Cosmological Tests of General Relativity with Tomographic Surveys

Cosmology on the Beach
January, 14th 2011

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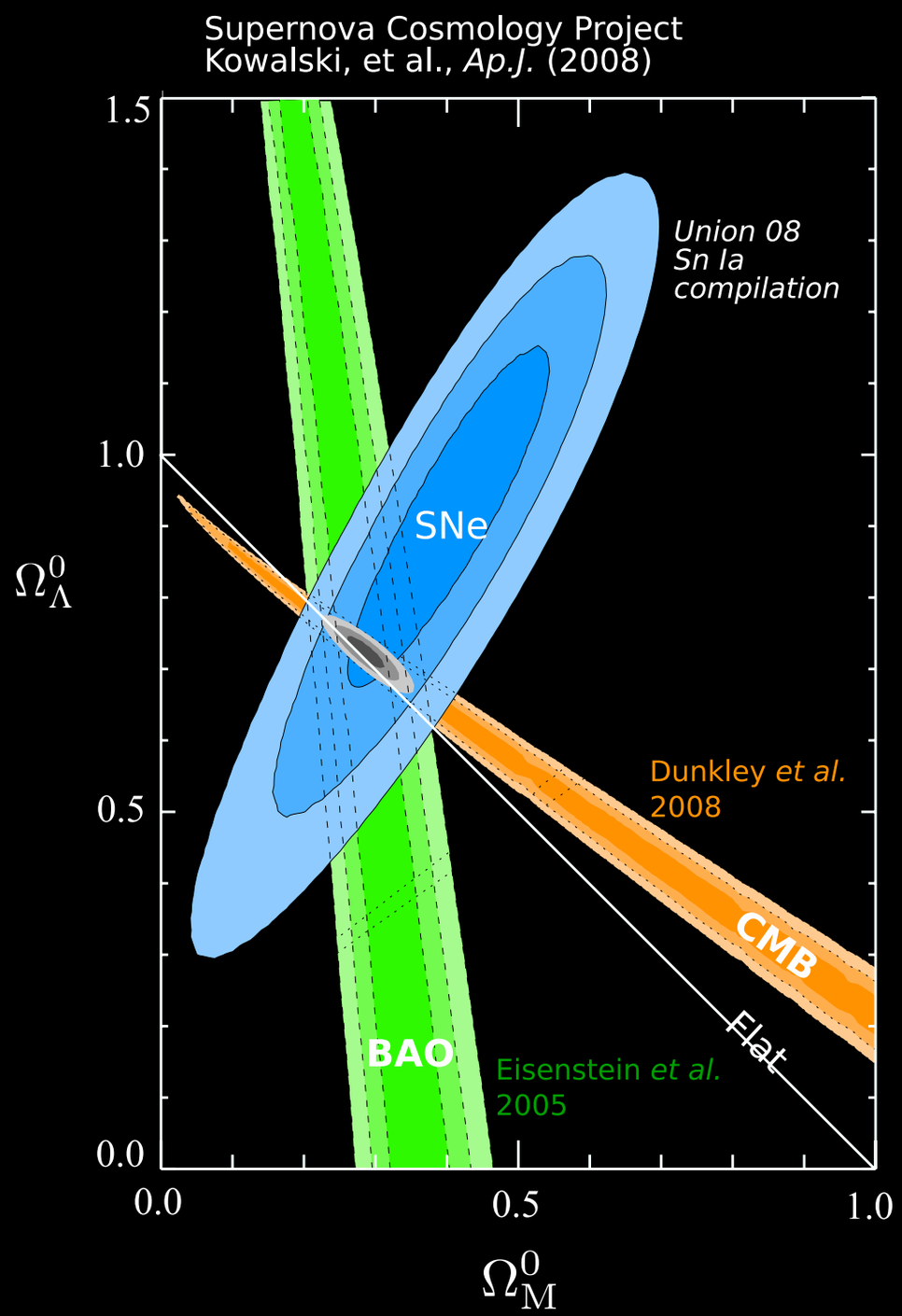
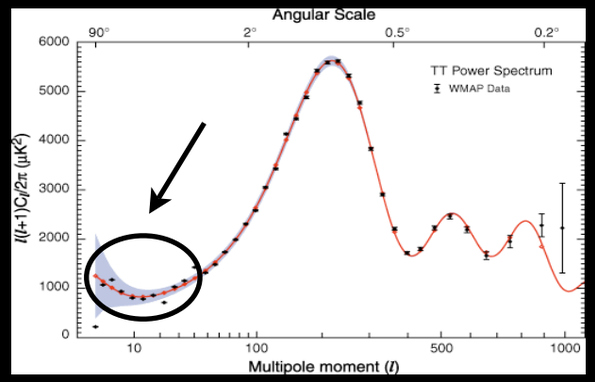
Phys.Rev.D81:103510 (2010) [arXiv:1003.0001]
Phys.Rev.Lett. 103,241301 (2009) [arXiv:0905.1326]
Phys.Rev.D81:104023 (2010) [arXiv:1002.2382]

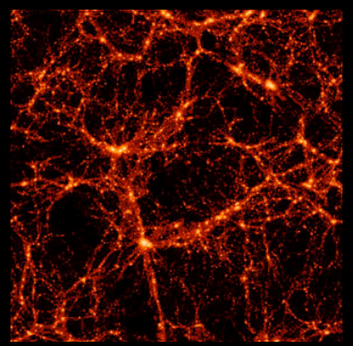
Tomographic Surveys and GR

Cosmic Acceleration: Λ? Modified Gravity ? Dark Energy?



THE GROWTH OF STRUCTURE





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!!

Tomographic Surveys and GR

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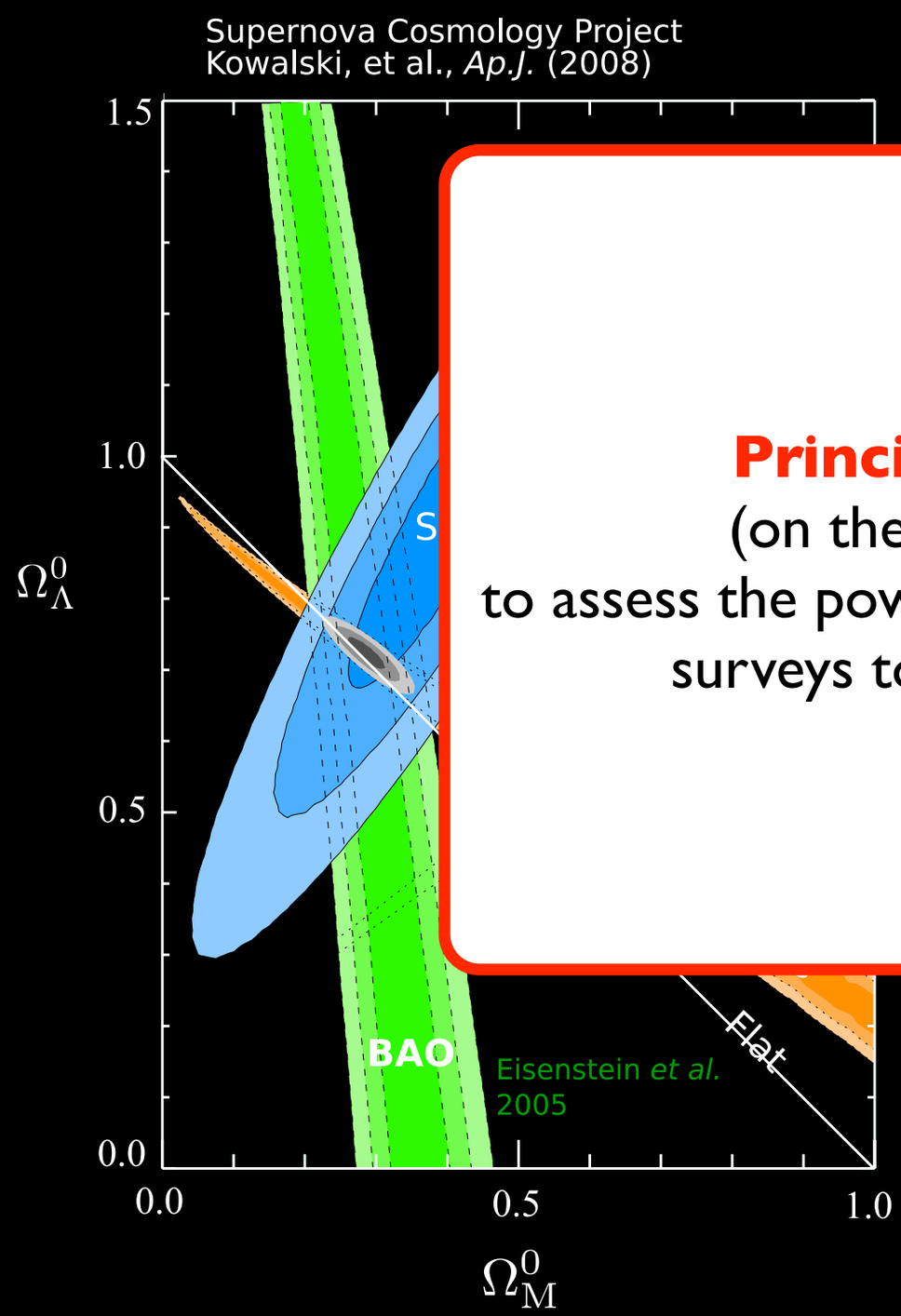
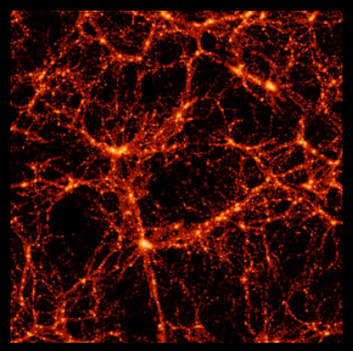


OF



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

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.

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

$$\delta' + \frac{k}{aH}v - 3\Phi' = 0$$

$$v' + v - \frac{k}{aH}\Psi = 0$$

Einstein eqs.

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

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

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 <u>model-independent</u> and <u>generic</u>.

Therefore we will treat μ and Σ as two unknown functions of time and <u>scale</u> 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 <u>survey-design</u> in order to test specific candidate models.

