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

Mateja Bošković

GWAT, DESY

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Overview

- Existence of ultra-light axions is highly motivated; can be probed via BH superradiance
- How to systematically describe the dynamics of scalar clouds in binaries? MB, Koschnitzke, Porto [250x.xxxxx], MB, Savić [25yy.zzzzz]
- 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]

Black hole probes of the ultra-light frontier

- (Ultra)-light and weakly-coupled particles: QCD axion (strong CP problem), string axiverse, ultra-light DM...
- 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 $\mu \times (f_a \lesssim m_{\rm Pl})$
  - ♡ Insensitive to the cosmo abundance
  - $\cdots$ Astrophysics / dynamics needs to be controlled for

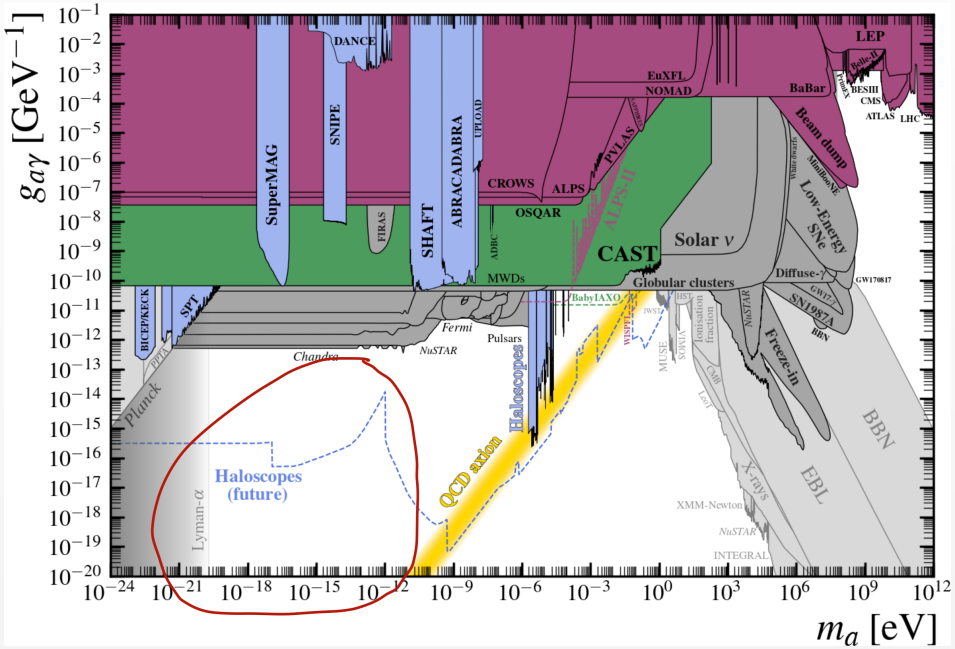
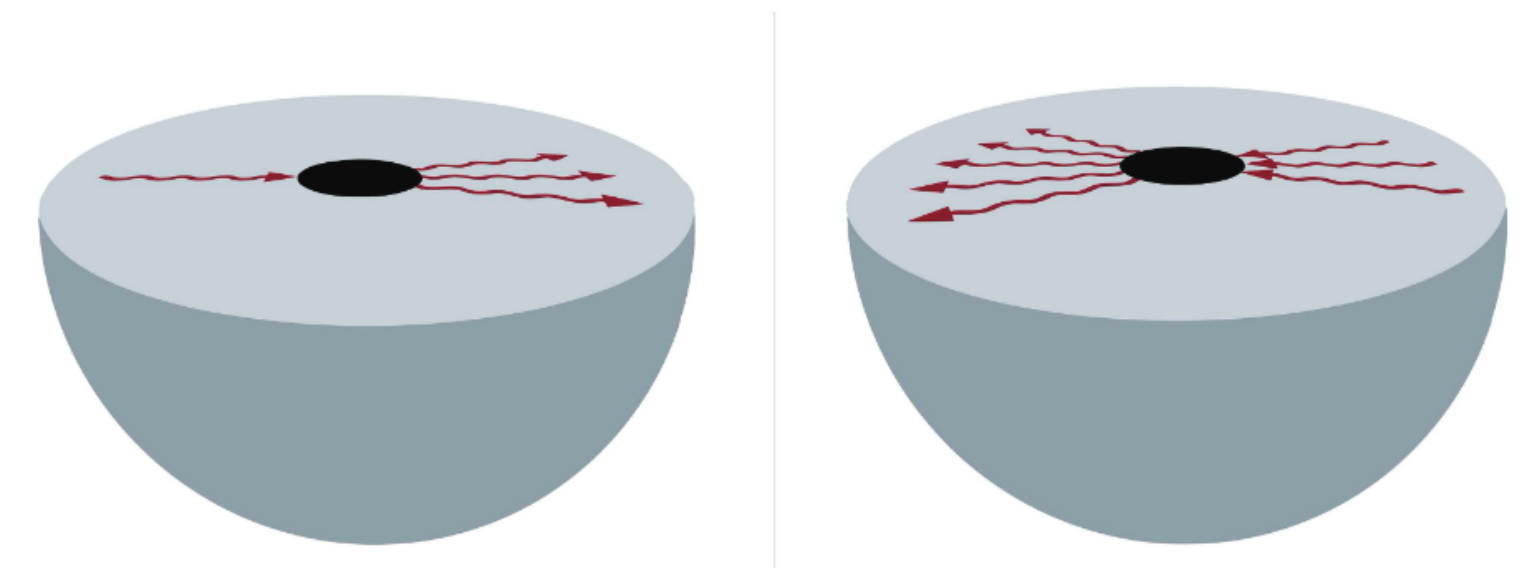


