Propagação de campos bosônicos ao redor de buracos negros

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Parte I: Nuvens e buracos negros cabeludos

Parte II: Absorção e espalhamento por buracos negros

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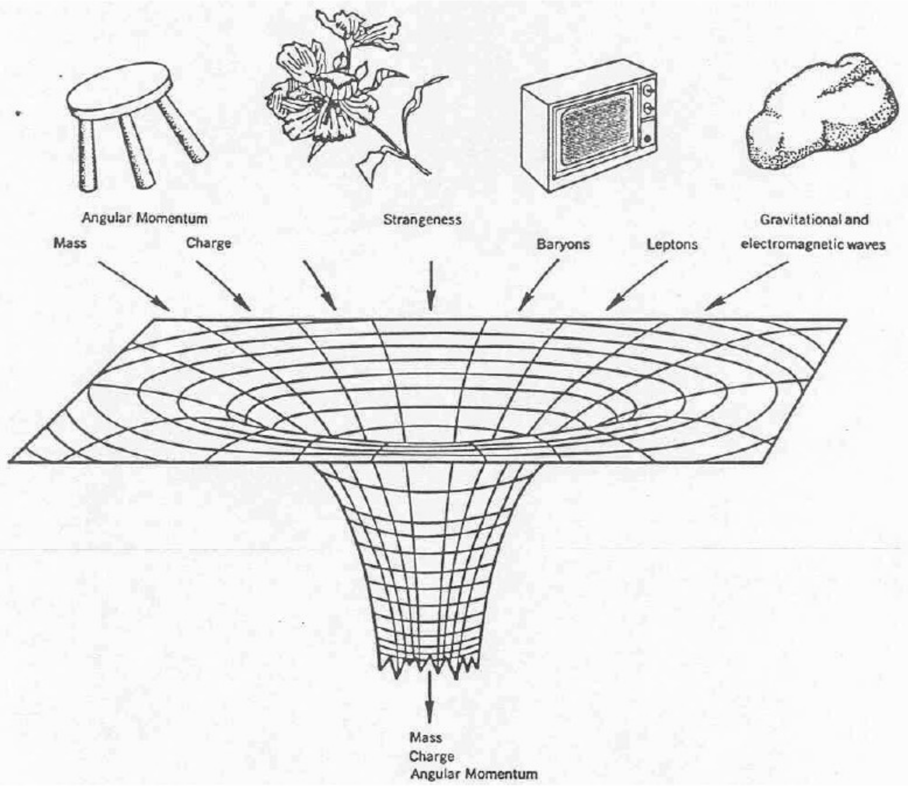
“Buracos negros não tem cabelo”

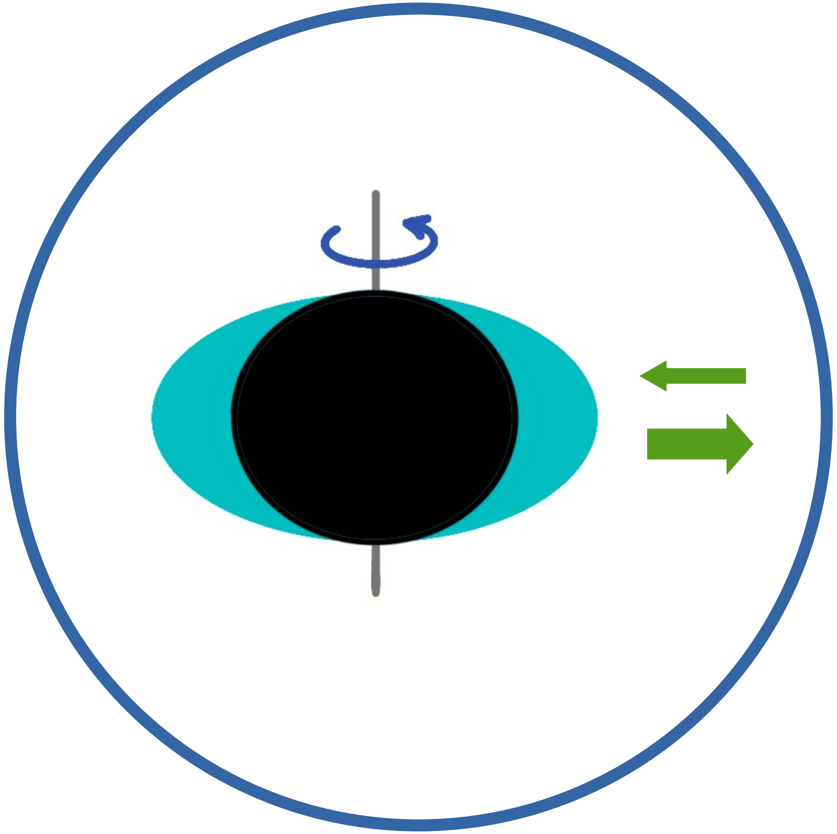
Israel (1967)
Carter (1971)

Bekenstein (1972)



Crédito: Ruffini&Wheeler (1971)

Superradiância



$$\frac{\omega}{m_j} < \Omega_{\rm H} \equiv \frac{a}{2Mr_{\rm H}}$$

$$\frac{\omega}{m_j} = \Omega_{\rm H}$$

Nuvens e BNs cabeludos

Hod (2012)
[arXiv:1211.3202]
Hod (2013)
[arXiv:1311.5298]
Herdeiro&Radu (2014)
[arXiv:1403.2757]

$$(\Box - \mu^2)\Psi = 0$$

$$\Psi_{lm} = R_{lm}(r) S_{lm}(\theta) e^{im\phi} e^{-i\omega t}$$

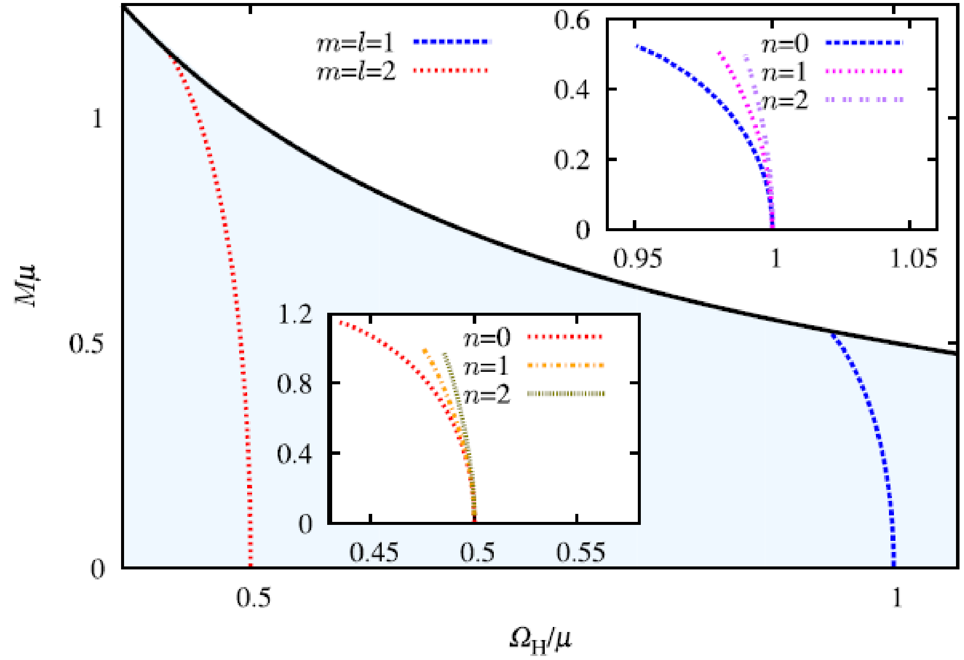
$$\Delta \frac{d}{dr}\left(\Delta \frac{dR_{lm}}{dr}\right) + [H^2 + (2ma\omega - K_{lm} - \mu^2(r^2 + a^2))\Delta] R_{lm} = 0$$

$$R_{lm}(r) \approx \begin{cases} e^{-i(\omega - \omega_c) r_*}, & \text{for } r \to r_+, \\ \frac{e^{-\sqrt{\mu^2 - \omega^2} r}}{r}, & \text{for } r \to \infty, \end{cases}$$

