Title: Ionization of Gravitational Atoms

Speakers: John Stout

Series: Particle Physics

Date: February 15, 2022 - 1:00 PM

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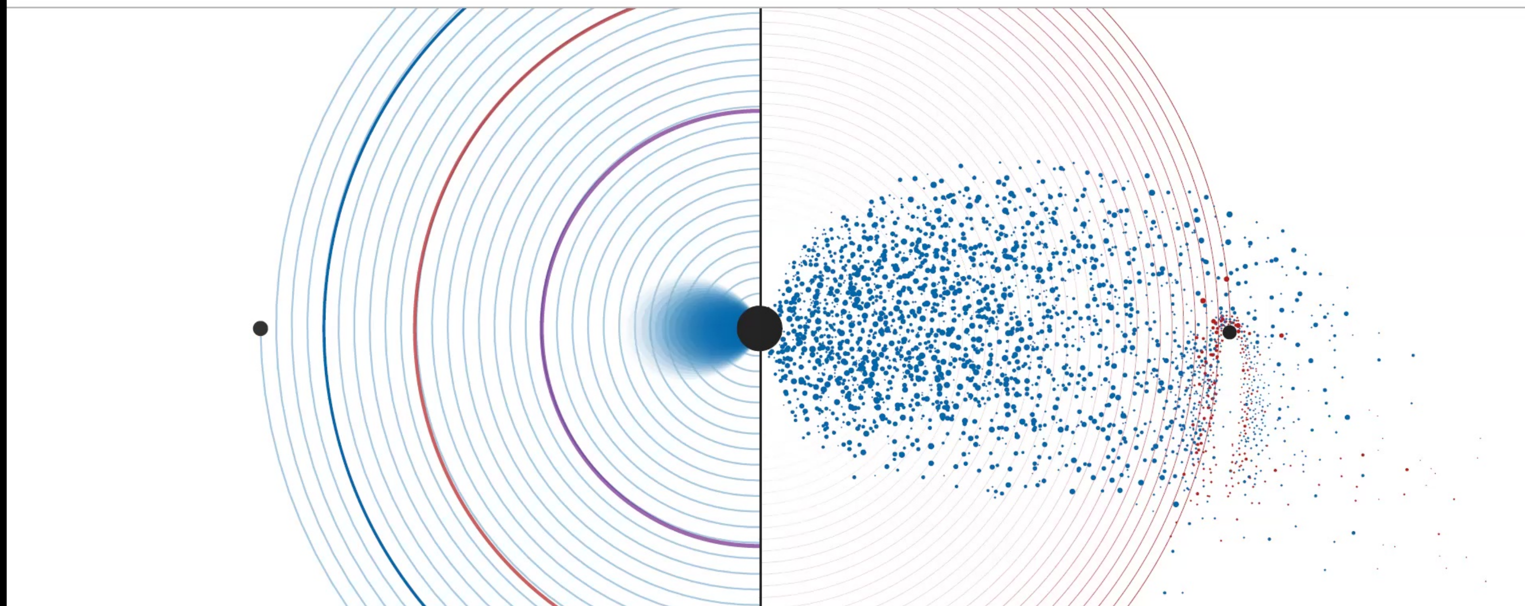
Abstract: Superradiant instabilities may create clouds of ultralight bosons around black holes, forming so-called "gravitational atoms." It was recently shown that the presence of a binary companion can induce resonant transitions between a cloud's bound states. When these transitions backreact on the binary's orbit, they lead to qualitatively distinct signatures in the gravitational waveform that can dominate the overall behavior of the inspiral. In this talk, I will show that the interaction with the companion can also trigger transitions from bound to unbound states of the cloud---a process which I will refer to as ``ionization," in analogy with the photoelectric effect in atomic physics. Here, too, there is a type of resonance with a similarly distinct signature, which may ultimately be used to detect any dark ultralight bosons that exist in our universe.

Zoom Link: https://pitp.zoom.us/j/97300299361?pwd=azhmVTR5VmpPQ1hwbkVHTUsrOGlJZz09

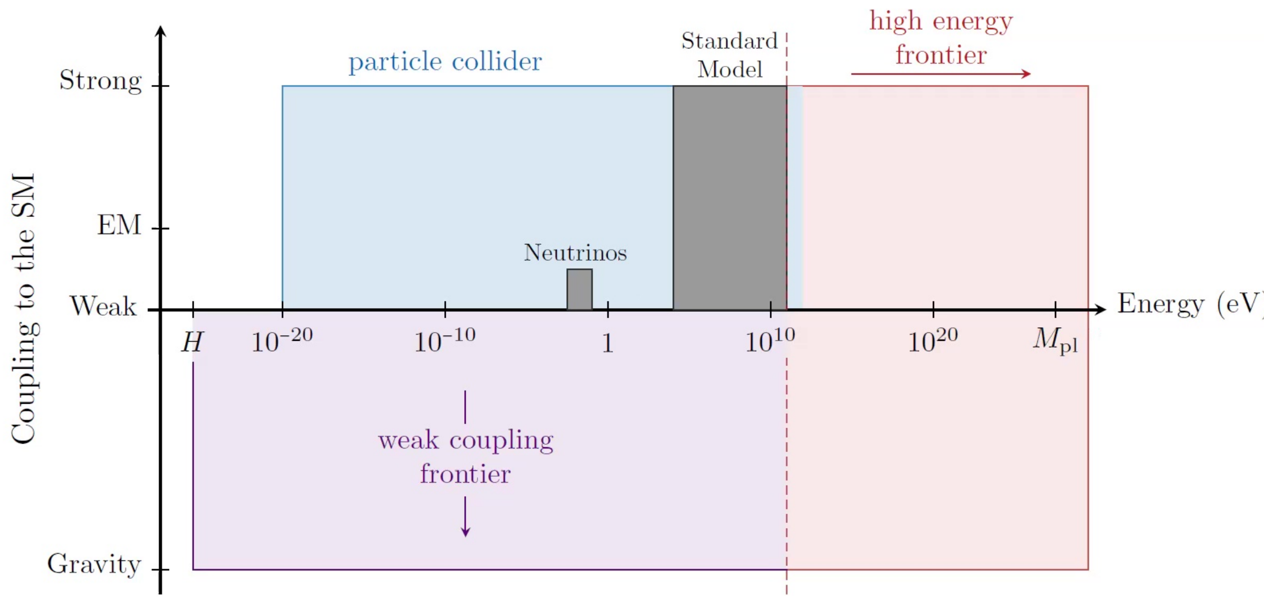
IONIZATION OF GRAVITATIONAL ATOMS



JOHN STOUT
HARVARD UNIVERSITY

Perimeter Particle Physics Seminar | February 15, 2022

Main Question | How do we explore the **weak coupling frontier**?



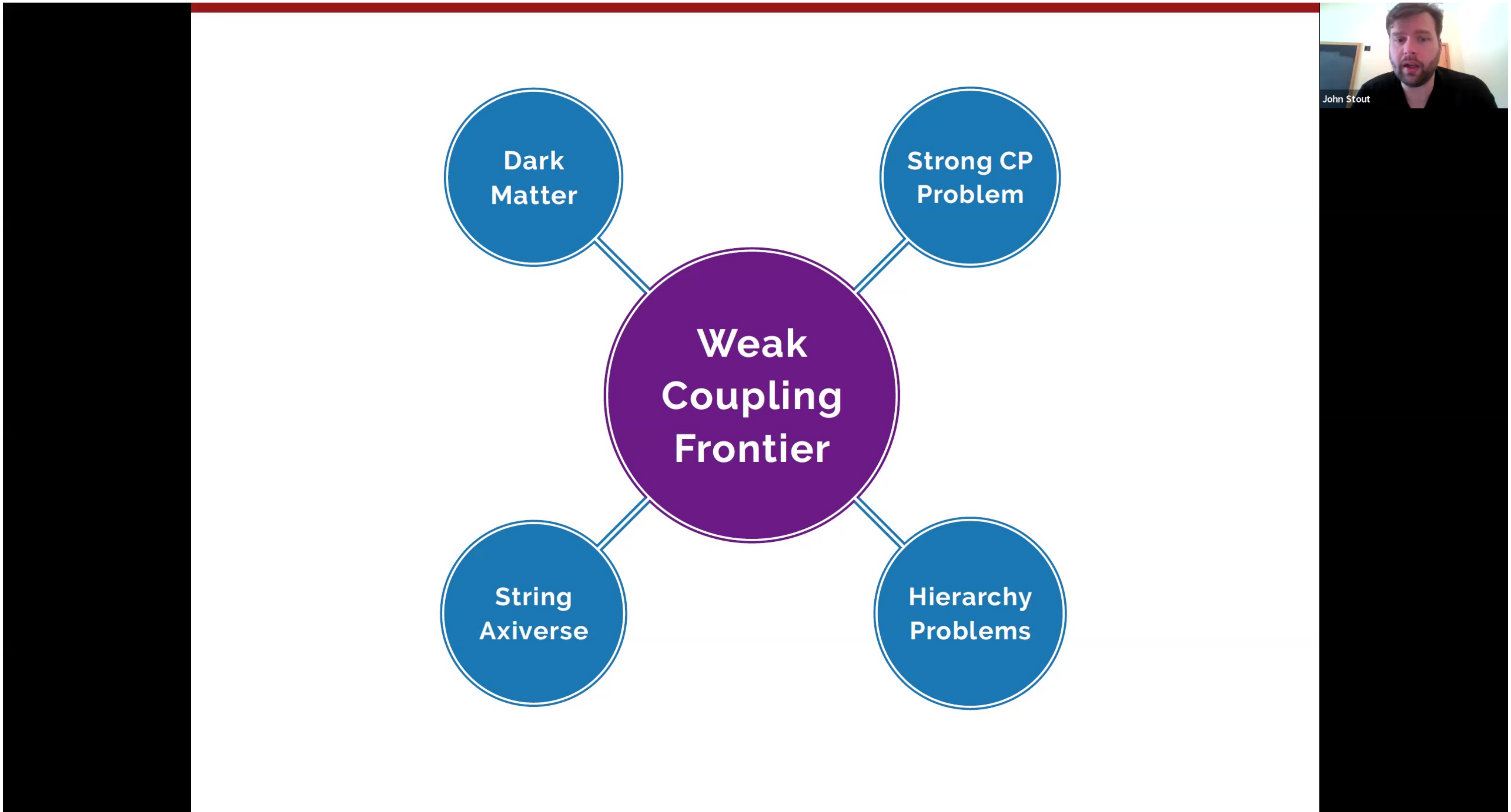
How do we detect an ultra-weakly coupled field that is **not abundant** in our universe?

Motivation

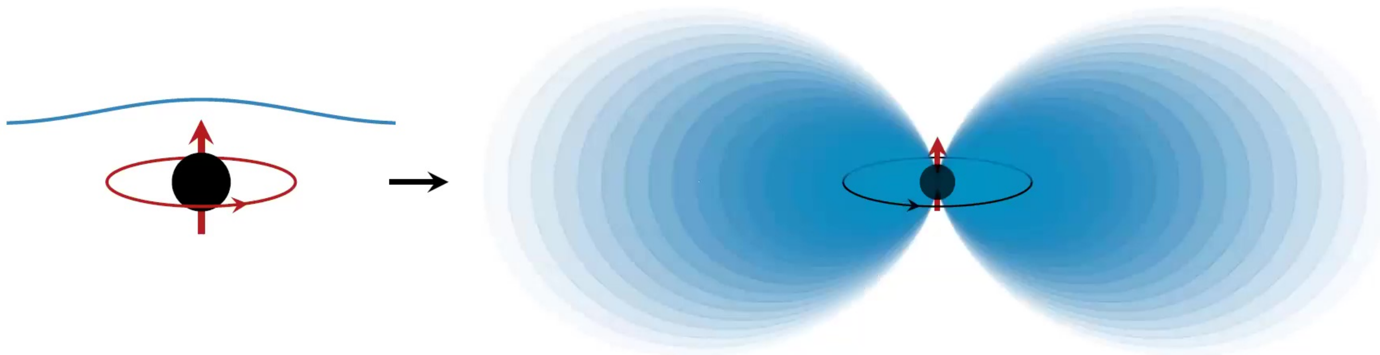
Solutions to many BSM puzzles involve **ultralight bosons**

- **Strong CP** | Why is the nEDM so small?
  [Peccei and Quinn '77; Wilczek '78; Weinberg '78; Kim '79; Zhitnitsky '80; Shifman, Vainshtein, Zakharov '80; Dine, Fischler, Srednicki '81; Arakawa, Rajaraman, Tait '19; ...]
- **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; Arias, Cadamuro, Jaeckel, Redondo, Ringwald '12; ...]
- **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; ...]
- **String Axiverse** | Generic in string compactifications
  [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell '09; Demirtas, Long, McAllister, Stillman '18; ...]

