Baryon Acoustic Oscillations: Current and Future Cosmological Constraints

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Outline

- What are BAOs
- Detection of BAOs in galaxy surveys
  - What we have learned from 2dFGRS and SDSS
- Future uses of BAOs
  - Cosmic surveying
  - Constraints on dark energy
  - Systematic uncertainties
- Forecasts for Future Surveys
  - Pan-STARRS
- Conclude

Origin of BAOs

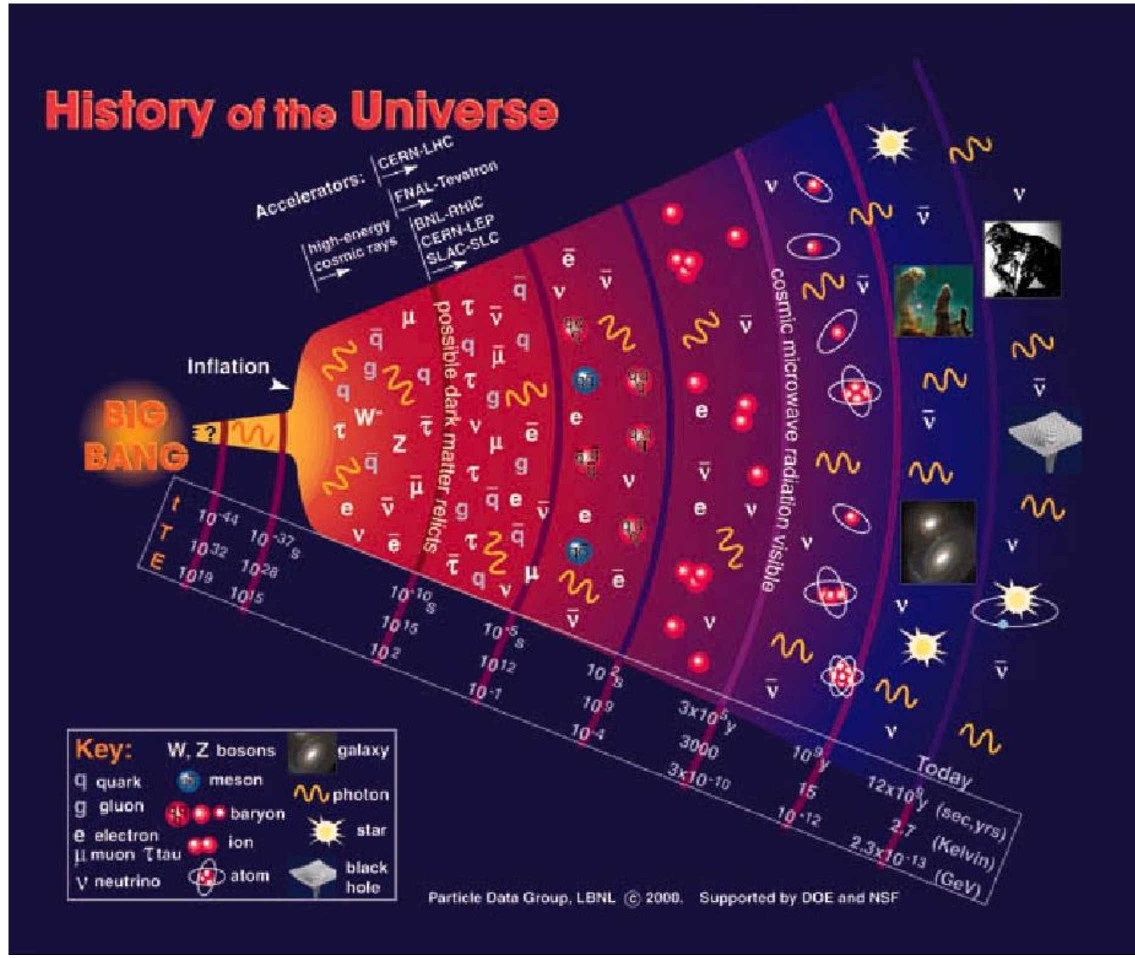
Prior to recombination the ionized plasma and photons are tightly coupled.

$$P = P_{\mathrm{gas}} + P_{\mathrm{rad}} = P_{\mathrm{gas}} + \rho_{\mathrm{rad}} c^2/3$$

$$\rho = \rho_{\mathrm{gas}} + \rho_{\mathrm{rad}}$$

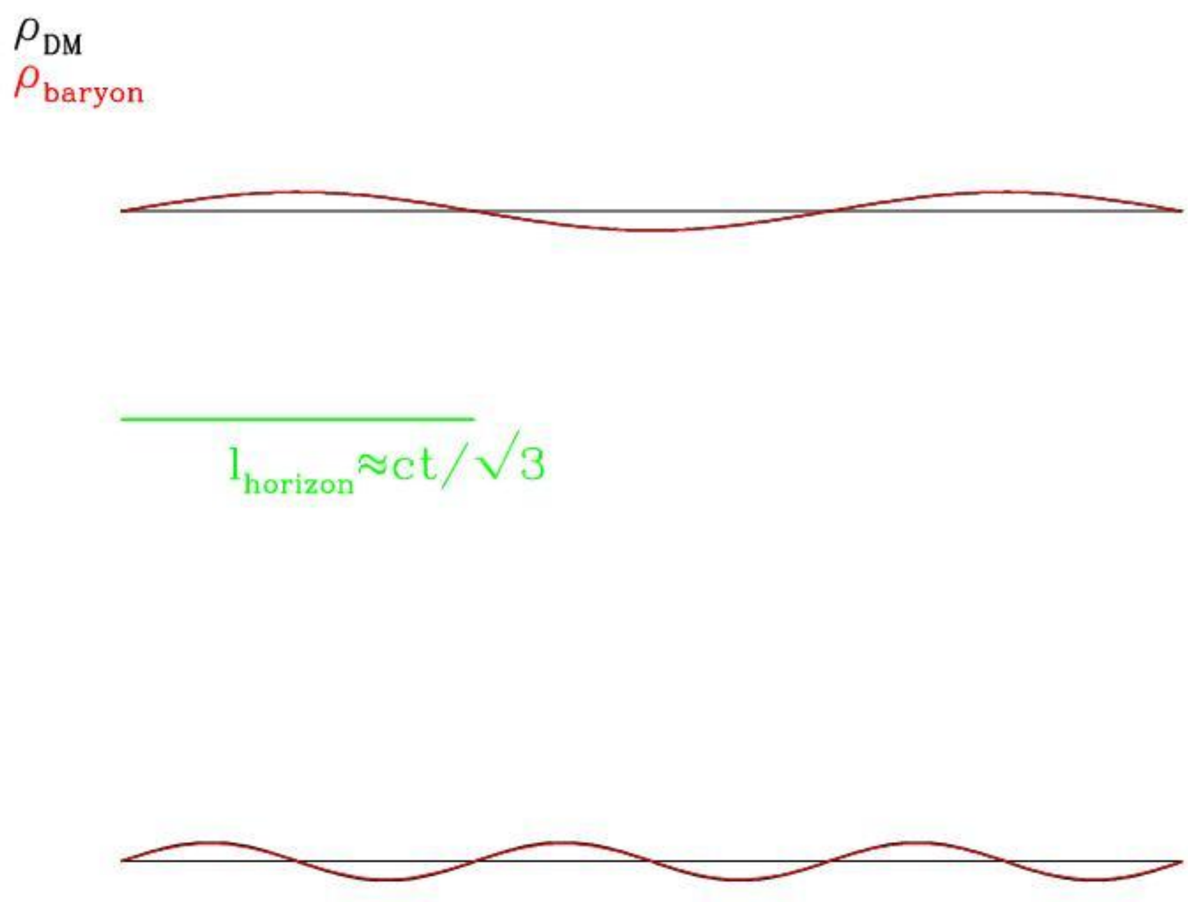
$$c_{\mathrm{S}}^2 = \frac{dP}{d\rho} \approx \frac{c^2}{3}\left(\frac{3\Omega_{\mathrm{b}}}{4\Omega_{\mathrm{m}}}\frac{a}{a_{\mathrm{eq}}} + 1\right)^{-1}$$

$$\approx c^2/3$$



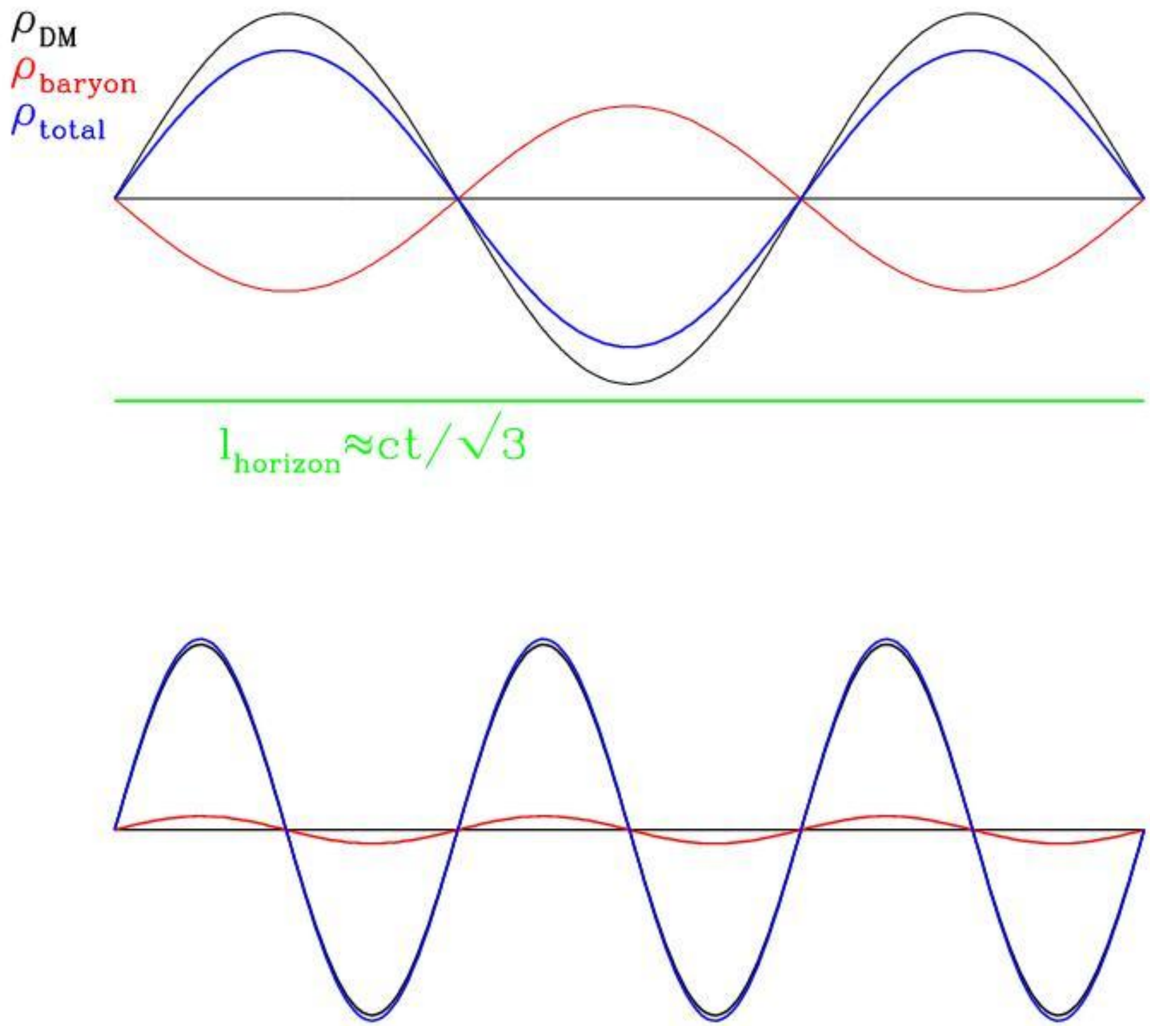
On entering the acoustic horizon perturbations in the photon-baryon fluid oscillate as sound waves.

At recombination the photons and baryons decouple. The sound speed drops and the oscillations cease.

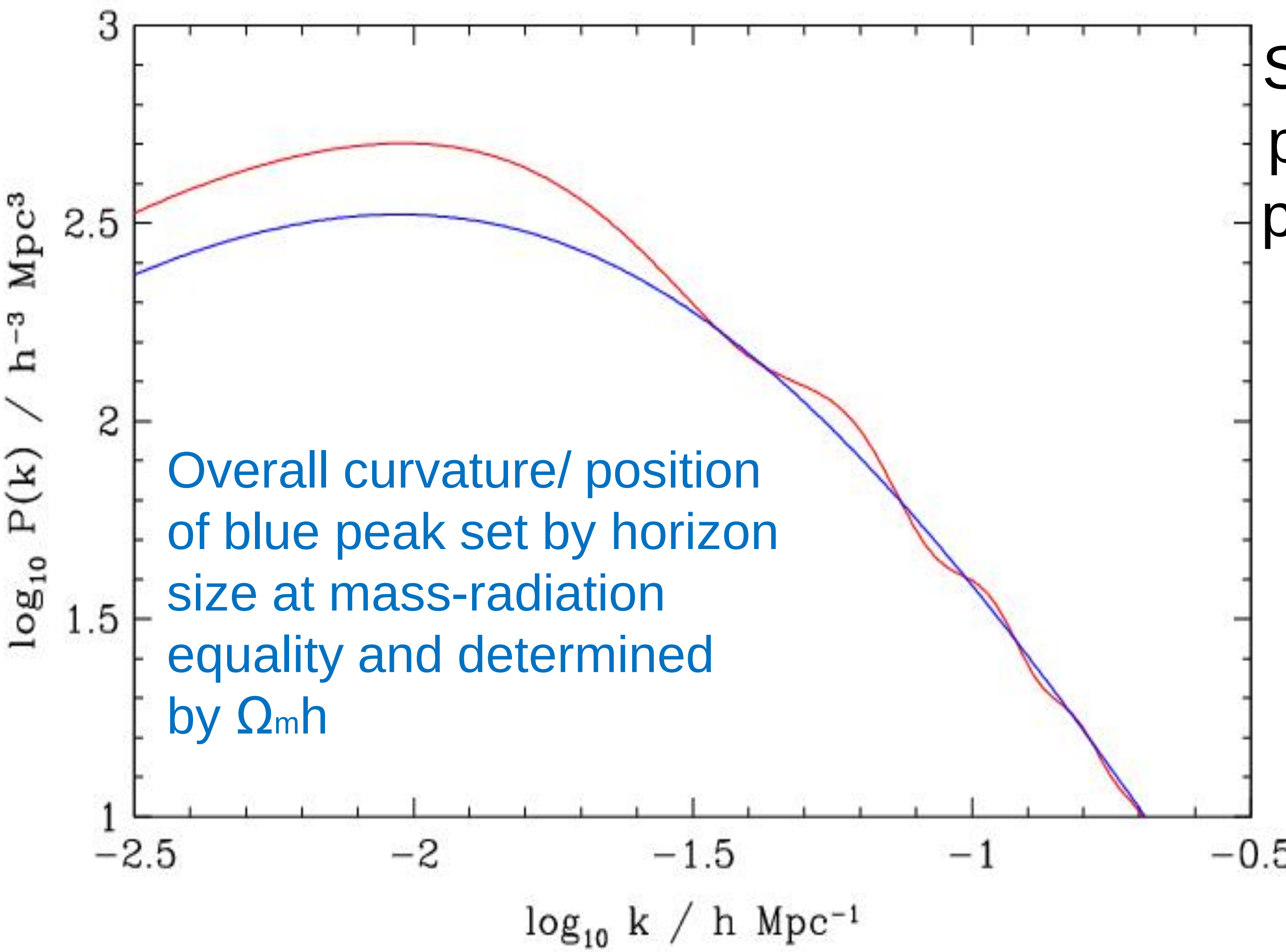


animation

Thus modes of specific wavelengths are enhanced while others are suppressed



Baryon Oscillations



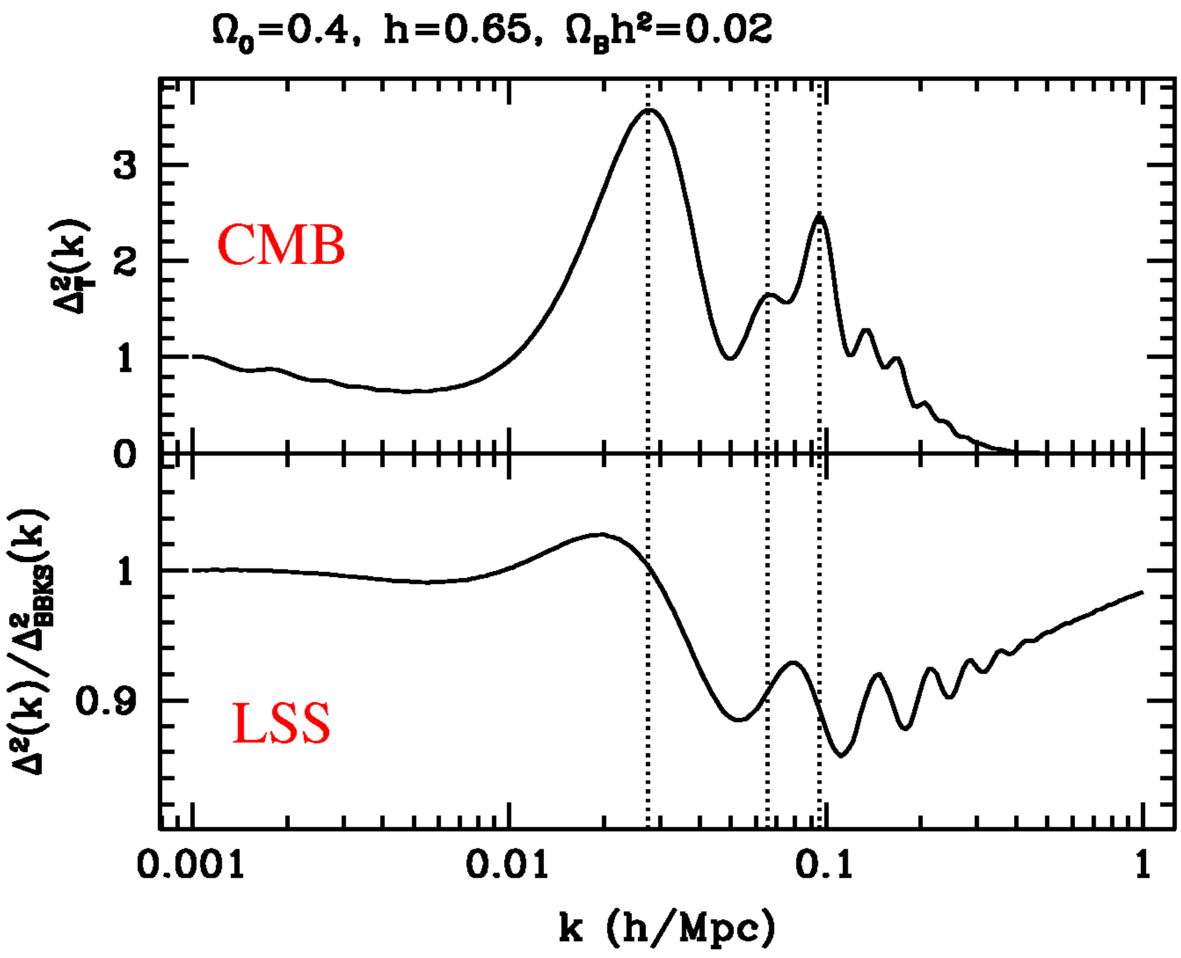
Overall curvature/ position of blue peak set by horizon size at mass-radiation equality and determined by $\Omega_m h$

Sound waves in the photon-baryon fluid produce oscillations

$$\text{scale} : c_s t_{rec}$$

$$\Rightarrow \Omega_b / \Omega_m$$

CMB anisotropies and large-scale structure

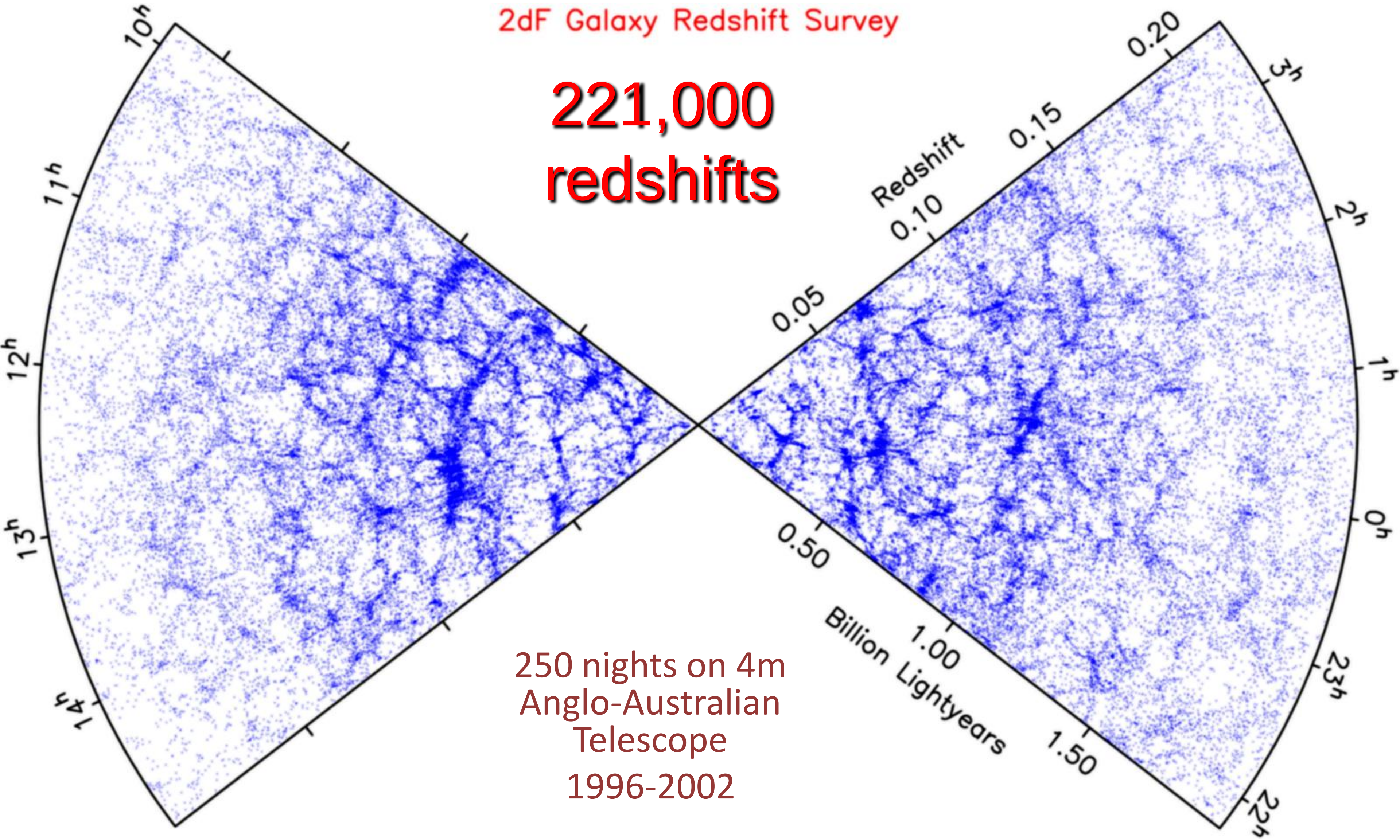


CMB and LSS out of phase:

