Constraints and tensions in MG parameters from Planck, CFHTLenS and other data sets including intrinsic alignments systematics

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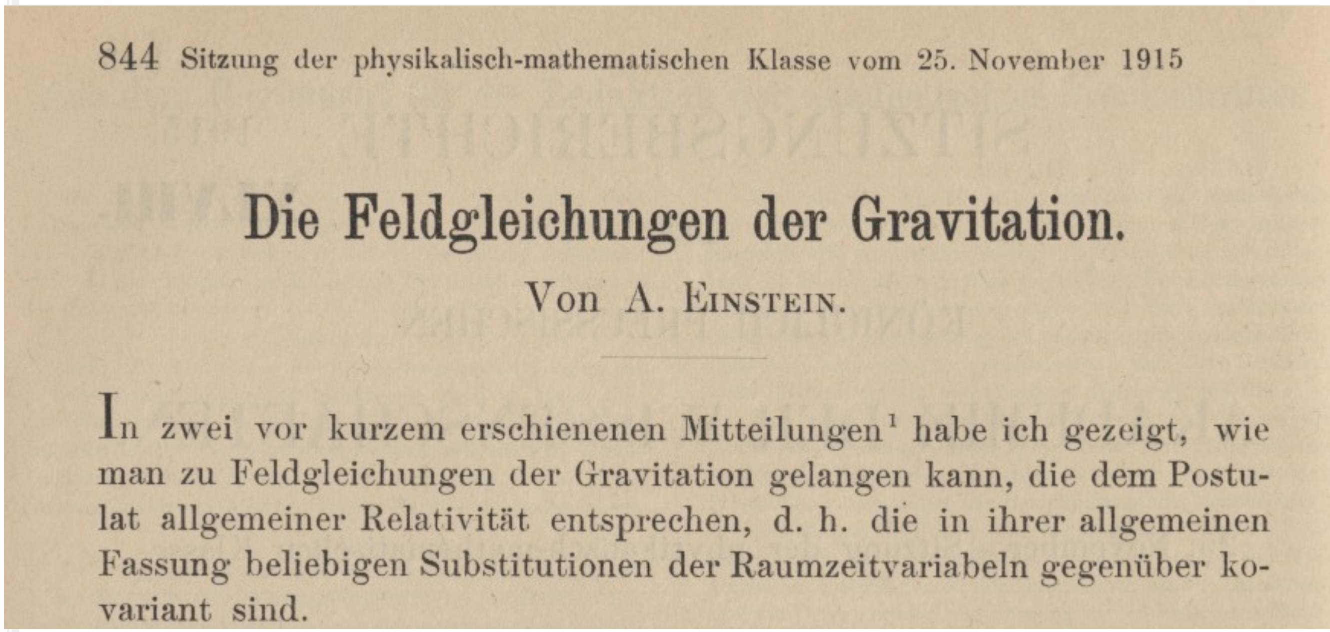
2015 IS THE 100TH ANNIVERSARY OF EINSTEIN'S GENERAL RELATIVITY

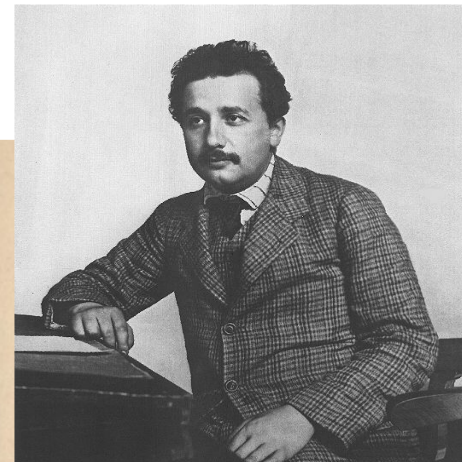


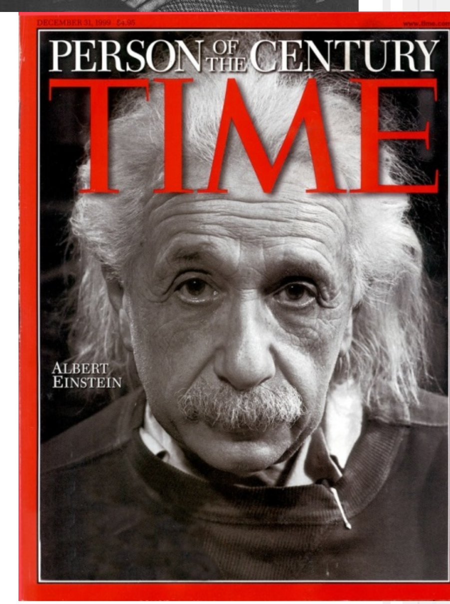
844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. EINSTEIN.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.