Forecasting constraints

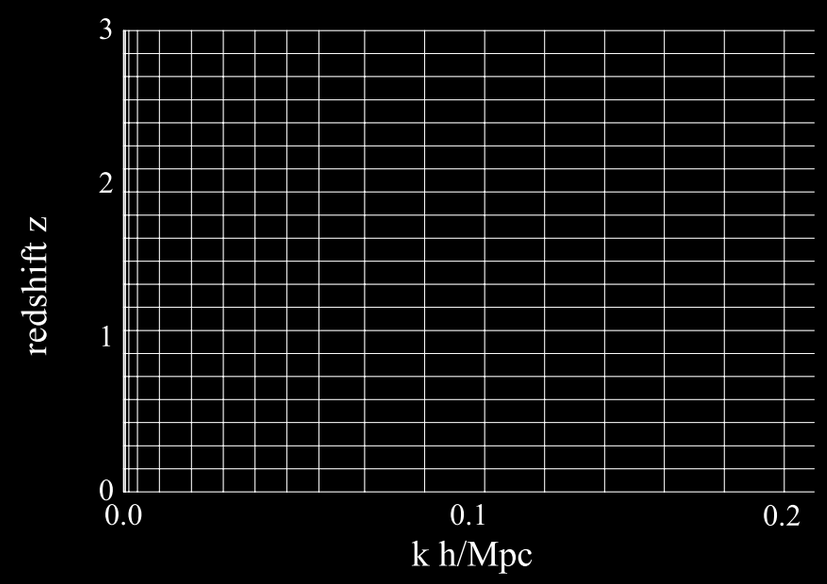
PRINCIPAL COMPONENT ANALYSIS

(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



Observables

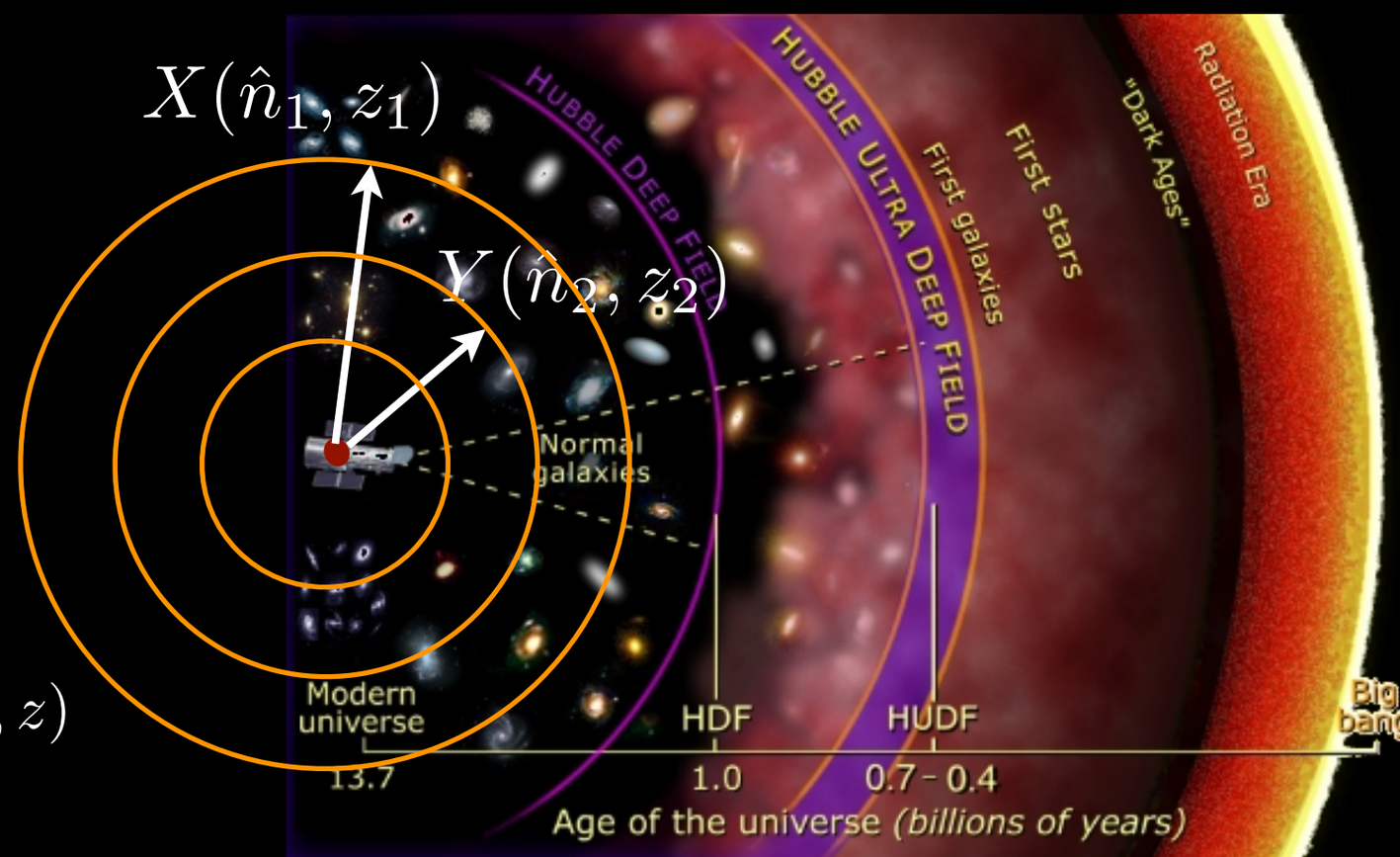
Upcoming and future tomographic surveys will map the evolution of matter perturbations and gravitational potentials from the matter dominated epoch until today.

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

Therefore the observables are the ANGULAR POWER SPECTRA:

$$C_l^{XY} = 4\pi \int \frac{dk}{k} \Delta_{\mathcal{R}}^2 I_l^X(k) I_l^Y(k)$$

$$I_l^X(k) = c_{x\mathcal{R}} \int_0^{z_*} dz\, W(z) j_l[kr(z)] \tilde{X}(k,z)$$



Theory & Surveys

THEORY:

set of parametrized equations → theoretical predictions for the observables

(from Boltzmann integrator MGCAMB)

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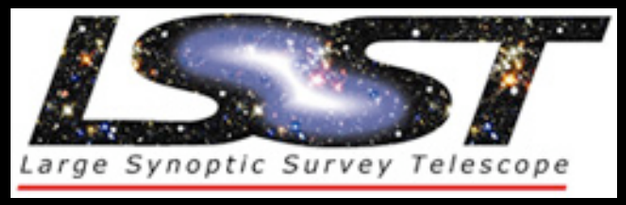
SURVEYS:

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

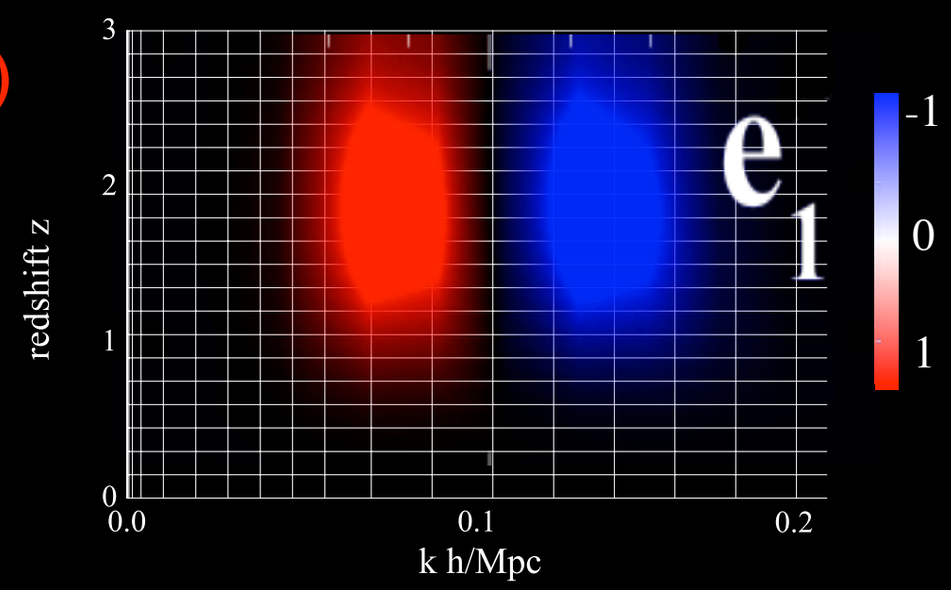


Principal Components of μ

...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:

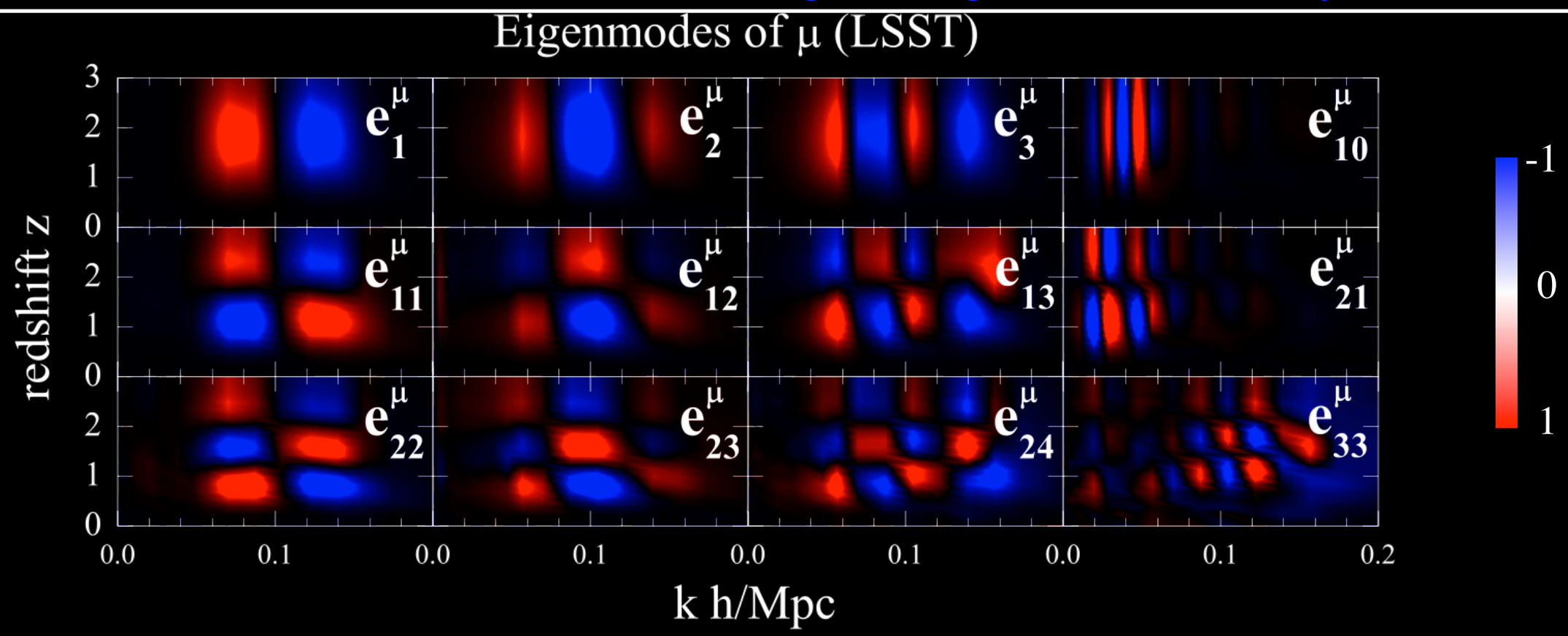
$$\mu(k,z) - 1 = \sum_m \alpha_m e_m(k,z)$$

