Constraining Black Hole Mass and Charge from Shadow and Inner Shadow Morphology

Julien A. Kearns,[1] Dominic O. Chang,[2,3] Daniel C. M. Palumbo[3,4]

[1] Departments of Astronomy & Physics, University of Virginia, Charlottesville, VA 22904, USA
[2] Department of Physics, Harvard University, Cambridge, MA 02138, USA
[3] Black Hole Initiative at Harvard University, 20 Garden Street, Cambridge, MA 02138, USA
[4] Center for Astrophysics, Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA

Abstract

- We investigate the effect of different spacetimes on the black hole inner shadow of thick and thin accretion disks.
- Using general relativistic ray tracing we primarily study the effect of charge, observer inclination, and disk scaling ratio on the size and asymmetry of the inner shadow.
- We show that inner shadow measurements give constraints independent from the black hole shadow.
- Finally, we comment on the accuracy of equatorial emission. Considering the degeneracy that arises between viewing inclination and scale height.

Introduction

- The photon ring consists of photons that can orbit the black hole many times before reaching the observer. They asymptotically approach a bound orbit at the critical curve, $r_c = 3M$. [4]
- The shadow is an image feature bounded by the critical curve at impact parameter $b = \sqrt{27}$ in the Schwarzschild metric. The inner shadow is the area bounded by the event horizon which corresponds to $r_h = 2m$ in 3-D space for the Schwarzschild metric.
- The Event Horizon Telescope (EHT) took the very first pictures of a black hole in 2017 using radio wave interferometry operating at $\lambda = 1.3mm$. [1]
- The EHT has a limiting resolution ~25 μas [2], but future projects like the next generation EHT (ngEHT) and the Black Hole Explorers (BHEX) project aim to increase telescope resolution to resolve black hole features like the photon ring.
- The images in **Modeling** show the inner shadow and shadow features. The first is a cross section of the 3D geometry of a black hole with the thin accretion disk in orange. The next three are black hole image models.

Modeling

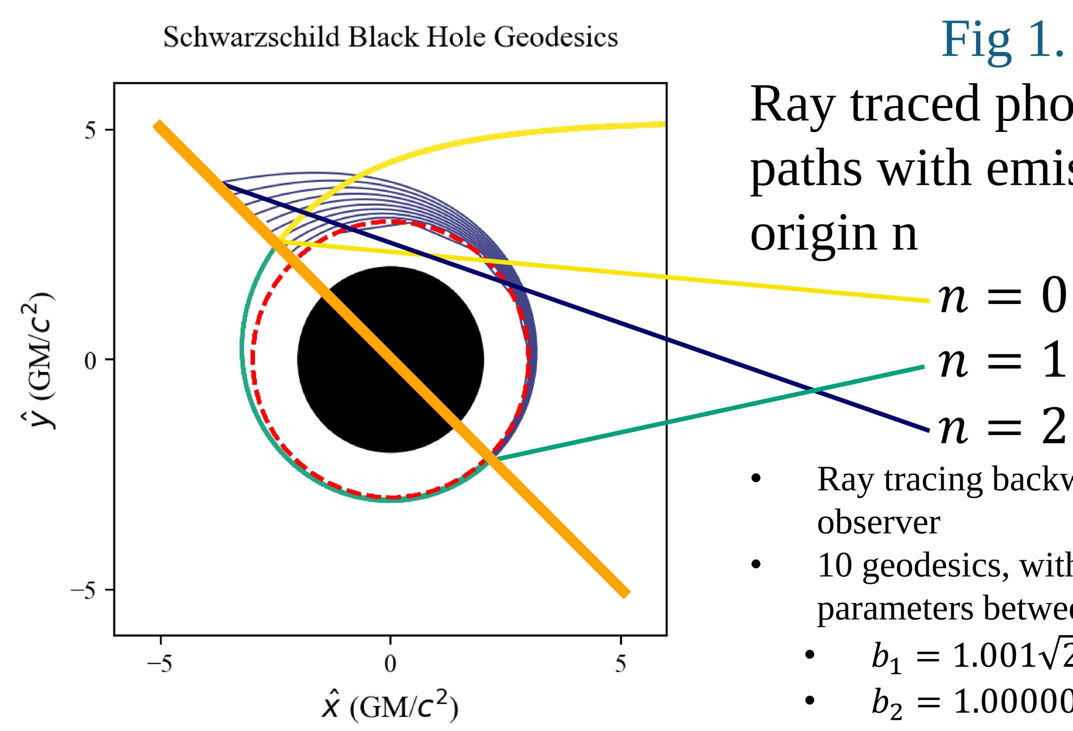


Fig 1.
Ray traced photon paths with emission origin n

- Ray tracing backwards from observer
- 10 geodesics, with impact parameters between :
  - $b_1 = 1.001\sqrt{27}$
  - $b_2 = 1.000001\sqrt{27}$

