The 2dF galaxy redshift survey and cosmological simulations

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The 2dF Galaxy Redshift Survey

1997- 2002

250 nights at 4m AAT

→221,000 redshifts to $b_j<19.45$

→median z = 0.11

First 100k z's released June/01

Full catalogue released July/03

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2dF Galaxy Redshift Survey:
Team Members

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Institutions

[1]Anglo-Australian Observatory
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[13] Liverpool John Moores University

33 people at 12 institutions

Institute for Computational Cosmology

The 2dF galaxy redshift survey

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The 2dF galaxy redshift survey

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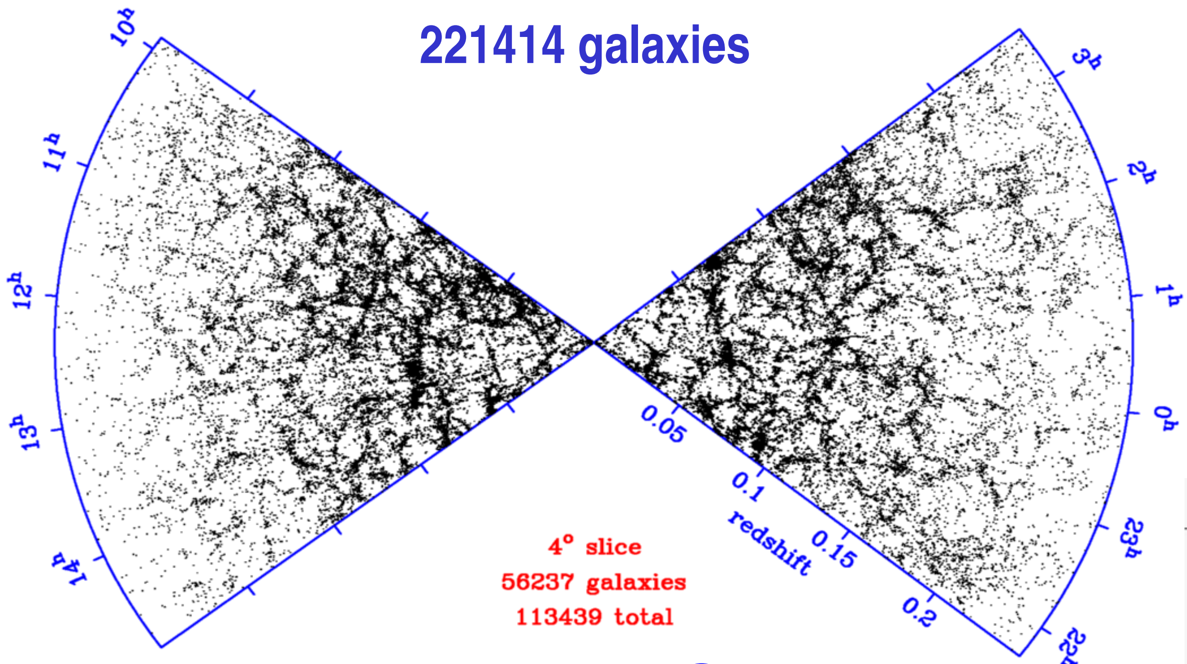
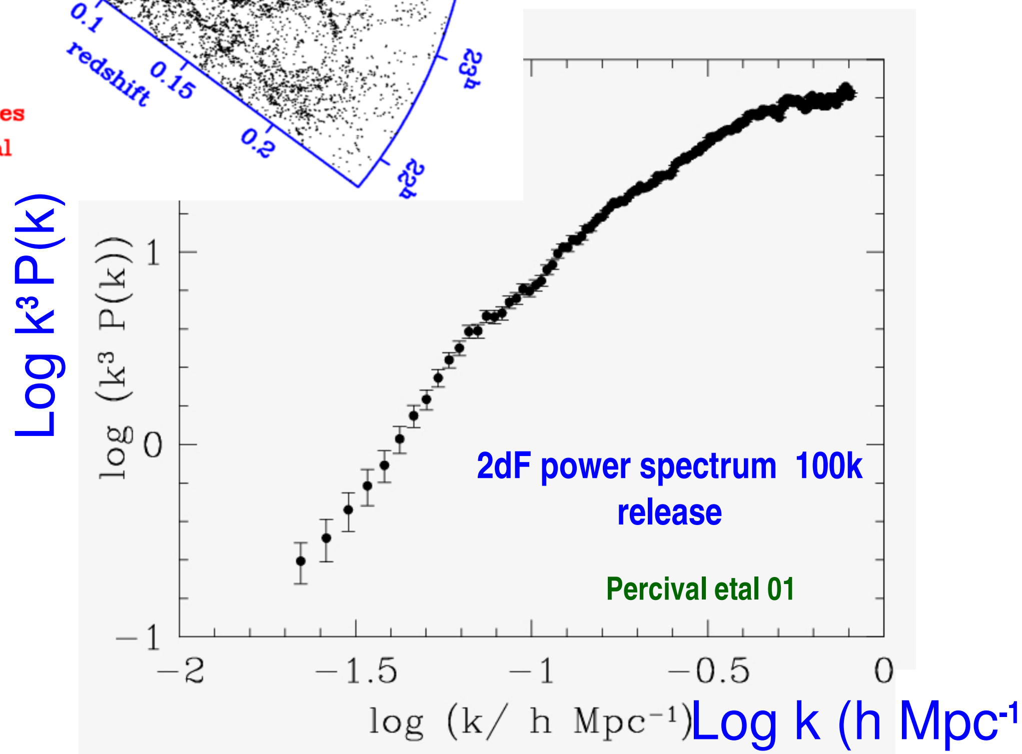


Galaxy power spectrum

in redshift space, convolved with survey window, inclunding non-linear effects



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Galaxy surveys and cosmological simulations

Simulations are essential for:

- Taking into account window function and selection effects
- Taking into account non-linear effects and 'galaxy bias'
- Assessing systematic and random errors
- Comparing data to theory

Simulations must:

- Be realistic
- Have a sufficiently large volume
- Resolve the structures of interest

$\Rightarrow$ Large number of particles

Hubble Volume
N-body simulat^{n}

Ω_Λ=0.7; Ω_m=0.3
h=0.7; σ_8=0.9

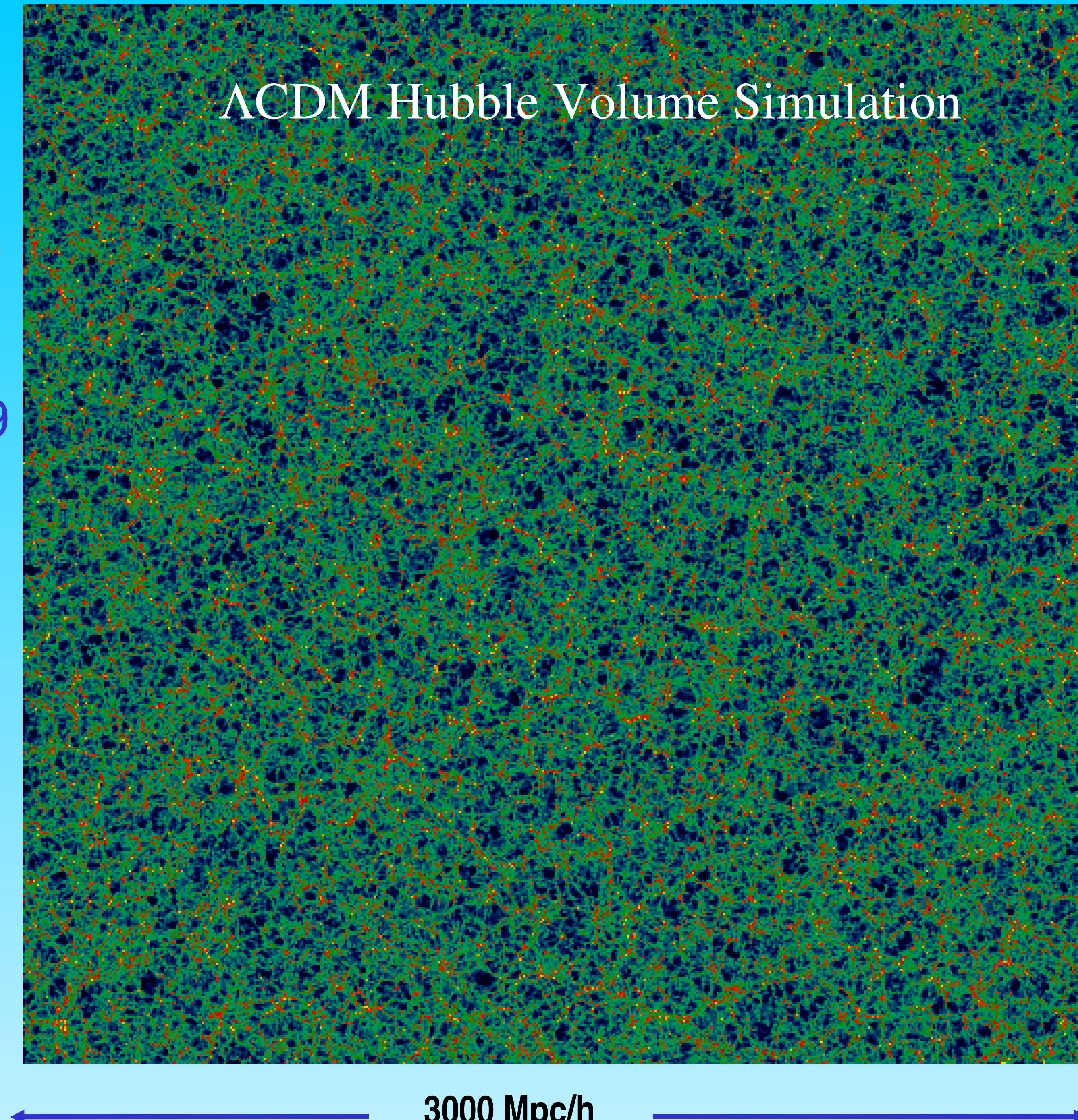
$N_p = 10^9$

L = 3000 Mpc

$m_p = 1 \times 10^{12} M_o$

Virgo consortium

(1999)



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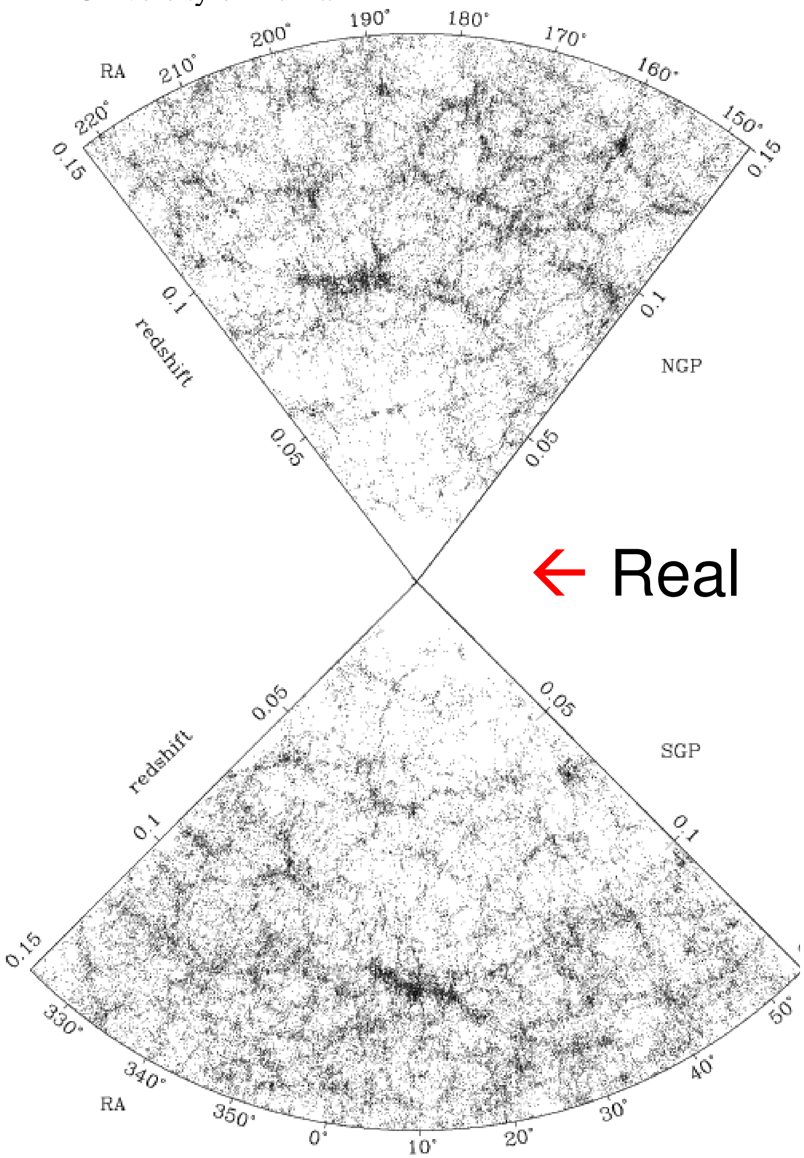
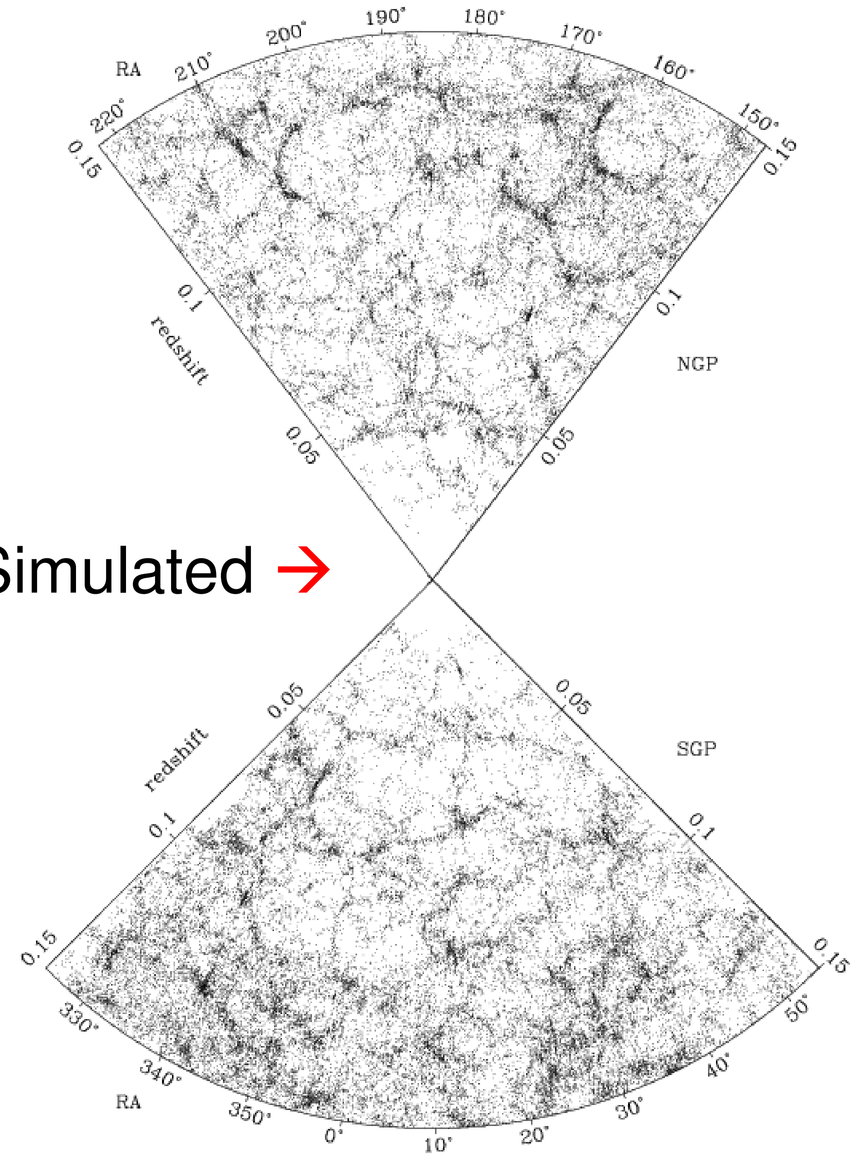
Real and simulated 2dF galaxy survey



← Real

Simulated →



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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

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)

The mass power spectrum

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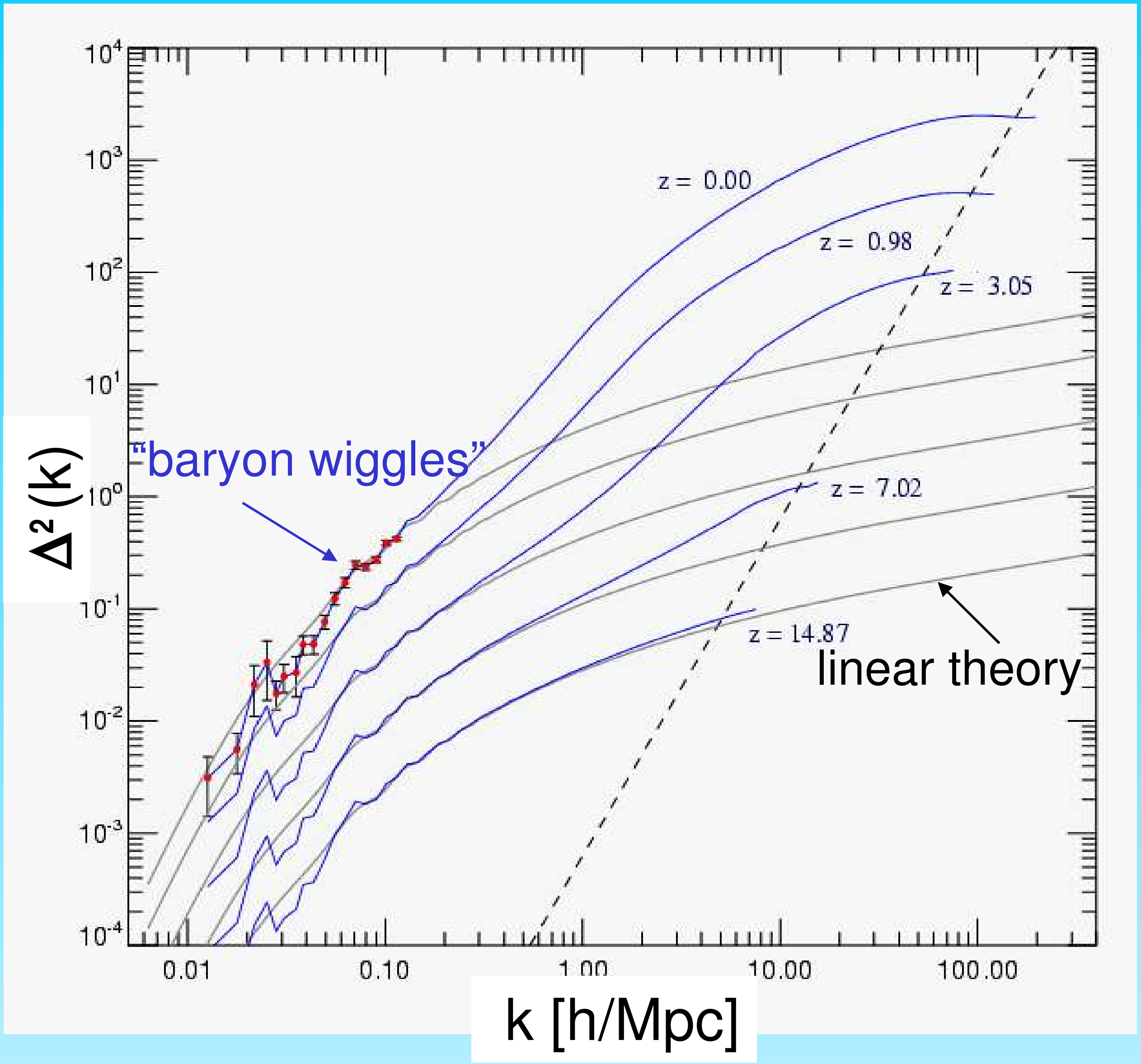
The non-linear mass power spectrum is accurately determined by the Millennium simulation over large range of scales