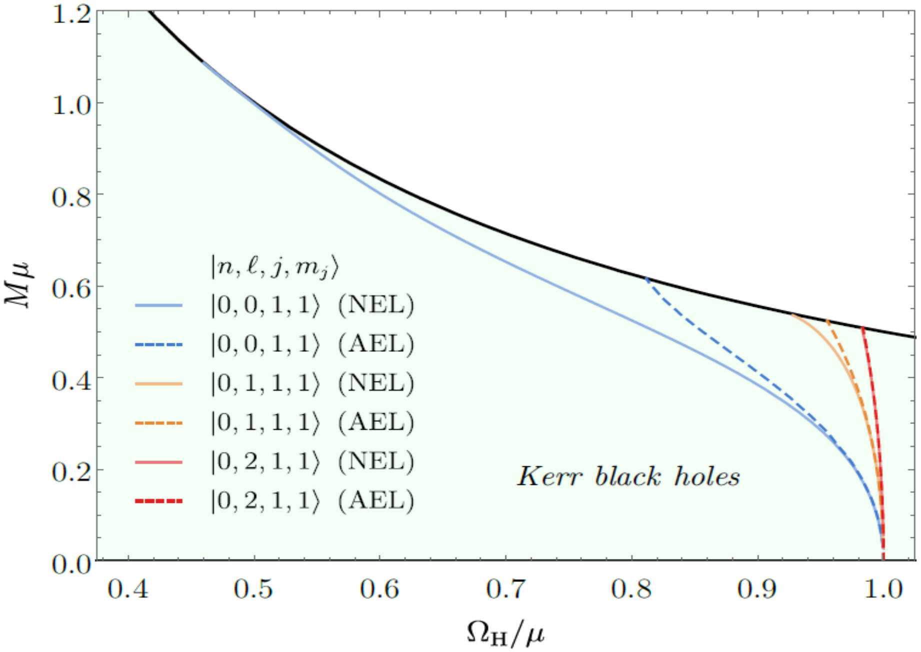
$$\omega = \omega_c = m\Omega_H$$

$$R_{lm} = R_0 \left(1 + \sum_{k \geq 1} R_k (r - r_+)^k\right)$$

Nuvens e BNs cabeludos

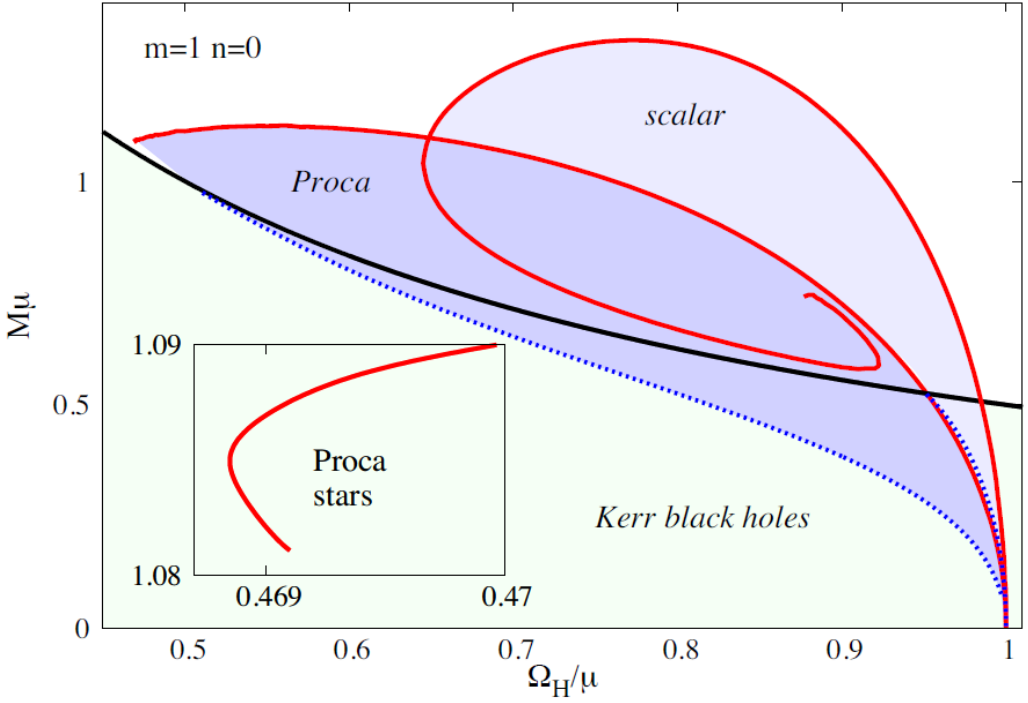


Benone+ (2014)
[arXiv:1409.1593v2]

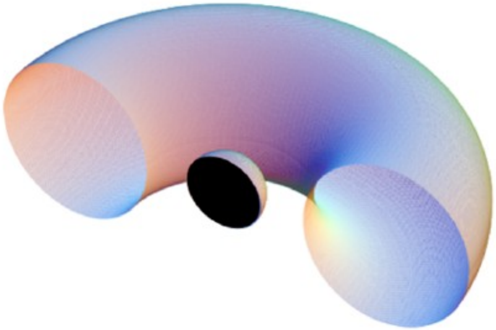


Santos+ (2020)
[arXiv:2004.09536]

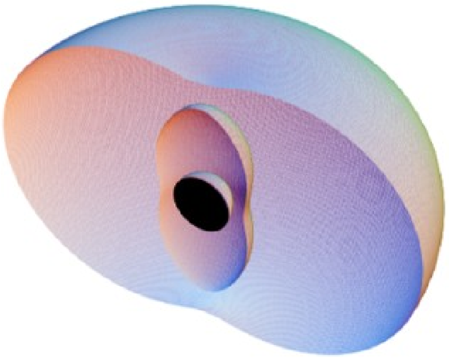
Nuvens e BNs cabeludos



Escalar



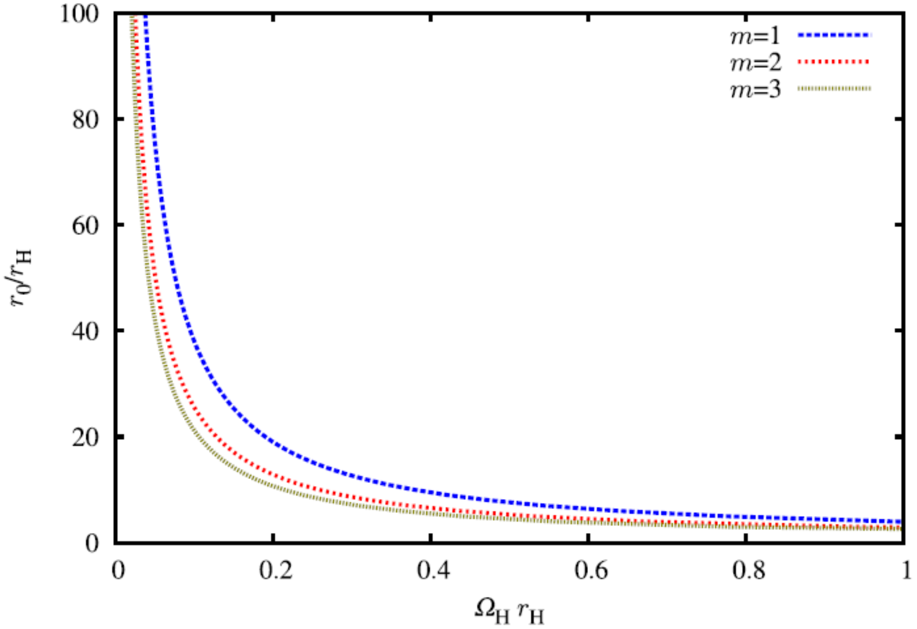
Proca



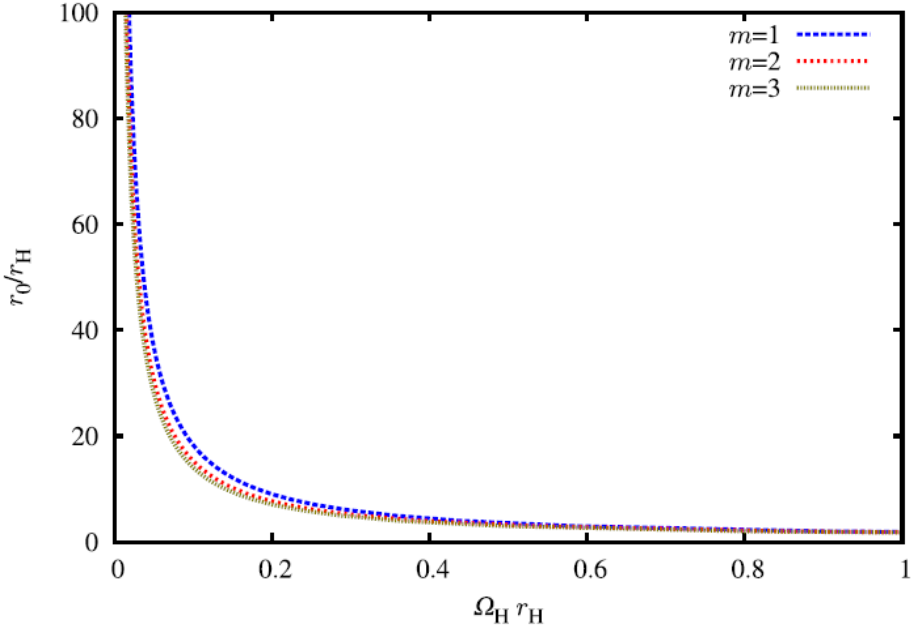
Santos+ (2020)
[arXiv:2004.09536]

Nuvens em análogos

$$\phi(r_0) = 0$$



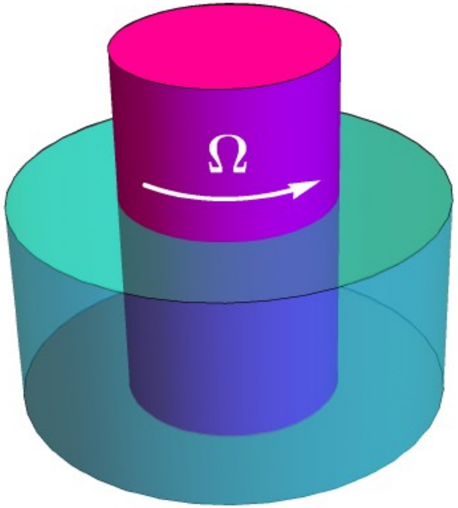
$$[d\phi(r)/dr]_{r=r_0} = 0$$



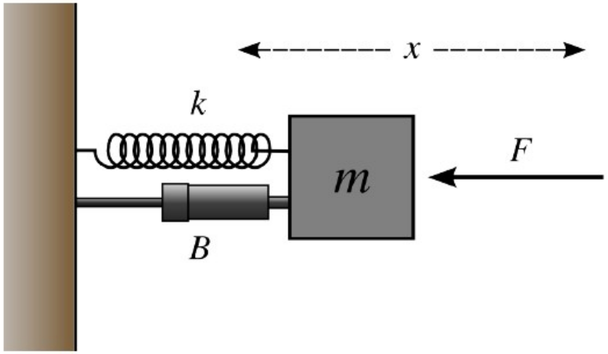
Benone+ (2015)
[arXiv:1412.7278]

