Modified gravity theories in the light of multi-messenger gravitational-wave astronomy

Celia Escamilla-Rivera
Instituto de Ciencias Nucleares (ICN-UNAM, Mexico)
Royal Astronomical Society (RAS, UK)

Cosmology from Home 2021

http://celrivera.wix.com/cosmology || celia.escamilla@nucleares.unam.mx

Goals

- The Universe is undergoing a late time acceleration. **Can this acceleration could be the consequence of gravitational leakage into extra dimensions on cosmological scales rather than the result of a non-zero cosmological constant?**

- The advancing gravitational wave multi-messenger astronomy opens a new era. **We investigate the capability of LIGO and LISA to probe modified gravity on large scales.**

Outline

- **The state-of-art:** Precision Cosmology vs Theories of gravity
- **The data:** on Gravitational Waves
- **The results:** Constraining theories of gravity using Precision Cosmology

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LCDM gravity model

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Data
(CMB, SN, BAO, GW, RSD…)

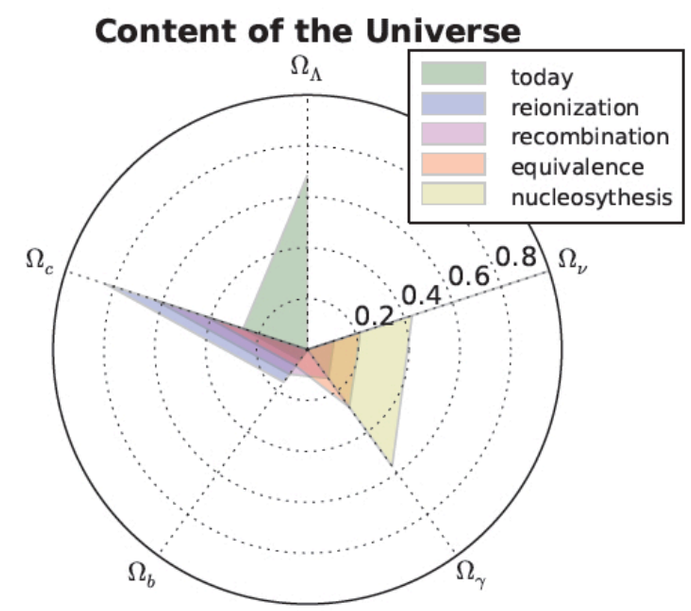
=

Inconsistency : Dark matter + Dark energy

Problems: H_0, and σ_8 tensions

New Physics?

Initial Conditions	Cosmic Structure	Late acceleration
Inflation	Dark Matter	Λ
Primordial GWs?	Ultra-light/Axion?	Modified Gravity?
	Primordial BHs?	



Three main roots to determining H_0

(1) **Distance ladder method**: Cepheids and TRGBs (calibrated to geometric anchor distances)

Improved: from 10% (2001) to < 2% (2019)

