MUNI SCI



Disentangling quasiperiodic eclipses of (active) galactic nuclei from stochastic variability

Michal Zajaček

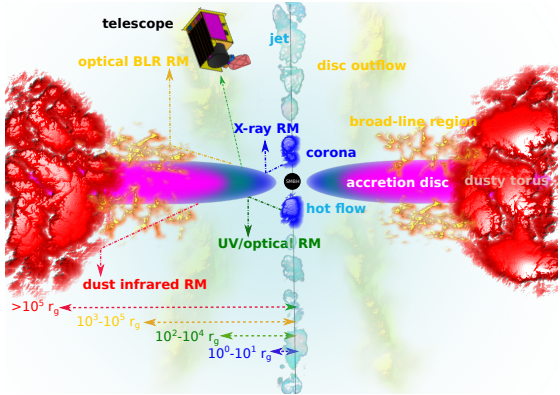
Faculty of Science, Masaryk University

Tatra Astro Summit 2026

October 6, 2026

(Active) galactic nuclei

- basic constituents: supermassive black hole (SMBH), accretion disc (flow), circumnuclear medium, dusty-molecular torus, and nuclear outflows/jet
- tools to study AGN: spectroscopy, reverberation mapping (photometry, spectroscopy), **TODAY also optical/NIR and radio interferometry**

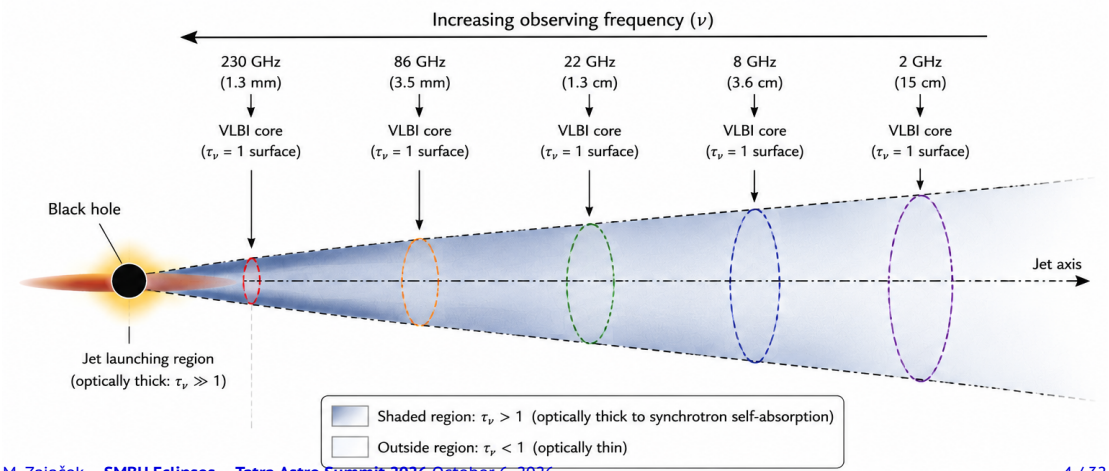


Eclipses of galactic radio cores

- radio core/jet base is the brightest, central part of the jet characterized by the optical depth of unity ($\tau_\nu = 1$)
- due to variable opacity, the jet base is a function of observing frequency, **core-shift effect**, $\theta_{\rm c} \propto \nu^{-1}$
- the radio core in radio AGN has the angular radius of $\theta_{\rm c} \sim (0.1-1)(\nu/1\,{\rm GHz})^{-1}\,{\rm mas}$ (Kovalev et al., 2005) at 1 GHz, which for $z = 0.1$ corresponds to the linear radius of $R_{\rm c} \approx \theta_{\rm c} D_{\rm A}(z) \sim 0.2-2\,{\rm pc} \rightarrow$ **eclipse by extended clouds and streamers**
- At $\nu = 230$ GHz and $z = 0.001$ the linear core radius is $R_{\rm c} \sim 400-4000\,R_\odot$, which is **comparable to the radii of evolved red giants/asymptotic giant-branch stars**

