Probing Ultralight Bosons with Compact Eccentric Binaries

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Introduction

A fast rotating BH of mass M can copiously produce light bosons of mass ν due to superradiance instability, a pure gravitational effect [1]. When the gravitational fine structure constant $\alpha \equiv M\nu \ll 1$, the boson σ can form nonrelativistic and metastable condensate around the BH with hydrogen-like spectrum. We can thus call the formed condensate a superradiance cloud (SC) and call the whole system of SC + central BH a gravitational atom (GA). For stellar-mass BHs, the corresponding mass of σ is around $\nu \sim 10^{-13}\mathrm{eV}(\alpha/0.01)(10M_\odot/M)$.

We show that a GA typically possesses a huge mass quadrupole Q, so that the GA in a binary system can induce significant apsidal precession of the eccentric orbit for a wide range of orbital parameters. We show that this signal can be very significant and potentially observable for BH-GA binaries and pulsar-GA binaries.

Superradiance Cloud

We consider a real scalar field σ of mass ν outside a Kerr BH of mass M and spin J. When $\alpha \ll 1$, one finds hydrogen-like bound states $|nlm\rangle$ [2], with nonzero imaginary parts in the energy eigenvalues due to the ingoing boundary condition at the BH horizon, which can trigger production or depletion of states. $|211\rangle$ and $|322\rangle$ are the two leading states that a spinning BH can produce, and the evolution of a typical SC in a Hubble time is shown in Fig. 1, taking account of the emission of GWs.

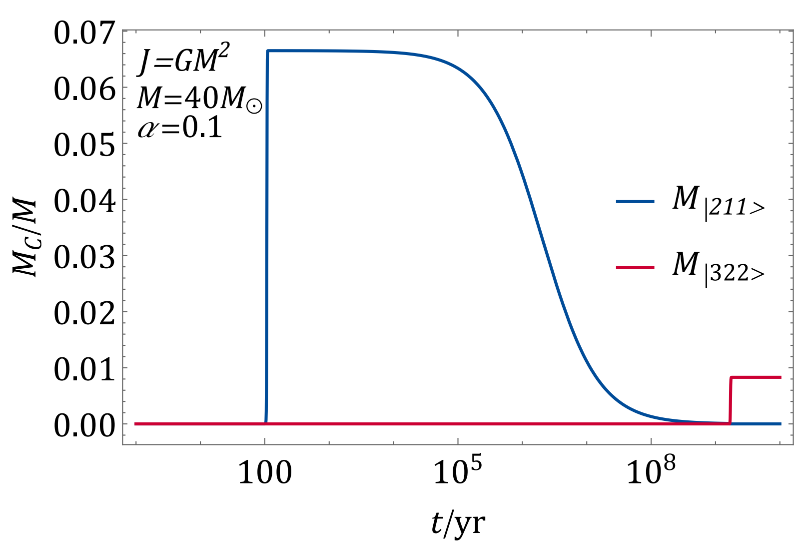

Fig. 1. The evolution of a typical SC in a Hubble time. The leading depletion channel for these states is GW radiation, so they can exist with astronomical lifetime.

We focus on $|211\rangle$ now. At the saturation, the total mass of the SC is $m_C \sim \alpha M$, just a small fraction of the BH mass, but the mass quadrupole is huge. In terms of a dimensionless quadrupole parameter $\kappa \equiv -QM/J^2$ (where J is the spin), the SC can have $\kappa \sim 10^3(0.1/\alpha)^3$.

GA-induced Apsidal Precessions

Let χ be the argument of periapsis in the orbital plane. The apsidal precession $\dot{\chi}$ has three contributions, from the GR precession at 1PN, mass quadrupole coupling, and the spin-orbit coupling, respectively $\dot{\chi} = \dot{\chi}_{\mathrm{GR}} + \dot{\chi}_{\mathrm{Q}} + \dot{\chi}_{\mathrm{S}}$. The GR precession can in principle be subtracted, but $\dot{\chi}_{\mathrm{S}}$ contaminates our signal by introducing new free parameter. So we impose a constraint that $|\dot{\chi}_{\mathrm{Q}}| \gg |\dot{\chi}_{\mathrm{S}}|$, and then our signal depends on a single constant parameter, the effective mass quadrupole $q_{\mathrm{eff}} \equiv \frac{Q}{M}(1-3\cos^2 n)$, where n is the angle between the BH spin and the orbital angular momentum.

