Accessing the axion via compact object binaries

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Growing Black Holes: Accretion and Mergers
Kathmandu, Nepal May 16, 2022.

Based on: JCAP 08 (2020) 005 (arXiv:1910.06977) with
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MK, ML & JS supported by the National Science Foundation grants:
AST-2011731,PHY-2000398, AST-2011757

Outline

Axions

Rotational Black Hole Superradiance

The Binary Pulsar – and example of observational precision

The effect of mass loss in compact object binaries

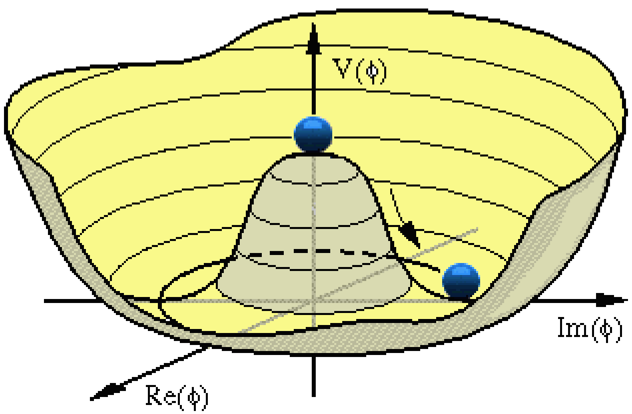
Summary

Axions

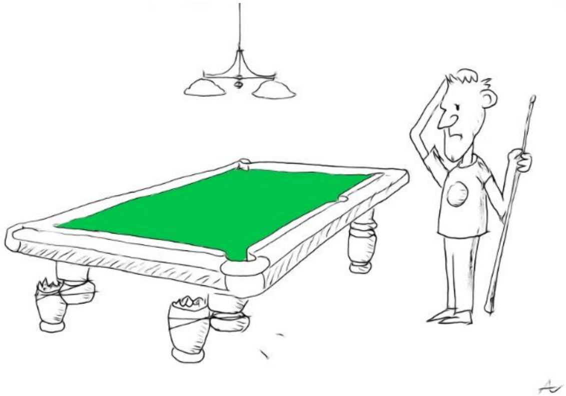
Proposed in the context of the Peccei-Quinn mechanism to solve the Strong CP problem in QCD.

$$\mathcal{L} \sim \theta \tilde{F}^{\mu\nu} F_{\mu\nu} \equiv \theta \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} F_{\mu\nu}$$

$$\theta \lesssim 10^{-10}$$



R. D. Peccei and Helen R. Quinn
Phys. Rev. Lett. **38**, 1440



Sikivie
Physics Today, Dec. 1996

The String Axiverse

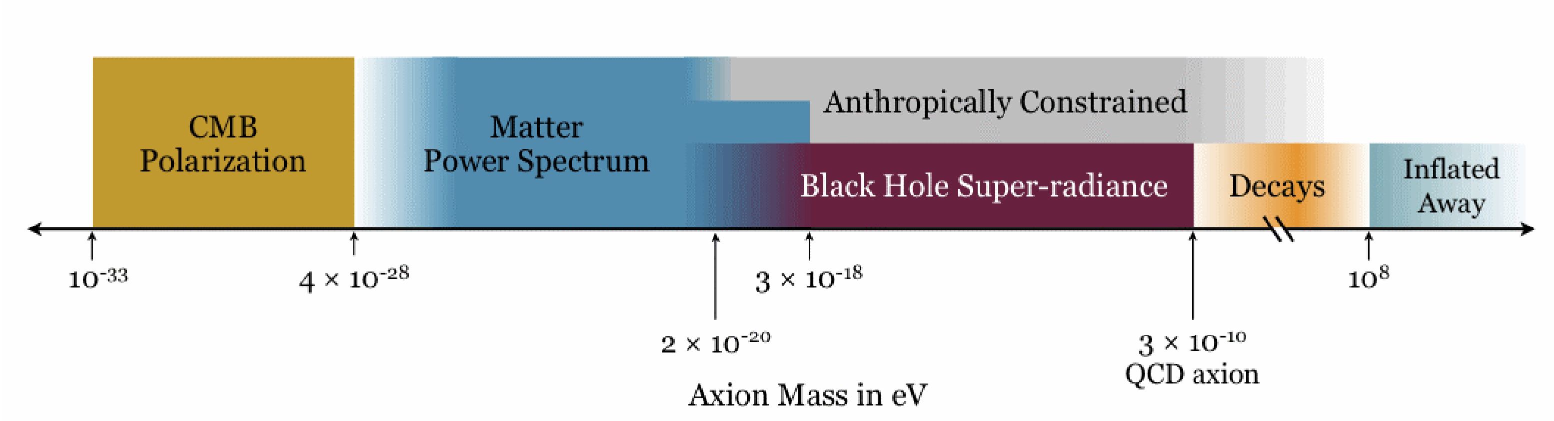
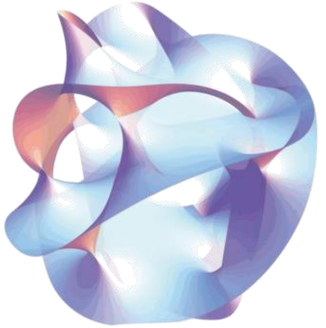