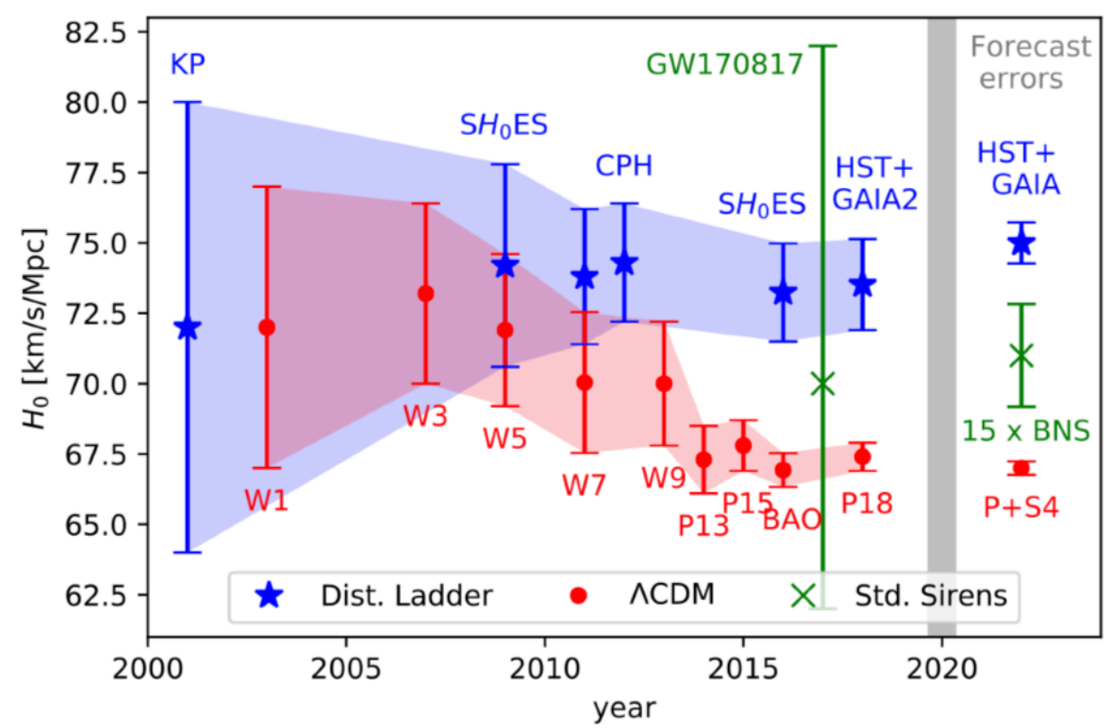
Value: $H_0 = 74.03 \pm 1.42$ km/s/Mpc

(2) **Via sound horizon observed from CMB**: not constrained directly. Using data at z ~ 1100 and extrapolated to z ~ 0, based on the physics of the early universe.

Value: $H_0 = 67.4 \pm 0.5$ km/s/Mpc

