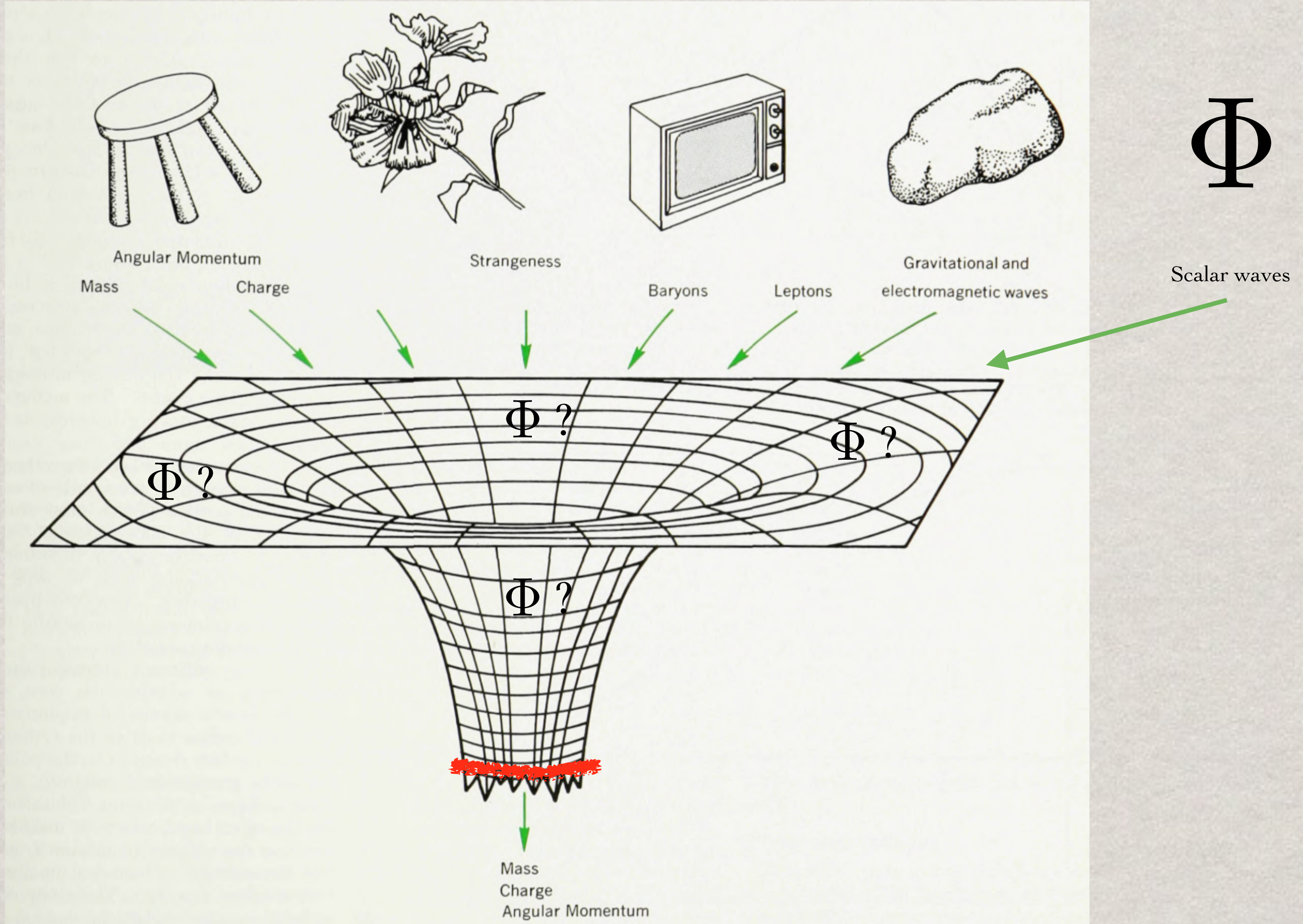
Kerr black holes with scalar hair



C. Herdeiro

Departamento de Física da Universidade de Aveiro, Portugal

VII Black Holes Workshop, Aveiro, 18-19 December 2014

based on

Physical Review Letters 112 (2014) 221101 (arXiv:1403:2757)

IJMPD 23 (2014) 1442014 (arXiv:1405:3696), honorable mention on GRF Awards 2014

with E. Radu

The "no-hair" idea

> The collapse leads to a black hole endowed with mass and charge and angular momentum but, so far as we can now judge, no other adjustable parameters: "a black hole has no hair." Make one black hole out of matter;
>
> 36 PHYSICS TODAY / JANUARY 1971

Ruffini, Wheeler (1971)

Original idea:
"gravitational collapse leads to equilibrium black holes uniquely determined by M,J,Q - asymptotically measured quantities subject to a Gauss law and no other independent characteristics (hair)"

Motivated by uniqueness theorems

e.g: Israel 1967, 1968; Carter 1970; Hawking 1972; Robinson 1975, 1977; and many others

Overview: "Four decades of black hole uniqueness theorems" D. Robinson (2004, 2009)

Hairy black hole solutions exist (D=4, asymptotically flat):

Early example: Einstein-Yang-Mills theory
Bizón 1990; Kunzle and Masood-ul-Alam, 1990; Volkov and Galtsov, 1990

Other examples were obtained in: Einstein-Skyrme, Einstein-Yang-Mills-Dilaton, Einstein-Yang-Mills-Higgs, Einstein-non-Abelian-Proca, etc
Review by Bizón 1994; Volkov and Gal'tsov (1999)

Show **mathematical** limitations of the `no-hair' idea.
But **(astro)physically** relevant?

`Hair' anchored on non-linearities of the field. Hard to have insights.

