Observational constraints in nonlocally modified gravity

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Introduction: Theory

- Inspiration (Arkani-Hamed et al. 2002, Dvali 2006)

$$\mathcal{L}_{\text{proca}} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} - \tfrac{m^2}{2}A_\mu A^\mu - A_\mu j^\mu \quad \Leftrightarrow \quad \mathcal{L}_{\text{nl}} = -\tfrac{1}{4}F_{\mu\nu}\left(1 - \tfrac{m^2}{\Box}\right)F^{\mu\nu} - A_\mu j^\mu$$

where $(\Box^{-1}\phi)(x) = \int d^4y \; G(x,y)\phi(y)$

- Applying the same idea to Fierz-Pauli massive gravity

$$\mathcal{L}_{\text{nl}} = \tfrac{1}{2}h_{\mu\nu}\left(1 - \frac{m^2}{\Box}\right)\mathcal{E}^{\mu\nu\rho\sigma}h_{\rho\sigma} - 2m^2\chi\tfrac{1}{\Box}\partial_\mu\partial_\nu(h^{\mu\nu} - \eta^{\mu\nu}h)$$

$\longrightarrow$ Obstruction: covariantization $\Rightarrow g^{\mu\nu}R_{\mu\nu} = 0$ "Covariant vDVZ discontinuity"

$$\left[\left(1 - \frac{m^2}{\Box_g}\right)G_{\mu\nu}\right]^T = 8\pi G T_{\mu\nu}$$

(Porrati 2002; Jaccard, Maggiore, Mitsou 2013)

- ▷ Unviable background cosmology
- ▷ $\Box^{-1}R_{\mu\nu} \subset \Box^{-1}G_{\mu\nu}$ generates instabilities (Ferreira, Maroto 2013)
- ▷ $g_{\mu\nu}\Box^{-1}R \subset \Box^{-1}G_{\mu\nu}$ stable (Foffa, Maggiore, Mitsou 2013)

Introduction: Phenomenology

Model RT : $$G_{\mu\nu} - m^2 \left(g_{\mu\nu}\Box^{-1}_{ret} R\right)^T = 8\pi G\, T_{\mu\nu}$$ (MM 2013)

where $(\Box^{-1}\phi)(x) = \int d^4y\; G(x,y)\phi(y)$

- Two models modifying General Relativity nonlocally – in the infrared
  - m^2 sets a new reference energy scale

    $\longrightarrow$ Nonlocal terms contributes for $\Box_g \ll m^2$ and vice versa
- Phenomenological approach
- Interesting cosmology:
  - FRW background/linear perturbations
  - Observational constraints and model comparison

Model RR : $$S_{\rm RR} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,\left[R - \frac{1}{2}m^2 R\frac{1}{\Box^2}R\right]$$ (MM, Mancarella 2013)

Application to Cosmology

Model RT

$$G_{\mu\nu} - m^2 (g_{\mu\nu} \Box^{-1}_{ret} R)^T = 8\pi G T_{\mu\nu}$$

Model RR

$$G_{\mu\nu} - m^2 K_{\mu\nu}(\Box^{-1}_{ret} R, \Box^{-2}_{ret} R) = 8\pi G T_{\mu\nu}$$

- Resolution method: Localisation

$$\Box V = R \quad \Rightarrow \quad V = \Box^{-1} R + V^{(hom)}$$

  - Auxiliary fields with *vanishing initial conditions*
  - They are not genuine (*freely* propagating) degrees of freedom

$$G_{\mu\nu} + m^2 \left[U g_{\mu\nu} - \frac{1}{2}(\nabla_\mu S_\nu + \nabla_\nu S_\mu) \right] = 8\pi G T_{\mu\nu}$$

$$\Box_g U = -R, \qquad \partial_\mu U = \frac{1}{2} \nabla_\nu (\nabla_\mu S^\nu + \nabla^\nu S_\mu)$$

$$G_{\mu\nu} - m^2 K_{\mu\nu}(V, S) = 8\pi G T_{\mu\nu}$$

$$\Box_g V = R \quad , \quad \Box_g S = V$$

- Specialisation to flat FRW

$$ds^2 = -dt^2 + a^2(t) \delta_{ij} dx^i dx^j$$

Background evolution

- Modified Friedmann equations :