These ultralight fields can be **extremely weakly-coupled** to the SM
Low or **no abundance** in our universe


Dark Matter
Strong CP Problem
Weak Coupling Frontier
String Axiverse
Hierarchy Problems
John Stout

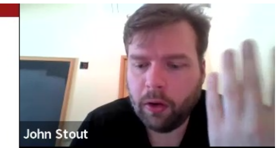
Ultralight bosons spontaneously form **bound states** around black holes

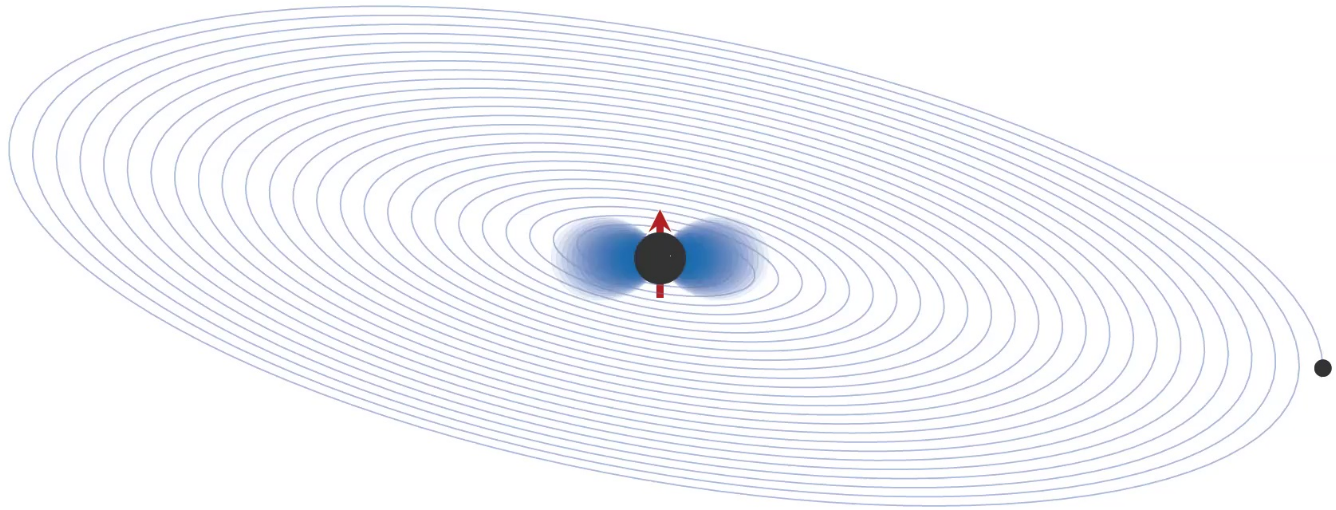


Physics governed by the **gravitational fine structure constant**

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

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



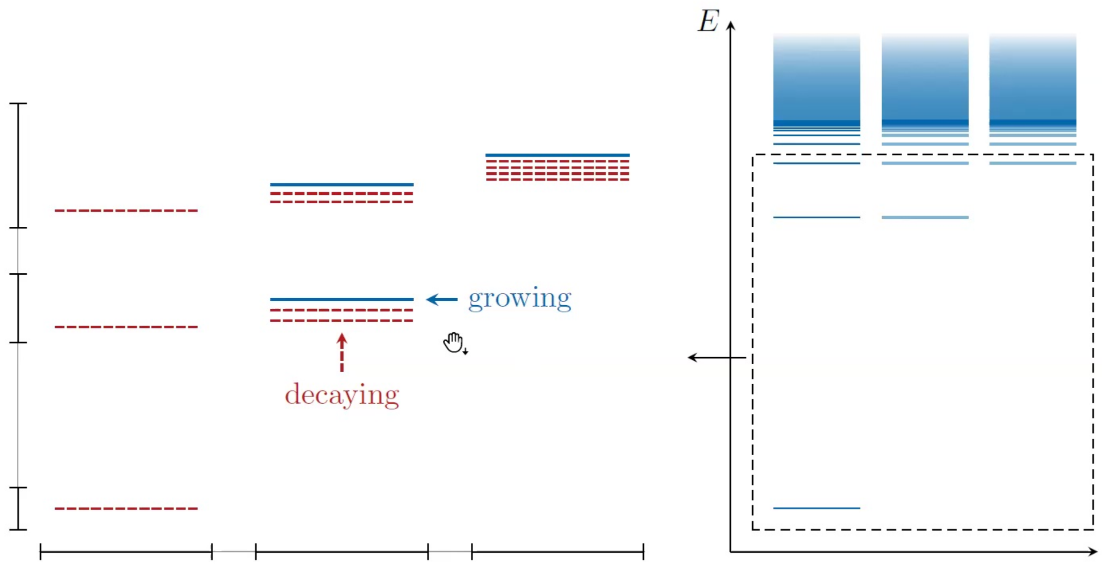


How does this cloud affect a binary inspiral?

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

Structure of the Atom

Growth is relatively fast on astrophysical timescales, **decay** is slow

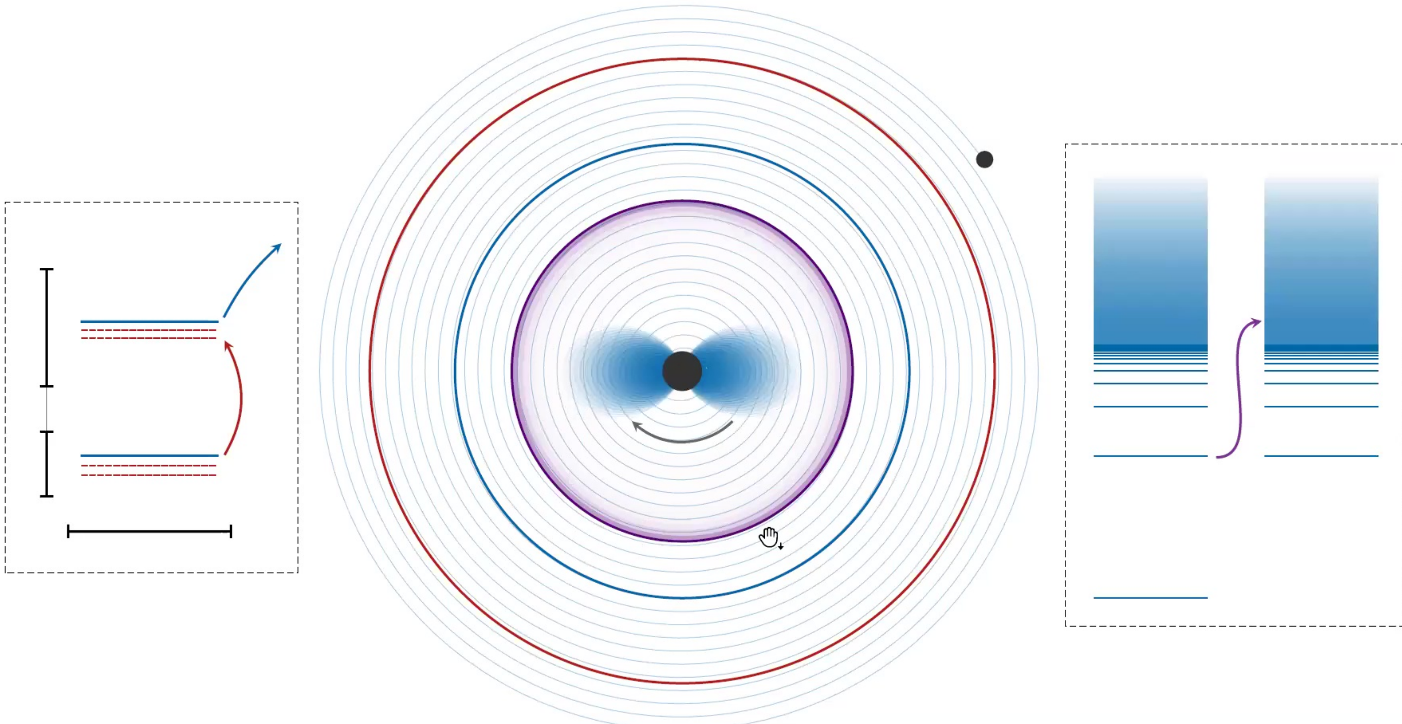


Cloud has structure of a **hydrogen atom**, states $|\psi\rangle$ with frequencies

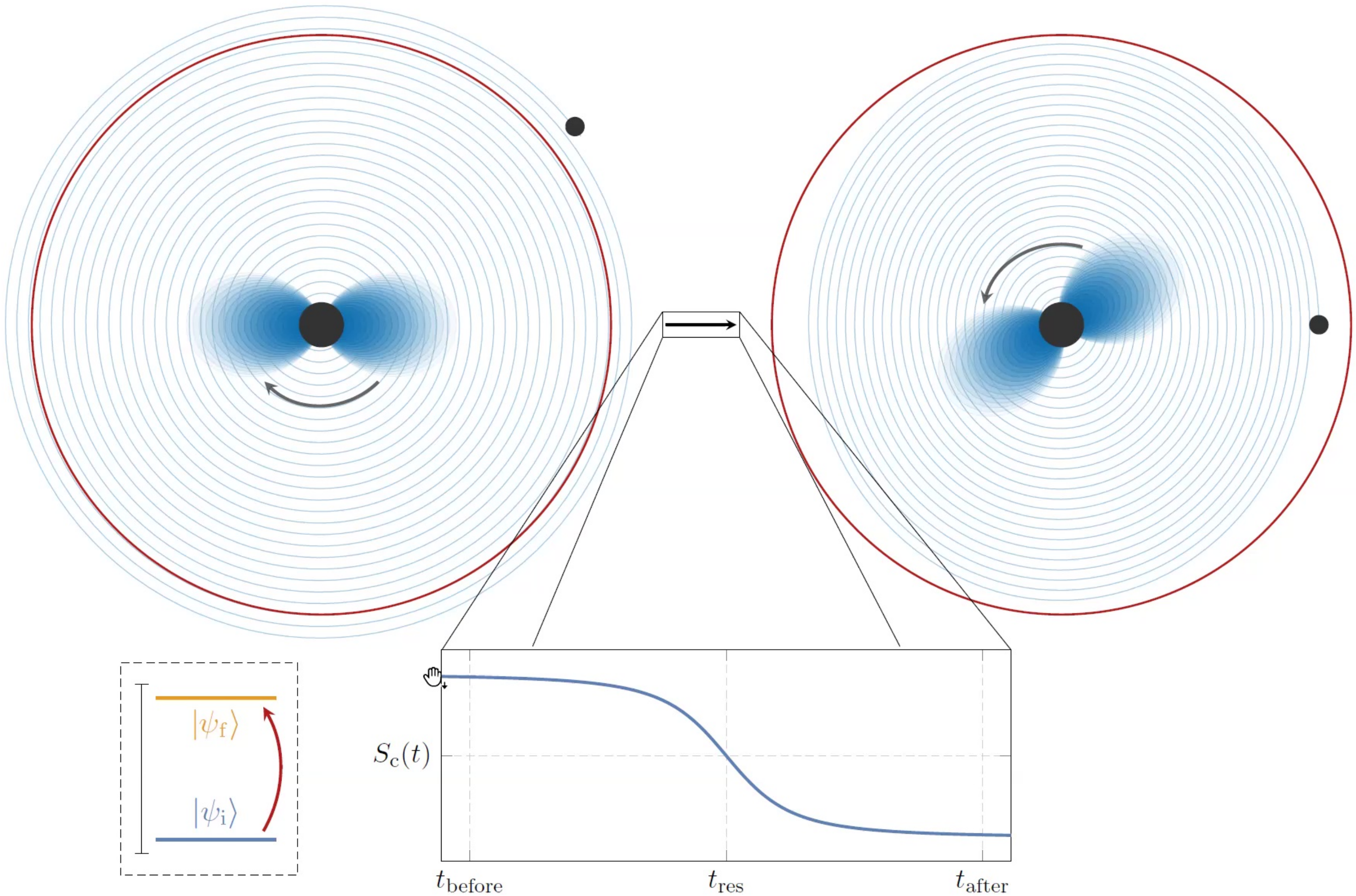
$$\omega = E + i\Gamma$$

Hydrogenic | Nearly Stable

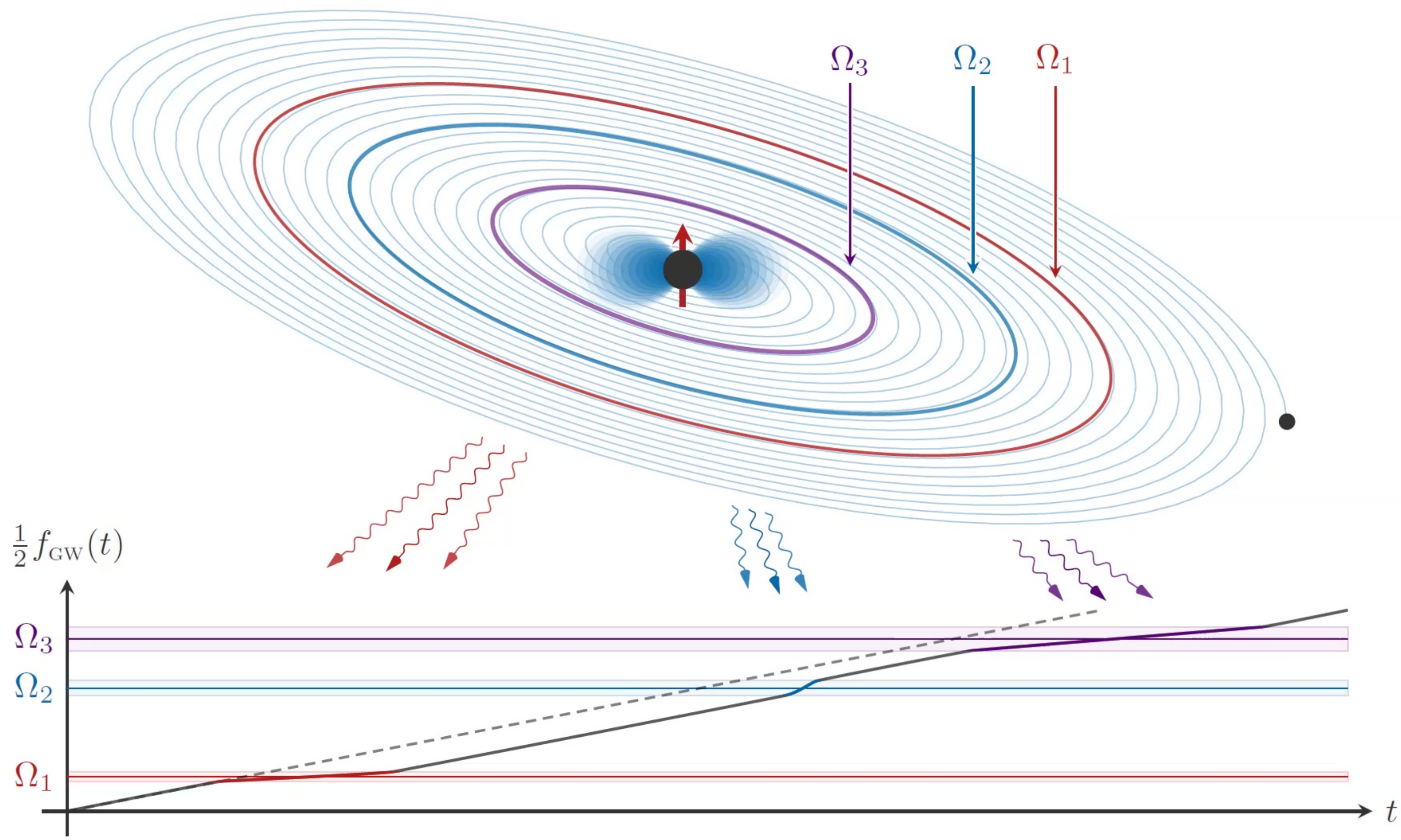
The companion perturbs the cloud at an **increasing** frequency