Plan:

- Report a new type of exact solution of hairy black holes (with scalar hair)

- Report a new type of **mechanism** to grow hair; based on the superradiant instability

Ingredient 1: Boson stars:

Kaup (1968); Ruffini and Bonazzola (1969)
Review: Liebling and Palenzuela (2012)

Einstein-Klein-Gordon theory:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R - \Phi^*_{,a}\Phi^{,a} - \mu^2\Phi^*\Phi\right]$$

Rotating boson stars:
Yoshida and Eriguchi (1997)
Schunck and Mielke (1998)

$$ds^2 = -e^{2F_0(r,\theta)}dt^2 + e^{2F_1(r,\theta)}\left(dr^2 + r^2 d\theta^2\right) + e^{2F_2(r,\theta)}r^2\sin^2\theta\,(d\varphi - W(r,\theta)dt)^2$$

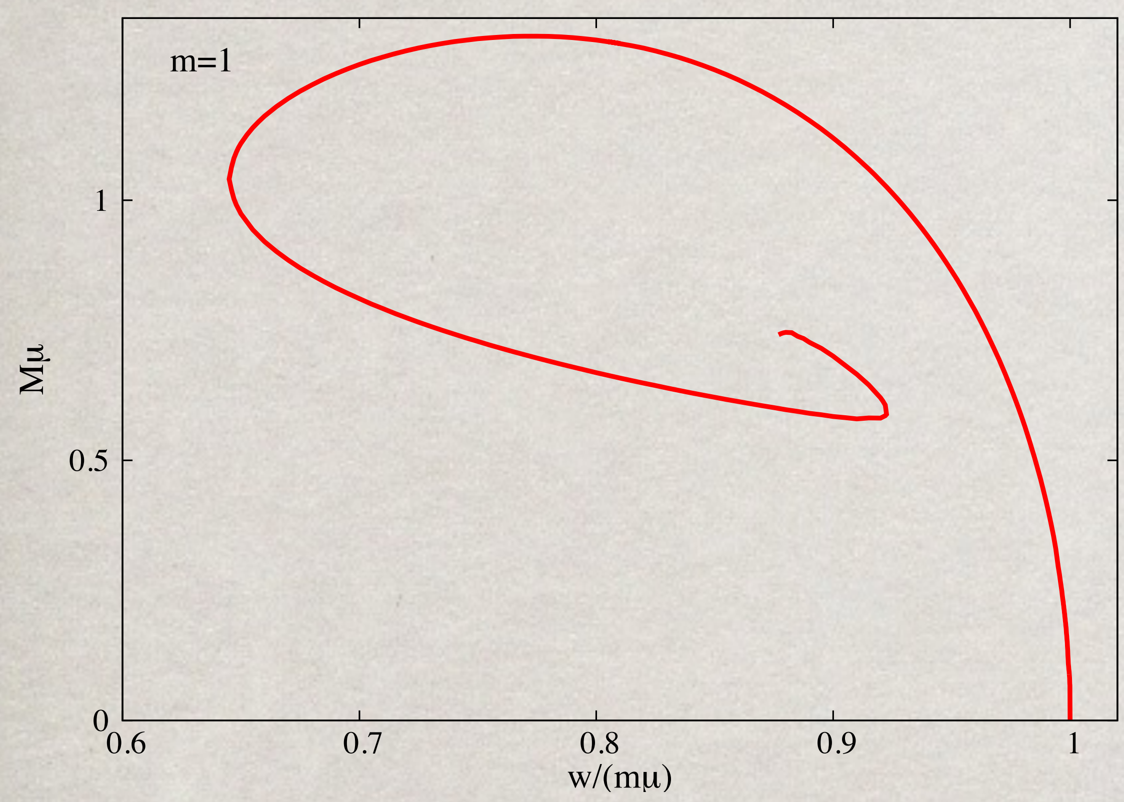
$$\Phi = \phi(r,\theta)e^{i(m\varphi - wt)}$$

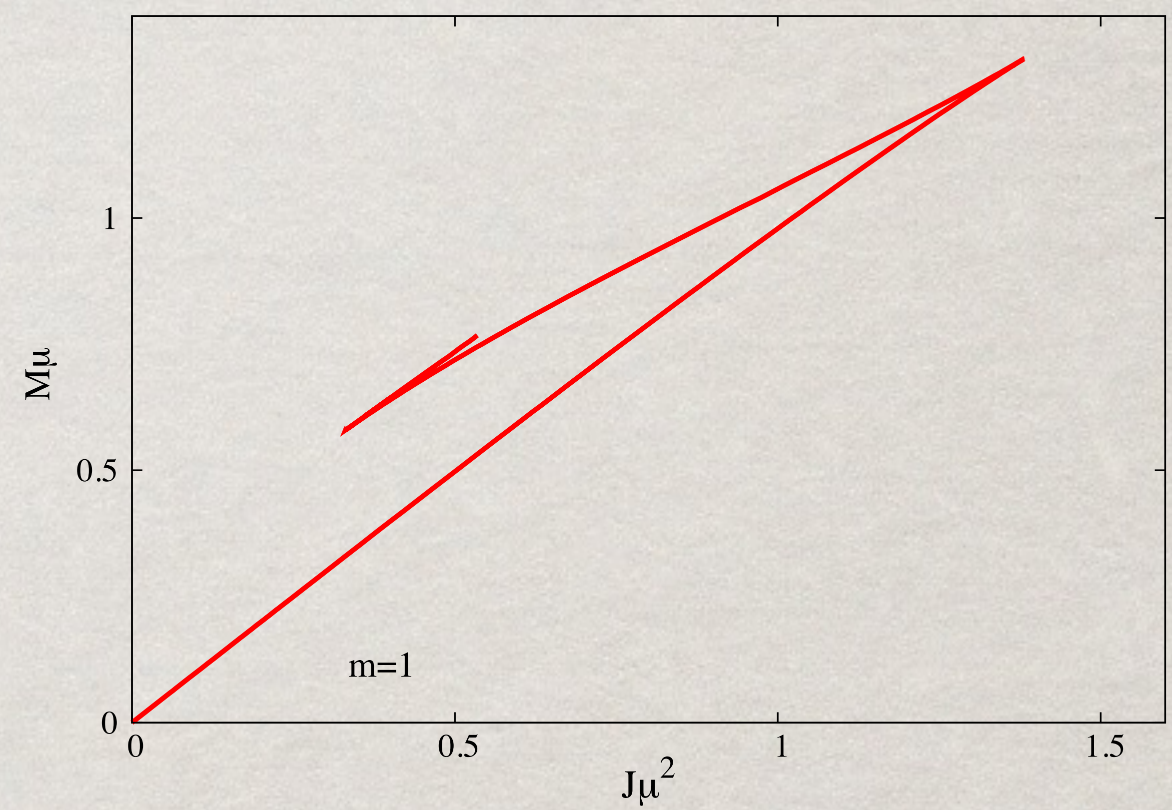
Three input parameters: (w,m,n)

