Tests of general relativity and cosmology with gravitational waves

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with
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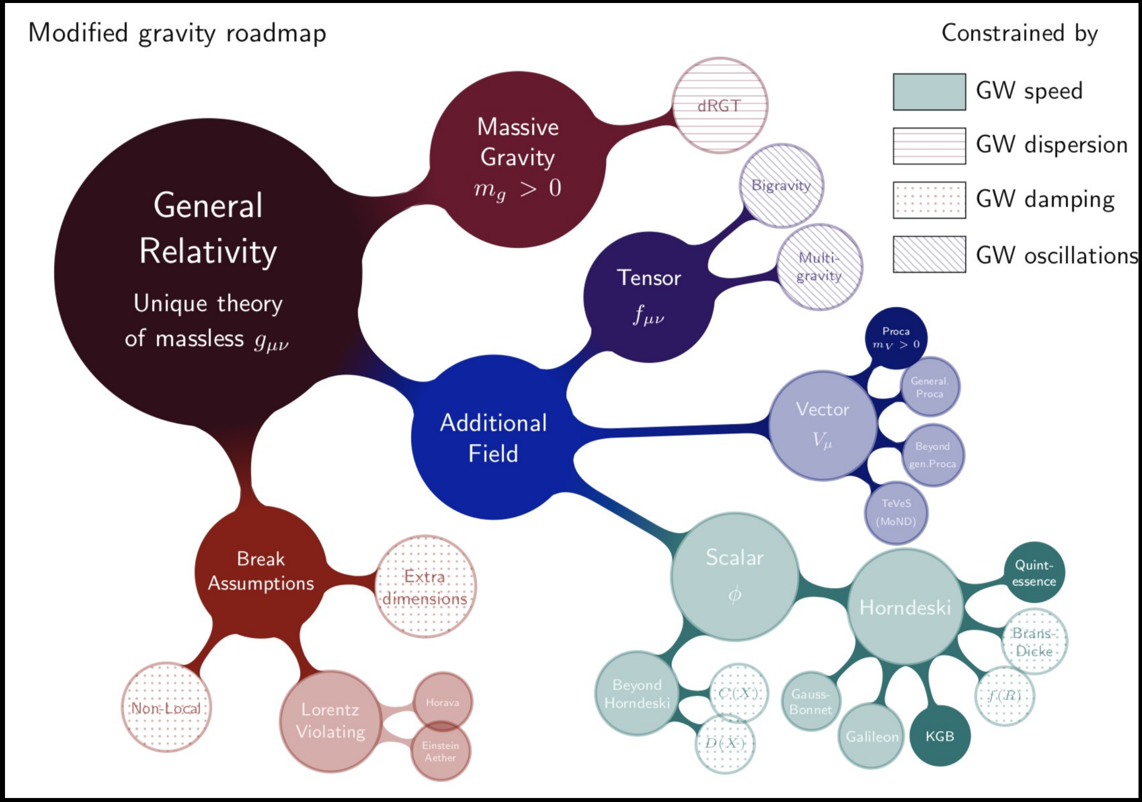
Based on:

***S. Mastrogiovanni+**, Phys. Rev. D 102, 044009 (2020)*
***S. Mastrogiovanni+**, arXiv 2010.04047 (2020)*

The search motivations

Why are we interested in modified theories of gravity at cosmological scales?

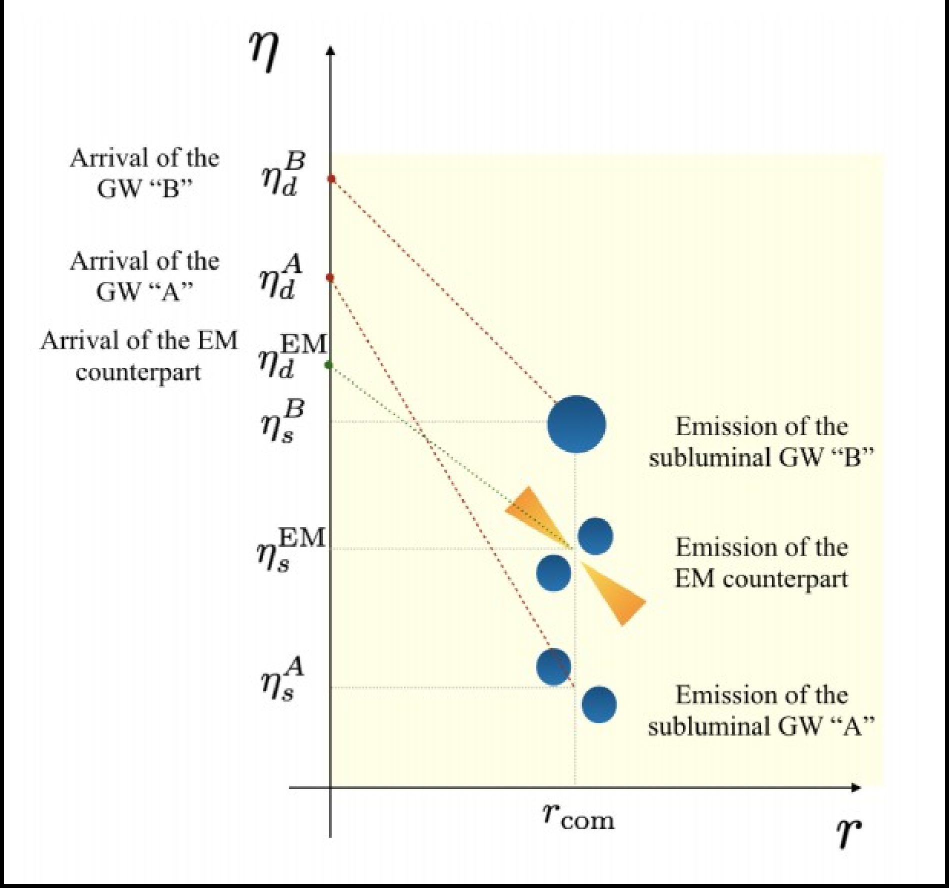
- Alternative GR theories are possible solutions to open issues in Standard cosmological model, e.g. dark energy, Hubble constant tension.
- We want to understand how Standard Cosmology parameters mix to GR deviation parameters.



