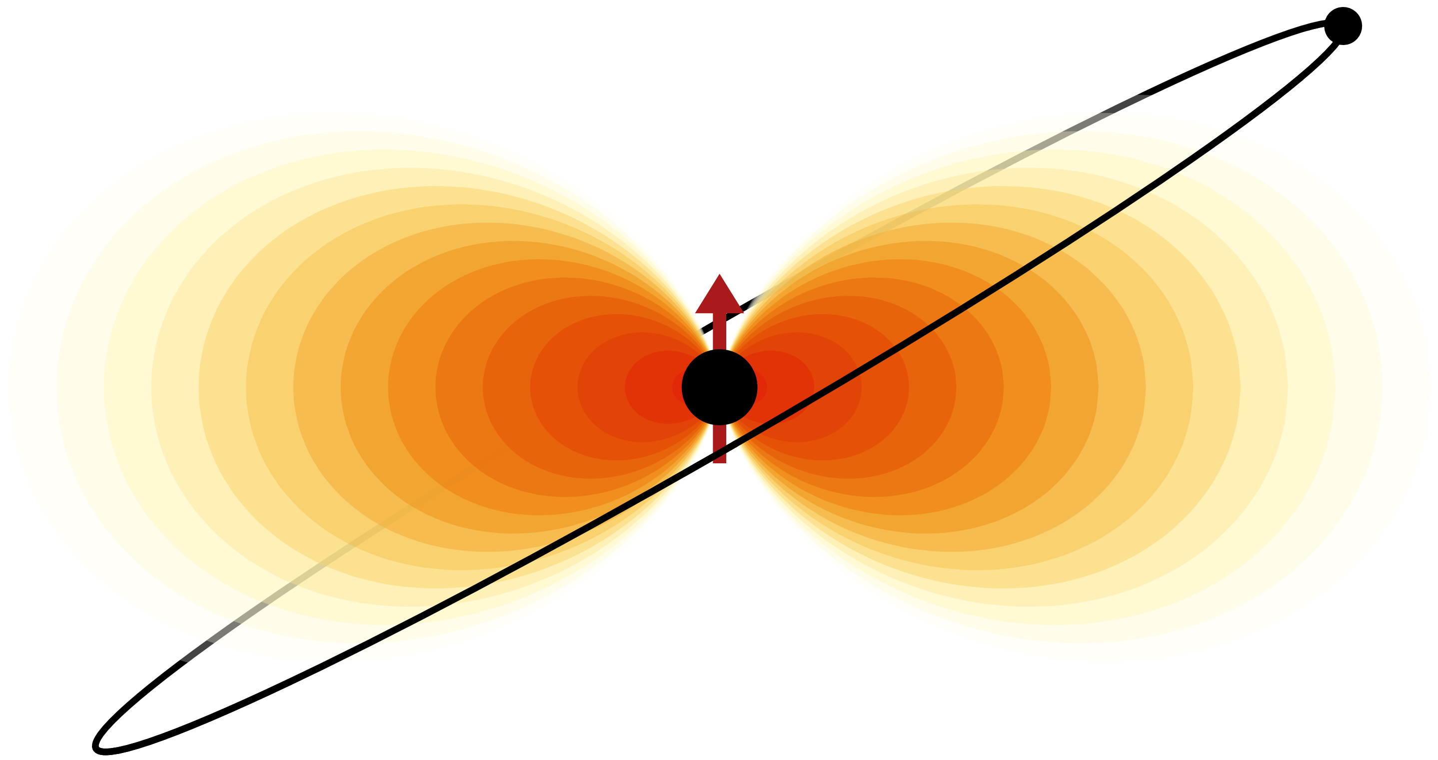
Probing Ultralight Bosons with Binary Black Holes in the Mid-frequency Band

Horng Sheng Chia

University of Amsterdam

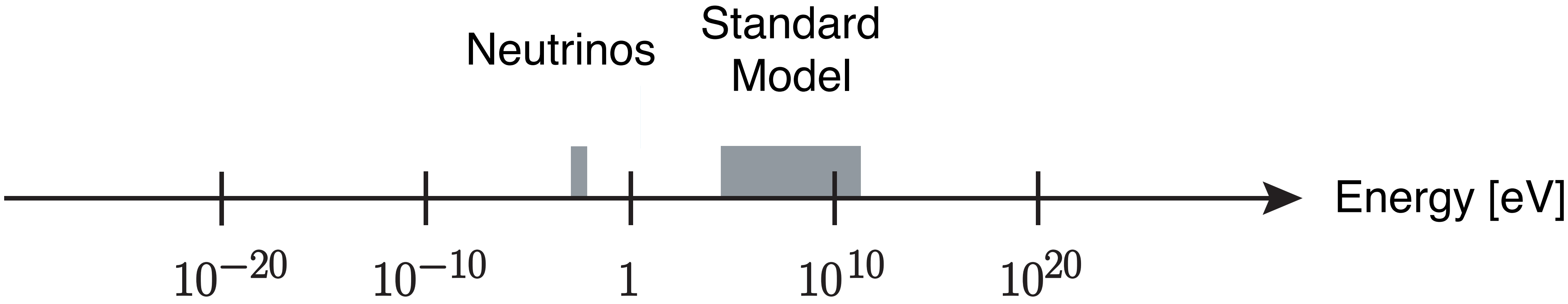


Work with

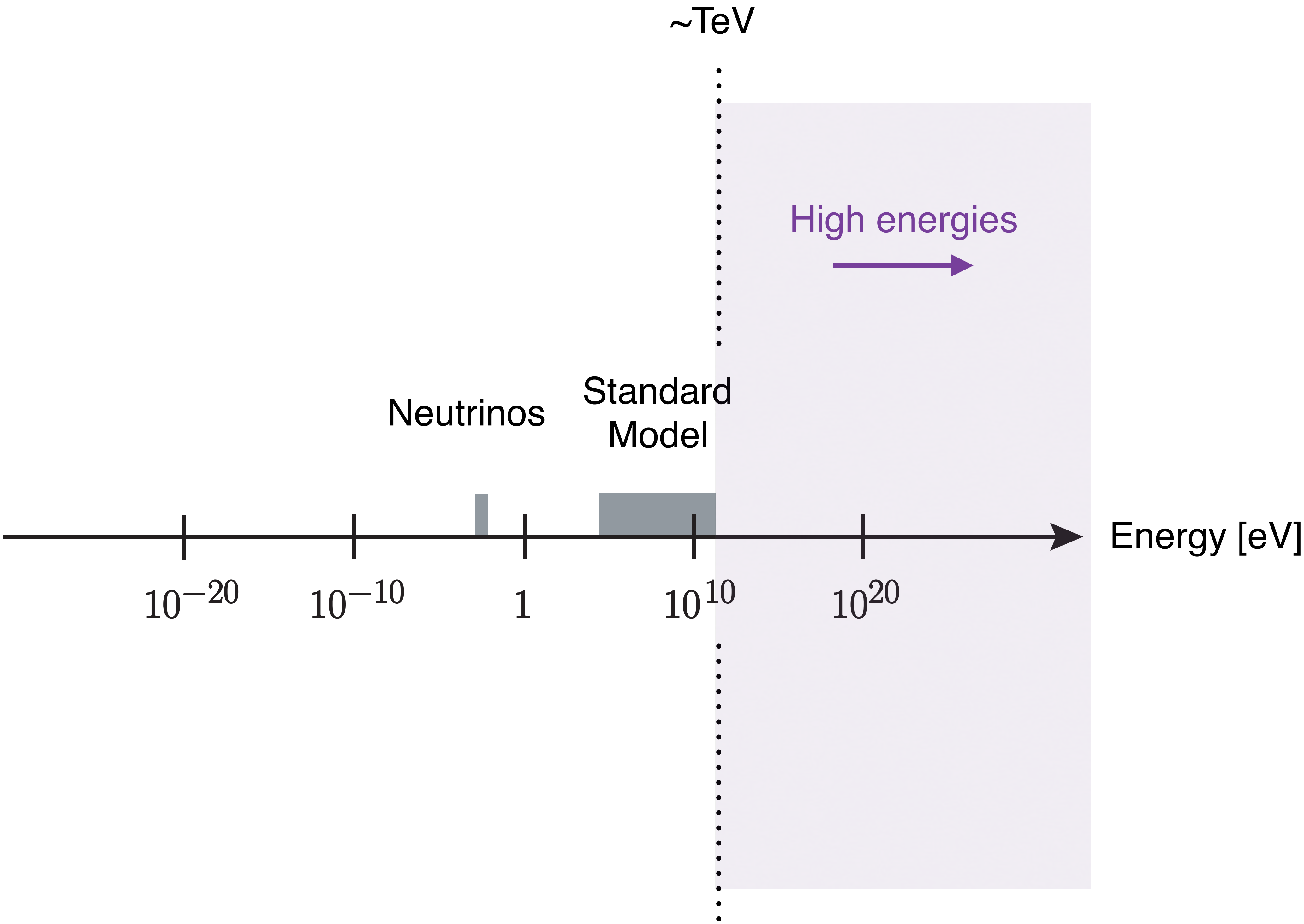
Daniel Baumann and **Rafael Porto [1804.03208]**

