GRAVITATIONAL WAVES: FROM DETECTION TO NEW PHYSICS SEARCHES

Masha Baryakhtar

New York University

Lecture 3 July 2, 2020
Superradiance and Black Holes

or

How to Extract Energy from Black Holes and Discover New Particles
Outline for Today

• Superradiance and rotating BHs
• Gravitational Atoms
• Signs of New Particles
  • Black Hole Spindown
  • Gravitational Wave Signals
Outline for Today

• Superradiance and rotating BHs

• Rotational, or Zeldovich, superradiance: extraction of an object’s rotational energy by an incident wave in the presence of dissipation

• Rotating (Kerr) black holes can superradiance and lose energy and angular momentum

• Gravitational Atoms

• Signs of New Particles

• Black Hole Spindown

• Gravitational Wave Signals
Outline for Today

- Superradiance and rotating BHs
- Gravitational Atoms
- Signs of New Particles
  - Black Hole Spindown
  - Gravitational Wave Signals
  - Ultralight fields can form macroscopic gravitationally bound states with astrophysical black holes, or "gravitational atoms"
  - Bosonic fields can form states with exponentially large occupation values which grow spontaneously through superradiance
Outline for Today

- Superradiance and rotating BHs
- Gravitational Atoms
- Signs of New Particles
  - Black Hole Spindown
  - Gravitational Wave Signals
- If there is a light axion (scalar/vector) with compton wavelength comparable to astrophysical BH sizes, it will cause astrophysical black holes to spin down
- The resulting bound states of light particles will source gravitational wave radiation that is observable by LIGO
Motivation

• Ultralight scalar particles often found in theories beyond the Standard Model

• E.g. the QCD axion solves the `strong-CP’ problem

• As already discussed, ultralight scalars can make up the DM
Black holes in our universe provide nature’s laboratories to search for light particles.

Set a typical length scale, and are a huge source of energy.

Sensitive to QCD axions with GUT-to Planck-scale decay constants $f_a$.

for a $10^{-12}$ eV particle:

Frequency $\pi$ kHz $^{-1}$

Compton wavelength $10^3$ km

black hole (30 M☉)
Superradiance: gaining from dissipation

• A an object scattering off a rotating cylinder can increase in angular momentum and energy.

• Effect depends on dissipation, necessary to change the velocity.

Ball incident on cylinder with lossy surface slows down due to friction
Superradiance: gaining from dissipation

- A an object scattering off a rotating cylinder can increase in angular momentum and energy.
- Effect depends on dissipation, necessary to change the velocity.

If the cylinder is rotating at angular velocity equal to the angular velocity of the ball about the axis, $\Omega_i = v_{\phi,i}$, the relative velocity at the point of contact is zero: no energy loss.
Superradiance: gaining from dissipation

- A an object scattering off a rotating cylinder can increase in angular momentum and energy.
- Effect depends on dissipation, necessary to change the velocity.

If the cylinder is rotating even faster, \( \Omega_i > u_{\phi,i} \)

Ball scattering off rapidly rotating cylinder with lossy surface speeds up!

Energy increase comes from cylinder slowing down, losing energy and angular momentum.
Superradiance: gaining from dissipation

- Scalar perturbations scattering off of rotating cylindrical medium with absorption

\[ \Phi = \phi(r)e^{-i\omega t + im\varphi} \]

The amplitude of the field will increase for

\[ u_{\varphi,i} < \Omega_i \rightarrow \frac{\omega}{m} < \Omega \]

superradiance condition
Superradiance: gaining from dissipation

• A wave scattering off a rotating object can increase in amplitude by extracting angular momentum and energy.

• Growth proportional to probability of absorption when rotating object is at rest: **dissipation** necessary to increase wave amplitude.

Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

\[ \Omega_a < \Omega_{BH} \]

Zel'dovich; Starobinskii; Misner
• A wave scattering off a rotating object can increase in amplitude by extracting angular momentum and energy.

• Growth proportional to probability of absorption when rotating object is at rest: dissipation necessary to change the wave amplitude.

Angular velocity of wave slower than angular velocity of BH horizon, \( \omega < \omega_{BH} \).

Superradiance condition: Zel’dovich; Starobinskii; Misner

Gravitational wave amplified when scattering from a rapidly rotating black hole.

