September 14, 2015
Properties of GW150914

Effective inspiral spin parameter $\chi_{\text{eff}}$:
- $-0.09^{+0.19}_{-0.17}$
- $-0.03^{+0.14}_{-0.15}$
- $-0.06^{+0.17}_{-0.18}$

Dimensionless primary spin magnitude $a_1$:
- $0.32^{+0.45}_{-0.28}$
- $0.31^{+0.51}_{-0.27}$
- $0.31^{+0.48}_{-0.28}$

Dimensionless secondary spin magnitude $a_2$:
- $0.57^{+0.40}_{-0.51}$
- $0.39^{+0.50}_{-0.34}$
- $0.46^{+0.48}_{-0.42}$

Final spin $a_f$:
- $0.67^{+0.06}_{-0.08}$
- $0.67^{+0.05}_{-0.05}$
- $0.67^{+0.06}_{-0.07}$

Taken from 1602.03840
New Era

- New telescope

- The violent Universe
  - Black Hole mergers, phase transitions, inflation

- New precision science
  - ~one merger per day — a lot of data per merger

- BSM physics?

New spectroscopy
Black Holes as Nature’s Detectors

(15 km) x (M / 10 M☉)

Range of astrophysical Black Holes:
- few M☉ to 10¹⁰ M☉
- Sensitive to boson masses 10⁻²⁰-10⁻¹⁰ eV

Focus on stellar black holes
Why is this interesting?

- The Strong CP problem and the QCD axion

\[ \mu_a \sim 6 \times 10^{-11} \text{ eV} \frac{10^{17} \text{ GeV}}{f_a} \sim (3 \text{ km})^{-1} \frac{10^{17} \text{ GeV}}{f_a} \]

- The String Axiverse

Arvanitaki, SD, Dubovsky, Kaloper, March-Russell (2009)

- Superradiance probes any boson in the right mass range
Black Holes and The QCD Axion at Advanced LIGO

Savas Dimopoulos
Stanford University

with
Arvanitaki, Dubovsky, Kaloper, March-Russell (2009)
Baryakhtar, Lasenby, Arvanitaki, Dubovsky (2016)

also based on
Arvanitaki, Dubovsky (2010)
Arvanitaki, Baryakhtar, X. Huang (2014)
Super-Radiance Cartoon

Super-radiant scattering of a massive object
Super-Radiance Cartoon

Super-radiant scattering of a massive object
Super-Radiance Cartoon

Super-radiant scattering of a wave
Super-Radiance Cartoon

Super-radiant scattering of a wave
Black Hole Superradiance

Penrose Process

Ergoregion: Region where even light has to be rotating
Black Hole Superradiance

Penrose Process

Extracts angular momentum and mass from a spinning black hole
Black Hole Bomb

Press & Teukolsky 1972

Photons reflected back and forth from the black hole and through the ergoregion
Black Hole Bomb

Press & Teukolsky 1972

Photons reflected back and forth from the black hole and through the ergoregion
Superradiance for a massive boson

Particle Compton Wavelength comparable to the size of the Black Hole

Damour et al; Zouros & Eardley; Detweiler; Gaina (Early 70s)
Superradiance for a massive boson

Particle Compton Wavelength comparable to the size of the Black Hole

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Gravitational Atom in the Sky

The gravitational Hydrogen Atom

Fine-structure constant:
\[ \alpha = G_N M_{BH} \mu_a = R_g \mu_a \]

Principal (n), orbital (l), and magnetic (m) quantum number for each level

Binding energy:
\[ E_{binding} = -\frac{\alpha^2 \mu_a}{2n^2} \]

Main differences from hydrogen atom:

Levels occupied by bosons - occupation number \(>10^{77}\)

In-going Boundary Condition at Horizon
Key Points About Superradiance

- For light axions (weak coupling) equation identical to Hydrogen atom

- Boundary conditions different:
  - Regular at the origin $\rightarrow$ Ingoing (BH is absorber)
  - Hermitian $\rightarrow$ Non-hermitian
Superradiance Parametrics

Superradiance Condition

\[ \omega_{\text{axion}} < m \Omega_+ \]

\( m \) : magnetic quantum number

\( \Omega_+ \) : angular velocity of the BH

Universal Phenomenon:

Superluminal rotational motion of a conducting cylinder

Superluminal linear motion - Cherenkov radiation

\[ \frac{1}{n(\omega)} < v \]

Condition can be extracted from requiring that \( dA_{\text{BH}} > 0 \)
Superradiance Parametrics

Superradiance Rate

\[ \tau_{sr} \approx 0.6 \times 10^7 R_g \text{ for } R_g \mu_a \approx 0.4 \]

As short as 100 sec vs \( \tau_{\text{accretion}} \approx 10^8 \) years

When \( R_g \mu_a \gg 1 \),

\[ \tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g \]

When \( R_g \mu_a \ll 1 \)

\[ \tau_{sr} = \left( \frac{24}{a} \right) (\mu_a R_g)^{-9} R_g \]
Evolution of Superradiance for an Axion