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

GR modifications and observables

Gravitational waves standard sirens offer a unique opportunity for probing cosmology on large scales.



Dispersion relation: GWs group velocity depend on their frequency.

- GWs modes arrive off-phased at the detector.
- GWs modes show a time delay w.r.t EM counterparts.

GW friction: GWs show an additional energy leakage as they travel.

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

GR modifications and observables

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

***R. A. Baytte**, Phys. Rev. D 98, 023504 (2018)*

***A. Nishizawa**, Phys. Rev. D 97, 104037*

Friction term: predicted by theories with extra energy dissipation terms, e.g. a running Planck mass, 4+n dimensional gravity, scalar-tensor theories.

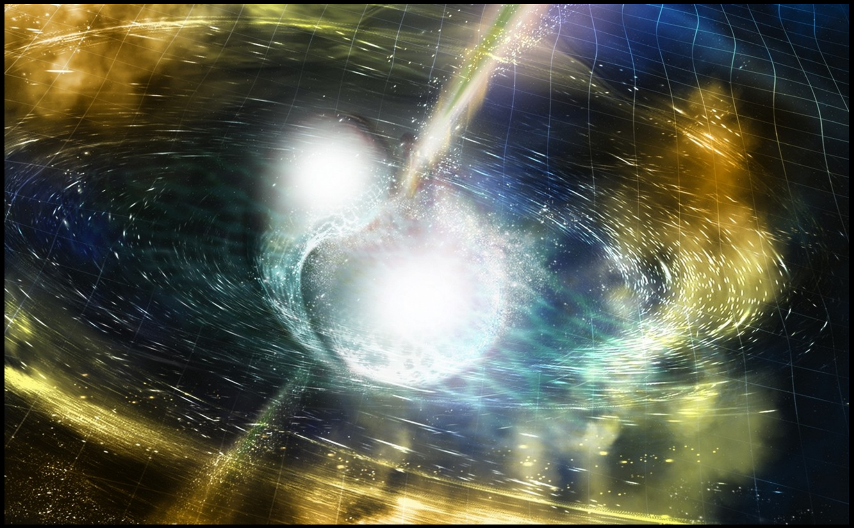
The friction term modifies the GW luminosity distance

Dispersion relation: Horava gravity, massive gravity, scalar tensor theories with field derivative couplings etc.

The dispersion relation introduces GWs modes different phases and a time delay with respect to an EM counterpart

