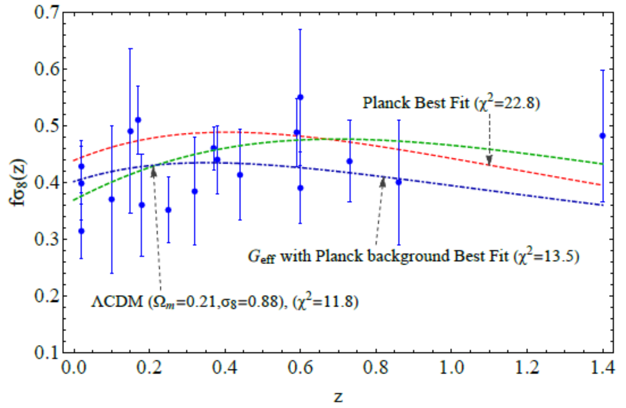
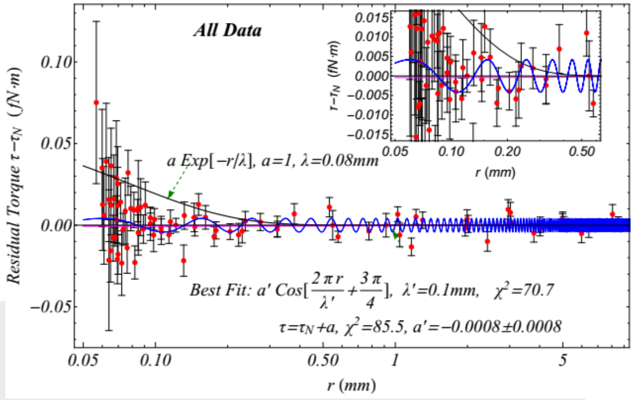
Hints of Modified Gravity in the Cosmos and in the Lab ?





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Talk based on:

Hints of modified gravity in cosmos and in the lab?
Leandros Perivolaropoulos, Lavrentios Kazantzidis (Ioannina U.). Apr 20, 2019. 38 pp.

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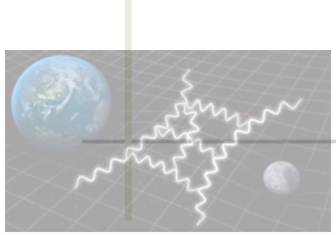
Structure of talk

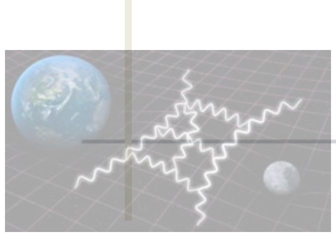


1. Scales of tests of General Relativity:
   Common Parametrizations measuring deviations.

2. Cosmological Scales
   Growth of Density Perturbations
   Tension of Growth Data with Planck/ΛCDM
   Easing the Tension with Evolution of Newton Constant $G_{eff}(z)$
   Reconstruction of Scalar-Tensor Theory.

3. Sub-mm new forces
   Oscillating Parametrizations of G(r): Improved fit to Data
   Theoretical Models: f(R) theories, Infinite Derivative Gravity

Scales of GR Tests I:
Sub-mm Scales: Space Translation Invariance

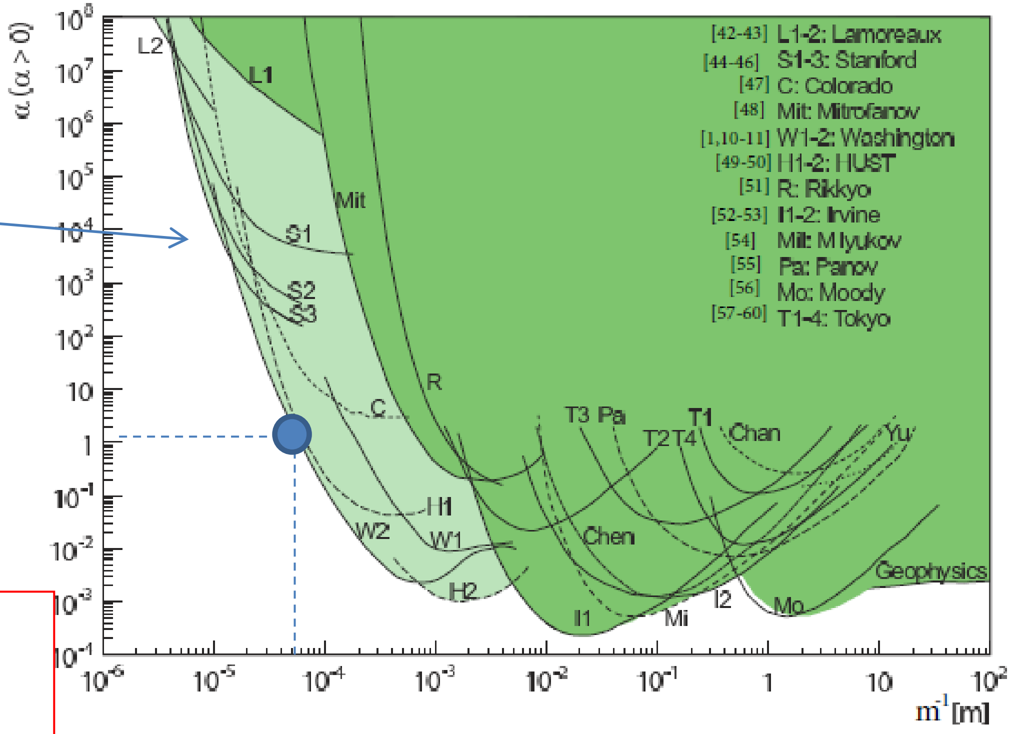


Yukawa Parametrization:

$$V_{eff} = -G\frac{M}{r}\left(1+\alpha e^{-mr}\right)$$

Constraints from

Jiro Murata and Saki Tanaka, "A review of short-range gravity experiments in the LHC era," Class. Quant. Grav. 32, 033001 (2015), arXiv:1408.3588 [hep-ex].



L. Perivolaropoulos, "PPN Parameter gamma and Solar System Constraints of Massive Brans-Dicke Theories," Phys. Rev. D81, 047501 (2010), arXiv:0911.3401 [gr-qc].

What if $1/6m^2 < 0$?

Theoretical Motivation:

$$f(R) = R + \frac{1}{6m^2}R^2$$

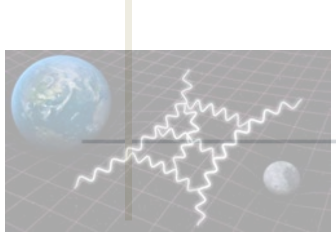
Chiba, T., "$1/R$ gravity and scalar-tensor gravity", Phys. Lett. B, 575, 1-3 (2003). [DOI], [ADS], [arXiv:astro-ph/0307338].

$$S_{BD} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[\Phi R - \frac{3}{2}m^2(\Phi-1)^2\right] + S_{matter}$$

$$T_{\mu\nu} = diag(M\delta(\vec{r}),0,0,0)$$
$$\Phi = 1+\varphi$$
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\varphi = \frac{2GM}{3r}e^{-mr}$$
$$h_{00} = \frac{2GM}{r}\left(1+\frac{1}{3}e^{-mr}\right)$$
$$h_{ij} = \frac{2GM}{r}\delta_{ij}\left(1-\frac{1}{3}e^{-mr}\right)$$

Scales of GR Tests II: Solar System Scales



PPN Parameters:

$$ds^2 = g_{00}c^2dt^2 + g_{rr}\left(dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)\right)$$

Spherically Symmetric Vacuum:

$$g_{00} = \left(\frac{1+\phi/2}{1-\phi/2}\right)^2 , \quad g_{rr} = -\left(1-\phi/2\right)^4 , \quad \phi \equiv -\frac{GM}{rc^2}$$

Small ϕ expansion:

$$g_{00} = 1 + 2\phi + 2\phi^2 + \ldots , \quad g_{rr} = -1 + 2\phi + \ldots$$

Small ϕ expansion deviating from GR:

$$g_{00} = 1 + 2\cancel{\alpha}\phi + 2\beta\phi^2 + \ldots , \quad g_{rr} = -1 + 2\gamma\phi + \ldots$$

Current Constraints:

$$\gamma - 1 = (2.1 \pm 2.3)\times 10^{-5} \qquad \beta - 1 = (1.2 \pm 1.1)\times 10^{-4}$$

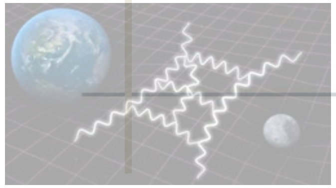
Alternative Parametrization:

$$g_{00} = [g_{00}]_{\mathrm{GR}} + \delta g_{00} , \quad \delta g_{00} = 2\phi(r)\ \alpha \exp\left(-\frac{r}{\lambda}\right)$$

$$\alpha < 10^{-10} \ \text{ at } \ \lambda \simeq \mathrm{Earth-Moon\ distance}$$

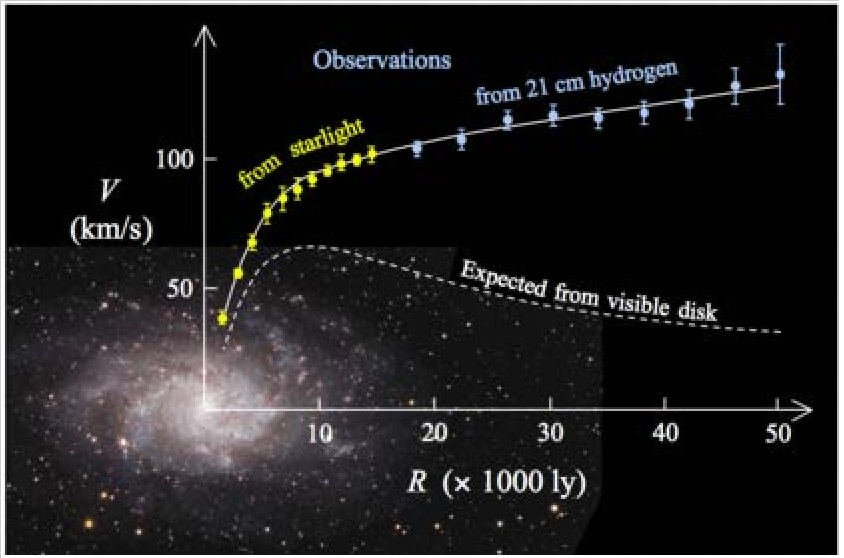
But: Pioneer Anomaly….

Scales of GR Tests III:
Galactic Scales – Dark Matter



GR is ruled out with only Luminous Matter (LM)

$$G_{\mu\nu} \neq T^{LM}_{\mu\nu}$$



Dark Matter Restores Validity of GR

$$G_{\mu\nu} = T^{LM}_{\mu\nu} + T^{DM}_{\mu\nu}$$

Alternatively GR could be modified (TEVES)

$$G_{\mu\nu} + G^{TEVES}_{\mu\nu} = T^{LM}_{\mu\nu} \quad \text{or} \quad G_{\mu\nu} + G^{TEVES}_{\mu\nu} = T^{LM}_{\mu\nu} + T^{DM}_{\mu\nu}$$

Dark Matter and/or MOND/TEVES ?

$$S_{\rm TeVeS} = \int (\mathcal{L}_g + \mathcal{L}_s + \mathcal{L}_v)\, d^4x.$$

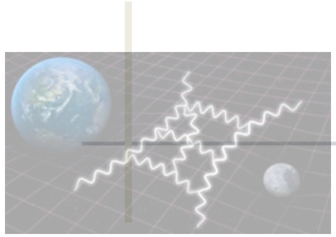
$$F = \mu\left(\frac{a}{a_0}\right) ma,$$

$$\mu(x) = \begin{cases} 1 & |x| \gg 1 \\ x & |x| \ll 1 \end{cases}$$

Scalar-tensor-vector gravity theory
J.W. Moffat (Perimeter Inst. Theor. Phys. & Waterloo U.). Jun 2005. 14 pp.
Published in **JCAP 0603 (2006) 004**

Bekenstein, J. D.; Sanders, R. H. (2006), "A Primer to Relativistic MOND Theory",
doi:10.1051/eas:2006075

Scales of GR Tests IV: Cosmological Scales-Λ, Dark Energy or Modified Gravity



Newtonian Gauge Cosmological Perturbations:

$$ds^2 = -(1+2\phi)dt^2 + a^2(1-2\psi)d\mathbf{x}^2$$

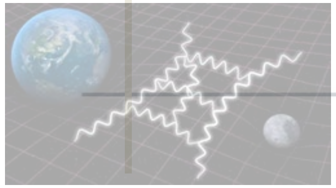
Modified Poisson equations:

$$\nabla^2\phi = 4\pi G_{eff} a^2 \rho \delta_m$$
$$\nabla^2(\phi+\psi) = 8\pi G_L a^2 \rho \delta_m$$

G_{eff} (matter density perturbations), G_L (lensing of light) parametrize deviations from GR ($G_{eff}=G_L=G_N$ in GR)

Present cosmological data can mainly test time translation invariance of G.

