Imaging Parallel Universes through Kerr Black Holes

Dávid Szepessy

PhD student, ELTE Eötvös Loránd University

FIKUT NEXTGEN, Budapest, 2026

Supervisors:

Bence Kocsis

University of Oxford

Gyula Dávid

ELTE

5. November 2026, Wigner RCP

Introduction

Goal:

- Observable predictions for Parallel Universes

Content

- Kerr Black Holes and Geodesics
- Research Question
- Results

Kerr Black Holes

- Kerr, R. P., 1963
- Static, axially symmetric vacuum solution
- Symmetries → spacetime around a rotating object
- Rotating black holes [1, 4, 3]



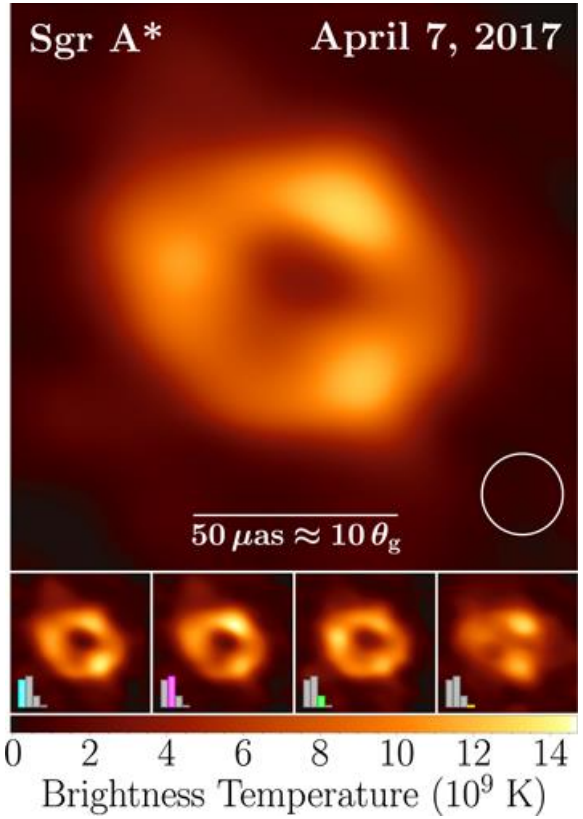
$$ds^2 = \left(1 - \frac{2r}{\Sigma}\right) dt^2 - \frac{\Sigma}{\Delta} dr^2 - \Sigma d\theta^2 - \left(r^2 + a^2 + 2\frac{ra^2}{\Sigma} \sin^2\theta\right) \sin^2\theta \, d\varphi^2 + 4\frac{ra}{\Sigma} \sin^2\theta \, dt \, d\varphi$$

$$\Sigma(r, \theta) = r^2 + a^2 \cos^2\theta,$$

$$\Delta(r) = r^2 - 2r + a^2.$$

Kerr Black Holes

- Kerr, R. P., 1963
- Static, axially symmetric vacuum solution
- Symmetries → spacetime around a rotating object
- Rotating black holes [1, 4, 3]



$$ds^2 = \left(1 - \frac{2r}{\Sigma}\right) dt^2 - \frac{\Sigma}{\Delta} dr^2 - \Sigma d\theta^2 - \left(r^2 + a^2 + 2\frac{ra^2}{\Sigma} \sin^2\theta\right) \sin^2\theta \, d\varphi^2 + 4\frac{ra}{\Sigma} \sin^2\theta \, dt \, d\varphi$$

$$\Sigma(r, \theta) = r^2 + a^2 \cos^2\theta,$$

$$\Delta(r) = r^2 - 2r + a^2.$$

Singularity Structure

Two horizons: $\Delta = 0$

Singularity: $\Sigma = 0$

- Ring-shaped

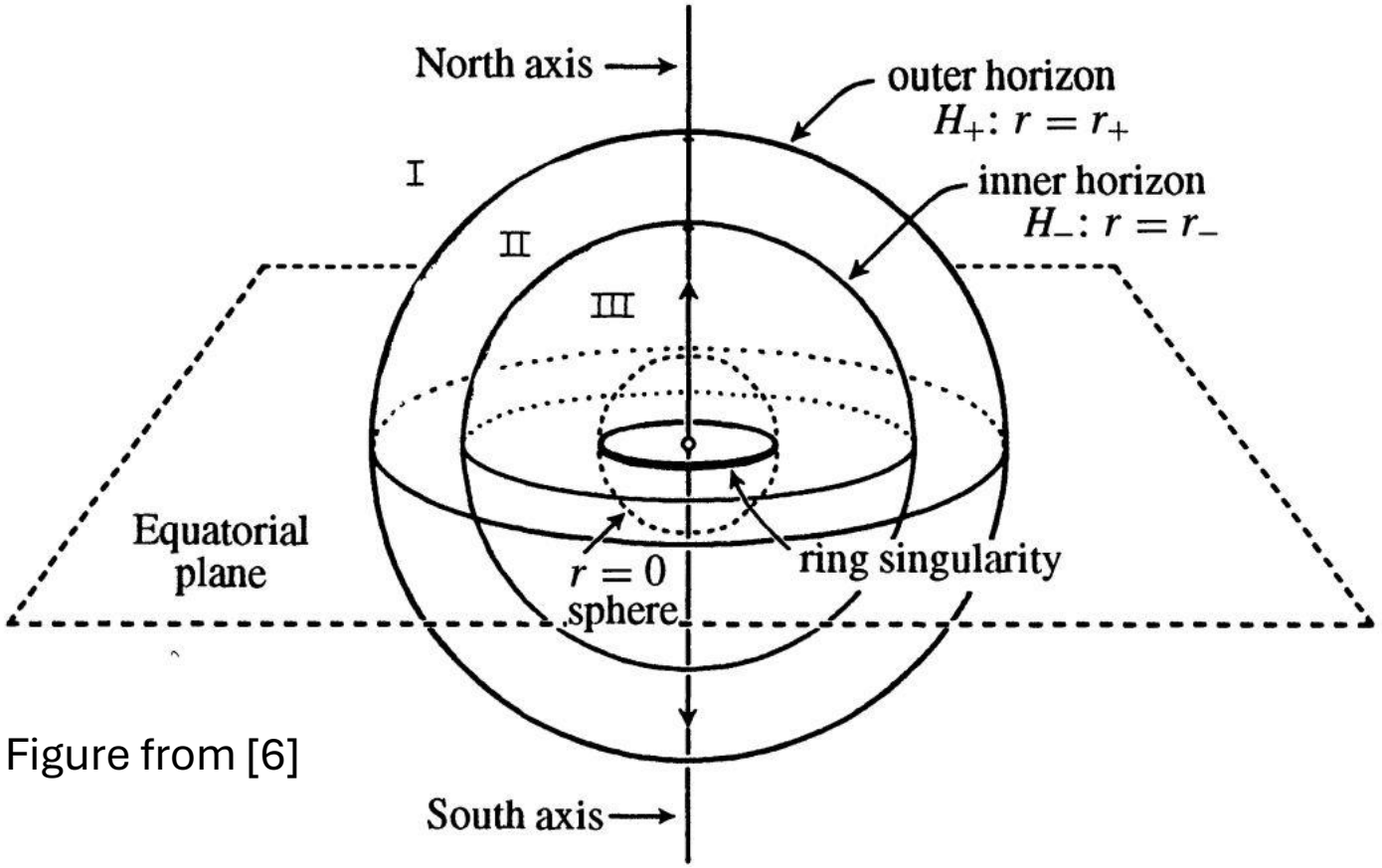
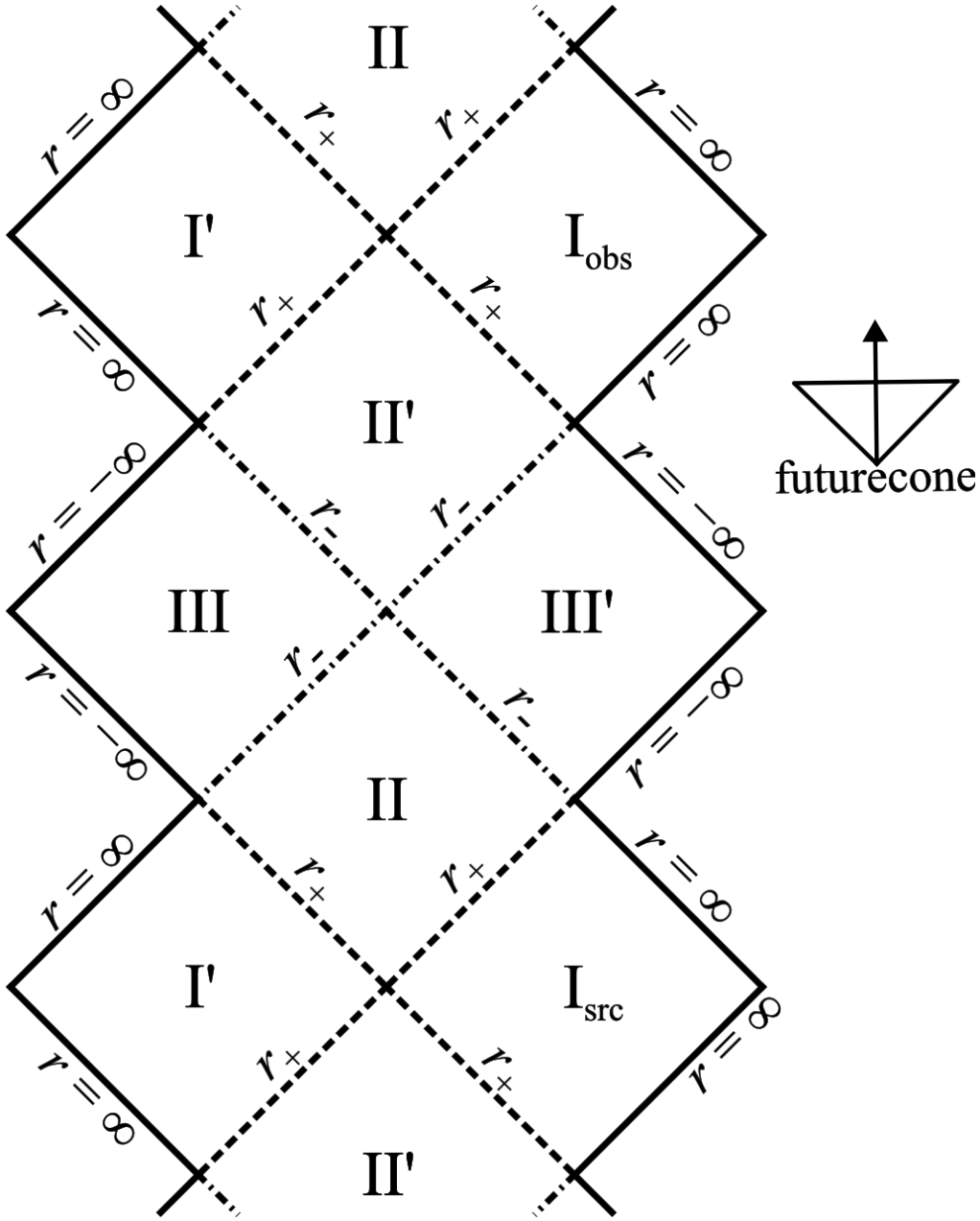


