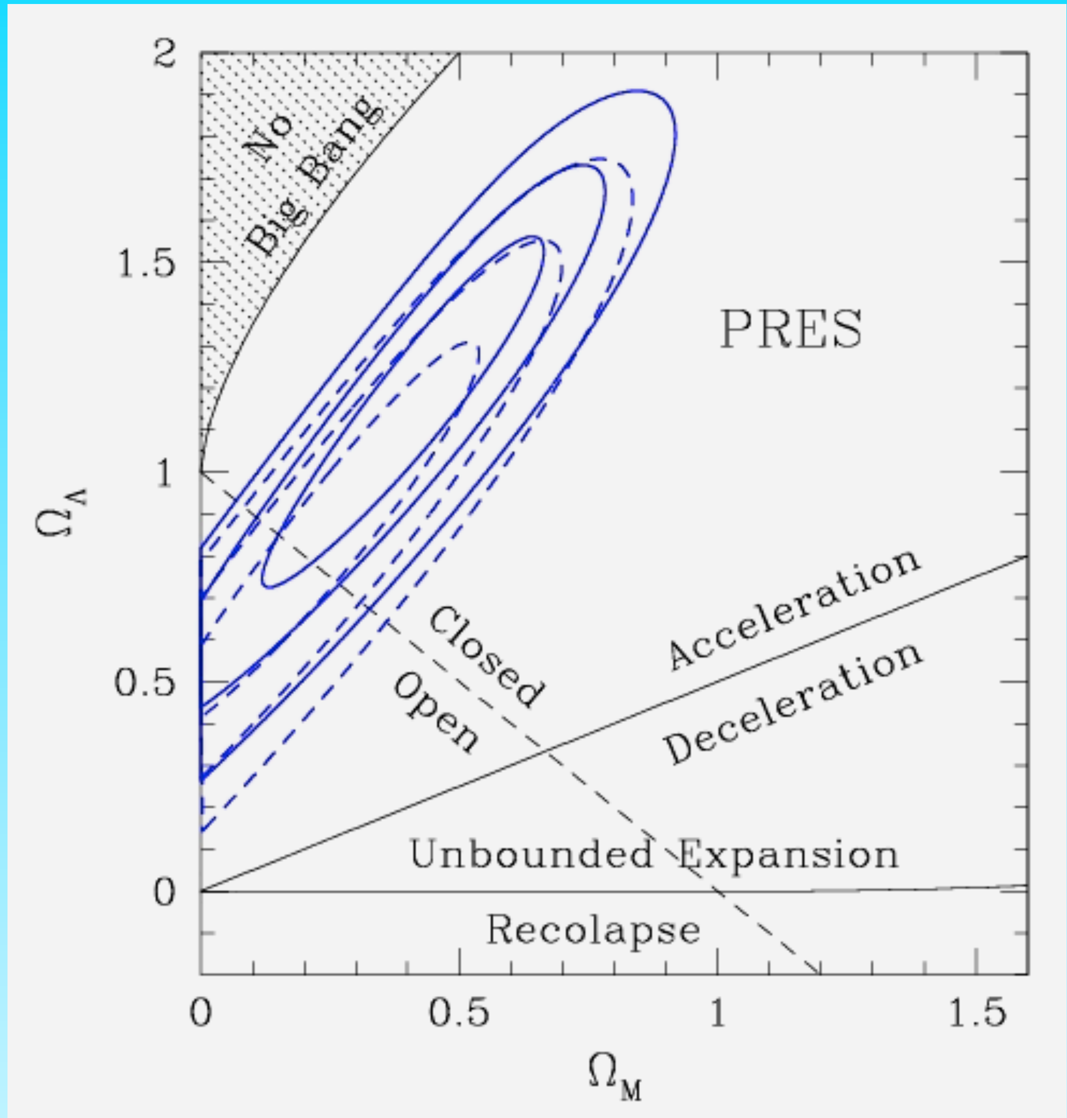


Evidence for Λ from high-z supernovae

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 $\Rightarrow \ddot{a} > 0 \quad \Rightarrow \quad 3w + 1 < 0$

$w < -\frac{1}{3} \quad \Rightarrow$ dark energy $[\rho_{vac} = \rho_{vac}(x,z)]$

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

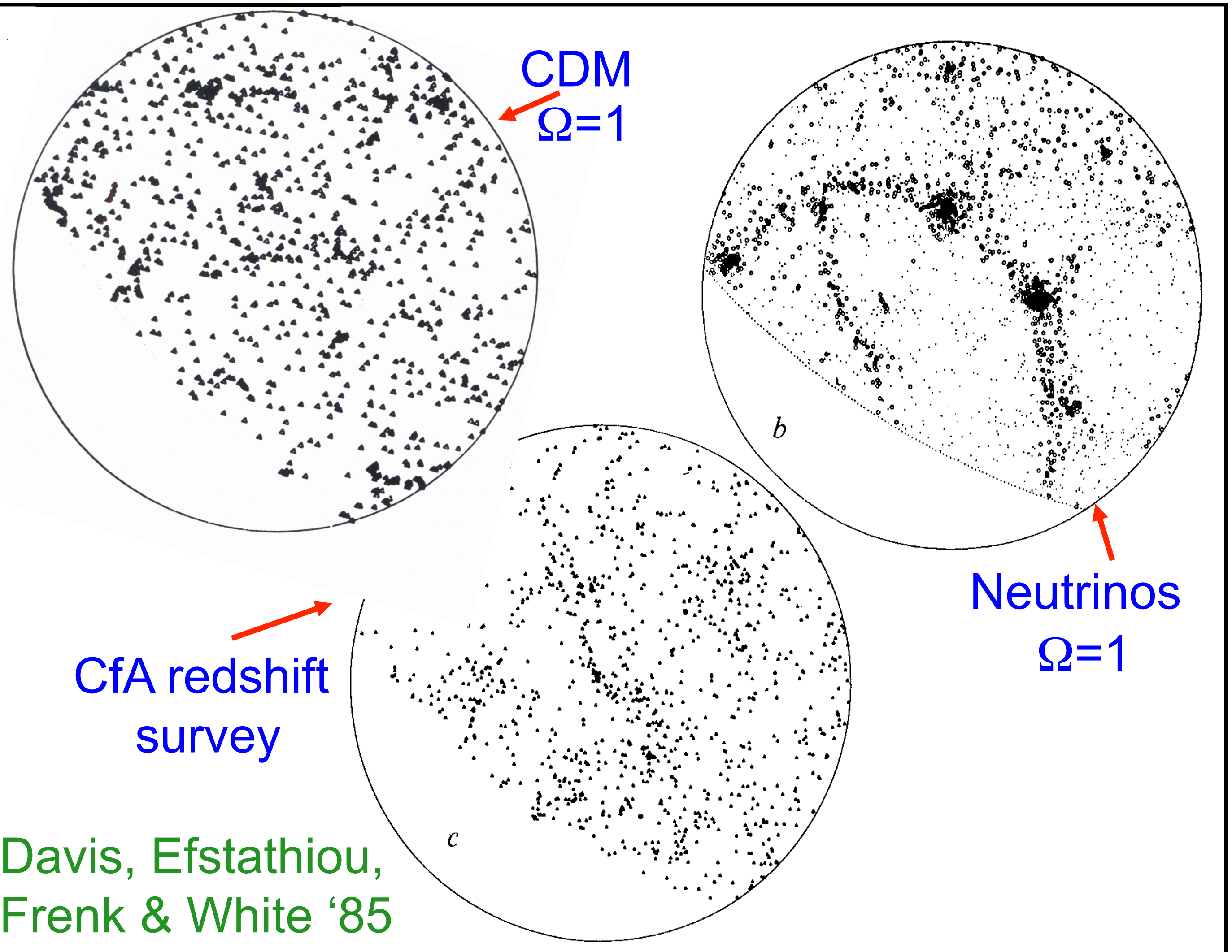
cosmological constant

Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



Davis, Efstathiou, Frenk & White '85

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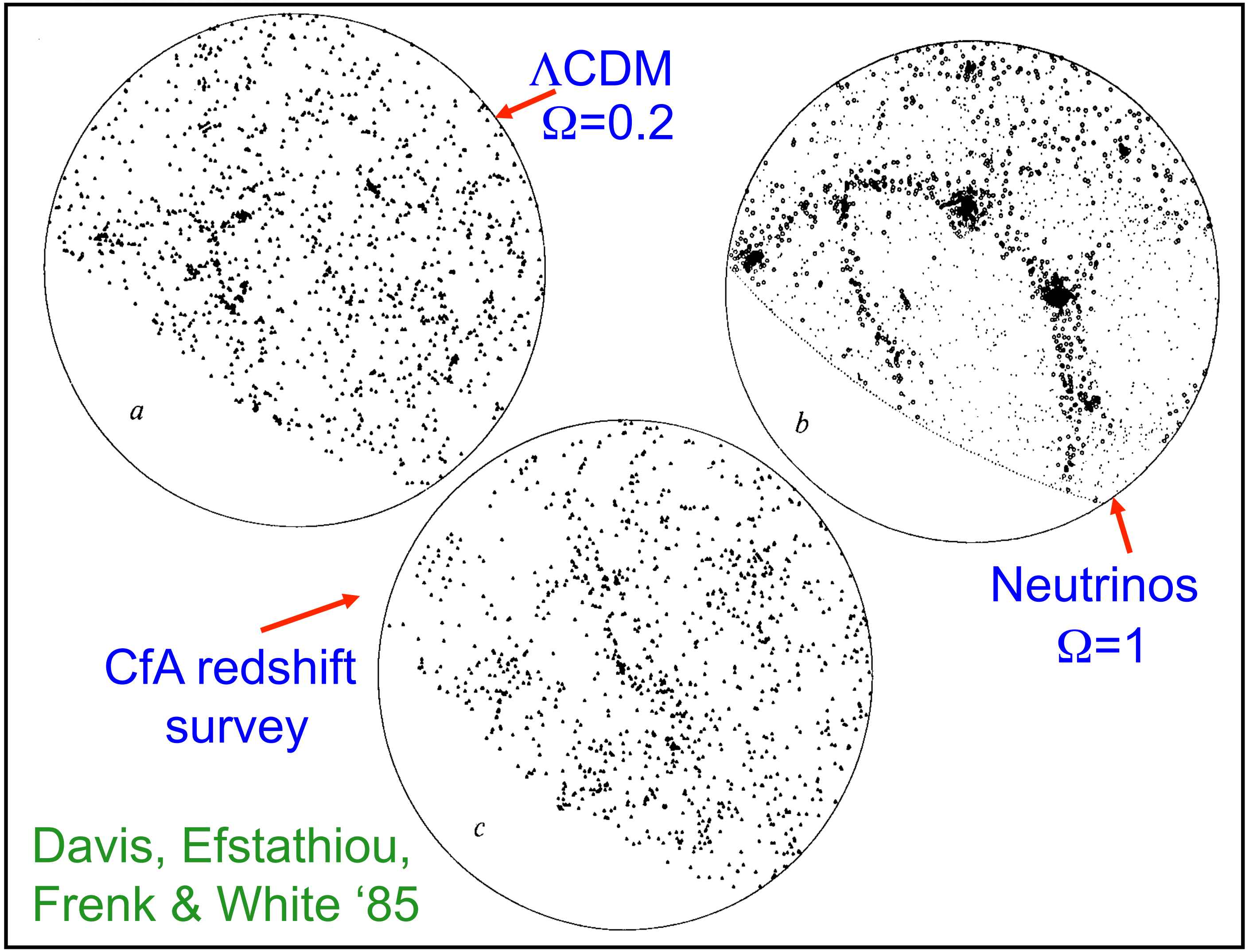


$\Omega_m = 1$

$\Omega_m = 1$
$\Omega_m = 0.25$
$\Omega_\Lambda = 0.75$
art-wallpaper.org

University of Durham

The cosmic dark energy

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

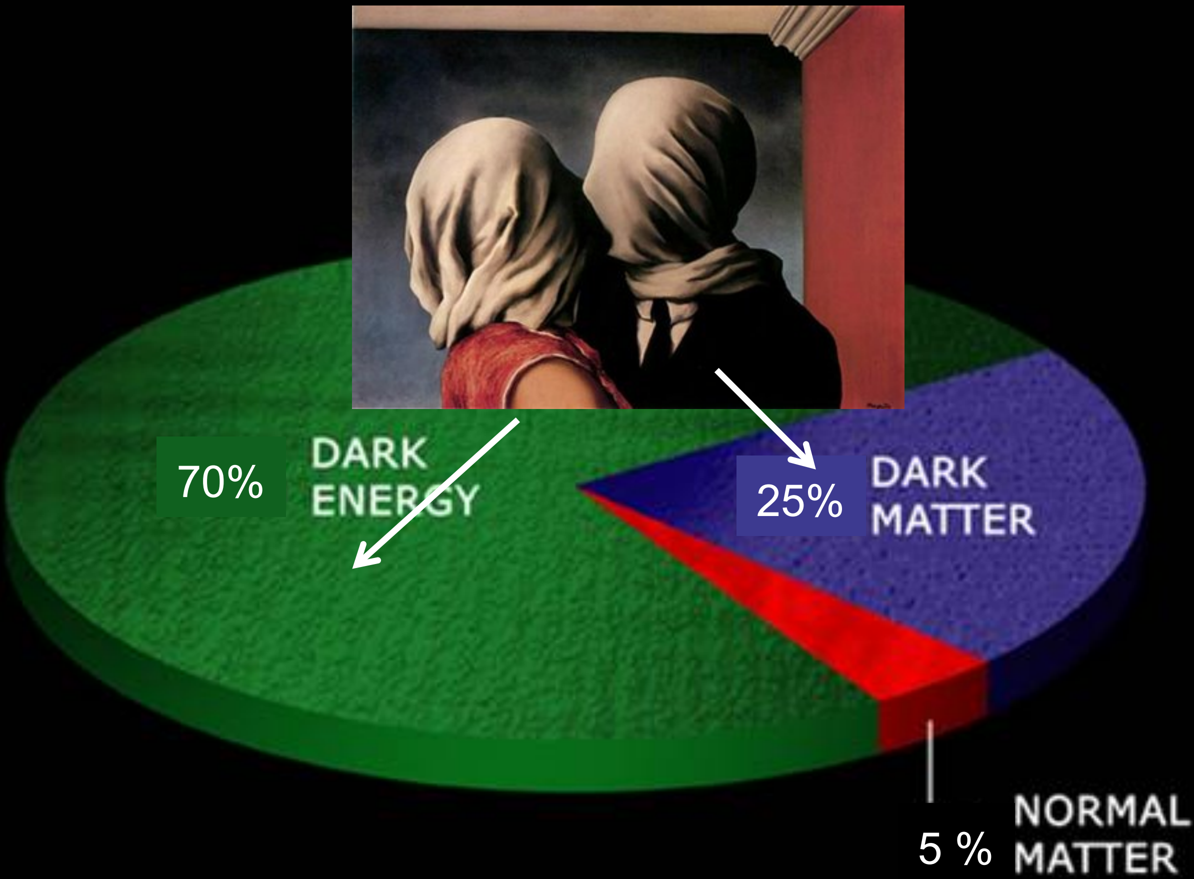
$$\rho_\Lambda^{PL} \sim M_{PL}^4 \sim (8\pi G)^{-2} \sim (10^{18} GeV)^4 \sim 2\times 10^{110} erg/cm^3$$

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

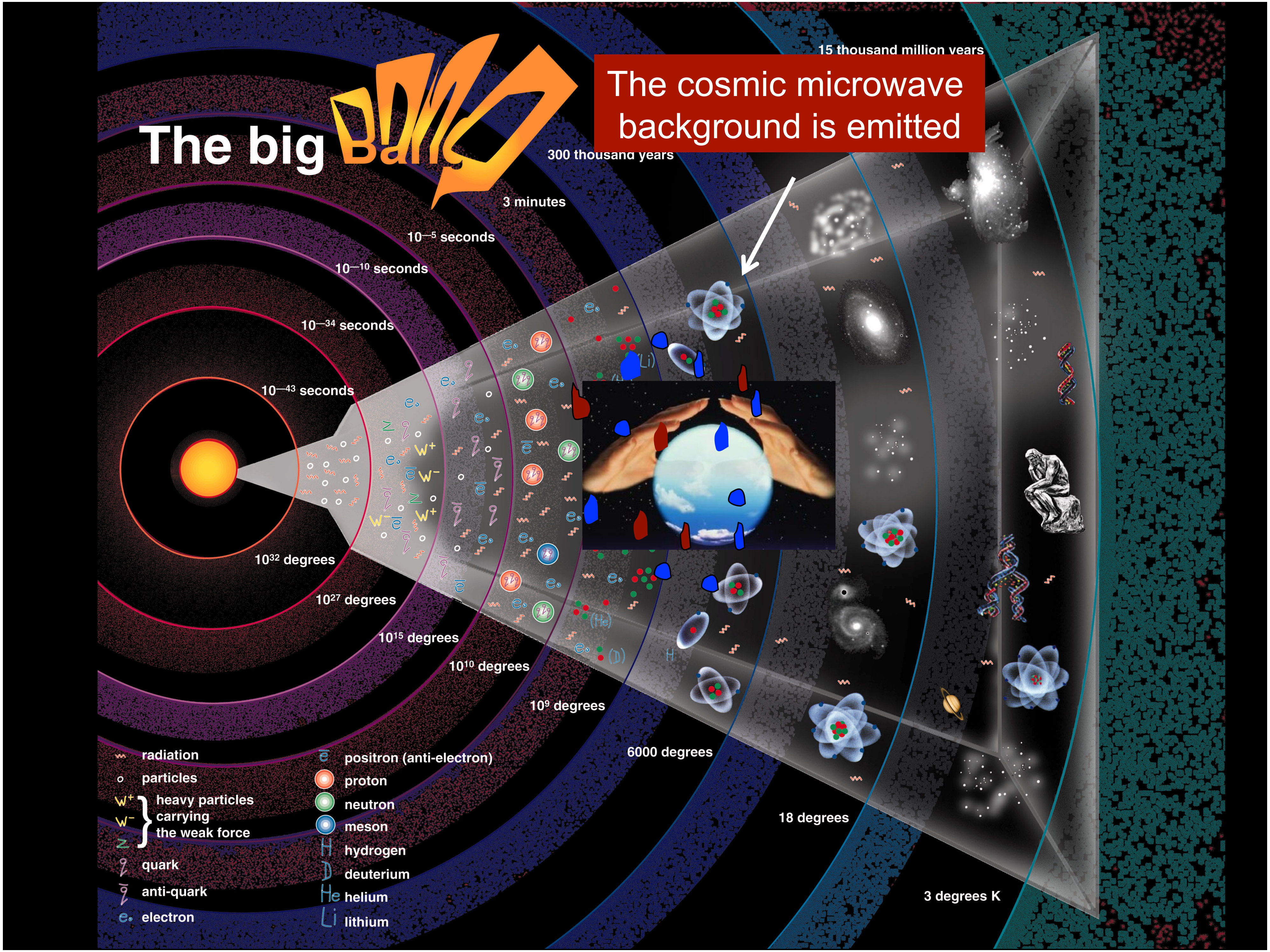
10^{120} larger than observed !!!

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

ΛCDM is an *a priori* implausible model



… but makes definite predictions and is therefore testable

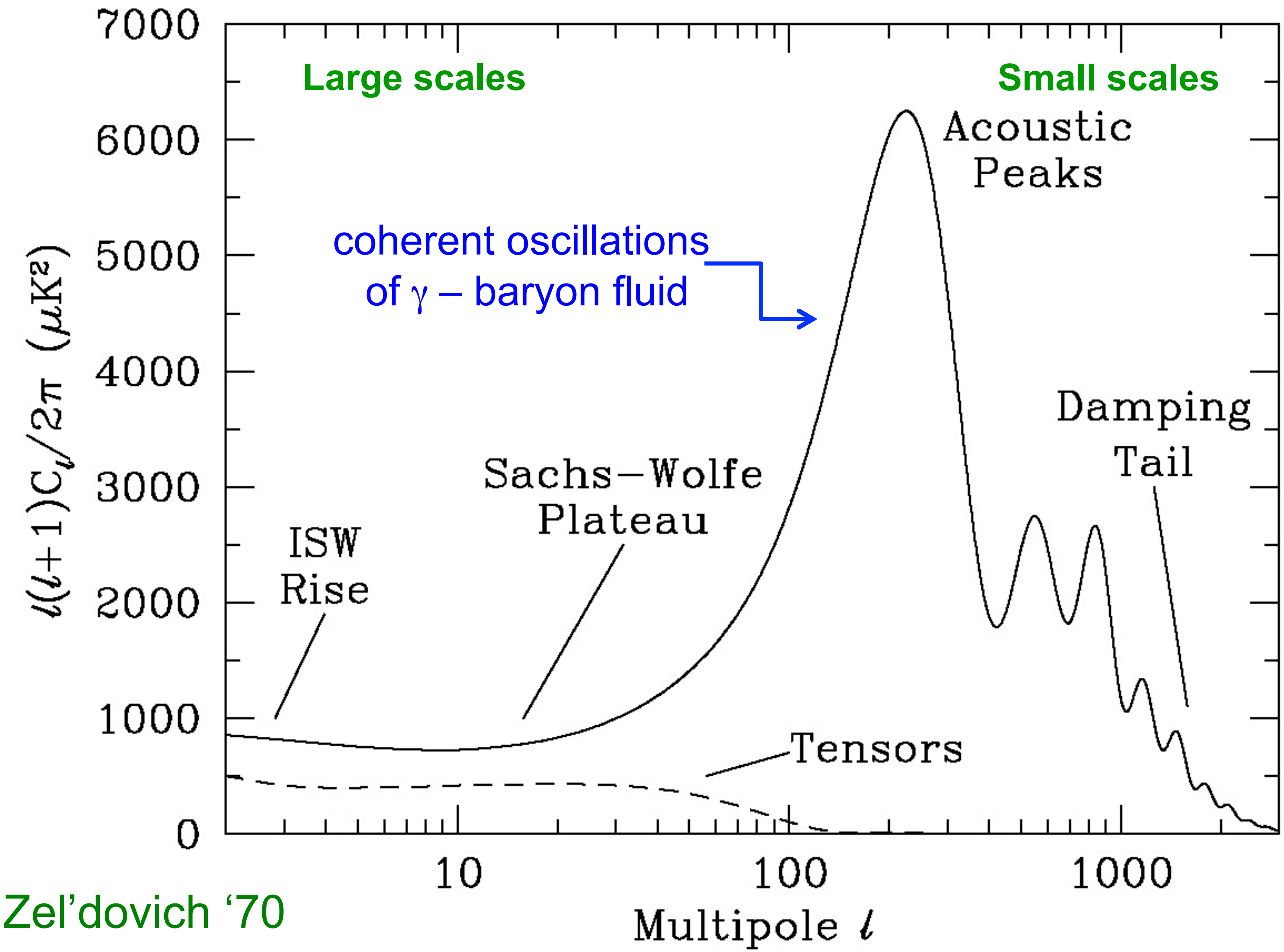


The big Bang
The cosmic microwave background is emitted
15 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles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

Temperature anisotropies in CMB

University of Durham

2D power spectrum

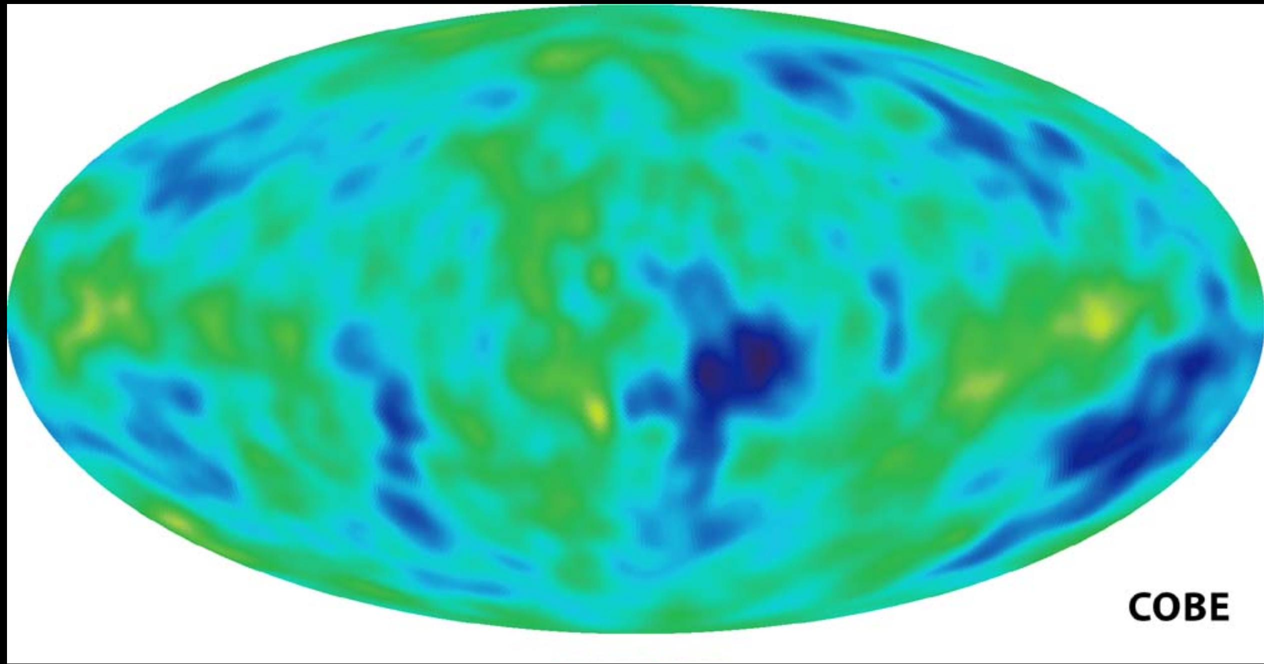


Sunyev & Zel'dovich '70

Peebles & Yu '70; Peebles '82; Bond &Efstathiou '84

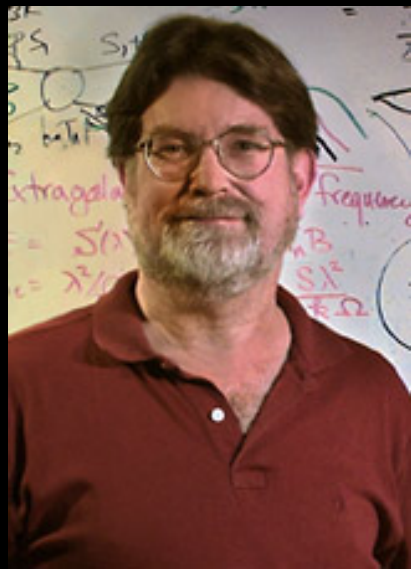
The CMB

1992



George Smoot - Nobel Prize 2006

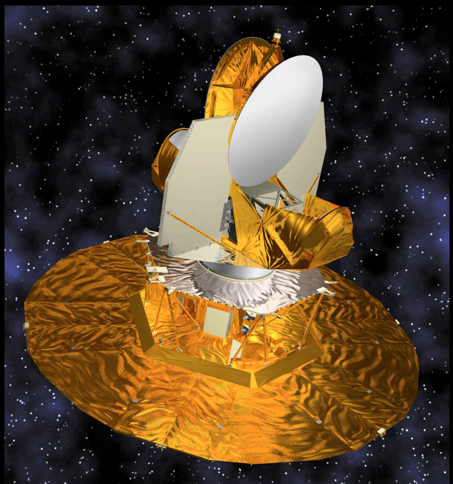
KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

