PREDICTING GRAVITATIONAL MICROLENSING EVENTS USING THE GAIA CATALOGUE

Intern: Mahima R. Srivastava

Supervisor: Prof. Bertrand Goldman

Faculté de physique et ingénierie
Université de Strasbourg

INTERNATIONAL SPACE UNIVERSITY

Summary

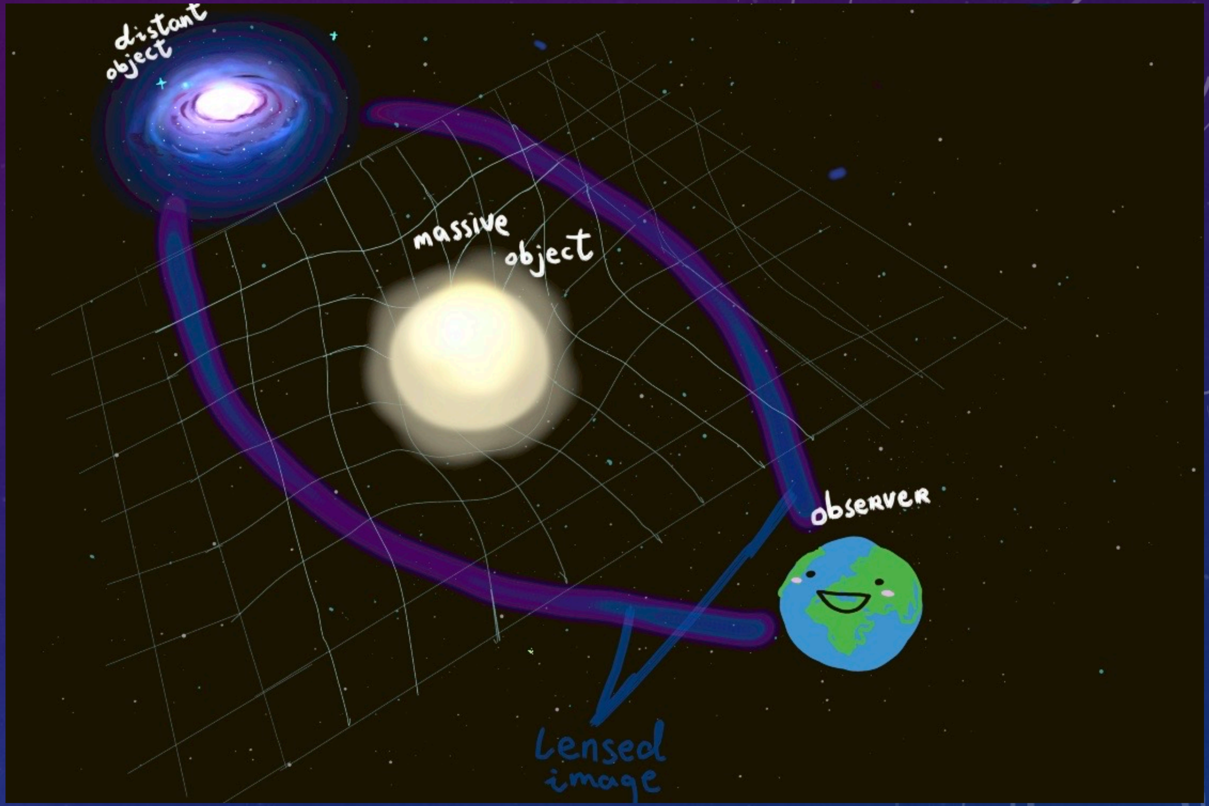
Motivation

Tools

Results

Gravitational Lensing

- Gravitational lensing is a natural phenomenon that takes place when there is an alignment of massive bodies in space.



An artist's rendition of Gravitational Lensing [1]

Gravitational Lensing

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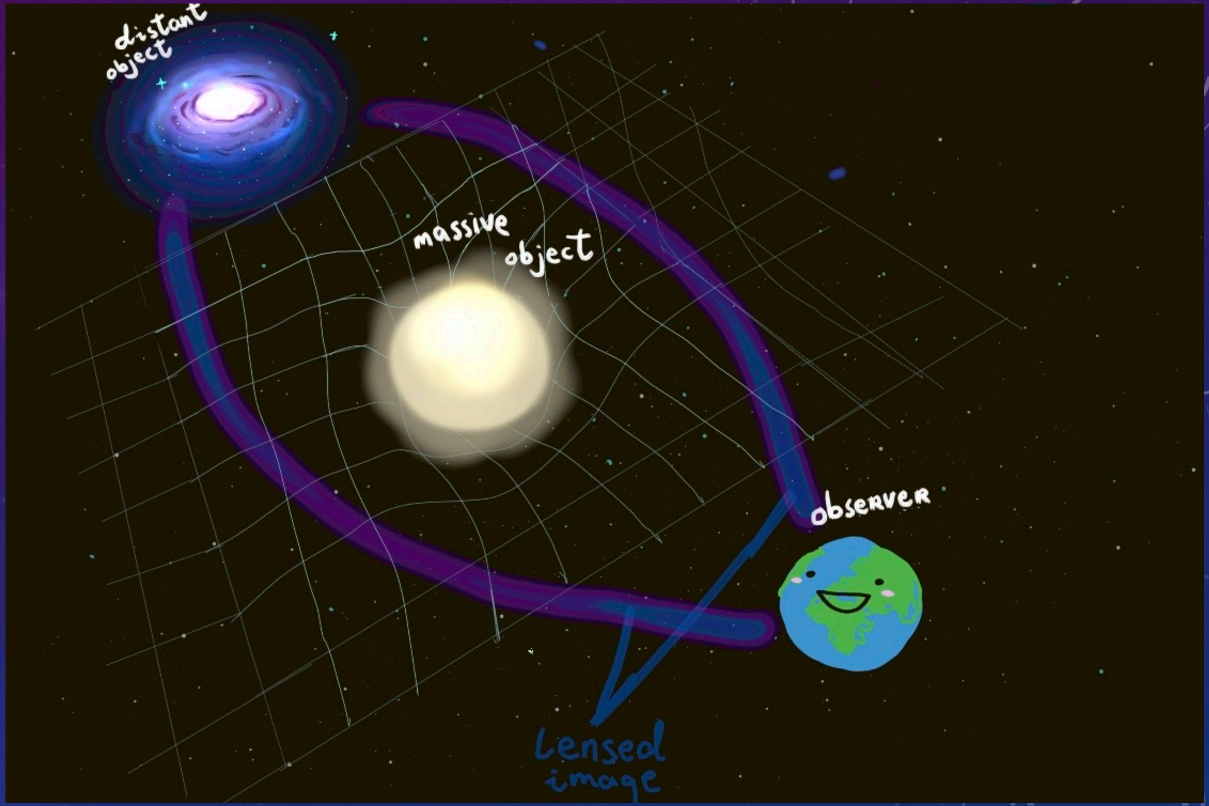
- When a massive object intervenes between an observer and a distant light source, it distorts the incoming light, due to the bending spacetime by its gravitational field.



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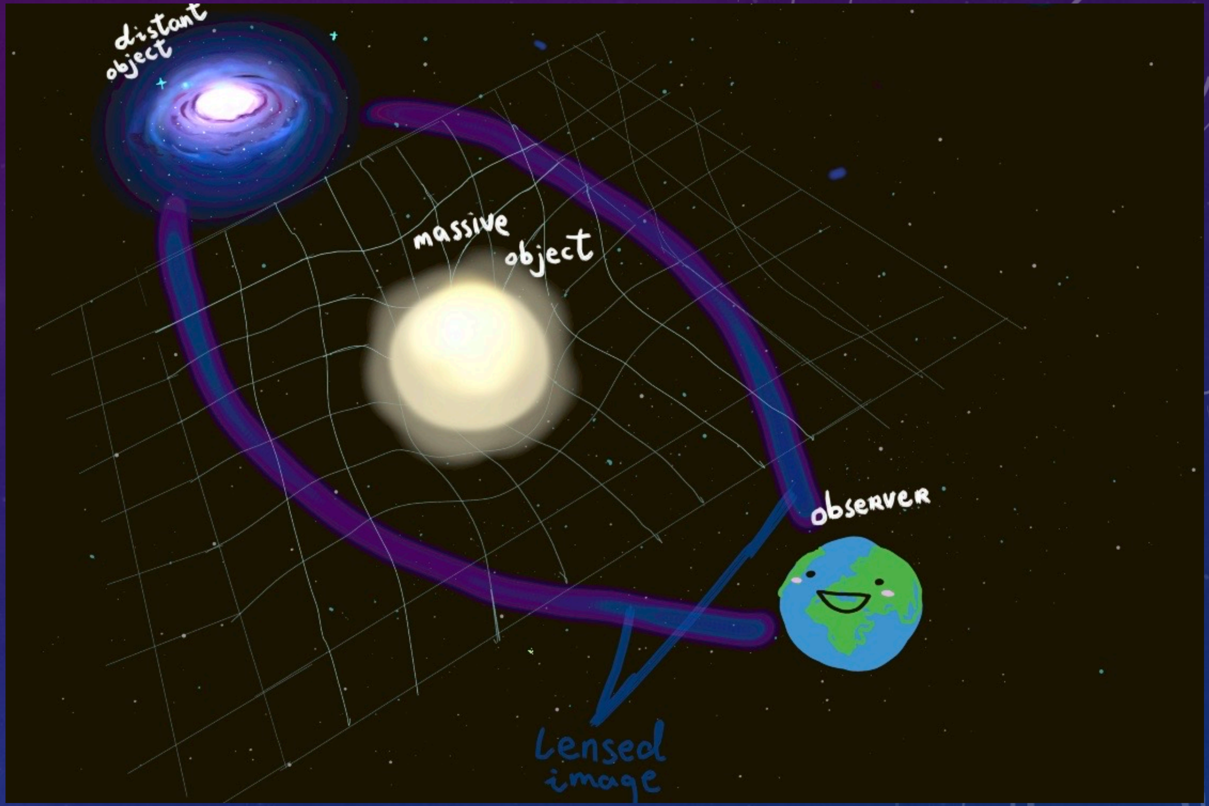
- Lensing can be used for detecting exoplanets, blackholes, stars, galaxies, galaxy clusters, and studying their properties.



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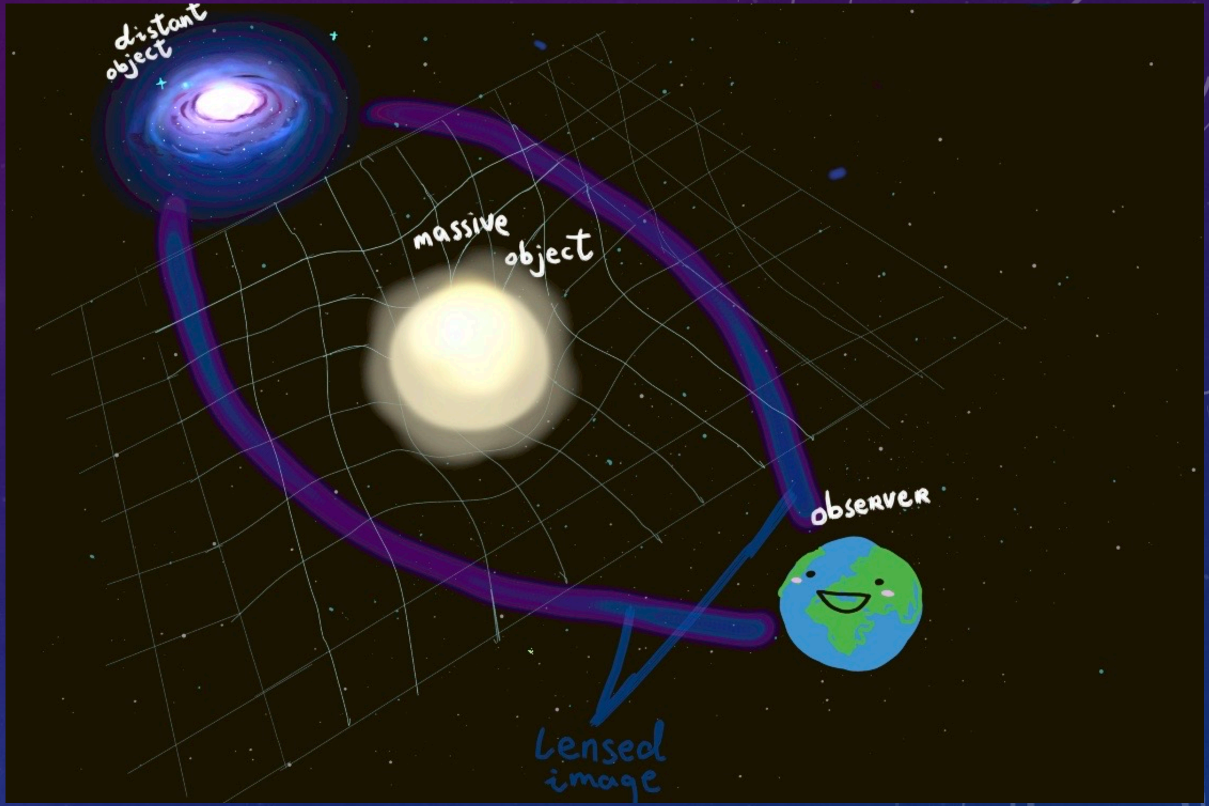
- Lensing can be used for detecting exoplanets, blackholes, stars, galaxies, galaxy clusters, and studying their properties.
- Microlensing is a case with low masses/ critical density objects, that do not lens strongly enough form multiple images (e.g., stellar lenses). These result in a uniform change in brightness, with a smooth increase followed by a smooth decrease.



