Detectability of the eclipses of galactic nuclei by stars

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Abstract

Searching for signatures of stars orbiting supermassive black holes (SMBHs) beyond the Galactic Center offers a promising way to probe otherwise unresolved nuclear stellar populations. Stellar transits have previously been explored at UV, optical, and X-ray wavelengths, alongside potential microlensing signatures from compact objects orbiting SMBH accretion disks. Here, we extend these studies to the millimeter domain, focusing on nearby ($z \sim 0.001$) millimeter-bright active galactic nuclei accessible to current observing facilities. At these wavelengths, the jet base and nuclear ring can be sufficiently compact to be occulted by large evolved stars in dense nuclear star clusters. We find that stars with radii $\gtrsim 500\,R_\odot$ can produce eclipses with relative depths of ~ 10–40%. Typical eclipse durations are of order 10 days, while recurrence timescales are generally $\gtrsim 10$ years. The eclipse profile is strongly frequency-dependent: towards lower frequencies, eclipses become broader and shallower, whereas at higher frequencies they become narrower and deeper. Although such events are expected to be rare because of geometric selection effects and the susceptibility of evolved stars to tidal disruption, their detection would provide a novel probe of stellar populations in unresolved galactic nuclei. Individual eclipses can constrain the stellar radius and orbital distance from the SMBH, while recurring events can additionally provide an independent estimate of the SMBH mass. **For details, see the paper by [Zajaček 2026] – scan the QR code on the top right.**

Motivation

Supermassive black holes (SMBHs) at the centers of galaxies are often surrounded by dense nuclear stellar clusters (NSCs), hence it is in principle possible that a single star passes between the SMBH and the observer. These transits could result in eclipses that are analogous to exoplanet transits and could be utilized in a similar way, i.e. for determining stellar distances, radii, and even SMBH masses for repeating eclipses. Below in Figure 1 we illustrate the basic model setup to investigate this phenomenon.

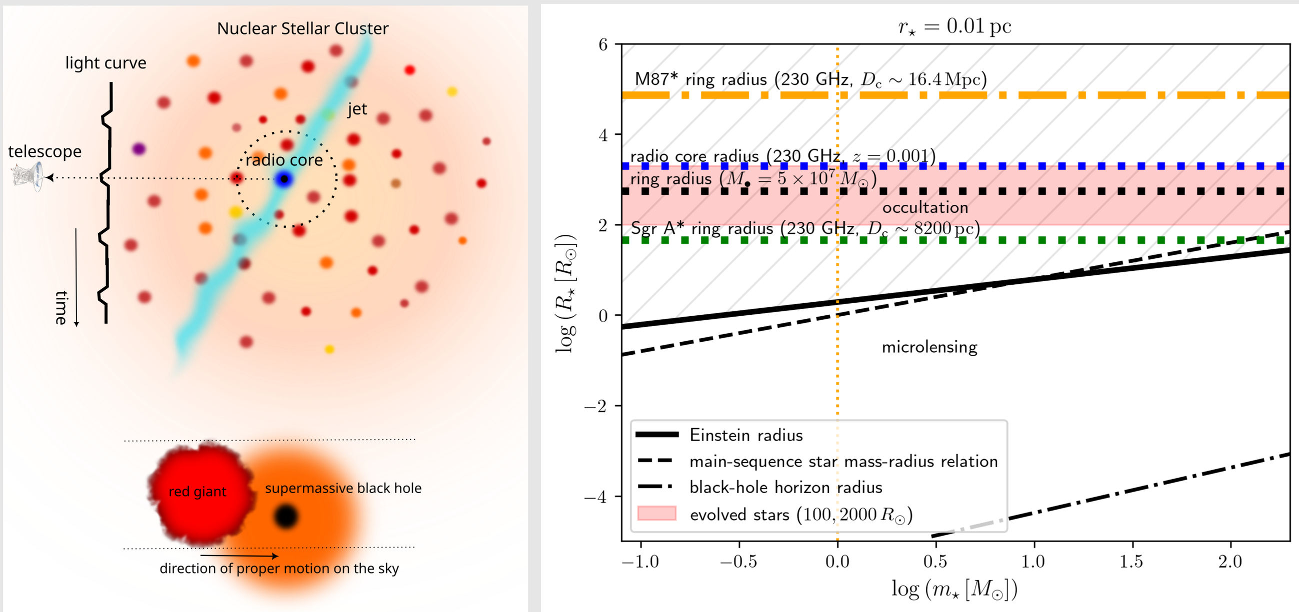

Figure 1. The SMBH embedded inside the dense and compact NSC where occasional eclipses of the jet base/millimeter ring can take place (left). The dependence of the stellar/object radius versus its mass, showing the parameter space where nuclear eclipses are possible (right).