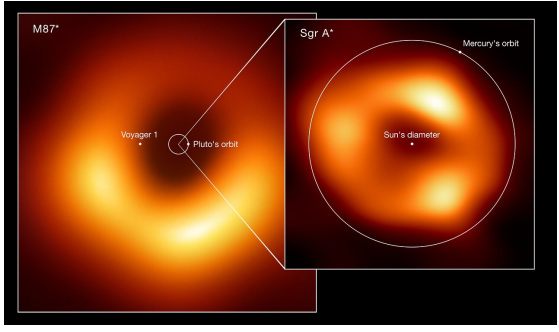
Eclipses of galactic radio cores

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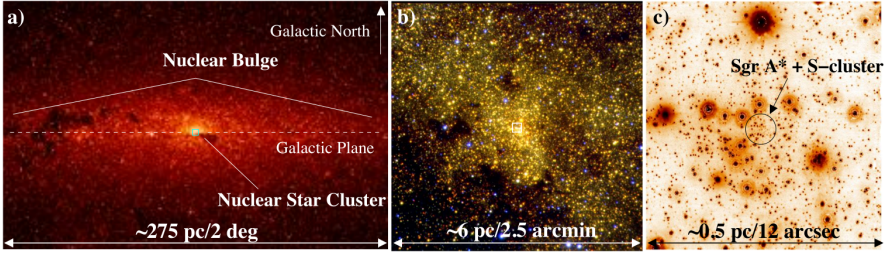
Eclipses of galactic radio cores

- in addition to the jet base, which is optically thick due to synchrotron self-absorption, at the millimeter wavelengths the emission can be dominated by the
  lensed accretion inflow with the central brightness depression – "shadow" or ring – with the radius of $R_{\rm r} = 3\sqrt{3} r_{\rm g} \sim 5.2\, r_{\rm g}$



Supermassive black holes inside dense Nuclear Star Clusters

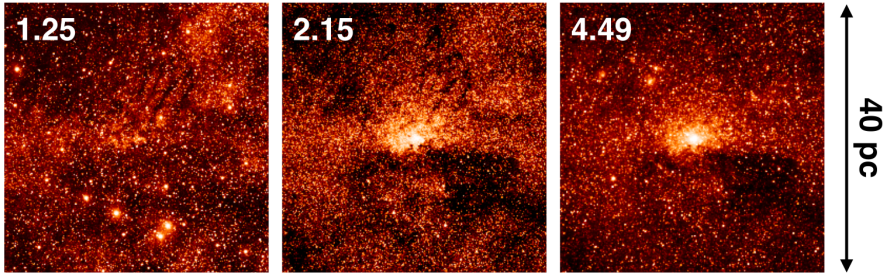
- densest and oldest clusters in galaxies
- the Milky Way Nuclear Star Cluster is slightly flattened: $r_{\rm h} \sim 4.2\,{\rm pc}$, $M_{\rm MWNSC} \sim 2.5 \times 10^7\,M_\odot$, $L_{\rm MWNSC} \sim 4.1 \times 10^7\,L_\odot$ (Schoedel et al., 2014)
- velocity distribution mostly isotropic, only slow rotation



Schoedel et al. (2014)

Supermassive black holes inside dense Nuclear Star Clusters

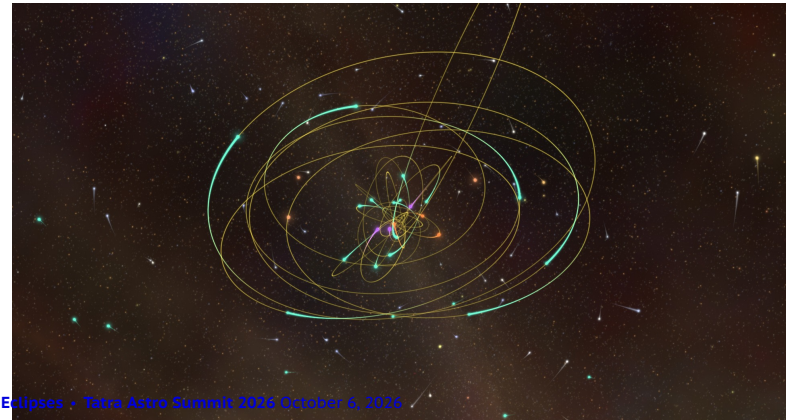
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- extinction law towards the GC: $A_{\rm H} = 4.48 \pm 0.13$ mag, $A_{\rm Ks} = 2.54 \pm 0.12$ mag, and $A_{\rm L} = 1.27 \pm 0.18$ mag



Schoedel et al. (2014)

Supermassive black holes inside dense Nuclear Star Clusters

- stars probe the central gravitational potential
- unique laboratory
- **Motivation: we detect stars orbiting the supermassive black hole in the Galactic center – can we detect their motion elsewhere? Extragalactic stars**