Figure from [6]

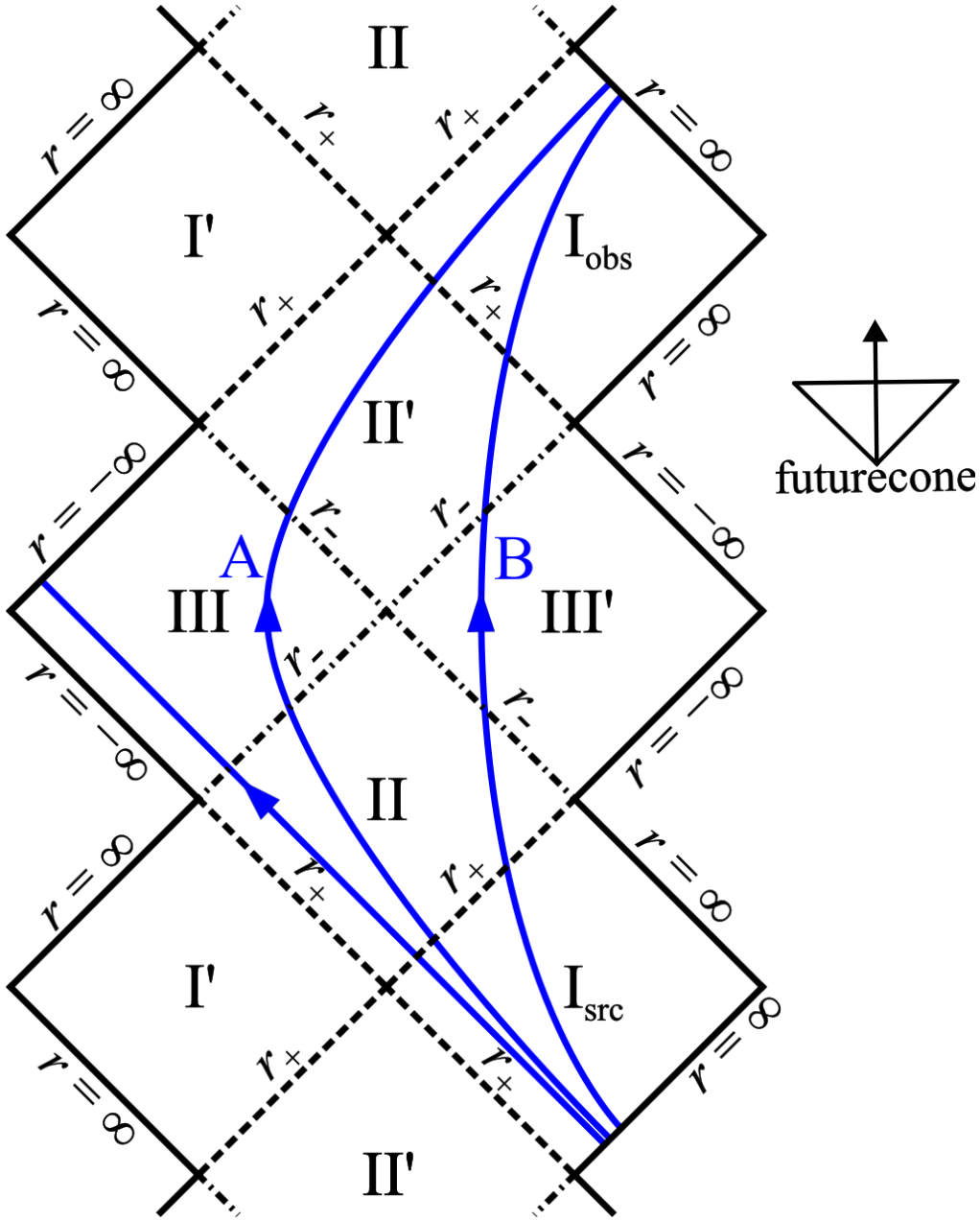
Extending Kerr Spacetime

- Null coordinates
- Coordinate extension
- Gluing
- Maximal extension
- Penrose diagram

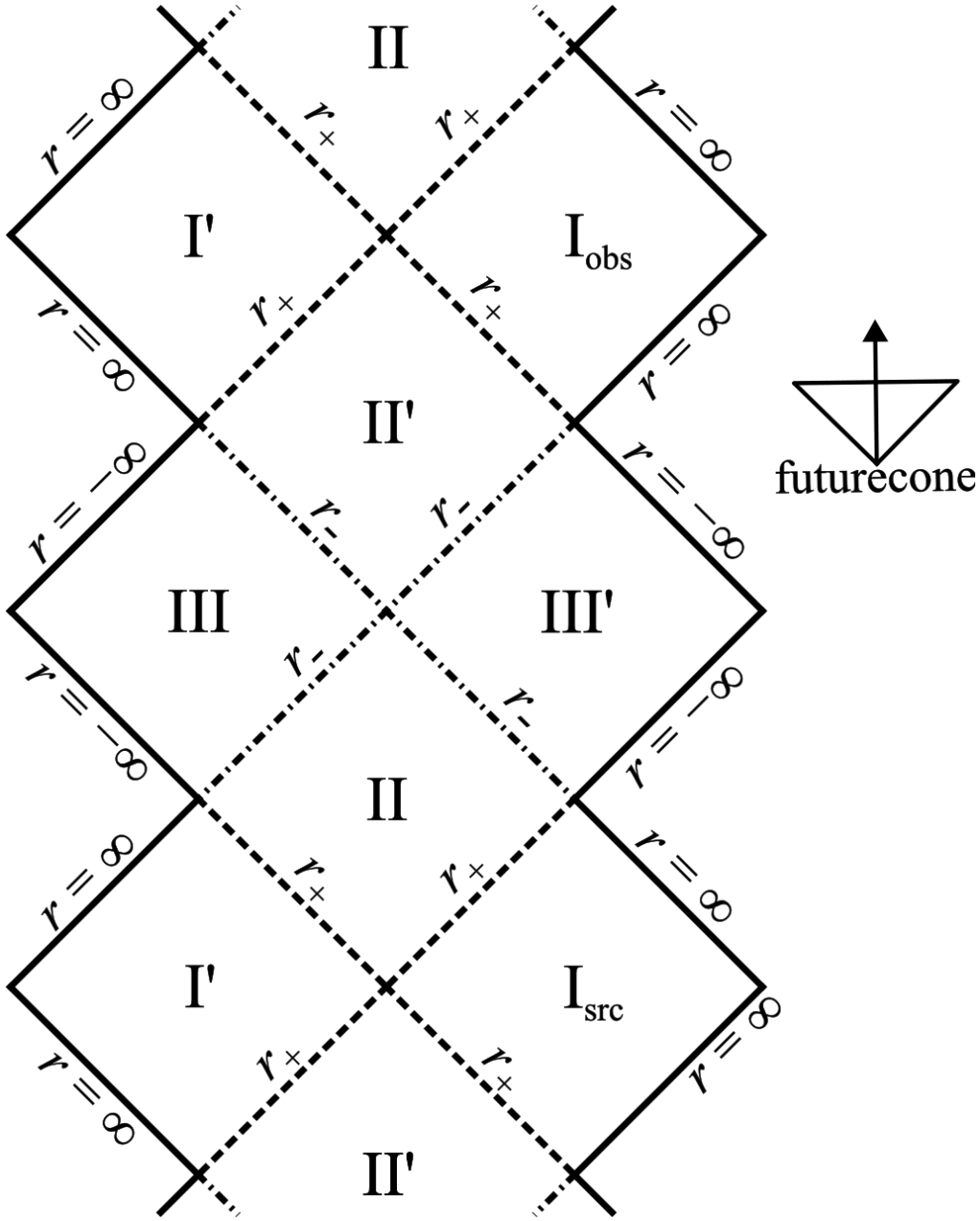


Extending Kerr Spacetime

- Null coordinates
- Coordinate extension
- Gluing
- Maximal extension
- Penrose diagram
- Traversing geodesics
- May be unstable? [7, 2, 5]