Two exceptional events for the measurement

GW170817 and NGC4993



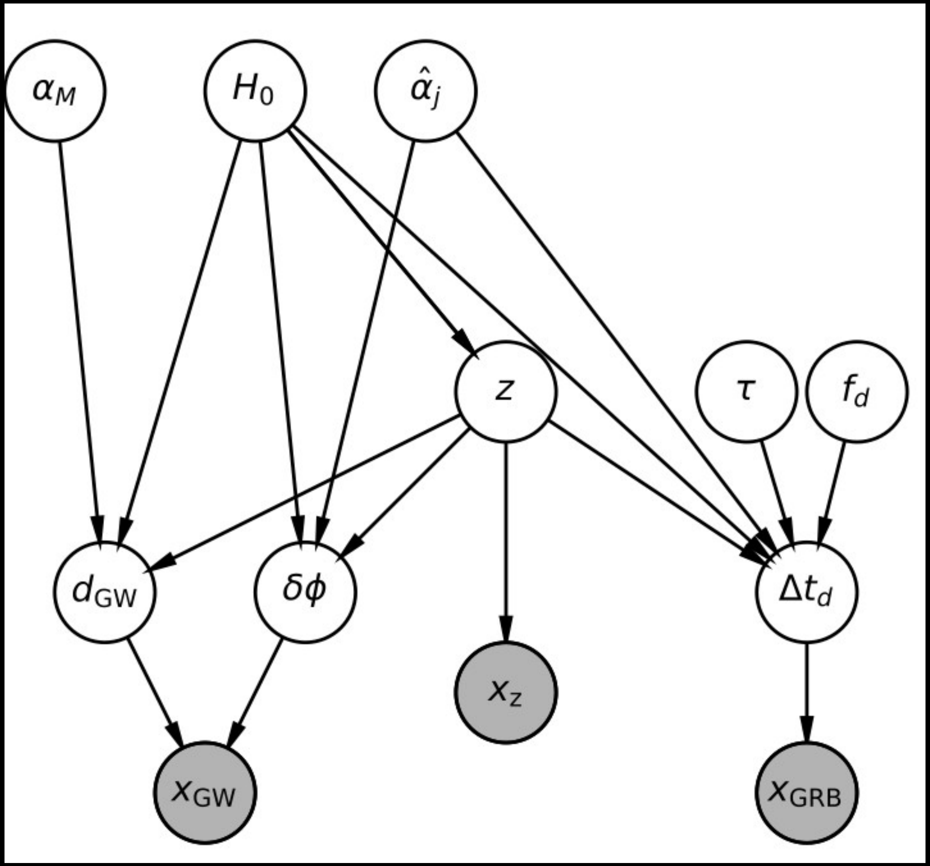
- A BNS merger at ~40 Mpc.
  ***B. P. Abbott**, Phys. Rev. Lett. 119, 161101(2017)*
- The identified hosting galaxy, NGC4993, is located at redshift ~0.01.
  ***B. P. Abbott+**, Nature volume 551, pages85–88(2017)*
- GW arrived 1.74s before its associated GRB.
- LIGO and Virgo provides also GW phase studies.

GW190521 and ZTF19abanrhr

- A BBH merger at ~3 Gpc (giving birth to an IMBH).
  ***R. Abbott+**, Phys. Rev. Lett. 125, 101102 (2020)*
- ZTF19abanrhr is an AGN flare associated with the merger of the two BBHs in an accretion disk. ***M. J. Graham+**, Phys. Rev. Lett. 124, 251102 (2020)*
- AGN redshift reported 0.438.

Provided by posterior samples we can compute the new inference by factorising the Bayesian network.

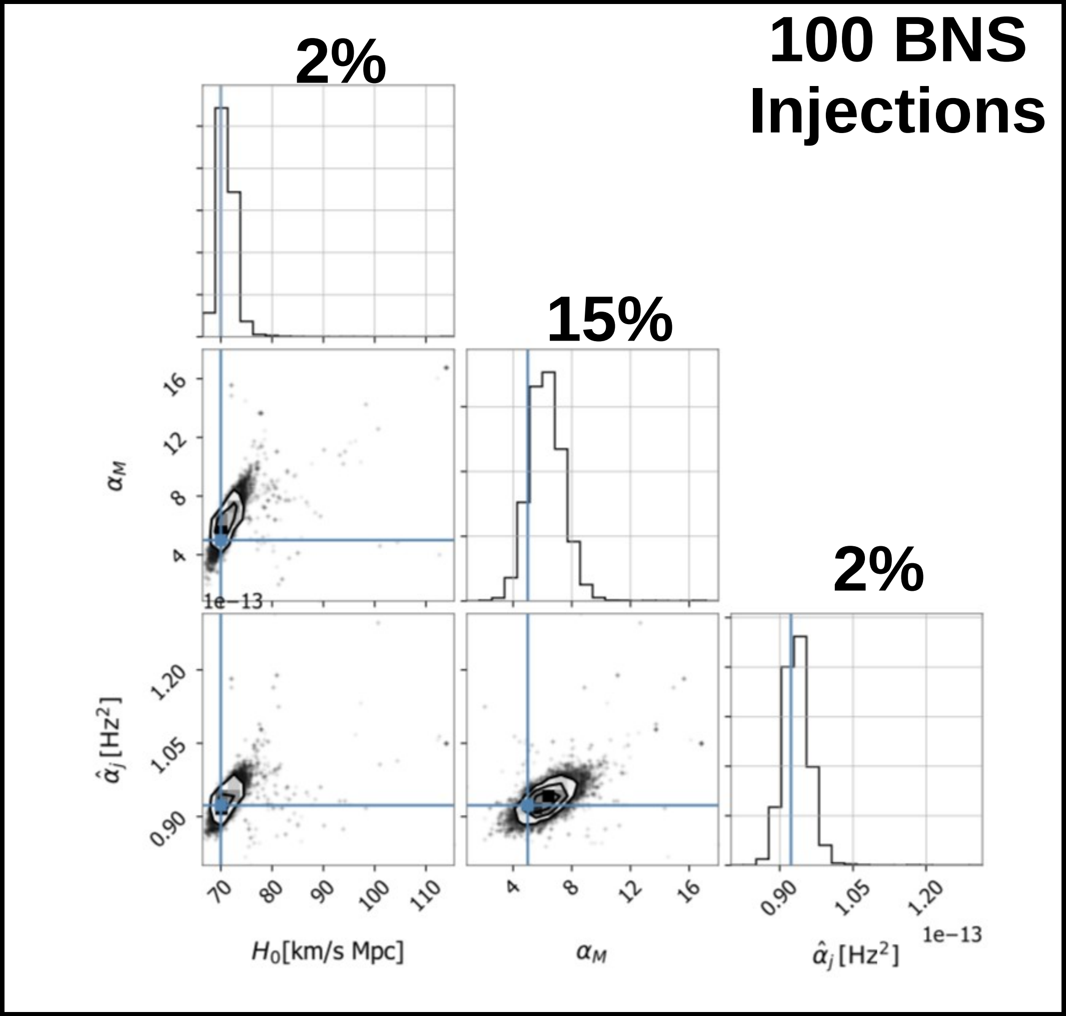
$$p(H_0, \alpha_M, \hat{\alpha}_j, \tau|\vec{x}) = \frac{p(\alpha_M)p(H_0)p(\hat{\alpha}_j)p(\tau)}{\beta(H_0, \alpha_M)} \int p(f_d)p(z|H_0)\frac{p(d_{\rm GW}, \delta\phi|x_{\rm GW})}{\pi(d_{\rm GW}, \delta\phi)}\frac{p(z|x_{\rm z})}{\pi(z)}\frac{p(\Delta t_d|x_{\rm EM})}{\pi(\Delta t_d)}dzdf_d$$



