INTERNATIONAL CONFERENCE

DARK MATTER AND STARS

Multi-Messenger probes of Dark Matter and Modified Gravity

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Black Hole Mergers

In Cubic Gravity

Jorge Rocha

ISCTE-Instituto Universitário de Lisboa & CENTRA-Instituto Superior Técnico

Motivation

Context: There exists a plethora of viable modified gravity theories.

Among these, higher curvature corrections to GR are particularly well motivated.

Aim: Test a family of such theories (Einsteinian Cubic Gravity) in a strong field, highly dynamical regime.

Namely, we study how higher derivative corrections to GR affect BH merger events.

Approach: Focus on the extreme mass ratio (EMR) regime and adopt ray tracing techniques to obtain the full evolution of the horizon.

(Emparan-Martínez (2016))

Acknowledgments

Based on joint work with: João M. Dias

Antonia M. Frassino

Valentin D. Paccoia

- **"Black hole-wormhole collisions and the emergence of islands"**

  [arXiv: 2304.06098] (submitted)

  (See Frassino's talk)

- **"The impact of higher derivative corrections to GR on black hole mergers"**

  [arXiv: 2306.?????] (work in progress)

Overview

1. Using ray-tracing to study BH mergers in the EMR regime

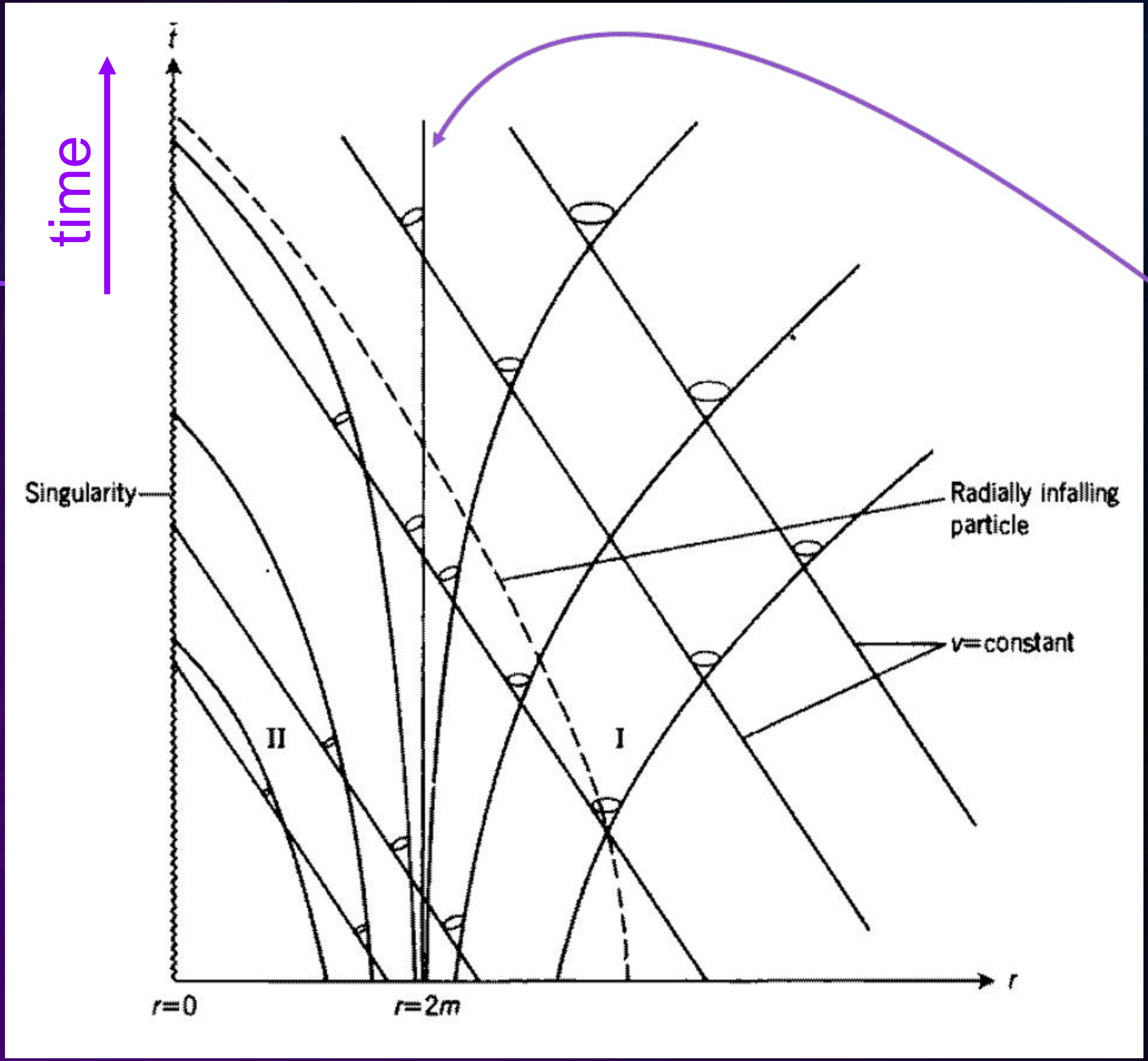
2. BHs in Einsteinian Cubic Gravity (ECG)

