Aspects of superradiant scattering off Kerr black holes

José Sá

Supervisor: João G. Rosa

Co-supervisor: Orfeu Bertolami

November 2017

Faculdade de Ciências da Universidade do Porto

Outline

- Introduction
- Kerr black hole and the Penrose process
- Newman-Penrose formalism and the Teukolsky equation
- Analytical approximated solutions
- Numerical methods
- Scattering of planes waves
- Conclusions and future work

Introduction

Superradiance

- Any radiation "enhancement" processes: scalar, electromagnetic, gravitational
- First cases being spontaneous pair creation: Klein paradox
- *Rotational superradiance:* Zeldovich absorbing cylinder

$$\omega < m\Omega$$

(Ω angular velocity, m azimuthal quantum number)

Motivation

- Kerr BHs can amplify EM and gravitational radiation
- Focus on EM wave scattering
- Future observational tests of BH superradiance and GR

Kerr black hole

Boyer-Lindquist coordinates

$$ds^2 = \left(1 - \frac{2Mr}{\rho^2}\right) \mathrm{d}t^2 + 2a \sin^2\theta \frac{(r^2 + a^2 - \Delta)}{\rho^2} \mathrm{d}t\mathrm{d}\varphi$$
$$- \frac{(r^2 + a^2)^2 - \Delta a^2 \sin^2\theta}{\rho^2} \sin^2\theta \mathrm{d}\varphi^2 - \frac{\rho^2}{\Delta}\mathrm{d}r^2 - \rho^2 \mathrm{d}\theta^2$$

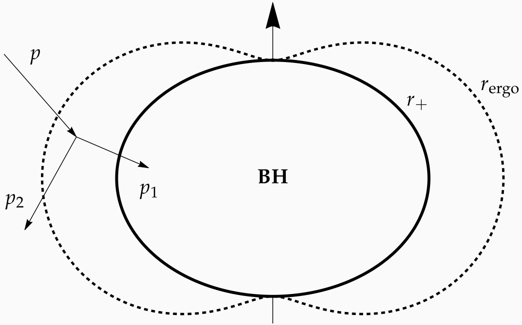
$$[\,\Delta = r^2 - 2Mr + a^2\ ,\ \ \rho^2 = r^2 + a^2\cos^2\theta\,]$$

- BH angular momentum $J = aM \quad [a = 0 \ \Rightarrow \text{Schwarzschild}]$
- Killing vectors ∂_t (stationary) and ∂_φ (axisymmetric)
- Horizons at $g^{rr} = 0 \ \Rightarrow\ \Delta = 0 \ \Rightarrow\ r = r_\pm \equiv M \pm \sqrt{M^2 - a^2}$
  Cosmic censorship conjecture $\ \Rightarrow\ |a| \leq M$
- Ergoregion $(g_{tt} < 0) \ \Rightarrow\ $ negative energy states

$$r_+ < r < r_{\text{ergo}}(\theta) \equiv M + \sqrt{M^2 - a^2\cos^2\theta}$$

Penrose process

- Particle decays into two inside the ergoregion: $\boldsymbol{p} = \boldsymbol{p_1} + \boldsymbol{p_2}$



Killing horizon

Hypersurface $r = r_+$ with normal null vector

$$\boldsymbol{\xi} = \partial_t + \Omega_H \partial_\varphi$$

Event horizon angular "velocity":

$$\Omega_H = \frac{a}{2Mr_+}$$

- We may have $E_1 = \boldsymbol{k} \cdot \boldsymbol{p_1} < 0 \ \Rightarrow E_2 = E + |E_1| > E$
- Local energy condition $\boldsymbol{\xi} \cdot \boldsymbol{p_1} > 0$ at $r = r_+ \ \Rightarrow E_1 - \Omega_H L_1 > 0$

$$\psi \sim e^{-i\omega t + im\varphi} \ \Rightarrow \ \frac{\delta J}{\delta M} = \frac{\hbar m}{\hbar \omega} \ \Rightarrow \ \boxed{\delta M < 0 \ \wedge \ \omega(\omega - m\Omega_H) < 0}$$

Energy extraction !

