Tensions Between CMB and Weak Lensing Data Sets when Testing General Relativity

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Ways to Test General Relativity

- Looking for inconsistencies in between expansion history and growth of structure
  - The growth rate of large scale structure is coupled to the expansion history via Einstein's equations. These two effects must be consistent.
- "Trigger parameters", γ. The logarithmic growth rate $f = d\ln\delta / d\ln a$ can be approximated by:

  $$f = \Omega_m^\gamma$$

  For different gravity models γ has a unique value.
- Gravitational Slip and Modifications to the Poisson Eqn. (We will focus on this)

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

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

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

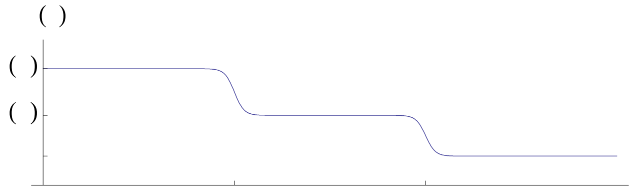
$$k^2(\Psi+\Phi) = -8\pi G a^2 \sum_i \rho_i \Delta_i \, \Sigma(k,a) \; - 12\pi G a^2 \sum_i \rho_i (1+w_i)\sigma_i \, Q(k,a)$$

$$\underset{\text{or } D}{\Sigma} = \frac{Q(1+R)}{2}$$

Evolving the Modified Gravity Parameters: Binning Methods

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

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



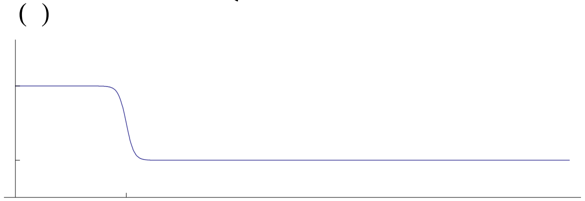
	Redshift bins	
Scale bins	$0.0 < z \leq 1$	$1 < z \leq 2$
$0.0 < k \leq 0.01$	Q_1, Σ_1	Q_3, Σ_3
$0.01 < k < \infty$	Q_2, Σ_2	Q_4, Σ_4

Scale Dependence

Traditional Binning Method (P1)

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

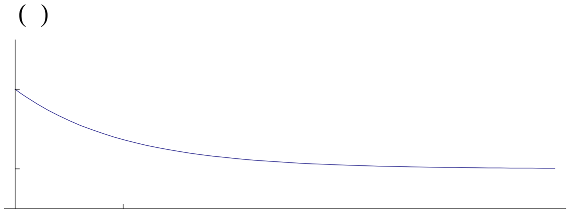
$$X_{z_2}(k) = \begin{cases} X_3 & \text{if } k < k_c \\ X_4 & \text{if } k \geq k_c. \end{cases}$$



Hybrid Method (P2)

