Gravitational atoms and black hole binaries

Giovanni Maria Tomaselli

IAS | Institute for Advanced Study

IBS CTPU-CGA

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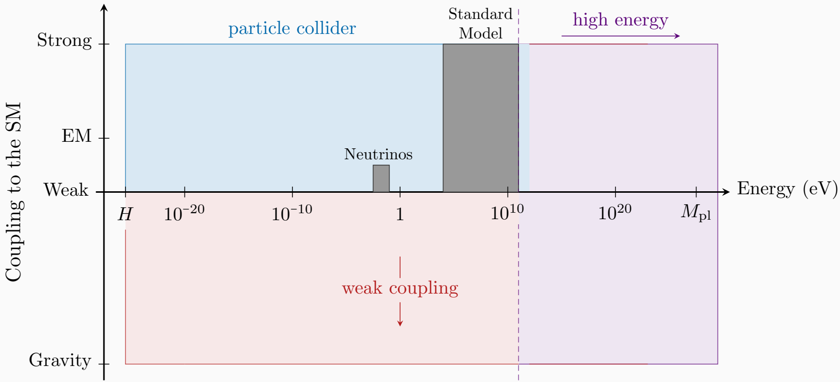
A series of papers from Amsterdam:

- 1804.03208 "Probing ultralight bosons with binary black holes" (PRD)
- 1908.10370 "The Spectra of Gravitational Atoms" (JCAP)
- 1912.04932 "Gravitational collider physics" (PRD)
- 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)

Authors: D. Baumann, H.S. Chia, R. Porto, J. Stout, L. Ter Haar, G.M.T., G. Bertone, J. Stout, T. Spieksma

Motivation



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

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]

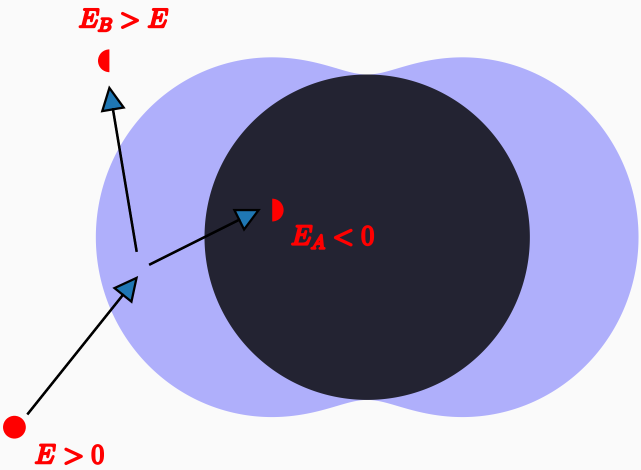
Weakly coupled fields, often with **no abundance** in the universe.

Rotating Black Holes

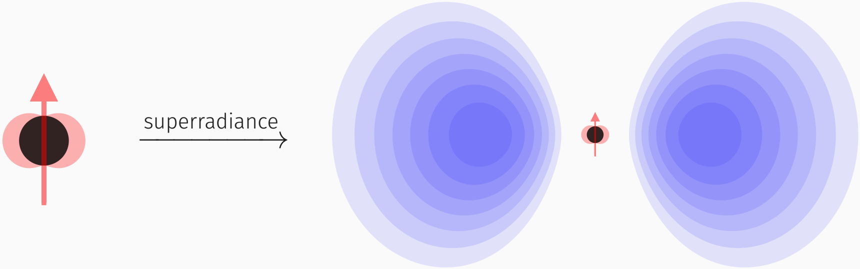
Event horizon surrounded by the ergosphere:

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

Penrose process: stealing energy from rotating black holes



Superradiance: The Gravitational Atom

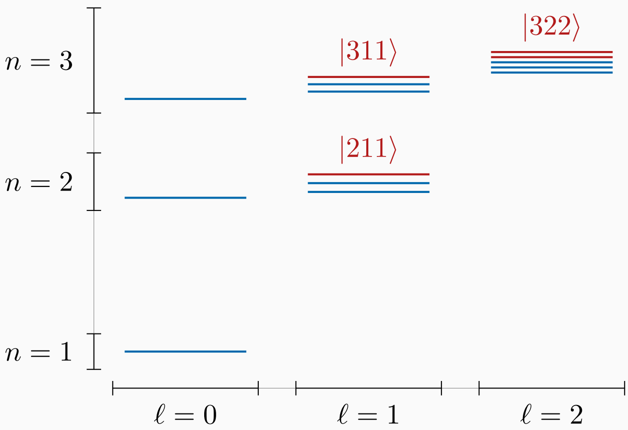


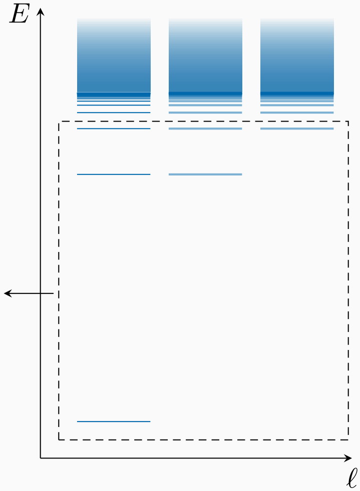
$$(\Box - \mu^2)\Phi = 0 \quad \longrightarrow \quad i\frac{\mathrm{d}\psi}{\mathrm{d}t} \approx \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \dots\right)\psi$$

Gravitational fine structure constant: $\alpha \approx \dfrac{\mu}{10^{-10}\,\text{eV}} \dfrac{M}{1M_\odot} \sim \mathcal{O}(0.1)$.

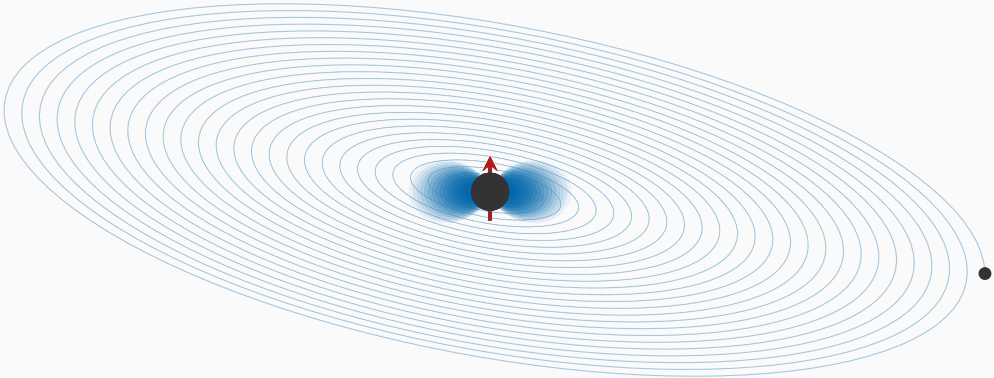
[Zeldovich '72; Starobinsky '73; Dolan '07; Arvanitaki et al. '09]

The spectrum



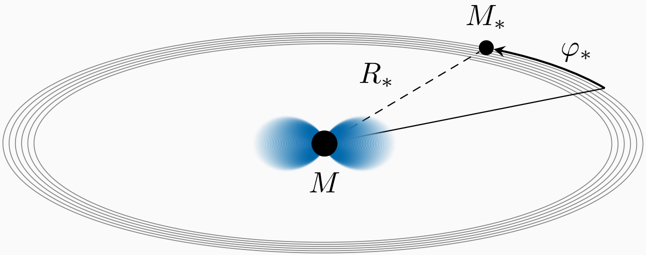


How does a cloud affect a **binary inspiral**?