Assumptions:

- GW and EM data are independent.
- Only the GW friction introduces selection biases.

S. Mastrogiovanni+, Phys. Rev. D 102, 044009 (2020)



How do we simulate posteriors?

Luminosity distance: Gaussian with std = 1/SNR.

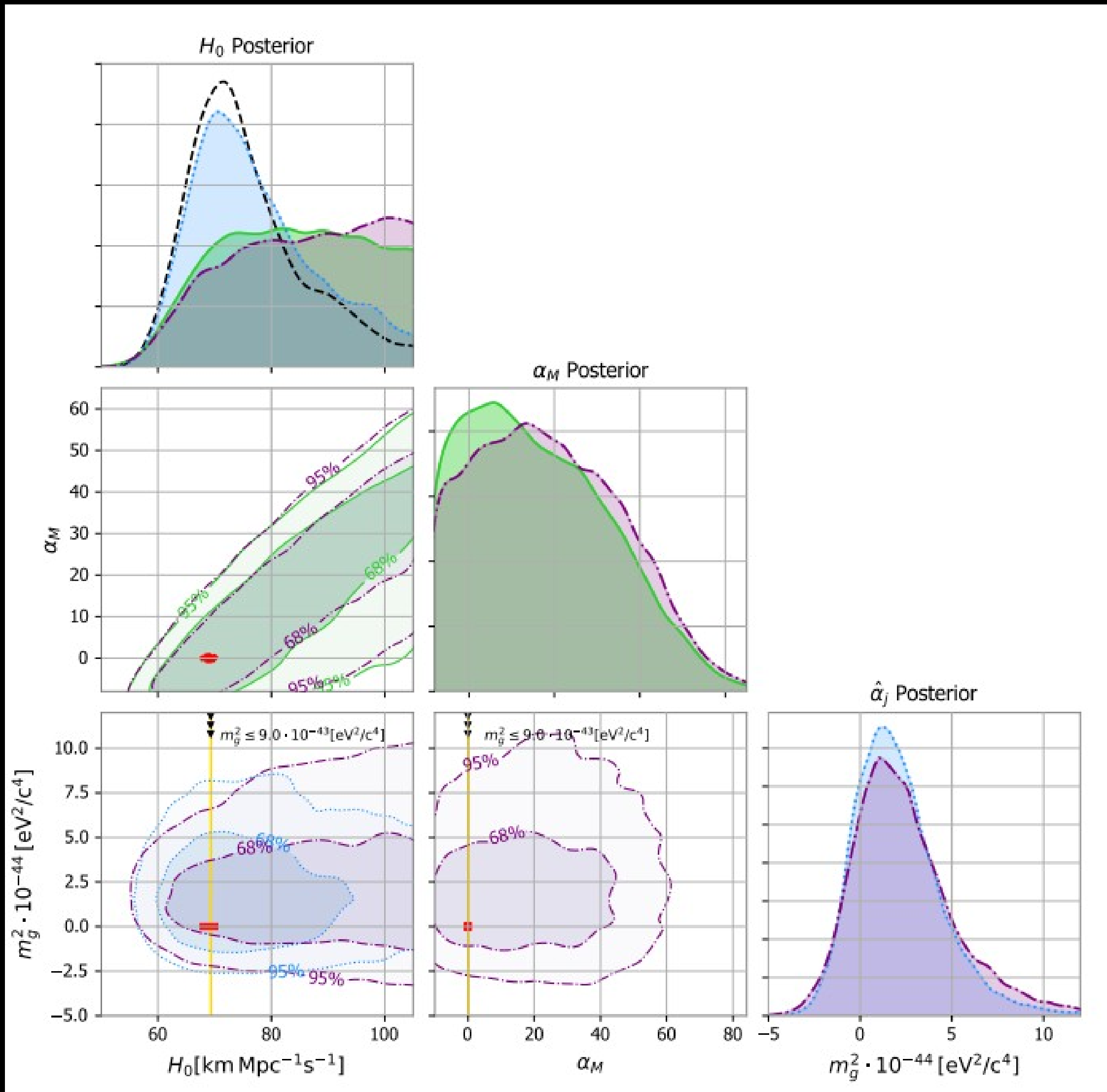
PN phase: Gaussian with a 10% std of the injected value.