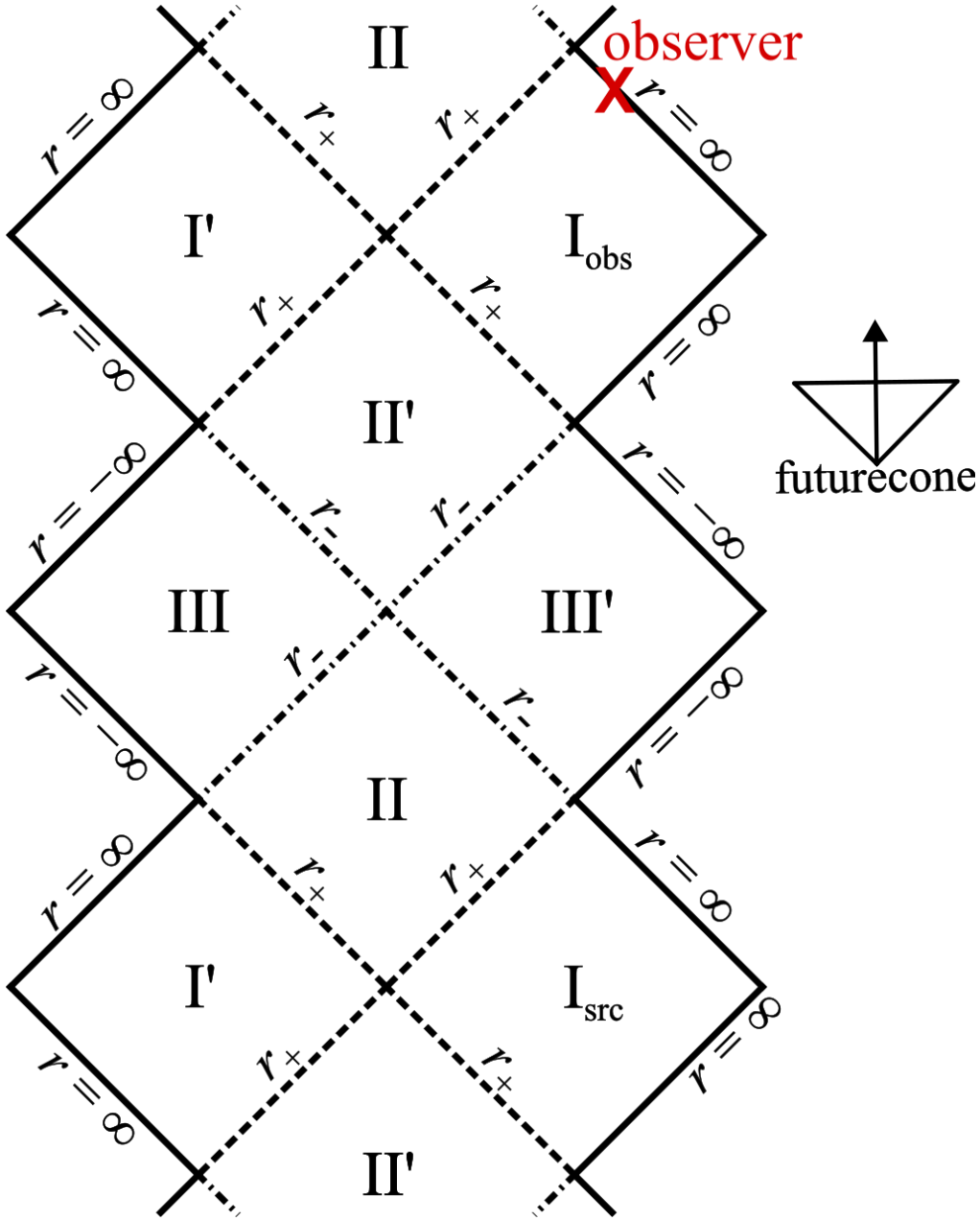


Research Question



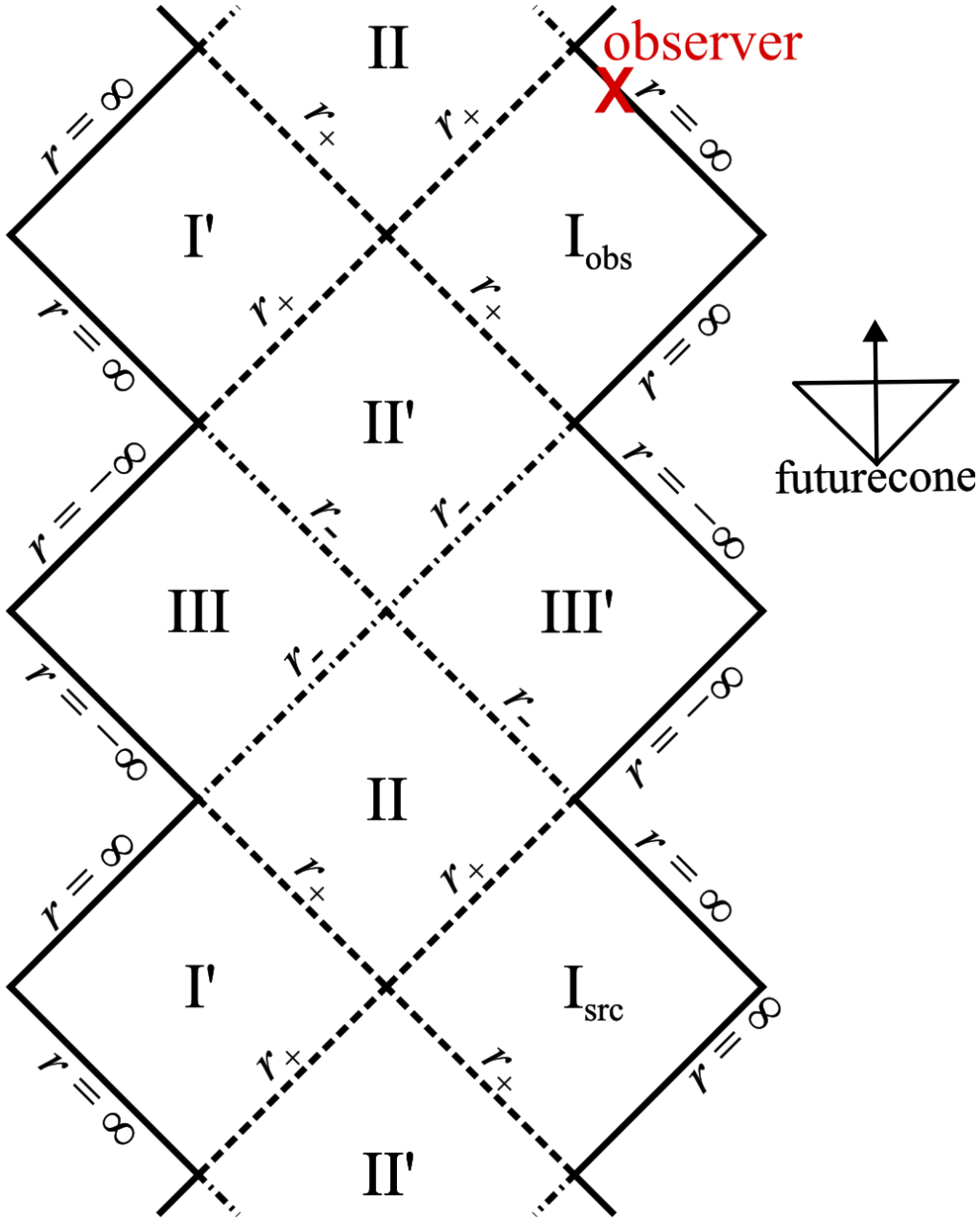
Research Question

- Observer



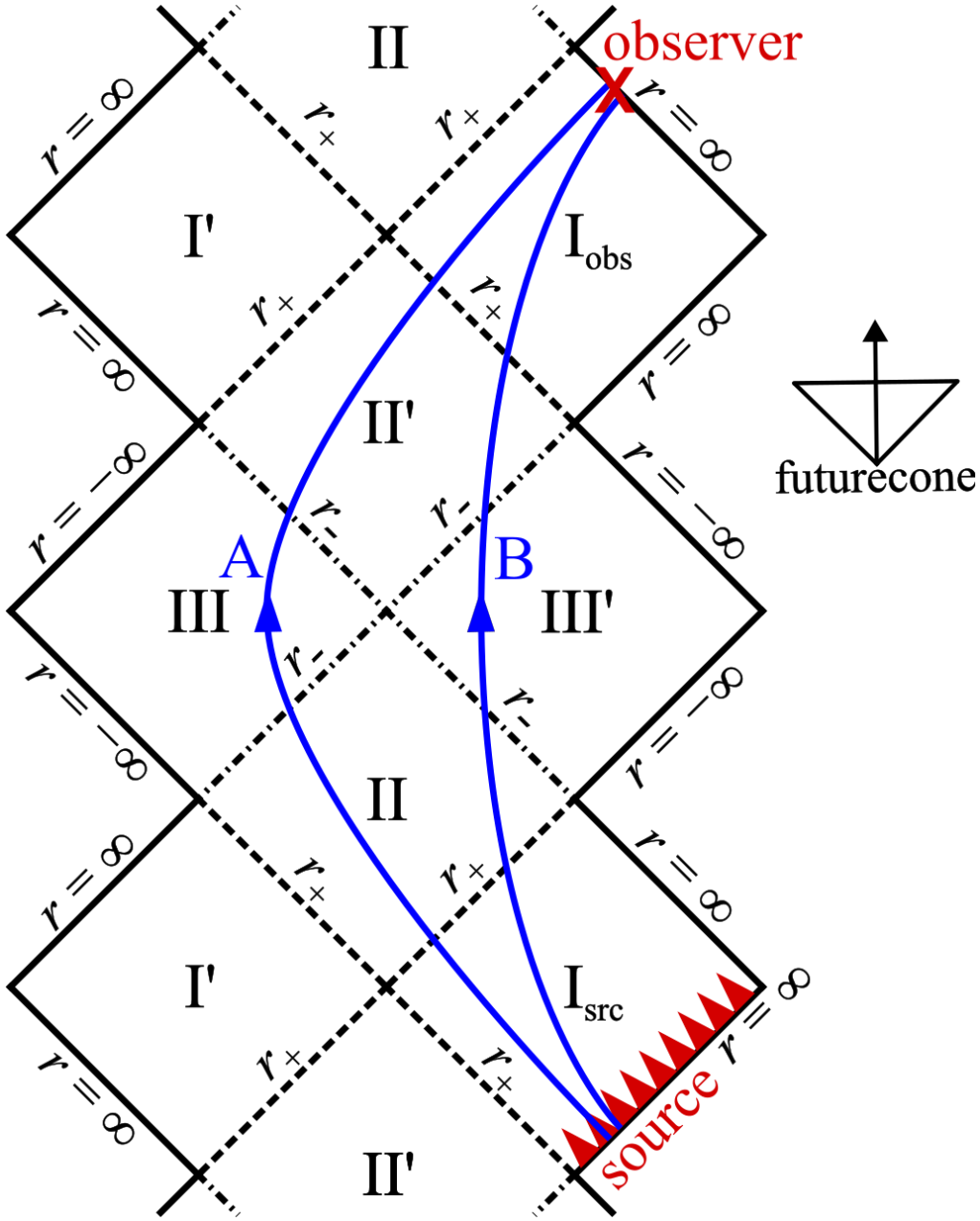
Research Question

- Observer
- Infalling radiation