Eclipses of jet bases/millimeter rings (like those observed for Sgr A* and M 87*) are possible when the stellar radius is comparable to or exceeds its Einstein radius, $R_\star \geq R_{\rm E}$. This parameter space is depicted in Figure 1 (right panel) in comparison with the typical jet base/millimeter ring size.

Jet base/accretion inflow ring – star size correspondence

For the jet base, the higher the frequency the smaller the angular radius due to the variable opacity and the core-shift effect, $\theta_{\rm c} = 0.5(\nu/1\,{\rm GHz})^{-1}\,{\rm mas}$, which corresponds to the linear radius of $R_{\rm c} \simeq \theta_{\rm c} D_{\rm A}(z) \sim 2000\,R_\odot$ at the redshift of $z = 0.001$ and the frequency of $\nu = 230\,{\rm GHz}$. In this case, the radio core size is distance-dependent and the occultations by stars are limited to nearby, millimeter bright sources. See also Fig. 2 (right panel) for the relative eclipse depths as a function of the stellar radius and the observing frequency.

At millimeter wavelengths, the lensed acretion inflow (ring – resolved for Sgr A* and M87*) can significantly contribute to the emission. The ring linear radius is distance-independent and for a non-rotating SMBH we have $R_{\rm r} = 3\sqrt{3}GM_\bullet/c^2 \sim 551\,(M_\bullet/5\times10^7\,M_\odot)\,R_\odot$, which only depends on the SMBH mass.

Table 1. Relative occultation depths of radio cores with the angular radius of $\theta_{\rm c} = 0.5\,(\nu/1\,{\rm GHz})^{-1}{\rm mas}$ (in percent) for different stellar radii and observing frequencies (in GHz) in the millimeter domain. The source redshift is set to z=0.001. The last column represents the maximum ring eclipse depth for $M_\bullet = 5\times10^7\,M_\odot$.

$R_\star/R_\odot$	86 GHz	230 GHz	345 GHz	ring
100	0.035	0.25	0.56	4.28
500	0.87	6.26	14.07	35.26
1000	3.50	25.02	56.30	100.0
2000	13.99	100.0	100.0	100.0

Eclipse duration and recurrence timescales

The recurrence timescale is set by the orbital timescale,

$$\tau_{\rm rec} \simeq 2\pi\frac{r_\star^{3/2}}{(GM_\bullet)^{1/2}} \sim 13.2\left(\frac{r_\star}{0.01\,{\rm pc}}\right)^{3/2}\left(\frac{M_\bullet}{5\times10^7\,M_\odot}\right)^{-1/2}\,\text{years}\,, \tag{1}$$

while the duration of the eclipse is given by the transverse velocity and the sum of the stellar and radio core radii,

$$\tau_{\rm dur} = \frac{2(R_\star + R_{\rm c})}{v_{\rm sky}} \propto \lambda\,, \tag{2}$$

which for $R_\star = 1000\,R_\odot$, $\nu = 230$ GHz, and $z = 0.001$ is,

$$\tau_{\rm dur} \simeq 10.4\left(\frac{r_\star}{0.01\,{\rm pc}}\right)^{1/2}\left(\frac{M_\bullet}{5\times10^7\,M_\odot}\right)^{-1/2}\,\text{days}\,. \tag{3}$$

In Fig. 2 (left panel) we show the recurrence (solid line) and the duration (dashed, dotted lines) timescales in years as a function of the distance of a star from the SMBH. The lower panel depicts the duty cycle, $D = \tau_{\rm dur}/\tau_{\rm rec}$, as a function of the distance.

