Our implausible Universe

•The standard model of cosmic structure

•ΛCDM

- 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:
  - •Gravitational instability
- Parameters:

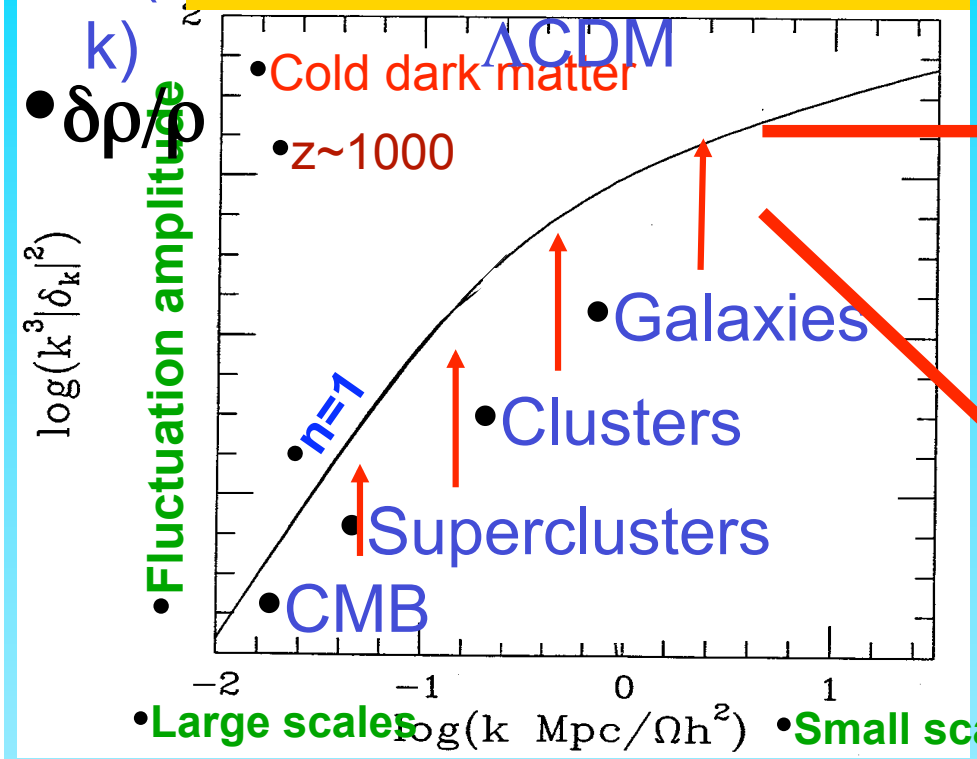
$$\Omega_{CDM} = 0.21,\ \Omega_b = 0.04,\ \Omega_\Lambda = 0.75,$$
$$h = 0.70, \sigma_8 = 0.8, \ldots$$

•Testing the CDM paradigm

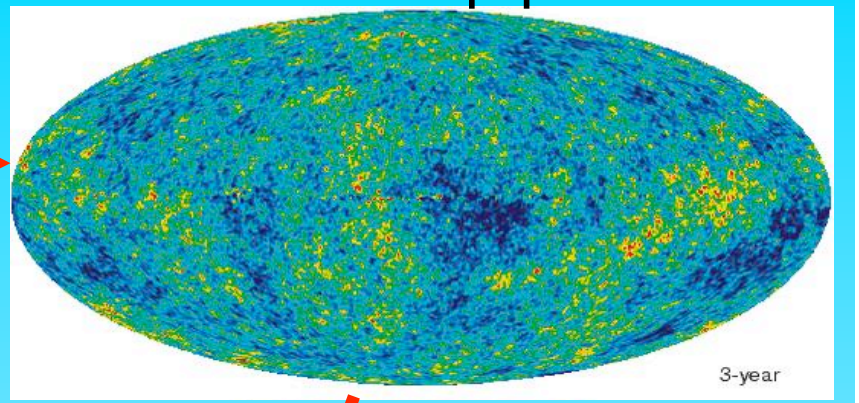
•P(•Initial conditions :

k)

•δρ/ρ



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



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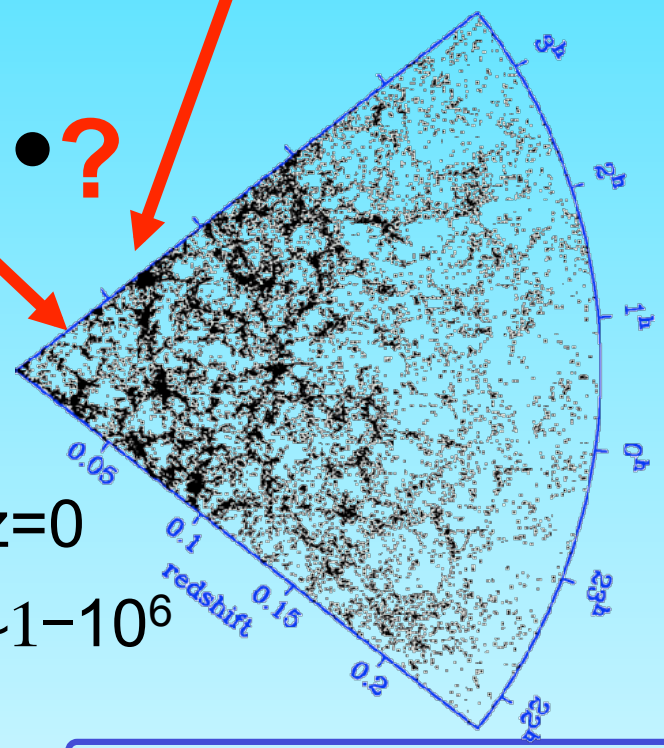
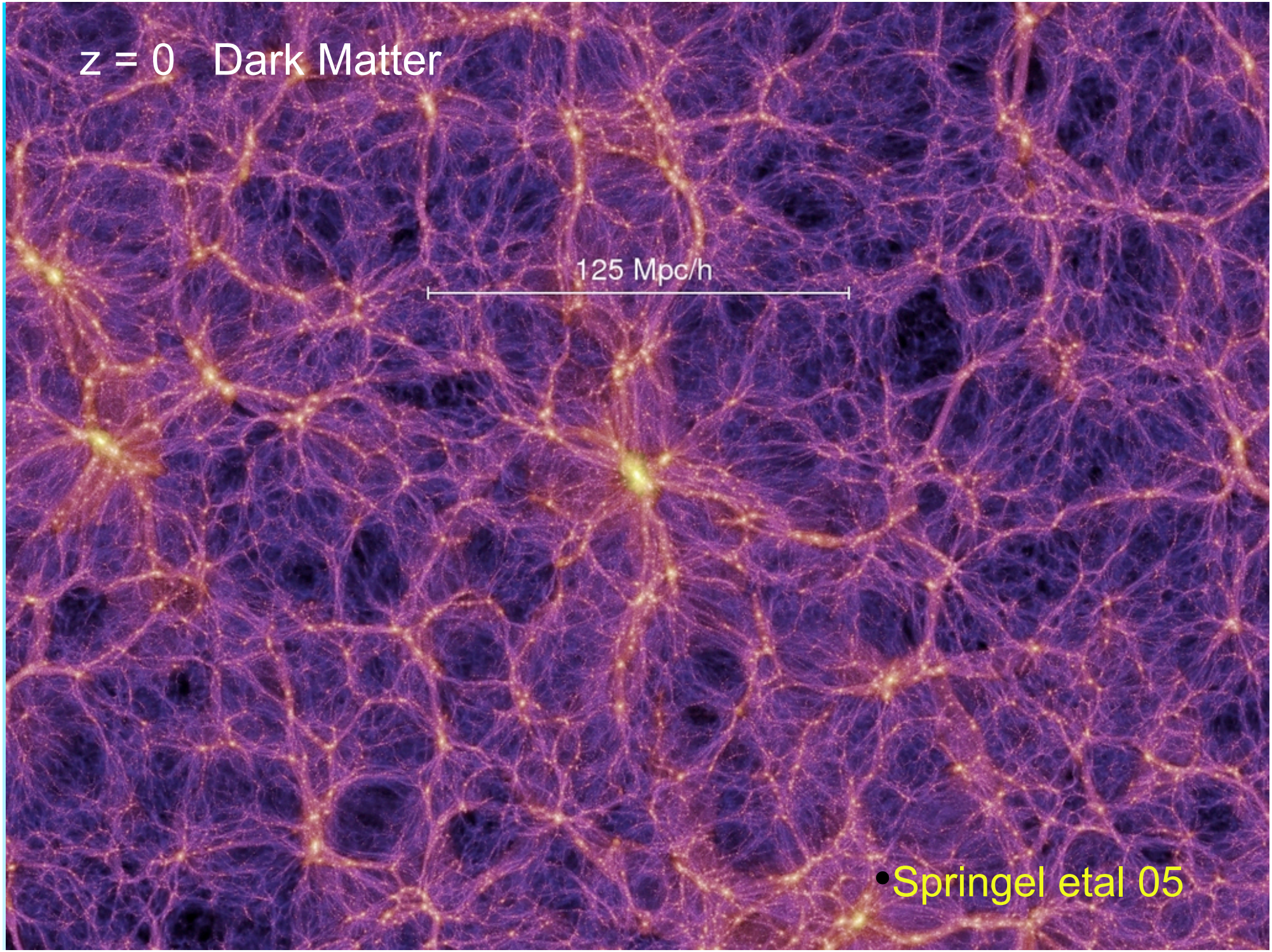


•z=0

•$\delta\rho/\rho \sim 1-10^6$

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

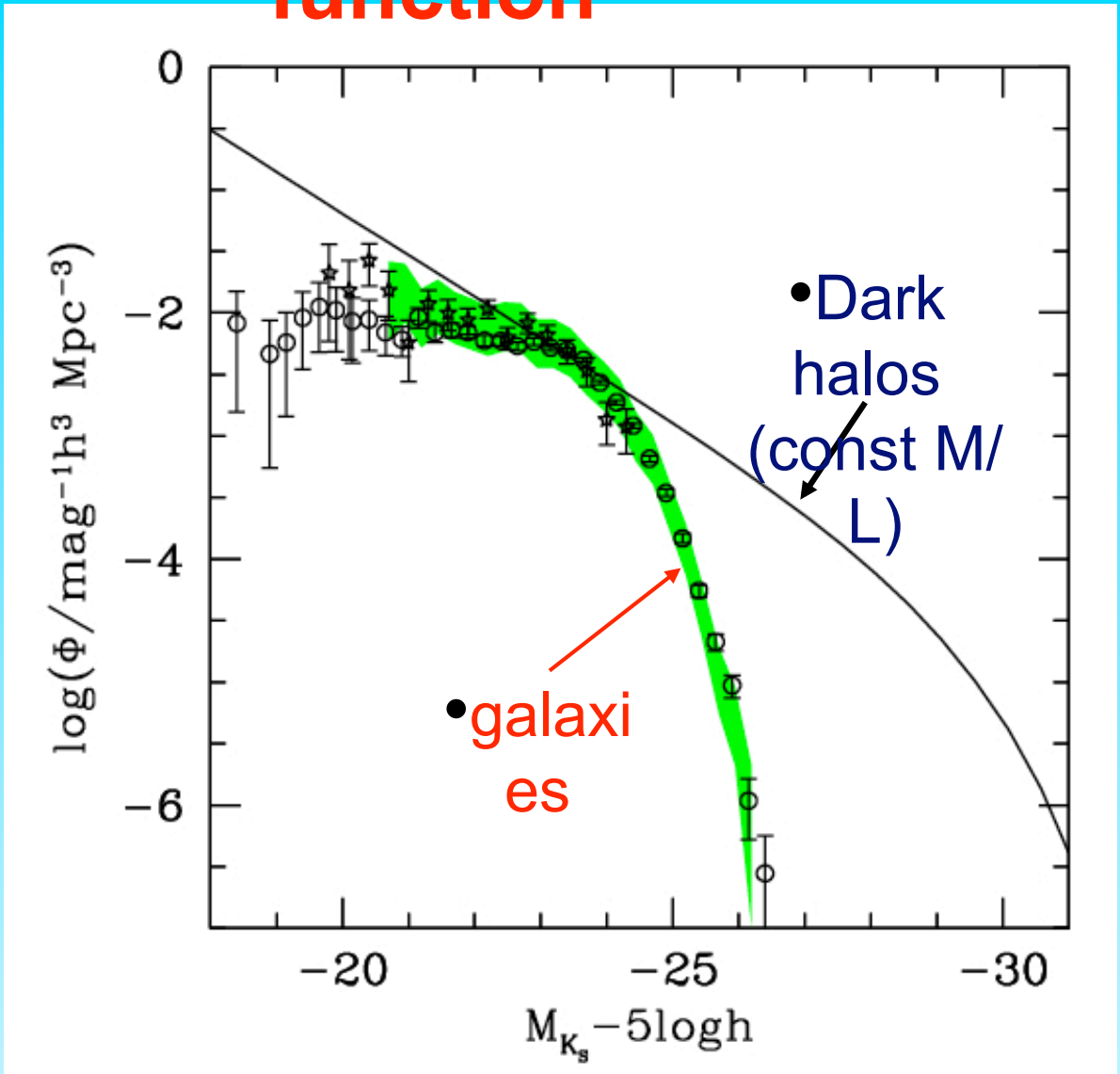


•Springel etal 05

•The galaxy luminosity function

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

•Complicated variation of M/L with halo mass



•Benson, Bower, Frenk, Lacey, Baugh & Cole '03

Modelling galaxy formation

University of Durham

- **Aim:** follow history of galaxy formation *ab initio*, i.e starting from a cosmological model for structure formation so as to predict observables

- **Main Physical processes:**
  - Assembly of dark matter halos
  - Shock-heating and radiative cooling of gas within halos
  - Star formation and feedback
  - Production & mixing of metals
  - Evolution of stellar populations
  - Dust extinction & emission
  - Black hole format'n, AGN feedback
  - Galaxy mergers

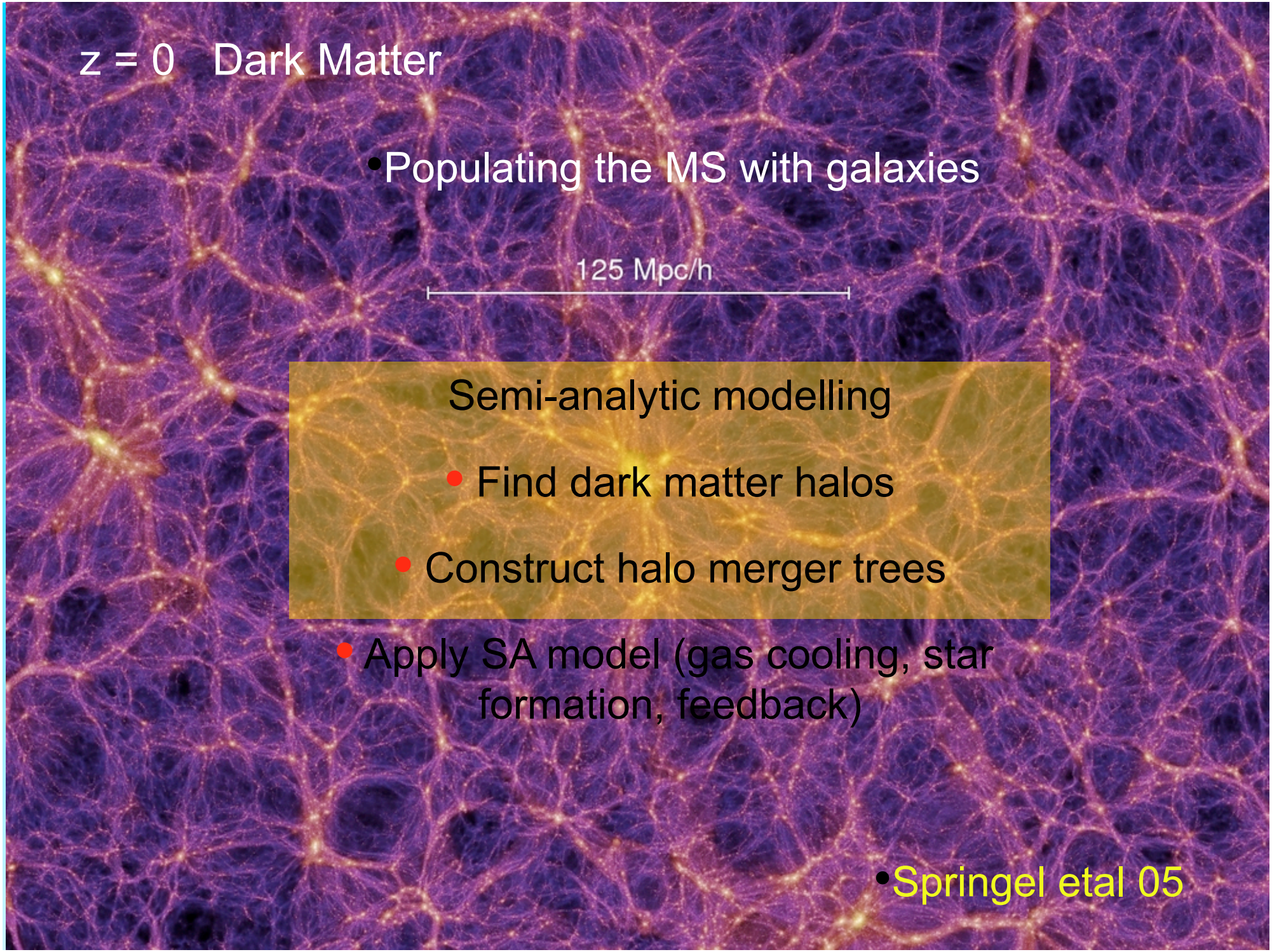
Sub-grid physics

Semi-analytical model

– Parametrize physics

– Set of coupled differential equations

– Predict galaxy prop. (lum, mass, B/T, radius, metallicity etc) and evolution with redshift

