Dark Energy Perturbations and Robust Cosmological Tests of General Relativity

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Motivation and Objectives

- Currently need "dark energy" to explain cosmic acceleration.
- Extensions to GR & modifications to gravity have been introduced.
- Need to distinguish between these two scenarios
  - Tests must be robust.
  - Must explore effects of different phenomena on the conclusions of tests.

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WAYS TO TEST GENERAL RELATIVITY

- Looking for inconsistencies in between expansion history and growth of structure
- "Trigger parameters", γ, the growth index. 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.
- Parameterizing deviations from known growth equations.

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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

$$\begin{aligned} k^2\phi &= -4\pi G a^2 \sum_i \rho_i \Delta_i \, Q \\ k^2(\psi - R\,\phi) &= -8\pi G a^2 \sum_i \rho_i w_i \Pi_i \, Q, \end{aligned}$$

Effects of Dark Energy Perturbations on the Tests

- Tests must be robust.
  - Can a more complicated dark energy model mimic a modified gravity model?
  - Will we be able to say for sure that a detected deviation in the MG parameter space is due to a departure from GR.

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DARK ENERGY PERTURBATIONS

$$\dot{\delta} = -(1+w)\left\{ \left[k^2 + 9\mathcal{H}^2(c_s^2 - c_a^2)\right] \frac{\theta}{k^2} - 3\dot{\phi} \right\} + 3\mathcal{H}(w - c_s^2)\delta$$

$$\dot{\theta} = (3c_s^2 - 1)\mathcal{H}\theta + k^2 \frac{c_s^2 \delta}{1+w} + k^2 \left(\psi - \frac{2}{3}\frac{w}{1+w}\Pi \right).$$

$$\dot{\Pi} + 3\mathcal{H}\Pi = 4\frac{c_{\rm vis}^2}{w}\theta$$

Effective sound speed

$$\frac{\delta P}{\delta \rho}\delta \equiv \frac{\delta P}{\rho} = c_s^2\delta + 3\mathcal{H}(1+w)(c_s^2 - c_a^2)\frac{\theta}{k^2}$$

Adiabatic sound speed

$$c_a^2 = \frac{\dot{P}}{\dot{\rho}} = w - \frac{\dot{w}}{3\mathcal{H}(1+w)}$$

Effect on the MG parameter Q

We combining the modified and unmodified growth equations

$$-Q\,4\pi G a^2 \sum_{i\neq DE} \rho_i \Delta_i = -4\pi G a^2 \sum_{i\neq DE} \rho_i \Delta_i - 4\pi G a^2 \rho_{DE} \Delta_{DE}$$

$$\Rightarrow Q = 1 + \frac{\rho_{DE}\Delta_{DE}}{\sum_{i\neq DE} \rho_i \Delta_i}$$

For DGP Models

$$Q_{DGP} = \frac{4 + 2\Omega_m(a)^2}{3 + 3\Omega_m(a)^2}$$

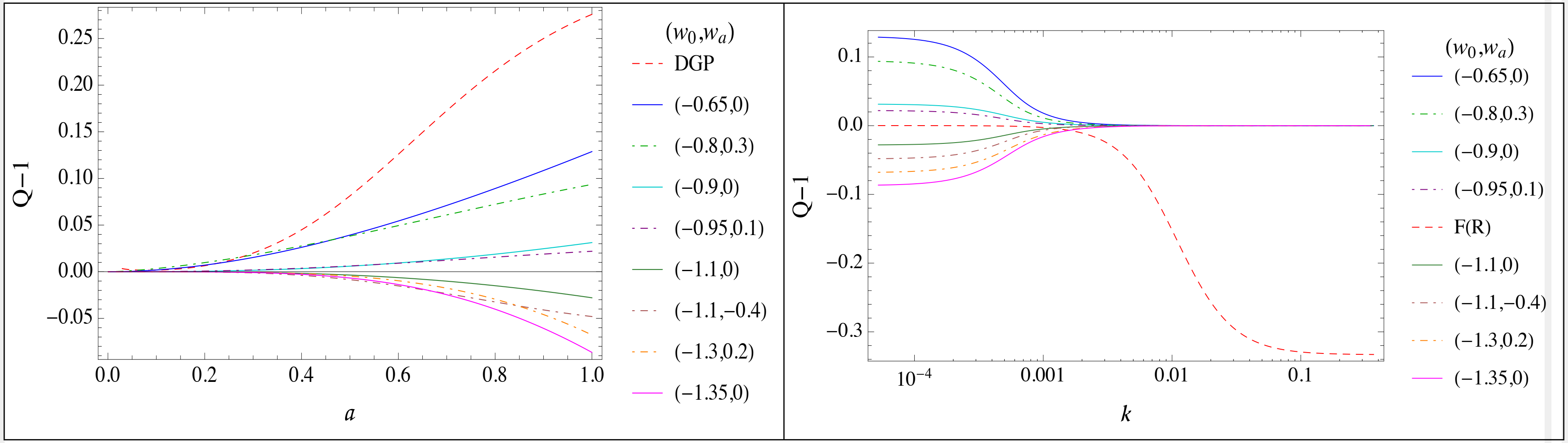
For f(R) Models

$$Q_{f(R)} = \frac{1}{1 - 1.4 \times 10^{-8} |\lambda_1|^2 a^3} \frac{1 + \frac{2}{3}\lambda_1^2 k^2 a^4}{1 + \lambda_1^2 k^2 a^4}$$