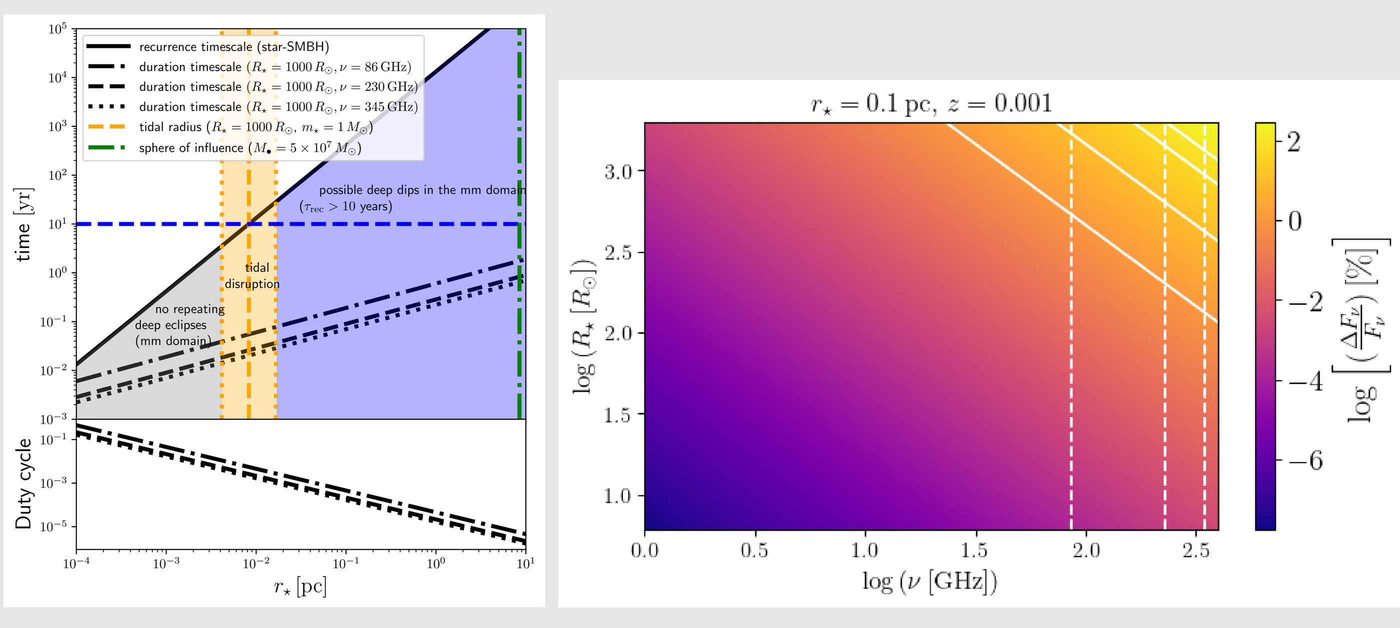

Figure 2. Recurrence and duration timescales (left) and relative eclipse depths (right).

Modelling eclipse profiles

We model eclipse temporal profiles as a function of the stellar orbital eccentricity and inclination, see Figs. 3 and 4, respectively. The eccentric orbits make the profile narrower in comparison with a circular orbit while the inclined orbits make it both narrower and shallower.

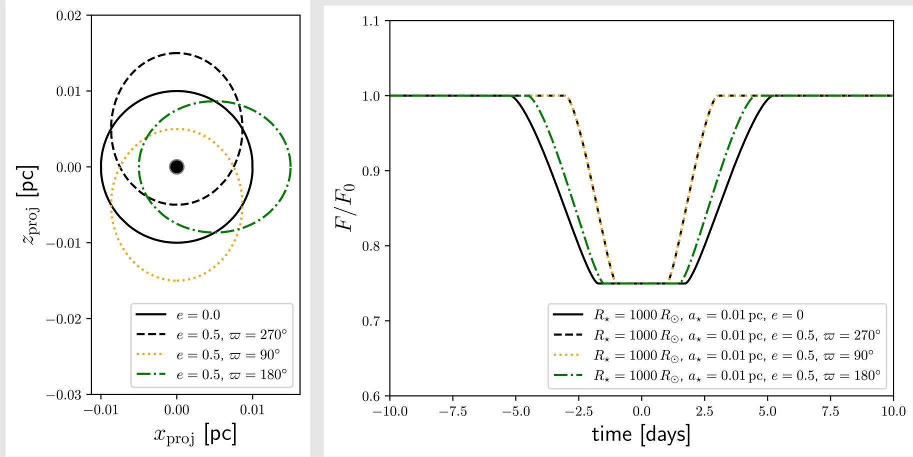

Figure 3. The effect of the orbital eccentricity on the eclipse temporal profile.

