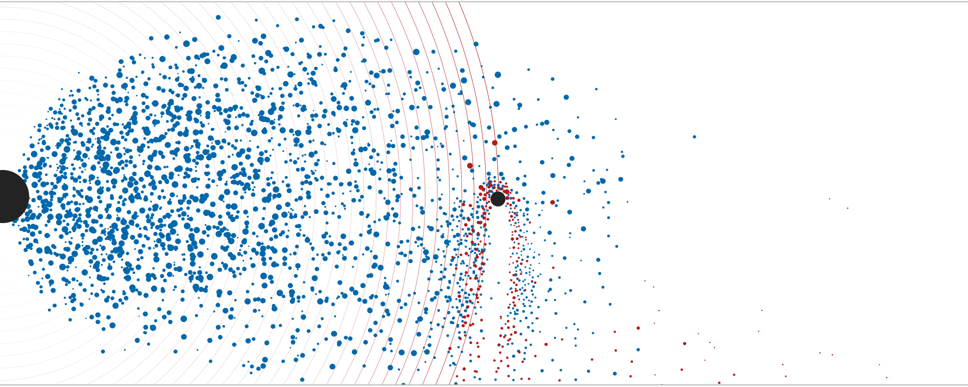
IONIZATION OF GRAVITATIONAL ATOMS



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Dark Sectors of Astroparticle Physics 2021 | December 6, 2021

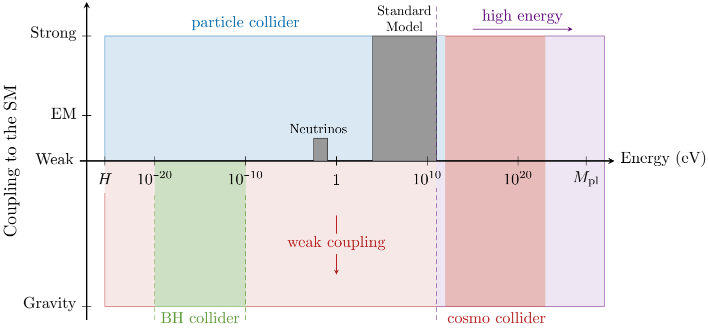
Motivation

String compactifications contain a **plethora** of four-dimensional scalars and vectors that are plausibly ultralight, i.e. $m \lesssim 10^{-10}\,\mathrm{eV}$.

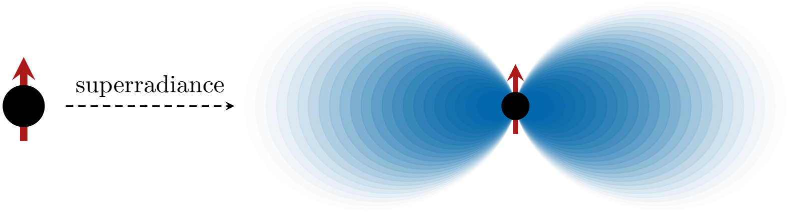
[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell '09; Demirtas, Long, McAllister, Stillman '18]

Where are they?

More generally, how do we explore the **weak coupling frontier**?



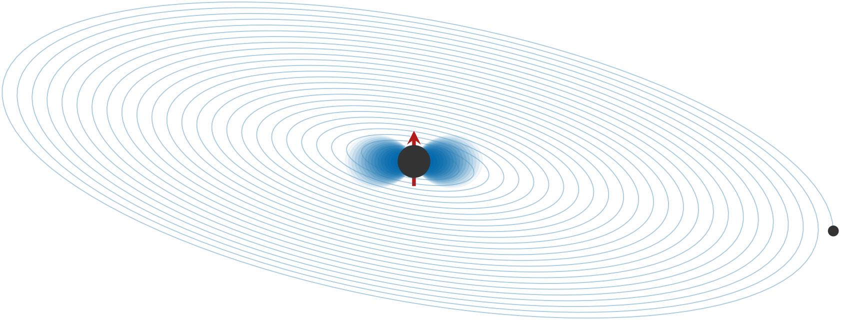
Ultralight bosons form **bound states** around spinning black holes



