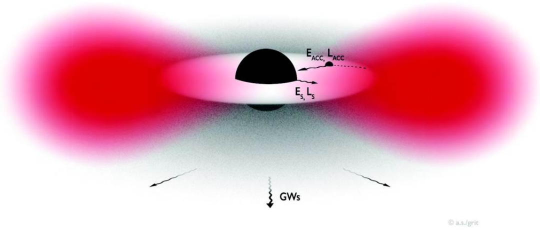
Stellar Superradiance from QFT at Finite Density

SEWM 2022 Paris 20-24 June 2022

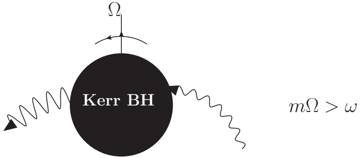
Jamie McDonald



UCLouvain

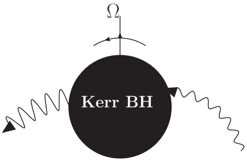
In progress with Francesca Chadha-Day (Durham) and Björn Garbrecht (TU Munich)

Superradiance



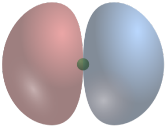
"Superradiance involves the extraction of rotational energy from spinning objects by low frequency modes $\omega < \Omega$ of an external field"

Superradiance



$m\Omega > \omega$

"Superradiance involves the extraction of rotational energy from spinning objects by low frequency modes $\omega < \Omega$ of an external field"

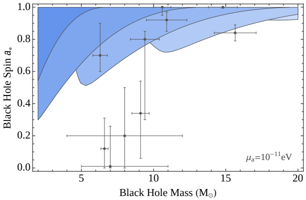


$$\phi = Y_{lm}(\theta, \phi)\psi_{lmn}(r)e^{\Gamma t}$$

Massive fields become gravitationally bound/trapped, leading to a superradiant instability that grows exponentially in time"

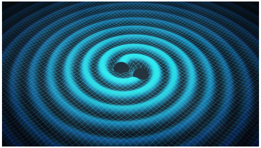
Signatures

- Constraints on light particles from BH spin

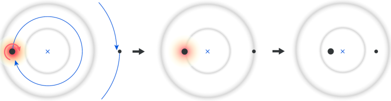


Arvanitaki,Dubovsky (2011)

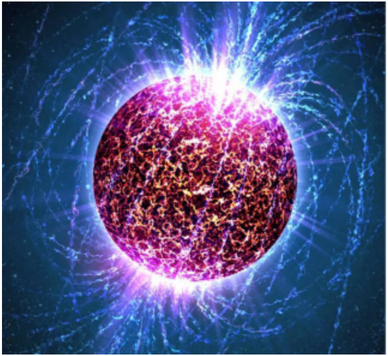
- Gravitational waves



- Effects on binaries: Baumann et al 2018

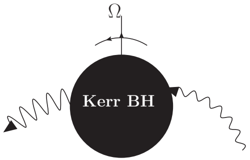


Superradiance

Neutron Star	Black Hole
	
?	GR
stellar matter	Horizon

Superradiance

$$g^{\mu\nu}\nabla_\mu\nabla_\nu\phi + m_\phi^2\phi = 0 \qquad r_g = GM$$



$m\Omega > \omega$

$$Z_{lm}^{\rm BH} = \frac{|\phi_{\rm out}|^2}{|\phi_{\rm in}|^2} - 1 = r_g^2(m\Omega_{\rm H} - \omega)(\omega r_g)^{2l+1} \cdot \frac{1}{r_g}$$

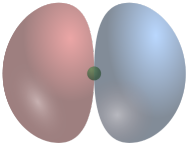
suppose for stars: $\partial^2\phi + \gamma\dot{\phi} = 0$

$$Z_{lm}^{\rm Star} = \frac{|\phi_{\rm out}|^2}{|\phi_{\rm in}|^2} - 1 = R^2\,(m\Omega - \omega)\,(\omega R)^{2l+1} \cdot \gamma$$

BH is damping membrane with effective damping $\sim 1/r_g$.

Low Mass Fields are Bound $\implies$ Unstable

$$\phi = Y_{lm}(\theta, \phi)\psi_{lmn}(r)e^{\Gamma t}$$



$$\Gamma_{n\ell m} = r_g\,(m\Omega_{\rm H} - \omega)\,(GM\omega)^{4\ell+5} \cdot \frac{1}{r_g} \qquad\qquad \omega \simeq m_\phi .$$

Expect stellar superradiance with

$$g^{\mu\nu}\nabla_\mu\nabla_\nu\phi + \gamma\dot{\phi} + m_\phi^2\phi = 0 \quad \implies \quad 1/r_g \to \gamma, \qquad r_g \to R$$

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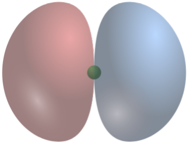

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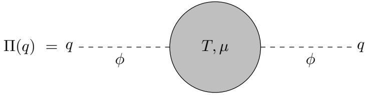
Where do such factors come from ?

