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# Microlensing towards the Galactic centre an analysis of the Galactic Bulge IMF

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*abstract* We analyse the most recent results of the microlensing observational campaigns carried out towards the Galactic centre by the MACHO, EROS and OGLE collaborations. We compare the expected and the observed optical depth and find a very good agreement for current models of the Galactic components, in particular as for the total mass, triaxial shape and inclination angle of the Galactic bulge. As expected, we find that only the Galactic luminous components, and in particular the bulge, contribute significantly to the lens populations. Further informations, in particular the possibility to distinguish among different bulge models, might be gained by better exploring regions closer to the Galactic centre.

As a second step in our analysis we exploit the relationship between the event duration and the lens mass so to probe the lens mass function by studying the timescale distribution of the observed events. To this purpose we make use of the maximum likelihood method. As for the bulge initial mass function that we want to probe, we assume a power law $\xi(\mu) \propto \mu^{-\alpha}$, and we study the slope $\alpha$ both in the brown dwarf and in the main sequence ranges. We find, for main sequence stars, a slope $\alpha \sim 1.7$, for all the three data sets. On the other hand, the lack of very short duration events, in particular in the EROS and OGLE data sets, makes the result in the brown dwarf range less robust. An observational strategy more suited to the exploration of this kind of events would be useful to better constrain the low mass tail of the lens mass function.

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## 1. Introduction

Since the original suggestion of Paczyński [1], microlensing has become a very efficient tool for the study of the (luminous or not) characteristics of the lens populations. As for the study of the dark matter contribution to galactic halos in form of MACHOs, analyses towards both the Magellanic Clouds [2, 3] and our nearby galaxy, M31 [4, 5], probed the efficiency of the method to approach this problem even if giving, up to now, somewhat contradictory results. As originally proposed by Paczyński [6], the Galactic centre is also a very interesting target. First, the number of expected, and observed, microlensing events, is much larger (by about two order of magnitude) than towards either LMC or M31. Second, the expected contribution of any would be dark component is negligible as compared to that of the luminous Galactic components (bulge and disc). Therefore microlensing, that allows one the study of the lens mass distribution through the analysis of the optical depth, probed to be efficient to assess the inner Galactic structure [7, 8]. Furthermore, the analysis of the event characteristics, such as the duration, has been used to study the lens mass function [9, 10, 11, 12]. In the present analysis we consider both these aspects taking advantage of the most recent observational results. Finally, we recall that microlensing observations towards the Galactic bulge are being increasingly finalised to the search of extra-solar planets [13].

## 2. The observational results

Popowski et al. [14], Hamadache et al. [15] and Sumi et al. [16], for the MACHO, EROS and OGLE collaborations, respectively, presented the final results out of their several-years campaigns carried out towards the Galactic centre. In Fig. 1 we show the position of the observed fields. Carrying out the analysis using the subsample of bulge *red clump* sources, so to avoid problems linked to blending, they reported the detection of 66, 120 and 32 events (MACHO, EROS and OGLE, respectively), and the analysis of the detection efficiency. Remarkably, their reported values for the optical depth are all in agreement among them, in particular with the value reported by the MACHO collaboration as evaluated in the “Central Galactic Region” (hereafter CGR, the set of 9 fields nearer to the Galactic centre where 42 of the events have been detected) $\tau = 2.17^{+0.47}_{-0.38}\, 10^{-6}$ for $(l,b) = 1^\circ.50, -2^\circ.68$. In Fig. 2 we show the duration distributions of the observed events. We note in particular the lack of very short duration events, Einstein time below 5 days, both in the EROS and the OGLE dataset as compared to the MACHO one. This turns out to be relevant in the study of the lens mass function but not for the evaluation of the optical depth.

