Cosmological Tests of GR with Tomographic Surveys

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Phys.Rev.Lett. 103,241301 (2009) [arXiv:0905.1326]
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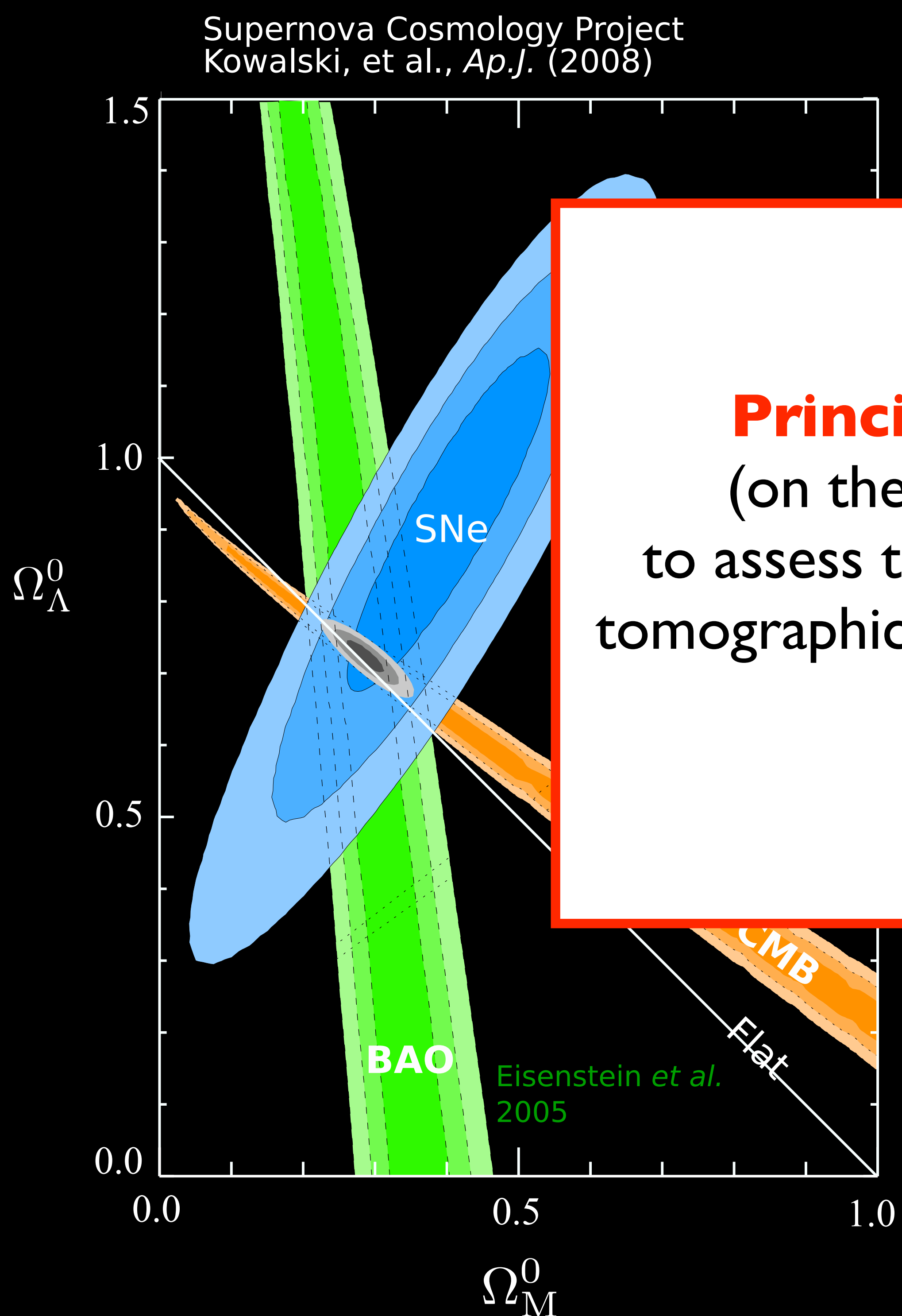
Tomographic Surveys and GR

Cosmic Acceleration: Λ? Modified Gravity ? Dark Energy?



