The Possibility of Finding Photon Subrings of a Kerr Black Hole

Yehu I. Maimon & Ofek Birnholtz

maimony4@biu.ac.il, ofek.birnholtz@biu.ac.il

2023 תשפ"ג ISRAEL SPACE WEEK

Bar-Ilan University אוניברסיטת בר-אילן

Introduction

The Event Horizon Telescope (EHT) Collaboration has published the image of M87's supermassive black hole [1] (Fig. 1). This image was formed by observing photons from across the accretion disk that were deflected around the black hole on their way to the screen, as General Relativity predicts. General Relativity also predicts that within this image lies a thin photon ring which is composed by an infinite number of subrings that are indexed by the half orbit number n around the black hole. In practice, the image was composed from photons that were lensed around the black hole. The image was dominated by photons with a half orbit index number $n = 0$. Higher resolution is needed to resolve higher n's. The resolution is strongly related to the Rayleigh Criterion and being used in terms of effective baseline.

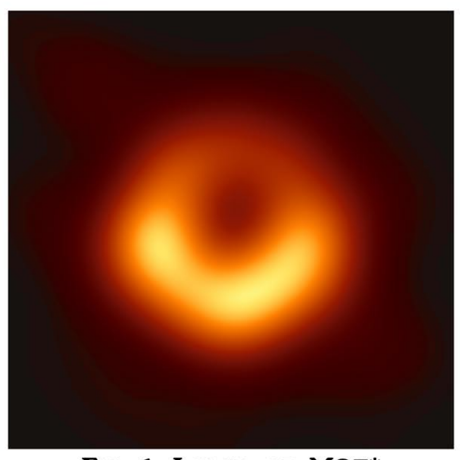

Fig. 1: Image of M87*.

The Problem

In order to resolve photons with higher half-orbit number, a longer baseline is needed [2]. From Earth, due to Rayleigh Criterion, such a thing is not possible. This notion is shown in Fig. 2 and Fig. 3.

