Black holes: Bald or hairy?

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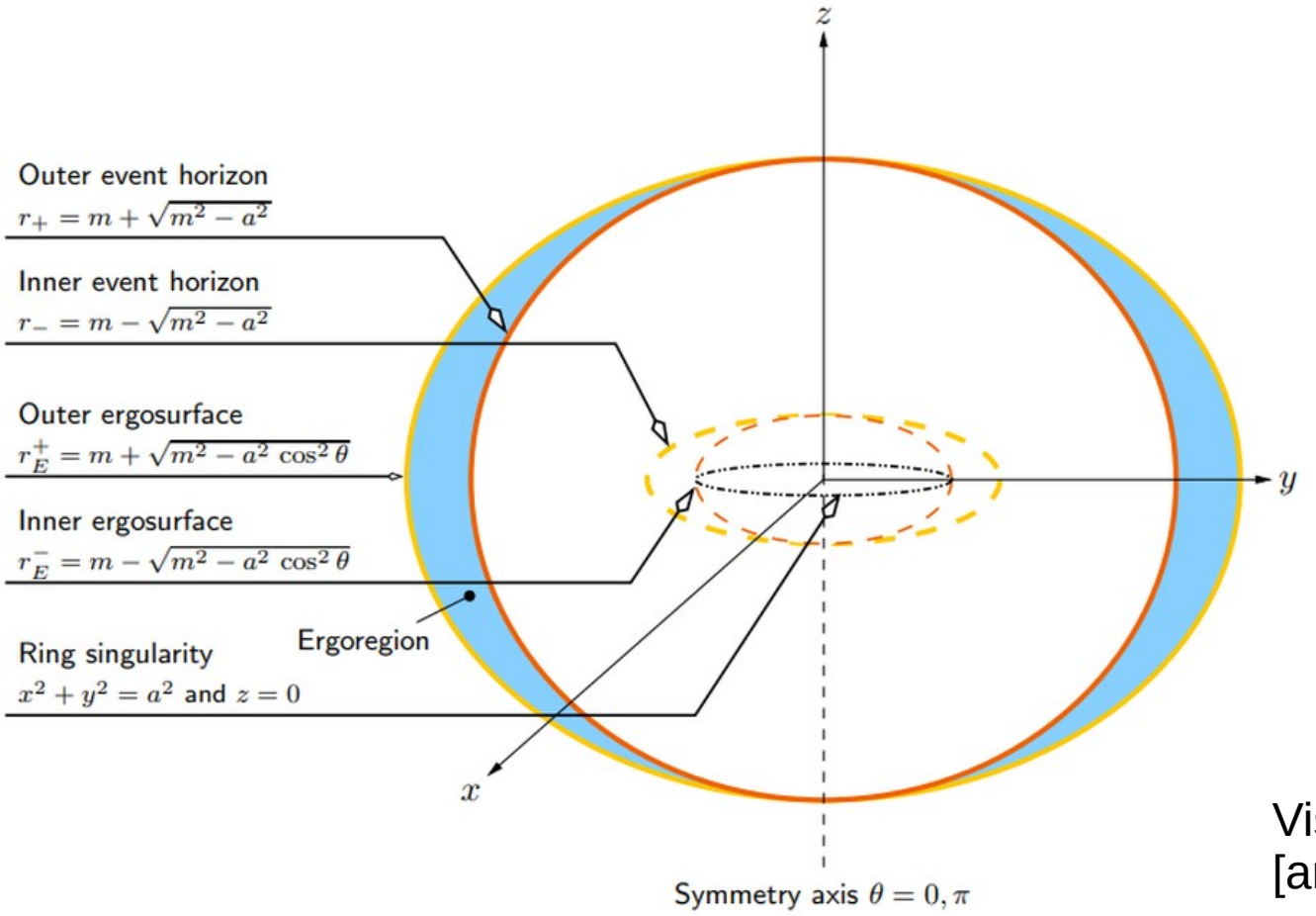
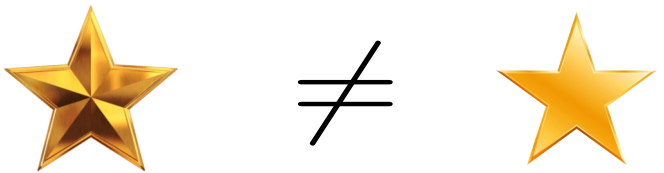
Black holes in electrovacuum

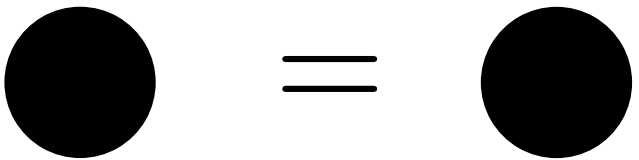


Visser(2008)
[arXiv:0706.0622v3]

Uniqueness theorems

M, J





Israel (1967)
Israel (1968)
Carter (1971)

“Black holes have no hair”

Bekenstein (1972)

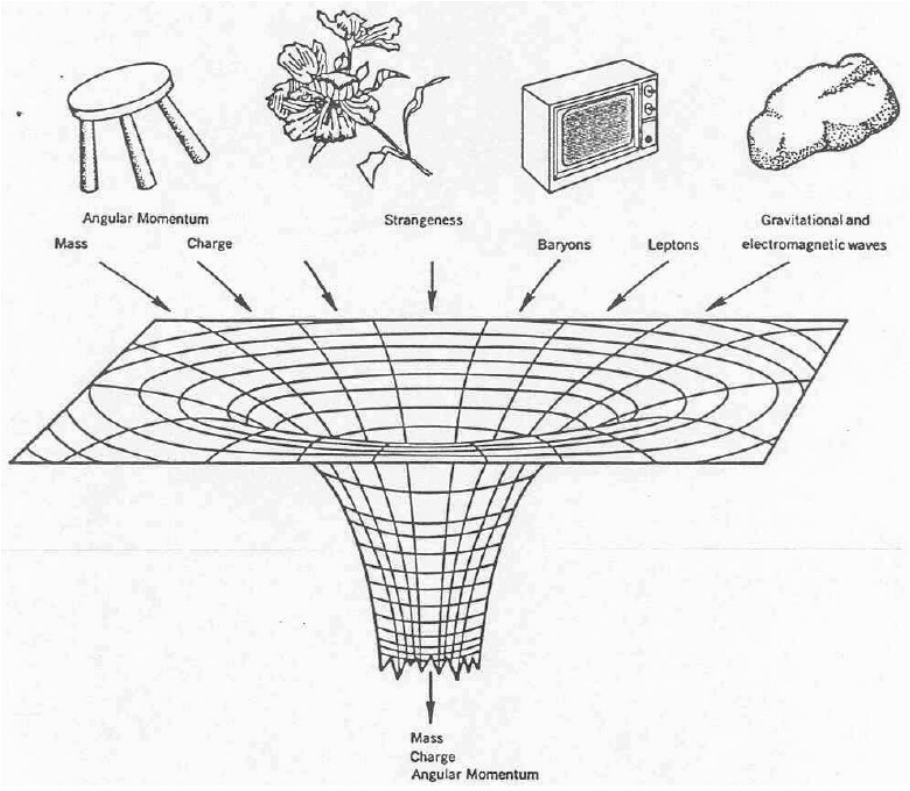
Herdeiro&Radu (2015)
[arXiv:1504.08209]