3. BH mergers in ECG

1 EMR – a small body falling into a large BH

Schwarzschild

Image credit:
d'Inverno (1992)



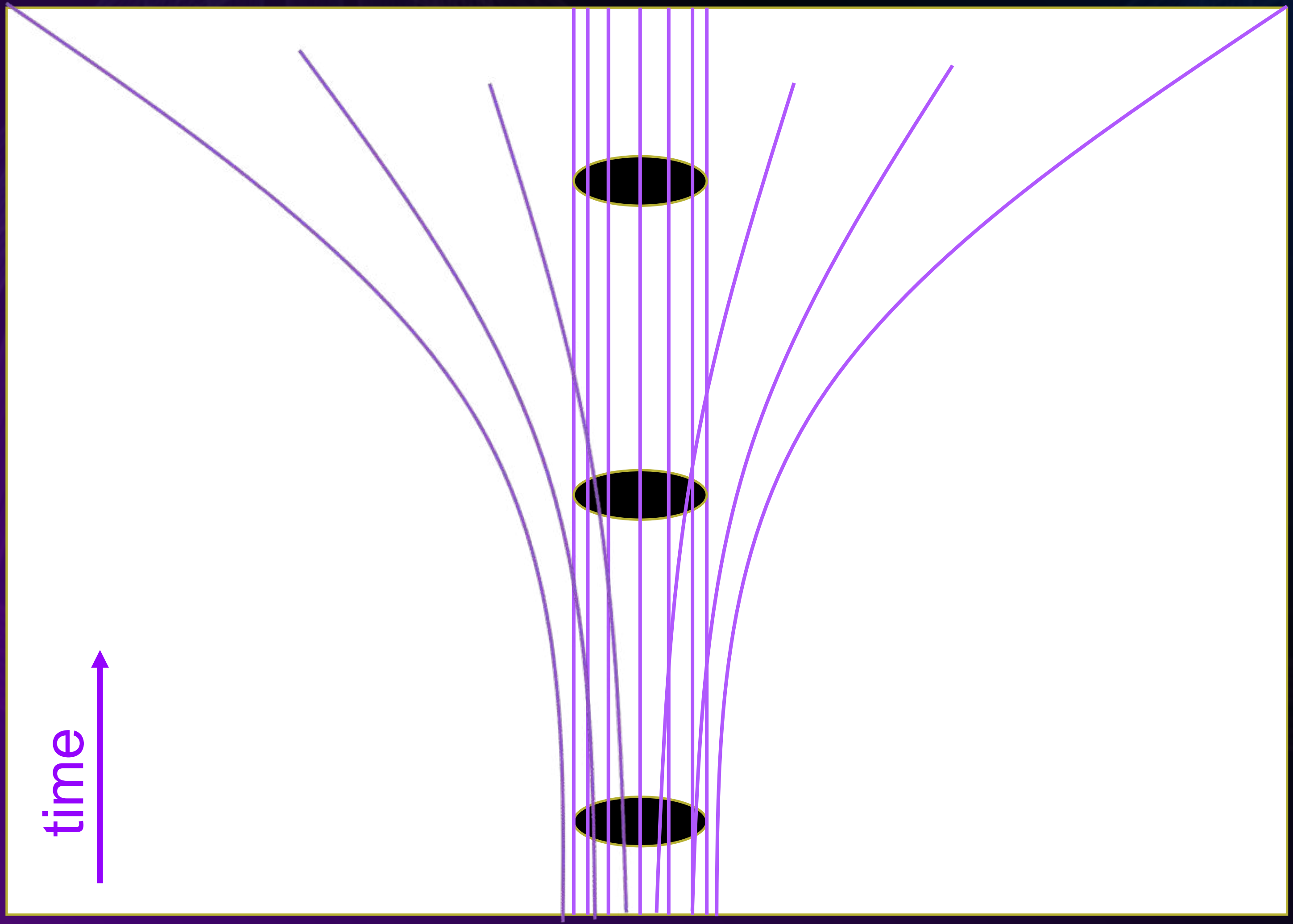
Event horizon:
a null hypersurface

1 A different way to take the EMR limit

Keep small BH finite and take large BH to be infinite

Equivalence principle:

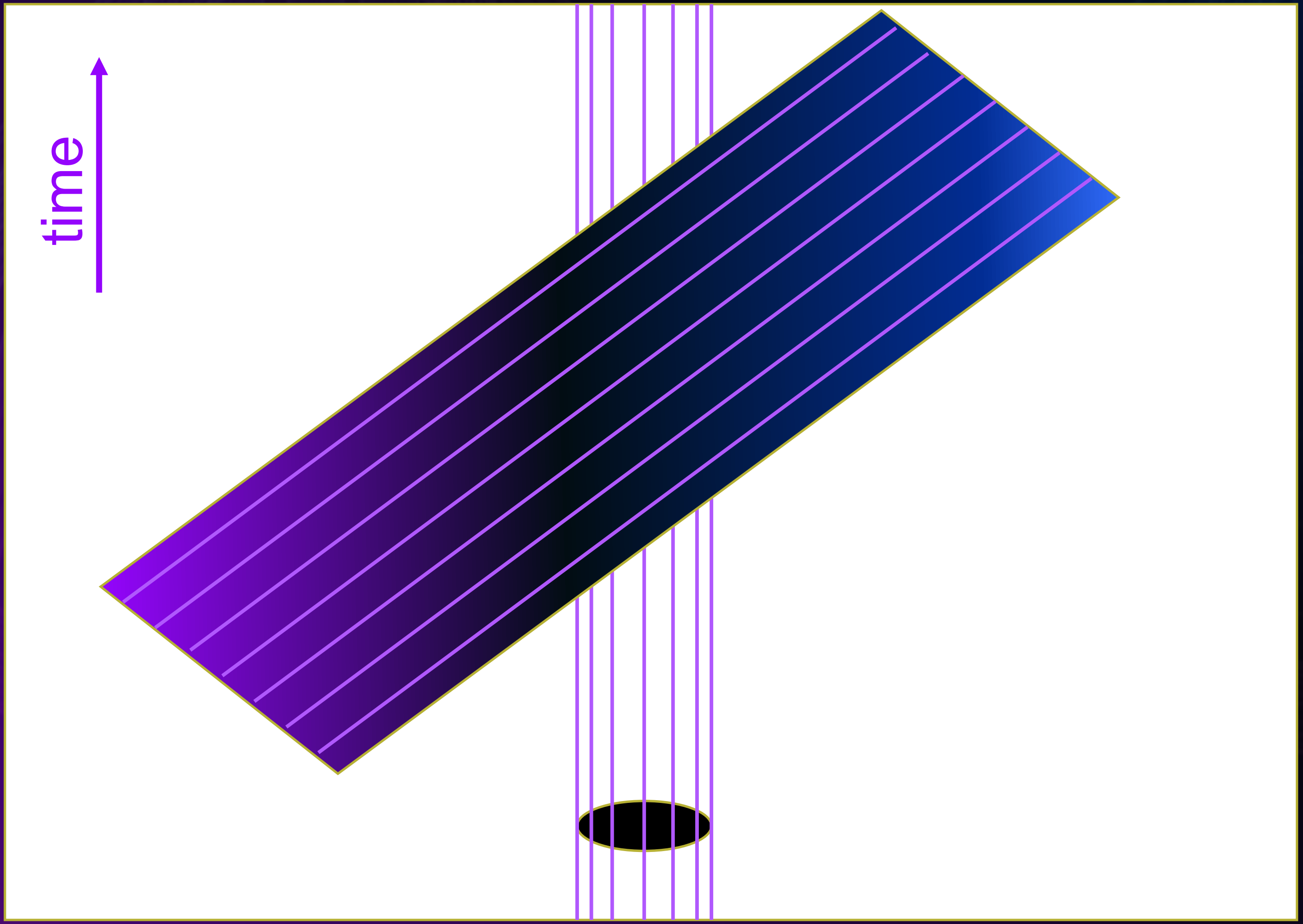
In reference frame of freely falling small BH the gravitational field from the large BH is unnoticeable



Where did the large BH go?

