Title: Gravitational atoms and black hole binaries

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Collection/Series: Particle Physics

Subject: Particle Physics

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Abstract:

Various models of physics beyond the Standard Model predict the existence of ultralight bosons. These particles can be produced through superradiant instabilities, which create boson clouds around rotating black holes, forming so-called "gravitational atoms". In this talk, I review a series of papers that study the interaction between a gravitational atom and a binary companion. The companion can induce transitions between bound states of the cloud (resonances), as well as transitions from bound to unbound states (ionization). These processes back-react on the binary's dynamics and leave characteristic imprints on the emitted gravitational waves (GWs), providing direct information about the mass of the boson and the state of the cloud. However, some of the resonances may destroy the cloud before the binary enters the frequency band of future gravitational wave detectors. This destruction leaves a mark on the binary's eccentricity and inclination, which can be identified through a statistical analysis of a population of binary black holes.

Gravitational atoms and black hole binaries

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February 18, 2025

Earlier works by: D. Baumann, H.S. Chia, R. Porto, J. Stout

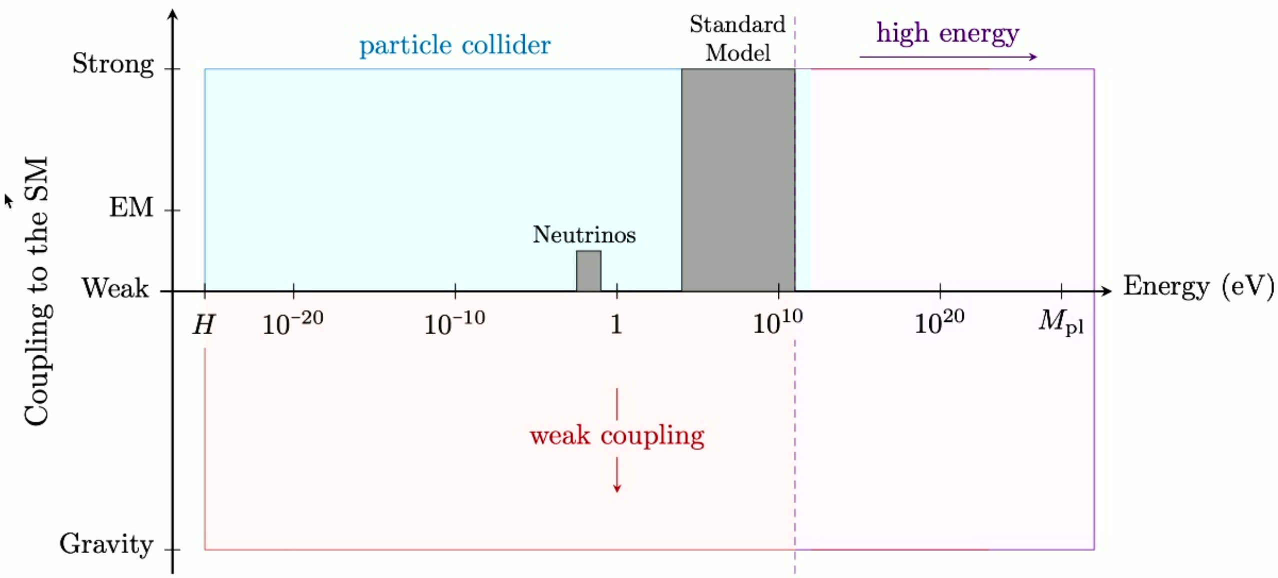
- `1804.03208` "Probing ultralight bosons with binary black holes" (PRD)
- `1912.04932` "Gravitational collider physics" (PRD)

My works:

- `2112.14777` "Ionization of gravitational atoms" (PRD)
- `2206.01212` "Sharp signals of boson clouds in black hole binary inspirals" (PRL)
- `2305.15460` "Dynamical friction in gravitational atoms" (JCAP)
- `2403.03147` "Resonant history of gravitational atoms in black hole binaries" (PRD)
- `2407.12908` "Legacy of boson clouds on black hole binaries" (PRL)

Collaborators: D. Baumann, G. Bertone, J. Stout, T. Spieksma

Motivation



How do we explore the **weak coupling** frontier?

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Motivation

Solutions to many BSM puzzles involve **ultralight bosons**.

- **Strong CP.** Why is θ_{QCD} so small?

  [Peccei and Quinn '77; Wilczek '78; Weinberg '78; Kim '79; Zhitnitsky '80; Shifman, Vainshtein, Zakharov '80; Dine, Fischler, Srednicki '81]
- **Dark Matter.** What comprises 85% of matter in our universe?

  [Preskill, Wise, Wilczek '83; Abbott and Sikivie '83; Dine and Fischler '83; Hu, Barkana, Gruzinov, '00]
- **String Axiverse.** Bosons from string compactifications?

  [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell '09; Demirtas, Long, McAllister, Stillman '18]
- **Hierarchy Problems.** Why is the weak force so strong?

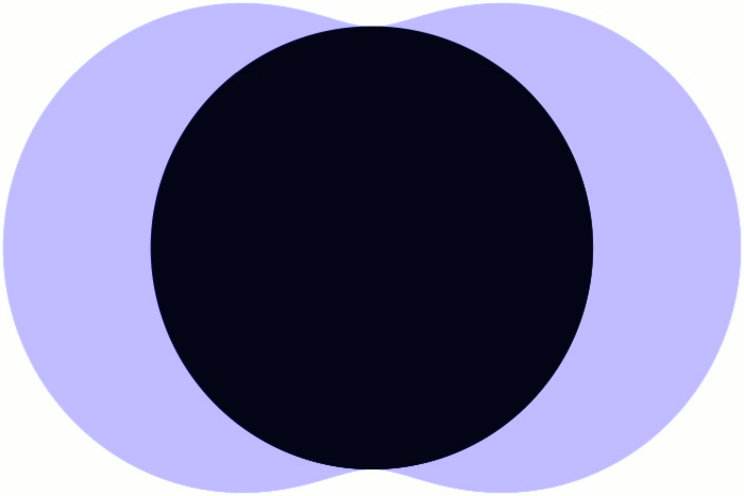
  [Graham, Kaplan, Rajendran '15, '19; Hook '18; Arkani-Hamed, Cohen, et. al. '17; D'Agnolo and Teresi '21]

Weakly coupled fields, often with **no abundance** in the universe.

Rotating Black Holes

Event horizon surrounded by the **ergosphere**:

$$g_{00} < 0 \implies \text{negative energy}$$



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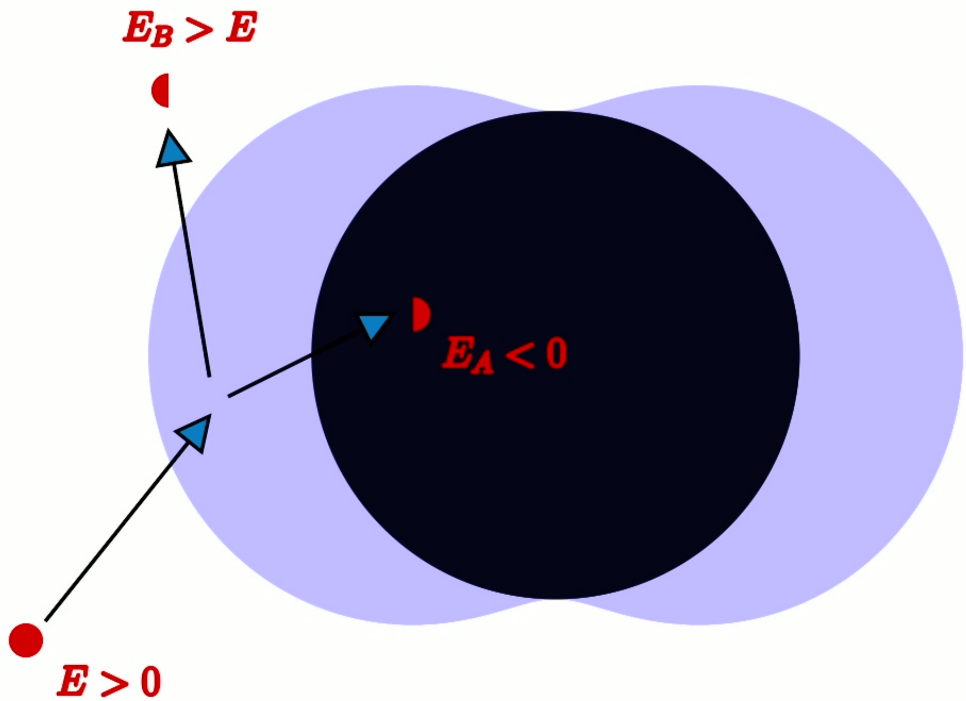
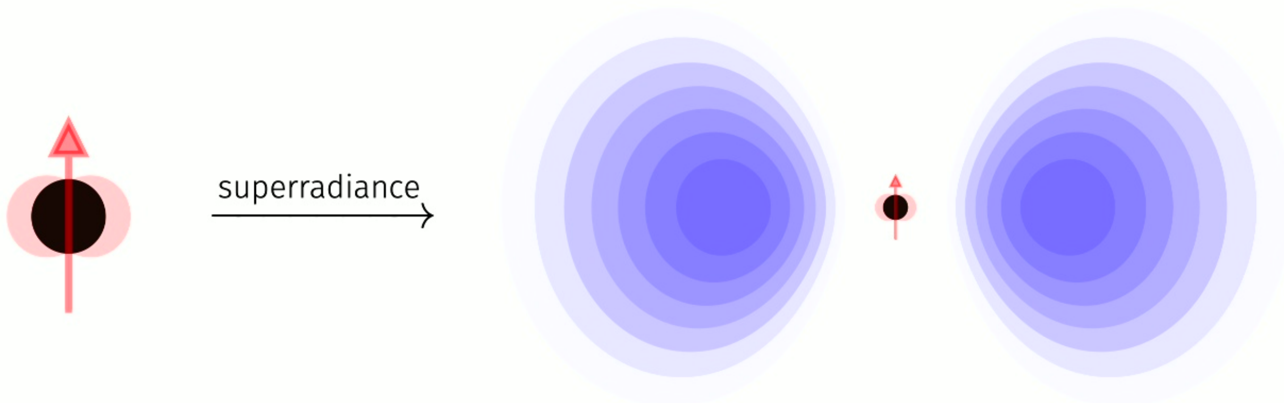
Penrose process: stealing energy from rotating black holes