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Types of observed shifts

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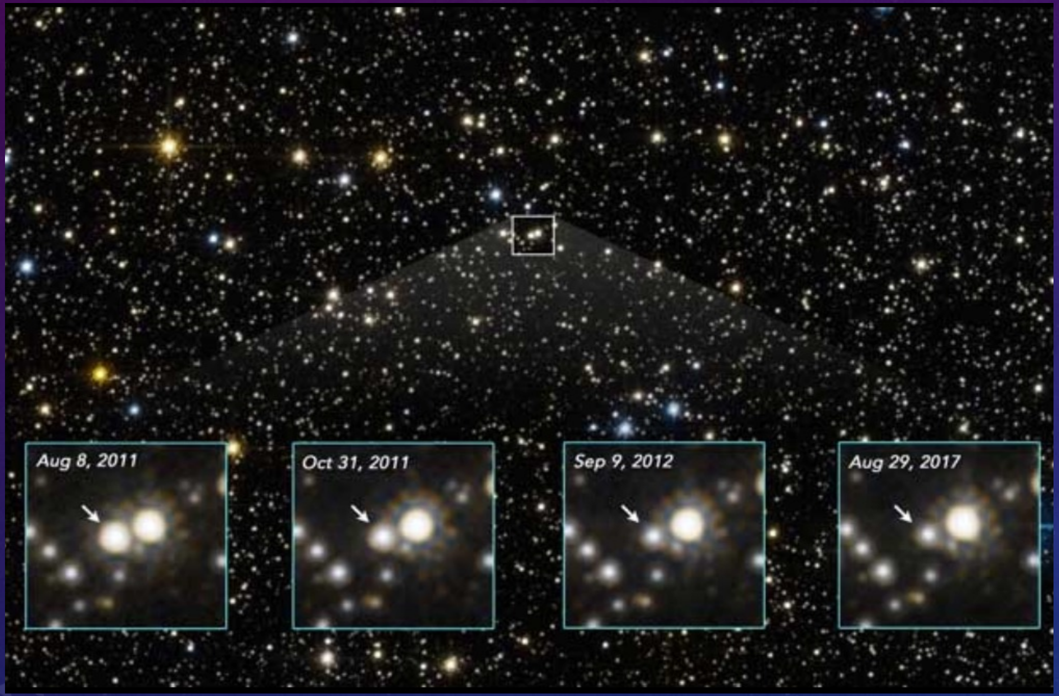
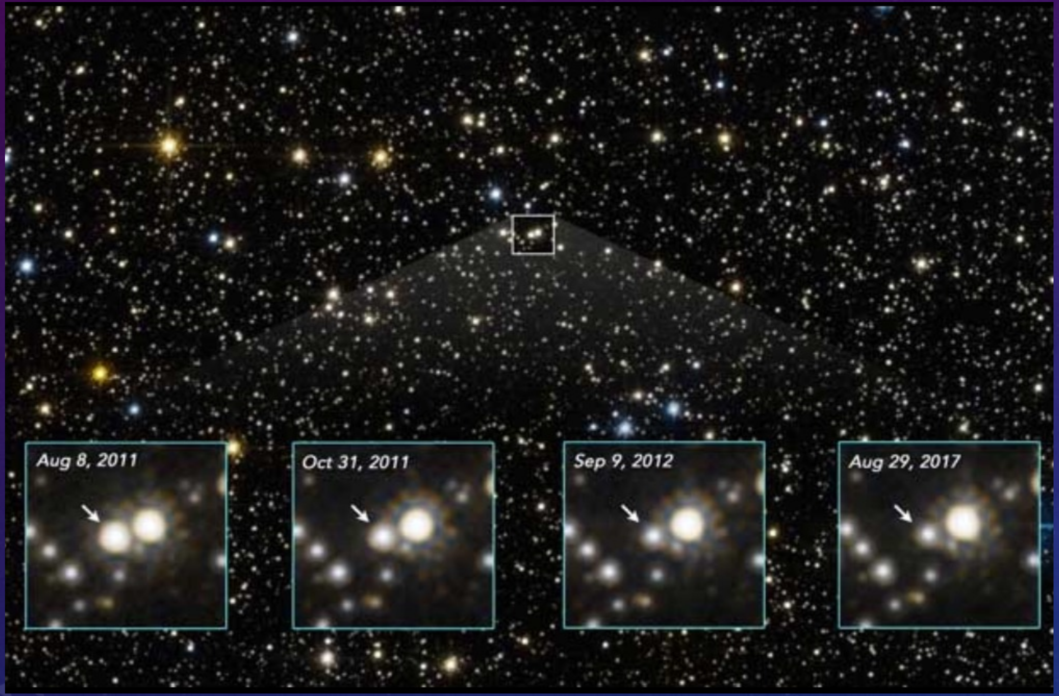
Photometric Shift



- Measured through change in magnitude

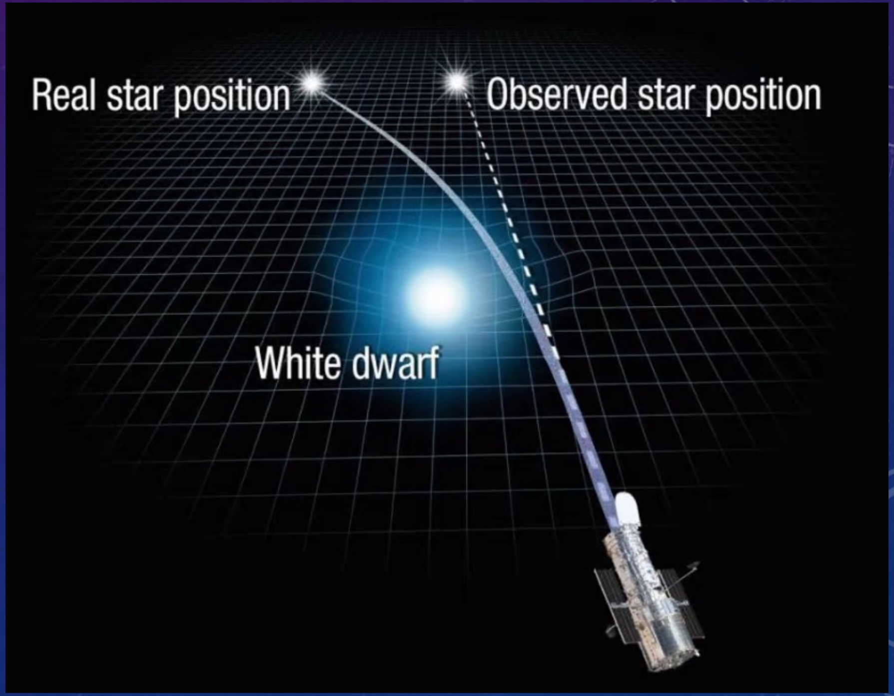
Types of observed shifts

Photometric Shift



- Measured through change in magnitude

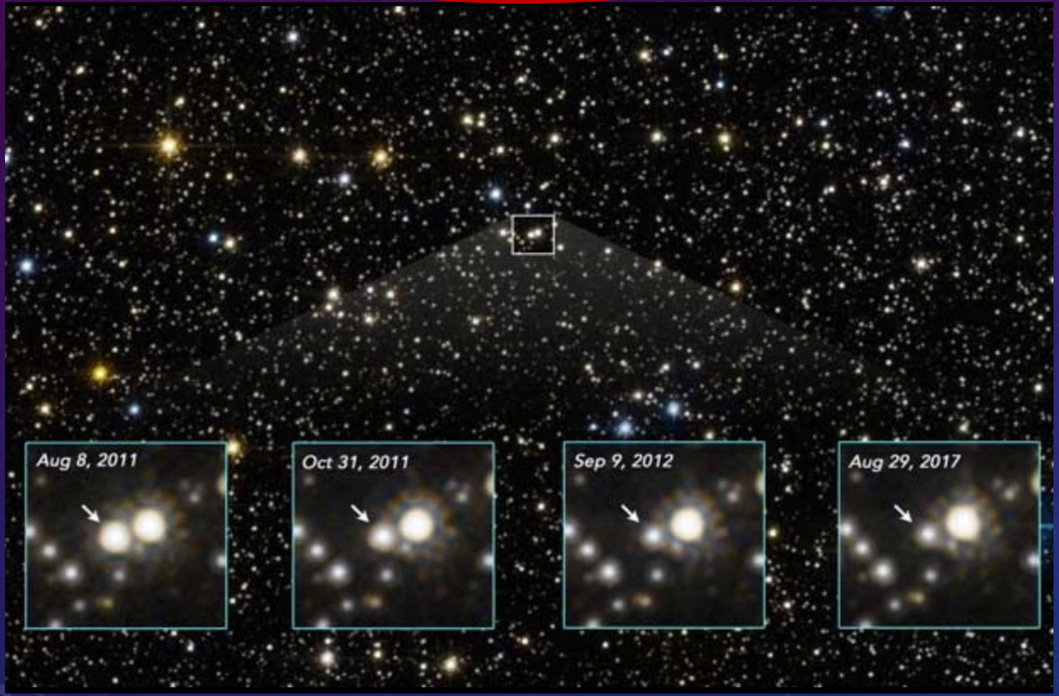
Astrometric Shift



- Measured through change in apparent position

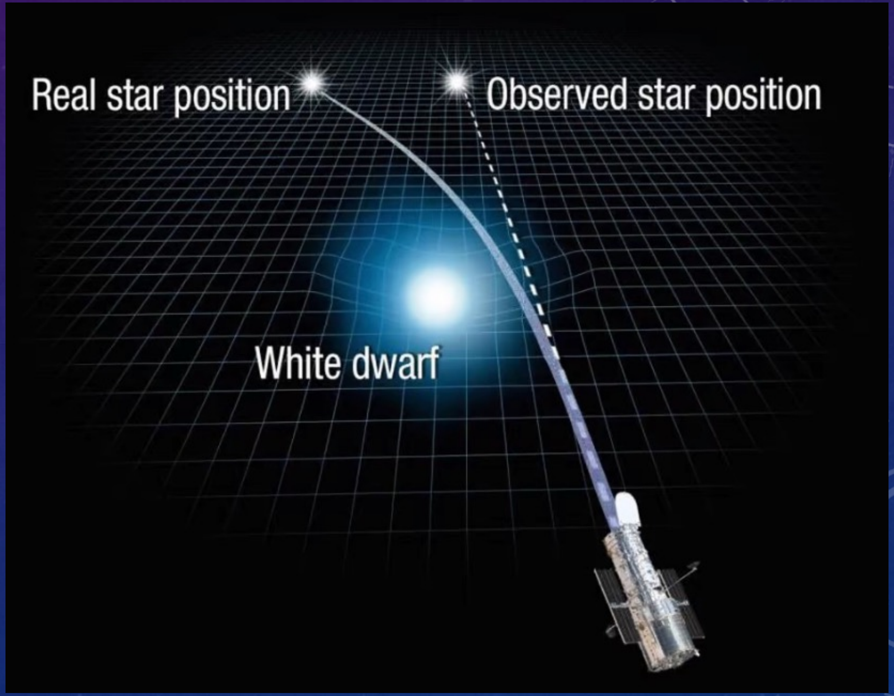
Types of observed shifts

Photometric Shift



- Measured through change in magnitude

Astrometric Shift



- Measured through change in apparent position

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Astronomy & Astrophysics

Prediction of astrometric microlensing events from *Gaia* DR2 proper motions

J. Klüter[1], U. Bastian[1], M. Demleitner[1], and J. Wambsganss[1,2]

[1] Zentrum für Astronomie der Universität Heidelberg, Astronomisches Rechen-Institut, Mönchhofstr. 12-14, 69120 Heidelberg, Germany
e-mail: klueter@ari.uni-heidelberg.de
[2] International Space Science Institute, Hallerstr. 6, 3012 Bern, Switzerland

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ABSTRACT

Context. Astrometric gravitational microlensing is an excellent tool to determine the mass of stellar objects. Using precise astrometric measurements of the lensed position of a background source in combination with accurate predictions of the positions of the lens and the unlensed source it is possible to determine the mass of the lens with an accuracy of a few percent.
Aims. Making use of the recently published *Gaia* Data Release 2 (DR2) catalogue, we want to predict astrometric microlensing events caused by foreground stars with high proper motion passing a background source in the coming decades.
Results. We selected roughly 148 000 high-proper-motion stars from *Gaia* DR2 with $\mu_{tot} > 150\,\mathrm{mas\,yr^{-1}}$ as potential lenses. We then searched for background sources close to their paths. Using the astrometric parameters of *Gaia* DR2, we calculated the future positions of source and lens. With a nested-intervals algorithm we determined the date and separation of the closest approach. Using *Gaia* DR2 photometry we determined an approximate mass of the lens, which we used to calculate the expected microlensing effects.
Conclusions. We predict 3914 microlensing events caused by 2875 different lenses between 2010 and 2065, with expected shifts larger than 0.1 mas between the lensed and unlensed positions of the source. Of those, 513 events are expected to happen between 2014.5 and 2026.5 and might be measured by *Gaia*. For 127 events we also expect a magnification between 1 mmag and 3 mag.

