Theory and Observational Constraints in Nonlocal Gravity

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FONDS NATIONAL SUISSE
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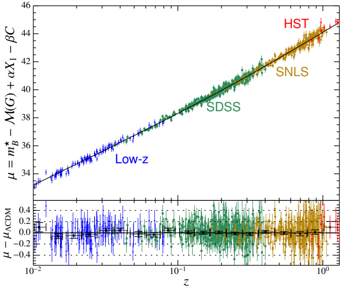
grit
gravitation in técnico

Outline

Introduction: Accelerated Expansion of the Late Universe

▷ Observation of Type Ia supernovae

⟶ Late accelerated cosmic expansion
[Riess+; Perlmutter+ (1999)]



[SNIa Hubble diag., Betoule+ (2014)]

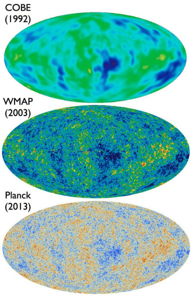
⟶ Introduction of Λ for ΛCDM

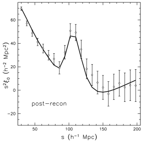
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda = 8\pi G\, T_{\mu\nu}$$

$\rightarrow \theta_{\rm base} = (\Omega_{\rm b}, \Omega_\Lambda, H_0, n_{\rm s}, A_{\rm s}, z_{\rm re})$

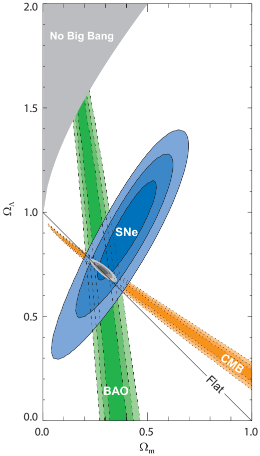
▷ CMB, BAO+ & complementarity

⟶ Λ compatible w/ high precision obs.





[Anderson+ (2013)]



[Kowalski+ (2008)]

Introduction: What is the Dark Energy?

▷ Theoretical and (potential) observational objections

- Cosmological Constant Problem

  ⟶ No understanding of fundamental vacuum (∼ QG)

- Coincidence problem

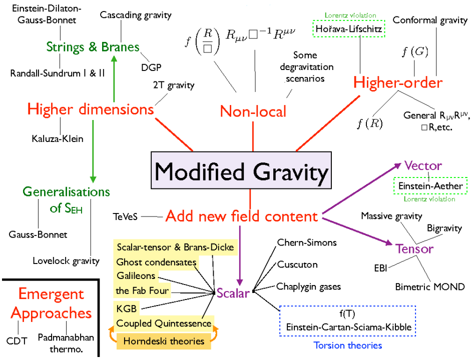
  ⟶ Violation of the Cosmological Principle

- Statistical inconsistencies

  H_0: CMB vs local measurements

  σ_8: cluster counts vs weak lensing

  Ω_K: CMB   [Di Valentino+ (2019)]



[Courtesy of Tessa Baker]

⟹ Search for modifications to GR

⟶ Design and test new alternative theories of gravity

⟶ Develop methodology for current/future experiments (e.g. LSS, GWs)

Introduction: Nonlocal Gravity Models

- Definition: Nonlocal field theories are those that are not local:

  Dynamics at x^μ not only depends on the values of $\{\phi_i\}$ and on $\{\partial_{\mu_1} \ldots \partial_{\mu_N} \phi_i\}$ with $N < \infty$ at x^μ.

- Examples: $\Box^{-1}$, ∂^∞, $\exp(M/\Box)$, $\log(\Box/M)$, $e^2(\Box)$, $f_R(\Box)$, ...

  $\longrightarrow$ where e.g. $(\Box^{-1}\phi)(x) \equiv \int \mathrm{d}^4 y \sqrt{-g}\; G(x,y)\phi(y)$

- From various contexts:
  - Effective QFT (vacuum pol. of light fields, conformal anomaly)
  - Extra-dimensions (DGP)
  - String theories (relevant in the UV)
  - Infrared ressumation on de Sitter
  - Quantum Gravity considerations
  - etc.

  $\longrightarrow$ Hard to handle and to understand from first principles

- Dark energy phenomenology: $f(R/\Box)$, $m^2 R \Box^{-2} R$, $R_{\mu\nu} \Box^{-1} R^{\mu\nu}$, more.