Nuvens em análogos

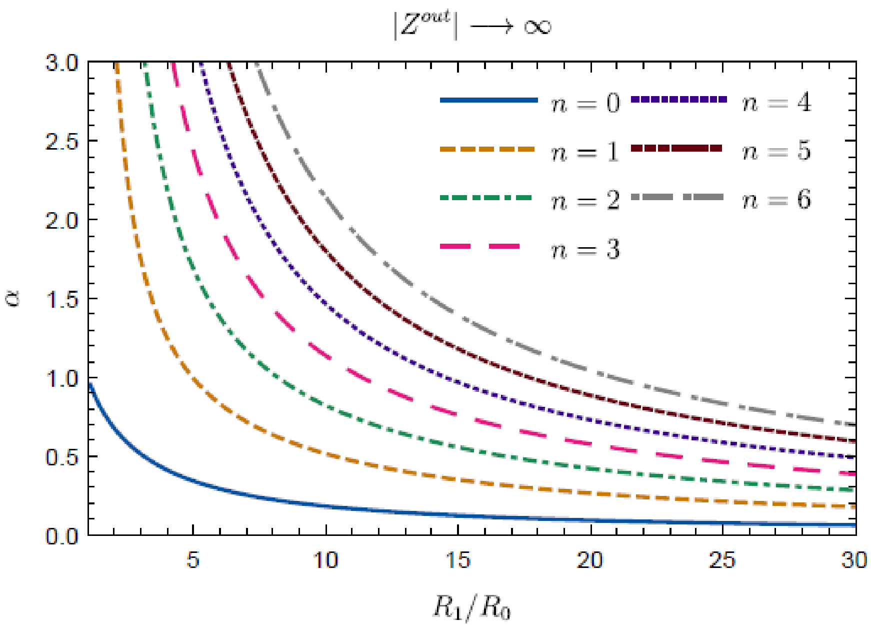
Cardoso+ (2016)
[arXiv:1607.01378v2]

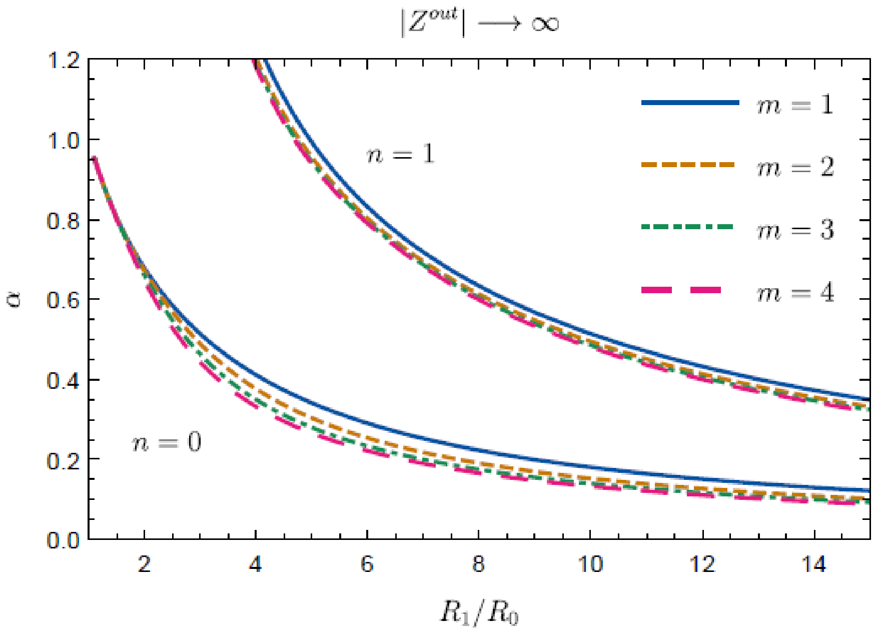


$$Z_\omega = R + i\left(\frac{k}{\omega} - m\omega\right)$$



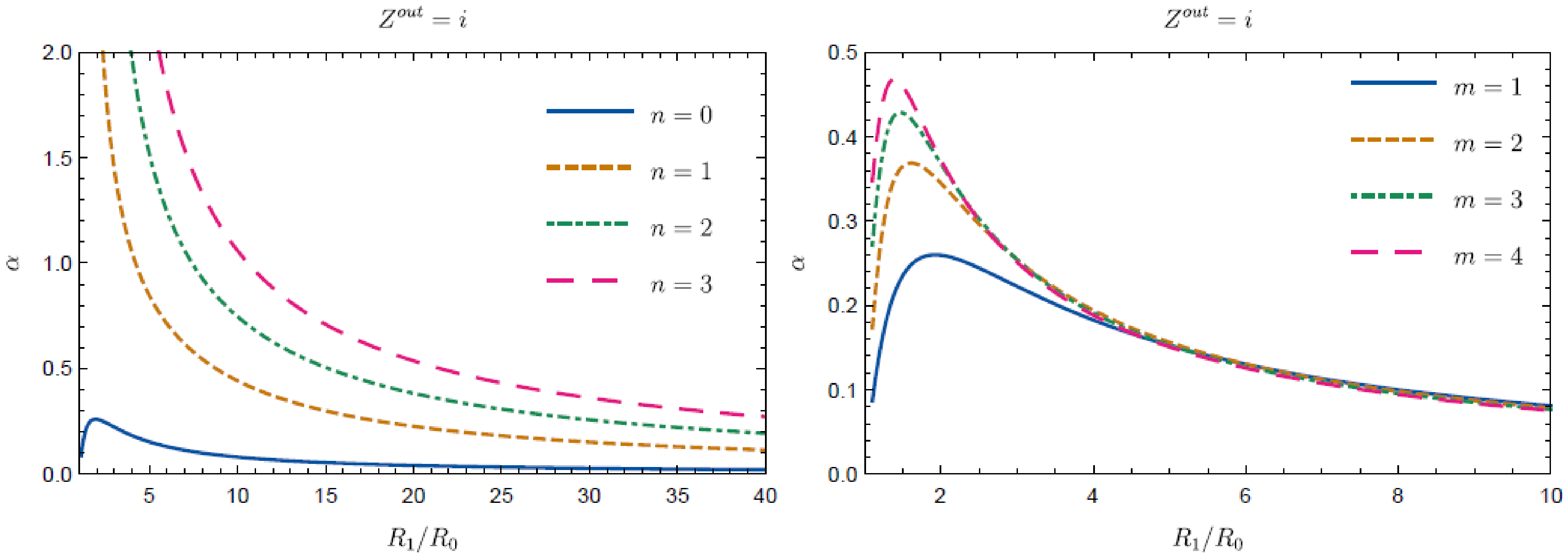
Nuvens em análogos





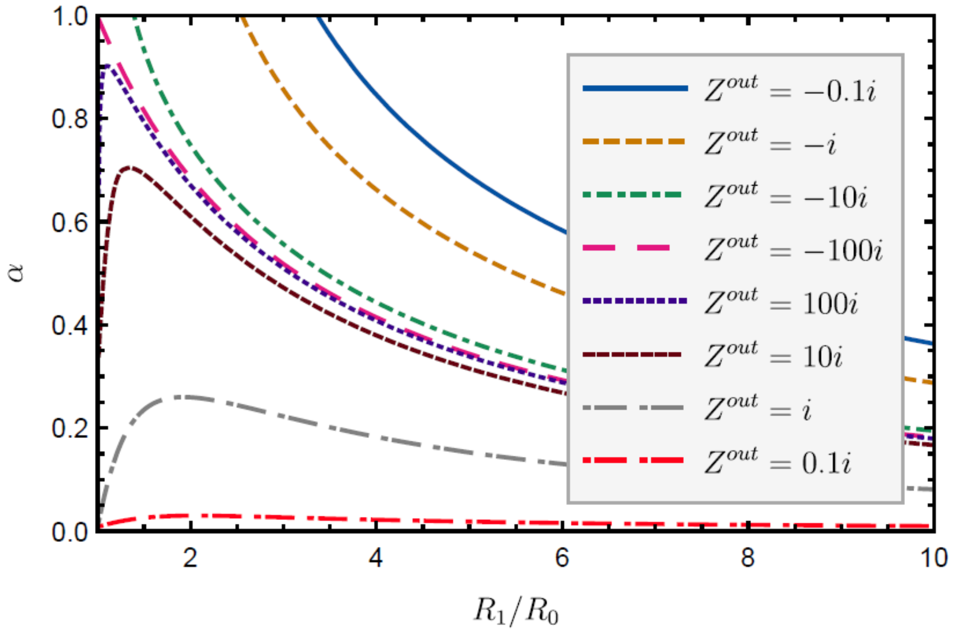
Benone+ (2018)
[arXiv:1809.03952v2]

