Testing LCDM on large and small scales

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

The emergence of a cosmological paradigm

$\Rightarrow$ ΛCDM model

cosmological constant or dark energy

cold dark matter

The CDM model:

- What is it?
- How do we test it?

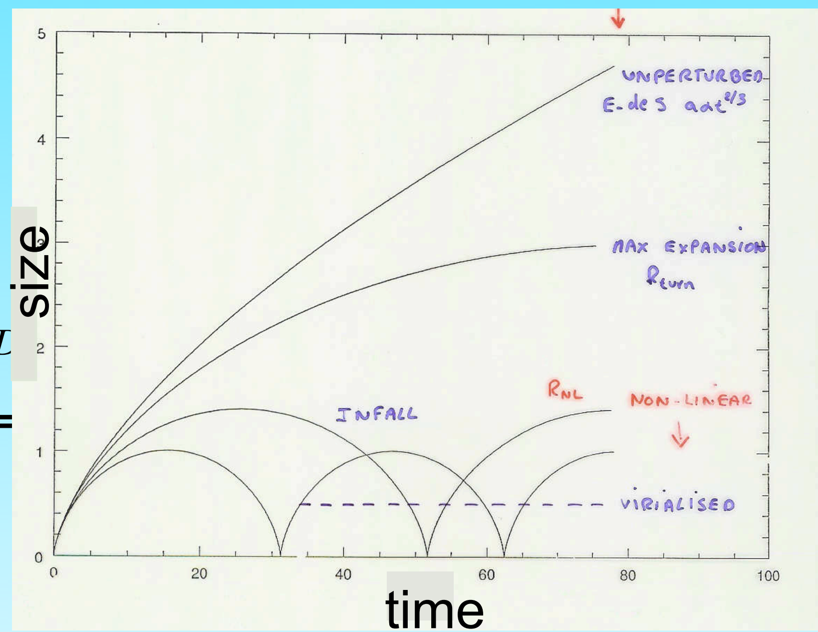
The ΛCDM model

- Material content: { Cold dark matter (eg neutralino;21%), baryons (4%), dark energy (Λ; 75%)

- Initial conditions for formation of structure:
  { Quantum fluctuations during inflation: $|\delta_k|^2 \propto k^n$, n≈1; Gaussian amplitudes

- Growth processes:

- Parameters: { Ω_{CD} ... , $h =$ ...



University of Durham

The density & geometry of the Universe

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

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

critical density = density that makes univ. flat:

In ΛCDM: $\Omega_{tot} = \Omega_{matter} + \Omega_{\Lambda} + \Omega_{radn} = 1$

consistent with the flat universe expected in inflation

The cold dark matter cosmogony

The CDM model is an intrinsically implausible model, all the more so when the cosmological constant Λ is required.

Couldn't we have something simpler?

In particular, couldn't we just have $\Omega_{matter} = 1$

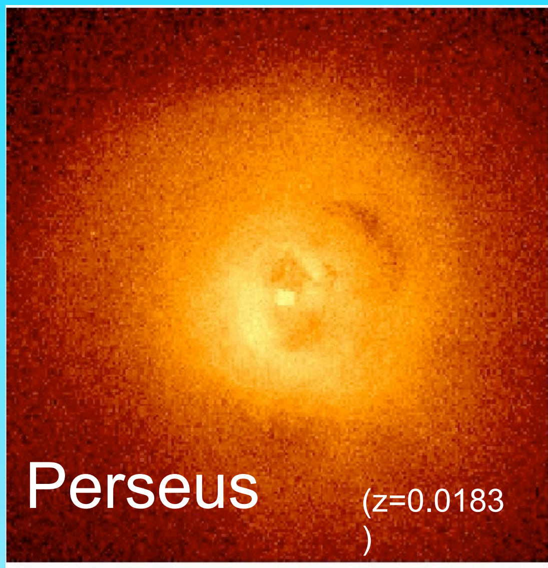
Clusters give direct evidence for $\Omega_{matter} < 1$

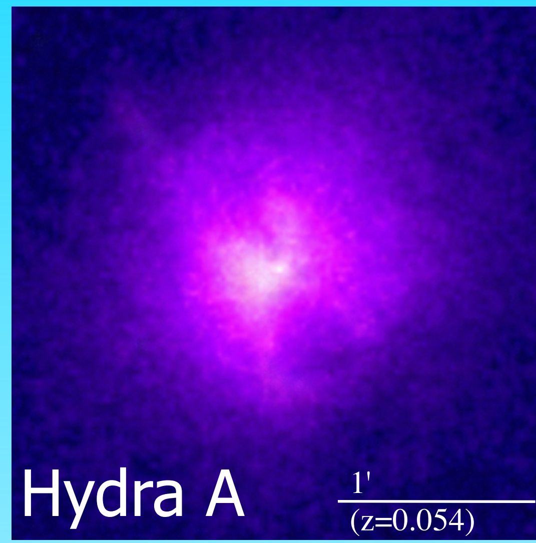
University of Durham

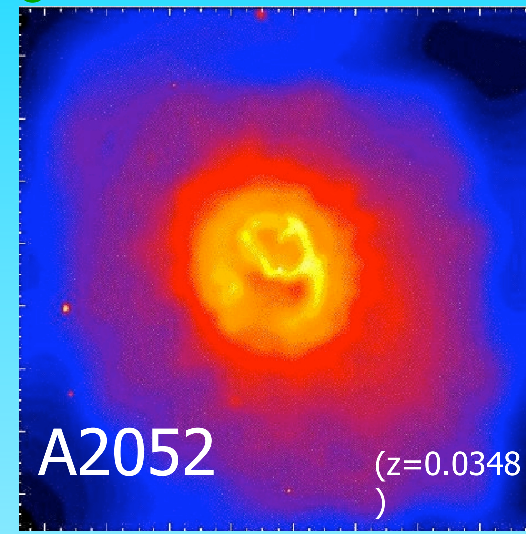
Galaxy clusters

X-ray emiss ot plasma in clusters

Images from David Buote







About 90% of baryons in clusters are in hot gas

X-rays ⇒ gas mass

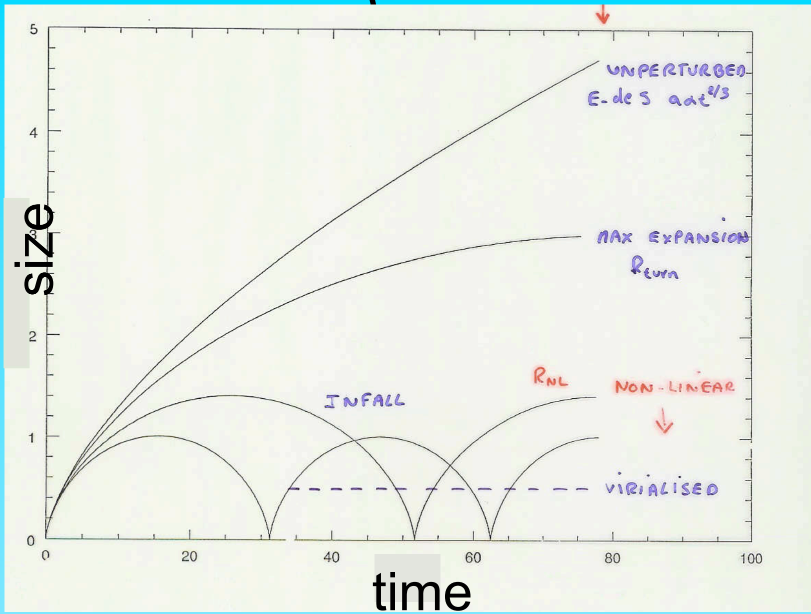
Photometry ⇒ stellar mass

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

} ⇒ Baryon fraction, f_b

University of Durham

Ω from the baryon fraction in clusters



In clusters matter that has fallen in is still in the cluster ($r_{vir} \sim r_{non\text{-}linear}$)

⇒ baryon fraction in clusters ≈ baryon fraction of universe

$$f_{baryon} = \frac{\text{mass in baryons}}{\text{total mass}}$$

$M_b = M_{gas} + M_{stars}$

$$f_b = \gamma \frac{\Omega_b}{\Omega}$$

White, Navarro, Evrard & Frenk '93

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

Simulations ⇒ $\gamma=0.9$

Ω from the baryon fraction in clusters

The baryon fraction in clusters, f_b, is related to the universal baryon fraction by:

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

White, Navarro, Evrard & Frenk '93

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

simulations → $\gamma = 0.9 \pm 10\%$

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

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

HST → $h = 0.7 \pm 10\%$

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

Allen etal '04

University of Durham

$\Omega < 1$: open or flat universe?

$\Omega_{matter} < 1 \Rightarrow$

- Open universe
- Cosmological constant to give $\Omega_{tot}=1$

White et al 1993

(Some) evidence for dark energy

University of Durham

Evidence for Λ from high-z supernovae

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

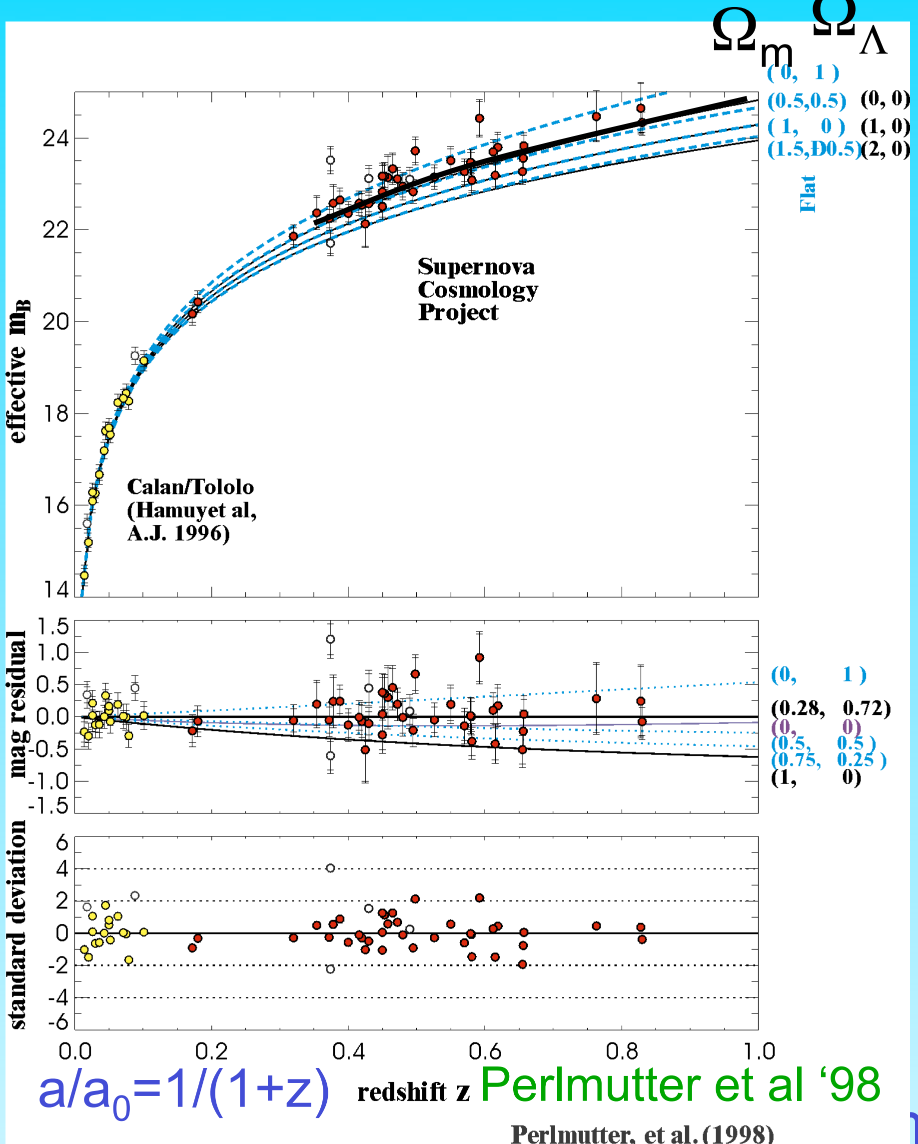
flux

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

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

where $p = w\rho c^2$

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



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

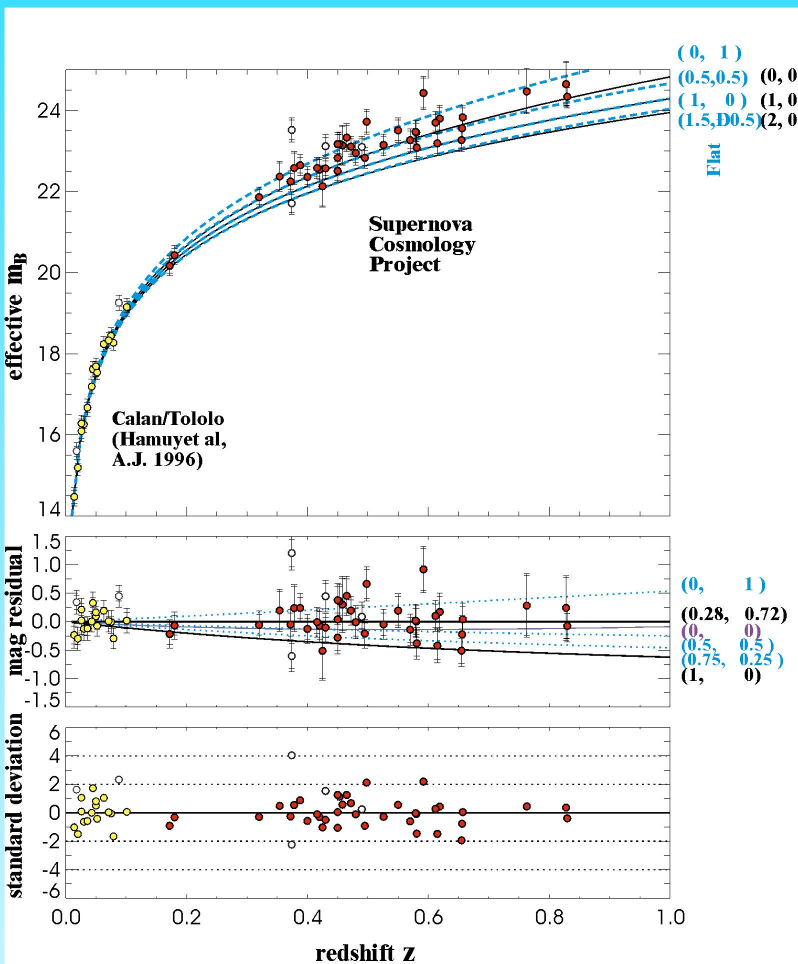
Perlmutter et al '98

Cosmology

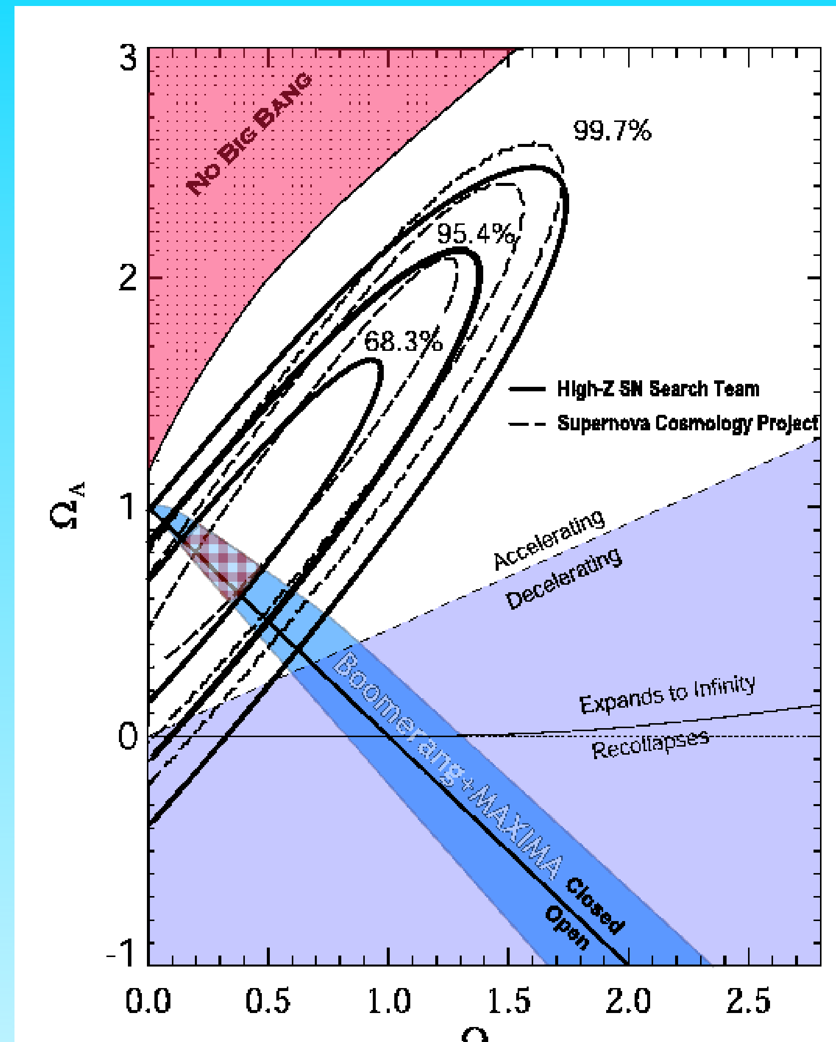
University of Durham

Evidence for Λ from high-z supernovae

Distant SN are fainter than expected if expansion were decelerating



Perlmutter, et al. (1998)



Riess et al '98

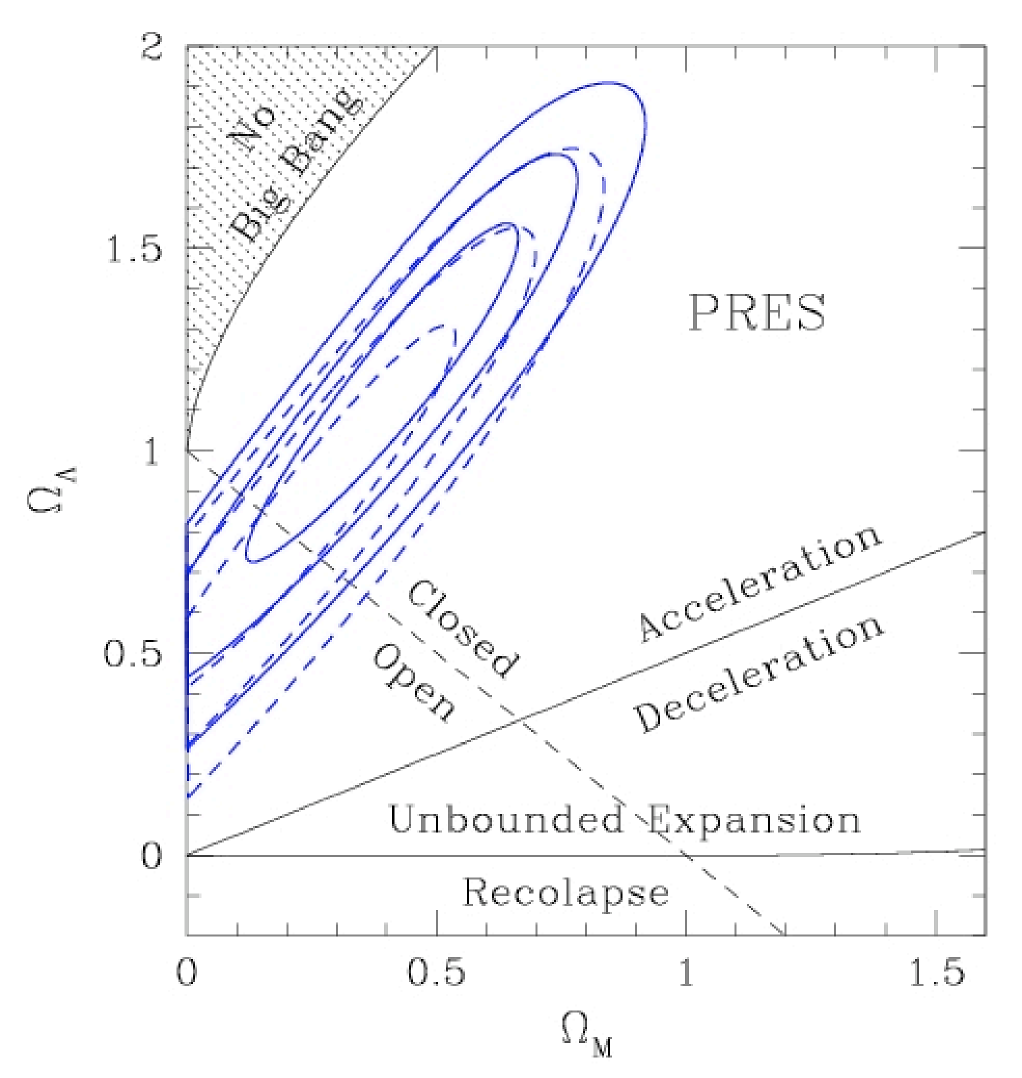
Evidence for Λ from high-z supernovae

University of Durham

Latest data rules out $\Omega_\Lambda = 0$.

Main concerns:

- Physics of SNIa not understood
- Systematic errors?



Clocchiatti et al '06

The cold dark matter cosmogony

So (implaussibly), we seem to need dark energy

But why cold dark matter?

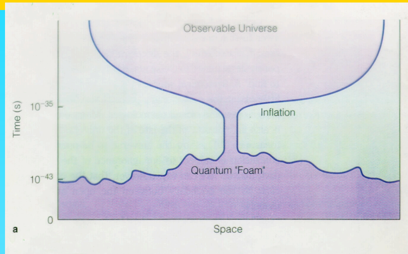
Non-baryonic dark matter candidates

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

University of Durham

The origin of cosmic structure

Inflation (t~10^{-35} s)



→ **QUANTUM FLUCTUATIONS:**

$$\left\{ \begin{array}{l} |\delta_k|^2 \propto k^n \quad n \approx 1 \\ \text{Gaussian amplitudes} \end{array} \right.$$

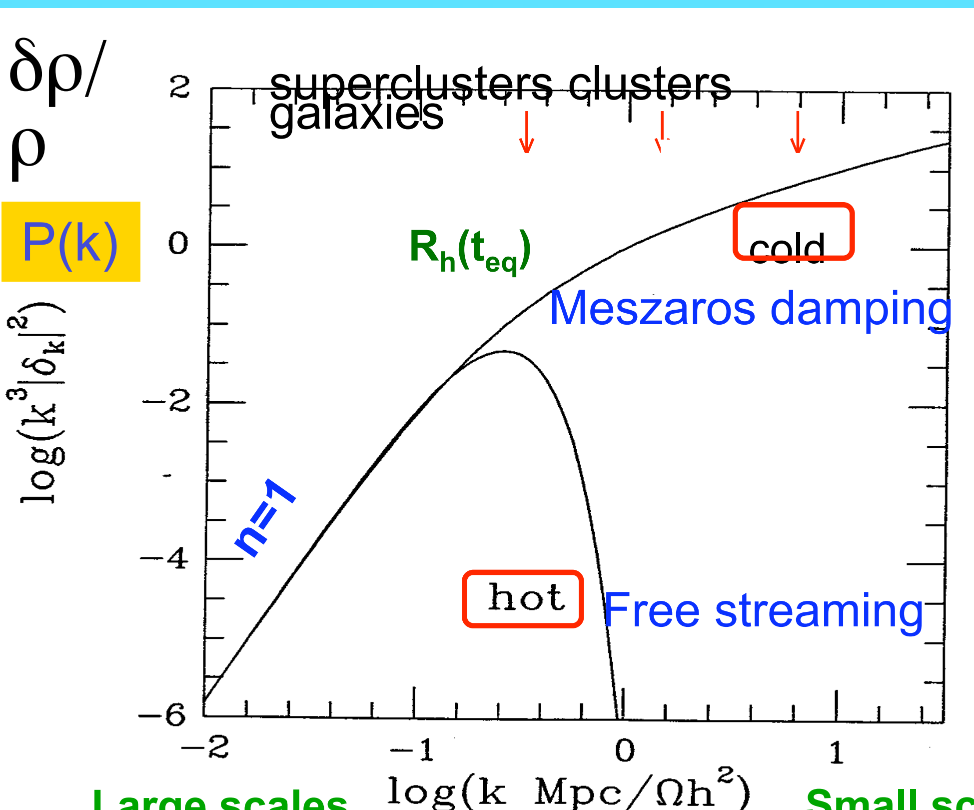
\+

Damping (nature of dark matter)

→ **FLAT UNIVERSE**

$$P(k) = A k^n \, T^2(k,t)$$

→ Transfer function



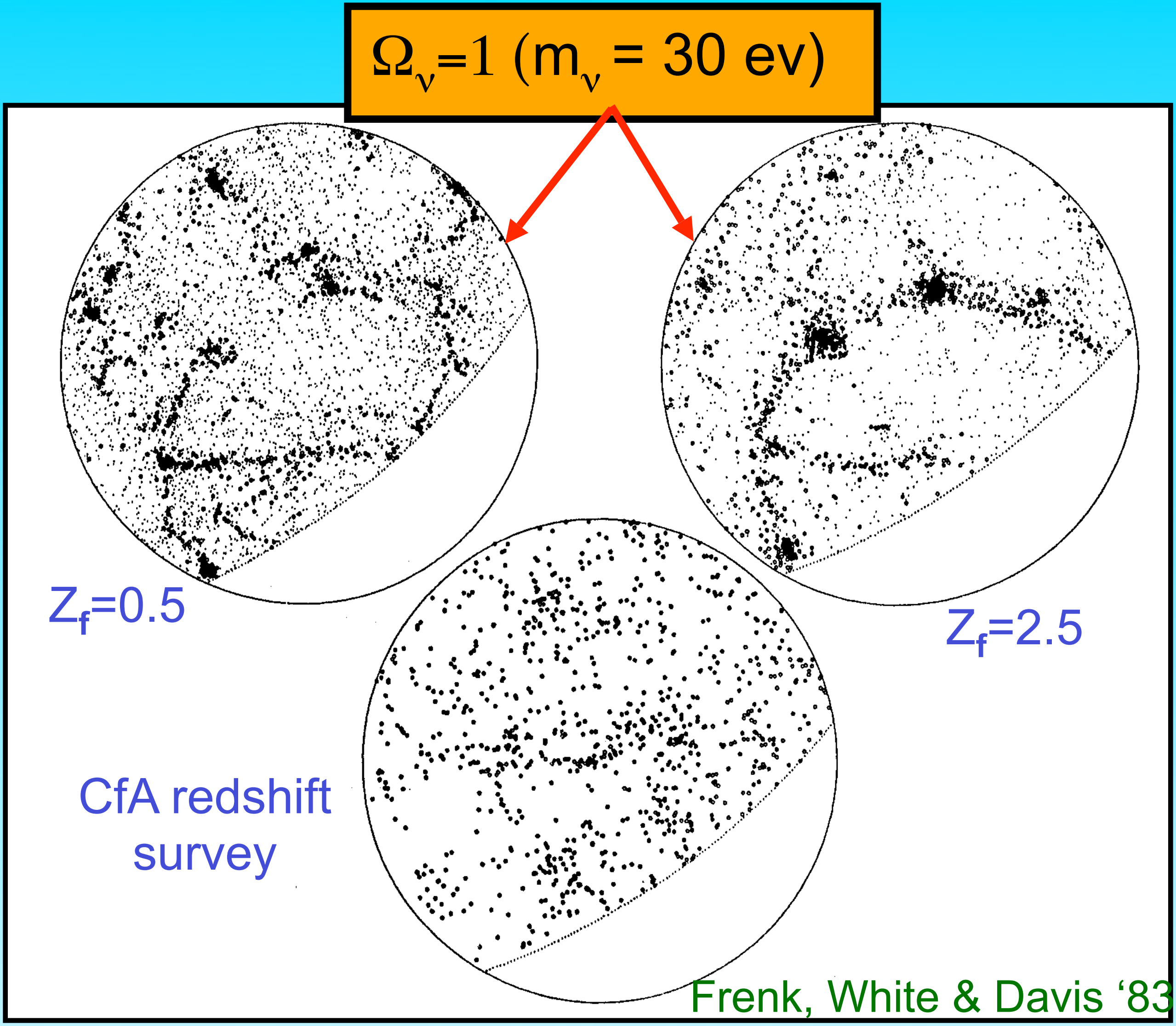
- Hot DM (eg ~30 ev neutrino)
  - Top-down formation
- Cold DM (eg ~neutralino)
  - Bottom-up (hierachical)

Neutrino (hot) dark matter

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

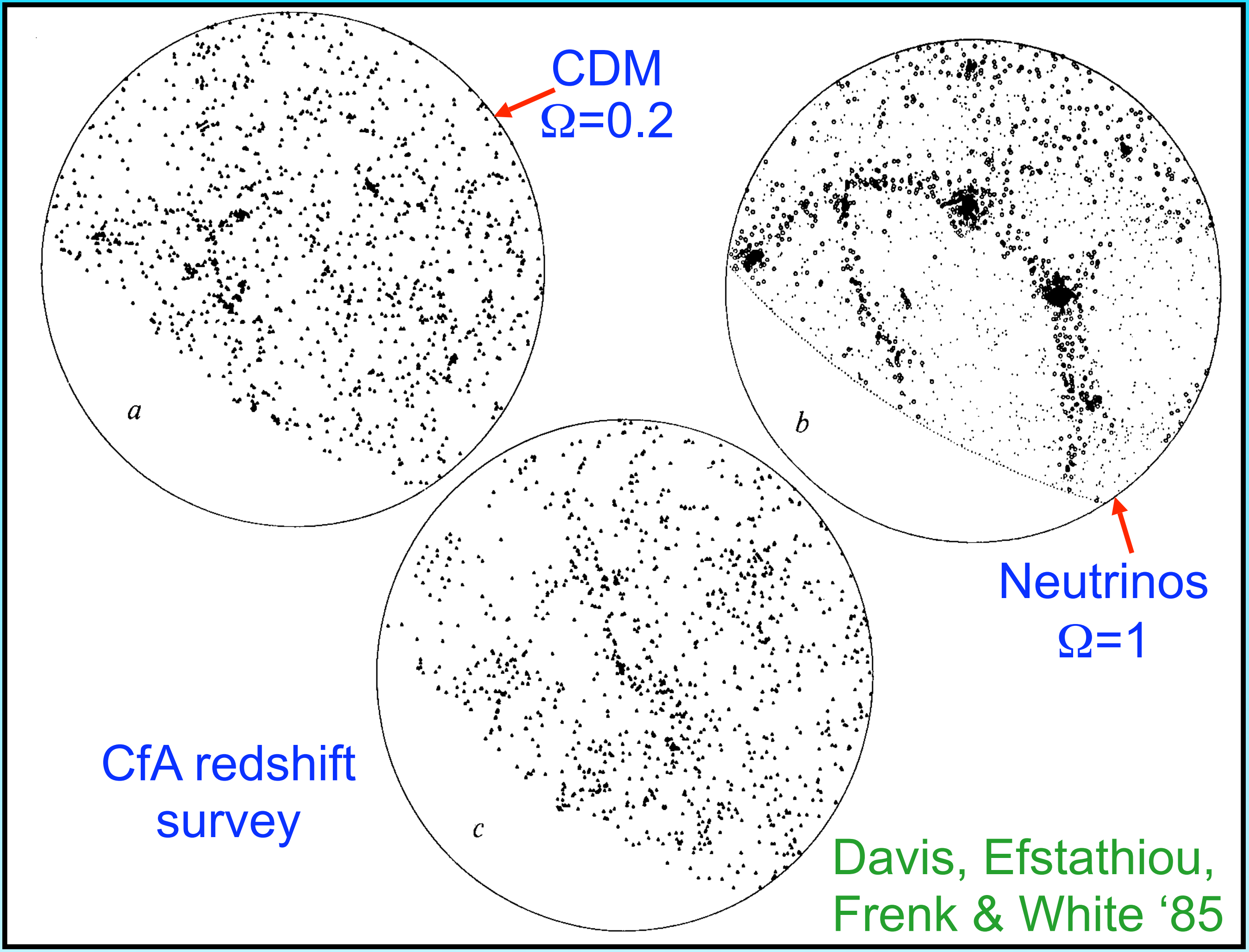


Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



University of Durham

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

THE ASTROPHYSICAL JOURNAL, 304:15–61, 1986 May 1

Bardeen, Bond, Kaiser & Szalay 1986

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

J. M. BARDEEN[1]
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

NATURE VOL. 311 11 OCTOBER 1984 — REVIEW ARTICLE — 517

Formation of galaxies and large-scale structure with cold dark matter

George R. Blumenthal* & S. M. Faber*
* Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA
Joel R. Primack†§ & Martin J. Rees‡§
† Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA
‡ Institute of Theoretical Physics, University of California, Santa Barbara, California 93106, USA

Blumenthal, Faber, Primack & Rees 1984

University of Durham

The cold dark matter cosmogony

Cold dark matter candidates:

- Axion $m_a \sim 10^{-5}$ eV
- Sterile neutrino $m_\nu \sim 100$ MeV
- Neutralino (lightest stable susy particle) $m_X > 100$ GeV

Modelling large-scale structure

Cosmological model

(Ω, Λ, h…); dark matter

Primordial fluctuations

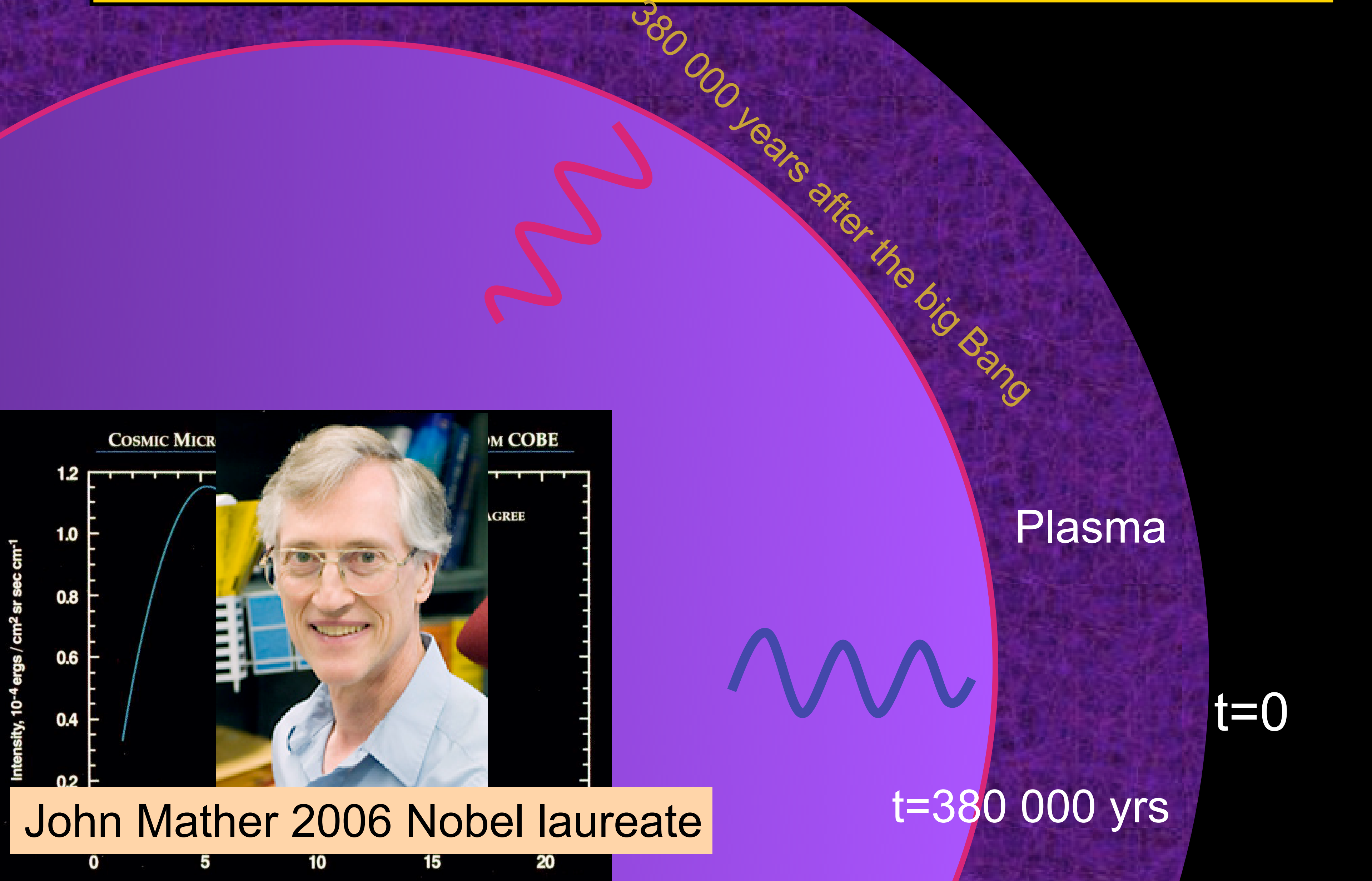
$\delta\rho/\rho(M, t)$

Standard model:
ΛCDM

- Material content: Cold dark matter (eg neutralino;21%), baryons (4%), dark energy (Λ; 75%)
- Initial conditions: Quantum fluctuations during inflation: $|\delta_k|^2 \propto k^n$, $n \approx 1$; Gaussian amplitudes
- Growth processes: Gravitational instability
- Parameters: $\Omega_{CDM} = 0.21,\ \Omega_b = 0.04,\ \Omega_\Lambda = 0.75,$ $h = 0.70, \sigma_8 = 0.9, \ldots$

