Kerr black holes with scalar (or Proca) hair

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Gravitational lensing of the Aveiro Campus by a Kerr black hole with scalar hair

IAU Symposium 324 "New Frontiers in Black Hole Astrophysics", Ljubljana, Slovenia
September 15th 2016

based on
PRL112(2014)221101
CQG32(2015)144001
PRL115(2015)211102

with E. Radu, P. Cunha, H. Rúnarsson

Take-home message:

It is common lore that,
in Einstein's gravity,
with reasonable matter sources
of Astrophysical interest…

…Black Holes cannot have hair
(for instance, simple scalar "hair")

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(for instance, simple scalar "hair")

They actually can,
if massive, complex, scalar fields exist.

Take-home message:

In Einstein's gravity minimally coupled to a massive, complex, scalar field there are BH solutions:

- **within GR** (not alternative theories of gravity);
- with matter **obeying all energy conditions**;

which are:

- asymptotically flat
- regular on and outside the horizon
- continuously connecting to the Kerr solution
- continuously connected to relativistic Bose-Einstein condensates (boson stars)
- with an independent scalar "charge" (primary hair)

- which can yield **distinct phenomenology**;

Kerr Black Holes with scalar hair

C.H. and Radu, Phys. Rev. Lett. 112 (2014) 221101

2) Why?

Linear analysis: Klein-Gordon equation in Kerr

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

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:

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

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$w_I < 0$ if $w_R > w_c$ decay

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

critical frequency

$$w_c = m\Omega_H$$

$w_I > 0$ if $w_R < w_c$ grow

Press and Teukolsky (1972)

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$w_I = 0$ if $w = w_c$ true bound states: *stationary clouds* Hod (2012)

$w_I > 0$ if $w_R < w_c$ grow Press and Teukolsky (1972)

Backreacting clouds
yield
Kerr black holes with scalar hair

Einstein Klein-Gordon: non-linear setup

Ansatz:

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

$$N = 1 - \frac{r_H}{r}$$

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

$$w = m\Omega_H$$

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"non-metric-symmetry inheritance" by matter field, circumvents generic no-scalar hair theorems

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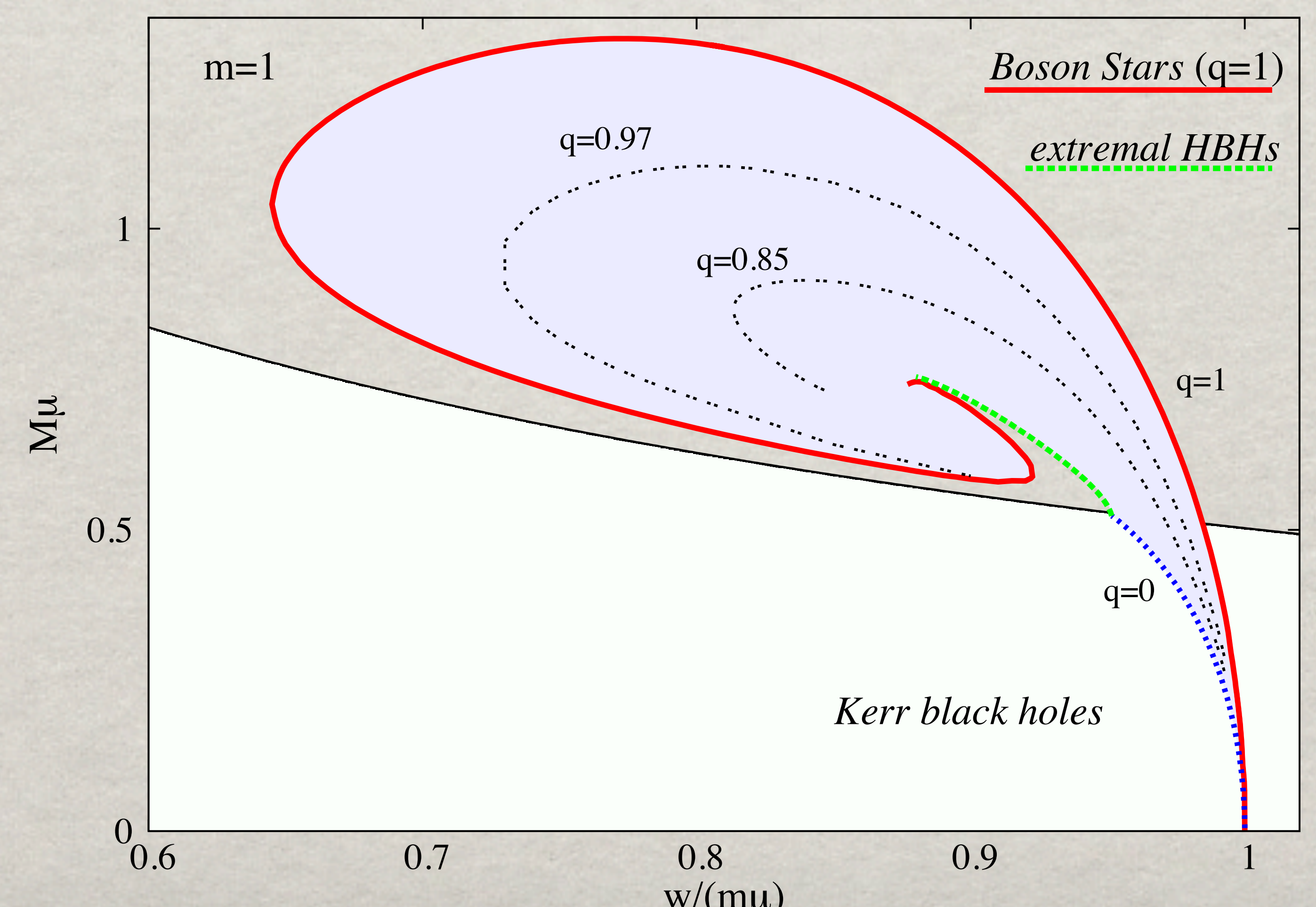
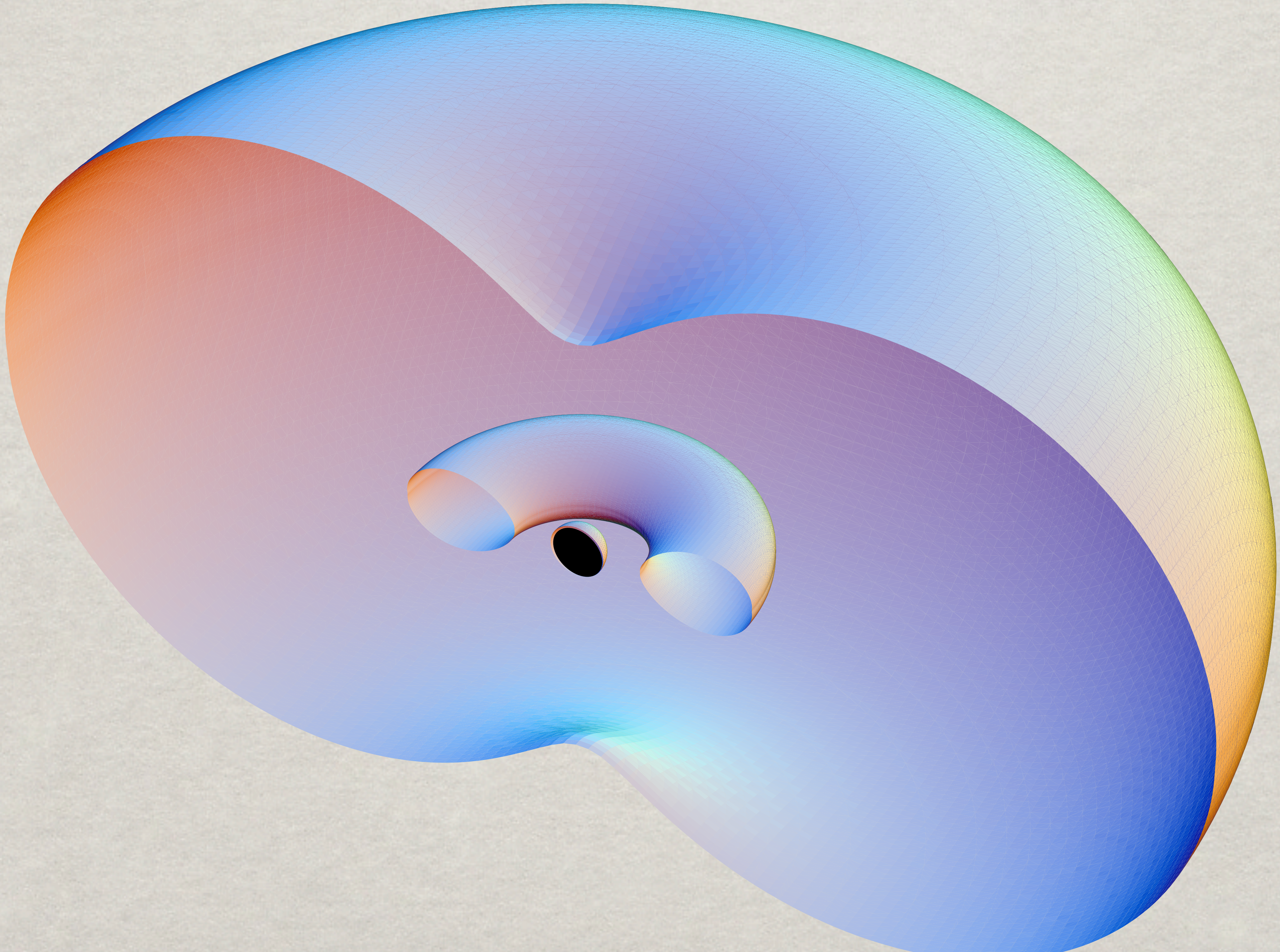
$$\Phi = \phi(r,\theta) e^{i(m\varphi - wt)} \qquad w = m\Omega_H$$

Space of solutions



Kerr BHs with scalar hair

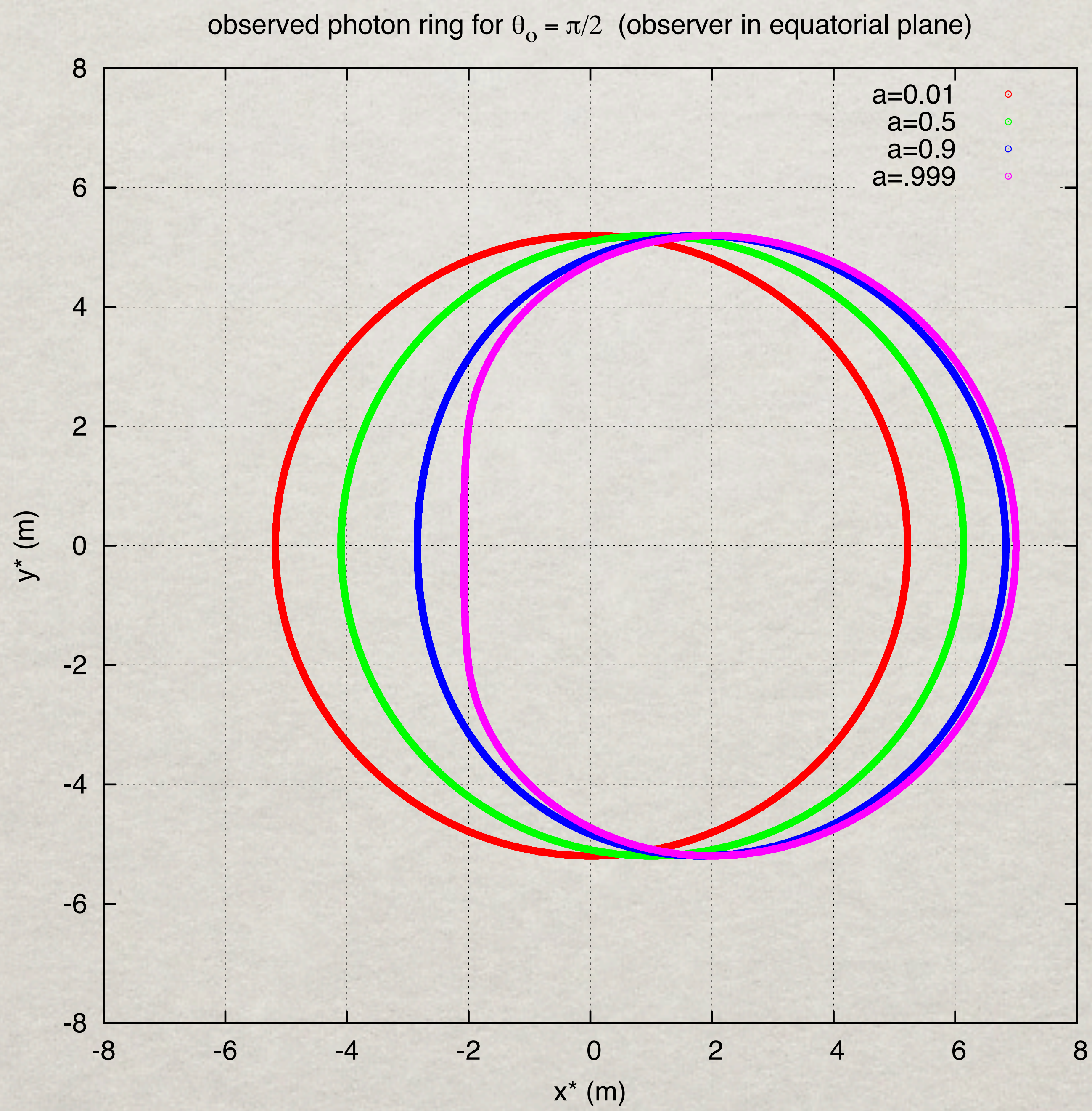
Numerical data: http://gravitation.web.ua.pt/



3) Could we distinguish them in the sky?