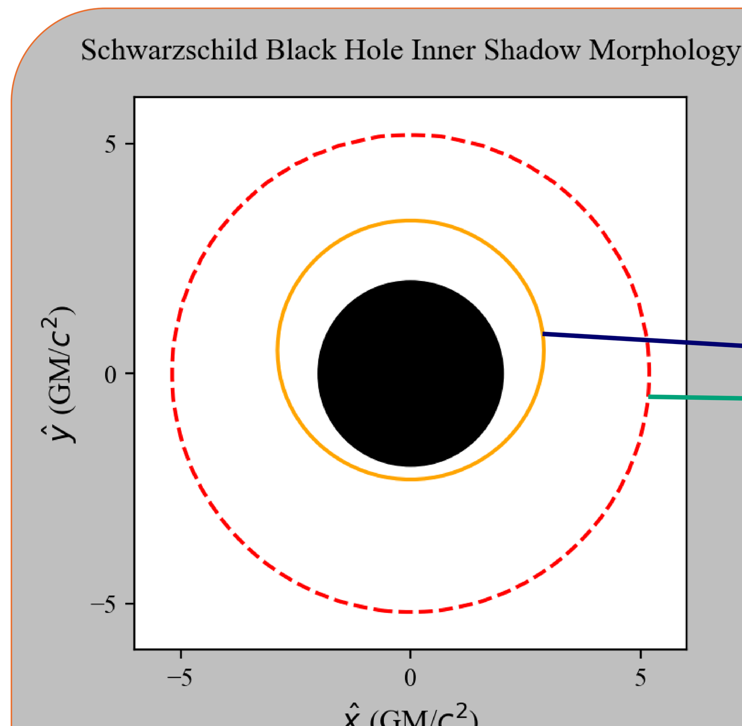
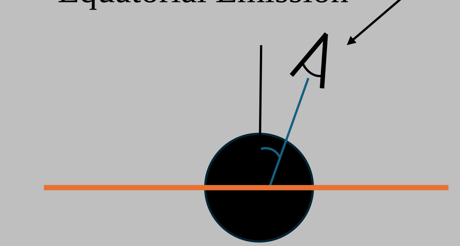


Fig 2.
Photon geodesic isoradial contour with black hole features:
Inner Shadow
Shadow

- Viewing Inclination $\theta_s = 20°$
- Equatorial Emission



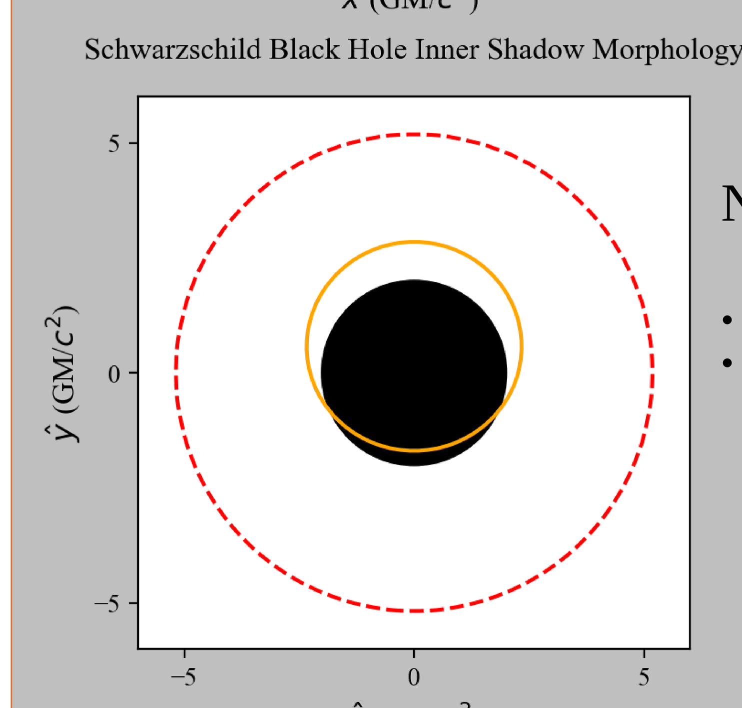
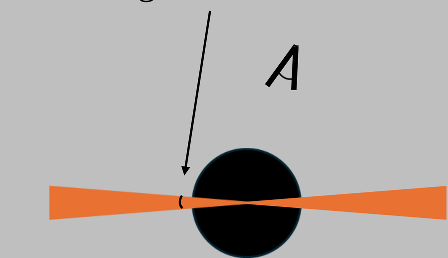


