VVVX Search for Isolated Black Holes in the Inner Regions of the Milky Way

Dante Minniti, 25 Sep 2020

Universidad Andrés Bello

Thanks very much to my main collaborators in this work:

María Gabriela Navarro,

Rodrigo Contreras Ramos,

Phil Lucas,

and also to the whole VVVX Science Team

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Our First BH Discovery

The Astrophysical Journal Letters, 810:L20 (5pp), 2015 September 10 doi:10.1088/2041-8205/810/2/L20

VVV SURVEY OBSERVATIONS OF A MICROLENSING STELLAR MASS BLACK HOLE CANDIDATE IN THE FIELD OF THE GLOBULAR CLUSTER NGC 6553

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ABSTRACT

We report the discovery of a large timescale candidate microlensing event of a bulge stellar source based on near-infrared observations with the VISTA Variables in the Vía Láctea Survey (VVV). The new microlensing event is projected only 3.5 arcmin away from the center of the globular cluster NGC 6553. The source appears to be a bulge giant star with magnitude $K_s = 13.52$, based on the position in the color–magnitude diagram. The foreground lens may be located in the globular cluster, which has well-known parameters such as distance and proper motions. If the lens is a cluster member, we can directly estimate its mass simply following Paczynski which is a modified version of the more general case due to Refsdal. In that case, the lens would be a massive stellar remnant, with $M = 1.5–3.5 M_{\odot}$. If the blending fraction of the microlensing event appears to be small, and this lens would represent a good isolated black hole (BH) candidate, that would be the oldest BH known. Alternative explanations (with a larger blending fraction) also point to a massive stellar remnant if the lens is located in the Galactic disk and does not belong to the globular cluster.

The Astrophysical Journal Letters, 810:L20 (5pp), 2015 September 10 doi:10.1088/2041-8205/810/2/L20

VVV SURVEY OBSERVATIONS OF A MICROLENSING STELLAR MASS BLACK HOLE CANDIDATE IN THE FIELD OF THE GLOBULAR CLUSTER NGC 6553

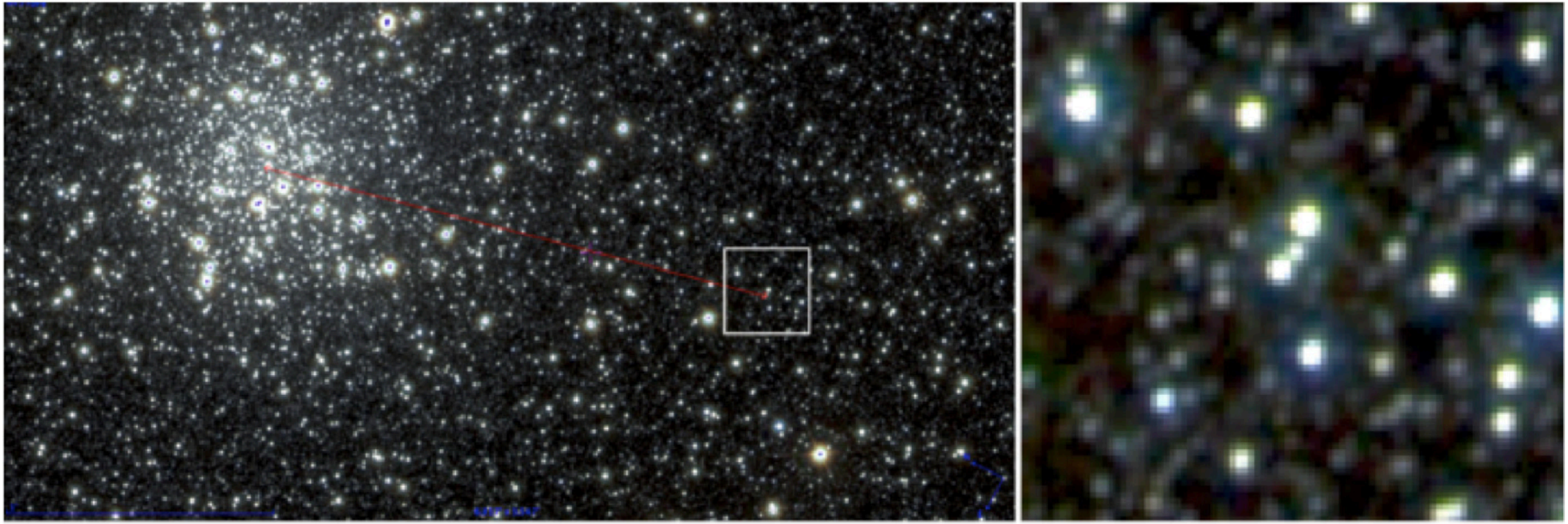


Figure 1. Left: 6.8 × 3.5 arcmin finding chart showing the position of the microlensing event with respect to NGC 6553. The projected distance to the cluster center is 3.5 arcmin, well within the cluster tidal radius of $R = 8.16$ arcmin. Right: zoomed 30 × 30 arcsec^2 region centered on the source star, showing that it is located just in between two brighter stars (with $K_s < 12$) that are separated by 3 arcsec. The seeing of the images is $0\farcs8$.

Microlensing light curve

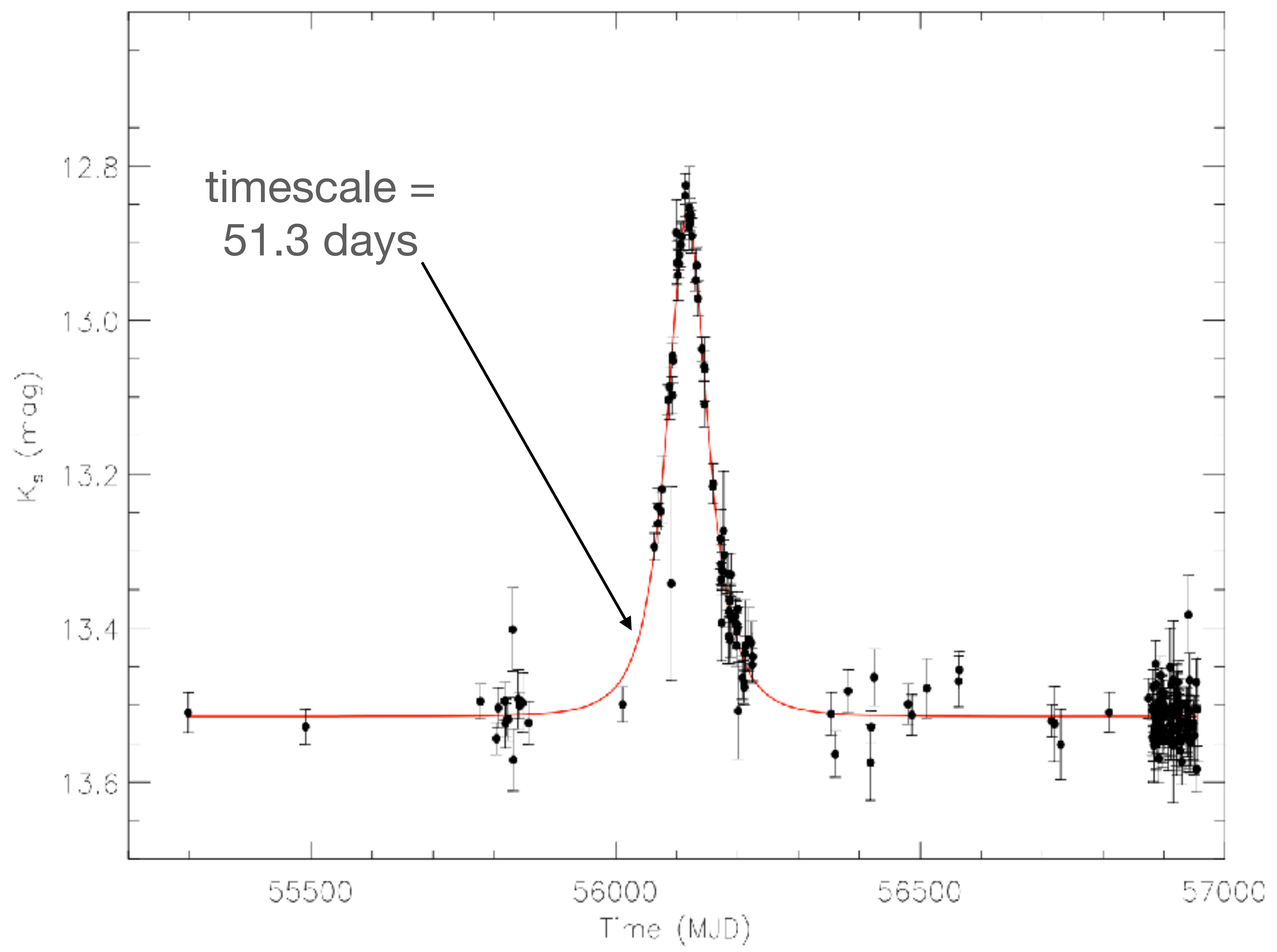


Figure 2. K_s-band light curve for this event, along with a simple microlensing fit (Paczynski 1994). The microlensing parameters of this fit are: baseline magnitude $K_{s,0} = 13.515 \pm 0.002$, impact $u_0 = 0.62 \pm 0.004$, time of closest approach $t_0 = 56117.5 \pm 0.43$, Einstein timescale $t_E = 51.3 \pm 0.8$, blending fraction $f = 1.00$, and $\chi^2 = 200$. The points with the larger error bars correspond to the worst seeing images.

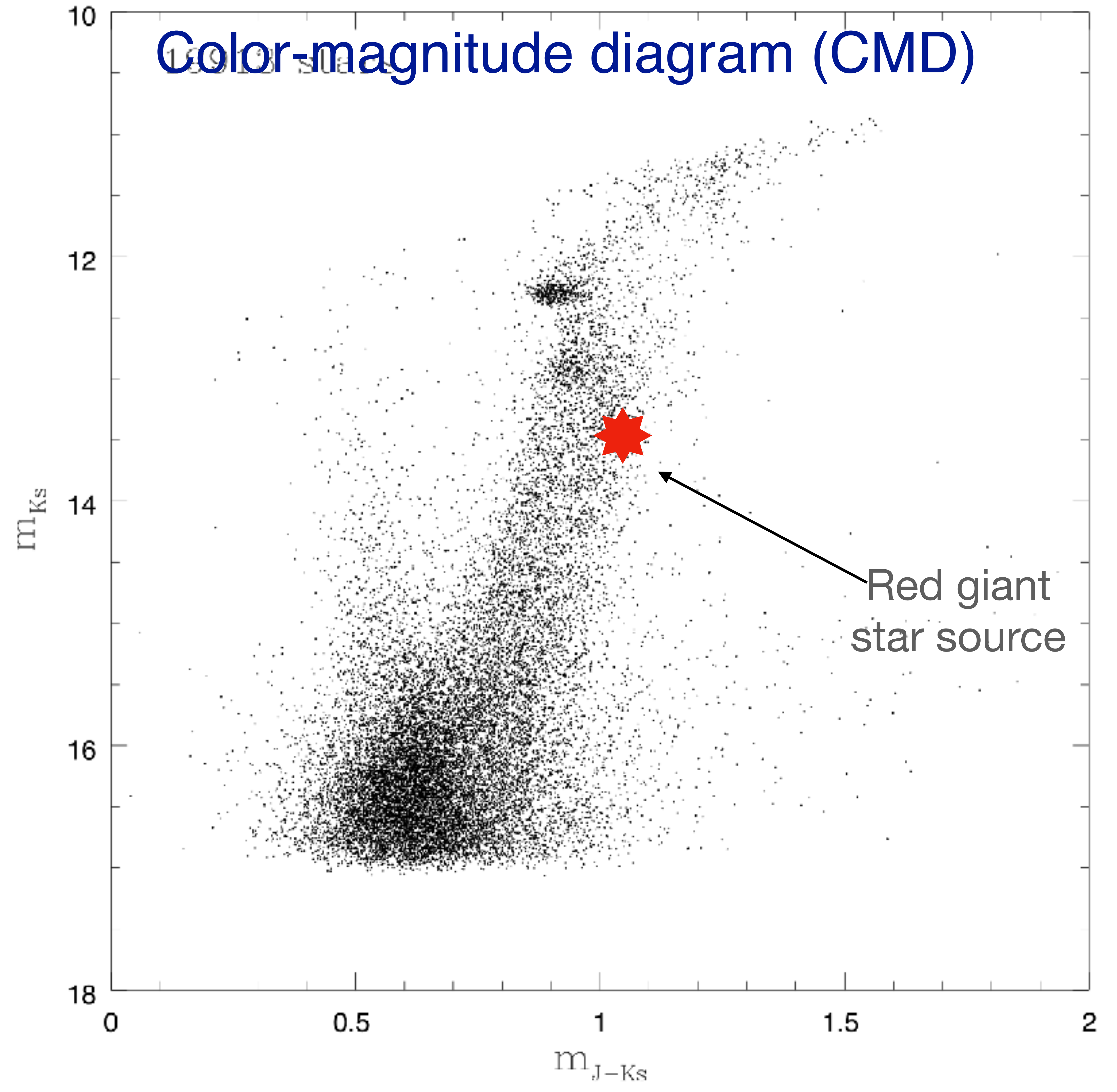


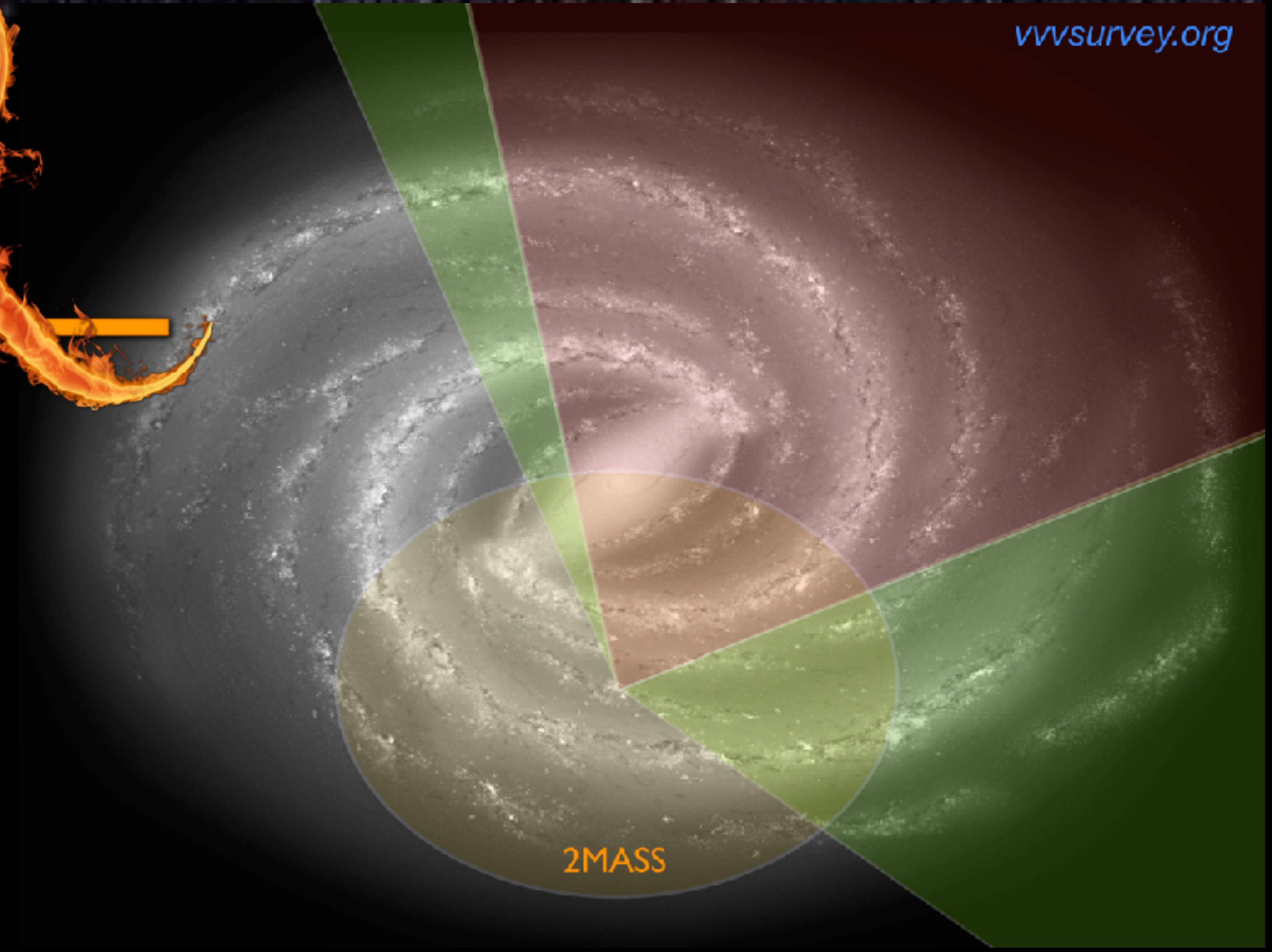
Figure 3. K_s vs. $J - K_s$ near-infrared color–magnitude diagram (CMD) of about 20,000 stars in 4×4 arcmin^2 field centered on the globular cluster NGC 6553. The red circle marks the source star of the microlensing event. This CMD shows the foreground disk main sequence, the populated globular cluster main-sequence (MS) turn-off, the cluster red giant branch (RGB), its red horizontal branch (HB), and its red giant bump, as well as a redder and wider background bulge RGB, including the bulge red clump. We caution that photometric nonlinearity and saturation starts at $K_s < 12.5$.

Our Area of Study

The Milky Way

A new near-IR survey of the inner MW

ESO VISTA Telescope
Total time ~2000 hs
Total area ~1700 sqdeg
Near-IR filters ZYJHKs
Multiple epochs
~10 yr baseline with VVV
~1 Petabyte database with
images, catalogs, maps, light curves…




Infrared
Visible


VISTA TELESCOPE
AT ESO PARANAL
OBSERVATORY


MILKY WAY
VVV
SUN
2MASS


2MASS


VVV

Basic Gravitational Microlensing

Brief (incomplete) Microlensing history

Effect predicted by Einstein 1931, but "*they cannot be observed*"

Refsdal 1964 equation for the lens masses

Specific microlensing predictions computed by Pacszynski 1986, "*observable towards the Galactic bulge and the Magellanic Clouds*"

Optical observations used to search for the "dark matter" since the 1990`s by the large collaborations MACHO, OGLE, EROS, MOA, KMTNET, etc.

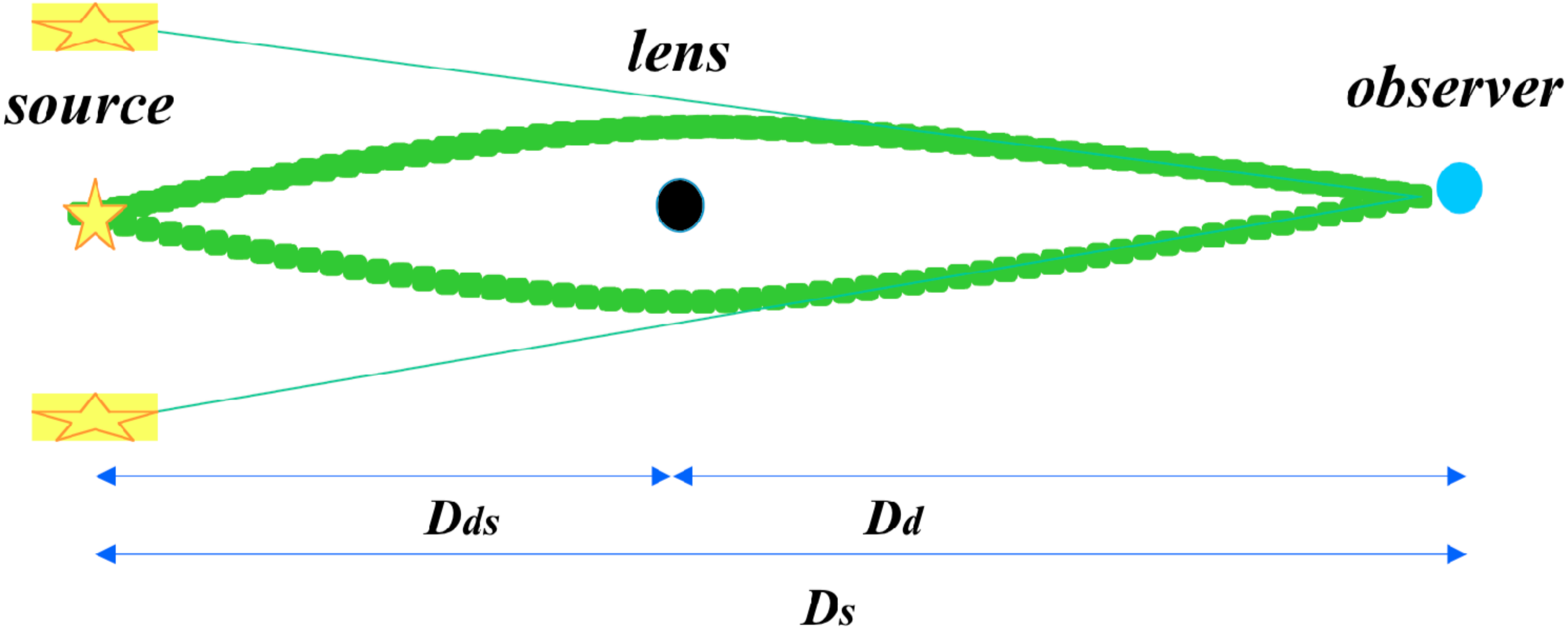
20th century also used to search for extrasolar planets orbiting distant stars.

What's new? VVV microlensing searches in the near-IR (since 2015).

Basic Microlensing

A depends on u_{min} (the impact parameter)

T depends on D, M, and Vt



Basic Microlensing

- **Light curve amplification** $$A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

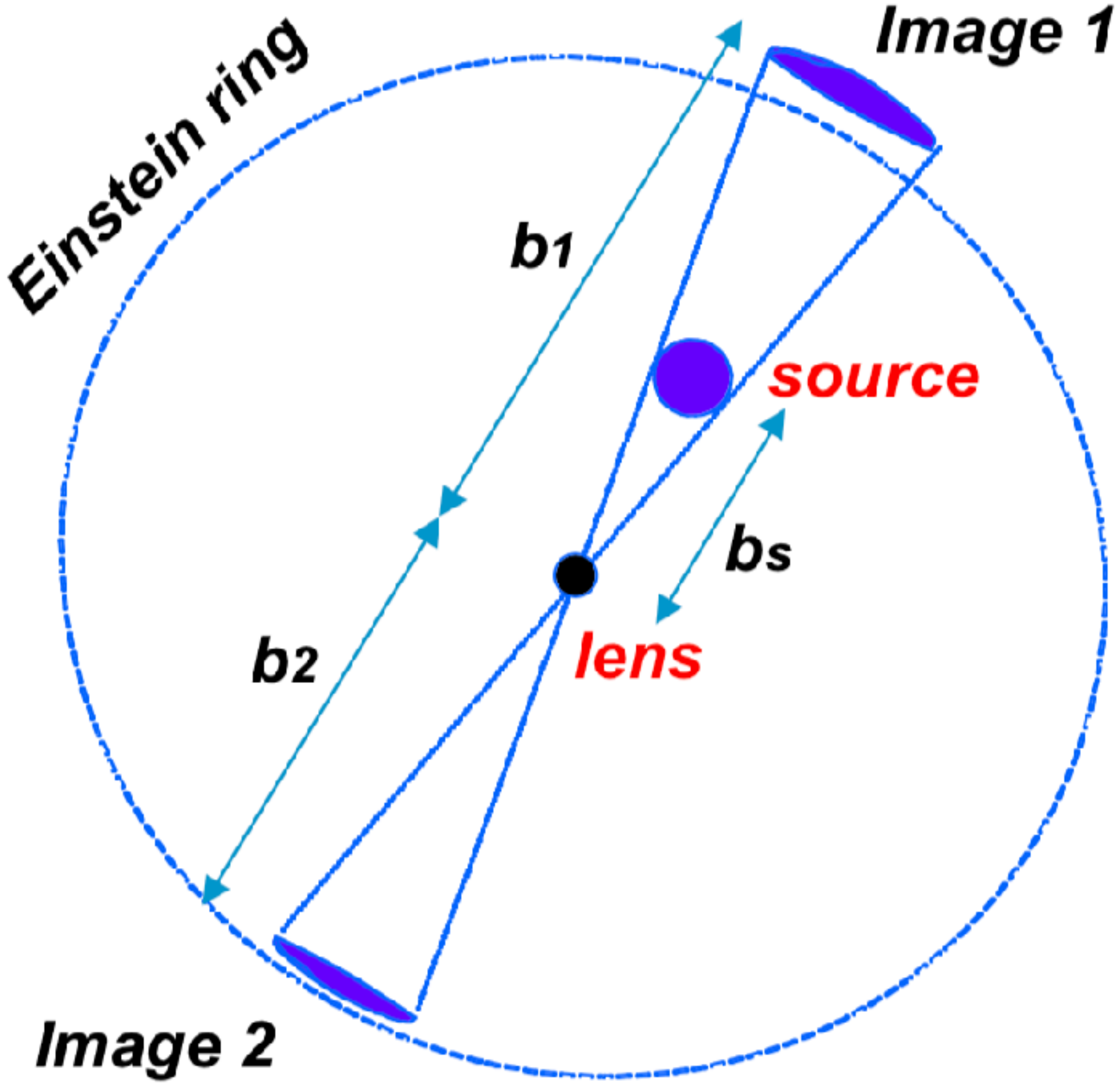
  with $$u^2(t) = u_{min}^2 + [2(t - t_{max})/\hat{t}]^2$$

- **Einstein radius** $$R_E = \sqrt{\frac{4GM}{c^2}\frac{D_d D_{ds}}{D_s}}$$

- **Timescale** $$\hat{t} = 2R_E/v_{tg}$$

- **Impact parameter** $$u_{min} = \sqrt{-2 + \frac{2A_{max}}{\sqrt{A_{max}^2 - 1}}}$$

Basic Microlensing



In the plane of the sky there are 2 stretched images of the source: one outside and one inside the Einstein ring.

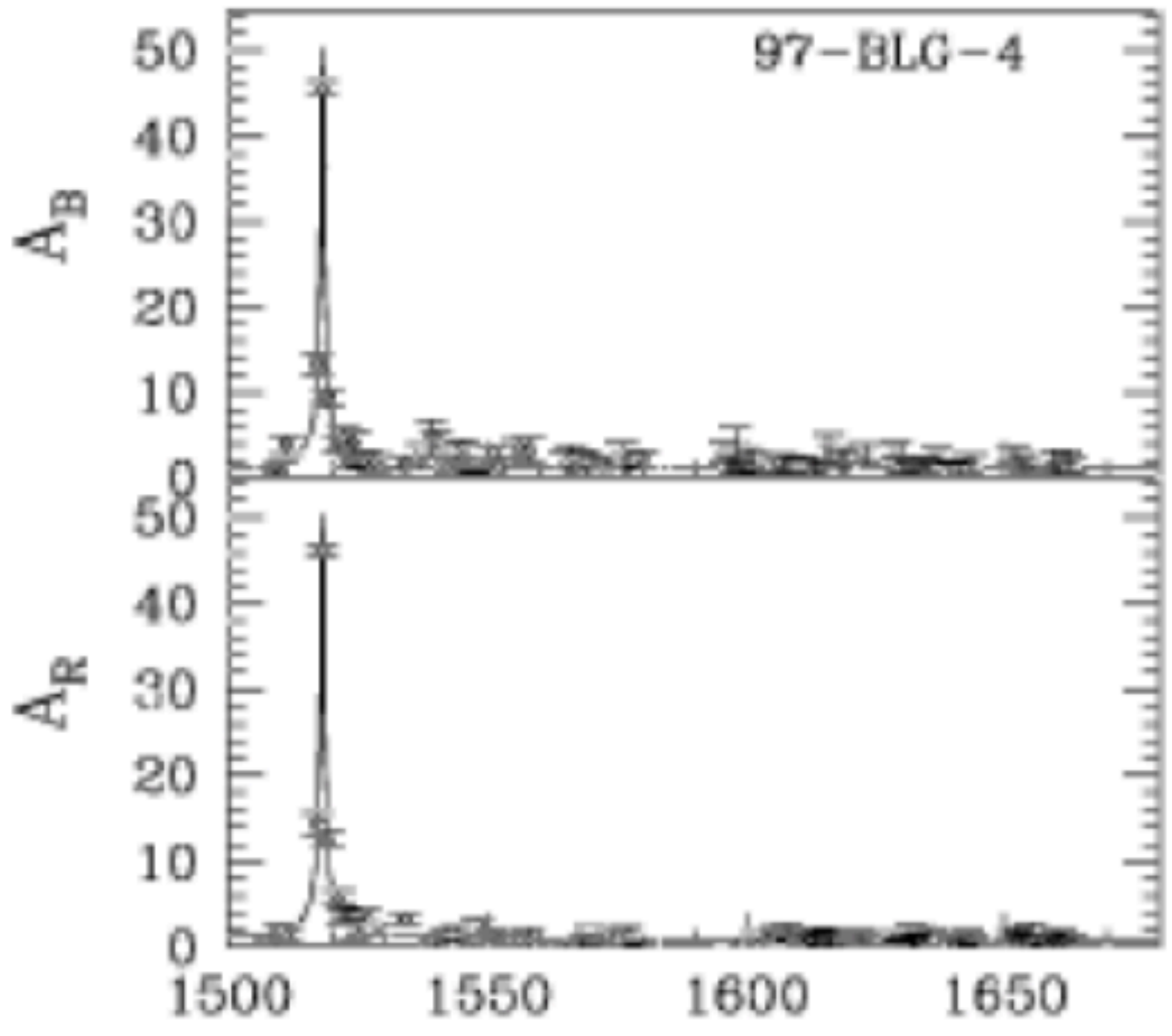
Similar to gravitational lensing images of clusters of galaxies, but at smaller angular scales.