Modified Growth Equations

Flat Perturbed FLRW Metric.

$$ds^2 = a(\tau)^2[-(1+2\Psi)d\tau^2 + (1-2\Phi)dx^i dx_i]$$

Modified Growth Equations

$$k^2\Phi \;=\; -4\pi G a^2 \sum_i \rho_i \Delta_i \, Q(k,a)$$

$$k^2(\Psi - R(k,a)\,\Phi) \;=\; -12\pi G a^2 \sum_i \rho_i (1+w_i)\sigma_i \, Q(k,a).$$

$$k^2(\Psi+\Phi) = -8\pi G a^2 \sum_i \rho_i \Delta_i \, \Sigma(k,a) \; - 12\pi G a^2 \sum_i \rho_i (1+w_i)\sigma_i \, Q(k,a)$$

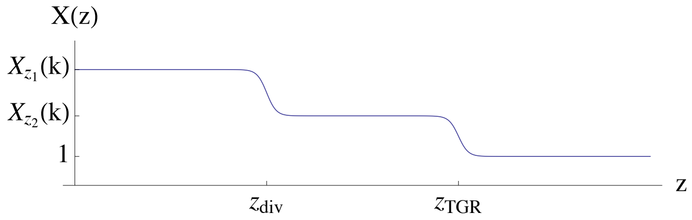
$$\Sigma = \frac{Q(1+R)}{2}$$

or D

Evolving the Modified Gravity Parameters: Binning Methods

Both Traditional binning (P1) and Hybrid Method (P2) evolve in redshift as:

$$X(k,z) = \frac{1+X_{z_1}(k)}{2} + \frac{X_{z_2}(k)-X_{z_1}(k)}{2}\tanh\frac{z-z_{div}}{z_{tw}} + \frac{1-X_{z_2}(k)}{2}\tanh\frac{z-z_{TGR}}{z_{tw}},$$



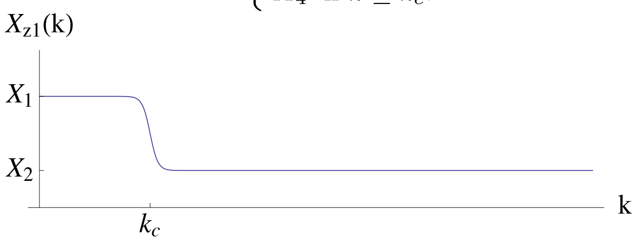
	Redshift bins	
Scale bins	$0.0 < z \le 1$	$1 < z \le 2$
$0.0 < k \le 0.01$	Q_1, Σ_1	Q_3, Σ_3
$0.01 < k < \infty$	Q_2, Σ_2	Q_4, Σ_4

Scale Dependence

Traditional Binning Method (P1)

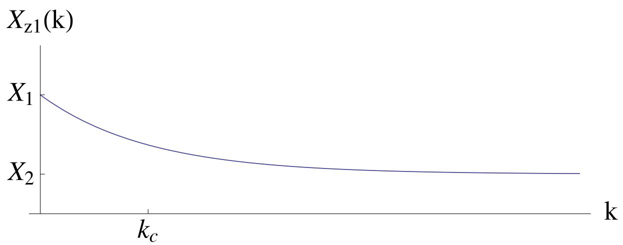
$$X_{z_1}(k) = \begin{cases} X_1 & \text{if } k < k_c \\ X_2 & \text{if } k \ge k_c, \end{cases}$$

$$X_{z_2}(k) = \begin{cases} X_3 & \text{if } k < k_c \\ X_4 & \text{if } k \ge k_c. \end{cases}$$



Hybrid Method (P2)

$$X_{z_1}(k) = X_1 e^{-k/k_c} + X_2(1-e^{-k/k_c})$$
$$X_{z_2}(k) = X_3 e^{-k/k_c} + X_4(1-e^{-k/k_c}),$$

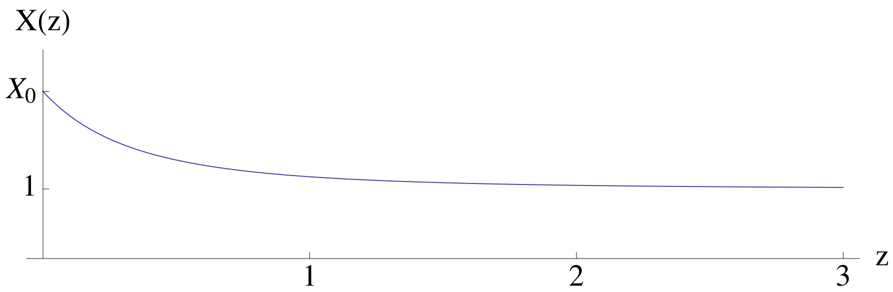


EVOLVING THE MODIFIED GRAVITY PARAMETERS: FUNCTIONAL EVOLUTION (P3)

In this evolution method we assume scale independent evolution. The parameters evolve in terms of the scale factor as:

$$X(a) = (X_0 - 1)\, a^s + 1$$

As a function of redshift with s = 3



ISiTGR:
Integrated Software in Testing General Relativity

Version 1.1

Developed by Jason Dossett, Mustapha Ishak, and Jacob Moldenhauer.

What is ISiTGR?

ISiTGR is an integrated set of modified modules for the software package CosmoMC for use in testing whether observational data is consistent with general relativity on cosmological scales. This latest version of the code has been updated to allow for the consideration of non-flat universes. It incorporates modifications to the codes: CAMB, CosmoMC, the ISW-galaxy cross correlation likelihood code of Ho et al, and our own weak lensing likelihood code for the refined COSMOS 3D weak lensing tomography of Schrabback et al to test general relativity.

A detailed explanation of the modifications made to these codes allowing one to test general relativity are described in our papers: arXiv:1109.4583 and arXiv:1205.2422.