Redshift: Perfectly observed

GRB-GW time delay: Gaussian with error 0.05s.

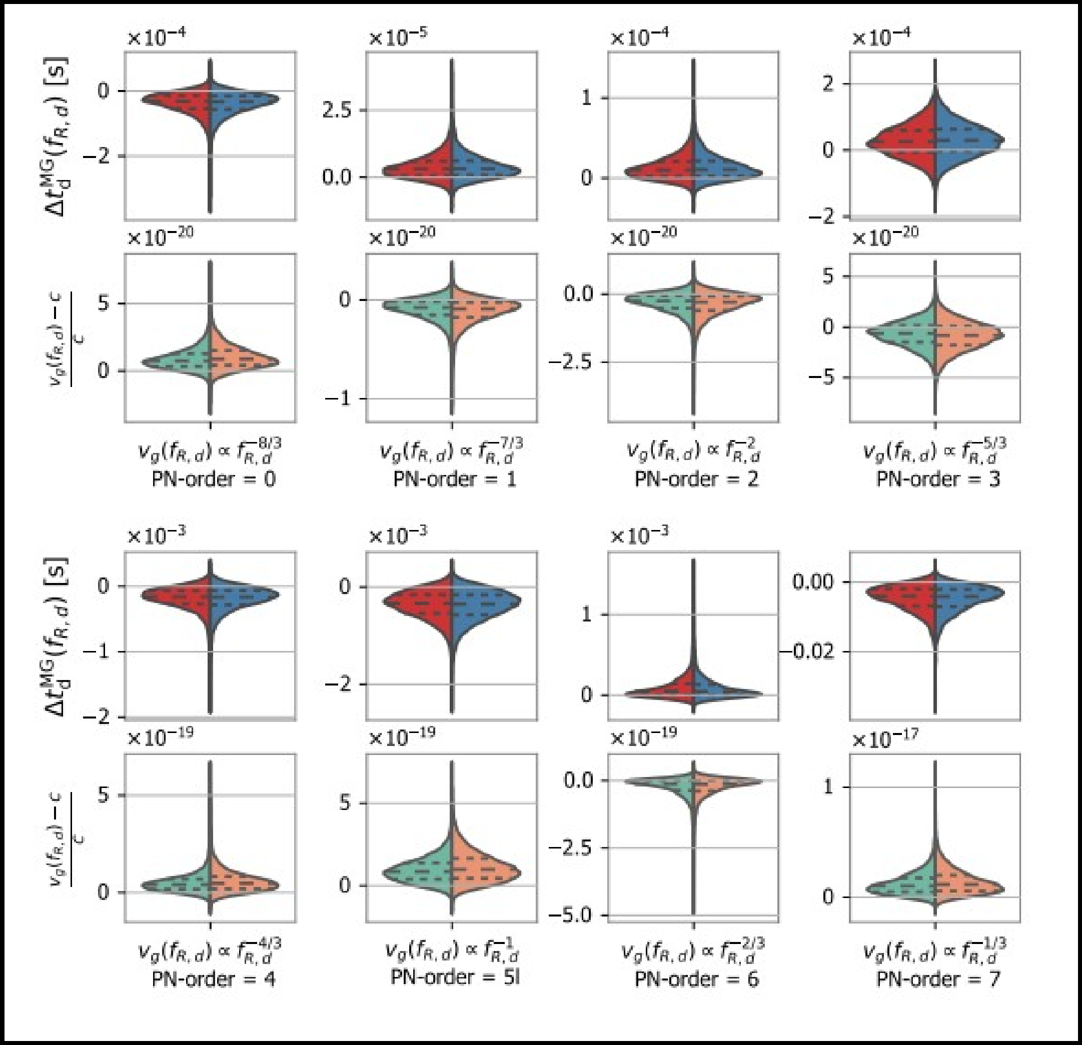
Cosmological parameters are correlated to GR deviation parameters

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



- Observed a strong degeneracy between the Hubble constant and the GW friction.
- The mass of the graviton upper-limit is mostly independent to the Hubble constant for GW170817.
- Results consistent with previous studies that fixed cosmology.