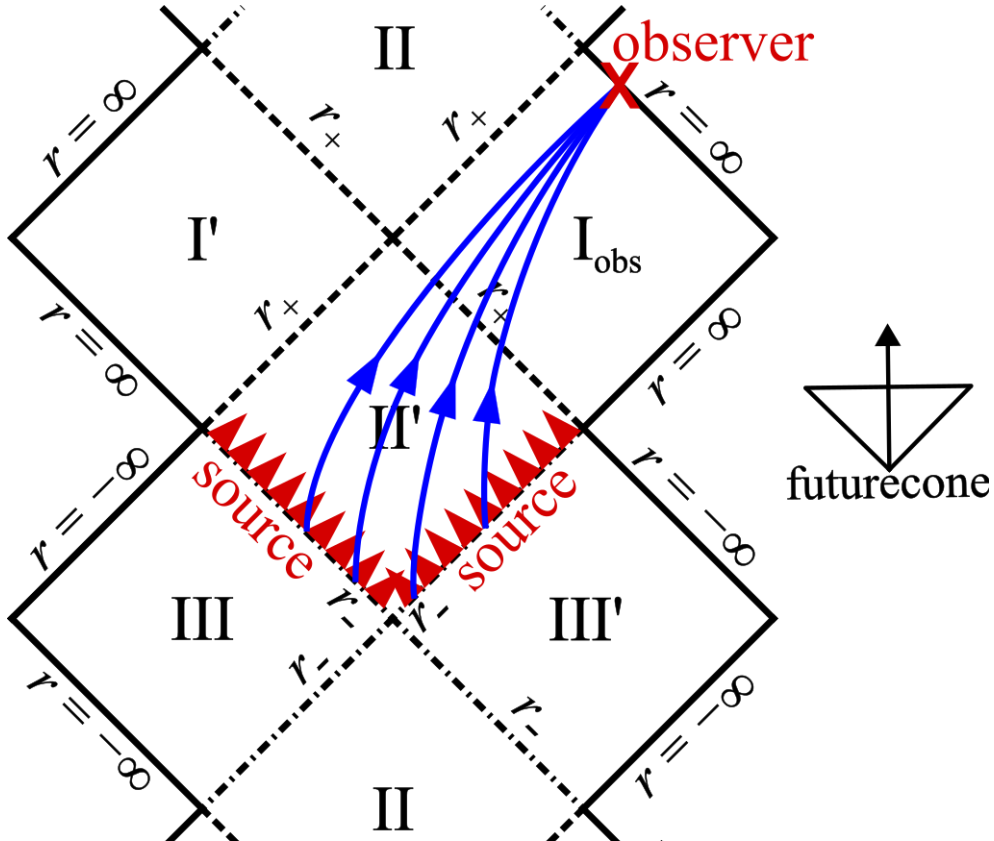
Research Question

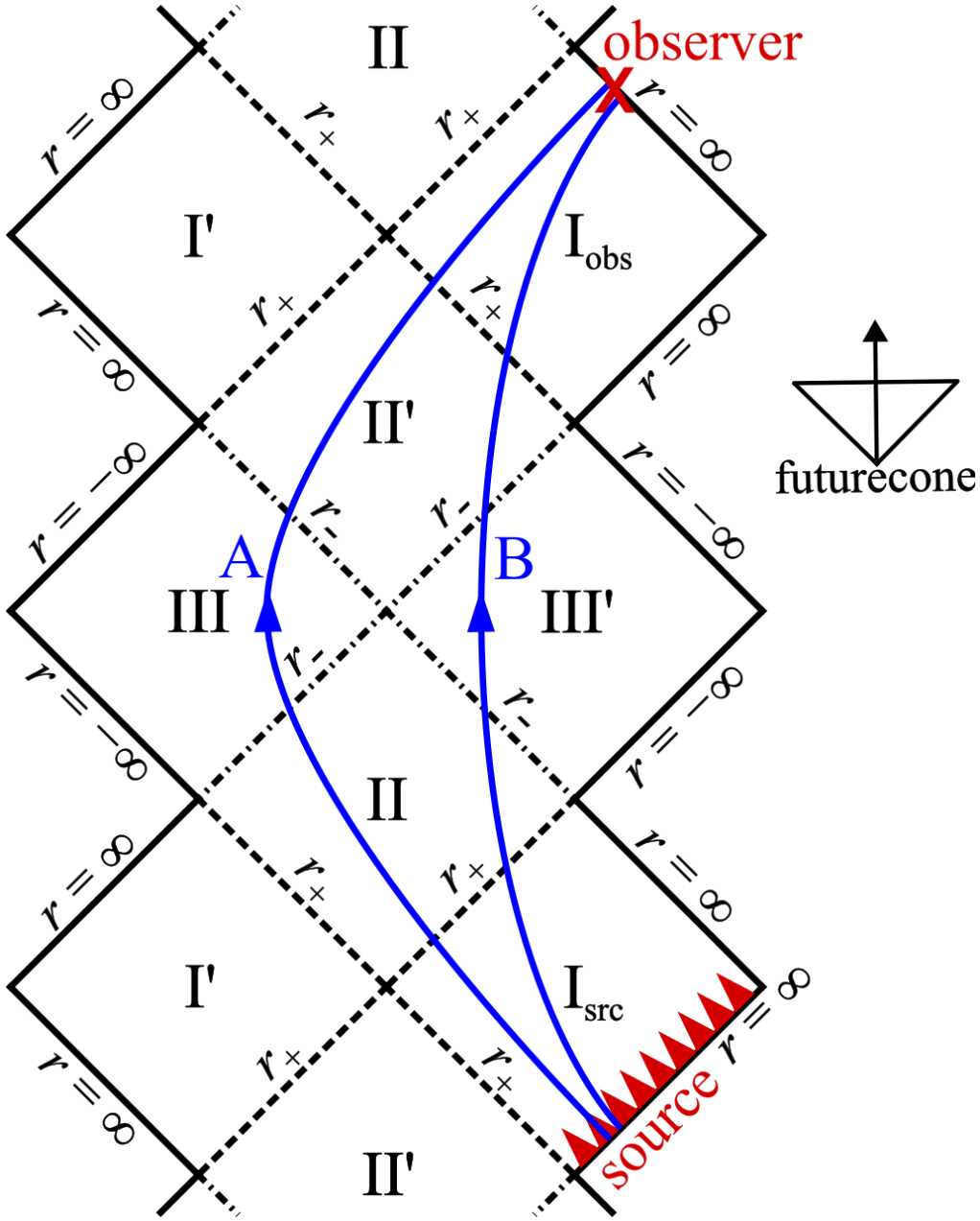
- Observer
- Infalling radiation



Research Question

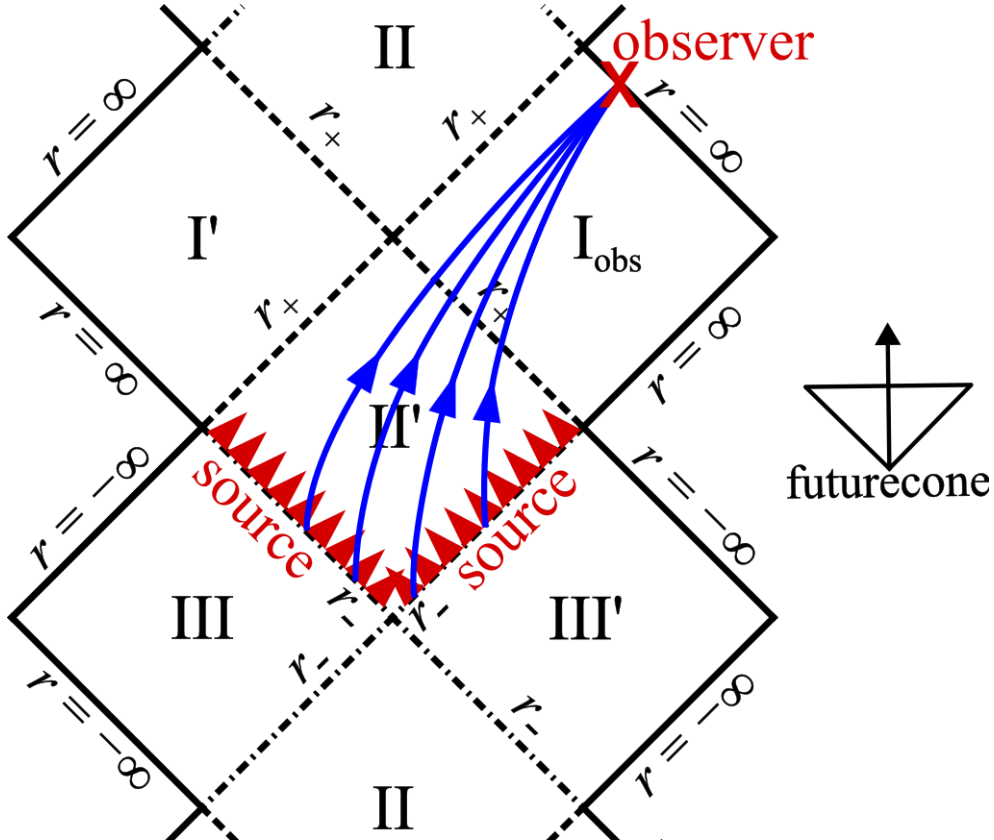
- Observer
- Infalling radiation

