TESTING GRAVITY WITH REDSHIFT GALAXY SURVEYS

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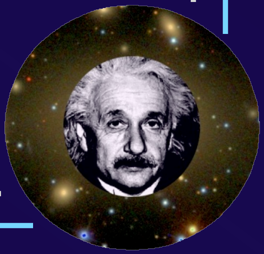


Outline

The expansion is accelerating

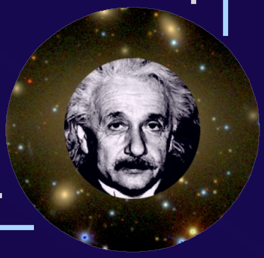
OH, REALLY?

Growth of structure is essential for the MoG/DE dilemma

OH, REALLY?

An observable test parameter for GR: ε

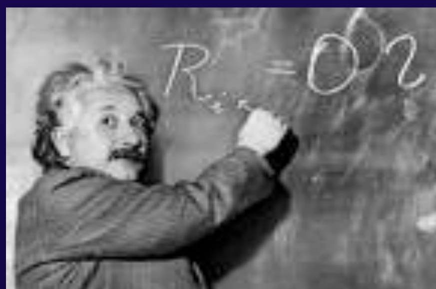
Constraining ε with galaxy surveys



$$\mathcal{S} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,R + \int d^4x\sqrt{-g}\,\mathcal{L}_M$$

Variational principle →

$$q = \frac{1}{2}\sum \Omega_i + 3\sum w_i\Omega_i \qquad 1 = \Omega_k + \Omega_i$$



NON-GR GRAVITY

Scalar-tensor theories, DGP

R → f (R)

GR + NEW INGREDIENT(S):

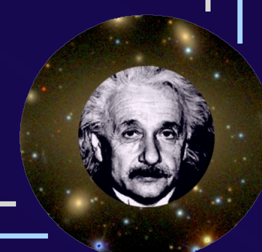
$\Lambda = \langle 0 \,|\, \text{Fundamental Theory} \,|\, 0 \rangle$

perfect fluid, variable w(z) : DE

CAN WE DISTINGUISH BETWEEN THEM?

ONE CAN BUILD ANY EXPANSION HISTORY

→ NOT WITH DISTANCE ONLY : GROWTH



GROWTH OF STRUCTURE IN GR + DE

two metric potentials
Φ, Ψ

$$\boxed{\delta G_{\mu\nu} = \delta T_{\mu\nu}}$$

4 matter variables
δ, v, δp, σ

density perturbation
$\delta = \delta\rho/\rho$

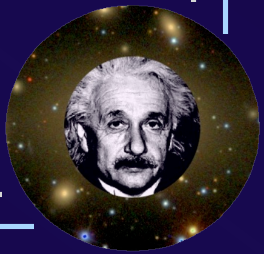
velocity field

clustering

anisotropic stress

SUB-HORIZON, LINEAR REGIME

$$\begin{array}{llcll}
 & \delta'_M & = & -\frac{k}{aH} v_M; & \text{continuity} \\
GR: & v'_M + v_M & = & \frac{k}{aH}\Psi; & \text{Euler} \\
 & k^2\Phi & = & -4\pi G\rho_M a^2 \delta_M; & \text{Poisson}
\end{array}$$



GROWTH OF STRUCTURE IN GR + smooth DE

two metric potentials
Φ, Ψ

$$\boxed{\delta G_{\mu\nu} = \delta T_{\mu\nu}}$$

4 matter variables
δ, v, δp, σ

density perturbation
$\delta = \delta\rho/\rho$

velocity
field

clustering

anisotropic
stress

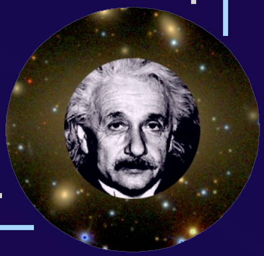
SUB-HORIZON, LINEAR REGIME

$$\text{assume } \Phi = \Psi; \quad \delta_M(k,z) = \delta_M(k, z=\infty) D(k,z)$$

$$D''(k,z) + \left(2 + \frac{H(z)'}{H(z)}\right) D'(k,z) - \frac{4\pi G}{H(z)^2} \rho_M(z) D(k,z) = 0$$