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



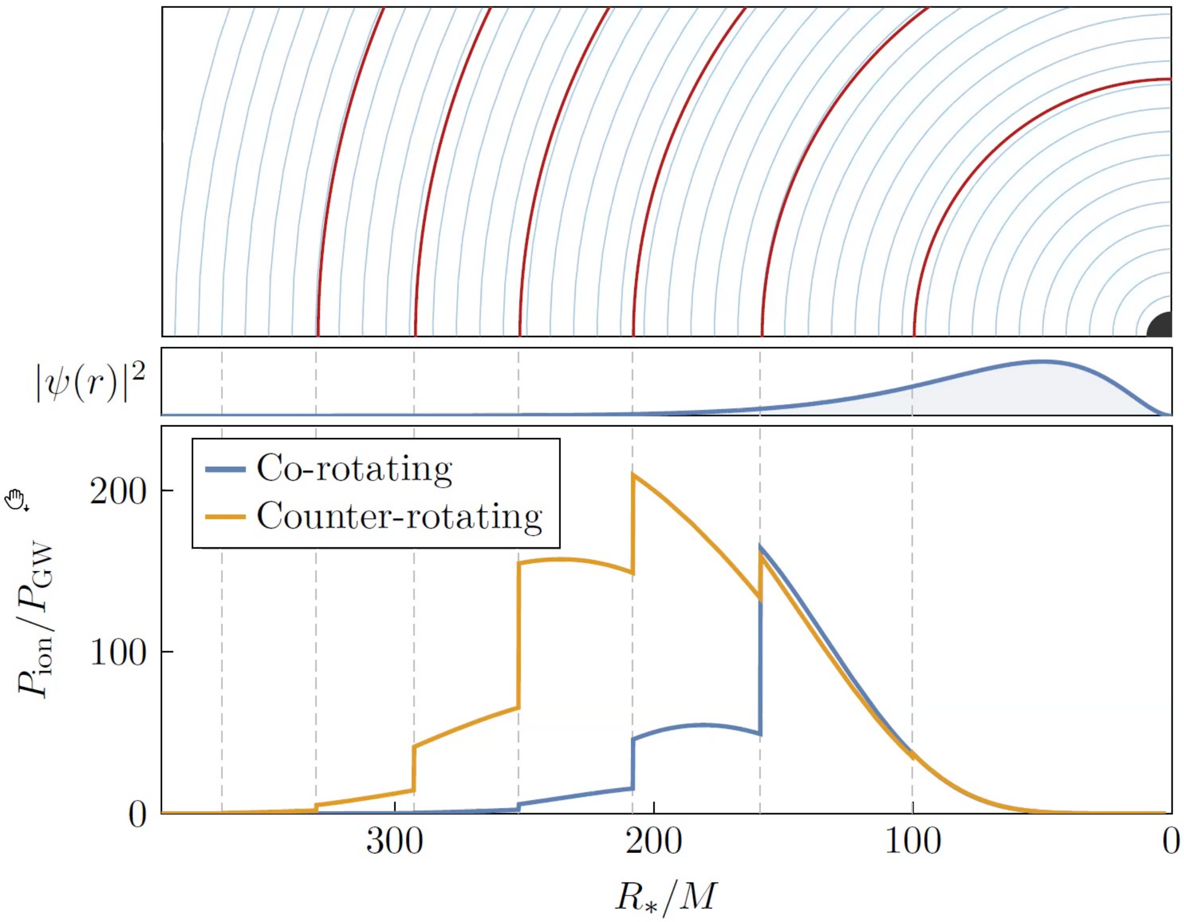
[Baumann, Chia, Porto, **JS** '19]

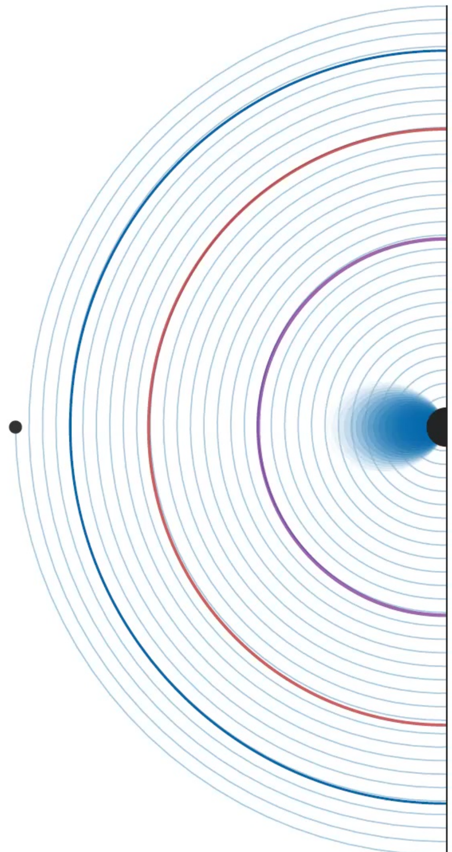


These resonances have a **large** and **sharp** impact on the inspiral.
When observed, can be used to detect the boson and measure its mass!

[Baumann, Chia, Porto, **JS** '19; Baumann, Bertone, **JS**, Tomaselli '21]

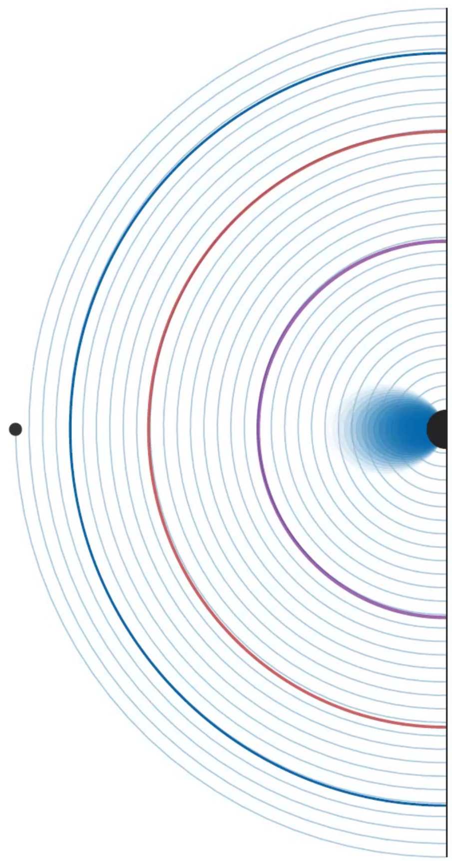
This Talk | What happens when the companion starts to **ionize** the cloud?

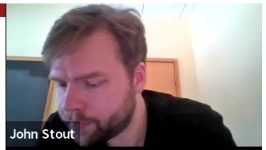




Overview

- Rapidly spinning black holes can spontaneously grow a large **cloud** of ultralight bosons
- Cloud has the same structure as the **hydrogen atom**
- Inspiraling companion **resonantly** ionize this gravitational atom
- Ionization has a **sharp** and **dominant** impact on GW signal





PART I

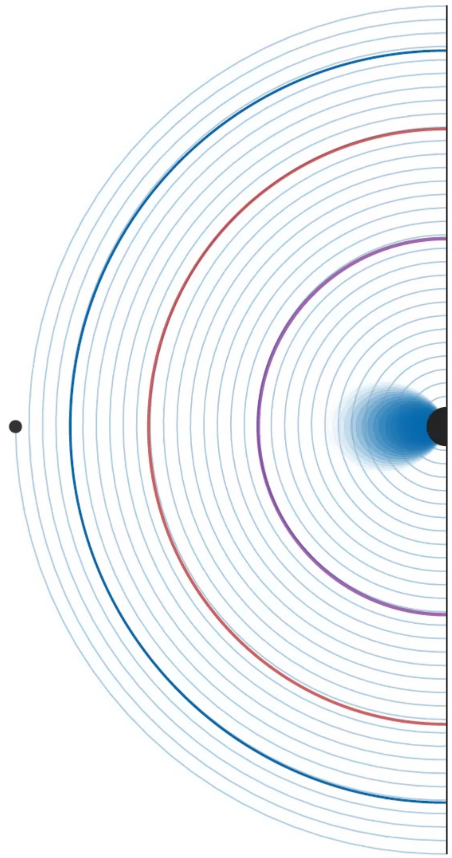
Ultralight Boson Clouds around Rotating Black Holes

PART II

Resonant Transitions from an Inspiraling Binary Companion

PART III

Gravitational Wave Signals from Resonant Ionization

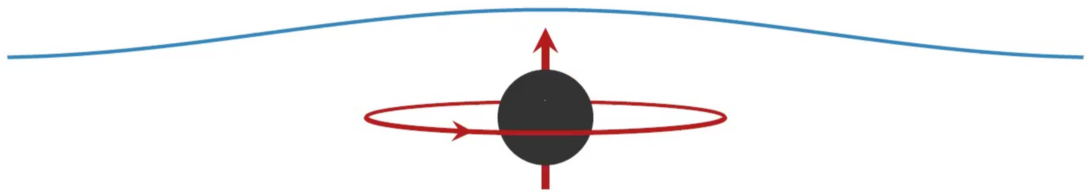


PART I

Ultralight Boson Clouds around Rotating Black Holes

A **scalar** field around rotating **black hole** described by KG equation

$$\left(g^{\alpha\beta}\nabla_\alpha\nabla_\beta - \mu^2\right)\Phi = 0$$



Focus on fields with Compton wavelengths much larger than the black hole

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

This ratio is called the **gravitational fine structure constant**

A **scalar** field around rotating **black hole** described by KG equation

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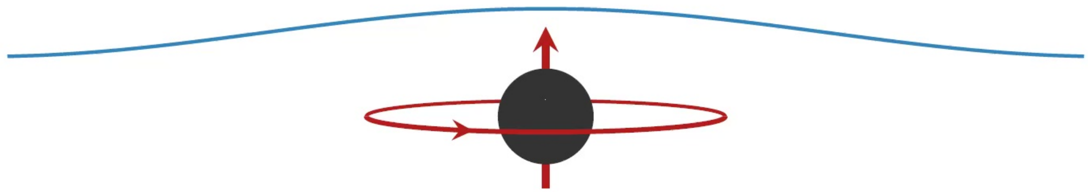


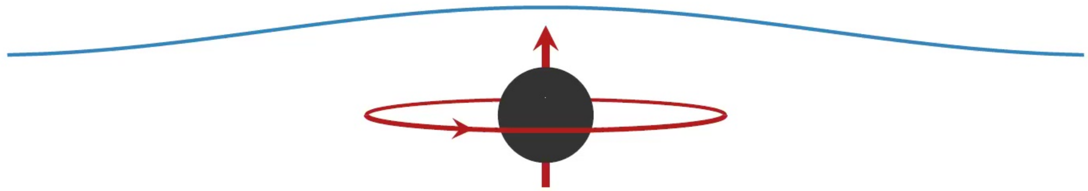
Since the boson is so **large**, it sees the far-field limit of BH geometry

$$\mu^2 \mathrm{d}s^2 = -\left(1 - \frac{2\alpha}{r}\right)\mathrm{d}t^2 + \left(1 + \frac{2\alpha}{r}\right)\mathrm{d}r^2 - \frac{4\alpha^2\tilde{a}\sin^2\theta}{r}\,\mathrm{d}t\,\mathrm{d}\phi + r^2\mathrm{d}\Omega_2^2$$

Contains both a **Coulombic** potential from the **gravitational redshift**, and a **magnetic field** from the **spin** $\tilde{a}$ of the black hole

A **scalar** field around rotating **black hole** described by KG equation

$$\left(g^{\alpha\beta}\nabla_\alpha\nabla_\beta - \mu^2\right)\Phi = 0$$



Dynamics of this cloud governed by a **hydrogenic** wave equation!

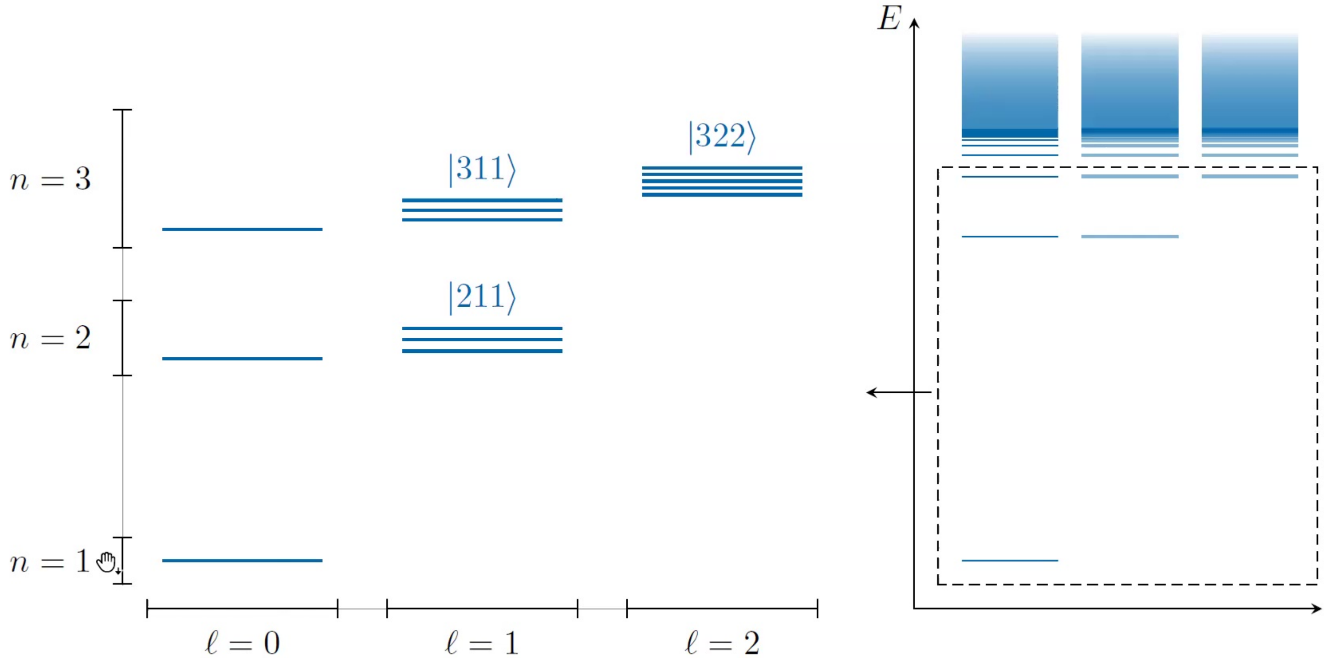
$$i\frac{\partial\psi}{\partial t} = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \cdots\right)\psi \quad \text{with} \quad \Phi = \frac{1}{\sqrt{2\mu}}\mathrm{Re}\left[\psi\, e^{-i\mu t}\right]$$

Coulomb potential from **gravitational redshift**

Fine/hyperfine structure from black hole's **spin**

Have two types of states: **bound** and **unbound**.