(3) **Standard sirens:** from merger events detected through GW (2017)

Value: $H_0 = 70^{+12}_{-8}$ km/s/Mpc



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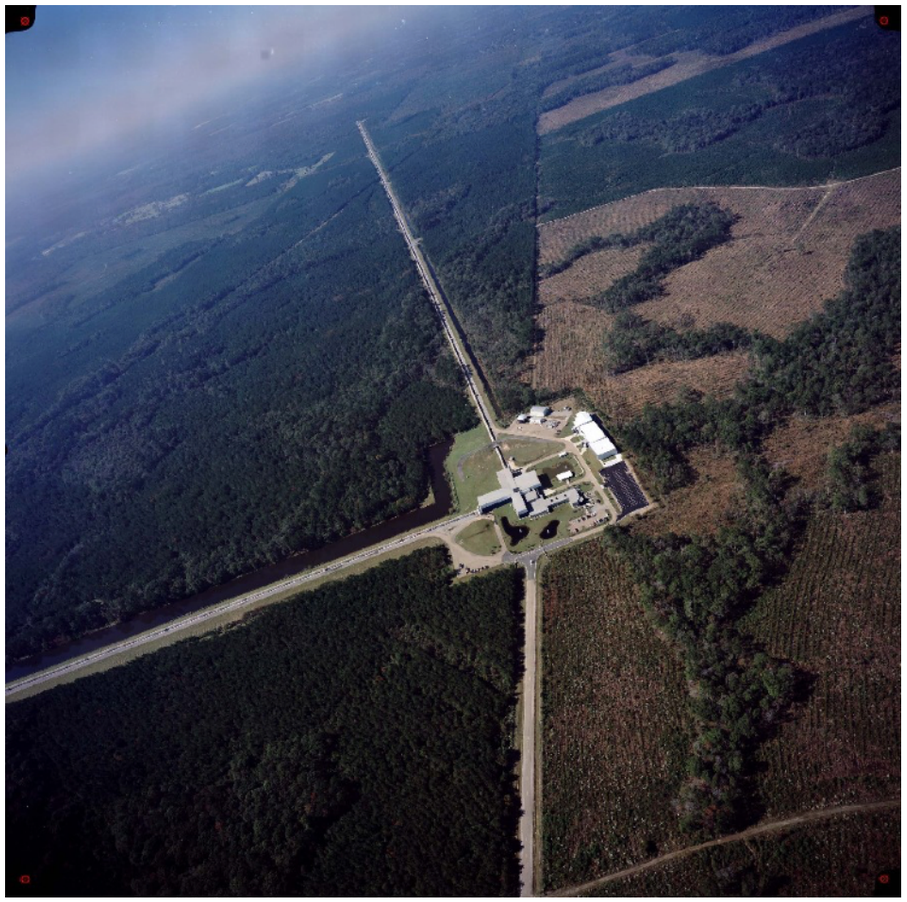
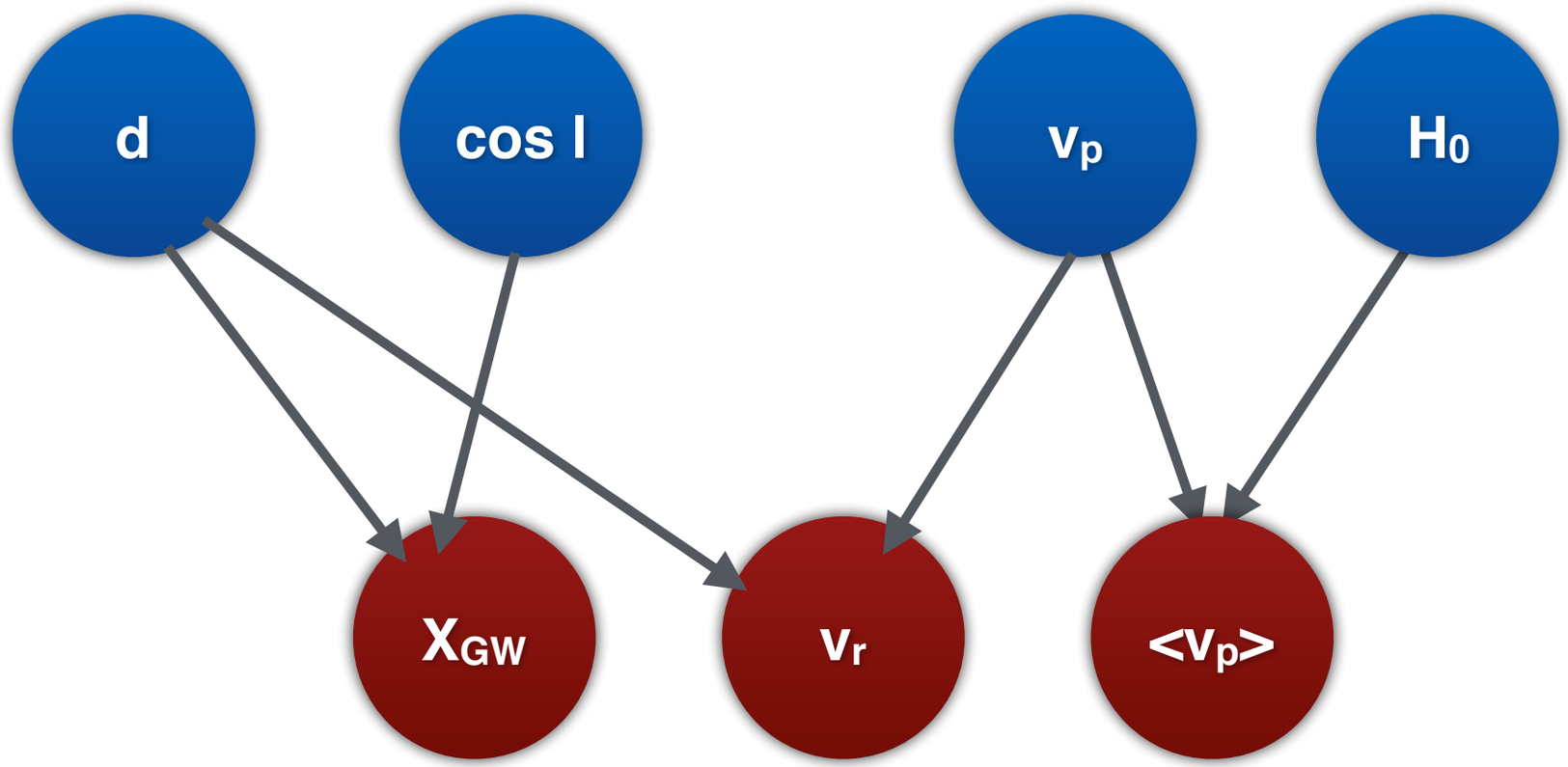
LSC LIGO Scientific Collaboration