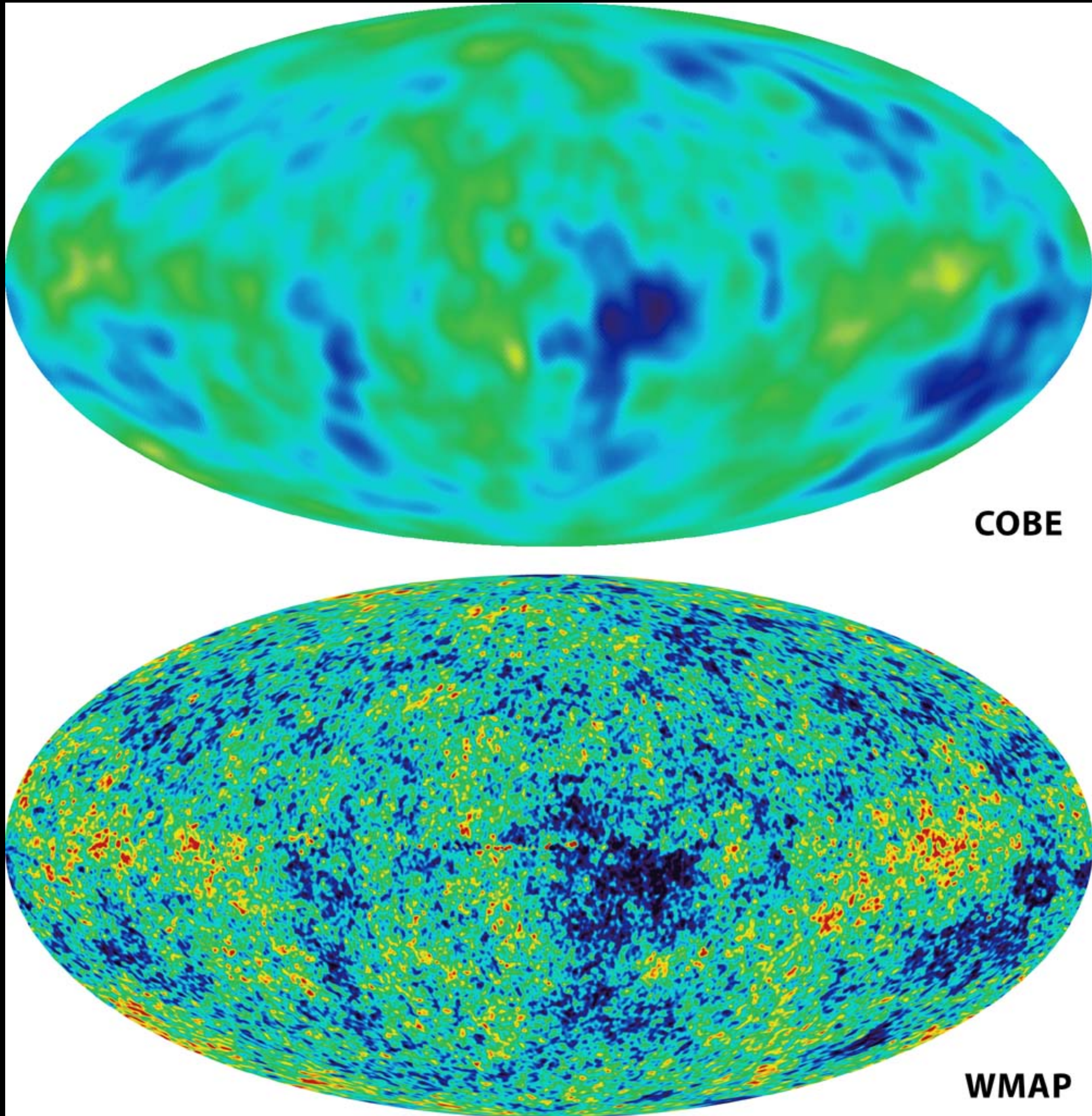


The CMB

1992

2003

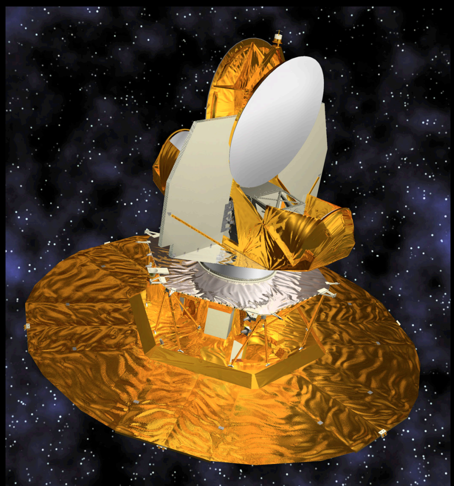


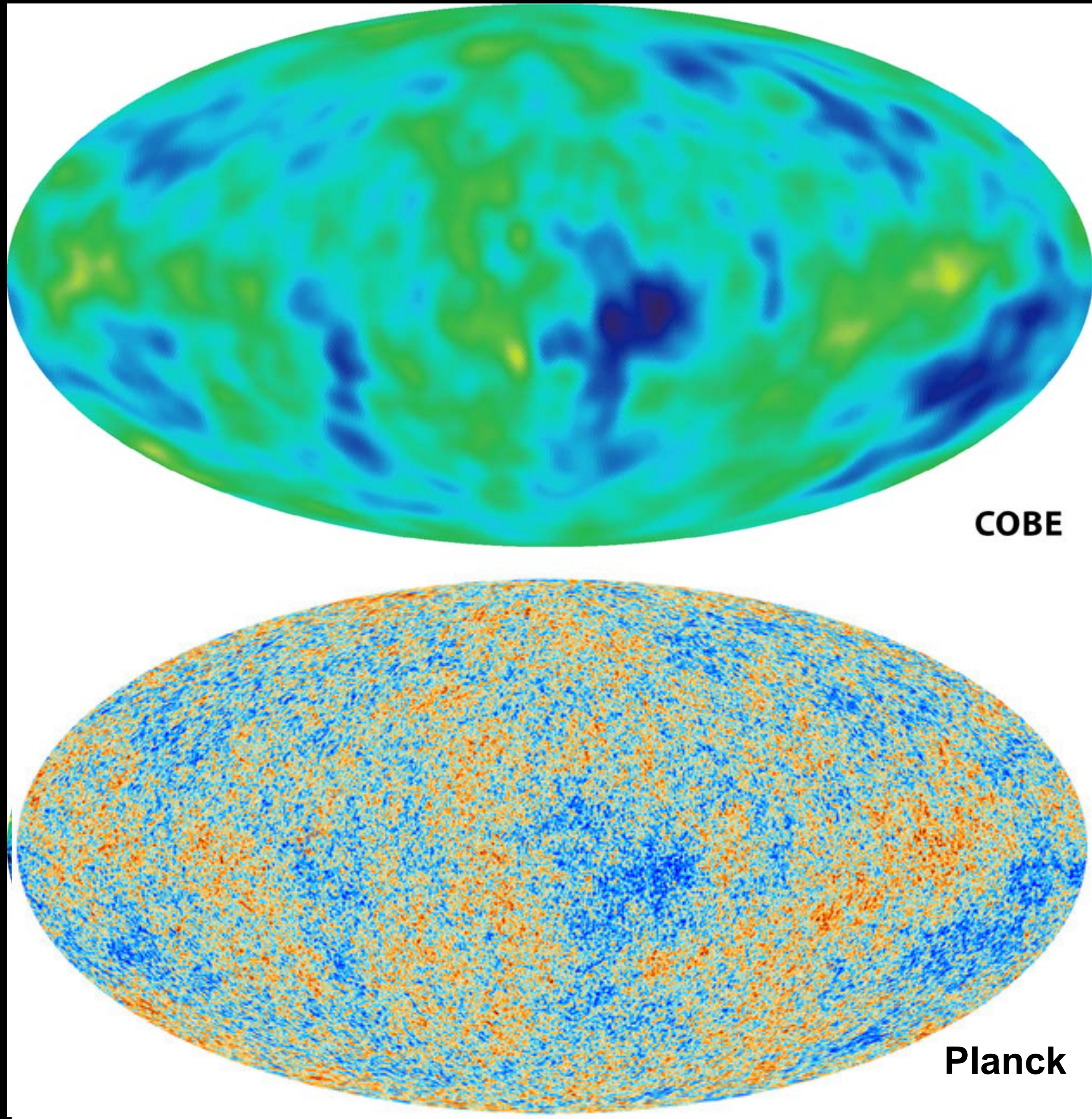


The CMB

1992

2012





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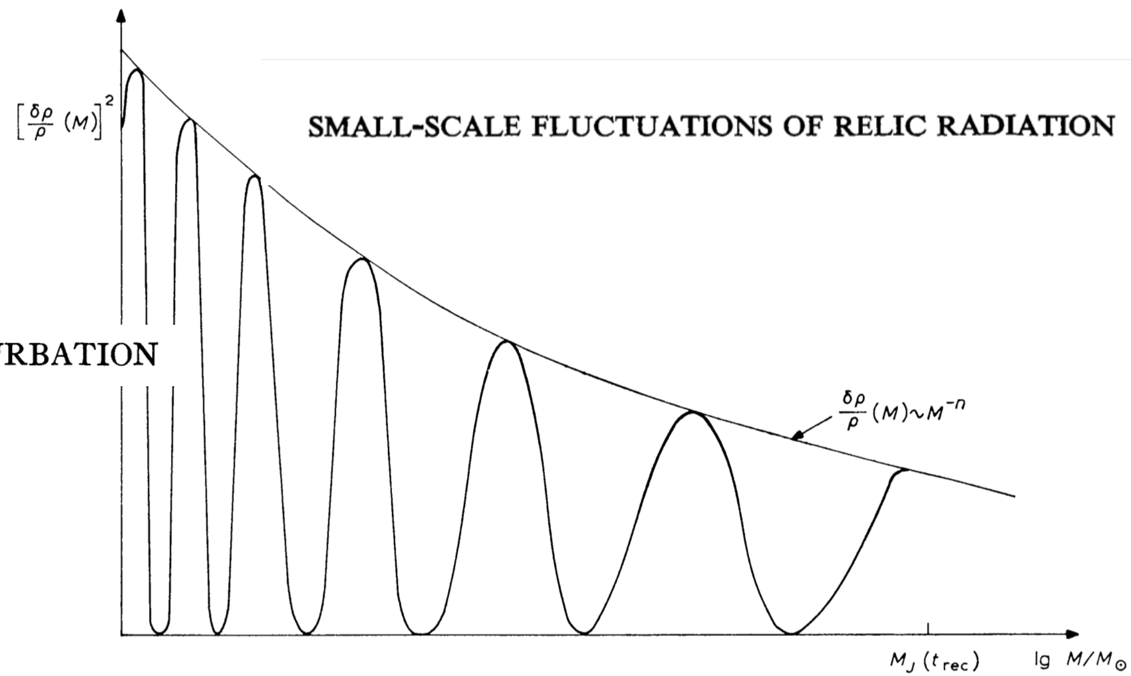
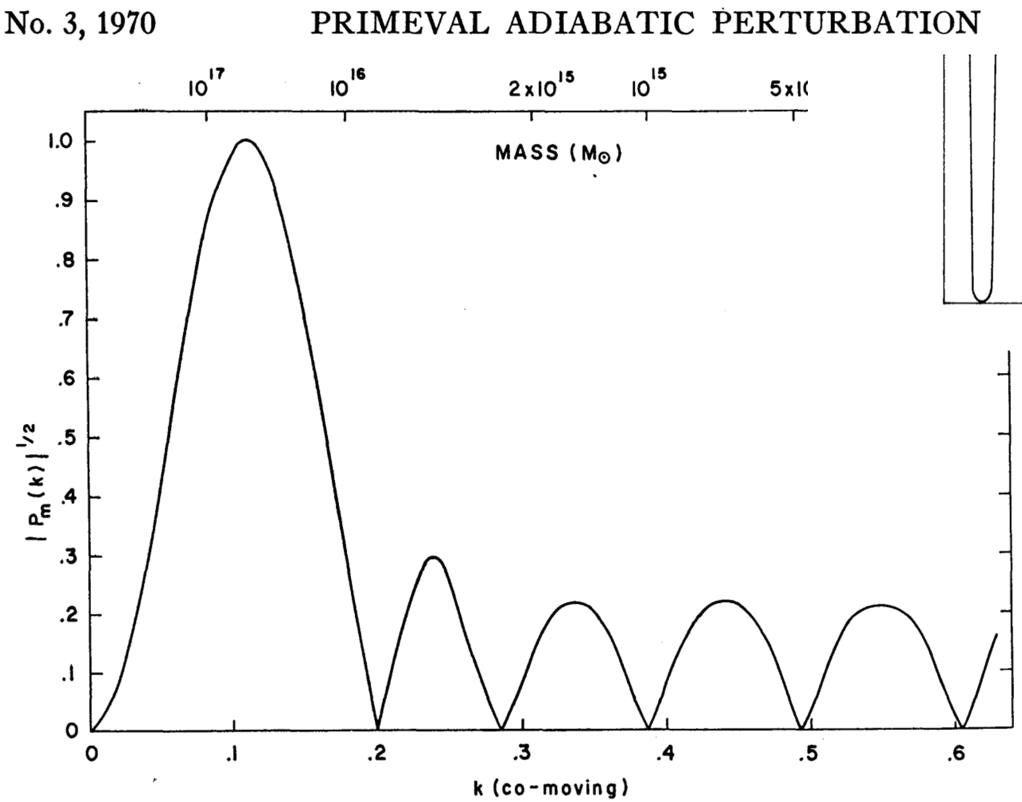
Temperature anisotropies in CMB



Sunyaev & Zel'dovich '70

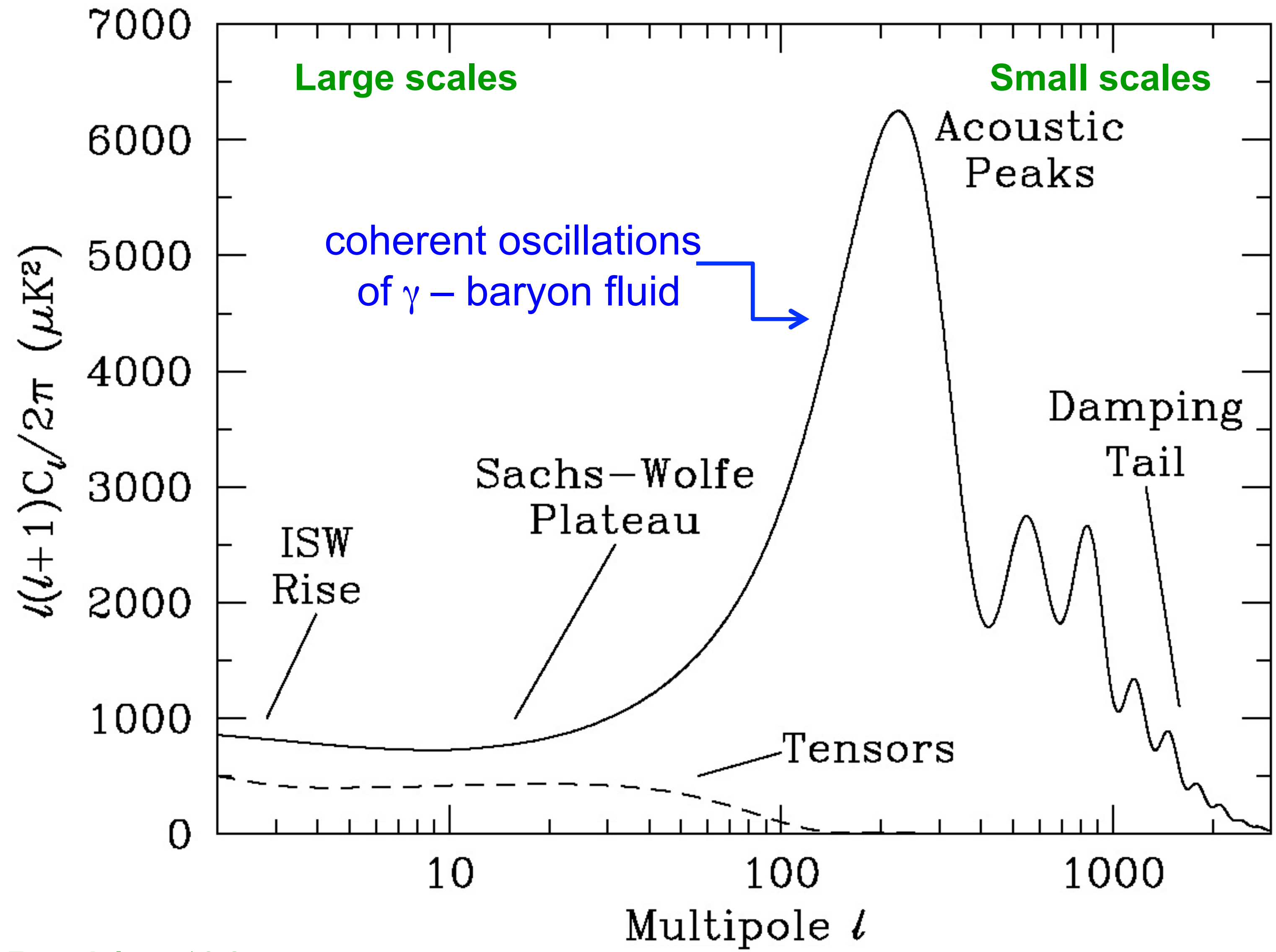


Peebles & Yu '70

Temperature anisotropies in CMB

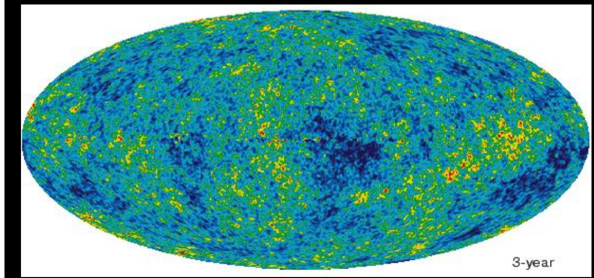
University of Durham

2D power spectrum

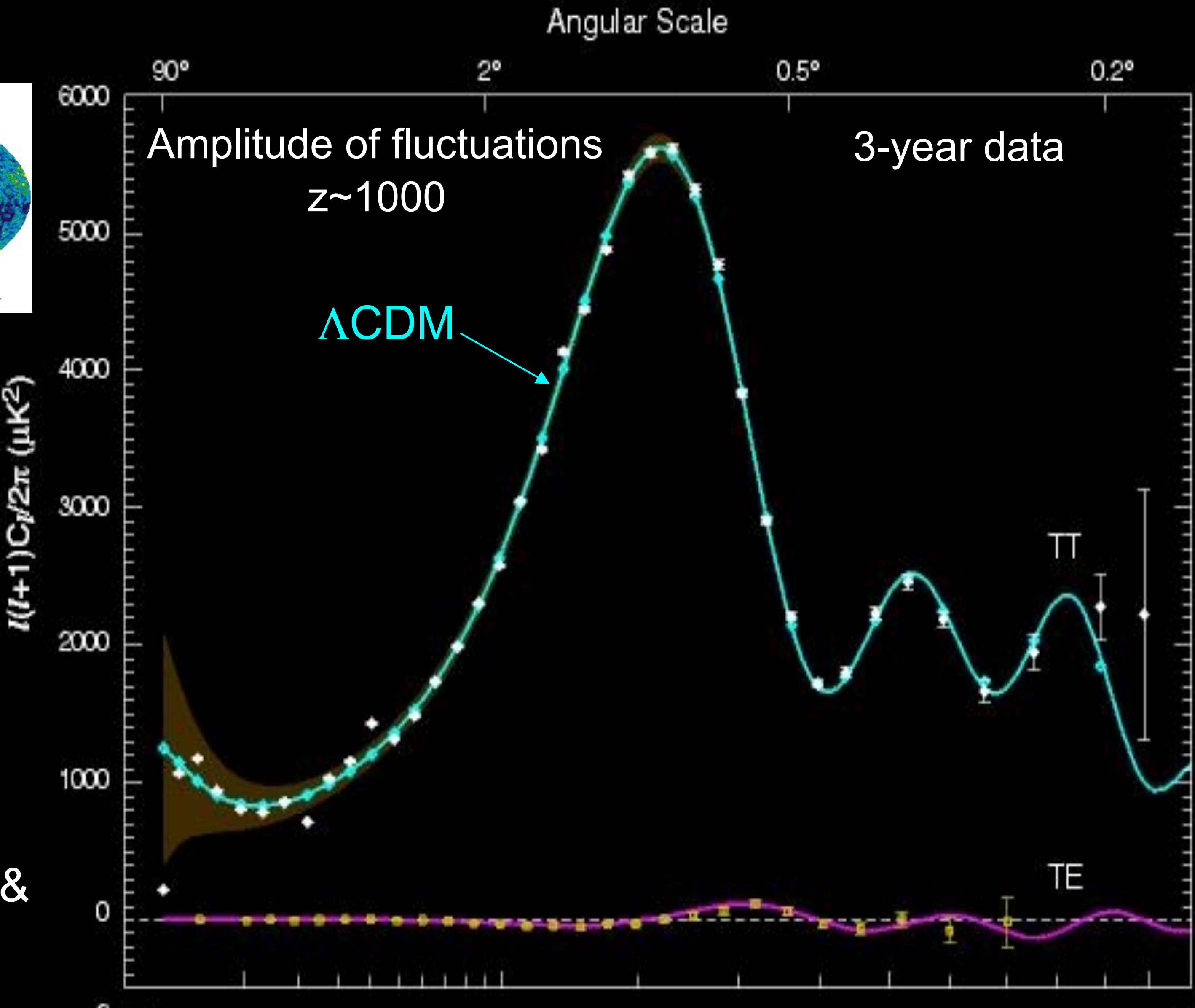


Peebles '82

WMAP temp anisotropies in CMB



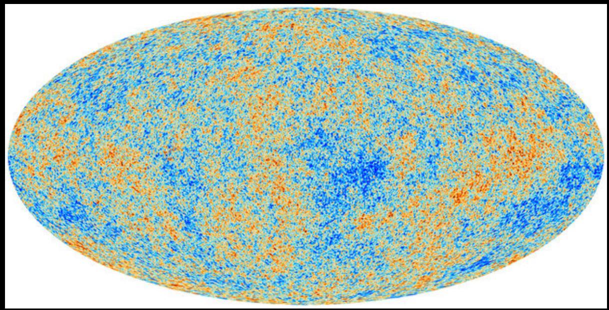
The data confirm the theoretical predictions (linear theory)



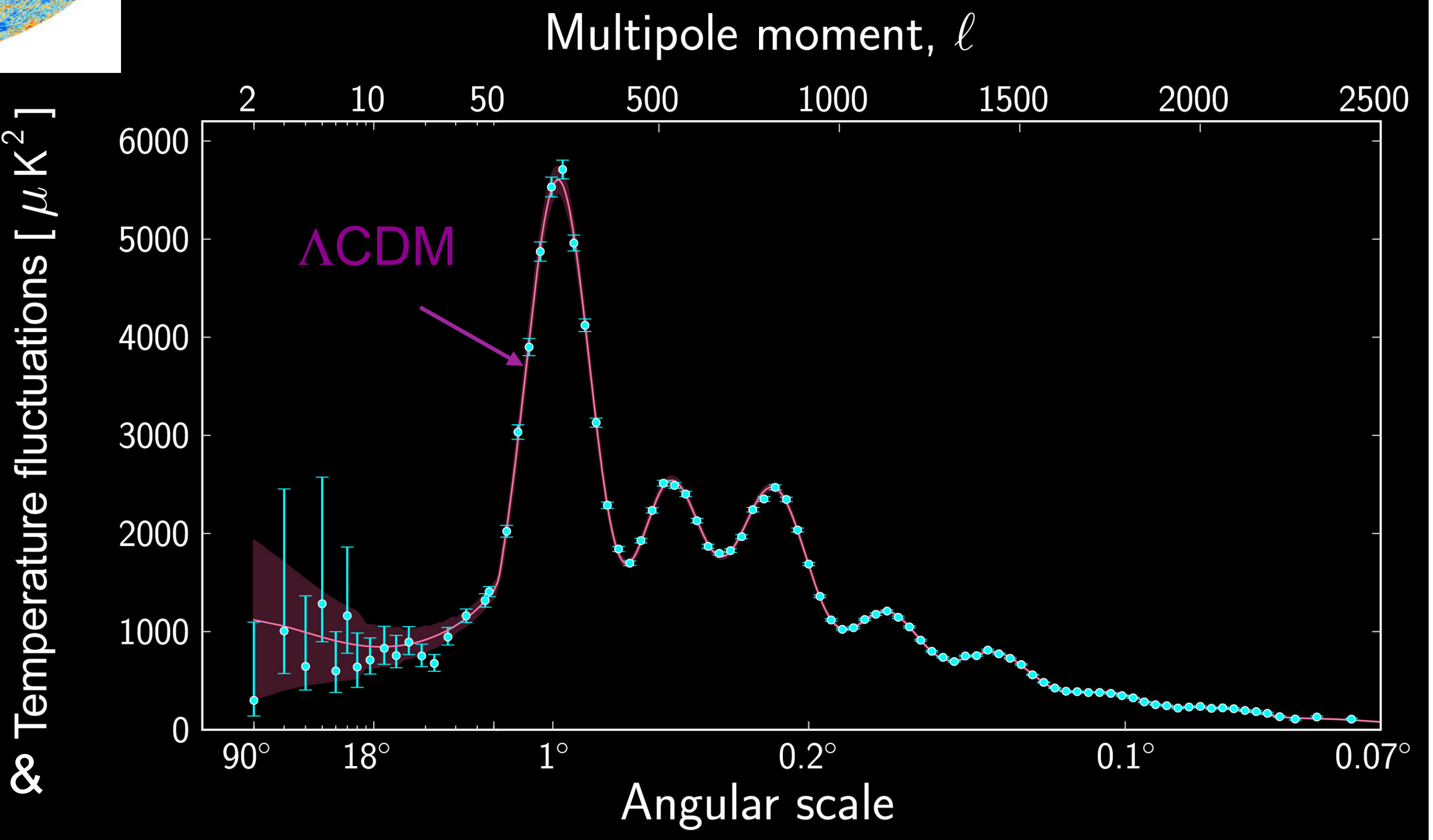
Peebles ’82; Bond & Efstathiou ‘80s

Hinshaw etal ‘06

Planck temp anisotropies in CMB



Amplitude of fluctuations at z~ 1000

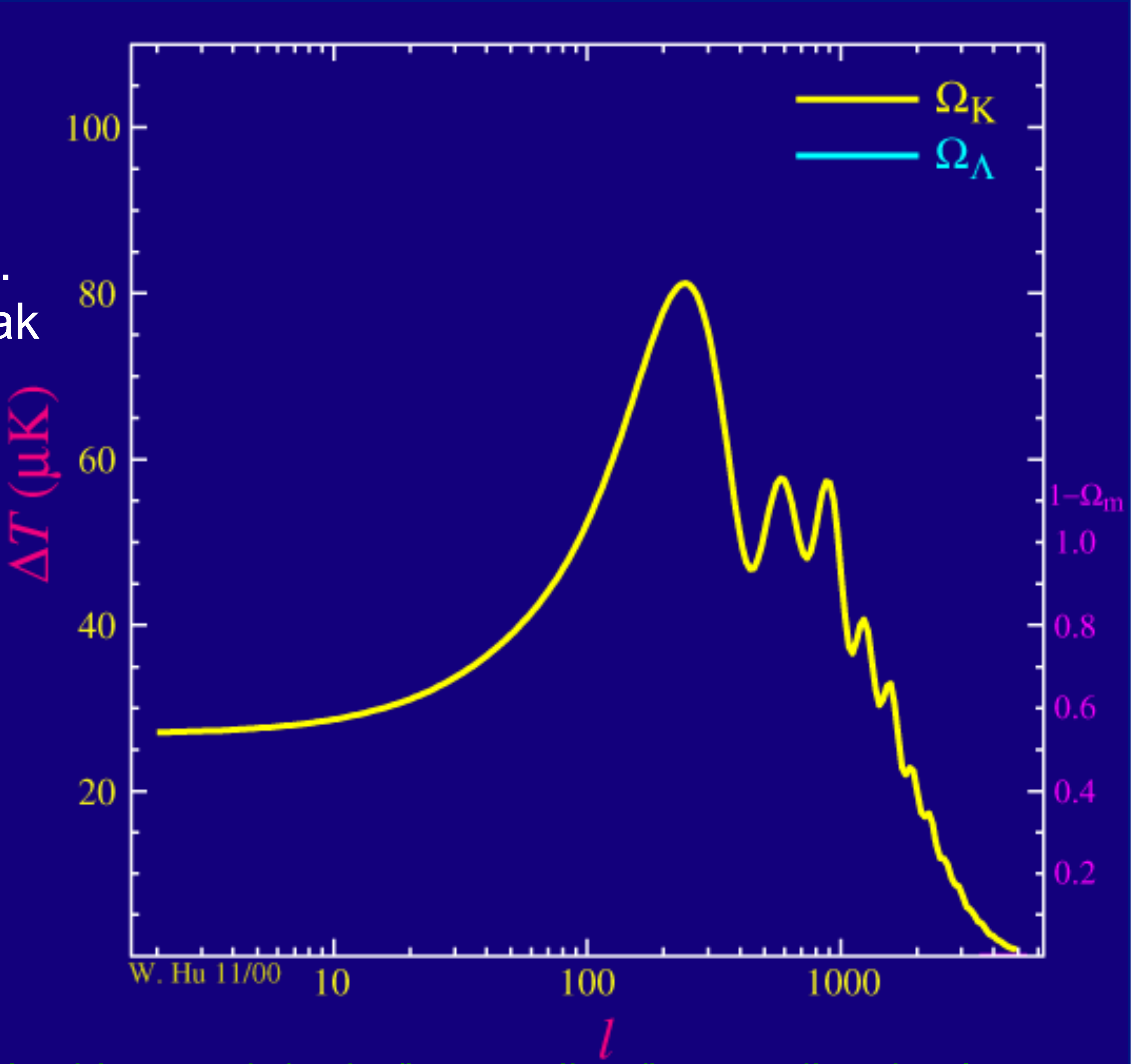


The data confirm the theoretical predictions (linear theory)