First AION Workshop
Imperial College London, March 2019

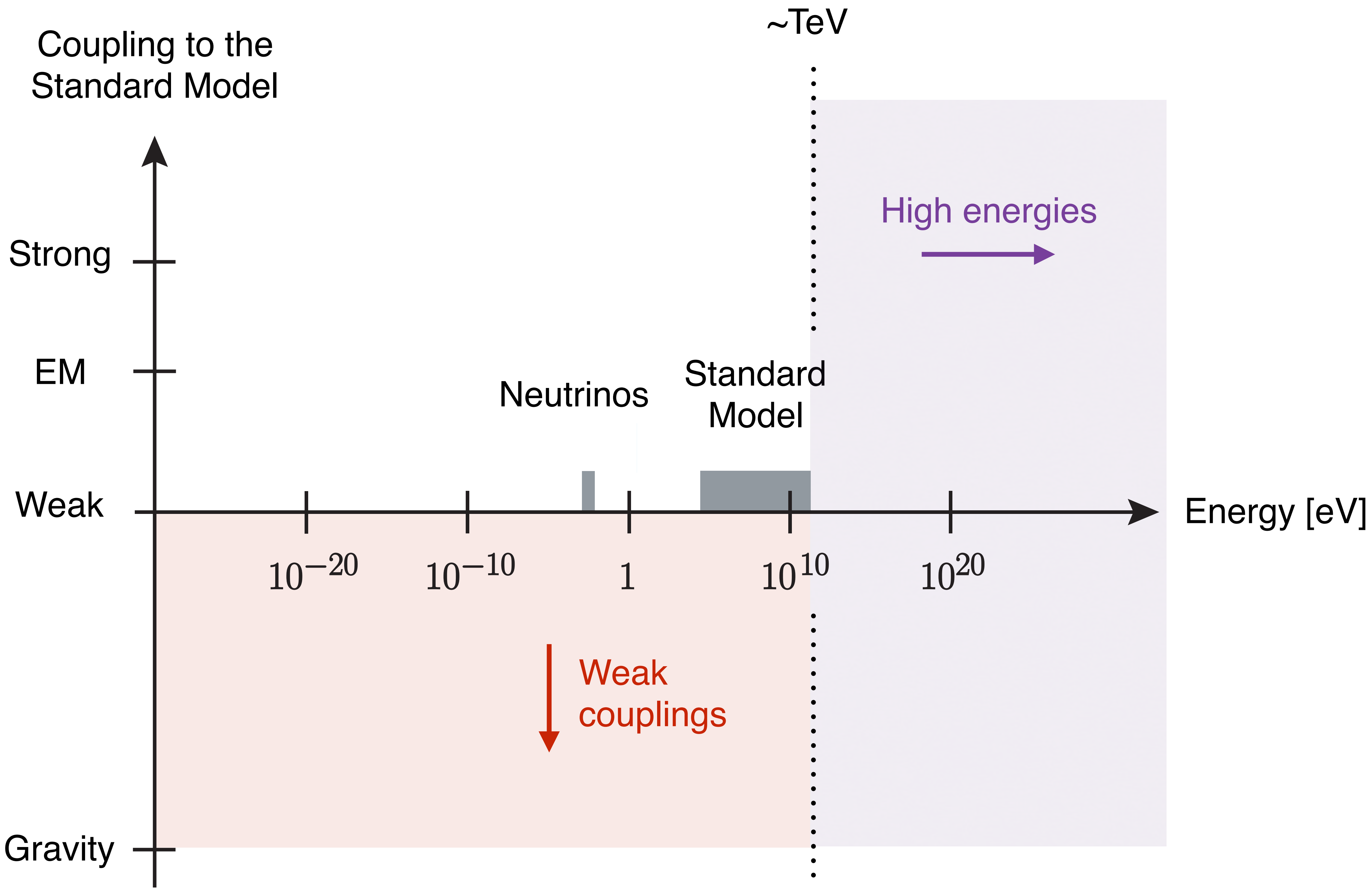
Two Avenues of New Physics



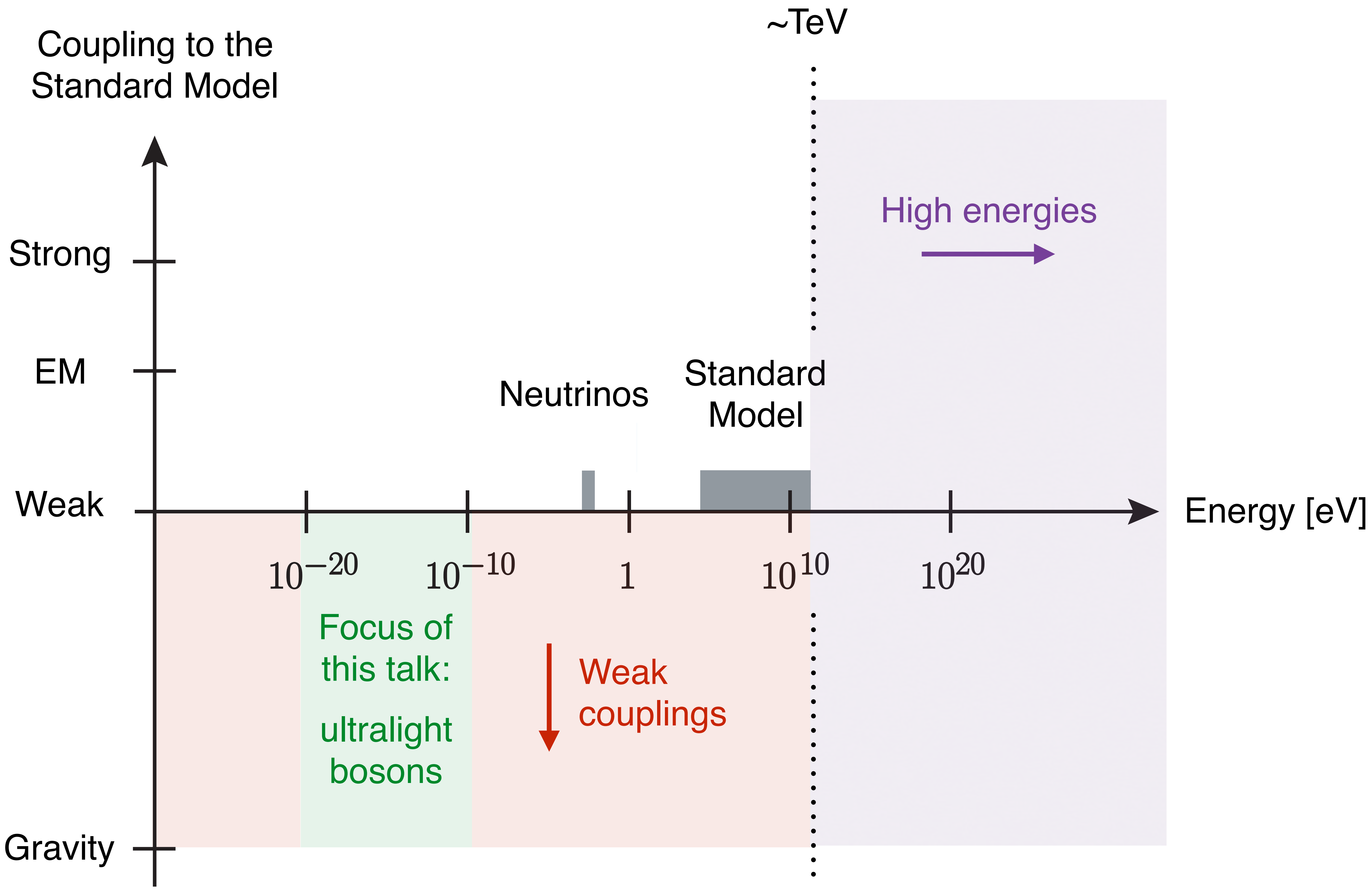
Two Avenues of New Physics



Two Avenues of New Physics

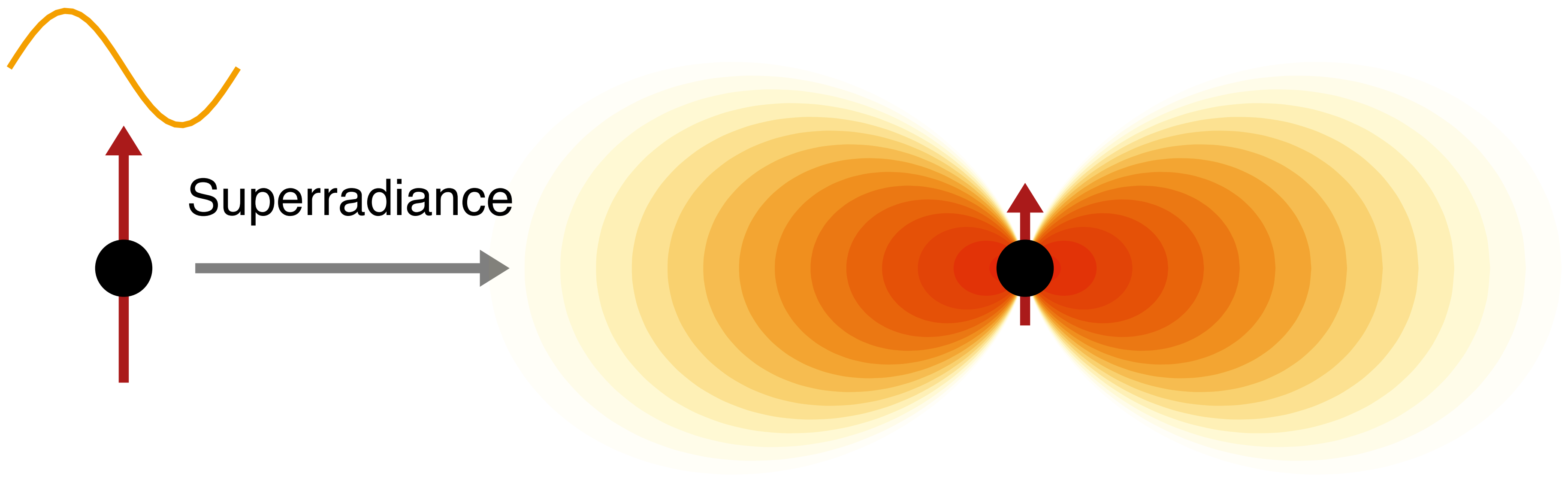


Two Avenues of New Physics



The Gravitational Atom

Ultralight boson condensates can be created around rotating black holes, if the Compton wavelength of the field ~ size of the black hole.

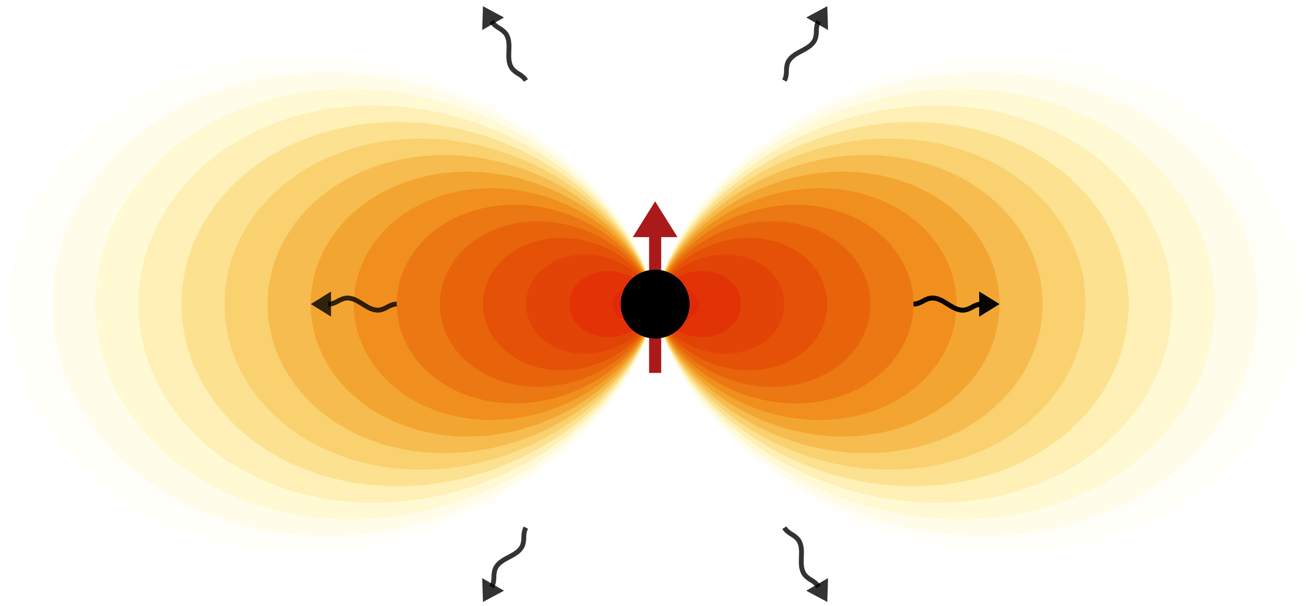


The structure resembles the hydrogen atom and is therefore often called the '**gravitational atom**'.