LSS amplitude smaller than CMB

Meiksin etal 99

Detection in Surveys



221,000 redshifts

250 nights on 4m Anglo-Australian Telescope
1996-2002

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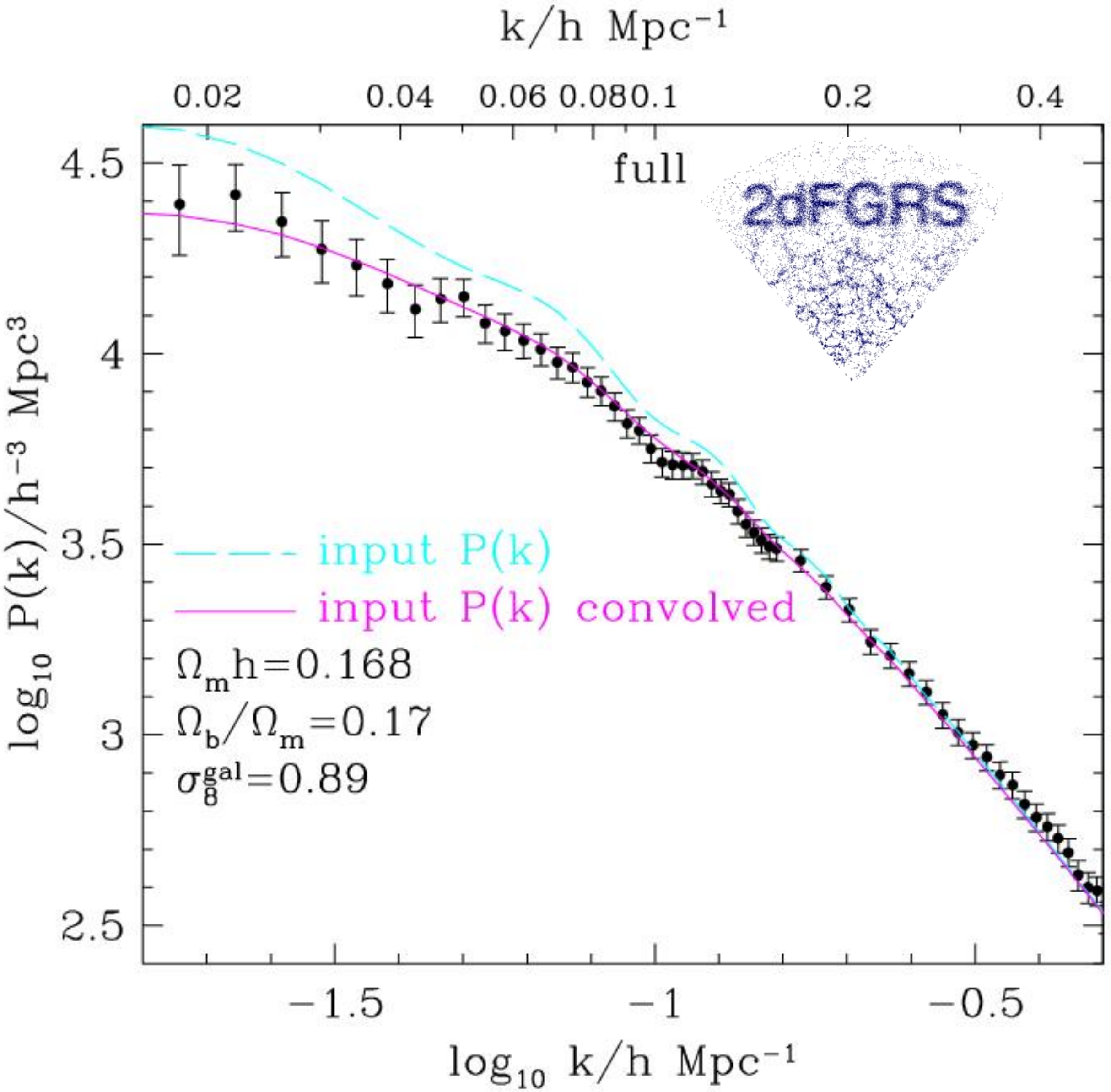
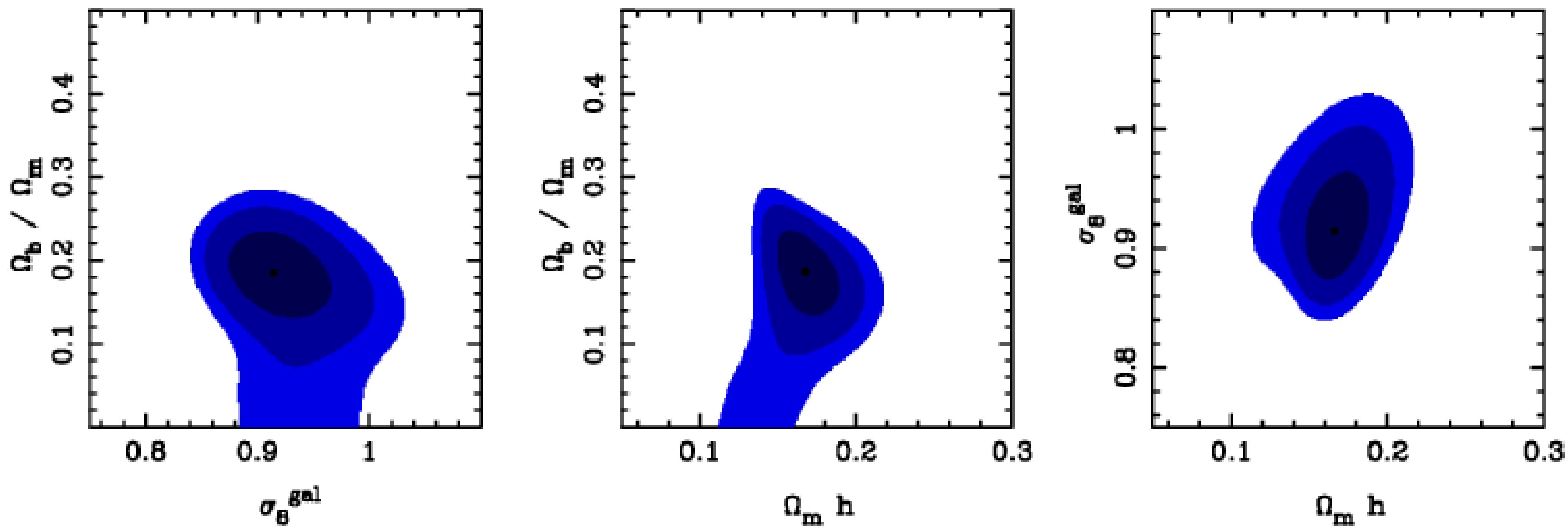
The 2dFGRS Power Spectrum



Cole et al (2005)

The 2dFGRS Power Spectrum parameter constraints



Cole et al (2005)

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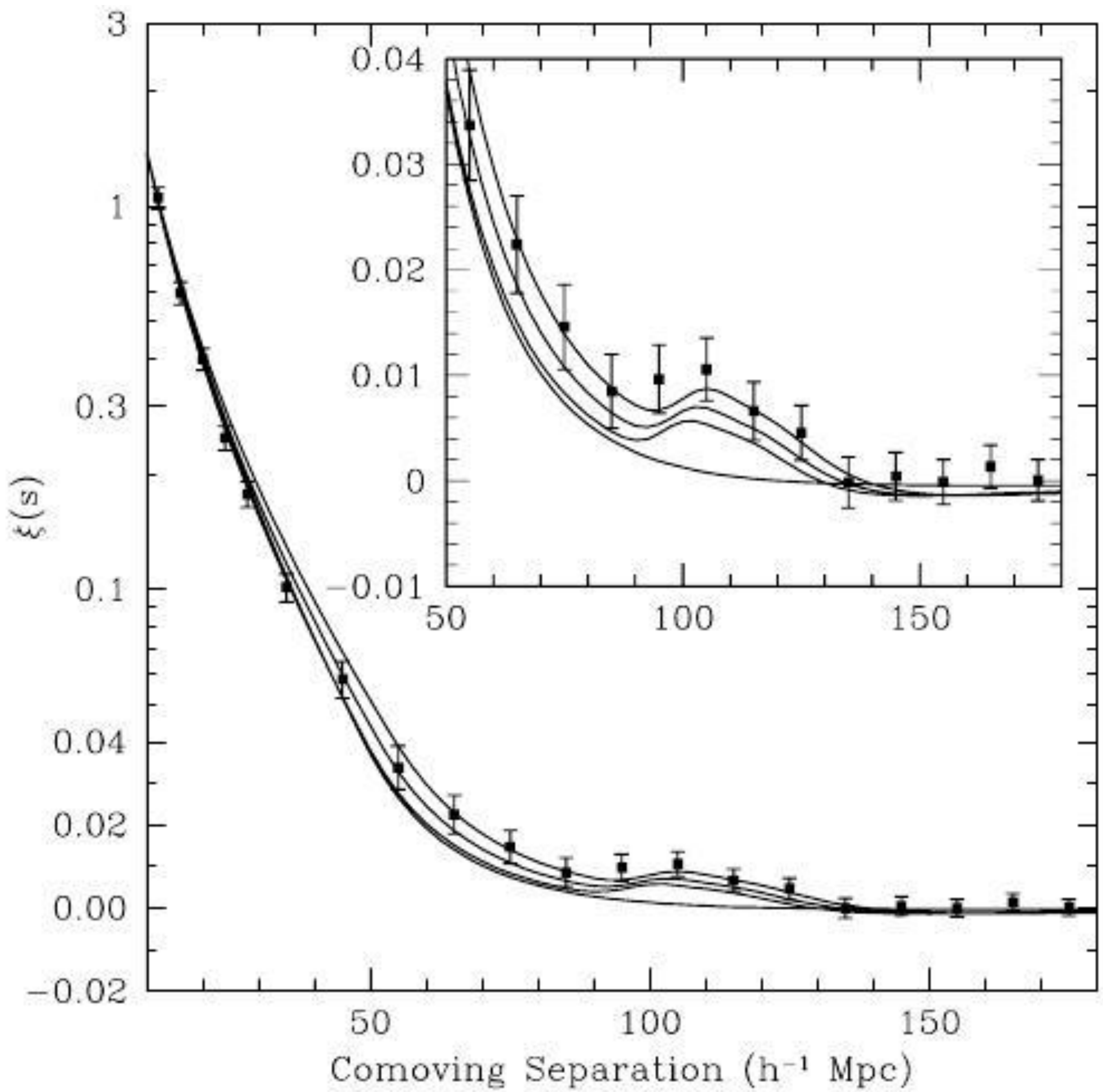
SDSS LRG survey

Wiggles in the power spectrum are detected as a peak in the correlation function at the sound horizon scale.

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(2005)

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Using BAOs to constrain DE

The nature of dark energy is one of the most intriguing questions in modern cosmology. It is a uniformly distributed component of the energy density of the universe with a negative pressure:

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

The evidence for the existence of dark energy (vacuum energy) comes from two sources.

Type Ia SNe

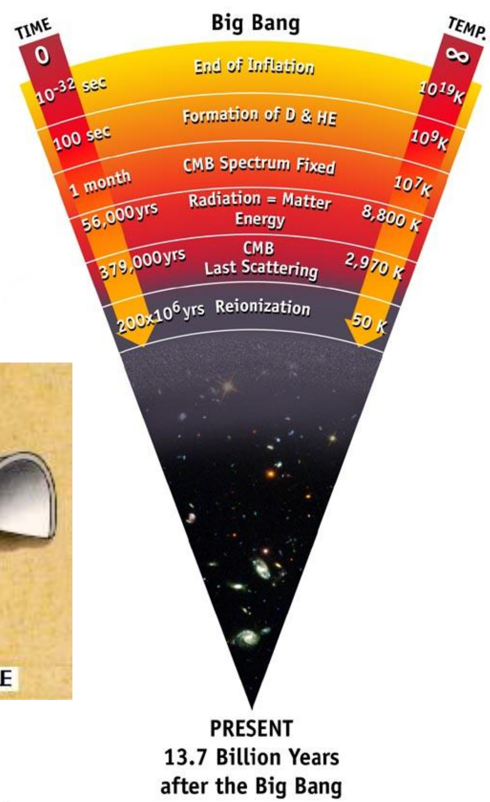
CMB + LSS

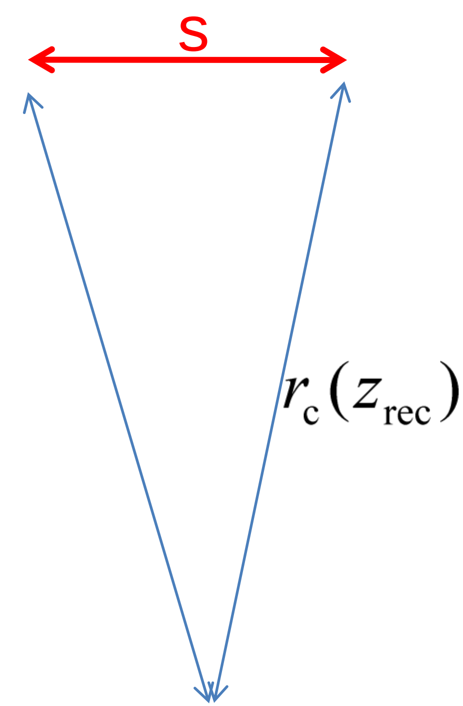
CMB constraints on DE

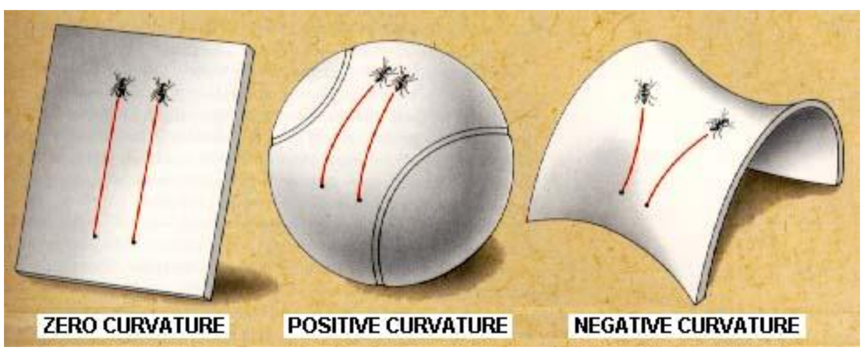
Comoving sound horizon at t_{rec}

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

$$s = \int_0^{t_{\rm rec}} \frac{c}{a}\, dt = \frac{1}{H_0 \Omega_{\rm m}^{1/2}} \int_0^{a_{\rm r}} \frac{c_{\rm s}}{(a + a_{\rm eq})^{1/2}}\, da$$







The comoving distance to a given redshift:

$$r_{\rm c} = \frac{c}{H_0 \Omega_{\rm m}^{1/2}} \int_0^z \left((1+z')^3 + (\Omega_{\rm DE}/\Omega_{\rm m})(1+z')^{3(1+w)} + (\Omega_k/\Omega_{\rm m})(1+z')^2 \right)^{-1/2} dz'$$

Which depends on

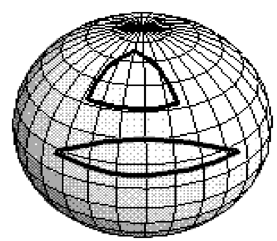
$$\Omega_{\rm m} h^2$$

$$\Omega_k / \Omega_{\rm m}$$

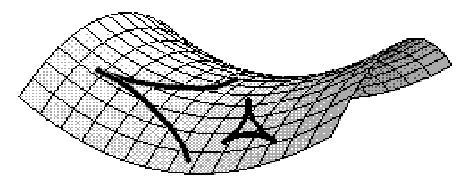
$$\Omega_{\rm DE} / \Omega_{\rm m}$$

$$w$$

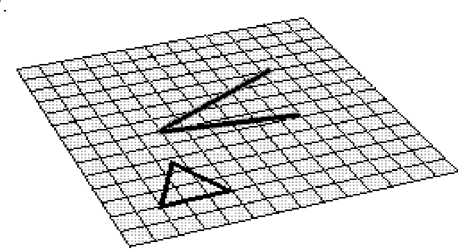
But in addition the angular size depends on Ω_k much more strongly through the curvature.



Universe with *positive* curvature. Diverging line converge at great distances. Triangle angles add to more than 180°.



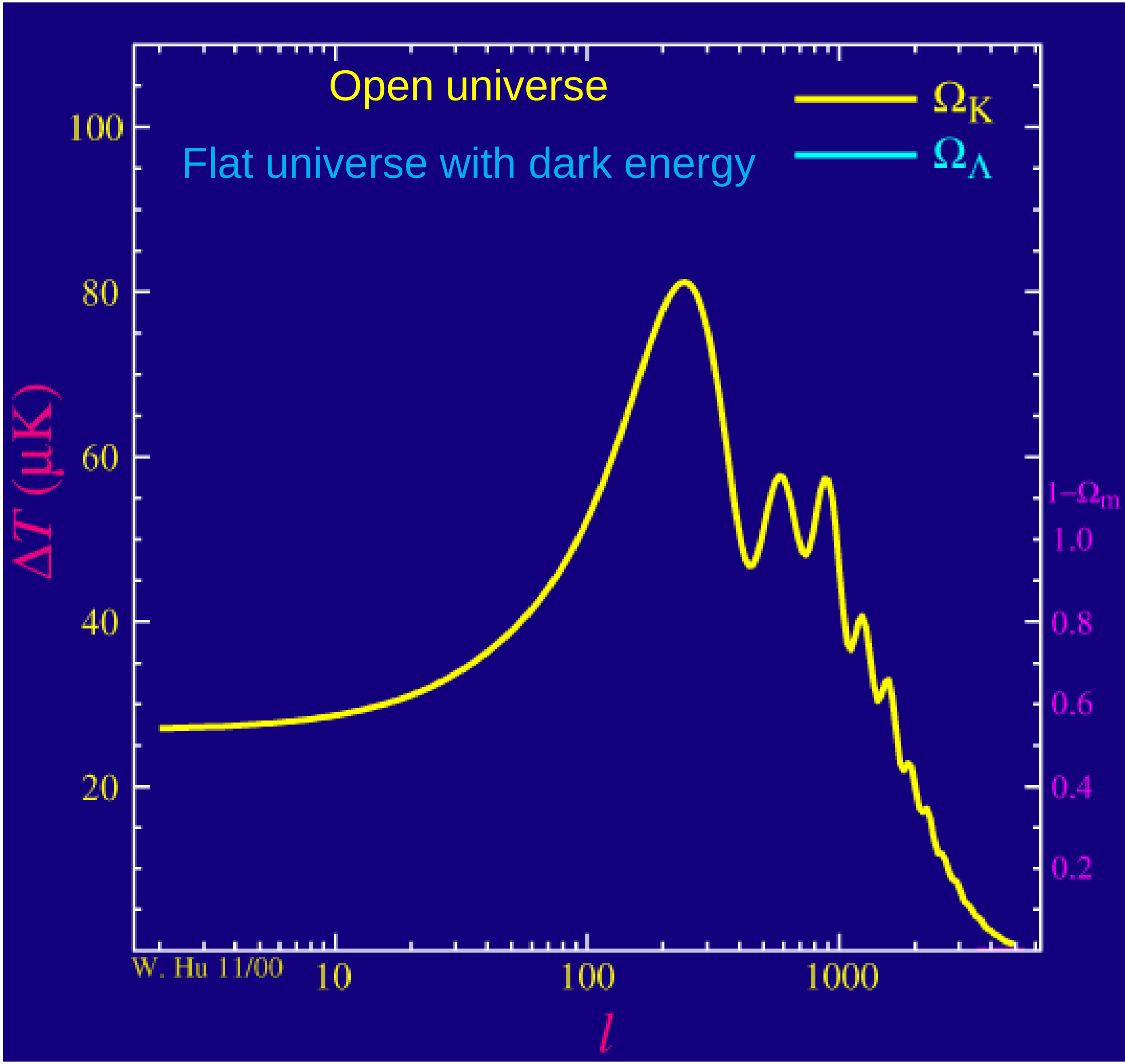
Universe with *negative* curvature. Lines diverge at ever increasing angles. Triangle angles add to less than 180°.



Universe with no curvature. Lines diverge at constant angle. Triangle angles add to 180°.