1. Canonical and minimally coupled field

2. Field inherits the spacetime symmetries

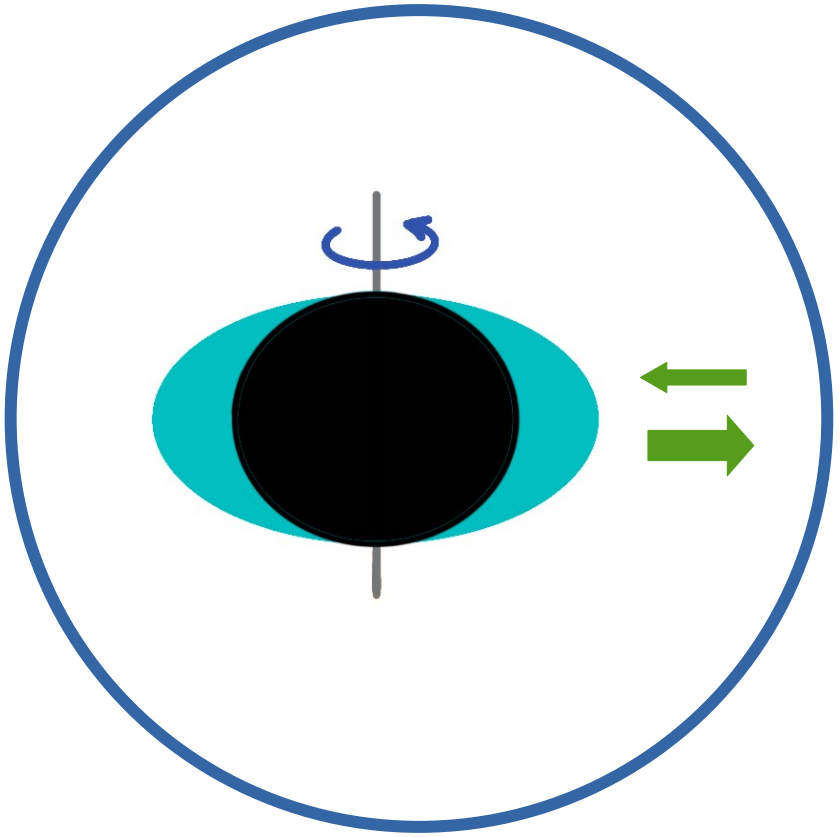
$$\partial_t \Phi = \partial_\phi \Phi = 0$$

3. Strong energy condition holds



Ruffini&Wheeler (1971)

Superradiance



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

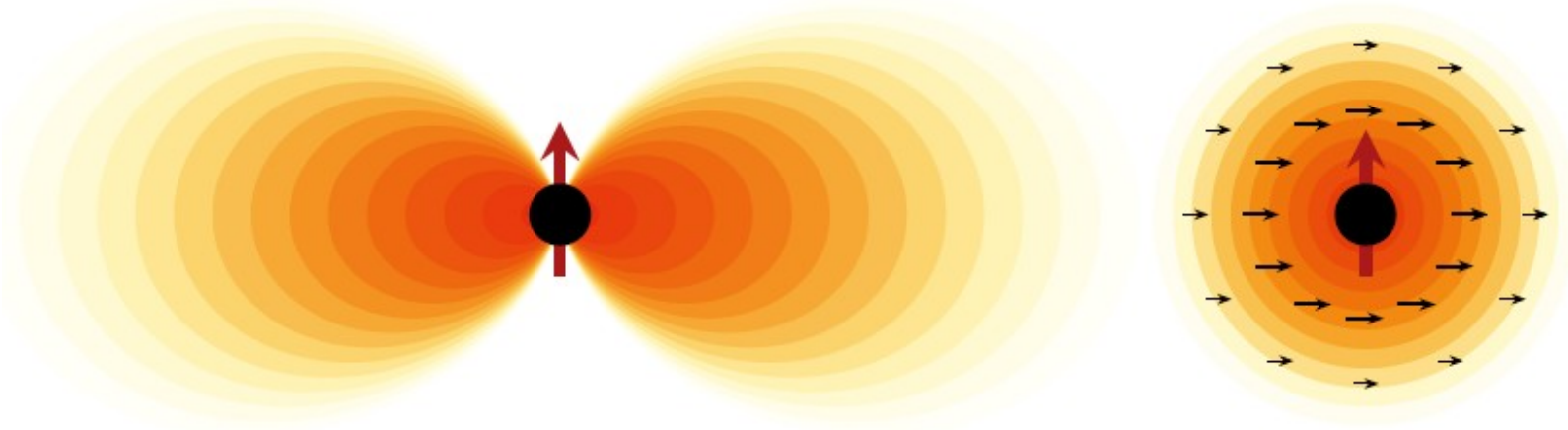
$$\frac{\omega}{m_j} = \Omega_{\mathrm{H}}$$

Gravitational atoms

Baumann+ (2019)
[arXiv:1908.10370]

Scalar

Proca



$|n,l,m\rangle$

$|n,l,j,m_j\rangle$

Scalar clouds

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

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

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

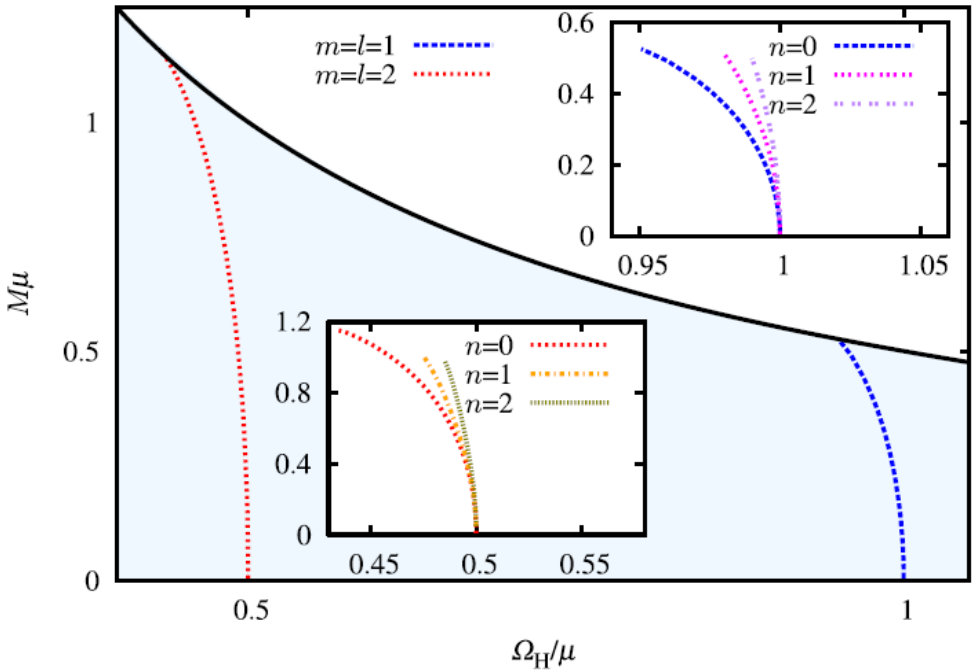
$$\Delta\frac{d}{dr}\left(\Delta\frac{dR_{lm}}{dr}\right) + [H^2 + (2ma\omega - K_{lm} - \mu^2(r^2+a^2))\Delta]R_{lm} = 0$$

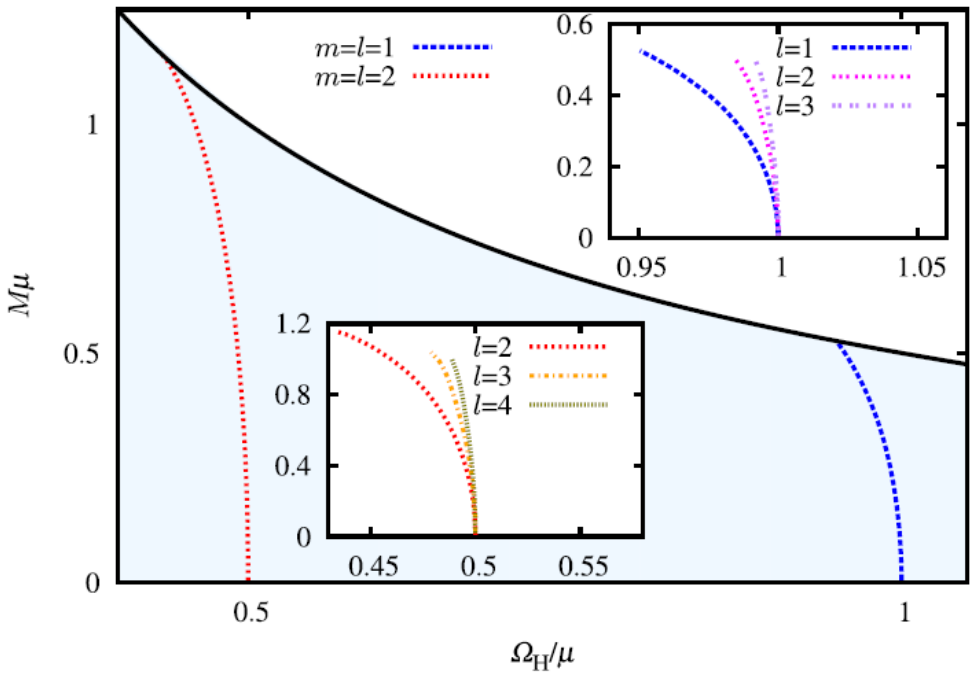
$$R_{lm}(r) \approx \begin{cases} e^{-i(\omega-\omega_c)r_*}, & \text{for } r \to r_+, \\ \frac{e^{-\sqrt{\mu^2-\omega^2}r}}{r}, & \text{for } r \to \infty, \end{cases}$$