## 3. The models

In order to study the microlensing quantities, optical depth and microlensing rate, we need to specify the models for the mass distribution, the kinematic and the mass function. As for the mass distribution, for the bulge we consider the triaxial models analysed by Stanek et al. [17], that we take as our “fiducial” model and compare it with that of Dwek et al. [18]. For the disc we consider a modified model of that presented by Han&Gould [19]. Having fixed the local density of the disc, we fix the overall mass of the bulge by normalising its mass distribution to the observed value of the optical depth. In particular it turns out a bulge mass value out to 2.5 kpc of $1.5\ 10^{10}\ \mathrm{M}_\odot$. As for

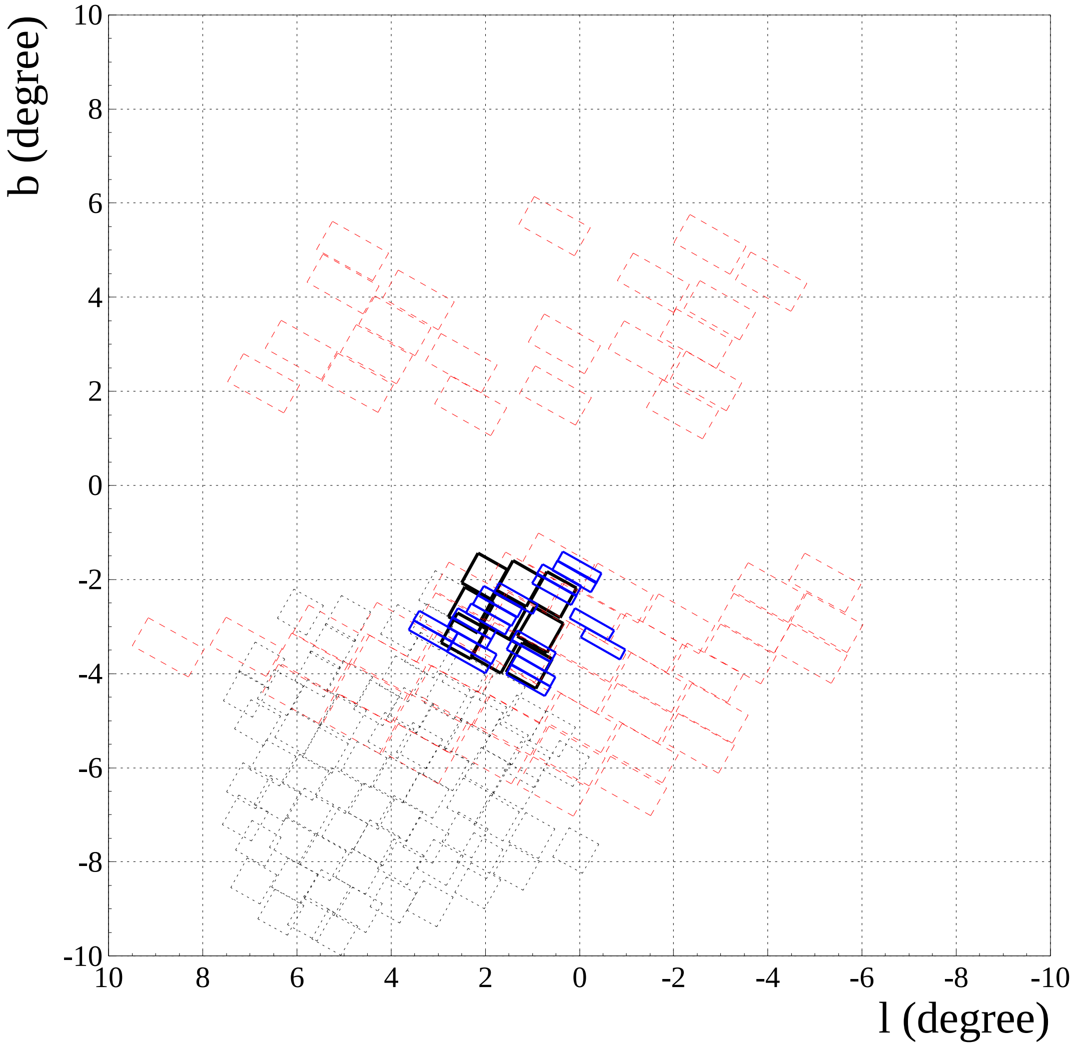


**Figure 1:** The observed fields towards the Galactic centre: the 94 fields of the MACHO collaboration [14], black dotted lines and bold solid lines (the 9 "CGR" fields near the Galactic centre), the 66 fields of the EROS collaborations [15], red dashed lines, and the 20 fields of the OGLE collaborations [16], blue thin solid lines.

the kinematic we consider both a bulk and a random motion. For the latter, for our fiducial model, we fix the values of the dispersion of the anisotropic Gaussian distribution of the bulge components making use of the virial theorem [20]. As a second estimate we make use of recent observational results [21]. Finally, we have to fix the lens mass function. For both the disc and the bulge we use a power law. For the former we use the values and the normalisation reported in [22]. For the bulge, we leave as free parameters in our analysis the slopes, $\alpha_{\rm BD}$, $\alpha_{\rm MS}$, in the brown dwarf $0.01-0.08~{\rm M}_\odot$ and in the main sequence $0.08-1~{\rm M}_\odot$ ranges. Following the analysis of Gould [23] we assume everything above 1 Solar mass to have evolved in a remnant phase.

