From Modified Gravity to Observations, and Back

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Future Surveys of Cosmic Structure

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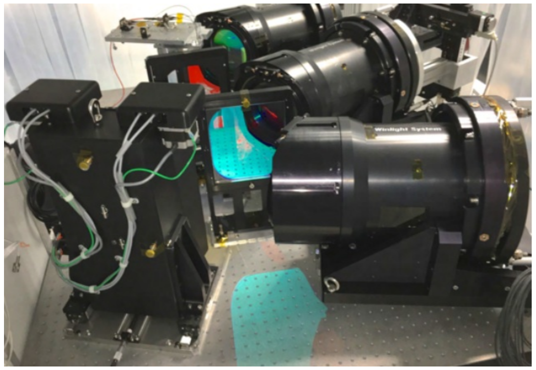
DESI will cover 14000 deg^2 with spectroscopy, measuring 3D clustering and BAO and RSD.



LSST will cover 18000 deg^2 with 6 band imaging, measuring weak lensing and photometric galaxy clustering.

WFIRST will go deep, with red/NIR imaging and IFU spectroscopy, measuring 3D clustering at z>1.5.

The Pull of Gravity

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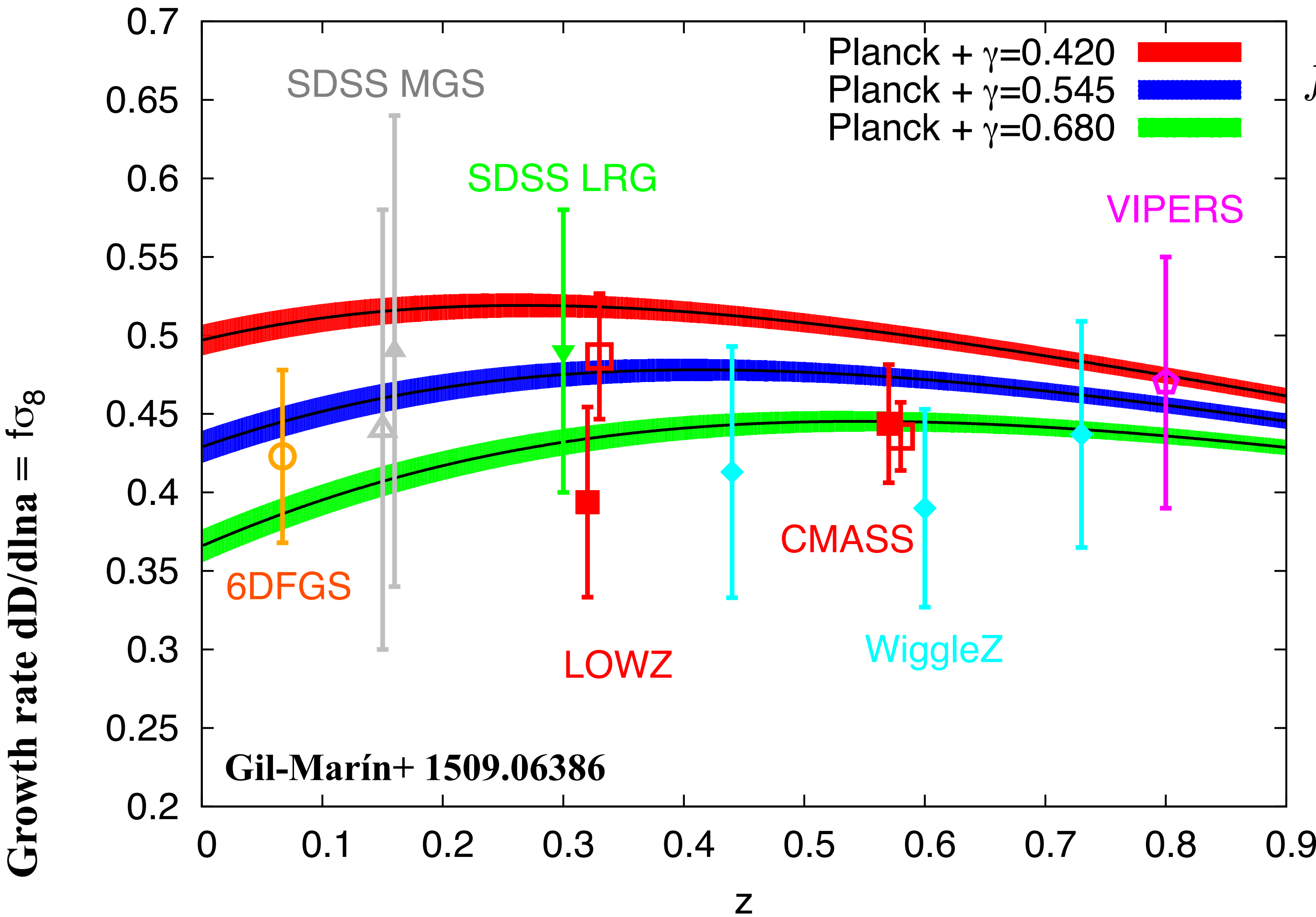
In general relativity, (linear) growth of structure and expansion are tied together – one predicts the other. Cosmic growth tests GR.



$$f = \frac{d\ln D}{d\ln a} \approx \Omega_m(a)^\gamma$$

Is growth suppressed?

Or is beyond linear modeling insufficient?

Gravitational Strength

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$$\nabla^2(\phi + \psi) = 8\pi G_N \, a^2 \, \delta\rho \times G_{\rm light} \longleftarrow \textbf{weak lensing}$$

$$\nabla^2\psi = 4\pi G_N \, a^2 \, \delta\rho \times G_{\rm matter} \longleftarrow \textbf{growth}$$

