

SIGNATURES OF ULTRALIGHT BOSONS IN THE ORBITAL EVOLUTION OF BINARY BLACK HOLES

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SISSA APG Seminar

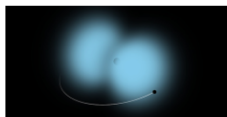
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Overview

- ▶ Existence of ultra-light bosons is highly motivated; can be probed via BH superradiance
- ▶ How to systematically describe the dynamics of scalar clouds in binaries? MB, Porto, Koschnitzke [2512.17887], MB, Savić [2604.xxxxx]
- ▶ BH clouds in binaries generically depleted → in-band signatures; trails of clouds in the orbital elements
MB, Koschnitzke, Porto [2403.02415, 2512.17887]

Physics VIEWPOINT



[Signatures of Gravitational Atoms from Black Hole Mergers](#)

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Gravitational-wave signals from black hole mergers could reveal the presence of “gravitational atoms”—black holes surrounded by clouds of axions or other light bosons.

Ultra-light frontier

- ▶ Strong CP problem (vanishing neutron eDM) \rightarrow QCD axion
Peccei & Quinn ('77); Weinberg ('78); Wilczek ('78)
- ▶ (Wave) DM candidates Hui+ [1610.08297, 2101.11735]
- ▶ IR probes of UV physics (e.g. string axiverse)
Arvanitaki+ [0905.4720]

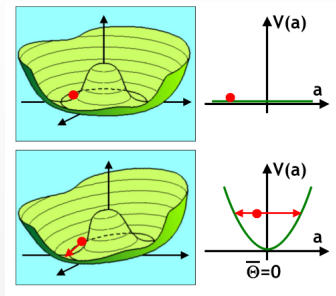
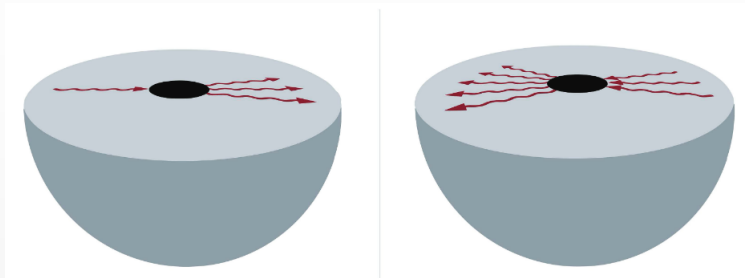


Fig: Raffelt (2010)

Environment production by the BH: Superradiance

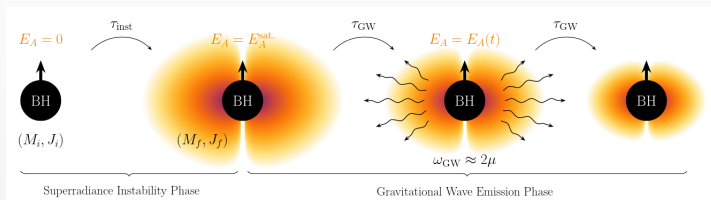
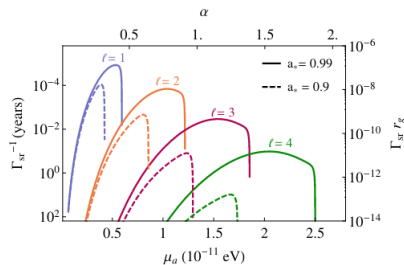
- ▶ BH rotational energy \rightarrow scalar field enhancement if $m\Omega_{\text{BH}} > \omega$
- ▶ Massive boson μ confined around the BH \rightarrow SR instability



Refs: Zeldovich ('71, '72); Press, Teukolsky ('72); Starobinsky ('73); Detweiler ('80); Arvanitaki, Dubovsky [1004.3558]; Endlich, Penco [1609.06723]; East [1807.00043]; Review/Fig: Brito, Cardoso, Pani [1501.06570]