LIGO VIRGO

NASA esa LISA Laser Interferometer Space Antenna

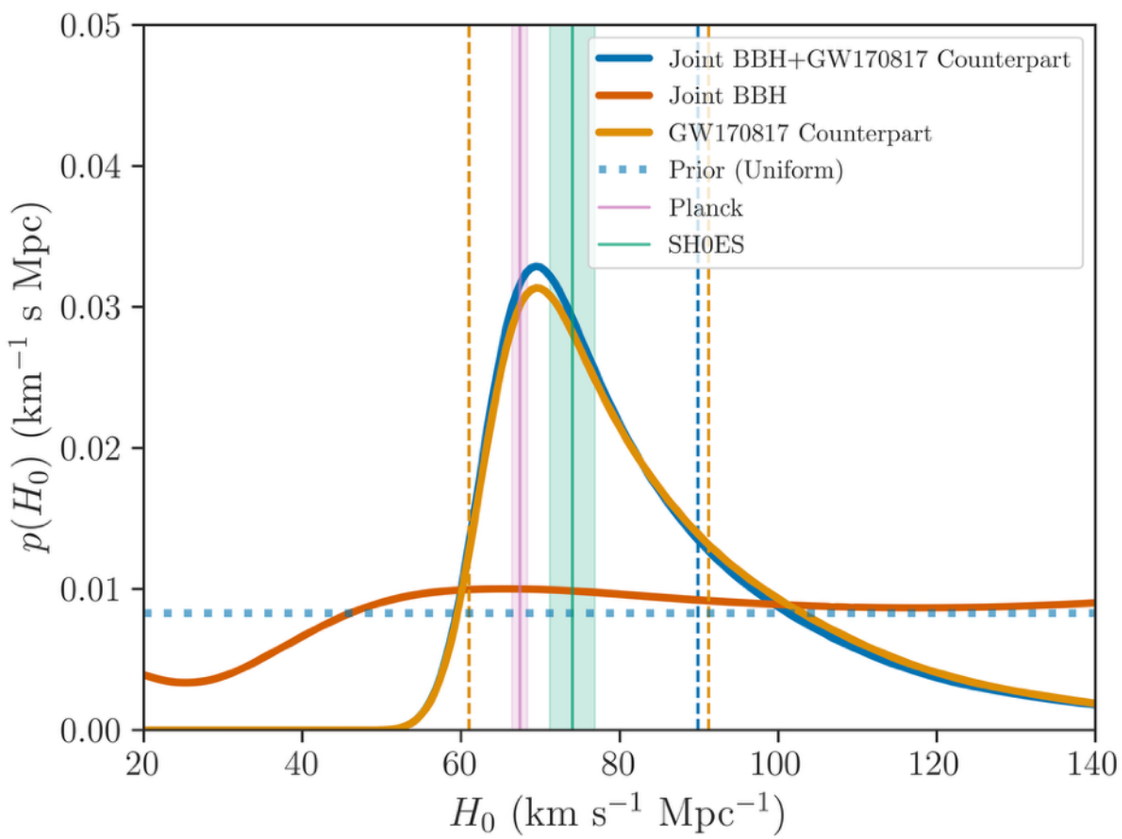


Novel measurements of H_0 : How we can compute H_0 from Standard Sirens?

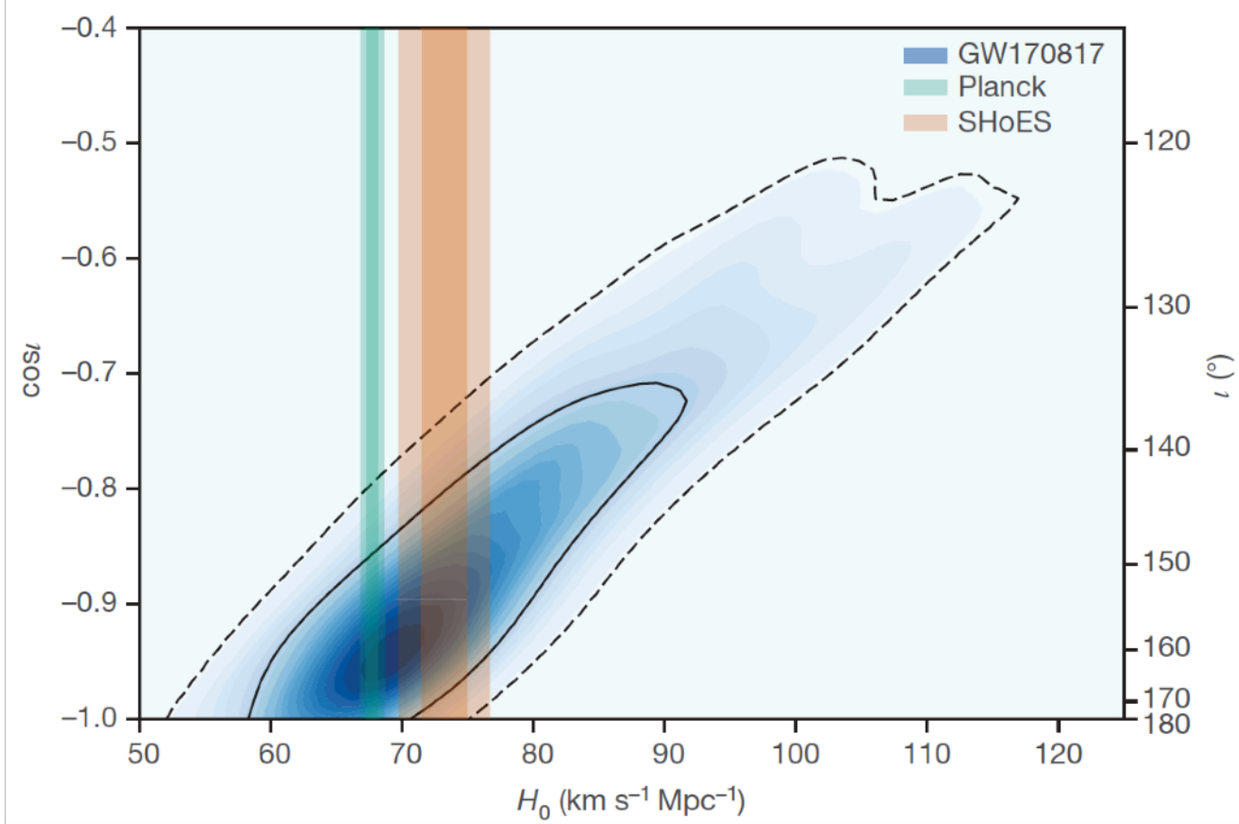


$$p(H_0, z, \cos\iota, v_p \mid x_{\rm GW}, v_r, \langle v_p \rangle)$$
$$\propto \frac{p(H_0)}{\mathcal{N}_{\rm s}(H_0)}\, p(x_{\rm GW} \mid d = cz/H_0, \cos\iota)\, p(v_r \mid z, v_p)$$
$$\times\; p(\langle v_p \rangle \mid v_p)\, p(z)\, p(v_p)\, p(\cos\iota),$$

Novel measurements of H_0 : How we can compute H_0 from Standard Sirens?