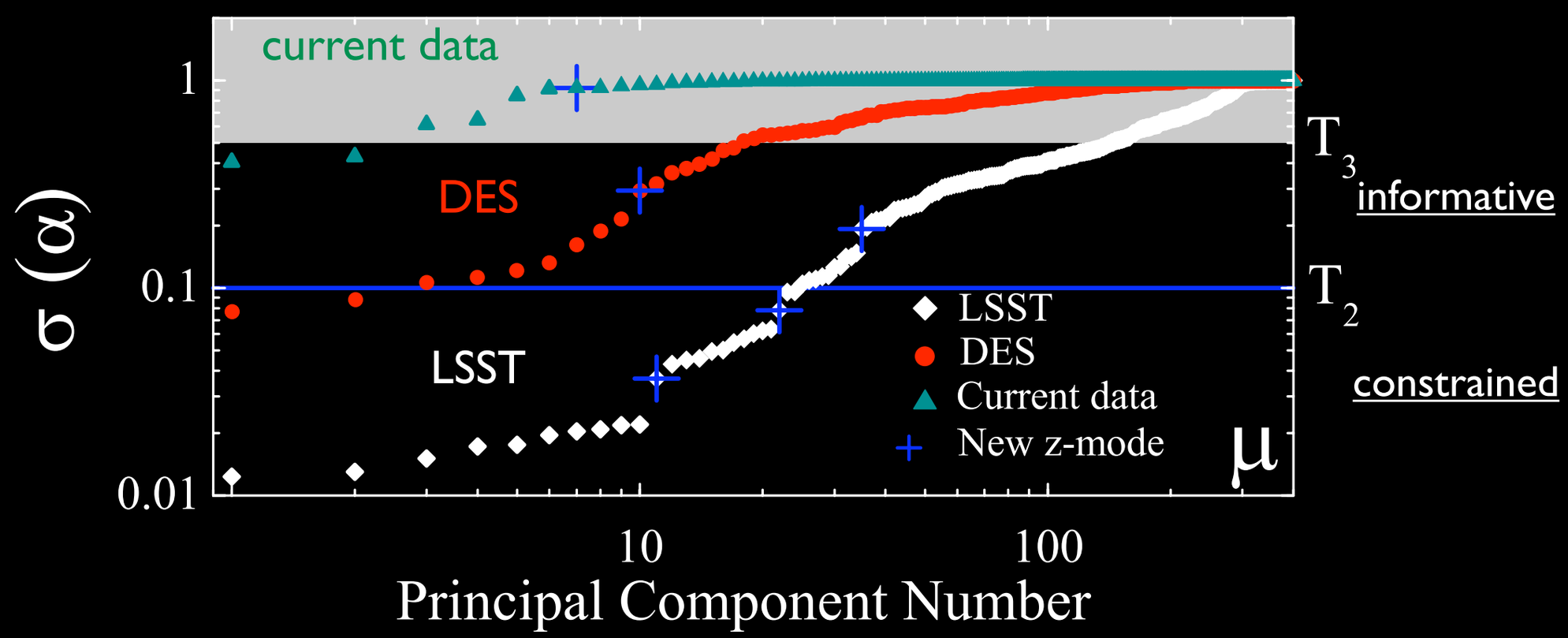
- the eigenvalues of the PCs correspond to the variances of the expansion coefficients

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

Principal Components of μ

...marginalizing over the other parameters...





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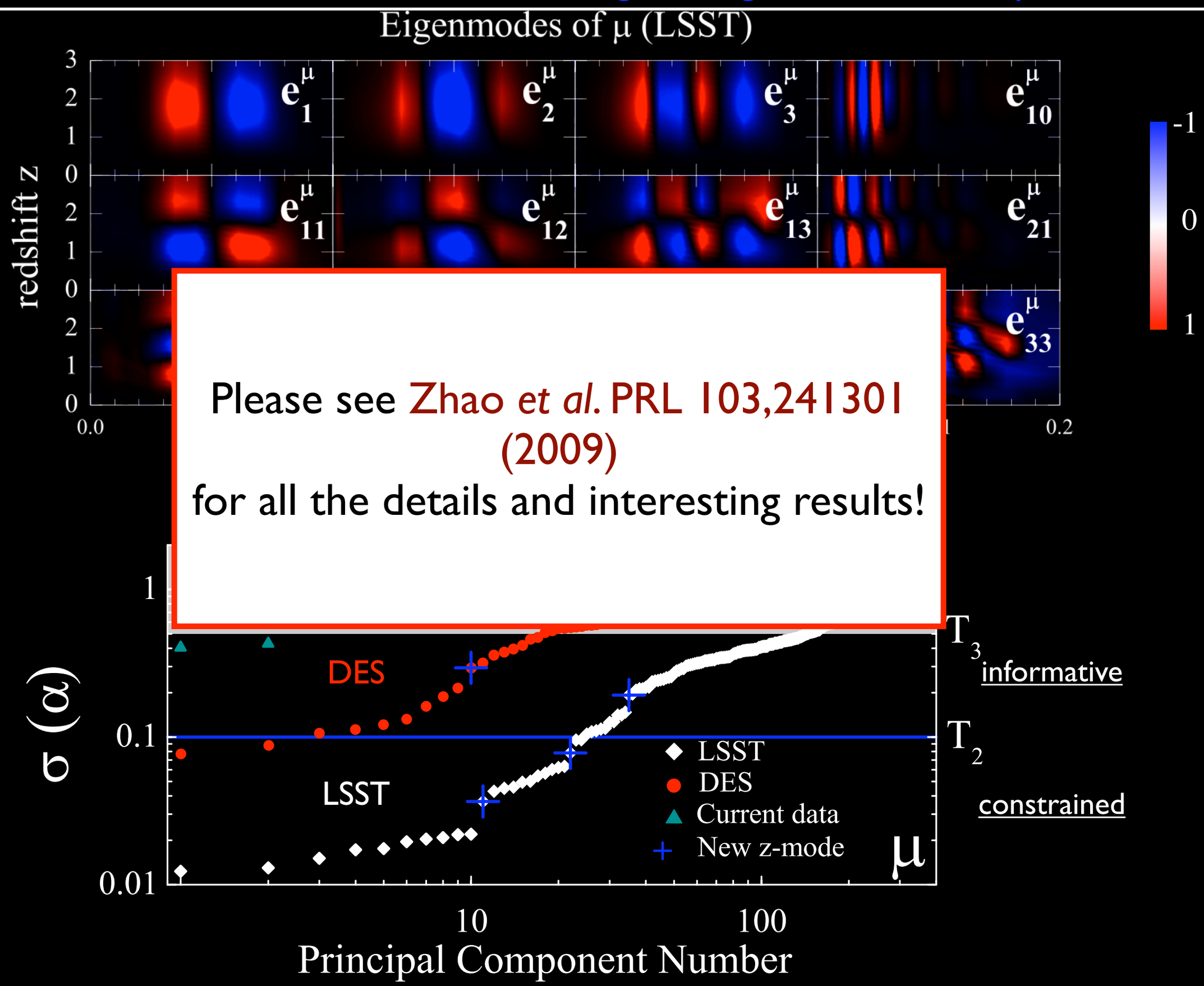


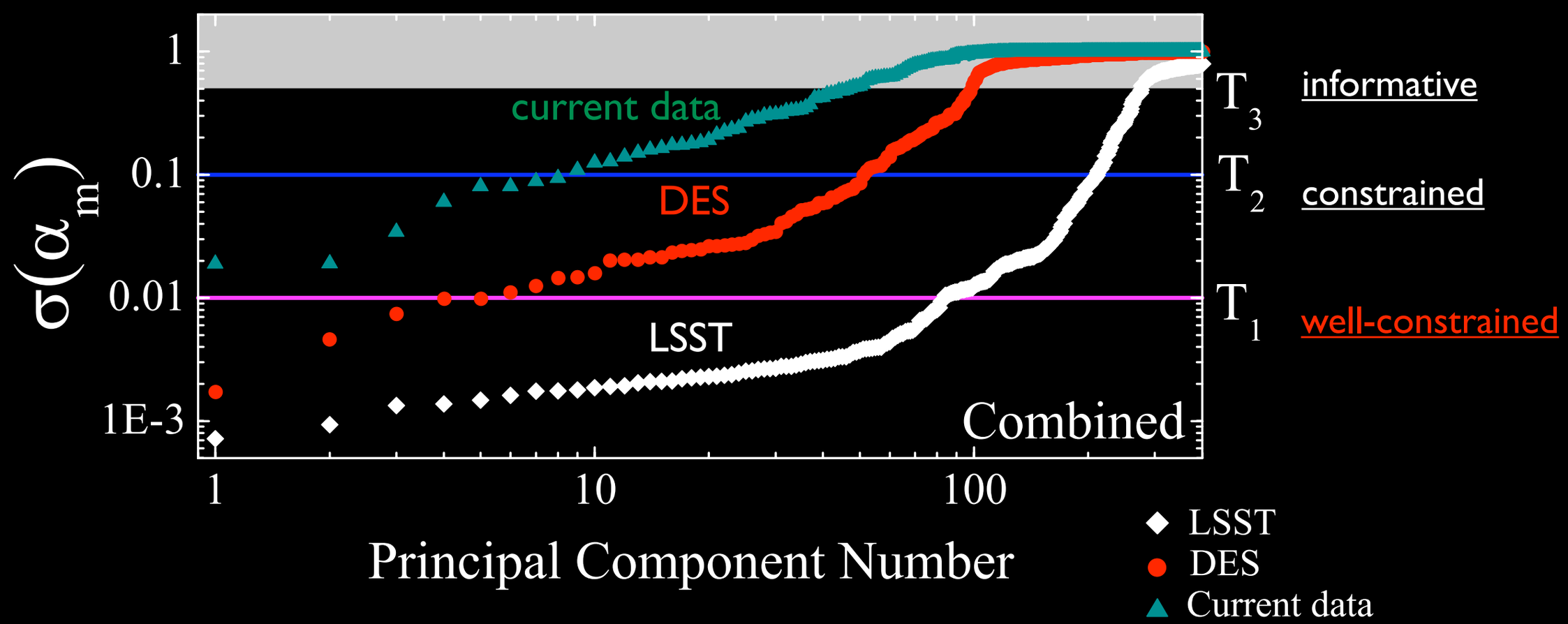
Please see Zhao *et al.* PRL 103,241301 (2009)
for all the details and interesting results!

