Signatures of ultralight bosons in the orbital evolution of binary black holes

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Overview

- Existence of ultra-light bosons is highly motivated; can be probed via BH superradiance
- BH clouds in binaries generically depleted; new class of pheno signatures $\rightarrow$ relics of the BH cloud in the distribution of the orbital elements MB, Koschnitzke, Porto [2403.02415]
- Towards broad and robust constraints on ultra-light bosons

Black hole probes of the ultra-light frontier

- ▶ BH SR $\rightarrow \rho_c \simeq 10^{35}\mathrm{GeV/cm^3}(M/M_\odot)(\mu/10^{-10}\mathrm{eV})^3$ overdensity w. rich pheno
- ♡ $\simeq$ 10x10 orders of magnitude in $\mu \times (f_a \lesssim m_{\mathrm{Pl}})$
- ♡ Insensitive to the cosmo abundance
- ··· Astrophysics / dynamics needs to be controlled for

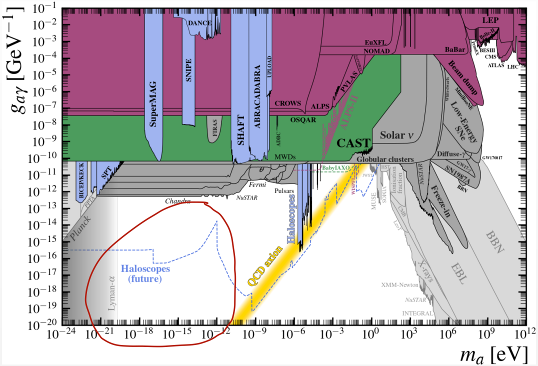
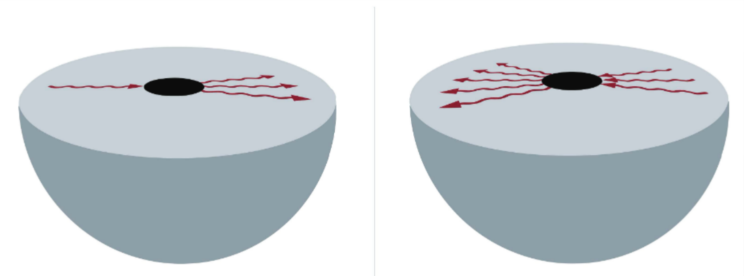


Fig: https://cajohare.github.io/AxionLimits/

Superradiant instability (1/2)

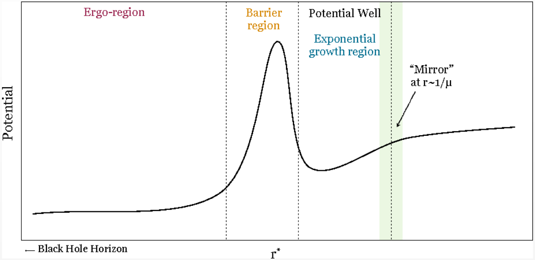
- BH rotational energy $\rightarrow$ scalar field enhancement if $m\Omega_{\rm BH} > \omega$
- Massive boson μ confined around the BH $\rightarrow$ SR instability



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 instability (2/2)

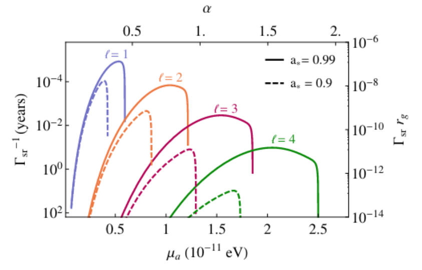
- Hydrogen-like spectrum $|nlm\rangle$ w. (hyper)fine corrections; structure constant $\alpha = \mu M / m_{\rm Pl}^2$
- Dissipation from the BH horizon $\Gamma \sim (\omega - m\Omega_{\rm BH})\alpha^{4l+5}$
- Fastest growing modes: $|211\rangle$, $|322\rangle$, $|433\rangle$...