Fig: https://cajohare.github.io/AxionLimits/

Superradiant instability

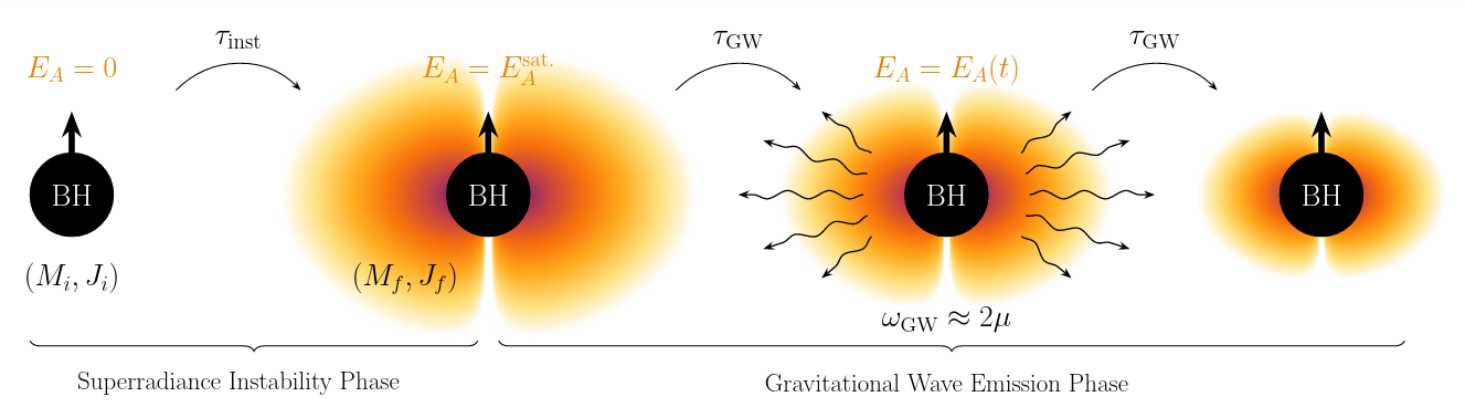
- BH rotational energy $\rightarrow$ scalar field enhancement if $m\Omega_{\rm BH} > \omega$
- Massive boson μ confined around the BH $\rightarrow$ SR instability



Refs: Zeldovich ('71, '72); Press, Teukolsky ('72); Starobinsky ('73); Detweiler ('80); Cardoso+ [hep-th/0404096]; Arvanitaki, Dubovsky [1004.3558]; East [1807.00043];
Review/Fig: Brito, Cardoso, Pani [1501.06570]

Superradiant dynamics

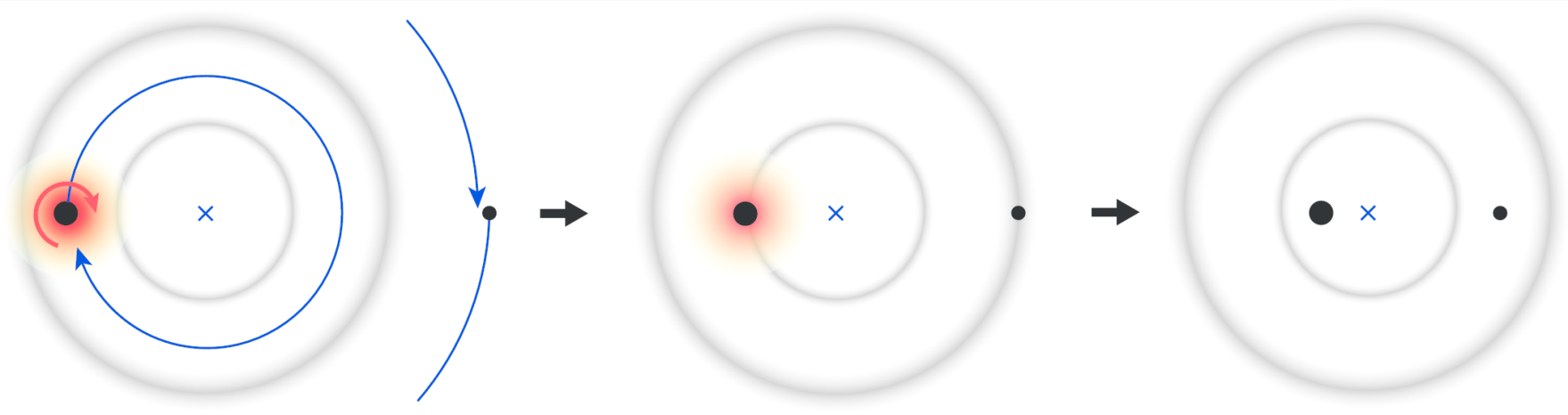
- Hydrogen-like spectrum $|nlm\rangle$ w. (hyper)fine corrections; structure constant $\alpha = \mu M/m_{\rm Pl}^2$
  - ⋆ Cloud peaks at $r_c \simeq M/\alpha^2$
- Dissipation from the BH horizon $\Gamma \sim (\omega - m\Omega_{\rm BH})\alpha^{4l+5}$
- Fastest growing modes: $|211\rangle$, $|322\rangle$,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



Refs: Detweiler ('80); Dolan [0705.2880]; Arvanitaki+ [0905.4720, 1004.3558, 1411.2263]; Yoshino, Kodama [1312.2326]; Brito+ [1411.0686, 1706.06311]; East+ [1807.00043, 2211.03845]; Baumann+ [1804.03208, 1908.10370]; Review: Brito, Cardoso, Pani [1501.06570]; Fig: Tsukada+ [2011.06995]

Clouds in binaries: gravitational atomic physics

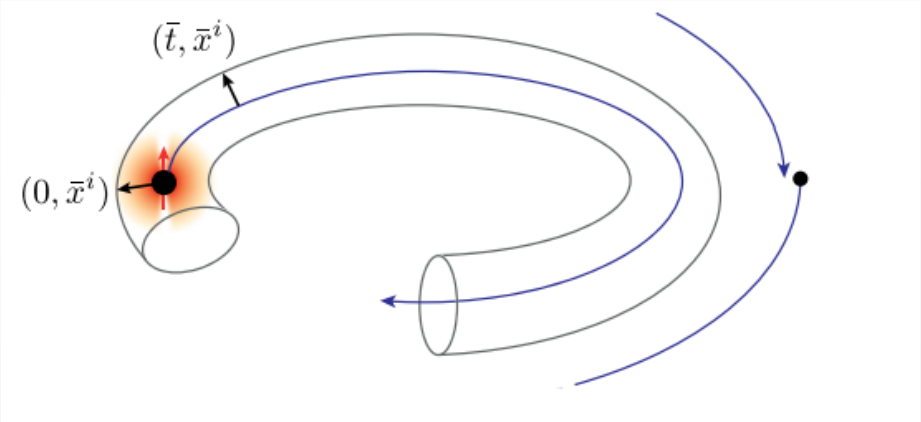
- Tidal perturbations from $M_\star \equiv qM$ ($l_\star \geq 2$)
- Resonantly enhanced level transitions; ionization
- Cloud survival entangled with the orbital dynamics
- Previous work: atomic physics analogies + cloud-orbit balance