The Gravitational Atom

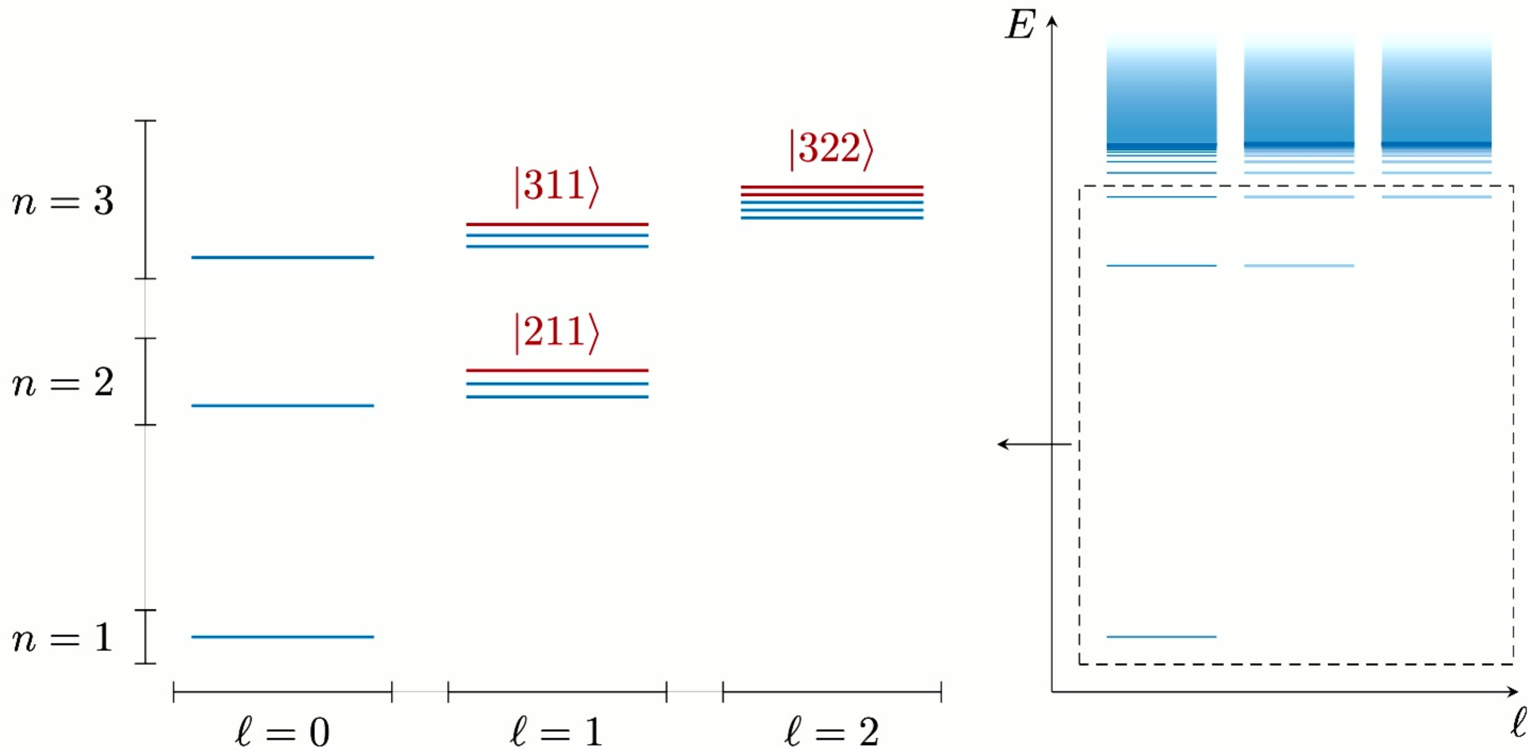


$$(\Box - \mu^2)\Phi = 0 \quad \longrightarrow \quad i\frac{\mathrm{d}\psi}{\mathrm{d}t} \approx \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \dots\right)\psi$$

Gravitational fine structure constant: $\alpha = \mu M \sim \mathcal{O}(0.1)$.

[Zeldovich '72; Starobinsky '73; Dolan '07; Arvanitaki et al. '09]

The spectrum



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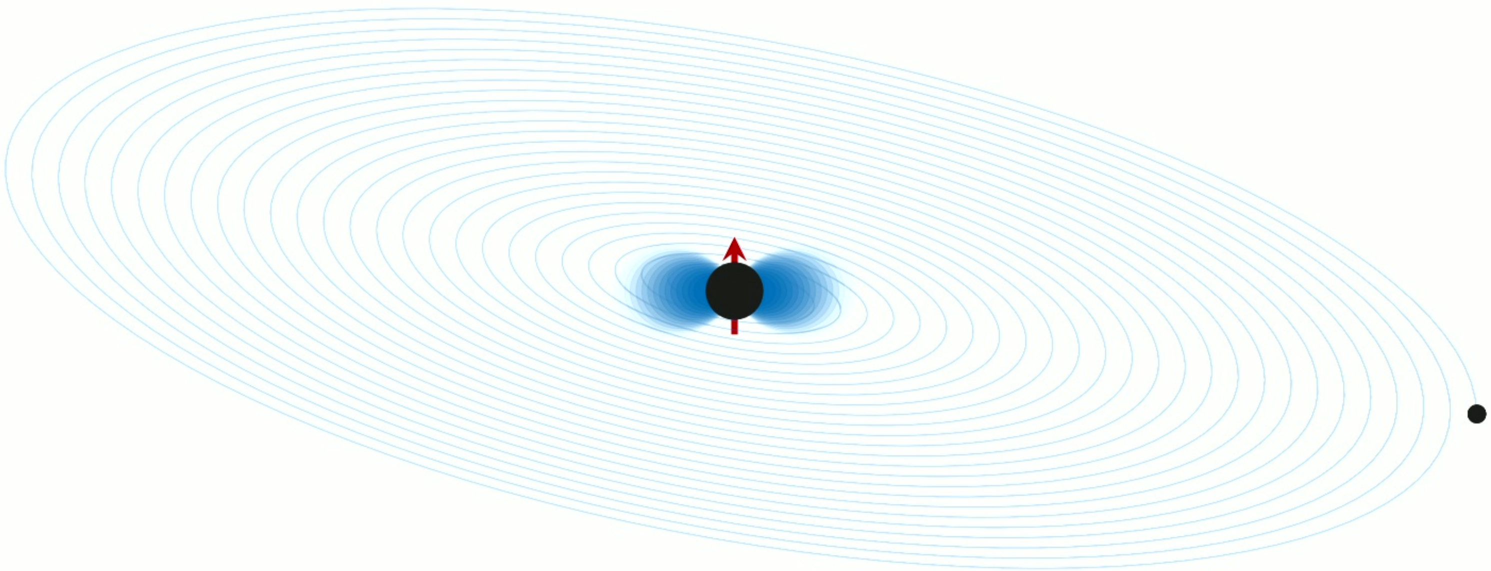
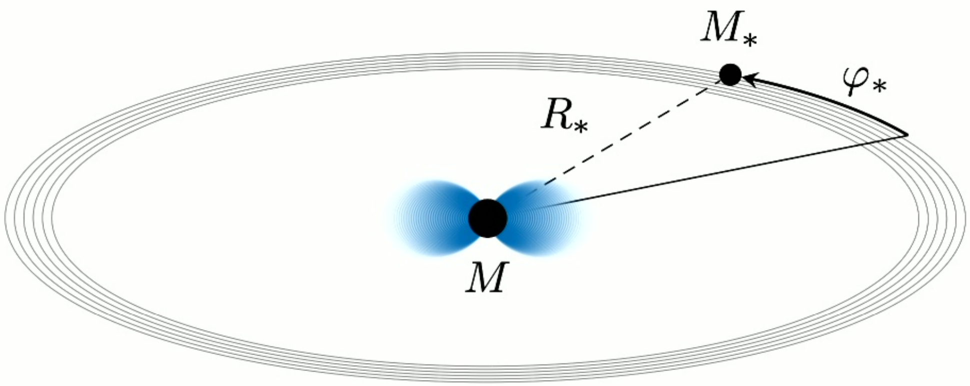
How does a cloud affect a **binary inspiral**?