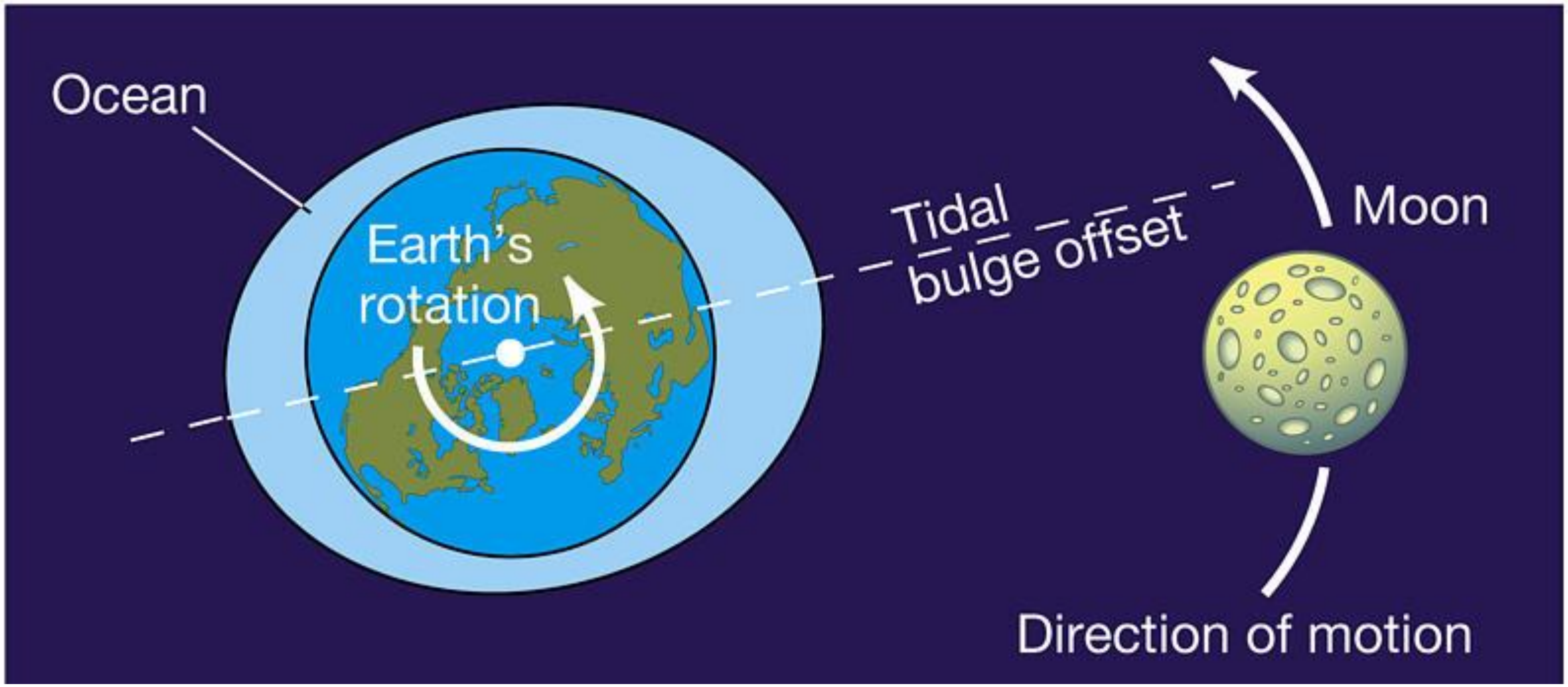
Figure: Arvanitaki et al

String theory predicts a spectrum of light axions that span many orders of magnitude in mass.



Arvanitaki et al: arXiv:0905.4720

Tidal Acceleration



$$\Omega_{\mathrm{Earth}} > \Omega$$

Tidal acceleration is a phenomena with deep connections to rotational superradiance.

