Cosmology Overview

Roman Scoccimarro (NYU)

Outline

- Summary of current cosmological constraints

- Cosmic Acceleration and Inflation

- Cosmic Acceleration: Dark Energy or Modified Gravity?

- Testing Inflationary Physics through primordial non-Gaussianity

- Future

Brief Summary of Current Cosmological Constraints

From the Cosmic Microwave Background (CMB) we know the universe is very close to flat, $\Omega_{tot} = 1$ or $\Omega_k = 0$ $\quad (\Omega_i = \rho_i/\rho_{\rm critical})$

Also from CMB, primordial fluctuation spectrum consistent with inflation (super-horizon fluctuations with a nearly scale-invariant spectrum, $n_s \sim 1$), Gaussianity, and no tensor fluctuations (stochastic gravity waves).

From measuring the recent expansion history, using standard candles (type-Ia Supernovae, SN) or standard rulers (Baryon Acoustic Oscillations, BAO), we infer the universe is accelerating.

The acceleration is consistent with the simplest model (a cosmological constant Λ, with $\Omega_\Lambda \sim 0.7$ and equation of state $w \equiv p/\rho = -1$), but uncertainties are still large and more generic models (dark energy with arbitrary equation of state, or large-scale modifications of GR) are allowed.

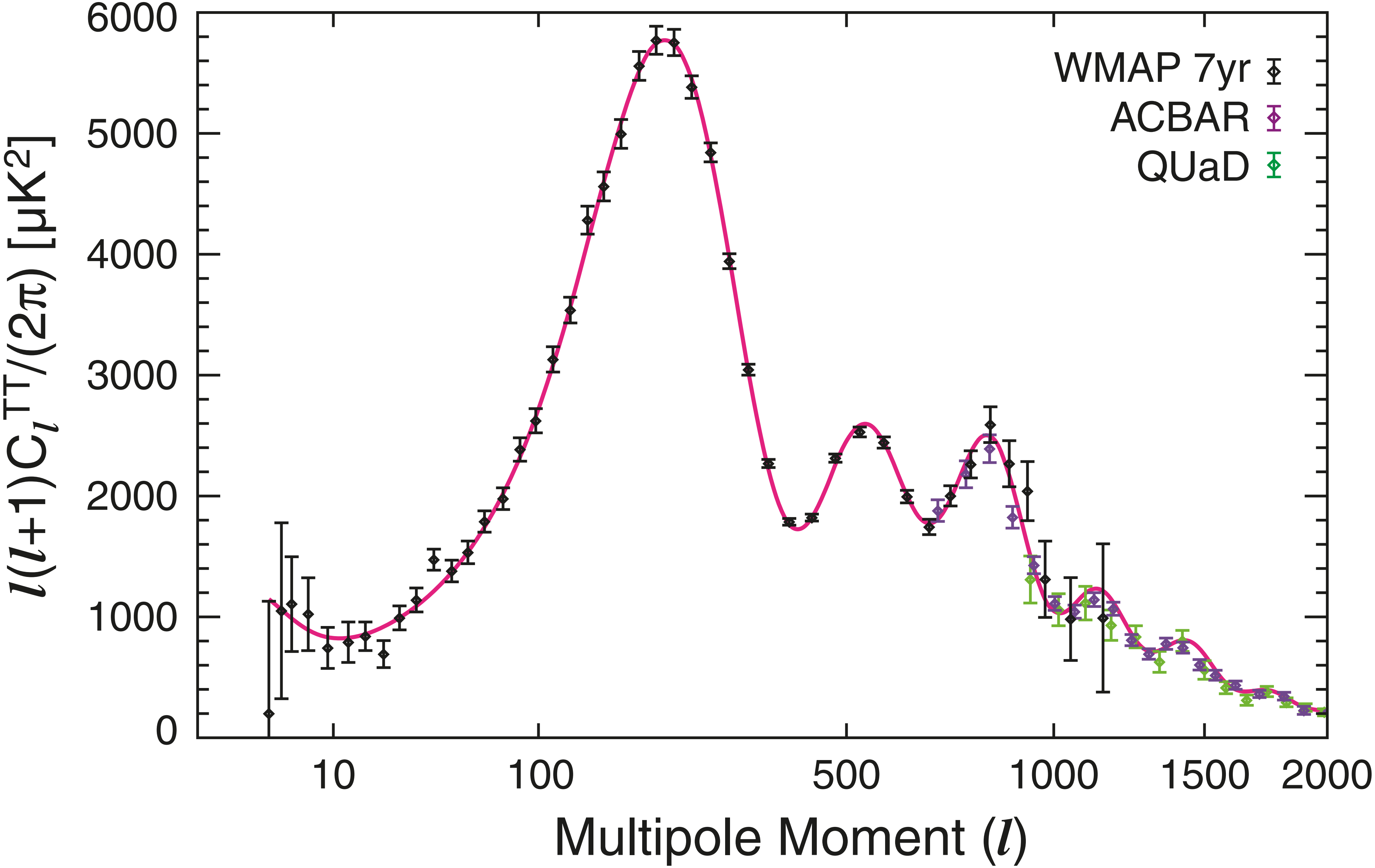


FIG. 7.— The *WMAP* 7-year temperature power spectrum (Larson et al. 2010), along with the temperature power spectra from the ACBAR (Reichardt et al. 2009) and QUaD (Brown et al. 2009) experiments. We show the ACBAR and QUaD data only at $l \geq 690$, where the errors in the *WMAP* power spectrum are dominated by noise. We do not use the power spectrum at $l > 2000$ because of a potential contribution from the SZ effect and point sources. The solid line shows the best-fitting 6-parameter flat ΛCDM model to the *WMAP* data alone (see the 3rd column of Table 1 for the maximum likelihood parameters).

WMAP 7-year results

TABLE 1
Summary of the cosmological parameters of ΛCDM model

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

Komatsu et al (2010)

WMAP 7-year results

TABLE 2

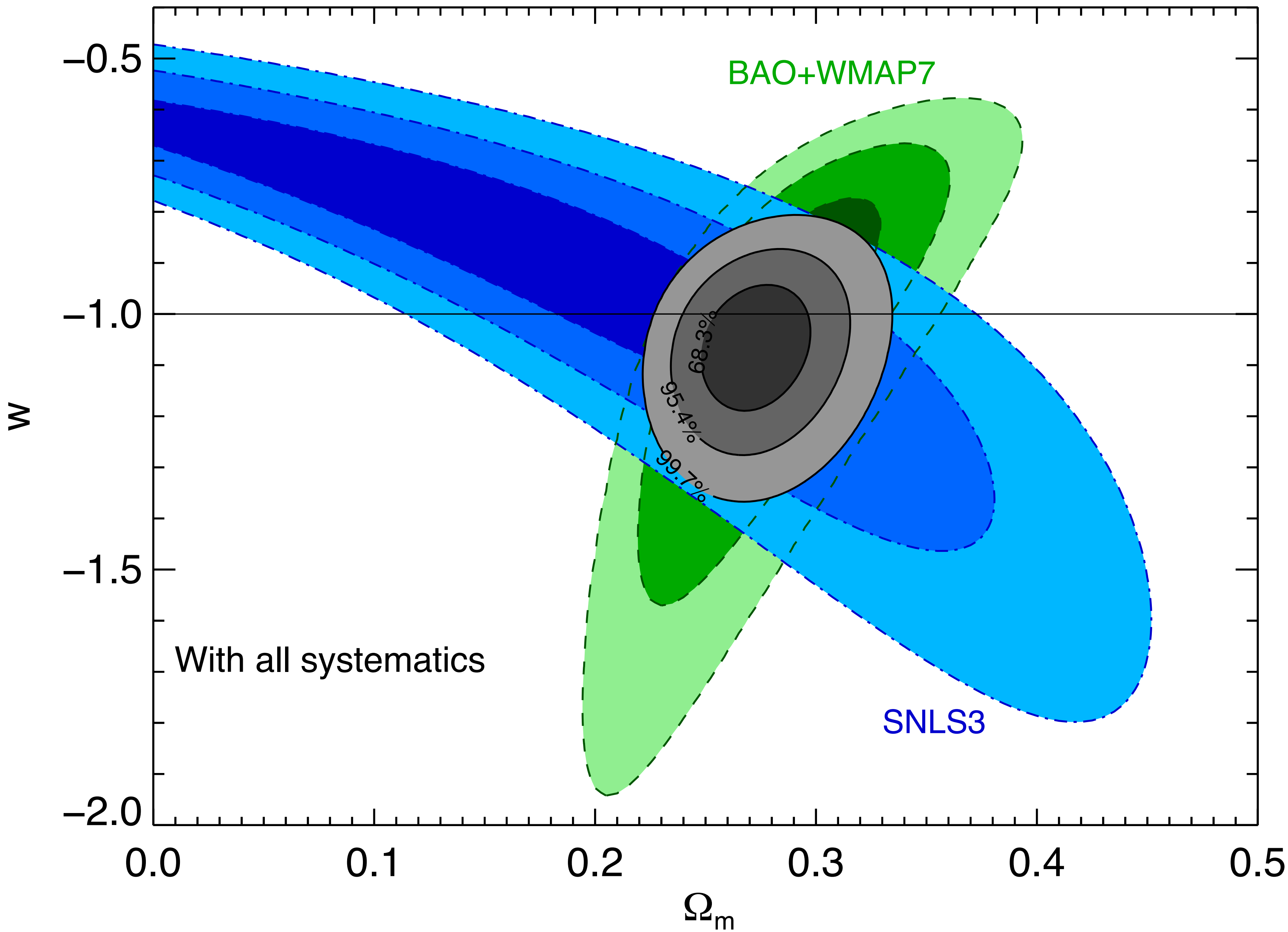
Summary of the 95% confidence limits on deviations from the simple (flat, Gaussian, adiabatic, power-law) ΛCDM model except for dark energy parameters

Sec.	Name	Case	*WMAP* 7-year	*WMAP*+BAO+SN[a]	*WMAP*+BAO+H_0
§ 4.1	Grav. Wave[b]	No Running Ind.	$r < 0.36$[c]	$r < 0.20$	$r < 0.24$
§ 4.2	Running Index	No Grav. Wave	$-0.084 < dn_s/d\ln k < 0.020$[c]	$-0.065 < dn_s/d\ln k < 0.010$	$-0.061 < dn_s/d\ln k < 0.017$
§ 4.3	Curvature	$w = -1$	N/A	$-0.0178 < \Omega_k < 0.0063$	$-0.0133 < \Omega_k < 0.0084$
§ 4.4	Adiabaticity	Axion	$\alpha_0 < 0.13$[c]	$\alpha_0 < 0.064$	$\alpha_0 < 0.077$
		Curvaton	$\alpha_{-1} < 0.011$[c]	$\alpha_{-1} < 0.0037$	$\alpha_{-1} < 0.0047$
§ 4.5	Parity Violation	Chern-Simons[d]	$-5.0^\circ < \Delta\alpha < 2.8^\circ$[e]	N/A	N/A
§ 4.6	Neutrino Mass[f]	$w = -1$	$\sum m_\nu < 1.3$ eV[c]	$\sum m_\nu < 0.71$ eV	$\sum m_\nu < 0.58$ eV[g]
		$w \neq -1$	$\sum m_\nu < 1.4$ eV[c]	$\sum m_\nu < 0.91$ eV	$\sum m_\nu < 1.3$ eV[h]
§ 4.7	Relativistic Species	$w = -1$	$N_{\rm eff} > 2.7$[c]	N/A	$4.34^{+0.86}_{-0.88}$ (68% CL)[i]
§ 6	Gaussianity[j]	Local	$-10 < f_{NL}^{\rm local} < 74$[k]	N/A	N/A
		Equilateral	$-214 < f_{NL}^{\rm equil} < 266$	N/A	N/A
		Orthogonal	$-410 < f_{NL}^{\rm orthog} < 6$	N/A	N/A