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:



Combined eigenmodes of μ and Σ

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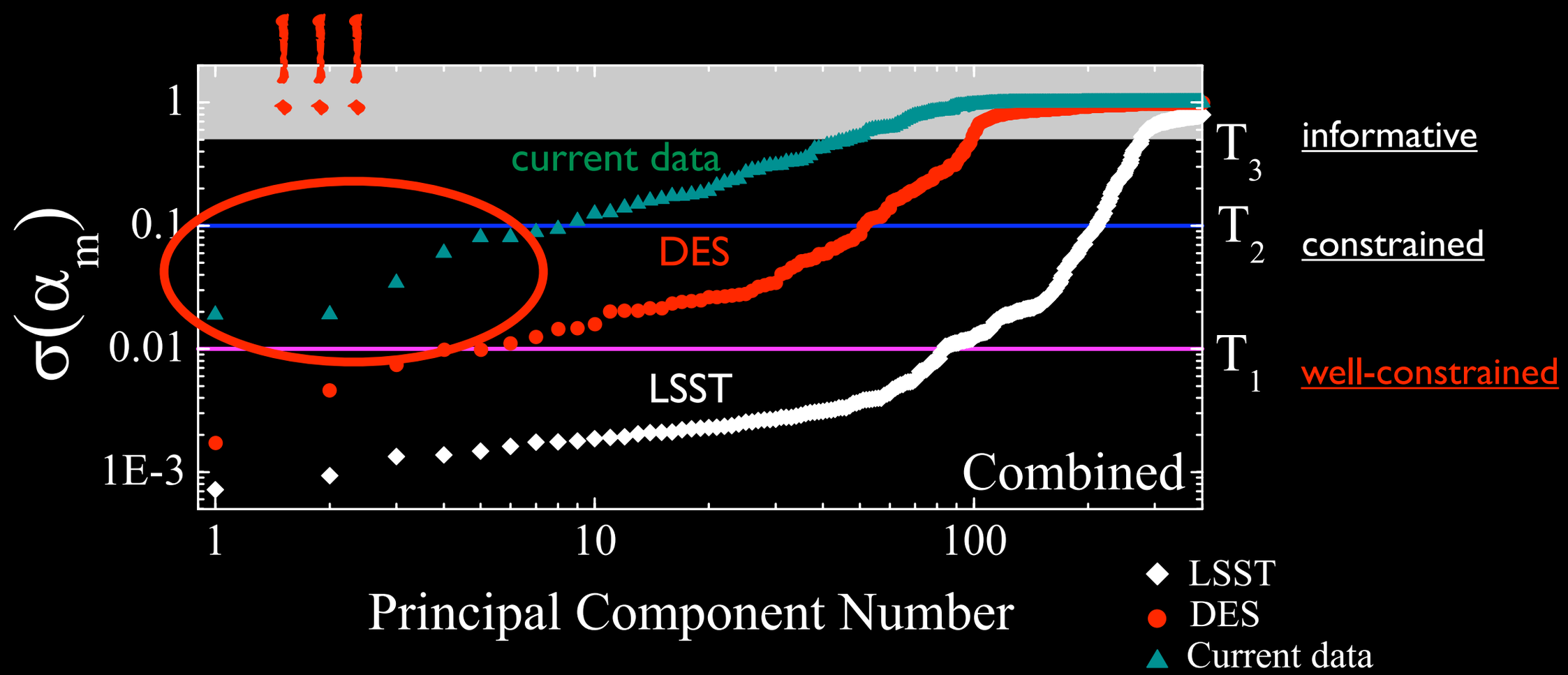

Combined eigenmodes of μ and Σ

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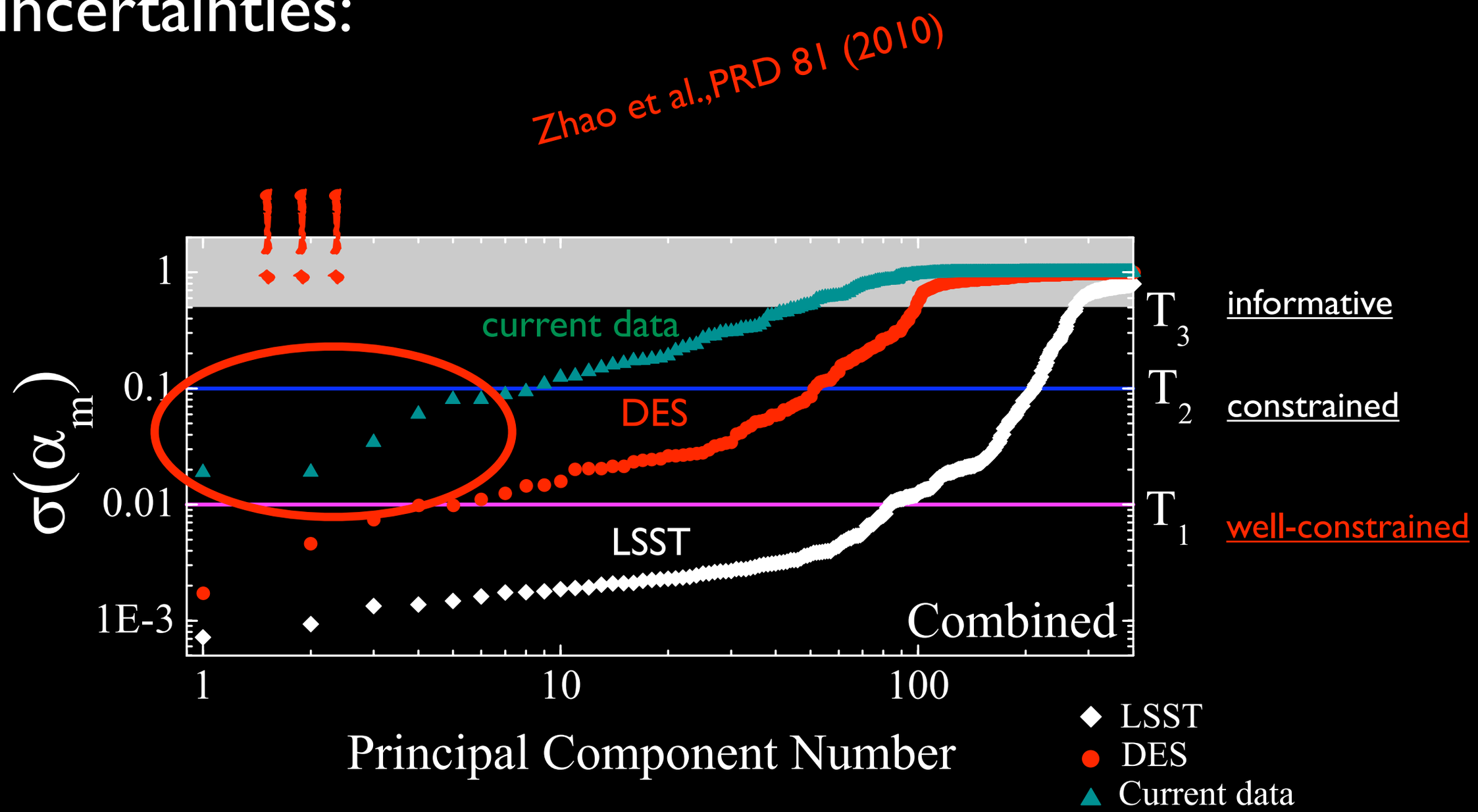

Conclusions

We have analyzed (in a model-independent way) the potential of cosmological data sets to constrain GR

Future surveys will offer a wealth of information on the relations between mass, gravitational potential and curvature of space on cosmological scales

Data is somewhat more sensitive to scale-dependent features

Pogosian et al.,PRD 81 (2010)

Current data has already some detecting/constraining power on departures from standard growth

Zhao et al.,PRD 81 (2010)

see also: Bean,R. et al., PRD 81 (2010) Daniel et al.,PRD 81 (2010)

THANK YOU!

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.)

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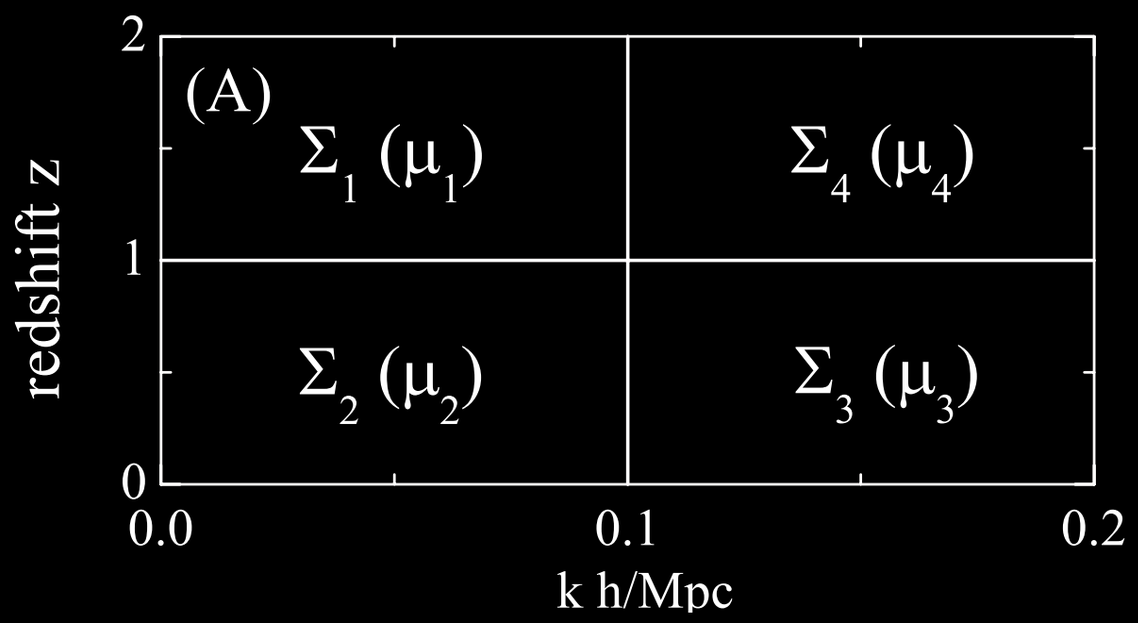

