Constraints on nonstandard propagating GWs with GWTC-3

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Based on 2405.10031 and 2405.xxxxx

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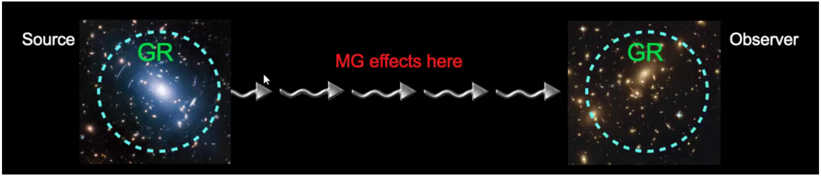
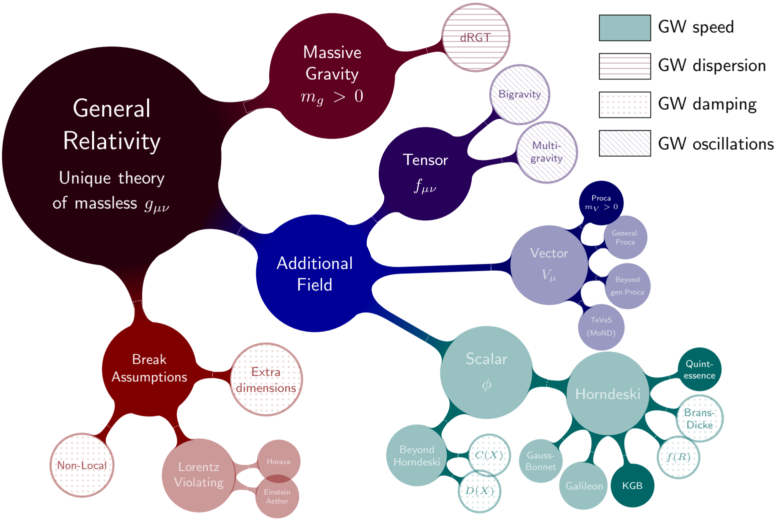
Cosmological Gravity Theories

- 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. GW170817: $\sim$ 40Mpc $\sim 1 \times 10^8$lyr

Modified gravity roadmap



Jose María Ezquiaga, Miguel Zumalacárregui, 1807.09241 (Front.Astron.Space Sci.)

FRW propagation (See also 朱涛's talk)

- Propagation equation is covariant, i.e. independent of GW sources and background spacetimes (NS, BH, supernova, pulsar, GWB etc.)
- EFT approach *Atsushi Nishizawa, 1710.04825 (PRD)*

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

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
$\mathrm{f(R)}$	$F'/\mathcal{H}F$	0	0	0
Einstein-aether	0	$c_\sigma/(1+c_\sigma)$	0	0
bimetric massive gravity	0	0	$m^2 f_1$	$m^2 f_1$
$\mathrm{f}(T)$	$-\frac{f'_T}{2\mathcal{H}f_T}$	0	0	0

See also *Tao Zhu, Wen Zhao, Jian-Ming Yan, Cheng Gong, Anzhong Wang, 2304.09025*

FRW propagation

- Consider $\Gamma = 0$

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

- Modified waveform

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

- Bonds from GWs
  - GW170817: $-3\times10^{-15} \leq c_g - 1 \leq 7\times10^{-16}$ *LVC, 1710.05832 (PRL)*
  - GW170104: $m_g \leq 7.7\times10^{-23}\mathrm{eV}$ *LVC, 1706.01812 (PRL)*
  - Bright siren GW170817 ($z = 0.008$): $-75.3 \leq \nu \leq 78.4$
    Shun Arai, Atsushi Nishizawa, 1711.03776 (PRD)

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.