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

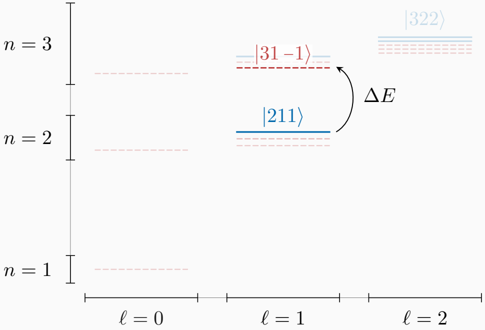
Newtonian perturbation with slowly increasing frequency:

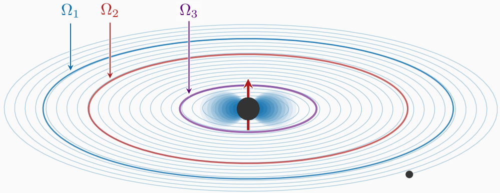


$$i\frac{\mathrm{d}\psi}{\mathrm{d}t} = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \underbrace{V_*(R_*, \varphi_*)}_{\text{perturbation}}\right)\psi$$

Level mixing:

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

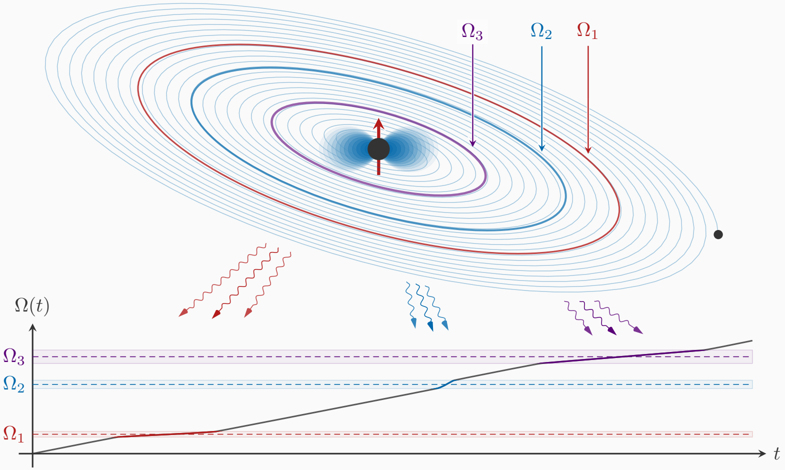




Resonance frequency: $\Omega_r = \left|\frac{\Delta E}{\Delta m}\right| \sim 10\,\mathrm{mHz}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3$

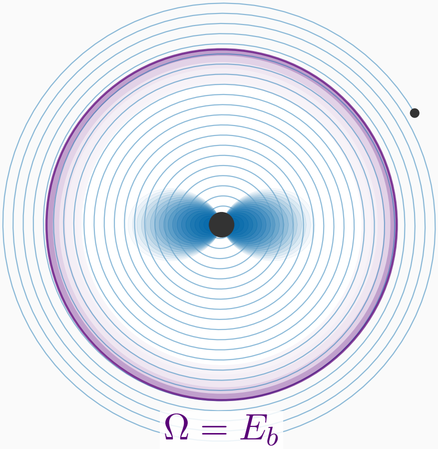
[Baumann, Chia, Porto, Stout '18]

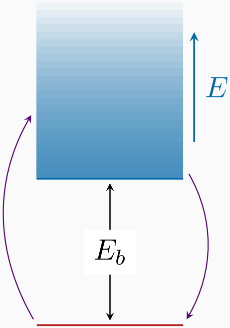
Floating and sinking resonances



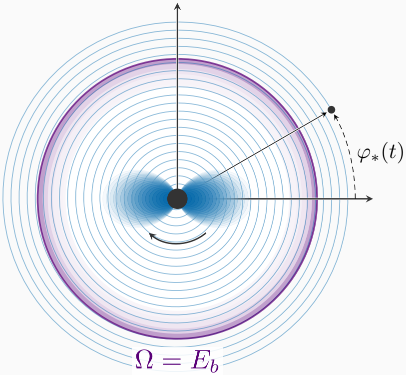
[Baumann, Chia, Porto, Stout '19]