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

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

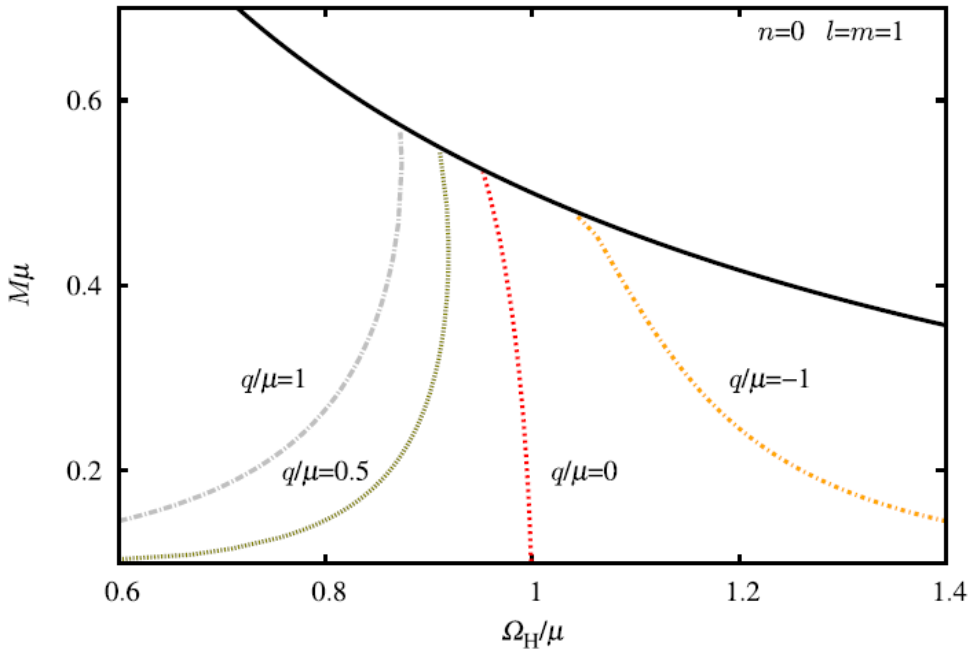
Scalar clouds

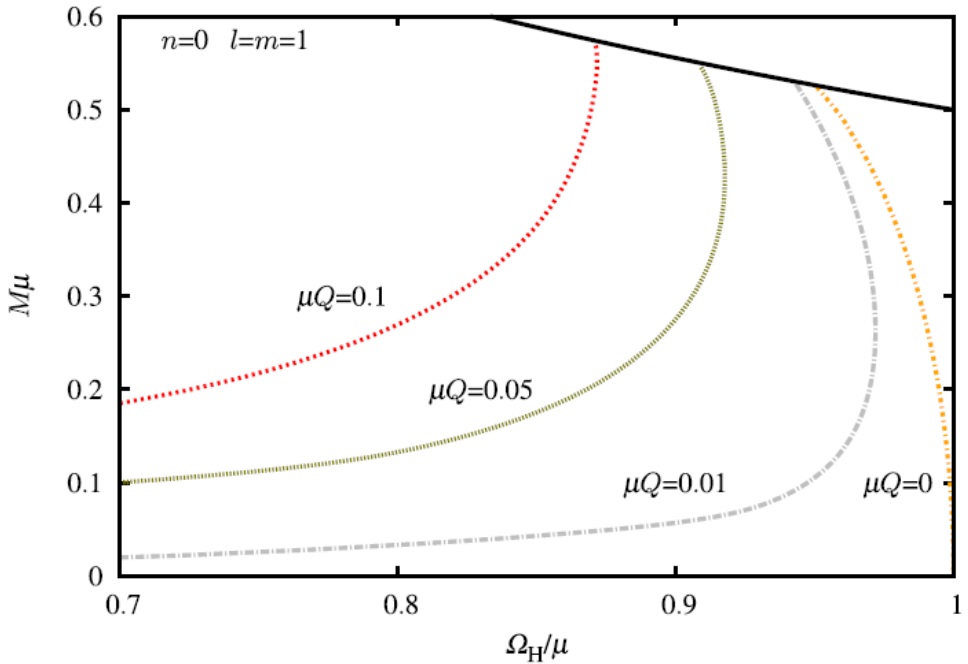




Benone+ (2014)
[arXiv:1409.1593v2]

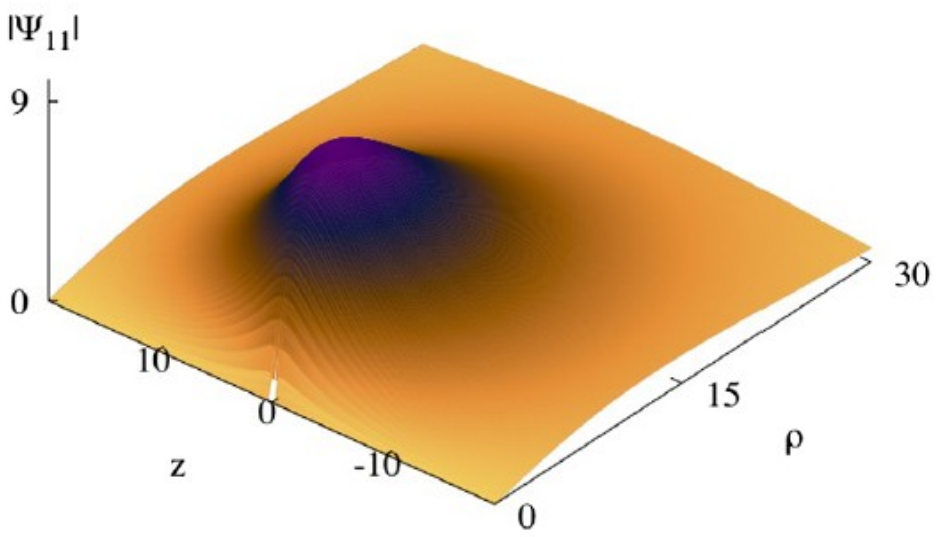
Scalar clouds

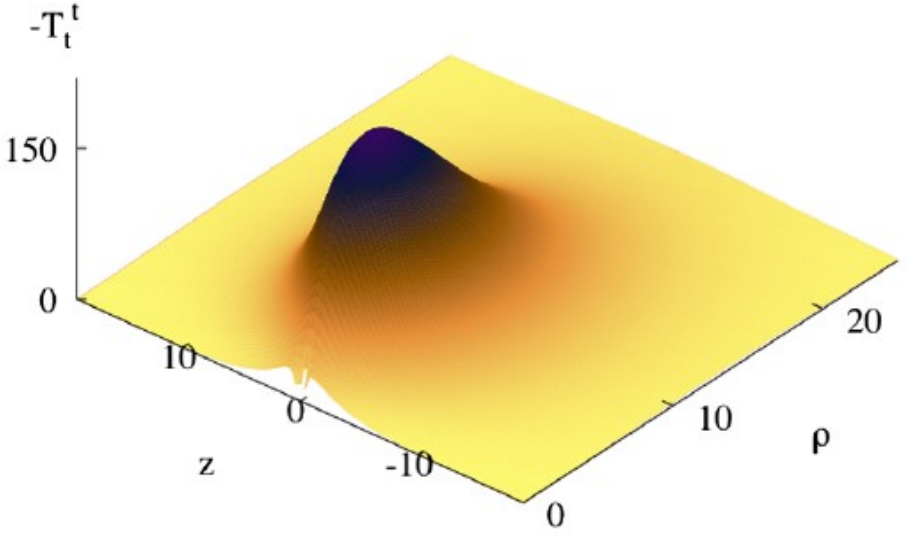




Benone+ (2014)
[arXiv:1409.1593v2]

Scalar clouds





Benone+ (2014)
[arXiv:1409.1593v2]