Nuvens em análogos



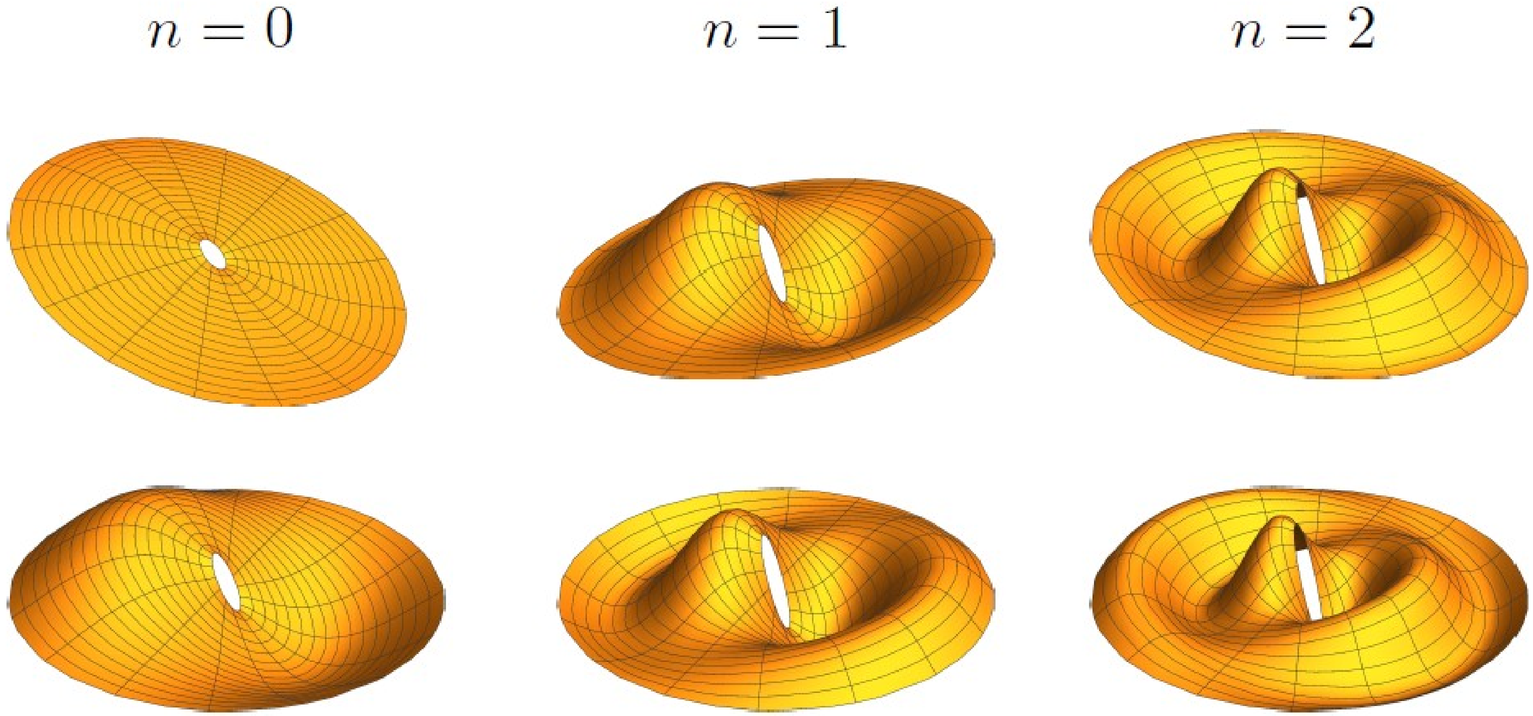
Benone+ (2018)
[arXiv:1809.03952v2]

Nuvens em análogos



Benone+ (2018)
[arXiv:1809.03952v2]

Nuvens em análogos

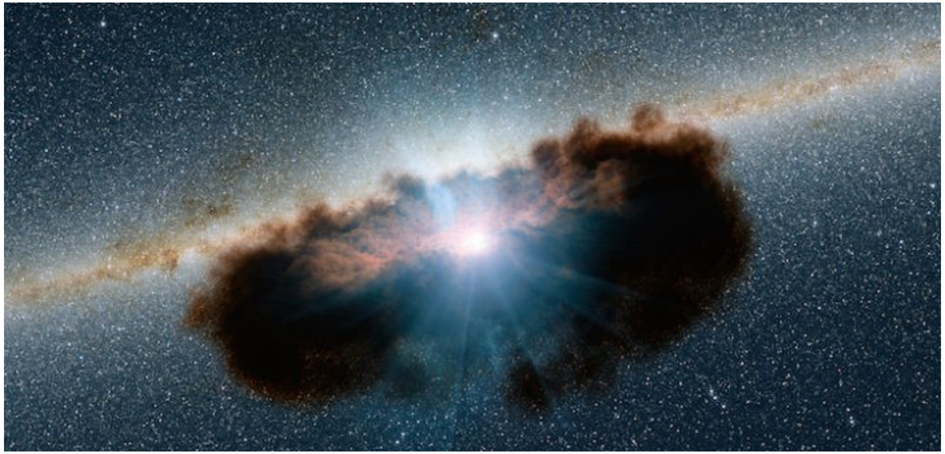


Benone+ (2018)
[arXiv:1809.03952v2]

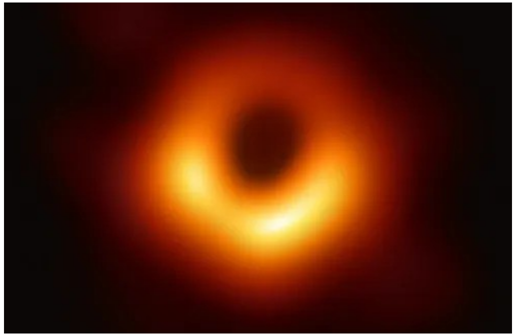
Parte I: Nuvens e buracos negros cabeludos

Parte II: Absorção e espalhamento por buracos negros

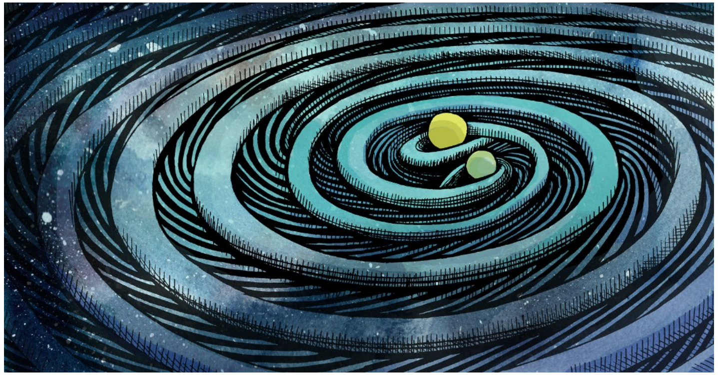
Absorção e espalhamento



Fonte: NASA/JPL-Caltech



Crédito: EHT



Crédito: Sandbox Studio

Absorção em ETs estáticos

Simpson&Visser (2019)
[arXiv:1812.07114v3]

$$ds^2 = -\left(1 - \frac{2M}{\sqrt{r^2 + a^2}}\right)dt^2 + \left(1 - \frac{2M}{\sqrt{r^2 + a^2}}\right)^{-1} dr^2 + (r^2 + a^2)(d\theta^2 + \sin^2\theta d\varphi^2)$$

$a = 0 \longrightarrow$ Buraco negro de Schwarzschild

$0 < a < 2M \longrightarrow$ Buraco negro regular

$a = 2M \longrightarrow$ Buraco de minhoca atravessável em um sentido

$a > 2M \longrightarrow$ Buraco de minhoca atravessável em dois sentidos

Absorção em ETs estáticos

$$\nabla^{\mu}\nabla_{\mu}\Phi = 0$$

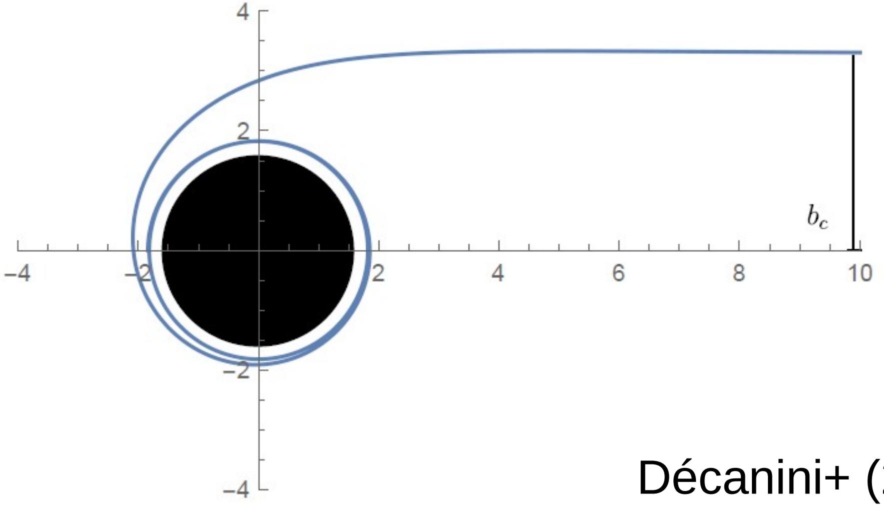
$$\Phi = \sum_{l,m} \frac{\phi(r)}{(r^2 + a^2)^{\frac{1}{2}}} Y_{lm}(\theta, \varphi) e^{-i\omega t}$$

$$f(r)\frac{d}{dr}\left(f(r)\frac{d\phi(r)}{dr}\right) + [\omega^2 - V_{\mathrm{eff}}]\phi(r) = 0$$

$$\phi(r) \approx \begin{cases} e^{-i\omega x} + e^{i\omega x} R_{\omega l}, & r \to +\infty (x \to +\infty), \\ T_{\omega l} e^{-i\omega x}, & r \to r_h (x \to -\infty). \end{cases}$$

$$\sigma_{\mathrm{abs}} = \sum_{l=0}^{\infty} \sigma_l \qquad \sigma_l = \frac{\pi}{\omega^2}(2l+1)|T_{\omega l}|^2$$