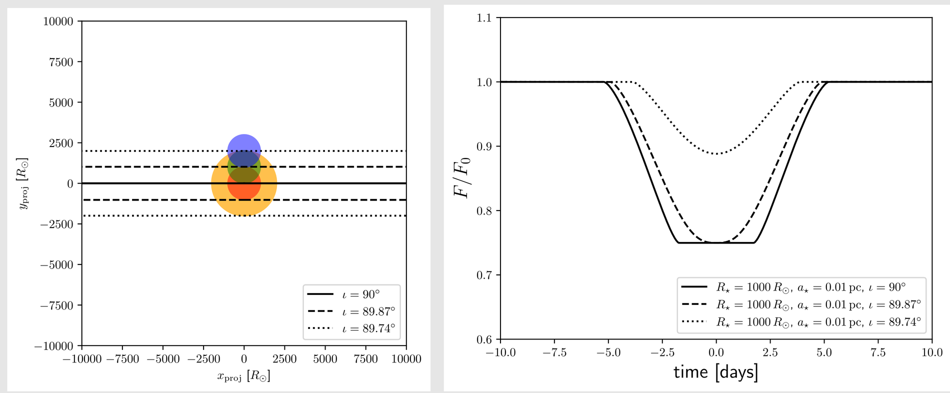

Figure 4. The effect of the orbital inclination on the eclipse temporal profile.

With the increasing observing frequency, the eclipse profile gets narrower and deeper since $\Delta F_\nu/F_\nu \propto \nu^2$ and $\tau_{\rm dur} \propto \nu^{-1}$. In this case we also include the intrinsic variability of the jet base modelled as a damped random walk with the rms amplitude of 15% and the characterisic timescale of 10 days, see Fig. 5 (left panel), and the intrinsic variability of the jet base as well as the measurement uncertainty of 5%, see Fig. 5 (right panel).

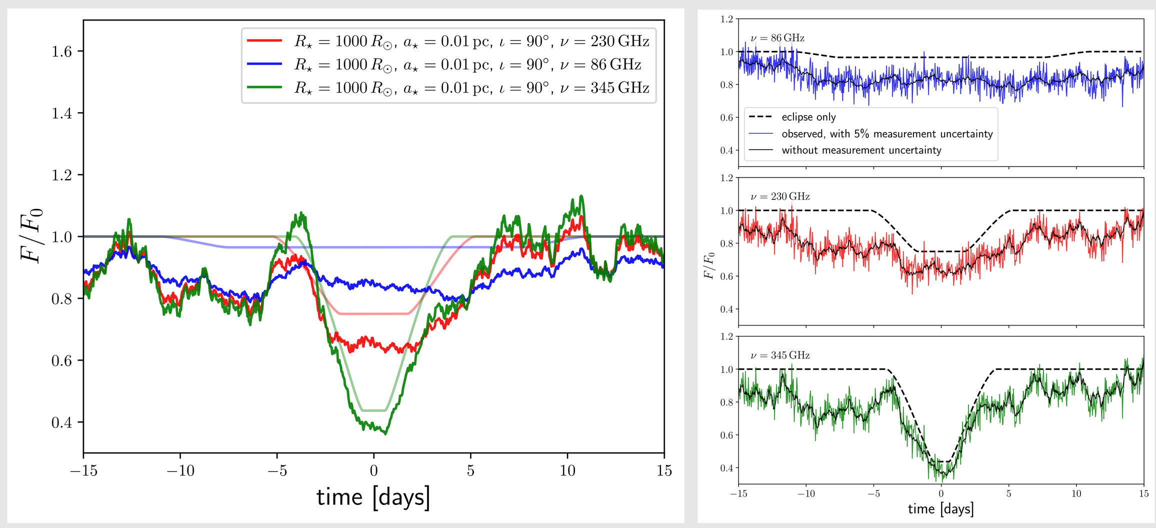

Figure 5. The eclipse temporal profiles for different observing frequencies: 86 GHz (blue), 230 GHz (red), and 340 GHz (green). The left panel includes the eclipse profile + intrinsic variability, while the right panel additionally includes measurement uncertainties.

