Shadows of Kerr black holes with scalar hair

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

GR 100 years in Lisbon

December 18th 2015

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

with E. Radu, P. Cunha, H. Rúnarsson

Plan:

1) Gravitational Lensing

2) Black hole shadows and lensing

3) Kerr black holes with scalar hair

4) Lensing by boson stars

5) Shadows of Kerr black holes with scalar hair

6) Outlook

1) Gravitational lensing

Gravitational lensing and the confirmation of General Relativity

LIGHTS ALL ASKEW IN THE HEAVENS

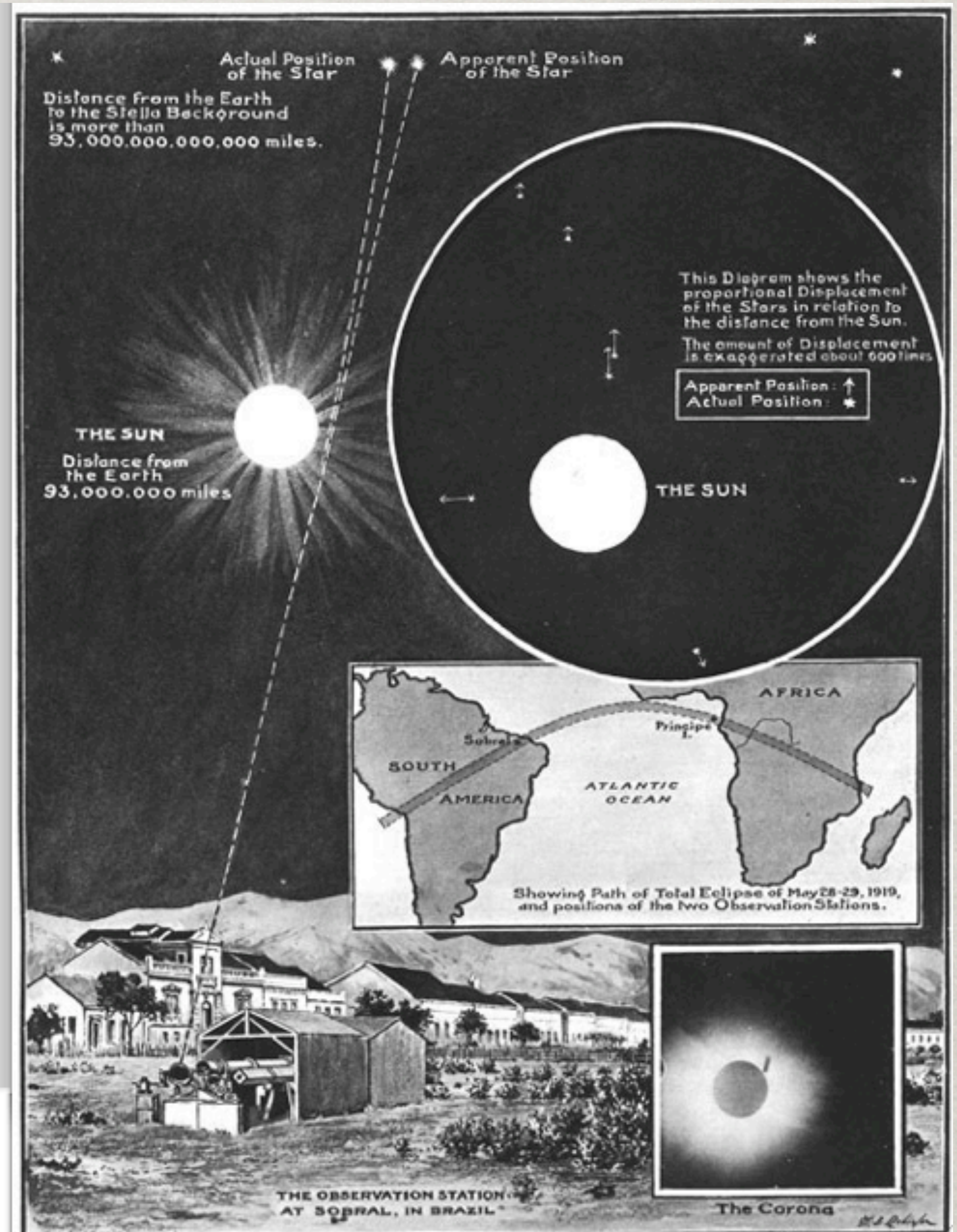
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

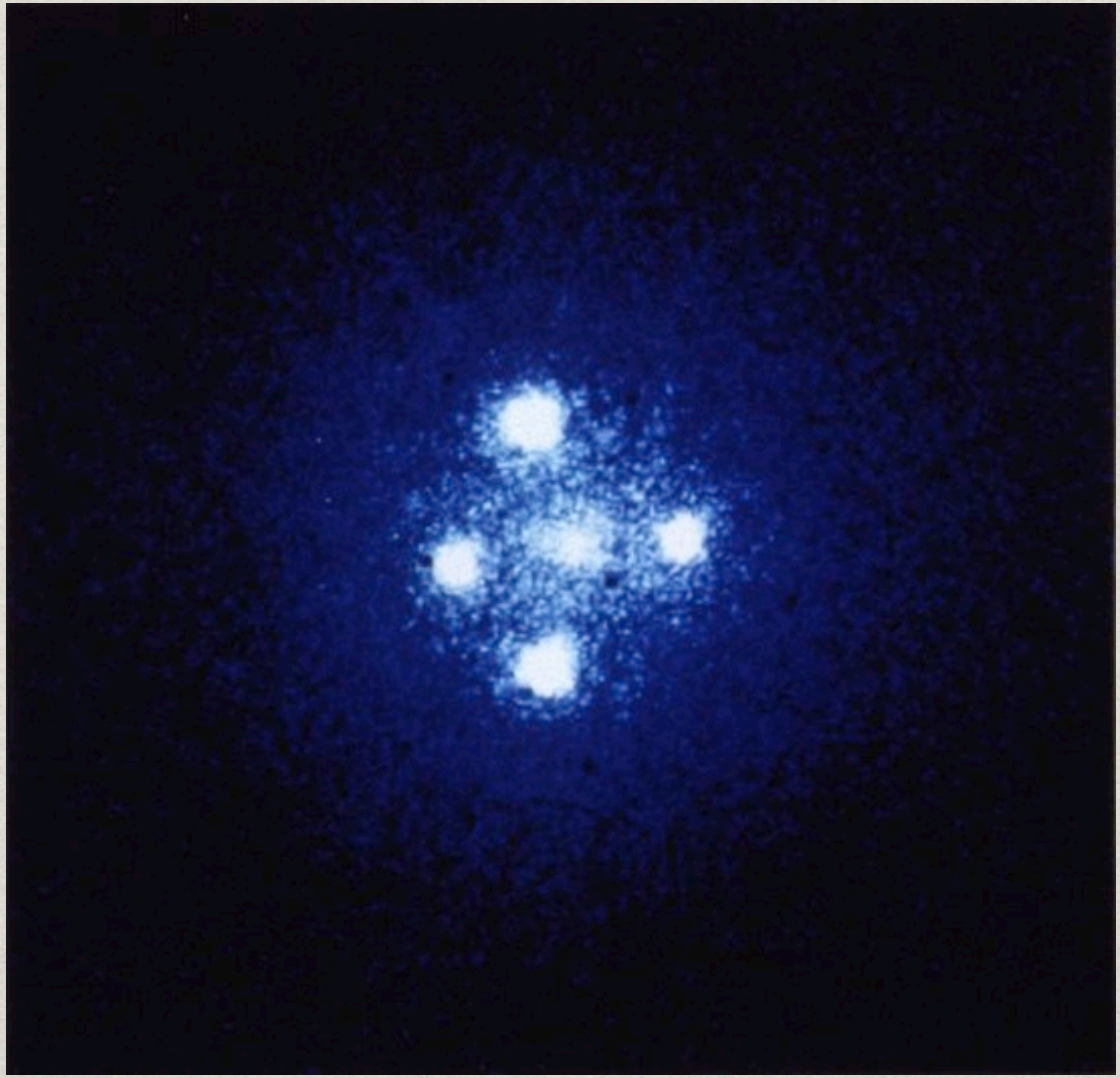
A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.



New York Times, 10 November 1919 (L); Illustrated London News, 22 November 1919 (R).

Einstein Cross



Gravitational lens G2237 + 0305.
Four images of a very distant quasar
due to a relatively nearby galaxy.
The angular separation between the upper and lower images is 1.6 arcseconds.

European
Southern
Observatory

ann15088 — Announcement

MUSE Observations Enable Prediction of Once-in-a-lifetime Supernova Replay

25 November 2015

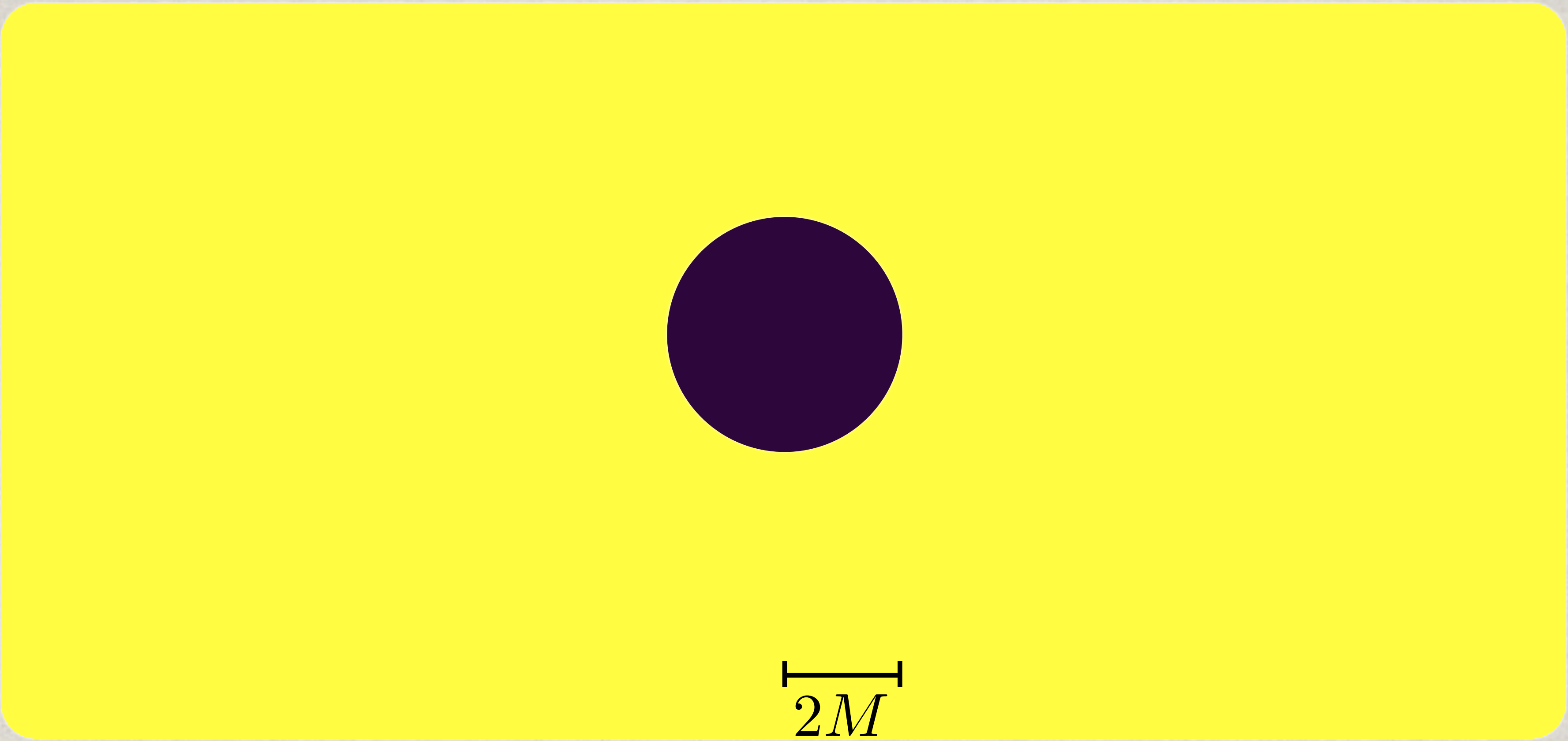
Using the
Multi Unit
Spectroscopic
Explorer
in VLT

Images of the galaxy cluster MACSJ1149+2233, in November 2014,
revealed a distant exploding star -- a supernova -- split into four separate images through gravitational lensing.

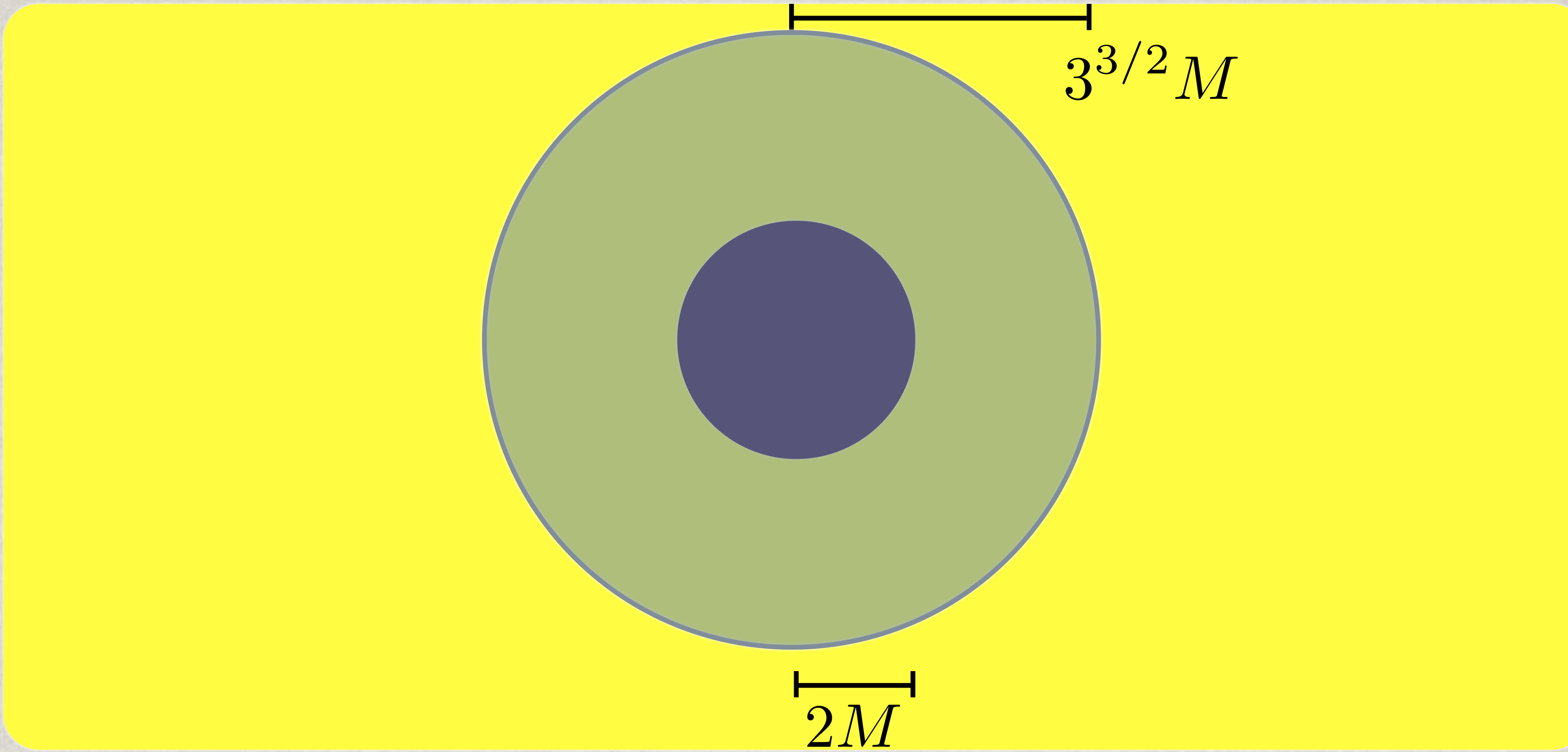
A further replay is expected to peak in brightness between March and June 2016,
with a possible first detection before the end of 2015.

2) Black hole shadows and lensing

Consider a “bright” homogeneous background with angular size much larger than the BH



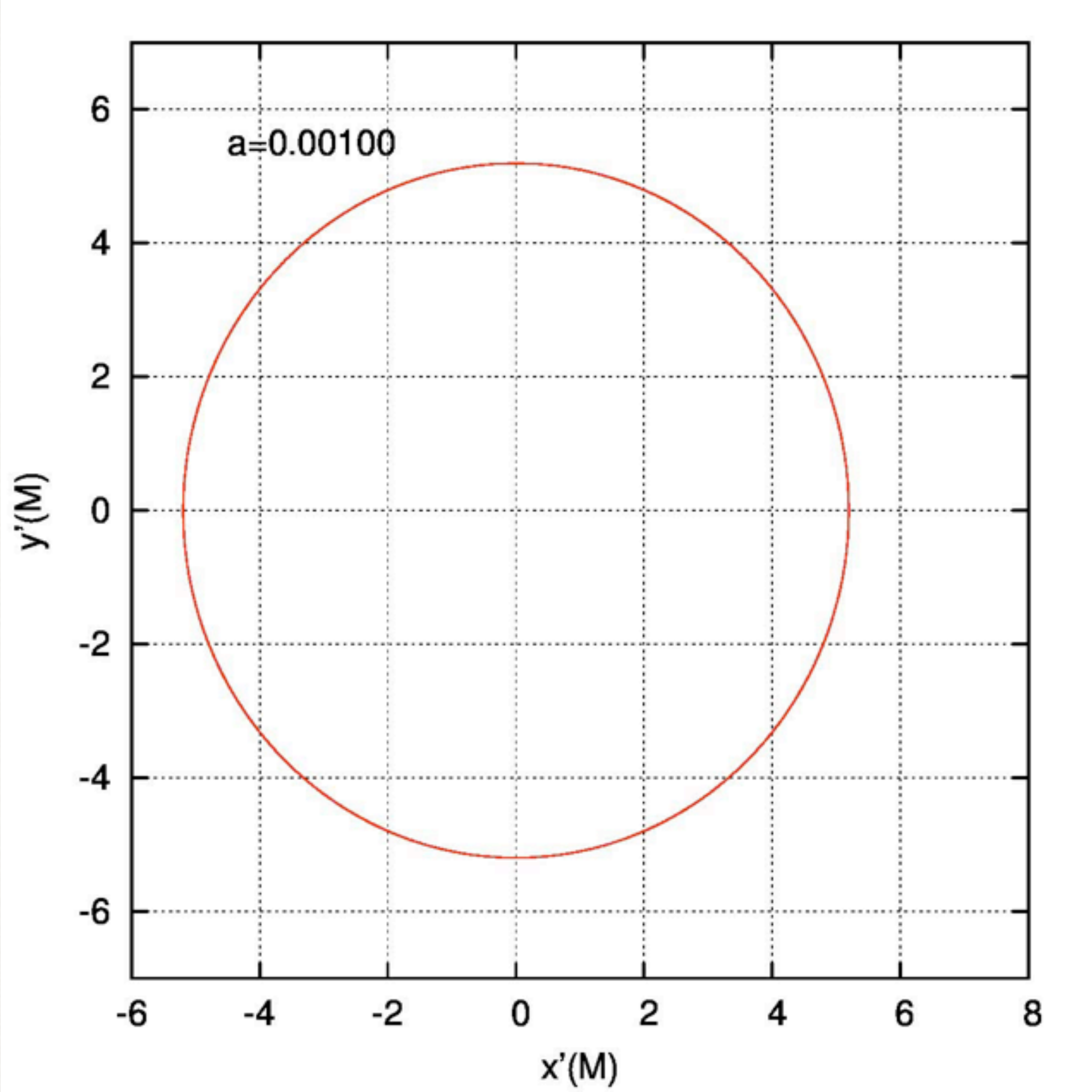
Consider a “bright” homogeneous background with angular size much larger than the BH



As seen by the distant observer the BH will cast a **shadow** in the middle of the large bright source, larger than the horizon scale

The rim of the BH **shadow** corresponds to a critical impact parameter:

$$d \equiv \frac{j}{E} = 3^{3/2}M$$



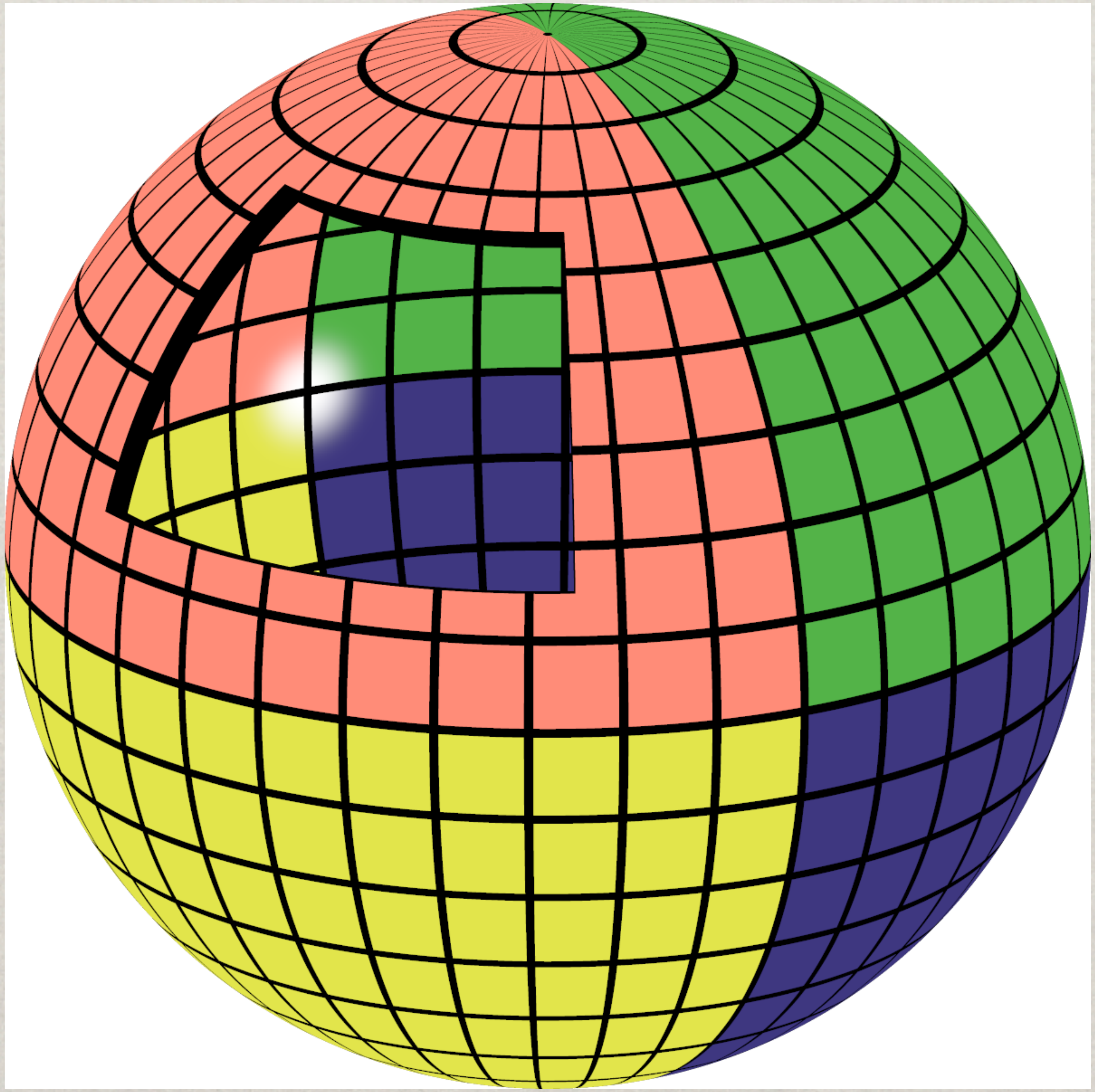
Pedro Cunha's M.Sc thesis (2015)

Technique: backwards ray-tracing

Cunha, M.Sc. Thesis

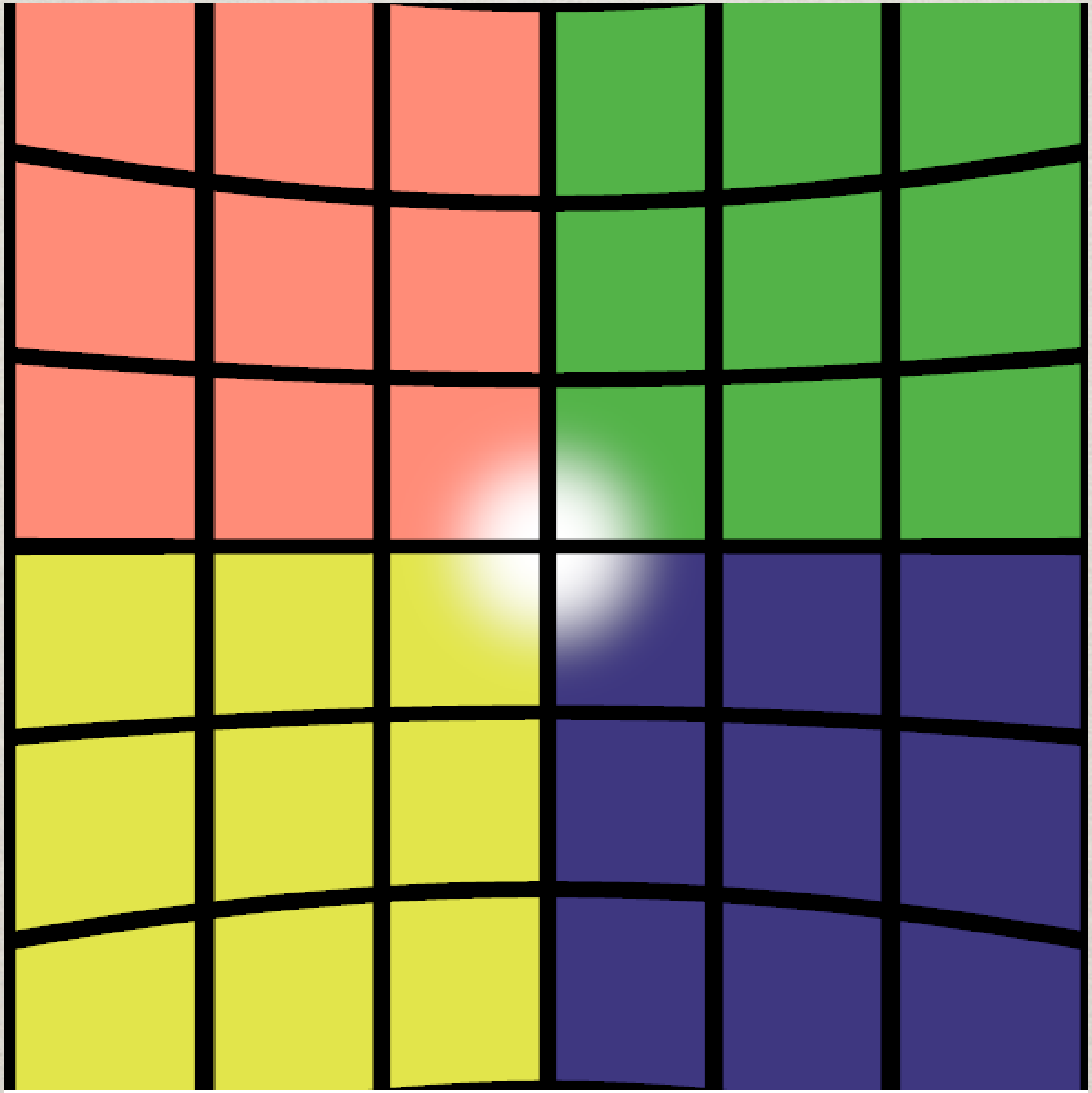
Light source is a "painted on" sphere at infinity:

- four colored quadrants with a superimposed grid;
- bright reference spot in the direction towards which we point the camera.



A. Bohn et al. arXiv:1410.7775

Visualization from camera (60° field of view): Minkowski

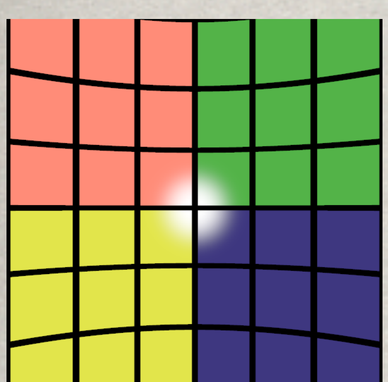


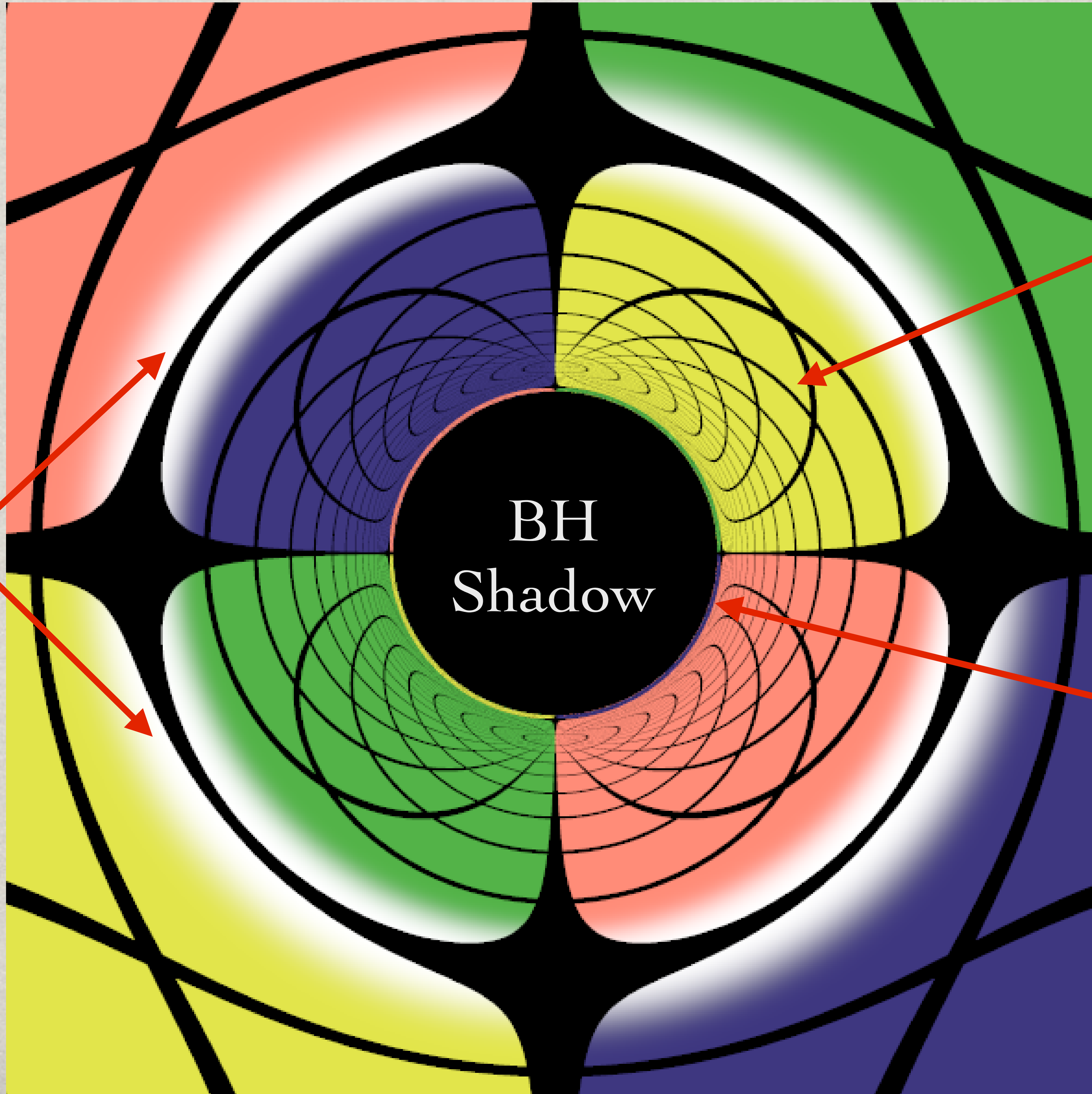
10° by 10° squares

- no deflection of light;
- bowing of the grid lines is an expected geometric effect of viewing a latitude-longitude grid.