Superradiant dynamics

- ▶ Hydrogen-like spectrum $|n/m\rangle$ w. (hyper)fine corrections
 - ★ Structure constant $\alpha = \mu M / m_{\text{Pl}}^2$
 - ★ Cloud peaks at $r_c \simeq M / \alpha^2$
- ▶ Dissipation from the BH horizon $\Gamma \sim (\omega - m\Omega_{\text{BH}})\alpha^{4l+5}$
- ▶ Fastest growing modes: $|211\rangle, |322\rangle, |433\rangle \dots$

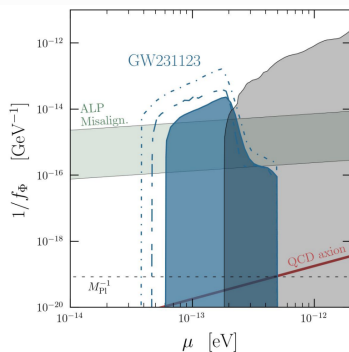
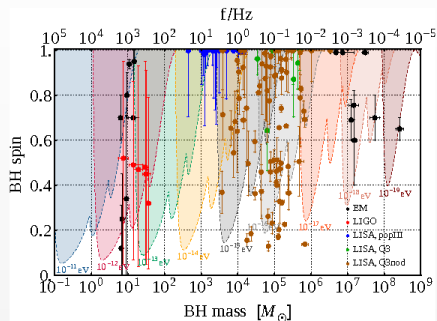


Refs: Detweiler ('80); Dolan [0705.2880]; Arvanitaki+ [0905.4720, 1004.3558, 1411.2263] (U); Brito+ [1411.0686, 1706.06311]; Hui+ [2208.06408]; Siemonsen, May, East [2211.03845]; Figs: (D) Tsukada+ [2011.06995]

Signatures of the cloud in isolation

- ▶ Gaps in the BH spin-mass plane
- ▶ GW emission of the cloud (axion annihilation, level transition)
→ continuous signal and stochastic background

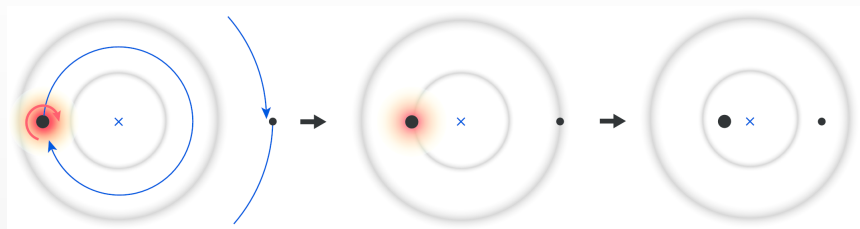
$$\star \tau_{\text{GW}} \simeq 10^8 \text{yr} \left(\frac{M}{10M_{\odot}} \right) \times \left(\frac{\alpha}{0.07} \right)_{|211\rangle}^{-14} \left[\left(\frac{\alpha}{0.2} \right)_{|322\rangle}^{-18} \right]$$



Refs: Arvanitaki+ [0905.4720, 1004.3558, 1411.2263];
 Brito+ [1706.06311 (L), 1501.06570]; Palomba+ [1909.08854]; Zhu+ [2003.03359];
 Khalaf+ [2408.16051]; Caputo, Witte [2507.21788 (R)]

Clouds in binaries: gravitational atomic physics

- ▶ Tidal perturbations from $M_\star \equiv qM$ ($l_\star \geq 2$)
- ▶ Resonantly enhanced level transitions; ionization
- ▶ Cloud survival entangled with orbital dynamics



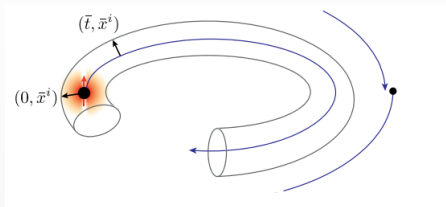
Refs: Baumann+ [1804.03208 (Fig), 1912.04932, 2112.14777];
Tomaselli+ [2305.15460, 2403.03147, 2507.15110];
MB, Porto, Koschnitzke [2403.02415, 2512.17887]