Peebles '82; Bond & Efstathiou '80s

Planck collaboration '13

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



Wayne Hu

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

University of Durham

Cosmological parameters from CMB data

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

Planck collaboration '13

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

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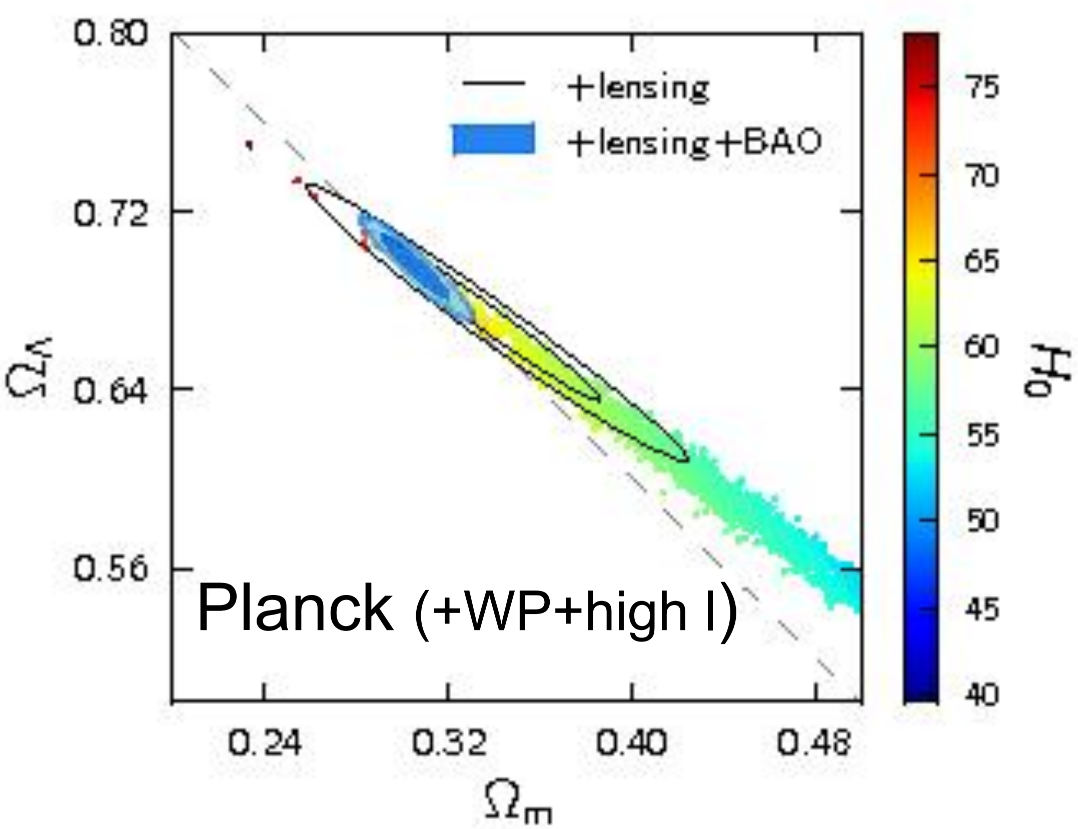
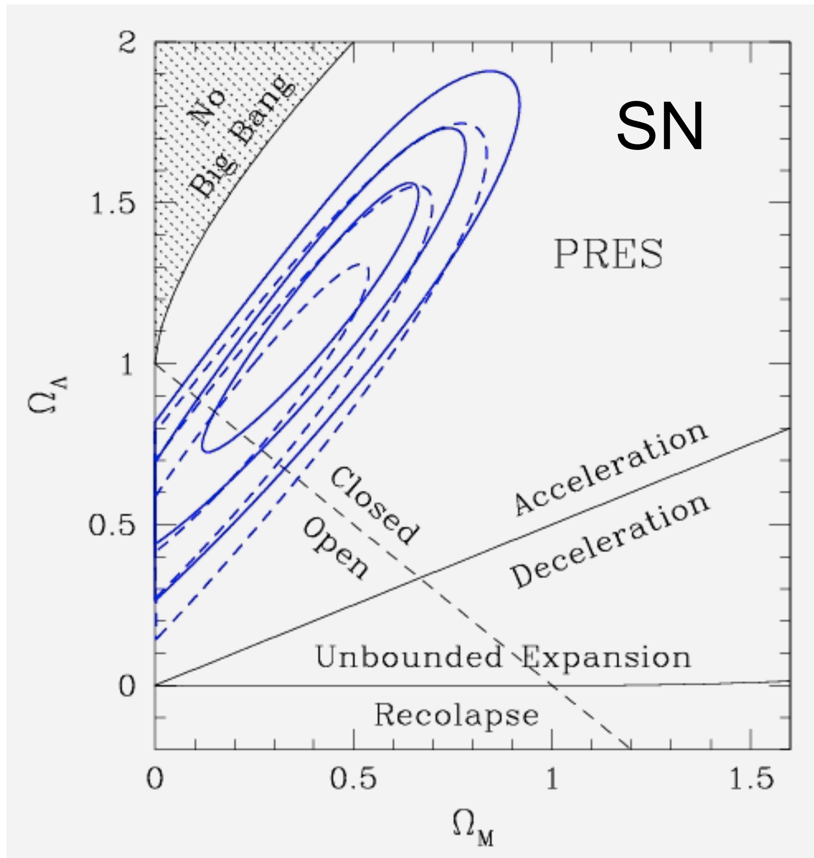
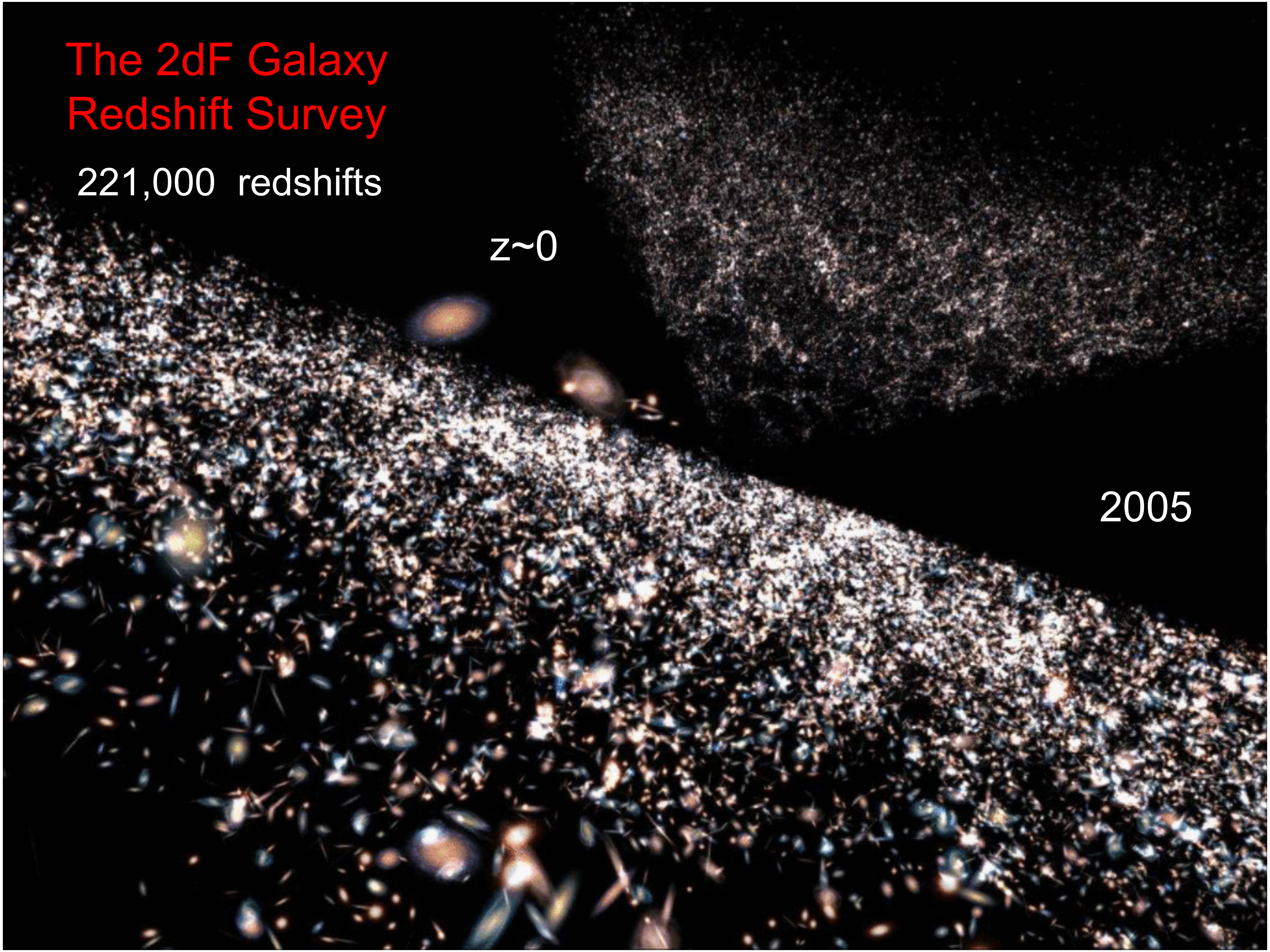
Planck breaks the degeneracy between Ω_{matter} and Ω_Λ