Physics governed by **gravitational fine structure constant**

$$\alpha \equiv \frac{r_{\mathrm{g}}}{\lambda_{\mathrm{c}}} \sim 0.04 \times \left(\frac{M_{\mathrm{BH}}}{60 M_{\odot}}\right) \times \left(\frac{\mu}{10^{-13}\,\mathrm{eV}}\right)$$

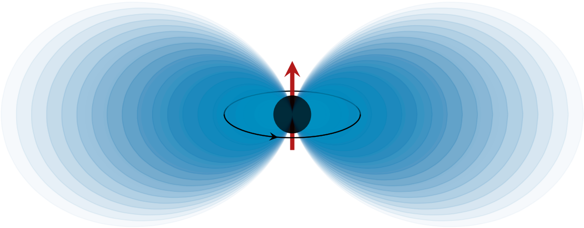
[Zeldovich '72; Starobinsky '73; Arvanitaki et al. '09]



How does the presence of a cloud affect a binary inspiral?

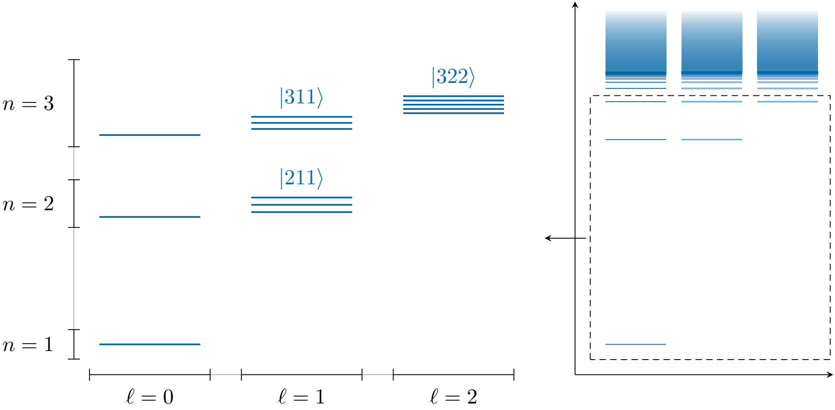
Can we detect these weakly-coupled, ultralight particles from their **impact** on the inspiral's waveform? Can we measure their properties?

Cloud has definite frequency states that are very similar to those of the **hydrogen atom**



We'll lean on quantum mechanical **intuition** and call these states $|n\ell m\rangle$

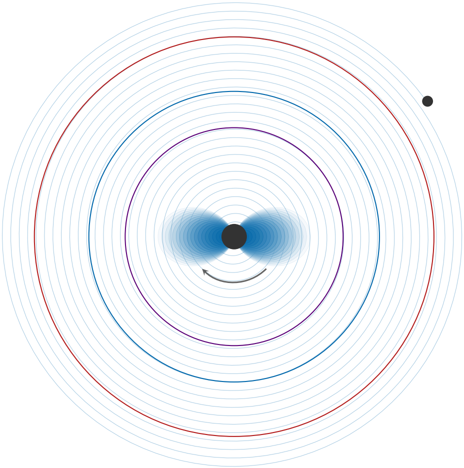
Superradiance **grows** the $|211\rangle$ state first.