CMB anistropies and large-scale structure

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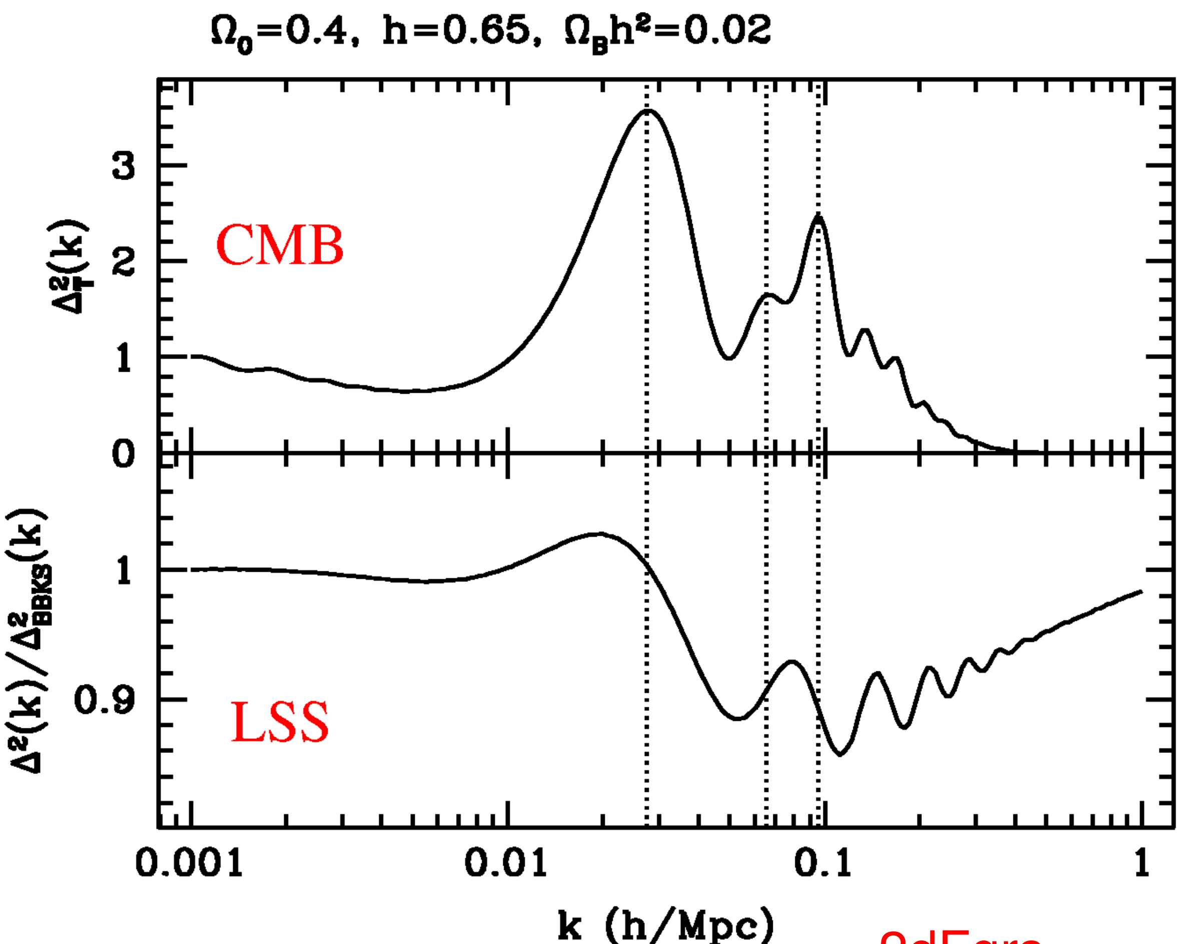


2dFgrs

CMB and LSS out of phase:

'velocity overshoot'

LSS amplitude smaller than CMB

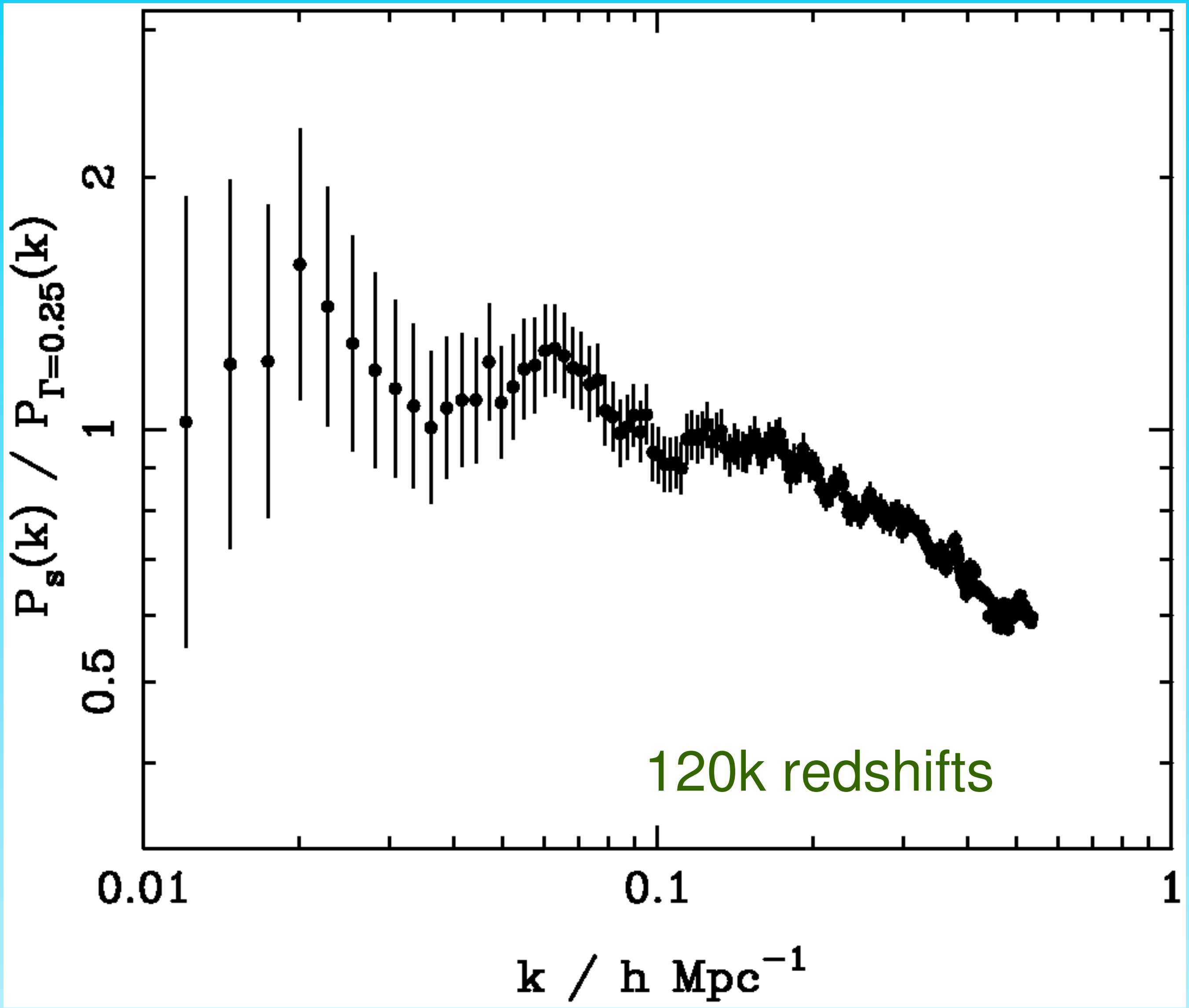
Baryon oscillations in the power spectrum

- Predicted by CDM model
- Can be used to estimate Ω_b / Ω_m
- Provide a “standard ruler” that can be used to measure w

First tentative detection in 100k 2dFGRS

100k 2dFGRS power spectrum

2dFGRS PS divided by Ωh=0.25 CDM model (zero baryons)



Percival etal 2001

Baryon oscillations in the power spectrum

Oscillations difficult to detect because:

- Amplitude is very small
- Survey window can smooth over features
- Non-linear effects can erase oscillations
- Wiggles are in mass, but we observe galaxies (in z-space)

→ Need to use large cosmological simulations to establish detectability of baryon oscillations.

Baryon oscillations

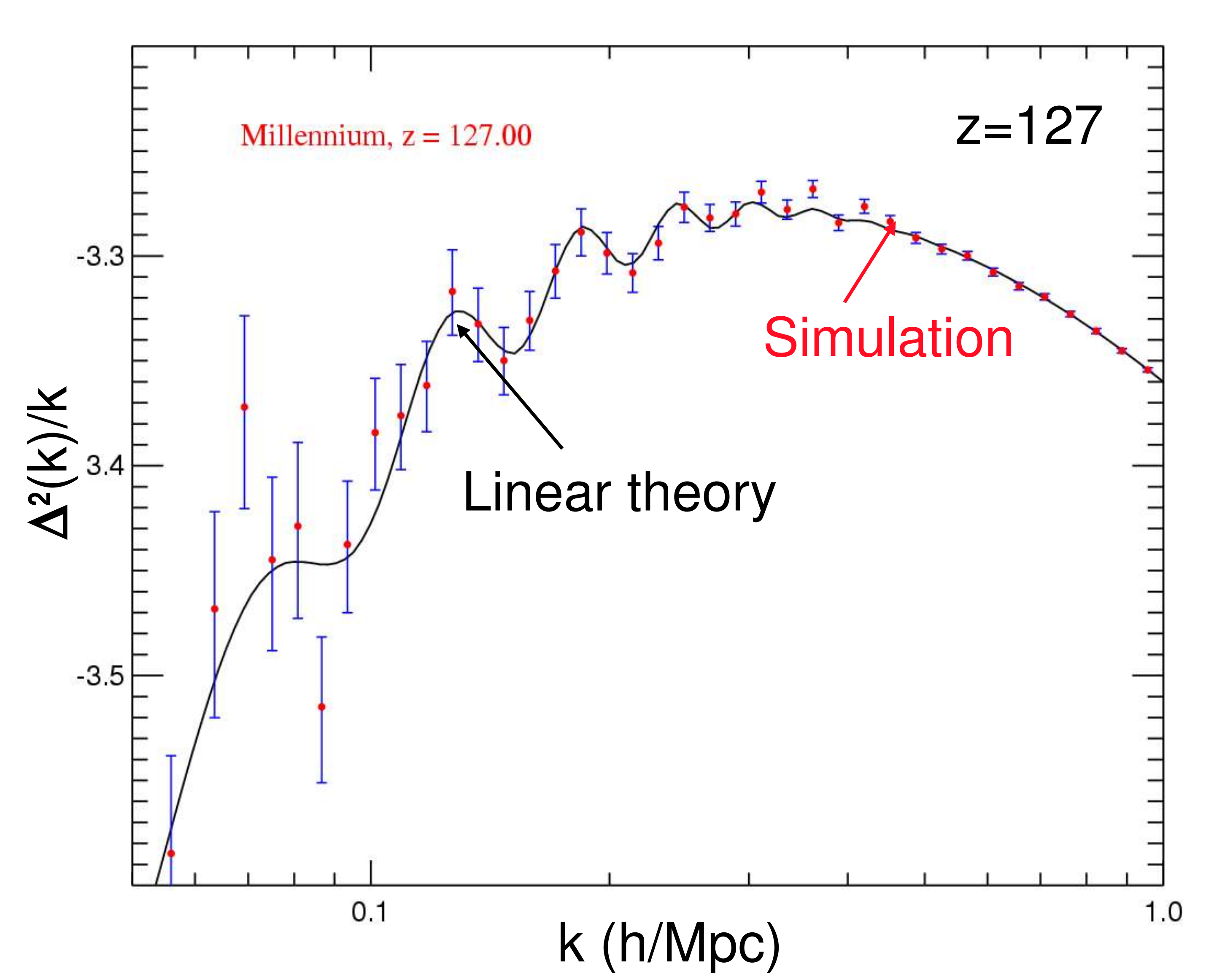
Baryon oscillations are predicted in the dark matter P(k) in linear theory:

1. Are they erased by non-linear evolution?
2. Are they also present in the galaxy distribution?

The mass power spectrum

University of Durham

Millennium simulation



The Millennium sim is large enough to resolve baryonic wiggles in the matter power spectrum

Virgo consortium
Springel etal ‘05

The mass power spectrum

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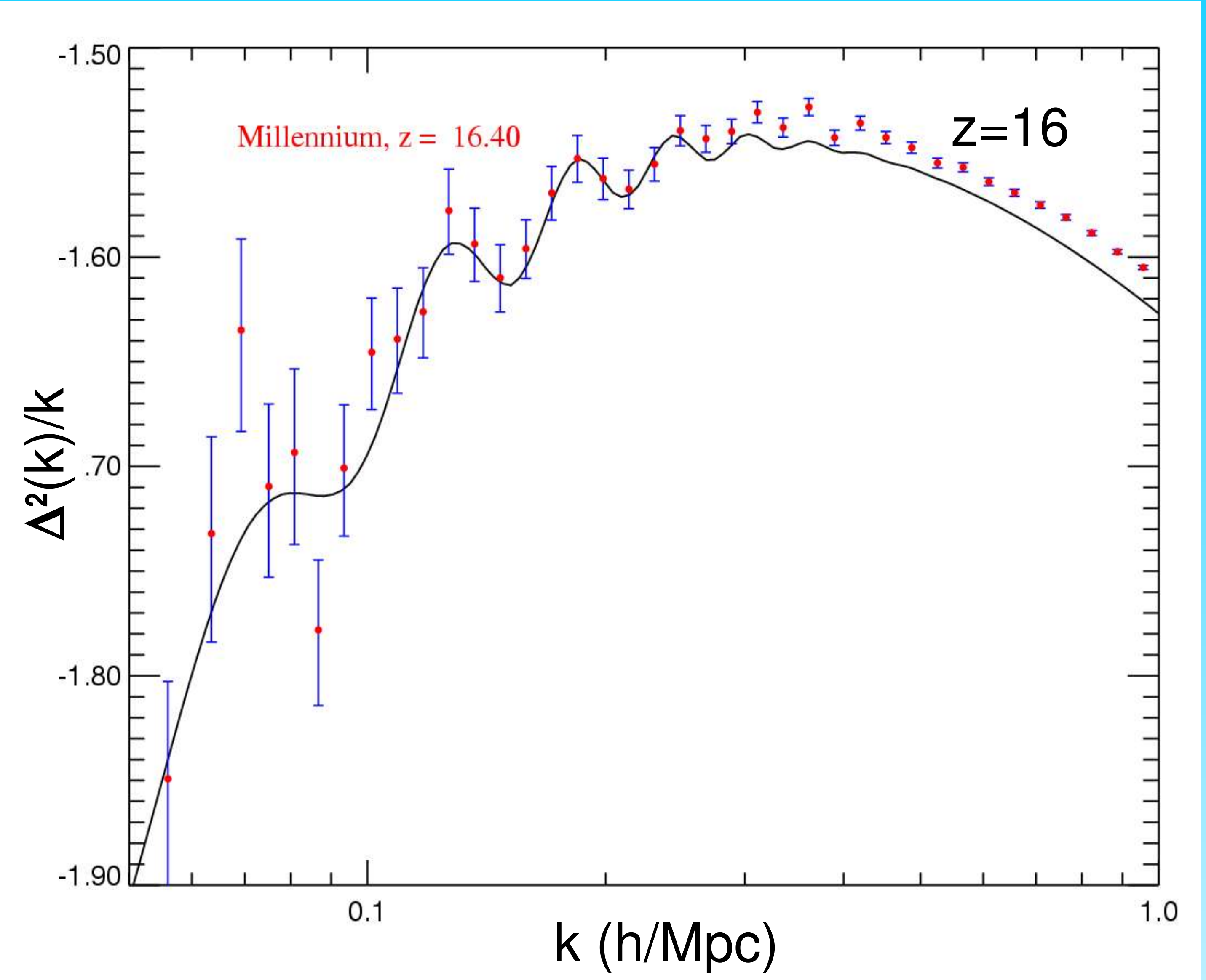
Millennium simulation



