Testing Massive-Field Modifications of Gravity via Gravitational Waves

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based on arXiv:1905.11859 w/ T. Narikawa & T. Tanaka

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Outline

- Introduction
- Parametrized modification for massive field
- Applications to LIGO/Virgo data
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Waveform for CBC in GR

- Waveform of inspiral phase from CBC in FD

$$\tilde{h}_{\rm GR}(f) = \mathcal{A}_{\rm GR}(f) e^{i\Psi_{\rm GR}(f)}$$

where

$$\mathcal{A}_{\rm GR}(f) \sim \frac{\mathcal{M}^{5/6}}{D_{\rm L}} f^{-7/6} + \cdots \, ,$$

$$\Psi_{\rm GR}(f) = 2\pi f t_0 + \phi_0 + \sum_{k=0} \psi_k^{\rm PN} u^{(k-5)/3}$$

$$\mathcal{M} = M_{\rm tot}\, \eta^{3/5}, \ \eta = \frac{m_1 m_2}{M_{\rm tot}^2}, \ u \equiv (\pi \mathcal{M} f)^{1/3} \sim \frac{v}{c}$$

Parametrized post-Einstein (ppE)

- Is considering only GR enough?
  - No, we may lose unexpected information.
- Introduce "ppE parameters" α, β, a, & b to describe modifications of GR in generic way [*Yunes & Pretorius (2009)*].
- The ppE waveform of inspiral phase is

$$\tilde{h}(f) = \tilde{h}_{\rm GR}\,(1+\alpha u^a)\,e^{i\beta u^b}.$$

Parametrized post-Einstein (ppE)

- E.g. in Einstein-dilaton-Gauss-Bonnet theory, [*Tahura & Yagi (2018)*]

$$\alpha = \frac{112}{3}\beta = -\frac{5\pi}{12}\frac{\alpha_{\rm EdGB}^2}{M_{\rm tot}^4}\frac{(m_1^2 s_2 - m_2^2 s_1)^2}{M_{\rm tot}^4 \eta^{18/5}},$$

$$a = b + 5 = -2,$$

$$s_A = 2\frac{\sqrt{1-\chi_A^2} - 1 + \chi_A^2}{\chi_A^2},$$

$\alpha_{\rm EdGB}$: coupling parameter

- -1PN correction (dipole rad.)

Sudden activation of dipole rad.

- Is the ppE waveform now complete?
  - Not, yet…
  - echos, sudden activation of modification…
- Dynamical scalarization of binary NSs [*Barausse+ (2013), Shibata+ (2014)*]
- MG (e.g. EdGB) with a massive scalar field

Why massive field?

- Dipole radiation is suppressed in scales lower than mass of the fields
    - can avoid the constraints of binary pulsars if

$$m \gg 10^{-16}\,\mathrm{eV}$$

- Ground based detectors are sensitive ~100 Hz

$$10^{-14}\,\mathrm{eV} \lesssim m \lesssim 10^{-13}\,\mathrm{eV}$$

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Scalar field & dipole radiation

- From Helmholtz eq., the scalar field is

$$\phi \sim ik \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \int dx^3 e^{-i\omega(t-t')} S(\boldsymbol{r}) (kr)^\ell h_\ell^{(1)}(kr) Y_{\ell m}^* Y_{\ell m},$$

$$\omega^2 = k^2 + m^2,\ \ S(\boldsymbol{r}) : \text{source term},$$

$$h_\ell^{(1)} : \text{spherical Hankel function.}$$

- Dipole radiation can be parametrized

$$\frac{(dE/dt)_D}{(dE/dt)_Q} = A \frac{k^3}{\omega^3} \Theta(\omega^2 - m^2)\, u^{-2}.$$

Parametrized modification

- The leading-order modification is

$$\frac{\delta \dot{f}}{\dot{f}_{\rm GR}} \simeq \frac{(dE/dt)_D}{(dE/dt)_Q} = A \frac{(\omega^2 - m^2)^{3/2}}{\omega^3} \Theta(\omega^2 - m^2)\, u^{-2}.$$

- The modified waveform is

$$\tilde{h}(f) = \tilde{h}_{\rm GR}(1 + \delta\mathcal{A}) e^{i\delta\Psi}, \qquad \text{for } \omega^2 > m^2$$

$$\delta\mathcal{A} = -\frac{1}{2} A \frac{(\omega^2 - m^2)^{3/2}}{\omega^3}\, u^{-2}, \quad \hat{f} = \pi f/m,$$

$$\delta\Psi = -\frac{5}{48} A \left(\frac{1}{m\,\mathcal{M}}\right)^{7/3} \int_{\hat{f}}^{\infty} d\hat{f}' \, \frac{\hat{f} - \hat{f}'}{\hat{f}'^{22/3}} \left[\hat{f}'^2 - 1\right]^{3/2}.$$