The binary can induce transitions between bound states ("resonances") and excite unbound states ("ionization")...

Perturbation with slowly increasing frequency:

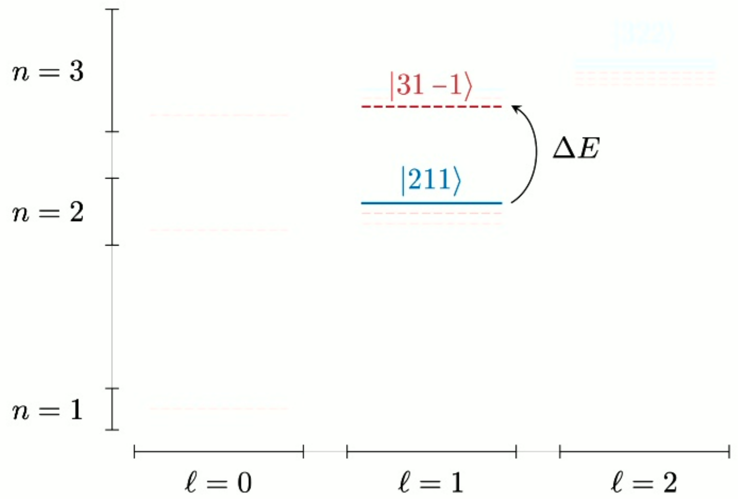


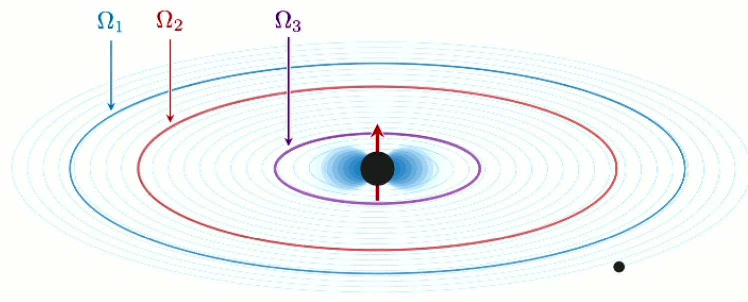
$$i\frac{\mathrm{d}\psi}{\mathrm{d}t} = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \underbrace{V_*(R_*, \varphi_*)}_{\text{perturbation}}\right)\psi$$

Level mixing:

$$\langle a|\, V_*(t)\, |b\rangle = \sum_g \eta^{(g)}\, e^{-ig\Omega t}$$

Resonances





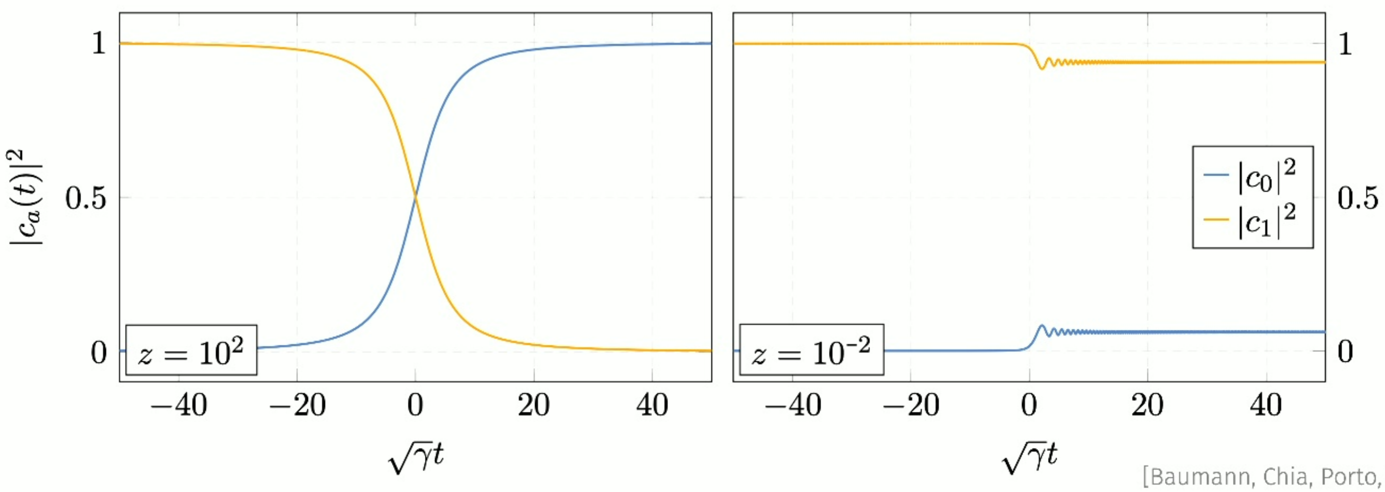
Resonance frequency: $$\Omega_r = \left|\frac{\Delta E}{\Delta m}\right| \sim 10\,\mathrm{mHz}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3$$

[Baumann, Chia, Porto, Stout '18]

“Linear” Landau-Zener transitions

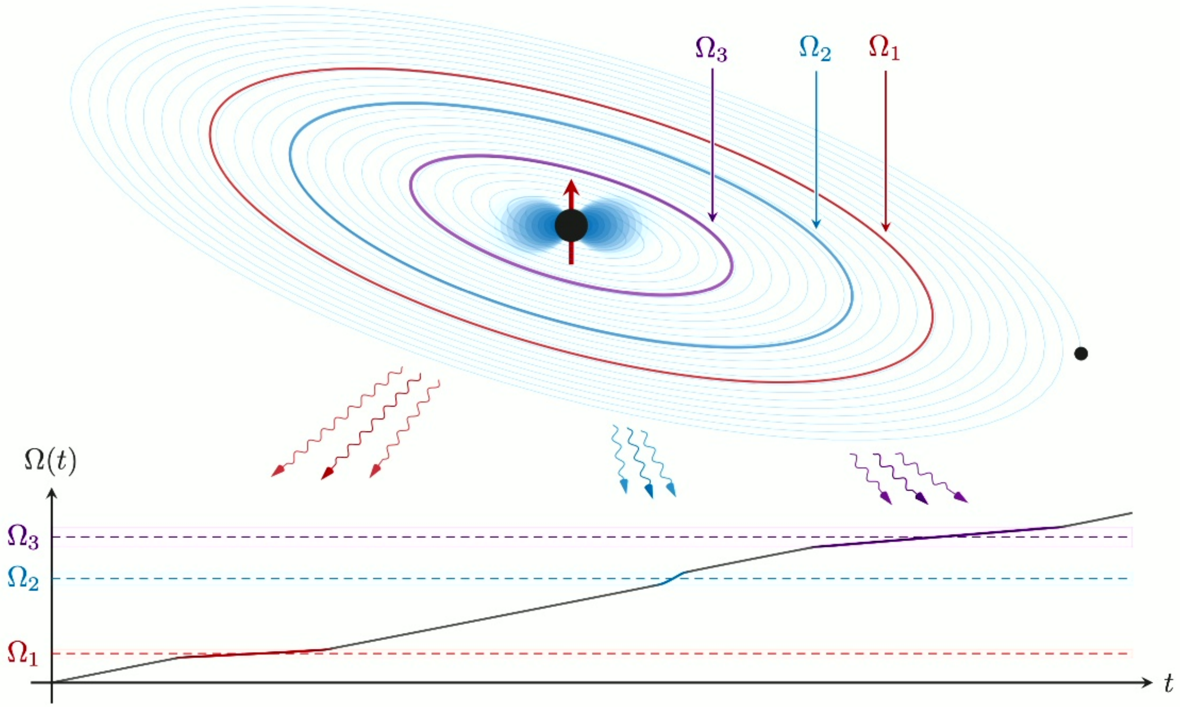
$$\mathcal{H} = \begin{pmatrix} E_1 & \eta\, e^{i\varphi(t)} \\ \eta^* e^{-i\varphi(t)} & E_2 \end{pmatrix} \xrightarrow{\dot{\Omega}=\text{const}} \mathcal{H}_D = \begin{pmatrix} \tau/2 & \sqrt{Z} \\ \sqrt{Z} & -\tau/2 \end{pmatrix}$$

Landau-Zener transition with parameter $Z \equiv \eta^2/\dot{\Omega}$. Final population: $e^{-2\pi Z}$.