Cardoso and Pani: arXiv:1205.3184

The Penrose Process

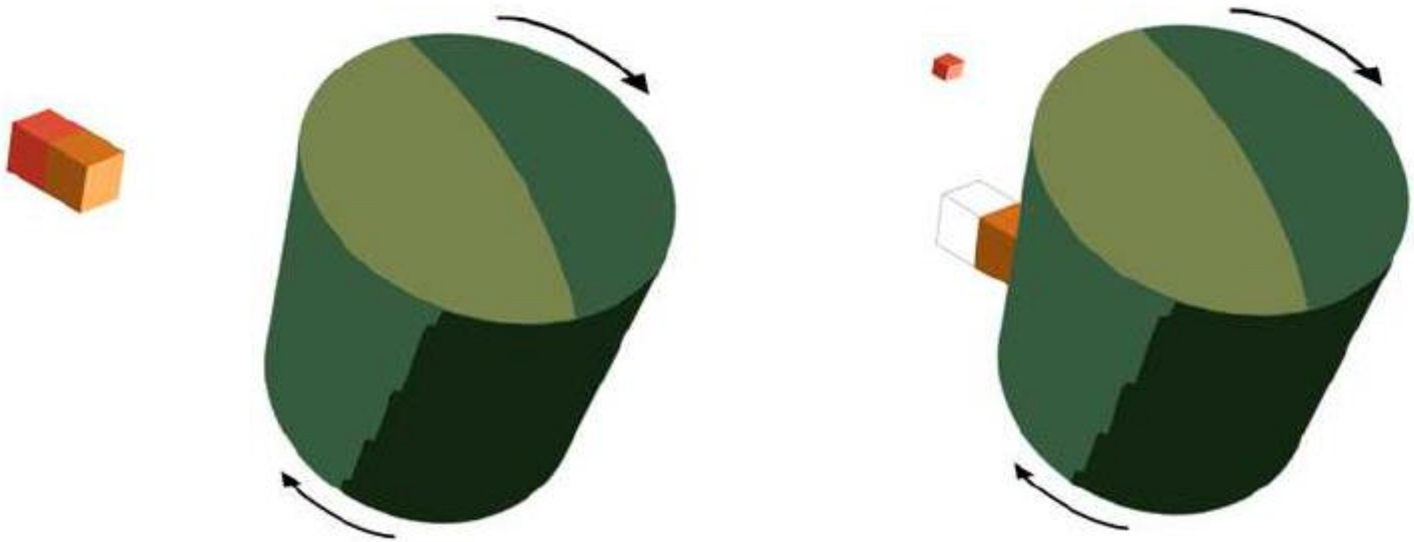
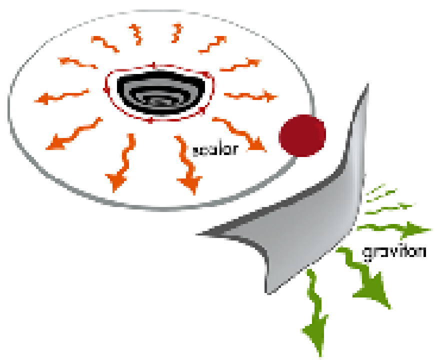


Figure: Cardoso and Pani

The Penrose Process demonstrates how energy may be extracted from a Kerr black hole by an object entering the ergosphere and breaking into two pieces. Frame dragging near the rotating black hole is central to this process.

Black Hole Superradiance



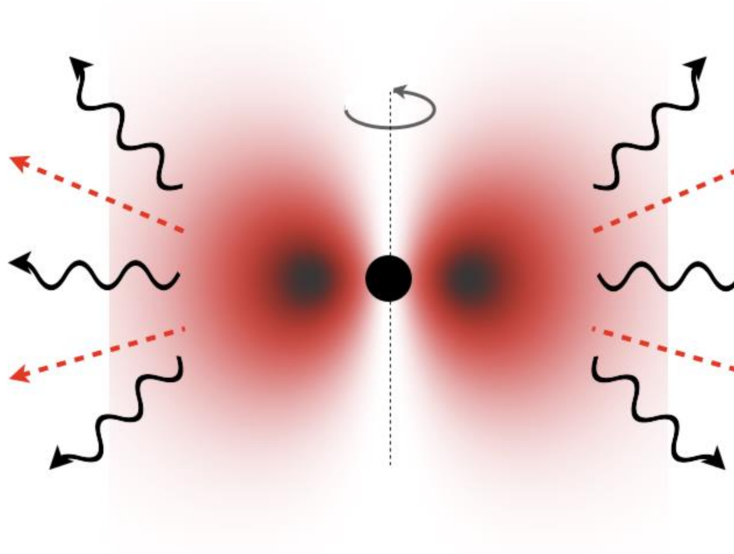


Figure: Cardoso and Pani

$$\alpha \equiv \frac{GM_{BH}}{c^2} / \frac{\hbar}{\mu c} \approx 0.02 \left(\frac{M_{BH}}{3M_\odot}\right)\left(\frac{\mu}{10^{-12}\ \mathrm{eV}}\right)$$

$$0.005\left(\frac{M_{BH}}{3M_\odot}\right) \leq \alpha \leq 0.5$$

$$\frac{dE_{GW}}{dt} \approx 0.01\,\frac{c^5}{G}\left(\frac{M_c(\alpha)}{M_{BH}}\right)^2 \alpha^{14}$$

$$\frac{\omega}{m} < \Omega_{\mathrm{H}} = \frac{a}{2Mr_+}$$

Baumann et al: arXiv:1804.03208

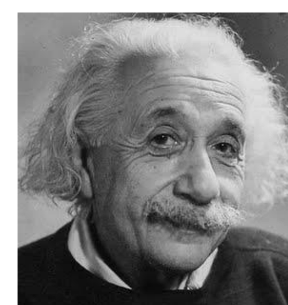
The “Binary Pulsar”
PSR B1913+16 (J1950+1606)

