GRAVITATIONAL COLLIDER PHYSICS

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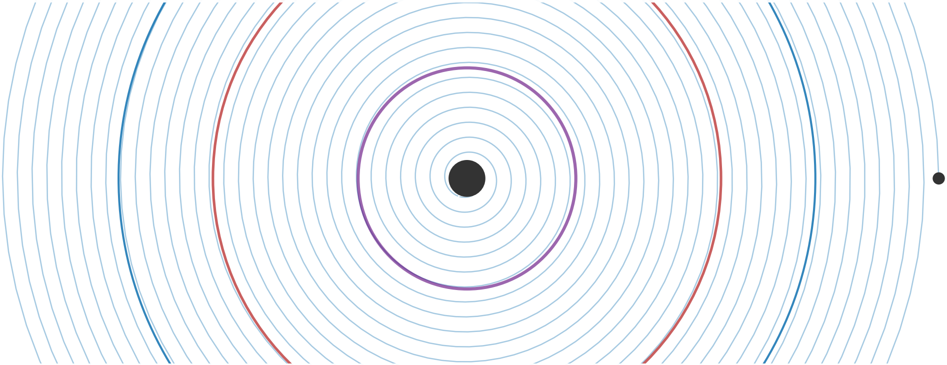


Based on [1908.10370, 1911.xxxxx]

with **Daniel Baumann**, **Horng Sheng Chia**, and **Rafael Porto**

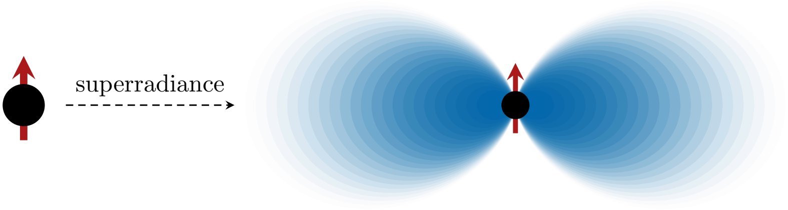
What is dark matter?

Quantum Gravity Input

Lots of dark sectors, completely "decoupled" from the Standard Model

Want a **universal** detector, that only relies on gravitational coupling

Ultralight bosons form **quasi-stable bound states** around black holes



Physics governed by **gravitational fine structure constant**

$$\alpha \equiv \frac{r_{\rm g}}{\lambda_{\rm c}} \sim 0.02 \times \left(\frac{M_{\rm BH}}{30 M_\odot}\right) \times \left(\frac{\mu}{10^{-13}\,{\rm eV}}\right)$$

[Zeldovich '72; Starobinsky '73; Arvanitaki et al. '09]
[See work by Cardoso, Pani, Witek, and many others...]

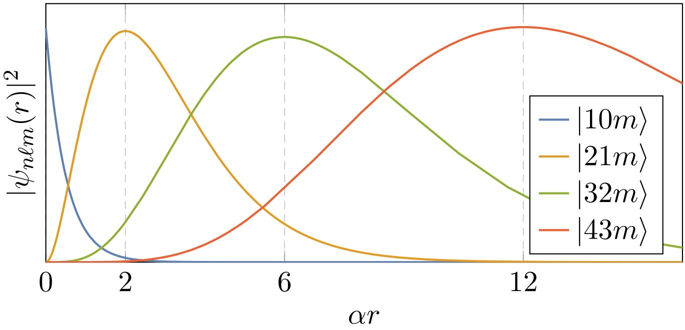
Gravitational Atom

For small α, cloud described by Schrödinger-like equation

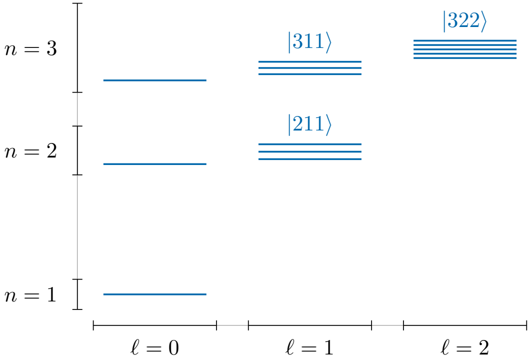
$$i\,\partial_t \psi = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \Delta V\right)\psi$$

Label the bound states or "energy eigenstates" using hydrogen's $|n\ell m\rangle$

$$\psi_{n\ell m}(\mathbf{r}) \propto e^{-\alpha r/n} r^\ell L^{(2\ell+1)}_{n-\ell-1}(2\alpha r/n)\, Y_{\ell m}(\theta,\phi)$$