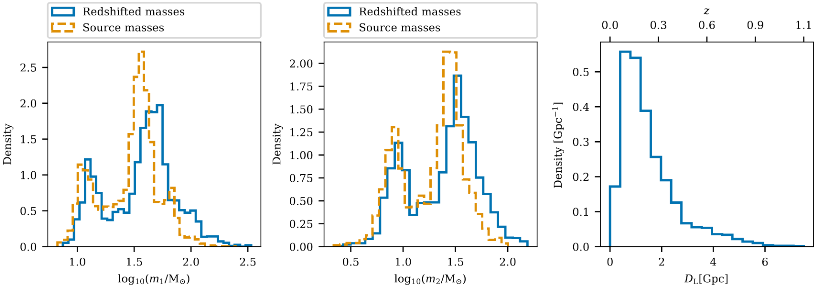
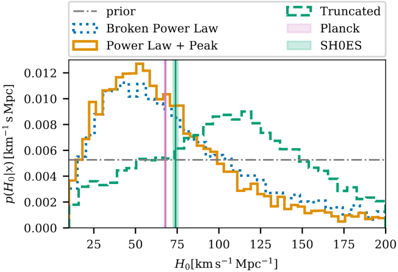


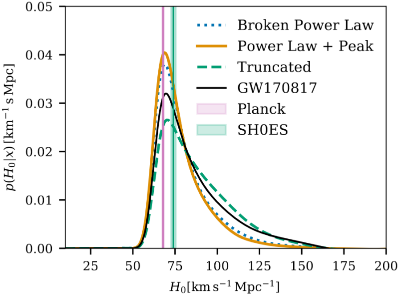
图: Masses and distance (redshift) distribution from GWTC-3.

Jose María Ezquiaga, Daniel E. Holz, 2202.08240 (PRL);

LVK, 2111.03604 (ApJ)

Spectral and bright sirens with GWTC-3 *LVK, 2111.03604 (ApJ)*





Hierarchical Bayesian Inference

$$\boxed{\mathcal{L}(\mathbf{d}|\Lambda) \propto e^{-N_{\rm exp}} \prod_{i=1}^{N_{\rm obs}} \int T_{\rm obs}\, \mathcal{L}(d_i|\theta)\, \mathcal{R}_{\rm pop}(\theta|\Lambda) d\theta} \quad (8)$$

- $\mathbf{d} = (d_1, \ldots, d_{N_{\rm obs}})$ are $N_{\rm obs}$ BBHs
- expected number of detections: $N_{\rm exp}(\Lambda) \equiv \xi(\Lambda) T_{\rm obs}$
- selection biases

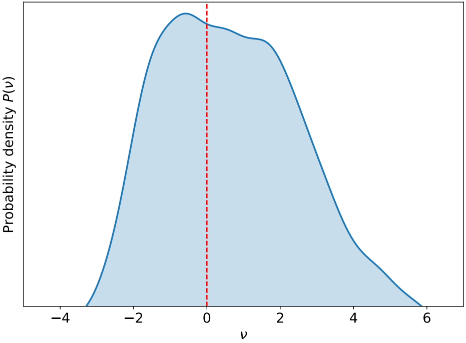
$$\xi(\Lambda) = \int P_{\rm det}(\theta)\, p_{\rm pop}(\theta|\Lambda)\, {\rm d}\theta \approx \frac{1}{N_{\rm inj}} \sum_{j=1}^{N_{\text{found}}} \frac{p_{\rm pop}(\theta_j|\Lambda)}{p_{\rm draw}(\theta_j)}$$

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: constant ν

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

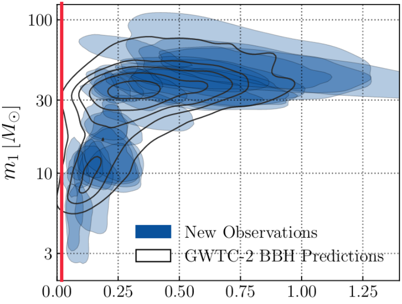


- Phenomenological mass models following LVK *LVK, 2111.03604 (ApJ)*
- Spectral siren: $-2.0 \le \nu \le 4.1$ at 90% C.I. *ZCC, Lang Liu, 2405.10031*
- An oder of magnitude tighter than the bound from bright siren: $-75.3 \le \nu \le 78.4$

Why does the spectral siren outperform the bright siren?