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]

Gravitational atom as an effective object

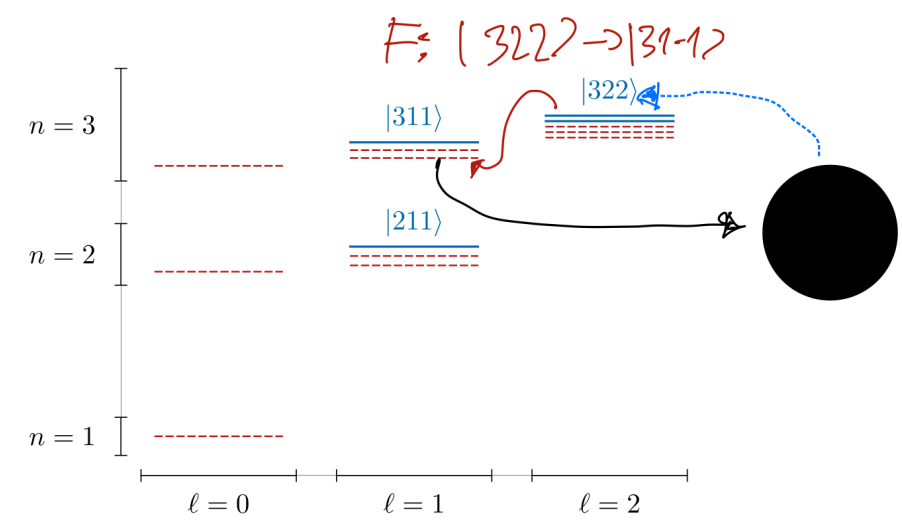
- Effective object - gravitational atom
  $S_{\rm WEFT} = -\int d\tau \left[M_{\rm GA} + Q_{ab} E^{ab} + ...\right],.$
- GAs are inherently rapidly rotating objects $\rightarrow$
  $Q_{\rm perm}$ LO finite size effect Baumann, Chia, Porto [1804.03208]
- Relativistic effects controlled by
  - the inspiral stage $(\Omega a)^2$ (worldline)
  - fine-structure constant α (microphysics)



Ref: MB, Koschnitzke, Porto [250x.xxxxx], MB, Savić [25yy.zzzzz];
Fig: Baumann, Chia, Porto [1804.03208]

Microphysics of the gravitational atom

- (Einstein-)Klein-Gordon in the non-relativistic limit
  $i\dot{\psi} + \mathscr{I} = \left(-\frac{1}{2\mu}\nabla\psi - \frac{\alpha}{r} + V_{\rm R} + V_\star + V_{\rm sg}\right)\psi$
- Perturbative treatment of the bound states / non-perturbative dynamics of state occupancies $\psi \sim \sum c_a(t)\,(\psi_a + \delta\psi_a)$
- BH-cloud co-evolution $\alpha = \alpha(t)$, $\tilde{a} = \tilde{a}(t)$



Ref: MB, Koschnitzke, Porto [250x.xxxxx], MB, Savić [25yy.zzzzz]

Perturbative mixing vs. resonance

- Strong orbital change at the (narrow) resonance $\Omega_0 = \Delta\varepsilon/\Delta m$ Baumann+ [1804.03208, 1912.04932]
  - Bohr ($\Delta n \neq 0$), fine ($\Delta l \neq 0$), hyperfine ($\Delta m \neq 0$)
  - Floating orbits for $\Delta\varepsilon < 0$ transitions
- ... if the cloud survives the early perturbative mixing ← large decay widths of $|n00\rangle$ states Tong, Wang, Zhu [2205.10527]
  - $|211\rangle$: can mix only in the Bohr regime;
    $l \geq 2$ states: driven by $l \geq 2$ multipoles

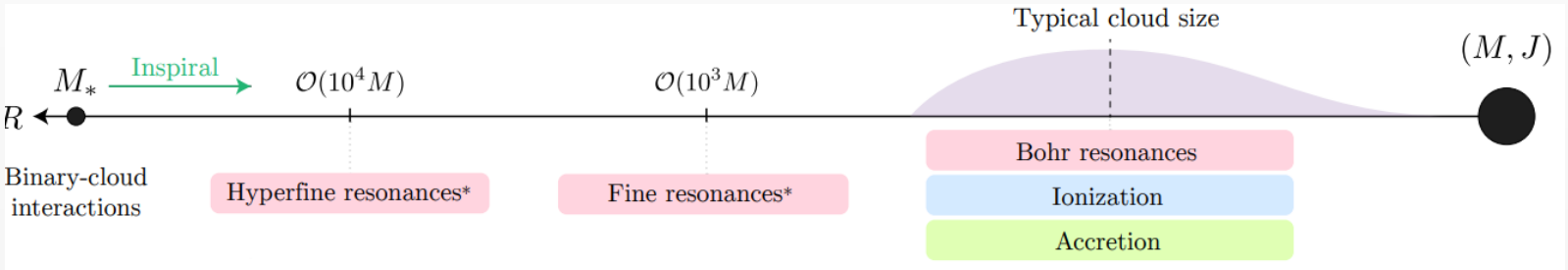
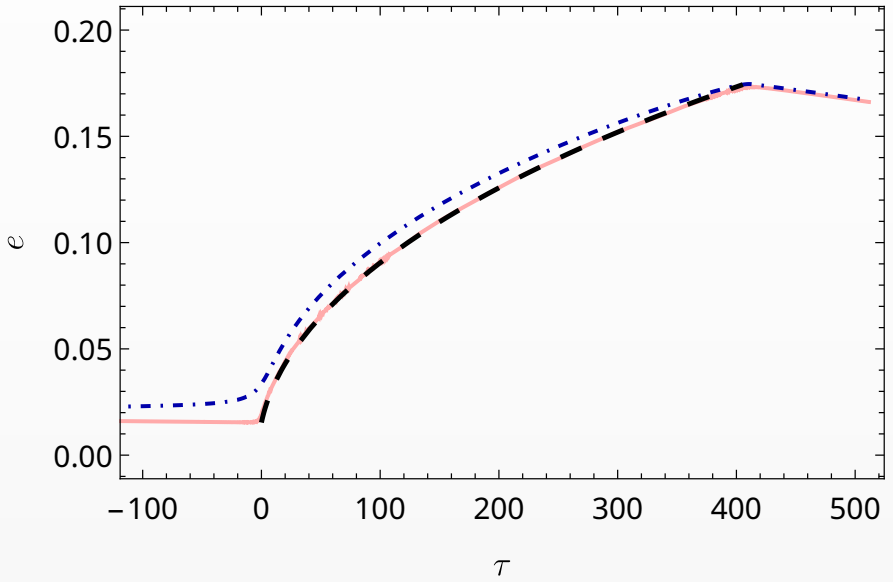