Newman-Penrose formalism

- EM waves on a fixed Kerr background spacetime
- Projection of Maxwell tensor onto a complex null tetrad $(\mathfrak{l}, \mathfrak{n}, \mathfrak{m}, \bar{\mathfrak{m}})$

$$\underbrace{\mathbf{E}\,,\ \mathbf{B}}_{\text{6 real components}} \longrightarrow \boxed{\begin{aligned} \phi_0 &= F_{\mu\nu}\mathfrak{l}^\mu \mathfrak{m}^\nu \\ \phi_1 &= \tfrac{1}{2}F_{\mu\nu}(\mathfrak{l}^\mu \mathfrak{n}^\nu - \mathfrak{m}^\mu \bar{\mathfrak{m}}^\nu) \\ \phi_2 &= F_{\mu\nu}\bar{\mathfrak{m}}^\mu \mathfrak{n}^\nu \end{aligned}}$$

- **Kinnersley tetrad**

$$\mathfrak{l} = \frac{1}{\Delta}\left(r^2 + a^2,\, \Delta,\, 0,\, a\right) \qquad \mathfrak{m} = \frac{1}{\sqrt{2}\bar{\rho}}\left(i\,a\sin\theta,\, 0,\, 1,\, i\csc\theta\right)$$

$$\mathfrak{n} = \frac{1}{2\rho^2}\left(r^2 + a^2,\, -\Delta,\, 0,\, a\right) \qquad \bar{\mathfrak{m}} = \mathfrak{m}^* \qquad [\,\bar{\rho} = r + i\,a\cos\theta\,]$$

Tetrad suitable for the study of incoming and outgoing radiation
$\Rightarrow$ decoupled and separable wave equations for ϕ_0 and ϕ_2

$$\begin{aligned}\nabla_\mu F^{\mu\nu} &= 0 \\ \nabla_{[\mu} F_{\nu\rho]} &= 0\end{aligned} \quad \Rightarrow \quad \text{NP equivalent equations} \quad \Rightarrow \quad \text{4 first-order coupled complex equations } (\phi_0, \phi_1, \phi_2)$$

$$\Downarrow$$

$$\boxed{\Upsilon_{+1} = \phi_0 \qquad \Upsilon_{-1} = 2(\bar{\rho}^*)^2 \phi_2}$$

Teukolsky's equation

$$\frac{1}{\Delta^s}\frac{\partial}{\partial r}\left(\Delta^{s+1}\frac{\partial \Upsilon_s}{\partial r}\right) + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Upsilon_s}{\partial\theta}\right) - \left[\frac{(r^2+a^2)^2}{\Delta} - a^2\sin^2\theta\right]\frac{\partial^2\Upsilon_s}{\partial t^2}$$
$$- \frac{4Mar}{\Delta}\frac{\partial^2\Upsilon_s}{\partial t\partial\varphi} - \left(\frac{a^2}{\Delta} - \frac{1}{\sin^2\theta}\right)\frac{\partial^2\Upsilon_s}{\partial\varphi^2} + 2s\left[\frac{M(r^2-a^2)}{\Delta} - r - ia\cos\theta\right]\frac{\partial\Upsilon_s}{\partial t}$$
$$+ 2s\left[\frac{a(r-M)}{\Delta} + \frac{i\cos\theta}{\sin^2\theta}\right]\frac{\partial\Upsilon_s}{\partial\varphi} - (s^2\cot^2\theta - s)\Upsilon_s = 0$$

Note: valid for scalar ($s = 0$) and gravitational waves ($s = \pm 2$)

General mode decomposition

$$\Upsilon_s = \int \mathrm{d}\omega \sum_{\ell,m} e^{-i\omega t + im\varphi}\, {}_sS_{\ell m}(\theta)\, {}_sR_{\ell m}(r)$$

Angular equation $[z = \cos\theta\ ,\ c = a\omega]$

$$\frac{\mathrm{d}}{\mathrm{d}z}\left[(1-z^2)\frac{\mathrm{d}\,{}_sS_{\ell m}}{\mathrm{d}z}\right] + \left[(cz)^2 - 2csz - \frac{(m+sz)^2}{1-z^2} + s + {}_s\mathcal{A}_{\ell m}\right]{}_sS_{\ell m} = 0$$

- $c = 0$ $\Rightarrow$ Spherical symmetry (closed form)

  $$e^{im\varphi}\,{}_sS_{\ell m}(\theta) = {}_sY_{\ell m}(\theta,\varphi) \qquad {}_s\mathcal{A}_{\ell m} = \ell(\ell+1) - s(s+1)$$