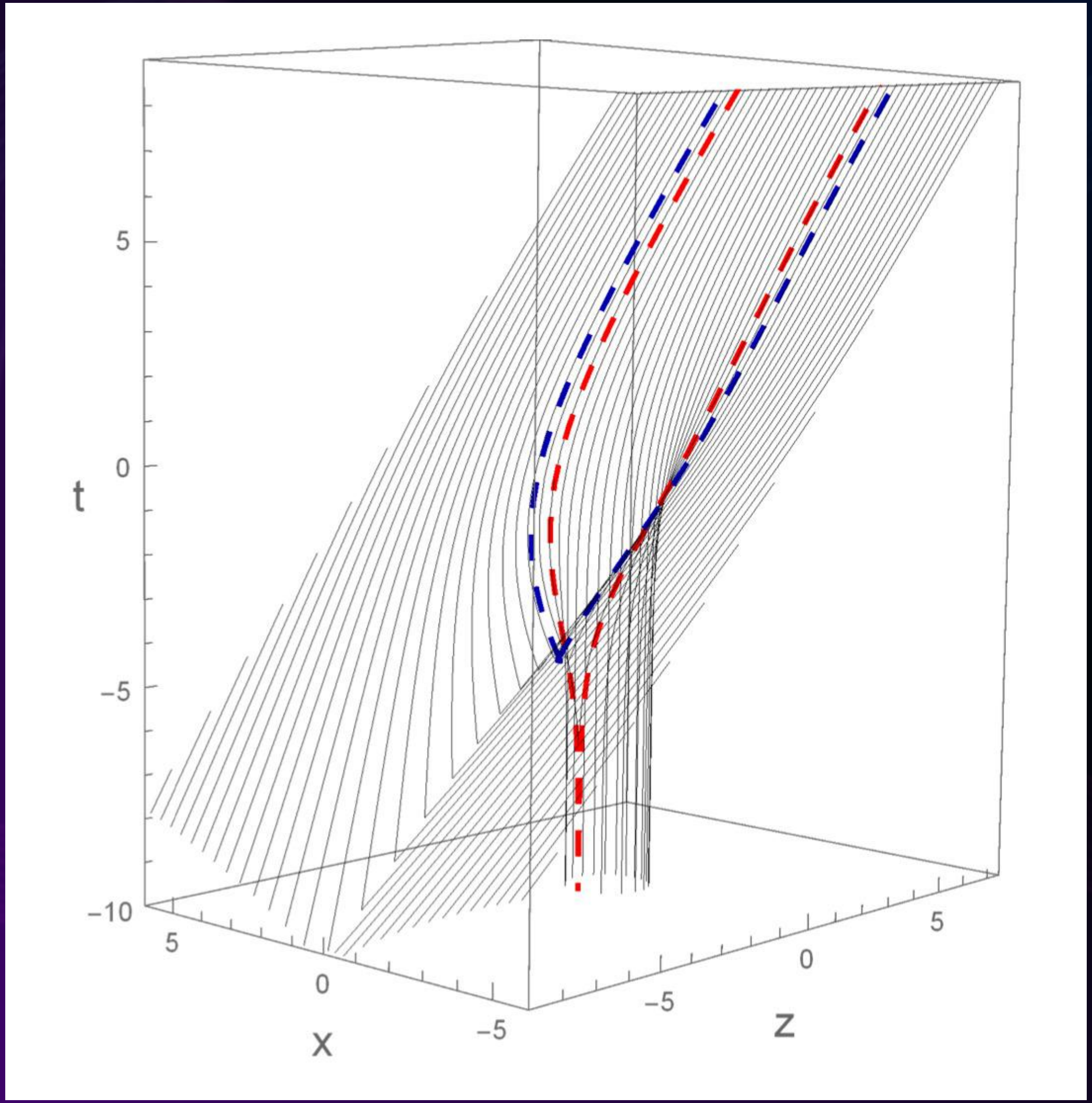
1 Determination of the event horizon

Boundary conditions select a congruence of null geodesics



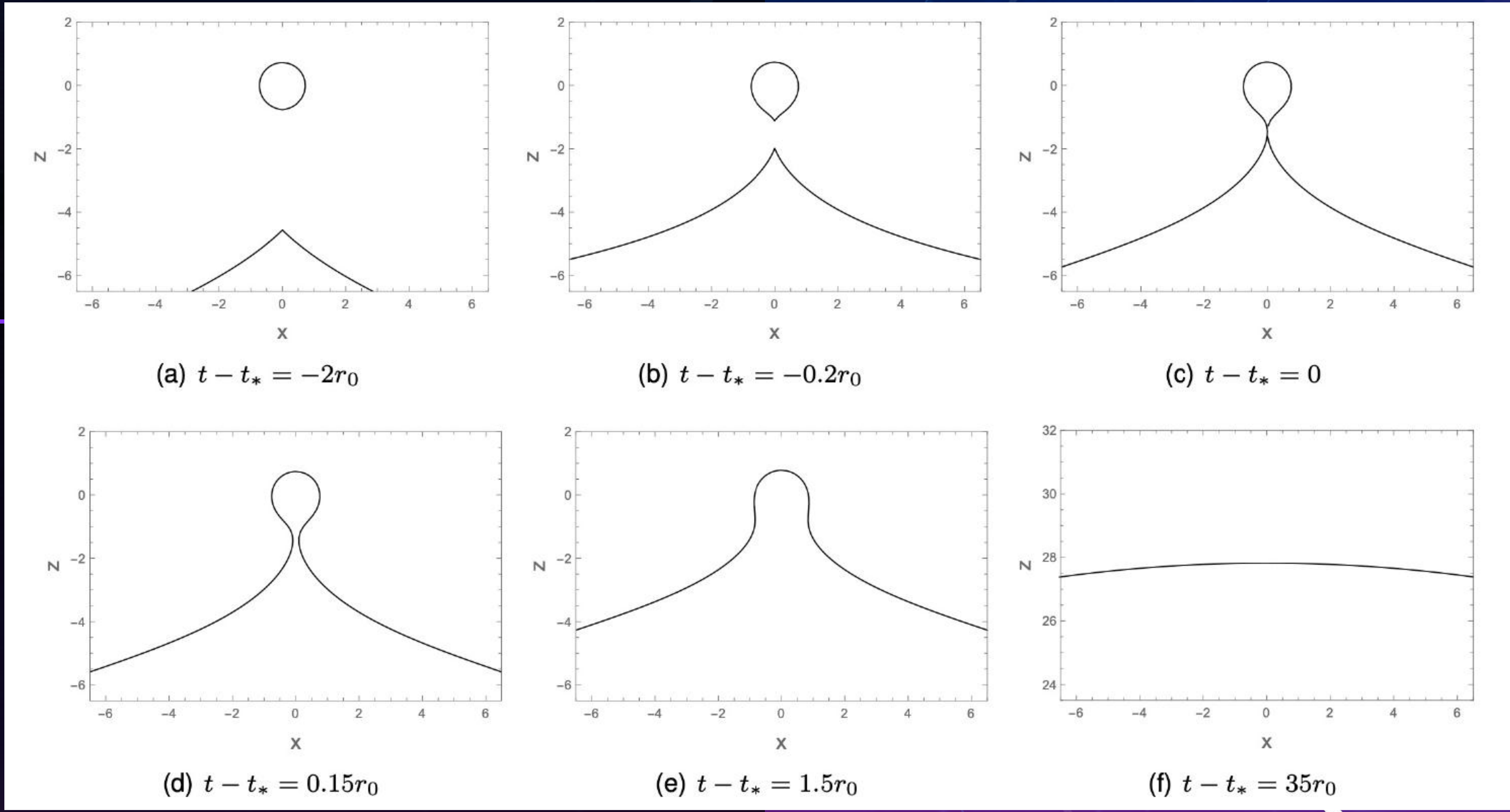
In the far future the generators of the event horizon must approach a null hyperplane.

1 3D rendering of the full event horizon



One spatial dimension suppressed

1 2D time frames (for charged BH merger)



(a) $t - t_* = -2r_0$ (b) $t - t_* = -0.2r_0$ (c) $t - t_* = 0$

(d) $t - t_* = 0.15r_0$ (e) $t - t_* = 1.5r_0$ (f) $t - t_* = 35r_0$

Image credit:
João M. Dias (2022)

1 This approach has been applied to...

- Mergers between non-rotating and neutral BHs. (Emparan-Martínez (2016))
- Mergers between spinning and neutral BHs. (Emparan-Martínez-Zilhão (2017))
- Mergers between a star and a large BH. (Emparan-Marín (2020))
- Mergers between charged, non-rotating BHs. (Pina-Orselli-Pica (2022))
- Mergers between a wormhole and a large BH. (Dias-Frassino-Paccoia-JR (2023))

  (See Frassino's talk)

2 Higher curvature corrections to GR

- In effective low-energy theory of gravity, it is natural to organize corrections to the Einstein-Hilbert term by the number of derivatives:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left\{R + \frac{1}{M_{Pl}^2}\text{(terms quadratic in Riemman)} + \frac{1}{M_{Pl}^4}\text{(terms cubic in Riemman)} + O\left(M_{Pl}^{-6}\right)\right\}$$

2 Einsteinian Cubic Gravity

(Bueno-Cano (2016))
(Hennigar-Kubiznak-Mann (2017))