Finally the eclipse profiles get more complex in case the millimeter emission is dominated by a lensed accretion flow (ring), see Fig. 6.

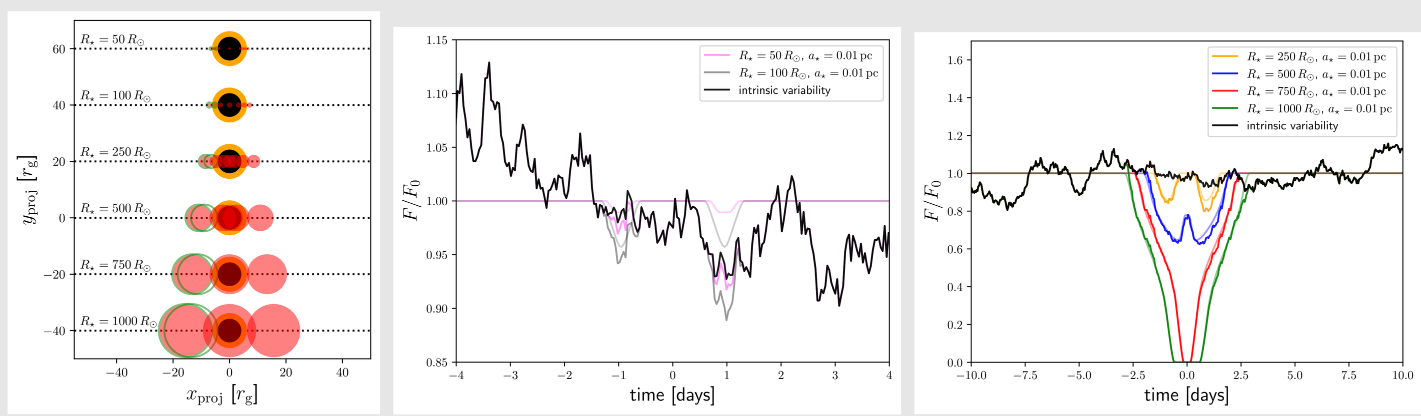

Figure 6. Temporal profiles for the SMBH millimeter ring eclipsed by stars of different radii.

Conclusions

- **Deep stellar eclipses are possible in nearby millimeter-bright nuclei** ($z \lesssim 0.001$, $\nu \gtrsim 86\,{\rm GHz}$) for evolved stars with $R_\star \gtrsim$ few $\times\,100\,R_\odot$. For our fiducial $R_\star = 1000\,R_\odot$ case at $230\,{\rm GHz}$, the eclipse reaches $\sim 25\%$ for the jet base and can completely occult a compact ring, with $\tau_{\rm dur} \sim 10$ d.
- **Eclipse profiles are chromatic and geometry-dependent**: they become **deeper and shorter at higher frequencies** and **shallower and longer at lower frequencies**; orbital eccentricity and inclination further modify their duration and depth.
- **Deep eclipses can be distinguished from intrinsic variability**: for $\sim 15\%$ stochastic variability, dips with $\Delta F_\nu/F_\nu \gtrsim 30\%$ should be recoverable with well-calibrated mm facilities and a cadence of $\gtrsim 1$ observation per day.
- **Eclipses provide a new probe of unresolved nuclear stars and SMBHs**: a single event can constrain $R_\star$ and $r_\star$, while repeating eclipses can constrain $M_\bullet$. Events are intrinsically rare ($\sim 10^{-4}$ per galaxy over 50 yr), but disk-like nuclear stellar populations may enhance the rate by 10^2–10^3 when aligned with the line of sight, motivating wide-field/long-term mm monitoring.

References

Zajaček, M. (Sept. 2026). "Eclipses of Nearby Millimeter-bright Galactic Nuclei by Stars in Nuclear Star Clusters". In: *The Astrophysical Journal* 1009.1, p. 60. DOI: 10.3847/1538-4357/ae9d76. URL: https://doi.org/10.3847/1538-4357/ae9d76.

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