(Binary) black holes as probes of ultra-light particles

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Seminar of Department of Astronomy, Belgrade
11.03.2025.

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, Koschnitzke, Porto [2504.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]

Ultra-light frontier

- (Ultra)-light and weakly-coupled particles
  - 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]

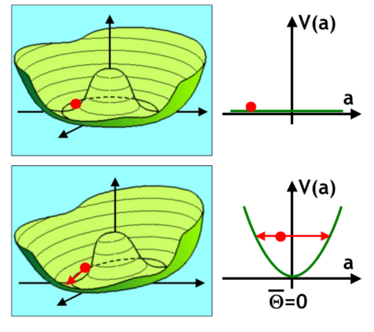


Fig: Raffelt (2010)

Black hole probes of the ultra-light frontier

- BH SR $\rightarrow \rho_c \simeq 10^{35}\mathrm{GeV}/\mathrm{cm}^3(M/M_\odot)(\mu/10^{-10}\mathrm{eV})^3$ 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

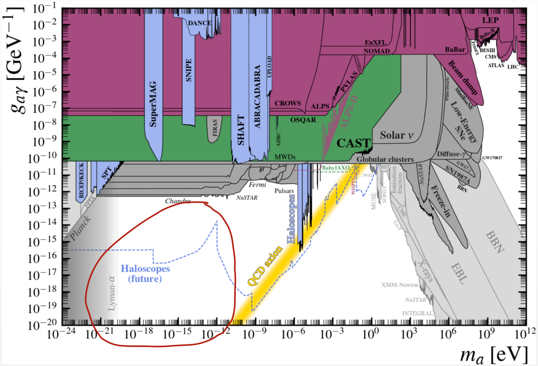


Fig: https://cajohare.github.io/AxionLimits/

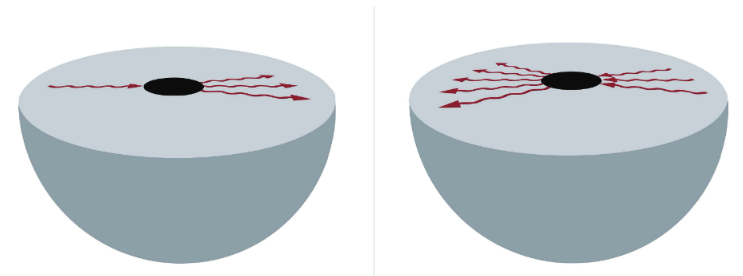
Superradiance

- 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 instability (1/2)

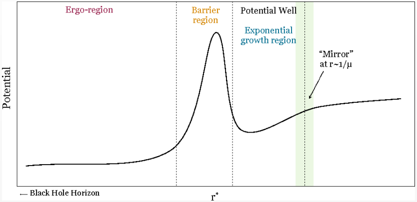
- BH rotational energy $\rightarrow$ scalar field enhancement if $m\Omega_{\rm BH} > \omega$
- Massive boson μ confined around the BH $\rightarrow$ SR instability



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)

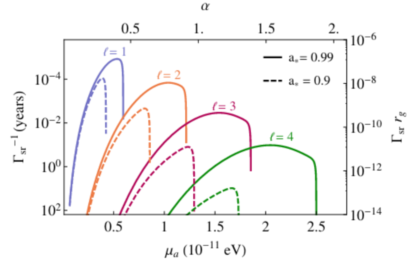
- Hydrogen-like spectrum $|nlm\rangle$ w. (hyper)fine corrections; structure constant $\alpha = \mu M / m_{\mathrm{Pl}}^2$
  - ⋆ Cloud peaks at $r_{\mathrm{c}} \simeq M/\alpha^2$
- Dissipation from the BH horizon $\Gamma \sim (\omega - m\Omega_{\mathrm{BH}})\alpha^{4l+5}$
- Fastest growing modes: $|211\rangle$,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