Primordial tilt n_s, running index $dn_s/d\ln k$, and tensor-to-scalar ratio r

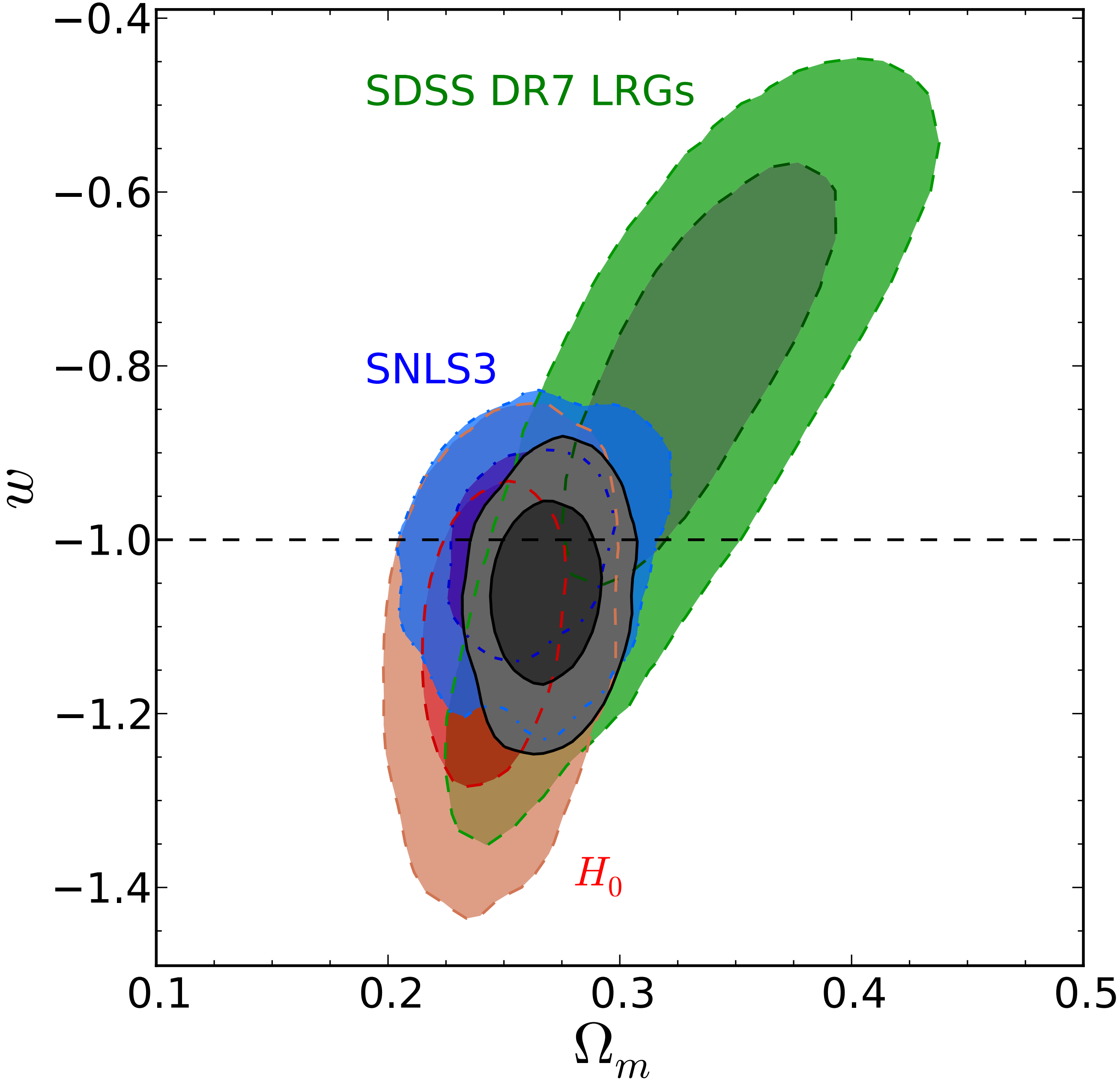
Section	Model	Parameter[a]	7-year *WMAP*[b]	*WMAP*+ACBAR+QUaD[c]	*WMAP*+BAO+H_0
Section 4.1	Power-law	n_s	0.963 ± 0.014	$0.962^{+0.014}_{-0.013}$	0.963 ± 0.012
Section 4.2	Running	n_s	$1.027^{+0.050}_{-0.051}$[d]	$1.041^{+0.045}_{-0.046}$	1.008 ± 0.042[e]
		$dn_s/d\ln k$	-0.034 ± 0.026	$-0.041^{+0.022}_{-0.023}$	-0.022 ± 0.020
Section 4.1	Tensor	n_s	$0.982^{+0.020}_{-0.019}$	$0.979^{+0.018}_{-0.019}$	0.973 ± 0.014
		r	< 0.36 (95% CL)	< 0.33 (95% CL)	< 0.24 (95% CL)
Section 4.2	Running +Tensor	n_s	1.076 ± 0.065	N/A	1.070 ± 0.060
		r	< 0.49 (95% CL)		< 0.49 (95% CL)
		$dn_s/d\ln k$	-0.048 ± 0.029		-0.042 ± 0.024

SNLS 3-year results



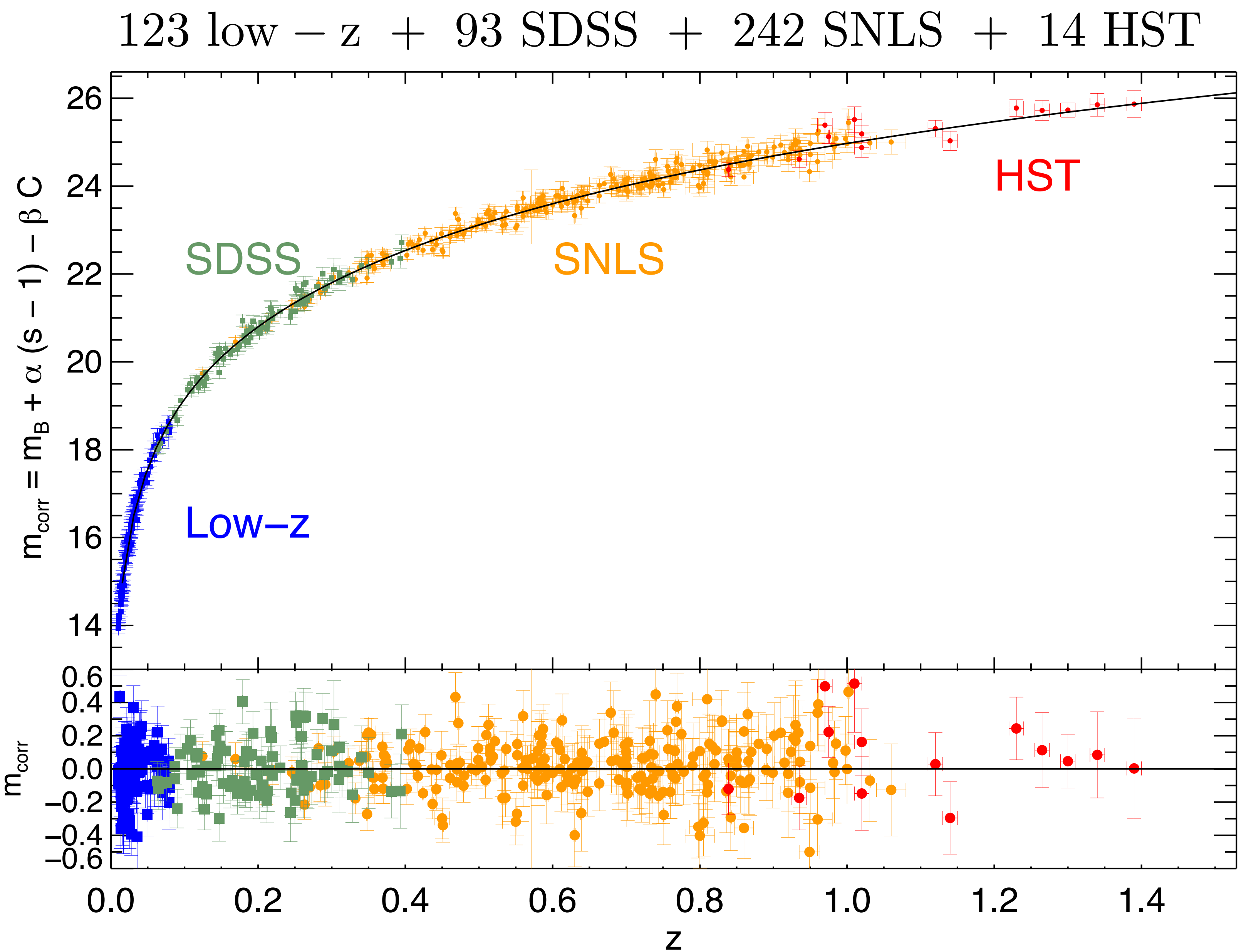
Sullivan et al (2011)

WMAP7 + ...