- $c \neq 0$ $\Rightarrow$ Series approximation or numerical methods (Leaver/Spectral)

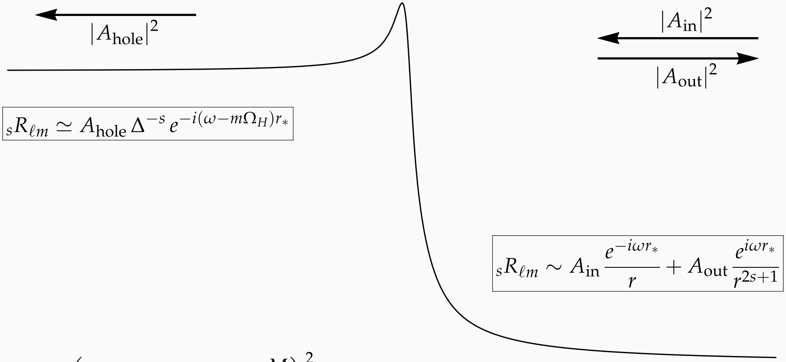
$$ {}_s\mathcal{A}_{\ell m} = \ell(\ell+1) - s(s+1) - \frac{2ms^2}{\ell(\ell+1)}c + \mathcal{O}(c^2)$$

Teukolsky equation

Radial equation $\frac{1}{\Delta^s}\frac{\mathrm{d}}{\mathrm{d}r}\left(\Delta^{s+1}\frac{\mathrm{d}\,{}_sR_{\ell m}}{\mathrm{d}r}\right)+\left[\frac{K^2-2is(r-M)K}{\Delta}+4is\omega r-\lambda\right]{}_sR_{\ell m}=0$

$$\Rightarrow \left(\frac{\mathrm{d}^2}{\mathrm{d}r_*^2}+V_{\text{eff}}\right){}_sU_{\ell m}=0 \qquad \left[\ \frac{\mathrm{d}r_*}{\mathrm{d}r}=\frac{r^2+a^2}{\Delta}\ \right]$$

where $\lambda={}_s\mathcal{A}_{\ell m}-2ma\omega+a^2\omega^2$ and ${}_sU_{\ell m}=\sqrt{\Delta^s(r^2+a^2)}\,{}_sR_{\ell m}$



$$\boxed{{}_sR_{\ell m}\simeq A_{\text{hole}}\,\Delta^{-s}\,e^{-i(\omega-m\Omega_H)r_*}}$$

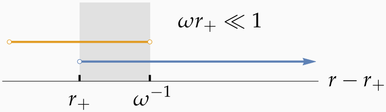
$$\boxed{{}_sR_{\ell m}\sim A_{\text{in}}\frac{e^{-i\omega r_*}}{r}+A_{\text{out}}\frac{e^{i\omega r_*}}{r^{2s+1}}}$$

$$V_{\text{eff}}\simeq\left(\omega-m\Omega_H-is\frac{r_+-M}{2Mr_+}\right)^2 \qquad V_{\text{eff}}\sim\omega^2+\frac{2is\omega}{r}$$

Analytical results

Matching of coefficients

- Solving radial equation for $r - r_+ \gg r_+$ (far) and $r - r_+ \ll \omega^{-1}$ (near)
- Extend solutions to opposite regions and match dominant monomials of $x^{\ell-s}$ and $x^{-\ell-1-s}$ $\Rightarrow$ valid for modes $\bar{\omega} \equiv \omega r_+ \ll 1$



- Obtain loss/gain factor $\boxed{{}_{\pm 1}Z_{\ell m} = \dfrac{\mathrm{d}E_{\rm out}}{\mathrm{d}t} \Big/ \dfrac{\mathrm{d}E_{\rm in}}{\mathrm{d}t} - 1}$

$$ {}_{\pm 1}Z_{\ell m} \simeq -4\bar{\omega}(\bar{\omega} - m\bar{\Omega}_H) \underbrace{(2-\tau)(2\bar{\omega}\tau)^{2\ell}\left[\frac{(\ell-1)!(\ell+1)!}{(2\ell)!(2\ell+1)!}\right]^2 \prod_{n=1}^{\ell}\left(n^2 + \frac{4\varpi^2}{\tau^2}\right)}_{\text{always } \geq 0} $$

- Mode amplification ${}_{\pm 1}Z_{\ell m} > 0 \;\Rightarrow\; \omega(\omega - m\Omega_H) < 0$