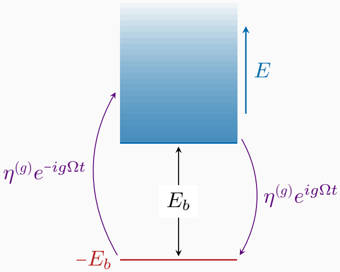
Orbital frequency above **threshold** to excite **transitions to unbound states**





[Baumann, Bertone, Stout, GMT '21]



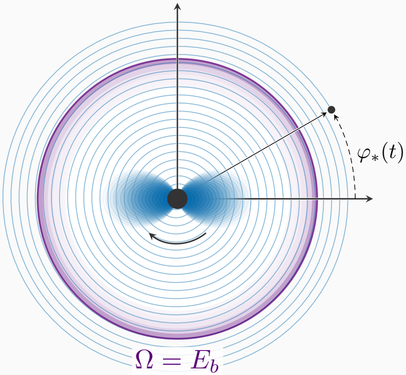


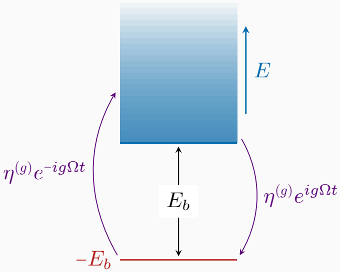
The transition rate (per unit energy) is given by Fermi's Golden Rule:

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

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

Ionization Power



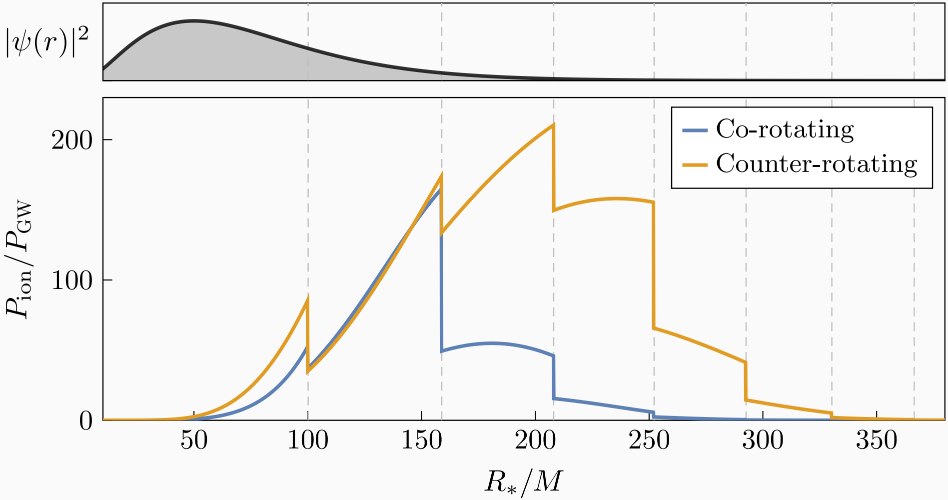


Summing over all bound states gives the total **ionization power**:

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

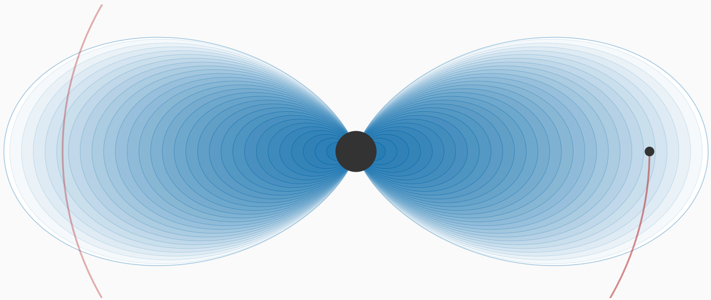
[Baumann, Bertone, Stout, GMT, '21]

Ionization Power



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

[Baumann, Bertone, Stout, GMT '21]



Ionization or **dynamical friction**?