Zeldovich (1972)
Starobinsky (1973)
Arvanitaki et al. [0905.4720]

Gravitational Atom in Isolation

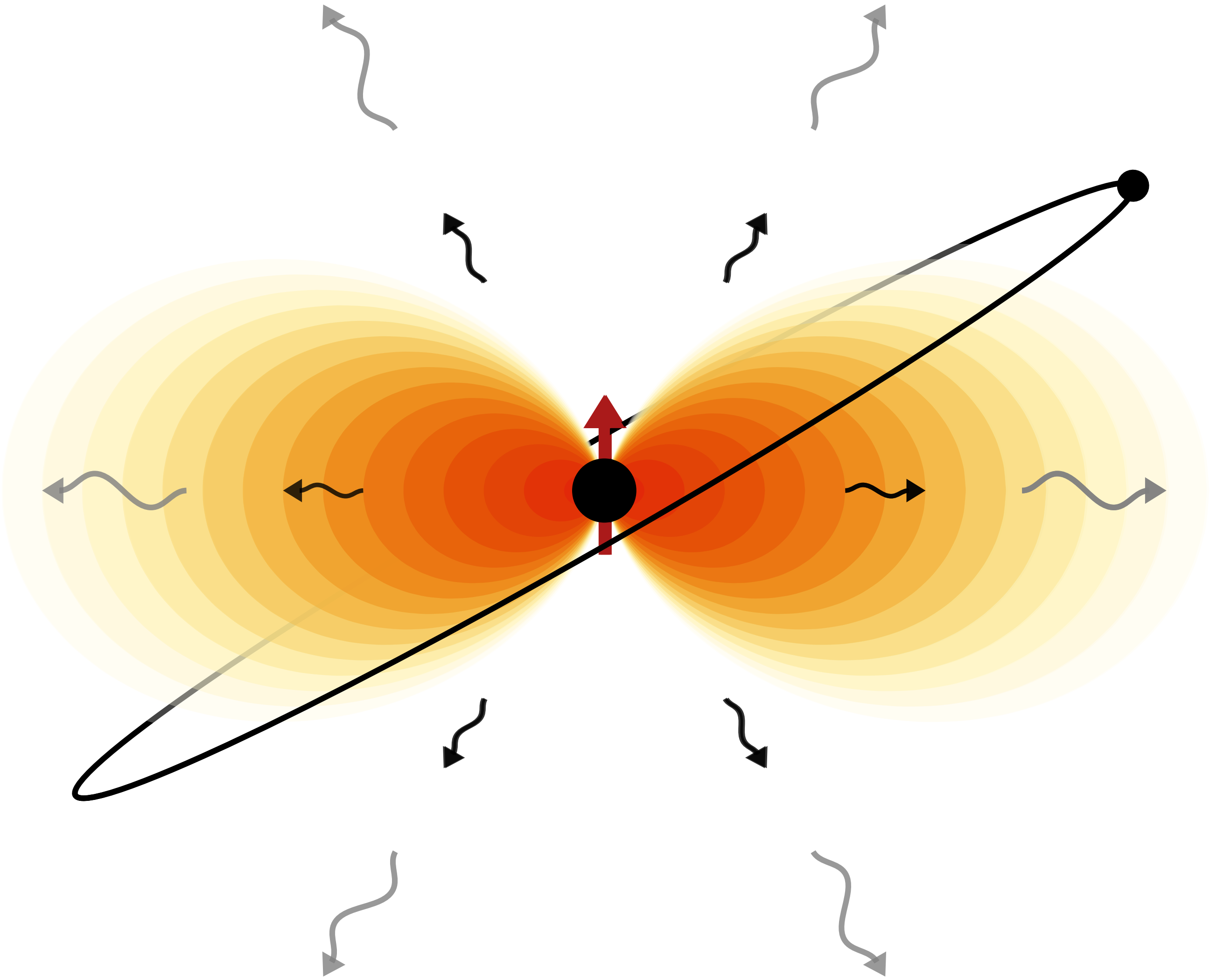
These clouds emit **continuous, monochromatic** gravitational waves.



Arvanitaki, Dubovsky [1004.3558]

Gravitational Atom in Binaries

A binary companion introduces **new dynamics** to the cloud.



Cloud perturbs the companion, affecting GW signal from the binary.

Outline

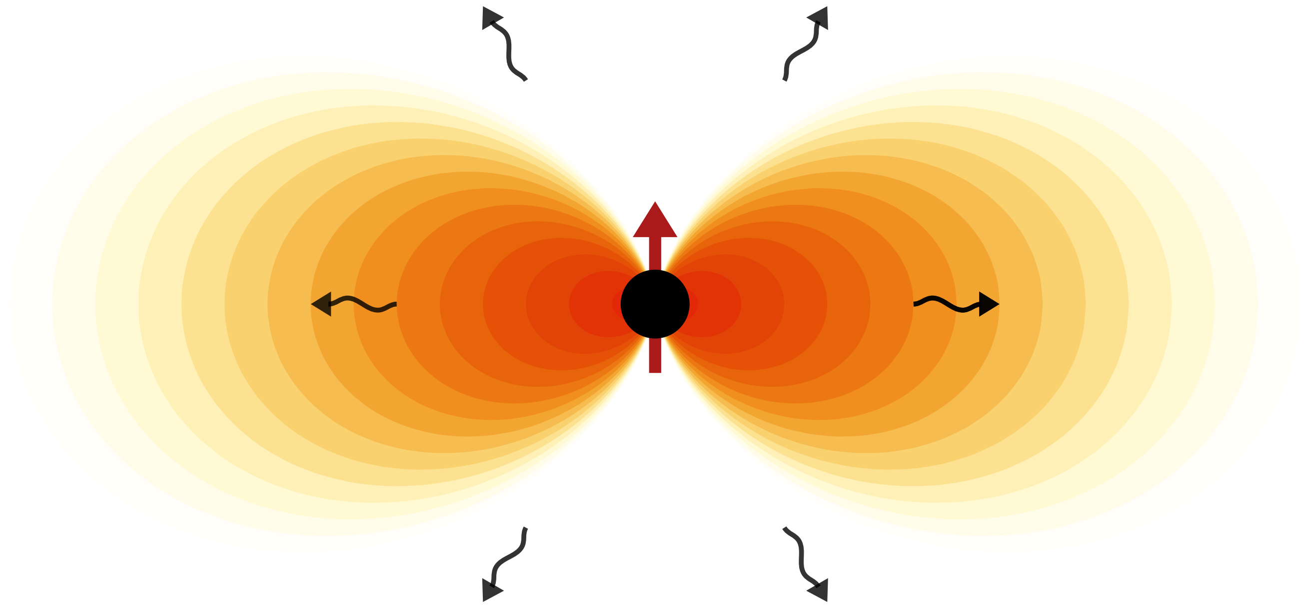
I. Gravitational Atom in Isolation

- Properties of the cloud
- Signal from the cloud

II. Gravitational Atom in Binaries

- Dynamics of the cloud in a binary — resonances
- Signal from the binary

I. Gravitational Atom in Isolation



Scalar Field in Kerr Background

Scalar field of mass μ around a Kerr background satisfies

$$\left(g^{ab}\nabla_a\nabla_b - \mu^2\right)\Phi(t,\mathbf{r}) = 0$$

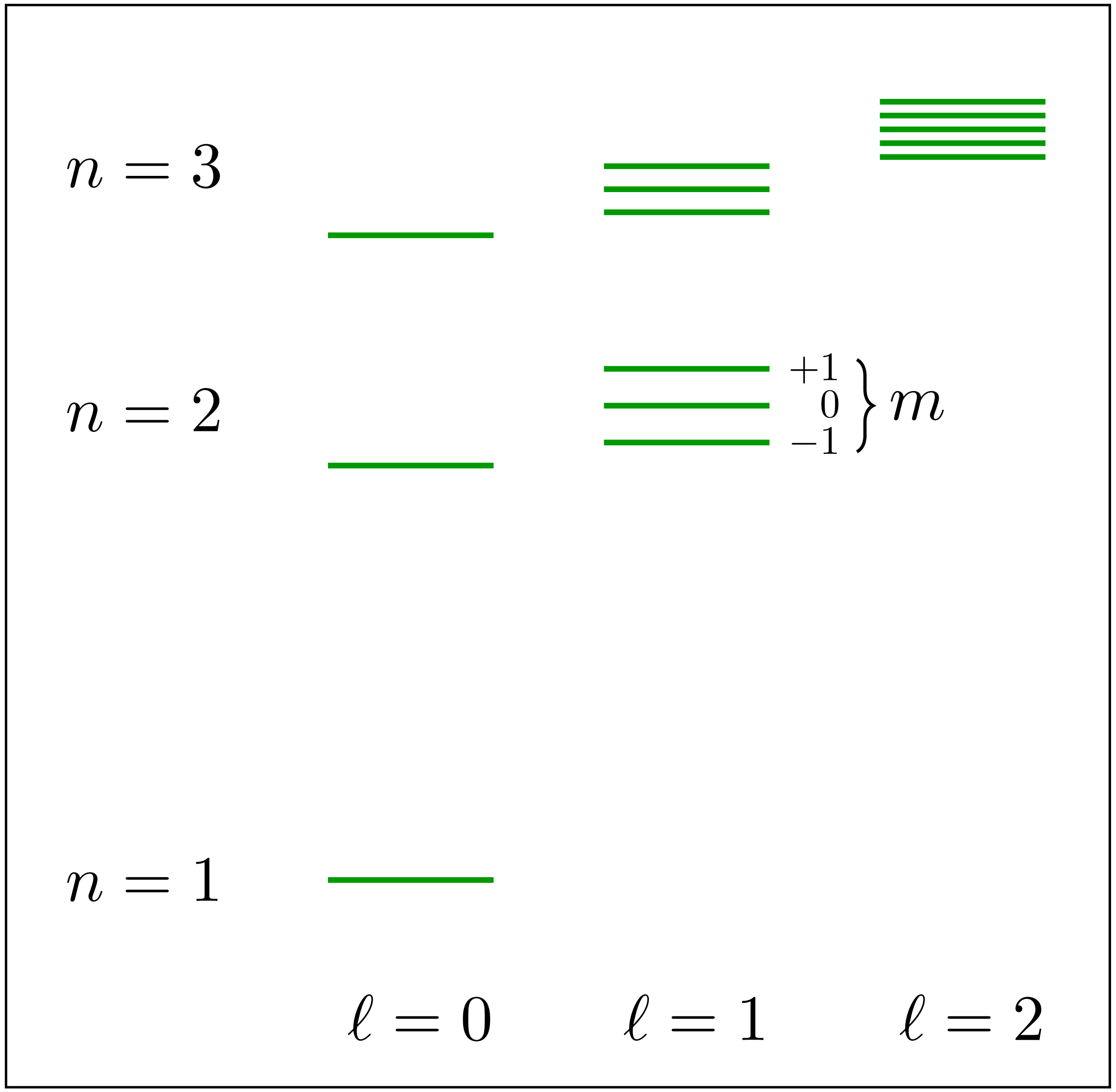
Substituting the ansatz $\Phi(t,\mathbf{r}) = e^{-i\omega t+im\phi}R(r)S(\theta)$, the radial equation at large distances satisfies a **hydrogen-like equation**

$$\left[-\frac{1}{2\mu r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}}{\mathrm{d}r}\right) - \frac{\alpha}{r} + \frac{\ell(\ell+1)}{2\mu r^2} + \frac{\mu^2-\omega^2}{2}\right]R = 0$$

where

$$\boxed{\alpha \equiv M\mu = \frac{\text{Gravitational radius}}{\text{Compton wavelength}}}$$

Energy Spectrum



The eigenstates are labelled by $\{n,\ell,m\}$, and the spectrum is

$$\omega^{(0)}_{n\ell m} = \mu\left(1-\frac{\alpha^2}{2n^2}\right)$$

Bohr energy

$$\omega^{(1)}_{n\ell m} = \mu\left(-\frac{\alpha^4}{8n^4}+\frac{(2\ell-3n+1)\,\alpha^4}{n^4(\ell+1/2)}\right)$$