[$x = (r - r_+)/r_+$, $\tau = (r_+ - r_-)/r_+$, $\varpi = (2-\tau)(\bar{\omega} - m\bar{\Omega}_H)$]

Numerical methods

- ${}_{\pm1}R_{\ell m} = (r_+)^{\mp 1}\, x^{\mp 1 - i\varpi/\tau} f_\pm(x) \Rightarrow$ removes singular points of the eq.
- Integrate from $\epsilon \ll 1$ (stiffness) up to $x_\infty = 2\pi/\bar{\omega} \times 200$

$$f_\pm(\epsilon) = \sum_{n=0}^{N_H} \left(\frac{a_n}{a_0}\right) \epsilon^n \;\; \Rightarrow f_\pm(\epsilon) \simeq 1\,,\;\; {f_\pm}'(\epsilon) \simeq 0$$

- Different asymptotic behavior: $\phi_0 \to A_{\text{in}}\,,\ \phi_2 \to A_{\text{out}}$
- Using conservation of energy $\frac{\mathrm{d}E_{\text{in}}}{\mathrm{d}t} - \frac{\mathrm{d}E_{\text{out}}}{\mathrm{d}t} = \frac{\mathrm{d}E_{\text{hole}}}{\mathrm{d}t}$

${}_{\pm1}Z_{\ell m}$	Solutions
$\frac{\mathcal{B}^2\tau^4}{4\varpi^2(\tau^2+4\varpi^2)} \left\lvert \frac{f_-(x_\infty)}{f_+(x_\infty)} \right\rvert^2 - 1$	ϕ_0 and ϕ_2
$-\frac{\bar{\omega}\tau^2}{\varpi} \left\lvert \frac{1}{f_+(x_\infty)} \right\rvert^2$	ϕ_0
$-1 \Big/ \left(1 + \frac{\mathcal{B}^2\tau^2 \lvert f_-(x_\infty)\rvert^2}{4\bar{\omega}\varpi(\tau^2+4\varpi^2)}\right)$	ϕ_2

$[\ \mathcal{B}^2 = ({}_{-1}\mathcal{A}_{\ell m} + a^2\omega^2 - 2ma\omega)^2 - 4a^2\omega^2 + 4ma\omega\ ]$

Numerical methods

- ${}_sZ_{\ell m}(-\omega) = {}_sZ_{\ell,-m}(\omega)$

- Maximum EM amplification:

  $\sim$ **4.4%**

  for $\ell = m = 1$, $\omega M \simeq 0.436$

- Superradiant modes

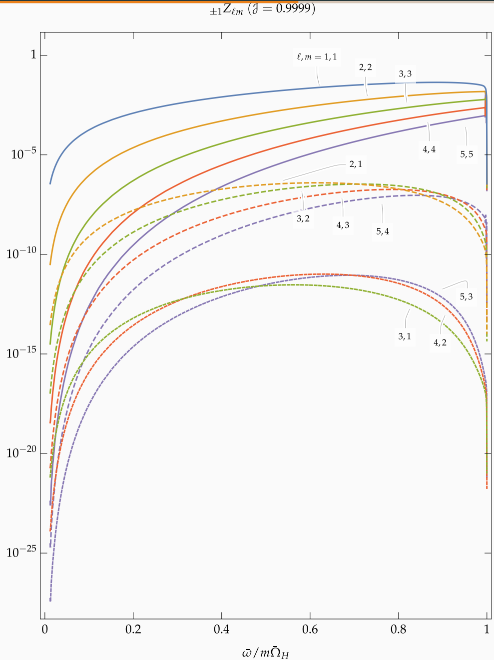
  increase ℓ $\Rightarrow$ ${}_{\pm1}Z_{\ell m} \to 0$

  (potential centrifugal barrier)

- Non-superradiant modes

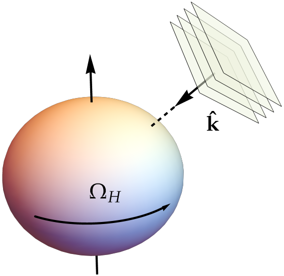
  $|\omega| \gg |m\Omega_h|$ $\Rightarrow$ ${}_{\pm1}Z_{\ell m} \to -1$

  (fully absorbed)