Superradiance instability

Self interactions
Evolution of Superradiance for an Axion

Superradiance instability

Self interactions

Gravity wave transitions of axions between levels
Evolution of Superradiance for an Axion

Superradiance instability

Self interactions

Gravity wave transitions of axions between levels

Gravity wave emission through axion annihilations
Superradiance Evolution

\[ \mu_a = 10^{-11} \text{ eV} \]
Superradiance Evolution

$\mu_a = 10^{-11}$ eV

Black Hole Spin $a_*$

Black Hole Mass ($M_\odot$)

$l = 1$ SR region

$l = 2$ SR region

$l = 3$ SR region

$l = 4$ SR region

$\sim 1.7$ years
Superradiance Evolution

![Graph showing superradiance evolution with axes for Black Hole Spin (a*) and Black Hole Mass (M_☉). Curves labeled l = 1 SR region, l = 2 SR region, l = 3 SR region, and l = 4 SR region. The graph indicates \( \mu_a = 10^{-11} \text{ eV} \). There is a note that remains for ~10^6 years and a note that ~1.7 years.](image-url)
Superradiance Evolution

\[ \mu_a = 10^{-11} \text{ eV} \]
Spin-Down of Astrophysical Black Holes

Range of the QCD axion excluded by current measurements

$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$
Black Hole Spins at aLIGO

BH distribution without an axion

Initial Spin (actual)
Black Hole Spins at aLIGO

BH distribution with an axion

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

(actual)
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Dimensionless primary spin magnitude $a_1$
- $0.32^{+0.45}_{-0.28}$
- $0.31^{+0.51}_{-0.27}$
- $0.31^{+0.48}_{-0.28\pm0.01}$

Dimensionless secondary spin magnitude $a_2$
- $0.57^{+0.40}_{-0.51}$
- $0.39^{+0.50}_{-0.34}$
- $0.46^{+0.48}_{-0.42\pm0.01}$

Final spin $\alpha_f$
- $0.67^{+0.06}_{-0.08}$
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- $0.67^{+0.06}_{-0.07\pm0.03}$

Taken from 1602.03840
Black Hole Spins at aLIGO

\[ \frac{\sigma_M}{M} \sim 0.1; \quad \sigma_{a*} \sim 0.25 \]

BH distribution with an axion including errors

\[ \mu_8 = 6 \times 10^{-13} \text{ eV} \]
(measured)
Super-Radiance Signatures
GW annihilations

- Signal enhanced by the square of the occupation number of the state

\[ h_{\text{peak}} \approx 10^{-22} \left( \frac{1 \text{ kpc}}{r} \right) \left( \frac{\alpha/\ell}{0.5} \right)^{3/2} \frac{\alpha^{-1/2}}{\ell} \left( \frac{M}{10M_\odot} \right) \]

- Signal duration determined by the annihilation rate (can last thousands of years)

\[ f = 10 \text{ kHz} \times \left( \frac{\mu_a}{10^{-11} \text{ eV}} \right) \]

E_{\text{graviton}} \approx 2 \, m_{\text{axion}} \quad \text{High frequency GWs}
Expected Events from Annihilations

- Large uncertainties coming from tails of BH mass distribution

Pessimistic: flat spin distribution and 0.1 BH/century

Realistic: 30% above spin of 0.8 and 0.4 BH/century

Optimistic: 90% above spin of 0.9 and 0.9 BH/century
Super-Radiance Signatures

GW transitions

\[ f \sim 15 \text{Hz} \times (\mu_\text{a}/10^{-11} \text{eV}) \]

Optimal frequency for LIGO

- Signal enhanced by the occupation numbers of excited and ground states

- Signal strength determined by the occupation number of the excited state
  \[ h \sim 3 \times 10^{-25} \text{ for a BH 10 kpc away} \]

- Signal duration determined by the superradiance rate (1-100 years duration)
Transition Events Estimates

- Lower number of observable sources due to signal duration

![Graph showing expected events for different gamma-ray burst scenarios.](image-url)
Real-Time Superradiance

Black Holes produced from mergers are point sources candidates
Superradiance Prospects

- Probes axions between $10^{-20}$ and $10^{-10}$ eV independent of DM abundance

- Spin-mass distribution measured from mergers may reveal the presence of an axion

- Blind searches at aLIGO for annihilations most promising for lighter axions

- Merger events allow to follow SR in real time
Just The Beginning
Super Radiance Effect: Increased Progress Towards International Peace

THROUGH GROUP PRACTICE OF THE TRANSCENDENTAL MEDITATION AND TM-SIDHI PROGRAM

![Graph showing Peace/War Index (standard scores) for different countries and periods, with arrows indicating an increase. The graph includes Israel, Utopia Assembly, Fairfield, Iowa, USA, Lebanon, Yugoslavia, Fairfield, Netherlands, and Washington D.C., USA. The p-value is less than 10^-19.](image-url)