[Baumann, Chia, Porto, Stout '19]

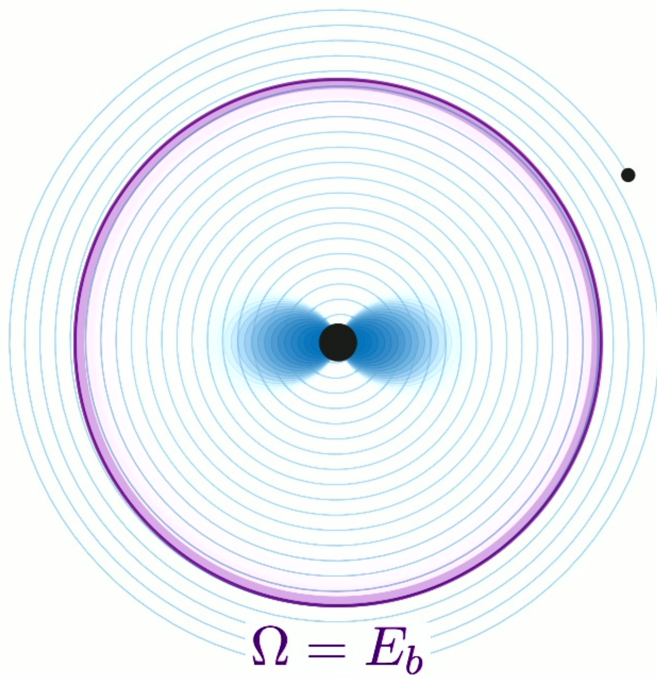
Floating and sinking resonances

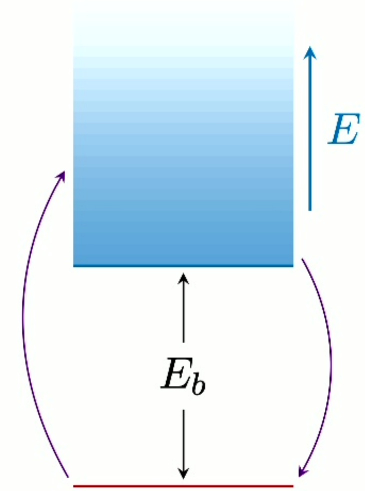


[Baumann, Chia, Porto, Stout '19]

Ionization

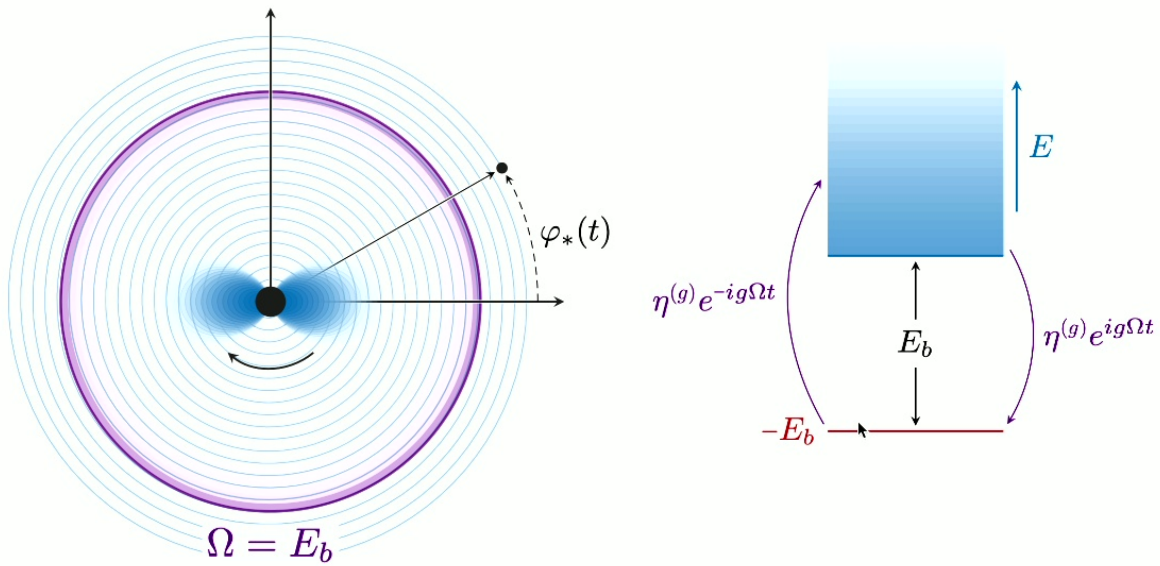
Orbital frequency above **threshold** to excite **transitions to unbound states**





[Baumann, Bertone, Stout, GMT '21]

Fermi's Golden Rule

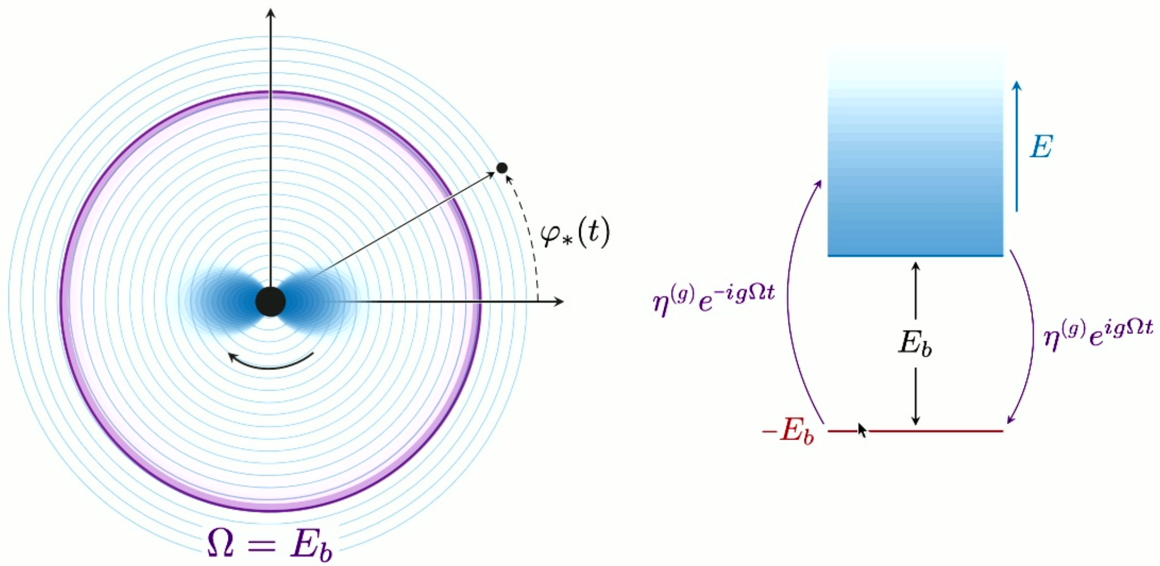


The transition rate (per unit energy) is given by Fermi's Golden Rule:

$$\mathrm{d}\Gamma = \mathrm{d}E \; \underbrace{|\eta^{(g)}|^2}_{\text{Level mixing}} \; \delta(\underbrace{E - E_b - g\Omega}_{E - E_*^{(m)}})$$

[Baumann, Bertone, Stout, GMT, '21]