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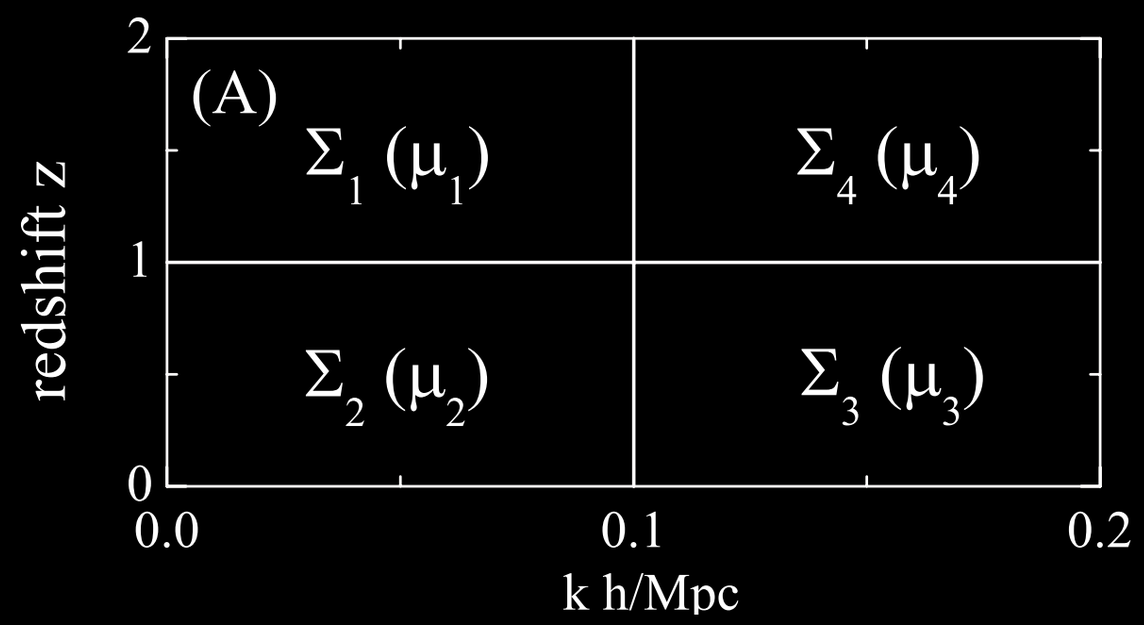
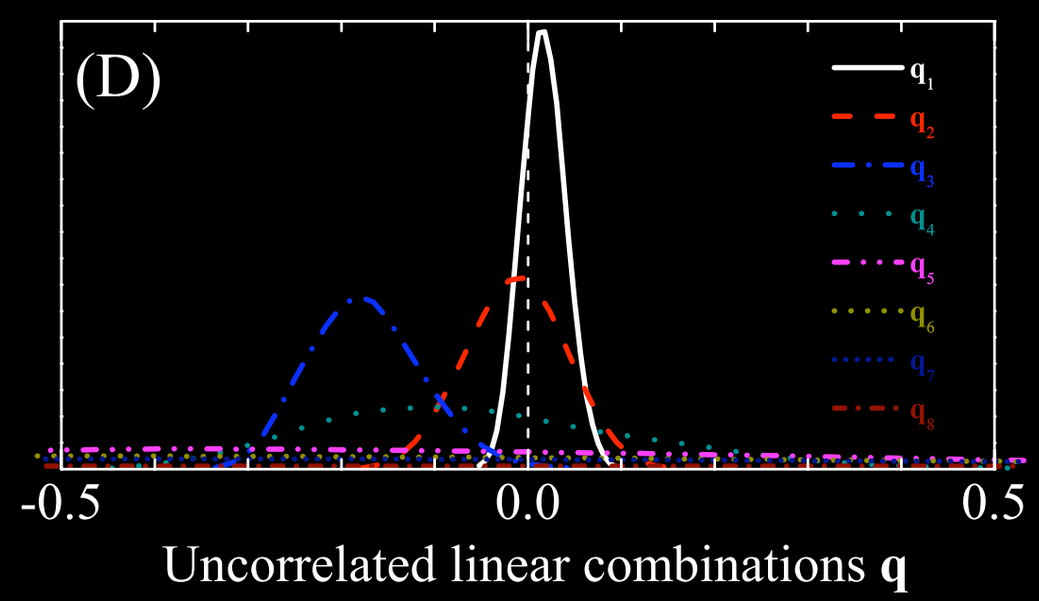
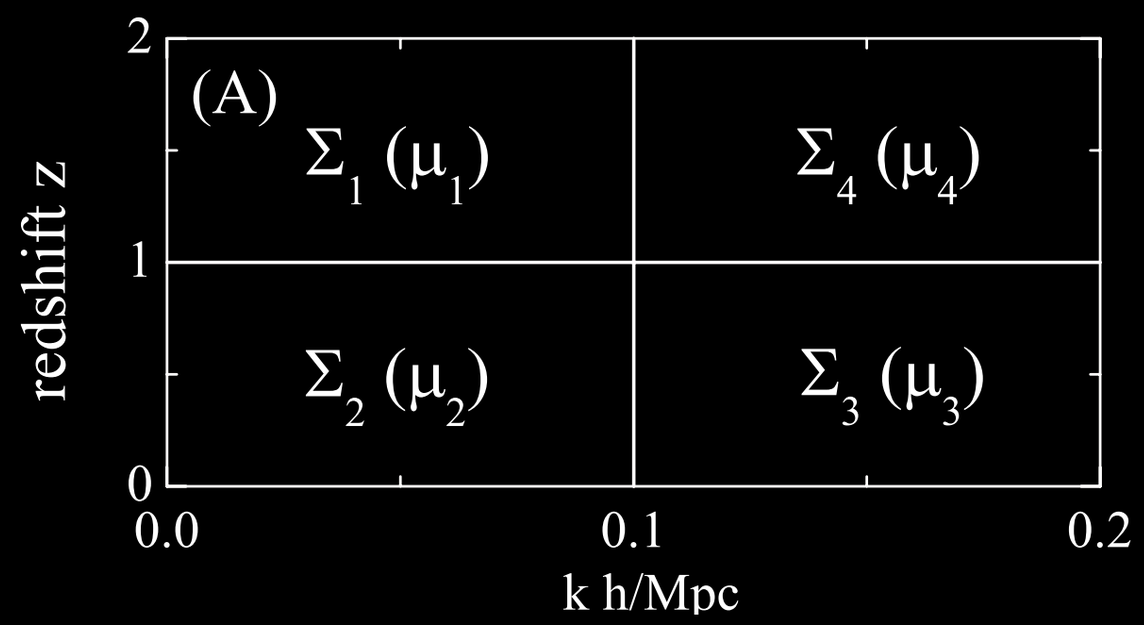
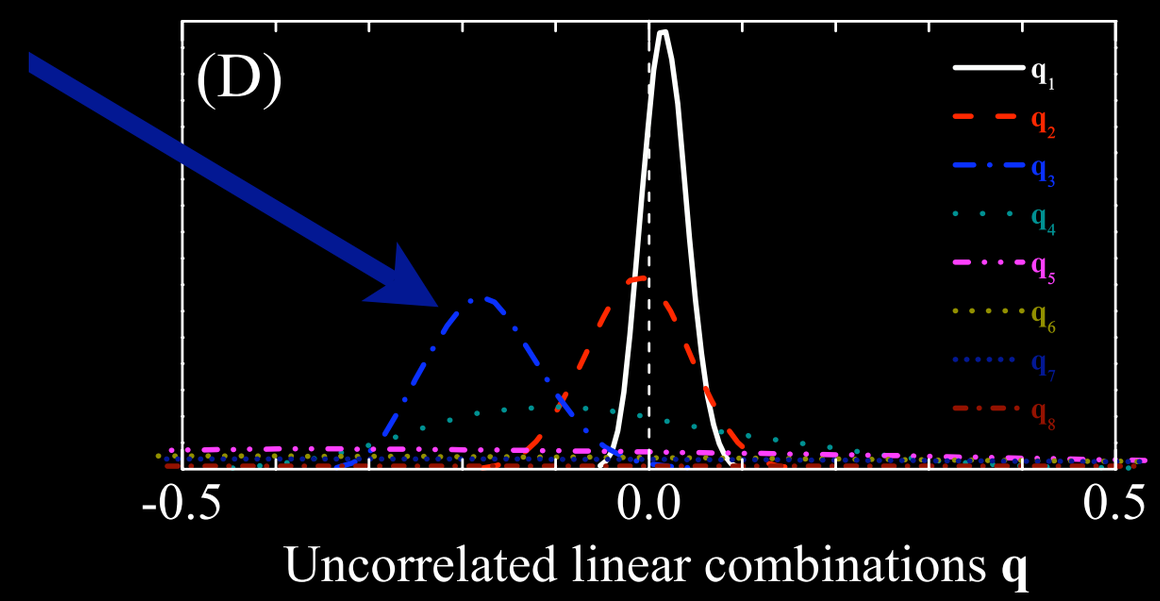