Fig: Della Monica, Brito [2503.23419]

Eccentric overtones and fixed points

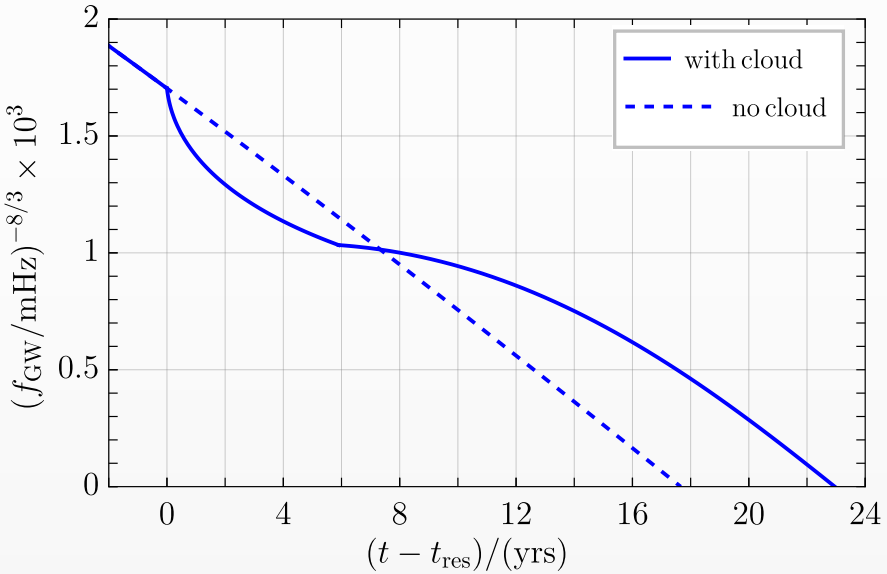
- Eccentric orbit generates overtone resonances
  $\eta_{gk} \sim \eta_0 \frac{(e)^{|k|}}{|k!|}$
- Resonance condition
  $\Omega_k = \frac{\Delta m}{\Delta m + k} \Omega_0$
- For the floating resonances:
  - Main/late overtones: $e \searrow$ (faster than via GW RR)
  - Early overtones: critical (fixed) point $e \to e_{\rm cr} \leftarrow e$
  - $e_{\rm cr} \in [0.3, 0.6]$



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

Eccentric in band

- (Hyper)fine transitions typically outside of the GW detectors
- not impossible! e.g. $M = 20 M_\odot$, $q = 2 \rightarrow f_{\rm res} \approx 10\,{\rm mHz}$
- In general $\alpha \gtrsim 0.2$ and $q \gtrsim 1$ have floating timescales $\sim \mathscr{O}({\rm yr})$
- 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]

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...
- ... 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

Superradiance

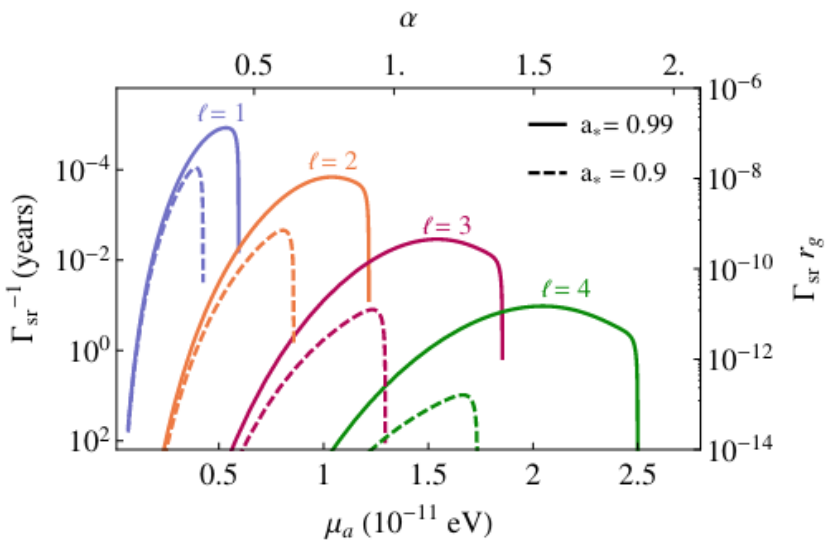
- Wave in the (rest frame of the) dissipative medium $\Box\psi - a\partial_t\psi - \mu^2\psi = 0,\ a > 0$
- Rotating cylinder: $\partial_t \to \gamma(\partial_t + \Omega R\partial_\phi)$
- Ansatz $\psi \sim \exp(-i\omega t + im\phi) \to -ia\gamma(\omega - m\Omega)\psi$
- SR condition: $\omega < m\Omega \to$ wave amplification

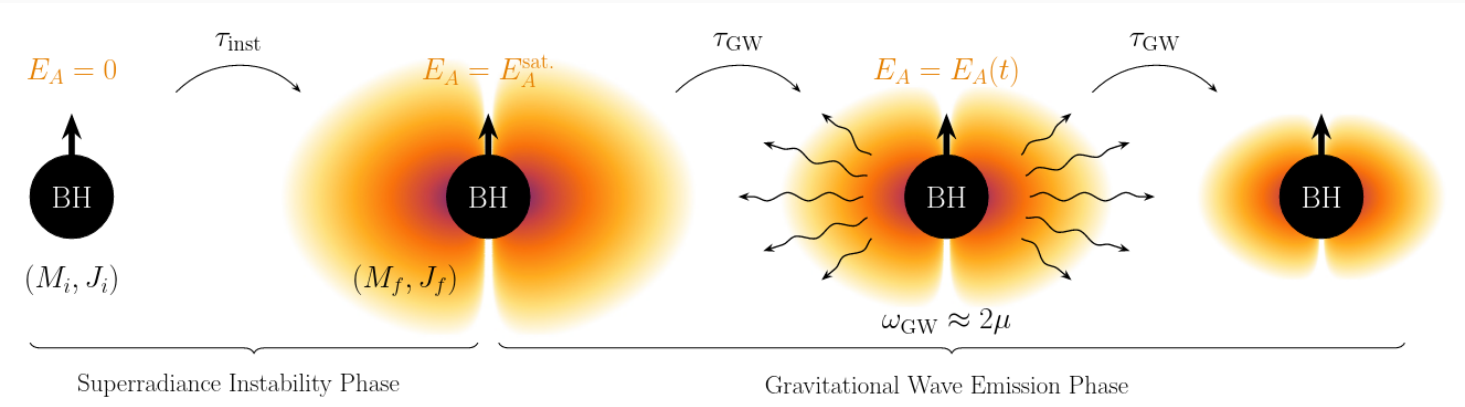
Ref: Zeldovich ('71)