Key words. astrometry – catalogs – proper motions – gravitational lensing: micro – methods: data analysis

1. Introduction

Gravitational lensing has become a powerful tool to study galactic and extragalactic objects (Wambsganss 2006). It is used for example to investigate the mass distributions of galaxies, to determine the Hubble constant, to discover distant quasars, and to find extrasolar planets. Gravitational lensing describes the deflection and magnification of background sources by an intervening massive object (Einstein 1915, 1936). For stellar lenses (microlensing), two images of the source are created, a bright image close to the unlensed source position and a fainter image close to the lens. Both images merge into a so-called Einstein ring when the source is perfectly aligned with the lens. The characteristic size of this ring is given by the Einstein radius

$$\theta_E = \sqrt{\frac{4GM_L}{c^2}\frac{D_S - D_L}{D_L D_S}}, \tag{1}$$

where M_L is the mass of the lens and D_S, D_L are the distances between the observer and the source or the lens (Chwolson 1924; Einstein 1936; Paczynski 1986). This is the most important quantity since it sets the scale for all lensing effects. For close-by stellar lenses (within 1 kpc) and distant sources, the Einstein radius is typically of the order of a few milliarcseconds. This is much smaller than the angular resolution of most of the currently available instruments. Due to the relative motion of source, lens, and observer, magnification and image geometry change over time. Up to now, mostly photometric magnification has been monitored and investigated by surveys such as the Optical Gravitational Lensing Experiment (OGLE, Udalski 2003) or the Microlensing Observations in Astrophysics (MOA, Bond et al. 2001) and has also led to the discovery of many exoplanets (e.g. Udalski et al. 2015), whereas the astrometric shift of the source was detected for the first time only recently (Sahu et al. 2017; Zurlo et al. 2018).

Astrometric microlensing provides the possibility to measure the mass of a single star with a precision of about one percent (Paczynski 1995). Furthermore, astrometric microlensing events can be predicted from stars with a known proper motion. This is the aim of the present study. For the prediction of astrometric events, faint nearby stars with high proper motions are of particular interest. High proper motions are preferred because the covered sky area within a given time is larger, hence microlensing events are more likely. Nearby stars are preferred because their Einstein radius is larger and therefore the expected shift is also larger, and faint lenses are favourable since the measurement of the source position is less contaminated by the lens brightness.

The first systematic search for astrometric microlensing events was done by Salim & Gould (2000). They found 146 candidates between 2005 and 2015. Proft et al. (2011) predicted 1118 candidates between 2012–2019. However, most of those predictions were based on erroneous proper motions in some of the catalogues used and only 49 events show reliable proper motions. High-accuracy proper motions are essential to make precise predictions. Today the *Gaia* mission (Gaia Collaboration 2016) provides the best data for such studies. Using the TGAS data of the first data release (*Tycho-Gaia* Astrometric Solution, Lindegren et al. 2016), McGill et al. (2018) predicted one event caused by a white dwarf in 2019. With the second data

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Prediction of Astrometric-Microlensing Events from *Gaia* eDR3 Proper Motions *†

Jonas Klüter,[1,2] Ulrich Bastian,[2] Markus Demleitner,[2] and Joachim Wambsganss[2,3]

[1]*Department of Physics and Astronomy, Louisiana State University, 202 Nicholson Hall, Baton Rouge, LA 70803 USA*
[2]*Zentrum für Astronomie der Universität Heidelberg, Astronomisches Rechen-Institut, Mönchhofstr. 12-14, 69120 Heidelberg, Germany*
[3]*International Space Science Institute, Hallerstr. 6, 3012 Bern, Switzerland*

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Submitted to AJ

ABSTRACT

Astrometric microlensing is a unique tool to measure stellar masses. It allows us to determine the mass of the lensing star with an accuracy of a few per cent. In this paper, we update, extend, and refine our predictions of astrometric-microlensing events based on Gaia's early Data release 3 (eDR3). We selected about 500.000 high-proper-motion stars from Gaia eDR3 with $\mu_{tot} > 100\,\mathrm{mas/yr}$ and searched for background sources close to their paths. We applied various selection criteria and cuts in order to exclude spurious sources and co-moving stars. By forecasting the future positions of lens and source we determined epoch of and angular separation at closest approach, and determined an expected positional shift and magnification. Using Gaia eDR3, we predict 1758 new microlensing events with expected shifts larger than 0.1 mas between the epochs J2010.5 and mid J2066.0. Further we provide more precise information on the angular separation at closest approach for 3084 previously predicted events. This helps to select better targets for observations, especially for events which occur within the next decade. Our search lead to the new prediction of an interesting astrometric-microlensing event by the white dwarf Gaia eDR3-4053455379420641152. In 2025 it will pass by a $G = 20.25$ mag star, which will lead to a positional shift of the major image of $\delta\theta_+ = 1.2^{+2.0}_{-0.5}$ mas. Since the background source is only $\Delta G = 2.45$ mag fainter than the lens, also the shift of the combined center of light will be measurable, especially using a near infrared filter, where the background star is brighter than the lens ($\Delta Ks = -1.1$ mag).

Keywords: Astrometry — Proper motions— Catalogues — Gravitational lensing: Astrometric-microlensing effect — Stellar properties: Stellar masses — White dwarf stars —

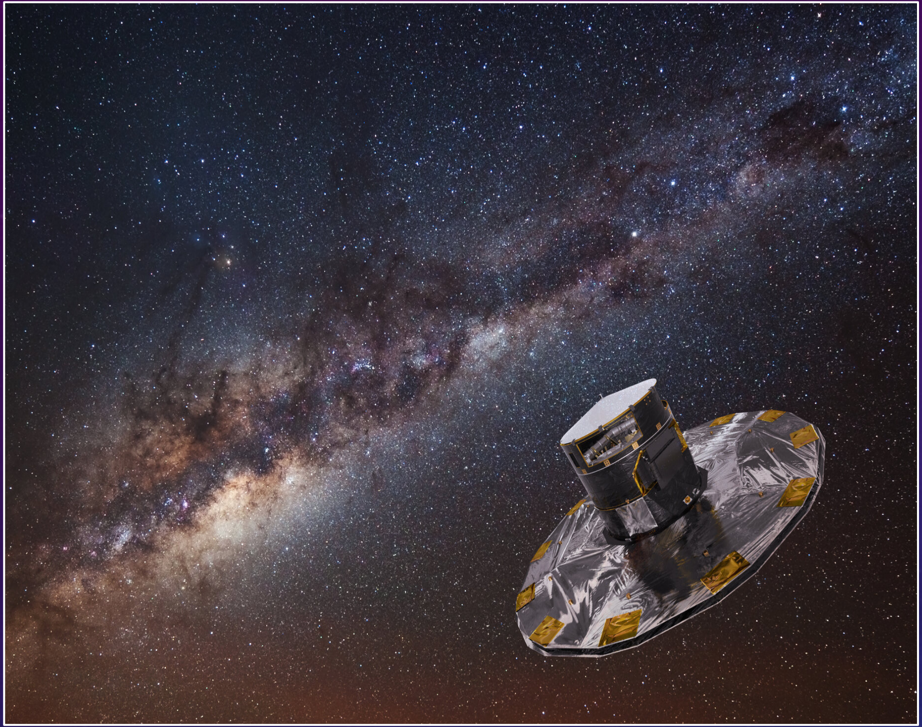
1. INTRODUCTION

The mass of a star is one of its most important parameters. It defines its luminosity, temperature, surface gravity, appearance, and evolutionary path. Testing evolutionary and stellar models requires accurate and direct measurements of fundamental stellar parameters. Direct masses are usually derived from double-lined spectroscopic and eclipsing binaries. However, for most of the isolated stars, masses can only be derived indirectly, typically by using the mass-luminosity or mass-radius relations. For the determination of such relations, a set of accurately known masses is required. These are mainly derived from binary stars (Andersen 1991; Torres et al. 2010). However, binary stars and isolated stars may evolve differently. Therefore it is not known how well these empirical relations describe the masses of single stars. For a better understanding of the mass-luminosity relations, direct mass measurements of single stars are important. Besides asteroseismology, which itself is strongly model dependent, gravitational microlensing is the only available tool. Further, the direct determined mass of white dwarfs provides a unique test sample for comparison with theoretical mass-radius relations and evolutionary cooling tracks of white dwarfs, a first such measurement was achieved by Sahu et al. (2017).

Corresponding author: Jonas Klüter
jklueter1@lsu.edu

* The results of the predicted microlensing events is available in electronic form via the GAVO Data Center https://dc.g-vo.org/amlensing/q3/q/form
† The source code for this study is made publicly available https://github.com/jkluter/amlensing

GAIA DR3



GAIA SATELLITE CREATING A MAP OF THE SKY, CREDIT: ESA'S WEBSITE

- 2013 – 2025 (DR3 : December 2020)
- Photometric as well as astrometric data
- ~1.5 billion sources

EROS 2

THE GROUND – BASED MARLY TELESCOPE, CREDIT: ESO

- 1996 - 2003
- Photometric telescope
- Monitored the luminosities of 8 million stars
- 1993: 2 candidates found, 1 later shown to be a variable star (1999)

Statement of the Objective

> *Using the proper motion, positions, parallax, etc. of stars observed in the Gaia DR3 catalogue, "predict" microlensing events that might have gone unidentified in previous catalogues, in this case, namely, the EROS 2 catalogue.*

Retrieving the data

- TOPCAT : Application for working with tabular data in astronomy (with built in features for mapping, cross matching, cone search, etc.)

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- TAP queries/ Virtual Observatory Protocols : A set of protocols used by services for data management and are hence essential for seamless data exchange between services (for e.g., VizieR) and clients (us), through TAP [Table Access Protocol] queries.

Synchronous mode

server immediately processes the request and provides a response

We are using this mode

Asynchronous mode

server begins a process (or a "job") to fulfill the request

Provides a link to monitor the status of the job

Preferred for very large jobs

Retrieving the data

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- ADQL : similar language to SQL, used to formulate requests to the TAP service, specifying which objects (generally randomly picked) with which parameters and in what ordered form are required.

