Probing modified gravity theories and cosmology using gravitational-waves and associated electromagnetic counterparts

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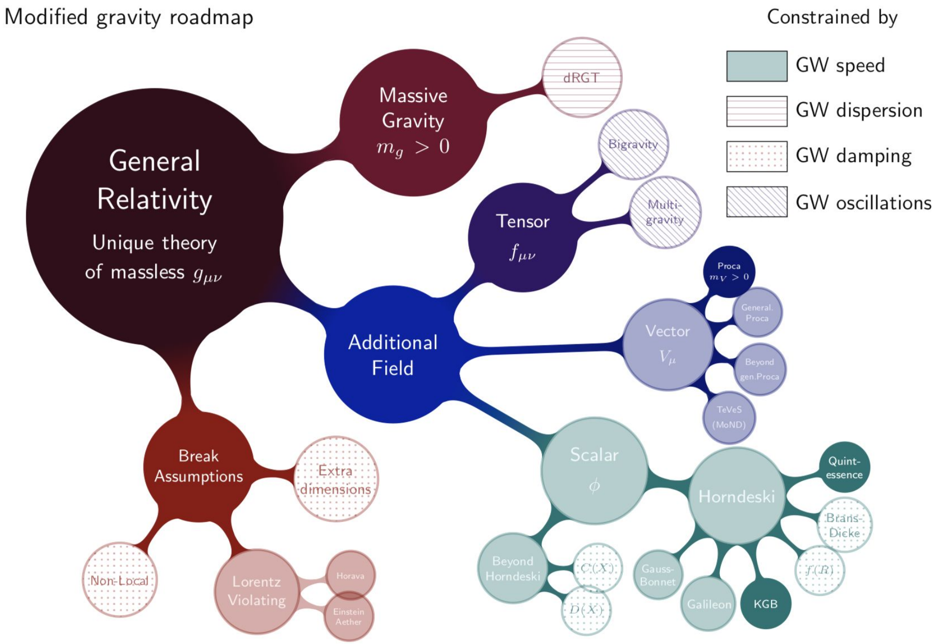
Based on:
SM+, Phys. Rev. D 102, 044009 (2020)
SM+ *JCAP02(2021)043*
LVK+, arXiv 2111.03604 (Accepted ApJ)

Why do we want to test GR on cosmological scales?

- Alternative GR theories are possible solutions to open issues in Standard cosmological model, e.g. dark energy, Hubble constant tension.
- We want to understand how Standard Cosmology parameters mix to GR deviation parameters.



J. M. Ezquiaqa+, Front. Astron. Space Sci. 5:44 (2018)

Why do we want to test GR on cosmological scales?

$$h'' + 2[1 + \alpha_M(\eta)]\frac{a'}{a}h' - c_T \nabla^2 h = 0$$

GW friction **Dispersion relation**

Dispersion relation:

- GWs group velocity depends on the frequency.
- GWs modes arrive off-phased at the detector.
- GWs modes show a time delay w.r.t EM counterparts.

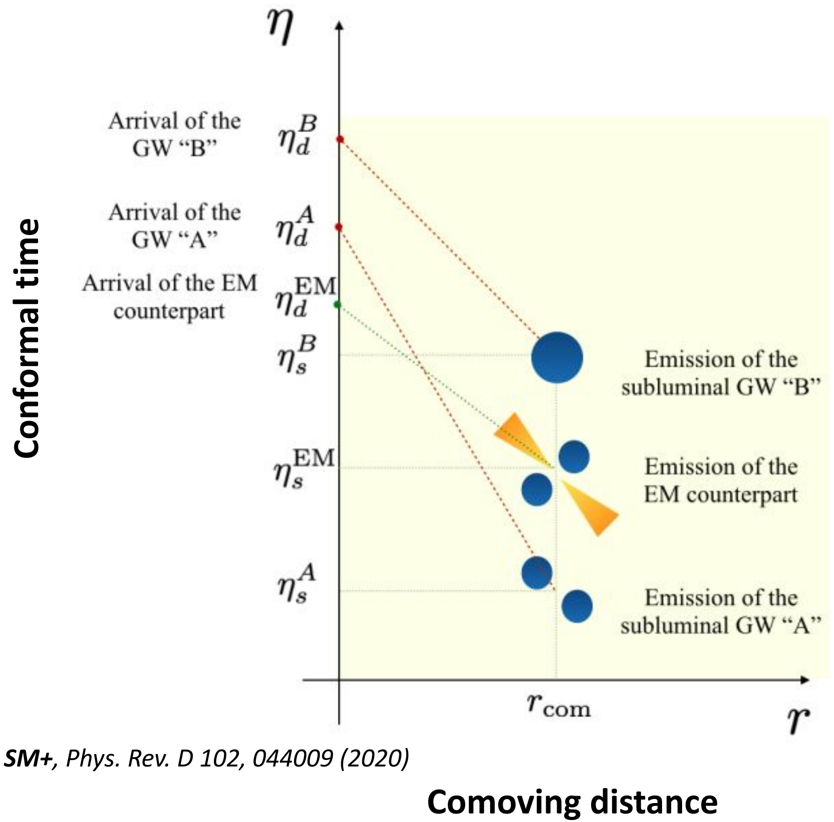
Horava gravity, massive gravity, scalar tensor theories with field derivative couplings