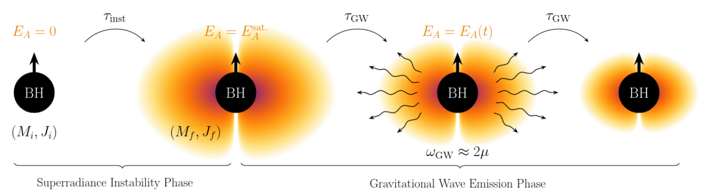


Refs: Detweiler ('80); Dolan [0705.2880]; Arvanitaki, Dubovsky [1004.3558]; Baumann+ [1804.03208, 1908.10370]; East [1807.00043];
Review: Brito, Cardoso, Pani [1501.06570]

Superradiant dynamics

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

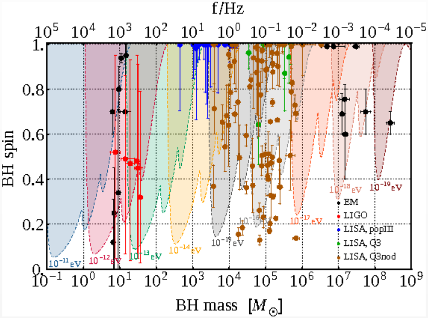


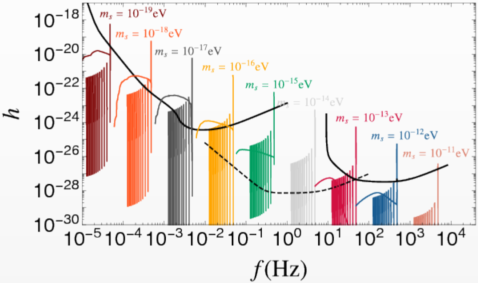


Refs: Arvanitaki+ [0905.4720, 1004.3558, 1411.2263]; Yoshino, Kodama [1312.2326]; Brito+ [1411.0686, 1706.06311, 1501.06570]; Siemonsen, May, East [2211.03845];
Fig: (U) Arvanitaki+ [1411.2263]; (D) Tsukada+ [2011.06995]

Signatures of the cloud

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

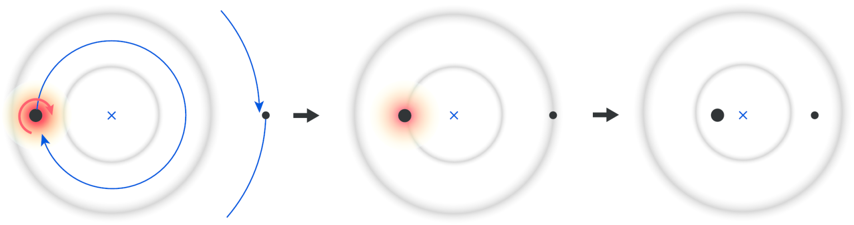




Refs: Arvanitaki+ [0905.4720, 1004.3558, 1411.2263]; Brito+ [1706.06311, 1501.06570]; Palomba+ [1909.08854]; Zhu+ [2003.03359], Khalaf+ [2408.16051]; Figs: Brito+ [1706.05097]

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]

Microphysics of the gravitational atom

- (Einstein-)Klein-Gordon in the non-relativistic limit
  $i\dot{\psi} + \mathscr{I} = \left(-\frac{1}{2\mu}\nabla\psi - \frac{\alpha}{r} + V_{\mathrm{R}} + V_{\star} + V_{\mathrm{sg}}\right)\psi$
- Perturbative treatmemt of the bound states...
  $\psi = \sum_a c_a(t)(R_a Y_a + \delta\psi)e^{-i(\varepsilon_a + \delta\varepsilon_a)t}$
- ... non-perturbative dynamics of state occupancies

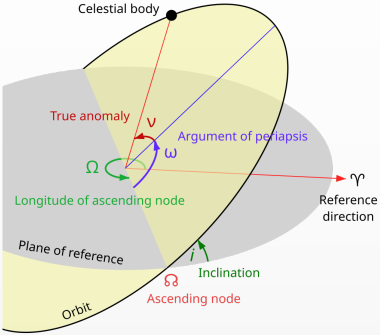
$$i\begin{pmatrix}\dot{c}_a \\ \dot{c}_b\end{pmatrix} = \begin{pmatrix}-\frac{\Delta\varepsilon}{2} & \langle a|\, V_\star \,|b\rangle_{lm} \\ \mathrm{c.c.} & \frac{\Delta\varepsilon}{2}\end{pmatrix}\begin{pmatrix}c_a \\ c_b\end{pmatrix},$$