Cosmic Growth + Light Deflection

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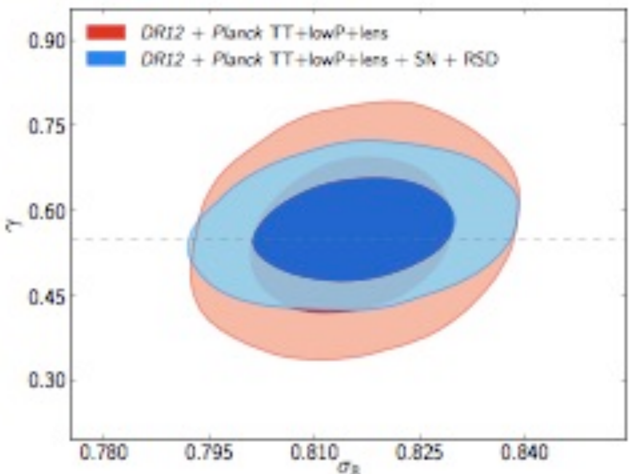
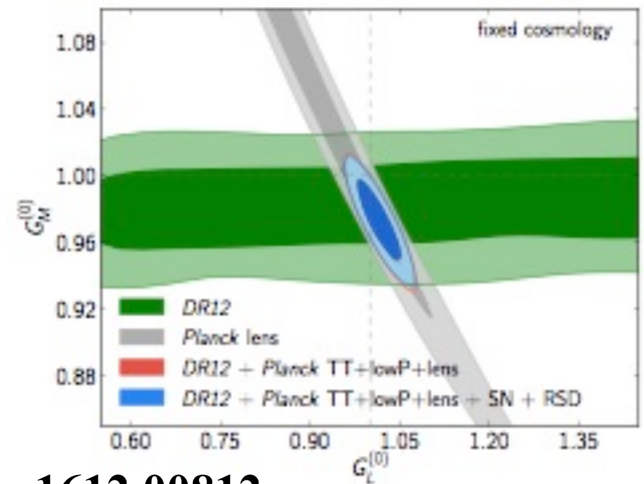
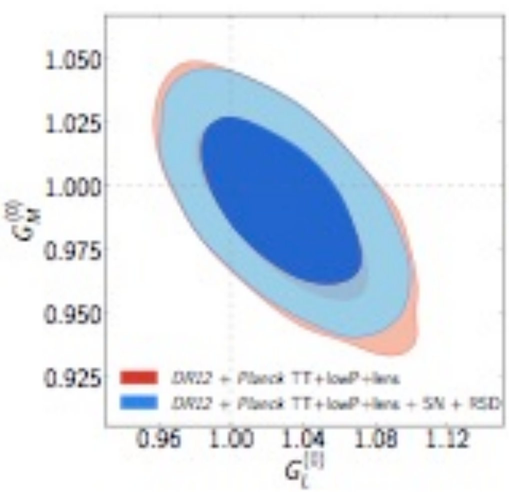
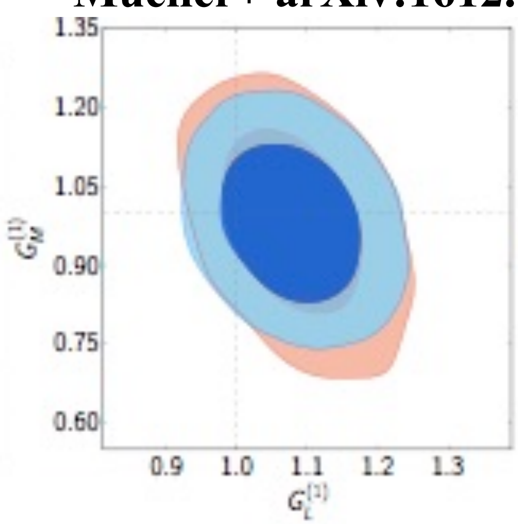
Modified gravity affects both the growth of structure and the deflection of light (lensing). Look at the effective gravitational strength for each: G_M, G_L.

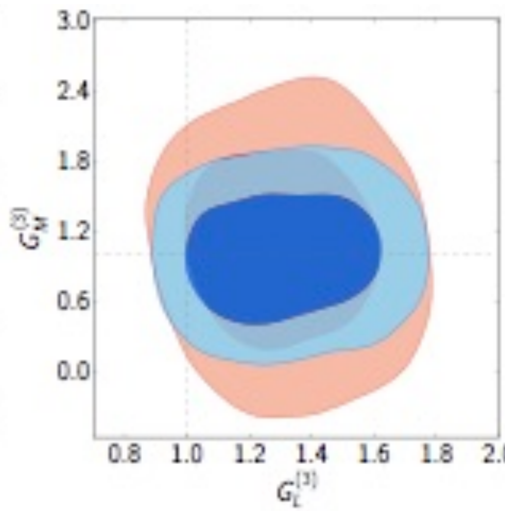




Mueller+ arXiv:1612.00812







Strengths of Gravity

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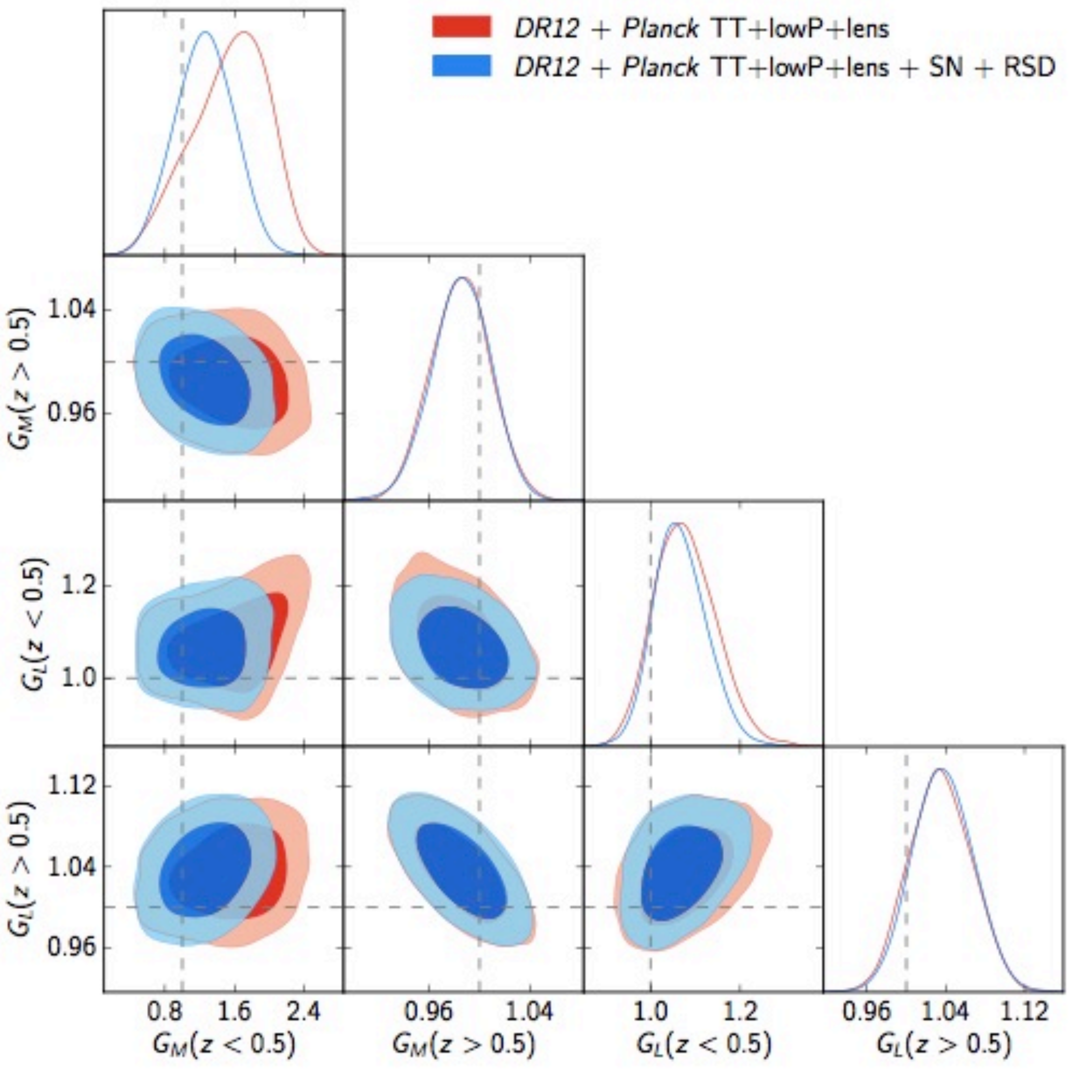
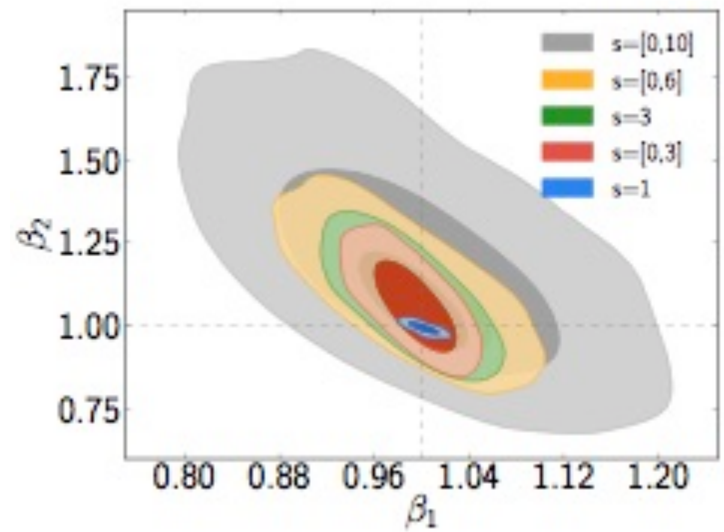
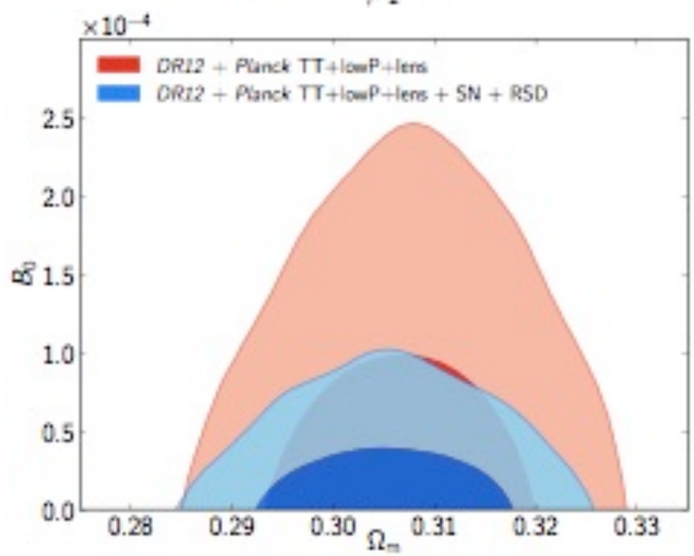
The assumed model or time variation has a major impact on observational constraints.