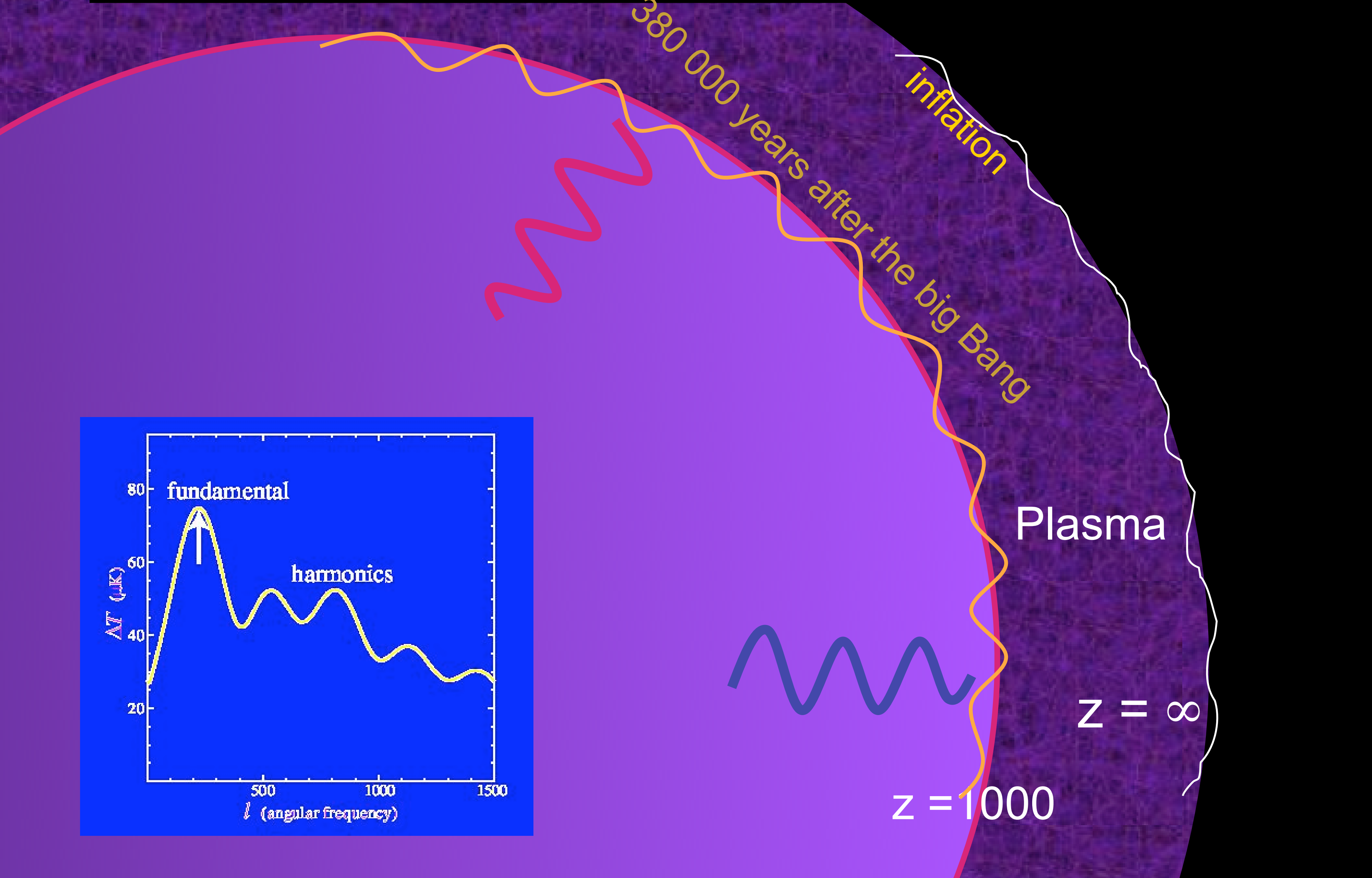
Testing ΛCDM on very large scales (and very early times)

The microwave background radiation



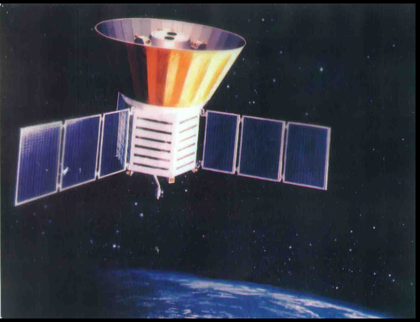
John Mather 2006 Nobel laureate

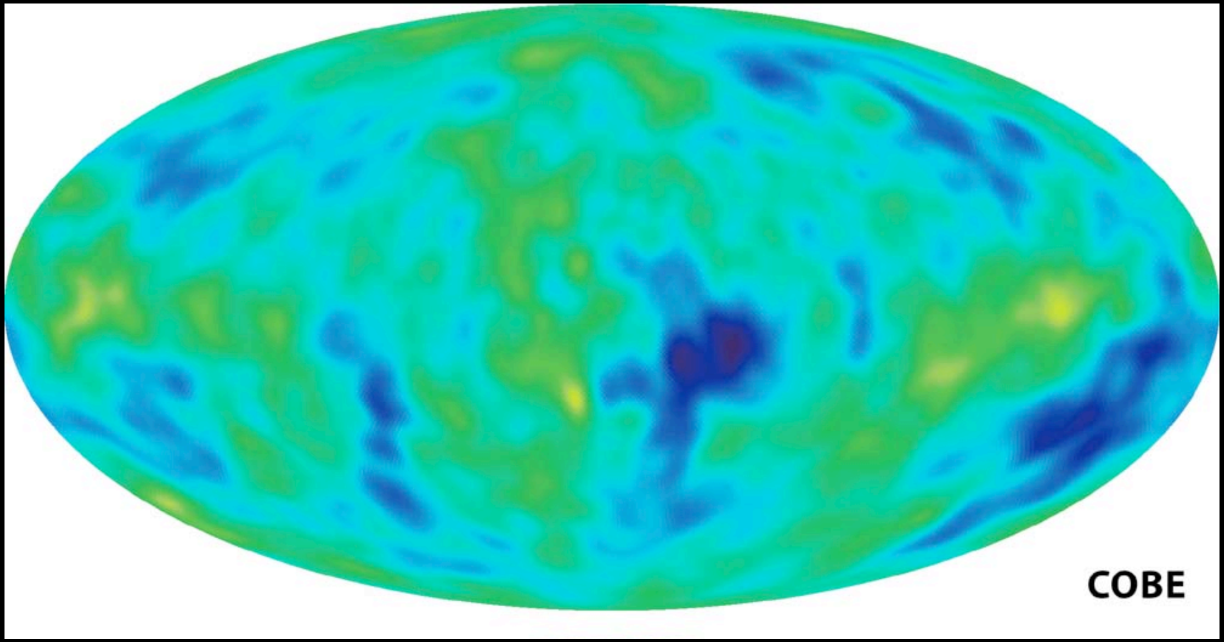
The microwave background radiation



The CMB

1992





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

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

The CMB

ICC

1992

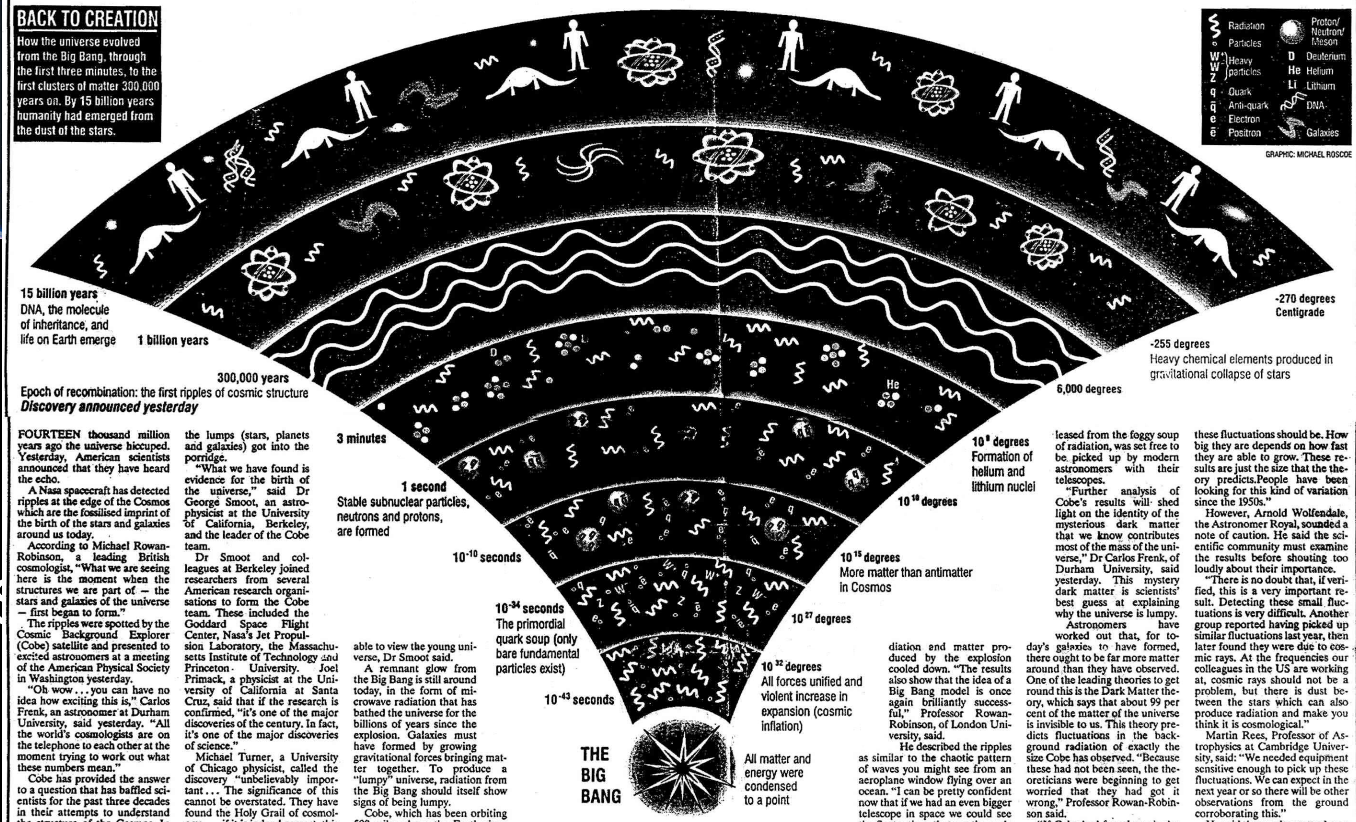
George S

THE INDEPENDENT

No 1,722 — FRIDAY 24 APRIL 1992 — ★★★ Published in London 40p

A Nasa spacecraft has detected echoes of the galaxies' birth fourteen thousand million years ago. The discovery about the formation of the stars after the Big Bang has been hailed by excited scientists as the Holy Grail of cosmology. **Susan Watts** and **Tom Wilkie** report

How the universe began



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

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

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

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

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

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

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

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

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

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

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

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

Cobe detected almost imperceptible variations in the temperature of the radiation, which measures 270C below zero. Those variations — only about thirty-millionths of a degree — represent slight differences in the density of matter at the edge of the universe, ripples of wispy clouds surrounded by slightly less dense matter, the scientists said yesterday. The smallest ripples the satellite picked up stretch across 500 million light years of space.

Cobe has taken a snapshot of the universe just 300,000 years after Big Bang itself — at a point in time when the foggy fireball of radiation and matter produced by the explosion cooled down. "The results also show that the idea of a Big Bang model is once again brilliantly successful," Professor Rowan-Robinson, of London University, said.

He described the ripples as similar to the chaotic pattern of waves you might see from an aeroplane window flying over an ocean. "I can be pretty confident now that if we had an even bigger telescope in space we could see the fluctuations that are the early signs of individual galaxies themselves. It's just a matter of technology now," he added.

The point in time of Cobe's snapshot is known as "the epoch of recombination". At this point, the early galaxies began to form and light from these galaxies, released from the foggy soup of radiation, was set free to be picked up by modern astronomers with their telescopes.

"Further analysis of Cobe's results will shed light on the identity of the mysterious dark matter that we know contributes most of the mass of the universe," Dr Carlos Frenk, of Durham University, said yesterday. This mystery dark matter is scientists' best guess at explaining why the universe is lumpy.

Astronomers have worked out that, for today's galaxies to have formed, there ought to be far more matter around than they have observed. One of the leading theories to get round this is the Dark Matter theory, which says that about 99 per cent of the matter of the universe is invisible to us. This theory predicts fluctuations in the background radiation of exactly the size Cobe has observed. "Because these had not been seen, the theoreticians were beginning to get worried that they had got it wrong," Professor Rowan-Robinson said.

"If Cobe had found no ripples the theoreticians would have been in disarray; their best shot at understanding how galaxies were formed would have been disproved," he added. "The cold dark matter theory is a very beautiful one which makes very exact predictions about what the size of these fluctuations should be. How big they are depends on how fast they are able to grow. These results are just the size that the theory predicts.People have been looking for this kind of variation since the 1950s."

However, Arnold Wolfendale, the Astronomer Royal, sounded a note of caution. He said the scientific community must examine the results before shouting too loudly about their importance.

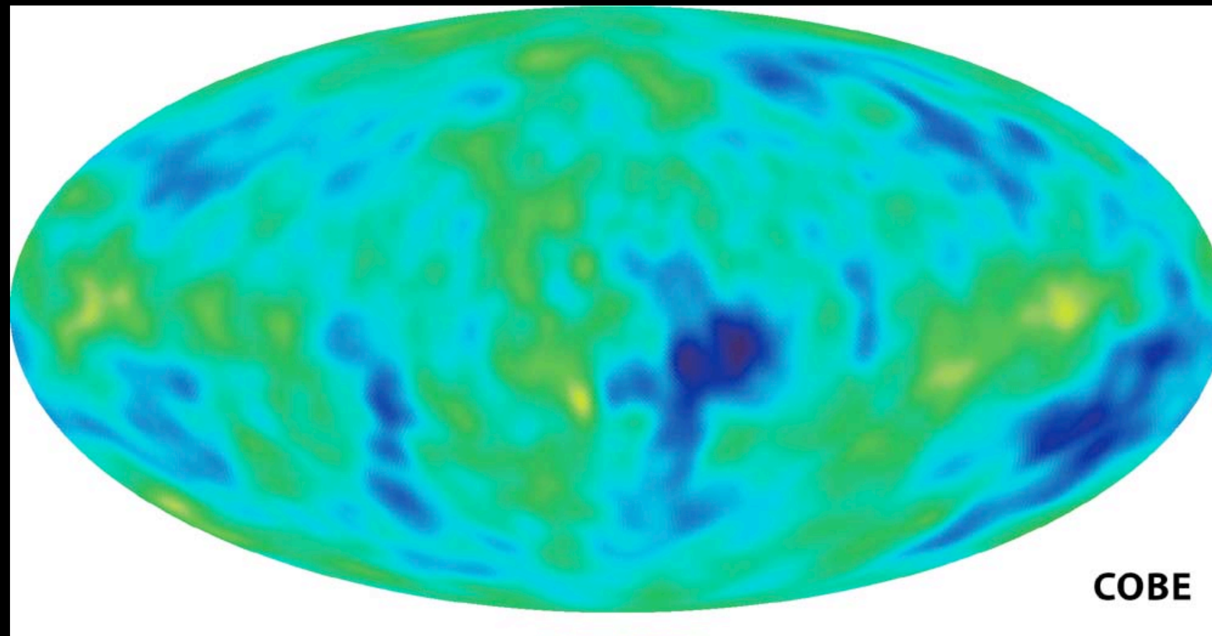
"There is no doubt that, if verified, this is a very important result. Detecting these small fluctuations is very difficult. Another group reported having picked up similar fluctuations last year, then later found they were due to cosmic rays. At the frequencies our colleagues in the US are working at, cosmic rays should not be a problem, but there is dust between the stars which can also produce radiation and make you think it is cosmological."

Martin Rees, Professor of Astrophysics at Cambridge University, said: "We needed equipment sensitive enough to pick up these fluctuations. We can expect in the next year or so there will be other observations from the ground corroborating this."

He said the results opened up a whole new area of astronomy. "Now we have seen them we can start analysing them. We can learn a lot about the history of the universe — what happened when. We might find, for example, that there was a second foggy era after the original fog lifted."

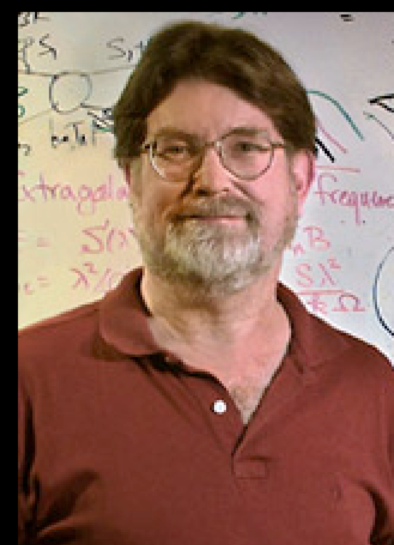
The CMB

1992



George Smoot - Nobel Prize 2006

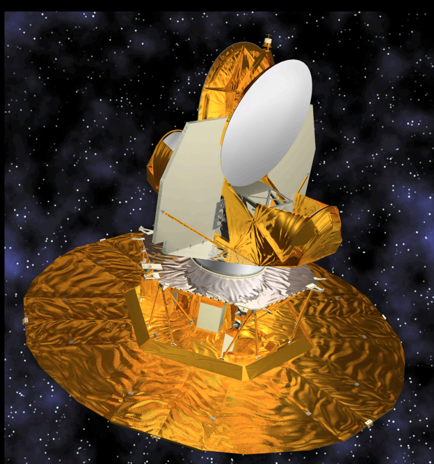
KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

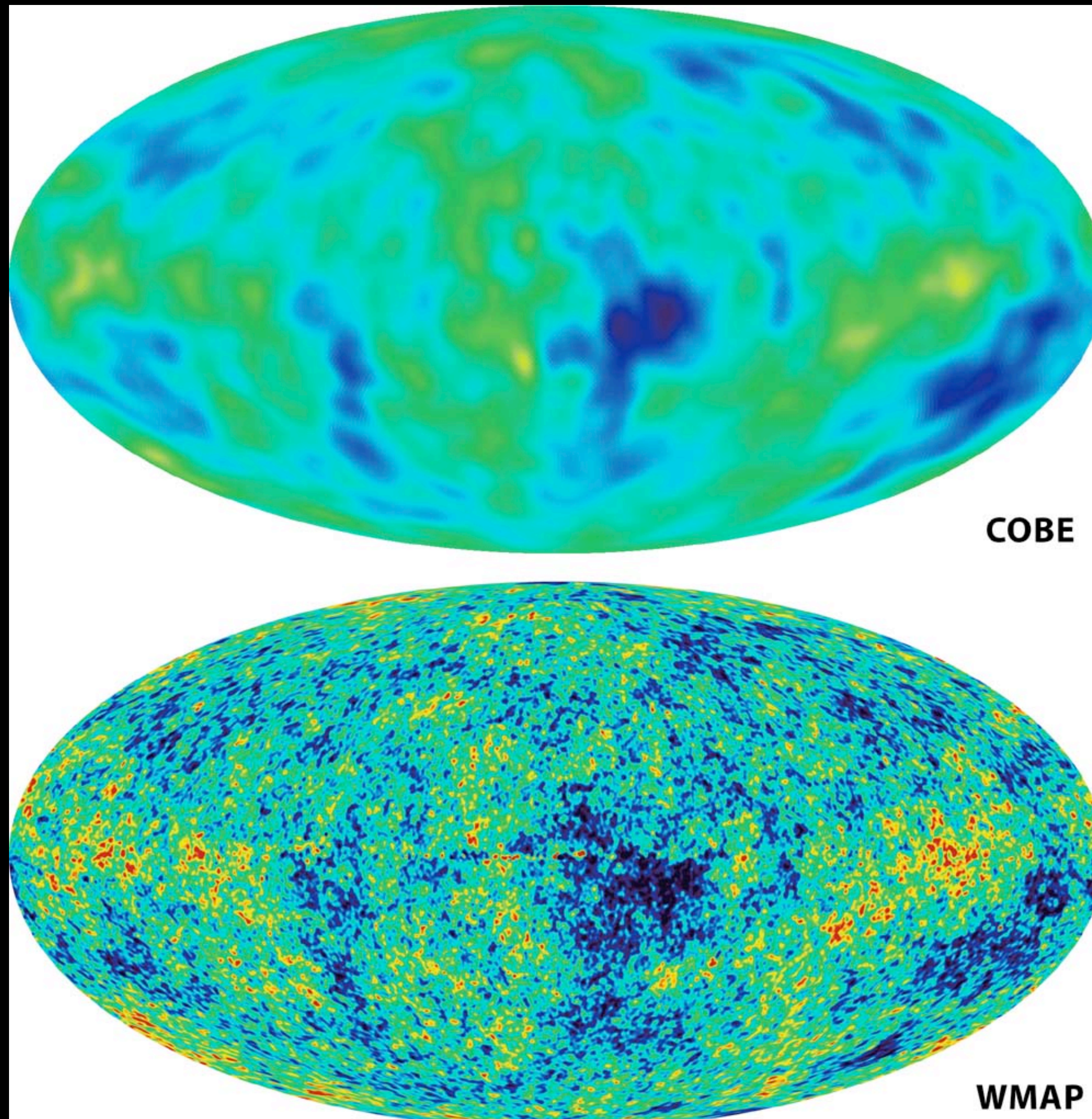


The CMB

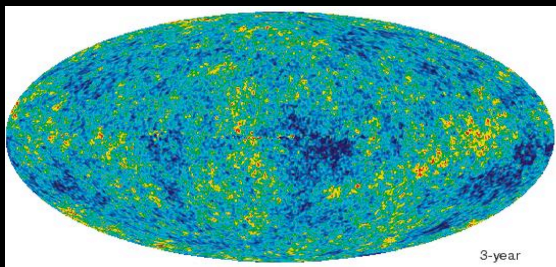
1992

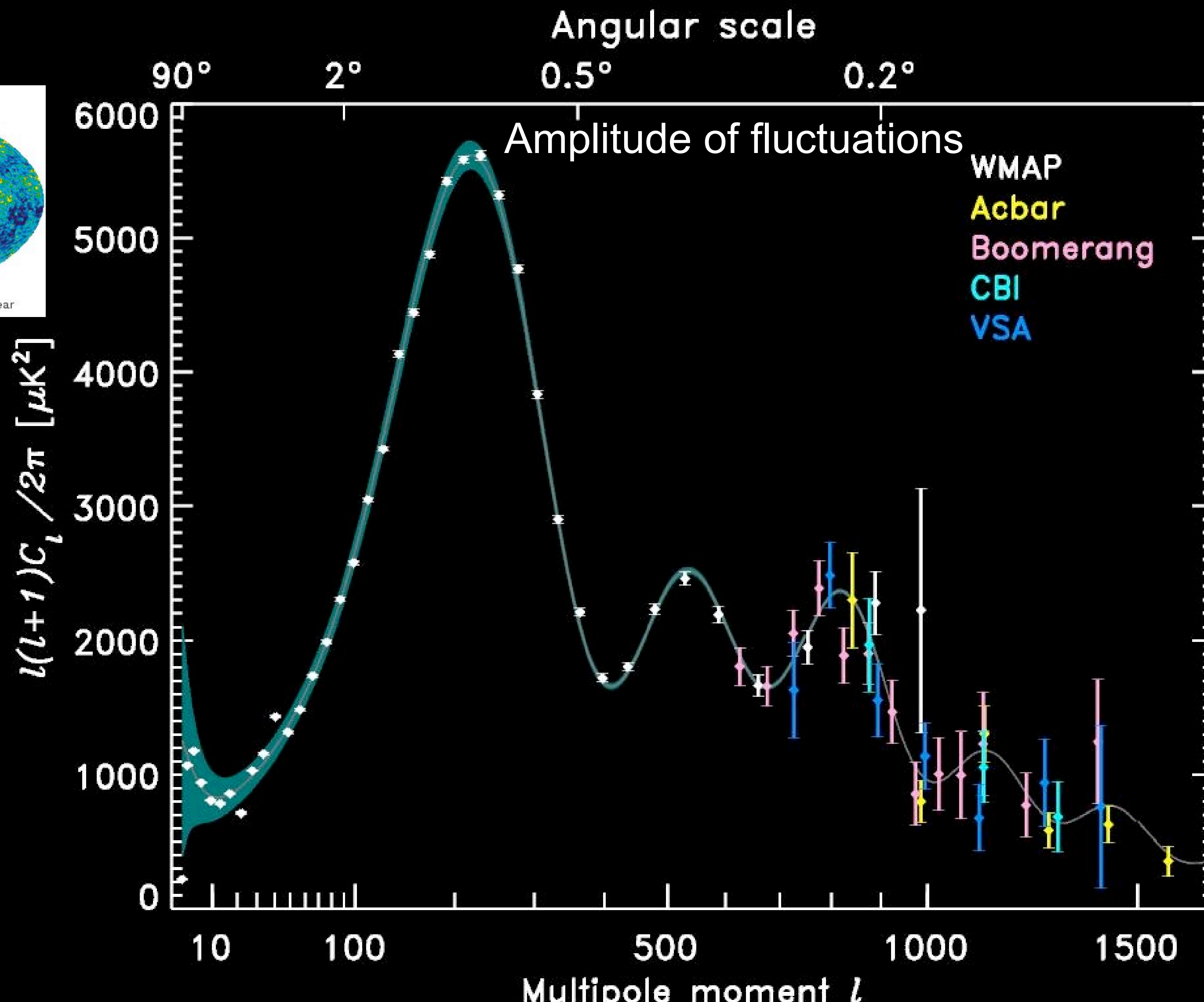
2003





WMAP temp anisotropies in CMB





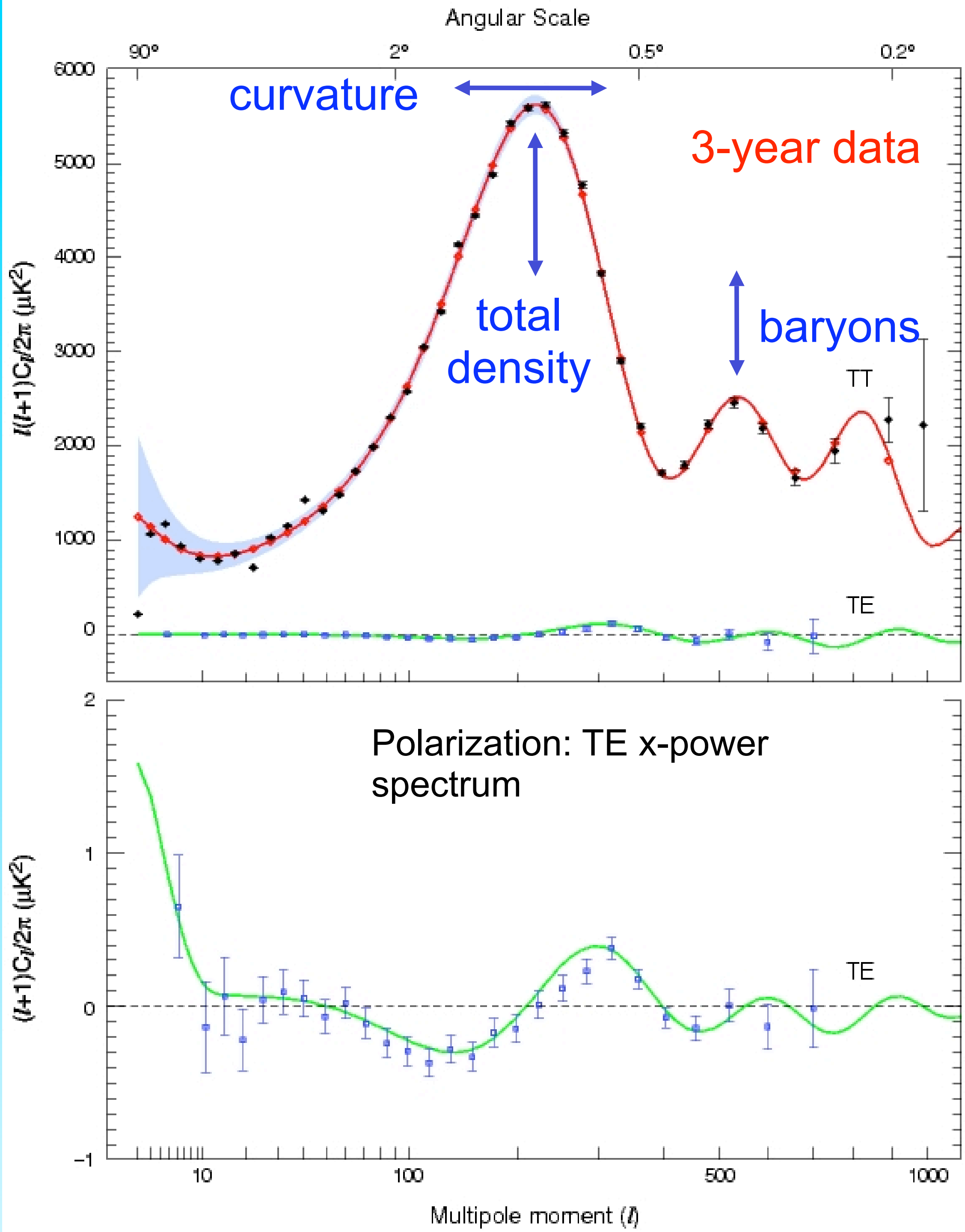
The amplitude of the CMB ripples is exactly as predicted by inflationary cold dark matter theory

The position of the first peak

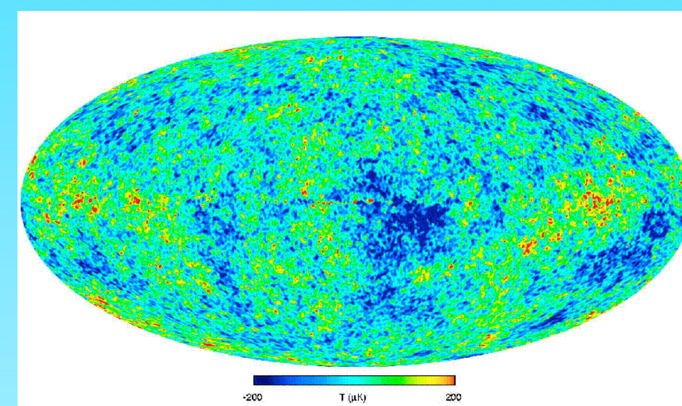
→ FLAT UNIVERSE

Hinshaw etal '06

The Emergence of the Cosmic Initial Conditions



> 105 independent ~ 5s measurements of T are fit by a priori model: LCDM



T-P x-corr →Adiabatic fluctns

Institute for Computational Cosmology

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

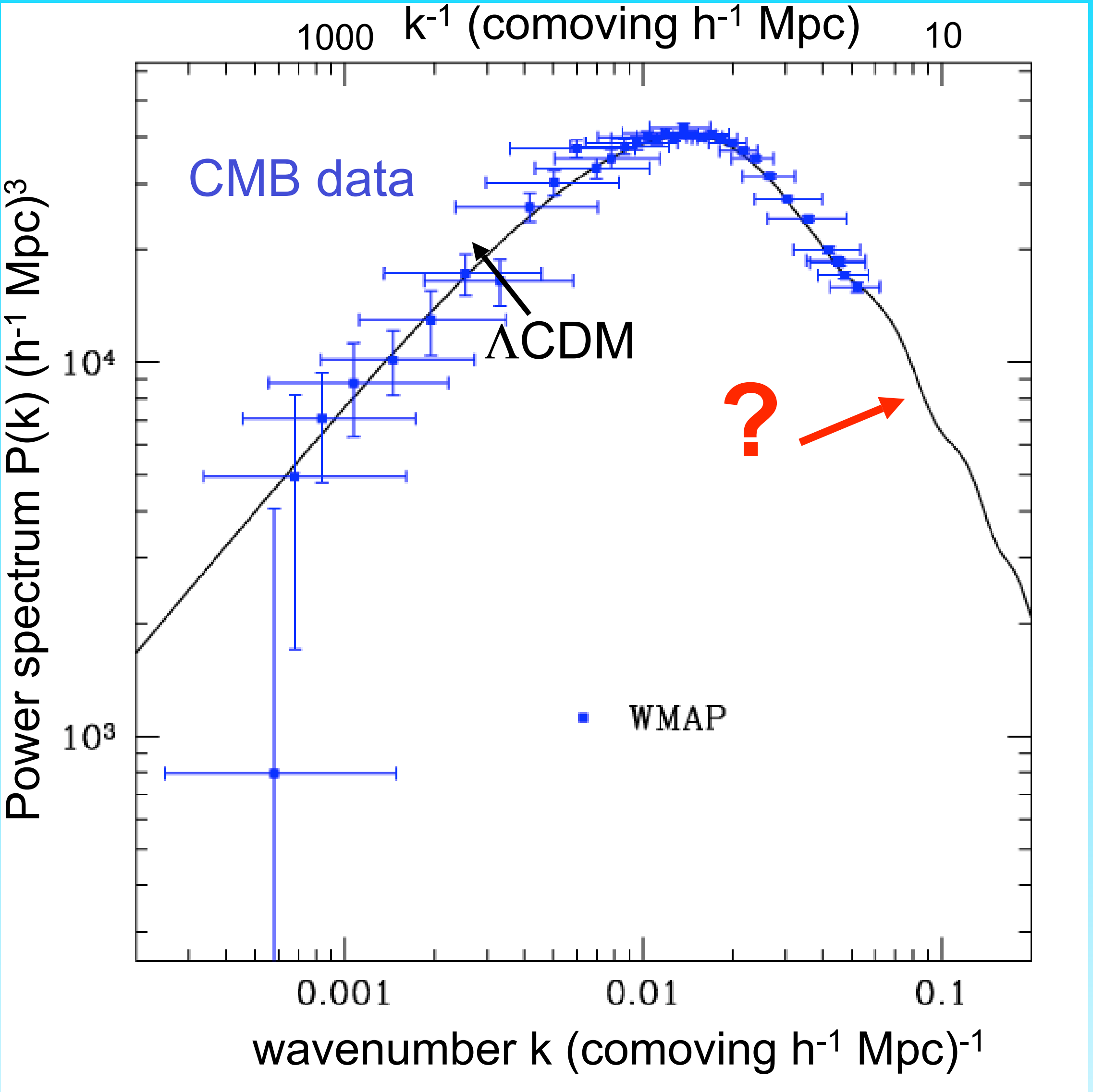
University of Durham

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

CMB:

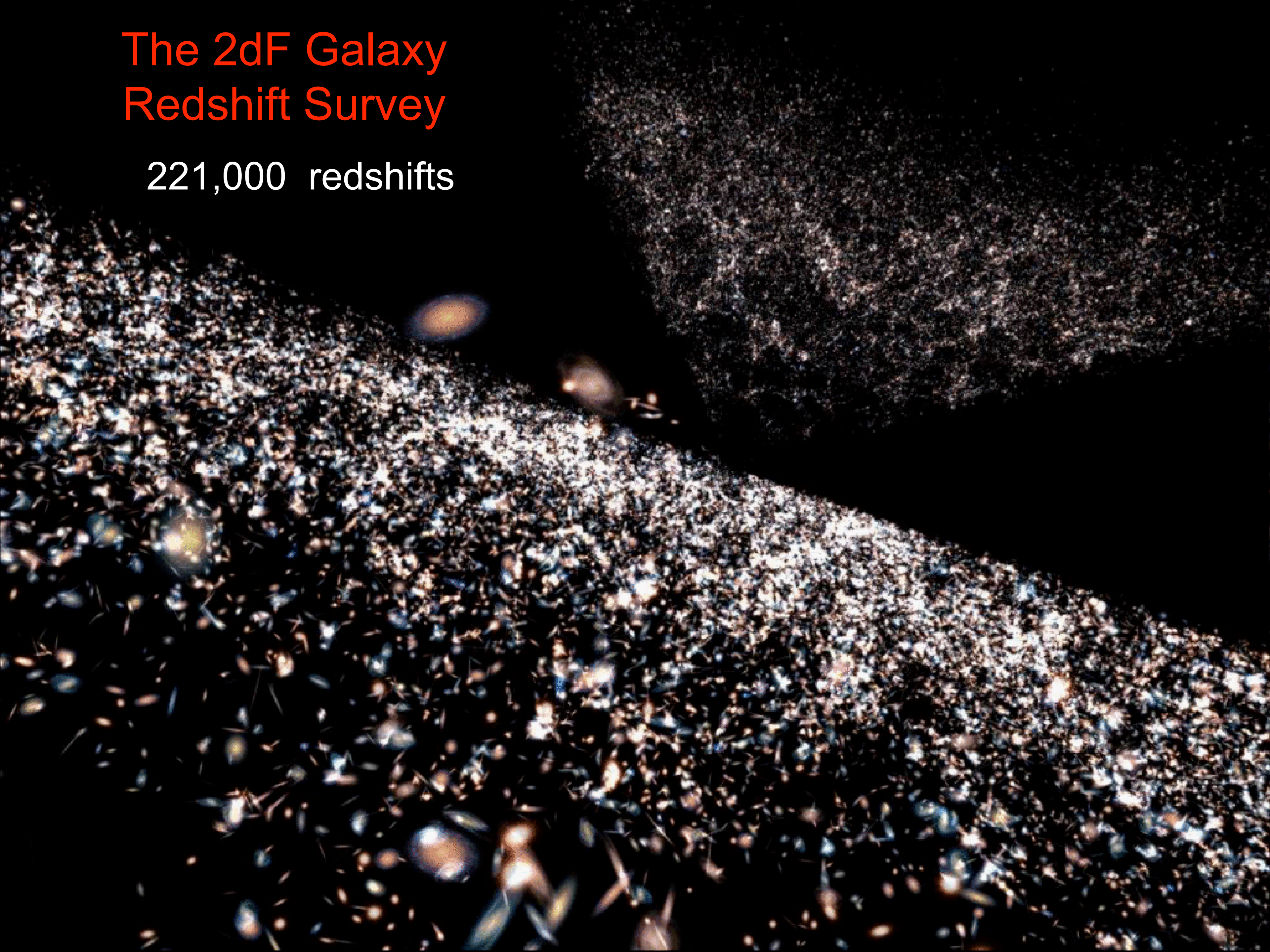
- Convert angular separation to distance (and k) assuming flat geometry
- Extrapolate to z=0 using linear theory