GW friction:

- GWs show an additional energy leakage as they travel.

extra energy dissipation terms, e.g. a running Planck mass, 4+n dimensional gravity, scalar-tensor theories

Why do we want to test GR on cosmological scales?



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GW friction:

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Observables for GR modifications

EM distance

GW friction

The GW luminosity distance

$$d^{\mathrm{GW}}(z) = d_{\mathrm{EM}}(z)\exp\left[\int_0^z \frac{\alpha_M(z)}{1+z}dz\right]$$

GW-GRB Prompt delay

GW Peak frequency

Mode-delay

$$\mathcal{T}_j = \int_0^{z_s} dz' \hat{\alpha}_j(z) \frac{(1+z')^j}{H_0 E(z')}$$

GW-GRB time delay

$$\Delta t_d^{\mathrm{GW-EM}} = (1+z_s)\Delta t_s^{\mathrm{GW-EM}} + \frac{f_{R,d}^j}{2}\mathcal{T}_j$$

Measured PN coefficient

GR PN coefficient

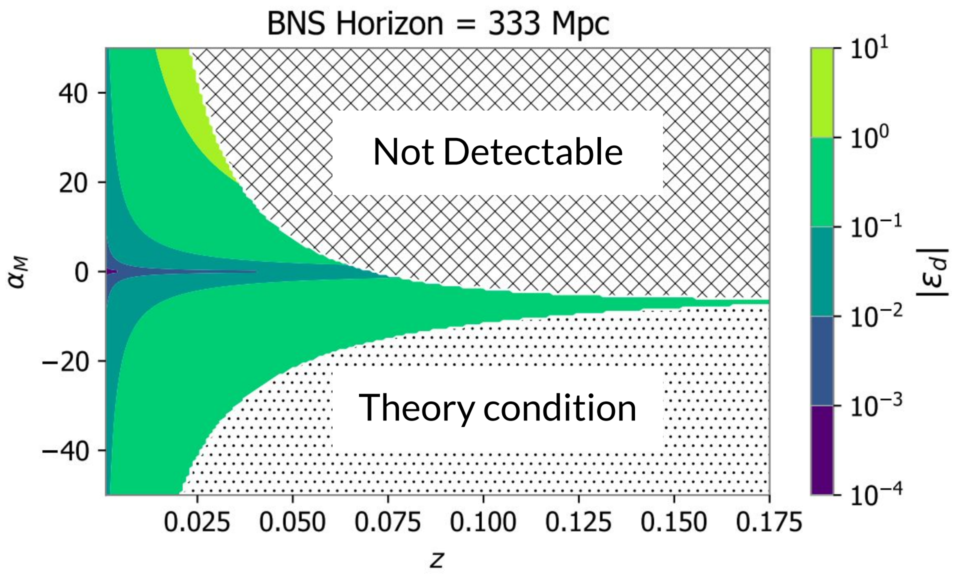
GW Phase modes

$$\frac{\psi_{3j+8}(f_d) - \psi_{3j+8,\mathrm{GR}}(f_d)}{\psi_{3j+8,\mathrm{GR}}(f_d)} = \pi \frac{\mathcal{T}_j}{\beta_{3j+8}^{\mathrm{PN}}(j+1)},$$

Observables for GR modifications

$$\epsilon_d \equiv \frac{d_{\rm GW} - d_{\rm EM}}{d_{\rm EM}} = \exp\left[\int_0^{z_s} \frac{\alpha_M(z)dz'}{1+z'}\right] - 1$$

- Modifications to GR have a stronger impact at higher redshift.
- GR modifications can be potentially excluded using events at higher redshift.
- Some GR modifications introduce a strong selection bias.



