Searching for ultralight bosons with supermassive black-hole ringdown

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Workshop on Very Light Dark Matter 2021

Introduction

- Ultralight boson: dark matter candidate
- Mass $\ll 1$ eV

Superradiance

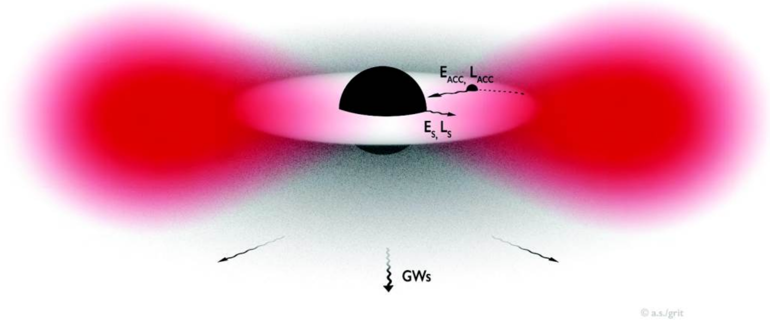


Figure taken from Richard Brito et al 2015 Class. Quantum Grav. 32 134001

Bosonic Cloud Wave function

Bosonic cloud wave function for $l = m = 1$ mode [1]

$$\Phi(t, r, \theta, \phi) = \sqrt{\frac{3M_s}{4\pi I M}}(M\mu)^3 \mu r e^{-M\mu^2 r/2} \sin\theta \cos(\phi - \mu t), \quad (1)$$

- I: $\mathcal{O}(1)$ factor
- M: BH mass
- M_s: Total mass of bosonic cloud
- $\mu = \frac{m_s}{\hbar}$

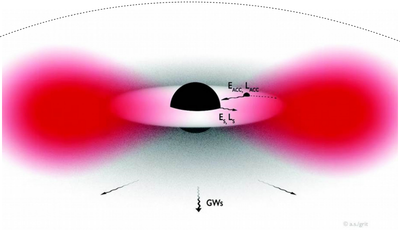
Energy-momentum tensor given by

$$T_{\mu\nu} = -g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha\Phi\partial_\beta\Phi + \frac{1}{2}\mu^2\Phi^2\right) + \partial_\mu\Phi\partial_\nu\Phi \qquad (2)$$

[1] Richard Brito et al 2015 Class. Quantum Grav. 32 134001

GW Emissions by Ultralight Bosons

dynamical friction extreme-mass-ratio inspiral



continuous gravitational waves

stochastic gravitational-wave background

Picture adapted from https://pages.jh.edu/eberti2/posts/gravitational-wave-detectors-and-dark-matter/

Ringdown Phase of Black Holes

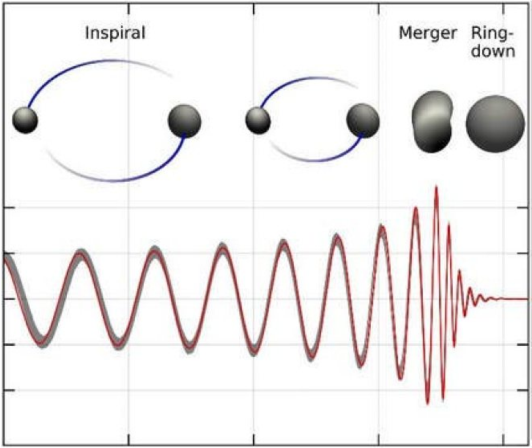
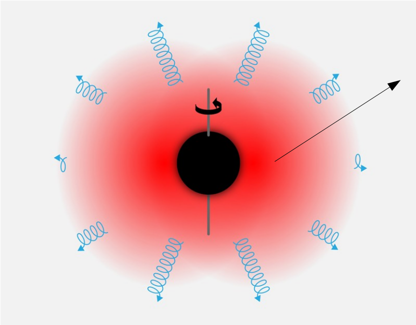


Figure taken from LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 116, 061102

Effects on the Ringdown Phase



∵ Ultralight bosons sources gravity
⇒ affect GWs propagation
⇒ shift QNMs

So,
1. How much is the shift?
2. Astrophysicall possible?

Figure adapted from https://physics.aps.org/articles/v10/83

The Teukolsky Equation

- Teukolsky equation for gravitational perturbations

$$\mathcal{L}\Psi = 4\pi\Sigma T \tag{3}$$

where $\Sigma = r^2 + M^2a^2\sin^2\theta$.