Relativistic kinetic energy

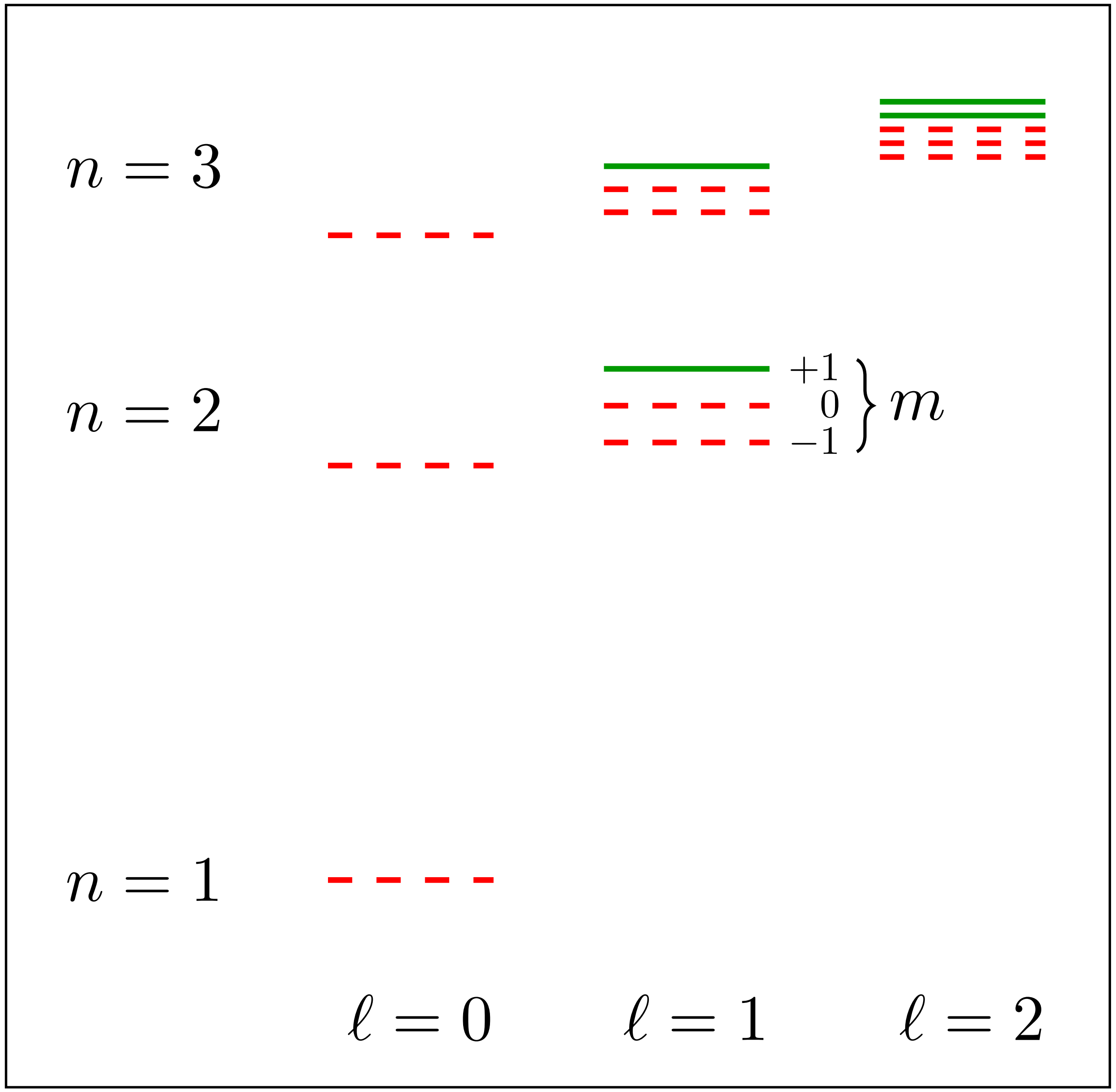
Fine structure splitting

$$\omega^{(2)}_{n\ell m} = \mu\left(+\frac{2\,(a/M)\,m\alpha^5}{n^3\ell(\ell+1/2)(\ell+1)}\right)$$

Hyperfine splitting

Baumann, HSC, Porto [1804.03208]

Growing and Decaying Modes



Due to the boundary condition at the black hole horizon, these are quasi-stationary states:

$$\omega_{n\ell m} \to \omega_{n\ell m} + i\Gamma_{n\ell m}$$

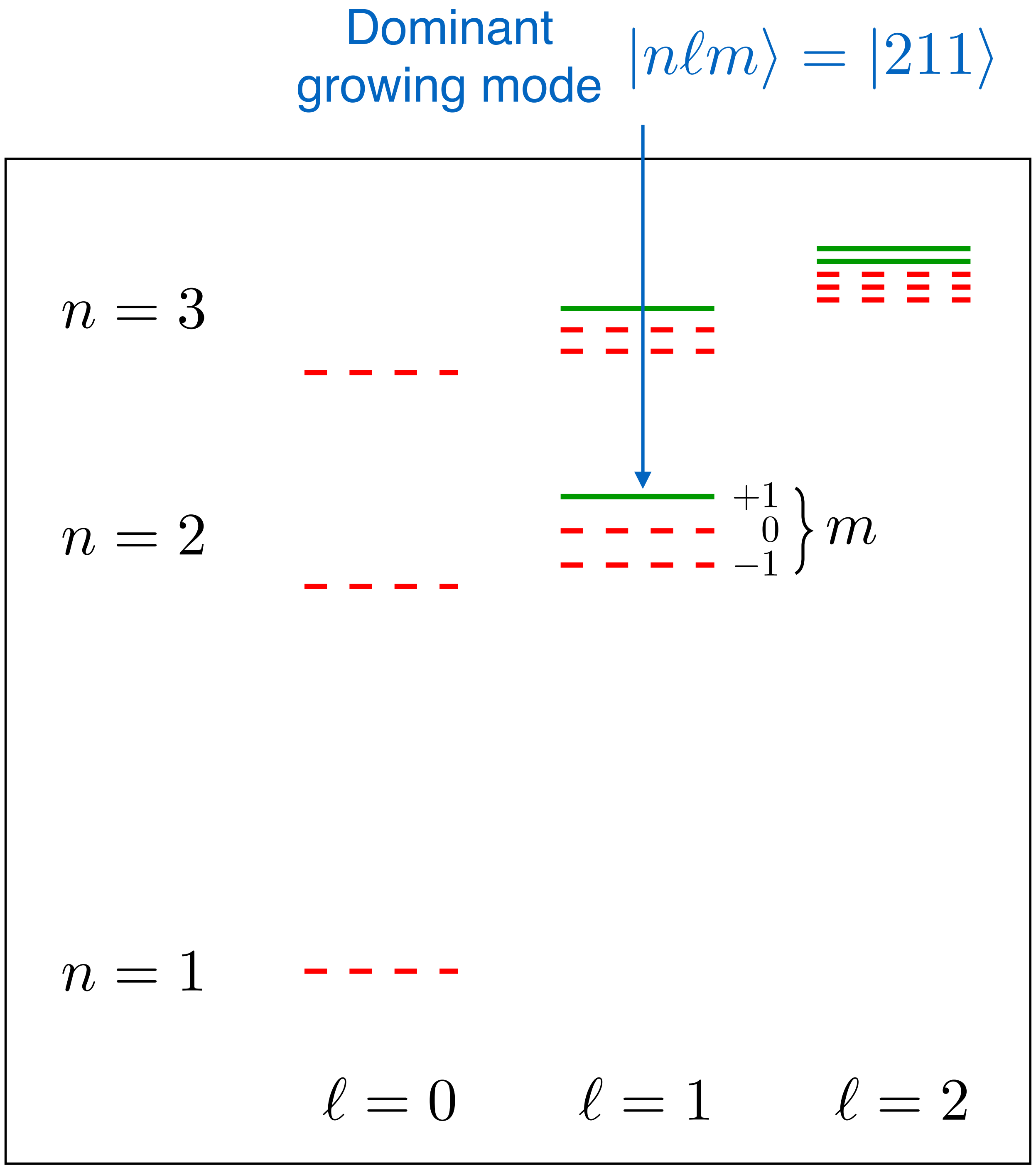
where $\Gamma_{n\ell m}$ is the instability rate

$$\Gamma_{n\ell m} \propto (m\Omega_H - \omega_{n\ell m})\, \alpha^{4\ell+5}$$

which gives rise to **growing** and **decaying** modes.

Detweiler (1980)

Dominant Growing Mode



Dominant growing mode $|n\ell m\rangle = |211\rangle$

For the $|211\rangle$ mode,

$$\Gamma_{211} \propto (m\Omega_H - \omega_{211})\alpha^9$$

Within the age of the universe, a black hole with mass M can grow clouds within the range

$$\alpha \simeq 0.005 - 0.5$$

which translates into probing **two orders-of-magnitude** of the ultralight boson mass μ

Detweiler (1980)

Signal from the Cloud

These clouds emit **continuous**, **monochromatic** gravitational waves, with frequency

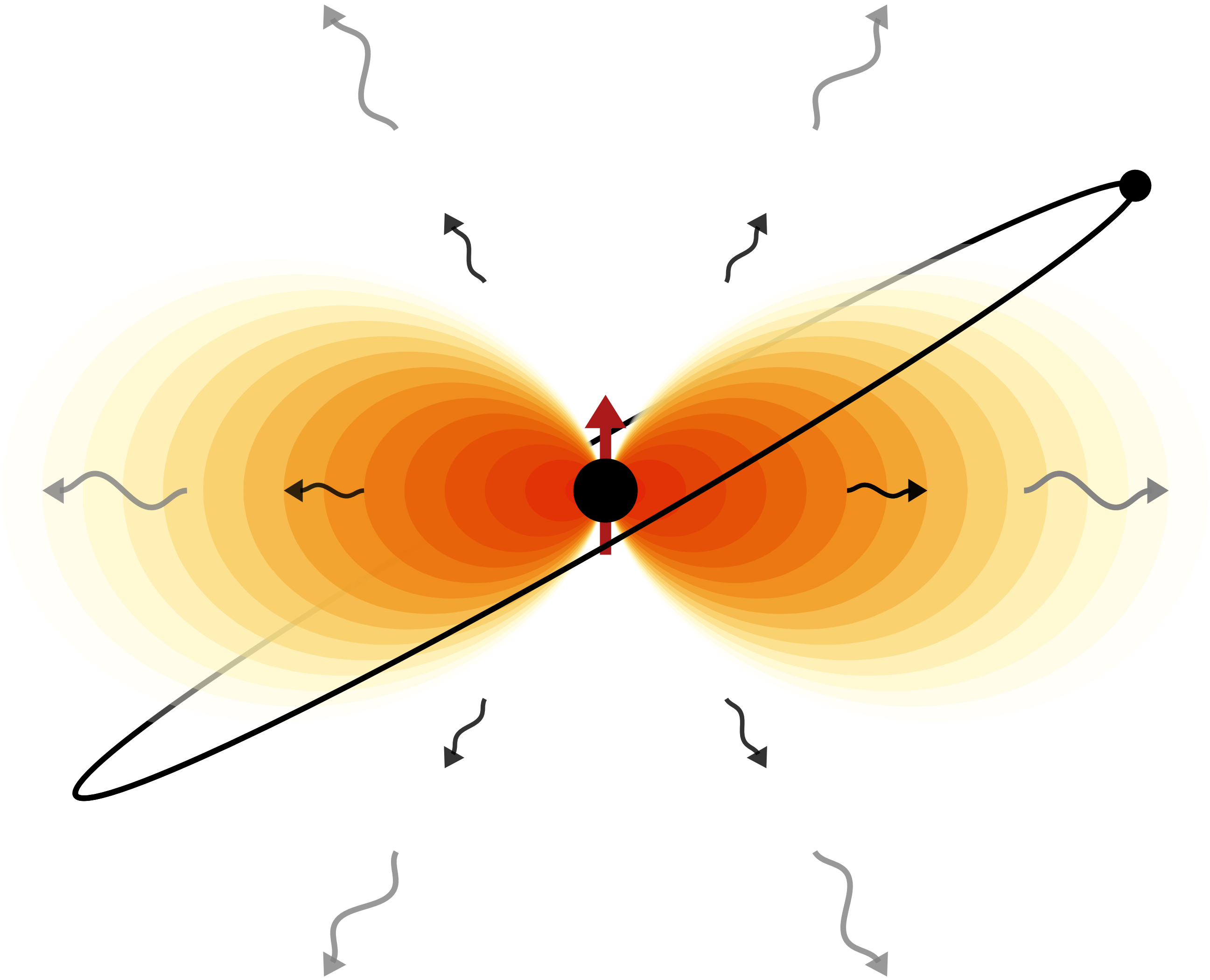
$$f_c \simeq 0.48\,\mathrm{Hz}\left(\frac{\mu}{10^{-15}\,\mathrm{eV}}\right)$$