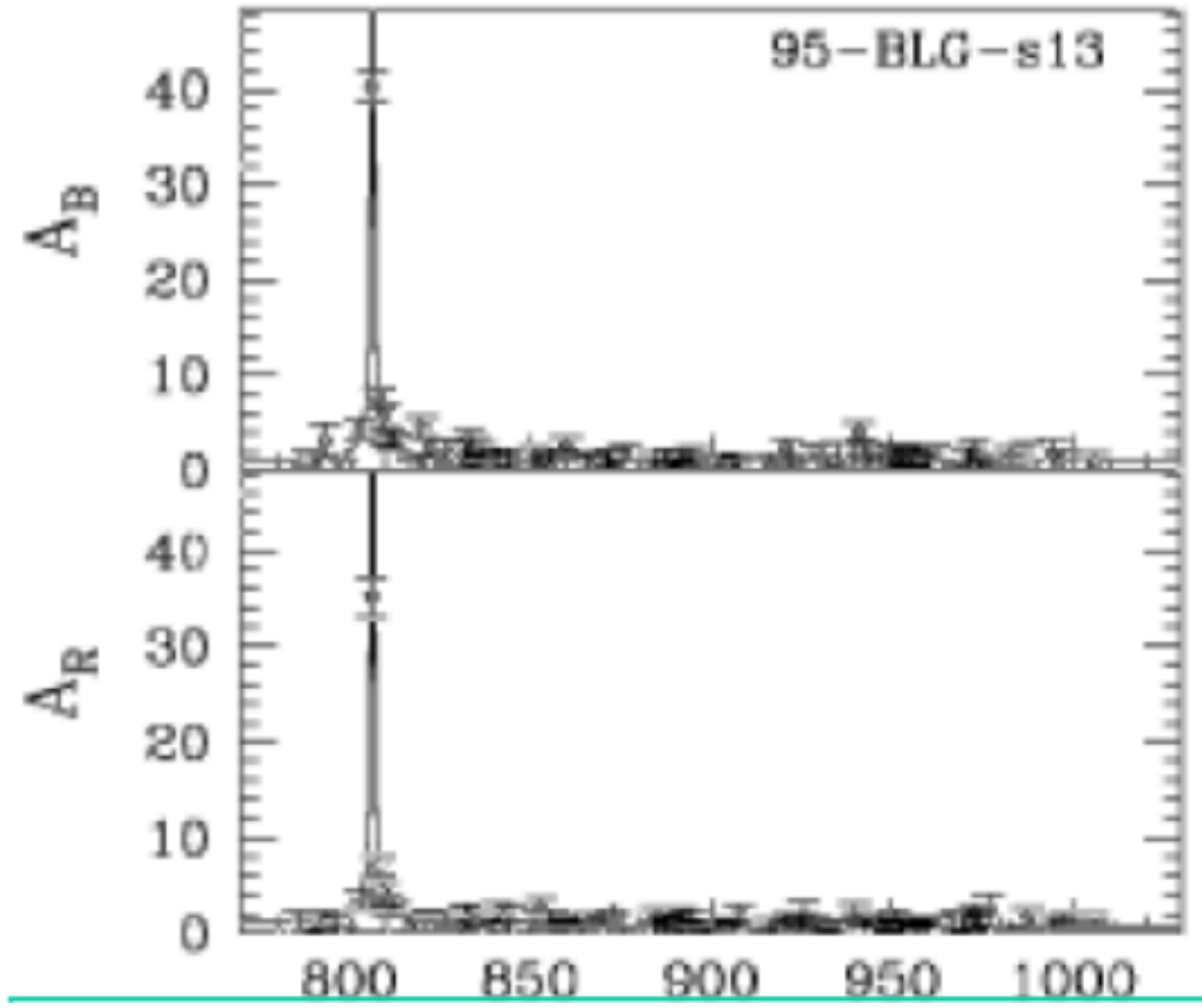

Sol
Lens
Source
2MASS IMAGE OF THE MILKY WAY

Alcock et al. 1993

vvvsurvey.org

Bulge Microlensing





lcock et al. 1999

- **Towards the MW bulge**

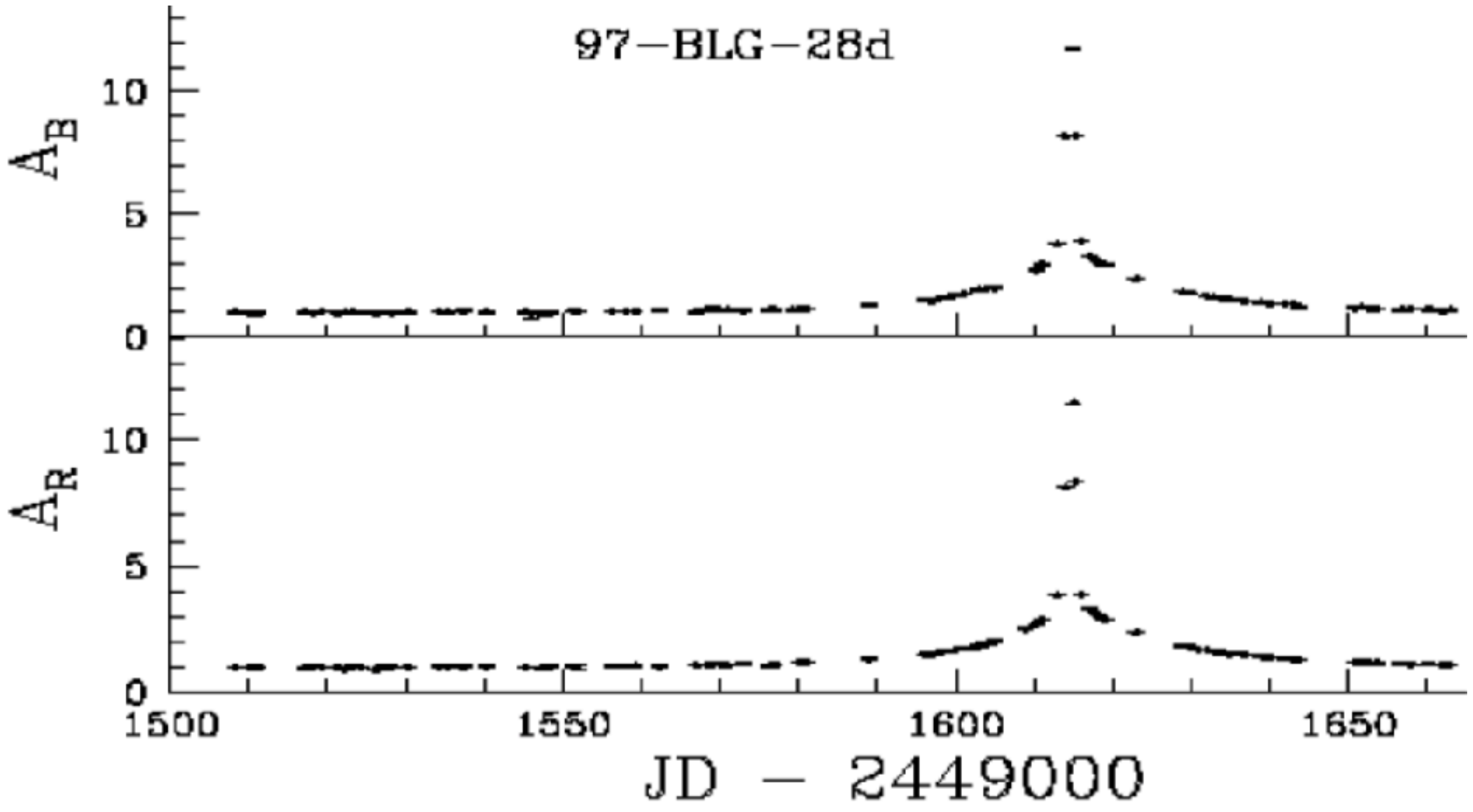
  $t = 40\ (M/M_\odot)^{1/2}$ days

OBJECT	*TIMESCALE*
Sun	*40 days*
Jupiter	*1 day*
Earth	*1 hour*

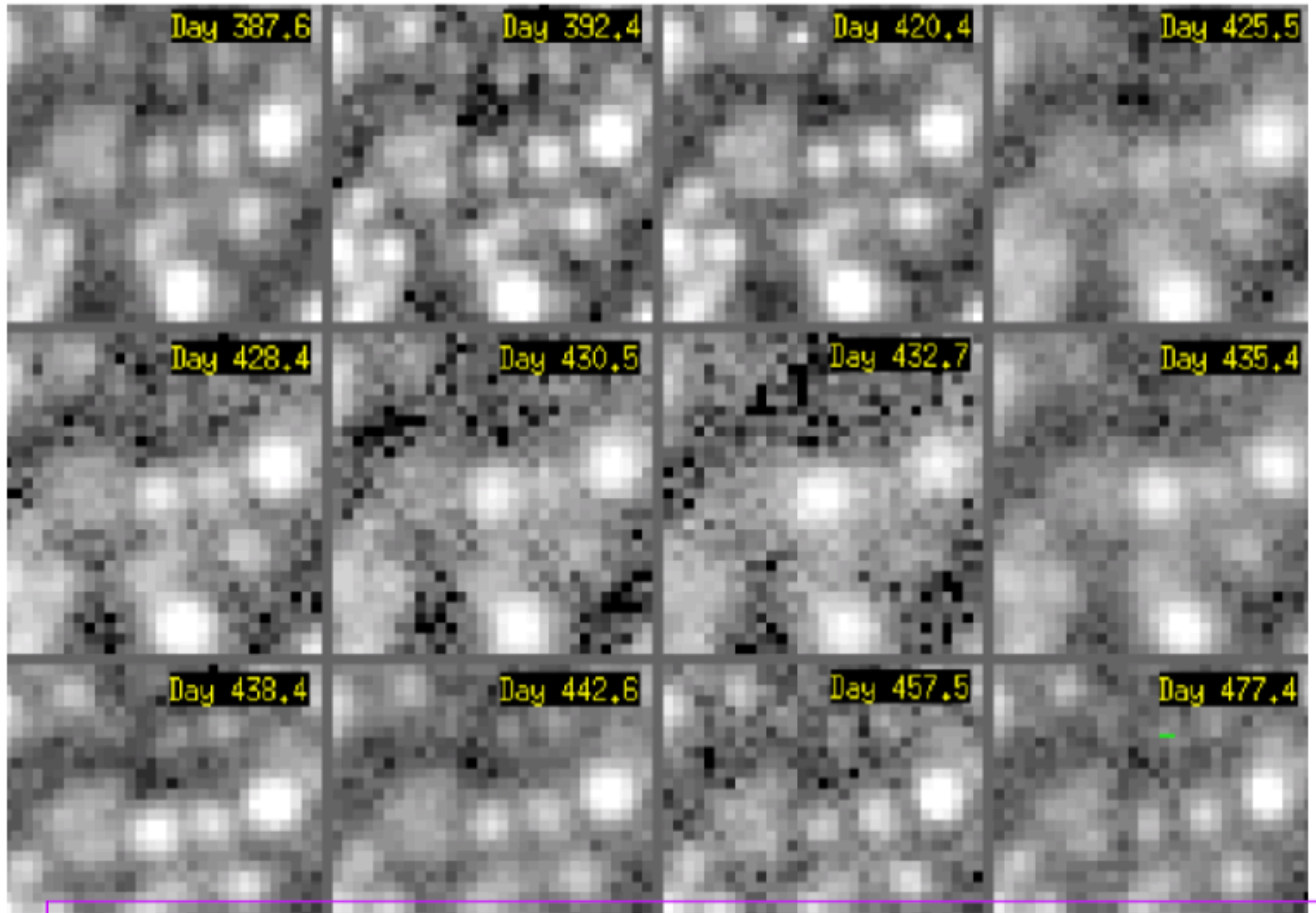
- **Einstein radius**

  $R_E = 3\ (M/M_\odot)^{1/2}$ AU

Photometric Effects



Alcock et al. 1993



Dramatic and easily recognized effect:

- characteristic light curve
- non repeatable
- achromatic

Basic Microlensing

We would like to know

- the lens mass
- the lens/source distance
- the relative velocities

The observables are:

- Timescale (Einstein radius crossing time)
- Amplitude of the light curve

Degeneracy: only one relevant observable for three physical parameters

The main problem is:

Events are extremely rare: typically 1 event per million stars

Paczynski 1986

The VVVX Microlensing Search

VVV SURVEY MICROLENSING: CATALOG OF BEST AND FORSAKEN EVENTS

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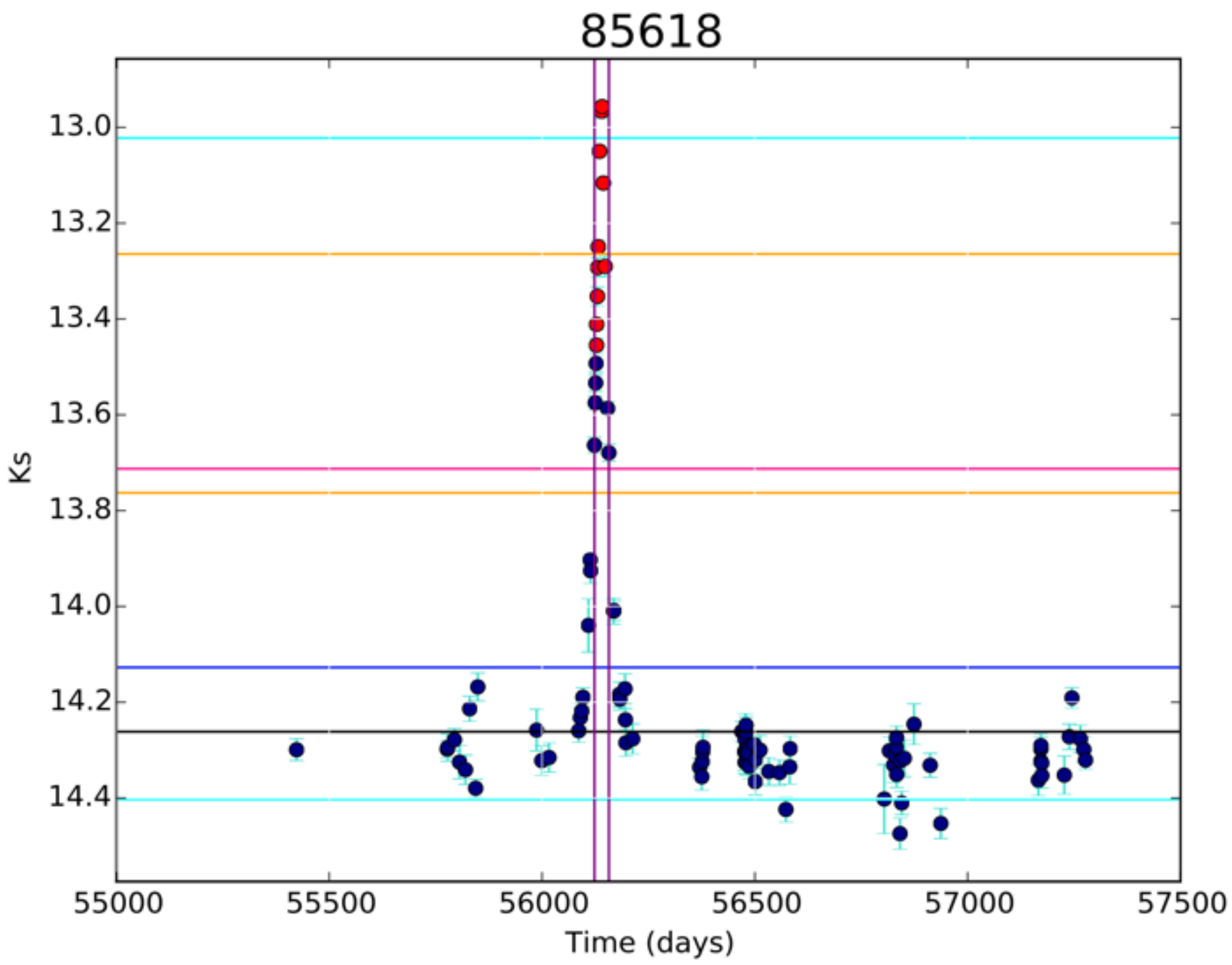
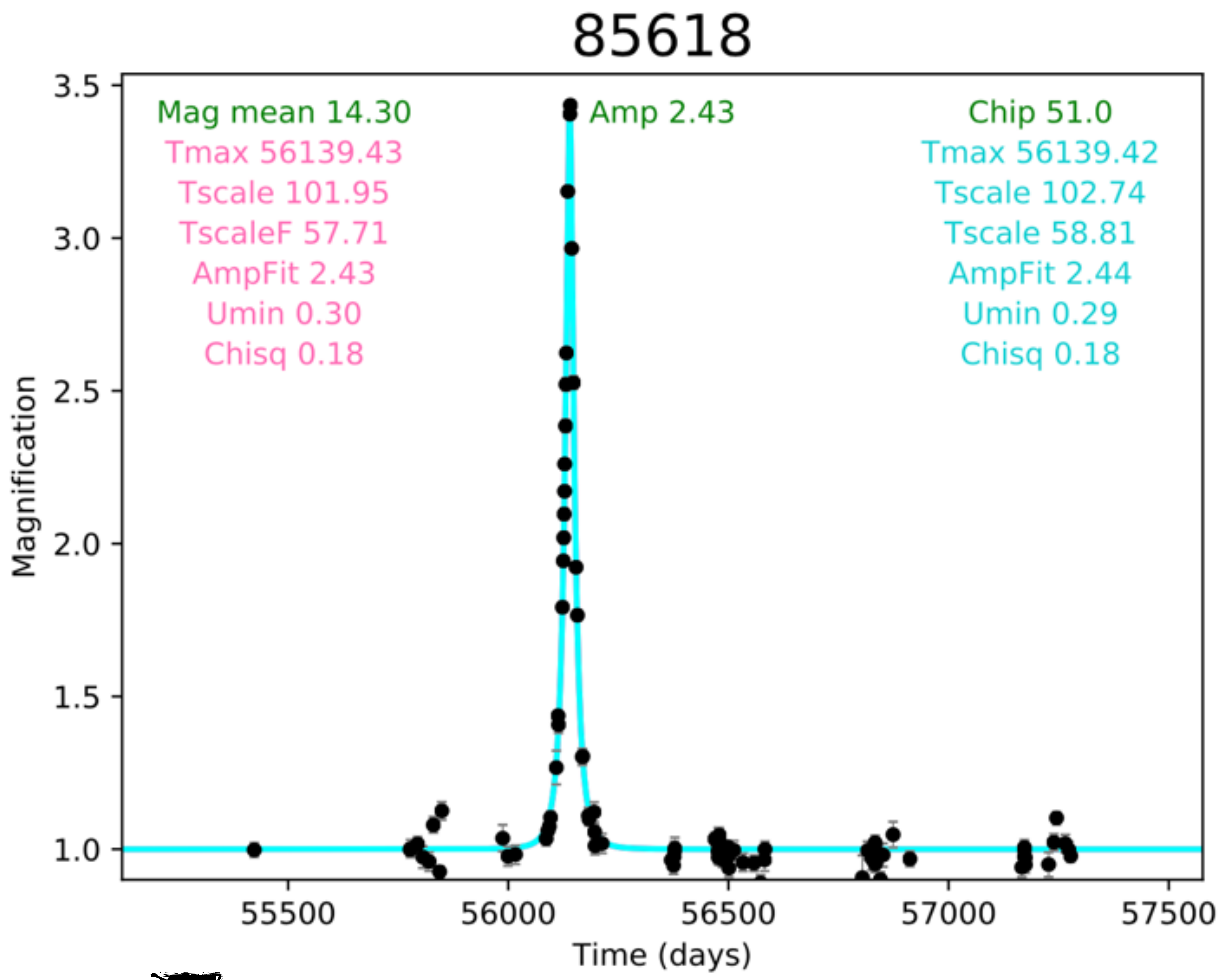
ABSTRACT

We search for microlensing events in the zero-latitude area of the Galactic Bulge using the VVV Survey near-IR data. We have discovered a total sample of $N = 630$ events within an area covering $20.68 deg^2$ between the years 2010 and 2015. In this paper we describe the search and present the data for the final sample, including near-IR magnitudes, colors and proper motions, as well as the standard microlensing parameters. We use the near-IR Color-Magnitude and Color-Color Diagram to select $N_{RC} = 290$ events with red-clump sources to analyze the extinction properties of the sample in the central region of the Galactic plane. The timescale distribution and its dependence in the longitude axis is presented. The mean timescale decreases as we approach the Galactic minor axis ($b = 0$ deg). Finally, we give examples of special microlensing events, such as binaries, short timescale events, and events with strong parallax effect.

MICROLENSING SEARCH PROCEDURE



Detect a single significant peak in an otherwise peacefully flat light curve.



First fit a standard microlensing model light curve. Then consider a blending fit.

REPEAT EVENTS

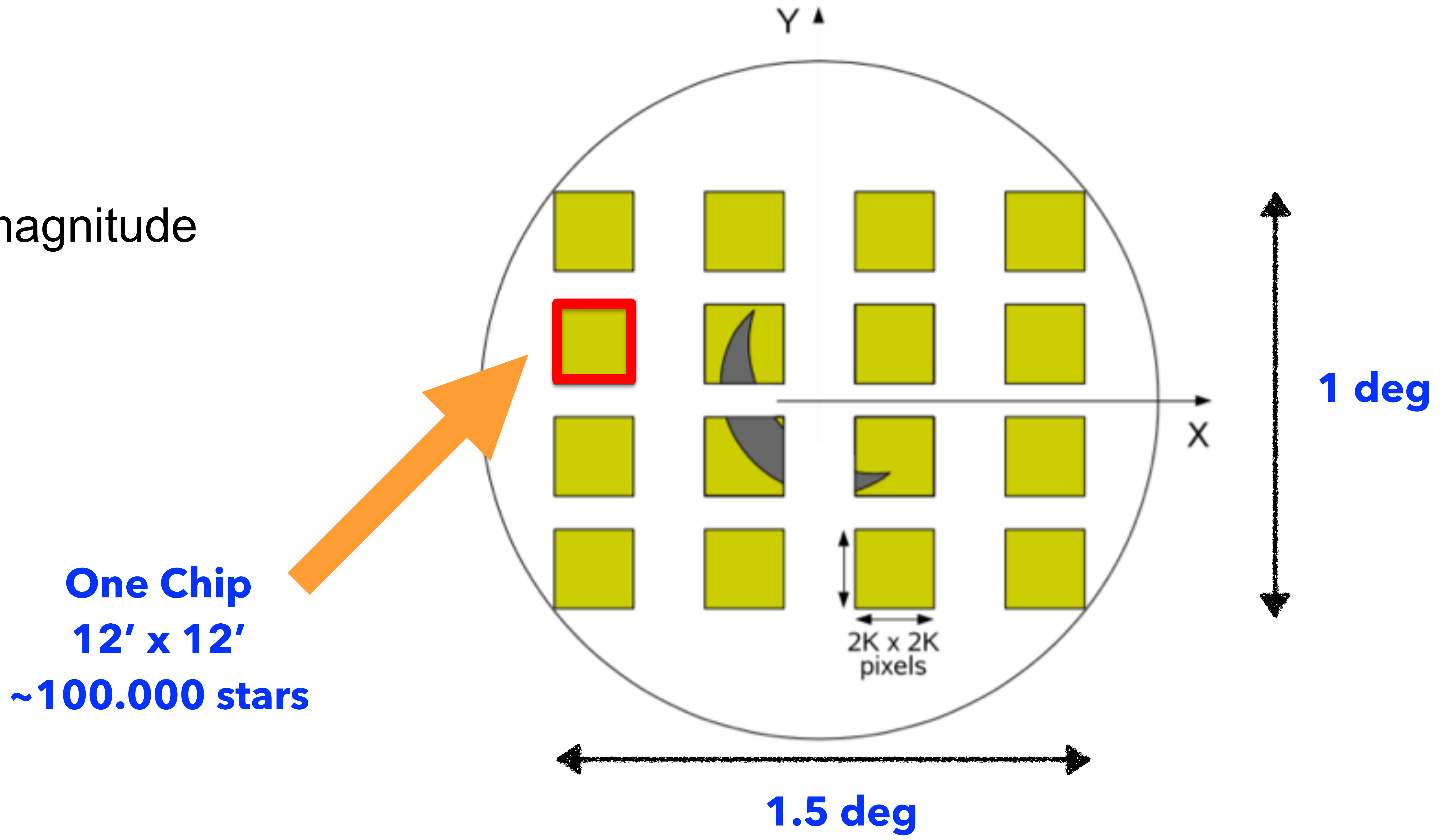
Repeat events definition:

- same position
d < 2 arcsec,

- same time
Tmax < 7days

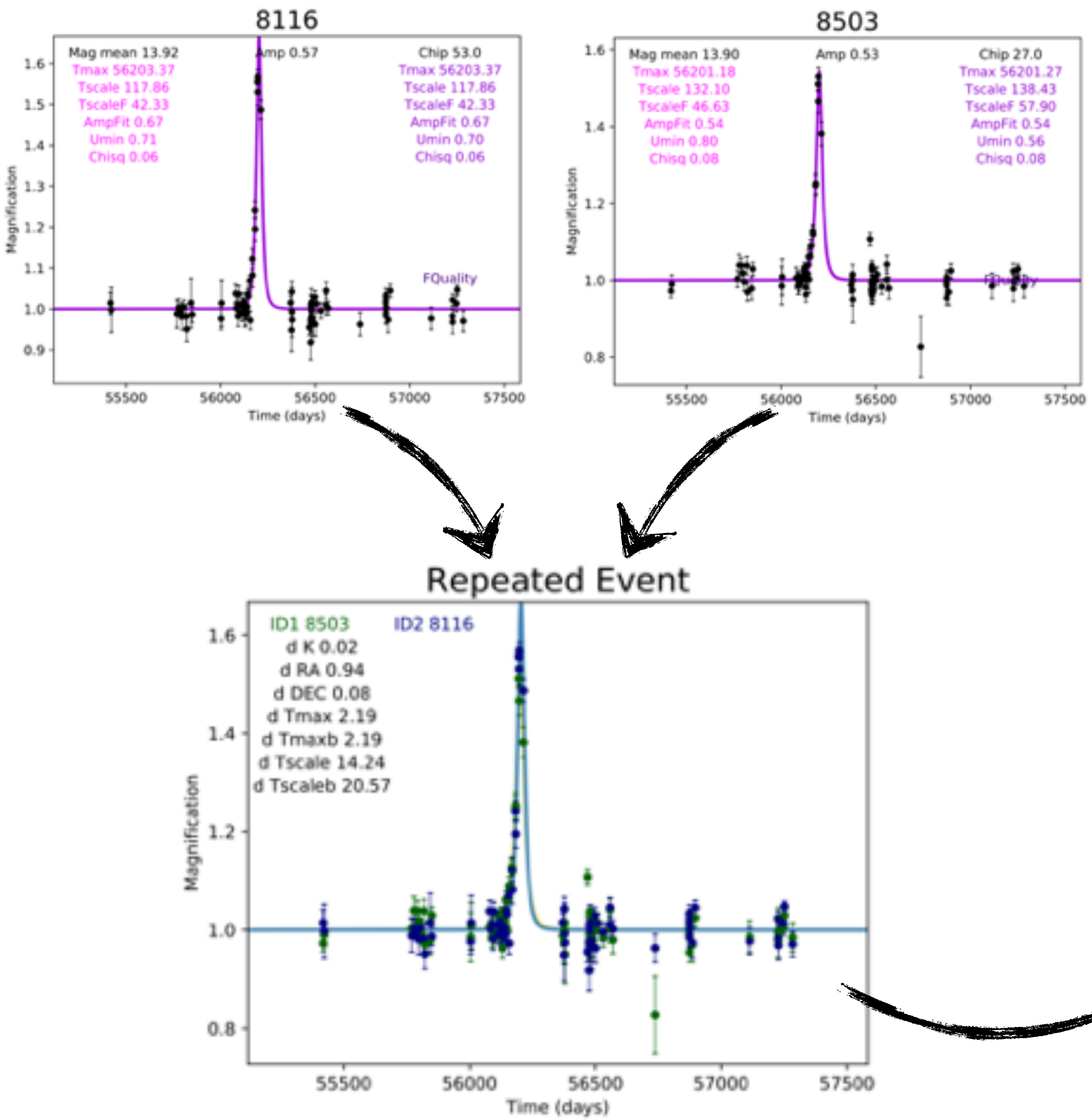
- similar source magnitude
Delta_Ks < 0.15

The VVV Survey Near-IR Observations
D. Minniti et al. 2010, New Astronomy

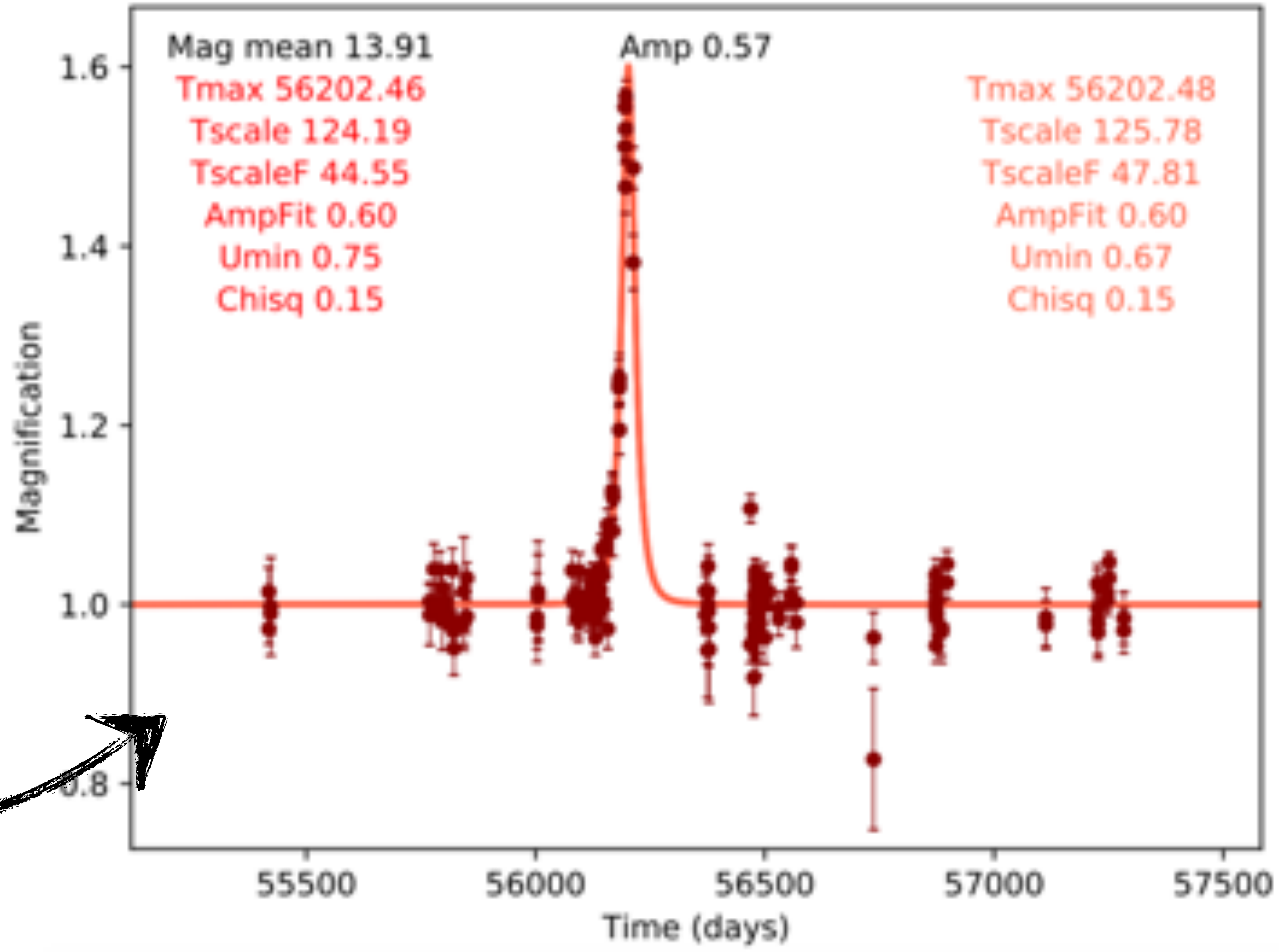


REPEAT EVENTS

The repeat events are very useful because they provide external measurements of the errors in the different parameters fitted to the individual events.