Bound States



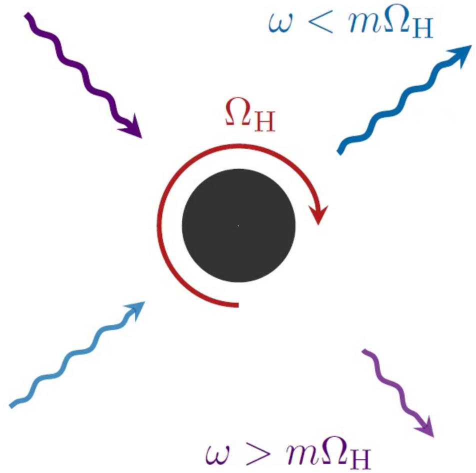
$$E_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} - f_{n\ell}\alpha^4 + h_{n\ell}\,\tilde{a}m\alpha^5 + \cdots\right)$$

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

Superradiant Scattering

A mode with frequency ω and azimuthal angular momentum m scattering off a spinning black hole can be **superradiantly amplified**

$$\Phi \propto \exp(im\phi - i\omega t) \propto \exp\big(im\big[\phi - \tfrac{\omega}{m}t\big]\big)$$

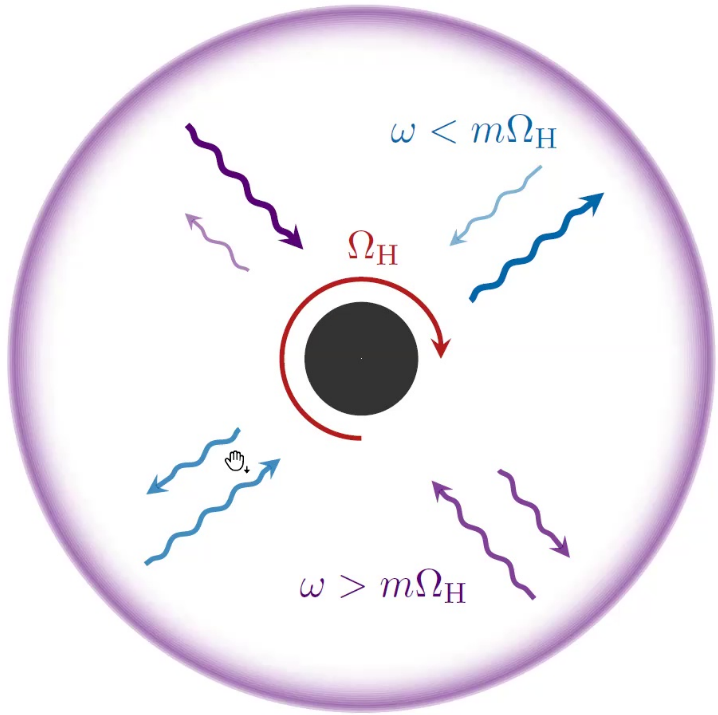


Mode is **amplified** if its angular velocity is less than horizon, $\Omega_{\rm H}$

[Zeldovich '72; Starobinsky '73]

Superradiance Instability

Potential amplifies and damps arbitrarily small (quantum) fluctuations

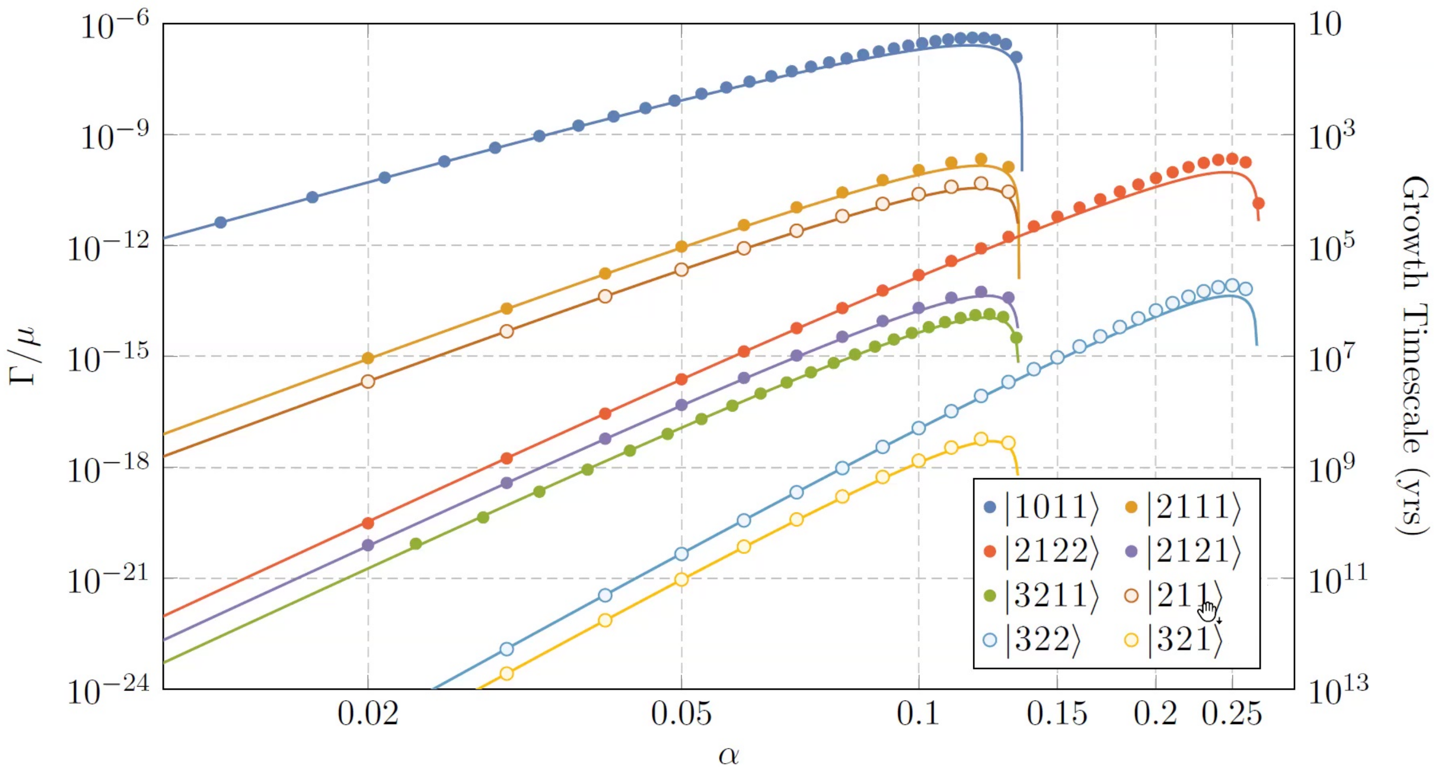


A mode with angular velocity less than horizon **grows** until $\Omega_H = \omega/m$

[Press, Teukolsky '72; Starobinsky '73; Detweiler '80]

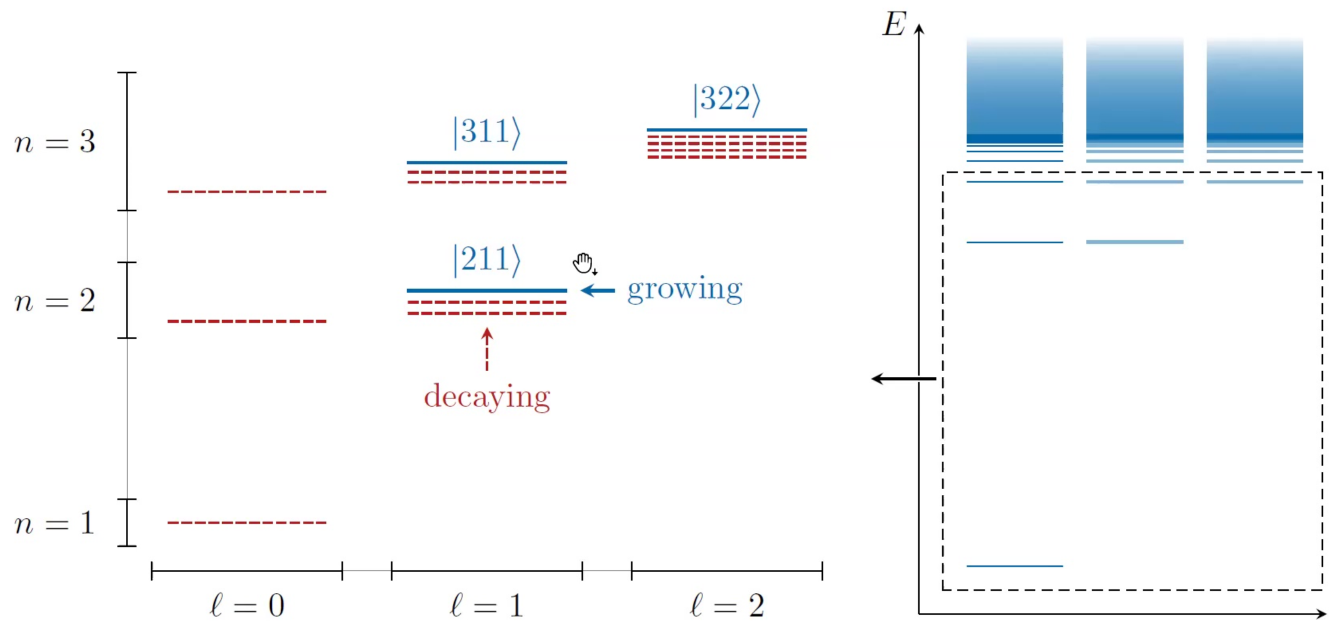
Growth Rates

$$\Gamma_{n\ell jm} \propto (m\Omega_{\rm H} - \omega_{n\ell jm})\alpha^{2j+2\ell+5}$$



[Baumann, Chia, **JS**, ter Haar '19]

Bound State Spectrum



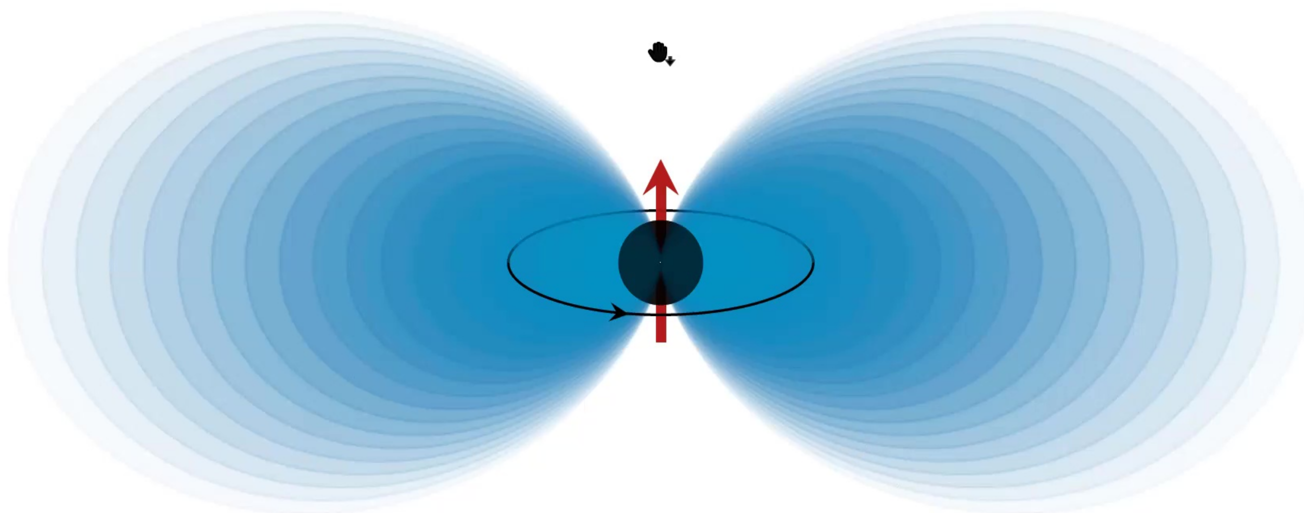
$$\omega_{n\ell m} = E_{n\ell m} + i\Gamma_{n\ell m}$$

Energies $E_{n\ell m}$ are **hydrogenic** while growth/decay rates $\Gamma_{n\ell m} \propto \alpha^{4\ell+5}$

[Dolan '07; Baumann, Chia, Porto '18; Baumann, Chia, **JS**, ter Haar '19]

Experimental Apparatus

The $|211\rangle$ state grows **quickly** on astrophysical timescales, looks like

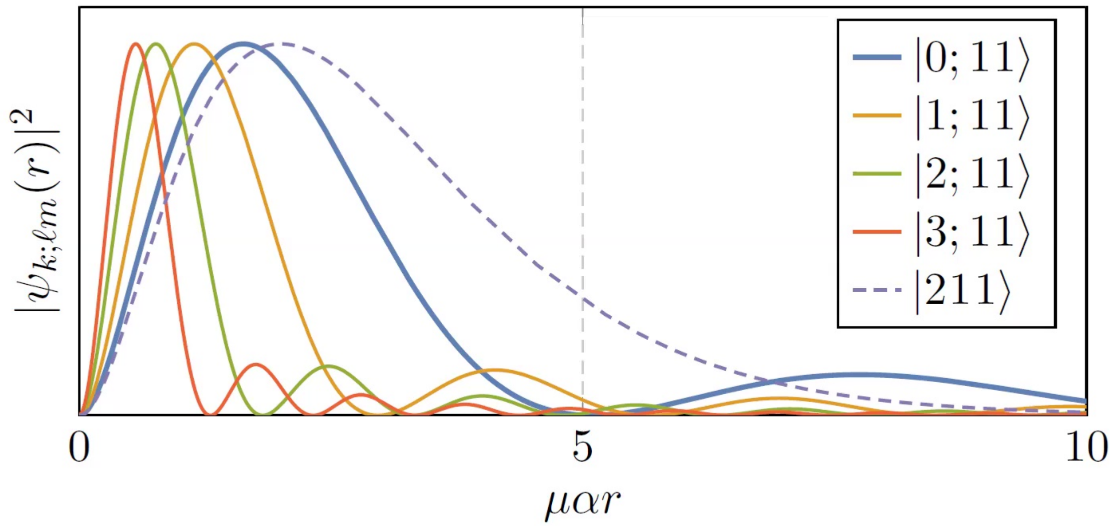


$$\Gamma_{211}^{-1} \simeq \frac{10^3\,\text{yrs}}{\tilde{a}}\left(\frac{M}{60M_\odot}\right)\left(\frac{0.04}{\alpha}\right)^9$$

Continuum States

There are also the **unbound**, or **continuum**, states $|\epsilon; \ell m\rangle$, $\epsilon = \frac{1}{2\mu}k^2$.

$$\psi_{k;\ell m}(\mathbf{r}) \propto (2kr)^\ell e^{-ikr}\,{}_1F_1\left(\ell + 1 + \tfrac{i\mu\alpha}{k}; 2\ell + 2; 2ikr\right) Y_{\ell m}(\theta, \phi)$$



Crucial Point | The **zero mode** is still localized about the black hole!