→ flat geometry

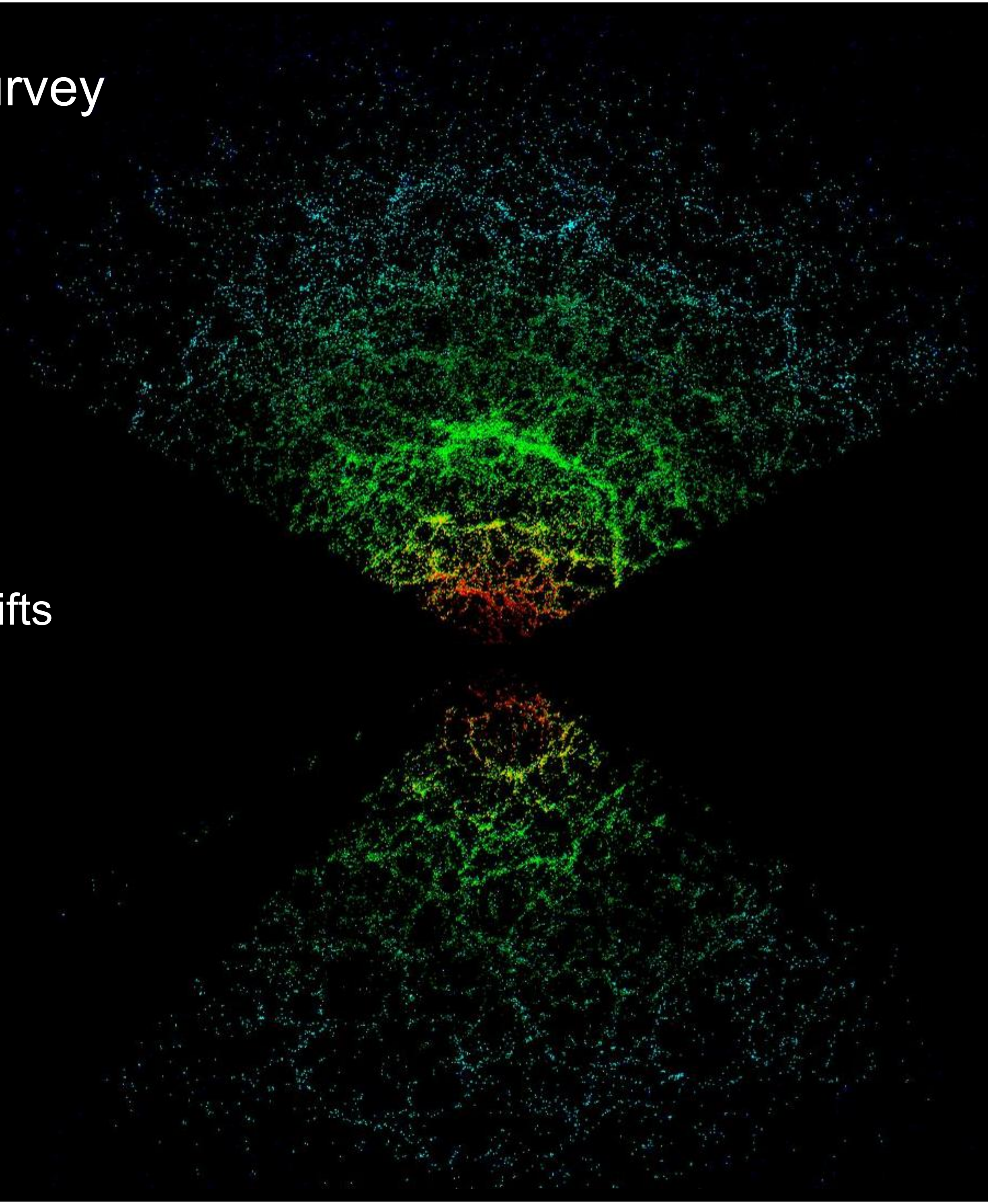





The 2dF Galaxy
Redshift Survey
221,000 redshifts
z~0
2005

Sloan Digital Sky Survey

~500,000 galaxy redshifts

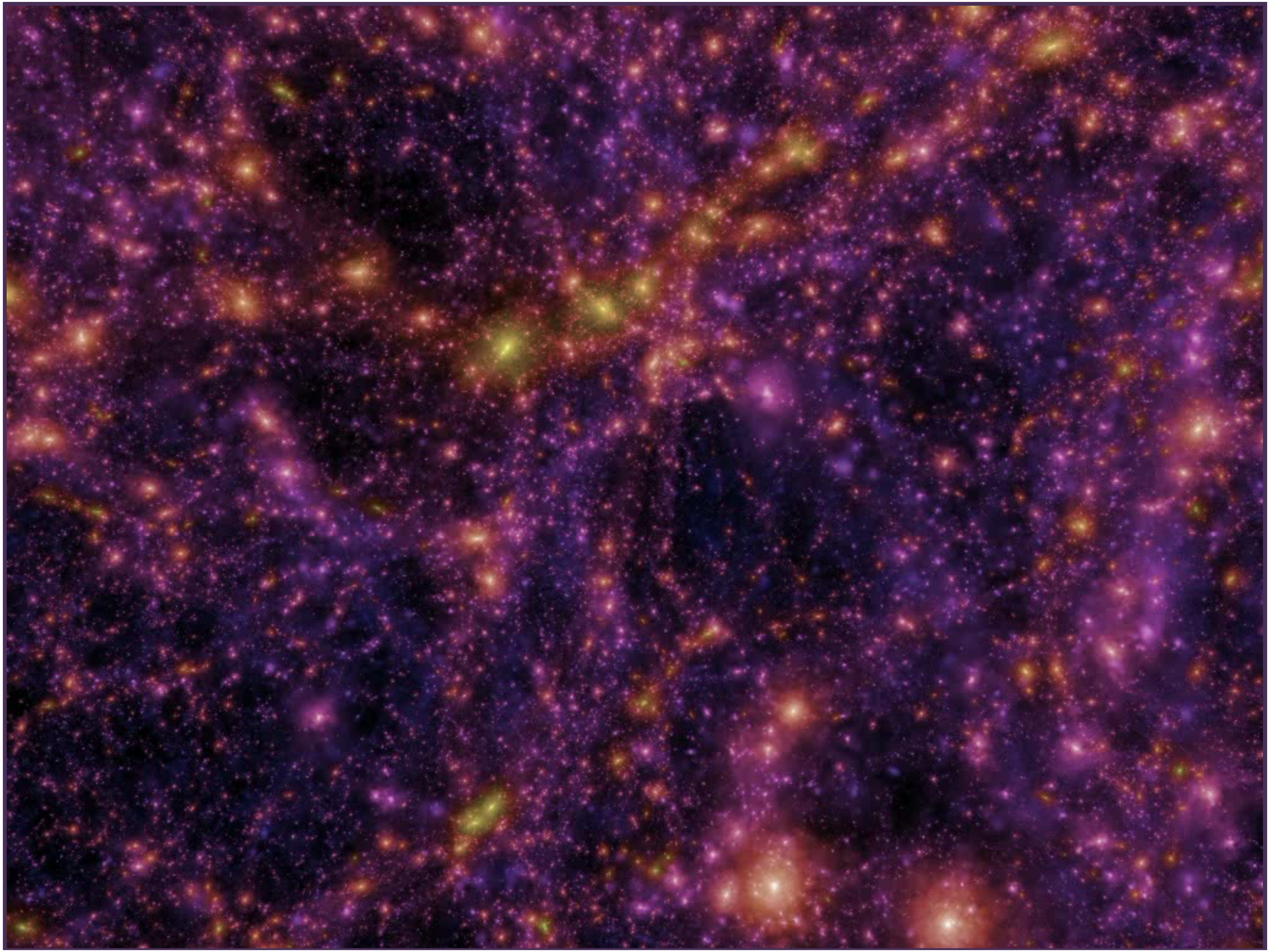


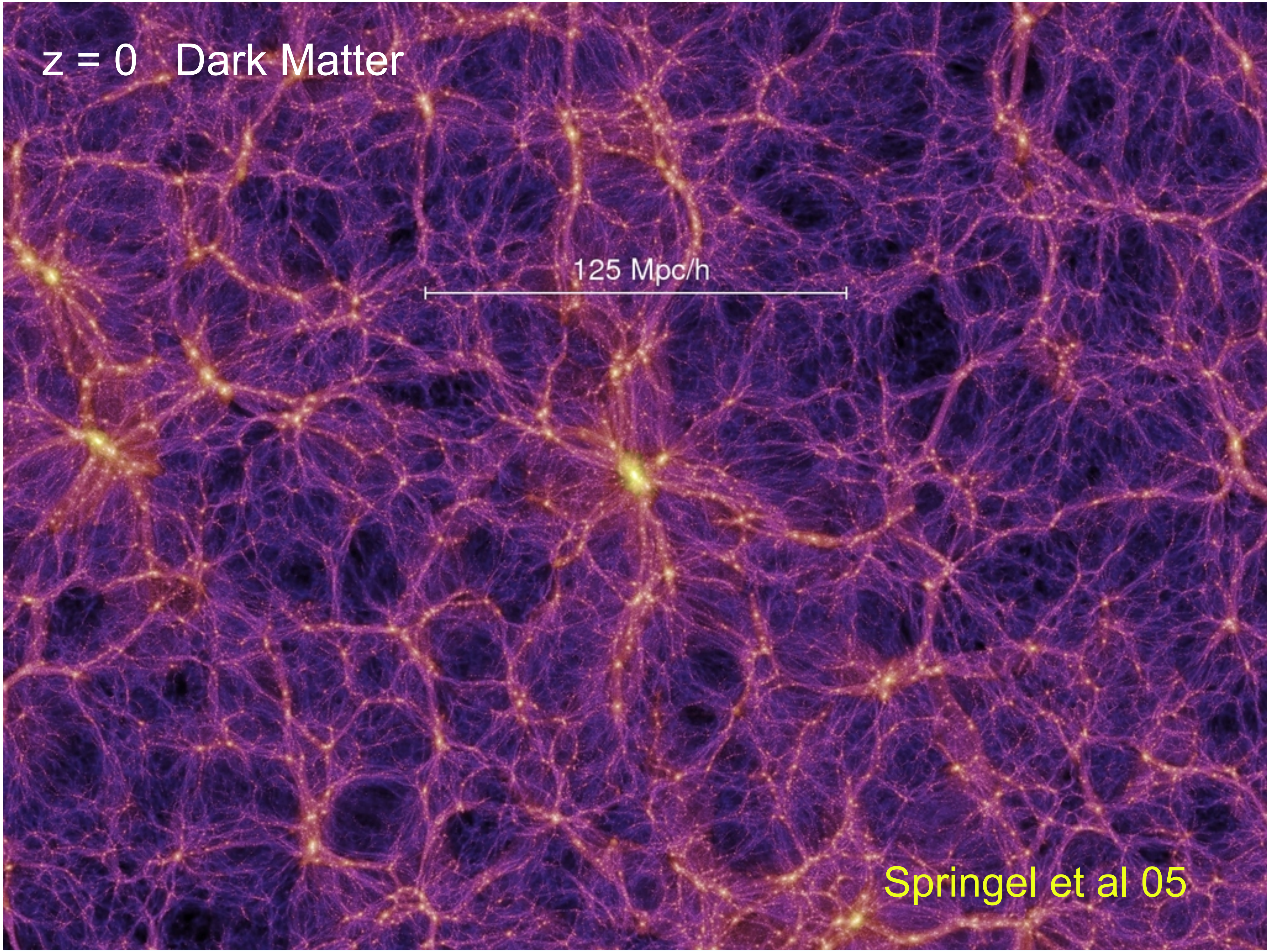
The 2dF Galaxy Redshift Survey

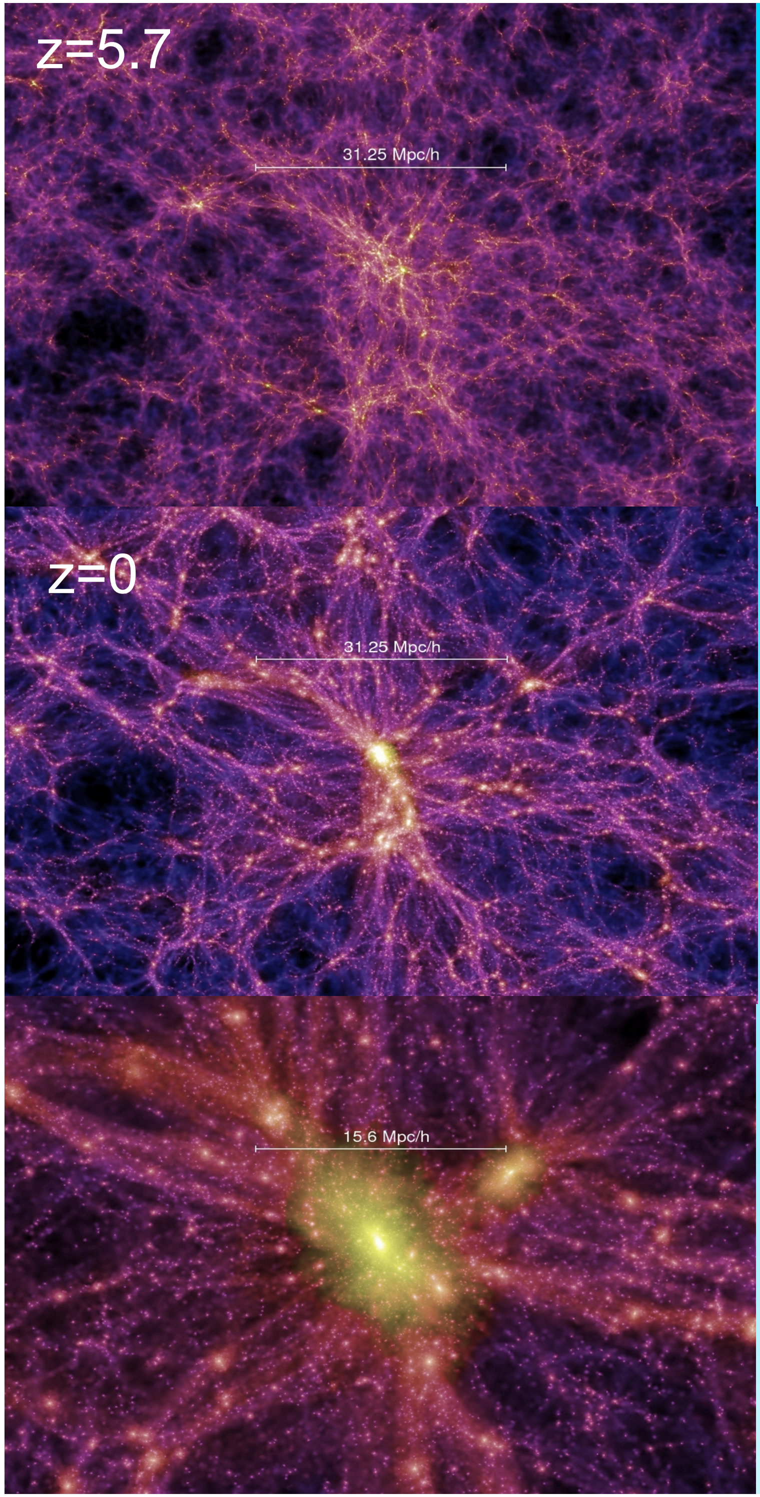
221,000 redshifts

z~0

2005



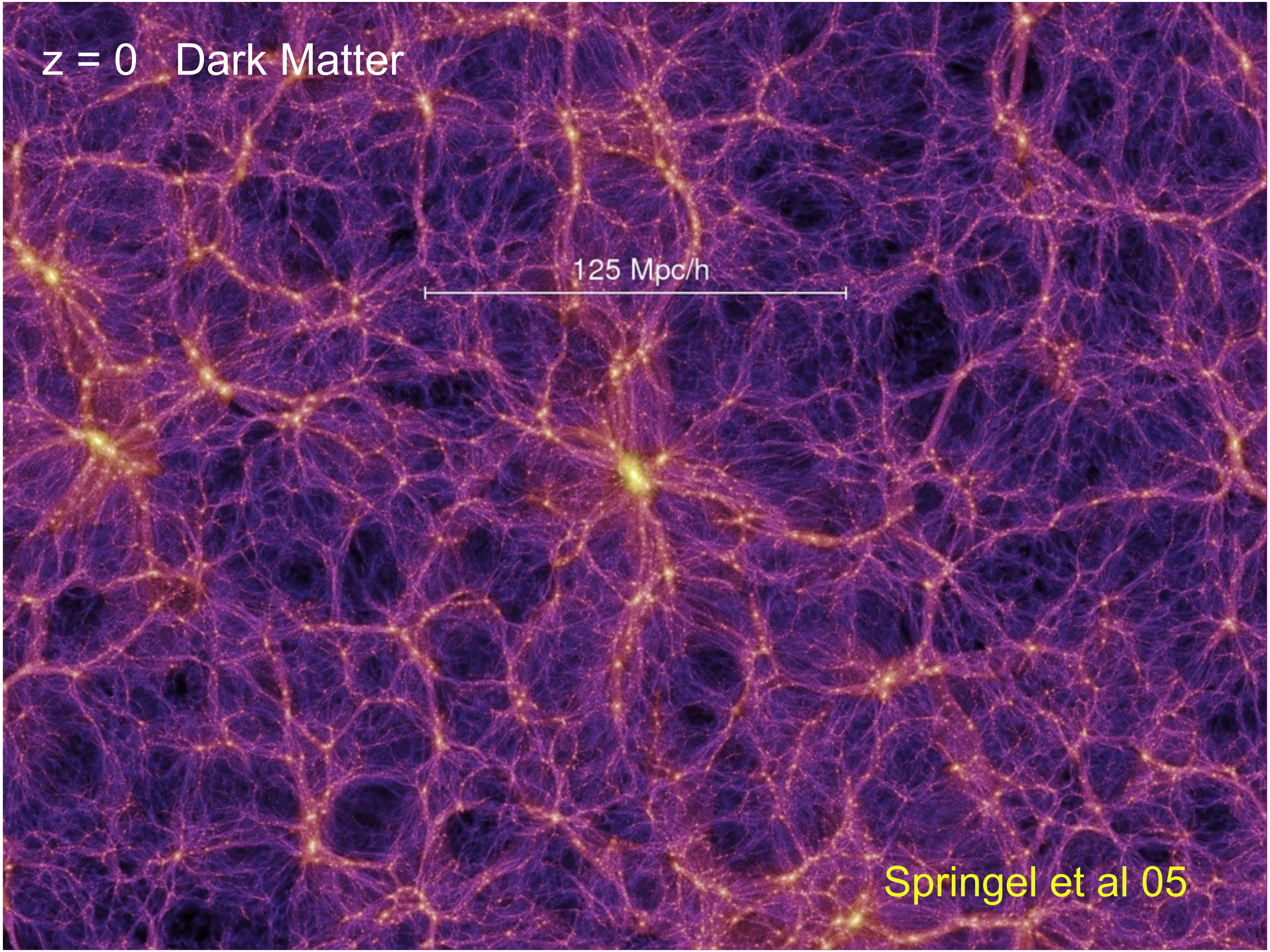

z = 0 Dark Matter
125 Mpc/h
Springel et al 05

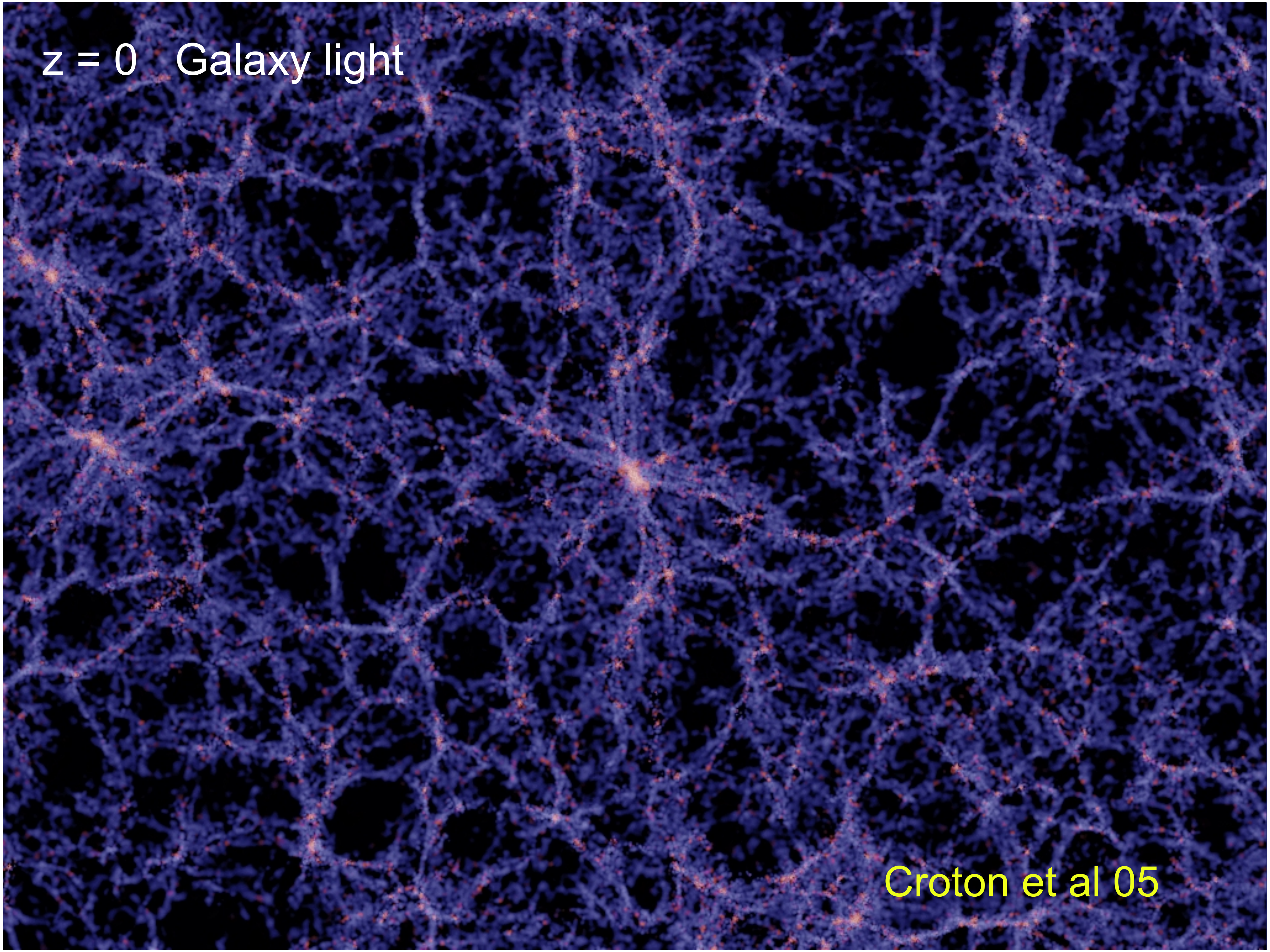


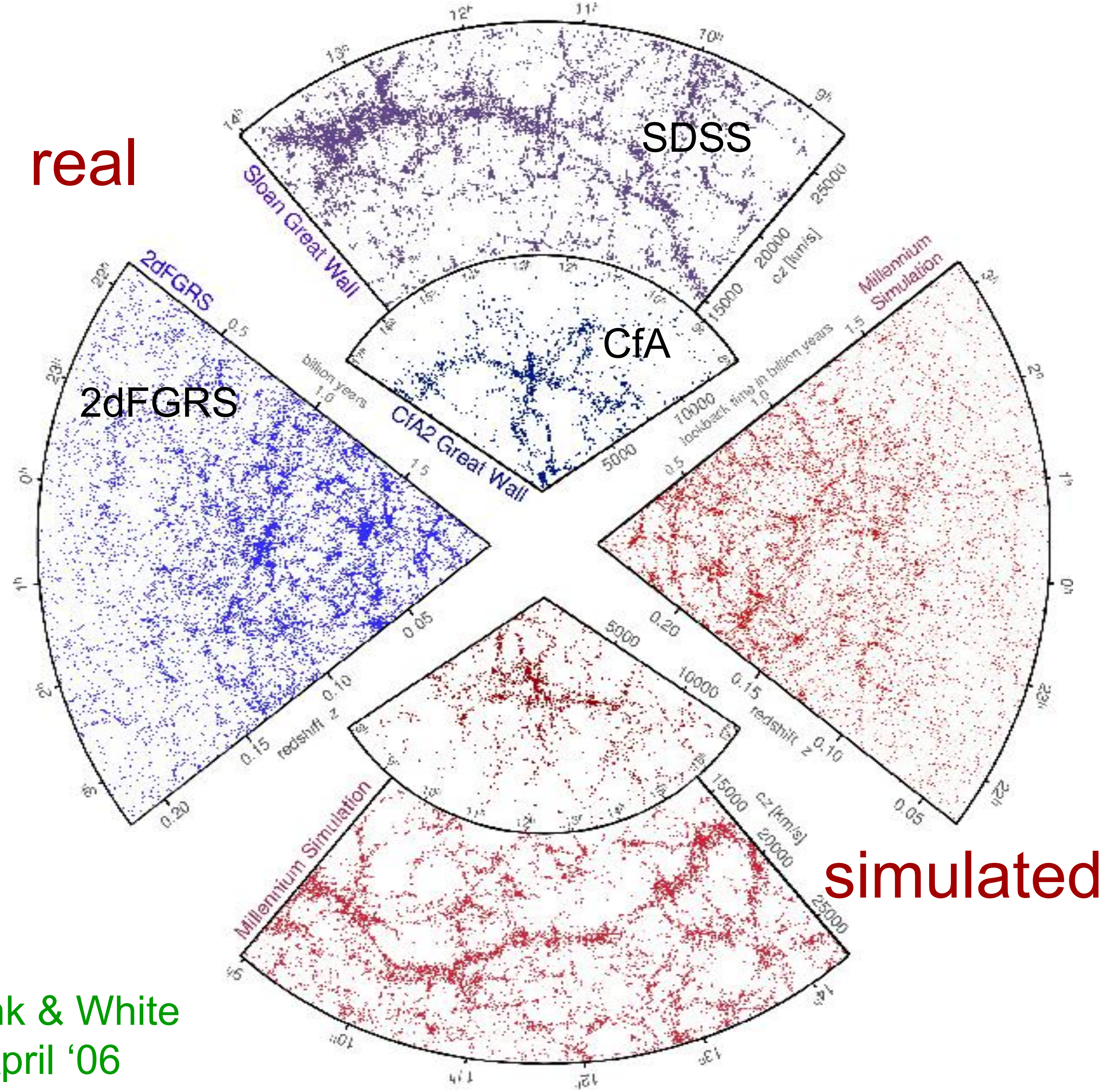
Galaxy formation theory

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


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

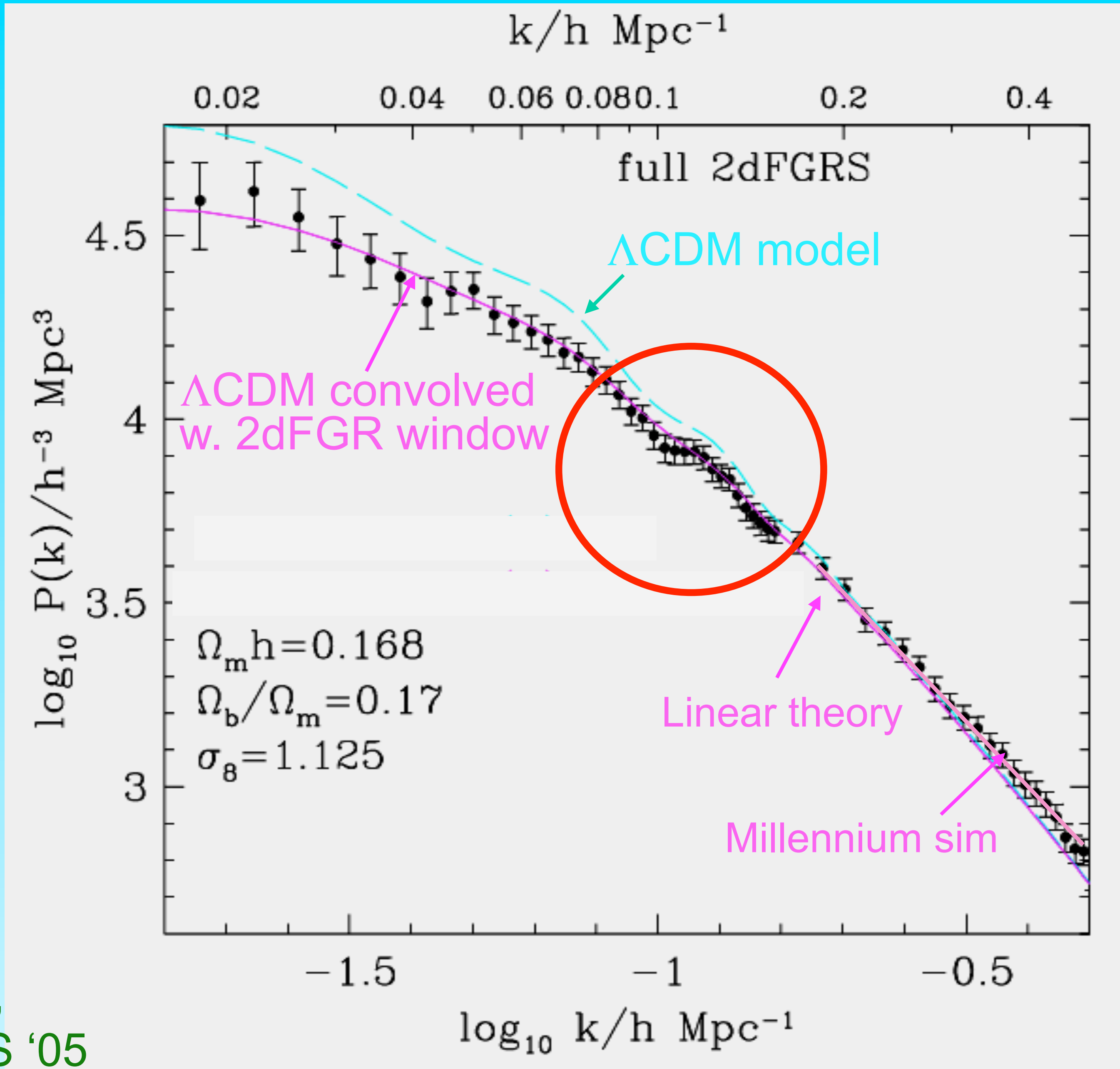

z = 0 Galaxy light
Croton et al 05



Springel, Frenk & White
Nature, April '06

The final 2dFGRS power spectrum

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



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

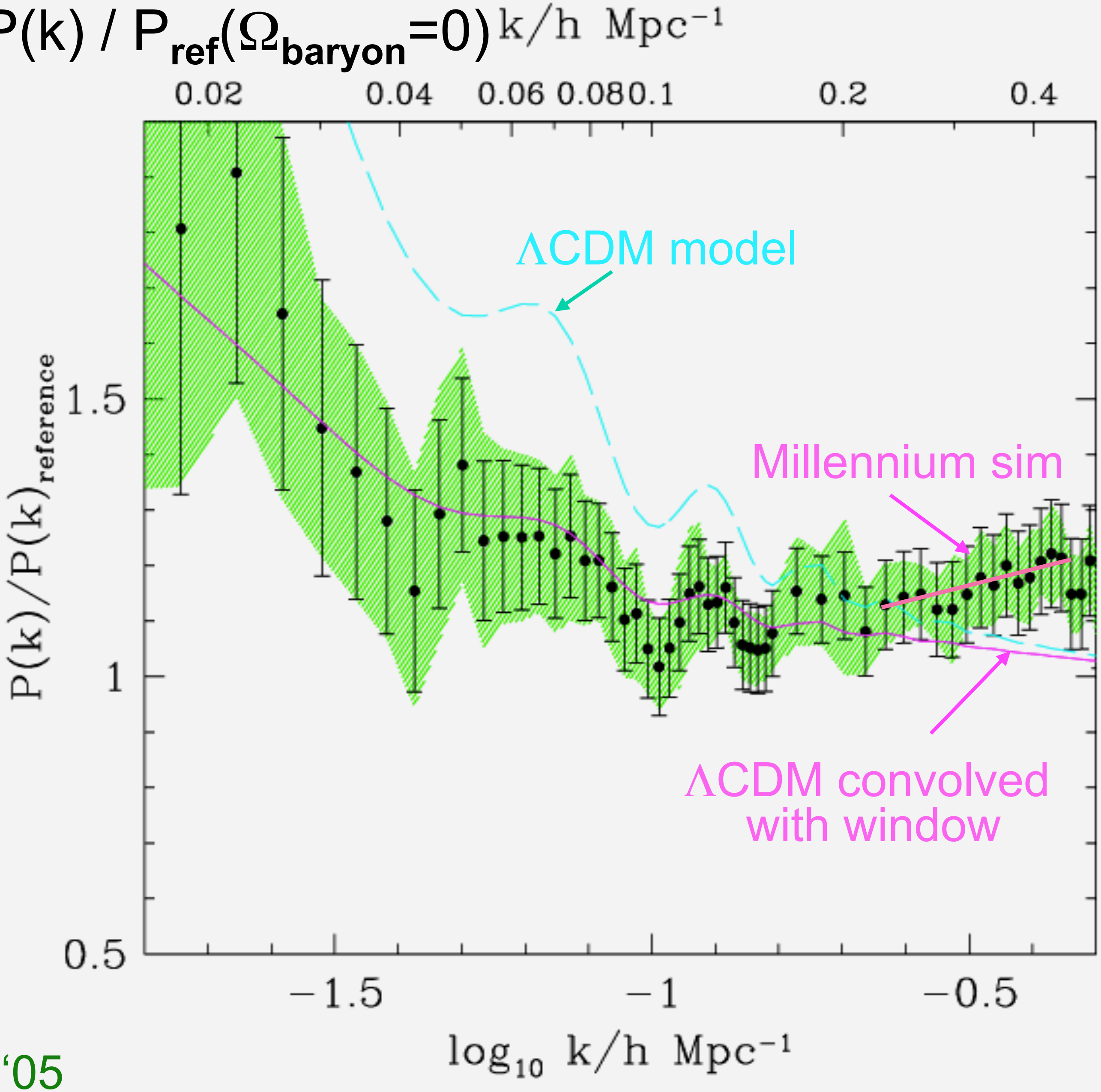
Baryon acoustic oscillations in 2dFGRS

University of Durham

220,000 redshifts

Baryon oscillations conclusively detected in 2dFGRS!!!

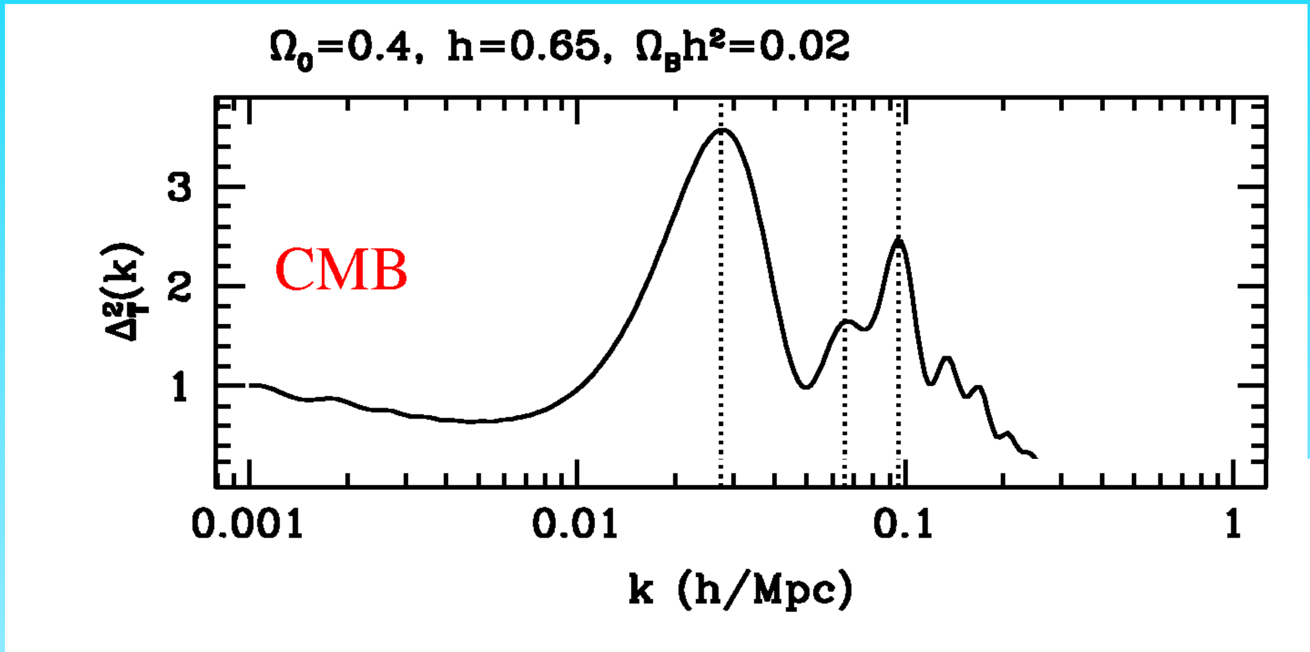
$P(k) / P_{ref}(\Omega_{baryon}=0)$



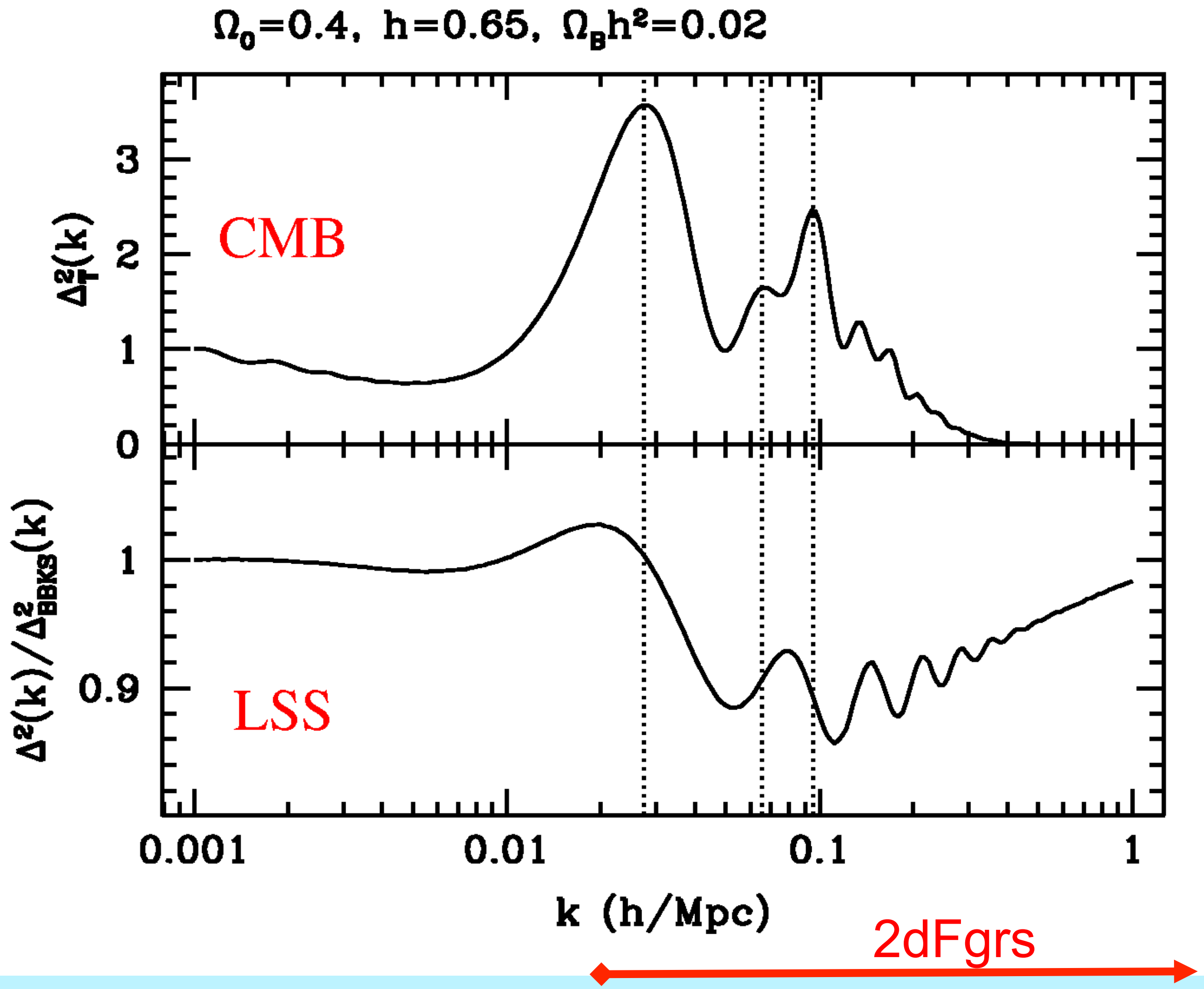
Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05

CMB anisotropies and large-scale structure

University of Durham



CMB anistropies and large-scale structure



CMB and LSS out of phase:

'velocity overshoot'

LSS amplitude smaller than CMB

Meiksin etal 99

University of Durham

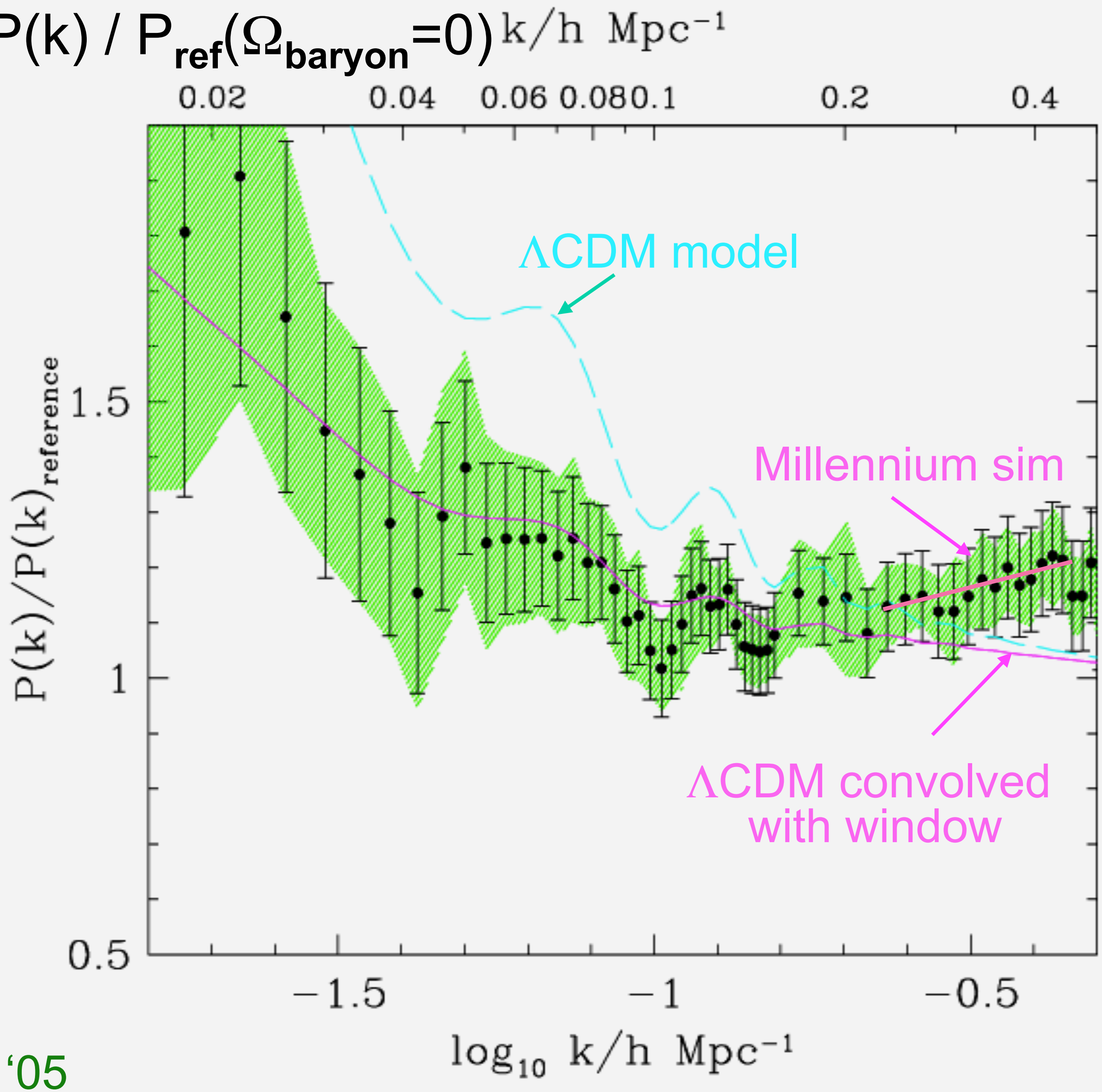
Baryon acoustic oscillations in 2dFGRS

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

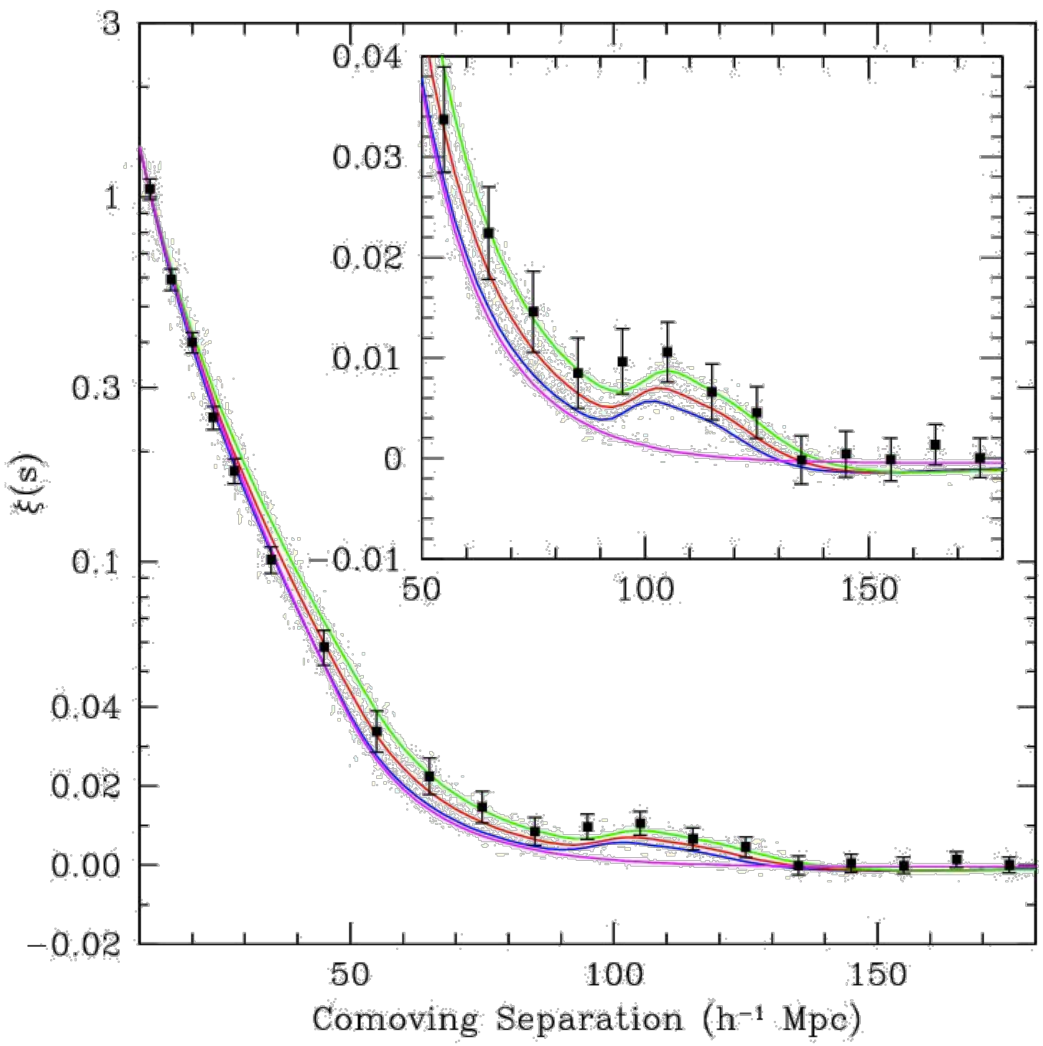
University of Durham

- 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

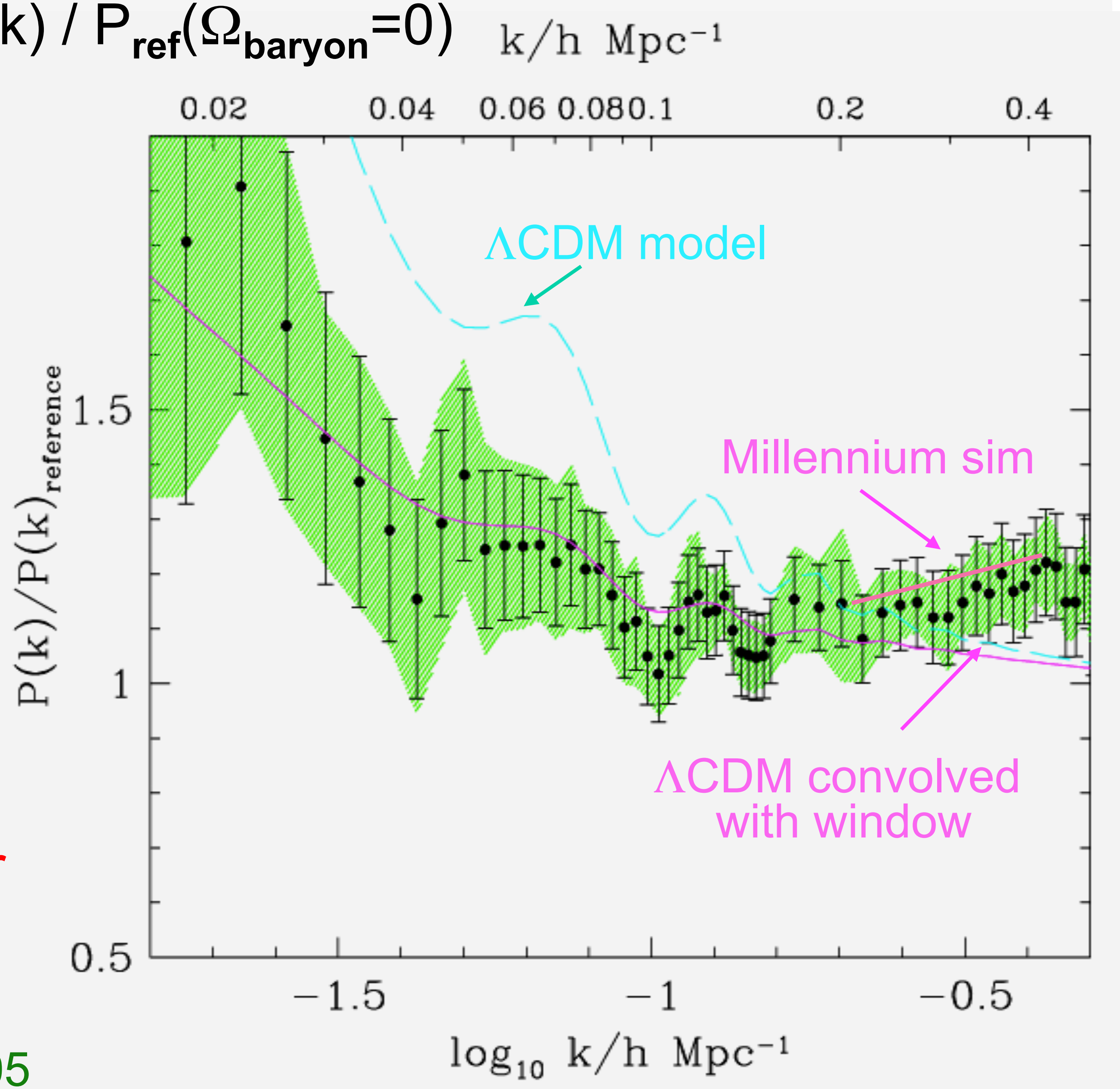
University of Durham

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

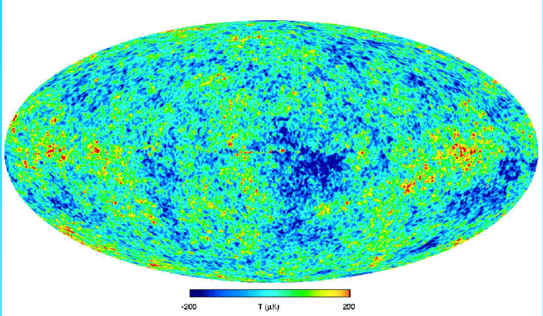
Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05