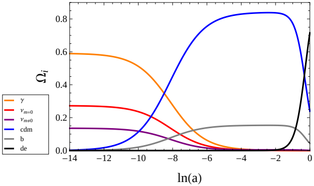
$$H^2(t) = 8\pi G \sum_i \bar{\rho}_i(t) + m^2 Y\left(\{\bar{V}_k\}, H(t)\right)$$
$$+ \quad \text{auxiliary EoM for } \{\bar{V}_k\}$$

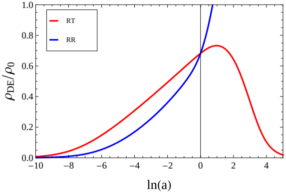
- $m^2 Y \equiv \bar{\rho}_{\rm DE}(t)$: Dynamical dark energy
- $\Box^{-1} R\big|_{\rm RD} = 0$: Late-time effectiveness
- Flatness today: $m_{\rm RT} \simeq 0.67 H_0$, $m_{\rm RR} \simeq 0.28 H_0$
- From $\dot{\bar{\rho}}_{\rm DE} = -3H(1 + w_{\rm DE})\bar{\rho}_{\rm DE}$

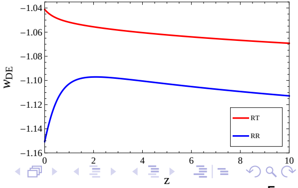
Fit : $\quad w(t) = w_0 + \left(1 - a(t)\right) w_a$

RT: $w_0 \simeq -1.04$, $w_a \simeq -0.02$
RR: $w_0 \simeq -1.15$, $w_a \simeq 0.08$

$\longrightarrow$ On the phantom side: $w_{\rm DE} < -1$



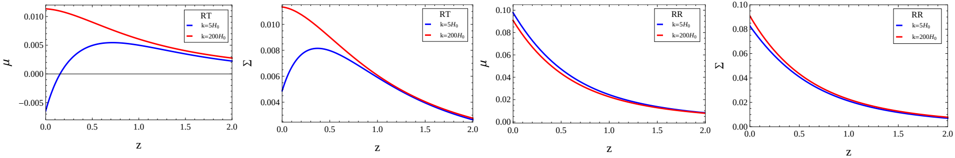




Scalar perturbations and Structure Formation

- Gravitational Ψ and lensing potential $(\Psi - \Phi)$ (YD, Foffa, Khosravi, Kunz, Maggiore 2014)

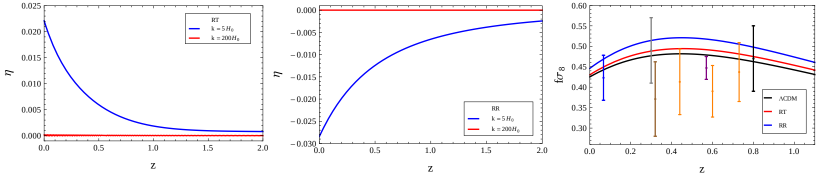
$$\Psi = \left[1 + \mu(z,k)\right]\Psi_{\Lambda\mathrm{CDM}}, \qquad (\Psi - \Phi) = \left[1 + \Sigma(z,k)\right](\Psi - \Phi)_{\Lambda\mathrm{CDM}}$$



▷ Fit: $\mu(t) = \mu_s a(t)^s$ RT: $\mu_s = 0.01$, $s = 0.8$, RR: $\mu_s = 0.09$, $s = 2$ (EUCLID: $\Delta\mu_s = 0.01$)

- Gravitational slip and RSD (6dF, SDSS LRG, BOSS LOWZ+CMASS, WiggleZ, VIPERS)

$$\eta = (\Psi + \Phi)/\Phi, \qquad f \equiv \frac{d\ln D}{d\ln a} \ \text{with} \ D(a) \sim \delta_M(a)$$



▷ Consistency with structure formation

▷ Nonlinear structure formation for RR: N-body simulation (Barreira et al. 2014)

Boltzmann Code and Parameter Inference

- Implementation in CLASS: Computation of CMB and LSS observables
- Observational constraints and model comparison with MONTEPYTHON

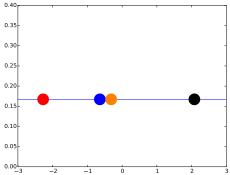
(Lesgourgues, Audren et al.)