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

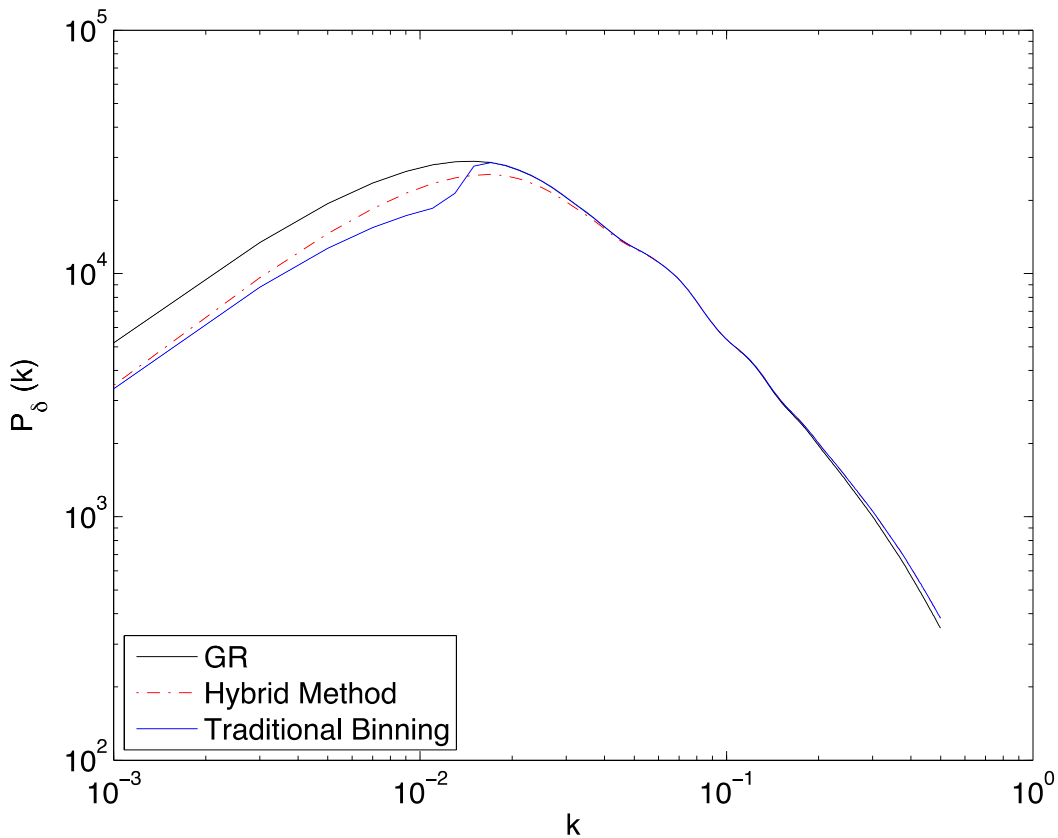
$$X_{z_2}(k) = X_3 e^{-k/k_c} + X_4(1-e^{-k/k_c}),$$



Evolving the Modified Gravity Parameters: Binning Methods

Both Traditional binning and Hybrid Method evolve in redshift as

X (... $\frac{z_{TGR}}{z_{tw}}$,

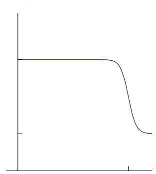


Traditio...

$X_{z_1}(k$ ... $k/k_c)$

$X_{z_2}(k$ ... $k/k_c)$,

( )

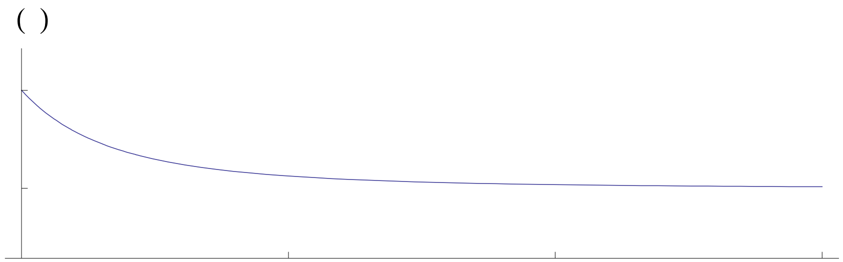


Evolving the Modified Gravity Parameters: Functional evolution (P3)

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 2.0

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, and the ISW-galaxy cross correlation likelihood code of Ho et al. Also included is our independently developed generalized weak lensing likelihood module with data sets for the CFHTLenS weak lensing tomography of Heymans et al and CFHTLens 2D weak lensing measurements from Kilbinger et al.

A detailed explanation of the modifications made to these codes allowing one to test general relativity are described in our papers: arXiv:1109.4583, arXiv:1205.2422, and arXiv:1501.03119.

How to get **ISiTGR**

New for version 2.0! The two versions of **ISiTGR** have been consolidated into a single package. The three methods of evolving the parameters used to test general relativity, as described in our paper arXiv:1109.4583, are all contained within the code below. Different evolution methods are chosen by using different `.ini` files and changing options within those files.

Download **ISiTGR**

This version of **ISiTGR** is for the **February 2015** version of `CosmoMC`. The original (flat only) verison of **ISiTGR** as well as builds for other versions of `CosmoMC` are available here .