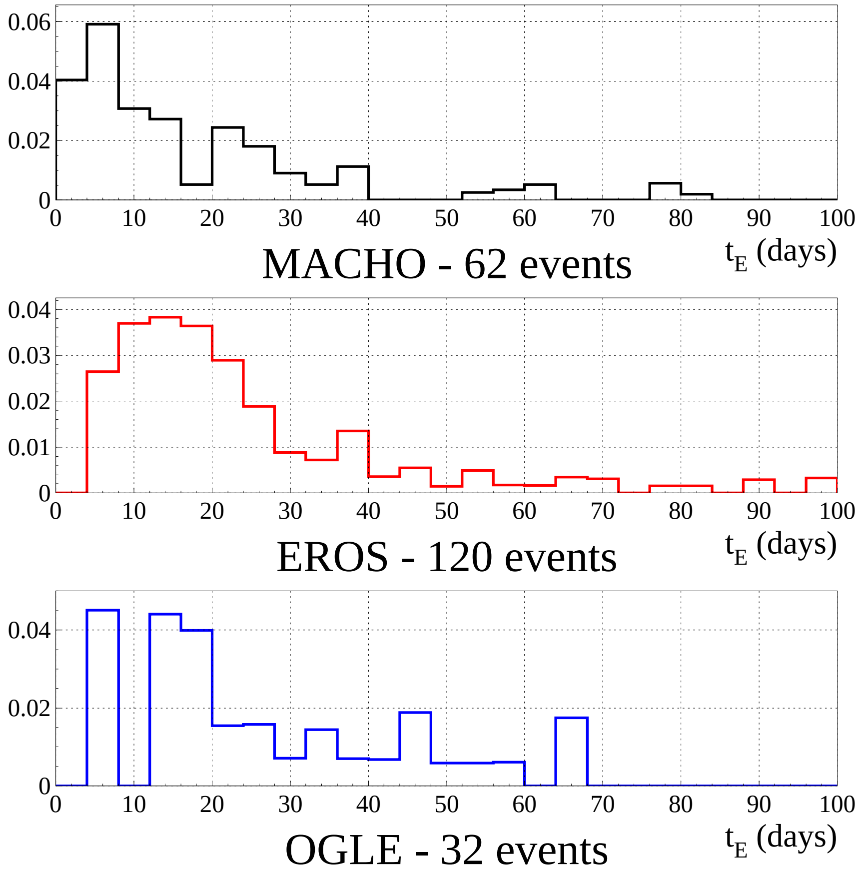
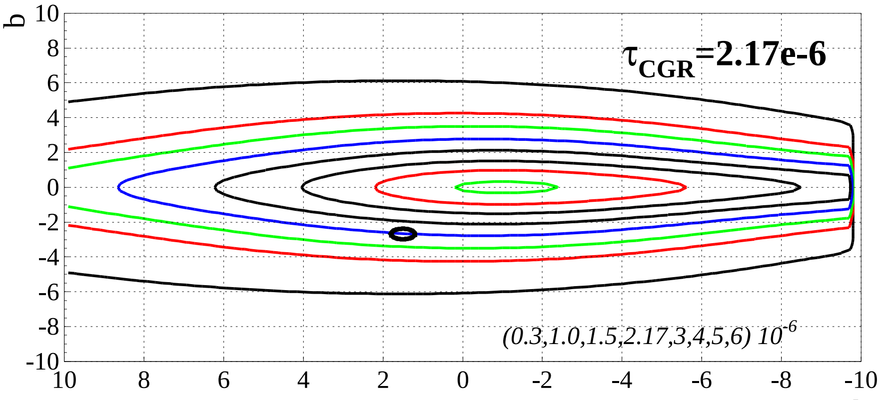


