Exotic MOTSs in Spherically Symmetric Black Holes

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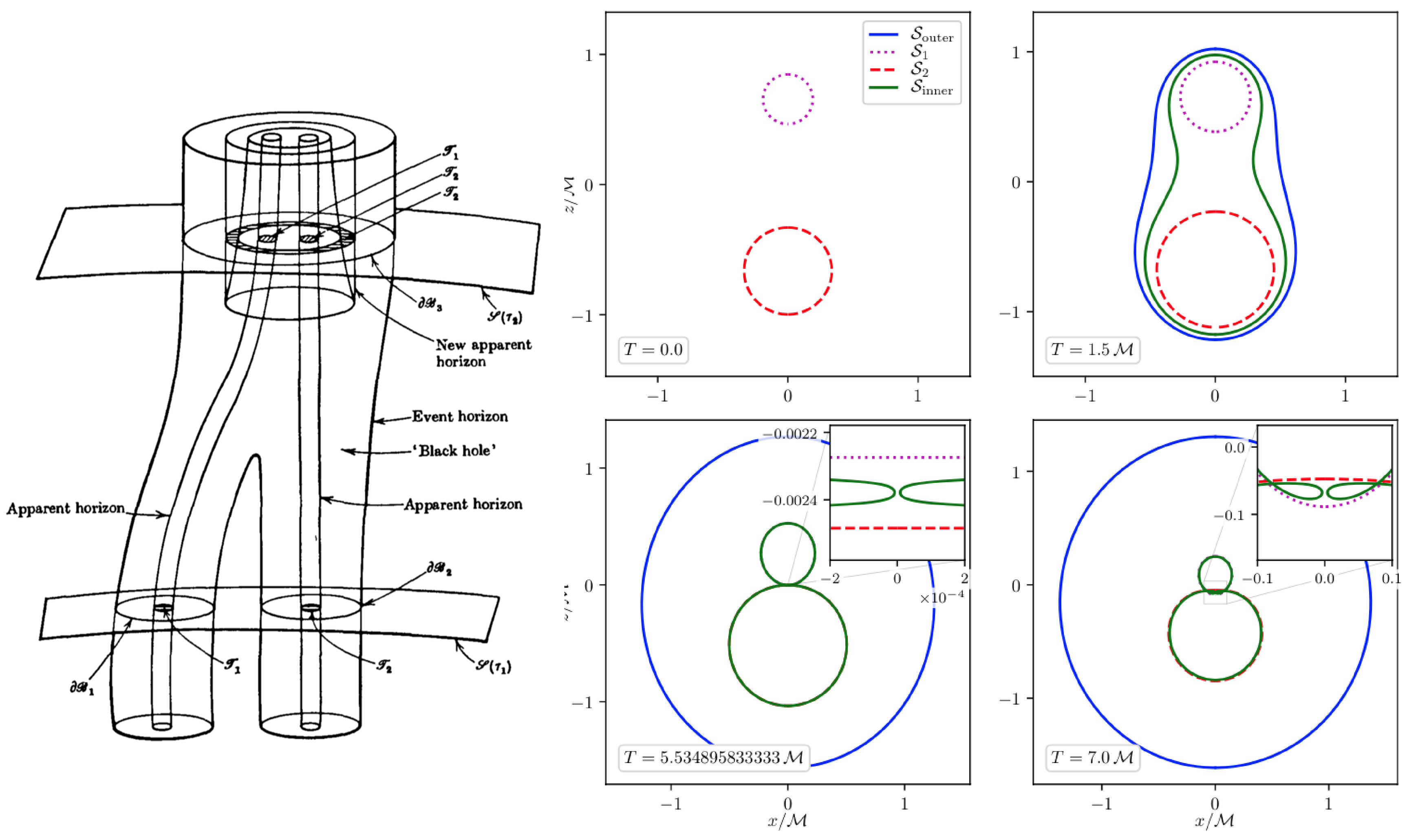
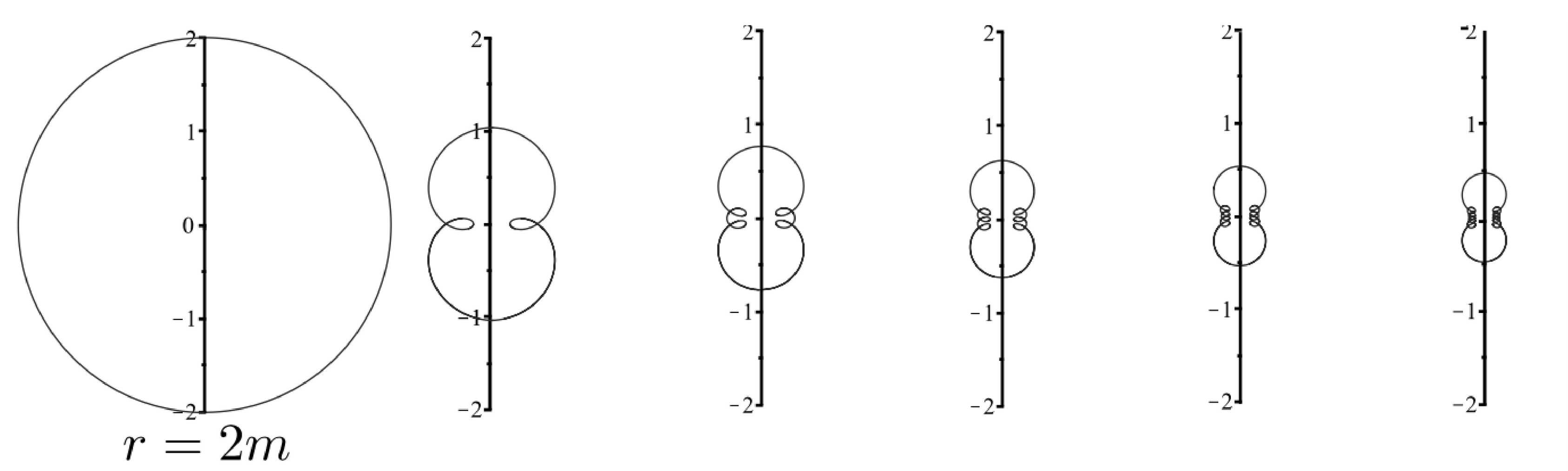
Introduction