Sanchez et al 06

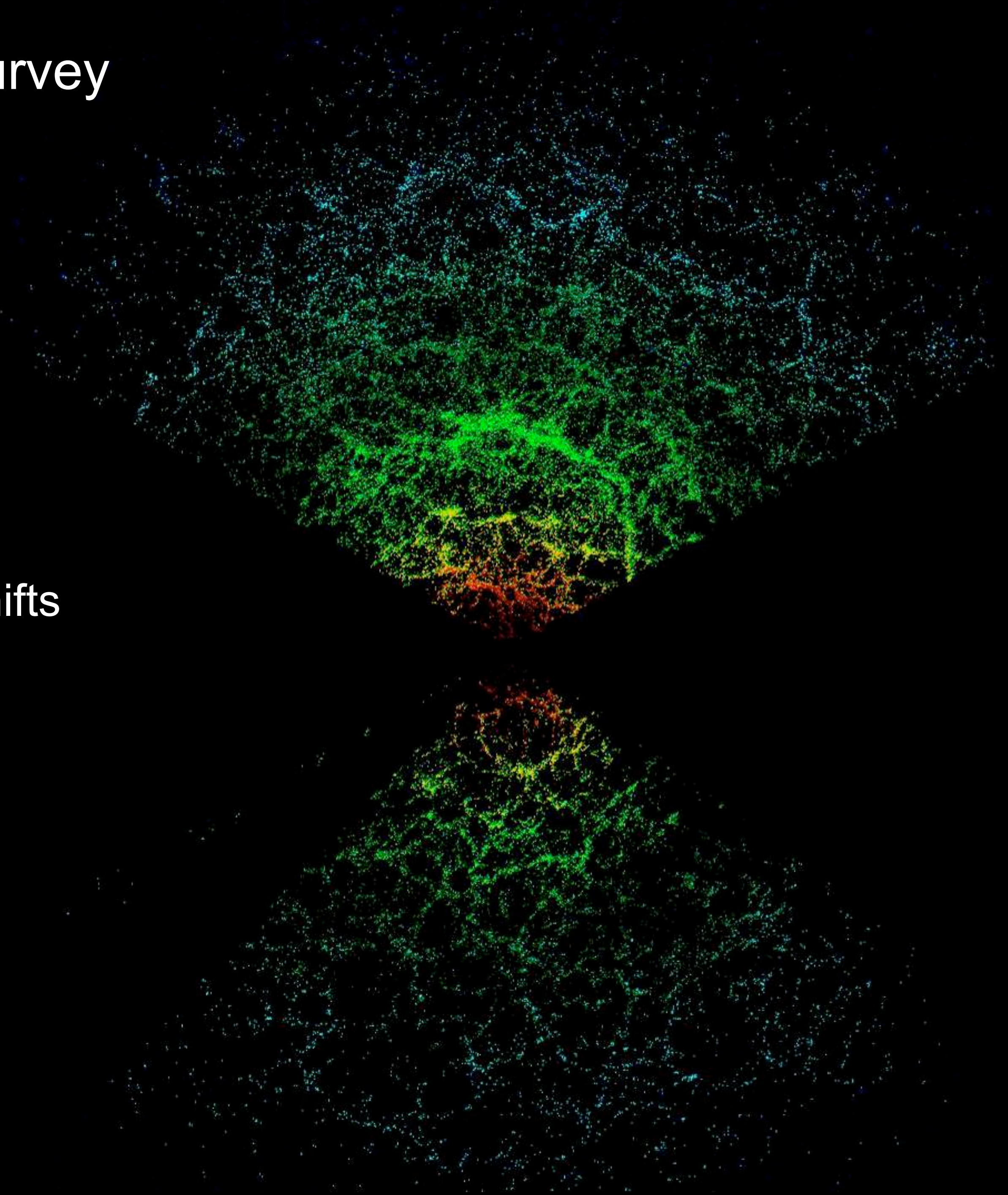


The 2dF Galaxy Redshift Survey

221,000 redshifts



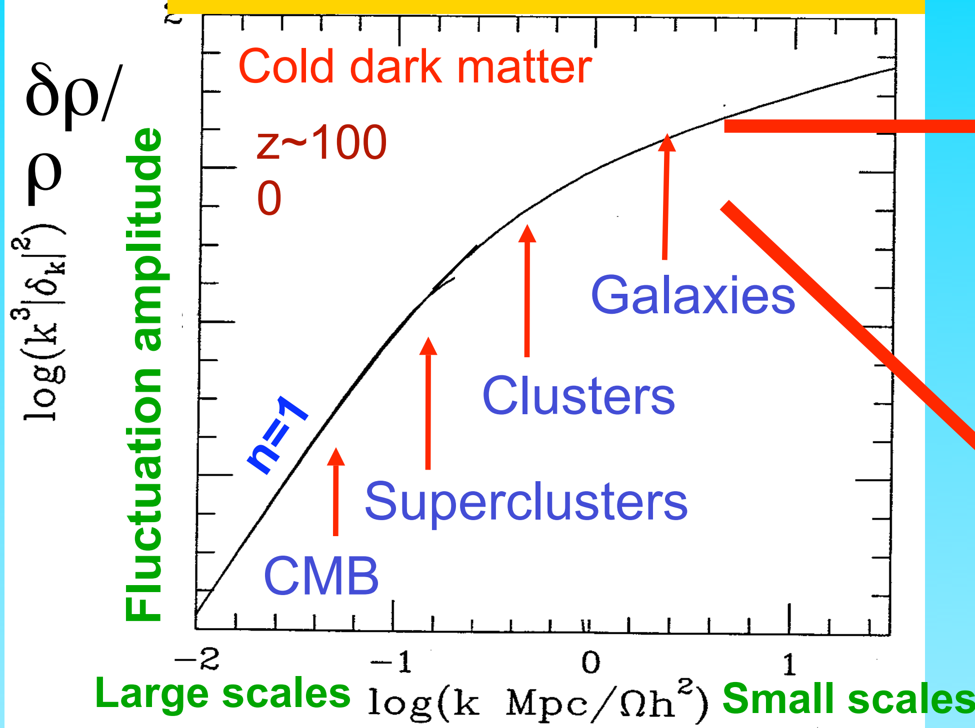
Sloan Digital Sky Survey



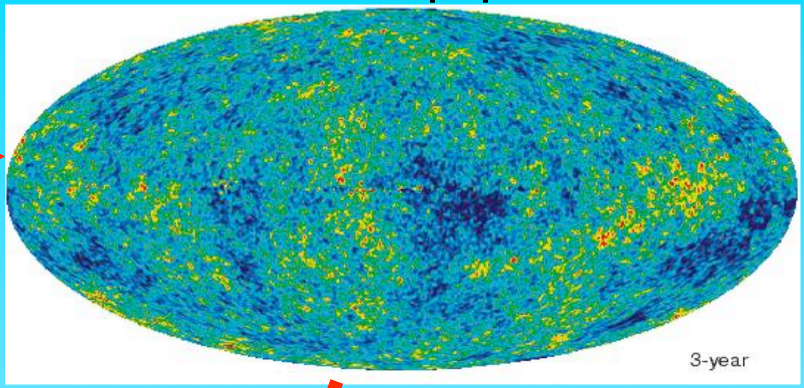
~500,000 galaxy redshifts

Testing the CDM paradigm

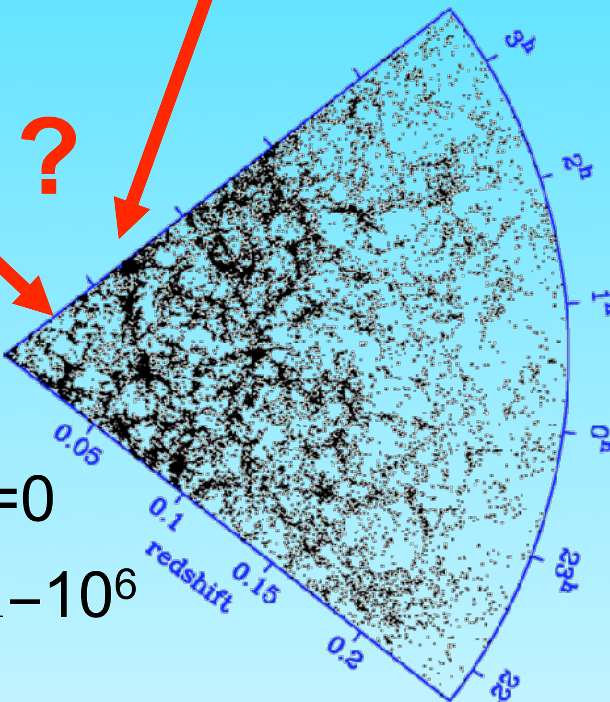
P(k) Initial conditions : ΛCDM



z=1000 $\delta\rho/\rho \sim 10^{-5}$



?



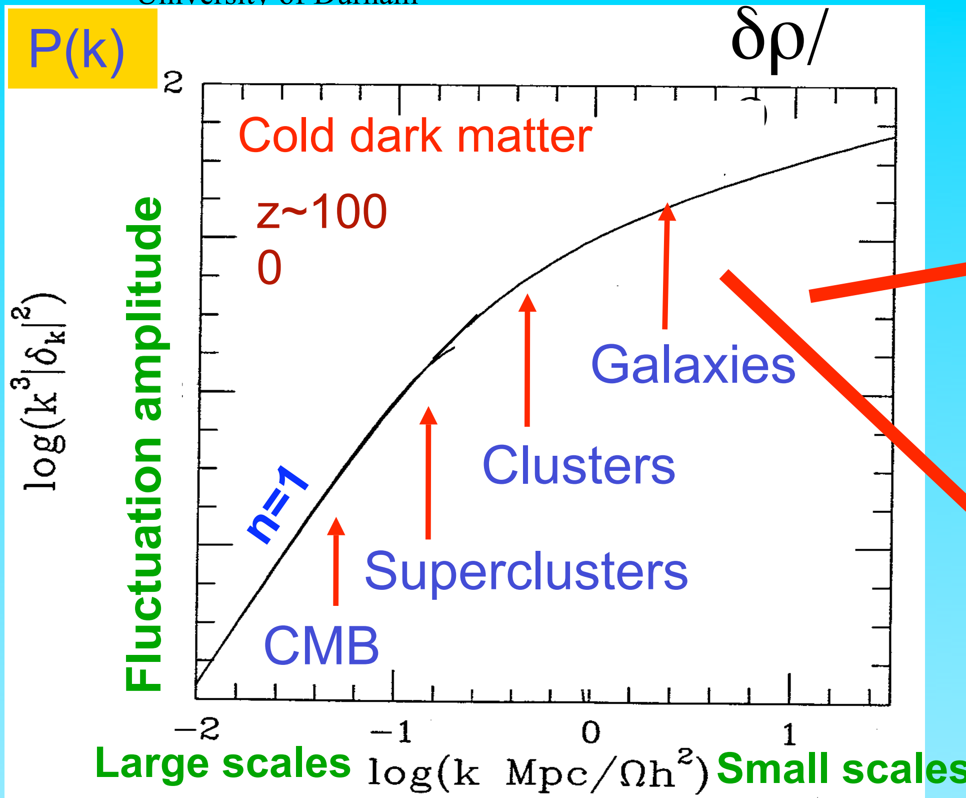
z=0

$\delta\rho/\rho \sim 1\text{–}10^6$

The galaxy distribution evolves from by fluctuationns seen in CMB by gravitational amplification.

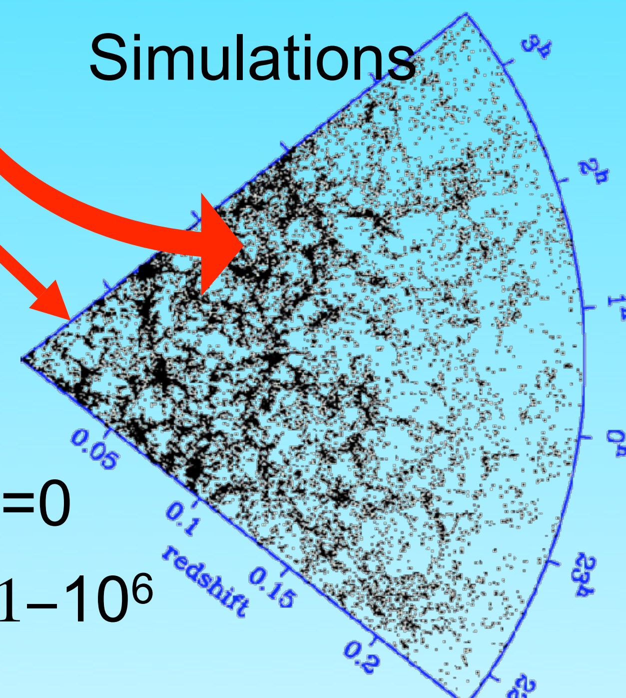
Testing the CDM paradigm

University of Durham



"Cosmology machine"

Simulations



Initial conditions : ΛCDM

Basic DM physics simple: structure grows primarily by gravity

z=0

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

→ N-body simulations

Institute for Computational Cosmology

dalla Vechia,
Jenkins & Frenk

Comoving
coordinates

University of Durham

The Millennium simulation

UK, Germany, Canada, US collaboration

Simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

Pictures and movies available at:

www.durham.ac.uk/virgo

Nature, June/05

Cosmological N-body simulation

- 10 billion particles
- 500 h^{-1} Mpc box
- $m_p = 8\times10^8\, h^{-1}\, M_o$
- $\Omega = 1$; $\Omega_m = 0.25$; $\Omega_b = 0.045$; $h = 0.73$; $n = 1$; $\sigma_8 = 0.9$
- 20×10^6 gals brighter than LMC

Carried out at Garching using L-Gadget by V. Springel

(27 Tbytes of data)

Institute for Computational Cosmology

Virgo consortium for supercomputer simulations

University of Durham

Core members and associates

- Carlos Frenk – ICC, Durham (P.I.)
- Adrian Jenkins – ICC, Durham
- Tom Theuns – ICC, Durham
- Gao Laing – ICC, Durham
- Simon White – Max Plank Institut für Astrophysik (co-P.I.)
- Volker Springel – Max Plank Institut für Astrophysik
- Frazer Pearce – Nottingham
- Naoki Yoshida – Tokyo
- Peter Thomas – Sussex
- Hugh Couchman – McMaster
- John Peacock – Edinburgh
- George Efstathiou – Cambridge
- Joerg Colberg – Pittsburgh
- Scott Kay – Oxford
- Rob Thacker – McGill
- Julio Navarro – Victoria
- Gus Evrard – Michigan
- Joop Schaye – Leiden

Simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

Pictures and movies available at:

www.durham.ac.uk/virgo

Virgo junior associates

The Millennium simulation

University of Durham

Cosmological N-body simulation

- 10 billion particles
- 500 h^{-1} Mpc box
- $m_p = 8\times10^8\, h^{-1}\, M_o$
- $\Omega = 1$; $\Omega_m = 0.25$; $\Omega_b = 0.045$; $h = 0.73$; $n = 1$; $\sigma_8 = 0.9$
- 20×10^6 gals brighter than LMC

Carried out at Garching using L-Gadget by V. Springel

(27 Tbytes of data)

UK, Germany, Canada, US collaboration

Simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

Pictures and movies available at:

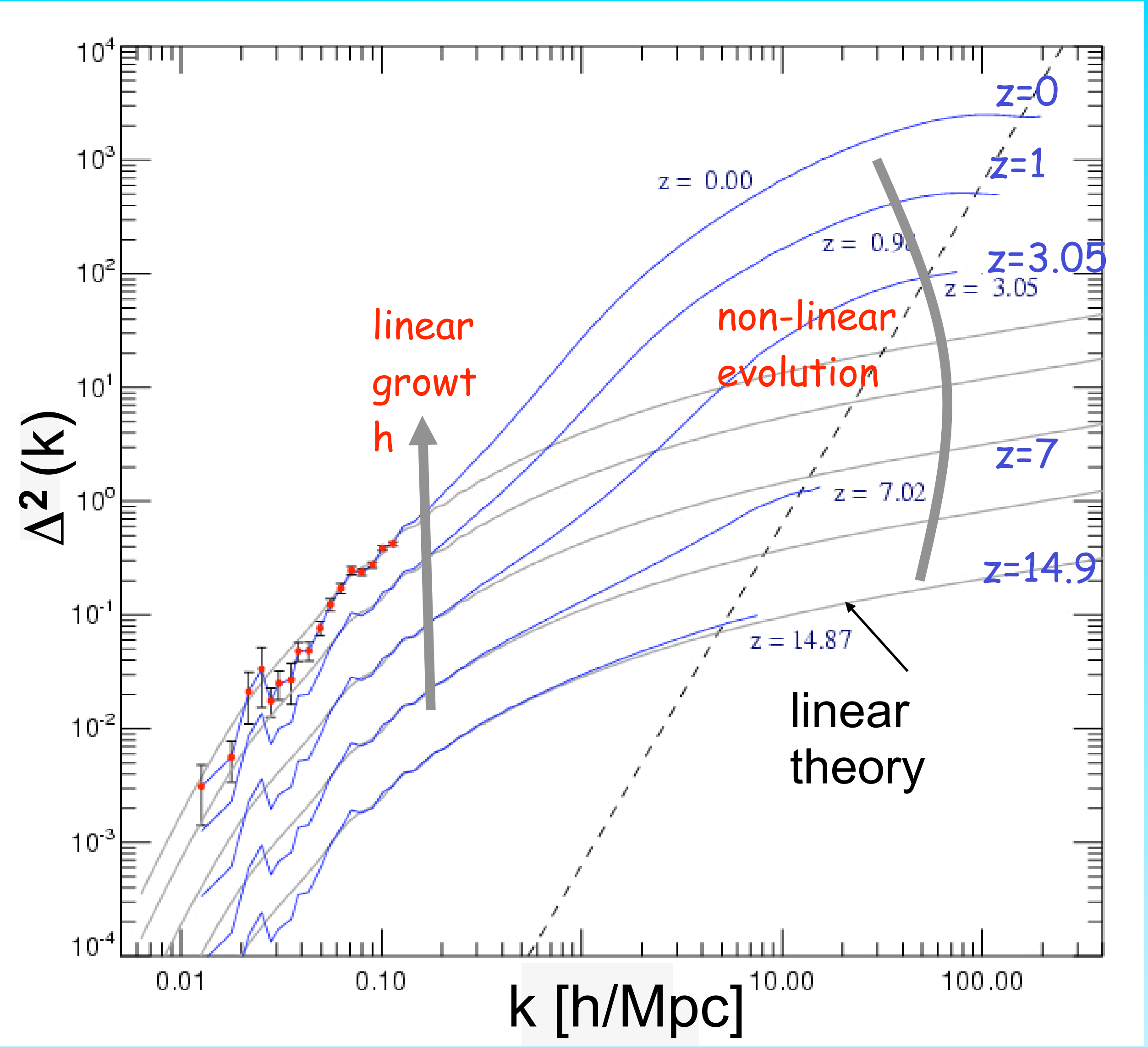
www.durham.ac.uk/virgo

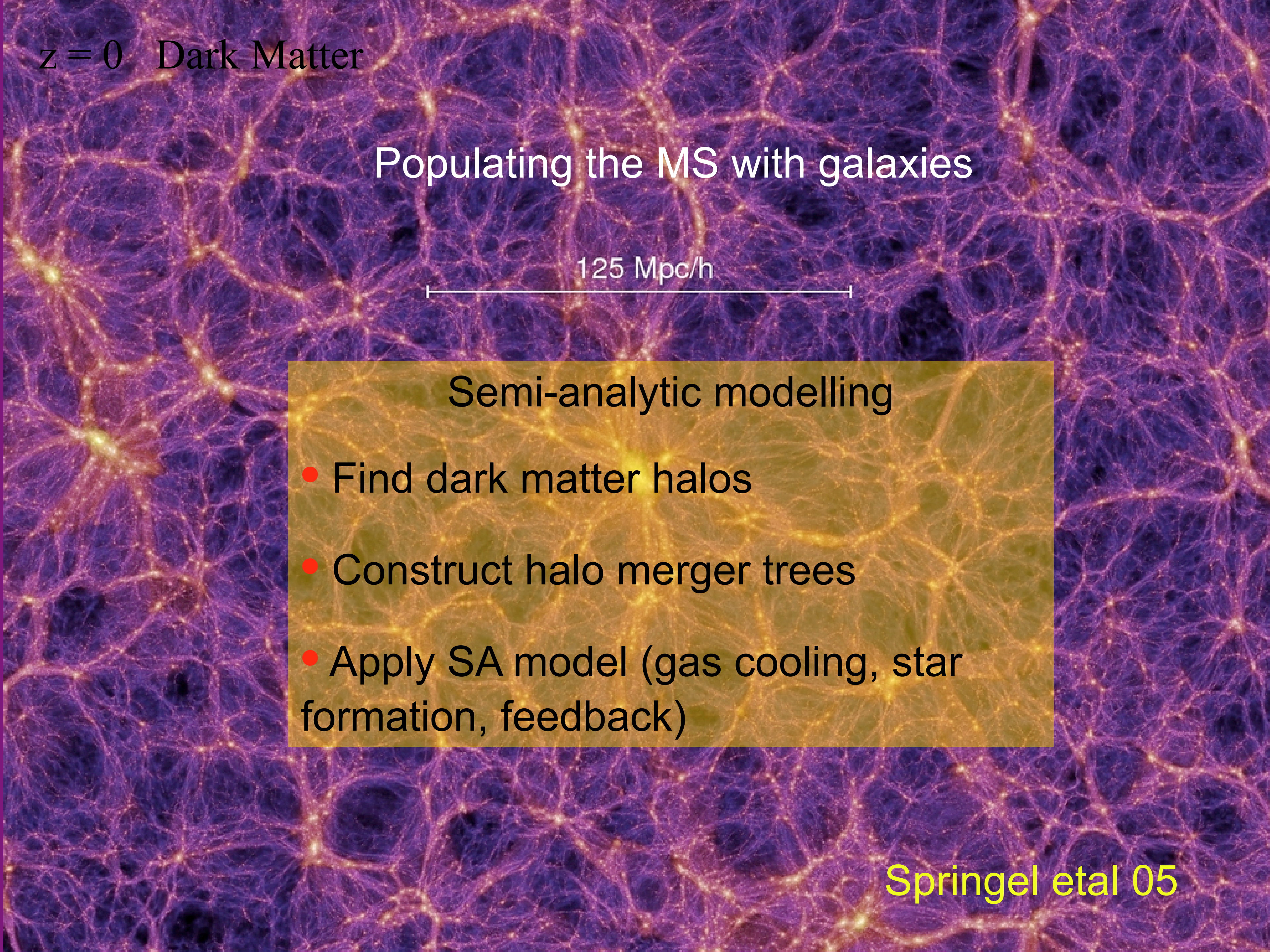
Nature, June/05

The mass power spectrum

University of Durham

The non-linear mass power spectrum is accurately determined by the Millennium simulation over large range of scales



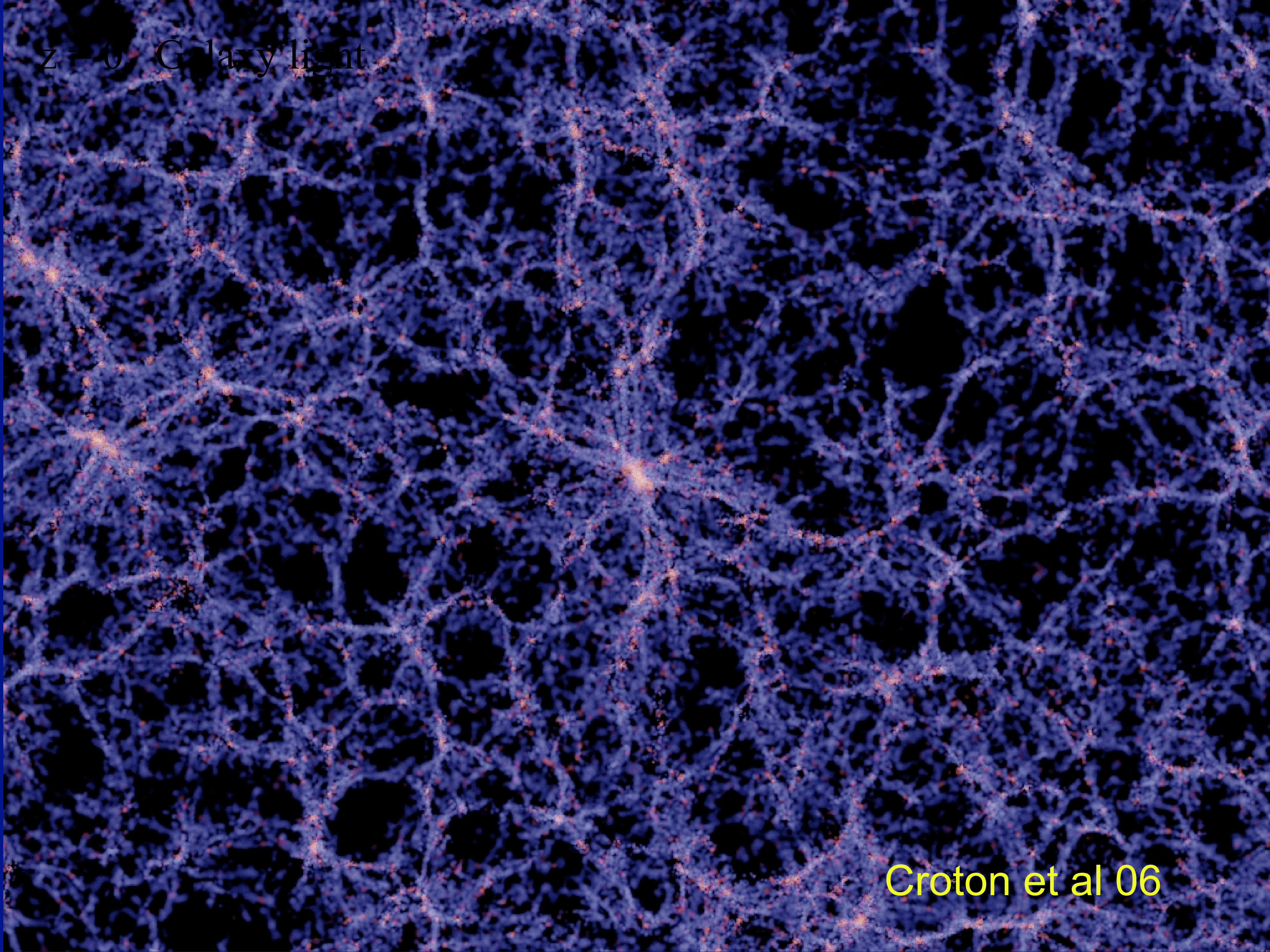


Populating the MS with galaxies

Semi-analytic modelling

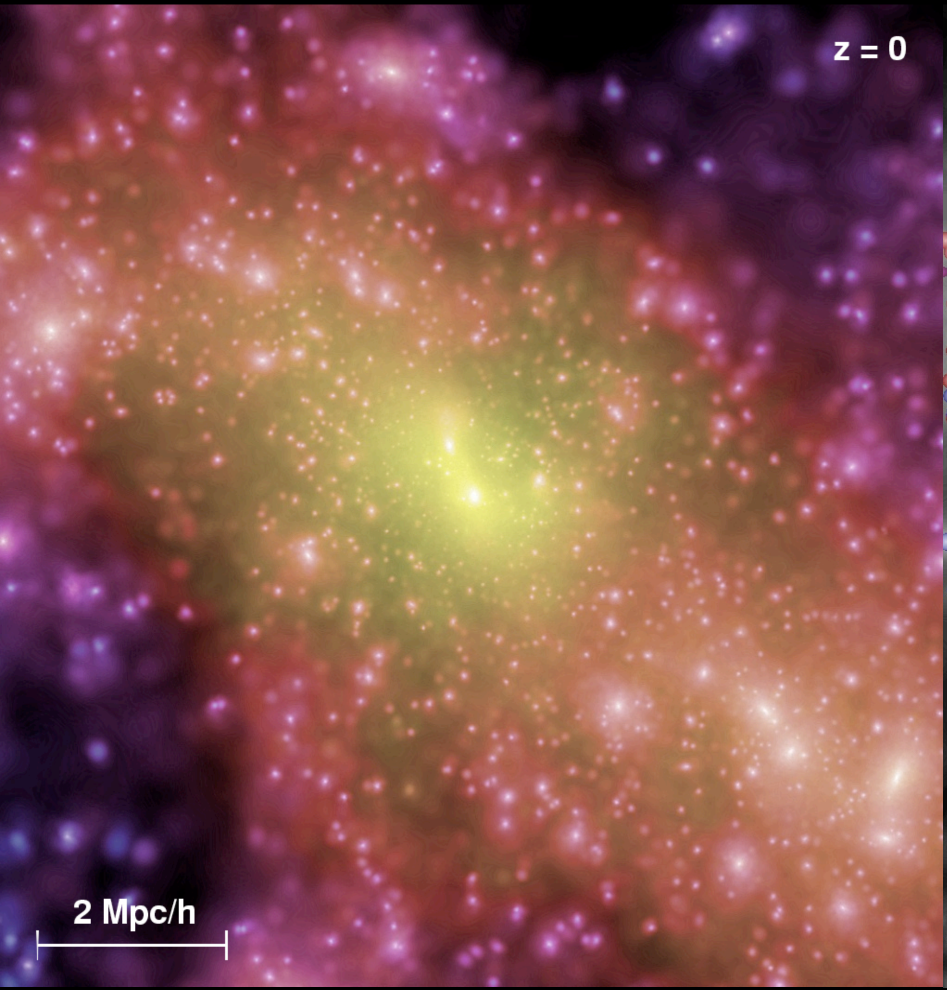
- Find dark matter halos
- Construct halo merger trees
- Apply SA model (gas cooling, star formation, feedback)