Virgo consortium
Springel etal '05

The mass power spectrum

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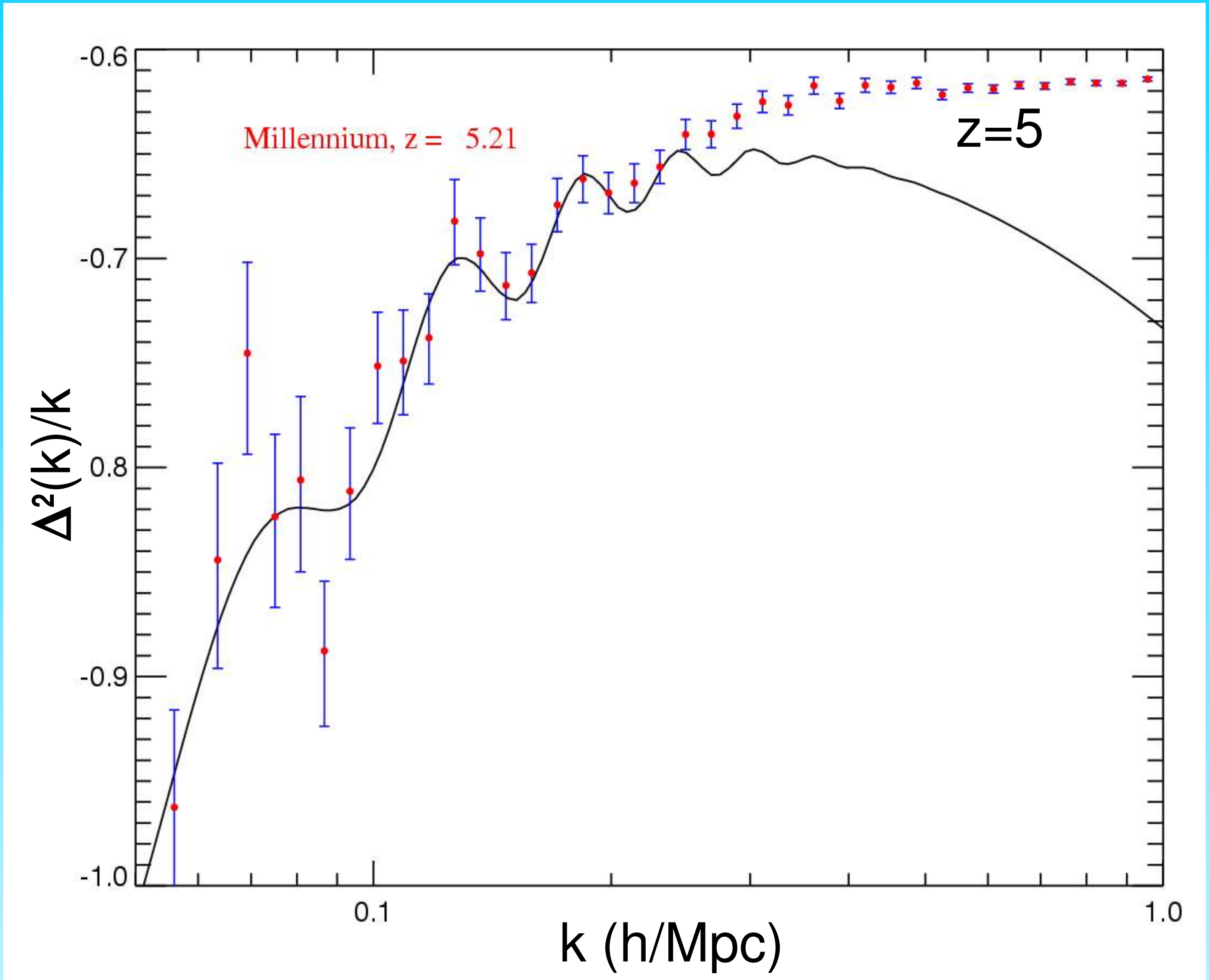
Millennium simulation



Virgo consortium
Springel etal '05

The mass power spectrum

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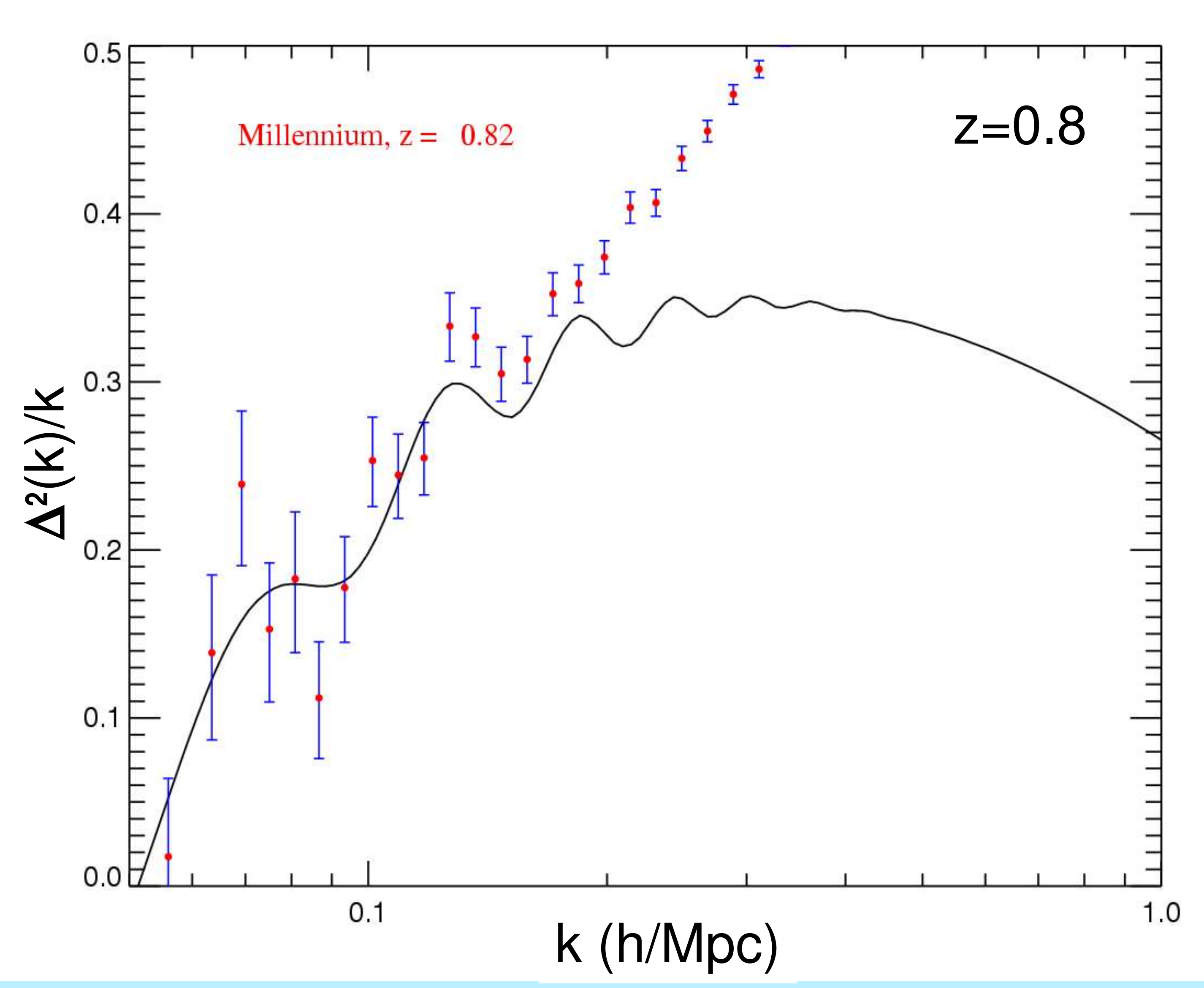
Millennium simulation

Non-linear evolution accelerates the growth of power and eliminates structure in the spectrum by mode-coupling

Virgo consortium
Springel etal '05



The mass power spectrum

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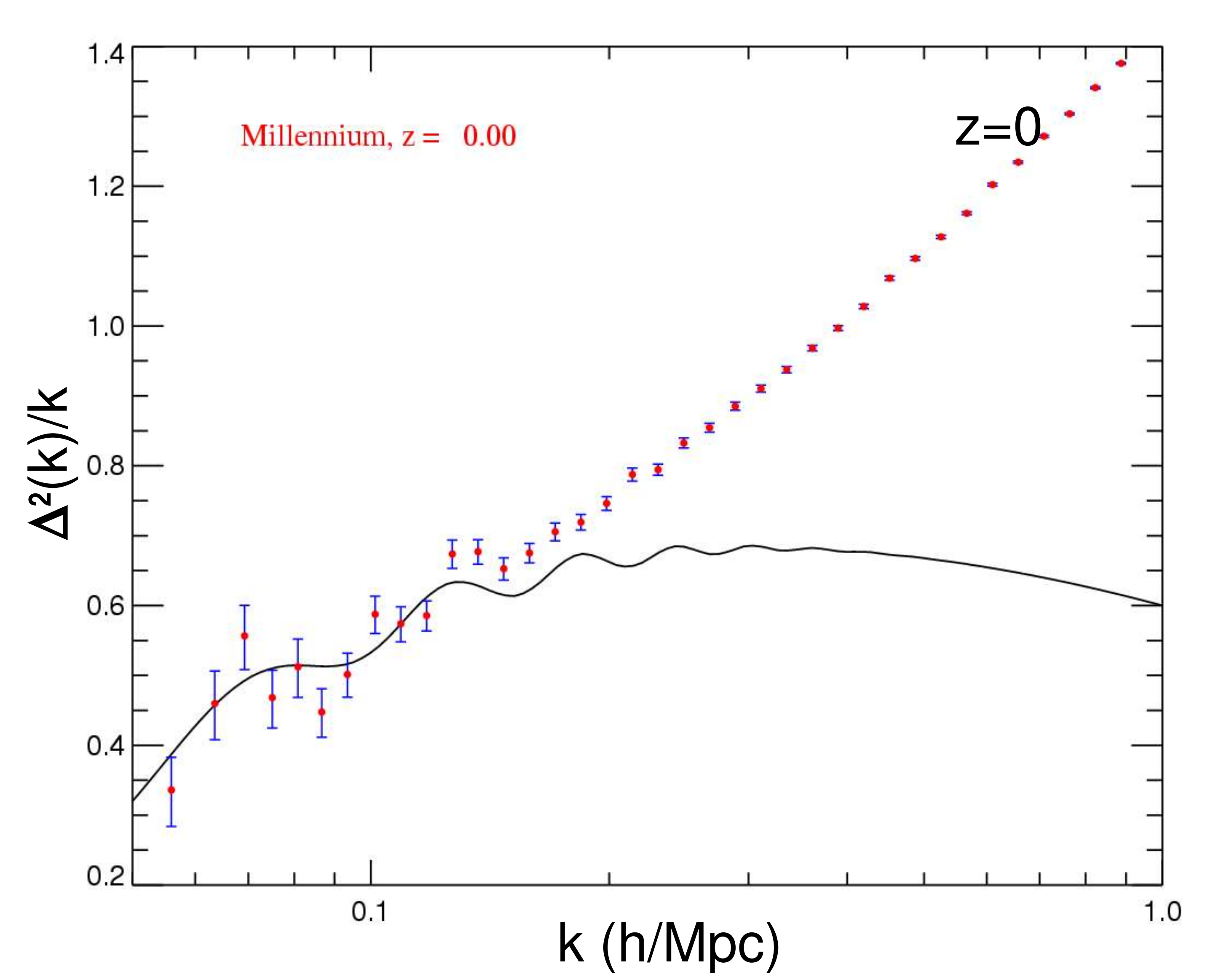
Millennium simulation

Non-linear evolution accelerates the growth of power and eliminates structure in the the spectrum by mode-coupling

Virgo consortium
Springel etal '05



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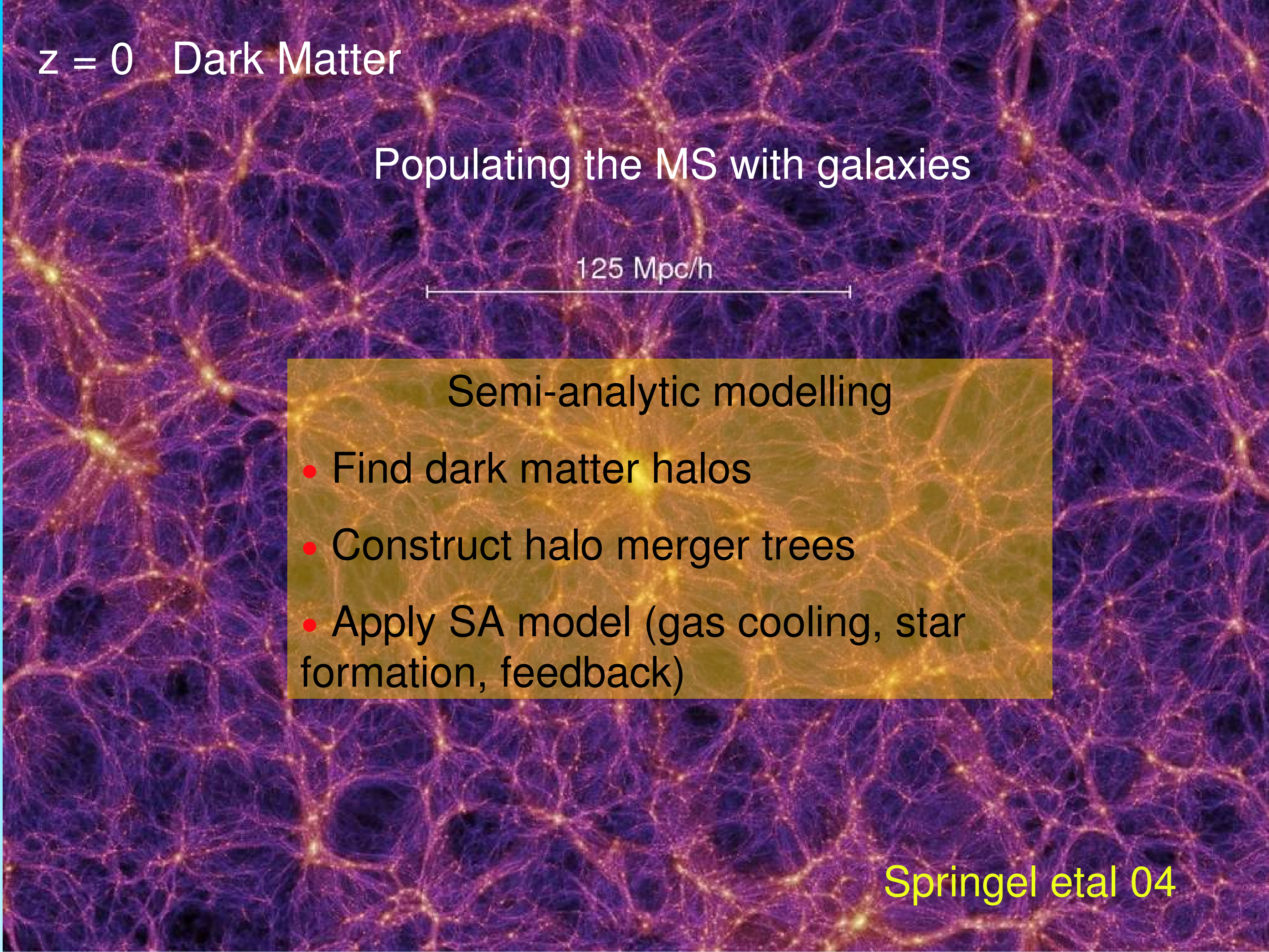
Baryonic wiggles in the power spectrum

Baryonic oscillations in the dark matter PS survive non-linear effects for log k ≤ -0.7

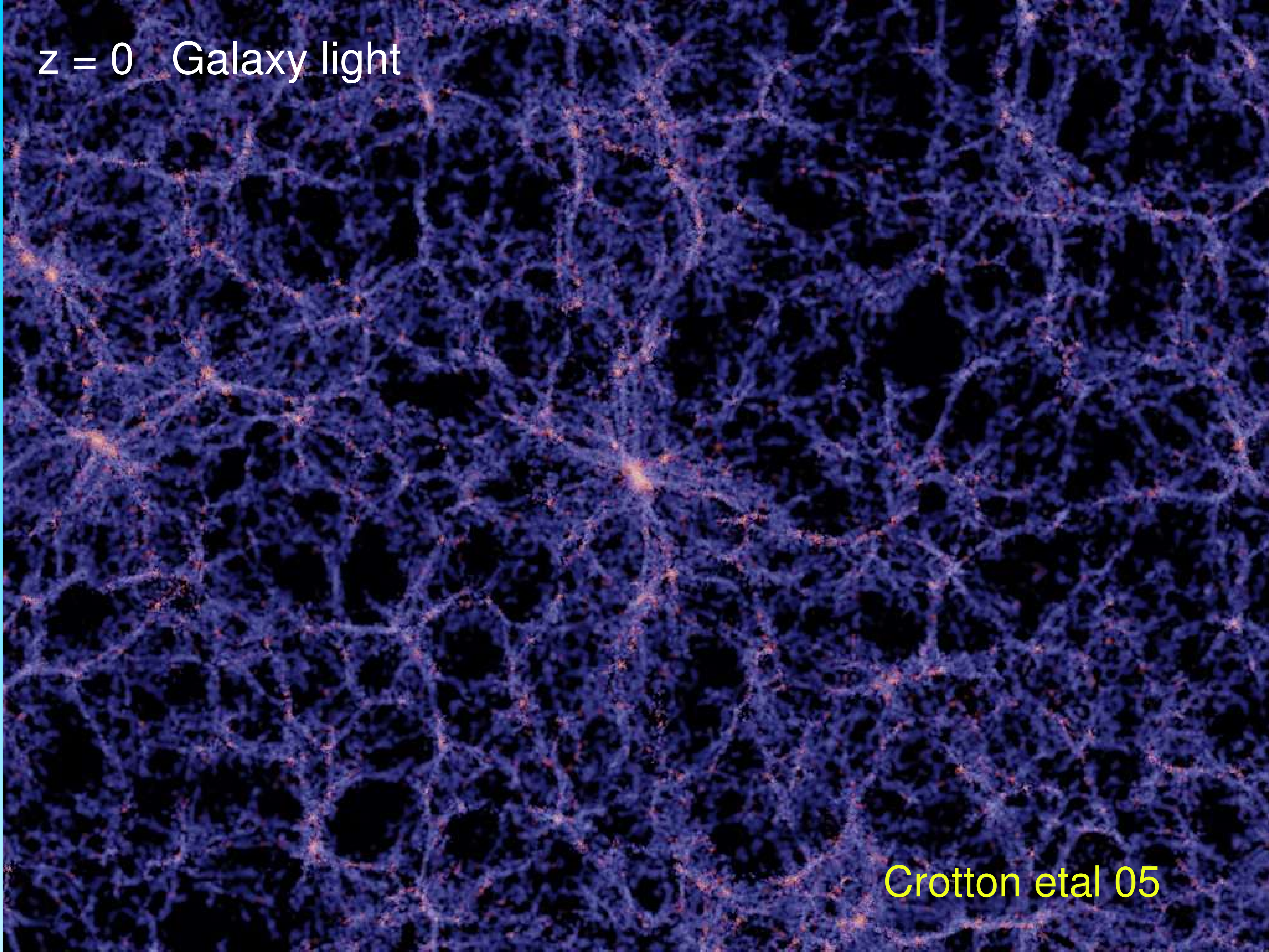
What about in the galaxy PS?