For mid-frequency band detectors, this translates into probing ultralight bosons with masses

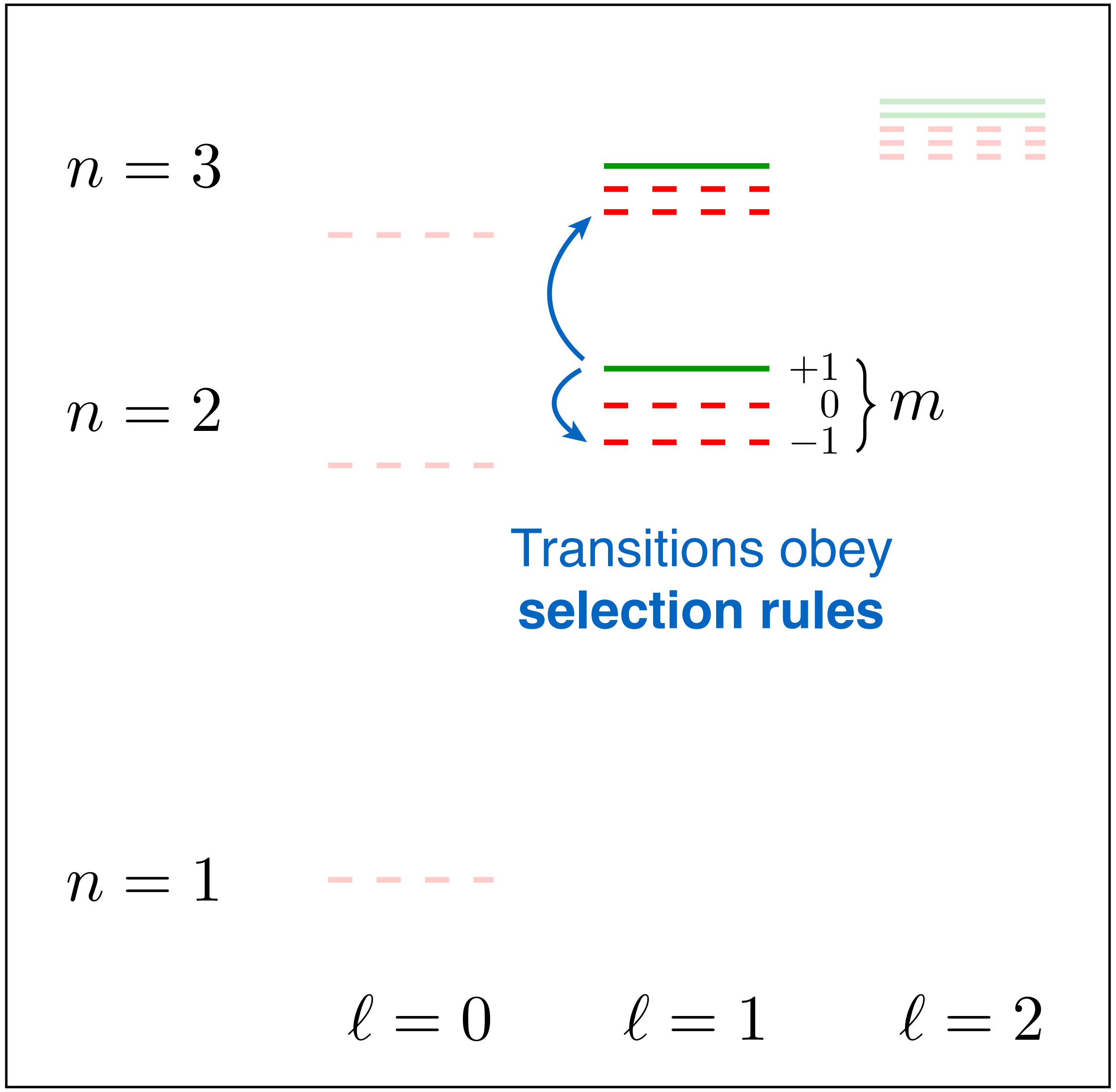
$$\mu \sim 10^{-16} - 10^{-14}\,\mathrm{eV}$$

This signal can either be **resolvable**, or contribute to the **stochastic GW background**.

II. Gravitational Atom in Binaries



Level Mixings



Transitions obey **selection rules**

In a binary system, the gravitational quadrupole created by the companion can induce **transitions** between the energy levels.

Baumann, HSC, Porto [1804.03208]

Rabi Oscillations

Rabi oscillations can be excited between the two energy level system.

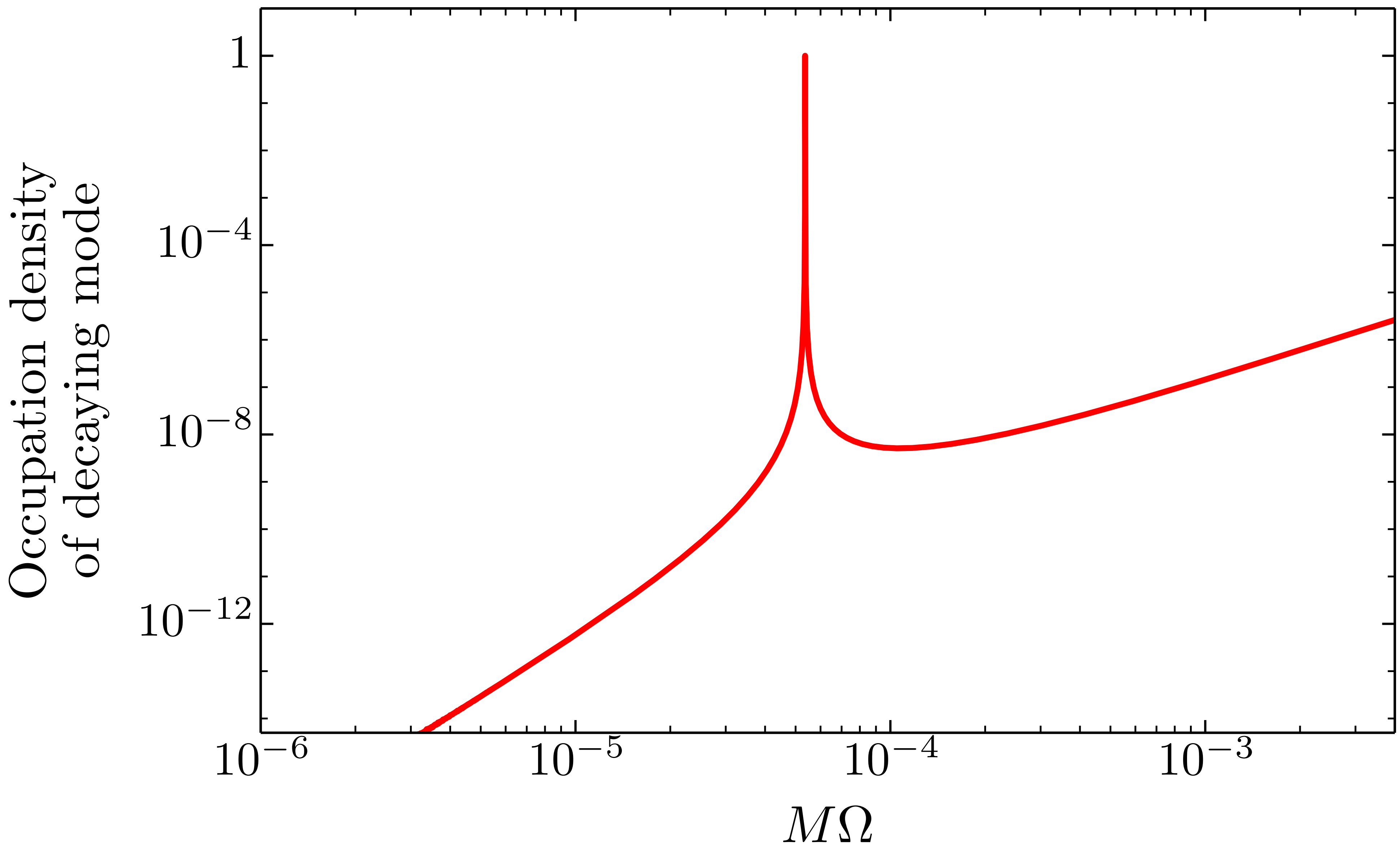
Oscillating gravitational quadrupole with orbital frequency Ω

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

Baumann, HSC, Porto [1804.03208]

Resonance Depletion

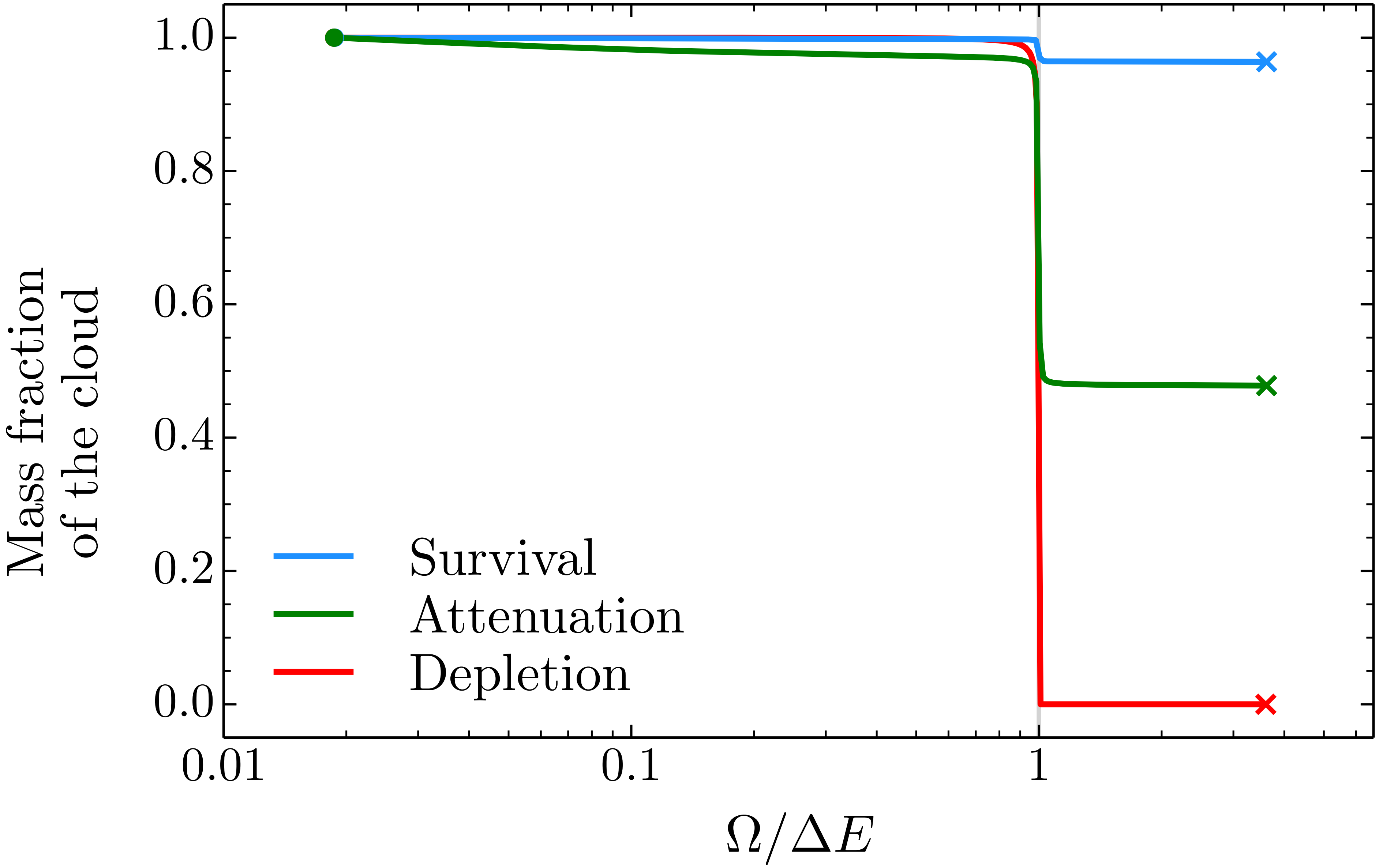
As the orbit shrinks due to GW emission, the binary scans through the resonance.