[LIGO-VIRGO. (2021)]



[LIGO-VIRGO. Nature 24471 (2017)]

Novel measurements of H_0 : Update of H_0 from Standard Sirens

- Modelling early data on the GRB170817 jet [Guidorzi et al 2017]

  Value: $H_0 = 74^{+11.5}_{-7.5}$ km/s/Mpc

- Late-time GRB170817 jet superluminical motion [Hotkezaka et al 2019]

  Value: $H_0 = 70.3^{+5.3}_{-5.0}$ km/s/Mpc

- Dark siren GW170814 BBH merger [Soares et al 2019]

  Value: $H_0 = 75^{+40}_{-32}$ km/s/Mpc

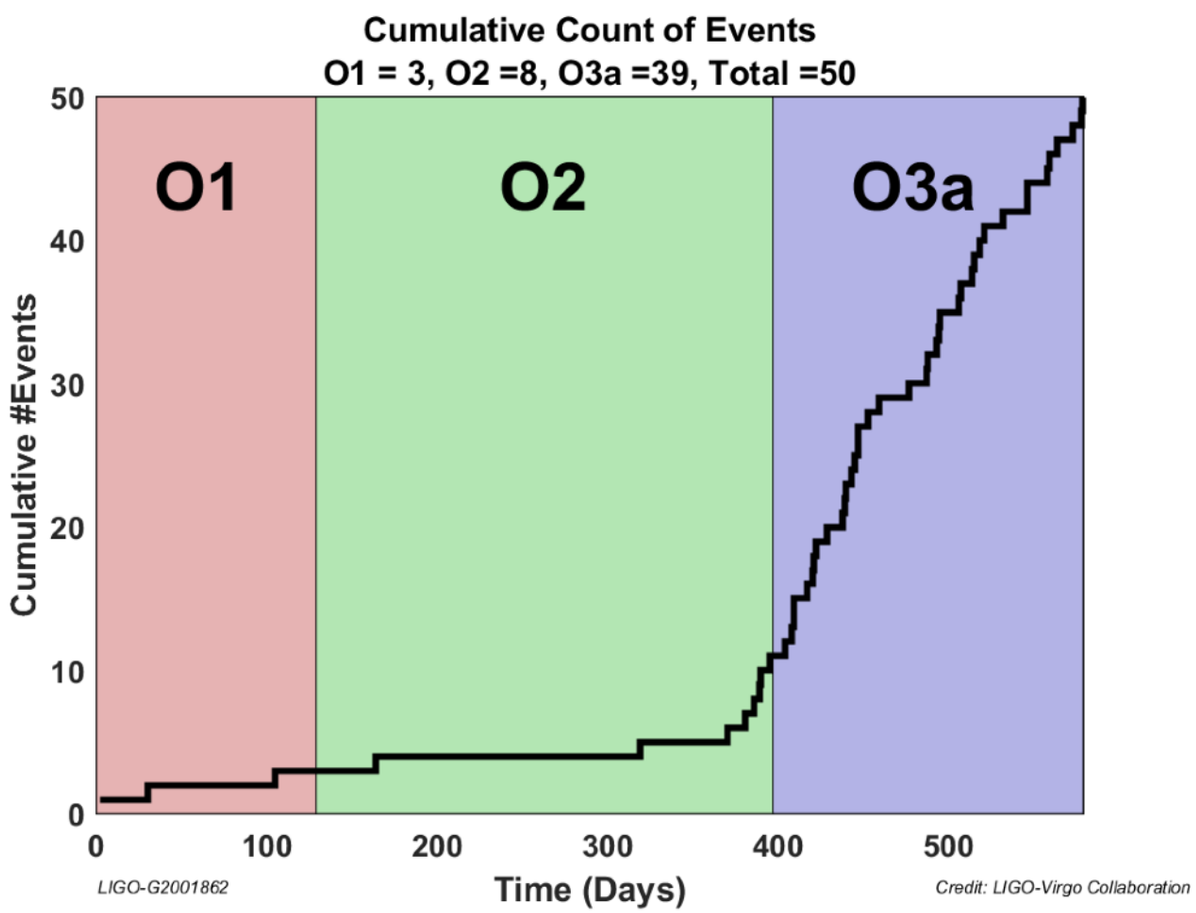
- GW170817 and 4 BBH from O1 and O2 [Abbott et al 2019]