Ionization Power

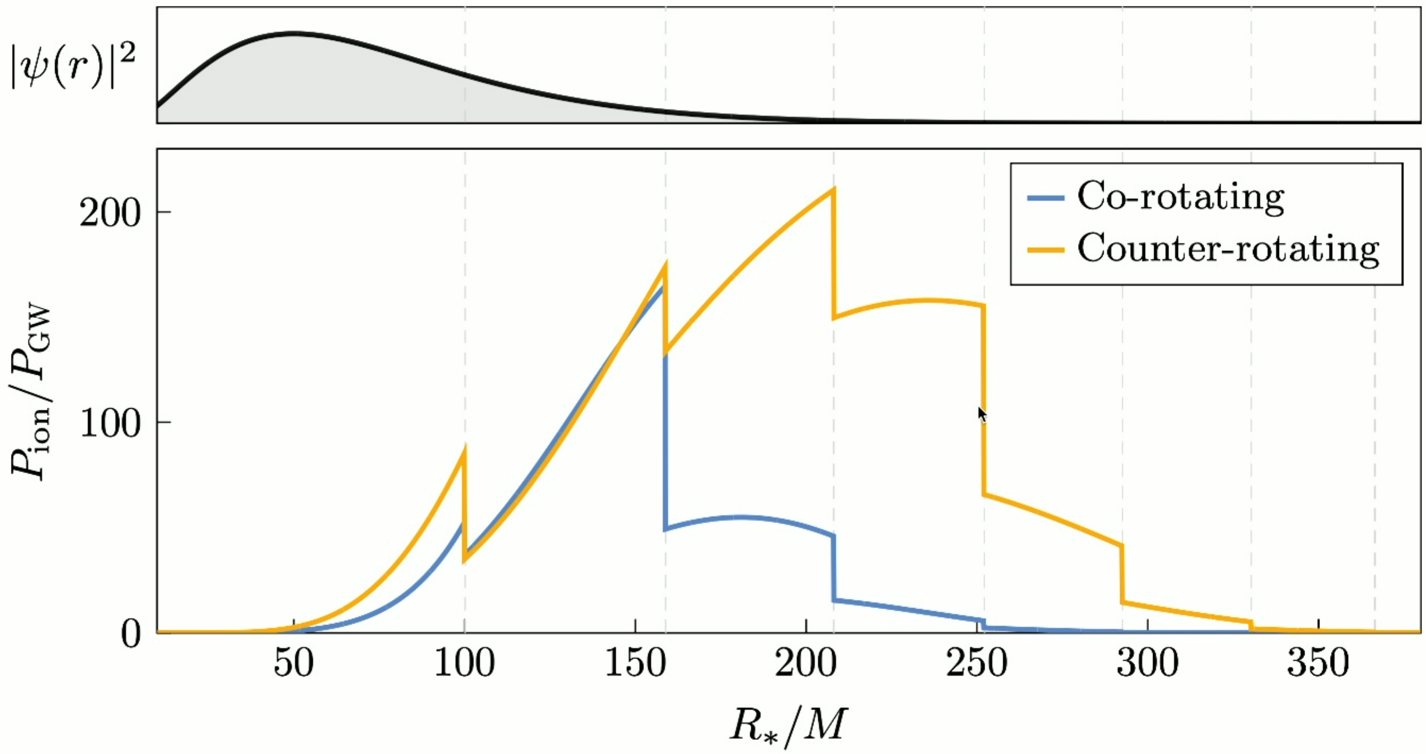


Summing over all bound states gives the total **ionization power**:

$$P_{\rm ion} = \frac{M_{\rm c}}{\mu} \sum_{\ell,m} g\Omega \, |\eta^{(g)}|^2 \, \Theta(E_*^{(m)})$$

[Baumann, Bertone, Stout, GMT, '21]

Ionization Power

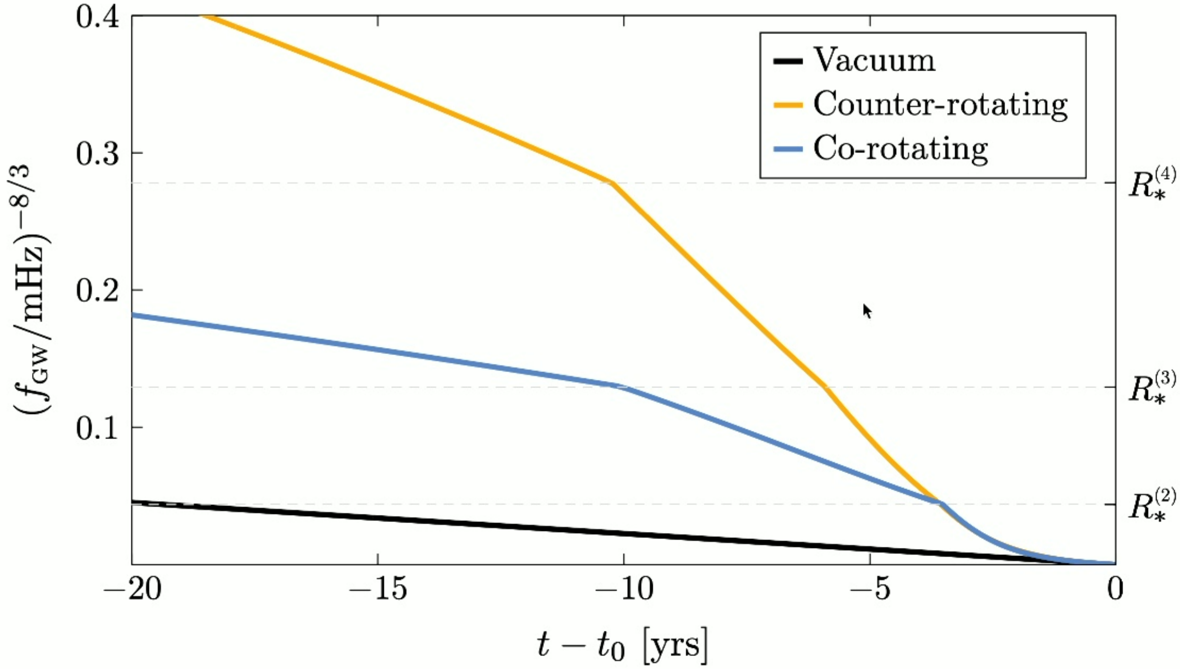


$[|211\rangle, \alpha = 0.2, M_{\rm c}/M = 0.01, q = 10^{-3}]$

[Baumann, Bertone, Stout, GMT '21]

Frequency evolution

Kinks in the frequency evolution: **signature** of the cloud!

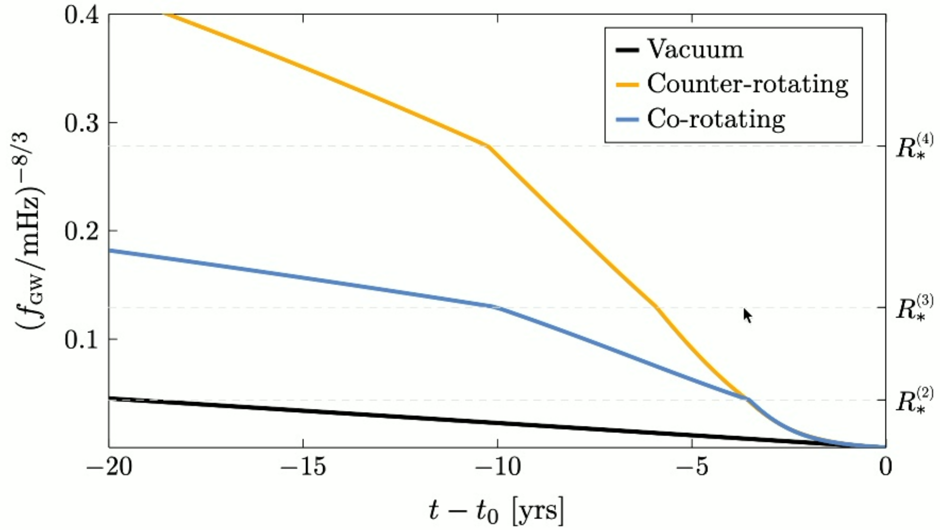


[$M = 10^4 M_\odot$, $|211\rangle$, initial: $R_* = 400M$, $M_*/M = 10^{-3}$, $M_c/M = 10^{-2}$]

[Baumann, Bertone, Stout, GMT, '22]

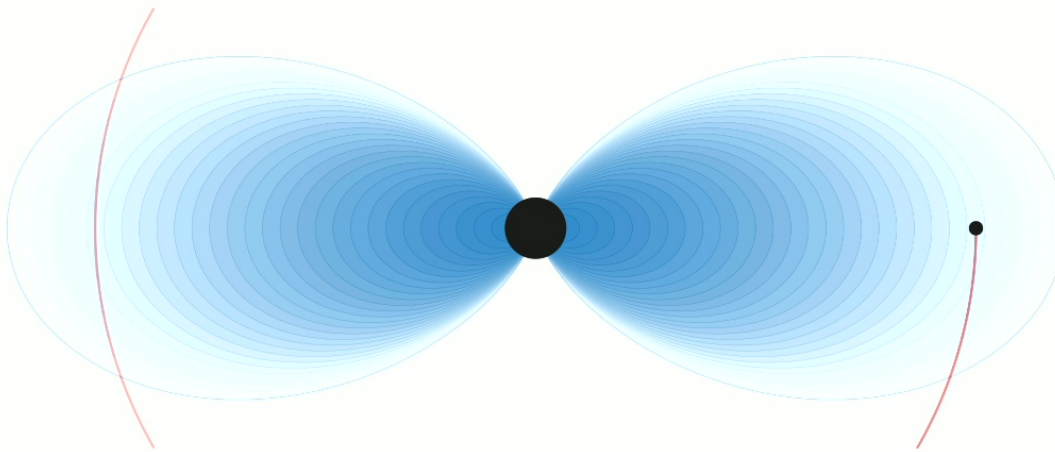
Kinks in the frequency

Kinks in the frequency evolution: **signature** of the cloud!



$$f_{\rm GW}^{(g)} = \frac{6.45\,\mathrm{mHz}}{g}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3\left(\frac{2}{n}\right)^2$$

[Baumann, Bertone, Stout, GMT, '22]



Ionization or **dynamical friction**?

$$P_{\mathrm{DF}} = \frac{4\pi M_*^2 \rho}{v} \log(v\mu b_{\max})$$

[GMT, Spieksma, Bertone '23]

The resonant history

Bohr resonances and **ionization**: observable when $R_* \sim 10^2 M$.