The behaviour of the horizons during a black hole merger had not been understood. Recently, there been computational work that show how the two apparent horizons become one.



Left: "Pair of Pants" diagram [2] depicting the event and apparent horizons throughout a binary black hole merger.
Right: Top-down plots of numerically obtained apparent horizons at time-slices [3].

The data suggested the merger process involves self-intersecting *marginally outer-trapped surfaces* (MOTSs, summary in [4]). It was then shown that (seemingly infinite) self-intersecting MOTSs also exist in analytical black hole spacetimes, such as the Schwarzschild spacetime [5].



Plots of the 6 outer-most MOTSs in the Schwarzschild BH [6].

Hypothesis: These self-intersecting MOTSs will appear in similarly simple black hole spacetimes.

Set-up

For an induced metric q_{AB} and null normal vector l^α of a surface, surface is a MOTS if it has vanishing outward expansion (by definition)

$$\Theta_{(+)} = q^{AB} e^\alpha_A e^\beta_B \nabla_\alpha l_\beta \ .$$

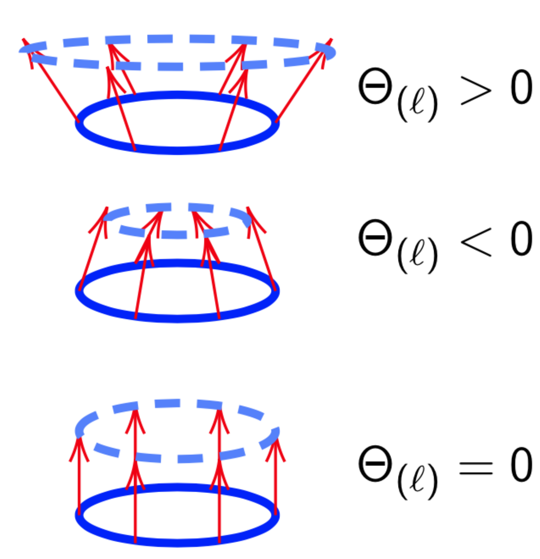


Figure picturing expansion via light spheres, the null normal vector l^α is in red and the surface is blue.