Discovered 1974
Nobel Prize 1993

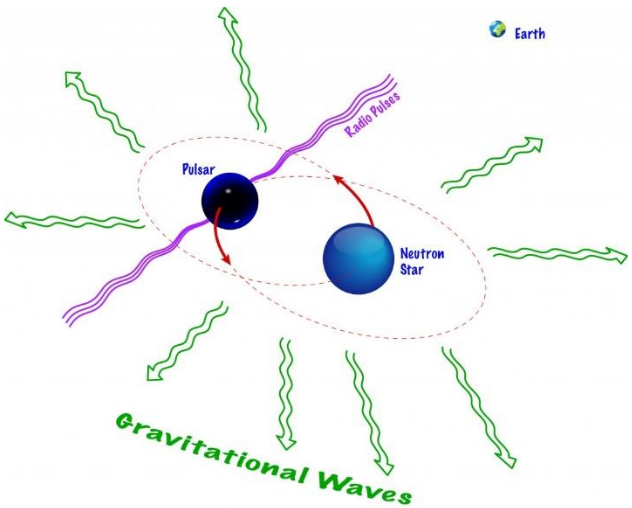
Russell Hulse

Joseph Taylor

Arecibo Observatory



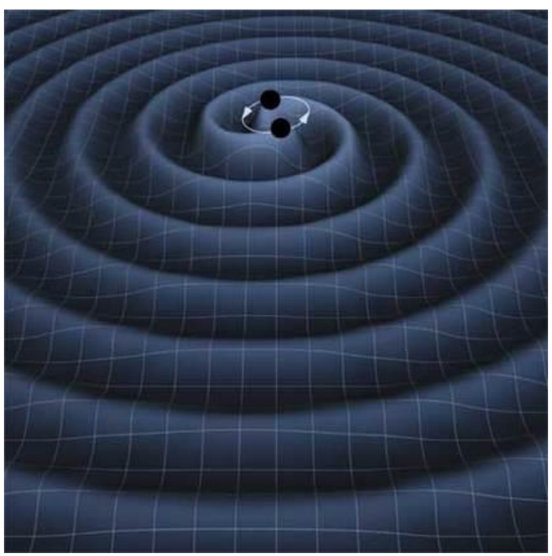
The Binary Pulsar: Test Bed for General Relativity

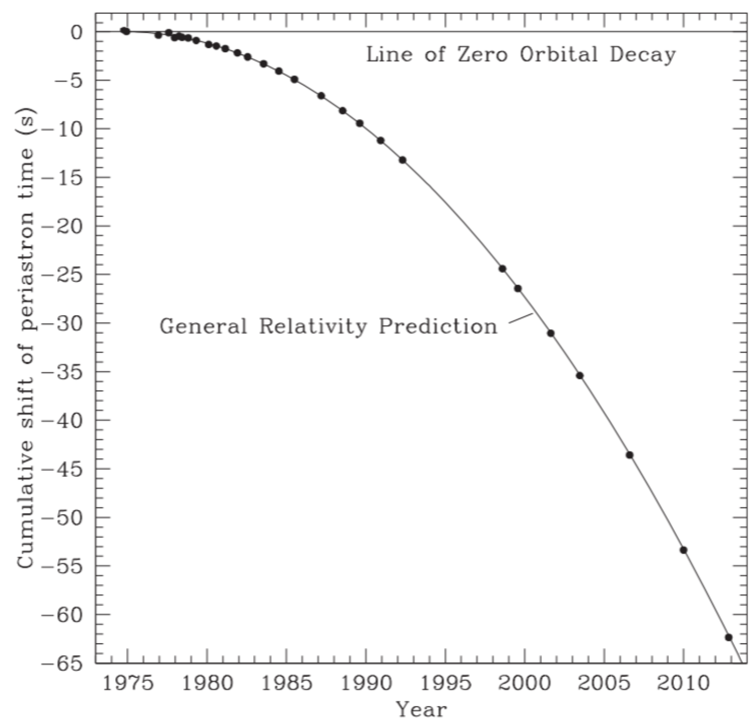


A "clean, simple system" --- what physicists love!

Precision orbital measurements using an accurate, orbiting clock.

Gravitational Radiation! Weisberg and Taylor





$L_{GW} = 7.35 \times 10^{24}$ W

https://writescience.wordpress.com/2015/05/13/gravity-12-listening-for-the-whispers-of-gravity/
Weisberg, Huang, ApJ, 829, 2016

The Binary Pulsar: Test Bed for General Relativity

Precision orbital measurements using an accurate, orbiting clock.

Parameter	Value
T_0 (MJD)	52144.90097849(3)
Pulse frequency (s^{-1})	$16.940537785677(3)$ (pulse period ≈ 0.06 s)
$a_p \sin i$ (s)	$2.341776(2)$
e	$0.6171340(4)$
P_b (days)	$0.322997448918(3)$ (≈ 7.75 h)
$\dot{P}_b$ (s/s)	$-2.423(1) \times 10^{-12}$
$\dot{\omega}$ (°/year)	$4.226585(4)$
γ (ms) Einstein Delay	$4.307(4)$
m_p ($M_\odot$)	$1.438(1)$
m_c ($M_\odot$)	$1.390(1)$

10^{-3} fractional error

10^{-6} fractional error

Weisberg, Huang, ApJ, 829, 2016

There are two possible observational effects of this process of spin/mass loss:

a) Measure the loss of angular momentum directly by measuring the change in the spin rate of the BH.