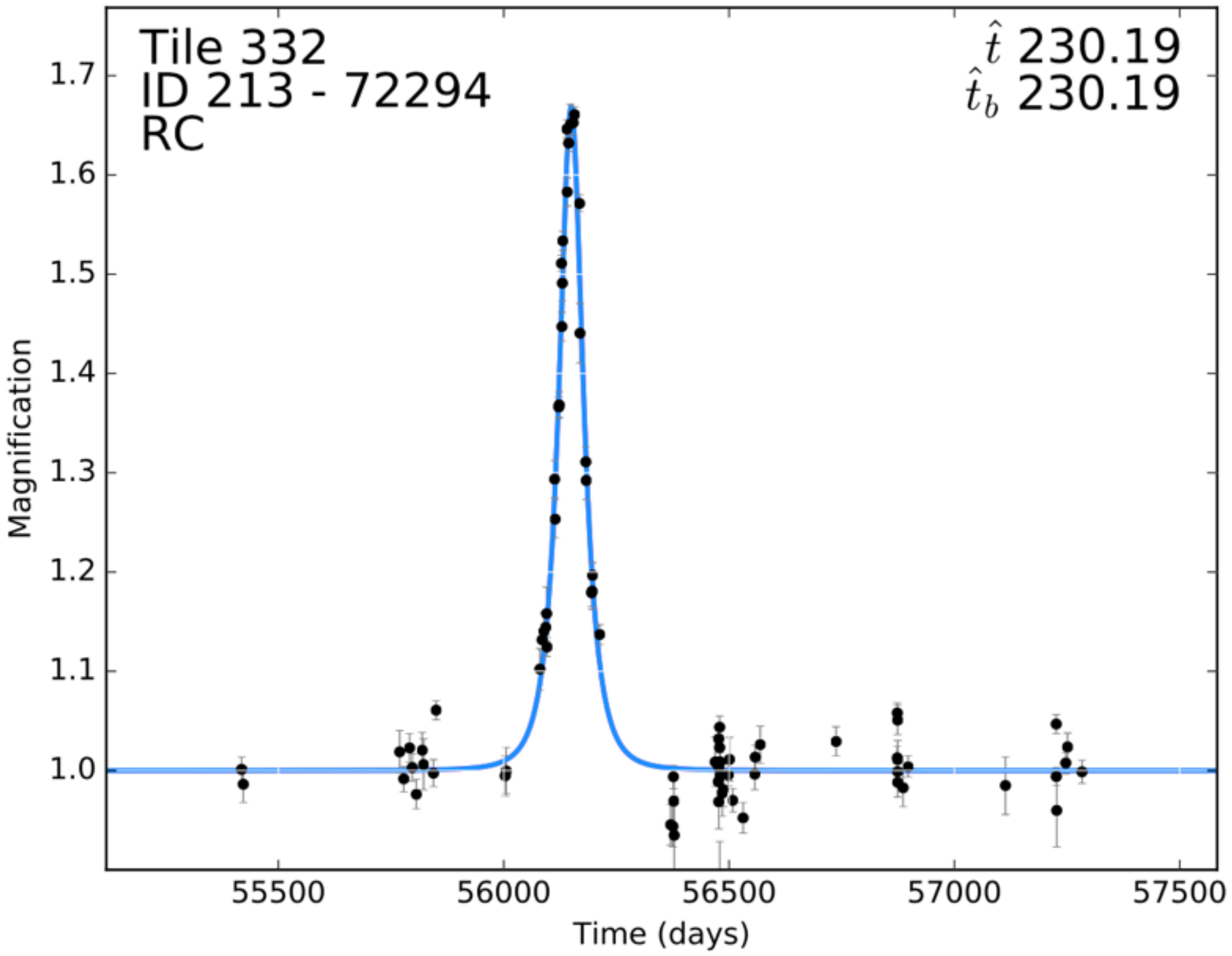


New fit



VISUAL INSPECTION

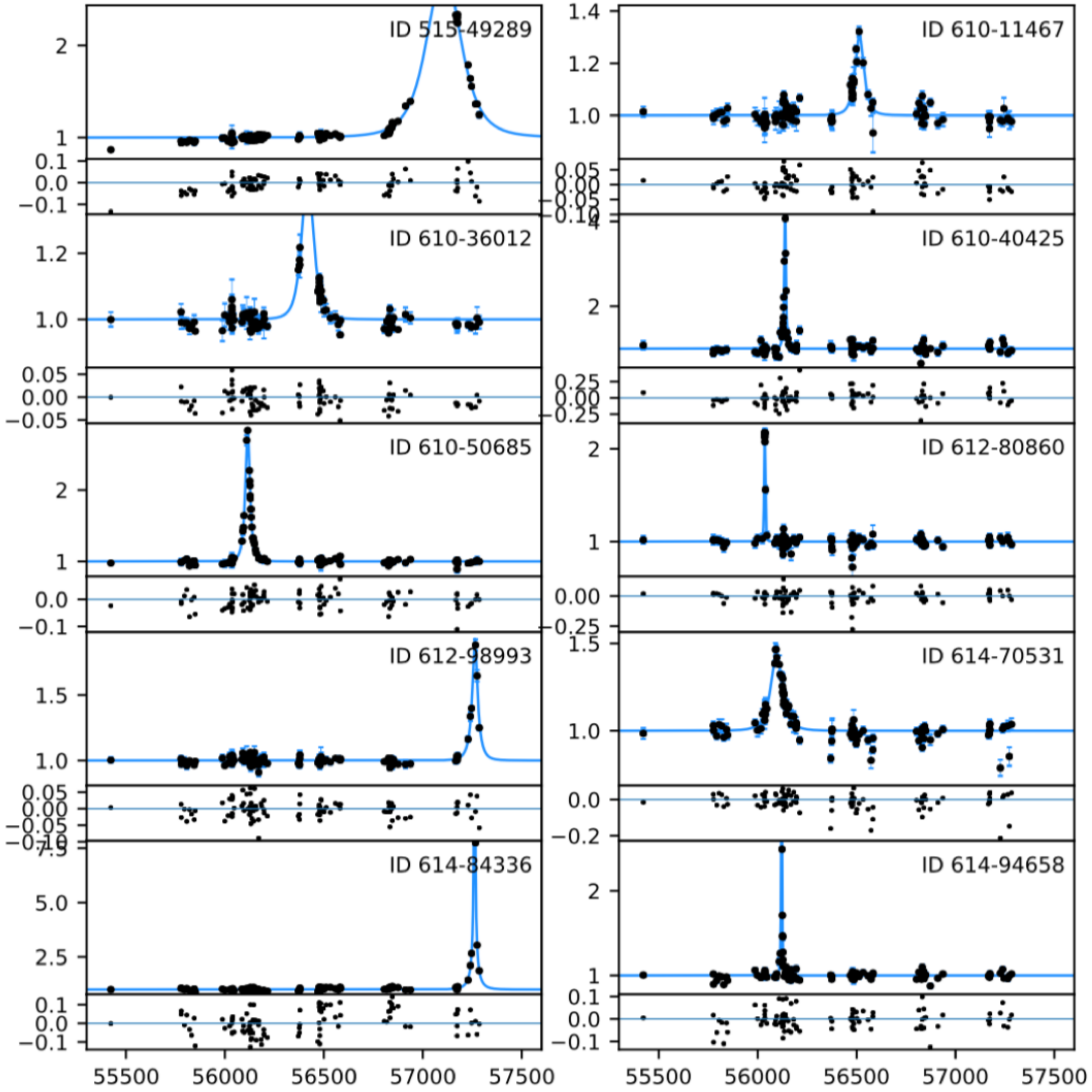
- Symmetry
- Number of data points
- Baseline
- Fit
- Timescale value



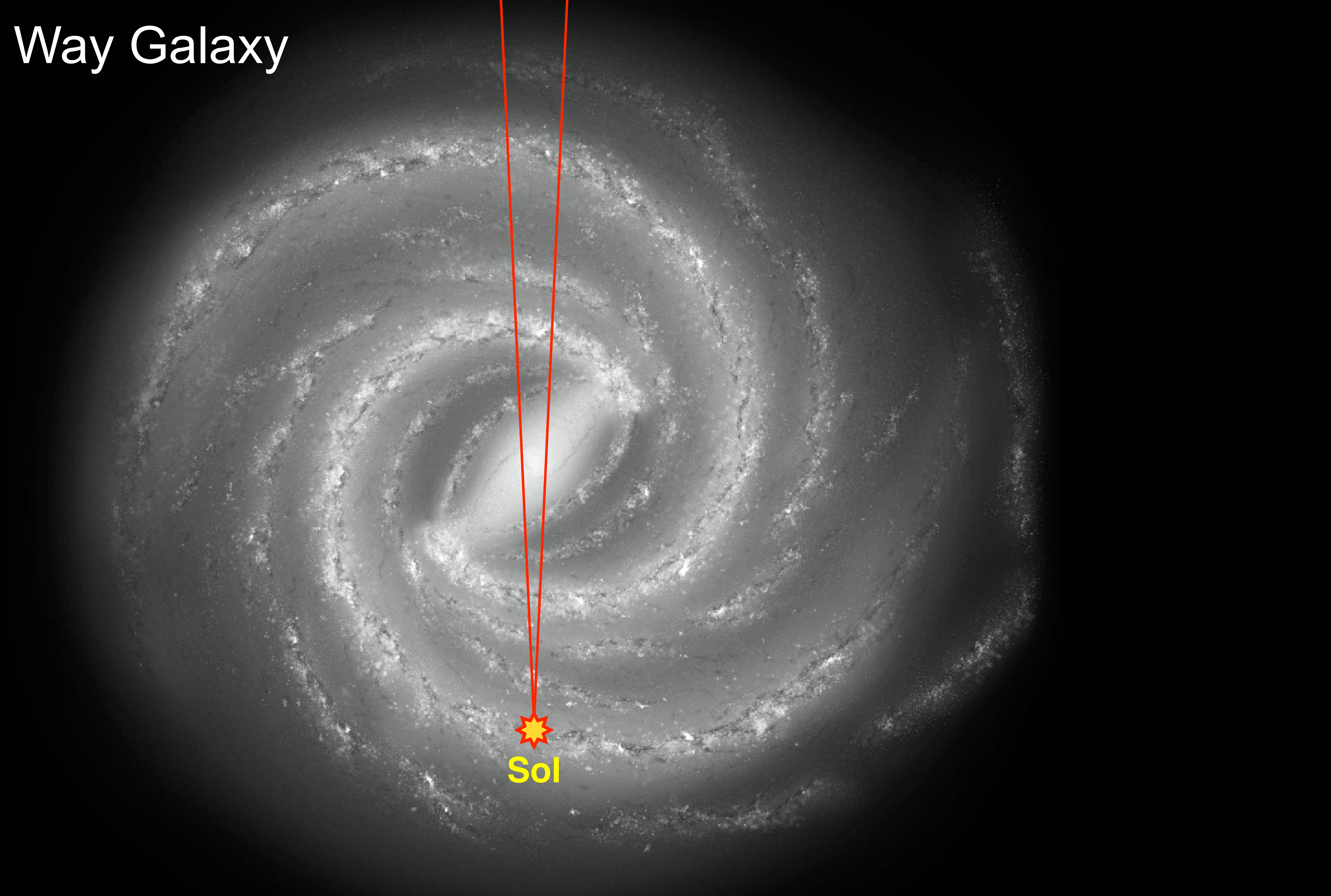
Thorough quality control is necessary to check all the events and rule out alternative variability scenarios and other artifacts. This is made by visual inspection of the individual light curves.

FIRST RESULTS

182 NEW MICROLENSING EVENTS IN THE GALACTIC CENTRE



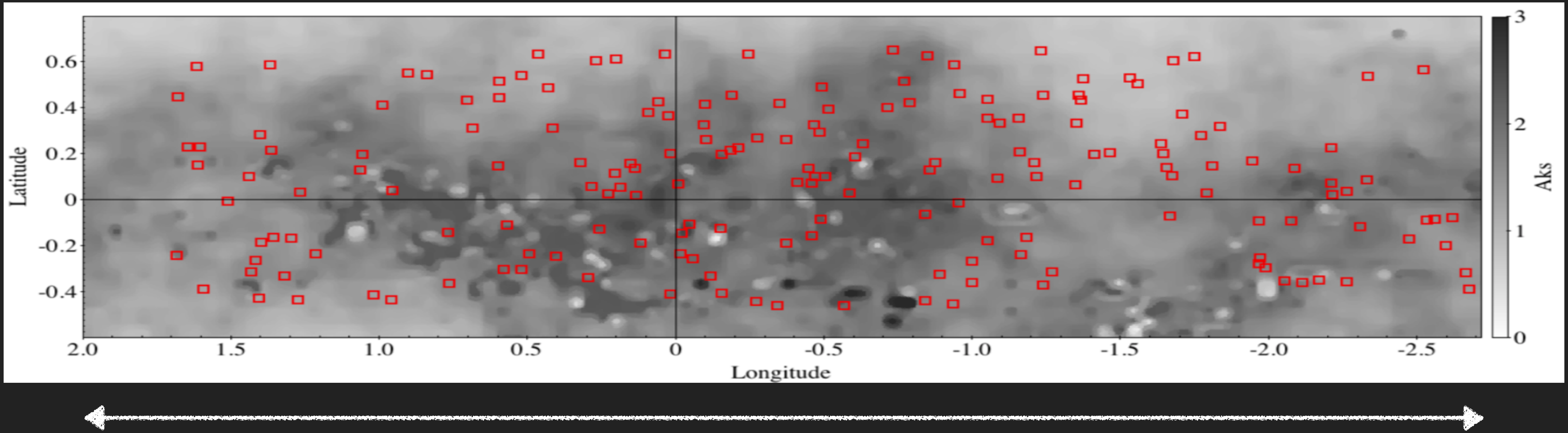
The Milky Way Galaxy



SPATIAL DISTRIBUTION

Navarro et al. 2017, ApJ

- 3 tiles (4.5 sq.deg.) surrounding the Galactic center



0.8 kpc

- underlying extinction map from Gonzalez et al. 2012 A&A

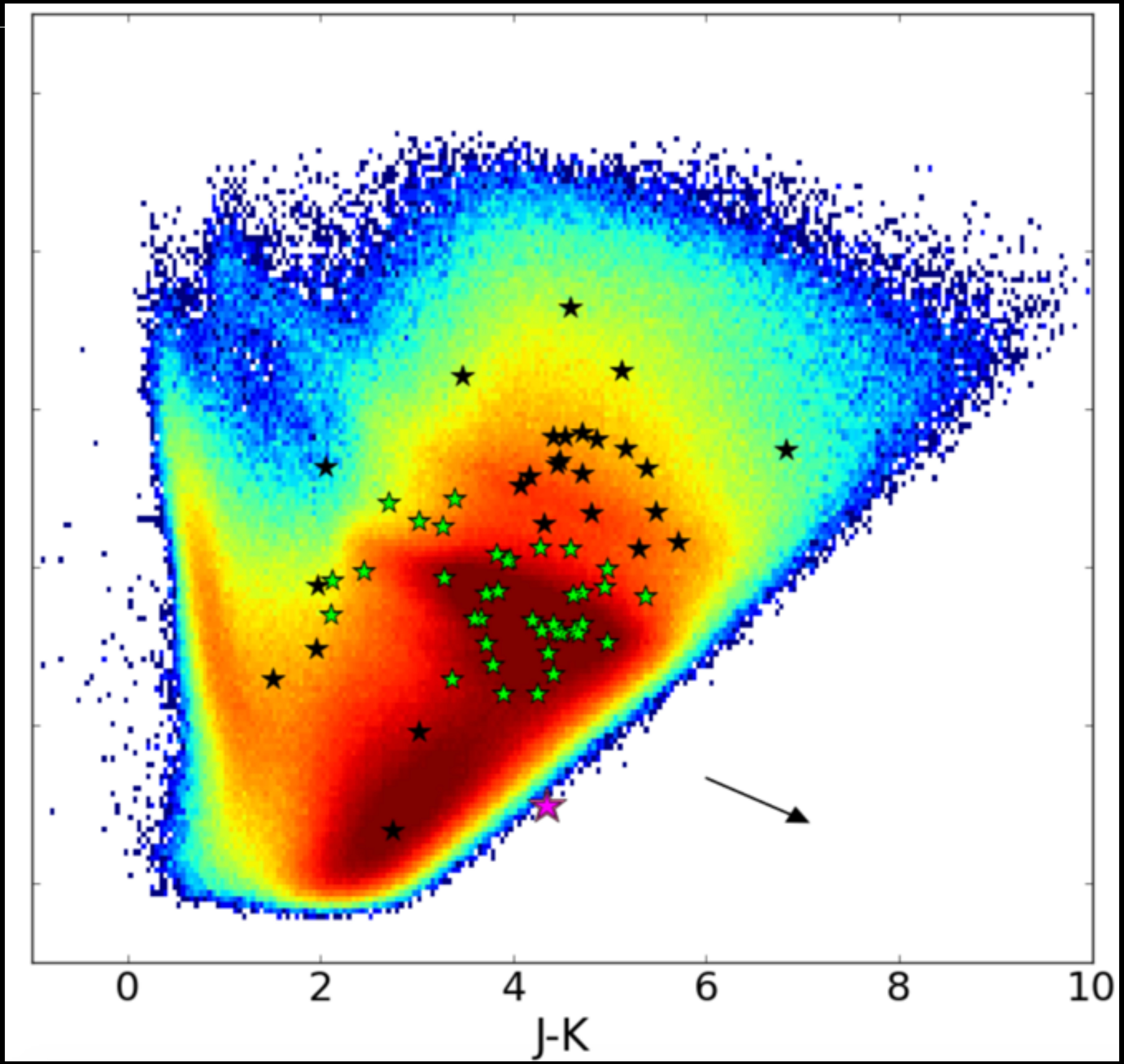
CMD

Near-IR color-magnitude diagram (CMD) of the Galactic centre region.

The big stars are the microlensing events.

The arrow shows the reddening vector.

VVV PSF photometry from Contreras Ramos et al. 2017

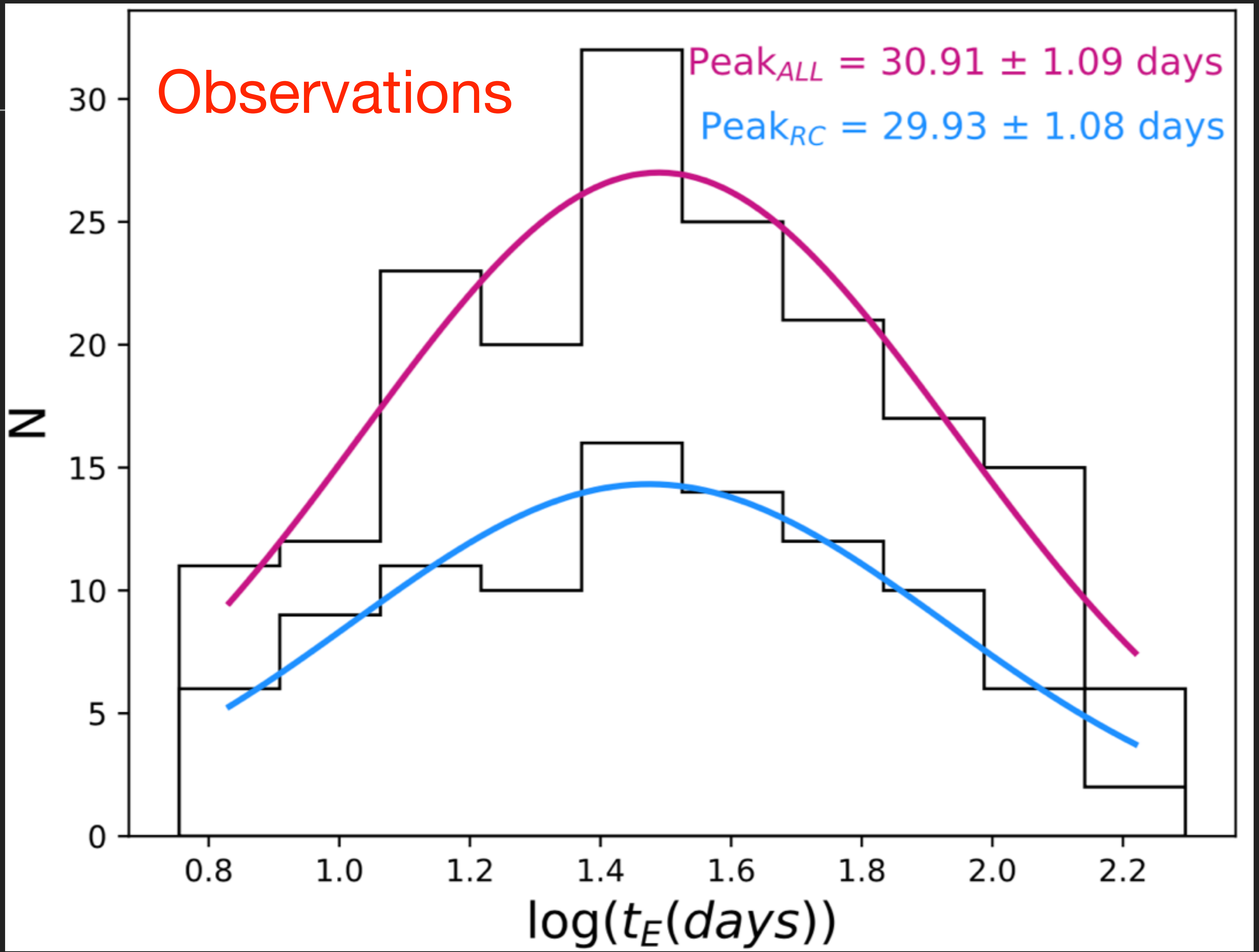


Navarro et al. 2017

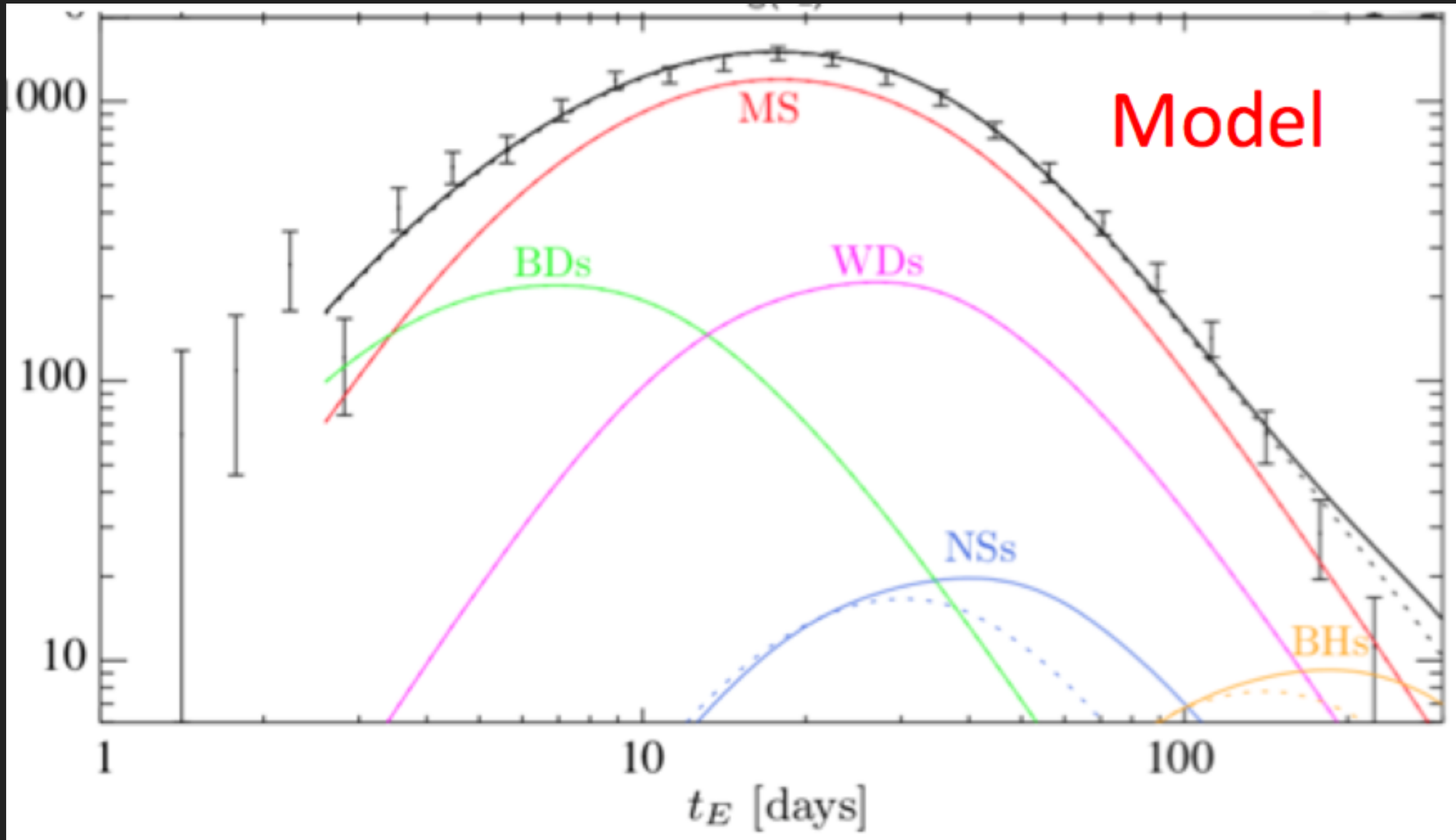
TIMESCALE DISTRIBUTION

The timescale distribution shows a number of long timescale (t>100 days) microlensing events.

A BH population in the Galactic centre region?