Fig 3.
Non-equatorial emission

- Viewing Inclination $\theta_s = 20°$
- Scale Angle $c = 20°$



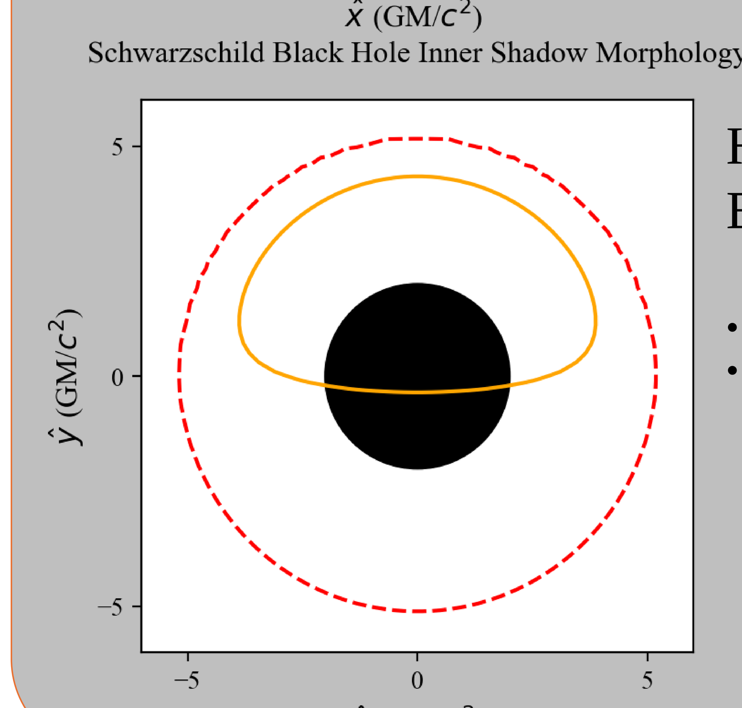
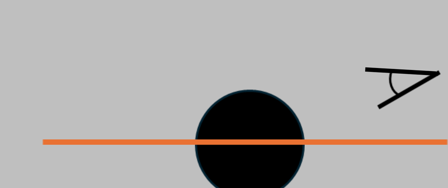


