Marie Curie RISE Action

FunFiCO

(Fundamental Fields and Compact Objects)

Meeting at UNAM, Cuernavaca Campus, Mexico

April 16th 2018

Marie Curie RISE Actions within Horizon2020

(Research and Innovation Staff Exchange)

4 years project (Dec 2017 - Nov 2021)

Fundamental Fields and Compact Objects (FunFiCO)

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Partners (at kick off meeting, December 20th 2017, Aveiro, Portugal):

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Testing the Kerr hypothesis

C. Herdeiro
Departamento de Física da Universidade de Aveiro, Portugal

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

Marie Curie RISE Action FunFiCO Meeting

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The Kerr hypothesis

"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's field equations of general relativity, discovered by the New Zealand mathematician, Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the Universe."

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Some healthy skepticism:

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1) are these untold numbers of massive black holes exactly represented by the Kerr metric ?

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2) are these black holes all of the same type ?

3) are these objects really black holes ?

Plan:

1) The Kerr model (uniqueness and no-hair theorems)

2) Black holes beyond Kerr (Non-Kerr/hairy BHs)
  a) In General Relativity
  b) Beyond General Relativity

3) Beyond black holes: Exotic Compact Objects   Pedro Cunha's talk

4) Outlook

1) The Kerr Model

1967-....: **The electro-vacuum uniqueness theorems**

Axisymmetric Black Hole Has Only Two Degrees of Freedom

B. Carter
Institute of Theoretical Astronomy, University of Cambridge, Cambridge CB3 0EZ, England
(Received 18 December 1970)

A theorem is described which establishes the claim that in a certain canonical sense the Kerr metrics represent "the" (rather than merely "some possible") exterior fields of black holes with the corresponding mass and angular-momentum values.

Phys. Rev. Lett. 26 (1971) 331-333

Vacuum:

$$\mathcal{S} = \frac{1}{16\pi} \int d^4x \sqrt{-g} R$$

Kerr Kerr 1963

Uniqueness Israel 1967; Carter 1971; D.C. Robinson, Phys. Rev. Lett. 34, 905 (1975).

Carter-Robinson theorem:
An asymptotically-flat stationary and axi-symmetric vacuum spacetime that is non-singular on and outside an event horizon, is a member of the two-parameter Kerr family.

The assumption of axi-symmetry was subsequently shown to be unnecessary, i.e. for black holes, stationarity $\Rightarrow$ axisymmetry (via the "rigidity theorem", relating the teleologically defined "event horizon" to the local "Killing Horizon" Hawking 1972; I. Rácz and R.Wald, Class. Quant. Grav. 13 (1996) 539).

1971: **Wheeler and Ruffini coin the expression "a black hole has no hair"**

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; another, of the same mass, angular momentum, and charge, out of antimatter. No one has ever been able to propose a workable way to tell which is which. Nor is any way known to distinguish either from a third black hole, formed by collapse of a much smaller amount of matter and then built up to the specified mass and angular momentum by firing in enough photons, or neutrinos, or gravitons. And on an equal footing is a fourth black hole, developed by collapse of a cloud of radiation altogether free from any "matter."

Electric charge is a distinguishable quantity because it carries a long-range force (conservation of flux; Gauss's law). Baryon number and strangeness carry no such long-range force. They have no Gauss's law. It is true that no attempt to observe a change in baryon number has ever succeeded. Nor has anyone ever been able to give a convincing reason to expect a direct and spontaneous violation of the principle of conservation of baryon number. In gravitational collapse, however, that principle is not directly violated; it is transcended. It is transcended because in collapse one loses the possibility of measuring baryon number, and therefore this quantity can not be well defined for a collapsed object. Similarly, strangeness is no longer conserved.

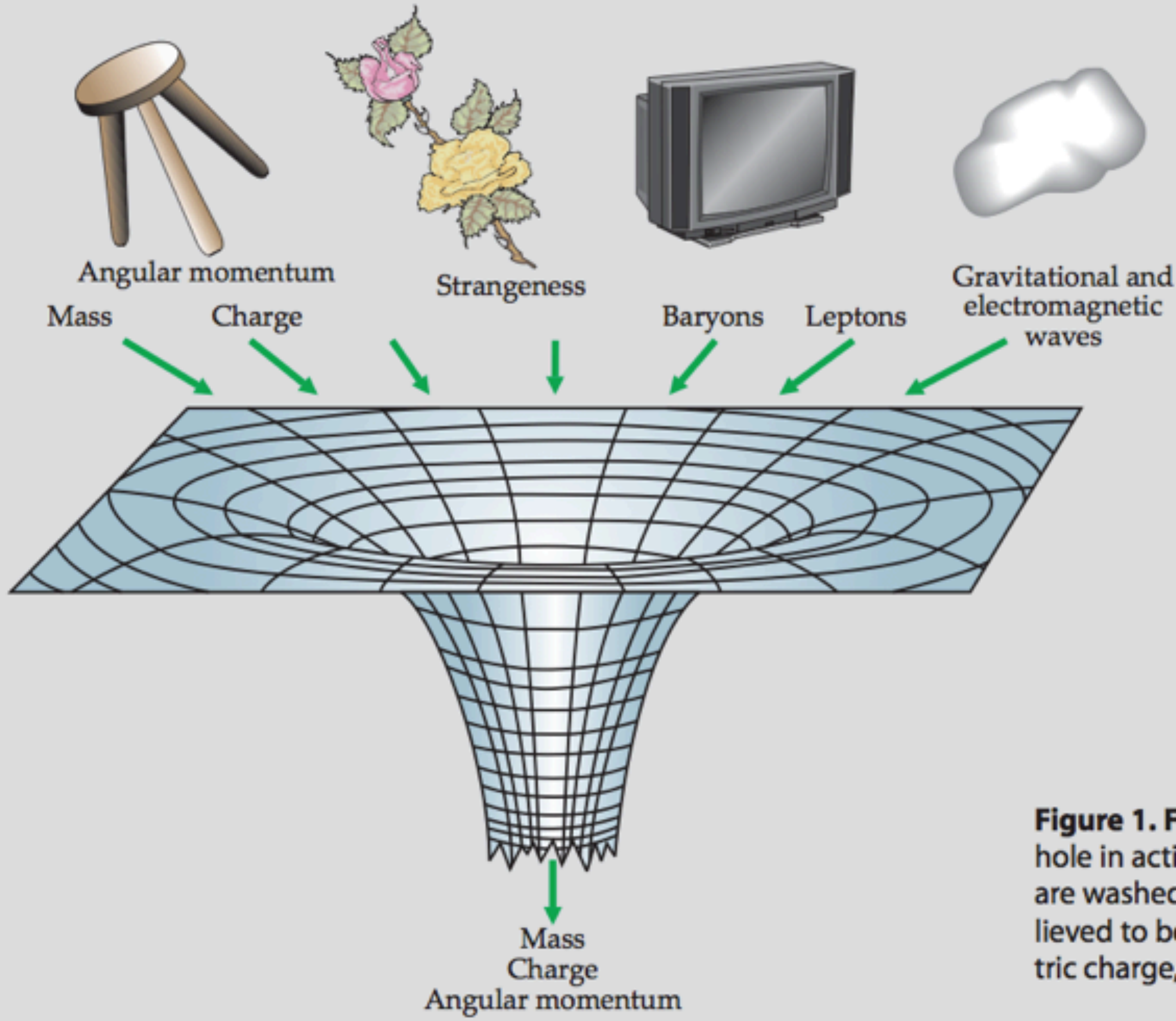

Figure 1. F
hole in acti
are washe
lieved to b
tric charge

R. Ruffini and John Wheeler, "Introducing the black hole", Physics Today, January 1971, Pages 30-41

The "no-hair" conjecture :

The "no-hair" original idea (1971):

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)

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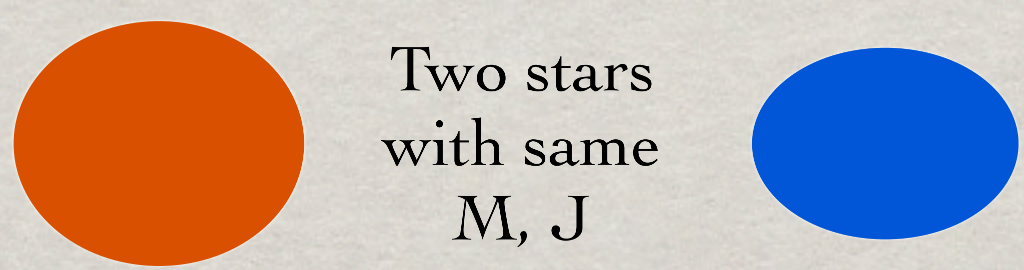
The idea is motivated by the uniqueness theorems and indicates black holes are very special objects



Can have a different mass quadrupole, etc...

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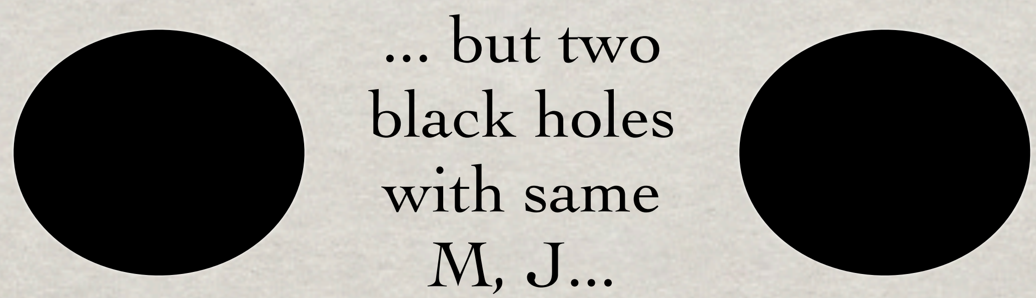

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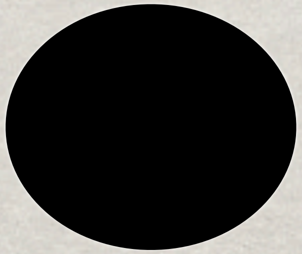
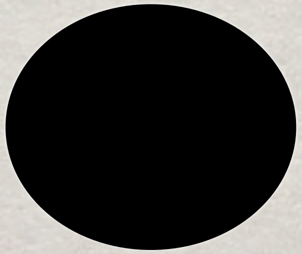


... but two black holes with same M, J...



...must be exactly equal...

Elegant multipoles formula (for the Kerr solution):
R. O. Hansen,
J. Math. Phys. 15 (1974) 46

$$M_\ell + iS_\ell = M(ia)^\ell$$

Kerr is not just the unique theoretical vacuum model; it is a <u>good</u> model:

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Three broad theoretical criteria for a <u>good</u> model of compact objects:

1) Appear in a well motivated and consistent physical model;

Kerr: General Relativity

2) Have a dynamical formation mechanism;

Kerr: gravitational collapse

Check list!

3) Be (sufficiently) stable.

Kerr: mode stability established (B. F. Whiting, J. Math. Phys. 30 (1989) 1301)

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Crucially, moreover, it must give the right phenomenology:

1) all electromagnetic observables
(X-ray spectrum, shadows, QPOs, star orbits,...);

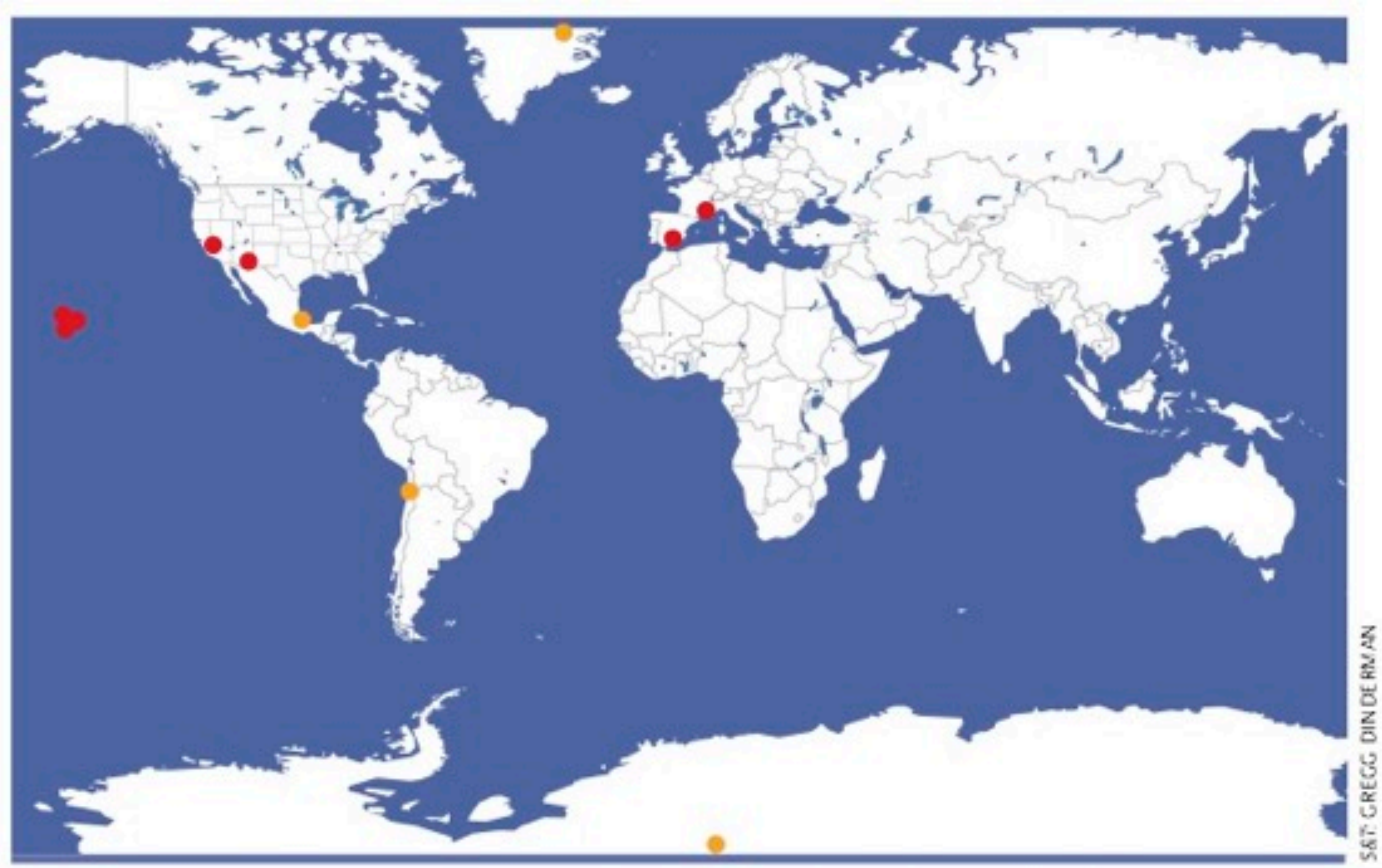
2) correct Gravitational wave templates

No clear tension between observations and the Kerr model

A key feature to assess the strong field phenomenology: Fundamental Photon orbits (define the black hole shadow)

First “image” of the black hole shadow may be around the corner:

EventHorizonTelescope



ALL OVER THE MAP Capturing a black hole takes a planet-sized telescope — or a planet covered in telescopes working together. Shown are the various international sites participating, or expected to participate, in Event Horizon Telescope observations.

Falcke, Melia, Agol, Astrophys. J. 528, L13 (2000);
A. E. Broderick and A. Loeb, MNRAS 367, 905 (2006);
S. Doeleman et al., 0906.3899