Consider spherically symmetric black hole spacetimes, write a Painlevé-Gullstrand-type metric

$$ds^2 = -f(r)\,dt^2 + 2\sqrt{1-p(r)f(r)}\,dt\,dr + p(r)\,dr^2 + r^2\,d\Omega^2 \ .$$

Only looking at axisymmetric MOTSs, q_{AB} is the orbit space and the problem boils down to solving a pair of coupled ODEs:

$$\ddot{r}(s) = -\frac{p'\dot{r}^2 - 2r\dot{\theta}^2}{2p} + \frac{r\dot{\theta}\kappa}{\sqrt{p}} \ ,$$

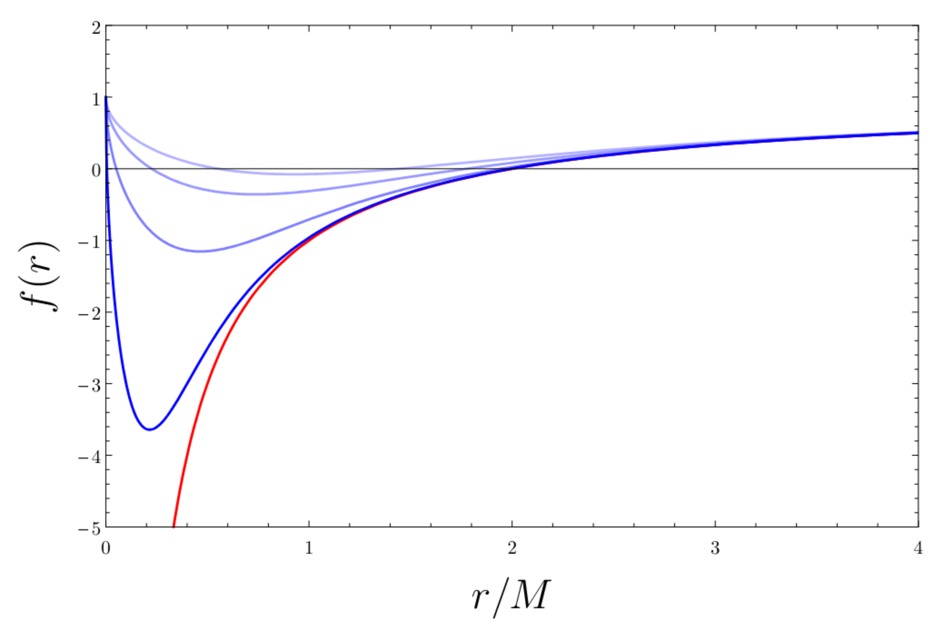
$$\ddot{\theta}(s) = -\frac{2\dot{r}\dot{\theta} + \sqrt{p}\dot{r}\kappa}{r} \ .$$

$$\kappa = -\frac{p\dot{r}\cot(\theta) - r\dot{\theta}}{r\sqrt{p}} + \frac{rp^2\dot{r}^2 f' + r\dot{r}^2 p' - 2(r^2\dot{\theta}^2 + 1)(1-pf)}{2r\sqrt{p(1-pf)}}$$

D → 4 Gauss-Bonnet : A Horndeski-type scalar-tensor theory obtained using dimensional reduction methods [6]:

$$S = \int d^4x\sqrt{-g}\,[R + \alpha(\phi\mathcal{G} + 4G^{\beta\gamma}\partial_\beta\phi\partial_\gamma\phi - 4(\partial\phi)^2\phi + 2(\partial\phi)^4)] \ .$$