Sullivan et al (2011)

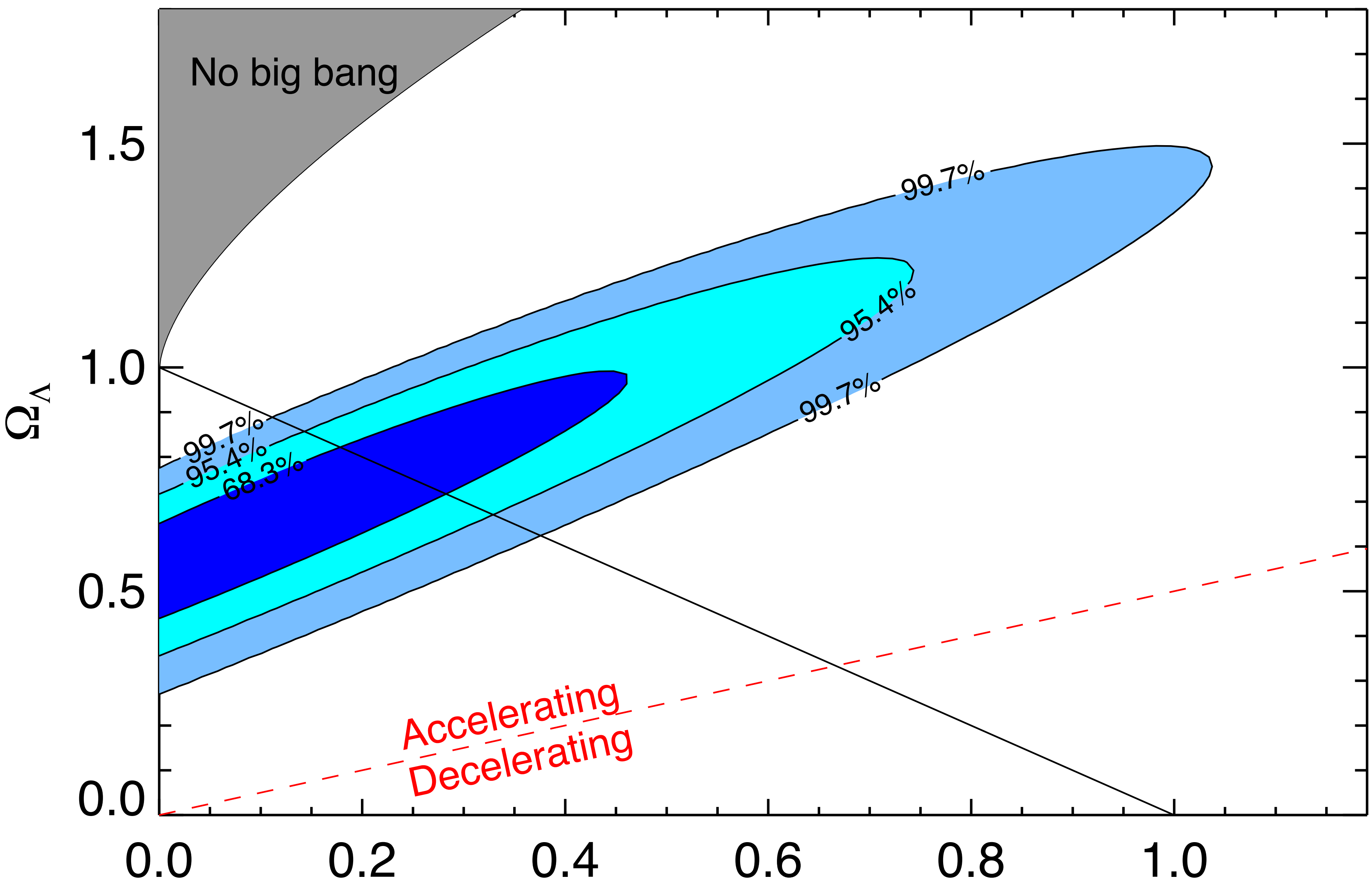
SNLS 3-year results (+ other SN)



Conley et al (2011)

SNLS 3-year results

SN alone require cosmic acceleration at $> 99.999\%$



Conley et al (2011)

Cosmic Acceleration and Inflation

- The universe's expansion is at present accelerating: why?

- The large-scale structure we see in CMB and galaxy surveys can be explained by gravitational instability from primordial fluctuations generated during inflation: what's the physics of inflation?

Both these questions can be addressed with large galaxy surveys presently under construction.

Galaxy Redshift Surveys

- It’s a map of the three-dimensional distribution of galaxies in the universe.

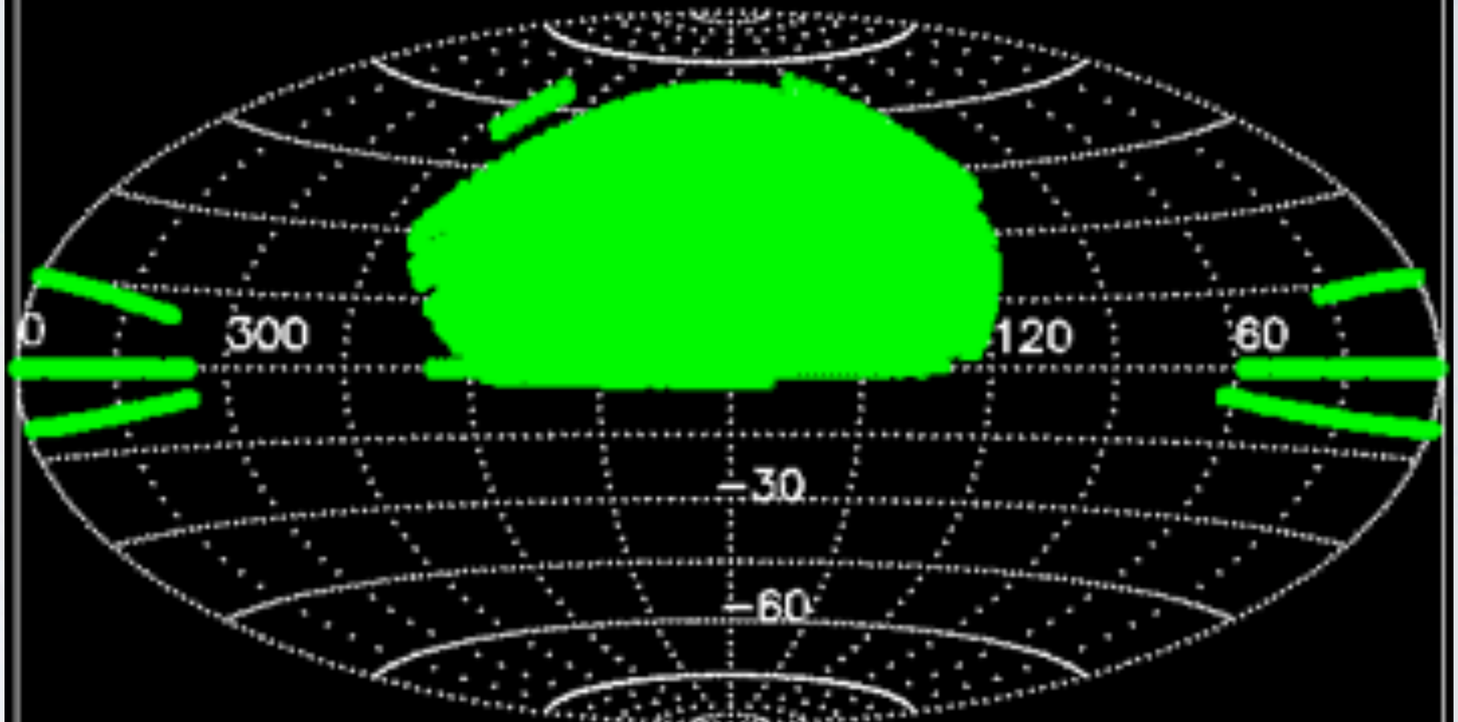
- The observables are angles in the sky plus the redshift of galaxy.

- Redshifts are due to recession velocities caused by the expansion of the universe (which through Hubble’s law $v=H*r$ can be translated into a distance).

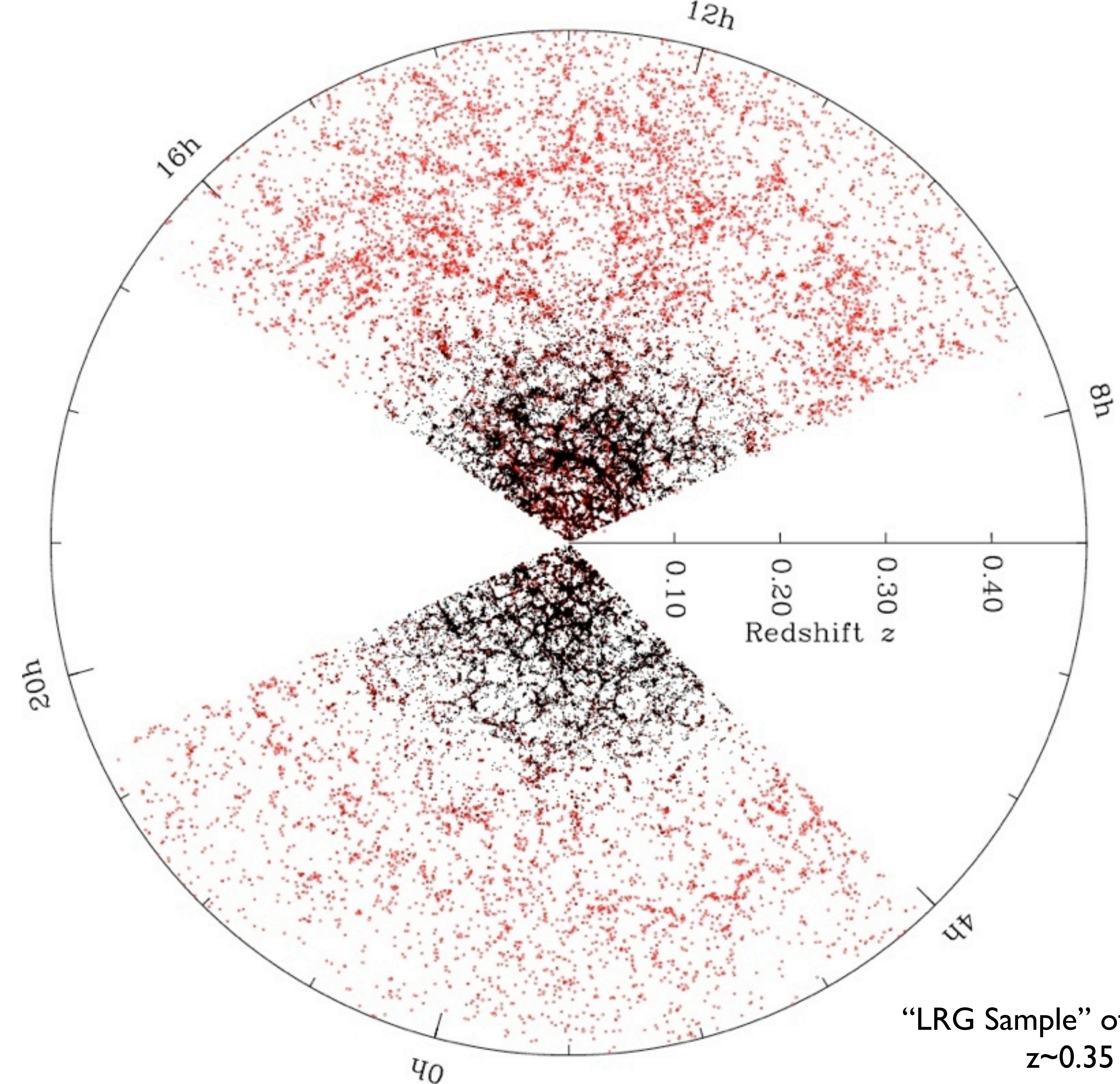
- However, in a clumpy universe, there are also dynamical velocities (from gravitational interactions between galaxies) that contribute to recession velocities: thus radial distances are “distorted” by gravitational dynamics.