1D Posterior distribution

Current Cosmological Data





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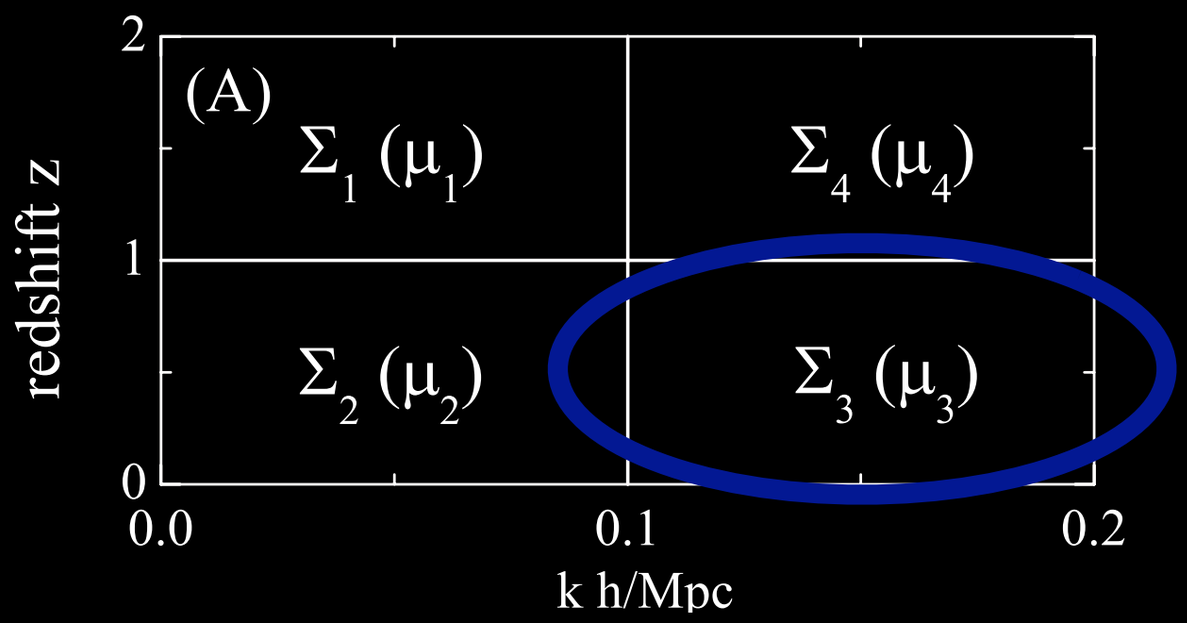
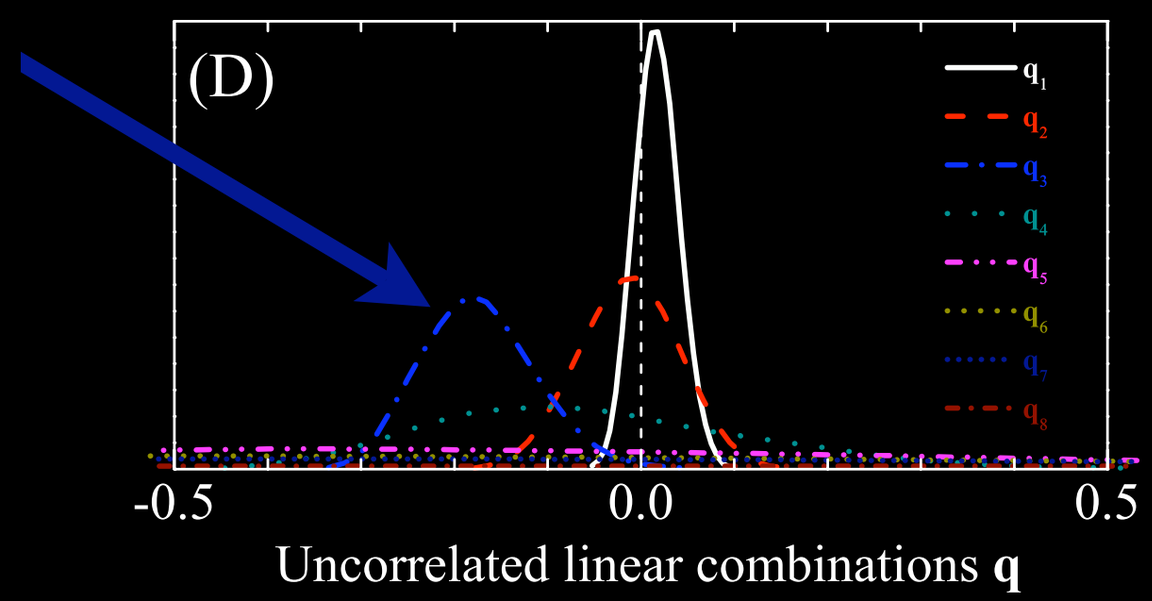


$$q_3 \approx \Sigma_3 - 1 = -0.17 \pm 0.06^{+0.13}_{-0.11}$$



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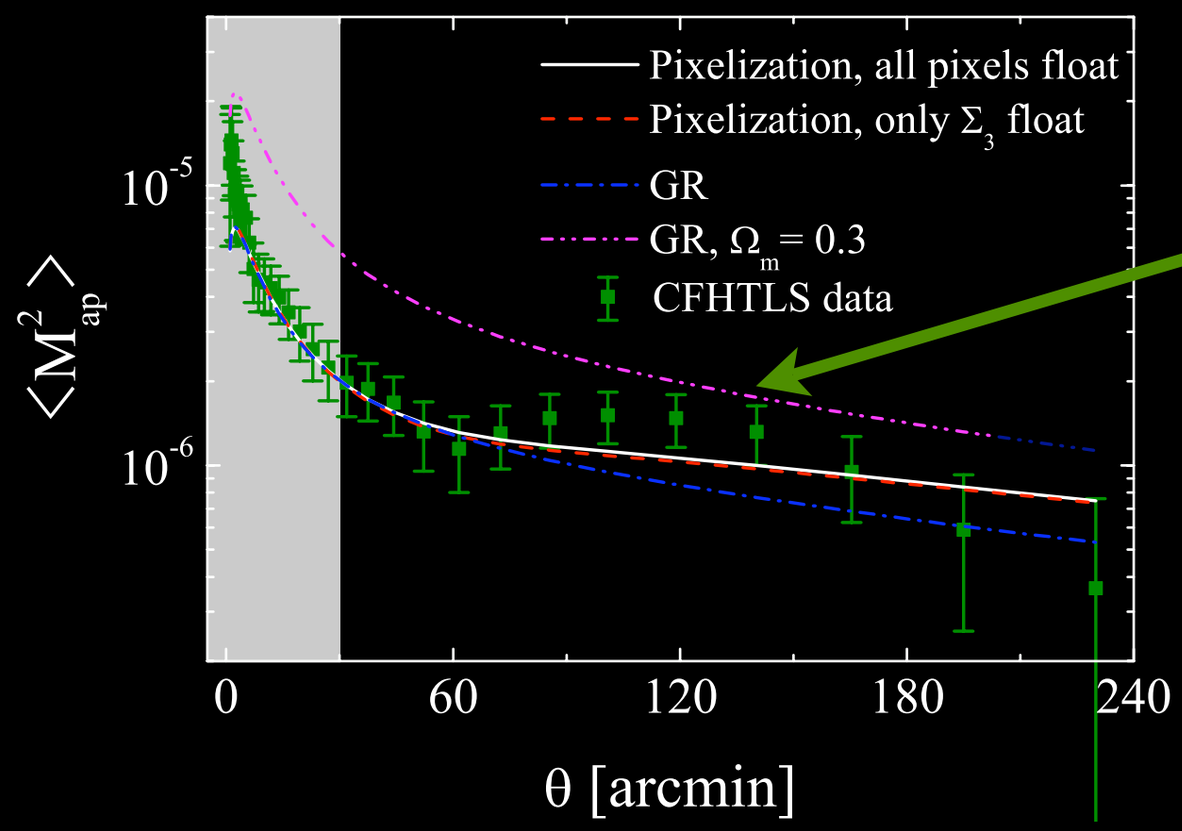
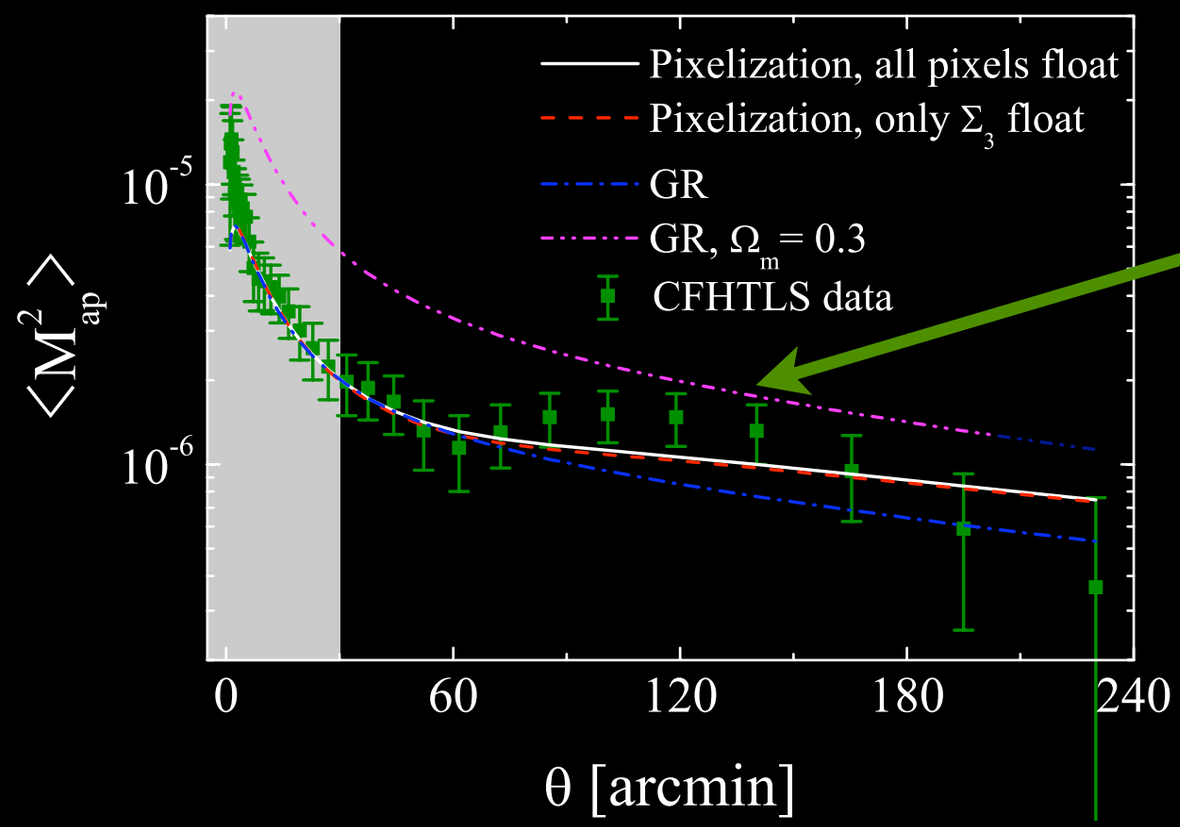