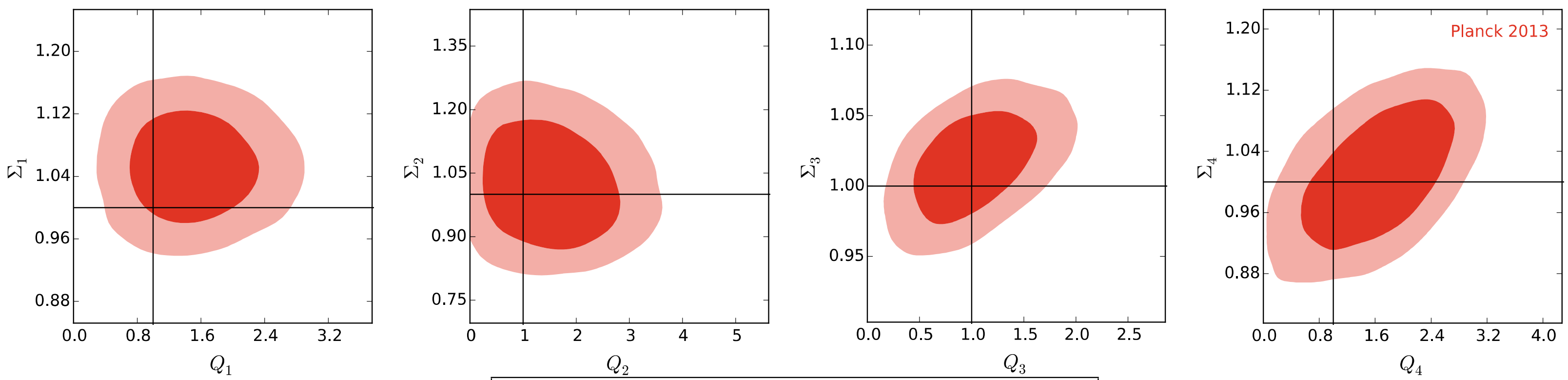
http://isit.gr

DATA SETS USED

- CMB temperature and polarization (PLC 2015) anisotropy power-spectrum from Planck Surveyor
- Low-l WMAP Polarization data (with PLC 2013)
- 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