Populating the MS with galaxies

Semi-analytic modelling

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


z = 0 Galaxy light
Crotton etal 05

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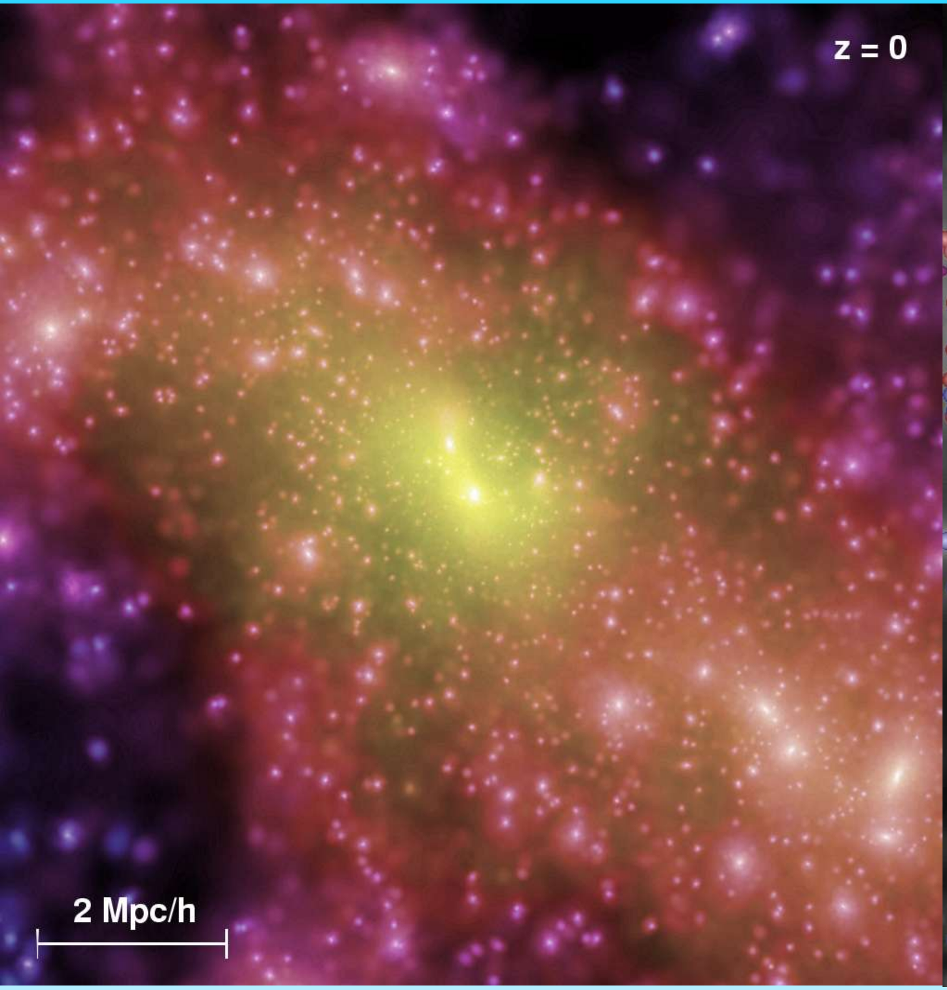
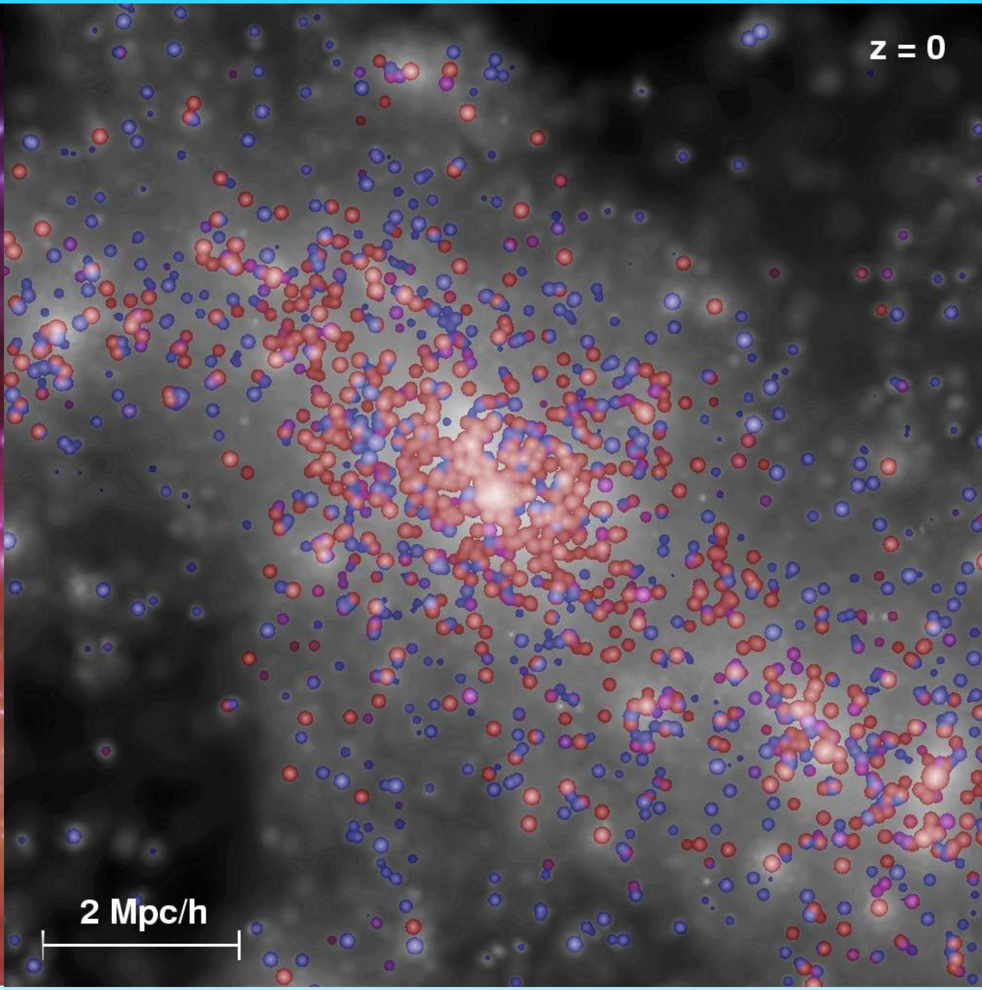
$10^{14}M_{o}$

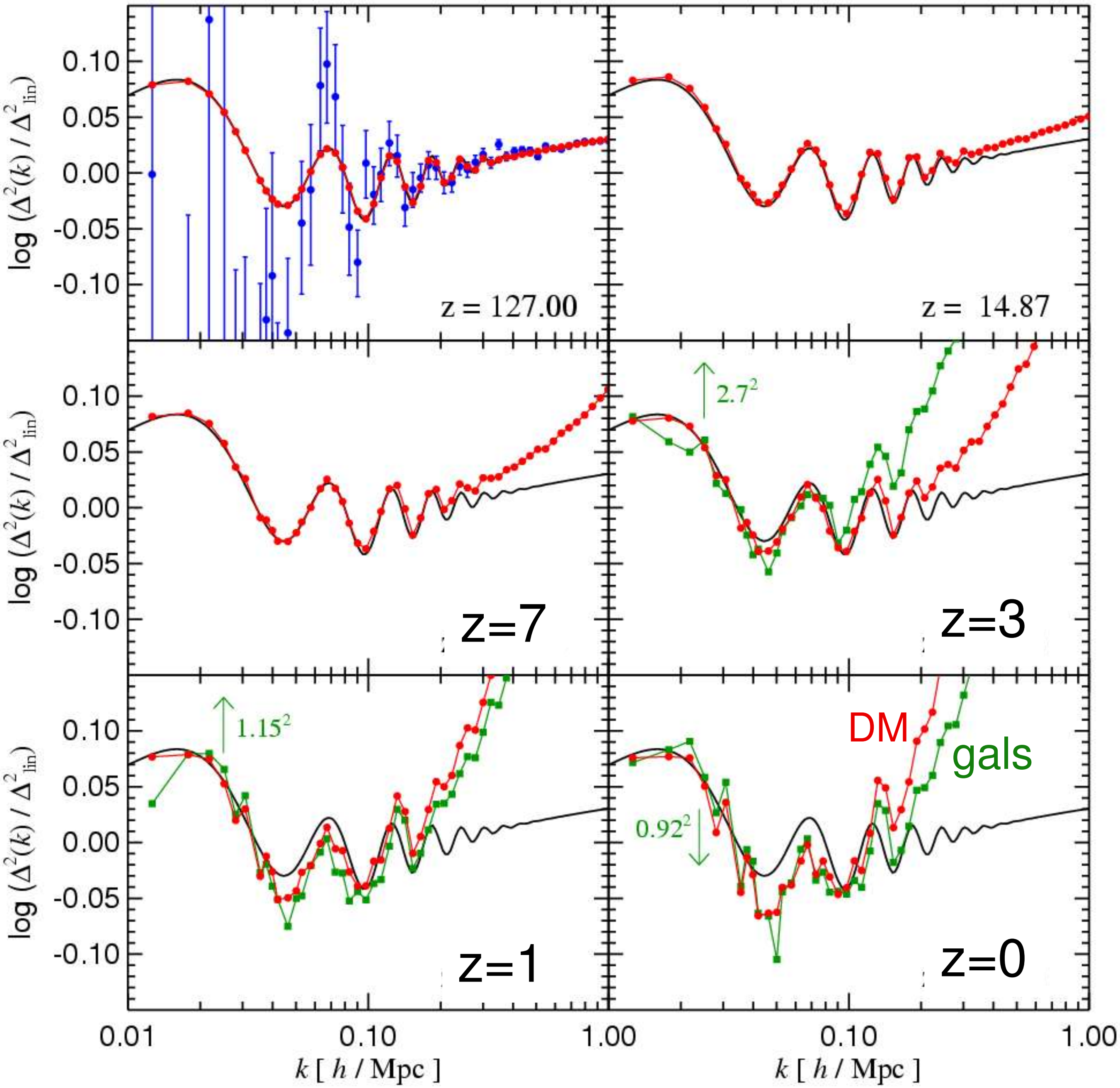
Dark matter

Galaxies





Baryon wiggles in the *galaxy* distribution



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

Galaxy samples matched to plausible large observational surveys at given z

Springel et al 2004

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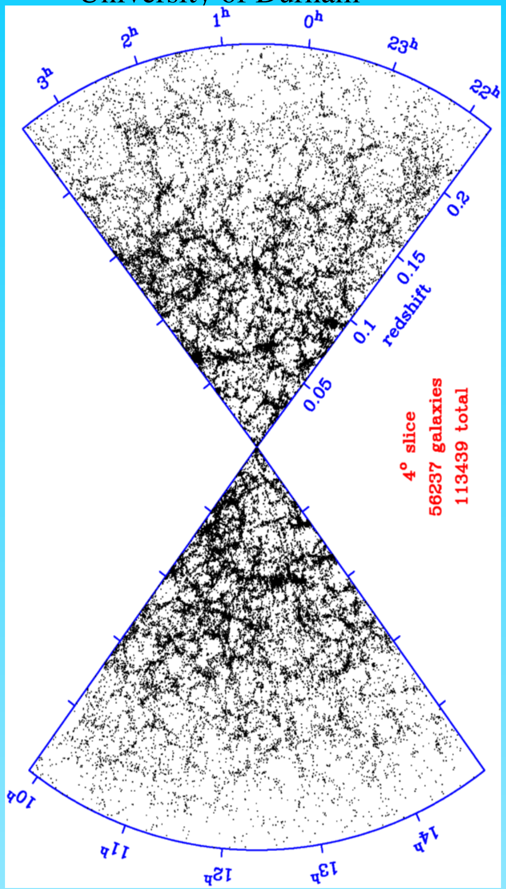
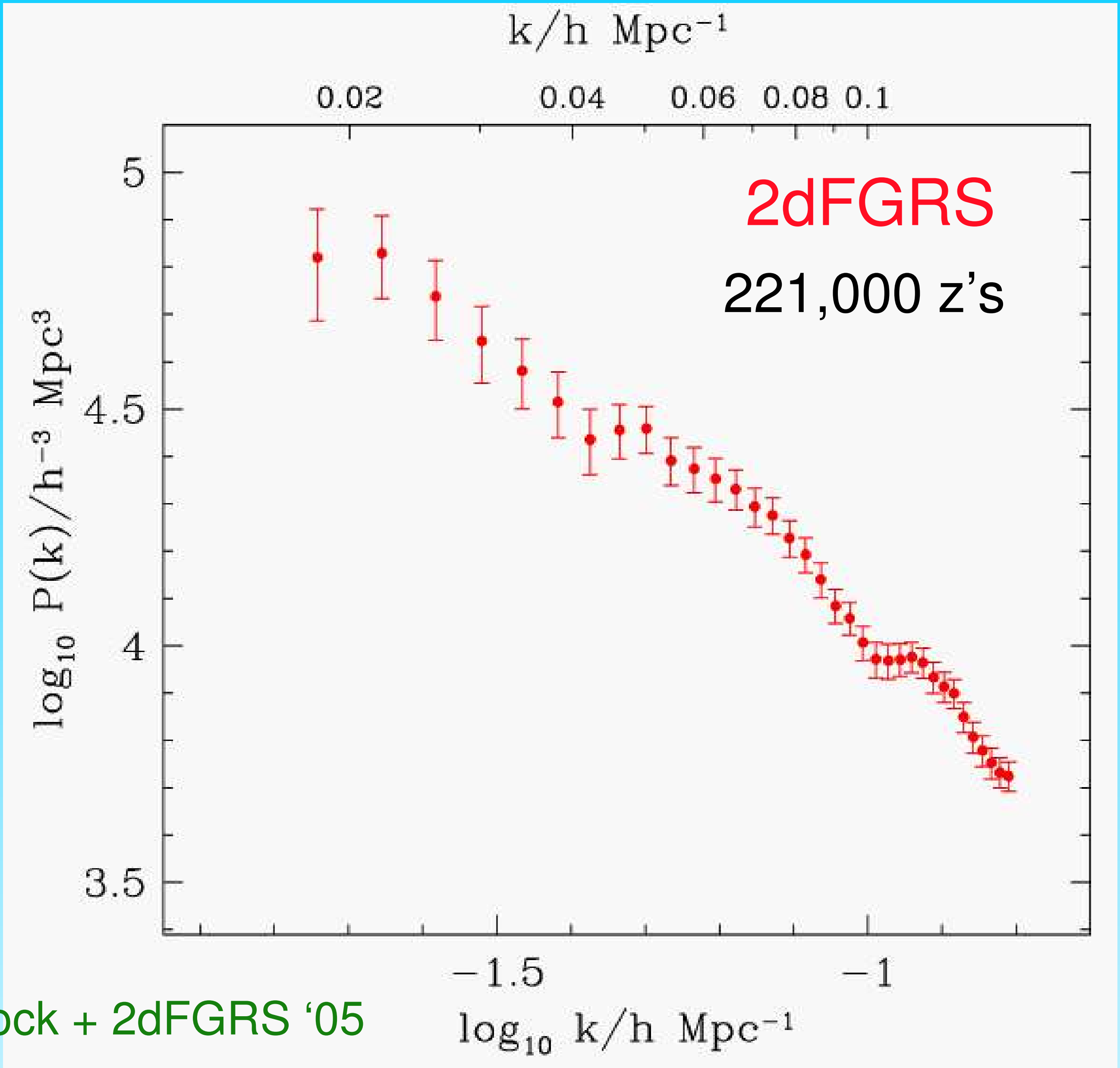
The final 2dFGRS power spectrum



Covariance matrix computed from mock catalogues



Cole, Percival, Peacock + 2dFGRS '05

The final 2dFGRS power spectrum

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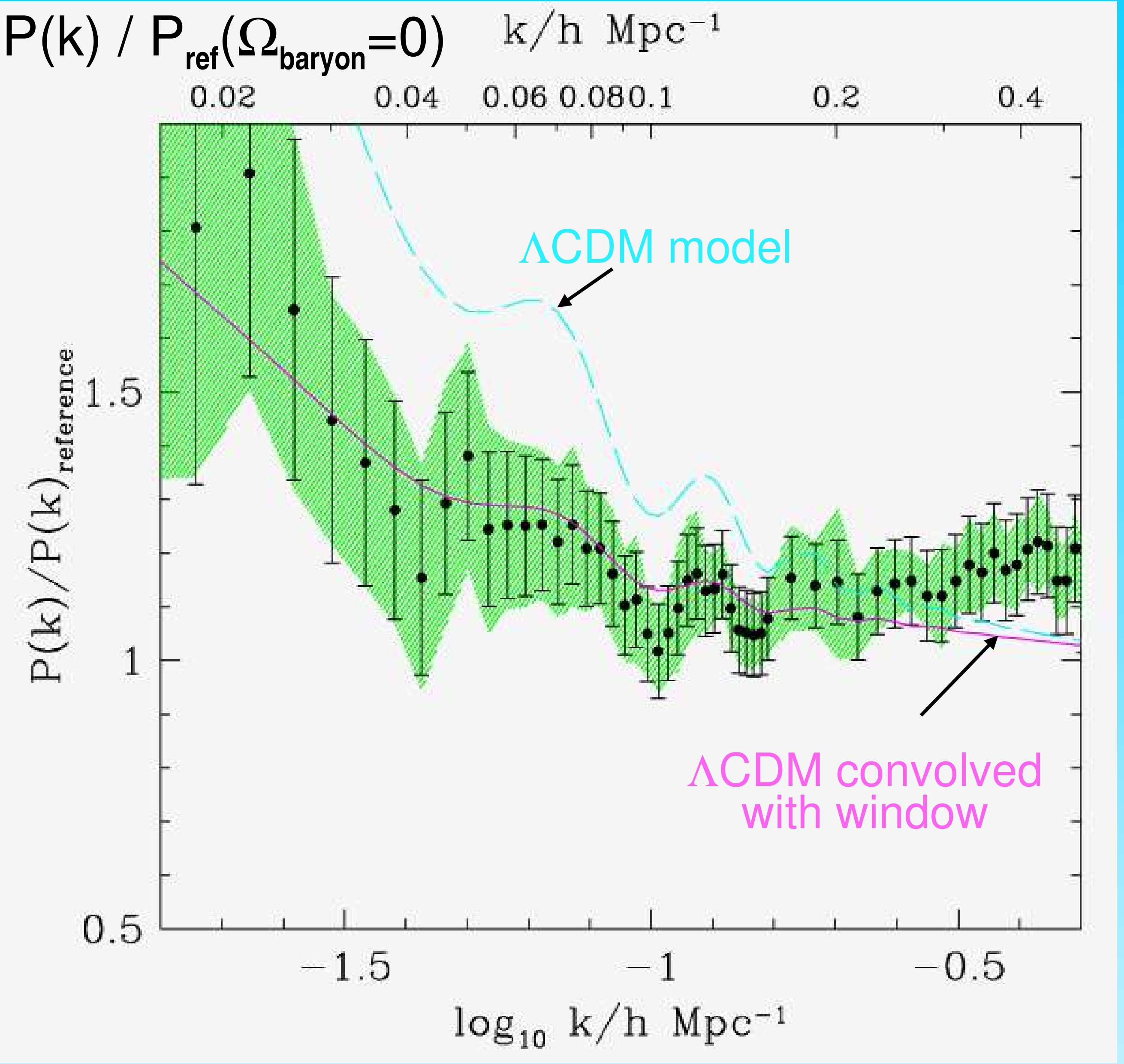
Baryon oscillations conclusively detected in 2dFGRS!!!