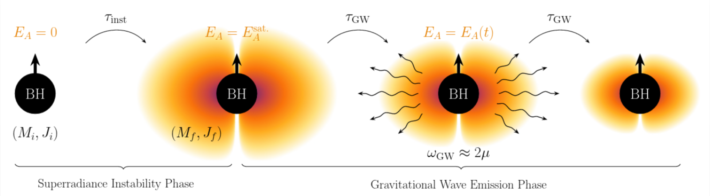


Refs: Detweiler ('80); Dolan [0705.2880]; Arvanitaki, Dubovsky [1004.3558]; Baumann+ [1804.03208, 1908.10370]; East [1807.00043]; Bao, Xu, Zhang [2301.05317]; Review: Brito, Cardoso, Pani [1501.06570]

Superradiant dynamics

- Superradiant growth
  - ⋆ Baryonic/DM accretion $\rightarrow$ heavier clouds
    Hui+ [2208.06408]
- GW emission of the cloud
  $\tau_{\rm GW} \simeq 10^8 {\rm yr} \left(\frac{M}{10 M_\odot}\right) \times$
  $\left(\frac{\alpha}{0.07}\right)^{-14}_{|211\rangle}$ / $\left(\frac{\alpha}{0.2}\right)^{-18}_{|322\rangle}$

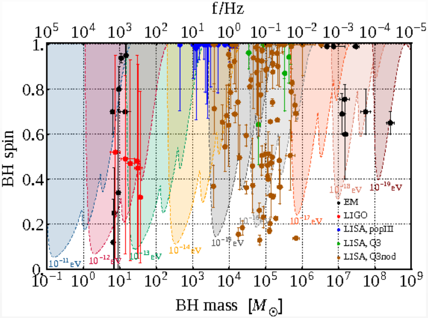


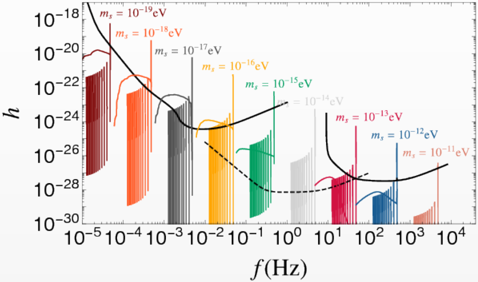


Refs: Arvanitaki+ [0905.4720, 1004.3558, 1411.2263]; Yoshino, Kodama [1312.2326]; Brito+ [1411.0686, 1706.06311, 1501.06570]; Siemonsen, May, East [2211.03845];
Fig: (U) Arvanitaki+ [1411.2263]; (D) Tsukada+ [2011.06995]

Signatures of the cloud

- Gaps in the BH spin-mass plane → systematics under control?
  (also talk by Lenoci)
- GW emission of the cloud (axion annihilation, level transition)

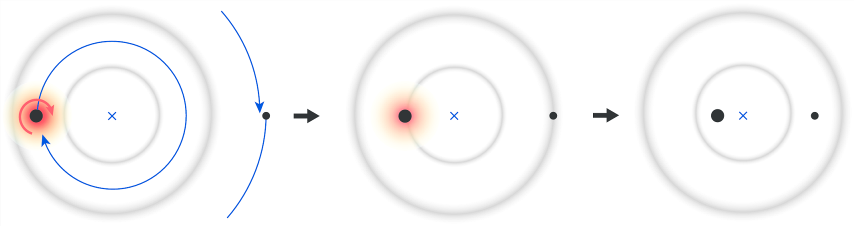




Refs: Arvanitaki+ [0905.4720, 1004.3558, 1411.2263];
Brito+ [1706.06311, 1501.06570]; Palomba+ [1909.08854]; Zhu+ [2003.03359]
Figs: Brito+ [1706.05097]