  Value: $H_0 = 68^{+14}_{-7}$ km/s/Mpc

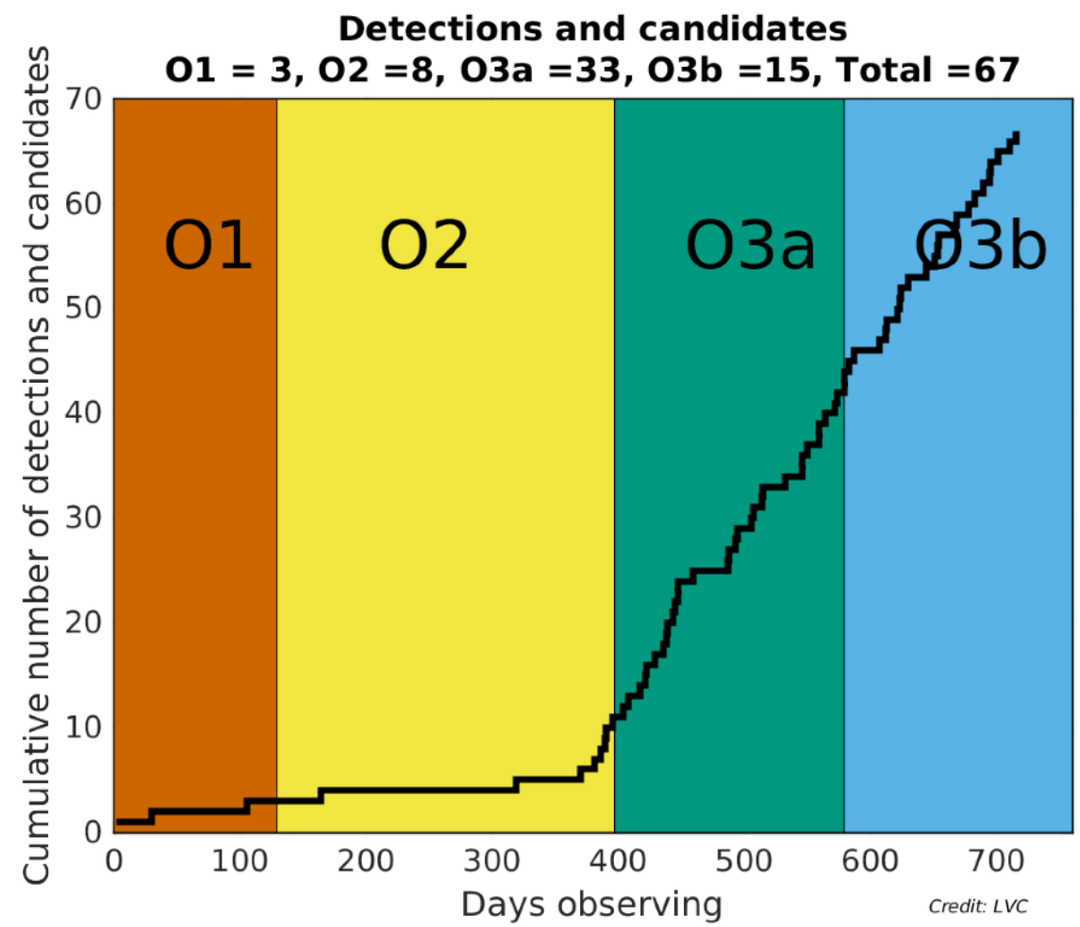
- GW190814 and GW170817 [Abbott et al 2020]

  Value: $H_0 = 70^{+17}_{-8}$ km/s/Mpc

(October 27 2020)



From Today (Nov 3 2020 ->)