Baumann, HSC, Porto [1804.03208]

Resonance Depletion

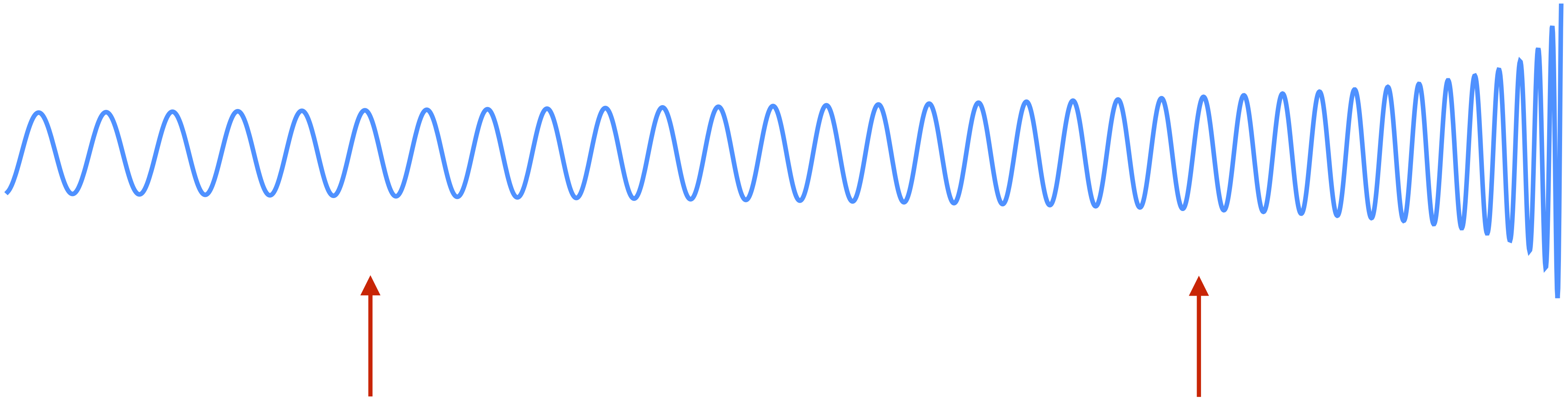
Depending on parameters, there are 3 qualitatively different scenarios:



Baumann, HSC, Porto [1804.03208]

Signals from the Binary

The cloud leaves its imprints on the **phase** of the waveform through finite-size effects.



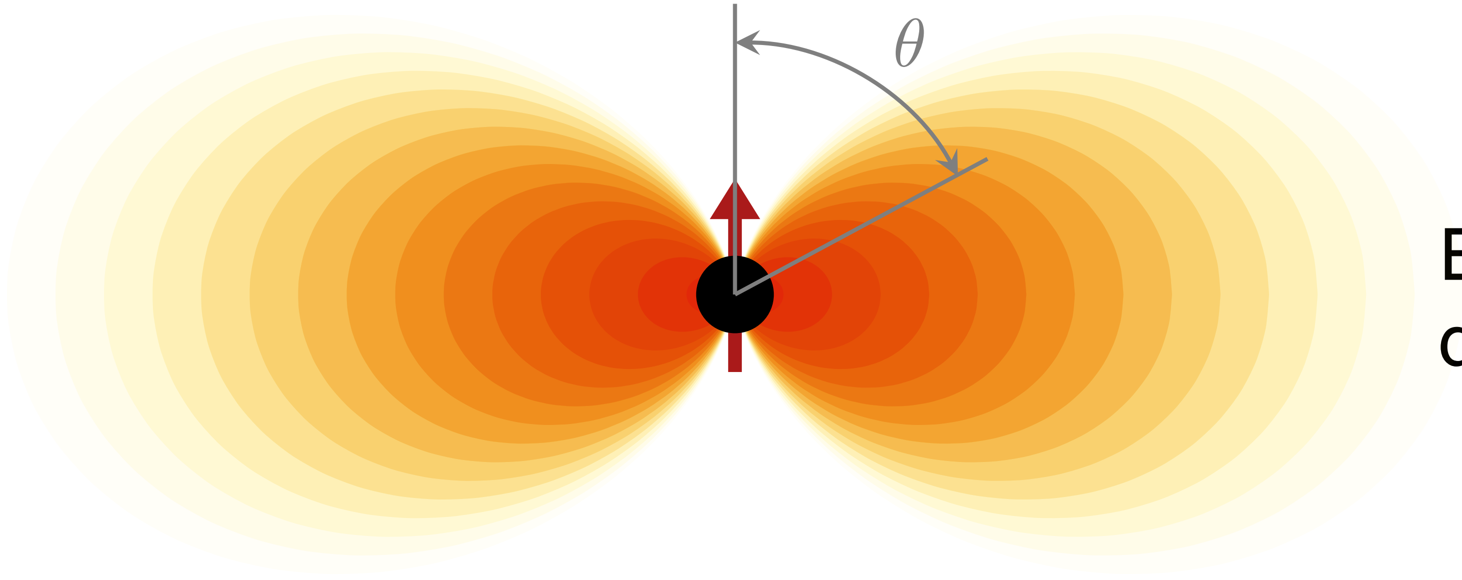
Spin-induced
quadrupole
(2PN)

Tidal
deformability
(5PN)

Furthermore, the resonance effects induce **time-dependent** changes to these finite-size effects.

Spin-Induced Quadrupole

Spinning motion of the cloud induces a quadrupole in the polar direction.



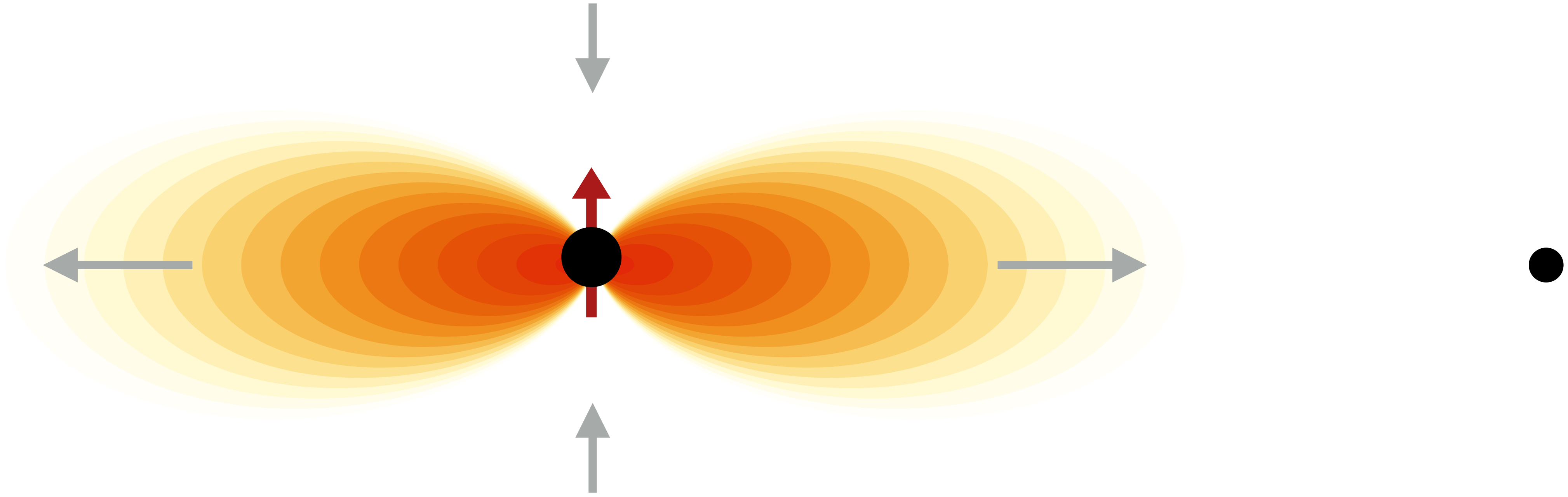
Energy density $\propto \sin^2\theta$

Imprints on the phase of waveforms at **2PN** order.

Laarakkers, Poisson [9709033]

Tidal Deformability

Tidal force exerted by the companion induces a quadrupole.



Imprints on the phase of waveforms at **5PN** order.

