Testing General Relativity at Cosmological Scales: Effects of Spatial Curvature

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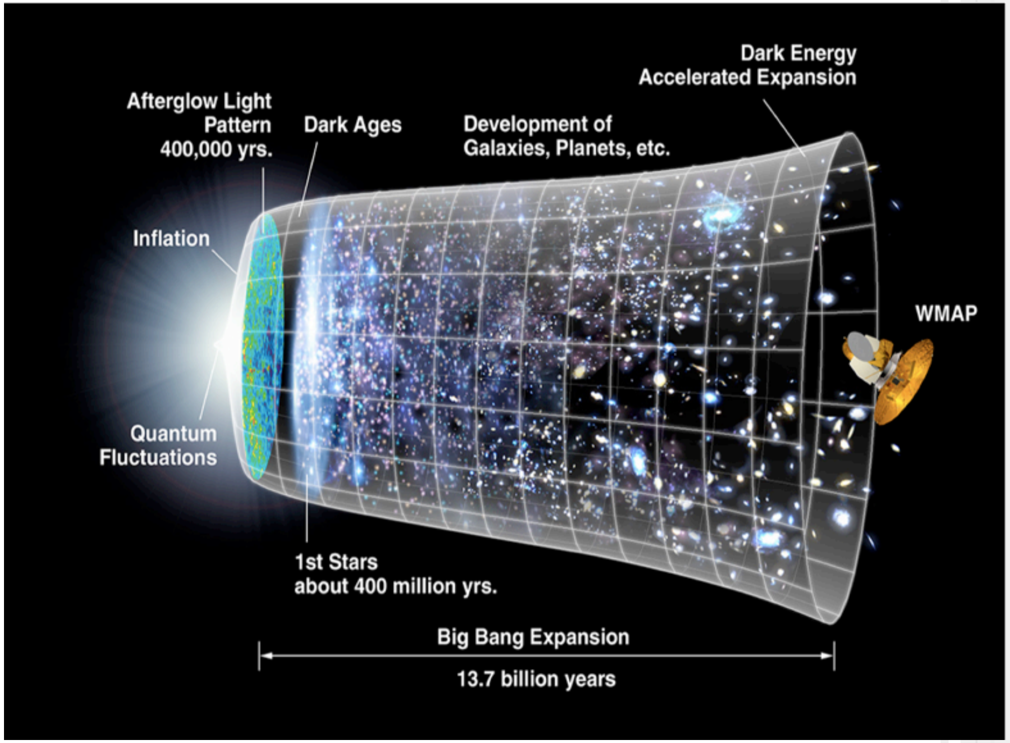
Motivations for Testing GR?

- Cosmic acceleration
  - Dark Energy
  - Modification to gravity at cosmological scales.
- Extend tests to other gravity theories.
  - Are gravity models proposed for quantizing gravity or unifying the four forces correct?



Methods of Distinguishing between GR and Modifications to Gravity

- Looking for inconsistencies 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 Growth Eqns.

Growth Equations

Perturbed FLRW Metric.

$$ds^2 = a(\tau)^2[-(1+2\psi)d\tau^2 + (1-2\phi)\gamma_{ij}dx^i dx^j]$$

where

$$\gamma_{ij} = \delta_{ij}\left[1 + \frac{K}{4}\left(x^2+y^2+z^2\right)\right]^{-2} \text{ and } \qquad K = -\Omega_k \mathcal{H}_0^2$$

Modified Growth Equations

$$\left(k^2 - 3K\right)\phi = -4\pi G a^2 \sum_i \rho_i \Delta_i Q$$

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

$$k^2(\psi + \phi) = \frac{-8\pi G a^2}{1 - 3K/k^2} \sum_i \rho_i \Delta_i \mathcal{D} - 12\pi G a^2 \sum_i \rho_i (1+w_i)\sigma_i Q.$$