Supermassive black holes inside dense Nuclear Star Clusters

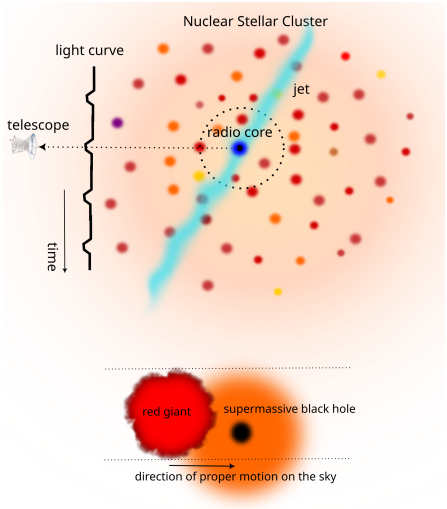
- outer radius: SMBH sphere of influence

$$r_{\mathrm{SI}} = \frac{GM_\bullet}{\sigma_\star^2} \simeq 8.5 \left(\frac{M_\bullet}{5\times10^7\,M_\odot}\right)\left(\frac{\sigma_\star}{159\,\mathrm{km\,s^{-1}}}\right)^{-2}\mathrm{pc}$$

- inner radius: tidal radius of a star

$$\begin{aligned} r_{\mathrm{t}} &\approx R_\star \left(\frac{M_\bullet}{m_\star}\right)^{1/3} \\ &\approx 4.15\times10^{-3}\left(\frac{R_\star}{500\,R_\odot}\right)\left(\frac{M_\bullet}{5\times10^7\,M_\odot}\right)^{1/3}\times \\ &\times\left(\frac{m_\star}{1\,M_\odot}\right)^{-1/3}\mathrm{pc} \end{aligned}$$

Nuclear Eclipses: basic geometry



Occultation vs. microlensing

- the basic condition for occultation is that the Einstein radius of an object is smaller than its physical radius, $R_{\rm E} < R_\star$
- Einstein radius:

$$R_{\rm E} = \left[4 \frac{G m_\star}{c^2} \frac{D_\star (D_{\rm c} - D_\star)}{D_{\rm c}} \right]^{1/2}$$

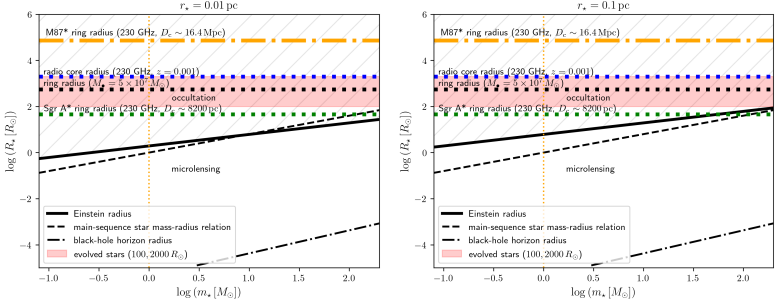
- distance limit for occultations by evolved stars

$$r_\star < \frac{c^2 R_\star^2}{4 G m_\star} \sim 665 \left(\frac{R_\star}{500\, R_\odot} \right)^2 \left(\frac{m_\star}{1\, M_\odot} \right)^{-1} \mathrm{pc}$$

- **evolved stars in nuclear star clusters can cause (repeating) eclipses**

Occultation vs. microlensing

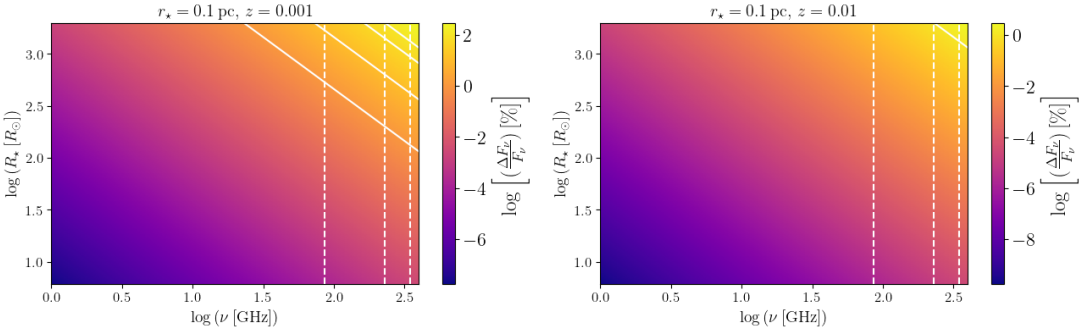
- **Stellar radius versus stellar mass**
- Star orbiting at $r_\star = 0.01$ pc (left) and at $r_\star = 0.1$ pc (right)
- occultation parameter space is above the Einstein radius
- evolved stars with $R_\star = 100 - 2000\,R_\odot$ could cause occultations of nearby jet bases/rings in the millimeter domain, including the Galactic center (however, not M87*)