Measure change in spin of the BH

b) Measure the mass loss rate by measuring the change in orbital period.

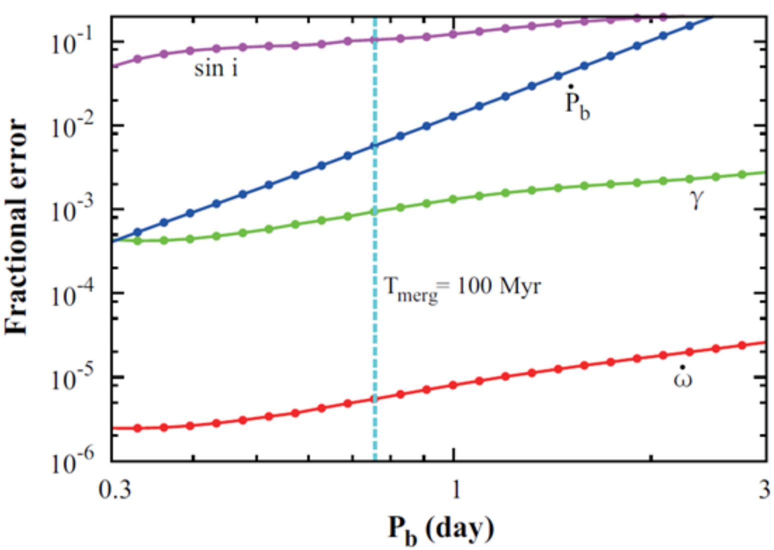
Measure $\dot{P}_b$

Turns out (b) is easier with better precision.

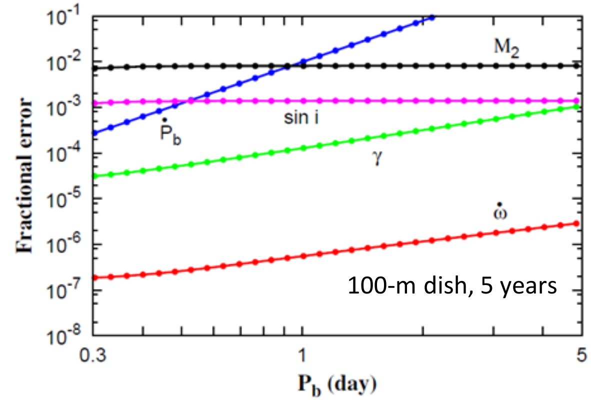
Precision on Solar-Mass BH-Pulsar system measurements
Liu et al., 2014

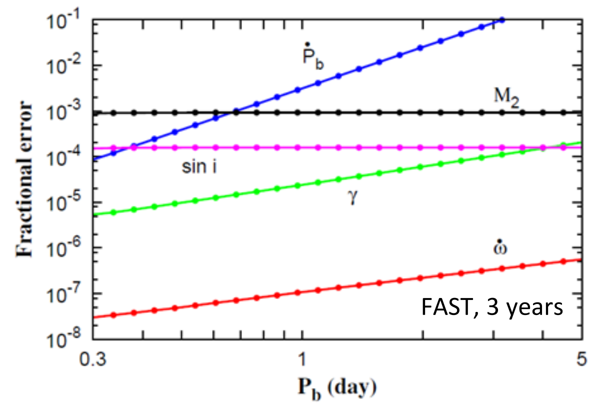
Mock data simulations
- Pulse generation TOAs with intrinsic noise
- Römer, Einstein, Shapiro delays
- TEMPO software package, least-squares model fit
- → Final uncertainties

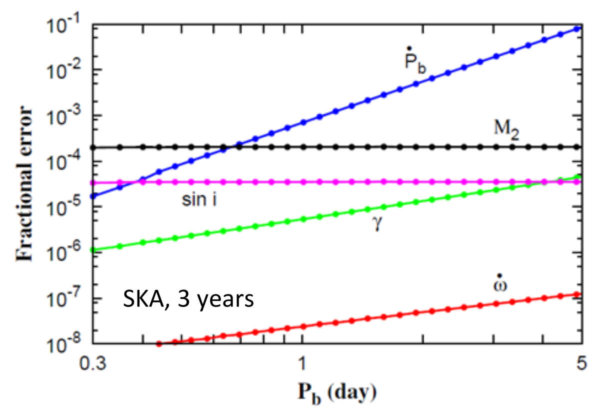
$P_p \sim 0.1-1$ s, non-rotating BH, $e = 0.8$, $M_p = 1.4$,
$M_{BH} = 10$, $i = 60°$, 5-year obs, 100-μs σ_{TOA}



The resulting uncertainties in
$\dot{P}_b$ and $\dot{\omega}$
are comparable to that obtained
in the binary pulsar.