$$\mathcal{D} = Q(1+R)/2$$

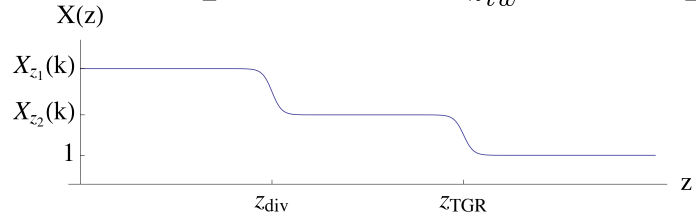
where

$$\Delta_i = \delta_i + 3\mathcal{H}\frac{q_i}{k}$$

Evolving the Modified Gravity Parameters: Binning Methods

Both Traditional binning and Hybrid Method evolve in redshift as

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

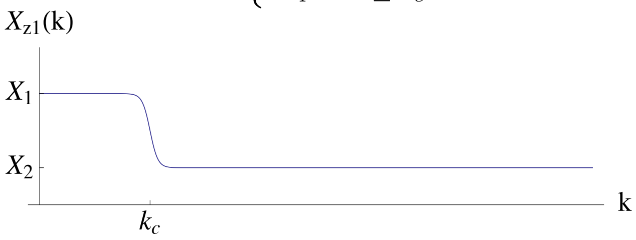


Scale Dependence

Traditional Binning Method

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

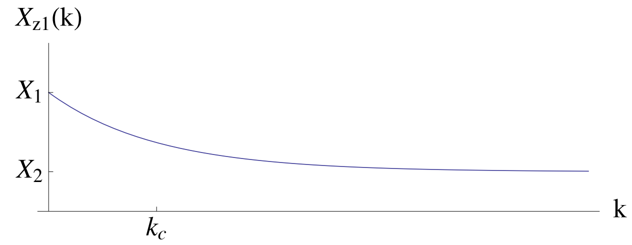
$$X_{z_2}(k) = \begin{cases} X_3 & \text{if } k < k_c \\ X_4 & \text{if } k \geq k_c. \end{cases}$$

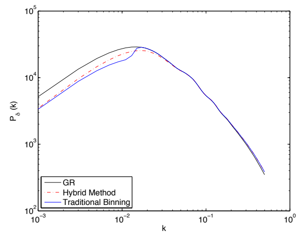


Hybrid Method

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

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





Evolving the Modified Gravity Parameters: Binning Methods

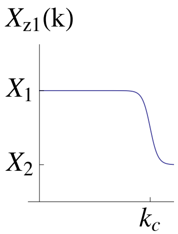
Both Traditional binning and Hybrid Method evolve in redshift as

