Probing Ultralight Bosons with Binary Black Holes

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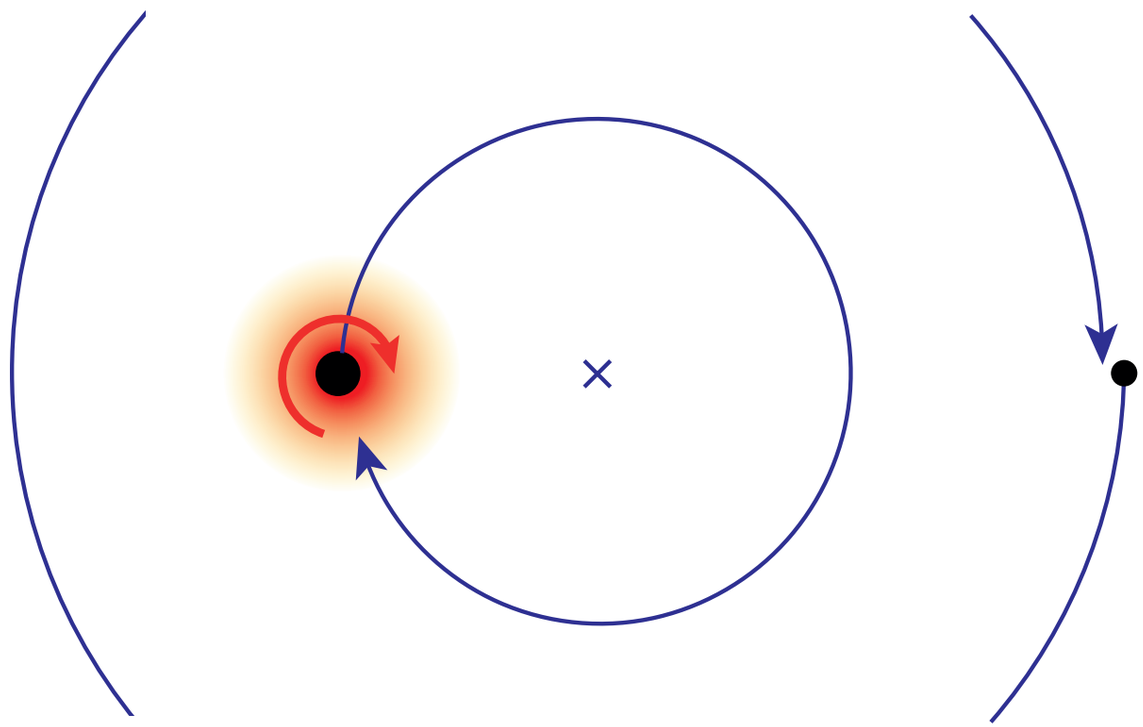


Work with **Daniel Baumann** and **Rafael Porto [1804.03208]**

University of Groningen, May 2018

New Light Species

An interesting class of new physics consists of particles that are **light** and **weakly-coupled** to the Standard Model.

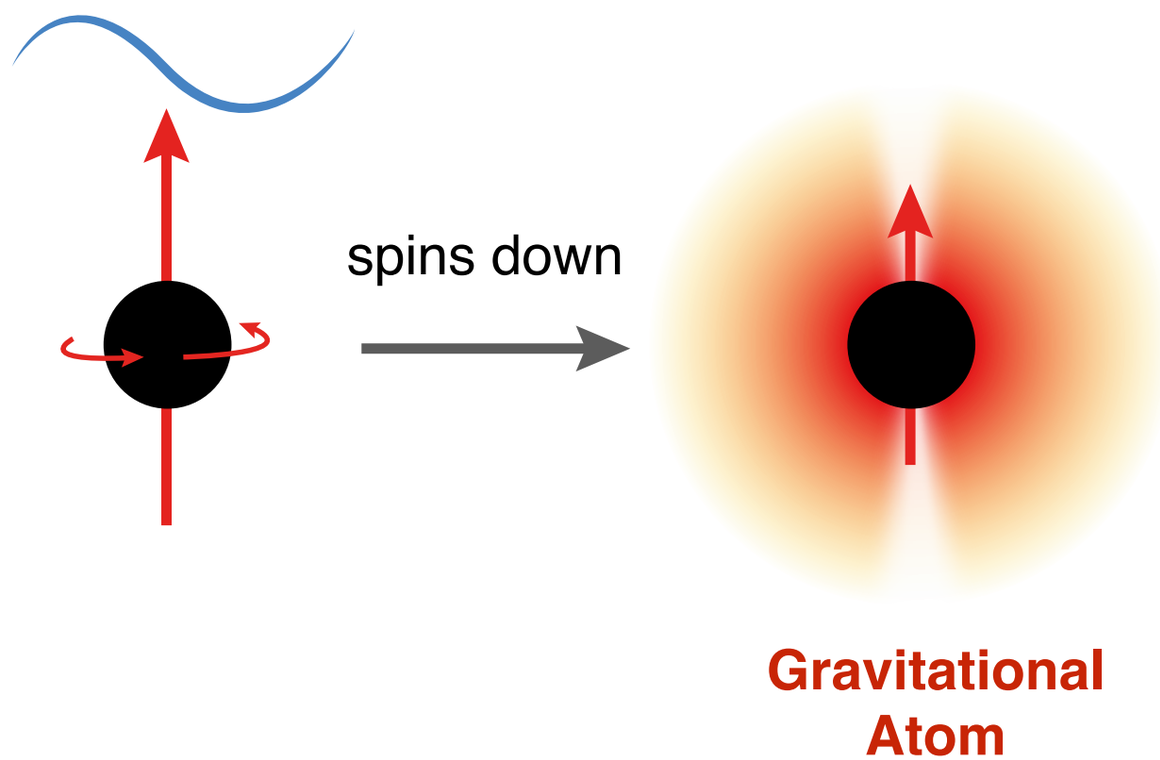
Examples:

- Spin-zero: QCD axion, String axions
- Higher spin: Dark radiation, Massive gravity

Weak couplings imply that they could **escape detection** from colliders.

Superradiance

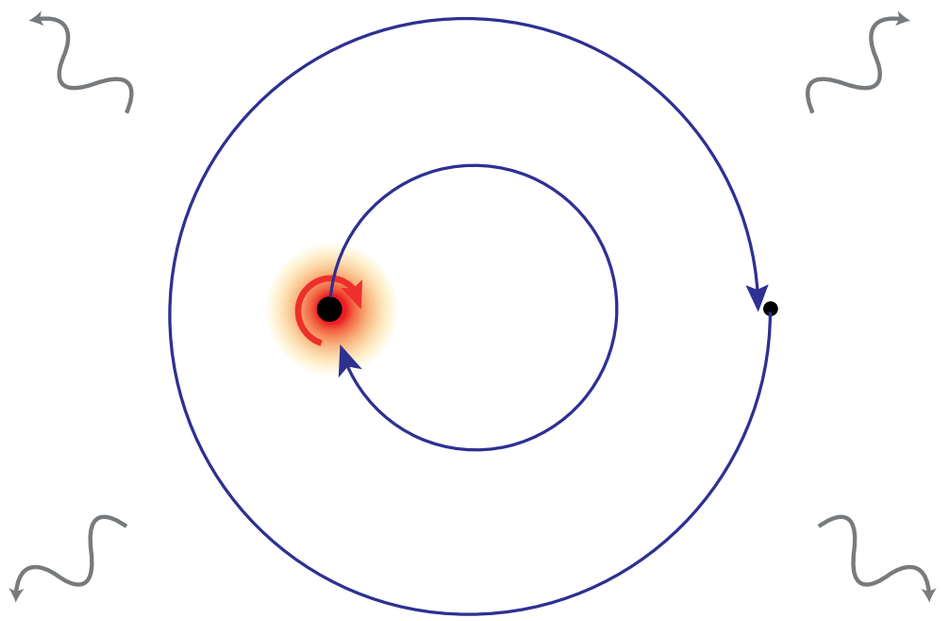
These particles, however, form clouds around **rotating black holes**, when the Compton wavelength is of the order of the size of the BH.



Zeldovich (1972)
Starobinsky (1973)

In this Talk

We studied the dynamics of these boson clouds in binary systems.



Presence of the companion introduces **new scales** and **new dynamics**.

Presence of the clouds induce **finite-size effects** on the waveforms.

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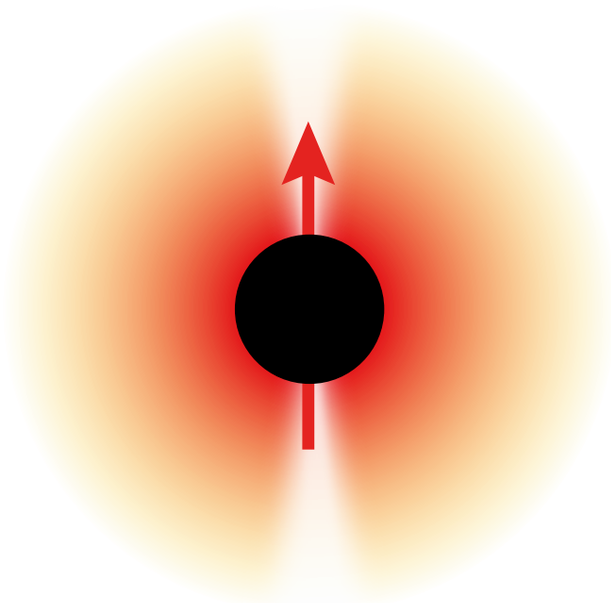
Spin-Induced Quadrupole

Spin of the cloud induces a quadrupole in the polar direction.