Demonstrates that structure grew by gravitational instability in ΛCDM universe



Cole + 2dFGRS '05

The final 2dFGRS power spectrum: parameter estimation

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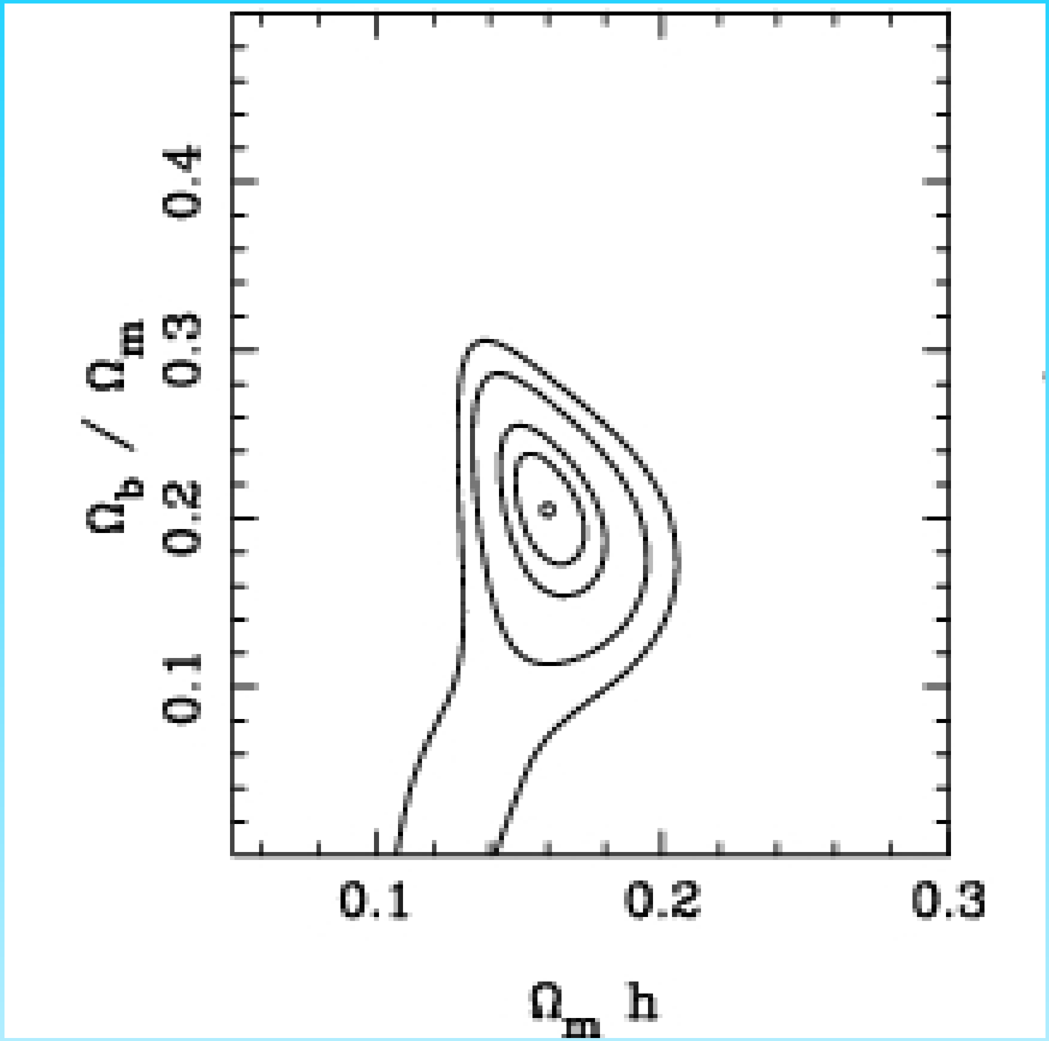
- Shape of P(K) depends on Ωh
- Oscillations depend on Ω_b / Ω_m
- Amplitude depends on σ_8^{gal}

$\Omega h = 0.161 \pm 0.015$

$\Omega_b / \Omega_m = 0.194 \pm 0.045$

$\sigma_8^{gal}(L_*) = 0.870 \pm 0.029$



Cole + 2dFGRS '05

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Cosmological parameters: CMB + 2dF

The 2dF power spectrum depends on $\Omega_m h$, Ω_b/Ω_m, $\boldsymbol{\sigma}_8^{gal}$, f_ν, …

The CMB power spectrum depends on

$$\left(\Omega_k, \Omega_L, w_b, w_{\mathrm{dm}}, f \qquad , w_{DE}, t, n_s, n_t, A_s, r, b\right)$$

Combining 2dF and CMB breaks parameter degeneracies

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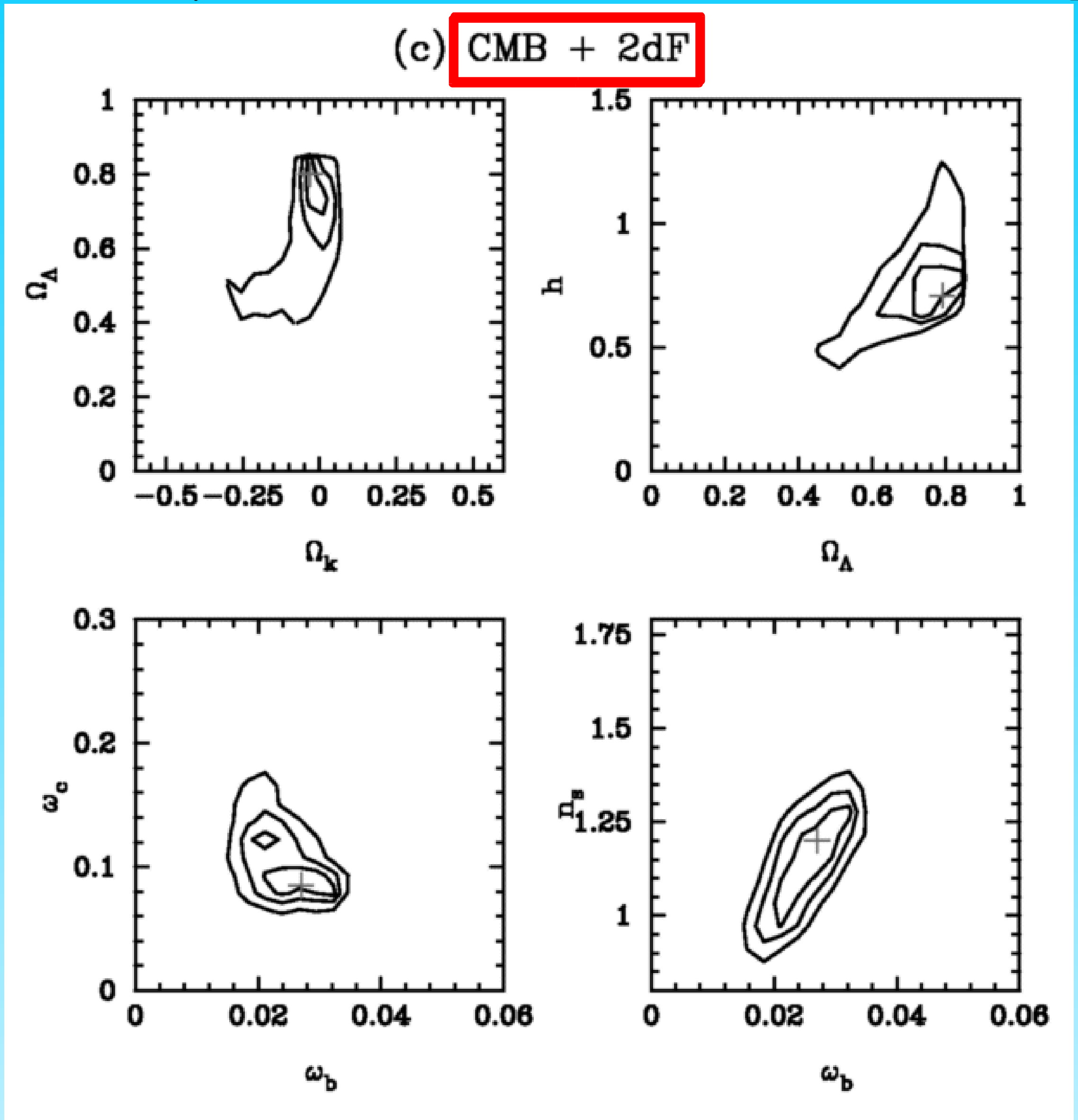
2dFGRS + CMB: flatness

Pre-WMAP

Boomerang, DASI, Maxma, CBI



CMB alone has a geometrical degeneracy: large curvature is not ruled out

Adding 2dFGRS power spectrum forces flatness:

$|1 - \Omega_{tot}| < 0.04$

2dFGRS 100k

Efstathiou + 2dFGRS team
MNRAS 330, L29 (2002)

Spergel etal '03

Table 7. Best Fit Parameters: Power Law Λ CDM

	WMAP	WMAPext [16a]	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
A	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	$0.75^{+0.08}_{-0.07}$
n_s	0.99 ± 0.04	0.97 ± 0.03	0.97 ± 0.03	0.96 ± 0.02
τ	$0.166^{+0.076}_{-0.071}$	$0.143^{+0.071}_{-0.062}$	$0.148^{+0.073}_{-0.071}$	$0.117^{+0.057}_{-0.053}$
h	0.72 ± 0.05	0.73 ± 0.05	0.73 ± 0.03	0.72 ± 0.03
$\Omega_m h^2$	0.14 ± 0.02	0.13 ± 0.01	0.134 ± 0.006	0.133 ± 0.006
$\Omega_b h^2$	0.024 ± 0.001	0.023 ± 0.001	0.023 ± 0.001	0.0226 ± 0.0008
χ^2_{eff}/ν	1429/1341	1440/1352	1468/1381	... [b]

[a] *WMAP* +CBI+ACBAR

[b] Since the Lyman α data points are correlated, we do not quote an effective χ^2 for the combined likelihood including Lyman α data (see Verde et al. (2003)).

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truly stunning. Cosmologists have been trying for years to confirm the hypothesis of a dark universe. Science is glad to recognize their success in this effort as the Breakthrough of the Year for 2003," said Don Kennedy, Editor-in-Chief of Science.

faster. By conducting redshift surveys of galaxy clusters, astronomers hope to learn ... > *full story*

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The Guardian

Dec/19/2003

Science breakthrough of the year proof of our exploding universe

Tim Radford Science editor

Welcome to the dark side. Around 73% of the universe is made not of matter or radiation but of a mysterious force called dark energy, a kind of gravity in reverse. Dark energy is listed as the breakthrough of the year in the US journal Science today.

The discovery — in fact, a systematic confirmation of a puzzling observation first made five years ago — paints an even more puzzling picture of an already mysterious universe. Around 200bn galaxies, each containing 200bn stars, are detectable by telescopes. But these add up to only 4% of the whole cosmos.

Now, on the evidence of a recent space-based probe and a meticulous survey of a million galaxies, astronomers have filled in at least some of the picture.

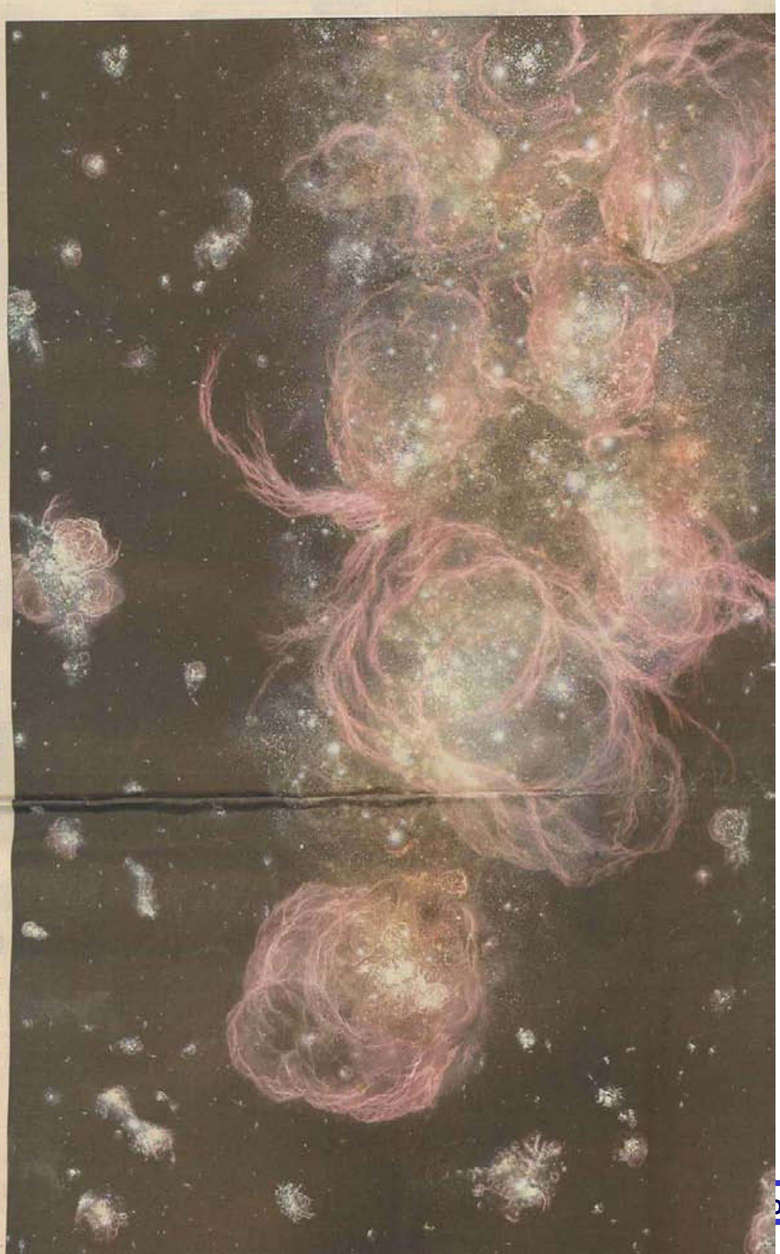
Around 23% of the universe is made up of another substance, called "dark matter". Nobody knows what this undetected stuff could be, but it massively outweighs all the atoms in all the stars in all the galaxies across the whole detectable range of space. The remaining 73% is the new discovery: dark energy. This bizarre force seems to be pushing the universe apart at an accelerating rate, when gravitational pull should be making it slow down or contract.

"The implications for these discoveries about the universe are truly stunning," said Don Kennedy, the editor of Science. "Cosmologists have been trying for years to confirm the hypothesis of a d[illegible] astronomer royal, called it a "discovery of the first magnitude".

The findings were made by an orbiting observatory called the Wilkinson Microwave Anisotropy Probe (WMAP). This measured tiny fluctuations in the cosmic microwave background, in effect the dying echoes of the Big Bang that launched time, space and matter in a tiny universal fireball.

These painstaking measurements were then backed up by the telescopes of the Sloan Digital Sky Survey, which mapped a million galaxies to see how they clumped together or spread out. Both confirmed that dark energy must exist.

The findings settle a number of arguments about the universe, its age, its expansion rate, and its composition, all at once. Thanks to the two studies, astronomers now believe the age of the universe is 13.7bn



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Cosmological parameters

$$P^o\left(\Omega_k, \Omega_L, w_b, w_{\mathrm{dm}}, f \qquad , w_{DE}, t, n_s, n_t, A_s, r, b\right)$$

Data:

- CMB $\rightarrow$ WMAP, CBI, ACBAR and VSA
- LSS $\rightarrow$ Full 2dFGRS

Method:

- MCMC
- Use halo Model to relate distribution of galaxies to distribution of mass (galaxy bias)

Sanchez, Padilla, Baugh ‘05

Parameter constraints

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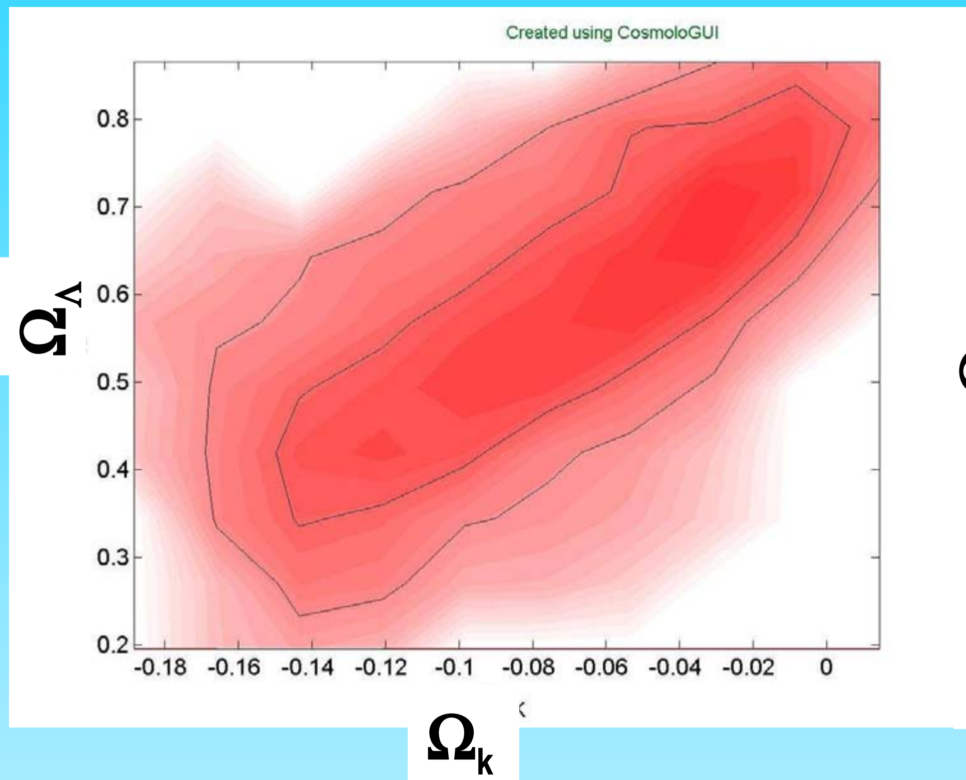
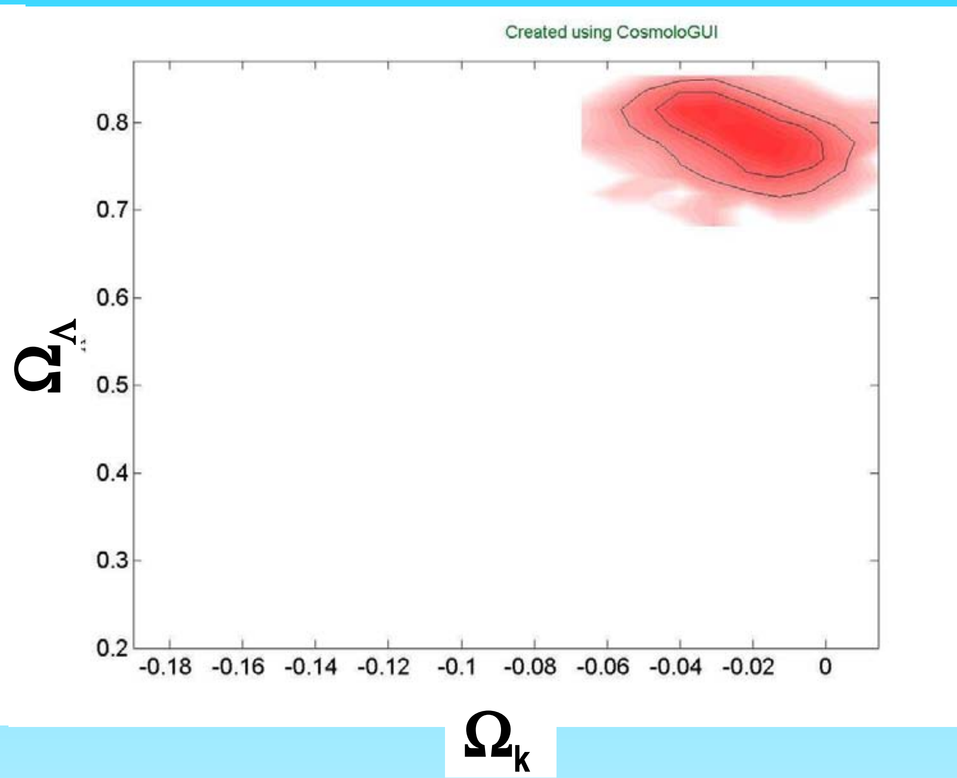
$$P^{o}\left(\Omega_k, \Omega_L, w_b, w_{dm}, t, n_s, A_s\right)$$