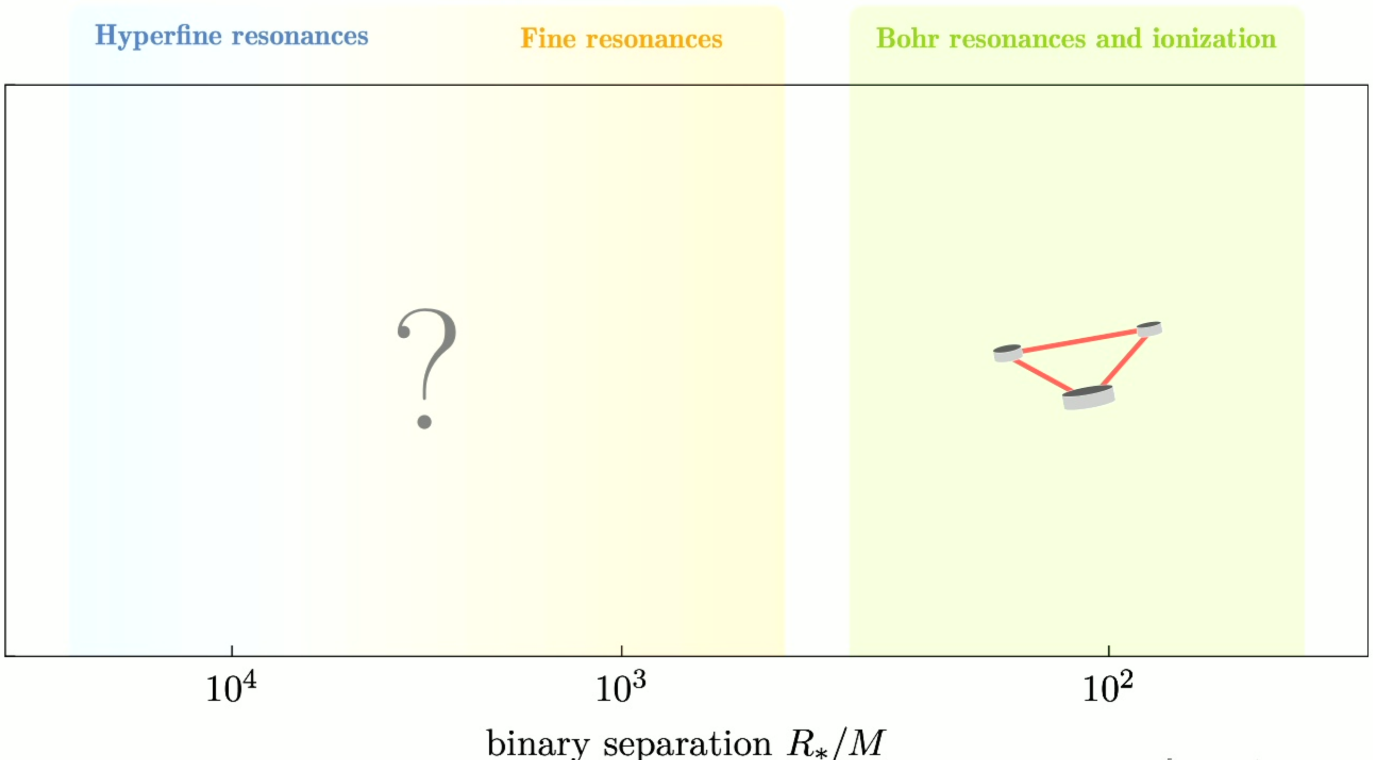
But **fine** and **hyperfine** resonances happen earlier ($\gtrsim 10^3 M$)!

So, when $R_* \sim 10^2 M$...

...what is the state of the cloud?
...is the cloud still there?
...what is the binary configuration?

[GMT, Spieksma, Bertone '24]

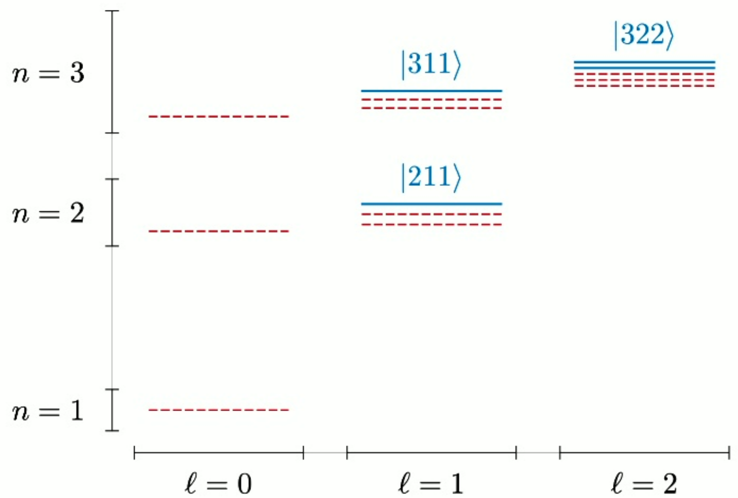
The resonant history

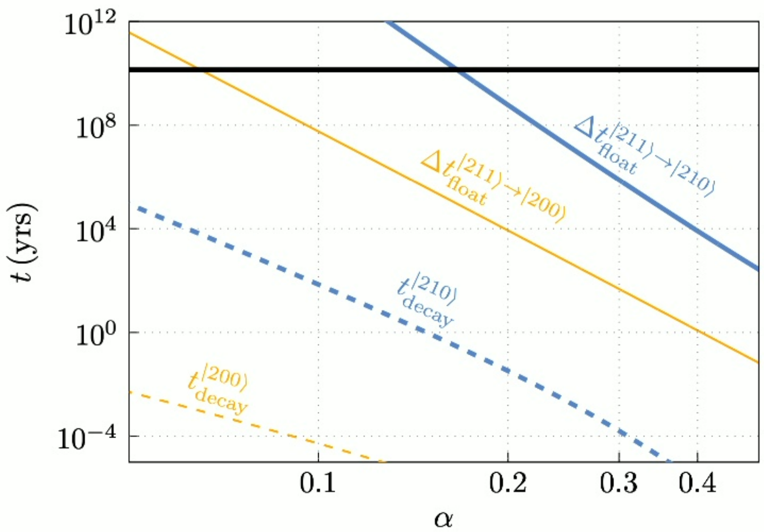


[GMT, Spieksma, Bertone '24]

Timescales

All **fine** and **hyperfine** resonances are **floating** and **decaying**.

