Theory and Phenomenology of Kerr–black bounces

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If quantum gravity resolves spacetime singularities and if it admits an effective description in terms of differential geometry, astrophysical black holes ought to be described in terms of effective 'regularised' metrics. Many such metrics have been proposed, but few correspond to stable and phenomenologically viable objects. In this poster, I will present an example of them: the Kerr black-bounce, a family of rotating regular geometries capable of mimicking a Kerr black hole. It extends the Kerr family by addition of a single parameter, according to the value of which it describes either a regular black hole or a traversable wormhole. I will address the question of its stability by considering a test scalar field propagating on a Kerr black-bounce background and describing its quasinormal mode spectrum; finally, I will comment on another phenomenological application: superradiant amplification. This analysis consolidates Kerr black-bounces' position as viable black hole mimickers and informs the wider debate on regular black holes. Its implications can be relevant to the field of compact object phenomenology and for ultra-light dark matter searches.

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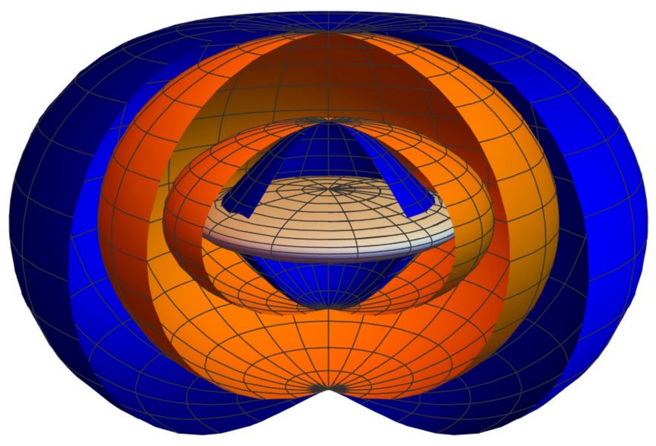
Kerr–black-bounce spacetimes

aka
(rotating) Simpson–Visser metric



What?

- One-parameter extension of Kerr
  (3 parameters in total: M, a, one more)
- No singularities!
  (ring singularity is 'regularised')
- Can 'mimic' a Kerr black hole

Why?

Quantum gravity phenomenology:

if quantum gravity 'cures' singularities
and if quantum gravity can be described, at low energy, with differential geometry (manifold, metric…)
then black holes in the sky should be described with effective regular metric

Theory

[JM, Franzin, Liberati JCAP04(2021)082 (2021)]

The metric:

$$ds^2 = -\left(1 - \frac{2M\sqrt{r^2+\ell^2}}{\Sigma}\right)\mathrm{d}t^2 - \frac{4Ma\sqrt{r^2+\ell^2}\sin^2\theta}{\Sigma}\mathrm{d}t\mathrm{d}\phi + \frac{\Delta}{\Sigma}\mathrm{d}r^2 + \Sigma\mathrm{d}\theta^2 + \frac{A\sin^2\theta}{\Sigma}\mathrm{d}\phi^2$$

$$\Delta = r^2 + \ell^2 - 2M\sqrt{r^2+\ell^2} + a^2,$$
$$\Sigma = r^2 + \ell^2 + a^2\cos^2\theta$$
$$A = (r^2+\ell^2+a^2)^2 - \Delta a^2 \sin^2\theta$$

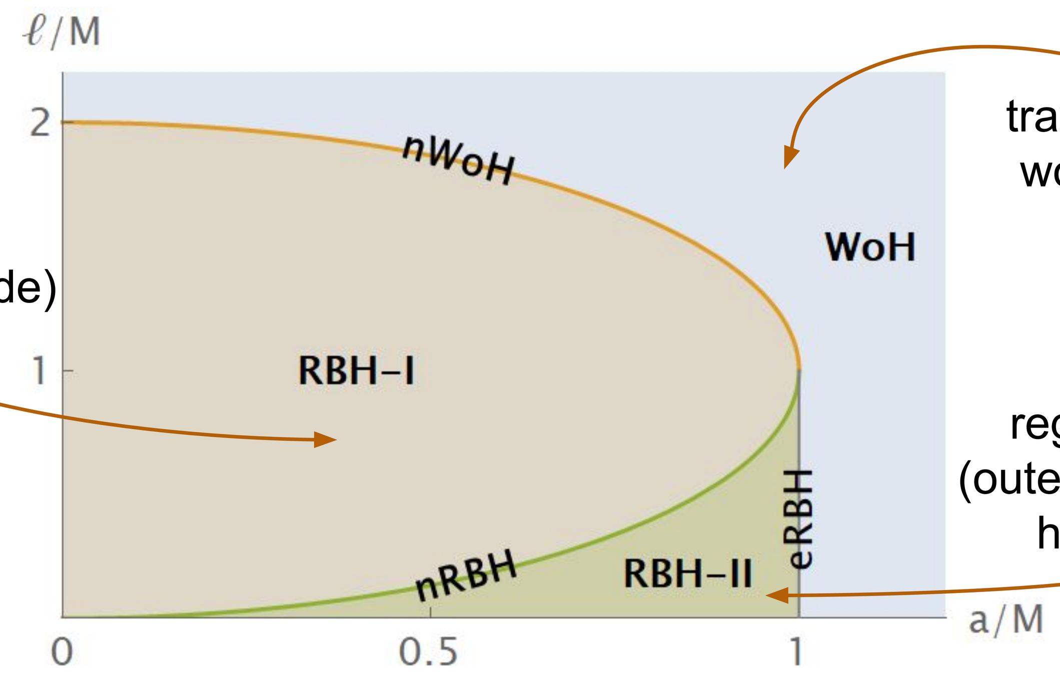
This is Kerr, in Boyer–Lindquist coordinates, plus a 'trick':

$$r \to \sqrt{r^2+\ell^2}$$

- $\ell = 0$ is Kerr
- $\ell \neq 0$ is singularity-free
- $\ell \sim L_{Planck}$ ok, but $\ell \sim O(M)$ possible too: e.g. because of some dynamical process

Now there's a reflection symmetry $r \to -r$
two identical 'universes', glued at $r = 0$ → it's a wormhole!