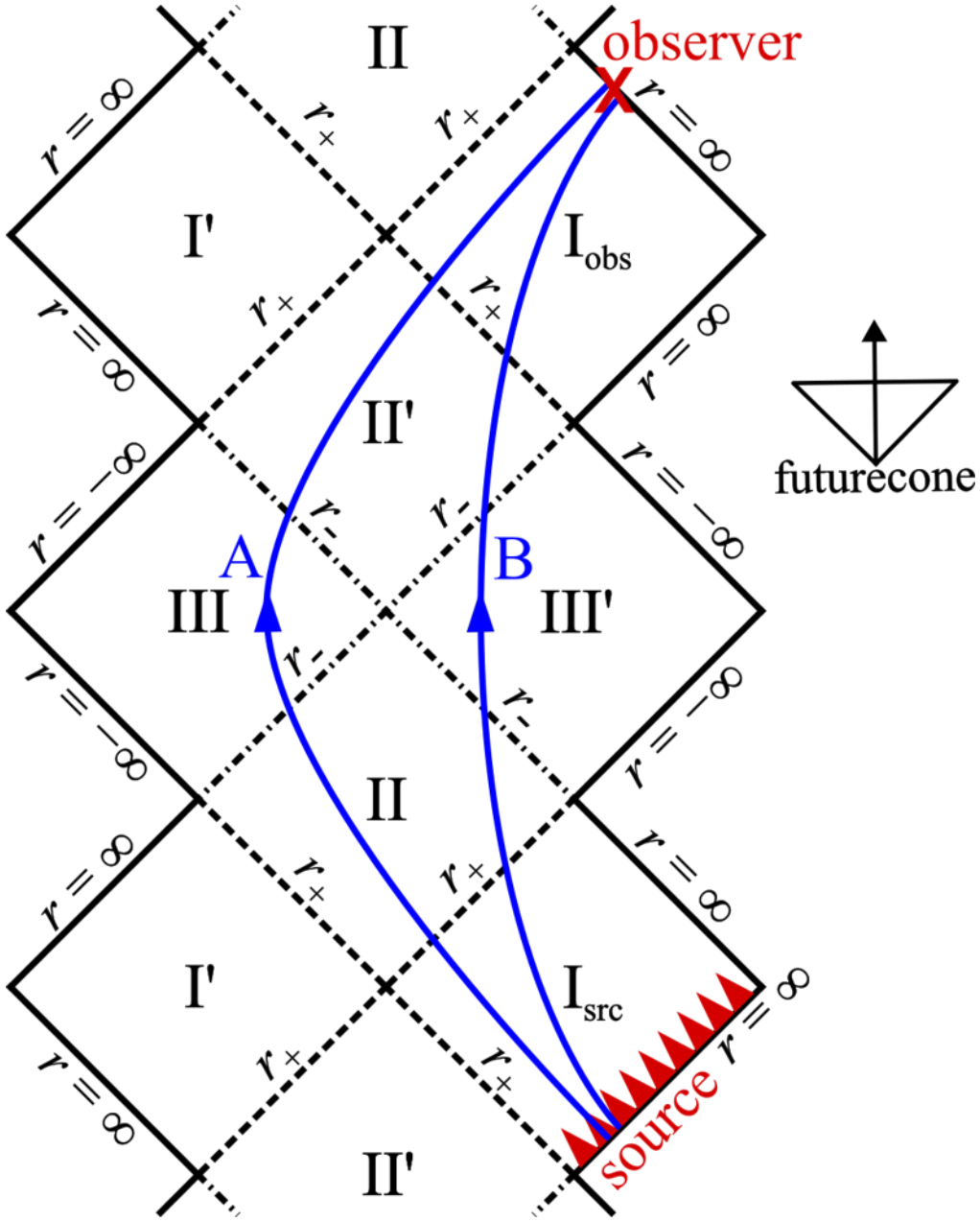




Research Question

- Observer
- Infalling radiation
- Light in the shadow





Null Geodesics

- Symmetries → conserved quantities
- p^2 =0, energy, angular momentum
- Carter's constant