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

Signals from the Binary

Mid-frequency band detectors probe the finite-size effects of a wide range of black hole binaries:

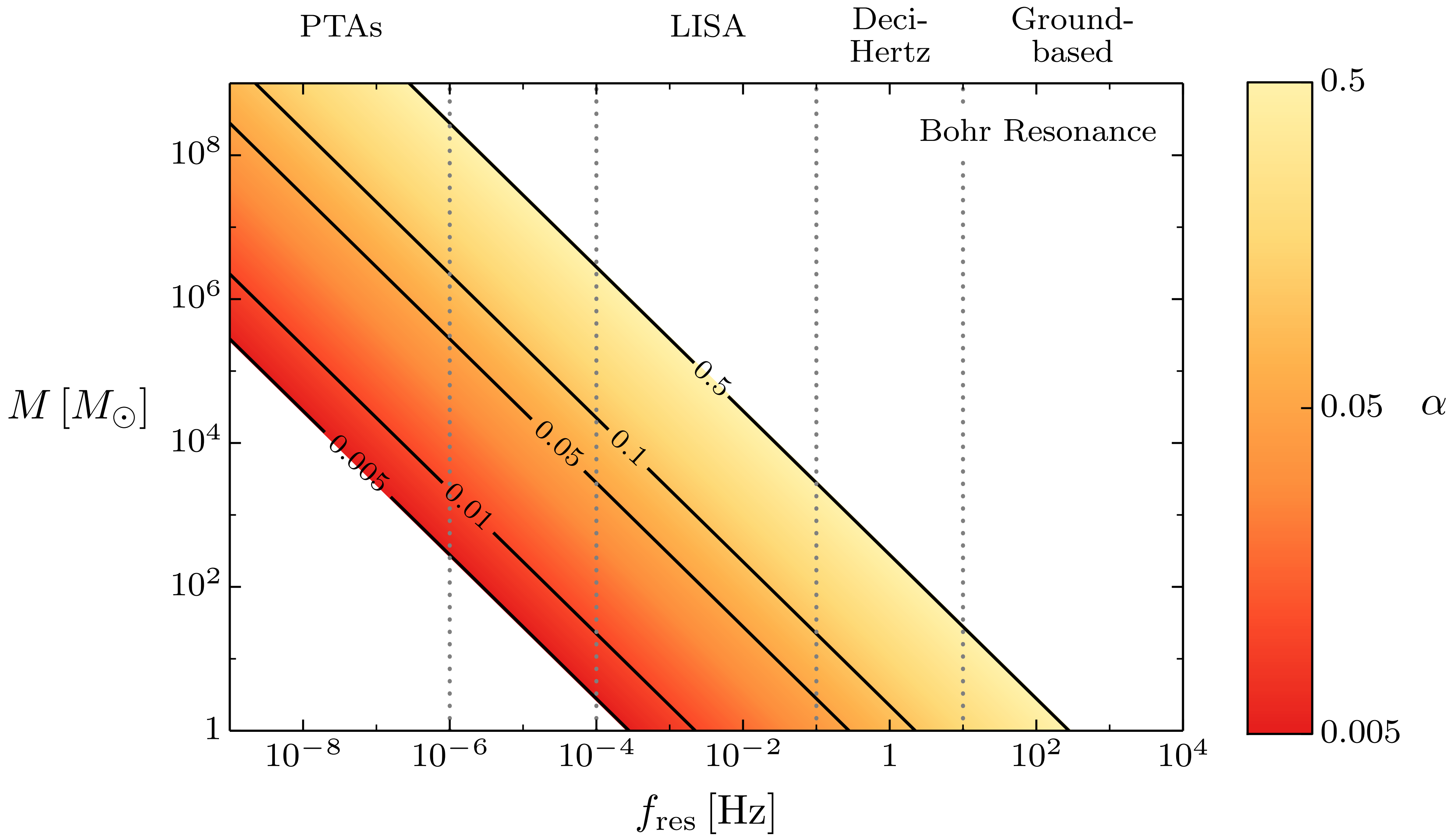
Solar mass black hole binaries	Intermediate mass black hole binaries	Intermediate mass ratio inspiral
$\text{e.g. } 10M_\odot - 10M_\odot$	$10^3 M_\odot - 10^3 M_\odot$	$10^5 M_\odot - 10M_\odot$

Since a black hole can probe two orders-of-magnitude in boson masses, this range of black hole masses translates into probing

$$\mu \sim 10^{-16} - 10^{-10}\,\mathrm{eV}$$

Resonance Frequency

Resonance depletion of finite-size effects occurs at specific GW frequency from the binary.

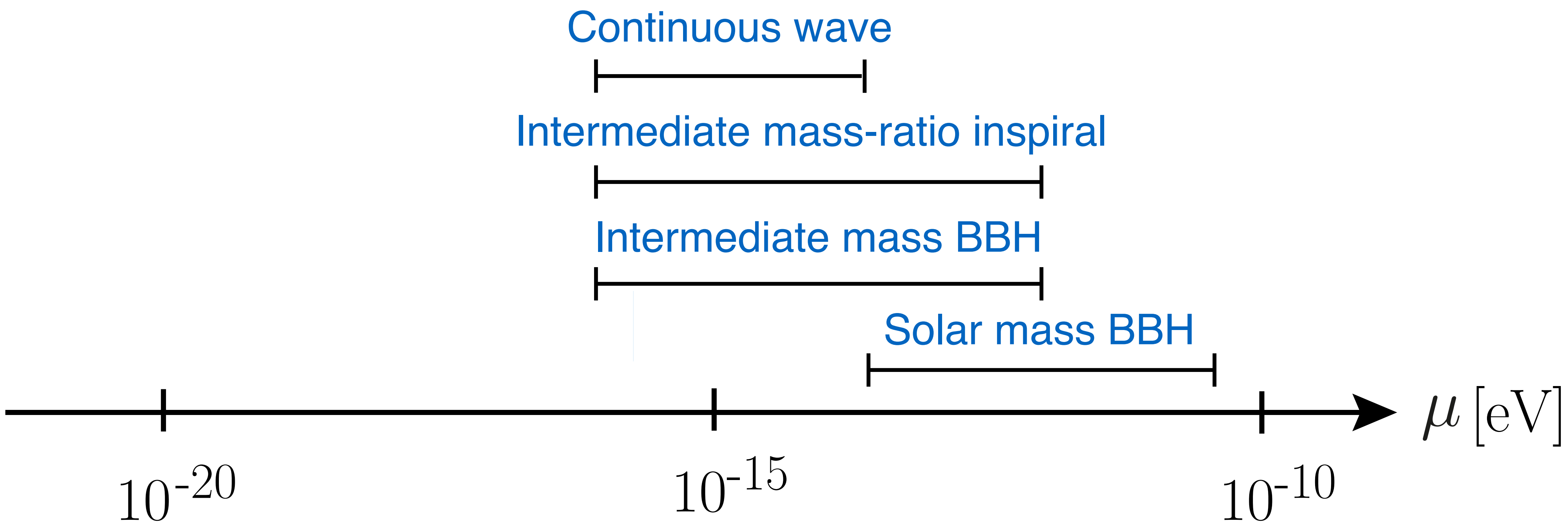


Baumann, HSC, Porto [1804.03208]

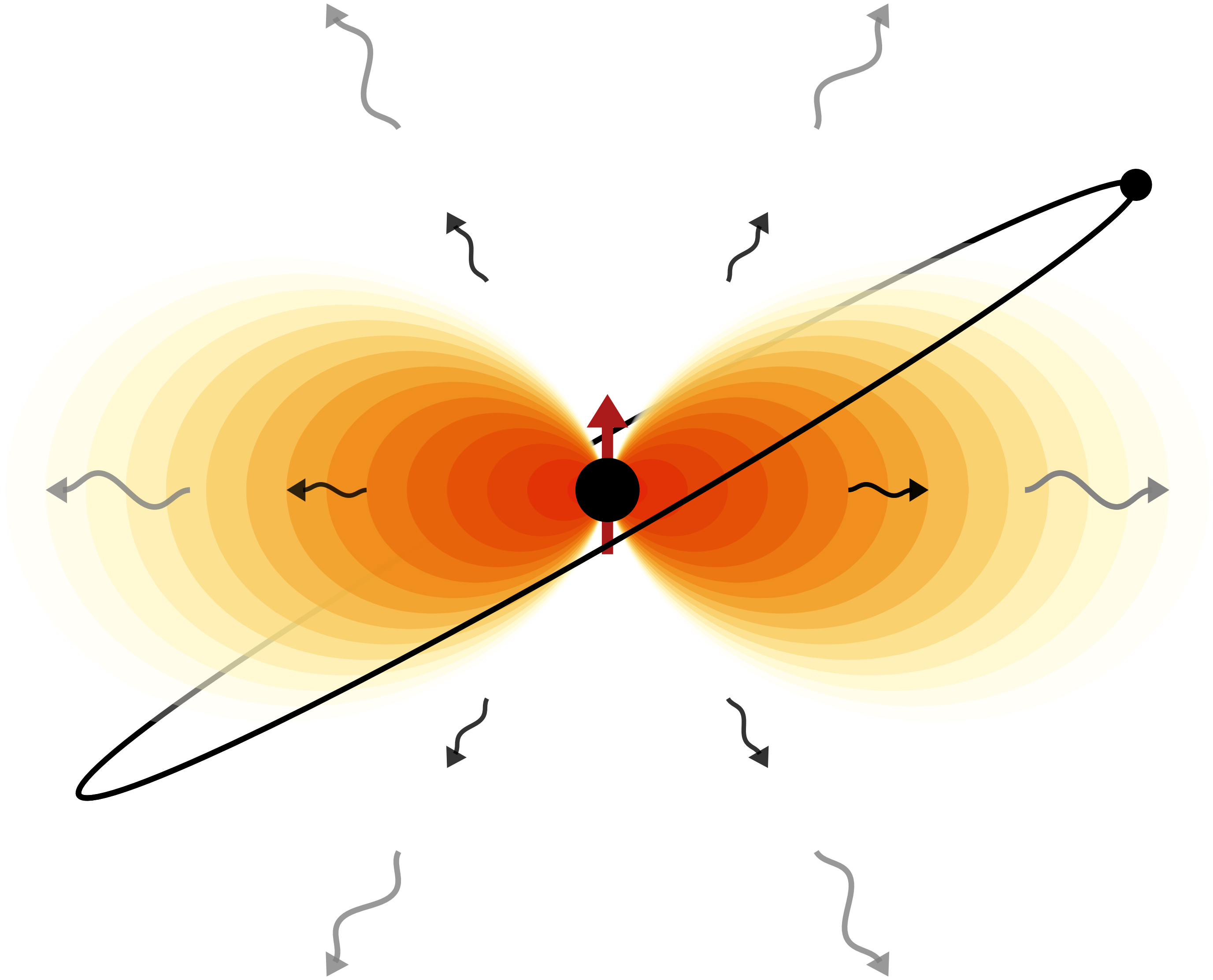
Summary for Mid-frequency Band

Observables for mid-frequency band detectors:

- Continuous, monochromatic GW
- Finite size effects
- Time-dependent changes in finite size effects induced by resonances



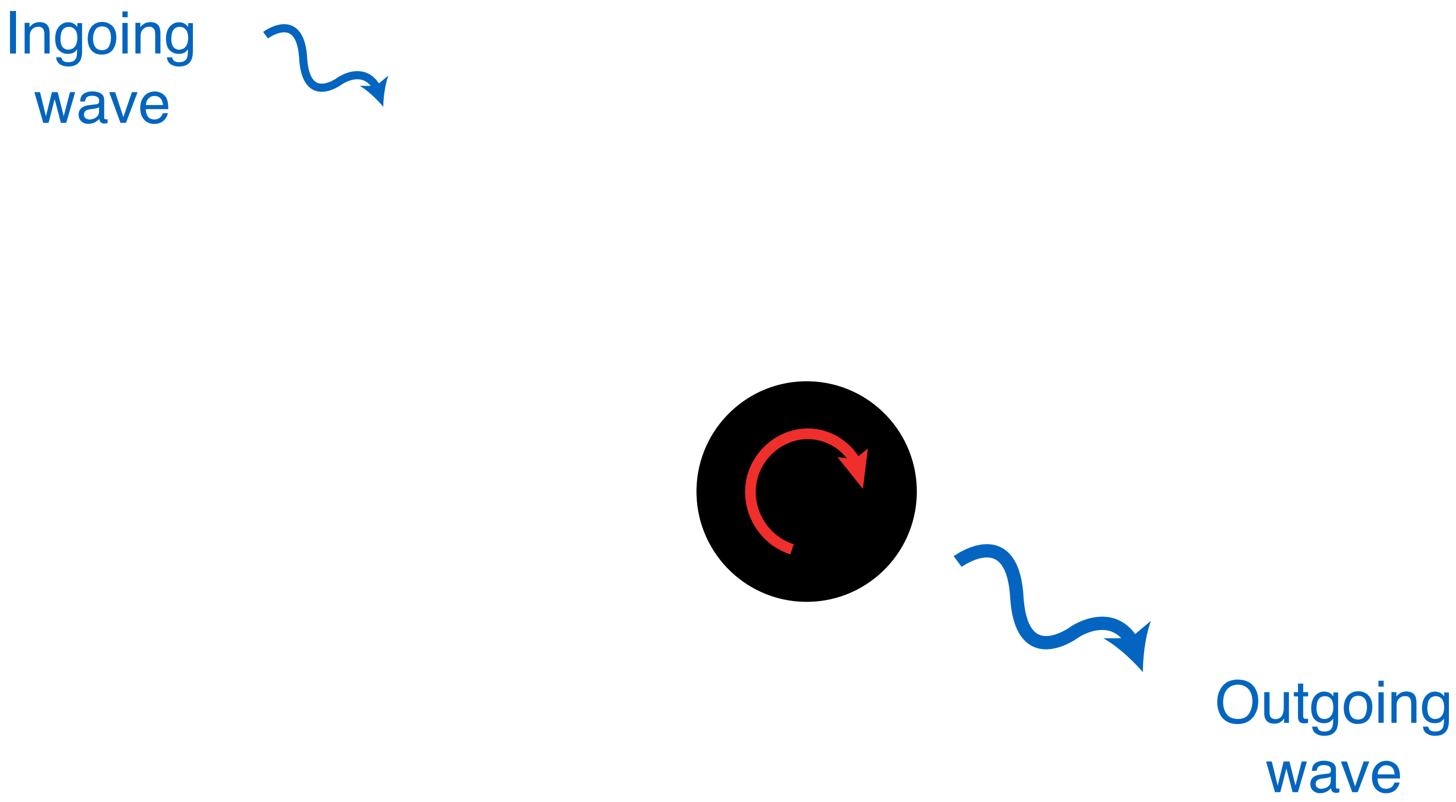
Thank You for Your Attention!