Gravitational atom as an effective object: worldline

- ▶ Effective object — gravitational atom:

$$S_{\text{WEFT}} = - \int d\tau \left[M_{\text{GA}} + \frac{1}{2} \omega_{\mu}^{ab} S_{ab} v^{\mu} + \frac{1}{2} Q_{ab} E^{ab} + \dots \right]$$

- ▶ \rightarrow interacting Hamiltonian

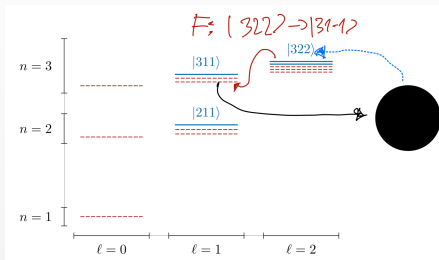


Refs: MB, Porto, Koschnitzke [2512.17887], MB, Savić [2604.xxxxx]

Fig: Baumann, Chia, Porto [1804.03208]

Gravitational atom as an effective object: microphysics

- ▶ (Einstein-)Klein-Gordon equation in the nonrelativistic limit:
$$i\dot{\psi} + \mathcal{I} = \left(-\frac{1}{2\mu} \nabla^2 - \frac{\alpha}{r} + V_R + V_\star + V_{\text{sg}} \right) \psi$$
- ▶ Hydrogenic expansion $\psi \sim \sum c_a(t) (\psi_a + \delta\psi_a)$
 - ★ $V_\star \rightarrow$ level mixing
- ▶ Adiabatic BH-cloud coevolution: $\alpha = \alpha(t)$, $\tilde{a} = \tilde{a}(t)$

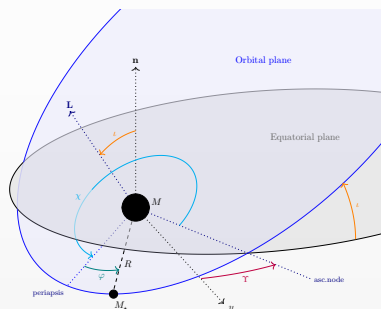


Gravitational atom as an effective object: matching

- ▶ Matching: $Q_{lm}^{\text{GA}} = \int d\mathbf{r} r^l \rho Y_{lm}^*$
 - ★ GAs are inherently rapidly rotating objects \rightarrow
 $Q_c/Q_{\text{BH}} \sim (M_c/M)\alpha^{-5}$
 - ★ $\frac{Q}{Q_{\text{ind}}} \sim \frac{q}{1+q} \alpha^2$ - permant dominates the induced
- ▶ Relativistic effects controlled by
 - ★ the inspiral stage $(\Omega a)^2$ (worldline)
 - ★ the fine-structure constant α (microphysics)

Orbital dynamics of gravitational atoms

- ▶ ≤ 2.5 PN
 - ★ 1 PN, 2 PN pp effects (conservative)
 - ★ SO coupling (conservative)
 - ★ Permanent quadrupole (conservative and mixing)
 - ★ Radiation reaction
- ▶ Lagrange's planetary eqns. $\rightarrow \dot{\mathbb{E}}$,
 $\mathbb{E} \equiv \{a, e, \iota, \vartheta, \chi, \Upsilon\}$ and spin dynamics
- ▶ Obliquity: $\beta \equiv \angle(\mathbf{S}, \mathbf{L})$