Visualization from camera (60° field of view): Schwarzschild

White dot on grid at "infinity" has been lensed into an Einstein ring

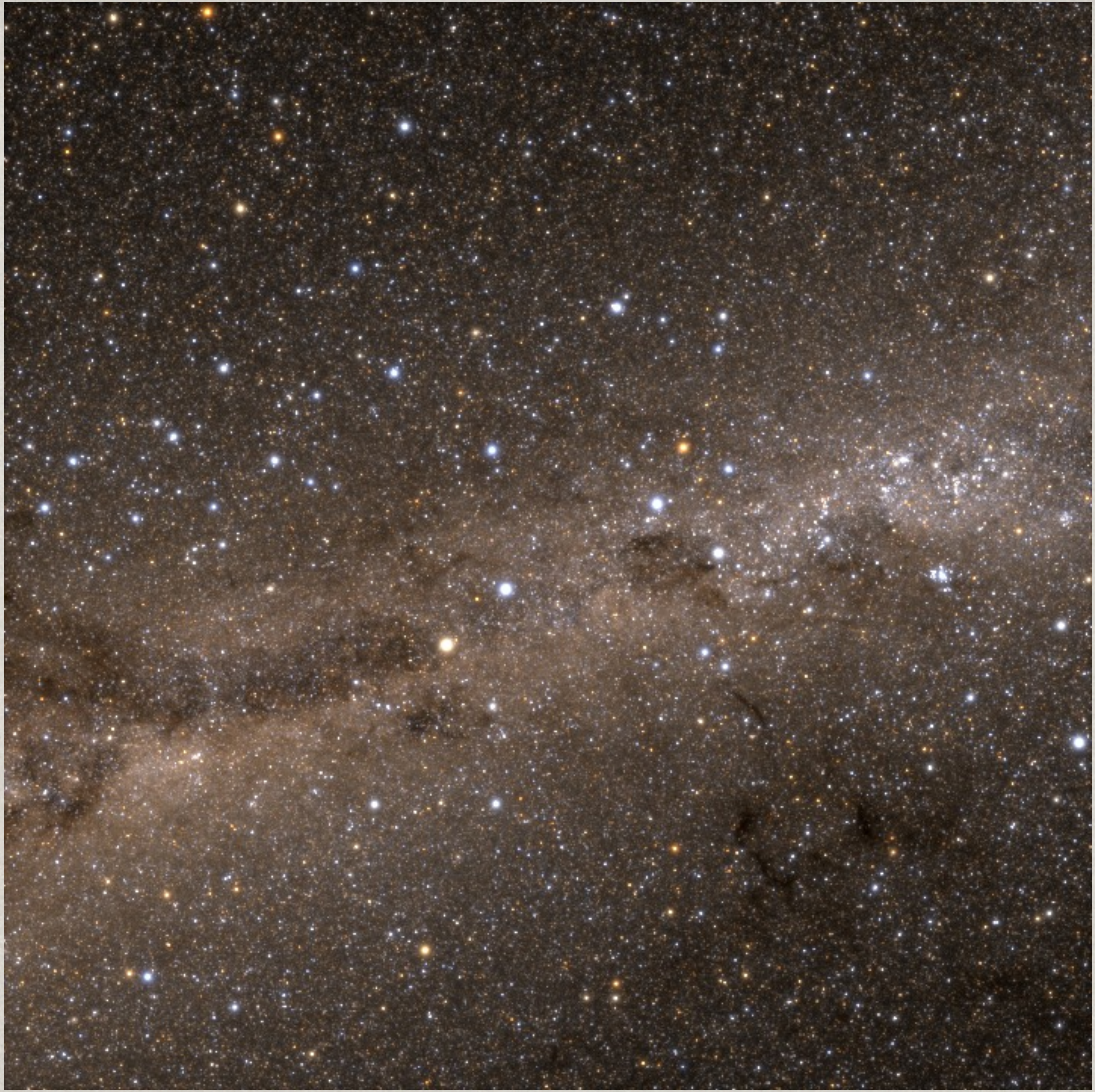




Regions inside the Einstein ring: photons deflected by larger angles than Einstein ring photons => inverted image of reference grid

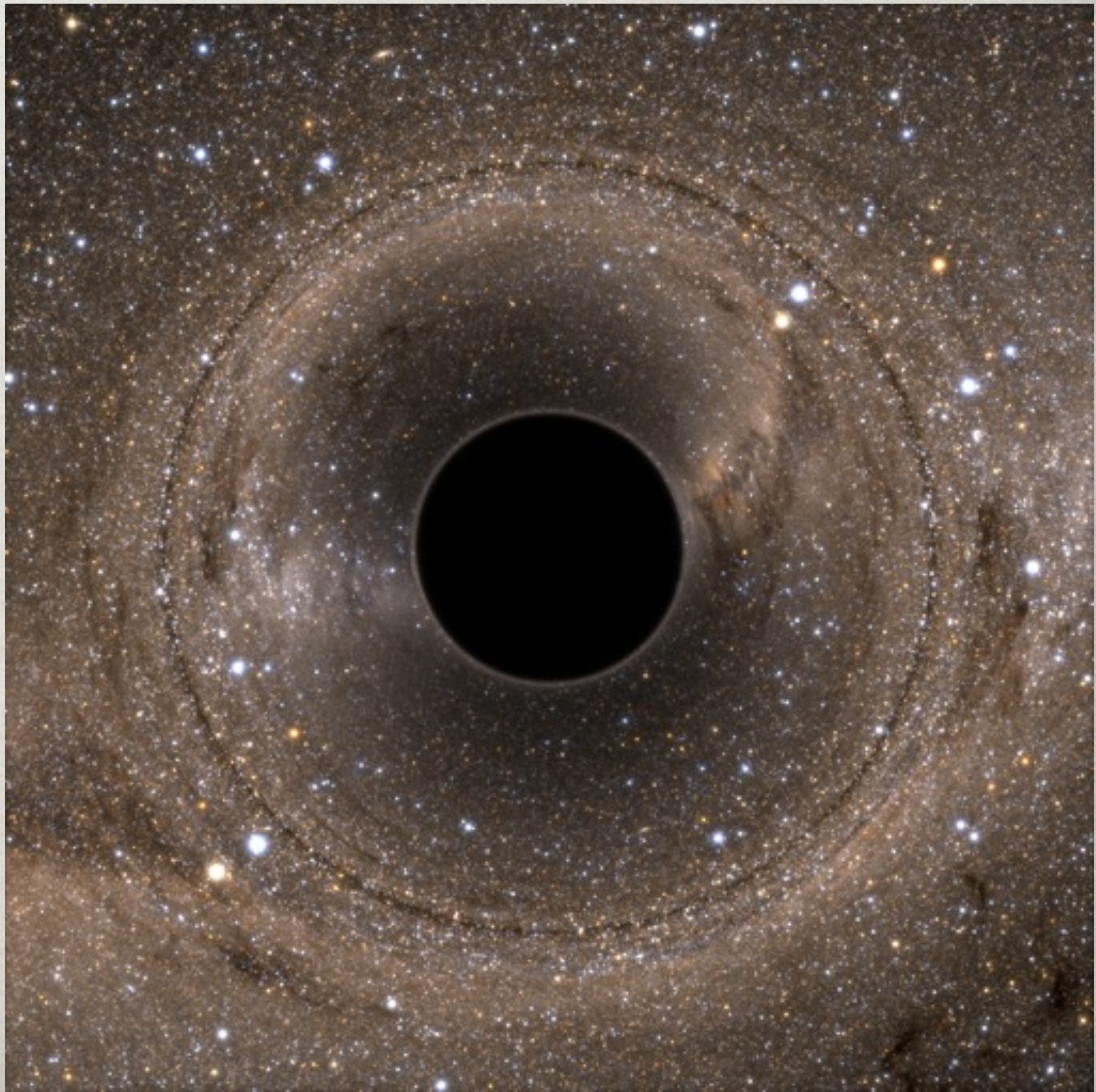
Second Einstein ring corresponding to light from a source behind the camera

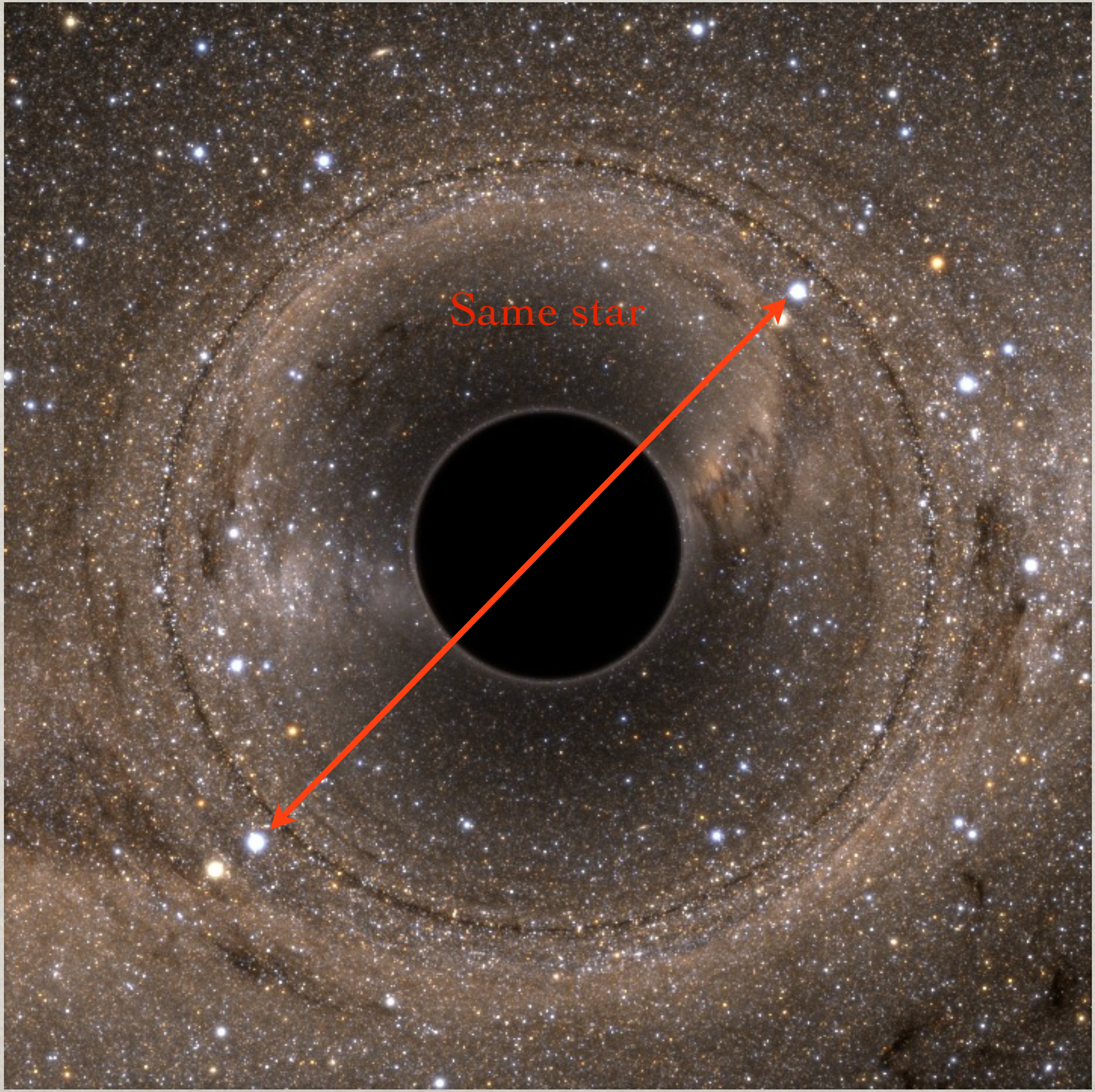
There will be an infinite number of Einstein rings

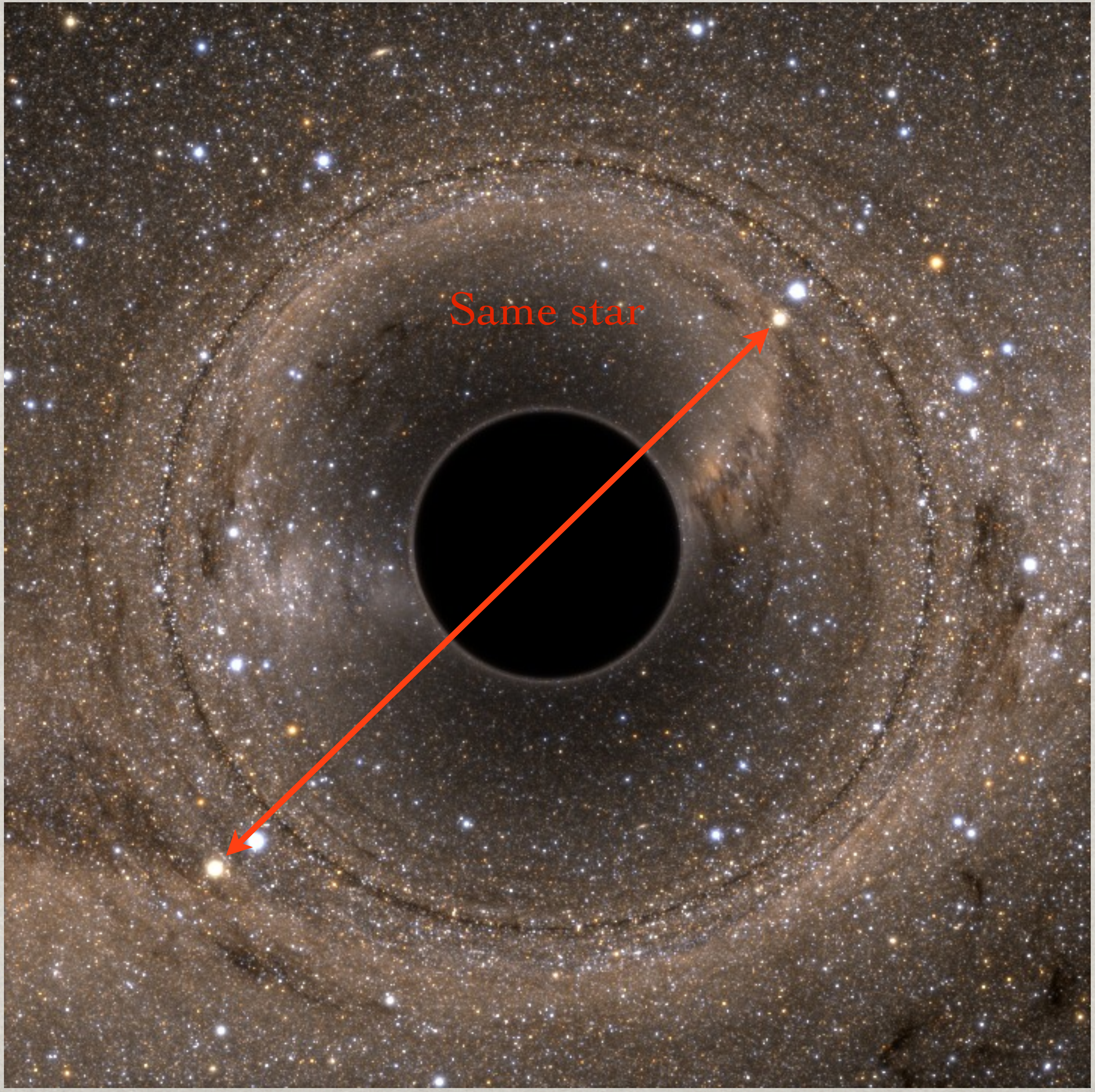


3.4*10^8
stars from
the Two
Micron All
Sky Survey
(2MASS)

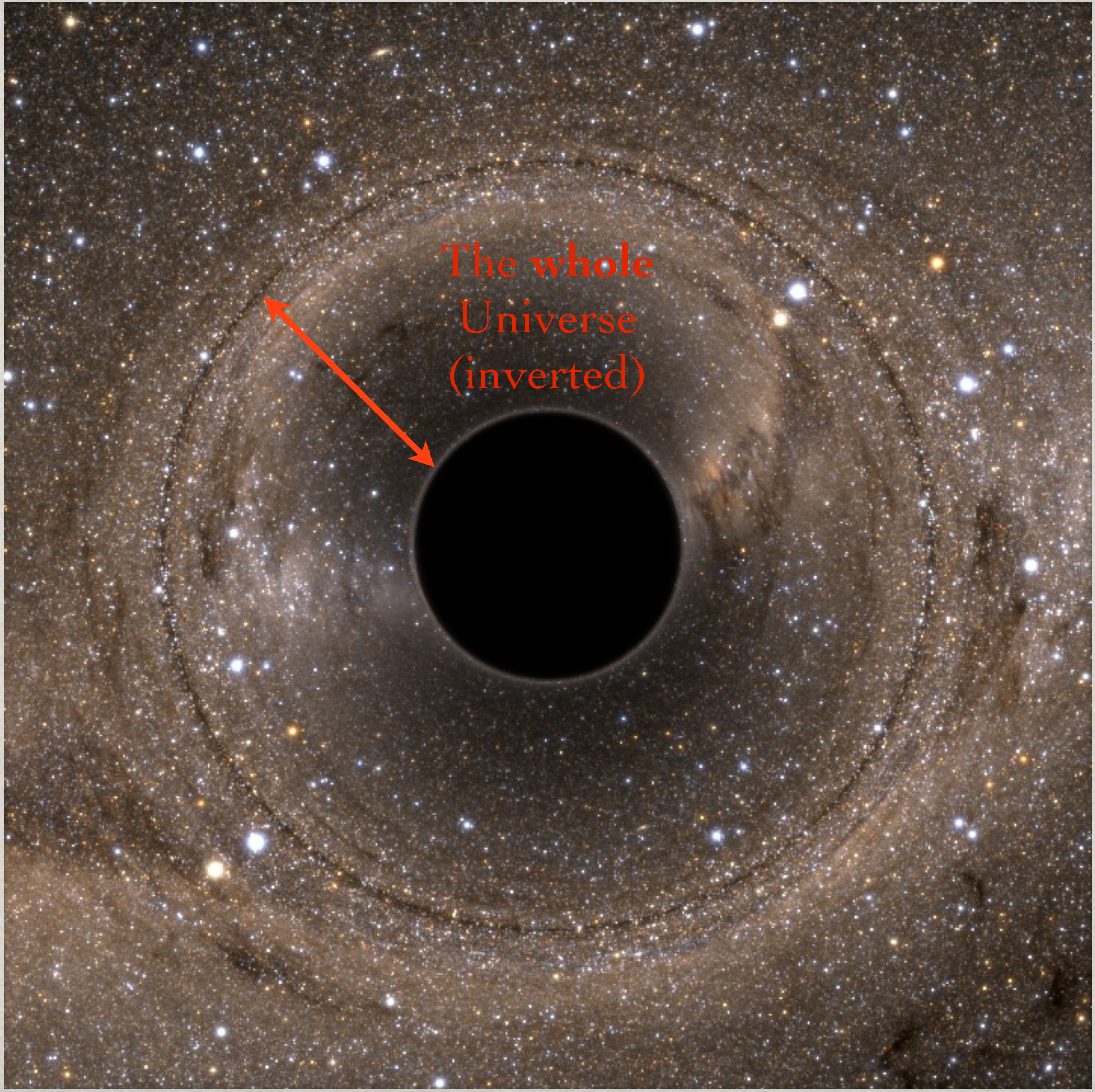
http://www.black-holes.org/the-science-numerical-relativity/numerical-relativity/gravitational-lensing


Same star


Same star

Between the 2nd and 3rd Einstein rings there is again the whole Universe (upright)



The lensing structure of a BH exhibits self-similarity.

3) Kerr black holes with scalar hair

An example of a model with very different shadows

Massive-complex-scalar-vacuum:

$$\mathcal{S} = \frac{1}{4\pi}\int d^4x\sqrt{-g}\left(\frac{R}{4} - \nabla_\mu\Phi^*\nabla^\mu\Phi - \mu^2\Phi^*\Phi\right)$$

There are BH solutions:

- **within GR** (not alternative theories of gravity);
- with matter **obeying all energy conditions**;
- which can yield **distinct phenomenology**;

which are:

- asymptotically flat
- regular on and outside the horizon
- continuously connecting to the Kerr solution
- continuously connected to gravitating solitons (boson stars)
- with an independent scalar charge (primary hair)

Kerr Black Holes with scalar hair

C.H. and Radu, PRL 2014

Einstein Klein-Gordon: non-linear setup

Ansatz:

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

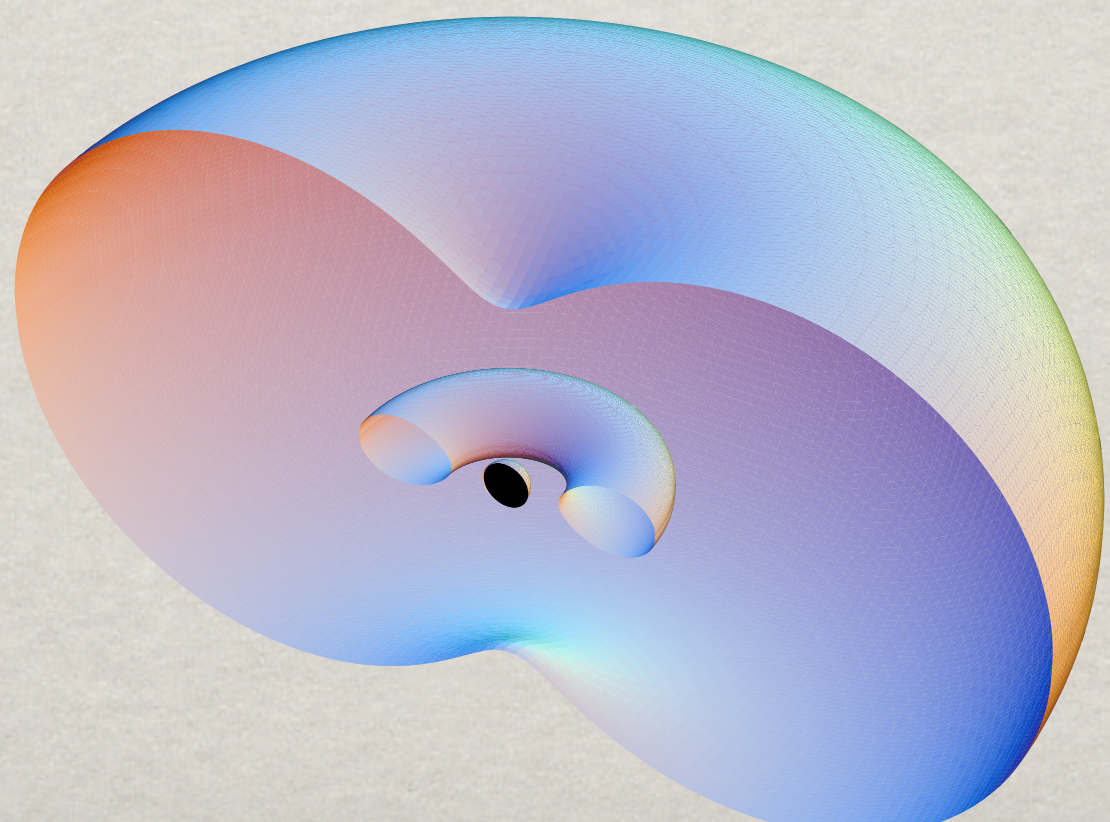
$$\Phi = \phi(r,\theta) e^{i(m\varphi - wt)}$$

Four input parameters:

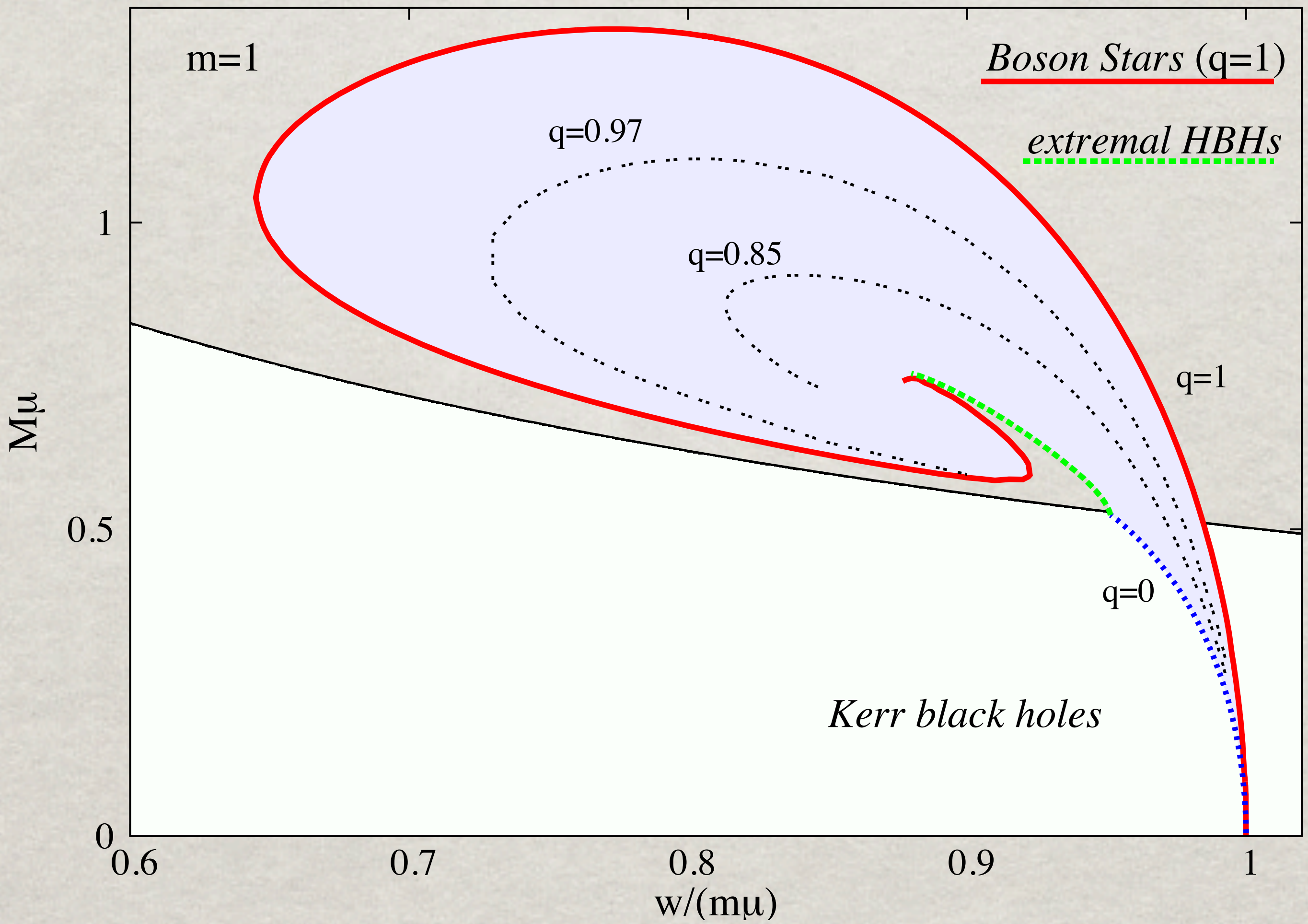
$$m, w, r_H, n$$

Synchronization condition:

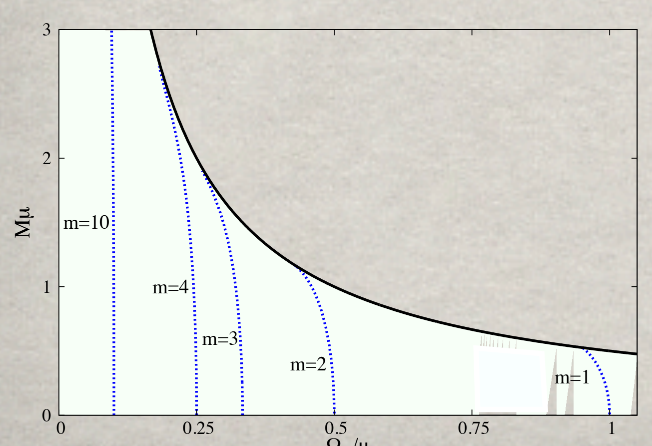
$$\Omega_H = \frac{w}{m}$$



Hairy black holes phase space



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



Five parameters family of solutions:
3 continuous parameters (M,J,q)
2 discrete parameters (m,n)

4) Lensing by boson stars

Spherical case

Boson Stars:

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

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

Rotating:

Yoshida and Eriguchi (1997)
Schunck and Mielke (1998)

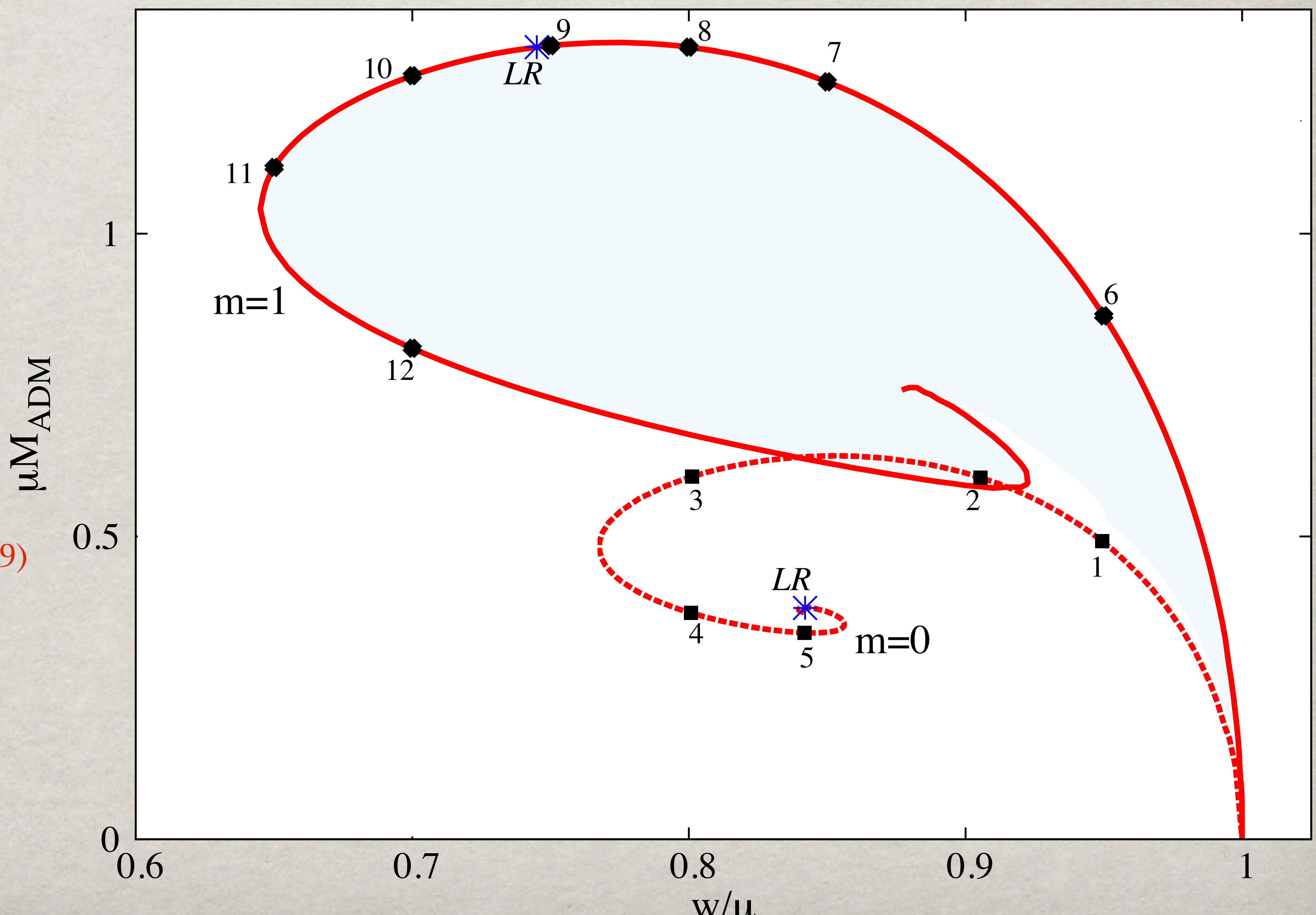
Three input parameters:
(w, m=1,2,3,..., n)

Spherical:

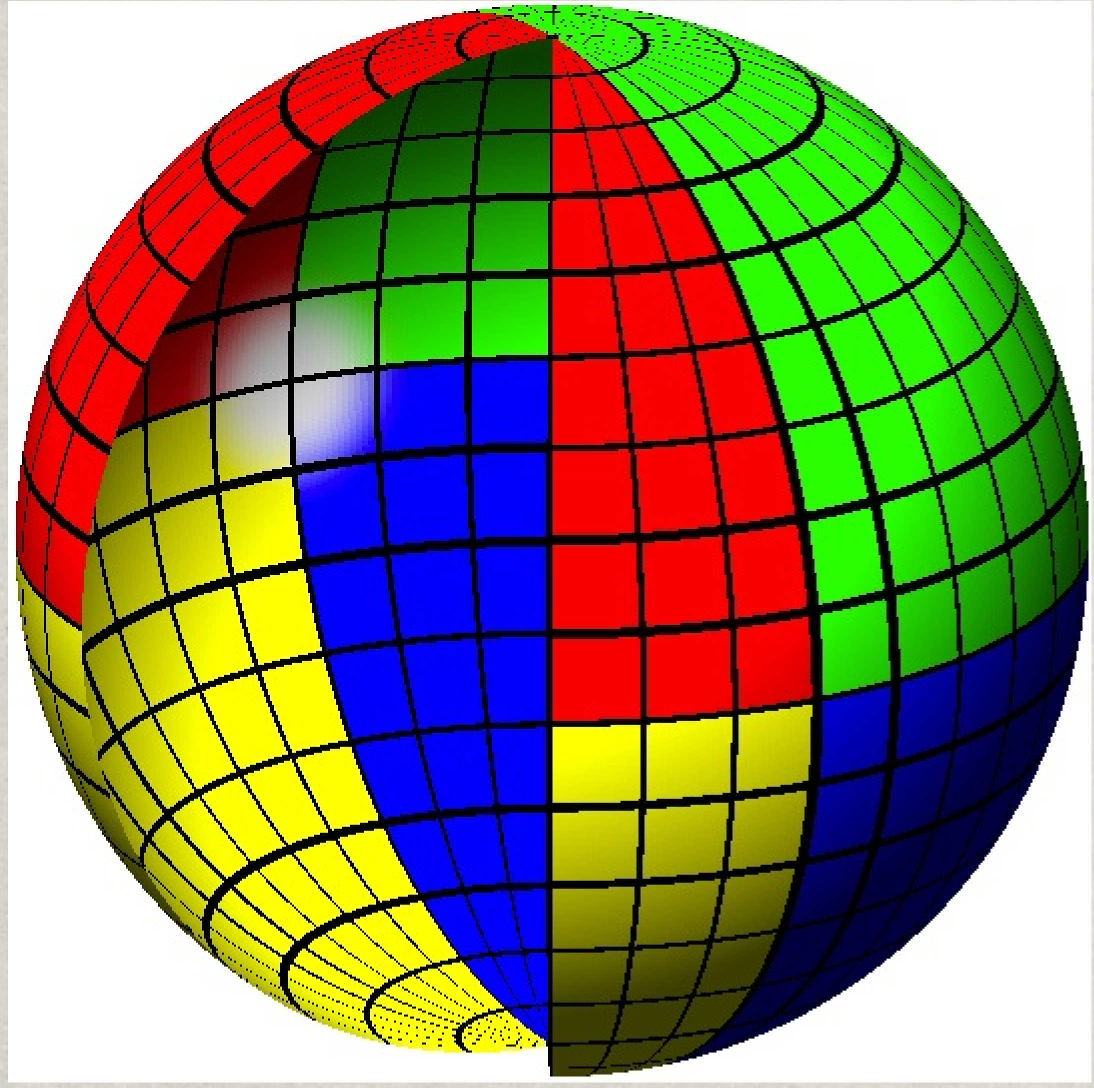
Kaup (1968); Ruffini and Bonazzola (1969)
Review: Liebling and Palenzuela (2012)

Two input parameters:
(w, m=0, n)

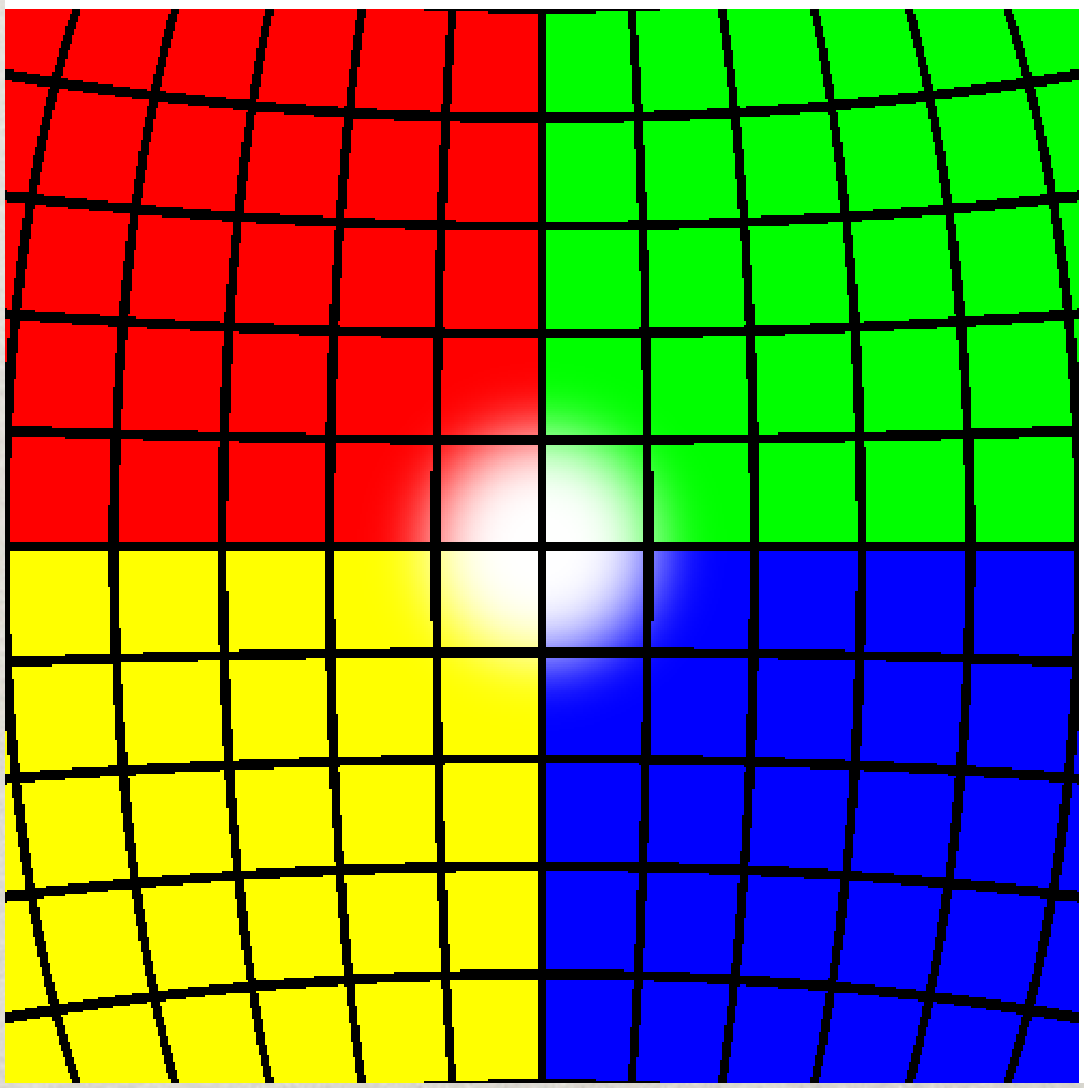
$F_1 = F_2 \ , \ W = 0$



We have performed ray tracing to compute lensing and shadows.