  $\longrightarrow$ no EFT-like techniques such as power-counting

Introduction: Nonlocal Gravity Models

- Specific models:

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

[Maggiore (2014)]

$$S_{\mathrm{RR}} = M^2 \int \mathrm{d}^4x \sqrt{-g} \left[R - \frac{1}{2} m^2 R \frac{1}{\Box^2} R\right]$$

[Maggiore, Mancarella (2014)]

$$S_{\mathrm{DW}} = M^2 \int \mathrm{d}^4x \sqrt{-g}\, R \left[1 + f\left(R/\Box\right)\right]$$

[Deser, Woodard (2007)]

Introduction: Nonlocal Gravity Models

- Degravitation idea [Arkani-Hamed+ (2002), Barvinsky (2003), Dvali (2006)]

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

where $(\Box^{-1}\phi)(x) = \int \mathrm{d}^4 y \; G(x,y)\phi(y)$ and $\partial_\mu \tilde{j}^\mu \equiv 0$

- Application to Fierz-Pauli massive gravity

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

$\longrightarrow$ 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+ (2013)]

▷ Unviable background cosmology

▷ $\Box^{-1}R_{\mu\nu} \subset \Box^{-1}G_{\mu\nu} \Rightarrow$ instabilities [Ferreira+ (2013), Amendola+ (2017)]

▷ $g_{\mu\nu}\Box^{-1}R \subset \Box^{-1}G_{\mu\nu}$ stable [Foffa+ (2013)]

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

$\downarrow$

$$\mathcal{L}_{lin} = \frac{1}{2} h_{\mu\nu}\mathcal{E}^{\mu\nu\alpha\beta}h_{\alpha\beta} - \frac{1}{2} m^2 h_{\mu\nu}P^{\mu\nu}P^{\alpha\beta}h_{\alpha\beta}$$

$\downarrow$ Covariantization

$$S_{\mathrm{RR}} = M^2 \int \mathrm{d}^4x\sqrt{-g}\left[R - \frac{1}{2}m^2 R\frac{1}{\Box^2}R\right]$$

Propagator $\downarrow$

$$\tilde{D}_{\mathrm{GR}}(k) + \frac{-i}{k^2} + \frac{-i}{-k^2+m^2}$$

$\rightarrow$ No vDVZ discontinuity

$\rightarrow$ Scalars are not genuine DoF

$\downarrow$ Localisation

$$S^{\mathrm{loc}}_{\mathrm{RR}} = \int \mathrm{d}^4x\sqrt{-g}\left[MR\Phi + \frac{1}{2m^2}(\Box\Phi)^2\right]$$

$\downarrow$ Einstein Frame

$$S^{\mathrm{loc}}_{\mathrm{RR}} = \int \mathrm{d}^4x\sqrt{-\bar{g}}\left[M^2\bar{R} - \frac{1}{2}\bar{\nabla}_\mu\phi\bar{\nabla}^\mu\phi + \frac{1}{2}\bar{\nabla}_\mu\psi\bar{\nabla}^\mu\psi - \frac{m^2}{2}e^{-(\phi+\psi)/\tilde{M}}\psi^2\right]$$

[YD, Mitsou (2014)]

$\downarrow$ Jordan Frame + Var. Principle
+ Solving for scalars w/ vanishing IC

$\downarrow$

Model RR : $G_{\mu\nu} - m^2 K_{\mu\nu}\left[\Box^{-1}_{ret}R, \Box^{-2}_{ret}R\right] = 8\pi G\, T_{\mu\nu}$

Application to Cosmology

Model RT

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

Model RR

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

- Resolution method: Localisation

$$\Box V = R \quad \Rightarrow \quad V = \Box_{ret}^{-1} R + V^{(hom)} = \int^{t} \mathrm{d}^4 x' \sqrt{-g}\, G(x, x') R(x') + V^{(hom)}$$

▷ Auxiliary fields with *vanishing initial conditions*

$\Longrightarrow$ Not in the spectrum (at least linearly)

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

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

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

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

- Specialisation to flat FRW

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\, \delta_{ij}\, \mathrm{d}x^i \mathrm{d}x^j$$

Background Evolution

- On flat FLRW: $\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}\vec{x}^2$
- Modified Friedmann equations :

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

$$+ \quad \text{auxiliary EoM for } \{\bar{V}_k\}$$

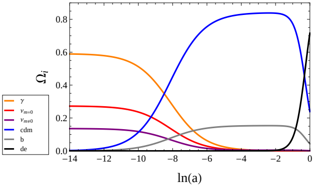
- $m^2 Y \equiv \bar{\rho}_{\mathrm{DE}}(t)$: Dynamical dark energy
- $\Box^{-1} R\big|_{\mathrm{RD}} \simeq 0$: Late-time effectiveness
- Flatness today: $m_{\mathrm{RT}} \simeq 0.67 H_0$, $m_{\mathrm{RR}} \simeq 0.28 H_0$
- From $\dot{\bar{\rho}}_{\mathrm{DE}} = -3H(1 + w_{\mathrm{DE}})\bar{\rho}_{\mathrm{DE}}$