Expansion History vs Growth History

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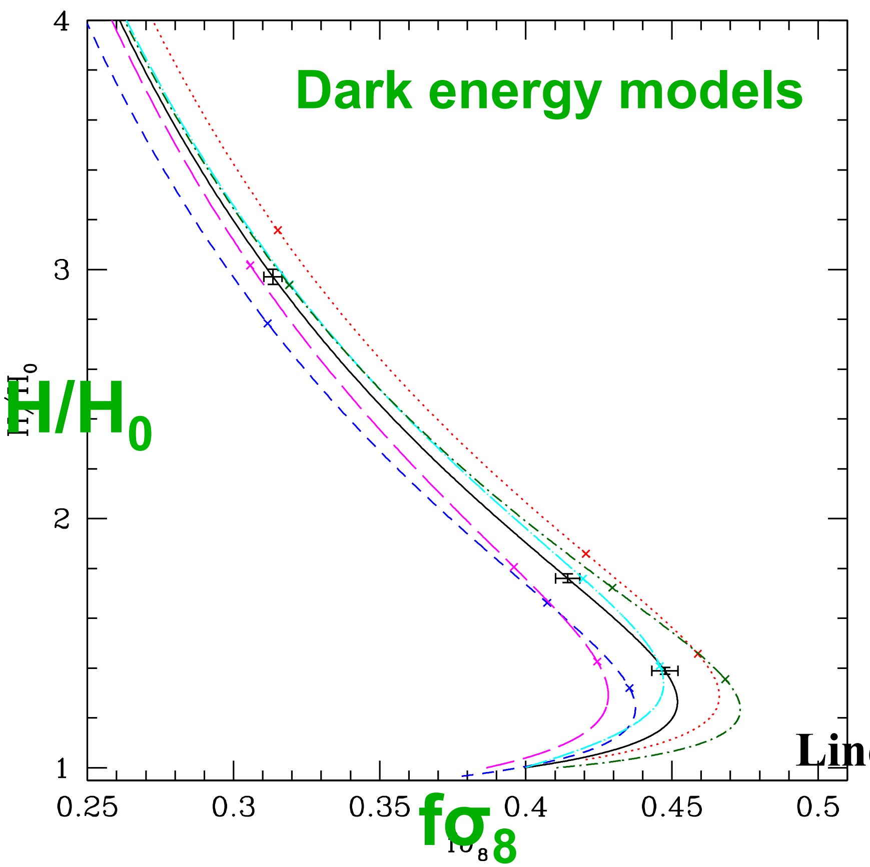
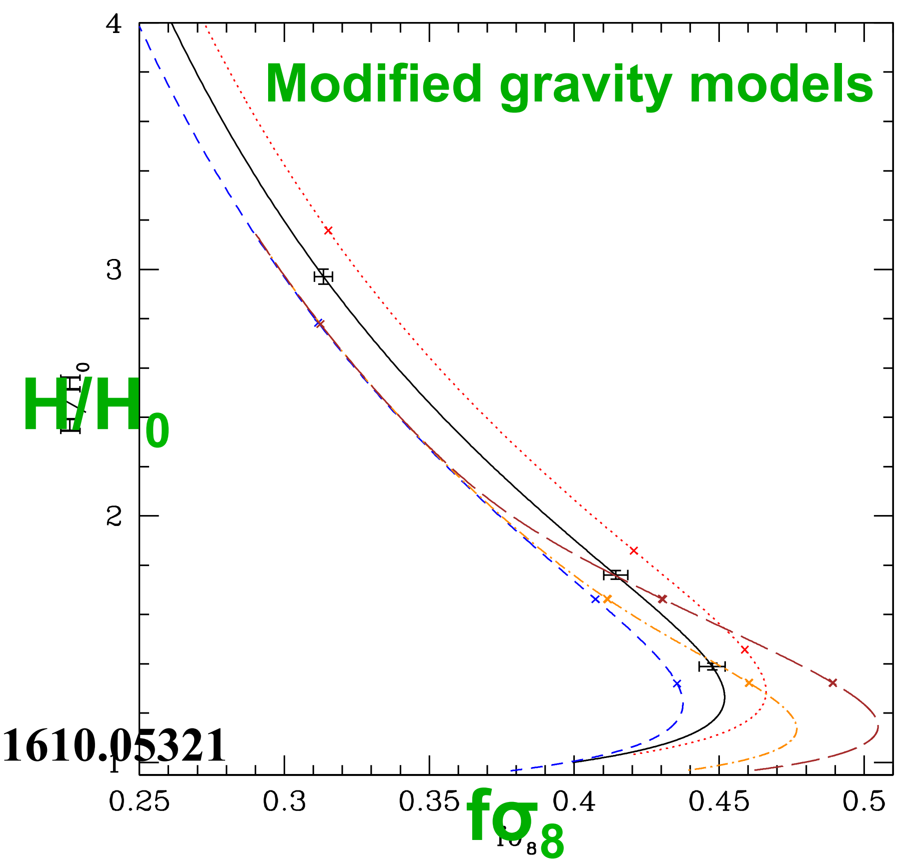
Since the growth rate is very flat with redshift, one can instead compare growth directly with expansion.