Numerical GR simulation by Will East
Superradiance condition for Black Holes

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

What is the `angular velocity’ of the BH horizon?
Kerr Metric

\[ ds^2 = - \left(1 - \frac{2r_gr}{\Sigma}\right) dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2r_gr a^2}{\Sigma} \sin^2 \theta\right) \sin^2 \theta d\phi^2 - \frac{4r_gr a}{\Sigma} \sin^2 \theta dt d\phi \]

\[ r_g \equiv GM, \quad a \equiv \frac{J}{M} \equiv a_* r_g, \quad \Sigma = r^2 + a^2 \cos^2 \theta, \quad \Delta = r^2 - 2r_gr + a^2 \]
Kerr Metric

\[ ds^2 = - \left( 1 - \frac{2r_g}{\Sigma} \right) dt^2 - \frac{\Sigma \Delta}{\Delta} dr^2 + \Sigma d\theta^2 - \left( r^2 + a^2 + \frac{2r_g a^2}{\Sigma} \sin^2 \theta \right) \sin^2 \theta d\phi^2 - \frac{4r_g a}{\Sigma} \sin^2 \theta dt d\phi \]

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**Horizon: coordinate singularity:** the purely radial component \(g_{rr}\) of the metric goes to infinity

\[r_{\text{H}}^\perp = 1 \pm \sqrt{1 - a^2}\]

\[r_{\text{H}}^\text{inner} = 1 \pm \sqrt{1 - a^2}\]

Symmetry axis \(\theta = 0, \pi\)
Kerr Metric

\[ ds^2 = -\left(1 - \frac{2r_g r}{\Sigma}\right) dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2r_g r a^2}{\Sigma} \sin^2 \theta\right) \sin^2 \theta d\phi^2 - \frac{4r_g r a}{\Sigma} \sin^2 \theta dt d\phi \]

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Ergoregion: purely temporal component \( g_{t\phi} \) of the metric changes sign

Outer ergosurface
\[ r_E^\pm = 1 \pm \sqrt{1 - a^2 \cos^2 (\theta)} \]

Inner ergosurface
\[ r_E^\pm = 1 \pm \sqrt{1 - a^2 \cos^2 (\theta)} \]
Kerr Metric

\[ ds^2 = - \left(1 - \frac{2r_g r}{\Sigma}\right) dt^2 + \frac{\Delta}{\Sigma} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2r_g r a^2}{\Sigma} \sin^2 \theta\right) \sin^2 \theta d\phi^2 - \frac{4r_g r a}{\Sigma} \sin^2 \theta dt d\phi \]

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Ergoregion: purely temporal component \( g_{tt} \) of the metric changes sign

Surface beyond which there are no stationary observers
Superradiance condition for Black Holes

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

What is the `angular velocity’ of the BH horizon?

`Blackboard’
Superradiance condition for Black Holes

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

For a scalar field mode with energy \(\omega\) and angular momentum \(m\),

$$\Phi = \phi(r)e^{-i\omega t + im\varphi}$$
Superradiance condition for Black Holes

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

For a scalar field mode with energy $\omega$ and angular momentum $m$,

$$\Phi = \phi(r)e^{-i\omega t + im\varphi}$$

And a Kerr black hole,

$$\frac{\omega}{m} < \frac{1}{2r_g} \frac{a_\star}{1 + \sqrt{1 - a_\star^2}}$$
Superradiance condition for Black Holes

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

For a scalar field mode with energy $\omega$ and angular momentum $m$,

$$\Phi = \phi(r)e^{-i\omega t+im\varphi}$$

And a Kerr black hole,

$$\frac{\omega}{m} < \frac{1}{2rg} \frac{a_*}{1 + \sqrt{1 - a_*^2}}$$

For a nonrelativistic field with mass $\mu$ and angular momentum $m$, the SR condition is

$$\frac{\mu rg}{m} < \frac{1}{2} \frac{a_*}{1 + \sqrt{1 - a_*^2}} < \frac{1}{2}$$
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Superradiance

Particles/waves trapped in orbit around the BH repeat this process continuously.