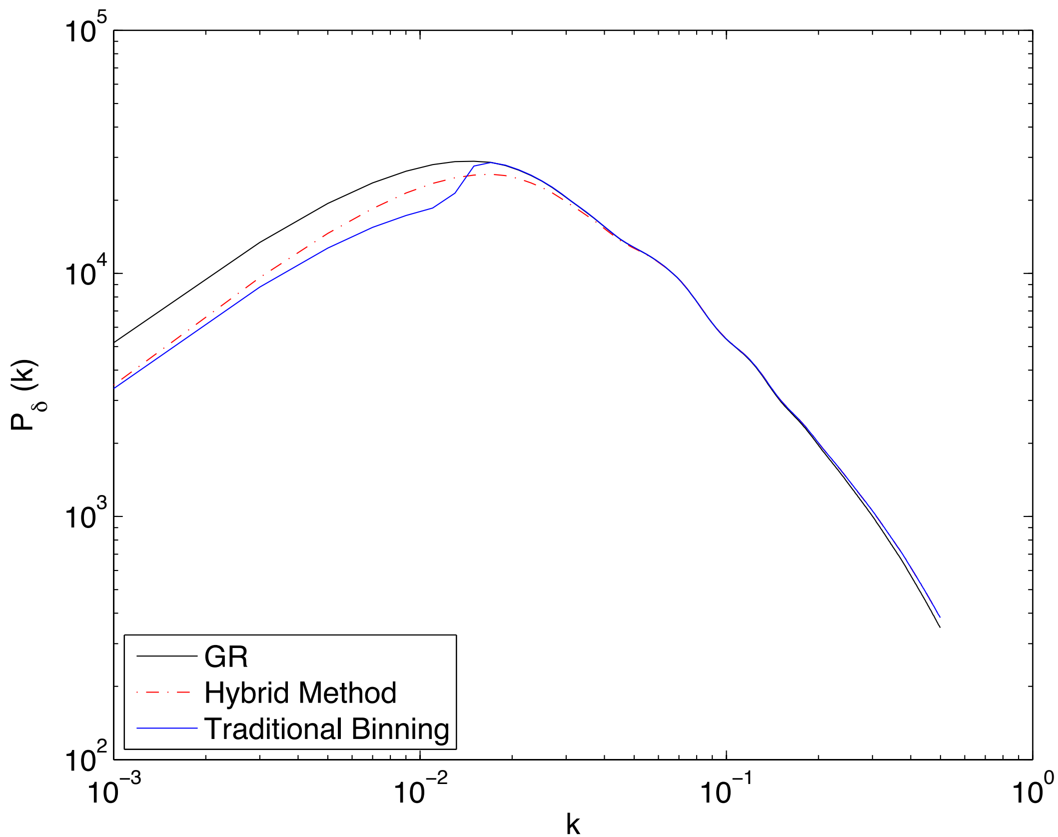
$X($ … $\frac{z_{TGR}}{z_{tw}},$

Traditio…

$X_{z_1}(k$ … $k/k_c)$

$X_{z_2}(k$ … $k/k_c),$





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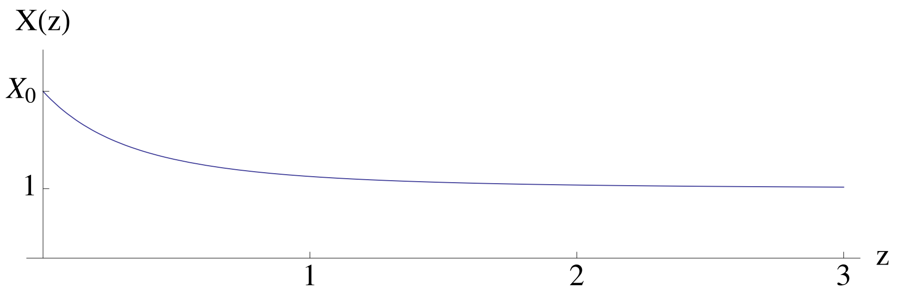
Evolving the Modified Gravity Parameters: Functional evolution

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



CORRELATIONS WITH CURVATURE PARAMETER Ω_k

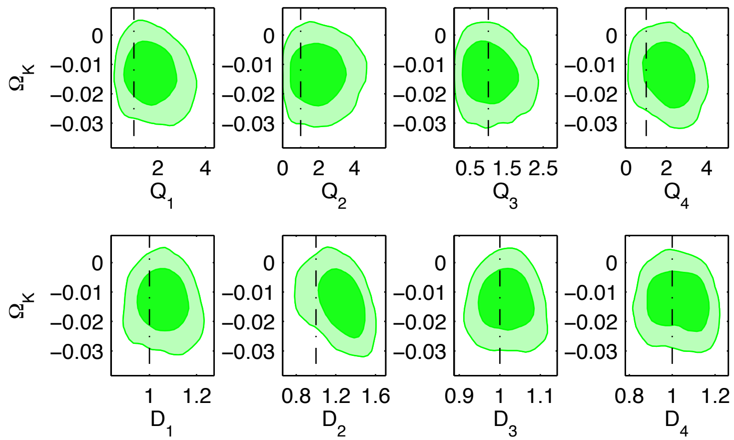
- What can we predict analytically?
  - We would expect the MG parameters to be positively correlated with Ω_k

$$k^2(\psi+\phi) = \frac{-8\pi G a^2}{1-3K/k^2}\sum_i \rho_i \Delta_i \mathcal{D} - 12\pi G a^2 \sum_i \rho_i (1+w_i)\sigma_i Q. \qquad K = -\Omega_k \mathcal{H}_0^2$$