The edge of the shadow is determined by the **Fundamental Photon Orbits**

Cunha, C.H., Radu, PRD 96 (2017) 024039

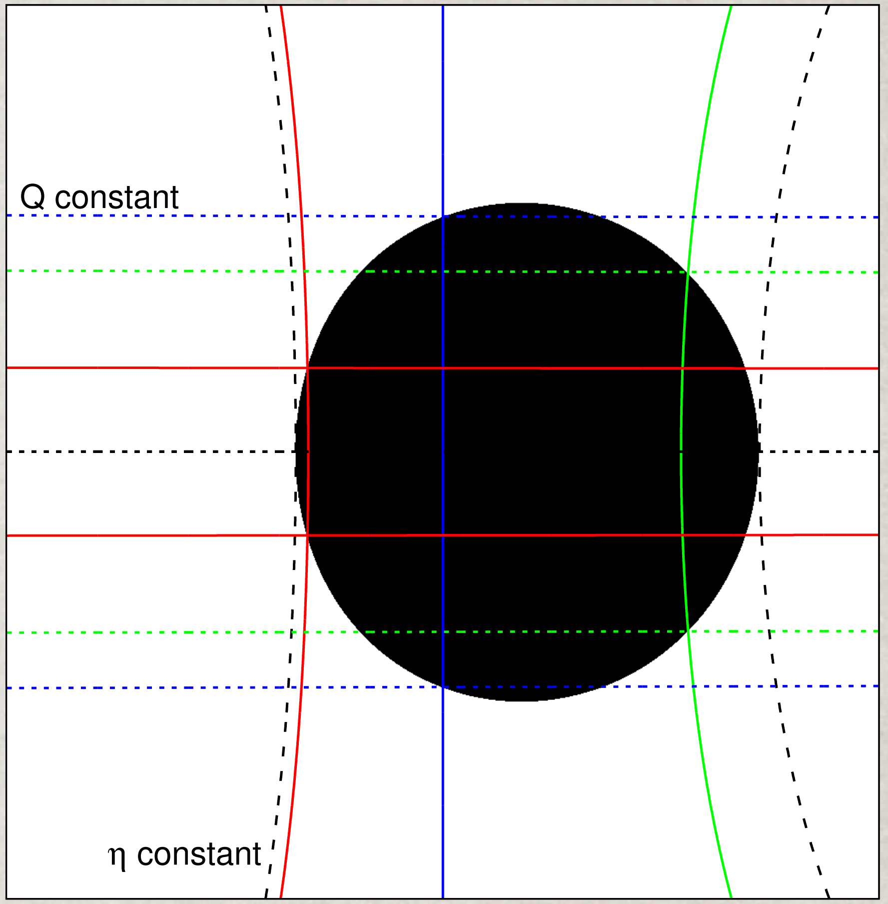
Called spherical orbits in Kerr case

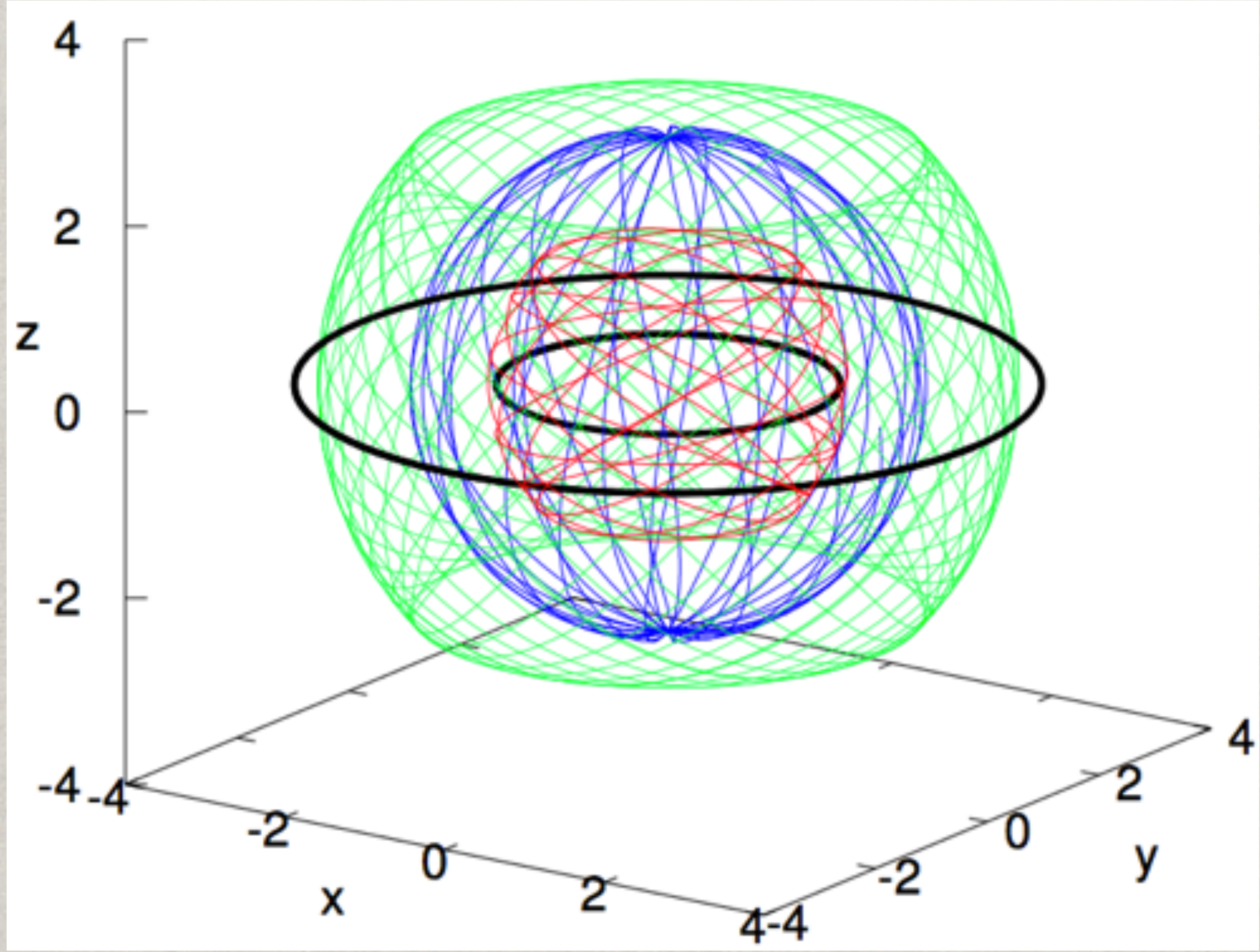
Teo, GRG 35 (2003) 1909

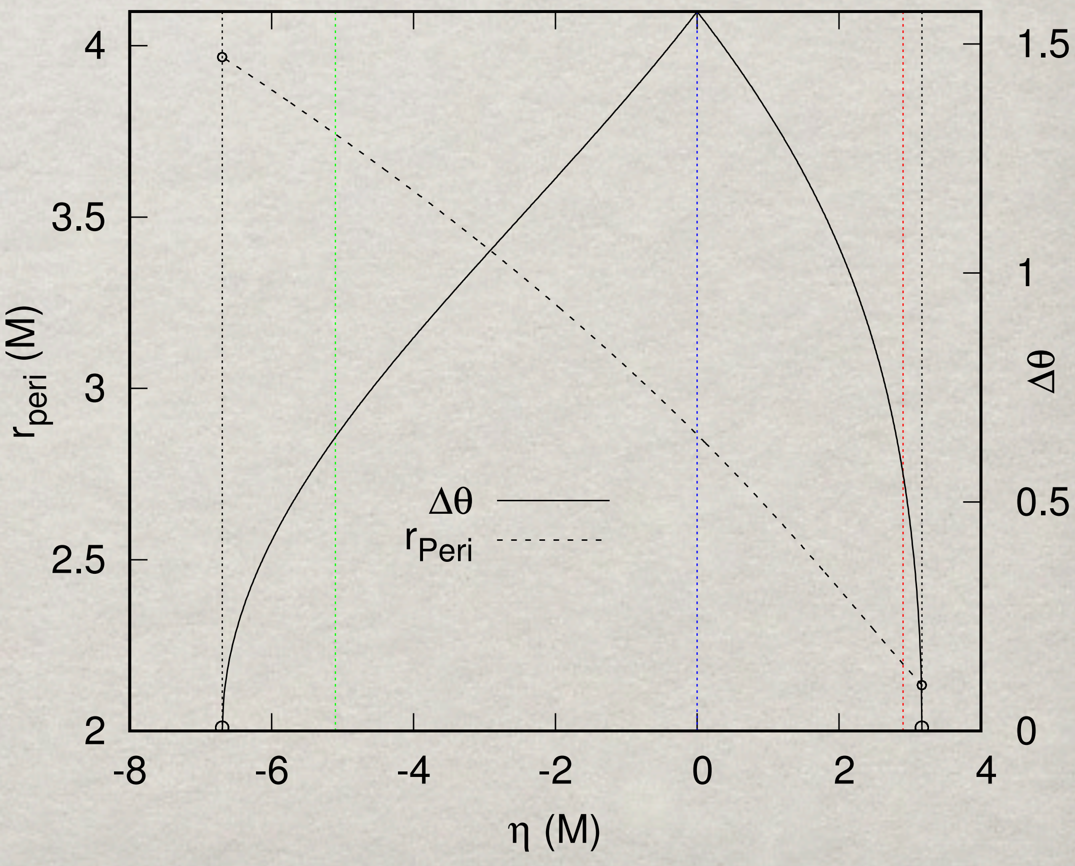
Relate to quasi-normal ringing

Goebel, Astrophys. J. 172 (1972) L95
Cardoso, Franzin and Pani, PRL 116 (2016) 171101

j~0.82







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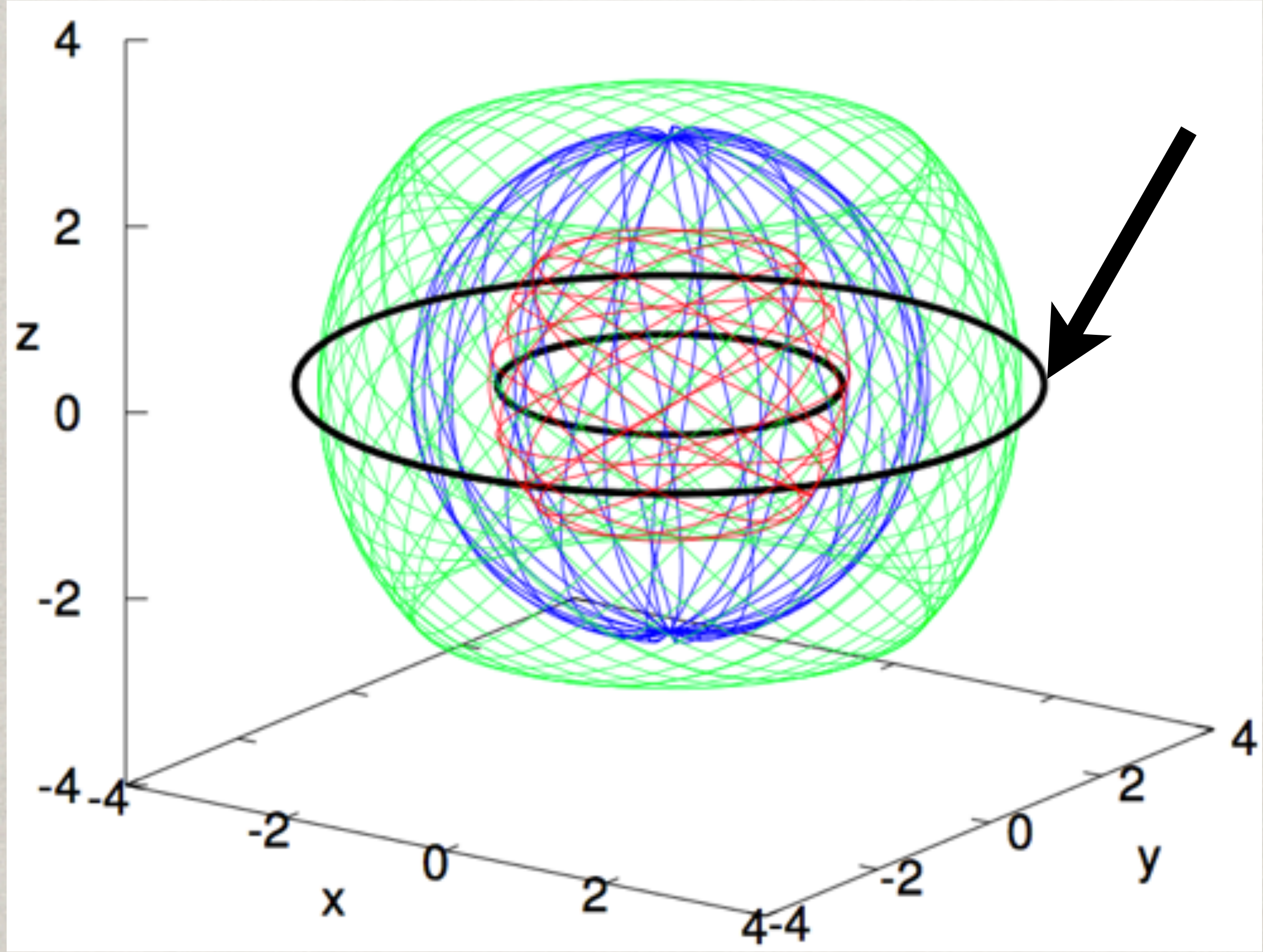