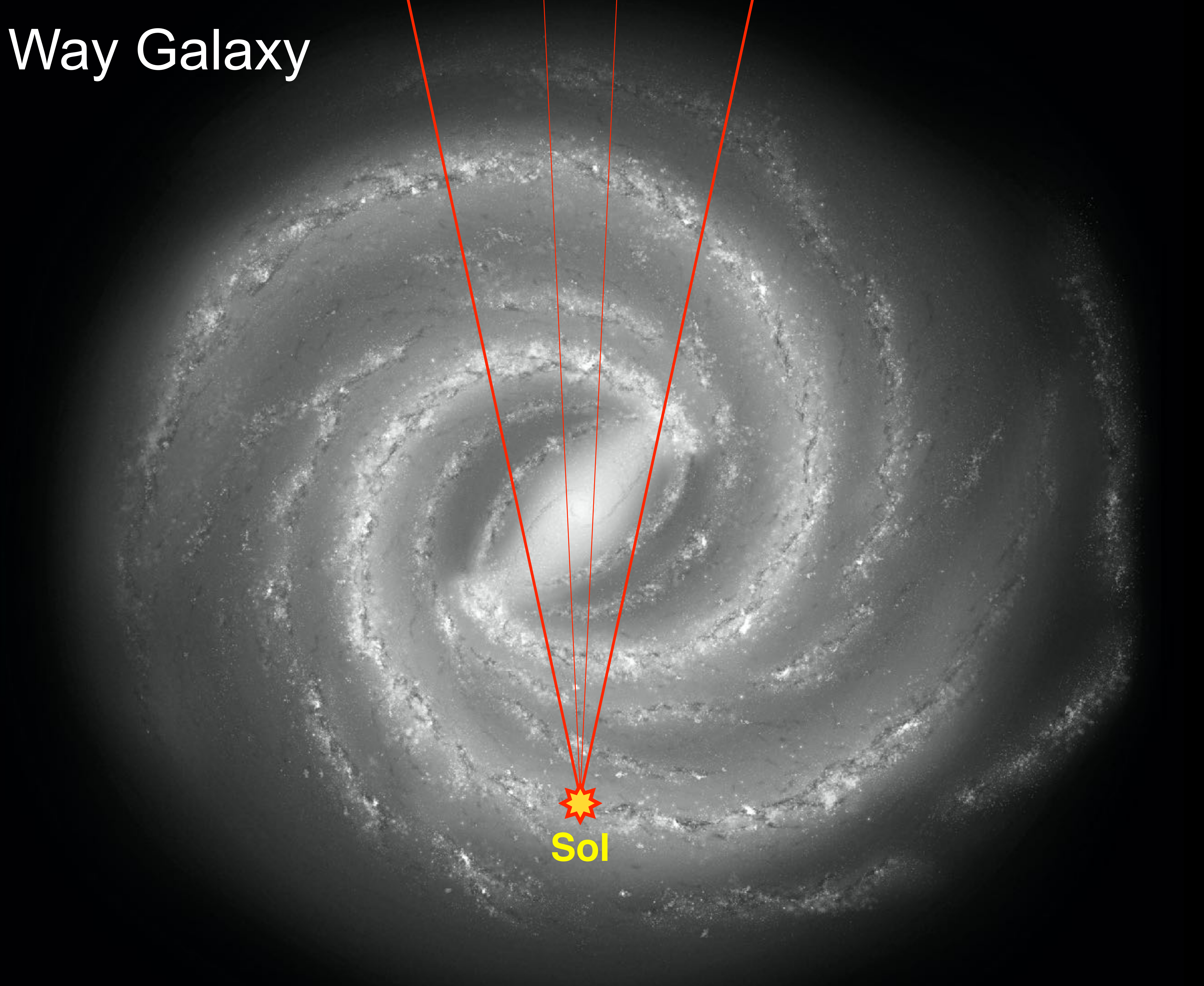


Navarro et al. 2017



Wegg et al. 2013

The Milky Way Galaxy



THE EXTENDED AREA SEARCH

Steps

10^7 time series

↓ **Automatic search**

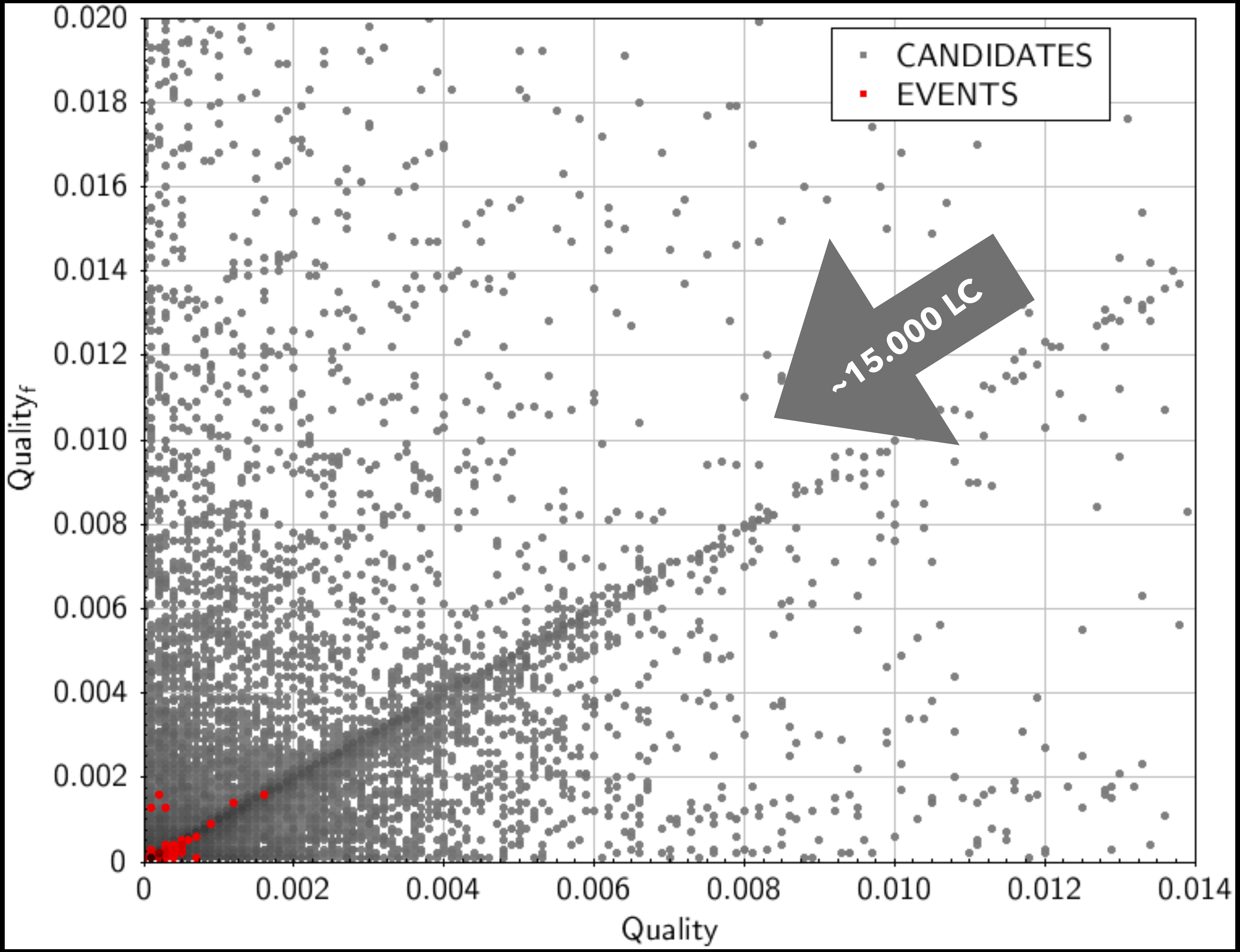
5 x 10^4 light curves

↓ **Visual inspection**

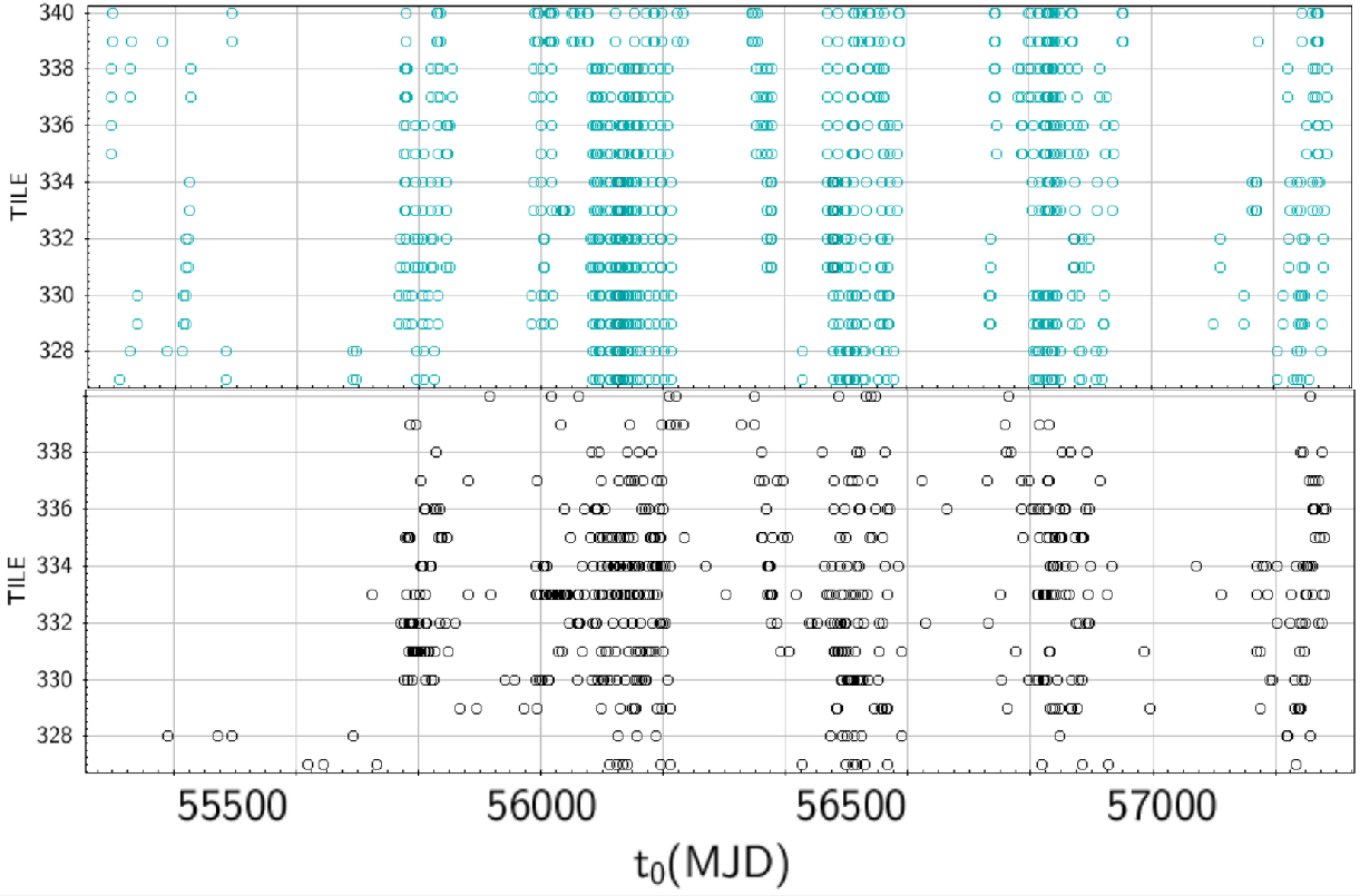
630 events

QUALITY CONTROL

Navarro et al., ApJ 2020

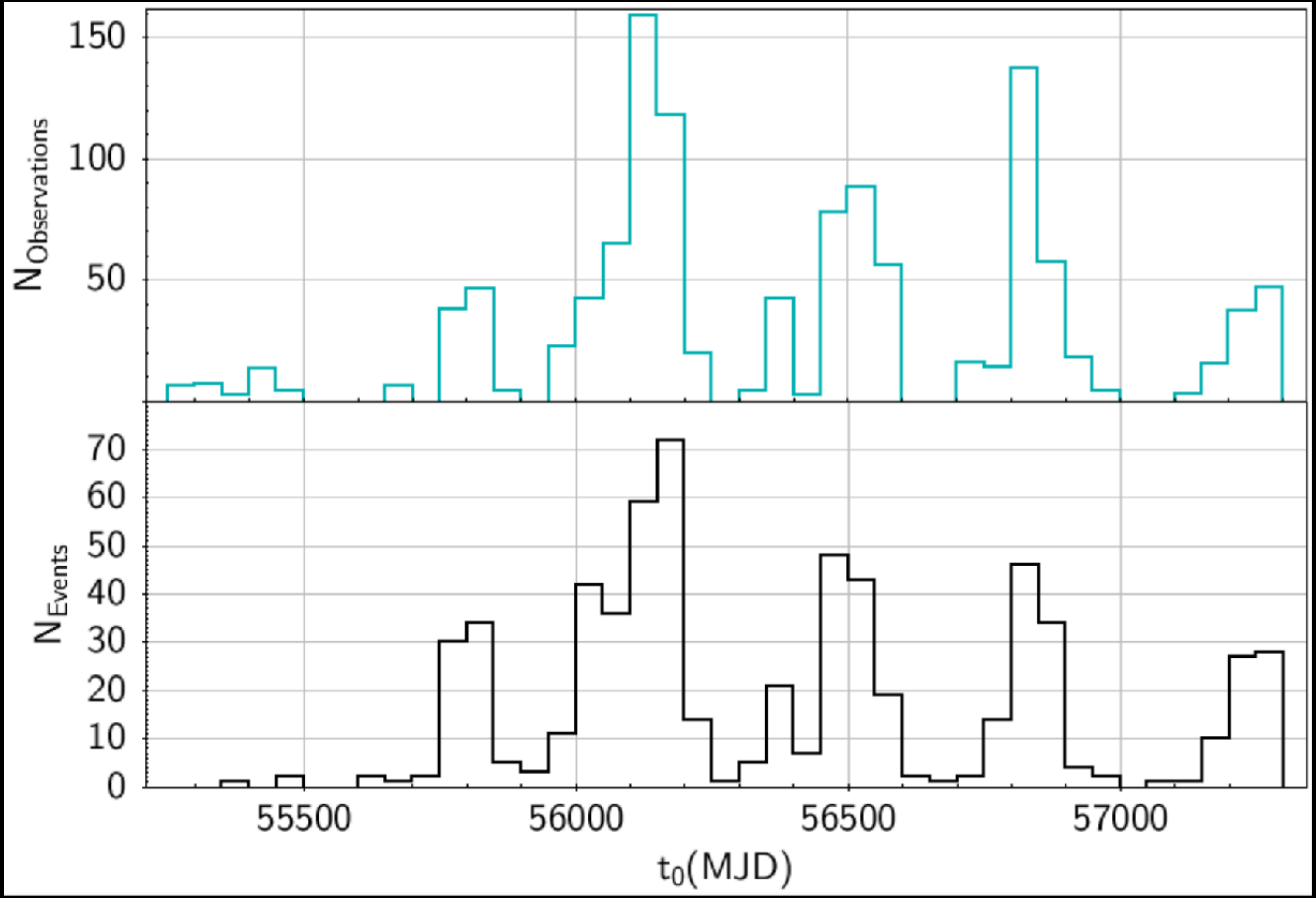


OBSERVATIONS PER TILE



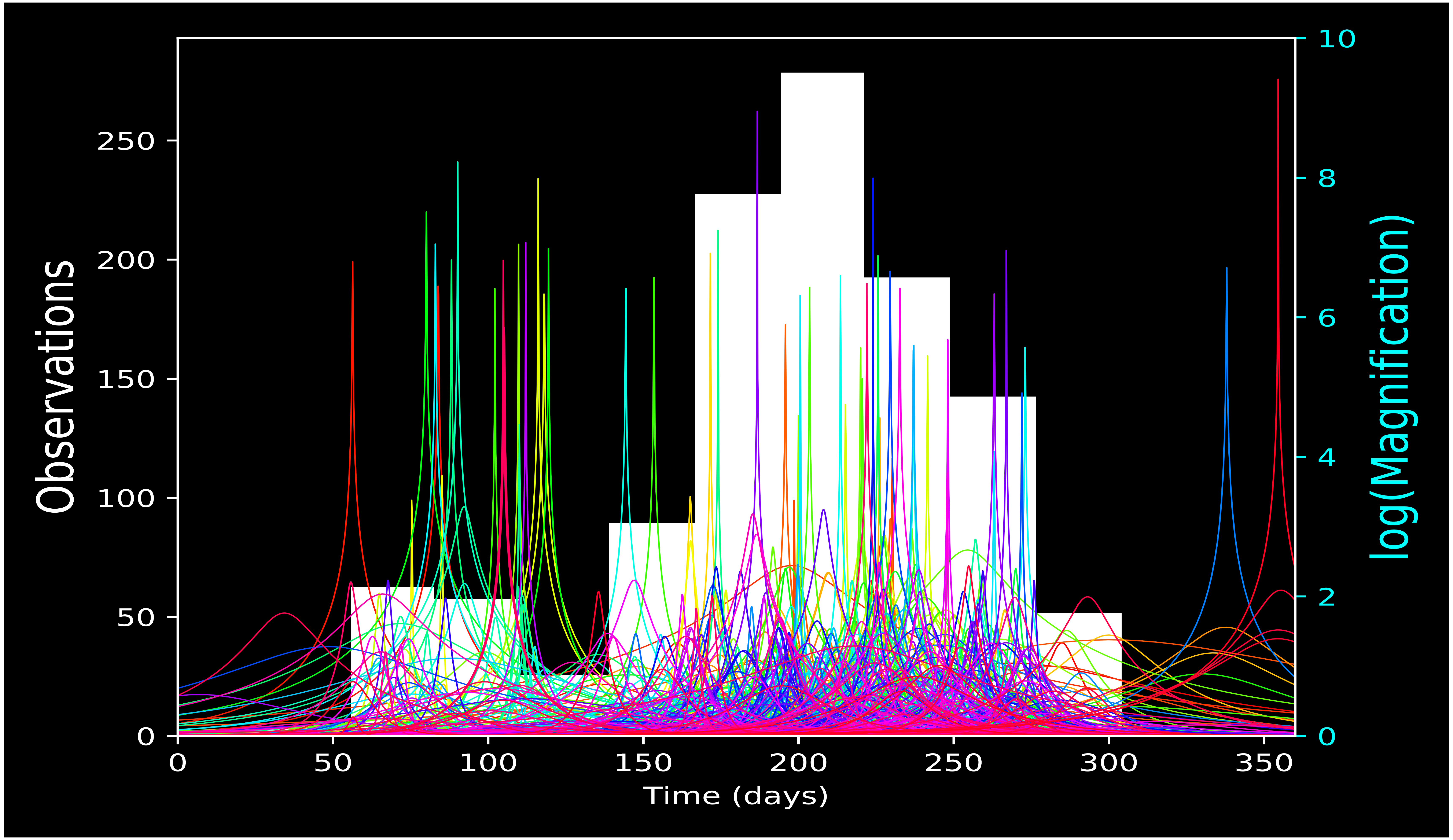
OBSERVATIONS AND DETECTIONS FOR ALL TILES

Navarro et al., ApJ 2020



Global Efficiency

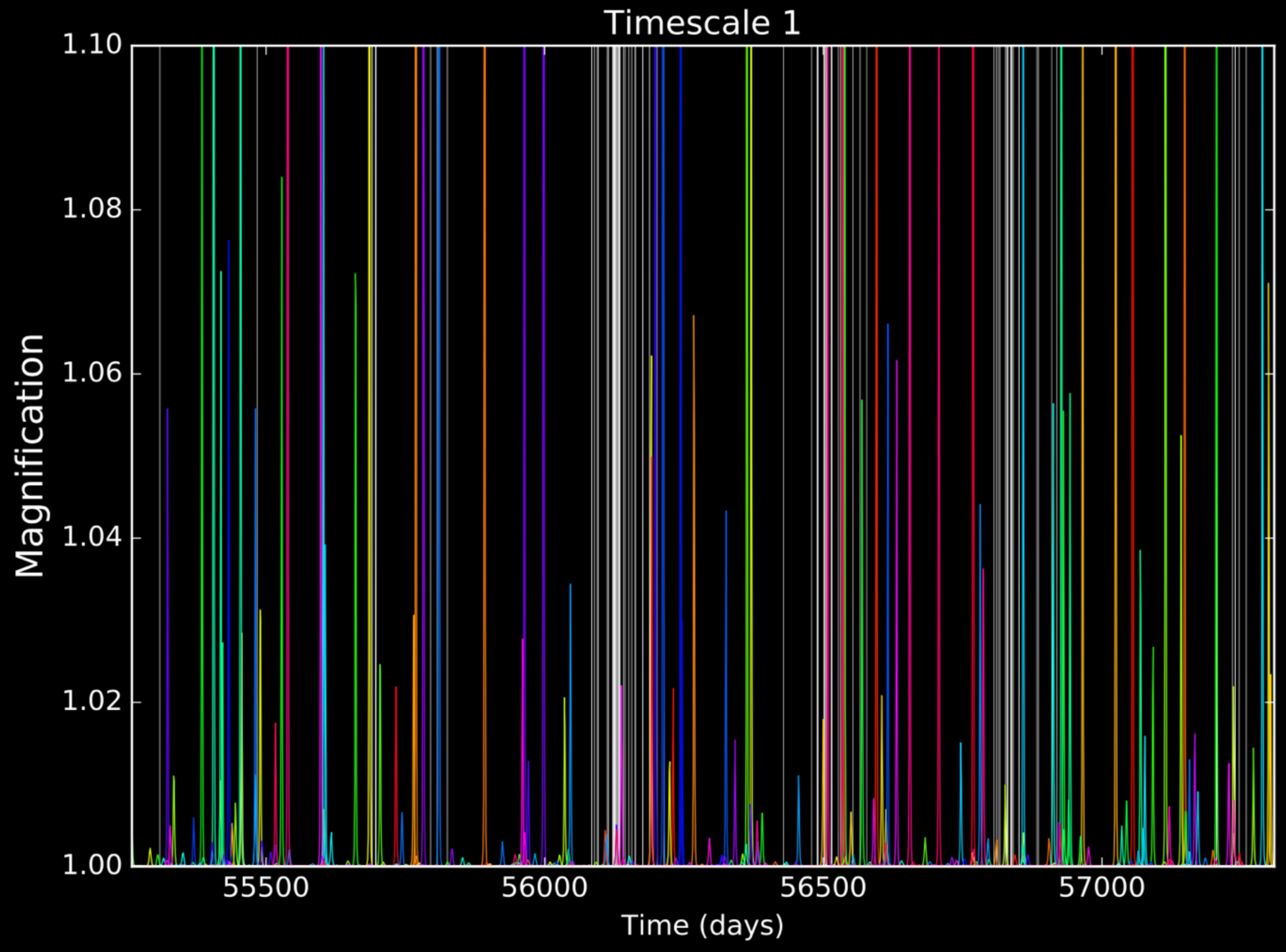
High Magnification Events

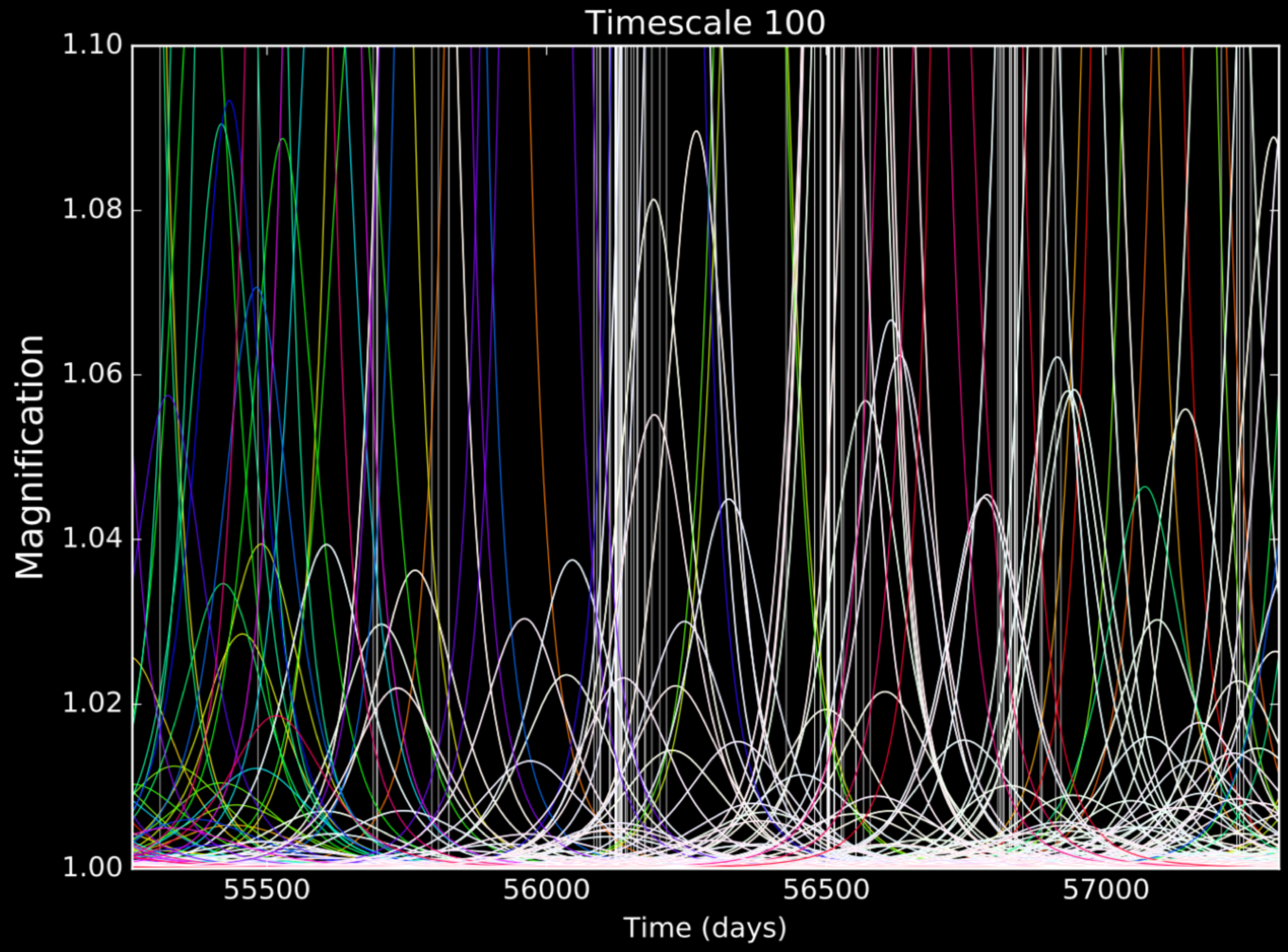


There are N=46 events with high magnification (peak log(magnification) >3). This s almost 10% of the total sample. They are more uniformly distributed and do not follow so closely the sampling of the observations, suggesting that these events are more easily detectable. During the months of multiple observations (excluding Jan, Feb, Nov and Dec) we compute an average of 5.5 high magnification events per month.