Absorção em ETs estáticos



$$\sigma_{\text{geo}} = \pi b_c^2$$

$$\sigma_{\text{hf}} \approx \sigma_{\text{geo}} + \sigma_{\text{osc}}$$

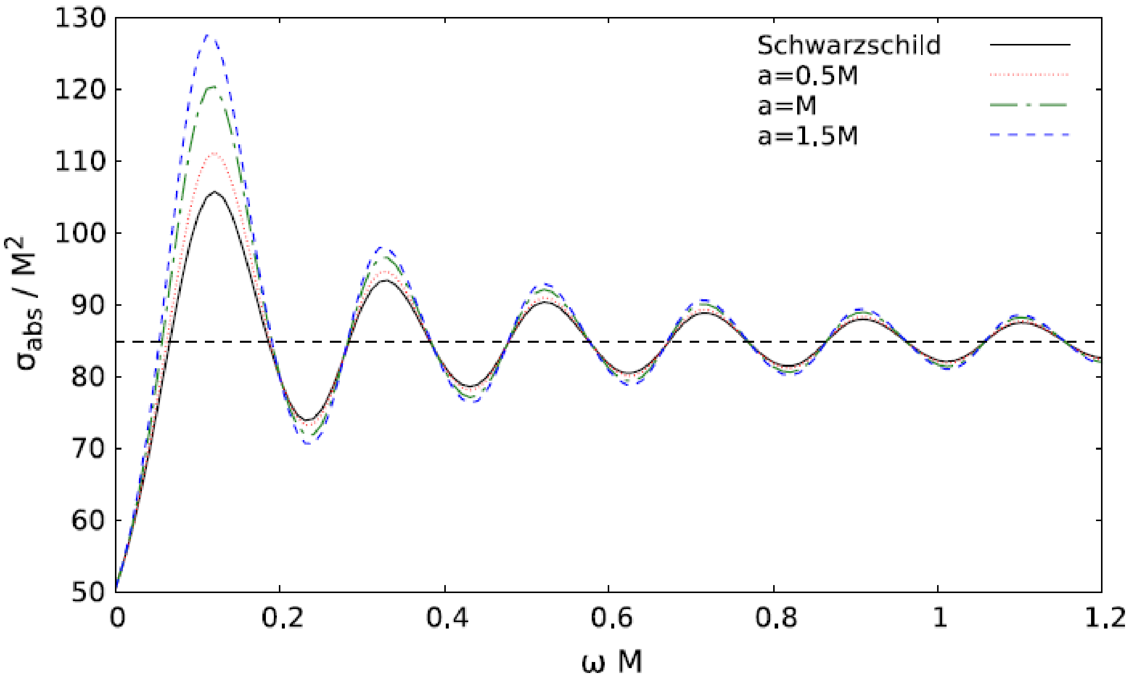
$$\sigma_{\text{osc}} = -\frac{8\pi\lambda_l}{\Omega_l} e^{-\frac{\pi\lambda_l}{\Omega_l}} \operatorname{sinc}\left(\frac{2\pi\omega}{\Omega_l}\right) \sigma_{\text{geo}}$$

Décanini+ (2011)
[arXiv:1101.0781v2]

$$\sigma_{lf} = A_h$$

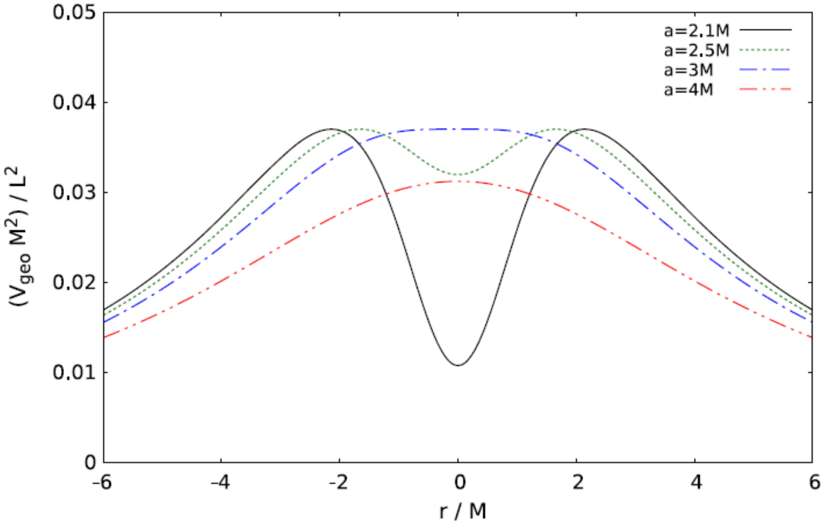
Das+ (1997)
[arXiv:hep-th/9609052]

Absorção em ETs estáticos

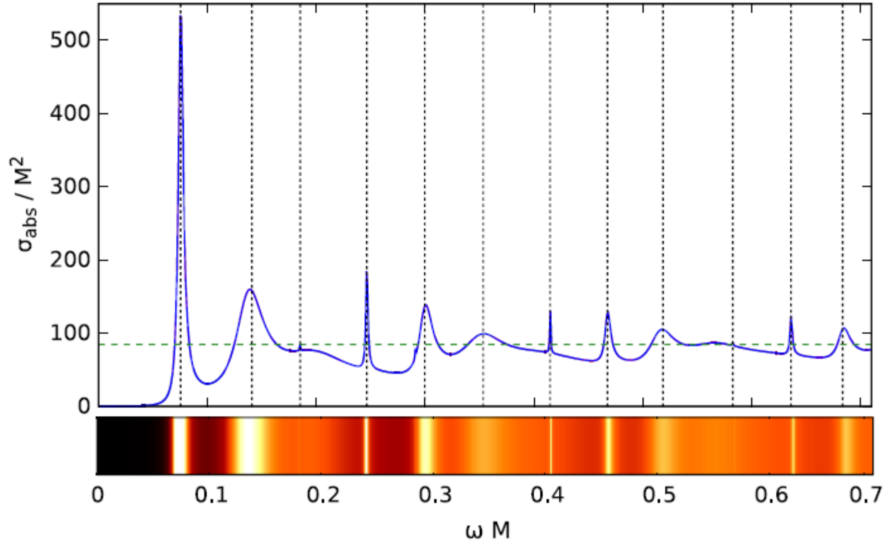


Junior+ (2020)
[arXiv:2006.03967]

Absorção em ETs estáticos

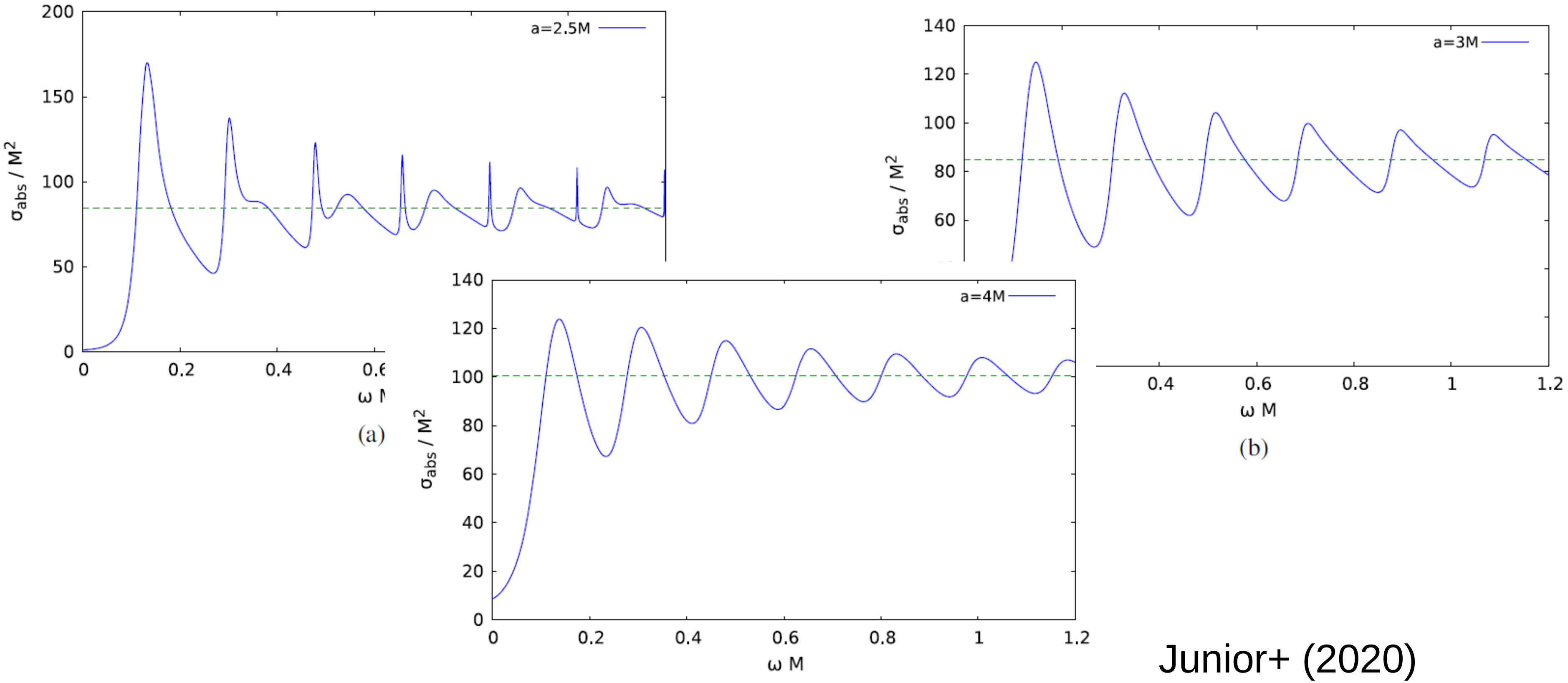


l	ω_R	$-\mathrm{i}\omega_I$	l	ω_R	$-\mathrm{i}\omega_I$
0	0.0753	2.673×10^{-3}	1	0.1852	4.249×10^{-5}
0	0.1408	8.304×10^{-3}	1	0.2464	1.011×10^{-3}
			1	0.2996	7.578×10^{-3}
			1	0.3532	9.417×10^{-3}
2	0.4147	3.432×10^{-4}	3	0.6360	1.222×10^{-3}
2	0.4674	3.154×10^{-3}	3	0.6834	6.861×10^{-3}
2	0.5184	9.281×10^{-3}	3	0.5825	1.096×10^{-4}