- $\mathcal{L}$: differential operator
- $\Psi \propto \ddot{h}_+ - i\ddot{h}_\times$.
- T: projection of $T_{\mu\nu}$ from bosonic cloud

The Effective Potentials [2]

- A term of $T \propto \Psi$.
- Let $\Psi = R(r)S(\theta)e^{im\phi - i\omega t}$, $R(r)$ satisfies,

$$\frac{\partial^2 R}{\partial x^2} + (\omega^2 - V(r) - V_{\rm ULB}(r))R(r,\omega) = 0 \tag{4}$$

- $V(r)$ usual potential
- $V_{\rm ULB}$ extra contribution from bosonic cloud

[2] Chung et al, arXiv: 2107.05492

Bosonic Cloud Potential

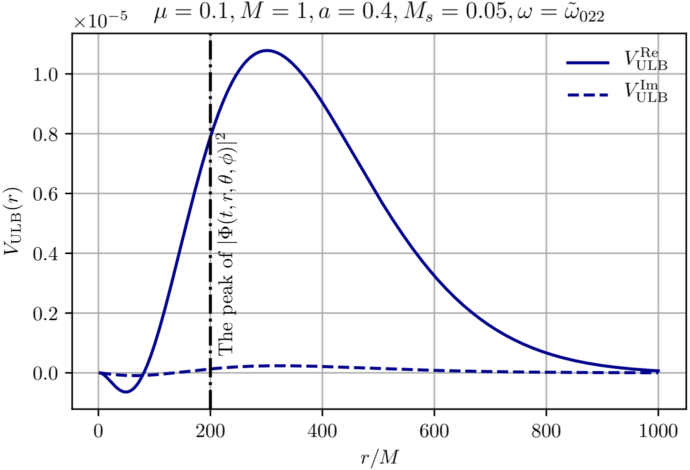
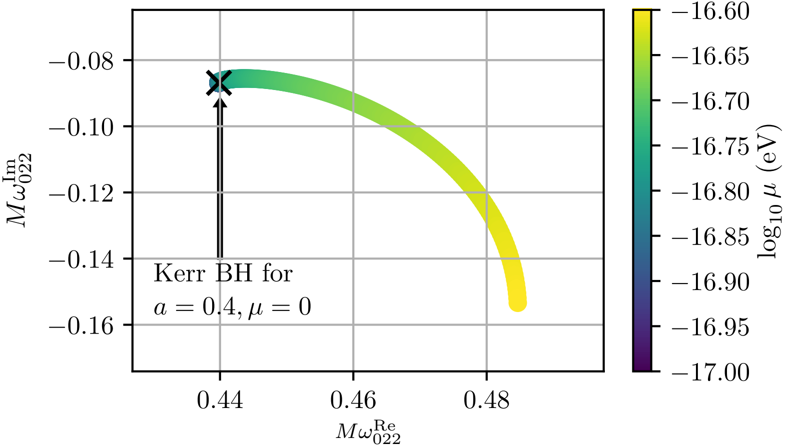


Figure 1: Peak of V_{ULB} at $r_{\mathrm{peak}} \propto \frac{1}{M\mu^2}$

Quasinormal-mode Frequency Shifts

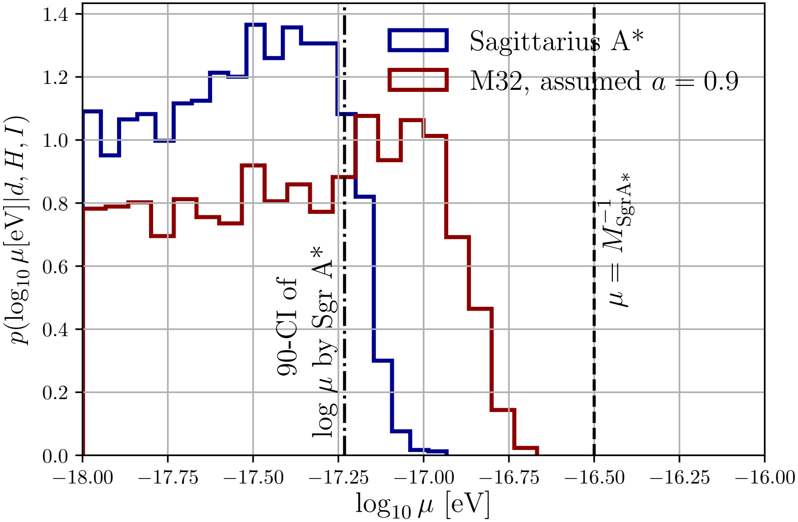
- Consistent with the shift due to dark-matter halo