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 the orbital dynamics



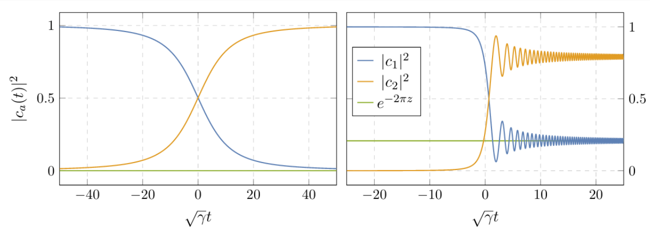
Refs: Baumann+ [1804.03208, 1912.04932, 2112.14777];
Tomaselli, Spieksma, Bertone [2305.15460, 2403.03147];
MB, Koschnitzke, Porto [2403.02415]; Fig: Baumann, Chia, Porto [1804.03208]

Landau-Zener transition

- Tidal mixing of states $|a\rangle, |b\rangle$ (if selection rules)

$$i\begin{pmatrix}\dot{c}_a \\ \dot{c}_b\end{pmatrix} = \begin{pmatrix} -\frac{\Delta\varepsilon}{2} & \eta_0 \left(\frac{R_\star}{R_0}\right)^{-(l_\star+1)} \exp\left[i\Delta m \varphi_\star\right] \\ \text{c.c.} & \frac{\Delta\varepsilon}{2}\end{pmatrix}\begin{pmatrix}c_a \\ c_b\end{pmatrix},$$

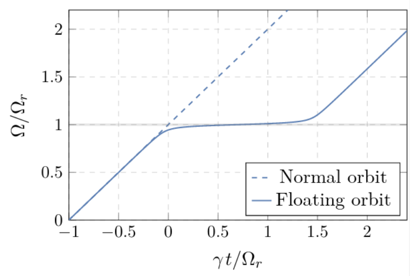
- Slow GW evolution $\Omega(t) \simeq \Omega_0 + \gamma_0 t$
- Transition is adiabatic if $z_0 = \eta_0^2/\gamma_0 \gtrsim 1$
- Bohr ($\Delta n \neq 0$), fine ($\Delta l \neq 0$) and hyperfine ($\Delta m \neq 0$) transitions $\eta_0 \sim \mu q(1+q)^{-(l_\star+1)/3}\alpha^x$
  for $l_\star = 2$: $x = \{2,6,8\} \rightarrow \{\text{B,F,HF}\}$

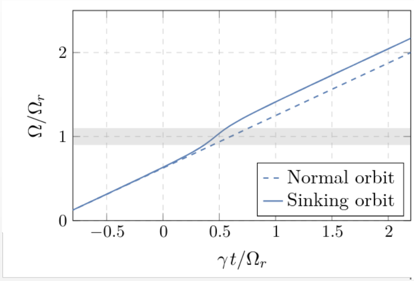


Ref/Fig: Baumann+ [1912.04932]

Orbital backreaction

- Energy-momentum transfer via level mixing and the GW emission balanced by the orbit
  - * If $\Delta\varepsilon < 0$ - floating: $\Omega \approx \mathrm{const}$; adiabaticity $\nearrow$
  - * If $\Delta\varepsilon > 0$ - sinking: Kick in Ω; adiabaticity $\searrow$
- Backreaction $b_0 \sim (M_c/M)[(1+q)^{1/2}/q^{3/2}]\alpha^{-y}$, $y = \{2.5, 3.5, 4\}$
  $\implies$ effective adiabaticity $\zeta = z/r(z,b)$
  - * Floating ($b \gg 1$): $r \sim \sqrt{z}/b$
  - * Sinking ($b \gg 1$): $r \sim (z^2 b^2)^{1/3}$

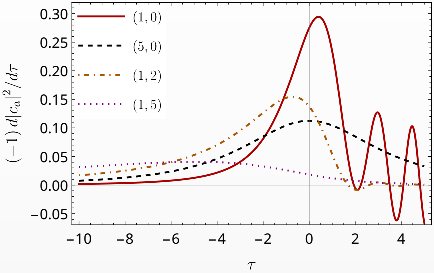




Refs: Baumann+ [1912.04932]; MB, Koschnitzke, Porto [2403.02415]; Tomaselli, Spieksma, Bertone [2403.03147]; Fig: Baumann+ [1912.04932]