SAMPLING EFFICIENCY FOR DIFFERENT TIMESCALES

tE = 1 day

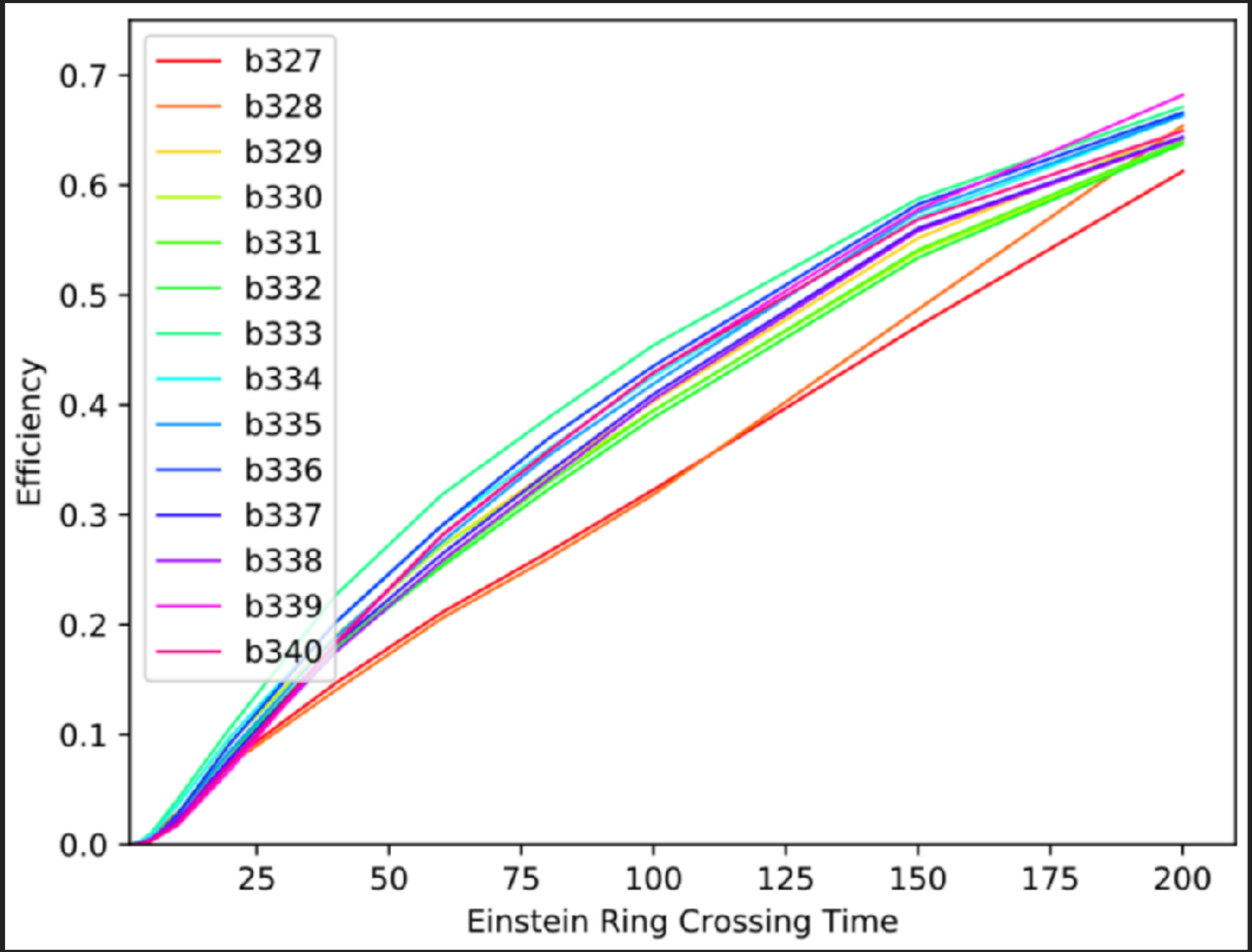




tE = 100 day

SAMPLING EFFICIENCY FOR DIFFERENT TILES

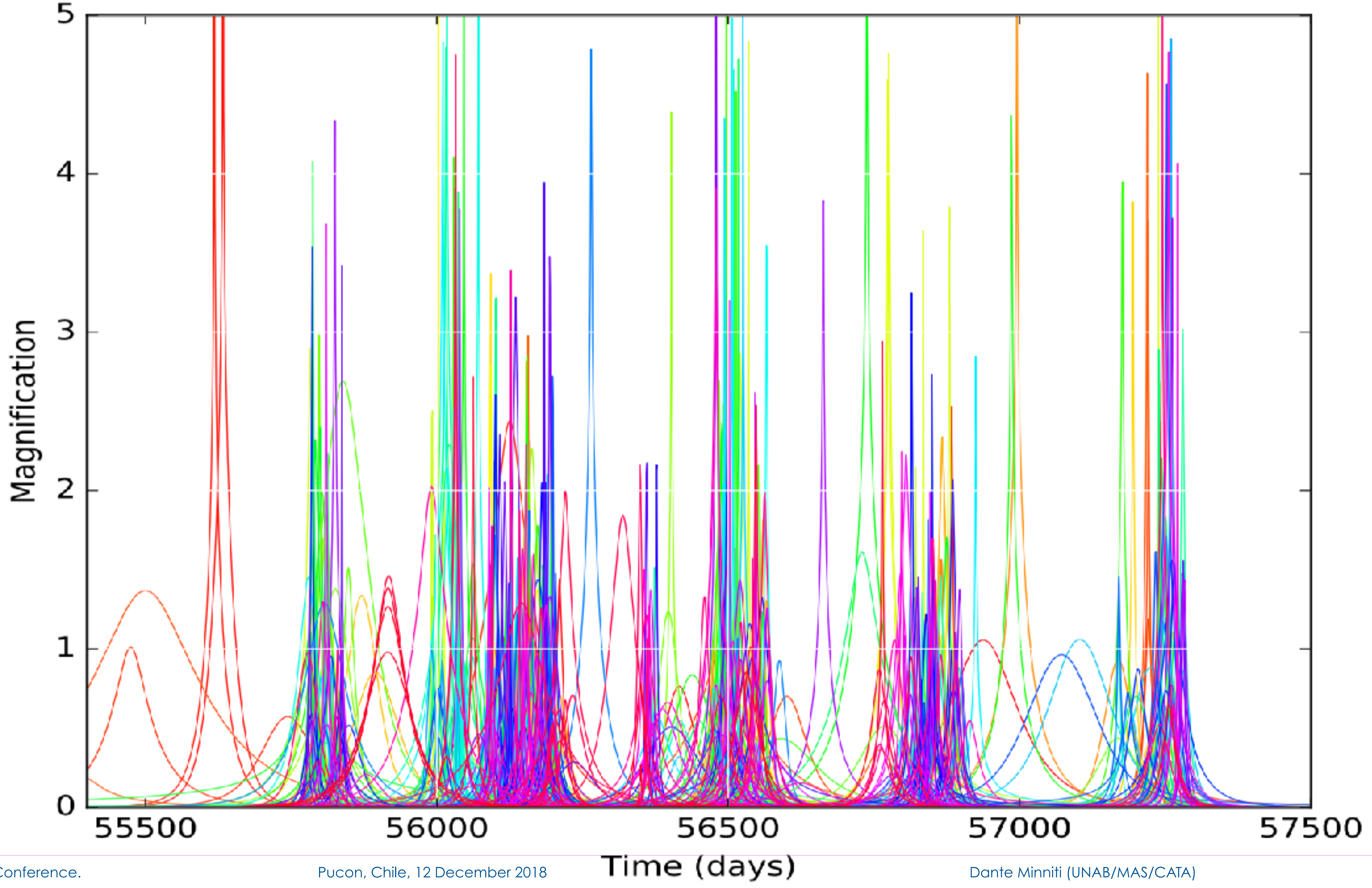
Navarro et al., 2020 ApJ



FINAL OBSERVED SAMPLE

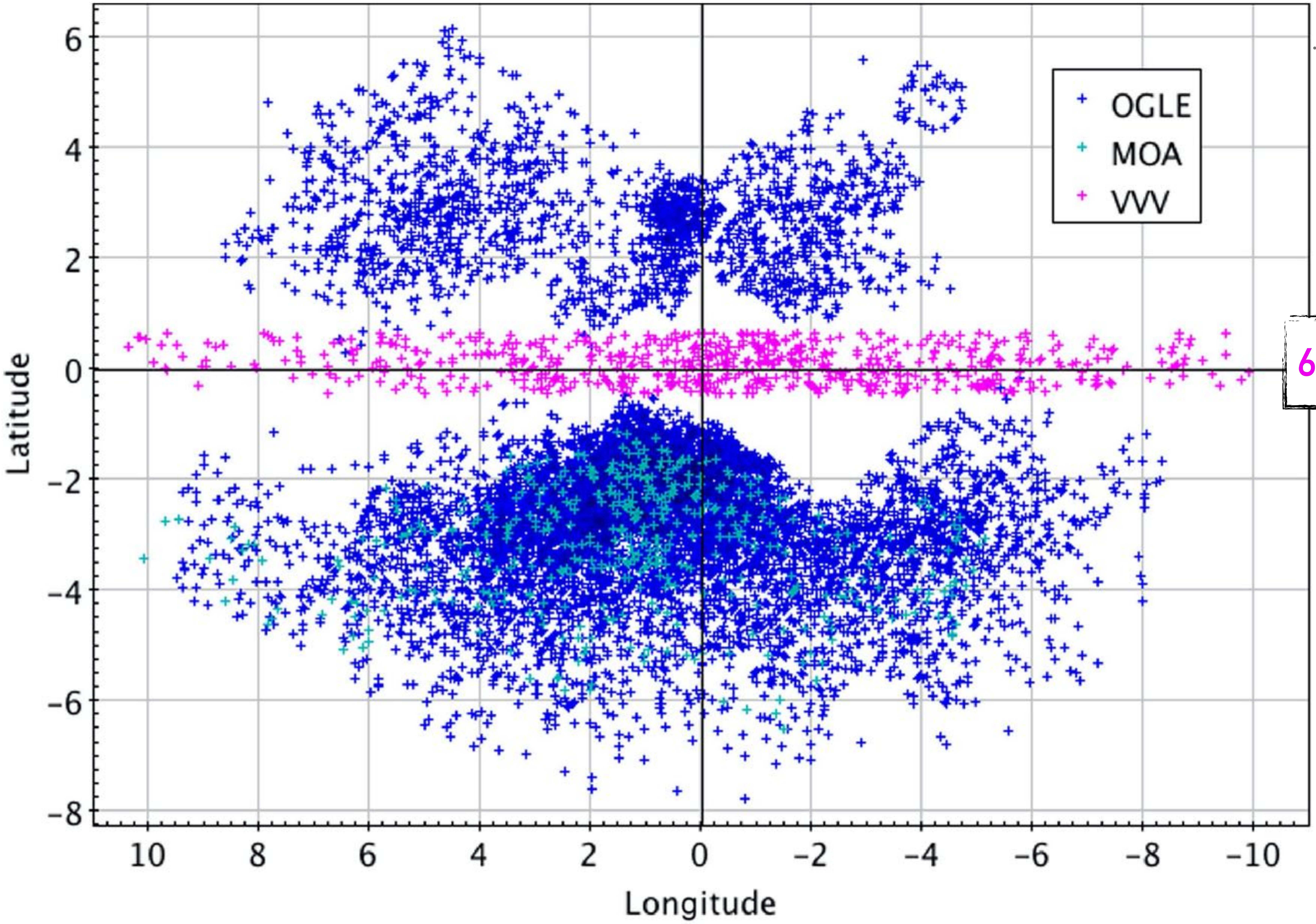
G. Navarro et al. 2016 ApJL
G. Navarro et al. 2017 ApJL
G. Navarro et al. 2020 ApJ

630 New Events




0.8 kpc

SPATIAL DISTRIBUTION



630 microlensing events

NAVARRO ET AL. 2017 (APJ, 851, L13)
NAVARRO ET AL. 2018 (APJ, 865, L5)

SPATIAL DISTRIBUTION

Spatial distribution of the 630 new microlensing events.
The sizes are proportional to the event timescales.
The background shows the near-IR extinction map.
Notice the concentration towards the Galactic centre.

Galactic centre

Discovery of a new low extinction window

SAITO, ET AL. 2019 (MNRAS, 494, 1)

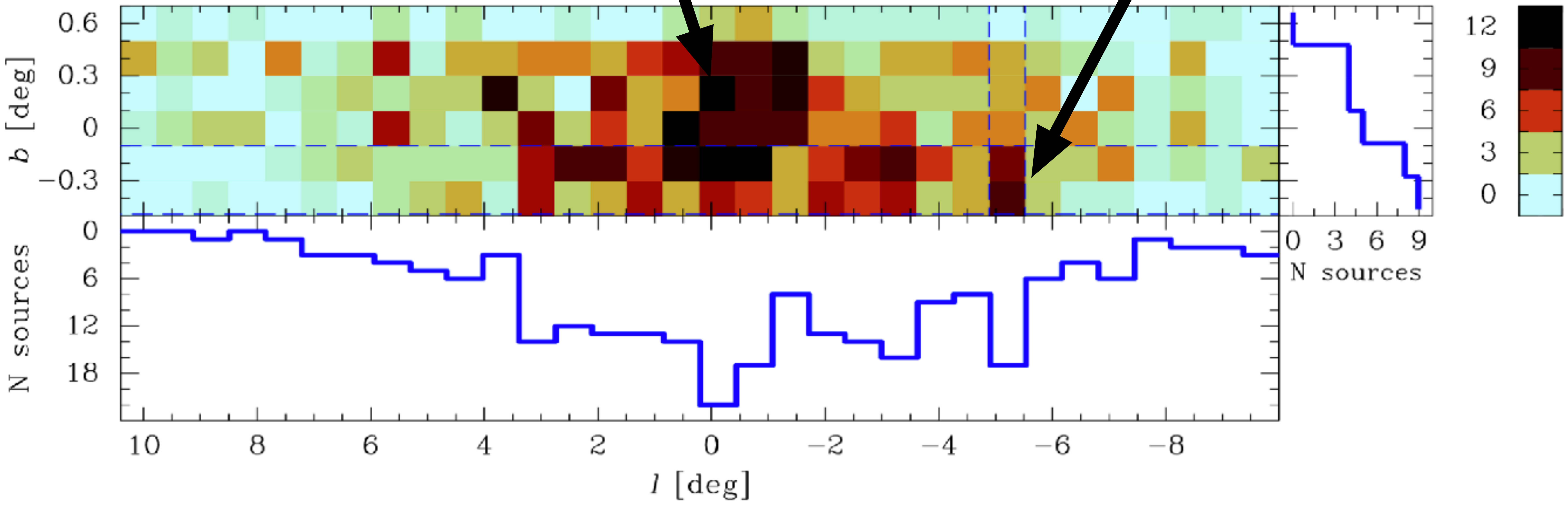
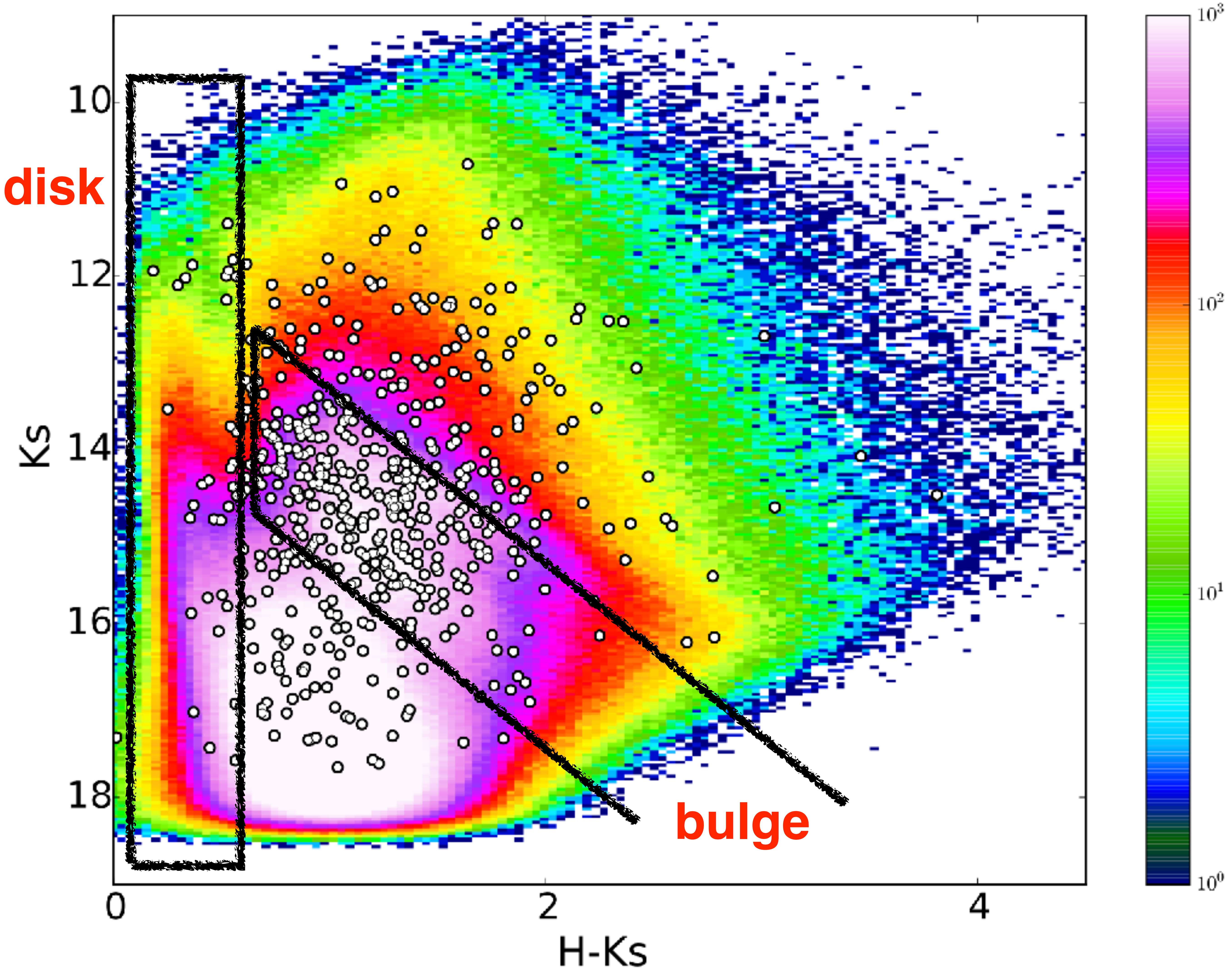


Figure 4. Density plot with the distribution of microlensing events in the inner bulge. An overdensity of events is present at the position of VVV WIN 1733−3349 ($l, b = -5.2, -0.3$ deg). Histograms for sources within the WIN 1733−3349 limiting coordinates (dashed lines) are also shown for both axes. A vertical bar shows the colour code in the map. Adapted from Navarro et al. (2018, 2019).

Selection of red clump giants

Mean intrinsic magnitude and color of the RC
Ks_0= -1.68+/- 0.03, (J-Ks)_0=0.60+/- 0.01
from Alves et al. (2002).
Mean bulge distance D=8300 pc, or m-M=14.60

The RC giants are less biased.
They are bright and red, and therefore less afected by reddening, blending, etc.
Their individual distances can be measured.
They are mostly located in the MW bulge.

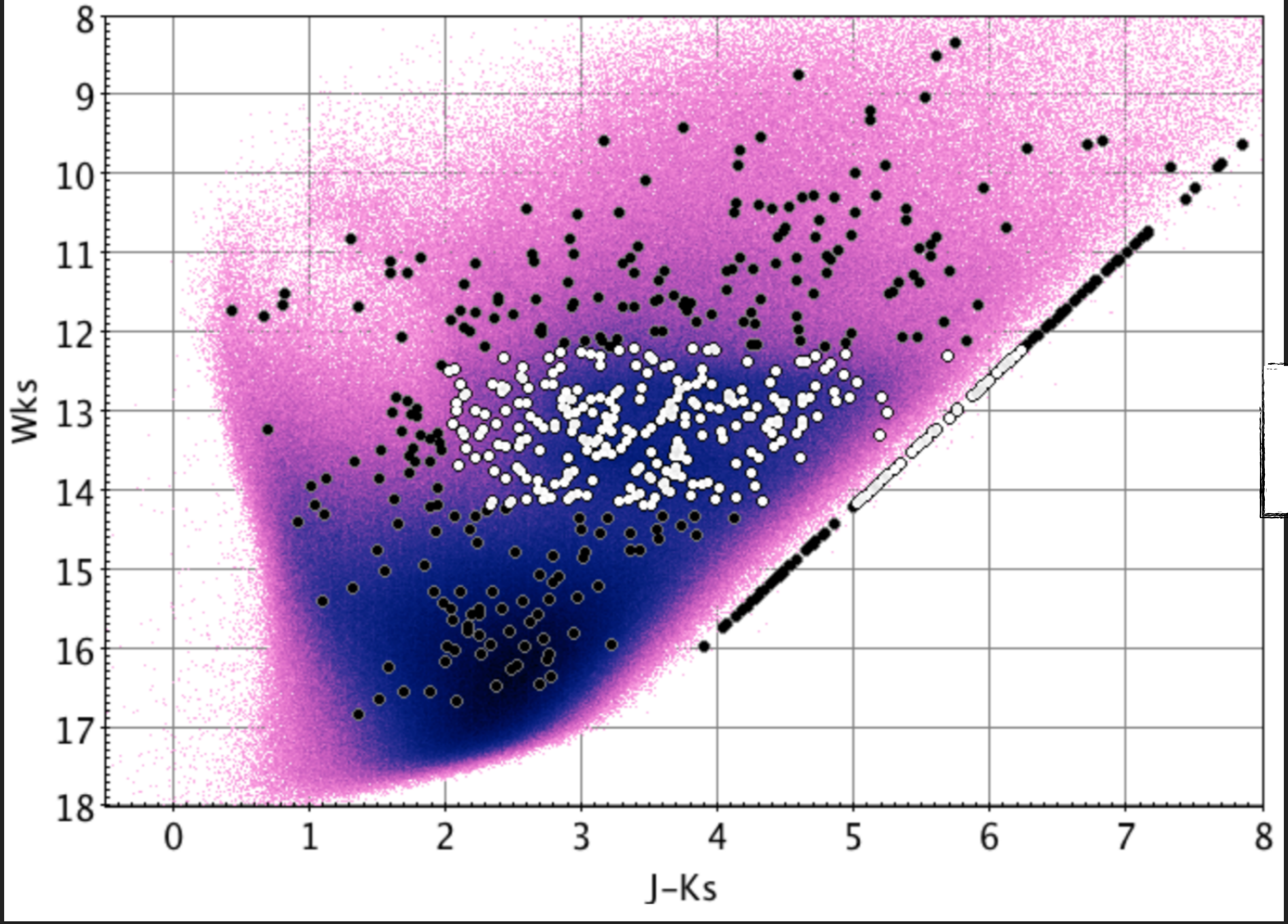


WESELINK COLOR-MAGNITUDE DIAGRAM

Navarro et al. 2018

The Weselink near-IR magnitude is independent of reddening, very important at these low Galactic latitudes.

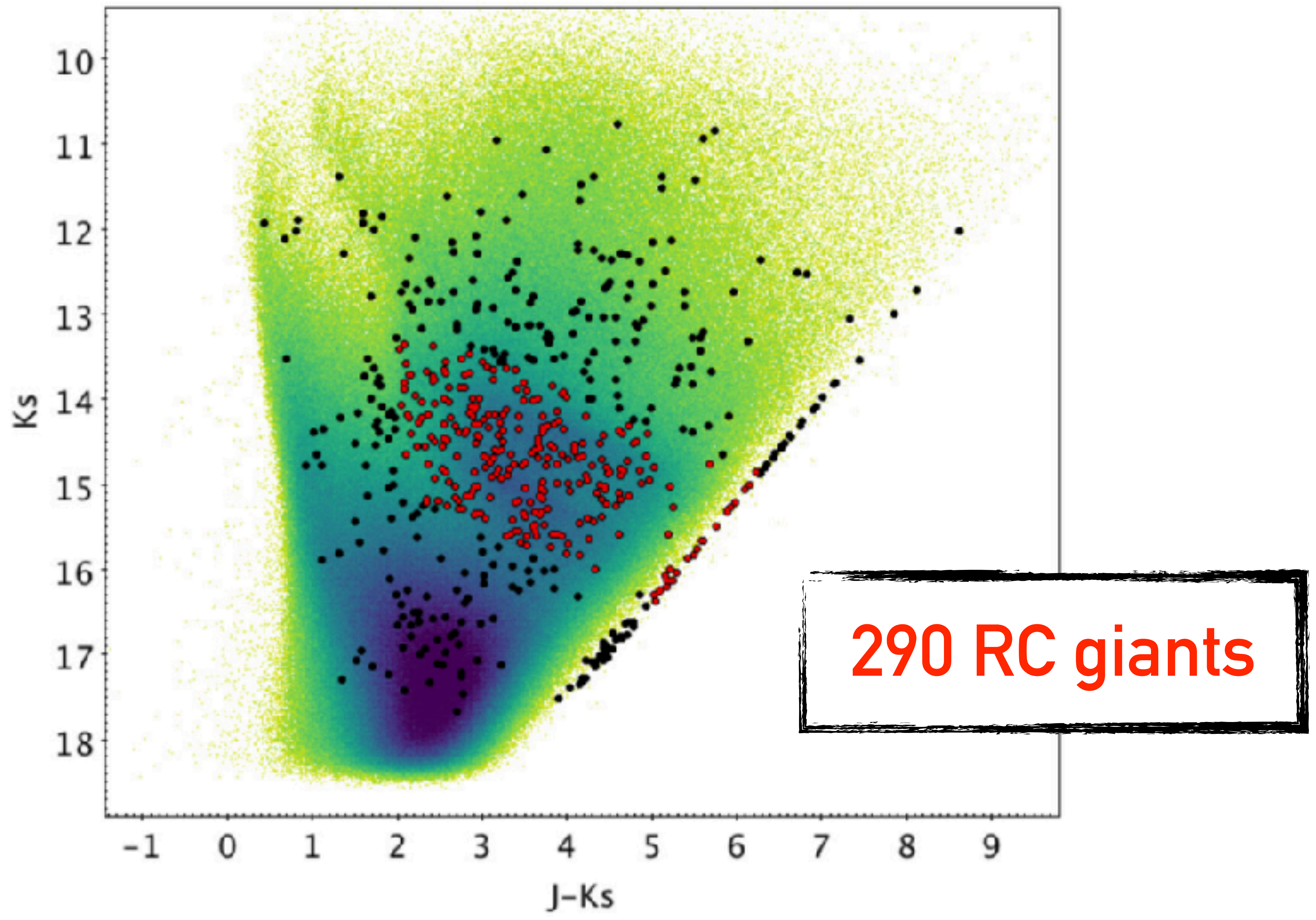
VVV PSF photometry from Contreras Ramos et al. 2017



290 RC giants out of 630 events

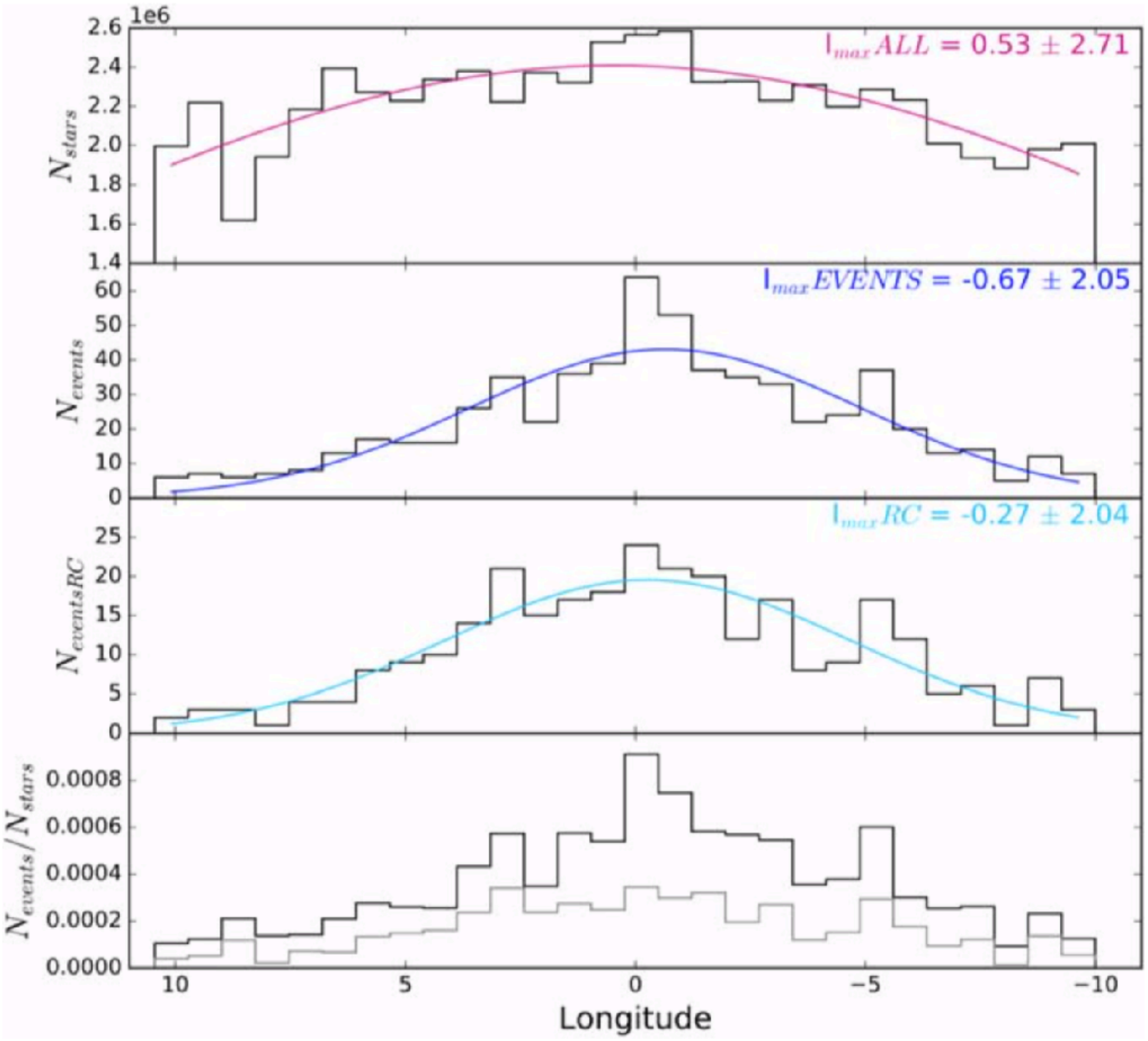
FINAL SAMPLE

COLOR MAGNITUDE DIAGRAM



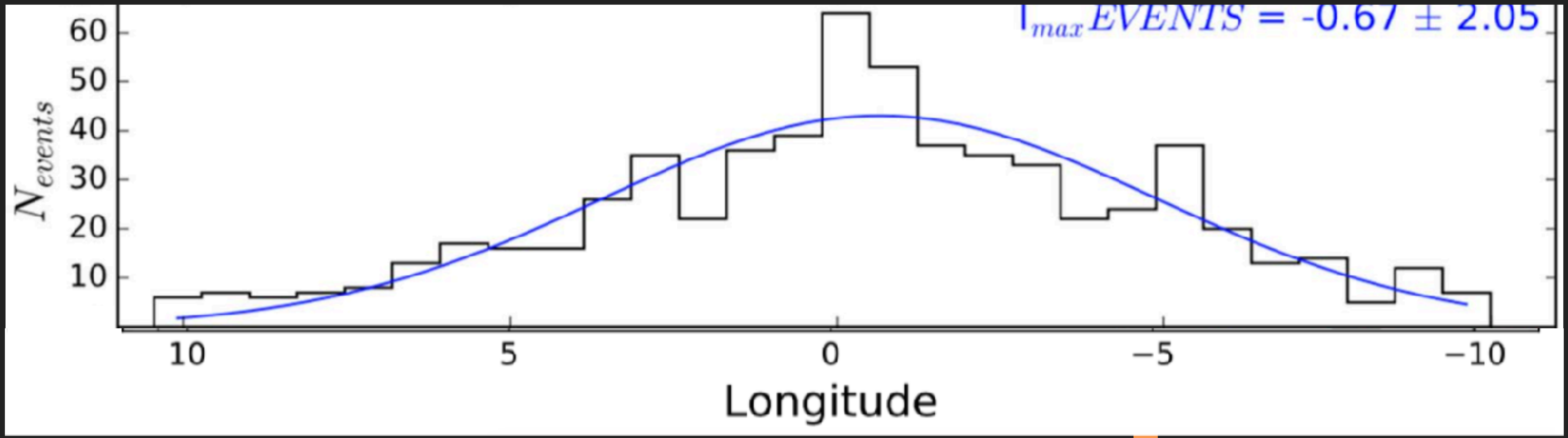
NAVARRO ET AL. 2019

GALACTIC LONGITUDE DISTRIBUTION

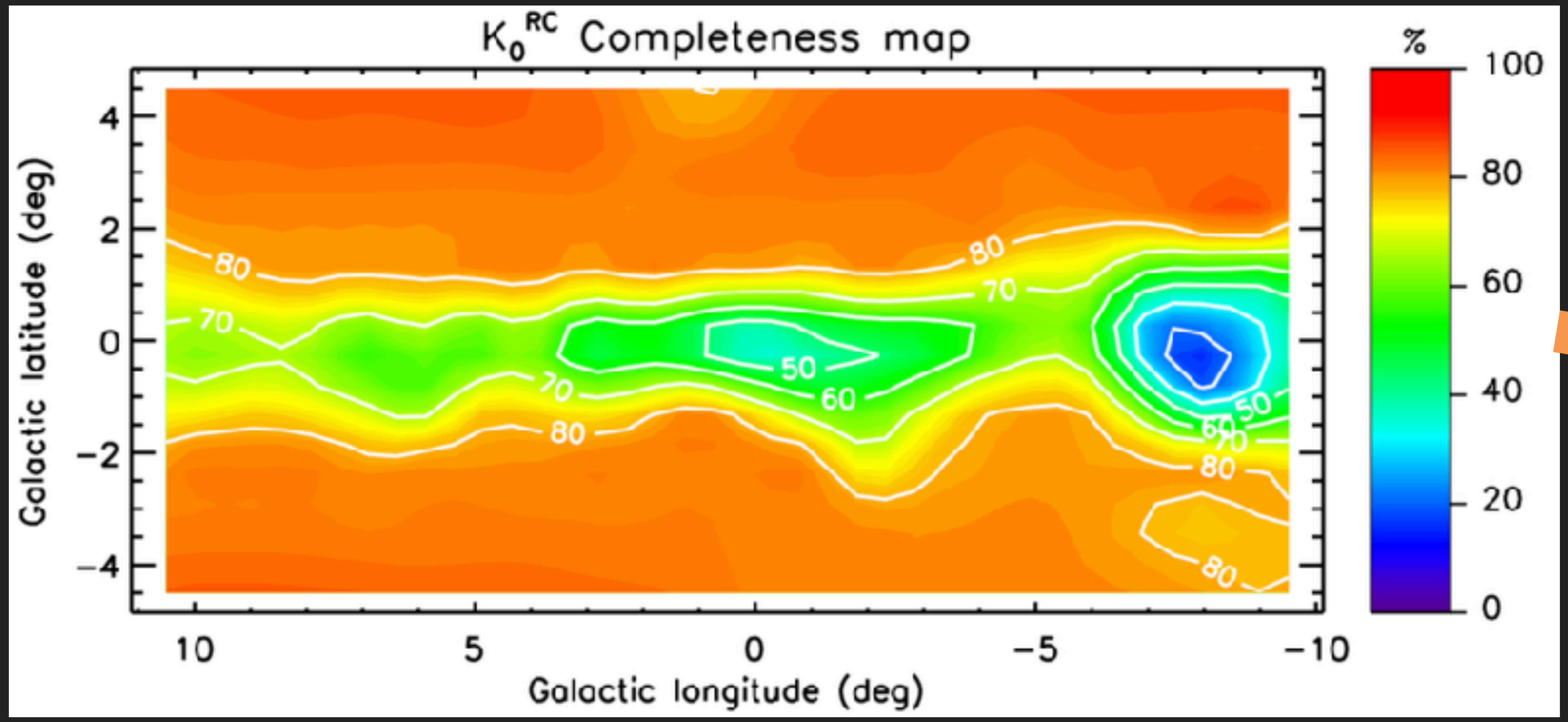


GALACTIC LONGITUDE DEPENDENCE

Navarro et al. 2018



Completeness corrections from Valenti et al. 2016



A clear excess at the Galactic Centre.