Combined with a constraint on $\Omega_m h$ from LSS the observed angular scale

$\Rightarrow \Omega_{DE}=0.75$



Thus for flat models

$$r_{\mathrm{c}} = \frac{c}{H_0 \Omega_{\mathrm{m}}^{1/2}} \int_0^z \left((1+\mathrm{z}')^3 + (\Omega_{\mathrm{DE}} / \Omega_{\mathrm{m}})(1+z')^{3(1+w)} \right)^{-1/2} dz'$$

which depends on

$$\Omega_{\mathrm{m}} h^2$$

$$\Omega_{\mathrm{DE}} / \Omega_{\mathrm{m}}$$

$$w$$

and the CMB gives a tight constraint on Ω_{DE} assuming w=-1

Standardizable candles, like Type Ia SNe, constrain the distance redshift relation at other redshifts

$$r_c = \frac{c}{H_0 \Omega_m^{1/2}} \int_0^z \left((1+z')^3 + (\Omega_{DE} / \Omega_m)(1+z')^{3(1+w)} \right)^{-1/2} dz'$$

$$r_c = \frac{c}{H_0} \left(z - (1-q_0) z^2 / 2 + \ldots \right)$$ -- Taylor Expansion

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left(\rho + 3P / c^2 \right)$$ -- Acceleration Equation (energy conservation)

$$q_0 = -\frac{\ddot{a} a}{\dot{a}^2} = \frac{\Omega_m}{2} + \frac{\Omega_{DE}(1+3w)}{2}$$ -- Matter and DE contributions

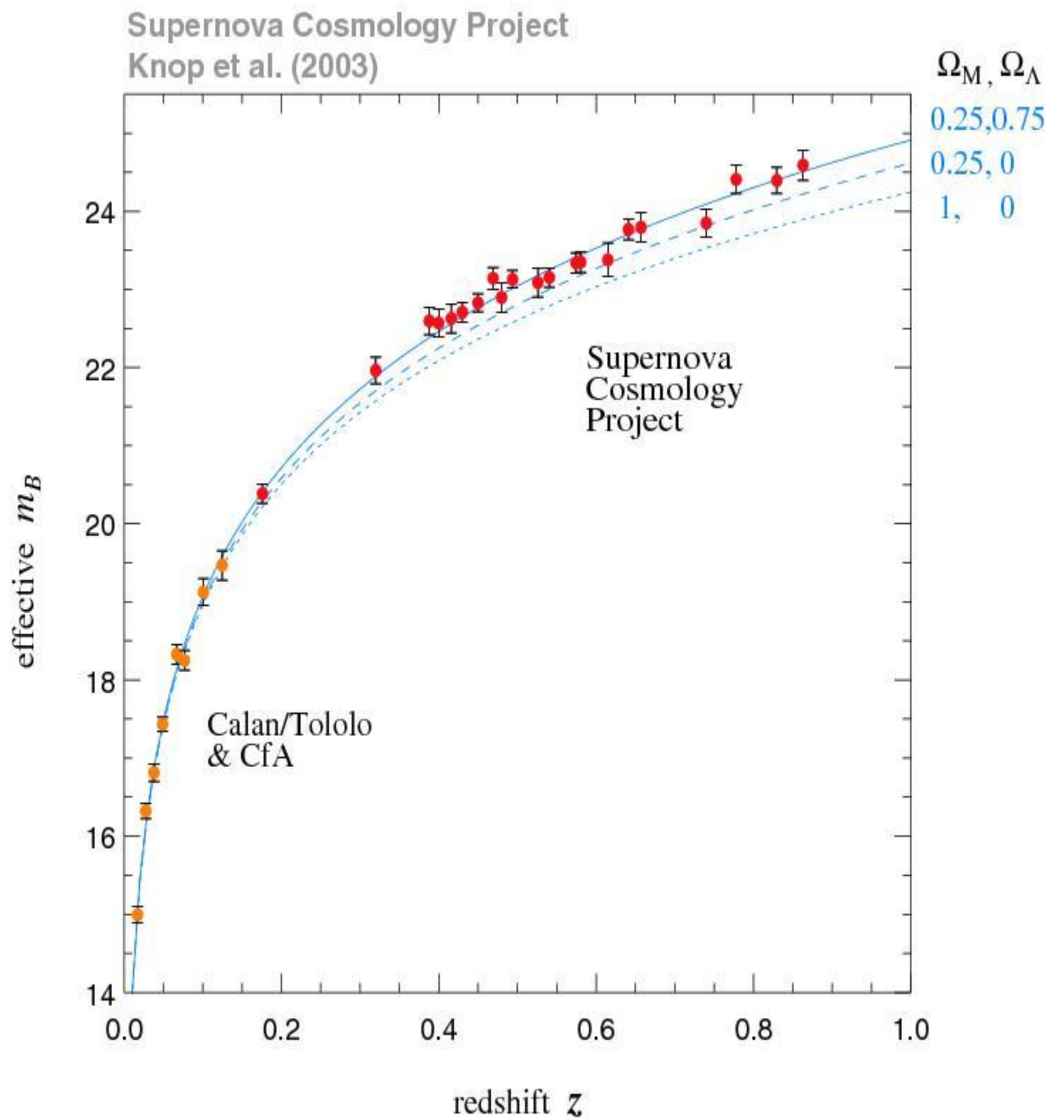
Type Ia SNe

SNe observations show that the expansion of the universe is accelerating.

$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} < 0$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P/c^2\right)$$

and so the acceleration equation implies a dominant component with a negative pressure .i.e DE



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Current Constraints on w

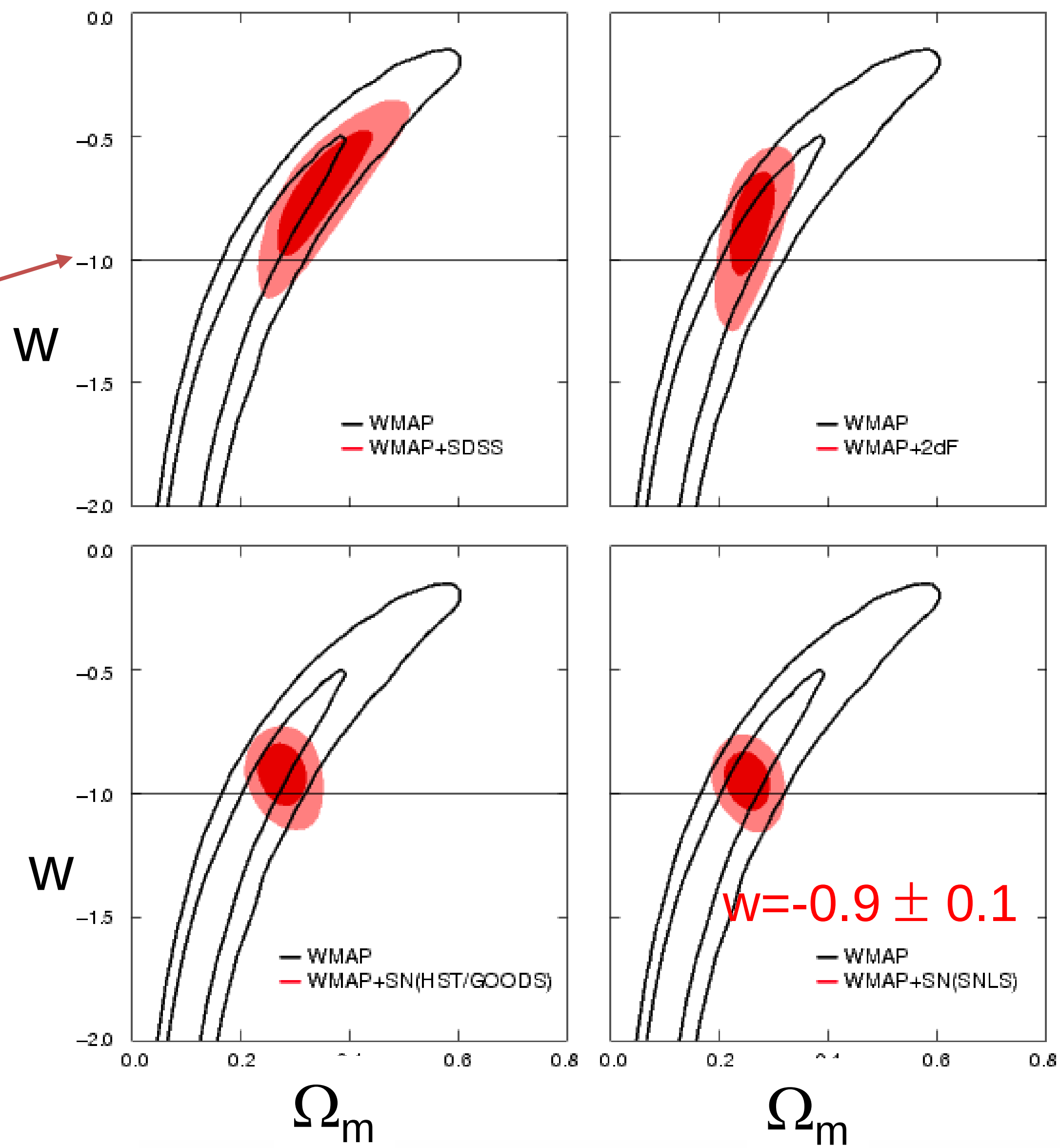
Constraints from CMB, SNIa and LSS ($\Omega_m h$)

Cosmological constant

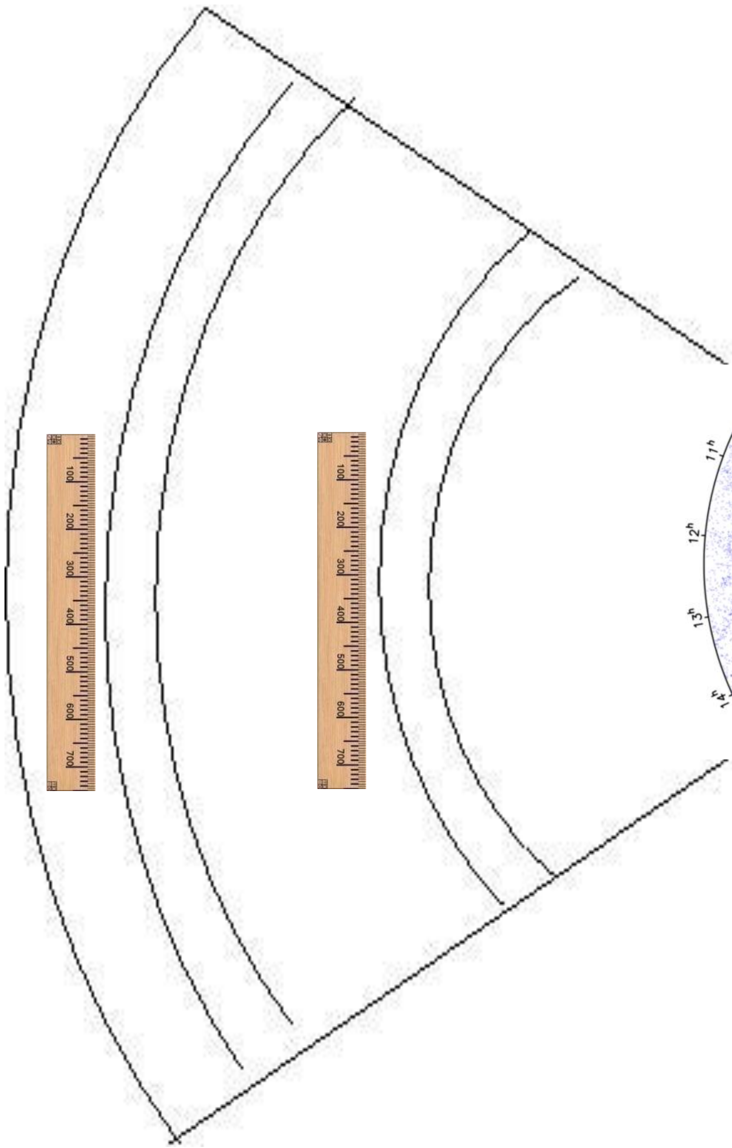
$$p = w\rho c^2$$

Assume w=constant

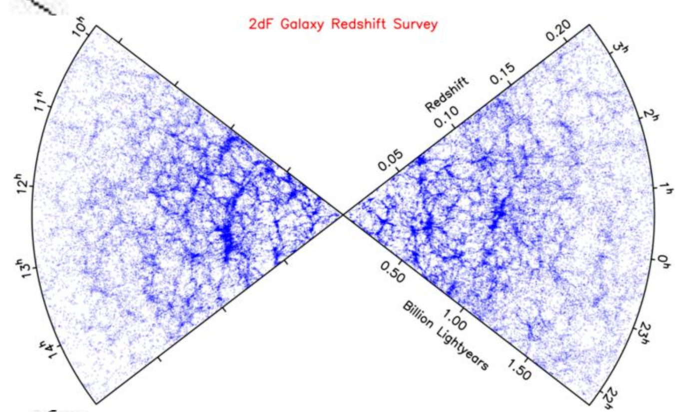
Spergel et al 2006



Future uses of BAOs



Measurements of $r_c(z)$ at several redshifts can constrain w.



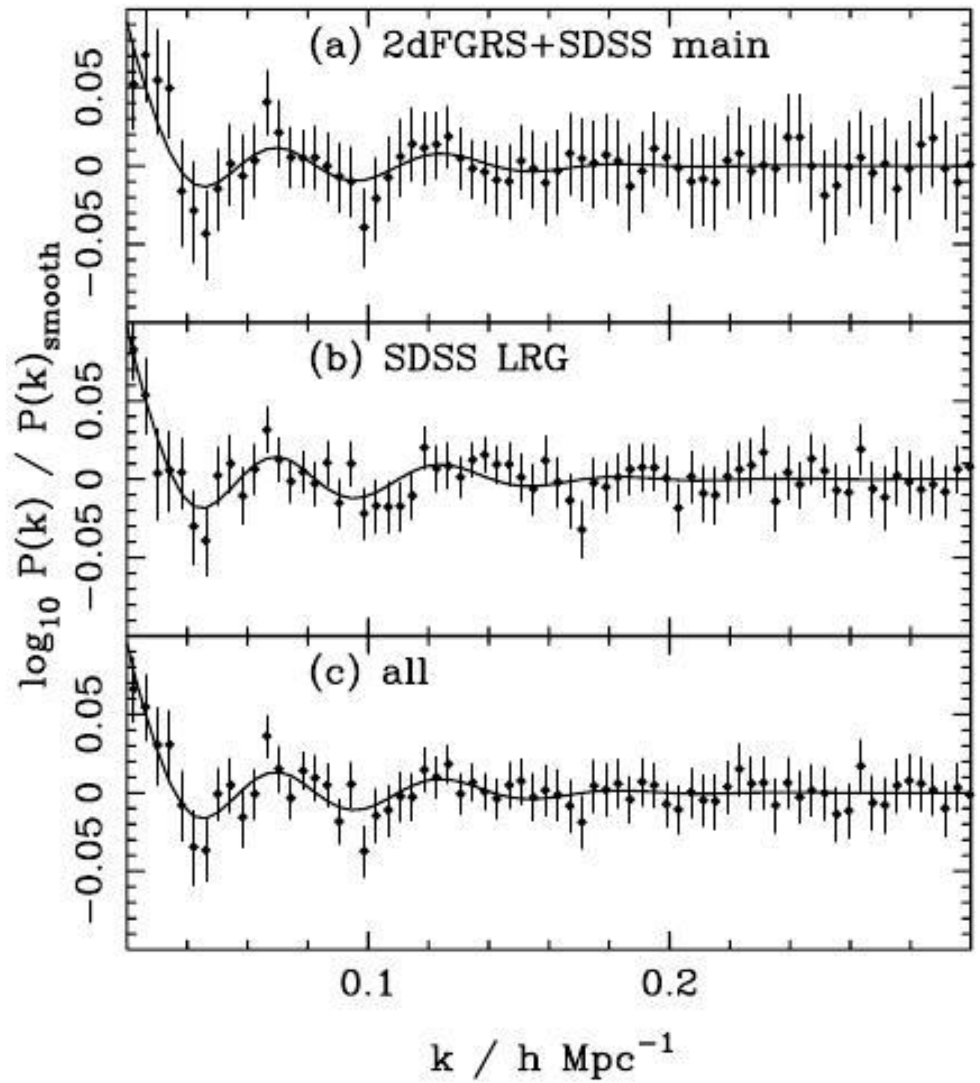
(e.g. Eisenstein & HU 1998; Blake & Glazebrook 2003, 2005; Seo & Eisenstein 2003; 2005……)

Current Constraints on w

Constraints from BAOs in LSS

Measures angular size of acoustic horizon at both z=0.2 and 0.35.

Can also be combined with the CMB measurement at z=1095.



Percival, Cole, Eisenstein ... (2007)

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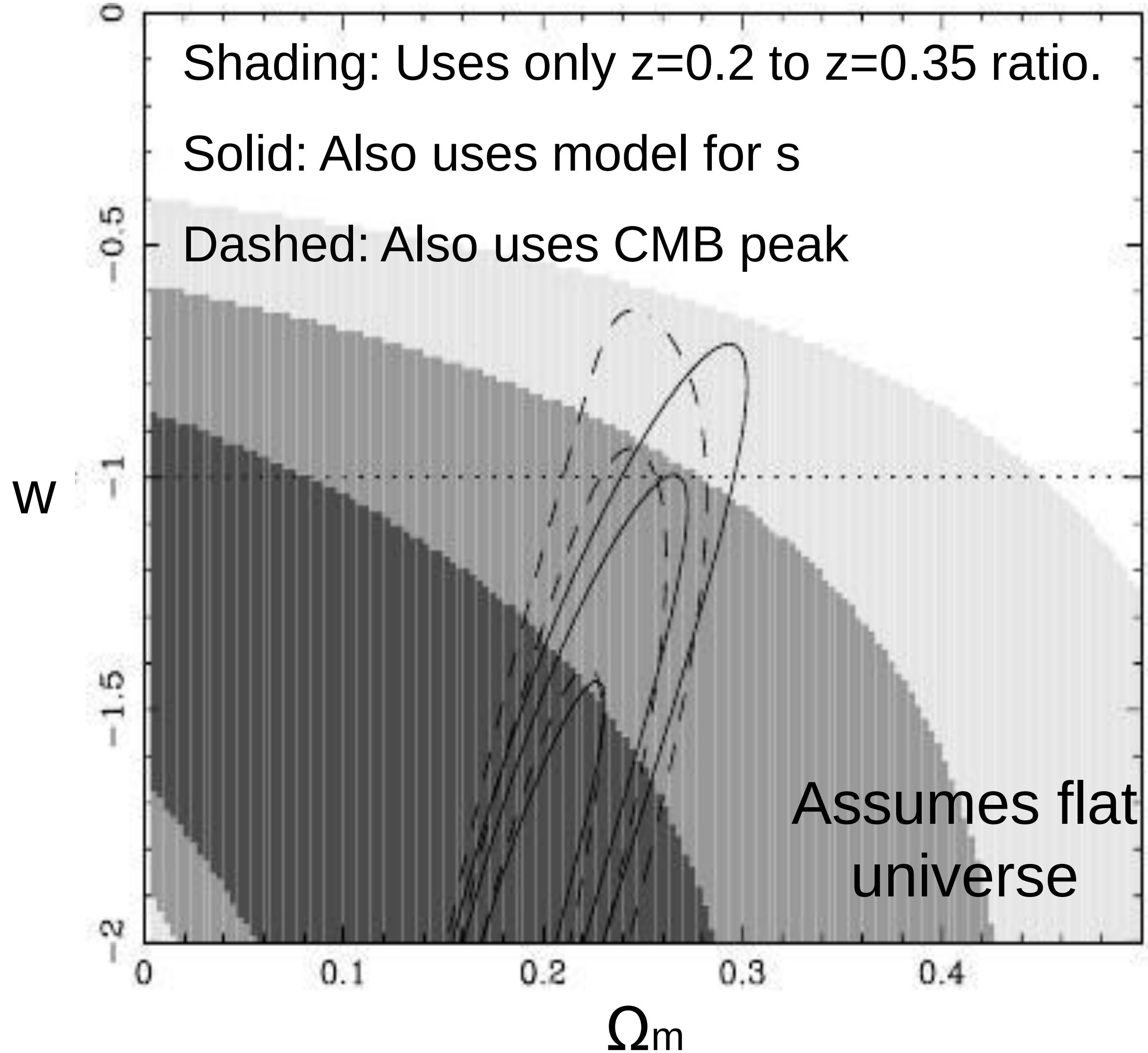