How to get ISiTGR

Two versions of ISiTGR are available. The normal version of ISiTGR uses a functional form to evolve the parameters used to test general relativity and is available here. ISiTGR_BIN, on the other hand, gives you two options to evovle the parameters used to test general relativity. The first option is to bin the parameters in two redshift and two scale bins, alternatively one can use the hybrid evolution method, as seen in our paper, where scale dependence evolves monotonically, but redshift dependence is binned. That code can be downloaded here.

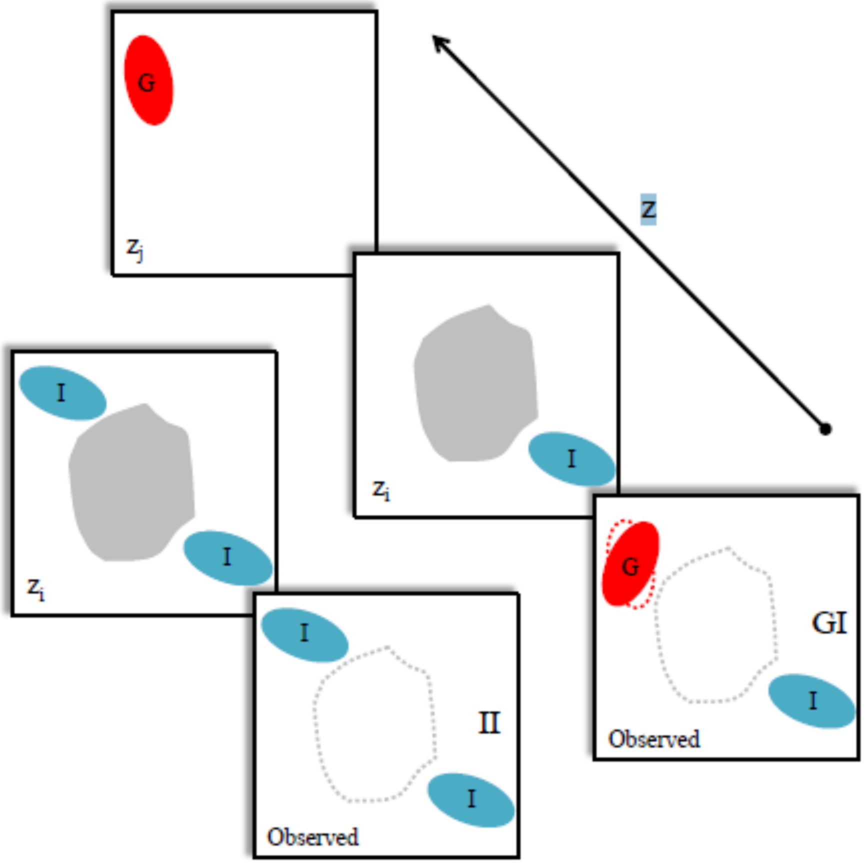
Download Here: ISiTGR ISiTGR_BIN

The original (flat only) verison of ISiTGR as well as builds for other versions of CosmoMC are available here (**this version is for CosmoMC 01/2012**).

http://isit.gr

Galaxy Intrinsic Alignments (IA) as a contaminant to Weak Lensing (WL) signal

- Contaminates WL signal by up to 15-20%. Ref
- 2 pt. IA biases cosmological parameters at 10%-50% level
- The measured correlation function = sum of GG, GI and II signals.
- Used a model for IA that is parameterized by an amplitude $A_{CFHTLenS}$



DATA SETS USED

- CMB temperature anisotropy power-spectrum from Planck Surveyor
- Low-l WMAP Polarization data
- Weak lensing tomography shear-shear cross correlations from the CFHTLenS
- Galaxy power spectrum from the WiggleZ survey
- ISW-galaxy cross correlations of Ho et al. (2008).
- BAO data from 6dF, SDSS DR7, and BOSS DR9.