- **P1**

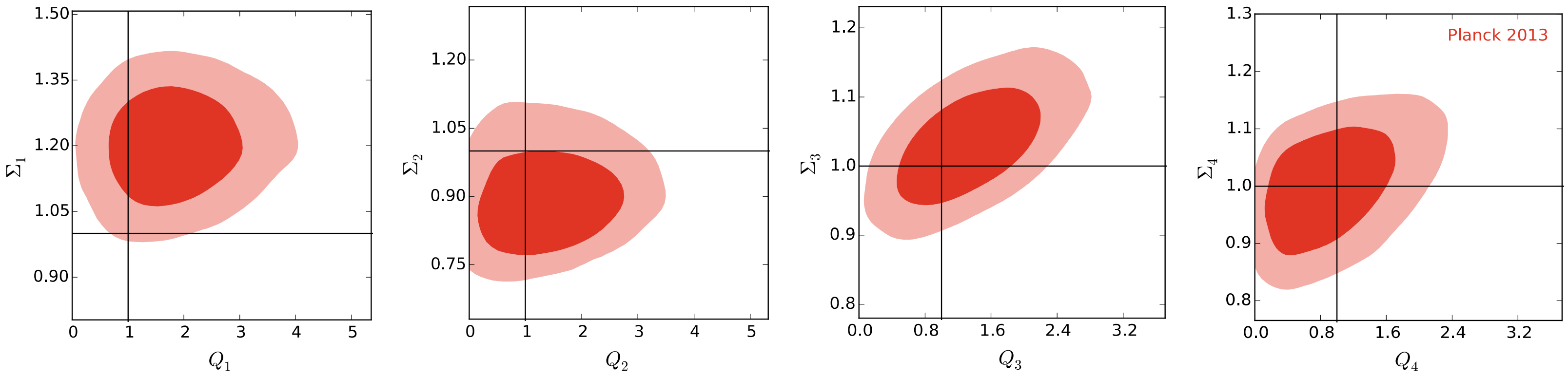


95% confidence limits on MG parameters evolved using form P1			
PLC 2013			
Q_1	[0.49,2.56]	Σ_1	[0.97,1.14]
Q_2	[0.05,3.08]	Σ_2	[0.84,1.22]
Q_3	[0.30,1.78]	Σ_3	[0.97,1.06]
Q_4	[0.28,2.88]	Σ_4	[0.90,1.12]
PLC 2015			
Q_1	[0.32,2.22]	Σ_1	[0.96,1.13]
Q_2	[0.27,3.28]	Σ_2	[0.90,1.23]
Q_3	[0.27,1.73]	Σ_3	[0.97,1.06]
Q_4	[0.55,2.92]	Σ_4	[0.93,1.12]

- **FoM increase of 8% from 2013 to 2015 release**

Results cont'd

- **P2**

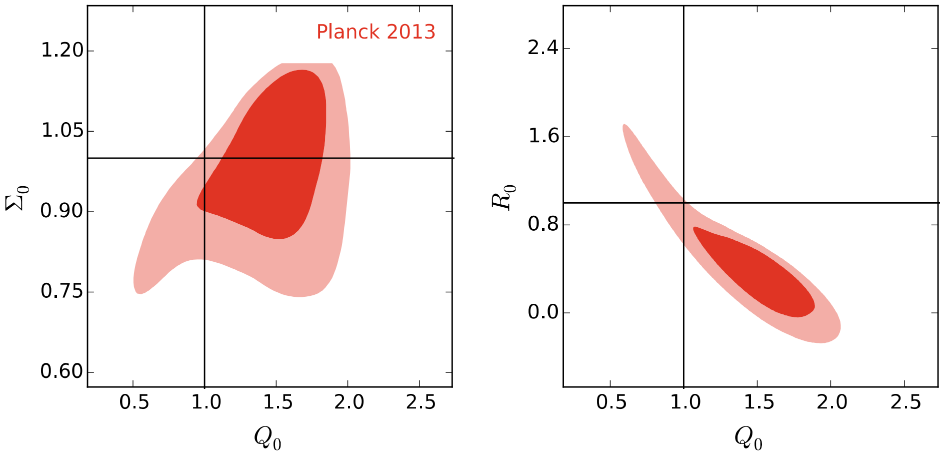


95% confidence limits on MG parameters evolved using form P2			
PLC 2013			
Q_1	[0.38,3.43]	Σ_1	[1.03,1.37]
Q_2	[0.00,2.86]	Σ_2	[0.75,1.07]
Q_3	[0.28,2.46]	Σ_3	[0.93,1.14]
Q_4	[0.05,1.99]	Σ_4	[0.86,1.14]
PLC 2015			
Q_1	[0.25,2.92]	Σ_1	[1.00,1.30]
Q_2	[0.27,3.24]	Σ_2	[0.80,1.11]
Q_3	[0.23,2.46]	Σ_3	[0.91,1.10]
Q_4	[0.20,2.30]	Σ_4	[0.92,1.15]