Superradiant dynamics (2/2)

- Superradiant growth
  - ⋆ Baryonic/DM accretion
    $\rightarrow$ heavier clouds
    Hui+ [2208.06408]
- GW emission of the cloud

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

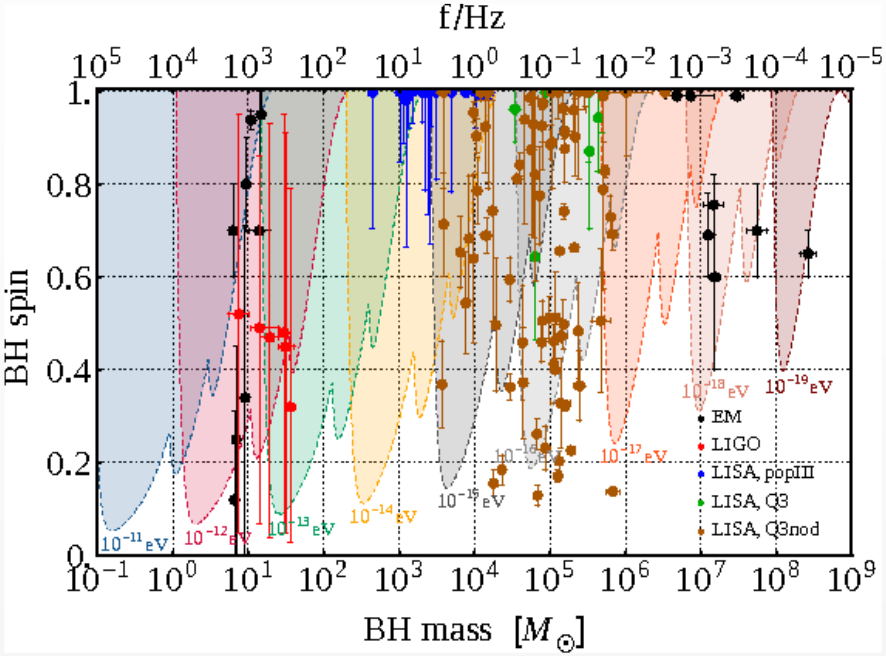


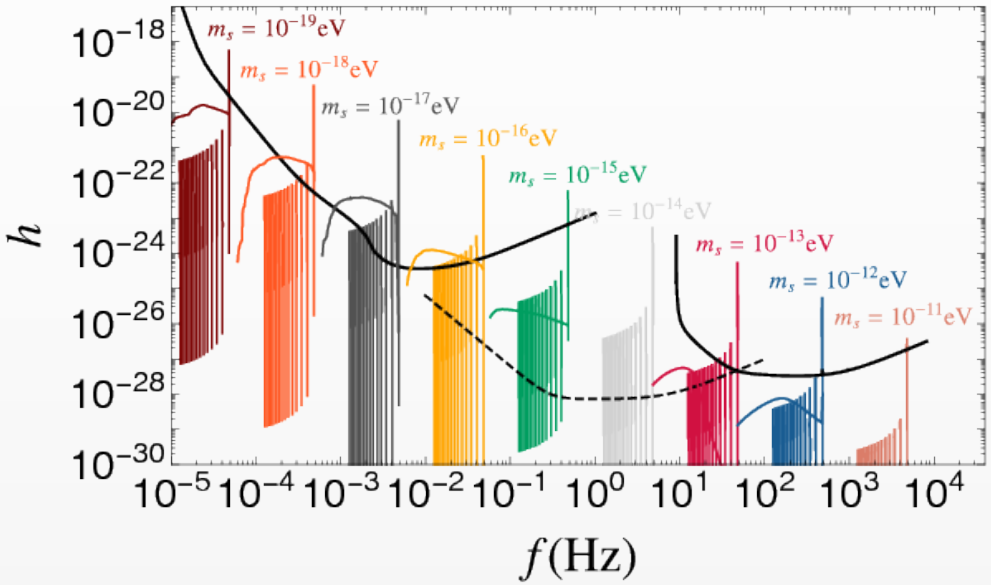


Refs: Arvanitaki+ [0905.4720, 1004.3558, 1411.2263]; Yoshino, Kodama [1312.2326]; Brito+ [1411.0686, 1706.06311, 1501.06570]; Siemonsen, May, East [2211.03845];
Fig: (U) Arvanitaki+ [1411.2263]; (D) Tsukada+ [2011.06995]

Signatures of the cloud

- Gaps in the BH spin-mass plane $\rightarrow$ systematics under control?
- GW emission of the cloud (axion annihilation, level transition) $\rightarrow$ continuous signal and stochastic background

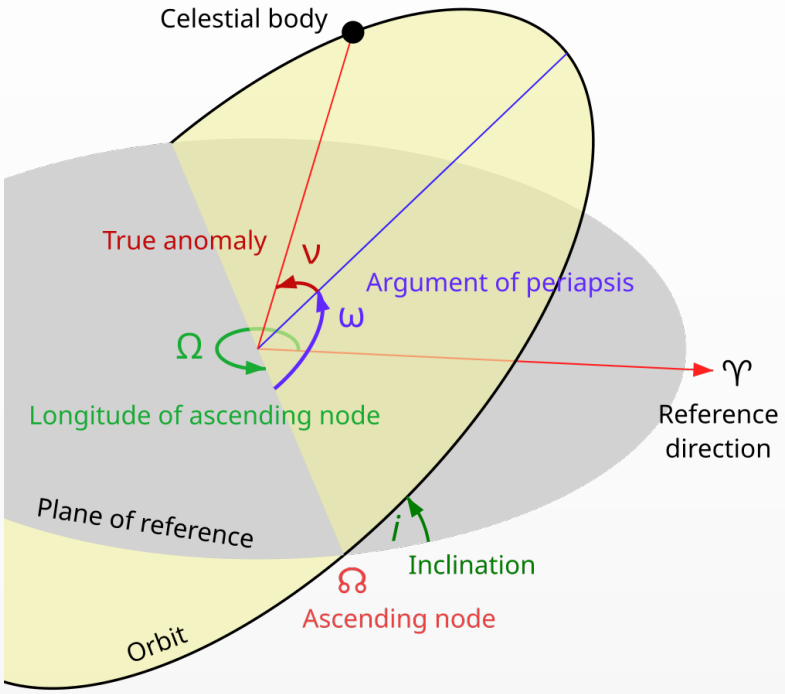




Refs: Arvanitaki+ [0905.4720, 1004.3558, 1411.2263]; Brito+ [1706.06311, 1501.06570]; Palomba+ [1909.08854]; Zhu+ [2003.03359], Khalaf+ [2408.16051]; Figs: Brito+ [1706.05097]