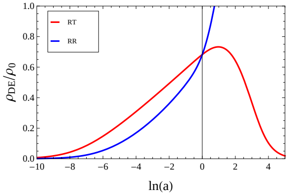
$\longrightarrow$ On the phantom side: $w_{\mathrm{DE}} < -1$

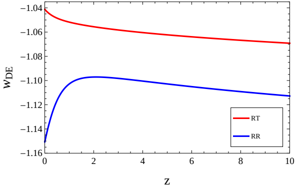
Fit : $w(t) = w_0 + \left(1 - a(t)\right) w_a$

RT: $w_0 \simeq -1.04$, $w_a \simeq -0.02$

RR: $w_0 \simeq -1.15$, $w_a \simeq 0.08$







Background Evolution

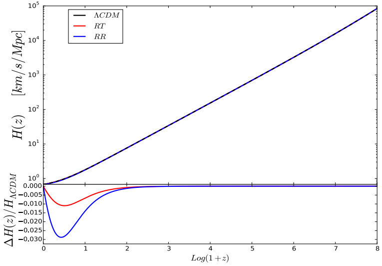
- From dark energy conservation:

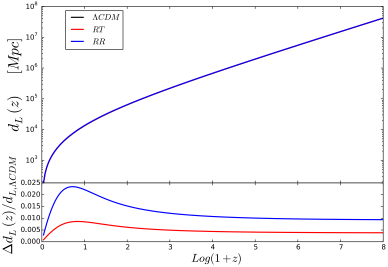
$$\Omega_{de}(z) = \Omega_{de,0}\ \exp\left(3\int_0^z \mathrm{d}z'\,\frac{1+w_{de}(z')}{(1+z')}\right)$$

writing $\quad w_{de}(z\approx 0) \simeq -1+\delta w_0, \quad \Rightarrow \quad \Omega_{de}(z\approx 0) \simeq \Omega_{de,0}\ (1+3z\,\delta w_0)$

$\longrightarrow$ Phantom dark energy: $\Omega_{de}(z \geq 0) < \Omega_\Lambda$

$$H(z) = \left[\Omega_M(z)\,h^2 + \Omega_{\rm de}(z)\,h^2\right]^{1/2} \times 100\,\mathrm{km/s/Mpc}$$

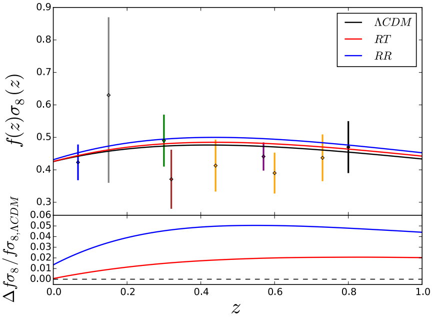




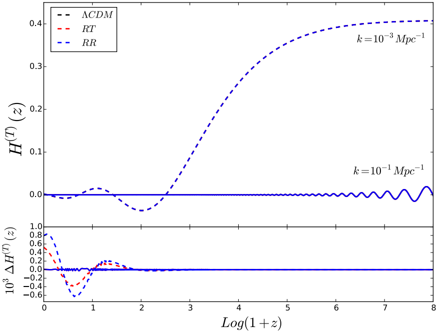
Linear Structure Formation and Gravitational Waves

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)[(1+2\Phi)\delta_{ij} + h_{ij}]dx^i dx^j$$

- Growth of structures RSD



- GWs: $h''_A + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$



▷ Forecasts for GC, WL+: *Euclid-like* [Casas, YD, Kunz, Maggiore, Pettorino (in prep.)]

▷ The lower $w_{\rm DE}(z=0)$ the stronger $f\sigma_8$

▷ Modified GWs amplitude

[YD, Foffa, Khosravi, Kunz, Maggiore (2014)]
[YD, Foffa, Kunz, Maggiore, Pettorino (2016)]

Boltzmann Code and Parameter Inference

- Implementation in CLASS (*https://github.com/dirian/class_public/tree/nonlocal*)

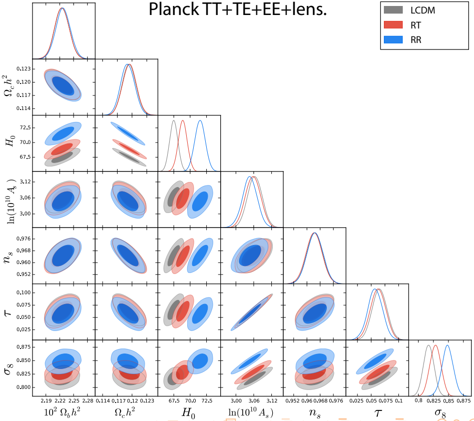
  $\longrightarrow$ Code tested against a modified version of CAMB [Bellini+ (2018)]