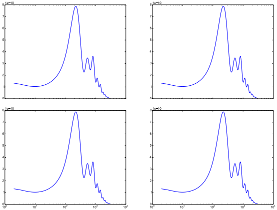
- Cosmological scenario: *Planck* baseline
  - ▷ 6 cosmo parameters varied: $\{\omega_b, \omega_c, H_0, A_s, n_s, z_{reio}\}$
  - ▷ Neutrino: Two massless species $N_{eff} = 2.03351$, one massive $m_\nu = 0.06eV$
- Datasets:
  - ▷ CMB: Planck 2013, Planck 2015
  - ▷ Supernovae: SDSS-II/SNLS3 Joint Light-Curve Analysis (JLA 2014)
  - ▷ BAO: BOSS LOWZ+CMASS DR10&11 (iso., aniso.), 6dF and SDSS MGS
  - ▷ H_0: HST $(70.6 \pm 3.3, 73.0 \pm 2.4, 73.8 \pm 2.4)$

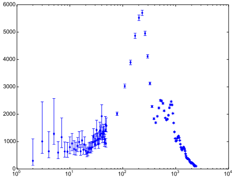
(YD, Foffa, Kunz, MM, Pettorino, 2014)
(YD, Foffa, Kunz, MM, Pettorino, in prep.)

Observational constraints and parameter inference

- Bayesian inference:
  - ▷ Observed datasets: Planck 2013/2015, JLA, BAO, HST, etc
  - ▷ Statistical models: ΛCDM, RT and RR with $\{\omega_b, \omega_c, H_0, A_s, n_s, z_{reio}\}$
  - ▷ Parameter estimation: Update our degree of belief through observations

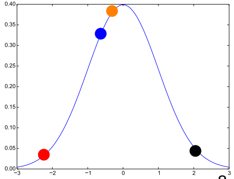


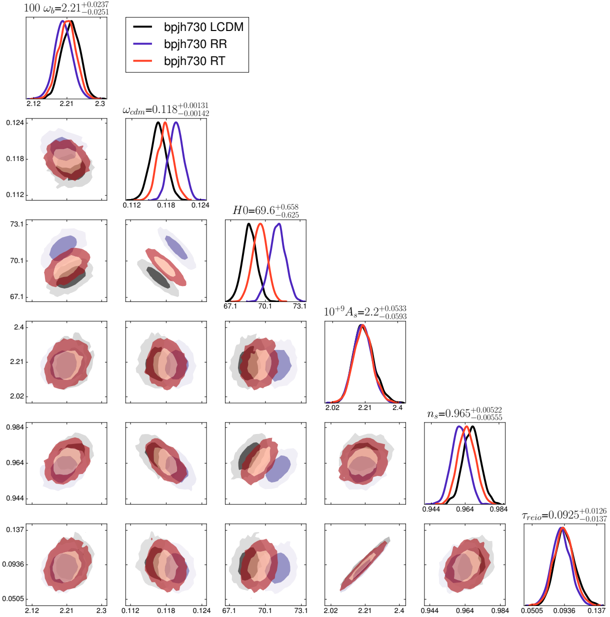




- ▷ Minimum χ^2 estimation:

$$\chi^2 = \sum_{\text{dataset}} \chi^2_{\text{dataset}} \quad \text{with} \quad \chi^2_{\text{dataset}} = \sum_i \frac{(\theta^i_{\text{theo}} - \theta^i_{\text{obs}})^2}{(\sigma^i_{\text{obs}})^2}$$



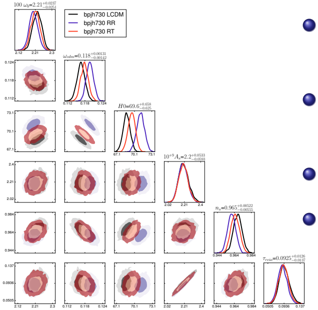


(YD, Foffa, Kunz, MM, Pettorino 2014)