Alternative parametrization: Gravitational slip $\quad \gamma = \frac{\psi}{\phi}$



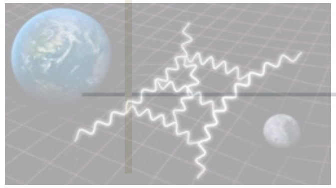
Basic Questions

1. Is GR consistent with data on each scale?

2. What is the optimum parametrization in providing the best quality of fit to the data?

3. What are the theoretical models that support such parametrization?

Cosmic Growth of Density Perturbations



Perturbed metric Newtonian gauge:

$$ds^2 = -(1+2\phi)dt^2 + a^2(1-2\psi)d\mathbf{x}^2$$

Define gauge invariant:

$$\delta_m \equiv \frac{\delta\rho}{\rho+p} + 3Hv$$

$$\delta u_\mu = -\partial_\mu v$$

$$\nabla_\mu T^\mu_\nu = 0$$

$$T_{\mu\nu} = (\rho+p)u_\mu u_\nu + p g_{\mu\nu}$$

$$\dot{\delta}_m = -\frac{k^2}{a^2}v + 3\frac{d(\psi+Hv)}{dt}$$

$$\phi = \dot{v} + \frac{p}{\rho}(2Hv - \delta_m)\ .$$

$p = 0$

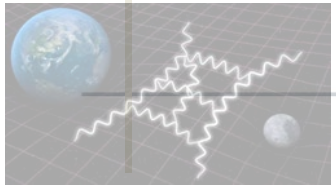
$k^2/a^2 \gg H^2$

$$\ddot{\delta}_m + 2H\dot{\delta}_m + \frac{k^2}{a^2}\phi \approx 0$$

$$\frac{k^2}{a^2}\phi \approx -4\pi G_{\rm eff}\rho\delta_m$$

$$\delta''(a) + \left(\frac{3}{a} + \frac{H'(a)}{H(a)}\right)\delta'(a) - \frac{3}{2}\frac{\Omega_{\rm m}G_{\rm eff}(a,k)/G_{\rm N}}{a^5 H(a)^2/H_0^2}\delta(a) = 0$$

Observational Probe of Perturbation Growth



Growth rate: $f(a) = \frac{dln\delta}{dlna}$

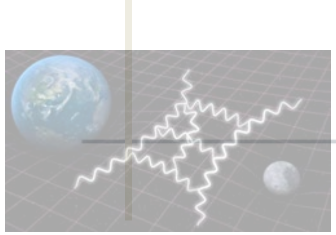
Density rms fluctuations within spheres of radius R = 8h^{-1}Mpc $\sigma(a) = \sigma_8 \frac{\delta(a)}{\delta(1)}$

Bias free combination: $f\sigma_8(a) \equiv f(a)\cdot\sigma(a) = \frac{\sigma_8}{\delta(1)}\, a\, \delta'(a)$, $b = \frac{\delta_g}{\delta}$

Datasets of fσ_8(z) datapoints from RSD survey measurements (each assuming different fiducial cosmology), 18 of them robust-independent

Model correction factor
(Alcock-Paczynski correction): $\text{ratio}(z) = \frac{H(z)d_A(z)}{H^{fid}(z)d_A^{fid}(z)}$

Construction of Likelihood Contours for GR



Define H(z) parametrization: $$E(a)^2 \equiv H(a)^2/H_0^2 = \Omega_{0m} a^{-3} + (1-\Omega_{0m})\, a^{-3(1+w)}$$

Solve the dynamical growth equation to obtain $\delta(a, w, \Omega_{0m})$ ($G_{eff}=1$):

$$\delta''(a) + \left(\frac{3}{a} + \frac{H'(a)}{H(a)}\right)\delta'(a) - \frac{3}{2}\frac{\Omega_{\rm m} G_{\rm eff}(a,k)/G_{\rm N}}{a^5 H(a)^2/H_0^2}\,\delta(a) = 0$$

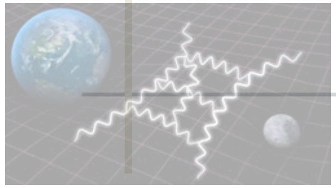
Construct theoretically predicted $f\sigma_8(a, \sigma8, w, \Omega_{0m})$: $$f\sigma_8(a) \equiv f(a)\cdot\sigma(a) = \frac{\sigma_8}{\delta(1)}\, a\, \delta'(a).$$

Construct $\chi^2(\sigma8,\ w, \Omega_{0m})$: $$V^i(z_i, p^j) = f\sigma_{8,i} - \mathrm{ratio}(z_i) f\sigma_8(z_i, p^j)$$ $$\chi^2_{growth} = V^i\, C_{ij}^{-1}\, V^j,$$

$$C_{ij}^{\rm growth,total} = \begin{pmatrix} \sigma_1^2 & 0 & 0 & \cdots \\ 0 & C_{ij}^{WiggleZ} & 0 & \cdots \\ 0 & 0 & \cdots & \sigma_N^2 \end{pmatrix}$$

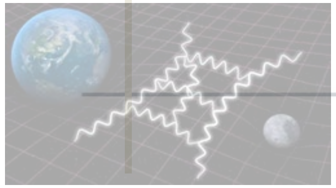
$f\sigma_8(z)$ Growth Data

S. Nesseris, G. Pantazis and L. Perivolaropoulos, arXiv:1703.10538 [astro-ph.CO] Phys.Rev. D96 (2017) no.2, 023542



Index	Dataset	z	$f\sigma_8(z)$	Refs.	Year	Notes
1	SDSS-LRG	0.35	0.440 ± 0.050	[58]	2006	$(\Omega_m, \Omega_K) = (0.25, 0)$
2	VVDS	0.77	0.490 ± 0.18	[58]	2008	$(\Omega_m, \Omega_K) = (0.25, 0)$
3	2dFGRS	0.17	0.510 ± 0.060	[58]	2009	$(\Omega_m, \Omega_K) = (0.3, 0)$
4	2MASS	0.02	0.314 ± 0.048	[59],[60]	2010	$(\Omega_m, \Omega_K) = (0.266, 0)$
5	SnIa+IRAS	0.02	0.398 ± 0.065	[61],[60]	2011	$(\Omega_m, \Omega_K) = (0.3, 0)$
6	SDSS-LRG-200	0.25	0.3512 ± 0.0583	[62]	2011	$(\Omega_m, \Omega_K) = (0.25, 0)$
7	SDSS-LRG-200	0.37	0.4602 ± 0.0378	[62]	2011	
8	SDSS-LRG-60	0.25	0.3665 ± 0.0601	[62]	2011	$(\Omega_m, \Omega_K) = (0.25, 0)$
9	SDSS-LRG-60	0.37	0.4031 ± 0.0586	[62]	2011	
10	WiggleZ	0.44	0.413 ± 0.080	[63]	2012	$(\Omega_m, h) = (0.27, 0.71)$
11	WiggleZ	0.60	0.390 ± 0.063	[63]	2012	$C_{ij} \rightarrow$ Eq. (2.8).
12	WiggleZ	0.73	0.437 ± 0.072	[63]	2012	
13	SDSS-BOSS	0.30	0.407 ± 0.055	[64]	2012	$(\Omega_m, \Omega_K) = (0.25, 0)$
14	SDSS-BOSS	0.40	0.419 ± 0.041	[64]	2012	
15	SDSS-BOSS	0.50	0.427 ± 0.043	[64]	2012	
16	SDSS-BOSS	0.60	0.433 ± 0.067	[64]	2012	
17	SDSS-DR7-LRG	0.35	0.429 ± 0.089	[65]	2012	$(\Omega_m, \Omega_K) = (0.25, 0)$
18	6dFGRS	0.067	0.423 ± 0.055	[66]	2012	$(\Omega_m, \Omega_K) = (0.27, 0)$
19	GAMA	0.18	0.360 ± 0.090	[67]	2013	$(\Omega_m, \Omega_K) = (0.27, 0)$
20	GAMA	0.38	0.440 ± 0.060	[67]	2013	
21	BOSS-LOWZ	0.32	0.384 ± 0.095	[68]	2013	$(\Omega_m, \Omega_K) = (0.274, 0)$
22	SDSS-CMASS	0.59	0.488 ± 0.060	[69]	2013	$(\Omega_m, h, \sigma_8) = (0.307115, 0.6777, 0.8288)$
23	Vipers	0.80	0.470 ± 0.080	[70]	2013	$(\Omega_m, \Omega_K) = (0.25, 0)$
24	SDSS-MGS	0.15	0.490 ± 0.145	[71]	2014	$(\Omega_m, h, \sigma_8) = (0.31, 0.67, 0.83)$
25	SDSS-veloc	0.10	0.370 ± 0.130	[72]	2015	$(\Omega_m, \Omega_K) = (0.3, 0)$
26	FastSound	1.40	0.482 ± 0.116	[73]	2015	$(\Omega_m, \Omega_K) = (0.270, 0)$
27	6dFGS+SnIa	0.02	0.428 ± 0.0465	[74]	2016	$(\Omega_m, h, \sigma_8) = (0.3, 0.683, 0.8)$
28	Vipers PDR-2	0.60	0.550 ± 0.120	[75]	2016	$(\Omega_m, \Omega_b) = (0.3, 0.045)$
29	Vipers PDR-2	0.86	0.400 ± 0.110	[75]	2016	
30	BOSS DR12	0.38	0.497 ± 0.045	[76]	2016	$(\Omega_m, \Omega_K) = (0.31, 0)$
31	BOSS DR12	0.51	0.458 ± 0.038	[76]	2016	
32	BOSS DR12	0.61	0.436 ± 0.034	[76]	2016	
33	Vipers v7	0.76	0.440 ± 0.040	[77]	2016	$(\Omega_m, \sigma_8) = (0.308, 0.8149)$
34	Vipers v7	1.05	0.280 ± 0.080	[77]	2016	

Robust Independent $f\sigma_8(z)$ Data
Gold 2017 Dataset



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2	SnIa+IRAS	0.02	0.398 ± 0.065	[61],[60]	2011	$(\Omega_m, \Omega_K) = (0.3, 0)$
3	2MASS	0.02	0.314 ± 0.048	[59],[60]	2010	$(\Omega_m, \Omega_K) = (0.266, 0)$
4	SDSS-veloc	0.10	0.370 ± 0.130	[72]	2015	$(\Omega_m, \Omega_K) = (0.3, 0)$
5	SDSS-MGS	0.15	0.490 ± 0.145	[71]	2014	$(\Omega_m, h, \sigma_8) = (0.31, 0.67, 0.83)$
6	2dFGRS	0.17	0.510 ± 0.060	[58]	2009	$(\Omega_m, \Omega_K) = (0.3, 0)$
7	GAMA	0.18	0.360 ± 0.090	[67]	2013	$(\Omega_m, \Omega_K) = (0.27, 0)$
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10	SDSS-LRG-200	0.37	0.4602 ± 0.0378	[62]	2011	
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12	SDSS-CMASS	0.59	0.488 ± 0.060	[69]	2013	$(\Omega_m, h, \sigma_8) = (0.307115, 0.6777, 0.8288)$
13	WiggleZ	0.44	0.413 ± 0.080	[63]	2012	$(\Omega_m, h) = (0.27, 0.71)$
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S. Nesseris, G. Pantazis and L. Perivolaropoulos,
arXiv:1703.10538 [astro-ph.CO] **Phys.Rev. D96 (2017) no.2, 023542**

Evolution of the $f\sigma_8$ tension with the Planck15/ΛCDM determination and implications for modified gravity theories

Lavrentios Kazantzidis, Leandros Perivolaropoulos. Mar 4, 2018. 16 pp.

