# A Figure of Merit Analysis of Current Constraints on Testing General Relativity using the Latest Cosmological Data Sets.

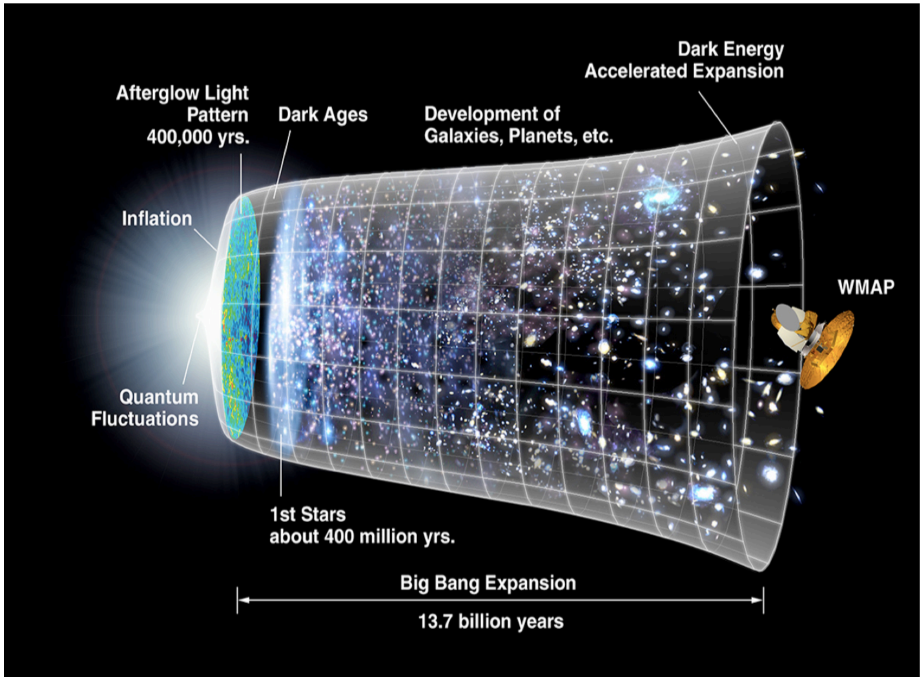
**Jason Dossett**

# Outline

- Motivations
- Ways to Test Gravity
- Growth Equations
- Modified Growth Equations
- Figures of Merit
- Results

# Motivations

- Cosmic acceleration




- Proposals of some extensions to general relativity that would manifest themselves at cosmological scales.

# 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", $\gamma$. The logarithmic growth rate $f = d\ln\delta/d\ln a$ can be approximated by:

  $$f = \Omega_m^\gamma$$

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

# Growth Equations

Flat Perturbed FLRW Metric.

$$ds^2 \; = \; -a(\tau)^2[1 + 2\psi(\mathbf{x}, t)]d\tau^2 + a(\tau)^2[1 - 2\phi(\mathbf{x}, t)]d\mathbf{x}^2$$

$$k^2\phi \; = \; -4\pi G a^2 \sum \rho_i \Delta_i \qquad \text{Poisson Eqn.}$$

$$\psi - \phi \; = \; -12\pi G a^2 \sum_i \rho_i (1 + w_i) \frac{\sigma_i}{k^2}. \qquad \text{Anisotropy Eqn.}$$

# Modified Growth Equations

## Modified Growth Eqns.

Parameteriztion 1 [Bean]:

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

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

Parameterization 2 [Zhao]:

$$k^2\psi \;=\; -4\pi G a^2 \sum_i \rho_i \Delta_i \, \mu(k,a).$$

$$\frac{\phi}{\psi} \;=\; \eta(k,a), \quad \Sigma(k,a) = \frac{\mu(1+\eta)}{2}$$

## Parameters Evolve as:

Functional form

$$Q(a) \;=\; (Q_0 - 1)\, a^s + 1,$$

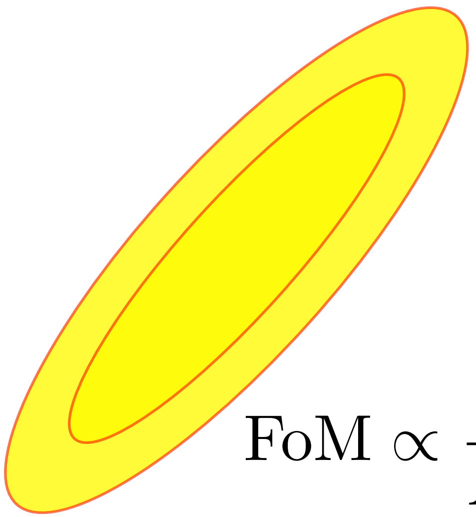
$$R(a) \;=\; (R_0 - 1)\, a^s + 1.$$

Binned

| | Redshift bins | |
|---|---|---|
| Scale bins | $0.0 < z \le 1,\ 1.5$ | $1,\ 1.5 < z \le 2,\ 3$ |
| $0.0 < k \le k_x$ | $\mu_1,\ \Sigma_1$ | $\mu_2,\ \Sigma_2$ |
| $k_x < k < \infty$ | $\mu_3,\ \Sigma_3$ | $\mu_4,\ \Sigma_4$ |

# Figures of Merit

- Used previously on the dark energy equations of state parameters.
- Quantifies how well constrained a set of parameters are by a given set of data.