Scattering of plane waves

- Realistic astrophysical source: pulsar-BH binary [Rosa, 2017]



$$\phi_2{}^{(\mathrm{pl})} \sim 2\pi\epsilon_R e^{-i\omega t} \sum_{\ell,m} \left(a_{\mathrm{out}} \frac{e^{i\omega r}}{r} + a_{\mathrm{in}} \frac{e^{-i\omega r}}{r^3} \right) \times {}_{-1}Y_{\ell m}(\hat{\mathbf{k}})^* {}_{-1}Y_{\ell m}(\hat{\mathbf{r}}) + (\epsilon_R \to \epsilon_L^*, \omega \to -\omega)$$

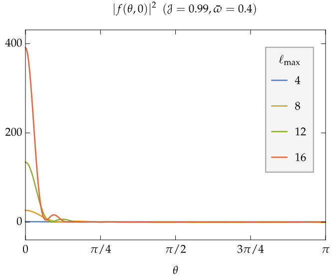
- Scattering theory description

$$\phi_2{}^{(\mathrm{scatt})} = \phi_2{}^{(\mathrm{pl})} + f(\theta,\varphi) e^{-i\omega(t-r_*)}/r$$

- Match *ingoing* part of $\phi_2{}^{(\mathrm{pl})}$ and $\phi_2{}^{(\mathrm{scatt})}$

$$f(\theta,\varphi) = -\frac{\pi\epsilon_R}{\omega} \sum_{\ell,m} \left[\frac{(-1)^{\ell+1}\ell(\ell+1)}{4\omega^2} \frac{A_{\mathrm{out}}}{A_{\mathrm{in}}} - 1 \right] \times {}_{-1}Y_{\ell m}(\hat{\mathbf{k}})^* {}_{-1}Y_{\ell m}(\hat{\mathbf{r}})$$

- Series divergences $\theta = \theta_0 \;\Rightarrow$ phase-shifts



Scattering of plane waves

- Separate long-range $V_{\text{eff}} \sim 1/r$ effects
  $\Rightarrow$ only phase-shifts, no effect on the amplitutes

$$f(\theta,\varphi) = f_N(\theta,\varphi) + f_D(\theta,\varphi)$$

- **Newtonian phase-shifts** $\delta_N = \arg\Gamma(\ell + 1 - 2iM\omega)$

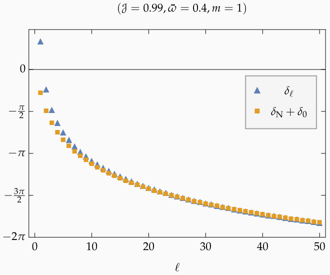
$$|f_N(\theta,0)|^2 \sim 1/\sin^4(\theta/2) \qquad (\theta_0 = 0)$$

$$\delta_\ell = \frac{1}{2}\arg\left[(-1)^{\ell+1}\frac{A_{\text{out}}}{A_{\text{in}}}\right] \longrightarrow \delta_N \qquad (\ell \to \infty)$$

- Dispersed wave

$$f_D(\theta,\varphi) = -\frac{\pi\epsilon_R}{\omega}\sum_{\ell,m}\left[\frac{\sqrt{{}_{\pm1}Z_{\ell m}+1}}{\ell(\ell+1)/\mathcal{B}}e^{2i\delta_\ell} - e^{2i\delta_{\text{N}}}\right] \times {}_{-1}Y_{\ell m}(\hat{\mathbf{k}})^* {}_{-1}Y_{\ell m}(\hat{\mathbf{r}})$$

- Superradiance effects masked from higher ℓ phase-shifts $\Rightarrow$ separate lower ℓ effects



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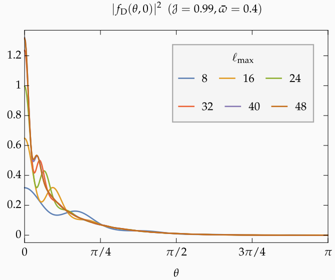

CONCLUSIONS / FUTURE WORK

Conclusions

- Development of computation routine that numerically computes global gain/loss factors and phase shifts
- Superradiant modes with lower $\ell = m$ have larger amplification (max. 4.4% in the EM case)
- Modes with higher ℓ are fully reflected (centrifugal barrier)
- Non-superradiant modes (higher frequencies) are fullly absorbed
- Phase-shifts for high ℓ modes mask superradiance

Future work

- Isolate lower ℓ modes
- Generalize to gravitational waves (max. amplification 138%)

Questions ?