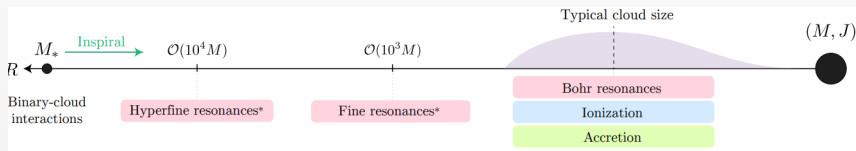
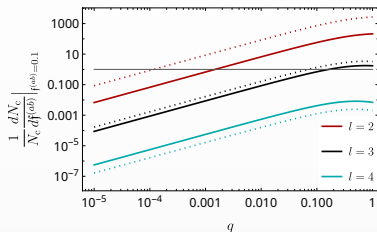


Resonances and non-resonant mixing

- ▶ Strong orbital change at the (narrow) resonance $\Omega_0 = \Delta\epsilon/\Delta m$

Baumann+ [1804.03208, 1912.04932]

- ★ $\Delta m \neq 0$: hyperfine
 - ★ $\Delta l \neq 0$: fine
 - ★ $\Delta n \neq 0$: Bohr
- ▶ ... on top of wide non-resonant mixing with $|n00\rangle$
 - ★ Orbital backreaction builds up over decades in frequency
 - ★ Pre-Bohr: forbidden for $|211\rangle$ (EP); largest for $|322\rangle$



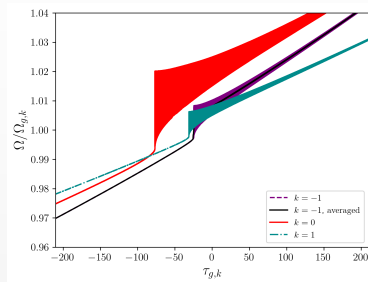
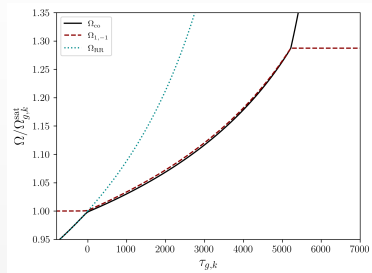
On wide transitions: Tong, Wang, Zhu [2205.10527], Tomaselli [2507.15110], MB, Porto, Koschnitzke [2512.17887] (U); Fig: Della Monica, Brito [2503.23419] (D)

Floating and sinking

- ▶ Strong orbital change at the (narrow) resonance

$$\Omega_0 = \Delta\epsilon / \Delta m \text{ Baumann+ [1804.03208, 1912.04932]}$$

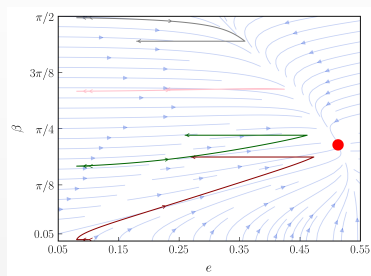
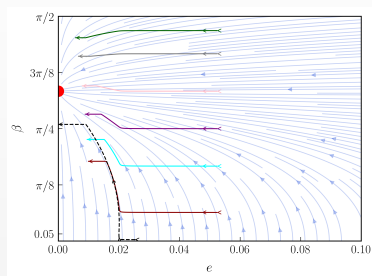
- ★ (Quasi-)floating orbits for $\Delta\epsilon < 0$ transitions
- ★ Sinking transitions for $\Delta\epsilon > 0$



Figs/Ref: MB, Porto, Koschnitzke [2512.17887]

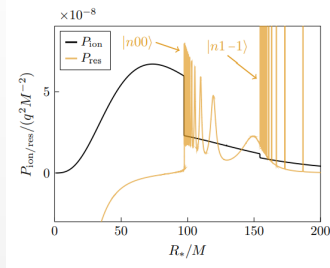
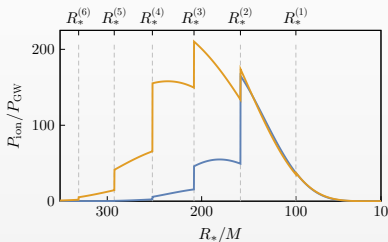
Eccentricity and obliquity: overtones and fixed points