Observational constraints and parameter inference

	Planck			BAO+Planck+JLA		
Param	ΛCDM	$g_{\mu\nu}\Box^{-1}R$	$R\Box^{-2}R$	ΛCDM	$g_{\mu\nu}\Box^{-1}R$	$R\Box^{-2}R$
ω_c	$0.1194^{+0.0027}_{-0.0026}$	$0.1195^{+0.0026}_{-0.0028}$	$0.1191^{+0.0027}_{-0.0028}$	$0.1175^{+0.0015}_{-0.0014}$	$0.1188^{+0.0014}_{-0.0014}$	$0.1204^{+0.0014}_{-0.0013}$
H_0	$67.56^{+1.2}_{-1.3}$	$68.95^{+1.3}_{-1.3}$	$71.67^{+1.5}_{-1.5}$	$68.43^{+0.61}_{-0.69}$	$69.3^{+0.68}_{-0.66}$	$70.94^{+0.74}_{-0.7}$
$\Delta\chi^2_{\rm min}$	9801.7	9801.3	9800.1	10485.5	10485.0	10488.7

	BAO+Planck+JLA+$H_0 = 73.0 \pm 2.4$		
Param	ΛCDM	$g_{\mu\nu}\Box^{-1}R$	$R\Box^{-2}R$
ω_c	$0.117^{+0.0014}_{-0.0014}$	$0.1182^{+0.0013}_{-0.0014}$	$0.1201^{+0.0013}_{-0.0013}$
H_0	$68.72^{+0.61}_{-0.63}$	$69.60^{+0.66}_{-0.63}$	$71.14^{+0.72}_{-0.69}$
$\Delta\chi^2_{\rm min}$	10488.9	10487.3	10489.3



- Few parameters with $\gtrsim 1\sigma$ deviation from ΛCDM
  $\longrightarrow$ Nonlocal models prefer a bigger H_0
- Nonlocal vs ΛCDM: Overall $|\Delta\chi^2| \lesssim 2$
  $\longrightarrow$ Mostly statistically equivalent to ΛCDM
- Planck: RR fits slightly better C_l^{TT} at low-l
- BAO+Planck+JLA: RR creates a Planck-JLA 1σ-tension

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$\Delta\chi^2_{\rm min}$	1.6	1.2	0	0.5	0	3.7

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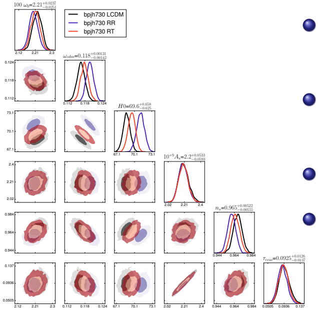

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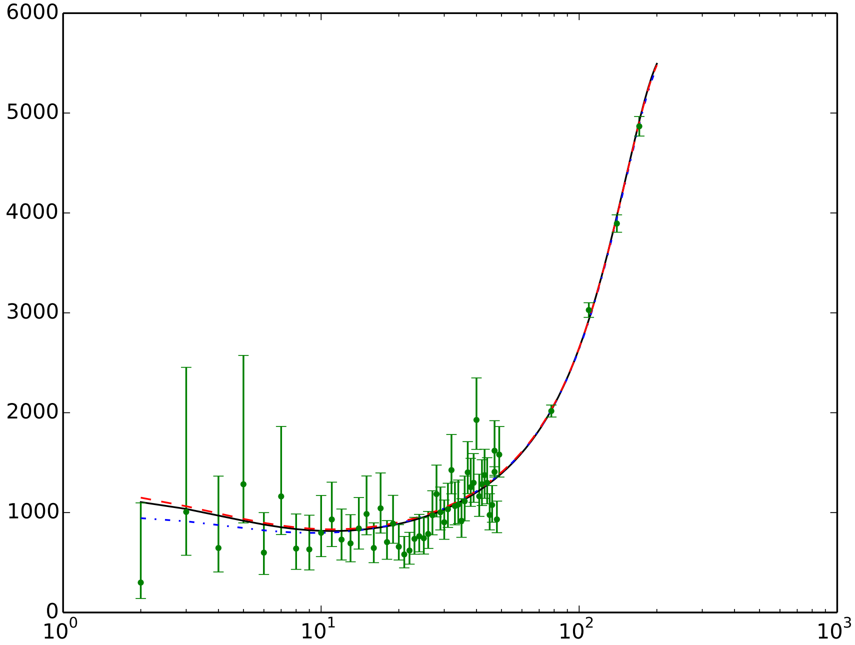
6000
5000
4000
3000
2000
1000
0
10^0
10^1
10^2
10^3