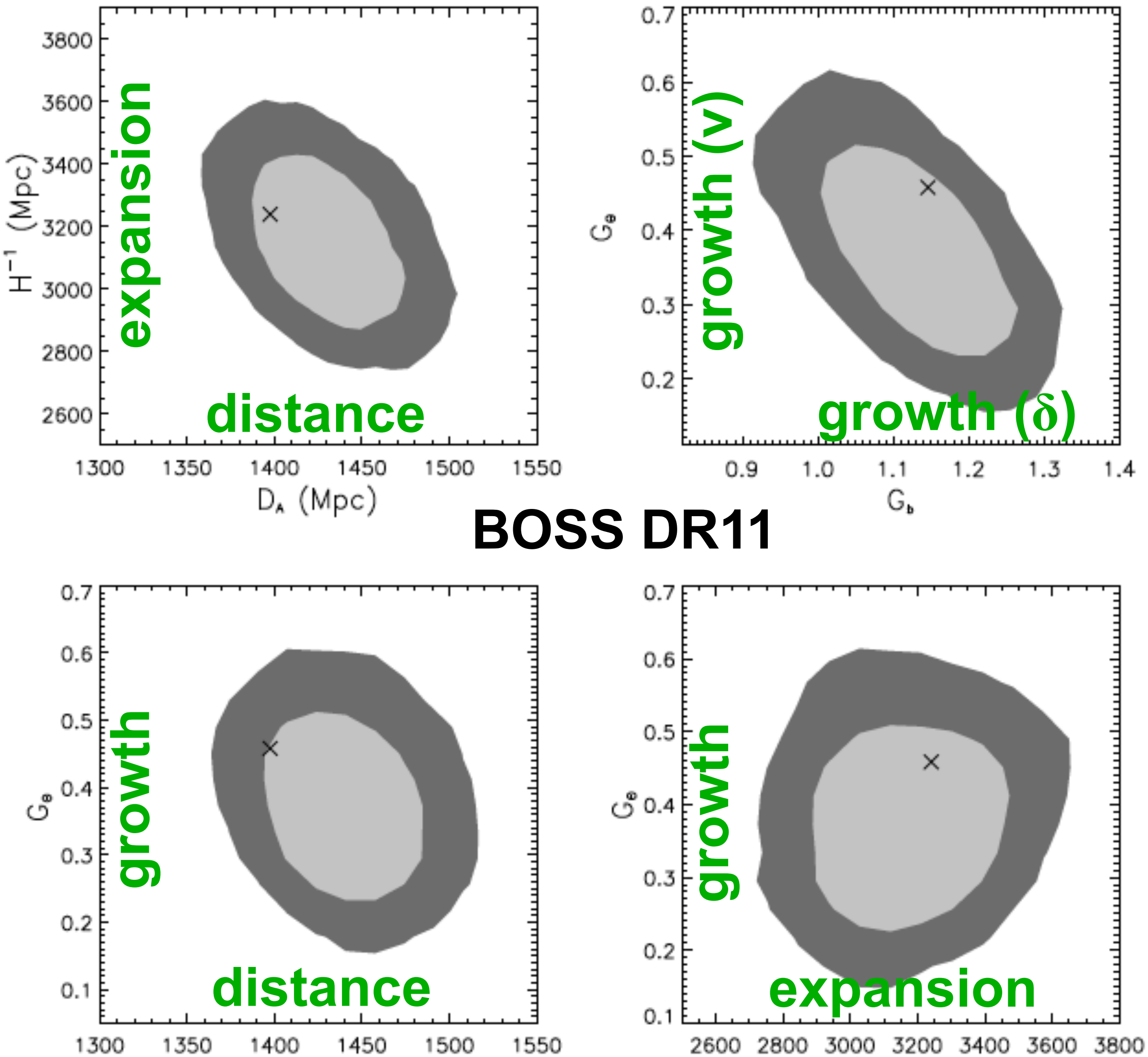
This has some features that show growth effects beyond expansion.





Linder 1610.05321

Cosmic Growth vs Expansion



BOSS DR11

Song+ 1507.01592

Growth vs expansion can be tested in a model independent way.

Beyond linear clustering must treat modGR consistently (perturbation theory).

Gernerally Testing Gravity

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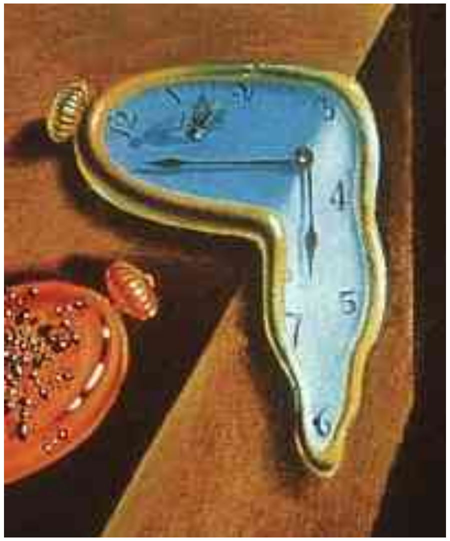
Cosmic acceleration suggests that Einstein relativity may need modification.

How should we test cosmic gravity, other than one model at a time? How do we connect observations and theory in a model independent manner?



Note the expansion history H(z) is merely one free function of time.

For cosmic structure we have 5 times as many! (kineticity, Planck mass running, braiding, tensor speed).

Now the tensor sector is as important as the scalar (matter) sector!

The Richness of Gravity

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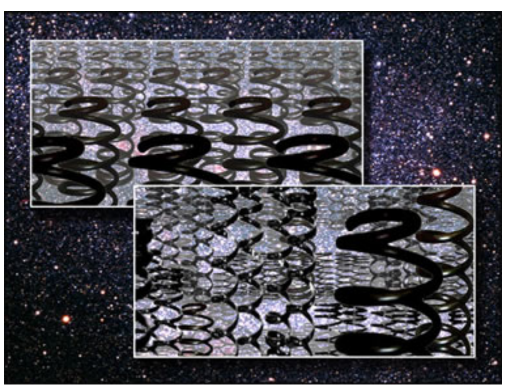
In GR, expansion determines growth.

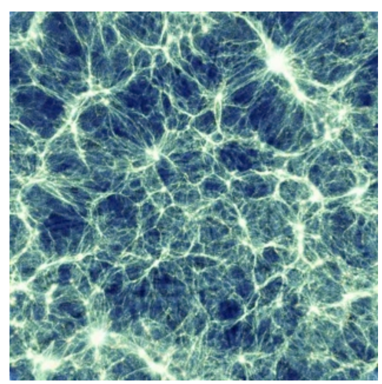
In modified gravity, cosmology is much richer.
Plus the tensor sector!

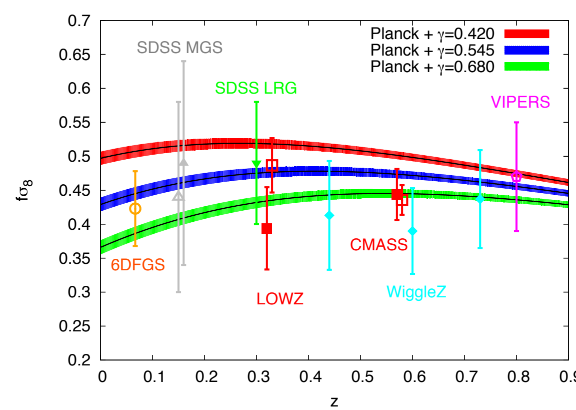
We have learned to fit H(z) with just a few parameters:
Ω_m, w_0, w_a.