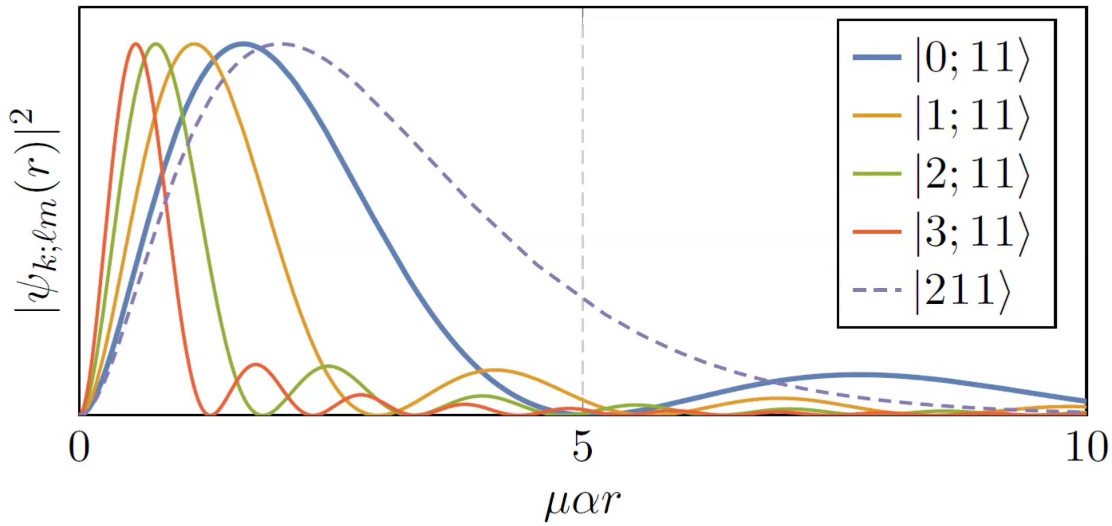
Long-ranged Coulomb potential traps **low energy** states.

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

Continuum States

Interested in **ionization**, which depends on the unbound states.

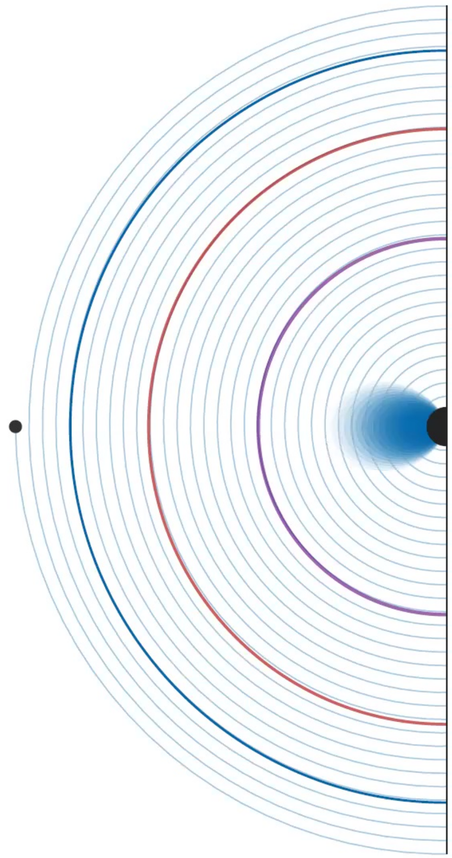
$$\psi_{k;\ell m}(\mathbf{r}) \propto (2kr)^{\ell} e^{-ikr}\,{}_1F_1\!\left(\ell + 1 + \tfrac{i\mu\alpha}{k}; 2\ell+2; 2ikr\right) Y_{\ell m}(\theta, \phi)$$



Crucial Point | The **zero mode** is still localized about the black hole!

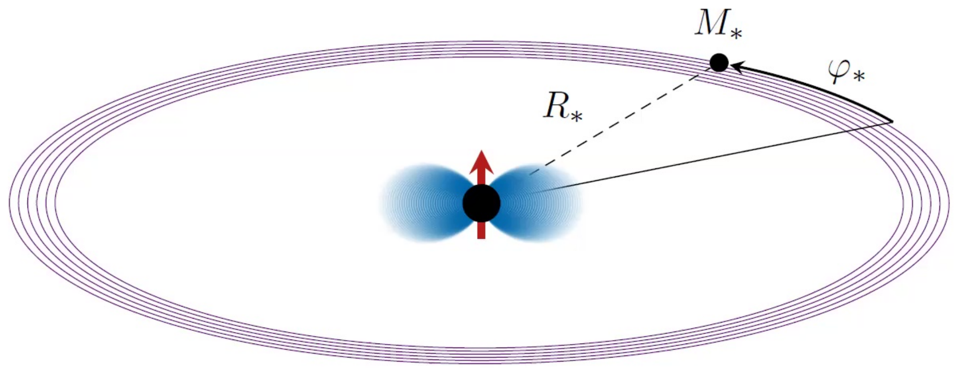
This implies that $|\langle \epsilon; \ell m | V | n \ell' m' \rangle|^2$ is **finite** as $\epsilon \to 0$!

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



PART II

Resonant Transitions from an Inspiraling Binary Companion

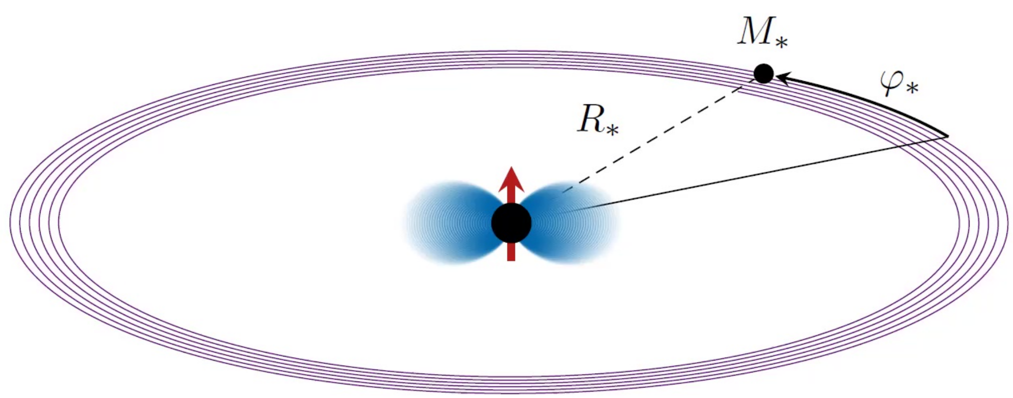


A binary companion with mass M_* will **perturb** the Schrödinger equation,

$$i\partial_t \psi = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \Delta V + V_*(R_*(t), \varphi_*(t)) \right) \psi$$

For simplicity, we'll only consider **equatorial orbits**.

Has a combination of **fast** $(\varphi_*(t))$ and **slow** $(R_*(t))$ motions



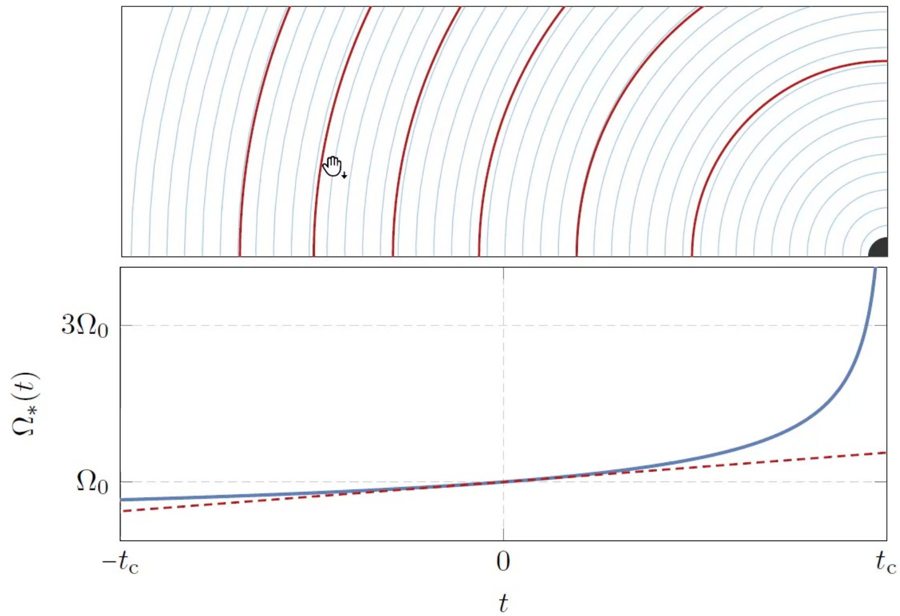
This **gravitational perturbation** induces **level mixing**!

For generic states $|a\rangle$ and $|b\rangle$ with definite azimuthal angular momentum

$$\langle a|V_*(t)|b\rangle = \eta_{ab}(t)e^{-i(m_a - m_b)\varphi_*(t)}$$

This perturbation is **quasi-periodic**, amplitude slowly varies in time

Gravitational wave emission causes frequency of perturbation to **chirp**

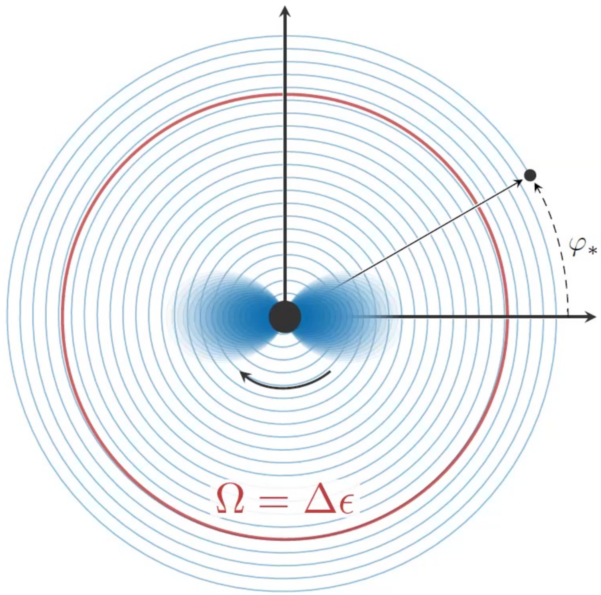


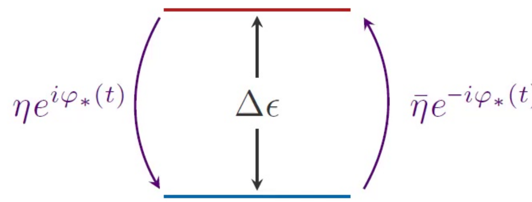
Does so nonlinearly, but in phase we're interested in we can **linearize**

$$\dot{\varphi}_*(t) = \Omega(t) \approx \Omega_0 + \gamma t + \cdots$$

What happens when Ω_0 is high enough to **ionize** the cloud?

Two State Resonance

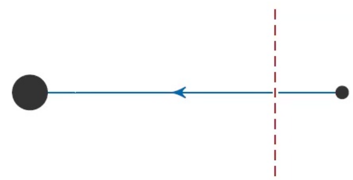




$$\mathcal{H} = \begin{pmatrix} -\frac{1}{2}\Delta\epsilon & \eta e^{i\varphi_*(t)} \\ \bar{\eta} e^{-i\varphi_*(t)} & \frac{1}{2}\Delta\epsilon \end{pmatrix}$$

$$\mathcal{H} = -\tfrac{1}{2}\Delta\epsilon|0\rangle\langle 0| + \tfrac{1}{2}\Delta\epsilon|1\rangle\langle 1| + \eta e^{i\varphi_*(t)}|0\rangle\langle 1| + \bar{\eta} e^{-i\varphi_*(t)}|1\rangle\langle 0|$$

There is **slow** motion if we rotate along with the companion



$\Omega = \Delta\epsilon$

In this **dressed** frame, the Hamiltonian evolves very slowly

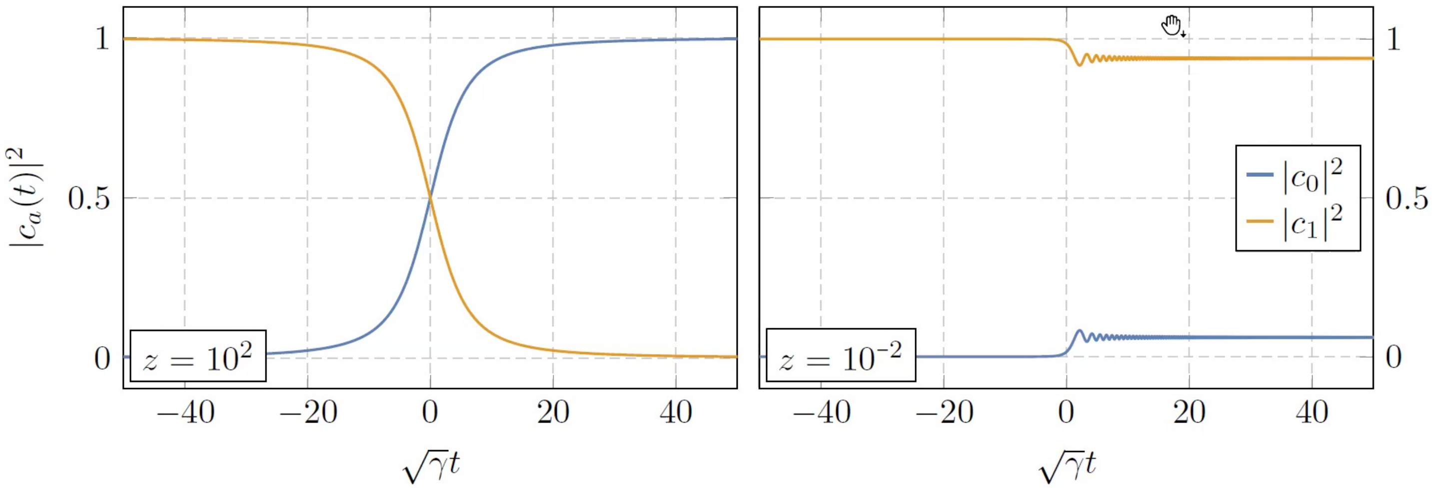
$$\mathcal{H}_{\mathrm{D}}(t) = \begin{pmatrix} (\Omega(t) - \Delta\epsilon)/2 & \eta \\ \bar{\eta} & -(\Omega(t) - \Delta\epsilon)/2 \end{pmatrix}$$