✓ ONCE H(z) IS KNOWN, D IS ALSO KNOWN

✓ NO SCALE DEPENDENCE: D(k,z) = D(z)



GROWTH OF STRUCTURE IN MoG THEORIES

two metric potentials
Φ, Ψ

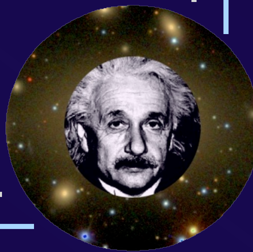
$$\boxed{\delta G_{\mu\nu} = \delta T_{\mu\nu}}$$

2 matter variables
δ, v

$$\boxed{\begin{array}{ccll} \delta'_M & = & -\frac{k}{aH} v_M; & // \\ v'_M + v_M & = & \frac{k}{aH}\Psi; & // \\ k^2\Phi & = & -4\pi G_{\rm eff}(k,z)\rho_M a^2 \delta_M; & \text{new physics} \\ \Phi & = & -(1+\eta(k,z))\Psi; & \text{new physics} \end{array}}$$

IN f(R) CASE, NEW DOF SOURCED BY 4th ORDER GRAVITY

- Newton Constant becomes $G_{eff}(k,z)$
- Nontrivial closure Φ, Ψ



GROWTH OF STRUCTURE IN MoG THEORIES

two metric potentials Φ, Ψ

$$\boxed{\delta G_{\mu\nu} = \delta T_{\mu\nu}}$$

2 matter variables δ, v

$$(\Phi - \Psi)/\Phi = 1 - \eta(k,z) = g(k,z); \quad \delta_M(k,z) = \delta_M(k, z=\infty) D(k,z)$$

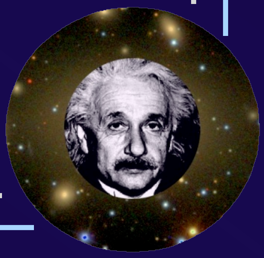
$$D''(k,z) + \left(2 + \frac{H(z)'}{H(z)}\right) D'(k,z) - \frac{4\pi G_{\rm eff}(k,z)}{H(z)^2}\left(g(k,z) - 1\right)\rho_M(z) D(k,z) = 0$$

✓ GROWTH ALSO DEPENDS ON $G_{eff}(k,z)$ AND $g(k,z)$

✓ POSSIBILITY OF A SCALE DEPENDENCE

GIVEN MoG THEORY, SPECIFIED BY H(z), g(k,z), $G_{eff}(k,z)$
CAN I BUILD A GR MODEL WITH SAME H(z), GROWTH?

NO!