- Observational constraints with MONTEPYTHON [Lesgourgues, Tram, Audren+ (2011)]

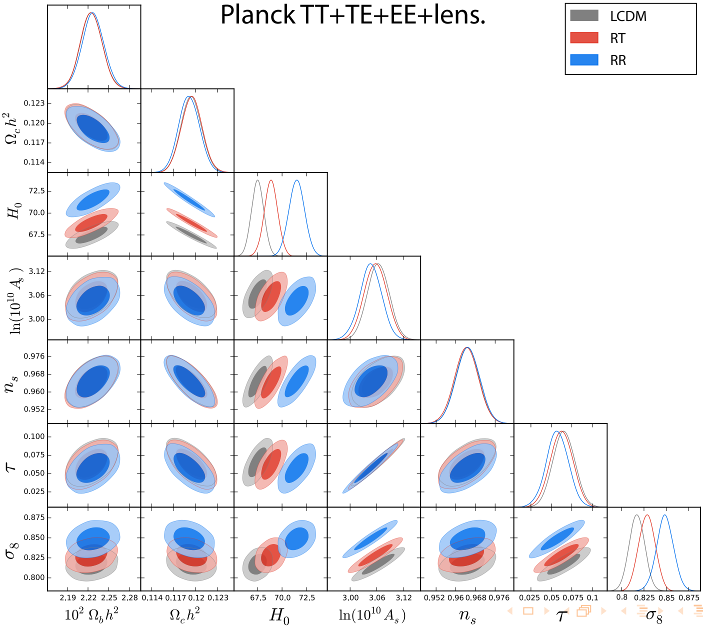
- Cosmological scenario: *Planck* baseline $\{\Omega_b, \Omega_c, H_0, A_s, n_s, z_{reio}\}$ and one massive ν

- Datasets:
  - ▷ CMB: *Planck* 2015
  - ▷ SNIa: *SDSS-II/SNLS3 JLA* 2014
  - ▷ BAO: *BOSS*, *6dF* and *SDSS* MGS
  - ▷ H_0: *HST* $(70.6 \pm 3.3, 73.8 \pm 2.4)$
  - ▷ RSD: $f\sigma_8$

[YD, Foffa, Kunz, Maggiore, Pettorino (2016)]

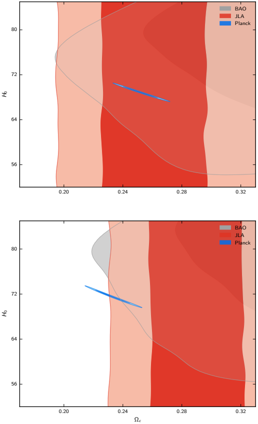


Observational Constraints



Observational Constraints

	Planck			BAO+*Planck*+*JLA*		
Param	ΛCDM	RT	RR	ΛCDM	RT	RR
ω_c	$0.1194^{+0.0015}_{-0.0014}$	$0.1195^{+0.0015}_{-0.0014}$	$0.1191^{+0.0015}_{-0.0014}$	$0.119^{+0.001}_{-0.001}$	$0.1197^{+0.001}_{-0.001}$	$0.121^{+0.001}_{-0.001}$
H_0	$67.5^{+0.65}_{-0.66}$	$68.86^{+0.69}_{-0.7}$	$71.51^{+0.81}_{-0.84}$	$67.67^{+0.47}_{-0.5}$	$68.76^{+0.51}_{-0.46}$	$70.44^{+0.56}_{-0.56}$
$\Delta\chi^2_{\rm min}$	1.6	1.5	0	0	0.6	6.0



- Few parameters with $\gtrsim 1\sigma$ deviation from ΛCDM

  $\longrightarrow$ Bigger H_0 in nonlocal models

- Nonlocal vs ΛCDM:

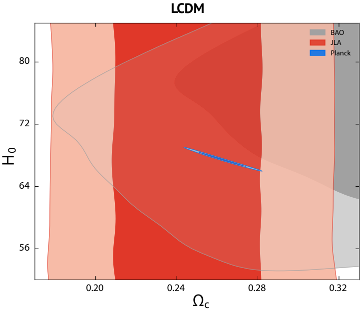
  $\longrightarrow$ RT statistically equivalent to ΛCDM

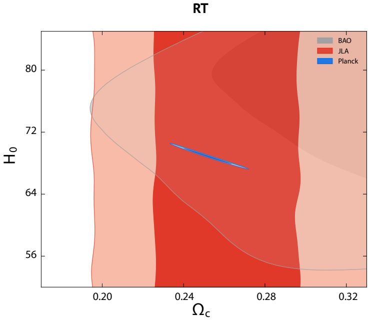
  $\longrightarrow$ RR disfavored with respect to ΛCDM