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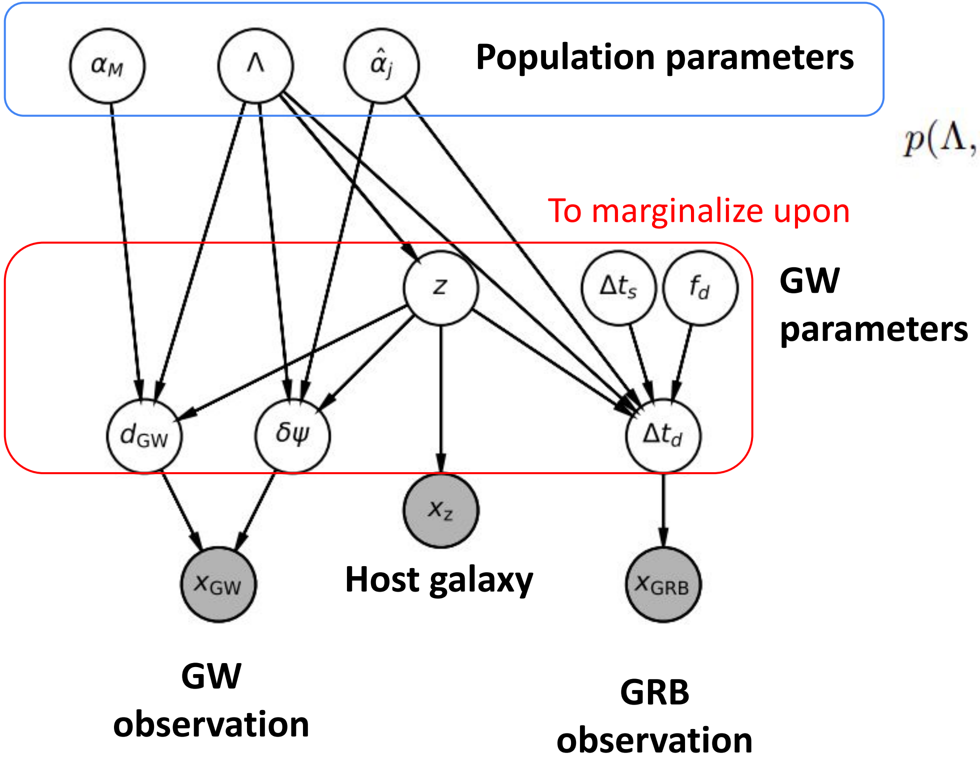
Observables for GR modifications: Statistics