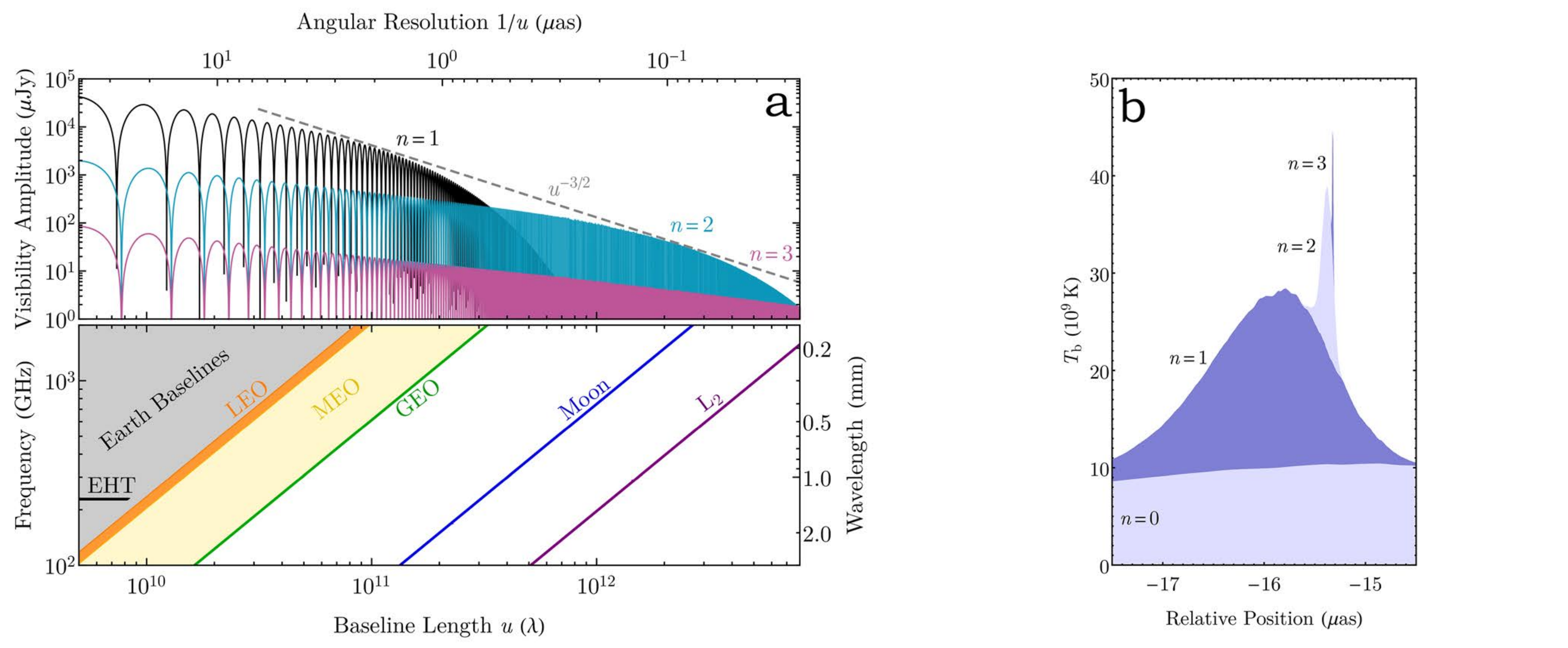

Fig. 2: From [2], a - Top: visibility amplitude as a function of the baseline length. Bottom: frequency dependent range of Earth baselines and representative Earth-space baselines. It shows how different lengths of baselines would resolve different half orbit numbers. b - brightness cross-section decomposed into subrings indexed by the number n.

Methods

Resolving two sources according to Rayleigh Criterion is not possible at the moment, hence we can ask a different yet relevant question: is it possible to identify the existence of two sources without resolving them? In my research I make use of the python library `dynesty`, which conducts Bayesian parameter estimation. In Fig. 3 we approximate the brightness cross-section in Fig. 2b, into two ideal circular apertures.

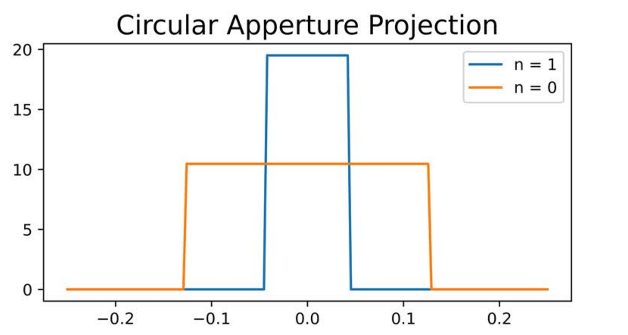

Fig. 3: An approximation of two consecutive photon ring cross-sections.

Preliminary Results

Here, we try to fit a signal into its two components with low and medium noise. In practice, we generated data of a noisy signal, and fitted it into two single signals and got their parameters - width and position in Fig. 5. The case we're dealing with right now is the simplest case. We assumed co-centered and perfectly circular rings. Thus, we approximated the circular aperture projections to be ideal. Our future work is composed from several points that take the simple case and expand it to a more general one.