residual field-to-field variations on the scale of the camera field of view

↓

probably systematics and NOT deviations from GR

Current Cosmological Data



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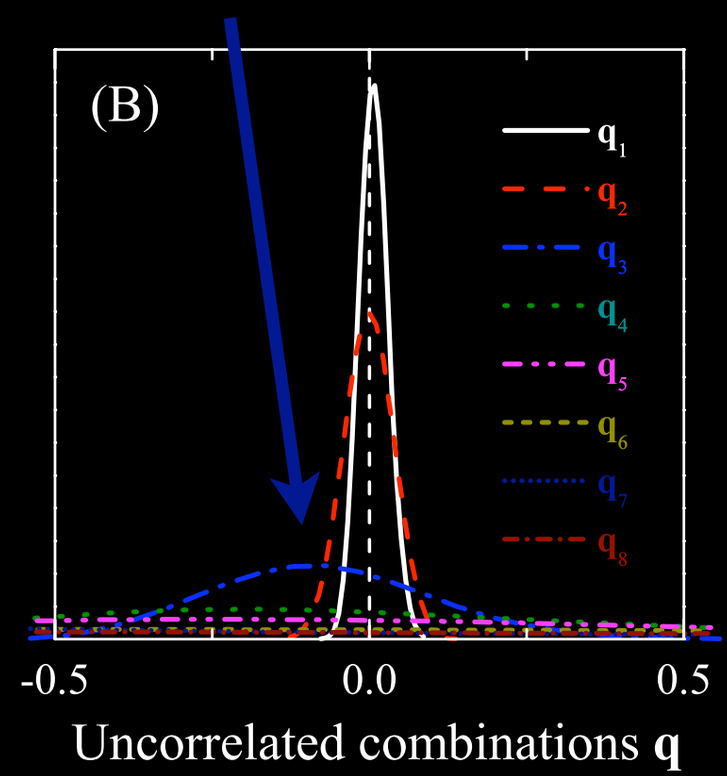
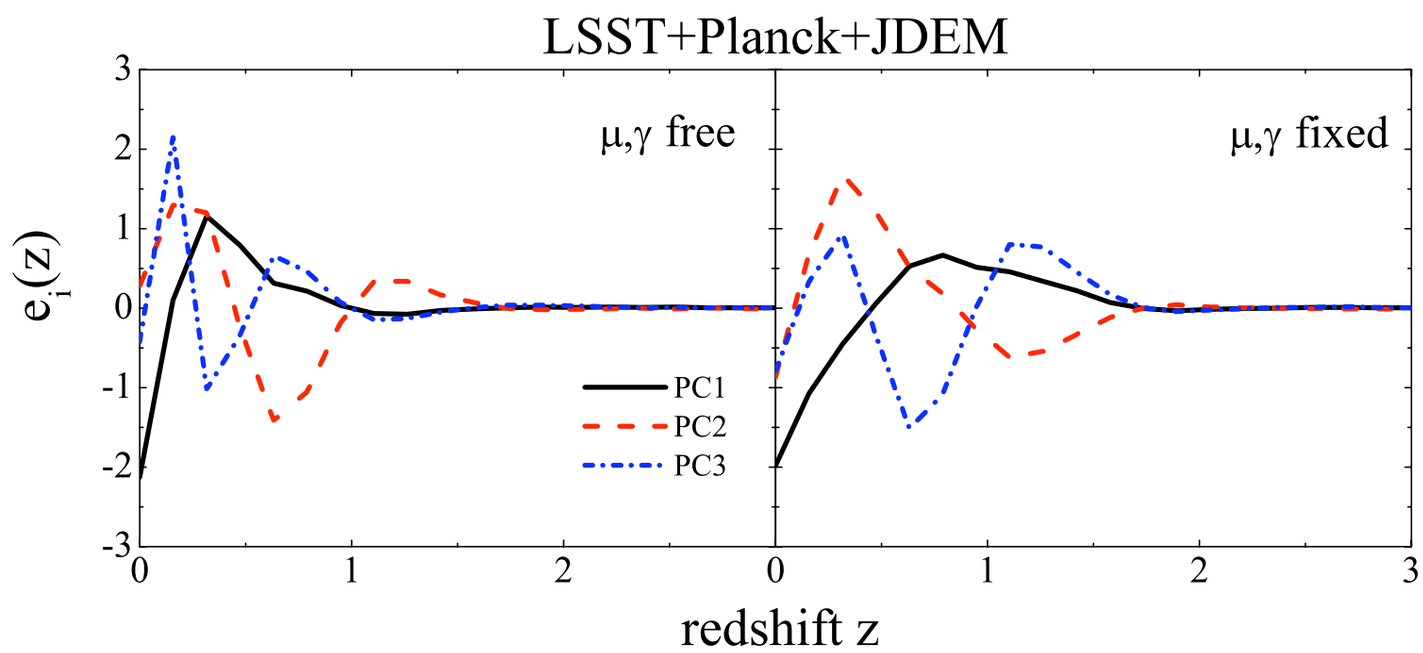
probably systematics and NOT deviations from GR

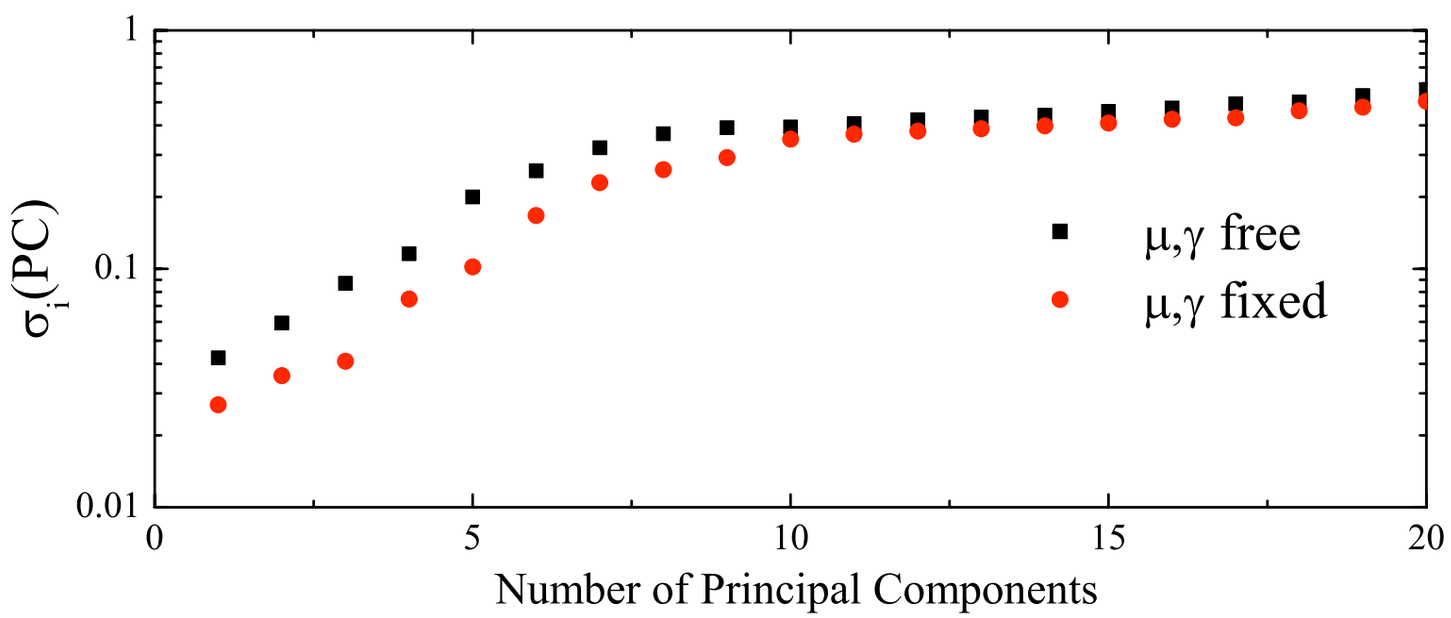
without WL data:



What happens to the constraints on the equation of state w(z)?