SM+, *Phys. Rev. D 102, 044009 (2020)*

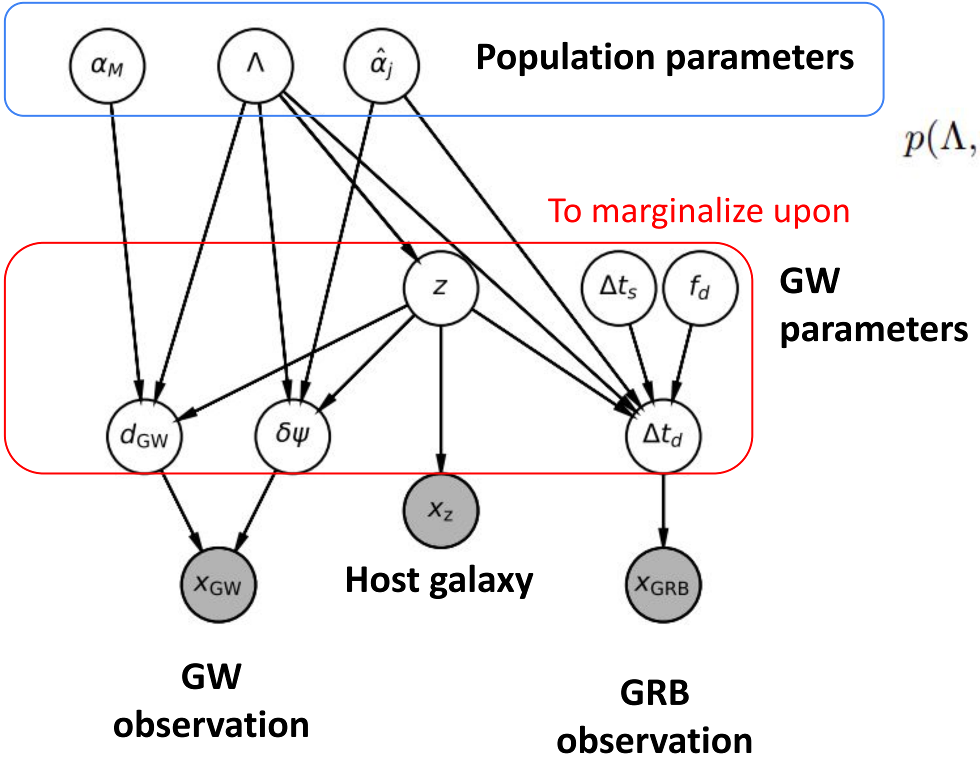
The Likelihood

$$p(\Lambda, \alpha_M, \hat{\alpha}_j|\vec{x}) = p(\alpha_M)p(\Lambda)p(\hat{\alpha}_j) \int p(\Delta t_s)p(f_d)p(z|\Lambda) \cdot \\ \cdot \frac{p(d_{\rm GW}(\alpha_M,\Lambda,z),\delta\psi(\hat{\alpha}_j,\Lambda,z)|x_{\rm GW})}{\pi(d_{\rm GW}(\alpha_M,\Lambda,z),\delta\psi(\hat{\alpha}_j,\Lambda,z))} \frac{p(z|x_{\rm z})}{\pi(z)} \cdot \\ \cdot \frac{p(\Delta t_d(\hat{\alpha}_j,\Lambda,\Delta t_s,f_d,z)|x_{\rm EM})}{\pi(\Delta t_d(\hat{\alpha}_j,\Lambda,\Delta t_s,f_d,z))} dz df_d d\Delta t_s. \quad (53)$$

The selection bias

$$\beta(\Lambda, \alpha_M, \hat{\alpha}_j) = \int P^{\rm GW}_{\rm det}(z, \Lambda, \alpha_M, \hat{\alpha}_j) P^{\rm z}_{\rm det}(z) p(z|\Lambda) \\ P^{\rm GRB}_{\rm det}(z, \Lambda, \hat{\alpha}_j, f_d, \Delta t_s) p(f_d) p(\Delta t_s) dz df_d d\Delta t_s. \quad ($$

Observables for GR modifications: Statistics



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Very complicated analysis from a statistical point of view!

Take home messages:

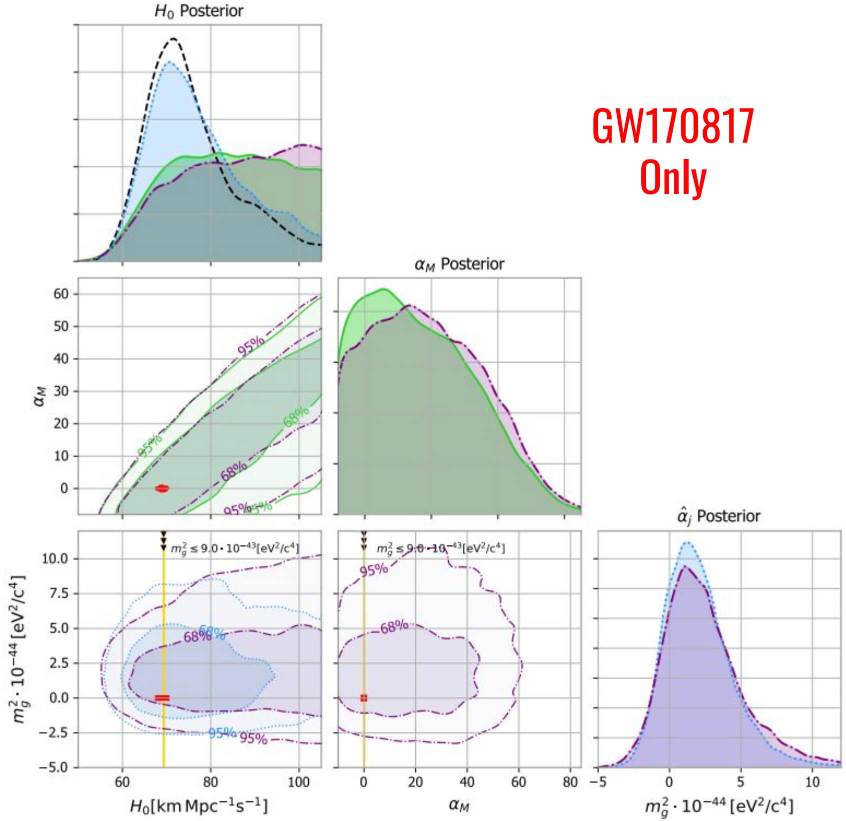
- We take the luminosity distance and phase studies of the GW.
- We take the measure of the time delay of the GRB.
- We take the redshift of the hosting galaxy.

Tests of GR in light of GW170817 and GW190521

- A BNS merger at ~40 Mpc.
- The identified hosting galaxy, NGC4993, is located at redshift ~0.01.
- GW arrived 1.74s before its associated GRB.