Setup

- Grid search using O1/O2 LVC catalog by KAGRA Algorithmic Library (KAGALI)
- IMRPhenomD as $\tilde{h}_{\rm GR}$
- Varying 2 additional parameters A & m as well as $\mathcal{M}$, η, etc.
- BUT fixing spins (approx. degeneracy w/ η)

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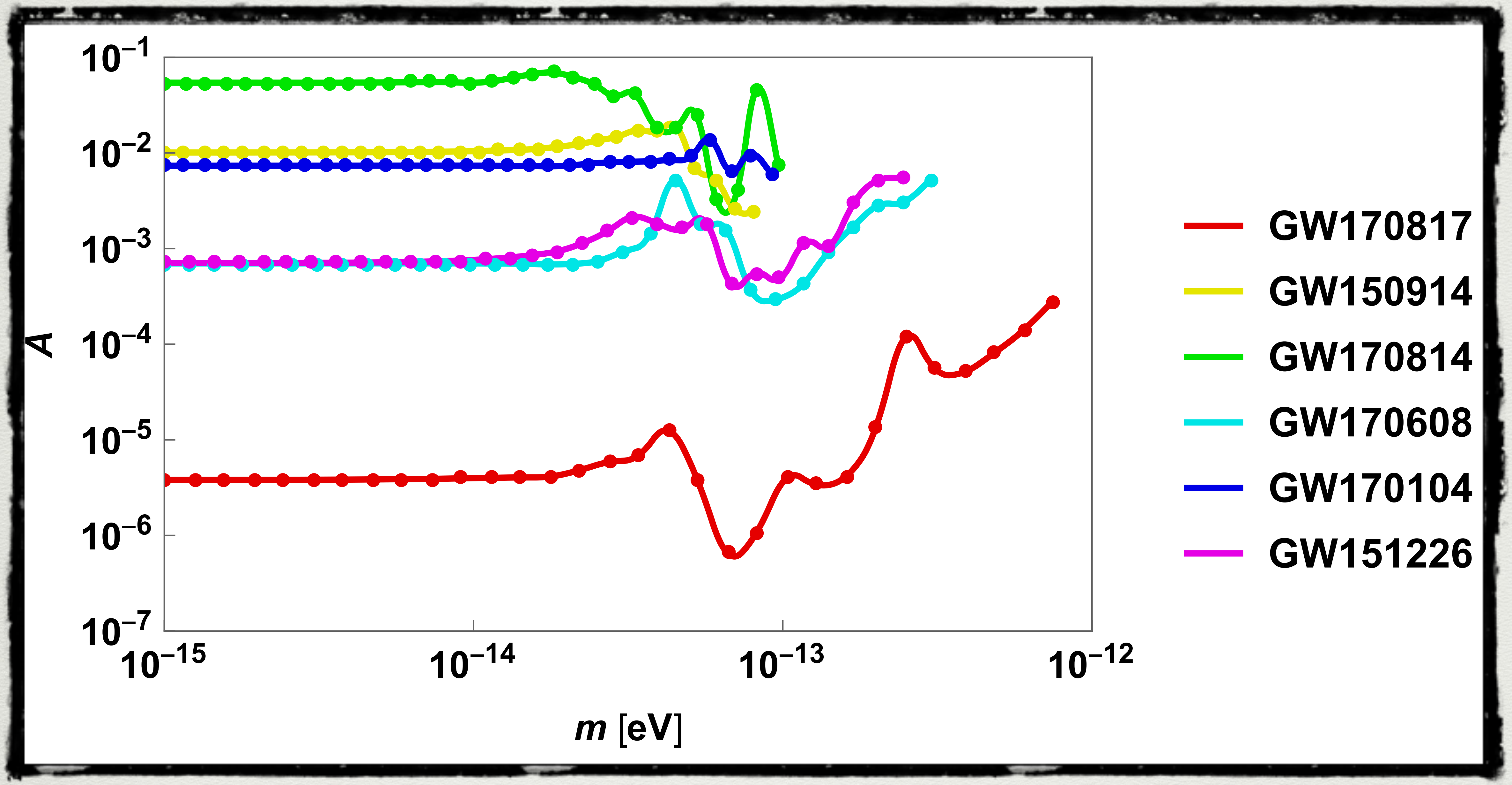