Symbols used

Symbol	Quantity
ϖ	Parallax
XMag	Magnitude in the X band; X = {G, R, B}
pm	Proper motion
σ	error associated to a quantity
Sou	prefix referring to the source object
HPMS	High Proper Motion Stars
BGS	Background Stars

Basic Schematic of the algorithm

- ruwe < 2
- $\frac{\varpi}{\sigma_{\varpi}} > 5$
- pm > 100 mas/yr
- $G_{mag} \neq 0$
- $\frac{G_{flux}}{\sigma_{G_{flux}}} > 3$

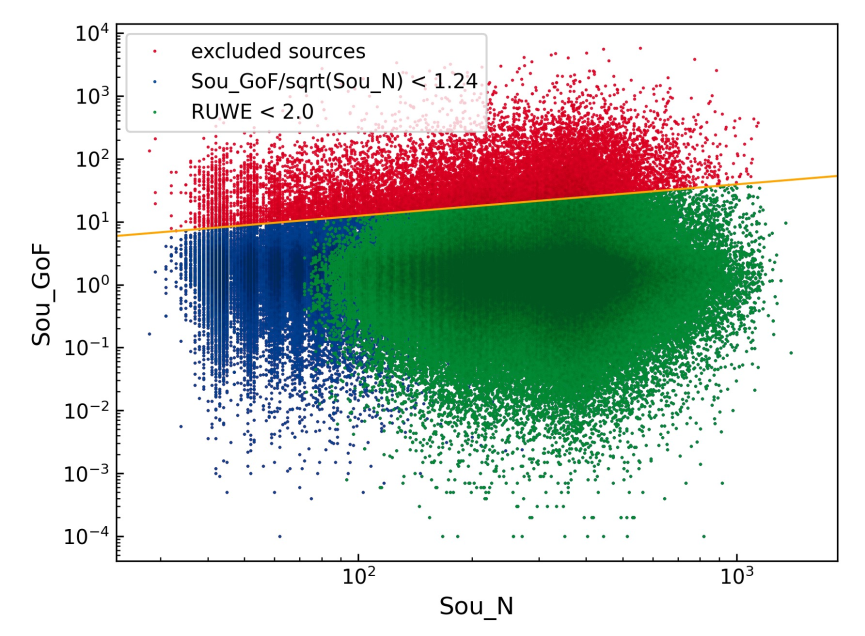
HPMS
442,681

```
SELECT
source_id, ra, dec, ra_error, dec_error, pmra, pmdec, pmra_error, pmdec_error, parallax,
parallax_error,
        phot_g_mean_mag, phot_rp_mean_mag, phot_bp_mean_mag,
parallax_over_error, ruwe,
        phot_g_mean_flux_over_error, phot_g_n_obs, astrometric_sigma5d_max
FROM gaiadr3.gaia_source
WHERE ruwe <2
    AND parallax_over_error > 5
    AND phot_g_mean_mag != 0
    AND pm > 100
    AND phot_g_mean_flux / phot_g_mean_flux_error > 3
```

BGS
443,481

- ruwe < 2
- $\frac{\varpi}{\sigma_{\varpi}} > -3$
- $G_{mag} > 15$
- $\varpi < 12$

(cross-matched with the HPMS with radius = 10 mas)



Basic Schematic of the algorithm

HPMS
442,681

↓

HPMS (good)
439,782

- $G_{mag} < 21$
- $\frac{G_{flux}}{\sigma_{G_{flux}}} . n_{obs}^{1.5} < 3 * 10^5$

BGS
443,481

↓

BGS (good)
327,640

$\sqrt{\sigma_{ra}^2 + \sigma_{dec}^2} < 10\ mas$

Basic Schematic of the algorithm

HPMS
442,681

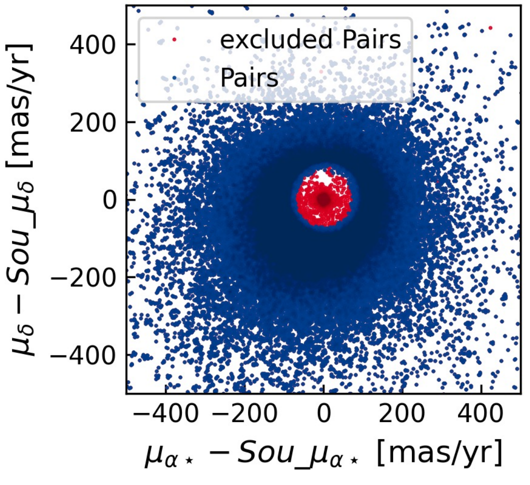
BGS
443,481

HPMS (good)
439,782

BGS (good)
327,640

- $\frac{Sou_{\varpi}}{\varpi} < 0.9$
- $\frac{Sou_{\mu-\mu}}{\mu_{tot}} > 0.7$
- $\frac{Sou_{\mu_{tot}}}{\mu_{tot}} < 0.8$

Viable Pairs
237,440



Basic Schematic of the algorithm

Viable Pairs
237,440

↓

$magnification > 0.001$

Final candidates from Gaia DR3
2,057

Basic Schematic of the algorithm

Viable Pairs
237,440

Final candidates from Gaia DR3
2,057

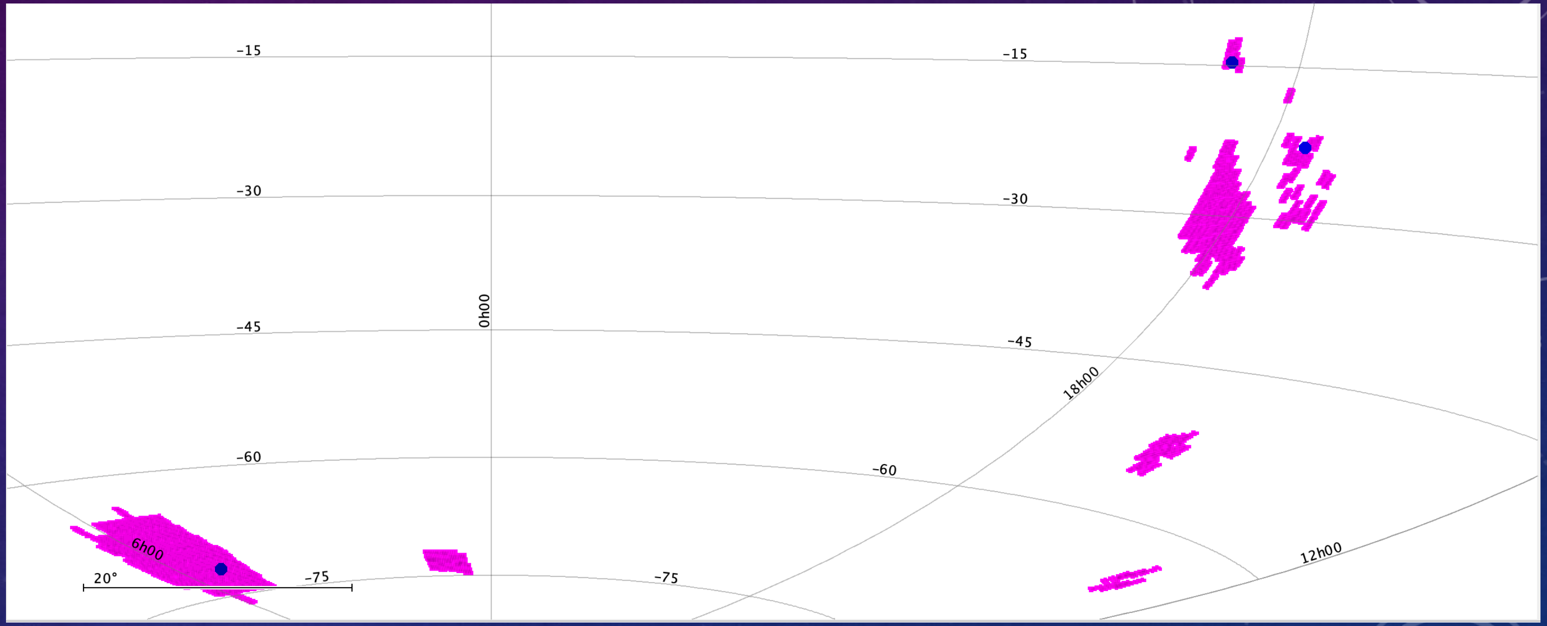
$$magnification + \sigma_{p_{magnification}} > 0.05$$

Candidates interesting for previous missions
3

Basic Schematic of the algorithm

Viable Pairs
237,440

EROS CCD Field



Final candidates from Gaia DR3
2,057

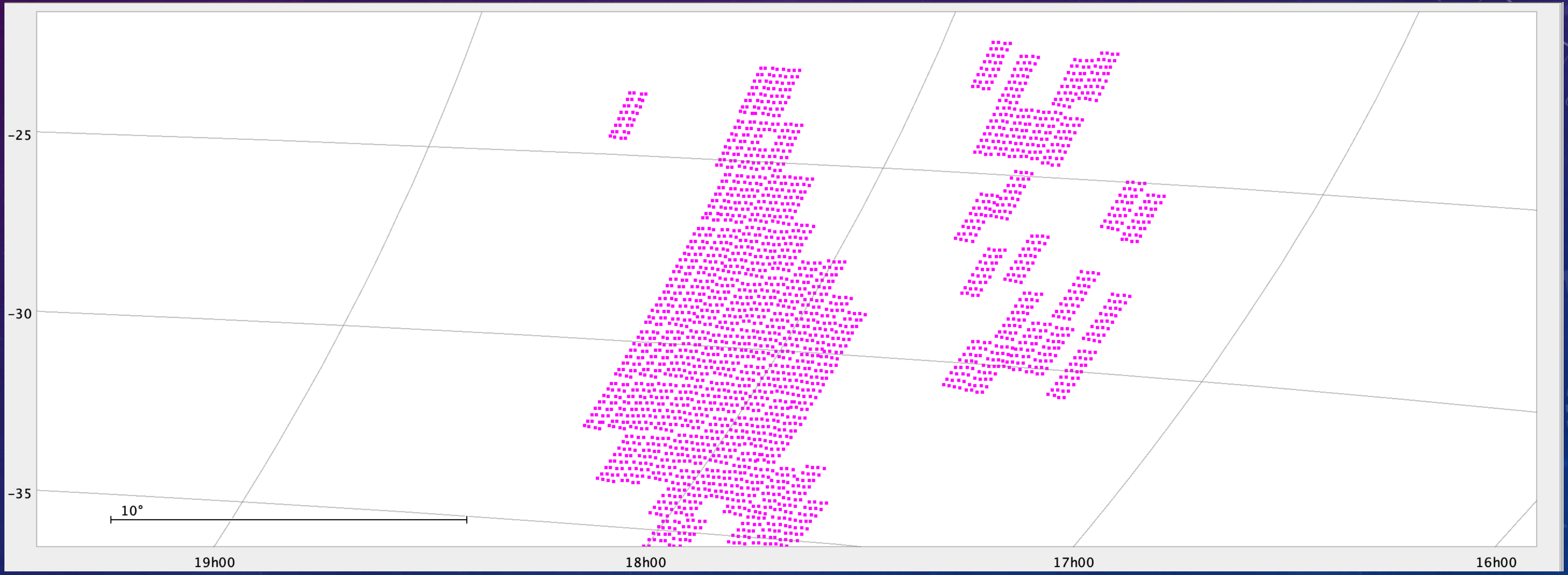
Candidates interesting for past missions
3