$\Longrightarrow$ Bayesian model comparison (SDDR) gives same conclusions

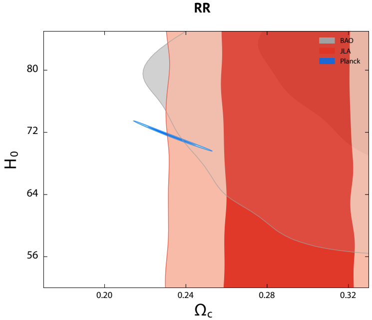
- BAO+*Planck*+*JLA*: RR creates a *Planck*-*JLA* tension

[YD, Foffa, Kunz, Maggiore, Pettorino (2016)]





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



Extending the Baseline

[YD (2017)]

$$H(z) \simeq \left[\Omega_M(z)\, h^2 + \Omega_{\rm de}(z)\, h^2\right]^{1/2}$$

- Phantom DE: $\Omega_{\rm de}(z) < \Omega_\Lambda$
- CMB constrains $\omega_M \equiv \Omega_M h^2 \sim 1\%$

$$\theta_* = \frac{r_s(z_*)}{D_A(z_*)} < 0.1\%$$

- Distant SNIa constrain Ω_M:

$$D_L(z, \Omega_M) \equiv (1+z) \int_0^z \frac{\mathrm{d}z'}{H(z', \Omega_M)}$$

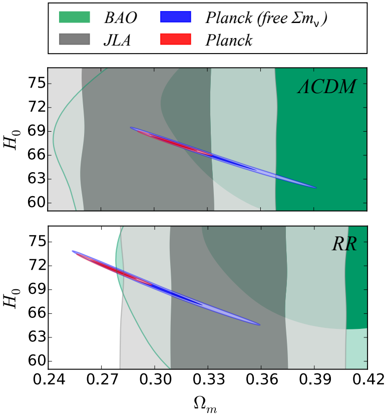
$\Rightarrow$ *Planck* prefers higher H_0 and fixes ω_M while SNIa prefer higher Ω_M

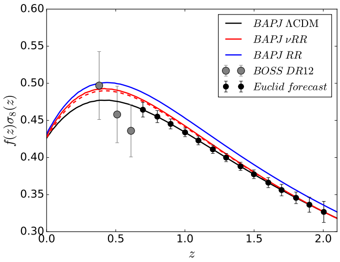
$\longrightarrow$ Solution: Extend the initial baseline

$\Longrightarrow$ νRR statistical equivalent to $\nu\Lambda$CDM

$\Longrightarrow$ RR prefers massive neutrino at 2σ

$\longrightarrow$ Future galaxy surveys could be decisive





Solving the tension

[YD (2017)]

- Compute the Bayes factor

$$B_{\nu\Lambda,\nu RR} \equiv \frac{P(d|\mathcal{M}_{\nu\Lambda})}{P(d|\mathcal{M}_{\nu RR})} = \frac{P(d|\mathcal{M}_{\nu\Lambda})}{P(d|\mathcal{M}_{\Lambda})}\frac{P(d|\mathcal{M}_{\Lambda})}{P(d|\mathcal{M}_{RR})}\frac{P(d|\mathcal{M}_{RR})}{P(d|\mathcal{M}_{\nu RR})}$$

$$= \frac{B_{RR,\nu RR}}{B_{\Lambda,\nu\Lambda}} B_{\Lambda,RR}\,,$$

- The tension gets resolved

$$\mathrm{BIC}: \Delta\chi^2\big|_{\Lambda,RR} = 6.0 \quad \rightarrow \Delta\chi^2\big|_{\nu\Lambda,\nu RR} = 3.4 \quad (\textit{weak})$$

$$\mathrm{Bayes}: B_{\Lambda,RR} = 22.7 \quad \rightarrow B_{\nu\Lambda,\nu RR} = 1.8 \quad (\textit{insignificant})$$

$\longrightarrow$ νRR model statistical equivalent to $\nu\Lambda$CDM

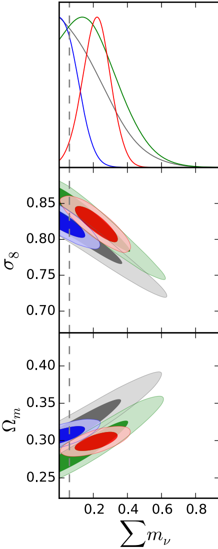
$\longrightarrow$ BIC "fails" in that case

- Bayesian paradigm incorporates Occam's razor

$\longrightarrow$ ΛCDM is penalized by its significant preference for small neutrino masses

$\longrightarrow$ RR prefers massive neutrino at 2σ

$\longrightarrow$ Future galaxy surveys could be decisive



Future Perspectives

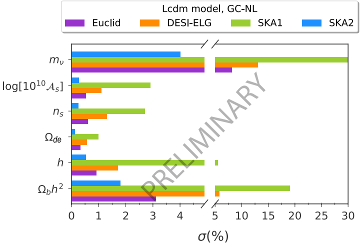
Galaxy survey Fisher forecast in RT

[Casas, YD, Kunz, Maggiore, Pettorino (in prep.)]