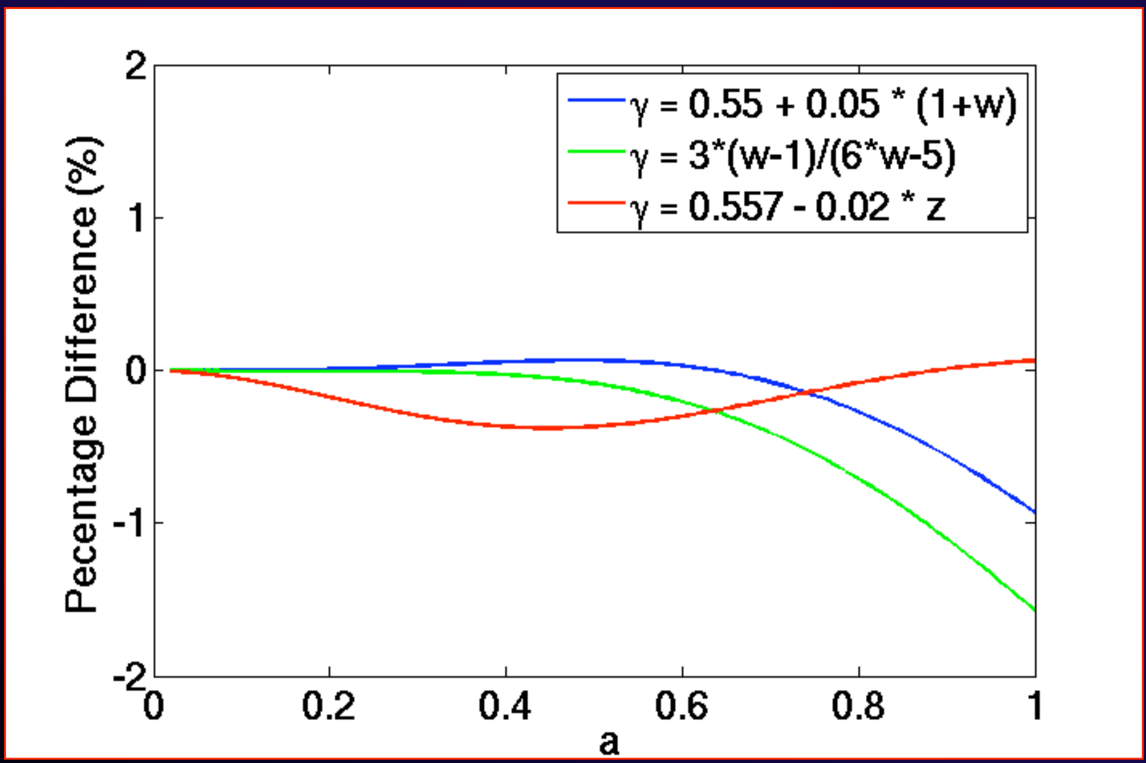


A NULL TEST PARAMETER FOR GR

two “GR” ingredients:

GROWTH IS DETERMINED BY H(a) AND SCALE-FREE

THE RELATION $d \ln D(a) / d \ln a = \Omega_m(a)^{\gamma}$ HOLDS AT 0.5 %

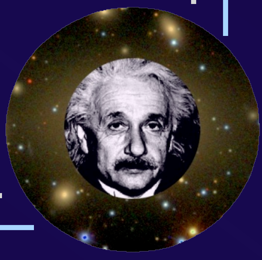


γ

either parameter
or simple function
of redshift

we use
Polarski & Gannouji 08

$\gamma = \gamma_0 + \gamma' z$



A NULL TEST PARAMETER FOR GR

two "GR" ingredients:

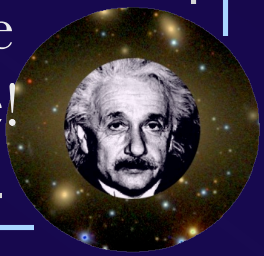