The spacetime structure depends on ℓ!



regular BH (an horizon per side)

traversable wormhole

regular BH (outer and inner horizon)

Penrose diagrams (and more!) in paper

Phenomenology

[Franzin, Liberati, JM, Dey, Chakraborty, Phys. Rev. D **105**, 124051 (2022)]

All results in paper

What would a Kerr–black bounce look like in the sky?

Previous studies: test-particle dynamics

- Electromagnetic shadows
- Emission profiles from accreting matter
- Gravitational-wave emission from inspirals of regular black hole binaries

Our study: test-field dynamics

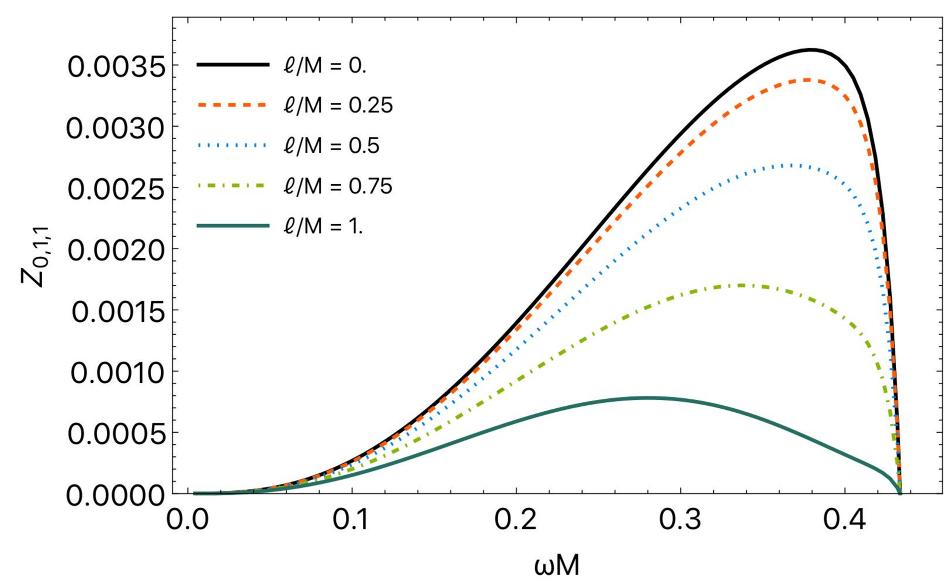
$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right) = \mu^2\phi$$

Quasinormal Modes

- RBH branch stable (small perturbations die off),
- Quasinormal frequencies depend on ℓ but regular black holes akin to black holes
- Wormholes modally unstable (small perturbations grow in time)

Superradiance

- RBHs superradiate in the same range of frequencies, but amplification is suppressed as ℓ is increased
- Wormholes do not superradiate (with our choice of boundary conditions)



Quantum gravity phenomenology possible, in principle, with observations at horizon scale!

Some highly relativistic phenomena might be different if the astrophysical black holes are not Kerr!

To learn more:

Our papers

- E. Franzin, S. Liberati, J. Mazza, R. Dey, S. Chakraborty,*Scalar perturbations around rotating regular black holes and wormholes: quasi-normal modes, ergoregion instability and superradiance,* Phys. Rev. D 105, 124051 (2022) [2201.01650]
- E. Franzin, S. Liberati, J. Mazza, *Charged black-bounce spacetimes*, JCAP07(2021)036 [2104.11376]
- J. Mazza, E. Franzin, S. Liberati, *A novel family of rotating black hole mimickers,* JCAP04(2021)082 [2102.01105]

The original black-bounce spacetime

- A. Simpson and M. Visser, *Black-bounce to traversable wormhole*, JCAP(2019)042 [1812.07114]

On matter sources and ideas similar to black bounces

- K.A. Bronnikov, R. K. Walia, *Field sources for Simpson-Visser spacetimes*, Phys.Rev.D 105 (2022) 4, 044039 [2112.13198]
- K.A. Bronnikov, H. Dehnen, V.N. Melnikov, *Regular black holes and black universes*, Gen Relativ Gravit 39, 973–987 (2007) [gr-qc/0611022]

On Kerr–black-bounce phenomenology

- S. Riaz et al., *Testing regular black holes with X-ray and GW data*, [2206.03729]
- R. Shaikh, K. Pal, K. Pal and T. Sarkar, *Constraining alternatives to the Kerr black hole*, Mon.Not.Roy.Astron.Soc. 506 (2021) 1, 1229-1236 [2102.04299]
- H.C.D. Lima Junior, L.C.B. Crispino, P.V.P. Cunha and C.A.R. Herdeiro, *Mistaken identity: Can different black holes cast the same shadow?*, Phys.Rev.D 103 (2021) 8, 084040 [2102.07034]
- S. Ul Islam, J. Kumar and S. G. Gosh, *Strong gravitational lensing by rotating Simpson–Visser black holes*, *JCAP* 10 (2021) 013 [2104.00696]