$$\Omega(t) = \Omega_0 + \gamma(t - t_0) + \dots$$

we'll set $\Omega_0 = \epsilon$

determines nature of transition

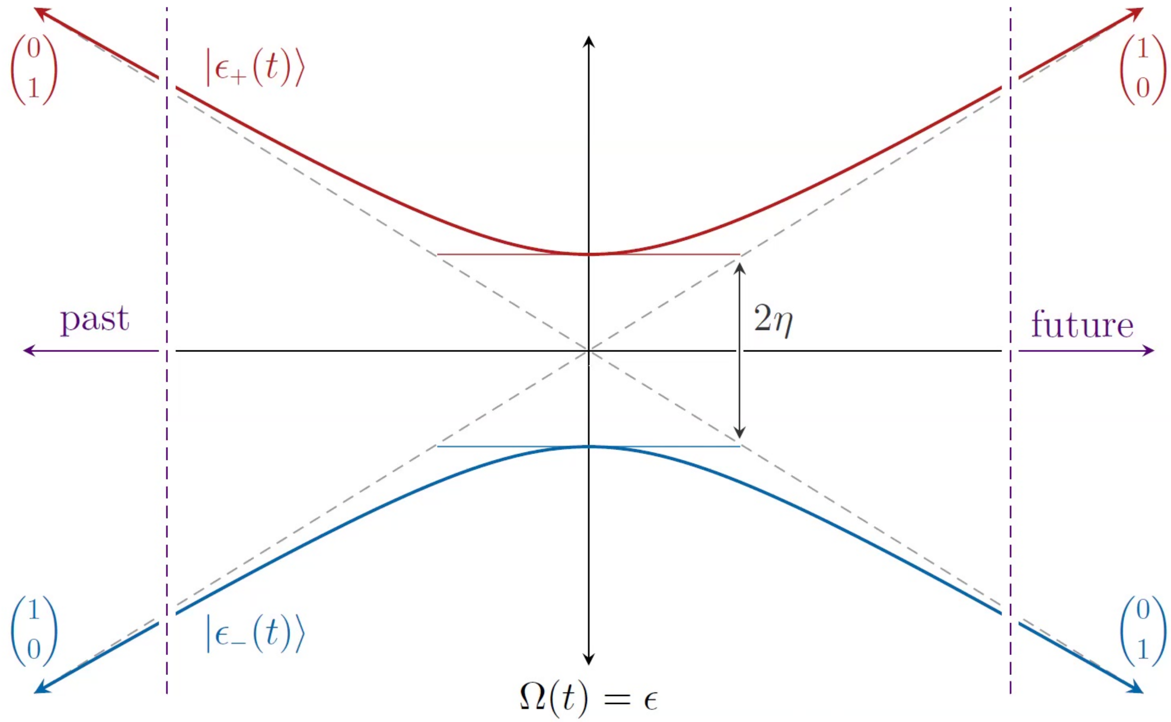
Find two different behaviors, depending on **LZ parameter** $z \equiv |\eta|^2/\gamma$.



For slow motion or strong coupling, $z \gg 1$, the initial state **smoothly and fully deoccupies**.

For fast motion or weak coupling, $z \ll 1$, both states are occupied; have **transient ringing**.

Strong Coupling



$$\mathcal{H}_{\rm D}(t) = \frac{\gamma t}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix} + \eta\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$$

Weak Coupling

At weak coupling, initial state is barely deoccupied.

$$i\frac{\mathrm{d}}{\mathrm{d}t}\left[e^{-i\epsilon t/2}c_0(t)\right] = \eta e^{-i\epsilon t + i\varphi_*(t)}\left[e^{i\epsilon t/2}c_1(t)\right]$$

$$i\frac{\mathrm{d}}{\mathrm{d}t}\left[e^{i\epsilon t/2}c_1(t)\right] = \bar{\eta} e^{i\epsilon t - i\varphi_*(t)}\left[e^{-i\epsilon t/2}c_0(t)\right]$$

Can **integrate out** $c_1(t)$, find **effective Schrödinger equation**

$$i\frac{\mathrm{d}\tilde{c}_0}{\mathrm{d}t} = \int_{-\infty}^{t}\mathrm{d}t'\,\Sigma(t,t')\tilde{c}_0(t') \approx \mathcal{E}(t)\tilde{c}_0(t)$$

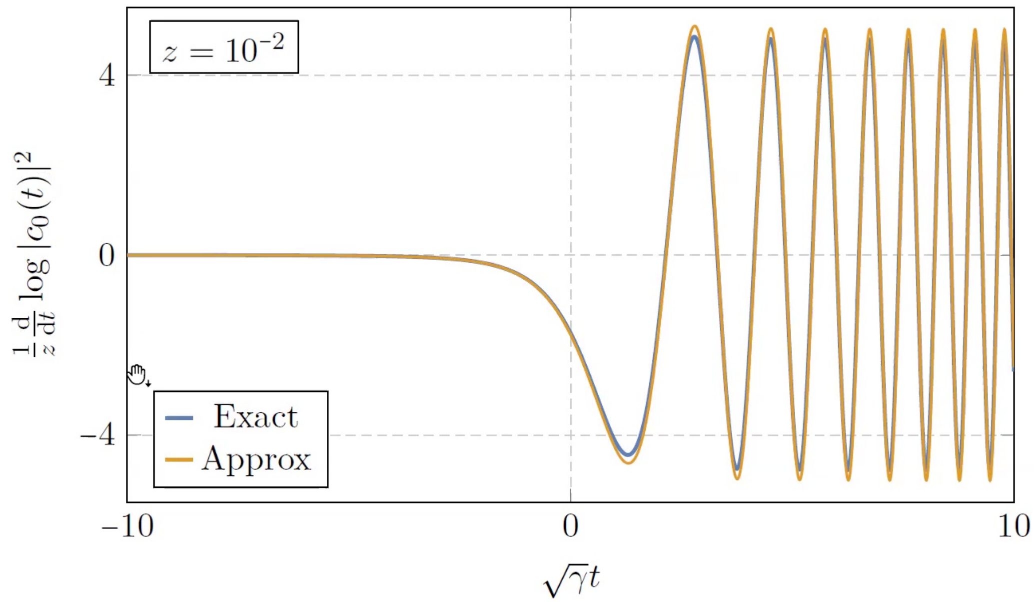
in terms of an **induced energy** for the state $|0\rangle$,

$$\mathcal{E}(t) = -i\int_{-\infty}^{t}\mathrm{d}t'\,|\eta|^2 e^{-i\epsilon(t-t')+i\varphi_*(t)-\varphi_*(t')}$$

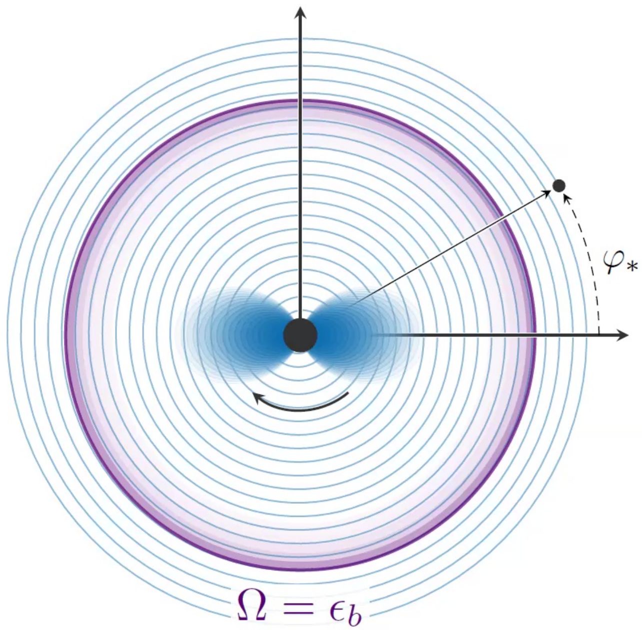
Induced Energy

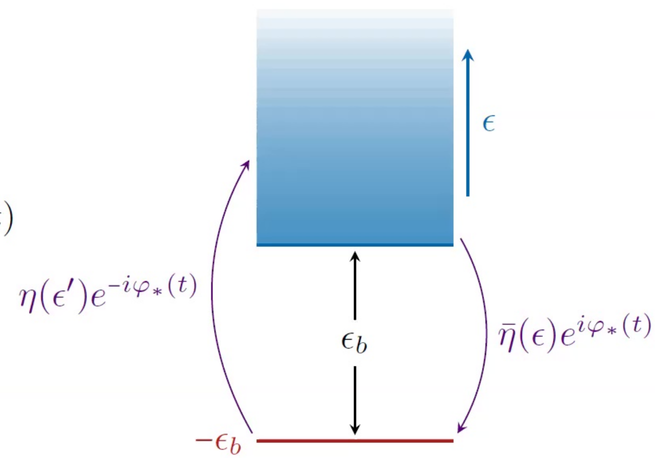
The **deoccupation** of the initial state is controlled by **induced energy**

$$\frac{\mathrm{d}\log|c_0|^2}{\mathrm{d}t} = 2\,\mathrm{Im}\,\mathcal{E}(t)$$



Continuum Toy Model

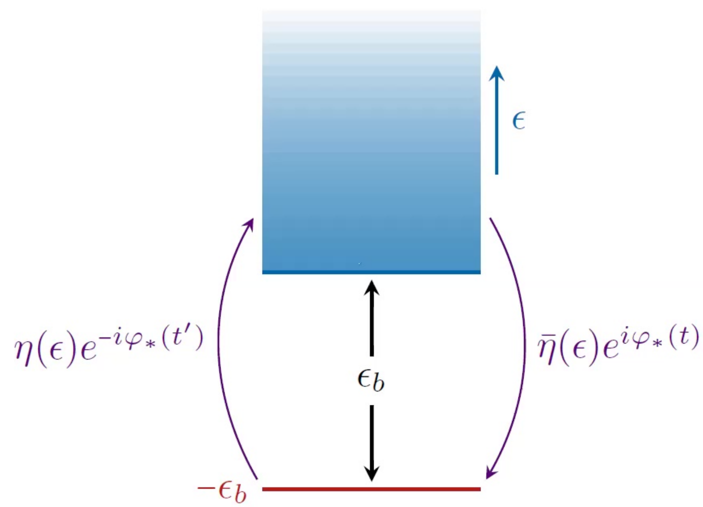




$$\mathcal{H} = -\epsilon_b |b\rangle\langle b| + \int_0^\infty \mathrm{d}\epsilon\, \epsilon\, |\epsilon\rangle\langle\epsilon|$$
$$+ \int_0^\infty \mathrm{d}\epsilon \left[\eta(\epsilon)e^{-i\varphi_*(t)}|\epsilon\rangle\langle b| + \bar{\eta}(\epsilon)e^{i\varphi_*(t)}|b\rangle\langle\epsilon|\right]$$

Induced Energy

We want to **integrate out** the continuum states, describe system purely in terms of the bound state amplitude $c_b(t)$



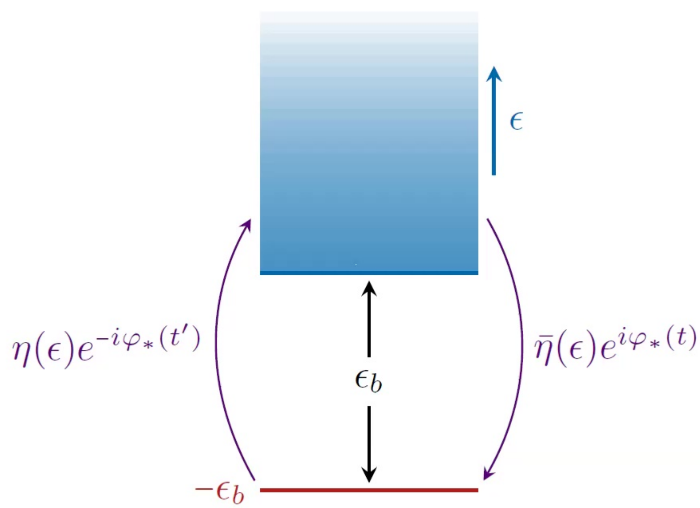
At weak-coupling, effects of continuum captured by the **induced energy**

$$i\mathcal{E}_b(t) = \int_0^\infty \mathrm{d}\epsilon \int_{-\infty}^{t} \mathrm{d}t' \left[\bar{\eta}(\epsilon)e^{i\varphi_*(t)}\right] e^{-i(\epsilon+\epsilon_b)(t-t')} \left[\eta(\epsilon)e^{-i\varphi_*(t')}\right]$$

Effective Dynamics

We can derive an **effective equation of motion** for the bound state amplitude in terms of this **induced energy**

$$i\mathcal{E}_b(t) = \int_{-\infty}^{t} \mathrm{d}t' \int_0^{\infty} \mathrm{d}\epsilon \, |\eta(\epsilon)|^2 e^{-i(\epsilon+\epsilon_b)(t-t')+i(\varphi_*(t)-\varphi_*(t'))}$$

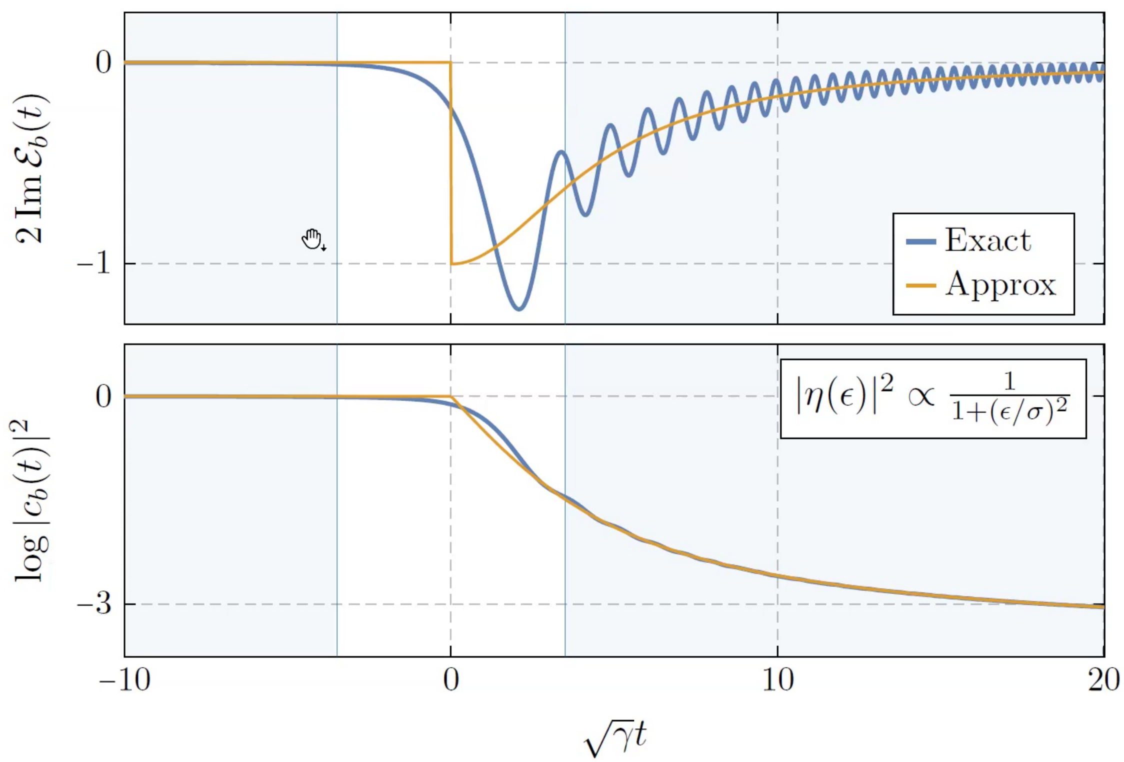


$$\frac{\mathrm{d}\log|c_b(t)|^2}{\mathrm{d}t} = 2\,\mathrm{Im}\,\mathcal{E}_b(t)$$

Reduces **complicated dynamics** to understanding a **single** function!