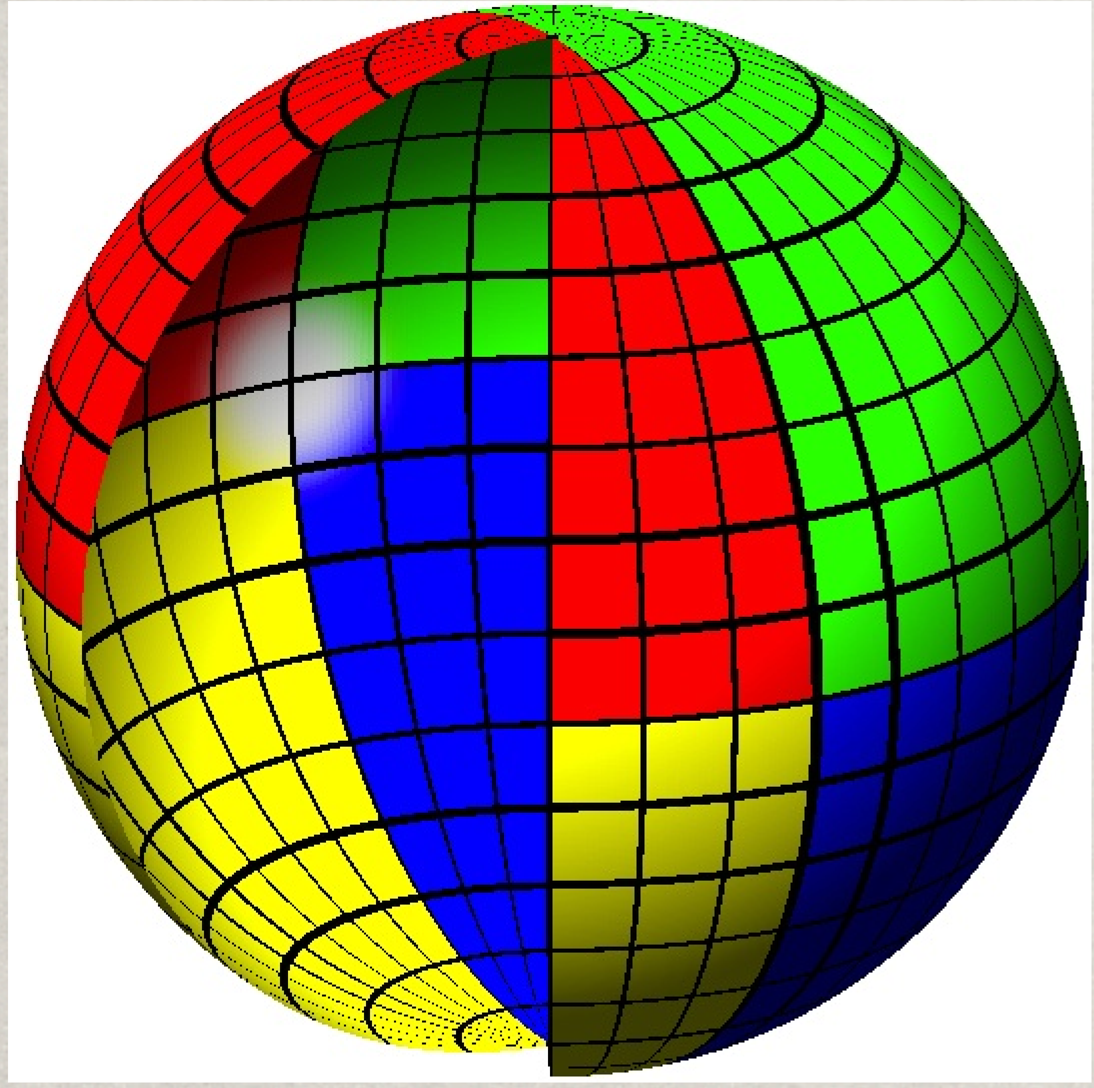
The shadow of a black hole:

Kerr

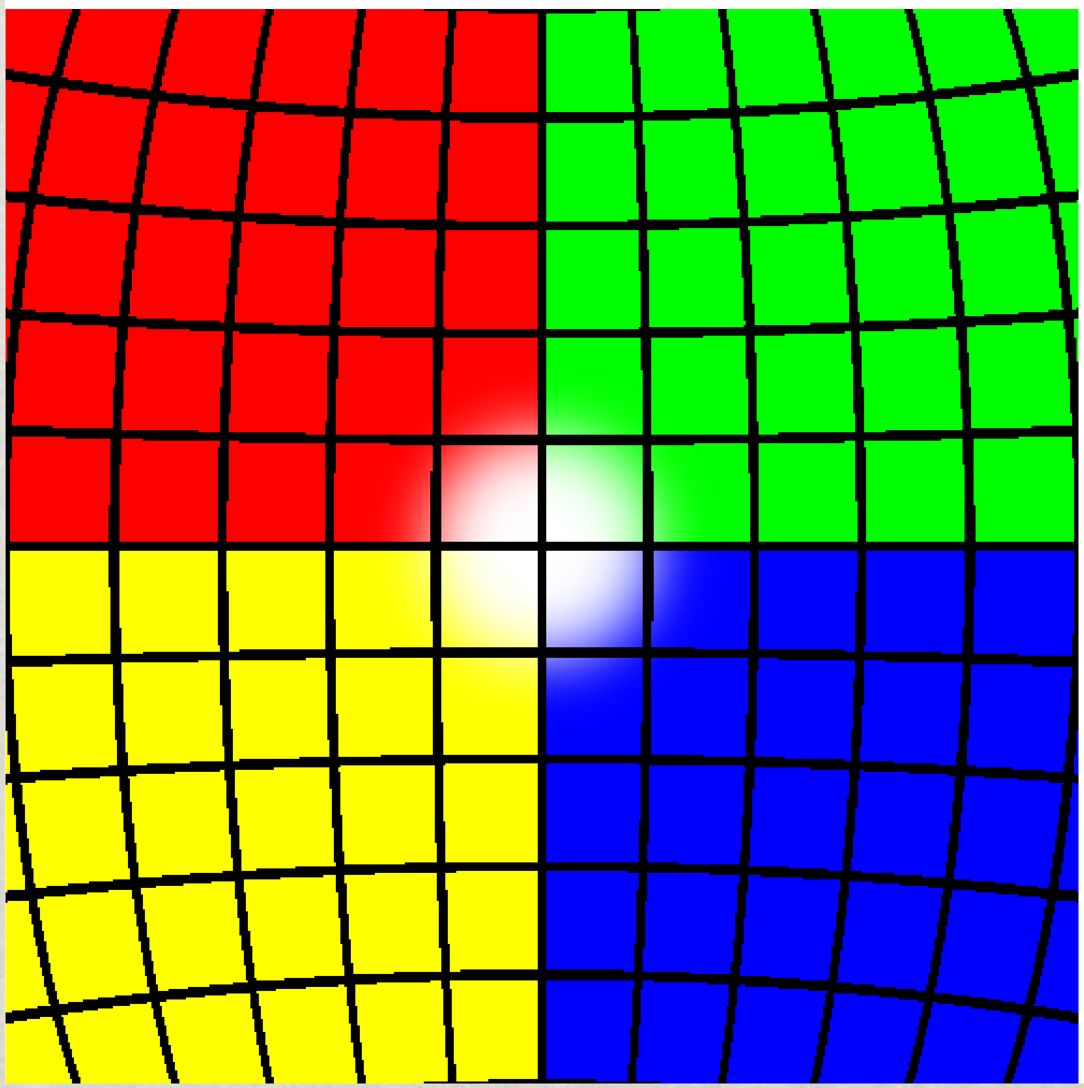


Cunha, M.Sc. Thesis

We have performed ray tracing to compute lensing and shadows.