1996 < TCA < 2003

Cross Matched with EROS
2

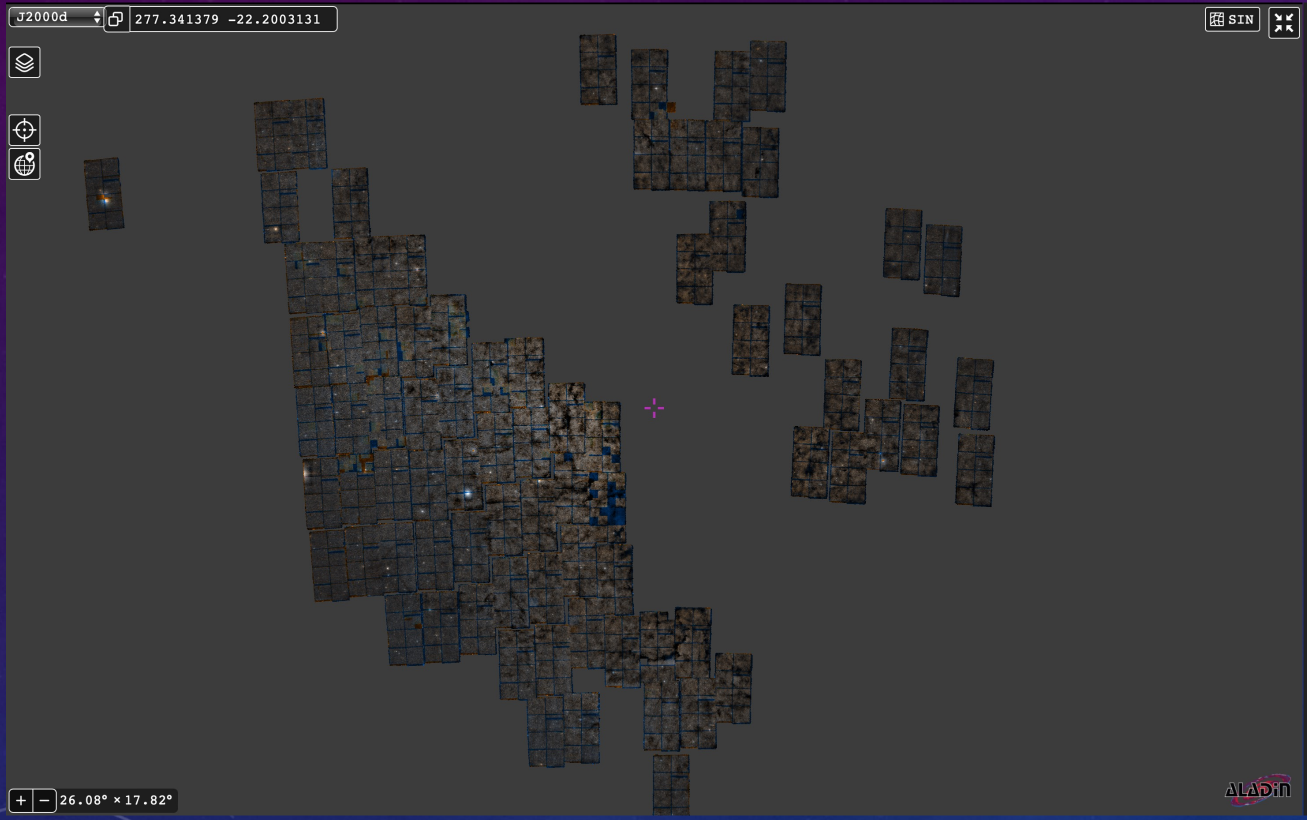
Basic Schematic of the algorithm

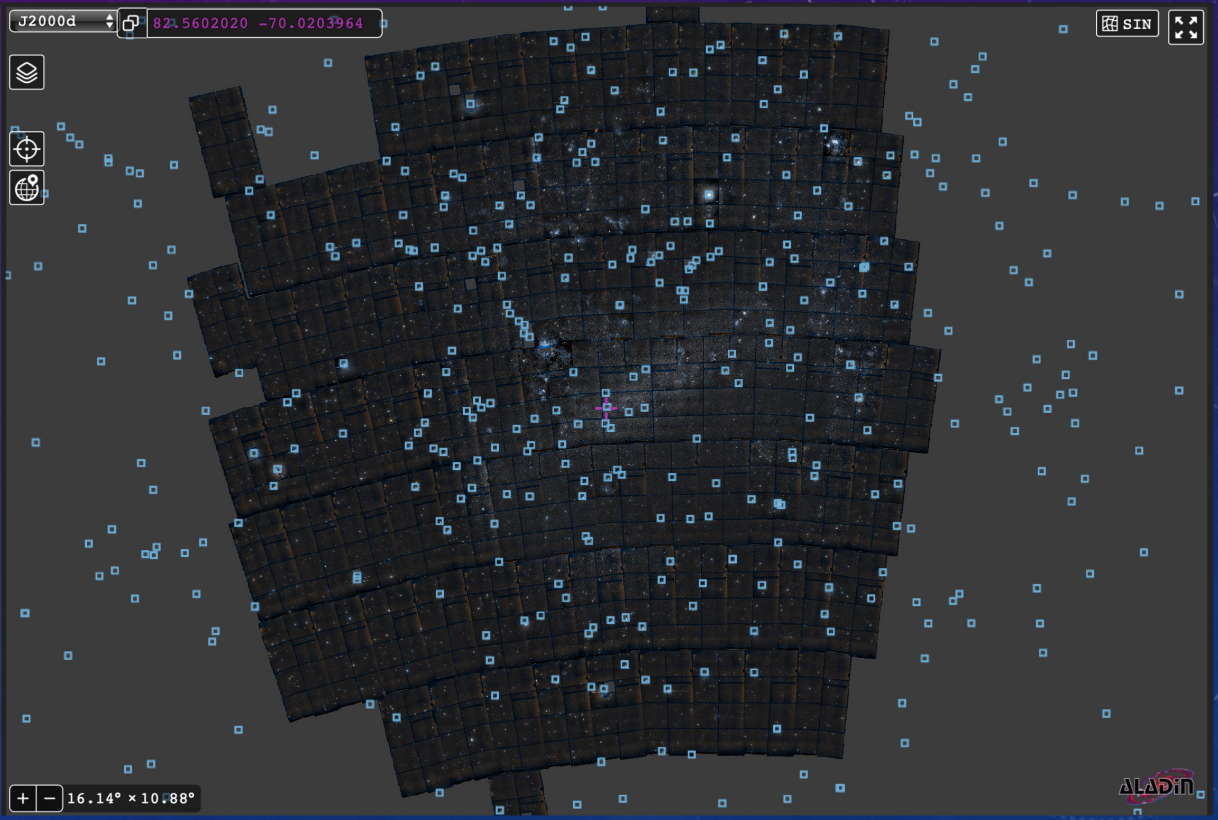
EROS CCD Field
side/gap = 10 arcmin
(determines the cross-match radius)



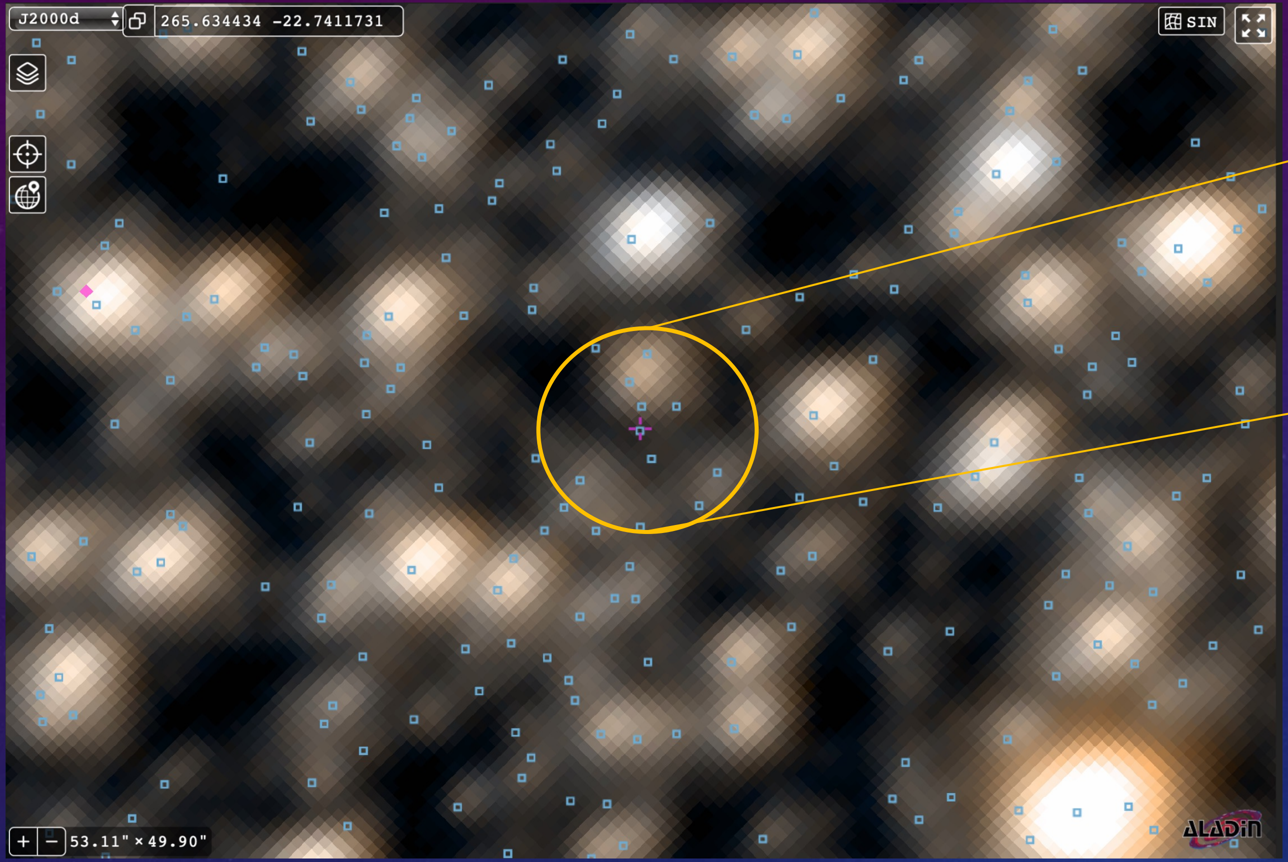
Results

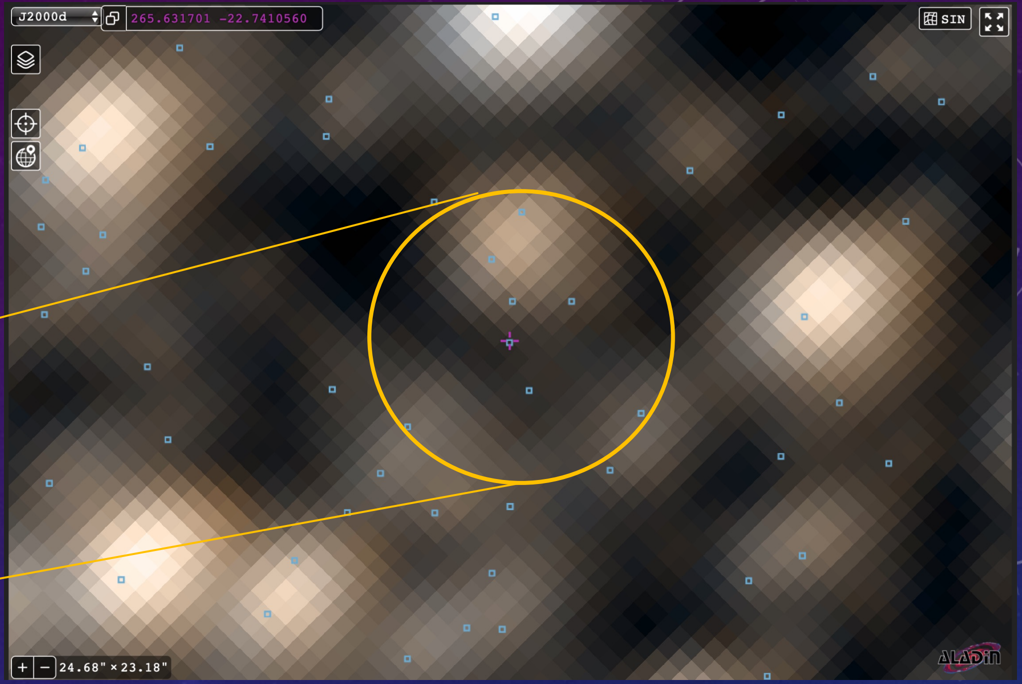
EROS 2 in color, overlayed with Gaia DR3 catalog