Published in **Phys.Rev. D97 (2018) no.10, 103503**

$f\sigma_8(z)$ Growth Data

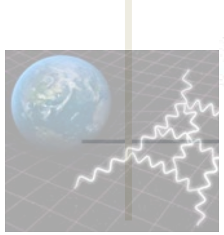
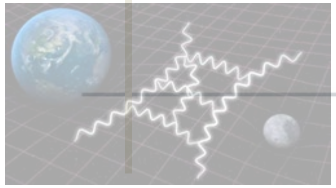
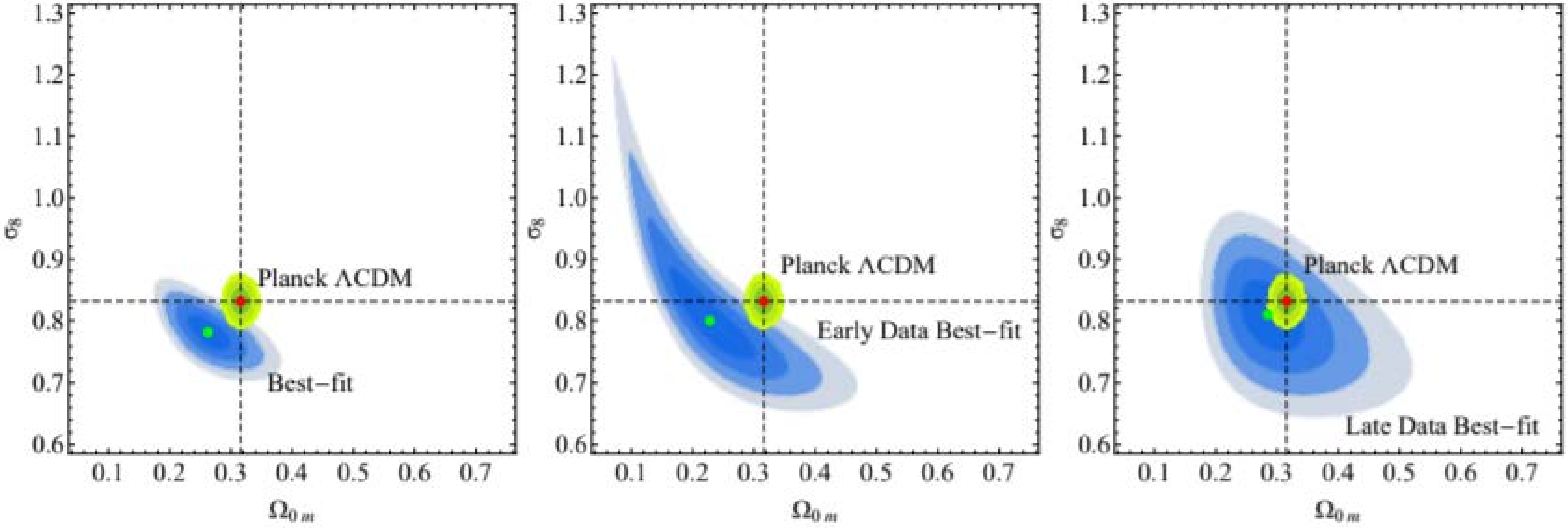


TABLE II: A compilation of RSD data that we found published from 2006 since 2018

Index	Dataset	z	$f\sigma_8(z)$	Refs.	Year	Fiducial Cosmology
1	SDSS-LRG	0.35	0.440 ± 0.050	[75]	30 October 2006	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.25, 0, 0.756)$[76]
2	VVDS	0.77	0.490 ± 0.18	[75]	6 October 2009	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.25, 0, 0.78)$
3	2dFGRS	0.17	0.510 ± 0.060	[75]	6 October 2009	$(\Omega_{0m}, \Omega_K) = (0.3, 0, 0.9)$
4	2MRS	0.02	0.314 ± 0.048	[77], [78]	13 Novemver 2010	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.266, 0, 0.65)$
5	SnIa+IRAS	0.02	0.398 ± 0.065	[79], [78]	20 October 2011	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.3, 0, 0.814)$
6	SDSS-LRG-200	0.25	0.3512 ± 0.0583	[80]	9 December 2011	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.276, 0, 0.8)$
7	SDSS-LRG-200	0.37	0.4602 ± 0.0378	[80]	9 December 2011	
8	SDSS-LRG-60	0.25	0.3665 ± 0.0601	[80]	9 December 2011	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.276, 0, 0.8)$
9	SDSS-LRG-60	0.37	0.4031 ± 0.0586	[80]	9 December 2011	
10	WiggleZ	0.44	0.413 ± 0.080	[46]	12 June 2012	$(\Omega_{0m}, h, \sigma_8) = (0.27, 0.71, 0.8)$
11	WiggleZ	0.60	0.390 ± 0.063	[46]	12 June 2012	$C_{ij} = Eq.(3.3)$
12	WiggleZ	0.73	0.437 ± 0.072	[46]	12 June 2012	
13	6dFGS	0.067	0.423 ± 0.055	[81]	4 July 2012	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.27, 0, 0.76)$
14	SDSS-BOSS	0.30	0.407 ± 0.055	[82]	11 August 2012	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.25, 0, 0.804)$
15	SDSS-BOSS	0.40	0.419 ± 0.041	[82]	11 August 2012	
16	SDSS-BOSS	0.50	0.427 ± 0.043	[82]	11 August 2012	
17	SDSS-BOSS	0.60	0.433 ± 0.067	[82]	11 August 2012	
18	Vipers	0.80	0.470 ± 0.080	[83]	9 July 2013	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.25, 0, 0.82)$
19	SDSS-DR7-LRG	0.35	0.429 ± 0.089	[84]	8 August 2013	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.25, 0, 0.809)$[85]
20	GAMA	0.18	0.360 ± 0.090	[86]	22 September 2013	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.27, 0, 0.8)$
21	GAMA	0.38	0.440 ± 0.060	[86]	22 September 2013	
22	BOSS-LOWZ	0.32	0.384 ± 0.095	[87]	17 December 2013	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.274, 0, 0.8)$
23	SDSS DR10 and DR11	0.32	0.48 ± 0.10	[87]	17 December 2013	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.274, 0, 0.8)$[88]
24	SDSS DR10 and DR11	0.57	0.417 ± 0.045	[87]	17 December 2013	
25	SDSS-MGS	0.15	0.490 ± 0.145	[89]	30 January 2015	$(\Omega_{0m}, h, \sigma_8) = (0.31, 0.67, 0.83)$
26	SDSS-veloc	0.10	0.370 ± 0.130	[90]	16 June 2015	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.3, 0, 0.89)$[91]
27	FastSound	1.40	0.482 ± 0.116	[92]	25 November 2015	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.27, 0, 0.82)$[93]
28	SDSS-CMASS	0.59	0.488 ± 0.060	[94]	8 July 2016	$(\Omega_{0m}, h, \sigma_8) = (0.307115, 0.6777, 0.8288)$
29	BOSS DR12	0.38	0.497 ± 0.045	[2]	11 July 2016	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.31, 0, 0.8)$
30	BOSS DR12	0.51	0.458 ± 0.038	[2]	11 July 2016	
31	BOSS DR12	0.61	0.436 ± 0.034	[2]	11 July 2016	
32	BOSS DR12	0.38	0.477 ± 0.051	[95]	11 July 2016	$(\Omega_{0m}, h, \sigma_8) = (0.31, 0.676, 0.8)$
33	BOSS DR12	0.51	0.453 ± 0.050	[95]	11 July 2016	
34	BOSS DR12	0.61	0.410 ± 0.044	[95]	11 July 2016	
35	Vipers v7	0.76	0.440 ± 0.040	[55]	26 October 2016	$(\Omega_{0m}, \sigma_8) = (0.308, 0.8149)$
36	Vipers v7	1.05	0.280 ± 0.080	[55]	26 October 2016	
37	BOSS LOWZ	0.32	0.427 ± 0.056	[96]	26 October 2016	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.31, 0, 0.8475)$
38	BOSS CMASS	0.57	0.426 ± 0.029	[96]	26 October 2016	
39	Vipers	0.727	0.296 ± 0.0765	[97]	21 November 2016	$(\Omega_{0m}, \Omega_K, \sigma_8) = (0.31, 0, 0.7)$
40	6dFGS+SnIa	0.02	0.428 ± 0.0465	[98]	29 November 2016	$(\Omega_{0m}, h, \sigma_8) = (0.3, 0.683, 0.8)$
41	Vipers	0.6	0.48 ± 0.12	[99]	16 December 2016	$(\Omega_{0m}, \Omega_b, n_s, \sigma_8) = (0.3, 0.045, 0.96, 0.831)$[12]
42	Vipers	0.86	0.48 ± 0.10	[99]	16 December 2016	
43	Vipers PDR-2	0.60	0.550 ± 0.120	[100]	16 December 2016	$(\Omega_{0m}, \Omega_b, \sigma_8) = (0.3, 0.045, 0.823)$
44	Vipers PDR-2	0.86	0.400 ± 0.110	[100]	16 December 2016	
45	SDSS DR13	0.1	0.48 ± 0.16	[101]	22 December 2016	$(\Omega_{0m}, \sigma_8) = (0.25, 0.89)$[91]
46	2MTF	0.001	0.505 ± 0.085	[102]	16 June 2017	$(\Omega_{0m}, \sigma_8) = (0.3121, 0.815)$
47	Vipers PDR-2	0.85	0.45 ± 0.11	[103]	31 July 2017	$(\Omega_b, \Omega_{0m}, h) = (0.045, 0.30, 0.8)$
48	BOSS DR12	0.31	0.469 ± 0.098	[49]	15 September 2017	$(\Omega_{0m}, h, \sigma_8) = (0.307, 0.6777, 0.8288)$
49	BOSS DR12	0.36	0.474 ± 0.097	[49]	15 September 2017	
50	BOSS DR12	0.40	0.473 ± 0.086	[49]	15 September 2017	
51	BOSS DR12	0.44	0.481 ± 0.076	[49]	15 September 2017	
52	BOSS DR12	0.48	0.482 ± 0.067	[49]	15 September 2017	
53	BOSS DR12	0.52	0.488 ± 0.065	[49]	15 September 2017	
54	BOSS DR12	0.56	0.482 ± 0.067	[49]	15 September 2017	
55	BOSS DR12	0.59	0.481 ± 0.066	[49]	15 September 2017	
56	BOSS DR12	0.64	0.486 ± 0.070	[49]	15 September 2017	
57	SDSS DR7	0.1	0.376 ± 0.038	[104]	12 December 2017	$(\Omega_{0m}, \Omega_b, \sigma_8) = (0.282, 0.046, 0.817)$
58	SDSS-IV	1.52	0.420 ± 0.076	[105]	8 January 2018	$(\Omega_{0m}, \Omega_b h^2, \sigma_8) = (0.26479, 0.02258, 0.8)$
59	SDSS-IV	1.52	0.396 ± 0.079	[106]	8 January 2018	$(\Omega_{0m}, \Omega_b h^2, \sigma_8) = (0.31, 0.022, 0.8225)$
60	SDSS-IV	0.978	0.379 ± 0.176	[107]	9 January 2018	$(\Omega_{0m}, \sigma_8) = (0.31, 0.8)$
61	SDSS-IV	1.23	0.385 ± 0.099	[107]	9 January 2018	
62	SDSS-IV	1.526	0.342 ± 0.070	[107]	9 January 2018	
63	SDSS-IV	1.944	0.364 ± 0.106	[107]	9 January 2018	