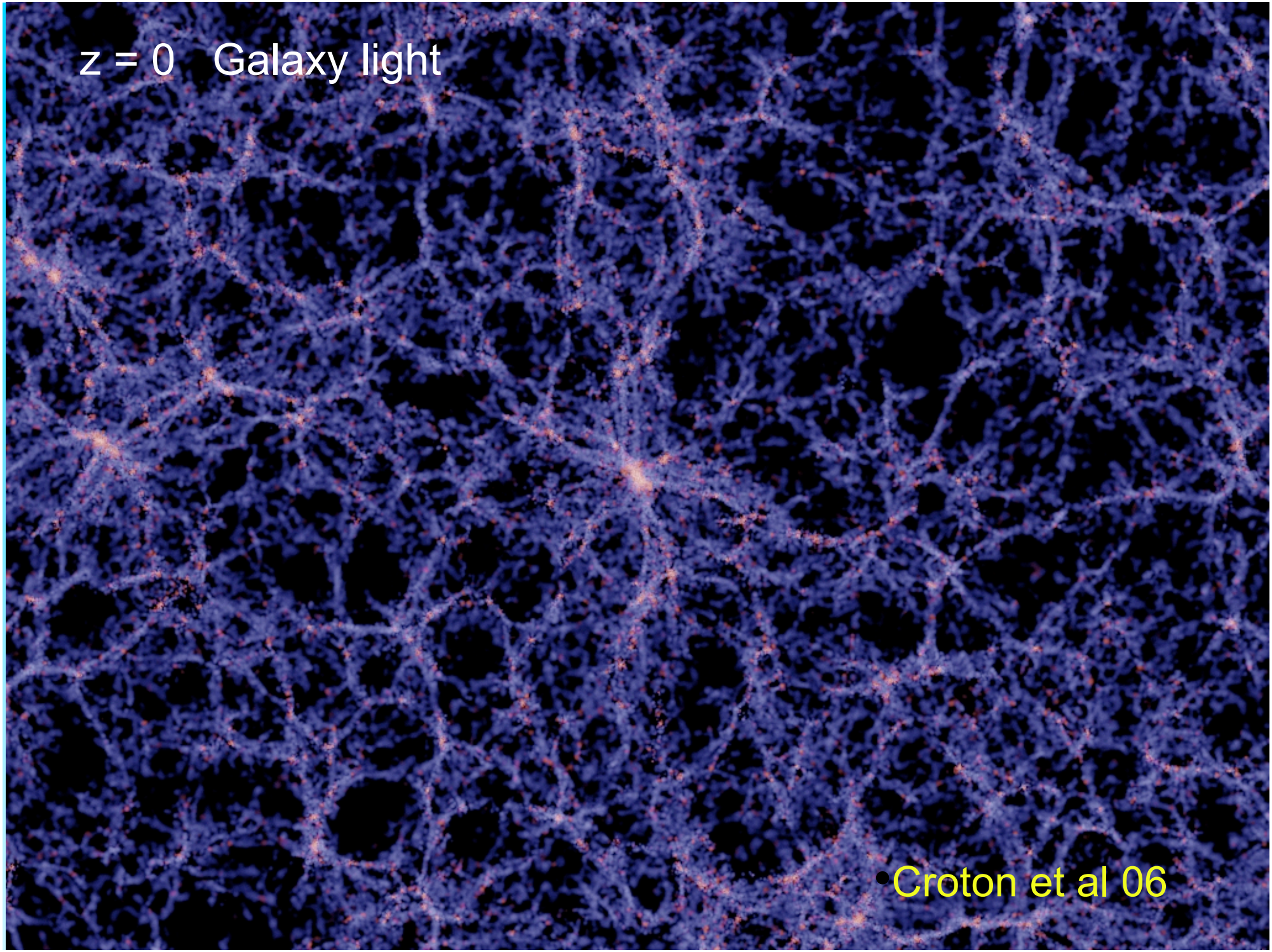


- Populating the MS with galaxies

Semi-analytic modelling

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

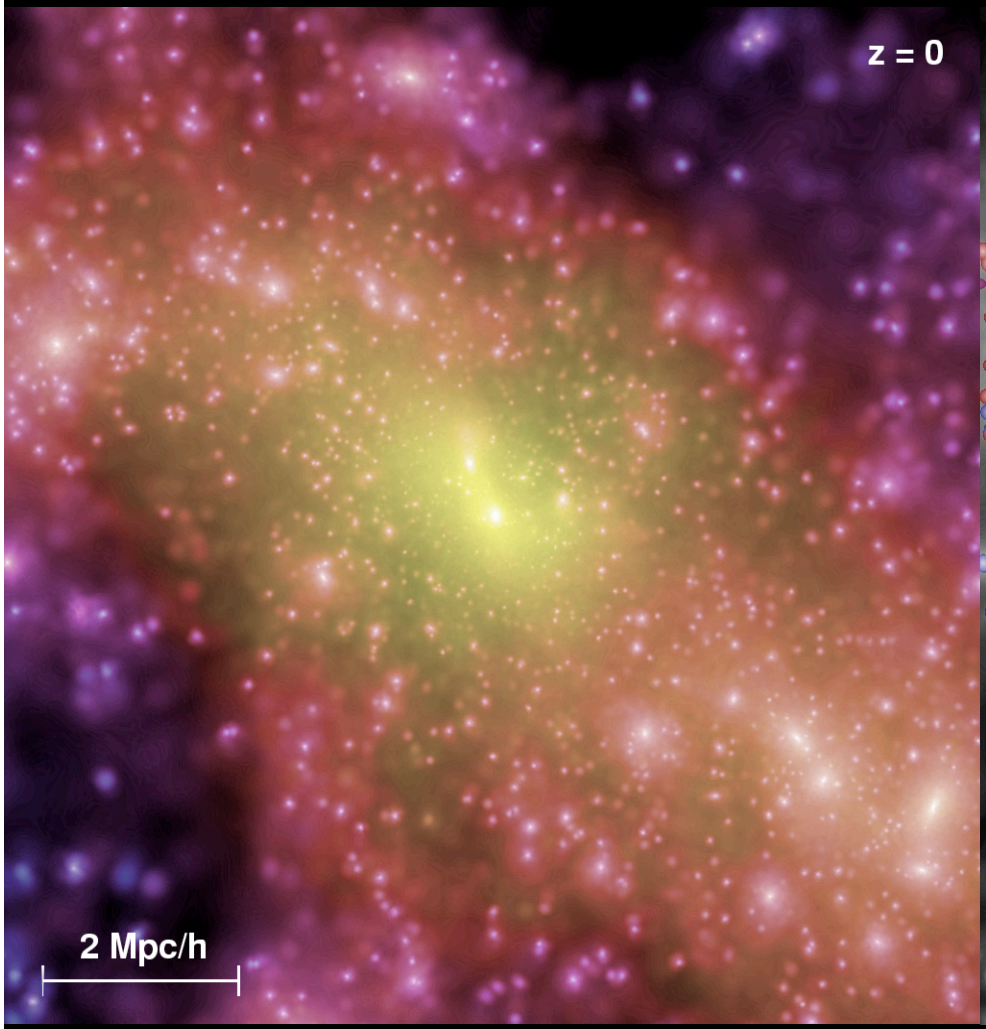
- Springel etal 05

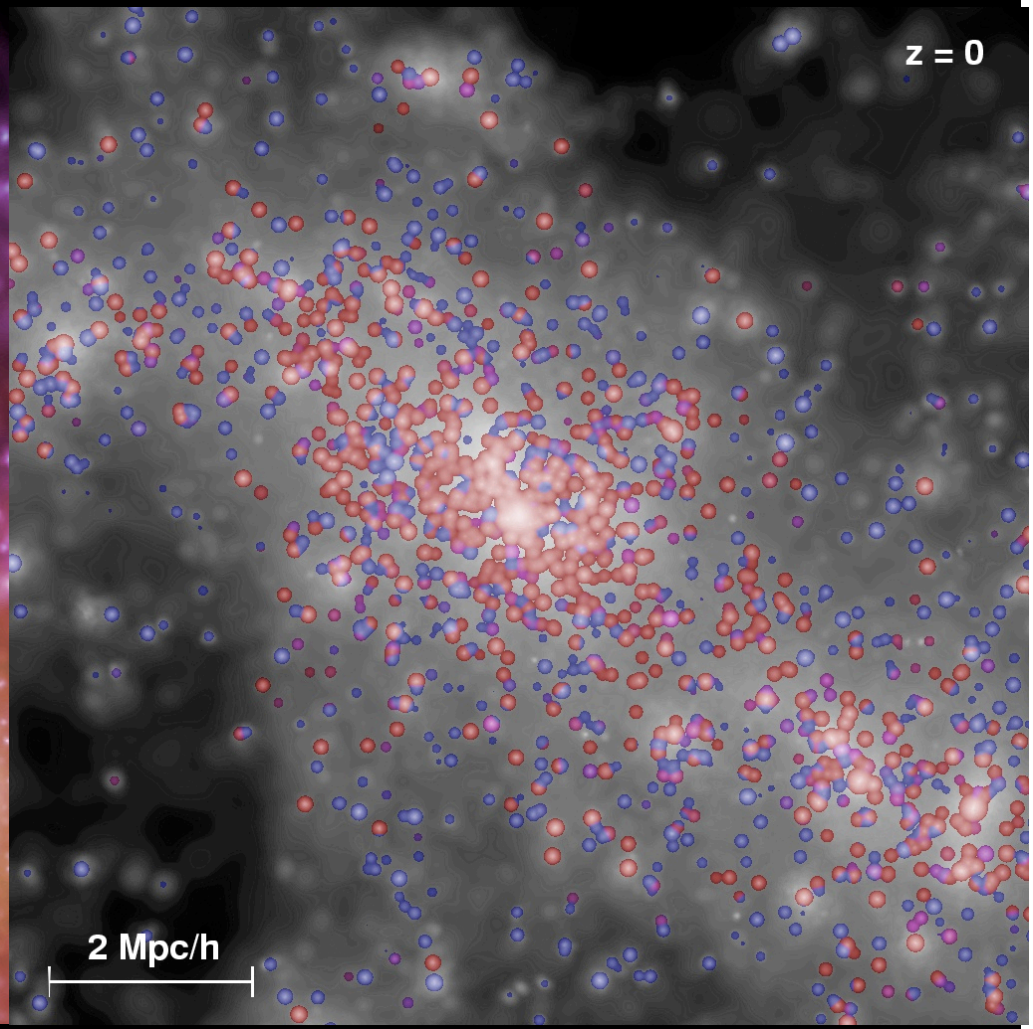

z = 0 Galaxy light
•Croton et al 06

$10^{14} M_o$

Dark matter

Galaxies





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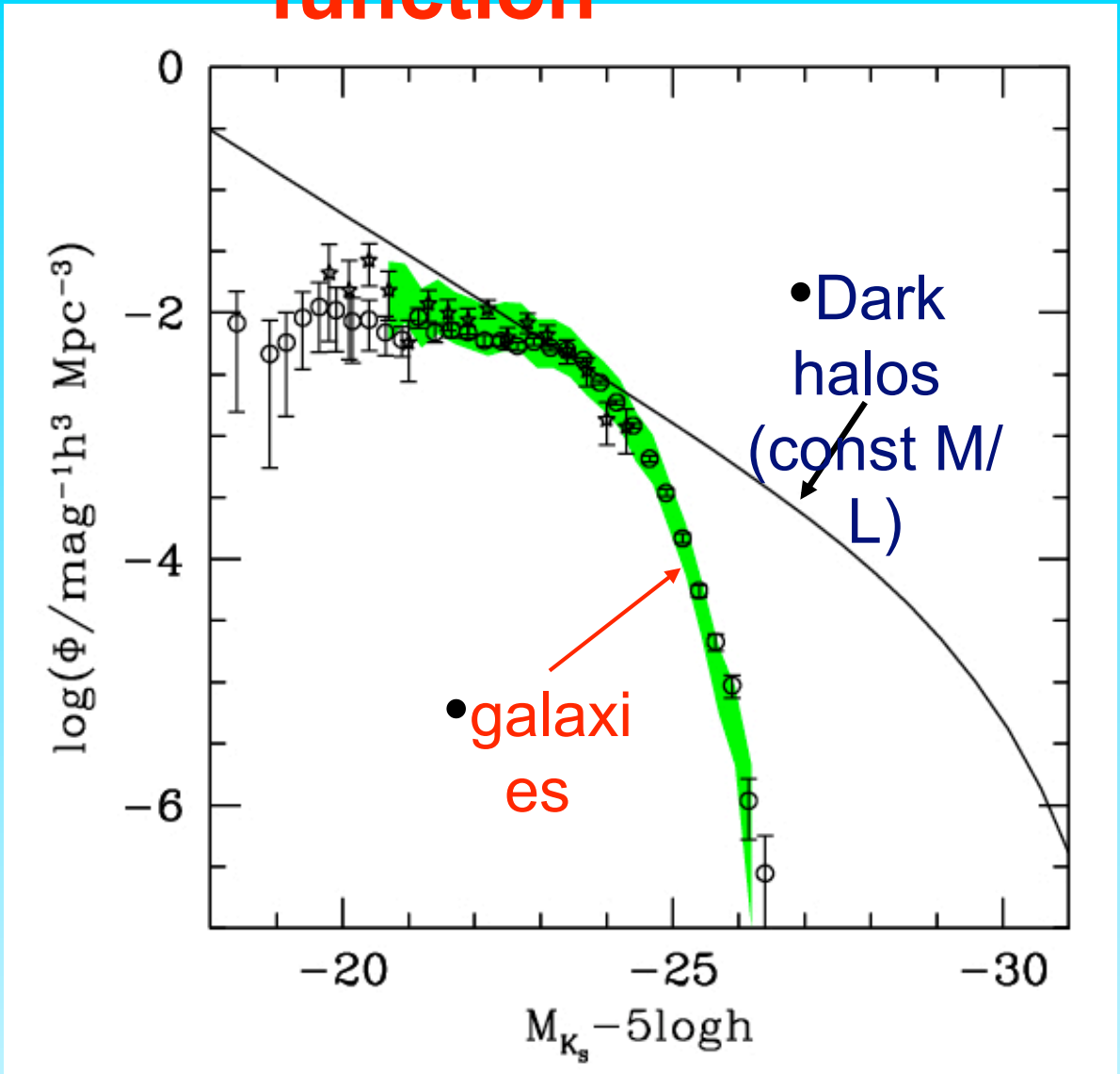


•Benson, Bower, Frenk, Lacey, Baugh & Cole '03

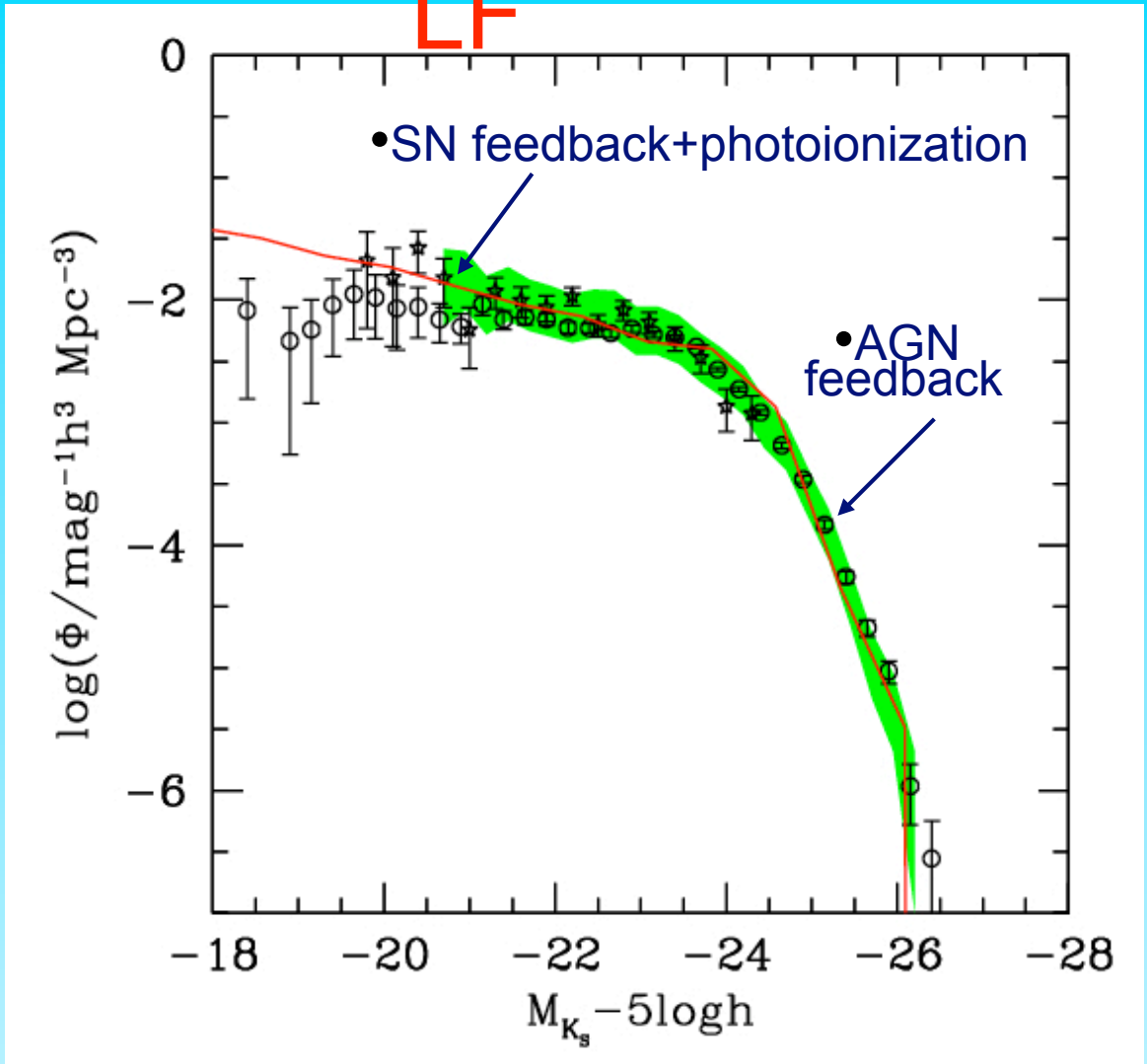
•Deconstructing the galaxy LF

•**Faint end:**

•Photoionization + reheating of cold disk gas by SN

•**Bright end:**

•AGN feedback: energy transported by bubbles



•Bower et al 06

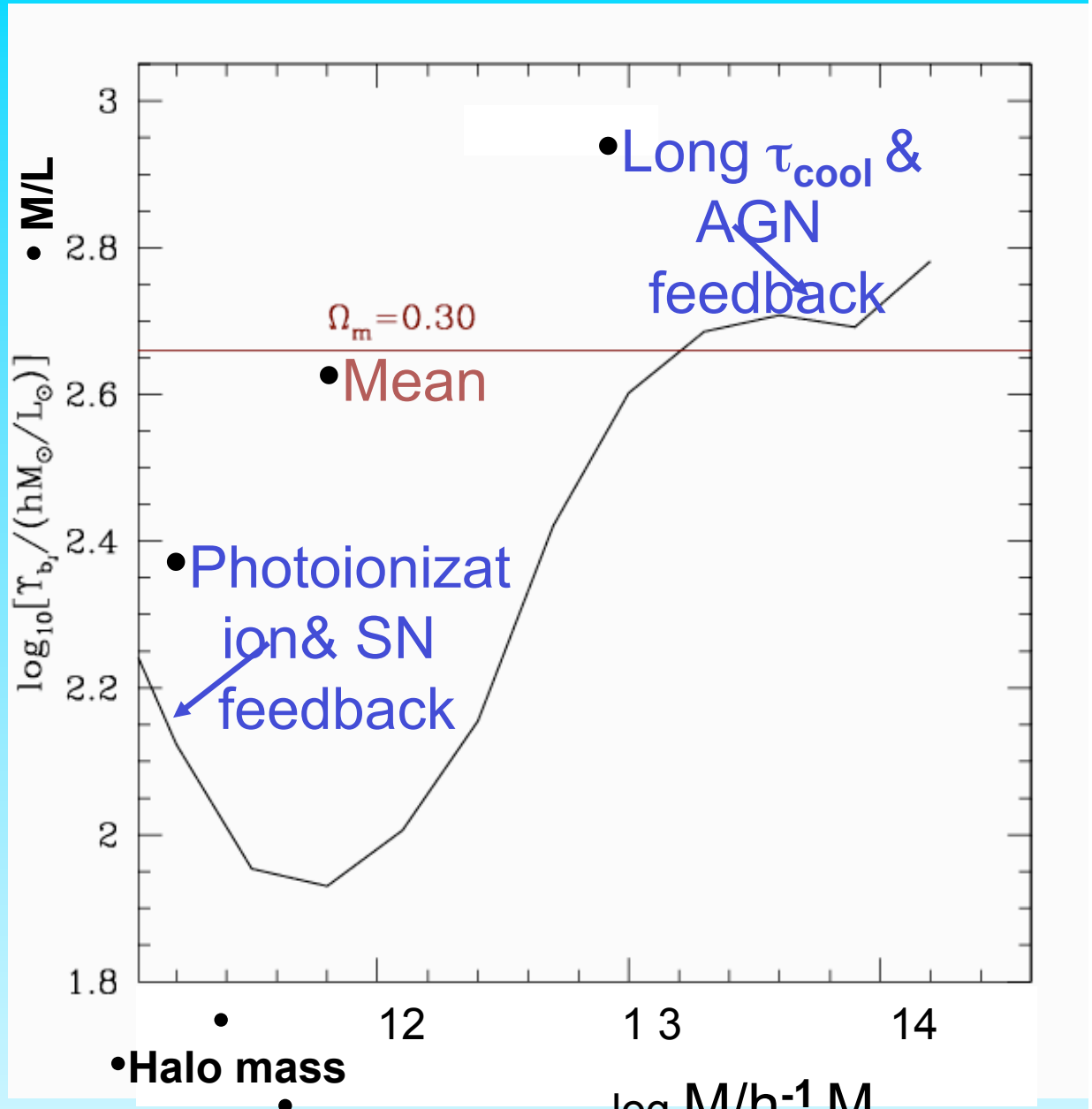
•Halo mass-to-light ratios

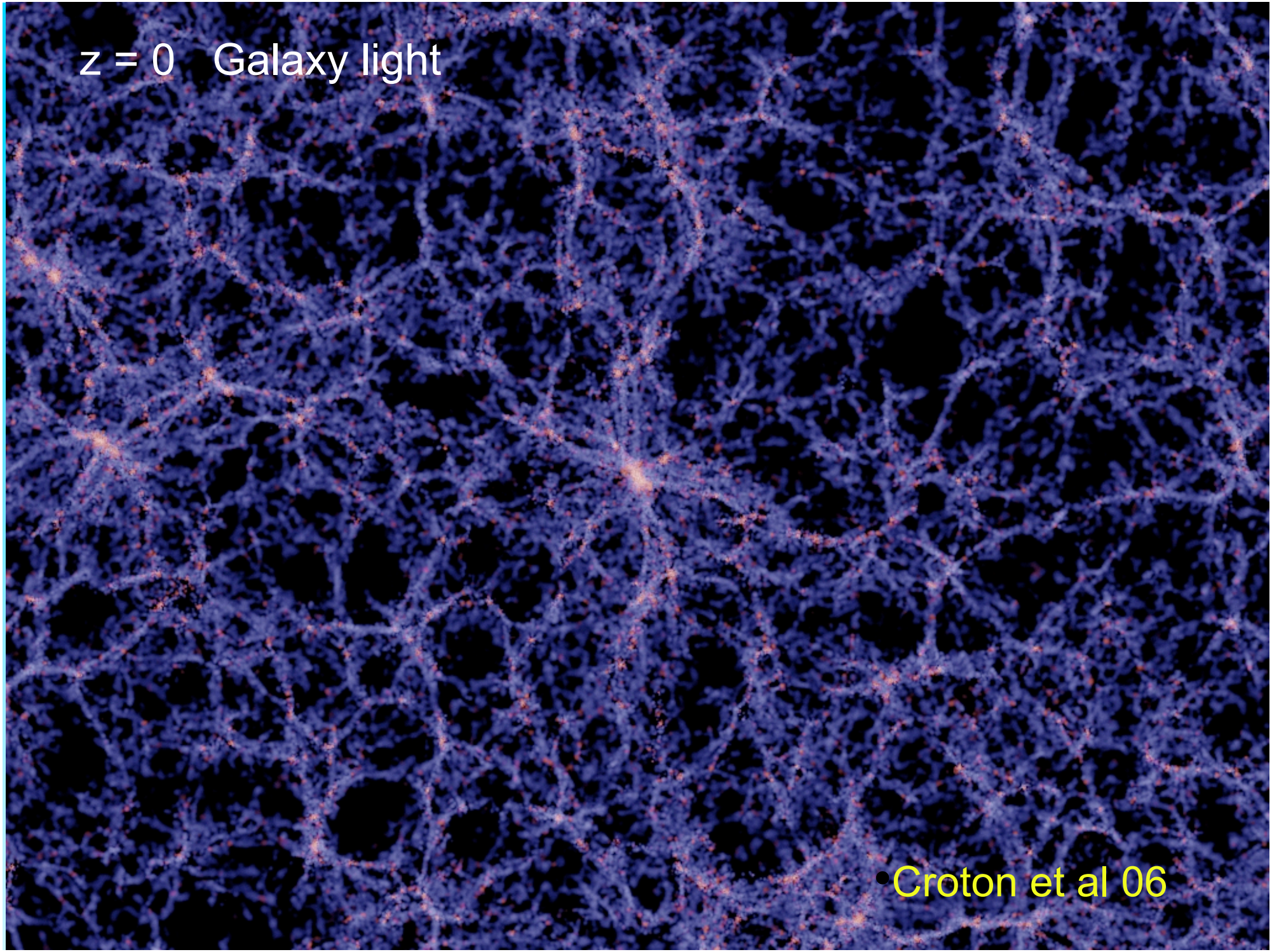
•The physics of galaxy formation

•Efficiency of galaxy formation

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

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

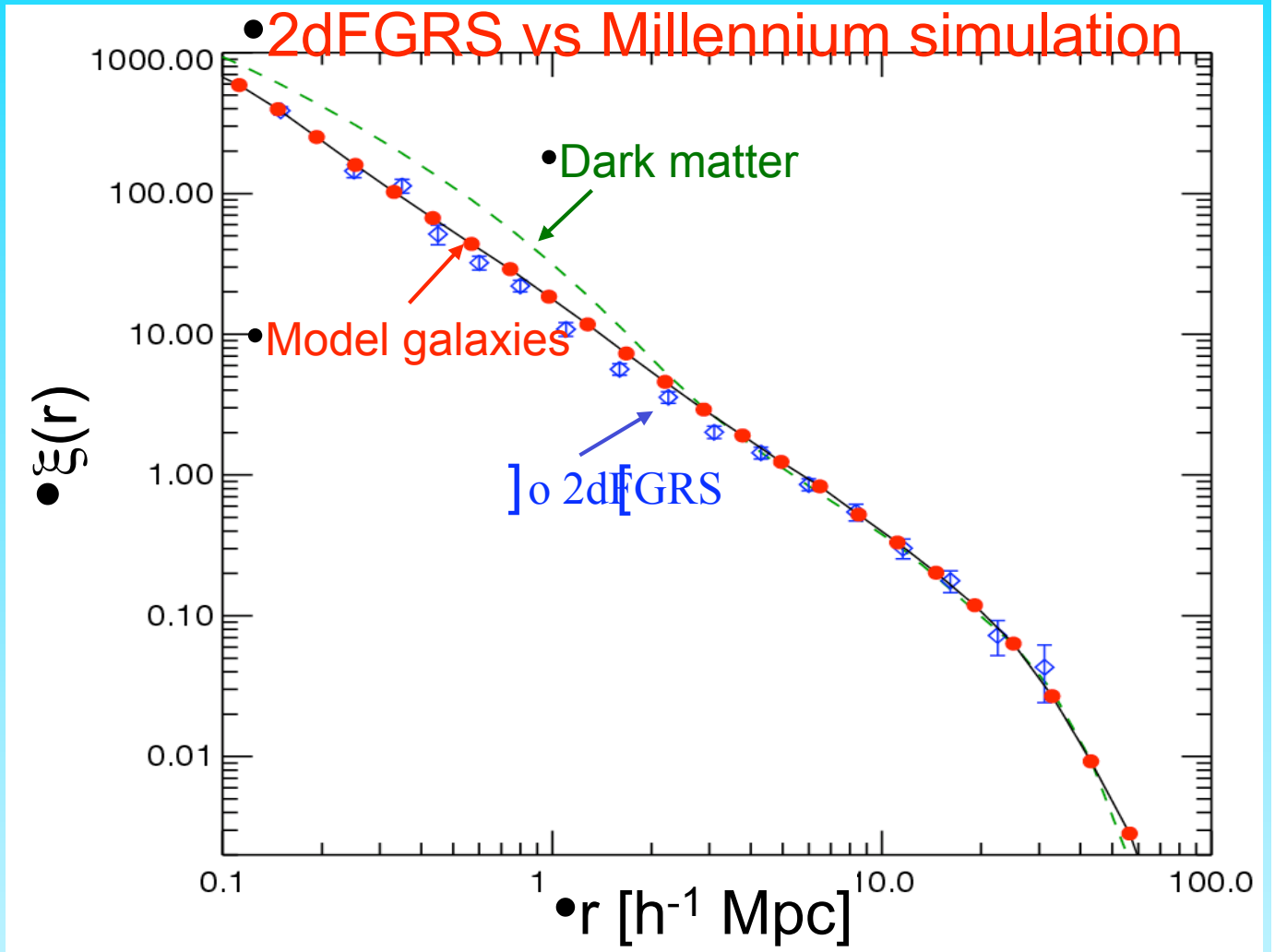



z = 0 Galaxy light
•Croton et al 06

Galaxy autocorrelation function

- The galaxy 2-point correlation function in the MS agrees well with 2dFGRS

- Galaxies are less clustered than DM on small scales



Springel et al 2005

University of Durham

•Testing the ΛCDM paradigm with galaxy surveys

•Three tests:

- Origin of fluctuations, nature of DM, cosm.parms
  (Power spectrum of galaxy distribution)

- Gravitational instability
  (z-space distortions)

- Hierarchical galaxy formation
  (non-linear clustering)

•A Cold dark matter universe

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•CDM has been ruled out many times in the past:

- 1984 Large cluster-cluster correlation function (Bahcall)
- 1986 Great Wall (Geller & Huchra)
- 1986 High –z qsos (various)
- 1989 Large-scale streaming motions (7-Samurai)
- 1990 Extra large-scale power (APM, QDOT)

•Some of these data were not robust;

- 1993 LSSM again (Lauer & Postman)

•other (APM, QDOT) ruled out Ω_m=1 standard CDM and replaced it with ΛCDM

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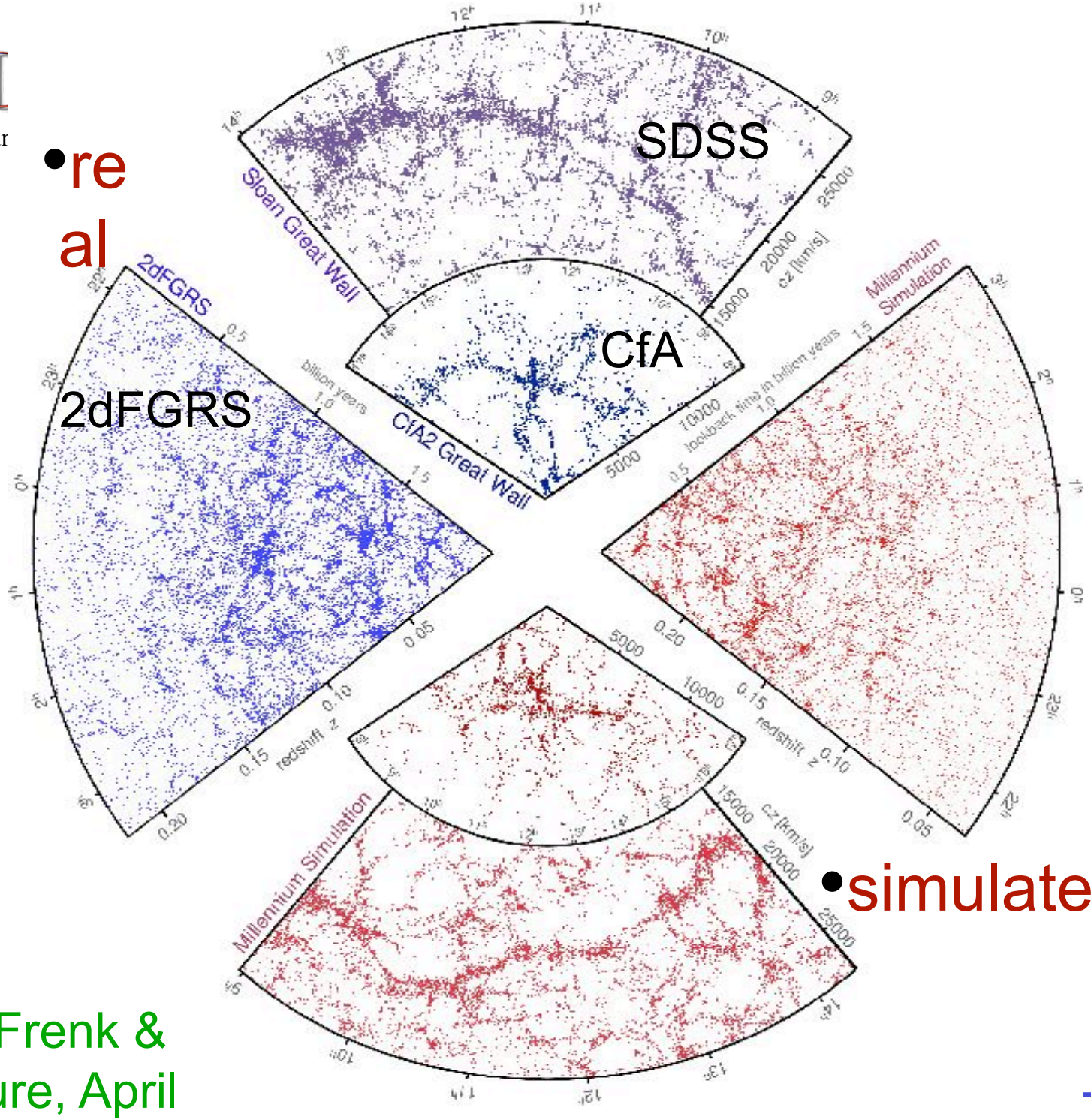
•re
al