Scalar Spectrum

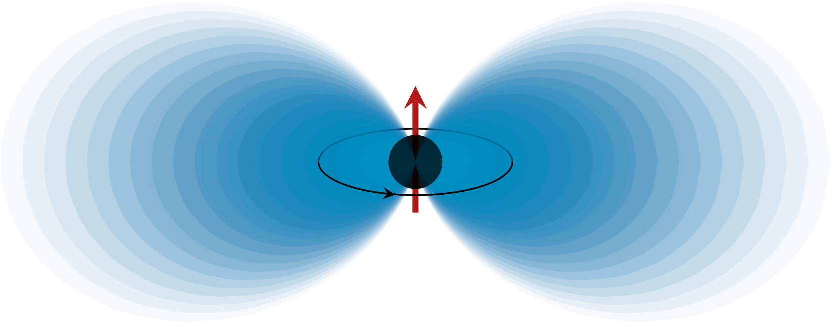


$$E_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} - f_{n\ell}\alpha^4 + h_{n\ell}\,\tilde{a}m\alpha^5 + \dots\right)$$

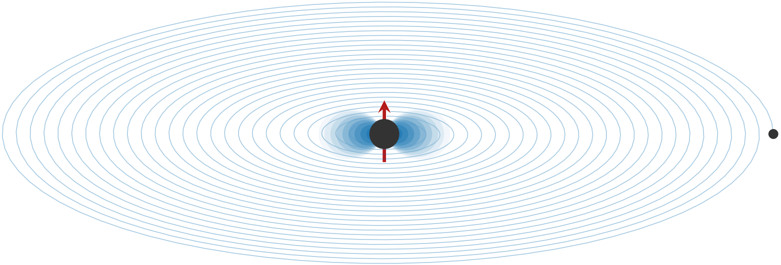
[Baumann, Chia, Porto '18; Baumann, Chia, JS, ter Haar '19]

Field Profile

The $|211\rangle$ state grows fastest, which roughly looks like

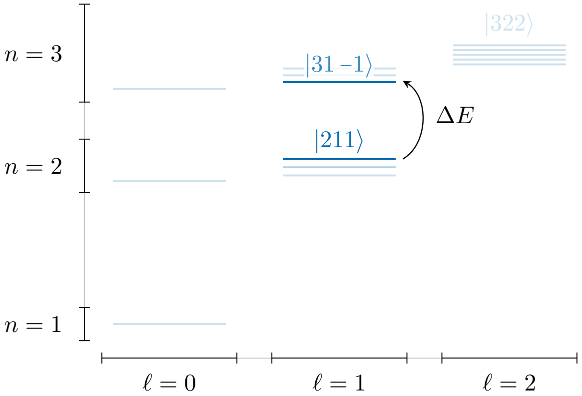


We can think of this as the "initial state," though if we wait long enough this will decay and the $|322\rangle$ will form.



A companion perturbs the **cloud** with slowly increasing frequency $\Omega(t)$

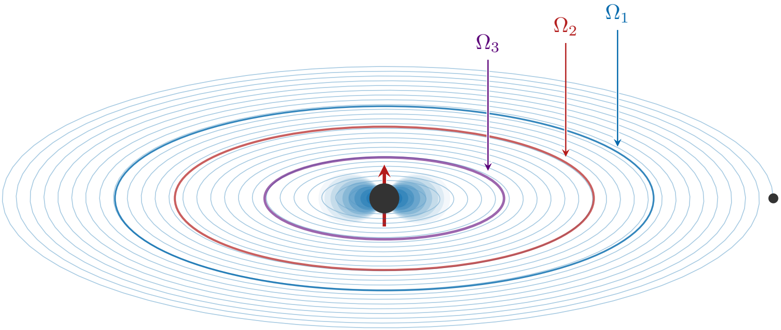
$$\langle n'\ell'm'|V_*(t)|n\ell m\rangle = \eta(t)\exp\left(-i\Delta m\int^t \mathrm{d}t'\,\Omega(t')\right)$$



Selection rules only allow specific transitions; depends on orientation.

Generally, the gravitational perturbation is weak and the cloud will remain relatively unaffected.