Orbital dynamics of gravitational atoms

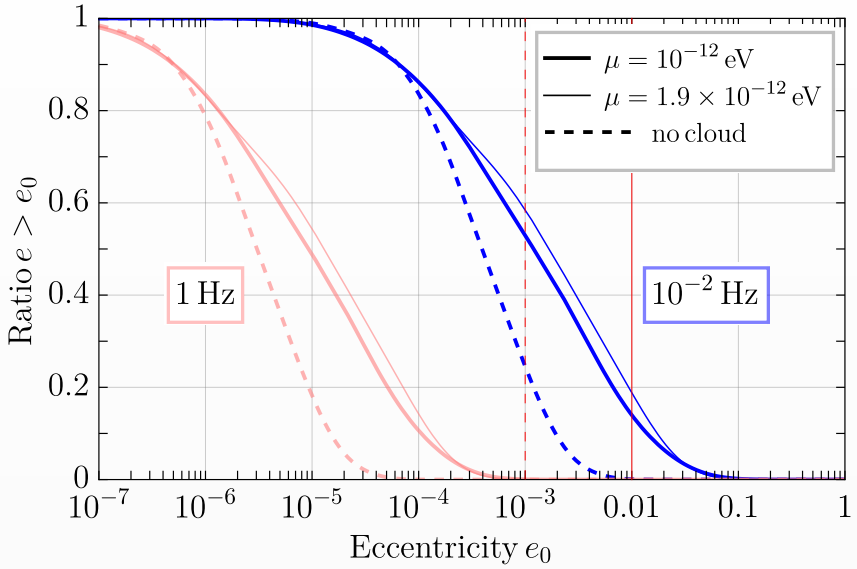
- $\leq 2.5\text{PN}$
  - 1PN, 2PN pp effects (conservative)
  - SO coupling (conservative)
  - Permanent quadrupole (conservative and mixing)
  - Radiation reaction
- Quadrupole of GA dominated by the cloud $\frac{Q_{\rm c}}{Q_{\rm BH}} \sim \alpha^{-5}$
- Lagrange's planetary eqns. $\to \dot{\mathbb{E}}$, $\mathbb{E} \equiv \{a, e, \iota, \vartheta, \chi, \Upsilon\}$

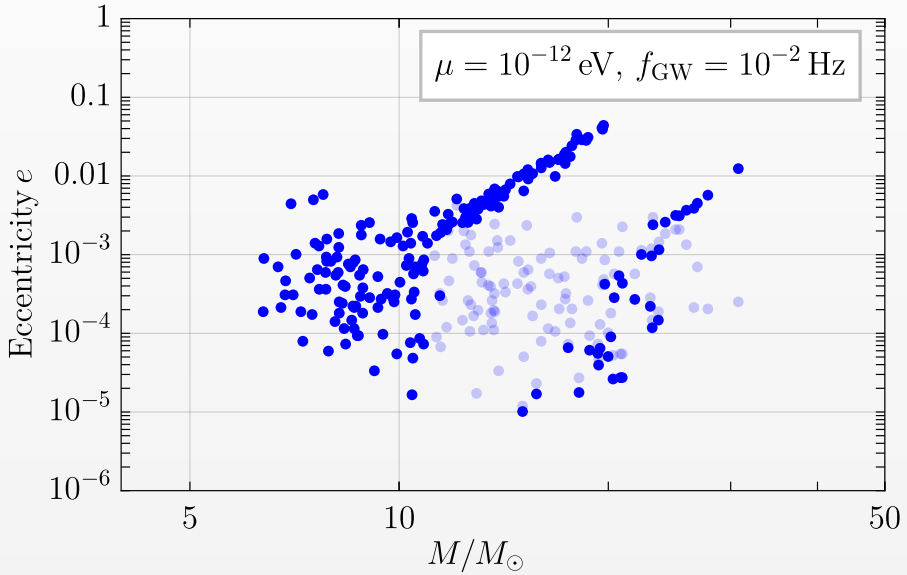


Ref: MB, Koschnitzke, Porto [250x.xxxxx]

The cloud's eccentric fossil (proof of concept)

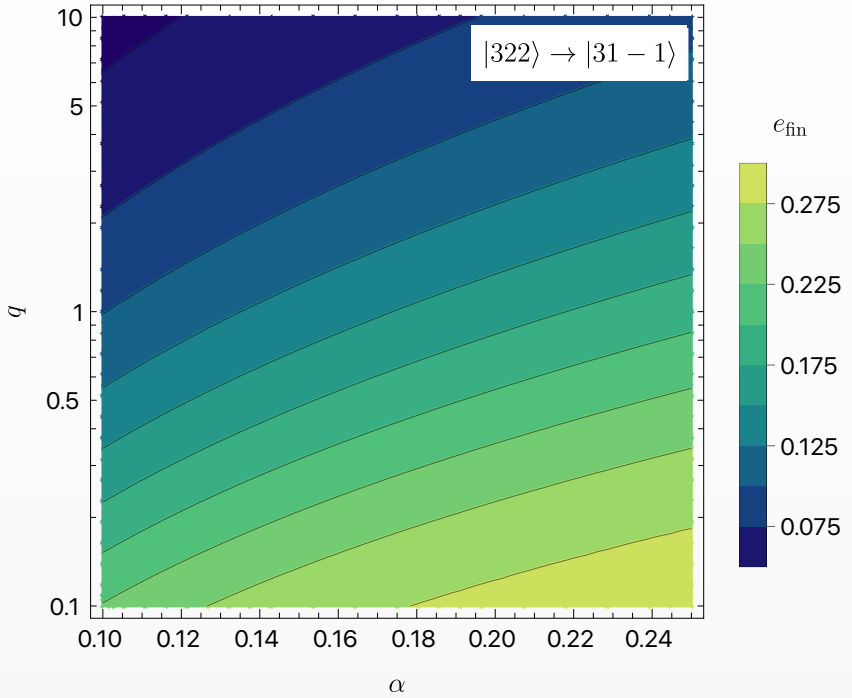
- BBH w. $\mathscr{M}_c \leq 10 M_\odot$; formed in isolation at $f_{\rm GW} \in \{10^{-5}, 10^{-4}\}{\rm Hz}$
  Breivik+ [1606.09558]
- Consider $\alpha \in \{0.1, 0.25\}$ such that $|211\rangle \to {\rm GW}$
  - Sensitive to $\mu \in [0.5, 2.5] \times 10^{-12}{\rm eV}$
- $|322\rangle$ experiences mostly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