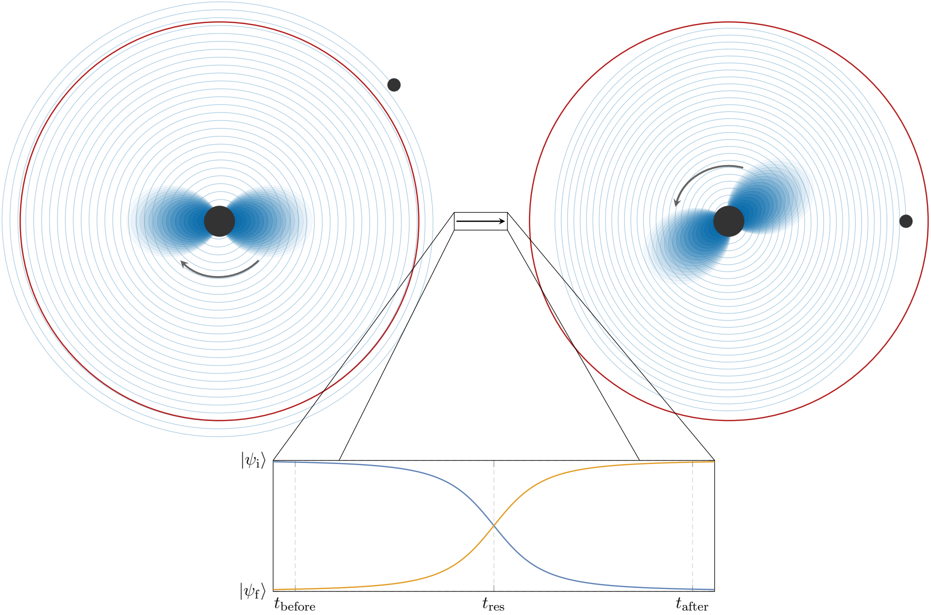
$$E_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} - f_{n\ell}\alpha^4 + h_{n\ell}\tilde{a}m\alpha^5 + \ldots\right)$$

[Baumann, Chia, Porto '18; Baumann, Chia, JS, ter Haar '19]

The companion perturbs the cloud at an **increasing** frequency

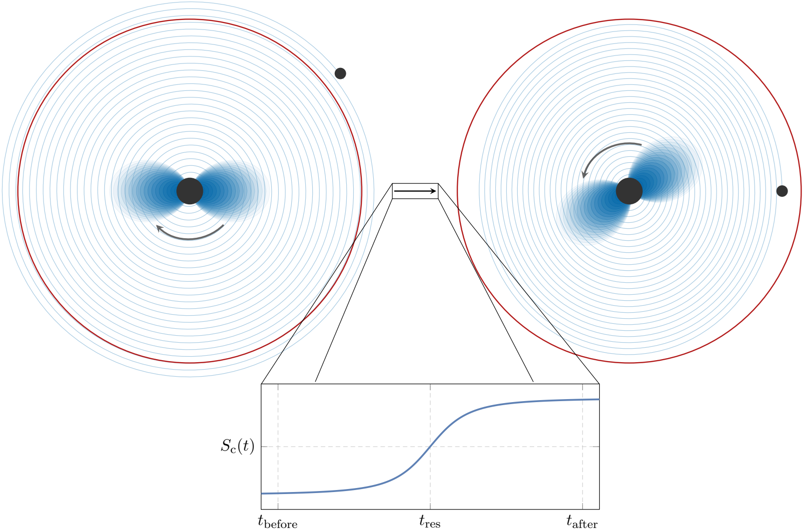


When this frequency matches the difference in frequencies of two states, the companion can **resonate** with the cloud



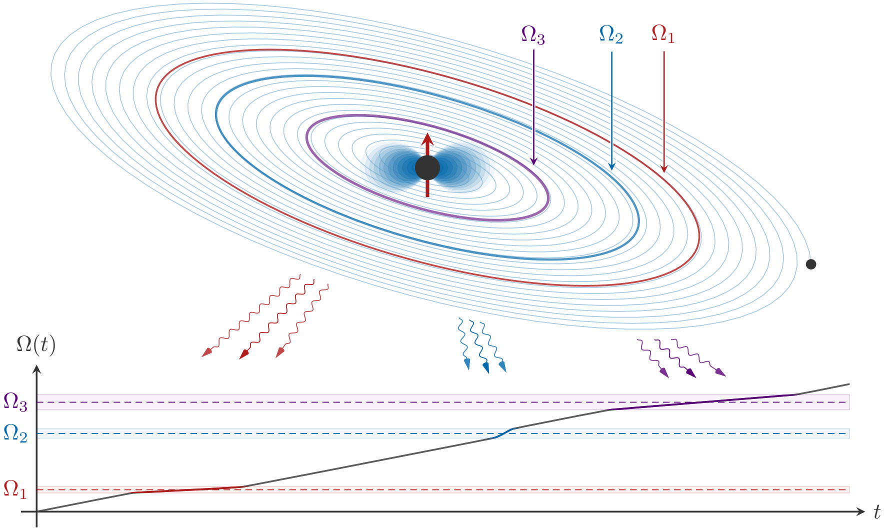
[Baumann, Chia, Porto, JS '19]