Can we do the same with gravity functions?

Need close connection between theory, computation, and data to test/interpret the results.







Property Functions

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How do we parametrize the modGR time dependence and how do we capture the general physics?

A relatively new approach is the Effective Field Theory of dark energy. This writes the most general theory possible, subject to symmetries – **model independent!**

Property functions give phenomenological combinations of EFT functions. Bellini & Sawicki 2014

α_B – braiding: mixing scalar and tensor sectors

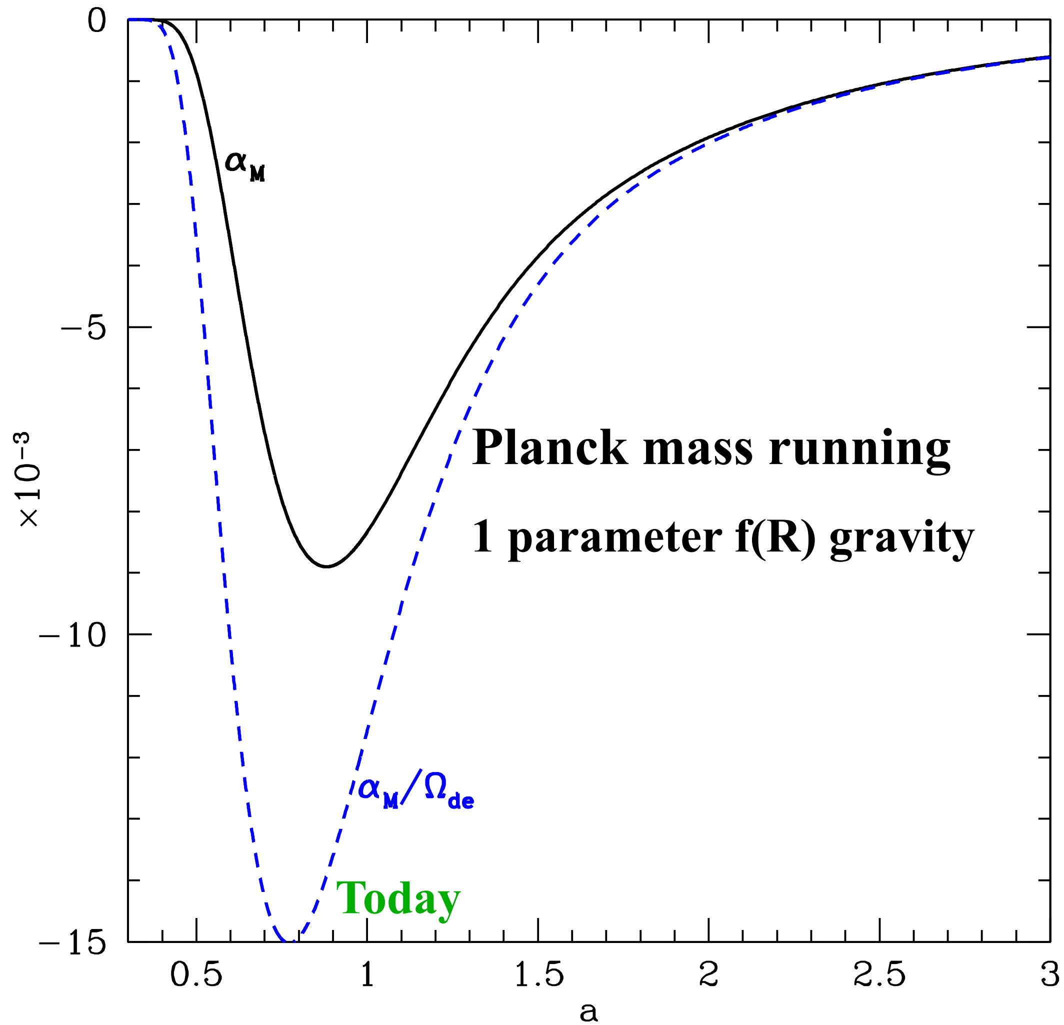
α_K – kineticity: kinetic structure

α_M – running Planck mass (coupling)

α_T – tensor wave speed deviation (c_T^2-1)

All are functions of time, and 0 within GR.

Fitting Property Functions



Linder 1607.03113

Very difficult to fit these modified gravity functions of time to observations with just a few parameters, even for simple theories.

Observations First

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Instead, put the observations in forefront. Modified Poisson equations **Bertschinger & Zukin 2008, Zhao+ 2009; Song+ 2010; Daniel+ 2010, Bertschinger 2011**

$$\nabla^2(\phi + \psi) = 8\pi G_N\, a^2\, \delta\rho \times G_{\rm light} \longleftarrow \text{weak lensing}$$

$$\nabla^2\psi = 4\pi G_N\, a^2\, \delta\rho \times G_{\rm matter} \longleftarrow \text{growth}$$

This is robust. The question is only how complicated is the time and space dependence of $G_m(k,a)$, $G_l(k,a)$.

Here we focus on the cosmic growth of structure and show that very simple parametrization of $G_m(k,a)$ works very well.

Cosmic Growth Rate

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For cosmic growth we focus on G_{matter}. Can we avoid parametrizing it (since it can be complicated)?

Look at the growth rate f.

$$\frac{d(f-f_\Lambda)}{d\ln a} + \left[(f-1)^2 - (f_\Lambda - 1)^2\right]$$
$$+ \left[4 + \frac{1}{2}\frac{d\ln H^2}{d\ln a}\right](f - f_\Lambda) = \frac{3}{2}\Omega_m(a)\left[G_{\mathrm{m}}(a) - 1\right]$$

Ignoring the small squared term, this has solution

$$\delta f(a) = \frac{3}{2}\int_0^a d\ln a' \left[\frac{a'^4 H(a')}{a^4 H(a)}\right]\Omega_m(a')\,\delta G_m(a')$$

Cosmic Growth Factor

Consider the integral form of the growth rate eq.

$$\int_0^a d\,\ln a' \left\{ \frac{d\delta f}{d\ln a'} + \left[4 + \frac{1}{2}\frac{d\ln H^2}{d\ln a'} \right] \delta f \right\}$$
$$= \frac{3}{2}\int_0^a d\ln a'\,\Omega_m(a')\,[G_m(a')-1]\,,$$

When one component dominates, the square bracket is constant and we have a term

$$\int_0^a d\ln a'\,\delta f$$

This is very interesting because the growth factor deviation

$$\frac{g}{g_\Lambda} = e^{\int_0^a d\ln a'\,[f(a')-f_\Lambda(a')]} = e^{\int_0^a d\ln a'\,\delta f(a')}$$

Parametrization without Parametrization

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For gravitational deviations during matter domination