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

[GMT, Spieksma, Bertone ’23]

The resonant history

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

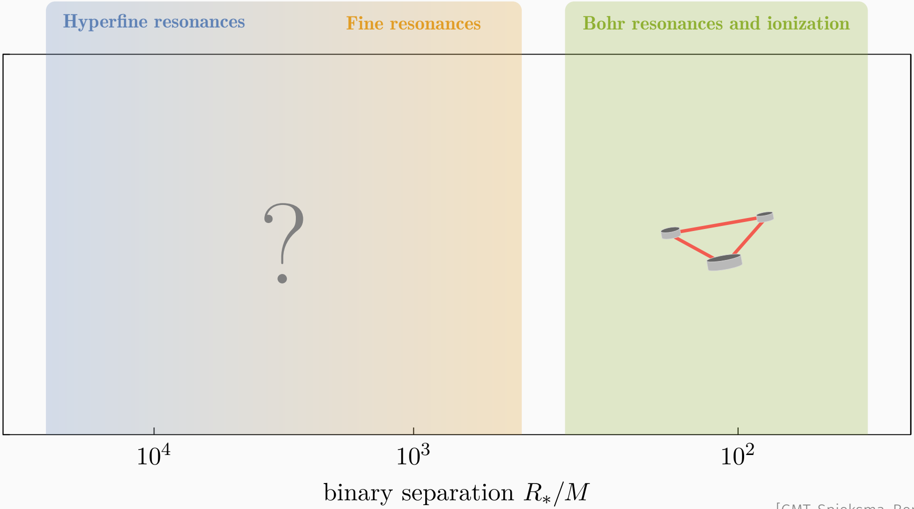
But **fine** and **hyperfine** resonances happen earlier ($\gtrsim 10^3 M$)!

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

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

[GMT, Spieksma, Bertone '24]

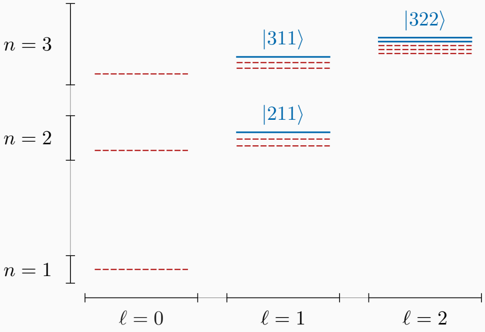
The resonant history

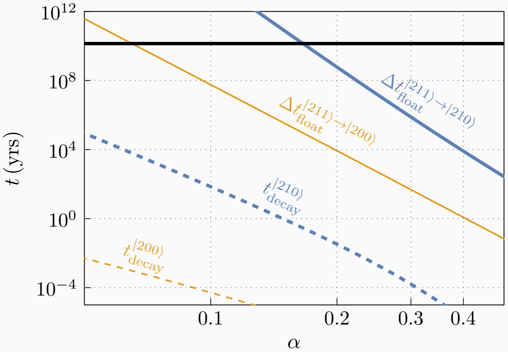


[GMT, Spieksma, Bertone '24]