GROWTH IS DETERMINED BY H(a) AND SCALE-FREE

THE RELATION d ln D(a) / d ln a = Ω_m^γ HOLDS AT 0.5 %

$$\epsilon = \frac{a^{3\gamma} H(a)^{2\gamma}}{(\Omega_{m,0} H_0^2)^2} \frac{d \ln D}{d \ln a} - 1 = 0 \quad \text{in GR}$$

determined by the CMB
at the 1.5% level by Planck

measuring this quantity
allows to detect any
deviation from GR
both as absolute value
and scale-dependence!



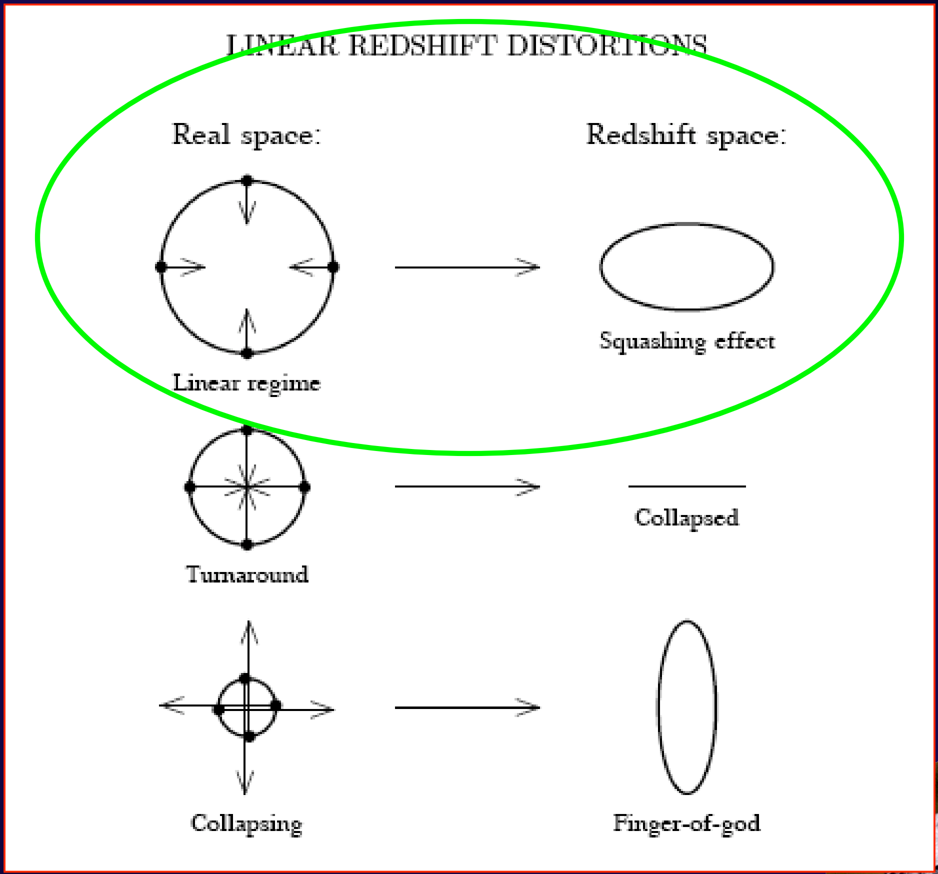
MEASURING ℇ WITH REDSHIFT GALAXY SURVEYS