A higher derivative extension of General Relativity

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,\left\{R - 2\lambda G^2\mathcal{P}\right\}$$

dimensionless coupling constant

where

$$\mathcal{P} \equiv 12 R_a{}^c{}_b{}^d R_c{}^e{}_d{}^f R_e{}^a{}_f{}^b + R_{ab}{}^{cd} R_{cd}{}^{ef} R_{ef}{}^{ab} - 12 R_{abcd} R^{ac} R^{bd} + 8 R_a{}^b R_b{}^c R_c{}^a$$

- ECG is the most general diff-invariant metric theory of gravity up to cubic order in curvature, whose linearized spectrum on maximally symmetric backgrounds coincides with that of GR (and for which the coefficients of higher-curvature corrections are dimension-independent).

2 Black holes in ECG

(Bueno-Cano (2016))
(Hennigar-Mann (2016))

- Static, spherically symmetric BH solutions of the form

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2$$

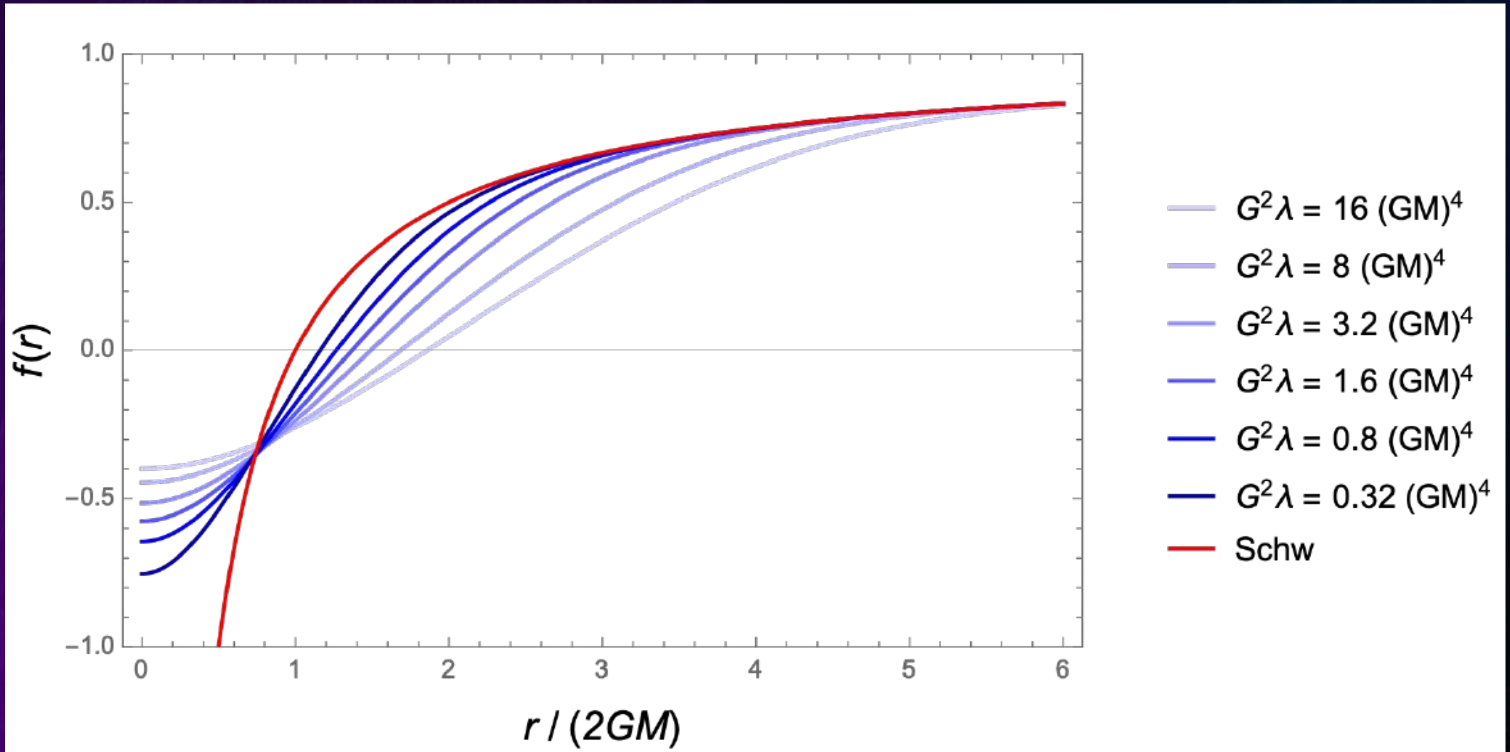
exist, as long as the blackening factor $f(r)$ satisfies:

$$2GM = -(f-1)r - G^2\lambda\left[4f'^3 + 12\frac{f'^2}{r} - 24f(f-1)\frac{f'}{r^2} - 12ff''\left(f' - \frac{2(f-1)}{r}\right)\right]$$