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



- Upper-limits on the GW speed are mostly independent on the GW friction.
- Speed of gravity correspondent to the merger constrained to a 1e-17 precision.
- GW-GRB time delay can also be used to improve the speed of gravity constrain if we reach a measurement precision of 1ms.

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

Parametrizations for GW190521 friction

Several parametrisation are possible for the GW friction, depending on the theory that we select. Here we consider three parametrizations

Extra-dimensions gravity: GW energy can leak in additional dimensions eventually resulting in a different luminosity distance.

G. Dvali+*, Physics Letters B Volume 485, Issues 1–3 (2000)*

$$d_L^{\rm GW} = \left(d_L^{\rm EM}\right)^{\frac{D-2}{2}}$$

CM-parametrization: A parametrization based on the evolution of the Dark Energy content of the Universe.

Lagos+. Phys. Rev. D 99, 083504 (2019)

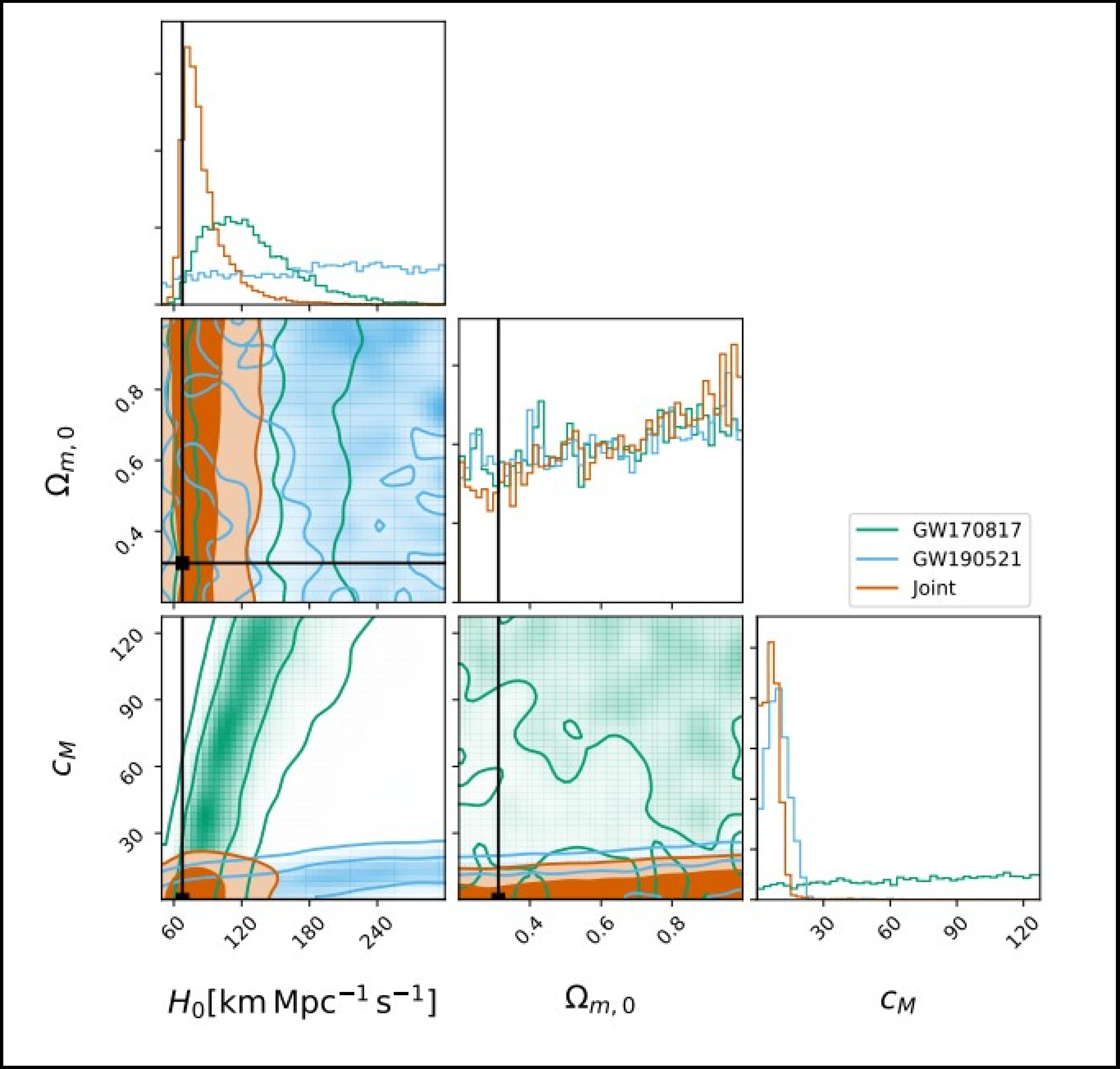
$$d_L^{\rm GW} = d_L^{\rm EM} \exp\left[\frac{c_{\rm M}}{2\Omega_{\Lambda,0}} \ln \frac{1+{\rm z}}{\Omega_{\rm m,0}(1+{\rm z})^3 + \Omega_{\Lambda,0}}\right]$$

Xi-parametrization: A theory-base parametrization able to fit many modified theories of gravity.