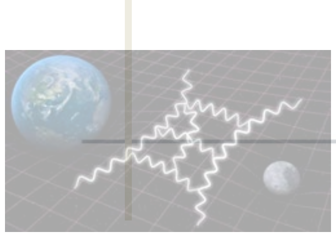
Likelihood Contours – Evolution of Tension

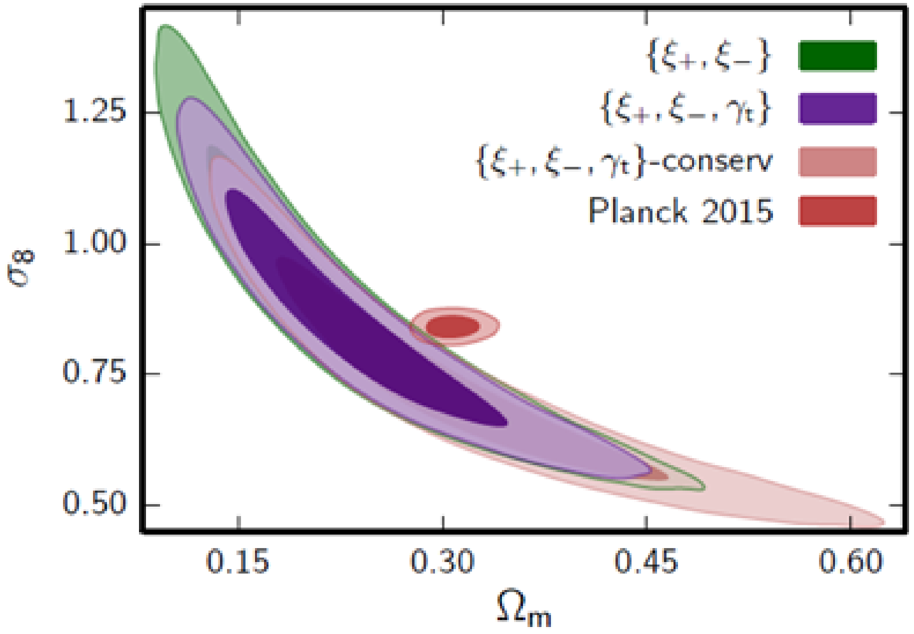




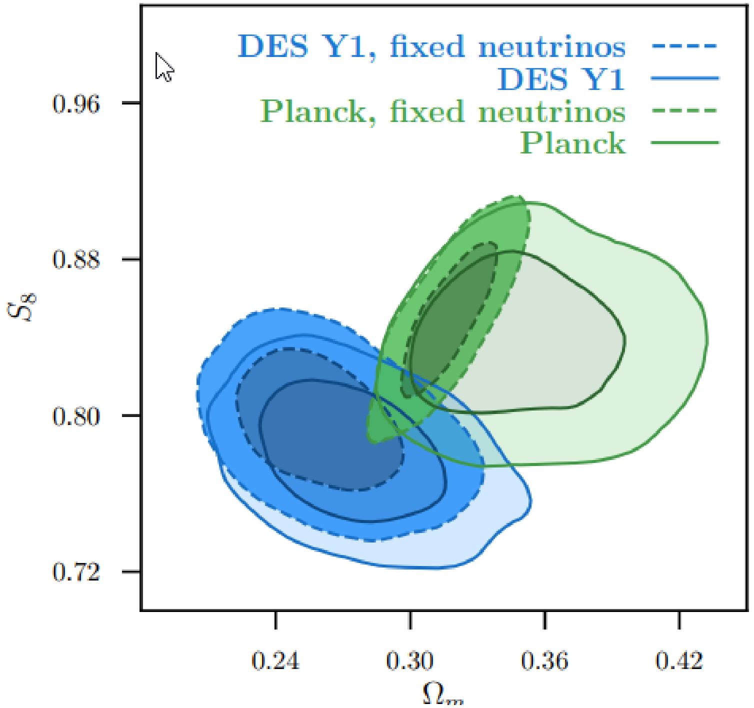
Tension between growth data contours and corresponding Planck15/ΛCDM best fit
Tension changes between early published and more recent data.

Weak Lensing + Clustering





KiDS-450 + 2dFLenS: Cosmological parameter constraints from weak gravitational lensing tomography and overlapping redshift-space galaxy clustering
Shahab Joudaki (Swinburne U., Ctr. Astrophys. Supercomput. & Oxford U.) *et al.*. Jul 20, 2017. 31 pp.
e-Print: arXiv:1707.06627

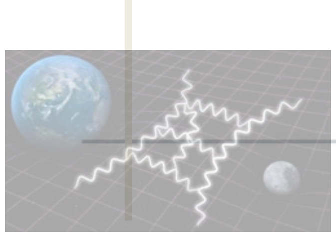


$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$$

Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing
DES Collaboration (T.M.C. Abbott (Cerro-Tololo InterAmerican Obs.) *et al.*). Aug 4, 2017. 31 pp.
FERMILAB-PUB-17-294-PPD
e-Print: arXiv:1708.01530

Tension level remains if weak lensing is also considered

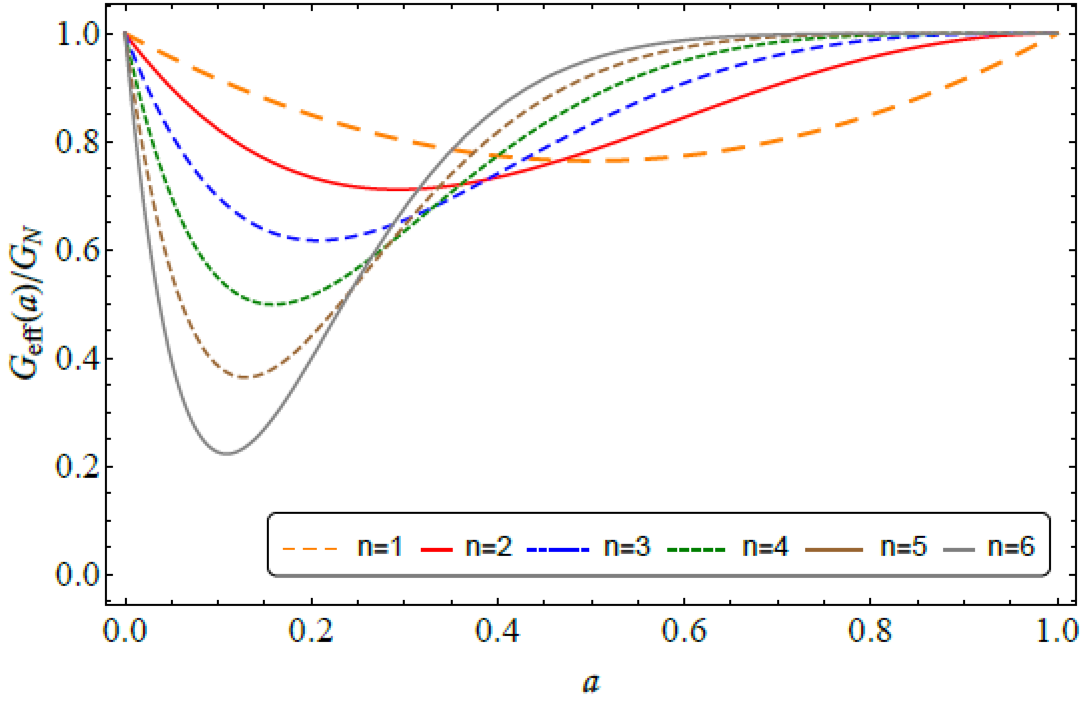
Evolving $G_{eff}(z)$



Conditions to be satisfied by viable $G_{eff}(z)$ parametrizations:

1. $\lim_{z\to 0} G'^{(z)}_{eff} \simeq 0$ (solar system tests)
2. $\lim_{z\to \infty} G'^{(z)}_{eff} \simeq 0$ (nucleosynthesis constraints)

The Limits of Extended Quintessence
S. Nesseris, Leandros Perivolaropoulos (Ioannina U.). Nov 2006. 9 pp.
Published in **Phys.Rev. D75 (2007) 023517**

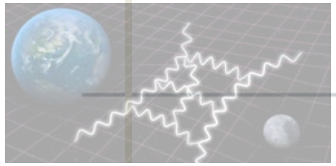


Viable parametrization:

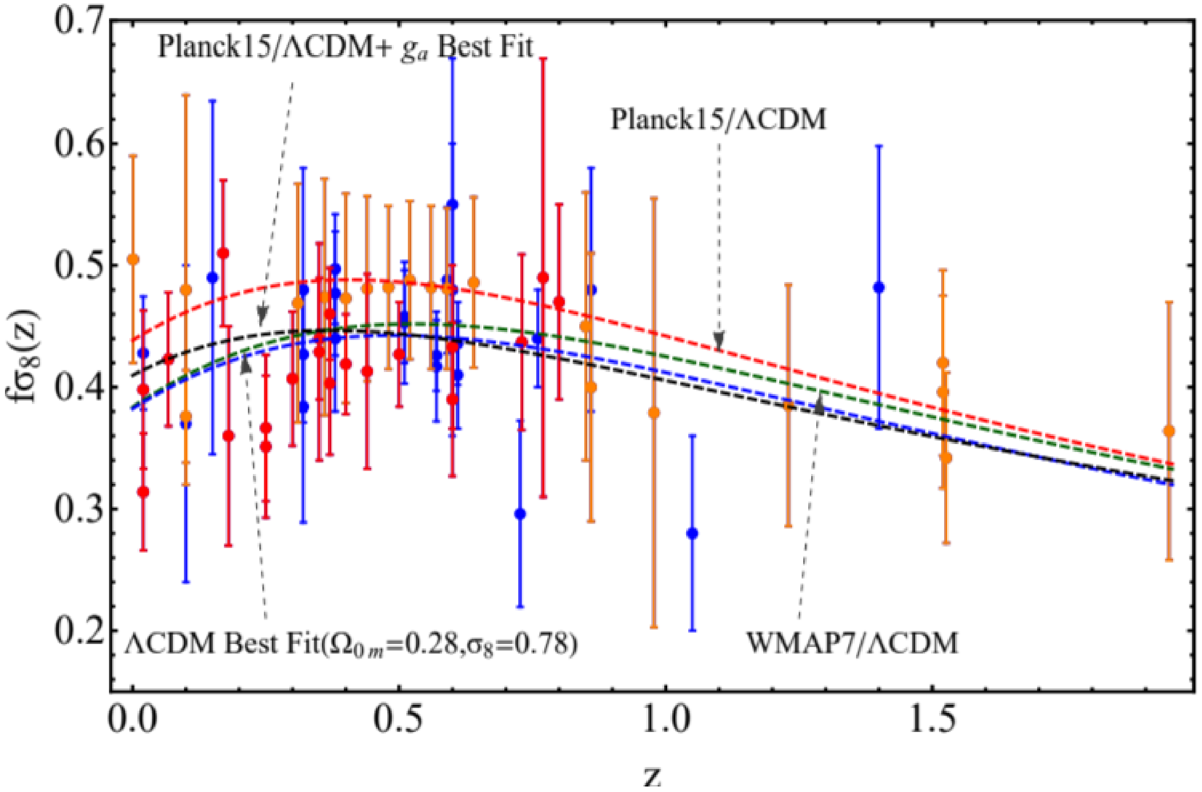
$$\frac{G_{\rm eff}(a,n)}{G_{\rm N}} = 1 + g_a(1-a)^n - g_a(1-a)^{2n} = 1 + g_a\left(\frac{z}{1+z}\right)^n - g_a\left(\frac{z}{1+z}\right)^{2n}$$