The full celestial sphere

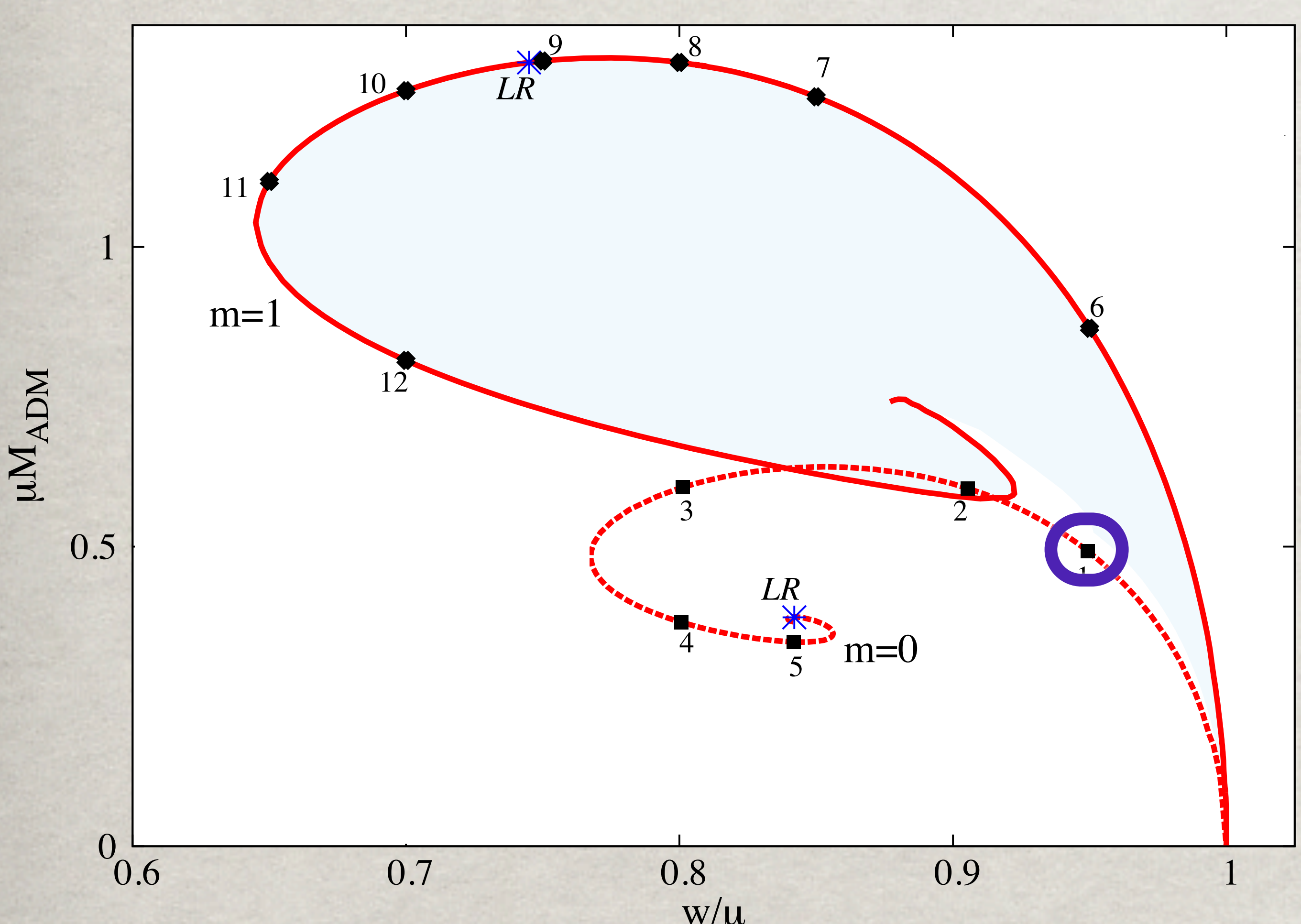


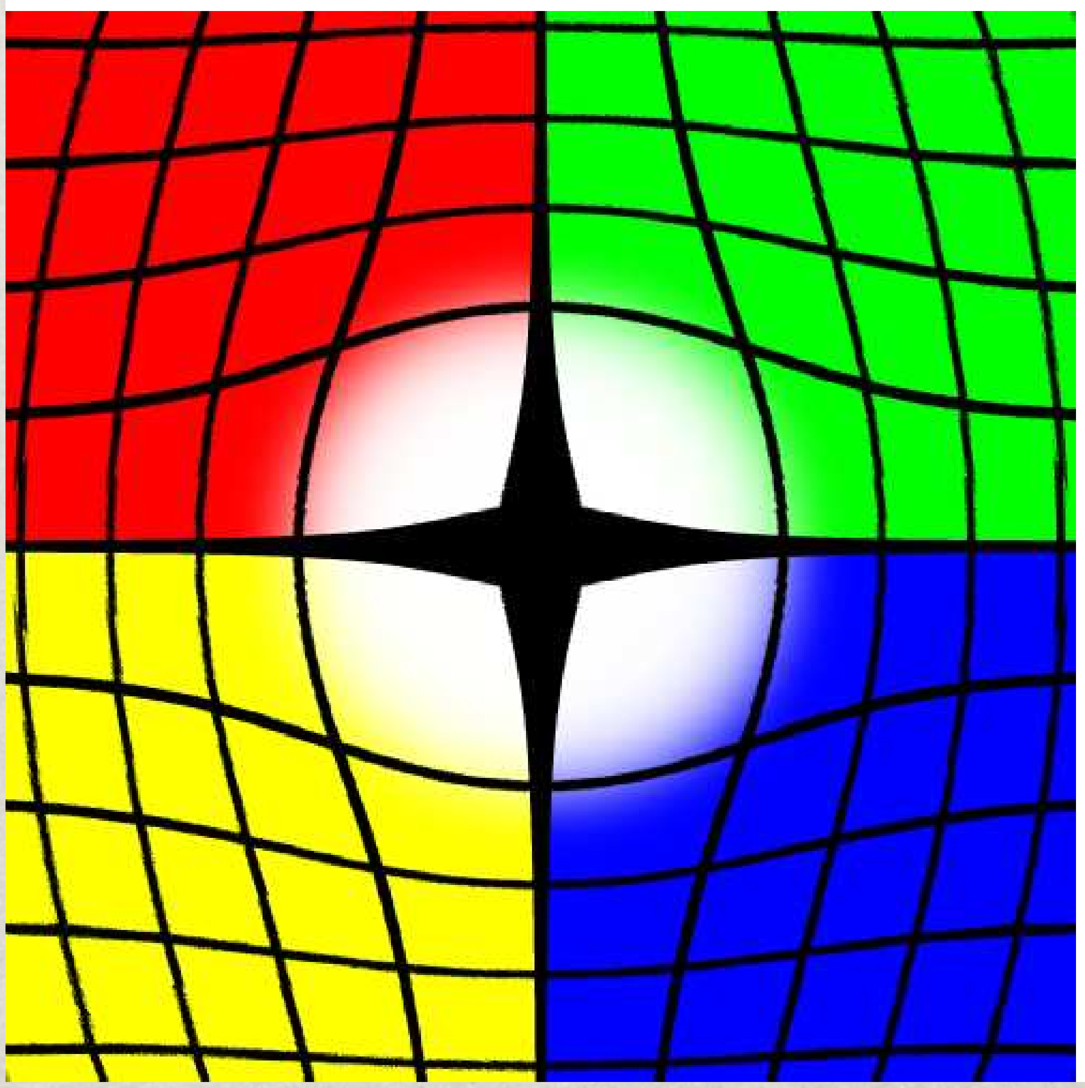
The “camera” opening angle

Following A. Bohn et al. arXiv:1410.7775

Spherical boson stars

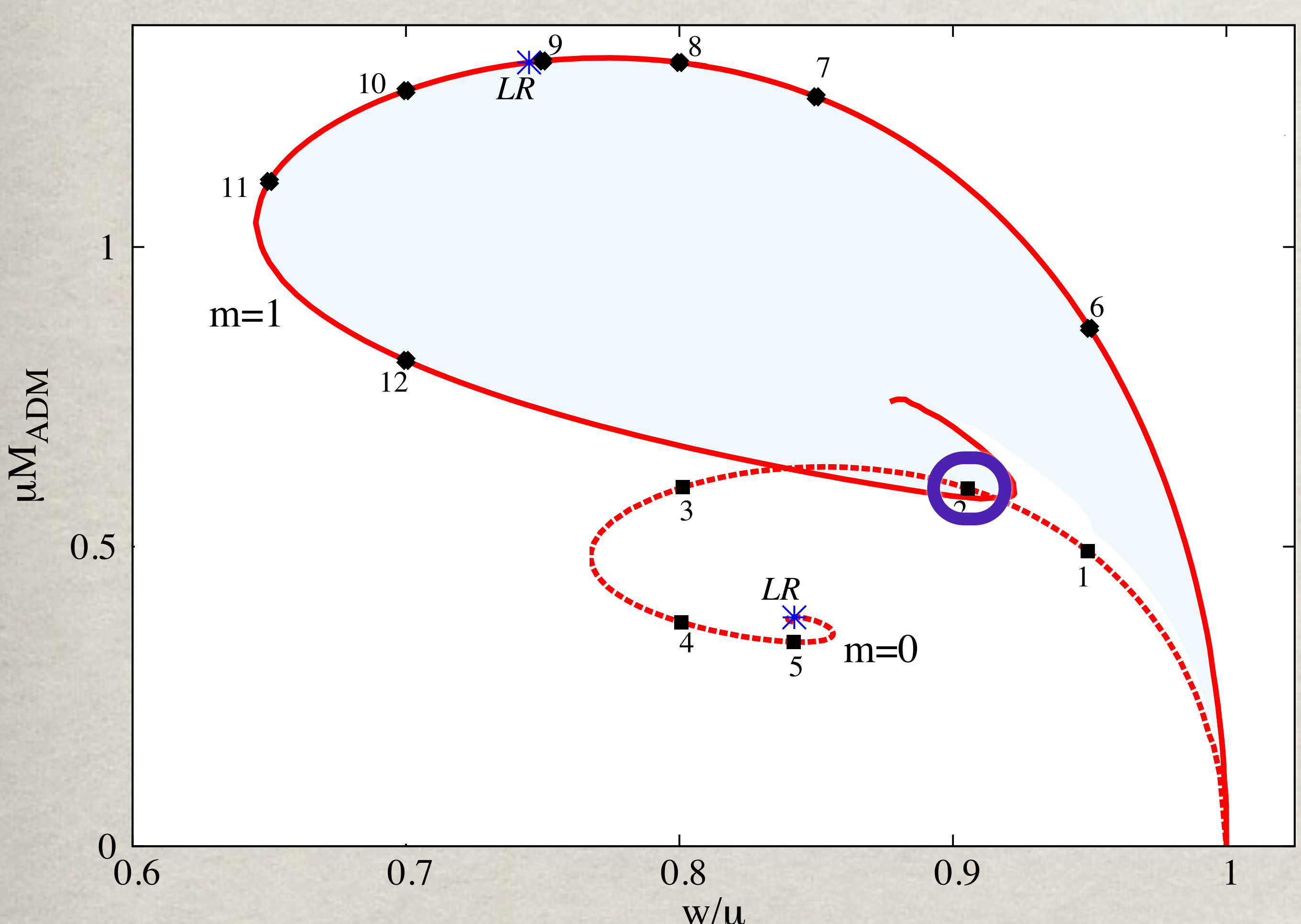
Fix the scalar field mass and observer's distance





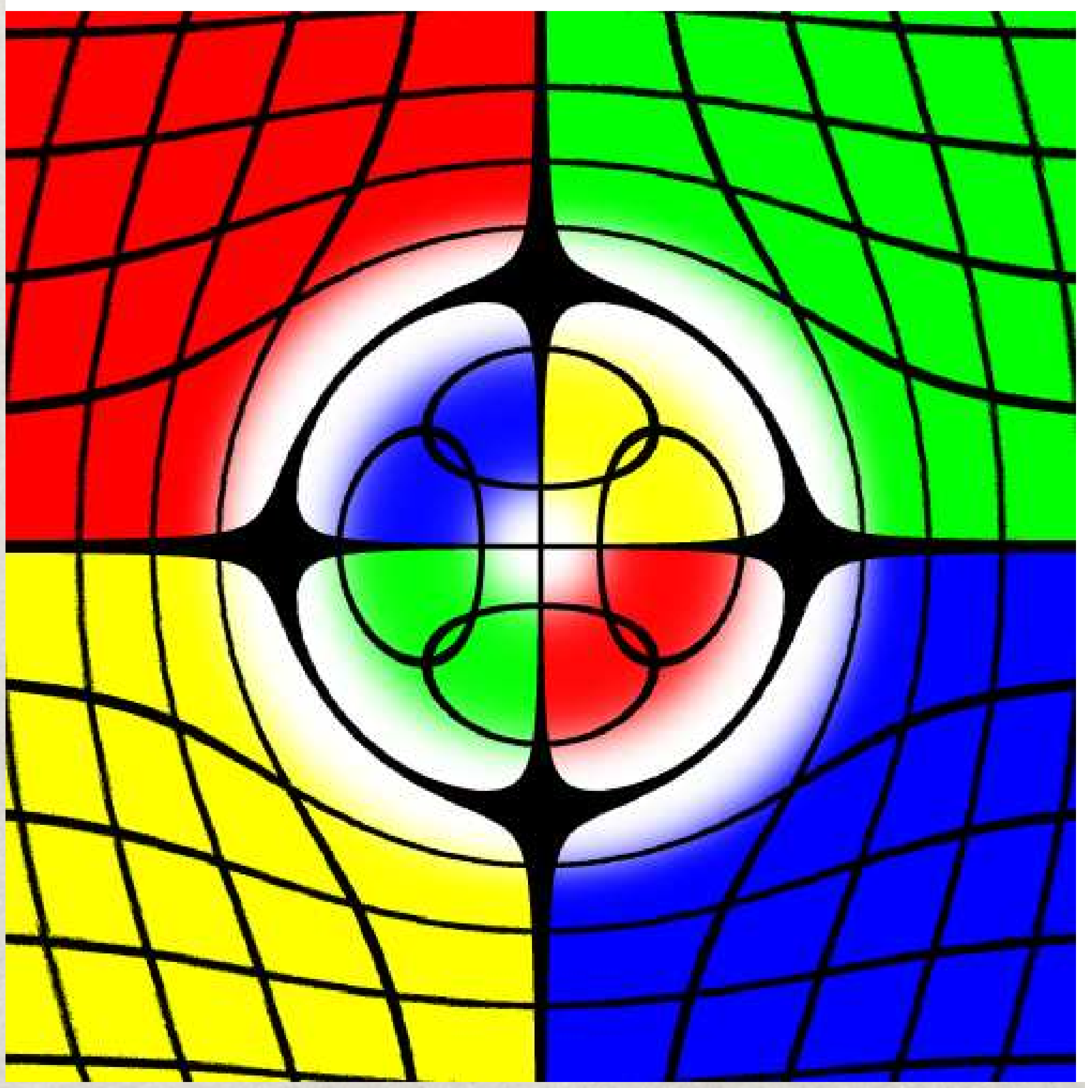
Non-compact BS

Spherical boson stars



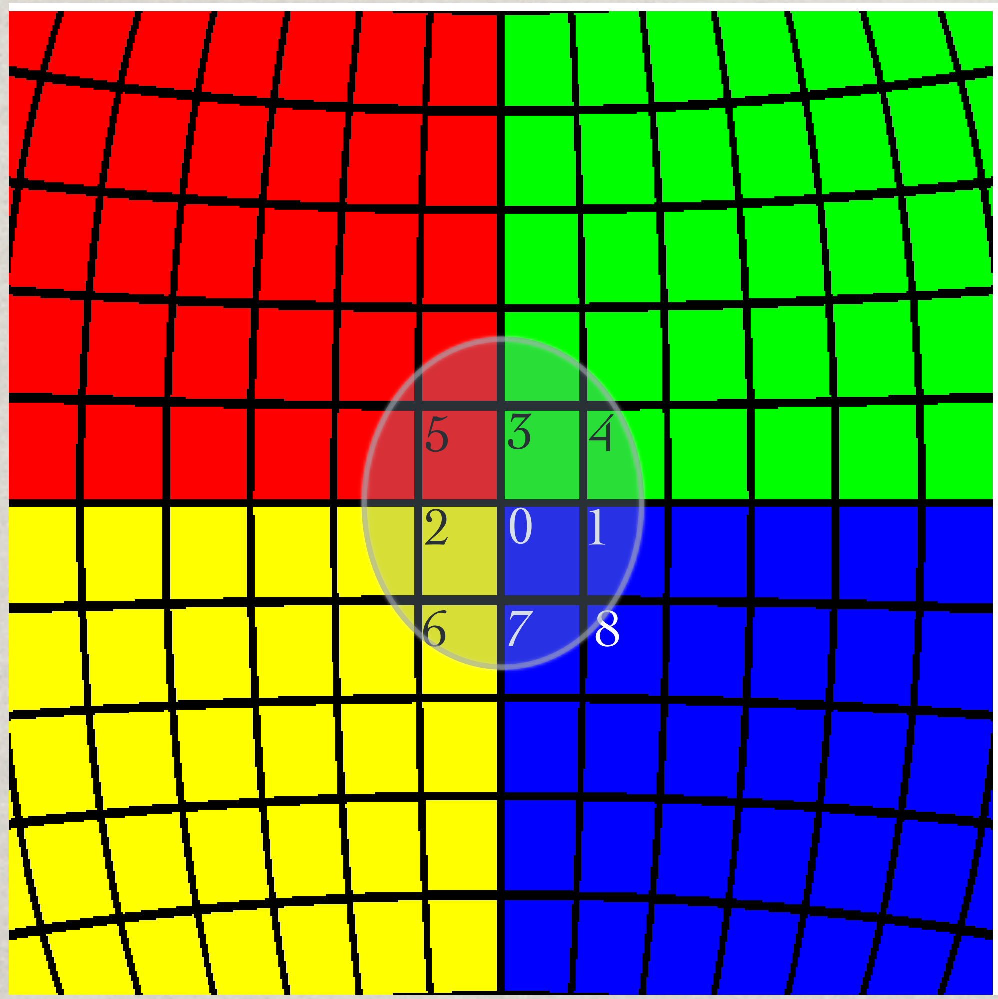
Einstein ring appears at:

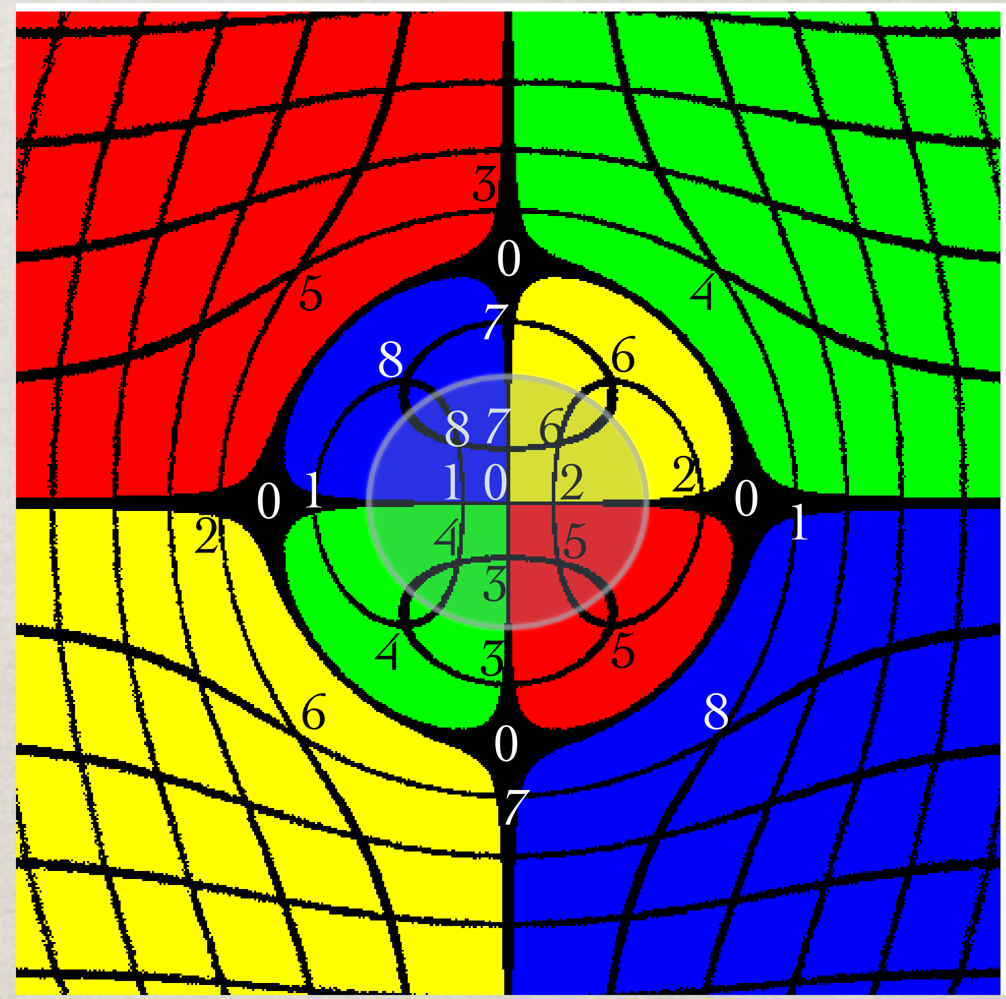
$$w_{ER1}^{(b1)} \simeq 0.94$$



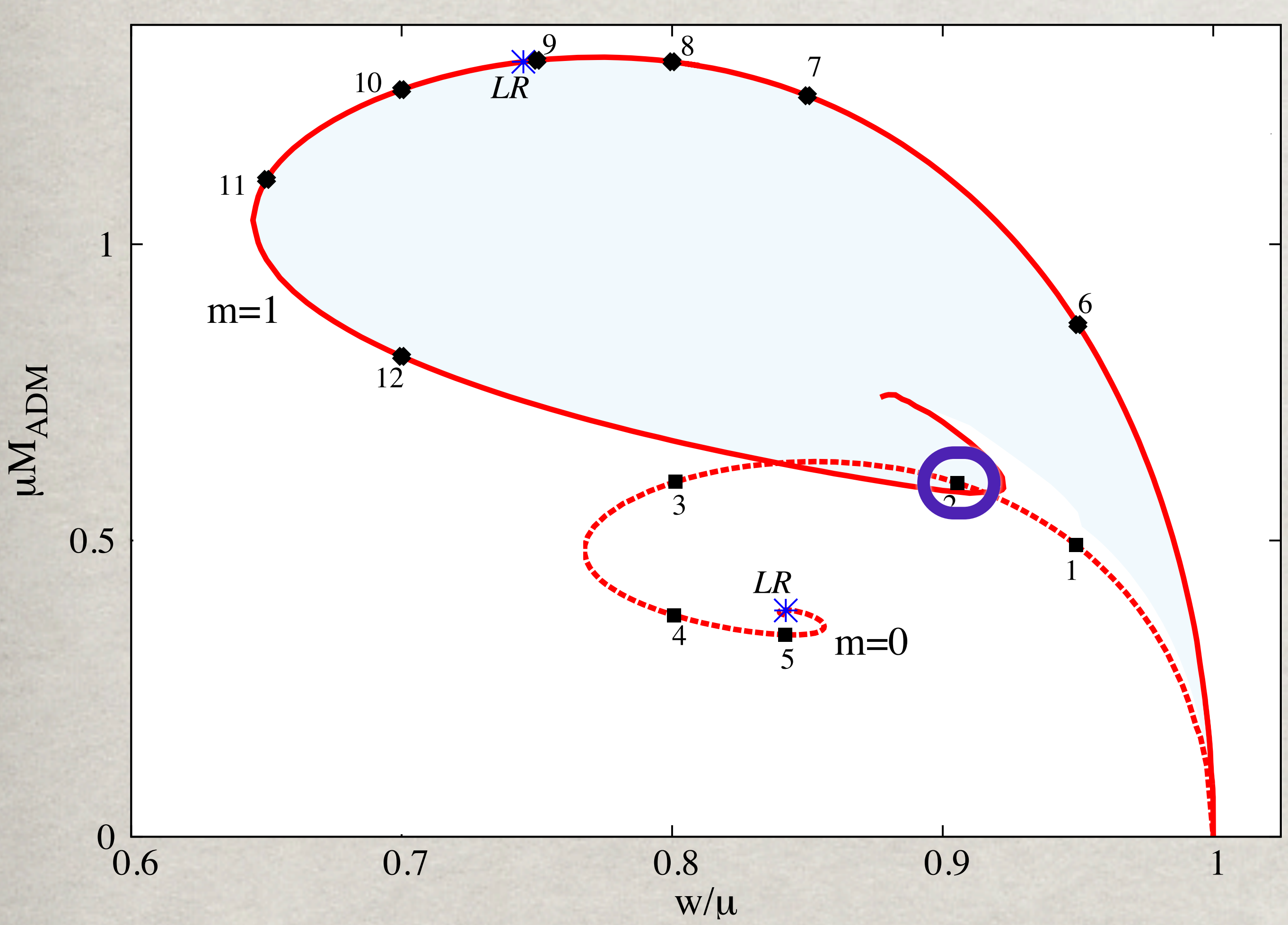
Compact BS

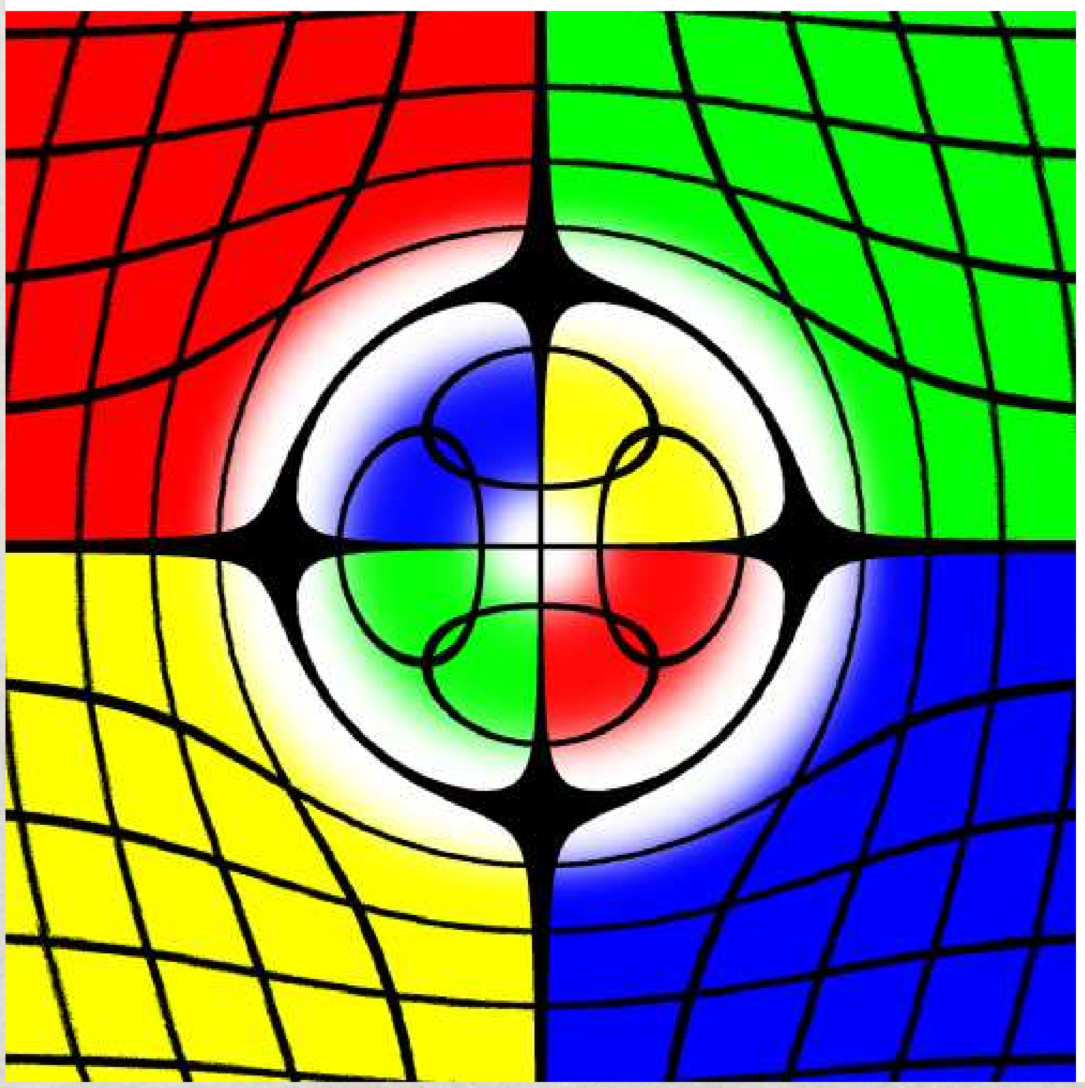
Two inverted copies inside the Einstein ring:





Spherical boson stars





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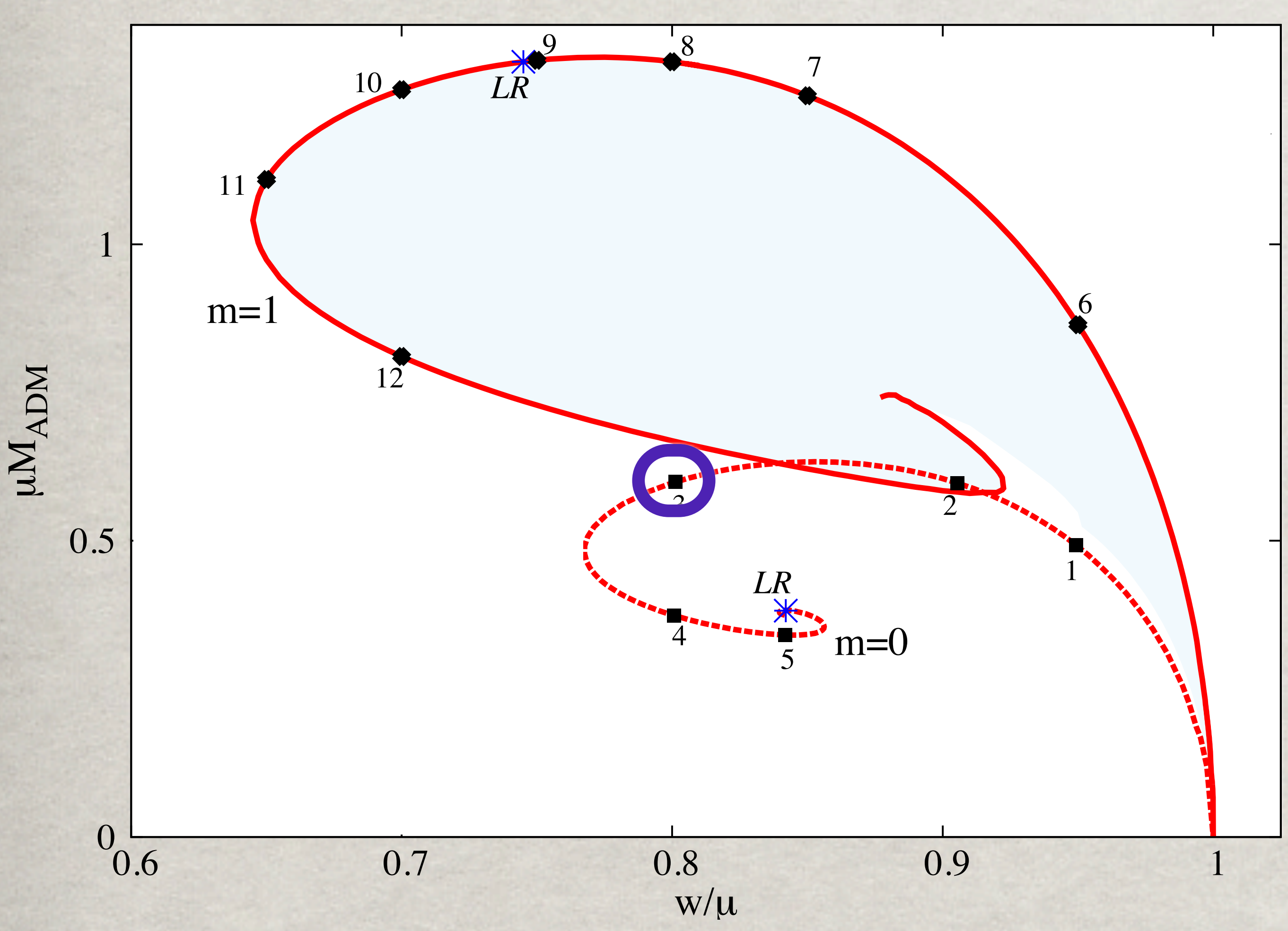
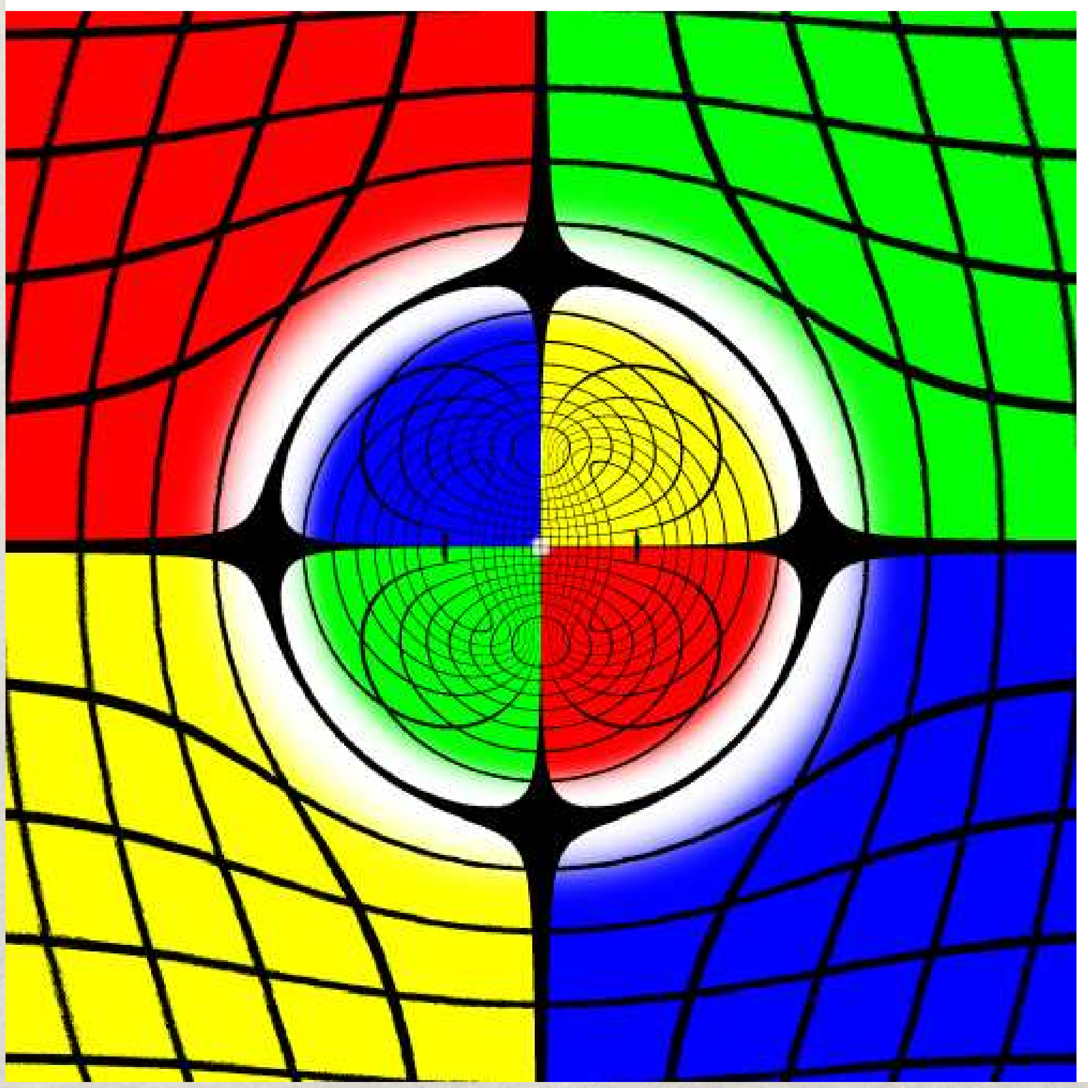
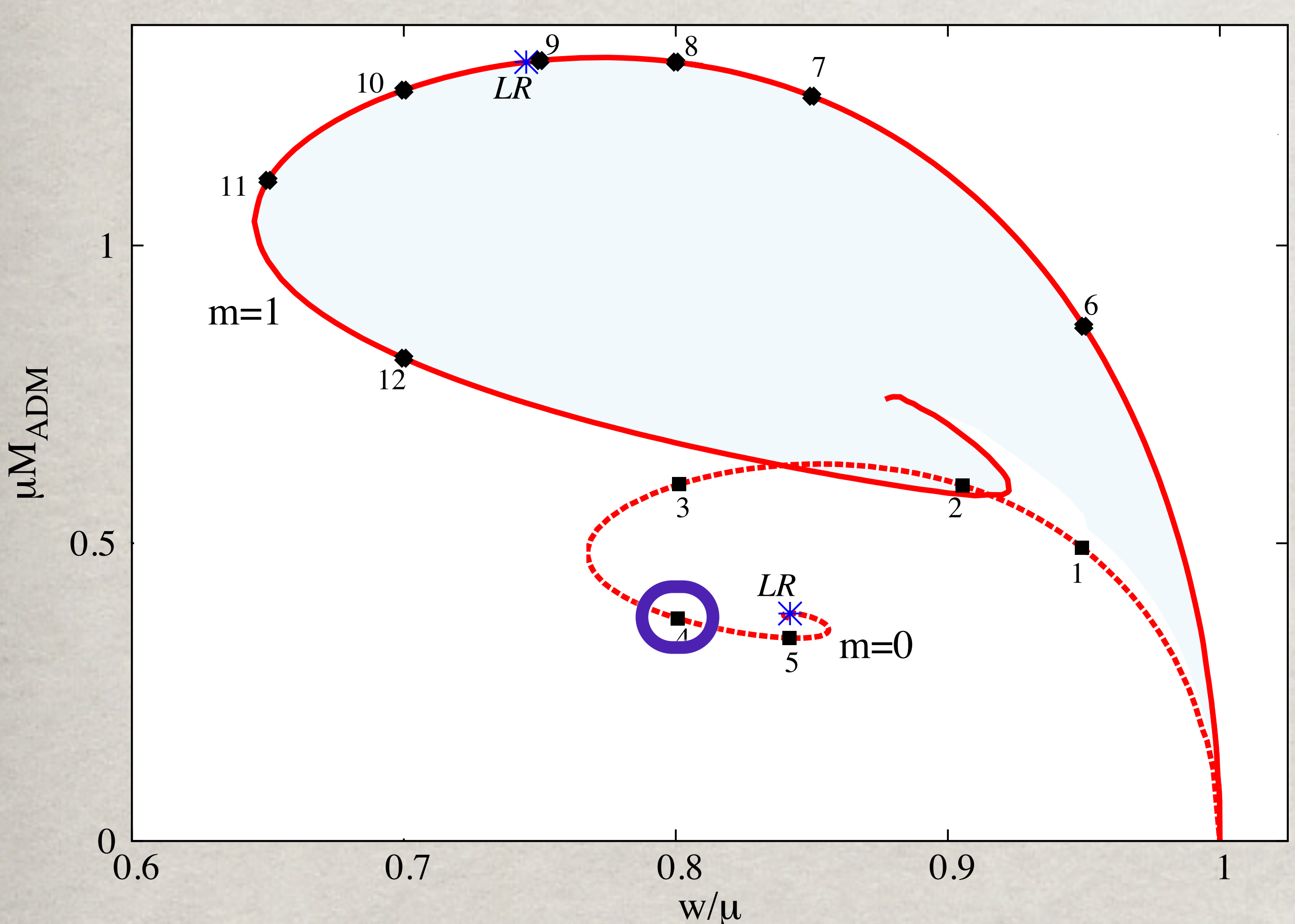