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

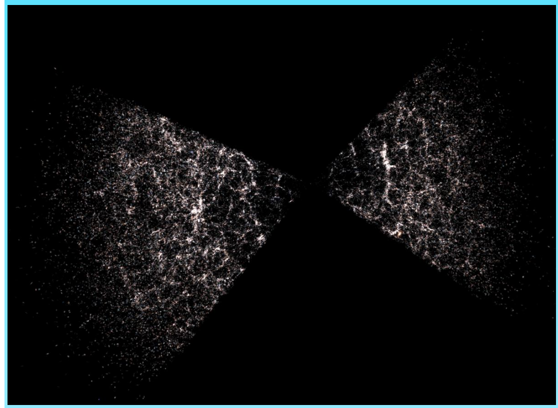


The cosmic power spectrum: from the CMB to the 2dFGRS

University of Durham



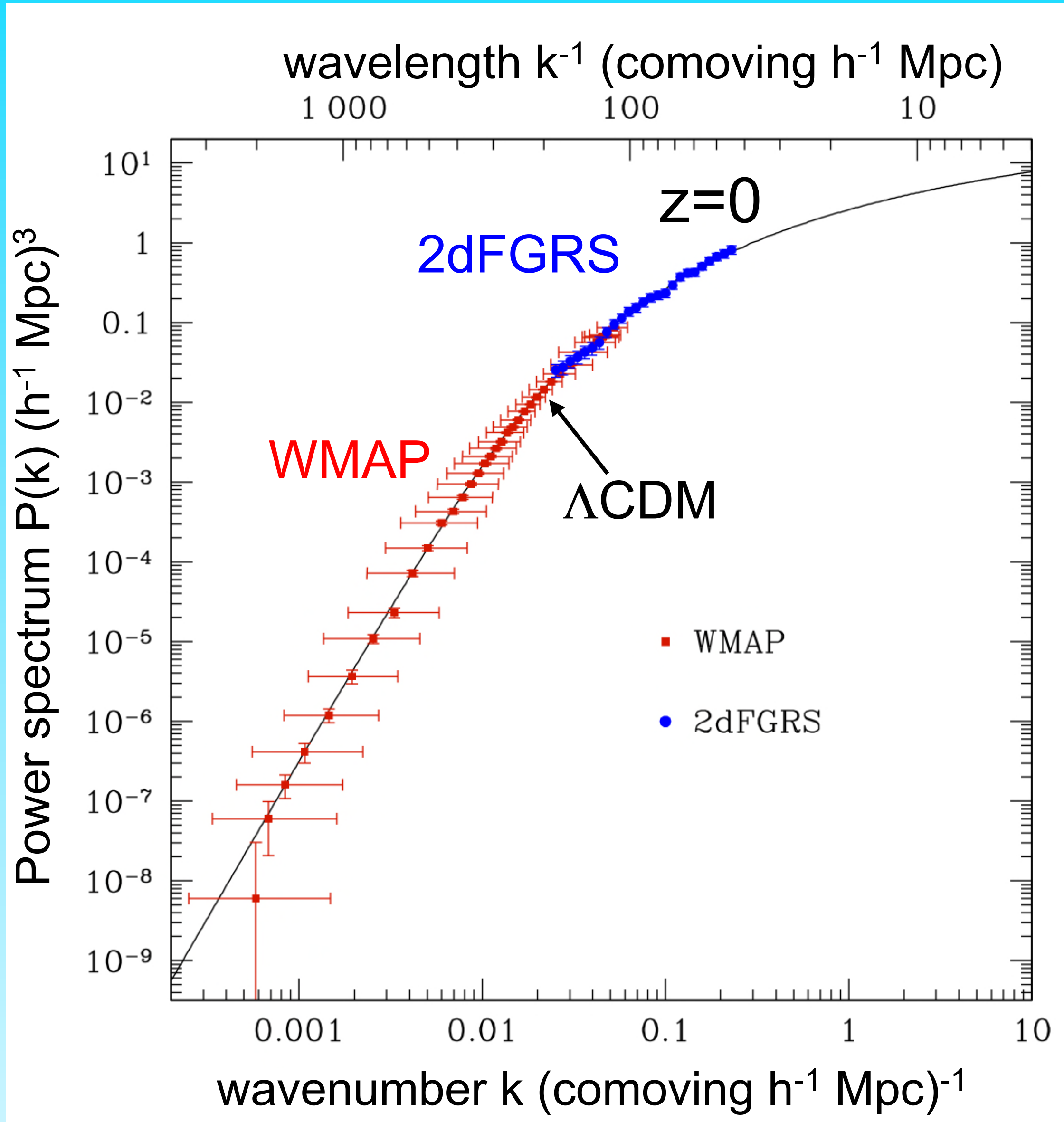
z~1000



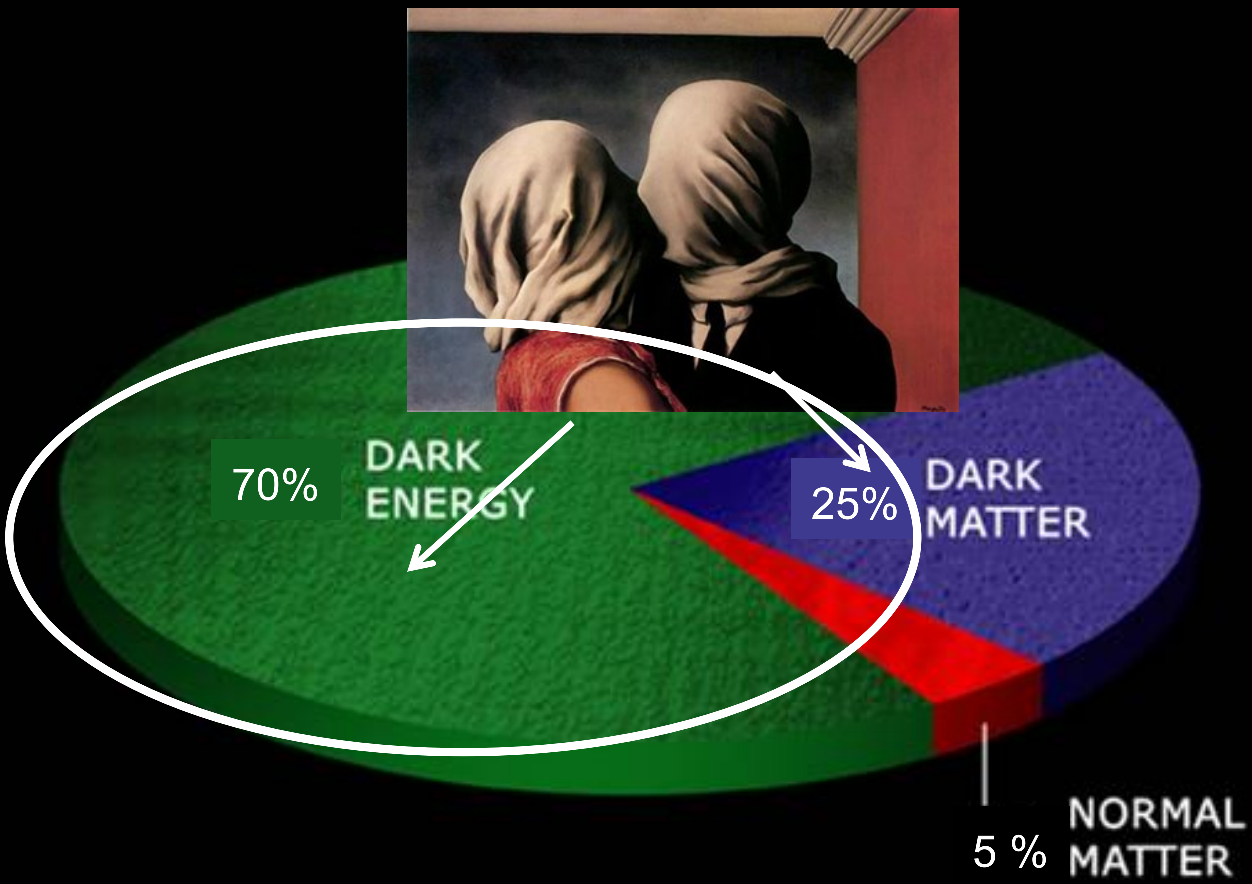
z~0

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

Sanchez et al 06



What next?



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What next?

Understanding the dark energy

At present 3 broad possibilities are considered:

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

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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 …)

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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

(easy to extend to variable w(a))

Eqn of state: $w = \frac{P}{\rho}$ $\quad w(a) = w_0 + w_a(1-a)$

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

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

Dynamical tests

Dark energy changes growth rate of structure

Relevant quantities are: δ_m, Ψ, Φ

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

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.

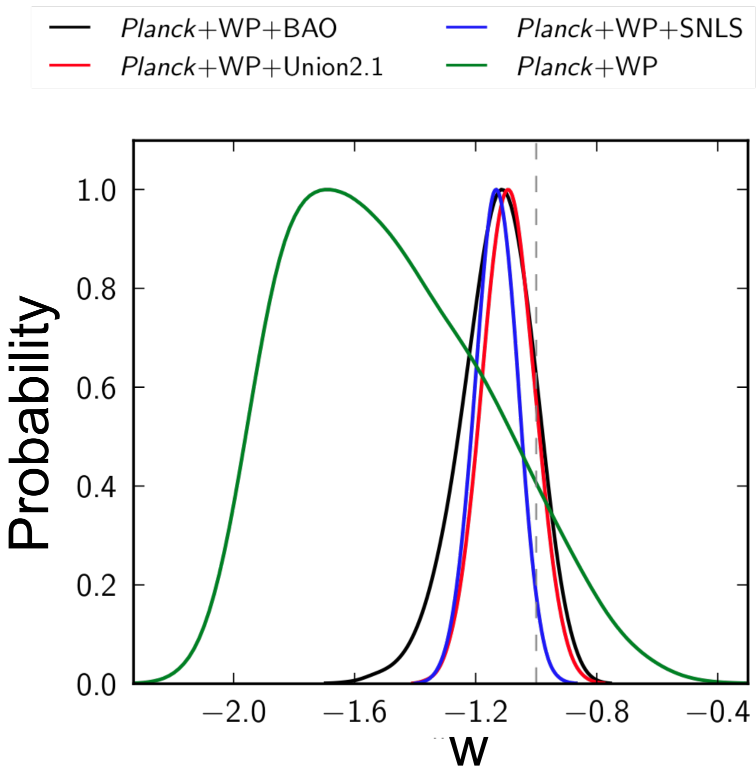
From Baojiu Li

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

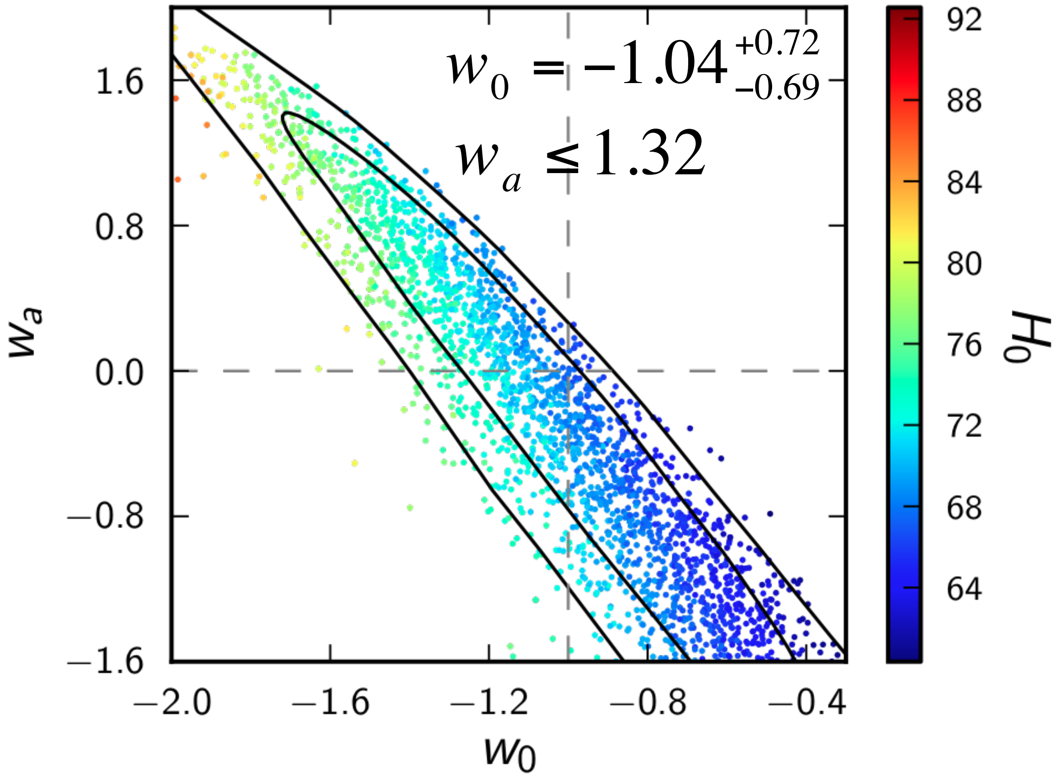


$$w = -1.13^{+0.13}_{-0.14}$$

(95% Planck+WP+SNLS)

Quintessence (variable w(a))

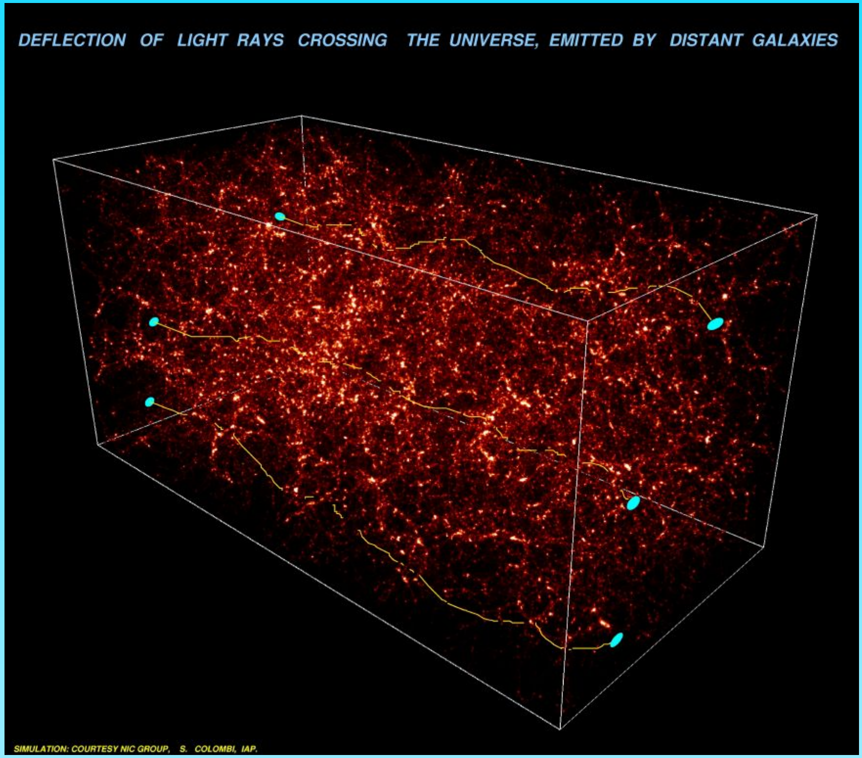
$$w(a) = \frac{P(a)}{\rho(a)} \qquad w(a) = w_0 + w_a(1-a)$$

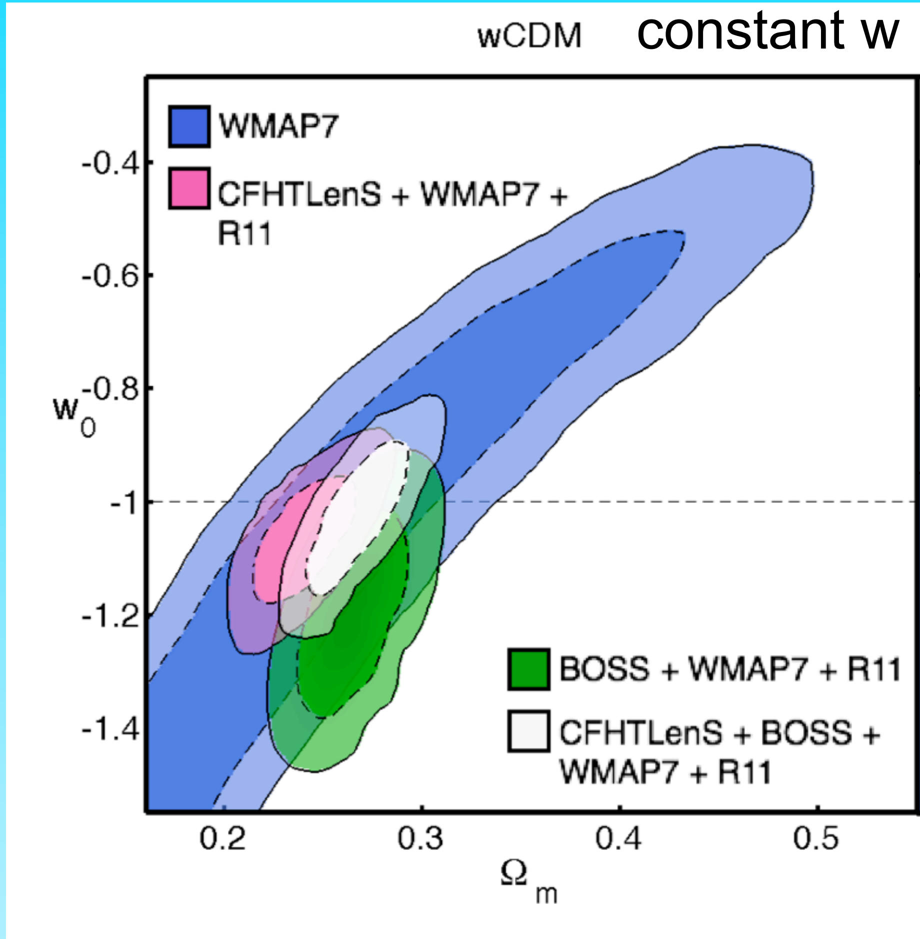


(95% Planck+WP+BAO)

ICC University of Durham

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

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How accurately do we need to measure the BAO scale?

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

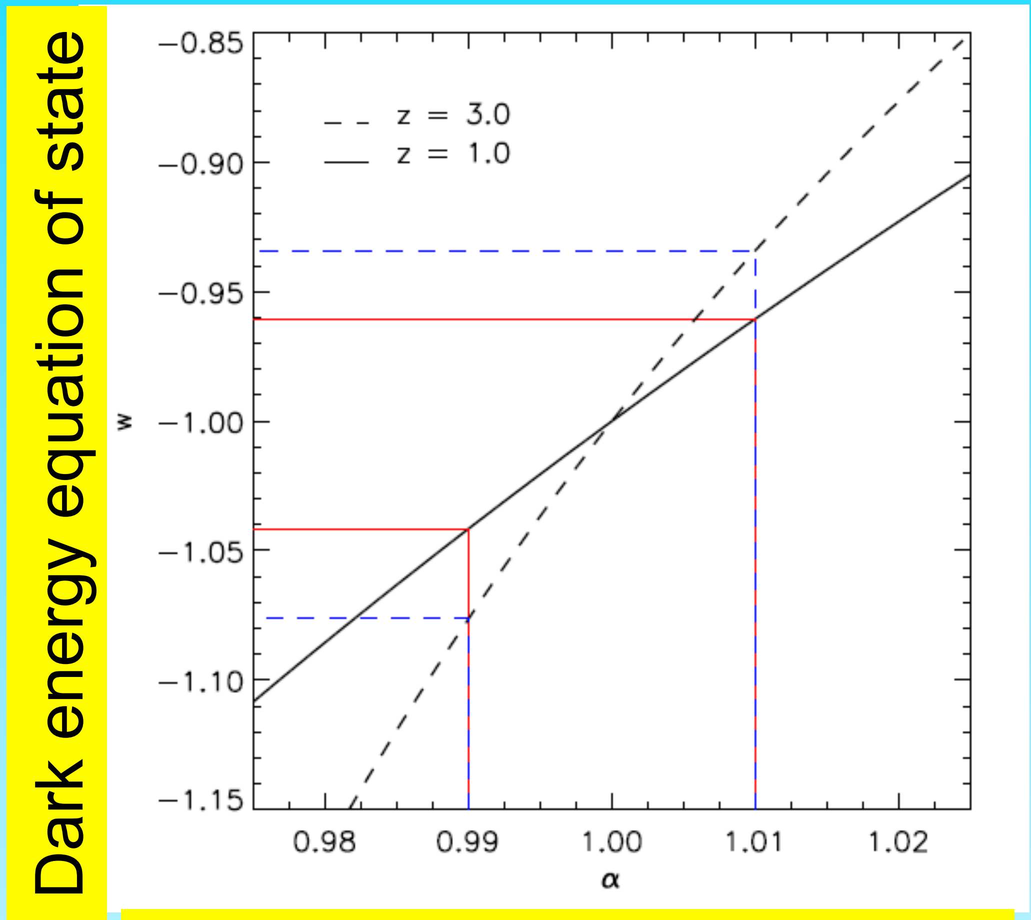
Hold other cosmological parameters fixed

- $\Delta w \sim 7\ \Delta s$ (z=3)
- $\Delta w \sim 4\ \Delta s$ (z=1)

$k = 2\pi/s$

$\alpha = k_{app}/k_{true}$

Angulo et al . 2008



distance scale measurement

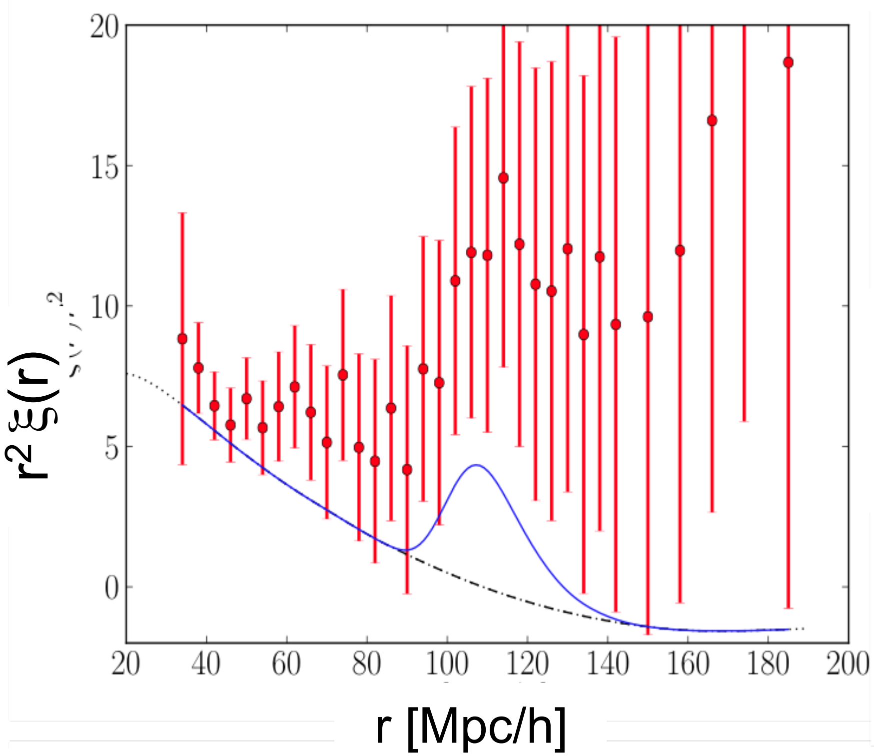
Detection of BAO in Lyman-α forest

University of Durham

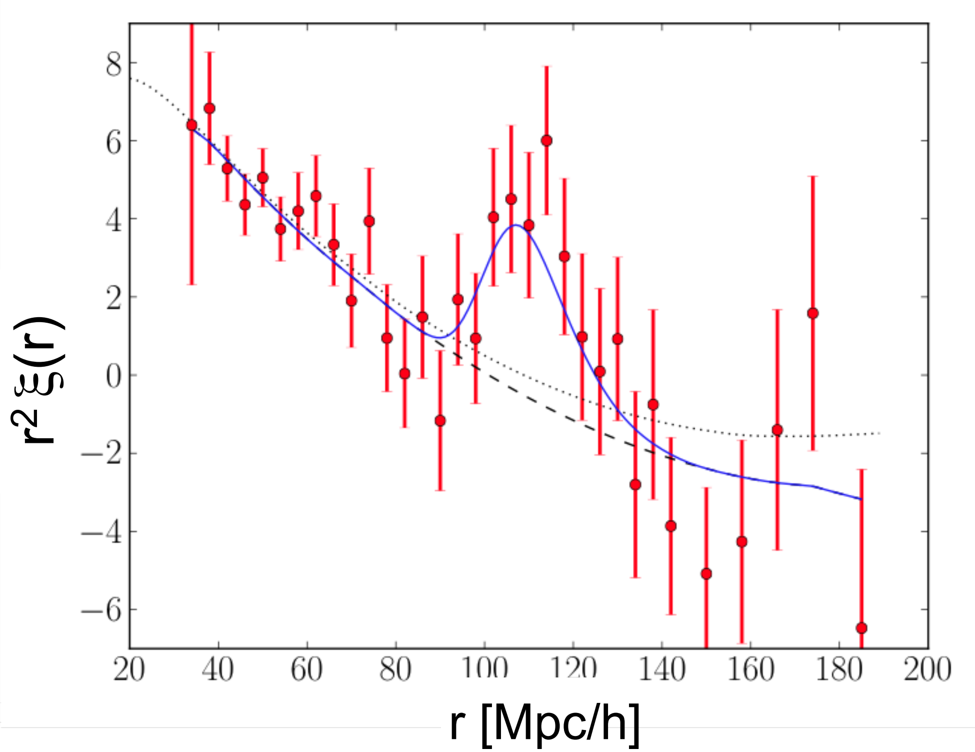
BOSS survey: detection of BAO in Ly-α forest at z=2.4
→ ideal for measuring w(a)

Slosar et al '13

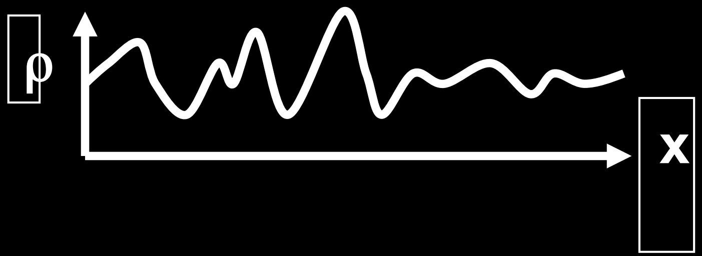
… in principle



… after some massaging

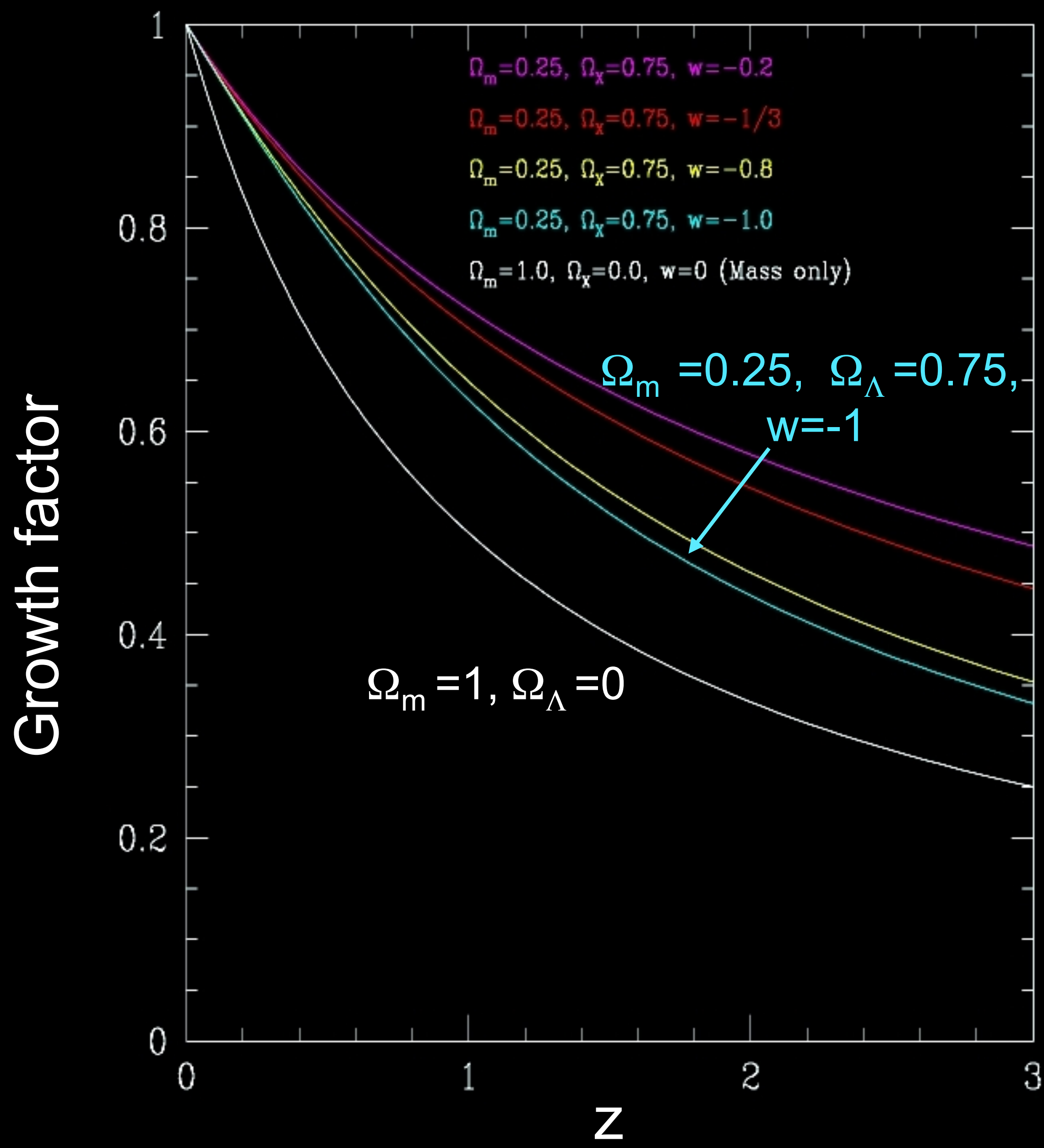


Linear theory: fluctuation growth rate



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)



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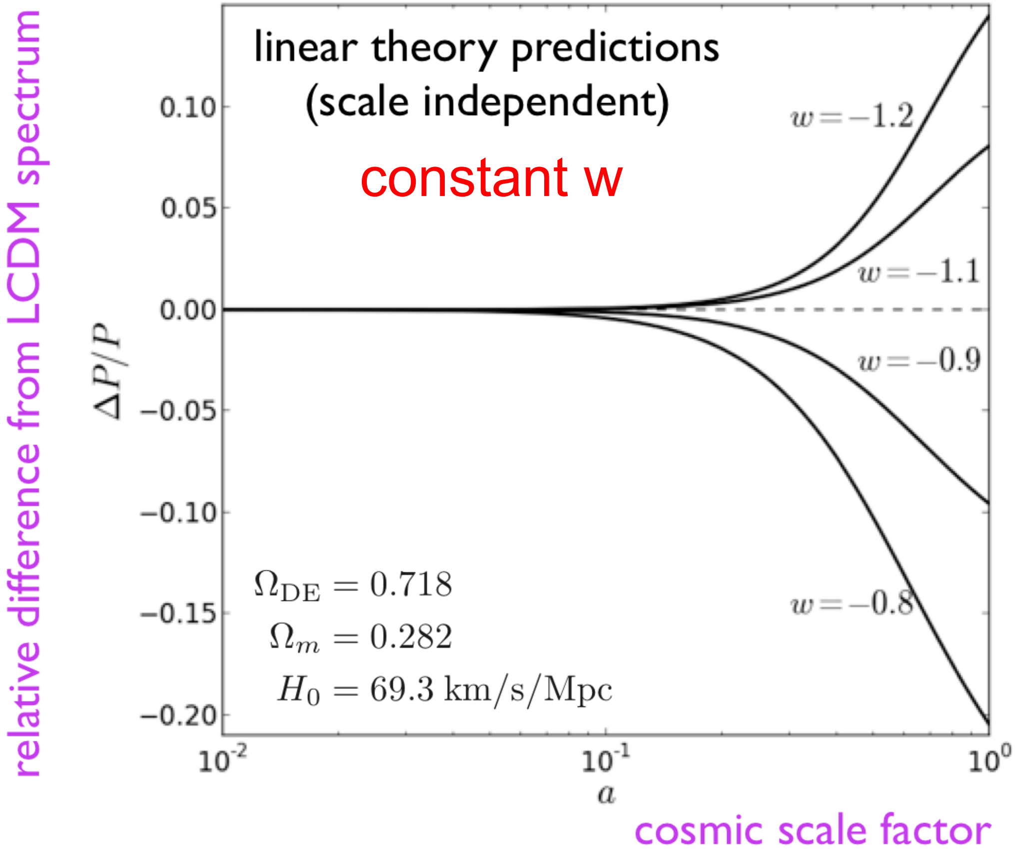
Dark energy with different w

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

expansion history is modified

negligible, as dark energy clusters very weakly



Differences from ΛCDM of only a few %!