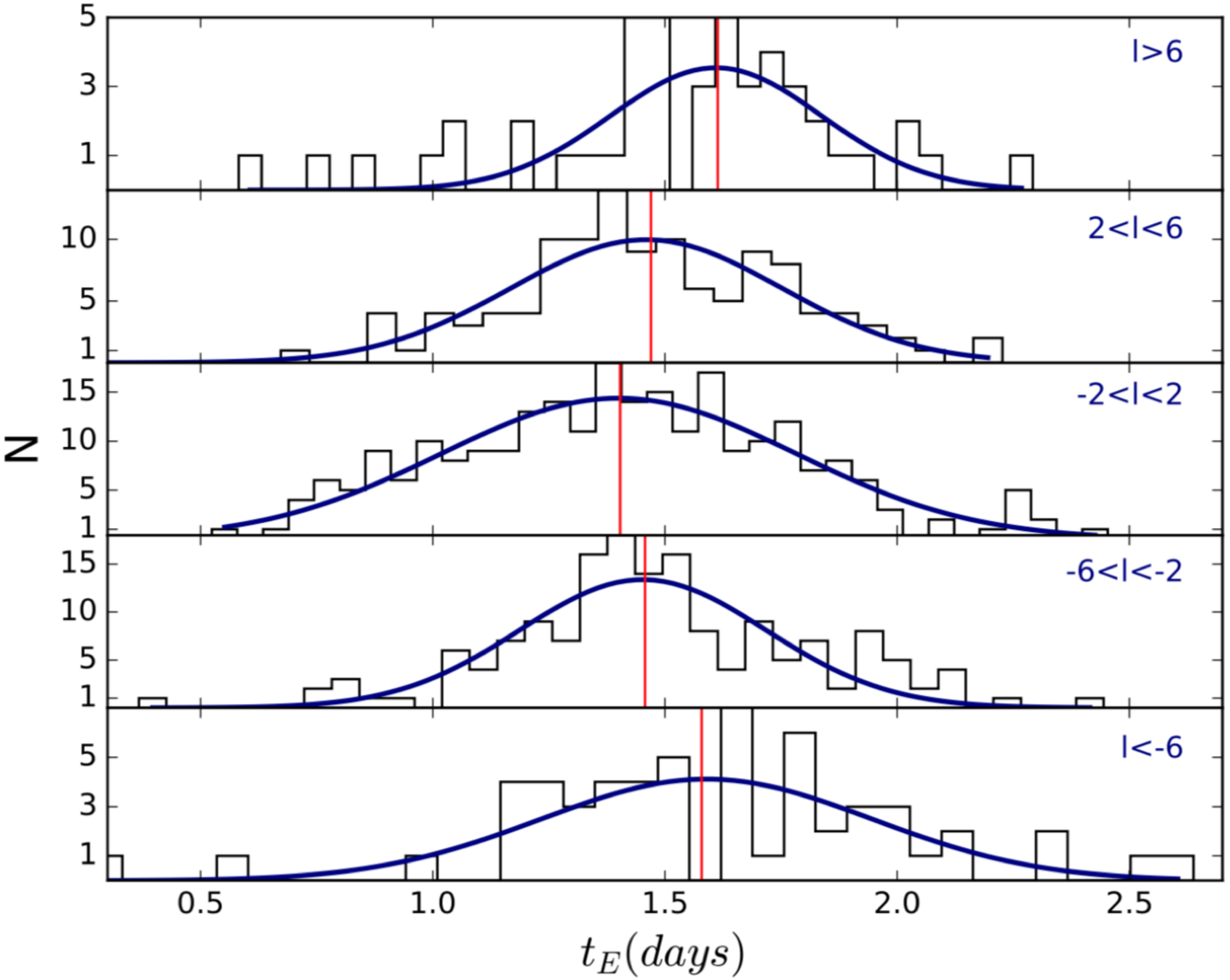
But the distribution is not symmetric.

And the distribution is not centred.

Due to the inclination of the bar?

FINAL SAMPLE

Timescale Distribution



The mean timescale changes with Galactic longitude.

There are long timescale events at all longitudes.

There are more events in the Galactic centre region.

NAVARRO ET AL. 2020B (APJ, 893, 1)

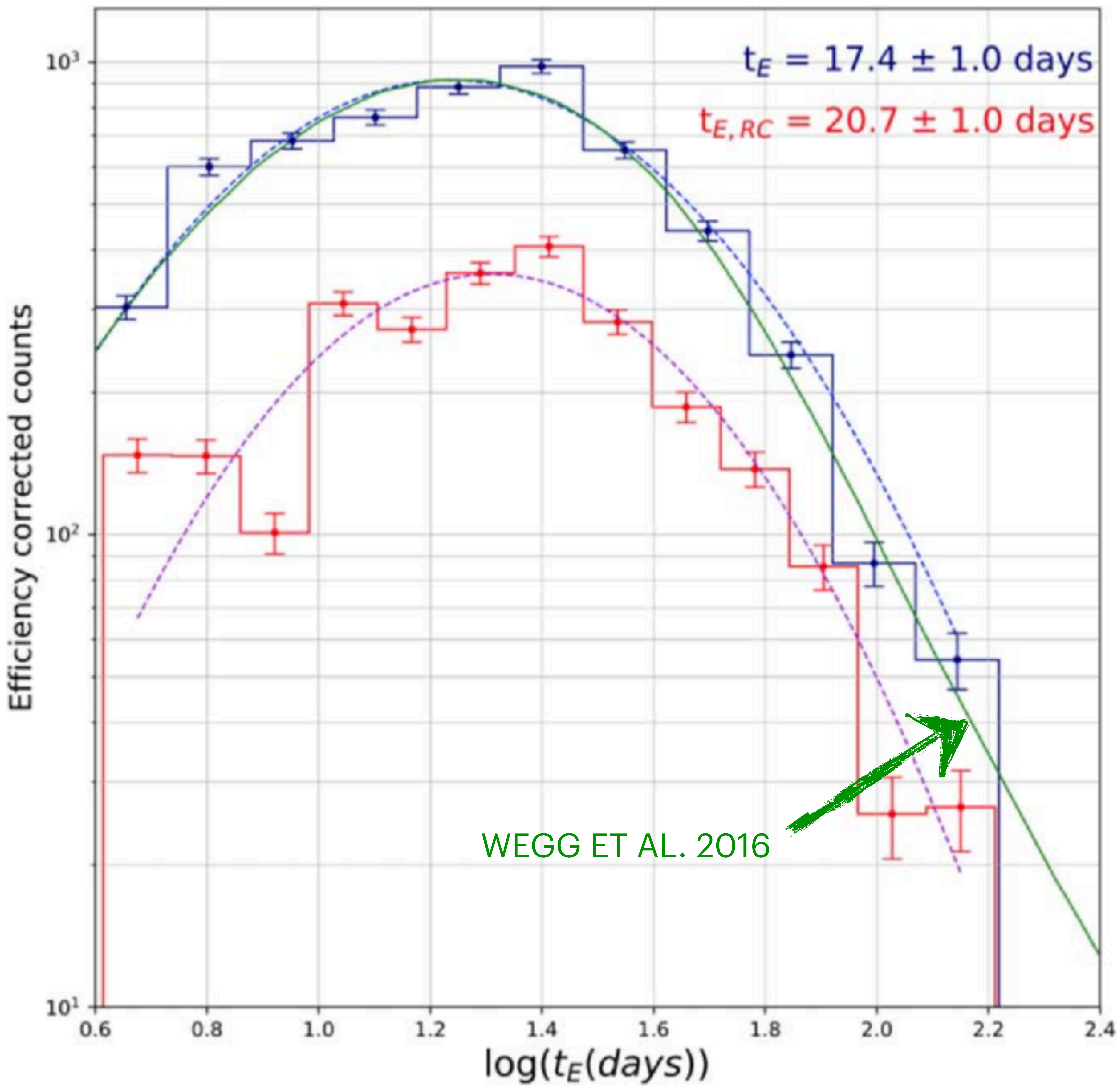
FINAL SAMPLE

Timescale Distribution

Good agreement with model predictions.

Similar RC vs total distribution.

RC events have longer mean timescales.



NAVARRO ET AL. 2020B (APJ, 893, 1)

Microlensing Events in the Far Disk

NAVARRO ET AL. 2020, APJ, IN PRESS (ARXIV 2009.06658)

VVV SURVEY MICROLENSING: CANDIDATE EVENTS WITH SOURCE IN THE FAR DISK

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Draft version September 16, 2020

ABSTRACT

The VVV microlensing search has recently surveyed the region of the Galactic plane at $b = 0$ within $-10 \leq l \leq 10.44$ deg. in the near-infrared (IR), discovering hundreds of microlensing events. In this paper we explore the microlensing events with background sources that could be located in the far disk of the Galaxy, beyond the bulge. We discuss the possible configurations for the microlensing lenses and sources located at different places within the Galactic plane. Then we search for these events using the local red clump centroids of the VVV near-IR color-magnitude diagrams and color-color diagrams. According to the estimated distances and proper motions, $N = 20$ events may have sources located in the far disk. The candidates for far-disk sources show on average longer timescales ($t_E = 49.3 \pm 7.9$ days) than the mean of the timescale distribution for the bulge red clump sources ($t_E = 36.4 \pm 1.1$ days). We conclude that the population of microlensing events in the region $-10 \leq l \leq 10.44$, $-0.46 \leq b \leq 0.65$ deg. contains a non-negligible number of events with candidate far-disk sources ($\sim 11\%$). Our results are relevant in view of the future microlensing plans with the Roman Space Telescope (formerly WFIRST) in the near-IR.


low PM sources, symmetric about l=0
Bulge — Bulge events
long t
med t
long t
Sol


low PM sources, dependent on longitude
Bulge — Disk events
med t
med t
long t
long t
Sol


low PM sources, independent of longitude
Disk — Disk events
long t
long t
long t
Sol

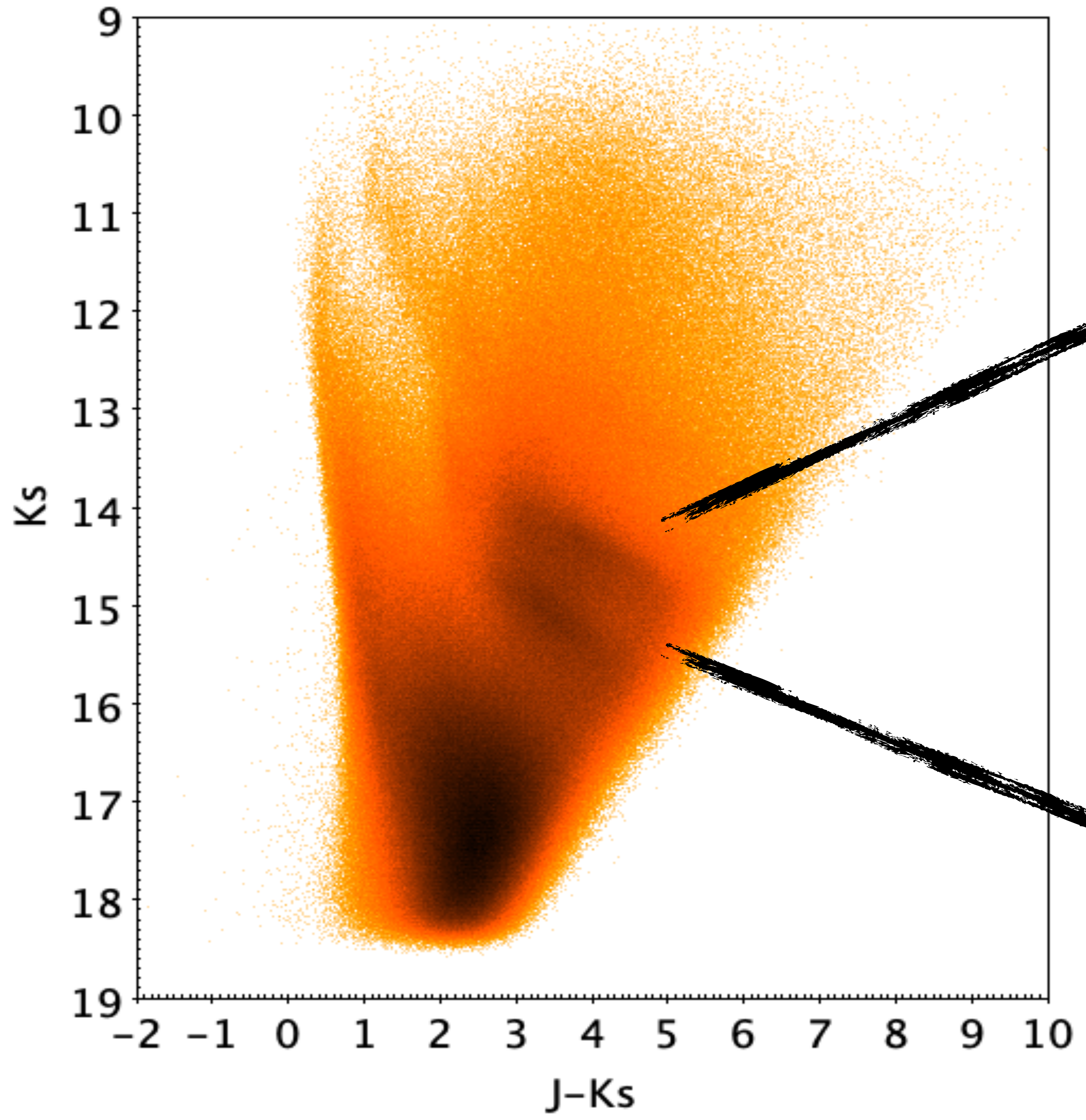

high PM sources, symmetric about l=0
long t
long t
long t
Far-Disk — Far-Disk events
Sol


high PM sources, dependent on longitude
long t
long t
med t
med t
Far-Disk — Bulge
events
Sol

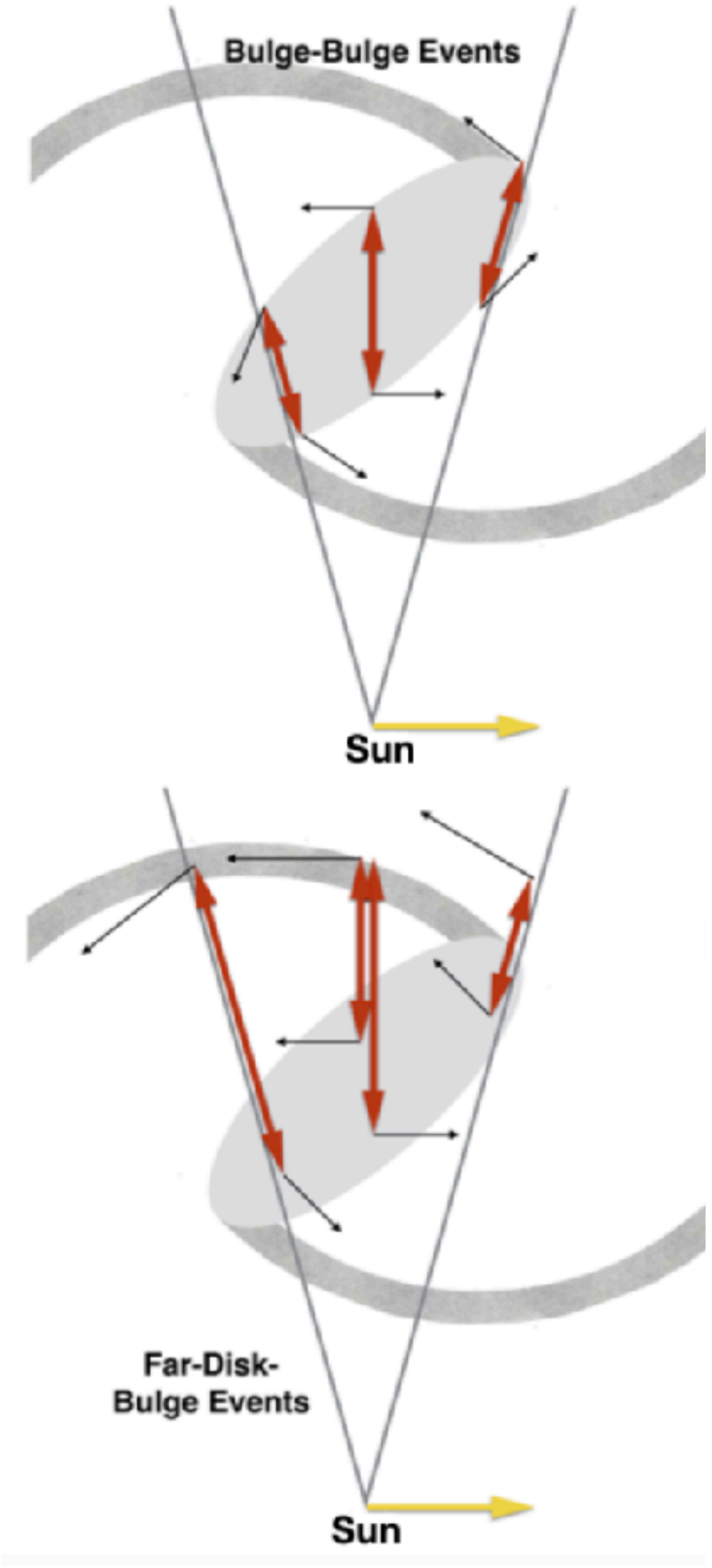

high PM sources, independent of longitude
short t
short t
short t
Far-Disk — Near Disk events
Sol

CANDIDATE EVENTS WITH A SOURCE IN THE FAR DISK

NAVARRO ET AL. 2020 APJ IN PRESS
(ARXIV 2009.06658)



COLOR MAGNITUDE DIAGRAM

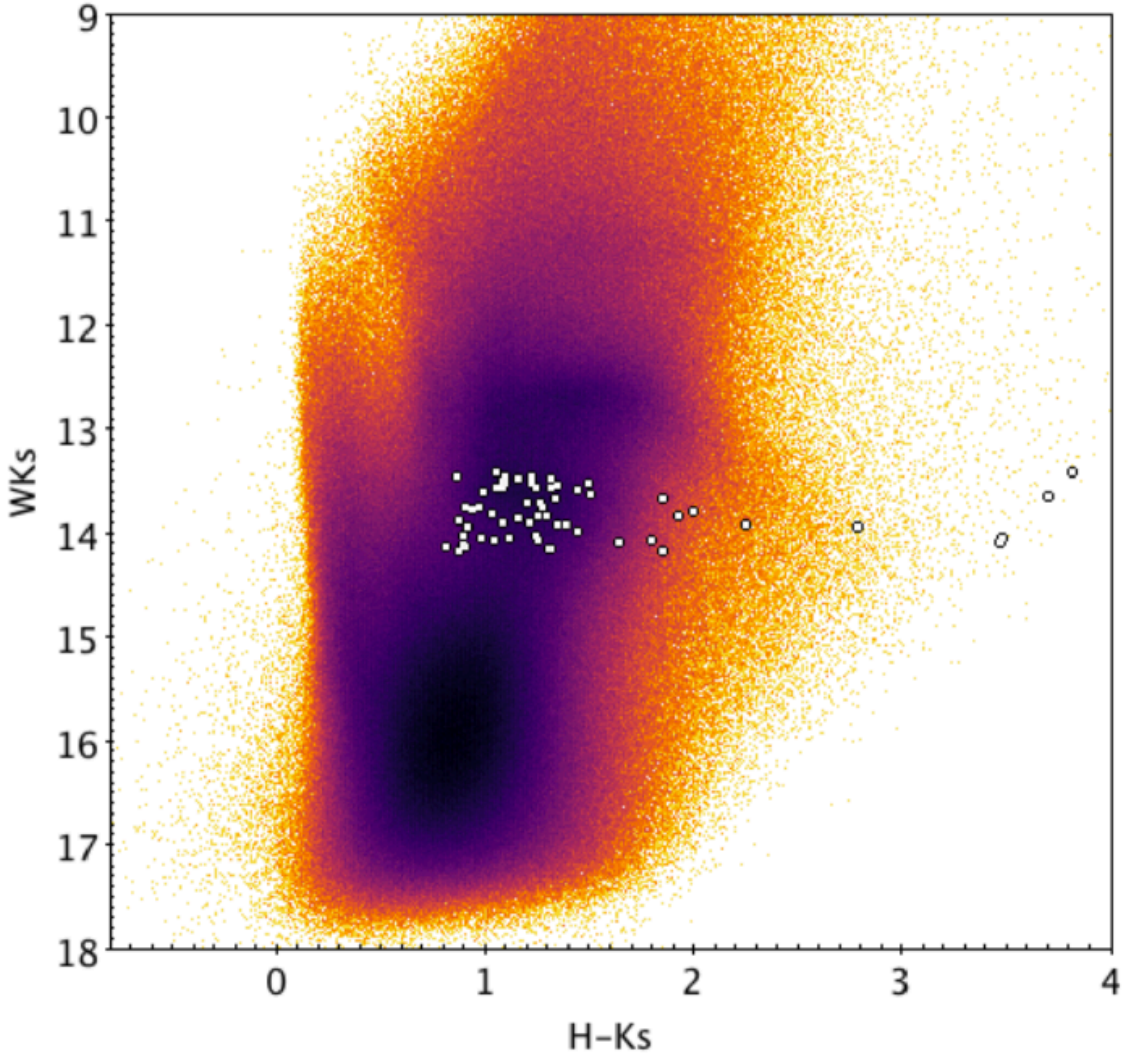


VVV PSF PHOTOMETRY FROM CONTRERAS RAMOS ET AL. 2017

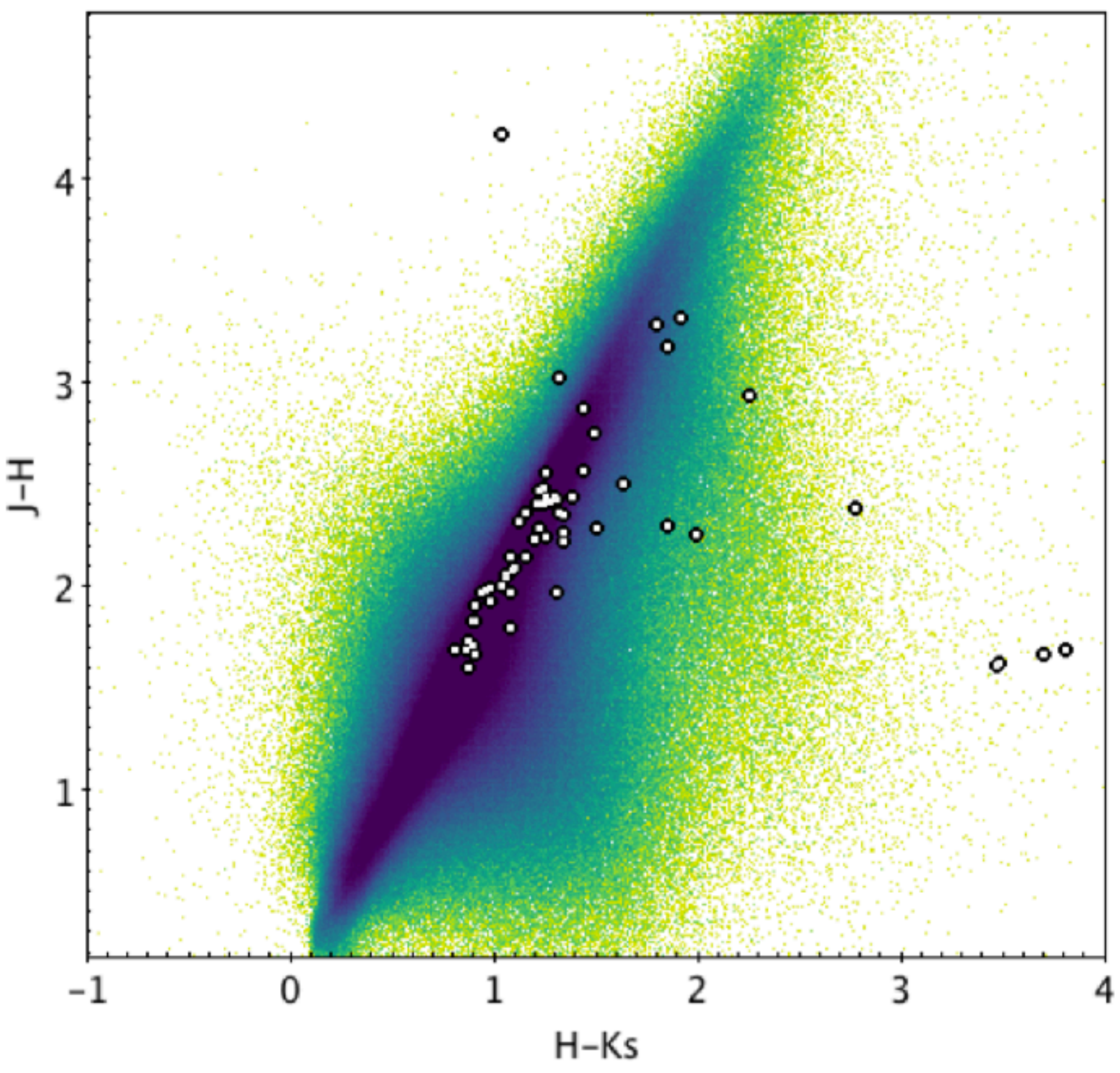
CANDIDATE EVENTS WITH A SOURCE IN THE FAR DISK

NAVARRO ET AL. 2020 APJ IN PRESS
(ARXIV 2009.06658)