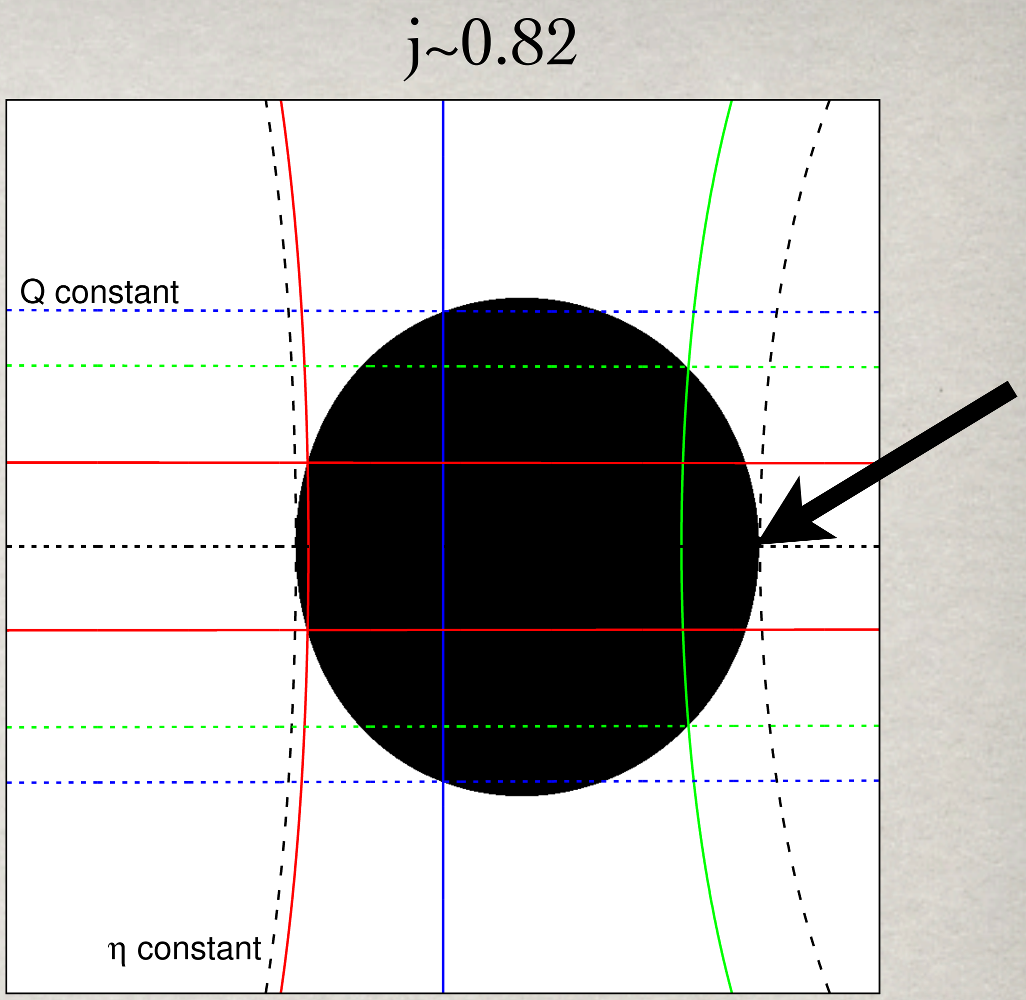

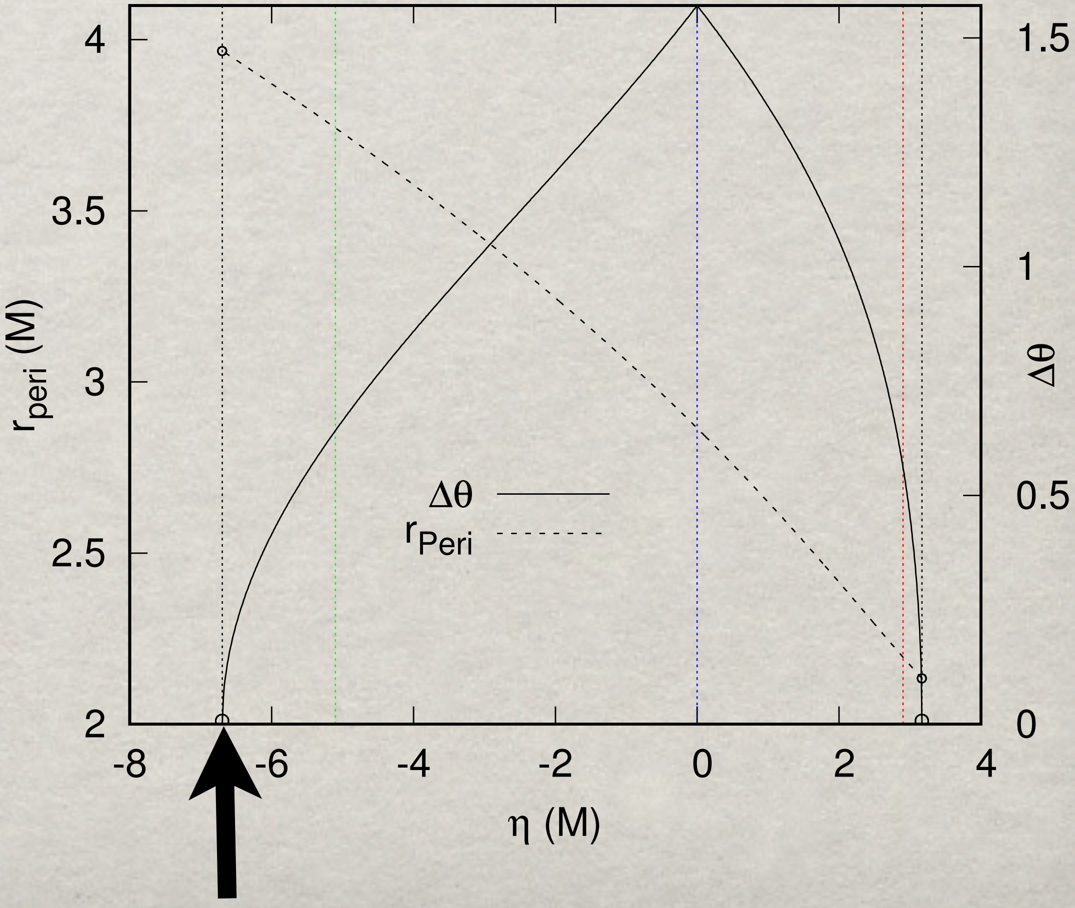

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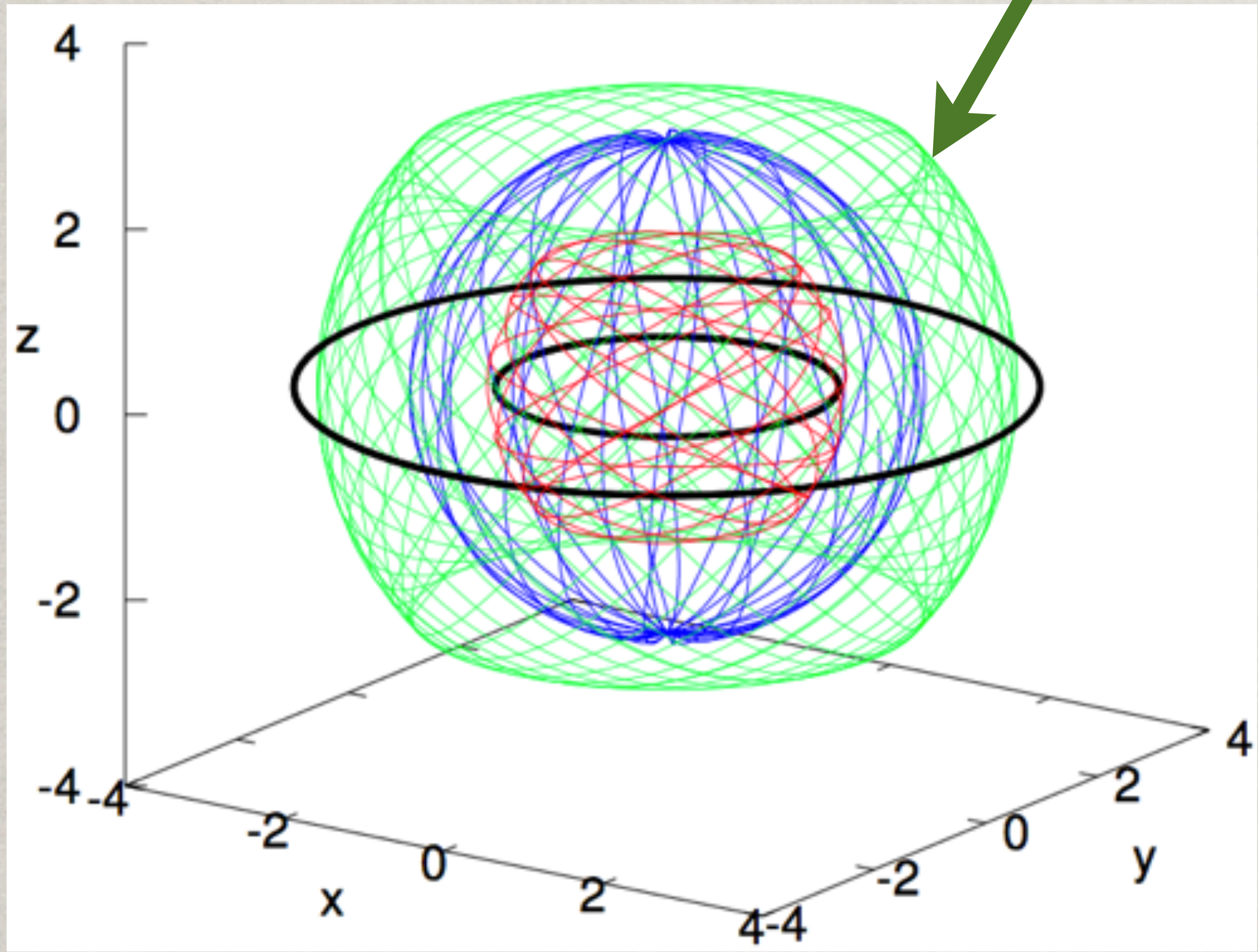

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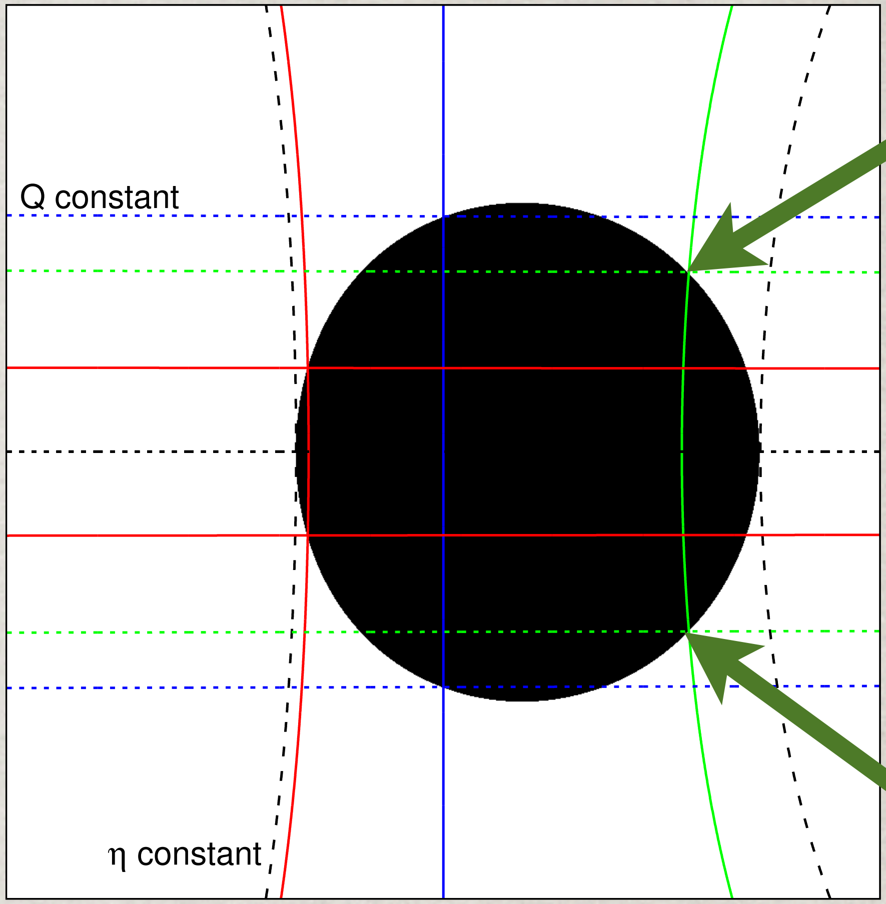

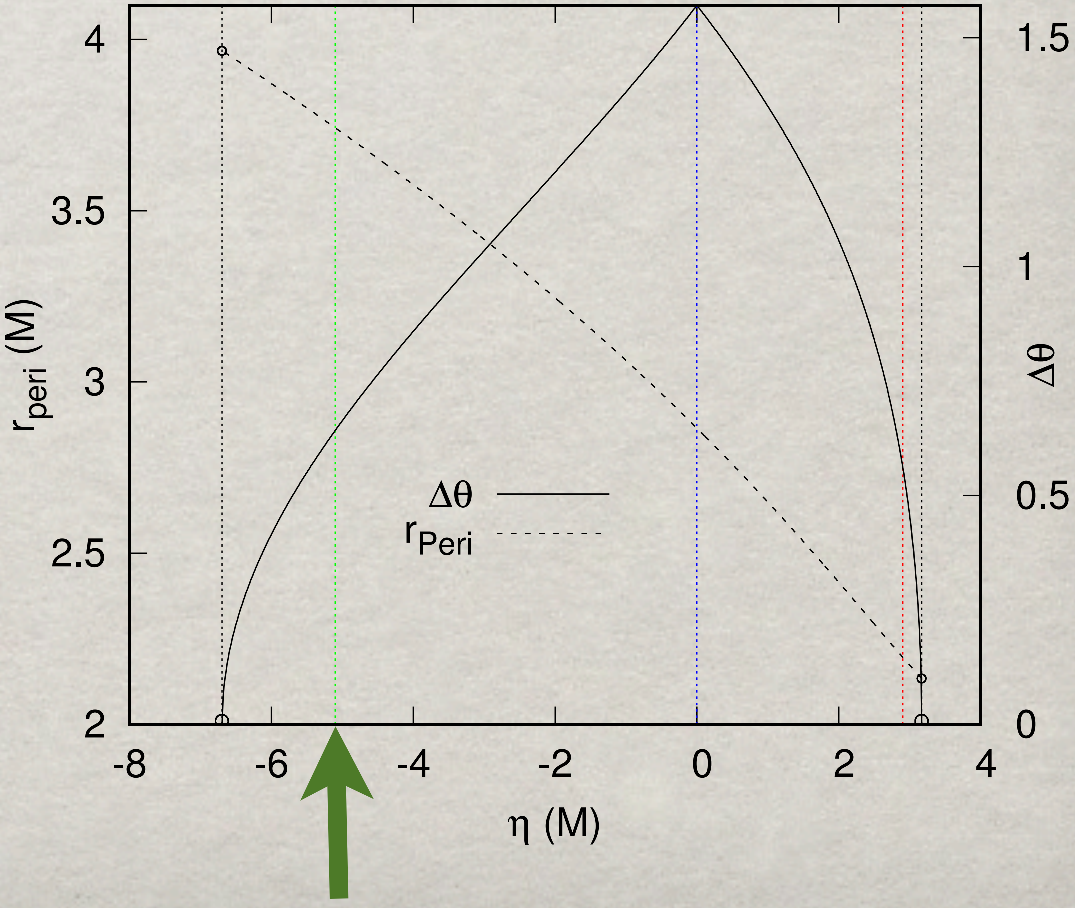

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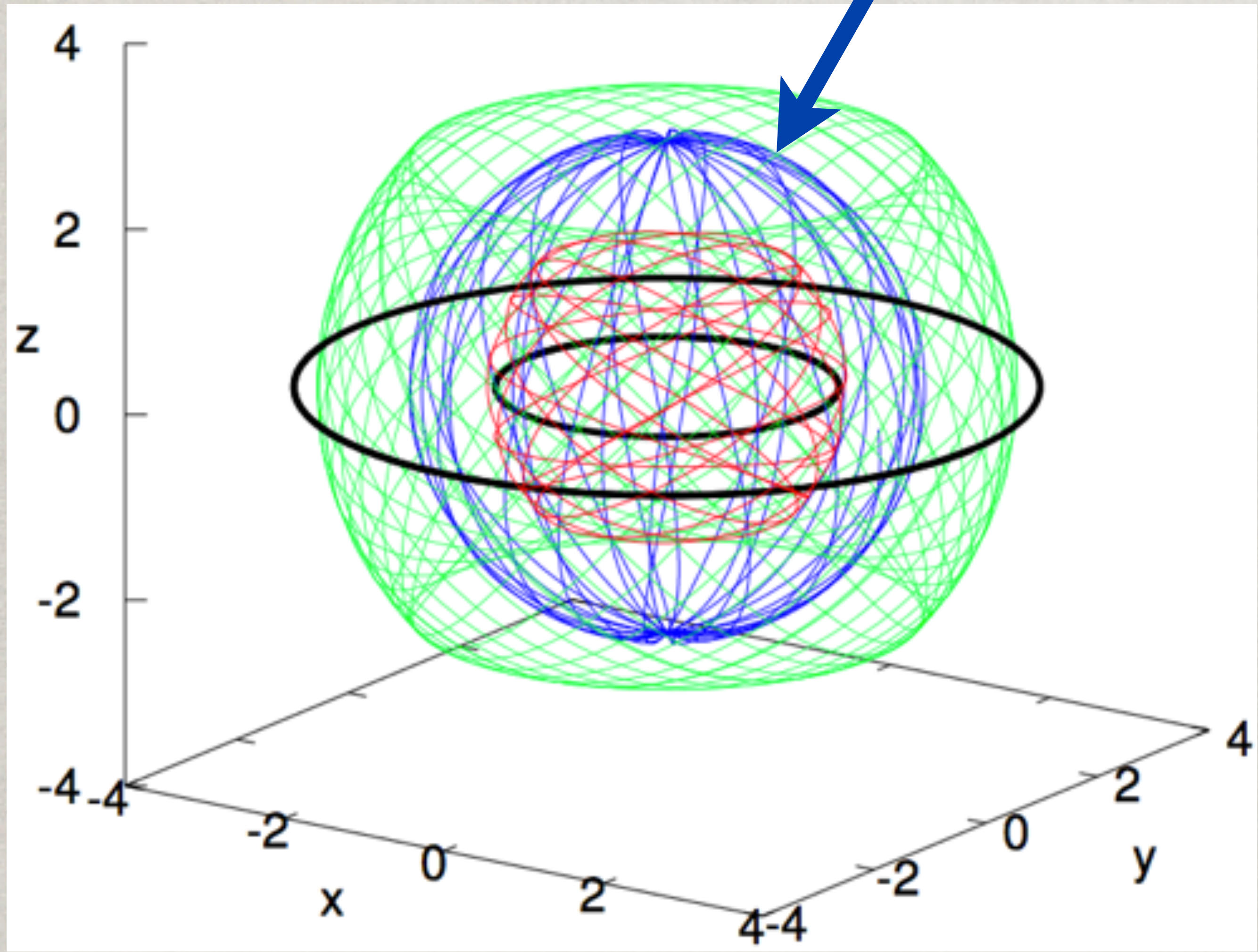

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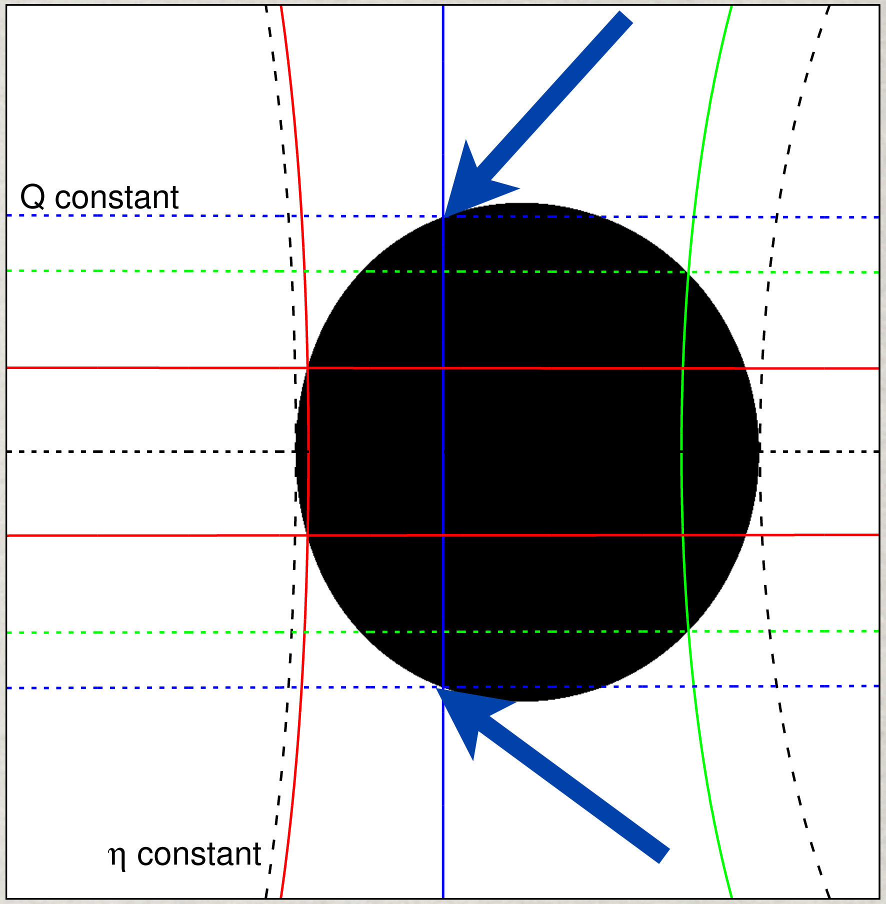

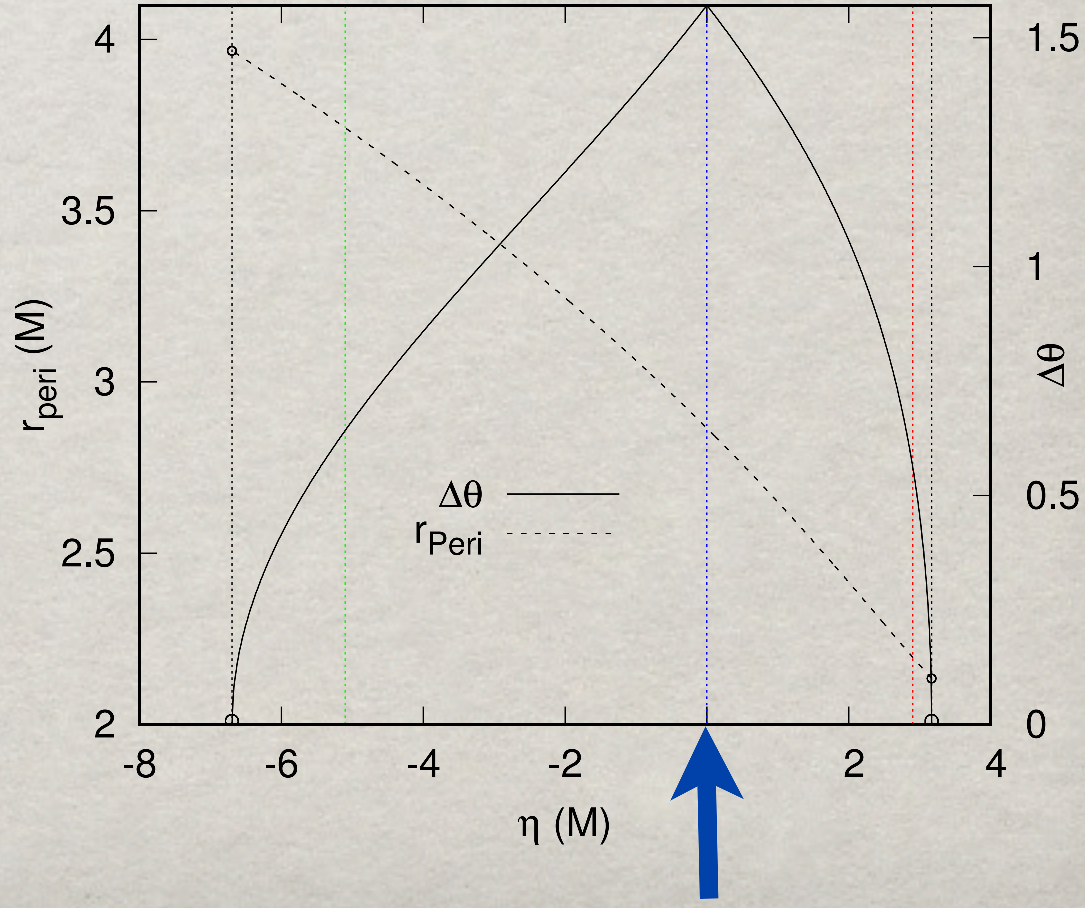

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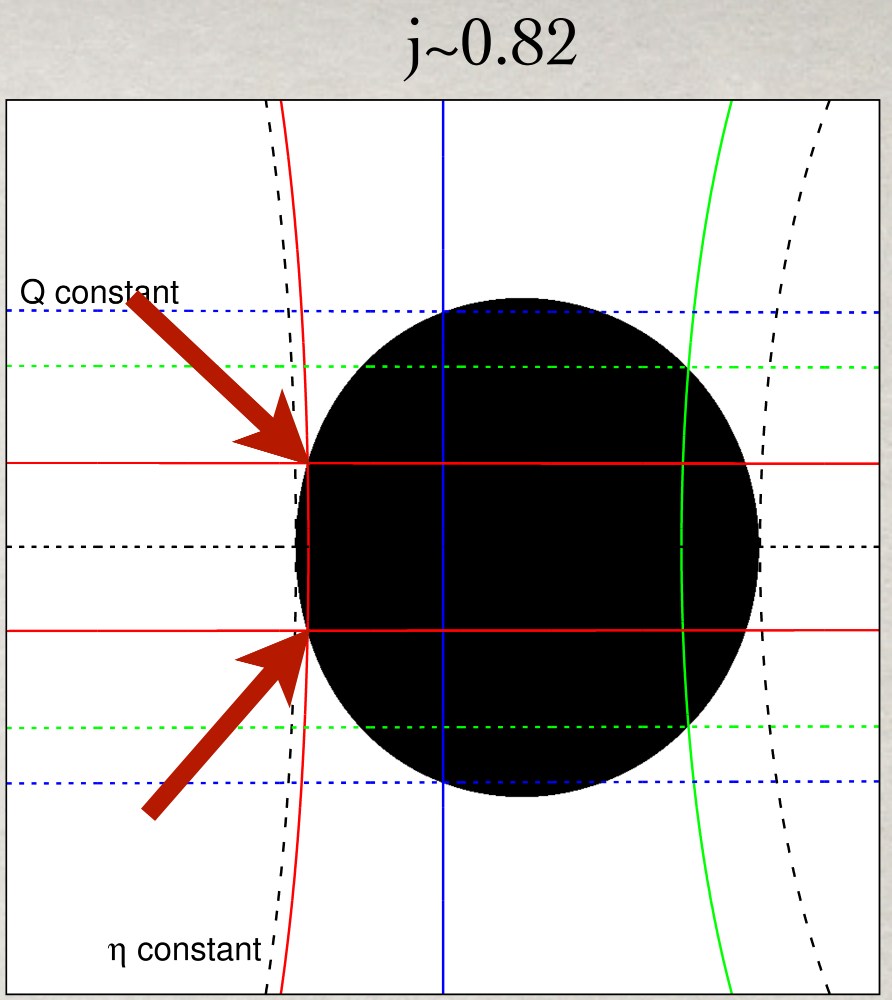

