Signatures of ultralight bosons in the orbital eccentricity of binary black holes [2403.02415]

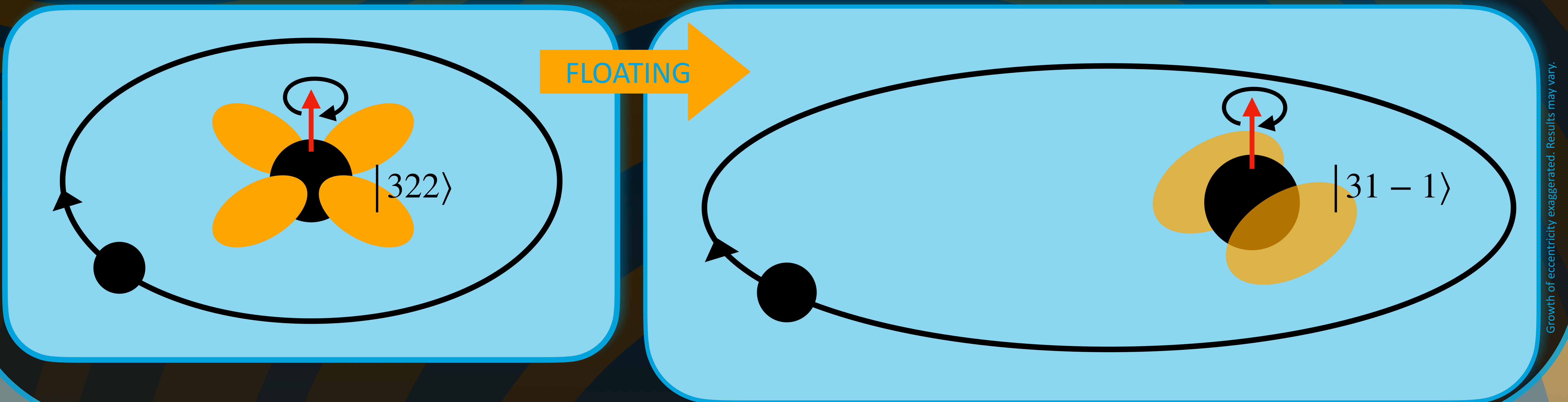
Mateja Bošković[1], **Matthias Koschnitzke**[1, 2], and Rafael A. Porto[1]

1): Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
2): II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

TL;DR

- If black holes carry a superradiant cloud of ultralight particles[1] (e.g., axion-like-particles), a perturbation by a binary object on an eccentric orbit can trigger overtones of the well-known Landau-Zener transition.
- If these transitions float (i.e., stall the mean orbital frequency), they can significantly increase the eccentricity of the orbit.



GRAVITATIONAL ATOM CRASHCOURSE[2]

= instead of proton + electron → **black hole + ultralight bosons**

$\alpha_{em} \rightarrow \alpha_{(grav)} \equiv GM\mu/(\hbar c)$

$\alpha \approx 0.1 \left(\frac{M}{15M_\odot}\right)\left(\frac{\mu}{10^{-12}\,\mathrm{eV}}\right)$

$\mathrm{Im}(\omega_{nlm}) = 0 \rightarrow \mathrm{Im}(\omega_{nlm}) \neq 0$
i.e. SUPERRADIANCE[3]