Select Distant (D >12 kpc) Red Clump giants



COLOR MAGNITUDE DIAGRAM

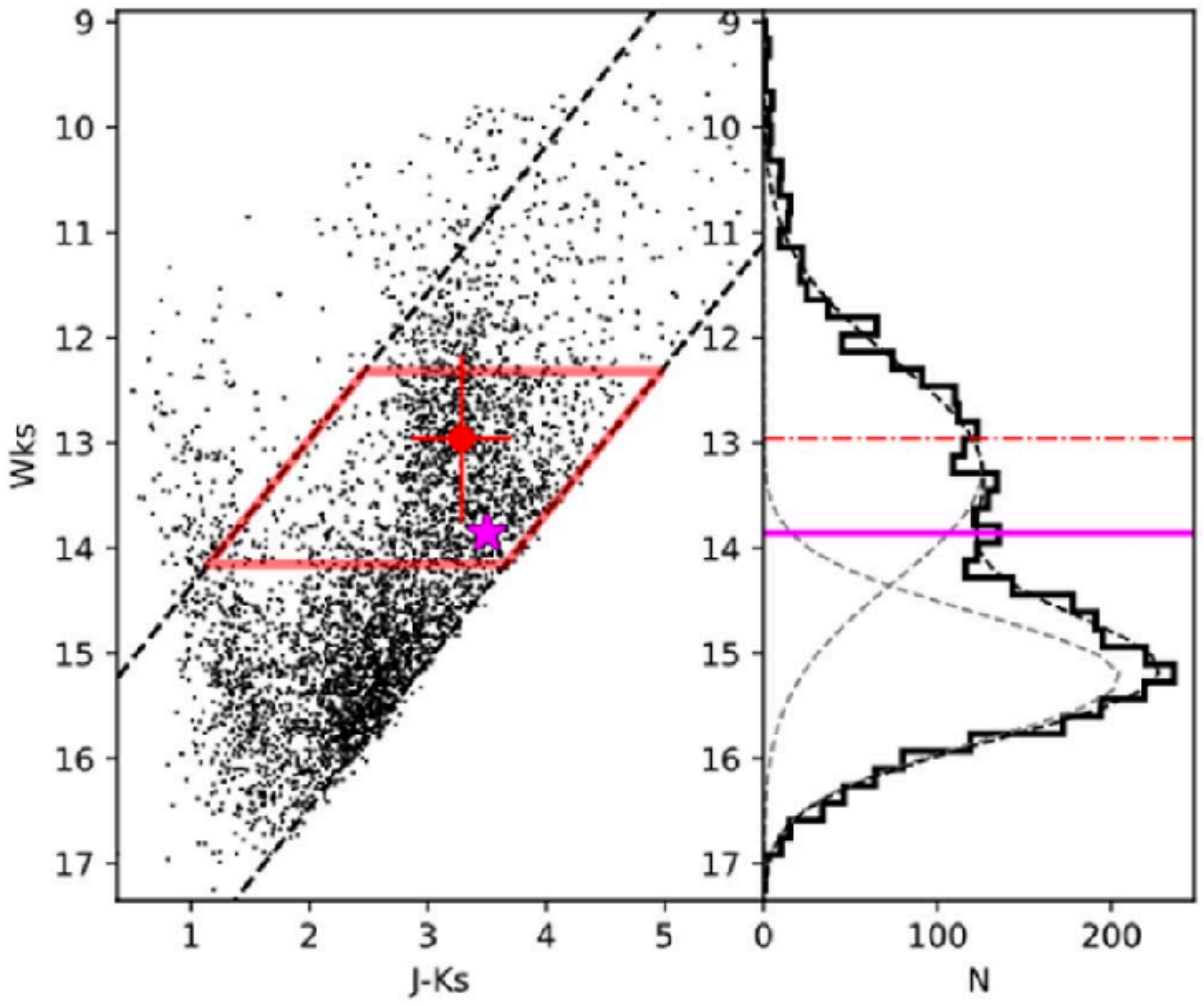


COLOR COLOR DIAGRAM

VVV PSF PHOTOMETRY FROM CONTRERAS RAMOS ET AL. 2017

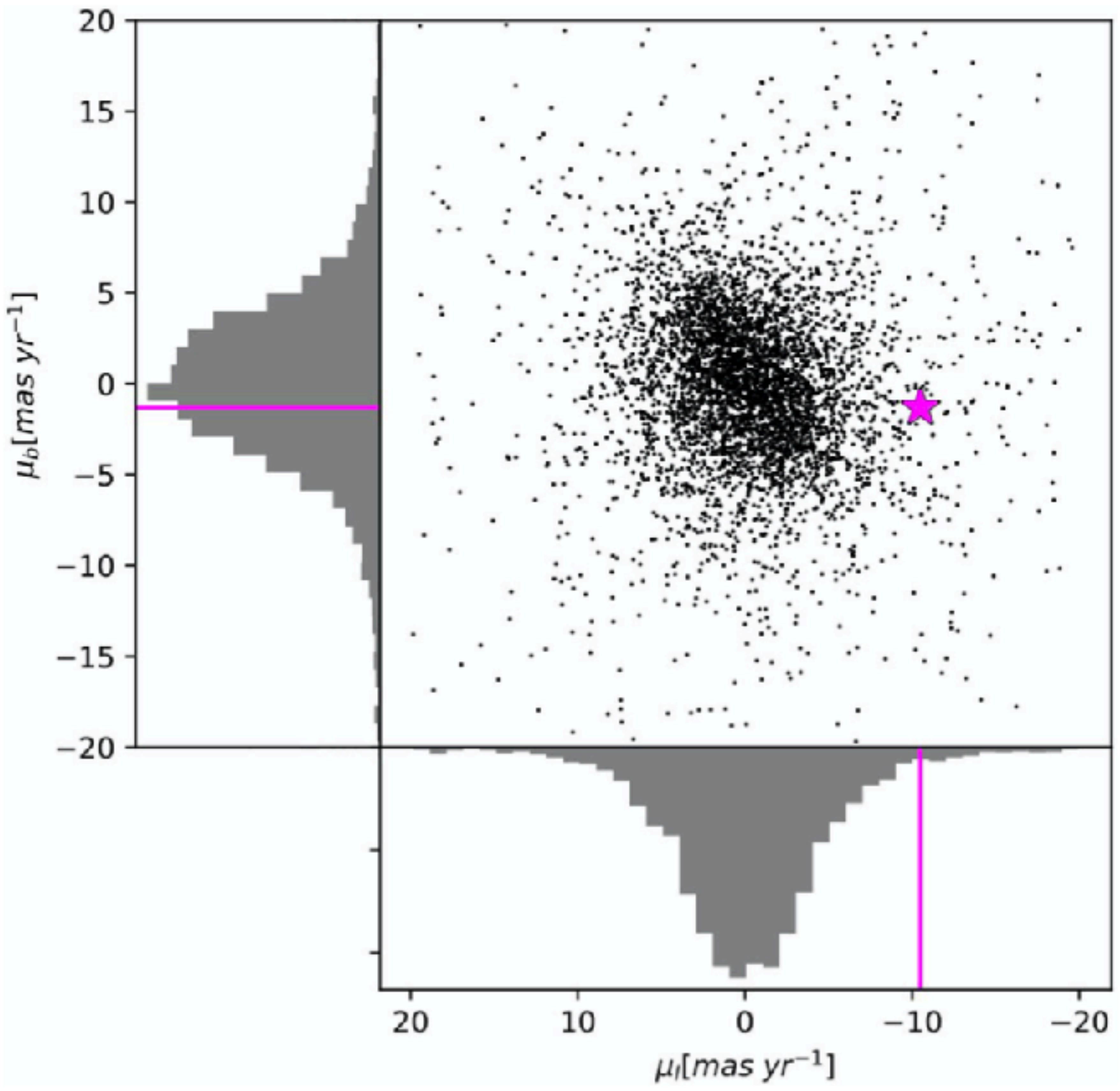
CANDIDATE EVENTS WITH A SOURCE IN THE FAR DISK

NAVARRO ET AL. 2020 APJ IN PRESS
(ARXIV 2009.06658)



20 Candidates confirmed with PMs

VPM DIAGRAM

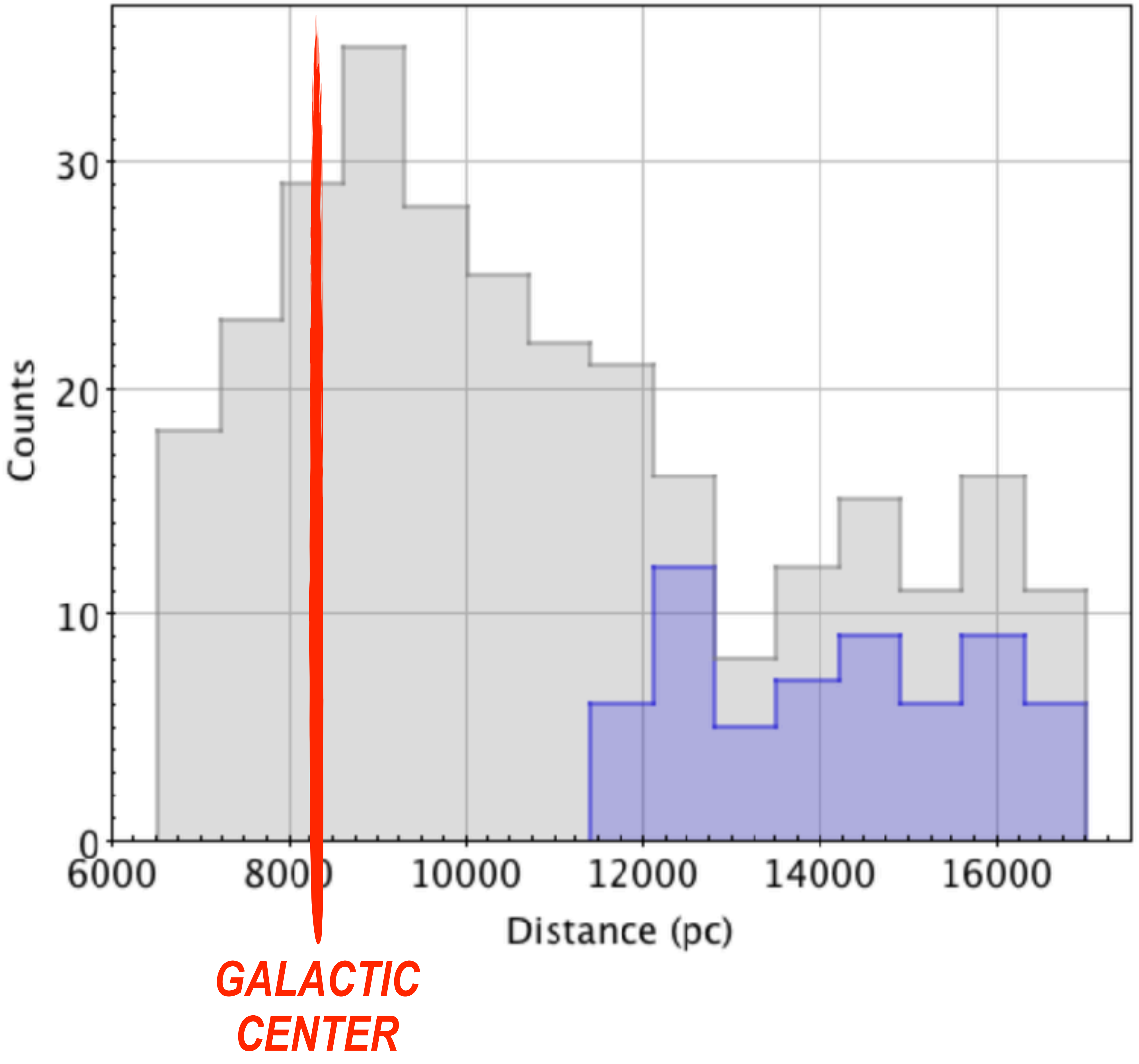


VVV PROPER MOTIONS FROM CONTRERAS RAMOS ET AL. 2017

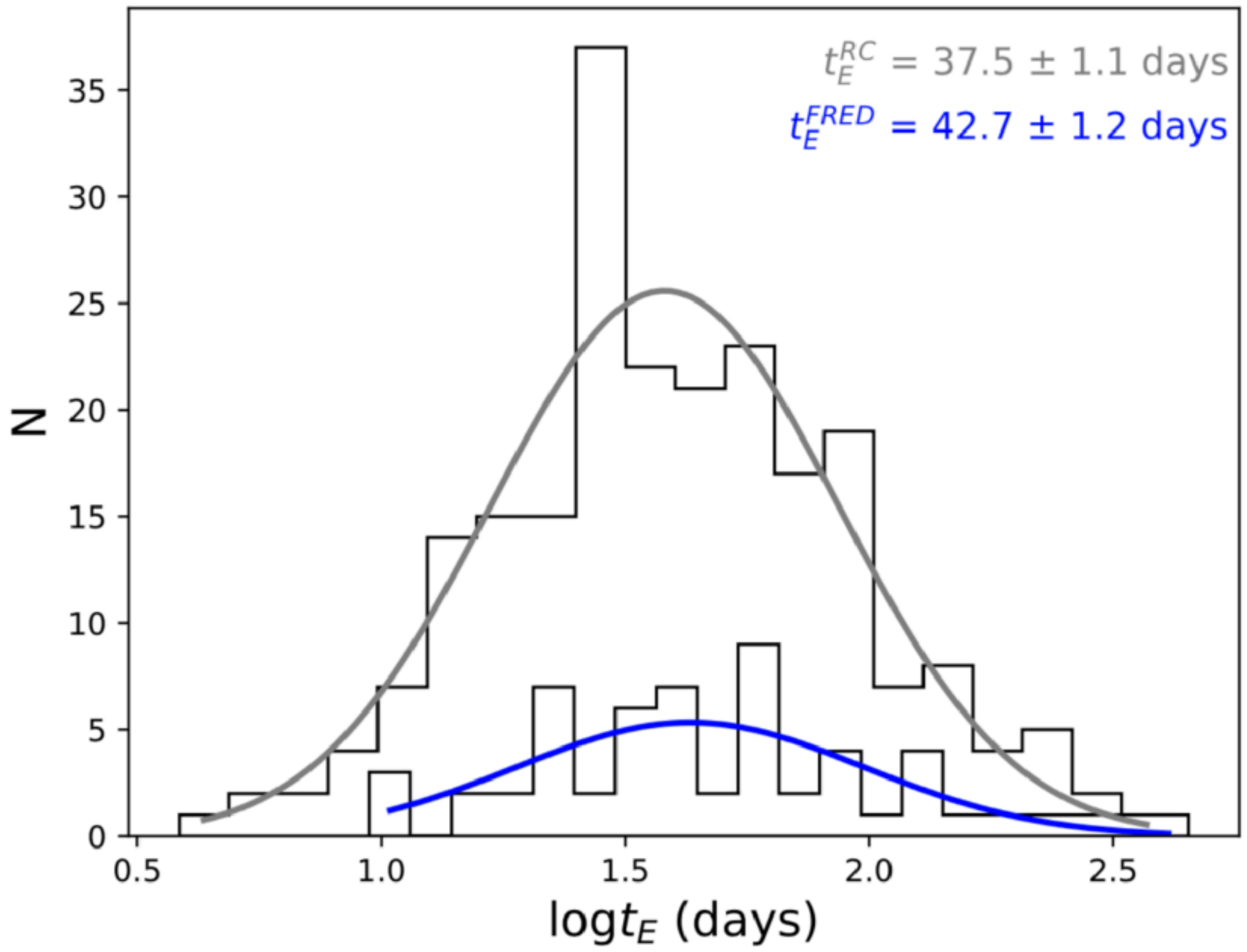
CANDIDATE EVENTS WITH A SOURCE IN THE FAR DISK

NAVARRO ET AL. 2020 APJ IN PRESS
(ARXIV 2009.06658)

DISTANCE DISTRIBUTION



TIMESCALE DISTRIBUTION



The Galactic Latitude Dependence

VVV SURVEY MICROLENSING: THE GALACTIC LATITUDE DEPENDENCE

MARÍA GABRIELA NAVARRO [1,2,3,*] DANTE MINNITI [1,3,4] JOYCE PULLEN [3] RODRIGO CONTRERAS RAMOS [3,5]
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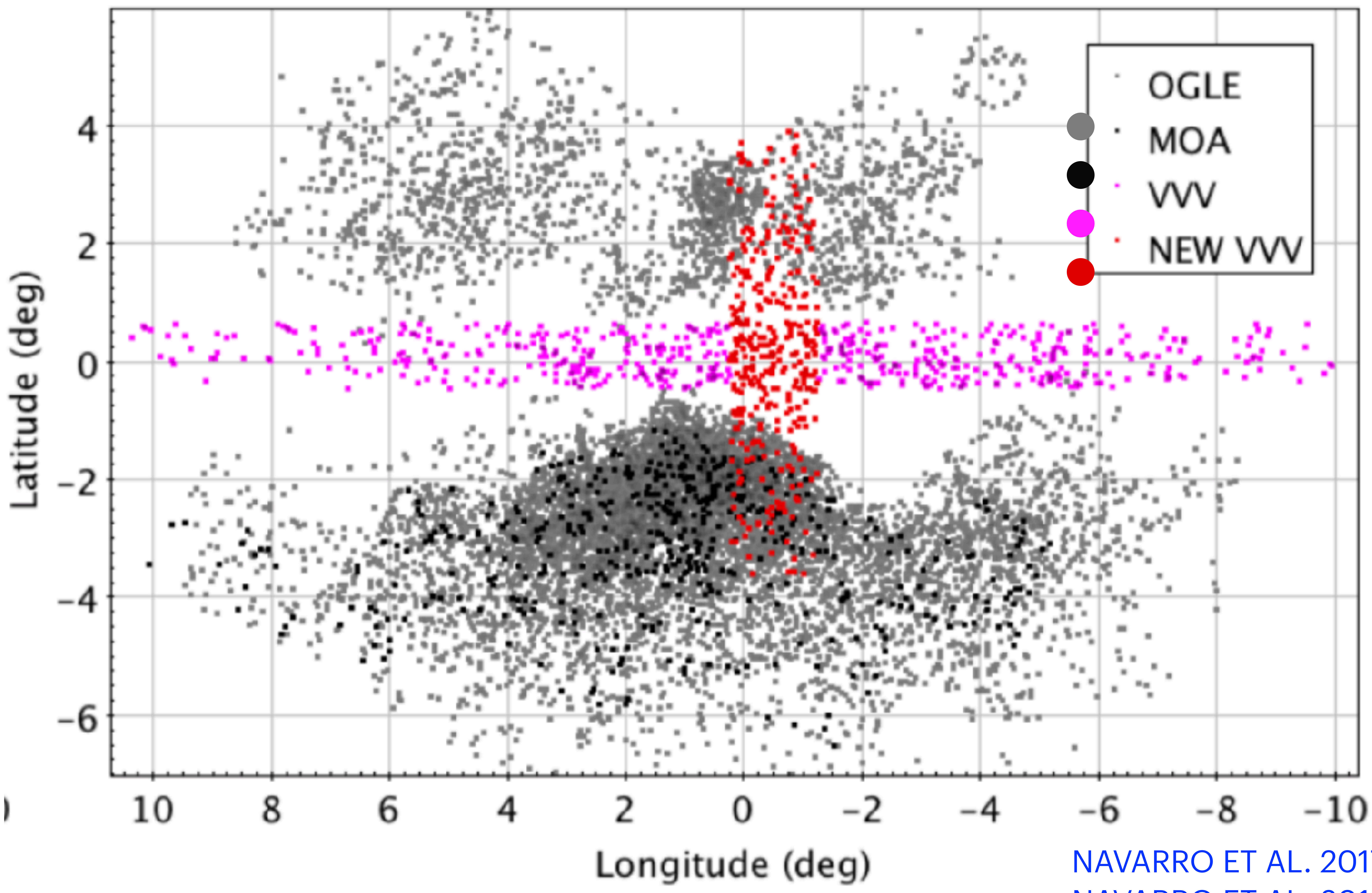
Dipartimento di Fisica, Università di Roma La Sapienza, P.le Aldo Moro, 2, I00185 Rome, Italy
Millennium Institute of Astrophysics, Av. Vicuna Mackenna 4860, 782-0436, Santiago, Chile
Vatican Observatory, V00120 Vatican City State, Italy and
Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuna Mackenna 4860, 782-0436 Macul, Santiago, Chile
Not to appear in Nonlearned J., 45.

ABSTRACT

We search for microlensing events in fields along the Galactic minor axis, ranging from the Galactic center to $-3.7 < b < 3.9$ deg., using the VVV survey near-IR photometry. The new search is made across VVV tiles $b291$, $b305$, $b319$, $b347$, $b361$ and $b375$, covering a total area of about 11.5 deg.^{2}. We find a total of $N = 238$ new microlensing events in this new area, $N = 74$ of which are classified as bulge red clump (RC) giant sources. Combining them with $N = 122$ events that we had previously reported in the Galactic center (VVV tile $b333$), allows us to study the latitude distribution of the microlensing events reaching the Galactic plane at $b = 0^0$ for the first time. We find a very strong dependence of the number of microlensing events with Galactic latitude, number that increases rapidly towards the Galactic center by one order of magnitude from $|b| = 2$ deg. to $b = 0$ deg. with a much steeper gradient than with Galactic longitude. The microlensing event population shows a flattened distribution (axial ratio $b/a \approx 1.5$). The final sample shows a shorter mean timescale distribution than the Galactic plane sample for both, the complete population and RC stars.

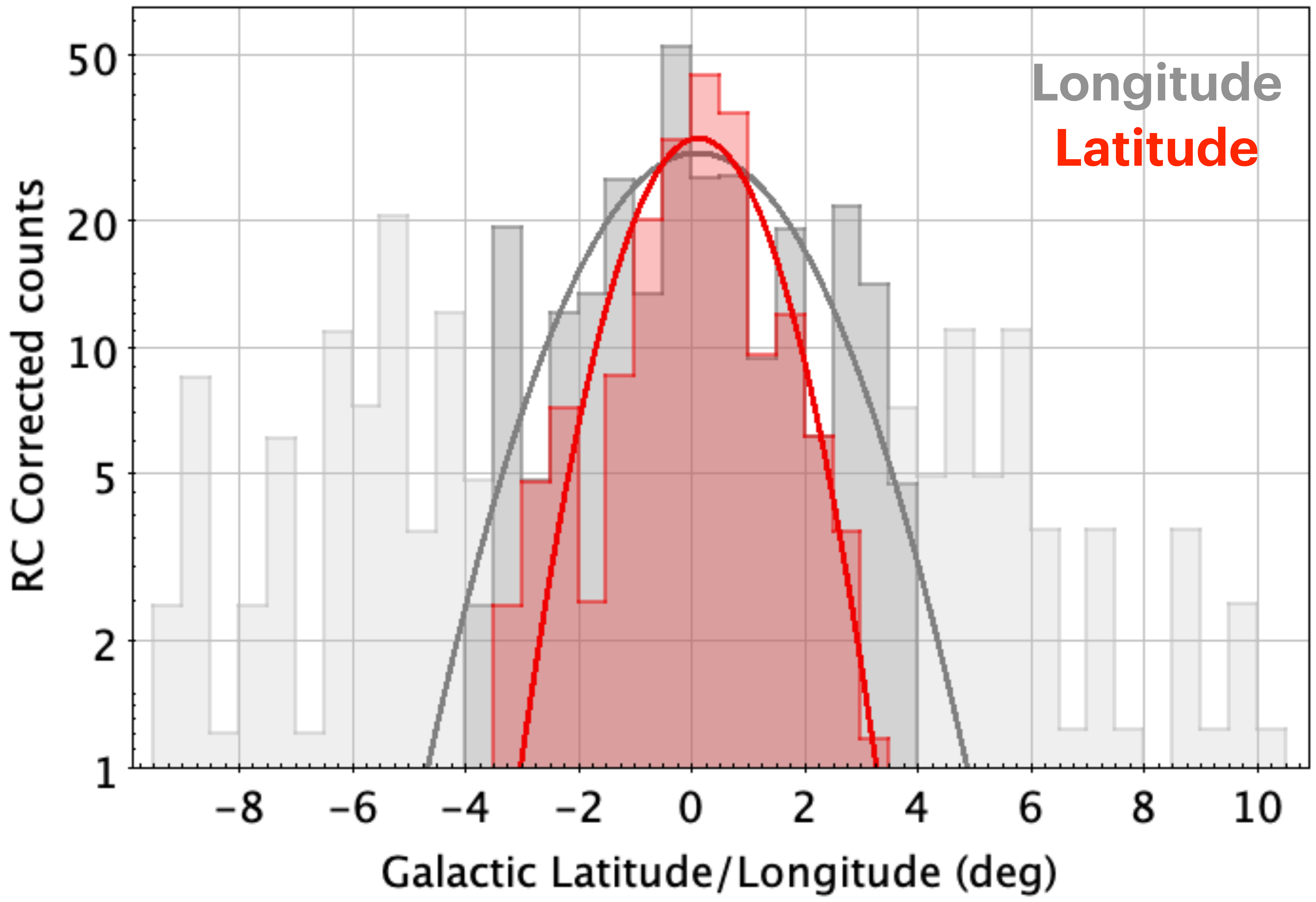
THE GALACTIC LATITUDE DEPENDENCE



868 VVV microlensing events in total

NAVARRO ET AL. 2017 (APJ, 851, L13)
NAVARRO ET AL. 2018 (APJ, 865, L5)
NAVARRO ET AL. 2020A (APJ, 889, 56)
NAVARRO ET AL. 2020B (APJ, 893, 1)
NAVARRO ET AL- 2020C (APJ, IN PRESS)

THE GALACTIC LATITUDE DEPENDENCE



FWHM = 4.32 deg. FWHM = 2.82 deg. ——-> Axial ratio b/a ≈ 1.5

NAVARRO ET AL. 2020A (APJ, 889, 56)

BH Search and Other Results

NAVARRO ET AL. 2020, APJ, 893, 1

Forsaken events

1955 NEW FORSAKEN MICROLENSING EVENTS

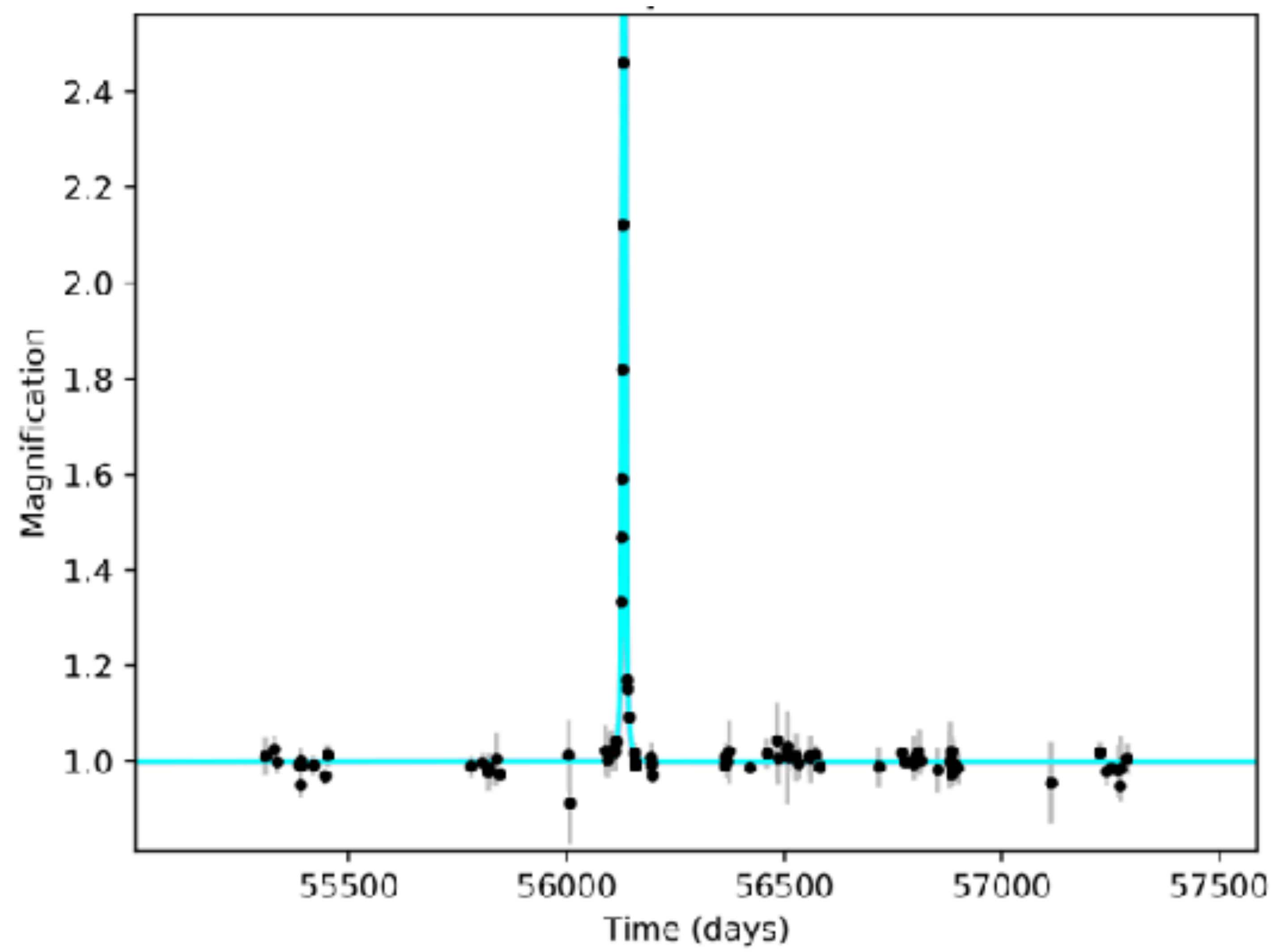
- Binary light curves
- Parallax events (BHs?)
- Free floating planets