Astrophysical Implications

- Mock signals of extreme-mass-ratio inspiral (EMRI) of a compact object of $10M_{\odot}$ hits Sgr A* and M32
- Assumed to be detected by LISA with noises

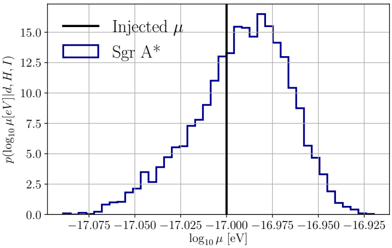
$\mu = 0$



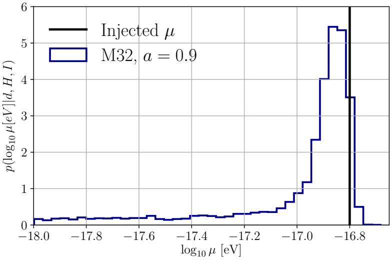
Sagittarius A*
M32, assumed $a = 0.9$
90-CI of
$\log \mu$ by Sgr A*
$\mu = M_{\mathrm{SgrA*}}^{-1}$
$p(\log_{10} \mu[\mathrm{eV}]|d, H, I)$
$\log_{10} \mu$ [eV]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
−18.00
−17.75
−17.50
−17.25
−17.00
−16.75
−16.50
−16.25
−16.00

Results of $\mu > 0$

We assume $M\mu \sim 0.3$.



(a) Sgr A*



(b) M32

Possibilities for better rates

- Main limitation: ringdown SNR scales as $q = (m/M)^2$

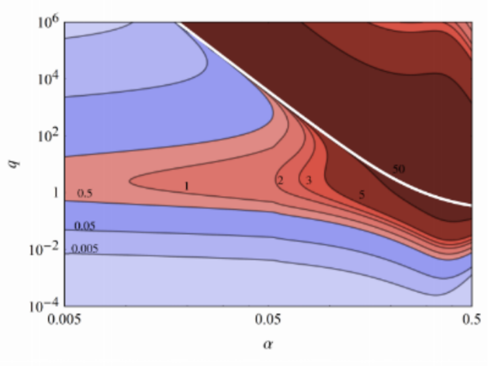


Figure 2: Cloud depletion as a function of $\alpha = M\mu$, from[3]

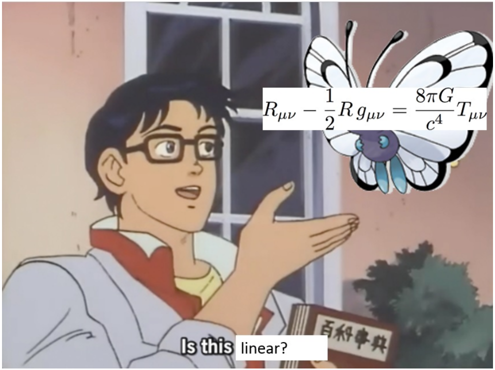
[3] E. Berti *.et al* Phys. Rev. D 99, 104039

Takeaways

- Computed shift of QNMs of rotating BHs due to bosons clouds.
- Probe for ultralight bosons.
- Other (dark-)matter sources?

Figure 3: Link to our manuscript on arXiv: 2107.05492

Q and A



Outline

Eigenfunctions

$$\psi_4 = \rho^4 \sum_{l,m} \int \frac{\mathrm{d}\tilde{\omega}}{\sqrt{2\pi}} S_{nlm}(\theta, \phi) e^{-i\tilde{\omega}t} R_{lm\tilde{\omega}}(r) \tag{5}$$

- $l = m = 2$ mode of spin-weighted spheroidal harmonic
- Extract Teukolsky source term

$$\tilde{T}(t, r, \Omega) \sim -\frac{1}{4}\rho^8 \bar{\rho} \Delta^2 \hat{J}_+[\rho^{-4} \hat{J}_+(\rho^{-2} \bar{\rho} T_{\bar{m}\bar{m}})] \tag{6}$$