THE GROWTH OF

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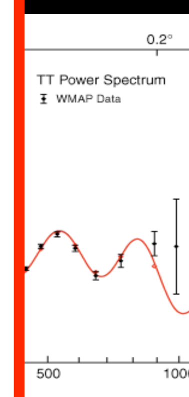
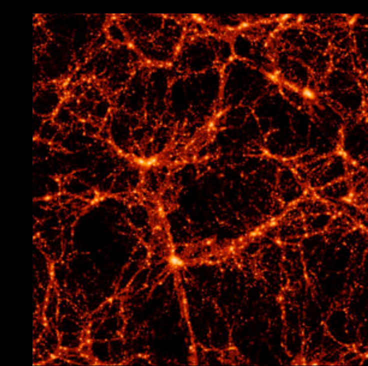




Principal Component Analysis

(on the line of what is done for w(z))

to assess the power of upcoming and future tomographic surveys to detect departures from LCDM

tomographic surveys: they will map the evolution of matter perturbations and gravitational potentials from the matter dominated epoch until today, offering an unprecedented opportunity to test gravity on cosmological scales!!

General Dynamics of Linear Perturbations

Scalar perturbations in Newtonian gauge

$$ds^2 = -a^2(\tau)\,(1+2\Psi)\,d\tau^2 + a^2(\tau)\,(1-2\Phi)\,d\vec{x}^2$$

$$\begin{cases} T^0_0 &= -\rho(1+\delta) \\ T^0_j &= (\rho+P)v_j \\ T^i_j &= (P+\delta P)\delta^i_j + \pi^i_j \end{cases}$$

Energy-momentum conservation eqs.

$$\nabla_\mu T^\mu_\nu = 0$$

$$\begin{aligned} \delta' + \frac{k}{aH}v - 3\Phi' &= 0 \\ v' + v - \frac{k}{aH}\Psi &= 0 \end{aligned}$$

Einstein eqs.

$$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\rho\Delta$$

$$k^2\,(\Phi+\Psi) = -\Sigma(a,k)\frac{a^2}{2M_P^2}\rho\Delta$$

General Dynamics of Linear Perturbations

In LCDM $\mu=1=\Sigma$, however in other models in general they are functions of time and space.

We expect them to differ from unity in:

- Scalar-tensor theories (e.g. f(R), Chameleon) (Brax et al., Amendola, L., Song et al., Pogosian et al., Bean et al., Tsujikawa)
- DGP and higher-dimensional gravity (Afshordi et al., Lue et al., Song et al., Cardoso et al., Koyama et al., Maartens et al.)
- LCDM + massive neutrinos (Lesgourgues et al., Brookfield et al., Hannestad et al., Melchiorri et al., Pettorino et al.)
- DE which clusters and/or carries anisotropic stress (Koivisto et al., Bean et al., Mota et al.)

Searching for modified growth patterns

What is the potential of current and upcoming tomographic surveys to detect departures from GR *(LCDM,quintessence)* **in the growth of structure?**

i.e. to constrain the functions μ and Σ ?

Constraining Departures

For some recent work in this direction see:

Caldwell et al.,PRD 76 (2007)
Zhang et al.,PRL 99 (2008)
Zhao et al.,PRL 103 (2009)
Daniel et al.,PRD 80 (2009)
Guzik et al., arXiv:0906.2221
Bean,R. et al., PRD 81 (2010)
Reyes,R. et al., Nature 464 (2010)
Pogosian et al.,PRD 81 (2010)
Zhao et al.,PRD 81 (2010)
Daniel et al.,PRD 81 (2010)