GWs from GA-BH Binaries

The true anomaly $\psi(t)$ executes nonuniform motion for eccentric orbit, resulting in overtones in GW spectrum with frequency $\omega_n = n\omega$ $(n = 1,2,\cdots)$. With nonzero $\dot{\chi}$, each harmonic component split into a triplet with frequencies $(\omega_n, \omega_{n\pm}) \equiv (n\omega, n\omega \pm 2\dot{\chi})$. It turns out that the ω_{n+} component almost always dominates the GW power in a triplet, as shown in Fig. 2. Therefore, we can retain the ω_{n+} component only. Then the effect of apsidal precession enters through the anharmonic overtones, namely, ω_{n+}/ω_{m+} is not integer for any $n \neq m$.

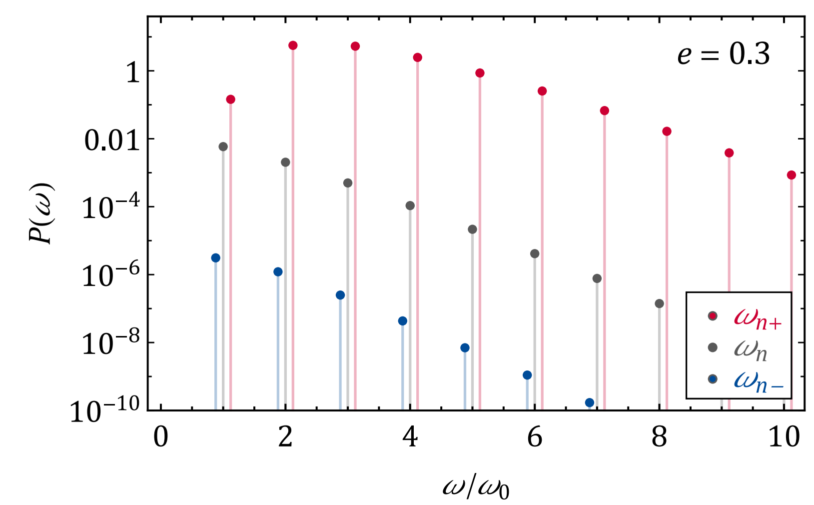

Fig. 2. The GW power spectrum of an eccentric binary with apsidal precession. The split in each triplet is exaggerated.

To assess more quantitatively the observability of the quadrupole-induced apsidal precession through GW, we perform a simplified Fisher analysis for a binary of (40 + 40) $M_\odot$. We apply a time-domain formula for a Fisher matrix, assume an N2A5 configuration of the LISA noise curve with 4yr of total observation time, and show the 1σ contours for $e_0 = (0.1, 0.3, 0.5)$ in Fig.3.