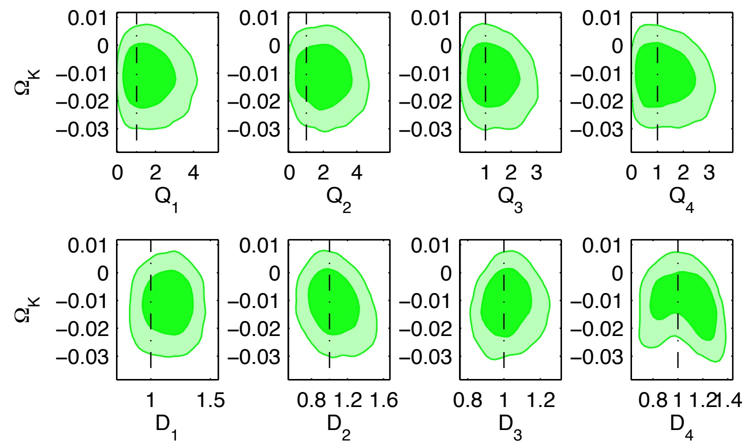
- Use current data to explore correlations.
  - WMAP 7 year temperature and polarization spectra
  - Union 2 Supernovae Data
  - BAO from Two-Degree Field, SDSS-DR7, and WiggleZ
  - Matter Power Spectrum (MPK) from SDSS-DR7
  - ISW-galaxy cross-correlations (SDSS-LRG, 2MASS, NVSS)
  - Refined HST COSMOS 3D weak lensing tomography.

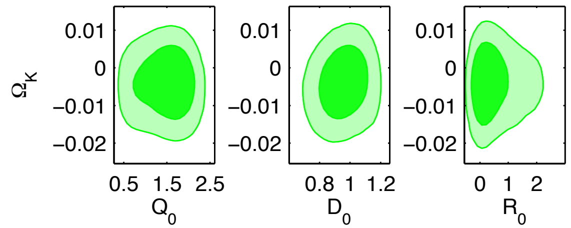
CORRELATIONS WITH CURVATURE PARAMETER Ω_k CONT'D