- ▶ Double overtone tower (g, k) $\rightarrow \Omega_{\text{res}} = \Delta\epsilon/(g - k)$
 - ★ $g \in [-l, l]$, $\eta_{g,k} \sim d_{mg}^{(l)}(\beta)$
 - ★ $k \in (-\infty, \infty)$, $\eta_{g,k} \sim e^{|k|}/k!$
- ▶ Floating: fixed points in the eccentricity $e \rightarrow [0.3, 0.6] \leftarrow e$ (early overtones)
- ▶ ... and obliquity $\beta = \angle(\mathbf{L}, \mathbf{S}) \rightarrow \{0, \pi, \pi/3, \dots\}$



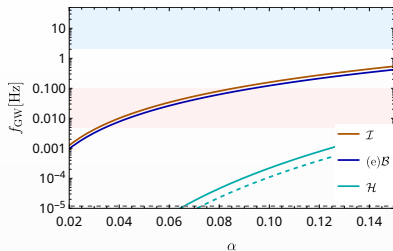
Bohr regime

- ▶ Complex dynamics in the Bohr regime $M\Omega_0 \sim \alpha^3$
 - ★ Transitions to unbound states (ionization)
 - ★ Many resonances (mostly sinking); dipole allowed
 - ★ Resonance accumulation
 - ★ Scalar accretion
 - ★ WEFT $\not\sim$, but selection rules truncate the multipolar expansion
- ▶ Ionization induces dynamical friction that dominates over RR
- ▶ Not yet under control, especially for $q \rightarrow 1$

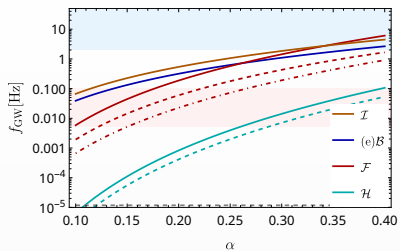


Refs: Baumann+ [2112.14777 (L)];
Tomaselli+ [2305.15460, 2403.03147, 2507.15110 (R)]; Dyson+ [2501.09806]

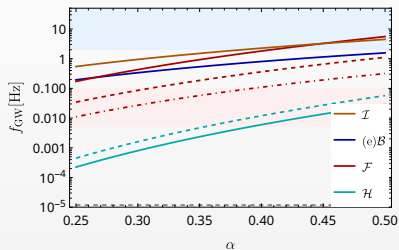
Stellar-mass range ($M = 10M_{\odot}$)



|211⟩

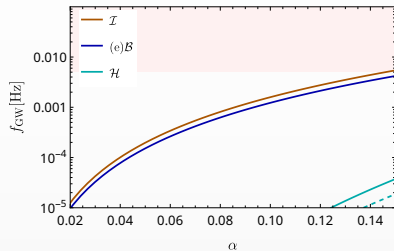


|322⟩

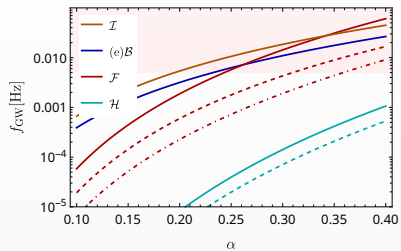


|433⟩

IMRI/EMRI range ($M = 10^3 M_\odot$)



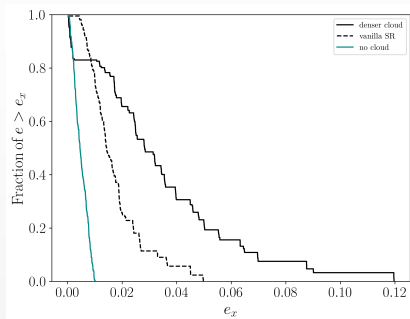
$|211\rangle$



$|322\rangle$

The cloud's eccentric fossil

- ▶ BBH w. $\mathcal{M}_c \lesssim 10M_\odot$; formed in isolation at $f_{\text{GW}} \in \{10^{-5}, 10^{-4}\}$ Hz Brevik+ [1606.09558]
- ▶ Eccentricity growth driven by the fine resonances of the |433⟩ cloud