- BH-cloud co-evolution

Ref: MB, Koschnitzke, Porto [2504.xxxxx]

Orbital dynamics of gravitational atoms

- ≤ 2.5PN
  - 1PN, 2PN pp effects (conservative)
  - SO coupling (mostly conservative)
  - Permanent quadrupole (conservative and mixing)
  - Radiation reaction
- Lagrange's planetary eqns. $\rightarrow \dot{\mathbb{E}}$, $\mathbb{E} \equiv \{a, e, \iota, \vartheta, \chi, \Upsilon\}$



Ref: MB, Koschnitzke, Porto [2504.xxxxx]

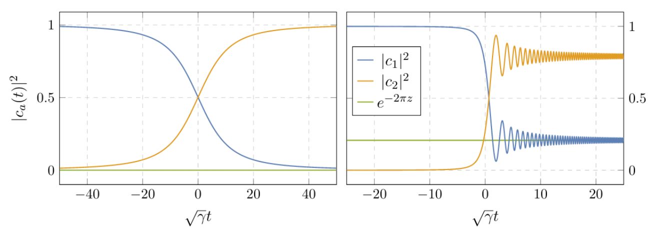
Time-dependent quadrupole

- Quadrupole of GA dominated by the cloud $\frac{Q_{\mathrm{c}}}{Q_{\mathrm{BH}}} \sim \alpha^{-5}$
- $V_Q \supset N_{\mathrm{c}}\sqrt{1-\sigma^2}\sum \eta \cos(\delta + \Delta m \vartheta)$
- $\eta = \langle a | V_\star | b \rangle_{lm}$, $\sigma = |c_a|^2 - |c_b|^2$
- Resonance at $\dot{\delta} = -\Delta m \Omega \to$ secular flow of $\{a, e, \imath\}$

Ref: MB, Koschnitzke, Porto [2504.xxxxx]

Landau-Zener phenomenology

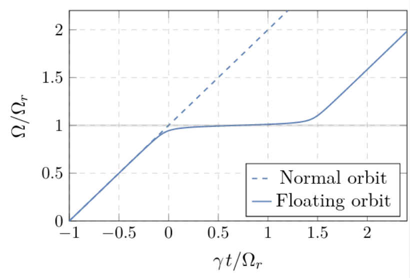
- (circular) Slow GW evolution in the early inspiral in the vicinity of the overtone resonance $\Omega(t) \simeq \Omega_0 + \gamma t$
- Main resonance at $\Omega_0 = \Delta\varepsilon / \Delta m$
- Transition is adiabatic if $z = \eta^2/\gamma \gtrsim 1$
- Bohr ($\Delta n \neq 0$), fine ($\Delta l \neq 0$) and hyperfine ($\Delta m \neq 0$) transitions

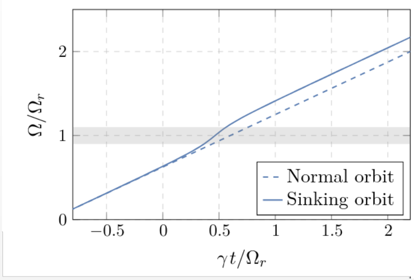


Ref/Fig: Baumann+ [1912.04932]

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 $b_0 \sim (M_c/M)/\sqrt{q^3\Omega} \implies$ effective adiabaticity $\zeta = z/r(z,b)$
  - Floating ($b \gg 1$): $r \sim \sqrt{z}/b$
  - Sinking ($b \gg 1$): $r \sim (z^2 b^2)^{1/3}$

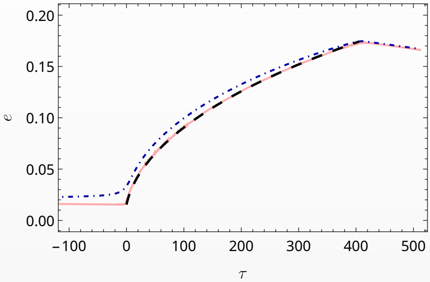




Refs: Baumann+ [1912.04932]; MB, Koschnitzke, Porto [2403.02415, 2503.xxxxx]; Tomaselli, Spieksma, Bertone [2403.03147]; Fig: Baumann+ [1912.04932]