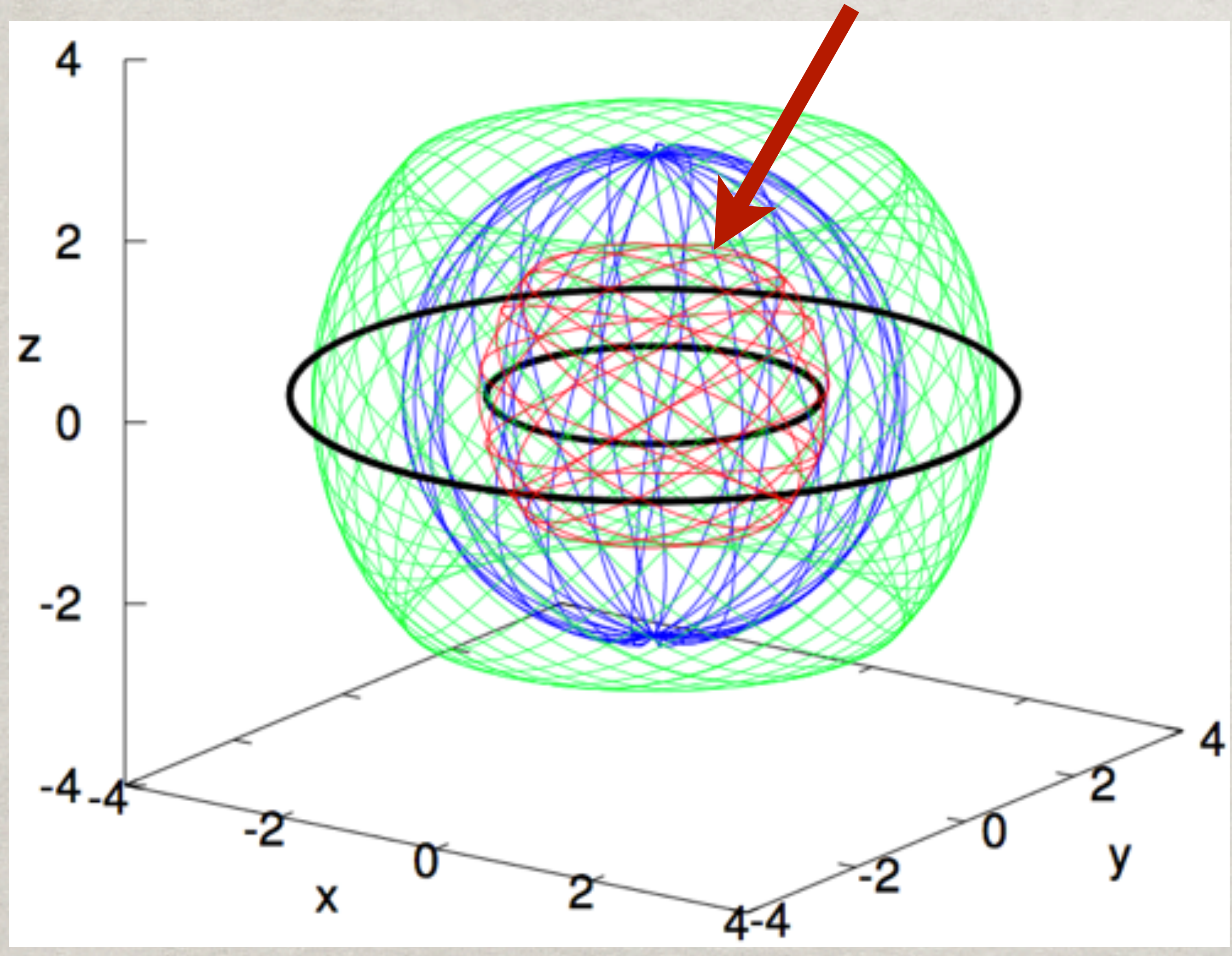

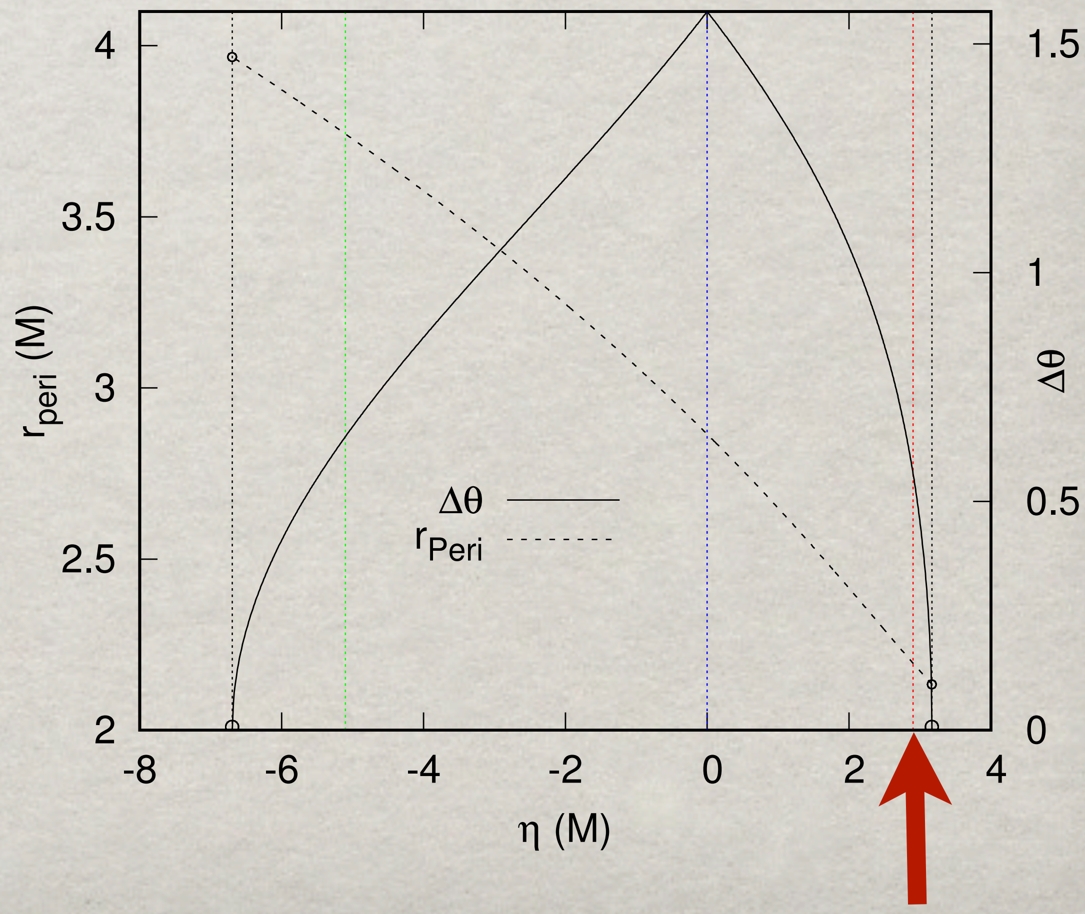

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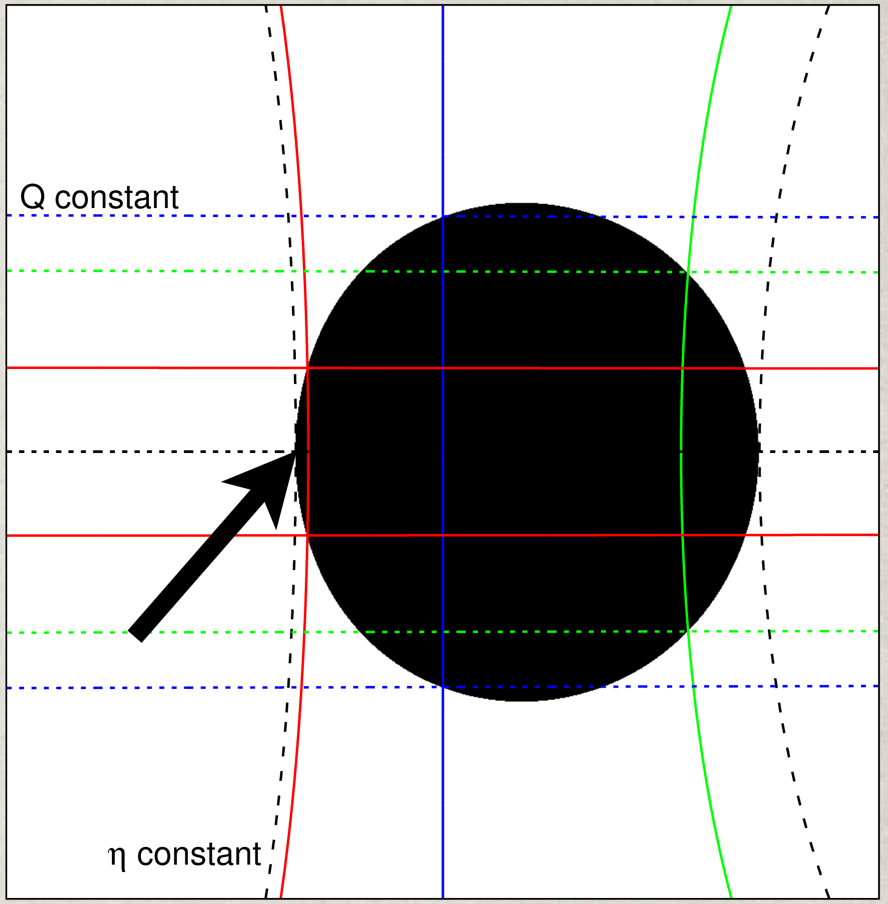

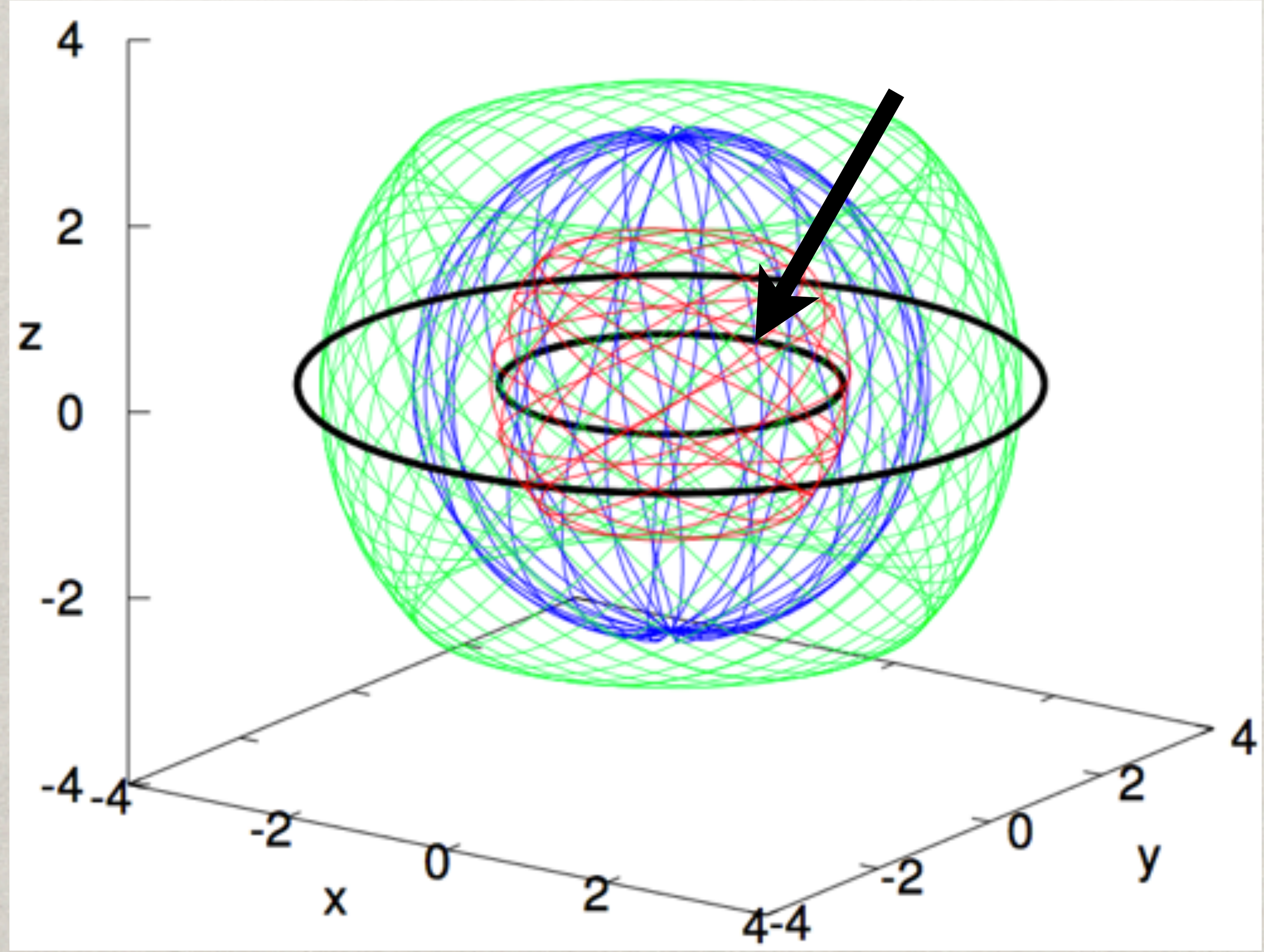

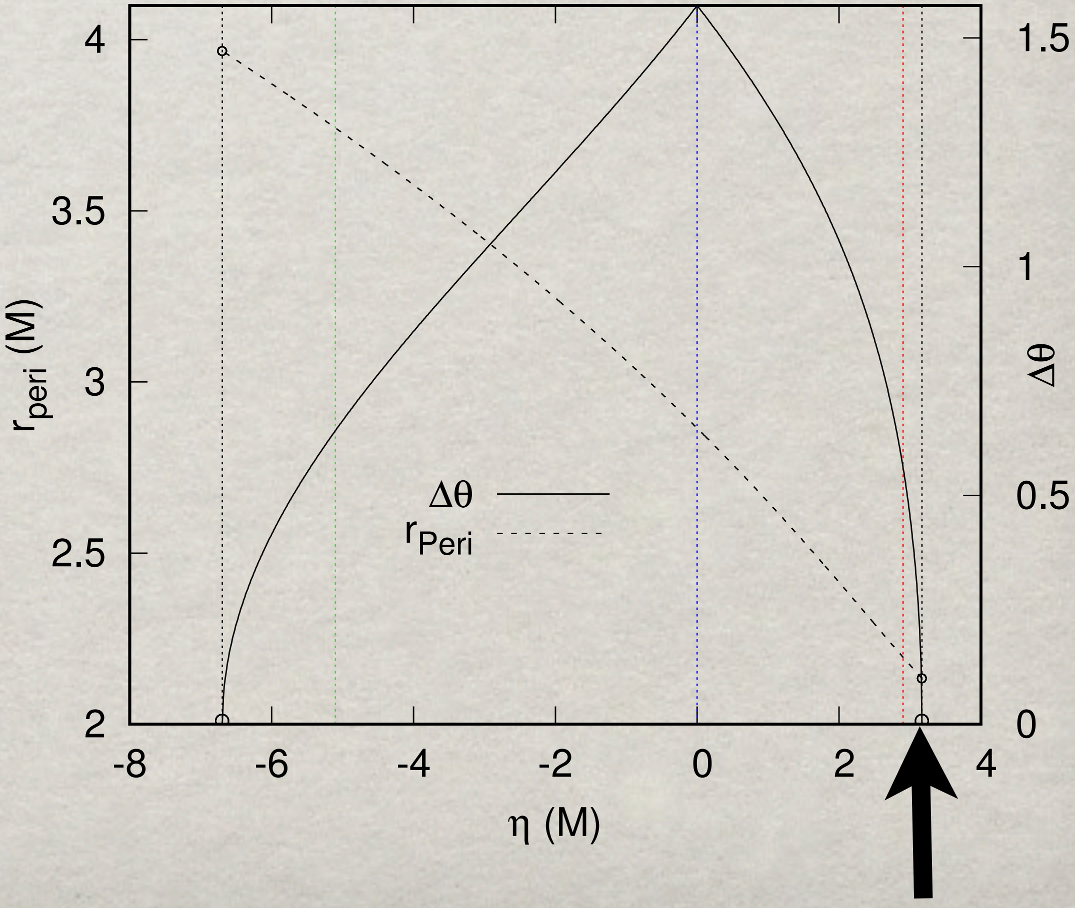

Are there other theoretically sound models
that have different black holes ?
How different from Kerr is the phenomenology?