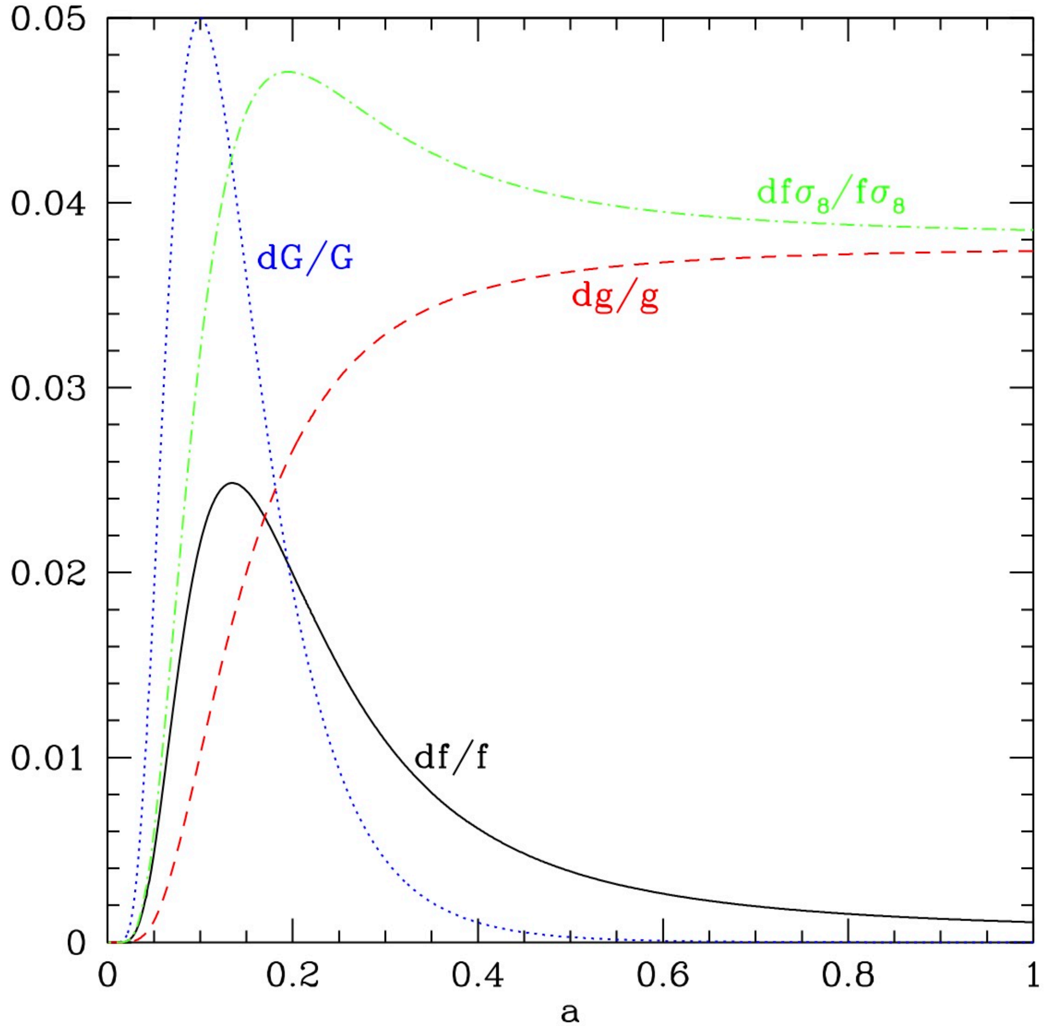
$$\int_0^a d\ln a'\,\delta f \approx \frac{3}{5}\int_0^a d\ln a'\,\delta G_{\rm m} - \frac{2}{5}\delta f(a)$$

After the deviation dG$_m$, df fades rapidly, as (a^{4}H)$^{-1}$~a$^{-5/2}$-a^{-4}. So growth deviations only depend on the "area" of the modification dG$_m$, not the whole dG$_m$(a). No need to parametrize dG$_m$(a)!

$$\begin{aligned}\frac{\delta g}{g_\Lambda} &\approx \frac{3}{5}\int_0^a d\ln a'\,\delta G_{\rm m} - \frac{2}{5}\delta f(a)\\ &\approx \frac{3}{5}\int_0^a d\ln a'\,\delta G_{\rm m}\left[1-\left(\frac{a'}{a}\right)^{5/2}\right]\\ &\approx \frac{3}{5}\,{\rm Area}\end{aligned}$$

Denissenya & Linder 2017

Signatures in Cosmic Growth



df is a lagged, skewed version of dG_m,
dg approaches a constant offset,
$df\sigma_8$ is a convolution of these two.