Analogous to **rotational flattening** in stars.

Poisson [9709032]

Tidal Deformability

Tidal forces of the companion induces deformation of the cloud.

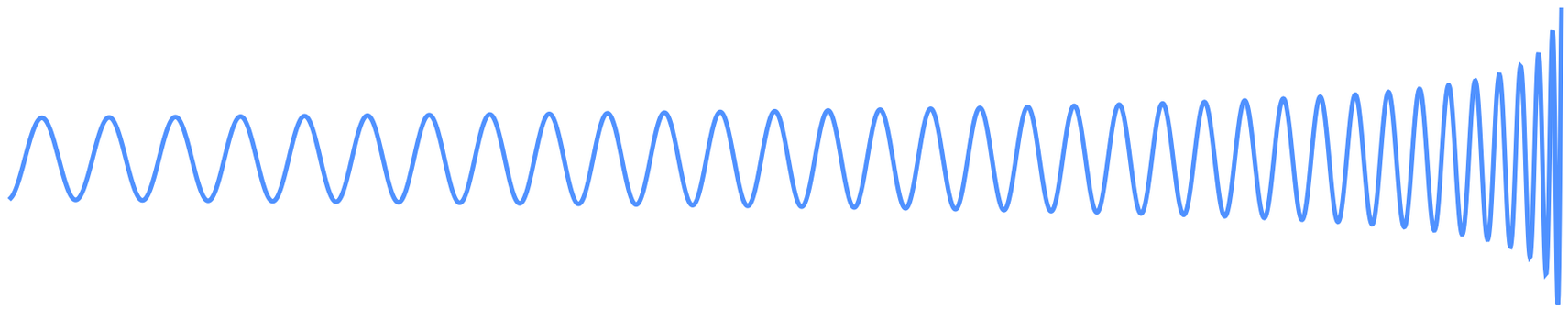
Flanagan, Hinderer [0709.1915]
Damour, Nagar [0906.0096]
Binnington, Poisson [0906.1366]

Imprints on Waveform

These **finite-size effects** leave imprints on the **phase** of the binary waveform.

Spin-induced quadrupole
(2PN)

Tidal deformability
(5PN)



Match-filtering is sensitive to phase variations, which motivates highly accurate waveform models that include these effects.

Cutler et. al. [9208005]

These finite-size effects are potentially measurable by current and future gravitational wave observations.

What are the **new dynamics** when the cloud is part of a binary?

The Gravitational Atom

In the non-relativistic limit, the Klein-Gordon equation of a massive scalar field in a Kerr background reduces to the Schrödinger equation:

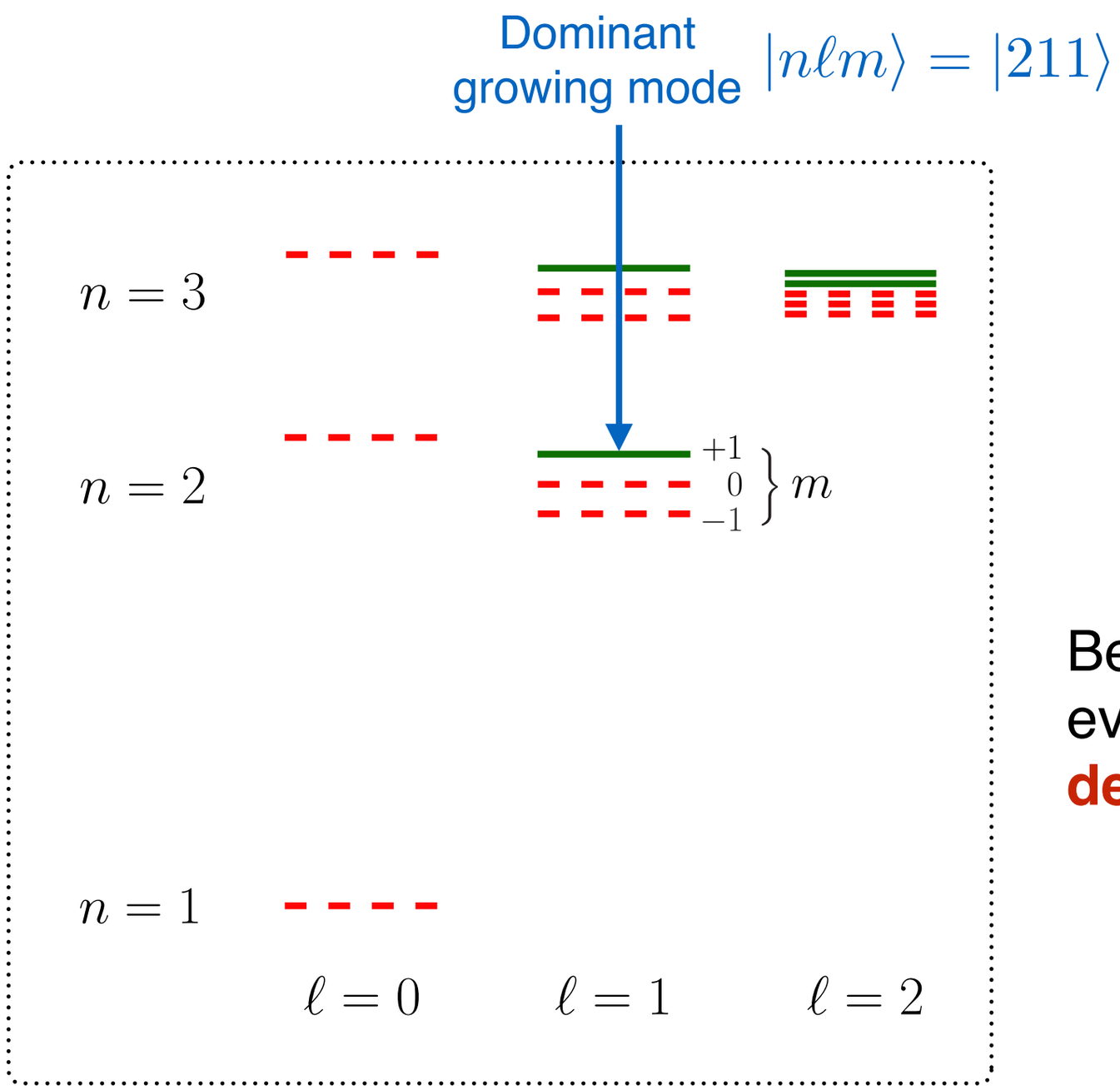
$$i\frac{\partial}{\partial t}\psi(t,\mathbf{r}) = \left[-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r}\right]\psi(t,\mathbf{r}) + \mathcal{O}\left(\frac{1}{r^2}\right)$$

with a central **Coulomb potential**, where

$$\alpha \equiv \frac{\text{Gravitational radius}}{\text{Compton wavelength}}$$

The system is analogous to the **hydrogen atom.**

Energy Spectrum



n : Principal

ℓ : Orbital

m : Azimuthal

Because of boundary conditions of event horizon, some states are **decaying modes**.