There are smaller uncertainties for millisecond pulsars, and better sensitivity. (Better timing precision)

Baumann et al. 2019

M_c = mass of the axion cloud

$$\frac{dE_{GW}}{dt} \approx 0.01\,\frac{c^5}{G}\left(\frac{M_c(\alpha)}{M_{BH}}\right)^2 \alpha^{14}$$

$$\alpha \equiv \frac{GM_{BH}}{c^2} \Big/ \frac{\hbar}{\mu c} \qquad 0.005\left(\frac{M_{BH}}{3M_\odot}\right) \leq \alpha \leq 0.5$$

$$\frac{dM_c}{dt} \approx -0.01\,\frac{c^3}{G}\left(\frac{M_c(\alpha)}{M_{BH}}\right)^2 \alpha^{14}$$

Taking $M_c \approx \alpha M_{BH}$ near maximal rotation:

$$\frac{dM_c}{dt} \approx -2 \times 10^{-8} \left(\frac{\alpha}{0.07}\right)^{16} M_\odot\ \mathrm{y}^{-1}$$

for $M_{BH} = 3M_\odot$

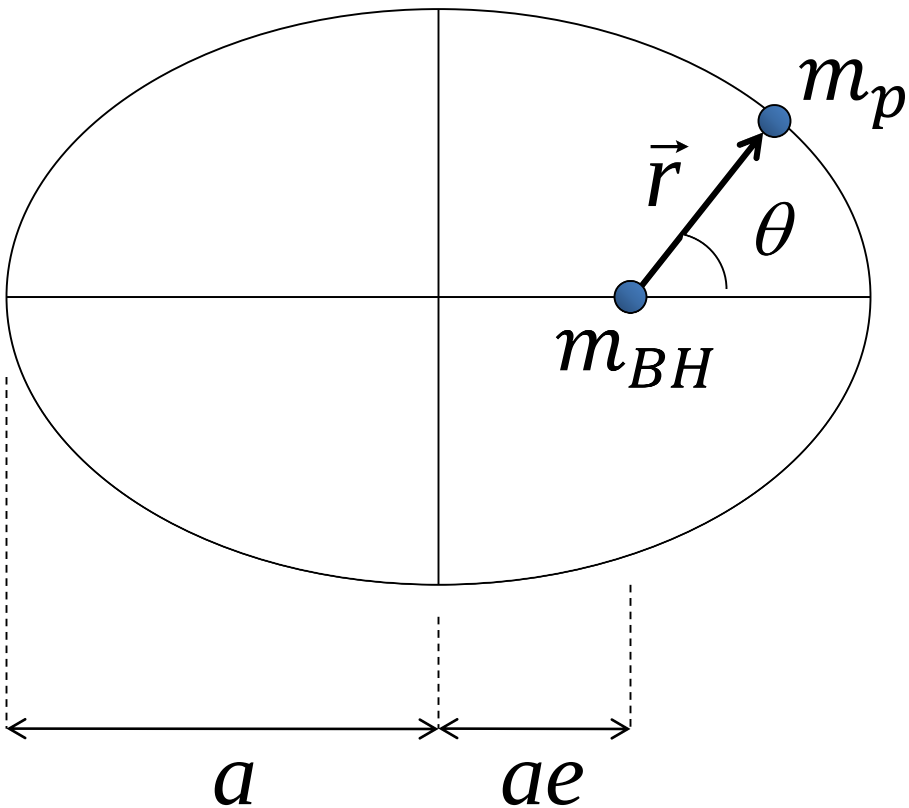
$L_{GW} \approx 1 \times 10^{32}$ W

$$\frac{dM_c}{dt} \approx -6 \times 10^{-6} \left(\frac{\alpha}{0.1}\right)^{16} M_\odot\ \mathrm{y}^{-1}$$

for $M_{BH} = 10^5 M_\odot$

$L_{GW} \approx 4 \times 10^{34}$ W

Hadjidemetriou (1963, 1966)
Binary systems with isotropic mass loss



$$\vec{r} = \vec{r}_p - \vec{r}_{BH}$$

$$\frac{d^2\vec{r}_p}{dt^2} = -\frac{Gm_{BH}(t)}{r^3}\,\vec{r}$$

$$\frac{d^2\vec{r}_{BH}}{dt^2} = \frac{Gm_p}{r^3}\,\vec{r}$$

$$\boxed{\begin{gathered}\frac{d^2\vec{r}}{dt^2} = -\frac{Gm(t)}{r^3}\,\vec{r} \\[2ex] m(t) = m_{BH}(t) + m_p\end{gathered}}$$