$$d_{\rm GW} = (1+z)^{\nu/2} d_{\rm EM} \tag{10}$$

$$d_{\rm EM} = \frac{(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_{\rm m}(1+z')^3 + (1-\Omega_{\rm m})}} \tag{11}$$



LVK, 2111.03634 (PRX)

- BBHs: redshift can reach $z \sim 1$
- GW170817: $z \sim 0.01$

f(T): non-constant ν

- Teleparallel spacetime (饶浩民's talk)
- power-law form

$$f(T) = T + \alpha(-T)^{\beta} \tag{12}$$

$$\alpha = (6H_0^2)^{1-\beta}\frac{1-\Omega_m}{2\beta-1} \tag{13}$$

- Modified luminosity distance

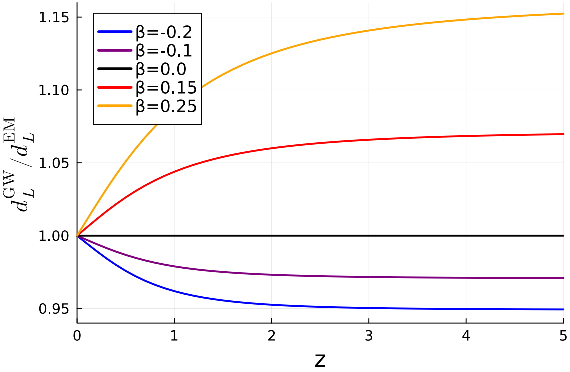
$$d_L^{\rm GW}(z) = d_L^{\rm EM}\exp\left[-\int_0^z \frac{dz'}{1+z'}\nu(z')\right] \tag{14}$$

- Friction term

$$\nu(z) = \frac{3(1-\Omega_m)\beta(1-\beta)\left[1-(1-\Omega_m)E(z)^{2\beta-2}\right]}{2\left[E(z)^{2-2\beta}(-1+2\beta)-(1-\Omega_m)\beta\right]\left[1-(1-\Omega_m)\beta E^{2\beta-2}\right]} \tag{15}$$

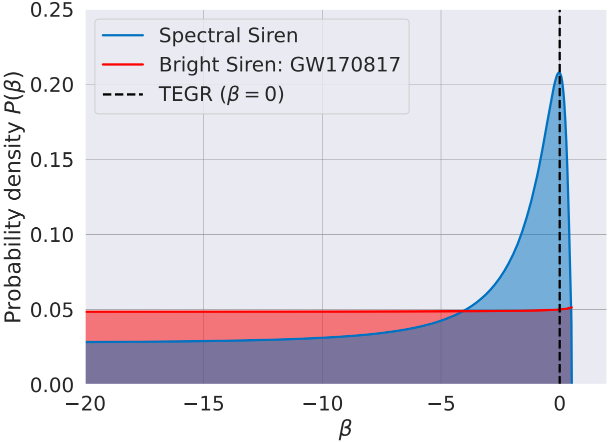
See e.g. *Yi Zhang, Hongsheng Zhang, 2108.05736 (EPJC); Celia Escamilla-Rivera, Rodrigo Sandoval-Orozco, 2405.00608; Yi-Fu Cai, Salvatore Capozziello, Mariafelicia De Laurentis, Emmanuel N. Saridakis, 1511.07586 (Rept.Prog.Phys.)*

Modified luminosity distance



Result from GWTC-3: power-law f(T)

$$f(T) = T + \alpha(-T)^{\beta} \tag{16}$$



ZCC, Wenbin Lin, Puxun Wu, Hongwei Yu, Feng-Yi Zhang, 2405.xxxxx

Summary

- GWs serve as a promising tool to probe non-standard propagation of GWs.

- The spectral siren method demonstrates superior performance compared to the bright siren method in constraining the friction term, owing to the higher redshifts of BBH mergers compared to BNS mergers.

- Overall, the improvement achieved by the spectral siren method can be significant, potentially reaching an order of magnitude or more.

  ZCC, Lang Liu, 2405.10031

  ZCC, Wenbin Lin, Puxun Wu, Hongwei Yu, Feng-Yi Zhang, 2405.xxxxx