•simulated

•Springel, Frenk & White Nature, April '06

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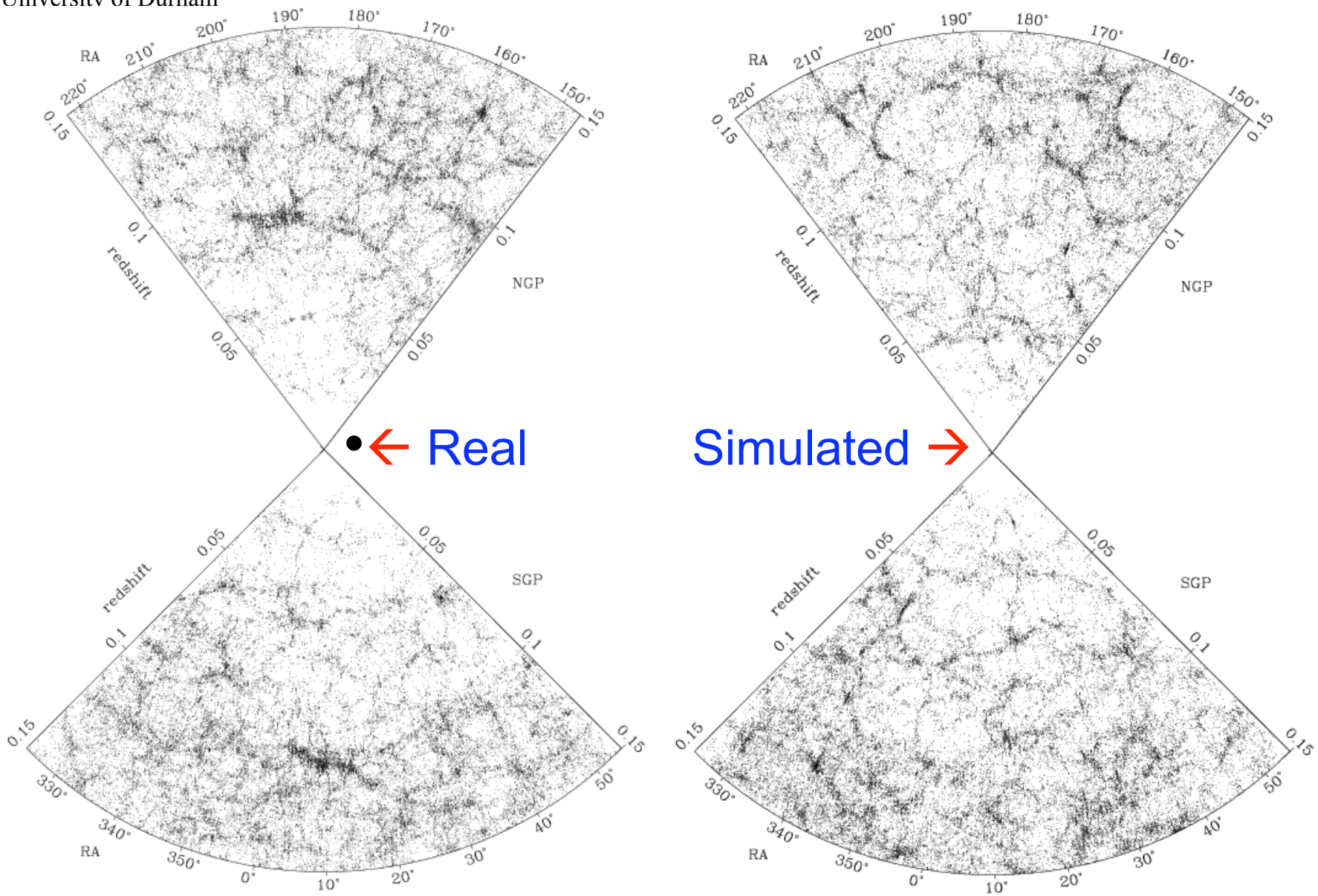
•Real and simulated 2dF galaxy survey



•← Real

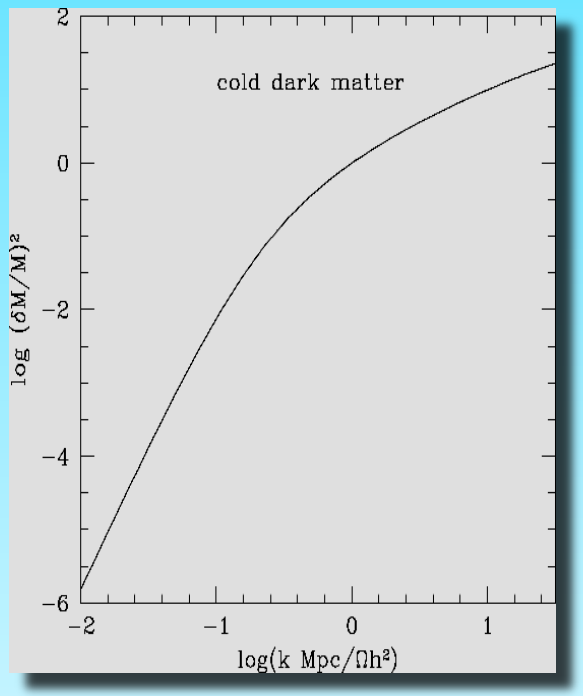
Simulated →

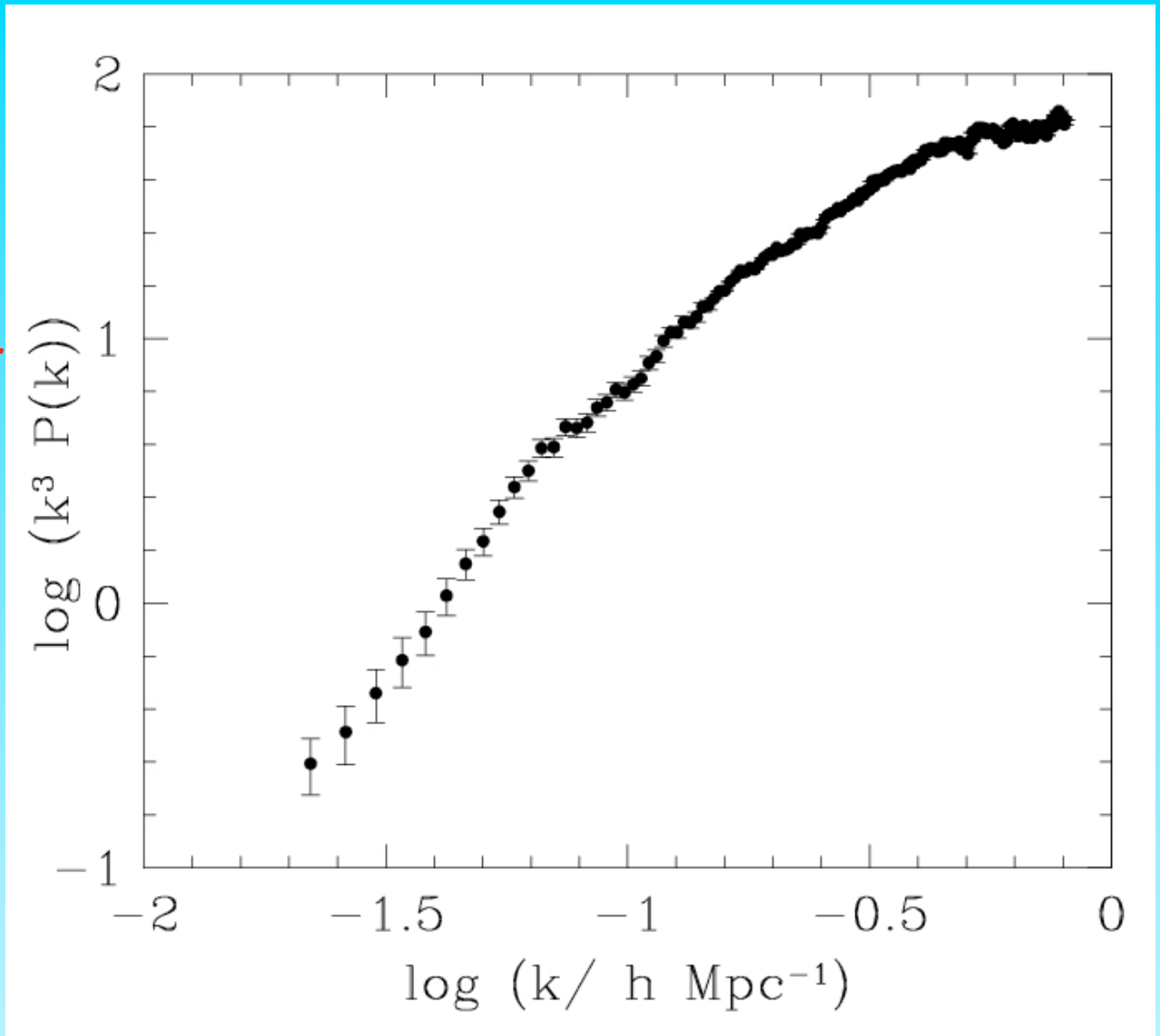
Institute for Computational Cosmology

•The 2dF galaxy power spectrum

University of Durham

•Galaxy power spectrum *in redshift space, convolved with survey window, inclunding non-linear effects*





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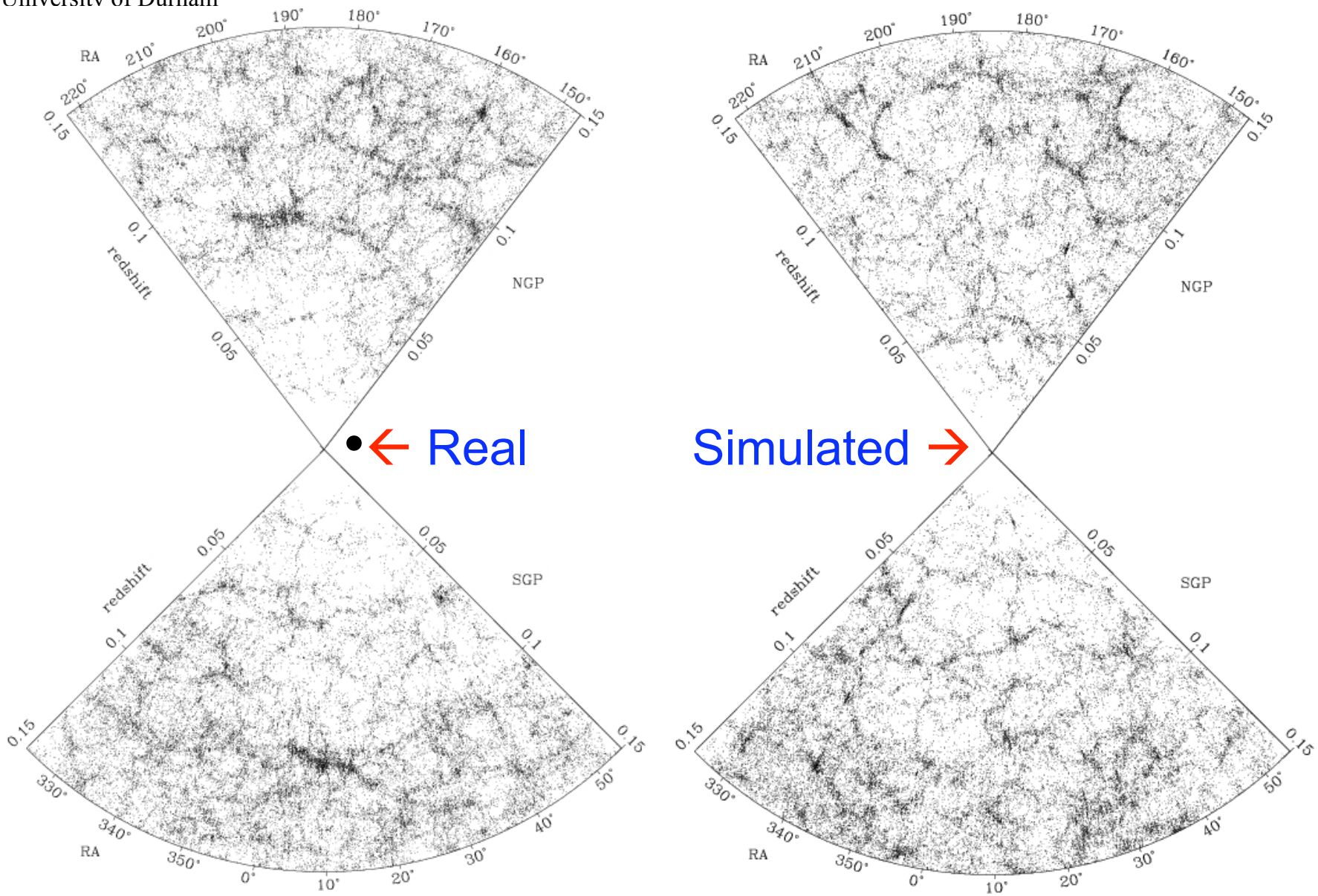
•Real and simulated 2dF galaxy survey



•← Real

Simulated →

Institute for Computational Cosmology

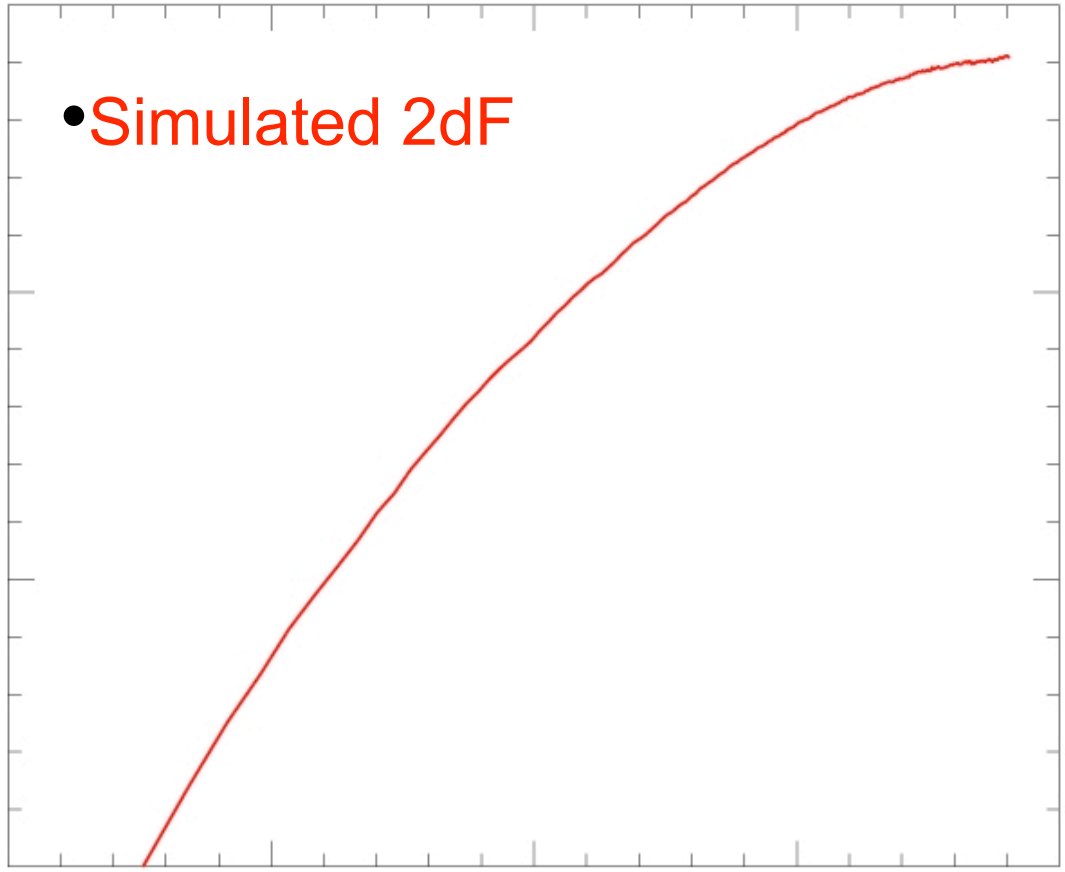
•The 2dF galaxy power spectrum

University of Durham

•From N-body simulation

•*Galaxy power spectrum in redshift space, convolved with 2dF window*

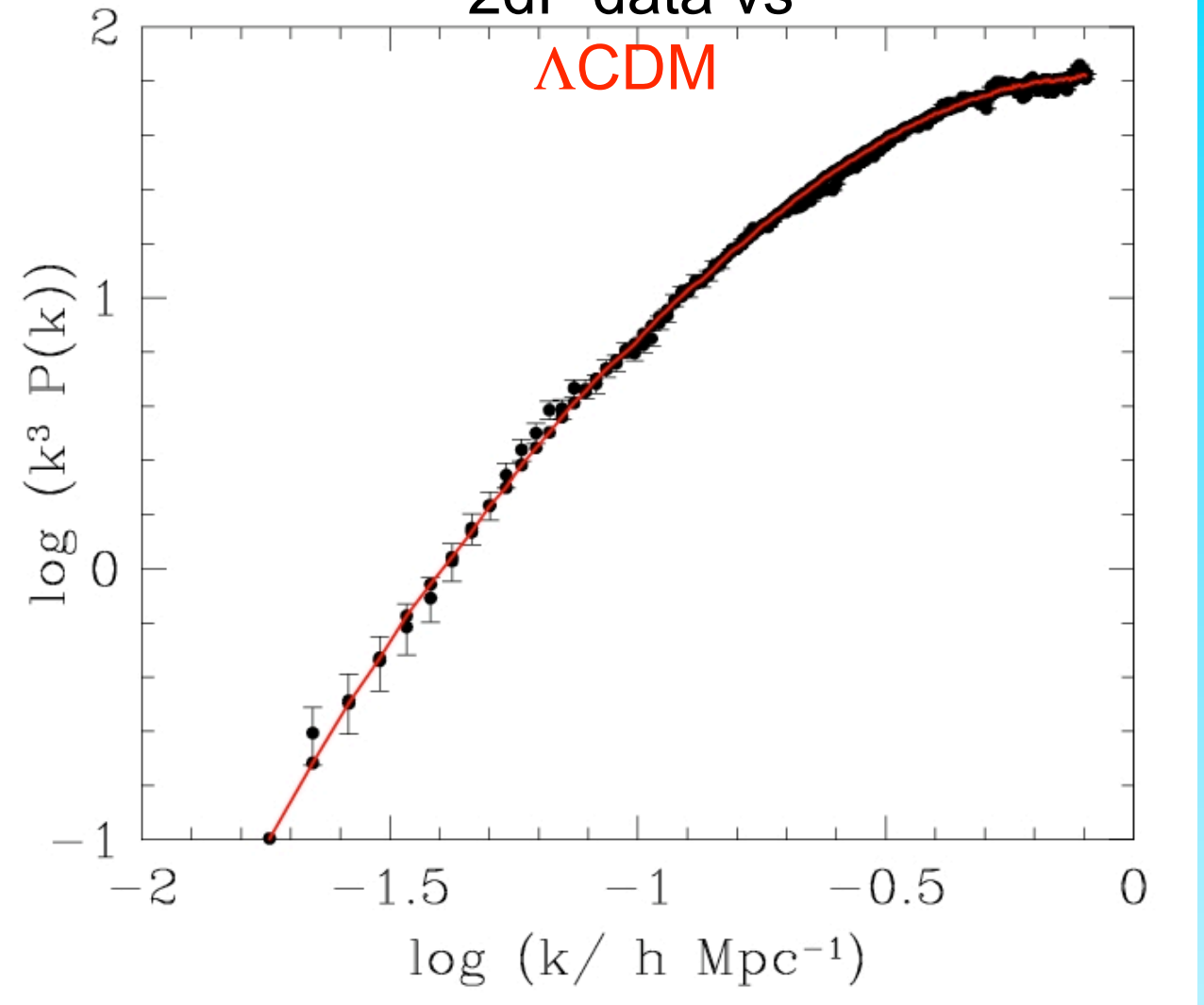
•ΛCDM ($\Omega = 0.3$, $\Lambda = 0.7$, h=0.7)



•The 2dF galaxy power spectrum

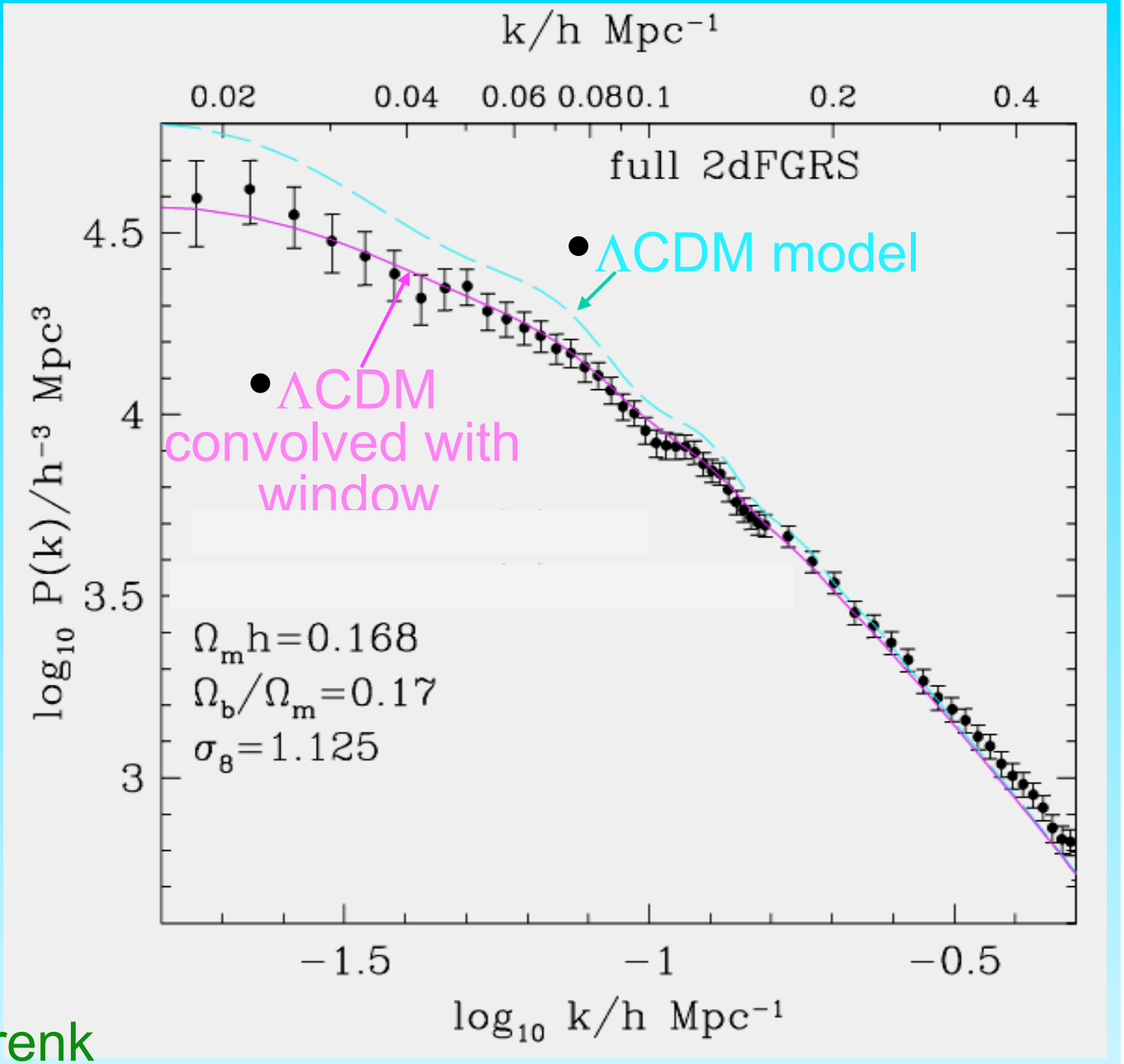
•Galaxy power spectrum in redshift space, convolved with 2dF window

•2dF data vs ΛCDM



•The final 2dFGRS power spectrum

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



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

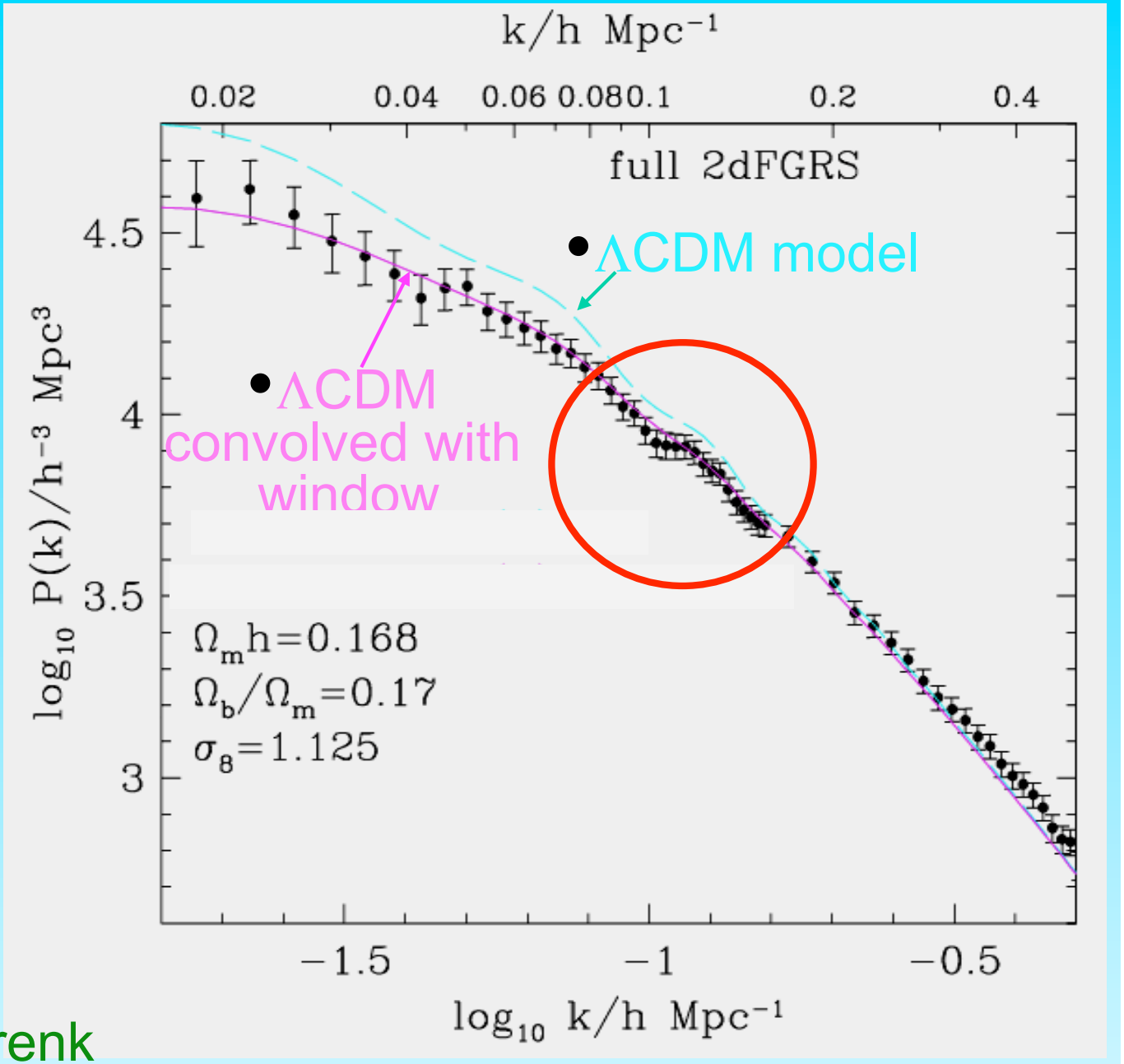
•The final 2dFGRS power spectrum

•Overall shape and amplitude of 2dFGRS P(k) extremely well fit by ΛCDM model convolved with window function