Injection & Recovery

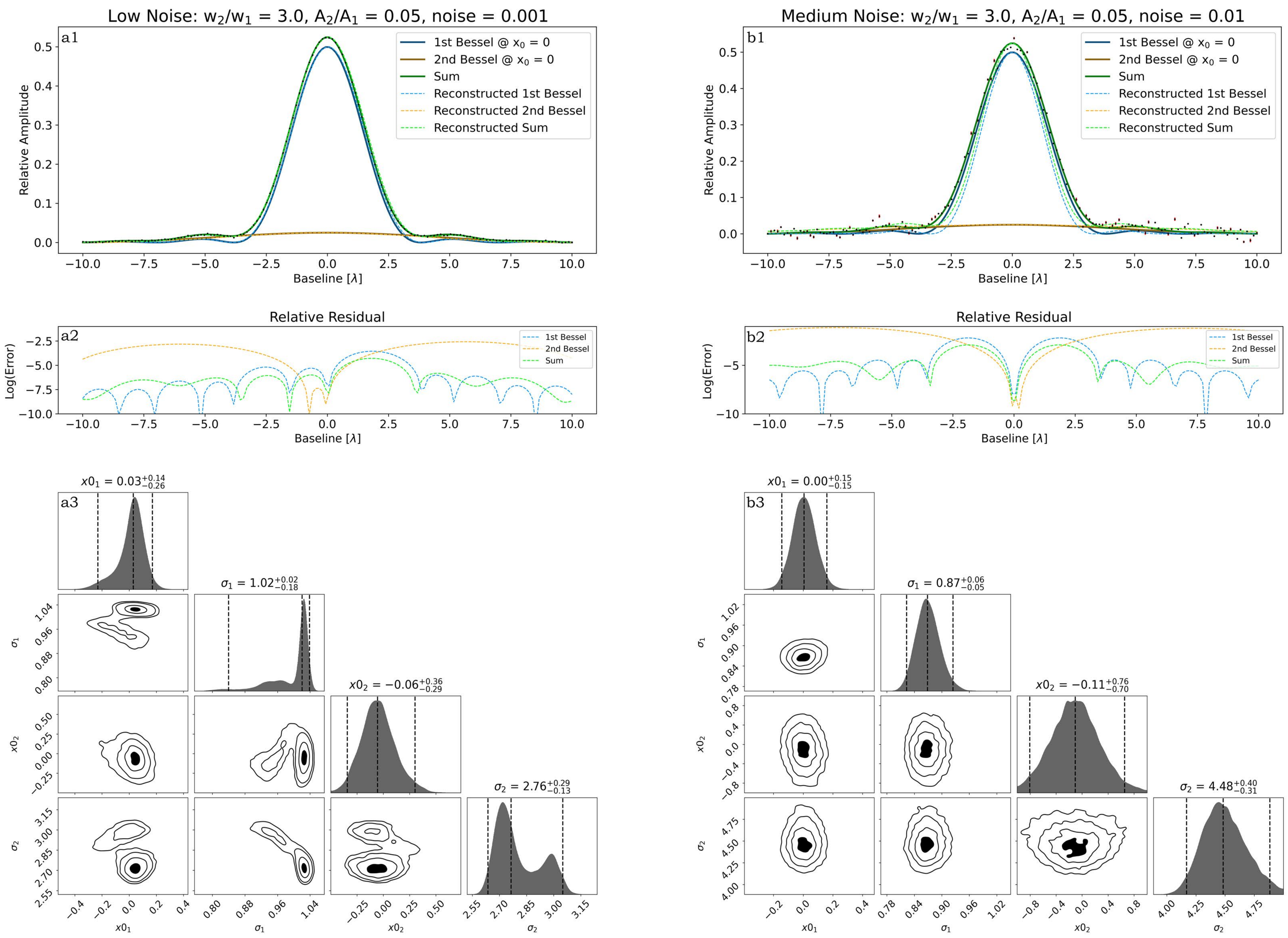

Fig. 4: A 3-piece analysis of each incoming signal. a1 and b1 - the same injected signal into two different noises, same model, different amplitudes and widths. a2 and b2 - residual plots of the signals and the reconstructed ones. a3 and b3 - cornet plot that shows the probability distribution of each parameter (center and width) using Bayesian Parameter Estimation.

Future Work

- Applying model selection algorithm onto the preliminary results. This would let us decide which model describes better the data (1 ring or 2 rings) while considering the Bayesian Information Criterion.

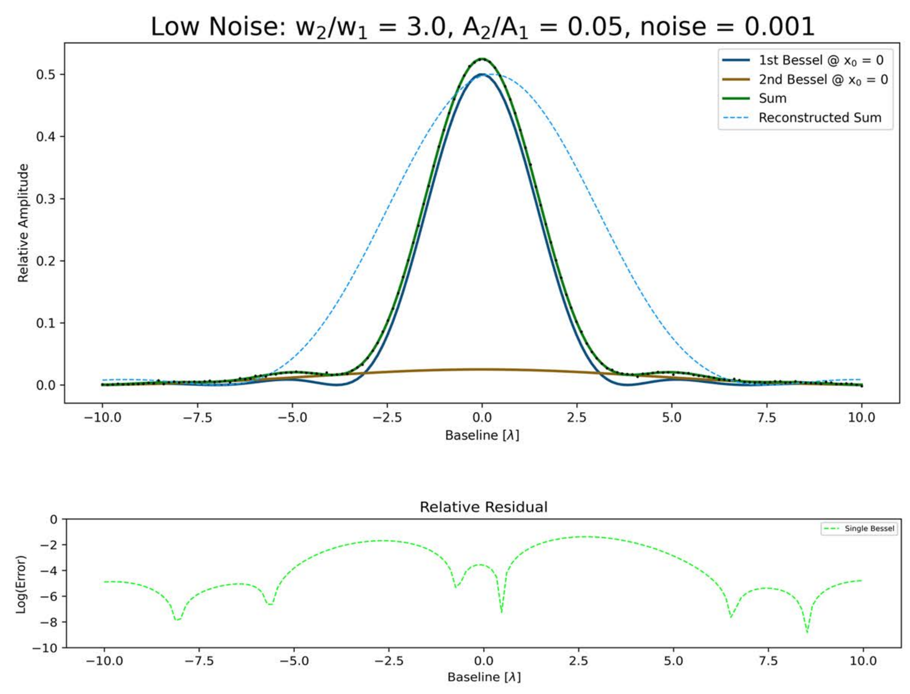

Fig. 5: Reconstruction of two rings (as in Fig. 4) but modeled by only one ring. This result shows a poor reconstruction compared to the one in Fig. 4. In the future model selection will decide which is better.

- Testing the same method to fit 3 rings instead of 2.
- Fitting not ideal cases, where the photon rings are non-concentric and not perfect circles, such as limaçon and ellipses which are more realistic.
- Analyze the real data from EHT and apply the methods onto it.
- Estimate the accuracy needed, considering typical noises, to identify with certainty photon subrings for $n > 0$.

References

[1] The Event Horizon Telescope Collaboration. First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole, ApJ, 875, L1, 2019.

[2] Michael D. Johnson, Alexandru Lupsasca, Andrew Strominger, George N. Wong, Shahar Hadar et al., ``Universal interferometric signature of a black hole's photon ring", 2020.