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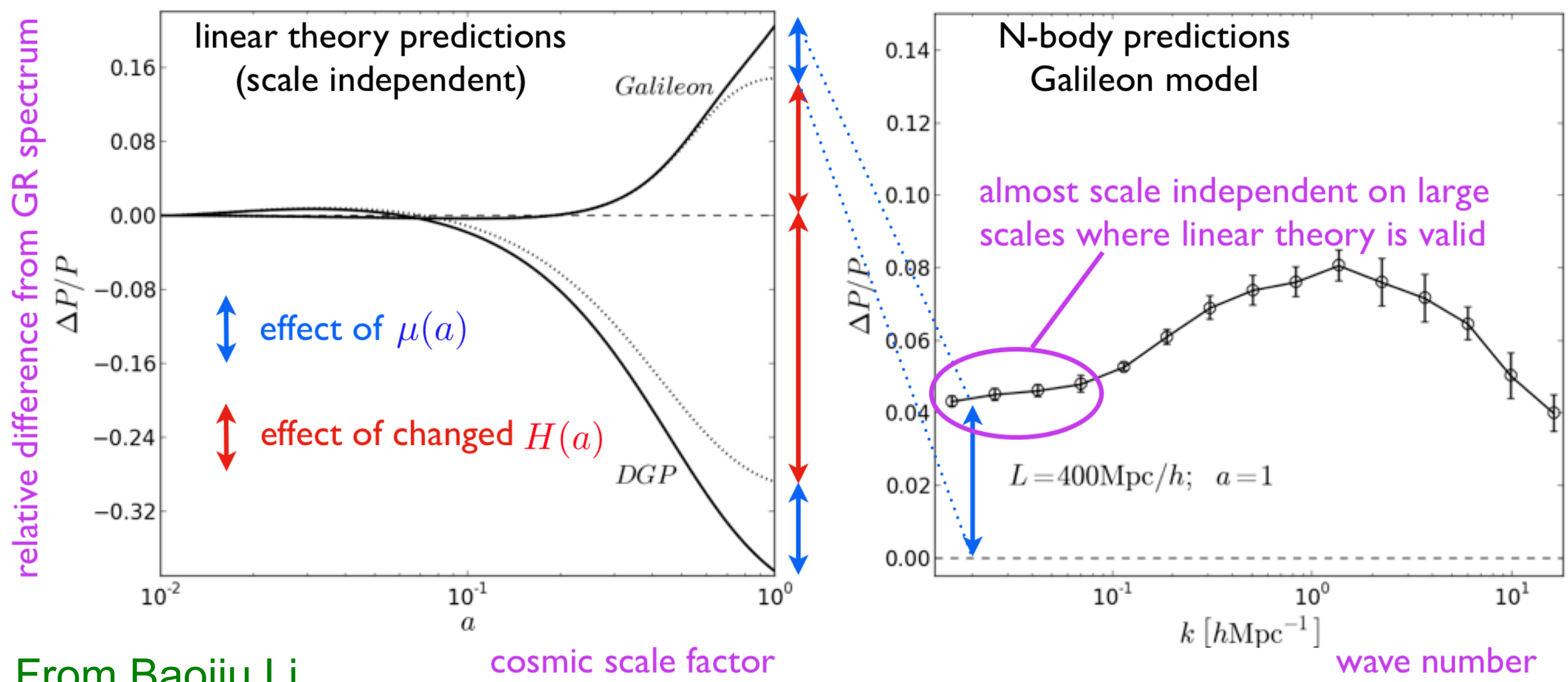
Modified gravity: DGP and Galileon

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

expansion history is modified

strength of gravity varies with time but is scale-independent



From Baojiu Li

University of Durham

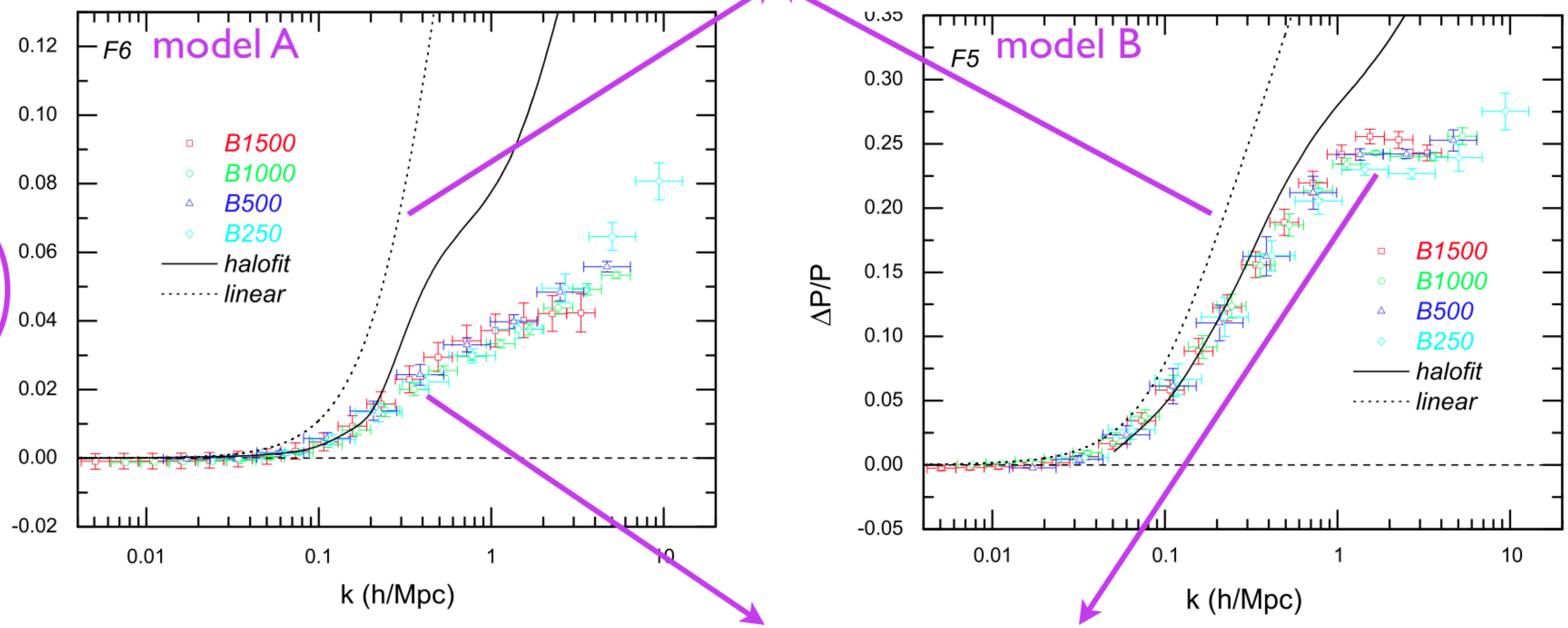
Modified gravity: f(R) gravity

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

expansion history mimics LCDM

strength of gravity varies with both time and scale

scale-dependent difference in linear theory



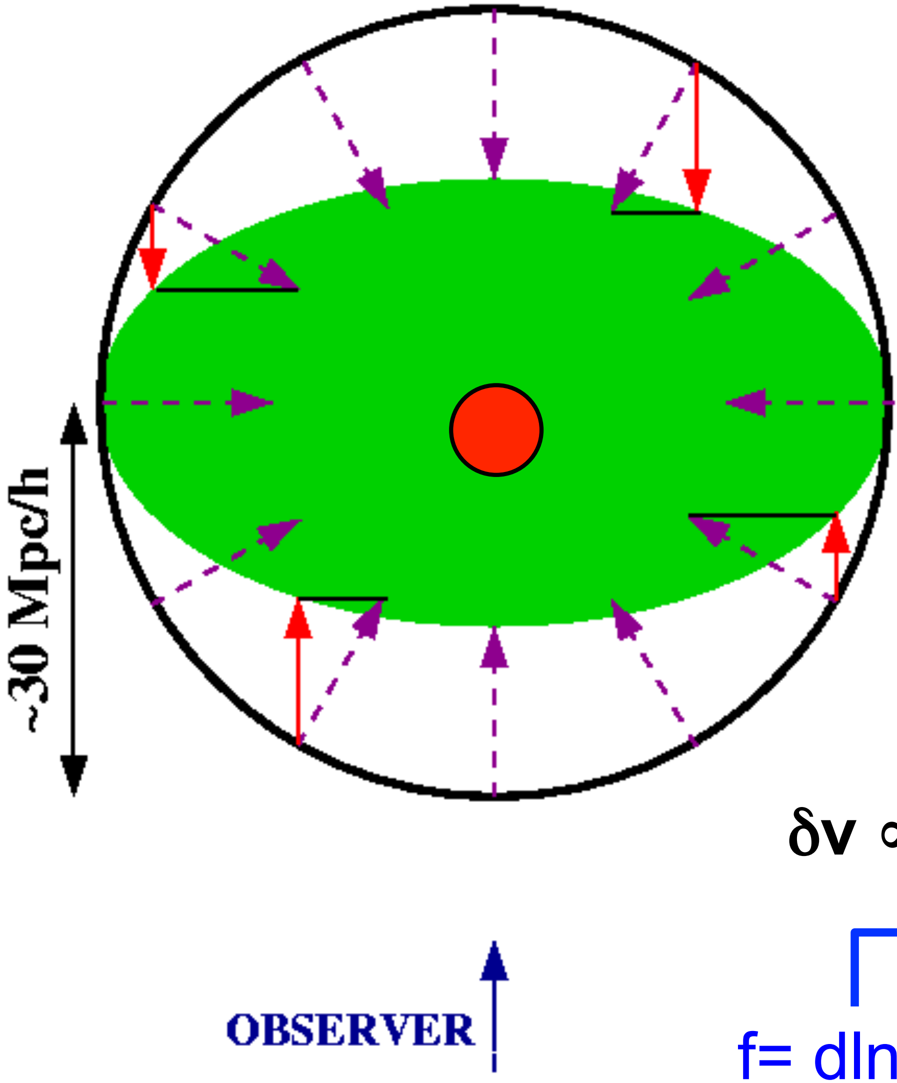
relative difference from LCDM power spectrum

nonlinearity suppresses the difference in full simulations

From Baojiu Li

University of Durham ICC

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

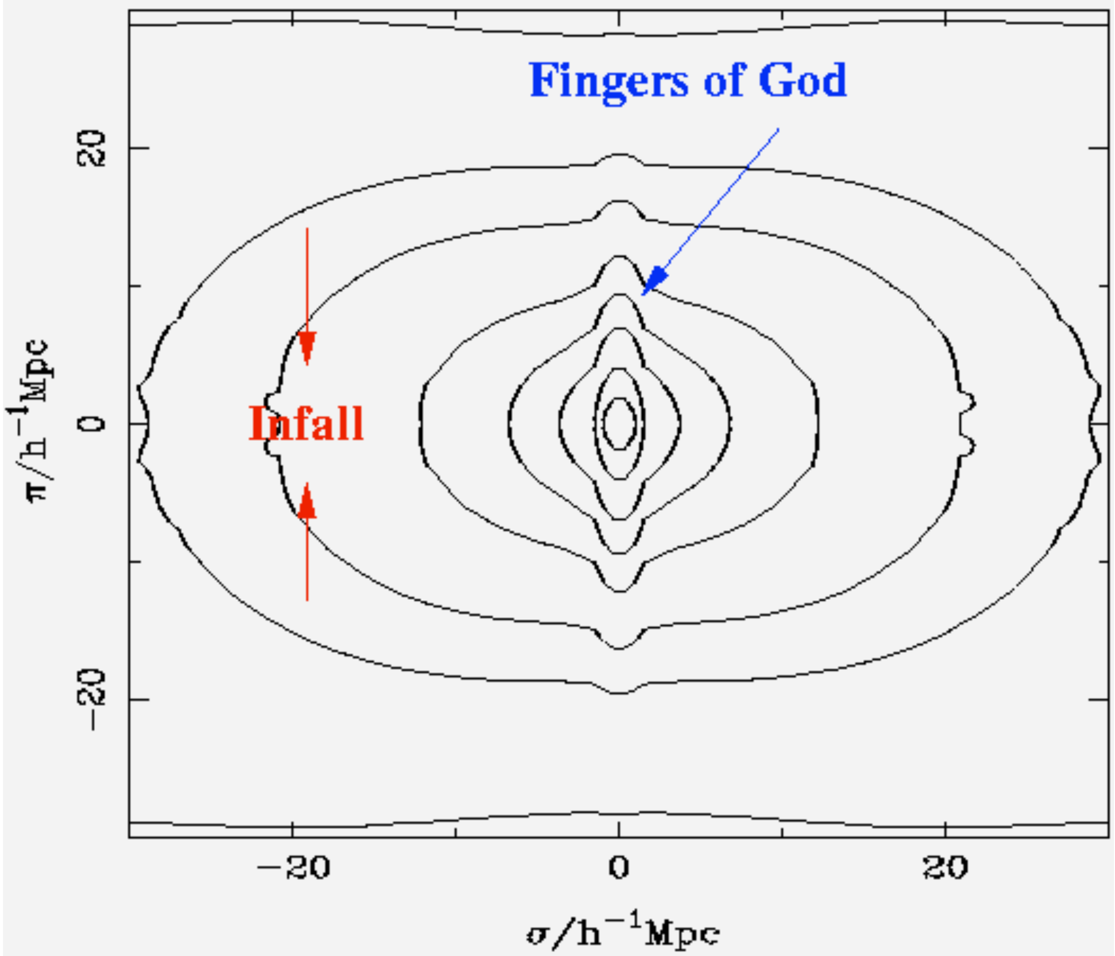
D(a) = linear growth factor

University of Durham

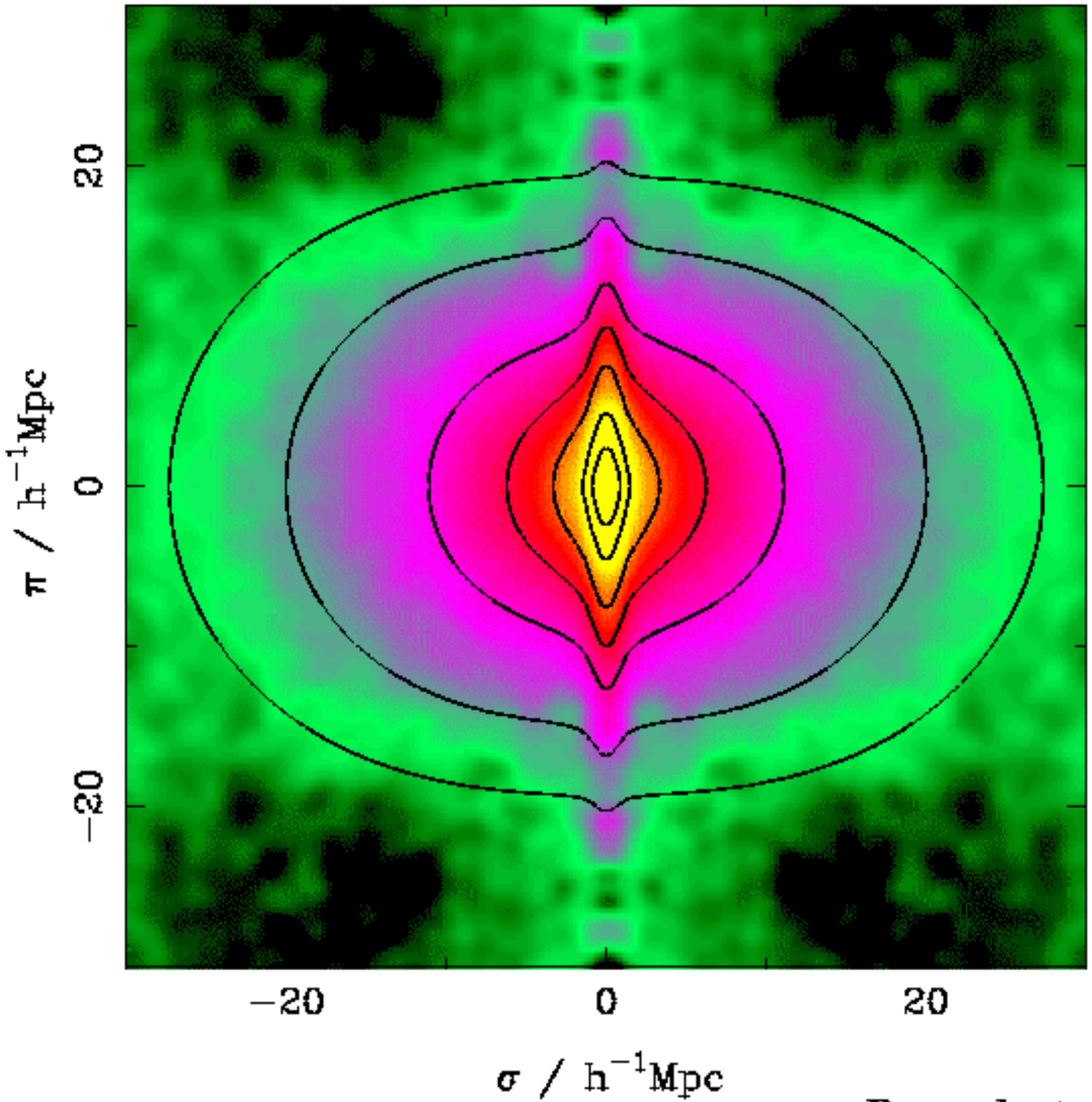
Flattening depends on $\beta = \Omega^{0.6} / b$

$\delta_{gal} = b\delta_{mass}$ **2dF** → β

APM (β=0.5) $\xi(\sigma,\pi)$=10,5,2,1,0.5,0.2,0.1,0,−0.1



2dF galaxy redshift survey



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

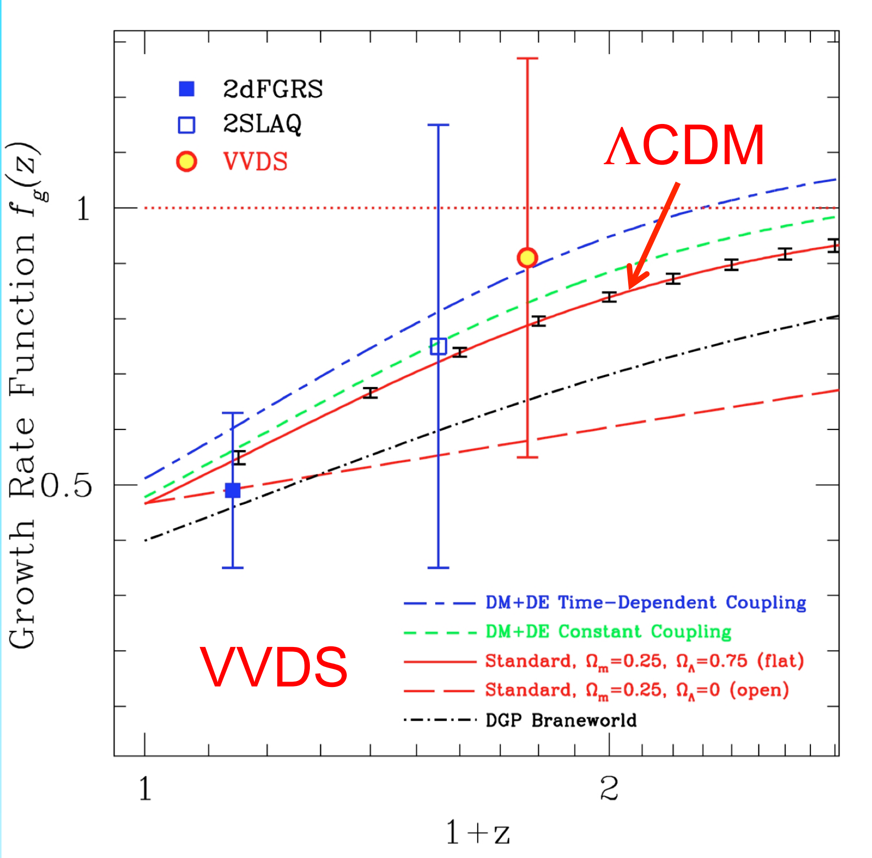
=> $\beta = \Omega^{0.6} / b$

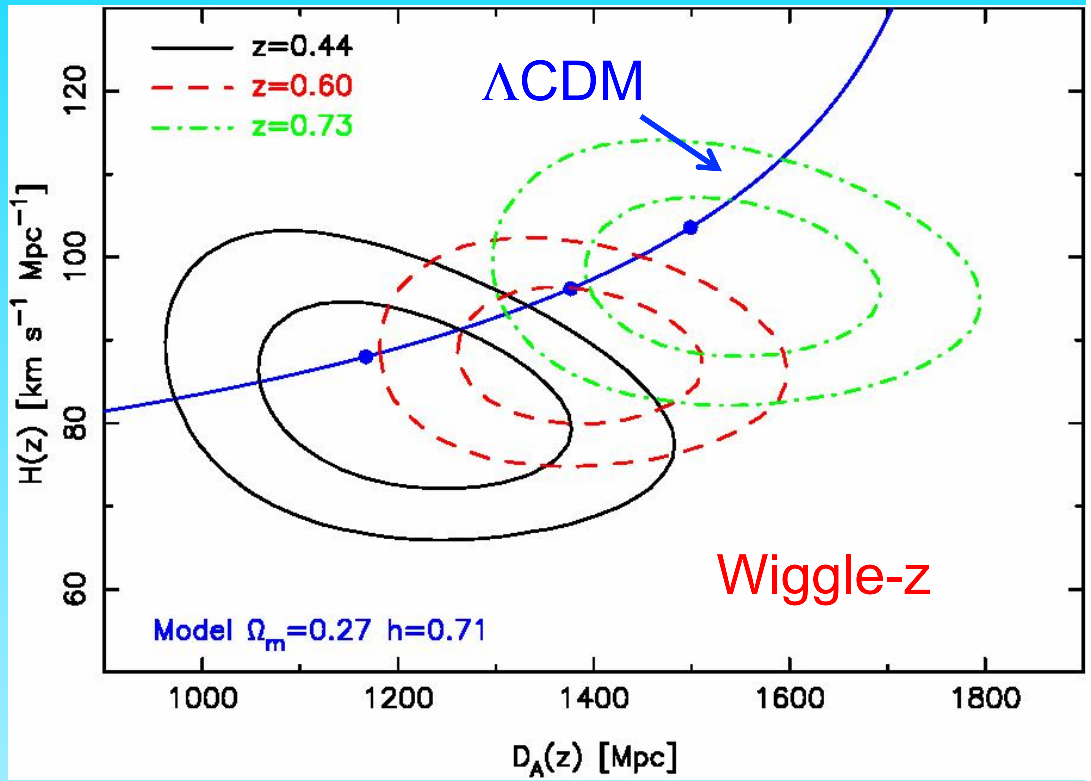
$= 0.43 \pm 0.07$

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

Redshift space distortions

Detected out to z~0.7





Blake et al '12

Guzzo et al '08

Institute for Computational Cosmology

ICC

University of Durham

LSST

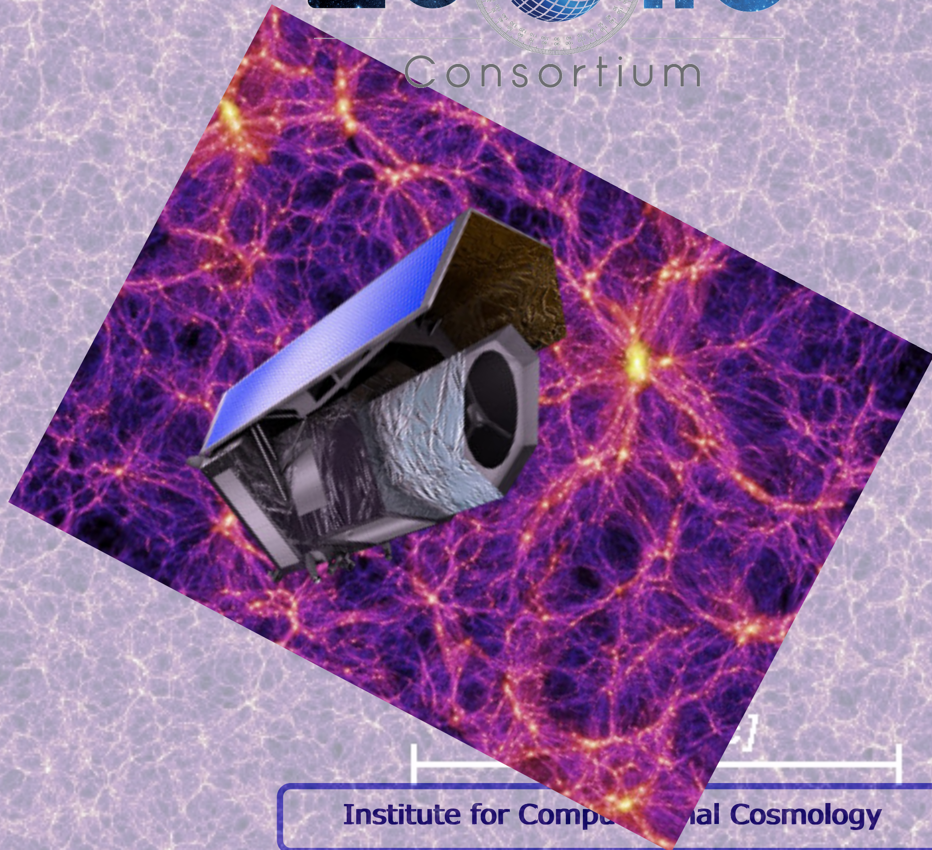
Large Synoptic Survey Telescope

MS-DESI

Euclid

Consortium

DES



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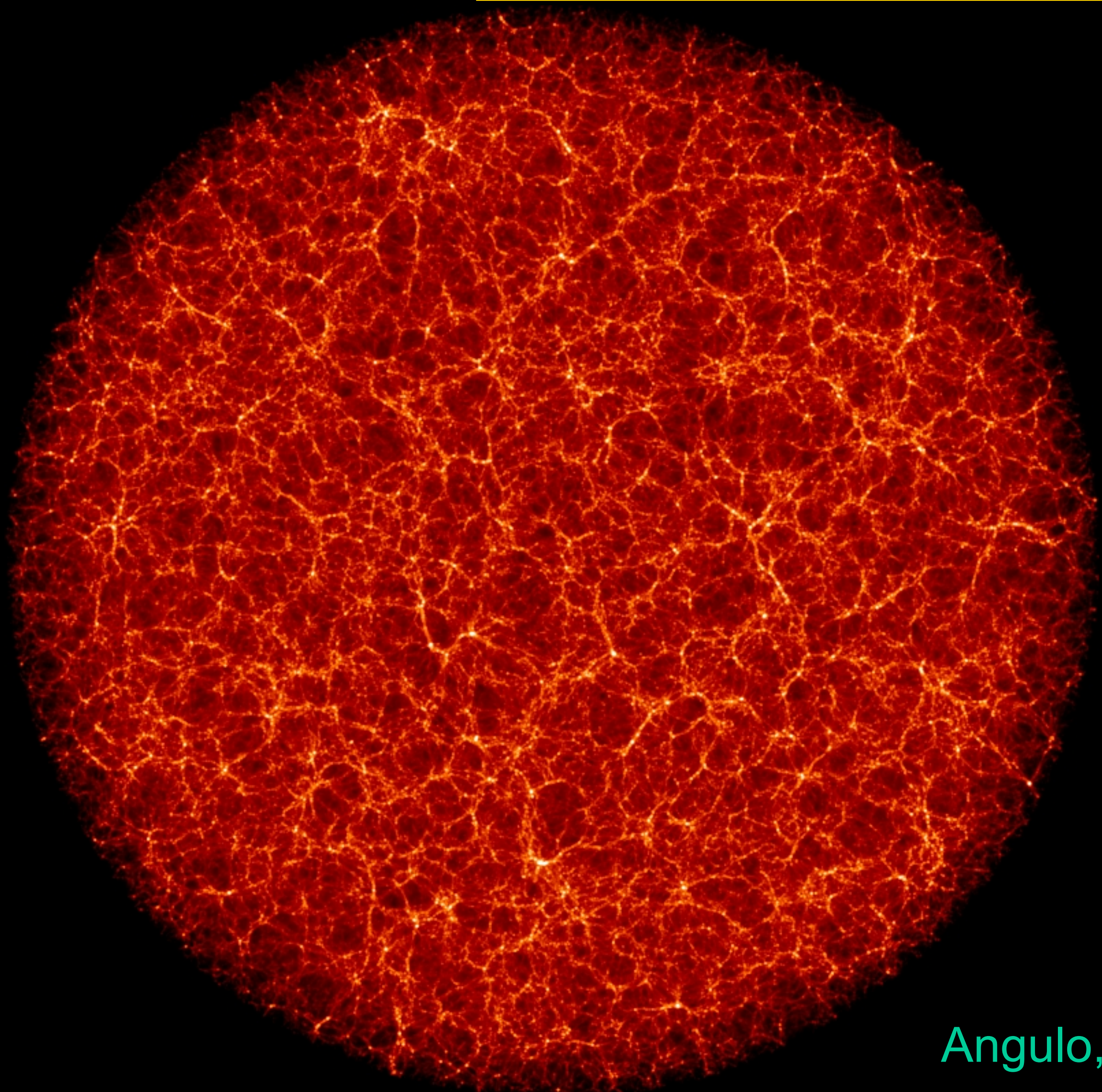
Theoretical challenges for precision cosmology