•Cole + 2dFGRS '05

•The final 2dFGRS power spectrum

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



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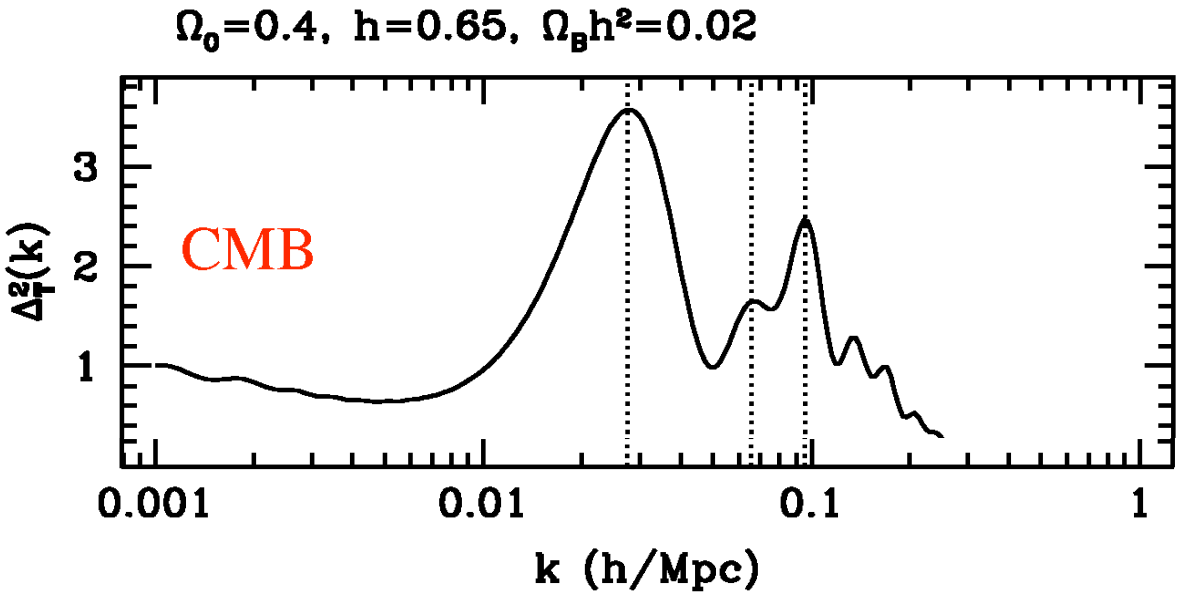
CMB anisotropies and large-scale structure



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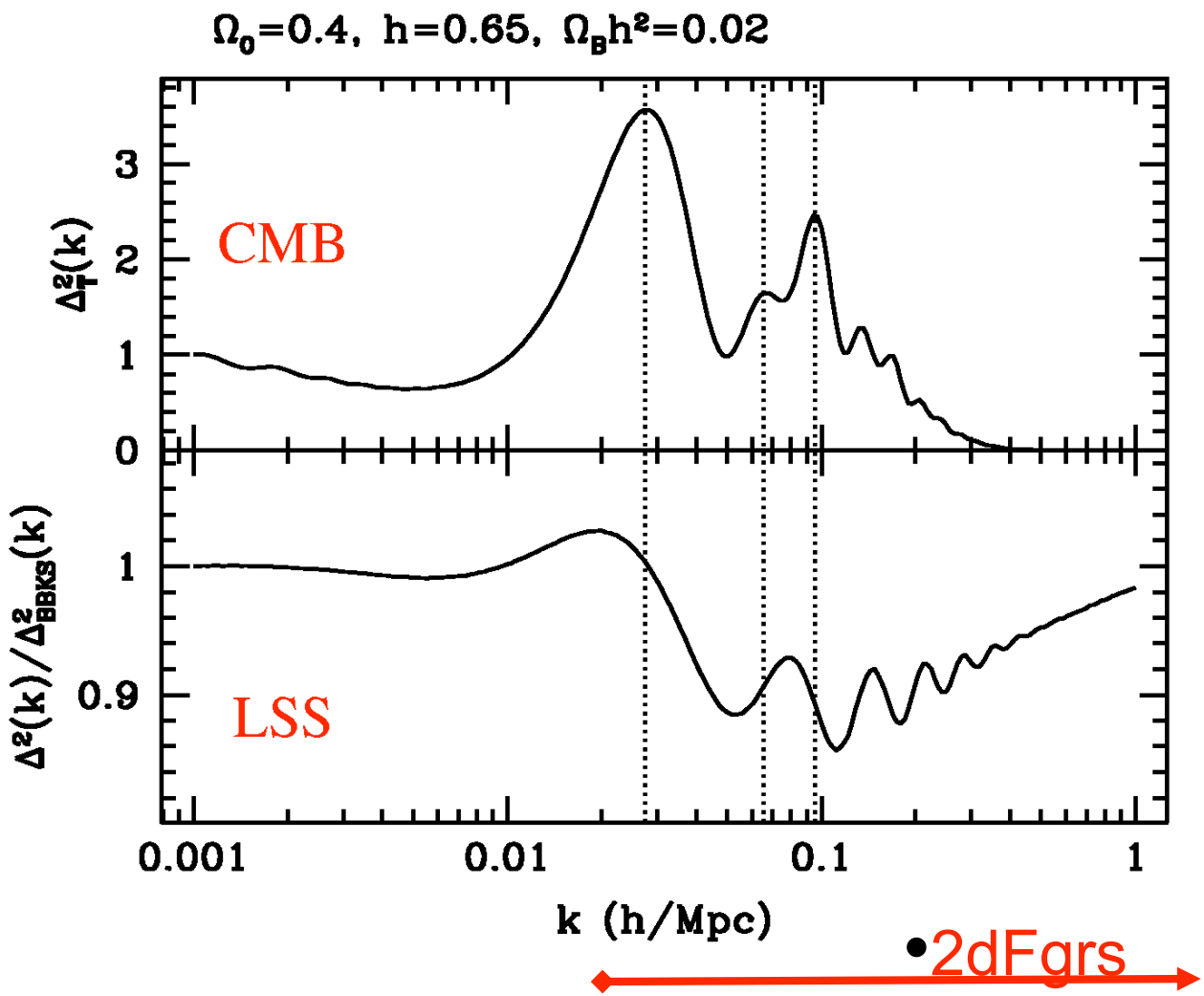
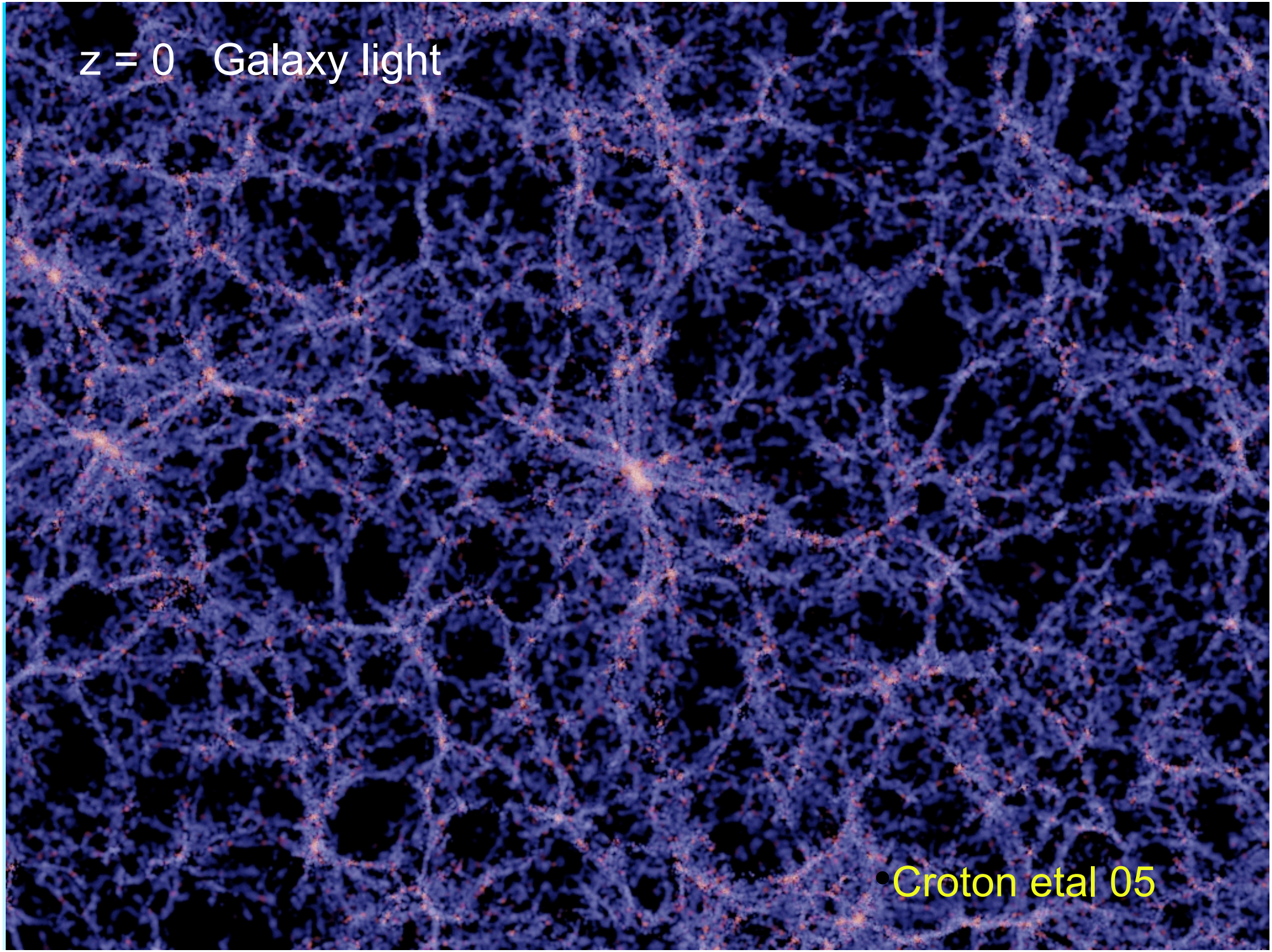


CMB and LSS out of phase:

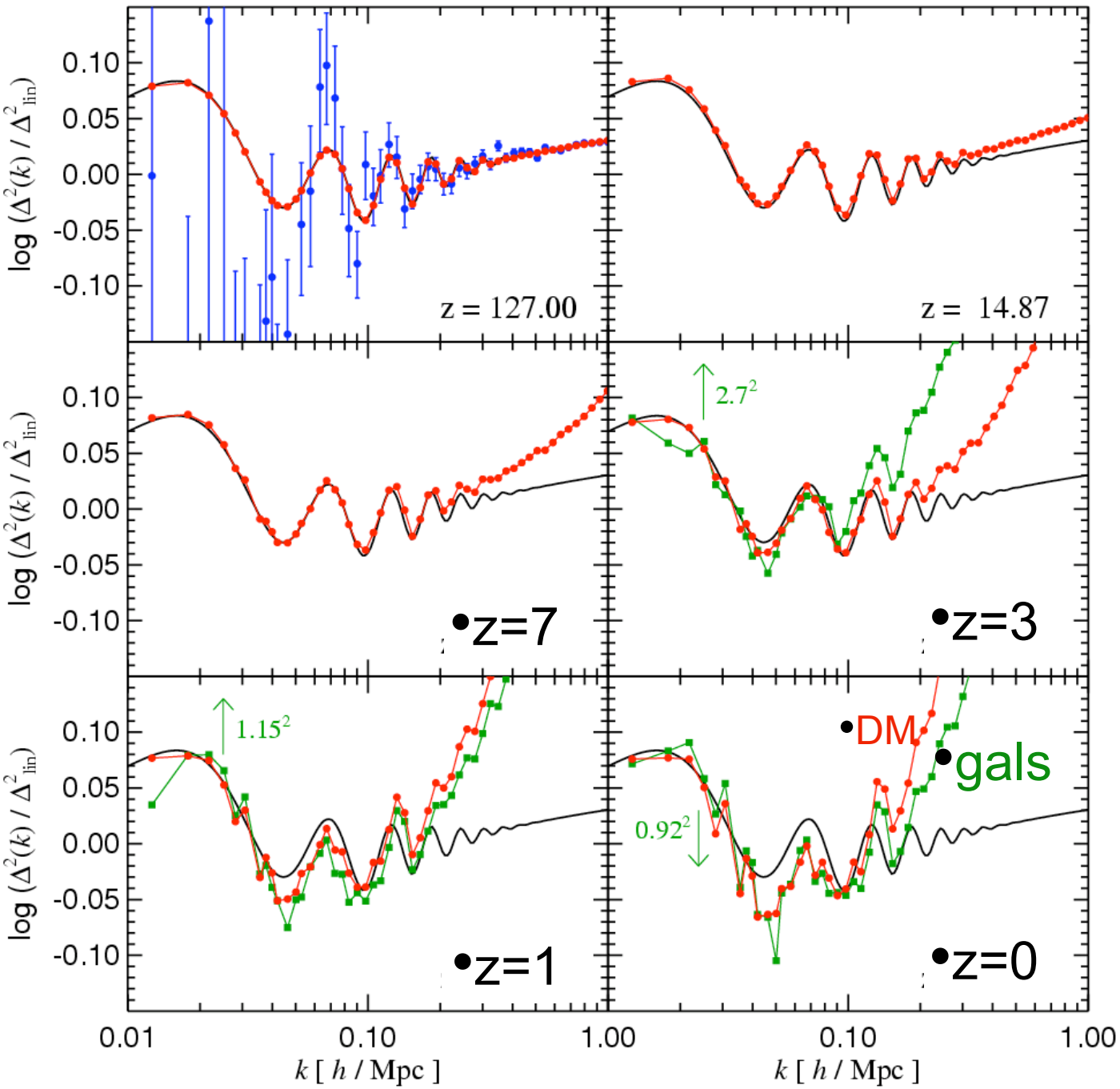
'velocity overshoot'

LSS amplitude smaller than CMB

•Meiksin etal 99


z = 0 Galaxy light
•Croton etal 05

Baryon wiggles in the *galaxy* distribution



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

Galaxy samples matched to plausible large observational surveys at given z

Springel et al 2004

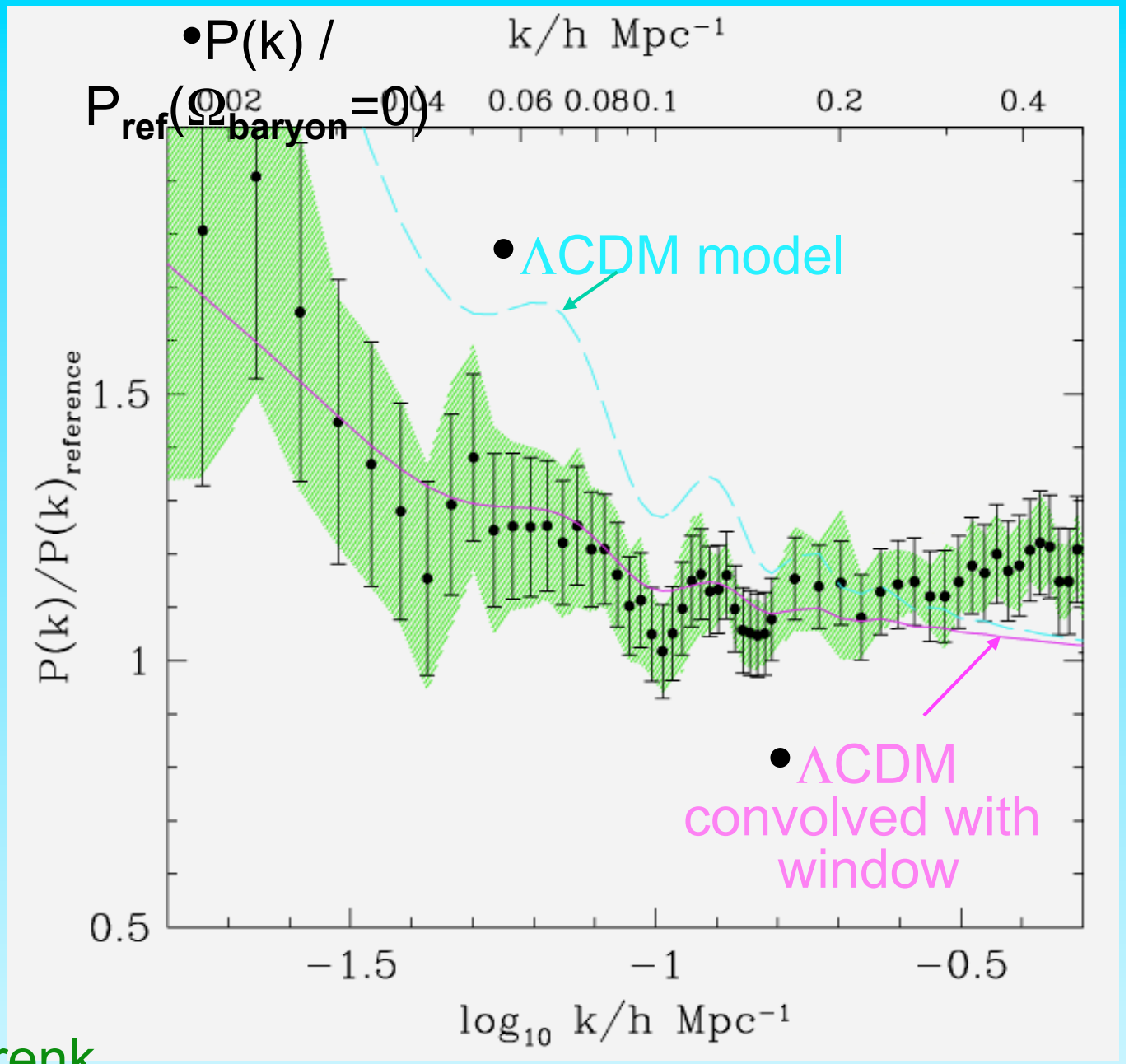
•The final 2dFGRS power spectrum

•Baryon oscillations conclusively detected in 2dFGRS!!!

•Suggests that structure grew by gravitational instability in ΛCDM universe

•Also detected in SDSS LRG sample (Eisenstein et al. 05)

•Cole, Percival, Peacock, Baugh, Frenk & 2dFGRS '05



•SDSS LRG correlation function

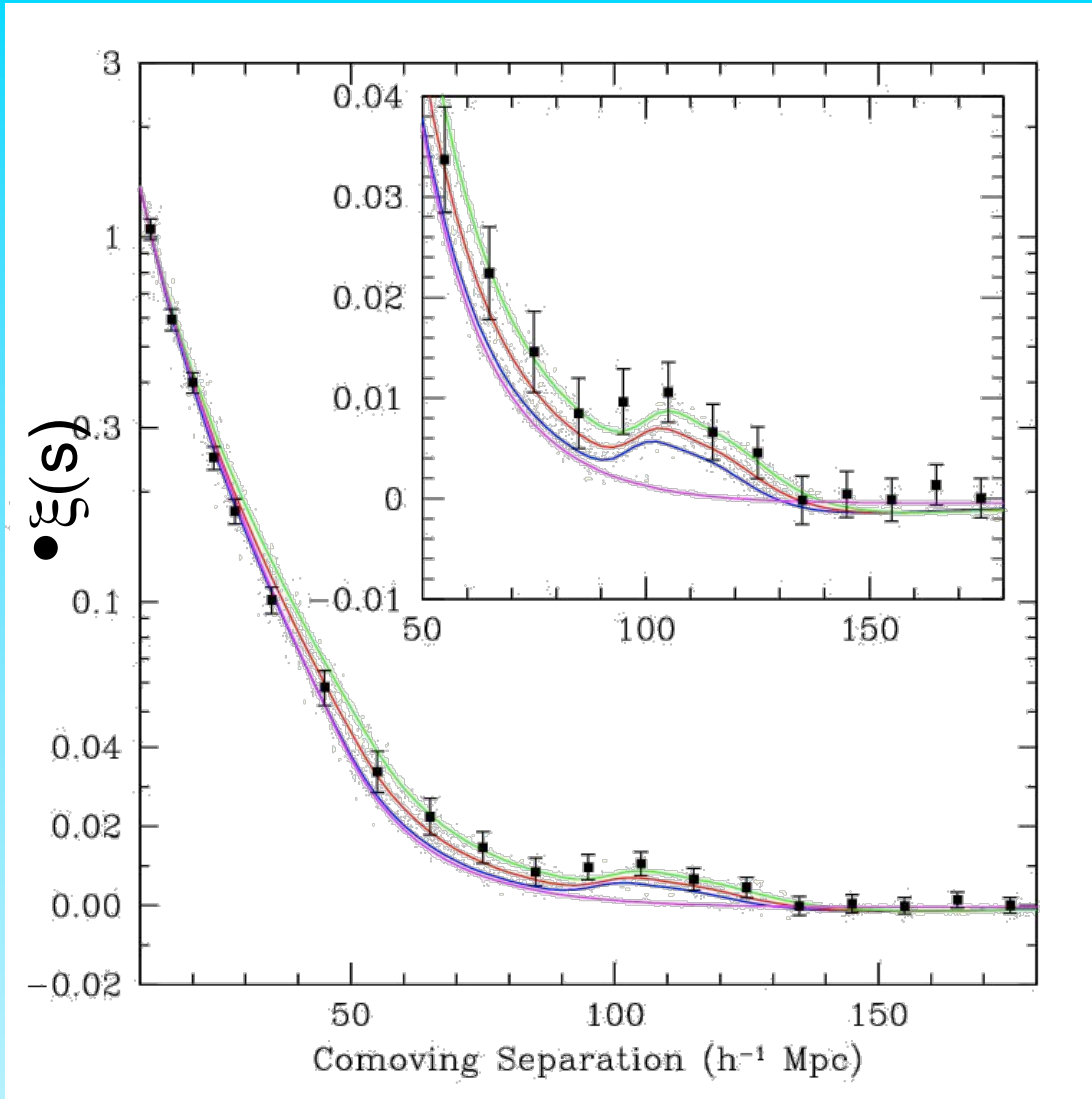
•Again, CDM models fit the correlation function adequately well (although peak height is slightly too large; assuming n_s=1, h=0.72)