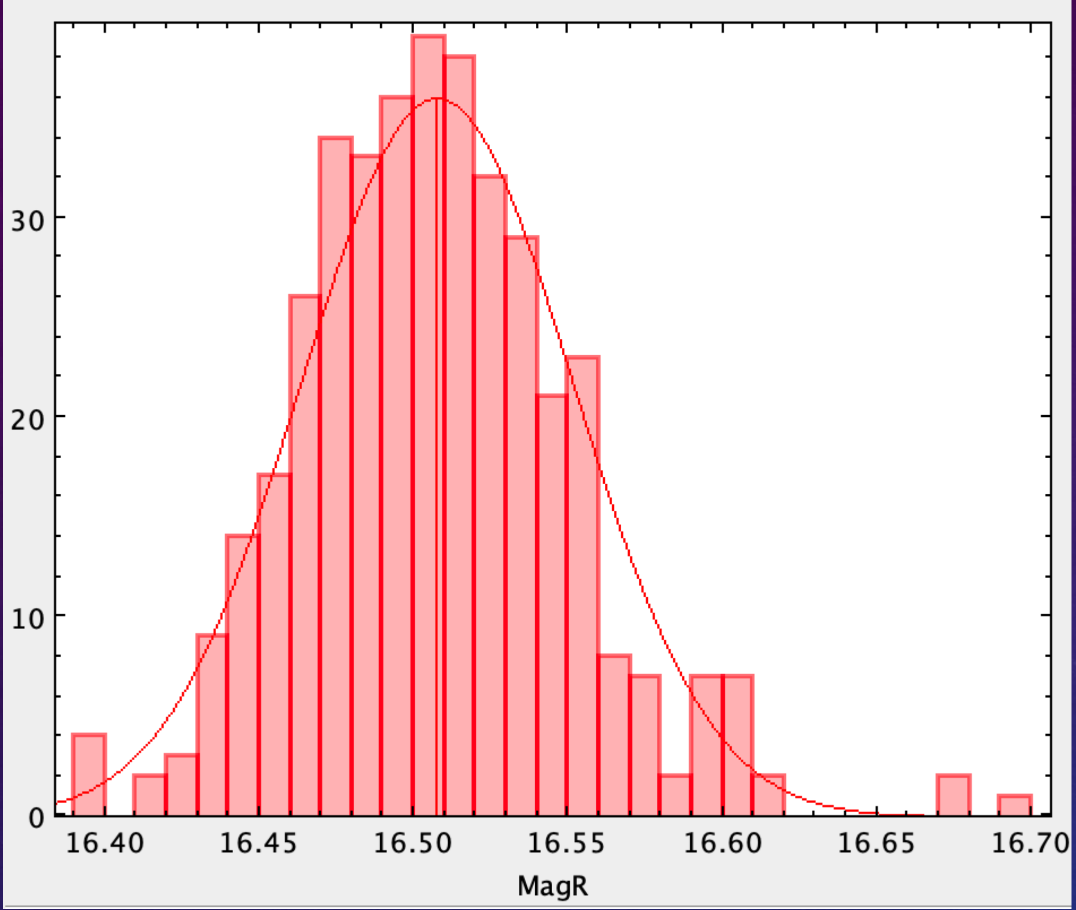
Final Matches





1

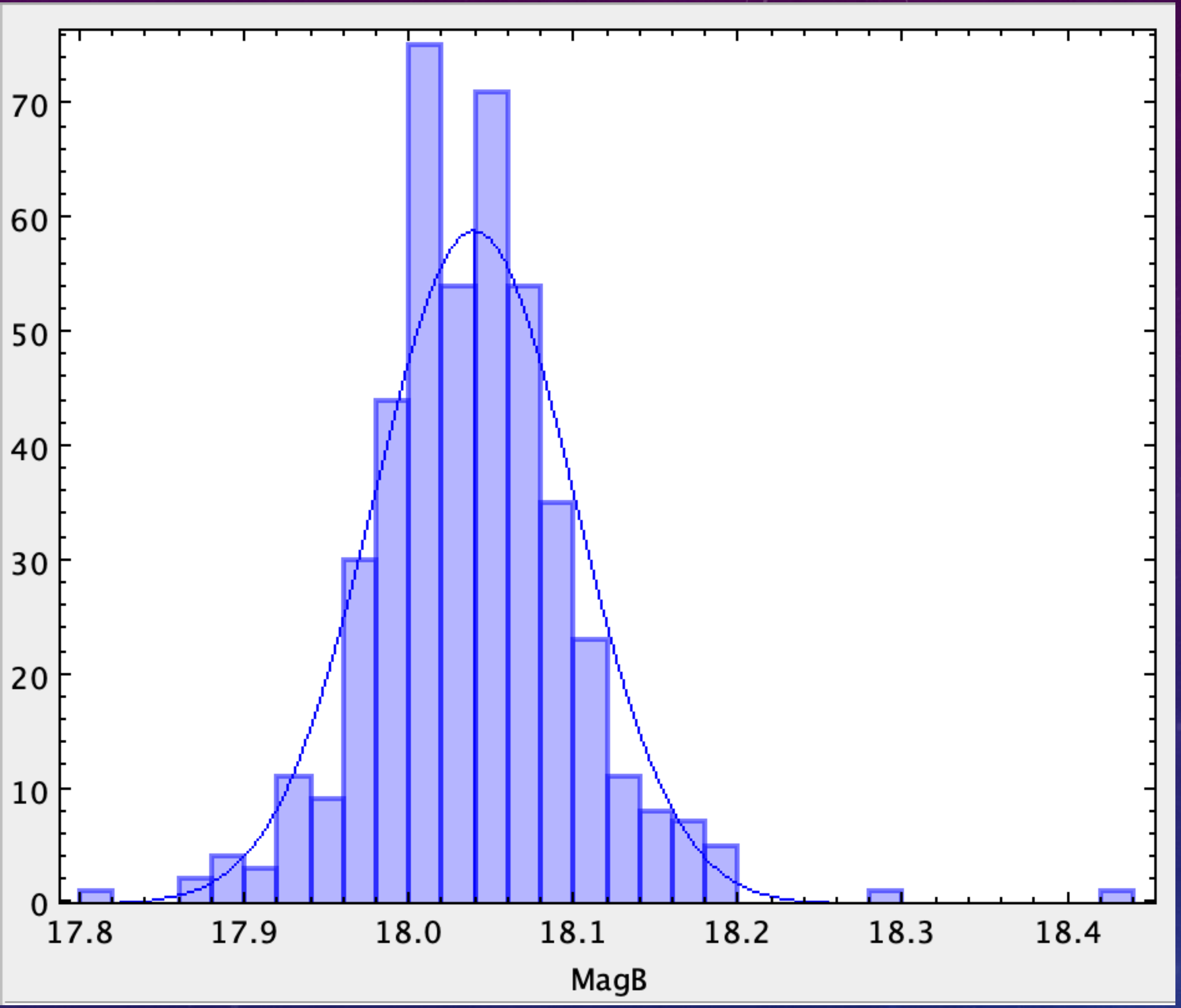
Source id : 4116933101975703808
Position : [265.6317015, -22.7410561]
Time of Closest Approach: 4 Aug 2002



- This histogram gives the distribution of MagR values for the first microlensing event we proposed.
- (Note: we can just use MagR or just MagB because a microlensing event is supposed to be achromatic, i.e., the same behavior observed across all wavelengths).
- The dispersion is fitted by a gaussian, with a dispersion of 4%.
- We must find outliers to this gaussian in the predicted TCA to declare an observation as a real microlensing event.

Mean:	16.50715
Standard Deviation:	0.04385343
Factor:	36.02481
Function:	36.02481 * exp(-0.5 * pow((x-16.50715)/0.04385343, 2))

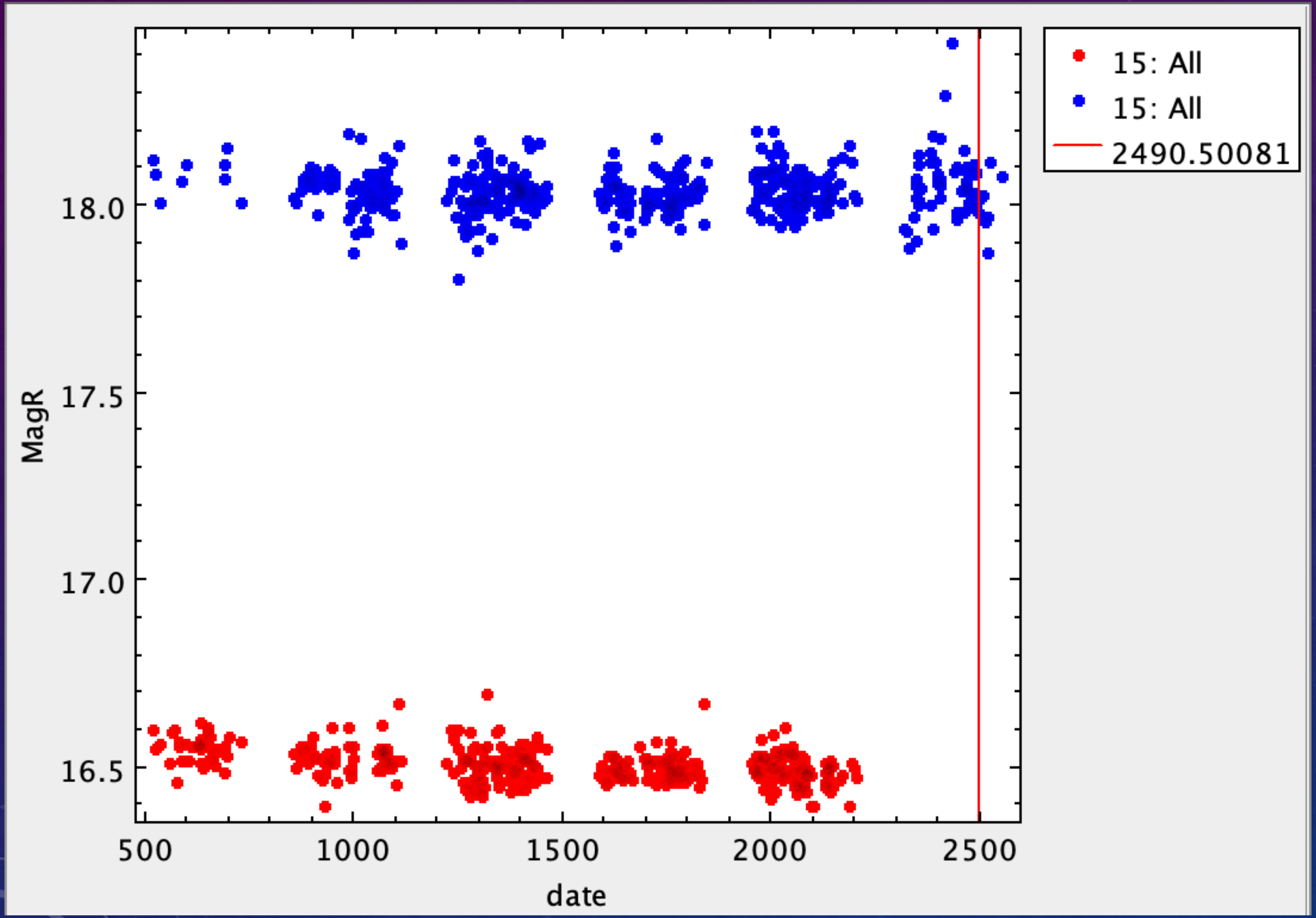
1



1

Mean:	18.038155
Standard Deviation:	0.060730793
Factor:	58.989872
Function:	58.989872 * exp(-0.5 * pow((x-18.038155)/0.060730793, 2))