$$\Sigma^2 r'^2 = R(r)$$

$$\Sigma^2 \theta'^2 = \Theta(\theta)$$

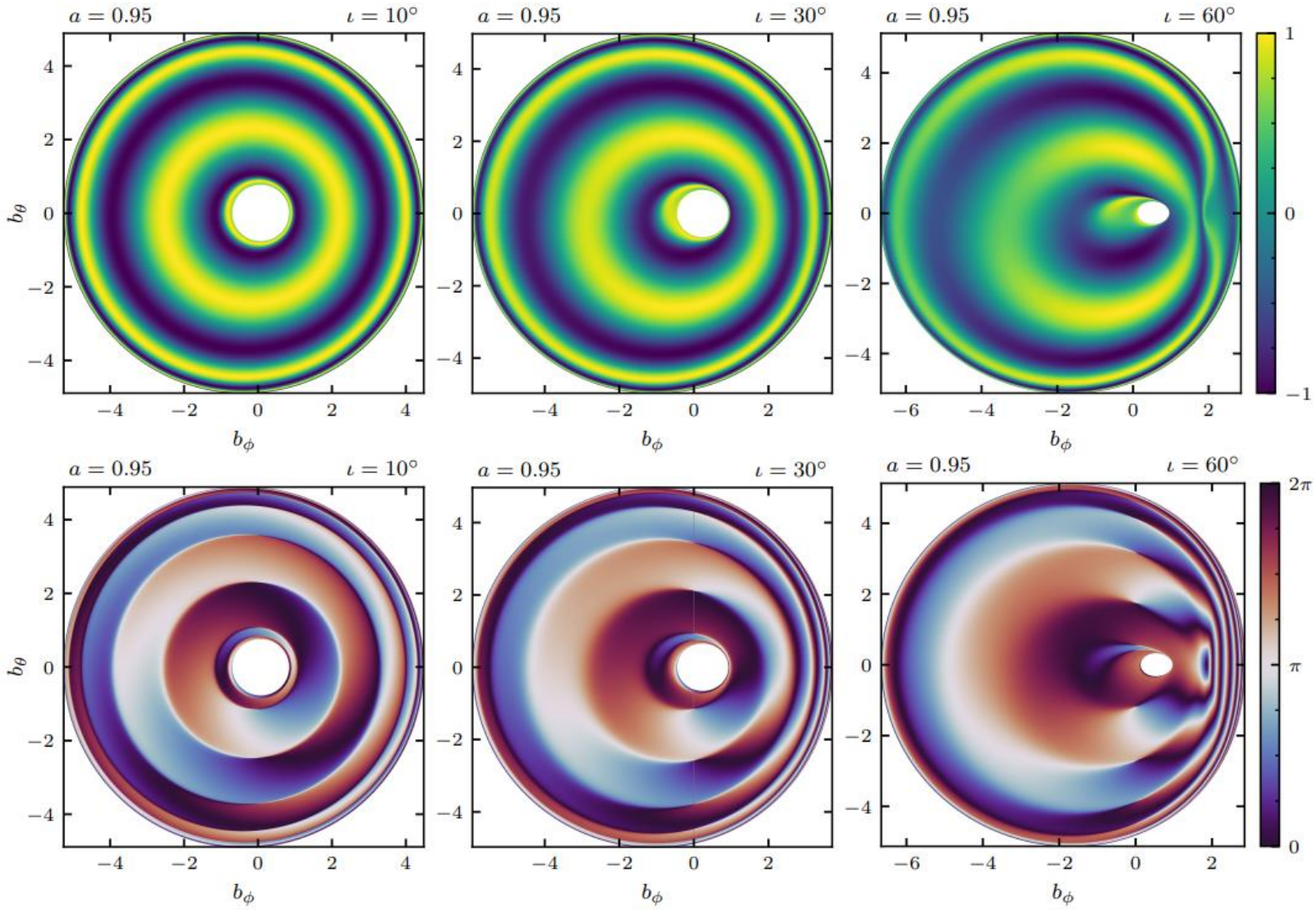
- Effective potentials

- Integrable → elliptic integrals

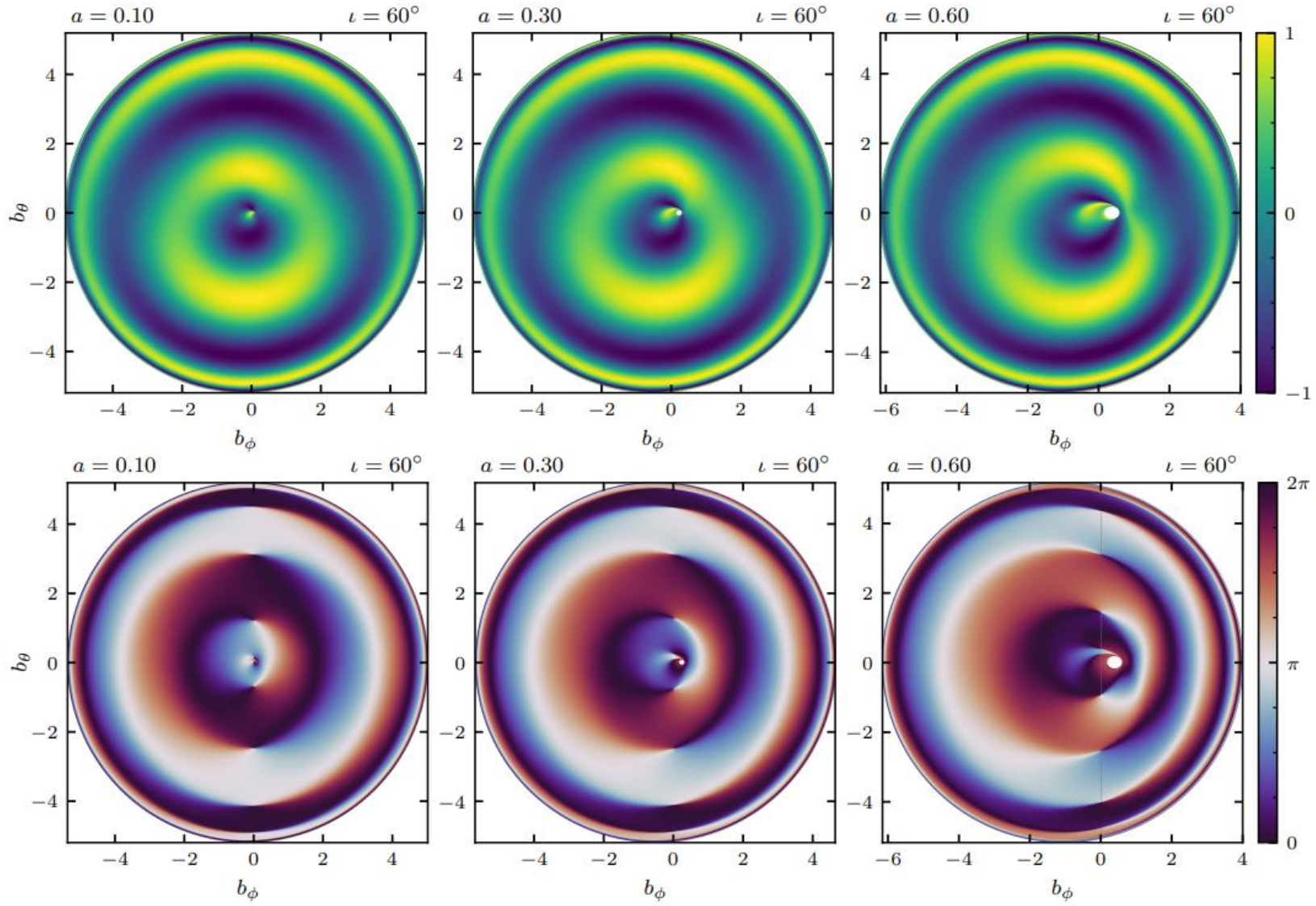
Backward Ray Tracing

- Goal: source sky → image plane
- Parallel beam, backward ray tracing
- Map: source sky ⟷ image plane