Traditional Binning



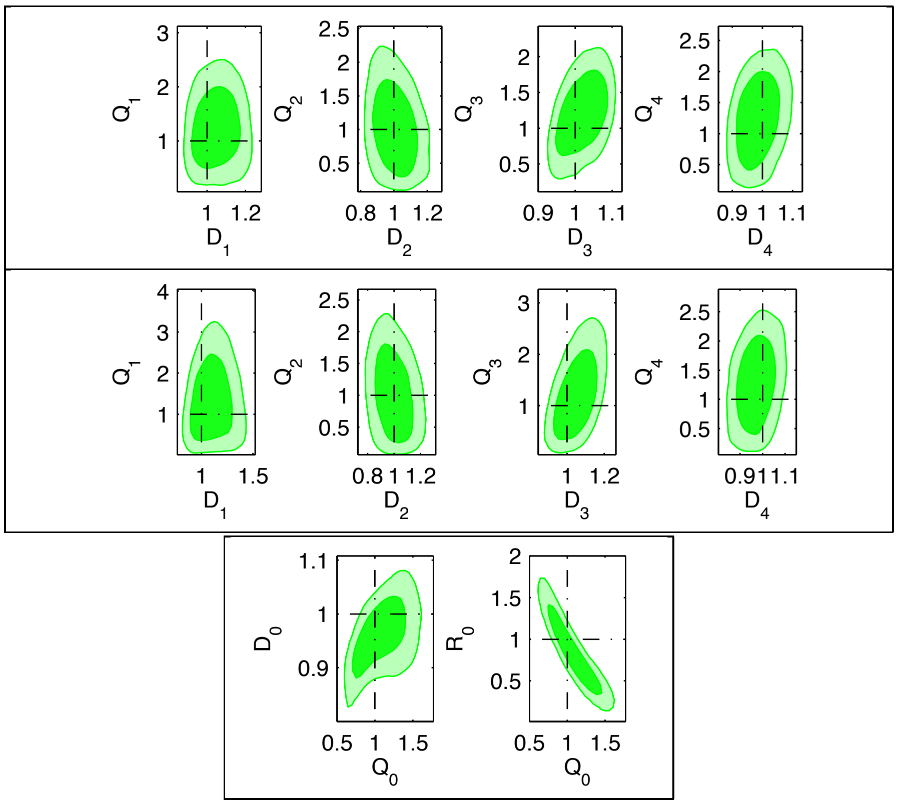
Hybrid Binning



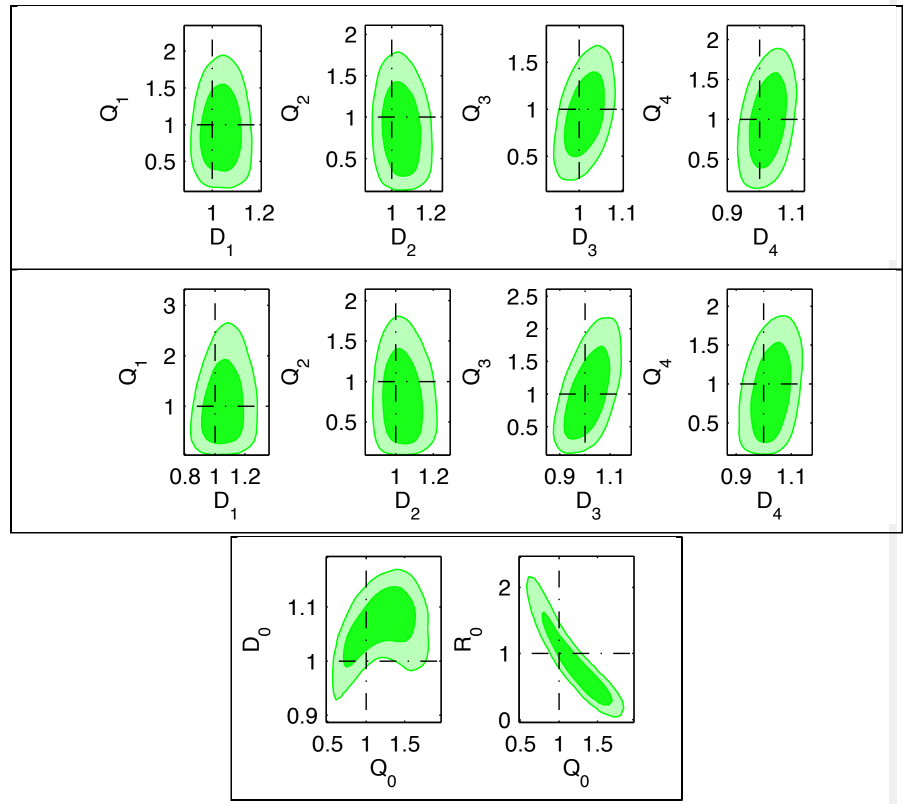


- Can assuming a flat universe when the universe is actually curved affect MG parameter constraints?
  - Generate simulated higher precision data to see.