**Figure 2:** Duration distributions for the three data sets we consider.

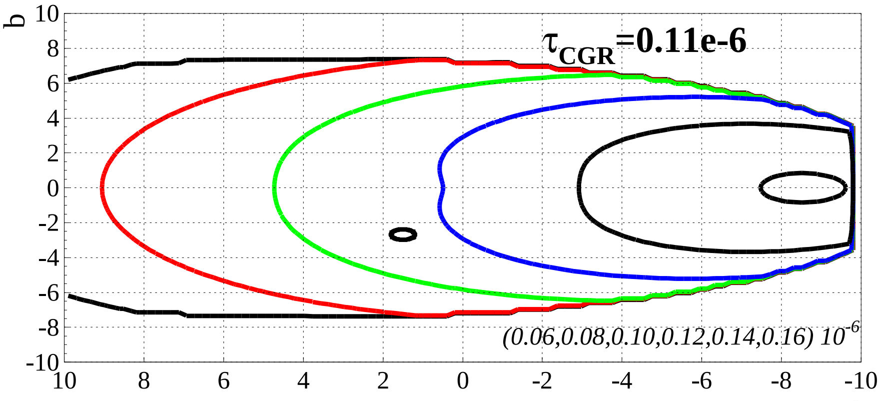
## 4. The optical depth : a study of the lens mass distribution

The acknowledgement of the *blending* issue, and the consequent choice to restrict the analysis to the subsample of bulge *red clump* sources has been essential to reach an agreement between the observed values and the theoretical estimate of the optical depth [19]. In Fig. 3 we show the profiles of the optical depth for bulge sources and both the luminous, bulge and disc, and “dark” populations of lenses. As expected, we find that the contribution of any would be MACHO population would be negligible as compared to that of the luminous components (by more than one order of magnitude even for a *full* MACHO halo).

As we have normalised the bulge mass distribution to the observed values of the optical depth (as evaluated at the centre of the CGR), we may ask whether the theoretical optical depth profile trace the observed one. To this purpose we carry out the following analysis. We bin the space of the theoretical optical depth, we note that each bin delimits a regions within the observed fields, and we compare the expected optical depth value with the observed one as evaluated whithin the corresponding region. As a result, Fig. 4, we find a very good agreement for all the three data sets and the two bulge models we have studied.



bulge and disc lenses



dark matter halo (f=1) lenses

**Figure 3:** Optical depth profiles for bulge sources and bulge and disc lenses (top) and dark matter halo lenses (for a full "standard" halo model [2]). The circle at $(l,b) = 1^\circ.50, -2^\circ.68$ marks the CGR centre where we have normalised the bulge mass distribution to the observed value of the optical depth, $\tau = 2.17\ 10^{-6}$ [14].

## 5. The microlensing rate : a study of the lens mass function

The microlensing rate allows the evaluation of the expected number of events and of their characteristics, in particular of their durations. Once given the characteristics of the observed events and the experimental detection efficiency, the evaluation of the microlensing rate allows us therefore to carry out a maximum likelihood analysis to determine the free parameters within our model, namely, the bulge mass function slopes $\alpha_{\mathrm{BD}}, \alpha_{\mathrm{MS}}$. Given the efficiency corrected differential rate, $\mathrm{d}\Gamma_{\mathscr{E}}/\mathrm{d}t_{\mathrm{E}}$, and allowing for the Poisson nature of the process, where in particular the event *number* itself is a random variable, the likelihood reads

$$L\left(\alpha_{\mathrm{BD}},\ \alpha_{\mathrm{MS}}\right) = \exp(-N_{\mathrm{exp}}) \prod_{i=1}^{N_{\mathrm{obs}}} \left.\frac{\mathrm{d}\Gamma_{i,\mathscr{E}}}{\mathrm{d}t_{\mathrm{E}}}\right|_{t_{\mathrm{E},event}} . \tag{5.1}$$

Here $N_{\mathrm{exp}}$ is the overall expected number of events, to be evaluated by integrating out the differential rate taking into account, besides the detection efficiency, the number of sources and the overall duration of the experiment. In particular it results $N_{\mathrm{exp}} = N_{\mathrm{exp}}(\alpha_{\mathrm{BD}},\ \alpha_{\mathrm{MS}})$. The product runs over the $N_{\mathrm{obs}}$ observed events.