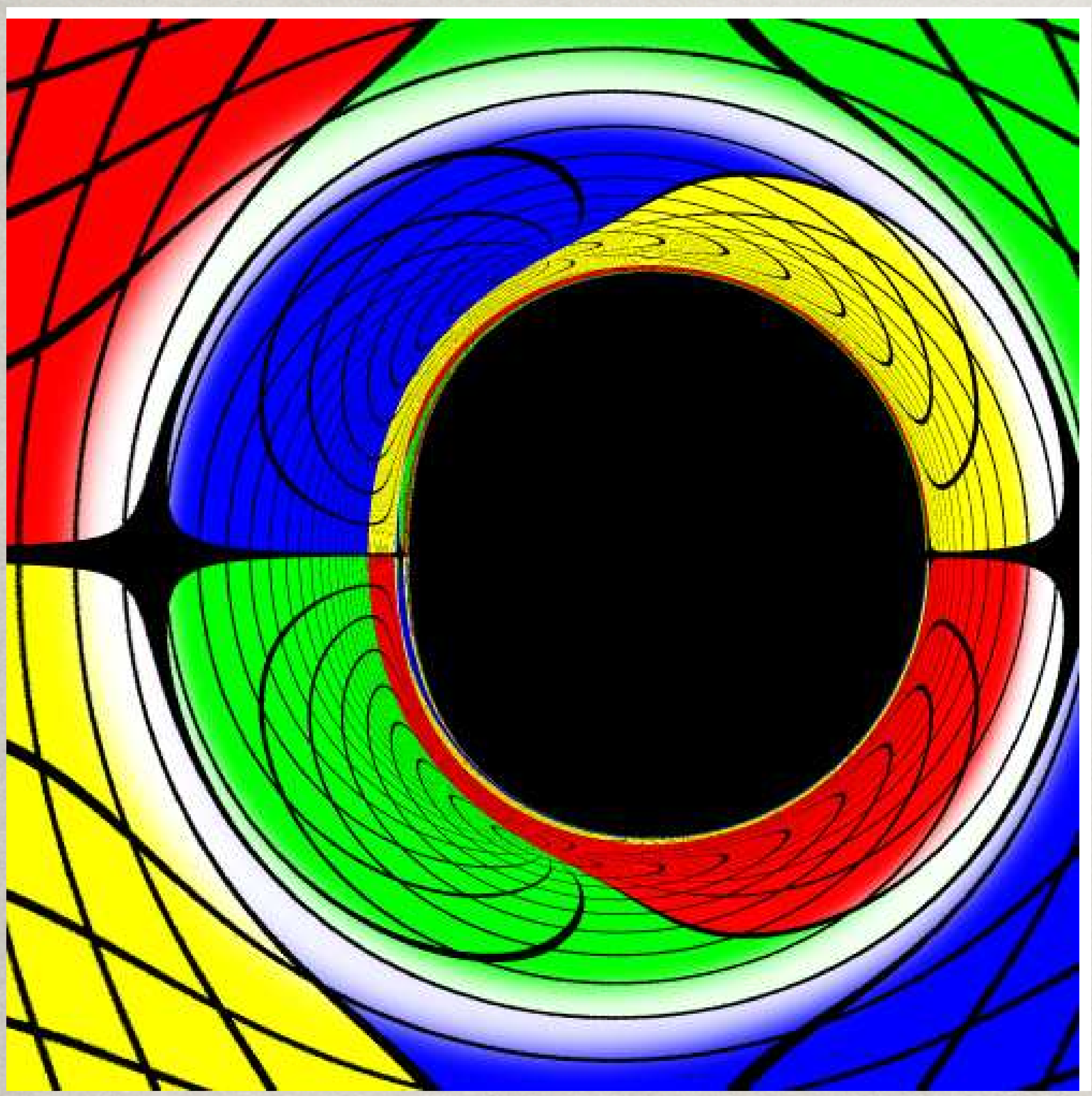
The full celestial sphere

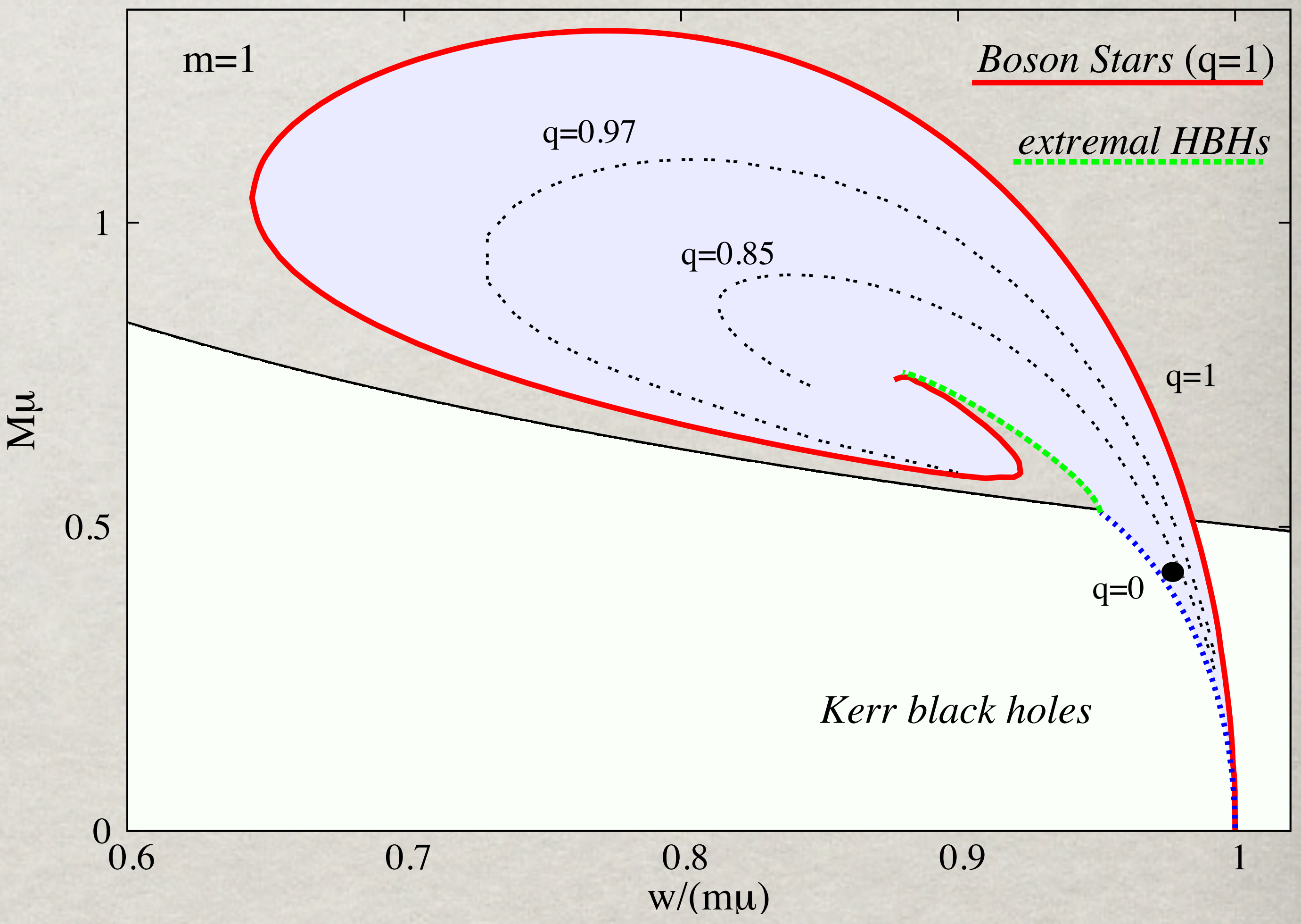


The "camera" opening angle

Following A. Bohn et al. arXiv:1410.7775

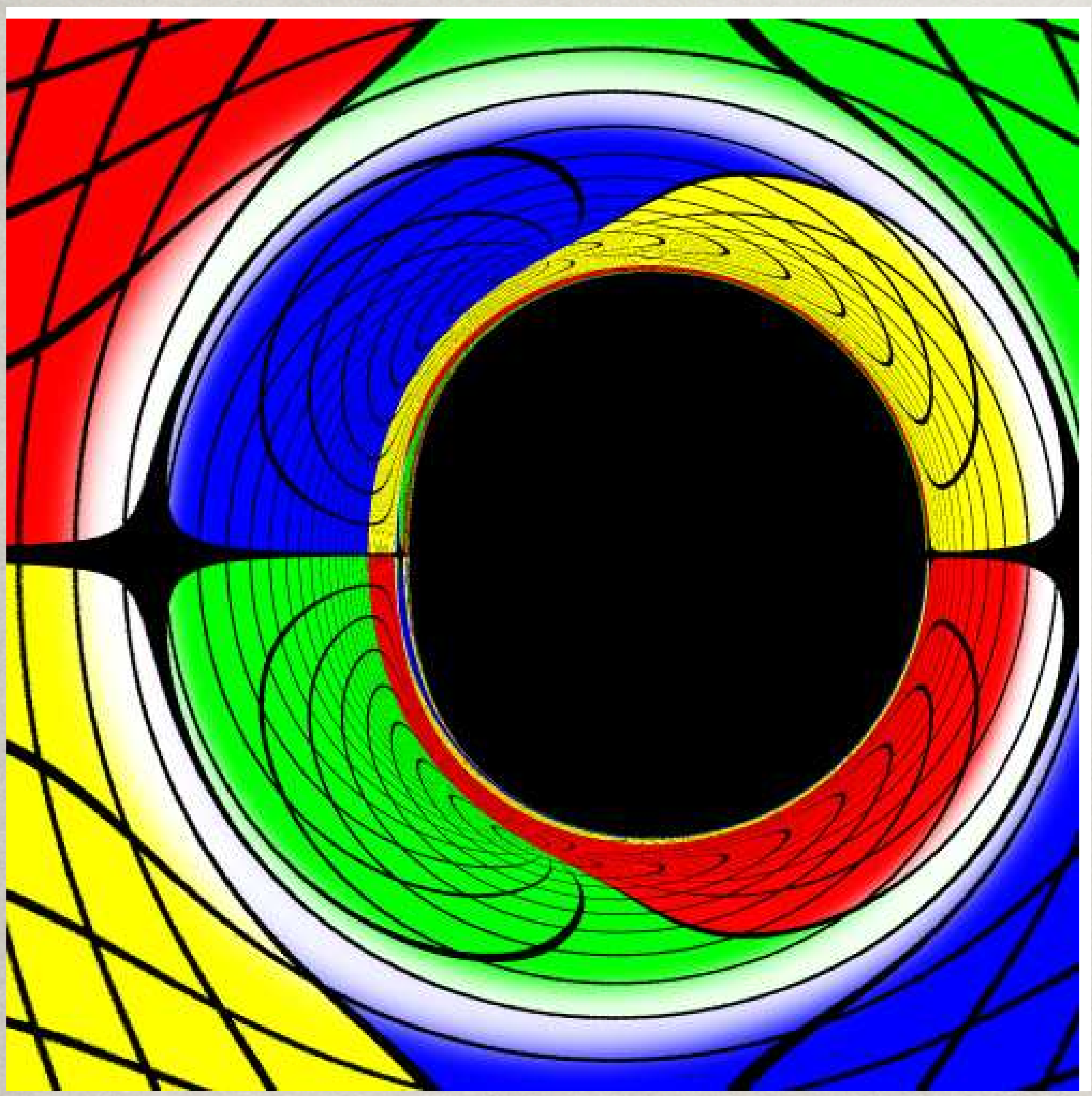
A Kerr-like hairy black hole



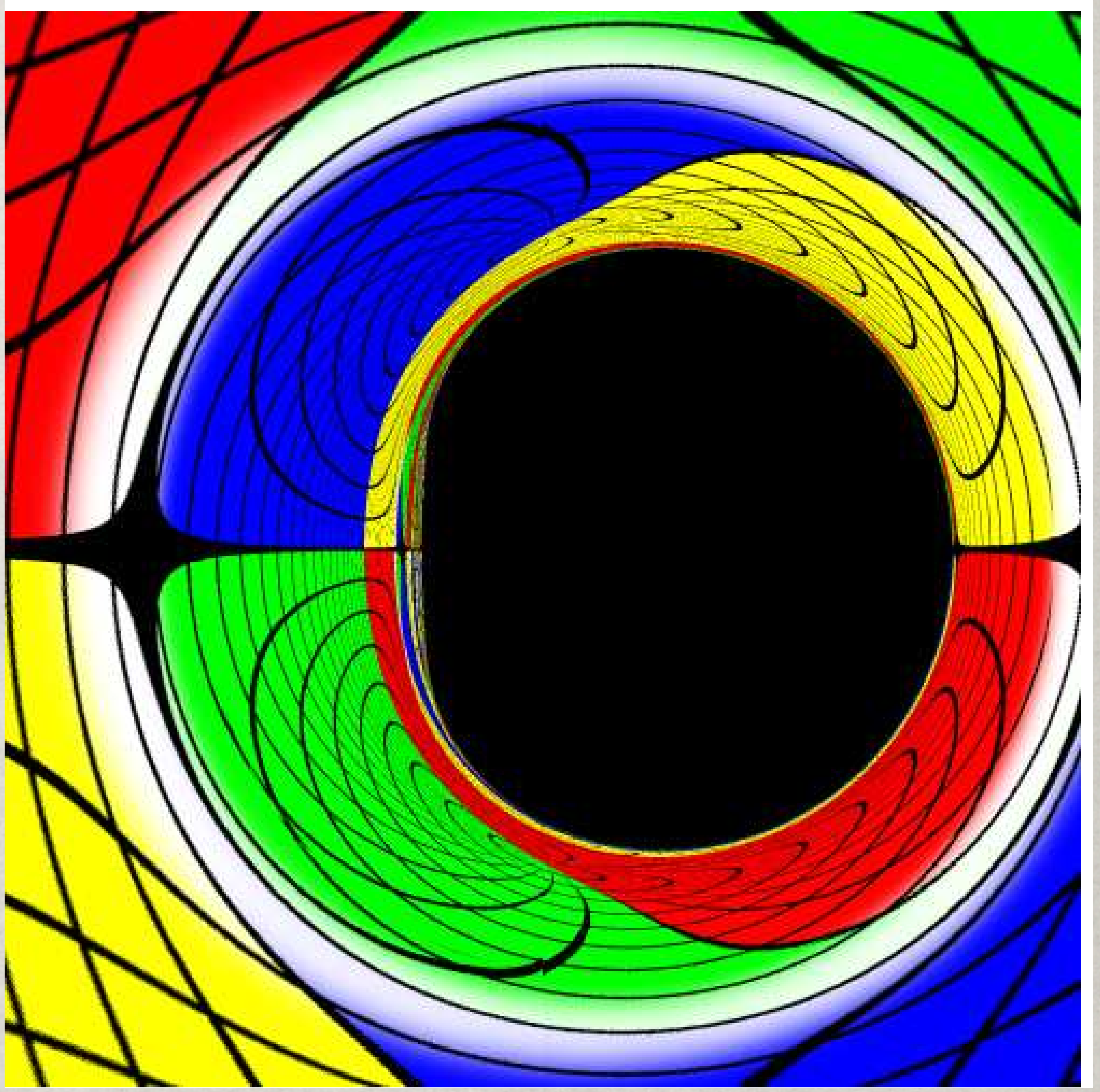


5% of mass;
13% of angular momentum
is stored in the scalar field

A Kerr-like Kerr BH with scalar hair

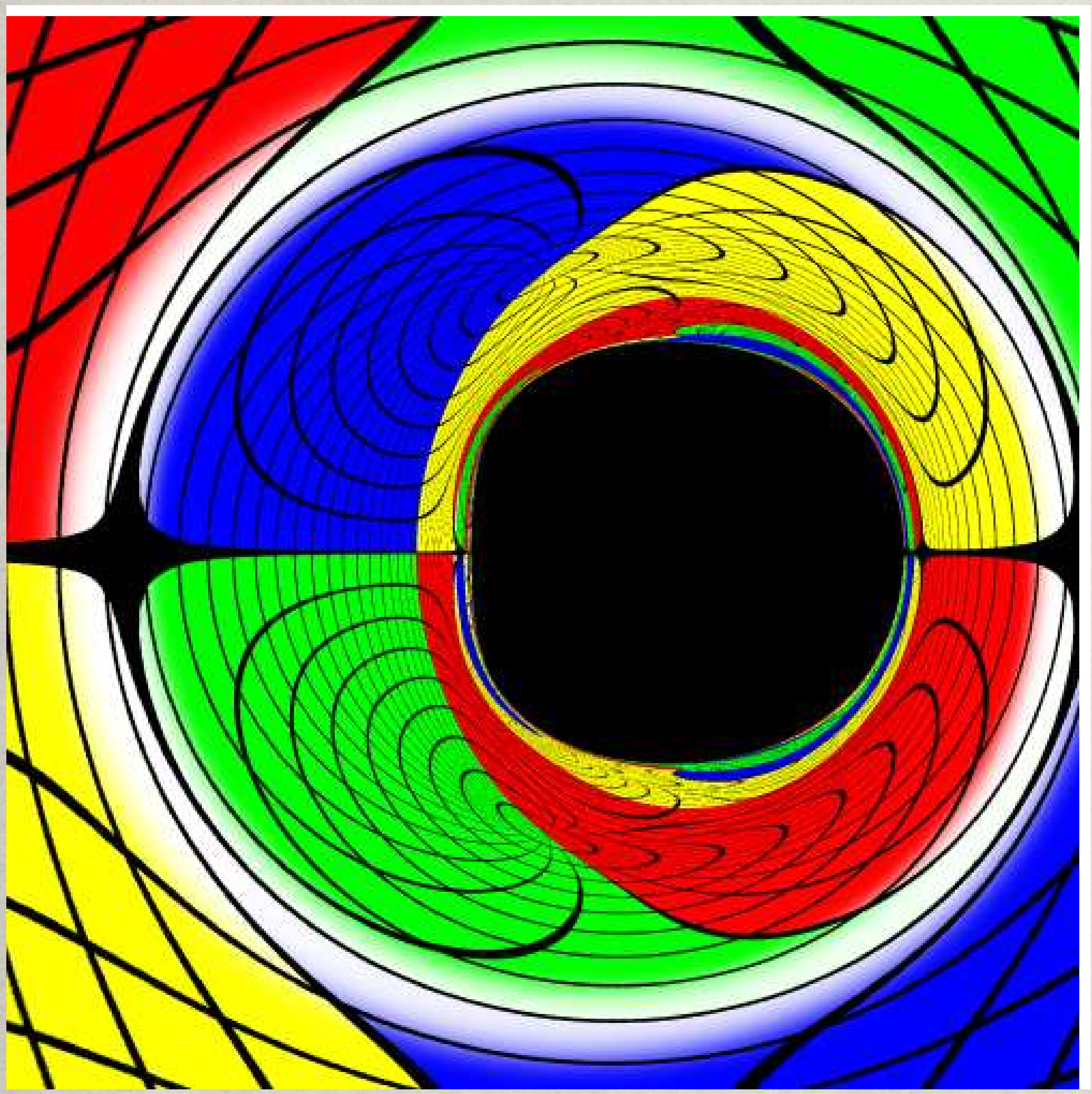


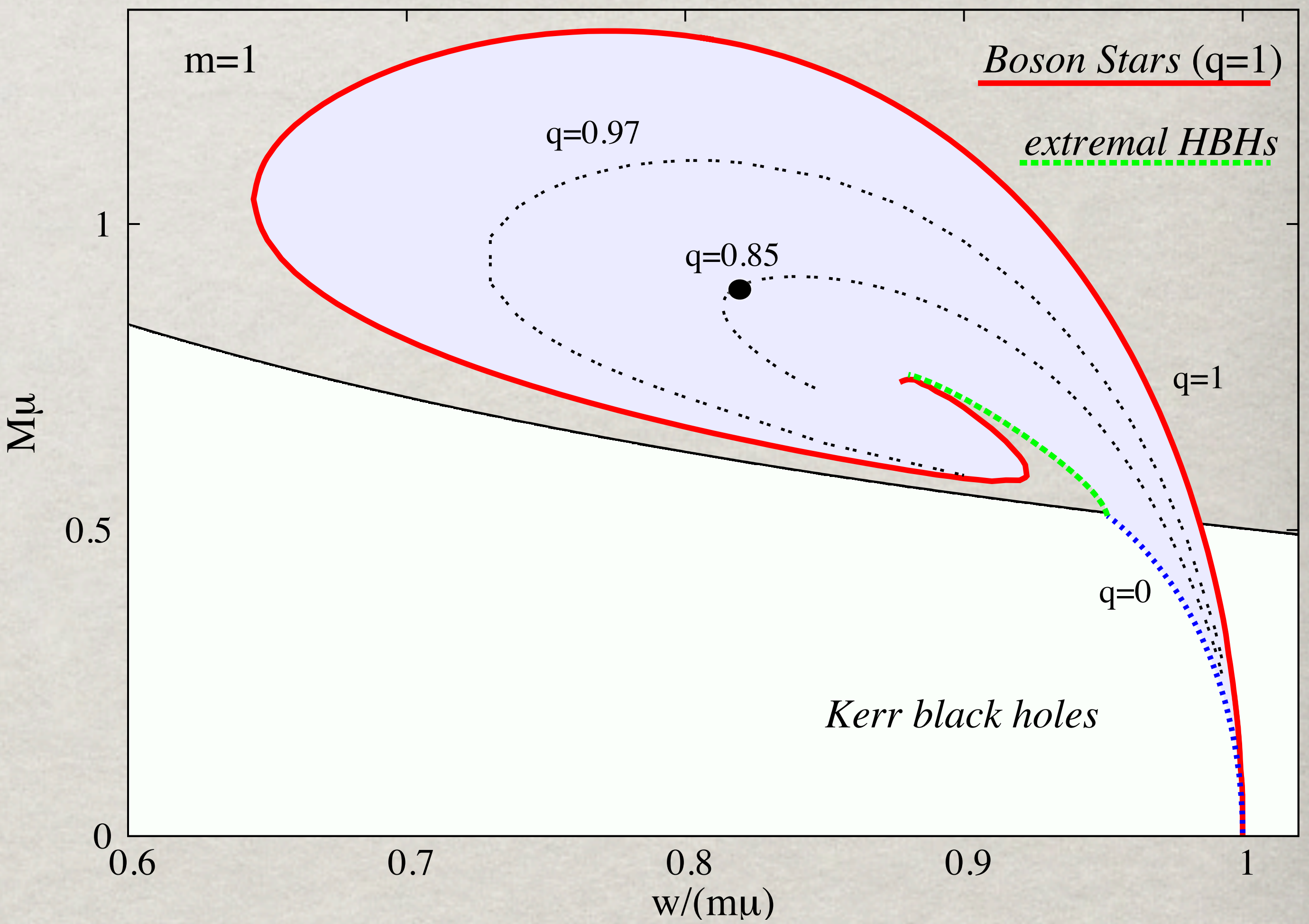
Kerr BH with scalar hair
M=0.393; J=0.15 (horizon)
M=0.022; J=0.022 (scalar field)