Proca clouds

$$\nabla_\beta F^{\alpha\beta} + \mu^2 A^\alpha = 0$$

$$(\Box - \mu^2) A^\alpha = 0$$

Frolov+ (2018)
[arXiv:1804.00030]

$$A^\alpha = B^{\alpha\beta}\nabla_\beta Z$$

$$Z(t, r, \theta, \phi) = R(r)S(\theta)e^{im_j\phi}e^{-i\omega t}$$

$$q_r \frac{\mathrm{d}}{\mathrm{d}r}\left[\frac{\Delta}{q_r}\frac{\mathrm{d}R}{\mathrm{d}r}\right] + \left[\frac{K_r^2}{\Delta} + \frac{2\lambda^2 - q_r}{q_r}\sigma\lambda - q_r\mu^2\right] R = 0$$

$$\frac{q_\theta}{\sin\theta}\frac{\mathrm{d}}{\mathrm{d}\theta}\left[\frac{\sin\theta}{q_\theta}\frac{\mathrm{d}S}{\mathrm{d}\theta}\right] - \left[\frac{K_\theta^2}{\sin^2\theta} + \frac{2\lambda^2 - q_\theta}{q_\theta}\sigma\lambda - q_\theta\mu^2\right] S = 0$$

Proca clouds

Baumann+ (2019)
[arXiv:1908.10370]

$$\lambda^{\rm E}_{\pm} = \sum_{n=0}^{\infty} \lambda^{\rm E}_{n,\pm} \alpha^n$$

$$\alpha = M\mu$$

$$\lim_{\omega^2 \to \mu^2} \lambda^{\rm M} = \frac{2a}{m_j + 1 - a\omega + \sqrt{(m_j + 1 - a\omega)^2 + 4a\omega}}$$

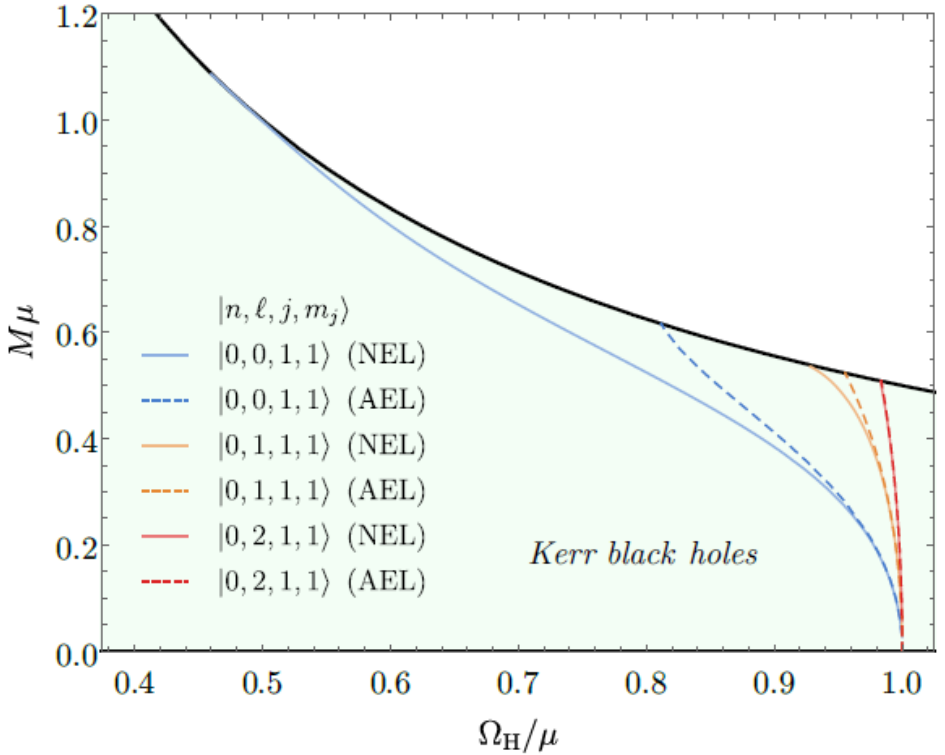
Dolan (2018)
[arXiv:1806.01604]

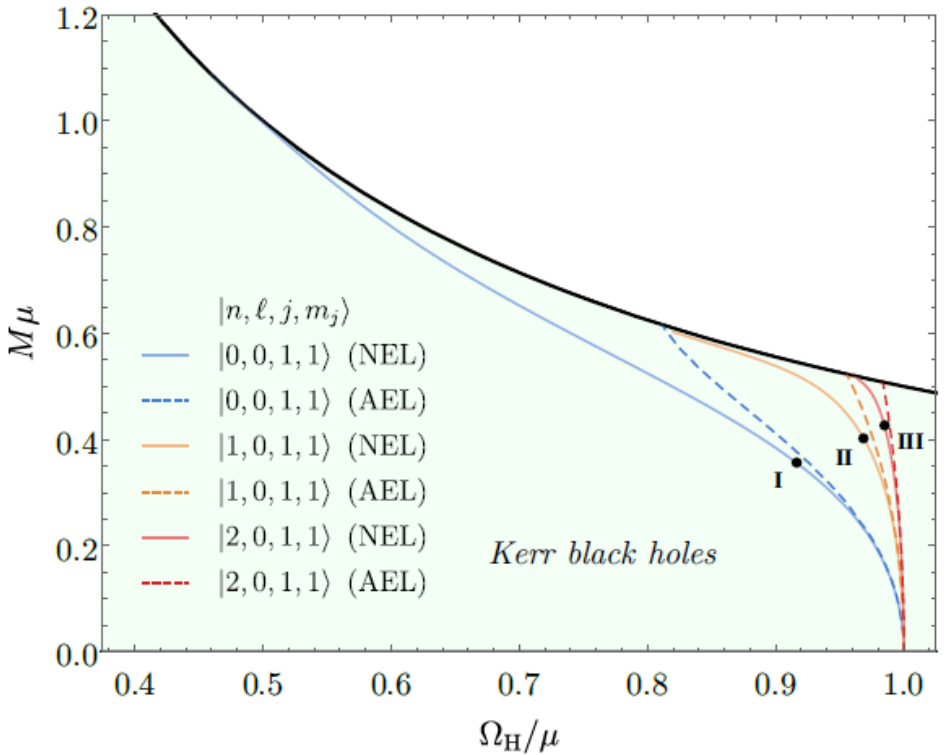
$$\omega^{(\rm V)}_{|n,\ell,j,m_j\rangle} = 1 - \frac{\alpha^2}{2\hat{n}^2} - \frac{\alpha^4}{8\hat{n}^4} + \frac{f_{\rm V}(n,\ell,j)}{\hat{n}^3}\alpha^4 + \frac{h_{\rm V}(\ell,j)}{\hat{n}^3}\frac{m_j a}{M}\alpha^5 + \dots$$

$$\alpha = \hat{n}(2\varpi)^{1/2}\left[1 - \frac{1}{4}g_{\rm V}\varpi + \frac{7}{32}g_{\rm V}^2\varpi^2 - \frac{33}{128}g_{\rm V}^3\varpi^3 + \dots\right]$$