The primary example of a Galaxy Redshift Survey is the Sloan Digital Sky Survey (SDSS)

sdss.org



Legacy DR7 Spectral Sky Coverage
(Aitoff projection of Equatorial coordinates)



“LRG Sample” of SDSS II
z~0.35

The Next Frontier: BOSS

- Baryon Oscillation Spectroscopic Survey (BOSS) is part of SDSS-III

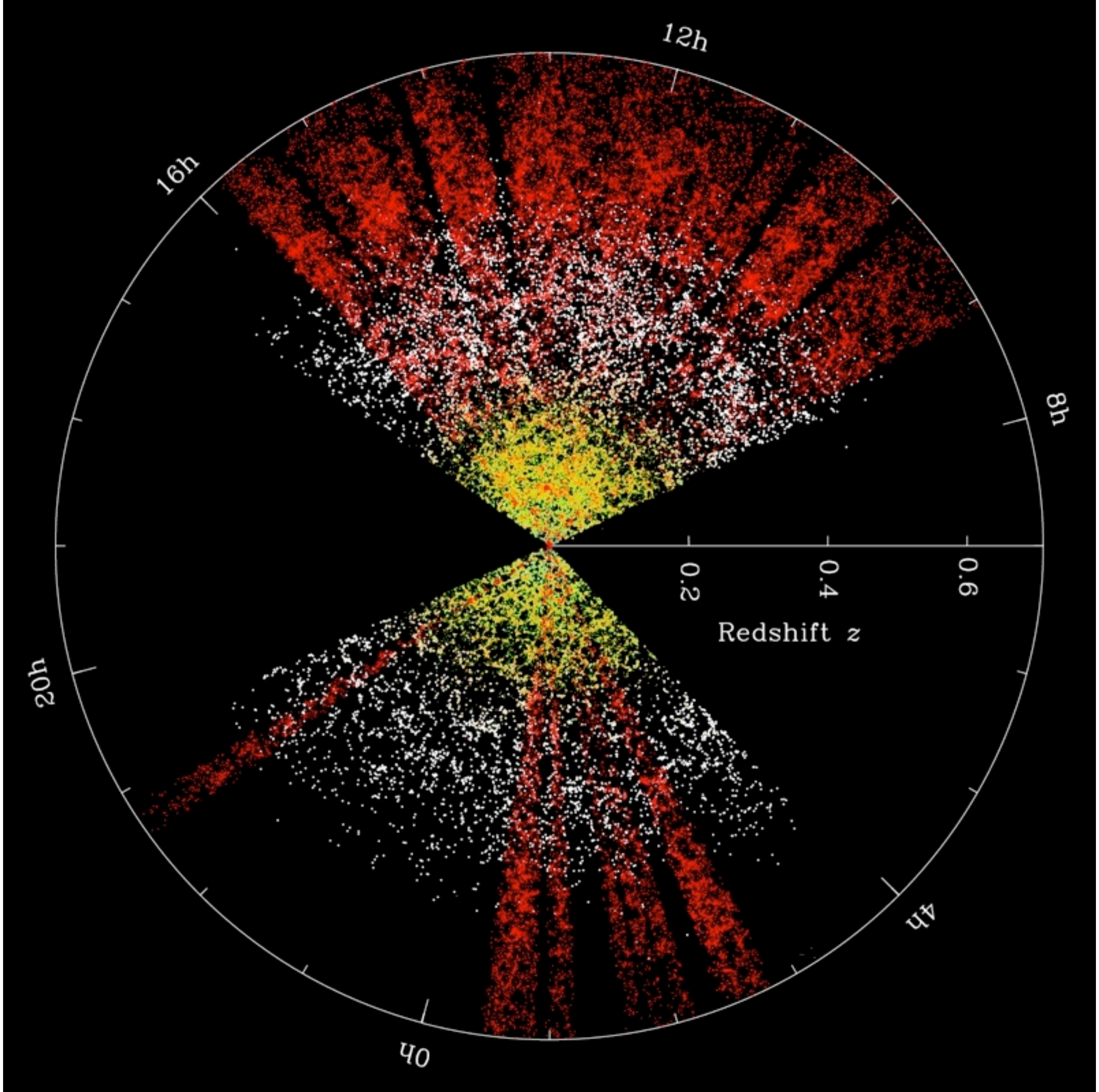
- 1.6 million galaxies between z=0.2 and z=0.7

- 2009-2014

- 10,000 sq deg

- geared towards constraining the physics of acceleration from the BAO method (measuring 1% distances to z=0.35, 0.6)

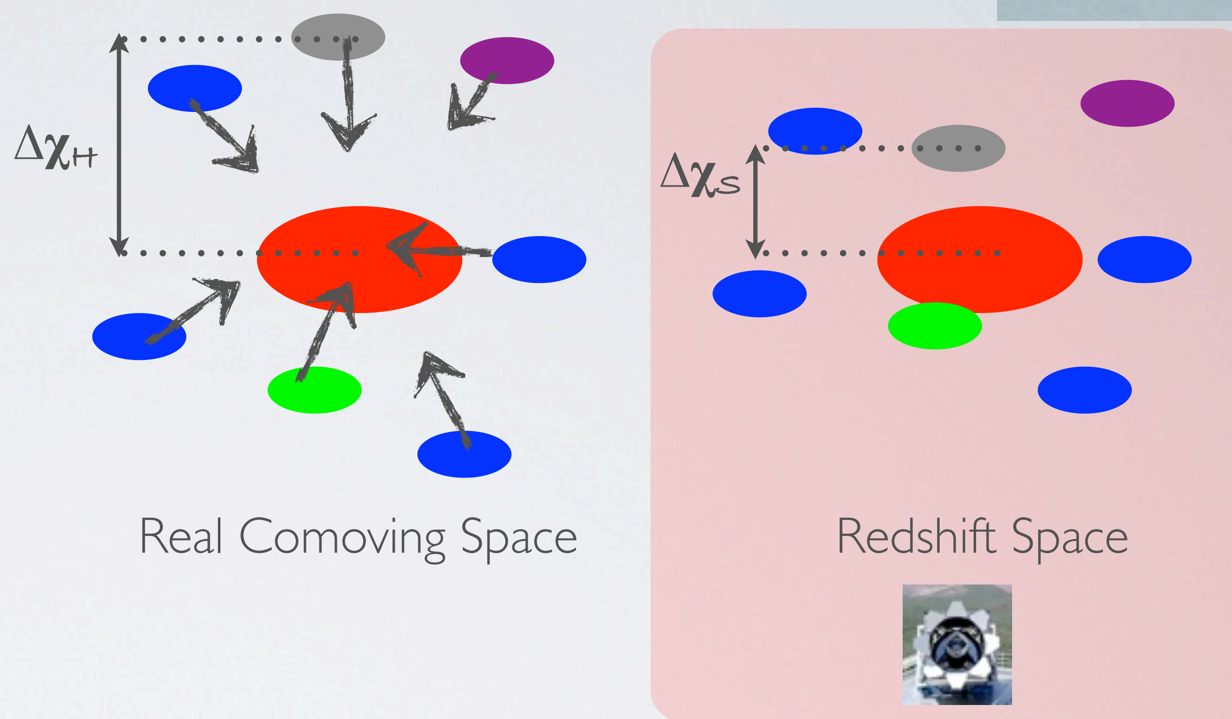
- will also constrain dark energy / modified gravity from redshift-space distortions, inflation from improved cosmological parameters + primordial non-Gaussianity



BOSS

Redshift Distortions

Squashing Effect
effects large scales ~10'sMpc



Velocity-Dispersion Effect
(aka Finger of God)
effects small scales ~ few Mpc

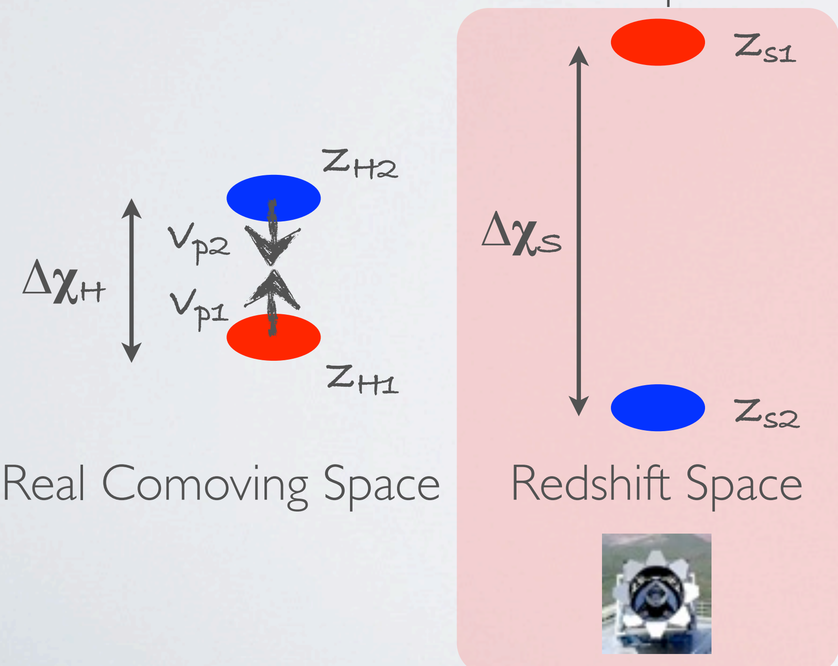
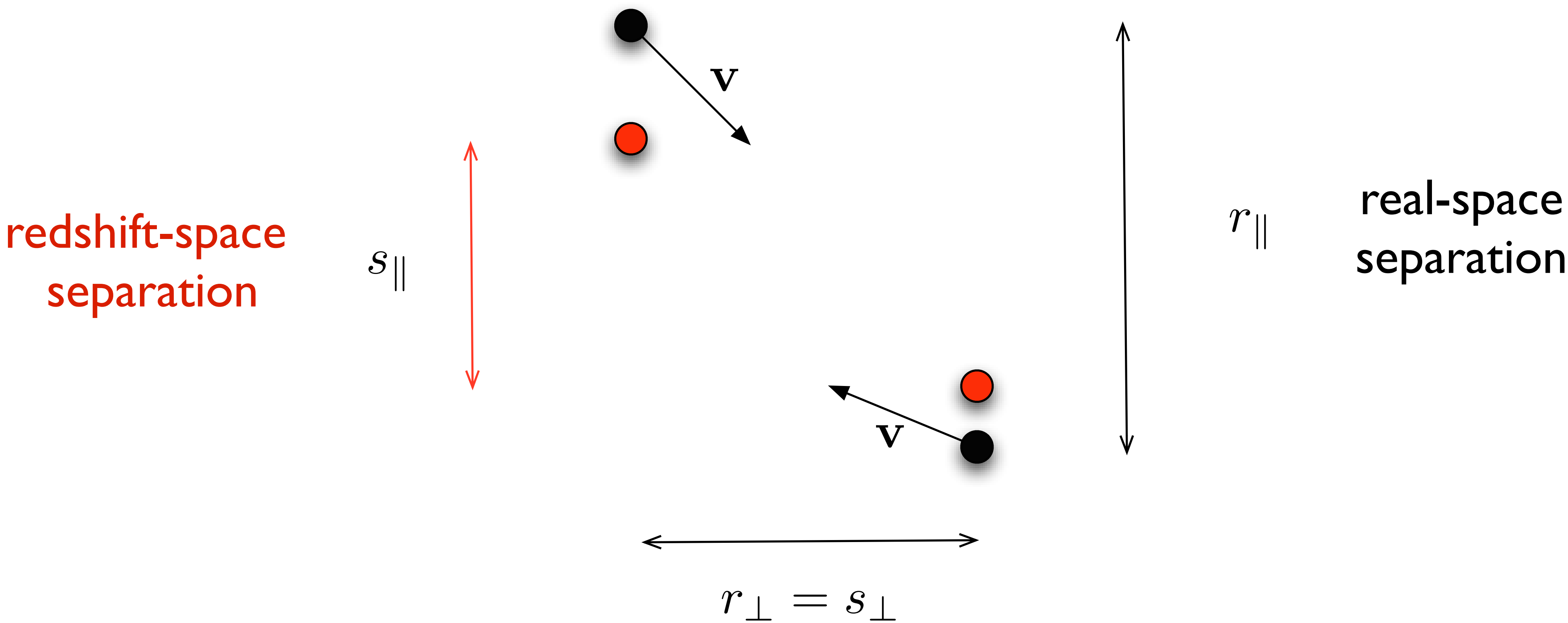