Vacuum Kerr BH
M=0.415; J=0.172

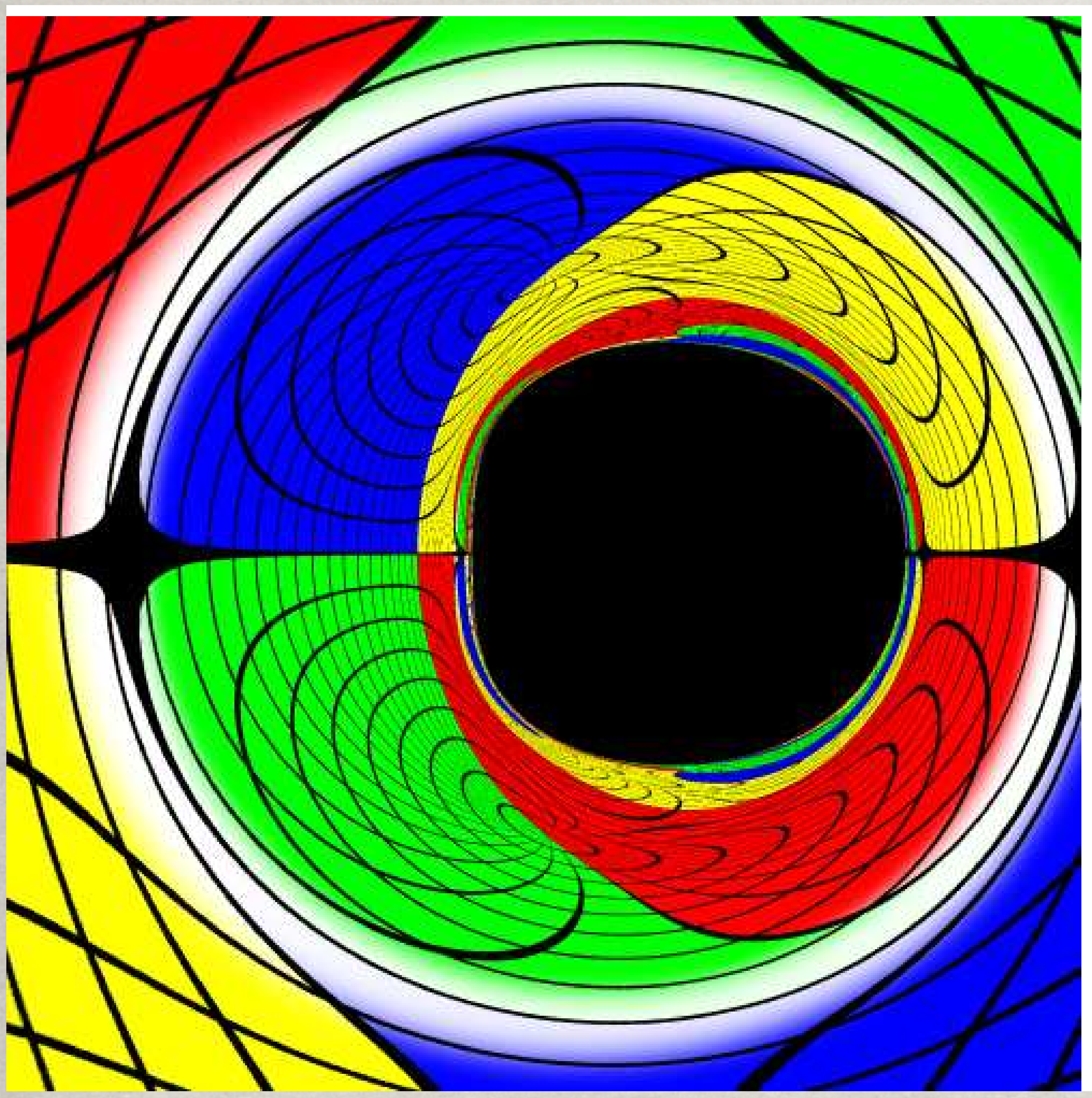
A non-Kerr-like hairy black hole



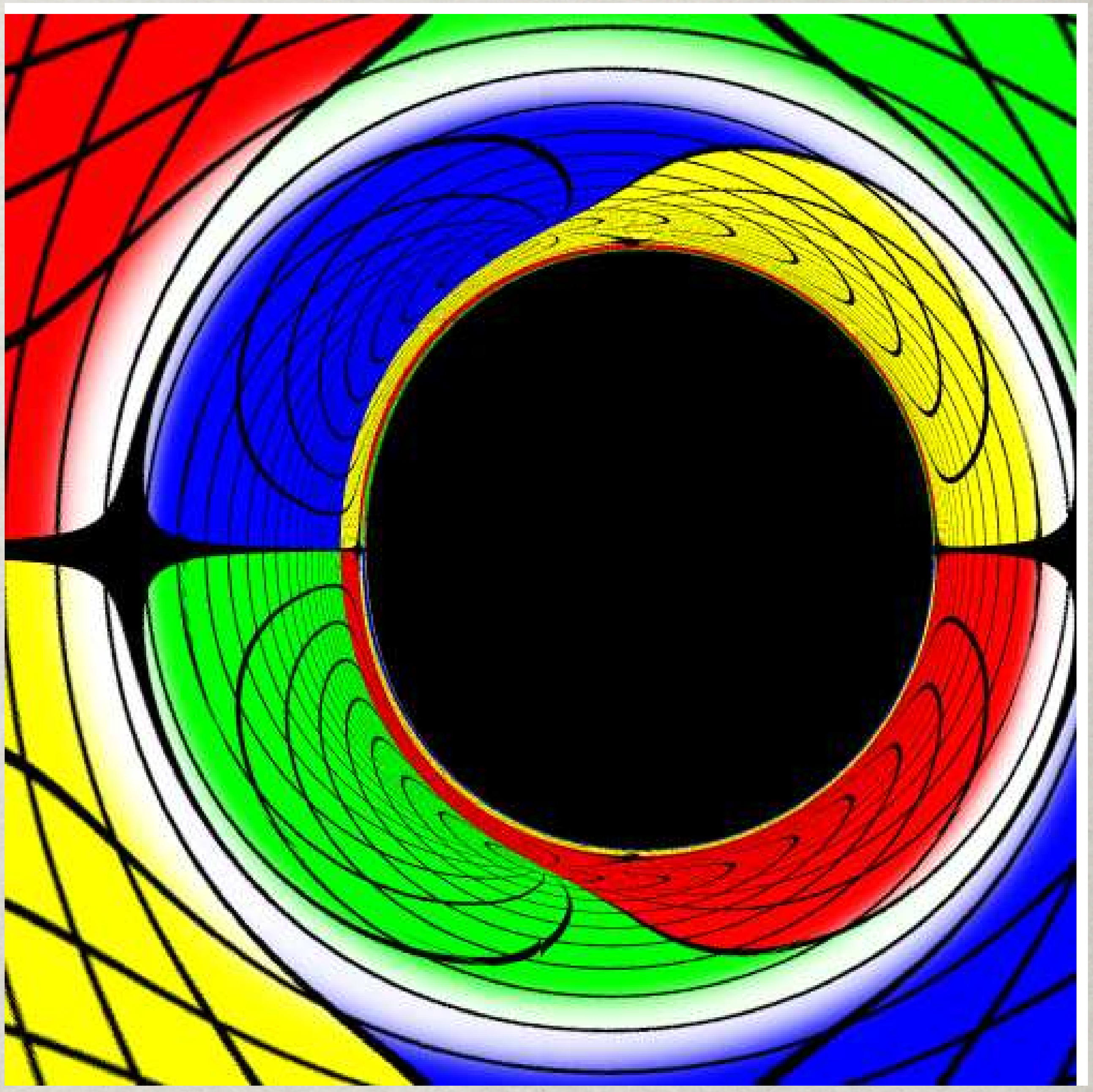


75% of mass;
85% of angular momentum
is stored in the scalar field

A non-Kerr-like hairy black hole

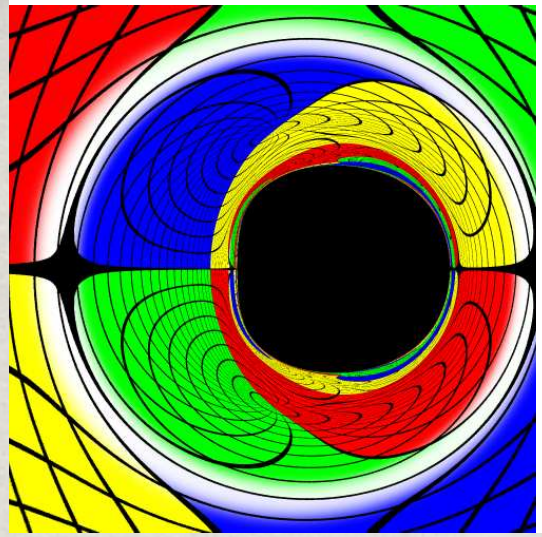


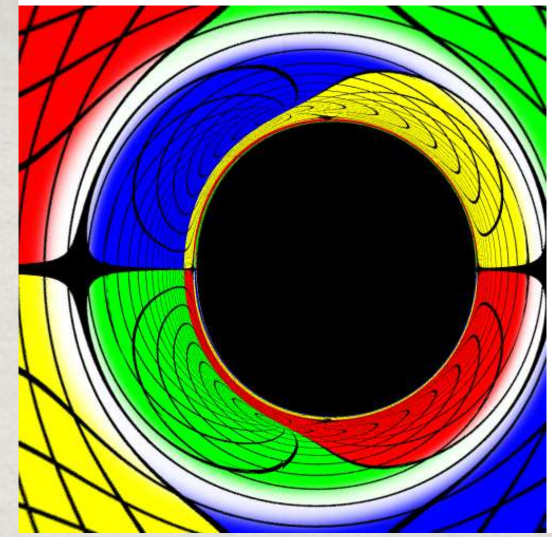
Kerr BH with scalar hair
M=0.234; J=0.114 (horizon)
M=0.699; J=0.625 (scalar field)

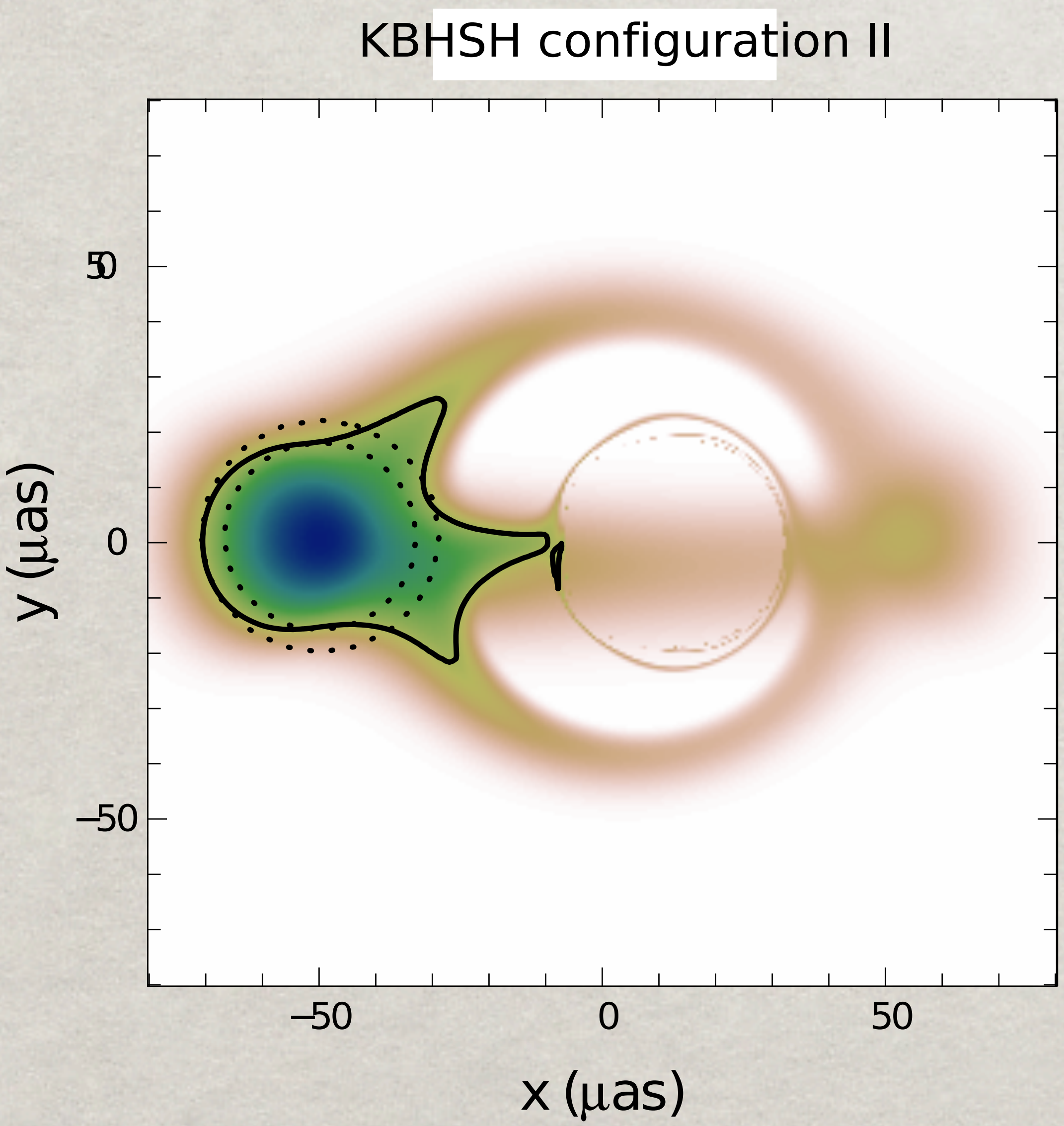


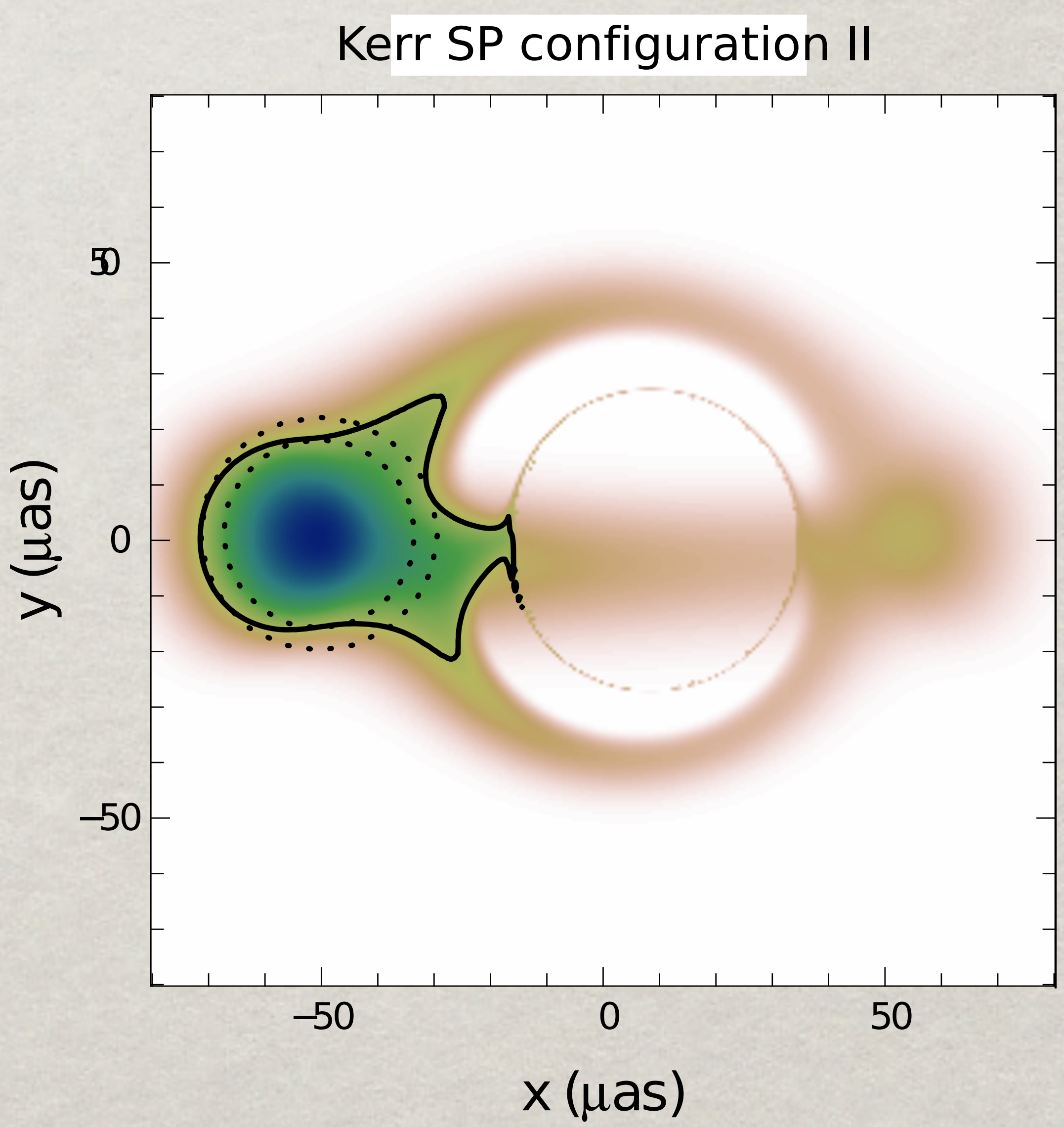
Vacuum Kerr BH
M=0.933; J=0.739

“Academic Setup”









Differences remain in an astrophysically more realistic setup

Vincent, Gourgoulhon, C.H., Radu, arXiv:160604246

4) Not one family of solutions… rather, one mechanism

A (hairless) BH which is afflicted by the superradiant instability of a given field for which the energy-momentum tensor is time-independent, allows a hairy generalization with that field.