[Baumann, Bertone, **JS**, Tomaselli '21]

$$\frac{\mathrm{d}\log|c_b(t)|^2}{\mathrm{d}t} = 2\,\mathrm{Im}\,\mathcal{E}_b(t) \approx -\left|\eta\big(\epsilon_*(t)\big)\right|^2, \quad \dot{\varphi}_*(t) \geq \epsilon_b$$



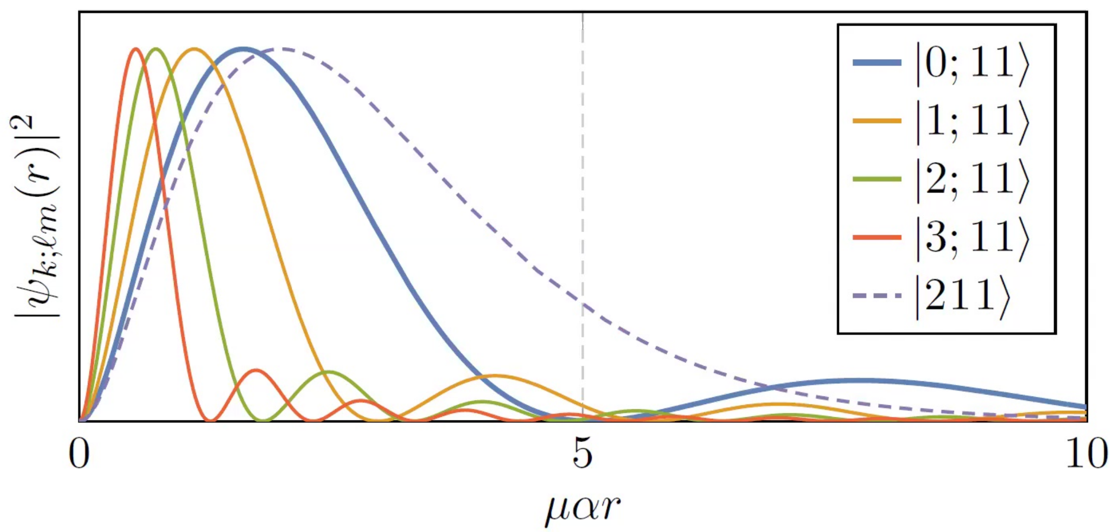
Bound state **transfers** population into state at $\epsilon_*(t) = \dot{\varphi}_*(t) - \epsilon_b$

[Baumann, Bertone, **JS**, Tomaselli '21]

Zero Mode

Crucial Point | The **zero mode** is localized about the black hole!

$$\psi_{k;\ell m}(\mathbf{r}) \propto (2kr)^{\ell} e^{-ikr} {}_1F_1\left(\ell + 1 + \tfrac{i\mu\alpha}{k}; 2\ell + 2; 2ikr\right) Y_{\ell m}(\theta, \phi)$$

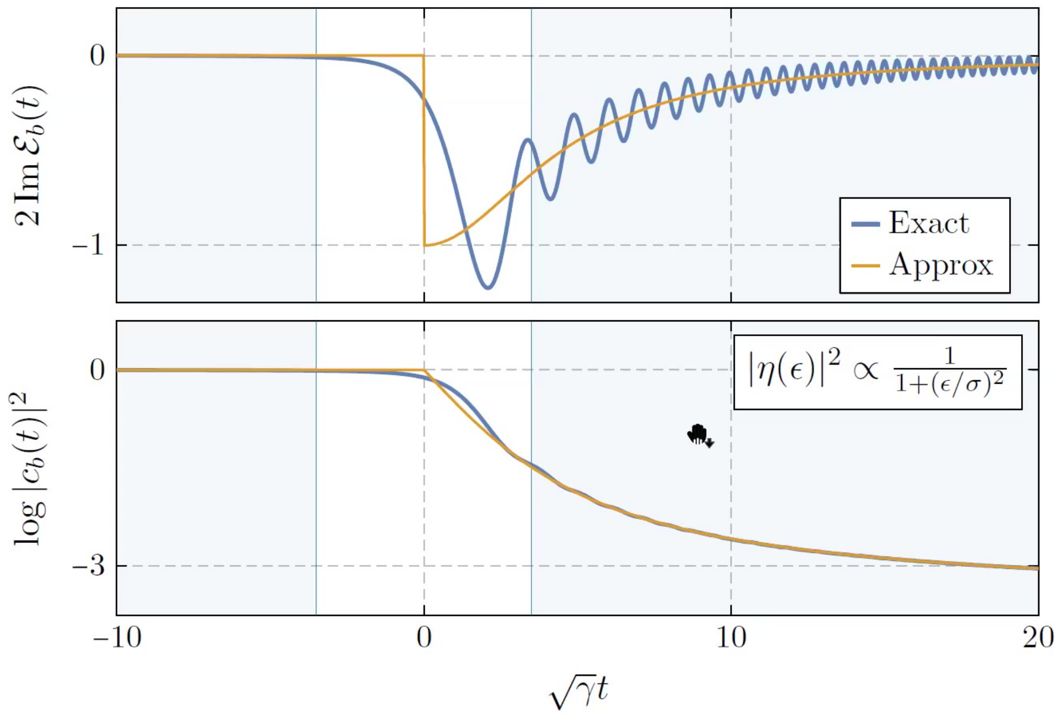


Special property due to **long-ranged** nature of **Coulomb** potential

This localization ensures that rate $|\eta(\epsilon)|^2$ is **finite** as $\epsilon \to 0$

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

$$\frac{\mathrm{d}\log|c_b(t)|^2}{\mathrm{d}t} \approx -\left|\eta\left(\epsilon_*(t)\right)\right|^2, \quad \dot{\varphi}_*(t) \geq \epsilon_b$$

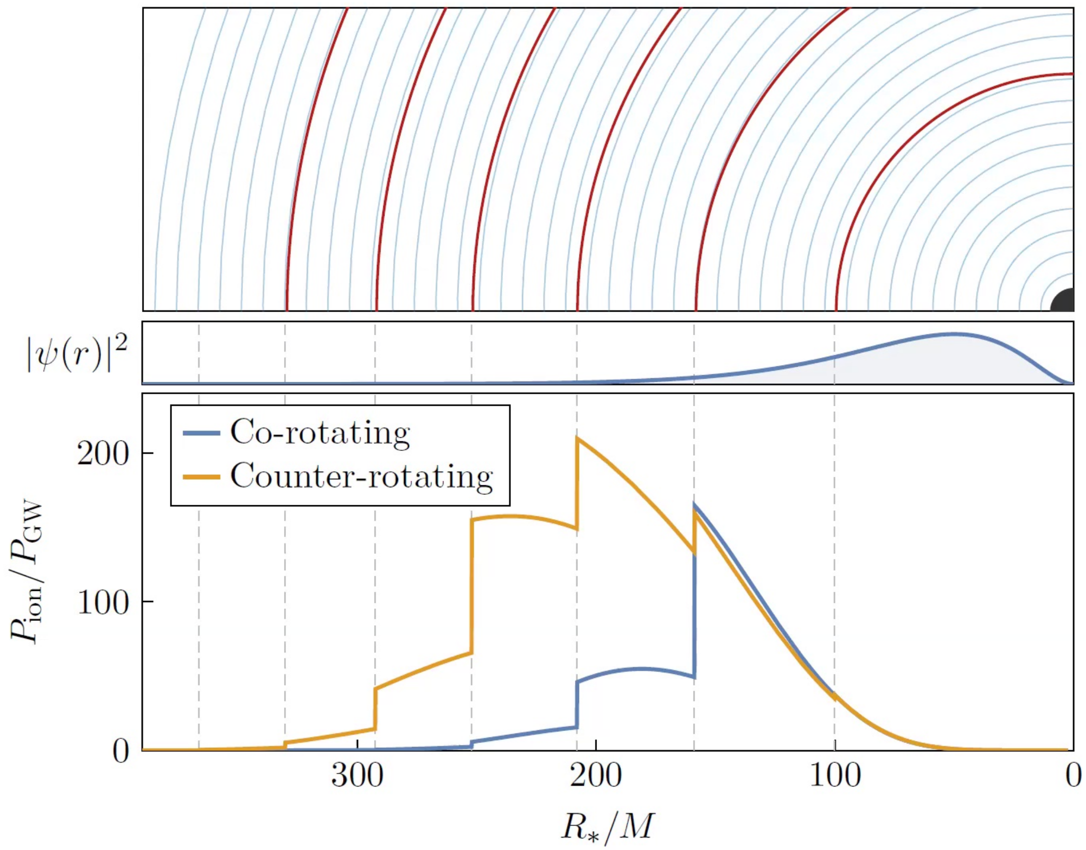


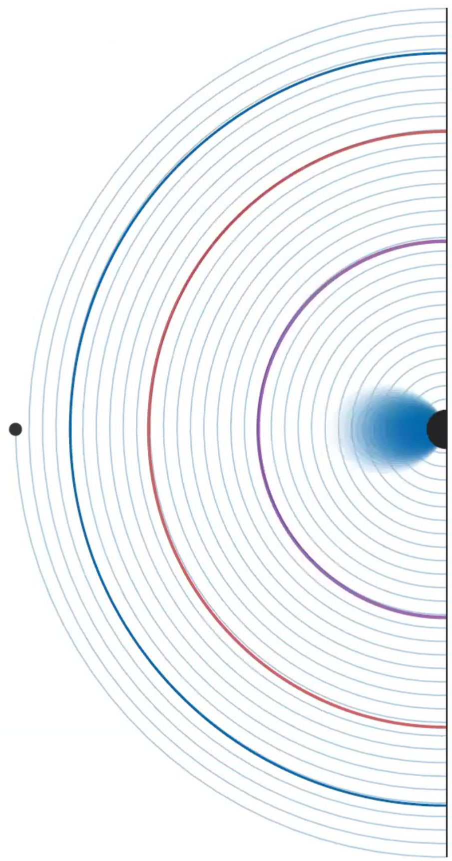
Fundamental properties of gravitational force imply that there are effective **discontinuities** in this system's time evolution.

[Baumann, Bertone, **JS**, Tomaselli '21]

Ionization Power

$$P_{\rm ion} = \frac{{\rm d}E_{\rm ion}}{{\rm d}t} \approx \dot{\varphi}_*(t)\left|\eta\big(\epsilon_*(t)\big)\right|^2 |c_b(t)|^2\,, \quad \dot{\varphi}_*(t) \geq \epsilon_b$$



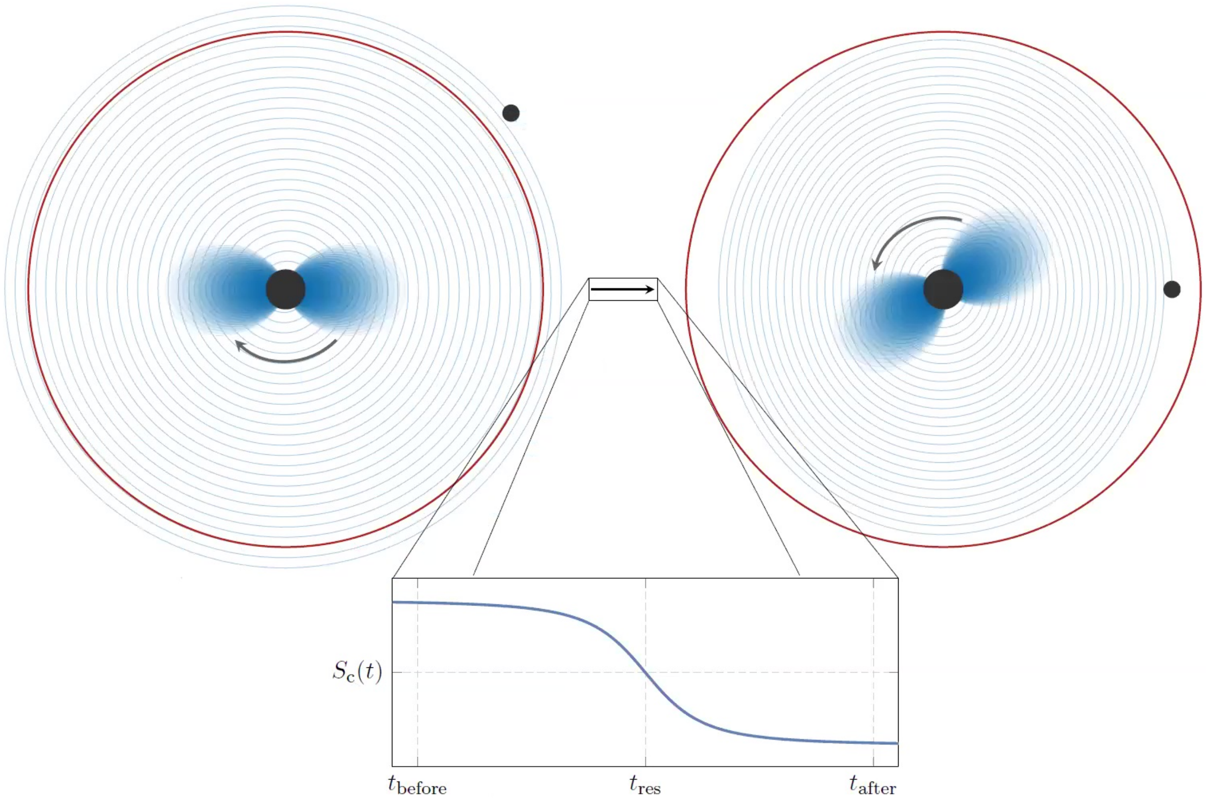


PART III

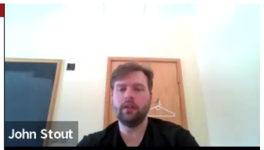
Gravitational Wave Signals from Resonant Transitions