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

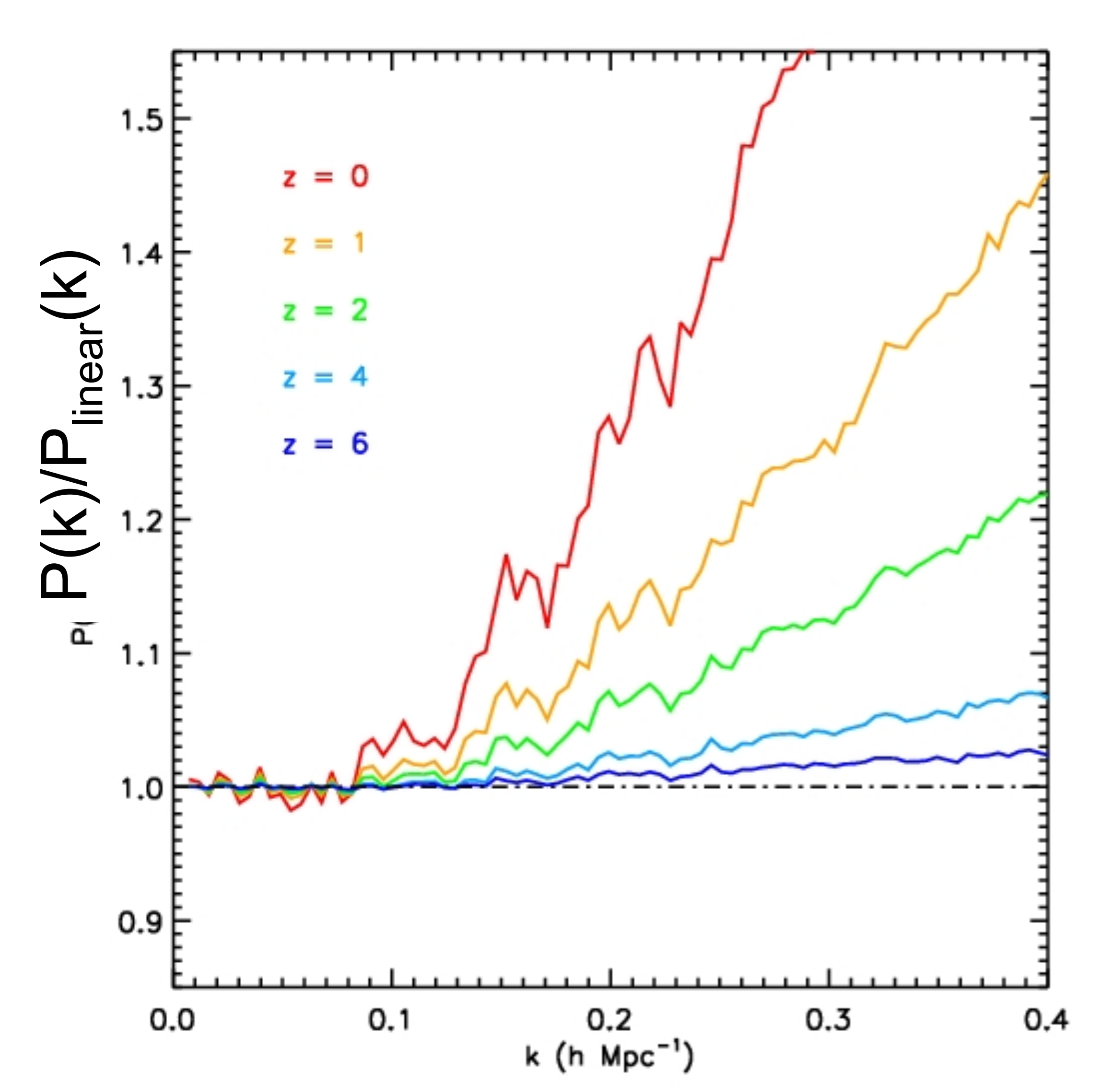
20 times the Millennium volume

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

130,000 cpu hours on the Cosmology Machine

Angulo, Baugh, Frenk & Lacey '08

Non-linear evolution of matter fluctuations



BASICC simulation dark matter real space

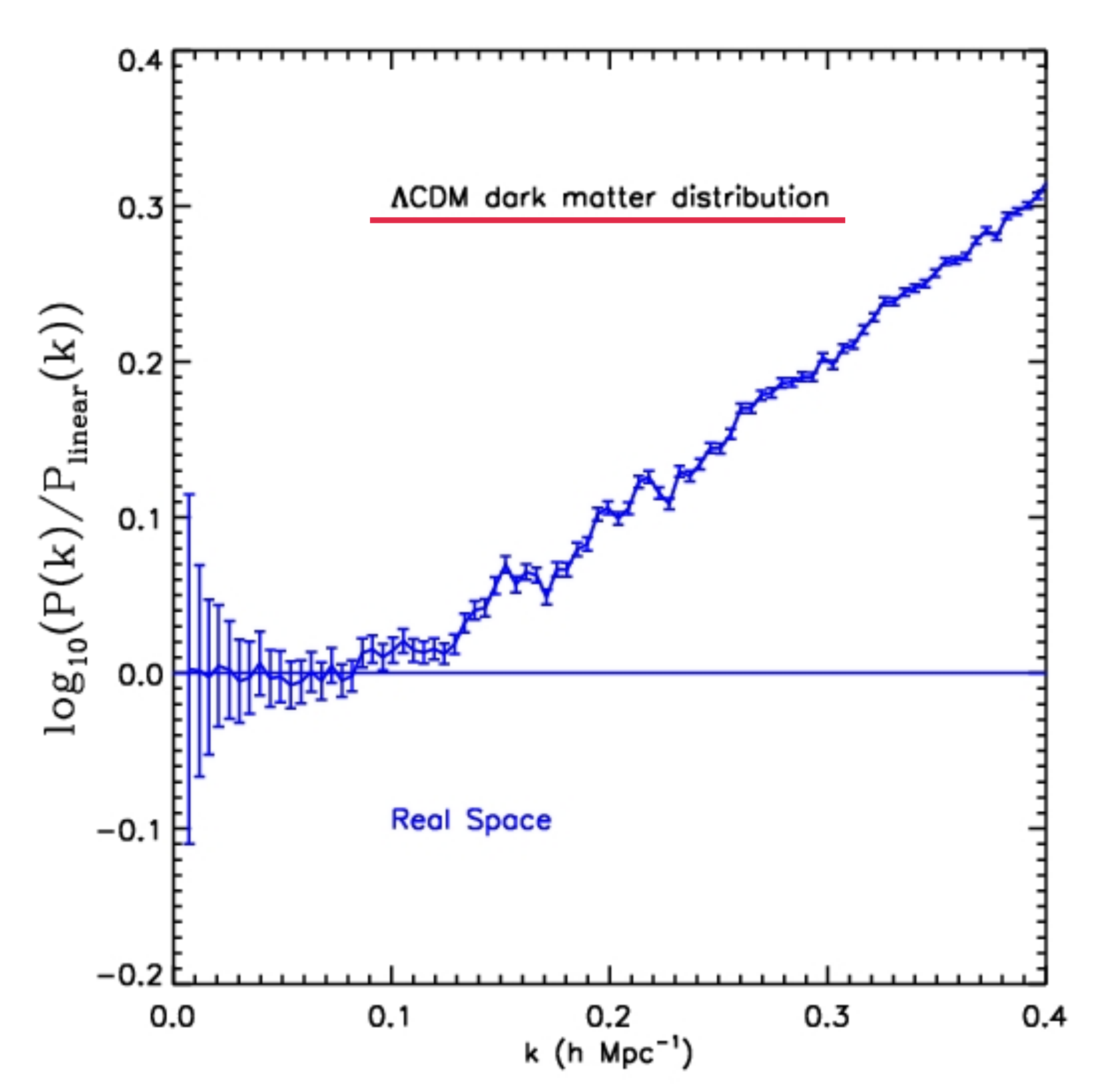
P(k) divided by linear theory P(k), scaling out growth factor

Angulo, Baugh, Frenk & Lacey '08

Institute for Computational Cosmology

Non-linear evolution of matter fluctuations

University of Durham



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

Angulo, Baugh, Frenk & Lacey '08

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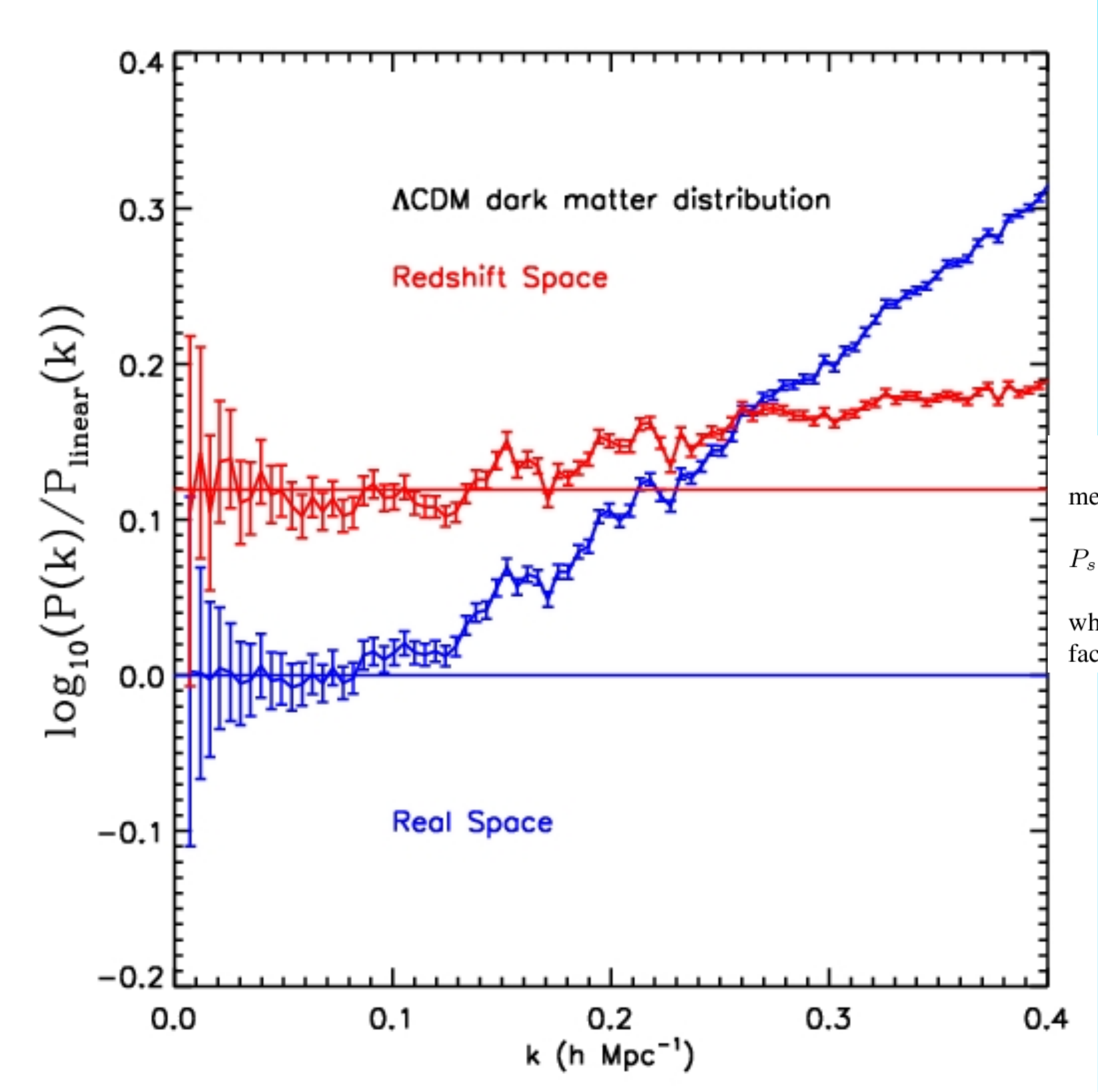
Redshift space distortions



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

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Redshift space distortions

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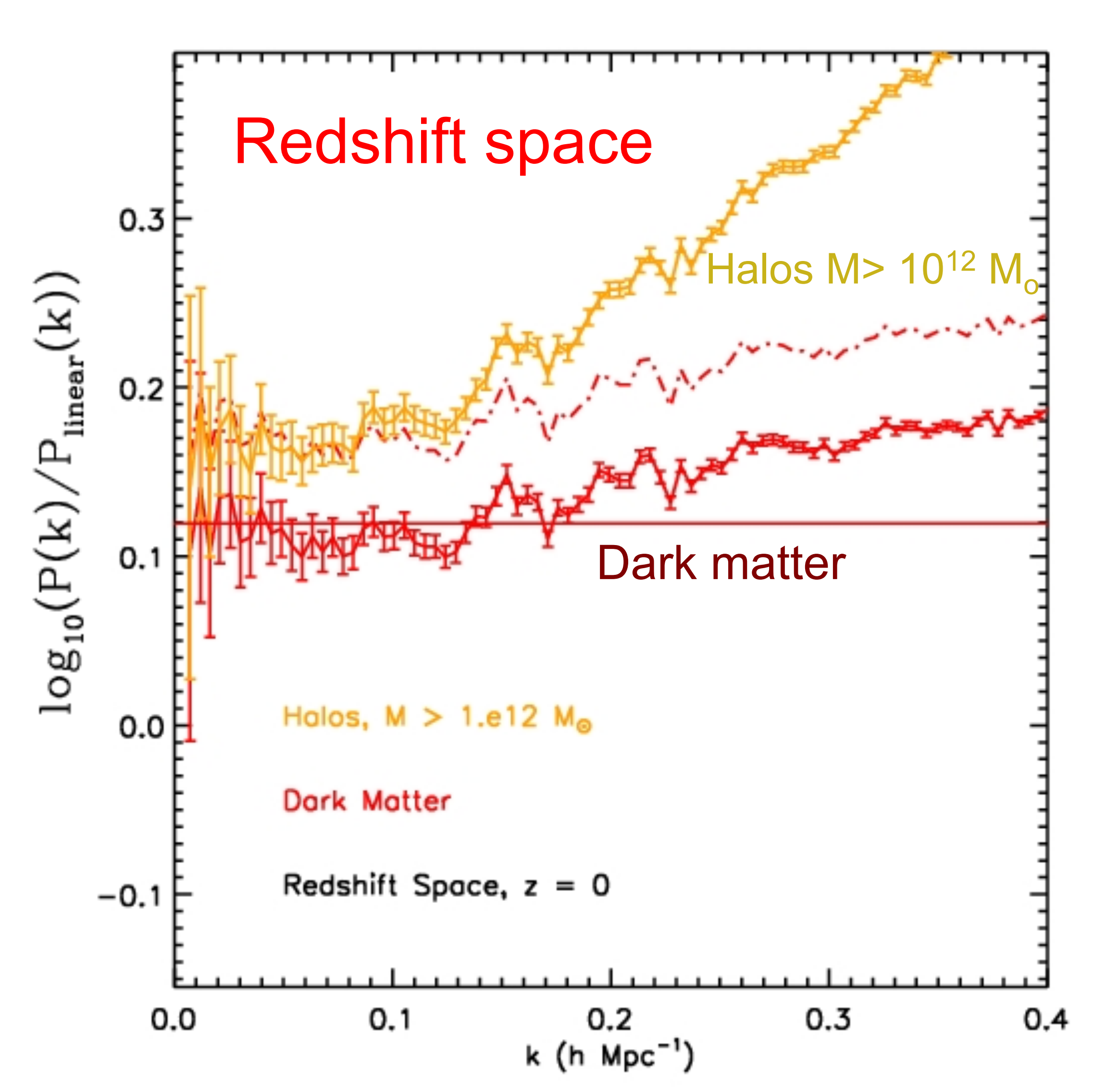

Peculiar motions distort clustering pattern

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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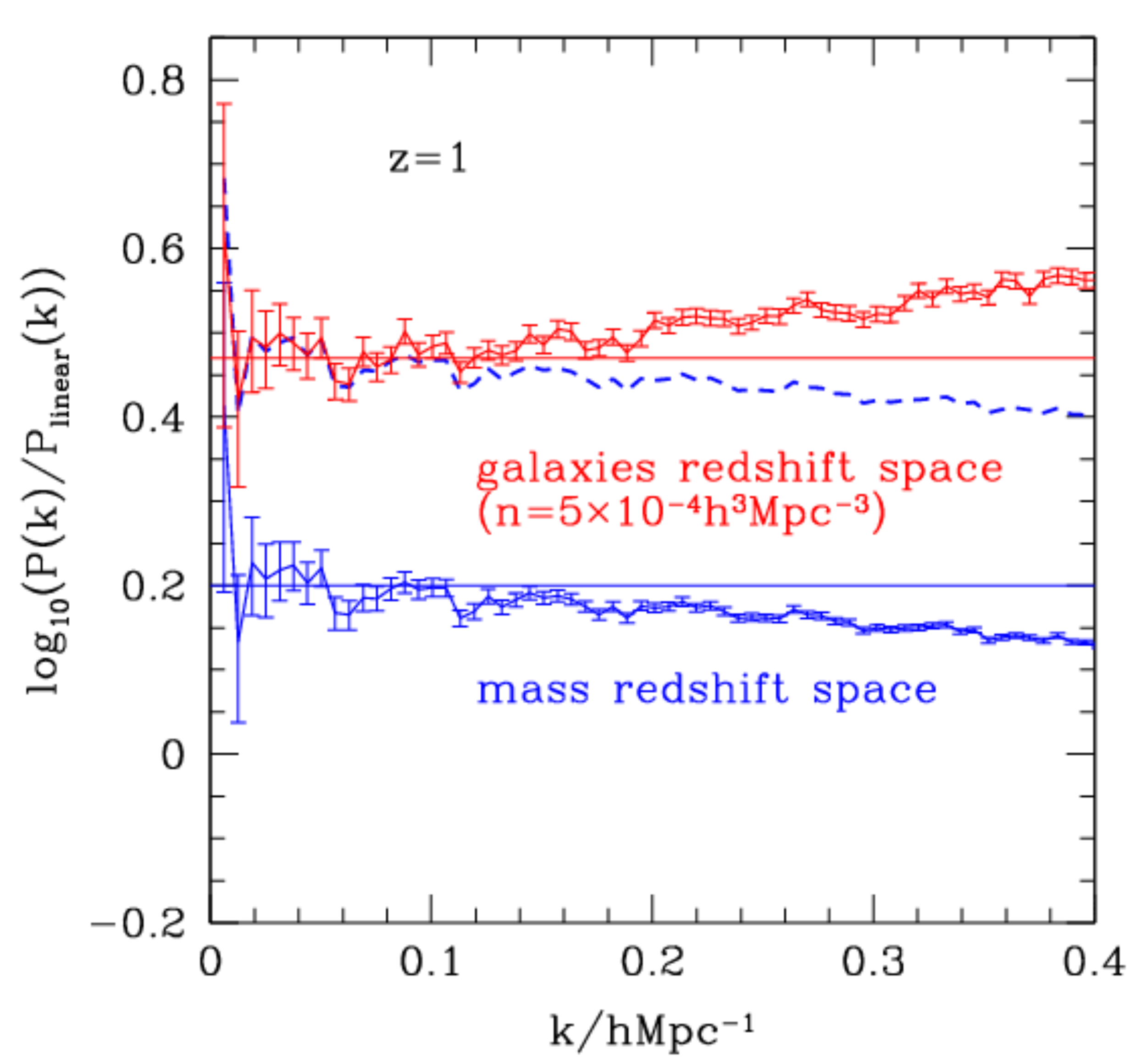
Galaxy bias in redshift space



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

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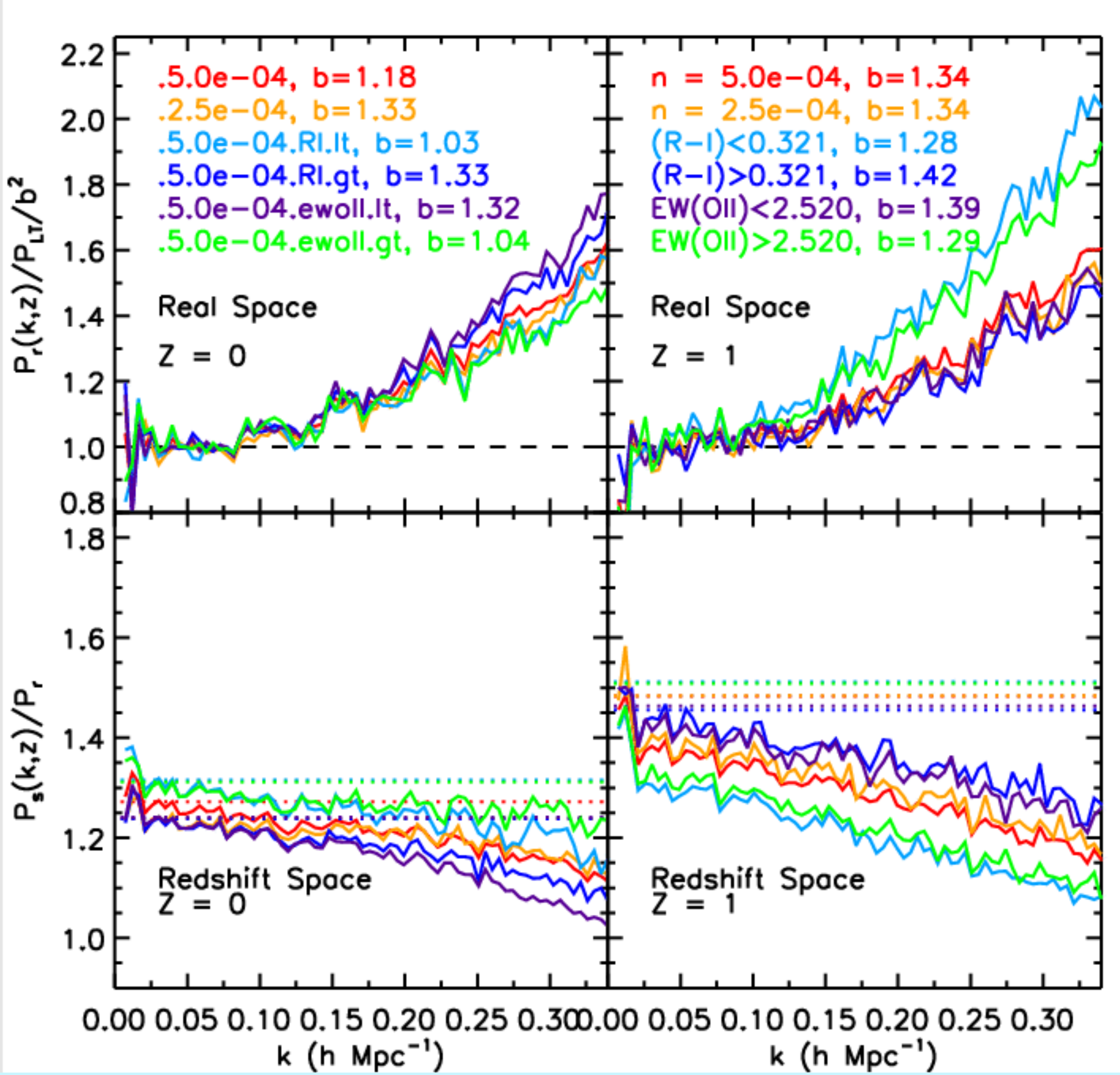
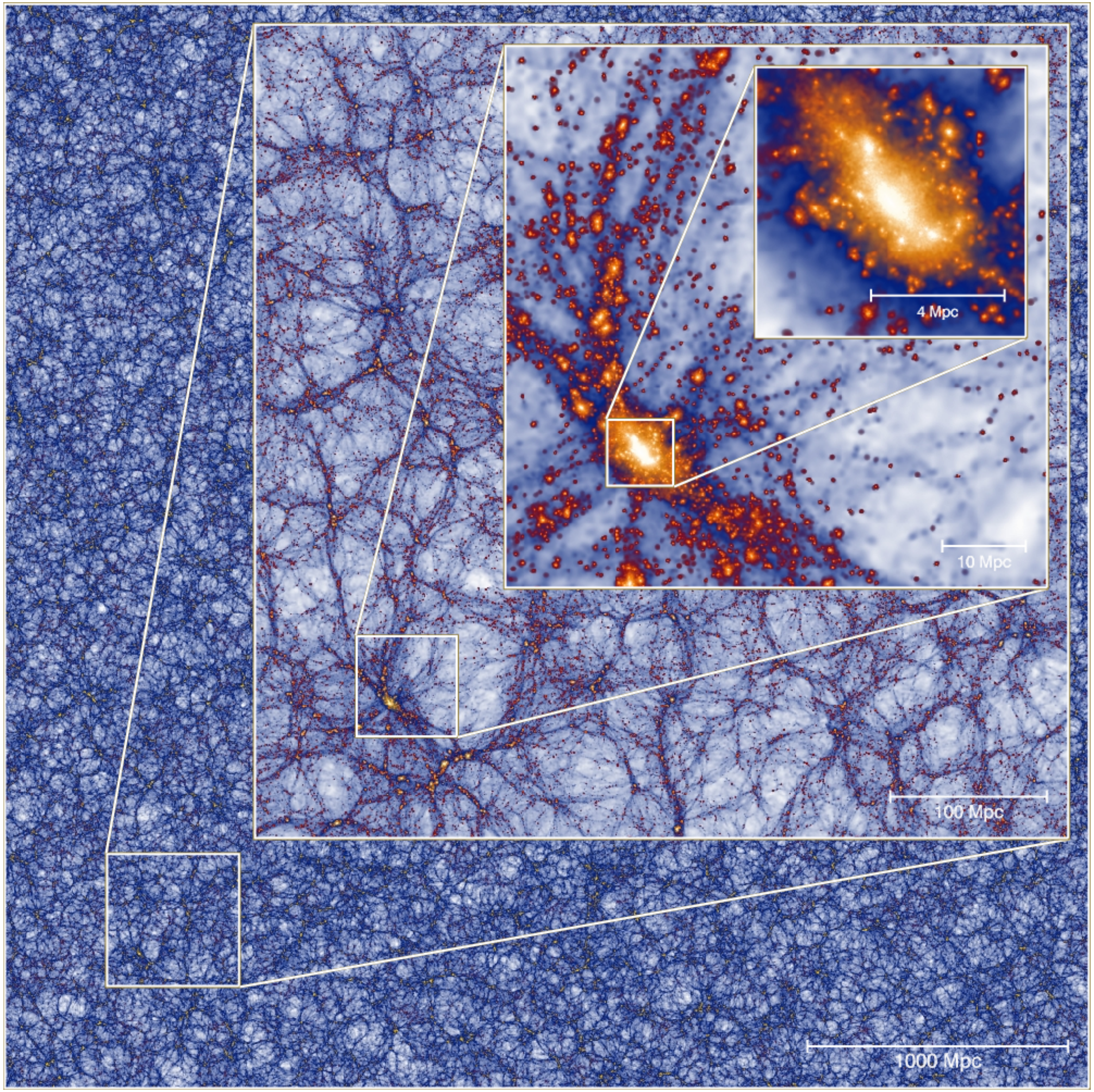
Galaxy bias in redshift space