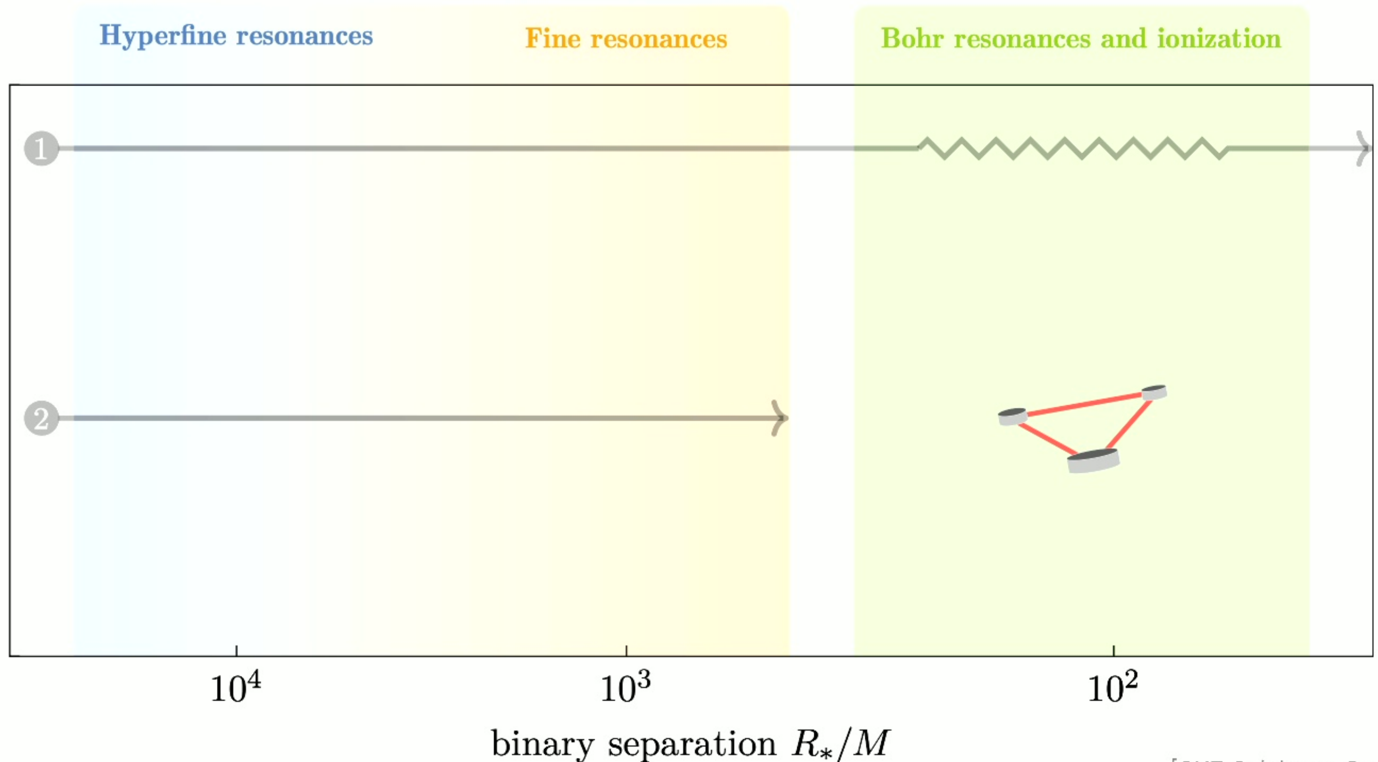




$\Delta t_{\text{float}} \gg t_{\text{decay}} \implies$ No state change, only **destruction** or **survival**.

[GMT, Spieksma, Bertone '24]

The resonant history

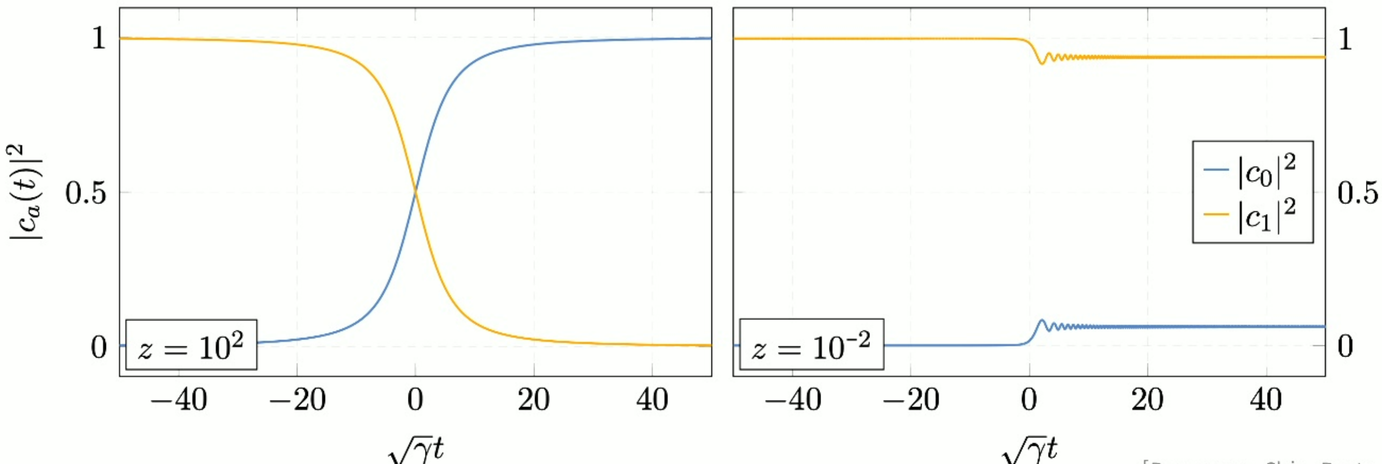


[GMT, Spieksma, Bertone '24]

“Linear” Landau-Zener transitions

$$\mathcal{H} = \begin{pmatrix} E_1 & \eta\, e^{i\varphi(t)} \\ \eta^*\, e^{-i\varphi(t)} & E_2 \end{pmatrix} \xrightarrow{\dot{\Omega}=\text{const}} \mathcal{H}_D = \begin{pmatrix} \tau/2 & \sqrt{Z} \\ \sqrt{Z} & -\tau/2 \end{pmatrix}$$

Landau-Zener transition with parameter $Z \equiv \eta^2/\dot{\Omega}$. Final population: $e^{-2\pi Z}$.



[Baumann, Chia, Porto, Stout '19]

“Nonlinear” Landau-Zener transitions

Landau-Zener transitions assume $\dot{\Omega} = \dot{\Omega}_{\mathrm{GW}}$.

In reality, there is **backreaction**:

$$\frac{\mathrm{d}}{\mathrm{d}t}(E_{\mathrm{binary}} + E_{\mathrm{cloud}}) = P_{\mathrm{GW}}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(L_{\mathrm{binary}} + L_{\mathrm{cloud}}) = \tau_{\mathrm{GW}}$$

[GMT, Spieksma, Bertone '24]

“Nonlinear” Landau-Zener transitions

Taking into account the **backreaction** (cloud + binary energy conserv.):

$$\mathcal{H}_D = \begin{pmatrix} \omega/2 & \sqrt{Z} \\ \sqrt{Z} & -\omega/2 \end{pmatrix}, \qquad \omega = \tau - \underset{\substack{\uparrow \\ \text{backreaction param.}}}{B}|\psi_{\text{final state}}|^2$$

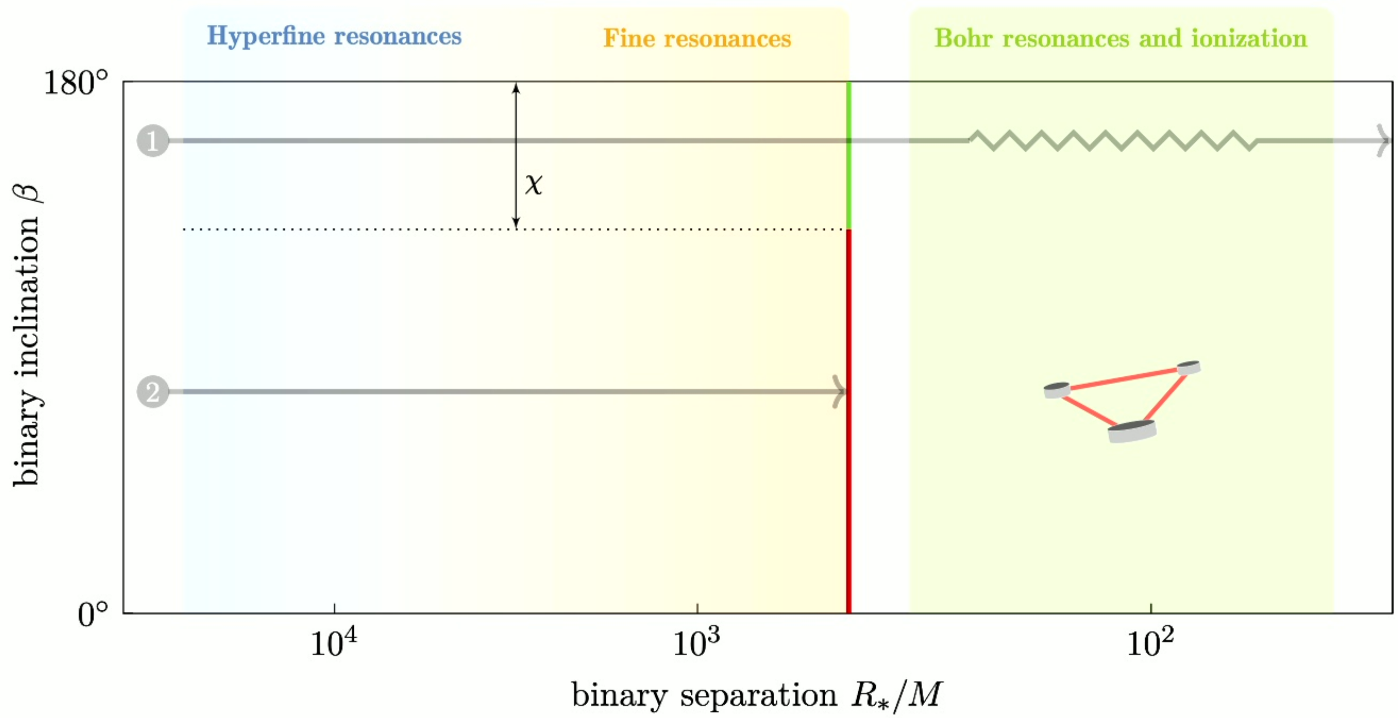
Very **complicated** phenomenology!

