# Krang: Kerr Raytracer for Analytic Null Geodesics

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Summary

Krang is a Julia[1] (Bezanson et al., 2015) package that implements efficient algorithms for raytracing emission geometries in the Kerr black hole space time. It is GPU compatible and is specialized for studies of sub-image contributions from gravitational lensed sources (Johnson et al., 2020). Such algorithms are of interest for modeling the sources seen by Very Long Baseline Interferometry (VLBI) observations of Low Luminosity Active Galactic Nuclei (LLAGN) such as those imaged by the Event Horizon Telescope Collaboration (EHTC).

Statement of need

Studies of the near horizon scale science around supermassive black holes have increased in interest due to results from the horizon scale observations of supermassive black holes by the Gravity Collaboration, the Atacama Large Millimeter Array (ALMA), and the EHTC. The Event Horizon Telescope, in particular (EHT, Event Horizon Telescope Collaboration, 2019b), produced the first images of the shadows of the supermassive black holes in the centers of M87 (Event Horizon Telescope Collaboration, 2019a) and the Milky Way (Event Horizon Telescope Collaboration, 2022) galaxies at event horizon scales. The emission from these sources originating from relativistic plasmas that are accreted by supermassive black holes in the presence of a magnetic field. Scientific analysis of the data from these sources often requires complicated source modelling that includes various relativistic effects which leave characteristic signatures in the observed images. The large scale of the black holes allows for many of these effects to be described within the geometric optics limit of electro-magnetism. Ray tracing techniques thus present viable options for modeling images of super massive black holes.

A relativistic image feature that has been theorized to exist, but is yet to be resolved, are the individual sub-image contributions to the overall image structure known as photon-rings, (Johnson et al., 2020). Photon rings are of particular interest because of their strong dependence on gravitational effects and their insensitivity to variations in the emission physics around the black hole. The observation of a photon ring would therefore serve as effective probe for measurements of black hole characteristics like spin or help facilitate tests of gravity. This feature could potentially be seen in the near future with a recent as a space extension to the EHT aimed of detection and measurement (Lupsasca et al., 2024).

Scientific studies of black hole images within the current software landscape often requires great compromise due to the computational complexity of the problem. Other difficultes can arise from interfacing existing raytracing software with the wider ecosystem of tools; it is difficult, for example, to apply machine learning optimization algorithms to existing python raytracing codes since they typically rely on special functions that are not implemented within current machine learning frameworks. Existing python implementations are also bounded to CPU evaluations, limiting their capability of accessing acceleration from specialized hardware. A Julia

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[1]https://julialang.org

implementation of raytracing algorithms is thus beneficial because of the languages modular design, differentiable programming and efficient execution. Krang therefore benefits from the 'plug and play' nature of the julia programming language, allowing for easy development and synergy with existing analysis pipelines, and fast CPU/GPU executions.

Similar Packages

- `AART` (Cárdenas-Avendaño et al., 2023): An adaptive analytical ray tracing code for geodesics in the Kerr space time in python.
- `KerrBam` (Palumbo et al., 2022): An analytical raytracing code for equatorial synchrotron models in python.
- `Gradus` (Baker & Young, 2022): A julia implementation of a numeric, general relativistic raytracer with radiative transfer.

Acknowledgements

References

Baker, F., & Young, A. (2022). *Gradus.jl*. Zenodo. https://doi.org/10.5281/ZENODO.6471796

Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2015). *Julia: A fresh approach to numerical computing*. https://doi.org/10.1137/141000671

Cárdenas-Avendaño, A., Lupsasca, A., & Zhu, H. (2023). Adaptive analytical ray tracing of black hole photon rings. *Phys. Rev. D*, *107*, 043030. https://doi.org/10.1103/PhysRevD.107.043030

Event Horizon Telescope Collaboration. (2019a). First M87 event horizon telescope results. I. The shadow of the supermassive black hole. *The Astrophysical Journal Letters*, *875*(1), L1. https://doi.org/10.3847/2041-8213/ab0ec7

Event Horizon Telescope Collaboration. (2019b). First M87 event horizon telescope results. II. Array and instrumentation. *The Astrophysical Journal Letters*, *875*(1), L2. https://doi.org/10.3847/2041-8213/ab0c96

Event Horizon Telescope Collaboration. (2022). First sagittarius a* event horizon telescope results. I. The shadow of the supermassive black hole in the center of the milky way. *The Astrophysical Journal Letters*, *930*(2), L12. https://doi.org/10.3847/2041-8213/ac6674

Johnson, M. D., Lupsasca, A., Strominger, A., Wong, G. N., Hadar, S., Kapec, D., Narayan, R., Chael, A., Gammie, C. F., Galison, P., Palumbo, D. C. M., Doeleman, S. S., Blackburn, L., Wielgus, M., Pesce, D. W., Farah, J. R., & Moran, J. M. (2020). Universal interferometric signatures of a black hole’s photon ring. *Science Advances*, *6*(12), eaaz1310. https://doi.org/10.1126/sciadv.aaz1310

Lupsasca, A., Cárdenas-Avendaño, A., Palumbo, D. C. M., Johnson, M. D., Gralla, S. E., Marrone, D. P., Galison, P., Tiede, P., & Keeble, L. (2024). *The Black Hole Explorer: photon ring science, detection, and shape measurement* (L. E. Coyle, S. Matsuura, & M. D. Perrin, Eds.; Vol. 13092, p. 130926Q). International Society for Optics; Photonics; SPIE. https://doi.org/10.1117/12.3019437

Palumbo, D. C. M., Gelles, Z., Tiede, P., Chang, D. O., Pesce, D. W., Chael, A., & Johnson, M. D. (2022). Bayesian accretion modeling: Axisymmetric equatorial emission in the kerr spacetime. *The Astrophysical Journal*, *939*(2), 107. https://doi.org/10.3847/1538-4357/ac9ab7