Equatorial example: Eccentric overtones and fixed points

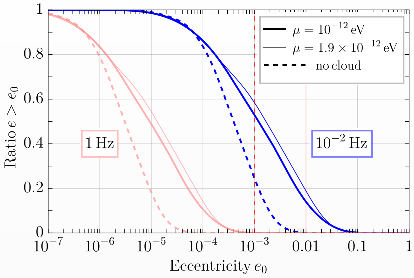
- Eccentric orbit generates overtone resonances $\eta_{gk} \sim \eta_0 \frac{(e)^{|k|}}{|k!|}$
- Resonance condition $\Omega_k = \frac{\Delta m}{\Delta m + k} \Omega_0$
- For the floating resonances:
  - Main/late overtones: $e \searrow$ (faster than via GW RR)
  - Early overtones: critical (fixed) point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

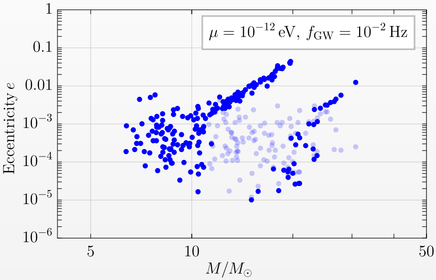


Ref/Fig: MB, Koschnitzke, Porto [2403.02415]

The cloud's eccentric fossil

- BBH w. $\mathscr{M}_c \leq 10 M_\odot$; formed in isolation at $f_{\rm GW} \in \{10^{-5}, 10^{-4}\}$Hz
  Breivik+ [1606.09558]
- Consider $\alpha \in \{0.1, 0.25\}$ such that $|211\rangle \to \mathrm{GW}$
  - ⋆ Sensitive to $\mu \in [0.5, 2.5] \times 10^{-12}$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 $\Delta\varepsilon < 0$

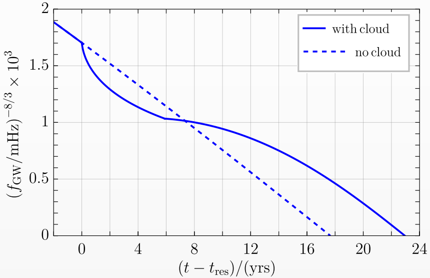




Ref/Figs: MB, Koschnitzke, Porto [2403.02415]

Eccentric in band

- (Hyper)fine transitions typically outside of the GW detectors
- not impossible! e.g. $M = 20M_\odot$, $q = 2 \to f_\mathrm{res} \approx 10\mathrm{mHz}$
- 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 $f_\mathrm{GW} \simeq \frac{\Omega}{\pi} \frac{(1+e)^{1.1954}}{(1-e^2)^{3/2}}$



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

Cirrus, cumulus, stratus...

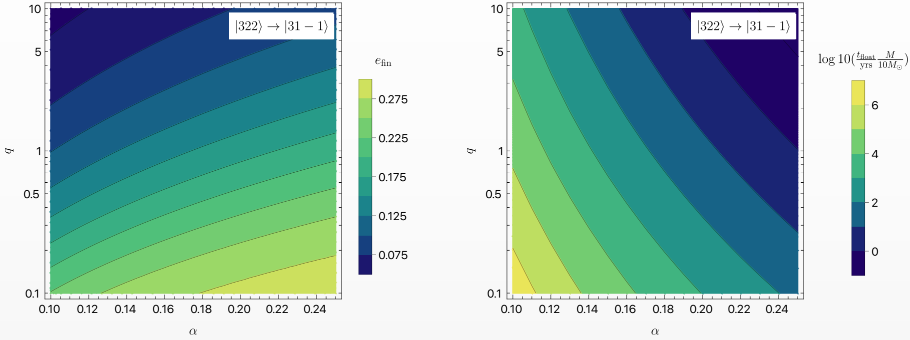
- Moderate/strong self-interactions change the SR evolution
- Vector clouds
  - ⋆ Phenomenology of isolated clouds similar to the axion casse $|nlm\rangle \to |nljm\rangle$ Baryakhtar, Lasenby, Teo [1704.05081]
  - ⋆ In a binary: multi-level transitons (degeneracy) [Baumann+ 1912.04932]
- SR clouds from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