- A BBH merger at ~3 Gpc (giving birth to an IMBH).
- ZTF19abanrhr is an AGN flare associated with the merger of the two BBHs in an accretion disk.
- AGN redshift reported 0.438.

Tests of GR in light of GW170817 and GW190521



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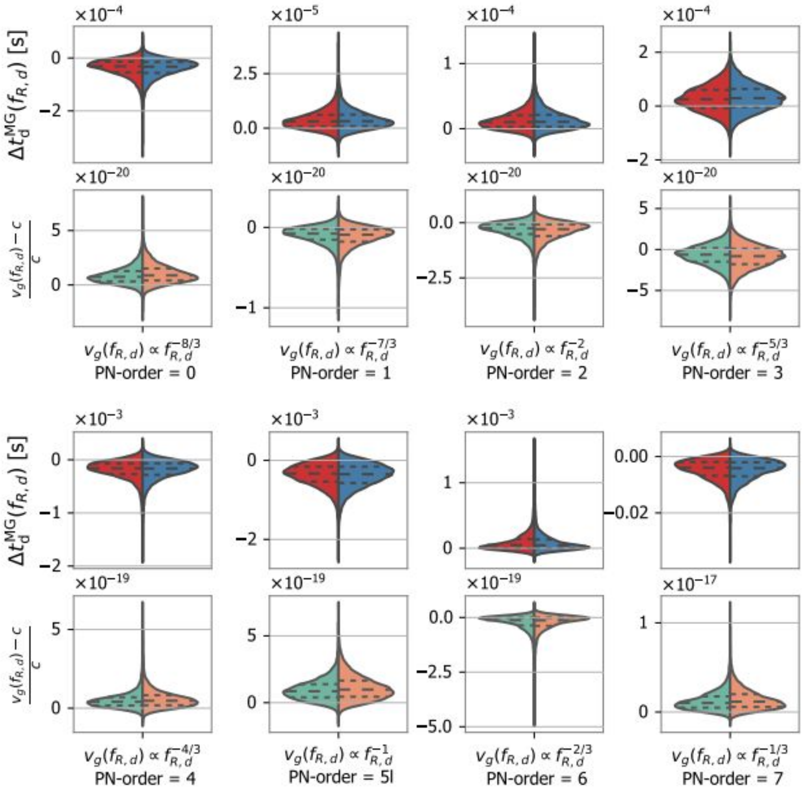
GW170817
Only

- GW damping term is not strongly constrained since GW170817 is a closeby event.
- Hubble constant strongly degenerate with the GW damping term: terms degenerate for the GW/EM luminosity distance.
- Graviton mass is not correlated with Hubble constant and damping term: GW phase is measured very well.

Tests of GR in light of GW170817 and GW190521



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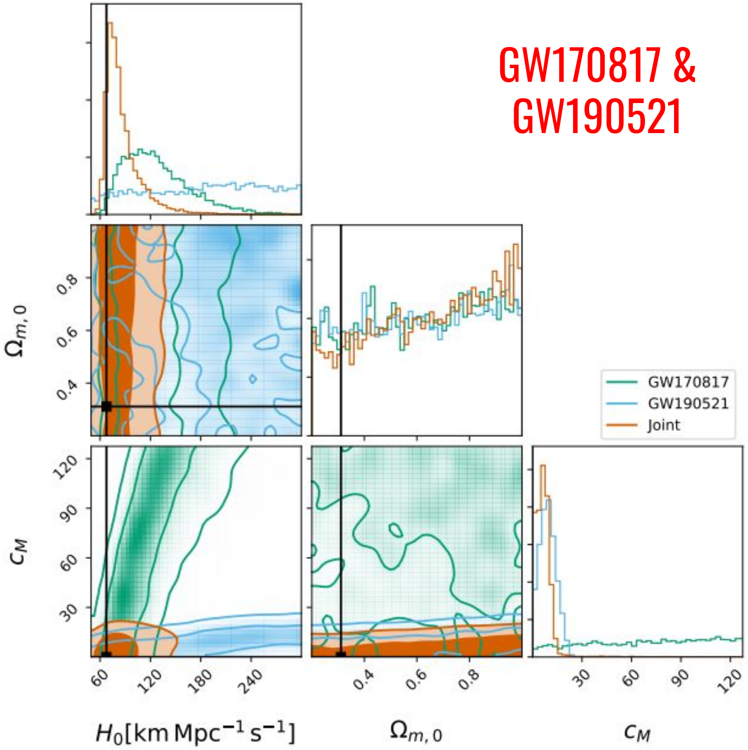
GW170817
Only

- The GW phase (PN orders) set a very tight constraint on the GW dispersion and speed of gravity.
- From the GW phase we can see that the speed of gravity (at merger) is constrained at 10^{-20} level.
- GW-GRB time delay can improve these constraints only if we time it with a precision of ten microseconds.