E. Belgacem+*, Phys. Rev. D 97, 104066 (2020)*

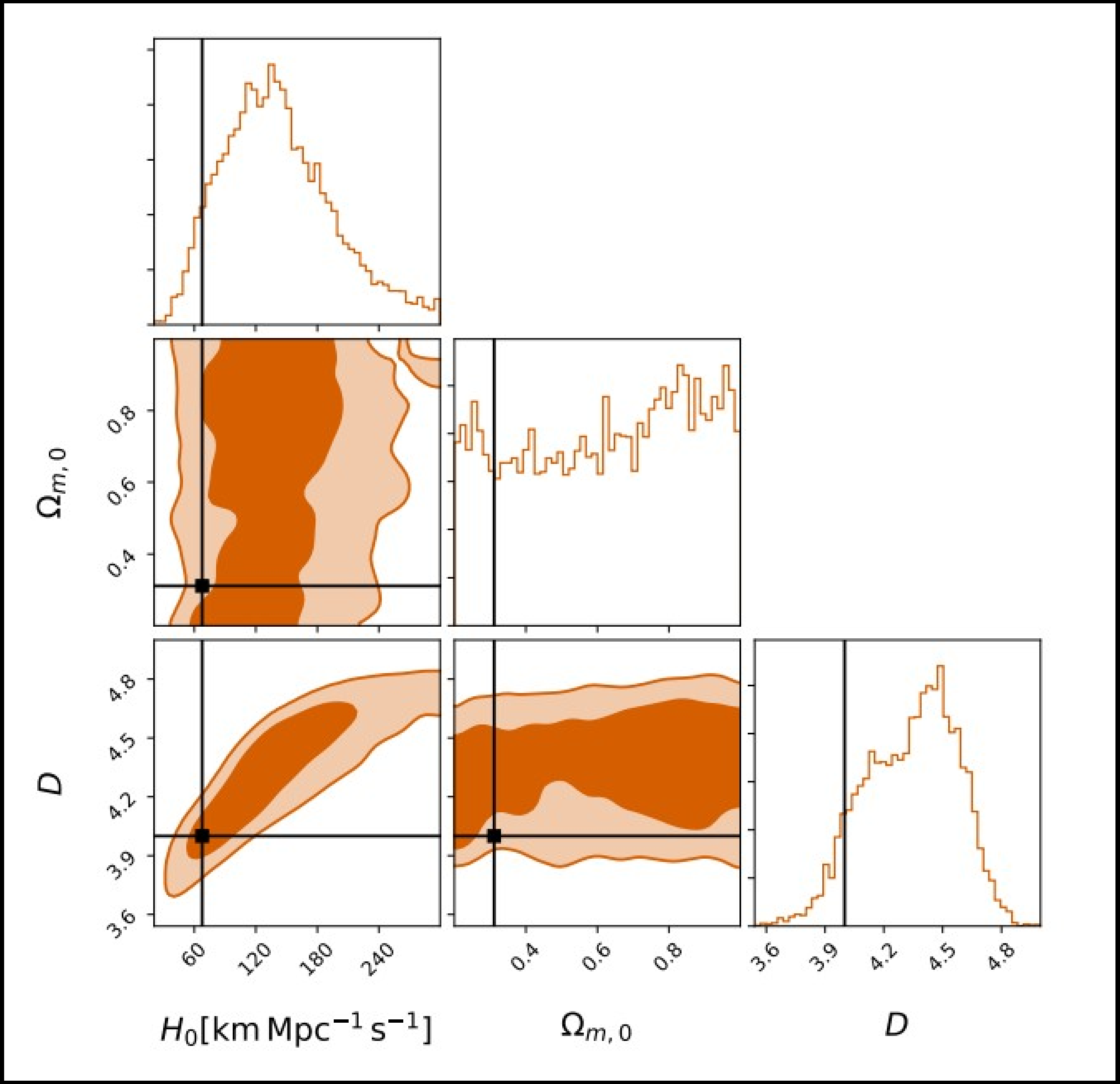
$$d_L^{\rm GW} = d_L^{\rm EM}\left[\Xi + \frac{1-\Xi}{(1+z)^n}\right]$$