$$\mathrm{FoM} \propto \frac{1}{A_{95}}$$

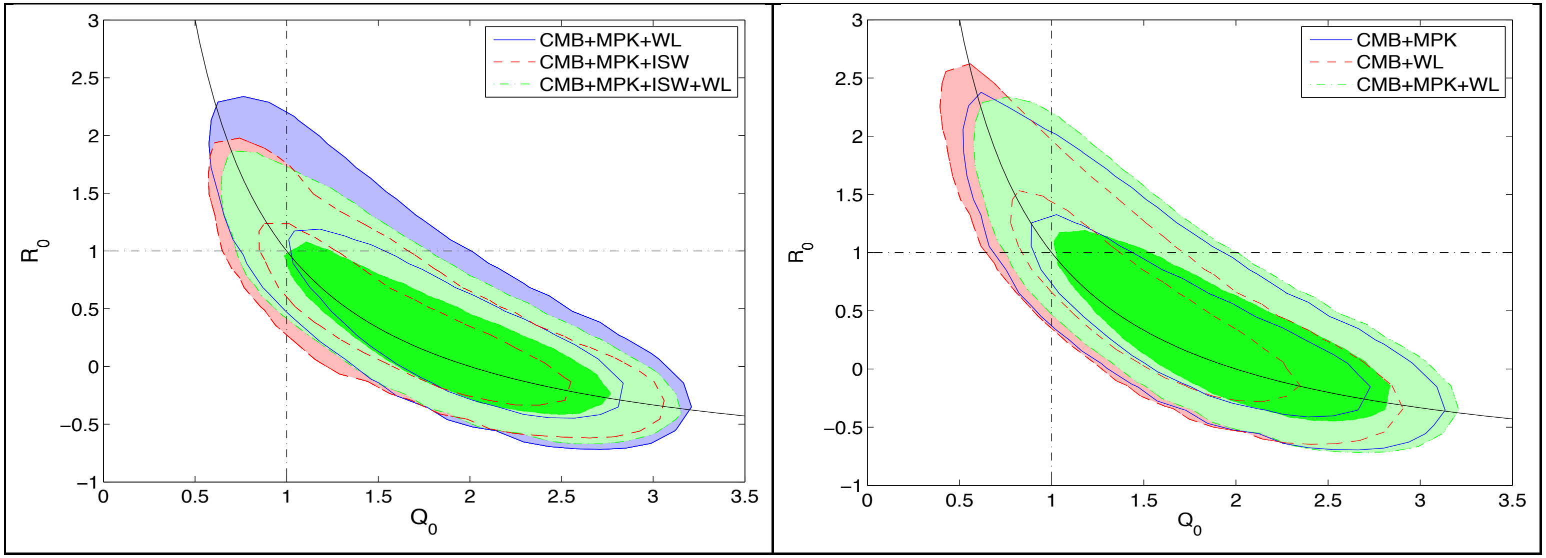
$$\mathrm{FoM} = (det\, C)^{-1/2}$$

# RESULTS

- Data sets used:
  - WMAP 7 year temperature and polarization spectra
  - Union 2 Supernovae Data
  - BAO from Two-Degree Field and SDSS-DR7
  - Matter Power Spectrum (MPK) from SDSS-DR7
  - ISW-galaxy cross-correlations (SDSS-LRG, 2MASS, NVSS)
  - Refined HST COSMOS 3D weak lensing tomography.
- Used a modified version of the publicly available code CosmoMC, a MCMC sampler.

# Results cont'd

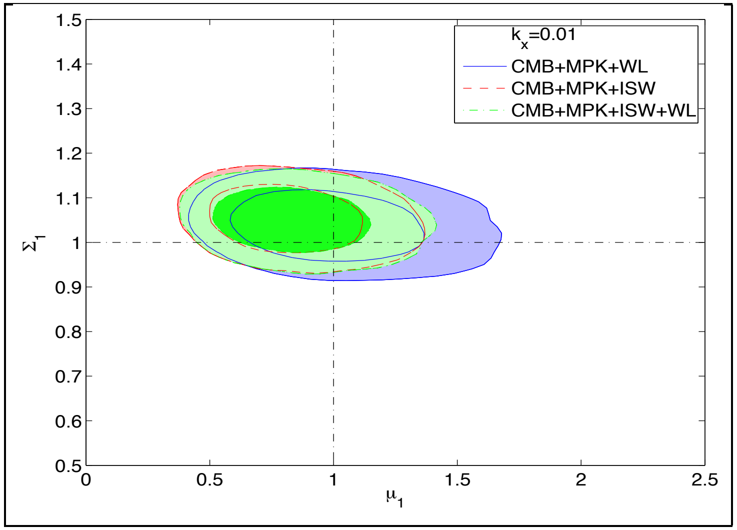
Parameterization 1




| Constraints for the parameters $Q_0$ and $R_0$ | | | |
|---|---|---|---|
| Data set | FoM | $Q_0$ | $R_0$ |
| CMB, MPK | 5.53 | [0.69, 2.79] | [−0.34, 2.04] |
| CMB, ISW | 6.15 | [0.70, 2.76] | [−0.33, 1.85] |
| CMB, WL | 6.44 | [0.57, 2.54] | [−0.30, 2.24] |
| CMB, ISW, WL | 8.46 | [0.67, 2.53] | [−0.33, 1.84] |
| CMB, MPK, ISW | 7.53 | [0.80, 2.73] | [−0.35, 1.62] |
| CMB, MPK, WL | 5.08 | [0.73, 2.80] | [−0.34, 2.13] |
| CMB, MPK, ISW, WL | 7.09 | [0.83, 2.82] | [−0.37, 1.60] |