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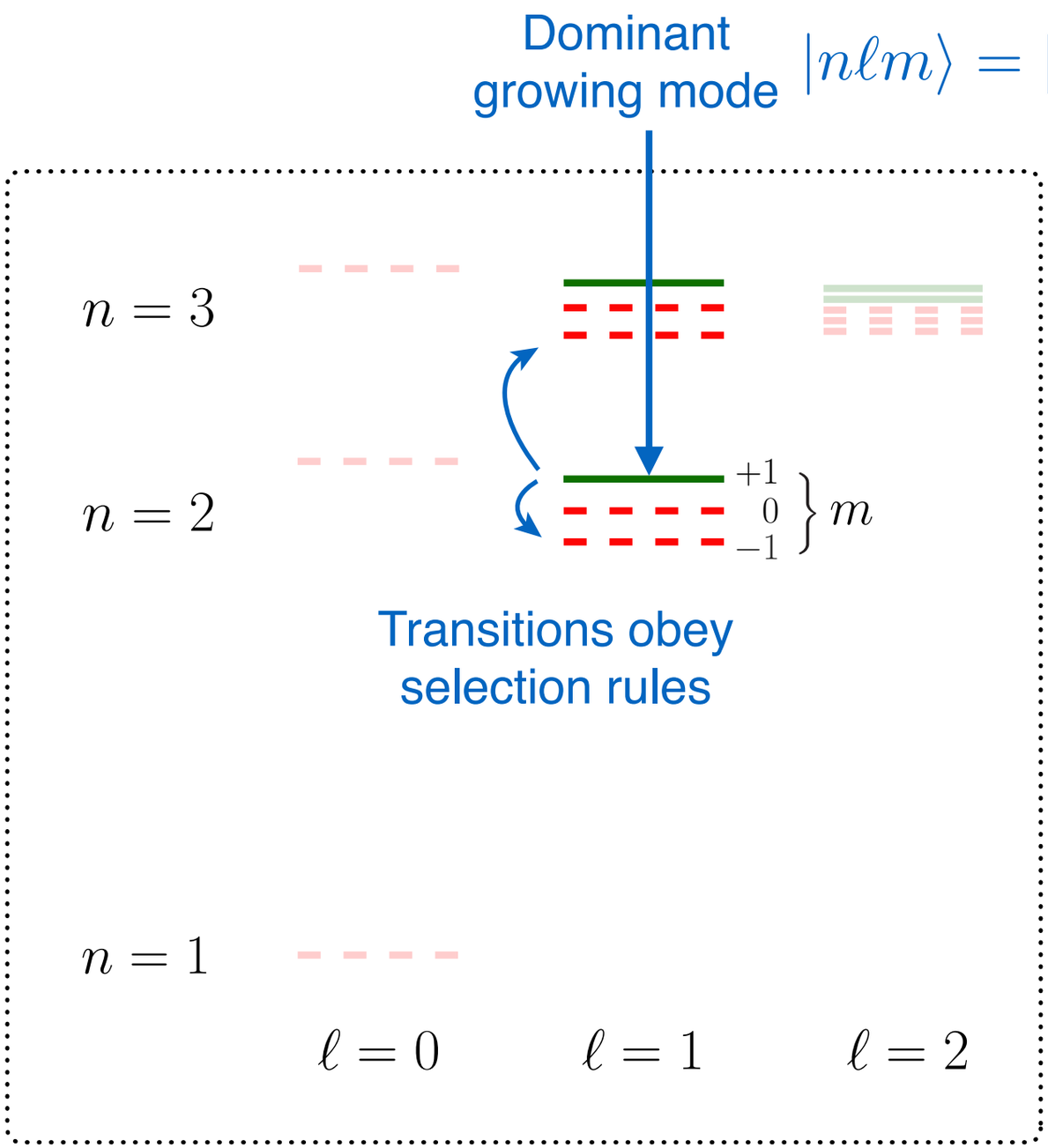
Level Mixings



Binary companion induces level mixings through the quadrupolar gravitational perturbation.

The dominant occupied mode can **transition to a decaying mode**.

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Rabi Oscillations

When the orbital frequency of the inspiral matches the energy difference between the two energy levels, **resonances** occur.

Analogous to **Rabi oscillations** in the hydrogen atom.