Tests of GR in light of GW170817 and GW190521

SM+ *JCAP02(2021)043*



- Including another GW event (GW190521), allows us to constrain conjointly GW damping and cosmology.
- GW190521 bring a good constraint for the GW damping since it is a far event.
- Unfortunately this event is poorly understood and its EM counterpart association is not confirmed.

Constraining GR with a population of Bright sirens

- We generate BNSs uniformly distributed in the comoving volume.

- We assume a Universe where GWs have a small GW friction and dispersion term (massive graviton of 10^{-22} eV/c^2).

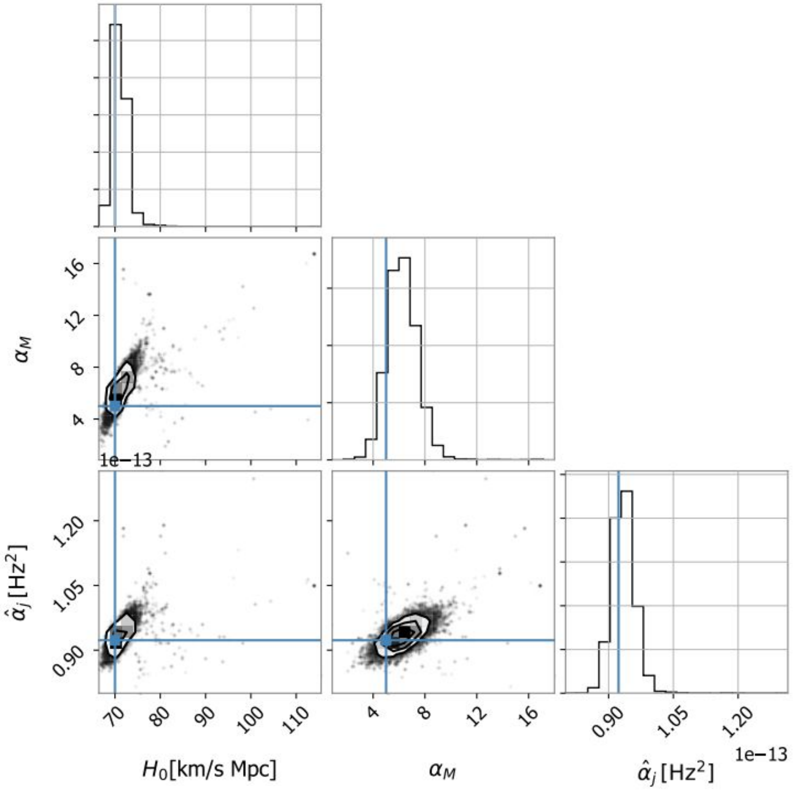
- We assume that the GW-GRB prompt time-delay is uniform between -10 and 10 s.

- We consider detected only bright sirens merging below a **GW luminosity distance** 100 Mpc.

- We assume some measured quantities:

    - GW luminosity distance estimated with 10% uncertainty.
    - GW-GRB time delay estimated with 0.05 s uncertainty.
    - GW phase measured with a precision of 10%.
    - Redshift perfectly known from spectroscopy.

Constraining GR with a population of Bright sirens



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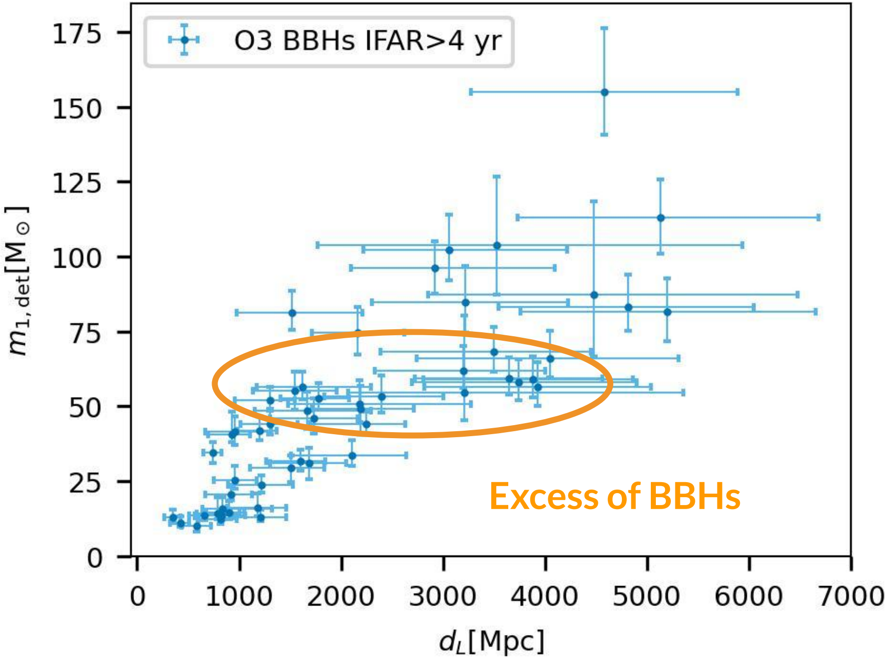
- Simulation with 100 BNSs with observed EM counterpart (redshift known).
- We use GW170817-like error budgets for luminosity distance, GW phase and GW-GRB time delay.
- Cosmological background parameters and modifications of GR will be correlated!