# RESULTS CONT'D

## Parameterization 2




| Constraints for $\{\mu_i, \Sigma_i\}$ binned parametrization $0 < z \leq 1$, $1 < z \leq 2$ | | | |
|---|---|---|---|
| | $k_x = 0.01$ | | |
| Data sets | WL | ISW | ISW, WL |
| $\mathrm{FoM}_1$ | 75.92 | 101.7 | 101.2 |
| $\mu_1$ | [0.559, 1.567] | [0.480, 1.227] | [0.494, 1.309] |
| $\Sigma_1$ | [0.940, 1.138] | [0.957, 1.145] | [0.955, 1.139] |
| $\eta_1$ (derived) | [0.281, 2.815] | [0.605, 3.486] | [0.563, 3.347] |
| $\mathrm{FoM}_2$ | 148.9 | 176.3 | 184.2 |
| $\mu_2$ | [0.614, 1.456] | [0.563, 1.289] | [0.580, 1.294] |
| $\Sigma_2$ | [0.955, 1.072] | [0.959, 1.075] | [0.959, 1.072] |
| $\eta_2$ (derived) | [0.376, 2.332] | [0.546, 2.649] | [0.554, 2.526] |
| $\mathrm{FoM}_3$ | 18.95 | 22.94 | 25.61 |
| $\mu_3$ | [0.439, 2.073] | [0.509, 1.588] | [0.544, 1.663] |
| $\Sigma_3$ | [0.851, 1.321] | [0.708, 1.268] | [0.818, 1.319] |
| $\eta_3$ (derived) | [0.069, 4.035] | [0.129, 2.889] | [0.244, 3.066] |
| $\mathrm{FoM}_4$ | 43.94 | 62.03 | 63.93 |
| $\mu_4$ | [0.553, 1.754] | [0.588, 1.404] | [0.593, 1.427] |
| $\Sigma_4$ | [0.887, 1.148] | [0.858, 1.134] | [0.878, 1.144] |
| $\eta_4$ (derived) | [0.152, 2.708] | [0.376, 2.424] | [0.398, 2.458] |

# Conclusions

- Tensions between the preferred MG parameter values of different datasets cause the constraints to not always get stronger when adding an additional data set.
- The tensions are more pronounced using parameterization 1 possibly due to the functional form imposed.
- The parameter values for general relativity are within 95% confidence level contours for all data sets.

# Acknowledgments


- DOE Office of Science Graduate Fellowship.
- DOE Grant DE-FG02-10ER41310.
- Part of the calculations for this work were performed on Cosmology Computer Cluster funded by Hoblitzelle Foundation.

# Bibliography


R. Bean and M. Tangmatitham, Phys. Rev. D.**81**, 083534 (2010), arXiv:1002.4197.

G. Zhao et. al. Phys. Rev. D.**81**, 103510 (2010), arXiv:1003.0001.

B. A. Reid et al. Mon. Not. R. Astron. Soc.Volume **404**, 60 (2010), arXiv:0907.1659.

W. J. Percival et al. Mon. Not. R. Astron. Soc.Volume **401**, 2148 (2010), arXiv:0907.1660.

J.Dunkley, E.Komatsu, D.L.Larson, and M.R.Nolta The WMAP Team likelihood `http://lambda.gsfc.nasa.gov/`; D. Larson et al., Astrophys. J. Suppl. Ser. **192**, 16 (2011), arXiv:1001.4635; N. Jarosik et al., Astrophys. J. Suppl. Ser. **192**, 14 (2011), arXiv:1001.4744; E. Komatsu et al., Astrophys. J. Suppl. Ser. **192**, 18 (2011), arXiv:1001.4538.

R. Amanullah et al., Astrophys. J. **716**, 712 (2010), arXiv:1004.1711.

S. Ho, C. Hirata, N. Padmanabhan, U. Seljak, and N. Bahcall, Phys. Rev. D.**78**, 043519 (2008), arXiv:0801.0642.

C. Hirata, S. Ho, N.Padmanabhan, U. Seljak, and N. Bahcall, Phys. Rev. D.**78**, 043520 (2008), arXiv:0801.0644.

T. Schrabback et al., Astron. Astrophys. **516**, A63 (2010), arXiv:0911.0053.

A. Lewis and S. Bridle, Phys. Rev. D.**66**, 103511 (2002). `http://cosmologist.info/cosmomc/`.

A. Lewis, A. Challinor, and A. Lasenby, Astrophys. J. **538**, 473 (2000); `http://camb.info`.

# ISITGR

- Software for testing general relativity
  - Available at:

    http://www.utdallas.edu/~jdossett/isitgr