“Black hole bomb” exponential instability when surround BH by a mirror

Kinematic, not resonant condition

Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

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Superradiance

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Angular velocity of wave slower than angular velocity of BH horizon,

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Superradiance

- Particles/waves trapped near the BH repeat this process continuously.

- For a massive particle, e.g. axion, gravitational potential barrier provides trapping

\[ V(r) = -\frac{G_N M_{BH} \mu_a}{r} \]

- For high superradiance rates, **compton wavelength** should be comparable to **black hole radius**:

\[ r_g \lesssim \mu_a^{-1} \sim 3 \text{ km} \frac{6 \times 10^{-11} \text{ eV}}{\mu_a} \]

[Zouros & Eardley’79; Damour et al ’76; Detweiler’80; Gaina et al ’78]
[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010]
Gravitational Atoms?

Axion Gravitational Atoms

\[ V(r) = -\frac{G_NM_{BH}\mu_a}{r} \]

\[ n = 1, \ell = 0, m = 0 \quad n = 2, \ell = 1, m = 1 \quad n = 3, \ell = 2, m = 2 \]

\[ ds^2 = -\left(1 - \frac{2r_o}{\Sigma}\right)dt^2 - \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 - \left(r^2 + \rho^2 + \frac{2r_o r}{\Sigma} \sin^2 \theta \right) \sin^2 \theta d\phi^2 - \frac{4r_o r}{\Sigma} \sin^2 \theta dt d\phi \]

\[ (D^2 - \mu^2)\varphi = 0 \]

\[ \left(\frac{\partial^2}{\partial t^2} - \nabla^2 + \mu^2 - \frac{2GM\mu^2}{r}\right) \varphi = 0. \]
Gravitational Atoms?

Axion
Gravitational Atoms

\[ V(r) = -\frac{G_N M_{BH} \mu_a}{r} \]

\begin{align*}
n &= 1, \ell = 0, m = 0 \\
n &= 2, \ell = 1, m = 1 \\
n &= 3, \ell = 2, m = 2
\end{align*}

\[ ds^2 = -\left(1 - \frac{2r_{eq}}{\Sigma}\right) dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 - \left(r^2 + \delta^2 + \frac{2r_{eq} \rho}{\Sigma} \sin^2 \theta \right) \sin^2 \theta d\phi^2 - \frac{4r_{eq} \rho}{\Sigma} \sin^2 \theta dt d\phi \]

\[ (D^2 - \mu^2) \varphi = 0 \]

\[ \left( \frac{\partial^2}{\partial t^2} - \nabla^2 + \mu^2 - \frac{2GM\mu^2}{r} \right) \varphi = 0 \]

\[ \varphi = \frac{1}{\sqrt{2\mu}} (\psi e^{-i\mu t} + \text{c.c}) \]

\[ i\hbar \frac{\partial}{\partial t} \Psi(r, t) = \left[ -\frac{\hbar^2}{2\mu} \nabla^2 + V(r, t) \right] \Psi(r, t) \]
Gravitational Atoms

Axion
Gravitational Atoms

\[ V(r) = - \frac{G_N M_{BH} \mu_a}{r} \]

\( n = 1, \ell = 0, m = 0 \quad n = 2, \ell = 1, m = 1 \quad n = 3, \ell = 2, m = 2 \)

Gravitational potential similar to hydrogen atom

`Fine structure constant`\

\[ \alpha \equiv G_N M_{BH} \mu_a \equiv r_g \mu_a \]

Constraint on \( \alpha \) from SR condition:

\[ \frac{\alpha}{m} < \frac{1}{2} \left( 1 + \frac{a_*}{\sqrt{1 - a_*}} \right) < \frac{1}{2} \]
Gravitational Atoms

\[ V(r) = -\frac{G_N M_{BH} \mu_a}{r} \]

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`Fine structure constant`

\[ \alpha \equiv G_N M_{BH} \mu_a \equiv r_g \mu_a \]

Radius

\[ r_c \approx \frac{n^2}{\alpha \mu_a} \sim 4 - 400r_g \]

Occupation number

\[ N \sim 10^{75} - 10^{80} \]
Gravitational potential similar to hydrogen atom

\[ V(r) = -\frac{G_N M_{BH} \mu_a}{r} \]