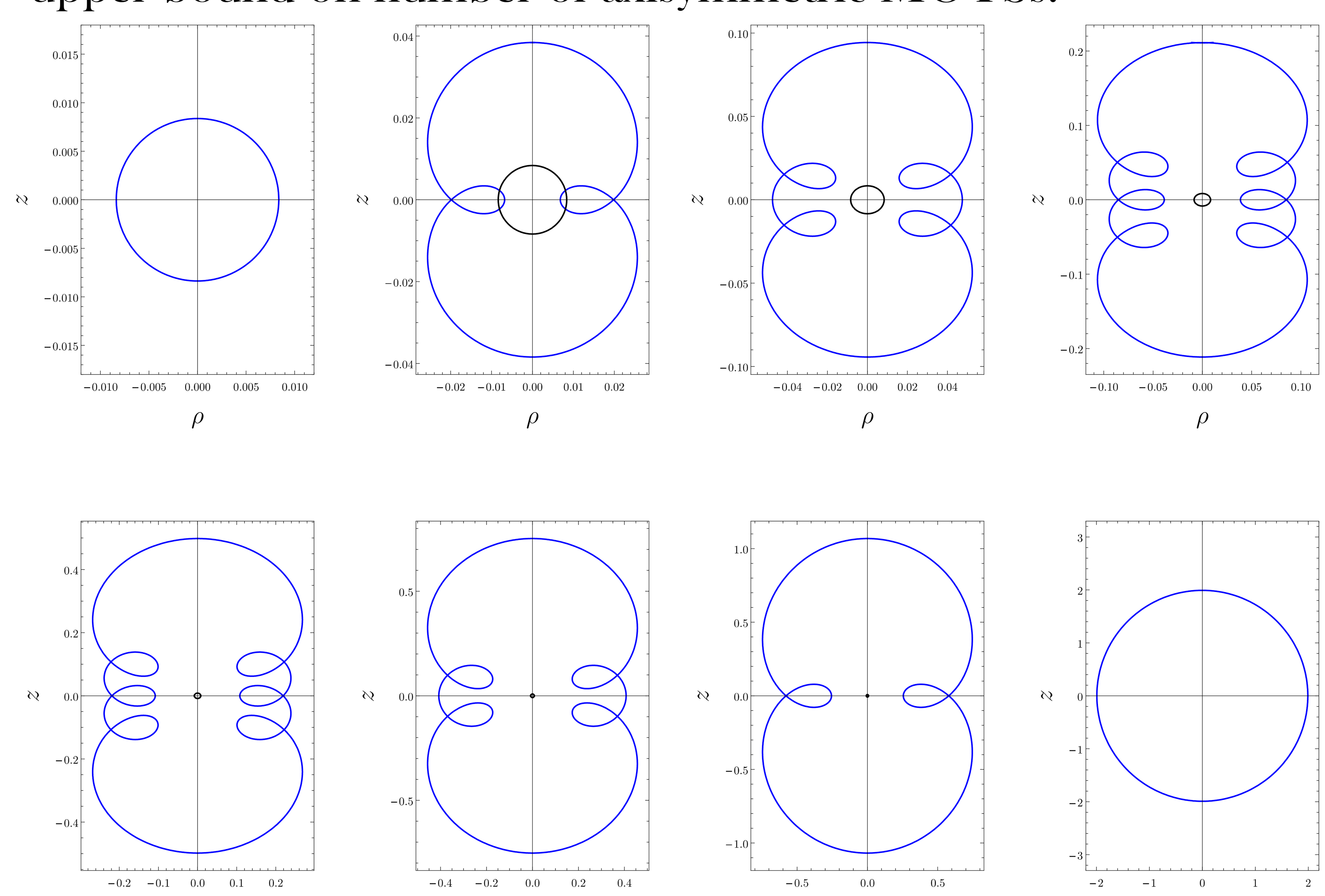
$$f(r) = 1 + \frac{r^2}{2\alpha}\left(1 - \sqrt{1 + \frac{8\alpha M}{r^3}}\right) \ .$$



Plot of $f(r)$ for varying α (blue). The red curve is Schwarzschild.

Results

The existence of an inner (spherical) horizon seems to put an upper bound on number of axisymmetric MOTSs.



These results are a first step to understanding evolution in black hole merger processes. Further published work have shown comparable results in spacetimes with rotation [7] and non-time-symmetric coordinates [8]. Current work investigates the behaviour of MOTSs in asymptotically AdS spacetimes.

References

[1] R. A. Hennigar, K. T. B. Chan*, L. Newhook, and I. Booth, "Interior marginally outer trapped surfaces of spherically symmetric black holes," Phys. Rev. D 105, 044024 (2022).
[2] S. W. Hawking and G. F. R. Ellis, The large-scale structure of space-time. (1973).
[3] D. Pook-Kolb, O. Birnholtz, B. Krishnan, and E. Schnetter, "Self-intersecting marginally outer trapped surfaces," Phys. Rev. D 100, 084044 (2019).
[4] I. Booth, R. A. Hennigar, and D. Pook-Kolb, "Ultimate fate of apparent horizons during a binary black hole merger. I. Locating and understanding axisymmetric marginally outer trapped surfaces," Phys. Rev. D 104, 084083 (2021).
[5] I. Booth, R. A. Hennigar, and S. Mondal, "Marginally outer trapped surfaces in the Schwarzschild spacetime: Multiple self-intersections and extreme mass ratio mergers," Phys. Rev. D 102, 044031 (2020).
[6] R. A. Hennigar, D. Kubizňák, R. B. Mann, and C. Pollack, "On taking the d → 4 limit of gauss-bonnet gravity: theory and solutions," Journal of High Energy Physics 2020 (2020), 10.1007/jhep07(2020)027
[7] I. Booth, K. T. B. Chan*, R. A. Hennigar, H. Kunduri, and S. Muth, "Exotic marginally outer trapped surfaces in rotating spacetimes of any dimension," Class. Quant. Grav. 40, 095010 (2023).
[8] K. T. B. Sievers, L. Newhook, S. Muth, I. Booth, R. A. Hennigar, H. K. Kunduri, "Marginally Outer Trapped Tori in Black Hole Spacetimes," Phys. Rev. D 109, 124023 (2024).