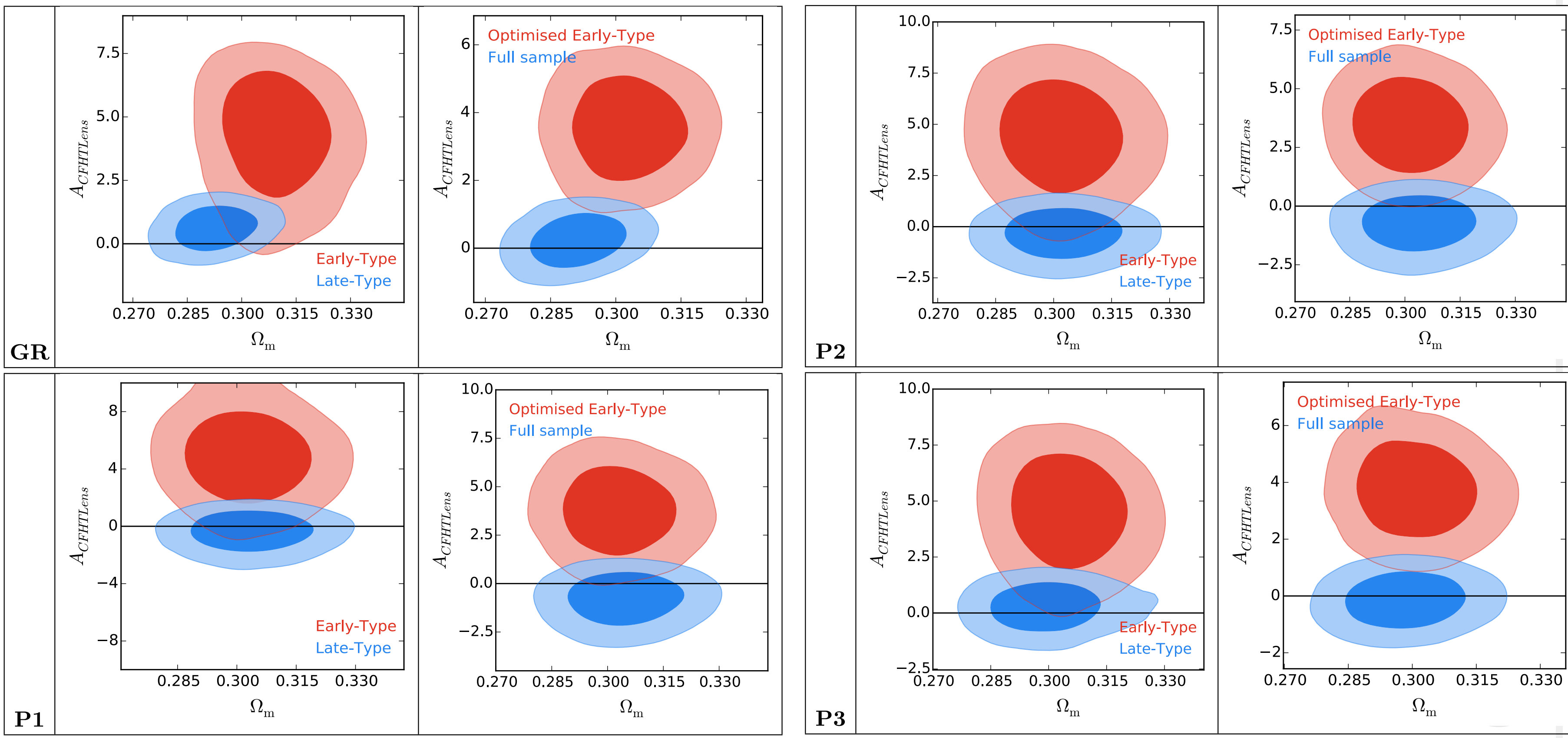
RESULTS IA: CORRELATIONS WITH MG PARAMETERS

- We find only weak to moderate correlations between MG parameters and the IA parameter.
  - Both scale dependent parameterizations show most correlation in low-z, high-k bins (bin probed most by lensing data).

Correlation table Binning parameterization (**P1**)								
	Q_1	Q_2	Q_3	Q_4	Σ_1	Σ_2	Σ_3	Σ_4
$A_{CFHTLenS}$	-0.021162	-0.29209	0.015916	0.0056355	-0.0014863	0.083586	0.015755	0.066954
σ_8	-0.012168	-0.53048	0.044293	-0.43088	0.045781	-0.61952	0.048845	-0.29894
Ω_m	-0.0012586	-0.072645	-0.051569	0.11762	-0.08057	-0.085185	-0.033916	-0.17292
Hybrid parameterization (**P2**)								
$A_{CFHTLenS}$	0.058535	-0.29535	-0.052588	0.095984	-0.14858	0.20636	-0.086038	0.10421
σ_8	0.2655	-0.70809	0.12172	-0.33026	0.32713	-0.59009	0.1362	-0.20504
Ω_m	0.027229	-0.065934	-0.028016	0.0803	0.01565	-0.15645	0.14932	-0.26513

Correlation table Functional parameterization (**P3**)		
	Q_0	Σ_0
$A_{CFHTLenS}$	-0.023164	0.10624
σ_8	-0.66775	-0.75738
Ω_m	-0.072171	0.052317

Results IA: Comparing different lensing datasets.



Results

- **P1**

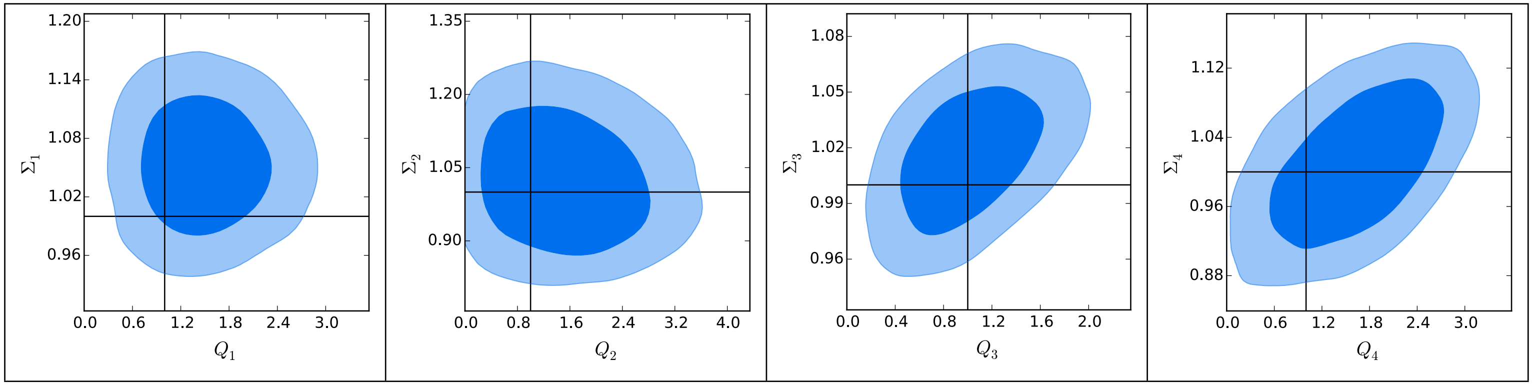


FIG. 1: 68% and 95% 2-D confidence contours for the parameters Q_i and Σ_i from parameterization **P1** for redshift and scale dependence of the MG parameters. All of the constraints for this evolution method are fully consistent with GR at the 68% level.