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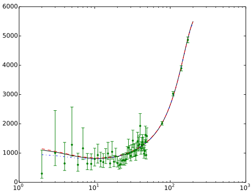

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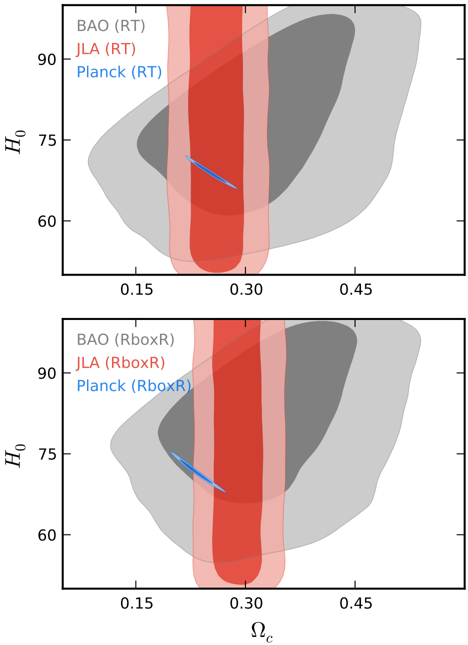
$$\Delta\omega_c = \Delta(\Omega_c h^2) \sim 1\%$$



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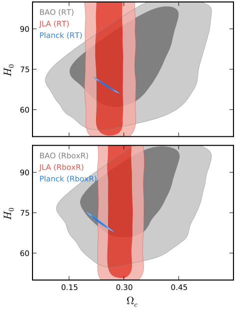

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Bayesian model selection

- Computation of the Bayes factor: done by considering the nested models

$$G_{\mu\nu} - m^2 (g_{\mu\nu} \Box_{\rm ret}^{-1} R)^T - g_{\mu\nu}\Lambda = 8\pi G T_{\mu\nu}$$

$$\mathcal{L} = \frac{1}{16\pi G}\left[R - 2\Lambda - m^2 R \Box^{-2} R\right] + \mathcal{L}_m$$

with cosmological parameter space $\{\omega_{\rm b}, H_0, A_{\rm s}, n_{\rm s}, z_{\rm reio}, \Omega_\Lambda, \Omega_{de}\}$

$\longrightarrow$ Non-informative priors are flat on Ω_Λ and Ω_{de}

- Three statistical models in each case: $\mathcal{M}_{\Lambda+de}$, $\mathcal{M}_\Lambda$, $\mathcal{M}_{de}$
- Bayes theorem

$$P(\theta|d,\mathcal{M}) = \frac{P(d,\mathcal{M}|\theta)P(\theta|\mathcal{M})}{P(d,\mathcal{M})}$$

- Savage-Dickey density ratio:

$$B_{\Lambda/(\Lambda+de)} = \frac{P(d,\mathcal{M}_\Lambda)}{P(d,\mathcal{M}_{\Lambda+de})} = \left.\frac{P(\Omega_{de}|d,\mathcal{M}_{\Lambda+de})}{P(\Omega_{de}|\mathcal{M}_{\Lambda+de})}\right|_{\Omega_{de}=0}$$

$\longrightarrow$ Model Λ (dis)favored with betting odds $B_{\Lambda/(\Lambda+de)}$: 1 wrt $\Lambda + de$

Conclusion

$$G_{\mu\nu} - m^2 (g_{\mu\nu} \Box_{\text{ret}}^{-1} R)^T = 8\pi G T_{\mu\nu}$$

$$\mathcal{L} = \frac{1}{16\pi G} \left[R - m^2 R \Box^{-2} R \right] + \mathcal{L}_m$$

- Two observationally viable models of gravity (JCAP 1504 (2015) 04, 044, arXiv:1411.7692)
- Phenomenological side
  - Well behaved dynamical dark energy
  - Same number of free parameters than ΛCDM
  - Fit the data as well as ΛCDM

  ⟶ Provide observationally consistent alternatives to ΛCDM
- Theoretical side: Effective models/terms
  - Suggest effects/mechanisms for dynamical dark energy generation
  - Dimensional transmutation, conformal anomaly (Maggiore 2015)