Key Point | During these transitions, cloud's angular momentum changes!



Changes in the cloud dramatically affect the inspiral!

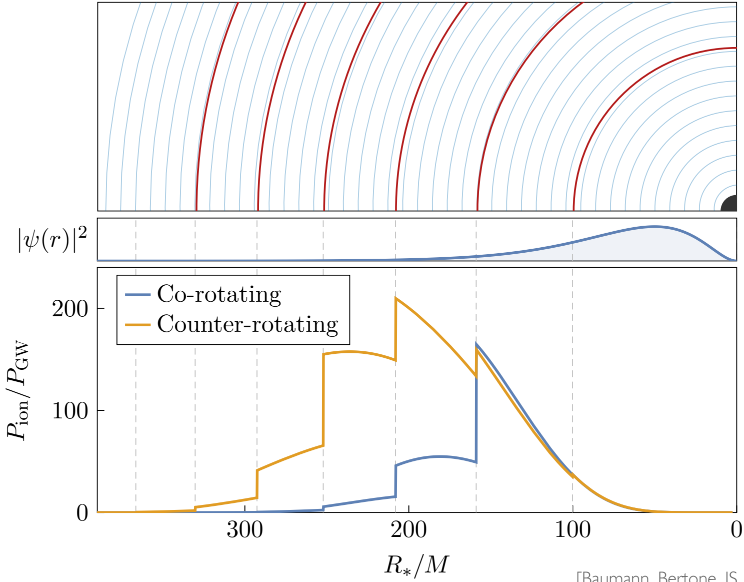
[Baumann, Chia, Porto, JS '19]



These resonances have a **large** and **sharp** impact on the inspiral.
When observed, can be used to detect the boson and measure its mass!

[Baumann, Chia, Porto, JS '19]

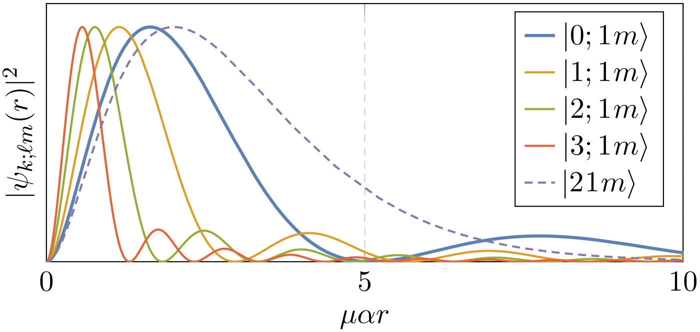
Main Point | What happens when the companion **ionizes** the cloud?



[Baumann, Bertone, JS, Tomaselli '21]

Continuum States

Interested in **ionization**, which depends on the unbound states $|k;\ell m\rangle$

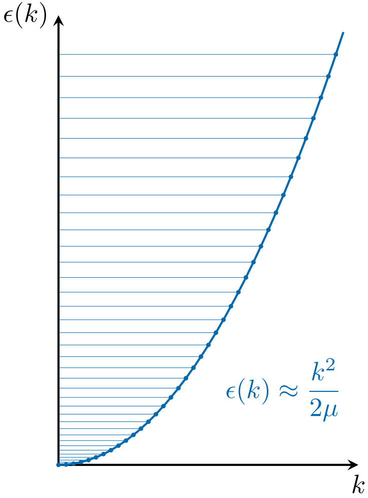


Crucial Point | **Low momentum** modes are localized about the black hole!