95% confidence limits on MG parameters evolved using form **P1**			
$\mathbf{Q_1}$	[0.49,2.56]	$\mathbf{\Sigma_1}$	[0.97,1.14]
$\mathbf{Q_2}$	[0.05,3.08]	$\mathbf{\Sigma_2}$	[0.84,1.22]
$\mathbf{Q_3}$	[0.30,1.78]	$\mathbf{\Sigma_3}$	[0.97,1.06]
$\mathbf{Q_4}$	[0.28,2.88]	$\mathbf{\Sigma_4}$	[0.90,1.12]

RESULTS CONT'D

- **P2**

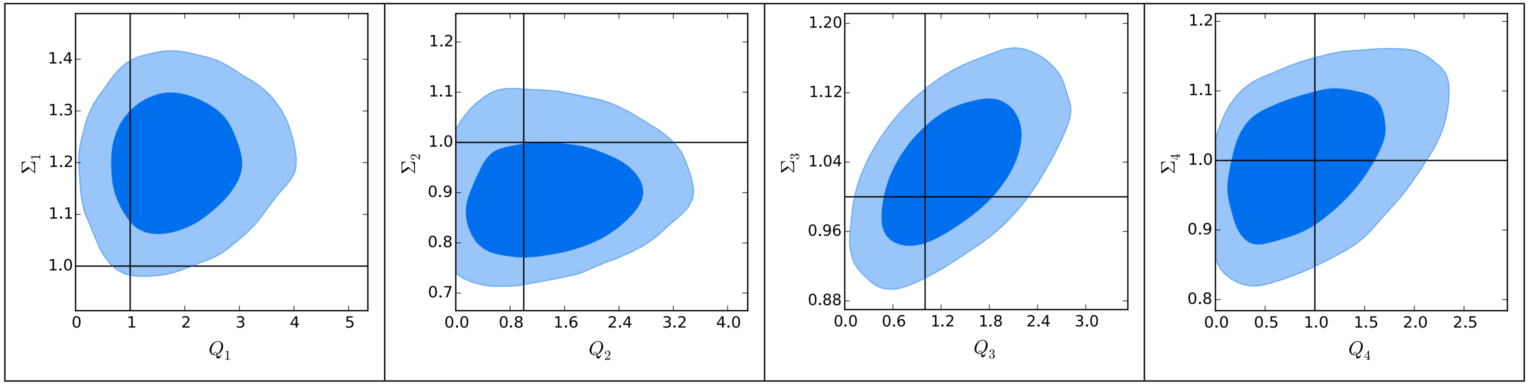


FIG. 2: 68% and 95% 2-D confidence contours for the parameters Q_i and Σ_i from parameterization **P2** for redshift and scale dependence of the MG parameters. As you can see in the first bin, there a tension with the GR value of 1. However, contrary to the marginalized 1-D constraints given in Table III the GR point is still within the 95% confidence region.

95% confidence limits on MG parameters evolved using form **P2**			
$\mathbf{Q_1}$	[0.38,3.43]	$\mathbf{\Sigma_1}$	[1.03,1.37]
$\mathbf{Q_2}$	[0.00,2.86]	$\mathbf{\Sigma_2}$	[0.75,1.07]
$\mathbf{Q_3}$	[0.28,2.46]	$\mathbf{\Sigma_3}$	[0.93,1.14]
$\mathbf{Q_4}$	[0.05,1.99]	$\mathbf{\Sigma_4}$	[0.86,1.14]