Relative Decrease in Flux: Dip depth

- For the uniform-brightness radio cores and stellar obscurers, the relative decrease in the flux density can be expressed as

$$\frac{\Delta F_\nu}{F_\nu} \simeq \frac{\pi\theta_\star^2}{\pi\theta_\mathrm{c}^2} = \left(\frac{R_\star}{R_{0\mathrm{c}}(\nu/\nu_0)^{-1}}\right)^2 = \left(\frac{R_\star}{R_{0\mathrm{c}}}\right)^2 \left(\frac{\lambda}{\lambda_0}\right)^{-2}$$



Relative Decrease in Flux: Dip depth

$R_\star/R_\odot$	86 GHz	230 GHz	345 GHz
100	0.035	0.25	0.56
500	0.87	6.26	14.07
1000	3.50	25.02	56.30
2000	13.99	100.09*	225.19*

Table: Relative occultation depths of radio cores with the angular radius of $\theta_\mathrm{c} = 0.5\,(\nu/1\,\mathrm{GHz})^{-1}\mathrm{mas}$ **in percent** for different stellar radii and observing frequencies (in GHz) in the millimeter domain.

Recurrence timescale and eclipse duration

- recurrent occultations of the central SMBH engine are the most relevant since they enable to infer the SMBH mass
- recurrence timescale can be approximated by the orbital timescale for bound orbits

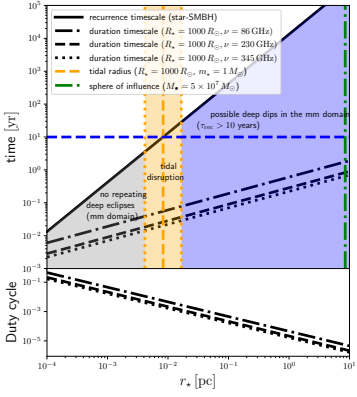
$$\tau_{\rm rec} \simeq 2\pi \frac{r_\star^{3/2}}{(GM_\bullet)^{1/2}} \sim 13.2 \left(\frac{r_\star}{0.01\,{\rm pc}}\right)^{3/2} \left(\frac{M_\bullet}{5\times 10^7\,M_\odot}\right)^{-1/2} {\rm yrs}$$

- eclipse duration is proportional to the wavelength: **shorter wavelengths, shorter and deeper eclipses**

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

$$\tau_{\rm dur} \simeq 10.4 \left(\frac{r_\star}{0.01\,{\rm pc}}\right)^{1/2} \left(\frac{M_\bullet}{5\times 10^7\,M_\odot}\right)^{-1/2} {\rm days}$$

Recurrence timescale and eclipse duration



Duty cycle gets larger for a smaller distance

$$D = \frac{\tau_{\rm dur}}{\tau_{\rm rec}} = \frac{R_\star + R_{\rm c}}{\pi r_\star} \propto \frac{1}{\nu r_\star}$$

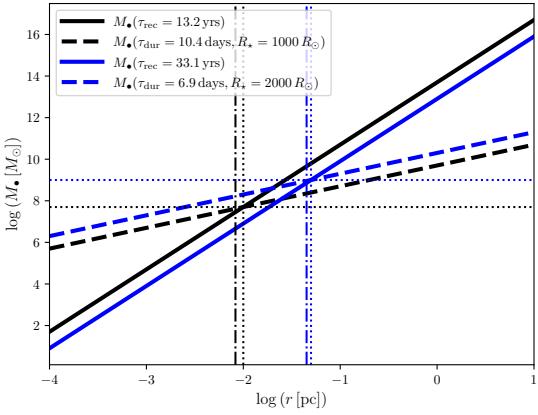
SMBH mass determination from repeating eclipses

- SMBH mass from the recurrence timescale: $M_\bullet = \frac{4\pi^2}{G\tau_{\rm rec}^2} r_\star^3$
- SMBH from the eclipse duration: $M_\bullet = \frac{4(R_\star + R_{\rm c})^2}{G\tau_{\rm dur}^2} r_\star$
- relation for the SMBH mass expressed using basic observables:

$$M_\bullet = \frac{4\theta_{\rm c}^3(\nu) D_{\rm A}^3(z) [1 + (\Delta F_\nu / F_\nu)^{1/2}]^3 \tau_{\rm rec}}{\pi G \tau_{\rm dur}^3}$$