Fastest growing modes: $|211\rangle$, $|322\rangle$

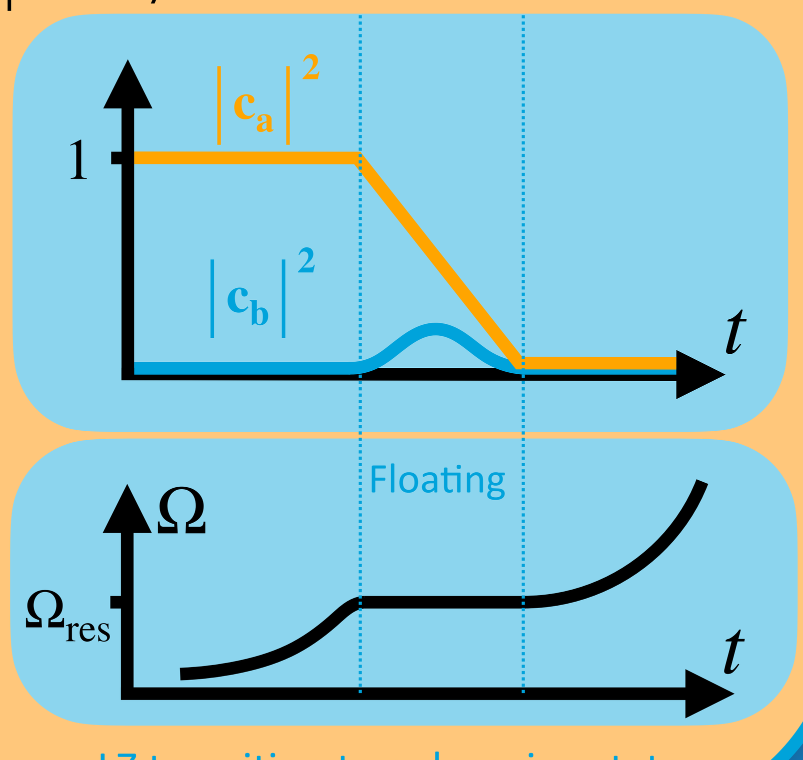
1 fermion → many bosons

Excitation via photons with $\omega \propto \omega_{n_2 l_2 m_2} - \omega_{n_1 l_1 m_1}$ → Excitation via binary companion:[4]

For a two-state system $|a\rangle \equiv |n_a l_a m_a\rangle$ and $|b\rangle \equiv |n_b l_b m_b\rangle$, we get at a Schrödinger eqn.:[5]

$$i\begin{pmatrix}\dot{c}_a\\ \dot{c}_b\end{pmatrix} = \begin{pmatrix}-\frac{\Delta E}{2} & \eta(R_*)\mathrm{e}^{i\Delta m\varphi_*}\\ \eta(R_*)\mathrm{e}^{-i\Delta m\varphi_*} & \frac{\Delta E}{2} - i\Gamma_b\end{pmatrix}\cdot\begin{pmatrix}c_a\\ c_b\end{pmatrix}$$

- ΔE, Δm: energy and angular momentum differences, respectively, Γ_b: decay rate of $|b\rangle$
- $\eta(R_*)$: mixing due to the perturbation by the companion, φ_*: the true anomaly of the orbit.
- When $\Omega_{res} \equiv \dot{\varphi}_* = \Delta E/\Delta m$, we get a Landau-Zener (LZ) transition.
- If the cloud loses energy, its backreaction to the orbit stalls the inspiral → the orbit floats!