•$\Omega_b h^2$ =0.024,

•$\Omega_m h^2$ =0.133±0.011,

•⇒ Ω_b/Ω_m= 0.18

•Eisenstein et al. 05



2dFGRS power-spectrum

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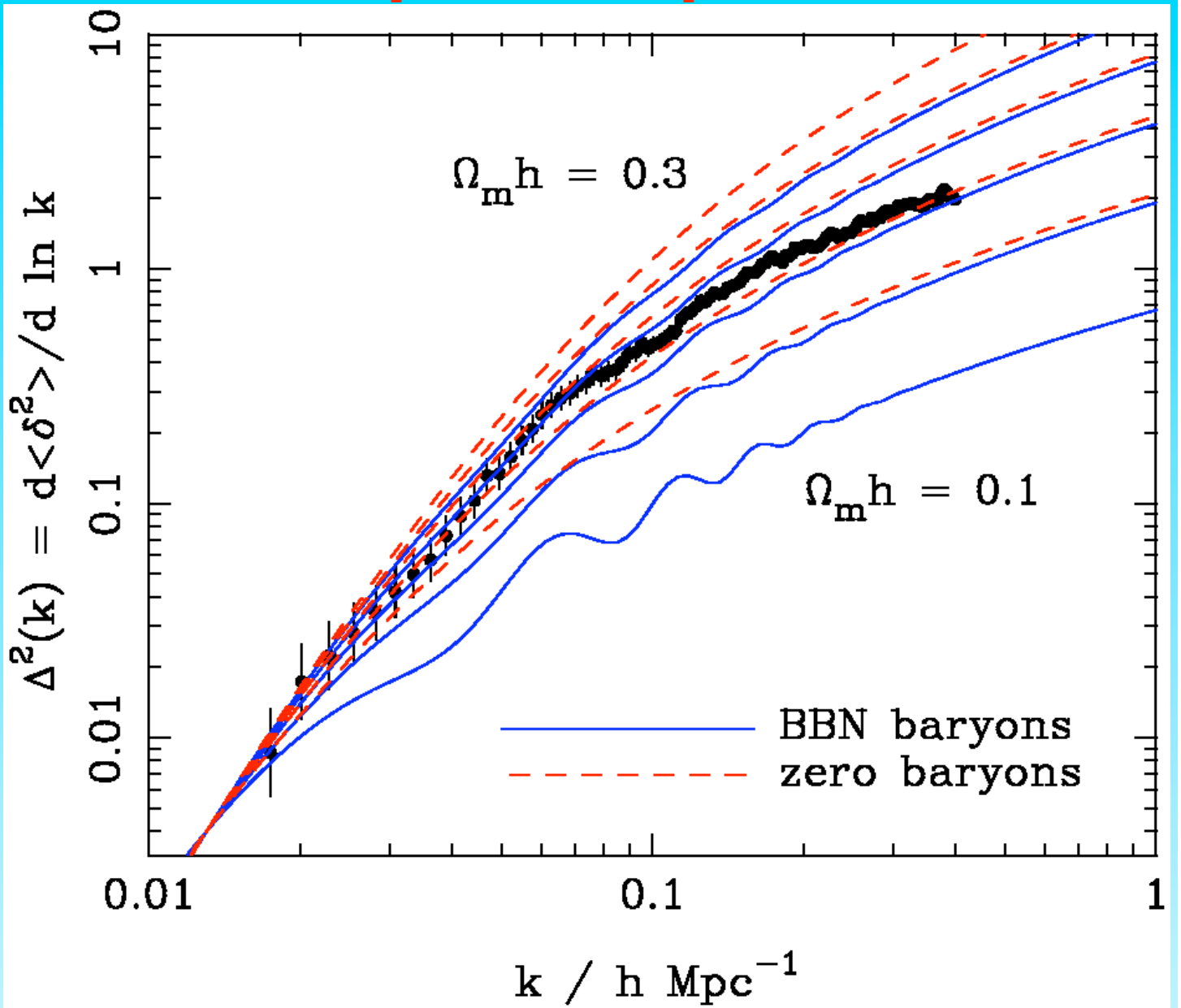
- Dimensionless power:
  Δ^2 (fractional variance in density) per ln k

$$\delta(\mathbf{r}) \equiv \frac{\delta\rho}{\rho} = \sum_k \delta_k \, e^{-i\mathbf{k}\cdot\mathbf{r}}$$

$$\Delta^2(k) \equiv \frac{d\sigma^2}{d\ln k} \propto k^3 \, |\delta_k|^2$$



- **Percival et al. MNRAS 327, 1279 (2001)**

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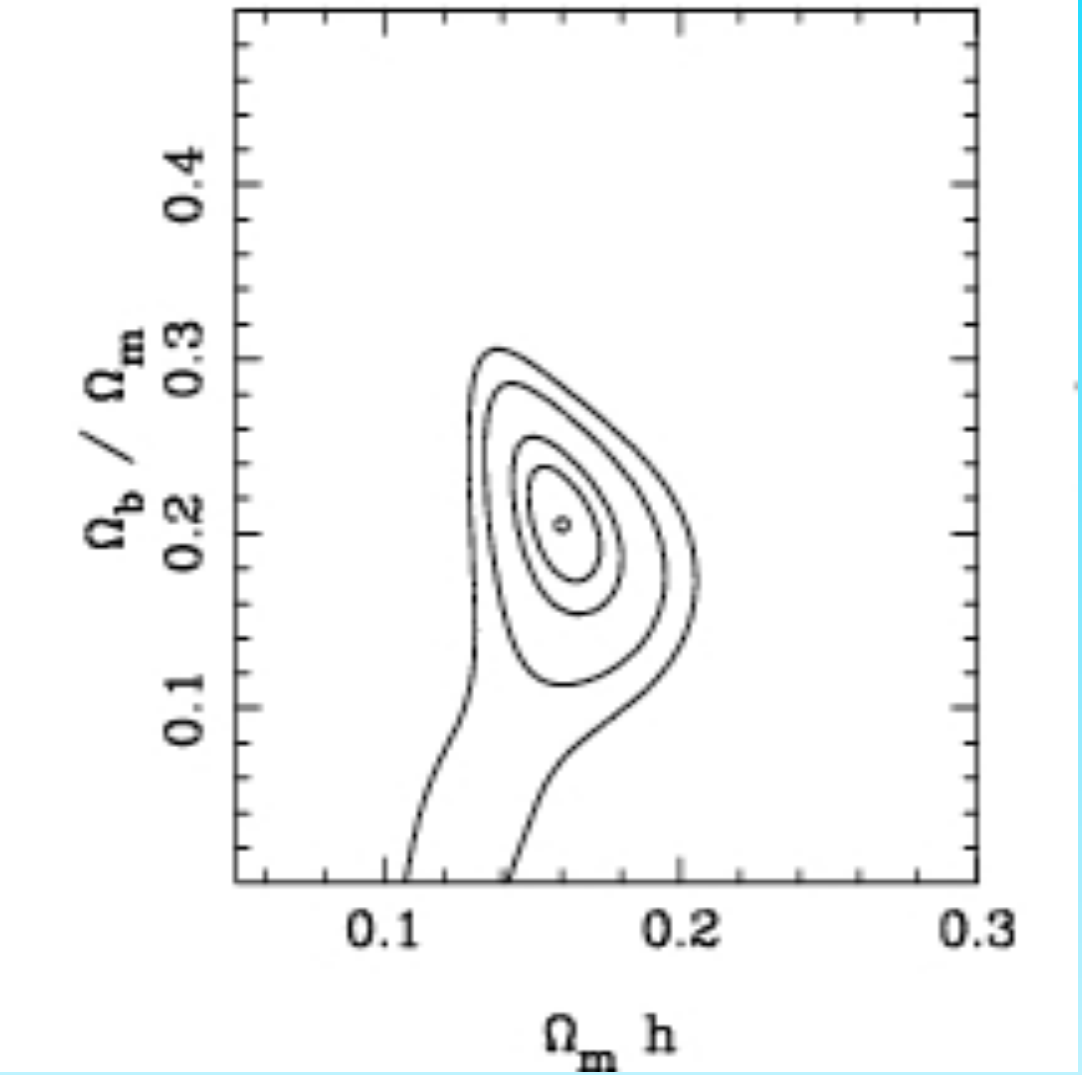
•The final 2dFGRS power spectrum: parameter estimation

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

•$\Omega h = 0.161 \pm 0.015$

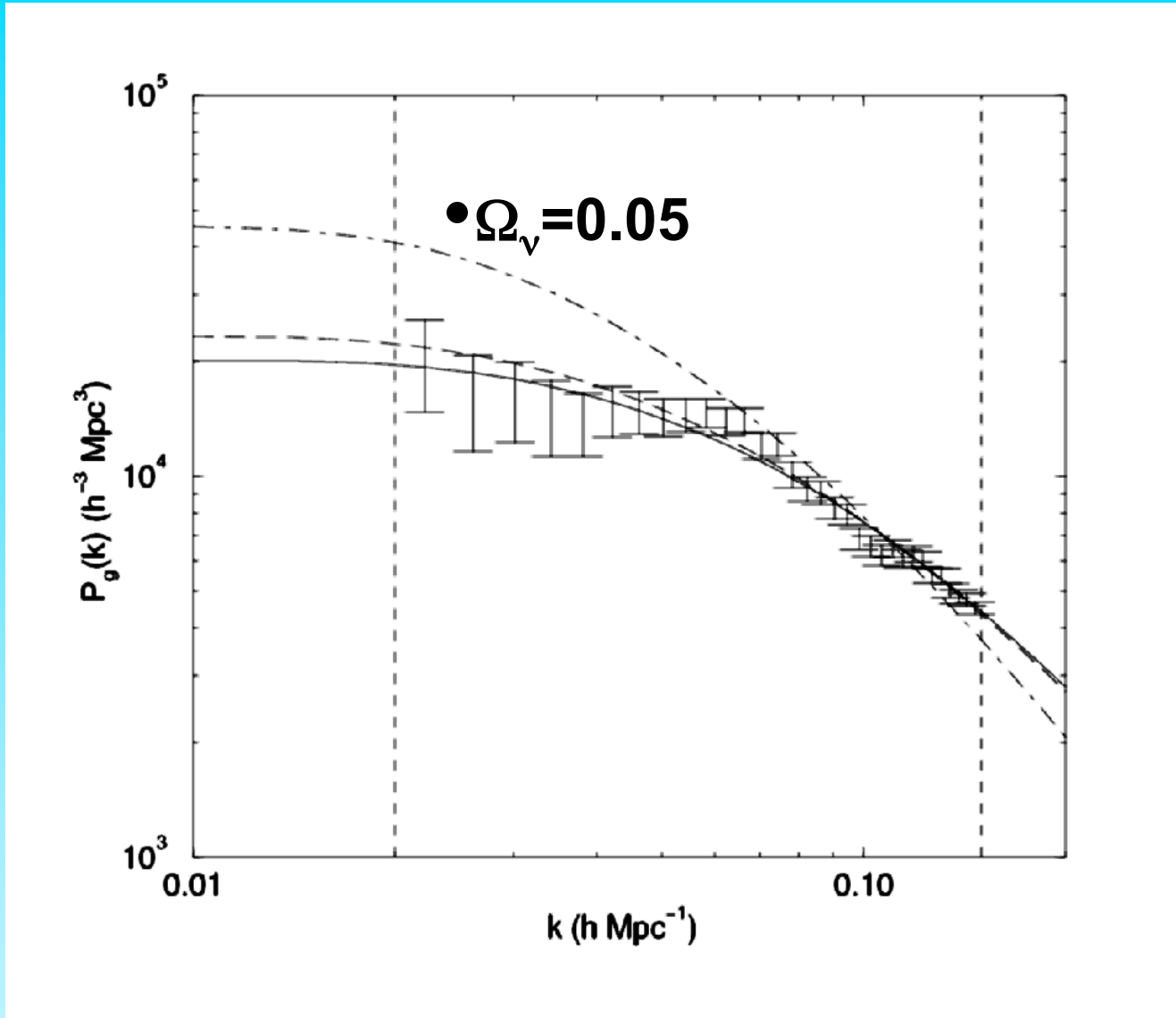
•$\Omega_b / \Omega_m = 0.194 \pm 0.045$

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



•Cole + 2dFGRS '05

•Effect of neutrinos



• Sanchez et al '06

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

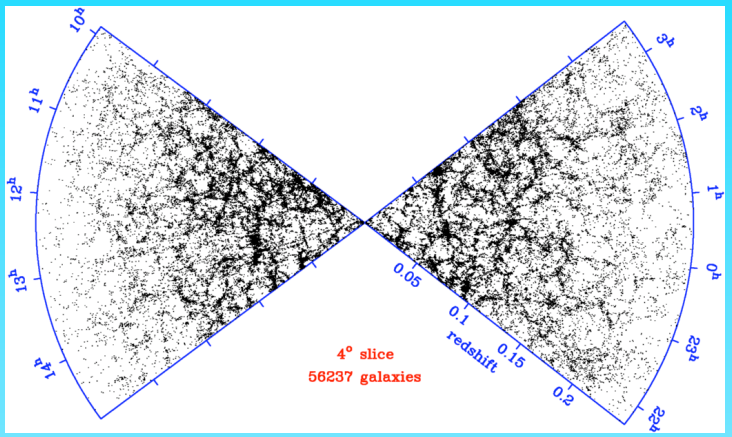
•($\Omega_m h^2 = \Sigma m_\nu / 93.5$ eV)

•$\Sigma m_\nu \sim 1$ eV causes lower power at almost all scales, or a bump at the largest scales

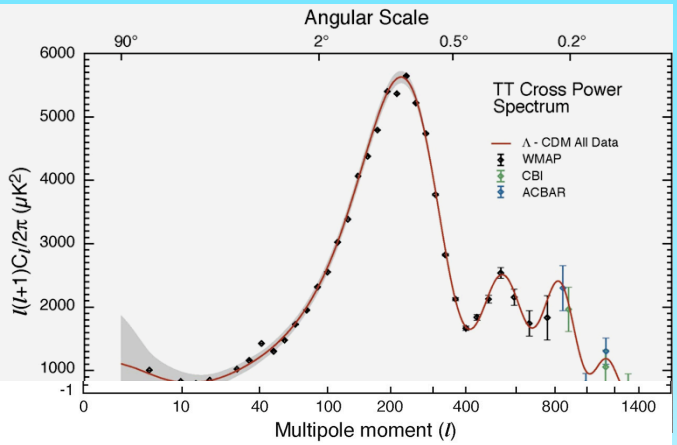
• 2dFGRS

→ $\Sigma m_\nu < 1.2$ ev

•Cosmological parameters: CMB + 2dF



- The 2dF power spectrum depends on
- $\Omega_m h$, Ω_b/Ω_m, σ_8^{gal}, f_ν, …



- The CMB power spectrum depends on

$$\left(\Omega_k, \Omega_\Lambda, \omega_b, \omega_{dm}, f_\nu, w_{DE}, \tau, n_s, n_t, A_s, r, b\right)$$

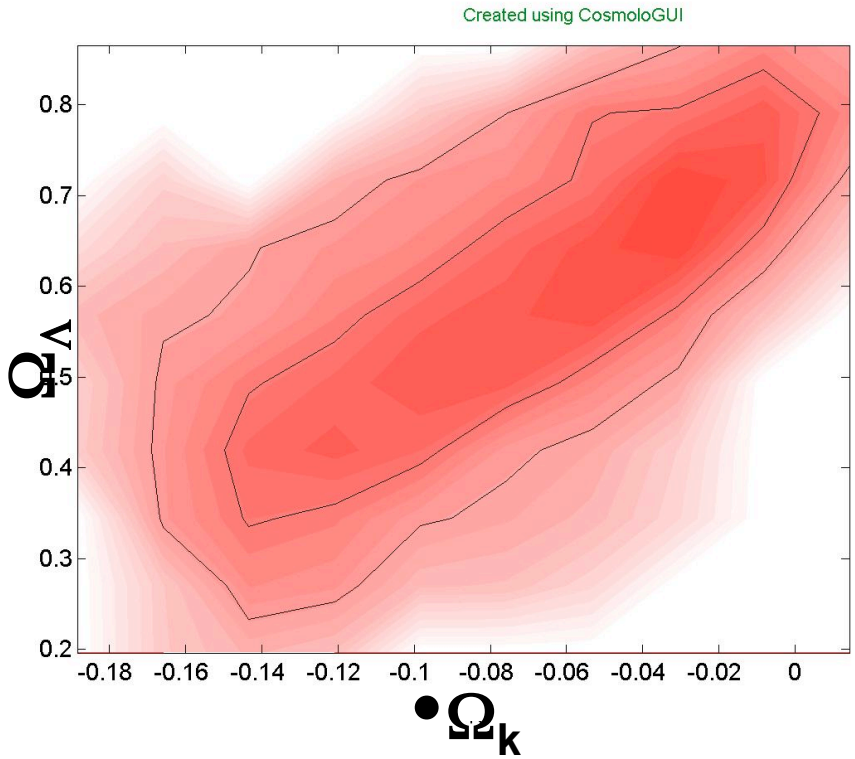
- Combining 2dF and CMB breaks parameter degeneracies

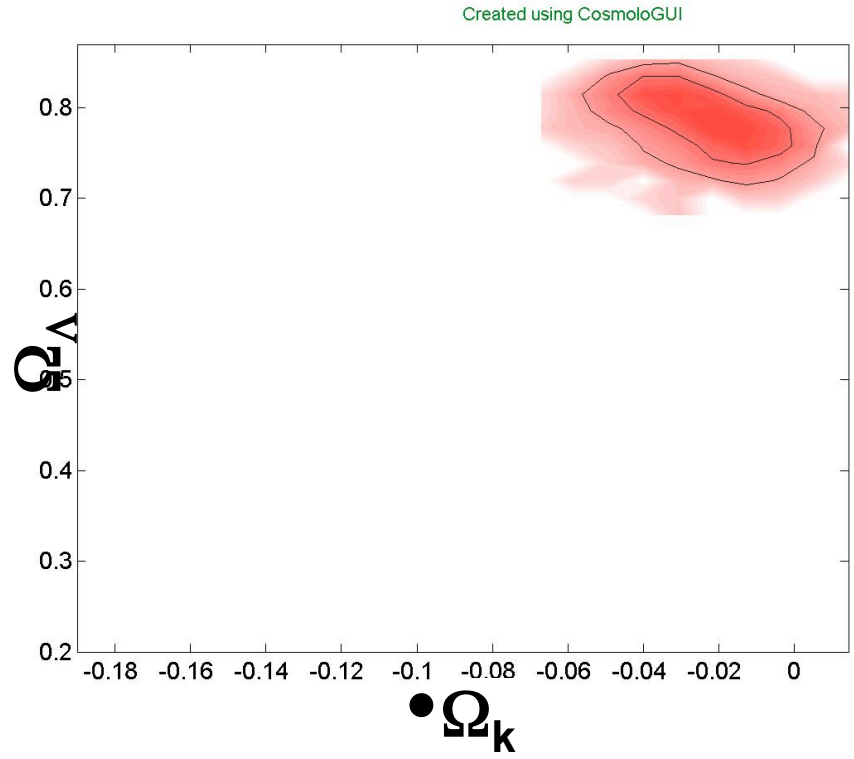
•Parameter constraints

$$\mathbf{P} \equiv \left(\Omega_k, \Omega_\Lambda, \omega_{\mathrm{b}}, \omega_{\mathrm{dm}}, \tau, n_s, A_s\right)$$

•CMB only…

•CMB + 2dF…





•Sanchez et al '06

•Results: comparison with WMAP3

•FLAT models	Sánchez et al. (2006, MNRAS, 366,189)	Spergel et al. (astro-ph/0603449)	
parameter	WMAP1(ext.)+2dFGRS	WMAP3 only	WMAP3+2dFGRS
ω_b	0.0225 ± 0.0010	0.0223 ± 0.0008	0.0222 ± 0.0007
ω_m	0.127 ± 0.005	0.126 ± 0.009	0.1262 ± 0.0048
h	0.735 ± 0.022	0.74 ± 0.03	0.732 ± 0.021
τ	0.118 ± 0.060	0.093 ± 0.029	0.083 ± 0.029
n_s	0.954 ± 0.023	0.961 ± 0.017	0.948 ± 0.016
σ_8	0.773 ± 0.053	0.76 ± 0.05	0.737 ± 0.039
Ω_m	0.237 ± 0.020	0.234 ± 0.035	0.236 ± 0.020

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•Testing the ΛCDM paradigm with galaxy surveys

•Three tests:

- Origin of fluctuations, nature of DM, cosm.parms
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- Gravitational instability
  (z-space distortions)
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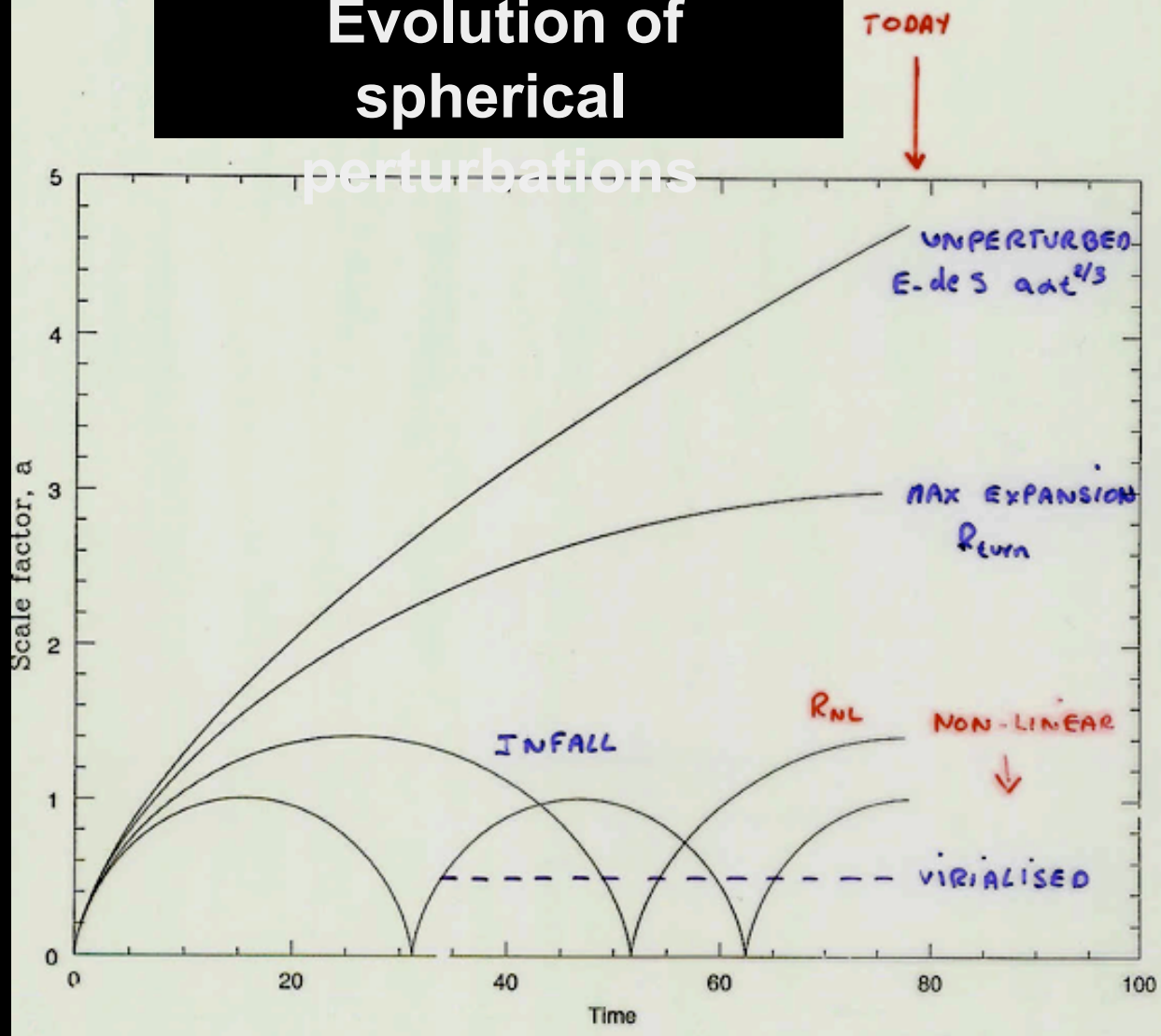
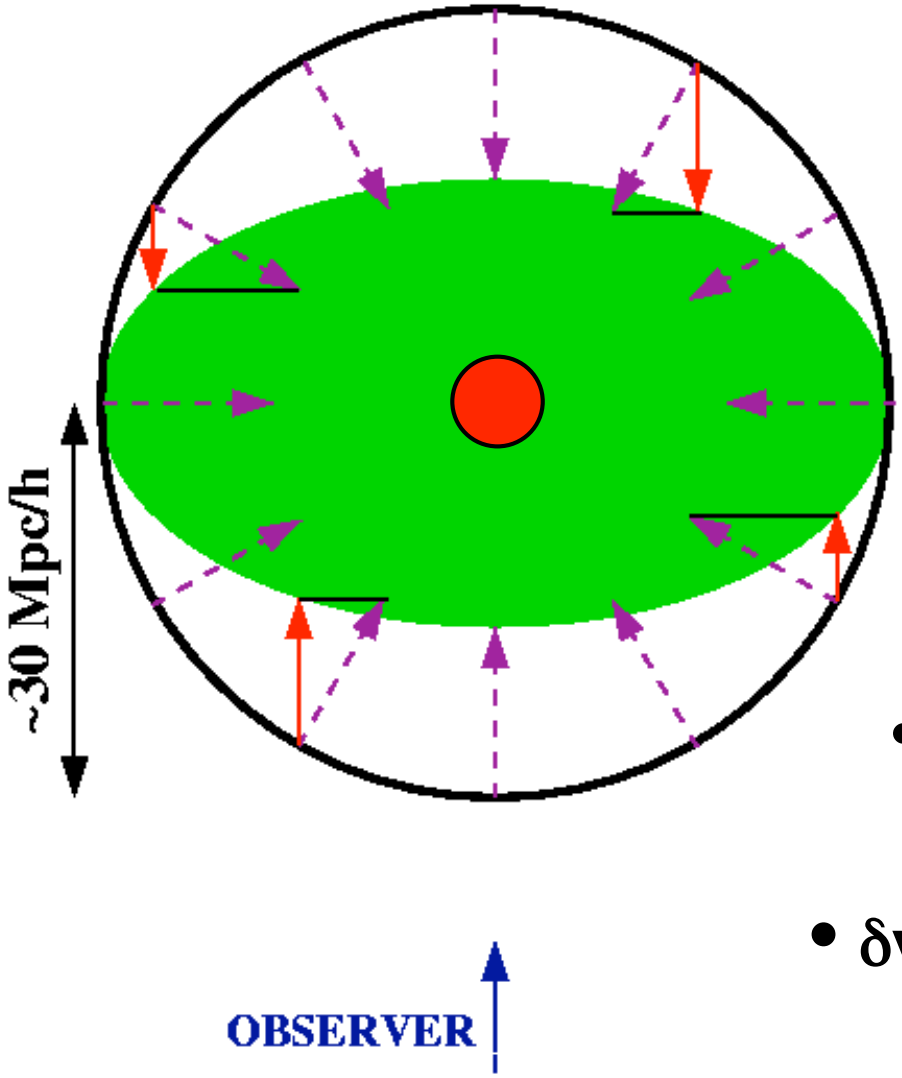
Evolution of spherical perturbations



R_{NL} SEPARATES UNMIXED, UNSHOCKED (PRIMORDIAL) MATERIAL FROM MIXED, SHOCKED, NON-LINEAR MATERIAL

IN E-d-S, R_{NL} CORRESPONDS TO $\delta\rho/\rho \sim 100$

Large Scale Flattening Due To Coherent Cluster Infall



- $V_{obs} = v_{hubb} + \delta v$
- $\delta v \propto \Omega^{0.6}\, \delta\rho/\rho = \Omega^{0.6}\, b^{-1}\, \delta n/n$
  - "bias" parameter