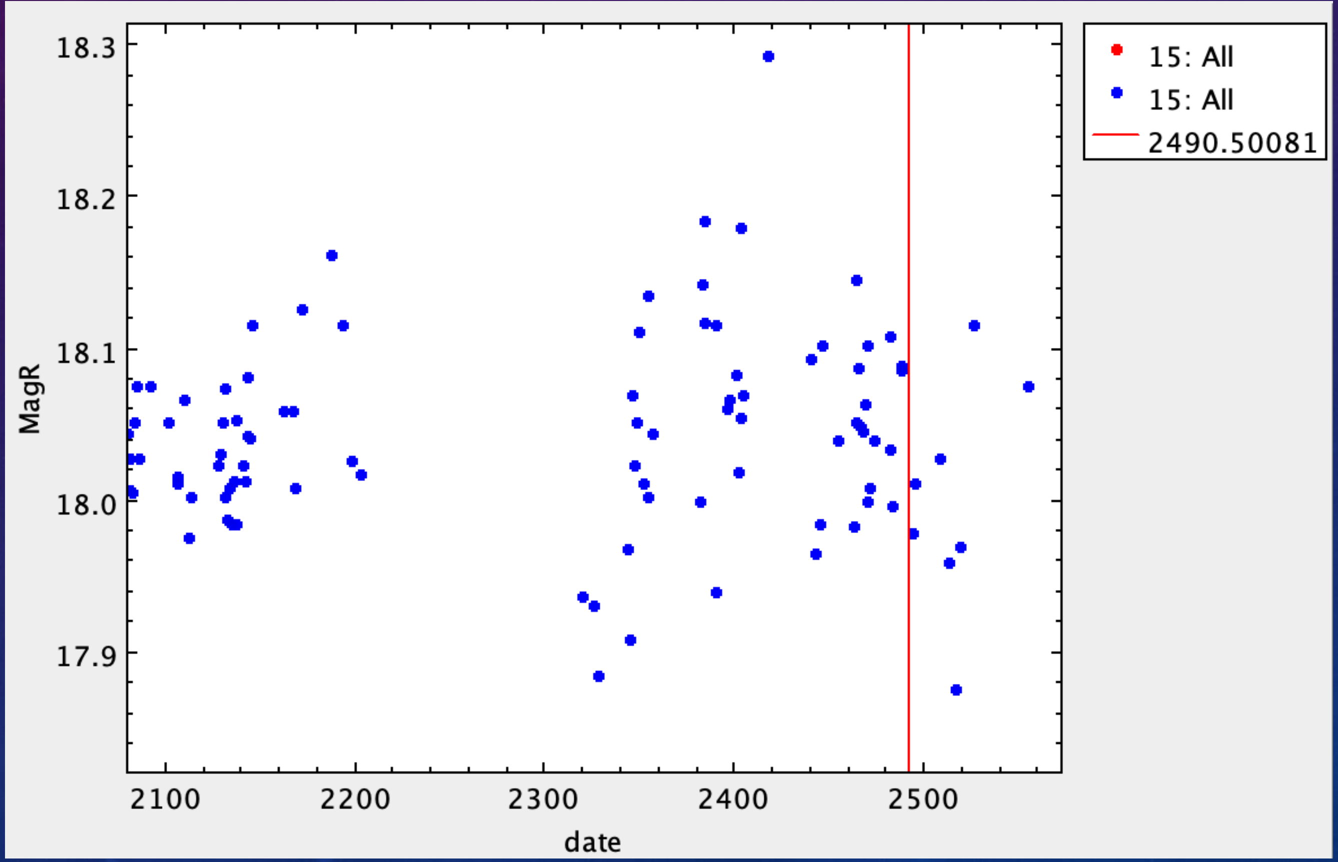
Light Curve



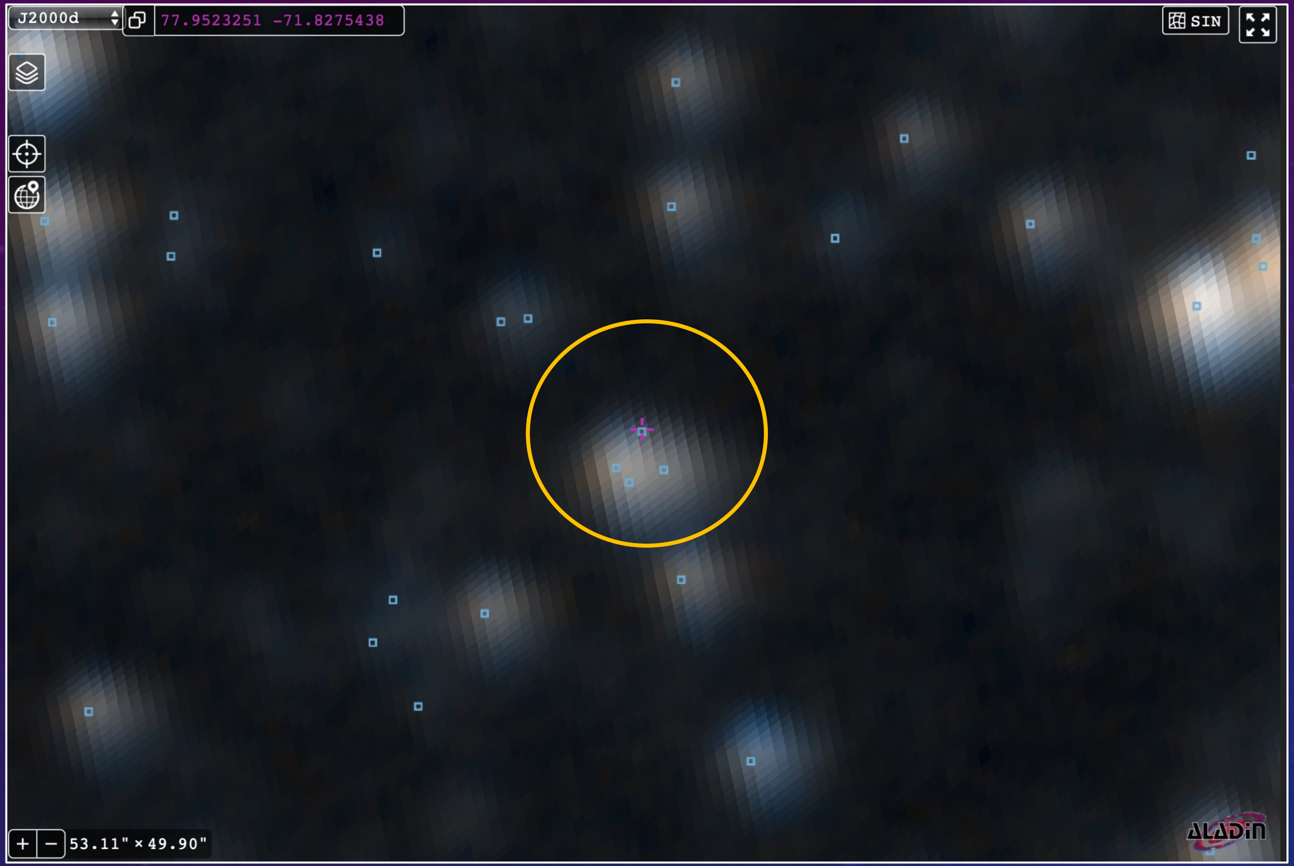
1

Light Curve

1

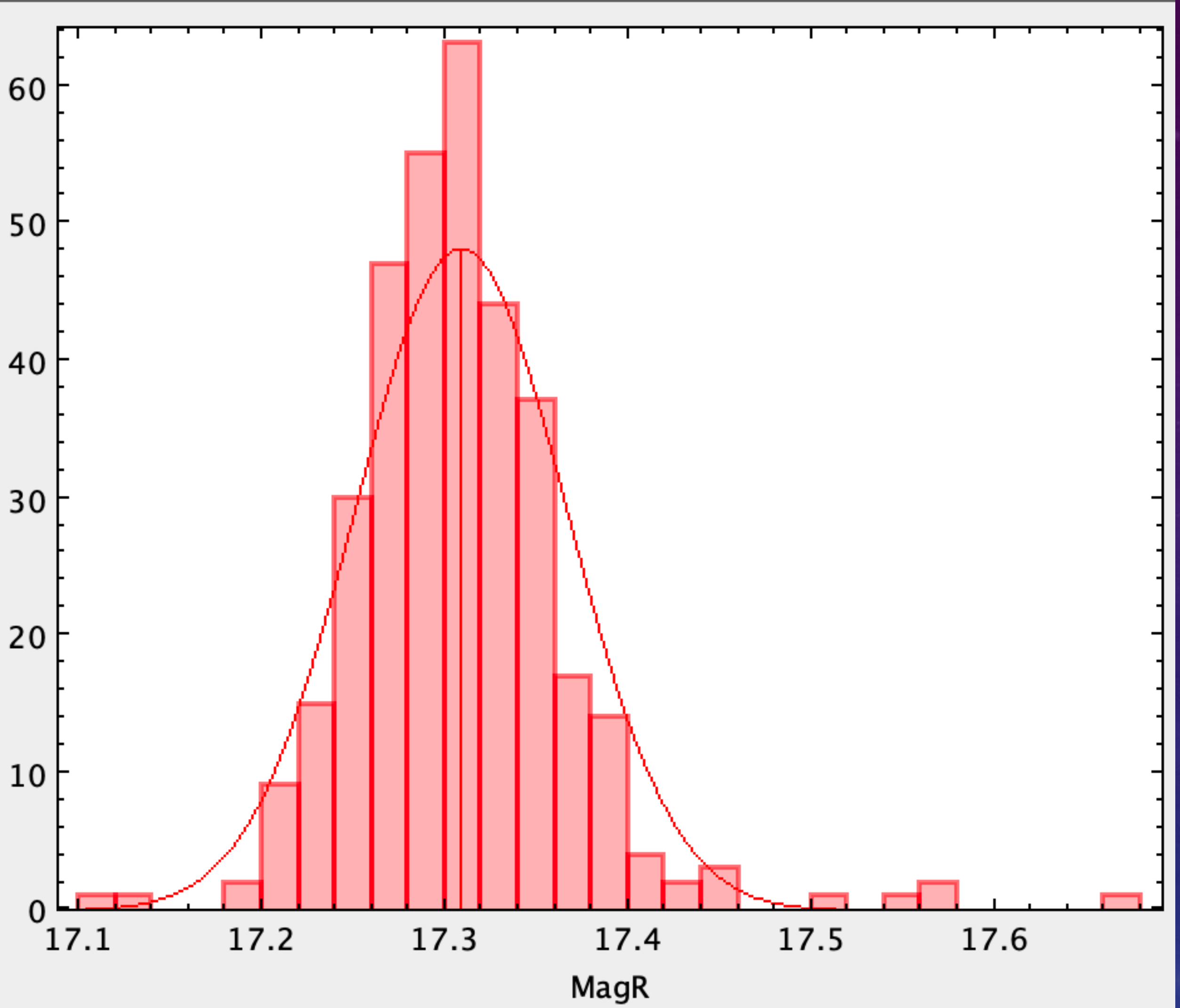


Final Matches



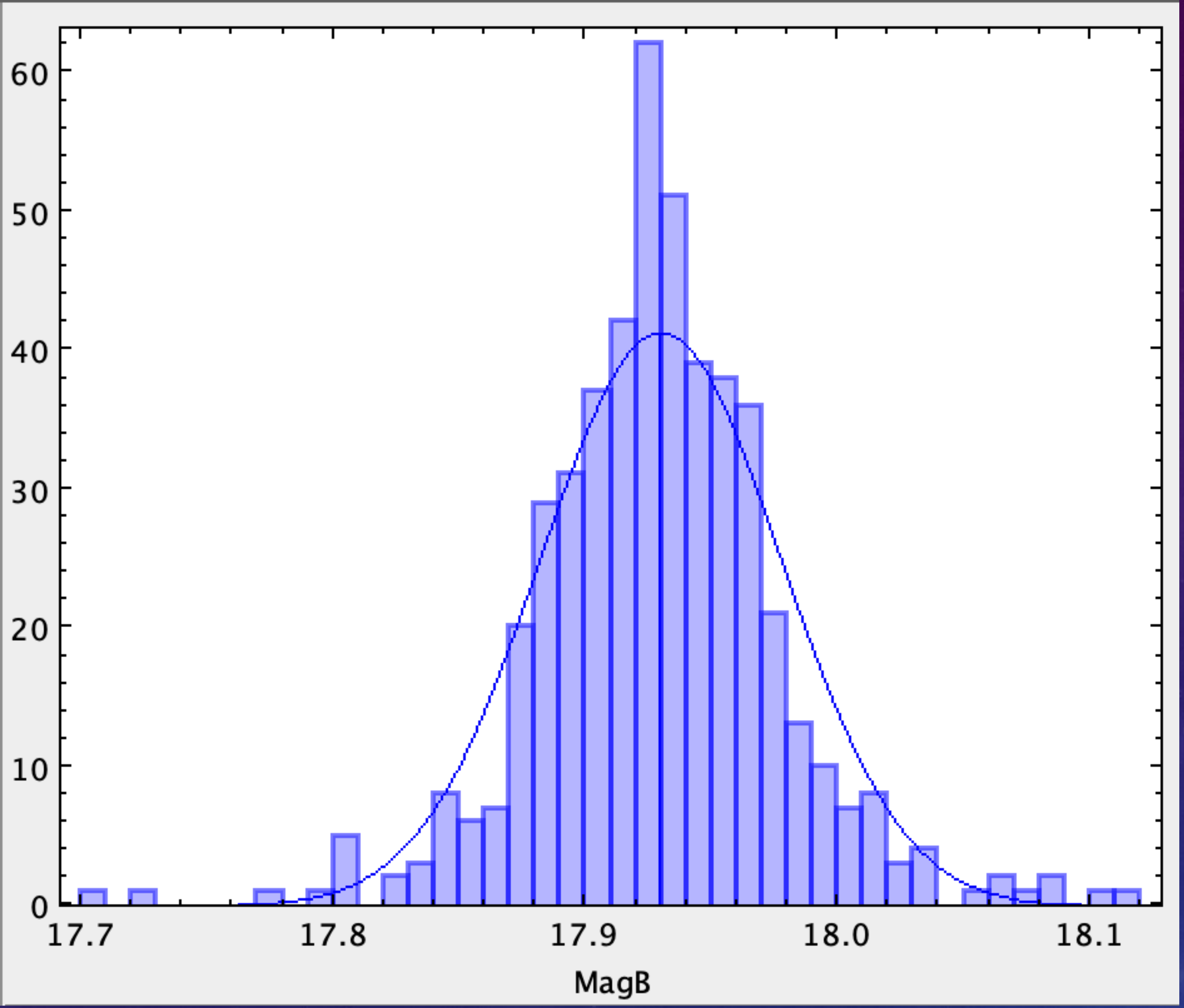
2

Source id : 4651544968498642432
Predicted position : [77.9523251, -71.8275439]
Position of object found : [77.9314231, -71.8260386]
Time of Closest Approach: 17 Jan 2002