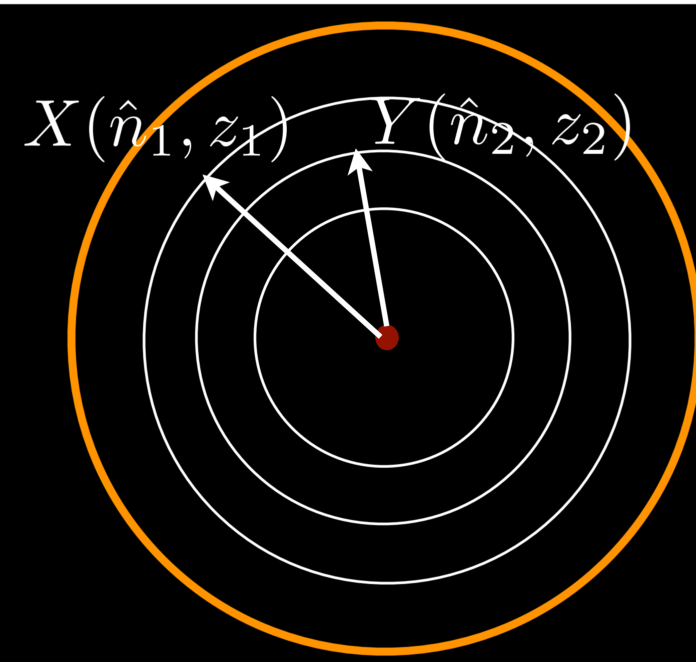
We want to stay as much as possible model-independent and generic.

Therefore we will treat μ and Σ as two unknown functions of time and scale and determine how many d.o.f. of these functions can be (well) constrained by upcoming surveys.

Also, a take-home result will be to determine the "sweet spots" in space and time where the experiments are most sensitive to departures from GR. Inversely, this can be used to guide survey-design in order to test specific candidate models.

Surveys and Observables

We wish to combine multiple-redshift information on Galaxy Count, Weak Lensing, CMB and their cross correlations:
ANGULAR POWER SPECTRA



- SNela (JDEM) + CMB (Planck): expansion history
- Weak Lensing (WL) surveys (DES, EUCLID,LSST): maps of (Φ+Ψ) at different epochs
- Galaxy Number Counts (GC) (DES, EUCLID, LSST): maps of Δ at different epochs
- Galaxy Number Counts x CMB: ISW effect: (Φ+Ψ)’ at different epochs

Forecasting constraints

main tool: Fisher matrix, i.e. the Hessian of the likelihood surface around its extremum.

$$F_{ij} \equiv -\frac{\partial^2 \ln \mathcal{L}}{\partial \theta_i \partial \theta_j}$$

It allows us to determine the shape of the likelihood function around its extremum and hence infer how well the parameters will be constrained.

Therefore it is very informative to diagonalize it, to determine its eigenvalues and eigenmodes. The eigenmodes will correspond to the combinations of parameters which are uncorrelated

Forecasting constraints

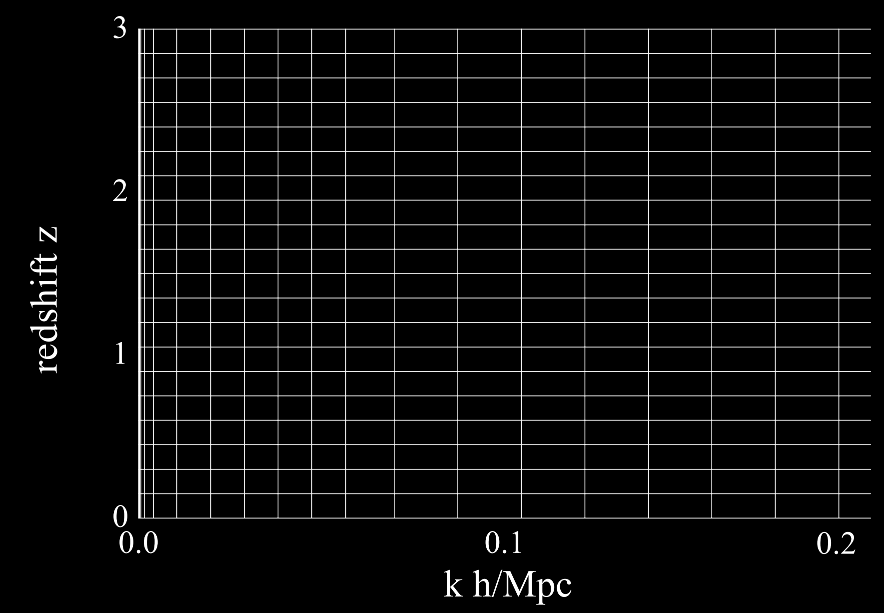
PRINCIPAL COMPONENT ANALYSIS

(A.J.S.Hamilton and M.Tegmark, astro-ph/9905192, MNRAS'00
D.Huterer and G.Starkman, astro-ph/0207517, PRL'03)