LZ transition to a decaying state

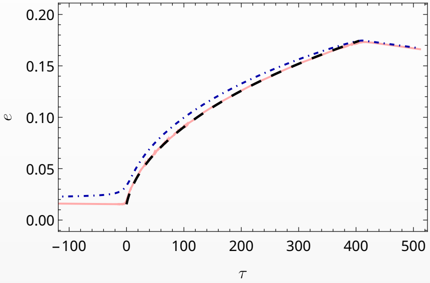
- Target states are decaying
- $v = \Gamma_b/\sqrt{\gamma_0}$ broadens and smooths the LZ effect
  Akulin, Schleich ('92);
  Vitanov, Stenholm ('97)
- Floating $b \gg 1$ and strong decay ($v \gg z$): $r \sim \sqrt{zv/b}$



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

Eccentric overtones and fixed points

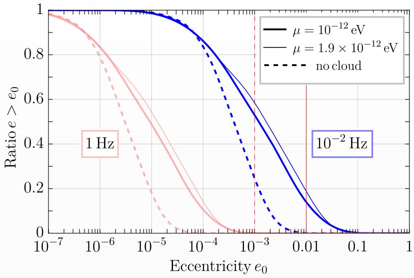
- Eccentric orbit generates overtone resonances $\exp[i\Delta m\varphi_\star] \simeq \sum_k \frac{e^{|k|}}{|k|!}\exp[i(k+\Delta m)\vartheta]$
- Resonance condition $\Omega_k = \frac{\Delta m}{\Delta m + k}\Omega_0$
- For the floating resonances:
  - Main/late overtones: $e \searrow$ (faster than via GW RR)
  - Early overtones: critical (fixed) point $e \to e_{\rm cr} \leftarrow e$
  - $e_{\rm cr} \in [0.3, 0.6]$

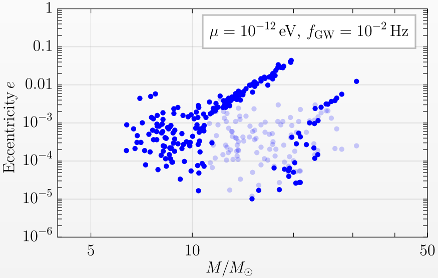


Ref/Fig: MB, Koschnitzke, Porto [2403.02415]

The cloud's eccentric fossil

- BBH w. $\mathscr{M}_c \leq 10 M_\odot$; formed in isolation at $f_{\rm GW} \in \{10^{-5}, 10^{-4}\}\mathrm{Hz}$
  Breivik+ [1606.09558]
- Consider $\alpha \in \{0.1, 0.25\}$ such that $|211\rangle \to \mathrm{GW}$
  - ⋆ Sensitive to $\mu \in [0.5, 2.5] \times 10^{-12}\mathrm{eV}$
- $|322\rangle$ experiences mostly
  - ∗ Hyperfine $|322\rangle \to |320\rangle$
  - ∗ Fine $|322\rangle \to |31-1\rangle$
  - ∗ Strongest overtones $|k| \simeq 0, 1$
  - ∗ All floating as $\Delta\varepsilon < 0$

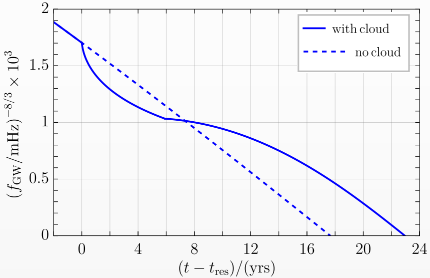




Ref/Figs: MB, Koschnitzke, Porto [2403.02415]