- Compute sensitivity to cosmo. param.: Fisher information matrix

$$F_{ij}^{\mathrm{GC}} = \int \mathrm{d}^3 k \frac{\partial \ln P_{\mathrm{obs}}(z, k_{\mathrm{ref}}, \mu_{\mathrm{ref}})}{\partial \theta_i} \frac{\partial \ln P_{\mathrm{obs}}(z, k_{\mathrm{ref}}, \mu_{\mathrm{ref}})}{\partial \theta_j} \times [\mathrm{noise}] \times V_s$$

where $P_{\mathrm{obs}} \equiv F[P_{\mathrm{theo}}, D_A, H, \sigma_8, P_s, \ldots]$



- Fisher code S4 galaxy surveys:

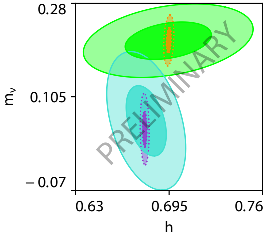
  → GCsp, GCph (Lin, NL), WL, 3x2pt, IM

- Projected Bayesian model comparison

$$B_{\Lambda\,\mathrm{RT}} = \frac{\sigma_{\Omega_\Lambda}}{\sigma_{\Omega_{X_{\mathrm{RT}}}}} \exp\left[-\frac{1}{2}\left(\frac{\bar{\Omega}^2_{X_{\mathrm{RT}}}}{\sigma^2_{\Omega_{X_{\mathrm{RT}}}}} - \frac{\bar{\Omega}^2_{\Lambda}}{\sigma^2_{\Omega_\Lambda}}\right)\right]$$

→ Prospects for testing ΛCDM vs MG

→ Test method's model independence



$\Longrightarrow$ Combine with current and future exp.

Cosmology of the Deser-Woodard model

- The Deser-Woodard model:

$$S_{\rm DW} = \frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\; R\left[1 + f\left(\frac{1}{\Box}R\right)\right]$$

$\longrightarrow$ Function f fixed to reproduce ΛCDM background [Deffayet, Woodard (2009)]

$$h_\Lambda^2(\zeta) \equiv \mathcal{H}_\Lambda^2(\zeta)/H_0^2 = [\Omega_\Lambda + \Omega(\zeta)]$$

$$f(\zeta) = -2\int_\zeta^\infty \mathrm{d}\zeta_1\,\zeta_1\phi(\zeta_1) - 6\Omega_\Lambda \int_\zeta^\infty \mathrm{d}\zeta_1 \frac{\zeta_1^2}{h_\Lambda(\zeta_1)\, I(\zeta_1)} \int_{\zeta_1}^\infty \mathrm{d}\zeta_2 \frac{I(\zeta_2)}{h_\Lambda(\zeta_2)\,\zeta_2^4} + \dots$$

$$X(\zeta) = -\int_\zeta^\infty \frac{\mathrm{d}\zeta_1\,\zeta_1^2}{h_\Lambda(\zeta_1)} I(\zeta_1)$$

$\longrightarrow$ Integro-differential system

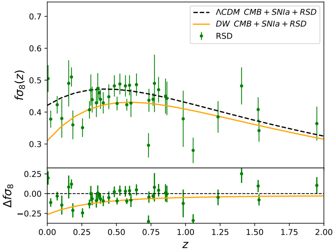
Cosmology of the Deser-Woodard model

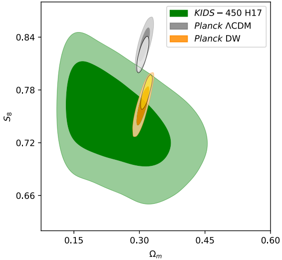
[Amendola, YD, Nersisyan, Park (2019)]

- The Deser-Woodard model:

$$S_{\rm DW} = \frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\; R\left[1+f\left(\frac{1}{\Box}R\right)\right]$$

- Phenomenology and observational constraints





⟶ Lower growth than ΛCDM: Lower σ_8

⟹ Describes cosmological observations as well as ΛCDM

⟶ Lack of screening mechanism [Belgacem+ (2019)]