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

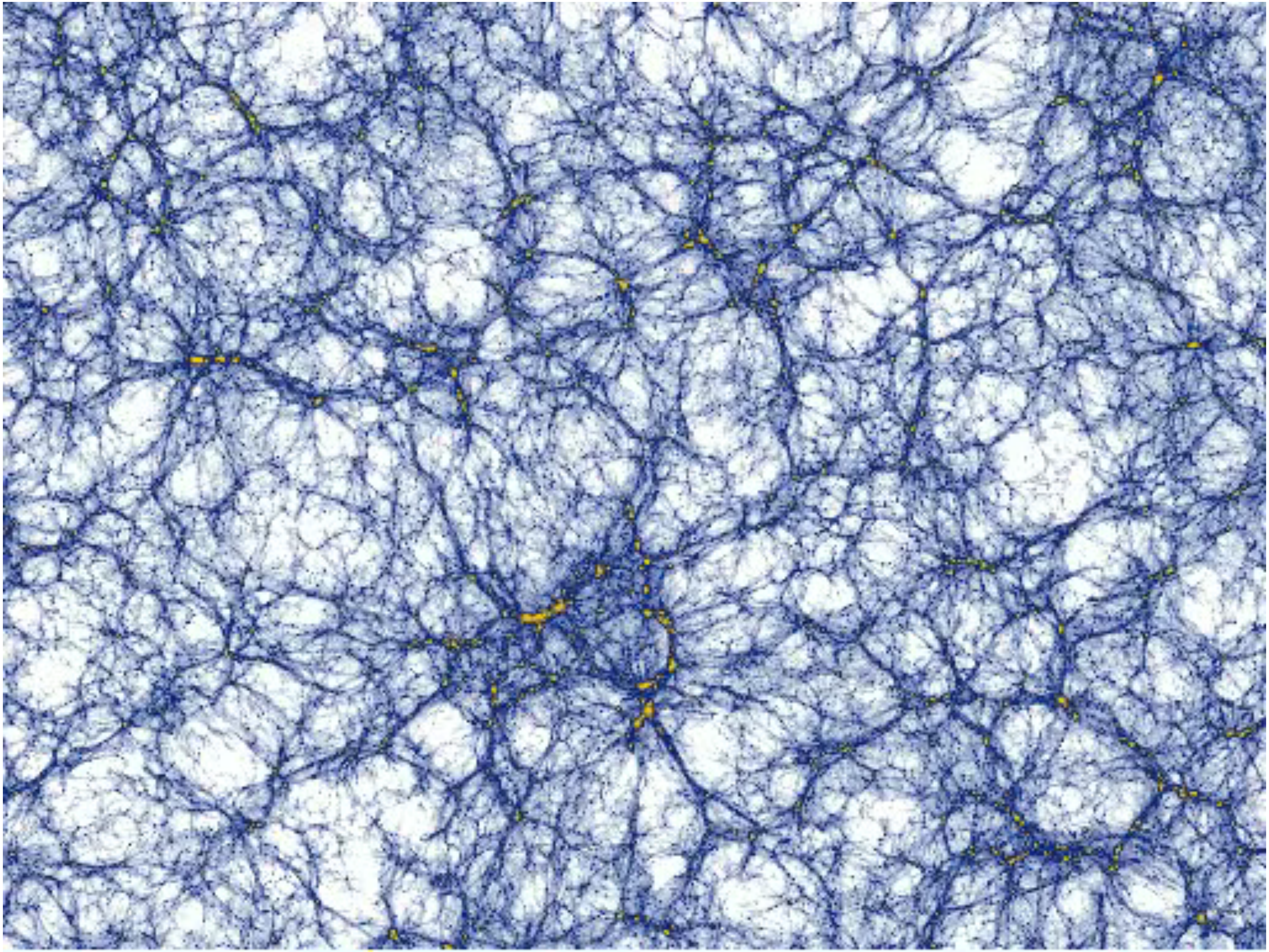
30 in $N_{particle}$

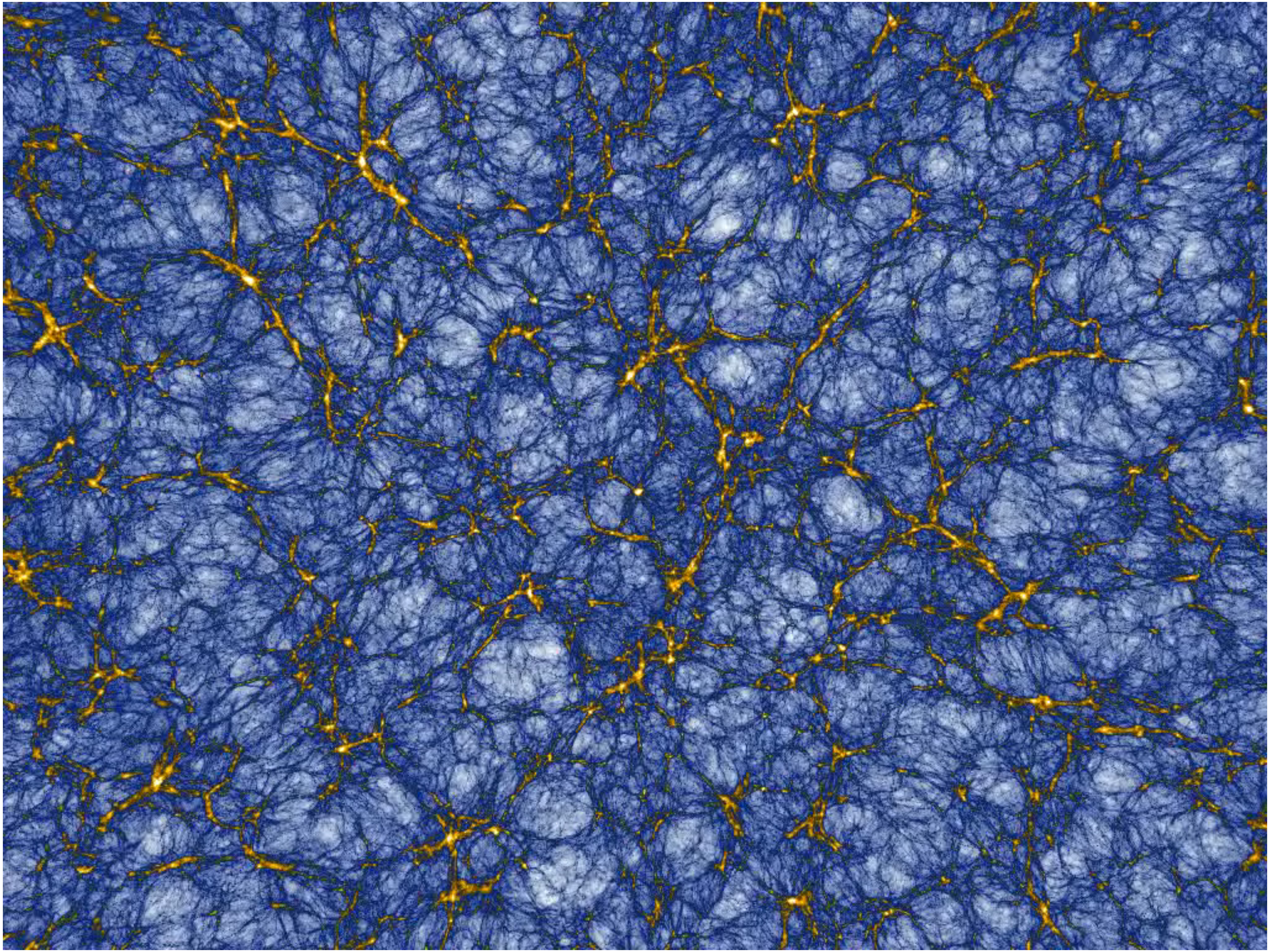
200 in volume

6 in $m_{particle}$

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

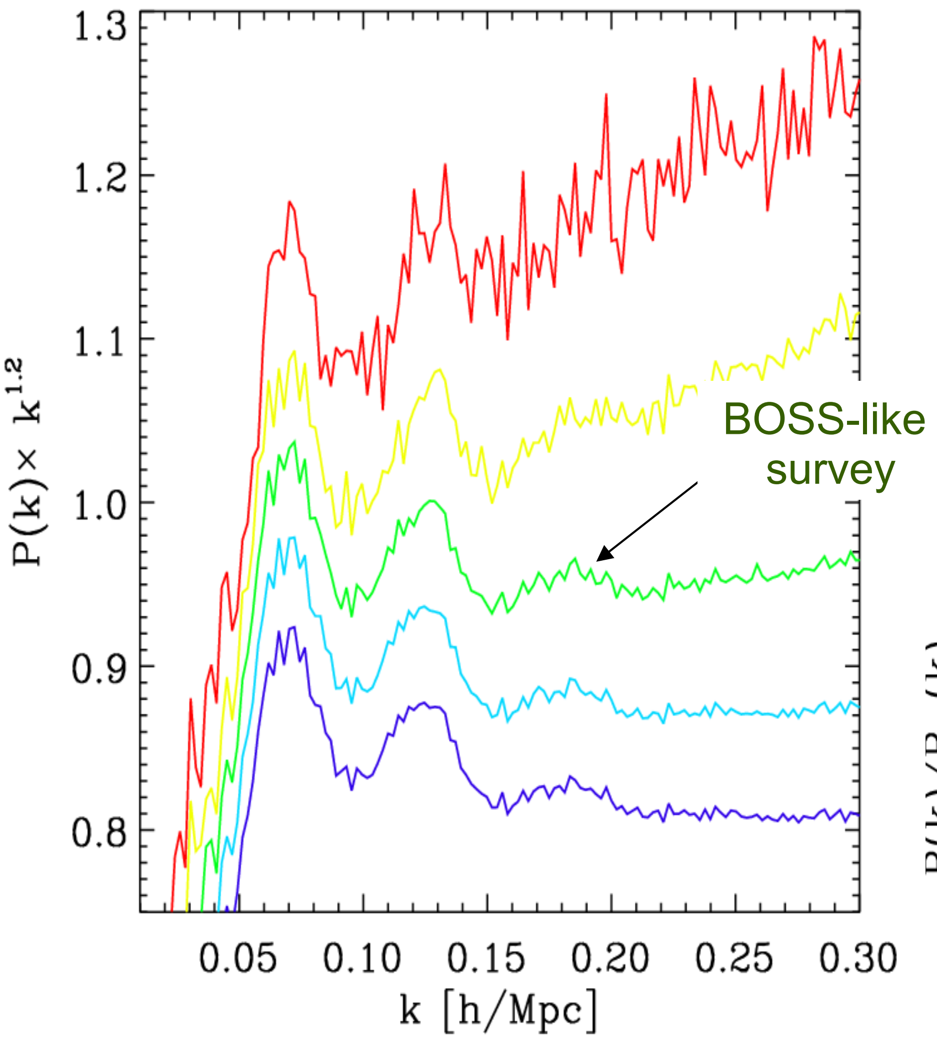
3×10^5 clusters $M_* > 10^{14} M_\odot$

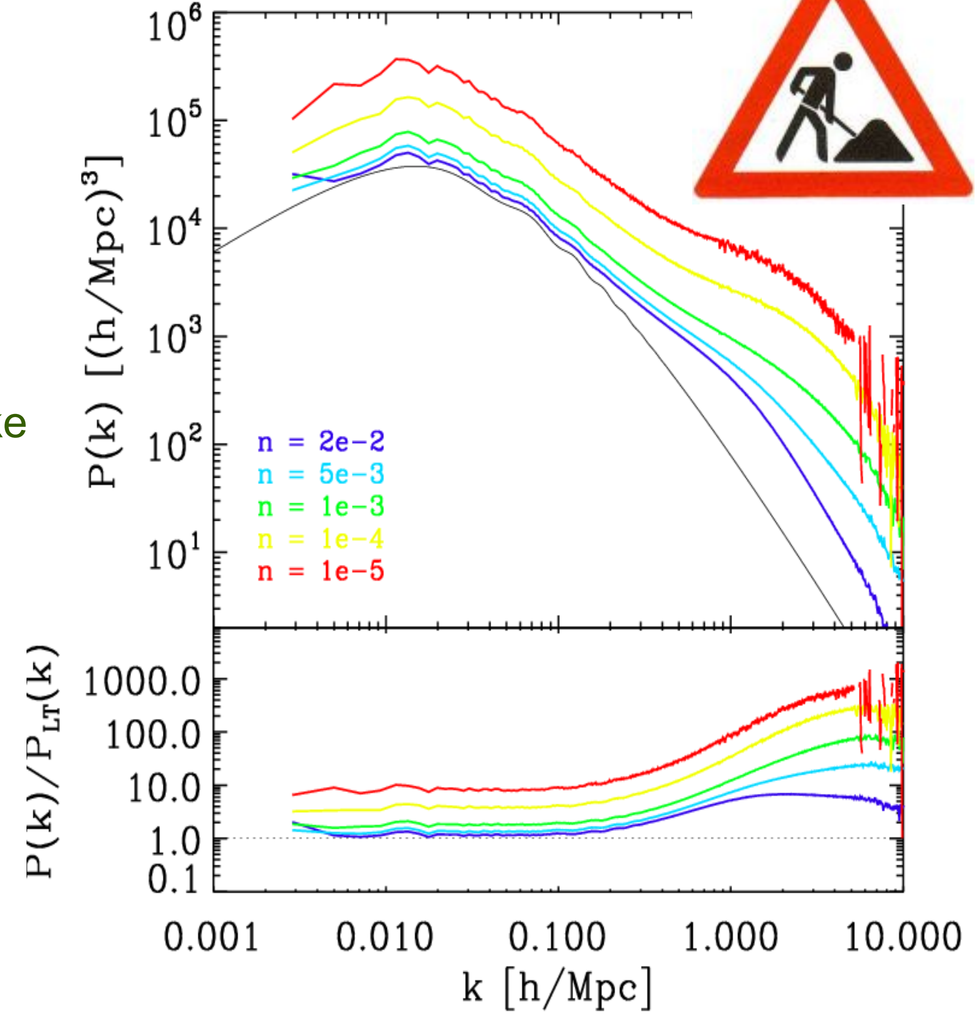




Different galaxy catalogues in the MXXL simulation trace the BAO features with a mass- and scale-dependent bias

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





Angulo et al. (2012)

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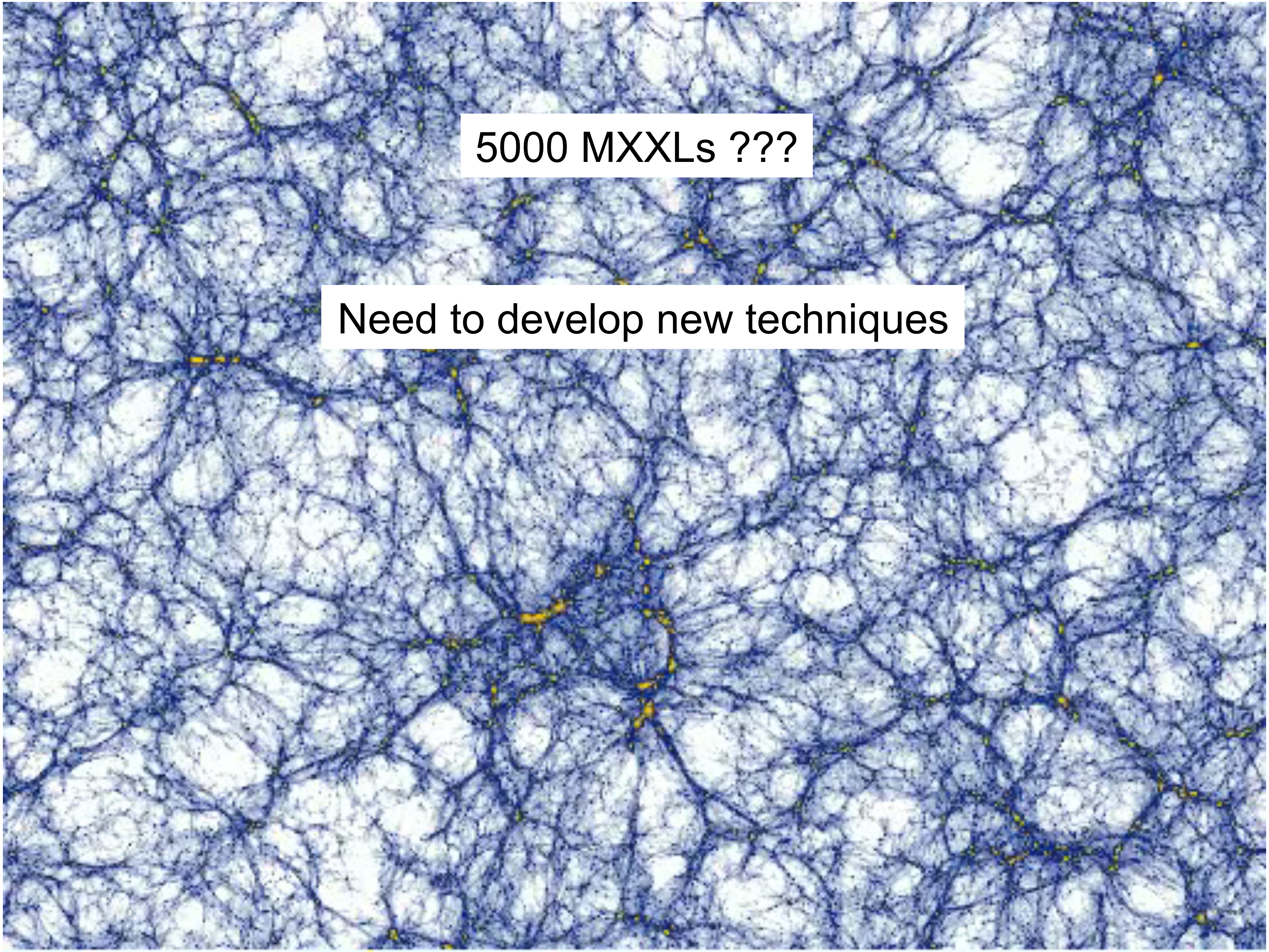
Estimating the PS covariance

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

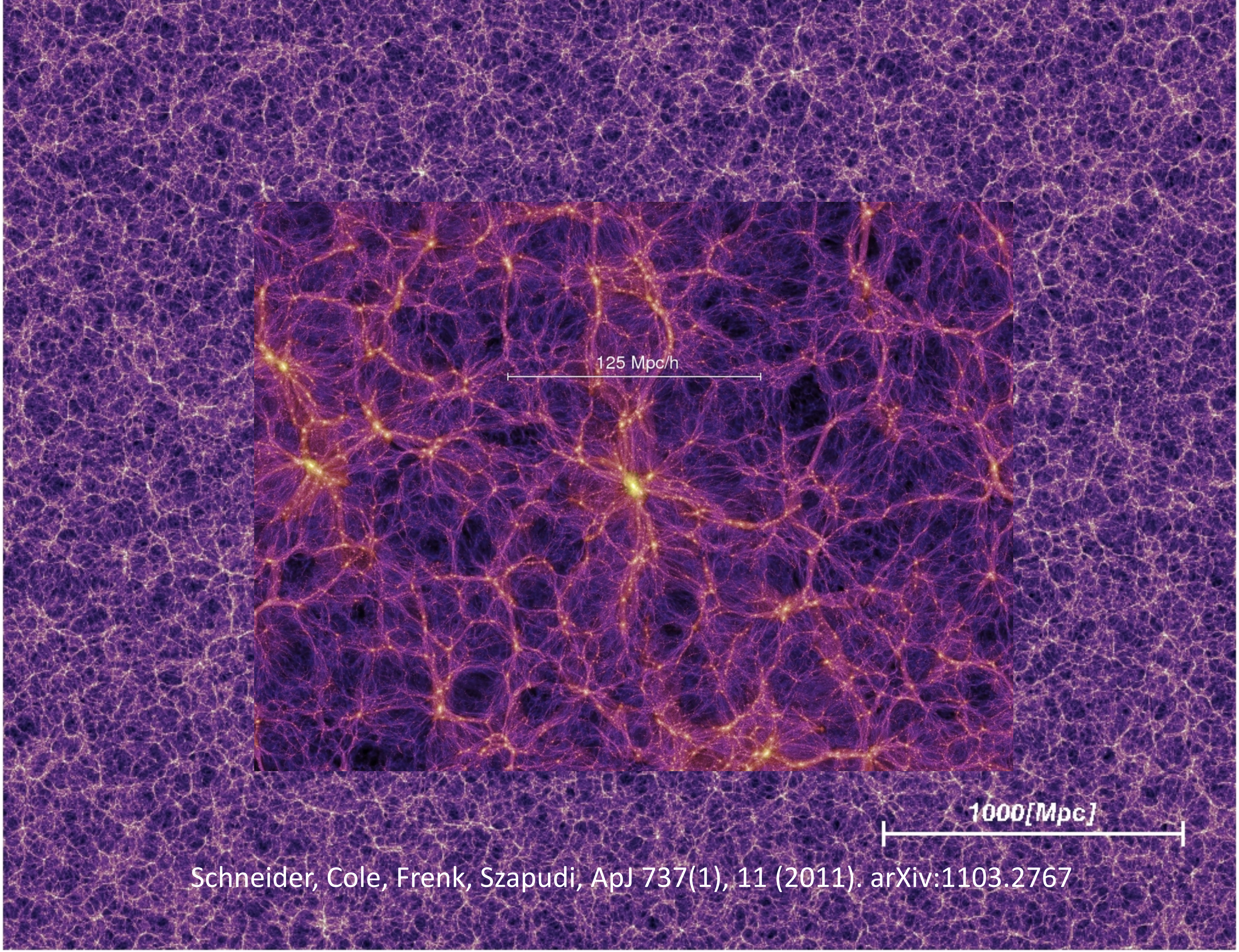
Takahashi et al '09 show that for a given cosmology, this can be achieved with …. 5000 large N-body simulations!!!


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

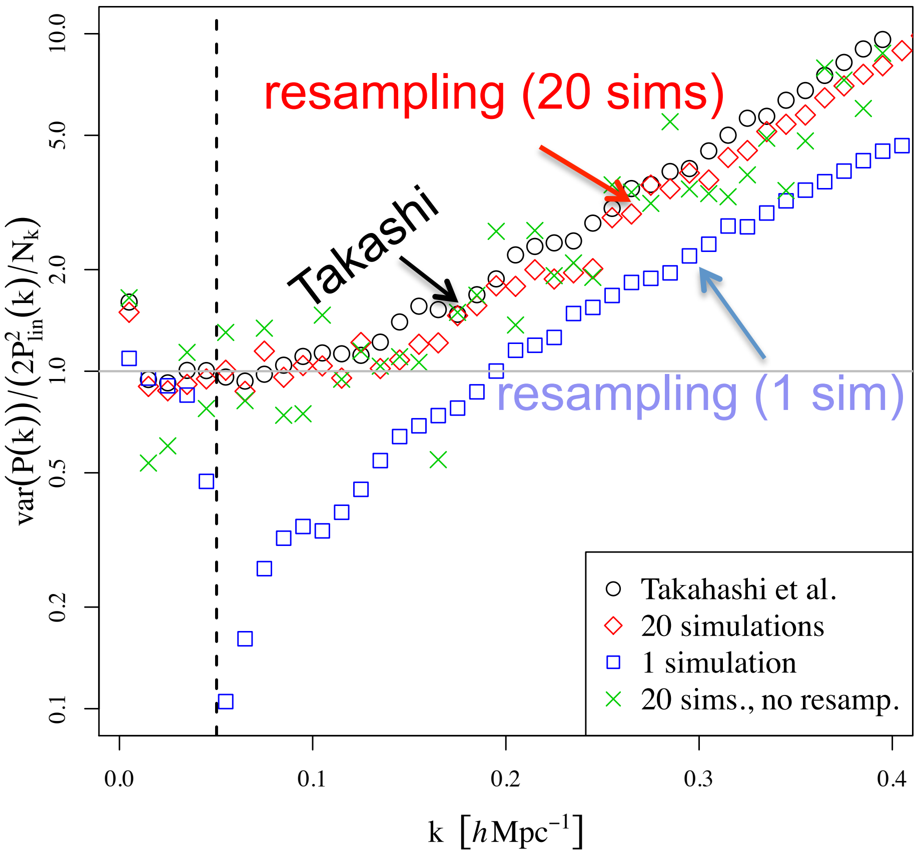


Schneider, Cole, Frenk, Szapudi, ApJ 737(1), 11 (2011). arXiv:1103.2767

Power spectrum covariance estimates

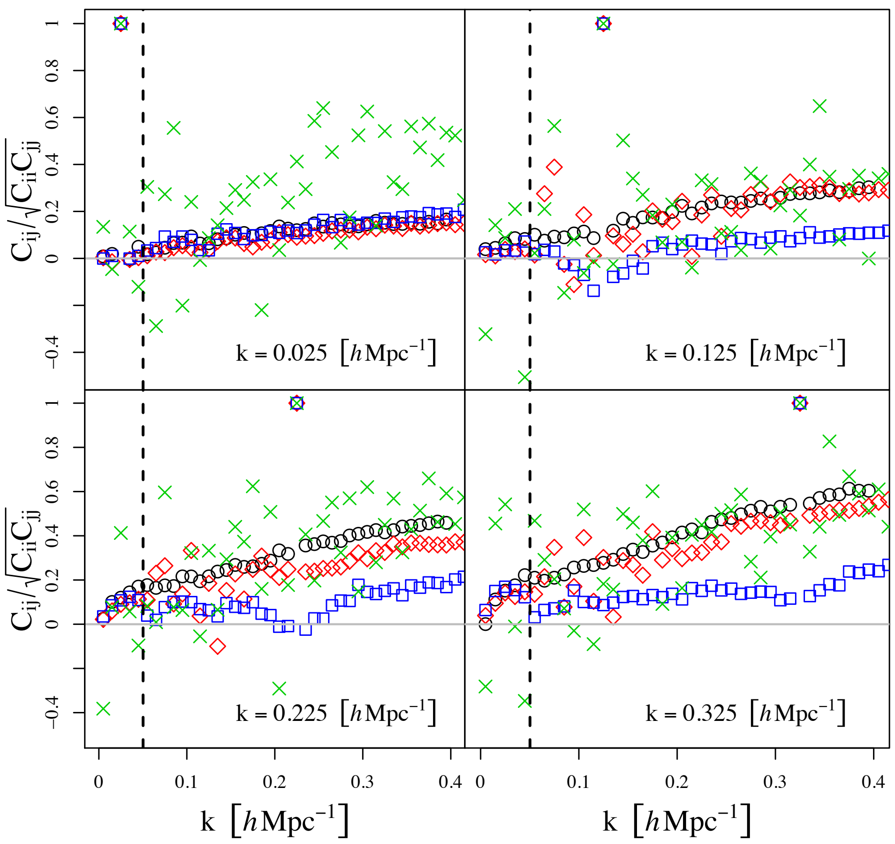
500 long-λ resamplings

P(k) variance



Schneider et al '11

Covariance matrix elements



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

Conclusions & challenges

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

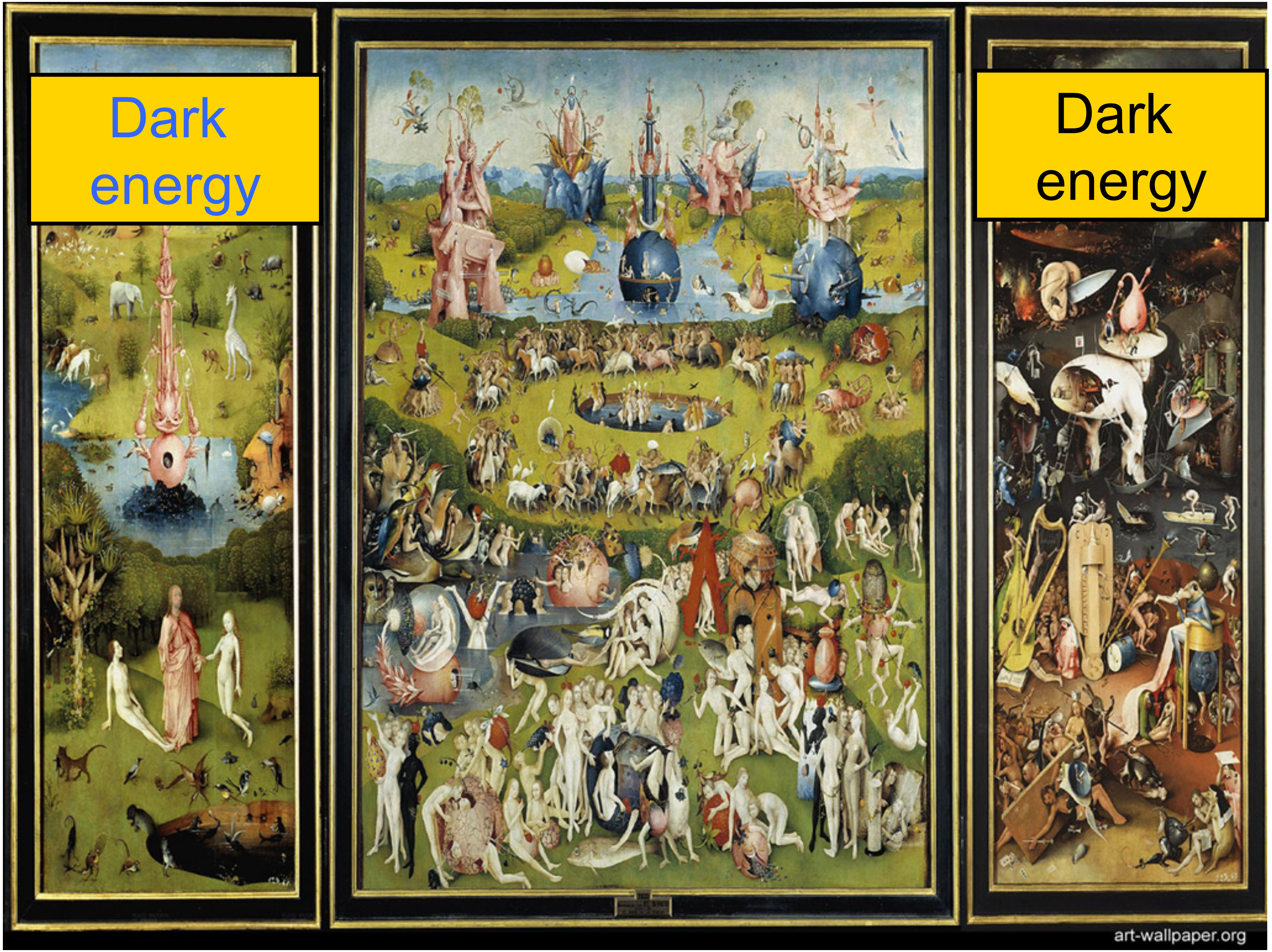
Along the way, we lost $\Omega_{matter}=1$ … and gained dark energy

→ 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