$$\varpi = 1 - m_j\Omega_{\rm H}$$

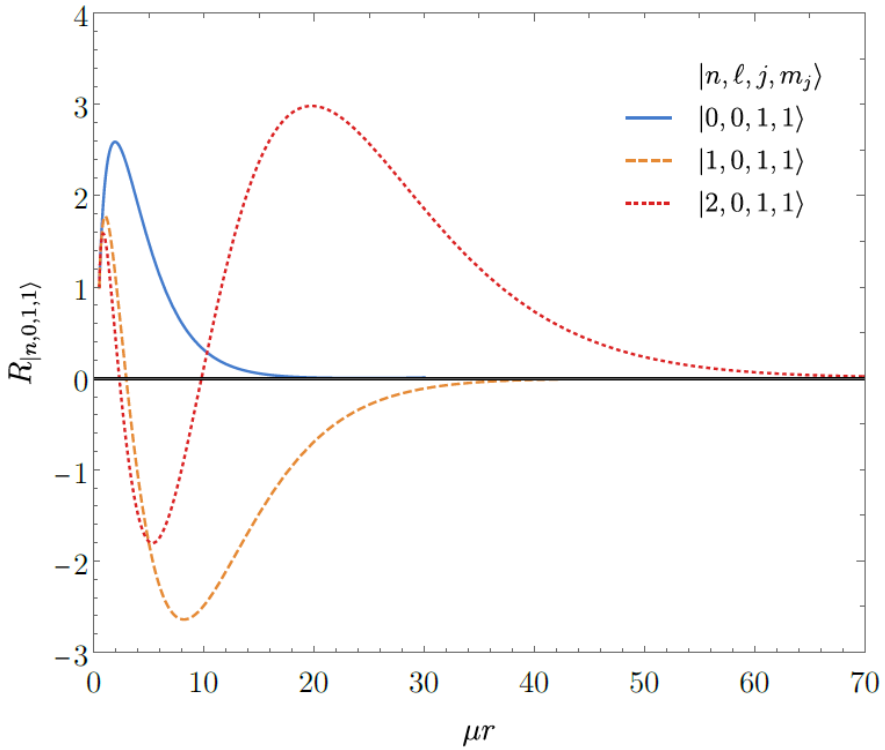
Proca clouds

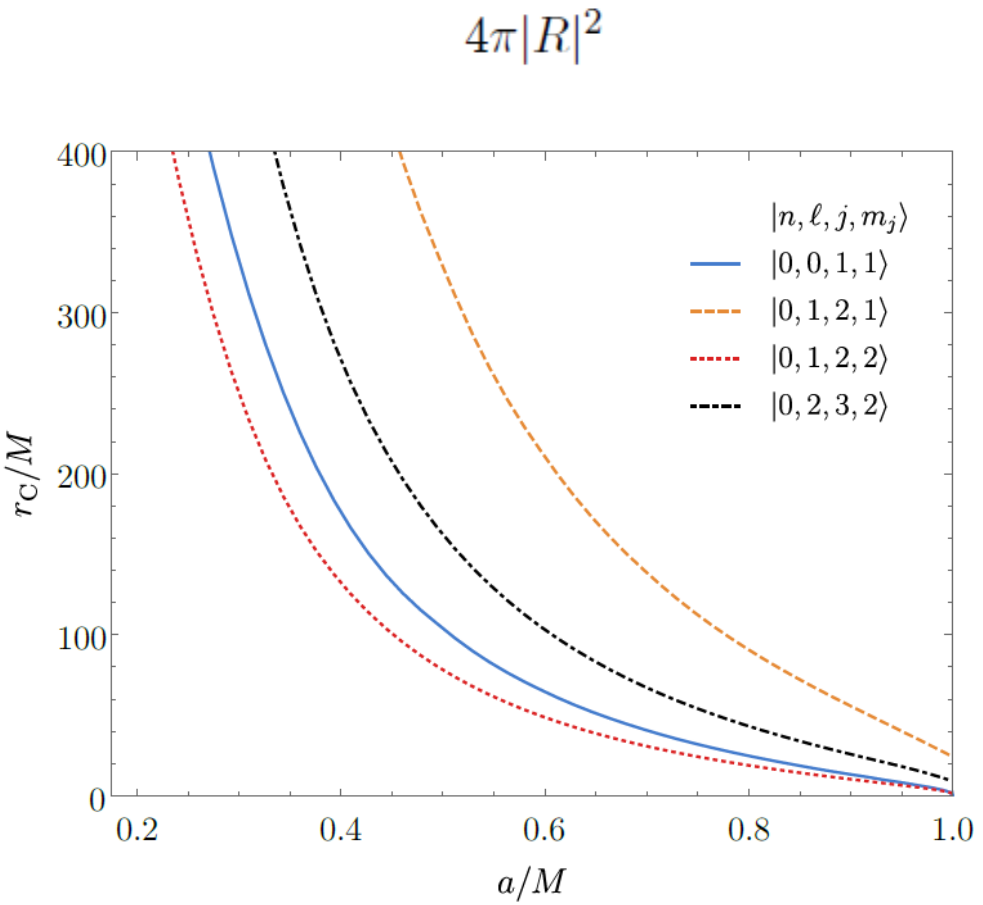




Santos+ (2020)
[arXiv:2004.09536]

Proca clouds

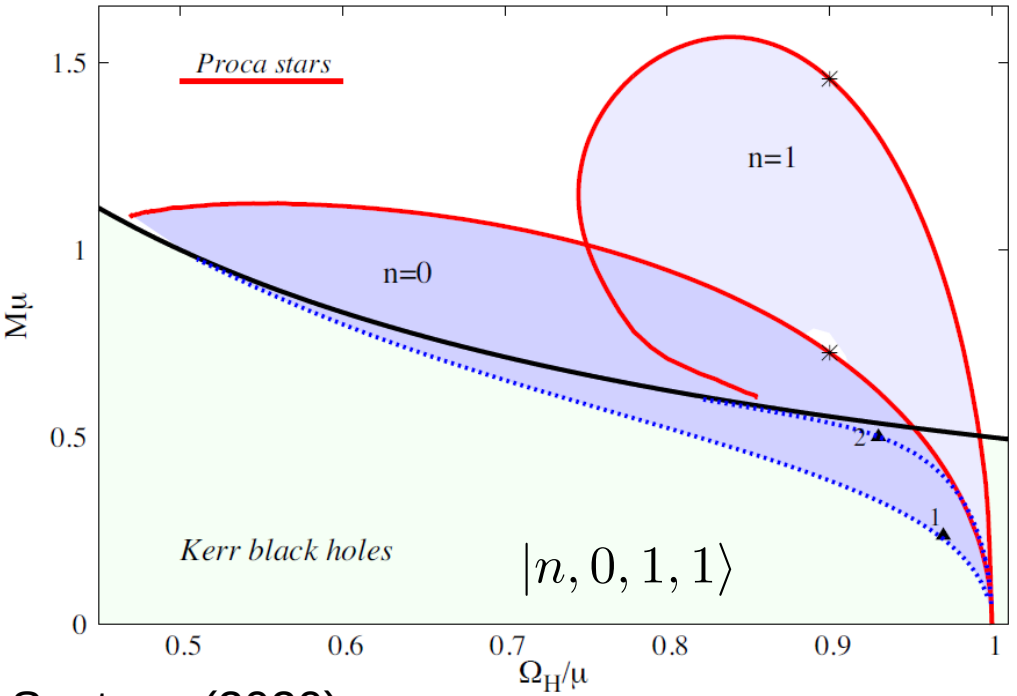


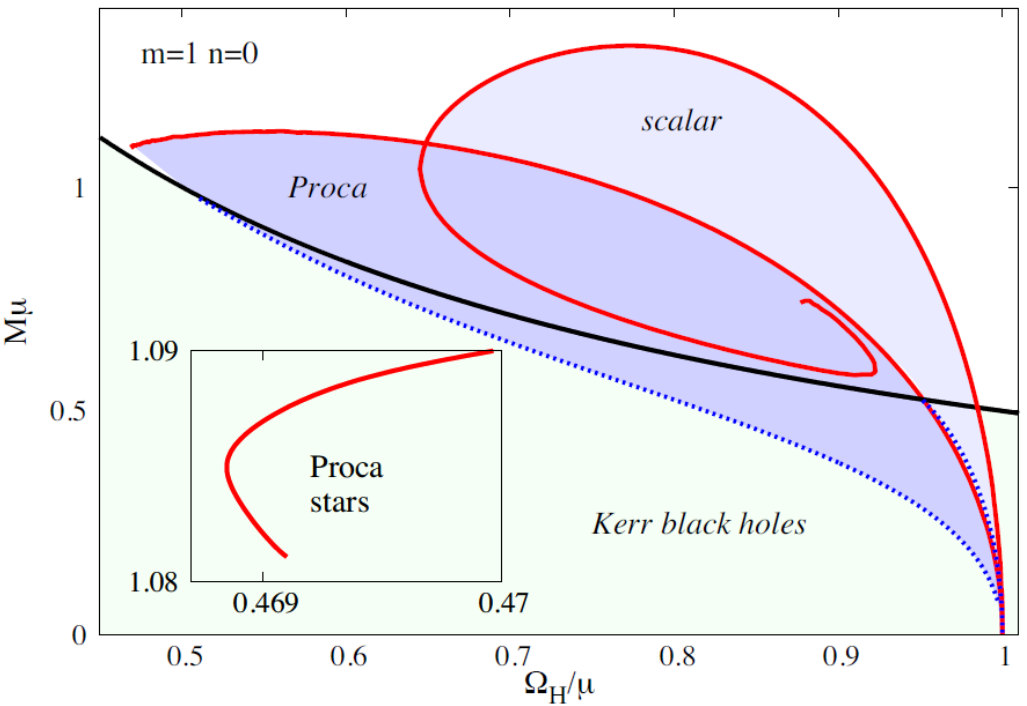


Santos+ (2020)
[arXiv:2004.09536]