Many no-scalar-hair theorems:

(only scalars, D=4, asymptotically flat)

Theory Lagrangian density $\mathcal{L}$	No-hair theorem	Known scalar hairy BHs with regular geometry on and outside $\mathcal{H}$ (primary or secondary hair; regularity)
Scalar-vacuum $\frac{1}{4}R - \frac{1}{2}\nabla_\mu\Phi\nabla^\mu\Phi$	Chase[22]	
Massive-scalar-vacuum $\frac{1}{4}R - \frac{1}{2}\nabla_\mu\Phi\nabla^\mu\Phi - \frac{1}{2}\mu^2\Phi^2$	Bekenstein[11]	
Massive-complex-scalar-vacuum $\frac{1}{4}R - \nabla_\mu\Phi^*\nabla^\mu\Phi - \mu^2\Phi^*\Phi$	Pena– –Sudarsky[61]	Herdeiro–Radu[136, 137] (primary, regular); generalizations:[159]
Conformal-scalar-vacuum $\frac{1}{4}R - \frac{1}{2}\nabla_\mu\Phi\nabla^\mu\Phi - \frac{1}{12}R\Phi^2$	Xanthopoulos– –Zannias[32] Zannias[33]	Bocharova–Bronnikov–Melnikov– –Bekenstein (BBMB)[16–18] (secondary, diverges at $\mathcal{H}$); generalizations:[87]
V-scalar-vacuum $\frac{1}{4}R - \frac{1}{2}\nabla_\mu\Phi\nabla^\mu\Phi - V(\Phi)$	Heusler[46, 47, 50] Bekenstein[26] Sudarsky[51]	Many, with non-positive definite potentials:[71–75, 78–80] (typically secondary, regular)
P-scalar-vacuum $\frac{1}{4}R + P(\Phi, X)$	Graham– –Jha[62]	
Einstein-Skyrme $\frac{1}{4}R - \frac{1}{2}\nabla_\mu\Phi^a\nabla^\mu\Phi^a$ $-\kappa\vert\nabla_{[\mu}\Phi^a\nabla_{\nu]}\Phi^b\vert^2$		Droz–Heusler–Straumann[126] (primary but topological; regular); generalizations:[129, 131]
Scalar-tensor theories $\varphi\hat{R} - \frac{\omega(\varphi)}{\varphi}\hat{\nabla}_\mu\varphi\hat{\nabla}^\mu\varphi - U(\varphi)$	Hawking[27] Saa[34, 35] Sotiriou– –Faraoni[31]	
Horndeski/Galileon theories Full $\mathcal{L}$ in eq. (41)	Hui– –Nicolis[45]	Sotiriou-Zhou[43] (secondary; regular) Babichev–Charmousis[88, 90] (secondary[88] or primary,[90] diverges at $\mathcal{H}^+$ or $\mathcal{H}^-$); generalizations:[91–93]

CH, Radu,
IJMPD 24(2015)1542014

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GR example

beyond GR example

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CH, Radu,
IJMPD 24(2015)1542014

2) Black Holes beyond Kerr

a) In General Relativity

Massive-complex-scalar-vacuum:

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

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 relativistic Bose-Einstein condensates (boson stars)
- with an independent scalar charge (primary hair)
- Can form dynamically and be sufficiently long lived

Black Holes with synchronised hair

CH and Radu, PRL112(2014)221101

a) In General Relativity

Massive-complex-scalar-vacuum:

New scale
could single out
BHs of a certain size
to become "hairy"

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$-V(|\Phi|)$

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- continuously connected to relativistic Bose-Einstein condensates (boson stars)
- with an independent scalar charge (primary hair)
- Can form dynamically and be sufficiently long lived

Black Holes with synchronised hair

CH and Radu, PRL112(2014)221101

a) In General Relativity

Massive-complex-scalar-vacuum:

New scale
could single out
BHs of a certain size
to become "hairy"

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

$$-V(|\Phi|) = -\lambda\Phi^4$$

CH, Radu, Rúnarsson, PRD92(2015)084059

There are BH solutions:

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

also
Kleihaus, Kunz and Yazadjiev
PLB744(2015)406

which are:

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Black Holes with synchronised hair
CH and Radu, PRL112(2014)221101

Existence proof
Chodosh and Shlapentokh-Rothman,
CMP356(2017)1155

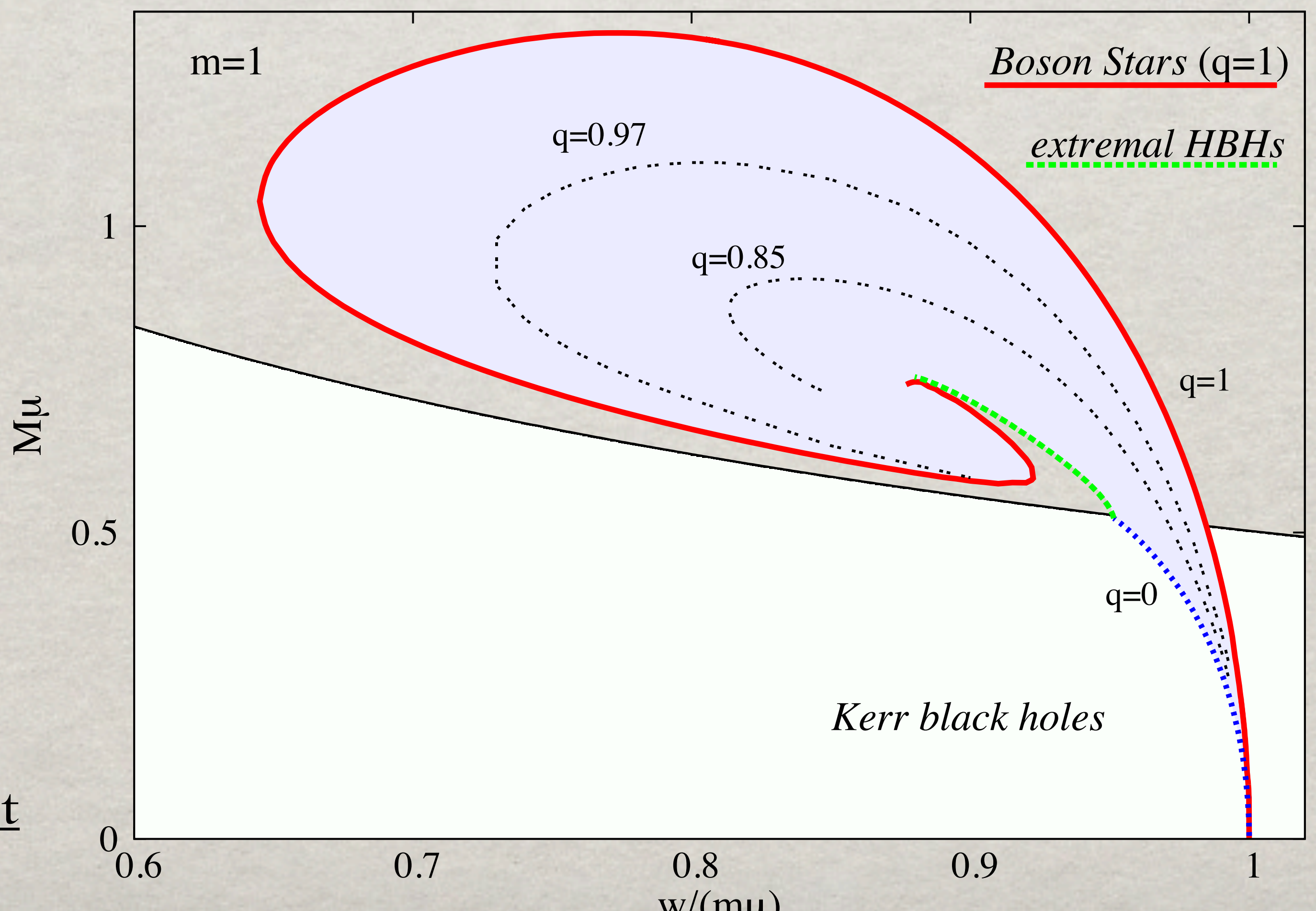
Black holes with synchronised scalar hair

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

Ansatz:

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

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



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

"synchronisation" condition

Data available online at:
http://gravitation.web.ua.pt

Can they form dynamically ?

Formation from Kerr

In the presence of these ultra-light fields,
vacuum Kerr black holes are **unstable**
(against superradiance).

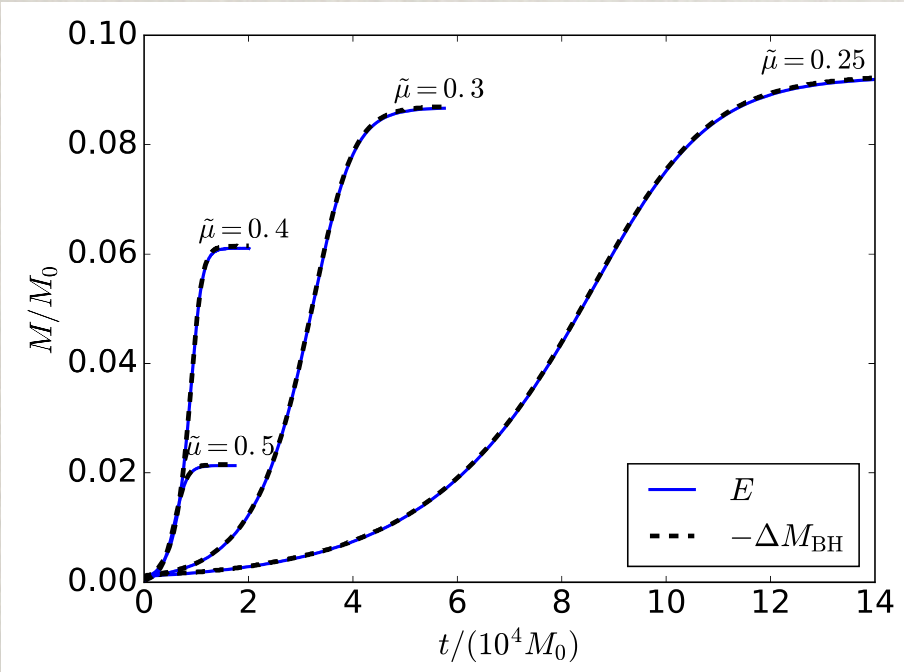
The instability is most efficient when the
Compton wavelength ~ Schwarzschild radius.

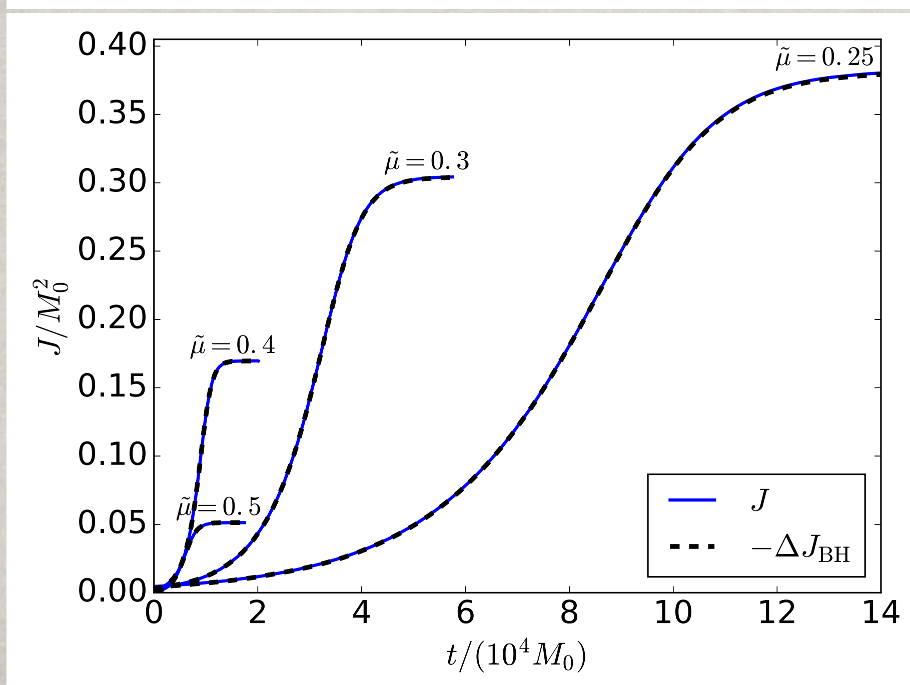
What is the endpoint of this instability?

Recent dynamical evidence (for the cousin Proca model) shows the process reaches an equilibrium state…

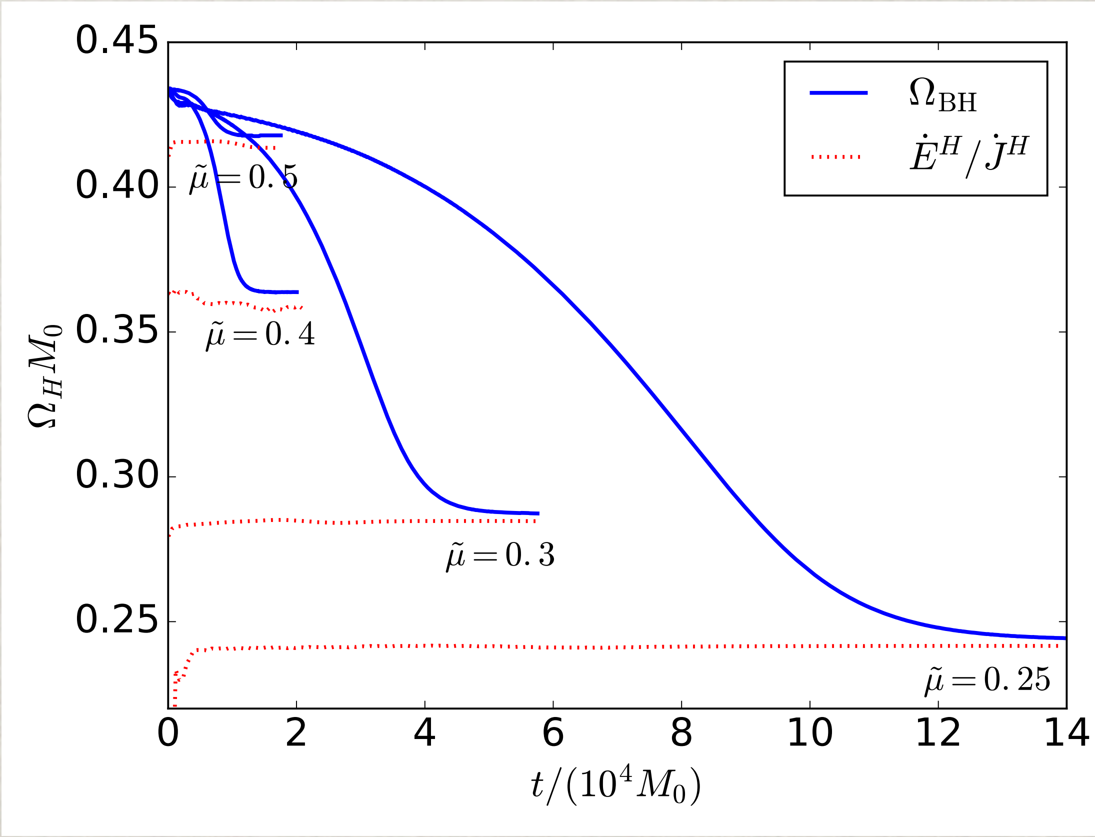
East and Pretorius, PRL119(2017)041101

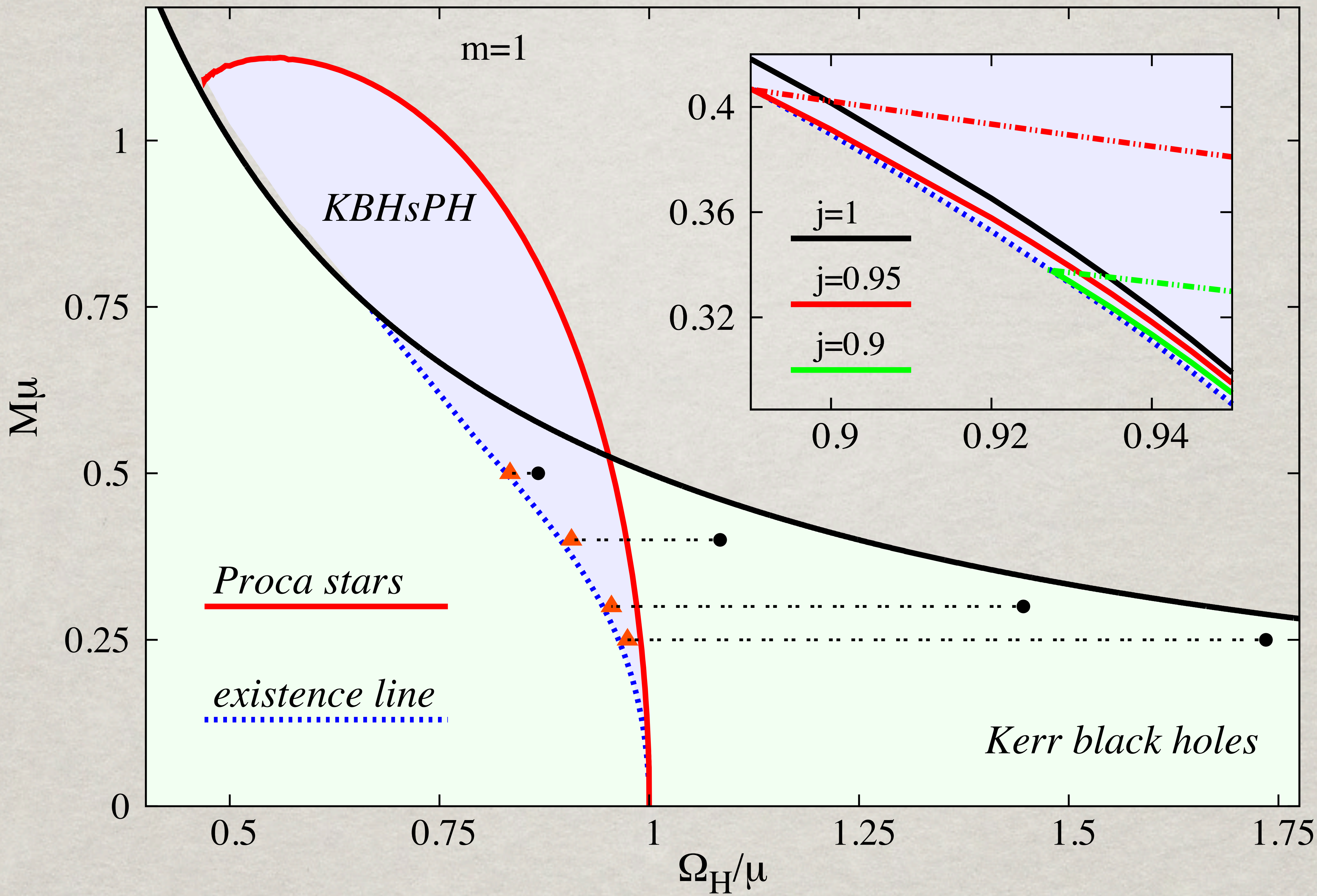
Mass and angular momentum in “hair”