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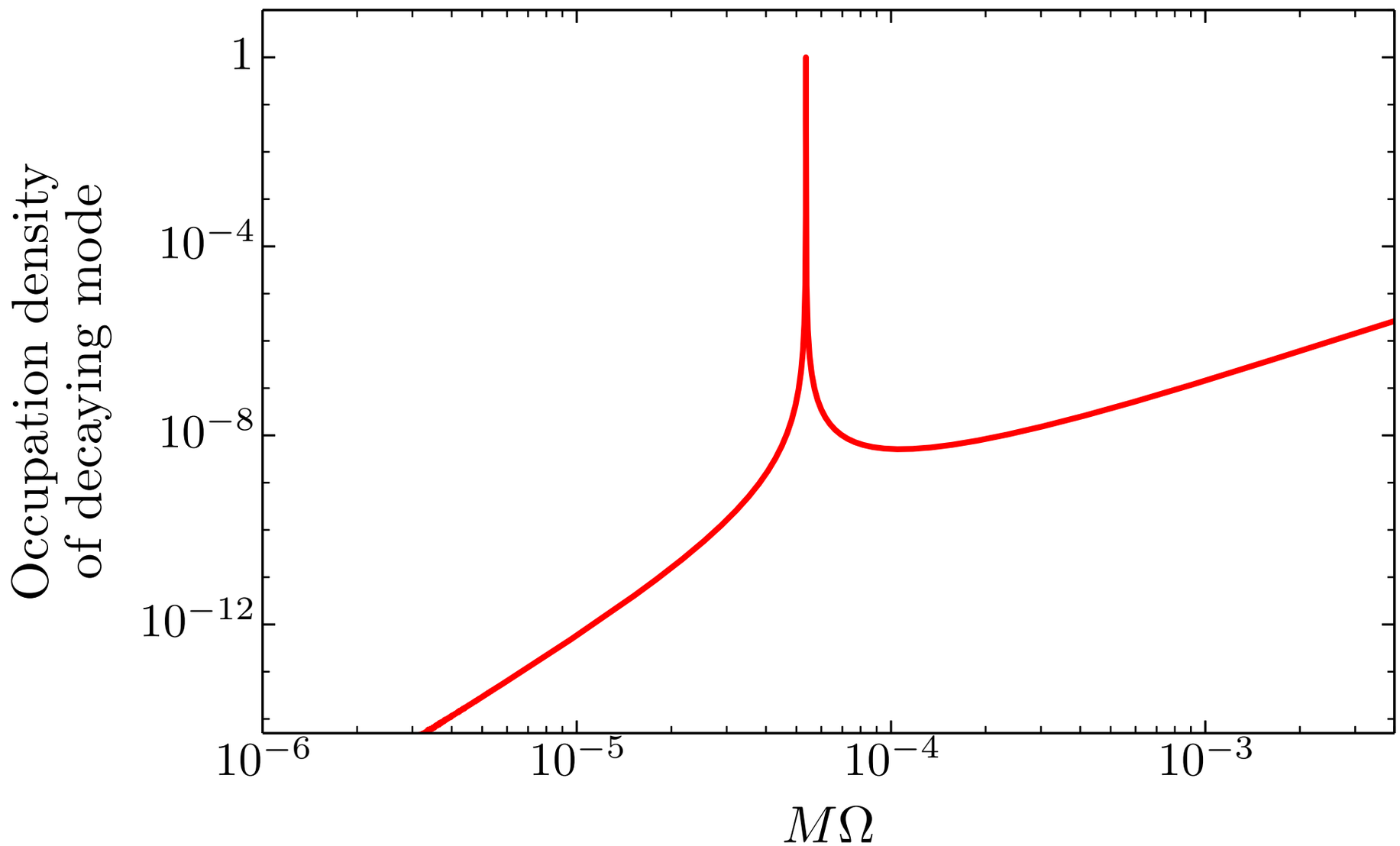
Resonance Depletion

As the orbit shrinks due to GW emission, the binary scans through the resonance.



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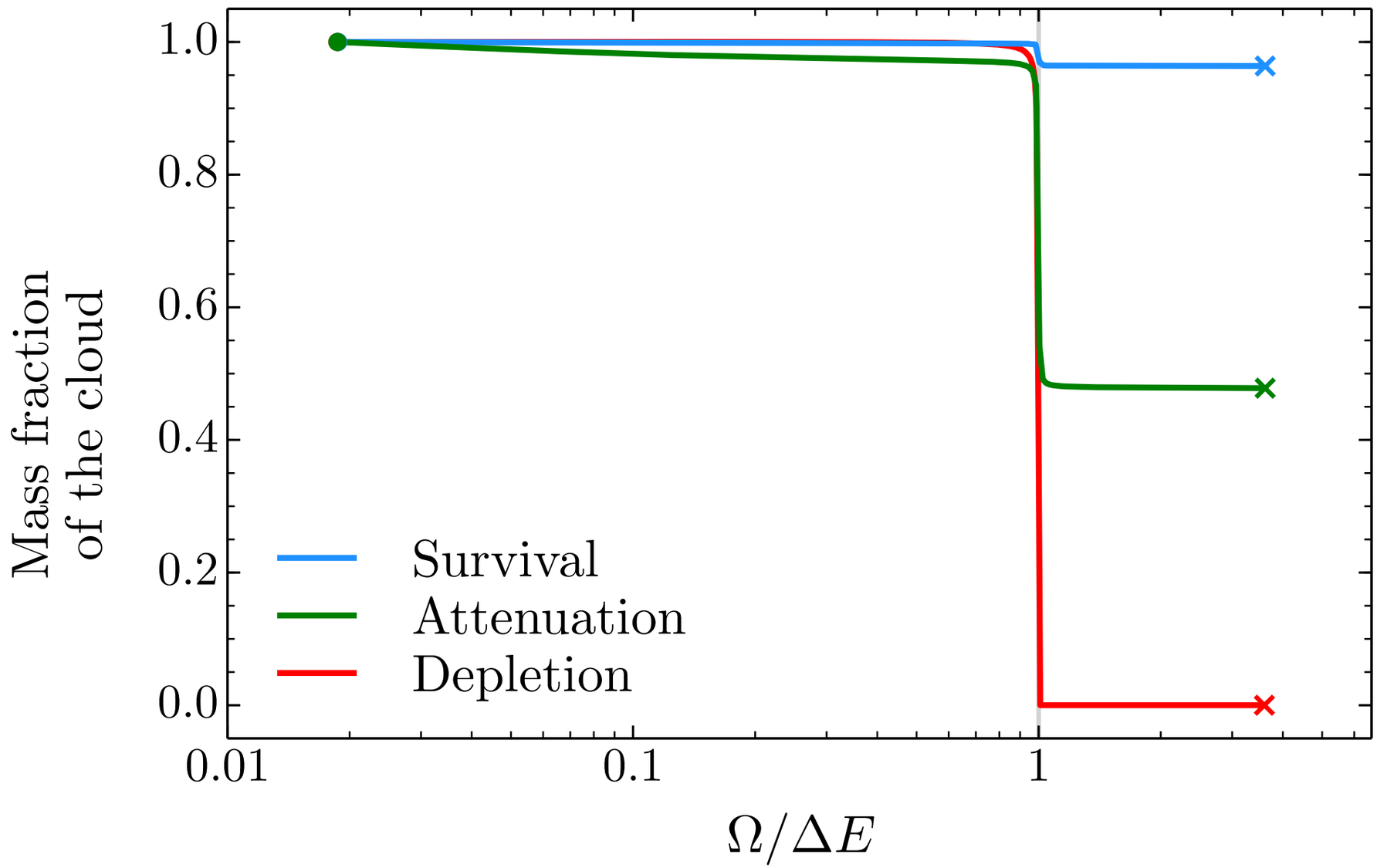
Resonance Depletion