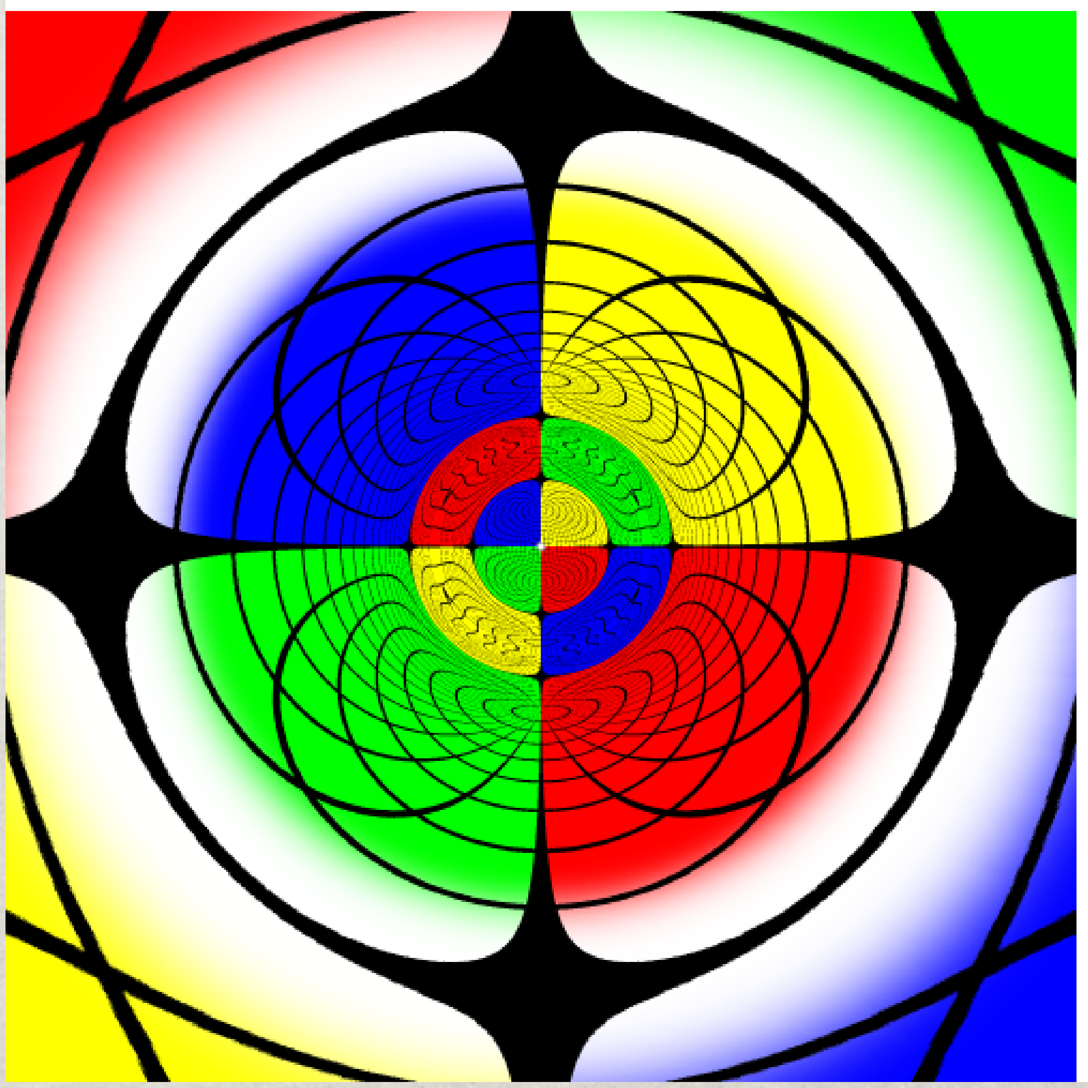


Larger region is “duplicated”

Compact BS

Spherical boson stars





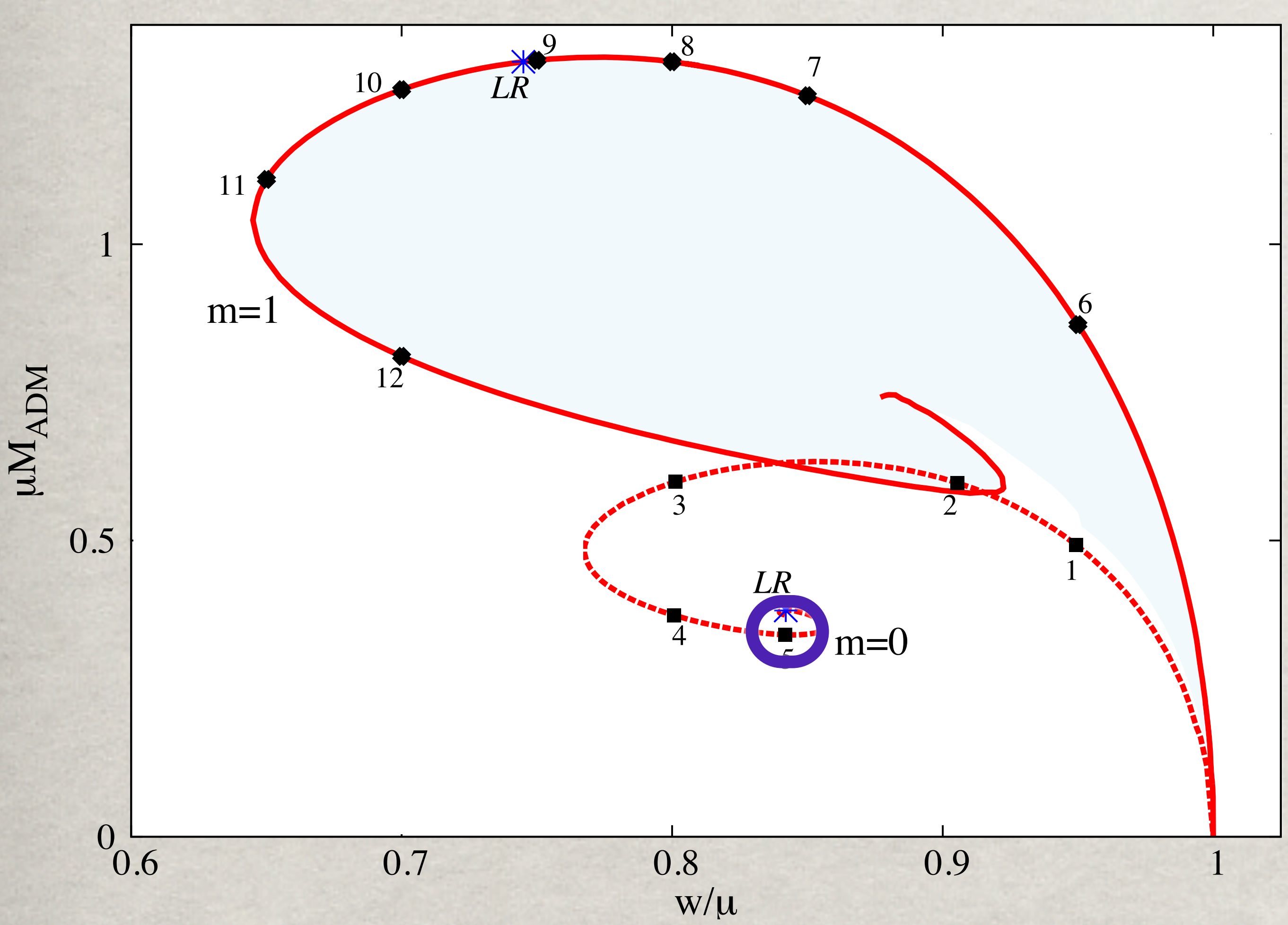
Full celestial sphere is “duplicated”
just after the backbending;

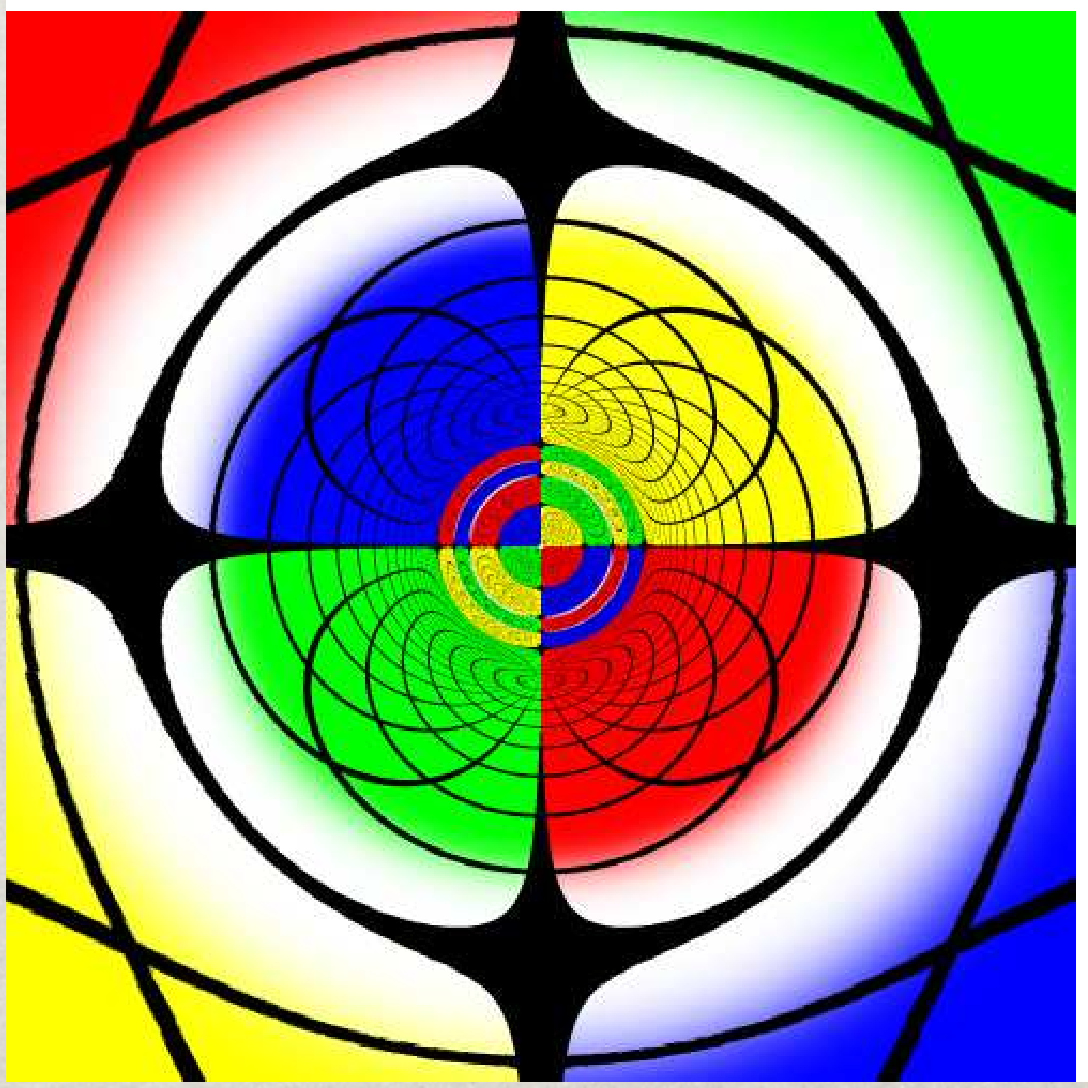
Then, a new pair of Einstein rings appears

Zoomed

Compact BS

Spherical boson stars

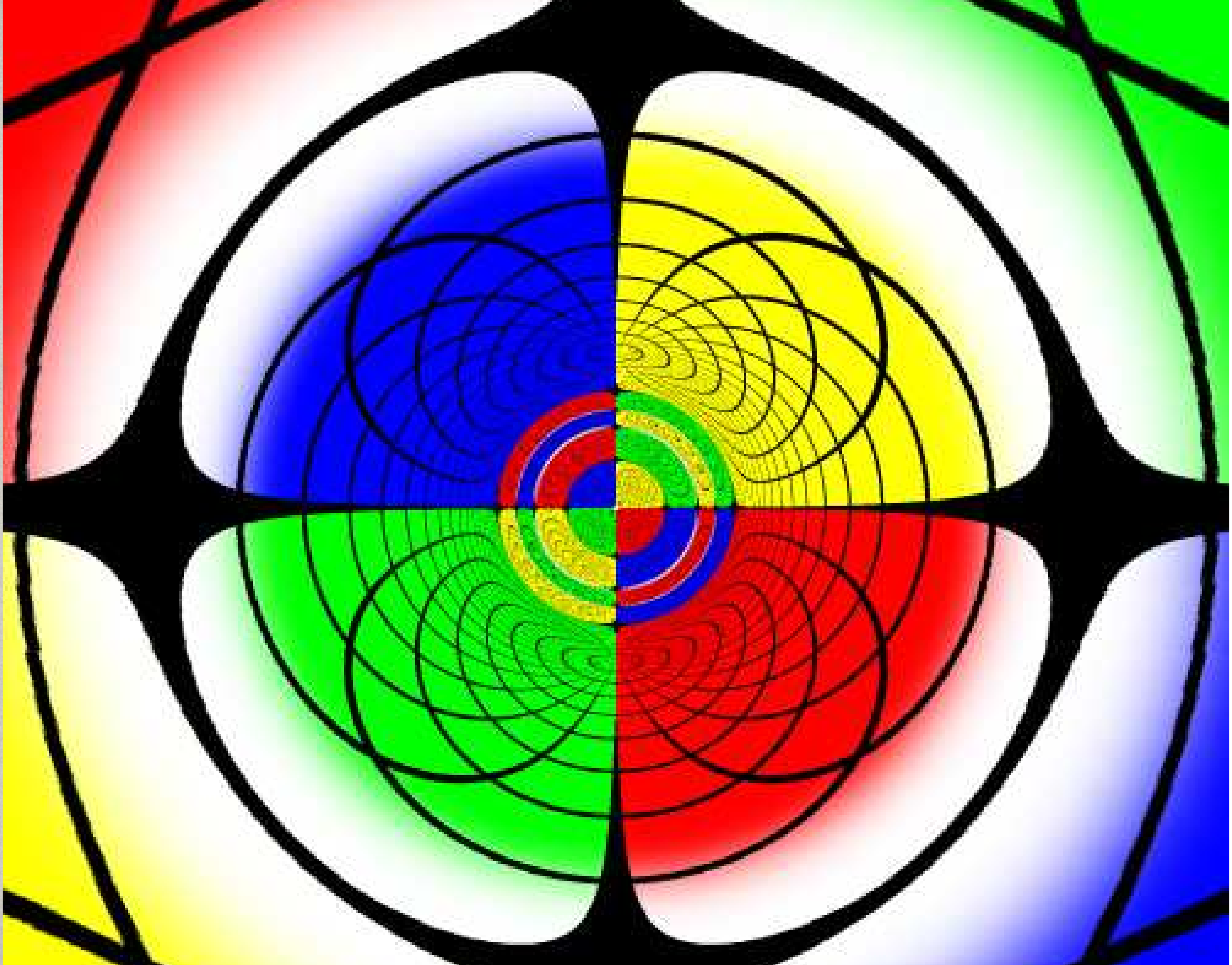




Zoomed

Compact BS

In between the latter pair of Einstein rings, new pairs of Einstein rings appear.



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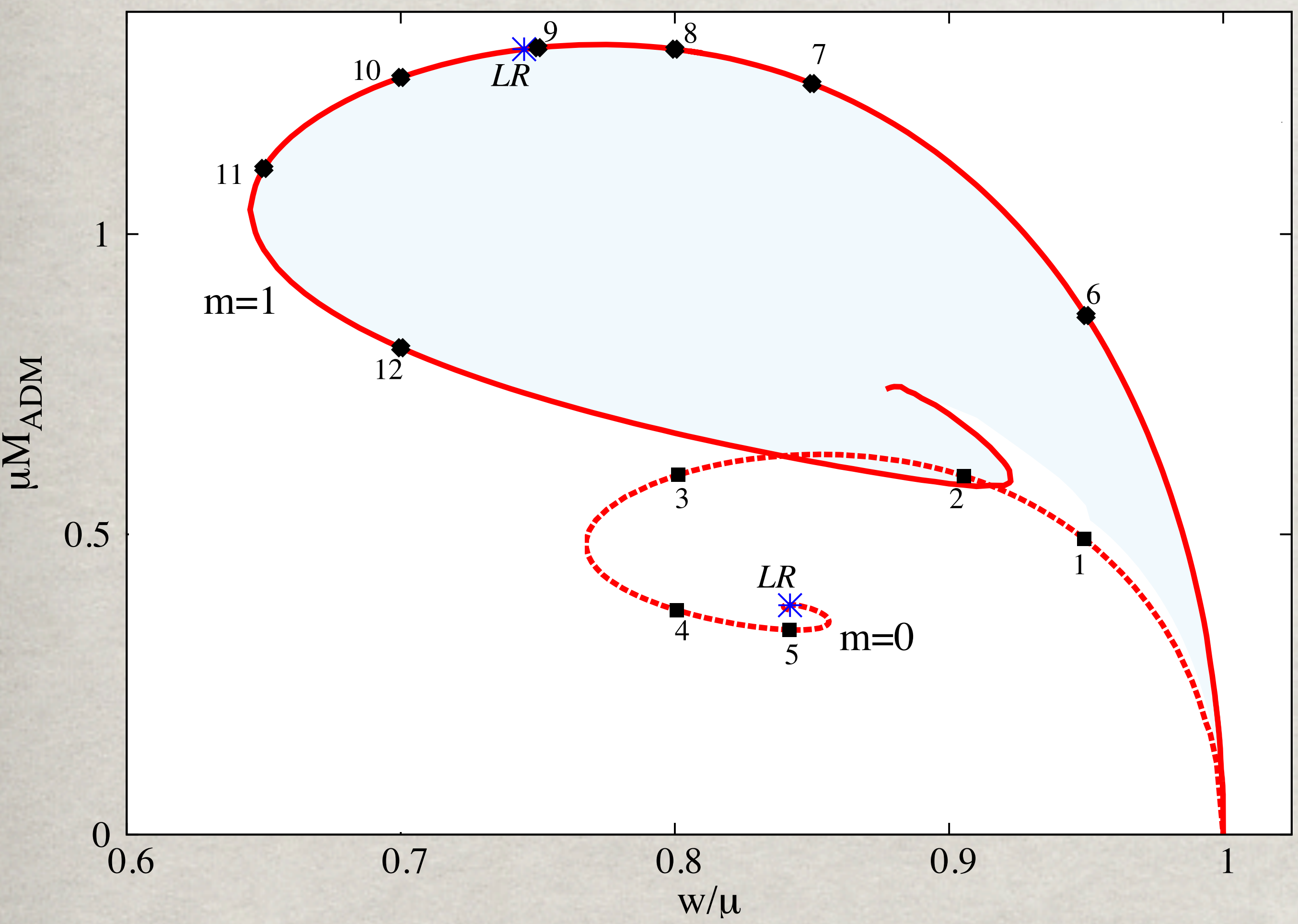
Spherical boson stars



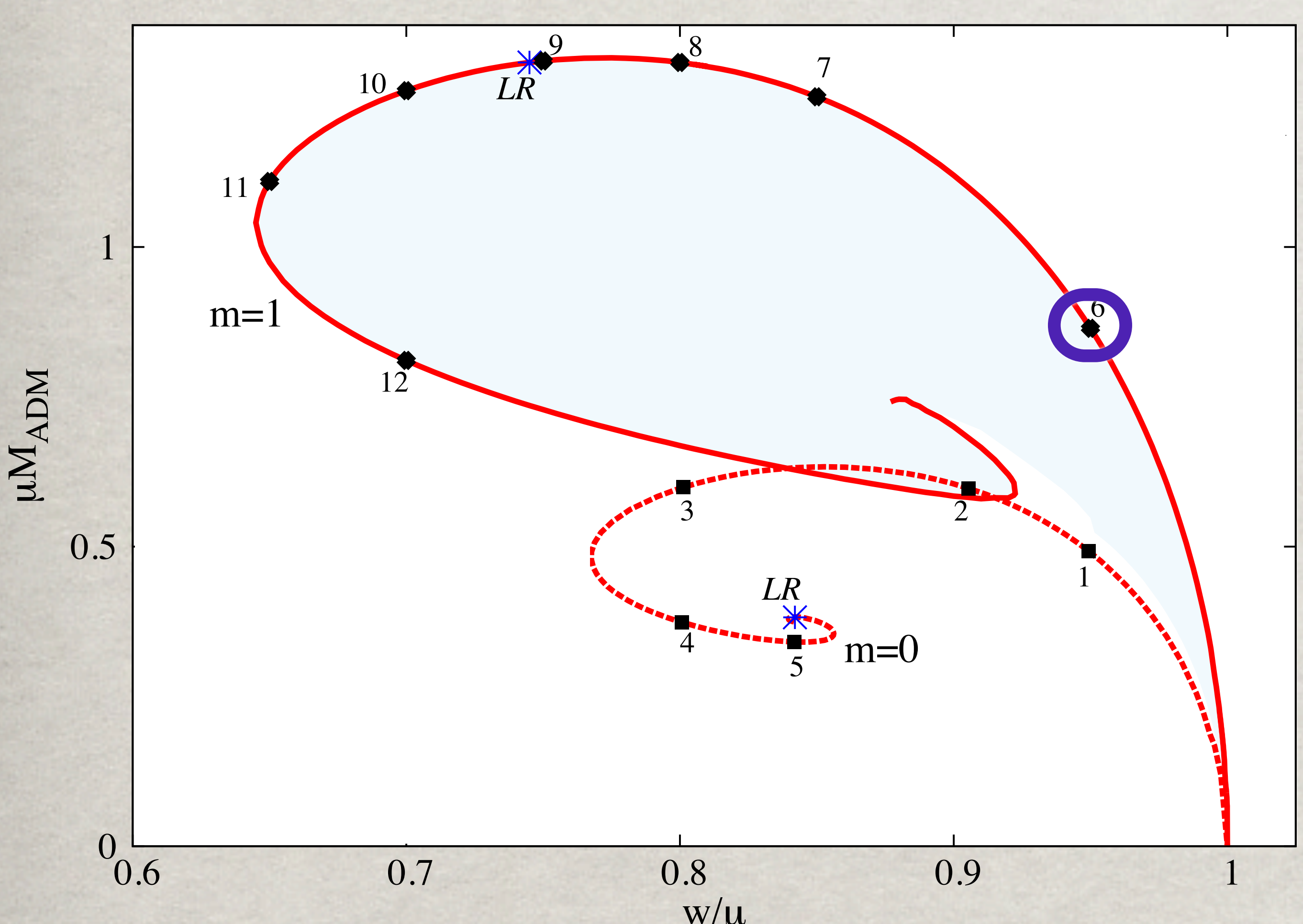
An infinite number of copies and the corresponding self-similar structure is expected when the light ring appears at:

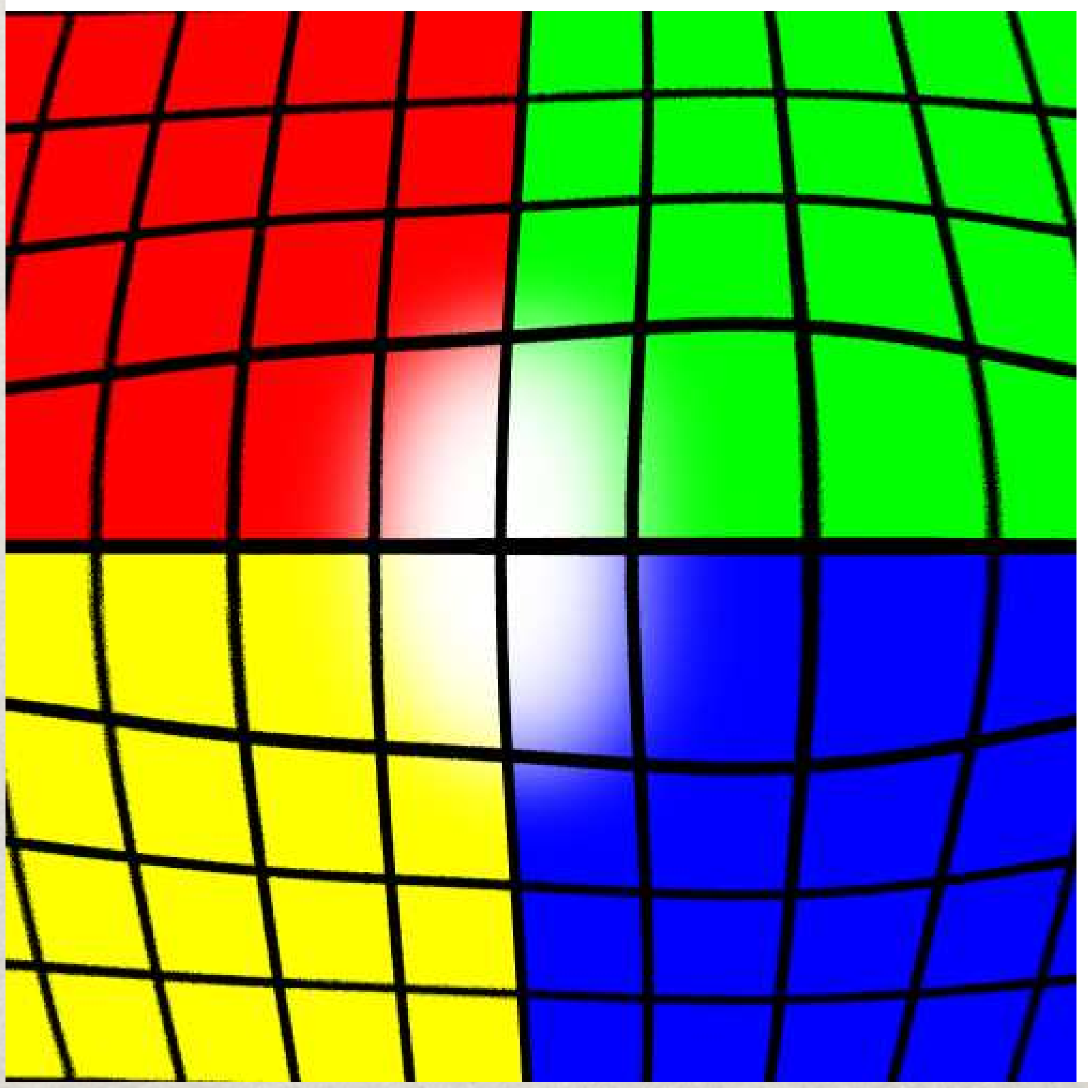
$$w_{LR}^{(b3)} \simeq 0.842$$

4) Lensing by boson stars

Rotating case

Rotating boson stars

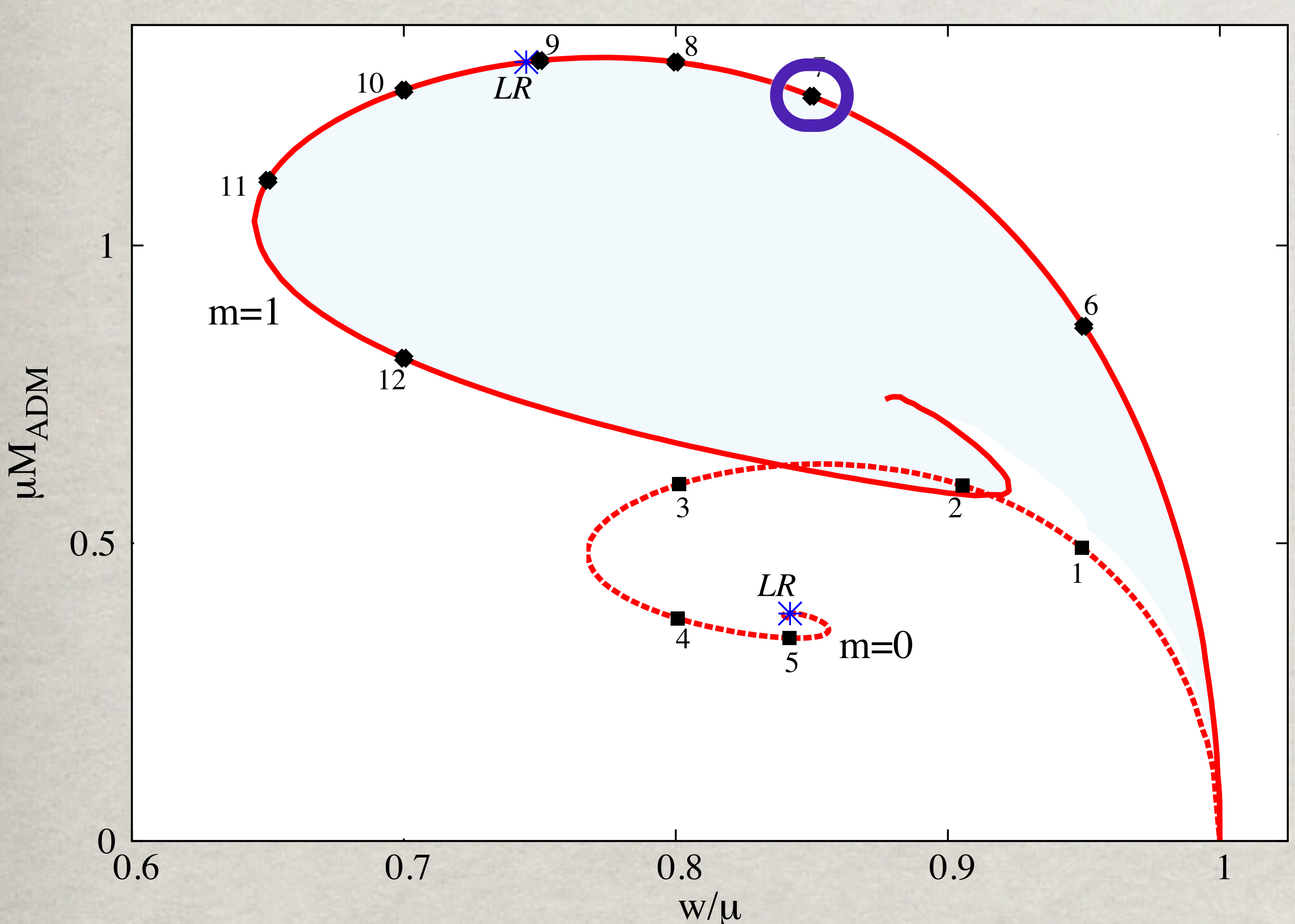


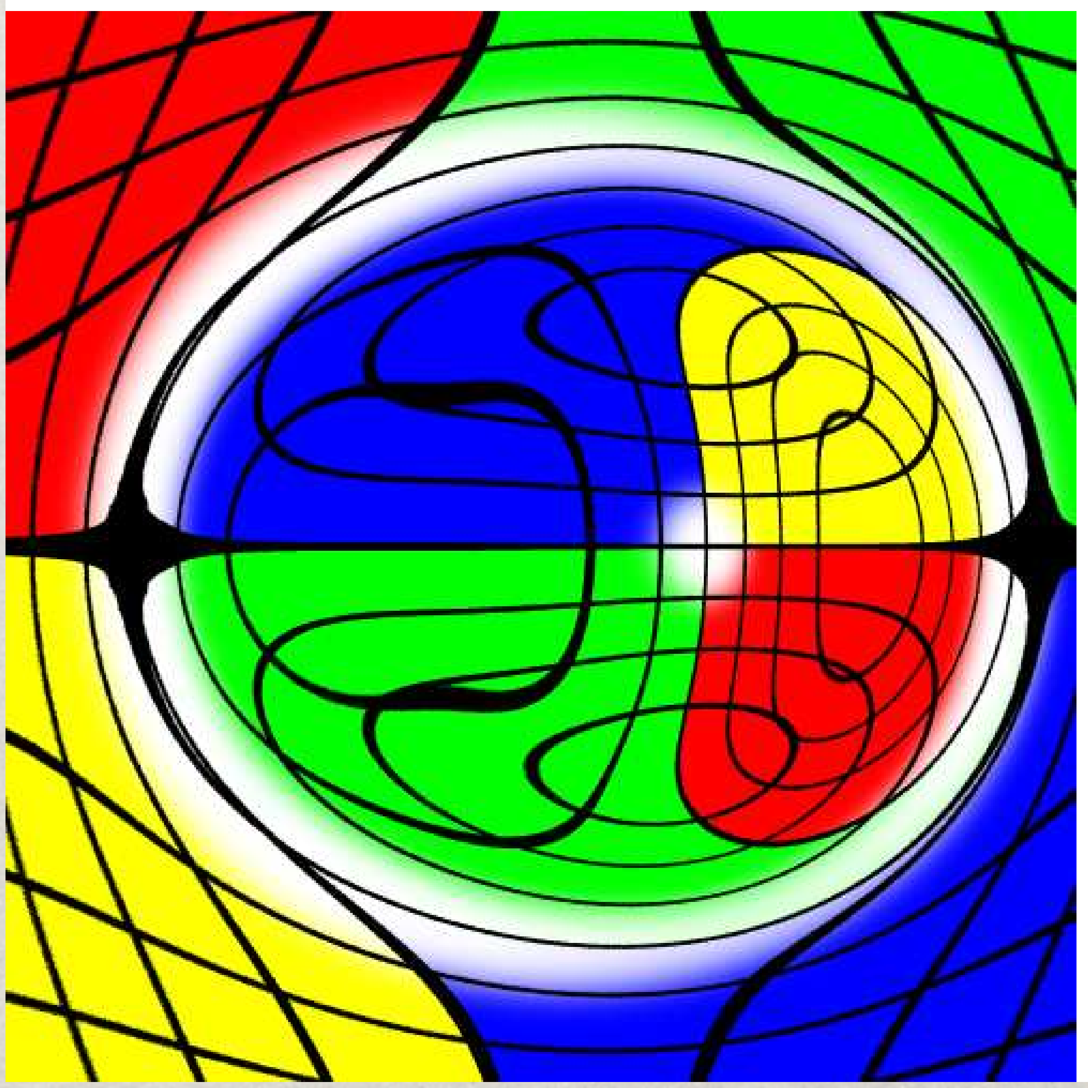


Asymmetric lensing

Non-compact RBS

Rotating boson stars



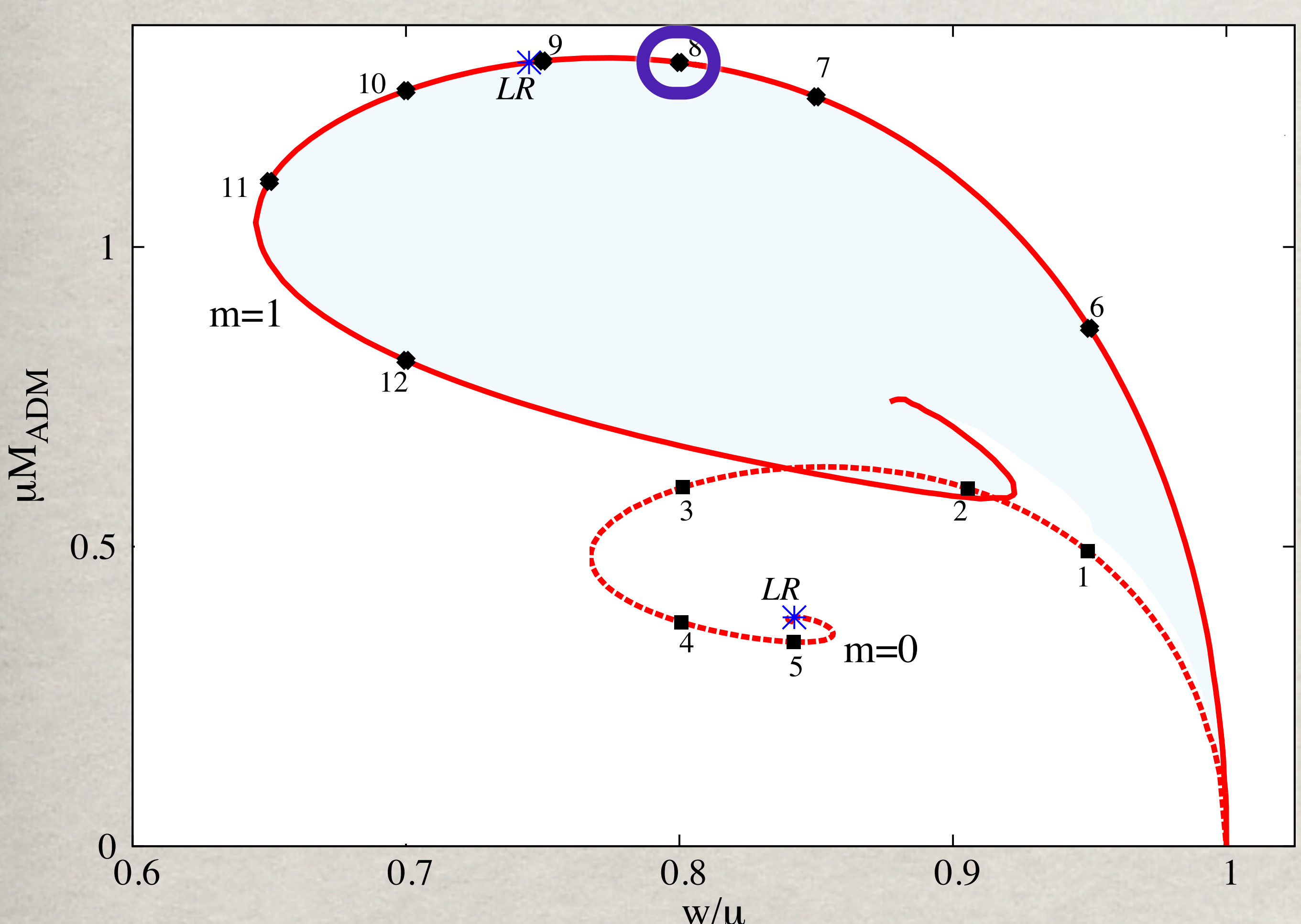


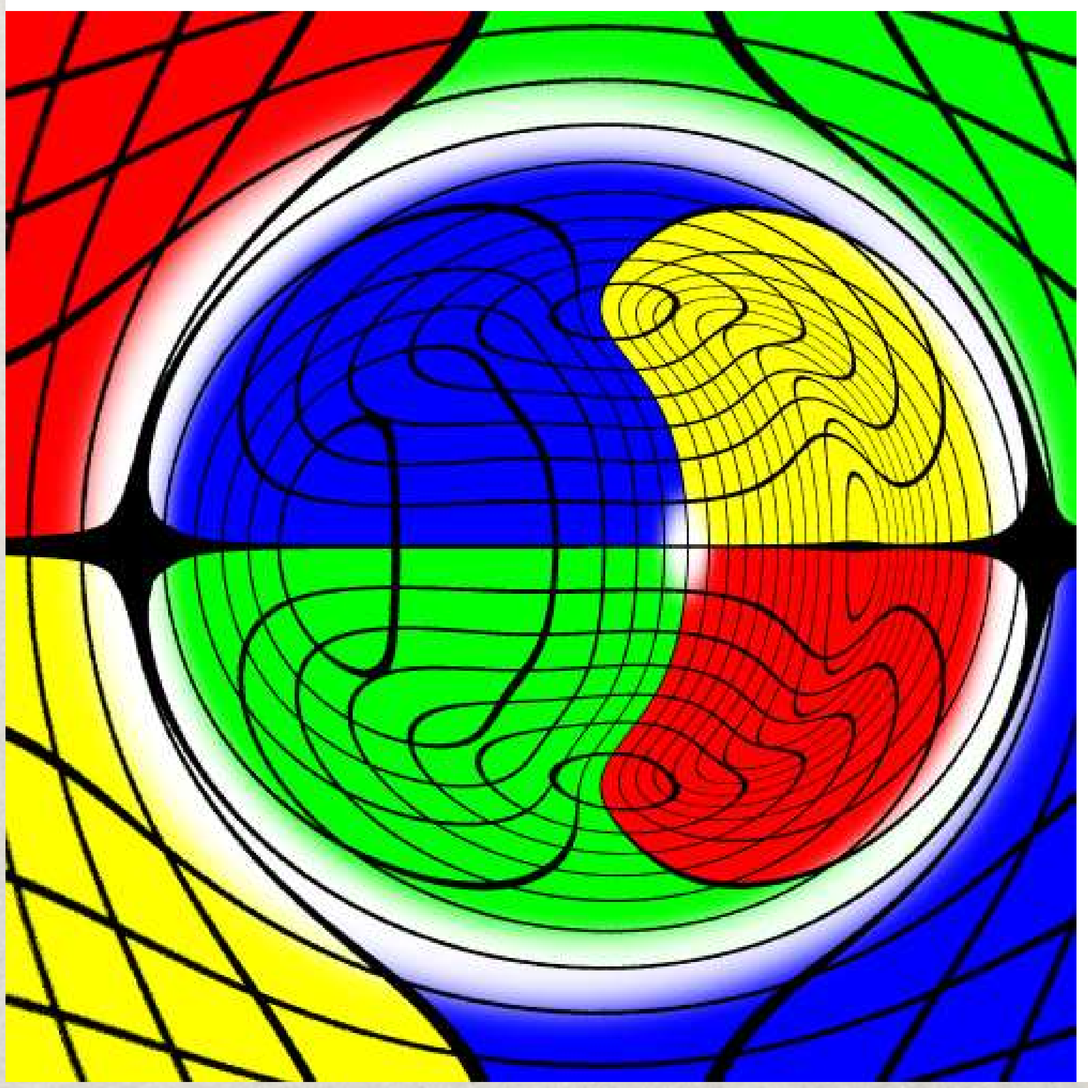
Einstein ring appears at:

$$w_{ER1}^{(b1)} \simeq 0.92$$

Compact RBS

Rotating boson stars

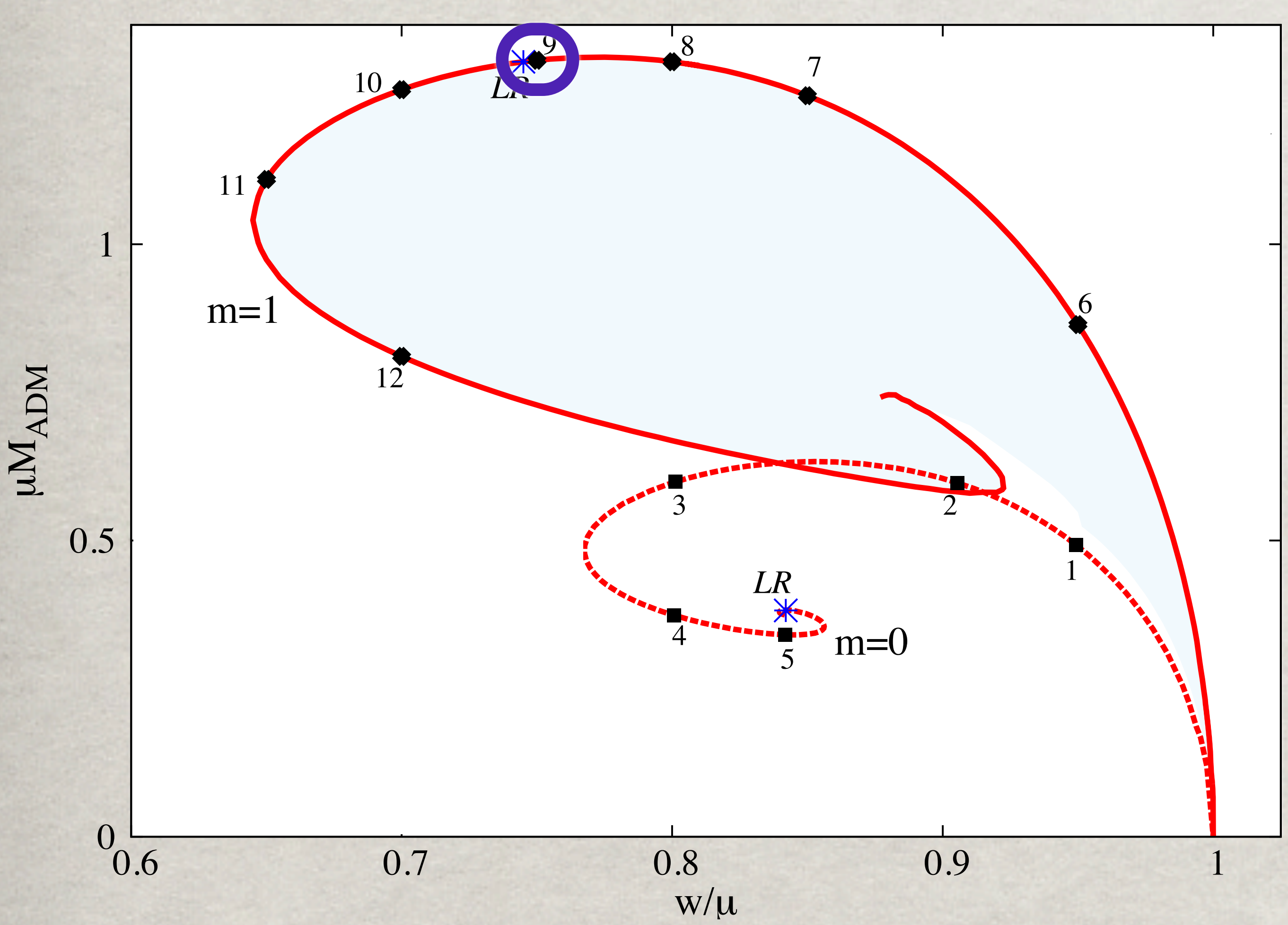


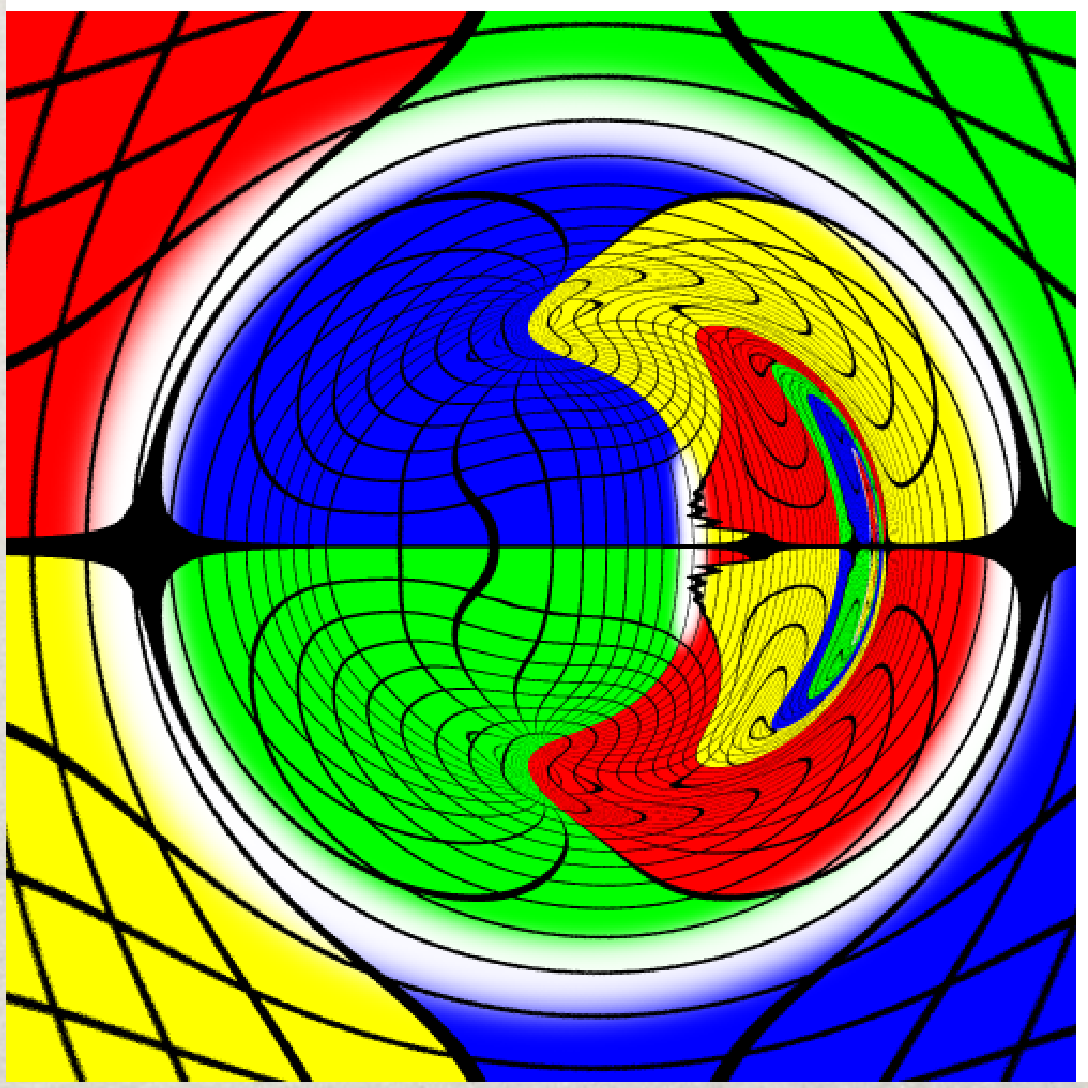


Larger region is “duplicated”

Compact RBS

Rotating boson stars

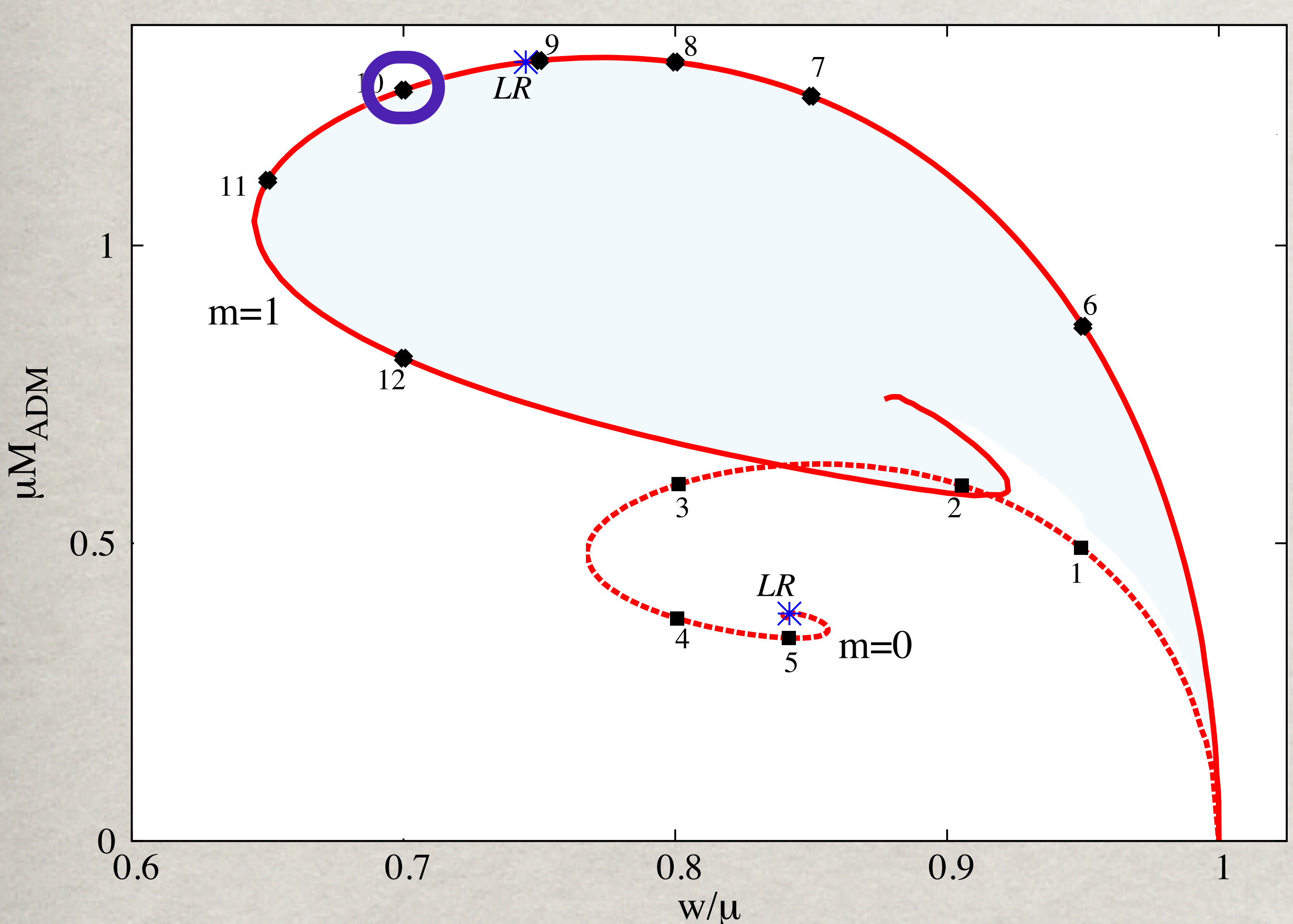




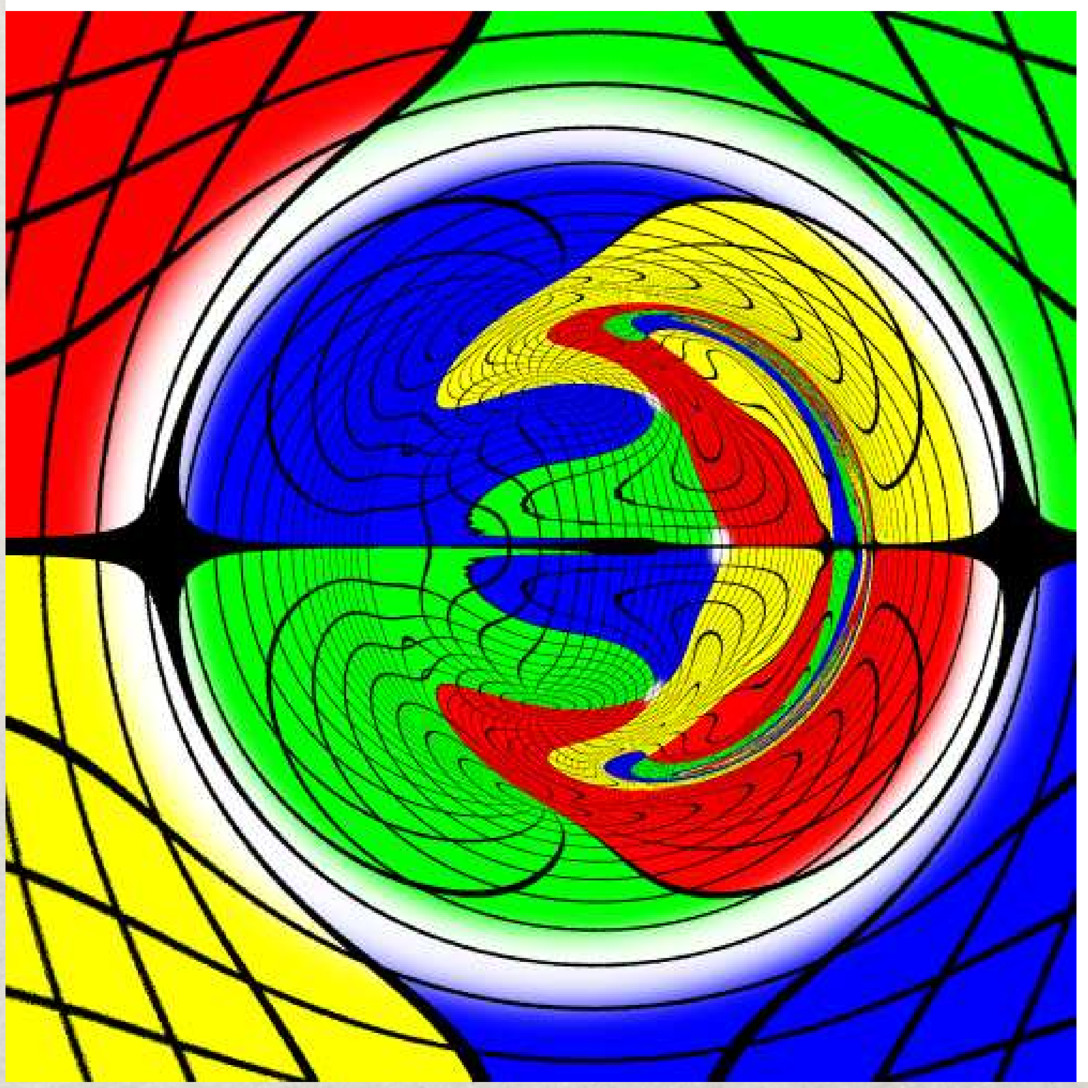
More Einstein rings but squashed D-shaped (not O-shaped)

Compact RBS

Rotating boson stars

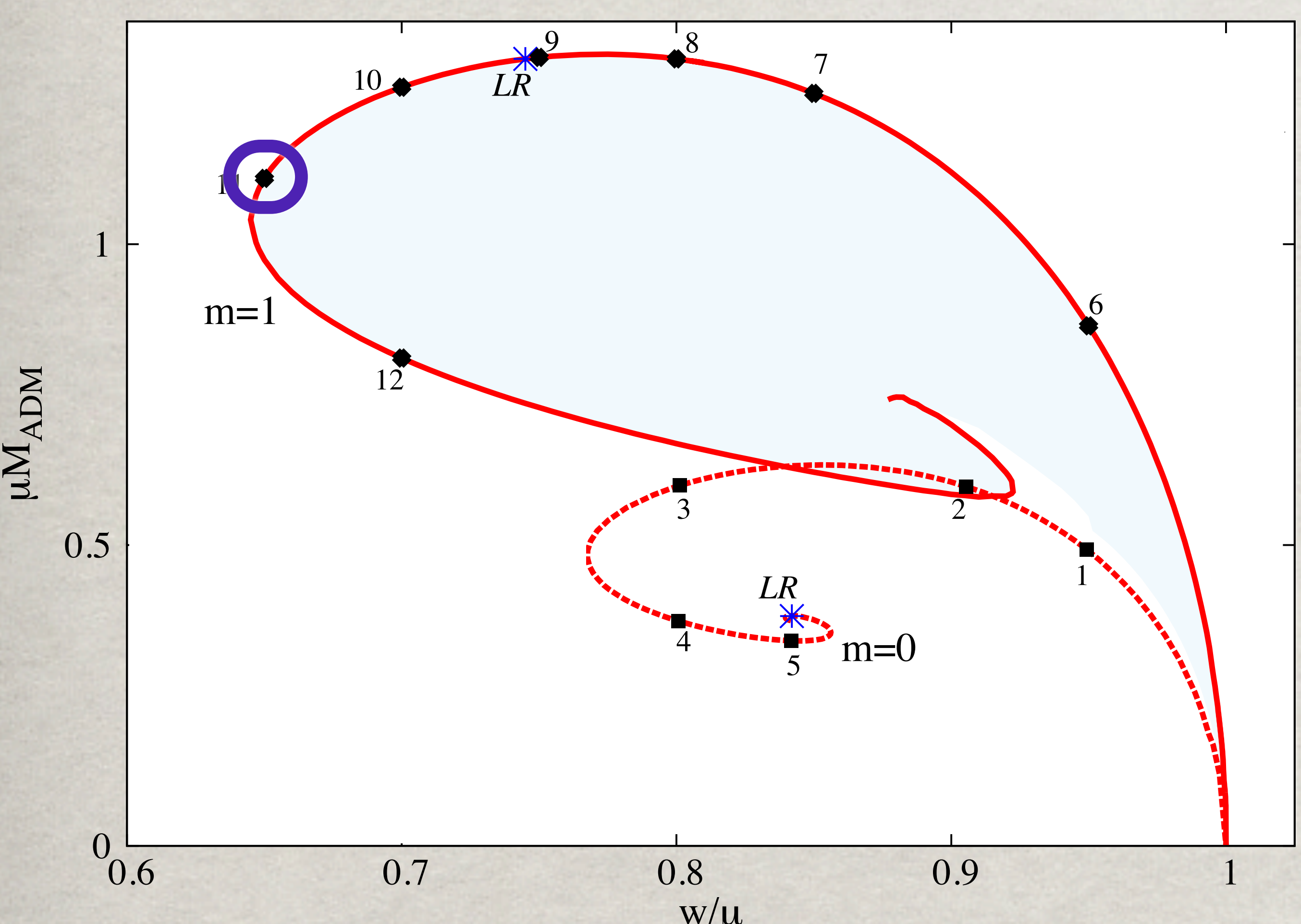


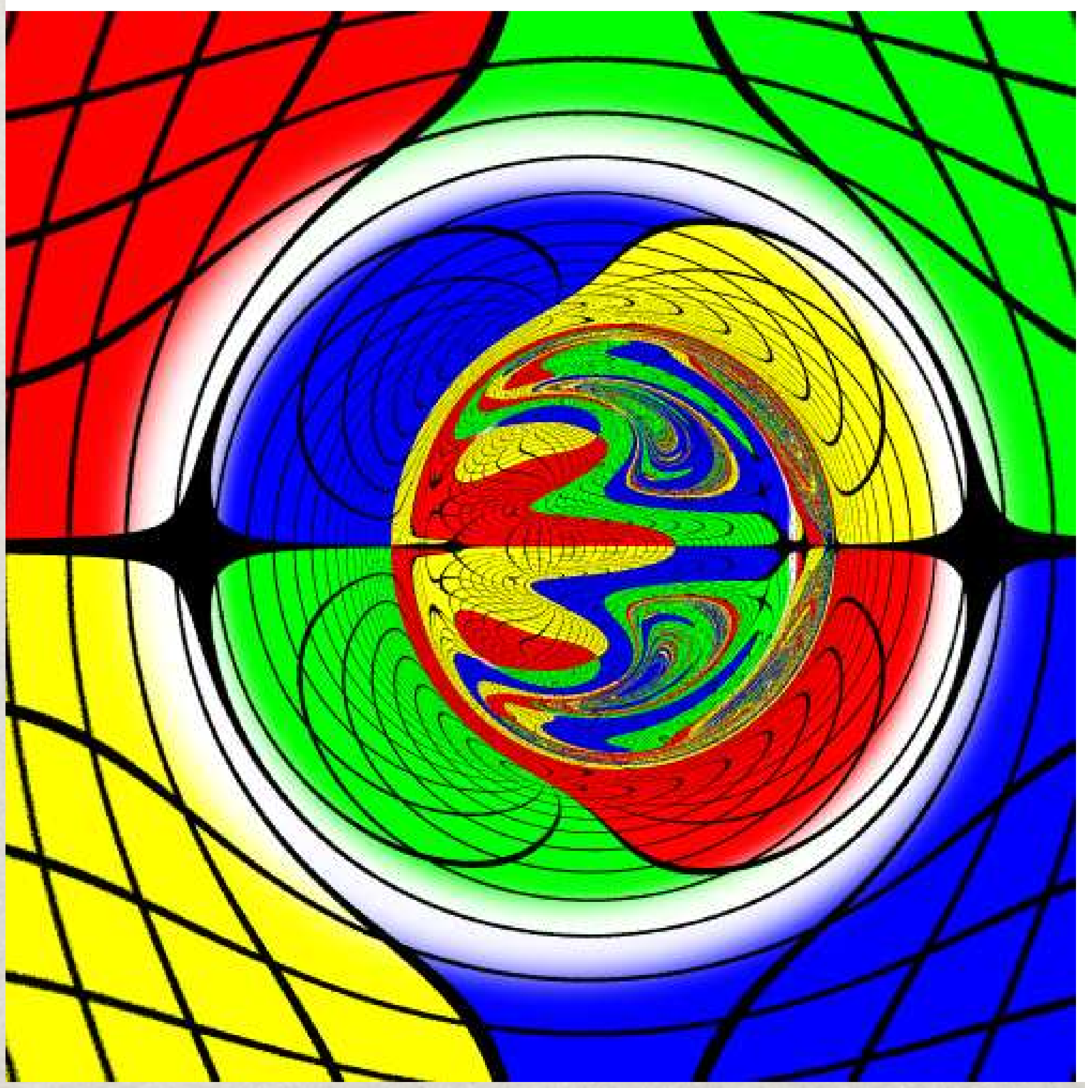
(Presumably)
Infinitely many copies of
the celestial sphere