Black hole spin down and “synchronisation”

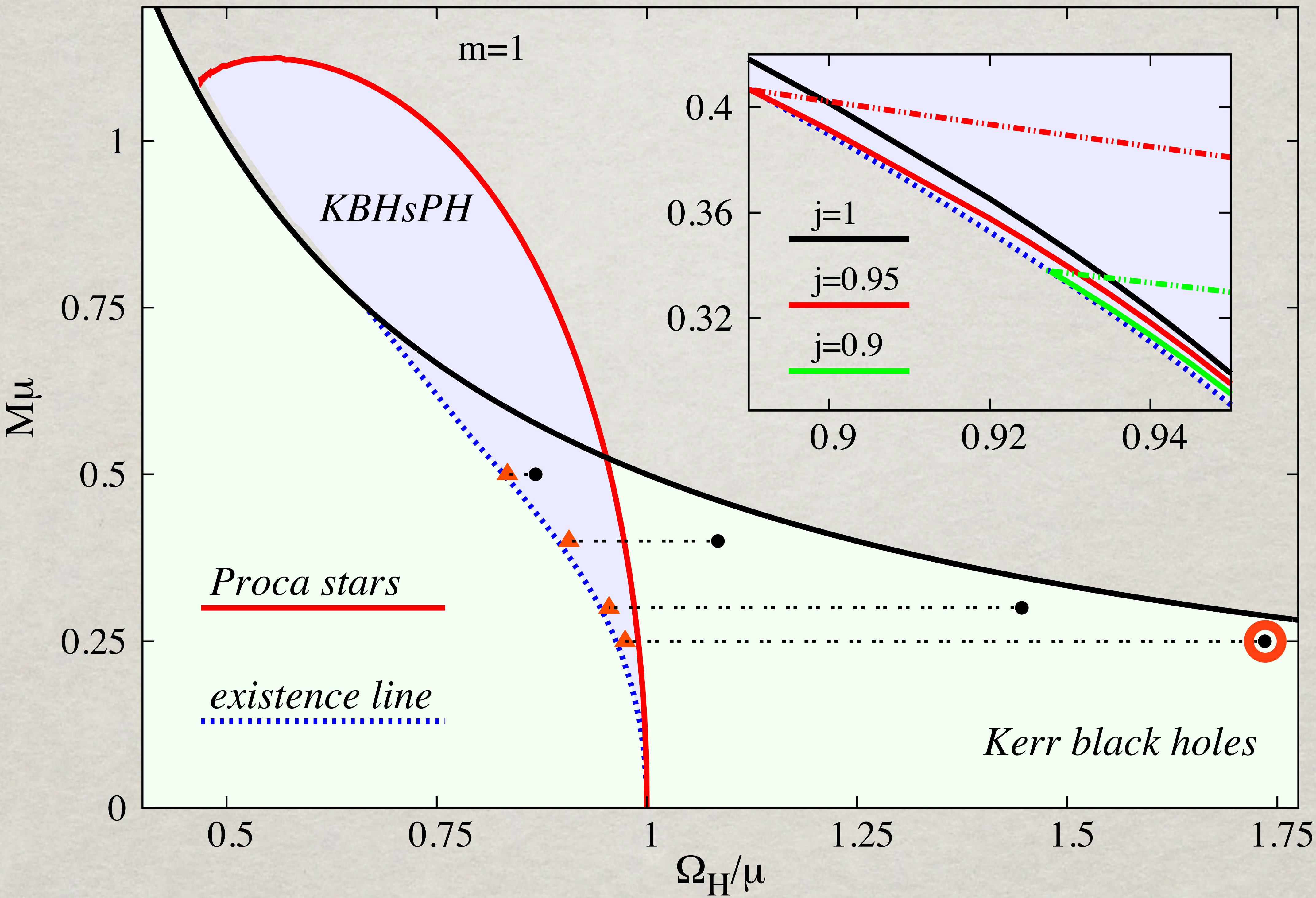




... which is a hairy black hole

CH, Radu, PRL 119 (2017) 261101

Dolan, Physics10(2017)83



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CH, Radu, PRL 119 (2017) 261101

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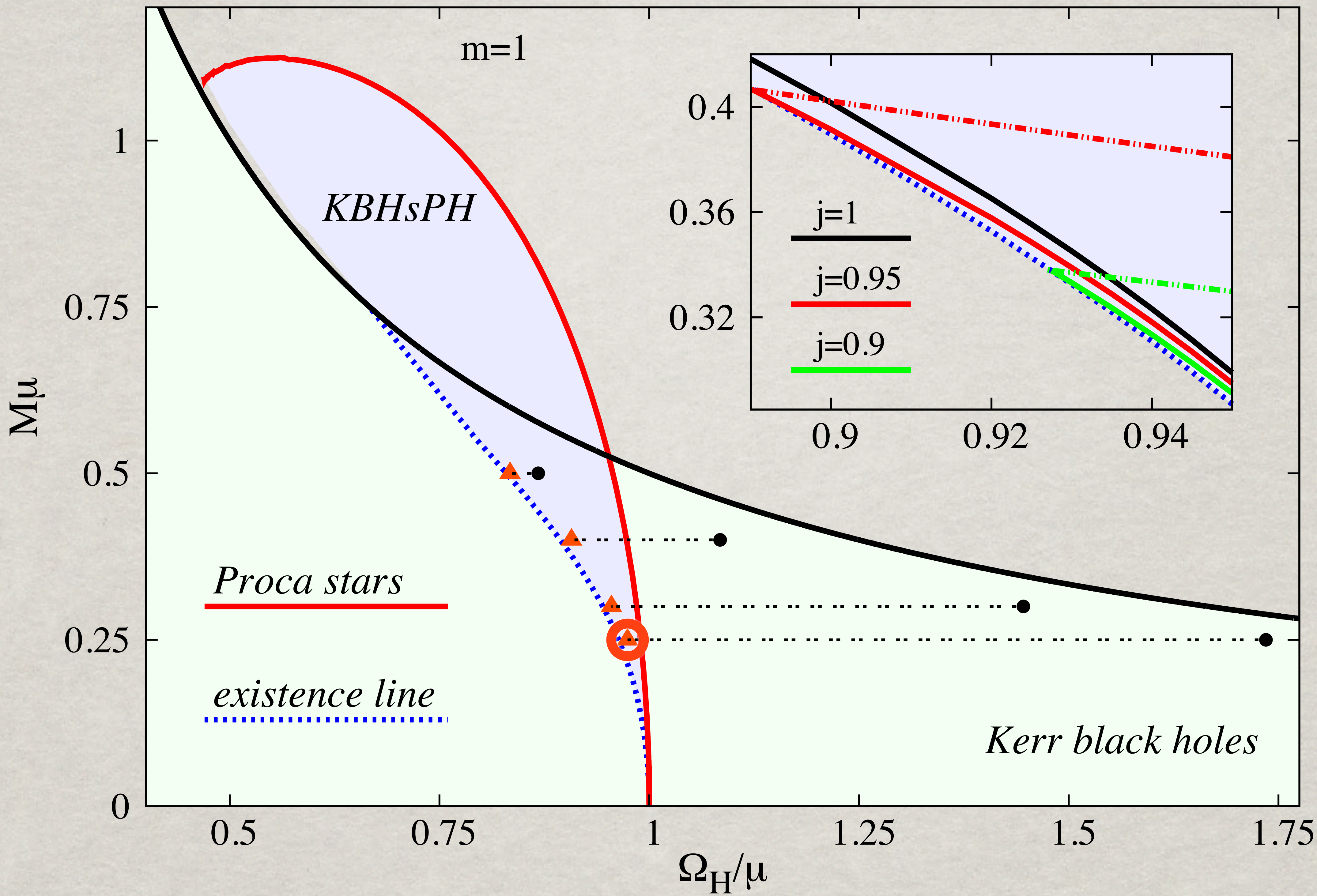

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CH, Radu, PRL 119 (2017) 261101

Dolan, Physics10(2017)83

Kerr $\xrightarrow{\Delta t}$ Hairy black hole

But is this the
end of the process?

Kerr $\xrightarrow{\Delta t}$ Hairy black hole

But is this the end of the process?

- These hairy black holes have an ergoregion themselves CH, Radu, PRD 89 (2014) 124018;

- Suggests they are also afflicted by superradiant instabilites of higher “m” modes (<u>when in the superradiant range</u>);

Δt

Kerr ----------> Hairy black hole

But is this the end of the process?

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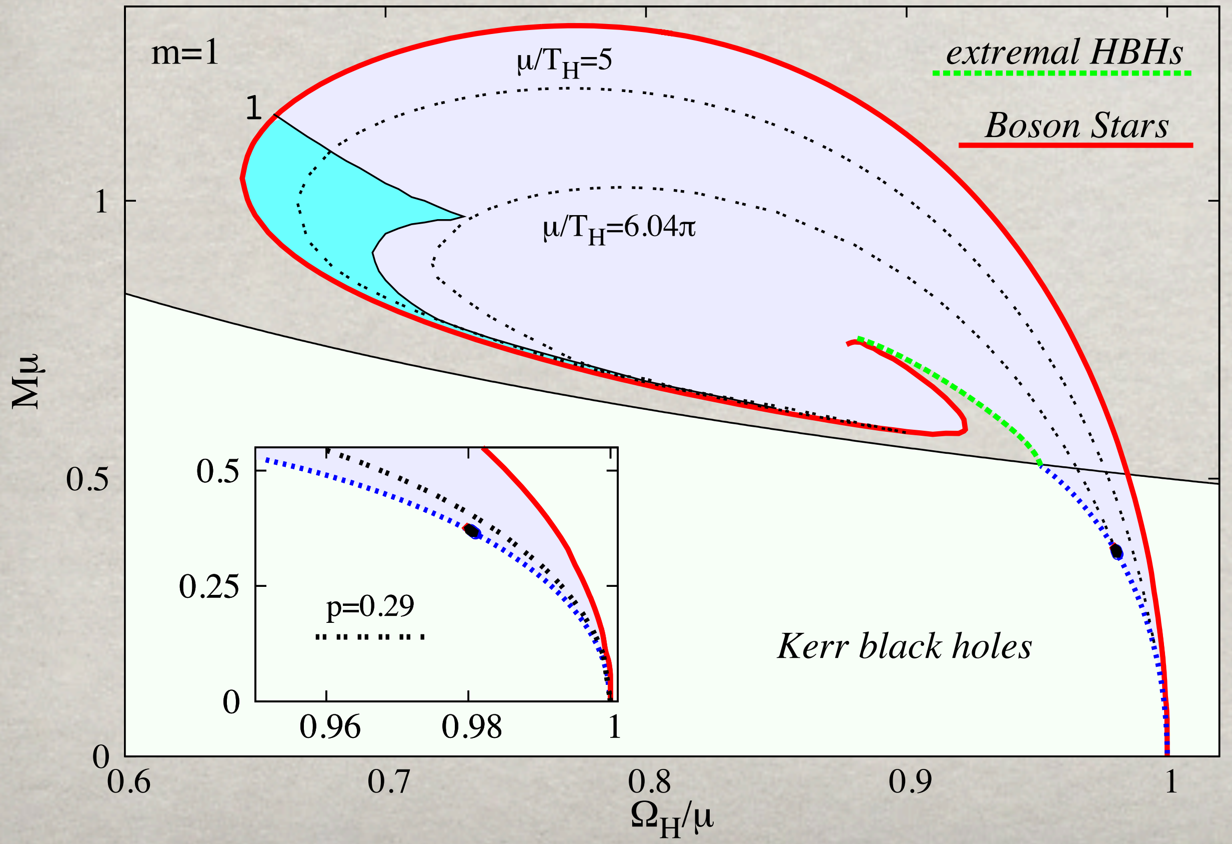
- Suggests they are also afflicted by superradiant instabilites of higher "m" modes (when in the superradiant range);

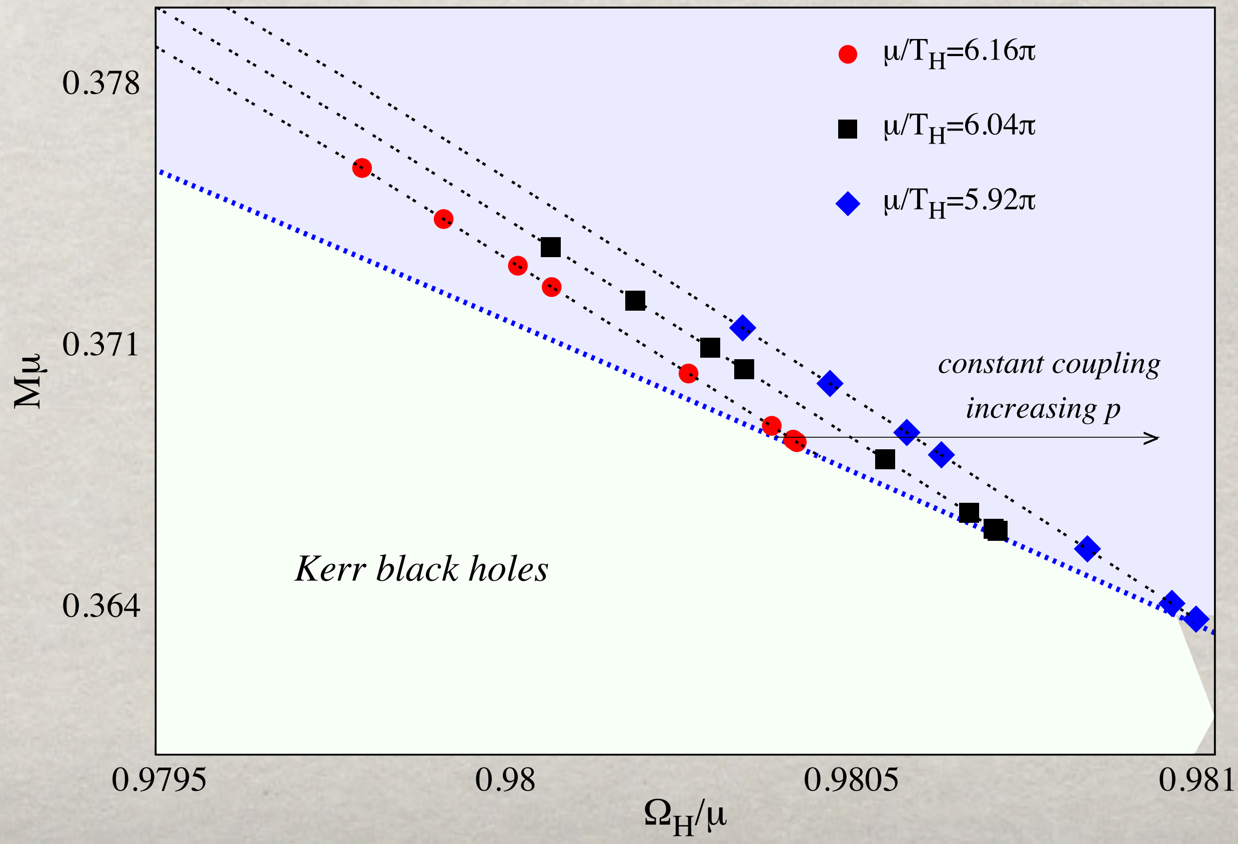
This was confirmed by Ganchev and Santos 1711:08464

1) the instability found is the anticipated superradiant instabilities

2) the claims therein concerning timescales are non-generic Degollado, CH, Radu, 1802.07266