C. H., E. Radu, IJMPD23(2014)1442014

e.g. Kerr black holes with Proca hair have been constructed:

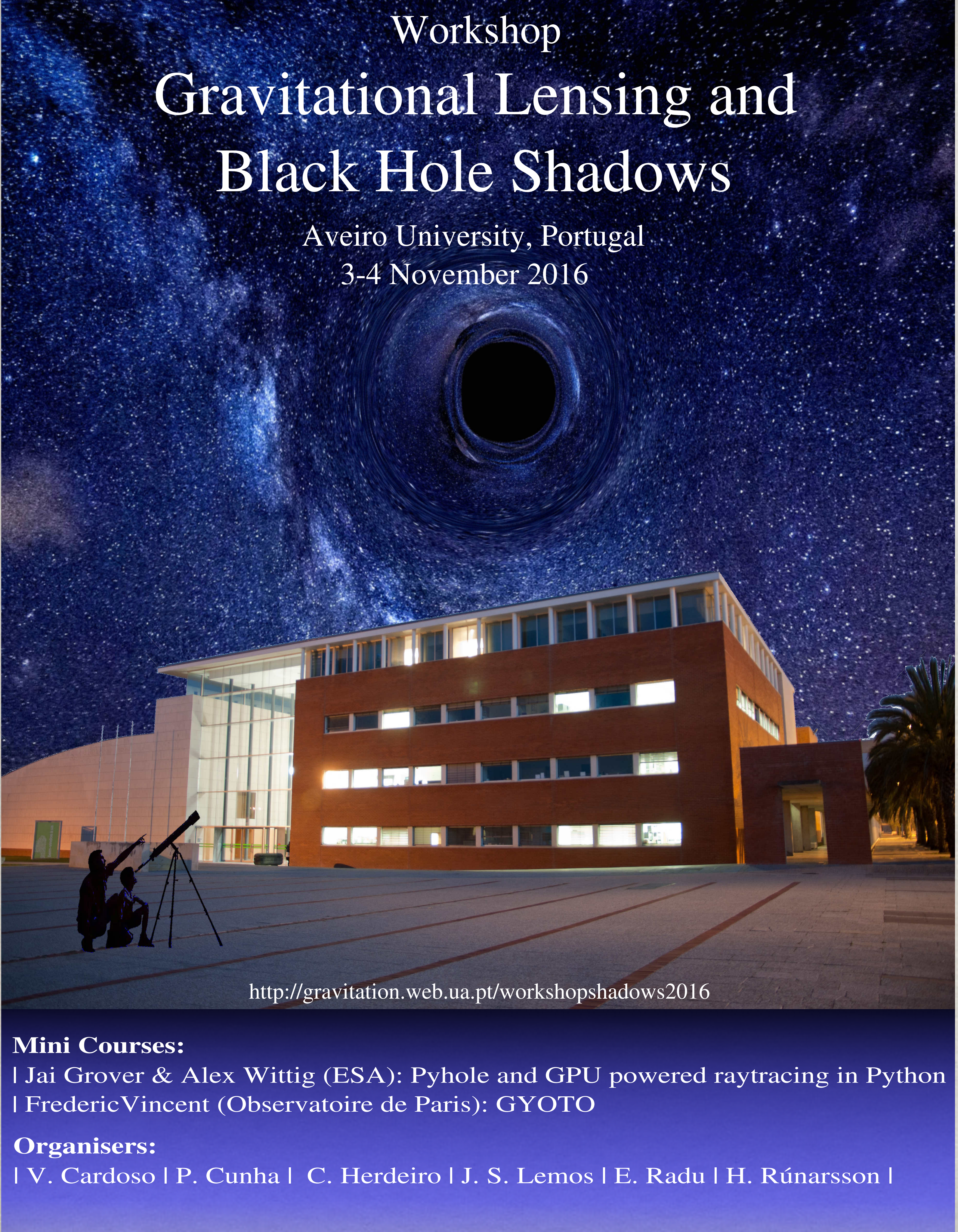
C.H., Radu and Rúnarsson,
CQG33(2016)154001

Conclusions:

- Timely to study alternatives to the Kerr paradigm, in view of all the ongoing and upcoming observations (electromagnetic and GWs)

- There is a new, physically reasonable model of black holes, within GR, which can be used to make contact with fundamental high energy physics

- Many open questions about the properties of these solutions, in particular about their dynamics, e.g. likelihood of formation and stability.



Thank you for your attention!

5) Could they form dynamically?

Question:

In these models
vacuum Kerr black holes are **unstable**
(against superradiance).

What is the endpoint of the instability?

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vacuum Kerr black holes are **unstable**
(against superradiance).

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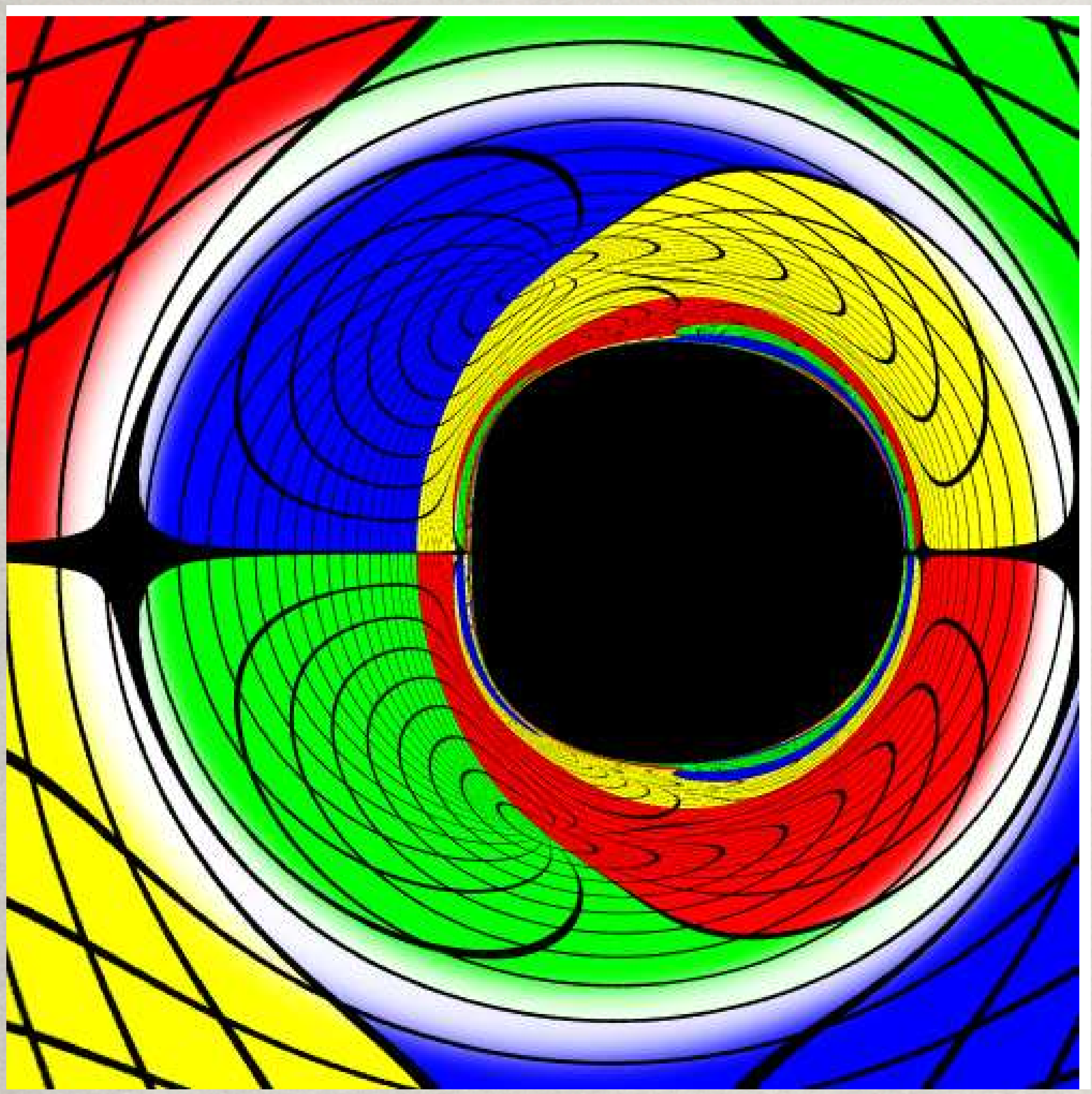
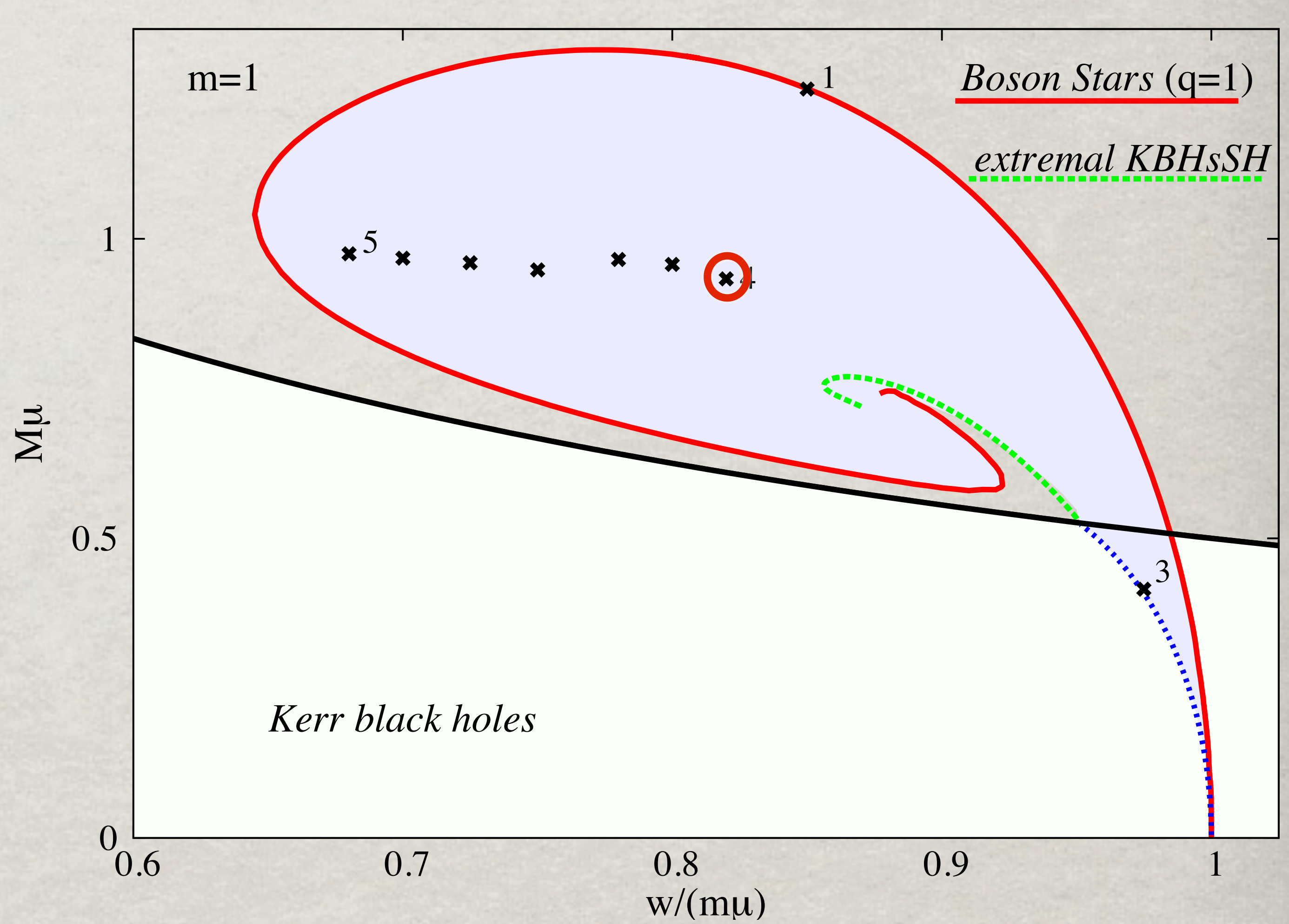
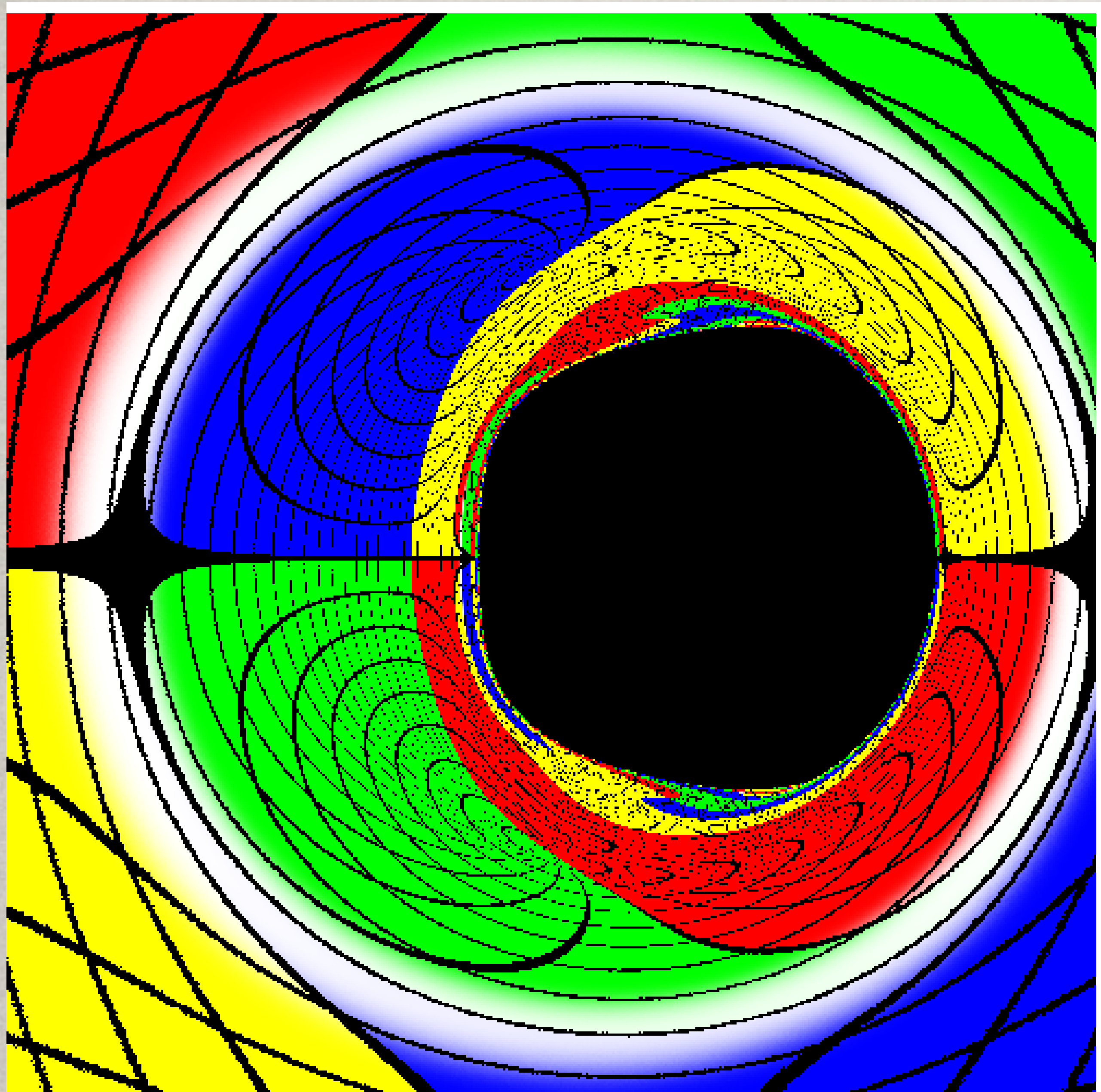
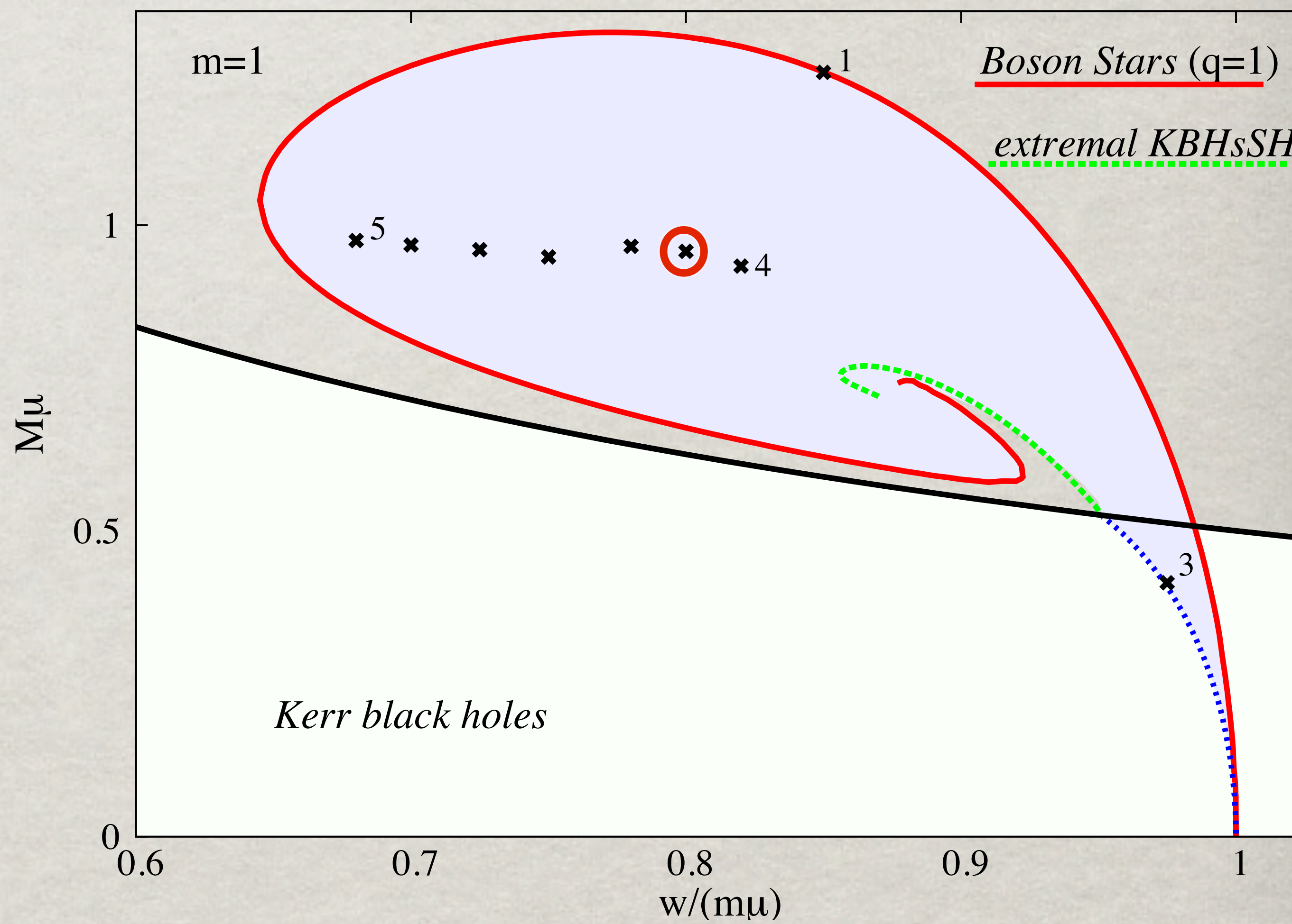
In a toy model it is a hairy black hole of this sort:
Sanchis-Gual, Degollado, Moreno, Font, C.H.,
PRL 116 (2016)141101