Springel etal 05

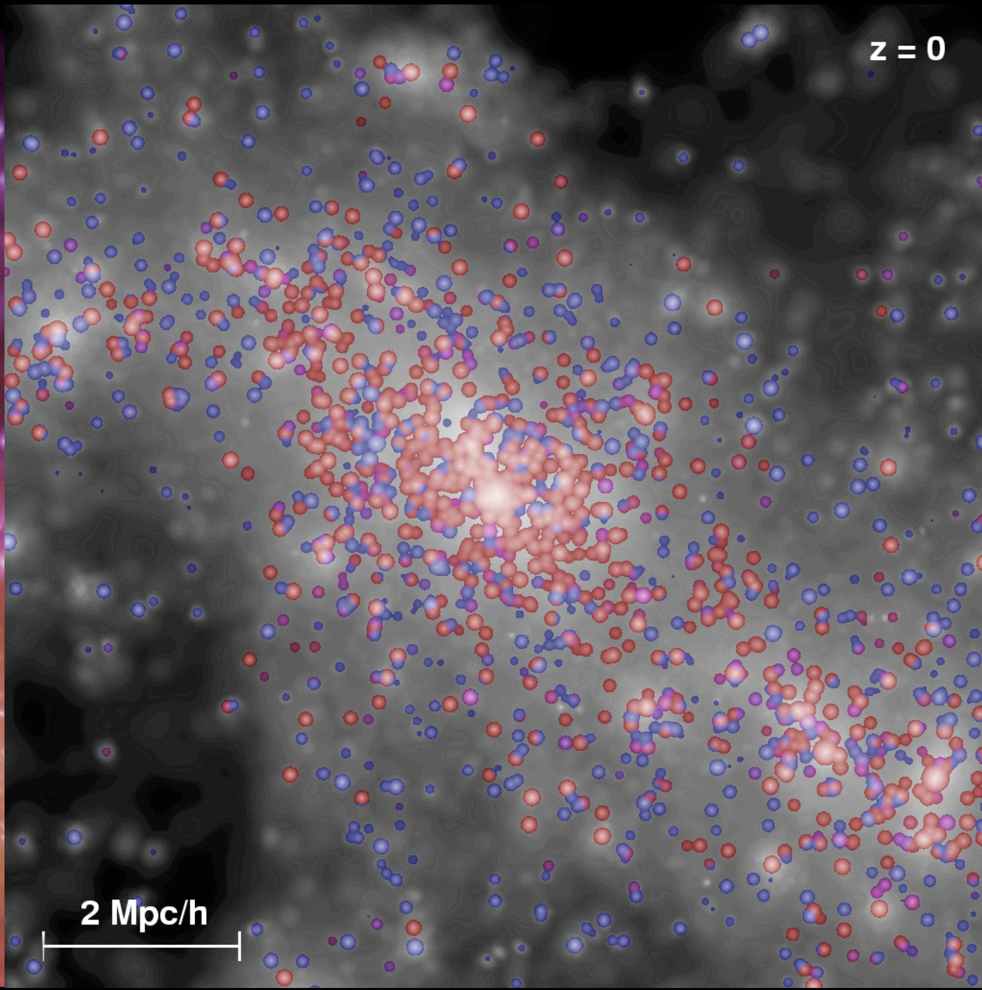

z = 0 Galaxy light
Croton et al 06

$10^{14}M_o$

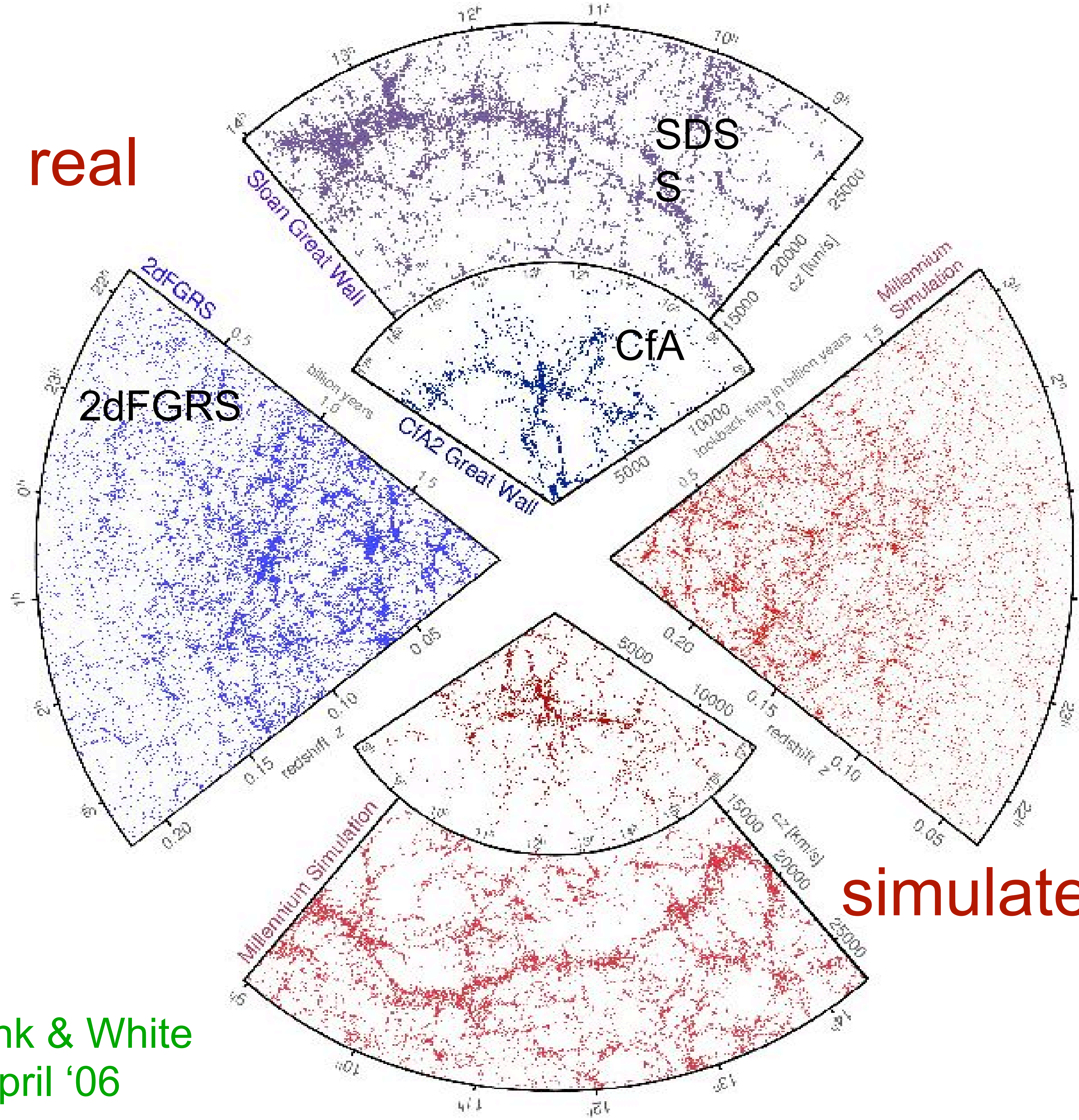
Dark matter



Galaxies



real

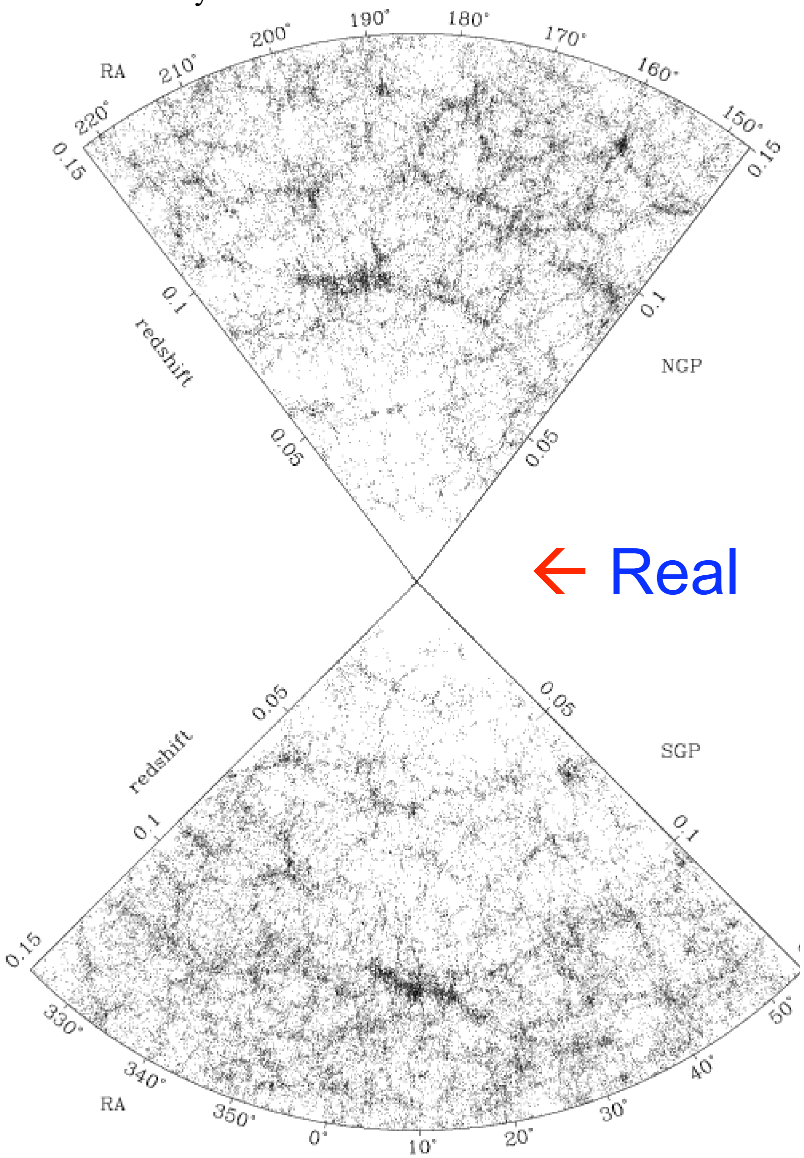


simulated

Springel, Frenk & White
Nature, April '06

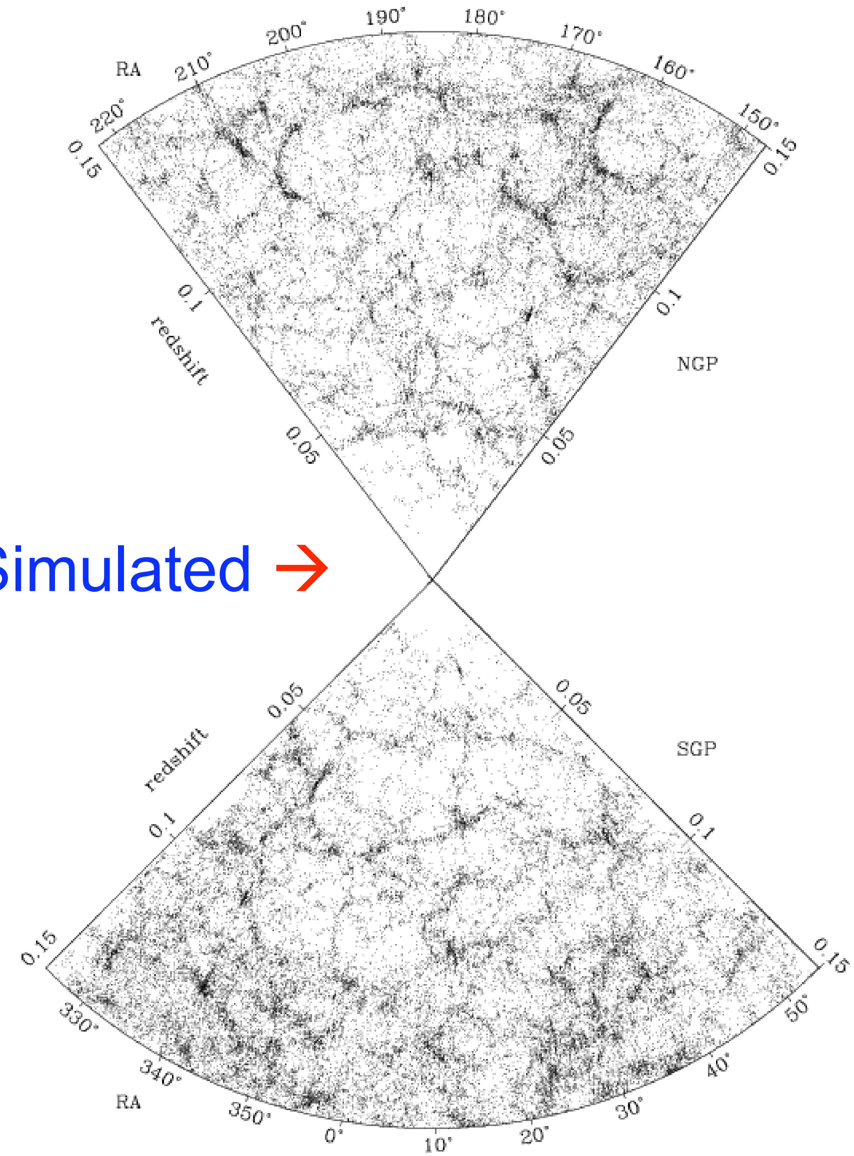
University of Durham

Real and simulated 2dF galaxy survey



← Real

Simulated →

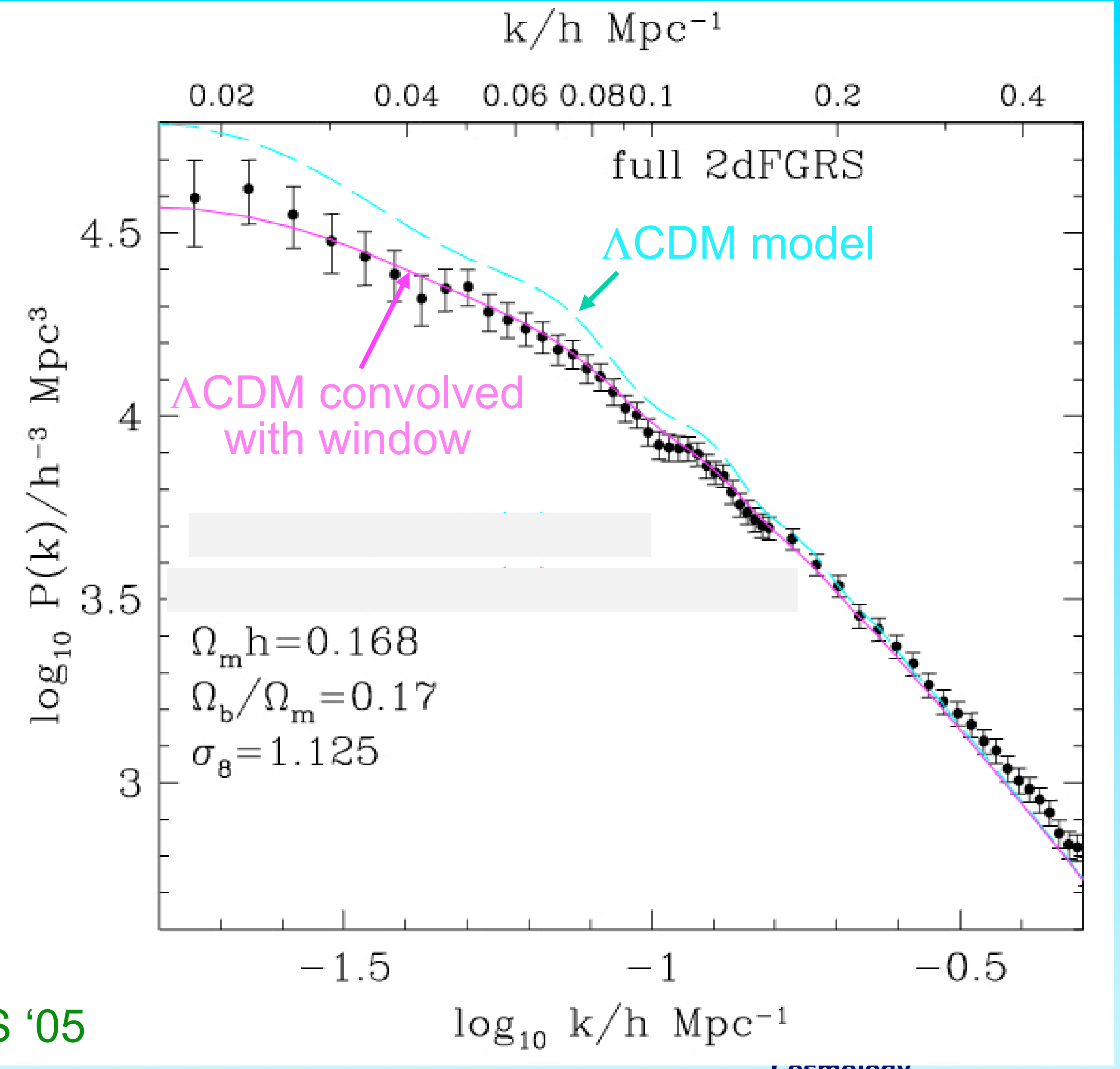


Institute for Computational Cosmology

University of Durham

The final 2dFGRS power spectrum

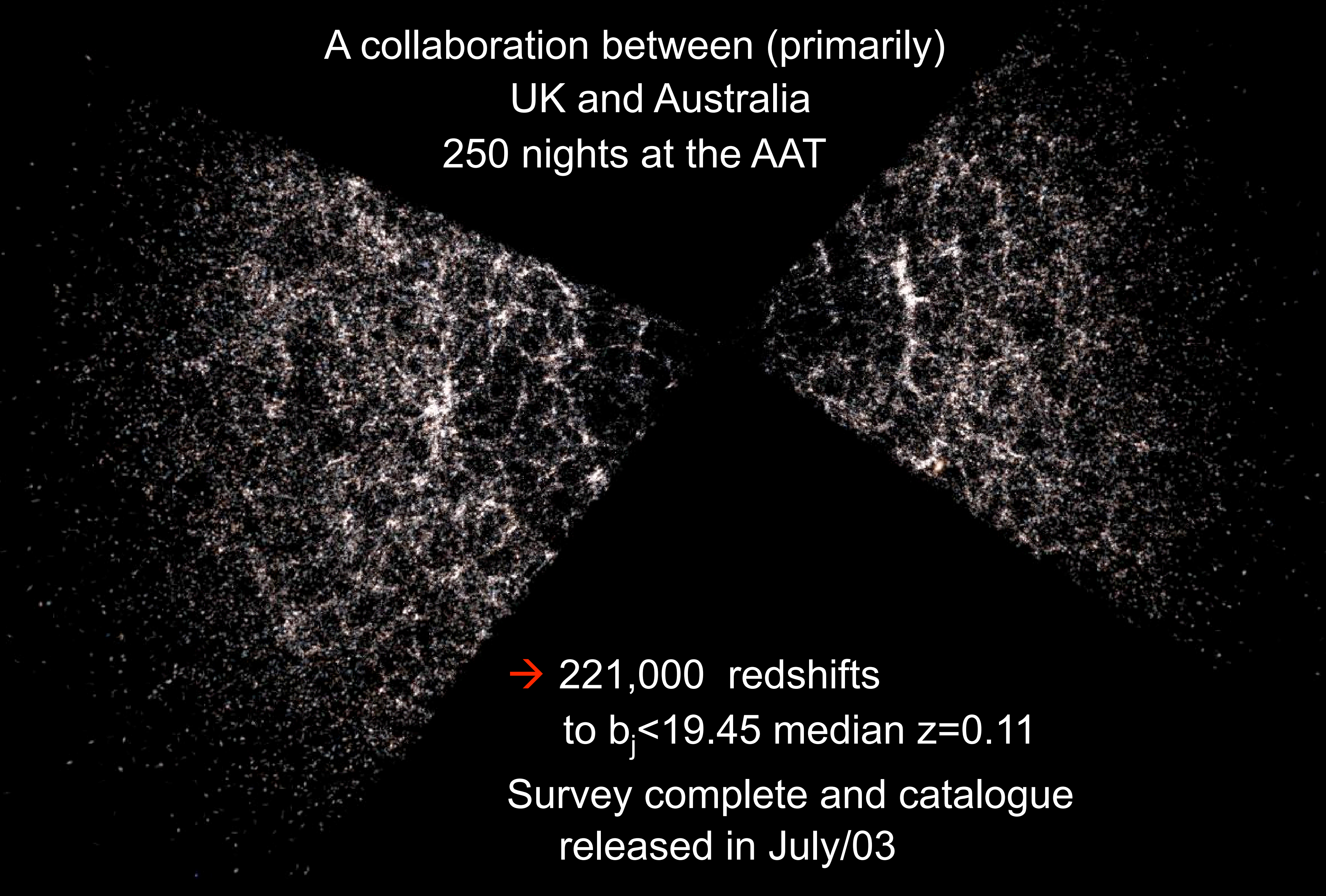
2dFGRS P(k) well fit by ΛCDM model convolved with window function



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

Cosmology

The 2dF Galaxy Redshift Survey

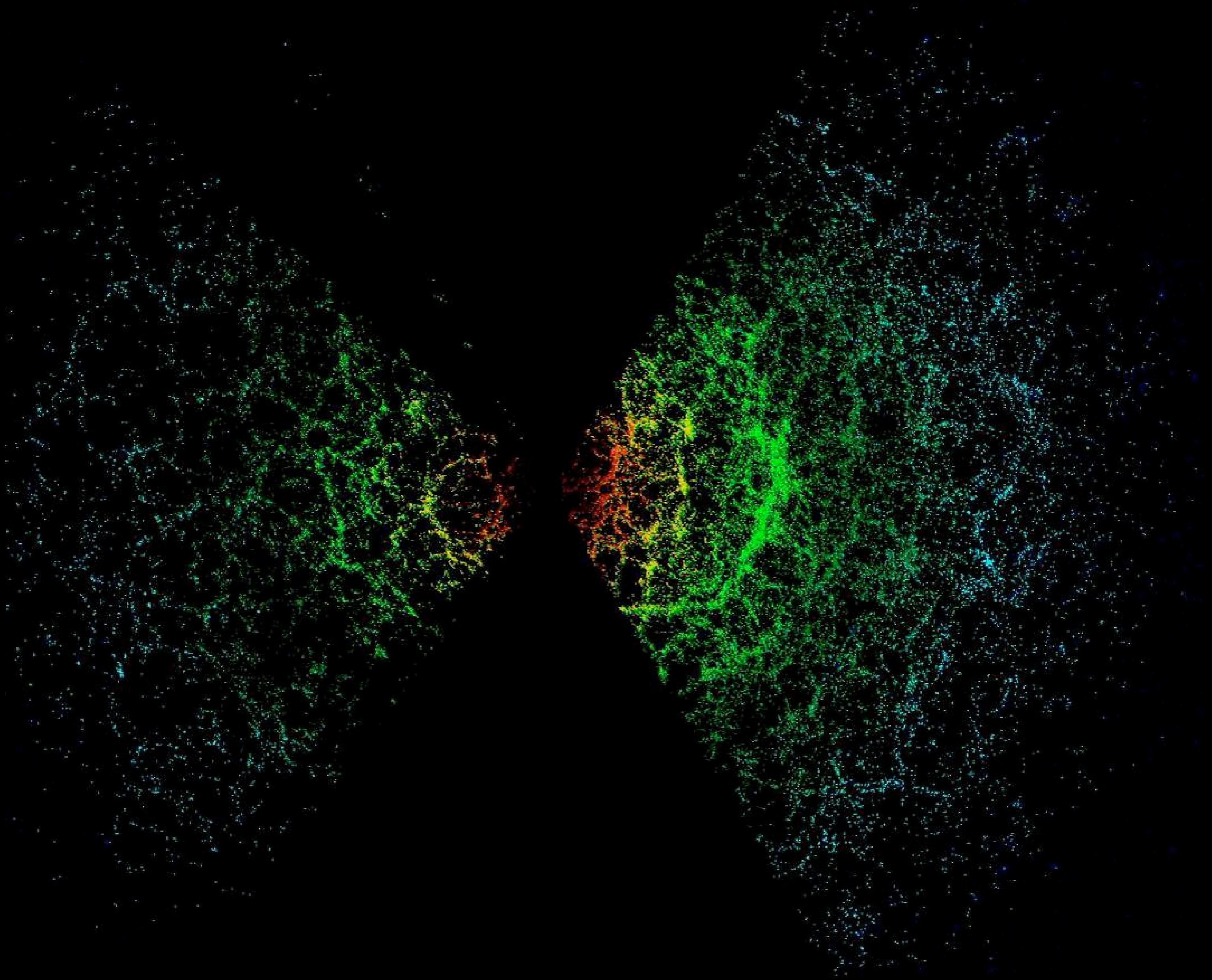


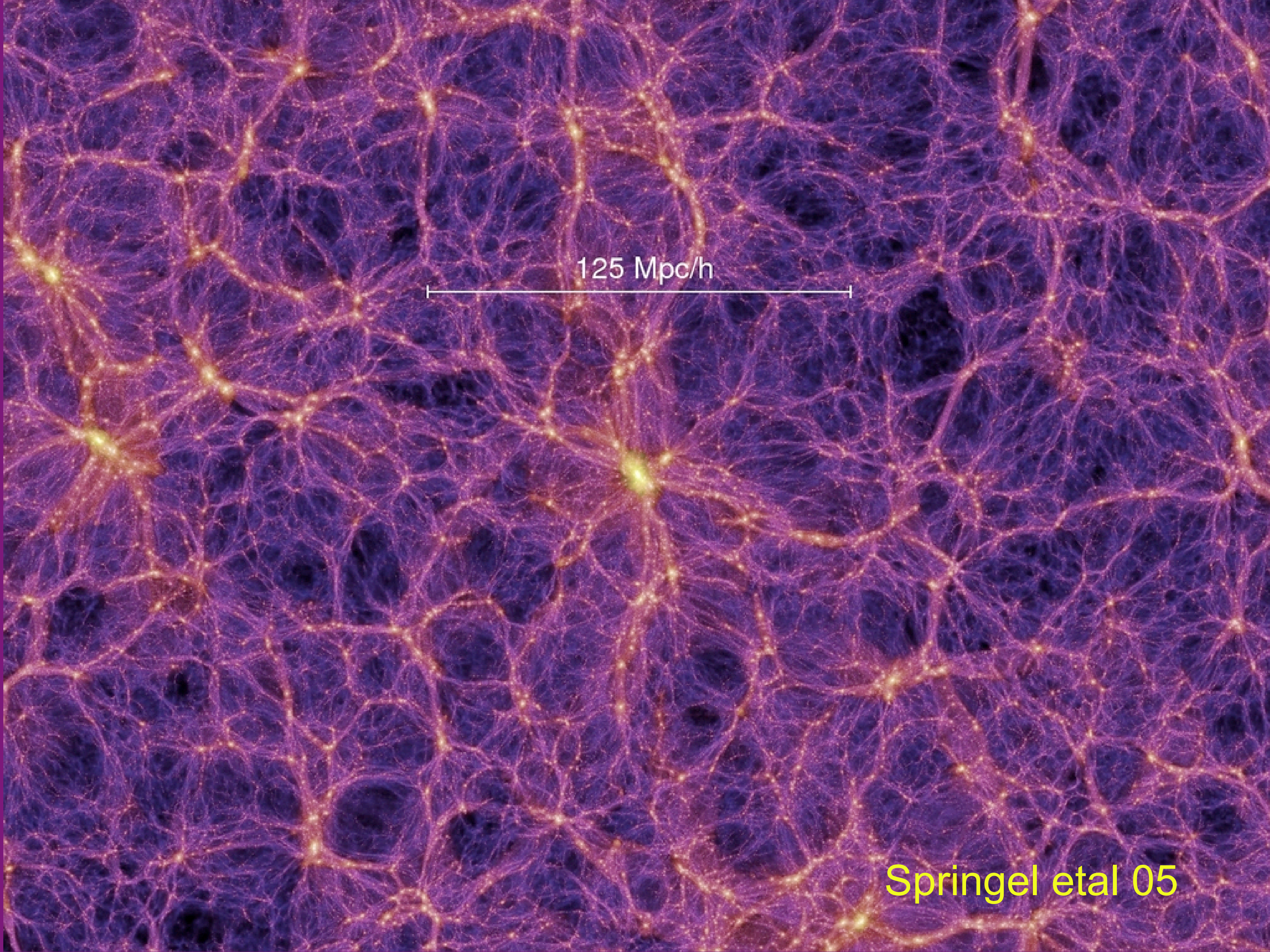
A collaboration between (primarily)
UK and Australia
250 nights at the AAT

→ 221,000 redshifts
to b_j<19.45 median z=0.11

Survey complete and catalogue released in July/03

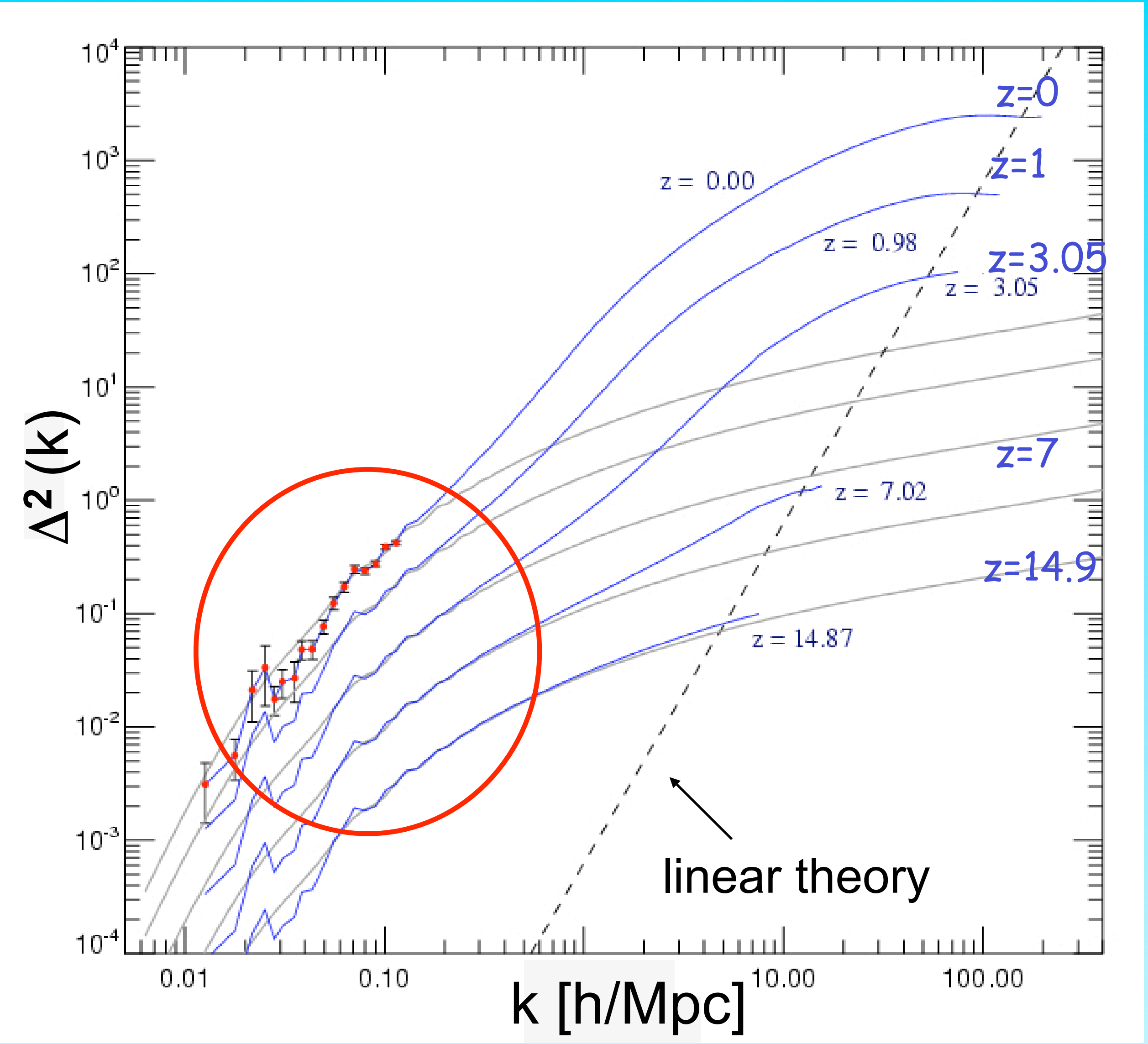
Sloan Digital Sky Survey ~500,000 galaxy redshifts



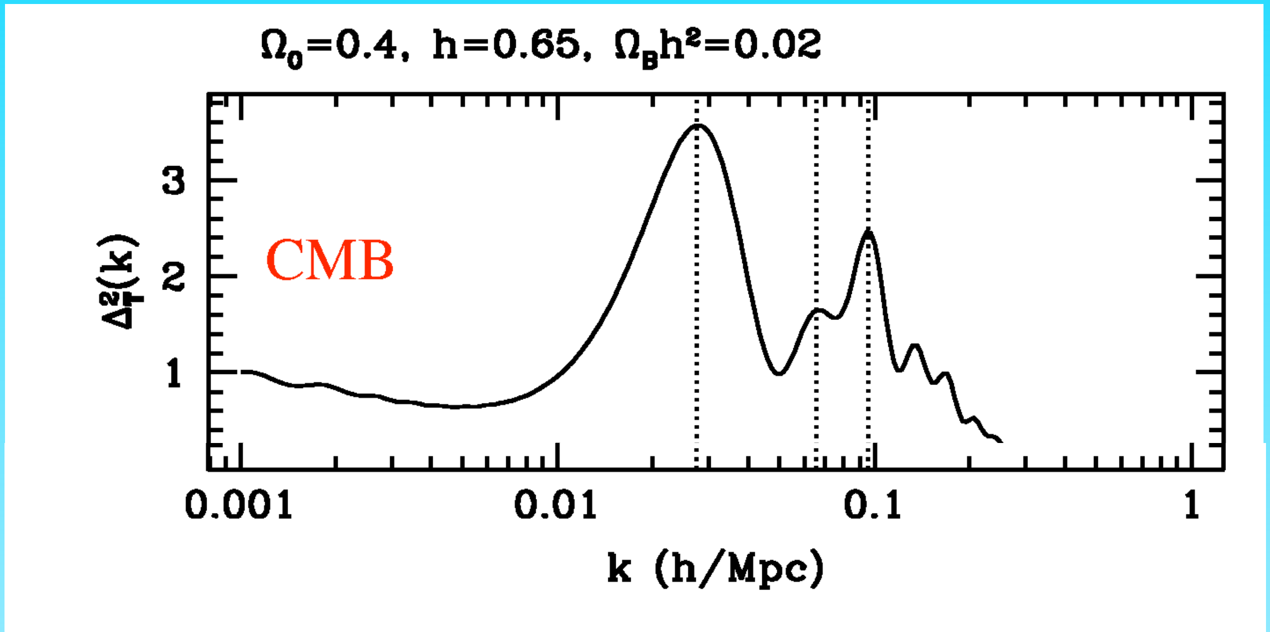

125 Mpc/h
Springel etal 05

The mass power spectrum

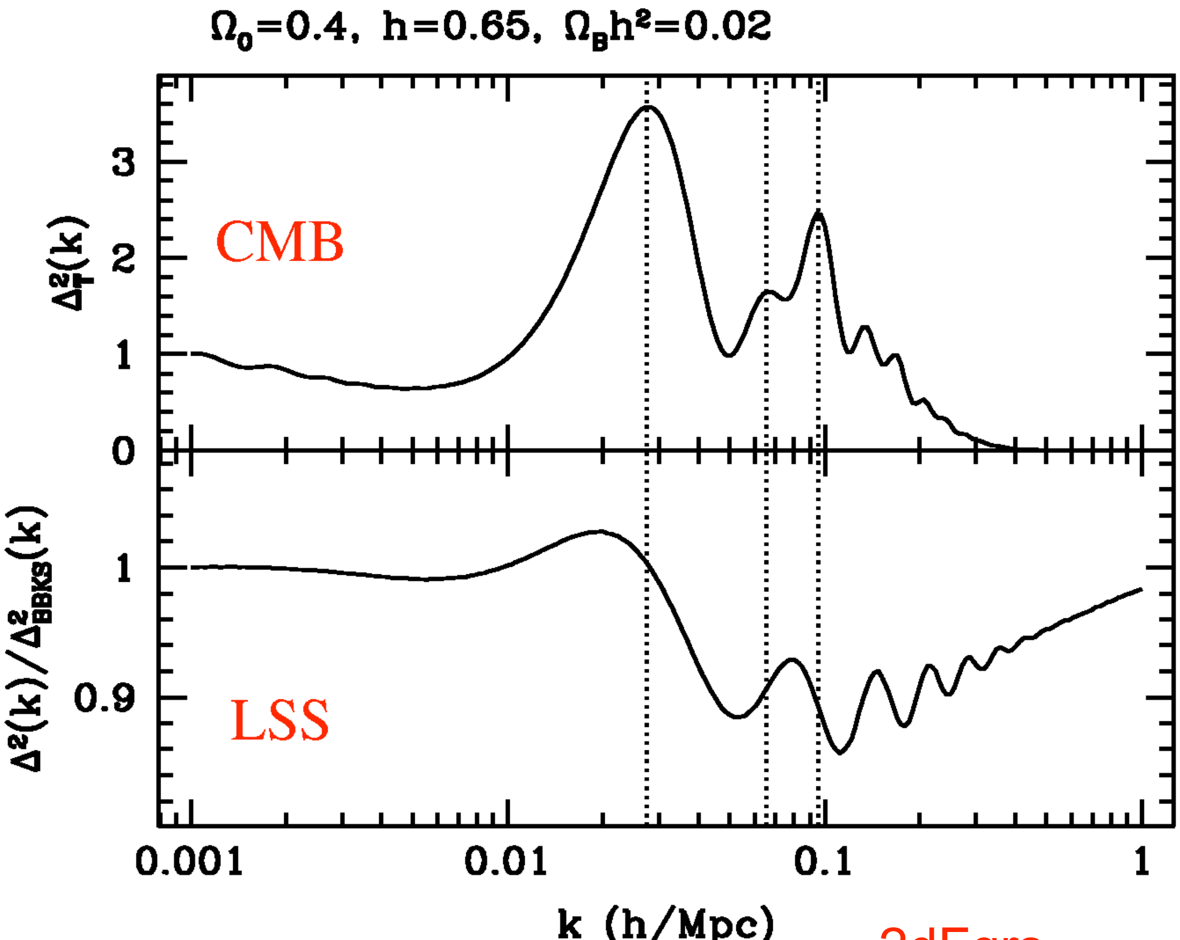
The non-linear mass power spectrum is accurately determined by the Millennium simulation over large range of scales



CMB anisotropies and large-scale structure



CMB anistropies and large-scale structure



2dFgrs

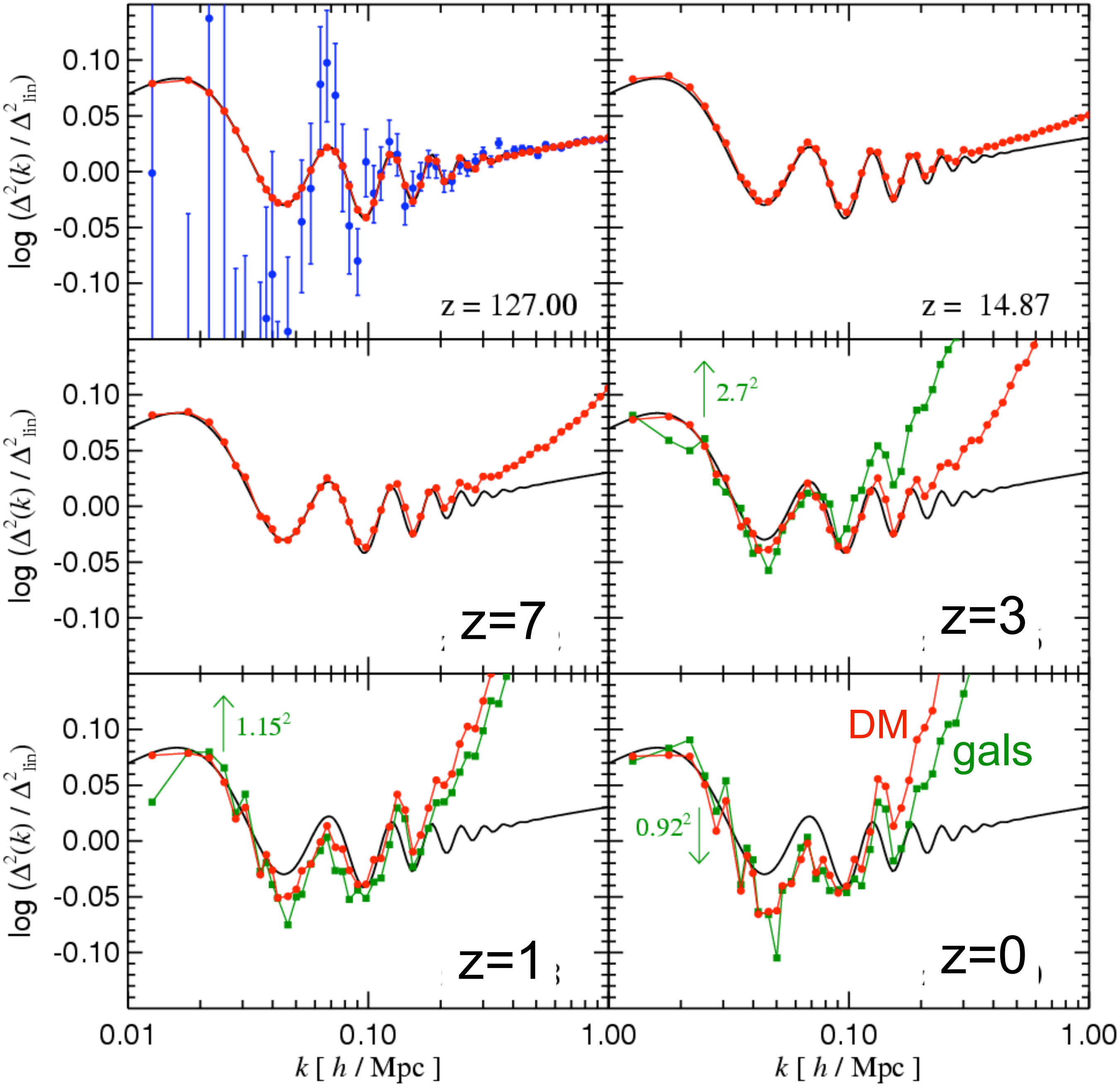
CMB and LSS out of phase:

'velocity overshoot'

LSS amplitude smaller than CMB

Meiksin etal 99

Millennium simulation



Baryon wiggles in the galaxy distribution

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

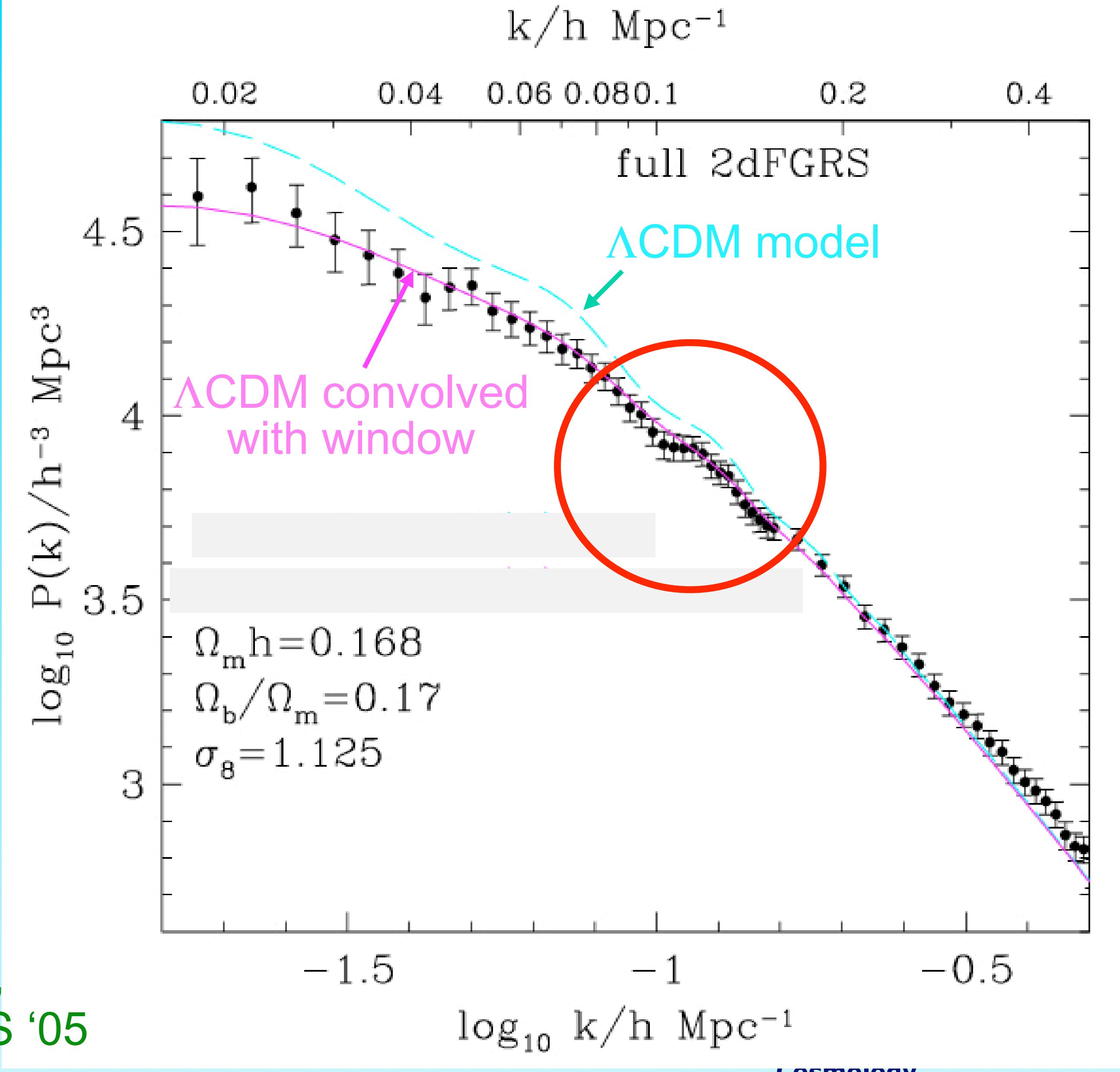
Galaxy samples matched to plausible large observational surveys at given z

Springel et al 2005

The final 2dFGRS power spectrum

University of Durham

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



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

Cosmology

The final 2dFGRS power spectrum

University of Durham

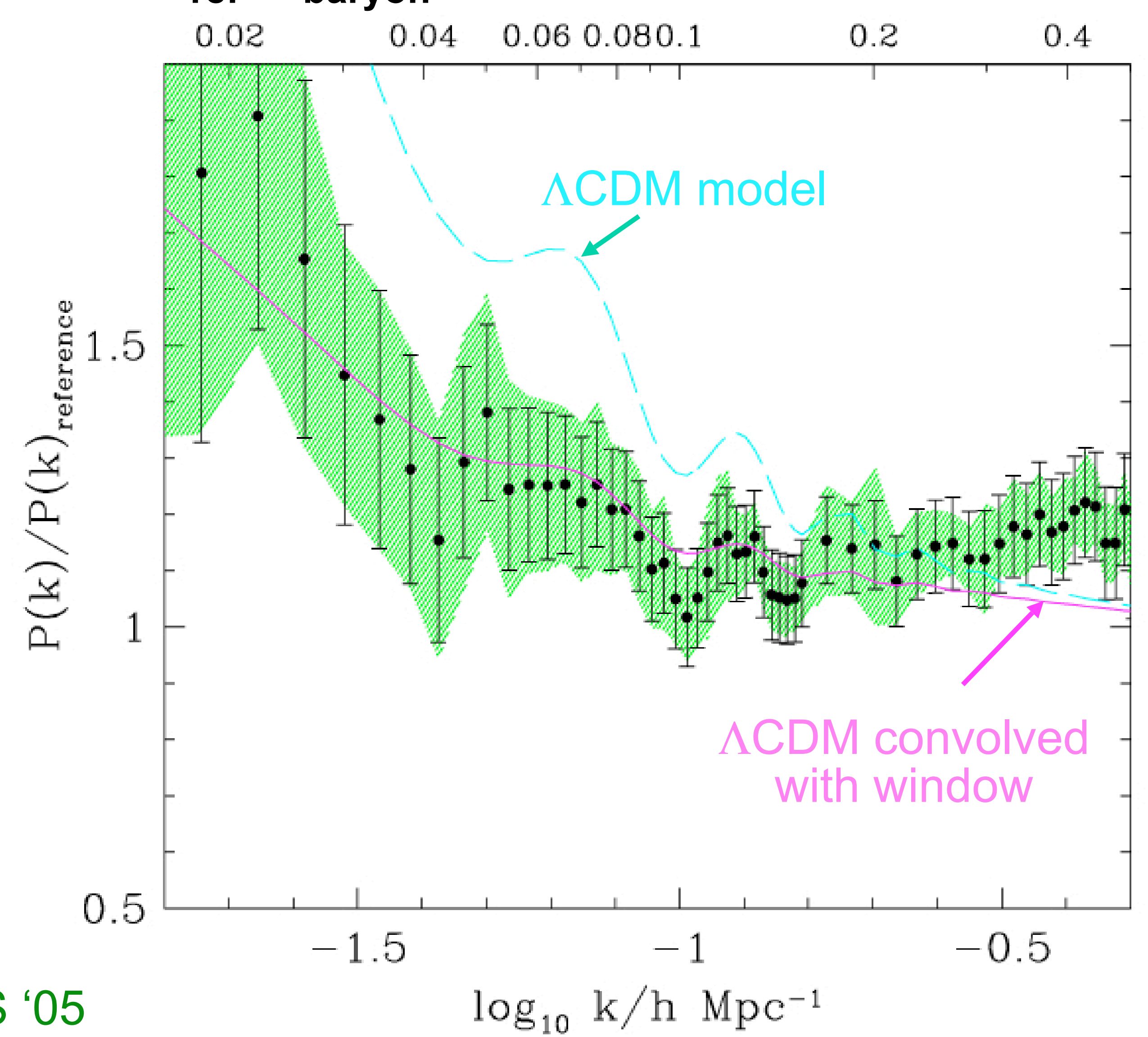
Baryon oscillations conclusively detected in 2dFGRS!!!