We will treat μ and Σ as two unknown functions of time and scale and determine how many d.o.f. of these functions can be (well) constrained by upcoming surveys

Detailed Procedure

- discretize μ and Σ on a (k,z) grid
- treat their values in each pixel, μ_{ij} and Σ_{ij}, as free parameters
- calculate the Fisher Matrix to forecast the covariance of ~ 840 parameters

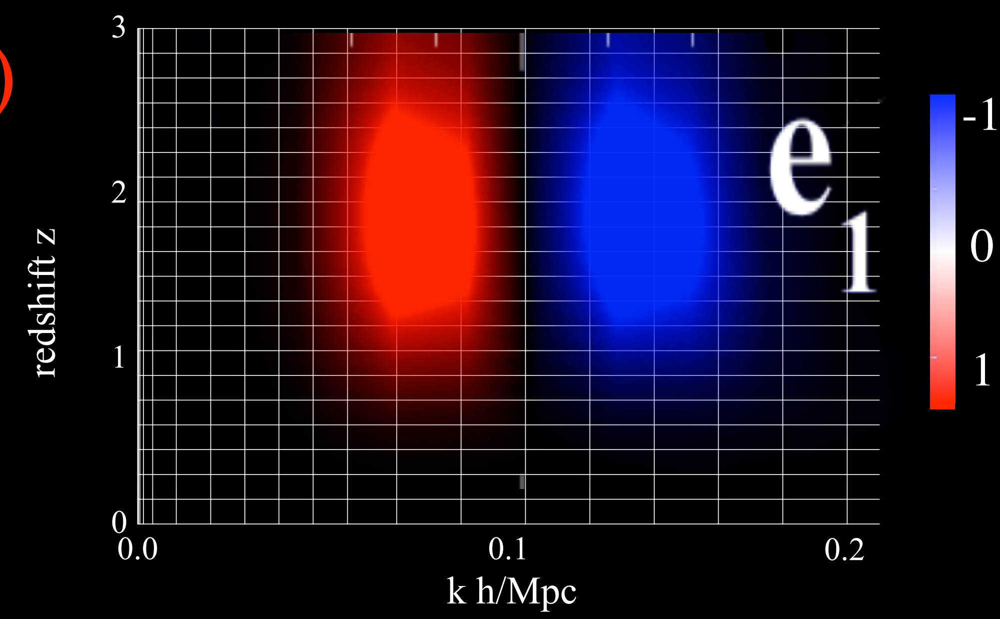


Principal Components of μ

...marginalizing over the other parameters...

- consider only its μ block and diagonalize it to find uncorrelated combinations of μ_{ij}

- each eigenmode represents a surface in the (k,z) space



- they form an orthonormal basis for the function μ:

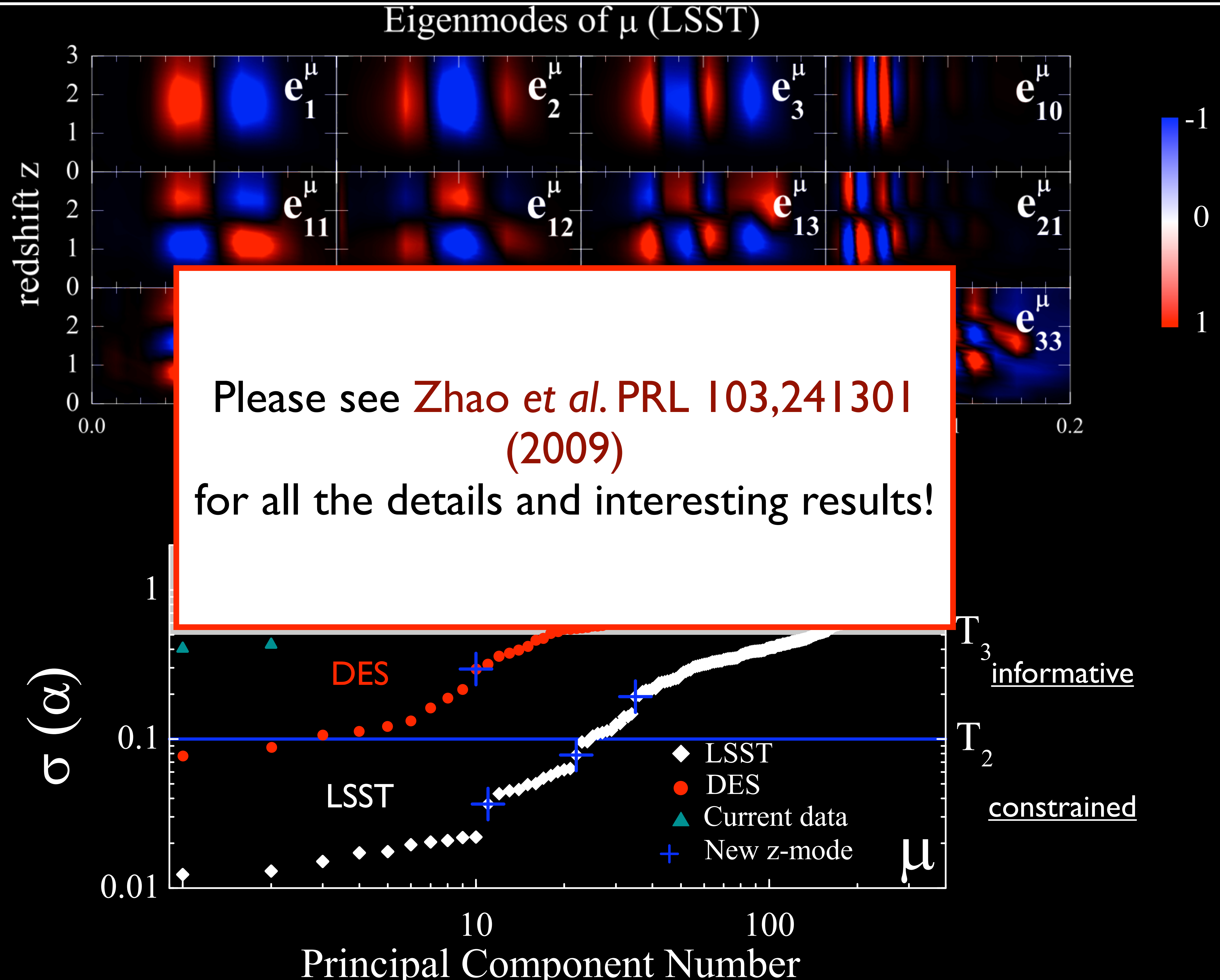
$$\mu(k,z) - 1 = \sum_m \alpha_m e_m(k,z)$$

- the eigenvalues of the PCs correspond to the variances of the expansion coefficients

$$\lambda_m = \left[\sigma^2(\alpha_m)\right]^{-1}$$

Principal Components of μ

...marginalizing over the other parameters...



Please see Zhao *et al.* PRL 103,241301 (2009)