In general:

$$\dot{a} = -a\,\frac{1 + 2e\cos\theta + e^2}{1 - e^2}\,\frac{\dot{m}}{m}$$

$$\dot{e} = -(e + \cos\theta)\,\frac{\dot{m}}{m}$$

In our case

$$\dot{m}P_b \ll m$$

So we average over one orbit, using $\langle\cos\theta\rangle = -e$

Sivardière (1985)
for a Keplerian orbit

The result is:

$$\dot{a} = -a\frac{\dot{m}}{m}$$

$$\dot{e} = 0$$

independent of eccentricity

The Assembled Ingredients

$$\dot{a} = -a\frac{\dot{m}}{m} = -a\frac{\dot{m}_{BH}}{m_{BH} + m_p}$$

"Binary Pulsar ballpark"

P_b = 10 hours

$$m_{BH} = 3M_\odot \qquad m_p = 1.4M_\odot$$

$$a = 2.68 \times 10^9 \text{ m} = 3.85\, R_\odot \qquad \text{(KIII)}$$

$$\dot{m}_{BH} \approx -2 \times 10^{-8} \left(\frac{\alpha}{0.07}\right)^{16} M_\odot \text{ y}^{-1}$$

$$\dot{a} = 1.4\ \mathrm{m\ y^{-1}} \left(\frac{m_{BH} + m_p}{4.4\mathrm{M}_\odot}\right)^{-\frac{2}{3}} \left(\frac{P_b}{10^{\mathrm{h}}}\right)^{\frac{2}{3}} \left(\frac{\alpha}{0.07}\right)^{16}$$

$P_b, a,$ and $m = m_{BH} + m_p$

must satisfy Kepler's third law at any moment, so…

$$\dot{P}_b = \frac{3}{2}\frac{P}{a}\dot{a}\left(1 - \frac{1}{3}\frac{\dot{m}}{m}\frac{a}{\dot{a}}\right) = 2\frac{P_b}{a}\dot{a}$$

$$\dot{P}_b = 0.04\ \mathrm{ms\ y^{-1}} \left(\frac{m_{BH} + m_p}{4.4\mathrm{M}_\odot}\right)^{-1} \left(\frac{P_b}{10^{\mathrm{h}}}\right) \left(\frac{\alpha}{0.07}\right)^{16}$$

$\mathbf{0.04\ ms\ y^{-1} \approx 1.4 \times 10^{-12}}$ s/s is about $\mathbf{10^3}$ times larger than the precision with which $\dot{P}_b$ was measured for the binary pulsar.

$$\dot{P}_b = 0.04\ \mathrm{ms\ y^{-1}}\ \left(\frac{m_{BH} + m_p}{4.4\mathrm{M}_\odot}\right)^{-1} \left(\frac{P_b}{10^{\mathrm{h}}}\right)\left(\frac{\alpha}{0.07}\right)^{16}$$

For comparison, gravitational radiation alone:

$$\dot{P}_{GR} = -\frac{192\pi G^{\frac{5}{3}}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-\frac{5}{3}} m_{BH} m_p (m_{BH} + m_p)^{-\frac{1}{3}} f(e)$$

$$f(e) = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1 - e^2)^{-\frac{7}{2}}$$

Peters & Matthews (1963)

$$\dot{P}_{GR} = -0.0076\ \mathrm{ms\ y^{-1}}\ \left(\frac{m_{BH}}{3M_\odot}\right)\left(\frac{m_p}{1.4M_\odot}\right)\left(\frac{m_{BH}+m_p}{4.4\mathrm{M}_\odot}\right)^{-\frac{1}{3}}\left(\frac{P_b}{10^{\mathrm{h}}}\right)^{-\frac{5}{3}} f(e)$$

$$\left|\dot{P}_b\right| = |\dot{P}_{GR}|$$

for

$$P_{critical} \approx 0.5^{\mathrm{h}} \left(\frac{m_{BH}}{3M_{\odot}}\right)^{\frac{3}{8}} \left(\frac{m_p}{1.4M_{\odot}}\right)^{\frac{3}{8}} \left(\frac{m_{BH}+m_p}{4.4M_{\odot}}\right)^{\frac{1}{4}} f(e)^{\frac{3}{8}} \left(\frac{\alpha}{0.07}\right)^{-6}$$

$P_b < P_{critical}$: gravitational radiation dominates, inspiral results

$P_b > P_{critical}$: mass loss dominates, outspiral results

Axion masses between 2.7×10^{-12} eV and 3.2×10^{-12} eV are detectable.

Are there any BH-NS binaries?

NS-NS binaries were a surprise
BH-BH binaries were a surprise
SN: if the system loses half its mass, it becomes unbound.

Candidate black hole-neutron star mergers detected by LIGO/VIRGO (#S190814bv, #S190426c & S191205ah).