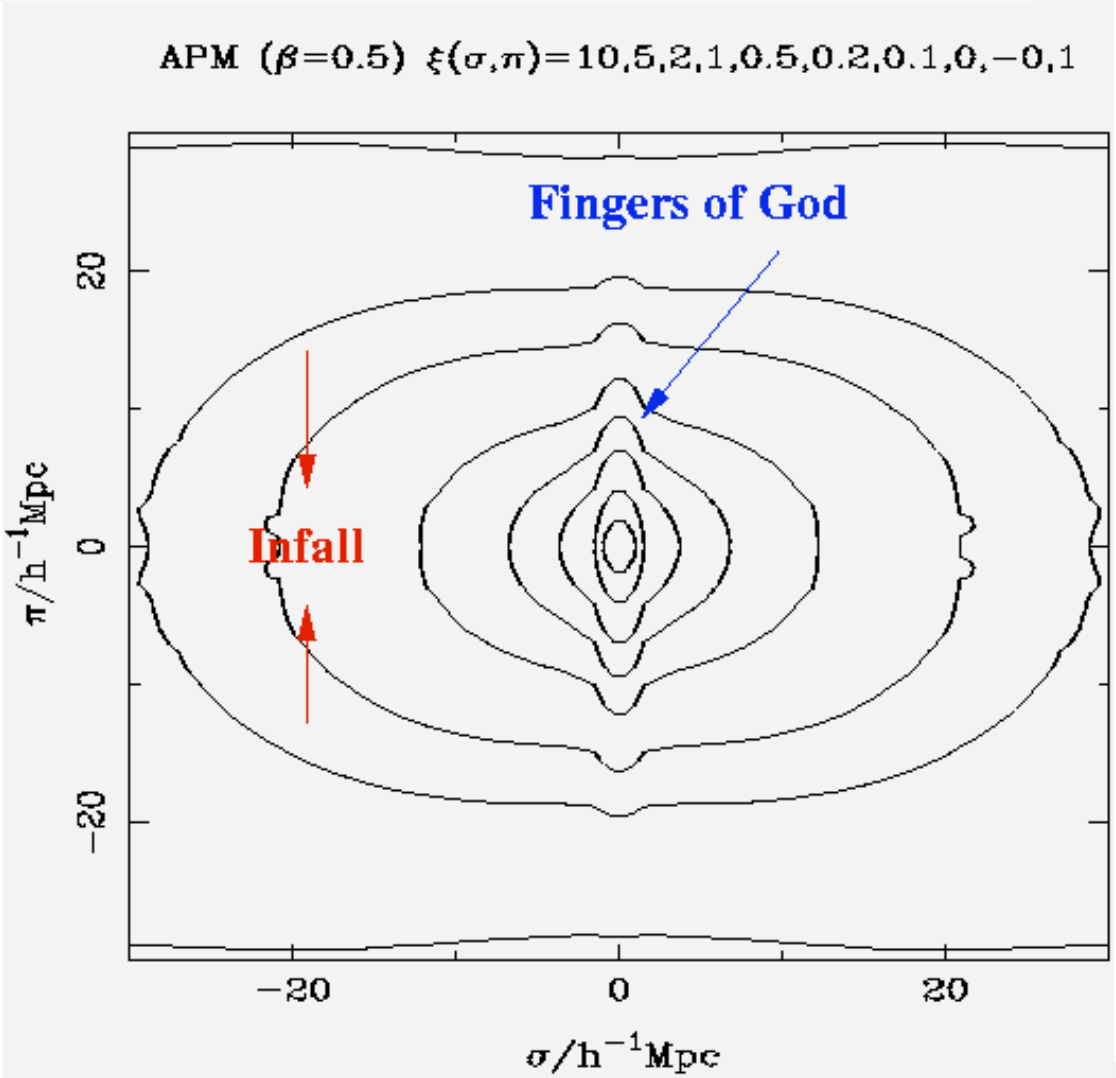
- Kaiser 1987

•The signature of hierarchical clustering

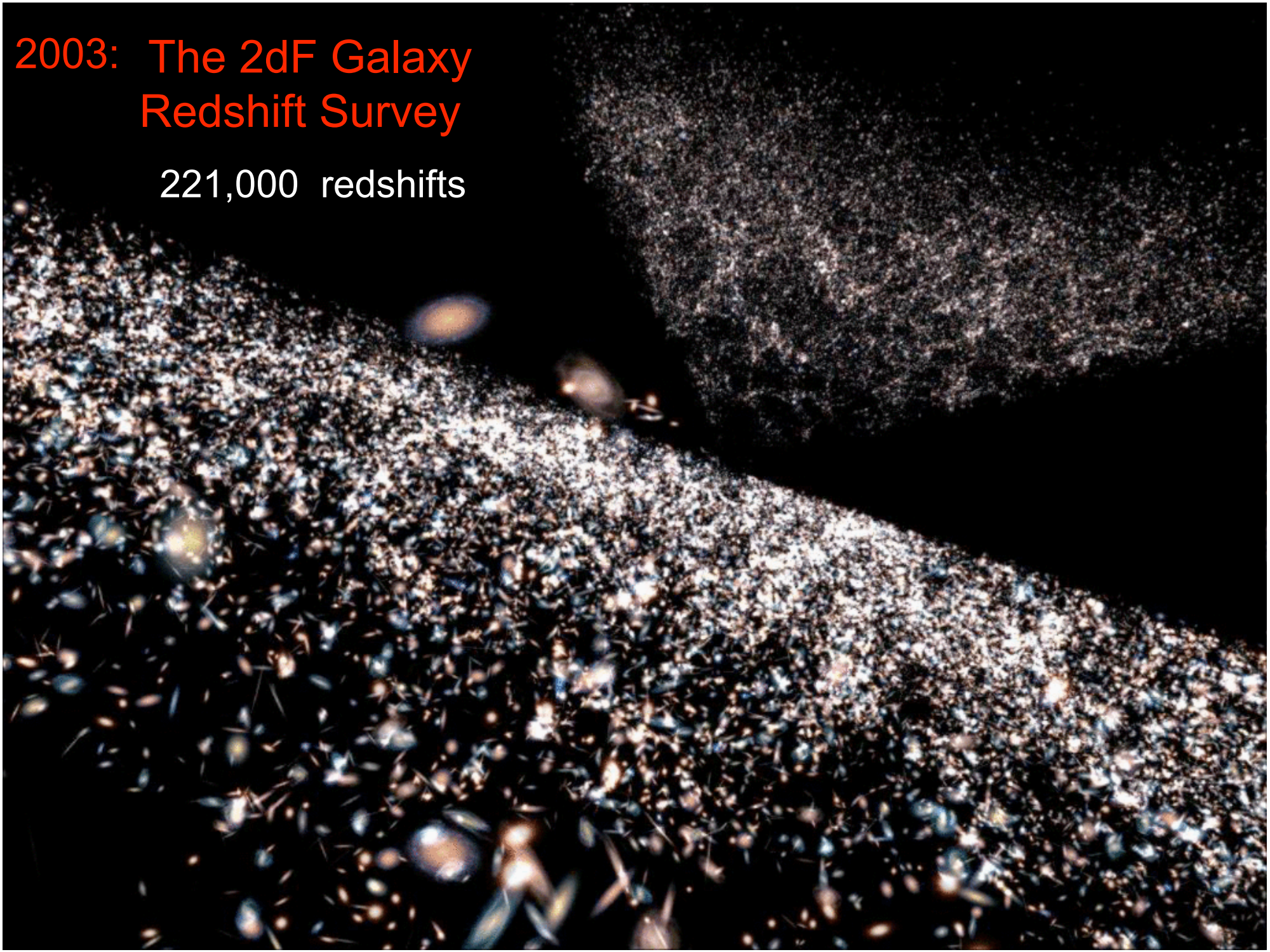
•Correlation function

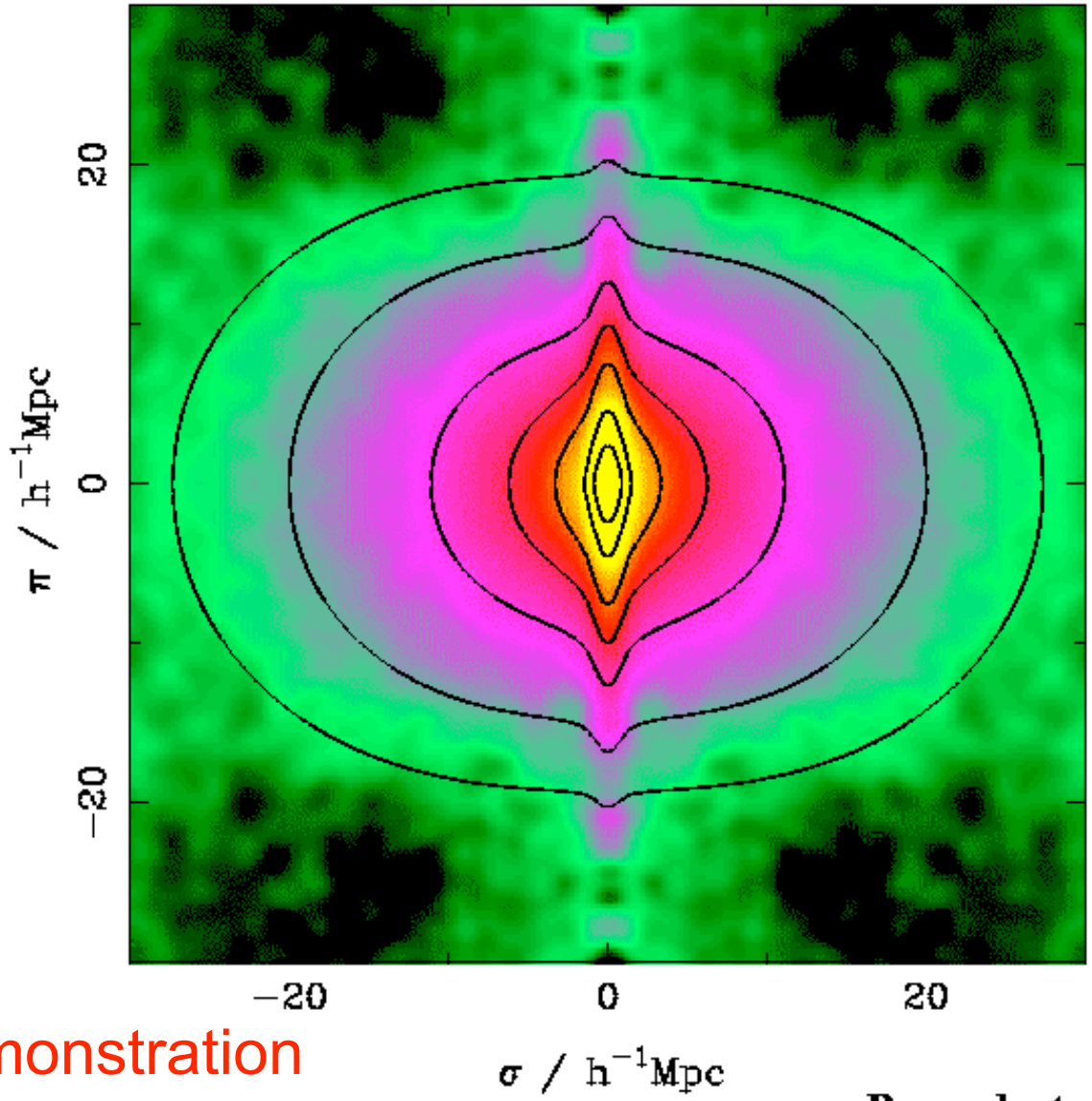
•$\xi(\sigma,\pi)$

•Paralle to l.o.s



•Perpendicular to l.o.s


2003: The 2dF Galaxy Redshift Survey
221,000 redshifts



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

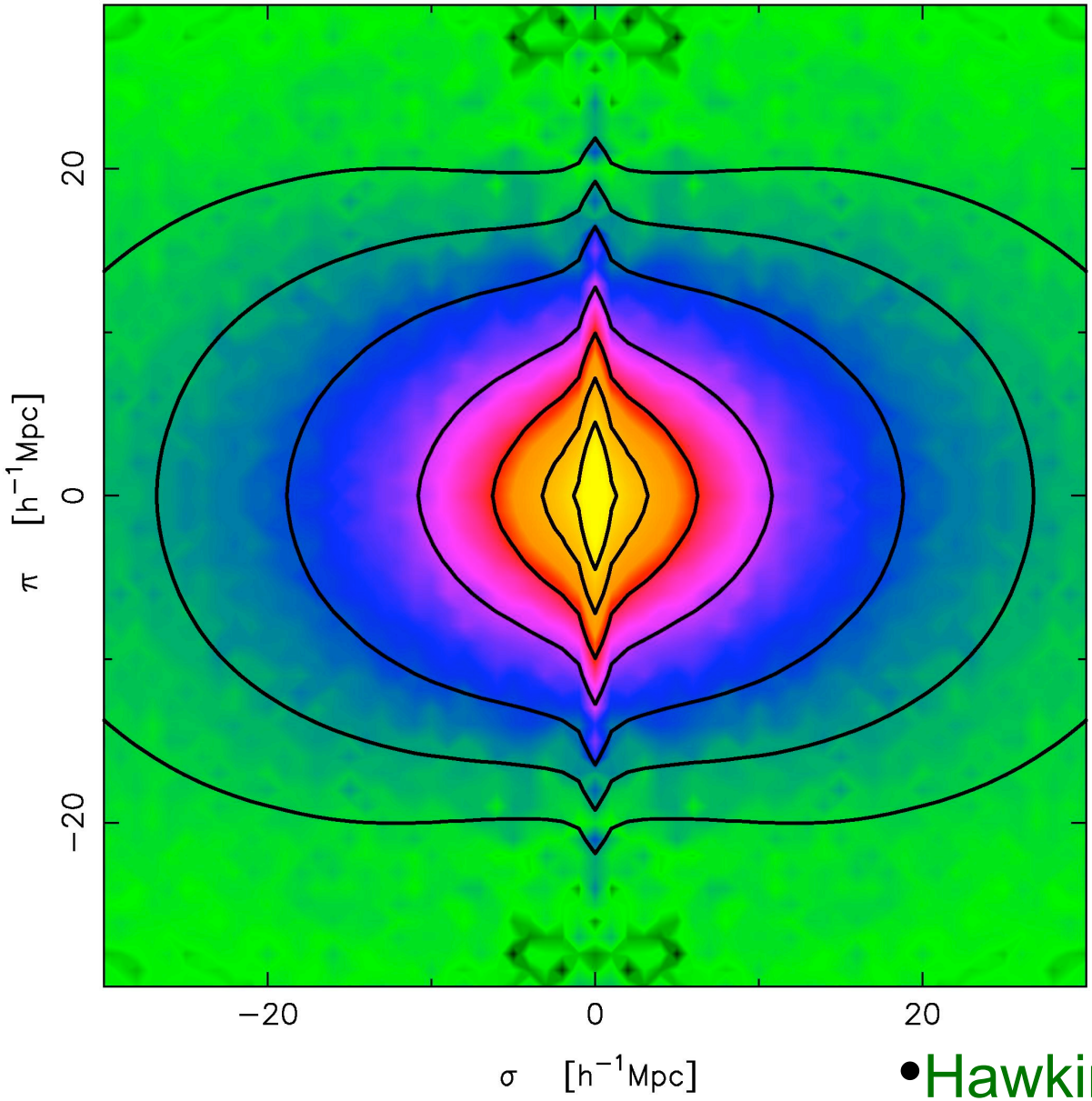
$\Rightarrow \beta = \Omega^{0.6} / b$

$= 0.43 \pm 0.07$

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

- Demonstration of gravitational instability

Hawkins et al. (2002), astro−ph/0212375
2dFGRS: $\beta = 0.49 \pm 0.09$



- Demonstration of gravitational instability

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

$= 0.49 \pm 0.09$

- b is ``biasing'' parameter

- b=1.0 ➔ Ω=0.3

- Hawkins + 2dFGRS astro-ph/0212375

•The case for dark matter

Baryon acoustic oscillations

+

Large–scale infall

Consistent with growth of structure by gravitational instability in CDM universe

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•Testing the ΛCDM paradigm with galaxy surveys

•Three tests:

- Origin of fluctuations, nature of DM, cosm.parms
  (Power spectrum of galaxy distribution)
- Gravitational instability
  (z-space distortions)
- Hierarchical galaxy formation
  (non-linear clustering)

•Halo mass-to-light ratios

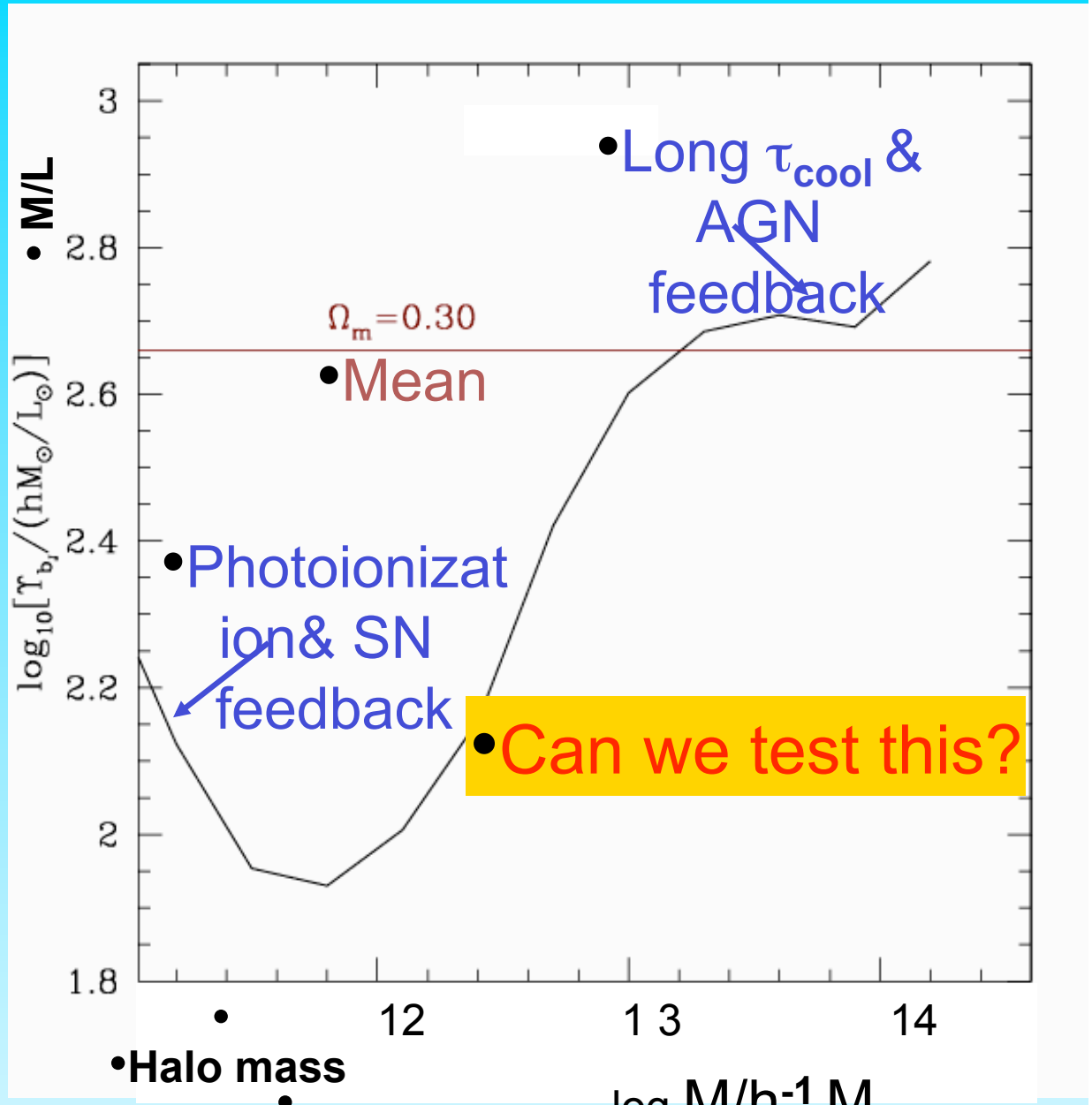
•**Theoretical prediction**

•**(semi-analytic)**

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

•Efficiency of galaxy formation

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



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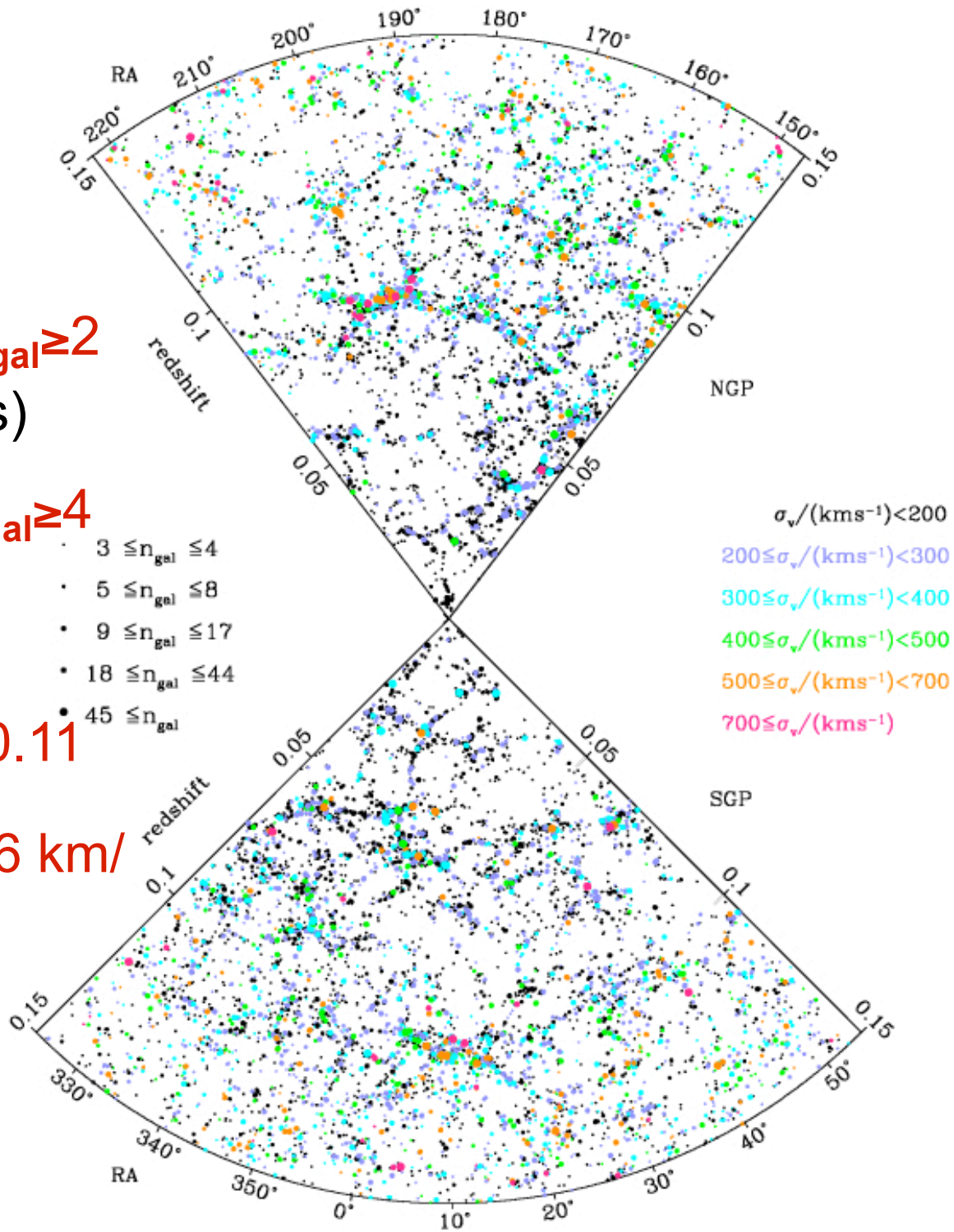
- Groups in 2dFGRS
- 28,213 groups with $n_{gal} \geq 2$
  - (53% of gals)
- 6,773 groups with $n_{gal} \geq 4$
  - $n_{gal} \geq 4$:
  - Median z 0.11
  - Median vel disp 266 km/s



- Eke, Frenk, Cole, Baugh + 2dFGRS 2003

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•2dFGRS groups and galaxy formation