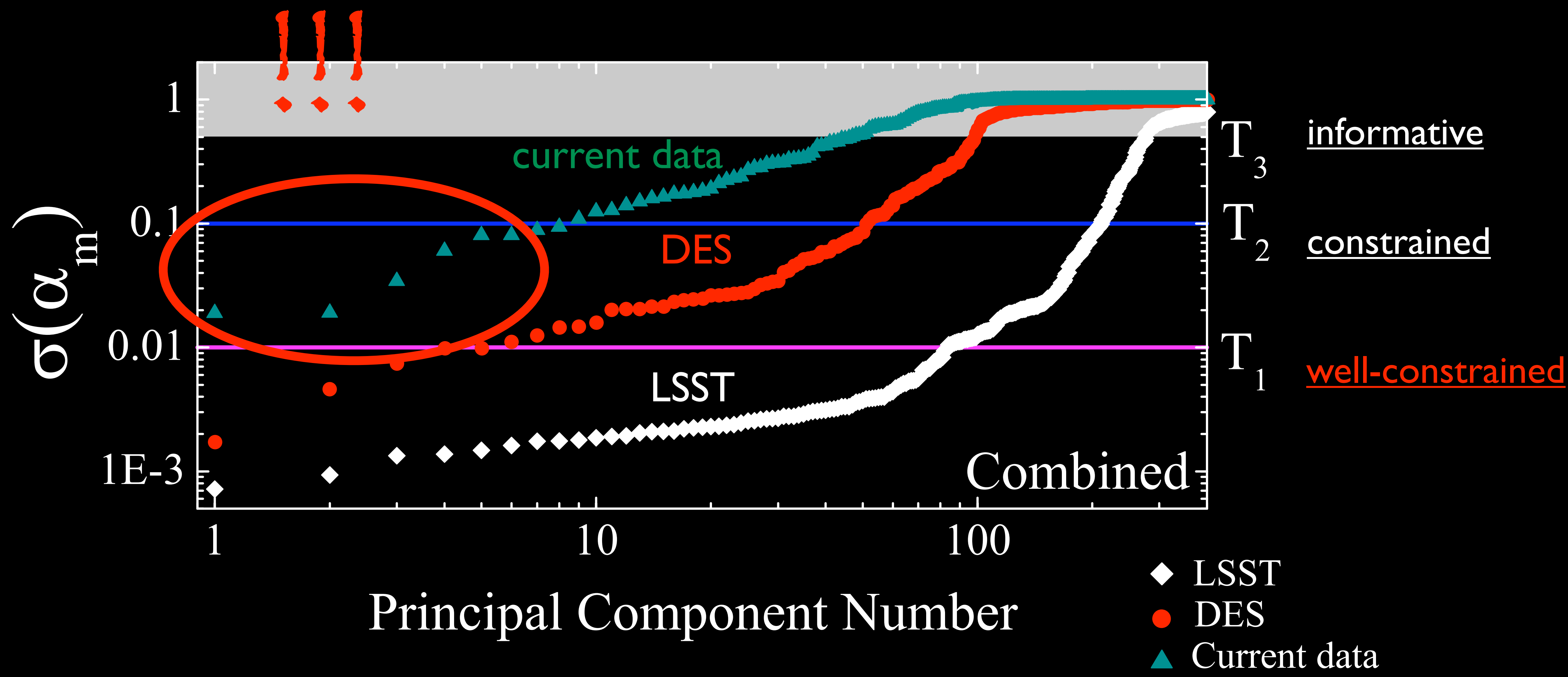
for all the details and interesting results!

What if we want to constrain ANY departure from LCDM?

To determine how well we can constrain *any departure* from LCDM we can find the *combined* eigenmodes of μ and Σ.

Combined eigenmodes of μ and Σ

uncertainties:



Current Cosmological Data

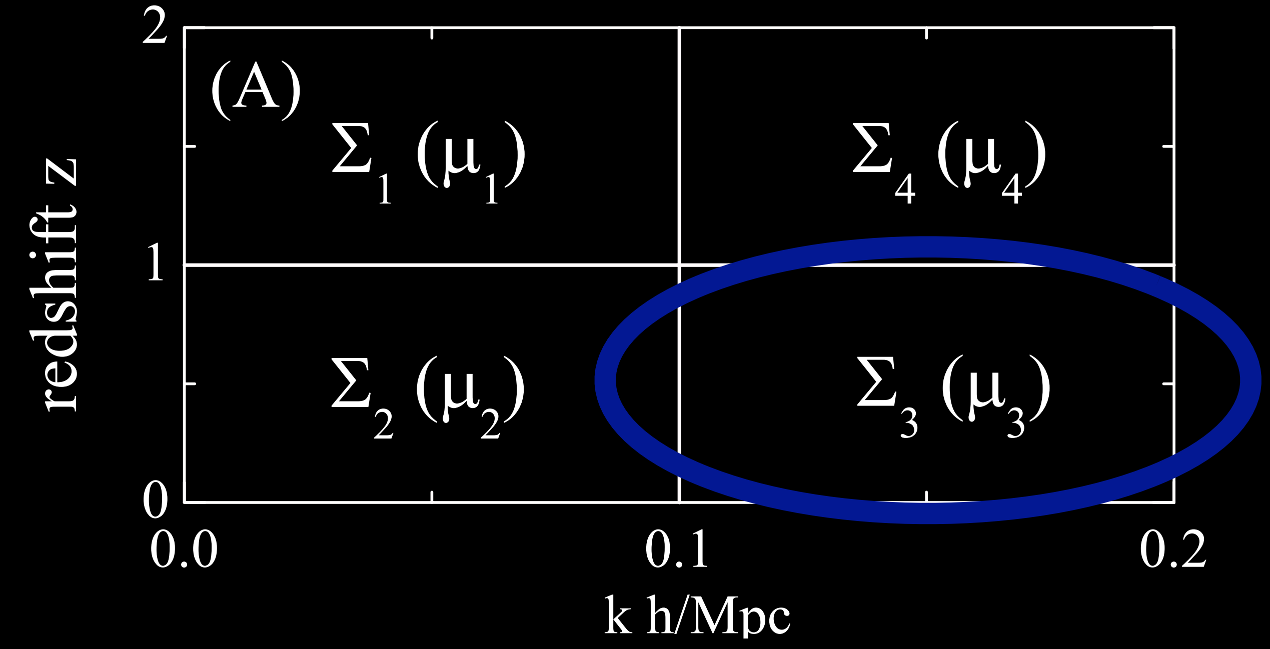
SNeIa: Kessler *et al.* 2009 combination of
Nearby+SDSS-II+ESSENCE+SNLS
+HST
(0.04 < z < 0.42)