Potentially, if you estimate the graviton mass with a wrong H0 value, you might get a bias.

Where are we now? Many BBHs

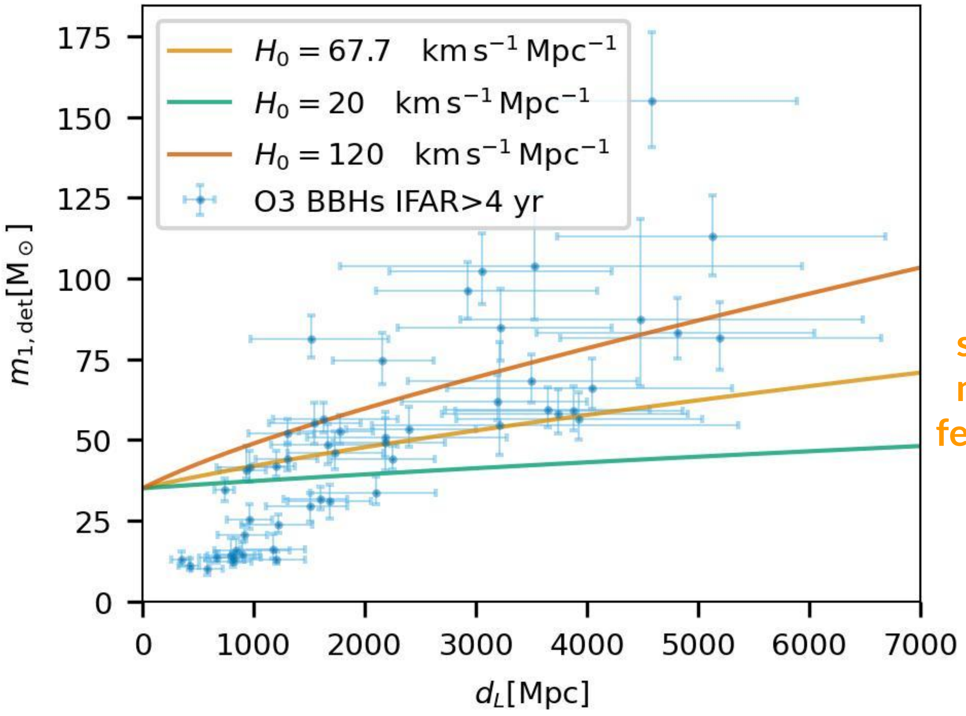
- Many GW are detected with large sky localizations and are very far (galaxy catalogs highly incomplete).
- If BBHs are *preferentially* produced at a given mass, we can exploit the mass-redshift relation to assign a redshift to the GW source *[SM+, PRD 104 (2021)]*.

$$m_{1,\mathrm{det}} = m_{1,\mathrm{s}}(1+z)$$



Where are we now? Many BBHs

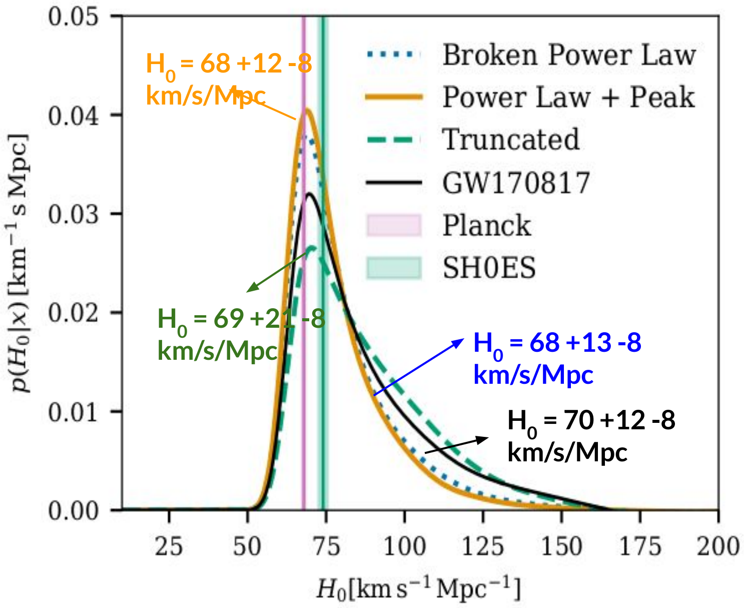
- If we assume an overdensity of BBHs produced at 35 solar masses, some “extreme” cosmologies can not fit the overdensity of BBHs.