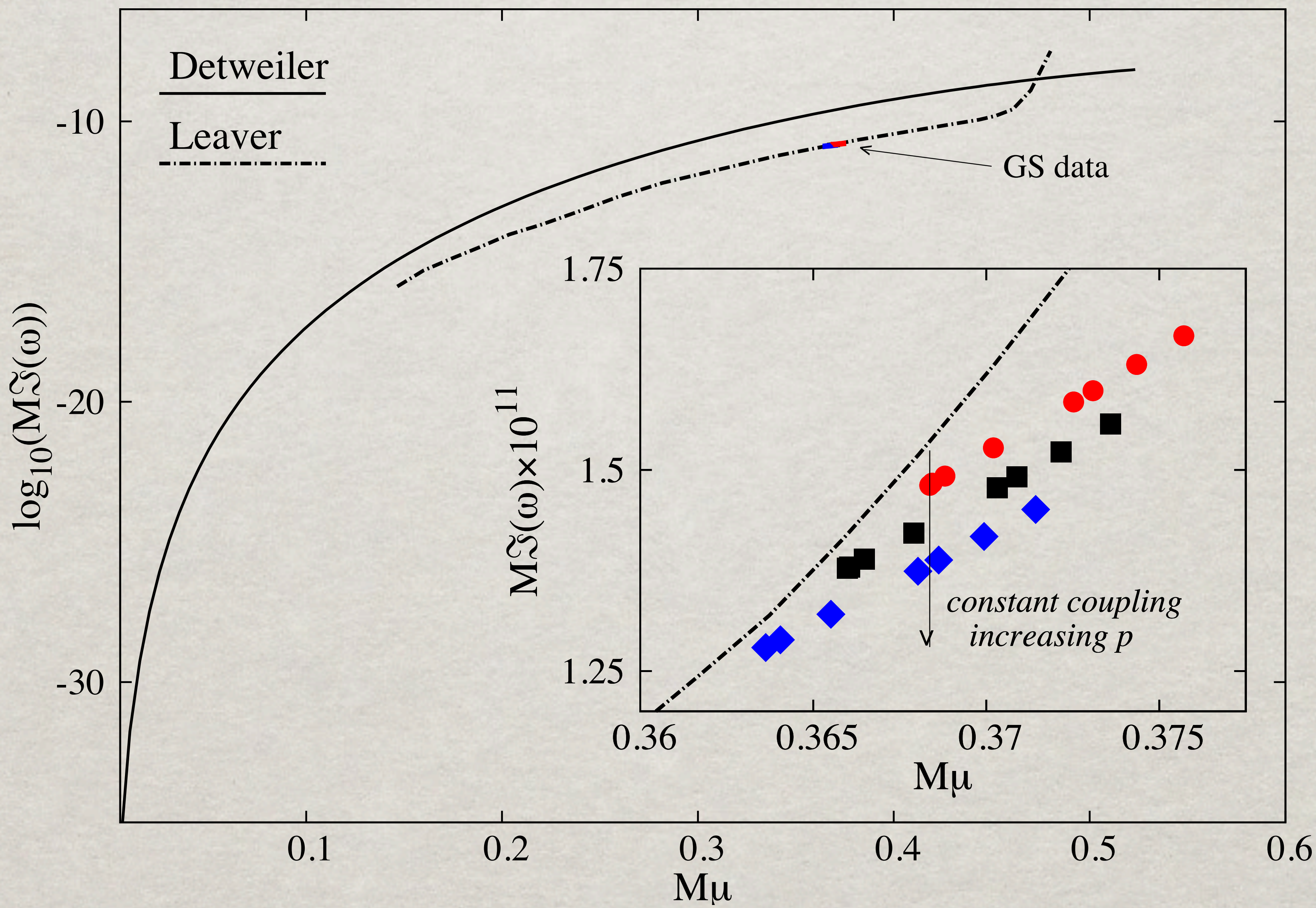
All have less than 2% of energy in "hair"





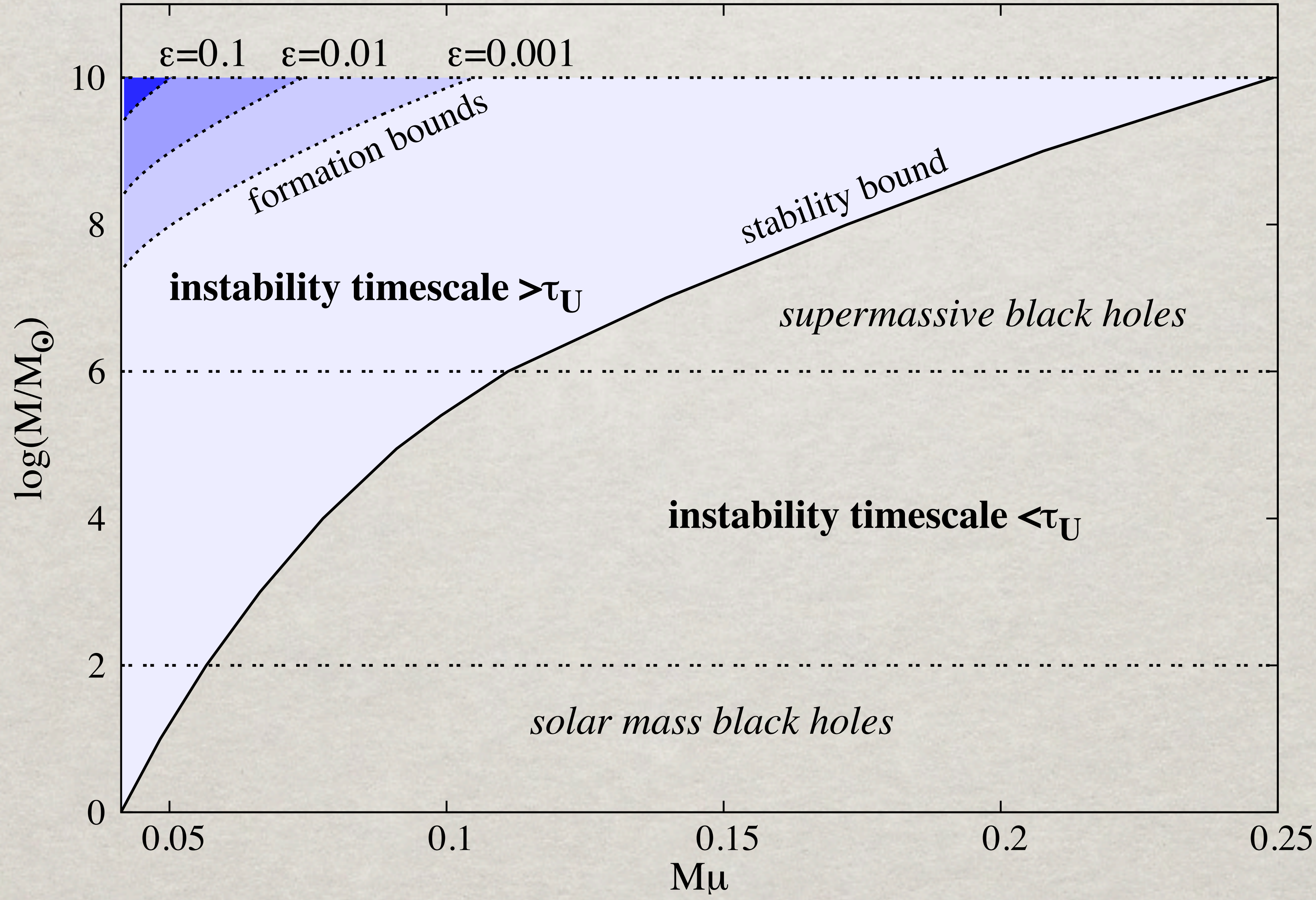
Observation 1 about timescales Degollado, CH, Radu, 1802.07266:

For fixed coupling, increasing "hairiness" decreases strength of instability.



Observation 2 about timescales Degollado, CH, Radu, 1802.07266:

There are hairy BHs for which the instability timescale is larger than the age of the Universe.



A conservative estimate of the Astrophysically viable region

$$\text{Kerr} \xrightarrow[\text{(astrophysical time scale)}]{\Delta t} \text{Hairy black hole}$$

2) Is this the end of the process?

$$\text{Kerr} \quad \xrightarrow{\Delta t} \quad \text{Hairy black hole}$$

(astrophysical time scale)

2) Is this the end of the process?

In *theory* no; they are still afflicted by superradiant instabilities of higher m modes, because they have ergo-regions CH and Radu PRD89(2014)124018 higher m superradiance instability

Kerr $\xrightarrow{\Delta t}$ Hairy black hole $\xrightarrow{> 1000\Delta t}$???

(astrophysical time scale) (astrophysical time scale at highest efficiency, but cosmological or beyond off highest efficiency)

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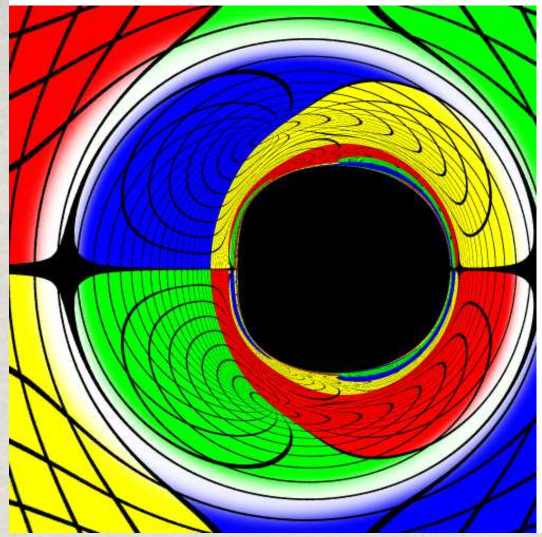
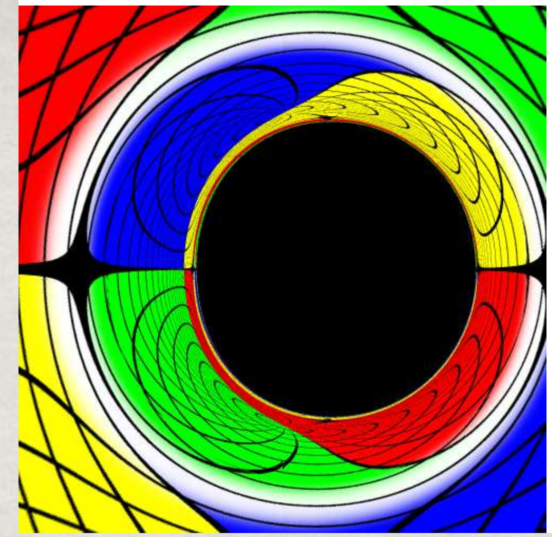
In *theory* no; they are still afflicted by superradiant instabilities of higher *m* modes, because they have ergo-regions CH and Radu PRD89(2014)124018

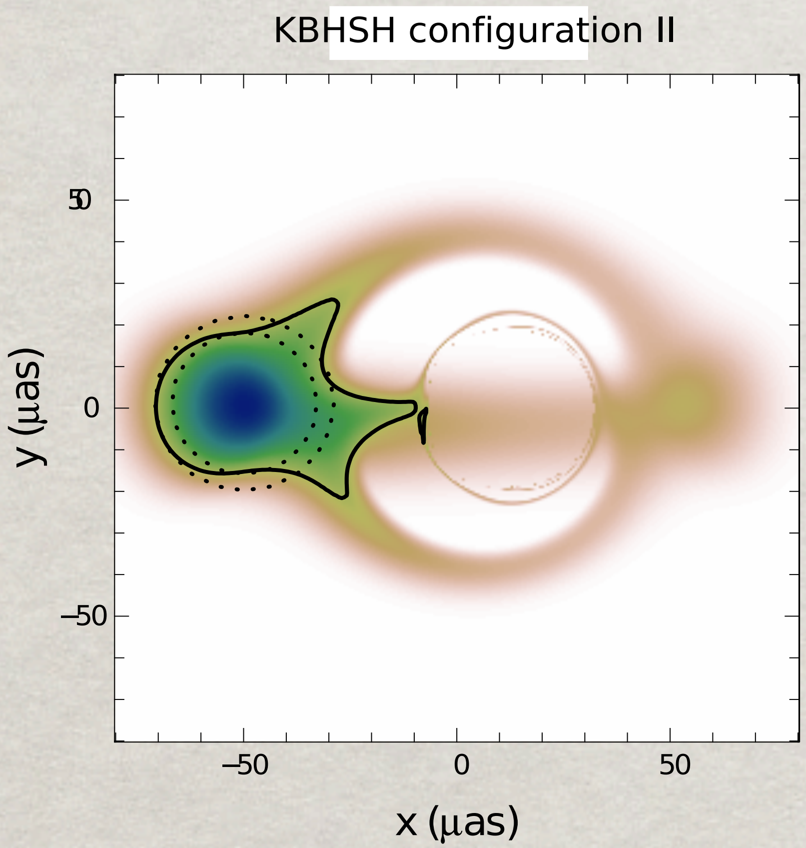
In *practice* it can be: **effective stability**

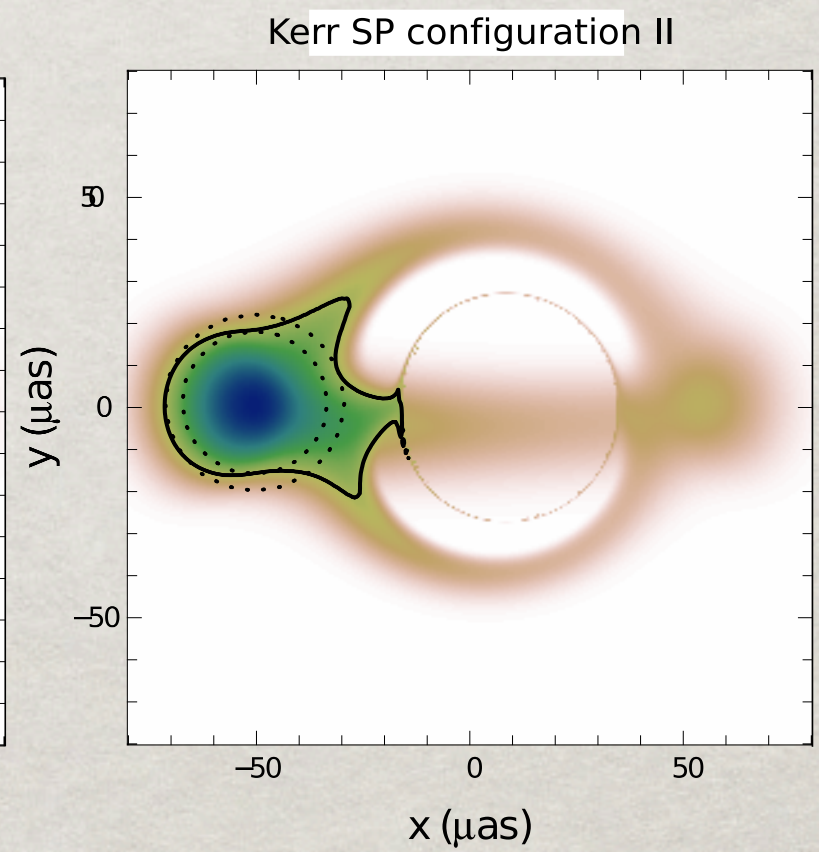
Degollado, CH, Radu, 1802.07266

“Academic Sky”