$$\lambda_1^2 = B_0 c^2 / (2H_0^2)$$

Effect on the MG parameter Q cont'd

without anisotropic stress



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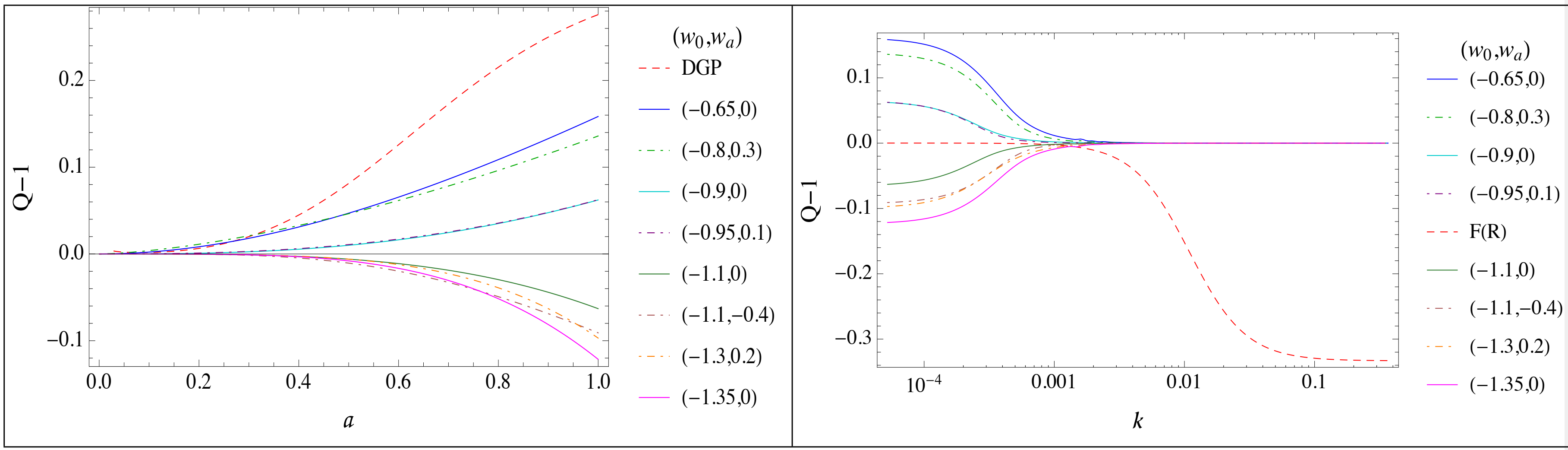
EFFECT ON THE MG PARAMETER Q CONT'D

With anisotropic stress



Effect on the MG parameter R

Again, we combining the modified and unmodified growth equations

$$k^2\psi = -\sum_{i\neq DE} \tilde{\rho}_i \left[w_i \Pi_i + \frac{\Delta_i}{2} \right] - \tilde{\rho}_{DE} \left[w_{DE} \Pi_{DE} + \frac{\Delta_{DE}}{2} \right]$$

$$k^2\psi = -Q \sum_{i\neq DE} \tilde{\rho}_i \left[w_i \Pi_i + R\frac{\Delta_i}{2} \right],$$

$$R = 1 + 2\frac{\rho_{DE} w_{DE} \Pi_{DE} - \frac{\rho_{DE}\Delta_{DE}}{\sum_{i\neq DE} \rho_i \Delta_i} \sum_{i\neq DE} \rho_i w_i \Pi_i}{\sum_{i\neq DE} \rho_i \Delta_i + \rho_{DE} \Delta_{DE}}$$