- The mass-to-light ratio and the efficiency of galaxy formation

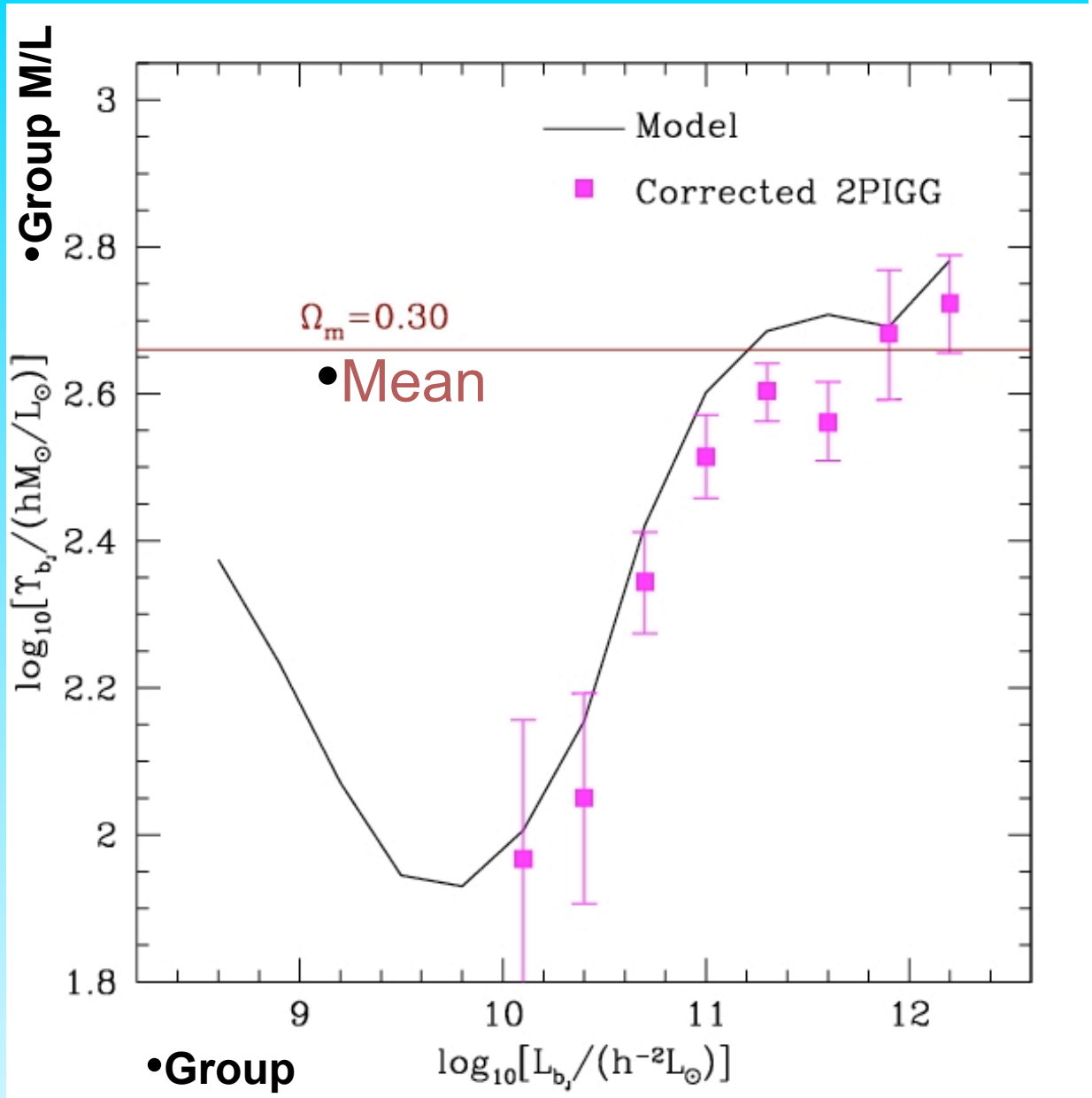
•Halo mass-to-light ratios

•N_{min}=2, z_{max}=0.07

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

•Efficiency of galaxy formation

•Eke etal '04



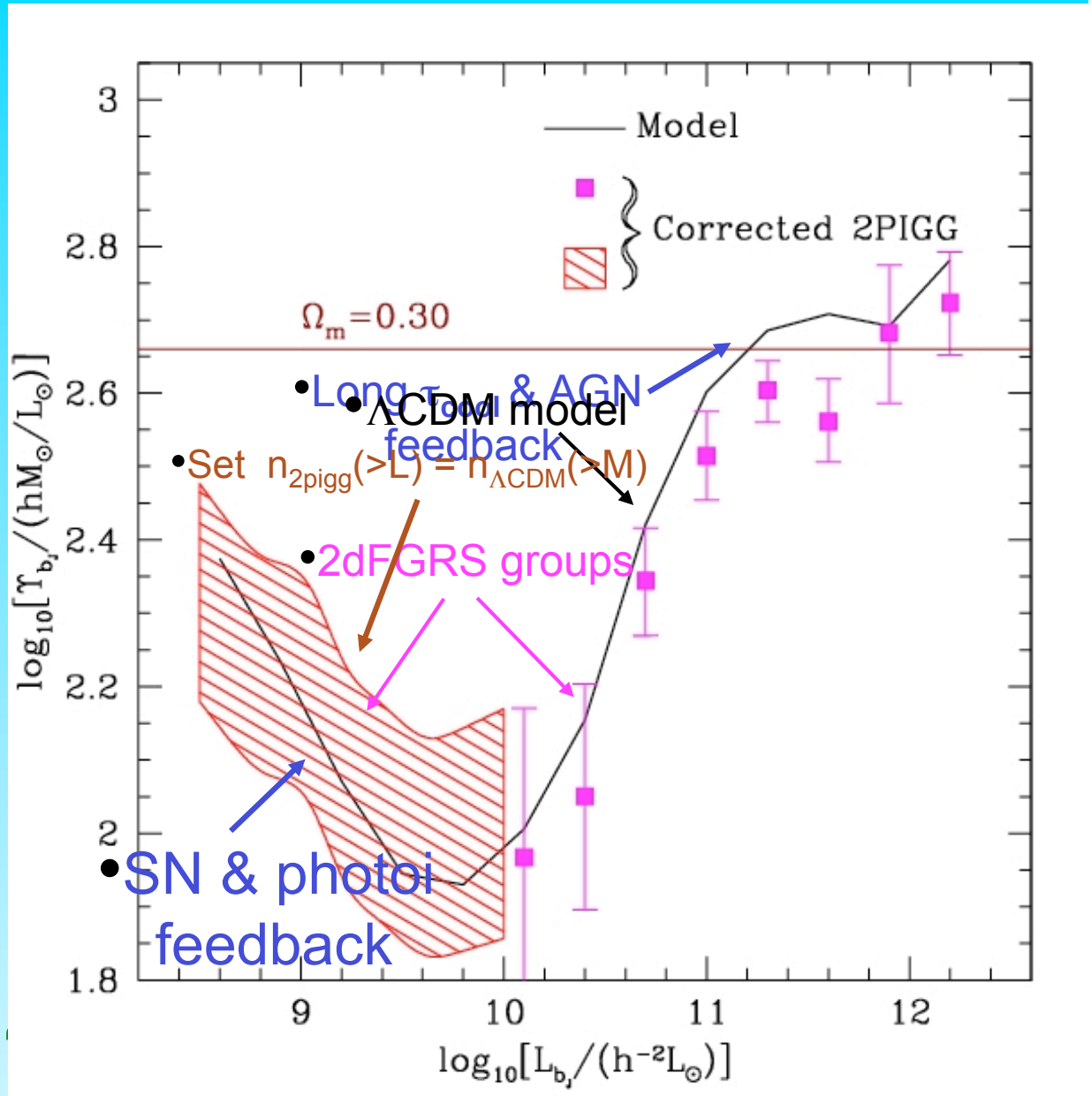
•Halo mass-to-light ratios

•N_{min}=2, z_{max}=0.07

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

•Minimum in M/L detected!

•Efficiency of galaxy formation



•Eke, Frenk, Baugh & Cole

luminosity

•Large-scale structure for the new generation

The use of baryon acoustic oscillations to constrain dark energy

•Baryon oscillations in the power spectrum

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•Comoving sound horizon at t_{rec}

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

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

•"wavenumber" of acoustic oscillations: •$k_A = 2\pi/s$

•Comoving distance/redshift:

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

•(depends on $\Omega_m h^2$ and w)

•Apparent size of standard ruler depends on cosmology

• $\Rightarrow$ dark energy eqn of state w

•(e.g. Eisenstein & HU 1998; Blake & Glazebrook 2003, 2005;

•Seo & Eisenstein 2003; 2005……)

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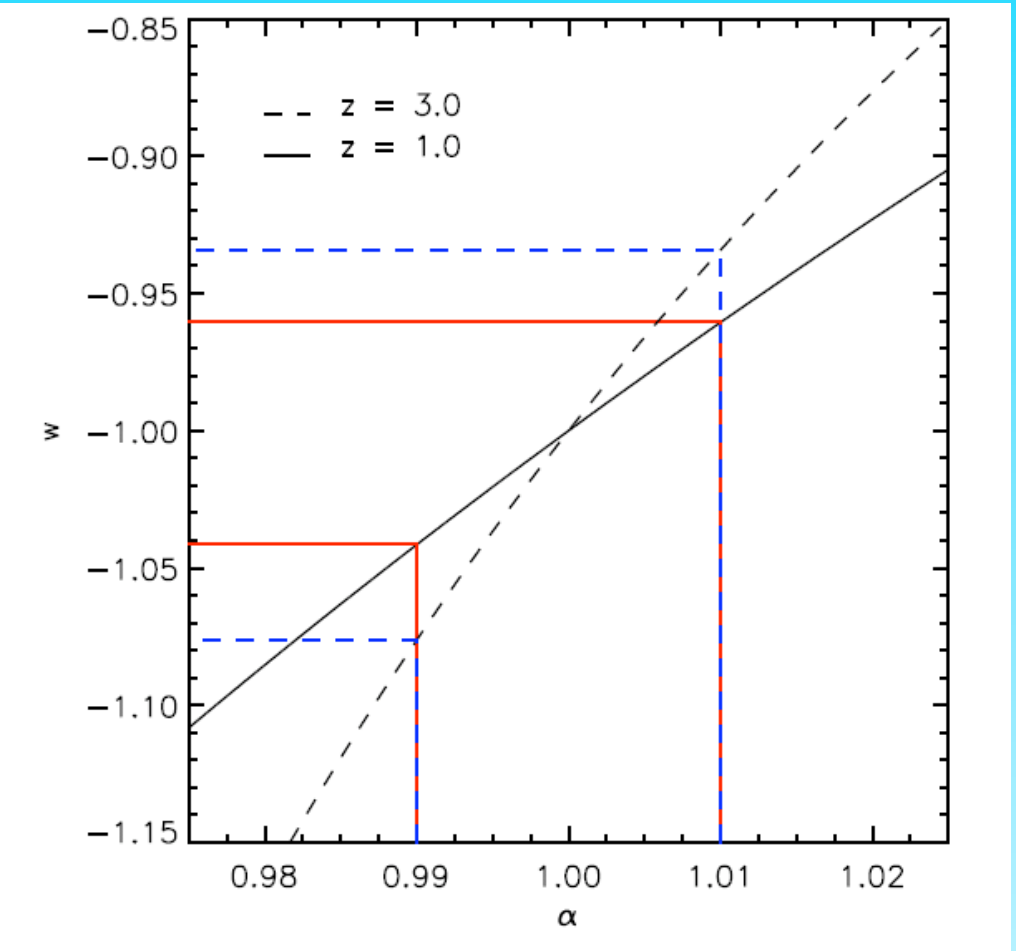
How well do we need to measure the BAO scale?

- Error in BAO scale translates to bigger error in dark energy w
- Size of shift depends on which other parameters are held fixed
- For fixed w require distance scale to 0.2% to get 1% in w
- Demands accurate knowledge of systematics



- Angulo et al. 2008

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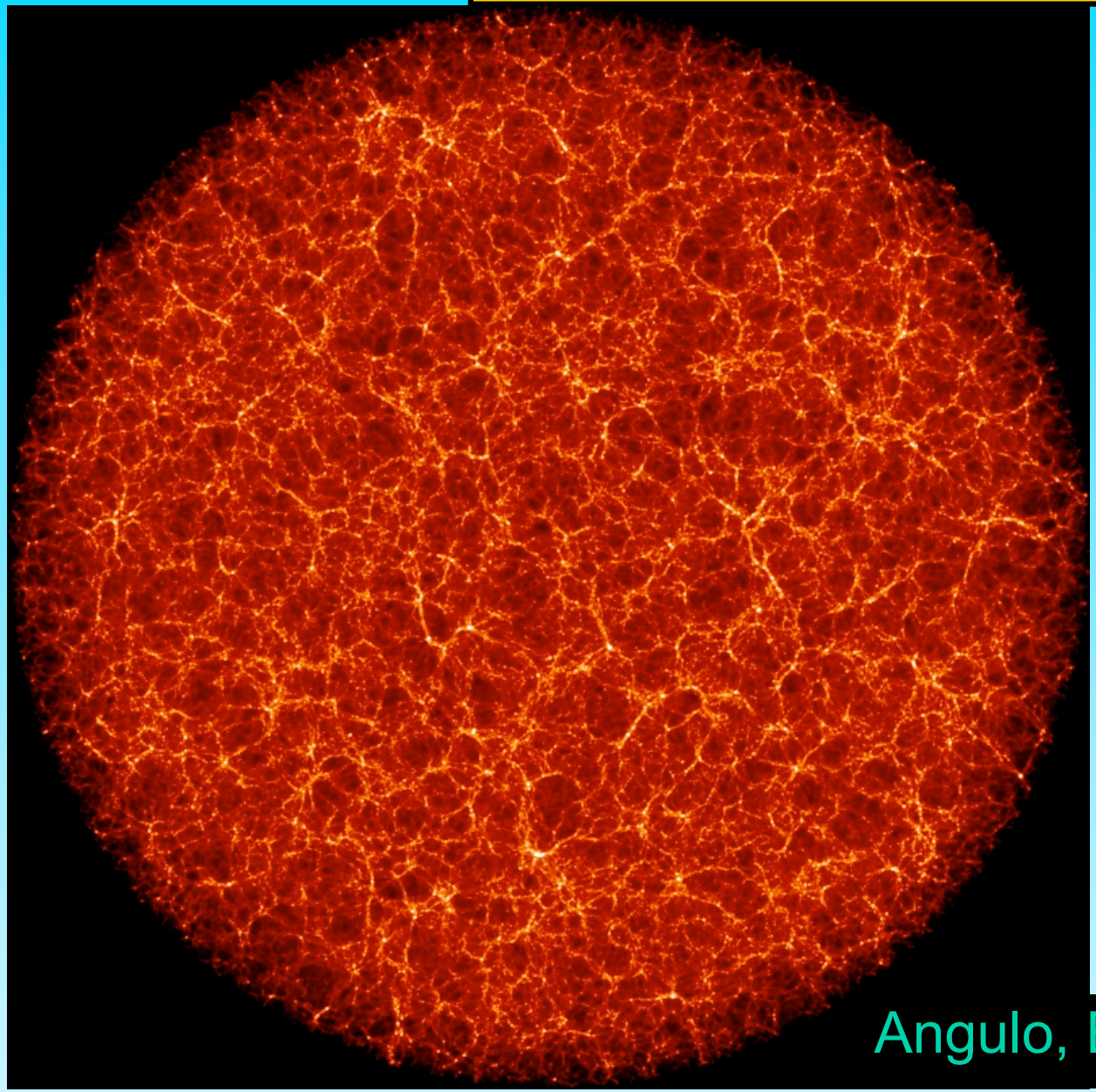
•N-body simulations of large cosmological volumes



•BASICC

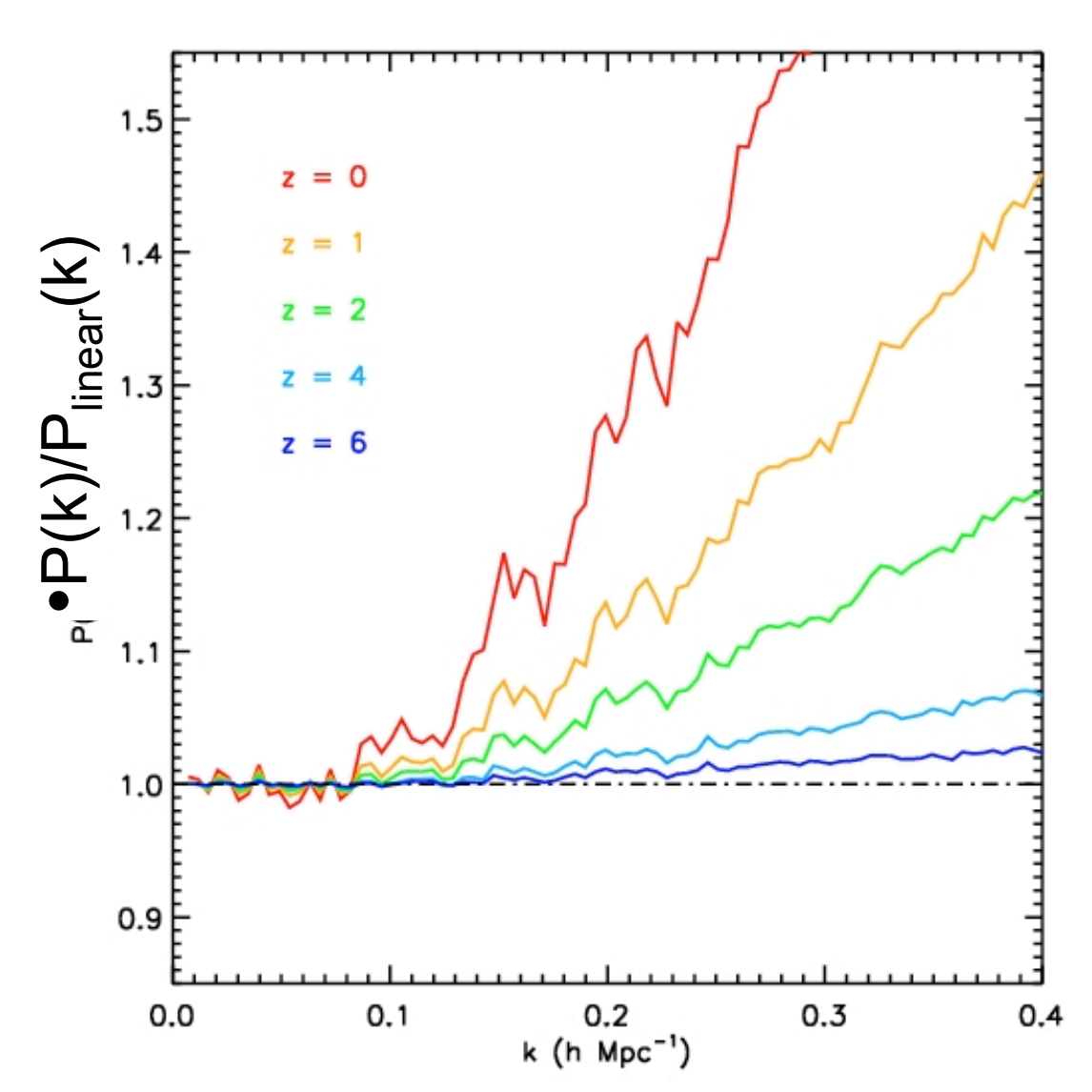
•L=1340/h Mpc

•N=3,036,027,392

•20 times the Millennium volume

Angulo, Baugh, Frenk & Lacey '07

•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

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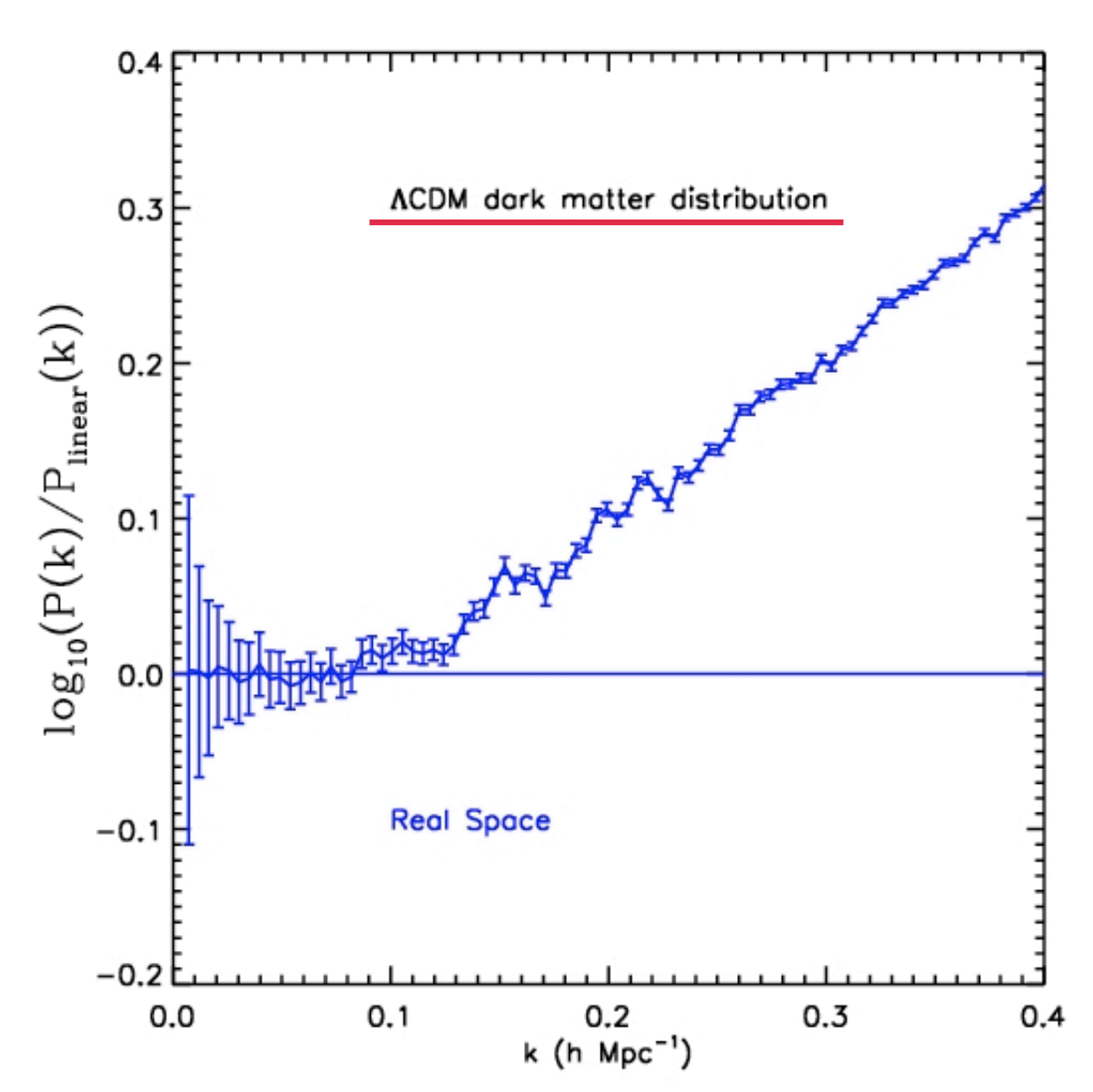
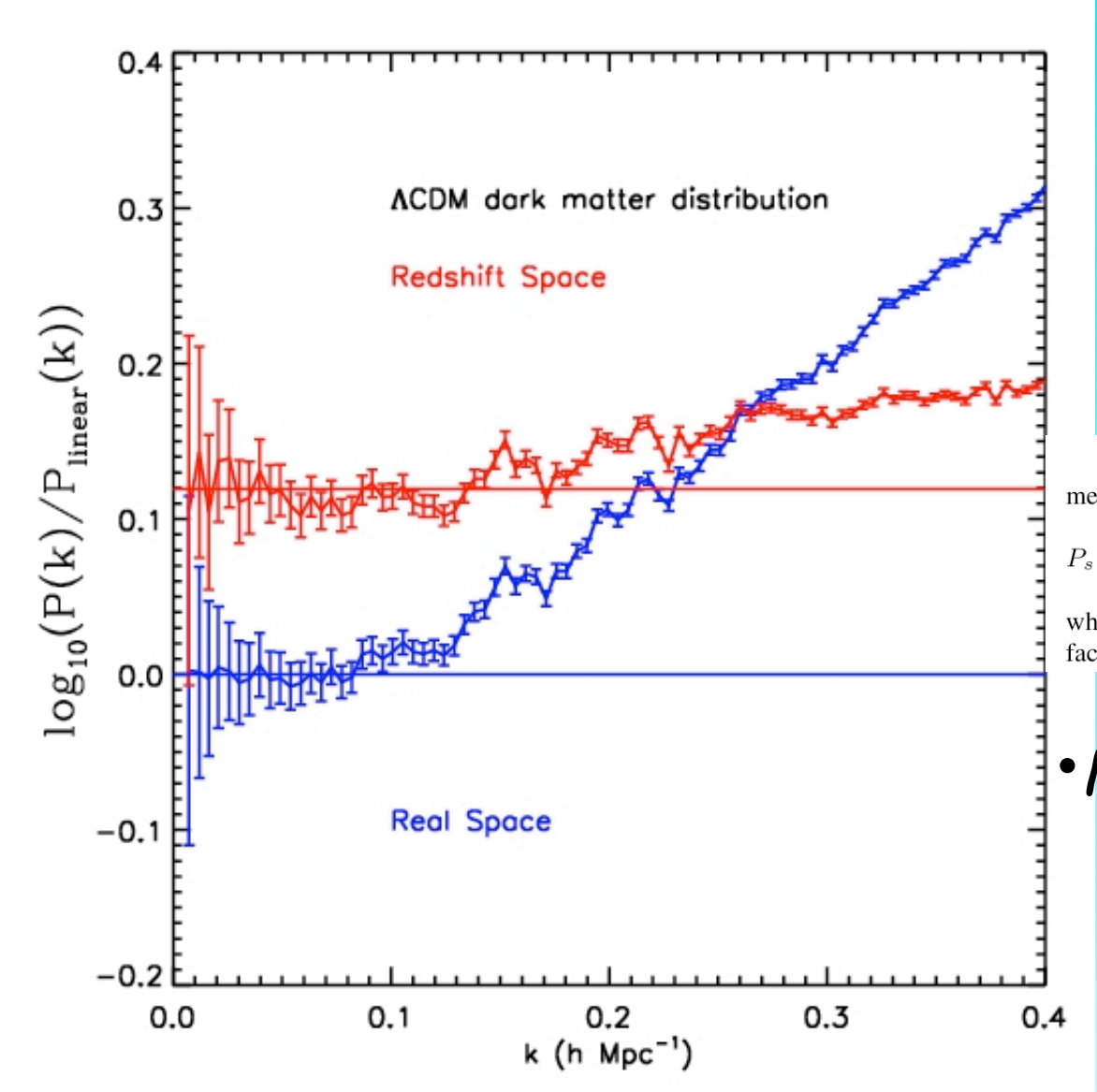
•Non-linear evolution of matter fluctuations



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

- Angulo, Baugh, Frenk & Lacey '07

•Redshift space distortions



- Peculiar motions distort
  - clustering pattern
  - Coherent bulk flows
  - boost large scale power (Kaiser 1987)