- **FoM increase of 21% from 2013 to 2015 release**

Results cont'd

- **P3**

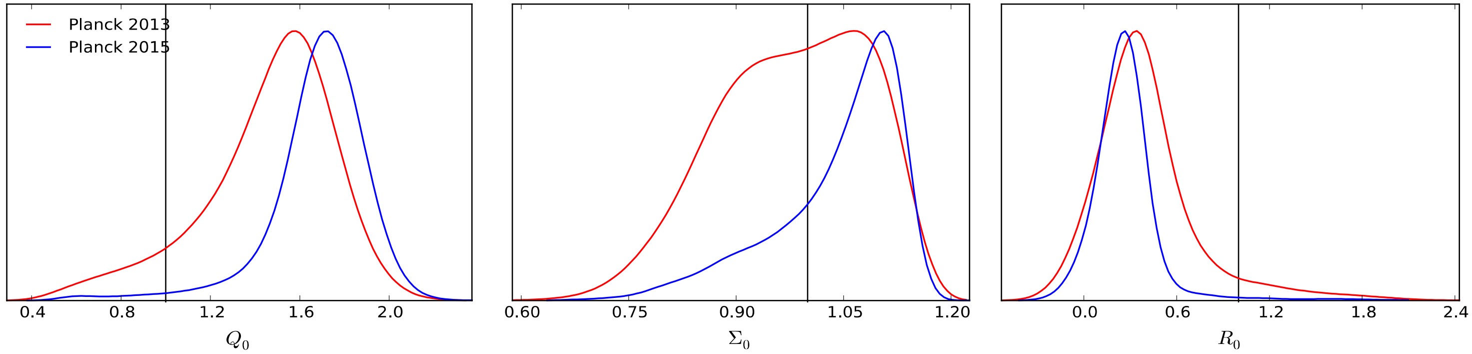


95% confidence limits on MG parameters evolved using form P3					
PLC 2013					
Q_0	[0.77,1.99]	Σ_0	[0.79,1.16]	R_0	[-0.23,1.18]
PLC 2015					
Q_0	[1.21,2.10]	Σ_0	[0.85,1.17]	R_0	[-0.15,0.61]

- **FoM increase of 43% from 2013 to 2015 release**

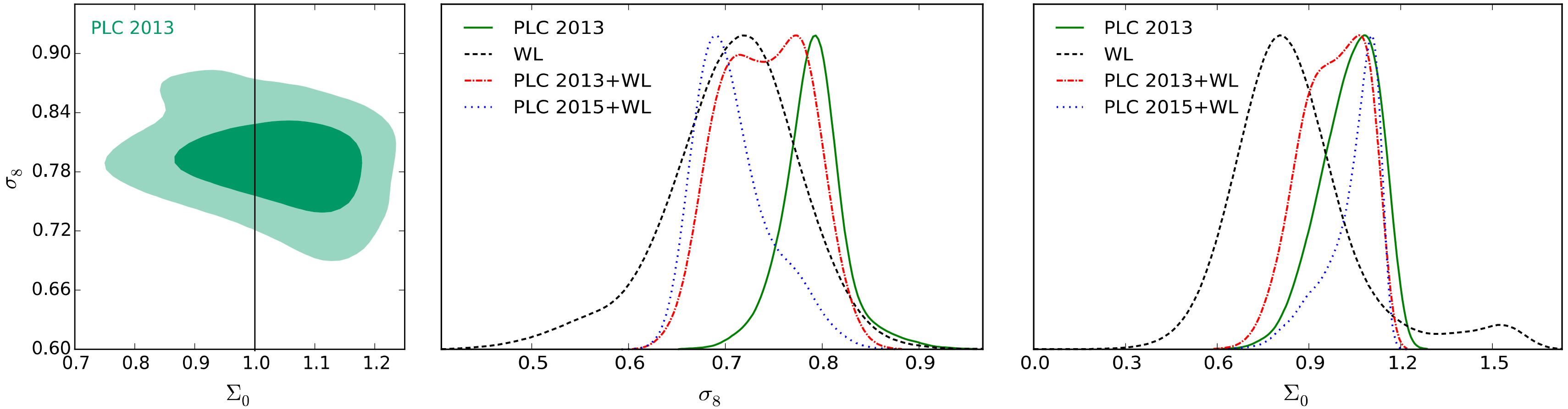
Results cont'd

- **P3 – A Hint of Tensions?**



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 up to a 43% improvement on figure of merit for the MG parameters between the 2013 and 2015 Planck data sets.
- A clear tension is present in the parameter Σ apparently related to the known tension between CMB and weak lensing.
- For P3, GR is no longer consistent with the data at the 95% CL when considering 2D contours.
  - We need to consider possible systematics related to nonlinear structure in the weak lensing data.