GRAVITATIONAL COLLIDER PHYSICS

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**

\[ \alpha \equiv \frac{r_g}{\lambda_c} \sim 0.02 \times \left( \frac{M_{\text{BH}}}{30M_\odot} \right) \times \left( \frac{\mu}{10^{-13} \text{ eV}} \right) \]

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

[See work by Cardoso, Pani, Witek, and many others...]

John Stout  john.e.stout@gmail.com  Gravitational Collider Physics
Gravitational Atom

For small $\alpha$, 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 $|n \ell m\rangle$

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

John Stout  
john.e.stout@gmail.com  
Gravitational Collider Physics  
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Scalar Spectrum

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

[Baumann, Chia, Porto '18; Baumann, Chia, JS, ter Haar '19]
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 $\Omega(t)$

$$\langle n'\ell'm'|V_*(t)|n\ell m \rangle = \eta(t) \exp \left( -i\Delta m \int_0^t dt' \Omega(t') \right)$$
Selection rules only allow specific transitions; depends on orientation.

Generally, the gravitational perturbation is weak and the cloud will remain relatively unaffected.
At specific frequencies that depend on the boson’s mass, this perturbation is **resonantly enhanced**, forcing the cloud to **evolve**

\[
\Omega_i = \left| \frac{\Delta E_i}{\Delta m_i} \right| \sim 2 \text{ mHz} \left( \frac{30M_\odot}{M} \right) \left( \frac{\alpha}{0.02} \right)^3
\]
Let's consider the simplest case

\[ \mathcal{H} = \begin{pmatrix} -\Delta E/2 & \eta e^{i\int^t dt' \Omega(t')} \\ \eta e^{-i\int^t dt' \Omega(t')} & \Delta E/2 \end{pmatrix} \]

and

\[ |\psi(-\infty)\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \]
There is slow motion if we rotate along with the companion

In this “dressed” frame, the Hamiltonian evolves very slowly

\[ H_D(t) = \begin{pmatrix} \frac{(\Omega(t) - \Delta E)}{2} & \eta \\ \eta & -\frac{(\Omega(t) - \Delta E)}{2} \end{pmatrix} \]

\[ \Omega(t) = \Omega_0 + \gamma(t - t_0) + \ldots \]

determines nature of transition
Find **two** different behaviors, depending on the size of $\gamma$.

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

For fast motion, both states are occupied; have **transient ringing**.
\[ \Omega(t) = \Delta E \]

\[ H_D(t) = \frac{\gamma t}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \eta \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \]
Key Point | During these transitions, cloud's angular momentum changes

Conservation of total angular momentum requires that

\[ \dot{L} + \dot{S}_c = T_{GW} \]

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 \textit{events}!

Resonances can evolve the cloud into superpositions of bound states. Intermediate and final states have rich, \textit{oscillatory}, finite size effects. Sensitive to boson's \textit{spin}; frequencies determined by its \textit{mass}.
Thanks!