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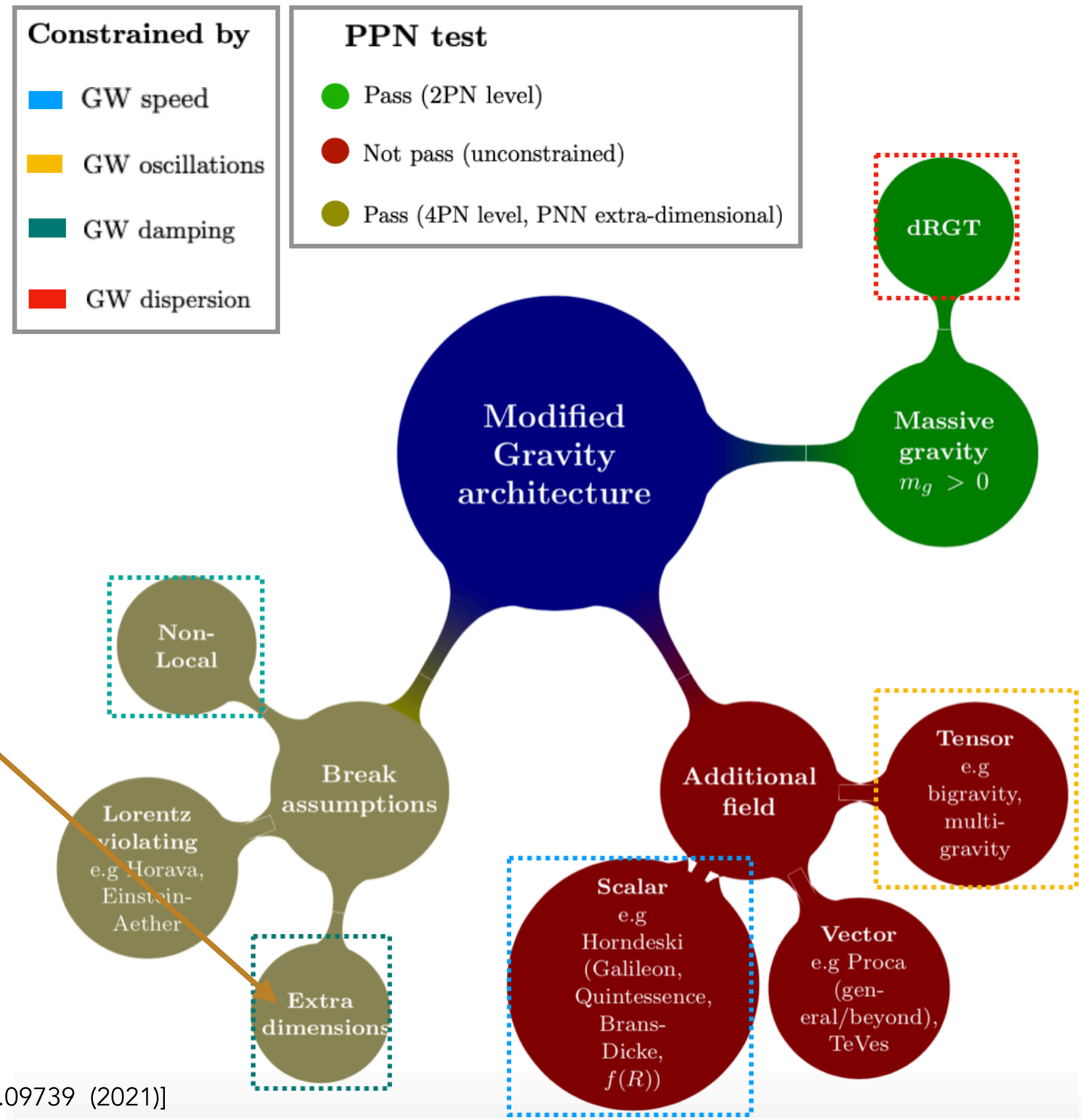


First target!

[**C. Escamilla-Rivera** and Júlio Fabris. 2005.09739 (2021)]

Our proposal: Modified Friedmann DGP gravity

$$H^2 + \frac{k}{a^2} = \left(\sqrt{\frac{\rho}{3M_{\rm P}^2} + \frac{1}{r_0^2}} + \epsilon\frac{1}{2r_0^2}\right)^2,$$

$$H^2(z) = H_0^2\left[\Omega_k(1+z)^2 + \left(\sqrt{\Omega_{r_0}} + \sqrt{\Omega_{r_0} + \Omega_M^0(1+z)^3}\right)^2\right].$$

Our method: Luminosity distances in higher dimensional theories with non-compact extra dimensions

Gravitational wave damping

$$h_{NGR} \propto \frac{1}{d_L^{GW}} = \frac{1}{d_L^{EM}\left[1 + \left(\frac{d_L^{EM}}{cR_c}\right)^n\right]^{(D-4)/2n}},$$

Supernovae (Pantheon)

$$\chi^2_{\mu(z)} = \sum_{i=1}^{N} \frac{\left[\mu_{\rm obs}(z_i) - \mu_{\rm DGP}(z_i;\Omega_M,\Omega_\Lambda,r_c)\right]^2}{\sigma^2_{\mu,i}},$$