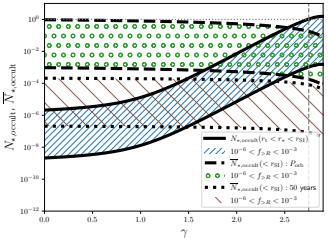
$$M_\bullet = 8.4 \times 10^7 \left(\frac{[1 + (\Delta F_\nu / F_\nu)^{1/2}]}{1.5} \right)^3 \left(\frac{\tau_{\rm rec}}{10.1\,{\rm yr}} \right) \left(\frac{\tau_{\rm dur}}{8\,{\rm days}} \right)^{-3} M_\odot$$

SMBH mass estimates from repeating eclipses



Different combinations of recurrence and duration timescales for $R_\star = 1000 R_\odot$ (**black lines**) and $R_\star = 2000 R_\odot$ (**blue lines**).

Likelihood of nuclear eclipses



- instantaneous number of occulting stars:

$$N_{\star,\mathrm{occult}} \simeq \frac{f_{>R}\pi R_{\mathrm{c}}^2 M_\bullet (3-\gamma)(r_{\mathrm{SI}}^{1-\gamma} - r_{\mathrm{t}}^{1-\gamma})}{2\pi \overline{m}_\star r_{\mathrm{SI}}^{3-\gamma}(1-\gamma)}$$

- mean number per orbital period and monitoring duration τ_{obs}

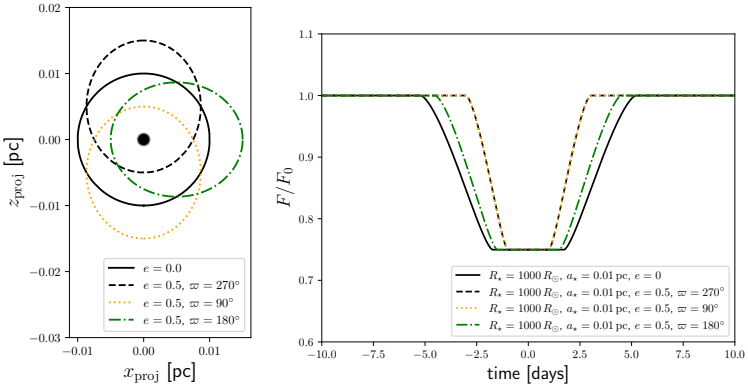
$$\overline{N}_{\star,\mathrm{occult}}(< r_{\mathrm{SI}}) = f_{>R} R_{\mathrm{c}} \frac{6\sigma_\star^2}{G\overline{m}_\star}\left(\frac{3-\gamma}{5-\gamma}\right)$$

$$\overline{N}^{\tau}_{\star,\mathrm{occult}}(< r_{\mathrm{SI}}) = \frac{3 f_{>R}\tau_{\mathrm{obs}} R_{\mathrm{c}}}{\pi \overline{m}_\star G^2 M_\bullet}\left(\frac{3-\gamma}{7/2-\gamma}\right)\sigma_\star^5$$

Expected eclipse profiles

Effect of stellar orbital eccentricity on the eclipse duration

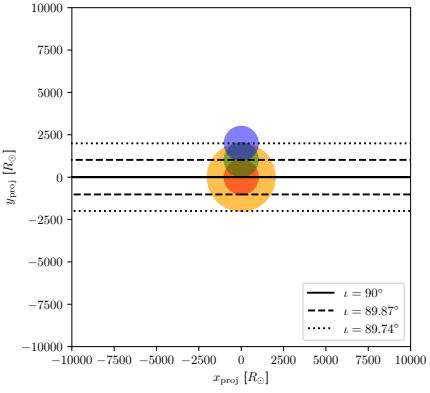
$$\frac{F(t)}{F_0} = 1 - \frac{S_{\rm block}}{\pi R_{\rm c}^2}$$