<table>
<thead>
<tr>
<th>(n)</th>
<th>(\ell)</th>
<th>(m)</th>
<th>(r_c)</th>
<th>(N)</th>
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<tr>
<td>1</td>
<td>0</td>
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<td>(\frac{n^2}{\alpha \mu_a}) (\sim 4 - 400r_g)</td>
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<td>2</td>
<td>1</td>
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`Fine structure constant`

\[ \alpha \equiv G_N M_{BH} \mu_a \equiv r_g \mu_a \]

Boundary conditions at horizon give imaginary frequency: exponential growth for rapidly rotating black holes

\[ E \approx \mu \left(1 - \frac{\alpha^2}{2n^2}\right) + i\Gamma_{sr} \]
## Superradiance Timescales

\[ \alpha = G_N M_{BH} \mu_a = r_g \mu_a \lesssim \frac{m}{2} a^* \]

<table>
<thead>
<tr>
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Superradiance Timescales

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Flux into horizon: \(\Gamma_{sr}^{\text{scalar}} \sim \int_{r=r_g} \psi^* \psi \cdot dA\)
Superradiance: a stellar black hole history

A black hole is born with spin $a^* = 0.95$, $M = 40 \, M_\odot$.

- BH rotates quickly enough to superradiate
- BH light crossing time: $0.2 \, \text{msec (60 km)}$
- Particle wavelength: $1 \, \text{msec (300 km)}$
- $\mu_a = 6 \times 10^{-13} \, \text{eV}$
Superradiance: a stellar black hole history

BH spins down and fastest-growing level is formed

Once BH angular velocity matches that of the level, growth stops

Cloud radius
6 msec (2000 km)

BH lightcrossing time
0.2 msec (60 km)

Particle wavelength
1 msec (300 km)

\( \mu_a = 6 \times 10^{-13} \text{eV} \)

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Superradiance: a stellar black hole history

Cloud can carry up to a few percent of the black hole mass: huge energy density

- Black hole angular momentum decreases by $10^{78} \hbar$
- no longer satisfies $l=1$ SR condition
- $\mu_a = 6 \times 10^{-13} \text{eV}$
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• If there is a light axion (scalar/vector) with compton wavelength comparable to astrophysical BH sizes, it will cause astrophysical black holes to spin down

• The resulting bound states of light particles will source gravitational wave radiation that is observable by LIGO
Black Hole Spins

Five currently measured black holes combine to set limit:

$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$$

1: M33 X–7
2: LMC X–1
3: GRO J1655–40
4: Cyg X–1
5: GRS 1915+105
Many BH-BH mergers detected

Each detection comes with a measurement of the initial black hole masses, and, to a lesser extent, spins.
Black Hole Spins
at LIGO

9-240 BBHs/Gpc$^3$/yr.: 1000s of BHs merging in low-redshift universe
Black Hole Spins at LIGO

If light axion exists, many initial BHs would have low spin due to superradiance, limited by age and radius of binary system.

\[ m_a = 6 \times 10^{-13} \text{ eV} \] (actual)

\[ \ell = 1, 2, 3 \]

10 billion years

Black Hole Mass ($M_\odot$)

Black Hole Spin $a_*$
Gravitational Wave Signals

- Transitions between levels
- Annihilations to gravitons
- Signals coherent, monochromatic, last hours to millions of years
Superradiance: a stellar black hole history

- BH spins down: next level formed; annihilations to GWs deplete first level
- Next level has a superradiance rate exceeding age of BH

\[ \mu_a = 6 \times 10^{-13} \text{eV} \]

\[ f_a \sim 10^{19} \text{GeV} \]

\[ \ell = 1 \]

\[ \ell = 2 \]

\[ \text{Number of axions} \]

```
\begin{align*}
N_{211} & \sim 10^{77} \\
N_{322} & \sim 10^{73}
\end{align*}
```

\[ t (\text{yr}) \]

\[ a_* \]

\[ t (\text{yr}) \]
Gravitational Wave Signals

• Gravitational wave strain emitted from a time-varying energy density

\[ h_{ij} = \frac{2G}{r} \frac{d^2 I_{ij}}{dt^2}, \quad I_{ij} = \int T_{00} x^i x^j d^3x \]
Gravitational Wave Signals