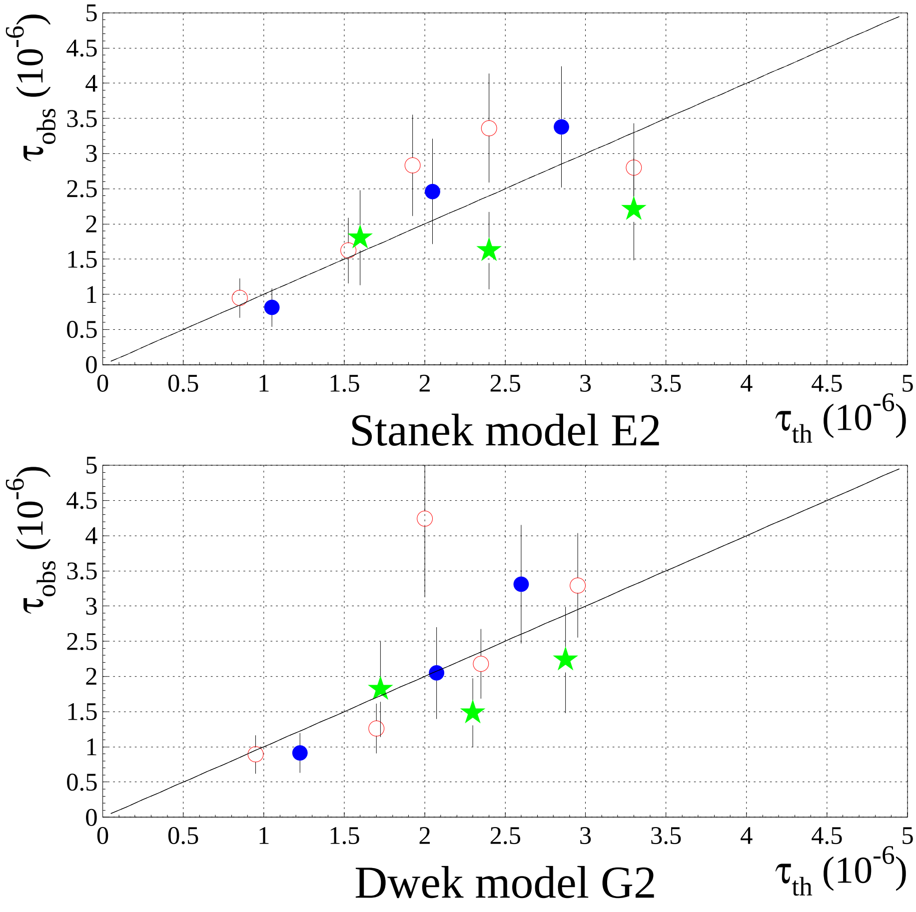


**Figure 4:** The observed versus the expected optical depth for the two bulge models considered. EROS, MACHO and OGLE data are the empty, filled circles and stars respectively. The solid line is the $y = x$ line. (Plot adapted from [24]).

In Fig. 5 we report the result of this analysis, restricted to the subsample of the 42 events reported by the MACHO collaboration within the CGR [14]. As it turns out, the main sequence slope is better constrained by the data than the brown dwarf one. It results respectively, after marginalisation over one variable, $\alpha_{MS} = 1.7 \pm 0.5$ and $\alpha_{BD} = 1.6 \pm 1.0$ (we note that the former value agrees well with the evaluation made by Zoccali et al. [25] in the main sequence range, $\alpha \sim 1.3$). Furthermore, as also shown in the plot, we find that the lines of equal expected duration closely follow the lines of degeneracy in the parameter space $\alpha_{BD} - \alpha_{MS}$, this being a consequence of the relationship between lens mass and event duration. As to be expected, larger values of the duration are found for smaller values of the IMF slopes. As for the *number* of expected events, corresponding to the maximum likelihood values, we estimate $N_{exp} = 38$ (with $\sim$ 80% to be attributed to the bulge), in excellent agreement with the 42 observed events used in this analysis. Finally, the analysis of the EROS and OGLE data sets gives, for the main sequence slope, a similar result. However, because of the lack of short duration events in these data sets, we find no lower bound for the brown dwarf slope, for which, therefore, we can only assess an upper limit. (We refer to Calchi Novati et al. [24] and references therein for more details and discussions.)