Ultra-compact RBS

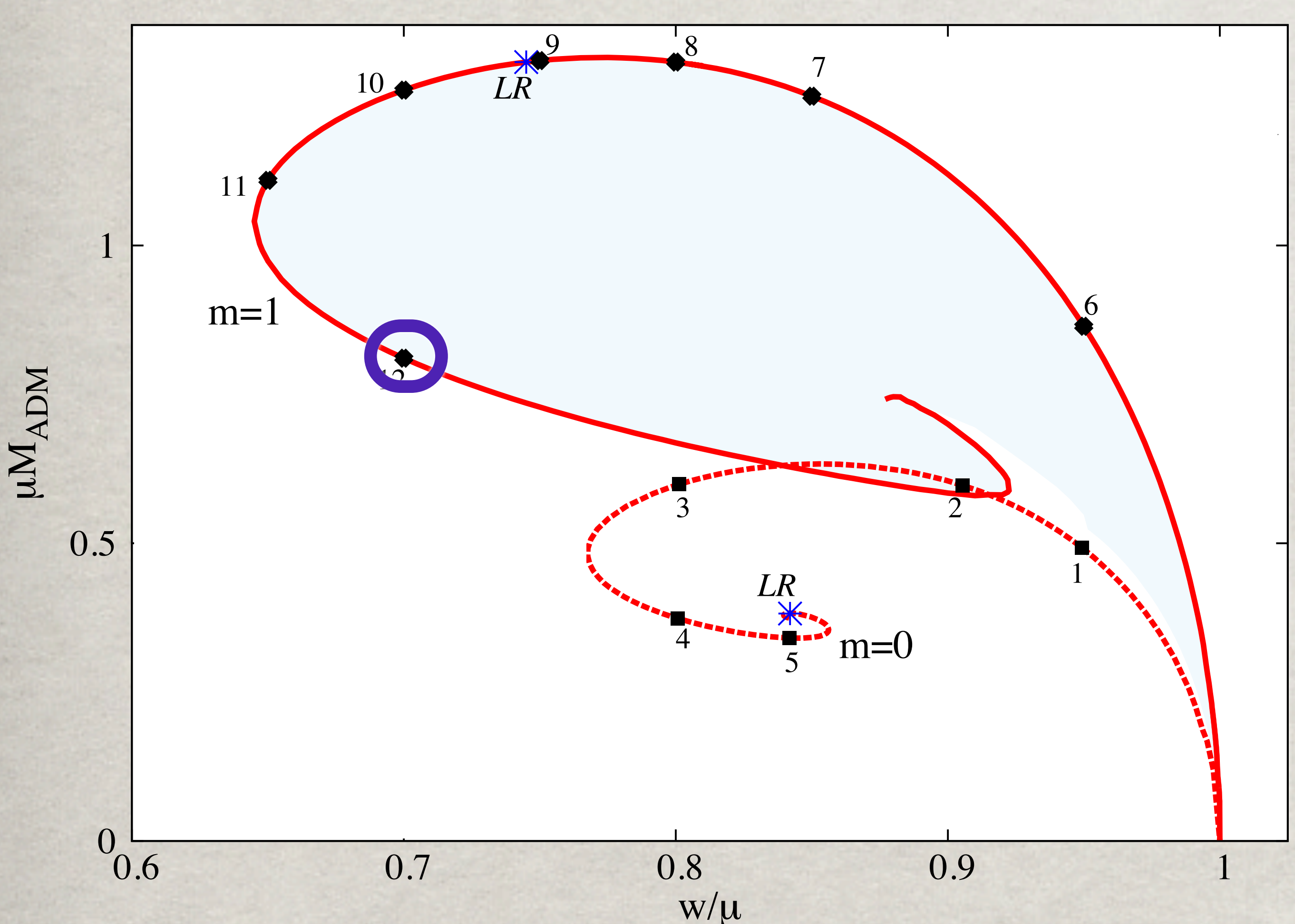
Rotating boson stars

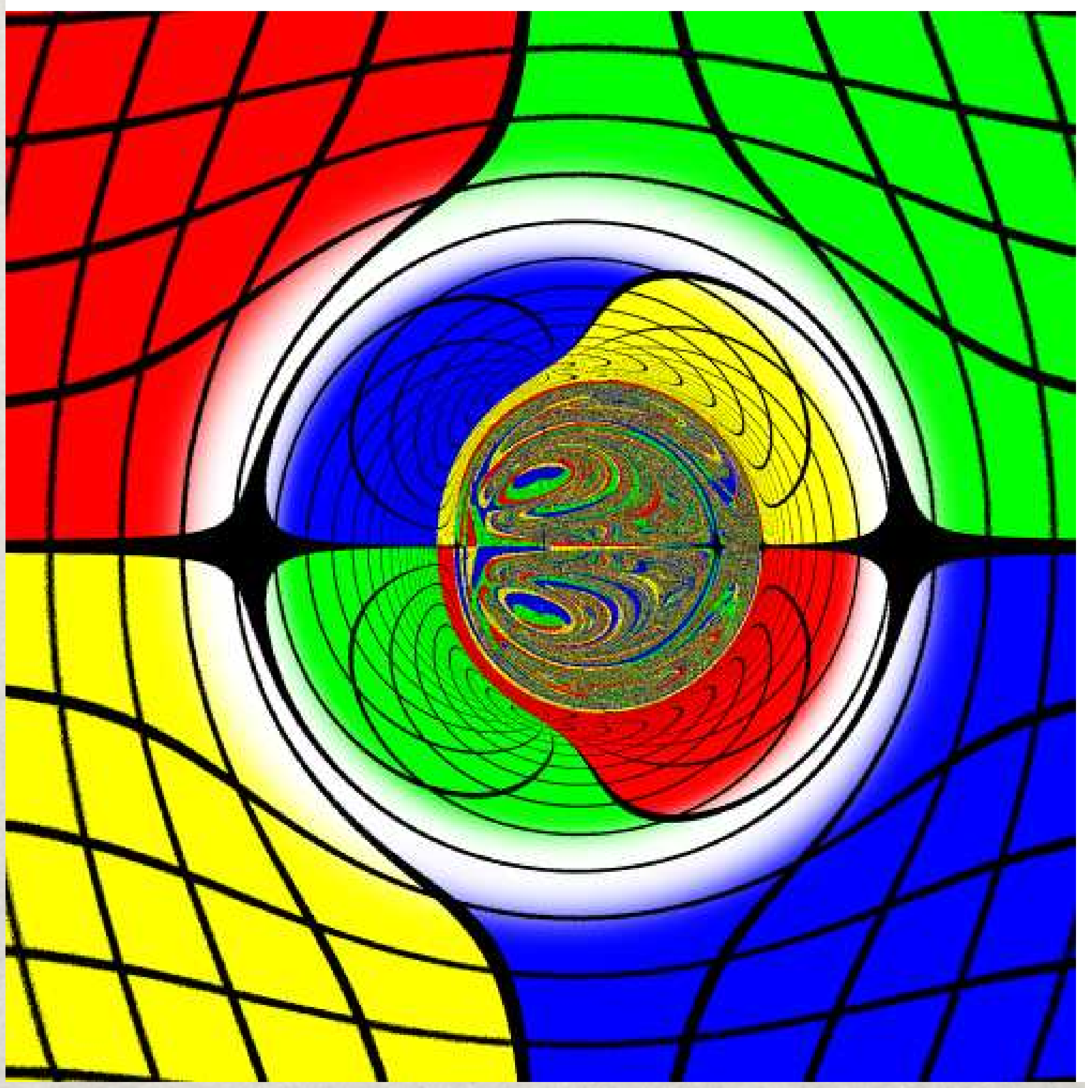




Ultra-compact RBS

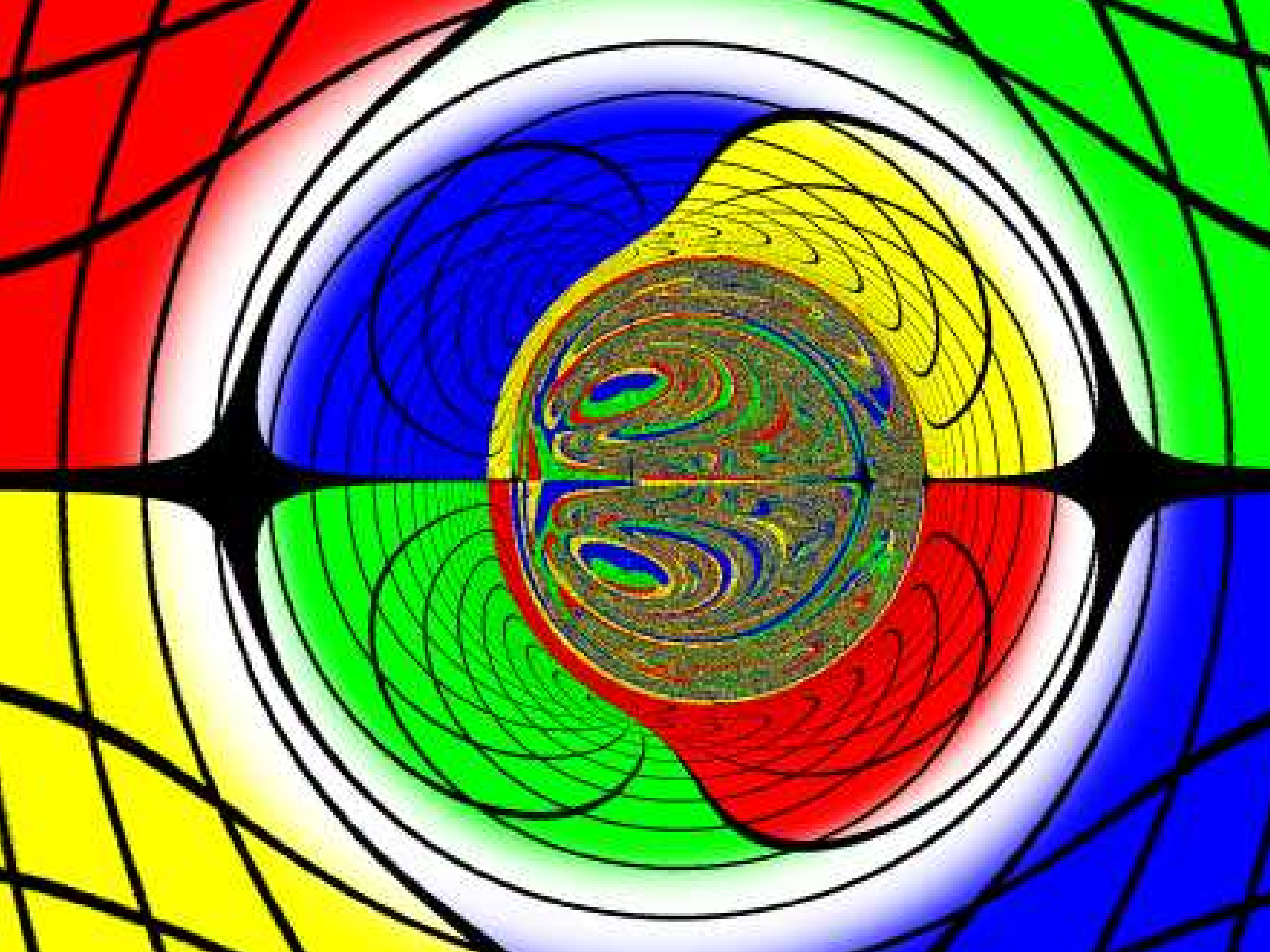
Rotating boson stars





Self similar structures?

Ultra-compact RBS



5) Shadows of Kerr black holes with scalar hair

Kerr black holes with scalar hair
may be regarded as a
boson star around and co-rotating
with a central horizon

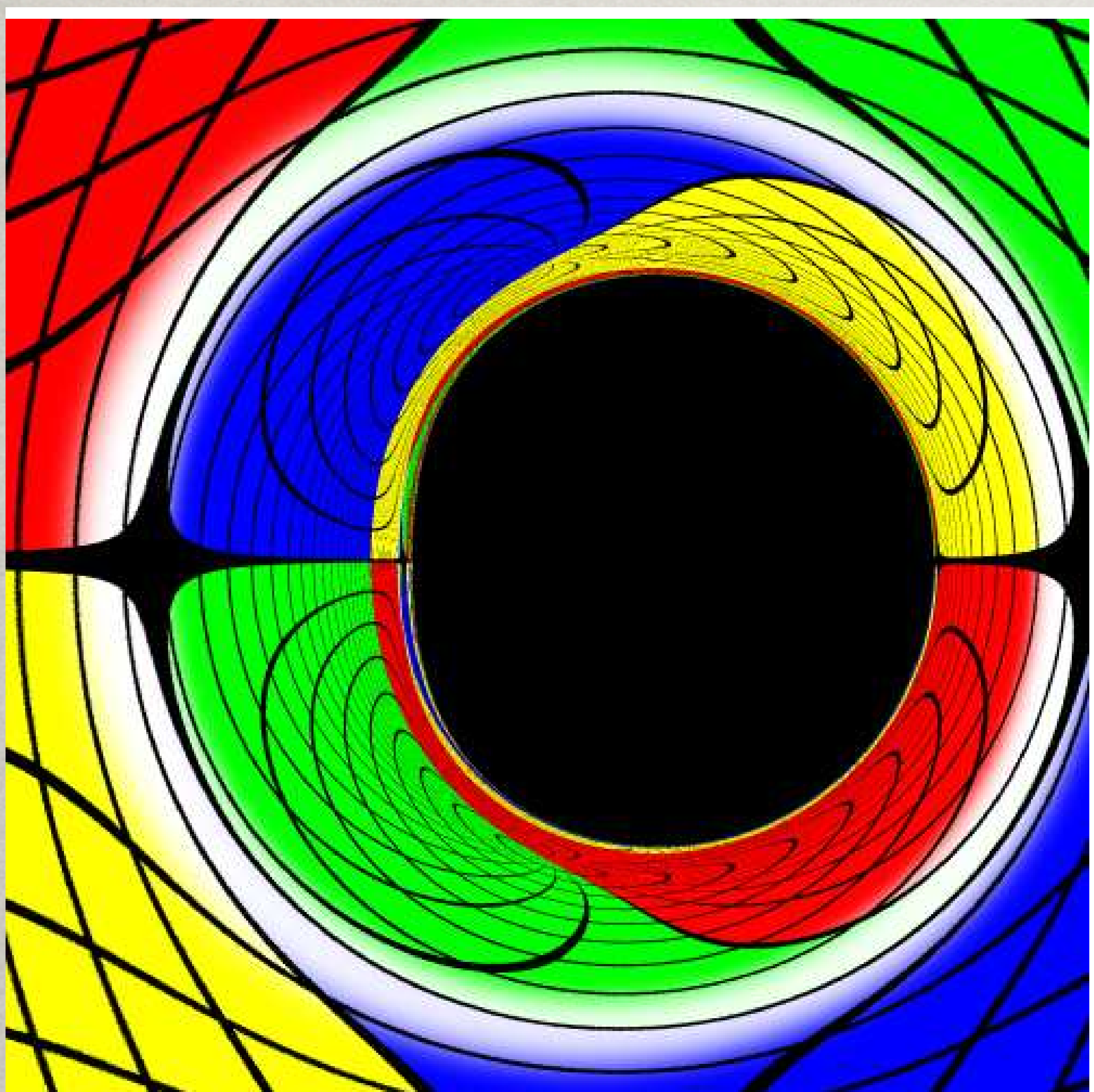
The central horizon may be
non-Kerr like
(violate the Kerr bound in terms of horizon quantities)
One may anticipate unfamiliar shadows.

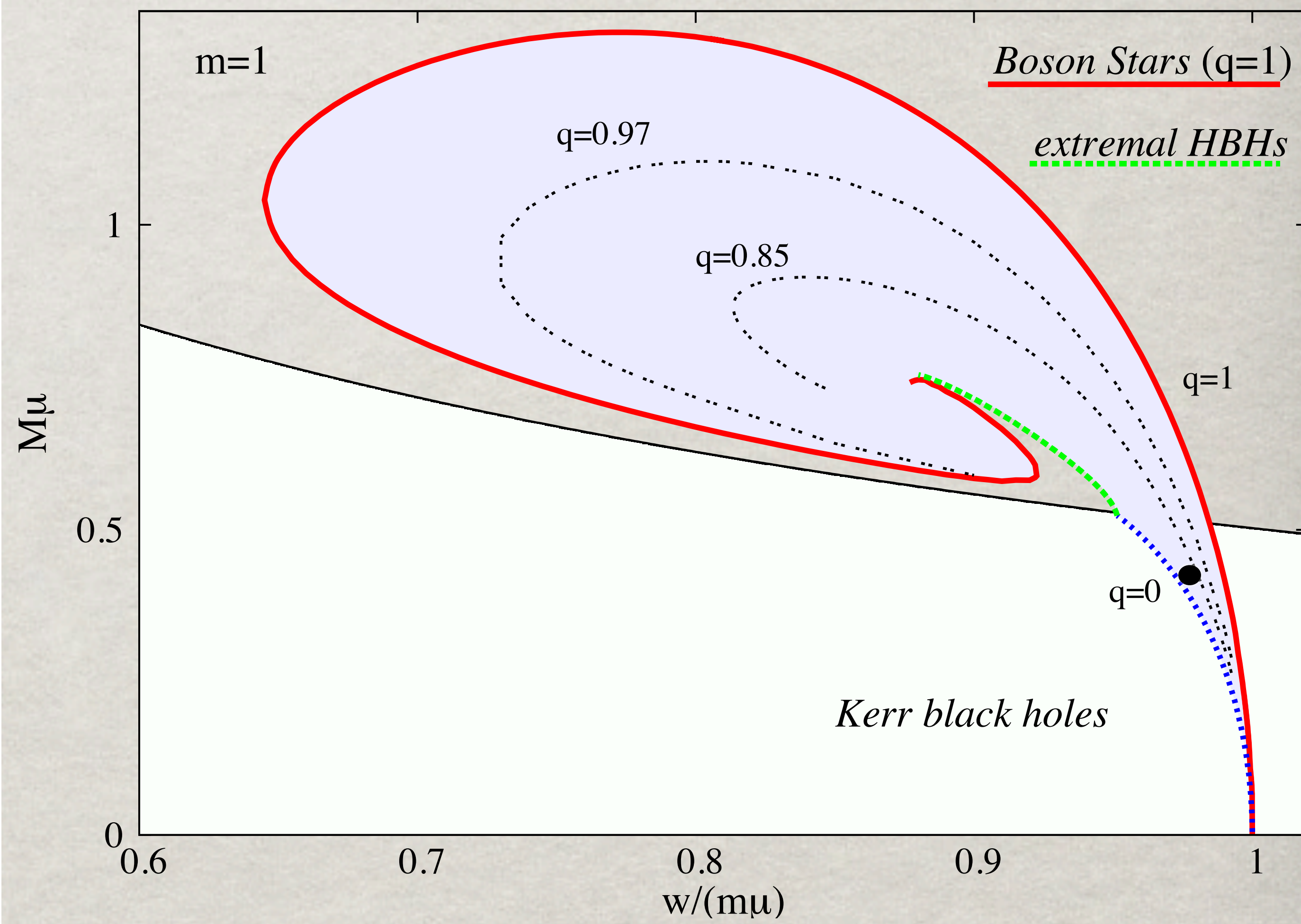
There is non uniqueness
(different solutions for same ADM M,J);
but degeneracy raised with q

Can we distinguish by a local measurement degenerate configurations?

A Kerr-like hairy black hole

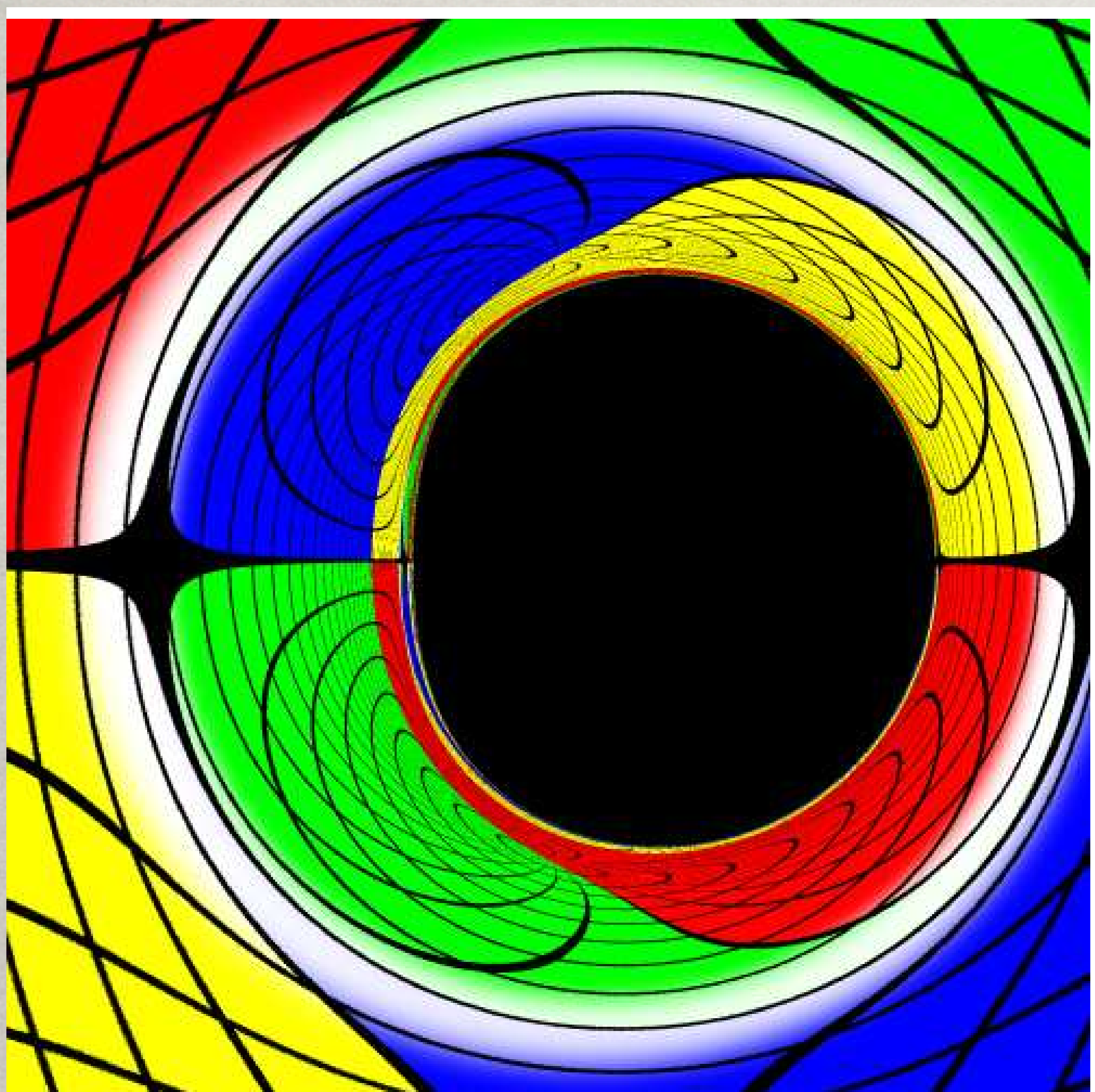
Fix the ADM mass and observer's distance



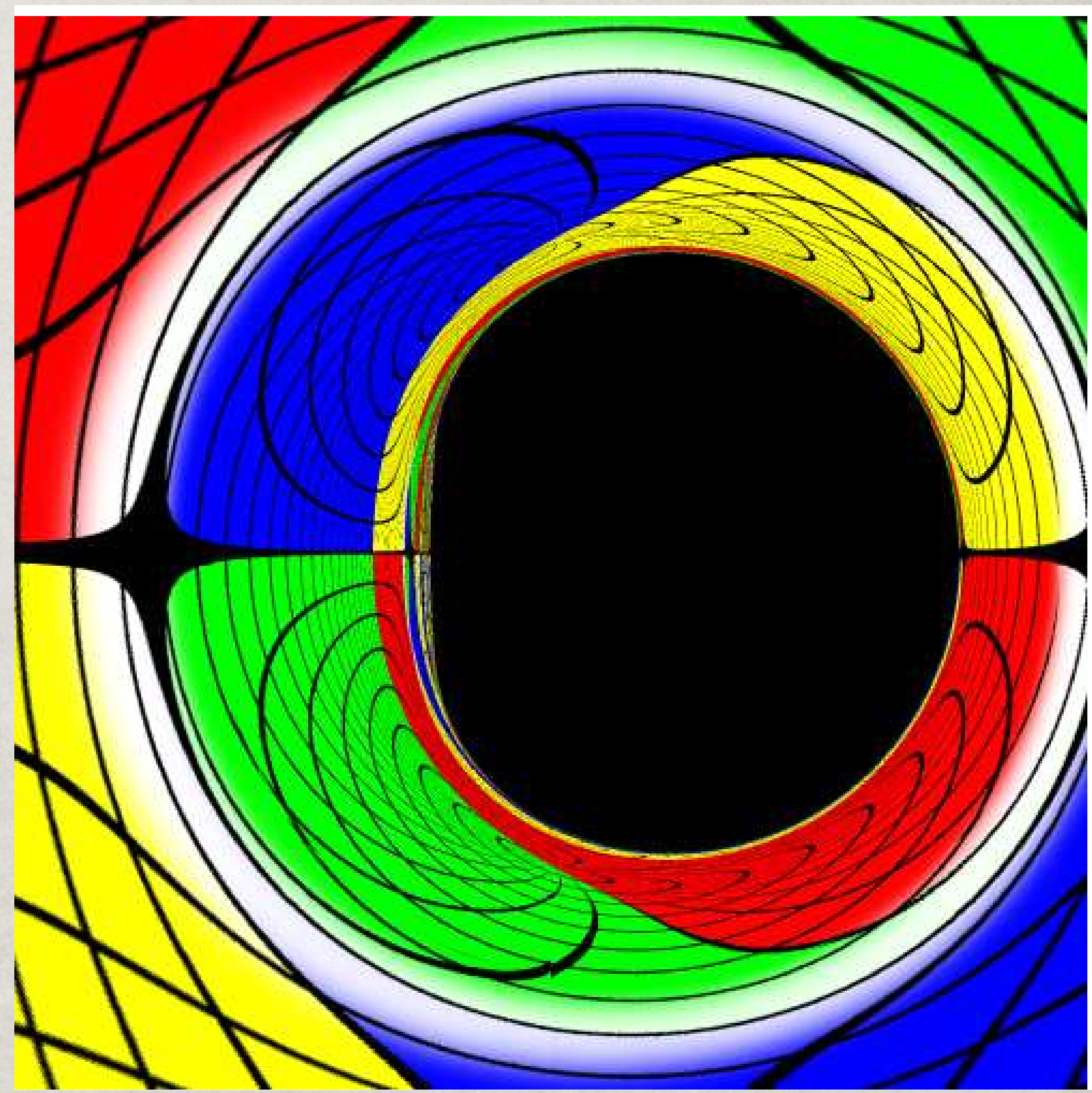


5% of mass;
13% of angular momentum
is stored in the scalar field

A Kerr-like Kerr BH with scalar hair

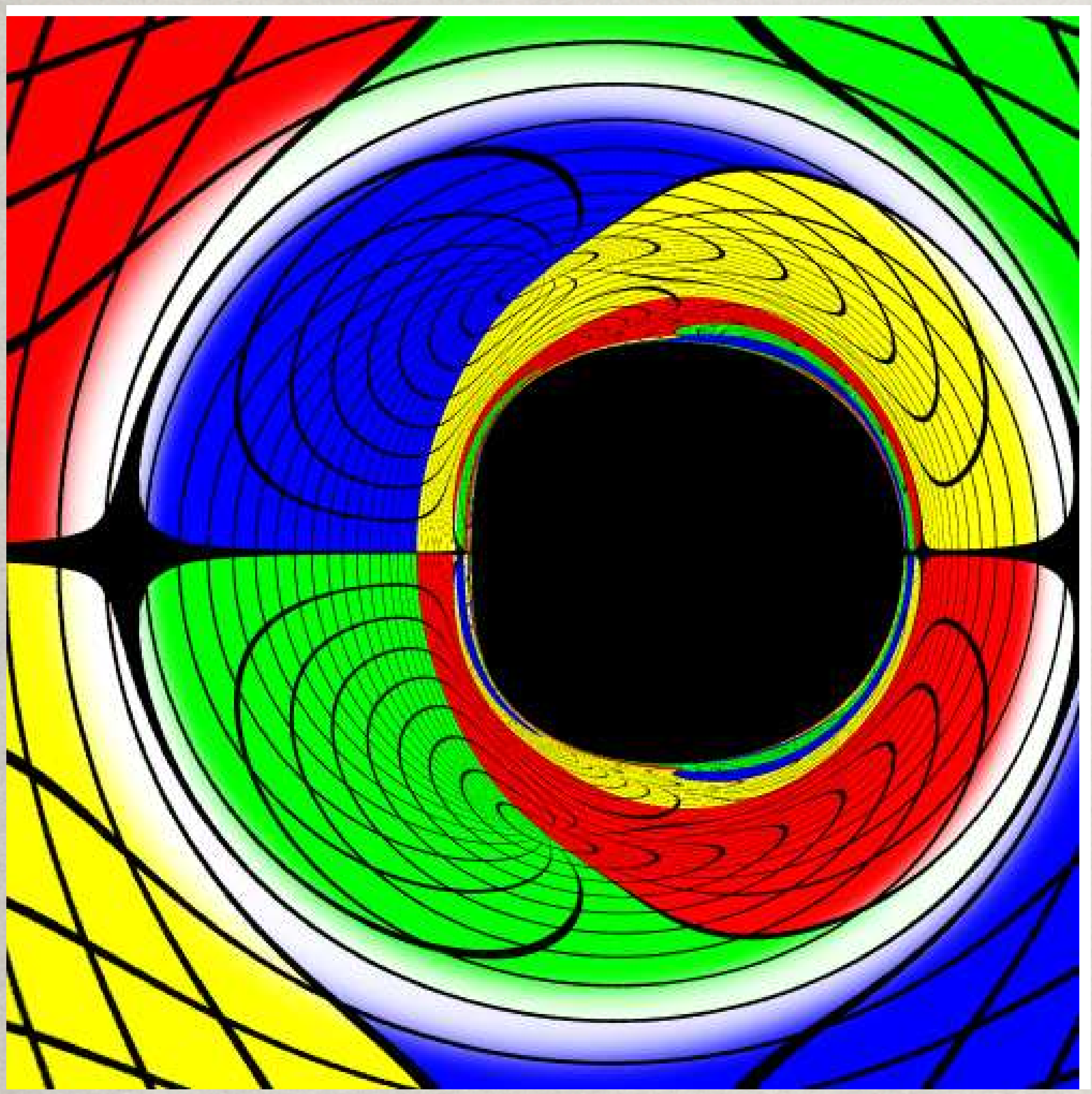


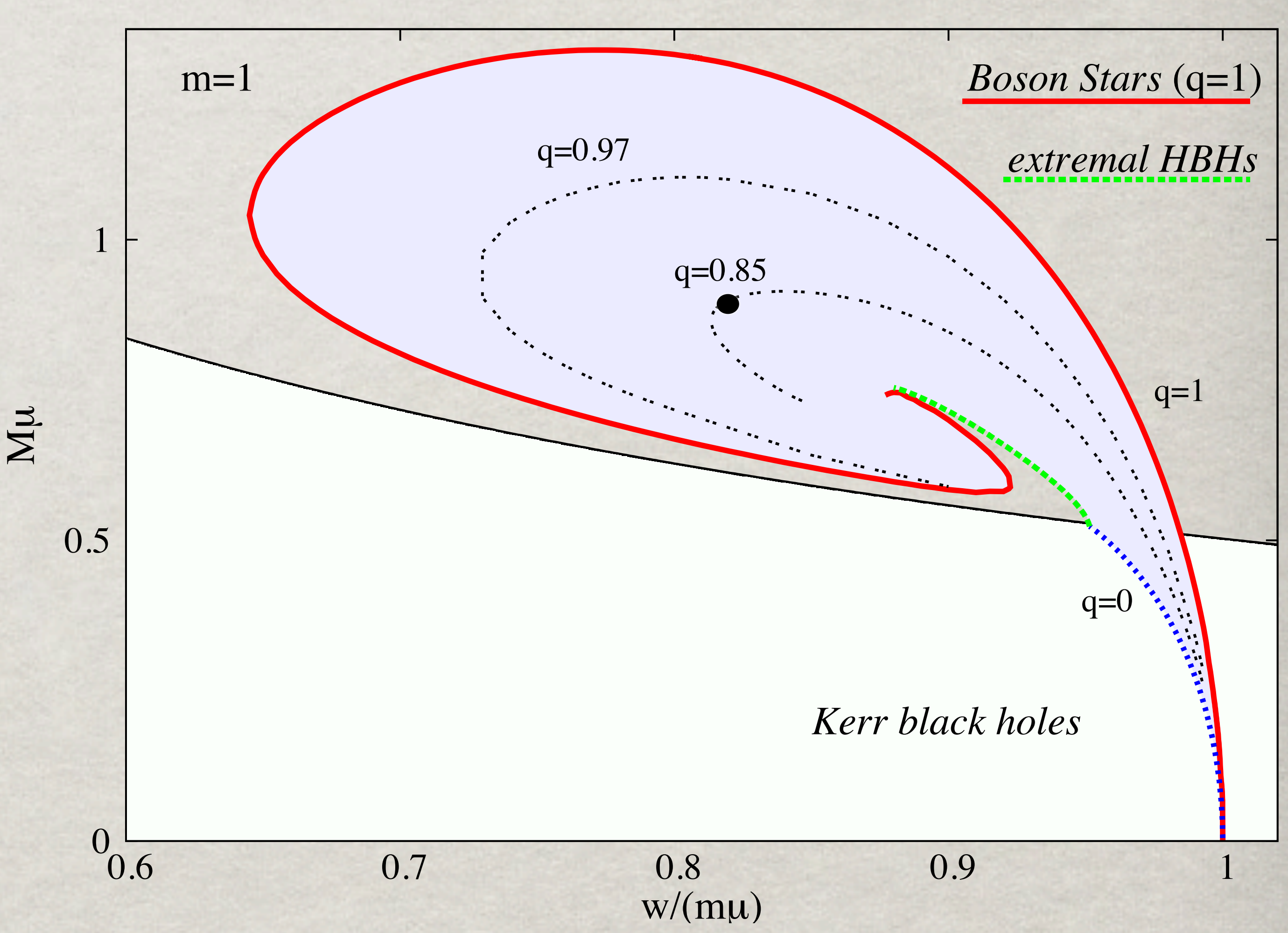
Hairy BH:
M=0.393; J=0.15 (horizon)
M=0.022; J=0.022 (scalar field)