Accurate Parametrization

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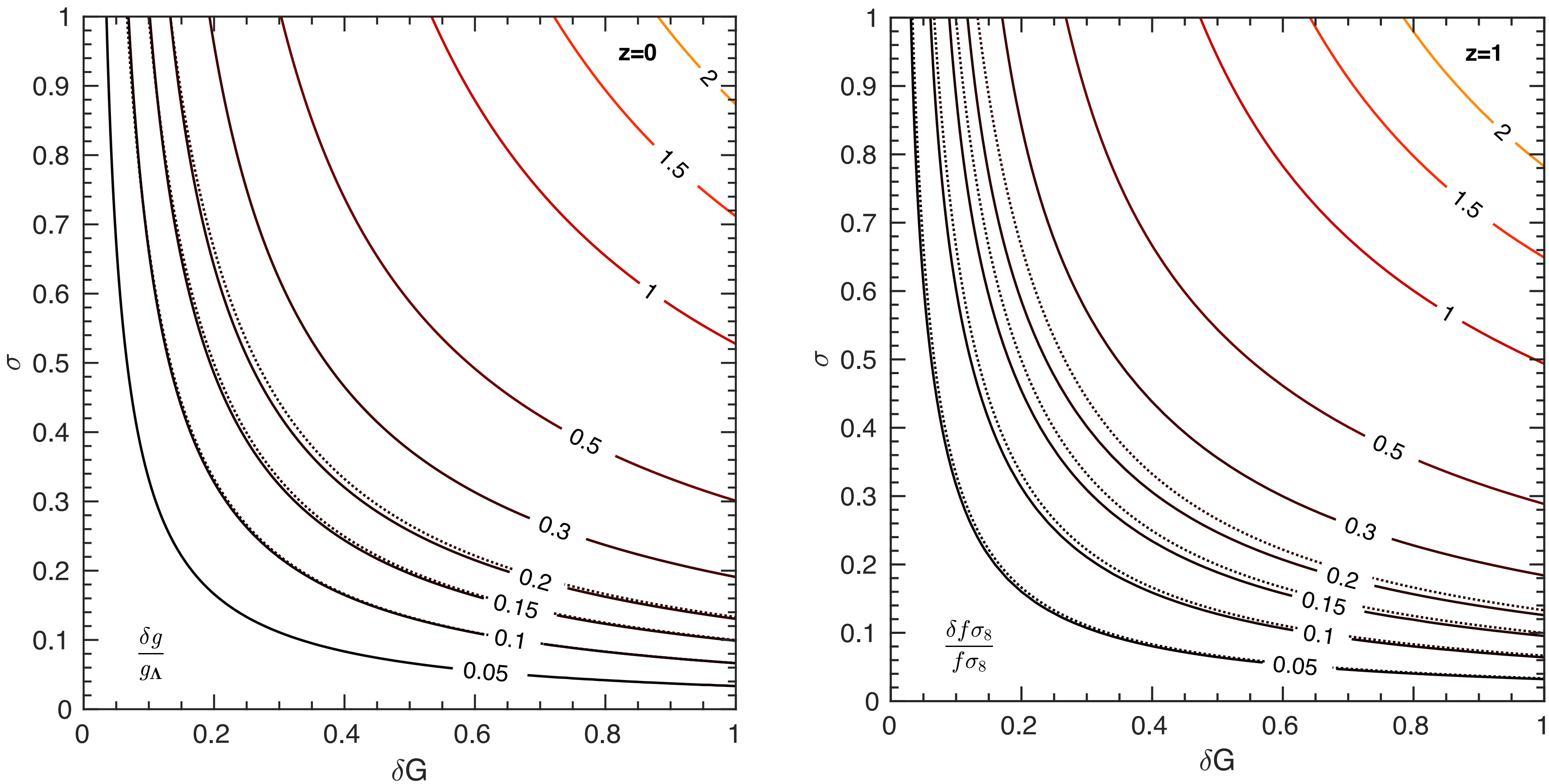
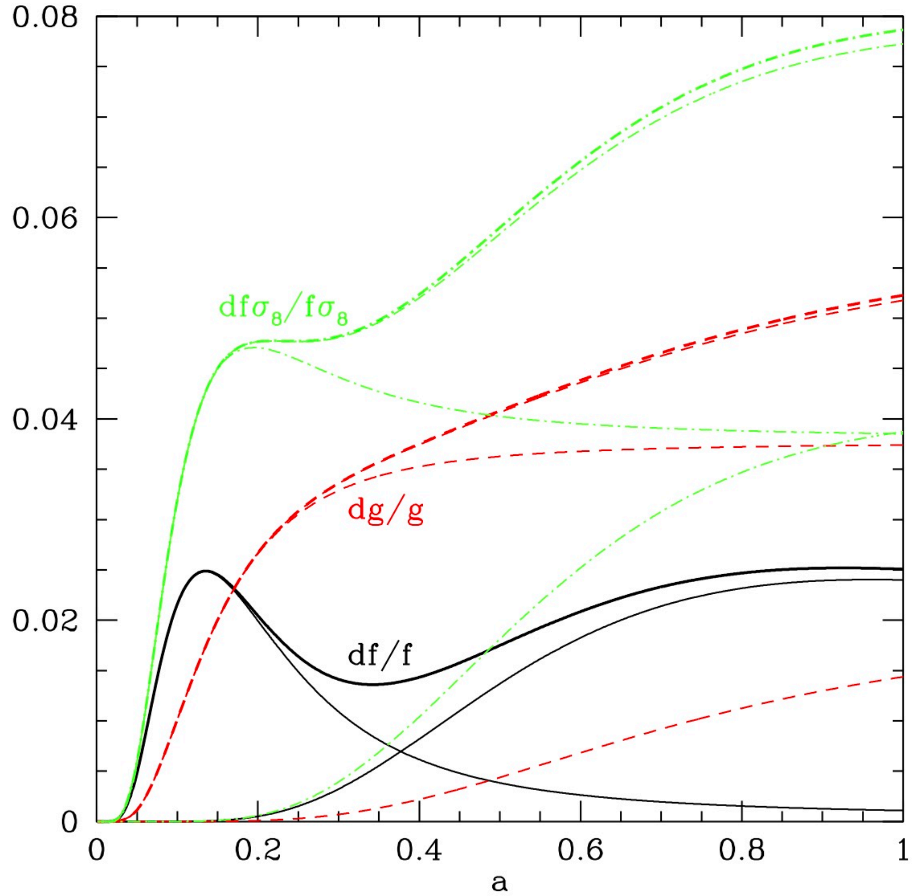
All that is important is the area under dG_m, not $G_m(a)$. This one parameter model is accurate to ~0.3% in the observables g, $f\sigma_8$.



Early and Late Gravity

Thus gravity in the entire matter dominated era, z~3-1000, can be dealt with by one parameter.

We also showed that one can simply add this early era to late time modifications.



1 parameter for early times.

Next: late times.

Late Gravity

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The simplest model independent parametrization for late time gravity is simply bins in a.

How many bins do we need for subpercent accuracy on the observable, $f\sigma_8$? (*not* on G_m)

- **Accuracy determined by next generation data, e.g. DESI.**
- **Want accurate parametrization for many different gravity theories.**
- **Want informative constraints, i.e. pointing to physics.**

Theories and Data

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We consider a suite of model behaviors for $dG_m(a)$:

- **Rising (power law)**
- **Falling (power law)**
- **Nonmonotonic (Gaussian pulse)**
- **Nonmonotonic (convolution of Gaussians)**
- **DGP**
- **f(R)**

We solve for the exact growth, and place error bars corresponding to DESI measurement precision.

Denissenya & Linder

Fitting Results

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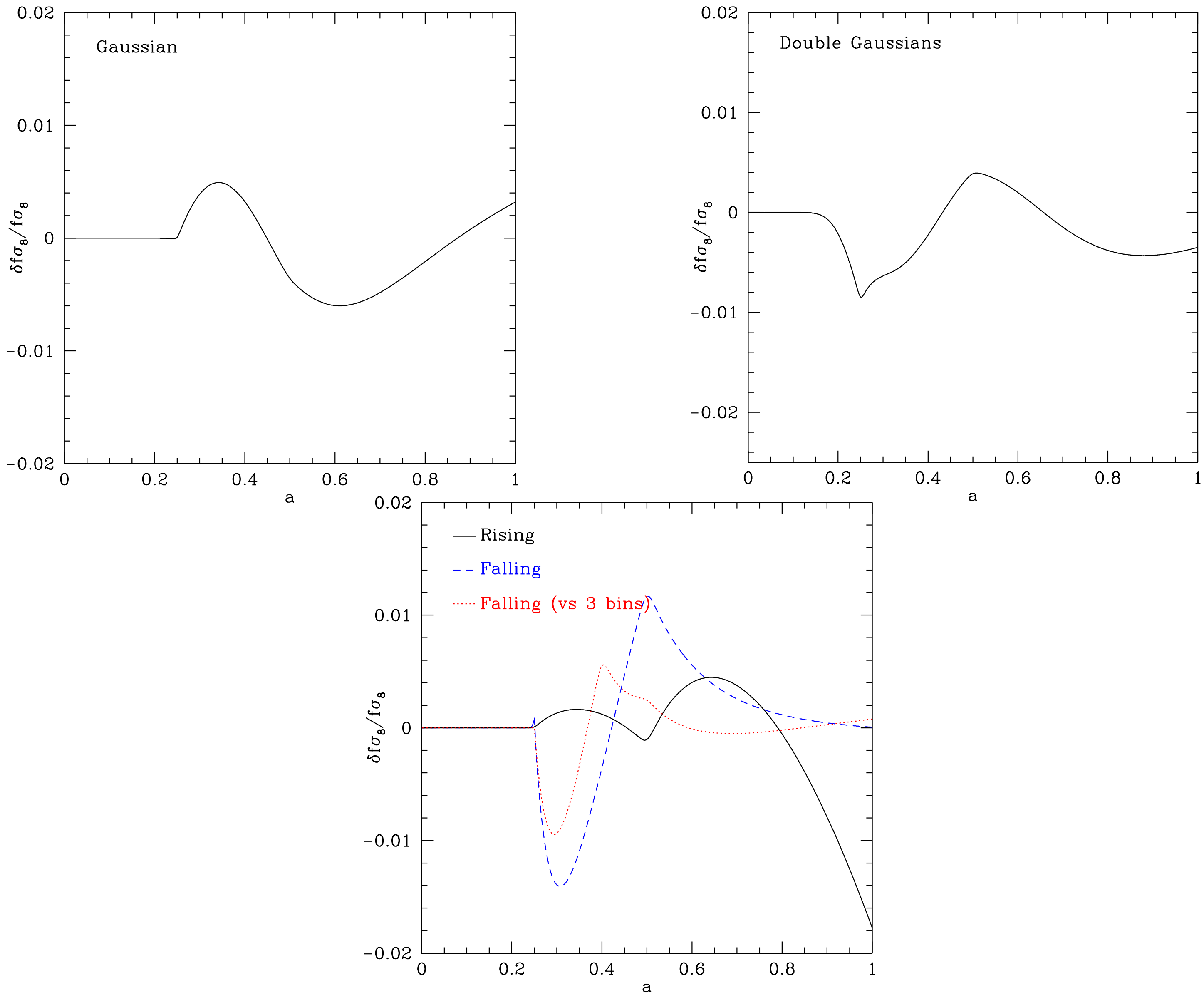
Comparison to using simple 2 bin values of G_m