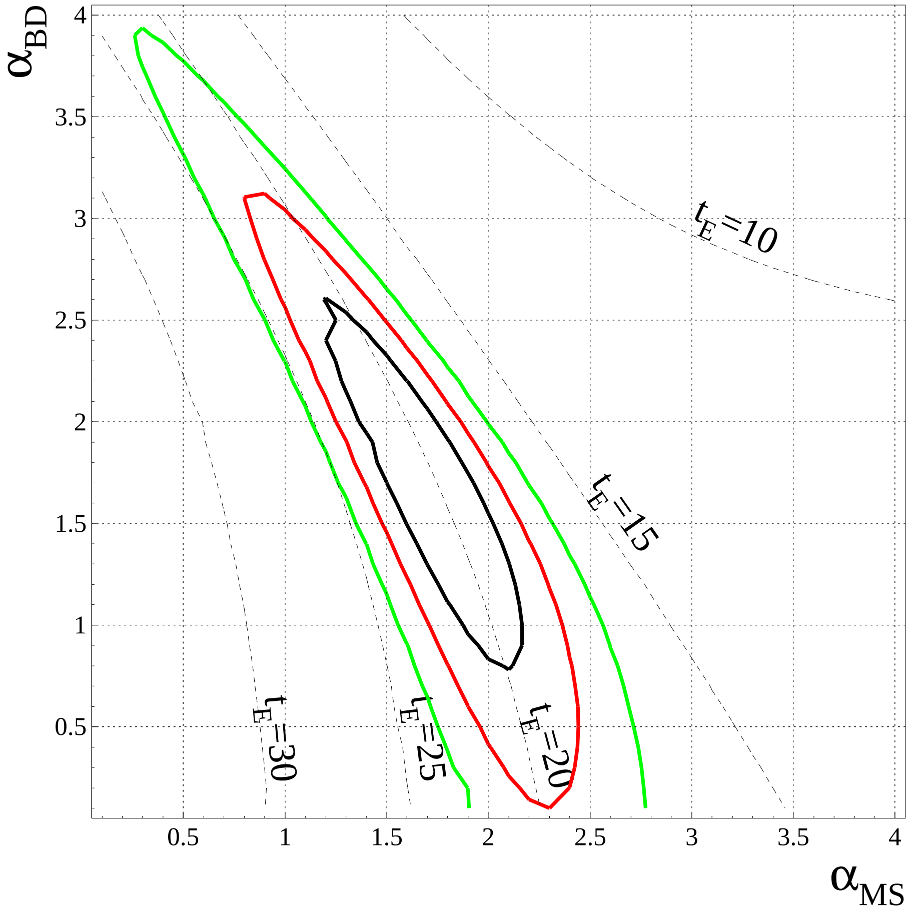


**Figure 5:** Probability isocontours with 34%, 68% and 90% regions in the $\alpha_{BD}$, $\alpha_{MS}$ plane (the slopes of the power law IMF of the Galactic bulge lenses, in the brown dwarf and main sequence range, respectively). The dashed lines are the lines of equal average expected event durations. Here the set of 42 events reported by the MACHO collaboration in the CGR, for which $\langle t_E = 20 \text{ d}\rangle$, is considered. (Plot adapted from [24]).

## 6. Conclusions

Microlensing observations towards the Galactic centre are a very efficient tool for the study of the lens mass distribution and characteristics. Using the most recent observational results of the MACHO, EROS and OGLE collaborations we have analysed the profiles of the optical depth and carried out a maximum likelihood analysis of the microlesing rate to constrain the bulge mass function. As for the optical depth, we have found a very good agreement of the theoretical profile with the observed one, through all the observed fields. The microlensing rate analysis allowed us to constrain the parameter of a power law bulge initial mass function. In particular we have found, in the main sequence range, a value for the slope $\alpha \sim 1.7$, in good agreement with previous results. In order to improve these estimates, in particular for the low mass tail of the mass function, it would be suitable to better probe also shorter duration events. A further issue that deserves better understanding is that of blending, that can bias the evaluation of the timescale and therefore the analysis of the lens characteristics.

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