Fig 4.
High viewing inclination, Equatorial Emission

- $\theta_s = 80°$
- $c = 0°$



Constraints

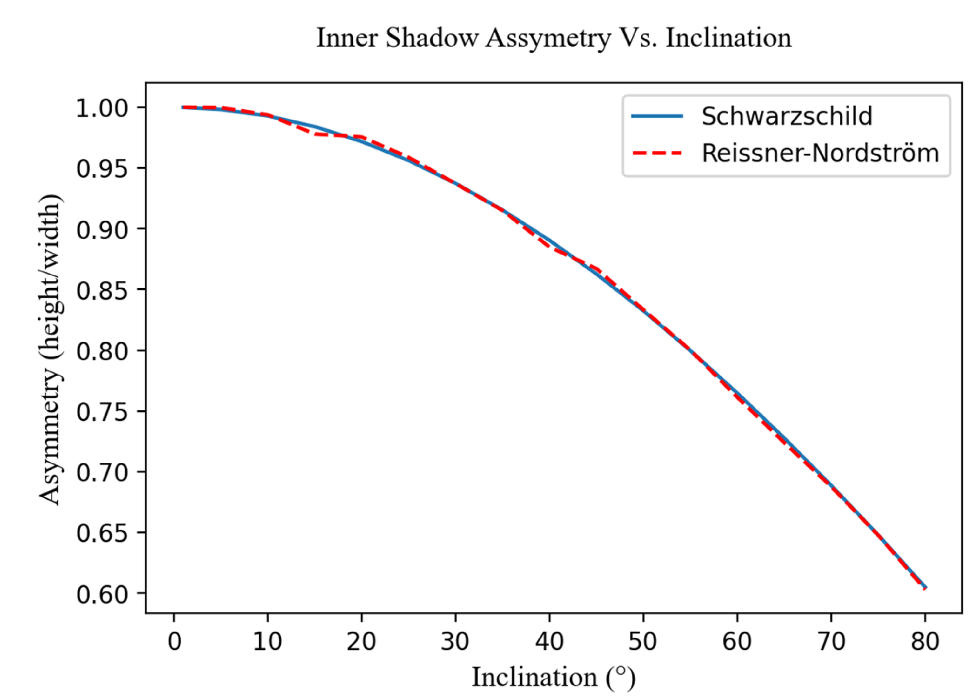


Fig 5.
Inner Shadow Asymmetry vs. Inclination for Reissner-Nordström (Q=.5) and Schwarzschild spacetimes

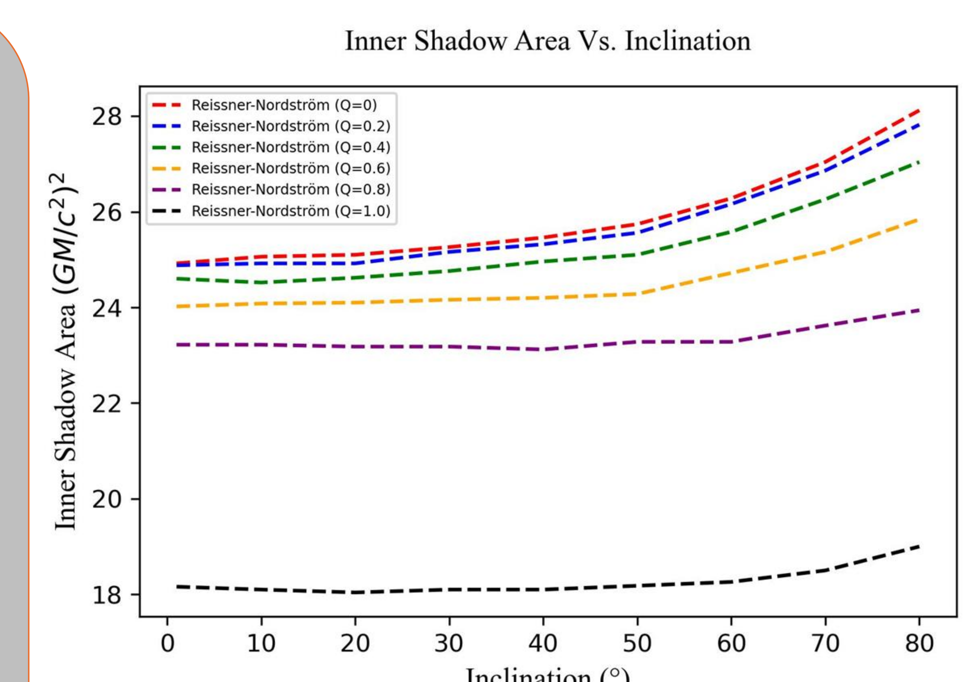


Fig 6.
Image area of the inner shadow for Schwarzschild ($Q = 0$) and Reissner-Nordström ($Q > 0$) spacetimes vs. θ_s