More non-Kerr-like hairy black holes

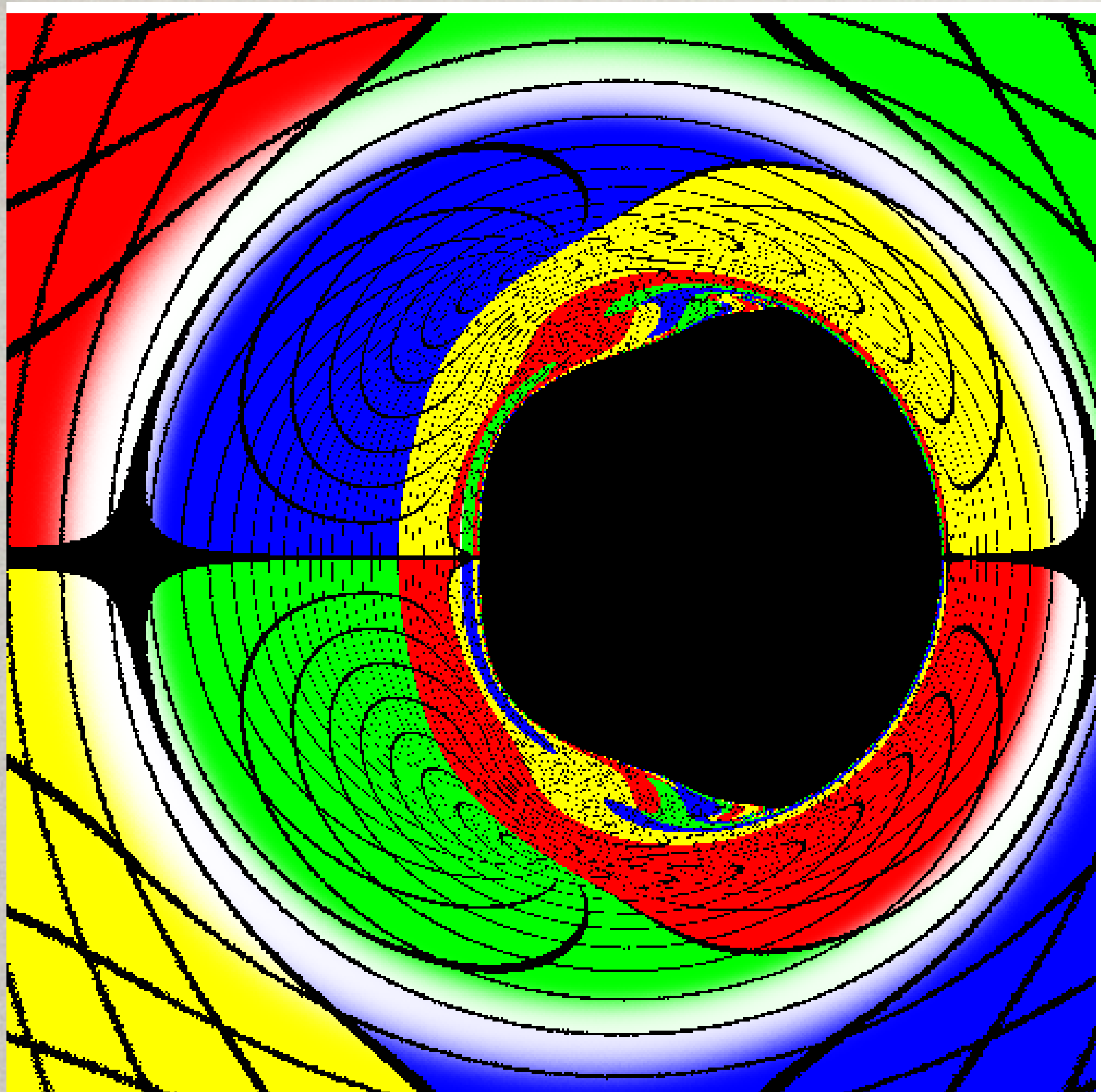


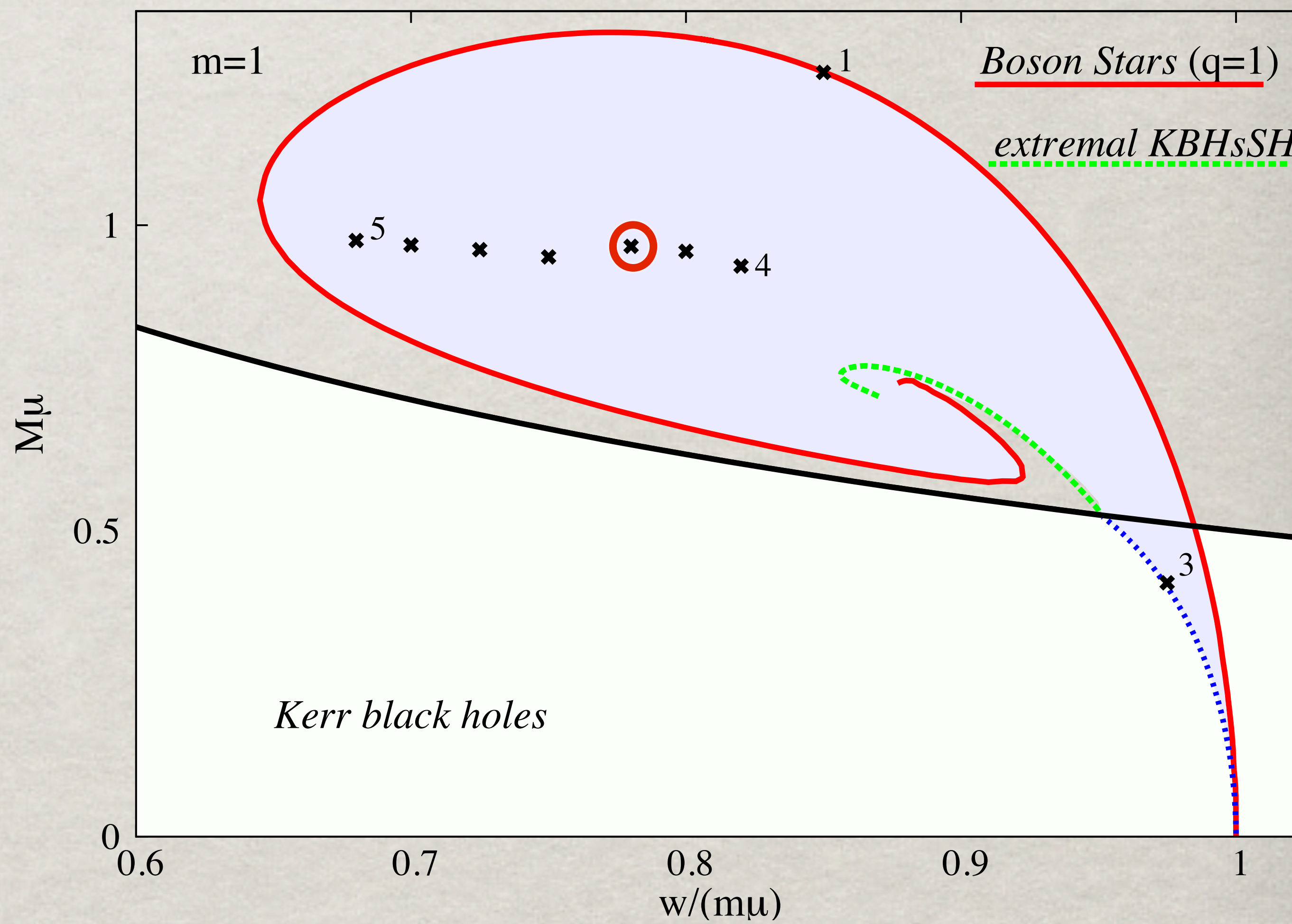






m=1
Boson Stars (q=1)
extremal KBHsSH
1
3
4
5
Kerr black holes
Mμ
w/(mμ)
0
0.5
1
0.6
0.7
0.8
0.9
1





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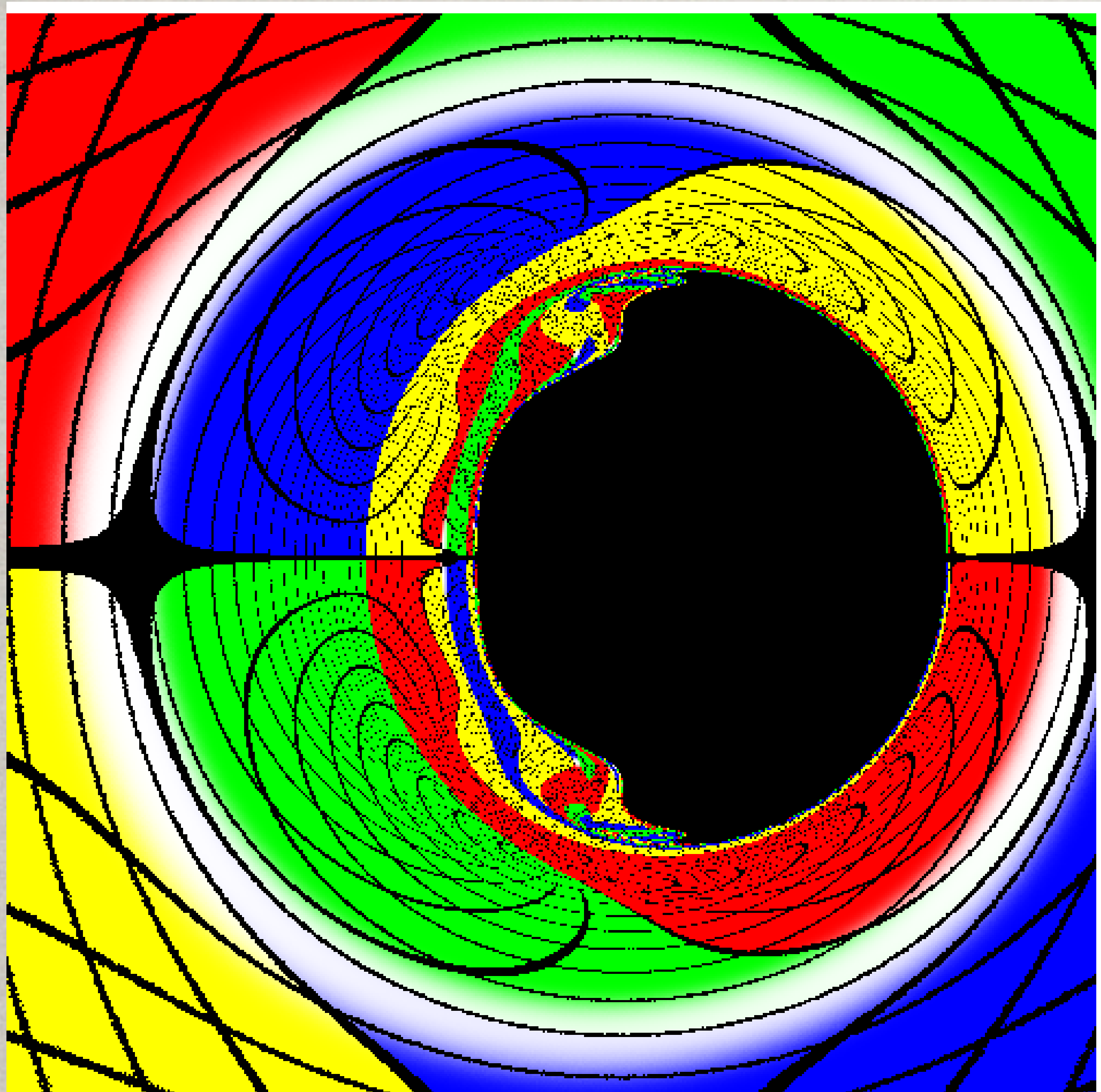