CMB: WMAP5

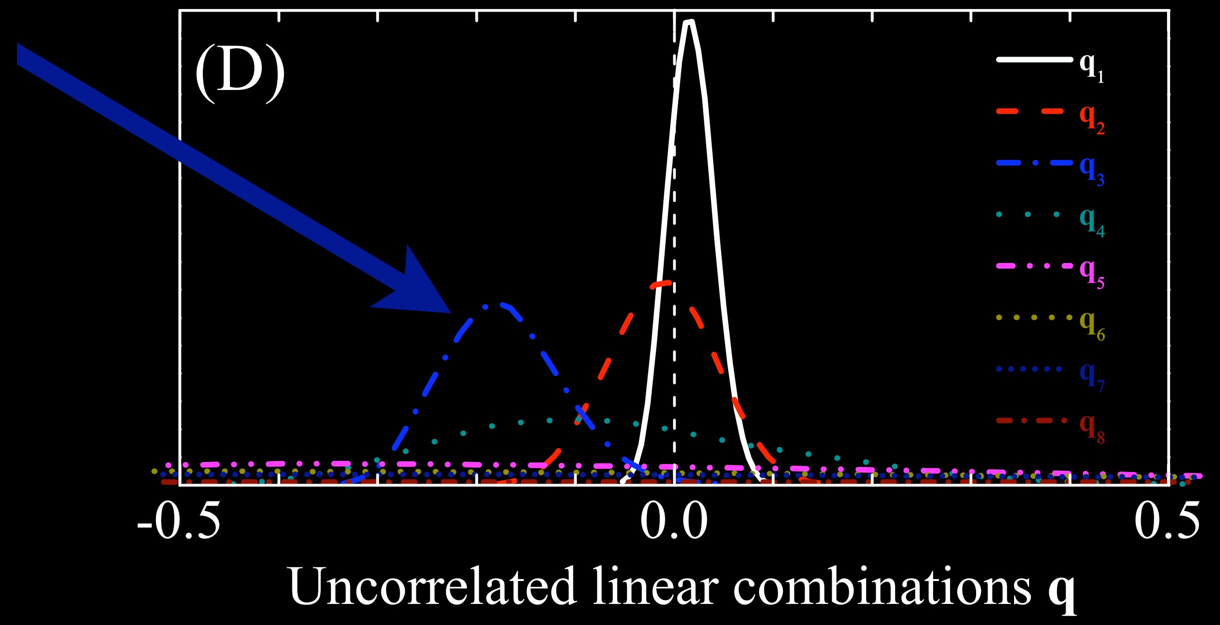
Weak Lensing: Fu *et al.* 2008 (Kilbinger *et al.* 2009)
CFHTLS-Wide 3rd year data
(2×10^6 galaxies, 57 sq. deg.)