Fitting Results

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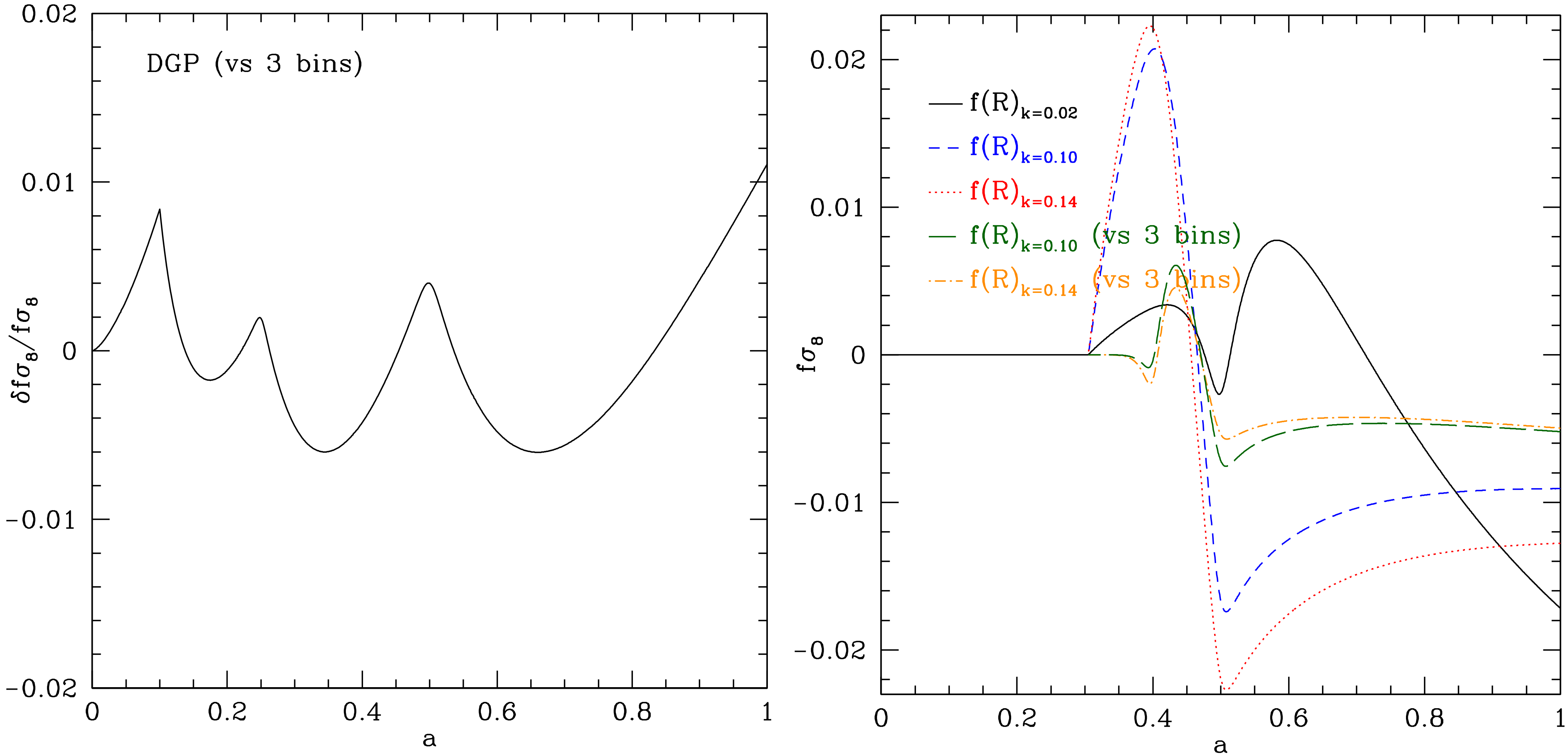

Fitting Results

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More important than the deviation is the **impact on cosmology** estimation – e.g. a sawtooth doesn't look like a change in cosmology.

We calculate the **bias** on cosmology (Ω_m,w_0,w_a) from using 2 bins to parametrize $G_m(a)$:

Model	$\Delta\chi^2$	$[\delta p/\sigma(p)]_{max}$	$\mathrm{Risk}_{\mathrm{max}}$
Gaussian ($a_c = 0.7$)	0.02	0.02	1.00
Gaussian ($a_c = 0.5$)	0.13	0.33	1.05
Gaussian ($a_c = 0.3$)	0.16	0.22	1.02
Gaussian ($a_c = 0.7$; $\delta G = 0.1$)	0.09	0.04	1.00
$\mathrm{Gaussian}_3$ ($a_c = 0.3$)	0.09	0.22	1.02
$\mathrm{Gaussian}^2$ ($\sigma = 0.25$)	0.03	0.09	1.00
$\mathrm{Gaussian}^2$ ($\sigma = 0.5$)	1.78	0.35	1.06
$\mathrm{Gaussian}_3^2$ ($\sigma = 0.5$)	0.03	0.07	1.00
Rising a^3	0.01	0.09	1.00
Falling a^{-3}	0.36	0.25	1.03
$\mathrm{Falling}_{3s}$ a^{-3}	0.10	0.23	1.03
DGP	2.28	0.45	1.10
DGP_3	0.00	0.02	1.00
$f(R)$ ($k_0 = 0.02$)	0.07	0.06	1.00
$f(R)$ ($k_0 = 0.10$)	1.81	1.34	1.67
$f(R)_{3s}$ ($k_0 = 0.10$)	0.18	0.40	1.08
$f(R)$ ($k_0 = 0.14$)	2.57	1.52	1.82
$f(R)_{3s}$ ($k_0 = 0.14$)	0.12	0.31	1.05

Negligible!

Much much less than 1σ ($d\chi^2$=2.3).

Only 2-3 parameters needed.

Summary & Future

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DESI, Euclid, LSST, WFIRST, etc. will have exciting next generation surveys providing accurate tests of gravity.

Very difficult to go from theory to observations in model independent way: H(z) + 4 functions.

Keeping observations in front, we show subpercent accuracy with just 2-3 gravity parameters, for cosmic growth.

Future: does it work for lensing? for tensors?