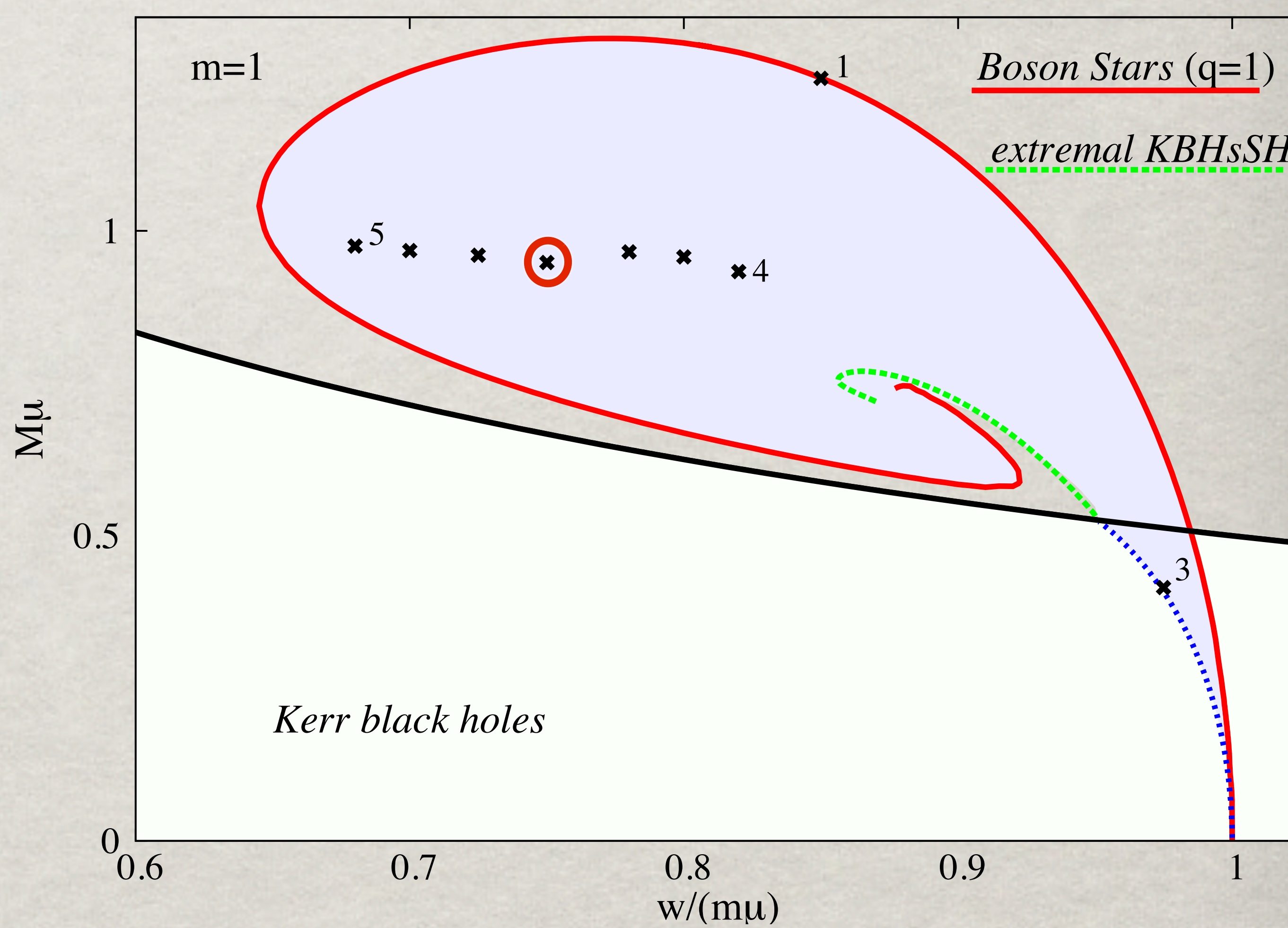
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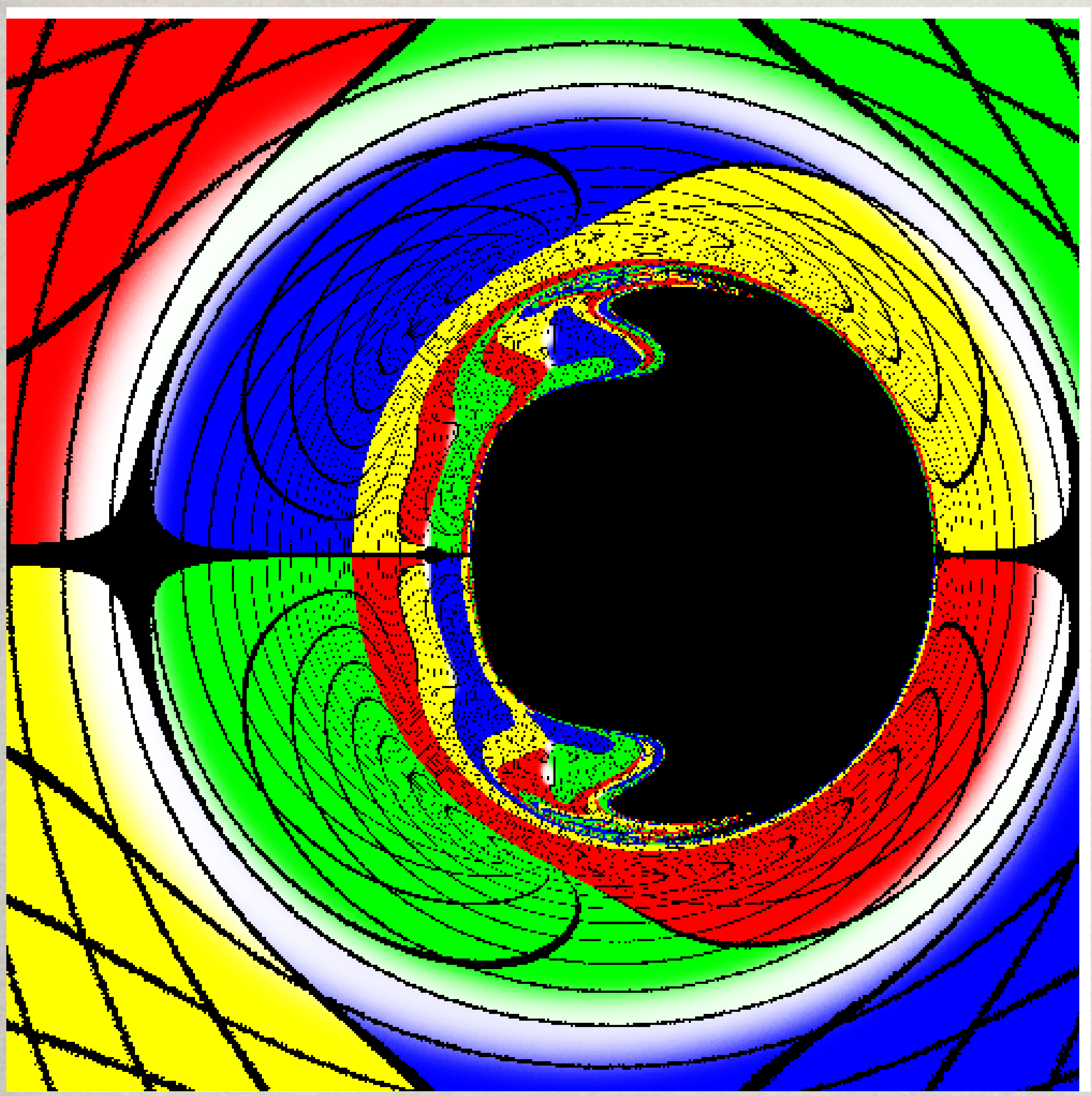

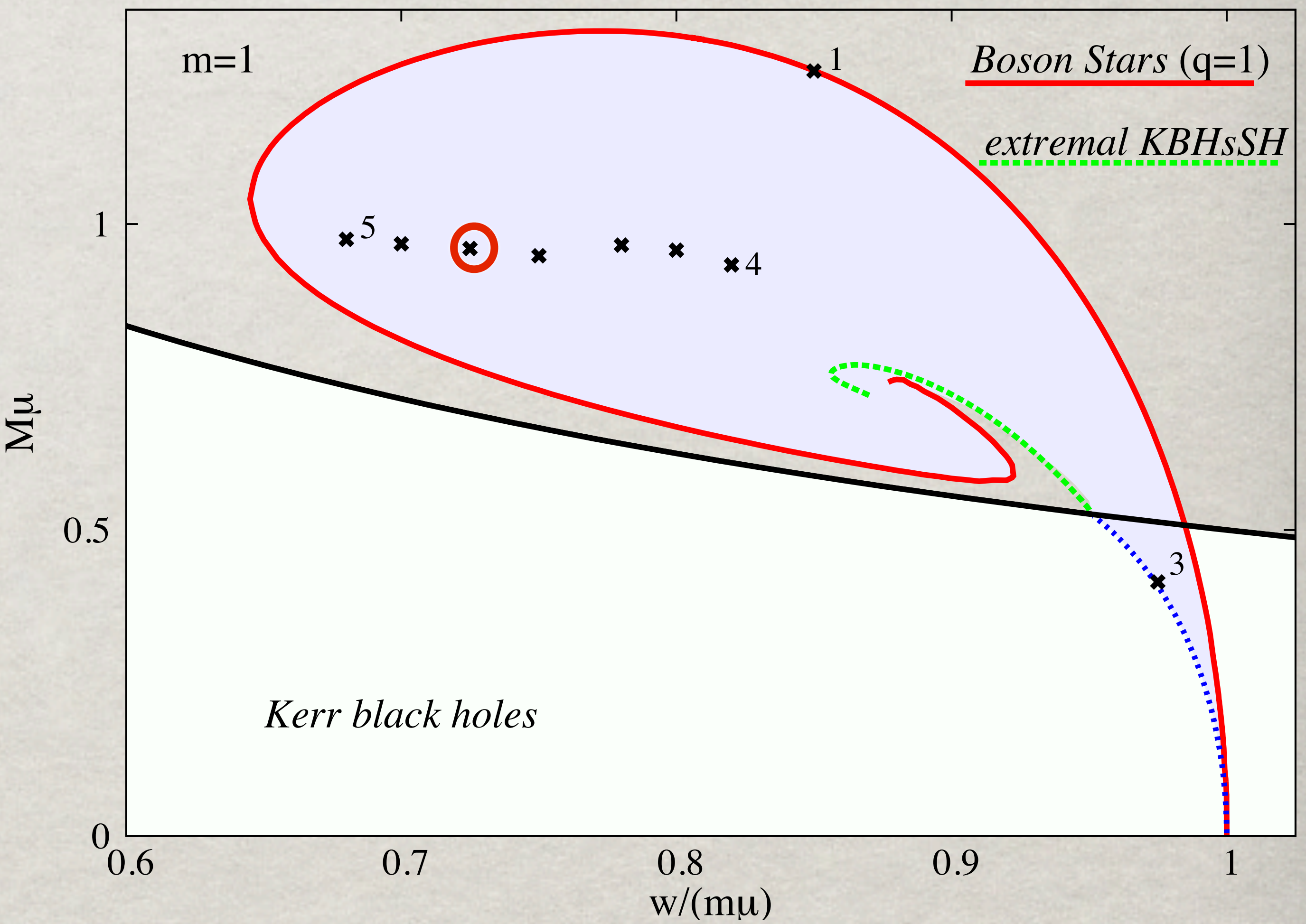

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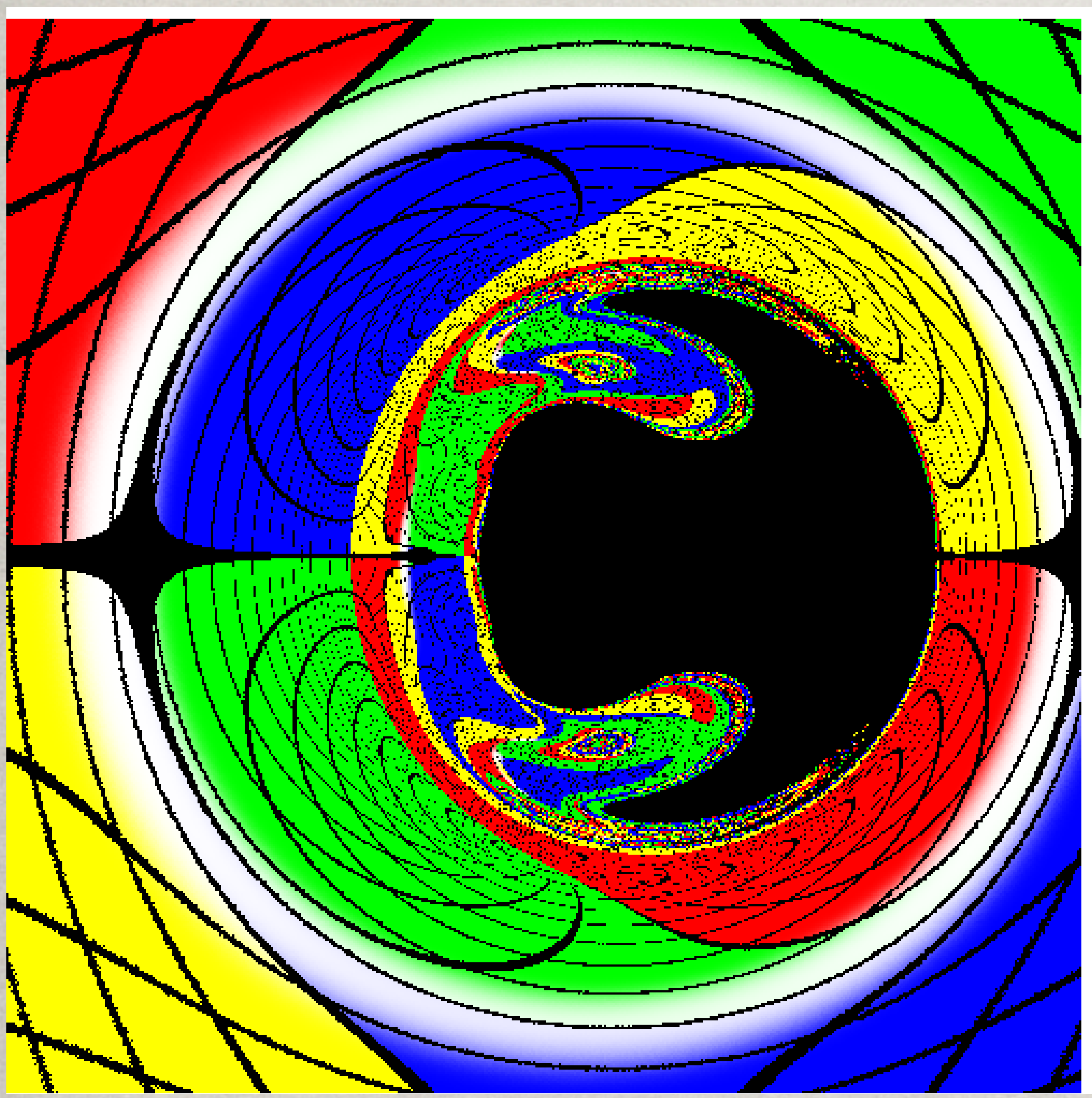