Supplementary Slides

Black Hole Superradiance

Wave amplification occurs when $\frac{\omega}{m} < \Omega_H$


Ingoing wave

Outgoing wave

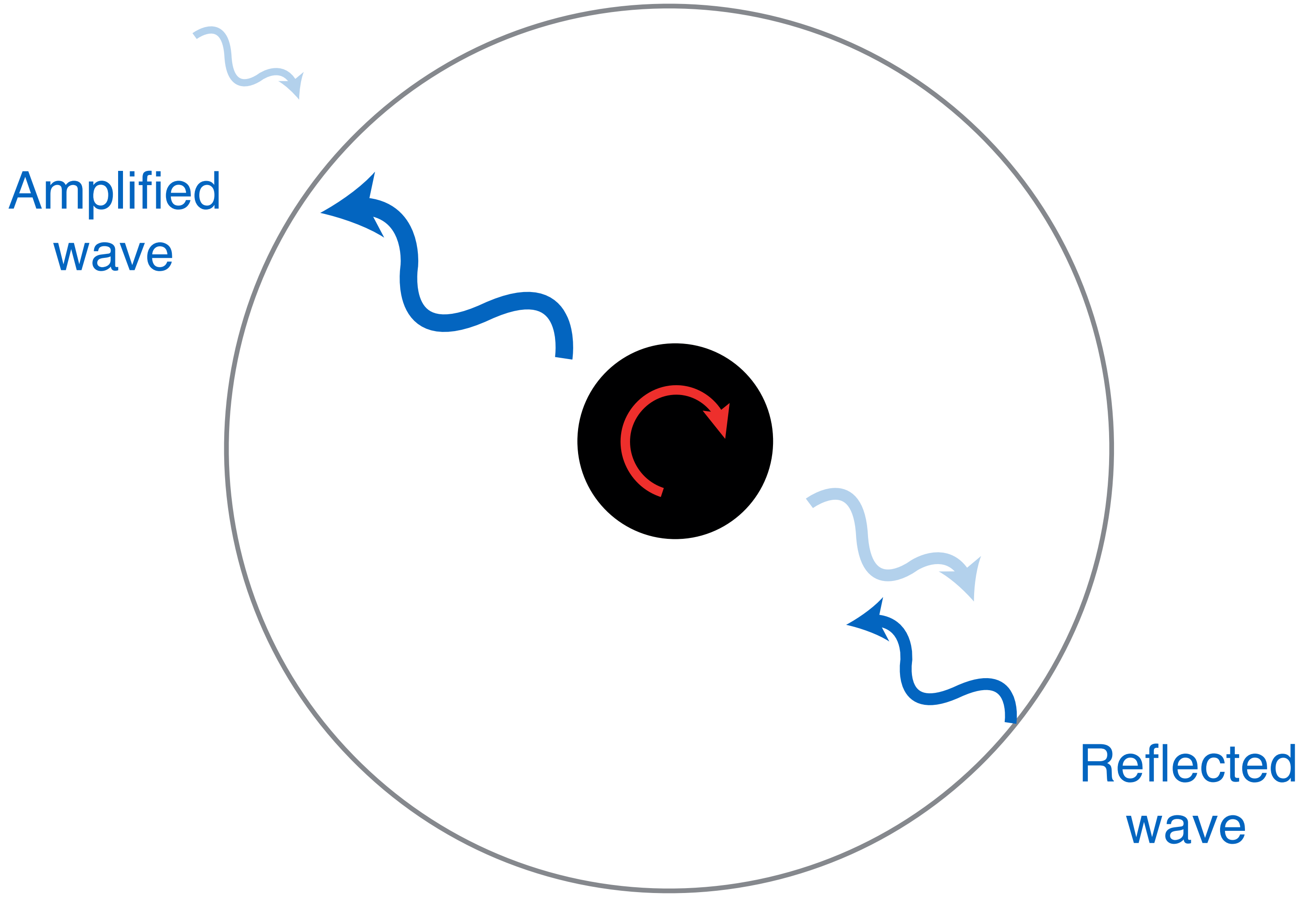
where ω and m are the frequency and azimuthal number of the wave, and Ω_H is the angular velocity of the black hole horizon.

Zeldovich (1972)

Starobinsky (1973)

Black Hole Superradiance

A reflecting mirror surrounding the BH creates a **black hole bomb**:

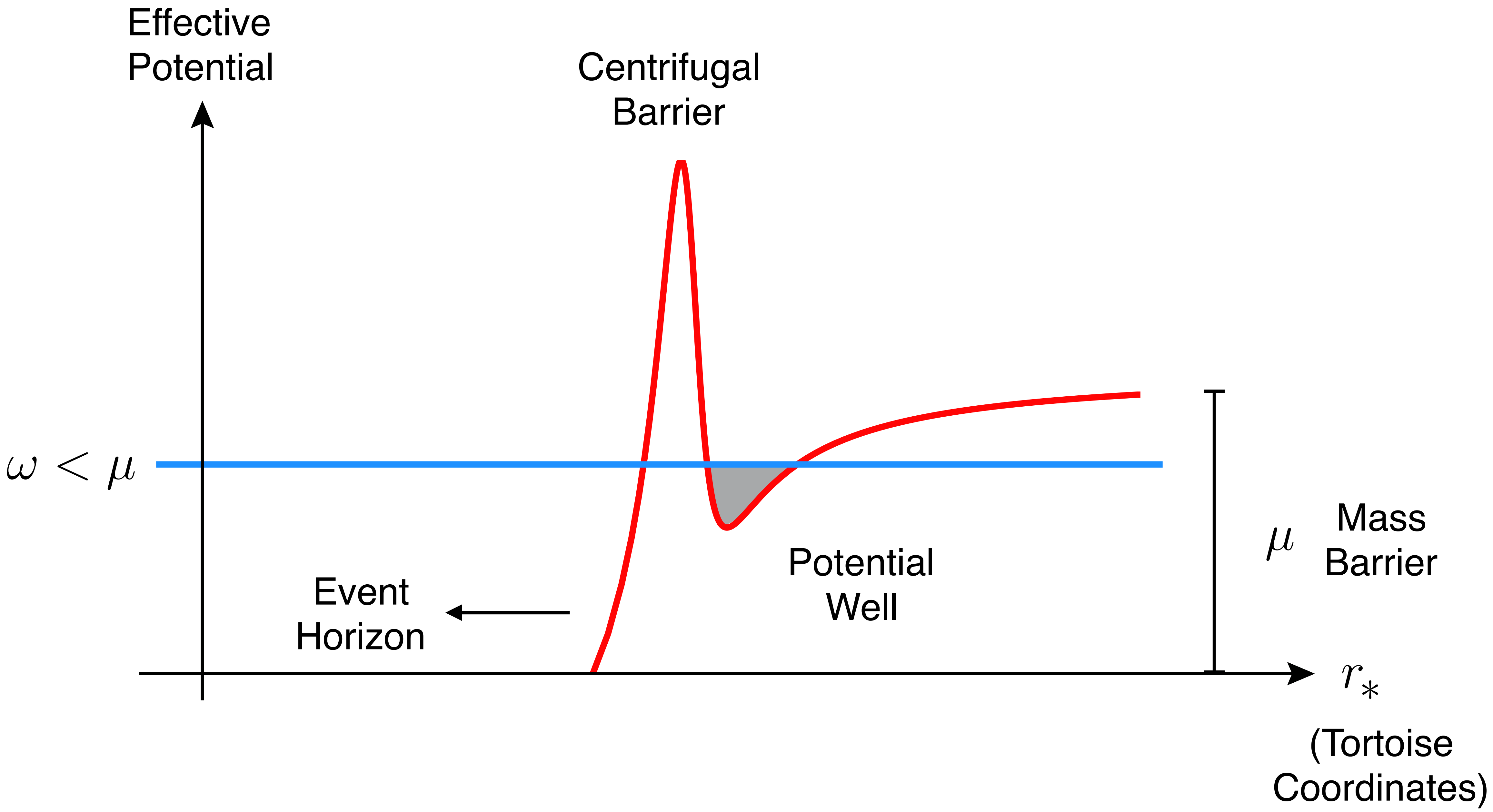


Superradiance occurs until $\frac{\omega}{m} = \Omega_H$.

Press, Teukolsky (1972)

Black Hole Superradiance

Massive fields naturally create this reflecting mirror.



Monochromatic Signal Strain

The root-mean-square strain of the continuous monochromatic GW is

$$h_c \simeq 2 \times 10^{-26} \left(\frac{M}{3M_\odot}\right) \left(\frac{M_c(\alpha)/M}{0.1}\right) \left(\frac{\alpha}{0.07}\right)^6 \left(\frac{10\,\mathrm{kpc}}{d}\right)$$

Clouds with $\alpha \lesssim 0.07$ and $M \lesssim 100 M_\odot$ may only be observable if they are in our galaxy, whereas extragalactic sources may be detected for larger values of α and M .

Spin-Induced Quadrupole

Parametrized in terms of **rotational Love number:**

$$Q_{\rm spin} = -\kappa M^3 \chi^2$$

where χ is the dimensionless spin of the object.

Examples of κ:

$$\kappa_{\rm BH} = 1$$

$$2 \lesssim \kappa_{\rm NS} \lesssim 10$$

$$\kappa_c \gtrsim 10^3 \left(\frac{M_c/M}{0.1}\right)\left(\frac{0.1}{\alpha}\right)^4$$

Tidal Deformability

Parametrized in terms of **tidal Love number:**

$$Q_{ij,\mathrm{induced}} = -\Lambda M^5 \mathcal{E}_{ij}$$

where $\mathcal{E}_{ij}$ is the external tidal tensor sourced by the companion.

Examples of Λ:

$$\Lambda_{\mathrm{BH}} = 0$$

$$\Lambda_{\mathrm{NS}} \lesssim 10^3$$

$$\Lambda_c \sim 10^7 \left(\frac{M_c/M}{0.1}\right)\left(\frac{0.1}{\alpha}\right)^8$$