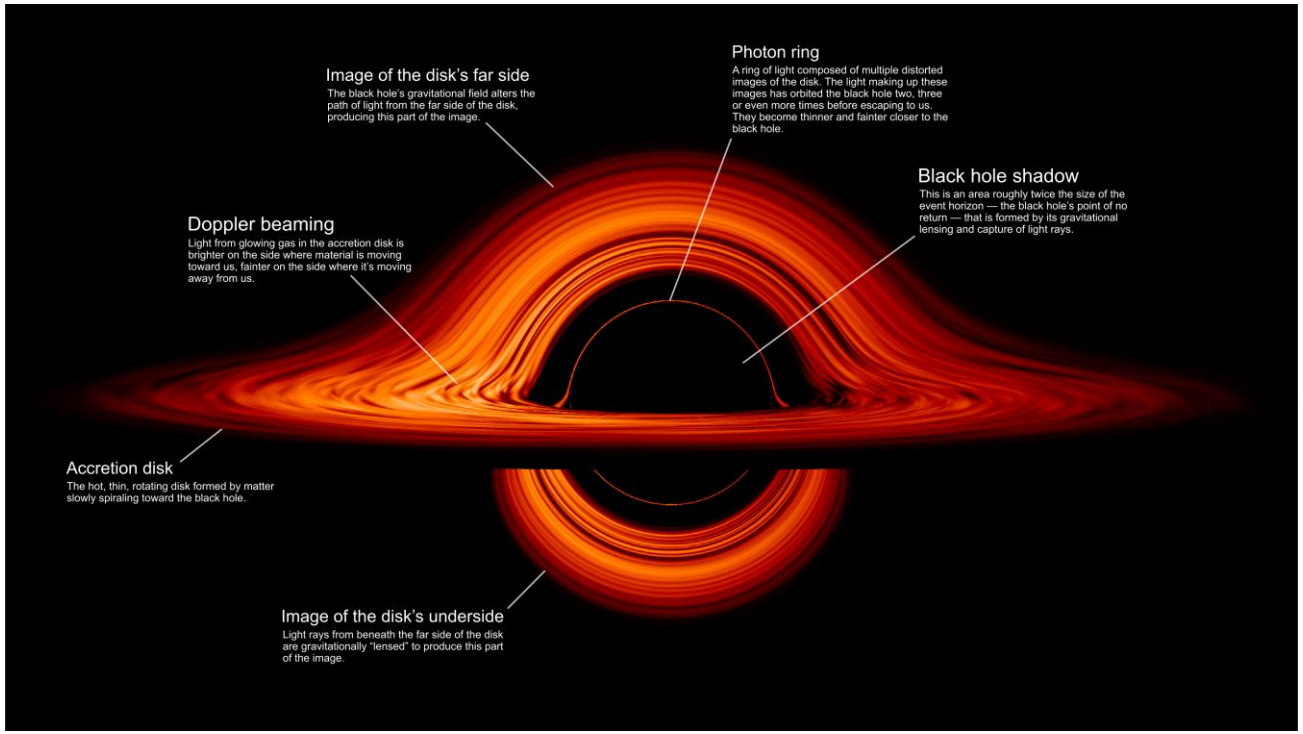
Results: Image Plane Maps

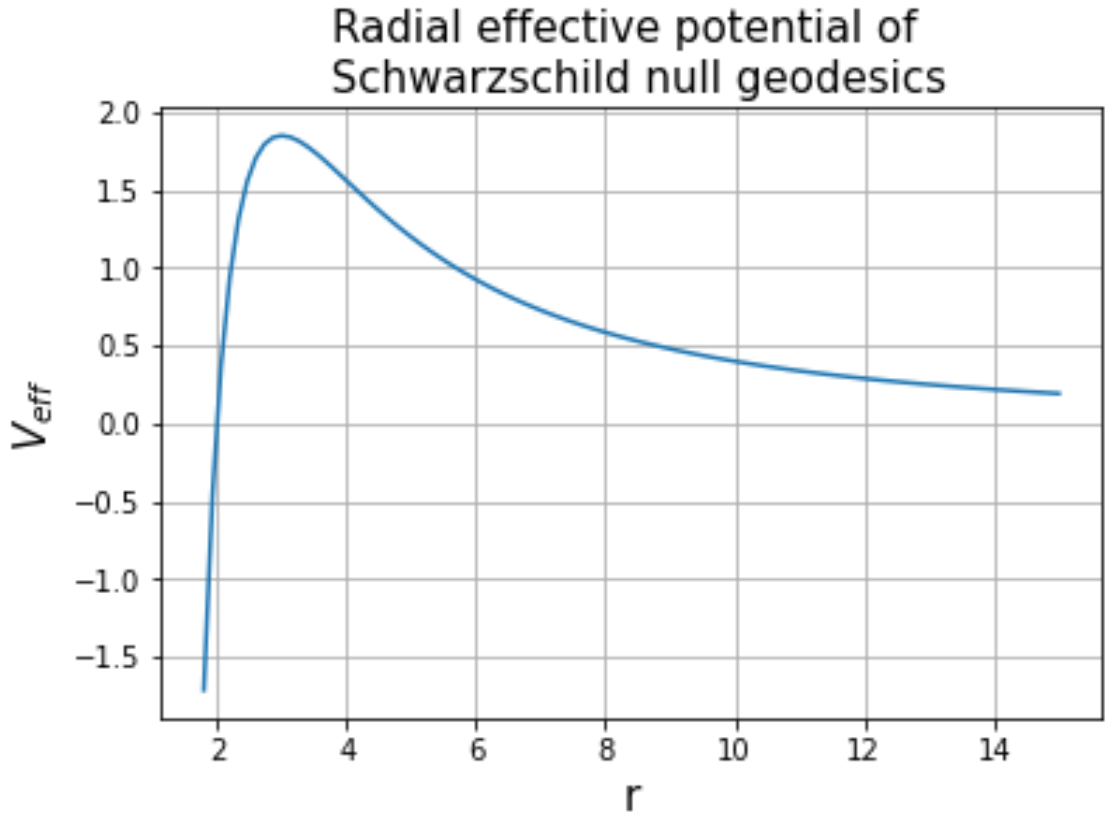


Results: Image Plane Maps

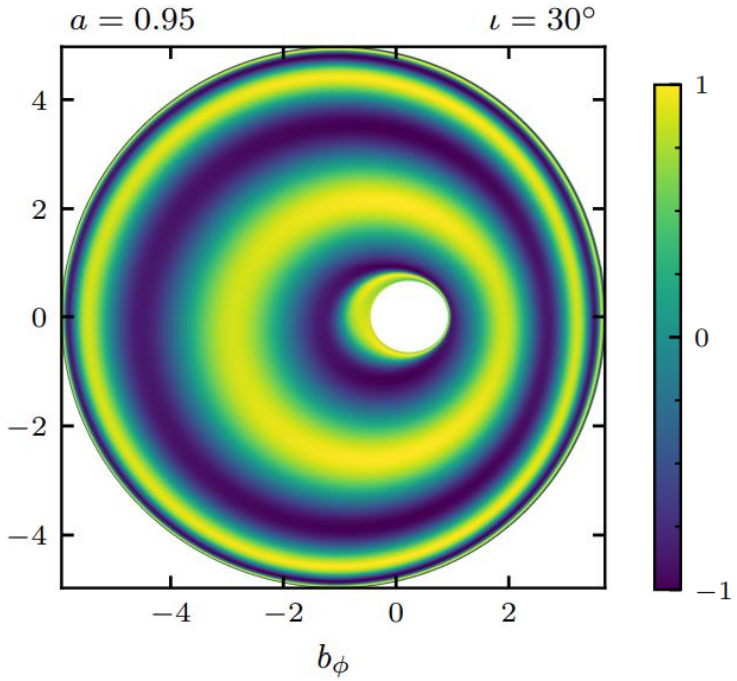


Interpretation: the Unstable Photon Sphere

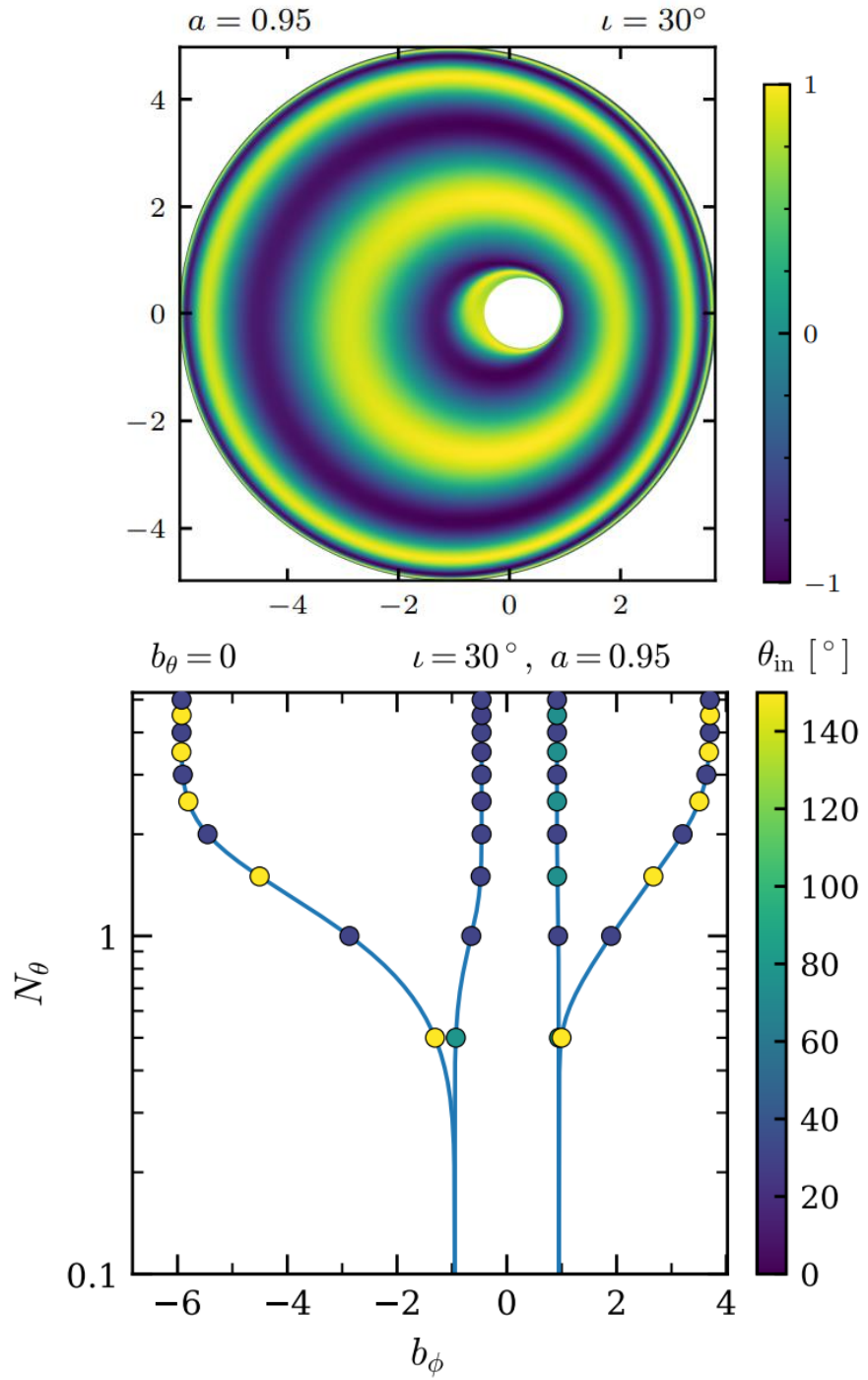




Photon Spheres



Photon Spheres



Summary and Outlook

Results:

- Observational prediction for Parallel Universes

Outlook:

- Paper in preparation (to be submitted to *Physical Review Letters*)
- Image of the Cauchy horizon
- Time-dependent signals (e.g. supernovae)

References

[1] R. Abbott et al. "GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run". In: *Physical Review X* 13.4, 041039 (Oct. 2023), p. 041039. DOI: 10.1103/PhysRevX.13.041039. arXiv: 2111.03606 [gr-qc].

[2] Lior M. Burko, Gaurav Khanna, and Anıl Zenginoğlu. "Cauchy-horizon singularity inside perturbed Kerr black holes". In: 93.4, 041501 (Feb. 2016), p. 041501. DOI: 10.1103/PhysRevD.93.041501. arXiv: 1601.05120 [gr-qc].

[3] Event Horizon Telescope Collaboration et al. "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole". In: 875.1, L1 (Apr. 2019), p. L1. DOI: 10.3847/2041-8213/ab0ec7. arXiv: 1906.11238 [astro-ph.GA].

References

[4] Event Horizon Telescope Collaboration et al. "First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way". In: 930.2, L12 (May 2022), p. L12. DOI: 10.3847/2041-8213/ac6674.

[5] R. P. Kerr. "Do Black Holes have Singularities?" In: *arXiv e-prints*, arXiv:2312.00841 (Nov. 2023), arXiv:2312.00841. DOI: 10.48550/arXiv.2312.00841. arXiv: 2312.00841 [gr-qc].

[6] Barrett O'Neill. *The geometry of Kerr black holes*. Dover Publications, 1995.