Demonstrates that structure grew by gravitational instability in ΛCDM universe

Also detected in SDSS LRG sample (Eisenstein etal 05)

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

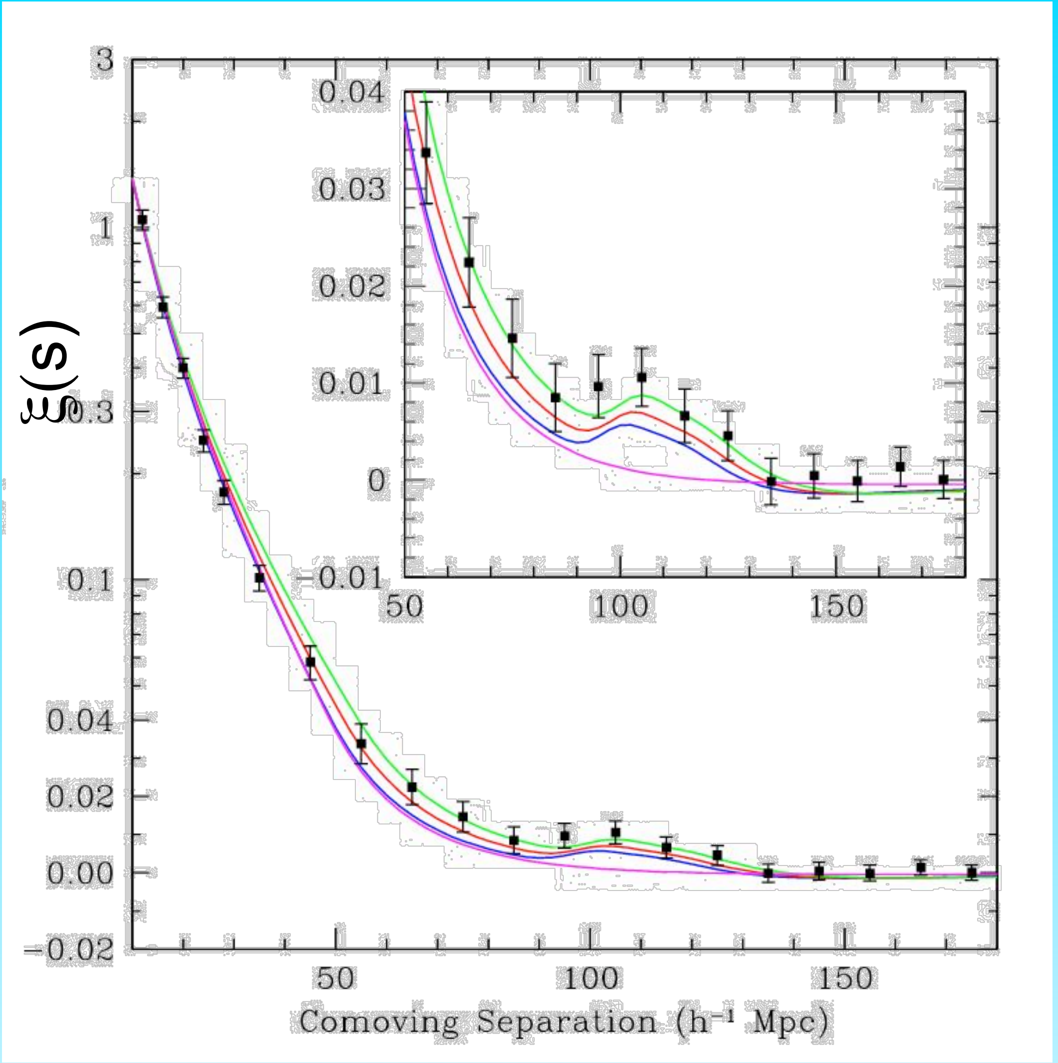
$P(k) / P_{ref}(\Omega_{baryon}=0)$



Cosmology

SDSS LRG correlation function

Again, CDM models fit the correlation function adequately well (although peak height is slightly too large; assuming n_s=1, h=0.72)



$\Omega_b h^2$ =0.024,

$\Omega_m h^2$ =0.133±0.011,

$\Rightarrow$ Ω_b/Ω_m= 0.18

Eisenstein et al. 05

University of Durham

Baryon oscillations in the power spectrum

Comoving sound horizon at t_{rec}

(depends mostly on $\Omega_m h^2$
and weakly on $\Omega_b h^2$)

$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a + a_{eq})^{1/2}} da$$

"wavenumber" of acoustic oscillations:

$$k_A = 2\pi/s$$

Comoving distance/redshift:

(depends on $\Omega_m h^2$ and w)

$$\frac{dx}{dz} = \frac{c}{H_0 \Omega_m^{1/2}} \frac{1}{\sqrt{(1+z)^3 + (\Omega_m^{-1} - 1)(1+z)^{3(1+w)}}}$$

Apparent size of standard ruler depends on cosmology

⇒ dark energy eqn of state w

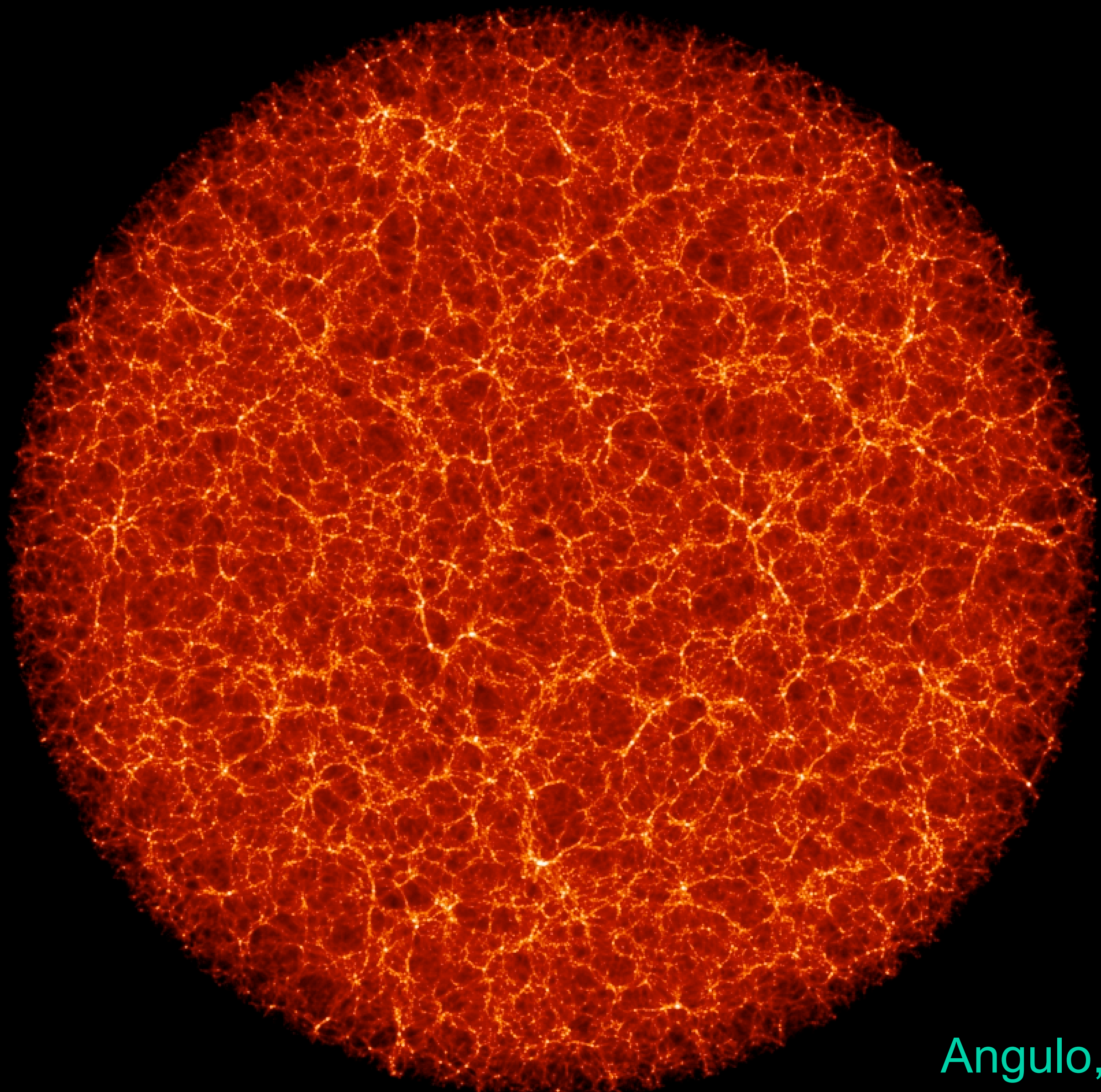
(e.g. Eisenstein & HU 1998; Blake & Glazebrook 2003, 2005; Seo & Eisenstein 2003; 2005……)

Baryon oscillations in the power spectrum

What are the prospects for determining k_A in realistic surveys?

What is the optimal strategy?

N-body simulations of large cosmological volumes



BASICC

L=1340/h Mpc

N=3,036,027,392

20 times the Millennium volume

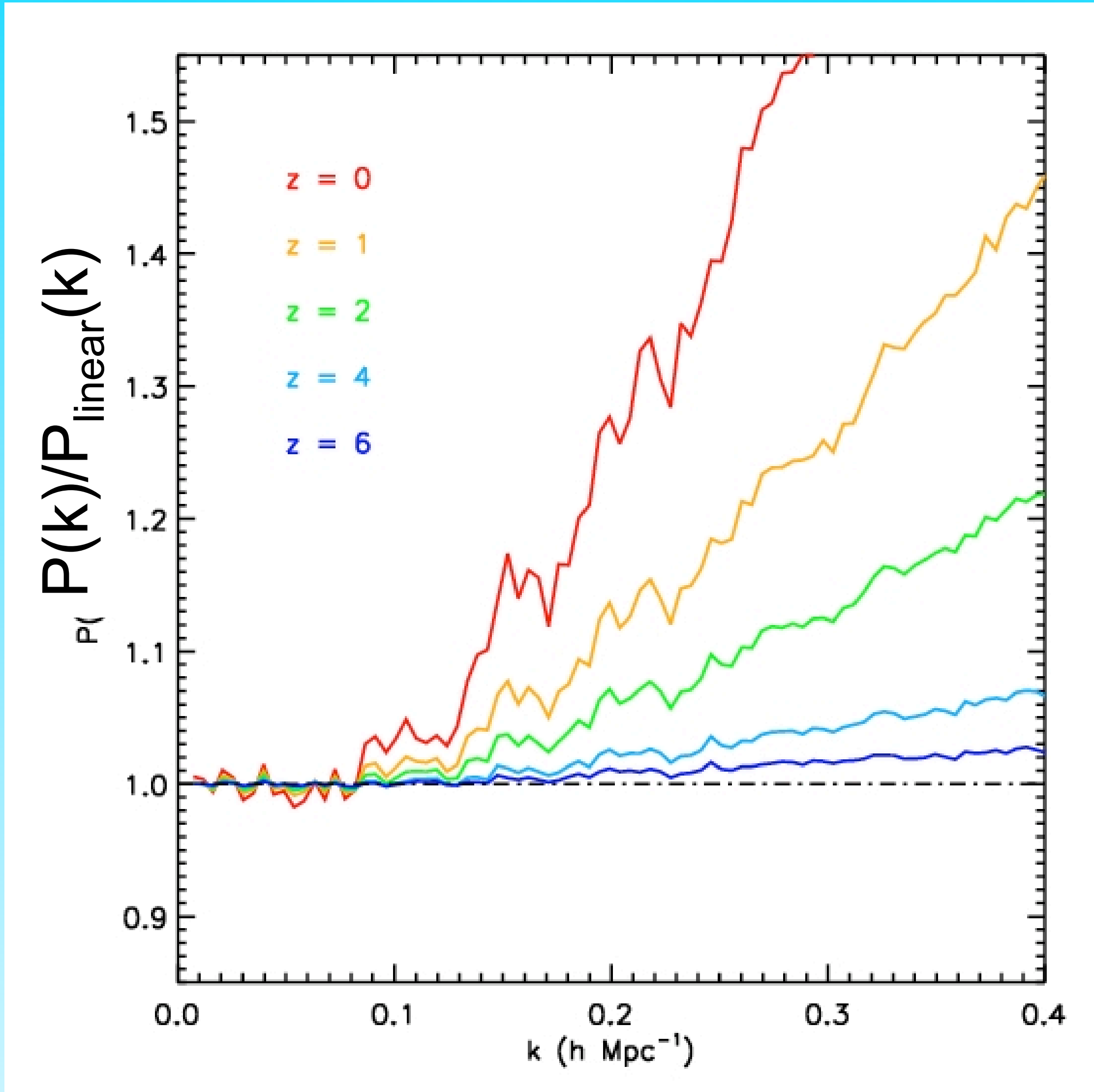
Halo resolution:
(10 particle limit)
5.5 e+11/h Mpc

130,000 cpu hours on the Cosmology Machine

Angulo, Baugh, Frenk & Lacey ‘07

University of Durham

Non-linear evolution of matter fluctuations



BASICC simulation dark matter real space

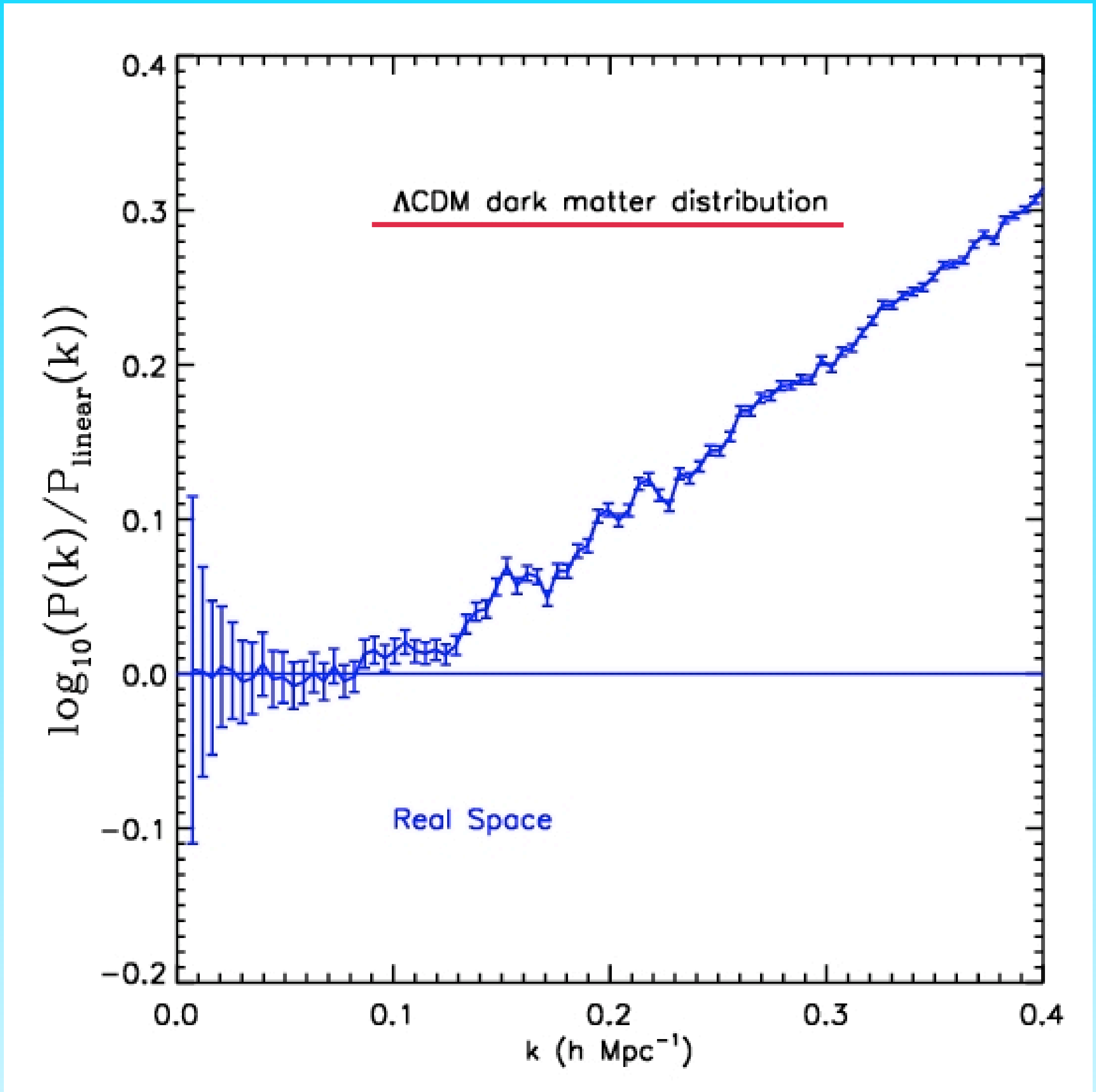
P(k) divided by linear theory P(k), scaling out growth factor

Angulo, Baugh, Frenk & Lacey '07

Institute for Computational Cosmology

University of Durham

Non-linear evolution of matter fluctuations

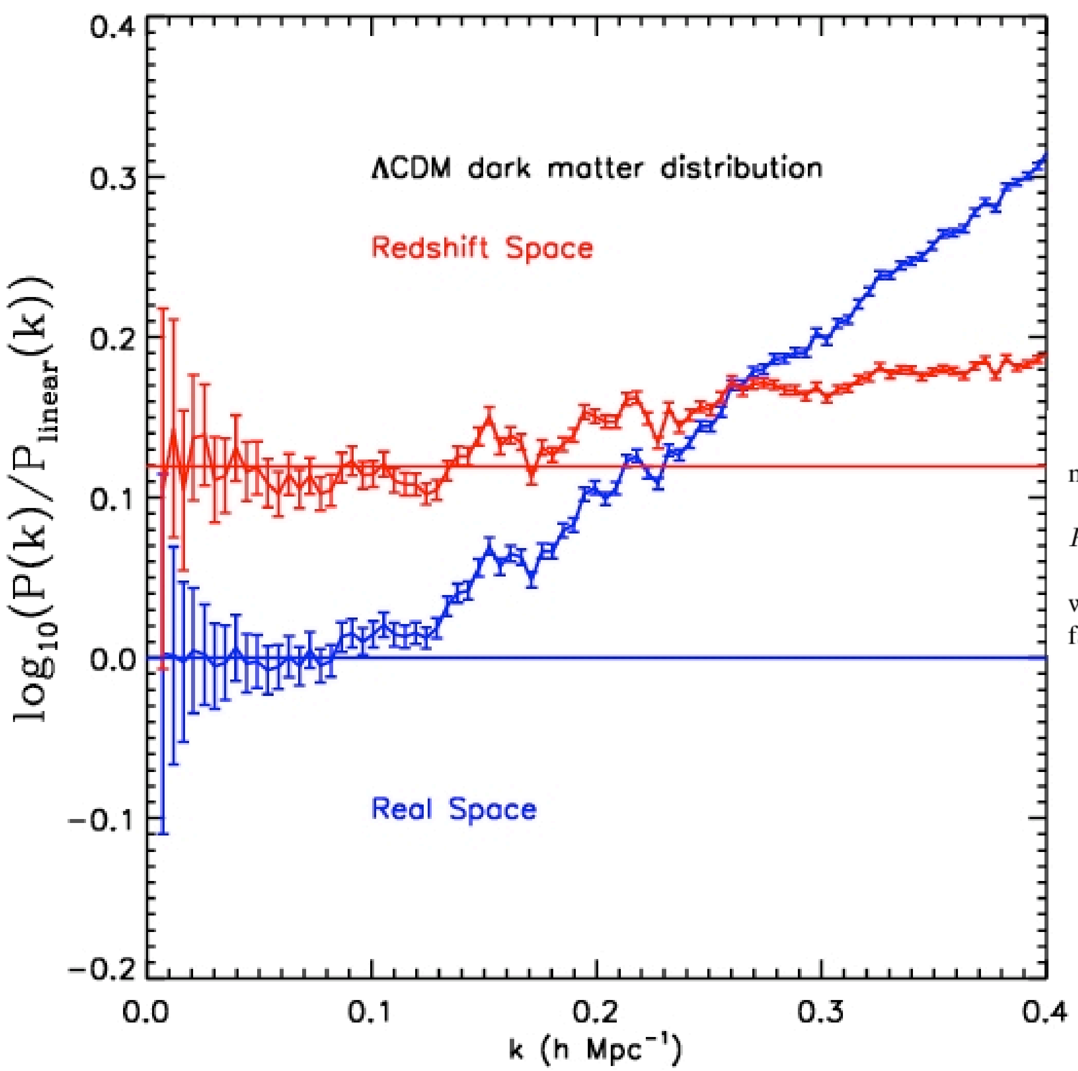


Log $(P(k)/P_{linear}(k))$
at z=1

Angulo, Baugh, Frenk & Lacey '07

Redshift space distortions

University of Durham



Peculiar motions distort clustering pattern

Coherent bulk flows boost large scale power (Kaiser 1987)

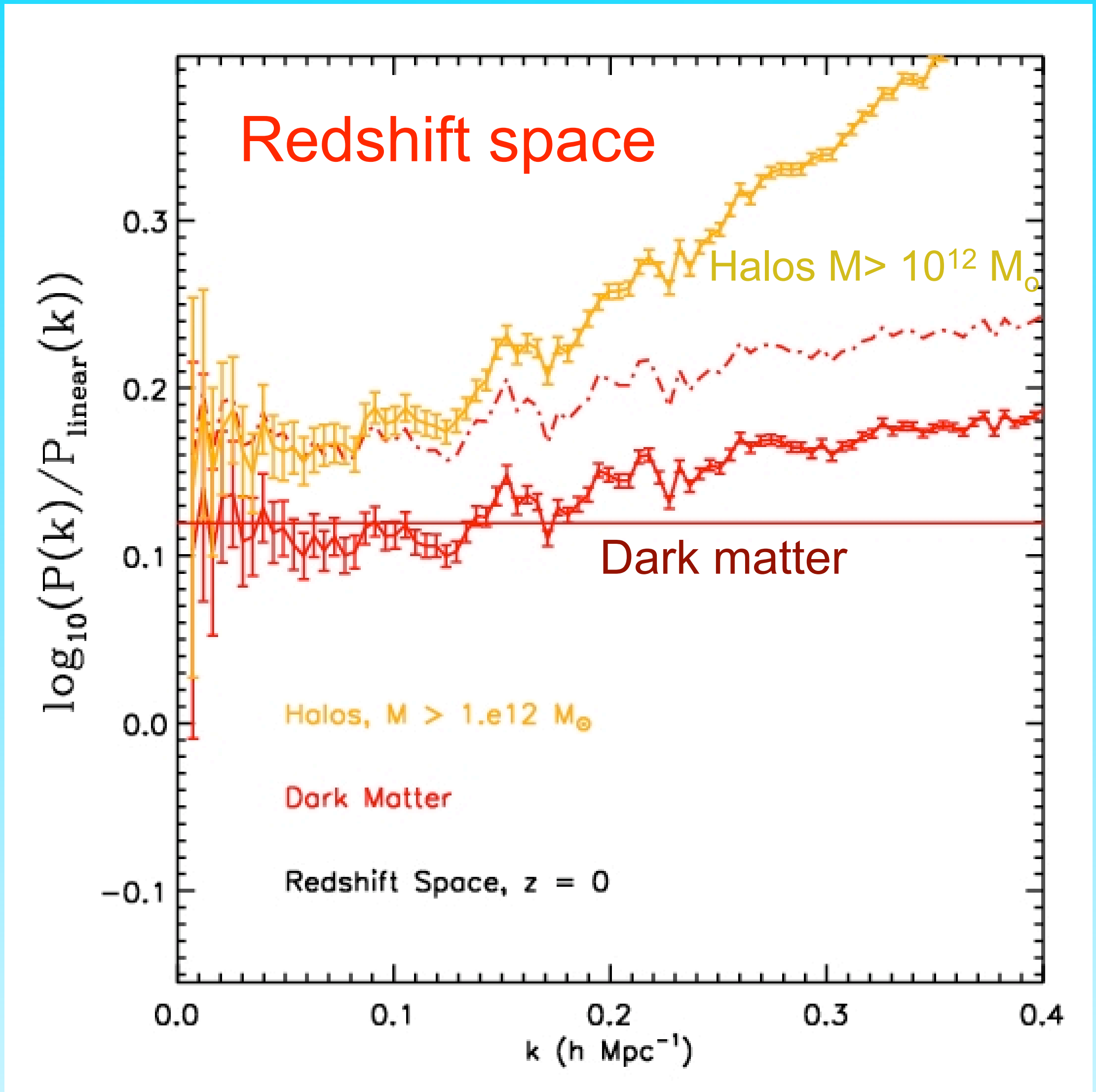
Kaiser (1987) related the spherically averaged power spectrum measured in redshift (P_s) and that in real space (P):

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

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

Redshift space distortions



Peculiar motions distort clustering pattern

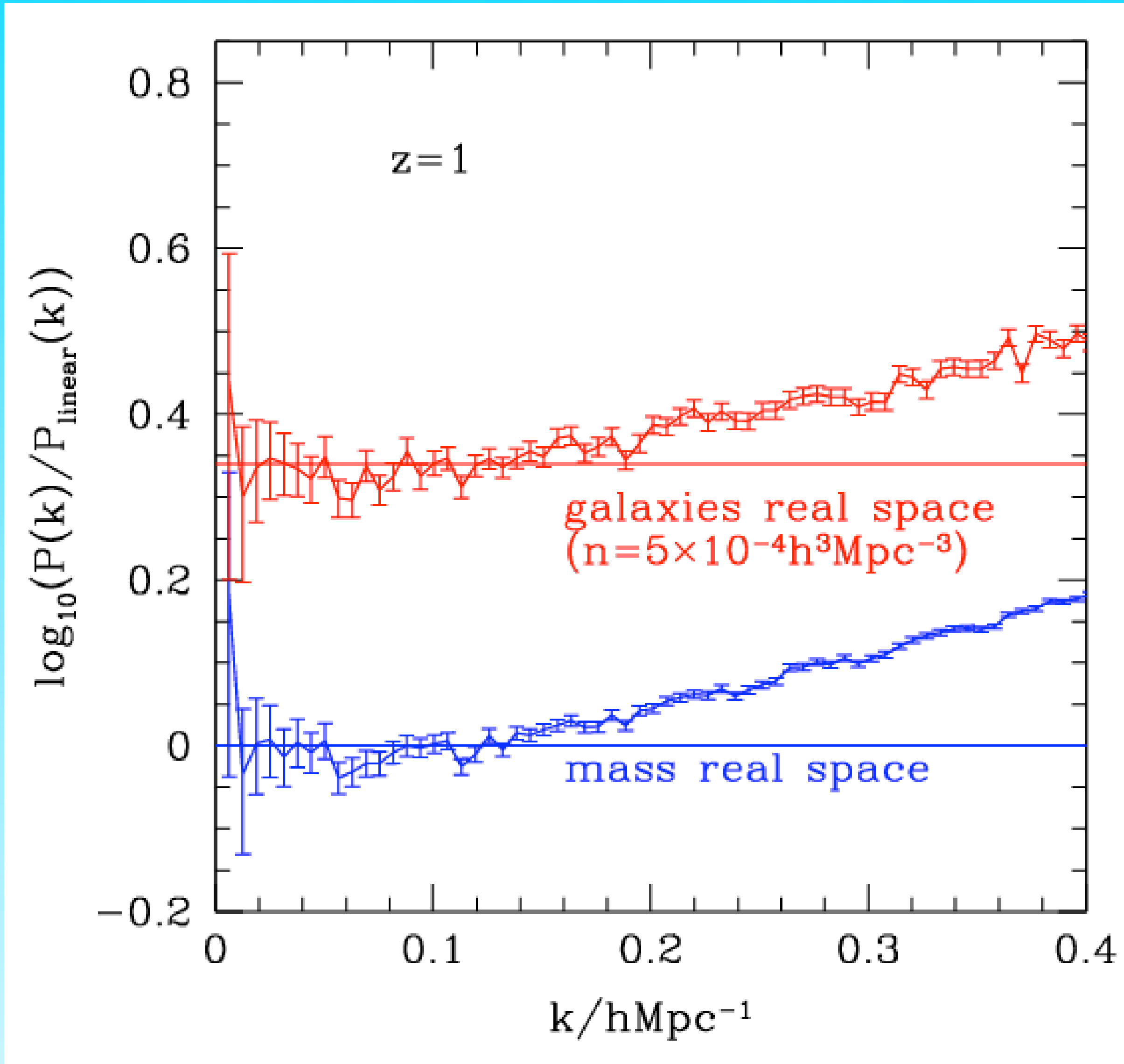
Boost in power on large scales due to coherent flows

Damping at higher k affects DM but not the halos

In z-space, halo bias is scale-dependent

Galaxy bias in real space

University of Durham



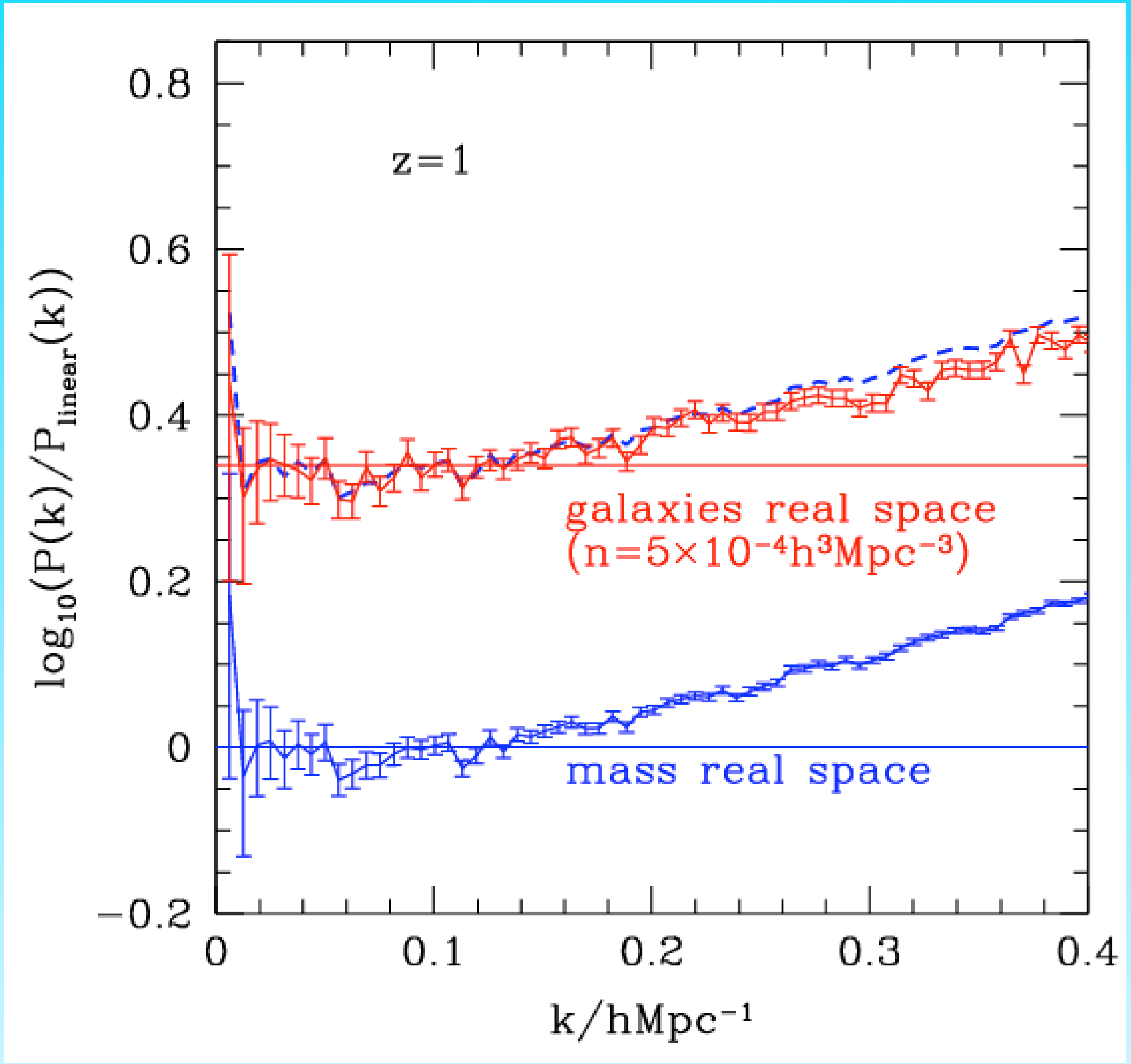
Magnitude limited sample.

Galaxy clustering boosted relative to mass in real space

Angulo, Baugh, Frenk & Lacey '07

Galaxy bias in real space

University of Durham

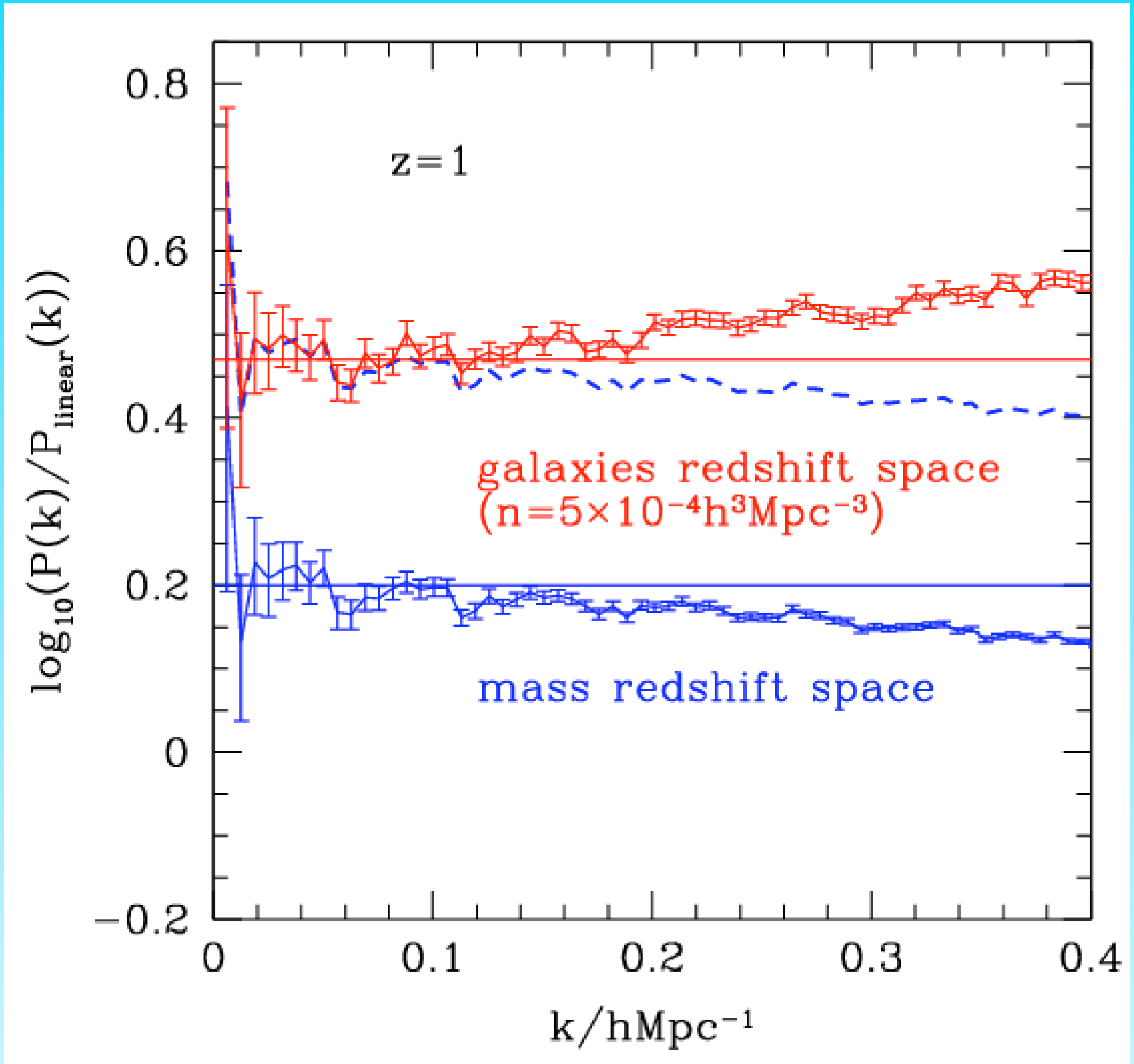


Boost in clustering approximates to a constant bias factor on large scales.