ISW: Giannantonio *et al.* 2008 cross-correlation of multiple galaxy catalogs (2MASS, SDSS, NVSS, HEAO) with CMB (WMAP3)
(0.1 < z < 1.5)

Current Cosmological Data

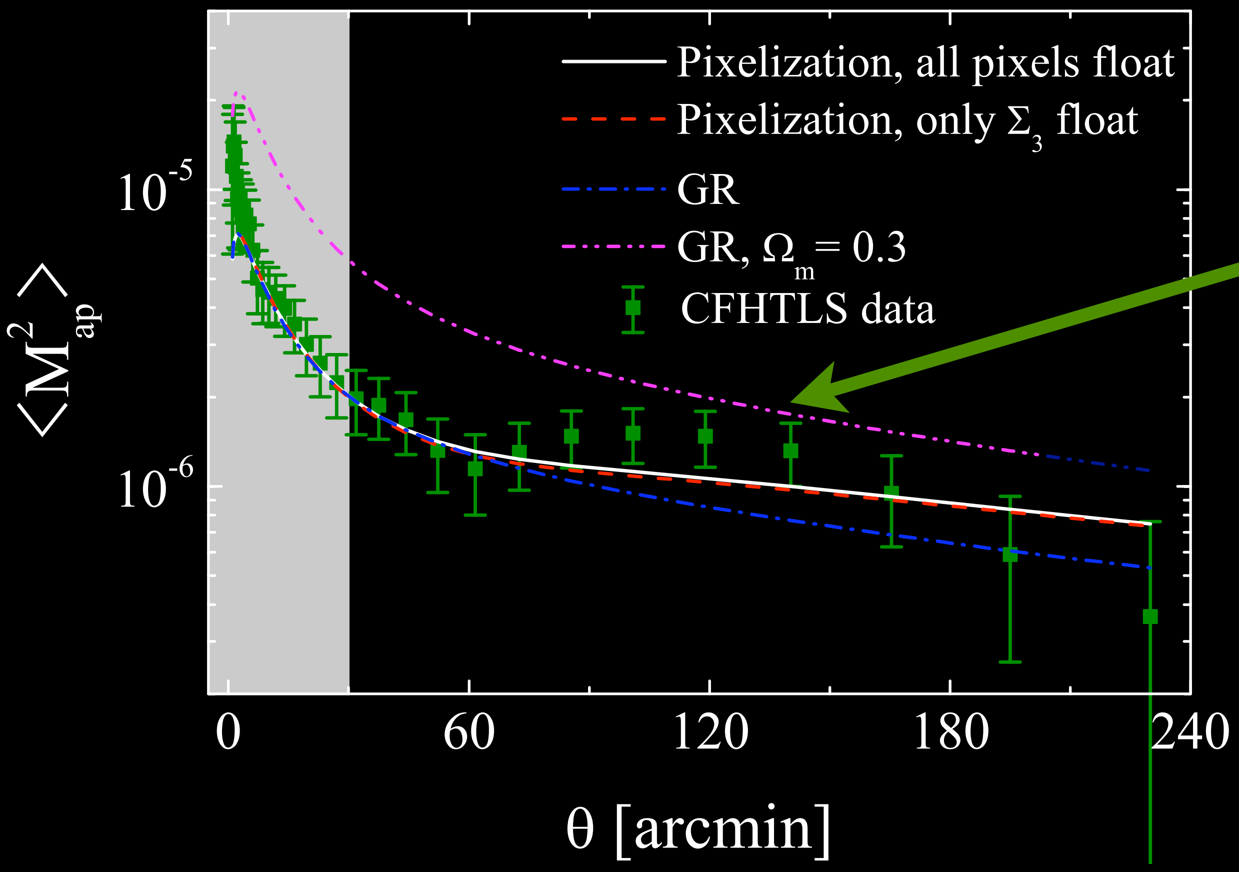


$$q_3 \approx \Sigma_3 - 1 = -0.17 \pm 0.06^{+0.13}_{-0.11}$$



1D Posterior distribution

Current Cosmological Data



residual field-to-field variations on the scale of the camera field of view

↓

probably systematics and NOT deviations from GR

Conclusions

We have analyzed the constraints on modifications of GR that one can expect from future and existing data sets:

This model-independent analysis shows that future surveys will offer a wealth of information on the relations between mass, gravitational potential and curvature of space

We find that data is somewhat more sensitive to scale-dependent than time-dependent modifications of growth

Current data can already put some constraints on the combination of μ and Σ, showing consistency with LCDM except for some "systematics" in the WL (CFHTLS) data.

THANK YOU!