2 Black holes in ECG

- Blackening factor profile for static, spherically symmetric, neutral BHs in ECG:

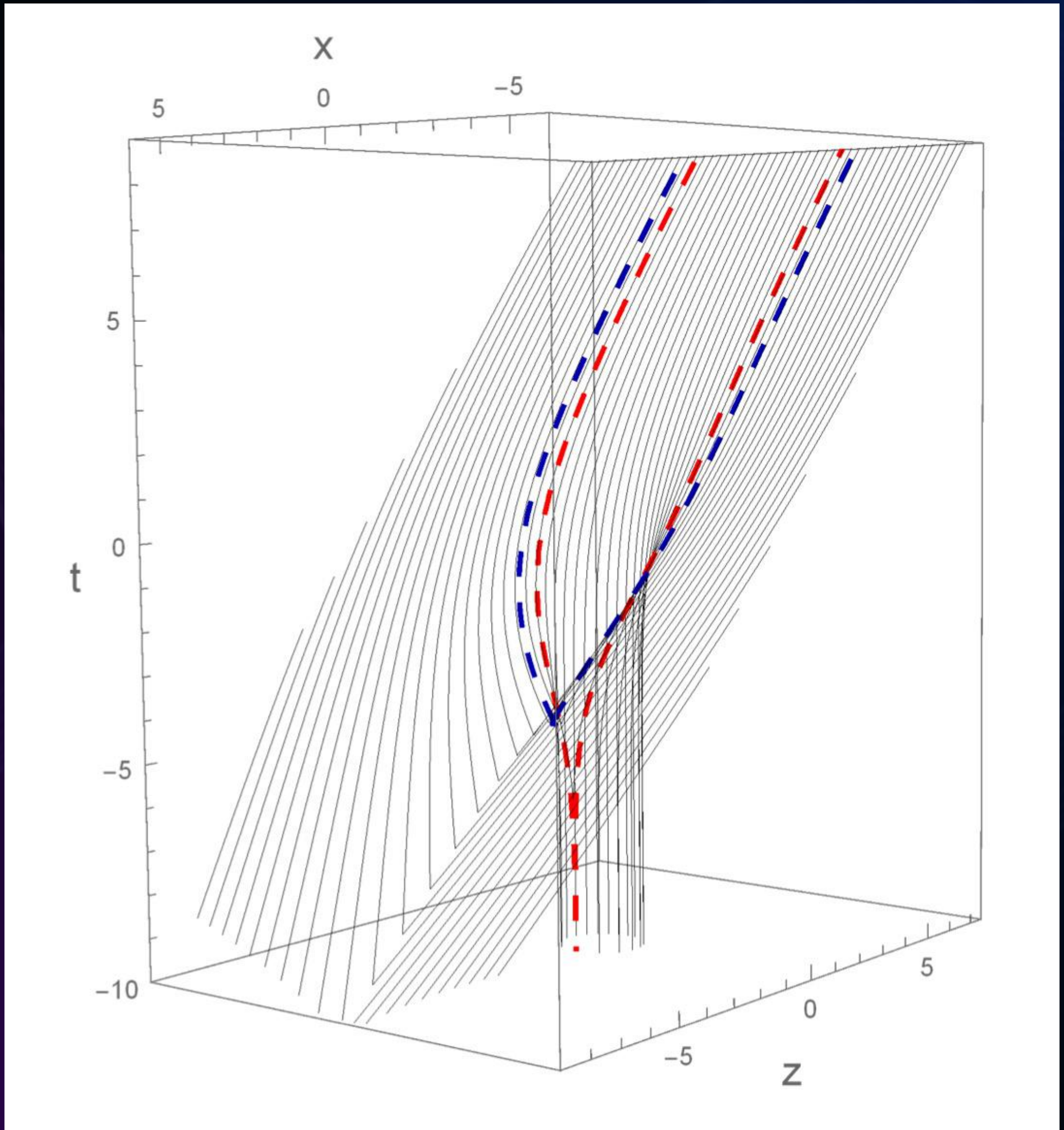
[Bueno-Cano (2016)]