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- We have a field described by

\[ \phi = \frac{1}{\sqrt{2\mu}} \sum_i \sqrt{N_i} \left( \psi_i e^{-i\omega t} + \psi_i^* e^{i\omega t} \right) \]
Gravitational Wave Signals

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• With stress-energy components of the form

\[ T_{\mu\nu} \supset \mu^2 \phi^2 + \ldots = \frac{1}{2\mu} \sum_{ij} \sqrt{N_i N_j} \left( \psi^i \psi^j e^{-i(\omega_i+\omega_j)t} + \psi^i \psi^j* e^{-i(\omega_i-\omega_j)t} + \text{h.c.} \right) + \ldots , \]
Gravitational Wave Signals

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Blackboard estimate for annihilations
## Superradiance Timescales

\[ \alpha = G_N M_{BH} \mu_a = r_g \mu_a \lesssim \frac{m}{2} a_* \]

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<td>( \tau_{ann} \propto \frac{1}{\alpha^{4 \ell + 11}} r_g )</td>
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**Gravitational Wave Power:**

\[ P_{GW} \sim G_N \omega^2 \overline{T}_{ij}(\omega, k) \overline{T}^*_{ij}(\omega, k) \]
Superradiance: gravitational wave emission

Cloud of axions sources coherent, monochromatic gravitational waves

Gravitational wave frequency is set by twice the axion energy

Emission can be observed in LIGO continuous wave searches

Cloud of axions sources coherent, monochromatic gravitational waves

\[ \mu_a = 6 \times 10^{-13} \text{eV} \]

annihilation signal lasts 3000 years

no longer satisfies \( l=1 \) SR condition

\( \sim 1 \text{ year} \)
Gravitational Wave Signals

Time-varying energy density sources gravitational waves:
  two bosons annihilating into gravitational waves
  • coherent and monochromatic:
  • fit into searches for long, continuous, monochromatic gravitational waves ("mountains" on neutron stars)

Numerical GR simulation by Will East
• **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy

• Event rates up to 10,000 — can be observed and studied in detail

  Arvanitaki, MB, Huang (2015)
  Arvanitaki, MB, Dimopoulos, Dubovsky, Lasenby (2017)
  Brito et al (2017)
Gravitational Wave Signals

- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to 10,000 — can be observed and studied in detail

- **Loud, short signals** last for ~ days - months, observable from BBH or NS-NS merger events
  - Event rates <1/year at design aLIGO sensitivity, up to 100's at future observatories

Arvanitaki, MB, Dimopoulos, Dubovsky, Lasenby (2017)
Isi, Sun, Brito, Melatos (2019)
Gravitational Wave Signals

- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to 10,000 — can be observed and studied in detail
    - Arvanitaki, MB, Dimopoulos, Dubovsky, Lasenby (2017)
    - Isi, Sun, Brito, Melatos (2019)
    - Zhu, MB, Papa, Tsuna, Kawanaka, Eggenstein (2020)

- **Loud, short signals** last for ~ days - months, observable from BBH or NS-NS merger events
  - Event rates <1/year at design aLIGO sensitivity, up to 100's at future observatories
    - Arvanitaki, MB, Dimopoulos, Dubovsky, Lasenby (2017)
    - Isi, Sun, Brito, Melatos (2019)
Gravitational Wave Searches

• Current searches for gravitational waves from asymmetric rotating neutron stars ongoing
• Targeted as well as all-sky searches, reaching to very weak signals with large computational efforts

Abbott et al PRD 96, 122004 (2017)
Gravitational Wave Signals

- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- See also papers by Brito et al on stochastic searches for these signals when many signals are present

- Weak, long signals last for ~ million years, visible from our galaxy
- Very sensitive to number of rapidly rotating black holes
- Weak dependence on mass distribution except at low axion masses

- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- See also papers by Brito et al on stochastic searches for these signals when many signals are present
If ultralight axions (bosons) exist, black holes spin down.

Measurement of high spin black holes places exclusion limits; LIGO will provide more data points.

Axion clouds produce monochromatic wave radiation; we are looking for these signals in LIGO data.
GRavitational Waves: From Detection to New Physics Searches

- Detection at LIGO and physics of LIGO
- Pulsar timing for GWs and ultralight scalar DM
- Axion clouds around black holes and GWs

Potentially new discoveries await!