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

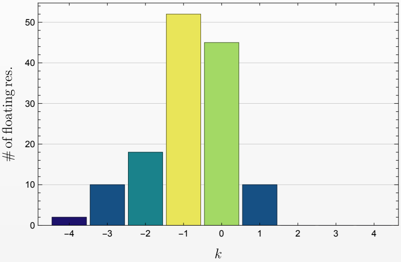
- Distinct phenomenological signatures in dynamic environments (resonances, ionization)...
  - shift in the e distribution for isolated BBH; in-band transitions; sharp features...
- ...(probably) weaken some of the presents constraints
- In order to have broad and robust constraints
  - General orbits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

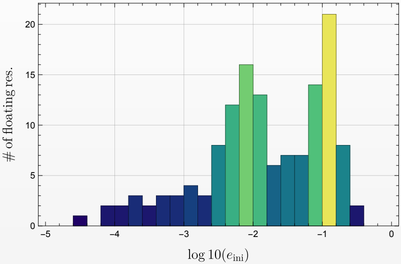
Supplementary material

Eccentricity growth / floating time

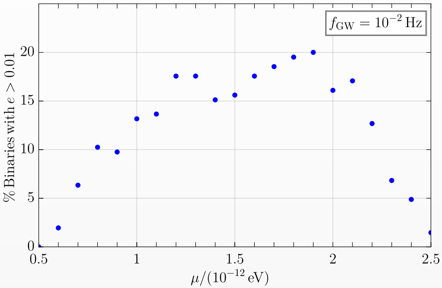


Resonance distribution

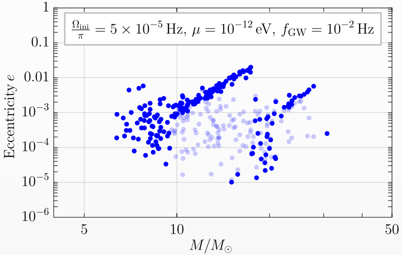


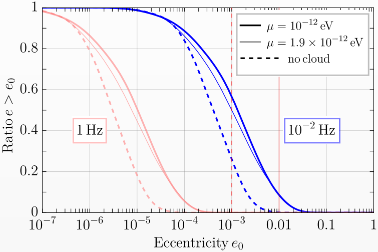


Scanning the axion mass



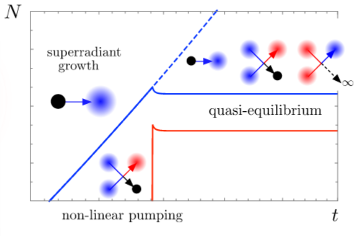
Lower birth frequency

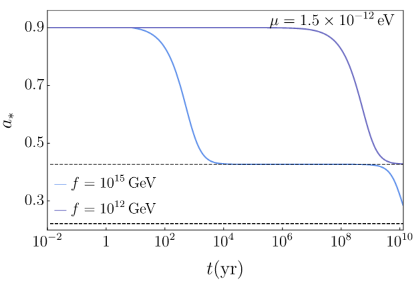




Self-interaction; coupling to other species

- 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?

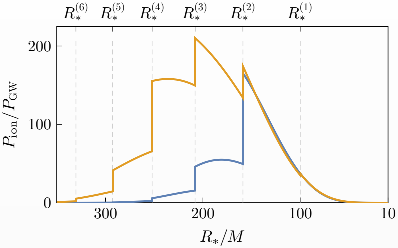


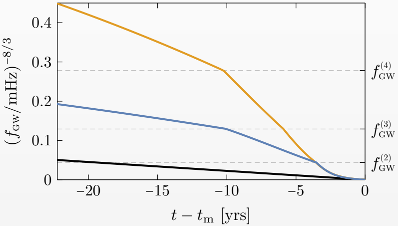


Figs: Baryakhtar+ [2011.11646]

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 $P_{\mathrm{ion}} \gg P_{\mathrm{GW}}$
- Dipole transitions allowed
  Tomaselli, Spieksma, Bertone [2403.03147]
- How likely are the clouds in the late inspiral?





Figs: Baumann+ [2206.01212]