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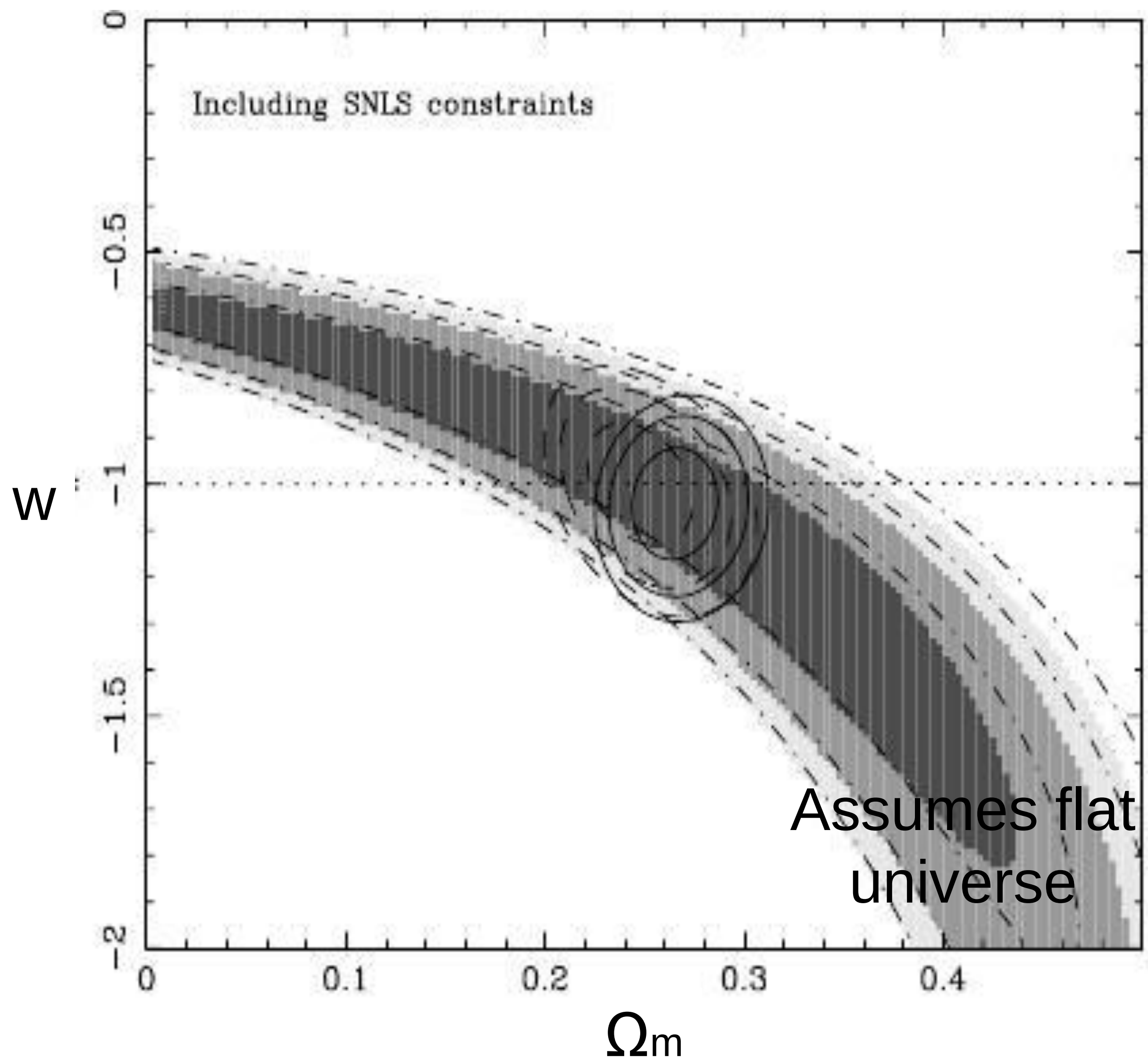
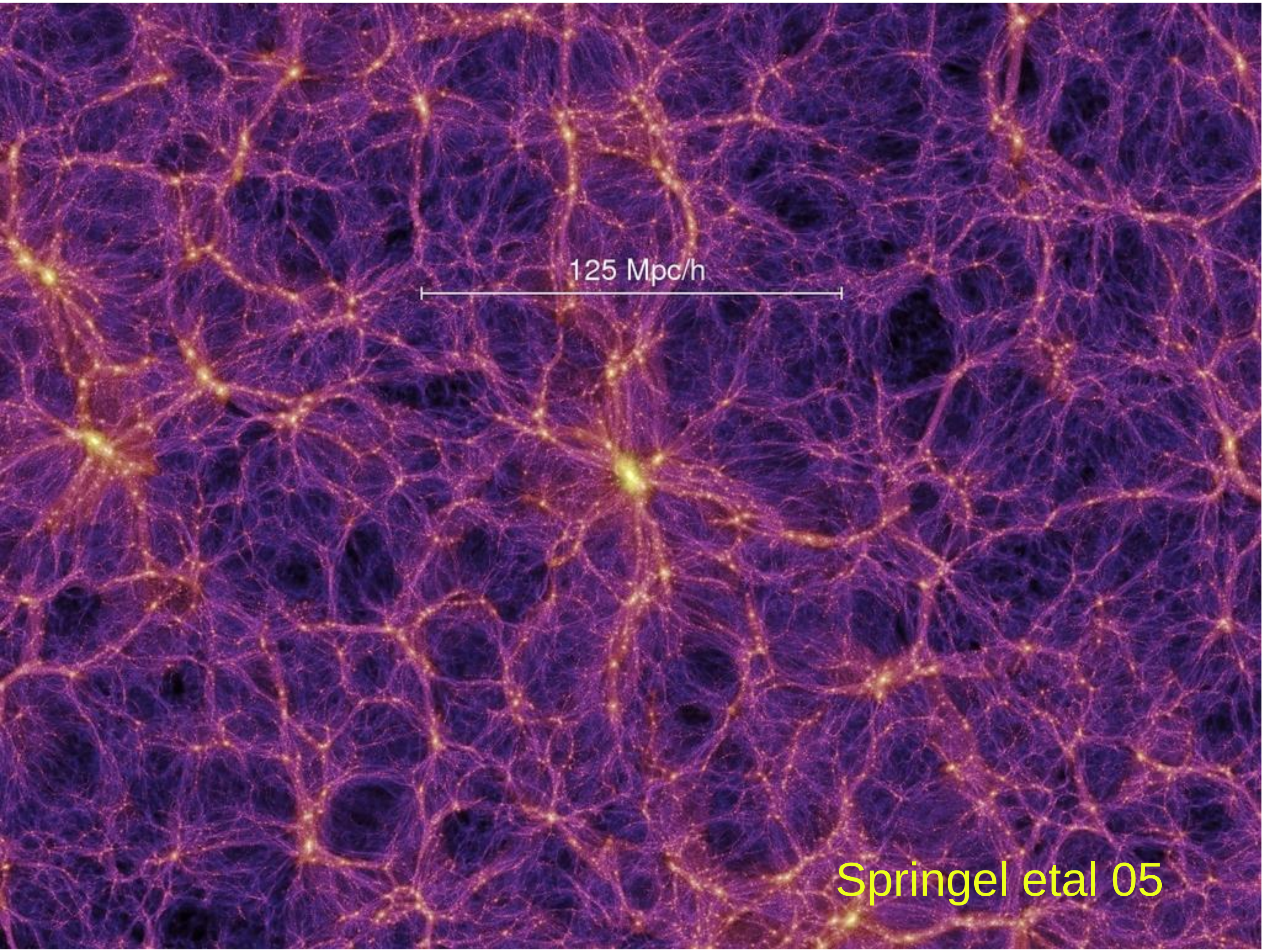


Percival, Cole, Eisenstein ... (2007)

Need to understand systematics



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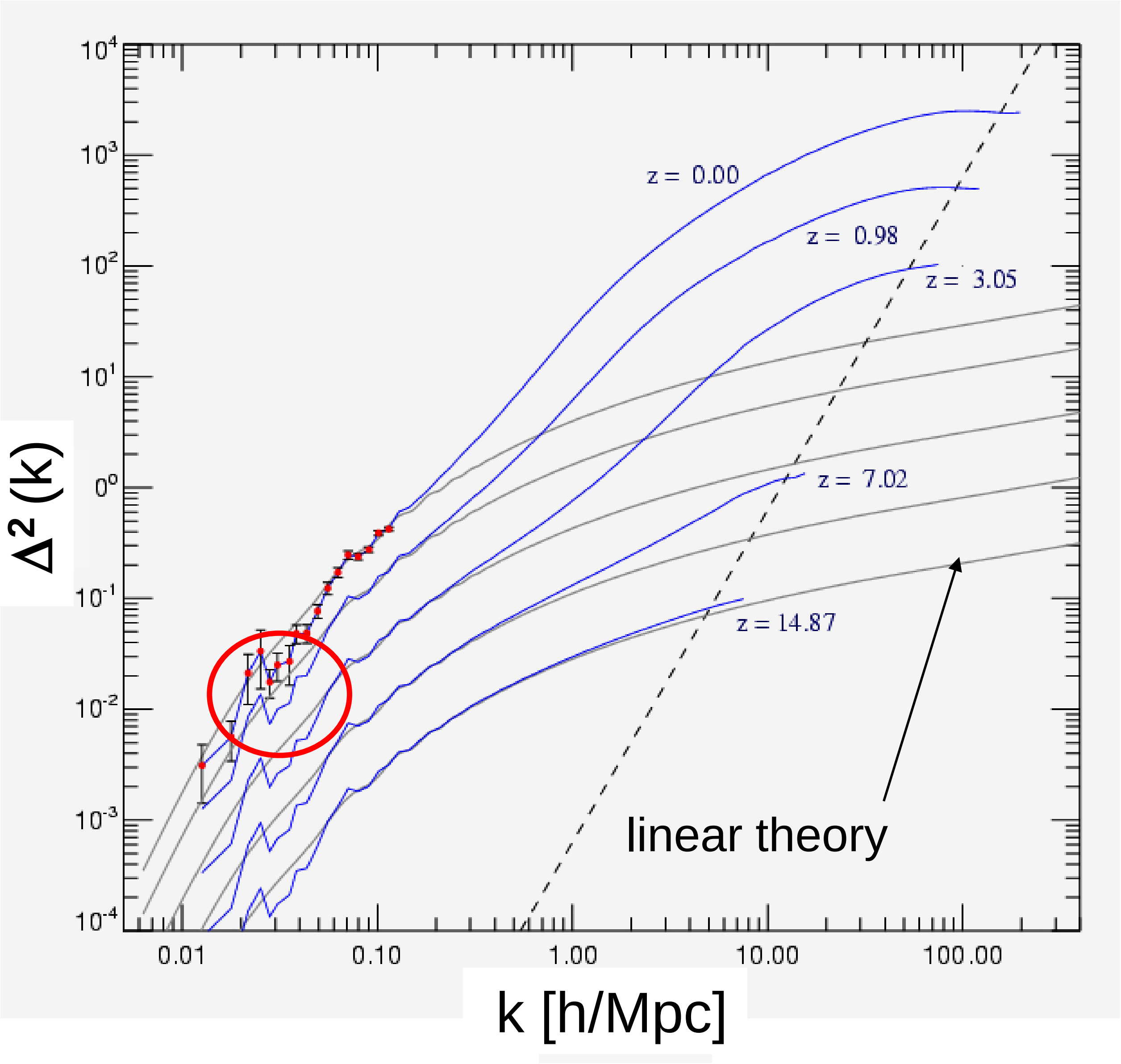
The mass power spectrum

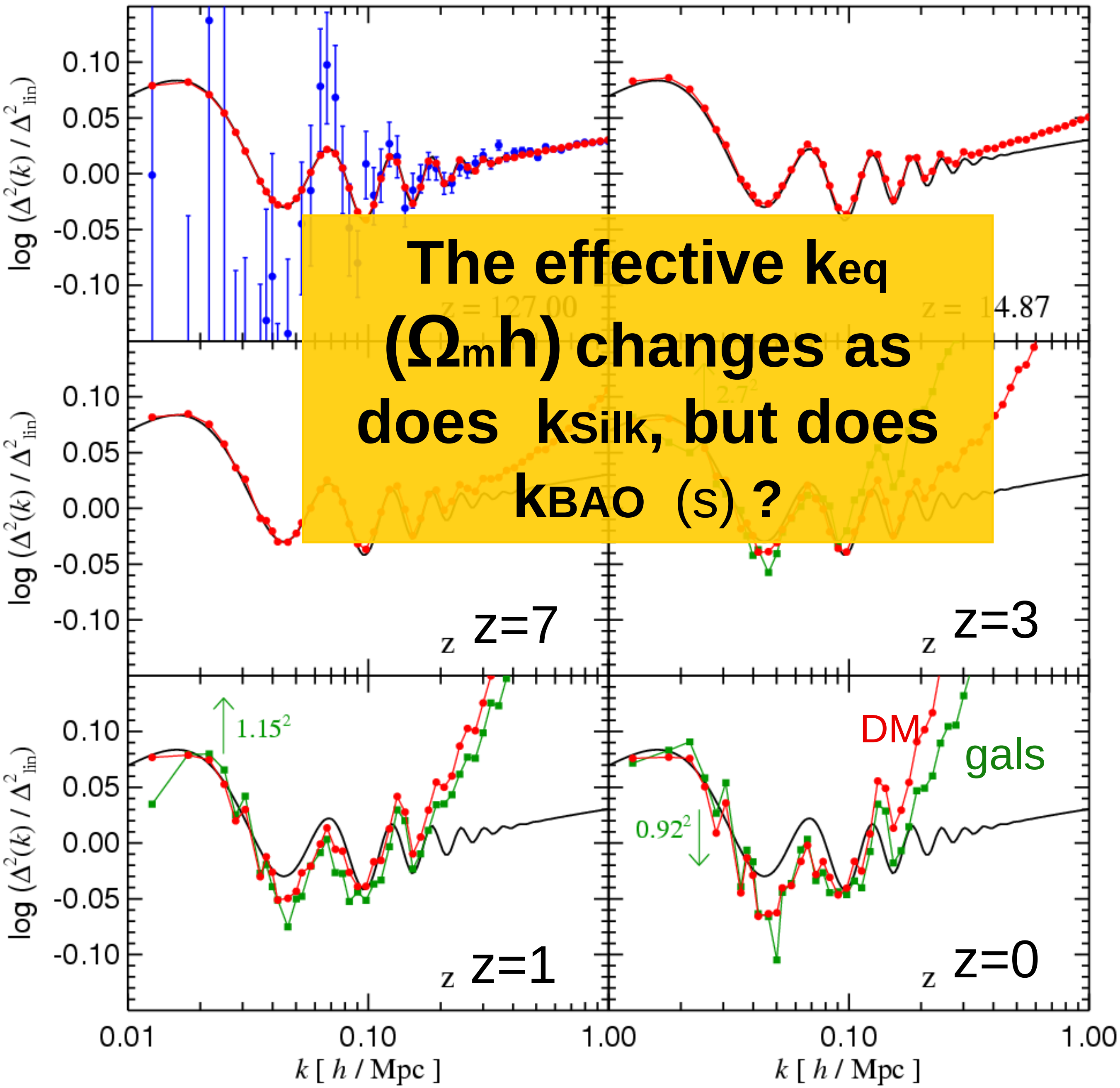
The non-linear mass power spectrum is accurately determined by the Millennium simulation over large range of scales

L_{box}=500Mpc/h



Baryon wiggles in the *galaxy* distribution

Millennium simulation



The effective k_{eq} ($\Omega_m h$) changes as does k_{Silk}, but does k_{BAO} (s) ?

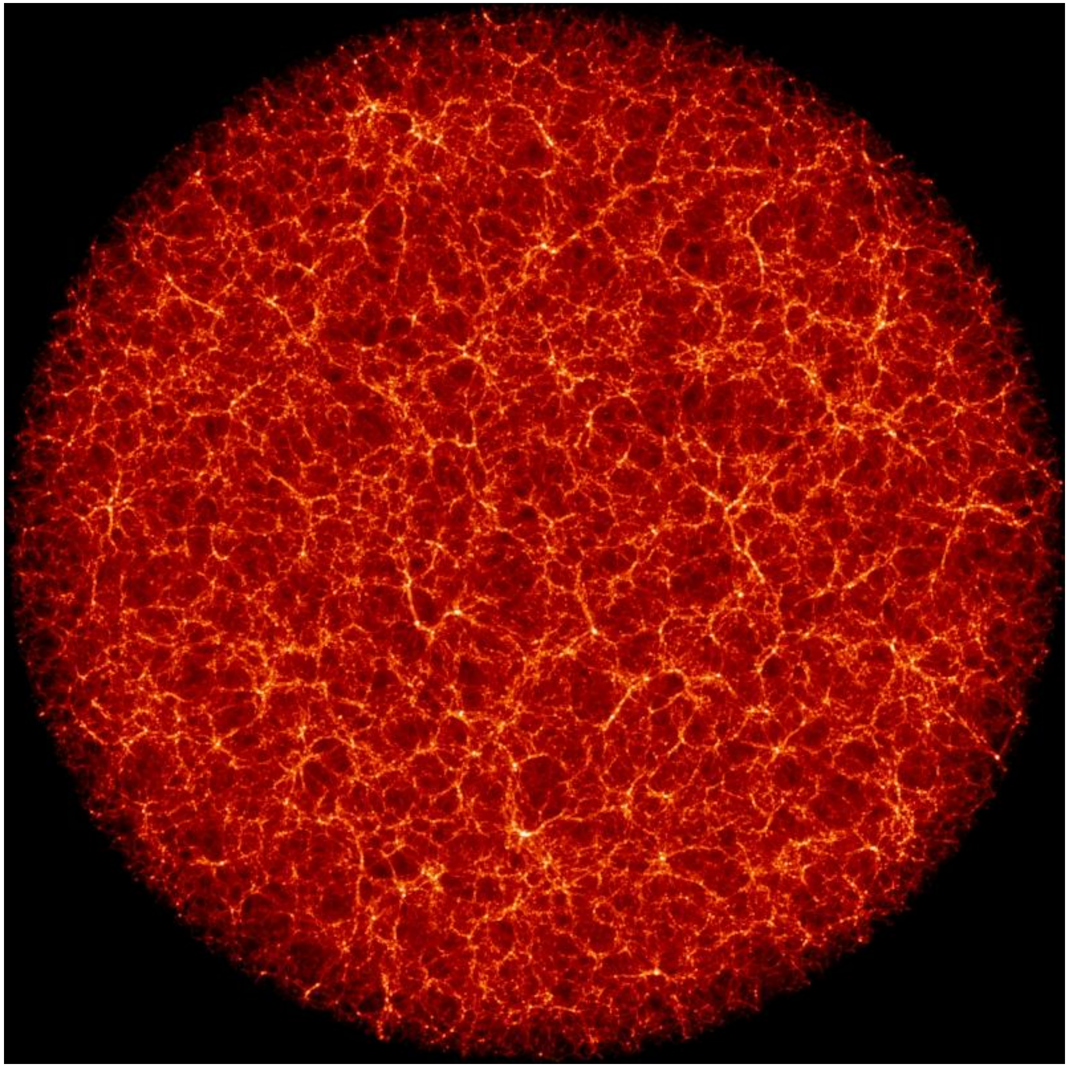
Power spectrum from MS divided by a baryon-free ΛCDM spectrum

Galaxy samples matched to plausible large observational surveys at given z

Springel et al 2005

Computational Cosmology

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 $M_\odot$/h

130,000 cpu hours on the Cosmology Machine

Angulo, Baugh, Frenk & Lacey '08

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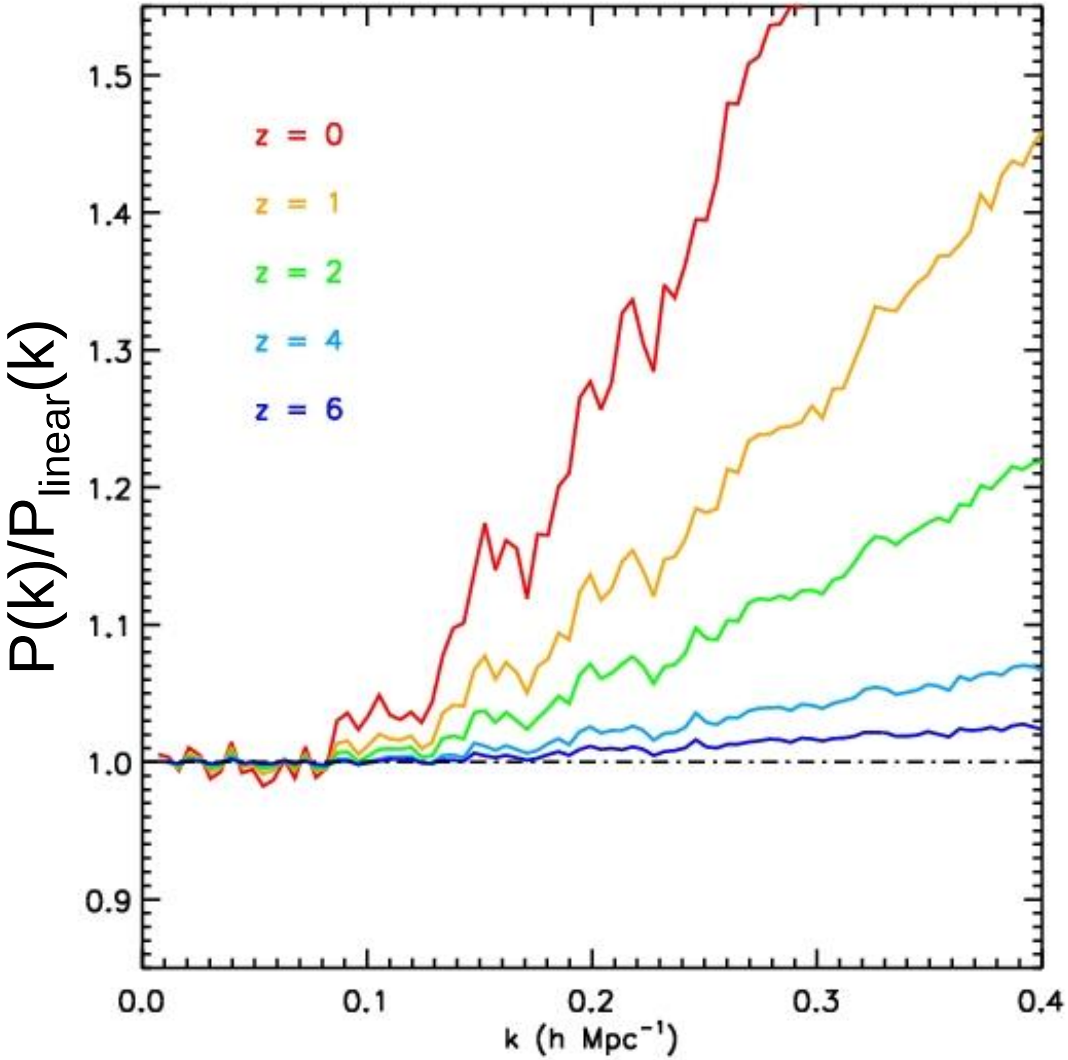
Non-linear evolution of matter fluctuations