Results cont'd

- **P3**

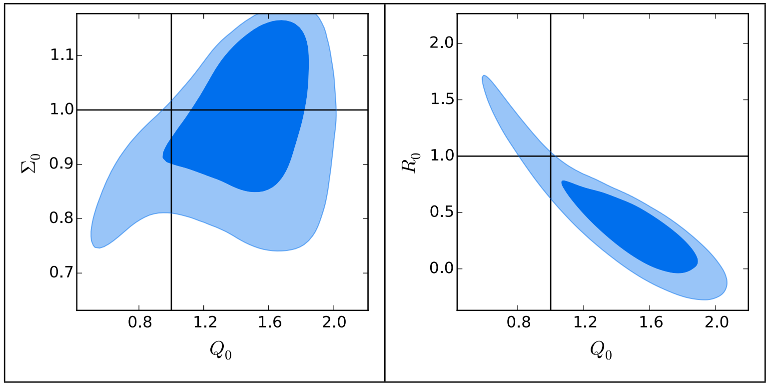
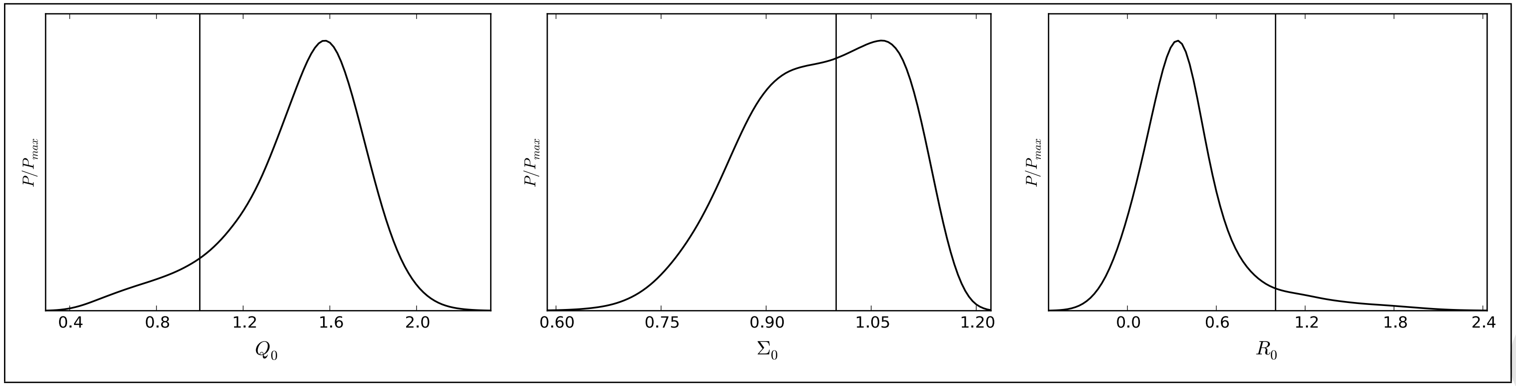


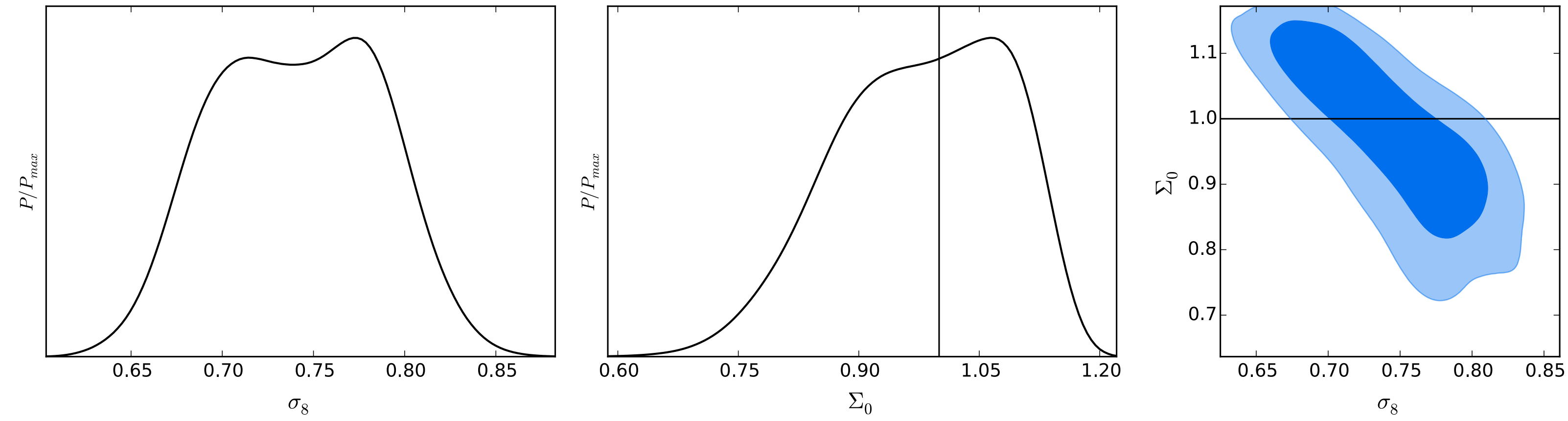
FIG. 3: 68% and 95% 2-D confidence contours for the parameters Q_0, Σ_0, and R_0 from the scale independent parameterization, **P3**, for the MG parameters. These constraints are consistent with GR a the 95% level, but a tension is evident. The tension is evident when viewing these plots is not easily seen using the 1-D constraints given in Table V. This is due to the non-Gaussianity of the probability distribution for these parameters as further Fig. 4.



95% confidence limits on MG parameters evolved using form **P3**					
$\mathbf{Q_0}$	[0.77,1.99]	$\mathbf{\Sigma_0}$	[0.79,1.16]	$\mathbf{R_0}$	[-0.23,1.18]

Tensions between the data sets

- We have seen indications of tensions in the MG parameter space for P2 and P3.
- Known tension between CMB and weak lensing, notably in constraints on σ_8.



- For P3 we get a bimodal σ_8, hinting the tension in MG parameter space is likely related to known tension between the data sets.