Angulo, Baugh, Frenk & Lacey '07

Galaxy bias in redshift space

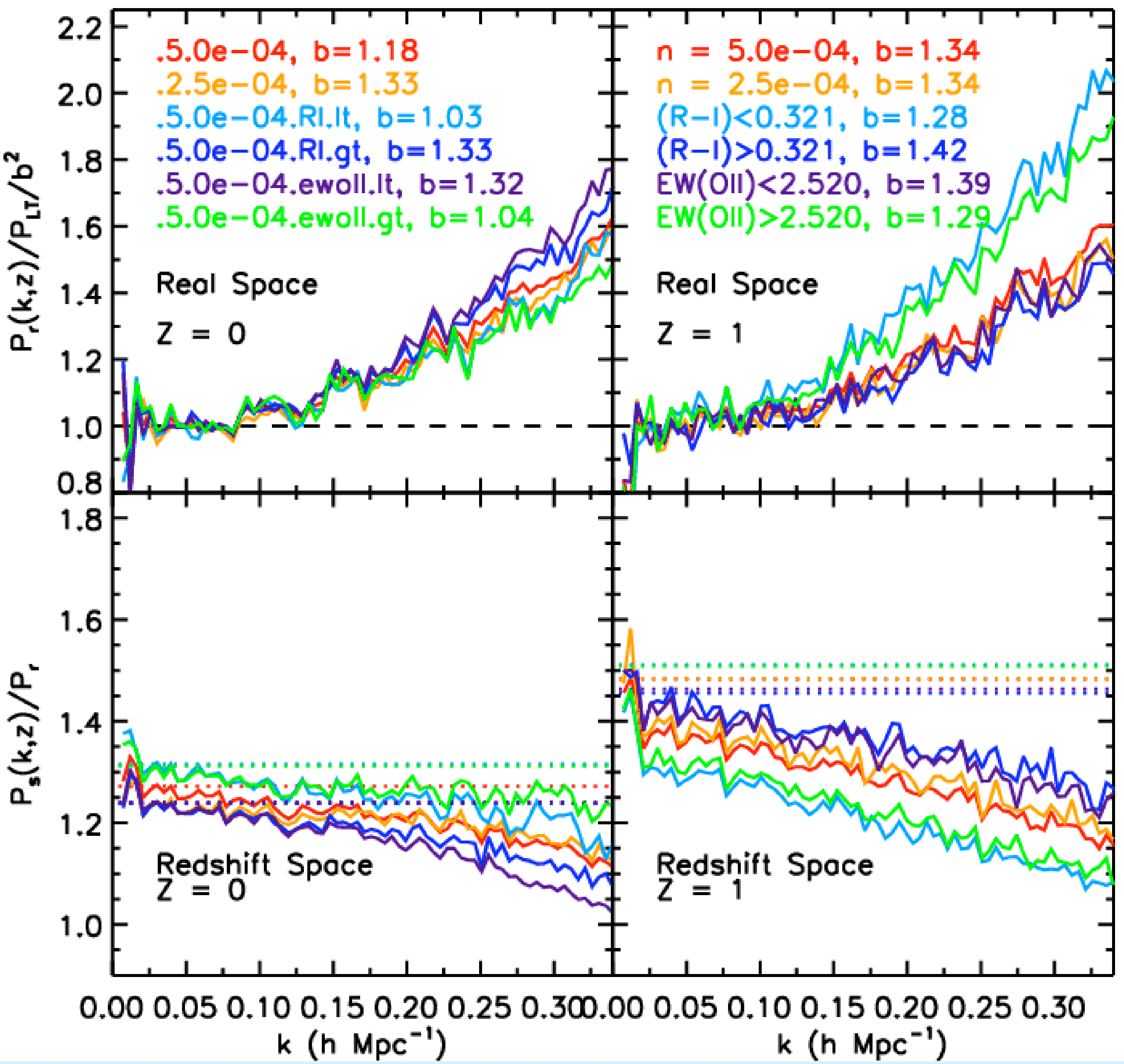
University of Durham



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

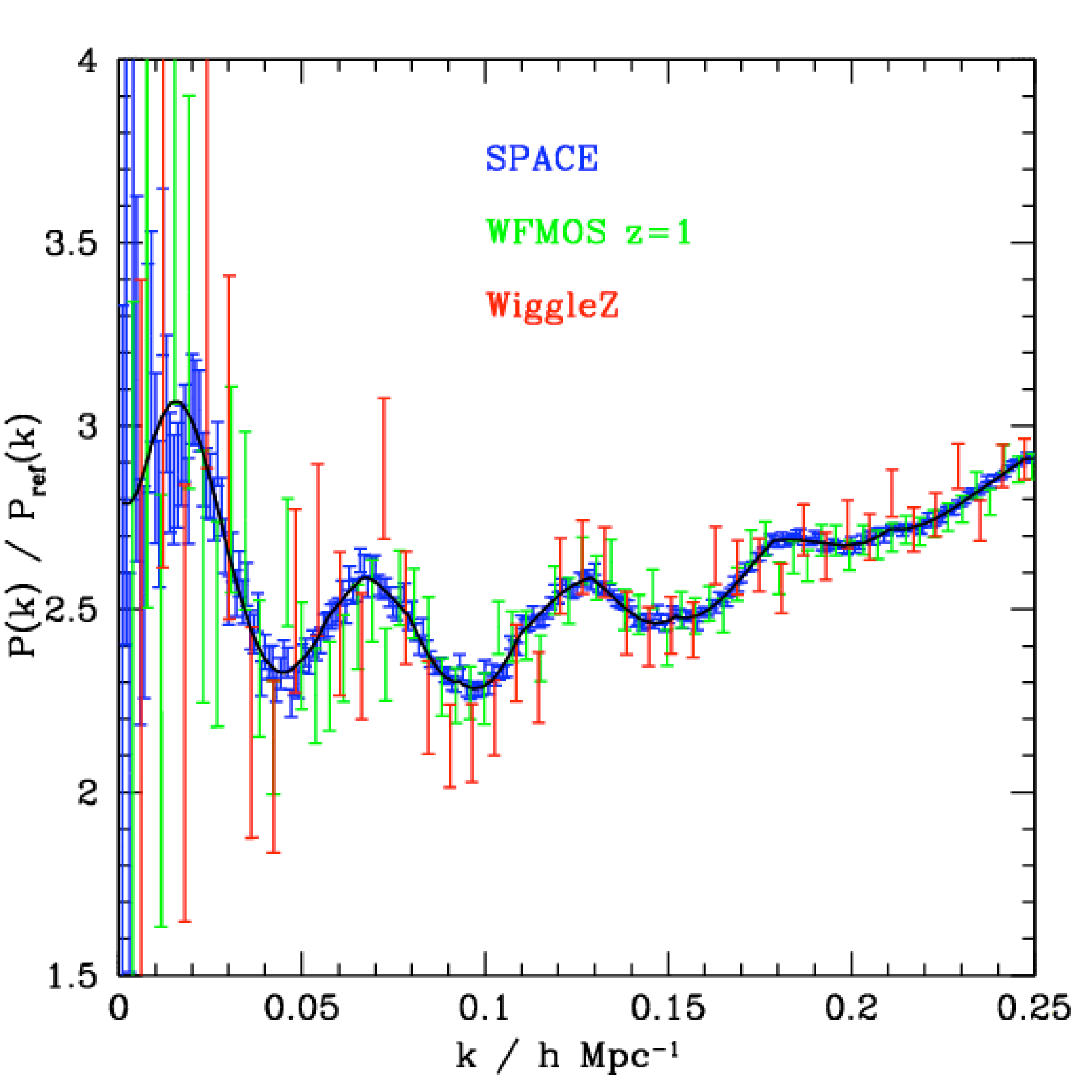


Comparison of different selections e.g. colour, emission line strength

Angulo et al ‘07

Projected BAO data for planned surveys at z=1

Projections based on mock catalogues made from large N-body simulation plus semi-analytic galaxy formation model



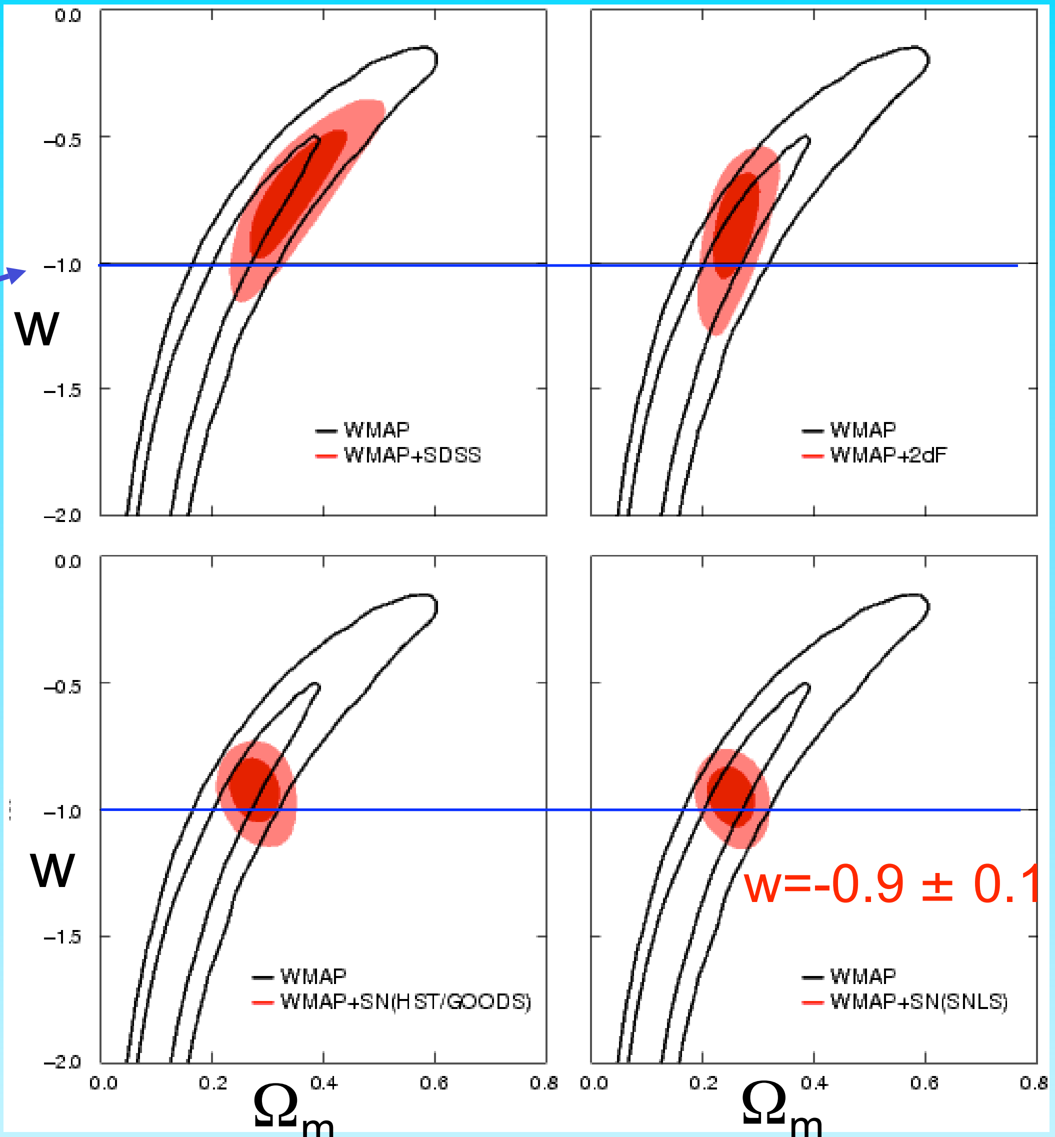
University of Durham

Constraints on w from SnIa, WMAP and 2dFGRS

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

Cosmological constant

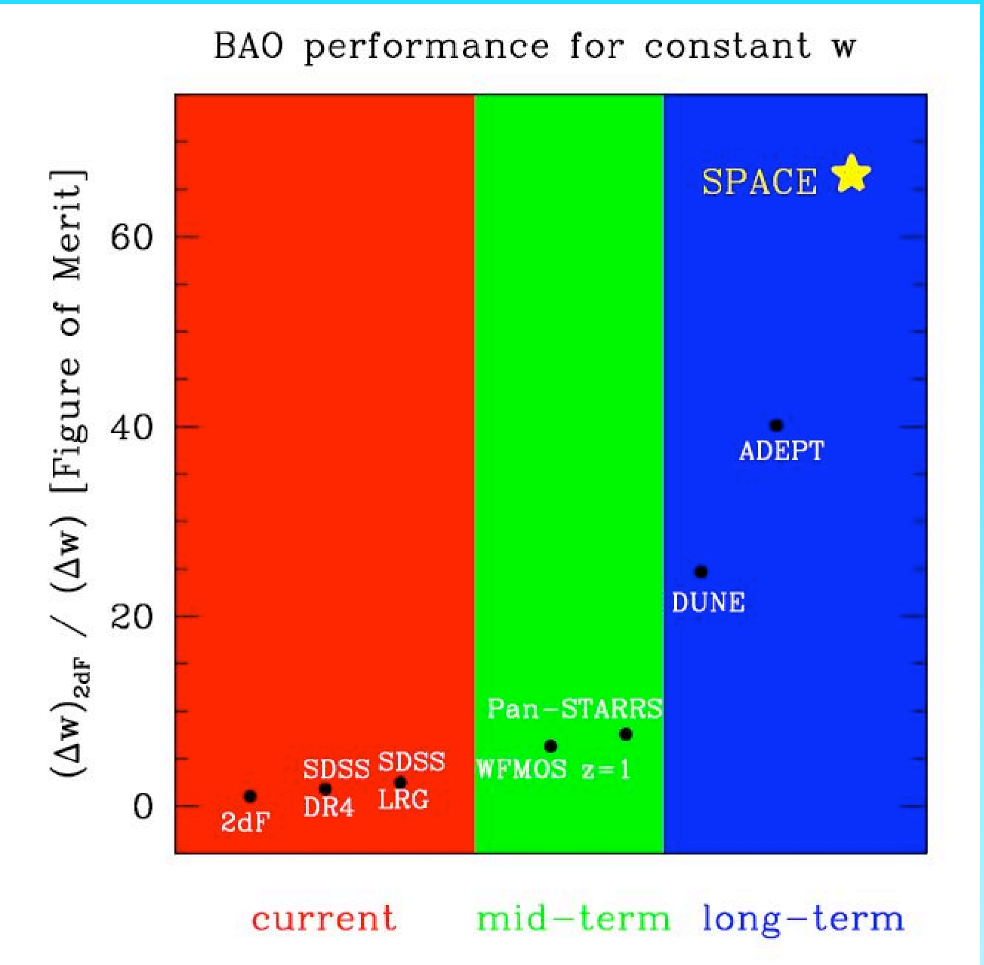
Assume w=const (cosmological constant)



Spergel et al 2006

Headline forecasts for w

University of Durham



Angulo et al 07

Survey	Error in w
WiggleZ	5.0 - 9.5 %
WFMOS	3.6 - 4.0 %
Pan-STARRS	
0.03 photo-z	1.6 - 3.5 %
0.06 photo-z	2.2 - 4.9 %
DUNE 3% photo-z 20,000 sq deg	1.2 - 2.5%
SPACE 10^9 galaxies 27,000 sq deg	0.25 - 0.5%

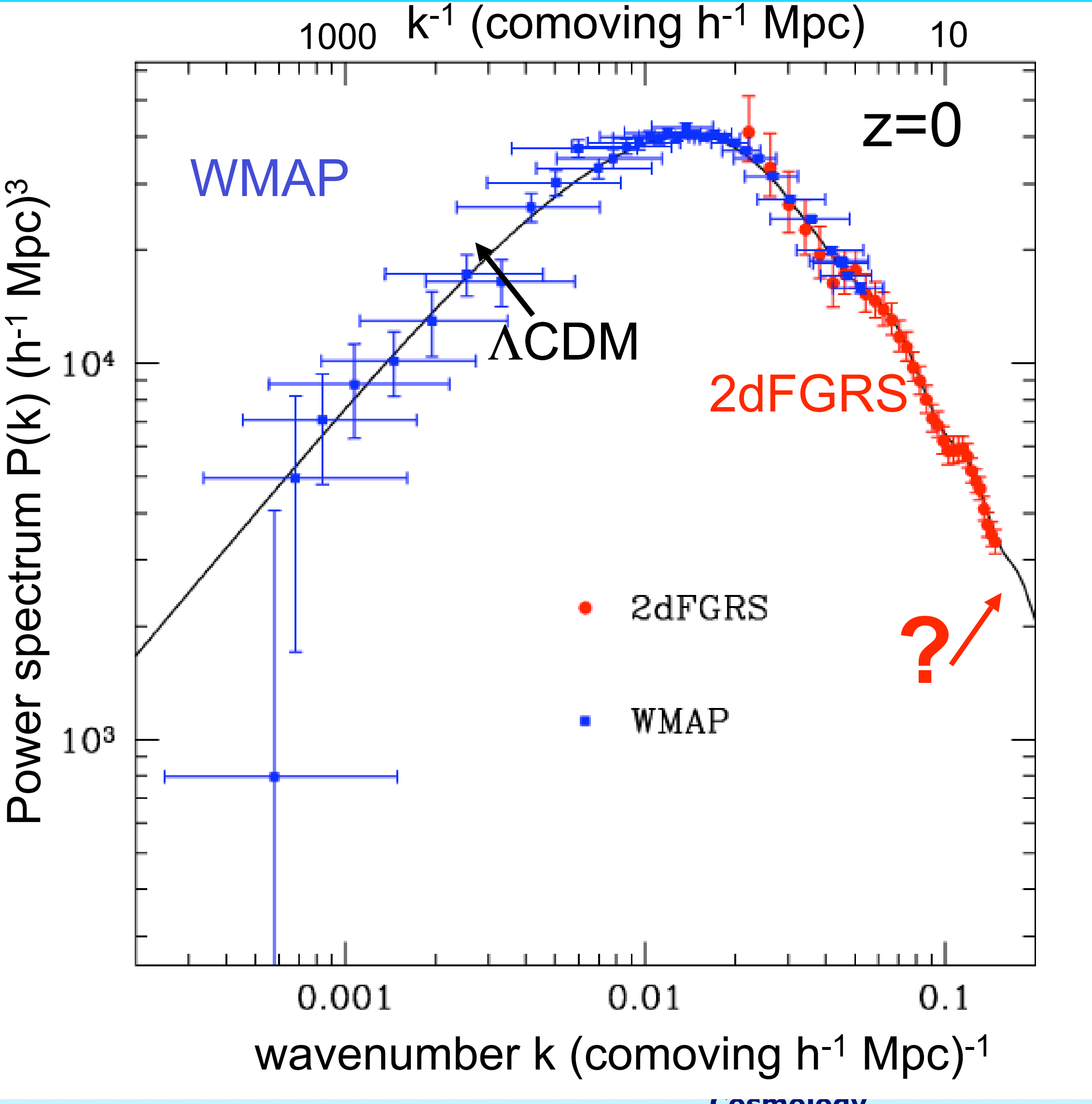
The cosmic power spectrum: from the CMB to the 2dFGRS

University of Durham

CMB:

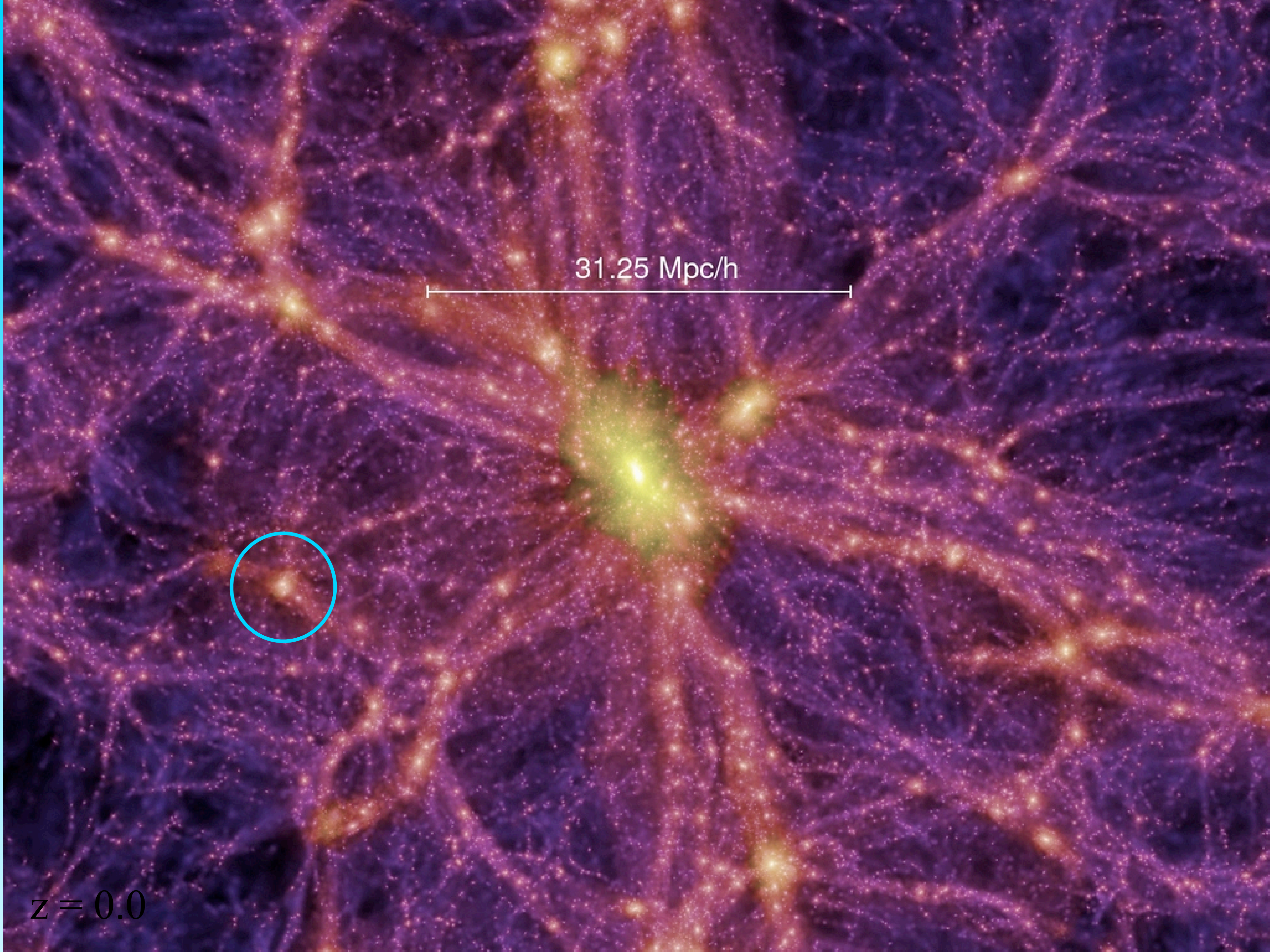
- Convert angular separation to distance (and k) assuming flat geometry
- Extrapolate to z=0 using linear theory

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

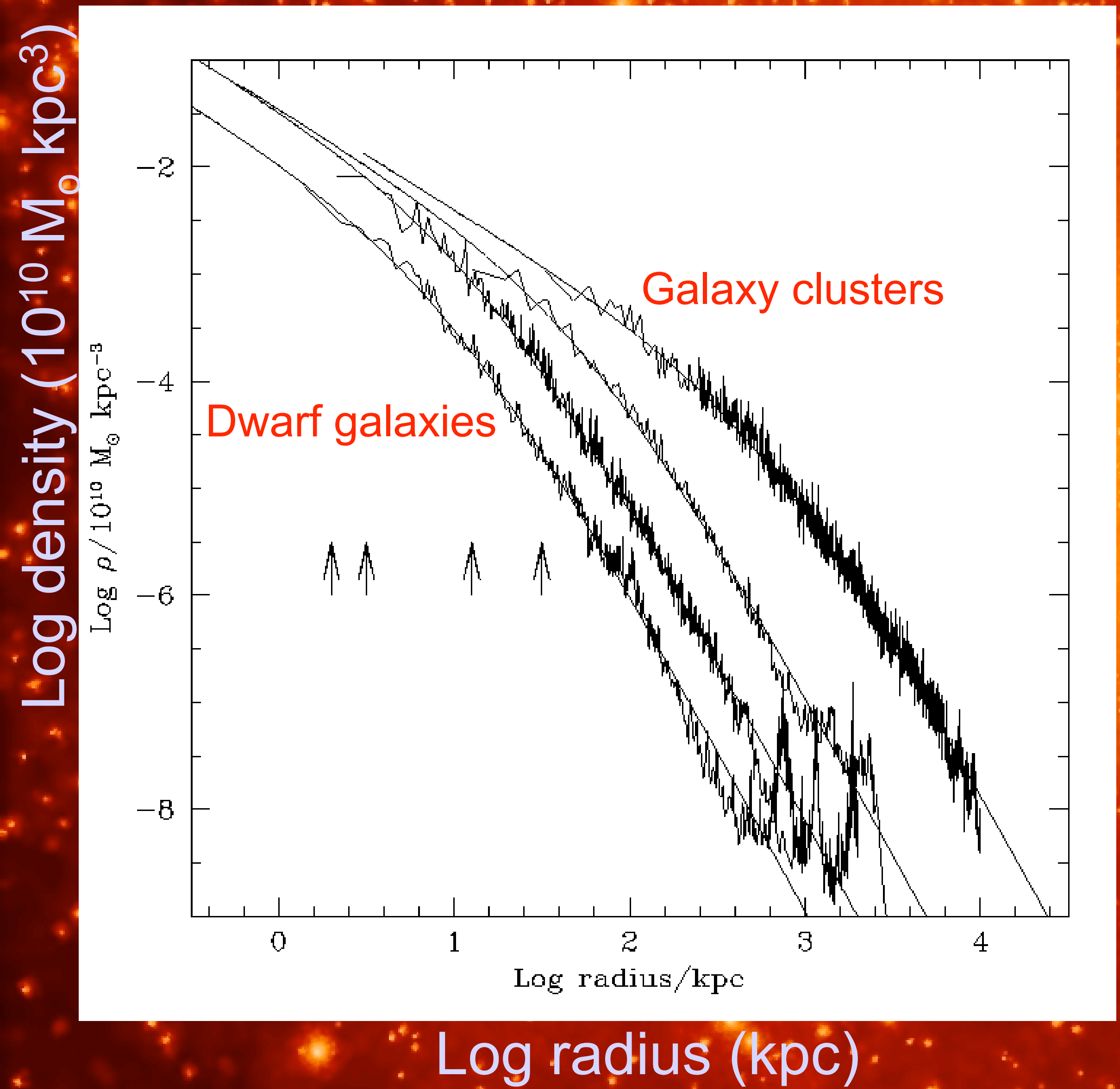


Sanchez et al 06

Cosmology


31.25 Mpc/h
z = 0.0

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

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

University of Durham

A cold dark matter universe

N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

- "Cuspy" density profiles
- Large number of self-bound substructures (10% of mass)

This has led to two well-publicized "problems":

- The "halo core" problem
- The "satellite" problem

University of Durham

Explanations for the core/satellite "crises"

- The dark matter is warm
- The dark matter has a finite self-scattering cross-section
- The primordial density power spectrum has a break (or running spectral index)
- There is no dark matter -- gravity needs modifying
- Astrophysics: baryon effects, black holes, bars
- The comparison of models and data is incorrect

A Cold dark matter universe

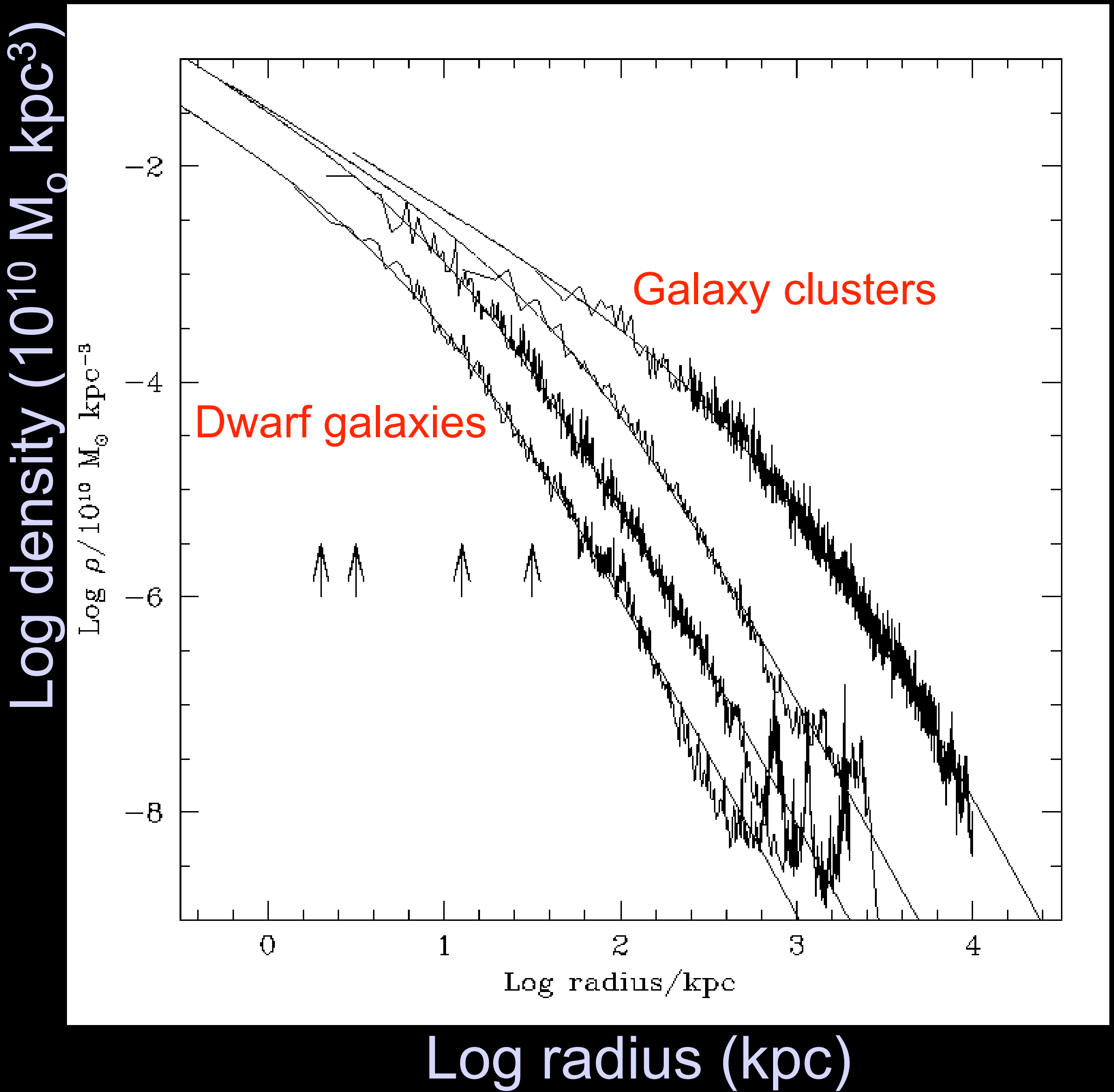
N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

- "Cuspy" density profiles
- Large number of self-bound substructures (10% of mass)

This has led to two well-publicized "problems":

- The "halo core" problem
- The "satellite" problem

The "halo core" problem

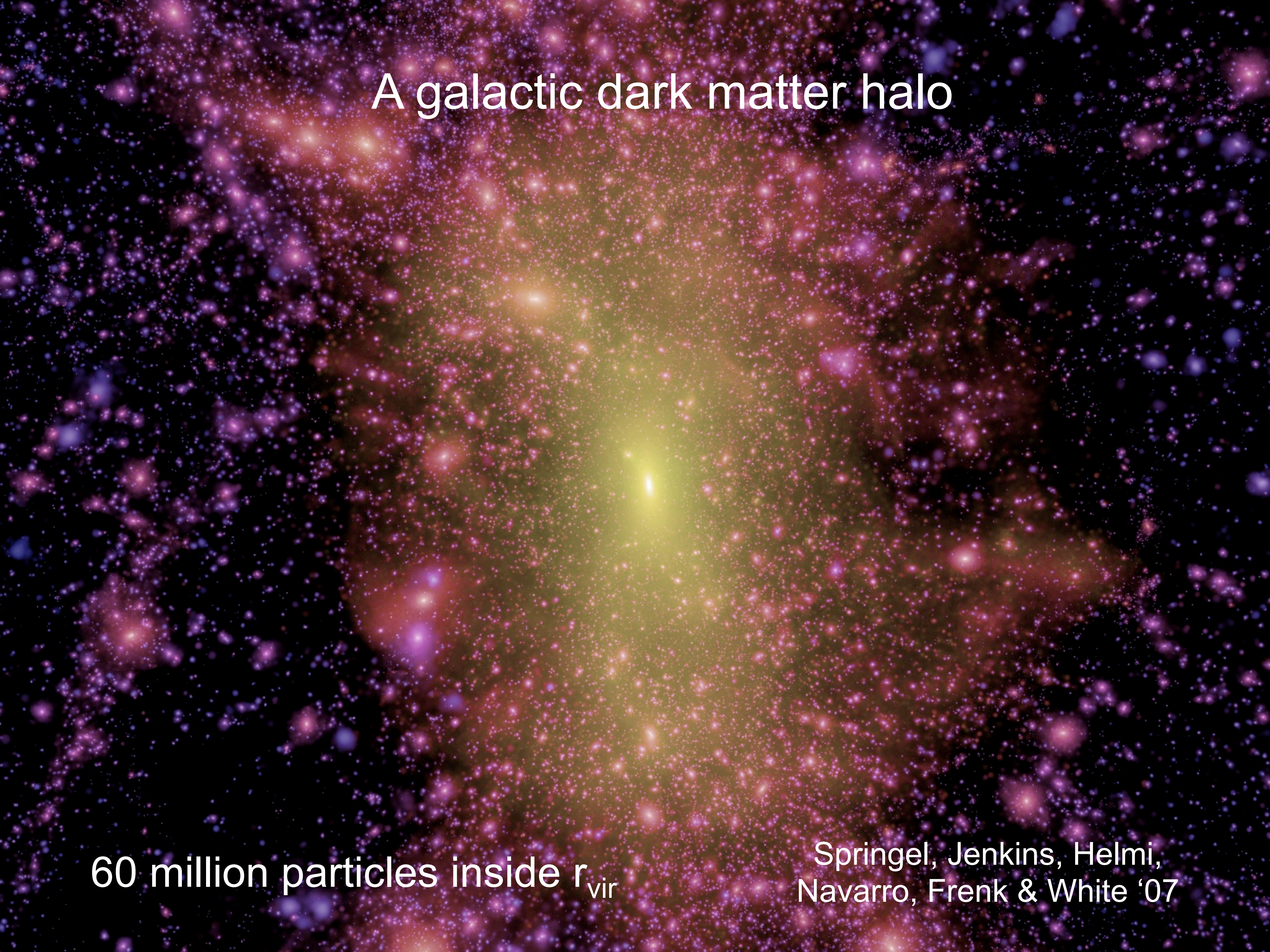


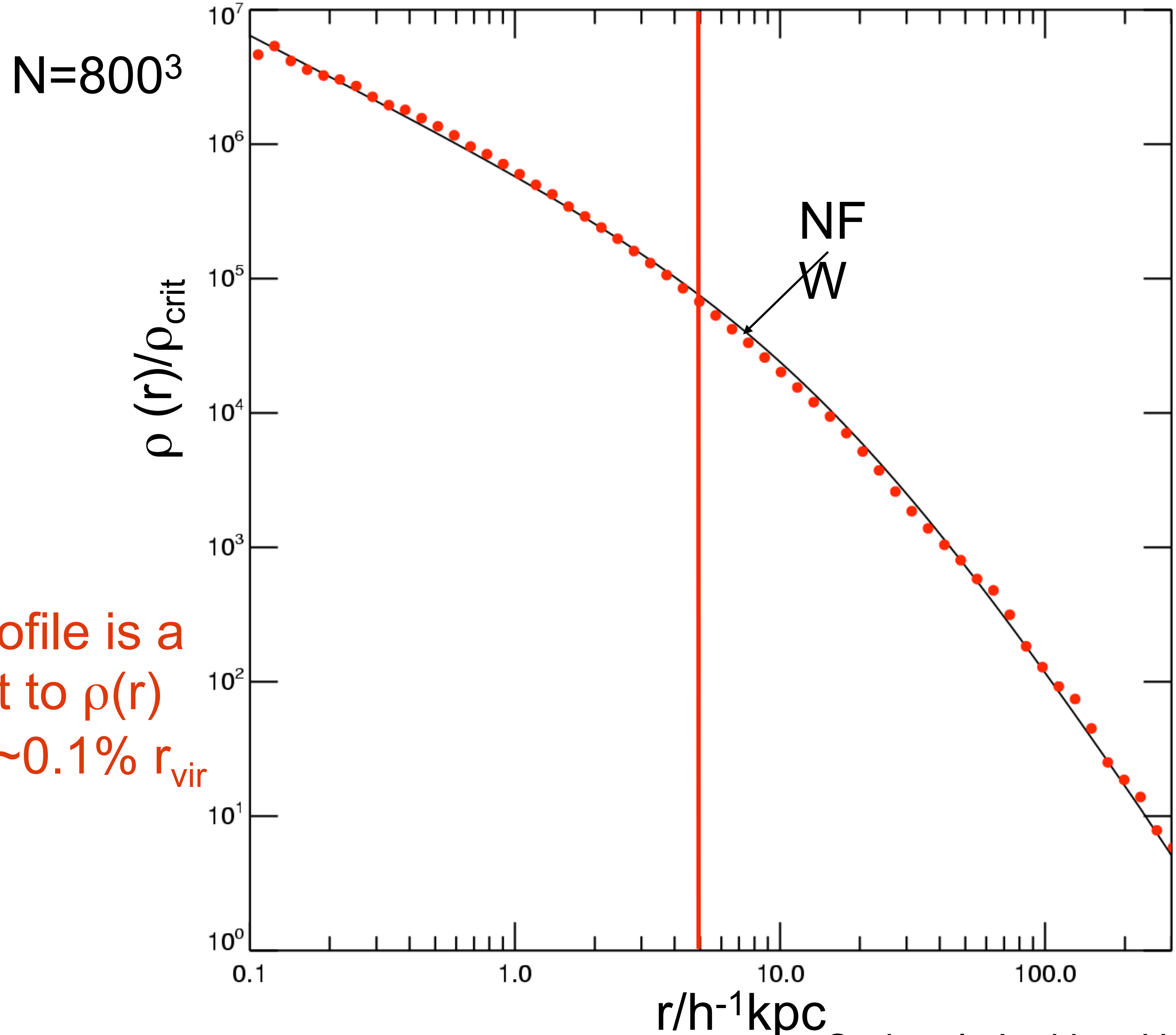
Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

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


A galactic dark matter halo
60 million particles inside r_{vir}
Springel, Jenkins, Helmi,
Navarro, Frenk & White ‘07



NFW profile is a good fit to $\rho(r)$ down to ~0.1% r_{vir}

Springel, Jenkins, Helmi, Navarro, Frenk & White '06

University of Durham

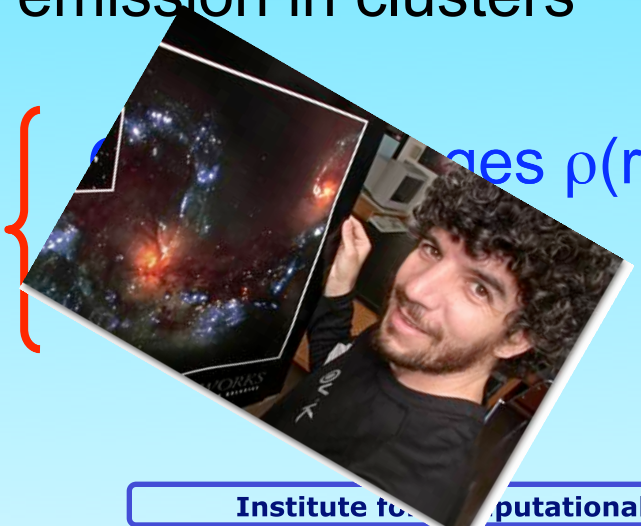
The density profile of galaxy cluster dark halos

Do real dark halos have the profiles found in the simulations?