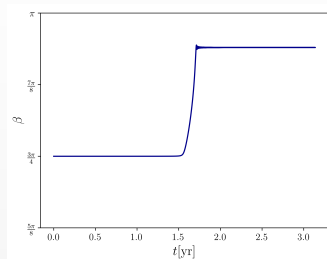
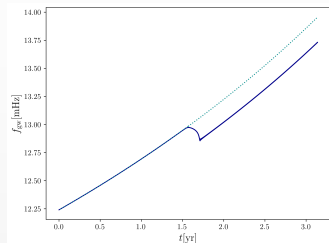


Ref/Fig: MB, Koschnitzke, Porto [2403.02415, 2512.17887]

ex: $\mu \simeq 10^{-13}$ eV, older BHs such that $\alpha \gtrsim 0.3$

In-band pheno: LISA (1/2)

- ▶ Distinctive features in the evolution of orbital elements; large spin-induced quadrupole
- ▶ ex: dynamical capture in the fine-resonance regime for the $|433\rangle$ cloud



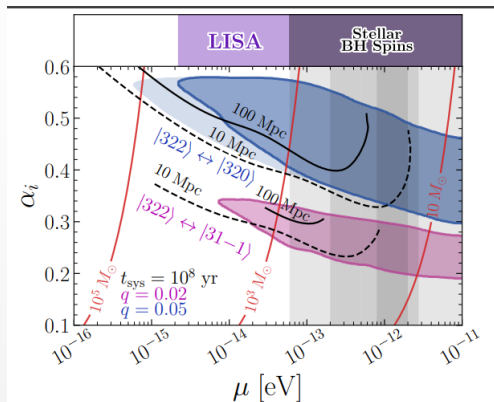
Ref/Figs: MB, Koschnitzke, Porto [2512.17887]

ex: $(50 + 30)M_{\odot}$

In-band pheno: LISA (2/2)

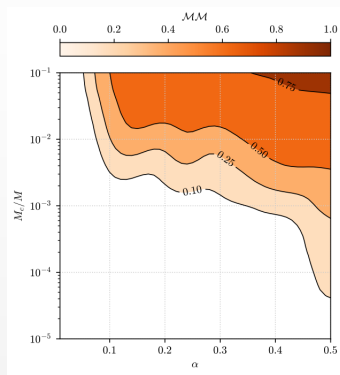
- ▶ More systematic analysis, for $(e, \beta, q) \simeq (0, 0, 10^{-2})$ and focusing on $|322\rangle$

Kim, Lenoci [2508.08367]



In-band pheno: ET

- ▶ Ionization dominates the signal from the $|211\rangle$ cloud in the ET band for $(e, \beta, q) \simeq (0, 0, 10^{-1})$ Della Monica, Brito [2503.23419]
- ▶ For higher- n states floating resonances can occur in the band



Cirrus, cumulus, stratus...

- ▶ Self-consistency of the minimal model
 - ★ Self-gravity effects [Kim, Lenoci \[2508.08367\]](#), [MB, Savić \[2604.xxxxx\]](#)
 - ★ Bohr regime
 - ★ $\alpha \rightarrow 1$ limit
- ▶ Beyond the minimal model
 - ★ Self-interactions
 - ★ Vector clouds
 - ★ other “nuclei”: NS, PBH, DM-induced...

BH superradiance is a powerful tool for constraining ultra-light bosons

- ▶ Distinct phenomenological signatures in dynamic environments (resonances, ionization)...
 - ★ shift in the (e, β) distribution for BBH; in-band transitions
- ▶ ...(probably) weaken some of the presents constraints (TBD!)
- ▶ SR in binaries - more involved but the evolution still tractable
- ▶ Opportunities with ET and LISA