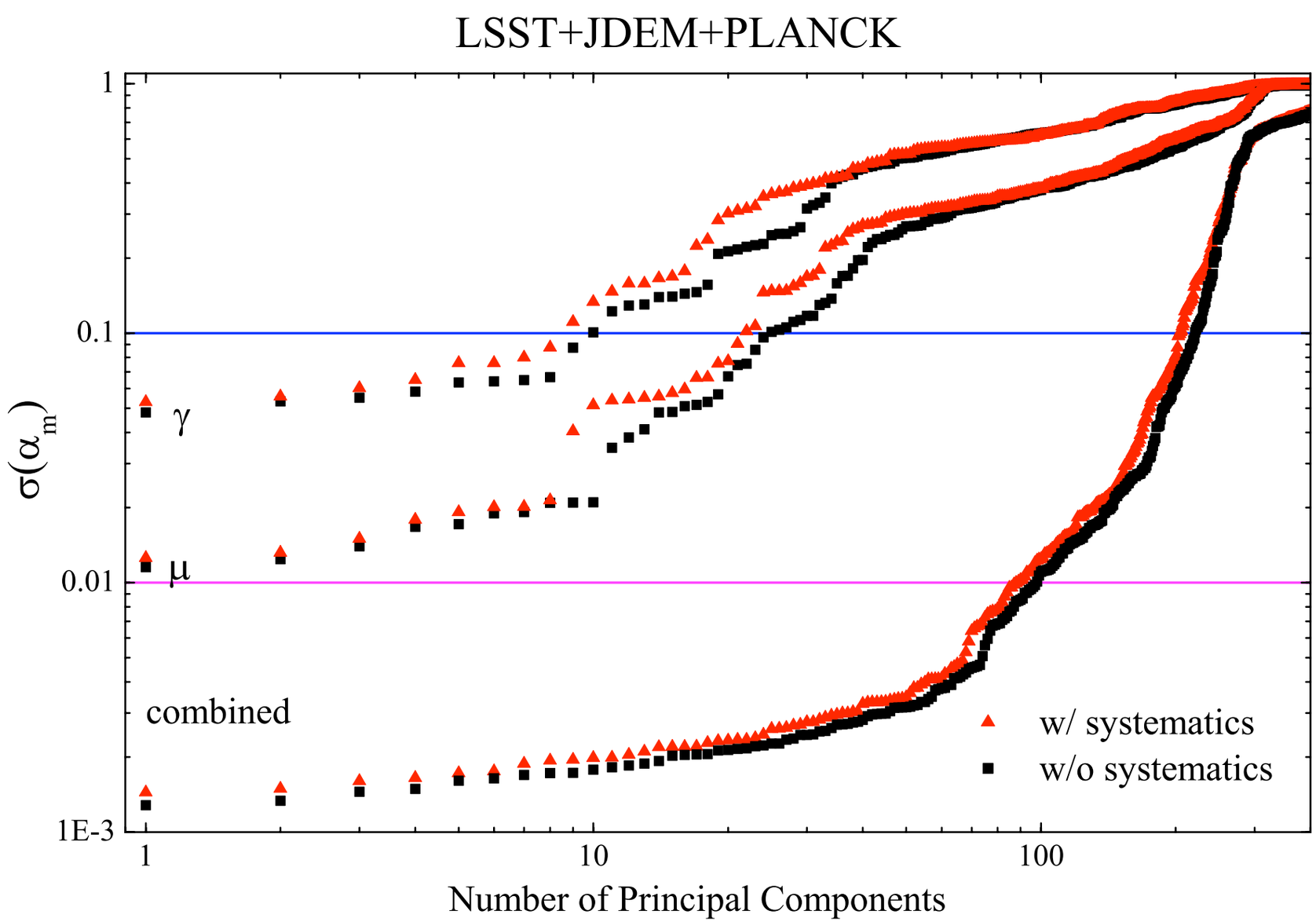
Constraining w





μ and Υ dilute constraints on w at higher redshifts

Systematics



Fisher matrix

$$F_{ab} = f_{\rm sky} \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{2\ell+1}{2} {\rm Tr}\left(\frac{\partial \mathbf{C}_\ell}{\partial p_a} \tilde{\mathbf{C}}_\ell^{-\mathbf{1}} \frac{\partial \mathbf{C}_\ell}{\partial p_b} \tilde{\mathbf{C}}_\ell^{-\mathbf{1}} \right) \ ,$$

$$F_{ab}^{\rm sub} = f_{\rm sky} \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} (2\ell+1) \sum_{\{ij\}=1}^{N} \sum_{\{mn\}=1}^{N} \frac{\partial \tilde{C}_\ell^{X_i X_j}}{\partial p_a} [\tilde{\mathbf{C}}_\ell^{\rm sub}]^{-1} \frac{\partial \tilde{C}_\ell^{X_m X_n}}{\partial p_b}$$

Angular Power Spectra

$$I_l^{G_i}(k) = b_i\, c_{\delta\mathcal{R}} \int_0^{z_*} dz\, W_{G_i}(z)\, j_l[kr(z)]\, \tilde{\delta}(k,z)$$

$$W_{G_i}(z) \propto \frac{N_{G_i}(z)}{N_i}$$

$$N_G(z) \propto z^2\, \exp(-z/z_0)^2$$

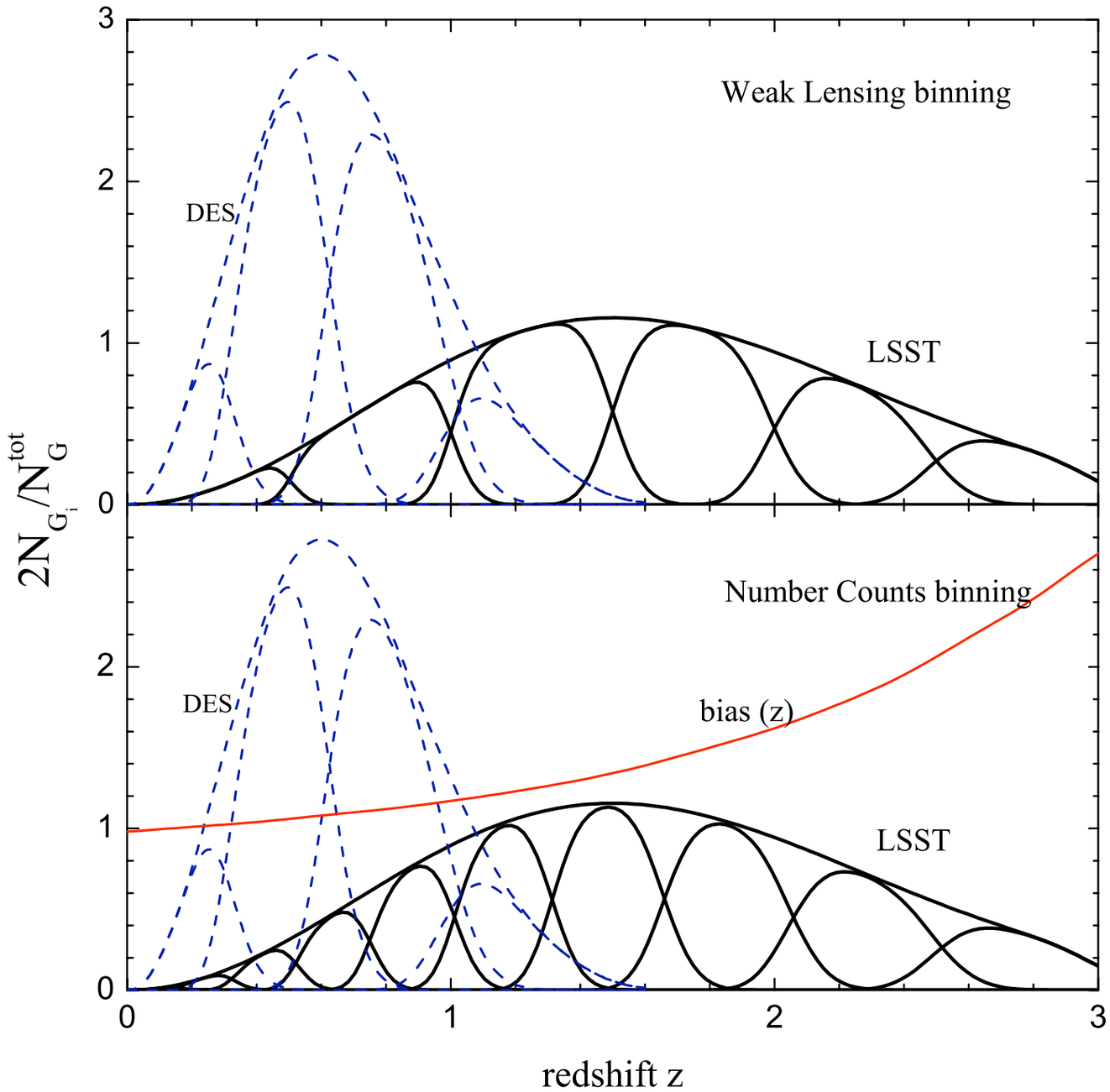
$$N_{G_i}(z) = \frac{1}{2} N_G(z) \left[\mathrm{erfc}\left(\frac{\mathrm{z_{i-1} - z}}{\sqrt{2}\sigma(\mathrm{z})} \right) - \mathrm{erfc}\left(\frac{\mathrm{z_i - z}}{\sqrt{2}\sigma(\mathrm{z})} \right) \right]$$

$$I_l^{\kappa_i}(k) = c_{\Psi\mathcal{R}} \int_0^{z_*} dz\, W_{\kappa_i}(z)\, j_l[kr(z)]\, \left(\tilde{\Psi} + c_{\Phi\Psi} \tilde{\Phi} \right)(k,z)$$

$$W_{\kappa_i}(z) \propto \frac{\chi(z_i) - \chi(z)}{\chi(z_i)}$$

$$I_l^{ISW}(k) = c_{\Psi\mathcal{R}} \int_0^{z_*} dz\, e^{-\tau(z)}\, j_l[kr(z)]\, \frac{\partial}{\partial z} \left[\tilde{\Psi} + c_{\Phi\Psi} \tilde{\Phi} \right]$$

Window



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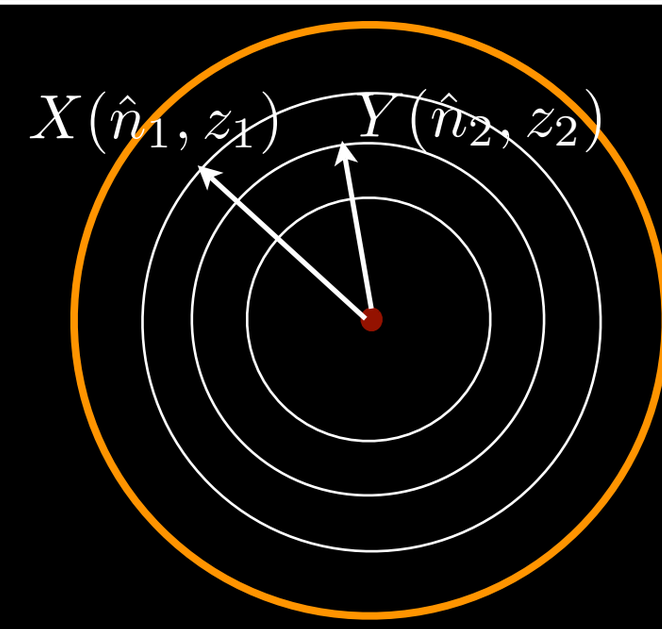
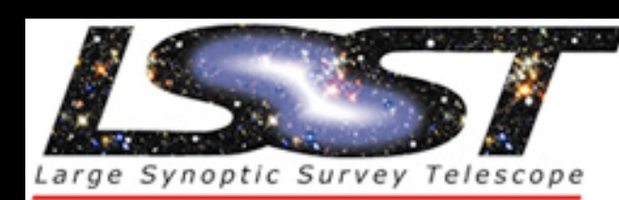
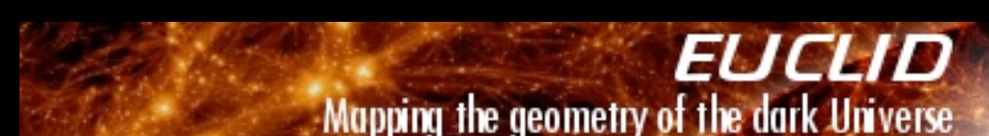
Surveys and Observables

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



- SNeIa (JDEM) + CMB (Planck): expansion history
- Weak Lensing (WL) surveys (DES, EUCLID, LSST): maps of $(\Phi+\Psi)$ at different epochs
- Galaxy Number Counts (GC) (DES, EUCLID, LSST): maps of Δ at different epochs
- Galaxy Number Counts x CMB: ISW effect: $(\Phi+\Psi)'$ at different epochs