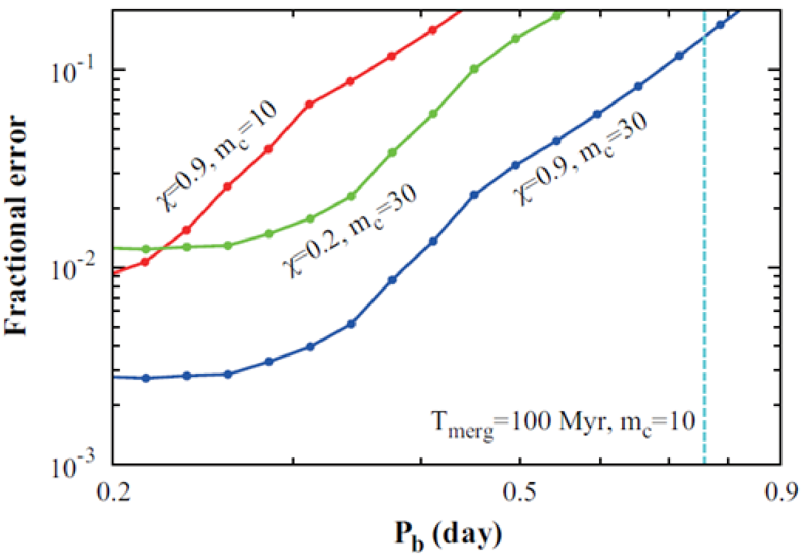
Summary

- Axions play an integral role in many theoretical models, including string theory and QCD.
- Rotational superradiance is a well understood process for extracting energy from BHs.
- A cloud of axions can form around a rotating BH, emitting gravitational waves.
- In a BH-Pulsar binary, the pulsar can act as an orbiting precision clock for measuring the effect of mass/energy loss from the BH.
- Observations of BH-Pulsar systems can rule out a certain mass range of axions.

BH Spin Measurements are more difficult

$$\chi = \frac{c}{G}\frac{J}{M_{BH}^2} \leq 1$$

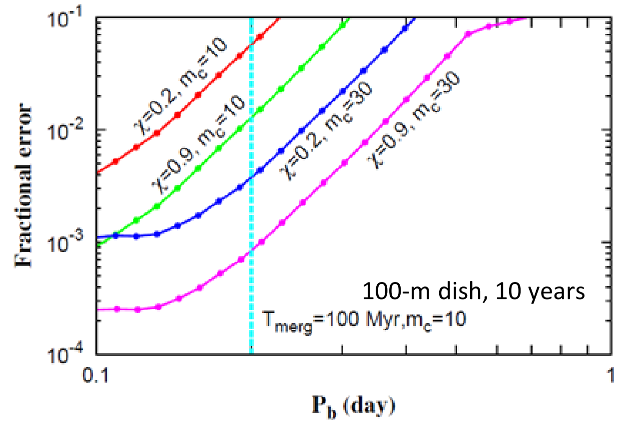
$P_p \sim 0.1 - 1$ s, $e = 0.8$, $M_p = 1.4$, $i = 60°$, 10-year obs, 100-μs σ_{TOA}



- 1% precision for $P_b < 0.5$ days, $e > 0.8$, for a wide range of stellar masses.
- For $P_b > 0.5$ days, need to be at the larger end of the BH mass spectrum.

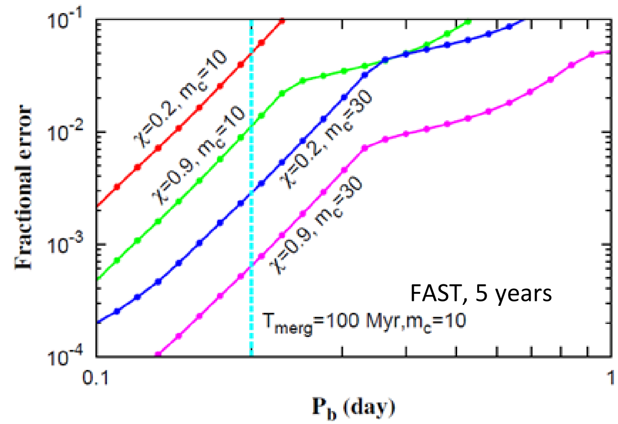
For Sgr A*, few years obs:

- 0.1% precision for $P_b <$ few months.

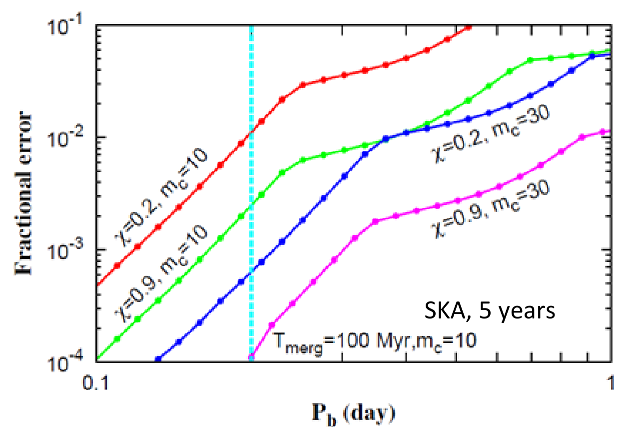


Again, better precision for MSPs.

(But not expected for Sgr A*)



Spin more difficult since must disentangle both
(a) monopole
(b) frame-dragging contributions to orbital parameters (e.g., $\dot{\omega}$).



MSP, $e = 0.1$, $M_p = 1.4$, $M_{BH} = 10$, $i = 60°$