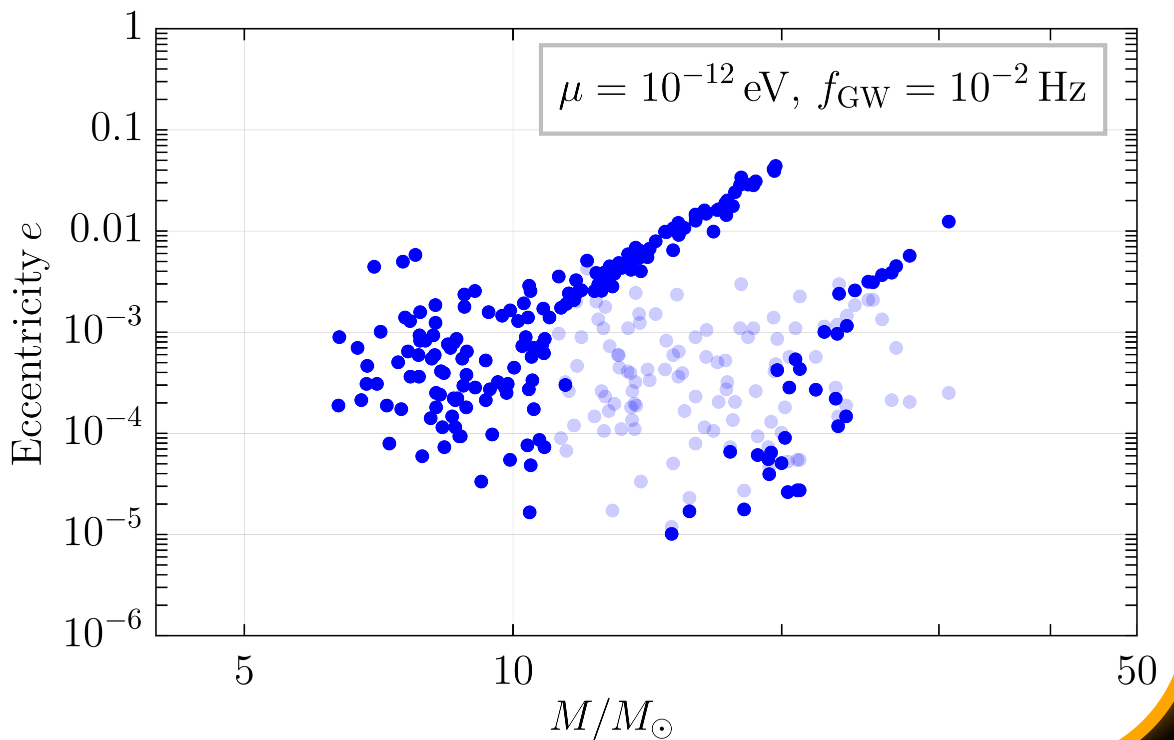
LZ transition to a decaying state

Binary Black Hole Populations in LISA[7]

We take a population of binary BHs with chirp masses $< 10M_\odot$, formed in isolation at an orbital frequency of $10^{-4}\pi$Hz. If the ultralight particle has a mass of 10^{-12} eV, the binaries experience hyperfine and fine transitions, mostly from $|322\rangle$ to $|31-1\rangle$.

At the strongest early resonances, $k \leq -1$, the eccentricity can grow. On the right, we show the eccentricity distribution at 10^{-2} Hz, possibly visible in LISA. Transparent dots show the distribution without the clouds.