GW190521 and GW170817 – CM parametrization



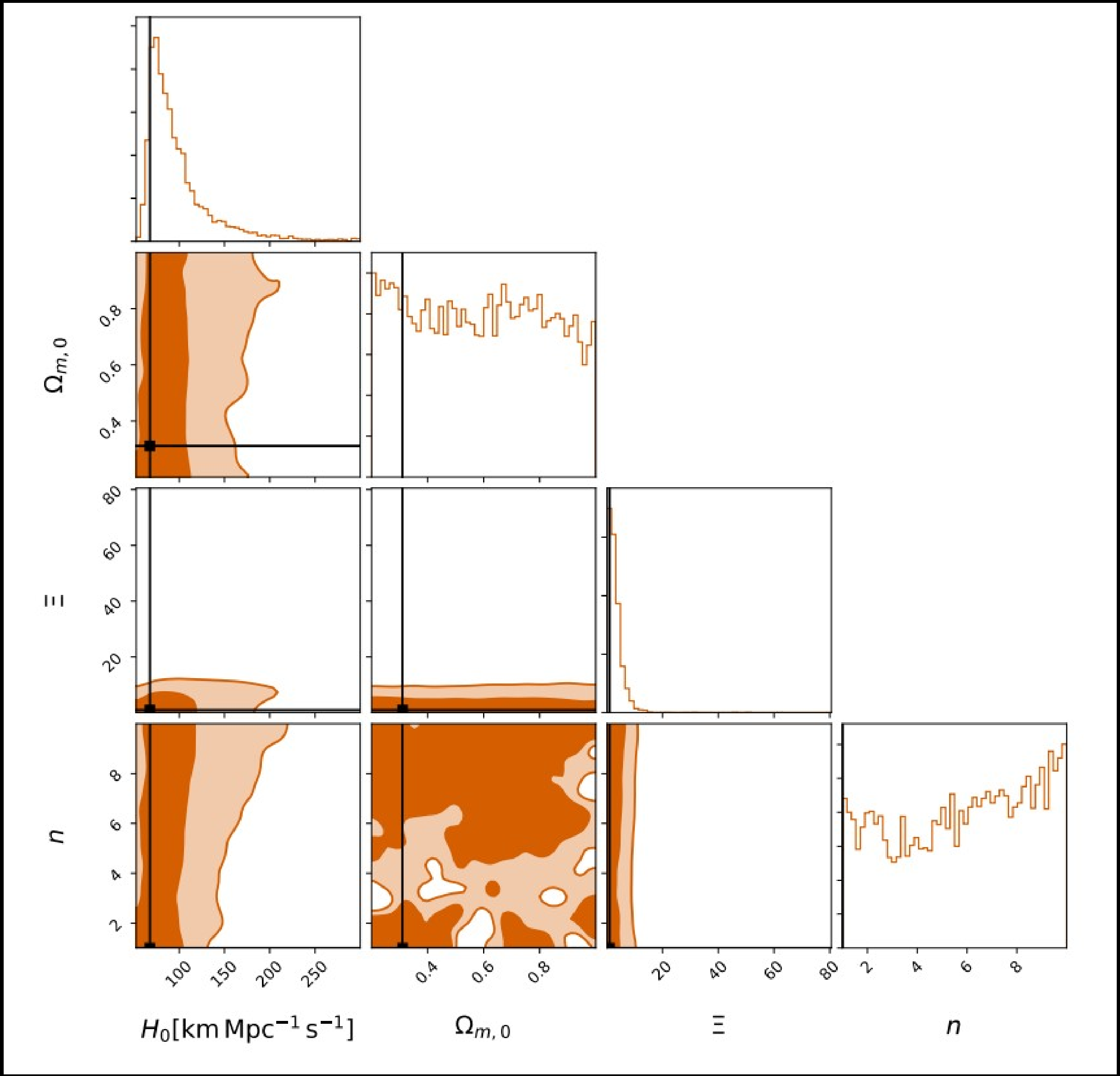
***S. Mastrogiovanni+**, arXiv 2010.04047 (2020)*

GW190521 and GW170817 – Extra dimensions



S. Mastrogiovanni+*, arXiv 2010.04047 (2020)*

GW190521 and GW170817 – Csi parametrization



***S. Mastrogiovanni+**, arXiv 2010.04047 (2020)*

Planck's priors

- The accuracy on number of space time dimensions improve by a factor of 2.
- The improvement on c_M limit improves by a factor of 40.
- We provide the first limit on the parameter csi.

Wide priors

- Omega_m: uniformative results.
- The improvement on c_M limit improves by a factor of 8 w.r.t previous studies.

$\frac{d_L^{GW}}{d_L^{EM}} = \sqrt{\frac{G(z)}{G_0}}$	GW170817 epoch	GW190521 epoch
Planck's priors	$\hat{G}(z) = 1.005^{+0.21}_{-0.06}$	$\hat{G}(z) = 1.10^{+6.13}_{-0.08}$
Wide priors	$\hat{G}(z) = 1.14^{+1.28}_{-0.17}$	$\hat{G}(z) = 5^{+57}_{-4}$

Previous constraints were between -1 and 8 at 68.3% CL.

Conclusions

- GWs and their EM counterparts provide a new channel for probing GR at cosmological scales.
- Standard cosmological and GR deviation parameters should be measured conjointly, in particular when combining events.
- GW170817 tightly constrain GW dispersion relation. The GR modifications are not strongly dependent on the assumed cosmology for this event.
- The addition of GW190521 significantly improves our constraints on GW friction.
- We improve constraints on theories related to GW friction by a factor 2-10.
- Our precision on GW friction (and DE theories) is now 10 times worse than CMB probes, GW could be a competitive probe.