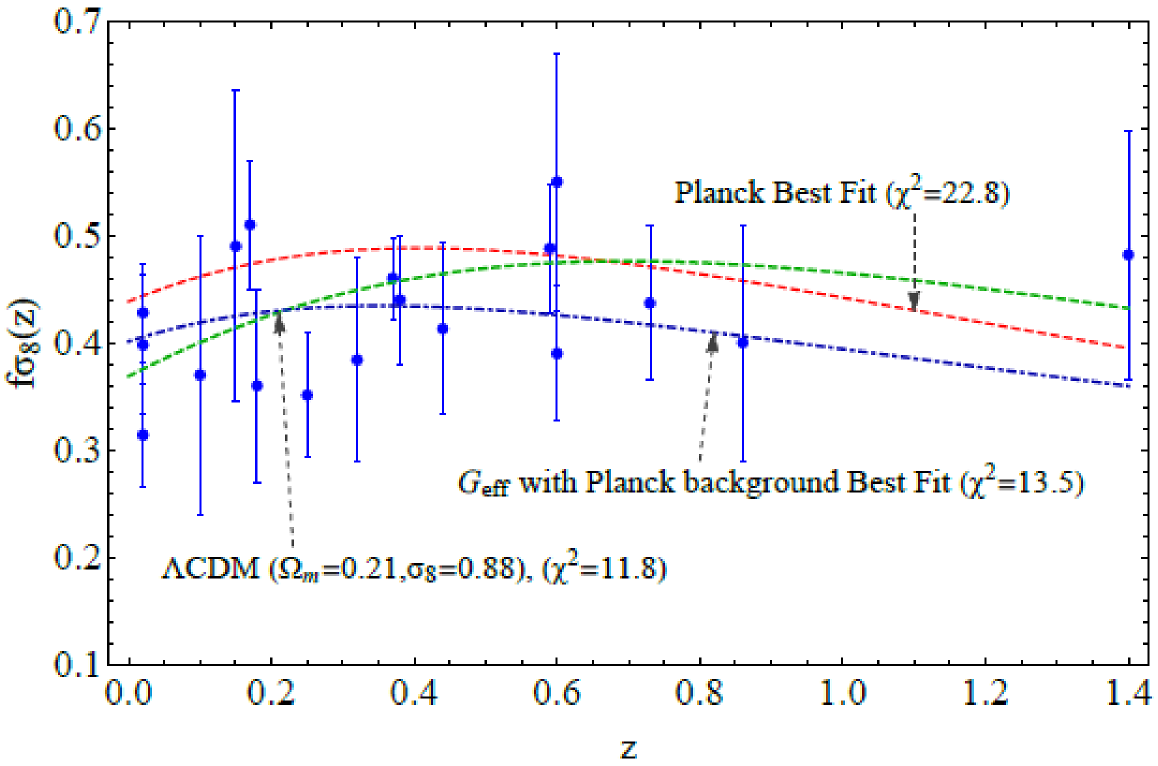
$n \geq 2$

Reducing the Tension with Planck/ΛCDM



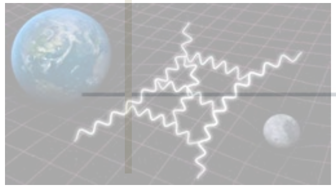
S. Nesseris, G. Pantazis and L. Perivolaropoulos,
arXiv:1703.10538 [astro-ph.CO] **Phys.Rev. D96 (2017) no.2, 023542**

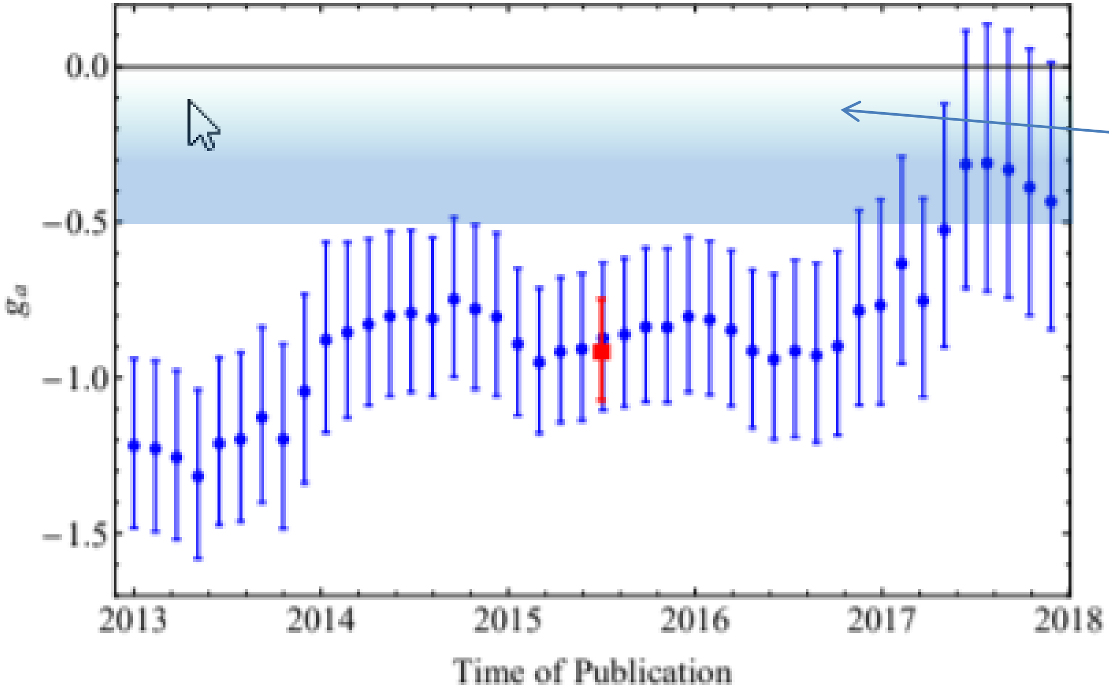




Evolution of the $f\sigma_8$ tension with the Planck15/ΛCDM determination and implications for modified gravity theories
Lavrentios Kazantzidis, Leandros Perivolaropoulos. Mar 4, 2018. 16 pp.
Published in **Phys.Rev. D97 (2018) no.10, 103503**

20-point moving average of the parameter g_a



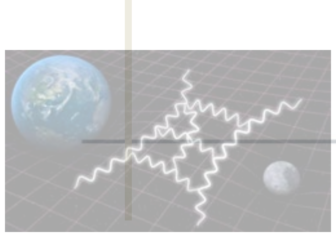


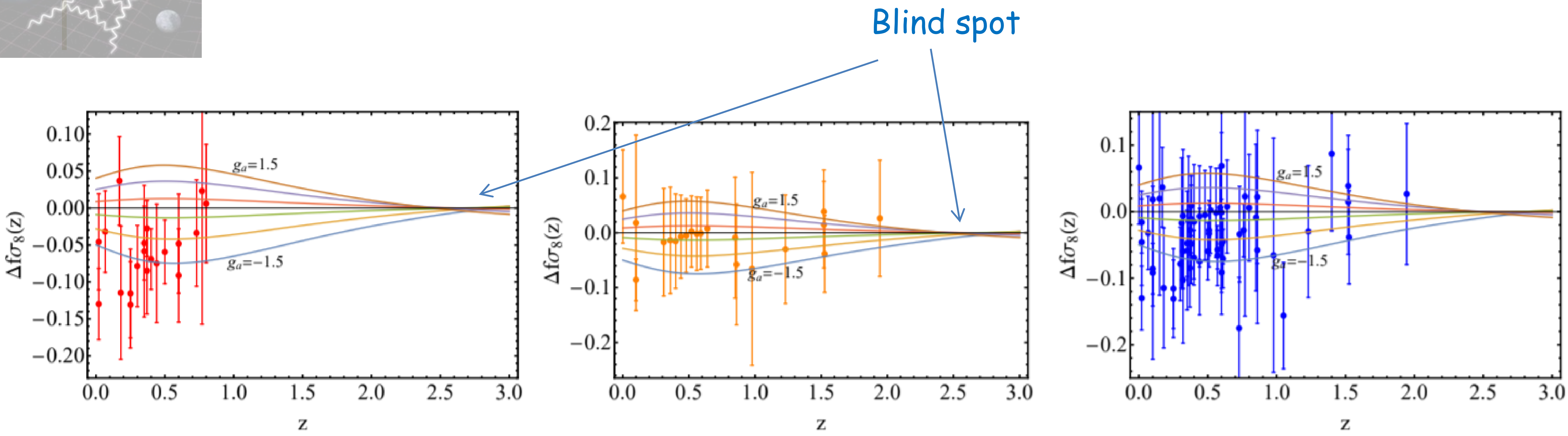
Allowed region by CMB ISW effect.

Late data have higher error bars and are at higher redshifts.
They are blind to deviations from GR.

Evolution of the $f\sigma_8$ tension with the Planck15/ΛCDM determination and implications for modified gravity theories
Lavrentios Kazantzidis, Leandros Perivolaropoulos. Mar 4, 2018. 16 pp.
Published in **Phys.Rev. D97 (2018) no.10, 103503**

Optimal redshifts and blind spots for detecting deviations from GR



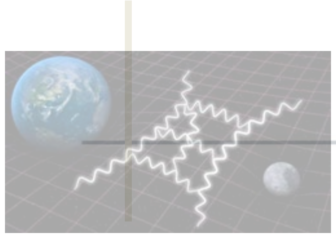


. **Constraining power of cosmological observables: blind redshift spots and optimal ranges**

L. Kazantzidis, L. Perivolaropoulos, F. Skara (Ioannina U.). Dec 13, 2018. 20 pp.

Published in **Phys.Rev. D99 (2019) no.6, 063537**

Basic Questions

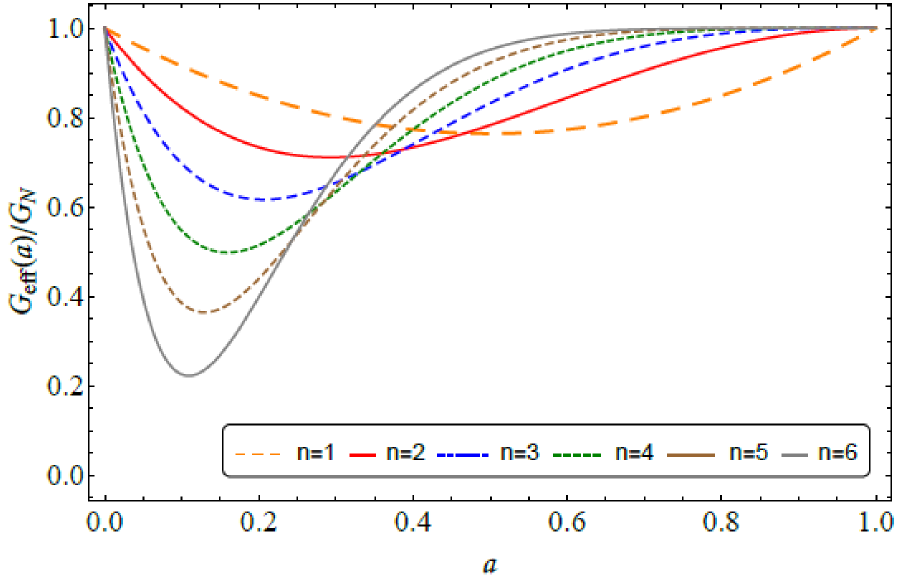


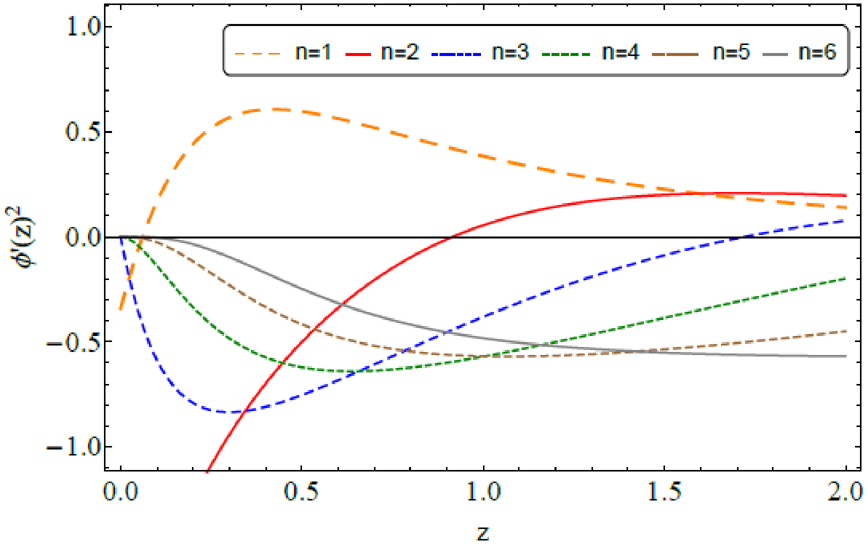
1. What Modified Gravity models are consistent with the best fit parametrizations $G_{eff}(z)$?