Known that they can measure growth… but it gets even better! :)

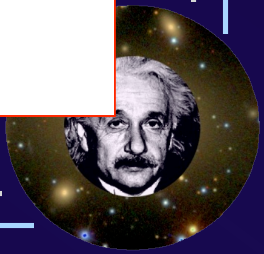
LINEAR REDSHIFT DISTORTIONS

Measurements of galaxy power spectrum in redshift space "remap" galaxies according to their peculiar velocities, which are interpreted as Doppler shifts

v is driven by δ via continuity equation



From Hamilton 97



MEASURING ε WITH REDSHIFT GALAXY SURVEYS

one can define
linear redshift distortion
parameter β:

$$\boxed{\beta\,\delta_G + \nabla\cdot\mathbf{v}_G = 0}$$

"observations"

from EOMs for D
one has

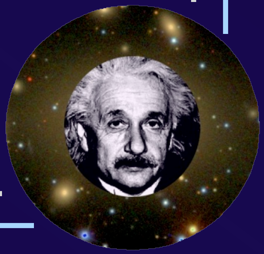
$$\boxed{\frac{d\ln D}{d\ln a}\delta_M + \nabla\cdot\mathbf{v}_\mathbf{M} = 0}$$

"theory"

assumption of linear bias for δ, no bias for v gives

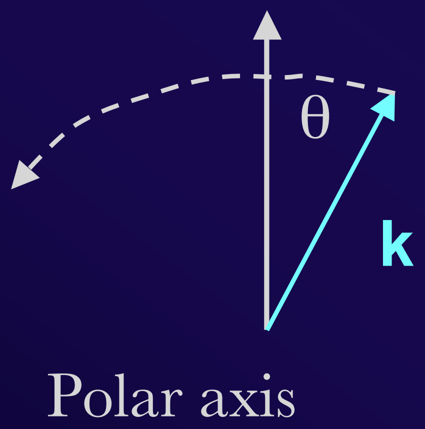
$$\boxed{\frac{d\ln D}{d\ln a} = b\cdot\beta} \Rightarrow \boxed{\epsilon(k,a) = \frac{a^{3\gamma}H(a)^{2\gamma}}{(\Omega_{m,0}H_0^2)^2}\beta(k,a)\cdot b(a) - 1 = 0 \quad \text{in GR}}$$

ε now written entirely in terms of observables
we assume all k-dependence in β in the following



MEASUREMENT OF β…

Observe $P^S(\mathbf{k})$, where **k** is a 2-component vector



$$P^s(\mathbf{k}) = (1 + \beta\mu_{\mathbf{k}}^2)^2 P(k); \quad \mu_{\mathbf{k}} = \cos\theta;$$

$$\mathrm{P(k)} = \text{angle-averaged, real space}$$

LINEAR KAISER EFFECT:

DISTORTION IS MAX ALONG LINE OF SIGHT

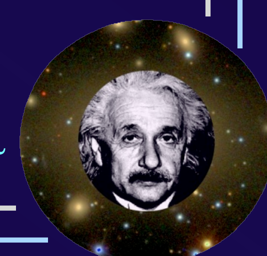
Integrating over θ:

$$P^{s(0)}(k) = \int d\theta P_L^0(\cos\theta) P^s(\mathbf{k}) = \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2\right) P(k)$$

$$P^{s(2)}(k) = \int d\theta P_L^2(\cos\theta) P^s(\mathbf{k}) = \left(\frac{3}{7}\beta + \frac{4}{7}\beta^2\right) P(k)$$

β is proportional to quadrupole to monopole ratio

No need to pass through real space power spectra



… AND OF BIAS!

Via correlation with CMB lensing

$$\phi(\hat{\mathbf{n}}) = -\int d\eta \frac{d_A(\eta_0 - \eta)}{d_A(\eta_0) d_A(\eta)} [\mathbf{\Phi}(d_A\hat{\mathbf{n}}, \eta) + \mathbf{\Psi}(d_A\hat{\mathbf{n}}, \eta)]; \quad \kappa = \frac{1}{2}\nabla^2\phi$$

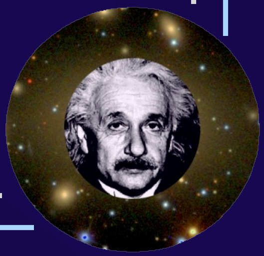
From CMB T and P field one can reconstruct the convergence field κ and its noise

Hu and Okamoto 01, Okamoto & Hu 02

Given a projected galaxy number density map, Σ, I can measure

$$C_\ell^{\kappa-\Sigma} = \frac{3}{2} b\, \Omega_m H_0^2 \int d\eta \frac{W(\eta)}{a(\eta)} P(\frac{\ell}{d_A}, \eta) \frac{d_A(\eta_0 - \eta)}{d_A(\eta) d_A(\eta_0)}$$

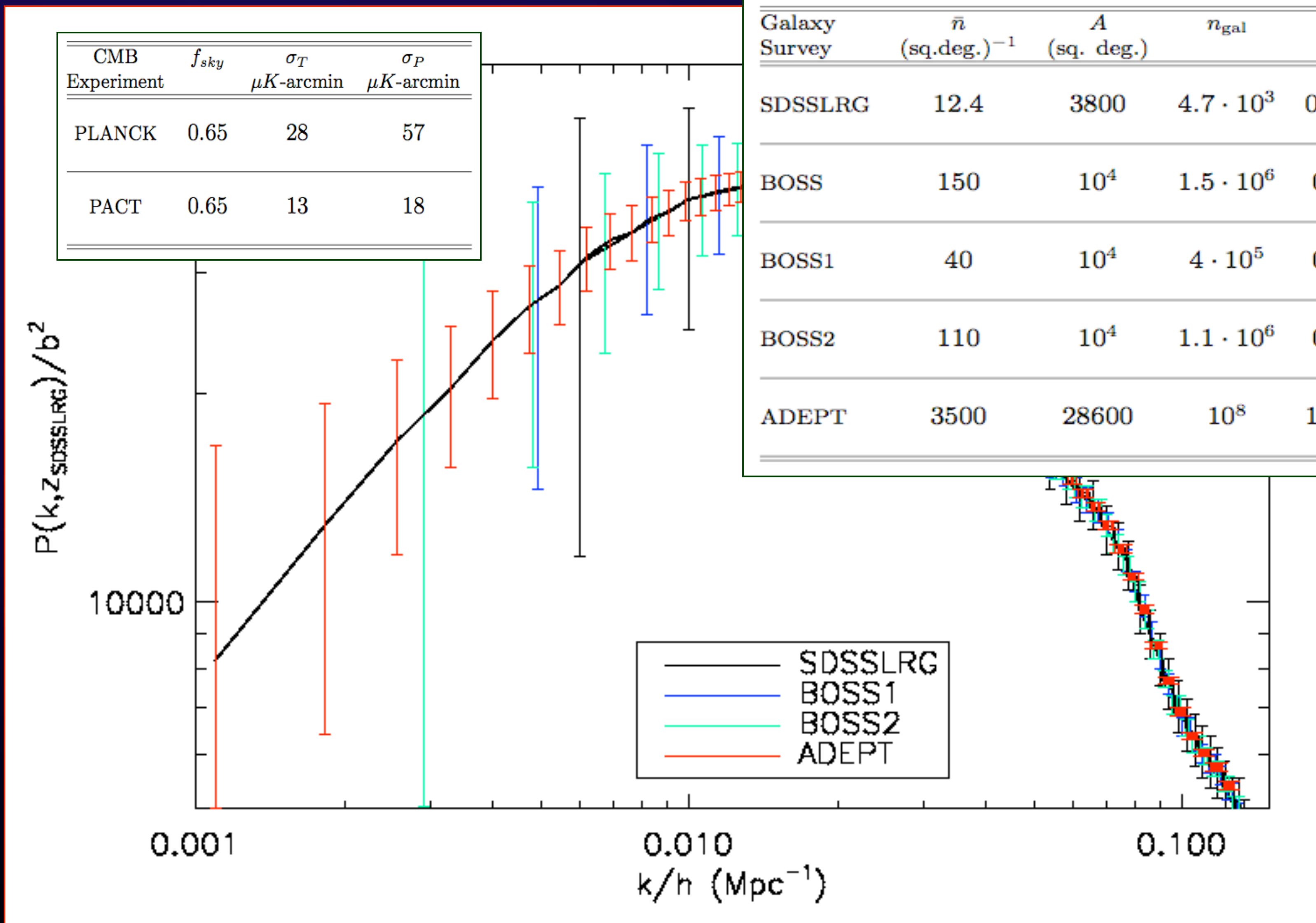
Compare it to theory curve (fixed cosm) → get b