Fig. by Eyal Kazin

An exact relationship between real and redshift-space clustering:



$$1 + \xi_s(s_{\parallel}, s_{\perp}) = \int_{-\infty}^{\infty} dr_{\parallel}\ [1 + \xi(r)]\ \mathcal{P}(\underbrace{r_{\parallel} - s_{\parallel}}_{\mathbf{v}_p}, \mathbf{r}),$$

Everything is encoded in the pairwise velocities PDF.

These are incorporated into the so-called "dispersion model", for the power spectrum,

$$P_s(k,\mu) = P_g(k)\ (1+\beta\mu^2)^2\ \frac{1}{1+k^2\mu^2\sigma_p^2/2},$$

which is used to constrain cosmological parameters from redshift surveys.

$$\beta = \frac{f}{b_1}, \qquad k\mu = k_z, \qquad \sigma_p^2 = \text{pairwise velocity dispersion}$$

- f is the most interesting part: it depends on the theory of gravity, e.g.

$$f = \Omega_m^\gamma, \qquad \gamma \approx 0.56\ (\text{GR}),\ 0.68\ (\text{DGP})$$

- b is the linear bias (that relates matter to galaxy clustering), can be obtained from the same data by measuring the galaxy bispectrum.

Cosmic Acceleration

One possible explanation in the context of GR is that the universe is presently dominated by dark energy (DE), a component with strong negative pressure.

Another possibility is that we are witnessing deviations of Einstein's GR at cosmic scales (comparable to H-radius today)

In these modified gravity (MG) models, gravity is weaker at cosmological scales, leading to acceleration with normal matter (i.e. without the need for DE).

For example, some theories postulate that the graviton is "massive", in a nutshell, the small value of the cosmological constant is traded for a small "mass" for the graviton.

PROBING MODIFIED GRAVITY

Cosmic Acceleration: Dark Energy or Modified Gravity?

BAO, Supernovae and Weak Lensing observations will give a precise determination of the expansion history of the universe since z=2 up to present.

Expansion History is not enough to tell them apart: need growth of structure

In DE models, growth of structure results from a competition between expansion of the universe and Einstein's gravity.

In MG models, for the same (observed) expansion history, modification of gravity will give a different growth rate at late times.

Modifying Gravity at Large Scales

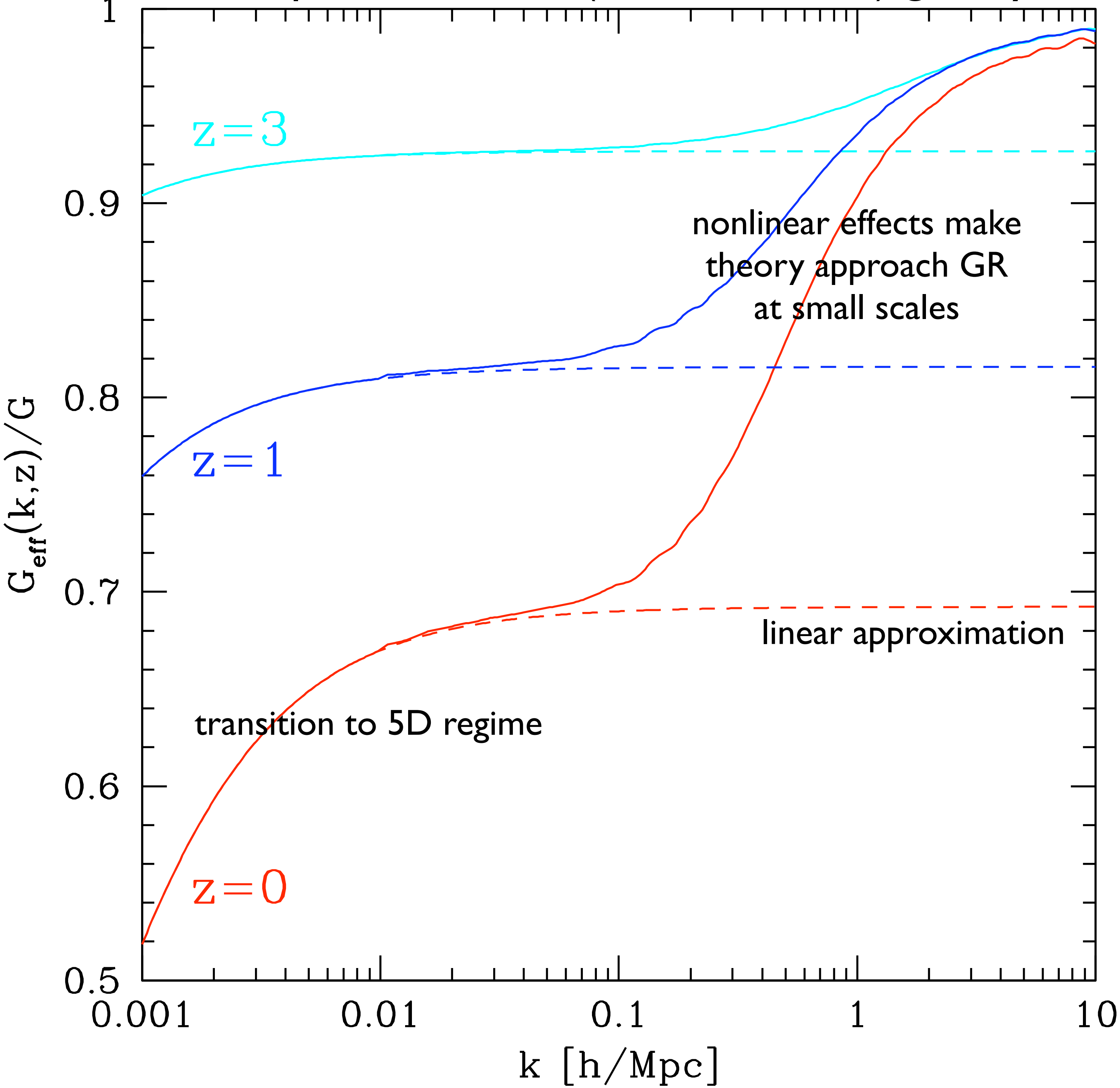
- GR is an extremely constrained theory (basically follows from massless graviton plus general covariance)

- Any deviation from it implies gravity cannot be meditated by a massless spin-2 particle: New degrees of freedom expected

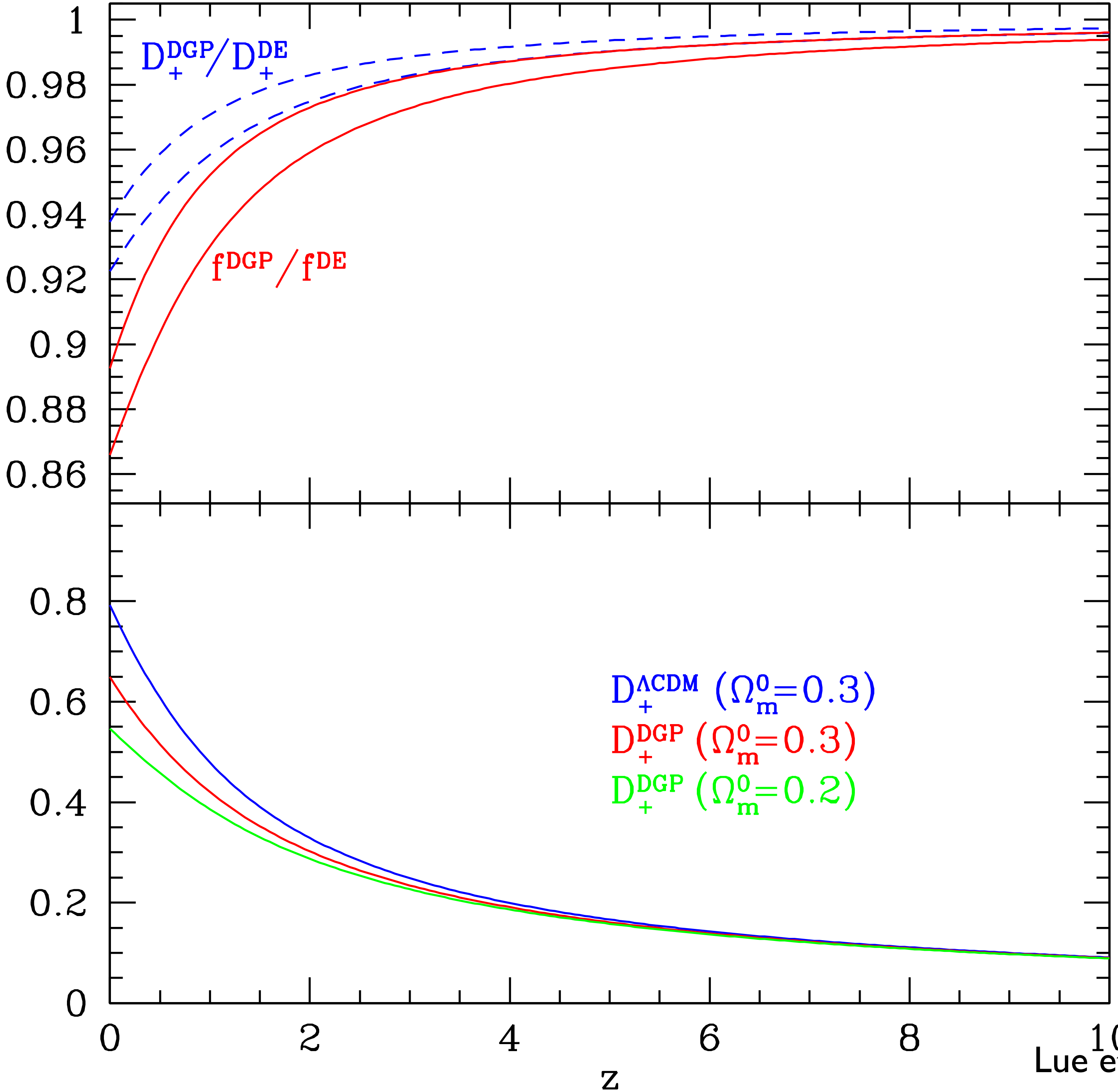
- "True" gravity modification leads to changes in the spin-2 sector (new polarizations for the graviton). Extra polarizations must be suppressed at small scales for consistency with solar system tests.