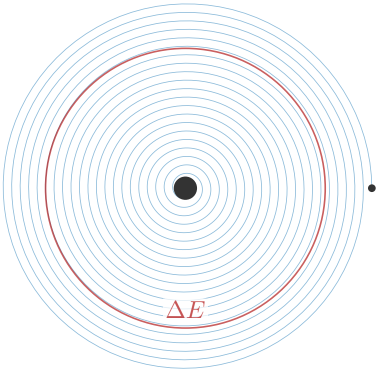
[Baumann, Chia, JS, Porto '19]



At specific frequencies that depend on the boson's mass,
this perturbation is **resonantly enhanced**, forcing the cloud to **evolve**

$$\Omega_i = \left|\frac{\Delta E_i}{\Delta m_i}\right| \sim 2\,\mathrm{mHz}\,\left(\frac{30 M_\odot}{M}\right)\left(\frac{\alpha}{0.02}\right)^3$$

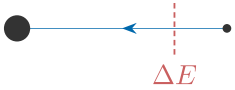
Two State System



Let's consider the **simplest** case

$$\mathcal{H} = \begin{pmatrix} -\Delta E/2 & \eta\, e^{i\int^t \mathrm{d}t'\Omega(t')} \\ \eta\, e^{-i\int^t \mathrm{d}t'\Omega(t')} & \Delta E/2 \end{pmatrix} \quad \text{and} \quad |\psi(-\infty)\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

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



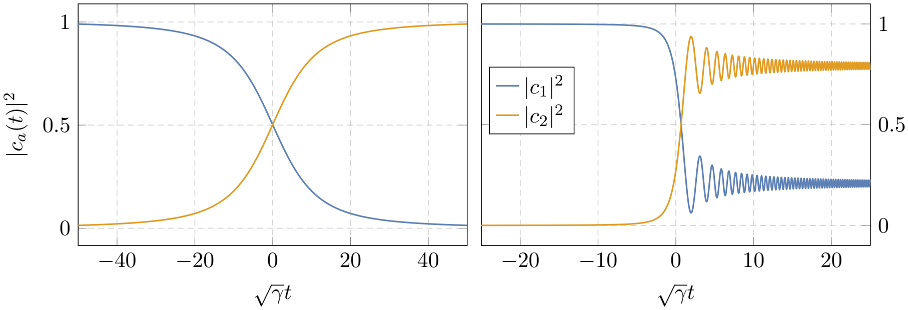
In this "dressed" frame, the Hamiltonian evolves very slowly

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

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

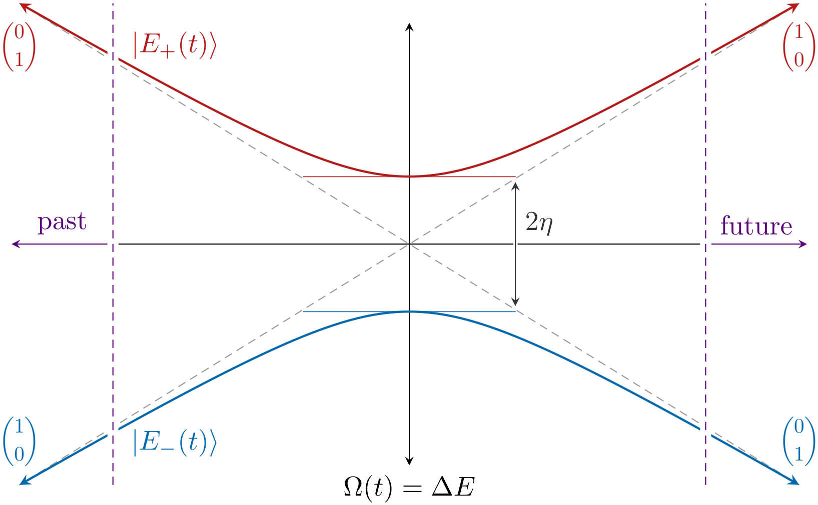
determines nature of transition

Find **two** different behaviors, depending on the size of γ.



For slow motion, the initial state **smoothly and fully deoccupies.**

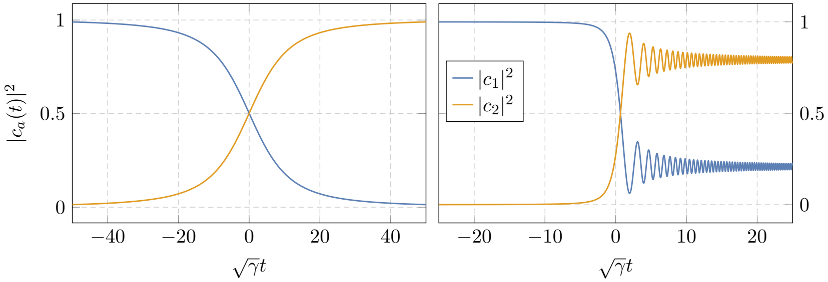
For fast motion, both states are occupied; have **transient ringing**.