Timescales

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

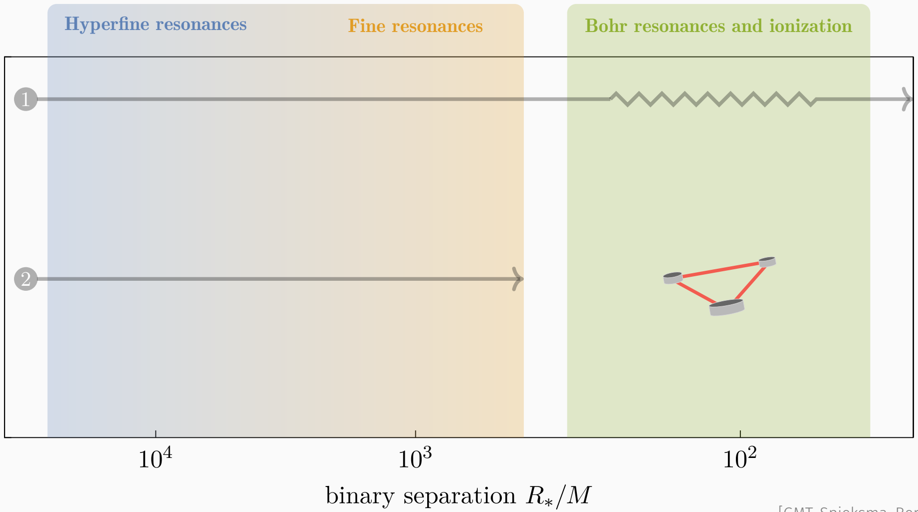




$\Delta t_{\mathrm{float}} \gg t_{\mathrm{decay}} \quad \Longrightarrow \quad$ No state change, only **destruction** or **survival**.

[GMT, Spieksma, Bertone '24]

The resonant history

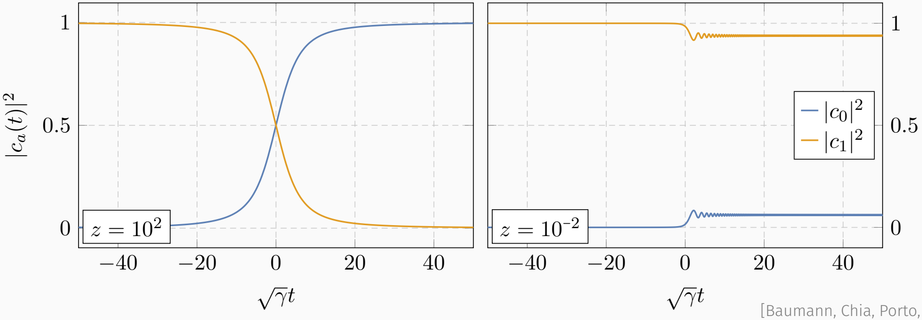


[GMT, Spieksma, Bertone '24]

"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 $\dot{\Omega} = \dot{\Omega}_{\rm GW}$.

In reality, there is **backreaction**:

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

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

[GMT, Spieksma, Bertone ’24]

"Nonlinear" Landau-Zener transitions

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

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

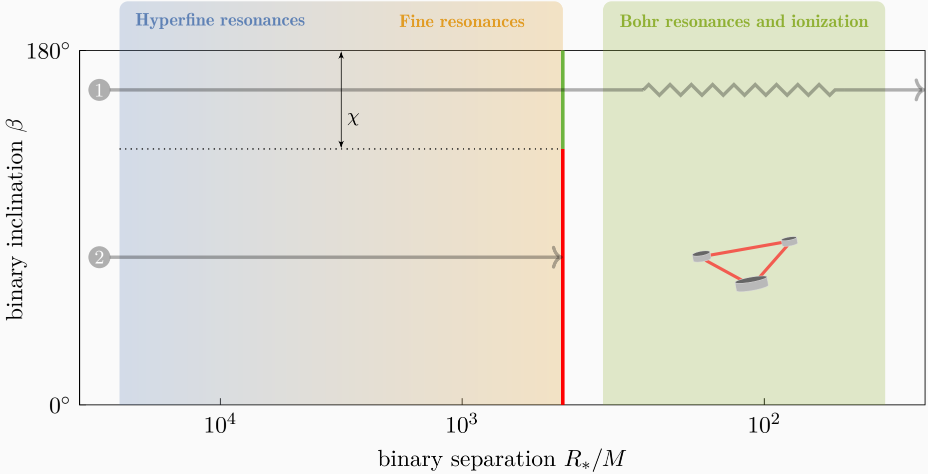
Very **complicated** phenomenology!

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...

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...

$\longrightarrow$ but it still leaves a “mark” on the binary: **indirect signatures**!

See Thomas’ talk for more!

Summary

- **Direct signatures:**
  - **Resonances** give peculiar GWs features and set the cloud's state.
  - **Ionization** dominates dynamics and has sharp 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 **indirect signatures** on vacuum binary.