BASICC simulation dark matter real space

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

Angulo, Baugh, Frenk & Lacey '08

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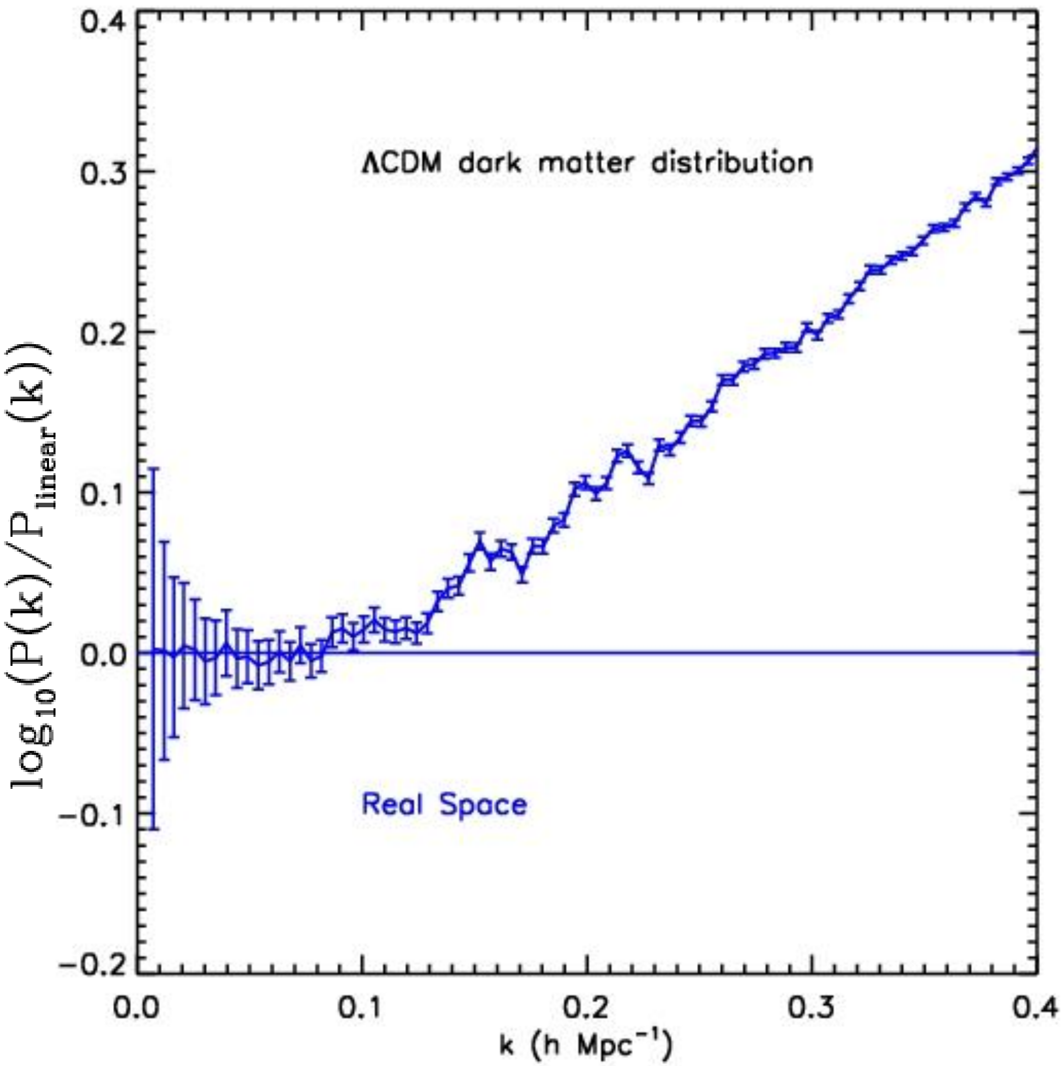
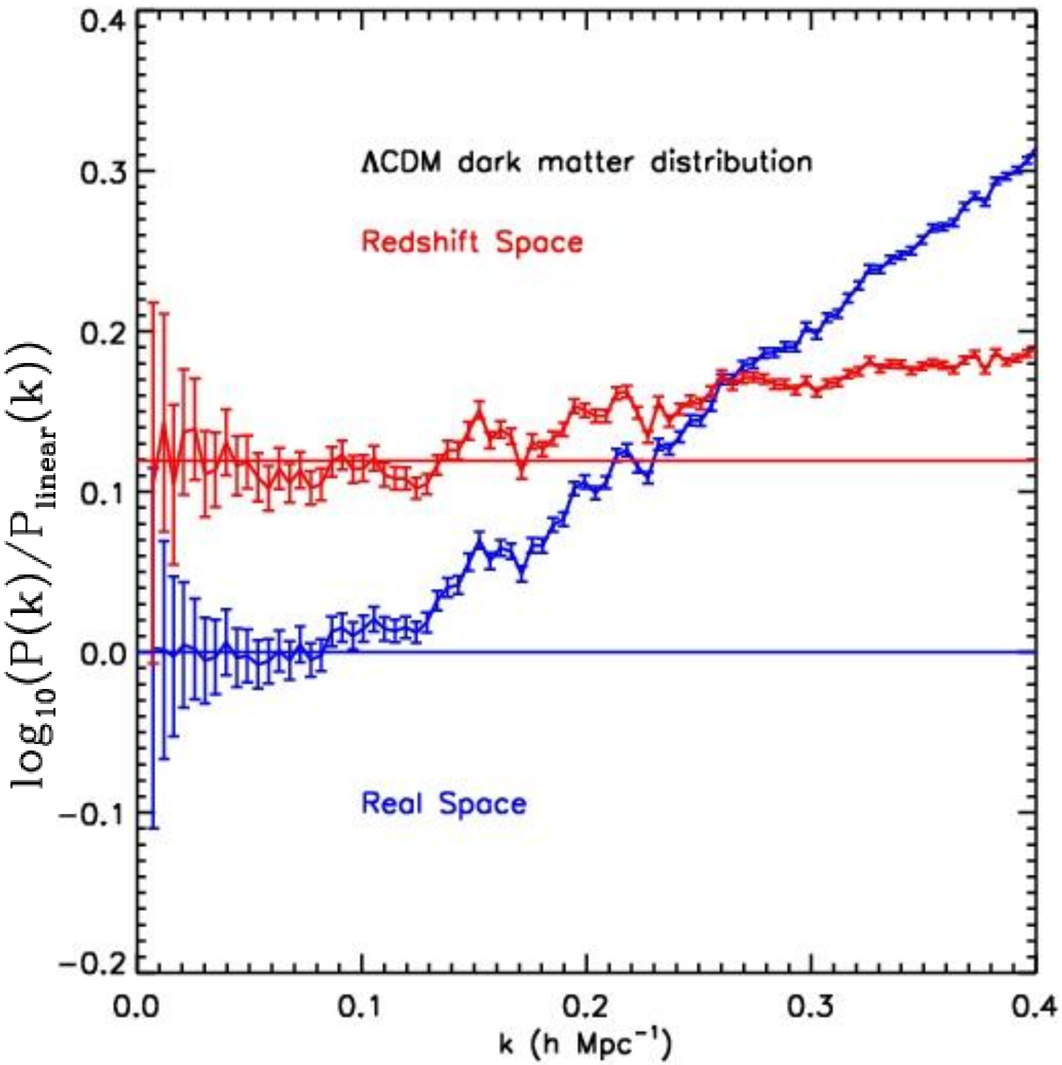
Non-linear evolution of matter fluctuations



Log $(P(k)/P_{linear}(k))$
at z=0

Angulo, Baugh, Frenk & Lacey '08

Redshift space distortions



Peculiar motions distort clustering pattern

Coherent bulk flows boost large scale power (Kaiser 1987)

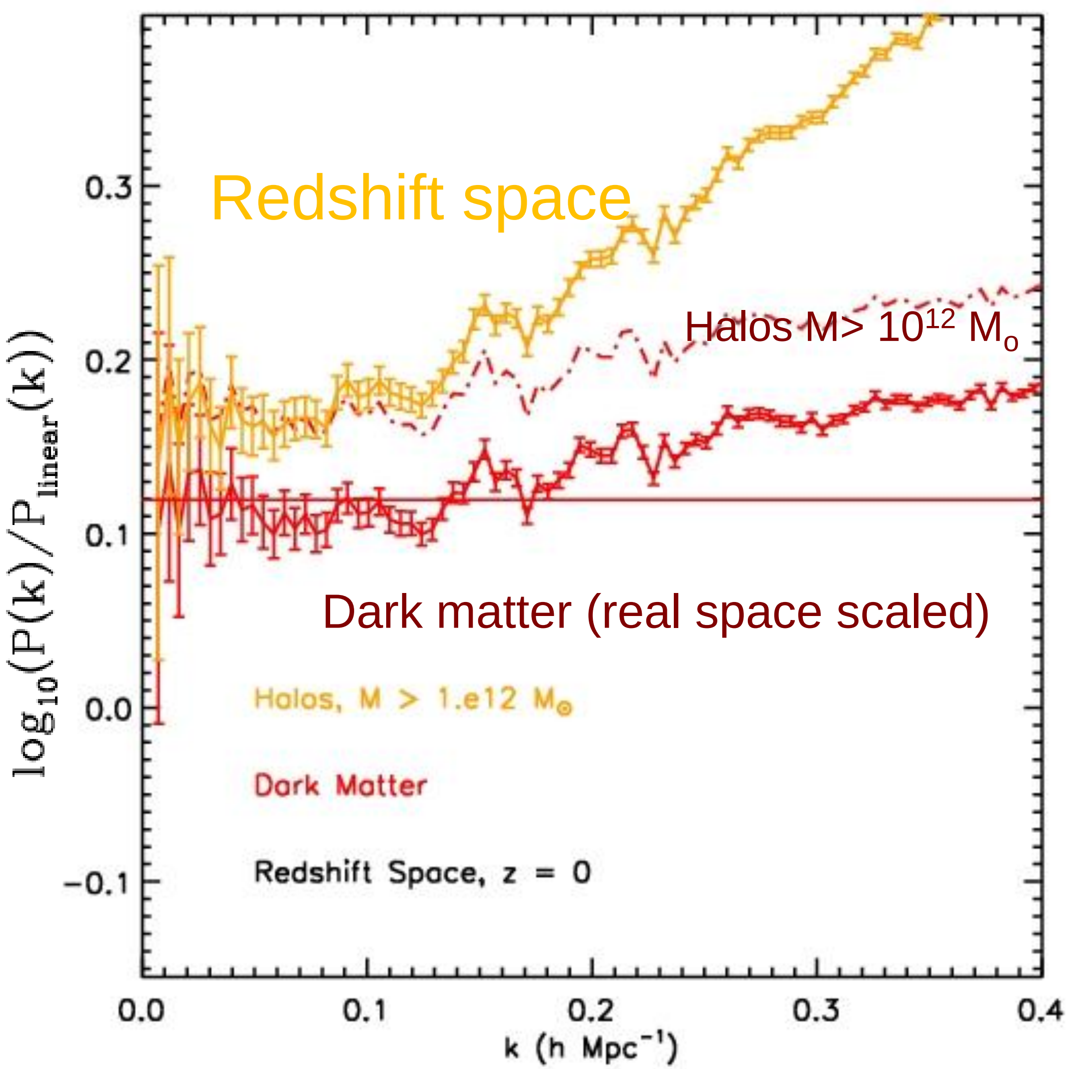
Kaiser (1987) related the spherically averaged power spectrum measured in redshift (P_s) and that in real space (P):

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

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

Motions of particles inside virialised structures damp power at high k

Redshift space distortions



Peculiar motions distort clustering pattern

Boost in power on large scales due to coherent flows

Damping at higher k affects DM but not the halos

In z-space, halo bias is scale-dependent

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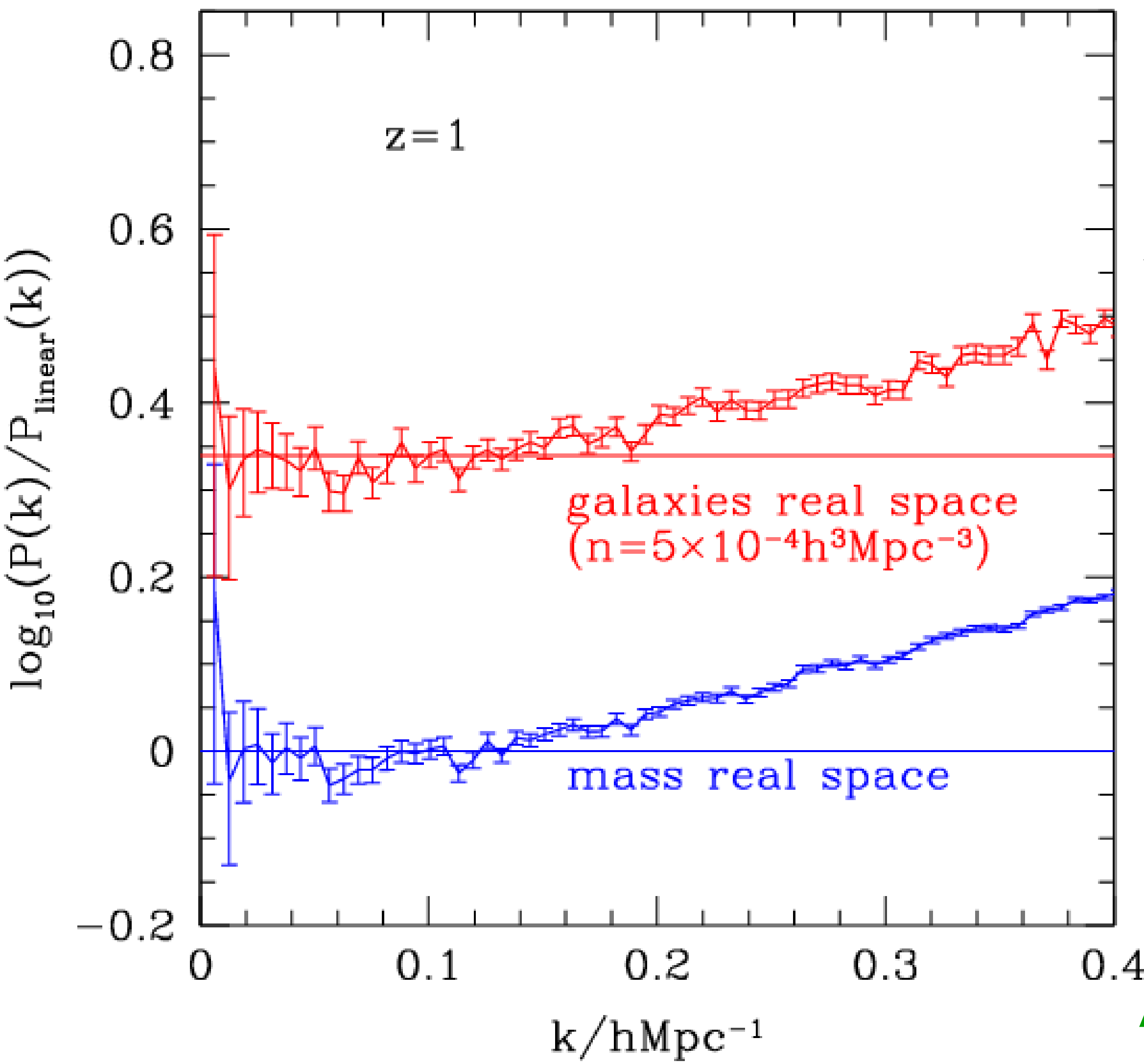
Galaxy bias in real space



Absolute Magnitude limited sample.

Galaxy clustering boosted relative to mass in real space

Angulo, Baugh, Frenk & Lacey ‘07

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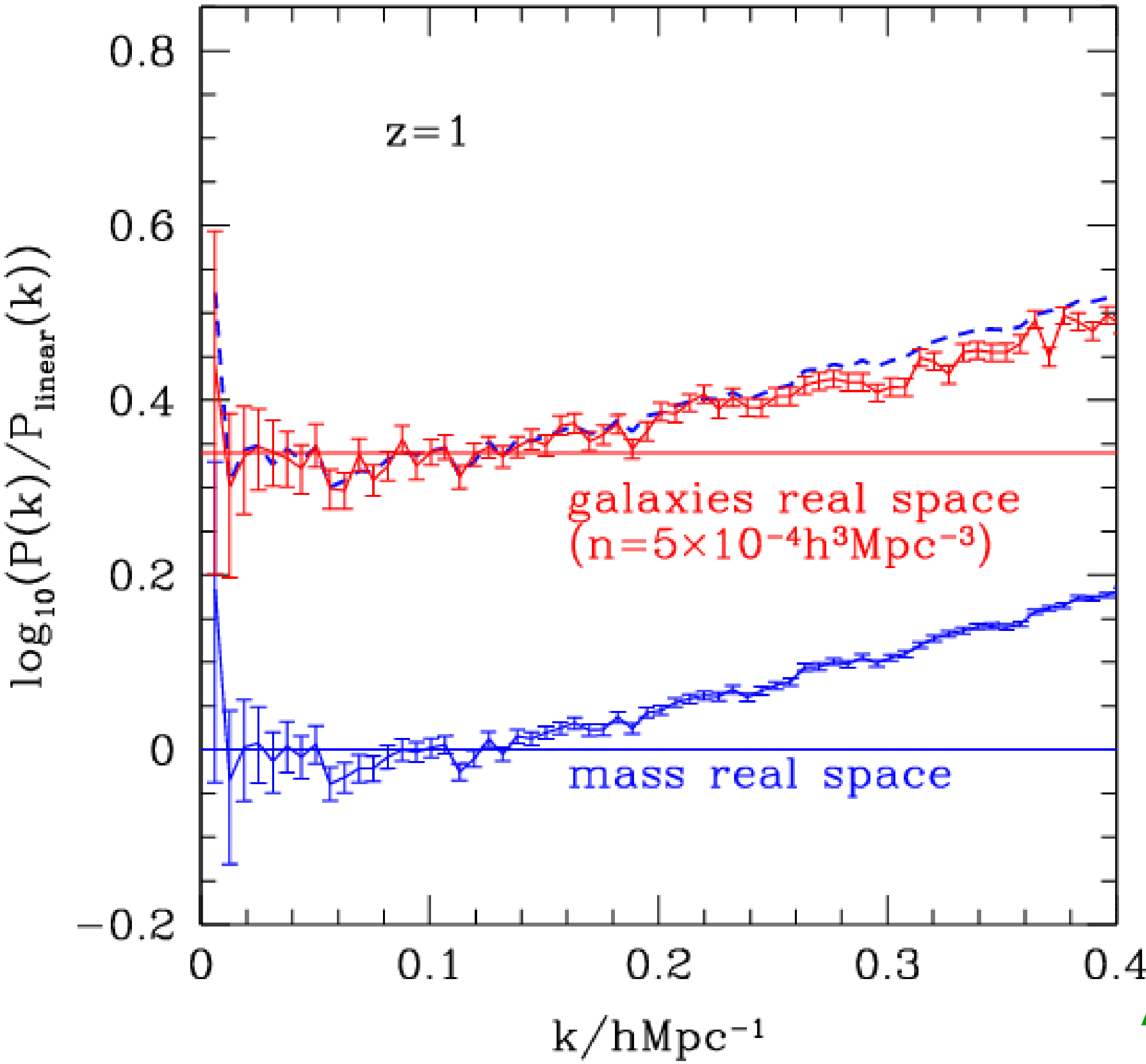
Galaxy bias in real space



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

Angulo, Baugh, Frenk & Lacey '08

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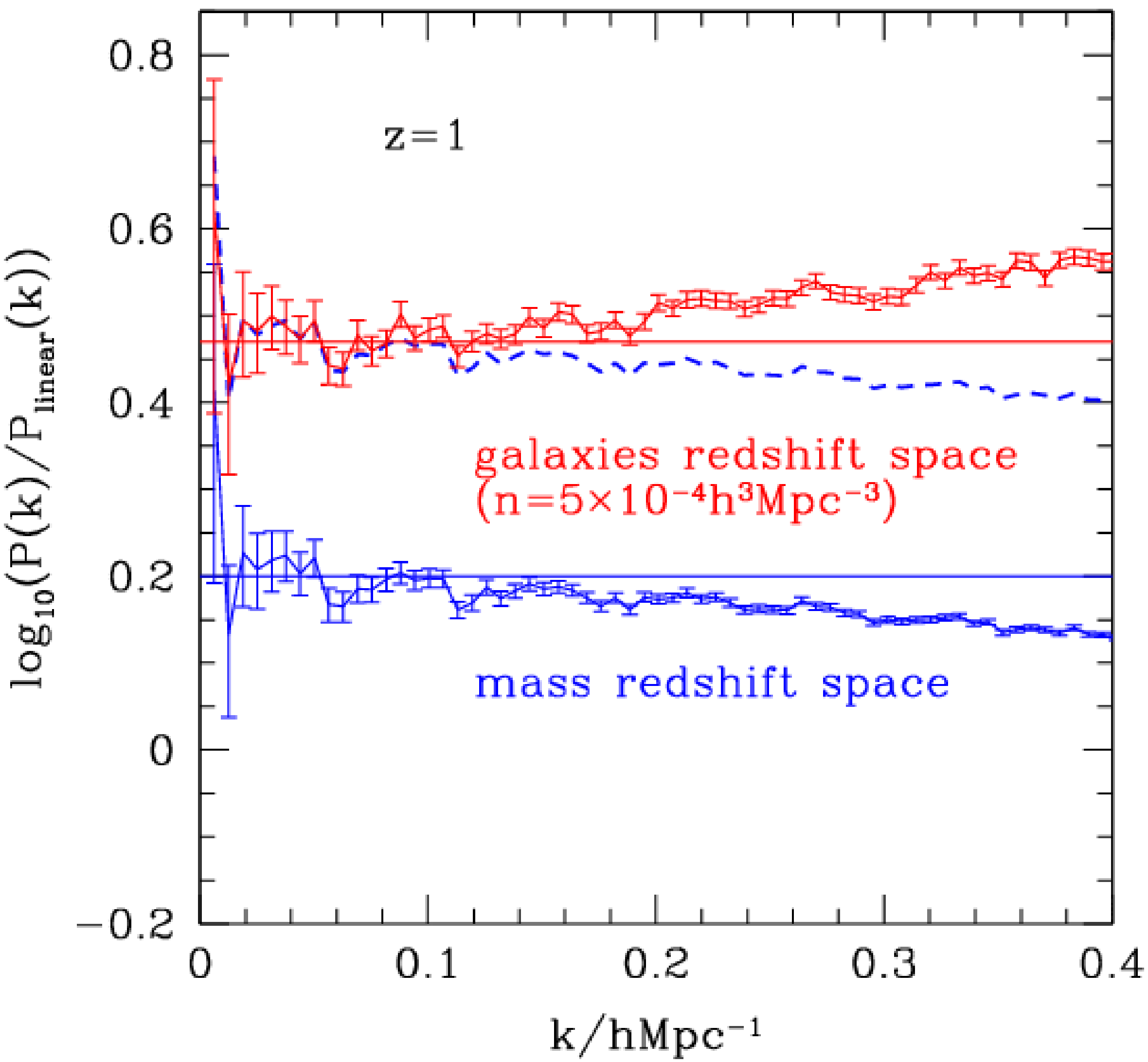
Galaxy bias in redshift space



