Constraints on the nonstandard propagating GWs with GWTC-3

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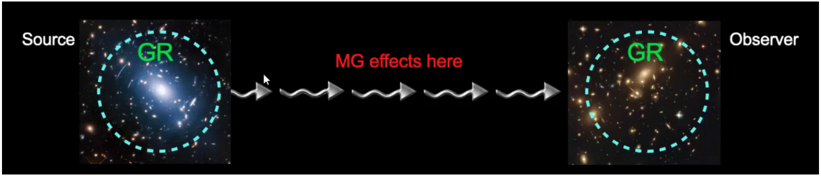
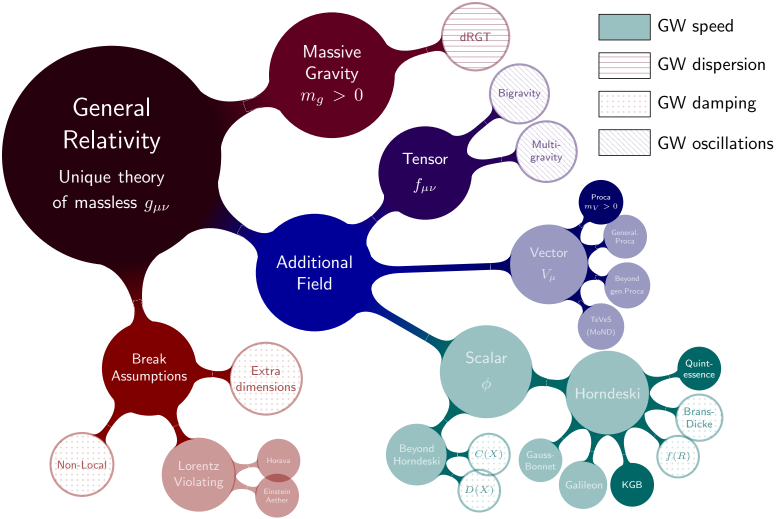
Cosmological Gravity Theories

- Why modified gravities?
  - Cosmic acceleration
  - Dark matter substitute
  - ...
- Modify weak-field regime (large scales)
- Reduce to GR in strong-field regime by Chameleon/Vainshtein/Symmetron screen mechnisms
- Cosmological tests focus on GW propagation (not generation)



- Even if modification on gravity is a tiny effect, propagation can accumulate the effect because of long distance.

Modified gravity roadmap



Ezquiaga, Zumalacárregui, Front.Astron.Space Sci. 5 (2018)

FRW propagation

- Propagation equation is covariant, i.e. independent of GW sources and background spacetimes (NS, BH, supernova, pulsar, GWB etc.)
- EFT approach [PRD 97 (2018) 10, 104037]

$$h''_{ij} + \underbrace{(2+\nu)}_{\text{damping}}\mathcal{H}h'_{ij} + \underbrace{c_g^2}_{\text{speed}} k^2 h_{ij} + \underbrace{m_g^2}_{\text{dispersion}} a^2 h_{ij} = \underbrace{\Gamma}_{\text{oscilltions}} \gamma_{ij} \tag{1}$$

gravity theory	ν	$c_g^2 - 1$	m_g	Γ
GR	0	0	0	0
extra-dim.	$(D-4)\left(1+\frac{1+z}{\mathcal{H}d_{\mathrm{L}}}\right)$	0	0	0
Horndeski	α_M	α_T	0	0
f(R)	$F'/\mathcal{H}F$	0	0	0
Einstein-aether	0	$c_\sigma/(1+c_\sigma)$	0	0
bimetric massive gravity	0	0	$m^2 f_1$	$m^2 f_1$

FRW propagation

- Consider $\Gamma = 0$

$$h''_{ij} + \underbrace{(2+\nu)}_{\text{damping}}\mathcal{H}h'_{ij} + \underbrace{c_g^2}_{\text{speed}} k^2 h_{ij} + \underbrace{m_g^2}_{\text{dispersion}} a^2 h_{ij} = 0 \quad (2)$$

- Modified waveform

$$h_{\mathrm{GW}} \sim h_{\mathrm{GR}} \underbrace{e^{-\frac{1}{2}\int \nu \mathcal{H} d\eta}}_{\text{Affects amplitude}} \underbrace{e^{ik\int \left(c_g^2 - 1 + a^2 m_g^2/k^2\right)^{1/2} d\eta}}_{\text{Affects phase}} \quad (3)$$

- Bonds from GWs
  - Bright siren GW170817 ($z = 0.008$): $-75.3 \leq \nu \leq 78.4$ [PRD 97 (2018) 10, 104038]
  - GW170817: $-3 \times 10^{-15} \leq c_g - 1 \leq 7 \times 10^{-16}$ [PRL 119 (2017) 16, 161101]
  - GW170104: $m_g \leq 7.7 \times 10^{-23}\mathrm{eV}$ [PRL 118(22):221101, 2017]

Question: Can we get a tighter constraint on ν?