- $\hat{J}_+ = \partial_r - \Delta^{-1}(r^2 \partial_t)$
- $R(r, \omega) \propto e^{i\omega r} \Rightarrow \frac{\partial R}{\partial r} \sim i\omega R(r)$

Derivation of the effective potential [4]

- Recall that,

$$T_{\mu\nu} = -g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha\Phi\partial_\beta\Phi + \frac{1}{2}\mu^2\Phi^2\right) + \partial_\mu\Phi\partial_\nu\Phi \quad (7)$$

- Ringdown phase $\Rightarrow g_{\mu\nu} = g^{(0)}_{\mu\nu} + h_{\mu\nu}$,

$$T_{\bar{m}\bar{m}} = -\frac{1}{2}\bar{m}^\beta\bar{m}^\gamma\left[h_{\beta\gamma}(\partial_\alpha\Phi\partial^\alpha\Phi + \mu^2\Phi^2)\right] \quad (8)$$

- In the far-field limit, $r \to +\infty$

$$T_{\bar{m}\bar{m}} = \bar{m}^\beta\bar{m}^\gamma T_{\beta\gamma} \text{ where } \bar{m}^\mu \to \frac{1}{\sqrt{2}}\left(\hat{\theta}^\mu - i\hat{\phi}^\mu\right), \quad (9)$$

$$\ddot{h}_{\beta\gamma} \approx -\omega^2 h_{\beta\gamma} \Rightarrow \psi_4(r \to +\infty) = -\frac{1}{2}\omega^2\bar{m}^\beta\bar{m}^\gamma h_{\beta\gamma} \quad (10)$$

and thus

$$T_{\bar{m}\bar{m}} \propto \psi_4\left[(\partial_\alpha\Phi\partial^\alpha\Phi + \mu^2\Phi^2)\right] \quad (11)$$

[4] Chung et al, arXiv: 2107.05492

Logarithmic perturbation theory

- Consider a perturbed Klein-Gordon equation,

$$\frac{\partial^2 u}{\partial r_*^2} + \left(\omega^2 - V(r) - V^{(1)}\right) u = 0, \tag{12}$$

- The leading order shift of QNMFs by logarithmic perturbation theory [5],

$$\omega^{(1)} = \frac{\langle u|V^{(1)}|u\rangle}{2\omega^{(0)}\,\langle u|u\rangle}. \tag{13}$$

[5] P. T. Leung, Y. T. Liu, W.-M. Suen, C. Y. Tam, K. Young, Phys.Rev. D59 (1999) 044034

Logarithmic perturbation theory

- where

$$\langle u|u\rangle = \int_{-\infty}^{+\infty} dx u^2(x),$$
$$\langle u|V^{(1)}|u\rangle = \int_{-\infty}^{\infty} dx u(x) V^{(1)}(x) u(x). \tag{14}$$

From Potentials to Quasinormal-mode Frequencies

- $V_{\rm ULB}(r) \propto (M\mu)^8 \ll 1$
- We solve for the GW QNMFs using logarithmic perturbation,

$$\tilde{\omega}_{n\ell m} \approx \tilde{\omega}^{(0)}_{n\ell m} + \frac{\Delta_{n\ell m}(\mu, M_s, M)}{2\tilde{\omega}^{(0)}_{n\ell m}} \tag{15}$$

Non-degeneracy

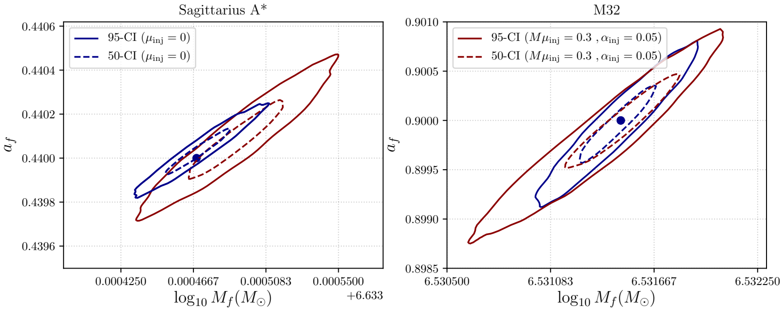


Figure 4: Two-dimensional posterior of M and dimensionless spin a of mock signal