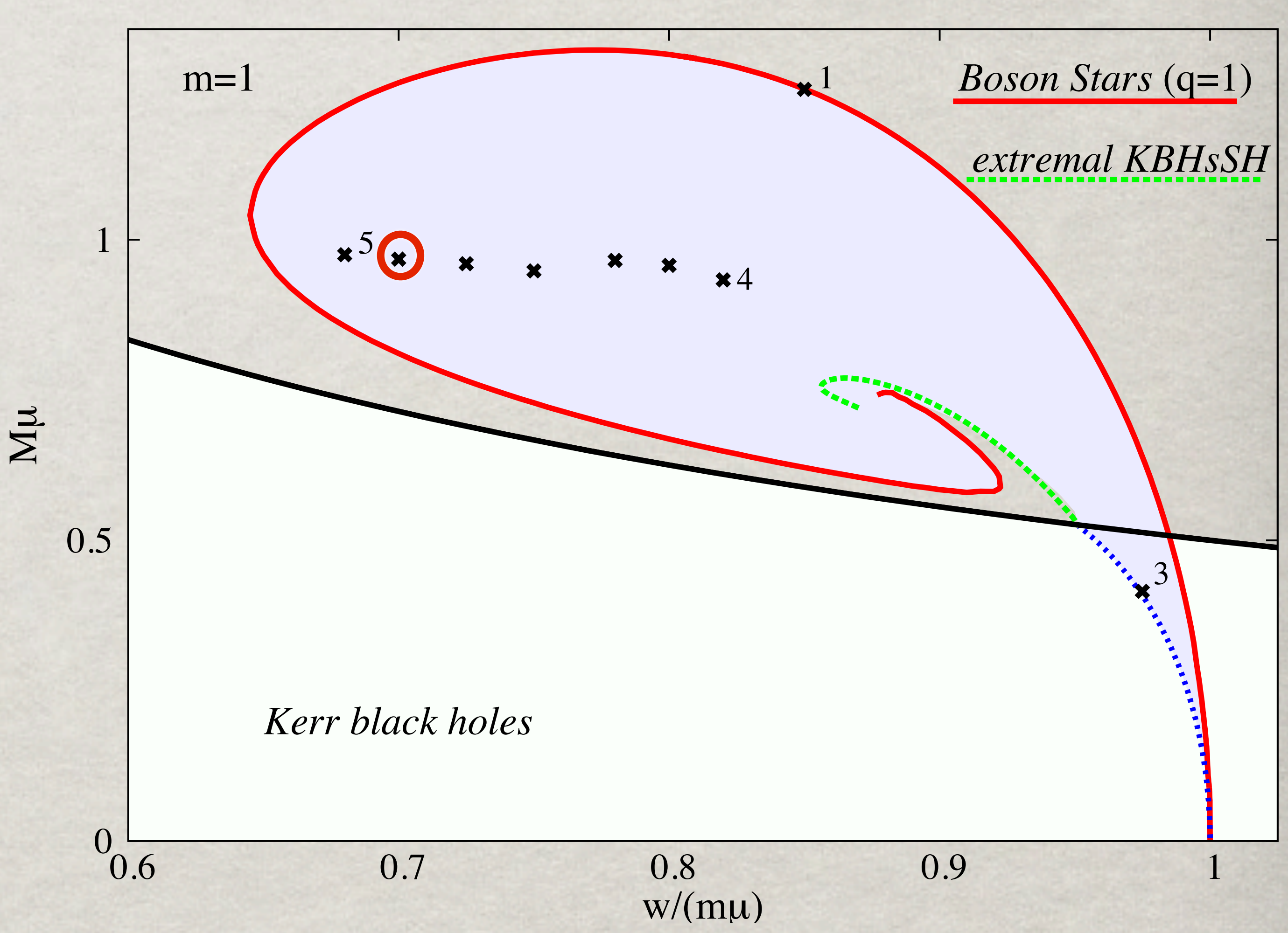

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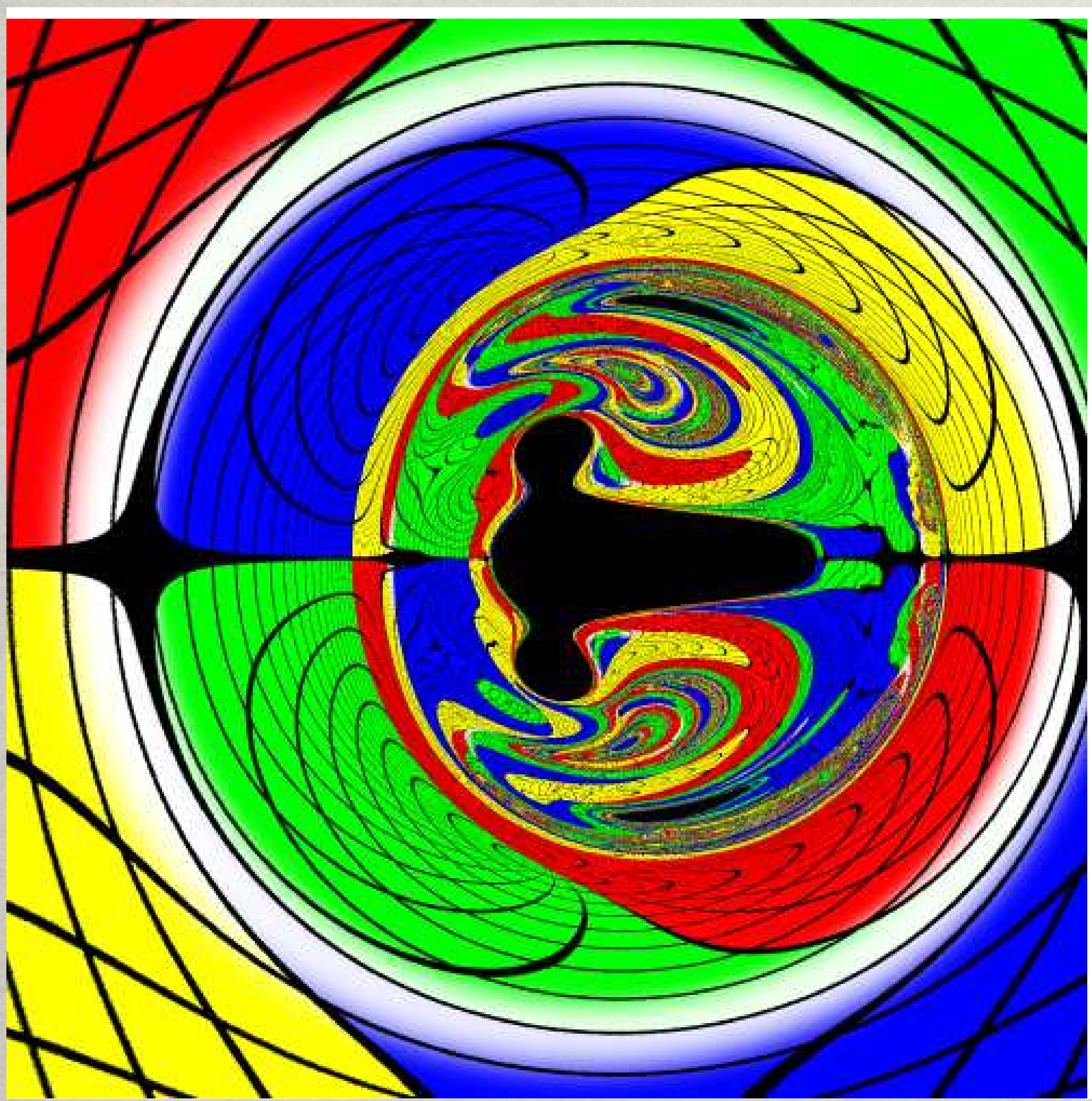

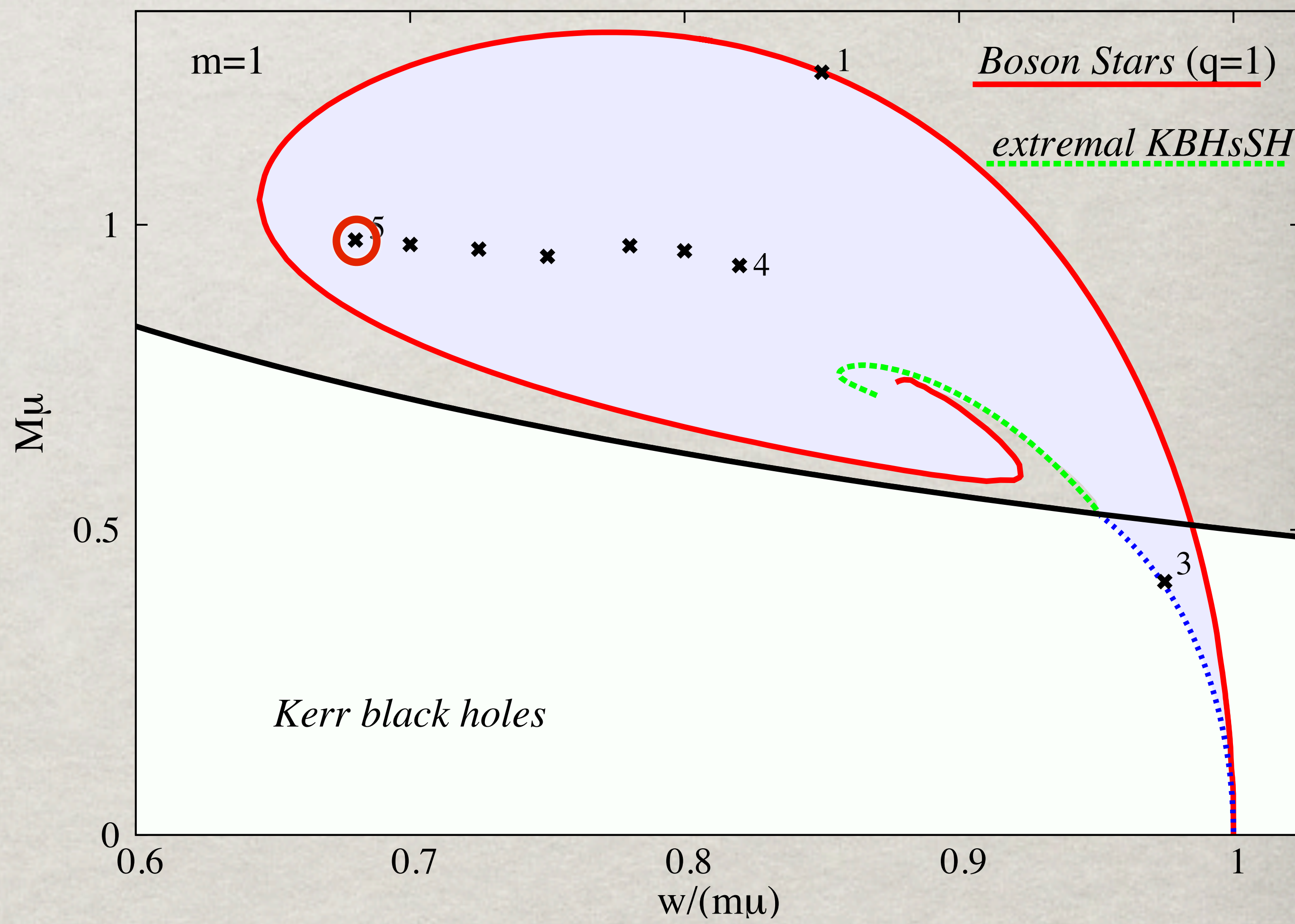

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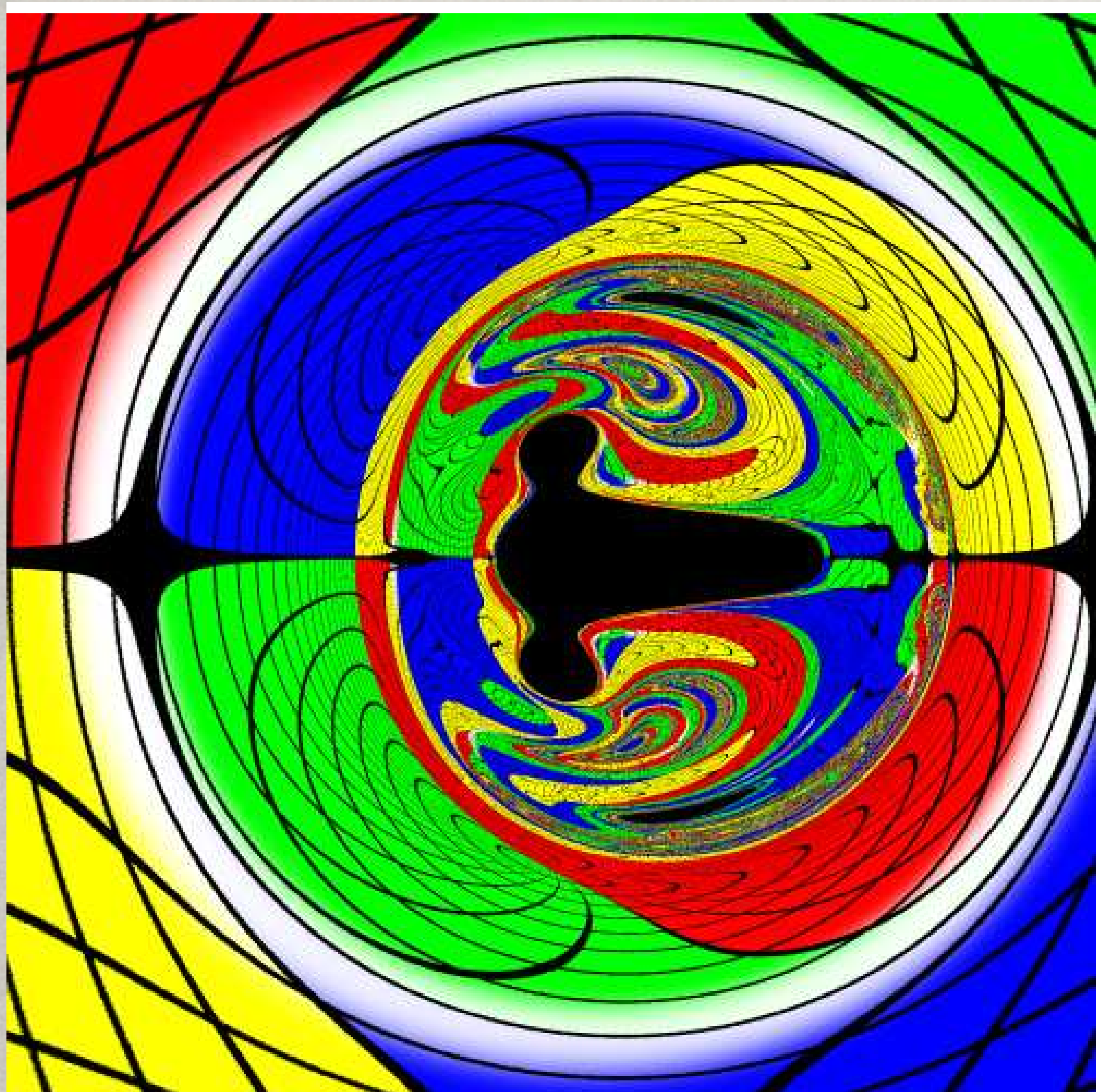
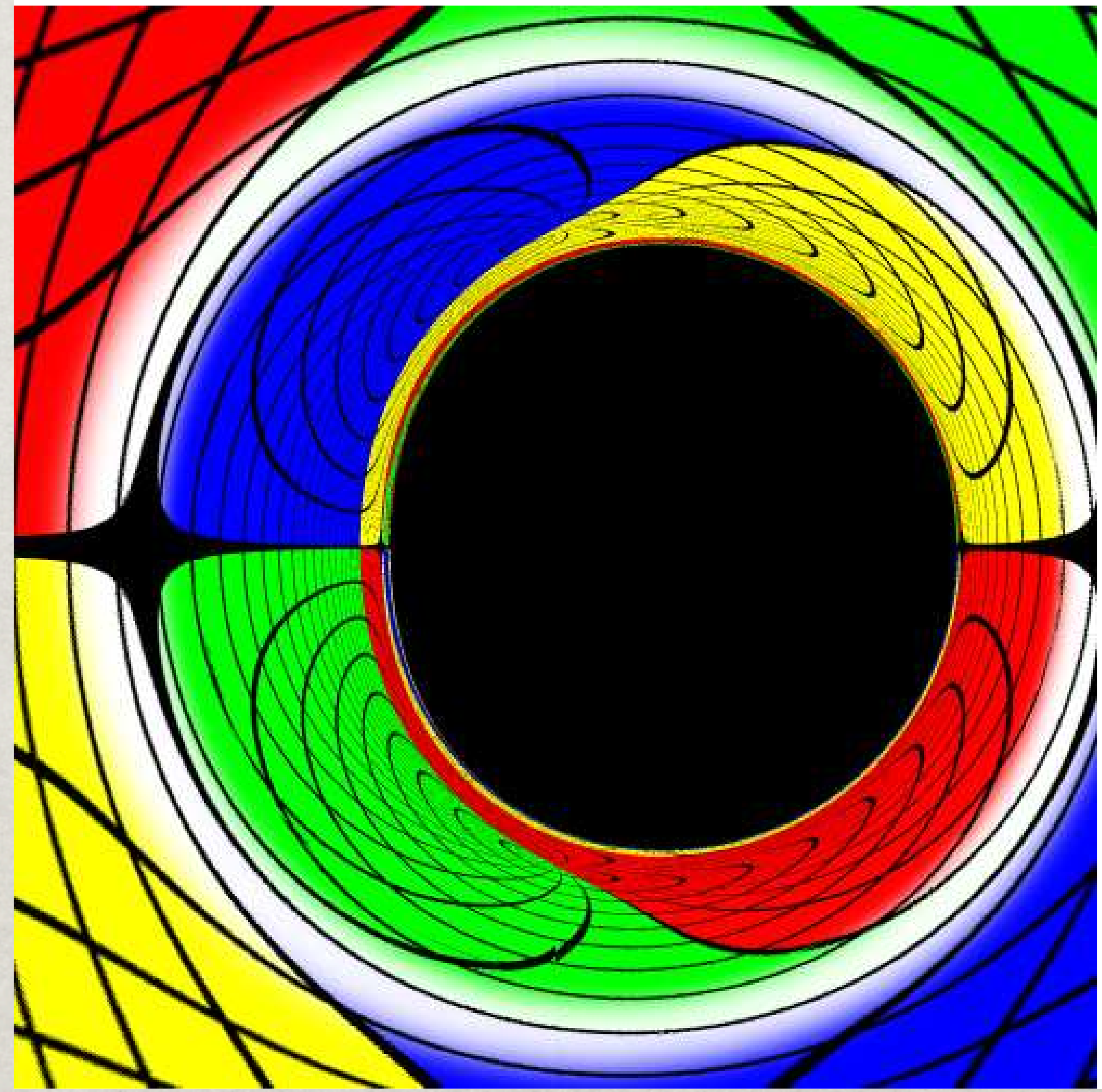
A very non-Kerr-like hairy black hole





Qualitatively new feature:
multiple shadows of a single black hole