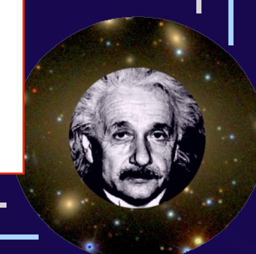


GALAXY SURVEYS AND CMB EXPERIMENTS

CMB Experiment	f_{sky}	σ_T μK-arcmin	σ_P μK-arcmin
PLANCK	0.65	28	57
PACT	0.65	13	18

Galaxy Survey	$\bar{n}$ (sq.deg.)$^{-1}$	A (sq. deg.)	$n_{\rm gal}$	z_c	b
SDSSLRG	12.4	3800	$4.7 \cdot 10^3$	0.31	2
BOSS	150	10^4	$1.5 \cdot 10^6$	0.5	2
BOSS1	40	10^4	$4 \cdot 10^5$	0.3	2
BOSS2	110	10^4	$1.1 \cdot 10^6$	0.6	2
ADEPT	3500	28600	10^8	1.35	1

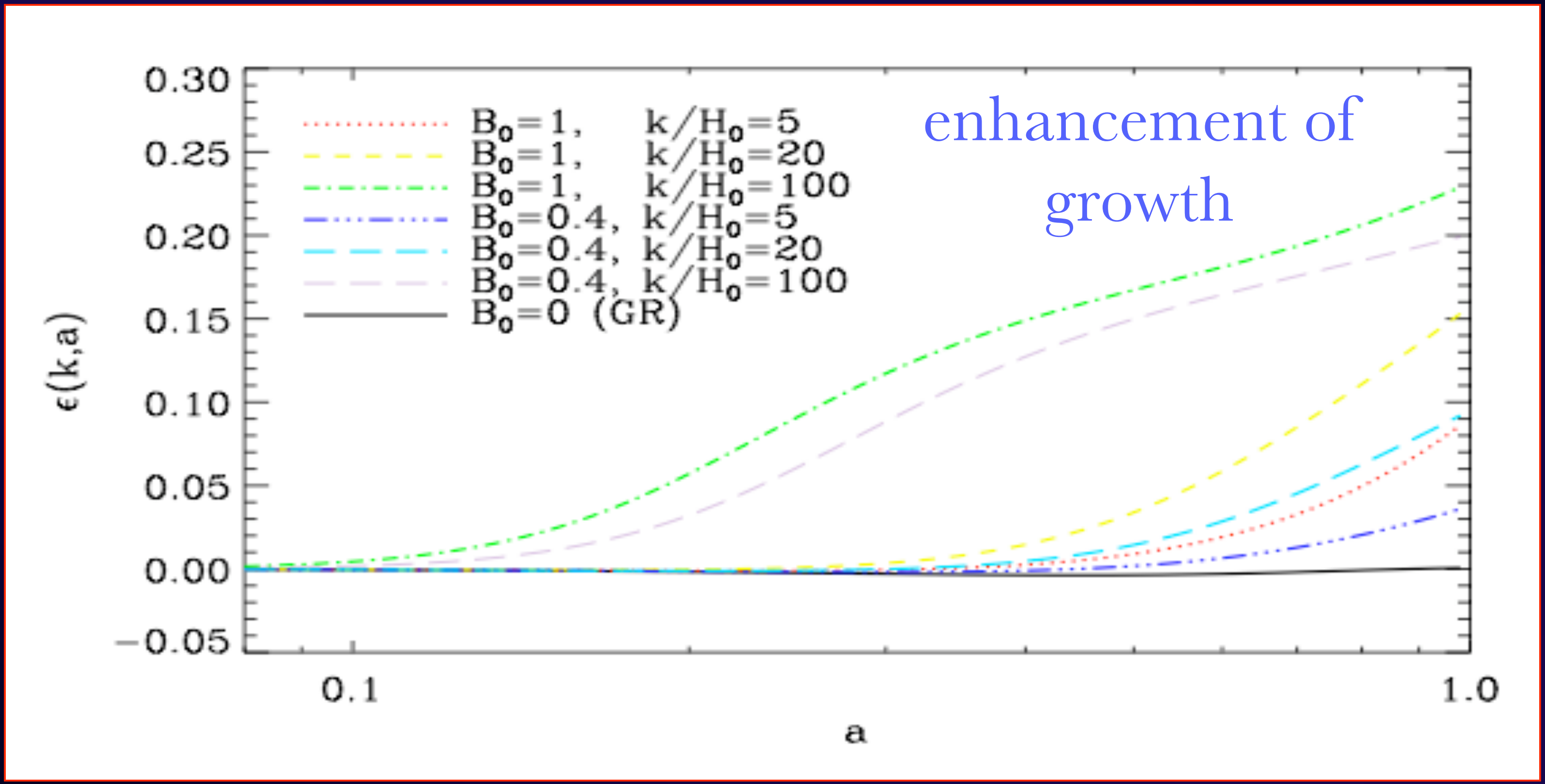




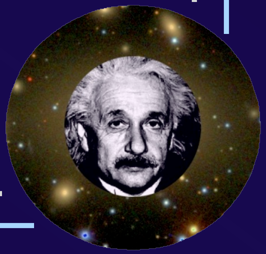
ε(k,a) in f (R) theories (ΛCDM background + B_0)