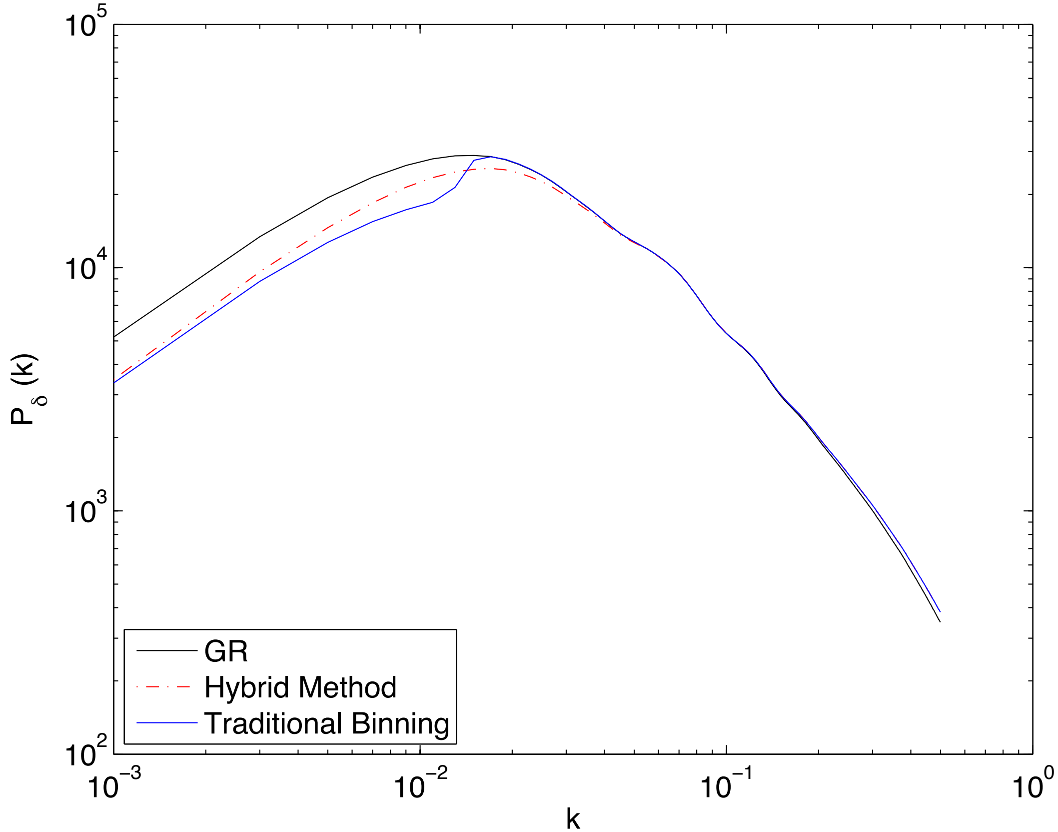
Summary

- We find a 40-53% improvement on figure of merit for the MG parameters over previous results.
- The intrinsic alignment amplitude shows weak to moderate correlation with the MG parameters (Q_2 & Σ_2 most correlated).
- GR & P3 show a clear IA signal for the optimized early-type galaxy sample
- GR is consistent with the data at the 95% CL when considering 2D contours.
- A clear tension is present in the parameter Σ apparently related to the known tension between CMB and weak lensing.

Evolving the Modified Gravity Parameters: Binning Methods

Both Traditional binning and Hybrid Method evolve in redshift as

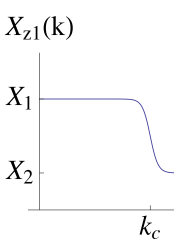
$X($ … $\frac{z_{TGR}}{z_{tw}},$



Traditio…

$X_{z_1}(k$ … $k/k_c)$

$X_{z_2}(k$ … $k/k_c),$



As usual, the shear cross correlation functions $\xi^{kl}_{+,-}(\theta)_{\rm GG}$ between bins k, l are given by

$$\xi^{kl}_{+,-}(\theta)_{\rm GG} = \frac{1}{2\pi}\int_0^\infty d\ell\ \ell\ J_{0,4}(\ell\theta)P^{kl}_\kappa(\ell), \tag{9}$$

where J_n is the n^{th}-order Bessel function of the first kind, ℓ is the modulus of the two-dimensional wave vector, and P^{kl}_κ is the convergence cross-power spectra between bins k and l is given by [75]

$$P^{kl}_\kappa(\ell) = \int_0^{\chi_h} d\chi\, g_k(\chi)g_l(\chi)\, P_{\phi,\phi}\Big(\frac{\ell}{f_K(\chi)},\chi\Big), \tag{10}$$

$$g_k(\chi) \equiv \frac{1}{a(\chi)}\int_\chi^{\chi_h} d\chi' p_k(\chi')\frac{f_K(\chi'-\chi)}{f_K(\chi')},$$

$$\hat{\xi}^{kl}_{+,-}(\theta) = \xi^{kl}_{+,-}(\theta)_{\rm II} + \xi^{kl}_{+,-}(\theta)_{\rm GI} + \xi^{kl}_{+,-}(\theta)_{\rm GG}.$$

$$C^{kl}_{\rm GI}(\ell) = \int_0^{\chi_h} d\chi\, \frac{g_k(\chi)p_l(\chi)+g_l(\chi)p_k(\chi)}{f_K(\chi)}\, F_{\rm I}\, P_{\phi,\delta_0}\Big(\frac{\ell}{f_K(\chi)},\chi\Big), \tag{13}$$

$$C^{kl}_{\rm II}(\ell) = \int_0^{\chi_h} d\chi\, \frac{p_k(\chi)p_l(\chi)}{[f_K(\chi)]^2}\, F_{\rm I}^2\, P_{\delta_0,\delta_0}\Big(\frac{\ell}{f_K(\chi)},\chi\Big), \tag{14}$$