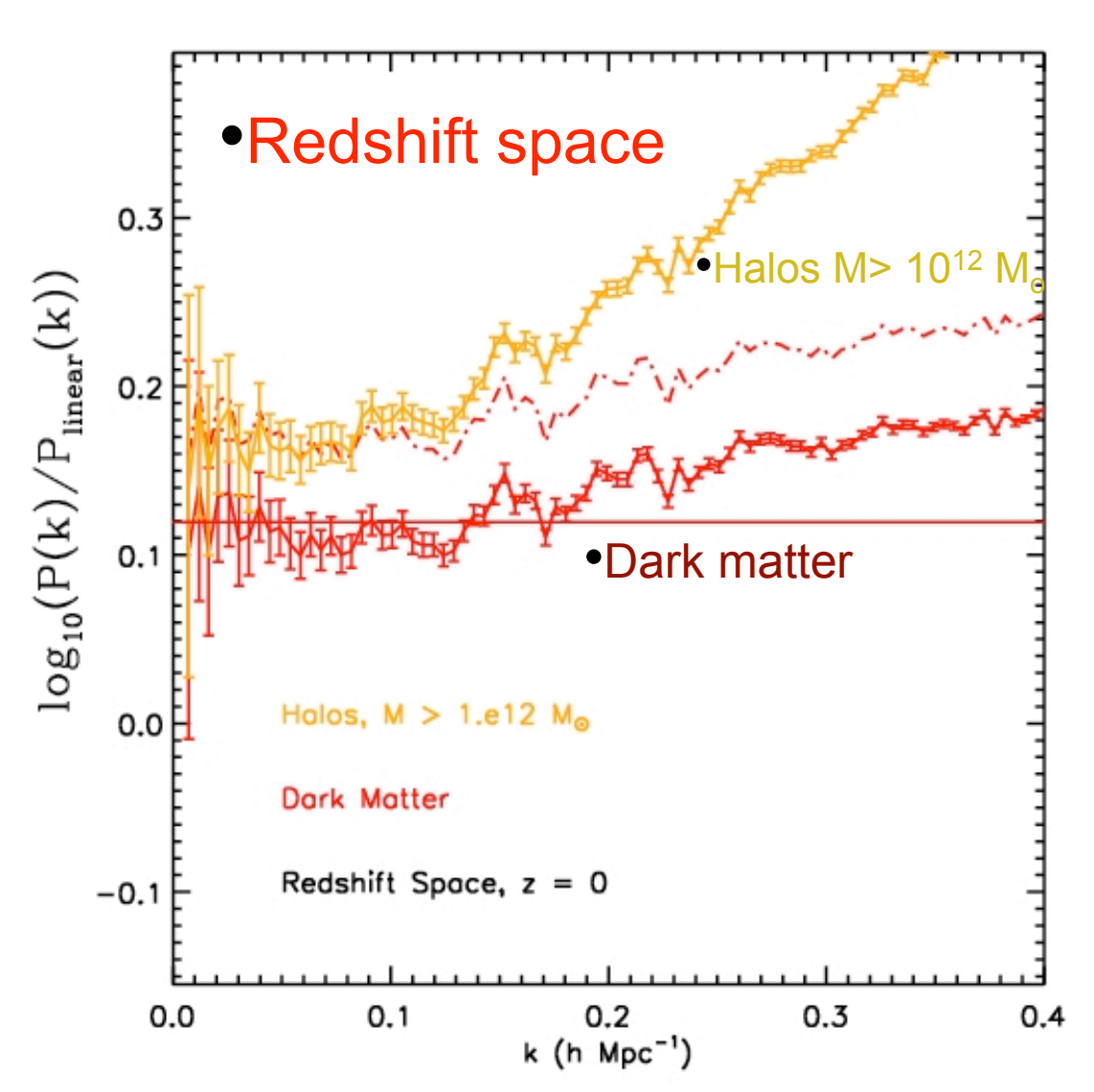
Kaiser (1987) related the spherically averaged power spectrum measured in redshift (P_s) and that in real space (P):

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

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

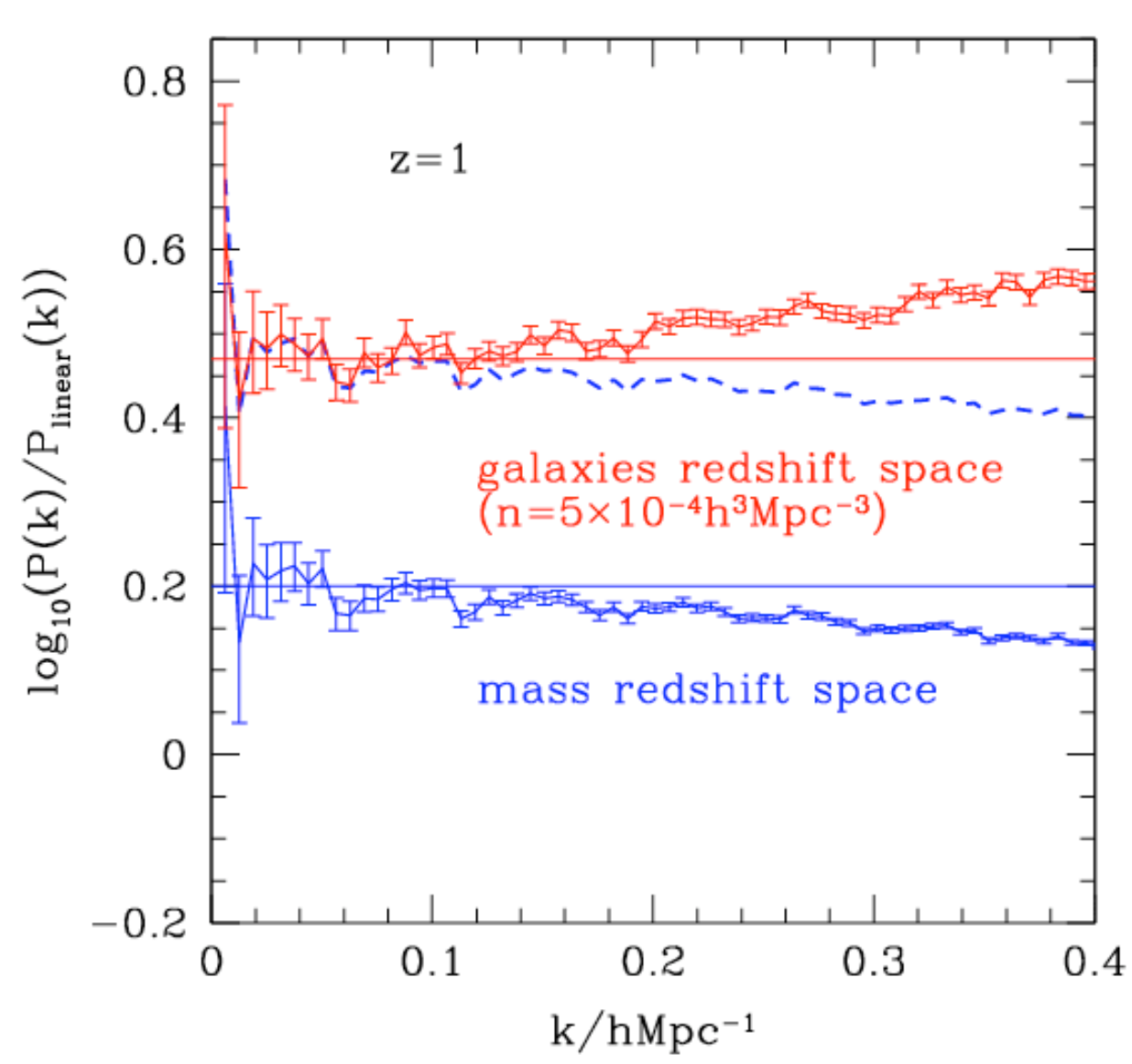
- Motions of particles inside
  - virialised structures
  - damp power at high k

•Redshift space distortions



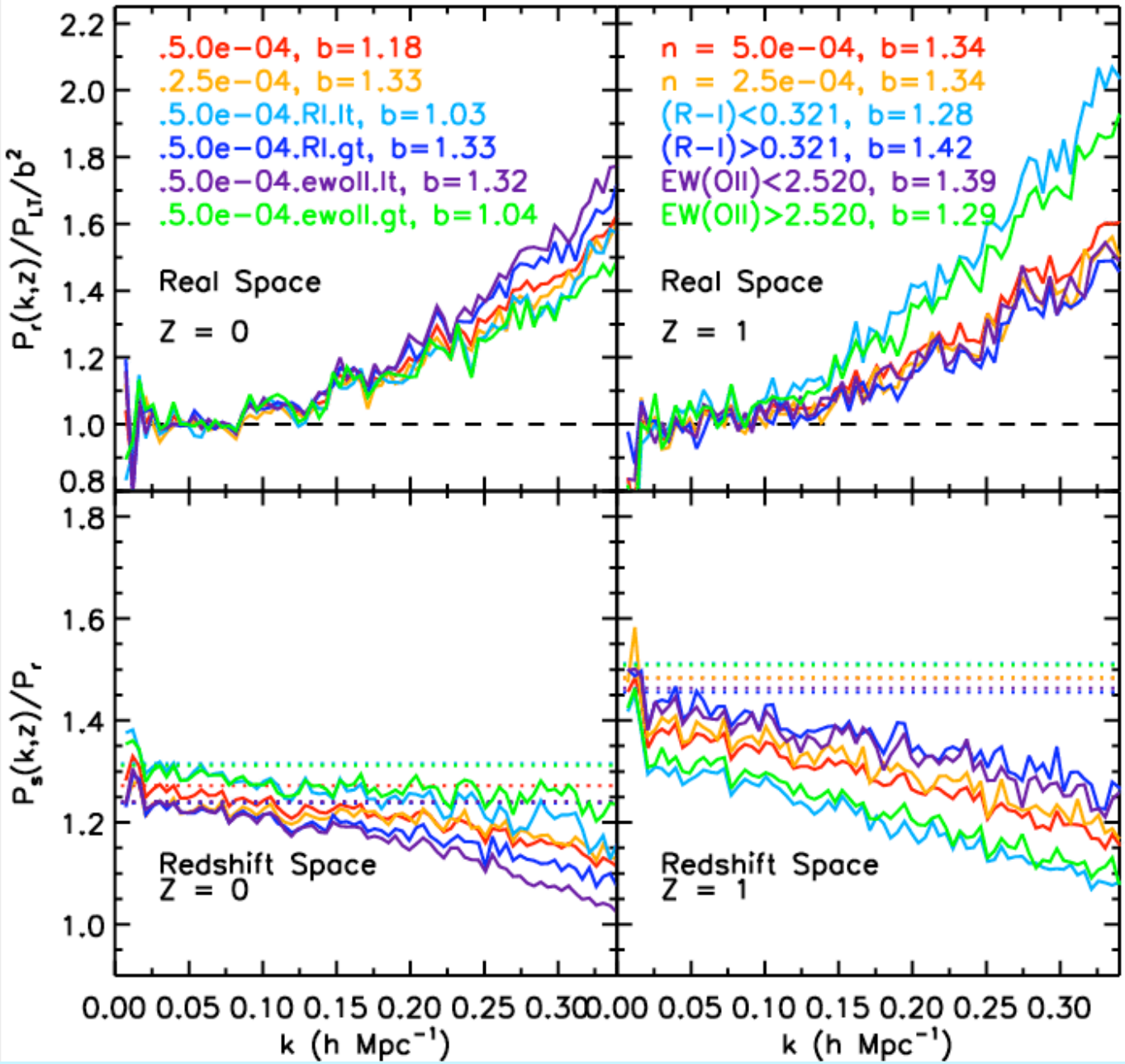
- •Peculiar motions distort
  - •clustering pattern
- •Boost in power on large
  - •scales due to coherent flows
- •Damping at higher k
  - •affects DM but not the halos

•Galaxy bias in redshift space



- Galaxy P(k) cannot
- be reproduced by
- multiplying mass
- P(k) by constant
- factor in redshift
- space.
- ⇒ In z-space, galaxies have a scale-dependent bias out to k~0.1

•Galaxy bias in redshift space



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

- Angulo et al '07

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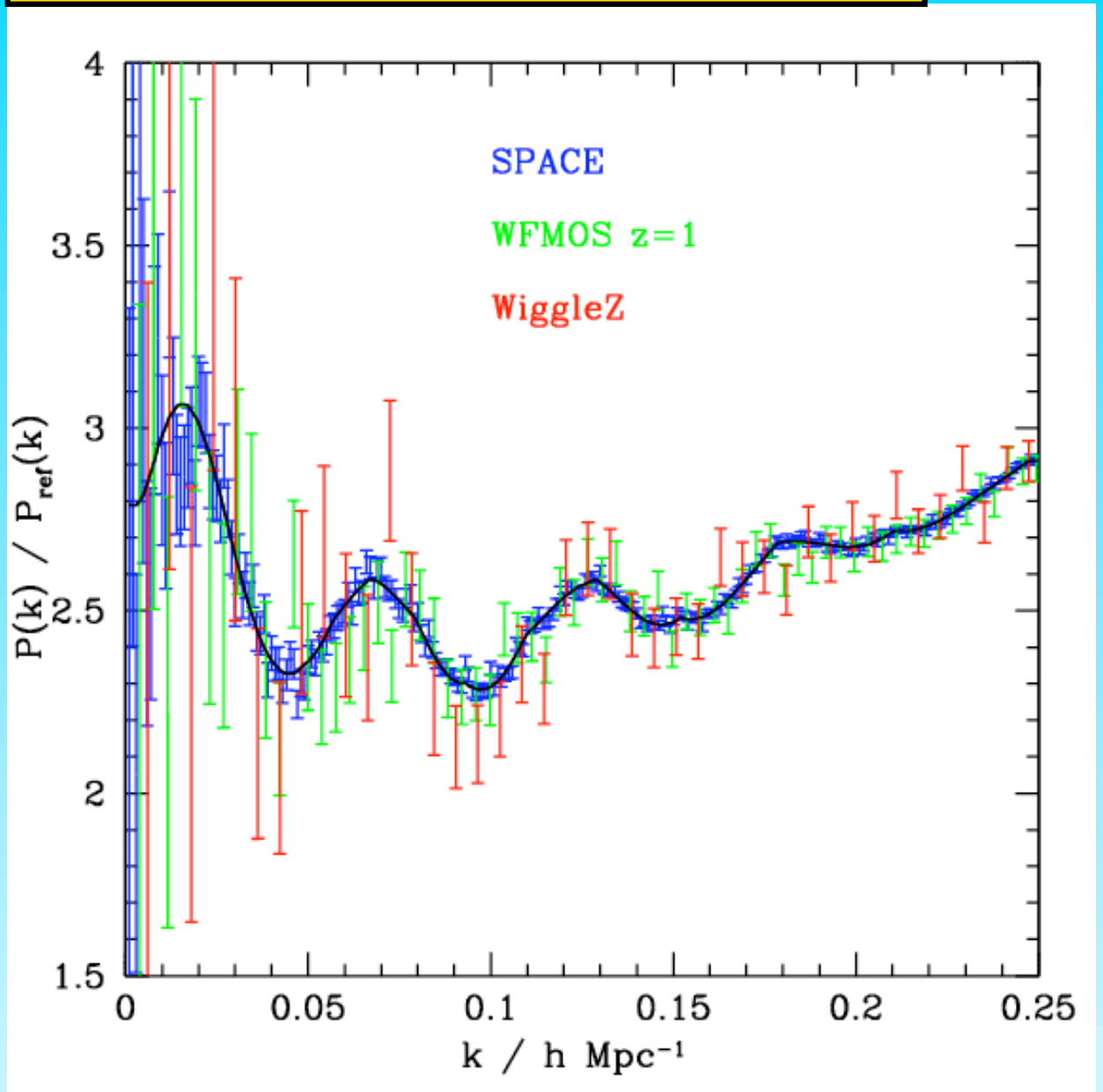
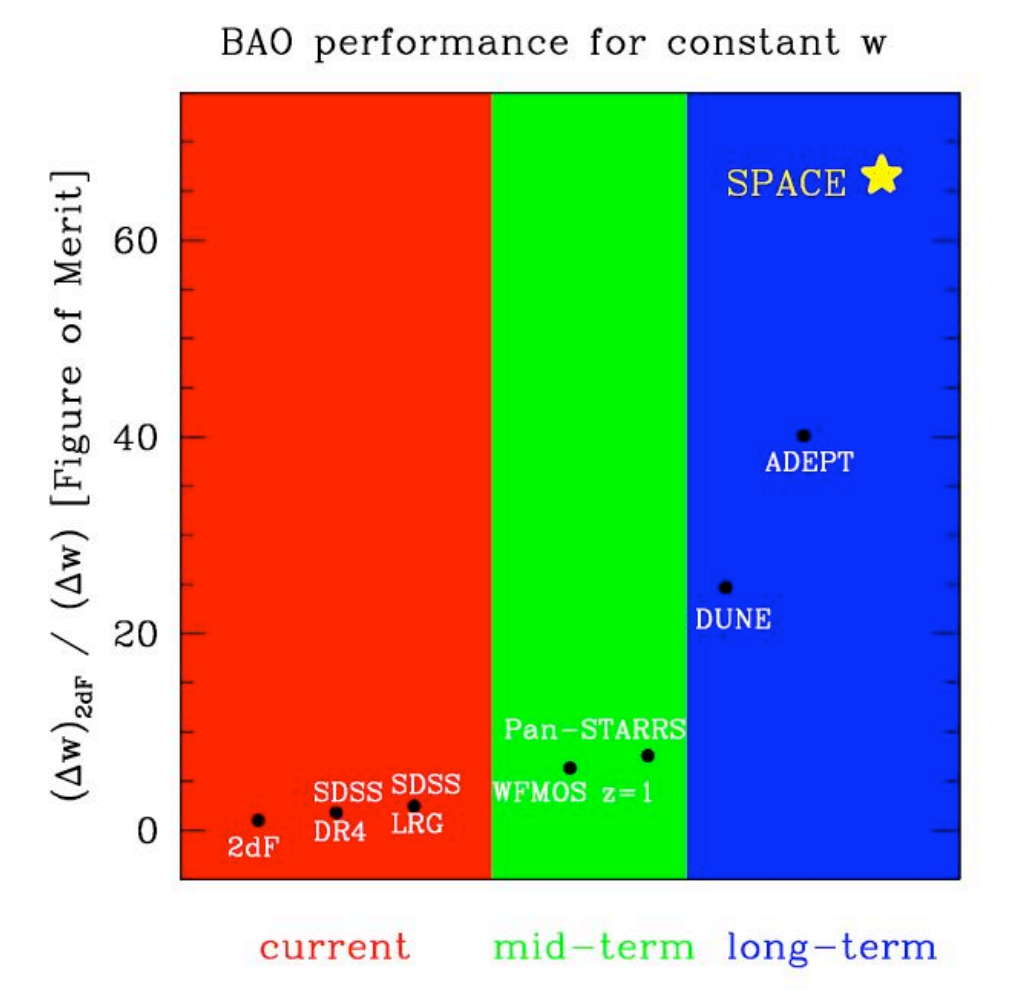
•Projected BAO data for planned surveys at z=1

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



•Headline forecasts for w



•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 %

•Angulo et al 07

•The origin of cosmic structure

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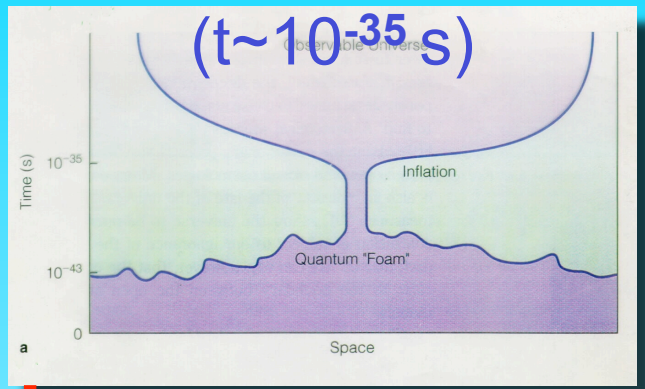
•1. FLAT GEOMETRY: $\Omega 2 + \frac{\Lambda}{3H^2} = 1$

•2. QUANTUM FLUCTUATIONS:
•adiabatic

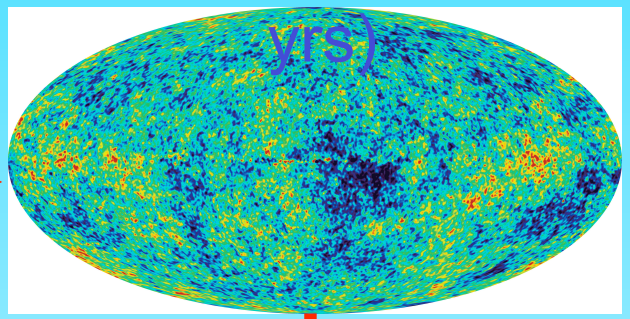
$$\begin{cases} |\delta_k|^2 \alpha\, k^n & n = 1 \\ \text{Gaussian amplitudes} \end{cases}$$

•Inflation
(t~10^{-35}s)

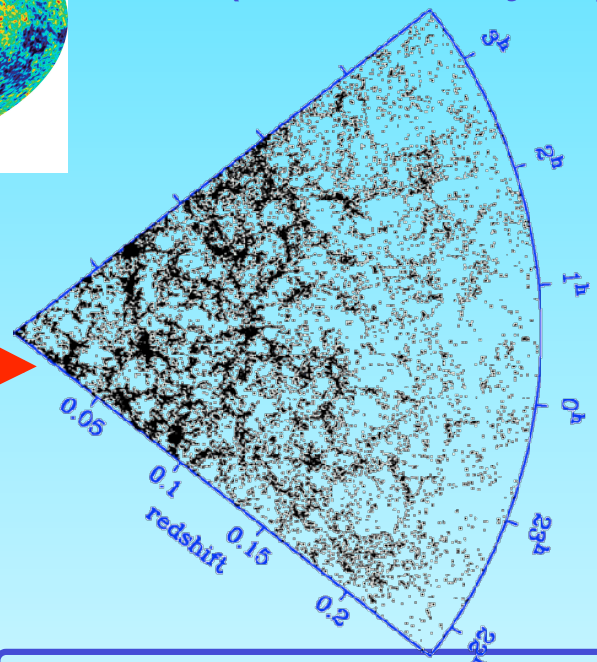


•Dark matter

•CMB (t~$3x10^5$ yrs)



•Structure
(t~$13x10^9$yrs)



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•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

➔ Existence of dark energy supported by WMAP+LSS

➔ Basic cosmological params determined by WMAP+LSS+SN+…

Current limits $w<-0.9$ ($p= w\rho c^2$)

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

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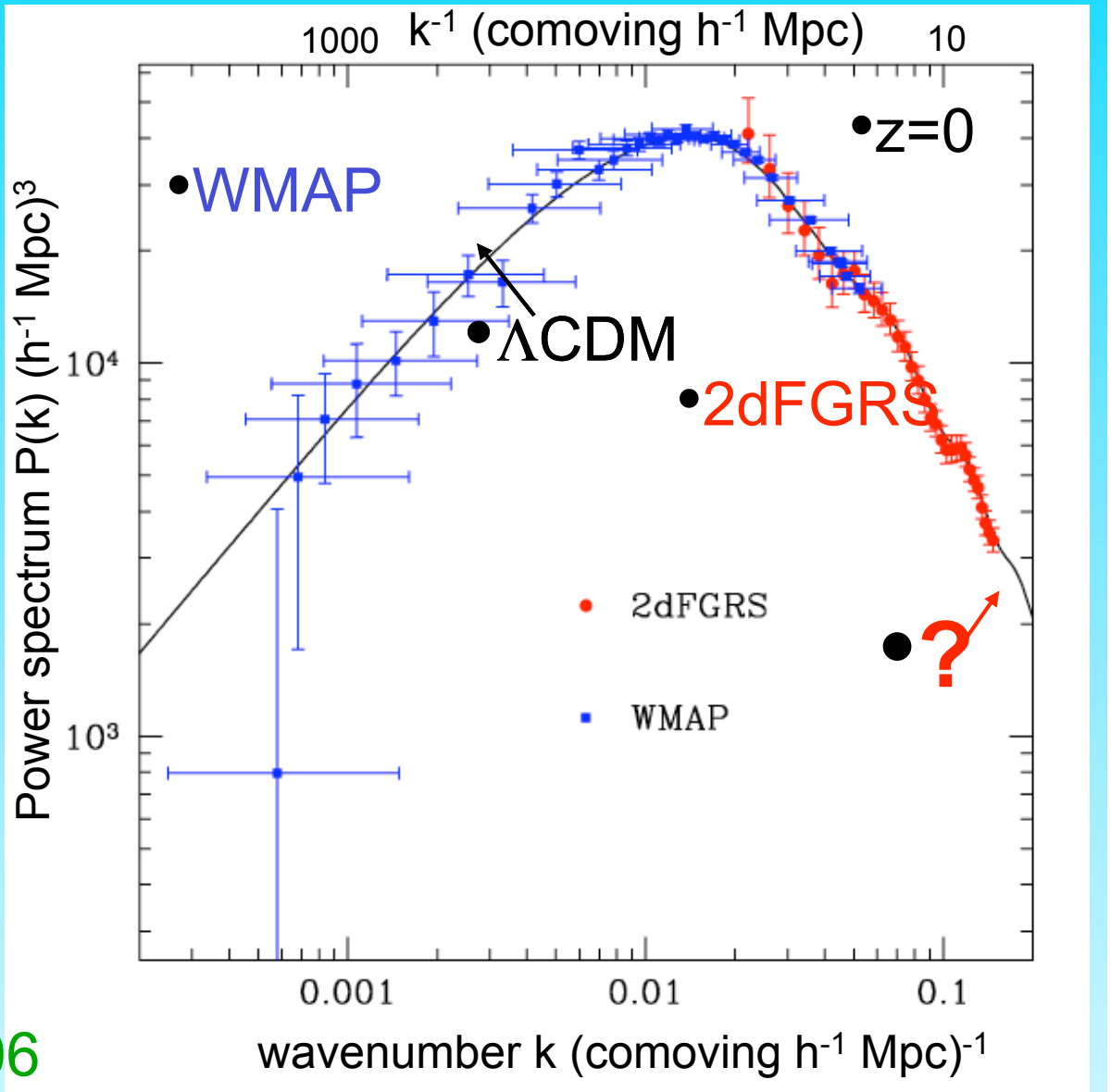
•CMB:

- 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



•Open questions

•Dark matter

- What is it?
  - If SUSY particle, will LHC make it?
  - Will direct or indirect earches find it?
- Is ΛCDM really right on large scales?
  - Map DM directly → gravitational lensing
  - Measure PS growth → galaxy surveys at high z
  - Do galaxies trace mass ? → galaxy formation theory
- Is ΛCDM right on small scales?
  - Detect dark substructures → gravitational lensing
  - Sort out rotation curve mess → simulations, observations
  - Further study of cluster halo structure → X-rays, lensing

•Open questions

•Dark energy

- What is it?
  - Nothing is known! → theory
- Is it:
  - constant in time (Λ) or varying (quintessence)?
    - Is it a reflection of non_Einsteinian gravity

- Fluctuation growth rate and geometry depend on w(z)
  - effects are small but perhaps measurable

Dark energy?

Help!