$B_0 = \propto f_{RR}/(1+f_R)$ measures deviation from GR

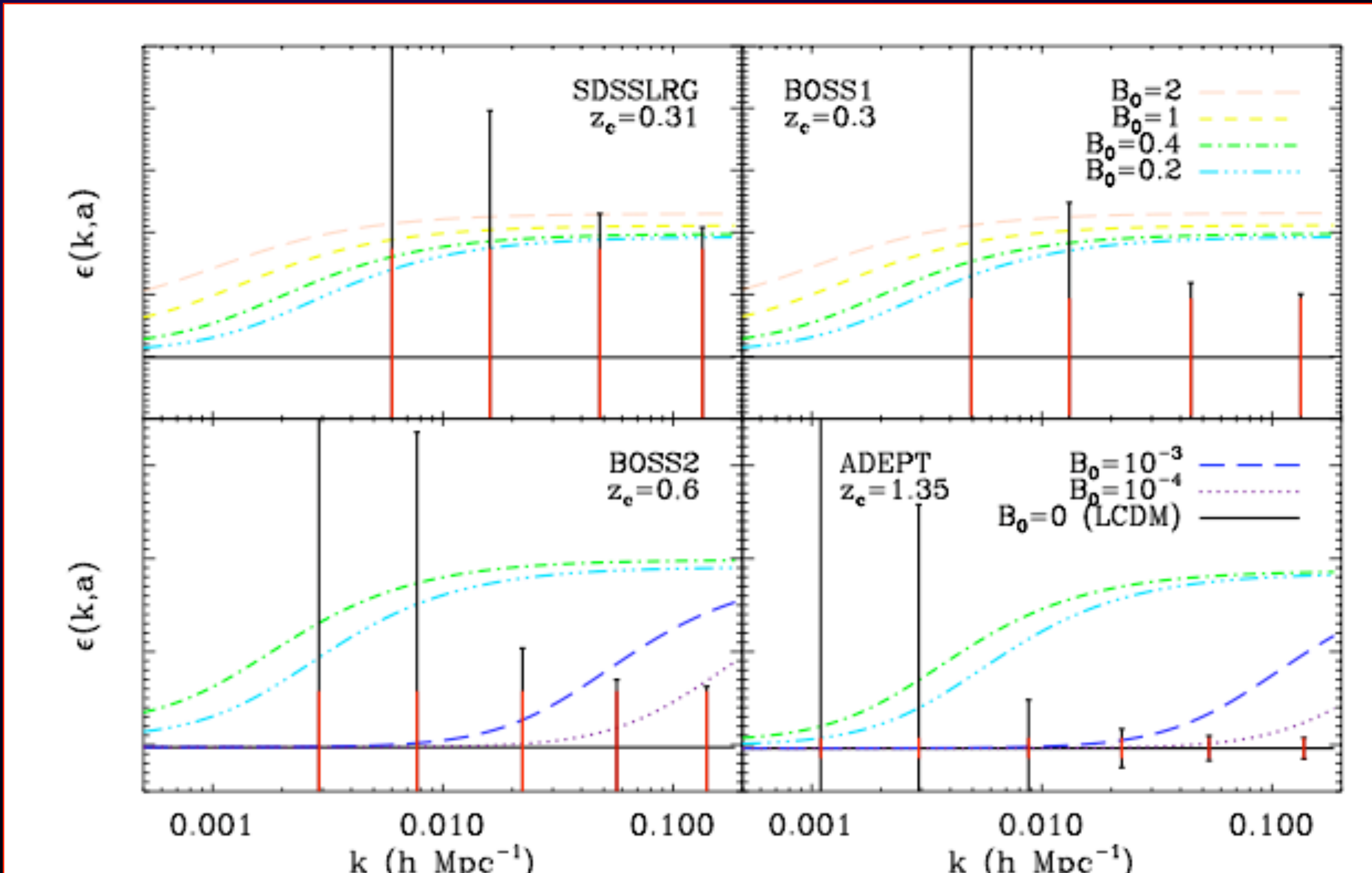
Song, Hu and Sawicki 07; Hu and Sawicki 07



$$\epsilon = \frac{a^{3\gamma} H(a)^{2\gamma}}{(\Omega_{m,0} H_0^2)^2} \frac{d \ln D}{d \ln a} - 1 = 0 \quad \text{in GR}$$

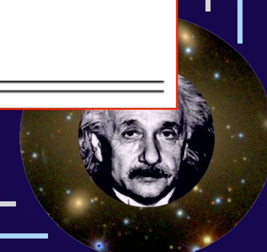


EXPECTED CONSTRAINTS ON ε(k,a)



EXPECTED CONSTRAINTS ON ε(k,a)

COMBINATION OF SURVEYS	z_c	$\Delta b/b(\%)$	$\Delta\epsilon/\epsilon(\%)$ @k/h $\simeq$ 0.02Mpc^{-1}	$\Delta\epsilon/\epsilon(\%)$ @k/h $\simeq$ 0.15Mpc^{-1}
SDSSLRG+PLANCK	0.31	17.3	39.5	21.0
BOSS+PLANCK	0.5	5.0	9.3	5.5
BOSS1+PLANCK	0.3	9.3	$\simeq$ 22	10.1
BOSS2+PLANCK	0.6	5.9	10.6	6.5
ADEPT+PACT	1.35	0.9	2.07	1.1



SUMMARY, CONCLUSIONS, SPARE THOUGHTS

✓ Redshift surveys together with the CMB are an excellent probe of growth

✓ Good probes of growth are essential if we want to be able to discriminate between GR with smooth DE and MoG

✓ We have built a parameter test for GR that tests both the H(z)-D(z) consistency and the scale dependence of MoG

✓ Even if our description is not totally general, many DE model are expected to have ε close to the GR value

✓ As a result, any detection of a non-null ε parameter would be a sign of exciting new physics