2. Can viable Scalar Tensor models get reconstructed from Planck/ΛCDM and the best fit $G_{eff}(z)$?

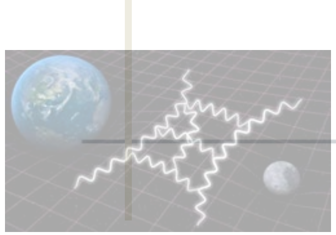
No!

Reconstruction leads to negative kinetic terms in the scalar tensor action





Reconstruction of Scalar-Tensor Quintessence



Scalar-Tensor Action:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2}F(\phi)R - \frac{1}{2}Z(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - U(\phi)\right] + S_m,$$

FLRW Metric:

$$ds^2 = -dt^2 + a^2(t)\left[dr^2 + r^2(d\theta^2 + \sin^2\theta\ d\phi^2)\right]$$

Dynamical Equations:

$$3FH^2 = \rho + \frac{1}{2}\dot{\phi}^2 - 3H\dot{F} + U$$

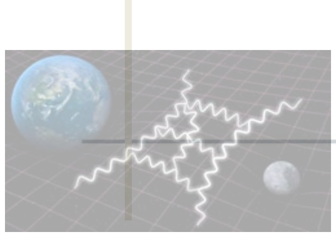
$$-2F\dot{H} = (\rho + p) + \dot{\phi}^2 + \ddot{F} - H\dot{F}$$

Dynamical Equation wrt Redshift (eliminate potential U):

$$F''(z) + F'(z)\left(\frac{q'(z)}{2q(z)} + \frac{2}{z+1}\right) - F(z)\frac{q'(z)}{(z+1)q(z)} + \frac{3\Omega_m(z+1)}{q(z)} = -\phi'(z)^2$$

$$q(z) \equiv E^2(z) = \frac{H^2(z)}{H_0^2}$$

Reconstruction of Scalar-Tensor Quintessence



Dynamical equation:

$$F''(z) + F'(z)\left(\frac{q'(z)}{2q(z)} + \frac{2}{z+1}\right) - F(z)\frac{q'(z)}{(z+1)q(z)} + \frac{3\Omega_m(z+1)}{q(z)} = -\phi'(z)^2$$

$$q(z) = \Omega_{0m}\,(1+z)^3 + (1-\Omega_{0m})(1+z)^{3(1+w_0)}$$

$$G_{\rm eff}(z) = \frac{1}{F}\,\frac{2F + 4\left(\frac{dF}{d\Phi}\right)^2}{2F + 3\left(\frac{dF}{d\Phi}\right)^2}\,G_N \simeq \frac{G_N}{F}$$

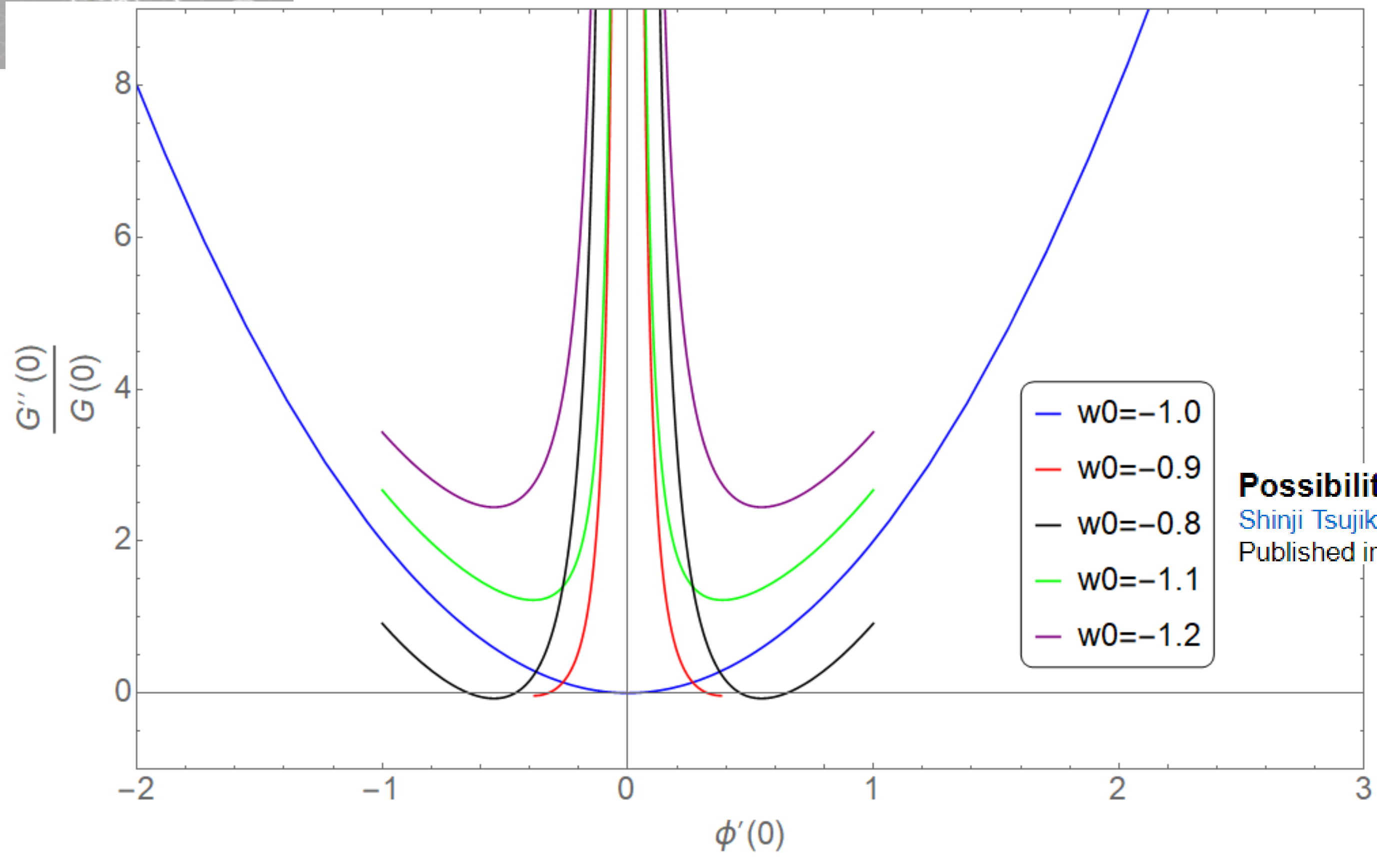
$$\frac{G_{\rm eff}(a,n)}{G_N} = 1 + g_a(1-a)^n - g_a(1-a)^{2n} = 1 + g_a\left(\frac{z}{1+z}\right)^n - g_a\left(\frac{z}{1+z}\right)^{2n}$$

At z=0 (F'(0)=0, F(0)=1):

$$G''(z=0)/G_N = 2\,\phi'^2(z=0) - 9\,(1-\Omega_{0m})(1+w_0) + \frac{9\,(1-\Omega_{0m})^2(1+w_0)^2}{\phi'^2(z=0)}$$

Increasing $G_{eff}(z)$ for $w_0 \leq -1$

Consistency of modified gravity with a decreasing $G_{\rm eff}(z)$ in a ΛCDM background
Radouane Gannouji (Valparaiso U., Catolica), Lavrentios Kazantzidis, Leandros Perivolaropoulos (Ioannina U.), David Polarski (U. Montpellier, L2C). Sep 19, 2018. 9 pp.
Published in **Phys.Rev. D98 (2018) no.10, 104044**



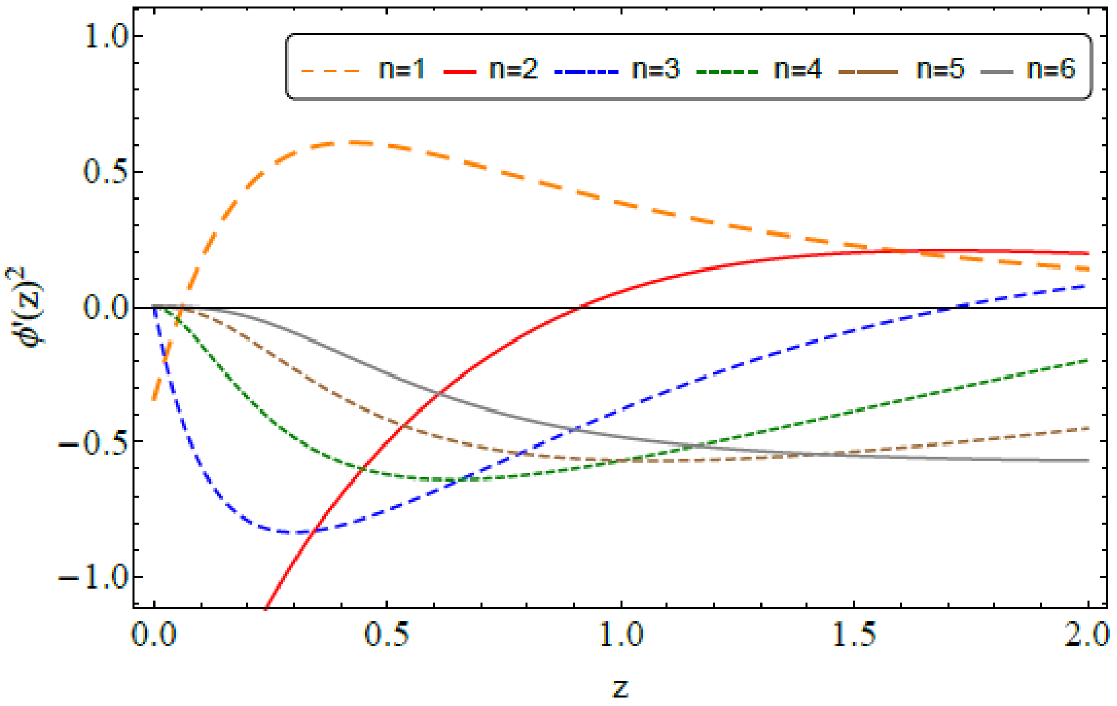
$$w_0 \simeq -1$$

$$G(z) \simeq G(0) + \frac{1}{2} G''(0)\ z^2 = G(0) + \phi'^2(0)\ z^2$$

Possibility of realizing weak gravity in redshift space distortion measurements
Shinji Tsujikawa (Tokyo U. of Sci.). May 10, 2015. 16 pp.
Published in **Phys.Rev. D92 (2015) no.4, 044029**

$$G''(z=0)/G_N = 2\,\phi'^2(z=0) - 9\,(1-\Omega_{0m})(1+w_0) + \frac{9\,(1-\Omega_{0m})^2(1+w_0)^2}{\phi'^2(z=0)}$$

The Reconstructed kinetic term is negative!

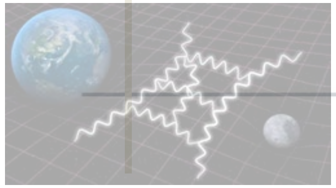


S. Nesseris, G. Pantazis and L. Perivolaropoulos, arXiv:1703.10538 [astro-ph.CO] Phys.Rev. D96 (2017) no.2, 023542

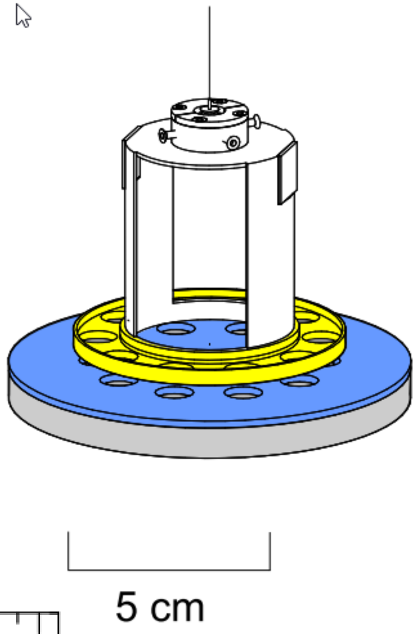
General Result: In a ΛCDM background, any $G_{eff}(z)$ initially decreasing with z leads to a reconstructed scalar-tensor negative kinetic term for some range of z.