Junior+ (2020)
[arXiv:2006.03967]

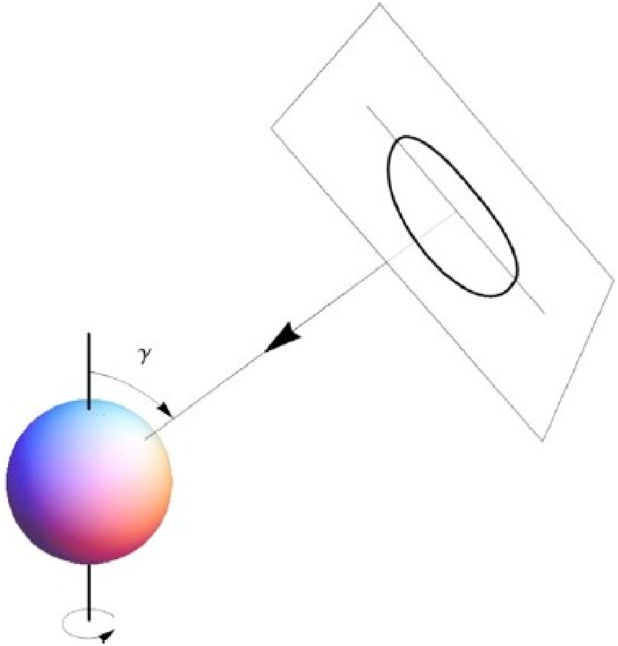
Absorção em ETs estáticos



(a) (b) (c)

Junior+ (2020)
[arXiv:2006.03967]

Absorção em ETs estacionários



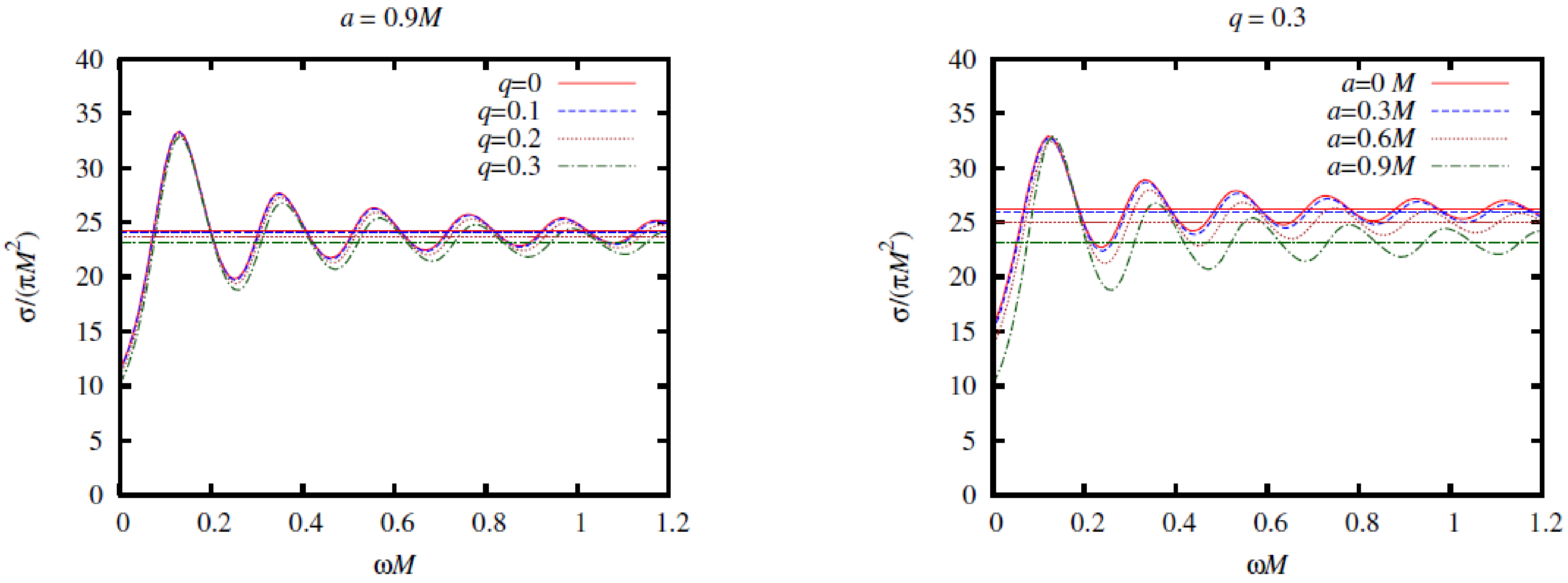
Fonte: Macedo+ (2013)
[arXiv:1308.0018]

$$\sigma = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{4\pi^2}{\omega^2} |S_{\omega lm}(\gamma)|^2 \left(1 - \left|\frac{\mathcal{R}_{\omega lm}}{\mathcal{I}_{\omega lm}}\right|^2\right)$$

$$\sigma^{\mathrm{co}} = \sum_{l=1} \sum_{m=1}^{l} \sigma_{l,m}$$

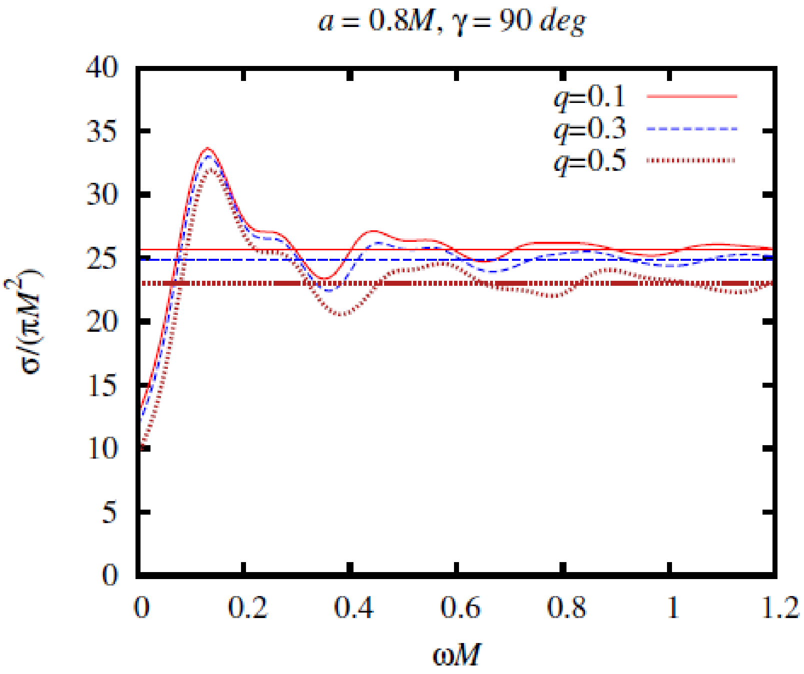
$$\sigma^{\mathrm{counter}} = \sum_{l=0} \sum_{m=0}^{l} \sigma_{l,-m}$$

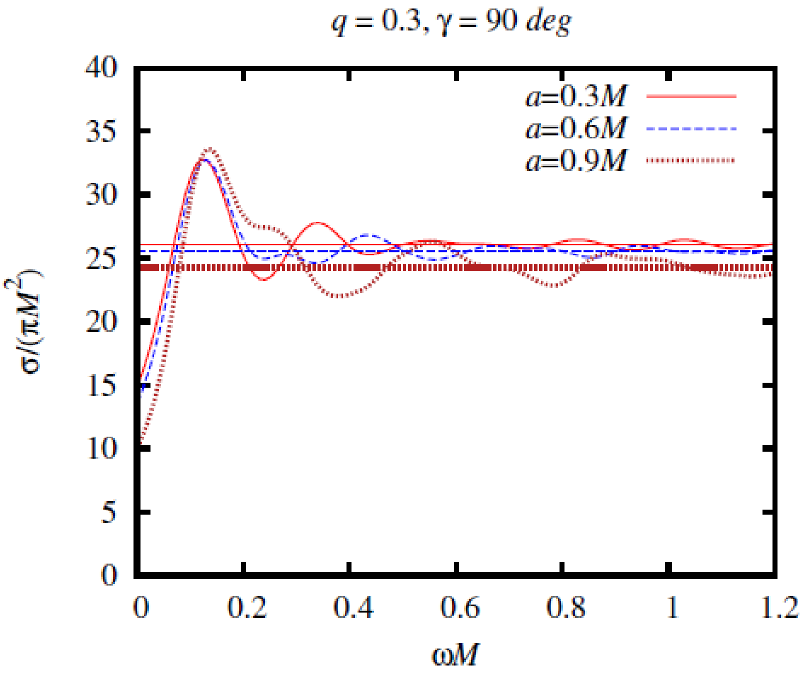
Absorção no eixo



Leite+ (2017)
[arXiv:1708.03370]