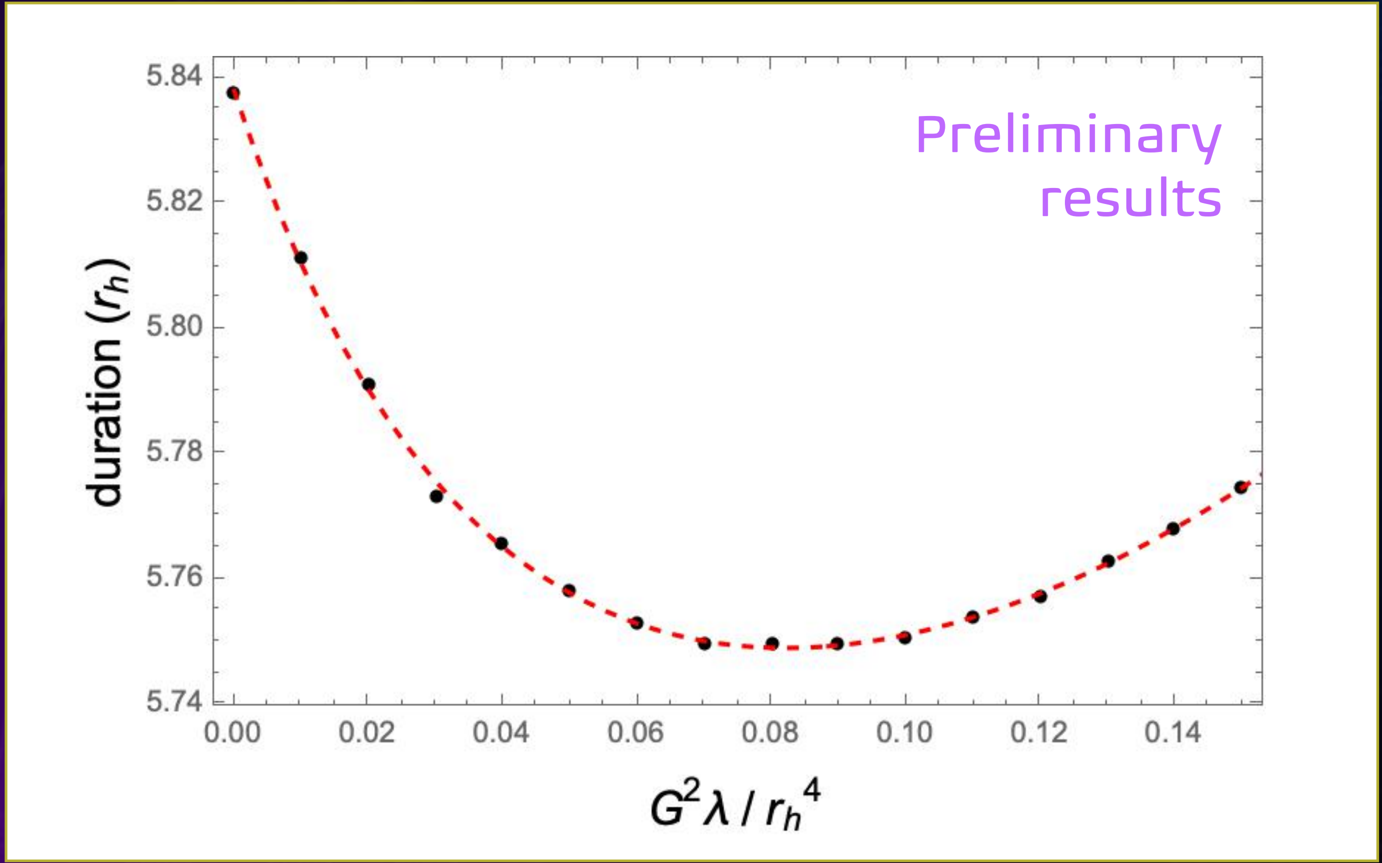
- Charged BHs in ECG have intriguing properties (e.g., non-uniqueness) [Frassino-JR (2020)]

3 Black hole mergers in ECG

- Having fixed a background geometry, integrate (backward in time) the null geodesic equations.
- Specific (asymptotic) boundary conditions are required.
- The collection of all these generators forms the event horizon.
- This can be done for any value of the coupling constant λ.



3 Comparing the duration of the merger



- There exists a coupling λ that yields the quickest merger.
- But large couplings λ result in mergers that are slower than those of GR.

Conclusion

Unconventional way of taking the EMR limit + + Equivalence Principle + Ray Tracing = quick route to obtain the time evolution of the merger of compact objects.

- This can be done for any (diff-invariant) modified theory of gravity.
- We applied it to determine the duration of BH mergers Einsteinian Cubic Gravity.

Outlook

- Bound coupling constants of modified gravity theories from gravitational waves detections.
- Useful as benchmark for numerical relativity simulations.