If the tension is physical and the background is Planck/Λ CDM, then a more general modified gravity theory than scalar-tensor is required

Testing homogeneity of Newton's constant on sub-mm scales

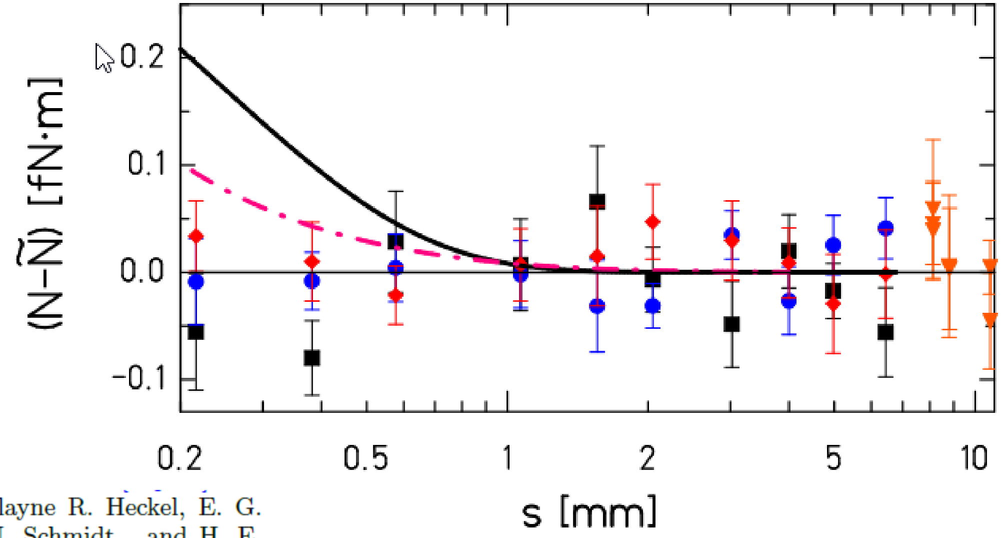


The Washington Experiment apparatus:



The torque from the holes of the rotating lower ring (attractor) on the holes of the upper ring (torsion pendulum) is measured by monitoring the pendulum twist for various ring separations and subtracted from the expected Newtonian torque.

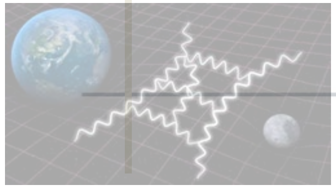
Torque residuals are measured and fit to Yukawa and power law parametrizations



D. J. Kapner, T. S. Cook, E. G. Adelberger, J. H. Gundlach, Blayne R. Heckel, C. D. Hoyle, and H. E. Swanson, "Tests of the gravitational inverse-square law below the dark-energy length scale," Phys. Rev. Lett. **98**, 021101 (2007), arXiv:hep-ph/0611184 [hep-ph].

C. D. Hoyle, D. J. Kapner, Blayne R. Heckel, E. G. Adelberger, J. H. Gundlach, U. Schmidt, and H. E. Swanson, "Sub-millimeter tests of the gravitational inverse-square law," Phys. Rev. **D70**, 042004 (2004), arXiv:hep-ph/0405262 [hep-ph].

Parametrizing Newton's constant on sub-mm scales



Dark Energy Scale: $\lambda_{de} \equiv \sqrt[4]{\hbar c/\rho_{de}} \approx 0.085mm$

Yukawa parametrization: $V_{eff} = -G\frac{M}{r}(1 + \alpha e^{-mr}) \longrightarrow f(R) = R + \frac{1}{6m^2}R^2 + ...$ $m^2 > 0$

Power law parametrization: $V_{eff} = -G\frac{M}{r}(1 + \beta^k(\frac{1}{mr})^{k-1})$ (brane world models)

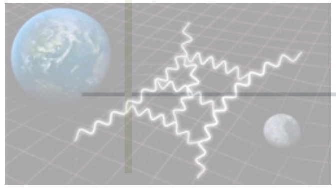
Oscillating parametrization: $V_{eff} = -G\frac{M}{r}(1 + \alpha_O \cos(\frac{2\pi}{\lambda}r + \theta)) \longrightarrow f(R) = R + \frac{1}{6m^2}R^2 + ...$ $m^2 < 0$

(f(R) theories (instabilities), Infinite Derivative Gravity)

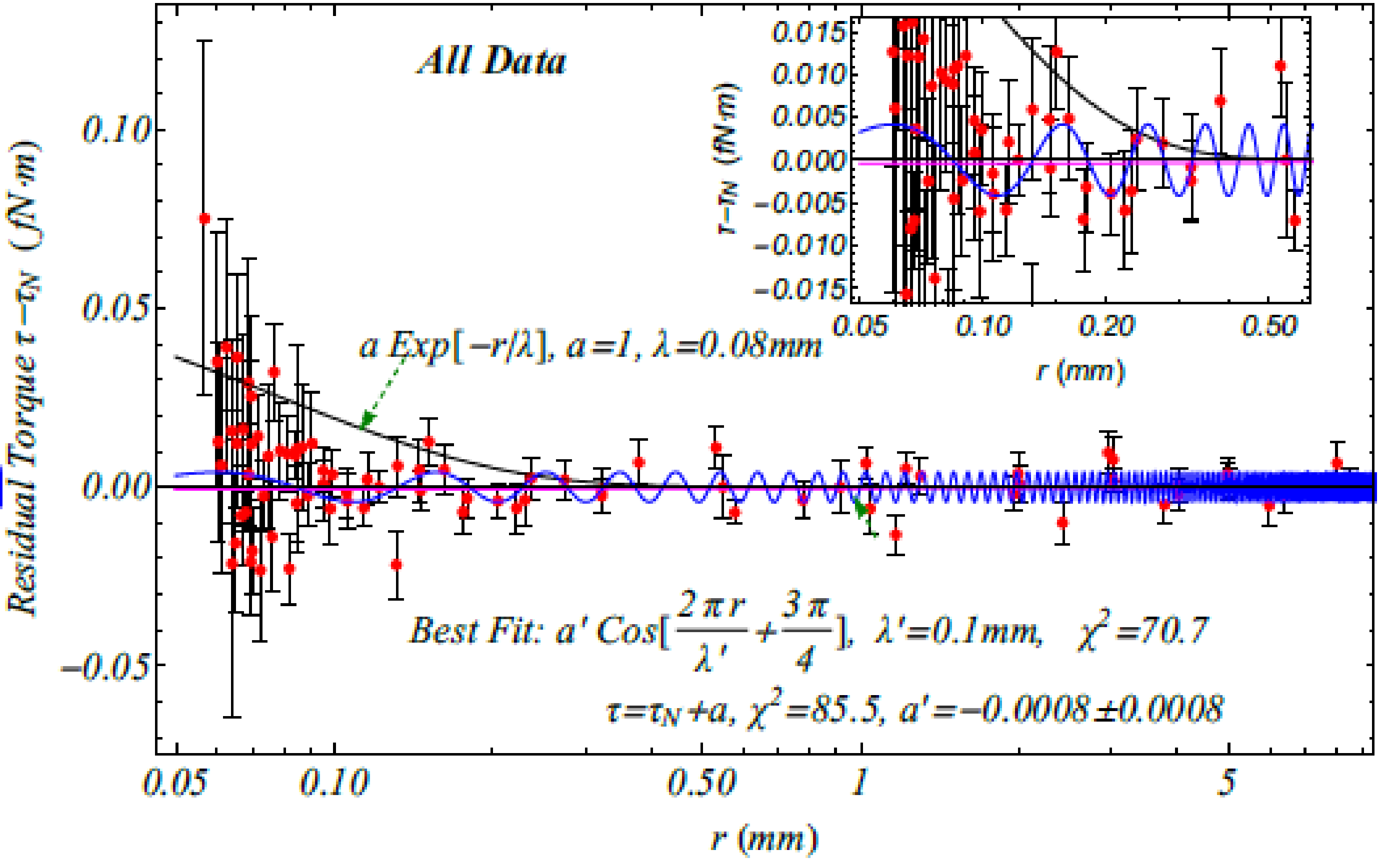
Leandros Perivolaropoulos, "Sub-millimeter Spatial Oscillations of Newton's Constant: Theoretical Models and Laboratory Tests," (2016), arXiv:1611.07293 [gr-qc].
Phys.Rev. D95 (2017) no.8, 084050

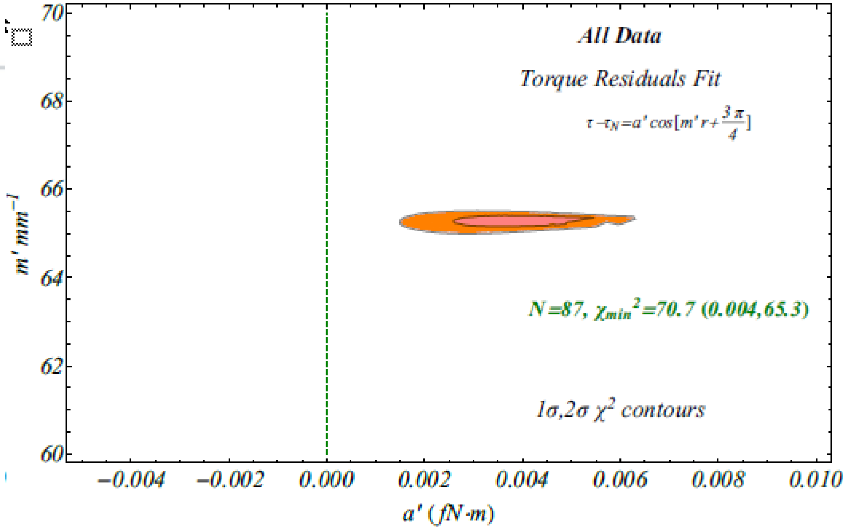
Fits to the Torque Residual Data

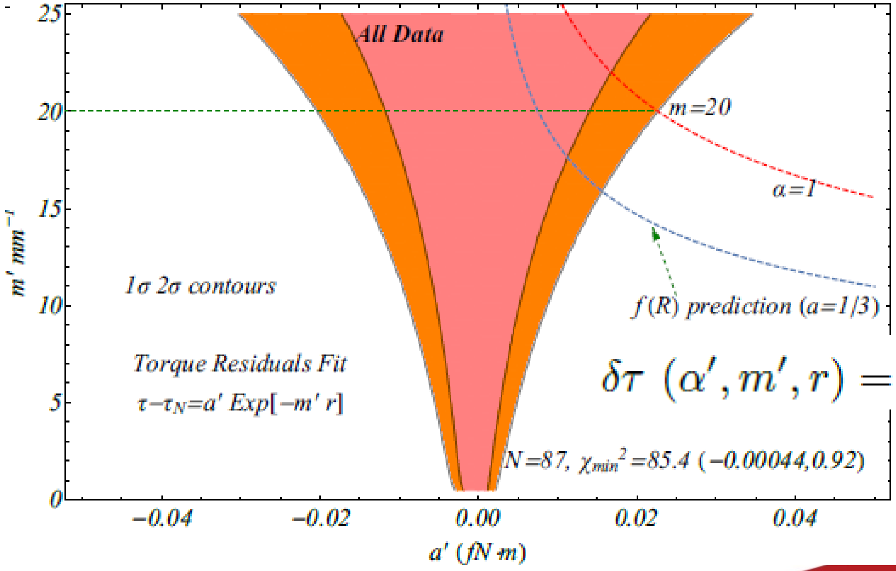
$$\delta\tau\ (\alpha', m', r) = \alpha' \cos(m' r + \frac{3\pi}{4})$$



$$\chi^2(\alpha', m') = \sum_{j=1}^{N} \frac{(\delta\tau(j) - \delta\tau_i(\alpha', m', r_j))^2}{\sigma_j^2}$$