(Some) Small Scale Solutions

RR and DW ruled out, RT viable

$$G_{eff,N}/G(z,|\vec{k}|) = \bar{F}(z)(1+\mathcal{O}(1/|\vec{k}^2|))$$

- Correction to GR of $\mathcal{O}(m^2 r^2)$ on Schwarzchild-like in $r_s \ll r \ll m^{-1}$ [Maggiore+ (2014)]
- No vDVZ discontinuity:

$$\tilde{D}_{\mathrm{GR}}(k) + \frac{-i}{k^2} + \frac{-i}{-k^2+m^2}$$

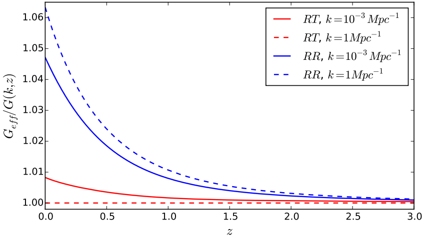
$\implies$ No Vainshtein screening (?)

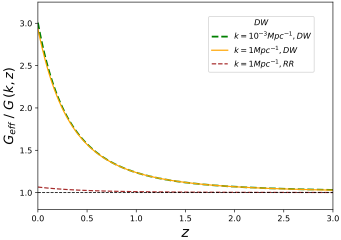
- $G_{eff,N}$ in quasi-static linearised FLRW: $\vec{k}|/H(z) \sim |\Box|/R \gg 1$ and $\not{\dot{\Phi}}$

  $\longrightarrow$ RR (and DW) claimed to be ruled out by Lunar Laser Ranging $\dot{G}/G$ [Belgacem+ (2019)]

- RT model passes all submitted tests ($R/|\Box| \ll 1$) [Belgacem+ (2020)]

$\implies$ Considered by *LSST* and *LISA* collaborations





Future Perspectives

Small Scale Dynamics in RT and Screening

- Corrections $\mathcal{O}(m^2 r^2)$ on Schwarzchild-like
- No vDVZ discontinuity:

$$\tilde{D}_{\rm GR}(k) + \frac{-i}{k^2} + \frac{-i}{-k^2 + m^2}$$

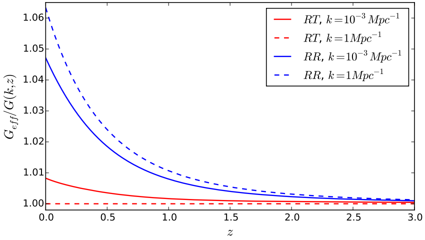
- $G_{eff,N}$ in quasi-static linearised FLRW:
  $\vec{k}|/H(z) \sim |\Box|/R \gg 1$ and $\not{\dot{\Phi}}$

  $\Longrightarrow$ Understand screening

- Caveat: in these tests
  $R/|\Box| \ll 1$ and $\Box \to \nabla_i^2$: non-dynamical

  $\Rightarrow$ Test RT in dynamical small scale regimes
  $(R/|\Box| \sim 1)$

$$G_{eff,N}/G(z,|\vec{k}|) = \bar{F}(z)\big(1 + \mathcal{O}(1/|\vec{k}^2|)\big)$$



$\Longrightarrow$ Compact objects tests: Collapsing star, BH perturbation theory, PN formalism, superradiance ?, etc.

$\Longrightarrow$ Theoretical tests: well-posedness, nonlinear Hamiltonian analysis, ...

Multi-Messenger Astronomy

New observational window for cosmology

- GWs from ~ 100 mergers by *LIGO*/*Virgo*/*KAGRA*
- GWs from 1 inspiralling BNS: GW170817

  $\longrightarrow$ γ-ray burst counterpart: GRB170817A by *FERMI* and *INTEGRAL*

  - $\tilde{h}''_{+,\times} + 2\mathcal{H}\tilde{h}'_{+,\times} + c_T^2(\eta)k^2\tilde{h}_{+,\times} = 0\,, \quad \Longrightarrow \quad |c_T(\eta_0) - c|/c \approx 10^{-15}$

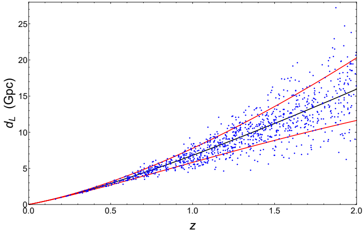
  $\longrightarrow$ Dramatic consequences for modified gravity theories

  [Creminelli+, Sakstein+, Ezquiaga+, Baker+ (2017)]

- BNS are "standard sirens" [Schutz (1986)]
  - GW amplitude $\sim d_L^{-1}$
  - Electromagnetic counterparts give z

  $\longrightarrow d_L(z) \Rightarrow$ Hubble diagram for GWs

$\Longrightarrow$ Cosmological constraints



[GW Hubble diag., Belgacem+ (2018)]