Effect of curvature on MG parameter constraints

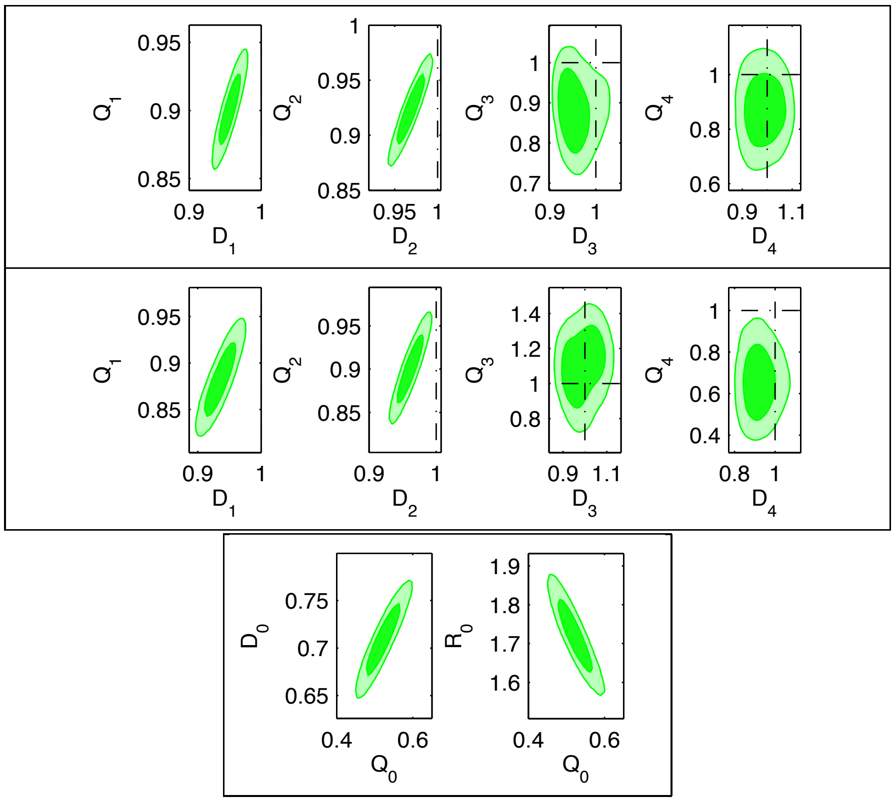


Ω_k=0.01

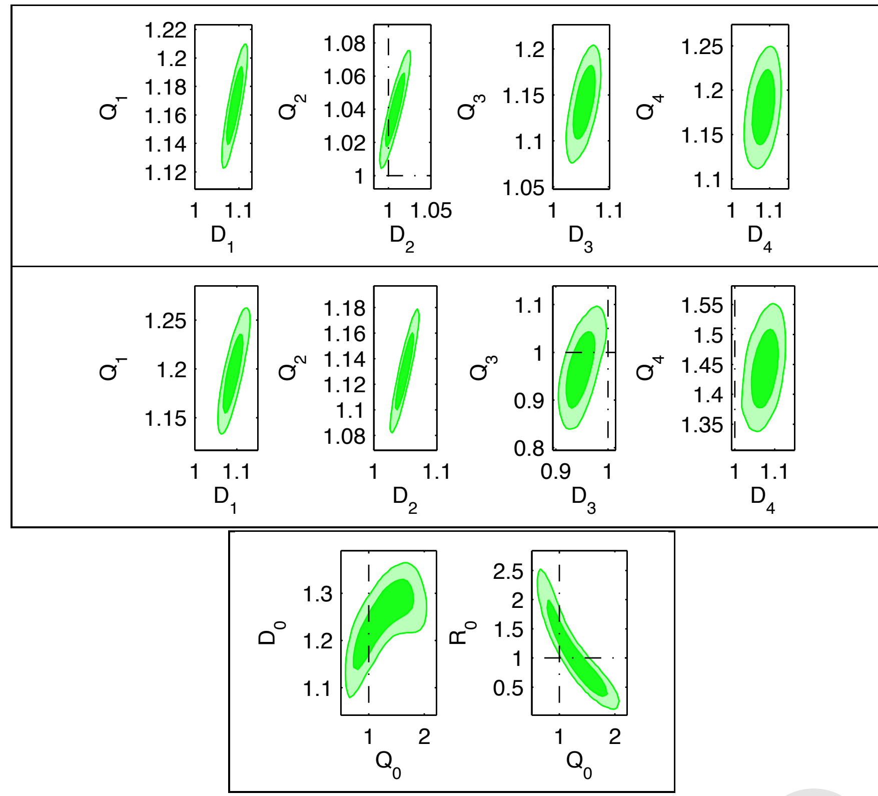


Ω_k=-0.02

Effect of curvature on MG parameter constraints cont'd

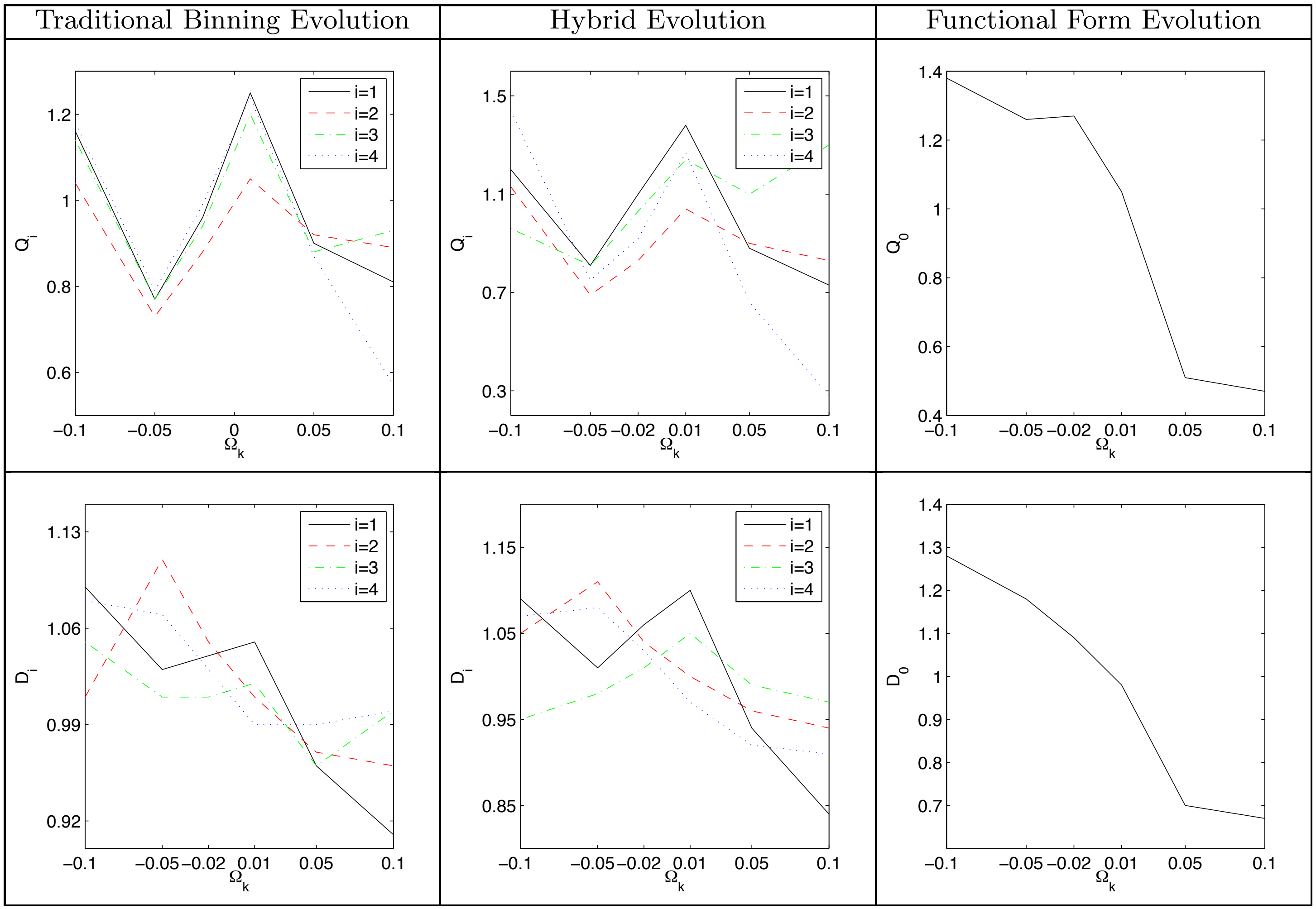


Ω_k=0.05



Ω_k=-0.1

Effect of curvature on MG parameter constraints cont'd



Conclusions

- Curvature is positively correlated with the MG parameters Q and D.
- Ignoring curvature can cause an apparent deviation from GR.
- Negatively curved models deviate more significantly than do positively curved models.
- Must include Ω_k in parameter analysis along with MG and other cosmological parameters when using future data.

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ISiTGR

- ISiTGR is publicly available at:

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

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