Equation of Motion



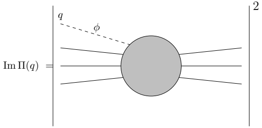
$$\partial^2\phi(x) + m_\phi^2\phi(x) + \int dy \Pi_R(x,y)\phi(y) = 0$$

Upon performing a Wigner transformation, defined by

$$\Pi(q,x) = \int dy \Pi(x + y/2, x - y/2) e^{iy\cdot q}$$

we can express this equation in Wigner space as

$$\partial^2\phi(x) + m_\phi^2\phi(x) + e^{i\partial_y\cdot\partial_q}\left[\Pi_R\left(q, \frac{x+y}{2}\right)\phi(y)\right]_{q\to 0, y\to x} = 0$$



$$\boxed{-\nabla^2\phi(\omega,\mathbf{x}) + (m_\phi^2 - \omega^2)\phi(\omega,\mathbf{x}) + i\mathrm{Im}[\Pi_R(\omega,\mathbf{x})]\phi(\omega,\mathbf{x}) \simeq 0}$$

Flat Space + Static Star

$$Z_{lm}^{\mathrm{scat}} = \frac{|\phi_{\mathrm{out}}|^2}{|\phi_{\mathrm{in}}|^2} - 1 = -\frac{4R\,(\omega R)^{2l+2}}{(2l+1)!!(2l+3)!!} \cdot \frac{\operatorname{Im}\Pi}{\omega}$$

Flat Space + Static Star

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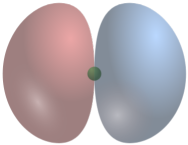
$$\downarrow$$

Add GR +Rotating Star

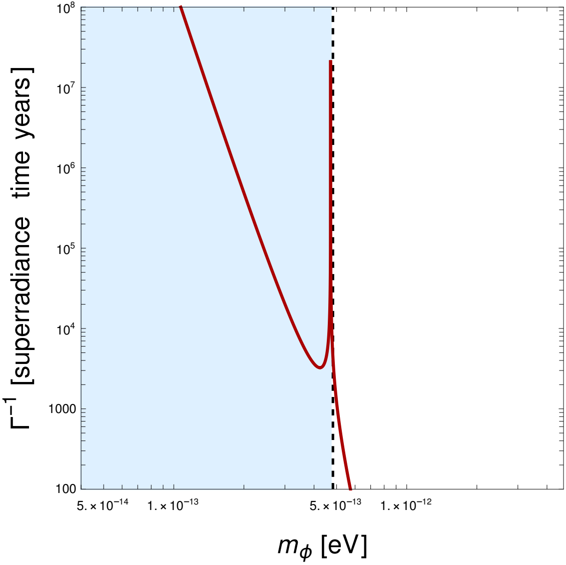
"A Modern approach to superradiance" Endlich, Penco JHEP 05 (2017) 052

$$\Gamma_{nlm} = (m_\phi R)^{(2l+3)}\,(m_\phi r_g)^{(2l+3)}\,\frac{\mathrm{Im}(\Pi)}{\omega}(\omega - m\Omega),$$

$$\phi = Y_{lm}(\theta,\phi)\psi_{lmn}(r)e^{i\Gamma t}$$



Instability Rate (PSR J17482446ad)



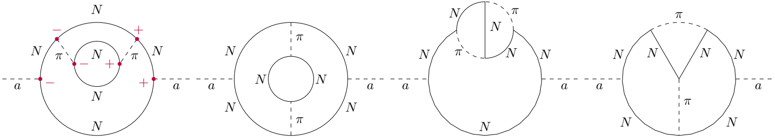
$$\mathrm{Im}\Pi/\omega \sim cm^{-1}$$

Axions

Axion nucleon interactions:

$$\mathcal{L}_{aNN} = G_{an}\partial_\mu \phi \bar{N}\gamma^\mu\gamma_5 N, \qquad \mathcal{L}_{\pi NN} = i(2m_n/m_\pi) f \pi_0 \bar{N}\gamma^5 N$$

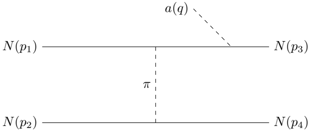
$$-\nabla^2\phi(\omega, \mathbf{x}) + (m_\phi^2 - \omega^2)\phi(\omega, \mathbf{x}) + i\mathrm{Im}[\Pi_R(\omega, \mathbf{x})]\phi(\omega, \mathbf{x}) \simeq 0$$



(i) (ii) (iii) (iv)

Optical Theorem

$\mathrm{Im}\,\Pi(q)$:

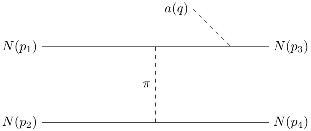


Axions

Superradiance rate for mode (l,m,n) :

$$\Gamma^{a}_{nlm} \simeq \frac{G_{an}^2 m_n^4}{m_\pi^4} p_F\, T^2 \cdot (m_\phi R)^{(2l+3)} \, (m_\phi r_g)^{(2l+3)} \cdot \frac{(\omega - m\Omega)}{\omega}$$

$\mathrm{Im}\,\Pi(q)$:



$$\mathrm{Im}\,\Pi = \prod_i \int \frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} f_i \prod_j \int \frac{d^3\mathbf{p}_j}{(2\pi)^3 2E_j} (1 \pm f_j) \left|\mathcal{M}_{aNN\to NN}\right|^2$$

(calculate integral from axion mean free path: Harris (2020), Brinkmann + Turner (1988))

We now understand superradiance in stars!

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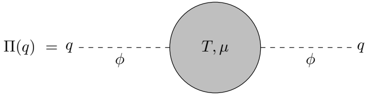
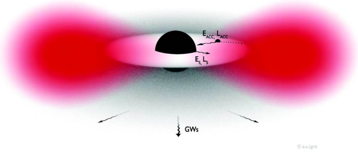
An we know how to calculate it:

$$-\nabla^2\phi(\omega,\mathbf{x}) + (m_\phi^2 - \omega^2)\phi(\omega,\mathbf{x}) + i\,\mathrm{Im}[\Pi_R(\omega,\mathbf{x})]\phi(\omega,\mathbf{x}) \simeq 0$$





Next Steps (in progress):

- scan all possible BSM interactions!
- Better modeling of stellar medium?

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