Solutions preserved by a single helicoidal Killing vector field:

$$\frac{\partial}{\partial t} + \frac{w}{m}\frac{\partial}{\partial\varphi}$$

Boson stars phase space (nodeless):





Conserved Noether charge:

$$Q = \int_{\Sigma} dr d\theta d\varphi j^t \sqrt{-g}$$

For rotating boson stars:

Schunck and Mielke (1998)

$$J = mQ$$

Convenient parameter:

$$q \equiv \frac{mQ}{J}$$

Ingredient 2: Klein-Gordon equation in Kerr (linear analysis)

$$\Box\Phi = \mu^2\Phi \qquad \Phi = e^{-iwt}e^{im\varphi}S_{\ell m}(\theta)R_{\ell m}(r)$$

Radial Teukolsky equation: Teukolsky (1972); Brill et al. (1972)

$$\frac{d}{dr}\left(\Delta\frac{dR_{\ell m}}{dr}\right) = \left(a^2w^2 - 2maw + \mu^2r^2 + A_{\ell m} - \frac{K^2}{\Delta}\right)R_{\ell m}$$

$$\Delta \equiv r^2 - 2Mr + a^2$$

$$K \equiv (r^2 + a^2)w - am$$

Generically one obtains *quasi*-bound states:

$$\omega = \omega_R + i\omega_I$$

critical frequency

$$w_c = m\Omega_H$$

$w_I < 0$ if $w_R > w_c$ — decay

$w_I = 0$ if $w = w_c$ — true bound states: *clouds*

$w_I > 0$ if $w_R < w_c$ — grow

Press and Teukolsky (1972)

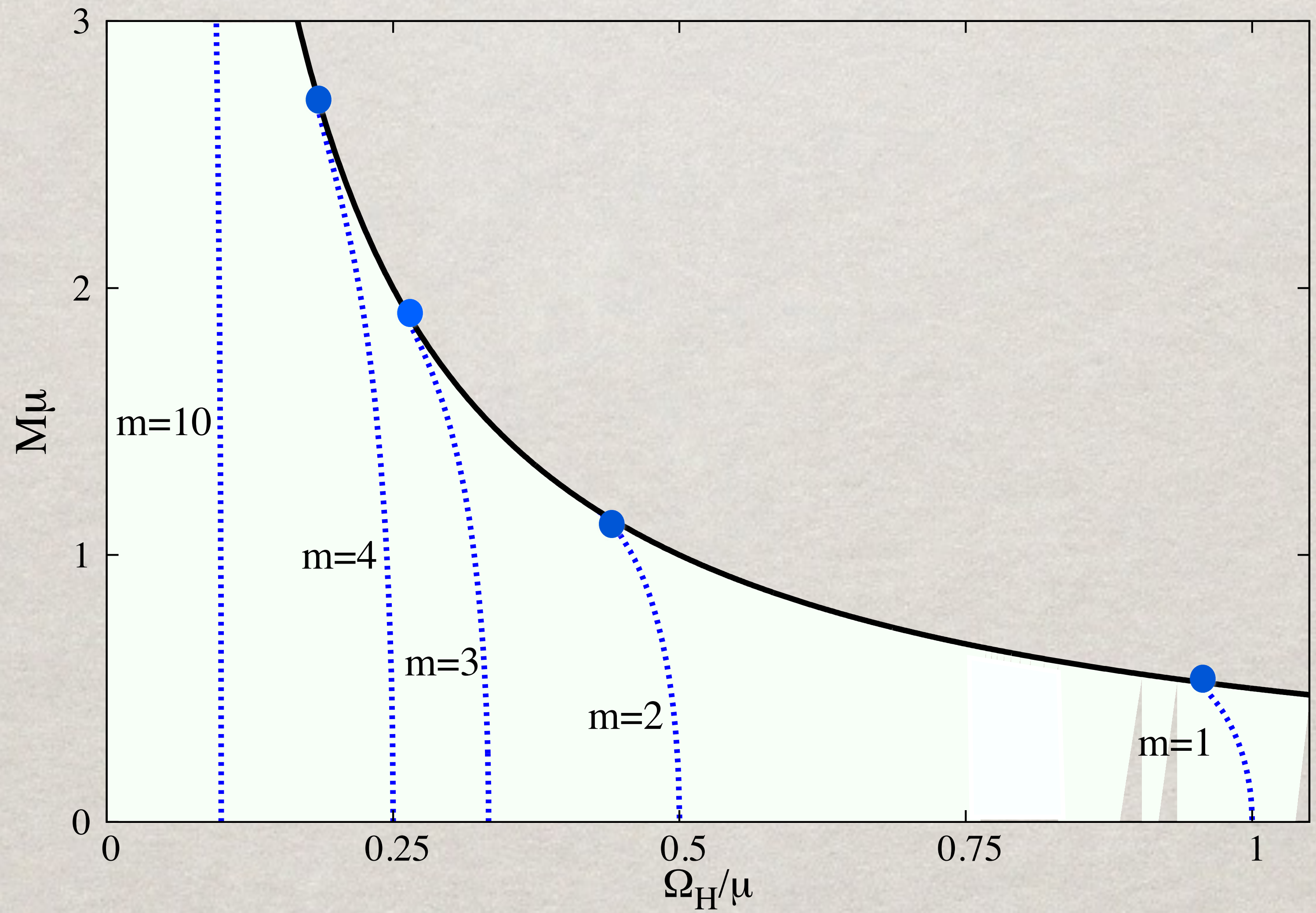
Klein-Gordon (linear) clouds around Kerr:

Damour, Deruelle and Ruffini (1976); Zouros and Eardley (1979); Detweiler (1980); Hod 2012;
(...); Yakov Shilapentokh-Rothman (2014)

Clouds for Kerr: discrete set labelled by (n,l,m) subject to one quantization condition which yields BH mass,spin. Hod (2012)

cloud condition

$$\boxed{\Omega_H = \frac{w}{m}}$$



See Benone's talk

Mix the ingredients: Einstein Klein-Gordon (non-linear setup)

Ansatz:

$$ds^2 = -e^{2F_0(r,\theta)} N dt^2 + e^{2F_1(r,\theta)} \left(\frac{dr^2}{N} + r^2 d\theta^2 \right) + e^{2F_2(r,\theta)} r^2 \sin^2\theta \left(d\varphi - W(r,\theta) dt \right)^2 \qquad N = 1 - \frac{r_H}{r}$$

$$\Phi = \phi(r,\theta) e^{i(m\varphi - wt)}$$

Single KVF BH c.f.
Dias, Horowitz and Santos (2011)

Asymptotically:

$$g_{tt} = -1 + \frac{2M}{r} + \ldots, \quad g_{\varphi t} = -\frac{2J}{r} \sin^2\theta + \ldots$$

$$\phi = f(\theta) \frac{e^{-\sqrt{\mu^2 - w^2}\, r}}{r} + \ldots$$

take: $w < \mu$

Near the horizon:

$$x \equiv \sqrt{r^2 - r_H^2}$$

$$F_i = F_i^{(0)}(\theta) + x^2 F_i^{(2)}(\theta) + \mathcal{O}(x^4)$$

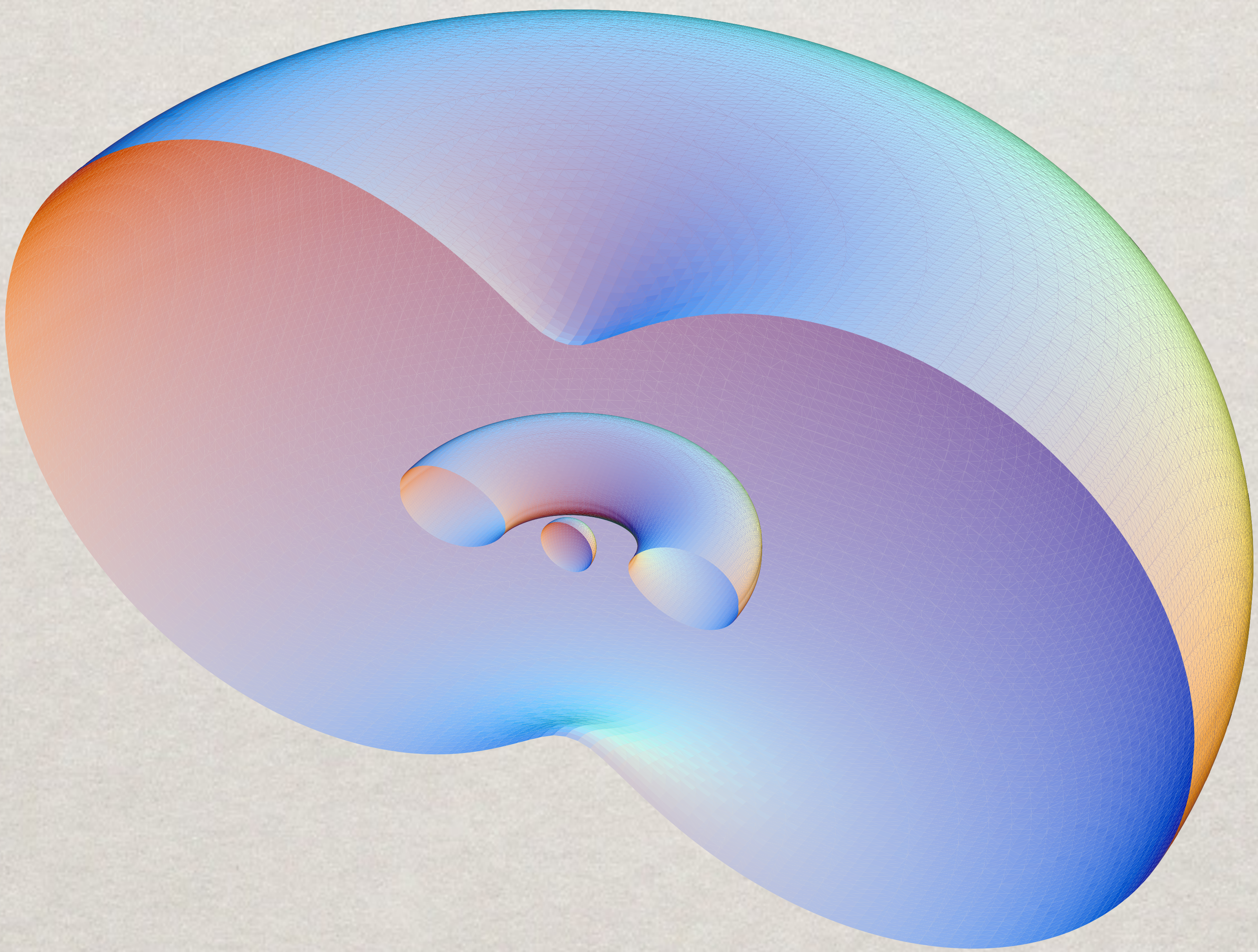
$$W = \Omega_H + \mathcal{O}(x^2)$$

$$\phi = \phi_0(\theta) + \mathcal{O}(x^2)$$

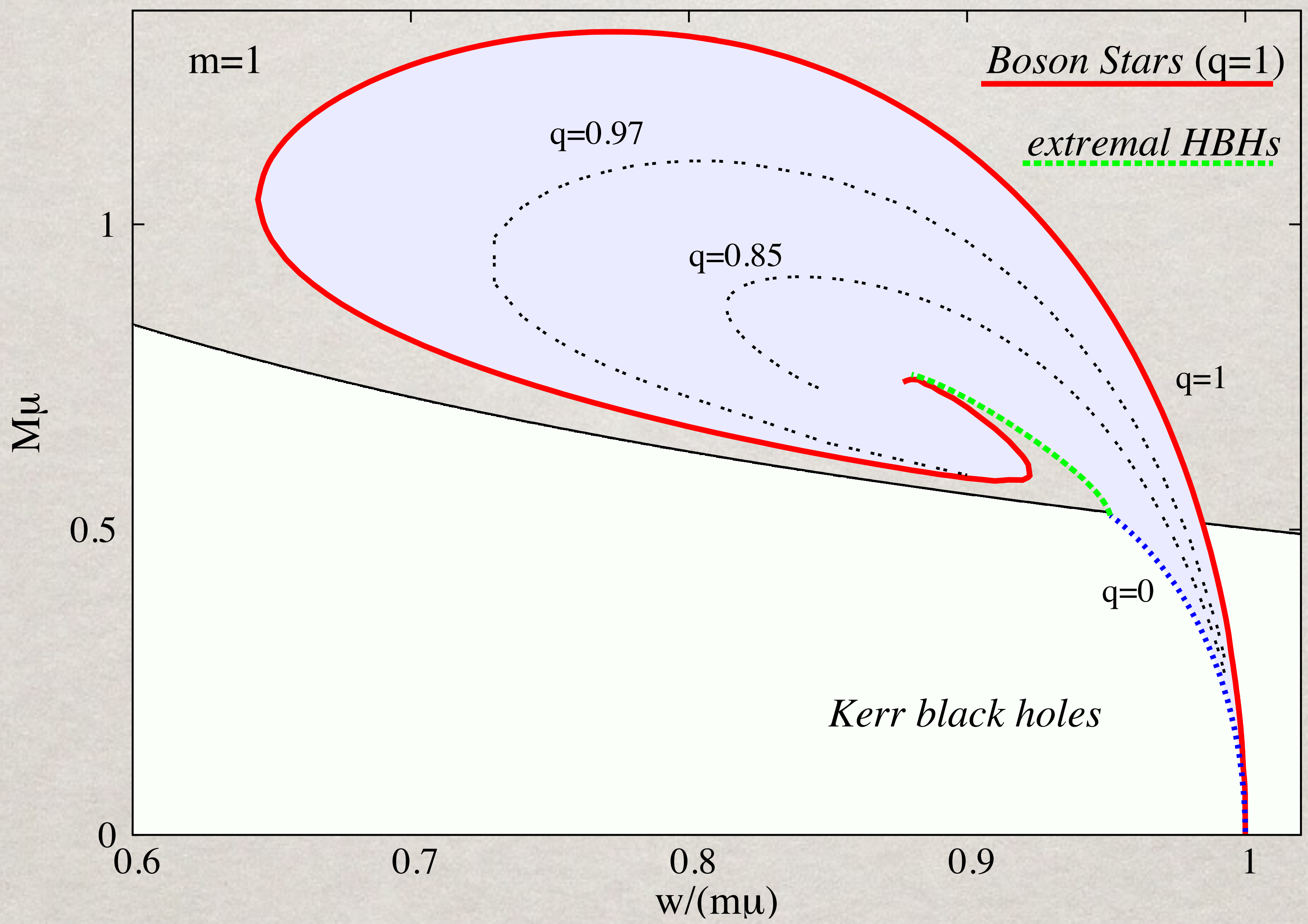
take: $\Omega_H = \dfrac{w}{m}$

Four input parameters: m, w, r_H, n

Hairy black holes



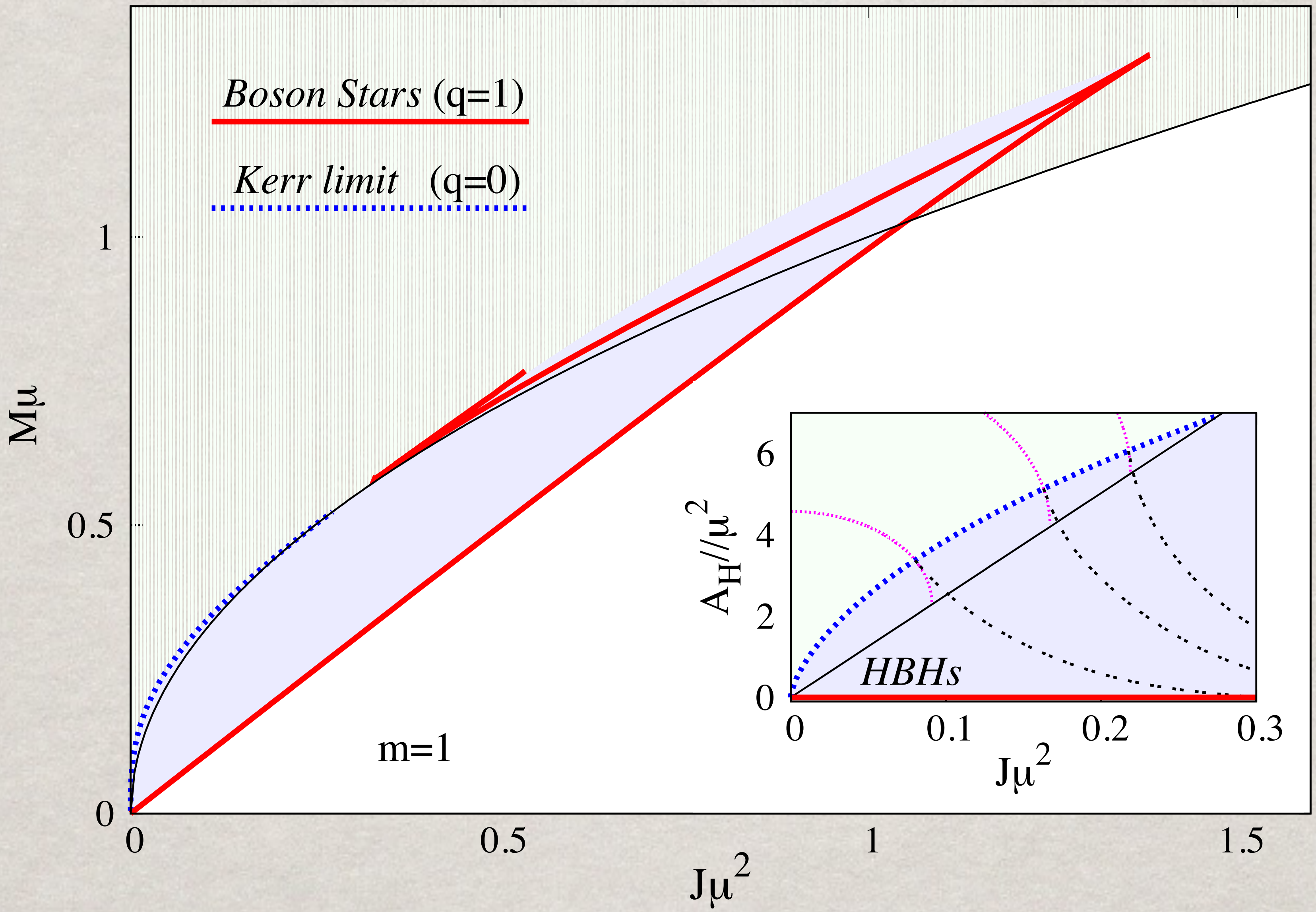
Hairy black holes phase space



$$\Omega_H = \frac{w}{m}$$