CMB only…



CMB + 2dF…



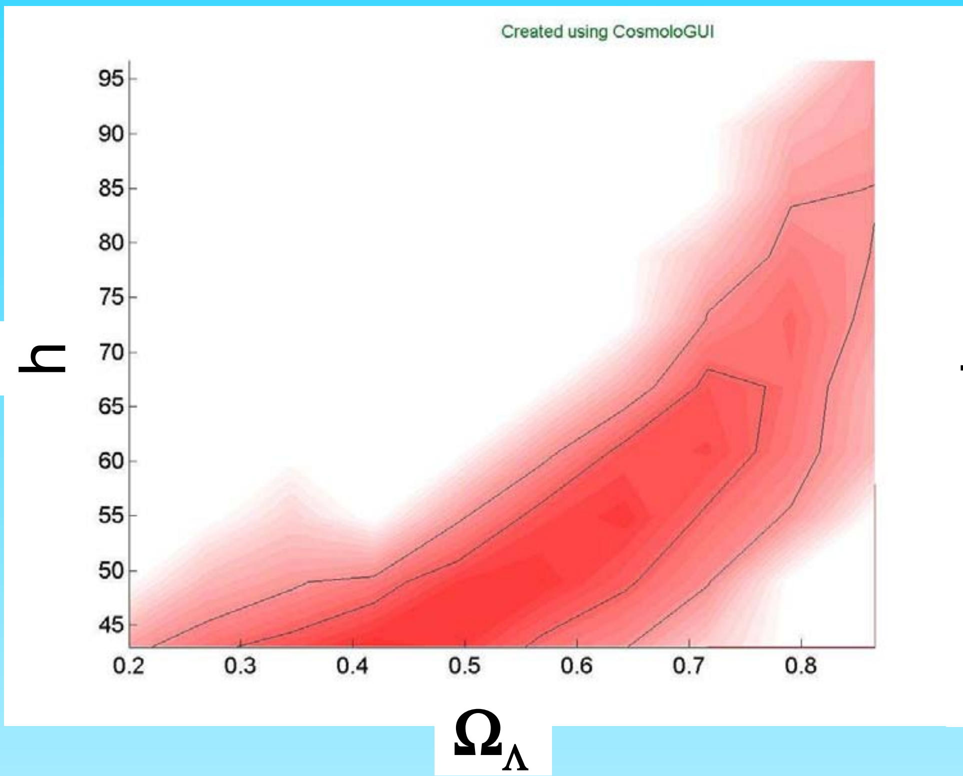
Sanchez etal '05

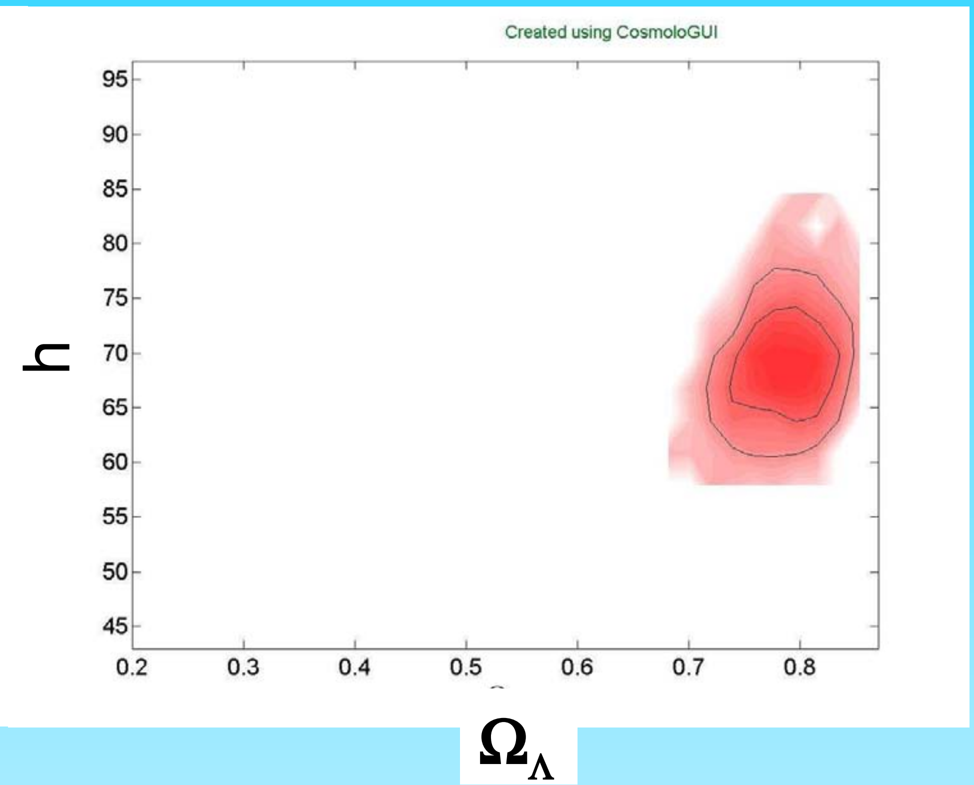
Parameter constraints

$$P^o\left(\Omega_k, \Omega_L, w_b, w_{dm}, t, n_s, A_s\right)$$

CMB only…

CMB + 2dF…





Sanchez etal '05

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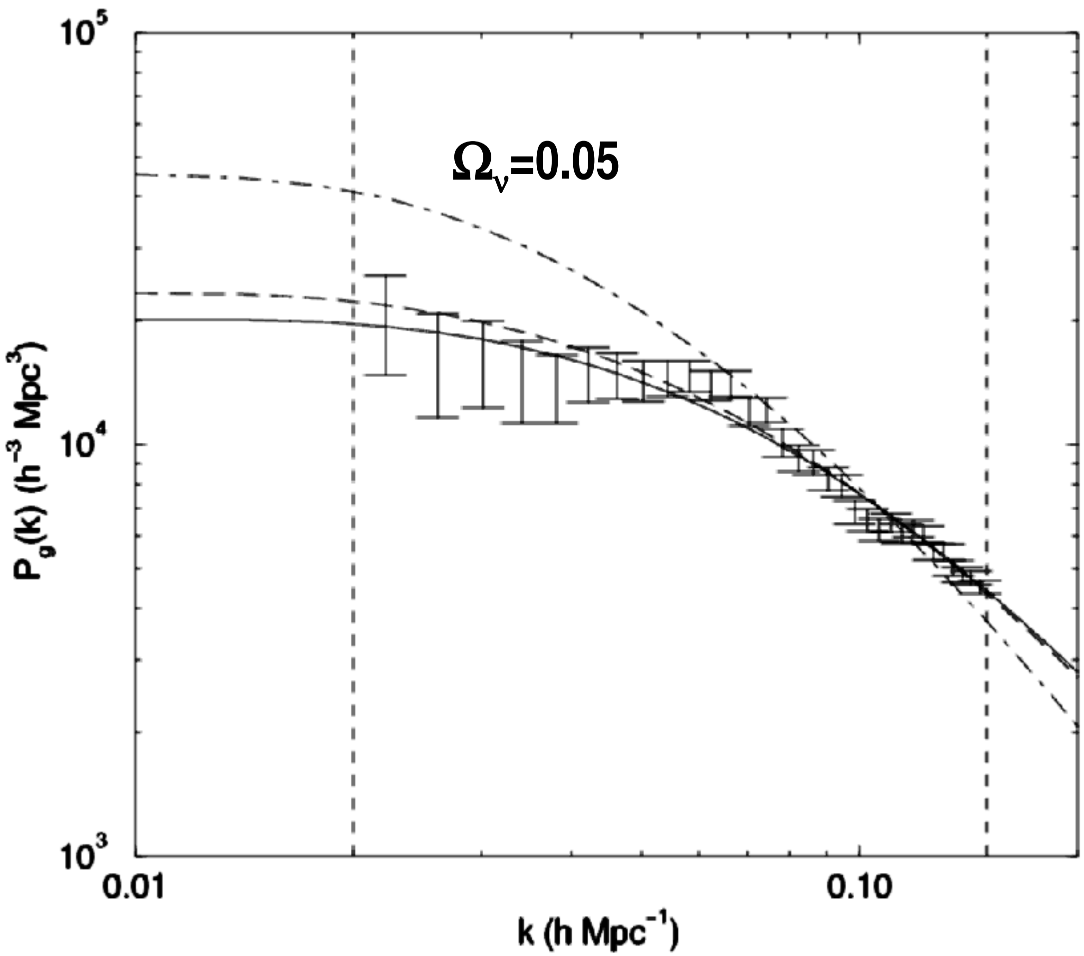
ICC

Effect of neutrinos



Eleroy + 2dFGRS team '02

Free-stream length: 80 $(\Sigma\, m_\nu /eV)^{-1}$ Mpc

$(\Omega_m h^2 = \Sigma m_\nu / 93.5\ eV)$

Σm_ν ~ 1 eV causes lower power at almost all scales, or a bump at the largest scales

100k 2dFGRS

→ Σm_ν < 1.8 ev

Parameter constraints

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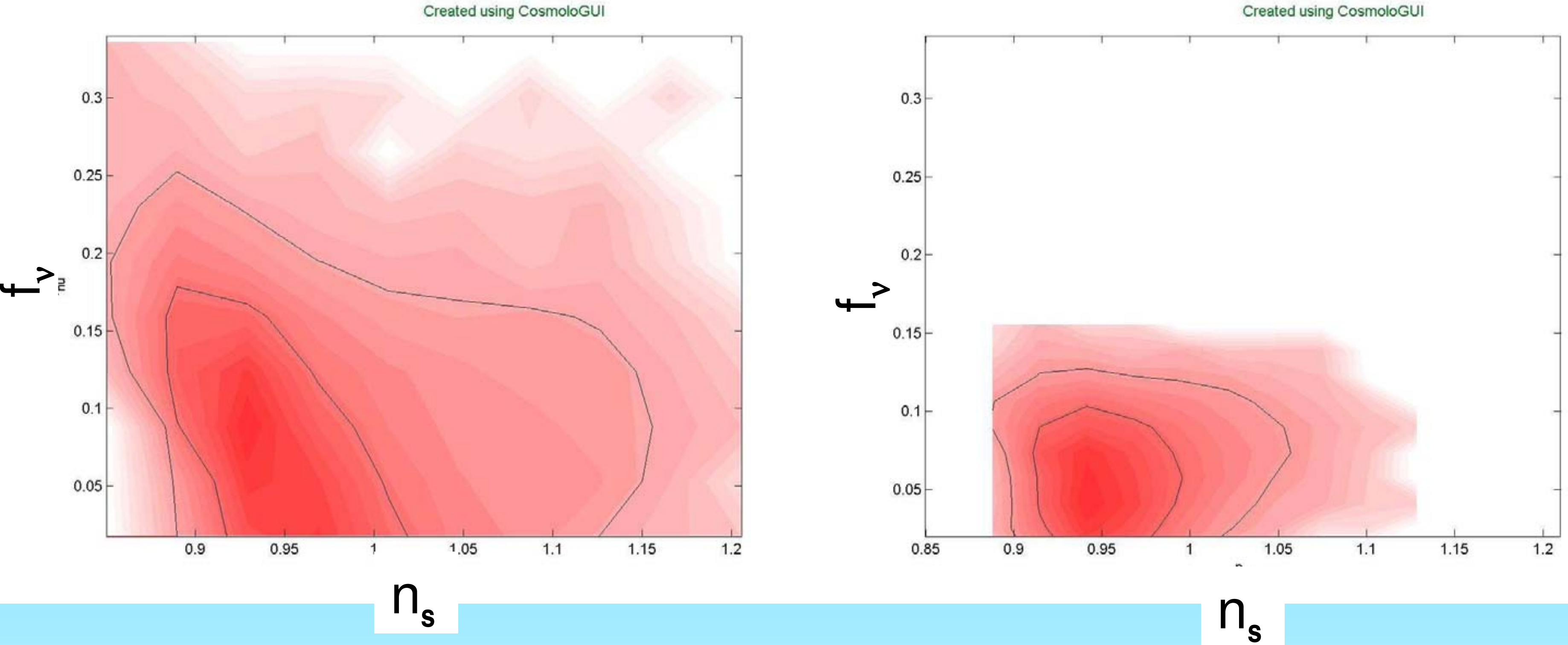
$$P^o\left(\Omega_L, w_b, w_{dm}, f \qquad , t, n_s, A_s\right)$$

CMB only… CMB + 2dF…



marginalizing → $\Sigma\, m_\nu < 1.1$ ev (95% c.l.)

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Parameter estimation

CMB + 2dFGRS

Data:

- CMB $\rightarrow$ WMAP, CBI, ACBAR and VSA
- LSS $\rightarrow$ 2dFGRS

Free parameters:

- $\Omega_k, \Omega_\Lambda, \Omega_{cdm}h^2, \Omega_b h^2, n_s, \tau, A_s$

Ω_m	=	0.224 ± 0.024
Ω_b	=	0.055 ± 0.007
Ω_k	=	-0.034 ± 0.018
Ω_Λ	=	0.809 ± 0.037
h	=	0.683 ± 0.031
n_s	=	1.07 ± 0.10
σ_8	=	0.812 ± 0.072

Sanchez etal '05

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Parameter estimation

CMB + 2dFGRS

Data:

- CMB → WMAP, CBI, ACBAR and VSA
- LSS → 2dFGRS

Free parameters:

- Ω_Λ, $\Omega_{cdm}h^2$, $\Omega_b h^2$, n_s, τ, A_s

Cole etal '05

For a flat model

Ω_m	=	0.238 ± 0.022
Ω_b	=	0.042 ± 0.003
h	=	0.734 ± 0.025
n_s	=	0.948 ± 0.027

2dFGRS and galaxy formation

In addition to cosmology, the 2dFGRS contains information about the physics galaxy formation

Efficiency of galaxy formation

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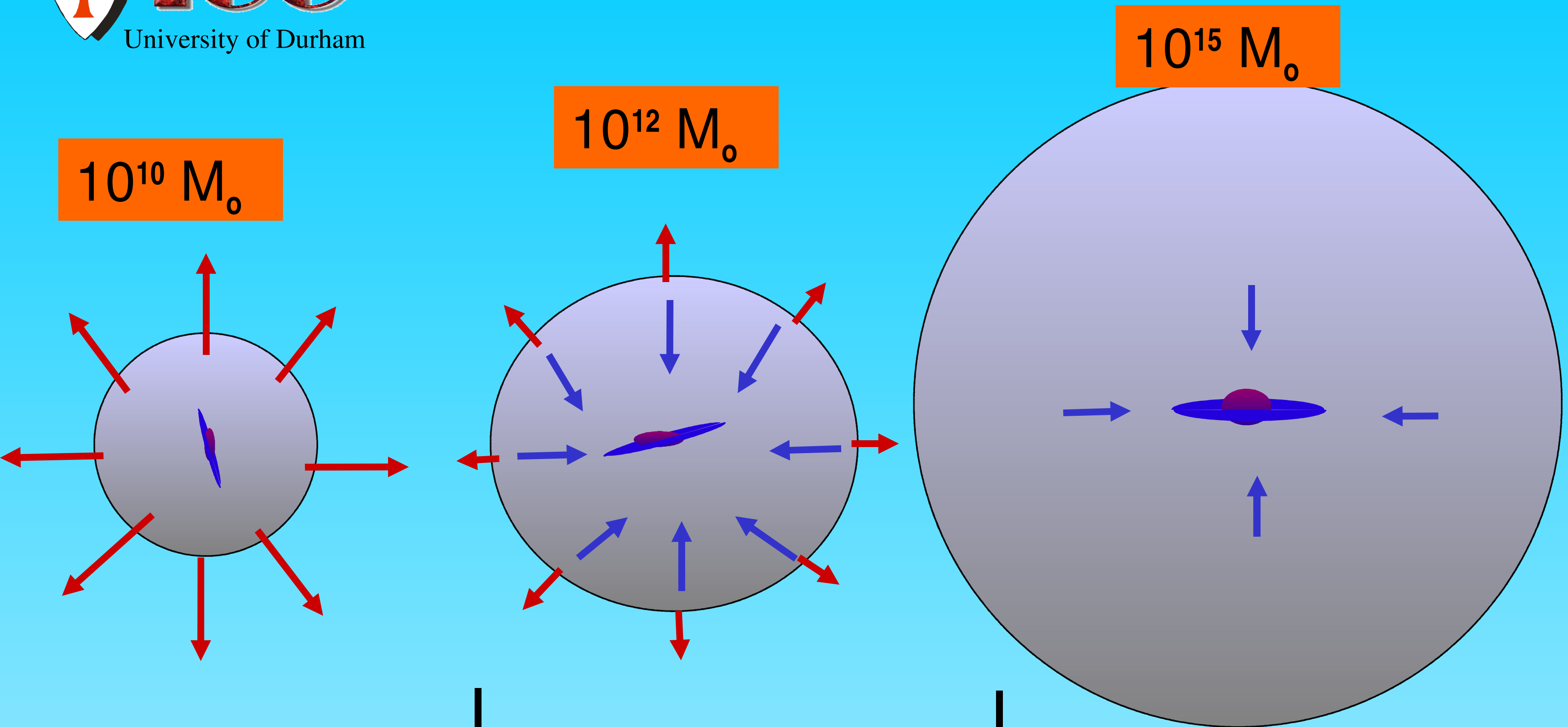