Reference

[1] Zel'dovich, Y. B. 1971, JETPl, 14, 180

[2] Baumann, D., Chia, H. S., Porto, R. A., & Stout, J. 2020, PhRvD, 101, 083019

[3] Stairs, I. H. 2003, LRR, 6, 5

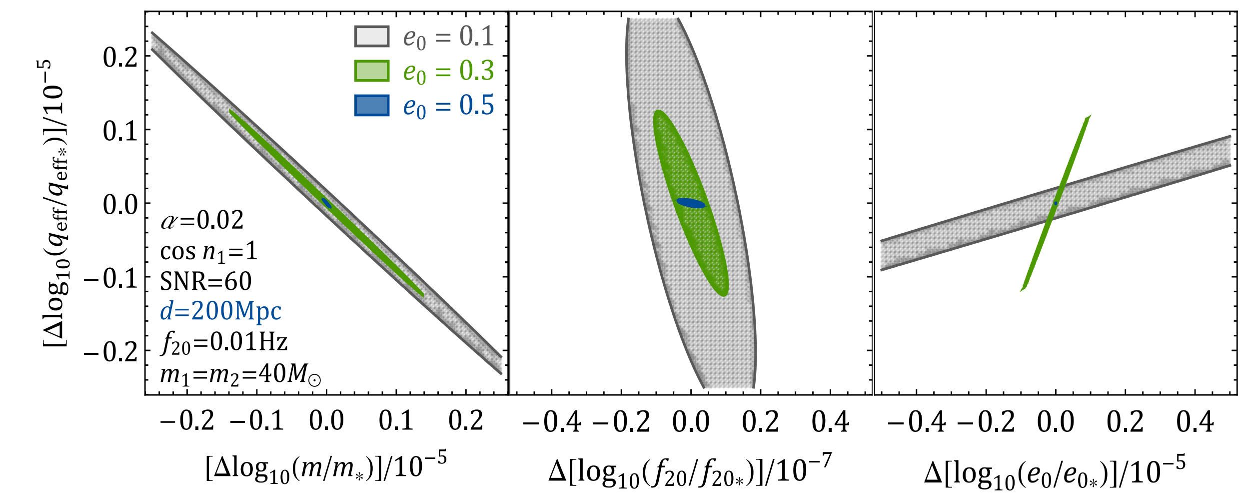

Fig. 3. The 1σ error contours of q_{eff} with the total mass m, the GW frequency of 2nd harmonic f_{20}, and the eccentricity e_0.

Cloud-induced Precession in Pulsar-GA Binaries

In pulsar binaries the five "Keplerian" parameters can often be very precisely measured, while in well-situated systems one can also measure several post-Keplerian (PK) parameters with good precision [3]. In GR, measuring two PK parameters can determine the two masses, conventionally denoted by m_p for the pulsar and m_c for the companion (which is the GA in our case). Measuring more than 2 PK parameters then serves as consistency check. In our case, the orbital evolution depends on further parameters which correct the PK parameters, so the consistency check would fail, as shown in Fig. 4.

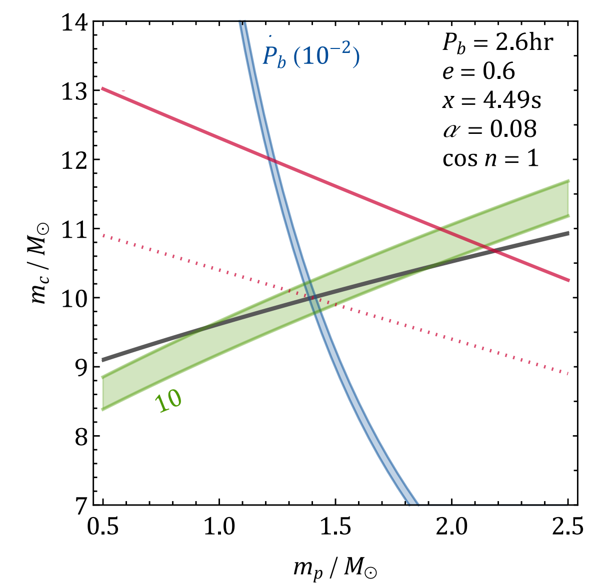

Fig. 4. The PK parameters fit in the (m_p, m_c) plane for a pulsar-GA binary with $\frac{\dot{\chi}_{\mathrm{quadrupole}}}{\dot{\chi}_{\mathrm{GR}}} = 0.1$. The error bands are taken with the same order of magnitude from known pulsar binaries [3]. The solid and dashed magenta curves show the $\dot{\chi}$ without and with subtracting the quadrupole contribution, respectively.

Conclusion

The large mass quadrupole of a GA can excite observable apsidal precession for eccentric binaries. The signal can be potentially observable for BH-GA binaries and pulsar-GA binaries.