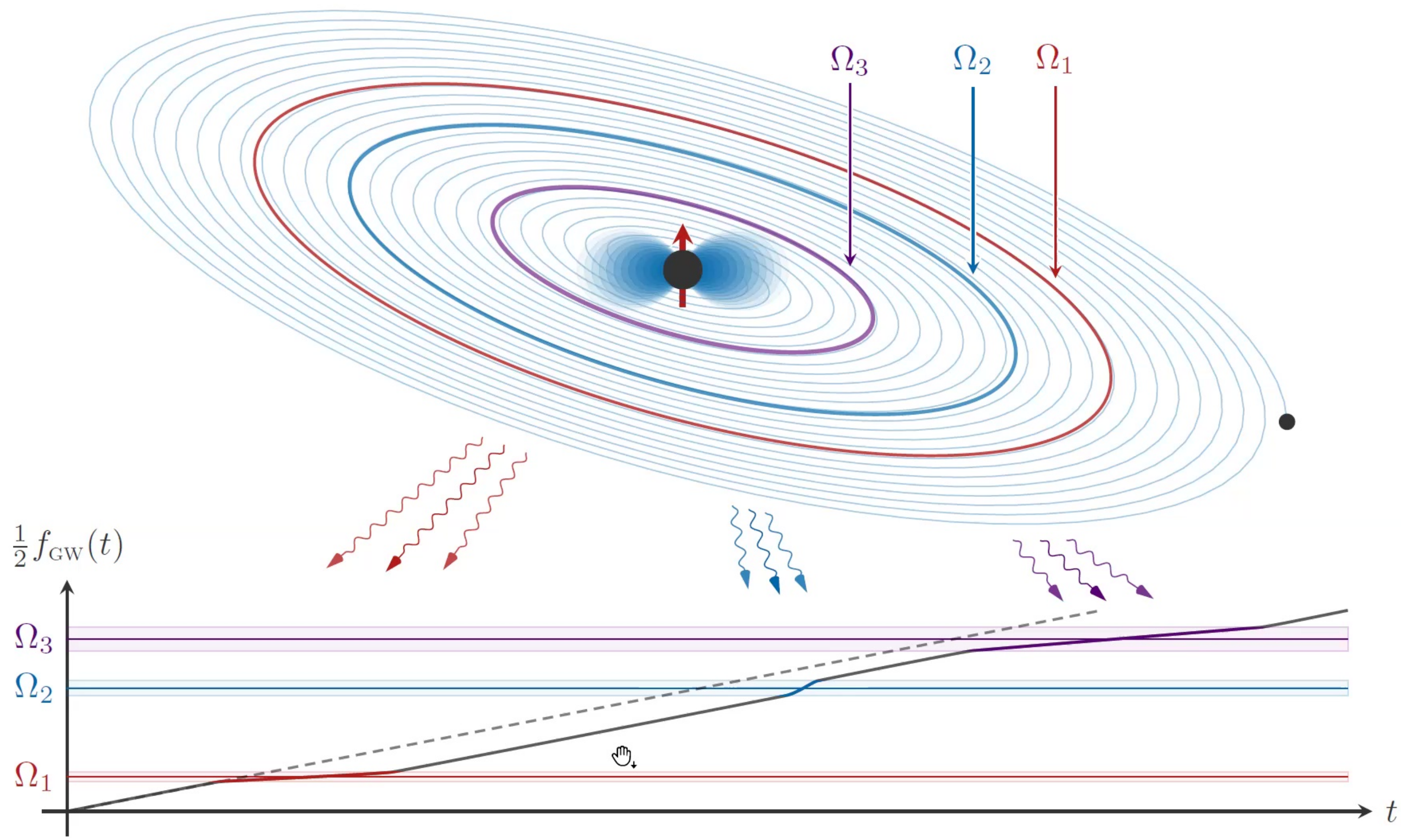
Backreaction on the Orbit

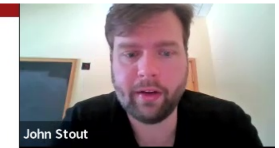
Key Point | Transitions force cloud's angular momentum, energy to change



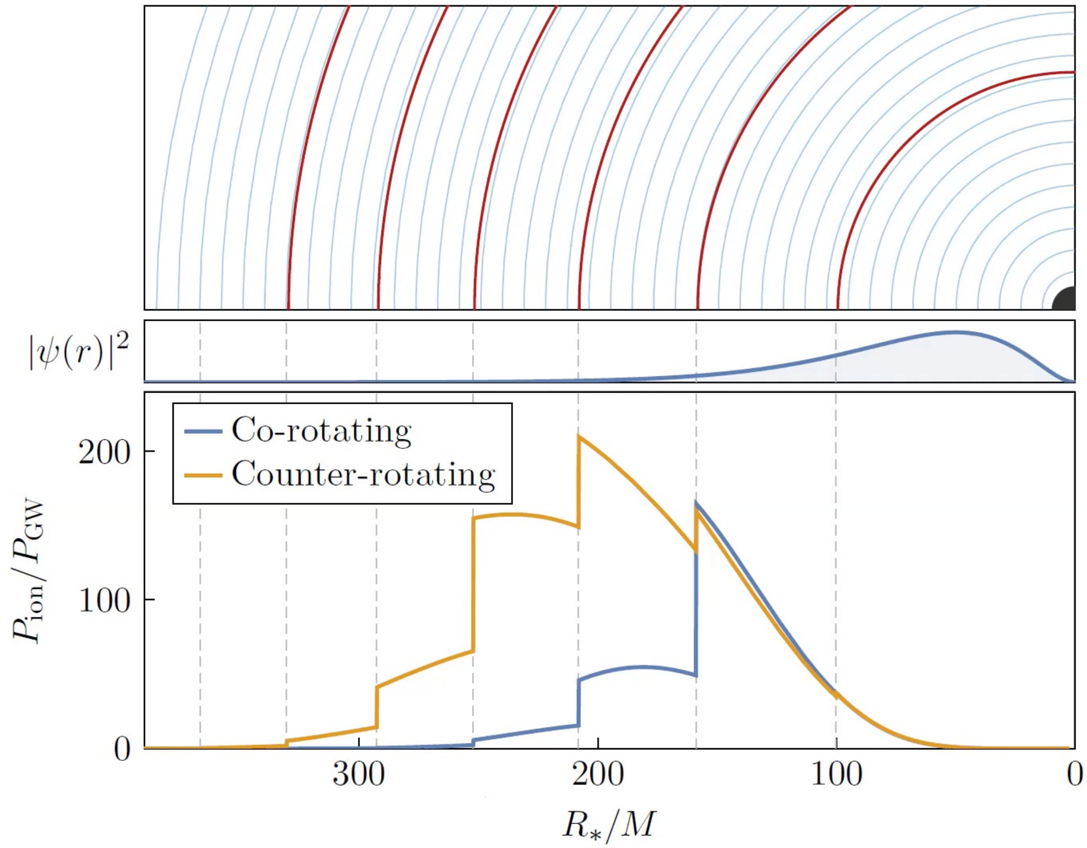
This must be balanced by the changes in the inspiral!







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

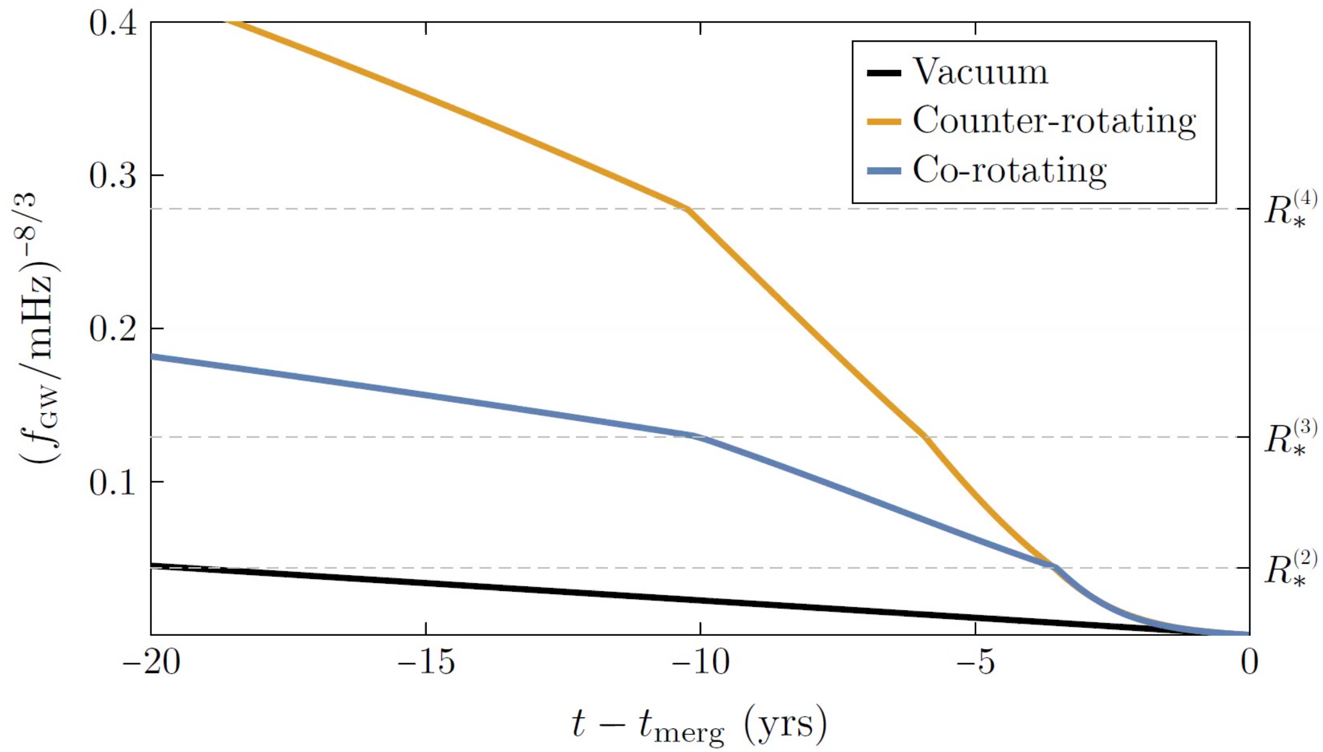


$$f_{\rm GW}^{(g)} = \frac{3.35\,\mathrm{mHz}}{g(n_{\rm b}/2)^2}\left(\frac{M}{10^3 M_\odot}\right)^2\left(\frac{\mu}{10^{-14}\,\mathrm{eV}}\right)^3$$

Ionization

See **discontinuities** if we observe the frequency of inspiral!

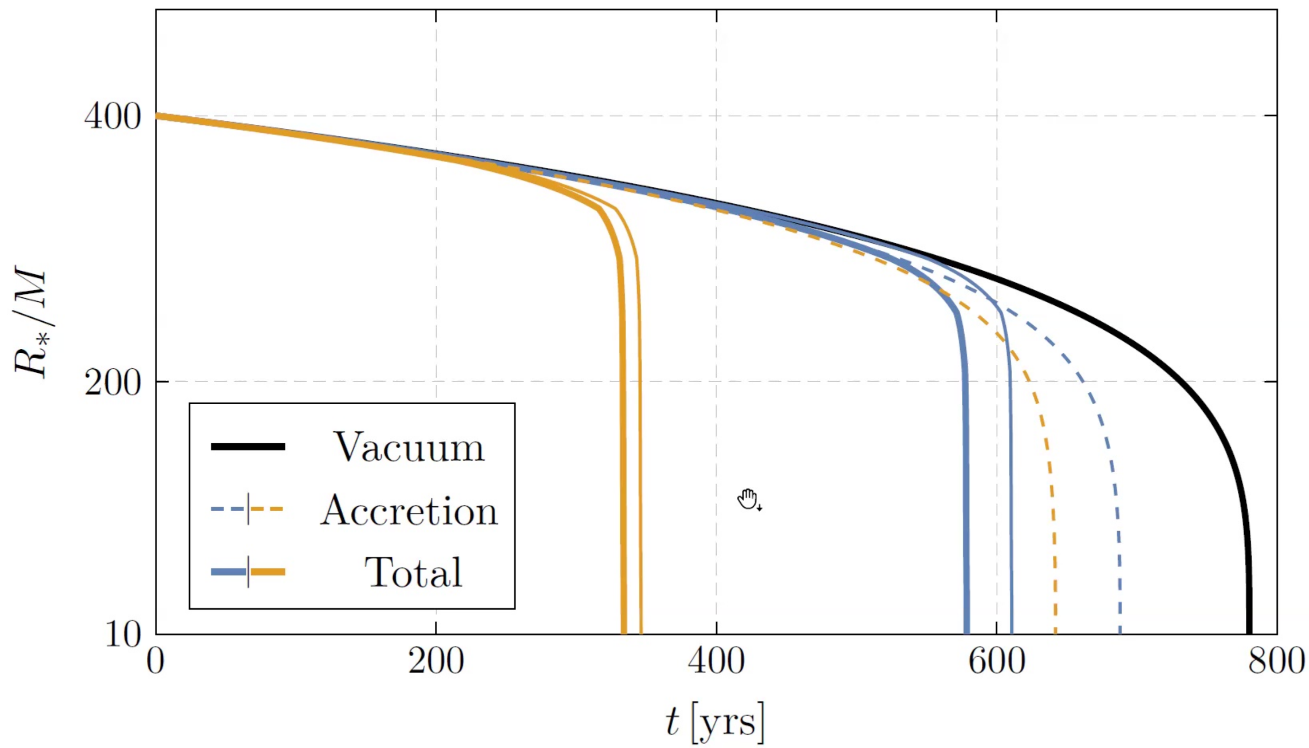
Signature of the cloud and ultralight boson!



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

Orbital Dynamics

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



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