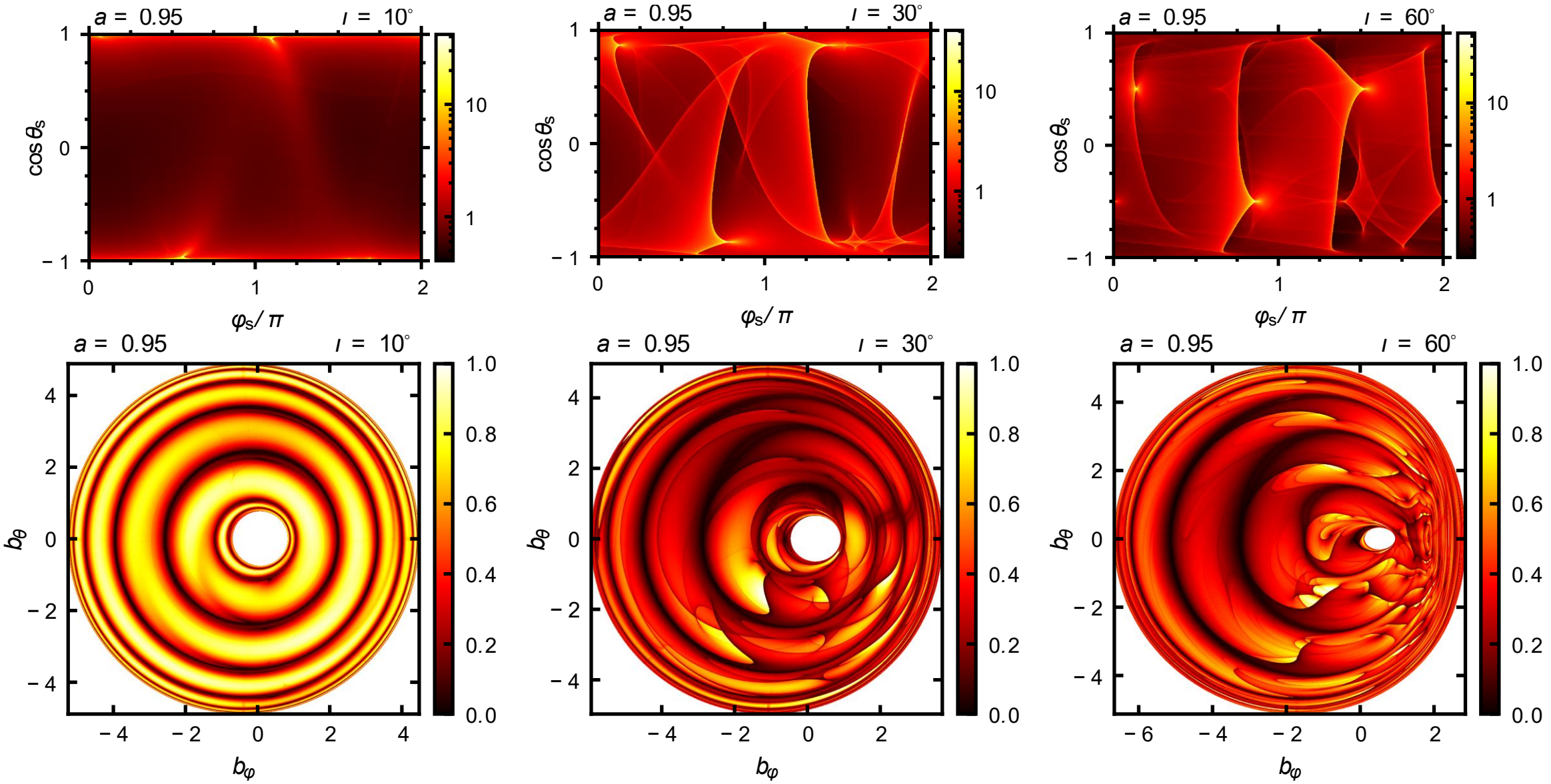
[7] Michael Simpson and Roger Penrose. "Internal Instability in a Reissner-Nordström Black Hole". In: *International Journal of Theoretical Physics* 7.3 (Apr. 1973), pp. 183–197. DOI: 10.1007/BF00792069.

Thank you for your attention.

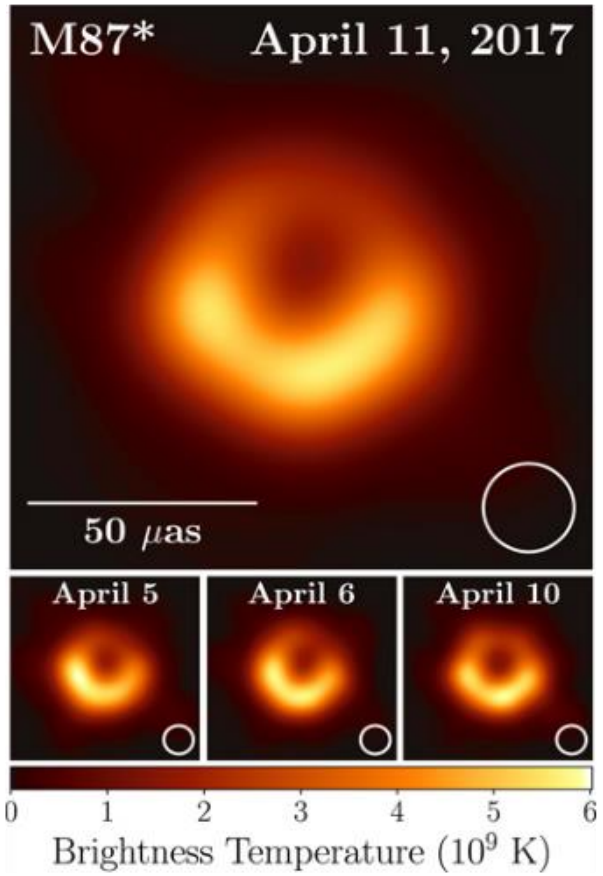
SUPPORTED BY THE EKÖP-26 UNIVERSITY RESEARCH SCHOLARSHIP PROGRAM
OF THE MINISTRY OF SCIENCE AND TECHNOLOGY FROM THE SOURCE OF
THE NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION FUND.

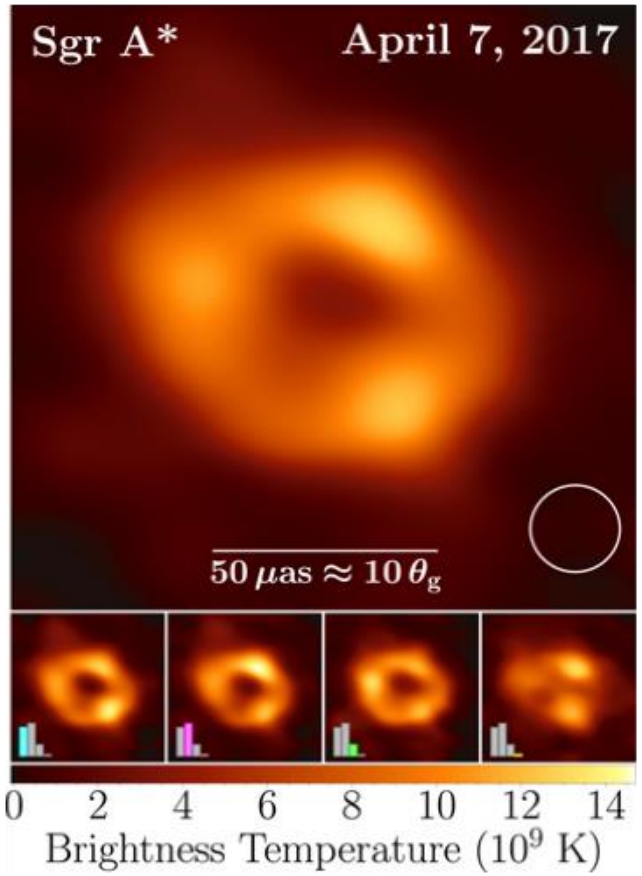


Results

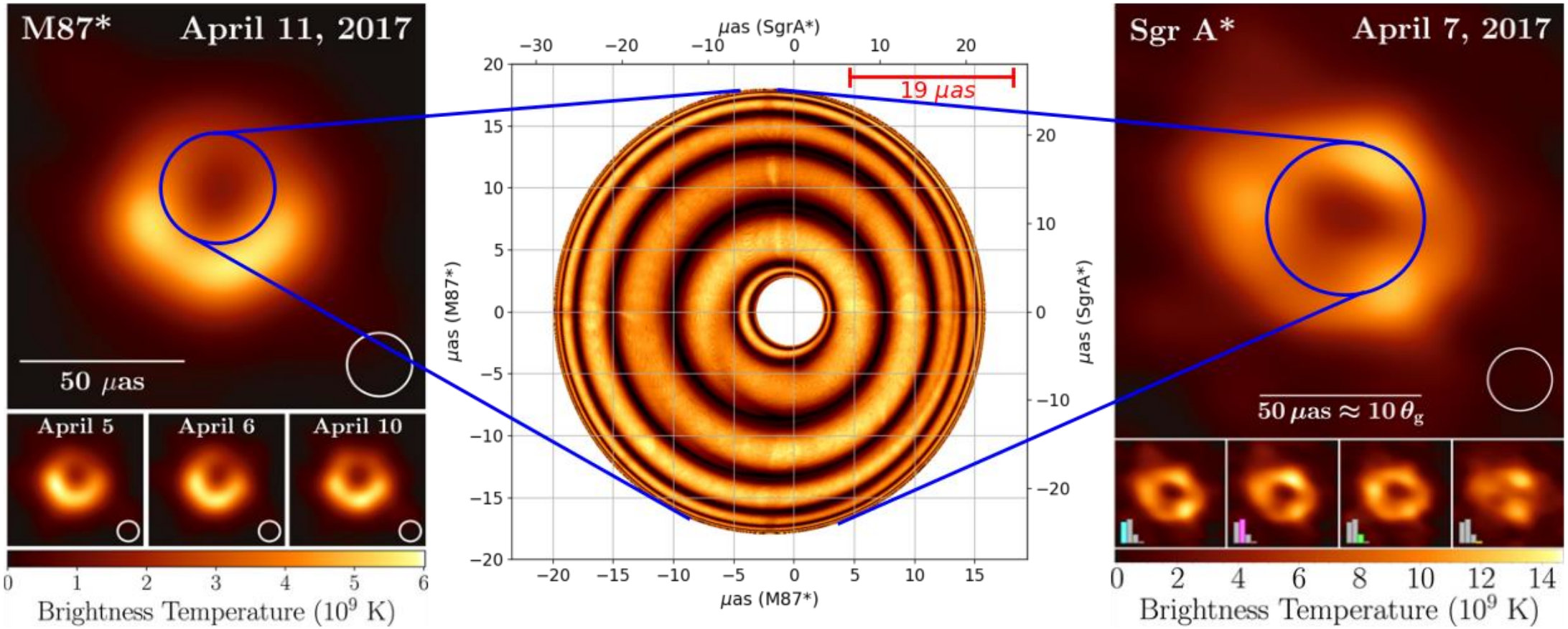


Observing with EHT





Observing with EHT



A z tengely mentén egzaktul megoldható: $r'^2 = E^2 - V_{\text{eff}}(r)$

$$V_{\text{eff}}(r) = \frac{r^2 - 2Mr + a^2}{r^2 + a^2}$$

maximum: $V_{\text{eff}}(r) = 1 + \frac{M}{a} \approx 2.053$