Vacuum Kerr BH:
M=0.415; J=0.172

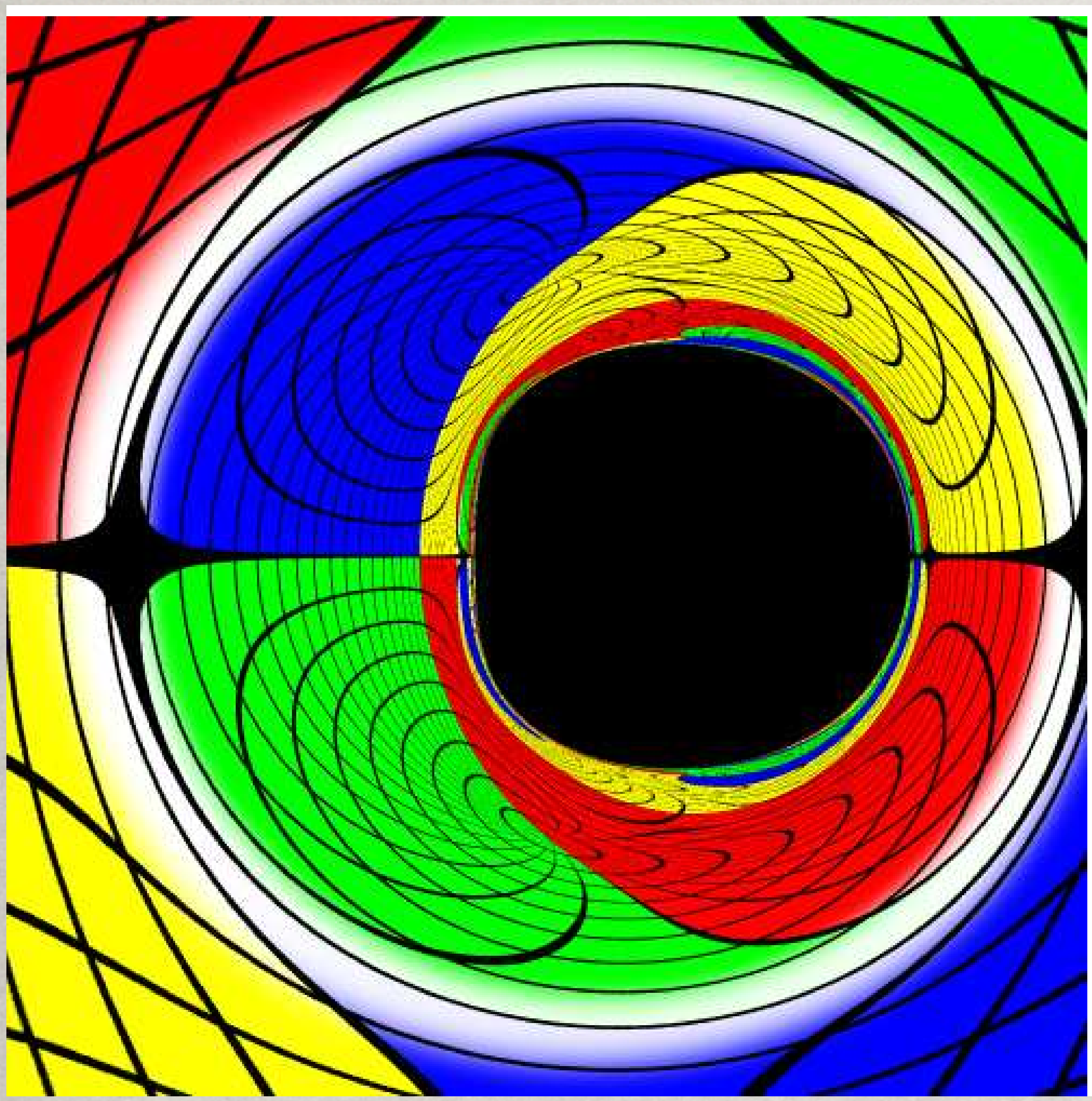
A non-Kerr-like hairy black hole



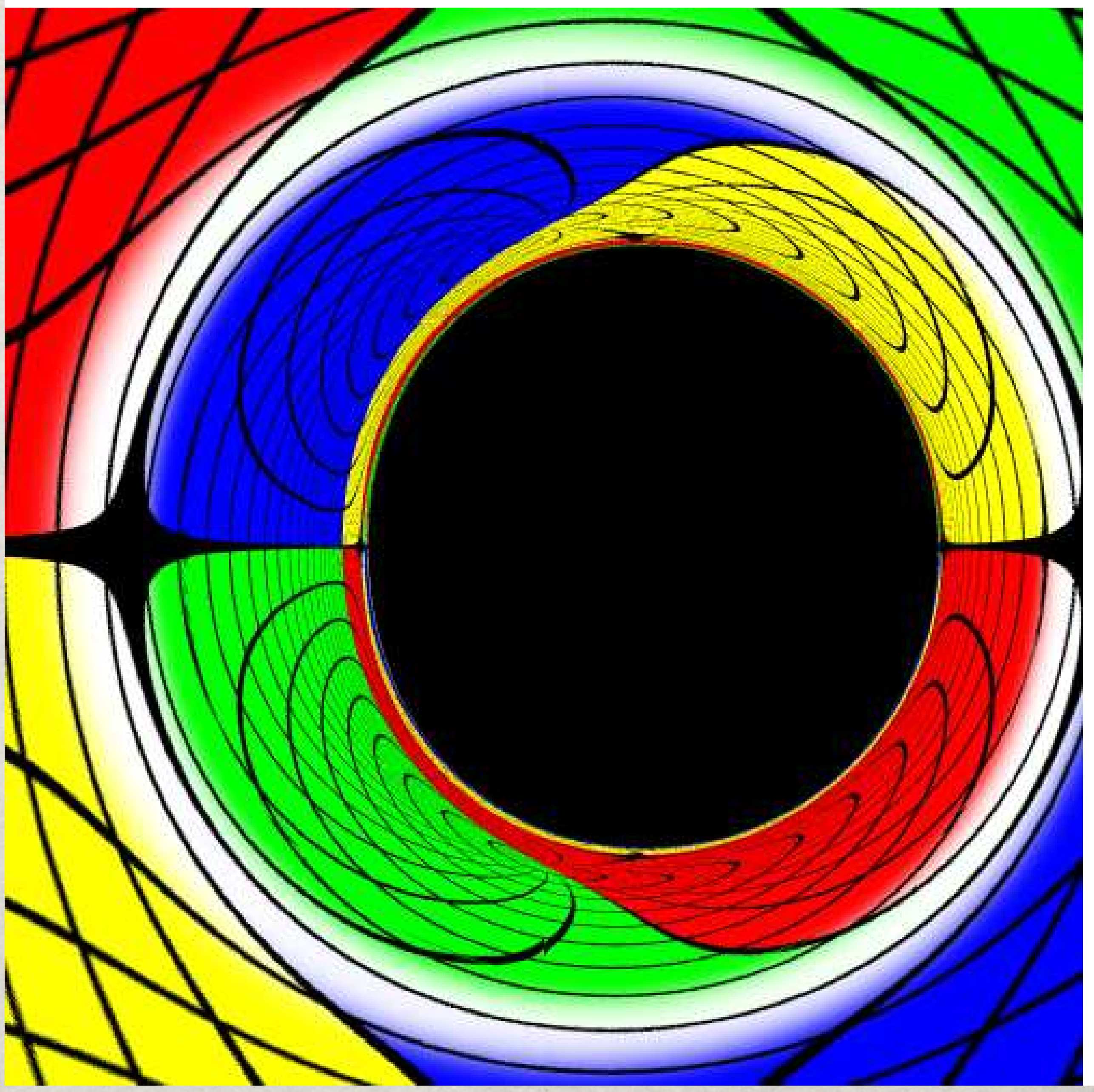


75% of mass;
85% of angular momentum
is stored in the scalar field

A non-Kerr-like hairy black hole

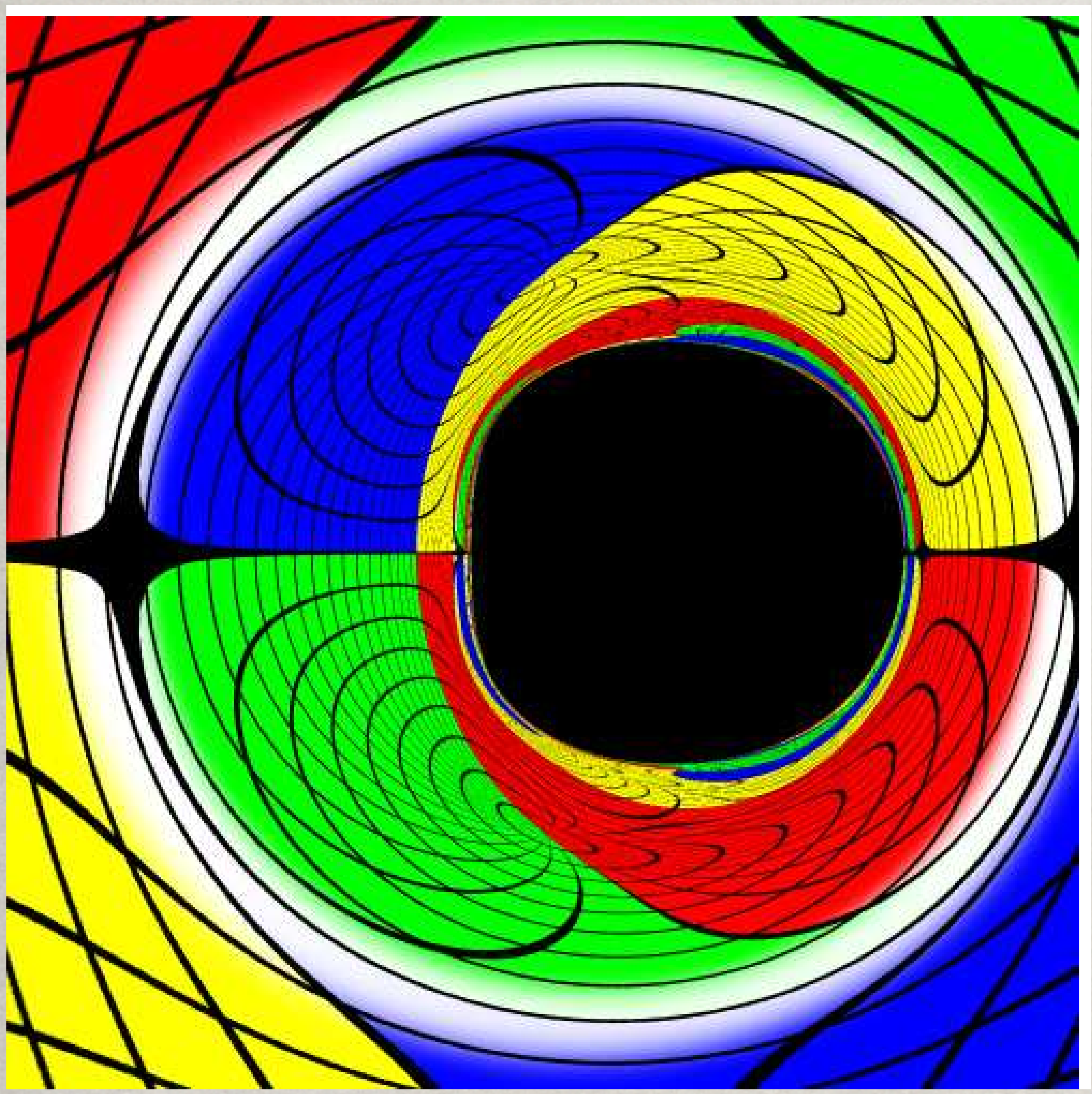


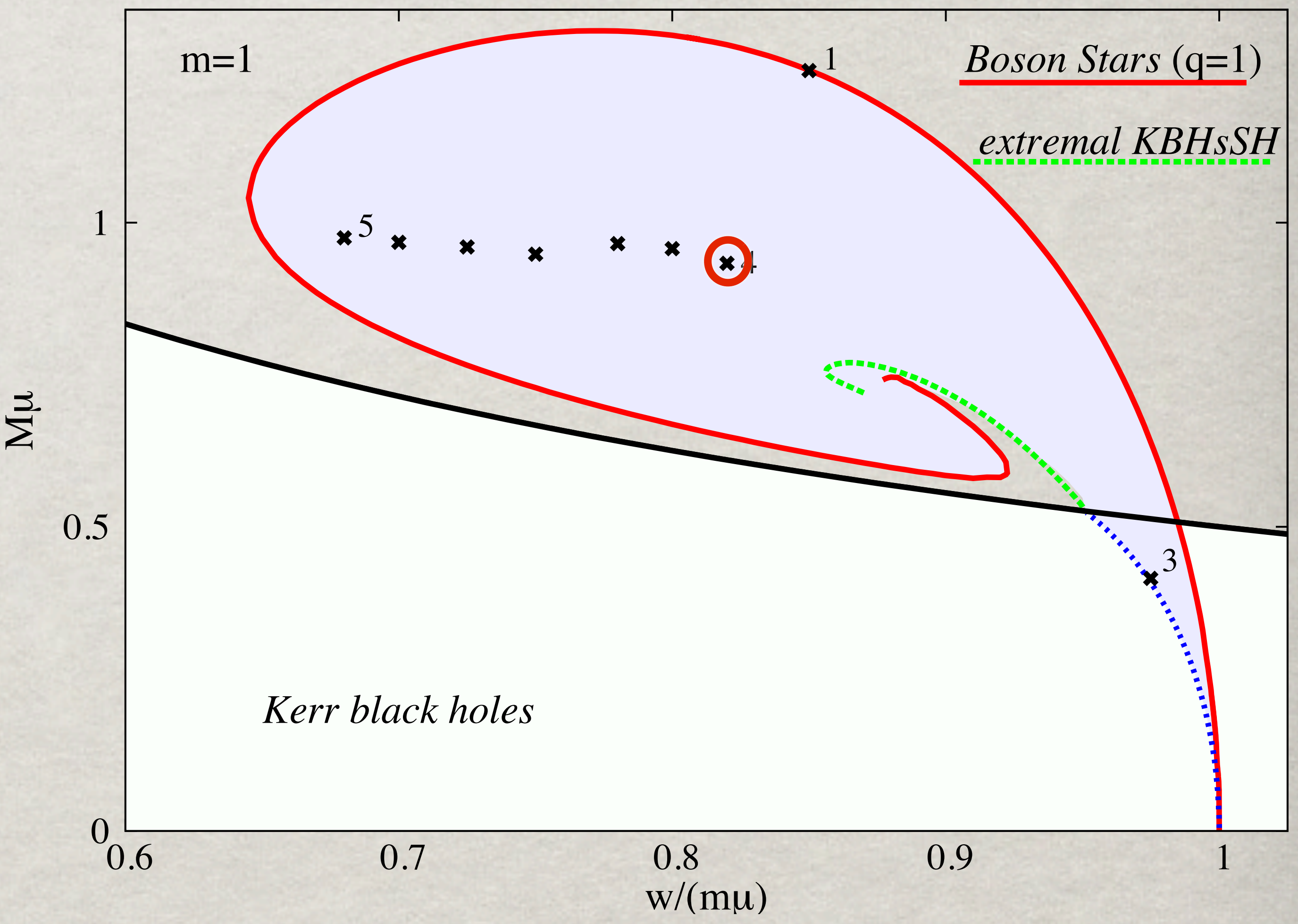
Hairy BH:
M=0.234; J=0.115 (horizon)
M=0.699; J=0.625 (scalar field)

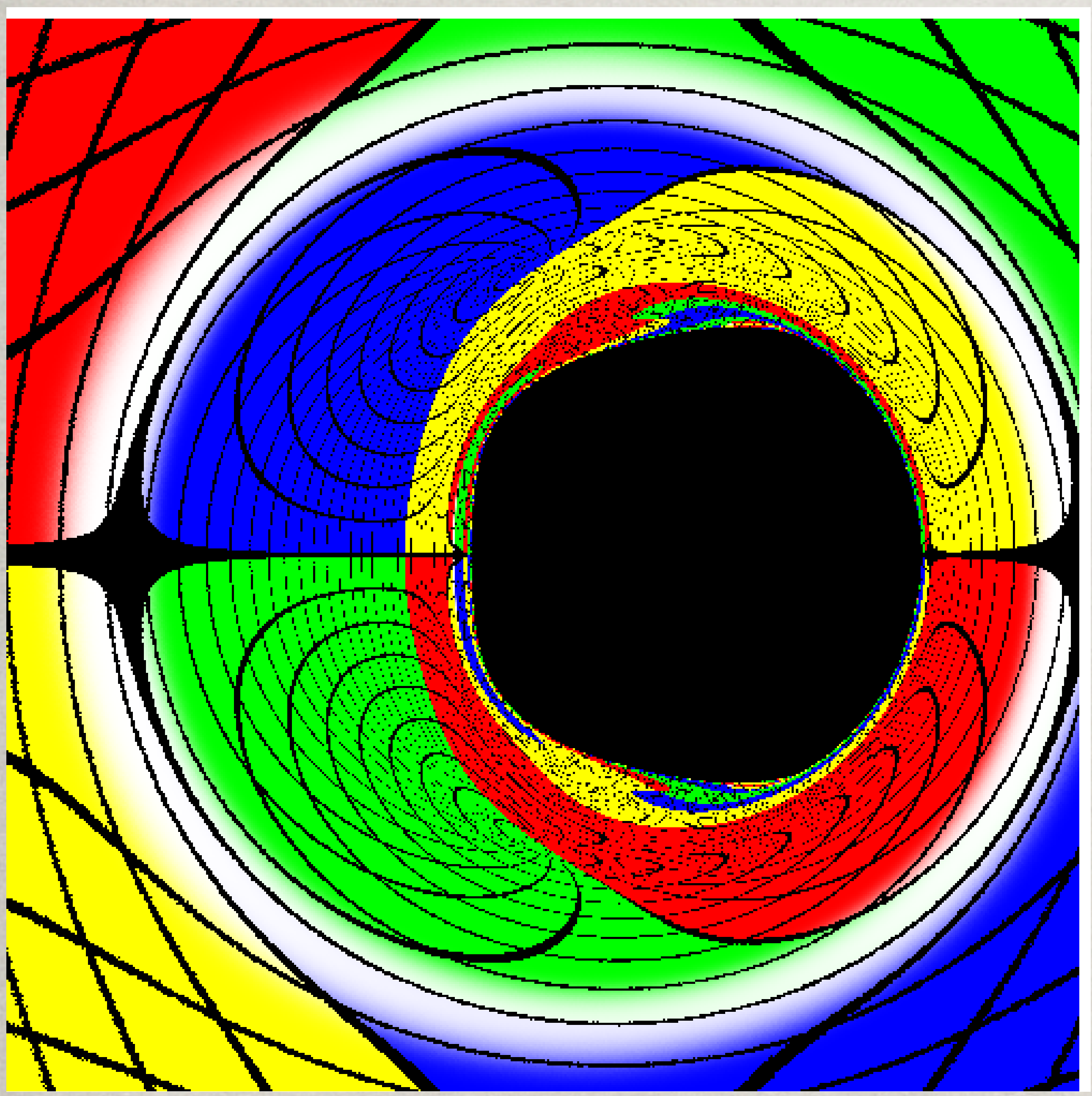


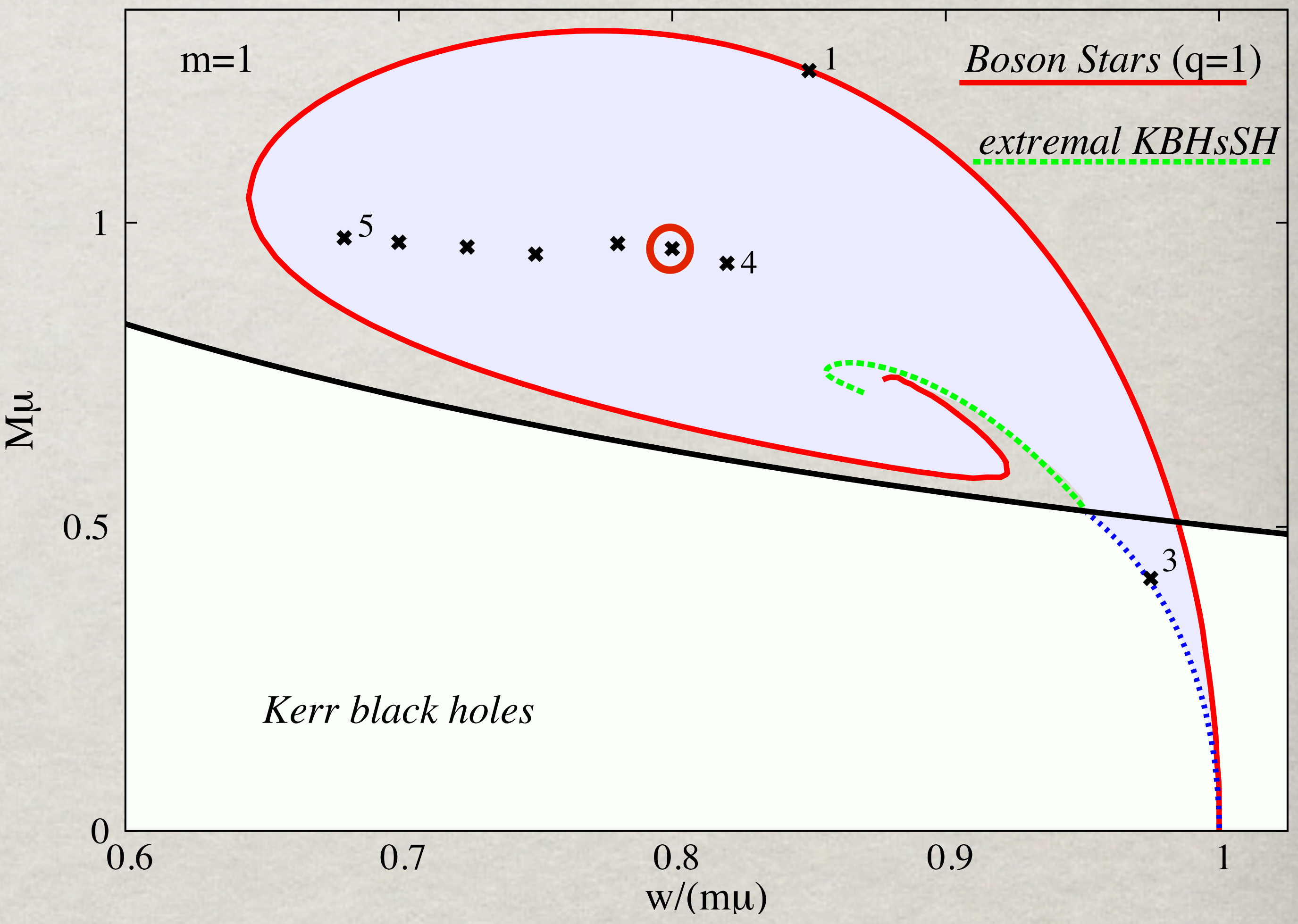
Vacuum Kerr BH:
M=0.933; J=0.740

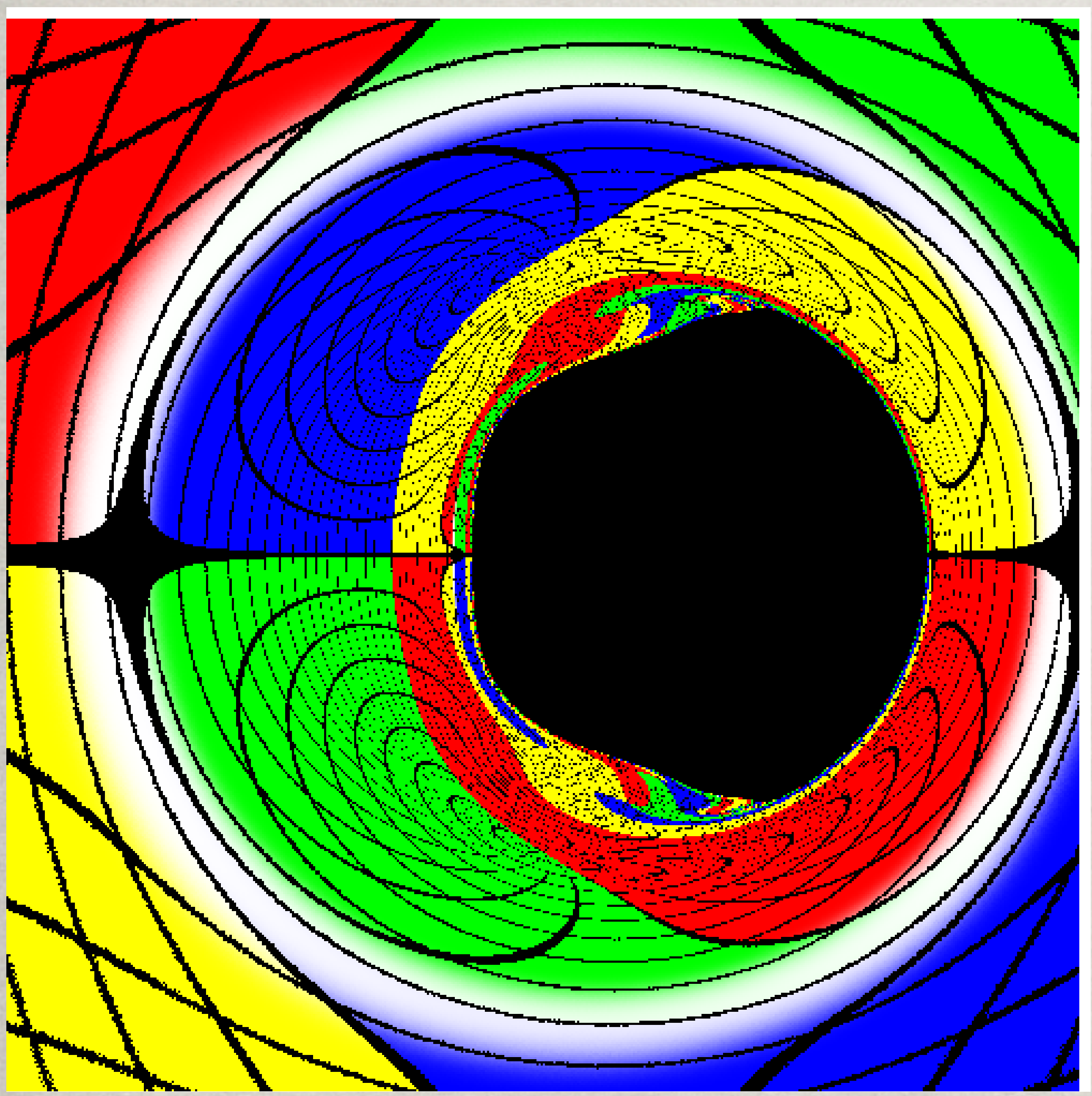
More non-Kerr-like hairy black holes

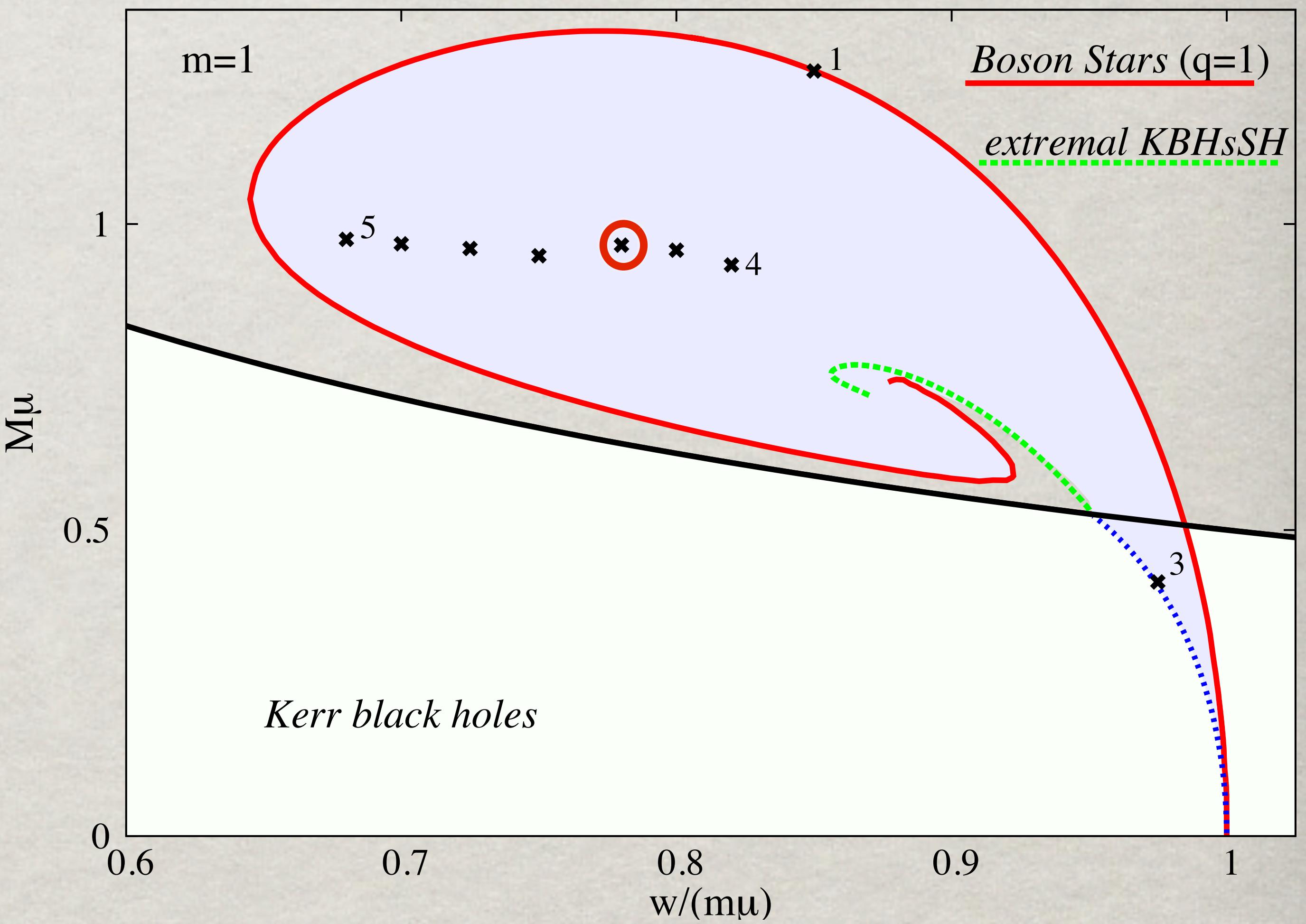




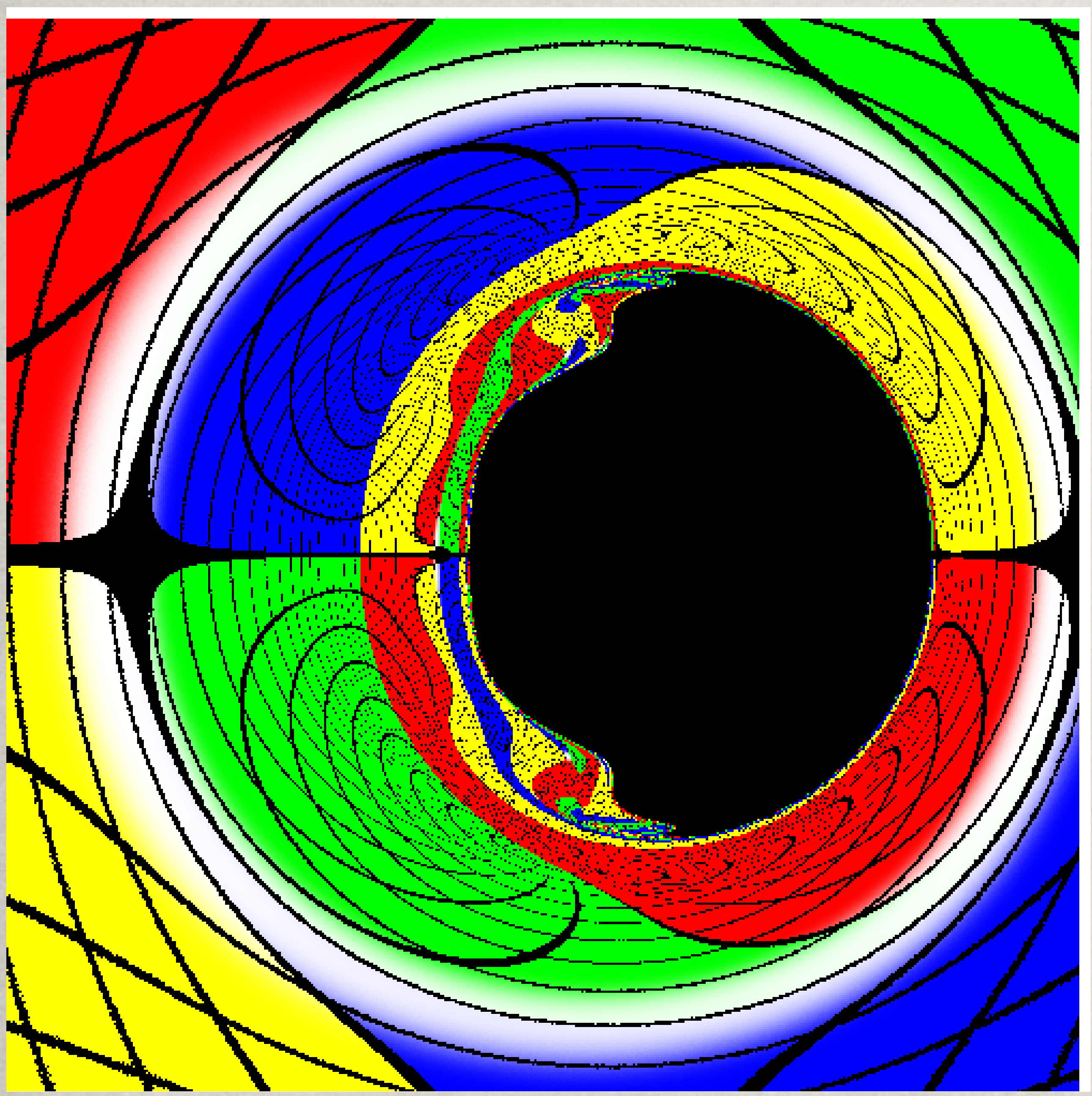


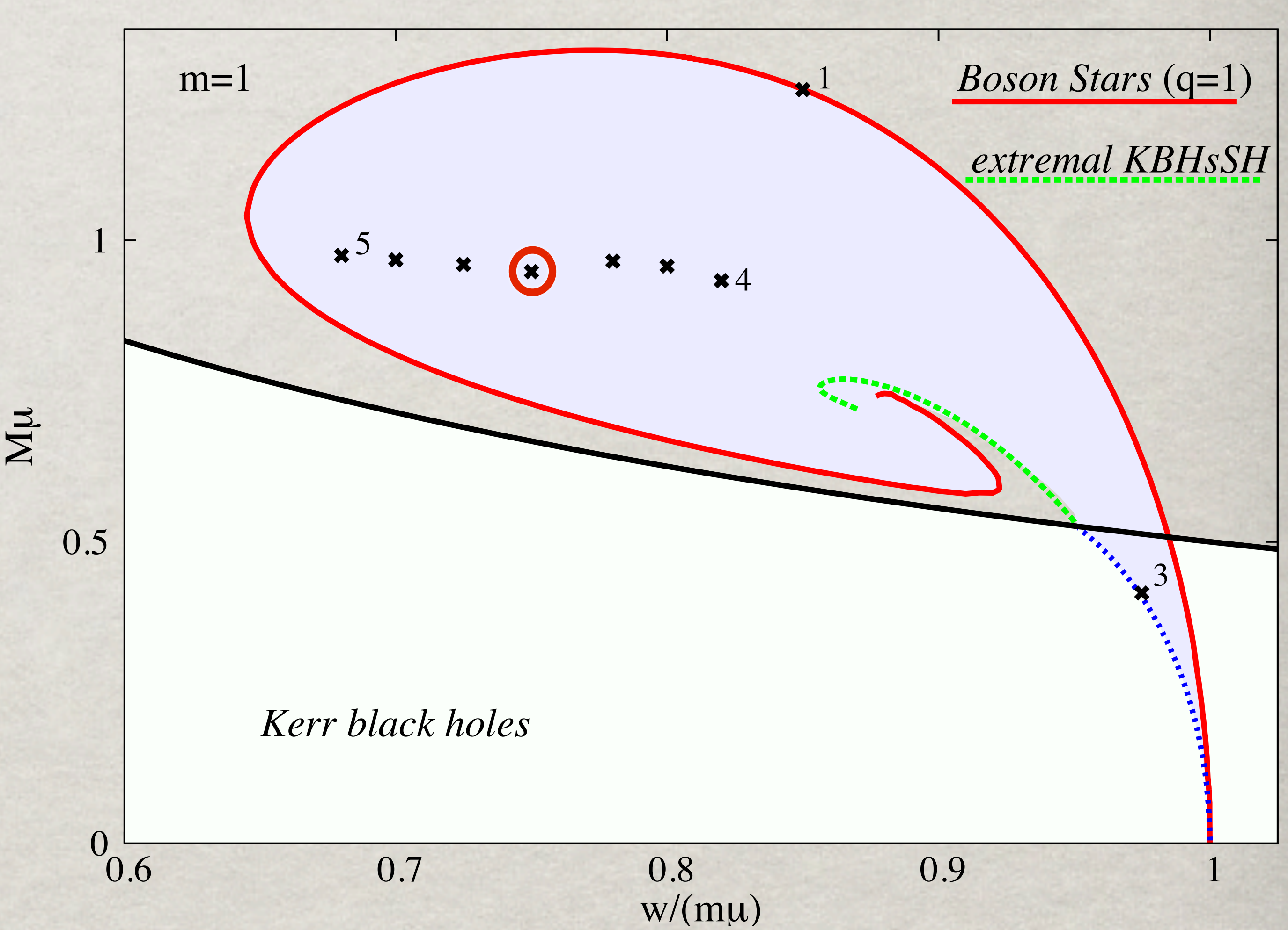

m=1
Boson Stars (q=1)
extremal KBHsSH
Kerr black holes
1
3
4
5
Mμ
w/(mμ)
0
0.5
1
0.6
0.7
0.8
0.9
1