Hairy black holes

Herdeiro+ (2016)
[arXiv:1603.02687]

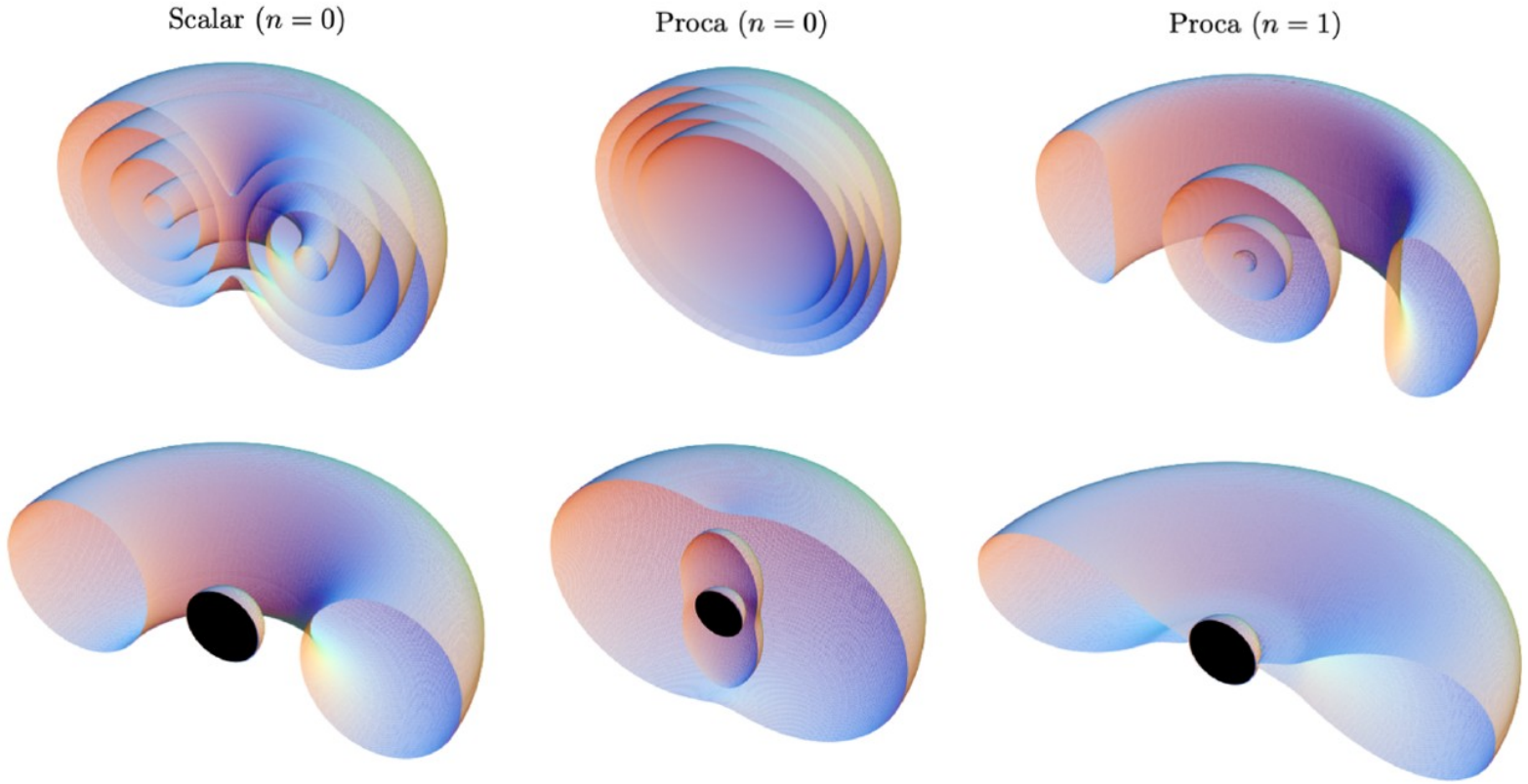




Santos+ (2020)
[arXiv:2004.09536]

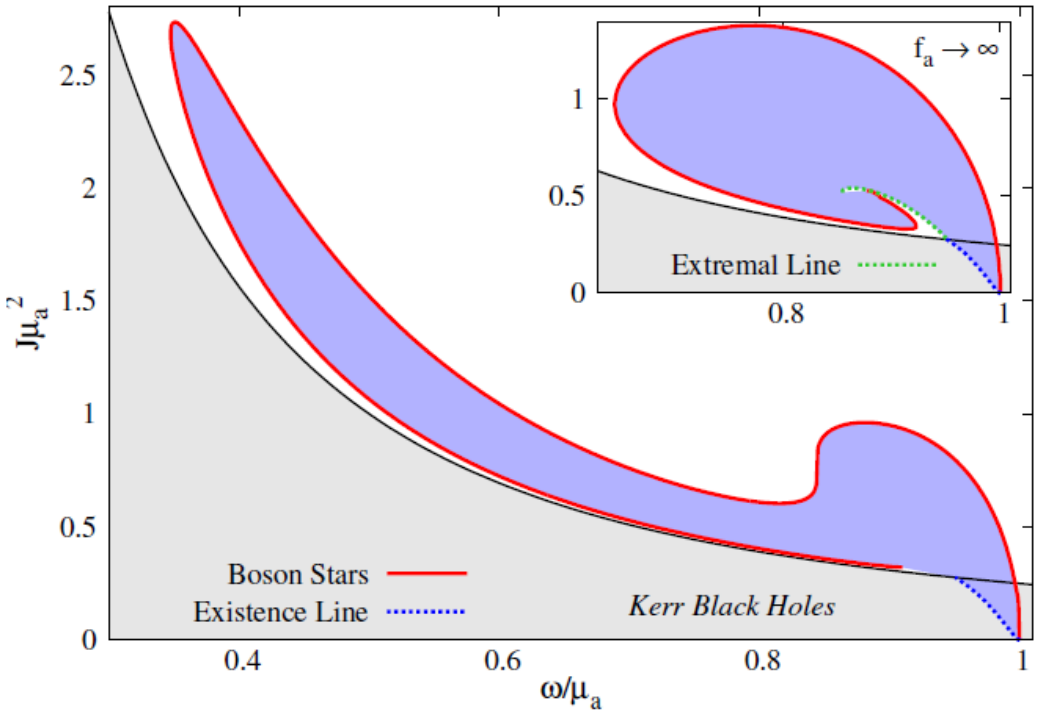
Hairy black holes

Sanchis-Gual+ (2016)
[arXiv:1907.12565]