- In cosmological setting, this is typically done through nonlinear effects, leading to observational signatures

Example from DGP (brane-induced) gravity

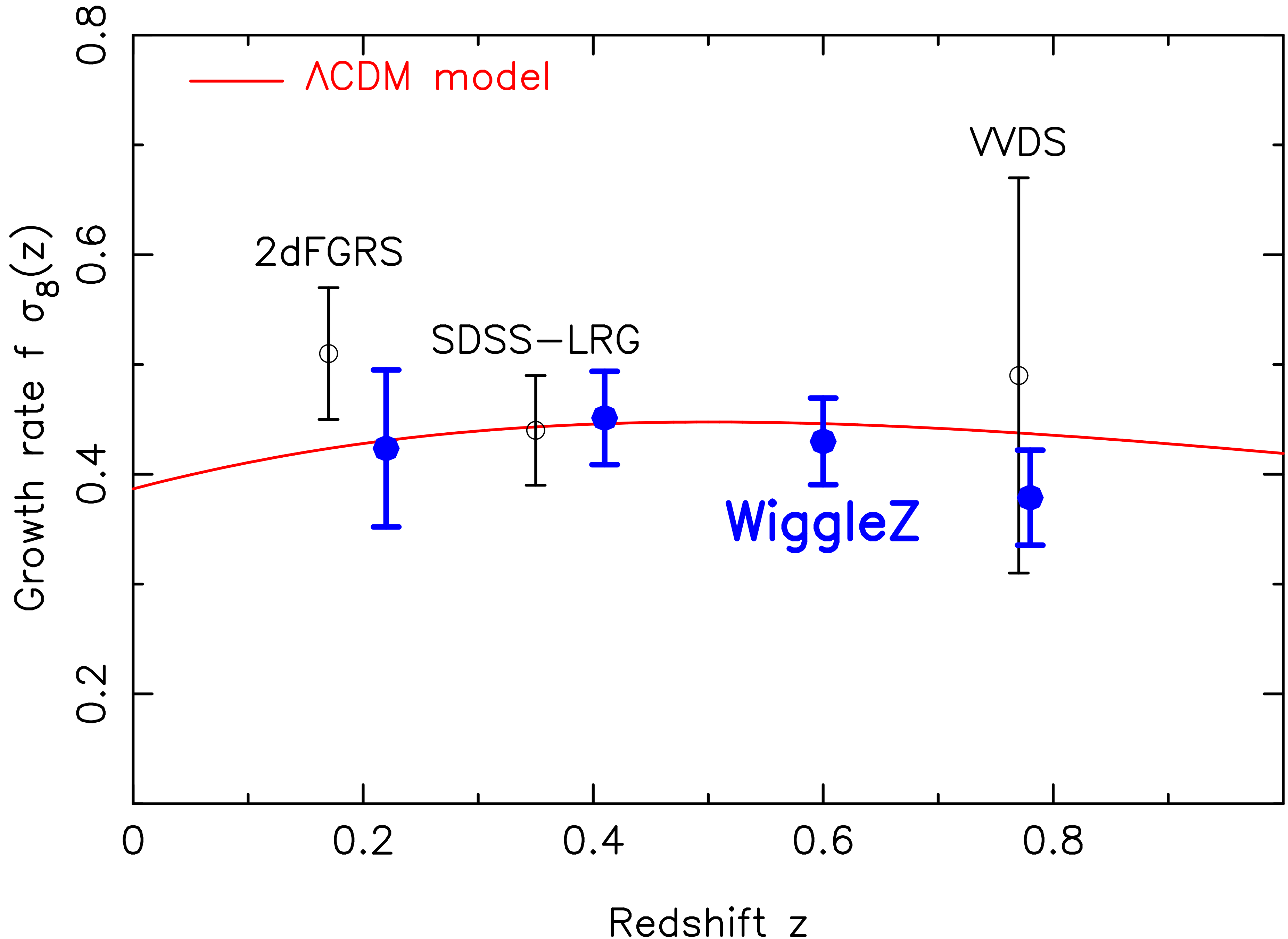


Growth of Structure in DGP Gravity



Lue et al. (2004)

Measurement of f from redshift-distortions (Blake et al. 2011)



Primordial Non-Gaussianity

So far we assumed inflation gives rise to Gaussian fluctuations in the gravitational potential.

In the simplest models of single-field inflation, Gaussianity is a consequence of the slow-roll conditions, i.e. that the inflaton potential being very flat. Indeed, the bispectrum of the curvature perturbation (or gravitational potential) is generically,

$$B_\zeta \sim (n_s - 1)\ P_\zeta^2$$

Maldacena (2002)

Since the tilt is constrained to be small (< 0.05), this is probably unobservable.

Gaussianity is a consequence of:

i) inflaton a single scalar field
i) slowly rolling
ii) in vacuum state
iii) with canonical kinetic terms

if we relax i) we have for the Bardeen potential,

$$\Phi = \phi + f_{\rm NL}\phi^2$$

which implies for it a bispectrum,

$$B = 2 f_{\rm NL} P_1 P_2 + {\rm cyc.} \qquad -10 < f_{\rm NL}^{\rm local} < 74$$

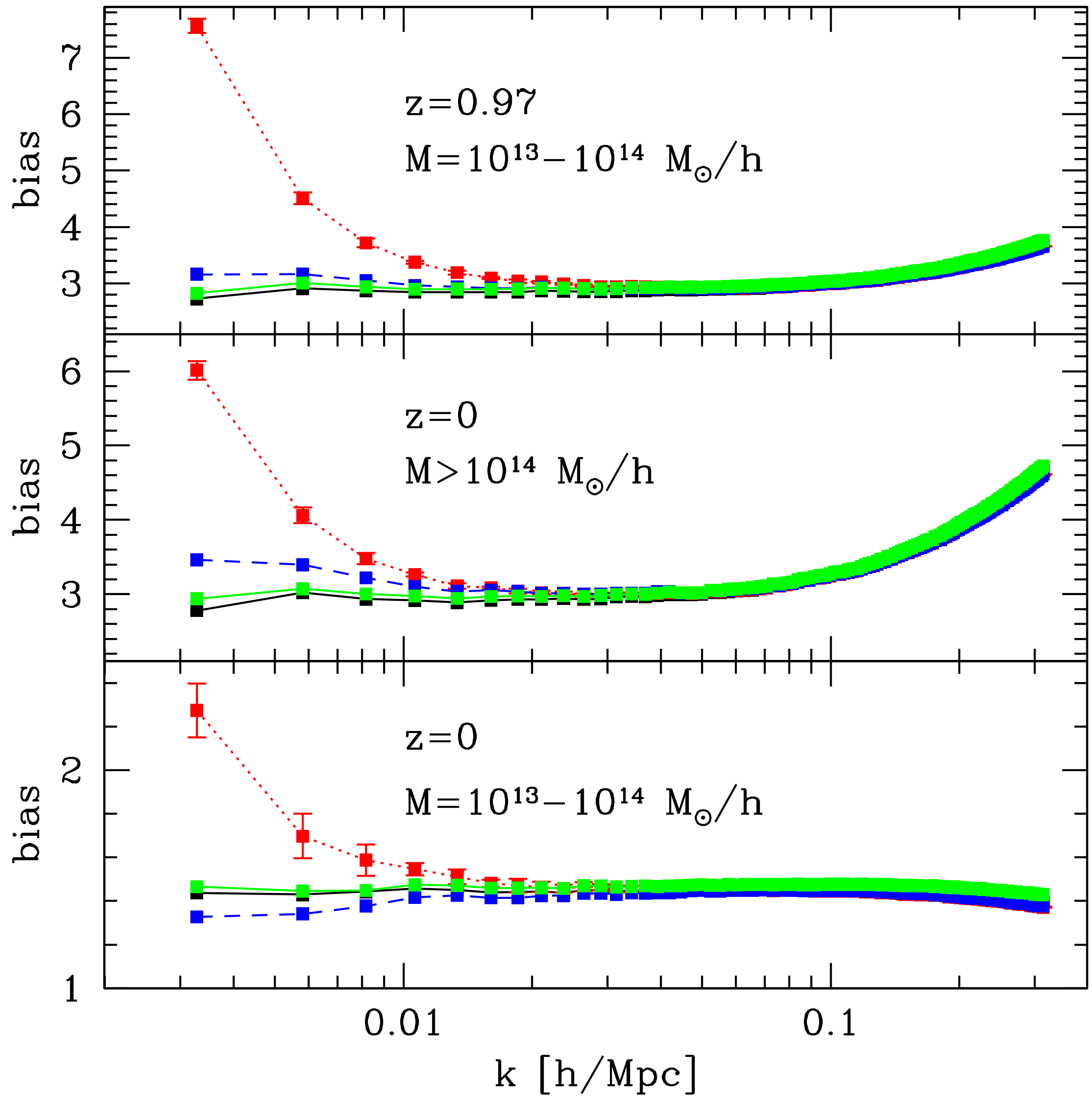
- For biased tracers (galaxies, halos), this model leads to a scale-dependent bias at large scales (Dalal et al 2008),

$$b_1(k) = b_{10} + \Delta b_1(k, f_{\rm NL})$$

with b~1/k^2 at low-k. Thus the power spectrum of galaxies is sensitive to fnl!!