Cooling: +++++

Feedback: +++++

Gal. Formation: - - - -

Inefficient

Cooling: ++++

Feedback: ++

Gal. Formation: ++++

Efficient

Cooling: - - - - -

Feedback: ++

Gal. Formation: - - - -

Inefficient

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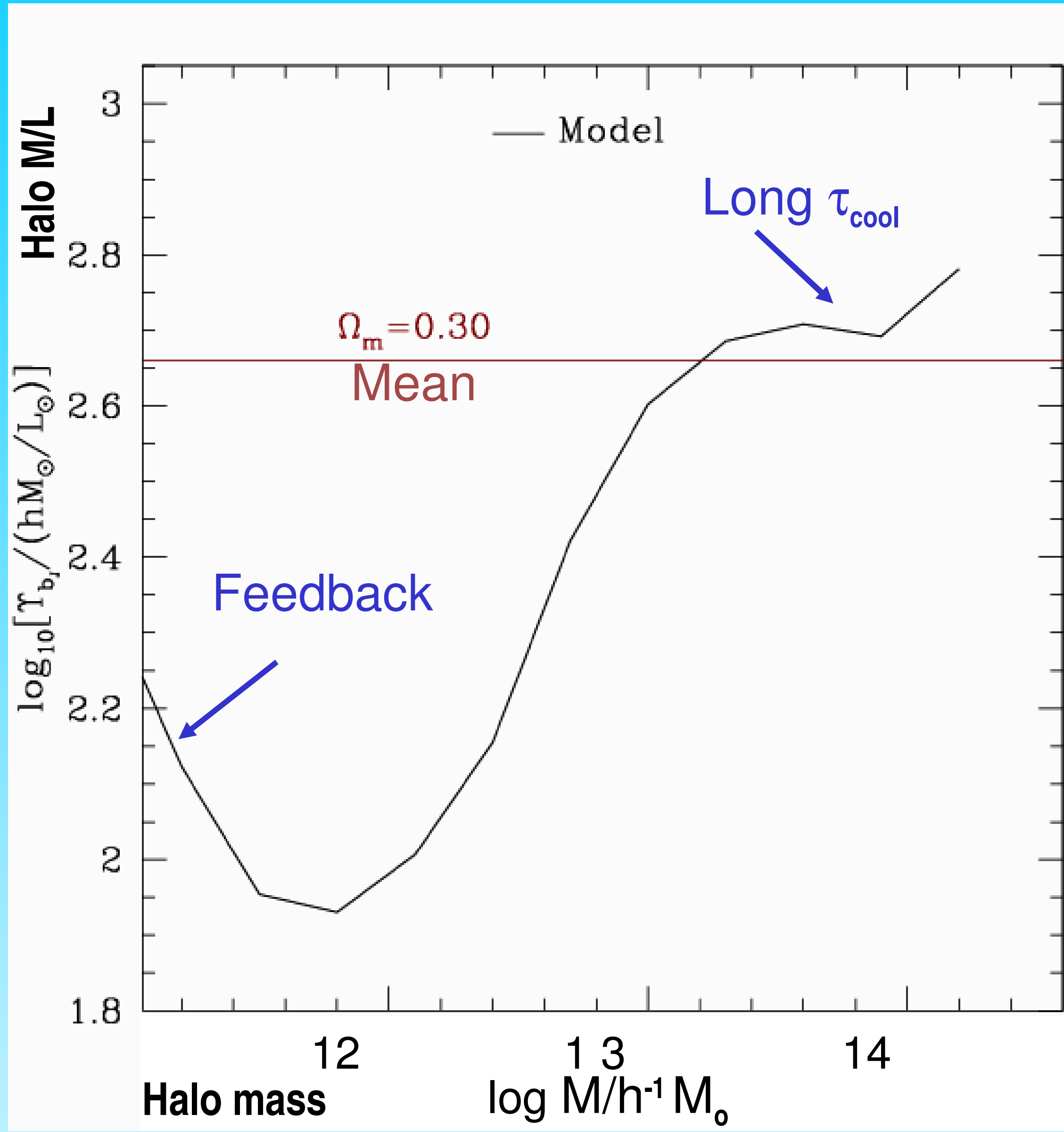
Halo mass-to-light ratios

Theoretical prediction

(semi-analytic)

Galaxy formation is most efficient in ~10^{12} M_o halos

Efficiency of galaxy formation



Benson, Cole, Baugh, Frenk & Lacey 2000, MNRAS

Groups and clusters in 2dFGRS

Test by:

- Finding groups and clusters in 2dFGRS
- Using simulations to relate groups ⟷ dark halos

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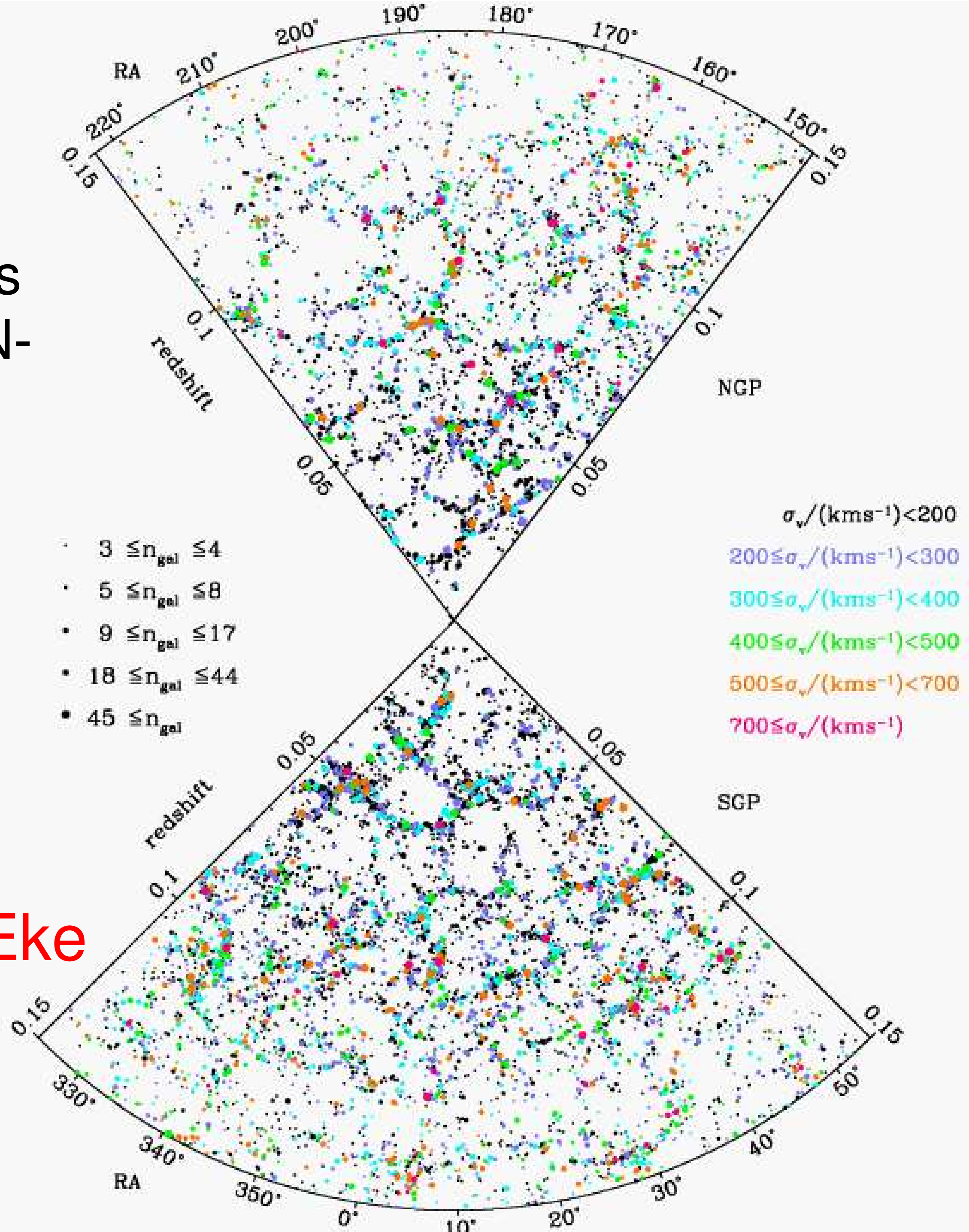
Mock 2dFGRS groups from Hubble volume N-body simulation

+

semianalytic galaxy formation model



Guest star: Vince Eke

Eke, Frenk, Cole, E
2dFGRS 2004

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Groups in 2dFGRS

28,213 groups with $n_{gal} \geq 2$ (53% of gals)

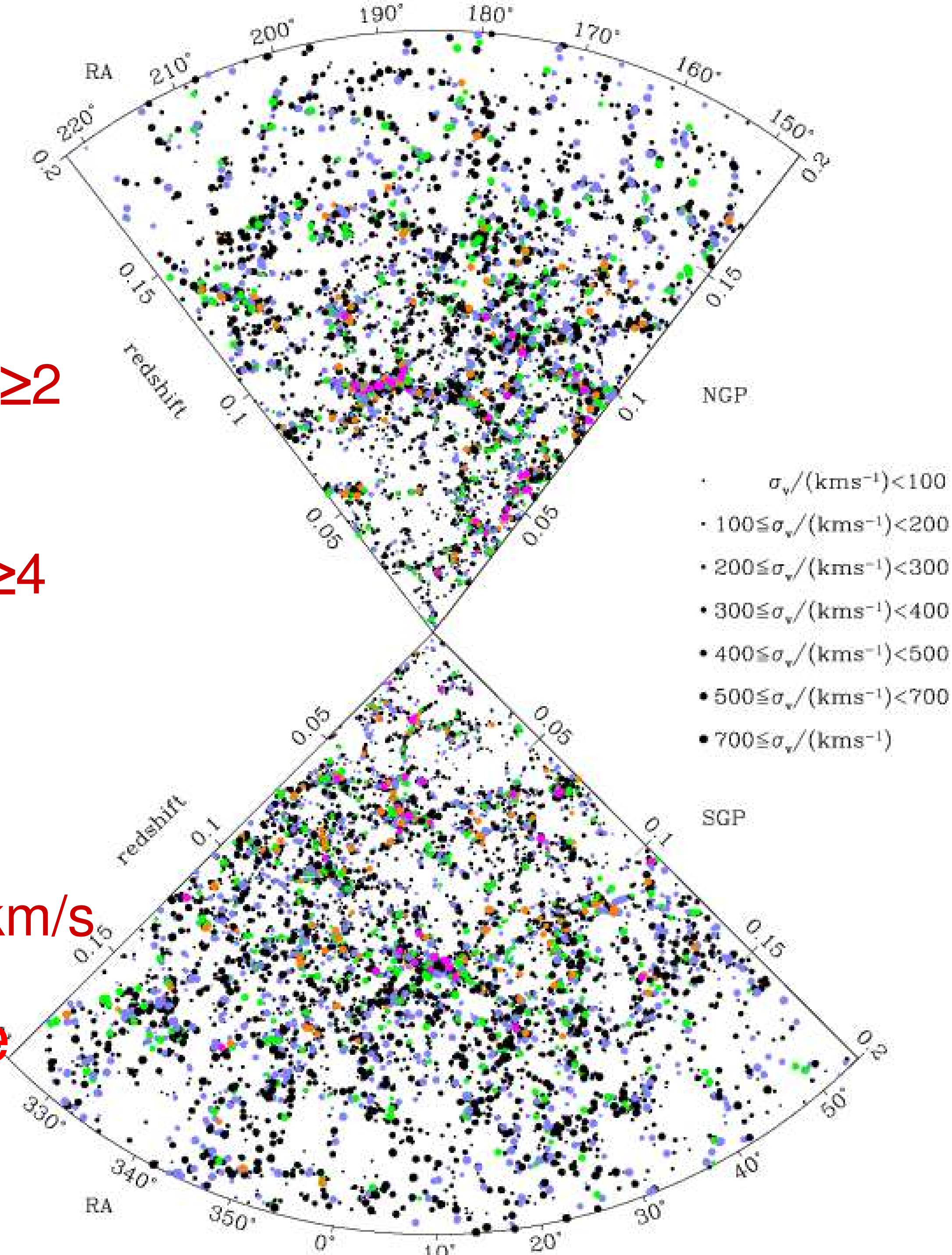
6,773 groups with $n_{gal} \geq 4$

$n_{gal} \geq 4$:

Median z 0.11

Median vel disp 266 km/s

Guest star: Vince Eke



Eke, Frenk, Cole, Baugh + 2dFGRS 2003

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Halo mass-to-light ratios

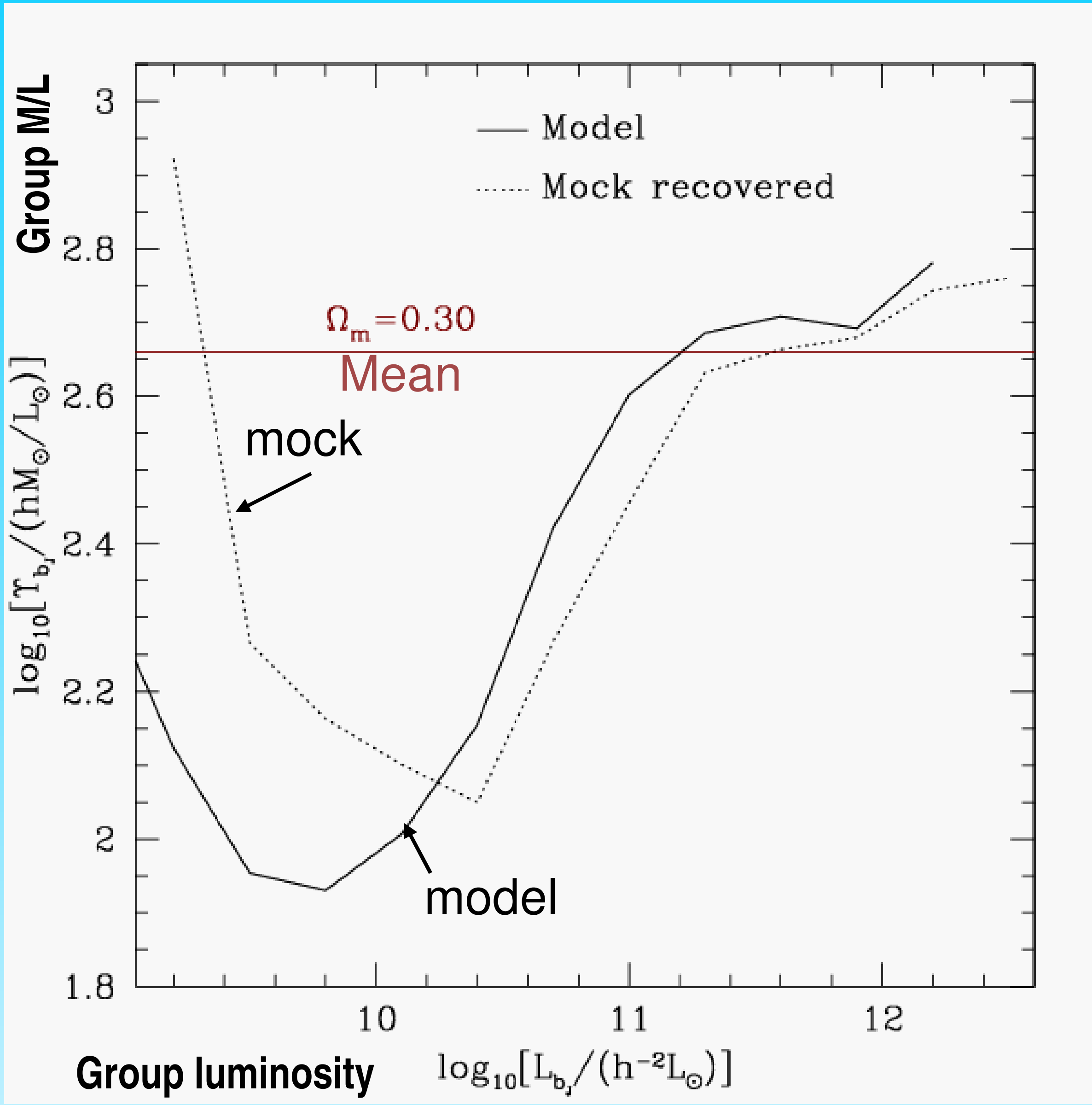
$N_{min}=2$, $z_{max}=0.07$

Errors in M and L cause mocks to deviate from model prediction

M/L overestimated for $L<10^{10}h^{-2}L_o$ because of scatter in L and errors in M

Efficiency of galaxy formation

Eke etal '04



Halo mass-to-light ratios

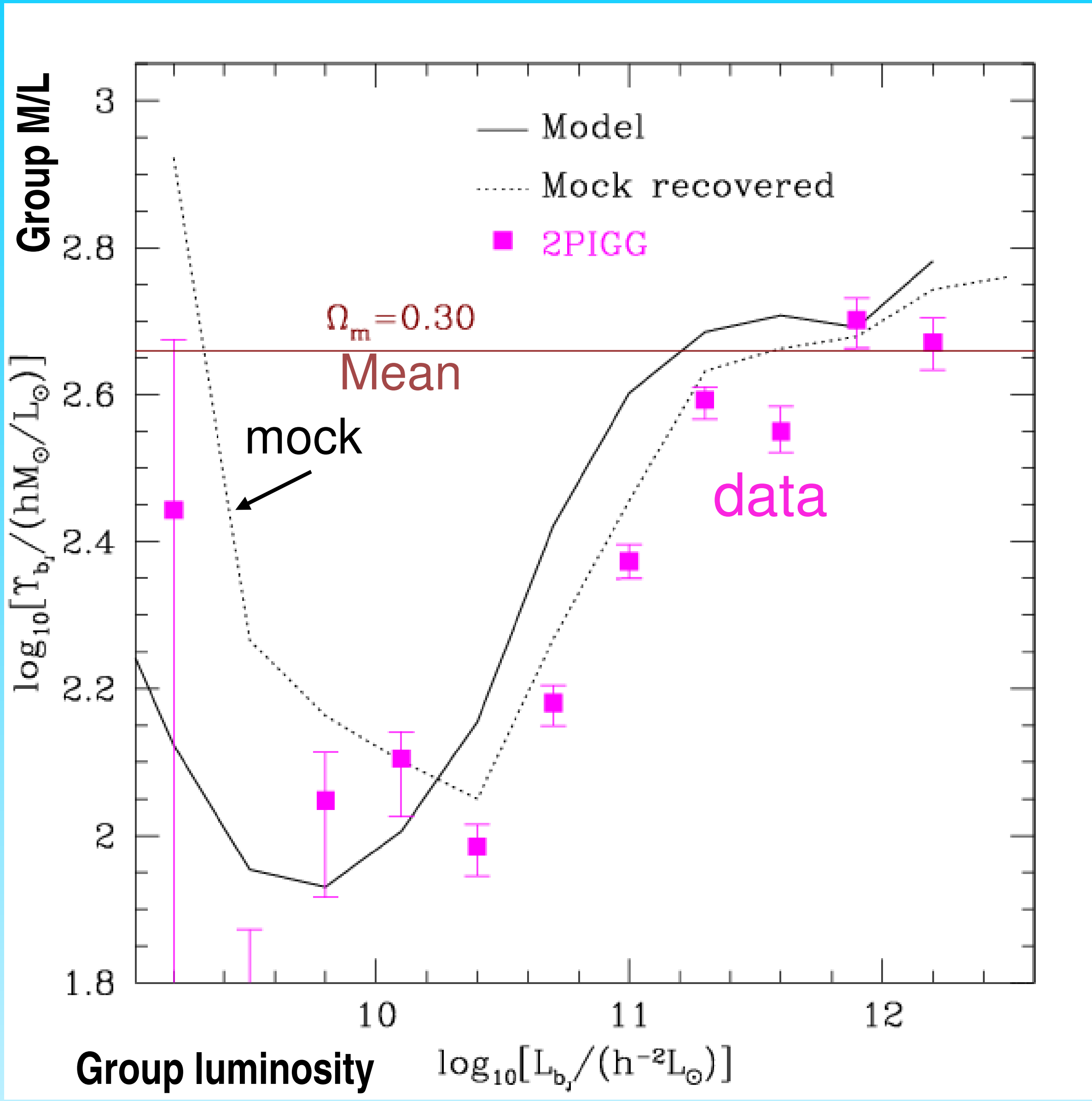
University of Durham

Errors in M and L cause mocks to deviate from model prediction

Mocks and data agree well!