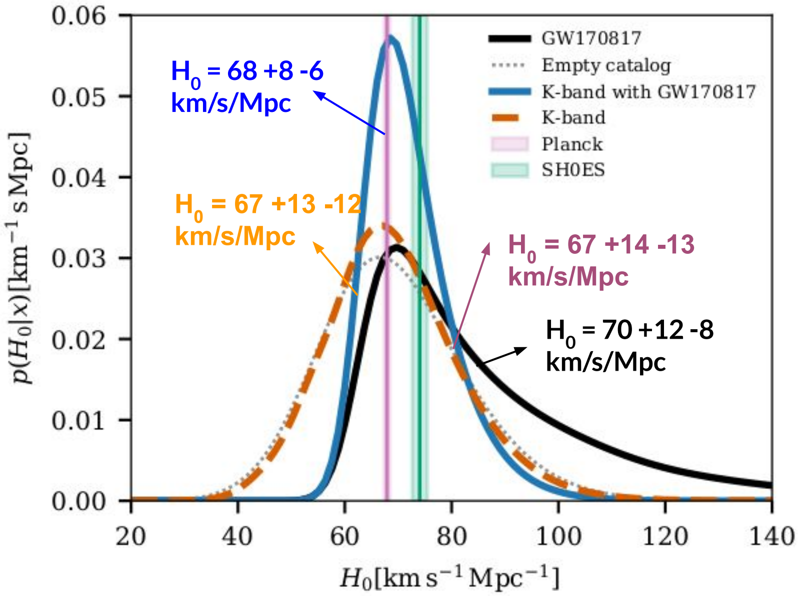
35 solar mass feature

Where are we now? Many BBHs

Spectral sirens



Dark sirens (galaxy catalogs)

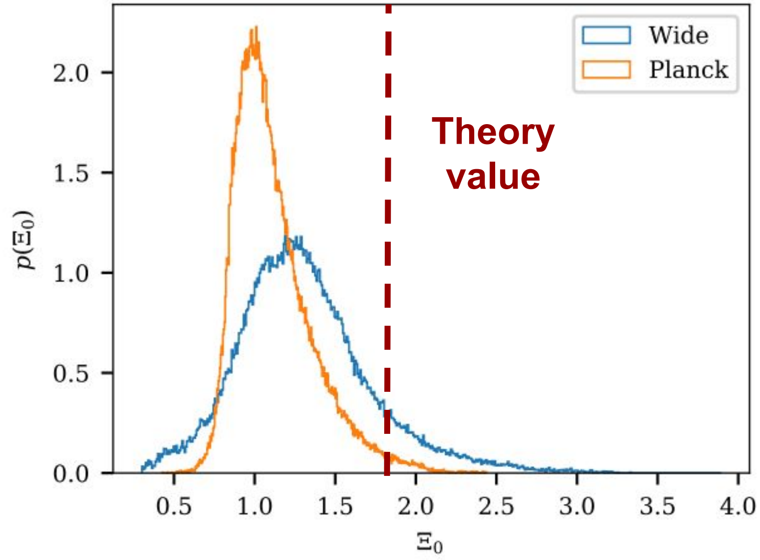


[LVK+, arXiv 2111.03604 (Accepted ApJ)]

Where are we now? Many BBHs

- Spectral sirens can also be used to to test GW friction.

- Using 42 BBHs from GWTC3 we constrain modifications of GR close to their theoretical expectation value.



K. Leyde, SM+, JCAP09 (2022)

Constraining GR with a population of Bright sirens

- Bright standard sirens are a fundamental tool to probe cosmology and modifications of gravity.
- It is important to infer conjointly the Standard cosmological model and modifications of gravity when using GW sources.
- 100 Bright sirens can potentially break the Hubble constant tension and provide stringent constraints on the graviton mass (though BBHs are better).
- Future development to include possible selection biases on the EM side are needed.
- Spectral and dark siren are still a good alternative to probe cosmology.

Thank you for the attention