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

Backreaction on the Orbit

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



Conservation of total angular momentum requires that

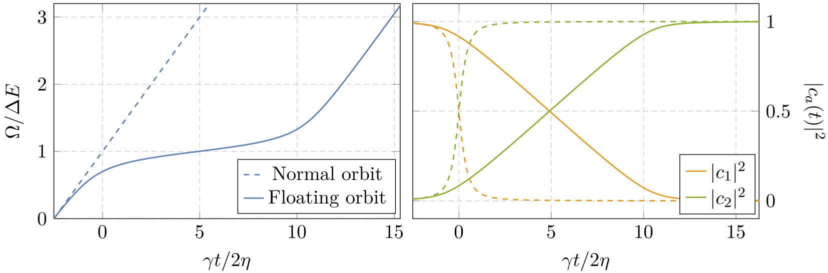
$$\dot{\mathbf{L}} + \dot{\mathbf{S}}_{\rm c} = \mathbf{T}_{\rm GW}$$

Phenomenology depends on if the cloud gives or takes angular momentum

Regardless, the cloud affects the orbital motion!

Floating Orbits

The binary **floats** when it absorbs angular momentum from the cloud during the transition, and **adiabaticity is enhanced**

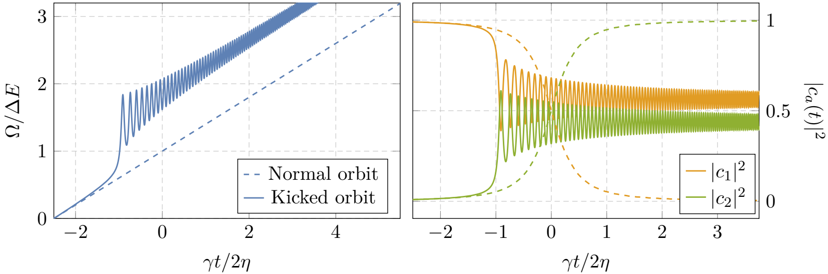


The binary emits nearly **monochromatic gravitational waves!**

[Baumann, Chia, JS, Porto '19]

Kicked Orbits

The binary receives a **sudden kick** when it releases angular momentum, and the transition can become **non-adiabatic**.



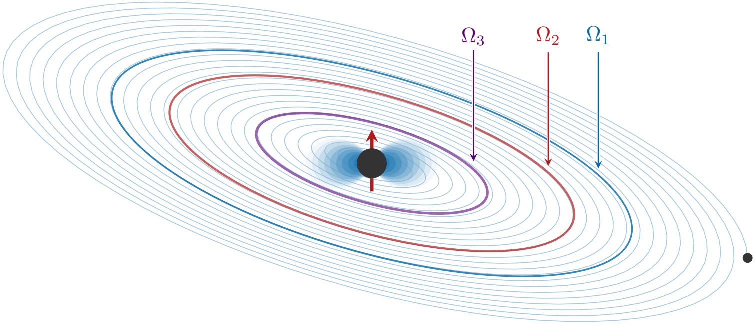
Dynamics of binary is now much richer, but requires detailed modeling!

Size of these effects depend on fraction of angular momentum in the cloud!

Huge effects for extreme mass inspirals.

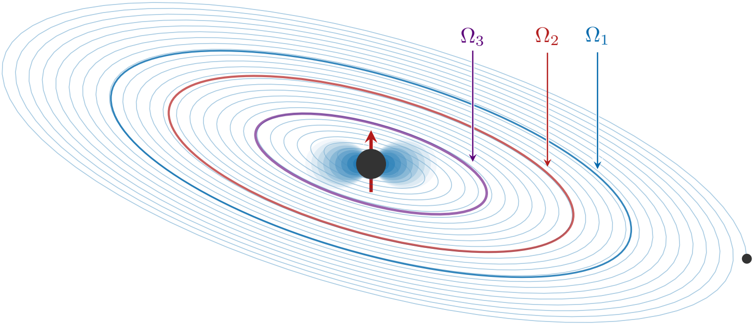
[Baumann, Chia, JS, Porto '19]

The cloud and orbit can transfer angular momentum during many **events!**



Resonances can evolve the cloud into **superpositions** of bound states.

Intermediate and final states have rich, **oscillatory**, finite size effects.
Sensitive to boson's **spin**; frequencies determined by its **mass**.



Thanks!