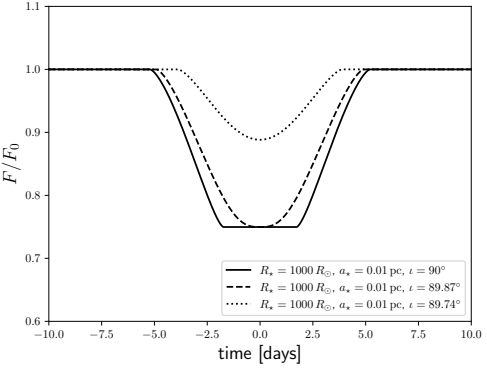


Expected eclipse profiles

Effect of stellar orbital inclination on the eclipse duration and depth

$$\frac{F(t)}{F_0} = 1 - \frac{S_{\rm block}}{\pi R_{\rm c}^2}$$

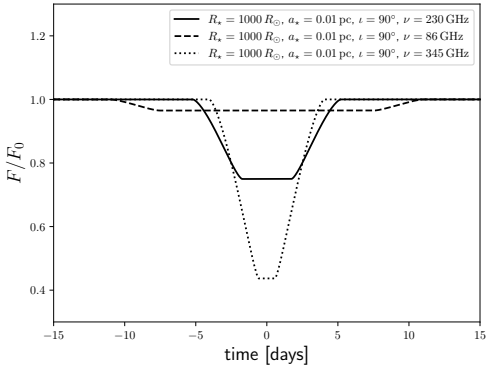




Expected eclipse profiles

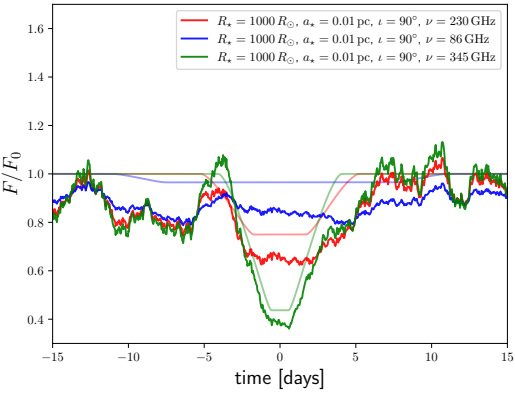
Effect of the observing frequency on the eclipse duration and depth

$$\frac{F(t)}{F_0} = 1 - \frac{S_{\rm block}}{\pi R_{\rm c}^2}$$

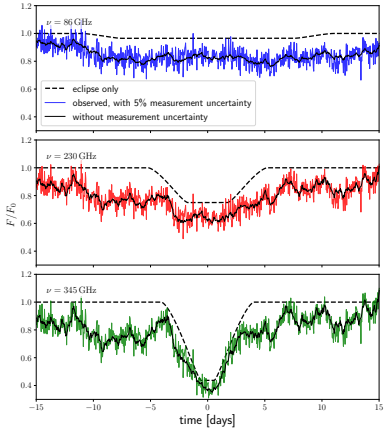


Eclipse + intrinsic stochastic variability

Stochastic variability modelled as a **damped random walk** (DRW)



Eclipse + DRW variability (15%, 10 days)



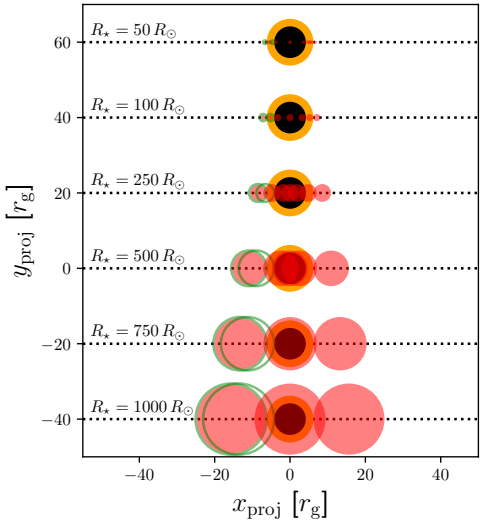
Eclipse + DRW variability + 10% measurement noise

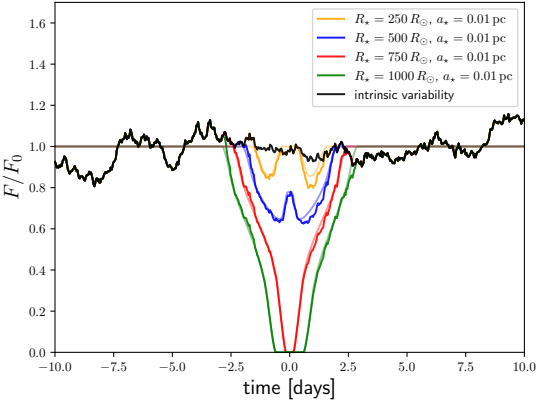
Expected eclipse profiles – ring geometry