$$q \equiv \frac{mQ}{J}$$

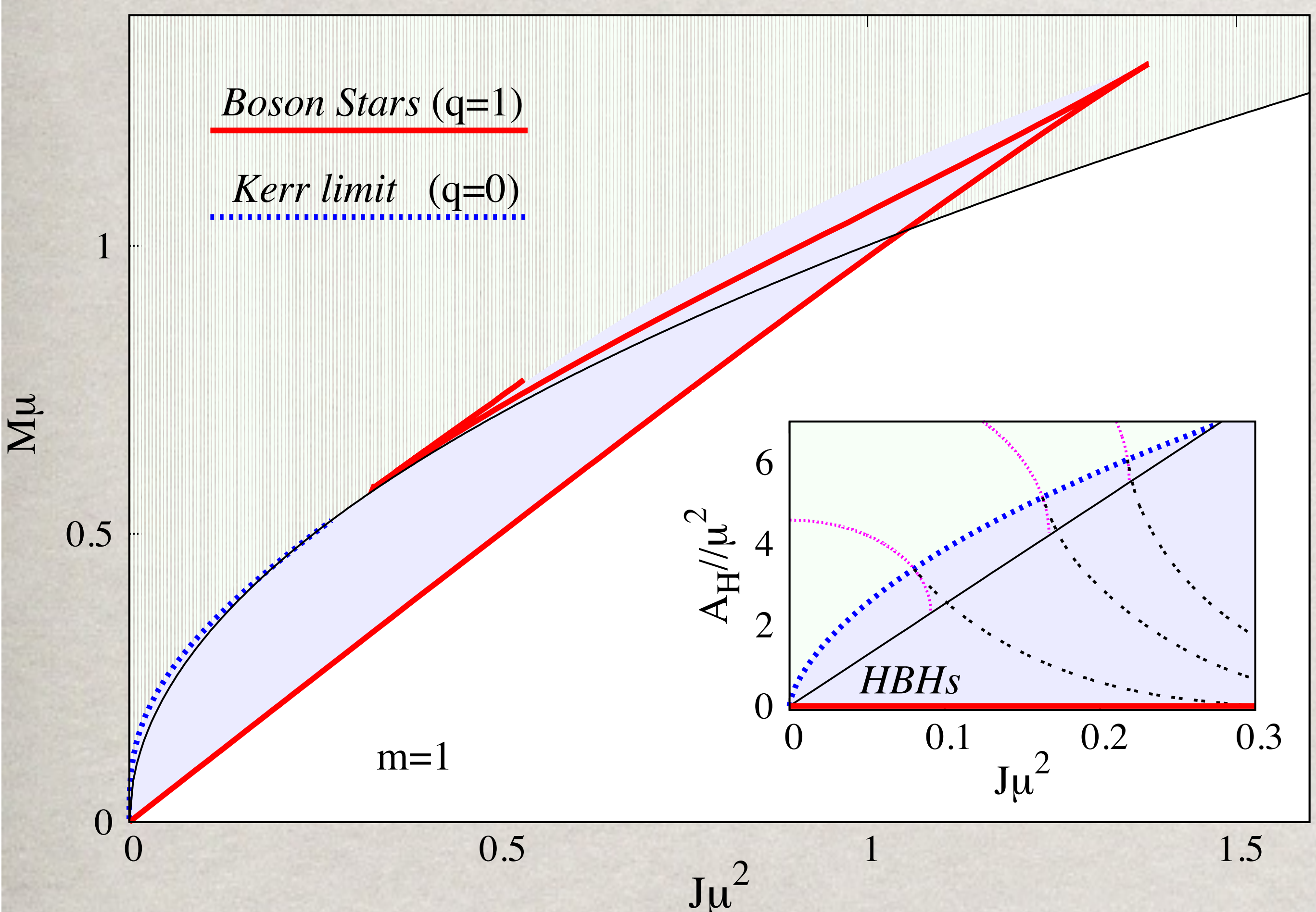
Hairy black holes phase space



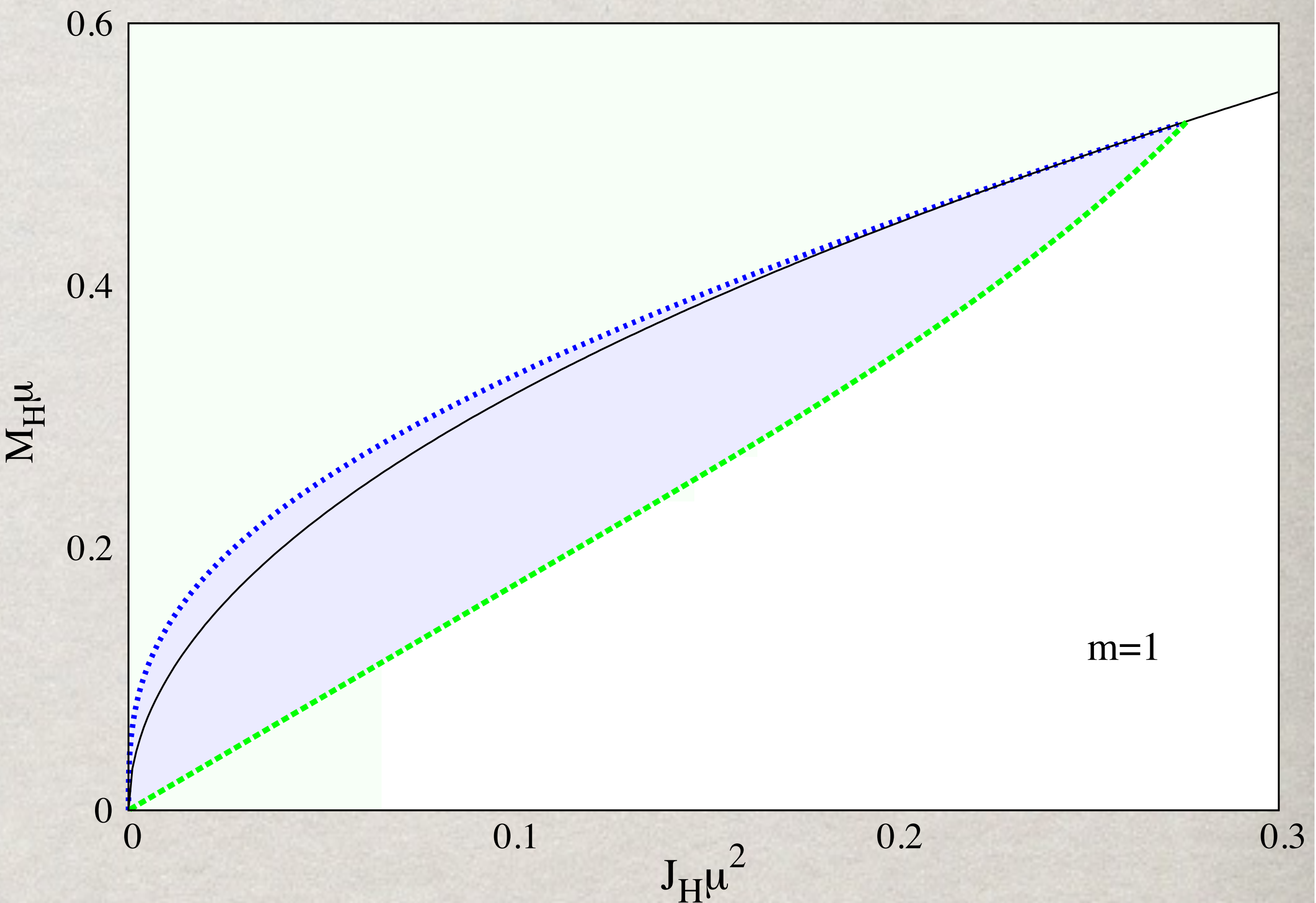
- Can violate Kerr bound

Hairy black holes phase space

ADM M and J

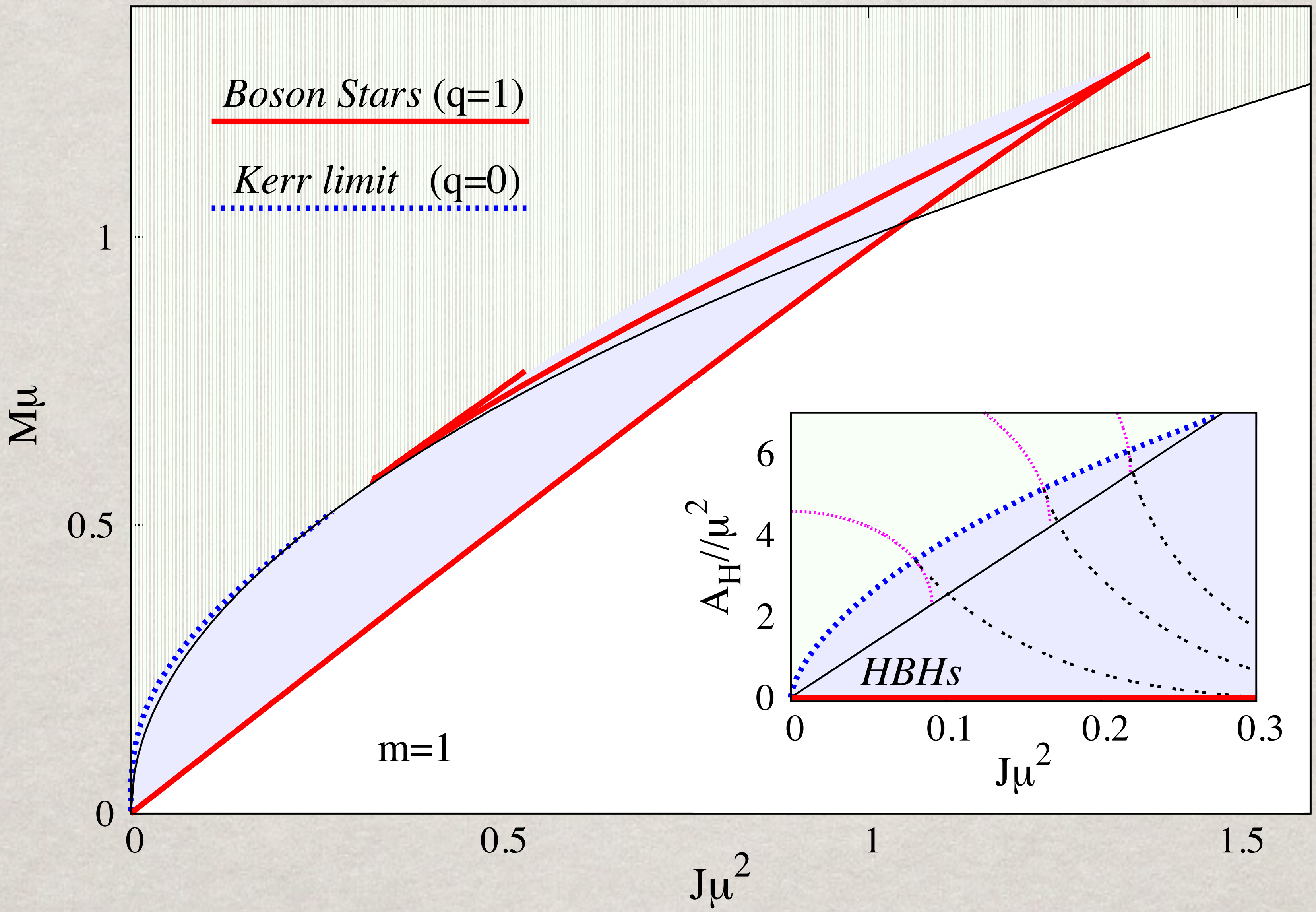


Horizon (Komar) M and J



- Can violate Kerr bound

Hairy black holes phase space



- Can violate Kerr bound

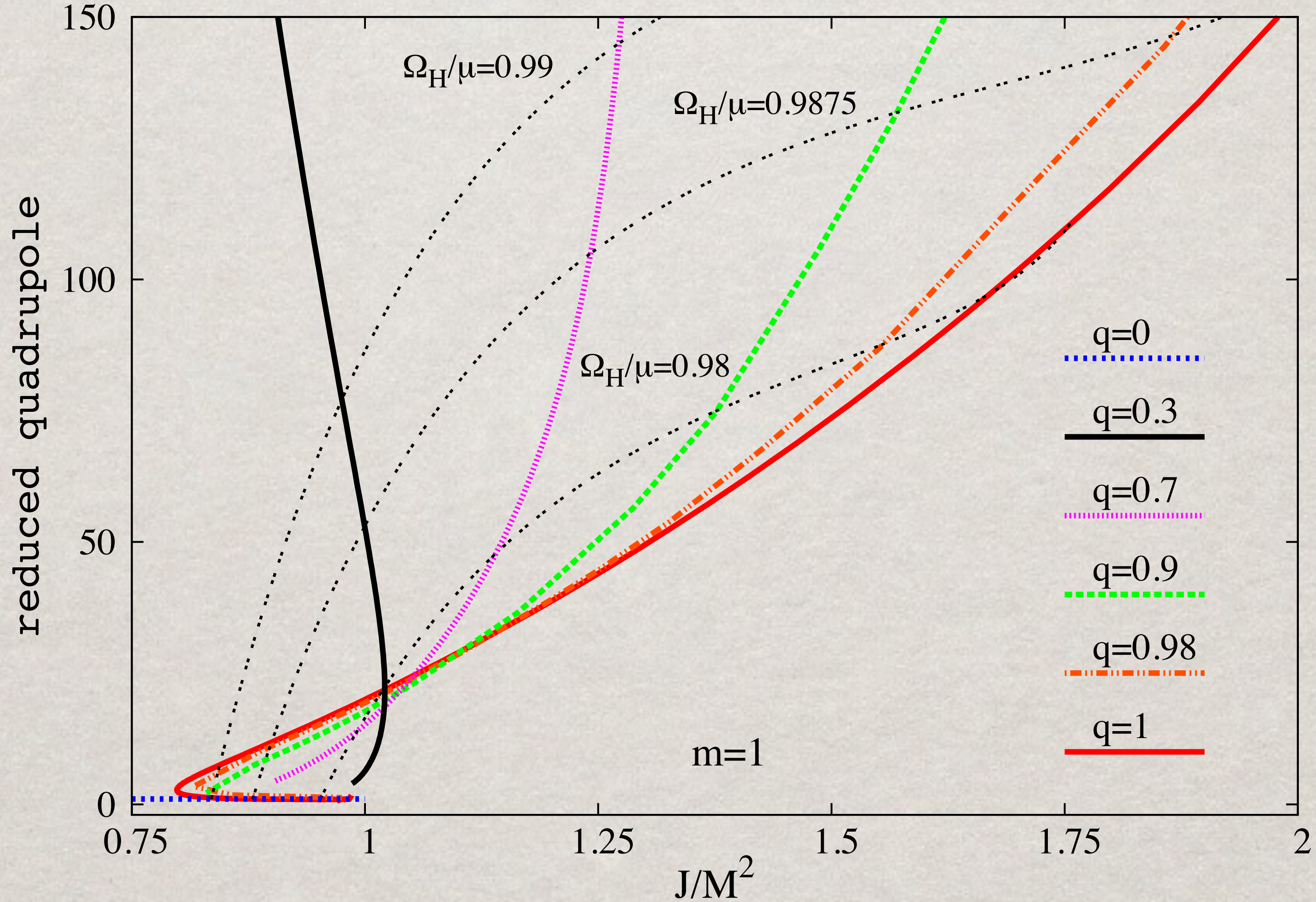
- Non-uniqueness (different solutions for same M,J); but degeneracy raised with q

- Entropically favoured;

Hairy black holes are more *star-like*

Geroch-Hansen quadrupole moment:

Geroch (1970); Hansen (1974); Pappas and Apostolatos (2012)



$$\text{reduced quadrupole} = \frac{\text{quadrupole}}{-J^2/M}$$

Similar considerable deviations occur for the orbital frequency at the ISCO.

Summary:

Kerr BHs with scalar hair interpolate between Kerr and boson stars.

Can be understood at linear level: not anchored on non-linear effects.

Branching of Kerr BHs towards a new family of solutions due to superradiant instability

How general is this mechanism?
A (hairless) BH which is afflicted by the superradiant instability of a given field allow a hairy generalization with that field.

Other properties deserve further study (stability, phenomenology, evolution… Cardoso's and Brito's talk)

Thank you for your attention!