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

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

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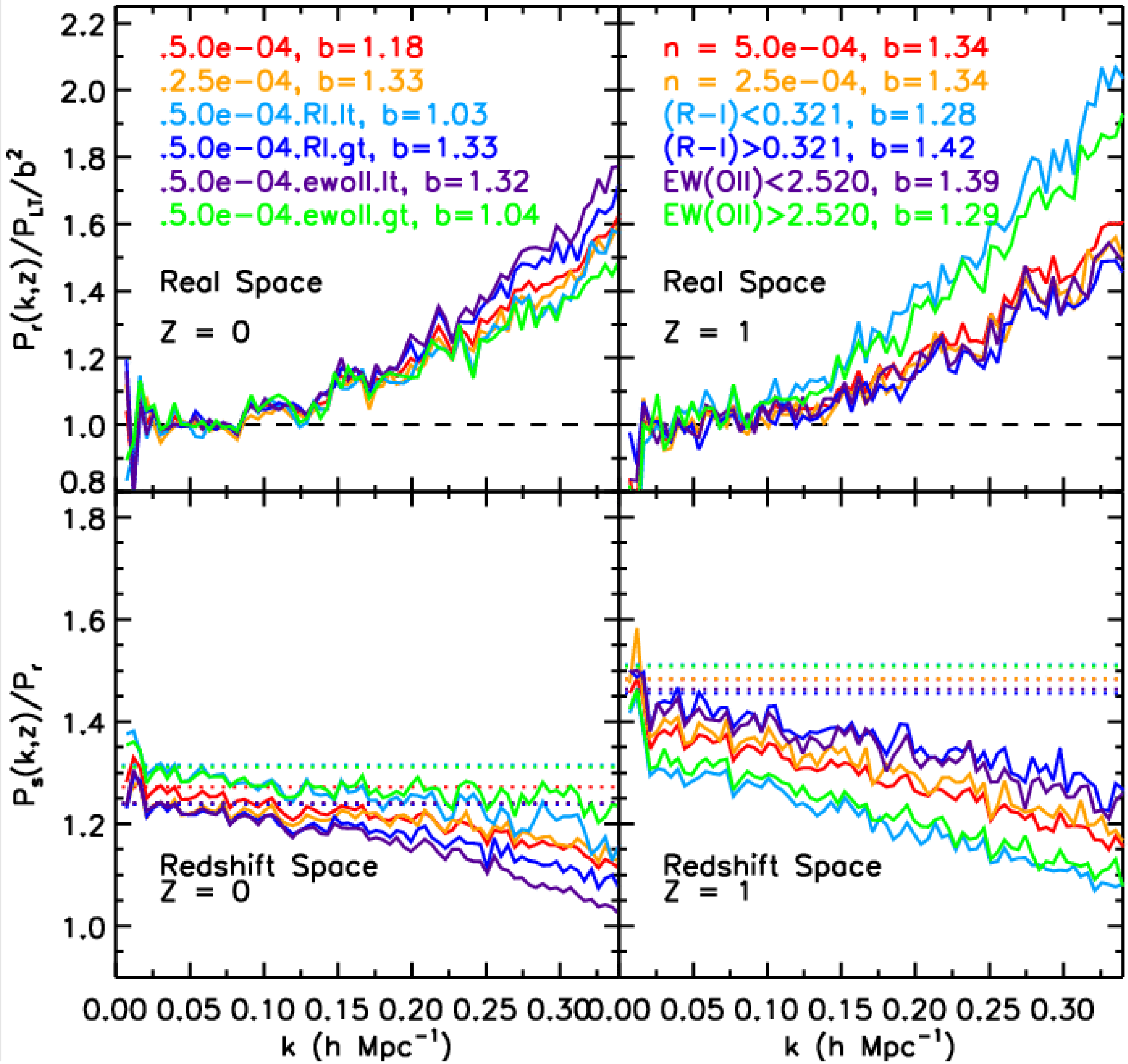
Galaxy bias in redshift space



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

Angulo et al '08

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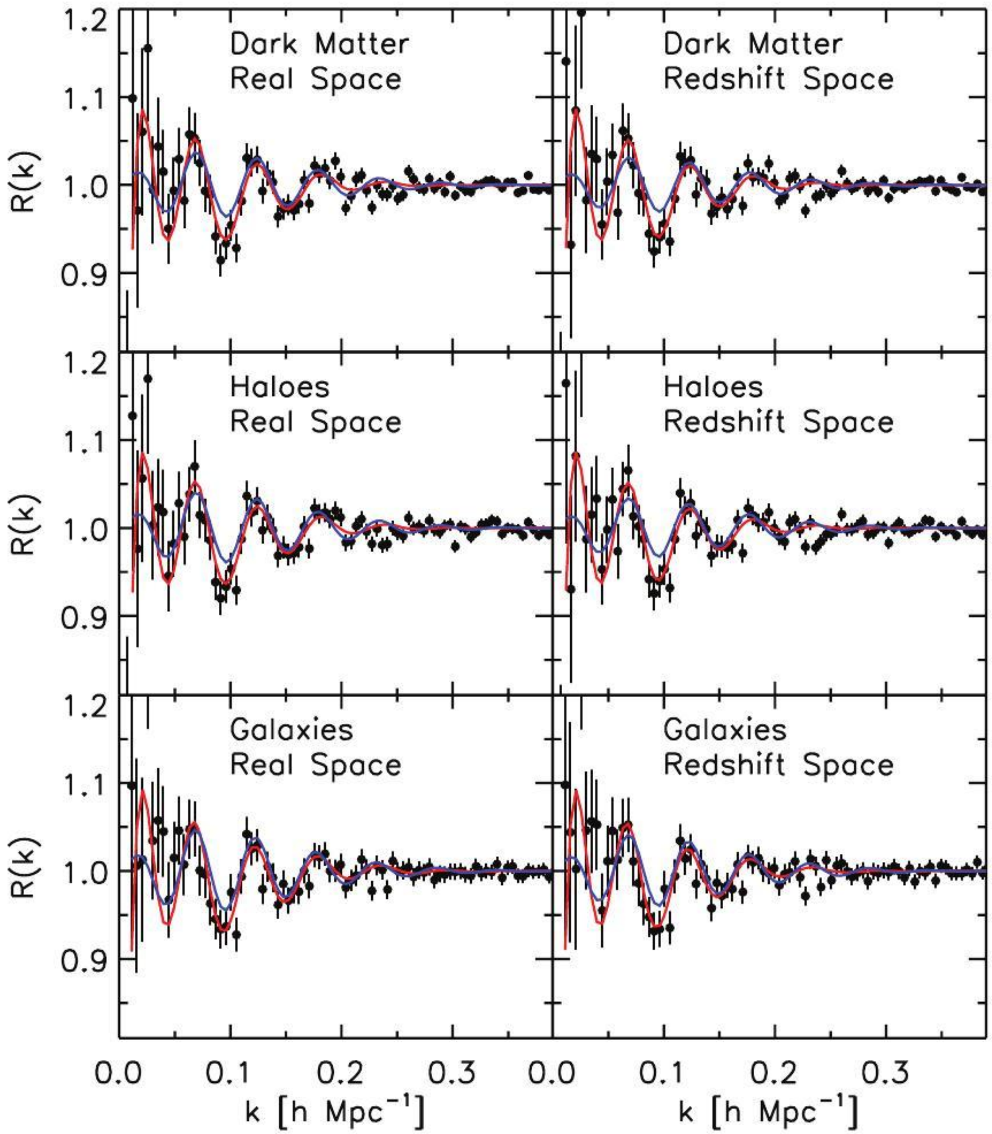
Fit BAO oscillations

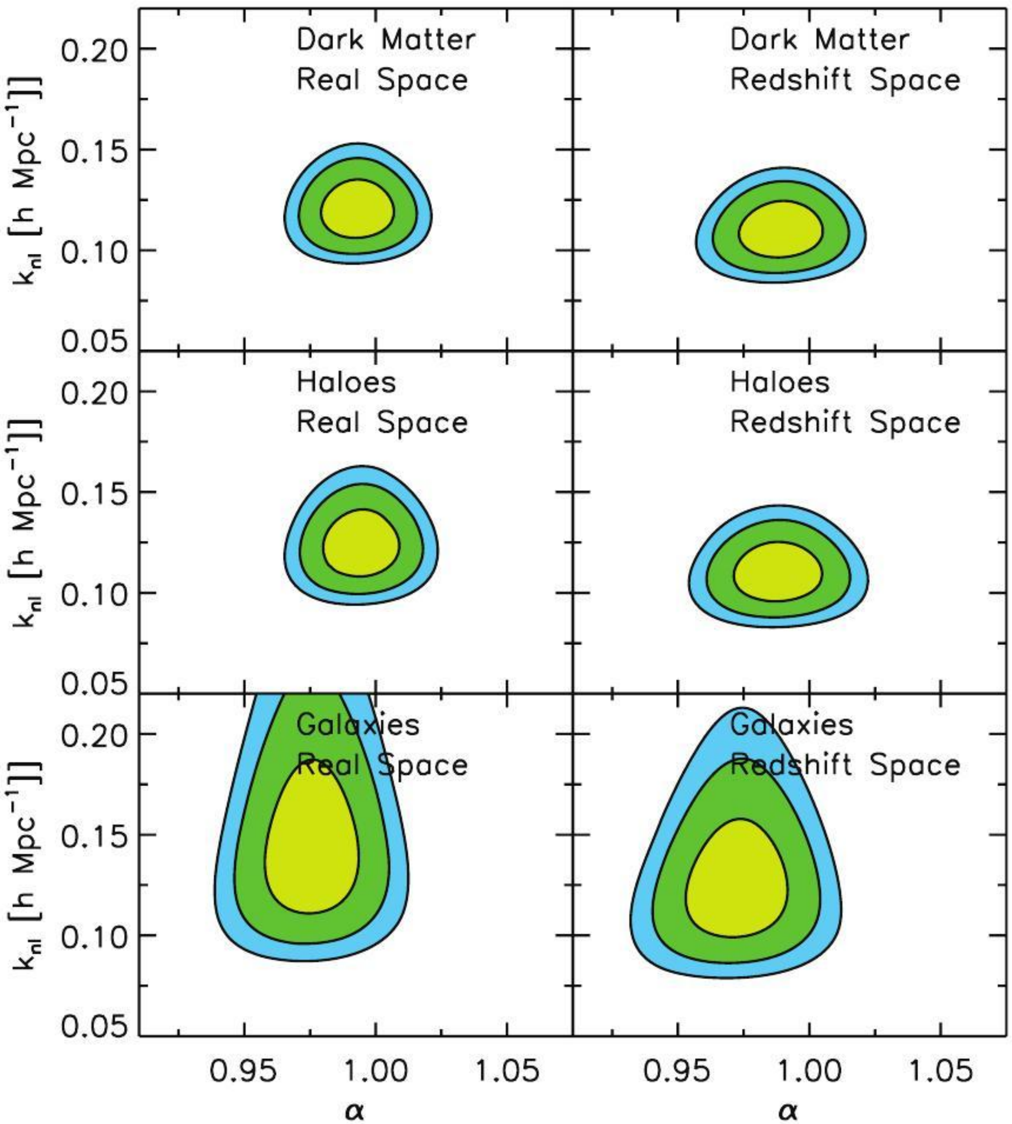


Remove effect of scale dependent bias by fitting a smooth spline and then take ratio $R(k)=P(k)/P_{smooth}(k)$.

Fit ratio, R(k), to determine both the stretch factor, α, and the damping scale, k_{nl}.

(Percival et al 2008)

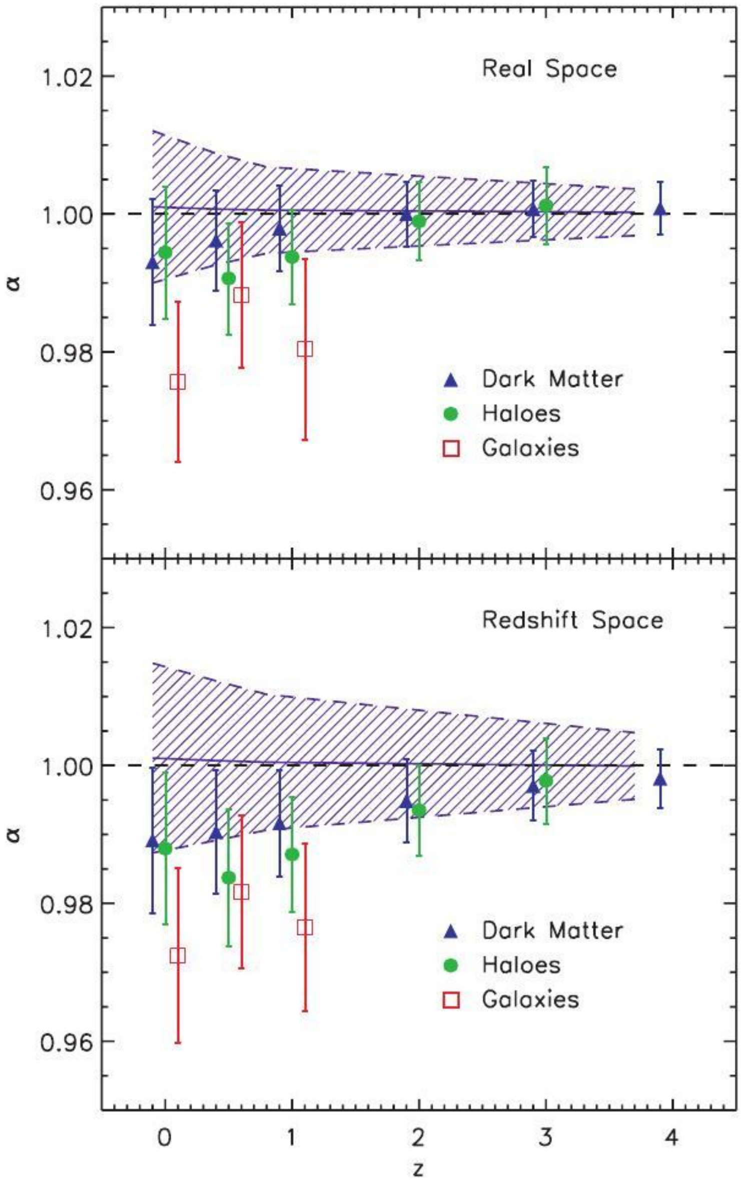
Recovered values



k_{nl} treated as a nuisance parameter.

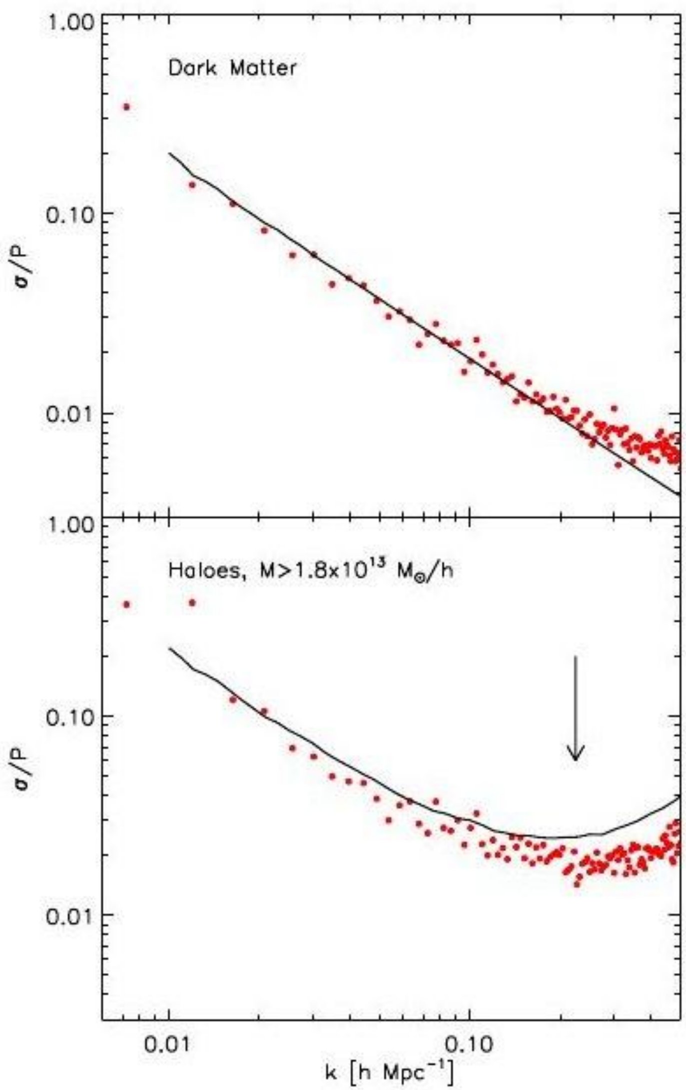
Small offsets in α, but are they significant?

Sample Variance



- 50 lower resolution "L-BASICC" simulations used to determine the sample variance.
- Particle mass 30 times larger.
- Bias not significant

Fractional error in P(k)



$$\frac{\sigma}{P} = \sqrt{\frac{2}{n_{\rm modes}}}\left(1 + \frac{1}{P\bar{n}}\right)$$

$$n_{\rm modes} = V4\pi k^2 \delta k / (2\pi)^3$$

(Feldman, Kaiser & Peacock 1994)

Survey Forecasts

Angulo et al (2008) tabulate rms error in α for different fiducial samples within the BASICC simulation

	Sel I	Sel II	Real-space						Redshift-space					
id	$\bar{n}$ $h^3\mathrm{Mpc}^{-3}$		b	$\bar{n}P$	$k_{\rm nl}$ h/Mpc	α	$\Delta\alpha$ %	$\Delta\alpha$ % (SE07)	b	$\bar{n}P$	$k_{\rm nl}$ h/Mpc	α	$\Delta\alpha$ %	$\Delta\alpha$ % (SE07)
DM			0.99	3567	0.120	0.993	0.91	1.02	1.15	3635	0.110	0.989	1.05	1.17
A	$5.0e-4$		1.18	1.78	0.144	0.975	1.16	1.10	1.32	2.15	0.125	0.972	1.26	1.23
B	$2.5e-4$		1.33	1.11	0.155	0.971	1.34	1.18	1.47	1.34	0.139	0.966	1.35	1.23
C	$2.5e-4$	red	1.32	1.15	0.152	0.978	1.35	1.21	1.46	1.36	0.127	0.975	1.49	1.37
D	$2.5e-4$	strong	1.06	0.67	0.155	0.956	1.75	1.41	1.20	0.86	0.138	0.956	1.67	1.42
E	$2.5e-4$	blue	1.03	0.66	0.141	0.964	1.92	1.56	1.17	0.83	0.130	0.962	1.79	1.53
F	$2.5e-4$	weak	1.30	1.16	0.132	0.980	1.55	1.40	1.44	1.34	0.115	0.972	1.66	1.54
haloes	$5.9e-5$		1.56	0.81	0.197	0.980	1.32	1.07	1.71	1.04	0.148	0.975	1.43	1.25

Table 2.2: The results of applying the general fitting procedure described in §2.4 to power spectra measured for different galaxy catalogues

Error on the measured power

BAO method: virtually free of systematics (c.f. lensing, SNIa)

(i) Sample variance

(ii) Shot noise

P = power

n = mean no density

$$\frac{\sigma}{P} = \sqrt{\frac{2}{n_{\rm modes}}}\left(1 + \frac{1}{P\bar{n}}\right)$$

$$n_{\rm modes} = V 4\pi k^2 \delta k / \left(2\pi\right)^3$$

Scaling error forecasts to different surveys:

delta(w) ~ 1/sqrt (V) x [1 + 1/(n P)]

Main future BAO surveys

Name	$N(z) / 10^6$	Stretch	Dates	Status
SDSS/2dFGRS	0.8	3.5%	Now	Done
WiggleZ	0.4	2%	2007-2011	Running
FastSound	0.6	2.8%	2009-2012	Proposal
BOSS	1.5	1%	2009-2013	Funded
HETDEX	1	1.5%	2010-2013	Part funded
WFMOS	>2	0.8%	2013-2016	Part funded
ADEPT	>100	0.2%	2012+	JDEM
EUCLID	>100	0.15%	2017+	ESA
SKA	>100	0.2%	2020+	Long term

IDECS

Original Peacock 2008

Future photo-z BAO surveys

Name	N(z) / 10^6	Stretch	Dates	Status
PS1	>100	0.6%	2009-2013	Funded
DES	50	<1%	2010-2014	Funded
PAU(BAO)	14	0.4%	2014+	planned

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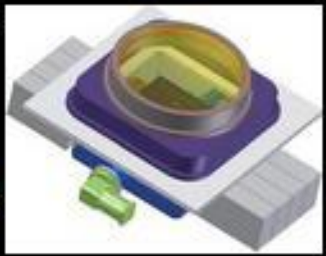
Dangers from space

Learn about the threat to Earth from asteroids & comets and how the Pan-STARRS project is designed to help detect these NEOs.

Learn more...

1,400,000,000 pixels

Pan-STARRS will have the world's largest digital cameras.



Read about them here...

The PS1 Prototype

PS1 consortium formed...

First light achieved!

More about PS1 here...

Image Gallery here...

Construction photos here ...