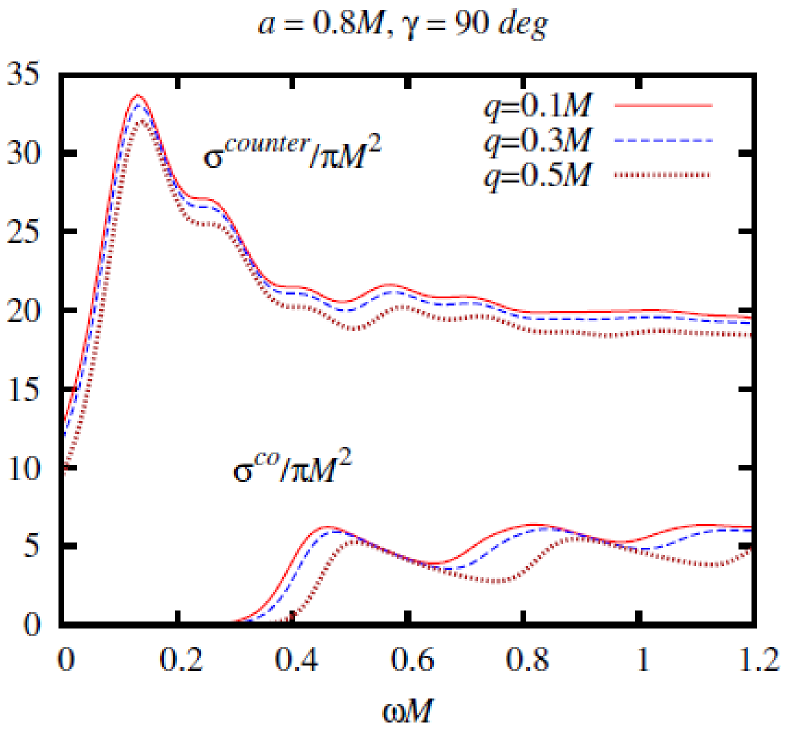
Absorção fora do eixo

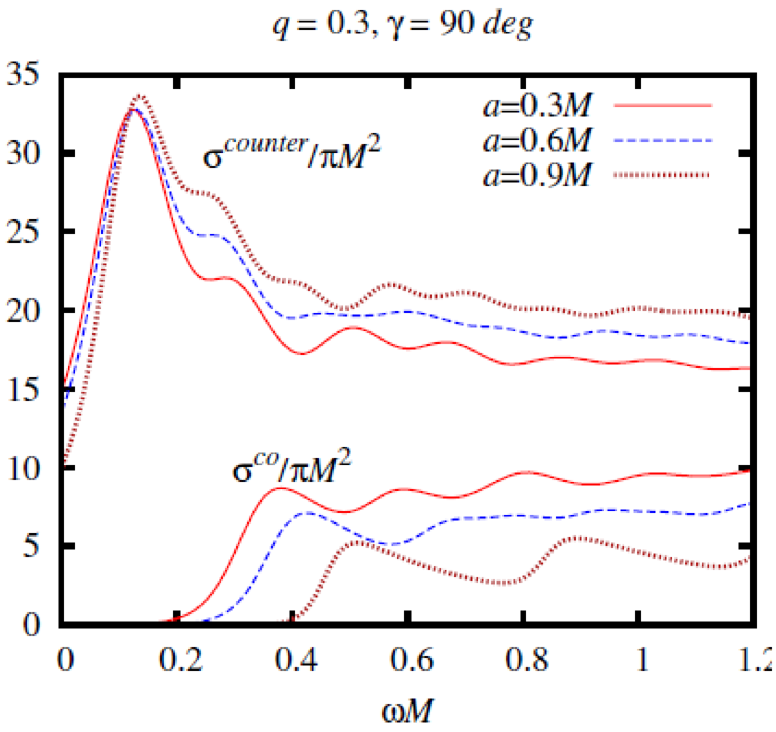




Leite+ (2017)
[arXiv:1708.03370]

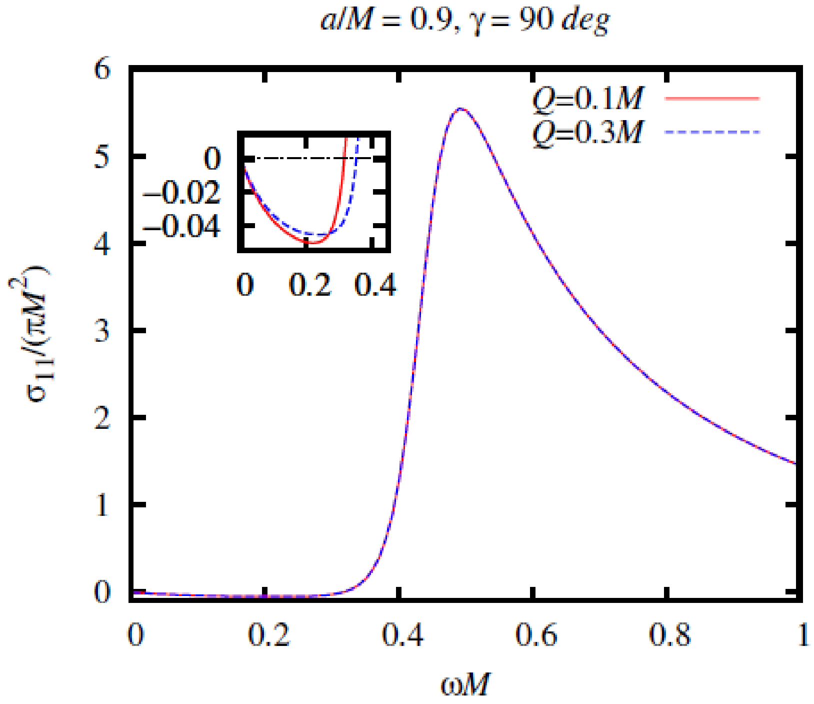
Absorção fora do eixo

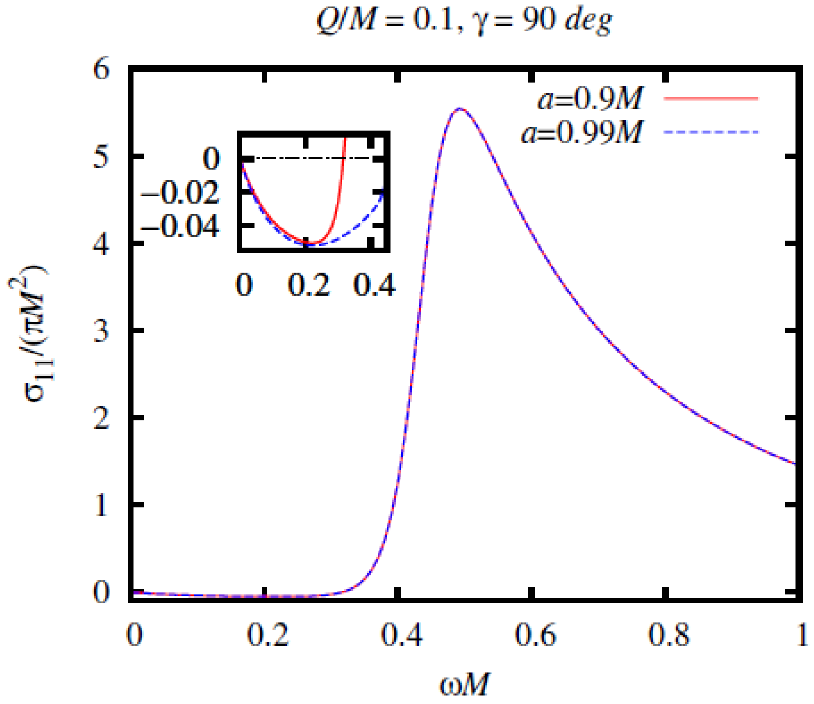




Leite+ (2017)
[arXiv:1708.03370]