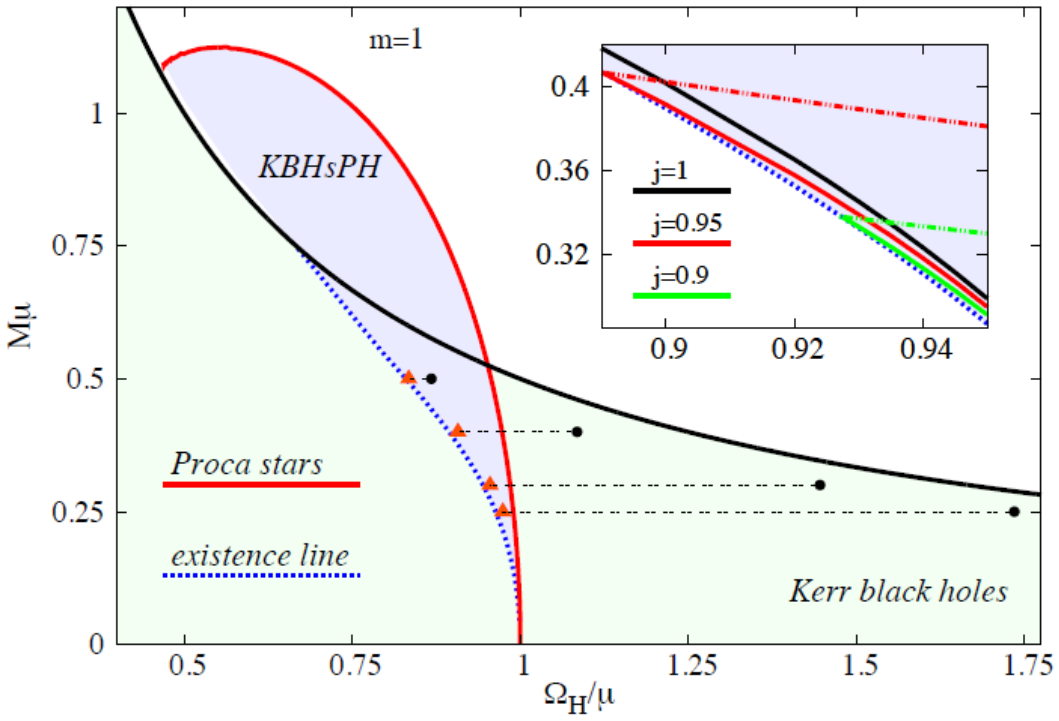


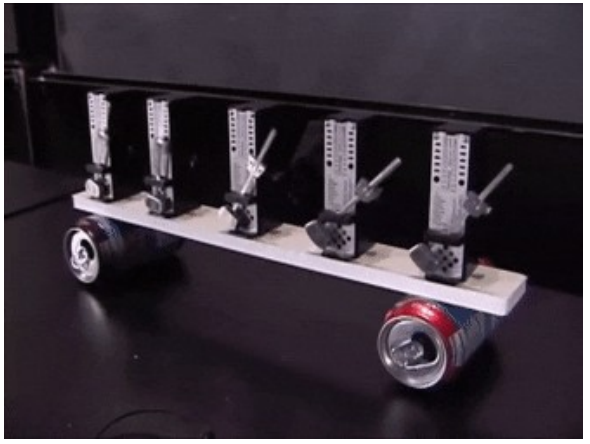
Hairy black holes

Delgado+ (2021)
[arXiv:2012.03952]



Formation mechanism

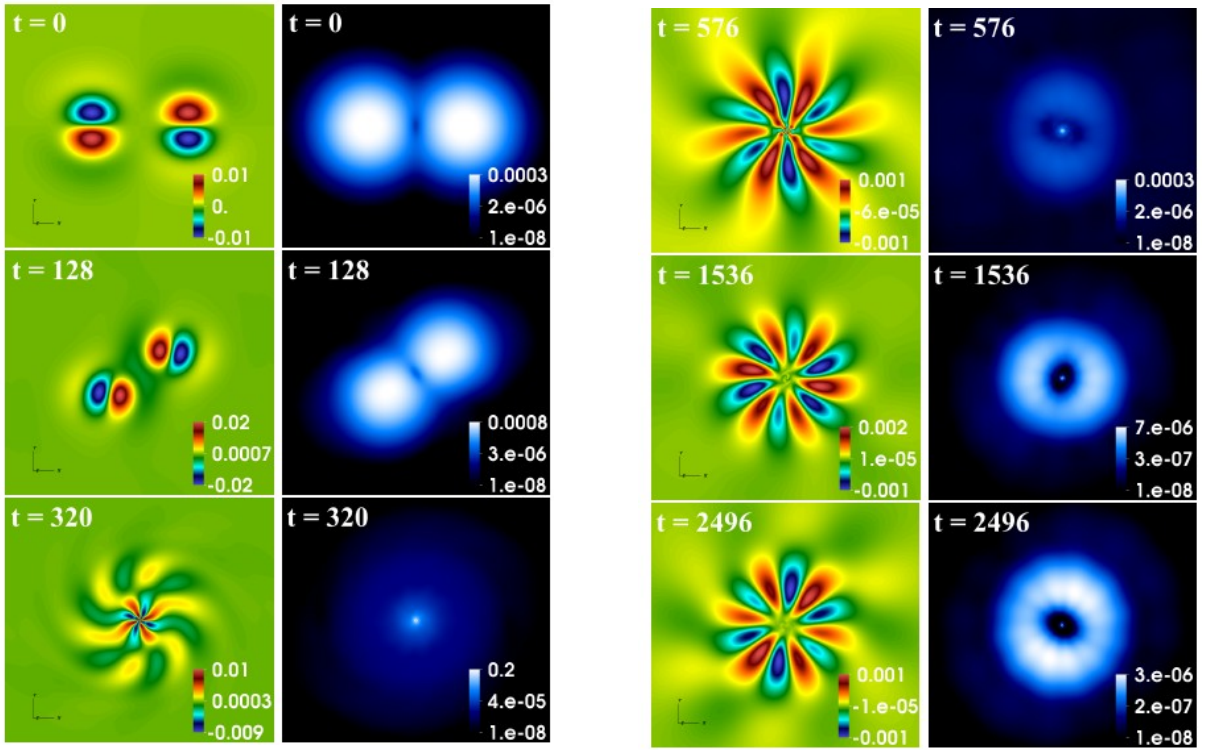




East&Pretorius (2017)
[arXiv:1704.04791]

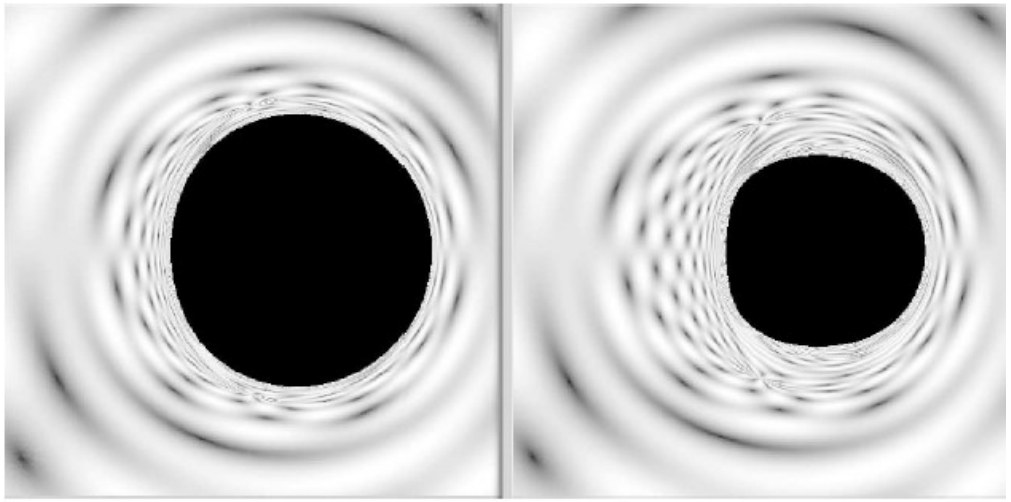
Herdeiro&Radu (2017)
[arXiv:1706.06597]

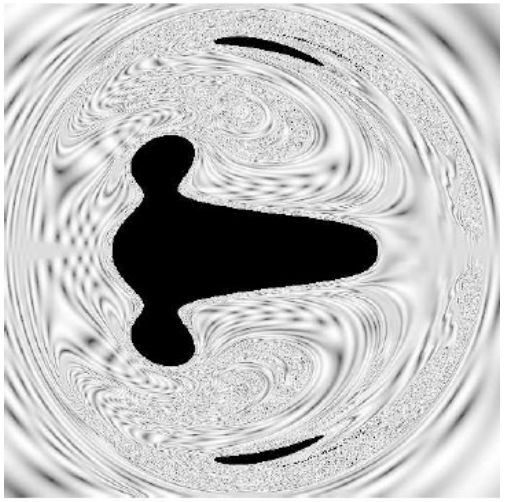
Formation mechanism



Sanchis-Gual+ (2020)
[arXiv:2007.11584]