Constraints on A for each event with 90% credible level

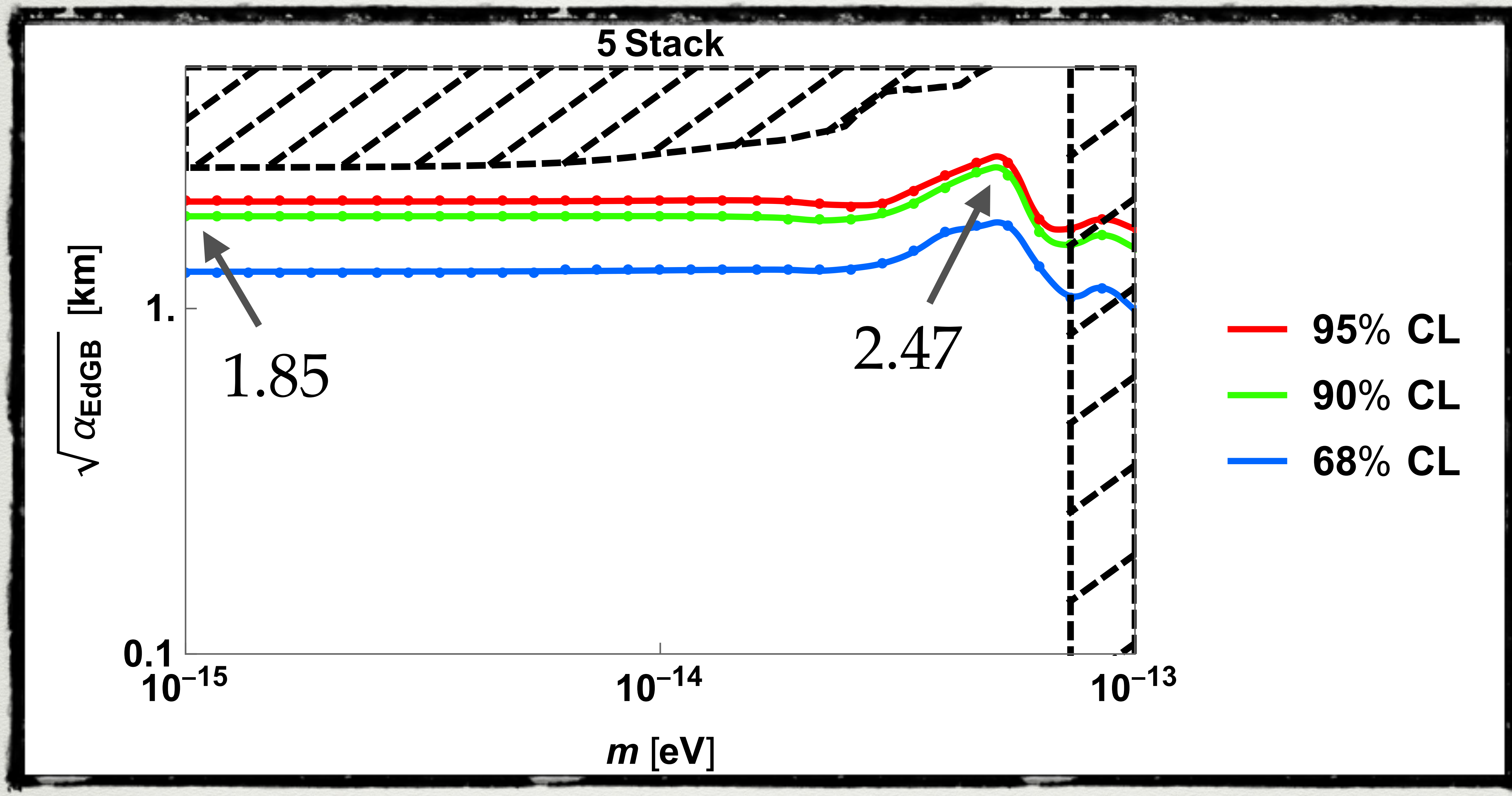
EdGB type coupling

- Parameter A depends on system parameters $(m_1, m_2, \chi_1, \chi_2)$, and theory as well.

- Assume theory to rewrite A, e.g. EdGB type coupling, $A \to \alpha_{\rm EdGB}$ by

$$A = \frac{5\pi}{6} \frac{\alpha_{\rm EdGB}^2}{M^4} \frac{(m_1^2 s_2^{\rm EdGB} - m_2^2 s_1^{\rm EdGB})^2}{M^4 \eta^{18/5}}.$$

- Combine BBH evens and constrain $\alpha_{\rm EdGB}$.



Constraints on $\alpha_{\rm EdGB}$ for each event with 90% credible level (cf. $\sqrt{\alpha_{\rm EdGB}} \lesssim 1.9\,{\rm km}$ for the massless limit obtained from low-mass X-ray binaries observations [*Yagi (2012)*])

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Summary

- Massive fields' modification is considered.
- Ground-based detectors are sensitive for

$$10^{-14}\,\mathrm{eV} \lesssim m \lesssim 10^{-13}\,\mathrm{eV}$$

- A is strongly constrained for lighter $\mathcal{M}$ w/ higher SNR events, e.g. $\text{a few } 10^{-6}$ for BNS.
- Assuming EdGB type coupling, we've combined 5 BBH events & found w/ 90%CL

$$\sqrt{\alpha_{\mathrm{EdGB}}} \lesssim 1.85\,\mathrm{km}$$

Prospects

- Massive field modification
  - especially, NS-BH is interesting:

$$A = \frac{5\pi}{6}\frac{\alpha_{\rm EdGB}^2}{M^4}\frac{(m_1^2 s_2^{\rm EdGB} - m_2^2 s_1^{\rm EdGB})^2}{M^4\eta^{18/5}}.$$

- Parity violation of gravity
- Echo

etc…

THANK YOU FOR YOUR ATTENTION