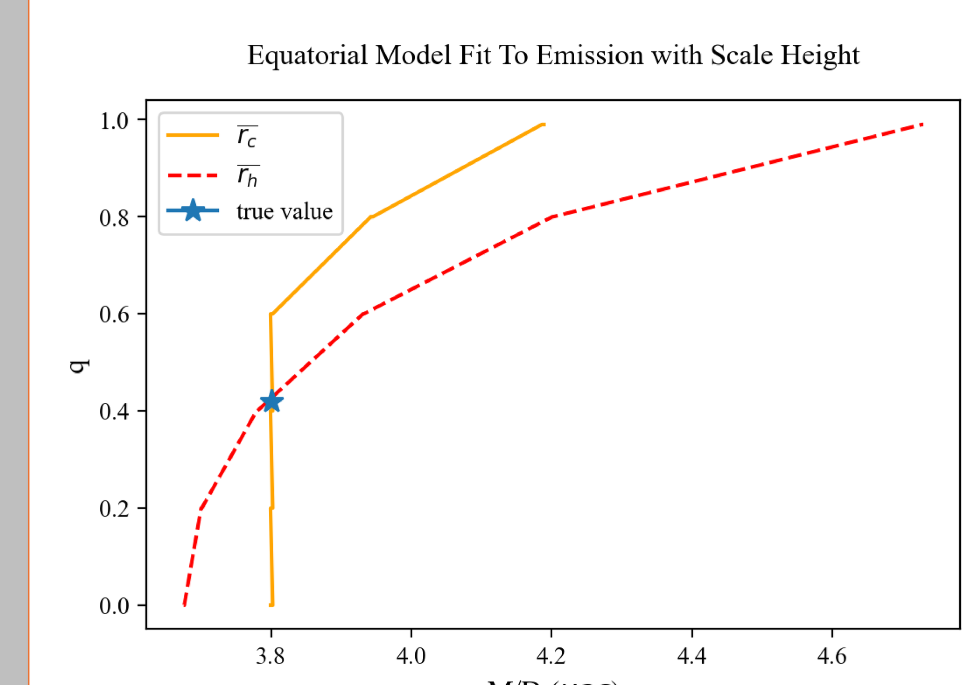


Fig 7.
Constraints on black hole mass to distance ratio M/D and charge q by independent measurements of the average radii of the lensed horizon r_h and critical curve r_c

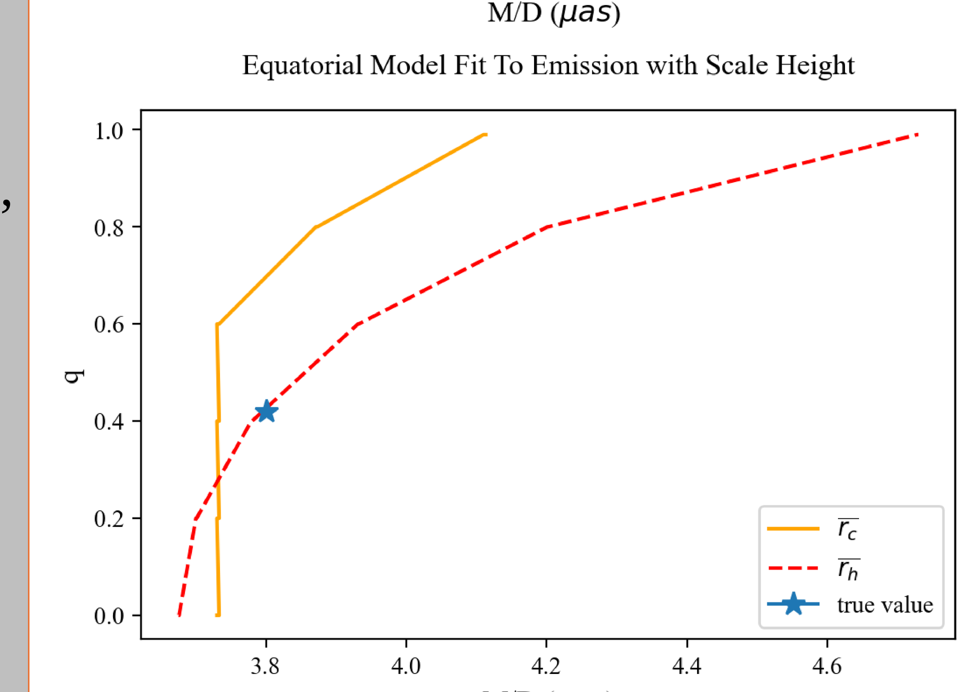


Fig 8.
Attempted constraints on M/D and q using equatorial emission model fit to simulated emission with scale angle

$c = 2°$

Conclusions

- Asymmetry changes with inclination but is agnostic to changes in charge
- Inner shadow area decreases with increasing charge
- We confirm that independent radii measurements of the shadow and inner shadow can constrain the mass and charge of a target Reissner-Nordström black hole with known viewing inclination. These results are analogous to results from [3], which prove the same constraints can be made on a Kerr black hole with mass and spin.
- We conclude that for a sufficiently small scale angle, degeneracies between viewing inclination and scale angle can result in false constraints on the mass and charge

References

[1] A. et. al., The Astrophysical Journal Letters 875, L1(2019).

[2] A. et. al, The Astrophysical Journal Letters 875, L2(2019).

[3] A. Chael, M. D. Johnson, and A. Lupsasca, The Astro-physical Journal 918, 6 (2021).

[4] S. E. Gralla, D. E. Holz, and R. M. Wald, Physical ReviewD 100 (2019), 10.1103/physrevd.100.024018.