Eccentric in band

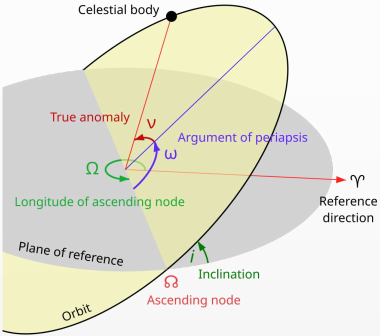
- (Hyper)fine transitions typically outside of the GW detectors
- not impossible! e.g. $M = 20 M_\odot$, $q = 2 \to f_{\rm res} \approx 10\mathrm{mHz}$
- In general $\alpha \gtrsim 0.2$ and $q \gtrsim 1$ have floating timescales $\sim \mathcal{O}(\mathrm{yr})$
- Orbital frequency stalls but not the (peak) GW frequency $f_{\rm GW} \simeq \frac{\Omega}{\pi} \frac{(1+e)^{1.1954}}{(1-e^2)^{3/2}}$



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

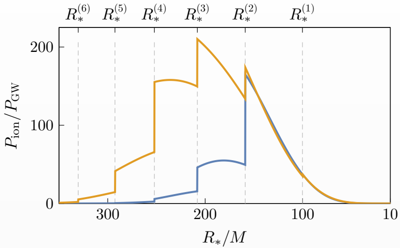
General orbital/BH evolution

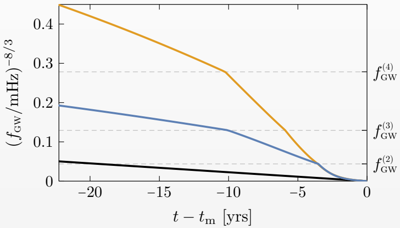
- General orbits → other BBH formation channels
- Consistent description: non-resonant mixing; host BH evolution
  - ⋆ Some steps in Tong, Wang, Zhu [2205.10527], Takahashi, Omiya, Tanaka [2301.13213], Tomaselli, Spieksma, Bertone [2403.03147]
- In progress! MB, Koschnitzke, Porto [24xx.yyyyy]



Bohr regime and late inspiral

- Bound-to-unbound transition: threshold effects
  Baumann+ [2112.14777]
  - Orbital backreaction is dynamical friction
    Tomaselli, Spieksma, Bertone [2305.15460]
  - In the Bohr regime $P_{\rm ion} \gg P_{\rm GW}$
- Dipole transitions allowed
  Tomaselli, Spieksma, Bertone [2403.03147]
- Large TLN due to the cloud $\Lambda \sim (M_{\rm c}/M)\alpha^{-8}$; can be probed already w LIGO
  Chia+ [2306.00050]





Figs: Baumann+ [2206.01212]

Robustness of SR constraints in dynamic environments

- Present constraints depend on highly dynamic environments
  - ∗ Binaries, accretion disks, EMRIs...
  - ∗ Cloud disruption?
  - ∗ Impact on the SR evolution?
- Towards $\alpha \to l/2$ - relativistic corrections
  Brito, Shah [2307.16093], Cannizzaro+ [2309.10021],

  Duque+ [2312.06767]

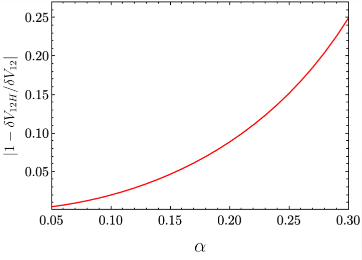
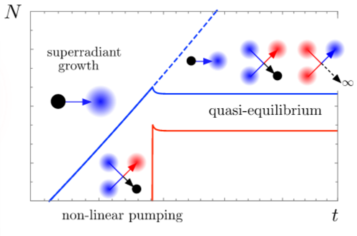
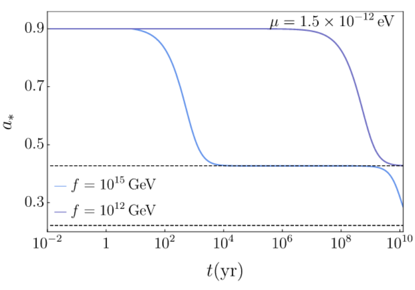


Fig: Cannizzaro+ [2309.10021]

Self-interaction; coupling to other species

- Clouds in the moderate/strong self-interacting regime
  Gruzinov [1604.06422], Baryakhtar+ [2011.11646]
  - ⋆ Mode mixing changes cloud evolution (e.g. early/simultaneous $|322\rangle$ growth); axion wind
  - ⋆ Self-interacting clouds in dynamic environments? Large α regime?
- Coupling to photons
  - ⋆ Parametric resonance Kephart, Rosa [1709.06581], MB+ [1811.04945], Spieksma+ [2306.16447]
  - ⋆ Phenomenology in a consistent EFT?