- Consider $m_g = \Gamma = 0$ and $c_g^2 = 1$

$$h''_{ij} + (2 + \nu)\mathcal{H}h'_{ij} + k^2 h_{ij} = 0 \tag{4}$$

- Modified luminosity distance

$$d_{\mathrm{GW}} = (1 + z)^{\nu/2} d_{\mathrm{EM}} \tag{5}$$

$$d_{\mathrm{EM}} = \frac{(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_{\mathrm{m}}(1+z')^3 + (1 - \Omega_{\mathrm{m}})}} \tag{6}$$

- GWs measure the luminosity distance d_{GW} and redshifted masses $m_1^{\mathrm{det}}, m_2^{\mathrm{det}}$

$$m_i = \frac{m_i^{\mathrm{det}}}{1 + z\left(D_{\mathrm{GW}}; H_0, \Omega_{\mathrm{m}}\right)} \tag{7}$$

- Bright siren: infer z with EM counterparts, such as GW170817.

- Dark siren: infer z with galaxy catalogue

Spectral siren

Even in the absence of electromagnetic observations, GWs alone can probe the expansion rate with the help of population properties, such as

- the peak of the mass distribution;
- the lower/upper mass cut-off;
- redshift distribution.

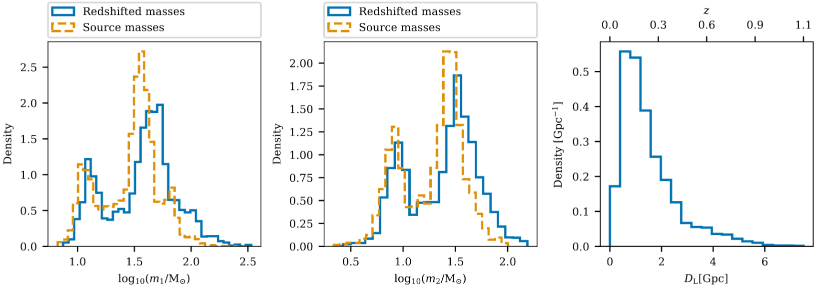
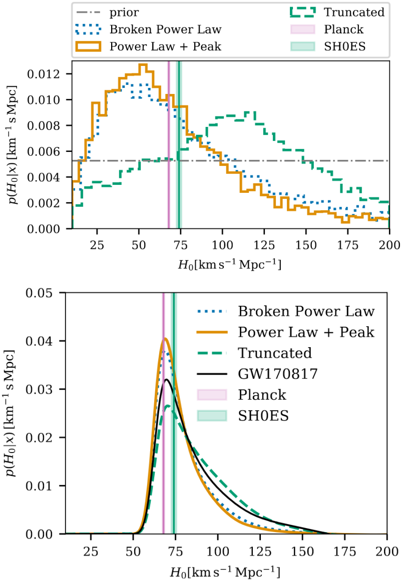


图: Masses and distance (redshift) distribution from GWTC-3.

Spectral and bright sirens with GWTC-3 [ApJ 949 (2023) 2, 76]



Hierarchical Bayesian Inference

$$\boxed{\mathcal{L}(\mathbf{d}|\Lambda) \propto N_{\exp}^{N_{\rm obs}} e^{-N_{\exp}} \prod_{i=1}^{N_{\rm obs}} \frac{1}{\xi(\Lambda)} \left\langle \frac{\mathcal{R}_{\rm pop}(\theta|\Lambda)}{d_L^2(z)} \right\rangle} \tag{8}$$

- $\mathbf{d} = (d_1, \ldots, d_{N_{\rm obs}})$ are $N_{\rm obs}$ BBHs
- $\xi(\Phi)$ quantifies selection biases

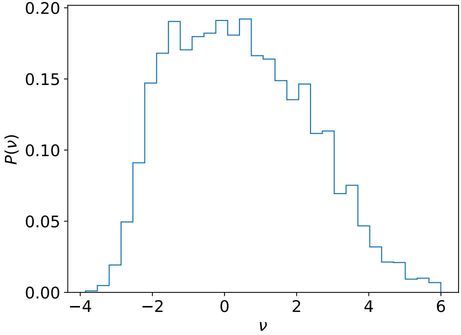
$$\xi(\Lambda) = \int P_{\rm det}(\theta)\, p_{\rm pop}(\theta|\Lambda)\, \mathrm{d}\theta \approx \frac{1}{N_{\rm inj}} \sum_{j=1}^{N_{\text{found}}} \frac{p_{\rm pop}(\theta_j|\Lambda)}{p_{\rm draw}(\theta_j)}$$

  where N_{inj} is the number of injections, N_{found} is the number of injections that are detected, and p_{draw} is the probability distribution from which the injections are drawn.

- $\mathcal{L}(d_i|\theta)$ is single event likelihood.

Result from GWTC-3

$$h''_{ij} + (2 + \nu)\mathcal{H}h'_{ij} + k^2 h_{ij} = 0 \tag{9}$$



- Phenomenological mass models following LVK [ApJ 949 (2023) 2, 76]
- Spectral siren: $-2.2 \le \nu \le 3.7$ at 90% C.I.
- An oder of magnitude tighter than the bound from bright siren: $-75.3 \le \nu \le 78.4$