2

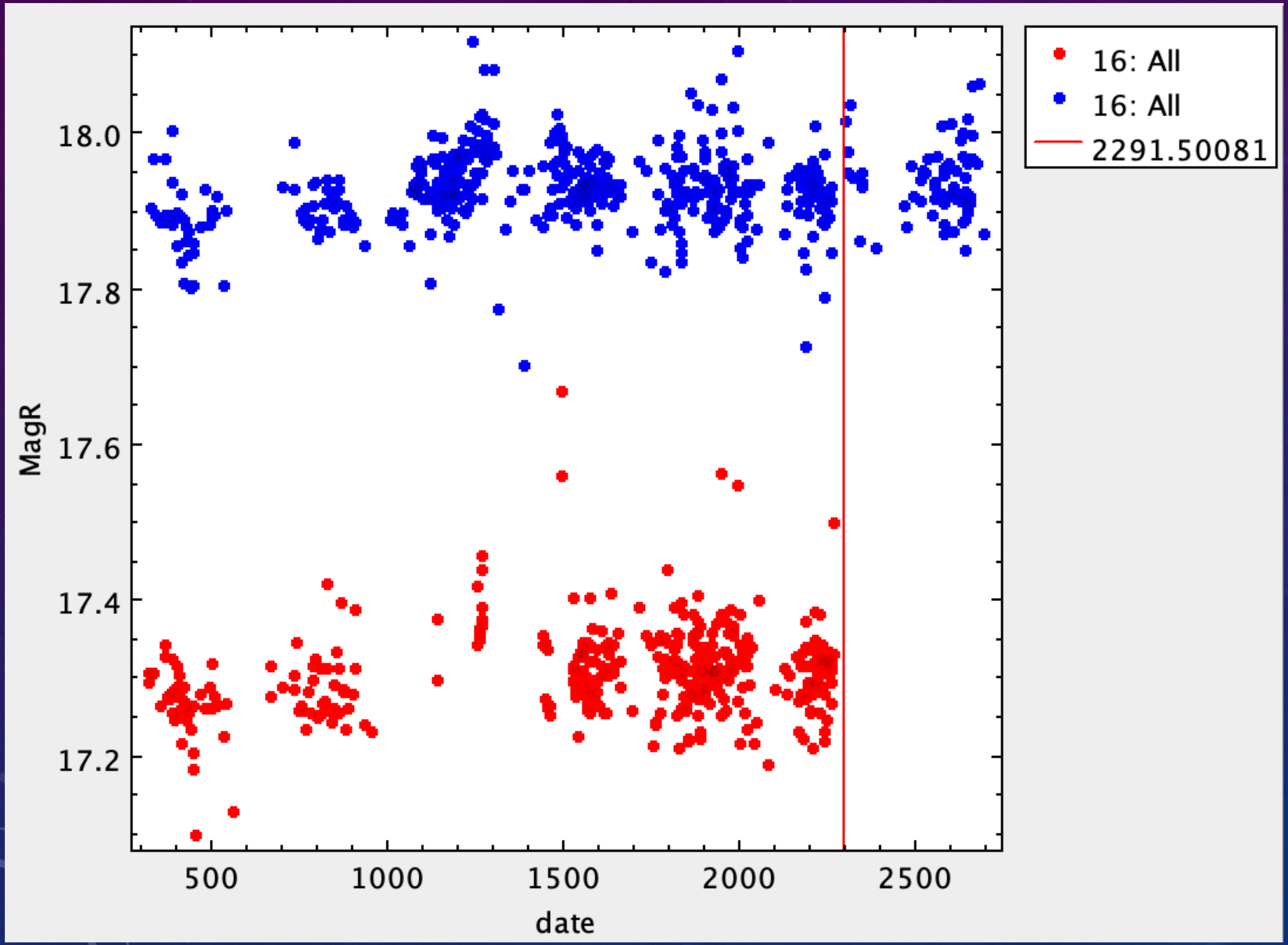
Mean:	17.307808
Standard Deviation:	0.057752535
Factor:	48.216362
Function:	48.216362 * exp(-0.5 * pow((x-17.307808)/0.057752535, 2))



2

Mean:	17.929298
Standard Deviation:	0.047682244
Factor:	41.33142
Function:	41.33142 * exp(-0.5 * pow((x-17.929298)/0.047682244, 2))

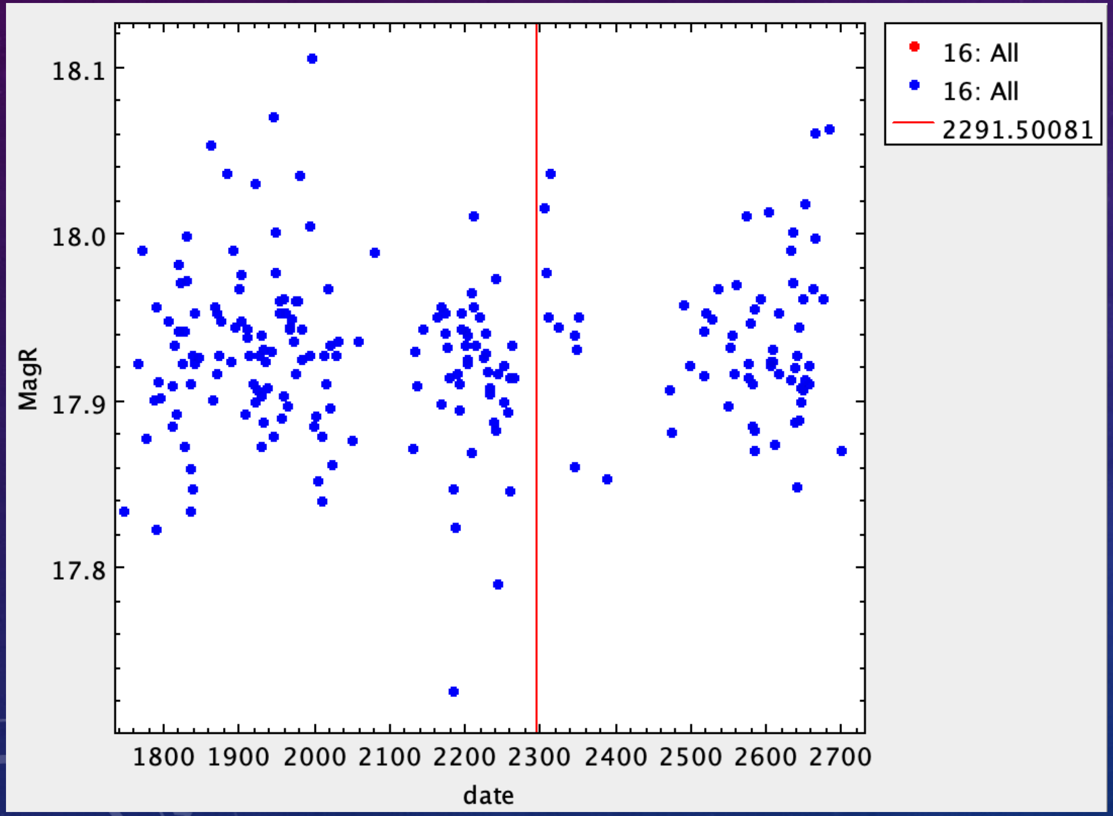
Light Curve

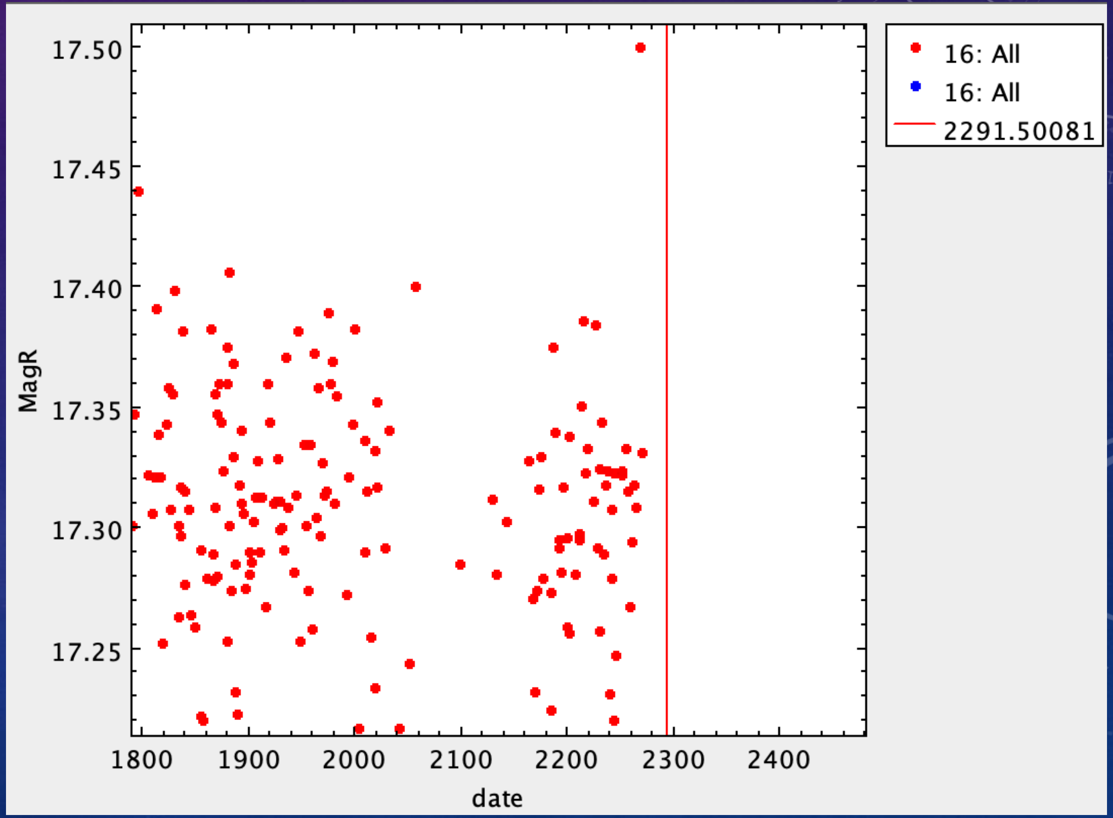


2

Light Curve

2





Conclusion

- Cross-match with more catalogues from other microlensing surveys such as OGRE, MACHOS, etc.
- Calculate precisely the duration of the event

Thank you for listening

💜

Bibliography

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2. Prediction of Astrometric-Microlensing Events from Gaia eDR3 Proper Motions – Klüter et al.

3. Prediction of astrometric microlensing events from Gaia DR2 proper motions – Klüter et al.

TOPCAT(2): Table Browser

Table Browser for 2: final matches

	source_id	ra	dec	ra_error	dec_error	pmra	pmdec	pmra_error	pmdec_error	parallax	parallax_error	phot_g_mean_mag	phot_rp_mean_mag	phot_bp_mean_mag
1	4116933101975703808	265.6317	-22.74106	0.23473	0.18347	-31.86	-153.77705	0.28407	0.18002	4.04986	0.33087	18.75699		
2	4116933101975703808	265.6317	-22.74106	0.23473	0.18347	-31.86	-153.77705	0.28407	0.18002	4.04986	0.33087	18.75699		
3	4116933101975703808	265.6317	-22.74106	0.23473	0.18347	-31.86	-153.77705	0.28407	0.18002	4.04986	0.33087	18.75699		
4	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
5	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
6	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
7	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
8	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
9	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
10	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
11	4651544968498642432	77.95233	-71.82754	0.49635	0.48062	67.77599	114.49445	0.77849	0.68382	9.85705	0.50193	20.21506		
12	4104062085674577664	277.97894	-14.70305	0.14924	0.15348	64.26018	-157.55688	0.20003	0.15161	3.61609	0.21246	18.00138		
13	4104062085674577664	277.97894	-14.70305	0.14924	0.15348	64.26018	-157.55688	0.20003	0.15161	3.61609	0.21246	18.00138		
14	4104062085674577664	277.97894	-14.70305	0.14924	0.15348	64.26018	-157.55688	0.20003	0.15161	3.61609	0.21246	18.00138		
15	4104062085674577664	277.97894	-14.70305	0.14924	0.15348	64.26018	-157.55688	0.20003	0.15161	3.61609	0.21246	18.00138		
16	4104062085674577664	277.97894	-14.70305	0.14924	0.15348	64.26018	-157.55688	0.20003	0.15161	3.61609	0.21246	18.00138		
17	4104062085674577664	277.97894	-14.70305	0.14924	0.15348	64.26018	-157.55688	0.20003	0.15161	3.61609	0.21246	18.00138		