Figs: Baryakhtar+ [2011.11646]

Cirrus, cumulus, stratus...

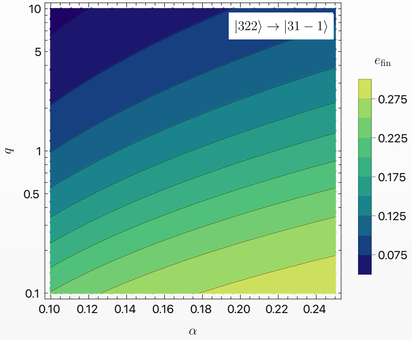
- Vector clouds
  - Phenomenology of isolated clouds similar to the axion casse $|nlm\rangle \to |nljm\rangle$ Baryakhtar, Lasenby, Teo [1704.05081]
  - In a binary: multi-level transitons (degeneracy) [Baumann+ 1912.04932]
- SR clouds from neutron stars
  - Dissipative channel is needed Cardoso, Brito, Rosa [1505.05509]
- SR from primordial BH
- DM-generated clouds: planets, stars, BHs... [Budker+ 2306.12477]

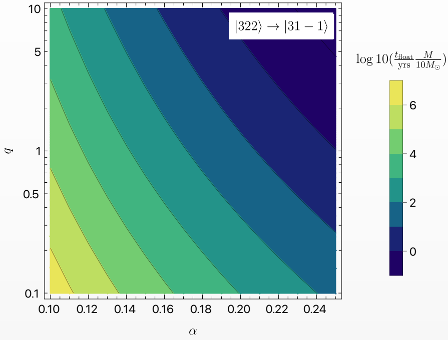
BH superradiance is a powerful tool for constraining ultra-light bosons

- Distinct phenomenological signatures in dynamic environments (resonances, ionization)...
  - ⋆ shift in the e distribution for isolated BBH; in-band transitions; sharp features...
- ...probably weaken some of the presents constraints
- In order to have broad and robust constraints
  - ⋆ General orbits $\rightarrow$ different BBH formation channels
  - ⋆ Relativistic regime $\rightarrow$ large-α
  - ⋆ Self-interacting clouds in dynamic environments
- SR evolution still tractable!

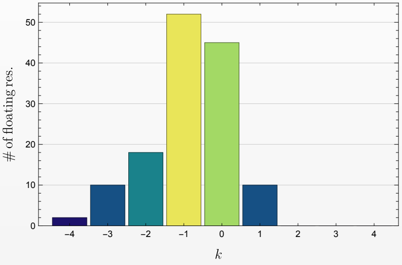
Supplementary material

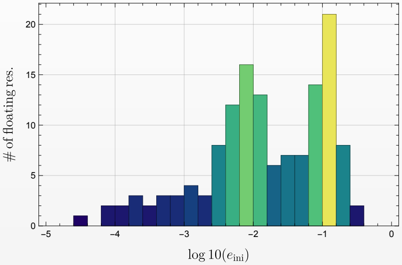
Eccentricity growth / floating time



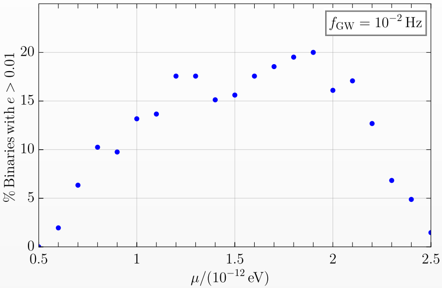


Resonance distribution





Scanning the axion mass



Lower birth frequency