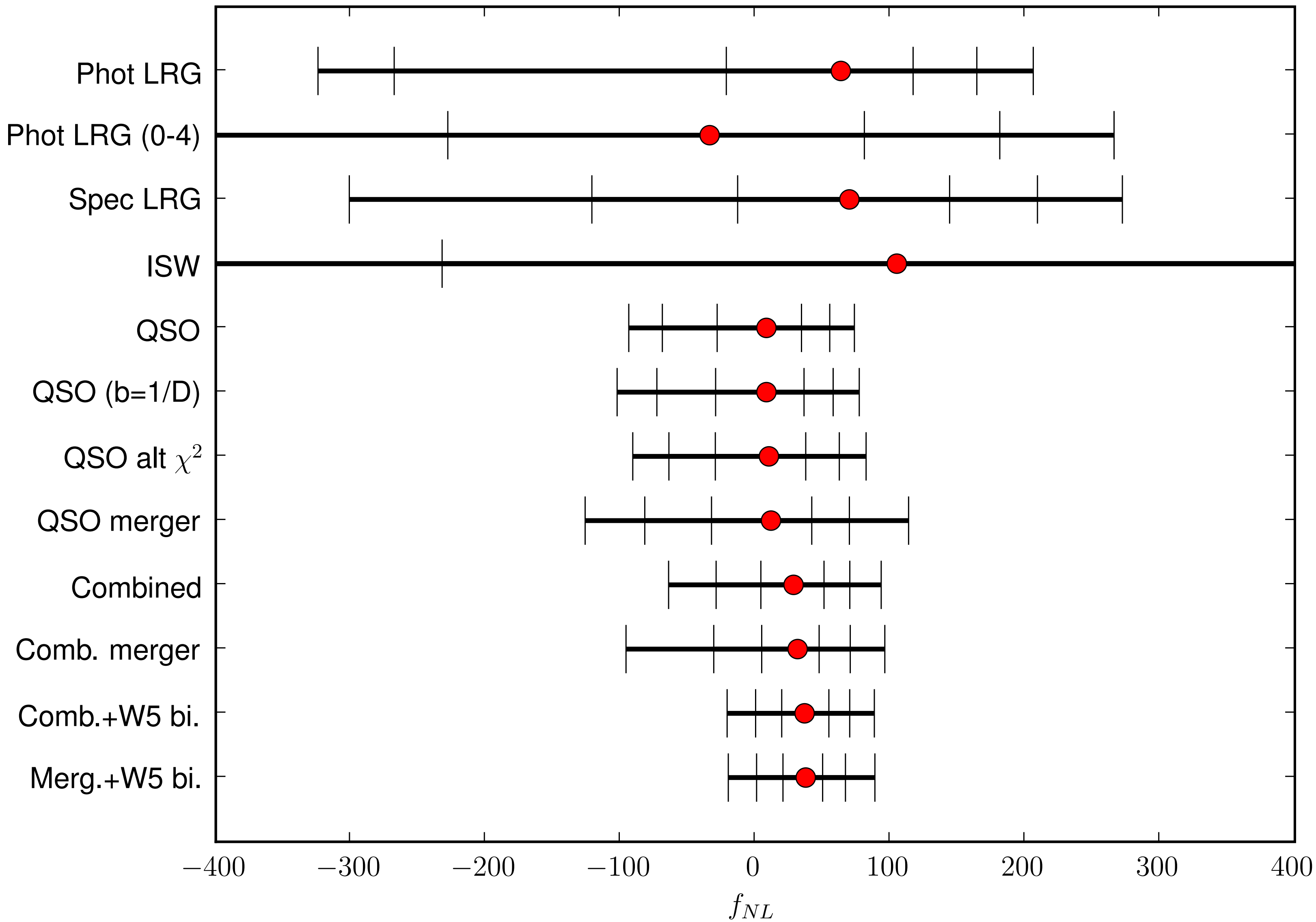
Scale-dependent Bias from Power Spectrum

$$b(k) = \frac{P_{gm}}{P_{mm}}$$



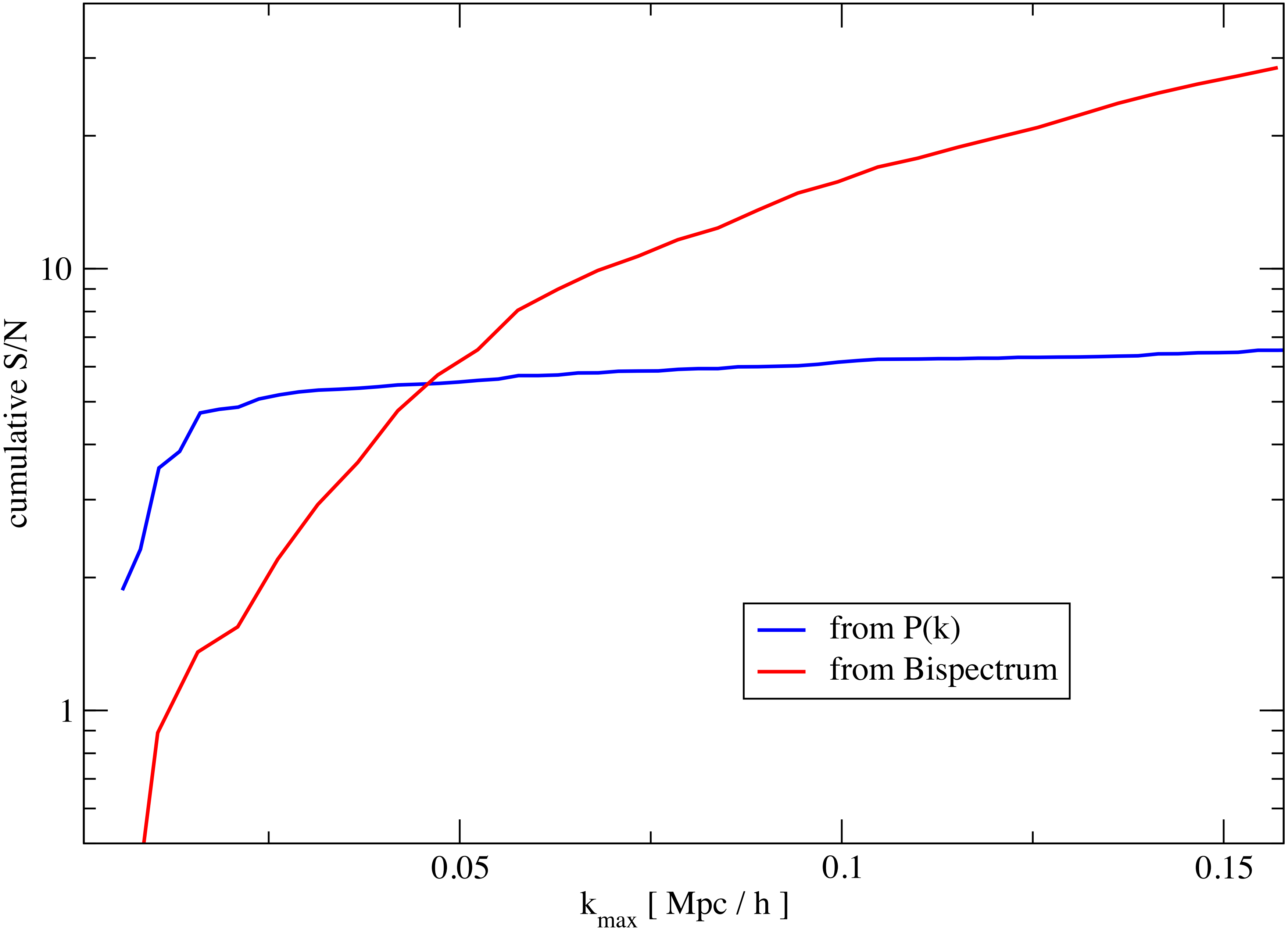
Halos in numerical simulations (R.S. et al. 2011)

SDSS II Constraints on local PNG from power spectrum (Slosar et al. 2008)



$$-29 < \mathrm{f}_{\mathrm{NL}}^{\mathrm{loc}} < 70 \quad (2\sigma)$$

expected BOSS signal to noise for local fnl=100



in pple enough statistics (pow + bisp) to detect fnl~3 (competitive with CMB)

Beyond Local Primordial Non-Gaussianity

- Within single-field inflationary models, we can break Gaussianity by introducing non-canonical kinetic terms, leading to the so-called equilateral and orthogonal shapes for the primordial bispectrum.

For example, the equilateral model has a Bardeen potential bispectrum,

$$(6f_{\rm NL})^{-1}B_{\rm equil} = -P_1P_2 - 2(P_1P_2P_3)^{2/3} + P_1^{1/3}P_2^{2/3}P_3$$