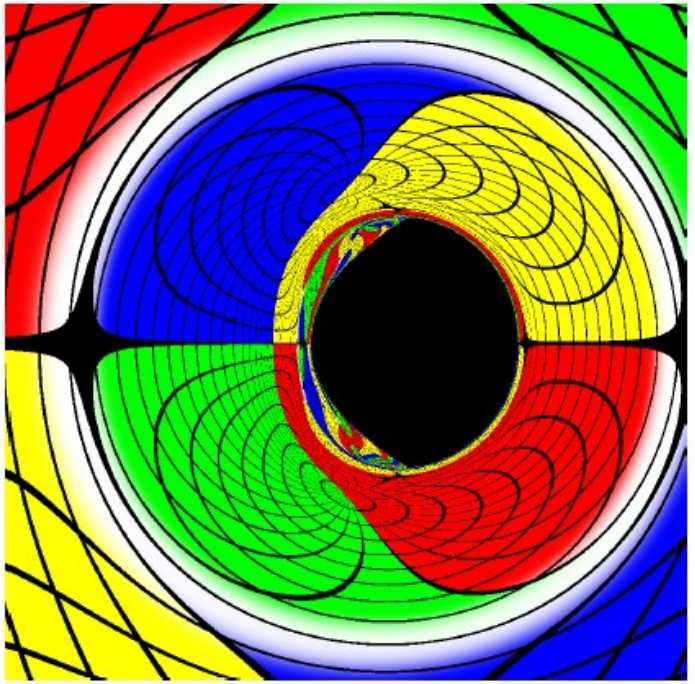
Finding hairy black holes

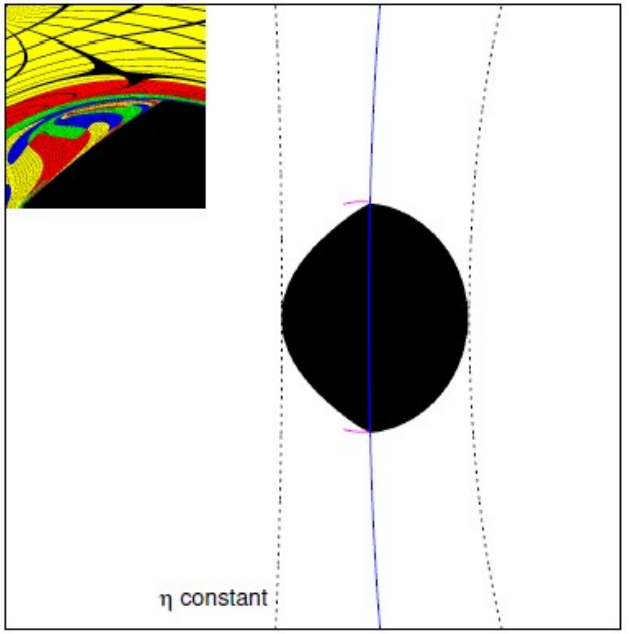




Cunha+ (2016)
[arXiv:1605.08293]

Finding hairy black holes



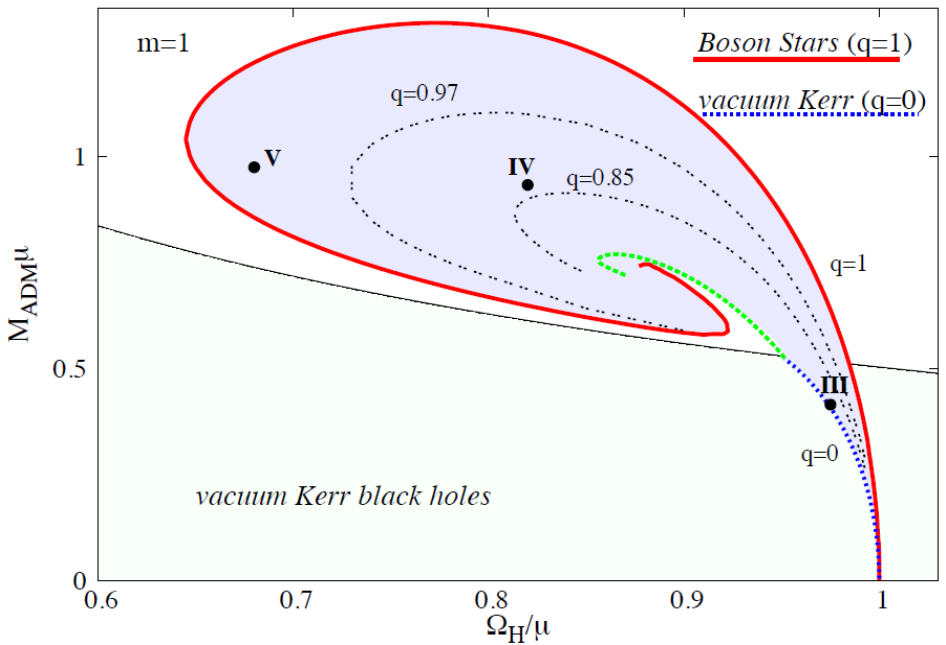


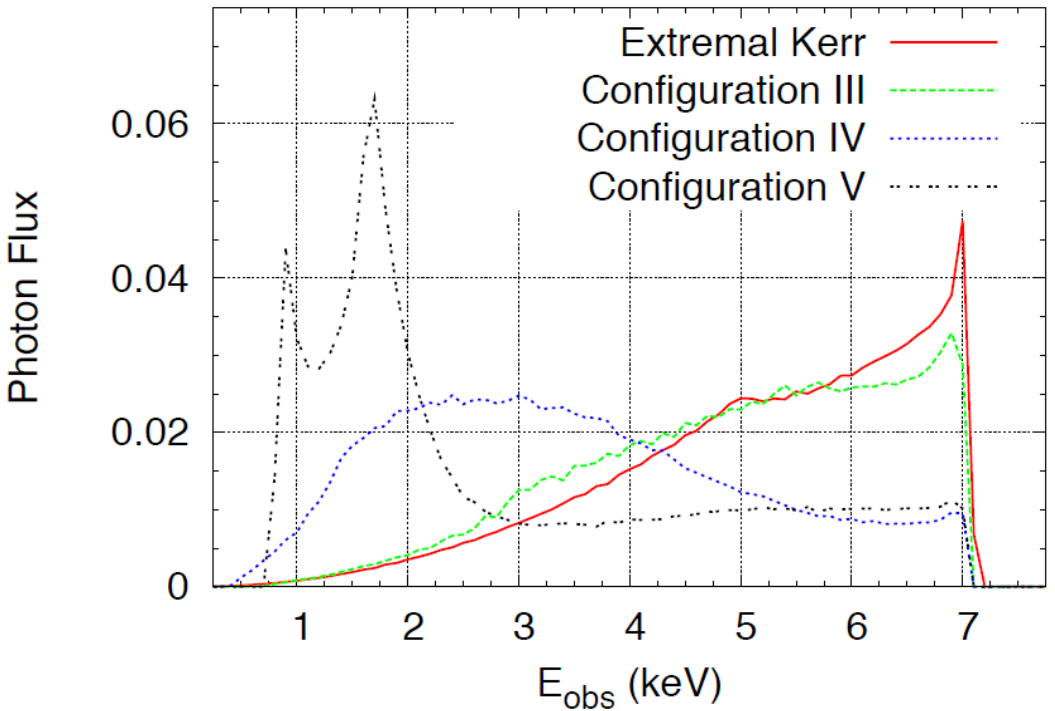
Cunha+ (2017)
[arXiv:1705.05461]

Finding hairy black holes

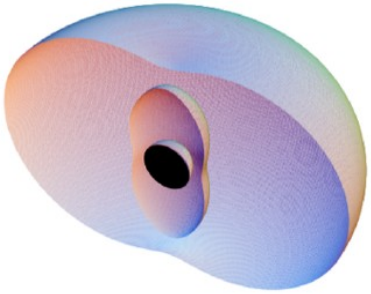
Ni+ (2016)
[arXiv:1606.04654]

Zhou+ (2017)
[arXiv:1703.06836]



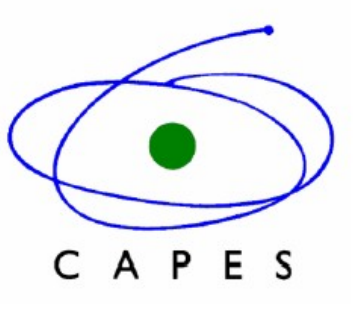


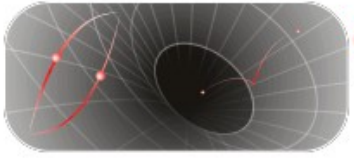
Final remarks



- The fundamental hairy black holes bifurcate from the existence line of the bound state $|0,0,1,1\rangle$
- The total angular momentum j allows for the existence of l = 0 bound states
- Cloud’s can form spontaneously
- Proca hair is dynamically more favorable than scalar hair
- Search for astrophysical observables

Obrigada! Thank you!





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