Cosmological Constraints from GW Standard Sirens

[Belgacem, YD, Foffa, Maggiore (2017,2018)]

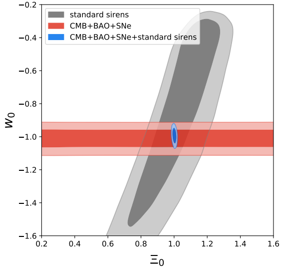
- Modified propagation for GWs: $\tilde{h}_A'' + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}_A' + k^2\tilde{h}_A = 0$

$$\Rightarrow \tilde{h}_A \sim \frac{1}{d_L^{gw}(z)}$$

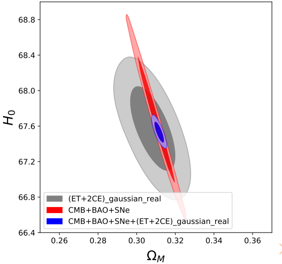
$$\text{with } d_L^{gw}(z) = d_L^{em}(z)\, \exp\left(-\int_0^z \frac{dz'}{1+z'}\delta(z')\right)$$

- Useful parametrisation:

$$\frac{d_L^{gw}(z)}{d_L^{em}(z)} = \Xi_0 + \frac{1}{(1+z)^n}(1-\Xi_0)$$



- Forecasts for next generation interferometers:
  - ▷ *ET+CE* [Belgacem, YD, Foffa, Howell, Maggiore, Regimbau (2019)]
  - ▷ LISA [LISA CosWG, Belgacem+ (2019)]



$\longrightarrow$ Improved prospects to test GR: $\Delta\Xi_0 = \Delta w_0/6$

$\longrightarrow$ New (multi-messenger) cosmic complementarity

$\longrightarrow$ $\#_{GW}\ /\ \#_{GW-GRB} = \mathcal{O}(10^2 - 10^4)$!

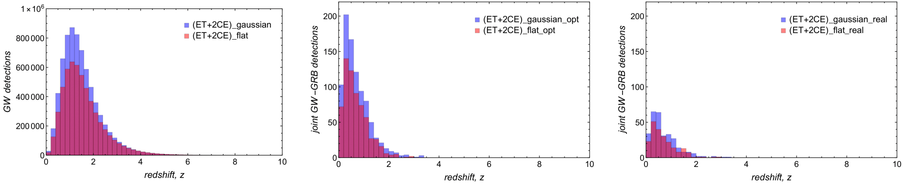
Number of BNS and BNS+GRB events

[Belgacem, YD, Foffa, Howell, Maggiore, Regimbau (2019)]

- For 10 years, for 2G+Fermi, (ET and ET+CE+CE) + full (1/3) THESEUS

Network	GW events	Joint GW-GRB events
HLVKI	814	15
ET	688,426	511 (169)
ET+CE+CE	7,077,131	907 (299)

- Redshift reach: ET: $z = 2 - 3$, +CE: $z \simeq 9$, +THESEUS: $z \simeq 3.4$



- Number of GW+GRB detections is orders of magnitude smaller than GW detections

  ⟶ GRB detector sensitivity is limited to smaller redshifts that GW detector threshold

  ⟶ GRB detection number "saturates": insufficient dedicated GRB/optical/IR telescopes

Future Perspectives

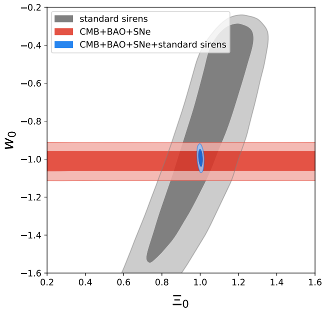
GW Luminosity Distance and Cosmic Inhomogeneities

- GW luminosity distance:

$$\tilde{h}_A \sim \frac{1}{d_L^{gw}(z)}\,, \qquad \text{with} \qquad d_L^{gw}(z) = d_L^{em}(z)\,\exp\left(-\int_0^z \frac{\mathrm{d}z'}{1+z'}\delta(z')\right)$$

- Useful parametrisation:

$$\frac{d_L^{gw}(z)}{d_L^{em}(z)} = \Xi_0 + \frac{1}{(1+z)^n}(1-\Xi_0)$$



- The dipole of d_L^{EM} measures $H(z)$ [Bonvin, Durrer, Kunz (2006)]

  $\longrightarrow$ How the dipole of d_L^{gw} measures $H(z)$ and $\delta(z)$?

  $\longrightarrow$ By how much do the (forecast) constraints improve?

- Effects of cosmic inhomogeneities

  $\longrightarrow$ How do linear FLRW perturbations affect d_L^{gw}?

Thank you!

[NASA APOD]