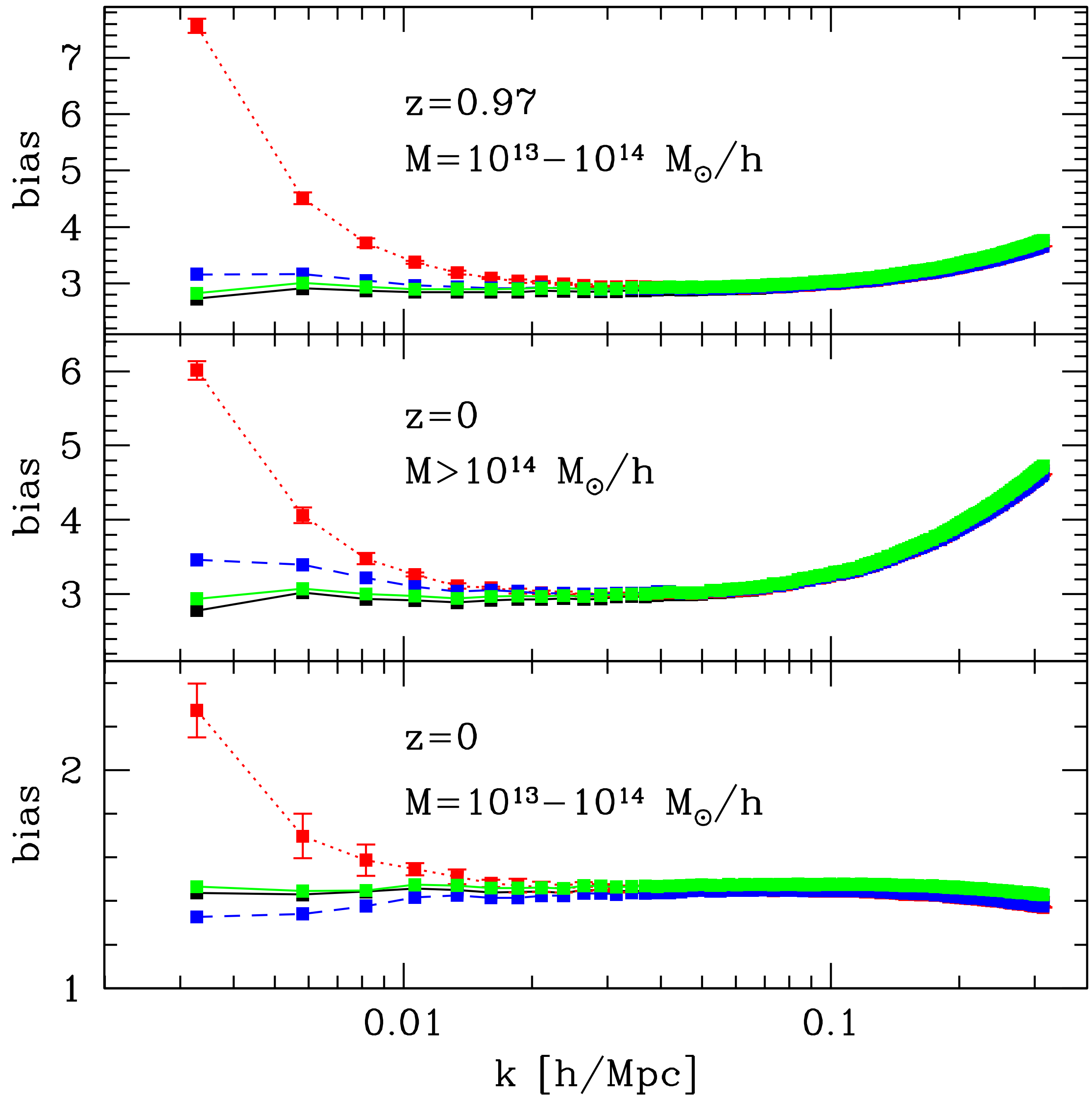
$$-214 < f_{\rm NL}^{\rm equil} < 266$$

(permutations are understood), whereas the orthogonal model reads

$$(6f_{\rm NL})^{-1}B_{\rm ortho} = -3P_1P_2 - 8(P_1P_2P_3)^{2/3} + 3P_1^{1/3}P_2^{2/3}P_3$$

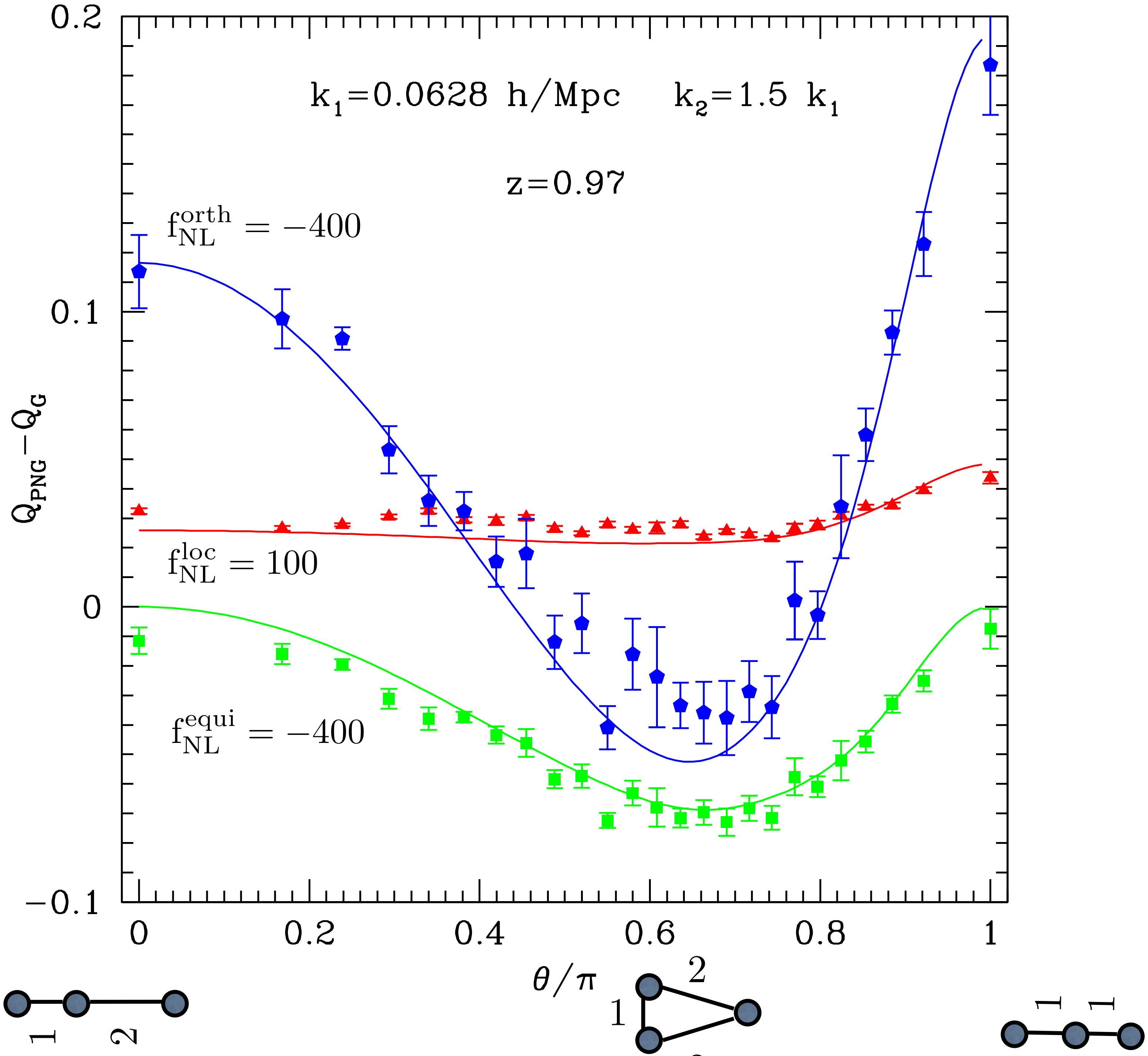
$$-410 < f_{\rm NL}^{\rm ortho} < 6$$

Scale-dependent Bias from Power Spectrum

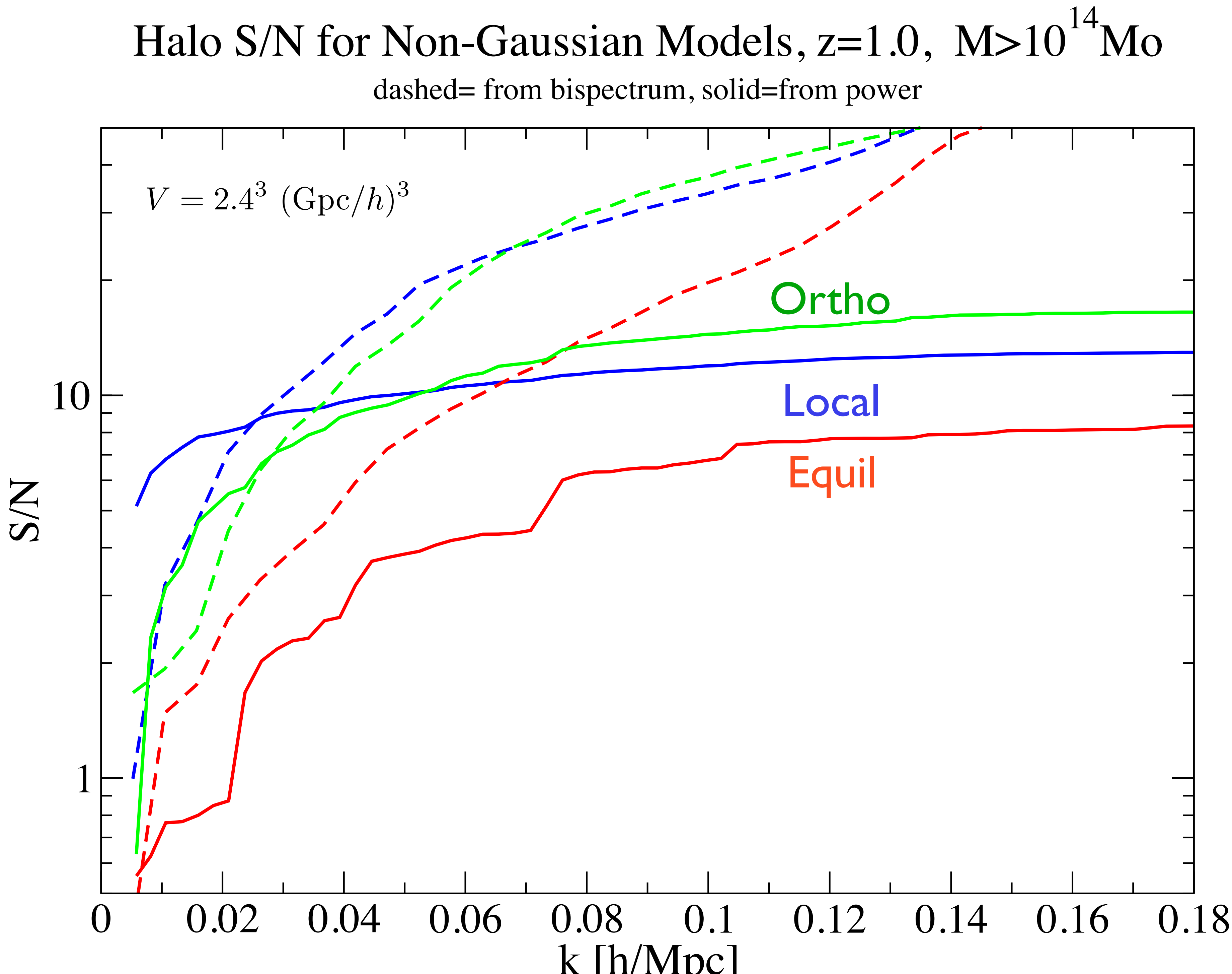


Halos in numerical simulations (R.S. et al. 2011)

Bispectrum



k1=0.0628 h/Mpc k2=1.5 k1
z=0.97
$f_{NL}^{orth} = -400$
$f_{NL}^{loc} = 100$
$f_{NL}^{equi} = -400$
$Q_{PNG} - Q_G$
θ/π
0.2
0.1
0
−0.1
0
0.2
0.4
0.6
0.8
1
1
2
1
2
1
1
1



Note bispectrum high StoN compared to power spectrum, for all models!

Future and Summary

Many independent cosmological probes paint a consistent picture.

Much more coming soon:

- Planck CMB satellite (much higher-resolution than WMAP), results expected by February 2013.

- For SN, going from hundreds to thousands (PTF, PanSTARRS, Skymapper, DES) in the next ~5 years and tens of thousands eventually with LSST.

- Euclid (ESA satellite) just selected (launch 2019, 6 years at L2): galaxy clustering, weak lensing, SN

- BigBOSS will significantly improve BOSS results (again ~ 2019)

- We can use redshift-space distortions in combination with the bispectrum to constrain the velocity growth factor and thus modifications of gravity.

- Different primordial non-Gaussianities motivated by inflation lead to significant changes in the galaxy bispectrum. BOSS will yield great statistical precision (competitive with Planck CMB satellite). First BOSS results expected 2012.

Both techniques in the next few years will give unprecedented constraints on fundamental physics of gravity and inflation.