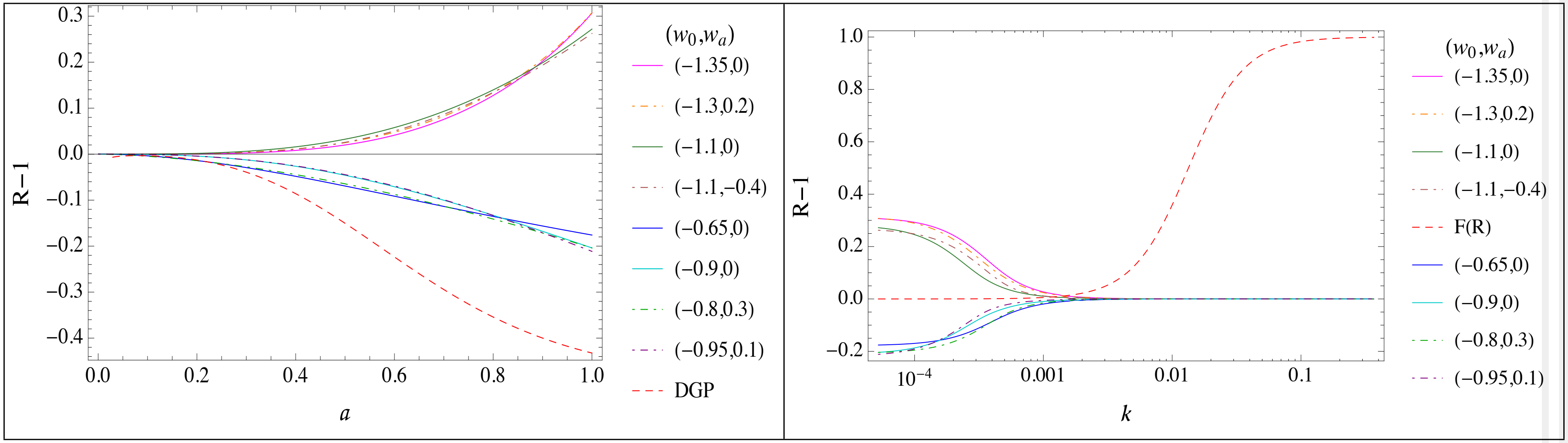
For DGP Models

$$R_{DGP} = \frac{1 + 2\Omega_m(a)^2}{2 + \Omega_m(a)^2}$$

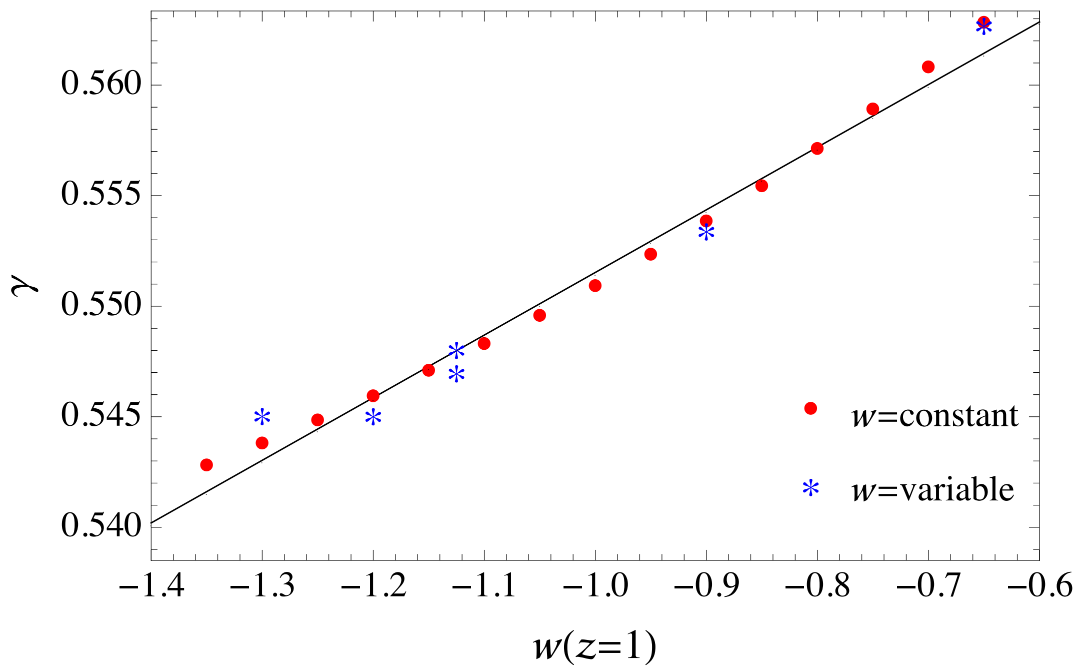
For f(R) Models

$$R_{f(R)} = \frac{1 + \frac{4}{3}\lambda_1^2 k^2 a^4}{1 + \frac{2}{3}\lambda_1^2 k^2 a^4}$$

Effect on the MG parameter R cont'd



Effect on the growth index, γ



$$\gamma = 0.552 + 0.028(1 + w(z = 1))$$

- Anisotropic stress of the form described earlier does not alter the results above.

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SUMMARY

- We derived relations between the MG parameters and dark energy perturbations.
- Though the MG parameters show some deviation for DE models with perturbations, this is not nearly as significant as those given by modified gravity models.
- The growth index is most robust to dark energy perturbations
- Our tests should be able to distinguish between dark energy and modified gravity models.
- Full work available as arXiv:1311.0726