- we consider a ring geometry that mimics SMBH shadows of Sgr A* and M87*
- the inner and outer radii of 4.2 and 6.2 gravitational radii, the mean radius of $R_{\rm r} \simeq 5.2\, r_{\rm g}$
- for the SMBH mass of $M_\bullet = 5 \times 10^7\, M_\odot$, $1\, r_{\rm g} \sim 106\, R_\odot$
- an evolved star orbits the SMBH on a circular orbit with the radius of $0.01\,{\rm pc}$
- $\tau_{\rm rec} = 13.25\, (r_\star/0.01\,{\rm pc})^{3/2} (M_\bullet/5\times10^7\, M_\odot)^{-1/2}\,{\rm years}$
-

$$\tau_{\rm dur} = \frac{2(R_\star + R_{\rm r2}) r_\star^{1/2}}{(GM_\bullet)^{1/2}}$$
$$\simeq 4.02 \left(\frac{R_\star + R_{\rm r2}}{500\, R_\odot + 6.2 \times 106\, R_\odot}\right) \left(\frac{r_\star}{0.01\,{\rm pc}}\right)^{1/2} \times$$
$$\times \left(\frac{M_\bullet}{5\times10^7\, M_\odot}\right)^{-1/2} \text{ days.}$$

Expected eclipse profiles – ring geometry





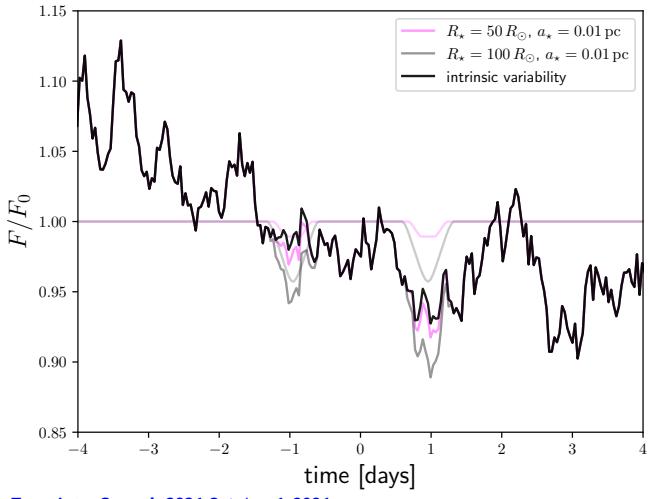
Expected eclipse profiles – ring geometry

Table: **Relative maximum flux density drops (in percent) for stars of different radii in the range between $50\,R_\odot$ and $1000\,R_\odot$ passing in front of the nuclear ring with the mean radius of $\sim 5.2\,r_\mathrm{g}$.**

$R_\star\ [R_\odot]$	max $\Delta F_\nu / F_\nu$ [%]
50	1.07
100	4.28
250	14.39
500	35.26
750	100.00
1000	100.00

Expected eclipse profiles – ring geometry

50 and 100 $R_\odot$ stars



Determination of distance and stellar radius

- for first contact times t_2 and t_1, the distance of the eclipsing star from the SMBH,

$$r_\star = GM_\bullet \left(\frac{\Delta t}{W}\right)^2 .$$

- The stellar radius can be inferred from the relation for any contact time

$$R_\star = W\frac{\bar{t}}{\Delta t} - R_\mathrm{r} ,$$

  where $\Delta t = t_2 - t_1$ and $\bar{t} = 0.5(t_2 + t_1)$ is the mean contact time.
- It is more convenient to express the ring radius as well as its width in gravitational radii, $R_\mathrm{r} = \xi_\mathrm{r} r_\mathrm{g}$ and $W = w r_\mathrm{g}$, respectively.

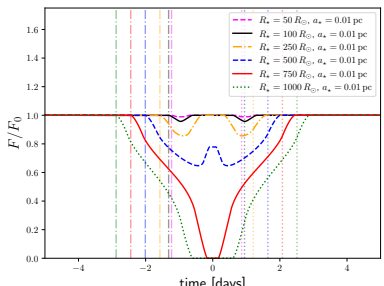
$$\frac{r_\star}{r_\mathrm{g}} = w^{-2}\left(\frac{\Delta t}{t_\mathrm{g}}\right)^2 ,$$