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Pan-STARRS

PS1 Science Consortium

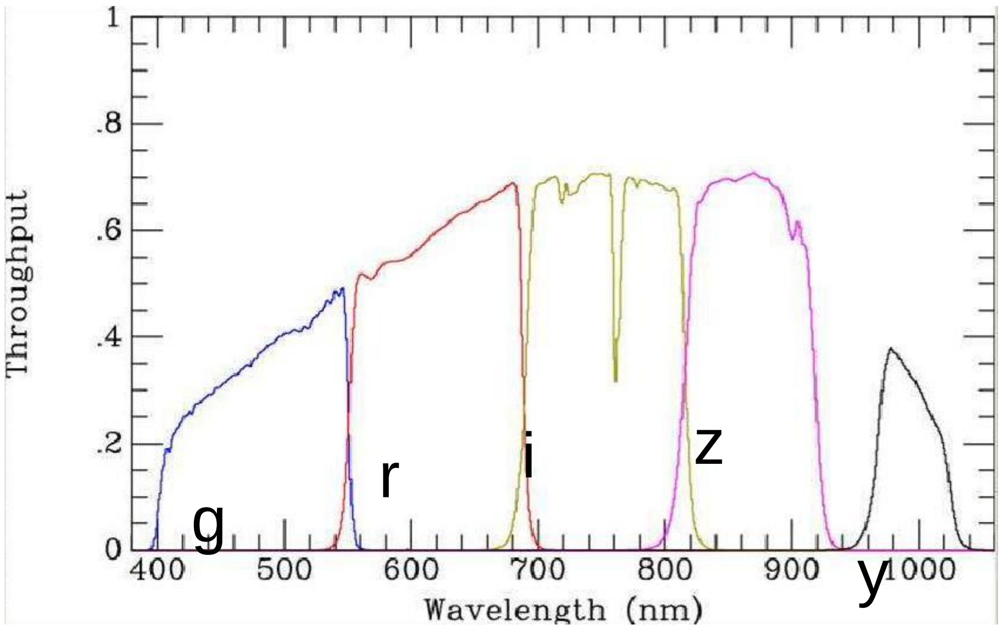
Panoramic **S**urvey **T**elescope & **R**apid **R**esponse **S**ystem

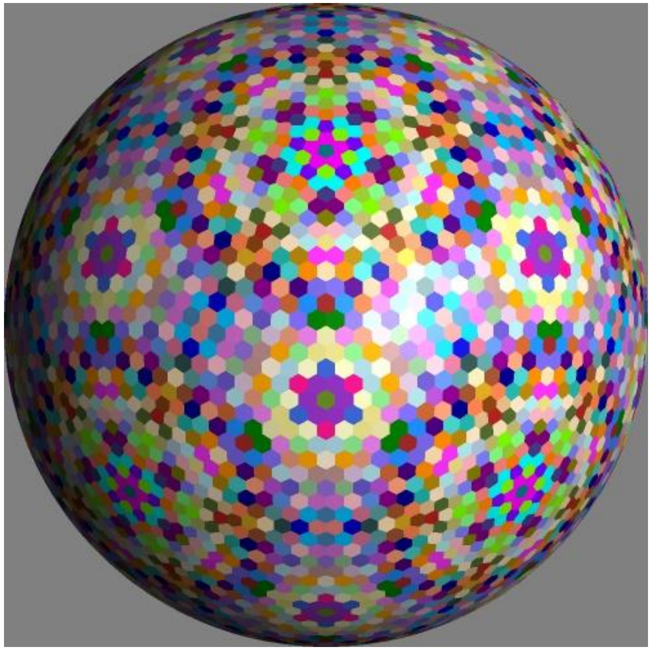
PS1 consortium members

University of Hawai'i · UH Institute for Astronomy · Max Planck Institute for Extraterrestrial Physics · Max Planck Institute for Astronomy · Johns Hopkins University Department of Physics and Astronomy · Harvard-Smithsonian Center for Astrophysics · Queen's University, Belfast · University of Edinburgh · Durham University Institute for Computational Cosmology · National Central University, Taiwan · Las Cumbres Observatory Global Telescope Network

Pan-STARRS1 3π Survey

Filter	Bandpass (nm)	m_1 AB mag	μ AB mag/arcsec ^{2}	exposure time in 1st yr (3π) sec	5σ pt. source in 1st yr (3π)	5σ pt. source in 3rd yr (3π)
g	405-550	24.90	21.90	60× 4	24.04	24.66
r	552-689	25.15	20.86	38× 4	23.50	24.11
i	691-815	25.00	20.15	60× 4	23.39	24.00
z	815-915	24.63	19.26	30× 4	22.37	22.98
y	967-1024	23.03	17.98	30× 4	20.91	21.52





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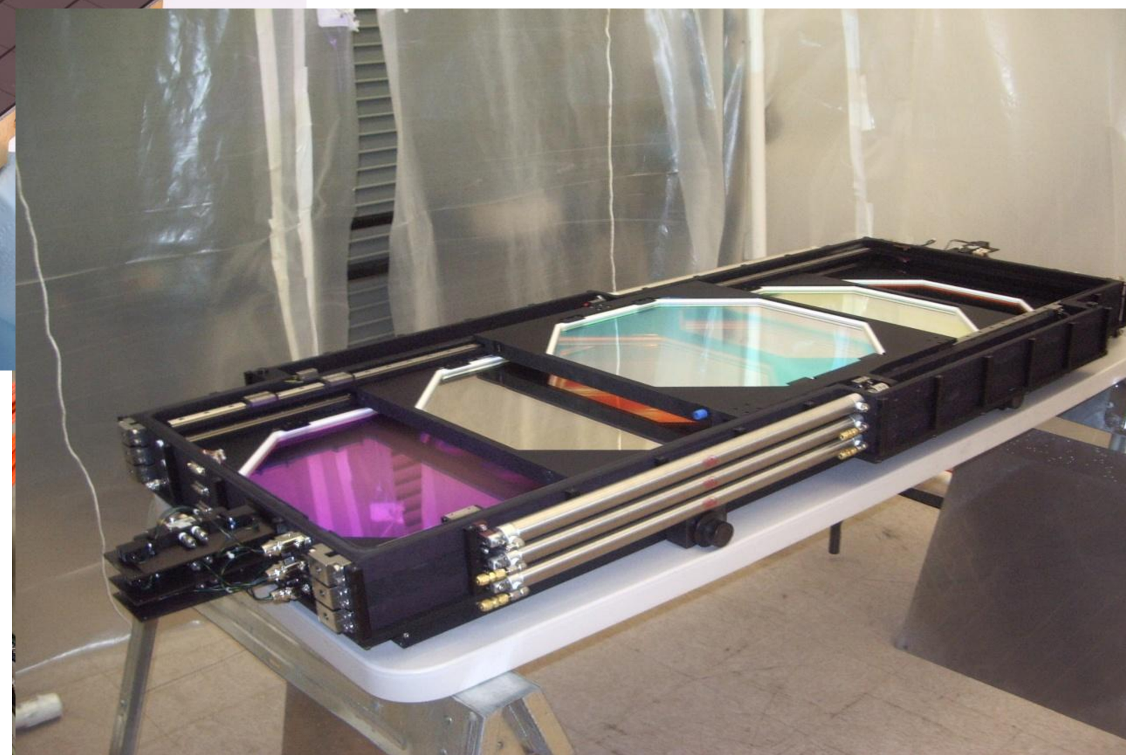
Telescope on Haleakala, Hawaii

60 OTC CCDS each

with 64 cells individually

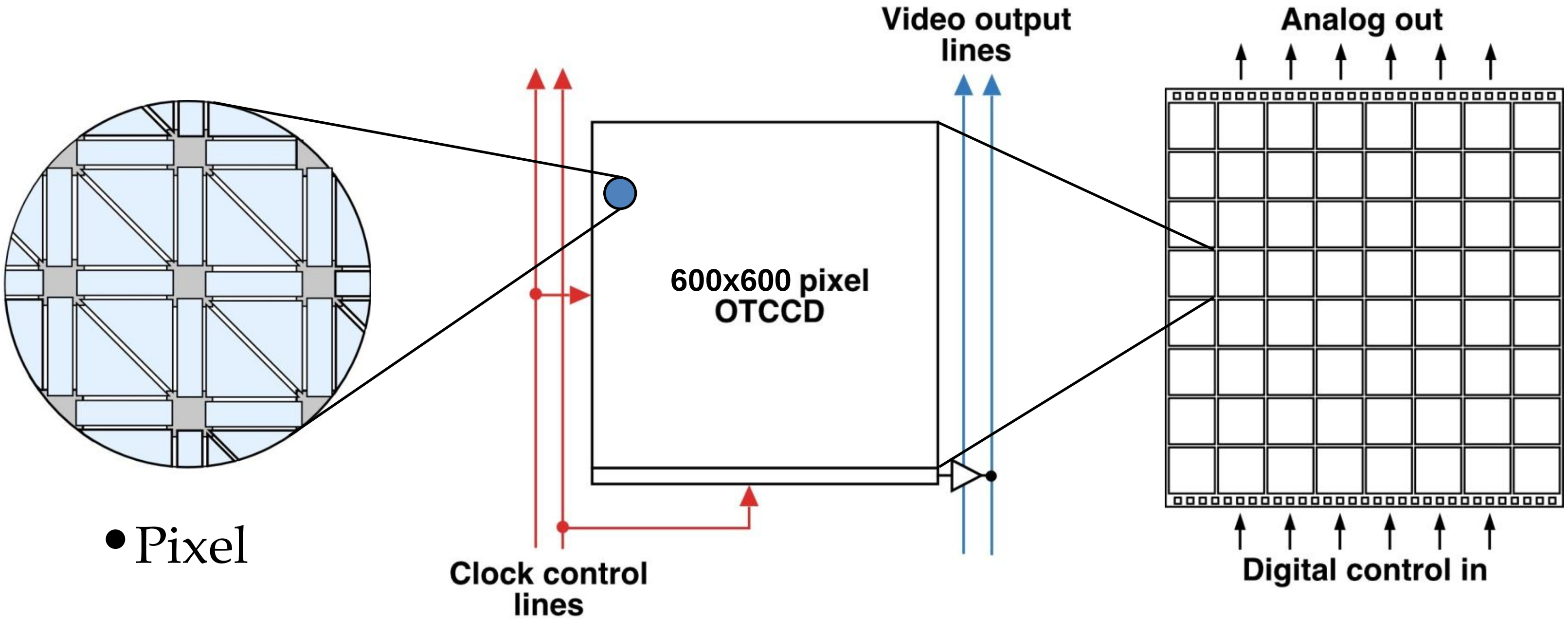
readable cells



1.4 Gpixel Camera

7 sq deg FoV

OTC cells

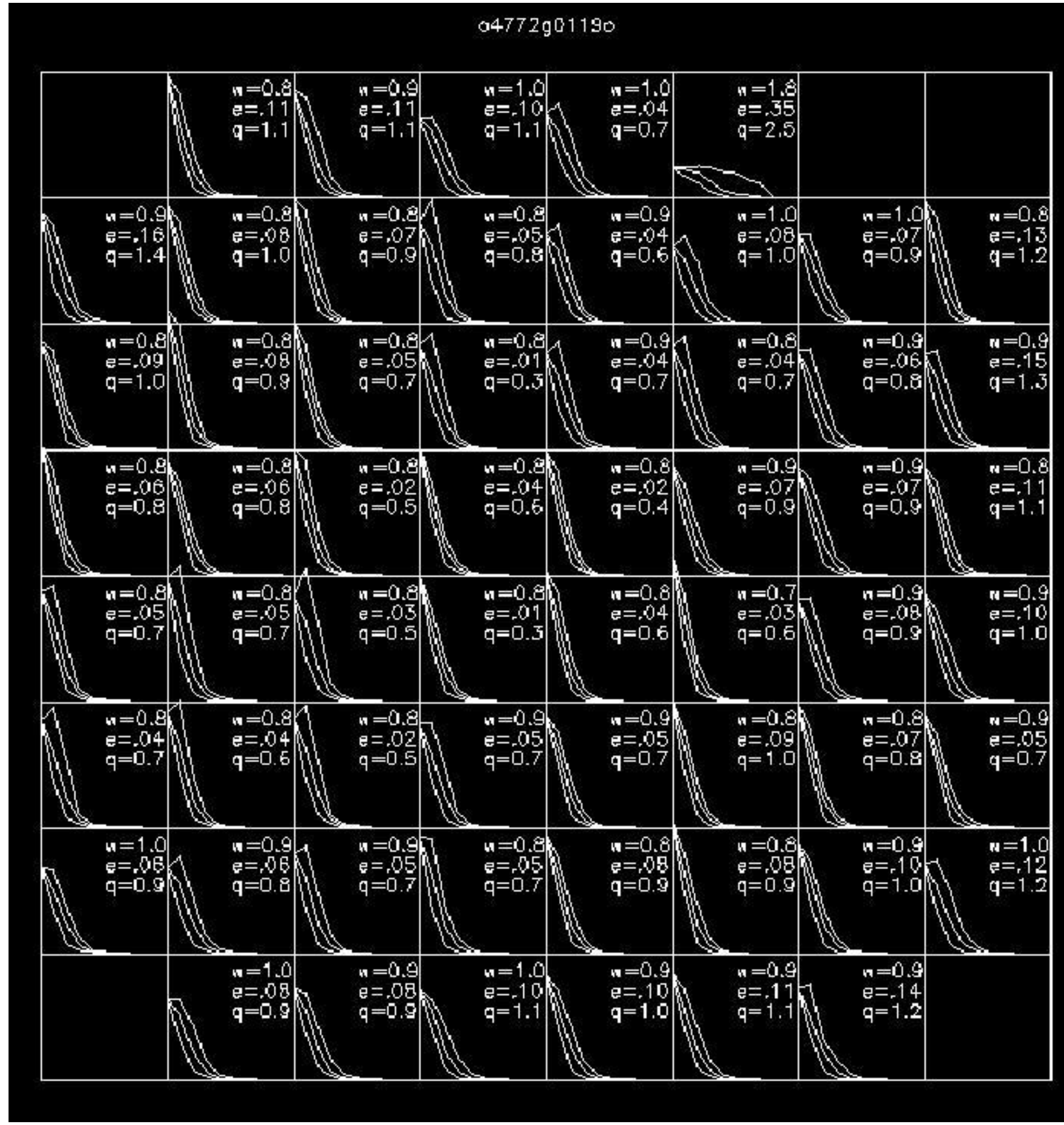


- Pixel
- structure

- OTA:
- 8x8 Array of Cells
- Pixel size 0.26 arc sec

Image Quality

Achieved image quality on all 60 CCDs of better than 1 arc sec



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PS1SC

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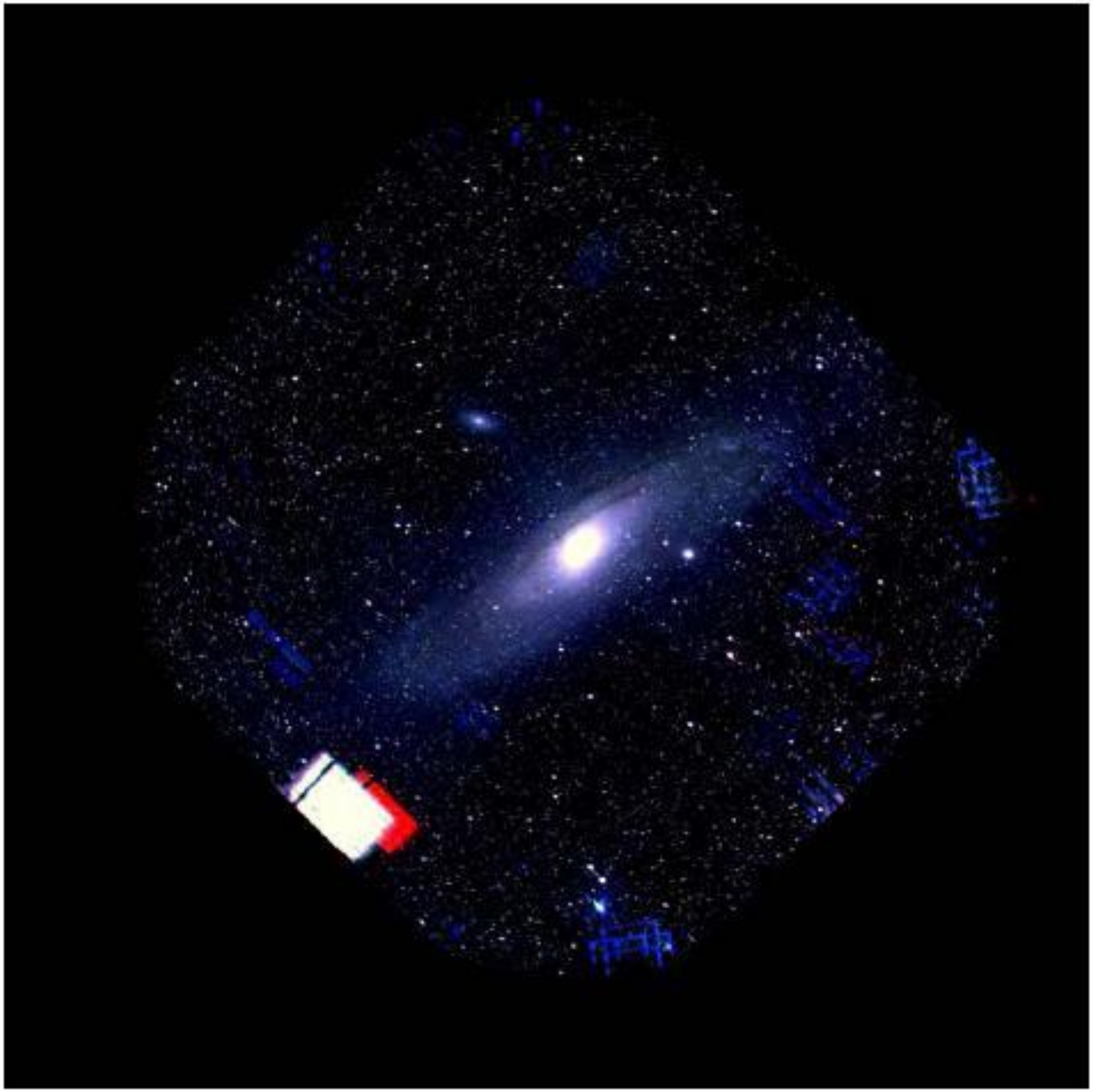
Single
Gpixel
Camera
Image
of M31

(also M51)



PS1SC

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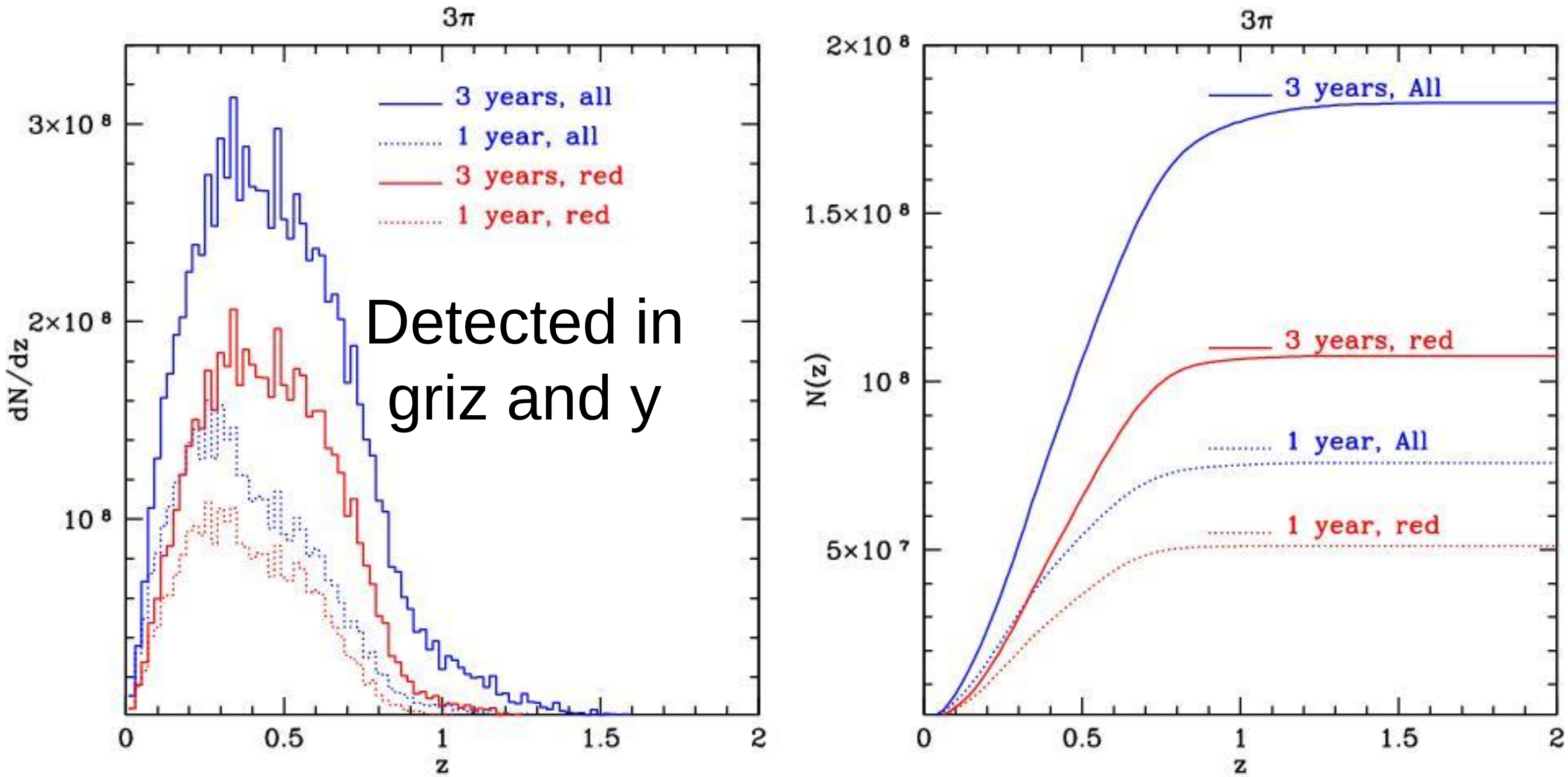
3π size and depth



Cai et al (2009)

More than 10^8 galaxies!