Depending on parameters, there are 3 qualitatively different scenarios:



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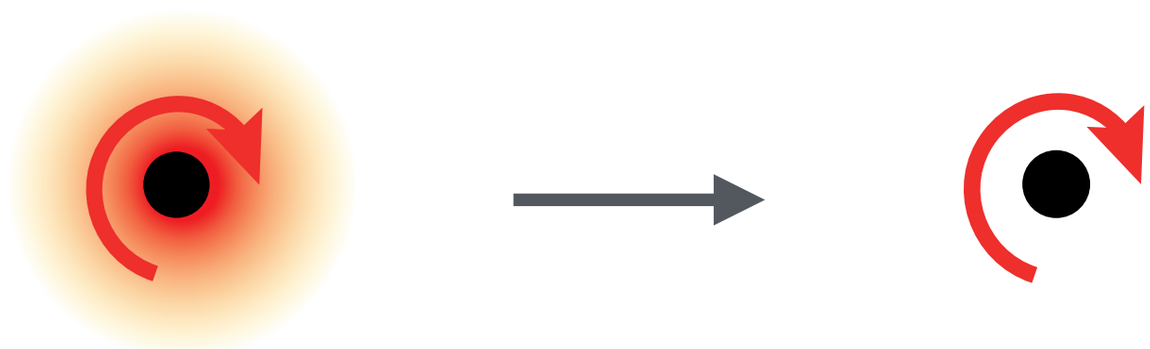
Time-Dependent Observables

Resonance depletion of the cloud creates a **time-dependent** change in finite-size effects.



The detection of these effects would provide an **independent probe** of the existence and the properties of these ultralight bosons.

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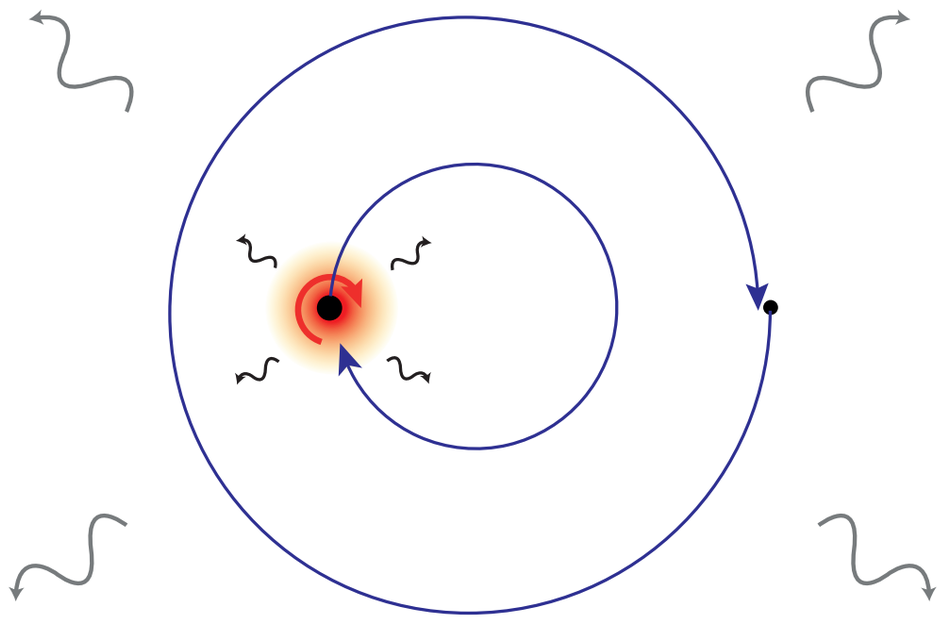
Thank You for Your Attention!