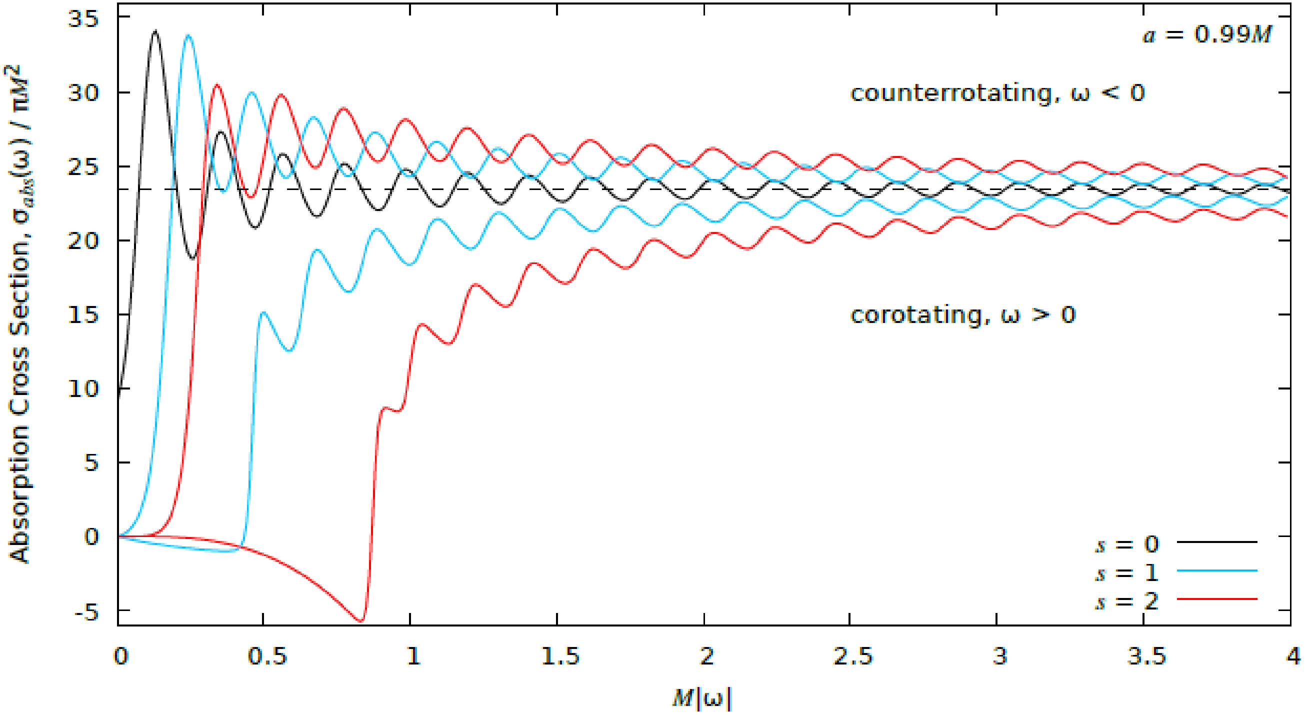
Superradiância





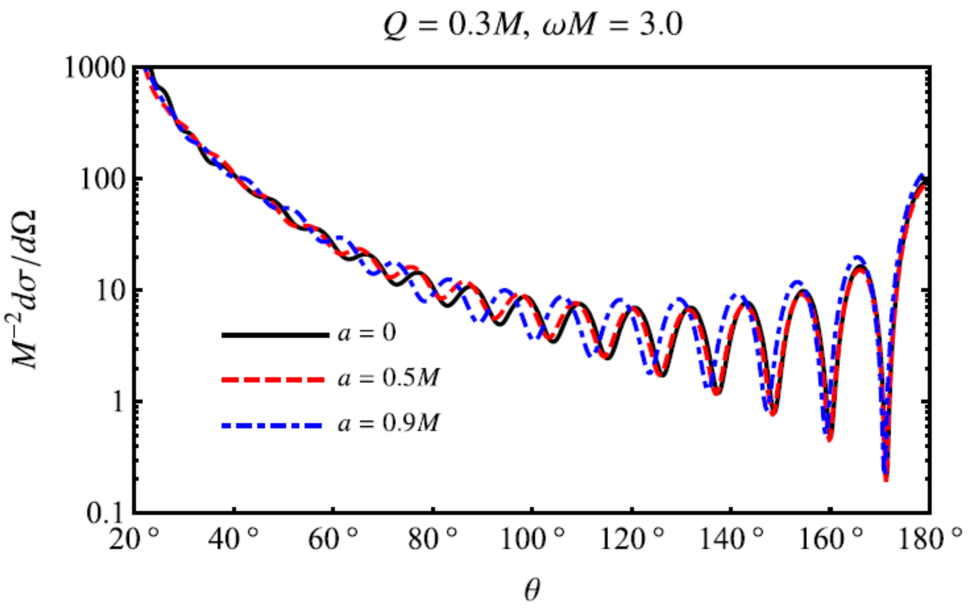
Leite+ (2017)
[arXiv:1708.03370]

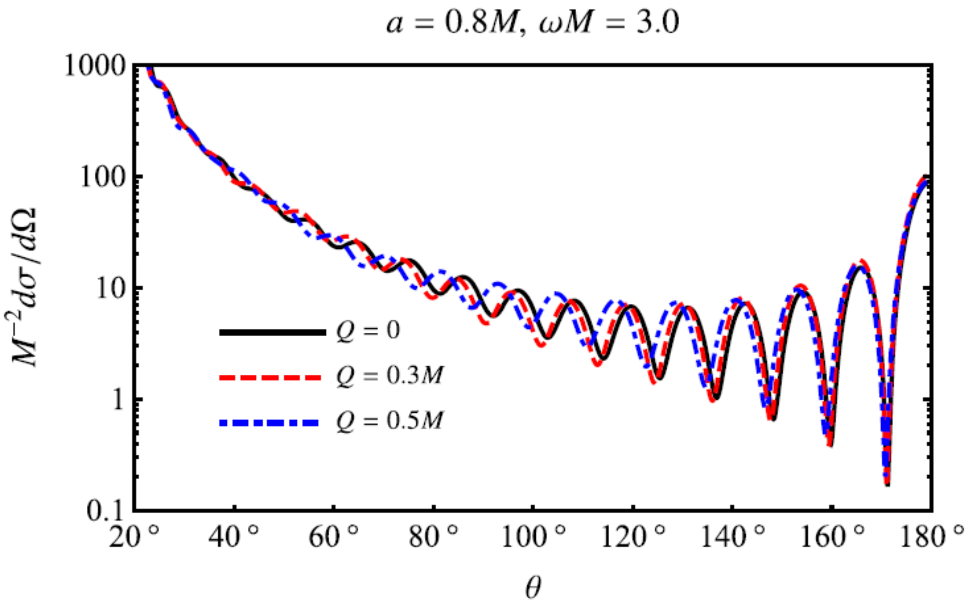
Absorção por campos bosônicos



Leite+ (2017)
[arXiv:1707.01144]

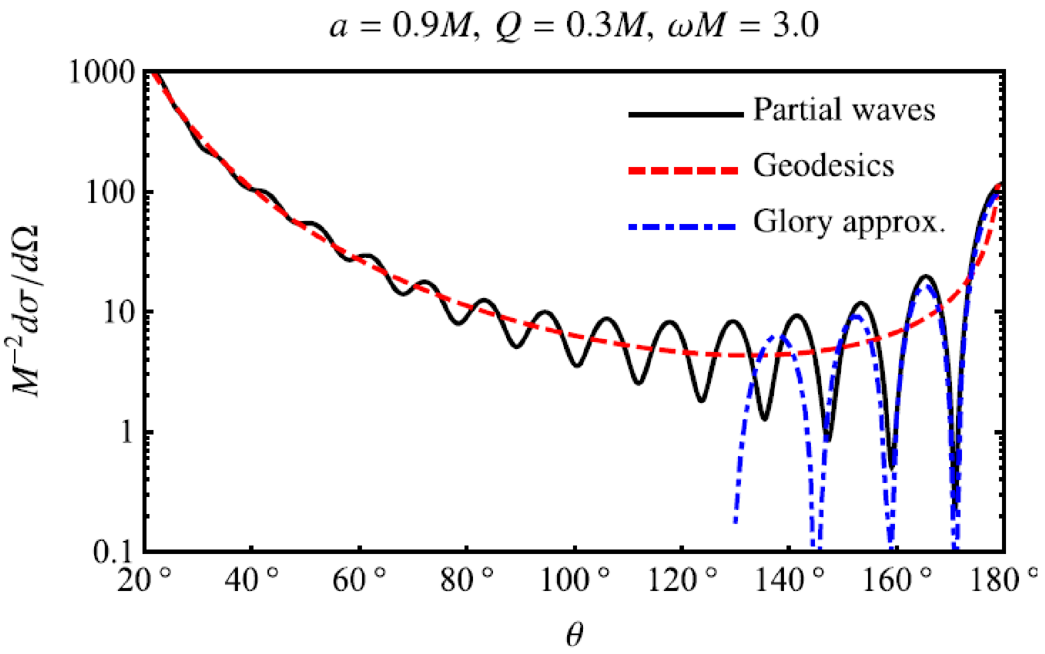
Espalhamento





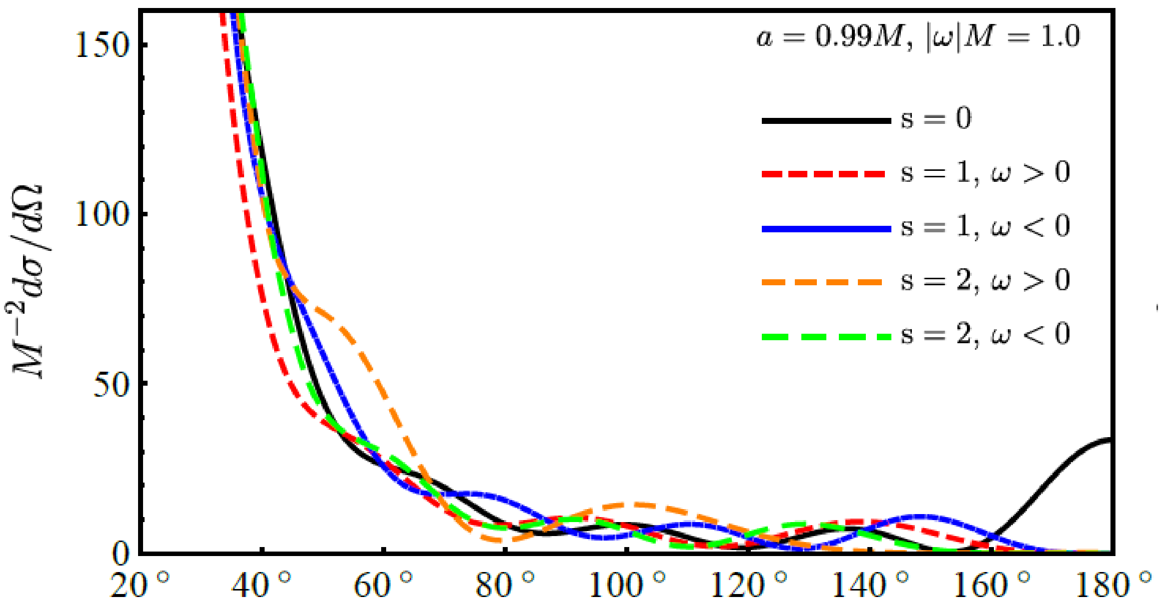
Leite+ (2019)
[arXiv:1907.04746]

Espalhamento



Leite+ (2019)
[arXiv:1907.04746]

Espalhamento



Leite+ (2019)
[arXiv:1910.07666]

Considerações finais

- Nuvens se formam espontaneamente
- Cabelo de proca é dinamicamente mais favorável do que cabelo escalar
- Objetos compactos podem apresentar características muito diferentes de buracos negros
- Observáveis astrofísicos?

Obrigada!