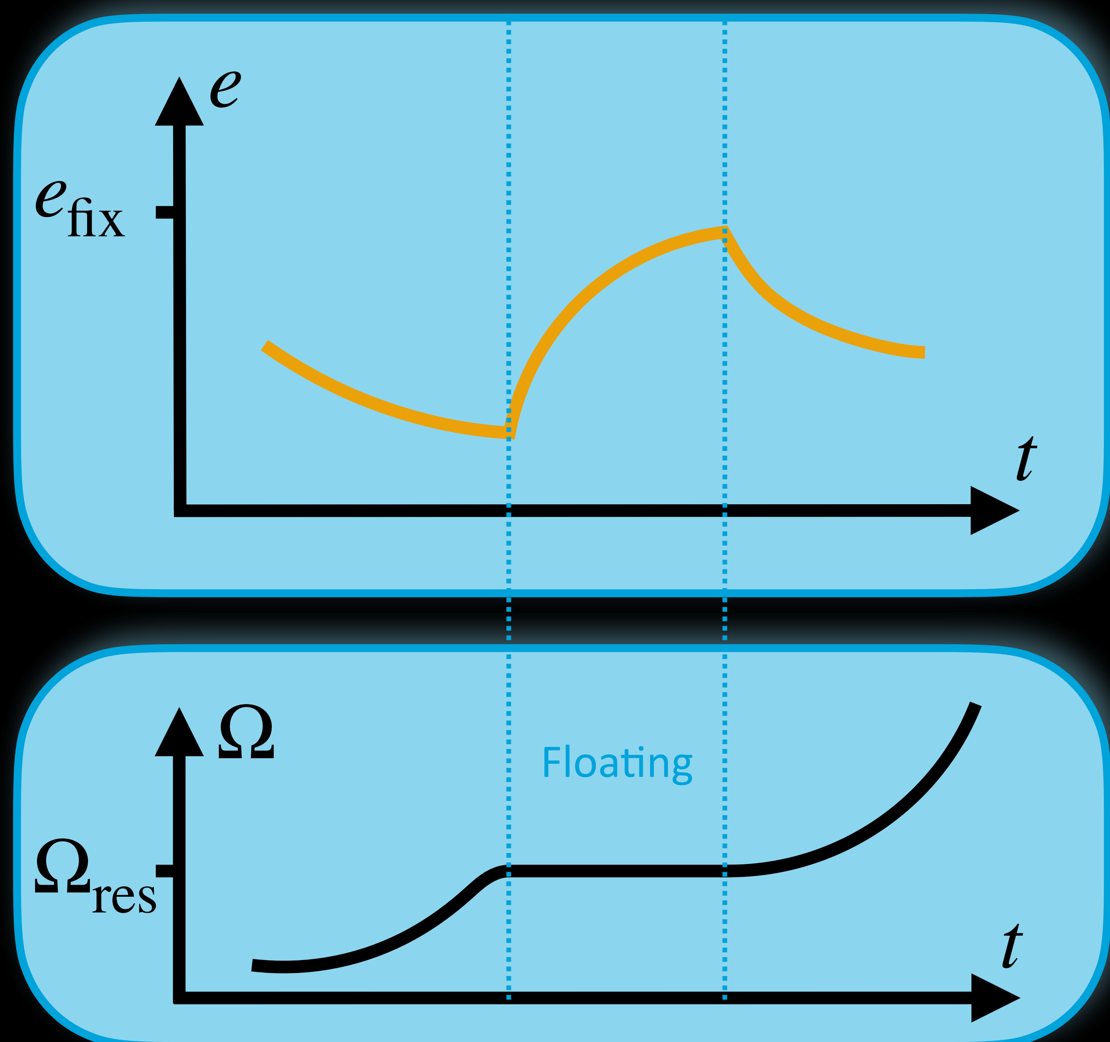
For larger masses, $M_1 = 20\,M_\odot$, with companion $M_2 = 40\,M_\odot$, the eccentricity growth can also fall into the LISA band, with floating times of $\mathcal{O}$(yrs).



If you can read only one panel today, let it be this one:

!Eccentricity Growth!

Because for eccentricity e: $\varphi_* = \vartheta + 2e\sin\vartheta + \mathcal{O}(e^2)$, with φ_*, ϑ the true and mean anomaly, respectively, we get $\mathrm{e}^{i2e\sin\vartheta} = \sum_{k=-\infty}^{\infty} e^k/(|k|!)\mathrm{e}^{ik\vartheta}$ in the mixing term. The condition for resonance becomes $\Omega_{\mathrm{res},k} \equiv \dot{\vartheta} = \Delta E/(\Delta m + k) \rightarrow$ we get early and late resonances due to overtones ($k \neq 0$).[6] During floating, the orbital energy is constant, while the angular momentum scales as $\dot{L}_0 \propto \Omega_{\mathrm{res},k} - \Omega_{\mathrm{res},0} + \mathcal{O}(e^2)$. We have $d(L_0^2) \propto -d(e^2)$, and find that e can change towards a non-zero fixed point! For early resonances, the eccentricity grows.



Eccentricity growth during floating

References:

[1] A. Arvanitaki, et al., Phys. Rev. D 81, 123530 (2010)
[2] R. Brito, V. Cardoso, and P. Pani, Lect. Notes Phys. 906, pp.1 (2015)
[3] S. L. Detweiler, Phys. Rev. D 22, 2323 (1980)
[4] D. Baumann, H. S. Chia, and R. A. Porto, Phys. Rev. D 99, 044001 (2019)
[5] D. Baumann, et al., Phys. Rev. D 101, 083019 (2020)
[6] E. Berti, et al., Phys. Rev. D 99, 104039 (2019)
[7] K. G. Arun, et al. (LISA), Living Rev. Rel. 25, 4 (2022)