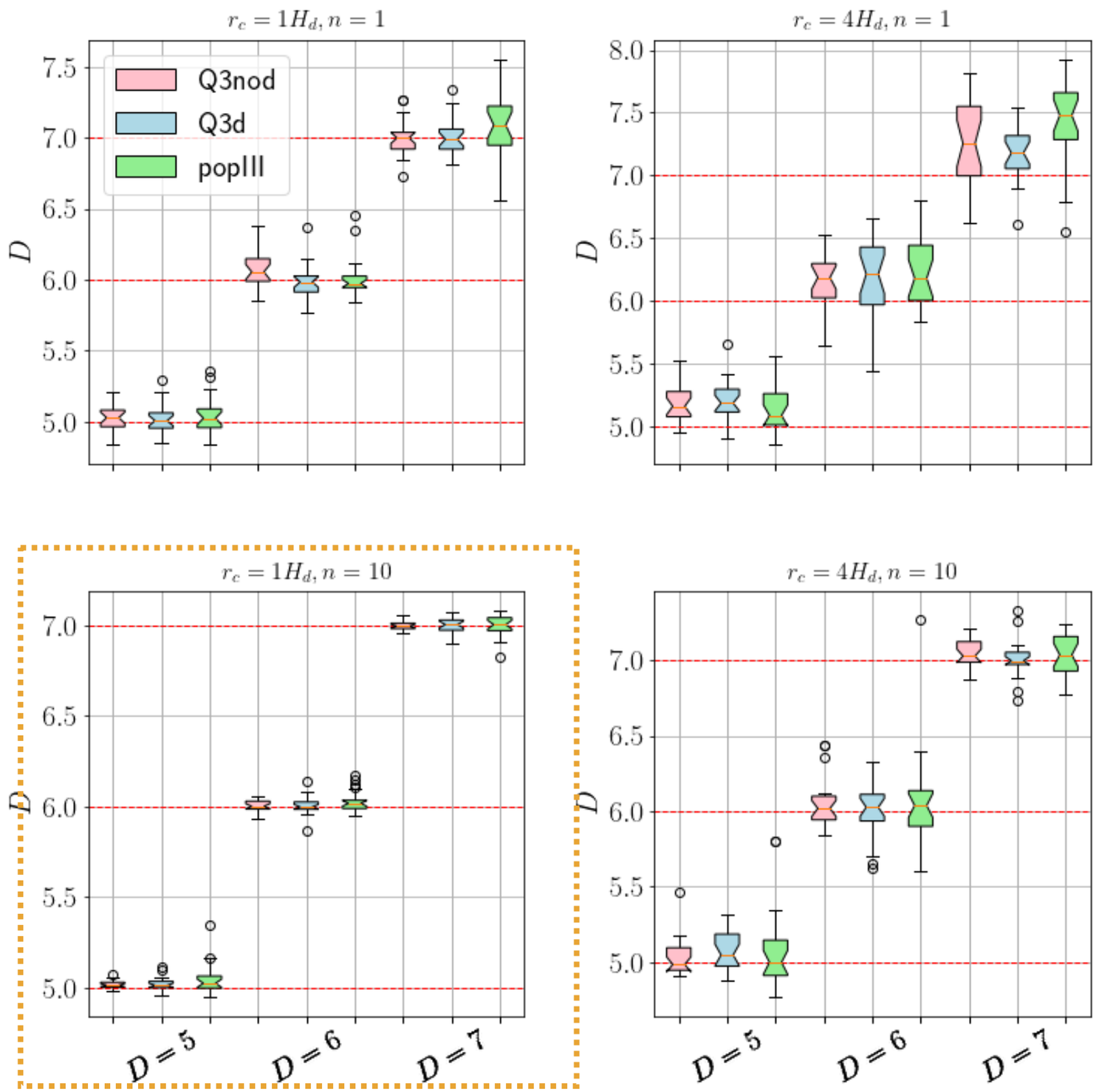
(1) **Model popIII**: A 'realistic' light-seed scenario in which the first massive BHs are assumed to form from the remnants of population III stars (popIII) and including a delay between the coalescence of MBHB host galaxies and that of the BHs themselves.

(2) **Model Q3d**: A 'realistic' heavy-seed scenario in which the first massive BHs are assumed to form from the collapse of protogalactic disks, also including delays.

(3) **Model Q3nod**: Same model as Q3d but ignoring delays, an assumption which significantly increases the BH merger rate. This model is thus considered to be an 'optimistic' scenario for LISA's observed merger rates.

Model	Total number	Δd_L (opt)	Δd_L (pess)
popIII	13.6	0.0929	0.139
Q3d	14.7	0.0645	0.122
Q3nod	28.3	0.0660	0.119

[M. Corman, **C. Escamilla-Rivera** and M. Hendry. JCAP (2020)]



$H_0 = 73.24 \pm 3.02$ km/s/Mpc

[M. Corman, **C. Escamilla-Rivera** and M. Hendry. JCAP02(2021)005

- **First step:** we have shown that standard sirens observed with LISA in the redshift range $1 < z < 8$ have the potential to test higher-dimensional theories.

- **Second step (soon to be released):** GW higher dimensions (LISA).

  M.Corman, A. Ghosh, C. Escamilla-Rivera, S. Marsat, M. Hendry, N. Tamanini

Thanks for your kind attention!

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