$$\frac{R_\star}{r_\mathrm{g}} = w\frac{\bar{t}}{\Delta t} - \xi_\mathrm{r} ,$$

Determination of distance and stellar radius

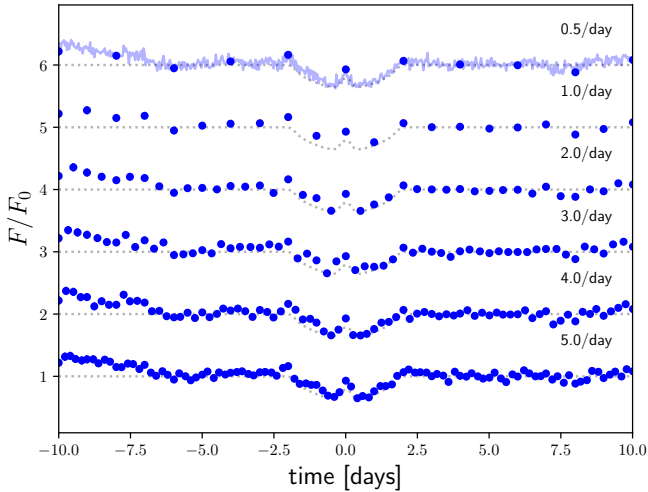
Table: **Stellar distance from the SMBH and radius determination based on the timing of the single eclipse of the nuclear ring in the millimeter domain.**

Eclipse [%]	$t_2 - t_0$ [day]	$t_1 - t_0$ [day]	$r_\star$ [pc]	$R_\star$ [$R_\odot$]
4.28	-1.32	-0.96	0.0096	120
35.26	-2.01	-1.63	0.011	464



Cadence requirements

We need essentially (at least) daily cadence to detect the eclipse.



Conclusions

- **Deep stellar eclipses are possible in nearby millimeter-bright nuclei** ($z \lesssim 0.001$, $\nu \gtrsim 86\,\mathrm{GHz}$) for evolved stars with $R_\star \gtrsim \mathrm{few} \times 100\,R_\odot$. For our fiducial $R_\star = 1000\,R_\odot$ case at 230 GHz, the eclipse reaches $\sim 25\%$ for the jet base and can completely occult a compact ring, with $\tau_{\mathrm{dur}} \sim 10$ 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.

More information

Zajaček, M., The Astrophysical Journal, 1009, 60, 18 , 2026
(https://arxiv.org/abs/2605.15145)

The Astrophysical Journal, 1009:60 (18pp), 2026 September 20 https://doi.org/10.3847/1538-4357/ae9d76
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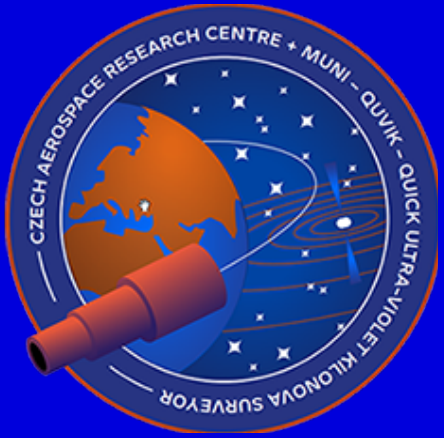
Eclipses of Nearby Millimeter-bright Galactic Nuclei by Stars in Nuclear Star Clusters

Michal Zajaček
Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czechia; zajacek@physics.muni.cz
Received 2026 May 14; revised 2026 August 7; accepted 2026 August 13; published 2026 September 16

Abstract

It is of a general interest to look for signatures of stellar bodies orbiting supermassive black holes (SMBHs) in galactic nuclei other than the Galactic center. Previously, stellar transits were analyzed in UV, optical, and X-ray domains as well as potential microlensing signatures due to more compact bodies orbiting SMBH accretion disks. Here, we complement previous studies by considering nearby ($z = 0.001$) millimeter-bright active galactic nuclei targeted by different facilities in the millimeter domain. At these wavelengths, the jet base and the nuclear ring are sufficiently compact for them to be occulted by large evolved stars in dense nuclear star clusters. We find that in the millimeter domain, evolved stars with stellar radii of $\gtrsim 500\,R_\odot$ can cause eclipses with the relative depth of $\sim$10%–40%. Typical recurrence timescales are at least 10 yr and the eclipse durations are $\sim$10 days. Towards lower frequencies, the eclipse temporal profiles become shallower and broader, while towards higher frequencies they are deeper and narrower. Although expected to be rare due to selection effects and evolved stars being prone to tidal disruption, eclipses of millimeter radio cores can be applied to estimate the distance of the extragalactic star from the SMBH and its stellar radius. In case the eclipse is recurring, we provide a relation for estimating the SMBH mass.

Unified Astronomy Thesaurus concepts: Supermassive black holes (1663); Late-type stars (909); Radio active galactic nuclei (2134)


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