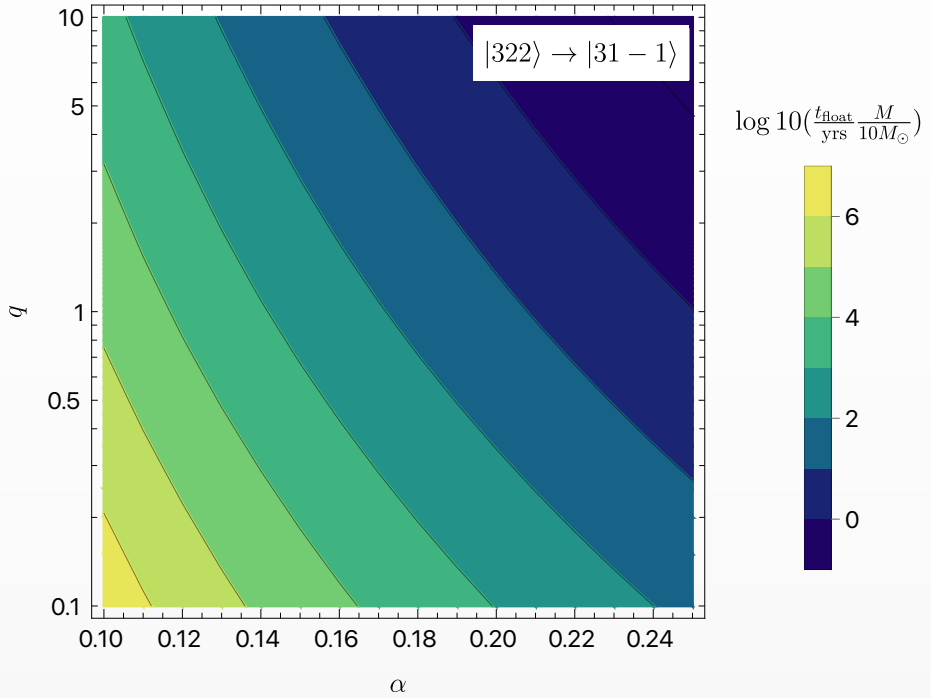




Ref/Figs: MB, Koschnitzke, Porto [2403.02415]

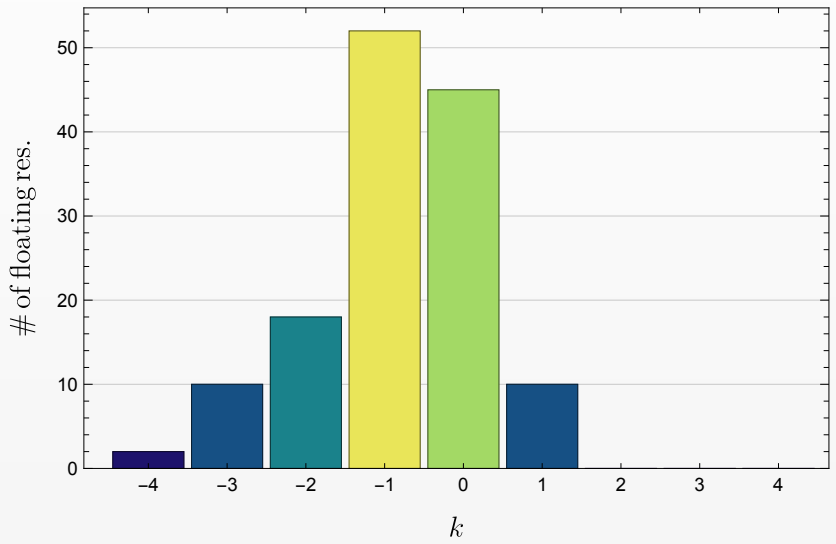
Eccentricity growth / floating time

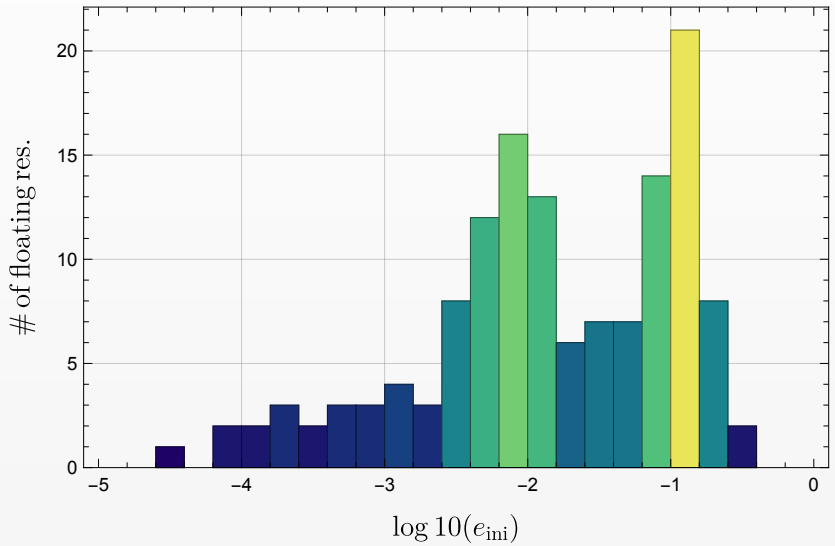




Ref/Figs: MB, Koschnitzke, Porto [2403.02415]