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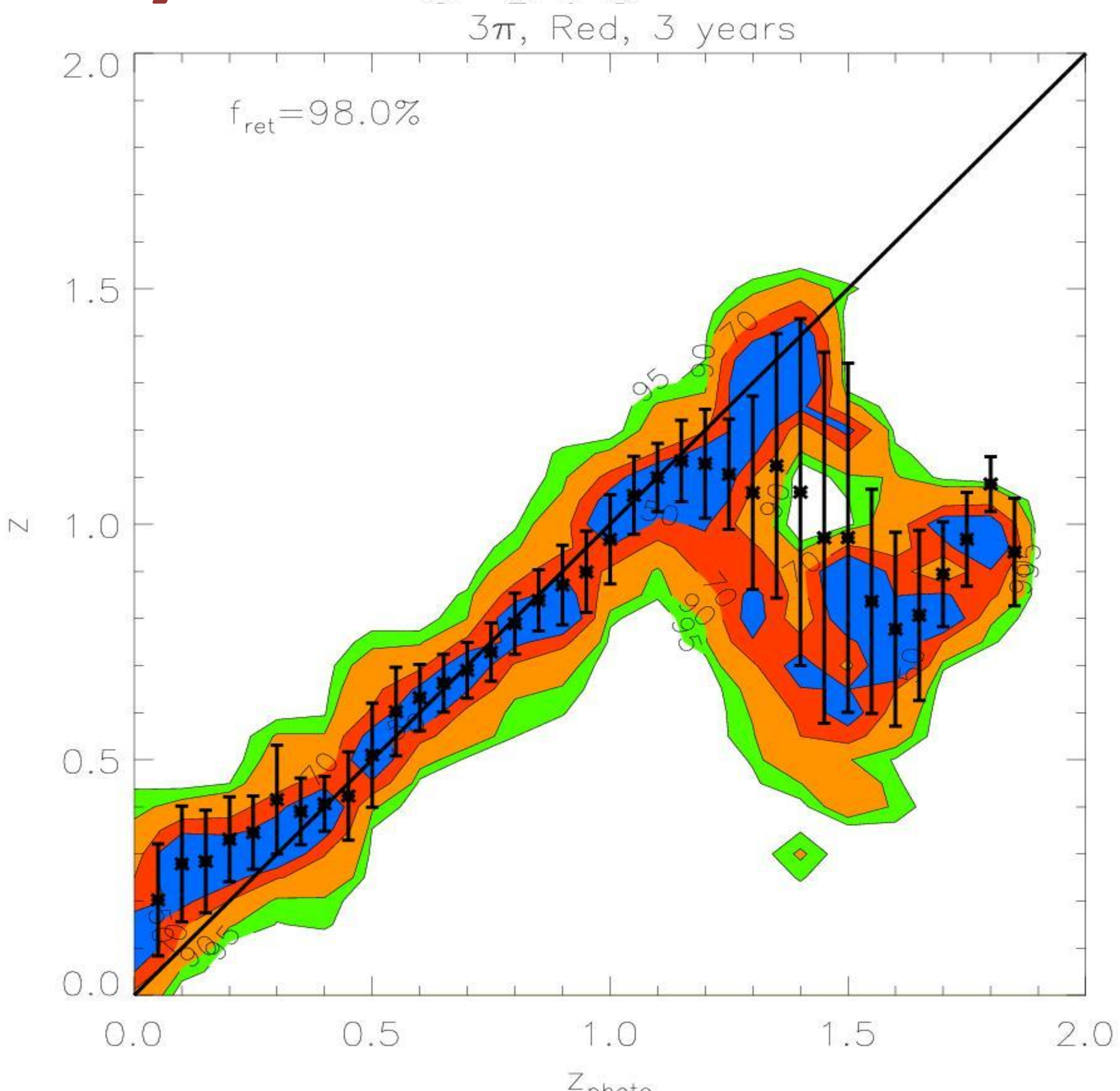
Photo-z accuracy

Initial estimates indicate that for red/early type galaxies

$$\sigma_z/(1+z) < 0.04$$

Cai et al (2009)



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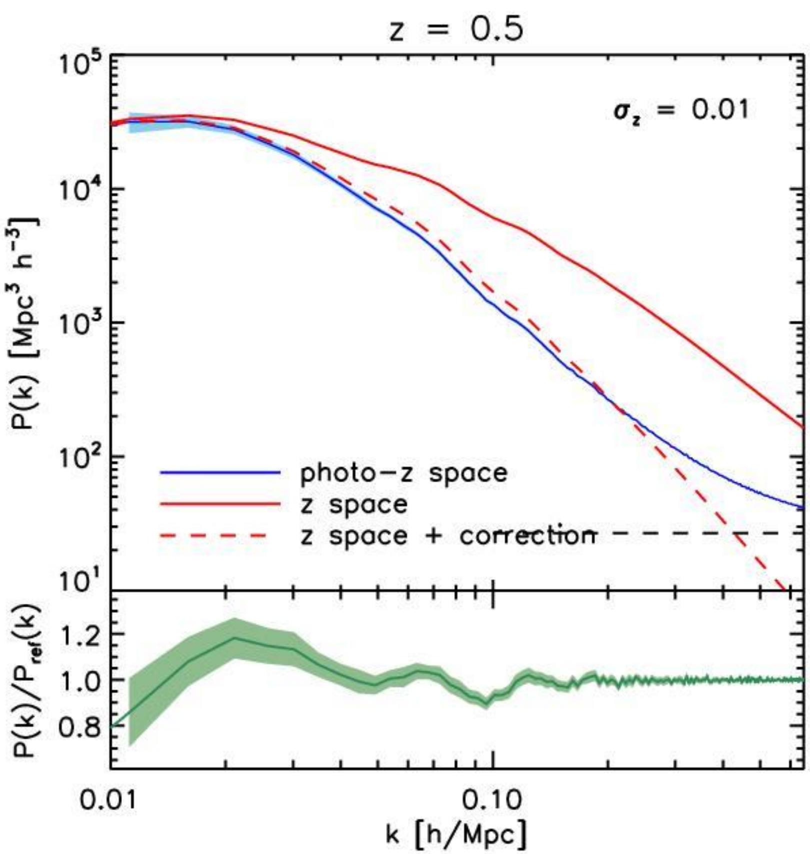
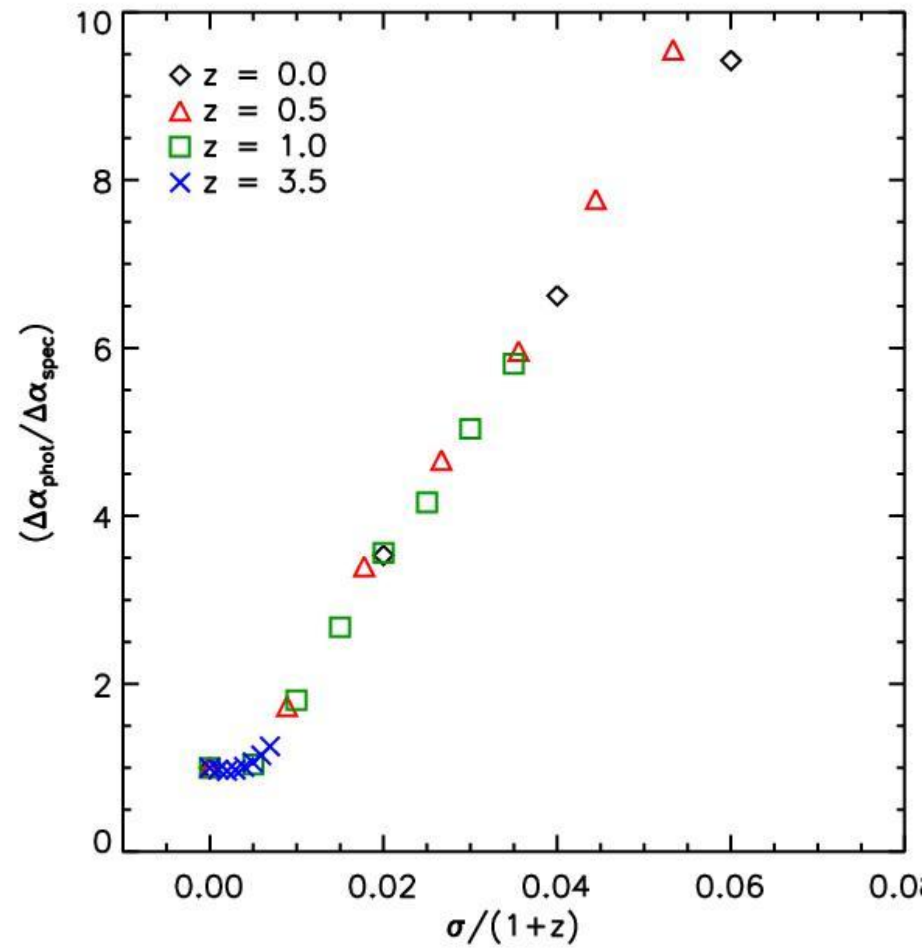
Damping effect on BAO

$$\delta_{\rm pz}(\underline{k}) = \delta_{\rm z}(\underline{k})\ \exp(-0.5 k_{\rm z}^2\ \sigma_{\rm z}^2)$$



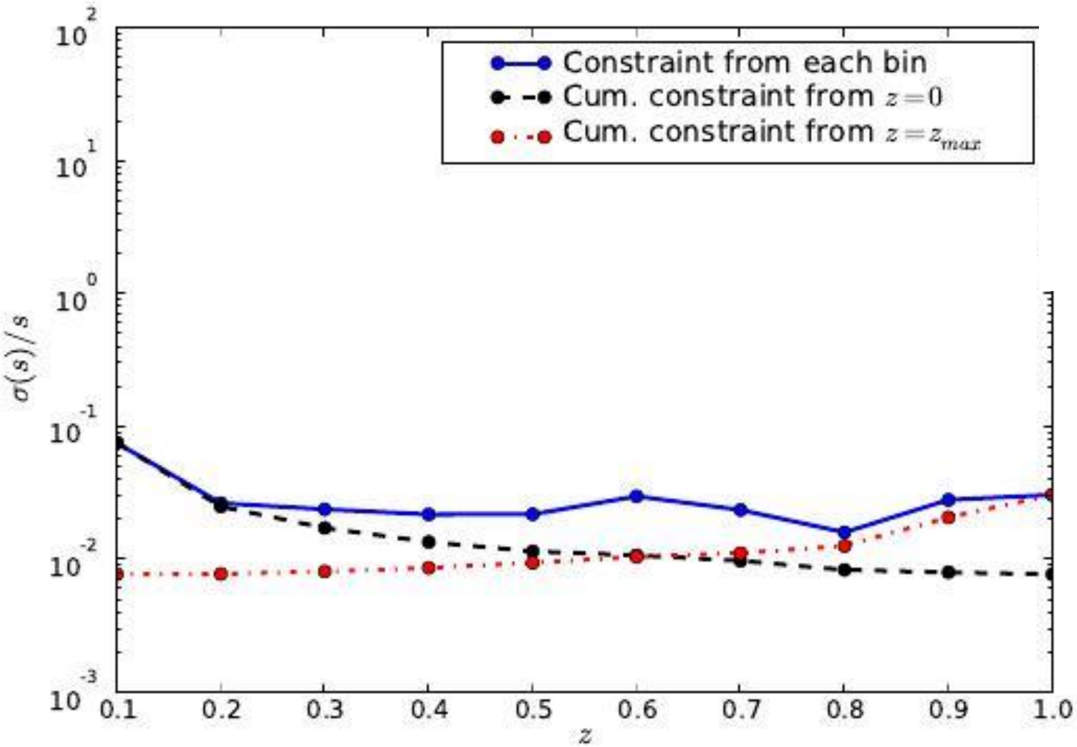


Yan-chuan Cai et al (2008)

Analysis Methods

Angular power spectra for 10 tomographic photo-z bins

$$C_\ell^{\alpha\beta} = b_g^\alpha b_g^\beta \int_0^\infty dz \left(\frac{d\chi}{dz}\right)^{-1} \frac{W_\alpha(z)\, W_\beta(z)}{d_A^2(z)} P\left(\frac{\ell}{d_A(z)}, z\right)$$



$$F_{pq} = \sum_{i=1}^{N_\ell} \frac{(2\ell_i + 1)\Delta\ell_i f_{\rm sky}}{2} \mathrm{Tr}\left[\mathbf{C}_{\ell_i}^{-1} \frac{\partial \mathbf{C}_{\ell_i}}{\partial p} \mathbf{C}_{\ell_i}^{-1} \frac{\partial \mathbf{C}_{\ell_i}}{\partial q}\right]$$

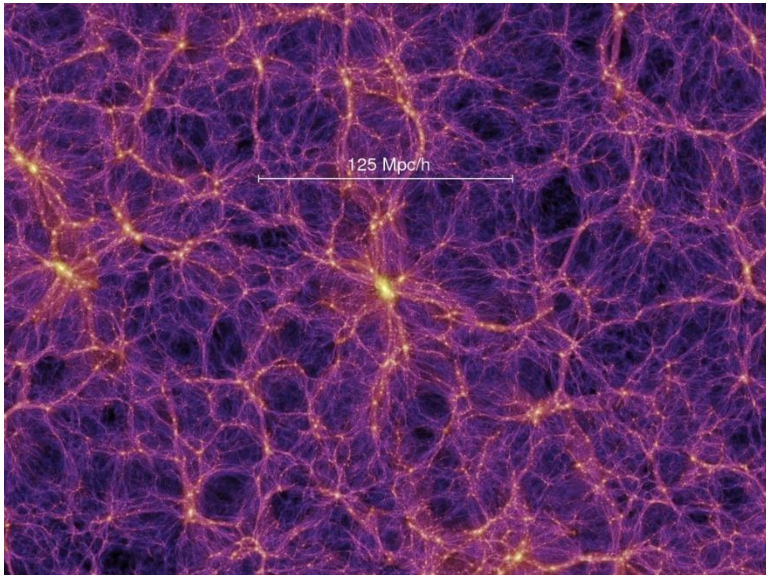
$$[\mathbf{C}_\ell]_{\alpha\beta} \equiv C_\ell^{\alpha\beta} + \frac{\delta_{\alpha\beta}}{\bar{N}_\alpha},$$

Linear theory forecast for red galaxies over 2pi steradians

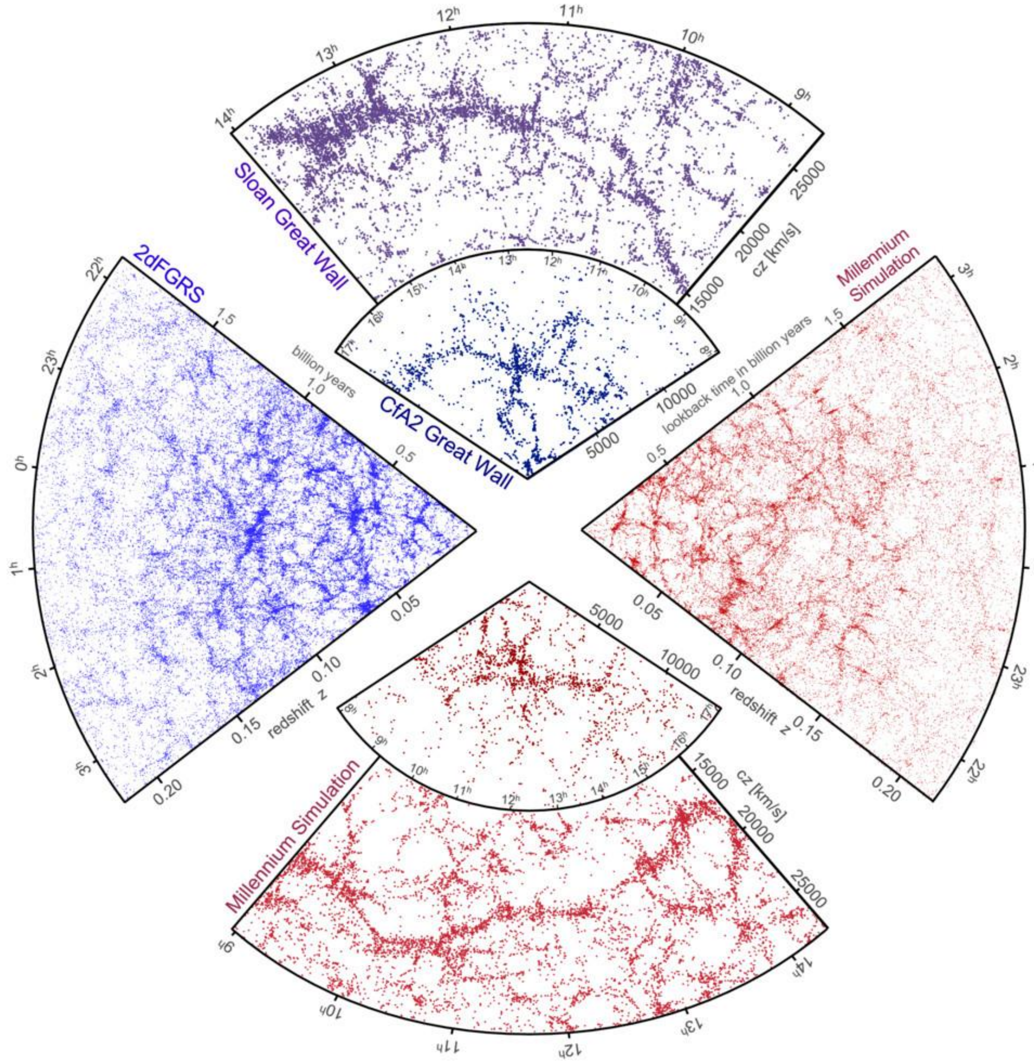
σ(s)/s=0.8%

Michael Schneider

Mock Lightcone catalogues

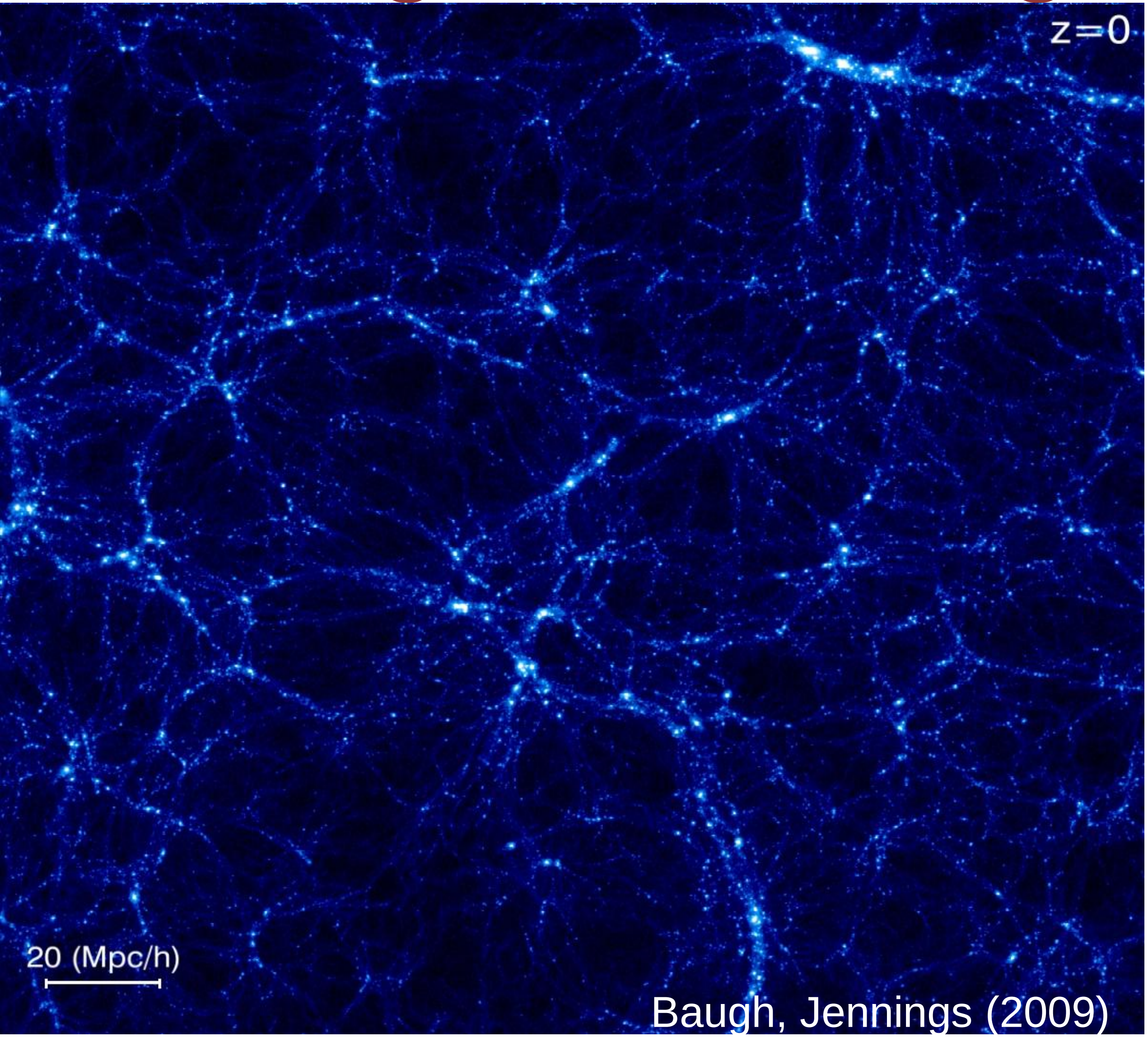


Millennium simulation not large enough to accommodate the new larger generation of surveys and WMAP1 cosmology



Springel etal 05

Mock Lightcone catalogues



New "Big Simulation"

With 8xVolume

$l_{box} = 1h^{-1}\text{Gpc}$

$n_{part} = 2200^3$

And "WMAP5+" cosmology

Ω_m=0.26

Ω_Λ=0.74

σ_8=0.8

n_s=0.96

Sanchez et al (2009)

Summary

- BAO have an important future as a cosmic standard ruler used to constrain $r_c(z)$ and hence Dark Energy.
- Systematic errors are not yet dominant, but more theoretical work is needed to ensure this remains true for the forthcoming generation of surveys
- In advance of the long term space projects, photo-z surveys, not least Pan-STARRS, promise interesting constraints