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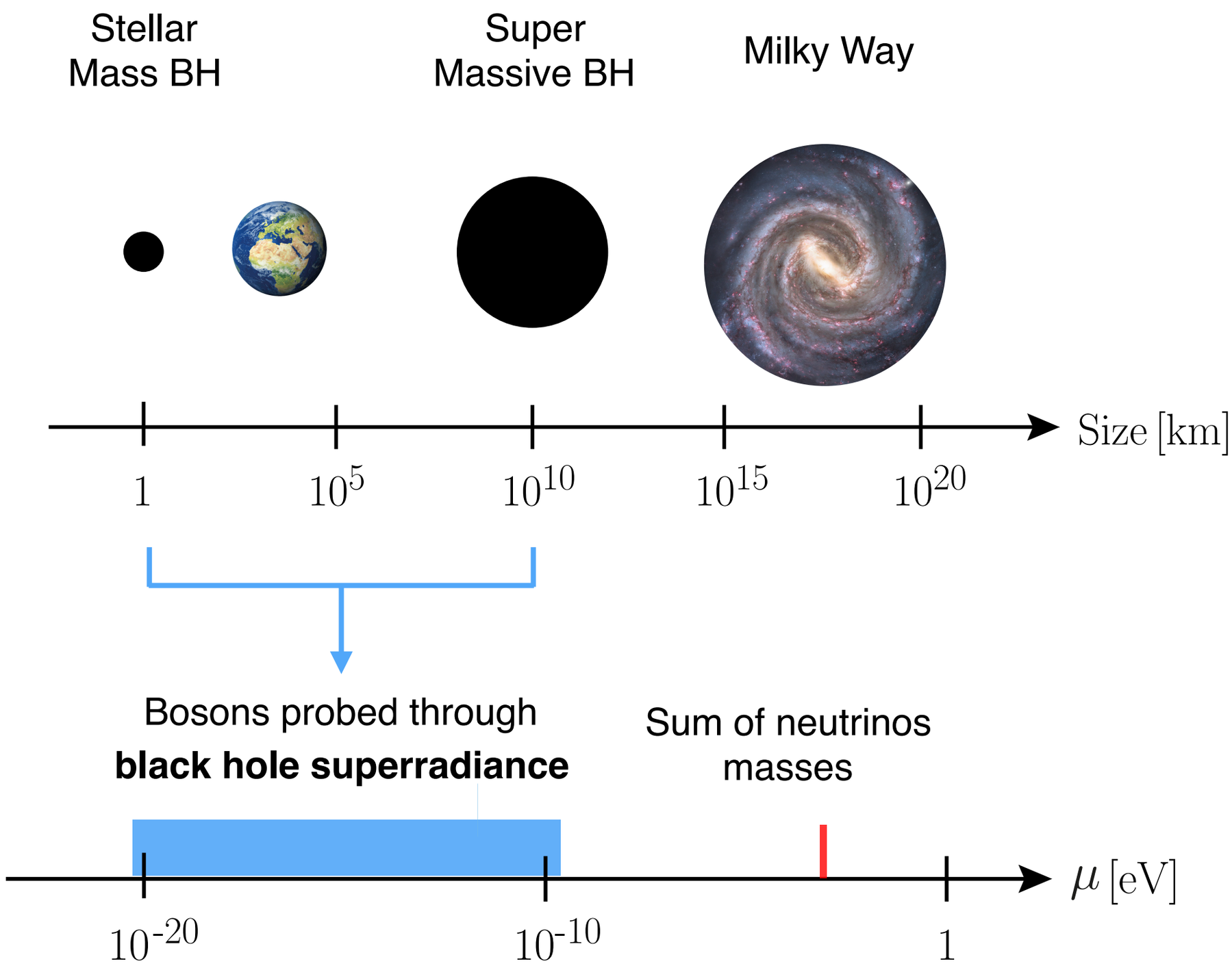
Supplementary Slides

Superradiance



Decay Timescale

The decay timescale of the dominant mode is

$$\Gamma_{211} \propto \frac{1}{M} \left(\Omega_H - \omega_{211}\right) \alpha^9$$

which depends sensitively on α, so the growth timescale can range from minutes to billions of years.