Resonance distribution





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

Bohr regime and late inspiral

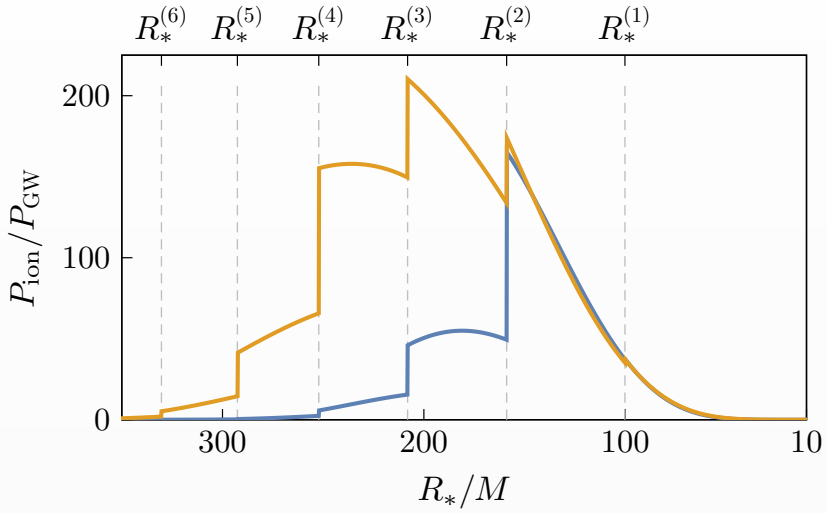
- Bound-to-unbound transition: threshold effects

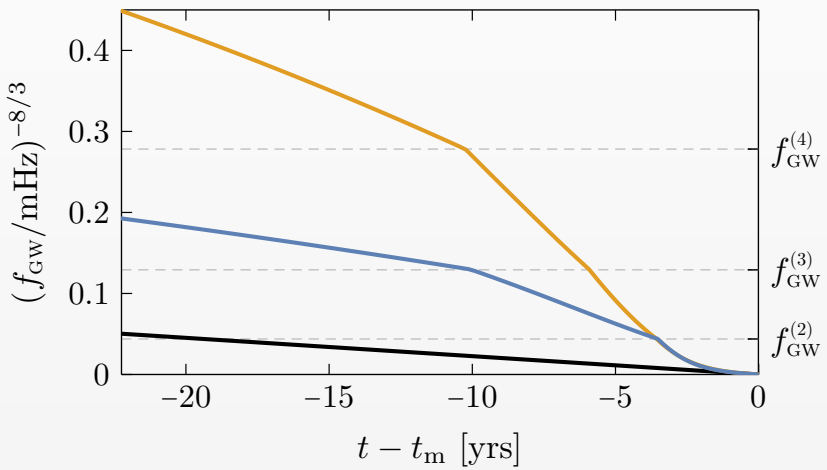
  Baumann+ [2112.14777]

  - 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]
- How likely are the clouds in the late inspiral?

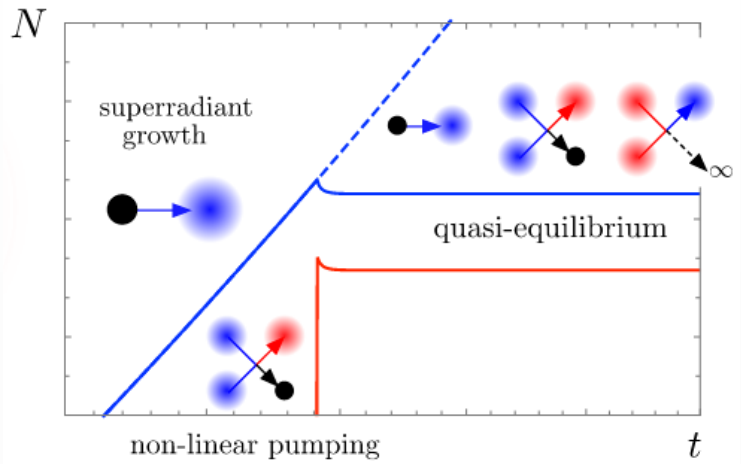


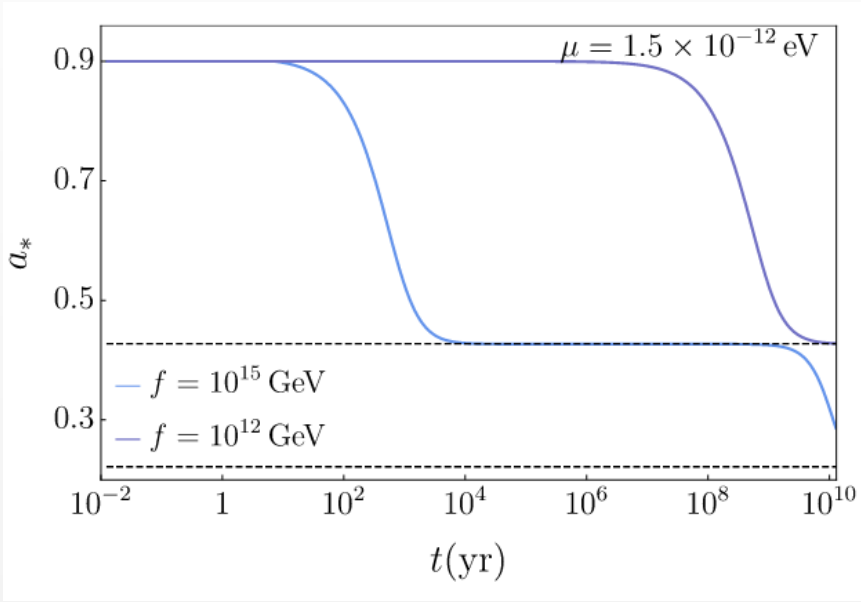


Figs: Baumann+ [2206.01212]

Self-interaction; coupling to other species

- Clouds in the moderate/strong self-interacting regime
  Gruzinov [1604.06422], Baryakhtar+ [2011.11646], Witte, Mummery [2412.03655]
  - ⋆ Mode mixing changes cloud evolution (e.g. early/simultaneous $|322\rangle$ growth); axion wind
  - ⋆ Self-interacting clouds in dynamic environments?
- Coupling to photons
  - ⋆ Parametric resonance
    Kephart, Rosa [1709.06581], MB+ [1811.04945], Spieksma+ [2306.16447]
  - ⋆ Phenomenology in a consistent EFT?





Figs: Baryakhtar+ [2011.11646]