Profiles can be probed by:

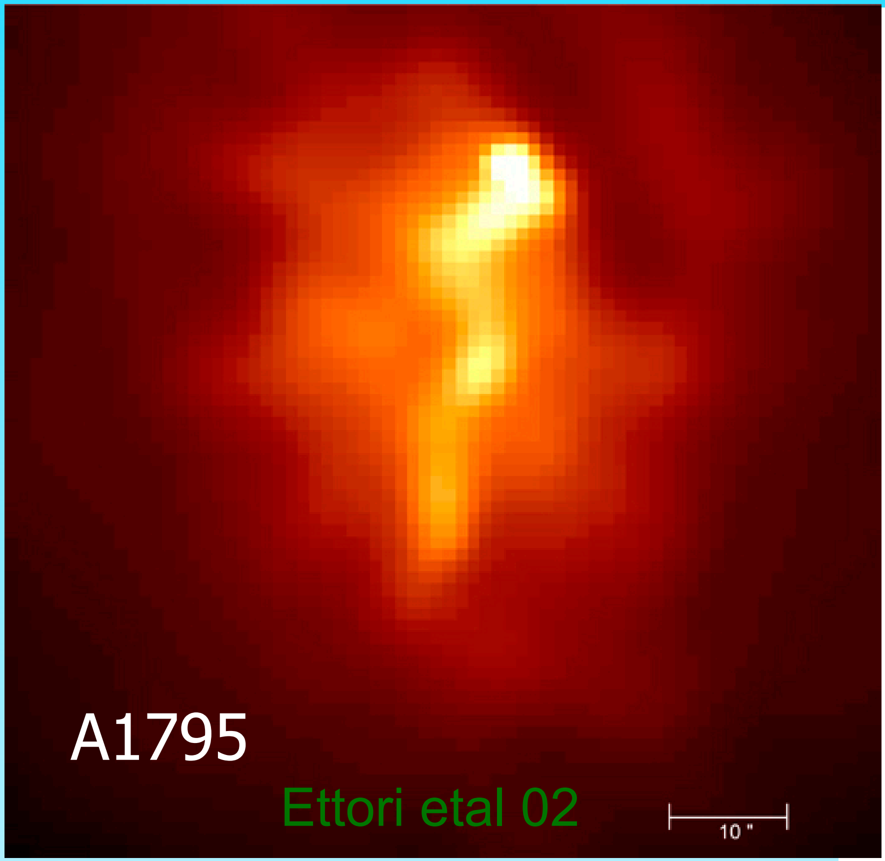
- Gravitational lensing and/or X-ray emission in clusters

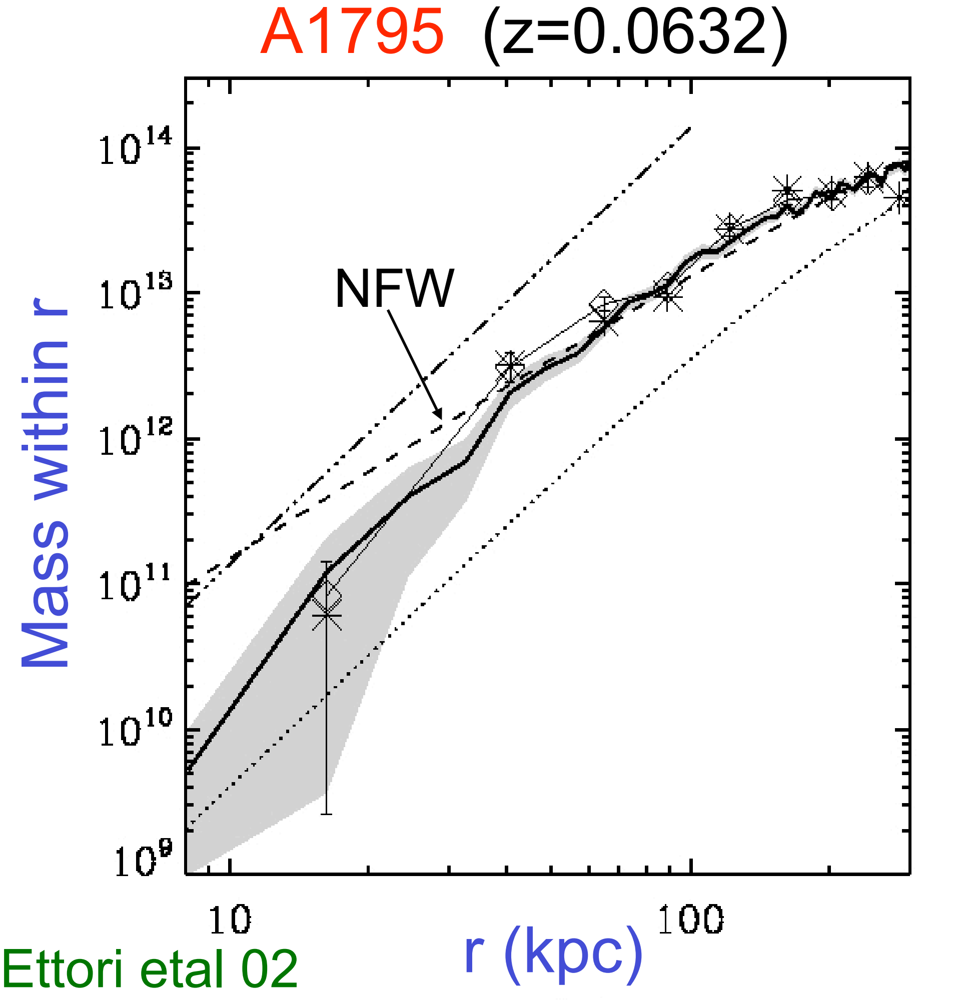
- Galaxy rotation curves → messy { ...ges $\rho(r)$



The central density profile of galaxy cluster dark halos

Inner DM density profile inferred from X-ray data (Chandra)





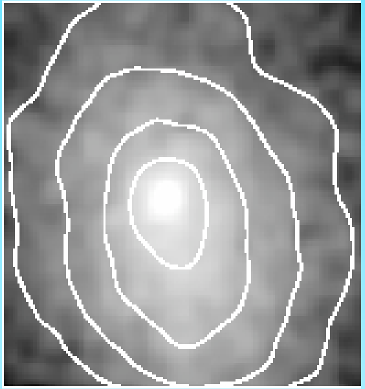
Profile shallower than NFW (β = 0.59 ±0.15)

The central density profile of galaxy cluster dark halos

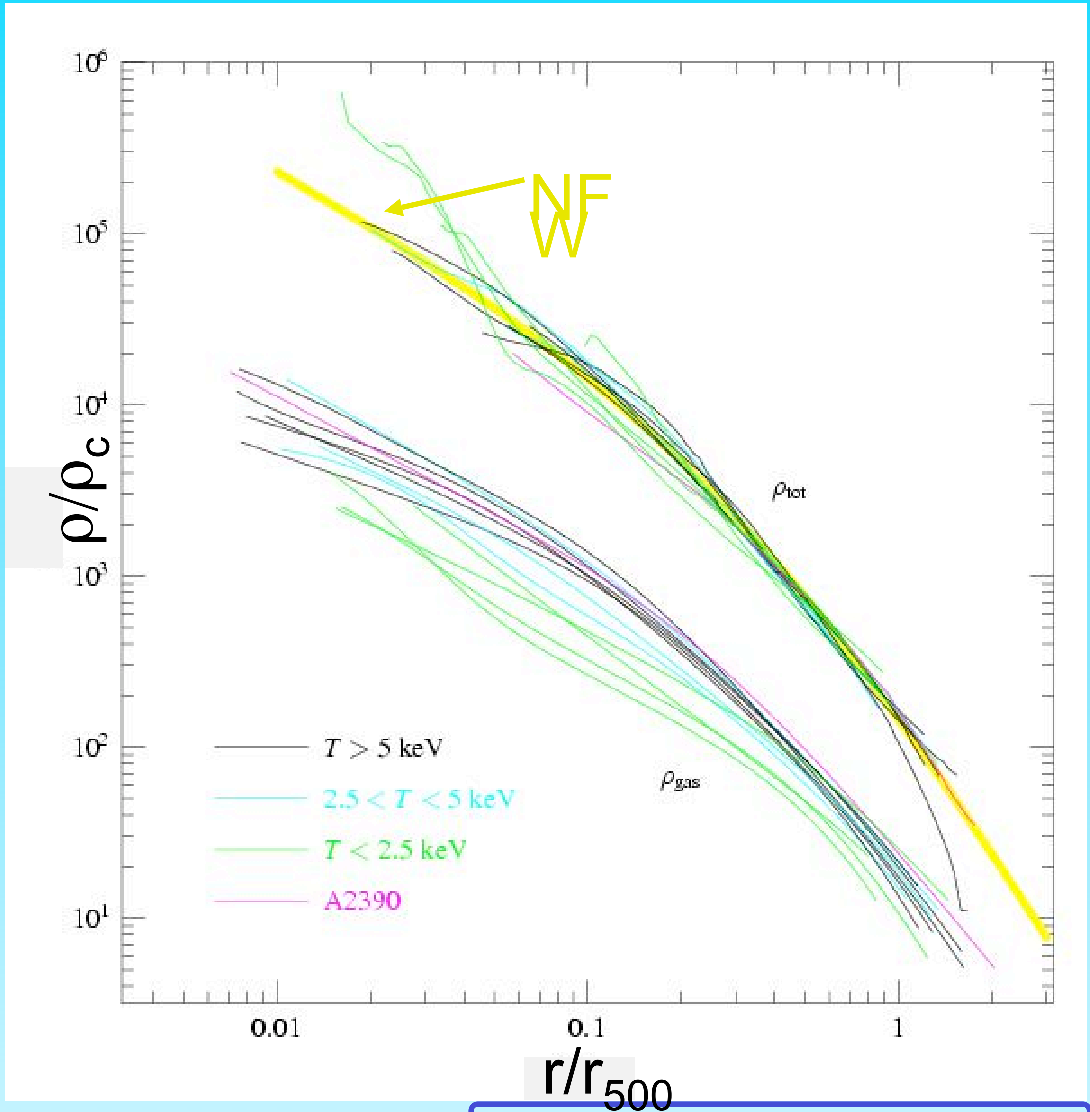
University of Durham

X-ray data

Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium



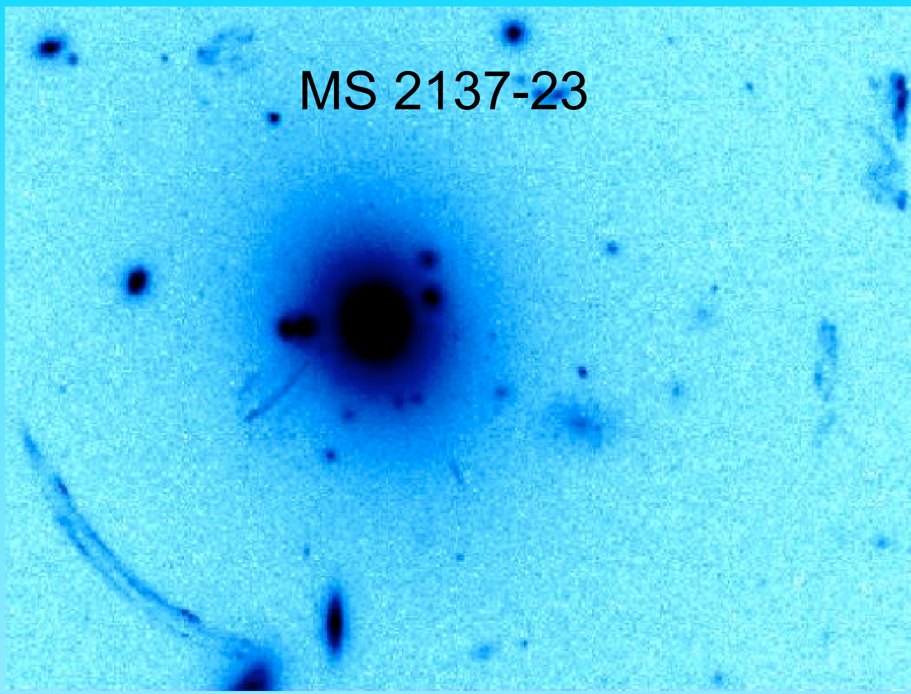
Excellent agreement with CDM halo predictions

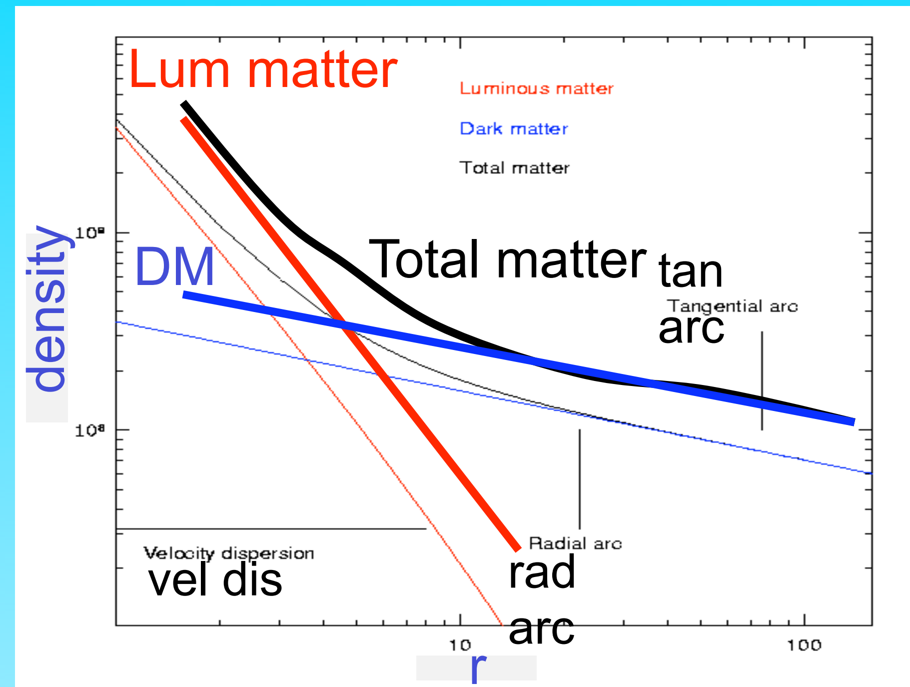


Vikhlinin et al '06

Mass profile in cluster cores from strong lensing

University of Durham





(kpc)

Sand etal 05

- Assume spherical symmetry
- Model potential as power-law DM + galaxy with constant M/L
- Constrain inner slope of DM profile using tangential arc,

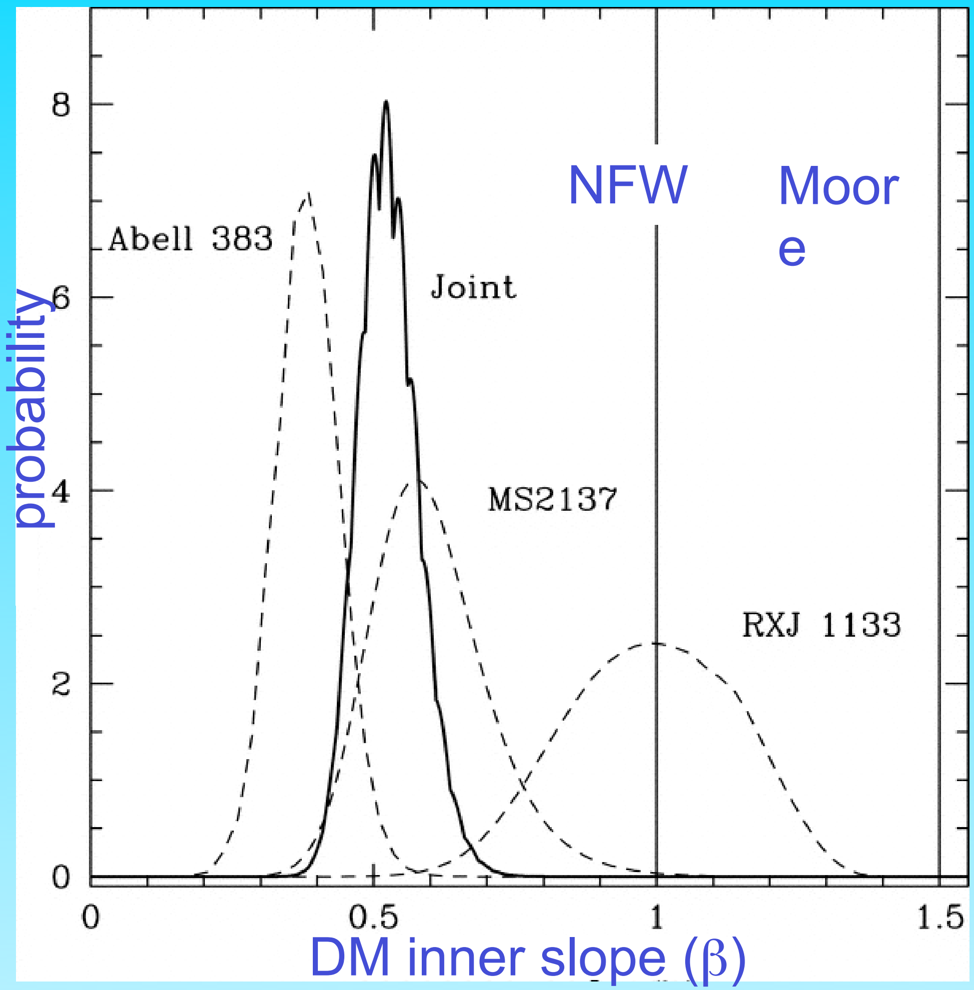
Mass profile in cluster cores from strong lensing

University of Durham

$$\rho(r) \propto r^{-\beta}(r_s + r)^{\beta-3}$$

β=1 for NFW

Sand et al find β=0.5, in disagreement with CDM



Sand et al 04

Cuspy Cold Dark Matter Halos

University of Durham

Mass profile in cluster cores from strong lensing

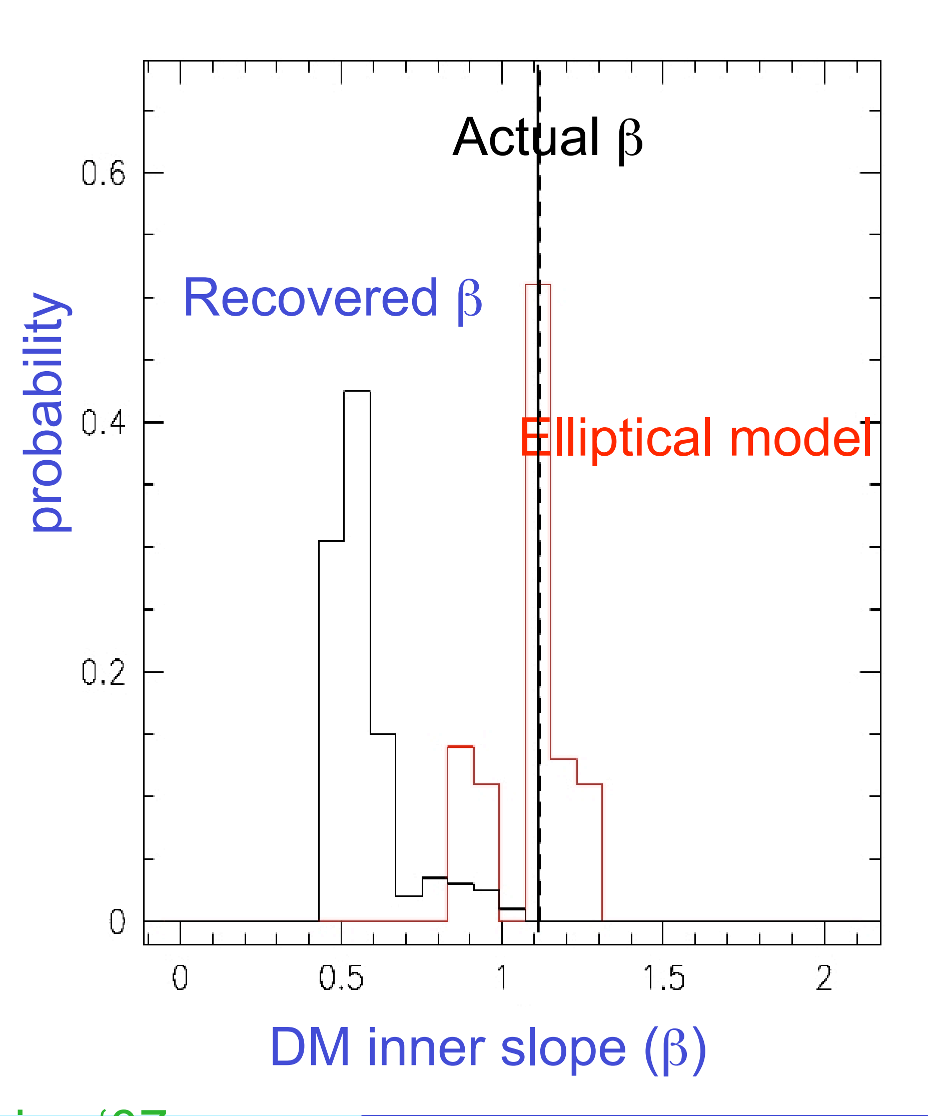
$$\rho(r) \propto r^{-\beta}(r_s + r)^{\beta-3}$$

β=1 for NFW

For this simulation, β=1.2

Sand etal (spherically symm) analysis returns β~0.5!!!

Reason: Sand et al assume spherical symmetry



Meneghetti, Bartelmann, Frenk & Jenkins '07

The “halo-core problem” ?

The inner profiles of cluster halos seen consistent with the cusps predicted in ΛCDM

A Cold dark matter universe

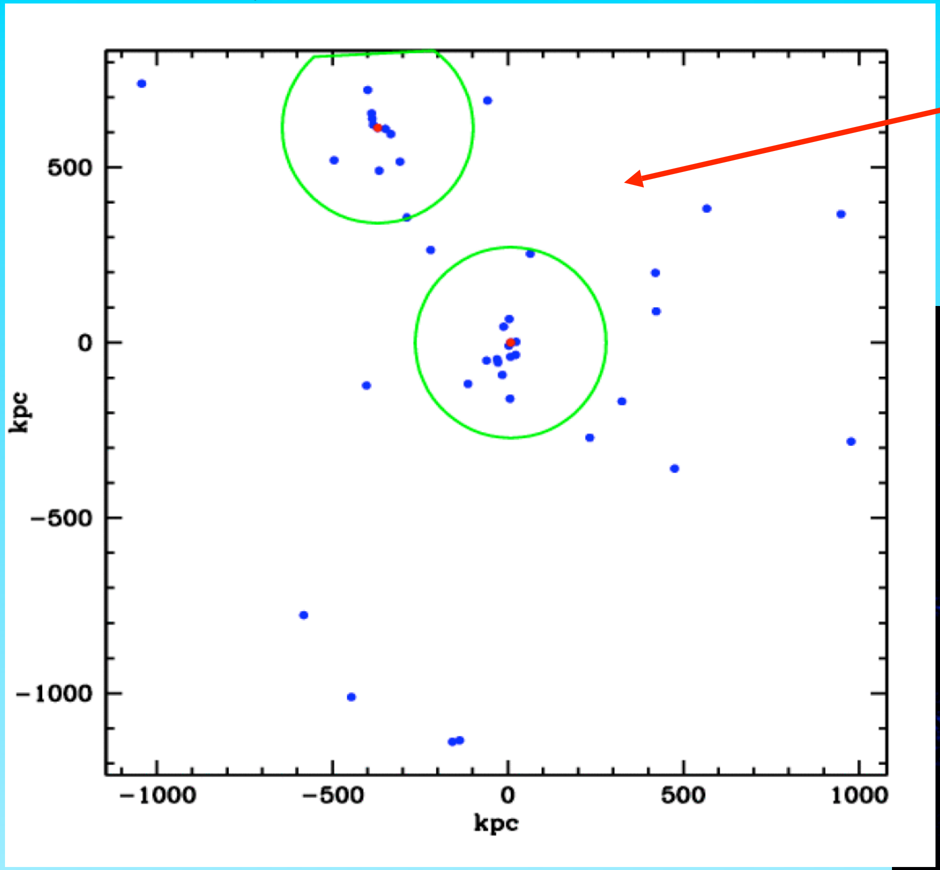
N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

- "Cuspy" density profiles
- Large number of self-bound substructures (10% of mass)

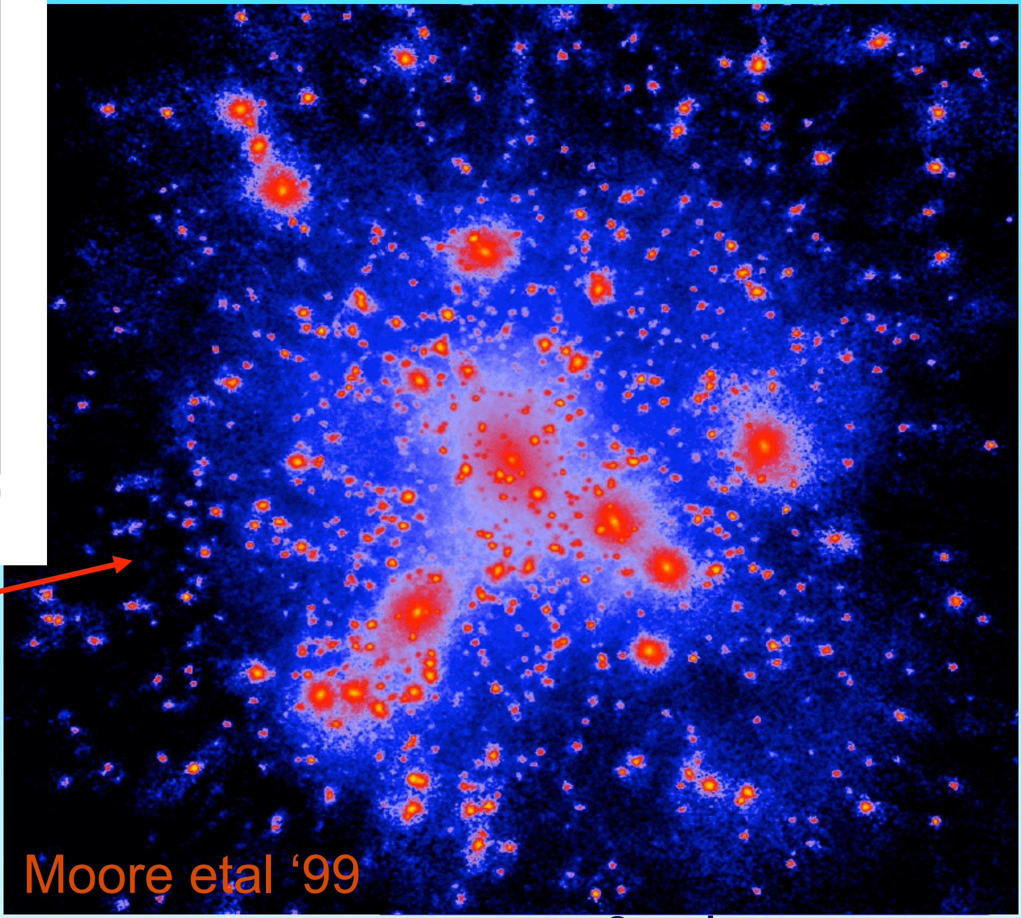
This has led to two well-publicized "problems":

- The "halo core" problem
- The "satellite" problem

The satellites of the Local Group

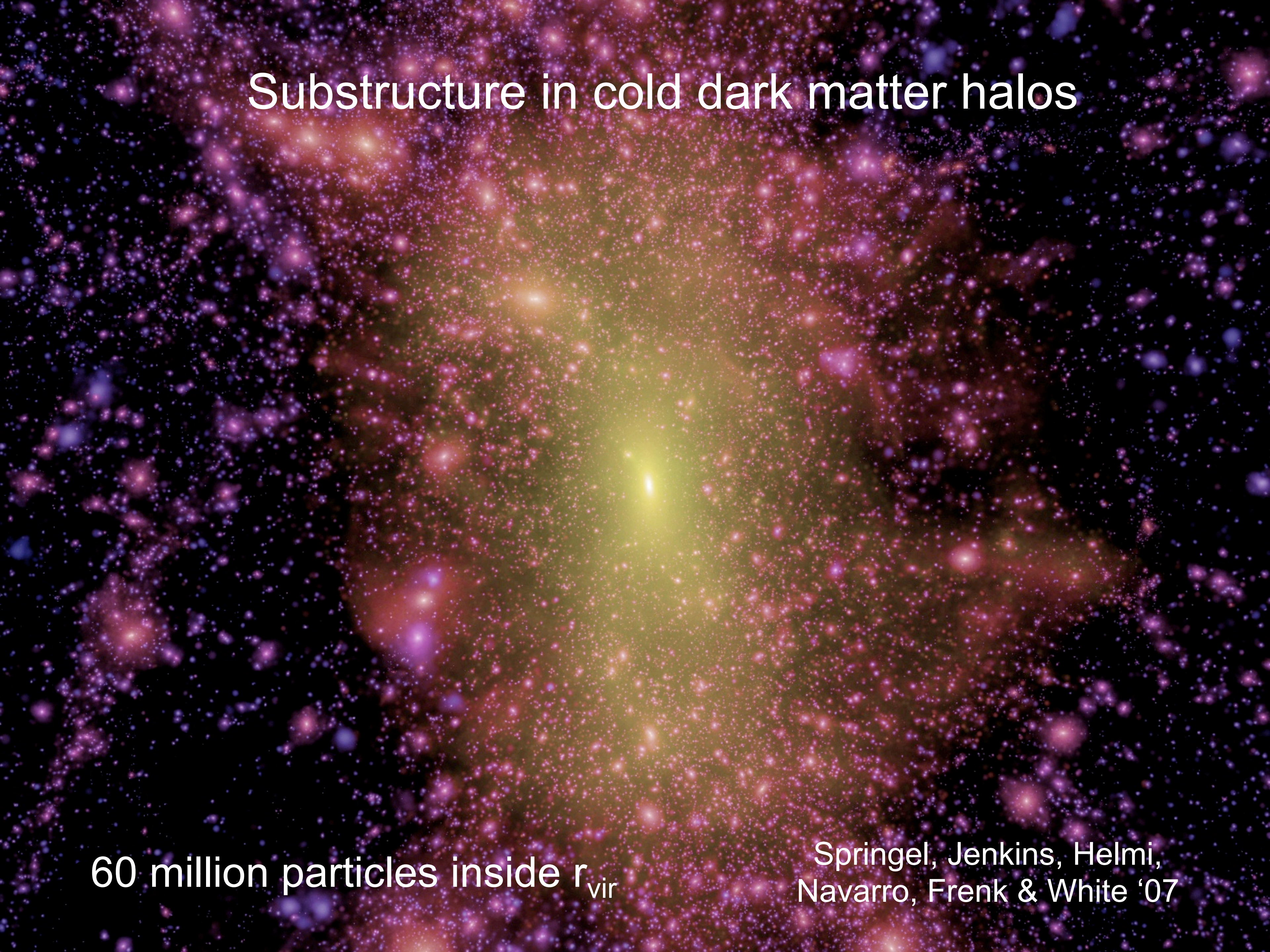


The Local Group contains only about 40 bright satellites



N-body simulations produce 1000s of small subhalos

Substructure in cold dark matter halos

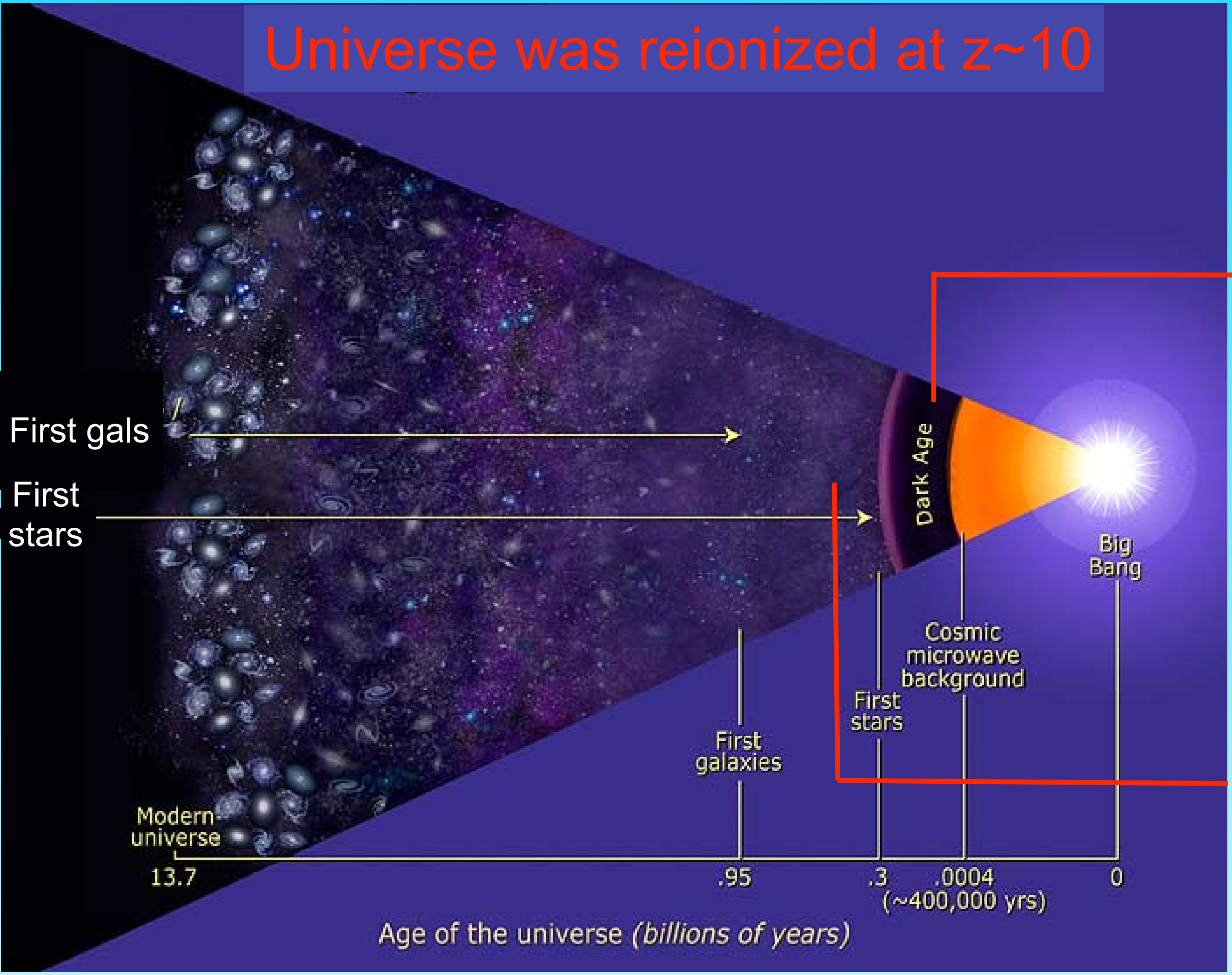


60 million particles inside r_{vir}

Springel, Jenkins, Helmi, Navarro, Frenk & White '07

University of Durham

Feedback in galaxy formation



From STSci picture gallery

Effects of reionization

Gas is neutral → cools in small halos

H is reionized at z~(10-6)