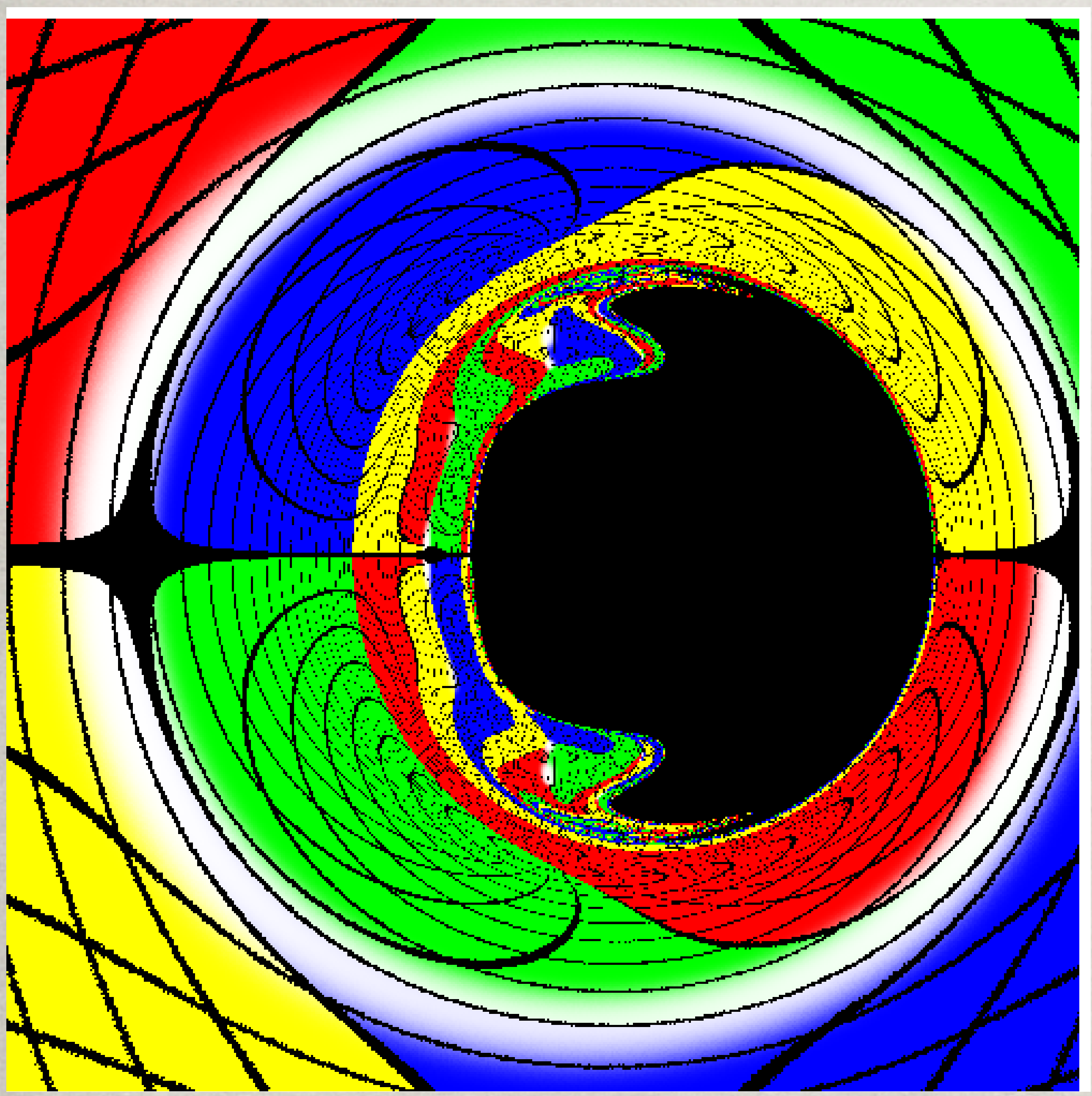


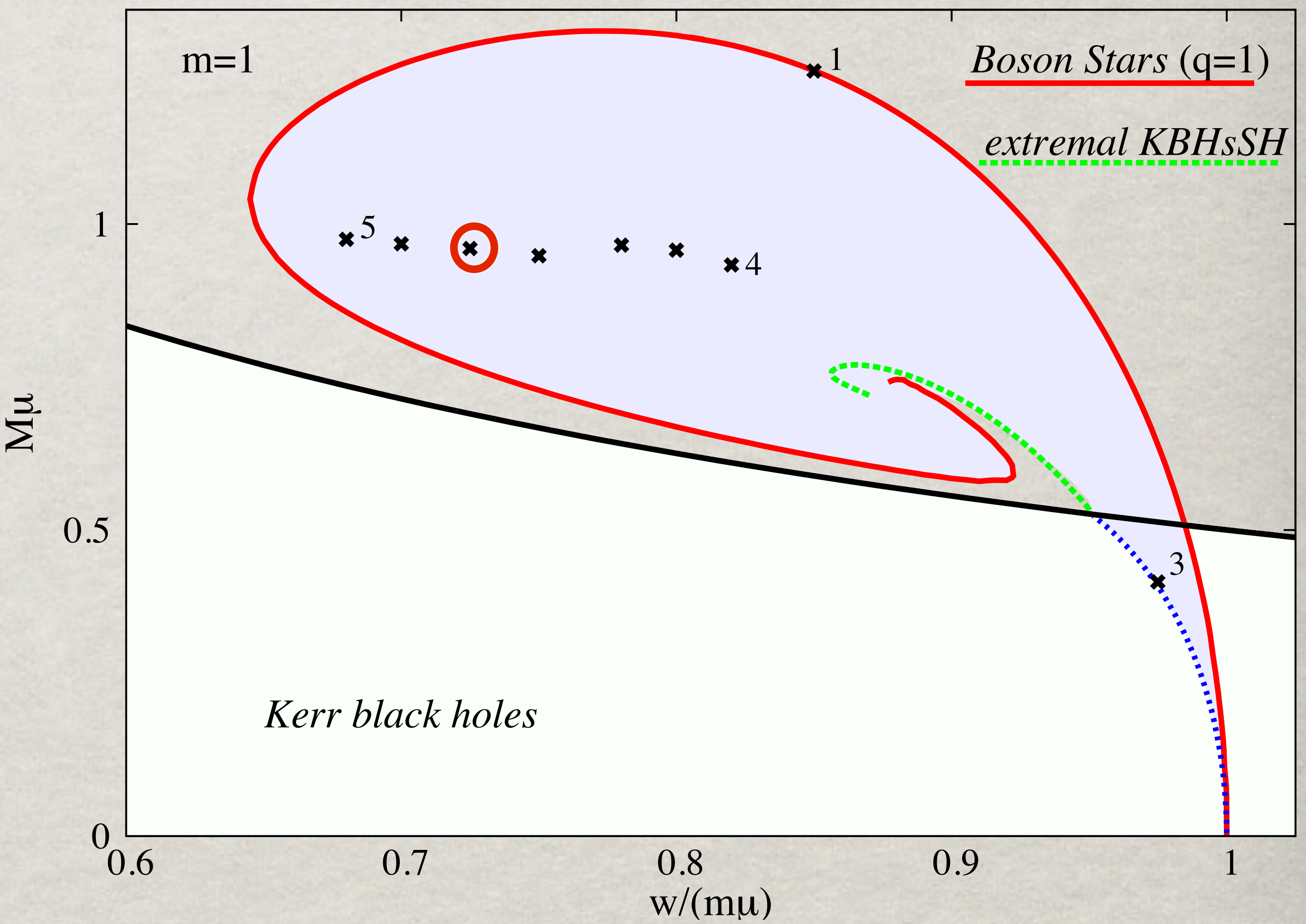
m=1
Boson Stars (q=1)
extremal KBHsSH
1
5
4
3
Kerr black holes
Mμ
w/(mμ)
0
0.5
1
0.6
0.7
0.8
0.9
1



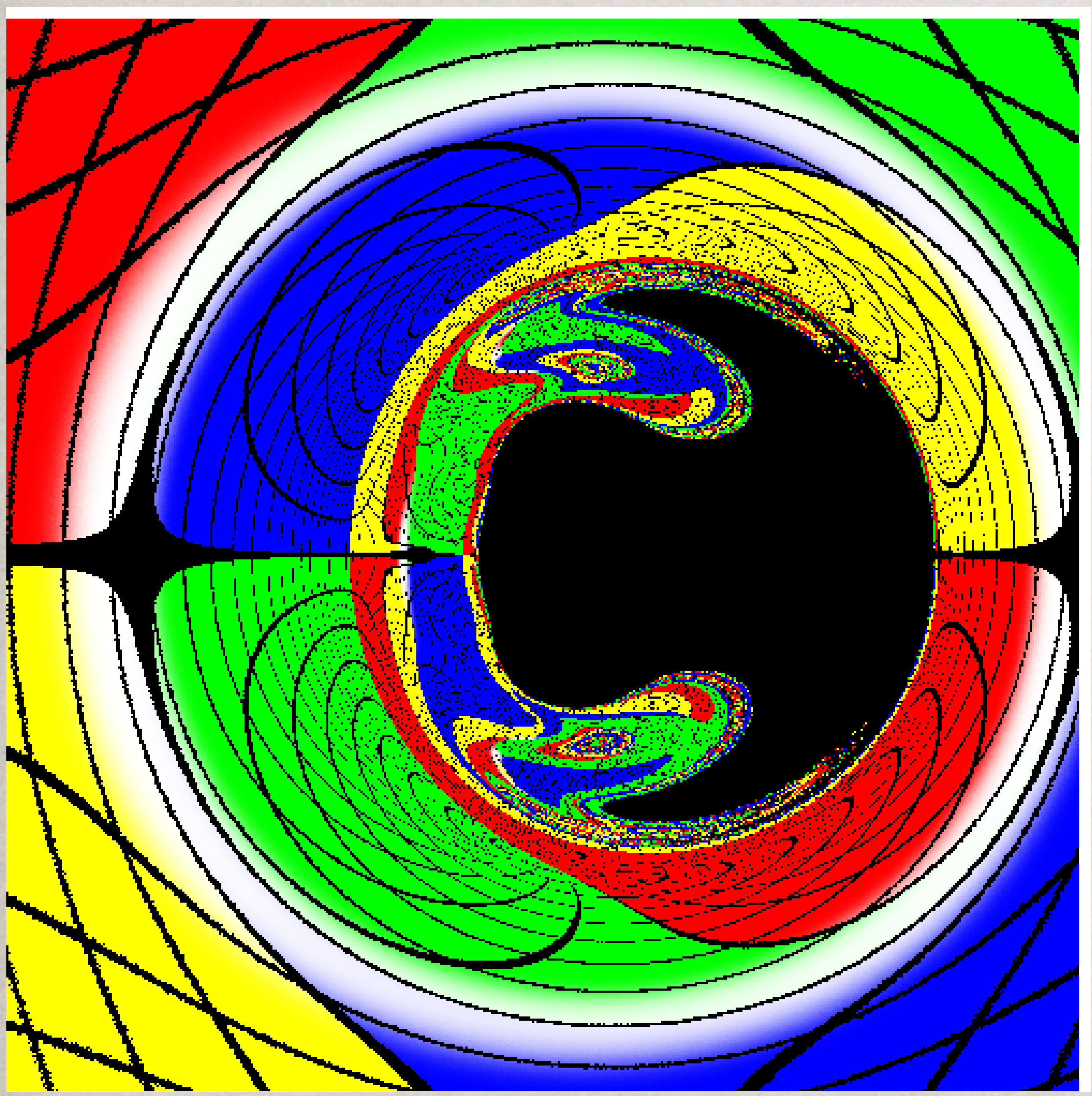


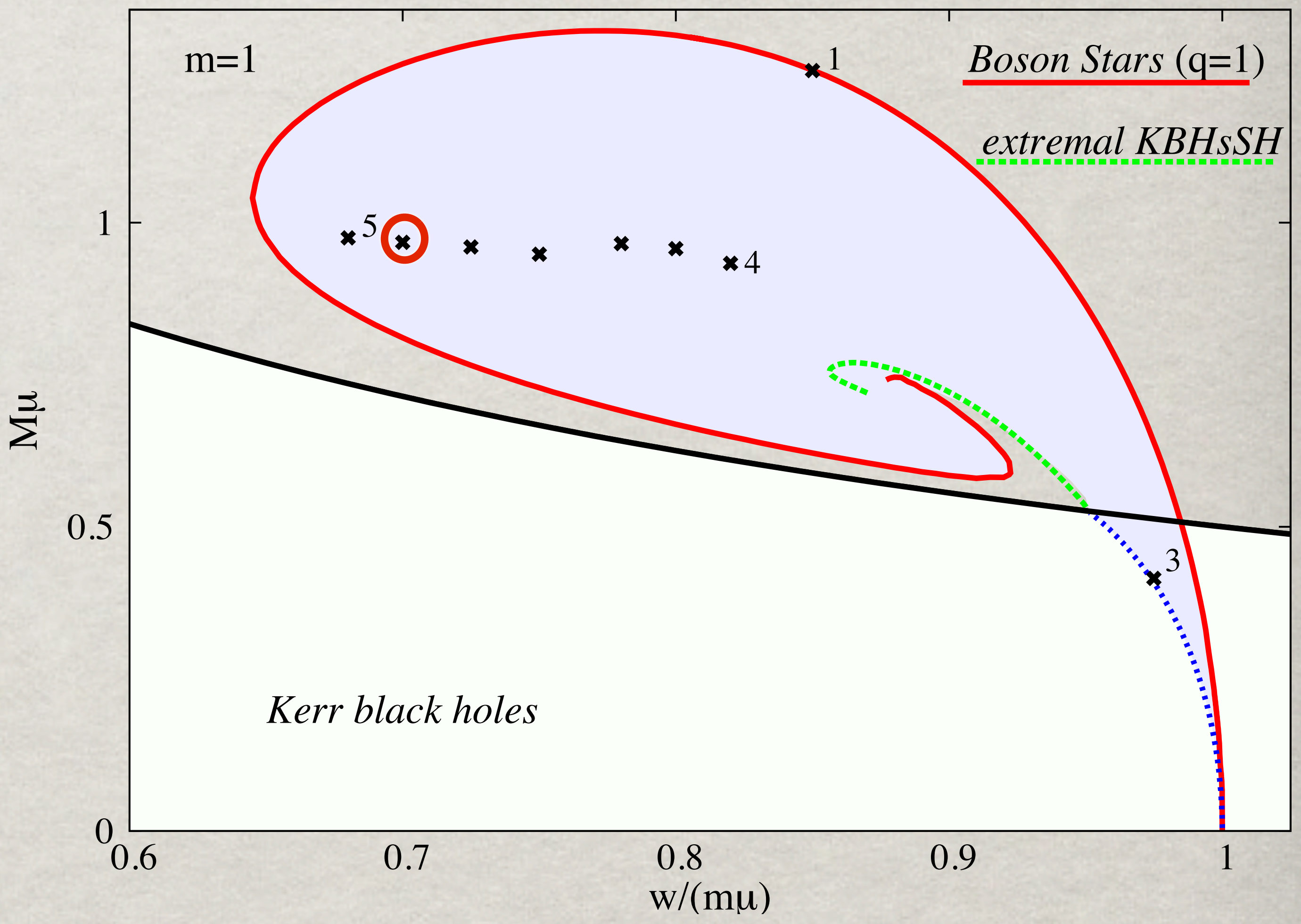
m=1
Boson Stars (q=1)
extremal KBHsSH
Kerr black holes
Mμ
w/(mμ)
0
0.5
1
0.6
0.7
0.8
0.9
1
1
3
4
5





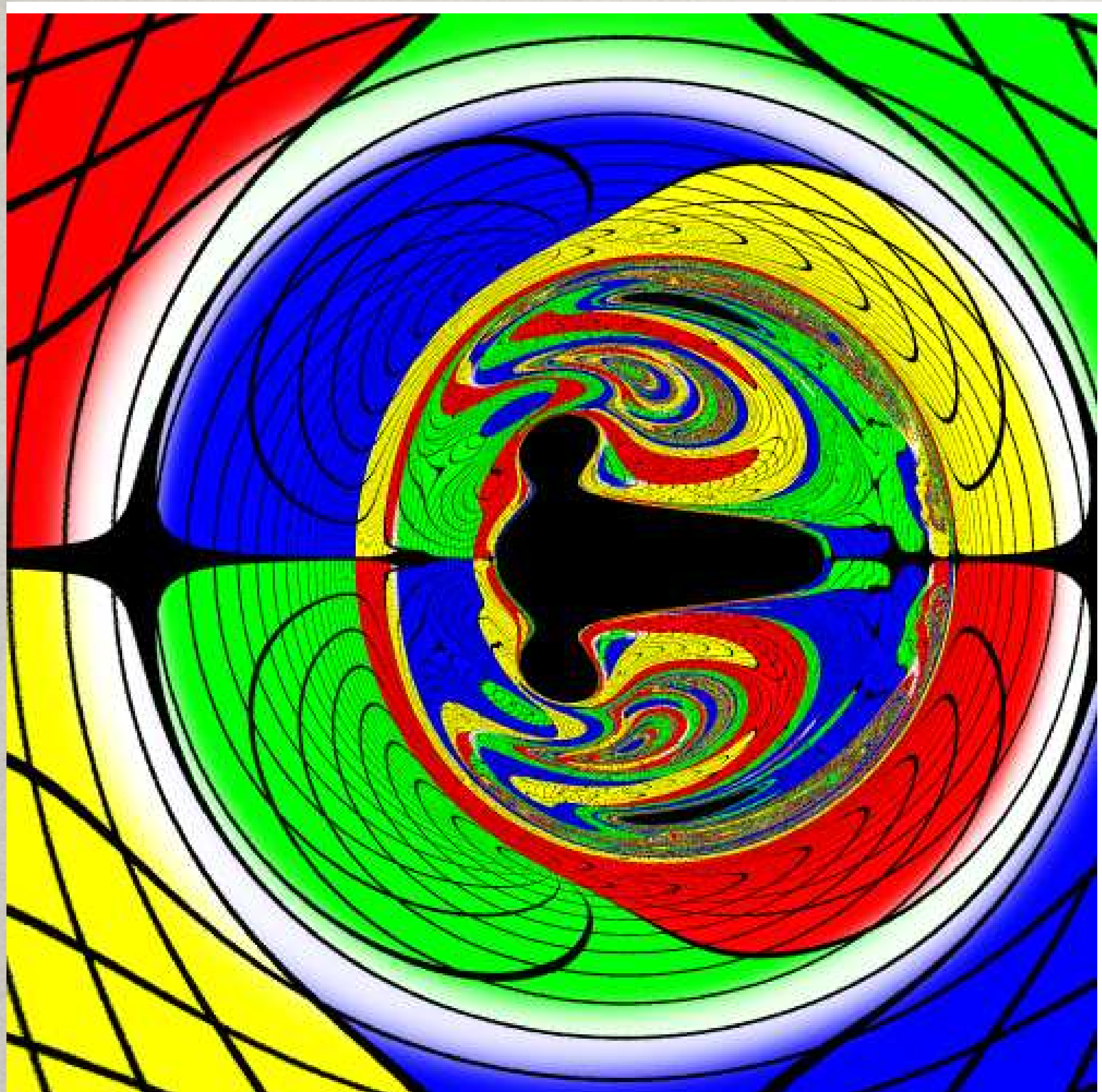
m=1
Boson Stars (q=1)
extremal KBHsSH
Kerr black holes
Mμ
w/(mμ)
1
3
4
5
0
0.5
1
0.6
0.7
0.8
0.9
1

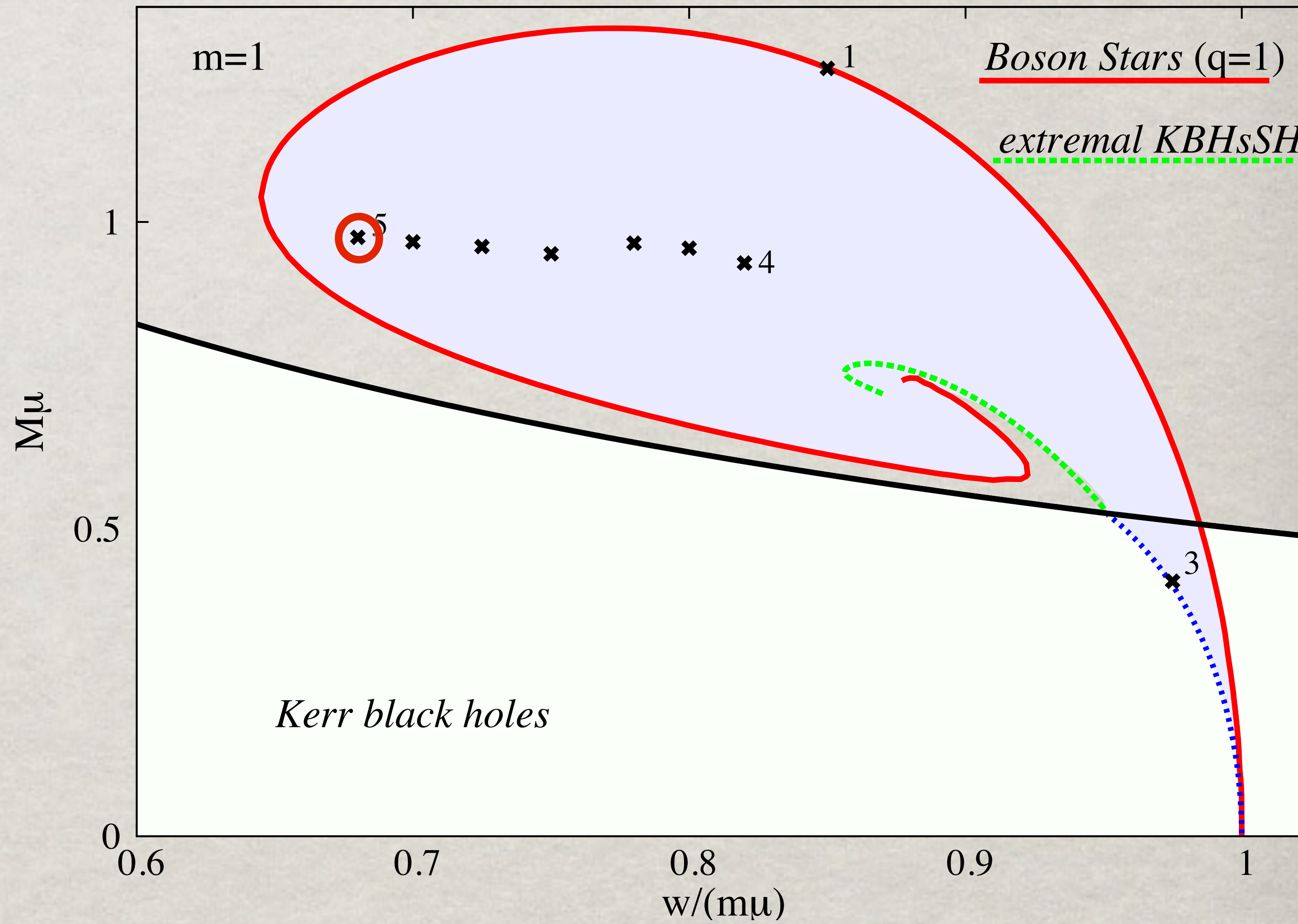




m=1
Boson Stars (q=1)
extremal KBHsSH
Kerr black holes
1
3
4
5
Mμ
w/(mμ)
0
0.5
1
0.6
0.7
0.8
0.9
1

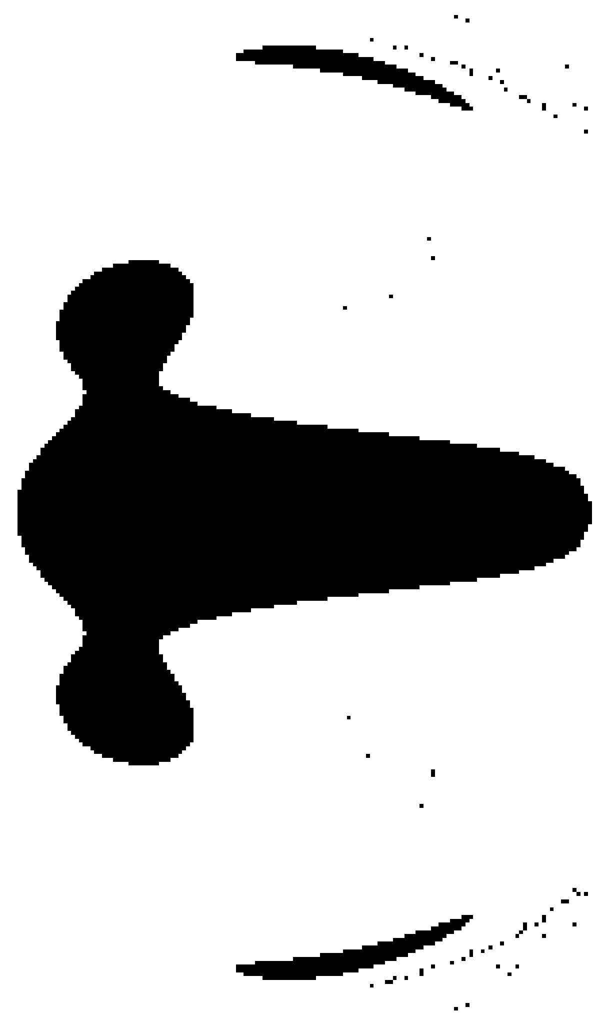
Hammer-like shadow:



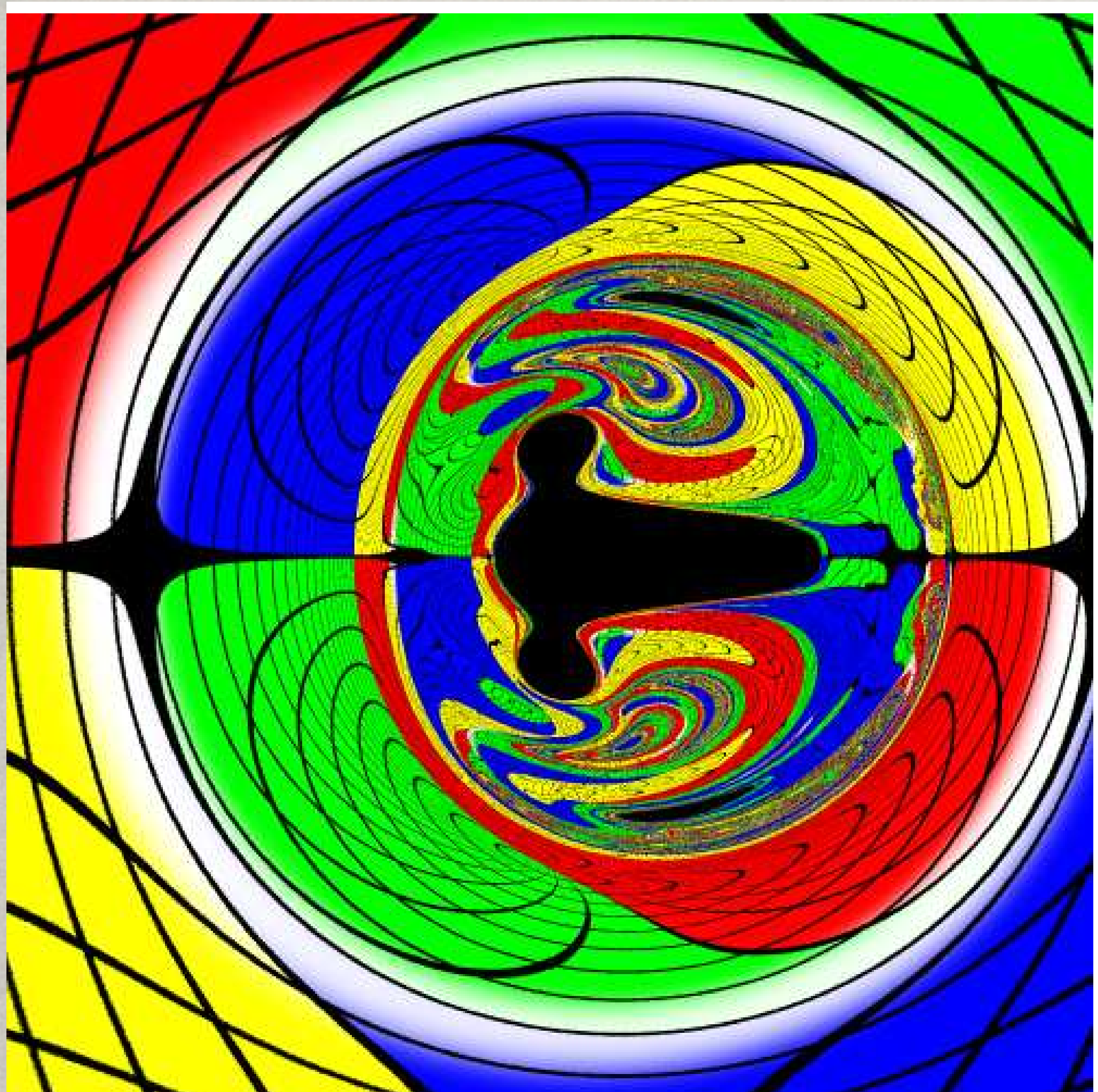


98.2% of mass;
97.6% of angular momentum
is stored in the scalar field

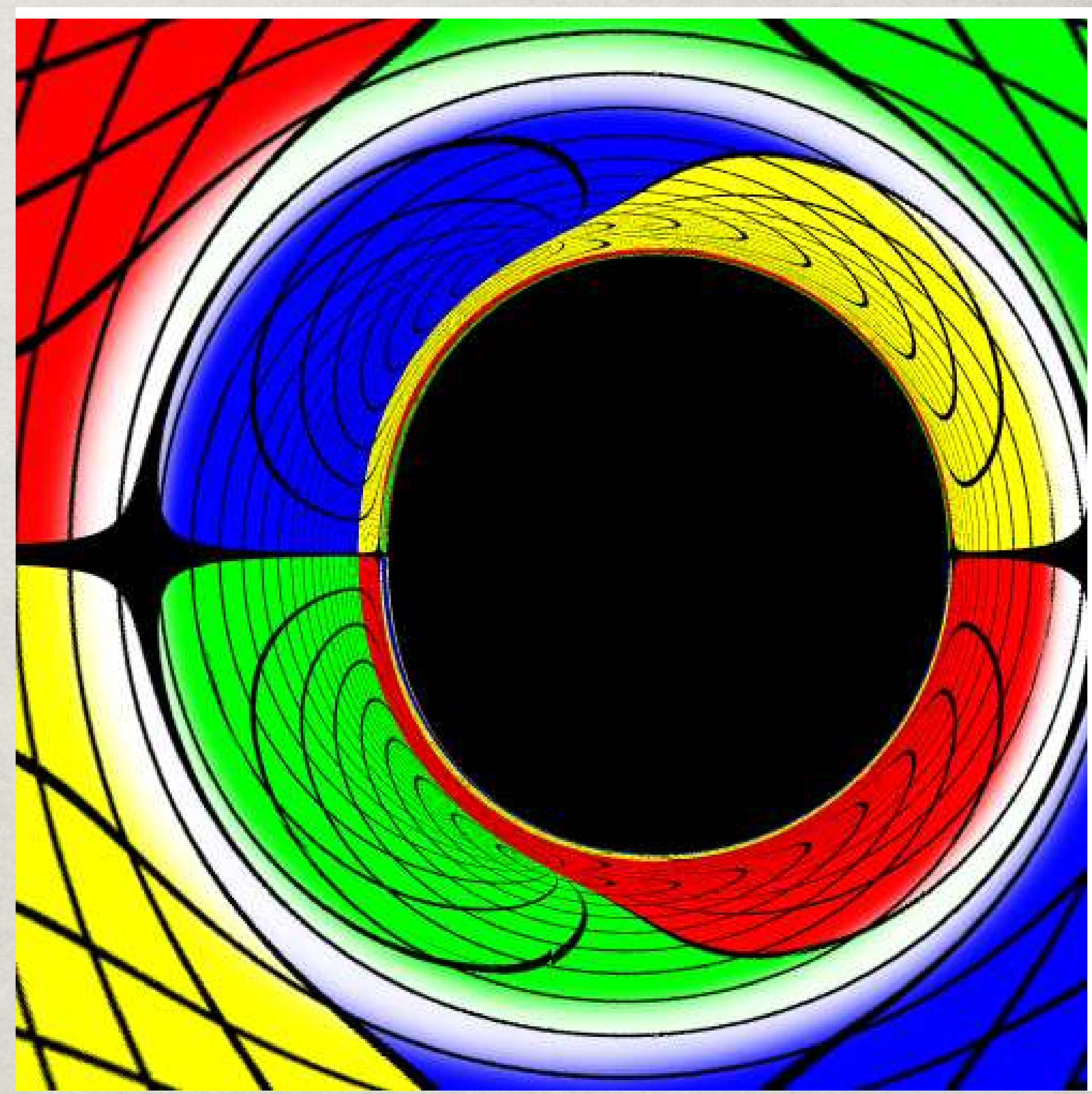
Qualitatively new feature:
multiple shadows of a single black hole



A very non-Kerr-like hairy black hole



Hairy BH:
M=0.018; J=0.002 (horizon)
M=0.957; J=0.848 (scalar field)



Vacuum Kerr BH
M=0.975; J=0.85

6) Outlook

Kerr black holes with scalar hair can provide remarkably different phenomenology,
and in particular
shadows
for a solution of General Relativity coupled to a simple matter system,
obeying all energy conditions.

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and in particular
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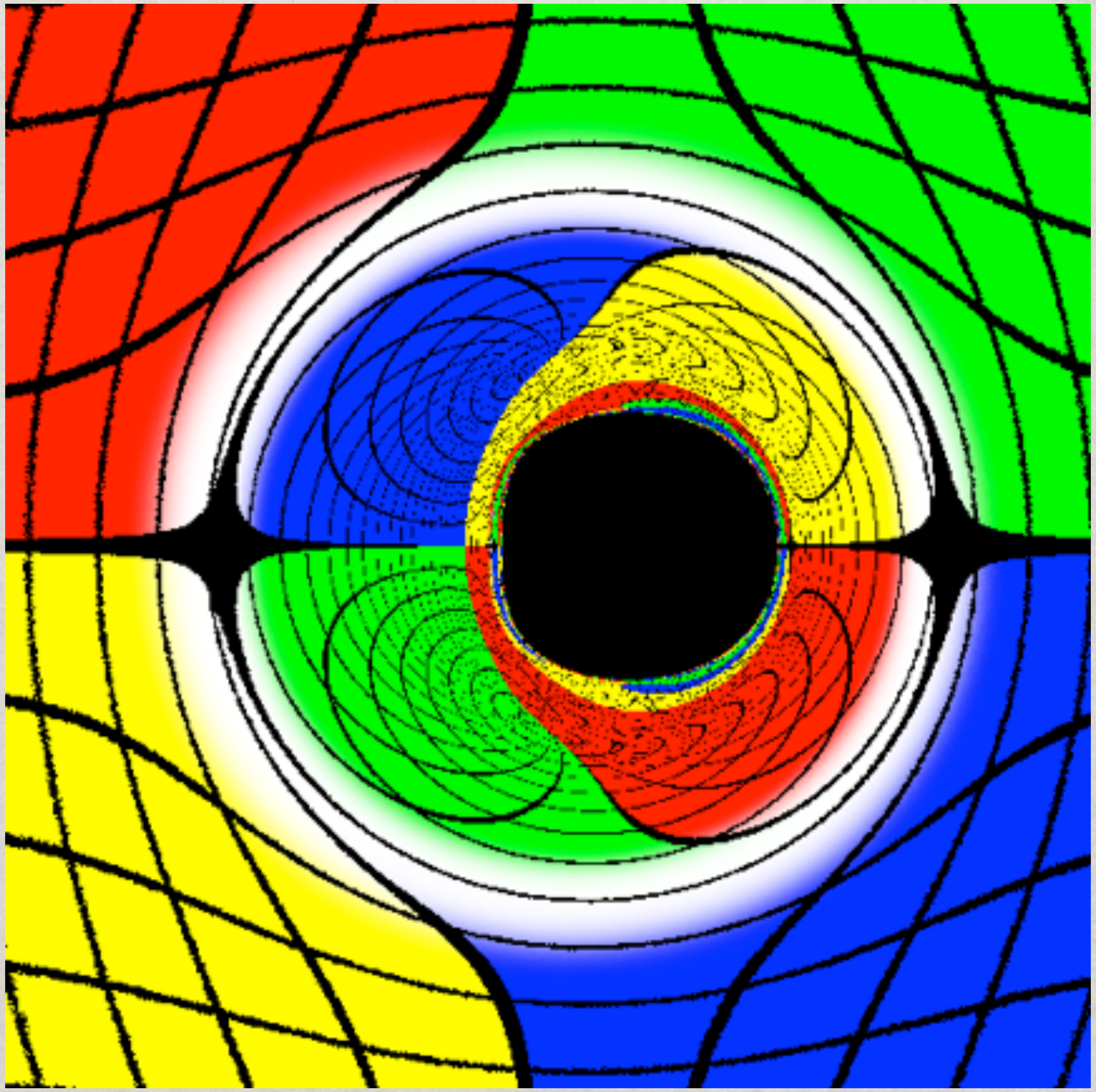

Movie by
Pedro Cunha

Thank you!