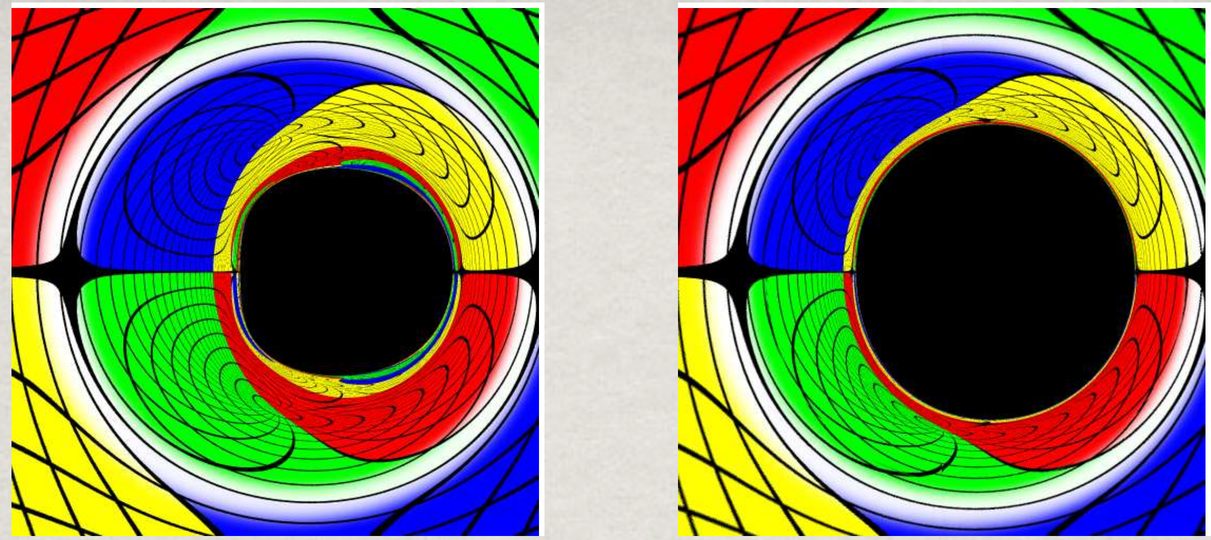


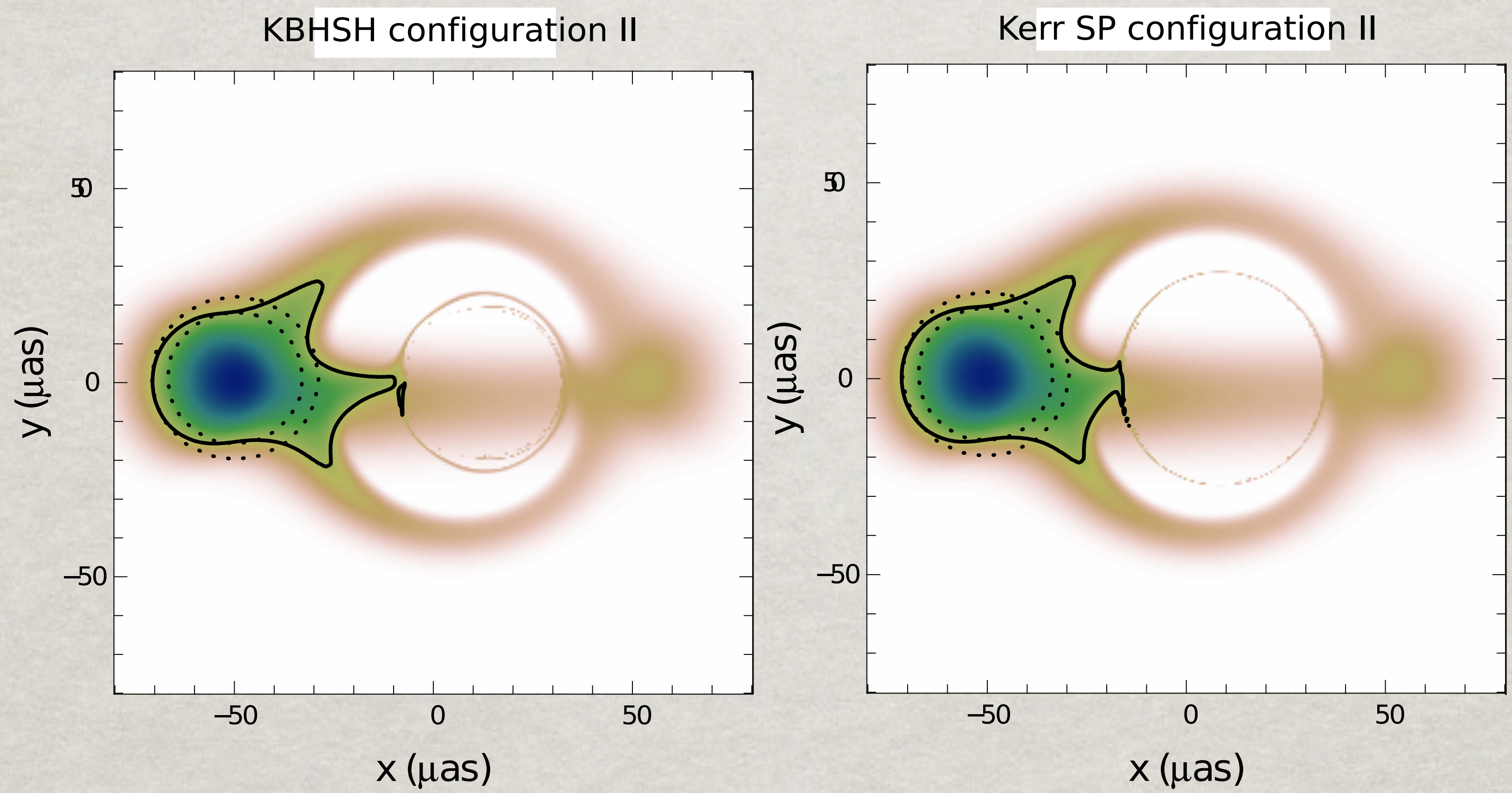


Differences remain in an astrophysically more realistic setup

Vincent, Gourgoulhon, CH, Radu, PRD94(2016)084045

"Academic Sky"





Differences remain in an astrophysically more realistic setup

Vincent, Gourgoulhon, CH, Radu, PRD94(2016)084045

Similar story for other observables such as the:

- iron Kα-line in the reflexion spectrum Ni, Zhou, Cardenas-Avendano, Bambi, CH, Radu, JCAP1610(2016)003
- QPOs Franchini, Pani, Maselli, Gualtieri, CH, Radu, Ferrari, PRD95(2017)124025

a) In General Relativity

1) Appear in a well motivated and consistent physical model;

Kerr black holes with synchronised hair: General Relativity minimally coupled to massive bosonic fields

Check list!

2) Have a dynamical formation mechanism;

Kerr black holes with synchronised hair: superradiance instability of Kerr

3) Be (sufficiently) stable.

Kerr black holes with synchronised hair: effective stability against superradiance in some range of masses and couplings

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Kerr black holes with synchronised hair: effective stability against superradiance in some range of masses and couplings

Issues:

- What is the ultralight scalar/vector field?
- Interaction with astrophysical environment/accretion ?
- Other instabilities ?

Kerr black holes with synchronised bosonic hair

other references:

IJMPD23(2014)1442014	PRD89(2014)12; 124018	PLB739(2014)1	PRD90(2014)10, 104024	PLB739(2014)302
IJMPD24(2015)1542014	PLB748(2015)30	PLB752(2016)291	PRD92(2015)084059	PRL116(2016)141101
PLB760 (2016) 279-287	PRD94 (2016)084045	JCAP1607(2016)049	PRD94(2016)044061	PLB761 (2016) 234
JCAP1610(2016)003	PRD94(2016)104023	CQG34(2017)165001	PRD95(2017)124025	JCAP1708(2017)014
PRD95(2017)104028	PRD95(2017)104035	PLB773(2017)129	PRL119(2017)261101	JHEP1711(2017)037

with

C. Bambi, C. Benone, Y. Brihaye, R. Brito, A. Cardenas-Avendano, Z. Cao, V. Cardoso, L. C. Crispino, P. Cunha, J. C. Degollado, J. F. M. Delgado, , V. Ferrari, J. A. Font, N. Franchini, E. Gourgoulhon, J. Grover, L. Gualtieri, J. Kunz, A. Maselli, P. J. Montero, Y. Ni, P. Pani, H. Rúnarsson, N. Sanchis-Gual, T. Shen, B. Subagyo, F. Vincent, A. Wittig, M. Zhou

Kerr black holes with synchronised bosonic hair

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Jorge Delgado's talk on the horizon geometry

João Oliveira's talk on virial identities

b) Beyond General Relativity

Many models

One illustrative example: Einstein-dilaton-Gauss-Bonnet
(arises in String Theory, second order equations of motion, etc...)

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - \frac{1}{2}(\partial_\mu\phi)^2 + \alpha e^{-\gamma\phi}R^2_{\rm GB}\right],$$

$$R^2_{\rm GB} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

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Schwarzschild/Kerr not solutions - new black holes which are stable in some regime, P. Kanti, N. E. Mavromatos, J. Rizos, K. Tamvakis and E. Winstanley, Phys. Rev. D 54 (1996) 5049; Phys. Rev. D 57 (1998) 6255; P. Kanti, B. Kleihaus and J. Kunz, Phys. Rev. Lett. 107 (2011) 271101

New qualitative features (minimal black hole size);

Various interesting cousin models changing the scalar/curvature coupling
Sotiriou and Zhou, Phys. Rev. D 90 (2014) 124063
Silva, Sakstein, Gualtieri, Sotiriou, Berti, arXiv:1711.02080 [gr-qc];

Dynamical formation
Benkel, Sotiriou and Witek, Phys. Rev. D 94 (2016) 121503

Phenomenology:
No large deviations from Kerr **occur;** e.g. shadows

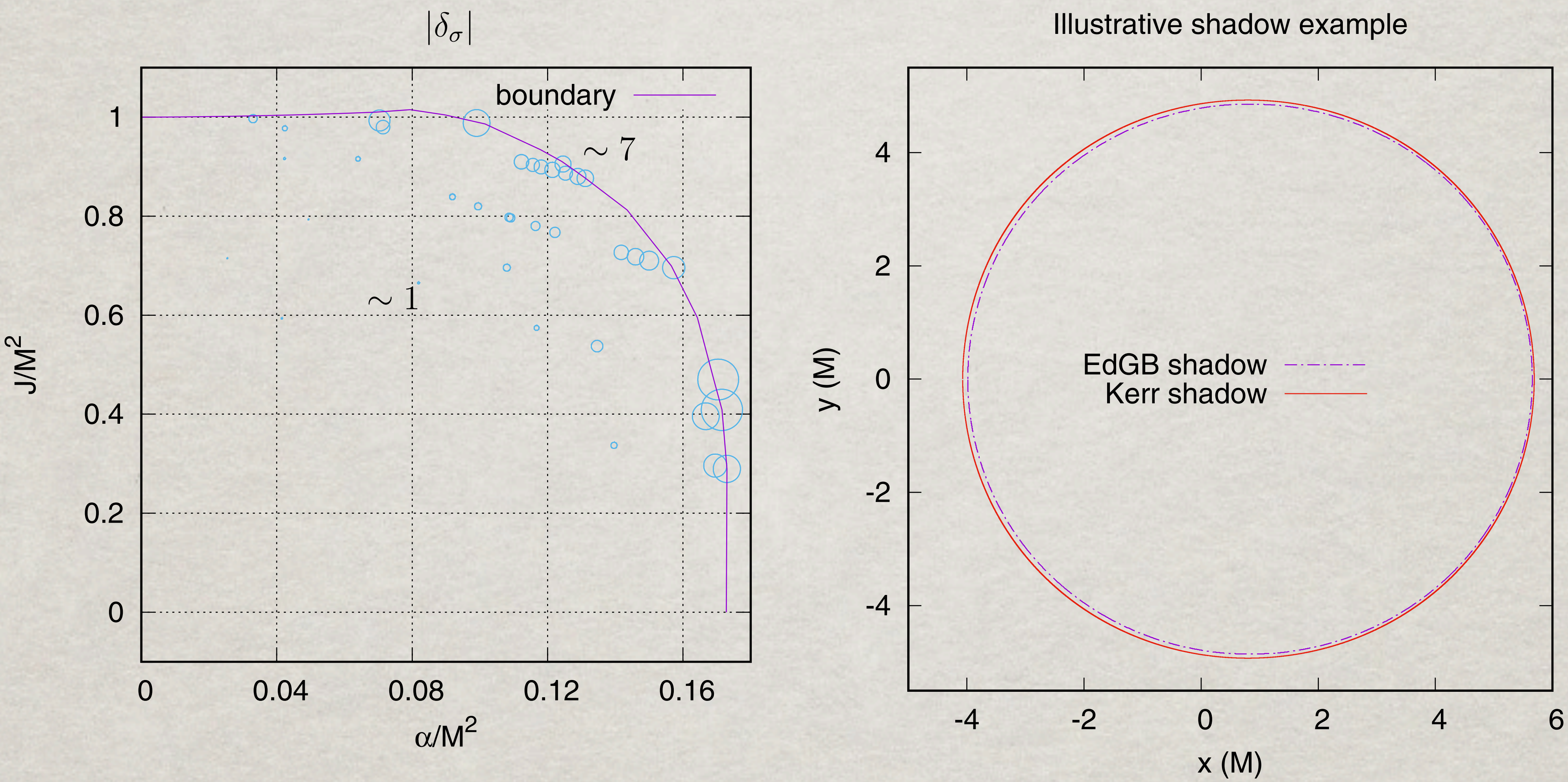

Fig. 4. (Left) Representation of $|\delta_\sigma|$ for EdGB solutions with $\gamma = 1$, in a α/M^2 vs. J/M^2 diagram. Each circle radius is proportional to the quantity represented, with some values also included for reference. All the values of δ_σ are negative. (Right) Depiction of the shadow edge of a EdGB BH with $\gamma = 1$ and $(\alpha/M^2, J/M^2) \simeq (0.172, 0.41)$, yielding $\bar{r} \simeq 4.85$, $\sigma = 0.3$, $x_C = 0.84$; the radial deviation δ_r with respect to the comparable Kerr case is $\simeq -1.35\%$. The observer is at a perimetral radius $15M$.

The case of Einstein-dilaton-Gauss-Bonnet:
the largest shadow deviation is (in the average radius) only ~ few %
Cunha et. al , PLB (2017)

Same for Kα line
Zhang, Zhou, Bambi, Kleihaus, Kunz and Radu, Phys. Rev. D 95 (2017) 104043

b) Beyond General Relativity

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1) Appear in a well motivated and consistent physical model;

Einstein-dilaton-Gauss-Bonnet (or variations thereof)

2) Have a dynamical formation mechanism;

Gravitational collapse or scalarisation

3) Be (sufficiently) stable.

Some solutions are stable

Check list!

b) Beyond General Relativity

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Gravitational collapse or scalarisation

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Some solutions are stable

Check list!

Issues:

- Why stop at quadratic curvature?
- Why a certain coupling?
- There are effective violations of energy conditions. Is it an issue?

3) Beyond black holes

Black holes have a horizon and (abiding energy conditions) a curvature singularity: issues

To avoid this difficulties, models of horizonless compact objects (black hole mimickers) have been considered:

a) “geons”, realized by Boson stars (Schunck, Mielke, CQG 20 (2003) R301) and Proca stars (Brito, Cardoso, CH, Radu, PLB752 (2016) 291); can form dynamically (Seidel, Suen, PRL 72 (1994) 2516); Perturbatively stable Gleiser and Watkins, NPB 319 (1989) 733; Lee and Pang, NPB 315 (1989) 477 ; Can be studied dynamically in binaries (Liebling and Palenzuela LRR 20 (2017) 5)

b) wormholes

c) gravastars (Mazur and Mottola, gr-qc/0109035)

d) fuzzballs (Mathur, Fortsch. Phys. 53 (2005) 793)

e) ...

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d) fuzzballs (Mathur, Fortsch. Phys. 53 (2005) 793)

e) ...

- To be able to mimic (up to a fine structure) the GW ringdown the object must be ultracompact, i.e. have a light ring Cardoso, Franzin and Pani, PRL 116 (2016) 171101

- Possible issue: for ultracompact objects resulting from a smooth, incomplete gravitational collapse, light rings come in pairs and one is stable Cunha, Berti, CH, PRL 119 (2017) 251102

Pedro Cunha’s talk

3) Beyond black holes

3) Beyond black holes

Check list:

1) Appear in a well motivated and consistent physical model;

Boson stars: General Relativity minimally coupled to massive bosonic fields

Check list!

2) Have a dynamical formation mechanism;

Gravitational cooling

3) Be (sufficiently) stable.

Some solutions are stable

3) Beyond black holes

Check list:

1) Appear in a well motivated and consistent physical model;

Boson stars: General Relativity minimally coupled to massive bosonic fields

Check list!

2) Have a dynamical formation mechanism;

Gravitational cooling

3) Be (sufficiently) stable.

Some solutions are stable

Issues:

- What is the scalar field?
- No known dynamical formation mechanism for rotating boson stars;
- Interaction with astrophysical environment/accretion ?
- Are there perturbatively stable boson stars with light rings?

4) Outlook

Concluding remark:

All these models have caveats, but they illustrate that there exist fairly reasonable theoretical possibilities (albeit with admittedly exotic physics) of alternative models to the Kerr paradigm.

High risk, high gain endeavour: producing detailed phenomenology will constrain the model and the corresponding exotic physics or, in the best case scenario, provide a smoking gun to this new physics.

Testing the Kerr hypothesis by looking for alternative models represents scientific open mindedness.

Muchas gracias
por su atencion!

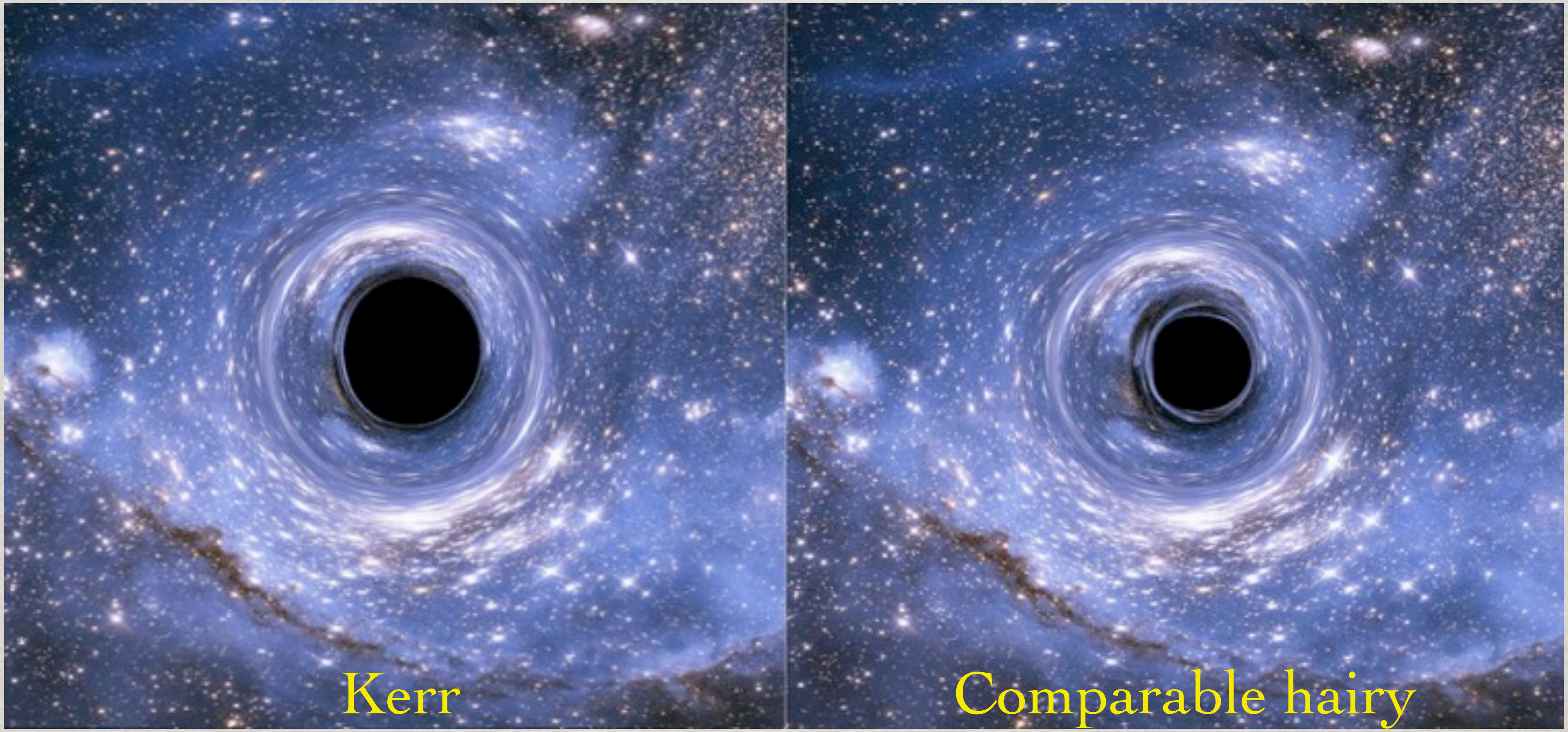

Image:
P. Cunha

Thank you for Your
Attention!