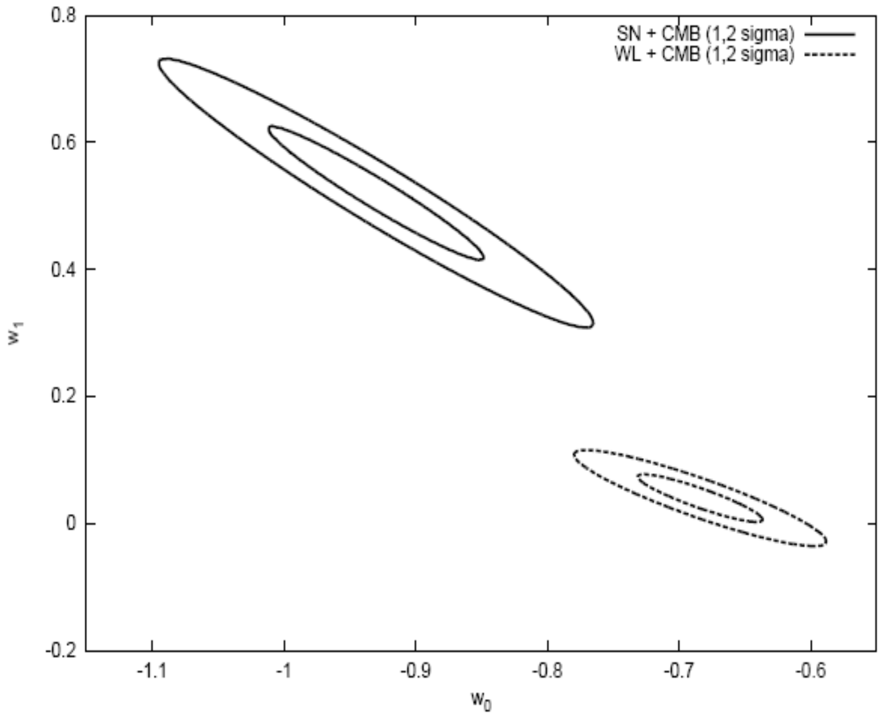
where δ_0 is the matter overdensity today and $F_{\rm I}$ is a cosmology dependent factor given by:

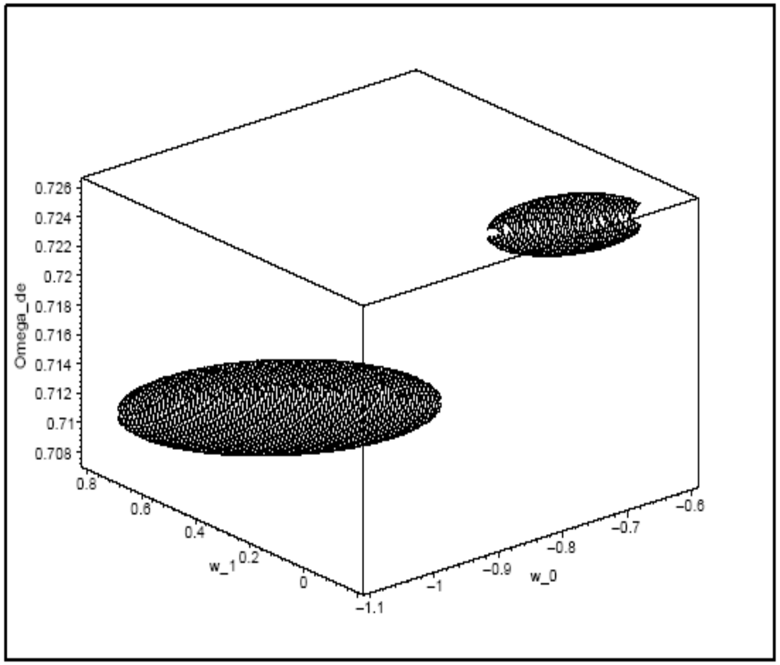
$$F_{\rm I} = -A_{\rm CFHTLenS}\, C_1\, \rho_{\rm crit}\, \Omega_m. \tag{15}$$

Above, $\rho_{\rm crit}$ is the critical density of the universe today, C_1 is a constant with a value $5\times10^{-14}h^{-2}M_\odot^{-1}{\rm Mpc}^3$, and $A_{\rm CFHTLenS}$ is a nuisance parameter that we will marginalize over in our likelihood analysis.

The consistency relation between the expansion history and the growth rate of large scale structure

(MI, Upadhye, and Spergel, PRD 2006, astro-ph 2005)





Results: Equations of state found using two different combinations of simulated data sets. Solid contours are for fits to the [Supernova + CMB] data combination, while dashed contours are for fits to [Weak Lensing + CMB] data combination.
(MI, Upadhye, and Spergel, Phys.Rev. D74 (2006) 043513, astro-ph-2005)

The significant difference (inconsistency) between the equations of state found using these two combinations is a due to the DGP model in the simulated data.

In this simulated case, The inconsistency tells us that we are in presence of modified gravity rather than GR+Dark Energy.