This implies that couplings between bound and continuum states go to zero **linearly** in k as $k \to 0$

[Working in units of $\mu\alpha$ for k]

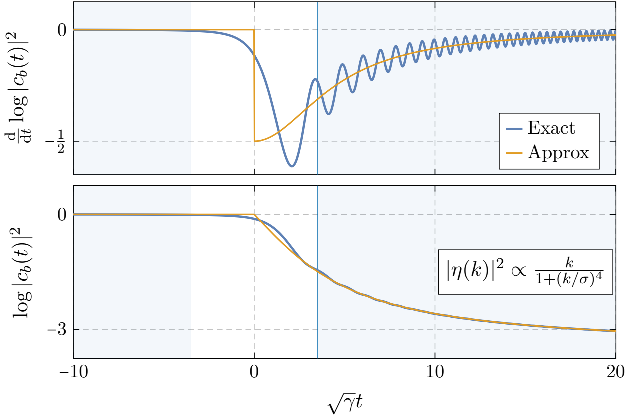
Continuum Energies



Crucial Point | Density of states $\dfrac{\mathrm{d}n}{\mathrm{d}\epsilon} = \dfrac{\mathrm{d}n}{\mathrm{d}k}\dfrac{\mathrm{d}k}{\mathrm{d}\epsilon} \propto \dfrac{\mu}{k}$ diverges as $k \to 0$!

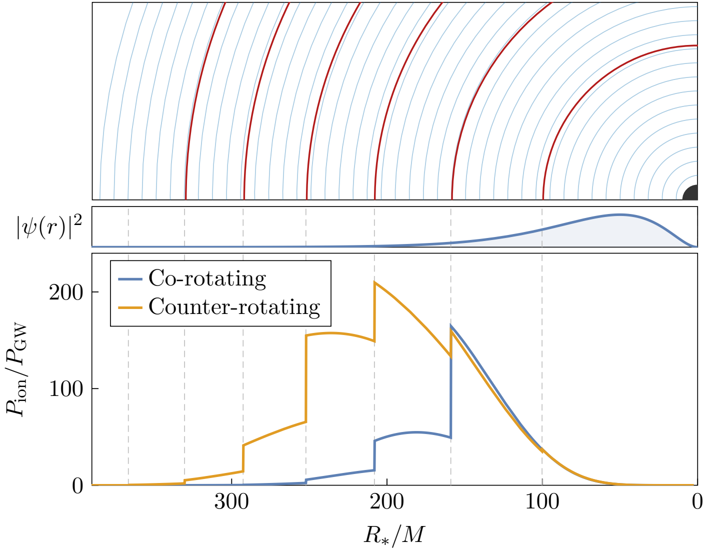
Derive **effective** Schrödinger equation for cloud, which **deoccupies** as

$$\frac{\mathrm{d}\log|c_b(t)|^2}{\mathrm{d}t} \approx -\big|\eta\big(k_*(t)\big)\big|^2 \left(\frac{\mu}{k_*(t)}\right), \quad \Omega(t) \geq \epsilon_b$$



Fundamental properties of hydrogen's spectrum imply that there are effective **discontinuities** in this system's time evolution.

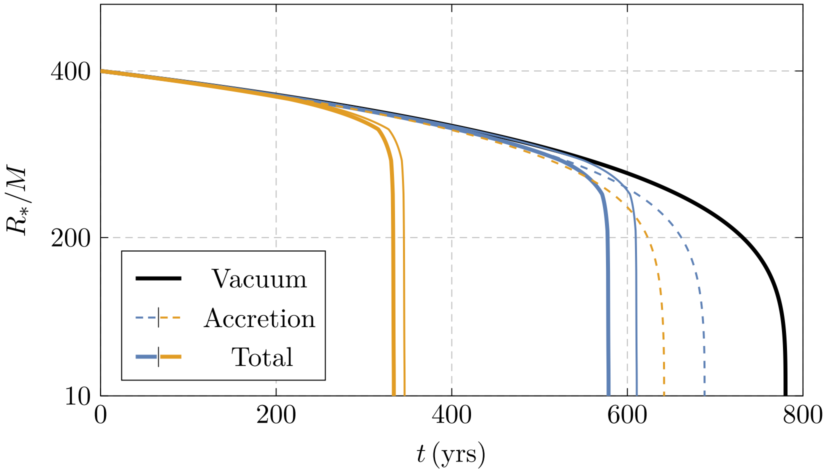
Main Point | Ionization of the cloud has large, sharp impact on the inspiral. Dominates over GW emission, signature of boson cloud!