Eke etal '04

Efficiency of galaxy formation



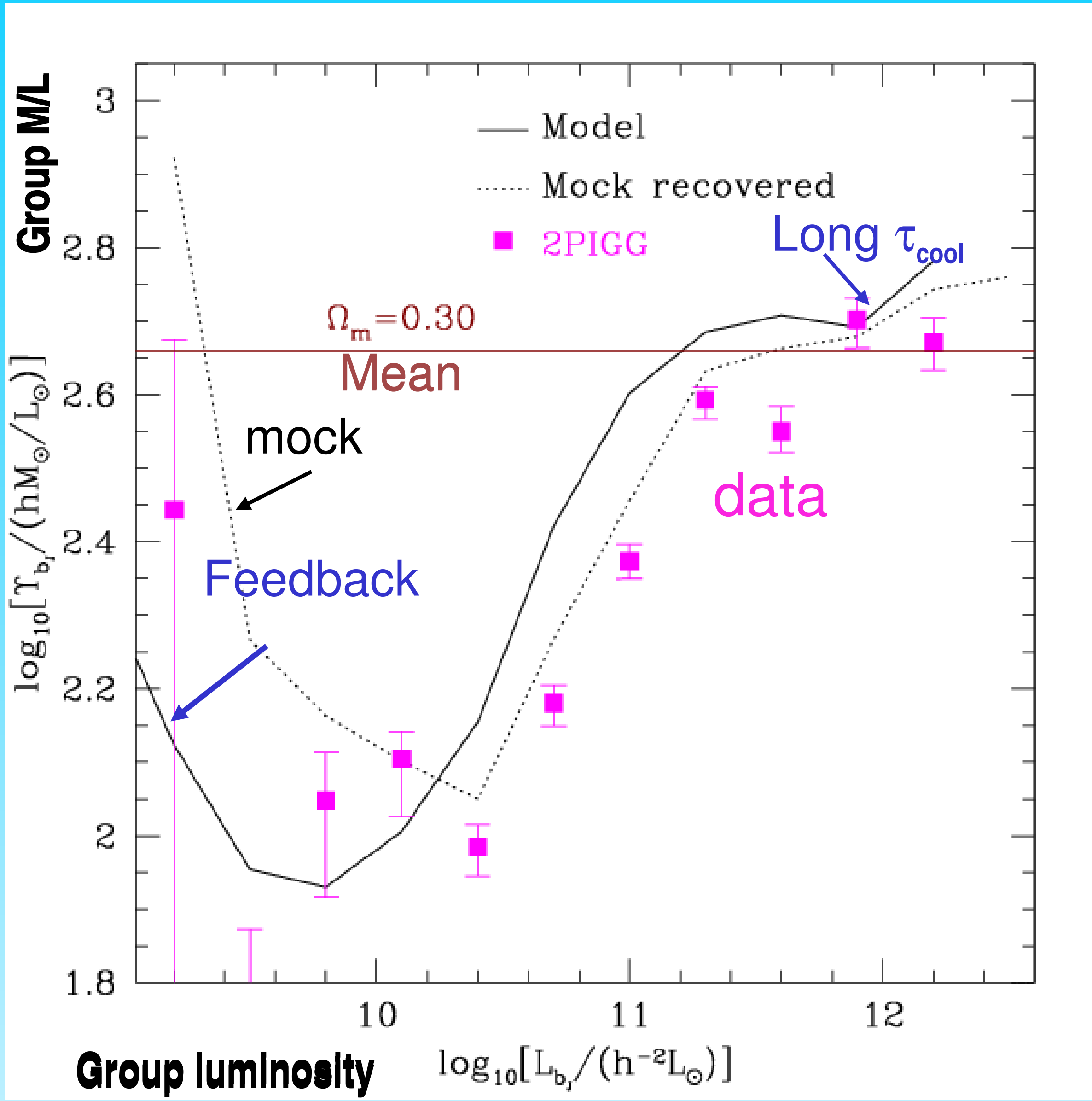
Halo mass-to-light ratios

$N_{min}=2$, $z_{max}=0.07$

Factor of 4 decrease in M/L from rich clusters to poor groups

Tentative detection of the minimum

Efficiency of galaxy formation



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How many stars are there and where are there?

Estimate stellar content of 2dFGRS groups using infrared photometry (R from Cosmos; J & K from 2MASS)

How many stars? $\Omega_{stars}h = (0.99 \pm 0.03)\times10^{-3}$ (Kennicutt IMF)

Galaxy formation theory

$\Rightarrow$ star formation efficiency depends on halo mass

Where are the stars today ?

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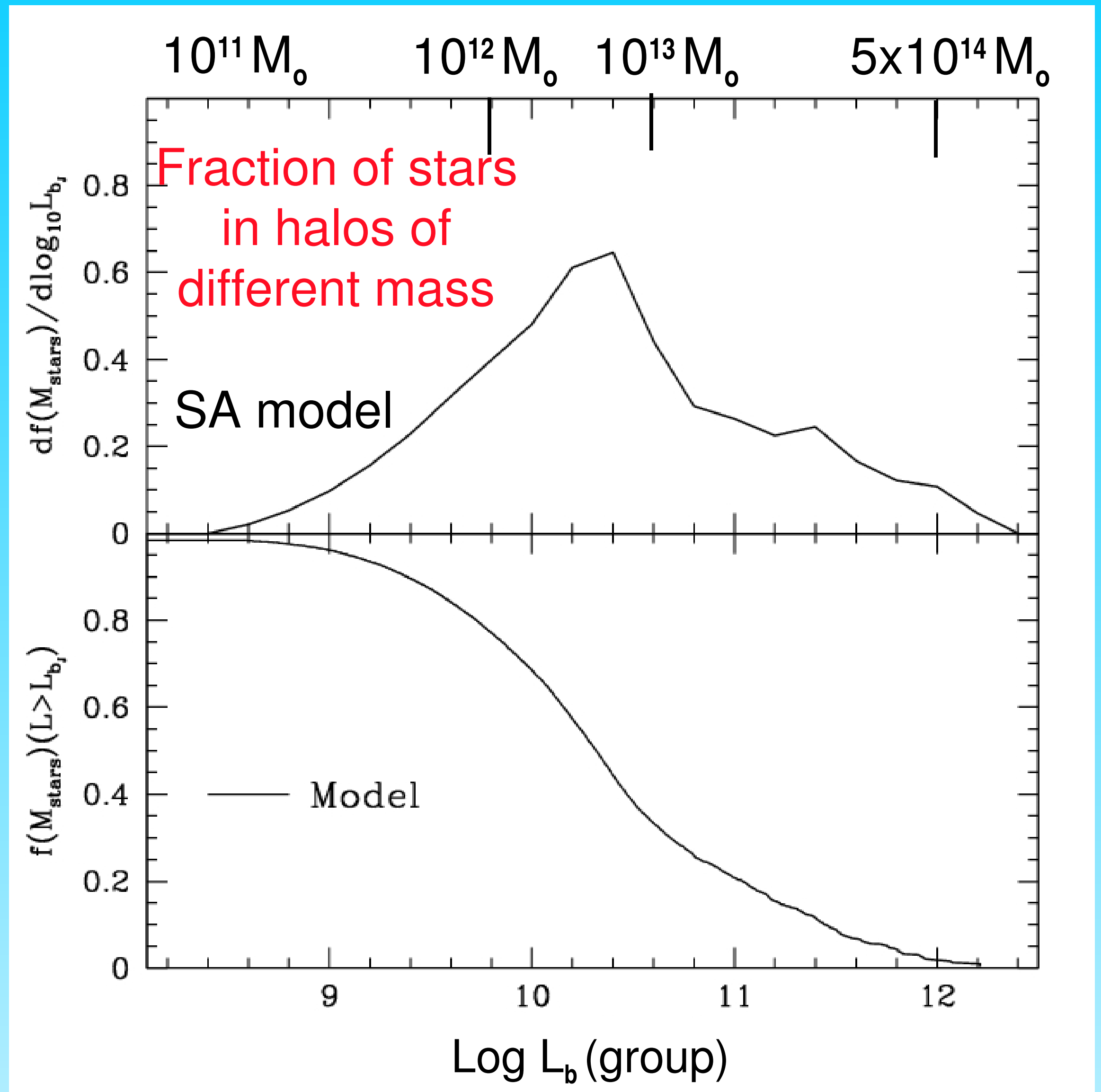
Where are the stars?

ΛCDM (semi-analytic) model predicts:

- Most stellar mass is in LG objects (M~3x10^{12} M$_o$)
- 50% of stellar mass in halos of M<5x10^{12} M$_o$
- 2% of stellar mass in clusters (M~5x10^{14} M$_o$)

differential

cumulative



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Where are the stars?

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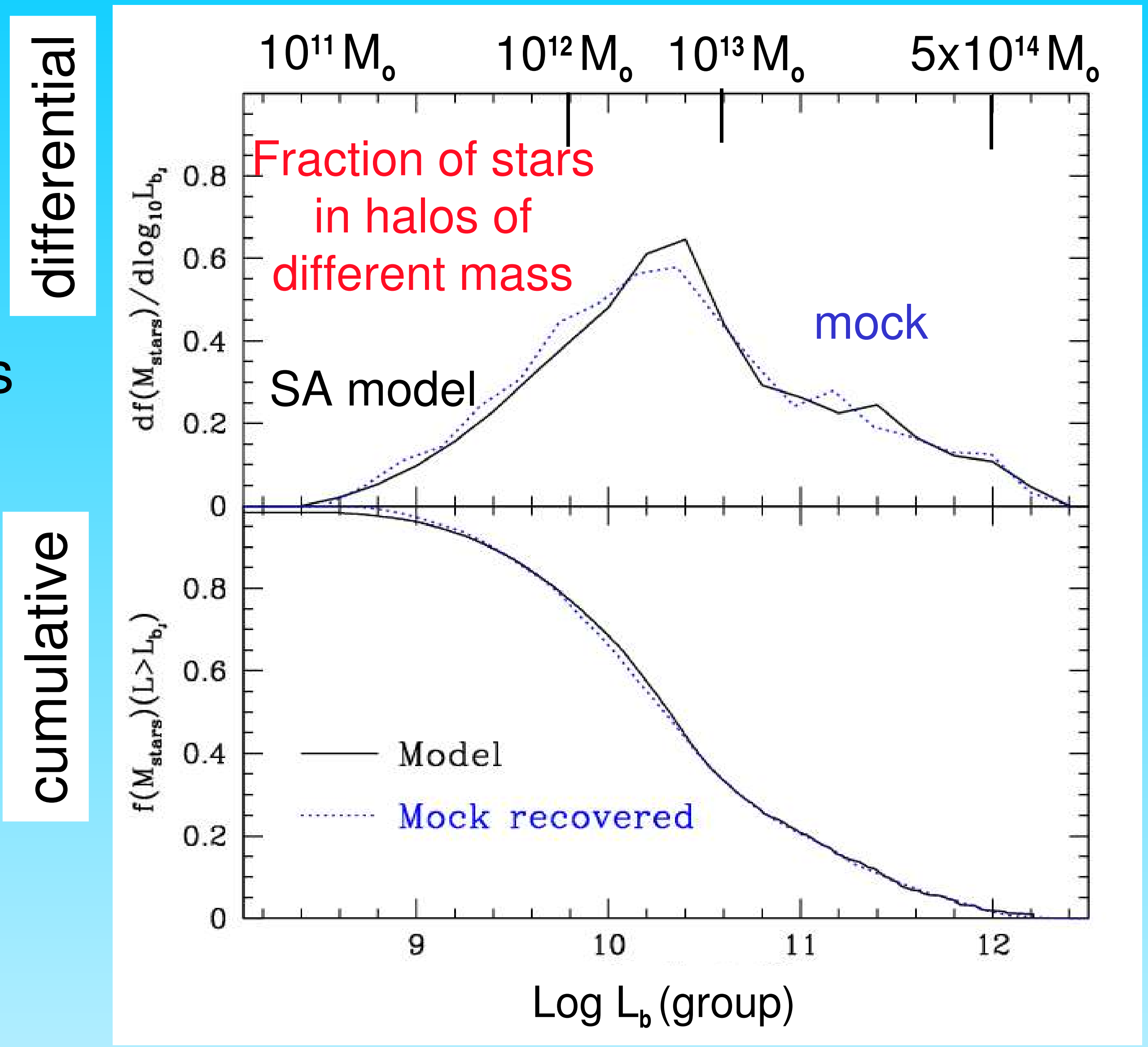

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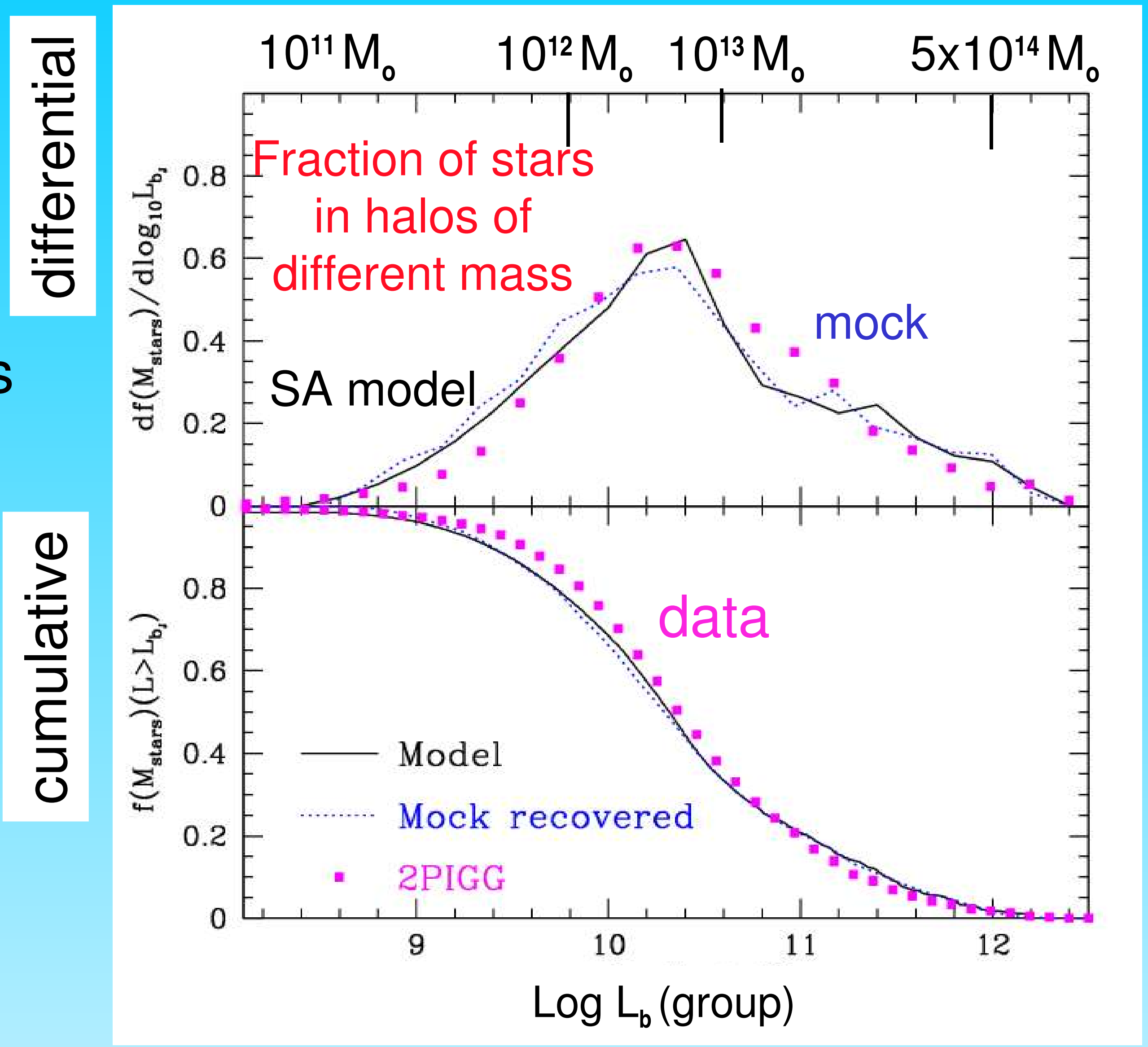

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Conclusions: 2dFGRS

Analysis of 2dFGRS data requires cosmological simulations

- Millennium sim ⇒ some baryon oscillations survive in gal distr.

From final (221,000 z's) 2dFGRS :

- Power spectrum ⇒ { Consistent with (flat) ΛCDM; Significant detection of baryons oscillations }

- 2dFGRS + CMB $\Delta T/T$ ⇒

Ω_m=0.238 ± 0.022, Ω_b=0.042 ± 0.003, h=0.734 ± 0.0025

- 2dFGRS + 2mass ⇒ $\Omega_{stars}h = (0.99 \pm 0.03)\times10^{-3}$ (Kennicutt IMF)

- 28,200 2dFGRS groups ⇒ { M/L ↑ by x4 from groups → clusters; 50% of stars in halos $M<5\times10^{12}M_o$ }

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Conclusions: groups and clusters in 2dFGRS

- Power spectrum ⇒
  - Consistent with ΛCDM
  - Significant distortions due to baryons
- 2dFGRS + CMB ΔT/T ⇒

  $\Omega_m=0.3 \pm 0.1$, $\Omega_\Lambda=0.7 \pm 0.1$, $\Omega_b=0.04 \pm 0.01$, $h=0.70 \pm 0.07$
- $\xi(\sigma,\pi)$ ⇒
  - evidence for gravitational instability
  - $b \cong 1$ ie on large scales gals trace mass
- Semi-analytic model ⇒
  - Clustering of halos
  - Occupation stats P(N,M)

Power-law $\xi(r)$: a coincidence

- 2dFGRS groups
  - Lum fn of all galactic systems
  - M/L as a fn of M_{halo}
  - P(N,M)

Agree with ΛCDM (SA)