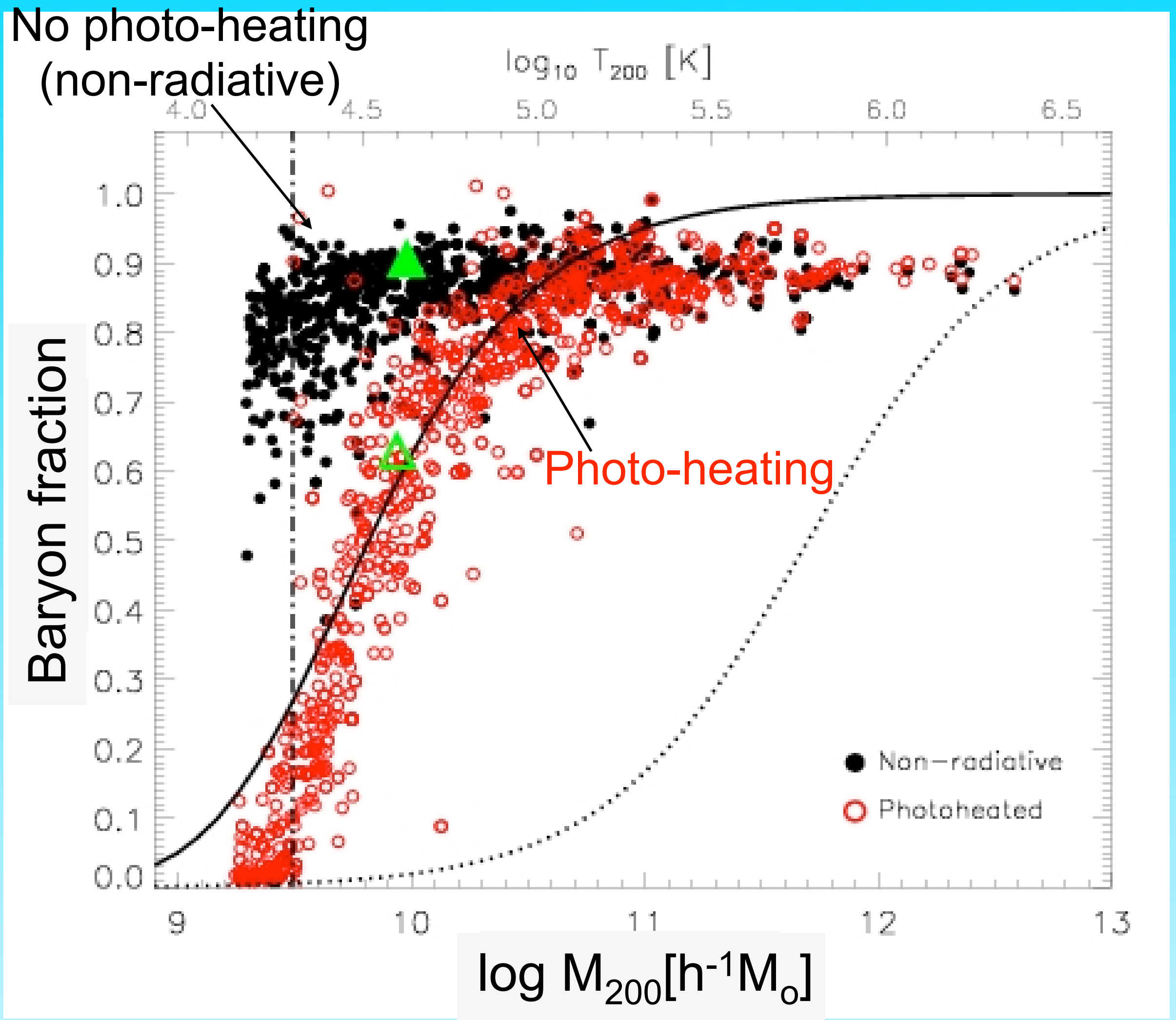
Gas heated ~10^4K → cannot cool in halos with V<40 km/s

Baryon habitats

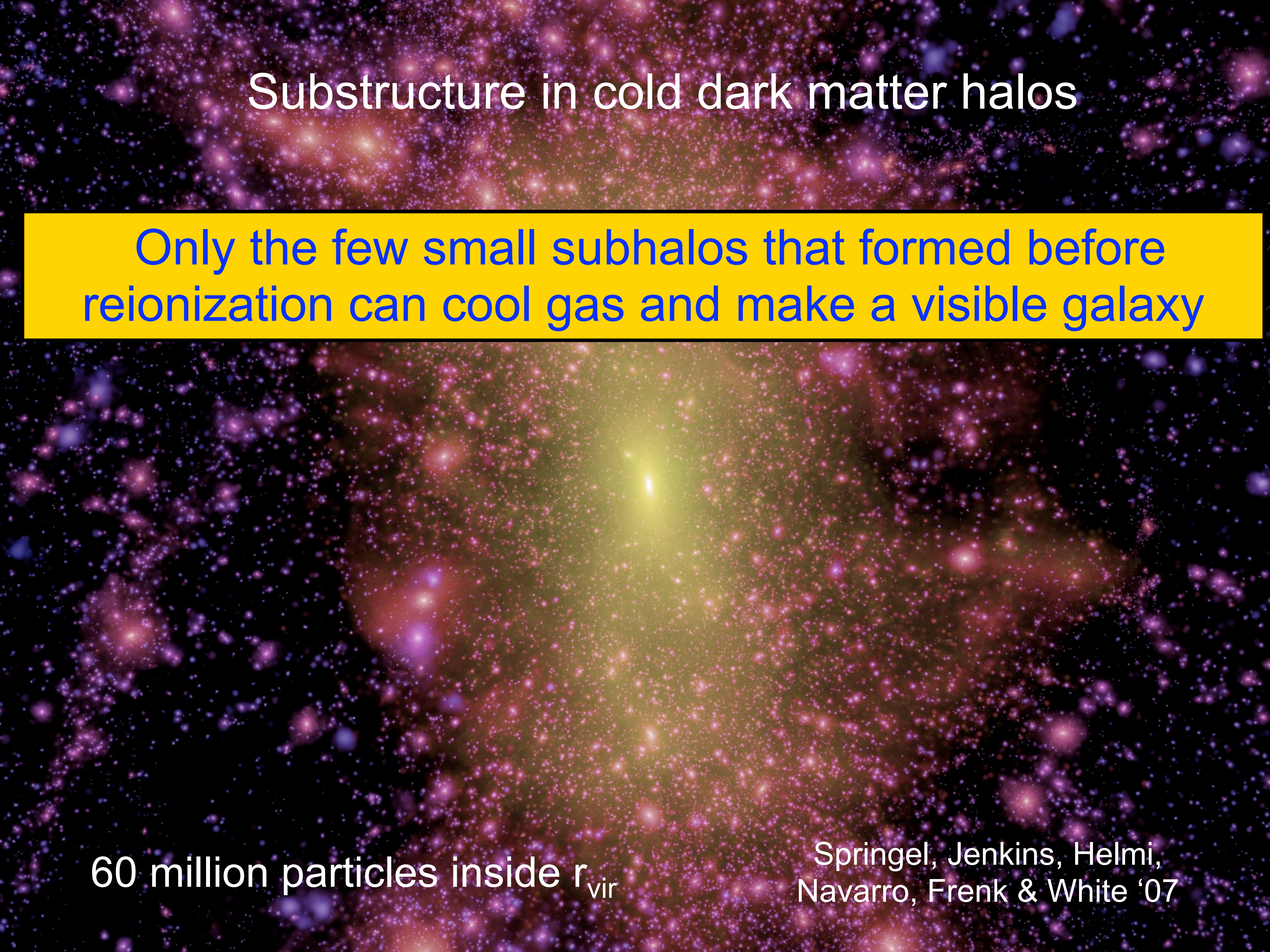
University of Durham

Simple photo-heating model: $T_{floor}=2\times10^4$K at z=11

Prevents collapse of baryons in halos with $V_{200}< 35$ km/s ($M_{200}<10^{10}\ M_o$)

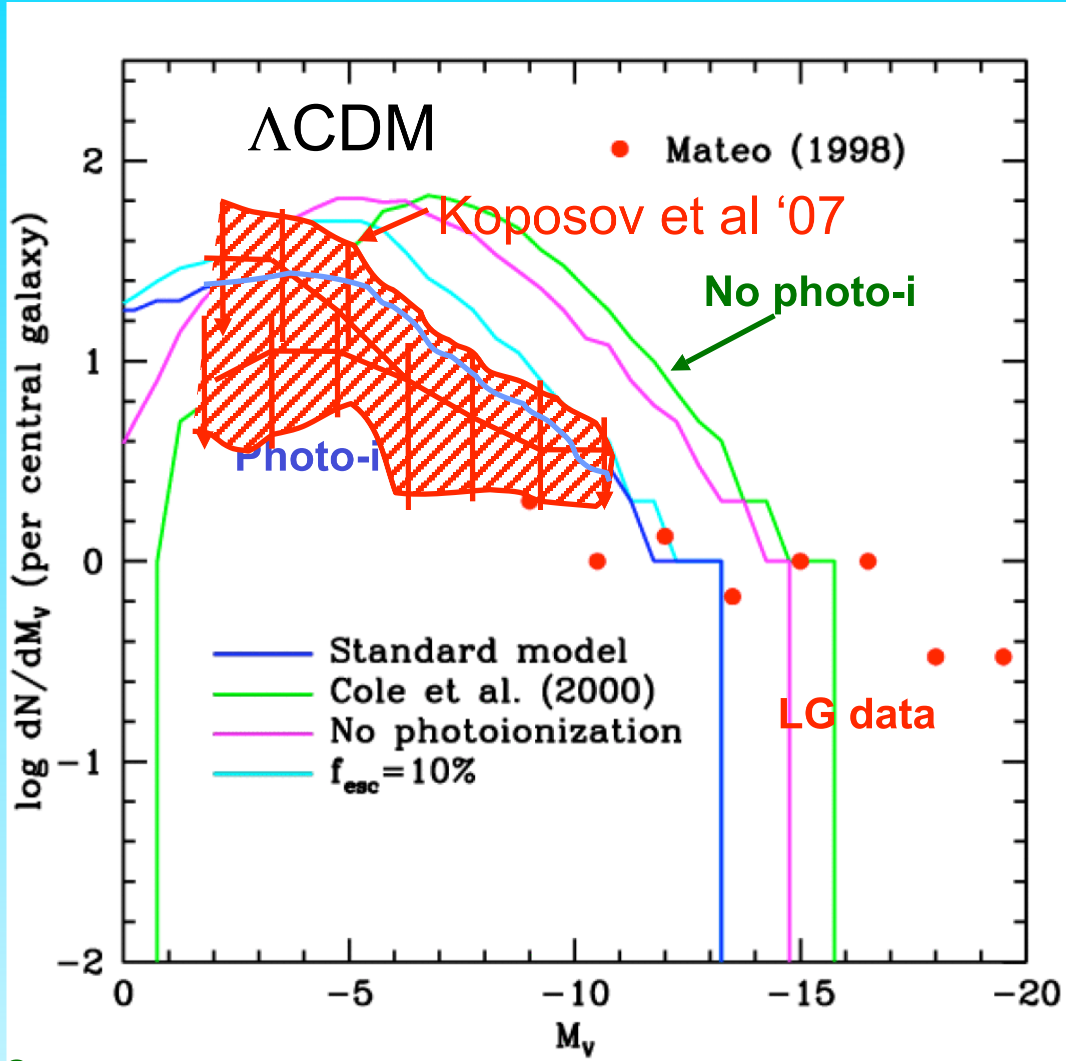


Crain, Eke, Frenk, Jenkins, McCarthy, Navarro & Pearce 07


Substructure in cold dark matter halos
Only the few small subhalos that formed before reionization can cool gas and make a visible galaxy
60 million particles inside r_{vir}
Springel, Jenkins, Helmi, Navarro, Frenk & White '07

Luminosity Function of Local Group Satellites

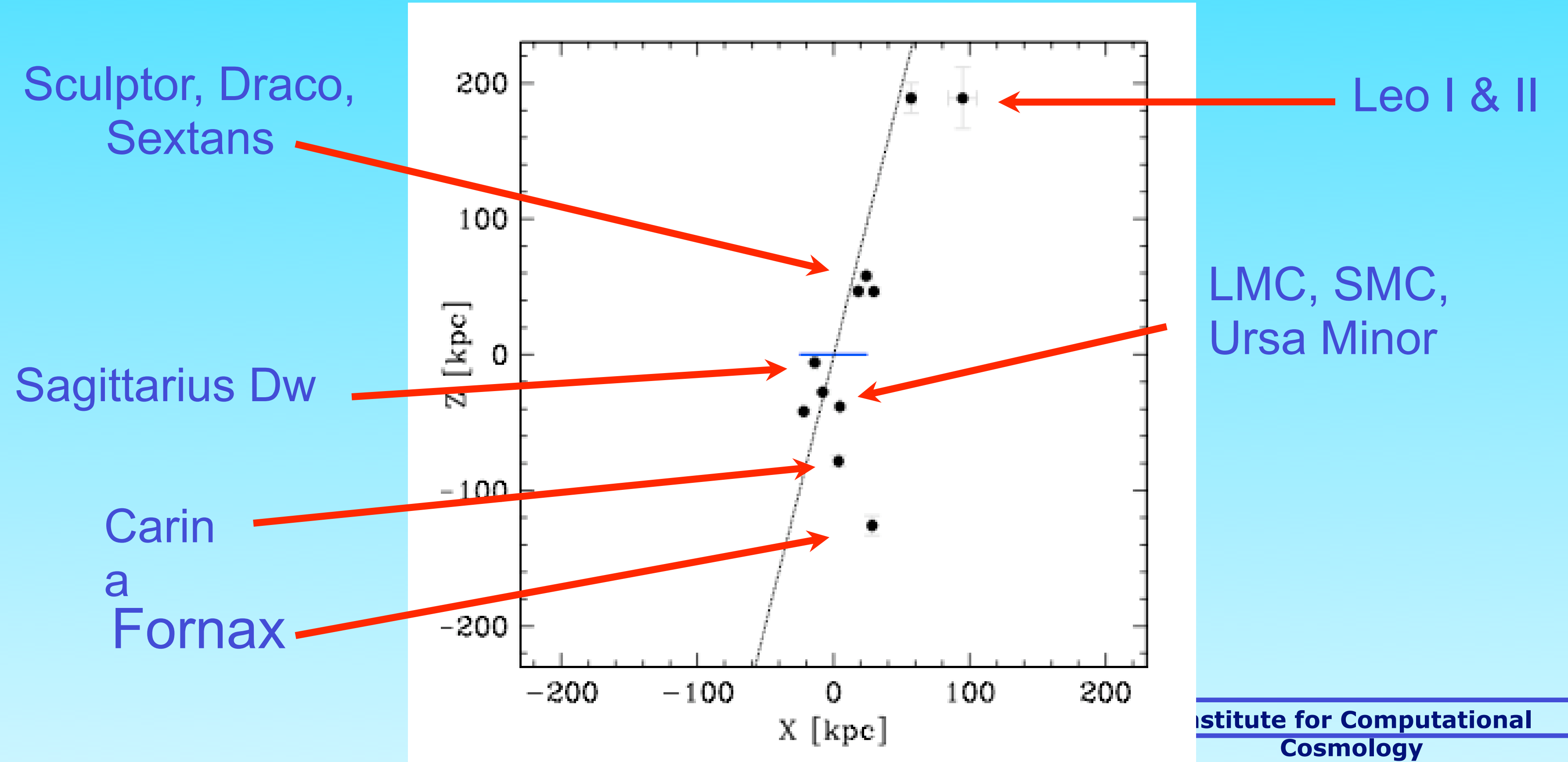
- Photoionization inhibits the formation of satellites
- Abundance reduced by factor of 10!
- Median model gives correct abundance of sats brighter than M_V=-9, V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

The satellites of the Milky Way

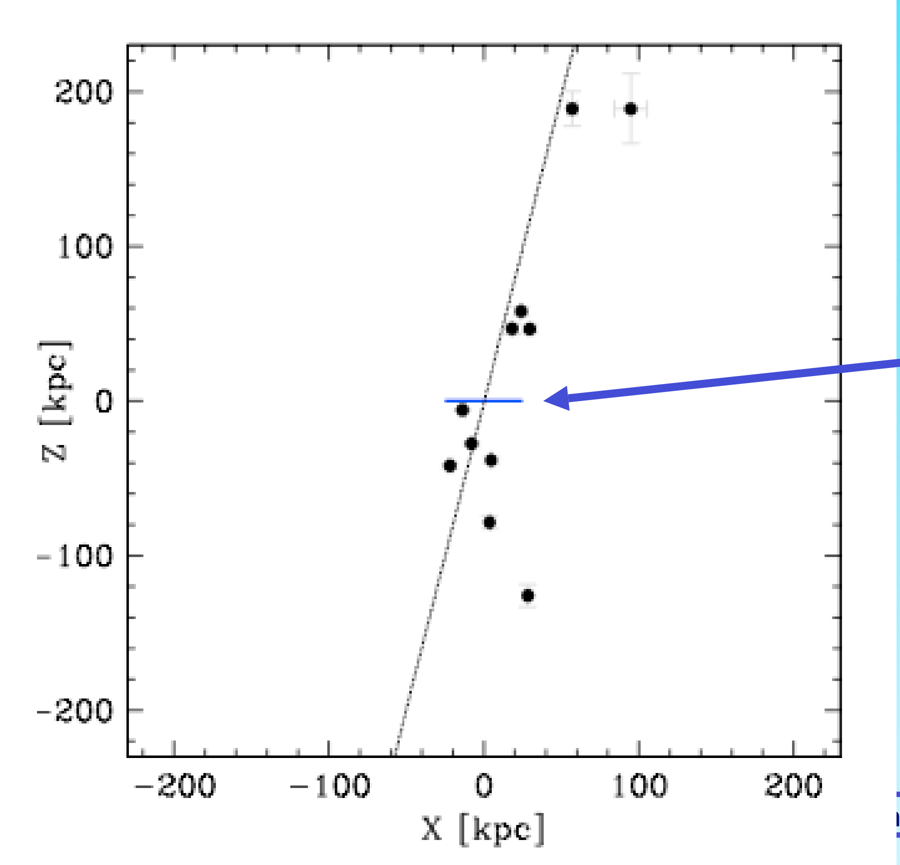
The 11 bright satellites within 250 kpc of the Milky Way lie roughly on a great circle on the sky (Lynden-Bell '67, Kroupa, etal '05)



University of Durham

The satellites of the Milky Way

The 11 bright satellites within 250 kpc of the Milky Way lie on a great circle on the sky (Lynden-Bell '67, Kroupa, etal '05)

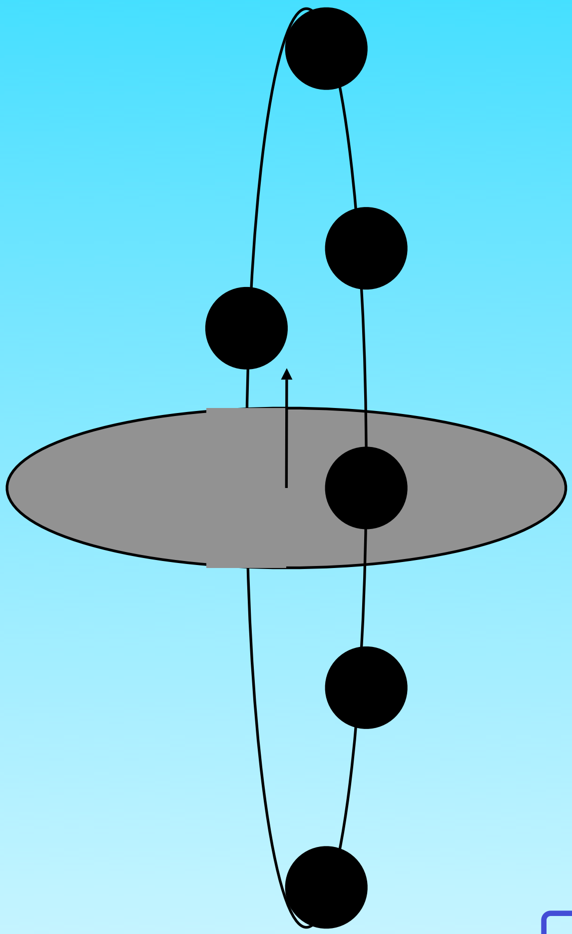


Milky Way's disk is perpendicular to the great circle

University of Durham

The satellites of the Milky Way

The 11 bright satellites within 250 kpc of the Milky Way lie on a great circle on the sky (Lynden-Bell ‘67, Kroupa, etal ‘05)



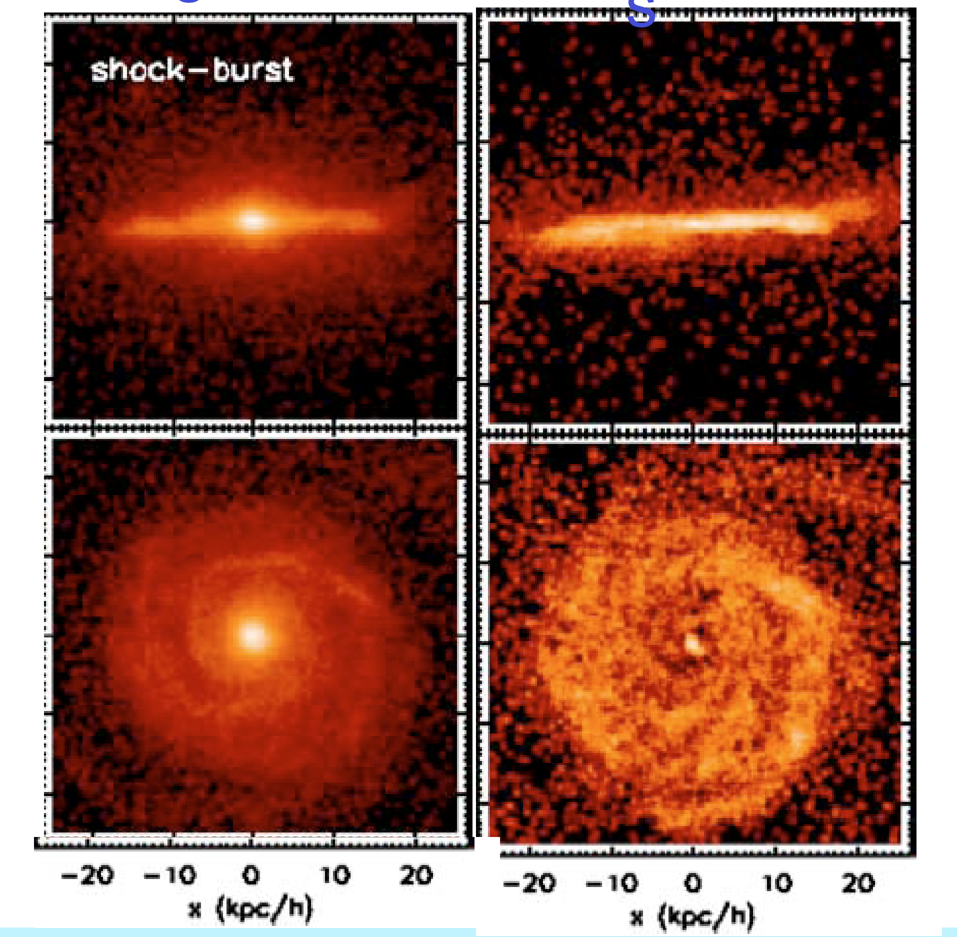
Simulations of disc galaxy formation

ΛCDM initial conditions

Smooth Particle Hydrodynamics (SPH)

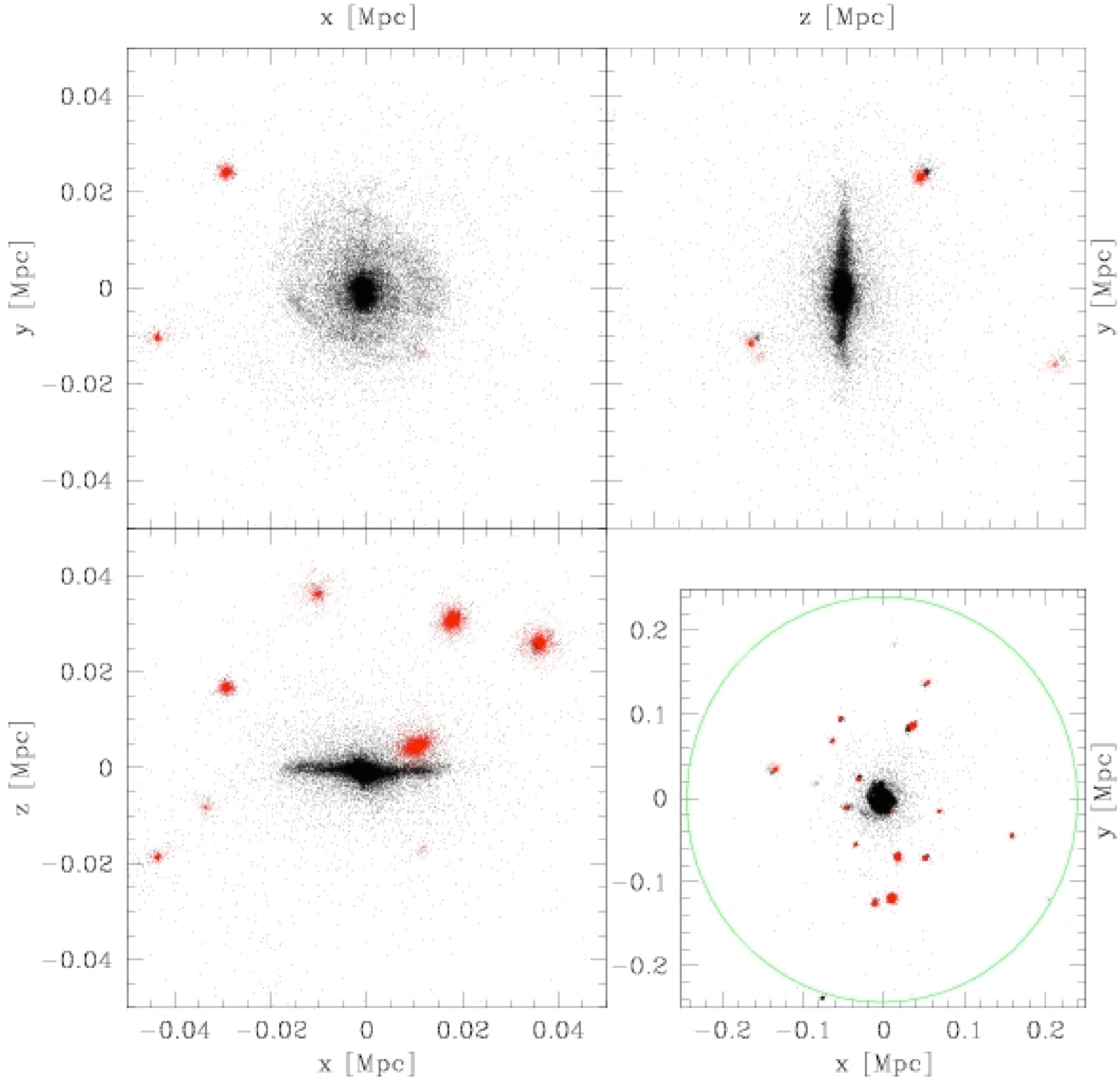
gas

star
s



Okamoto, Jenkins, Eke, & Frenk ‘05

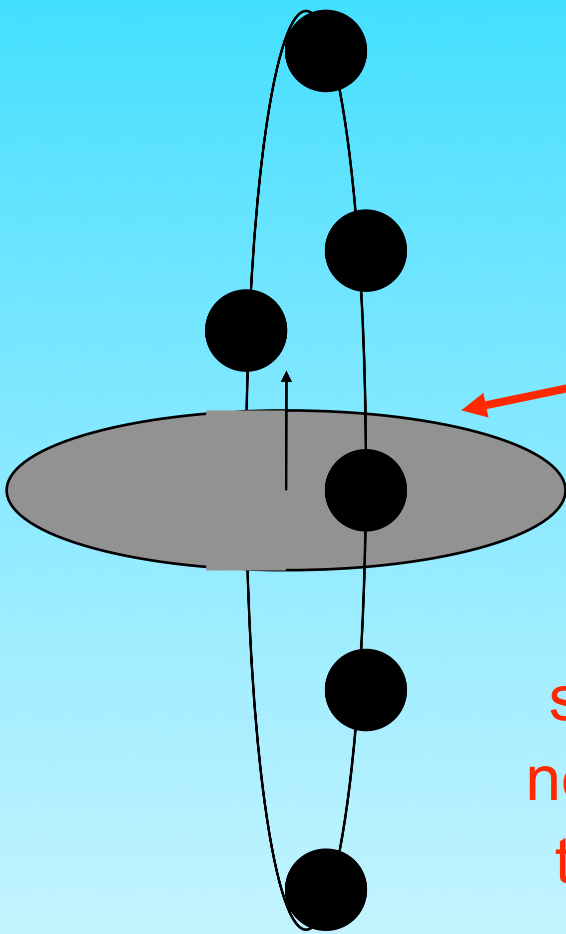
University of Durham

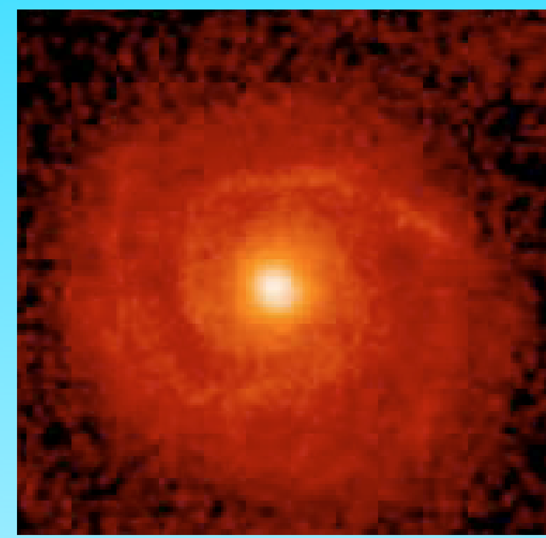


University of Durham

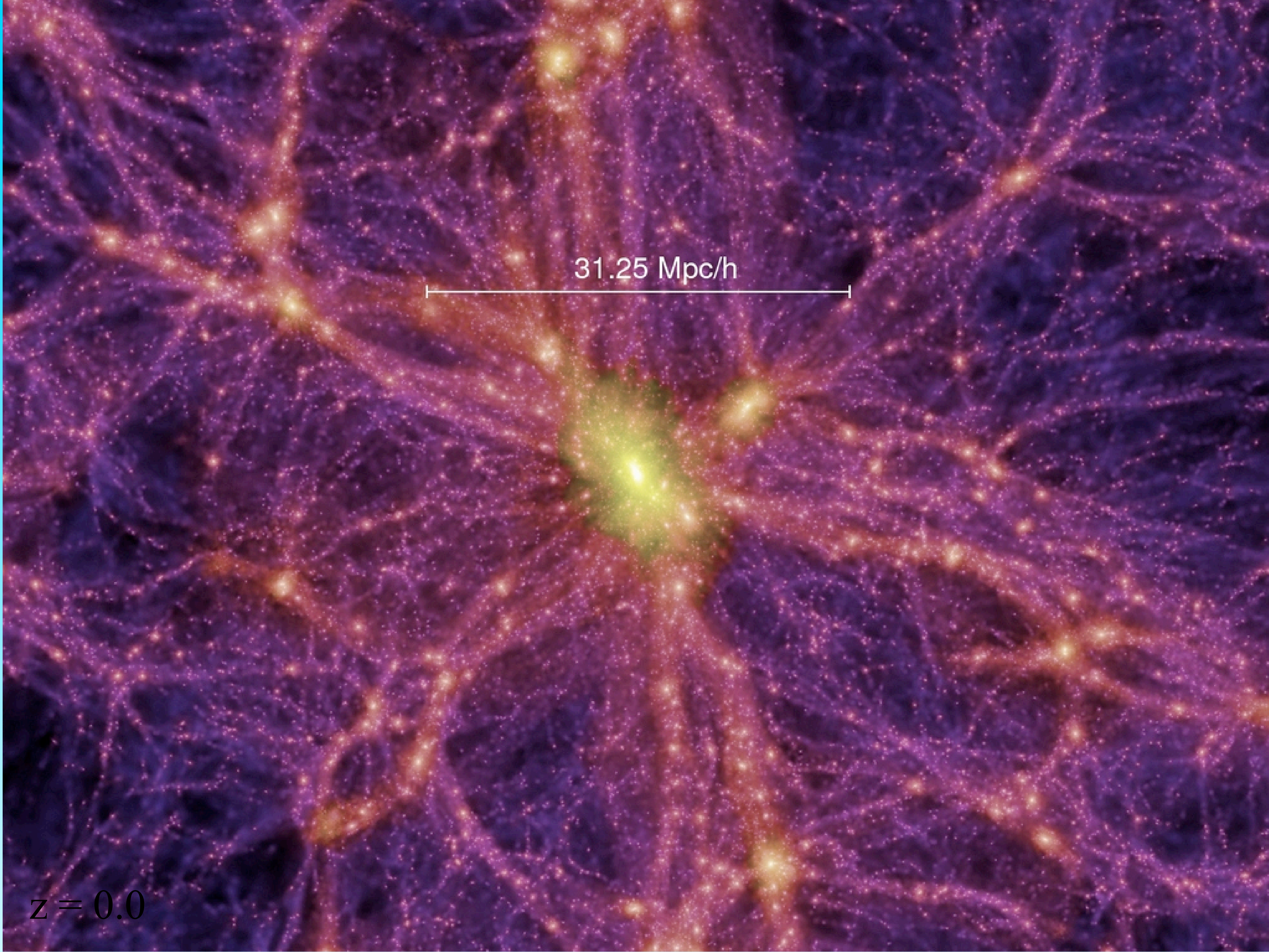
The satellites of the Milky Way

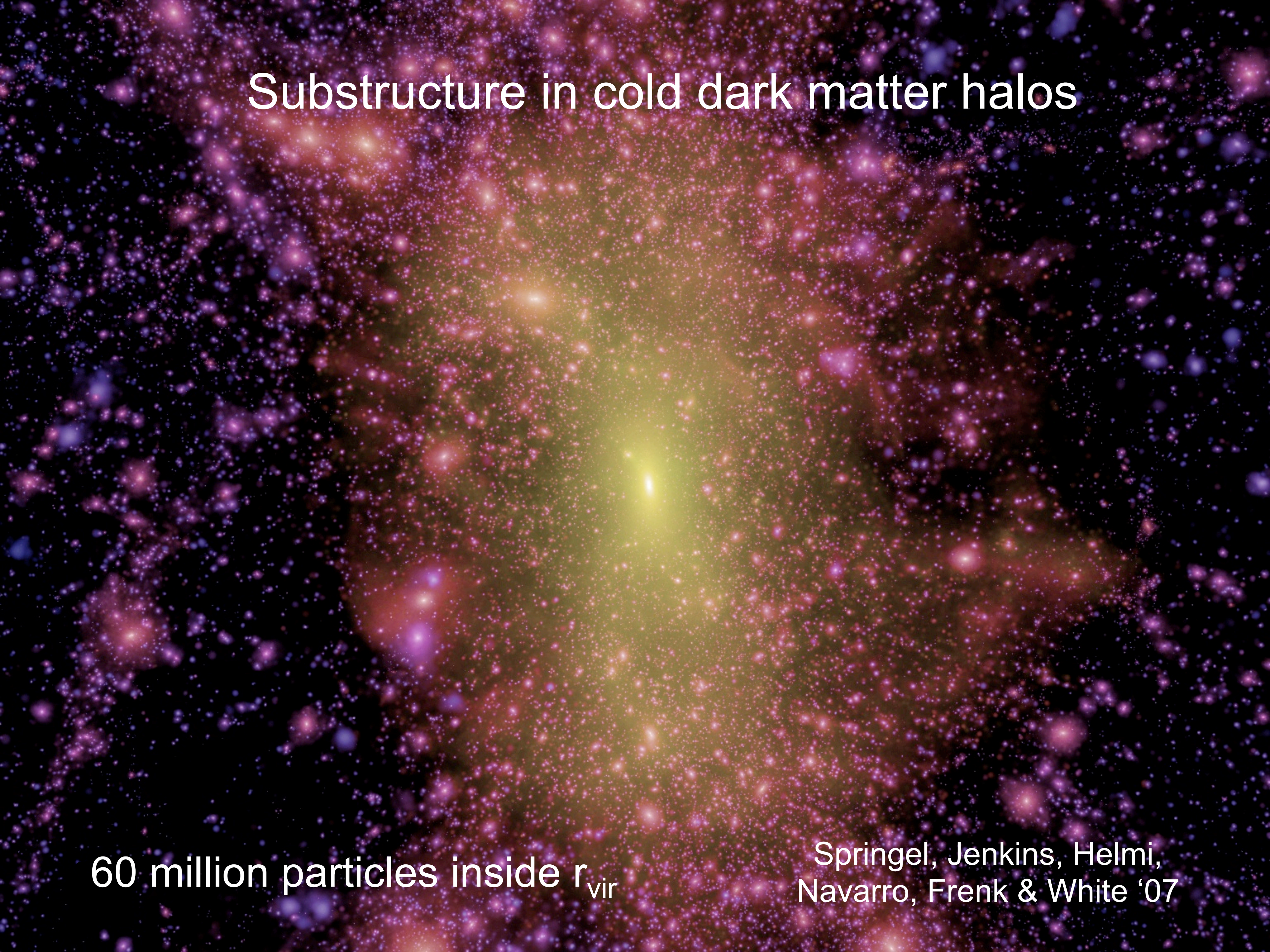
The 11 bright satellites within 250 kpc of the Milky Way lie on a great circle on the sky (Lynden-Bell ‘67, Kroupa, etal ‘05)





In 2/3 simulations, satellites system is nearly perpendicular to disk (within 20°)


31.25 Mpc/h
z = 0.0

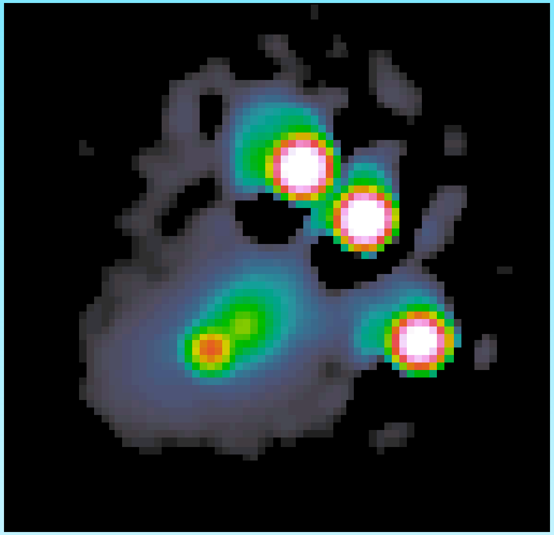

Substructure in cold dark matter halos
60 million particles inside r_{vir}
Springel, Jenkins, Helmi,
Navarro, Frenk & White ‘07

University of Durham

Substructure in CDM halos

Halos have large number of self-bound substructures containing ~10% of the masss and with $dN/dM \sim M^{-1.8}$

→ Substructures may be observable { Gravitational lensing effects; γ -ray annihilation emission



Anomalous flux ratios in multiply-imaged quasars ⇒ Substructure

Dalal & Kochanek '02, Metcalfe & Zhao '02

University of Durham

Conclusions: the ΛCDM model

➔ ΛCDM is an intrinsically implausible model that requires:

- An early epoch of inflation
- Quantum fluctuations in the early universe
- Non-baryonic dark matter
- Dark energy

➔ Yet, it agrees with staggering amount of data, from CMB to gals

➔ Baryon acoustic oscillations detected in 2dFGRS and SDSS

➔ Current generation of surveys to detect BAO at z~1 will constrain w but only to ~5%

➔ Data consistent with cusps in cluster halos

➔ "Satellite problem" probably solved by photoionization


The “golden” era in cosmology is not over
It has probably just begun!