[Baumann, Bertone, JS, Tomaselli '21]

Orbital Dynamics

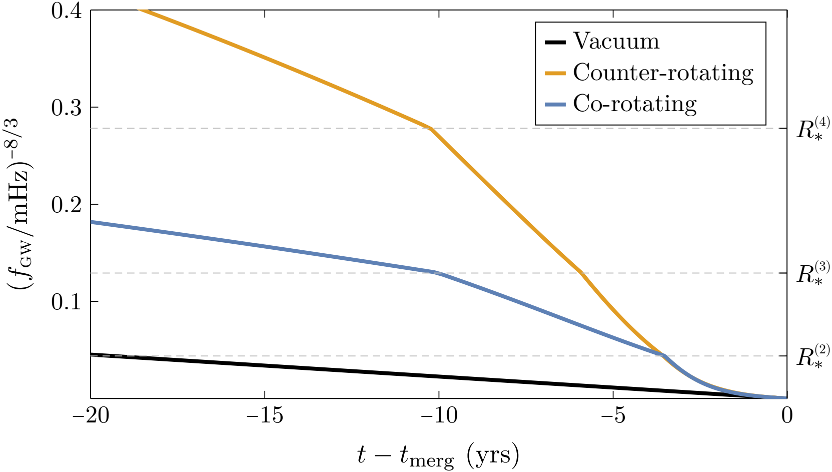
Large impact on both **co-rotating** and **counter-rotating** inspirals



$[M = 10^4 M_\odot,\ R_{*,0} = 400M,\ M_*/M = 10^{-3},\ \alpha = 0.2,\ M_c/M = 10^{-2}]$

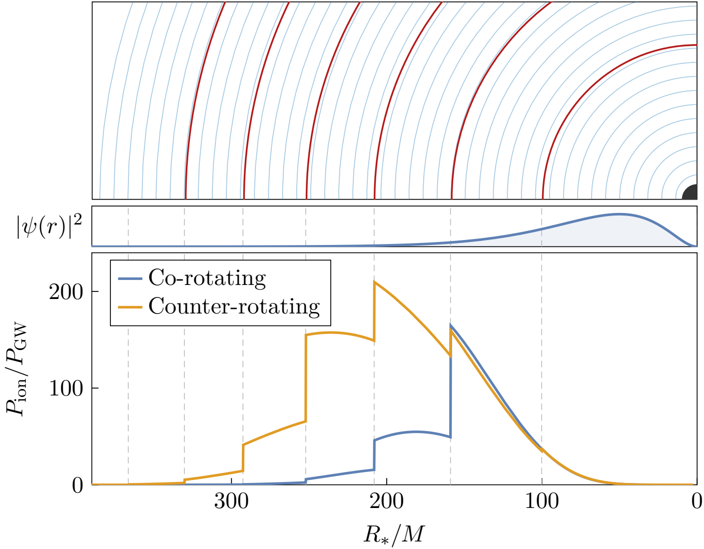
Frequency

See **discontinuities** if we observe the frequency of inspiral!
Signature of the cloud and ultralight boson!



$[M = 10^4 M_\odot,\ R_{*,0} = 400M,\ q = 10^{-3},\ \alpha = 0.2,\ M_c/M = 10^{-3}]$

Main Point | Ionization of the cloud has large, sharp impact on the inspiral. Dominates over GW emission, signature of boson cloud!



[Baumann, Bertone, JS, Tomaselli '21]