Resonances can “start” and “break”... But in a few words:

- **weak** resonances when binary and cloud are approx. **counter-rotating**;
- **strong** resonances otherwise.

[GMT, Spieksma, Bertone '24]

The resonant history



[GMT, Spieksma, Bertone '24]

Two outcomes

The cloud survives...

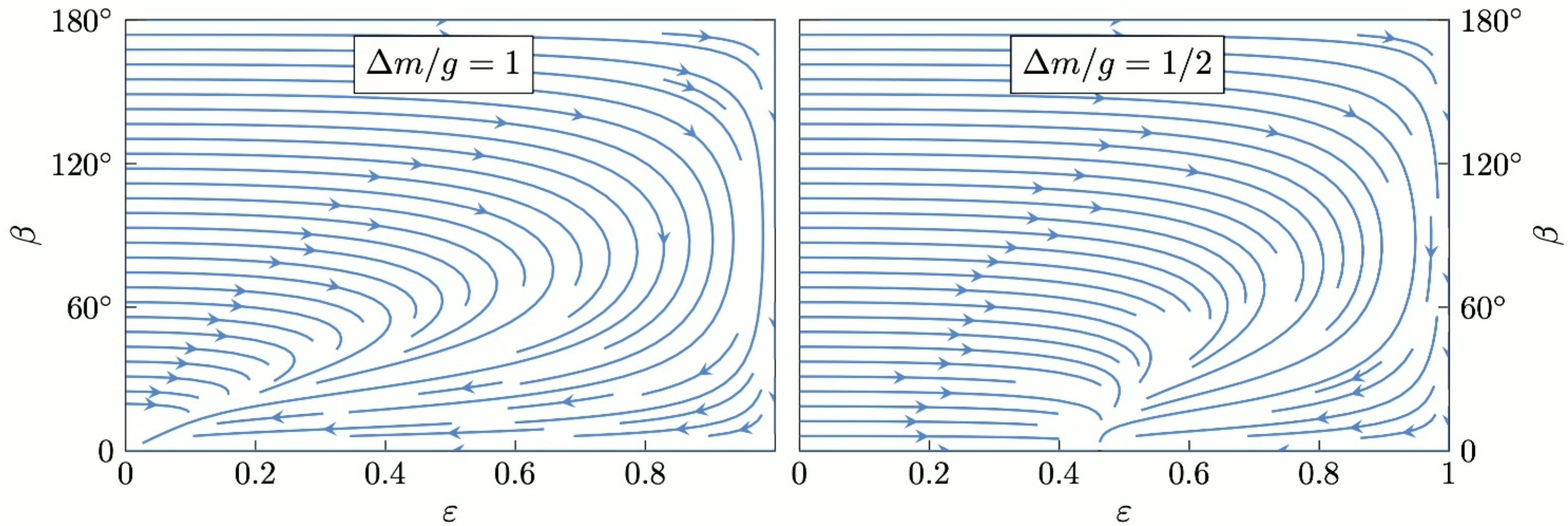
$\longrightarrow$ **Direct signatures** via **ionization** and **Bohr sinking resonances**!

- Initial state unchanged ($|211\rangle$, $|322\rangle$, ...)
- Near-counter rotating ($\beta \approx \pi$).

Otherwise, the cloud is destroyed...

Eccentricity and inclination

During the float, the eccentricity ε and inclination β change dramatically.

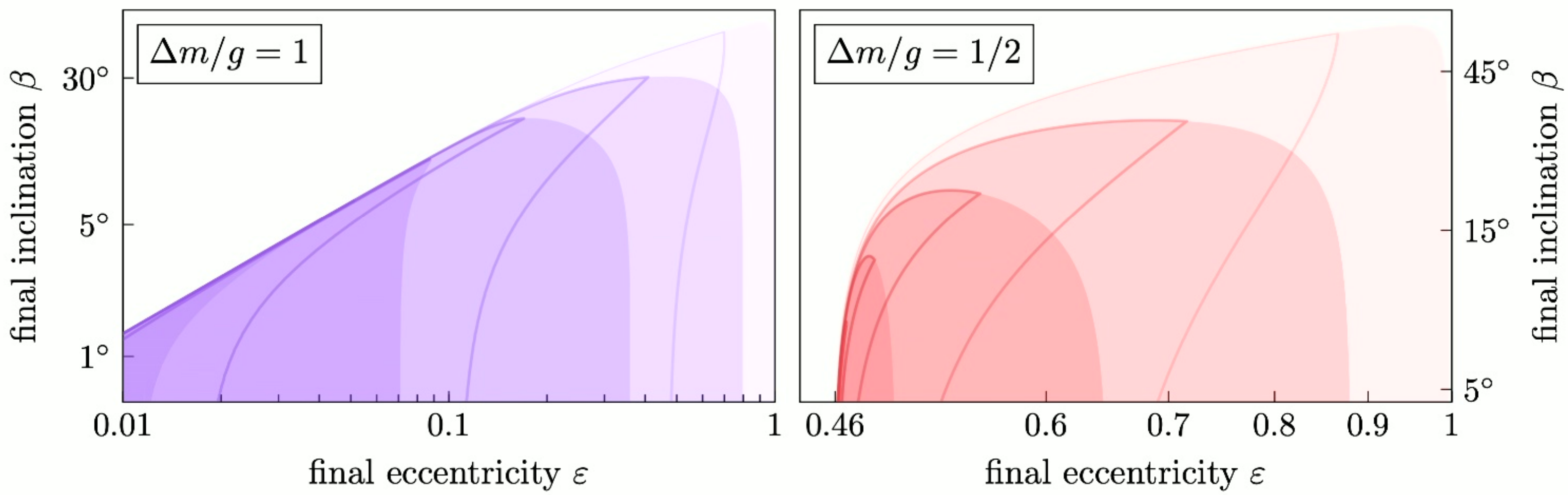


Fixed points at $\varepsilon \approx 0,\ 0.46,\ 0.58,\ 0.65,\ \ldots$

[GMT, Spieksma, Bertone '24] 30

Final eccentricity and inclination

Final values of (ε, β) controlled by a single parameter: $D \propto M_c q^{-1} \alpha \tilde{a}$.



Statistical test could distinguish from astrophysical distributions of (ε, β).

[GMT, Spieksma, Bertone '24]

Summary

- **Resonances** give peculiar GWs features and set the cloud's state.
- **Ionization** dominates dynamics and has sharp GWs features.

- **Resonant history** determines the observed configuration:
  - possible states: $|211\rangle$, $|322\rangle$, ...
  - near-counter-rotating inclination $\beta \approx \pi$.

- The cloud can be **destroyed**, leaving a vacuum binary with:
  - near-co-rotating inclination $\beta \sim 0$,
  - eccentricity close to fixed points (partially washed away by GWs).

As a concluding remark, we note that the results derived here and in Section 3 are specific to resonances involving two states only. We have explicitly checked that this is the case for the resonances discussed in the next sections, so we apply the results of Section 3 without further modification.

5.2 Evolution from a $|211\rangle$ initial state

The $|211\rangle$ state is the fastest-growing superradiant mode and represents therefore a natural assumption for the initial state of the cloud. The requirements that the superradiant amplification takes place, and does so on timescales no longer than a Gyr, set a constraint on α:

$$0.02\left(\frac{M}{10^4 M_\odot}\right)^{1/9} \lesssim \alpha < 0.5\,. \tag{5.3}$$

Once grown, the cloud will decay in GWs with a rate roughly proportional to $M_\mathrm{c}^2\alpha^{14}$, assuming the scalar field is real. The resulting decay of M_c is polynomial, rather than exponential in time; as such, we will not impose a further sharp bound on α, and treat M_c/M as an additional free parameter.

There are two possible hyperfine resonances, with the states $|210\rangle$ and $|21\,{-1}\rangle$. Following the line of reasoning laid down in Section 5.1, we ignore the fact that the same resonances can be triggered at multiple points if the orbit is eccentric. Both resonances are then mediated by $g = -2$ and they are positioned at

$$|211\rangle \xrightarrow{g=-2} |210\rangle \qquad \frac{R_0}{M} = 8.3\times 10^3 \left(\frac{\alpha}{0.2}\right)^{-4}\left(\frac{\tilde{a}}{0.5}\right)^{-2/3}, \tag{5.4}$$

$$|211\rangle \xrightarrow{g=-2} |21\,{-1}\rangle \qquad \frac{R_0}{M} = 5.2\times 10^3 \left(\frac{\alpha}{0.2}\right)^{-4}\left(\frac{\tilde{a}}{0.5}\right)^{-2/3}, \tag{5.5}$$

where the value of the spin should be set equal to the threshold of superradiant instability of $|211\rangle$, that is, $\tilde{a} \approx 4\alpha/(1+4\alpha^2)$. Both resonances become non-adiabatic in an interval $\pi - \delta_1 < \beta \leq \pi$,