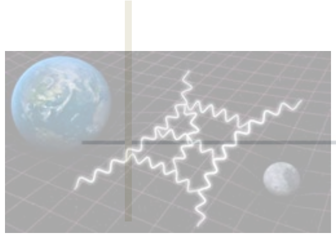




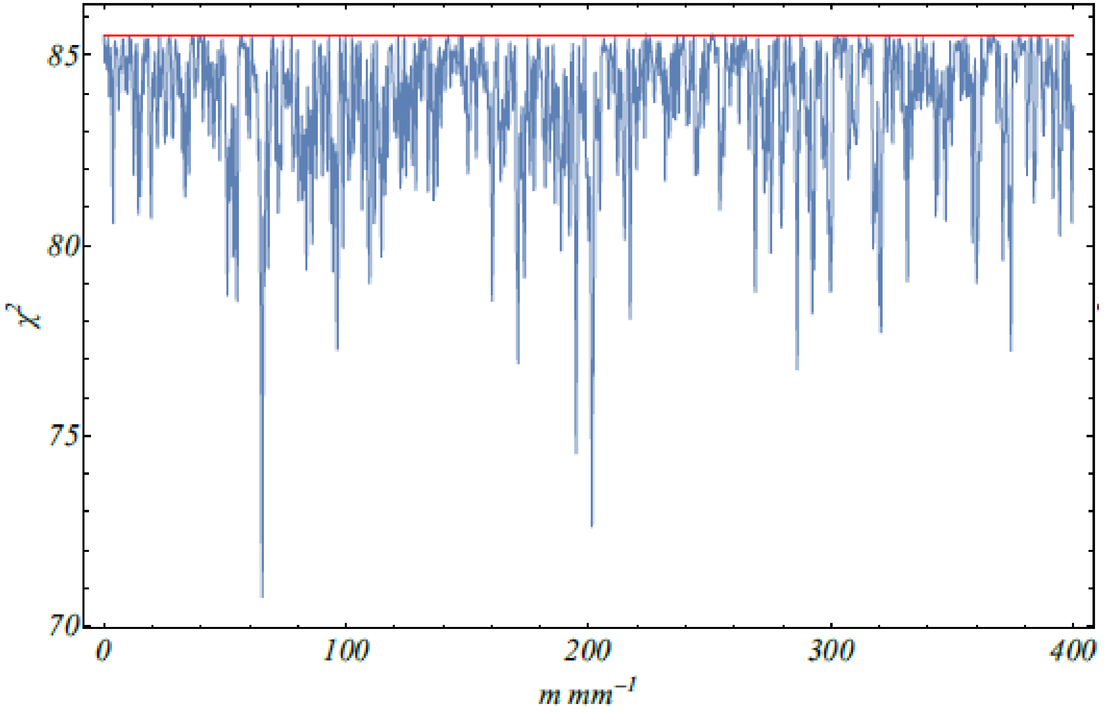


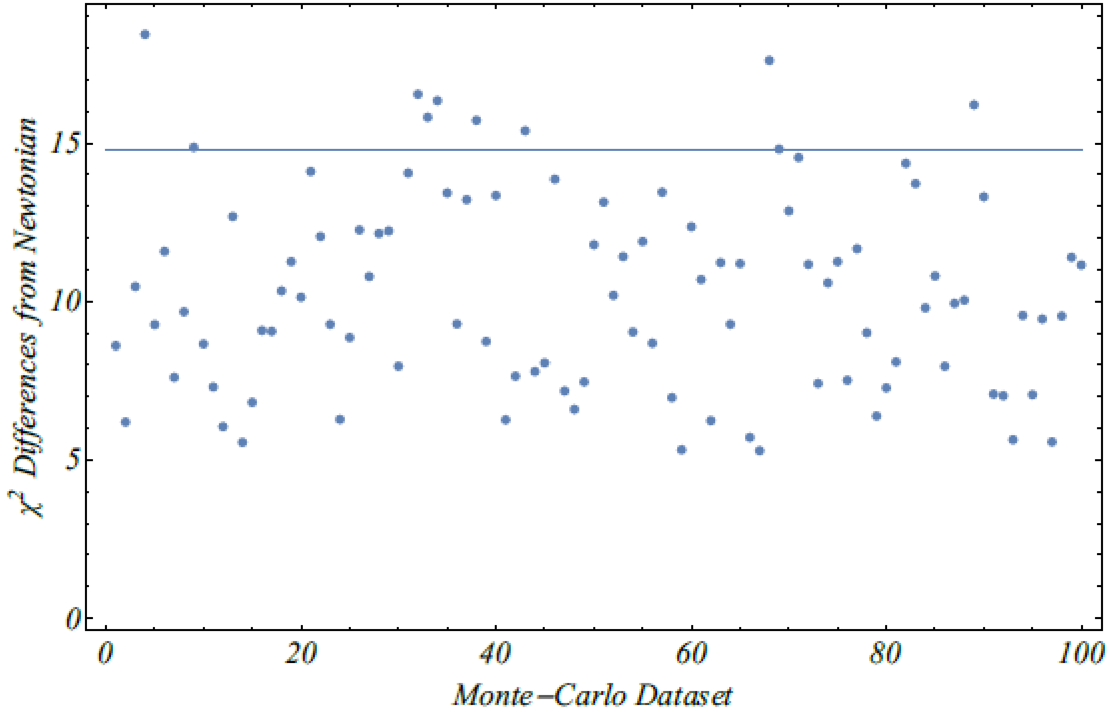
$$\delta\tau\ (\alpha', m', r) = \alpha' e^{-m' r}$$

Statistical Significance



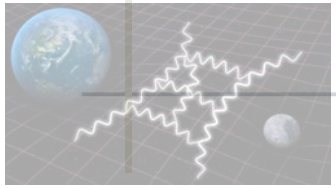
About 10% of Newtonian Monte Carlo Datasets have deeper oscillating χ^2 minima than the actual Washington experiment dataset





There is about 10% probability that the signal is a statistical fluctuation.
It could also be a systematic effect.

Theoretical Models I: f(R) theories



Weak field gravity:

$$f(R) = R + \frac{1}{6m^2} R^2$$

Chiba, T., "$1/R$ gravity and scalar-tensor gravity", *Phys. Lett. B*, **575**, 1–3 (2003). [DOI], [ADS], [arXiv:astro-ph/0307338].

$$T_{\mu\nu} = diag(M\delta(\vec{r}), 0, 0, 0)$$

$$h_{00} = \frac{2GM}{r}\left(1 + \frac{1}{3}e^{-mr}\right) \quad m^2>0$$

$$V_{eff} = -\frac{h_{00}}{2} = -\frac{GM}{r}\left(1 + \frac{1}{3}\cos(|m|r + \theta)\right) \quad m^2<0$$

$m^2>0$: Stability

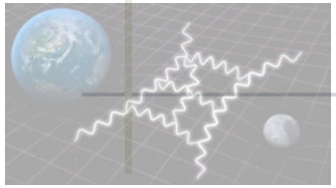
$m^2<0$: Instabilities

Valerio Faraoni, "Matter instability in modified gravity," Phys. Rev. **D74**, 104017 (2006), arXiv:astro-ph/0610734 [astro-ph].

A. D. Dolgov and Masahiro Kawasaki, "Can modified gravity explain accelerated cosmic expansion?" Phys. Lett. **B573**, 1–4 (2003), arXiv:astro-ph/0307285 [astro-ph].

Leandros Perivolaropoulos, "Sub-millimeter Spatial Oscillations of Newton's Constant: Theoretical Models and Laboratory Tests," (2016), arXiv:1611.07293 [gr-qc].
Phys.Rev. D95 (2017) no.8, 084050

Theoretical Models II: Infinite Derivative Gravity



$$\mathcal{L}_{\mathrm{IDG}} = \frac{1}{8\pi G}\sqrt{-g}\left[R + \alpha\left(RF_1(\Box)R + R^{\mu\nu}F_2(\Box)R_{\mu\nu} + R^{\mu\nu\rho\sigma}F_3(\Box)R_{\mu\nu\rho\sigma}\right)\right]$$

$$F_i(\Box) = \sum_{n=0}^{\infty} f_{i_n}\left(\frac{\Box}{M^2}\right)^n \qquad \Box = g^{\mu\nu}\nabla_\mu\nabla_\nu$$

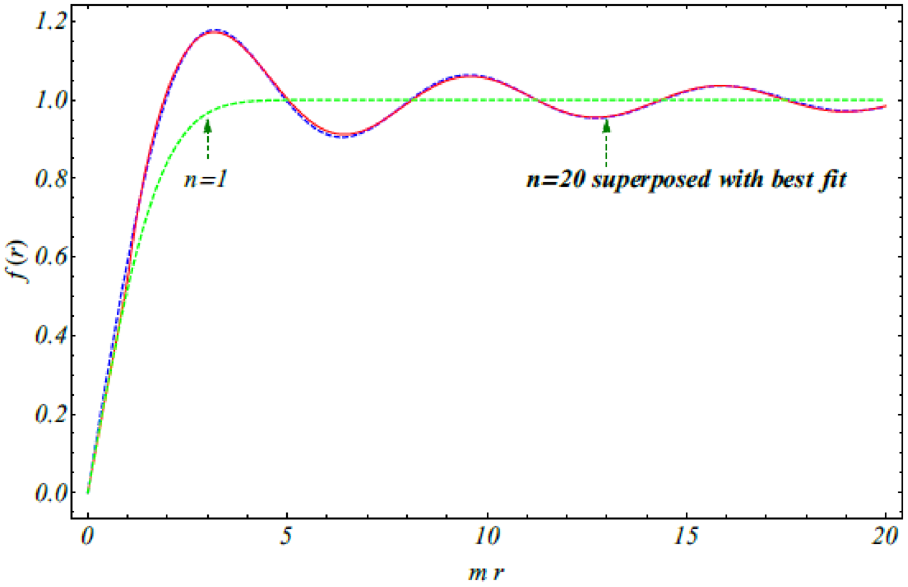
T. Biswas, E. Gerwick, T. Koivisto and A. Mazumdar, "Towards singularity and ghost free theories of gravity," Phys. Rev. Lett. **108**, 031101 (2012) arXiv:1604.01989 [gr-qc].

No instabilities for proper choice of F_i (eg exponential).

$$f(r,m) = \frac{1}{\pi}\int_{-\infty}^{+\infty} dk\,\frac{\sin(kr)e^{-\tau(k,m)}}{k}$$

$$\tau = \frac{k^{2n}}{m^{2n}}$$

Predicted gravitational potential: $V_{eff}(r) = -\frac{GM}{r}f(r,m)$



n>10 is well fit as:

$$f(r) = \alpha_1 \bar{r} \quad 0 < \bar{r} < 1$$

$$f(r) = 1 + \alpha_2 \frac{\cos(\bar{r}+\theta)}{\bar{r}} \quad 1 < \bar{r}$$

$\alpha_1 = 0.544,\ \alpha_2 = 0.572,\ \theta = 0.885\pi$

No singularities!

Leandros Perivolaropoulos, "Sub-millimeter Spatial Oscillations of Newton's Constant: Theoretical Models and Laboratory Tests," (2016), arXiv:1611.07293 [gr-qc].
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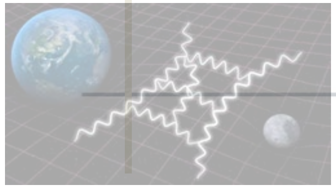
Conclusions



Tension within ΛCDM: The best fit Plank15/ΛCDM σ_8-Ω_{0m} parameter values are about 3σ away from the corresponding best fit parameter values obtained using the latest RSD growth rate data assuming a Planck15/ΛCDM background cosmology.

Reduced Tension with $G_{eff}(z)$: The tension can be reduced if an evolving Newton's constant is allowed leading to weaker gravity at $z \approx 1$. This type of evolution can not be reproduced in scalar-tensor theories with a ΛCDM background.

Sub-mm Spatially Oscillating Newton Constant: Higher derivative gravity models generically predict sub-mm spatial oscillations of Newton's constant. Hints for such oscillations have been demonstrated to exist in the Washington torsion-balance experiment.