OTHER RESULTS

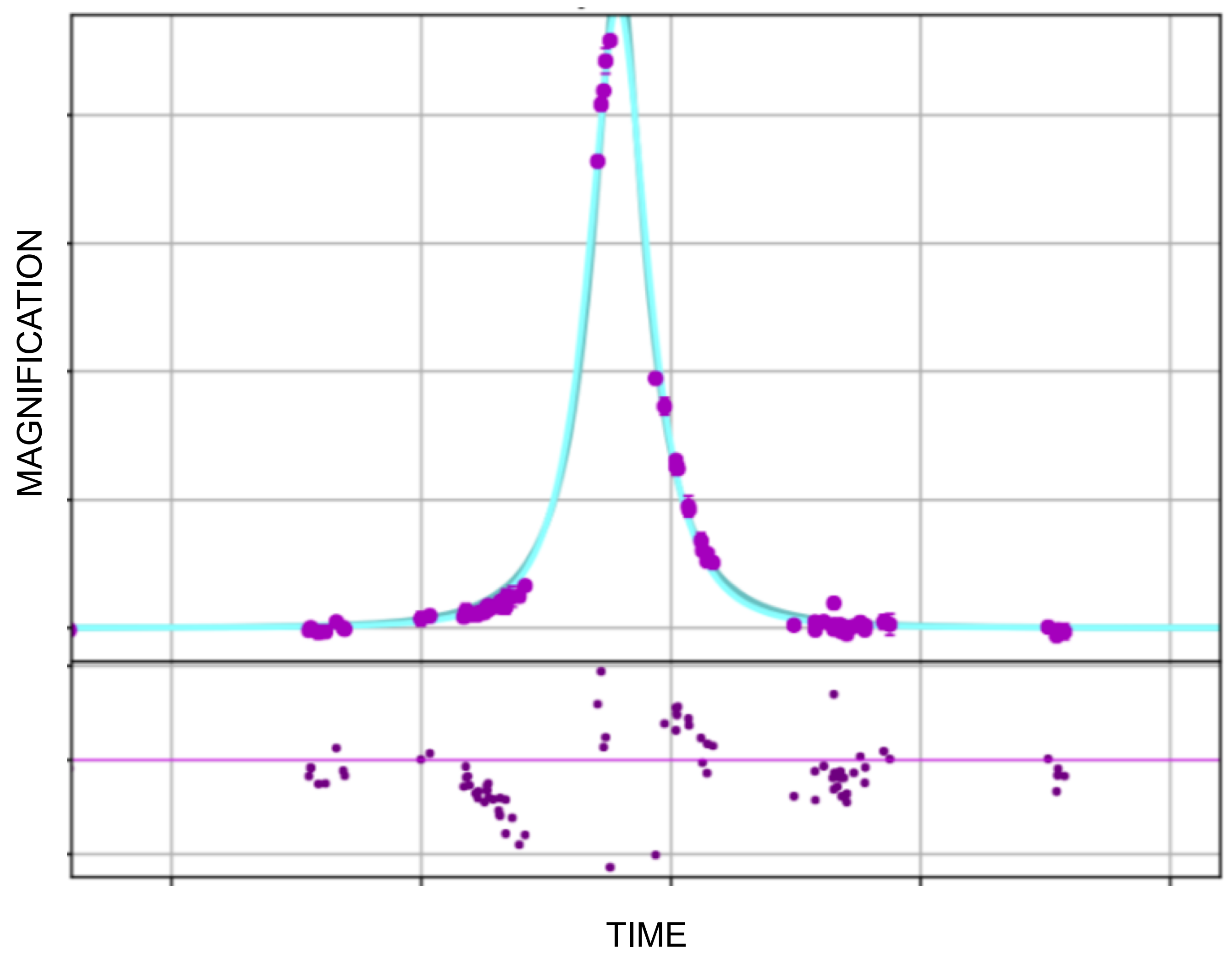
Forsaken events

~ 2,000 forsaken events

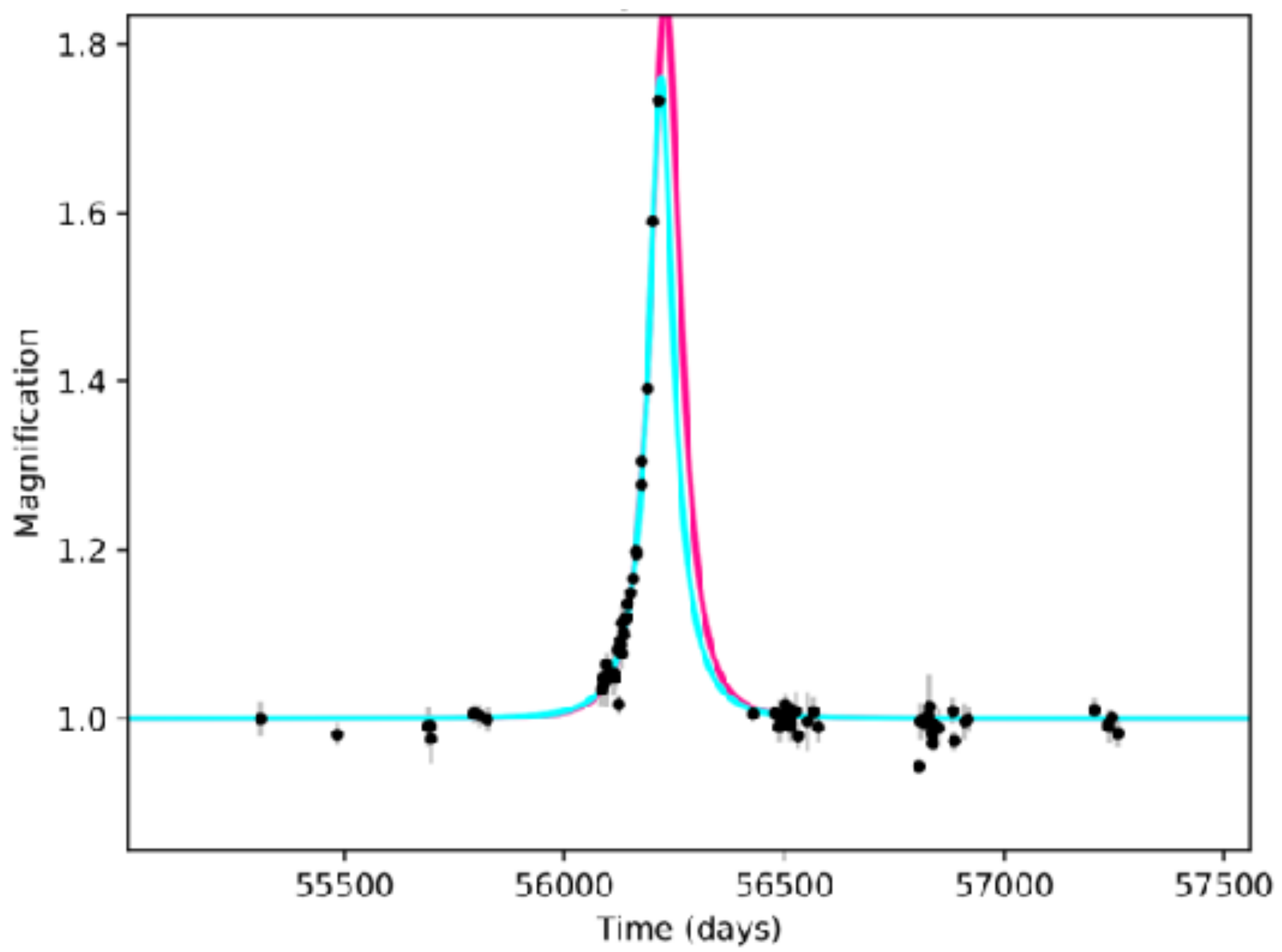
SHORT TIMESCALE



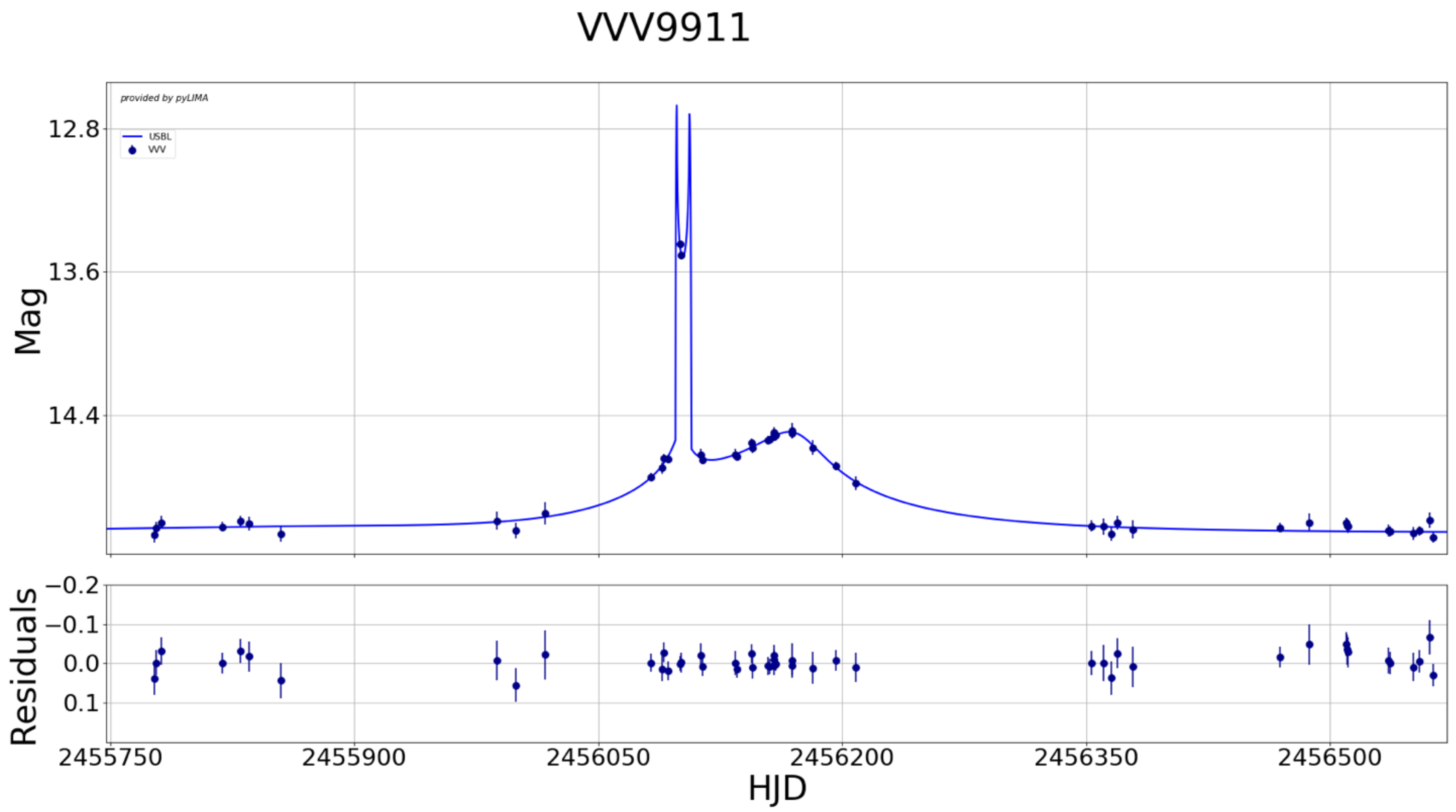
PARALLAX EFFECT



INCOMPLETE

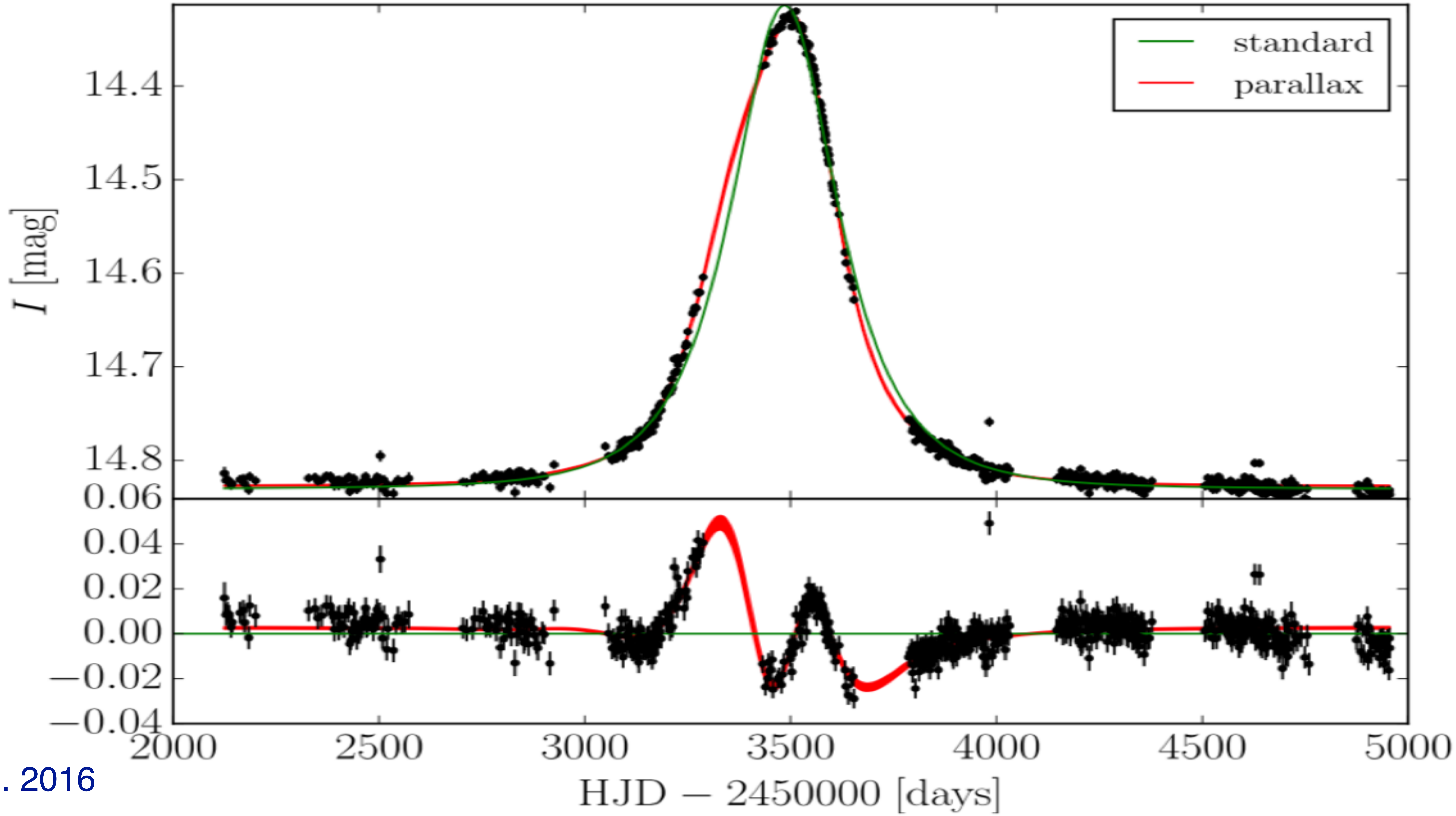


BINARIES



Parallax effect (also Xallarap)

Long timescale microlensing events often show the parallax effect.
This effect allows to constrain the lens mass and distance.



Wyrzykowski et al. 2016

Parallax effect (also Xallarap)

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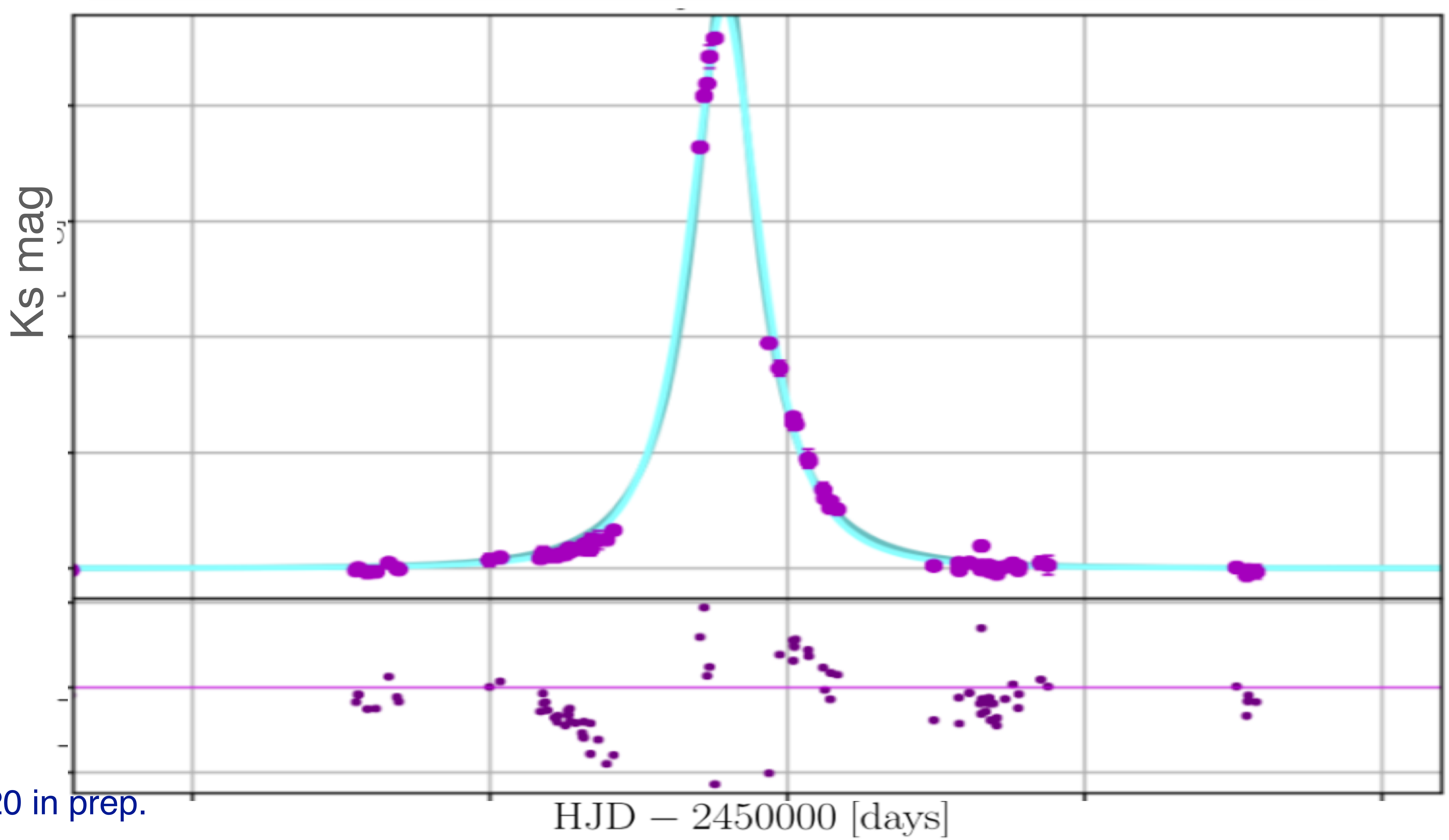
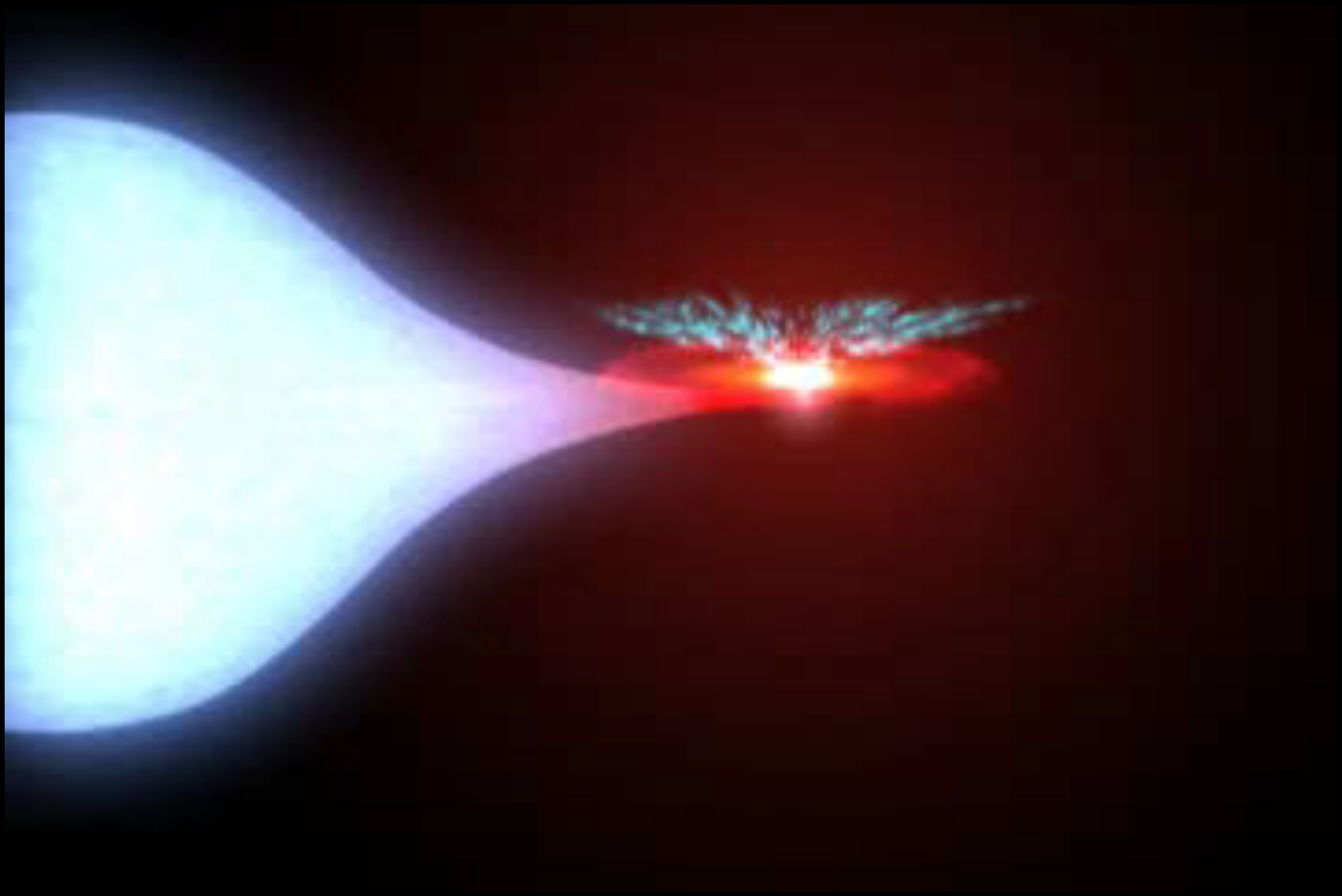
This effect allows to constrain the lens mass and distance.



Navarro et al. 2020 in prep.

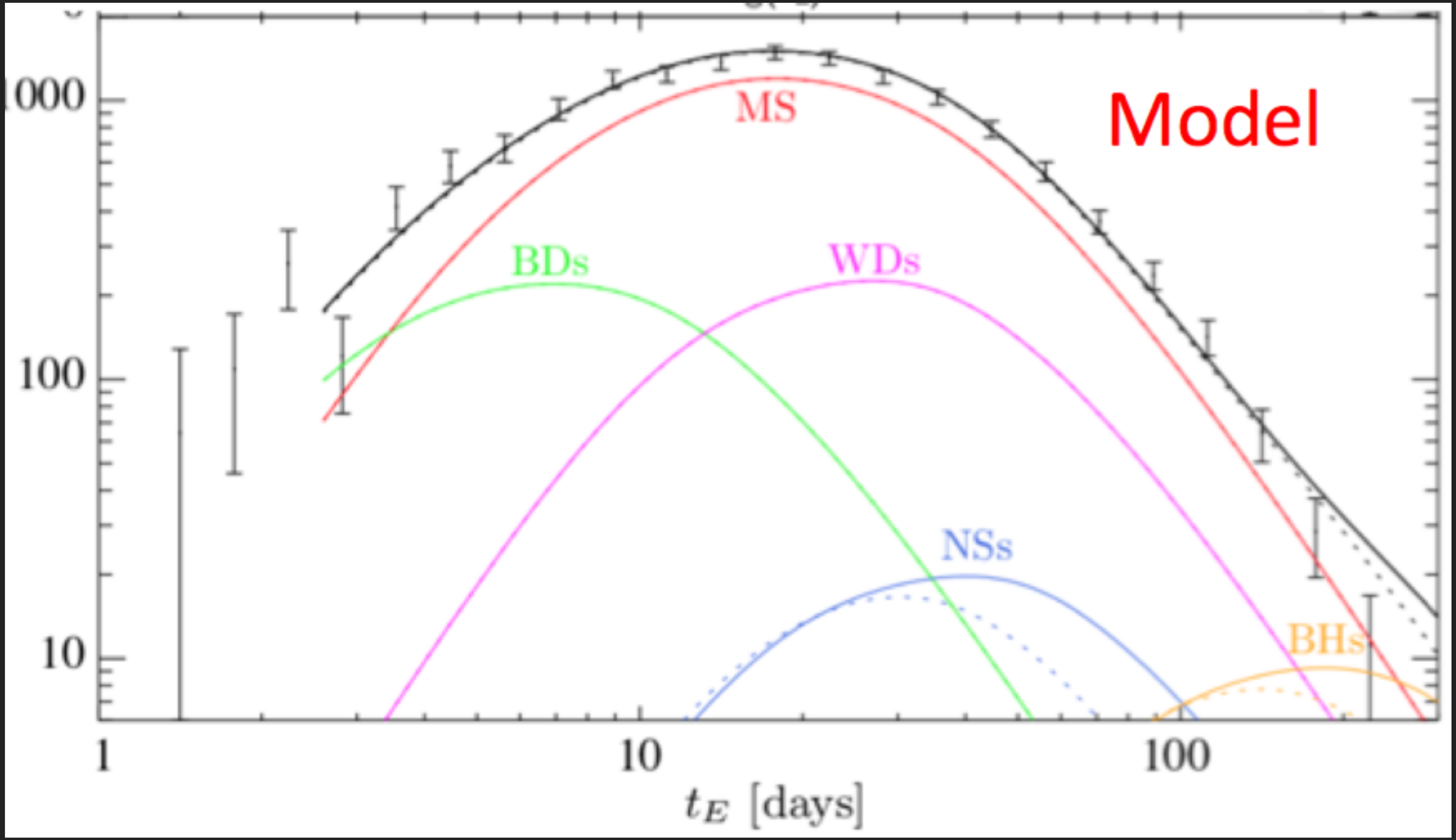
Black Holes

BHs can be detected in binaries.



Isolated BHs are much harder to detect:
long timescale microlensing events

TIMESCALE DISTRIBUTION



The models predict a small contribution from stellar mass BHs (Wegg et al. 2013)

LONG TIMESCALE EVENTS

Navarro et al., ApJ 2020

The distribution of long timescale (T >100 days) microlensing events is very concentrated towards the Galactic center.
We have also detected a couple of very long (T >2 yr) events.
This is very exhiting!!!

Problems:
- unknown distances and relative velocities
- longer term monitoring needed in order to have enough baseline to discard the long period variables

SUMMARY

- **868 new** microlensing events ✓
- Asymmetry in the distribution ✓
- Excess at the Galactic Centre ✓
- Long timescale events – isolated BH searches ✗
- **1955 new** forsaken events: some candidates for binary and parallax ✗
- Short timescale events – exoplanet searches ✗

FUTURE WORK

We still have a lot of Galaxy to cover!

Microlensing Search for Extrasolar Planets

VVV Microlensing:

Search for Exoplanets, including Free Floating Planets and Exomoons

Extrasolar Planets

Advantages of the gravitational microlensing method for the exoplanet searches:

- detection of free floating planets.

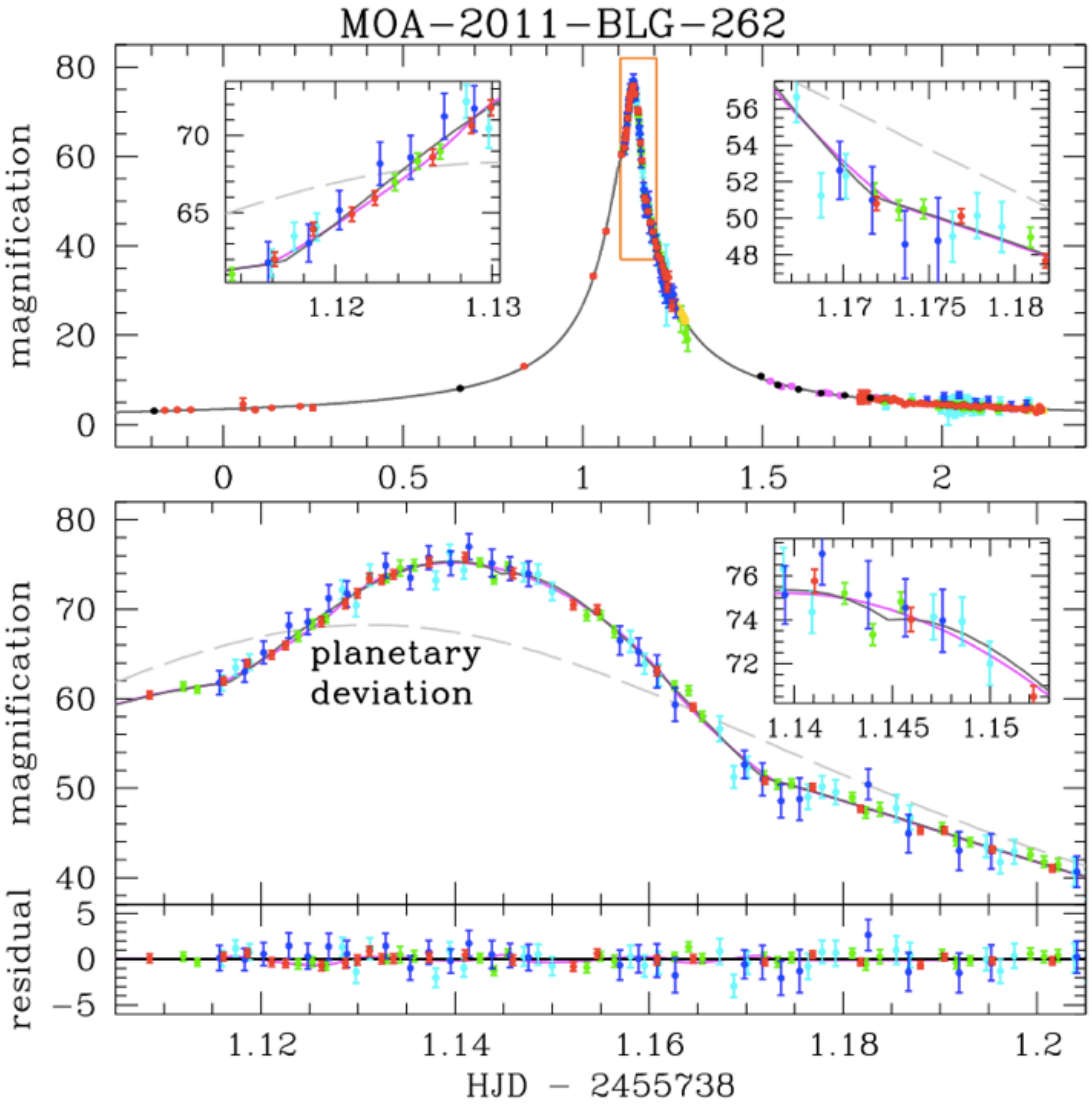
- detection of very long period massive planets, beyong the snow line

- discovery of Earth-mass planets in the habitable zone of Solar type stars
- detection of exomoons

- detection of planets in very distant stars (including other galaxies)

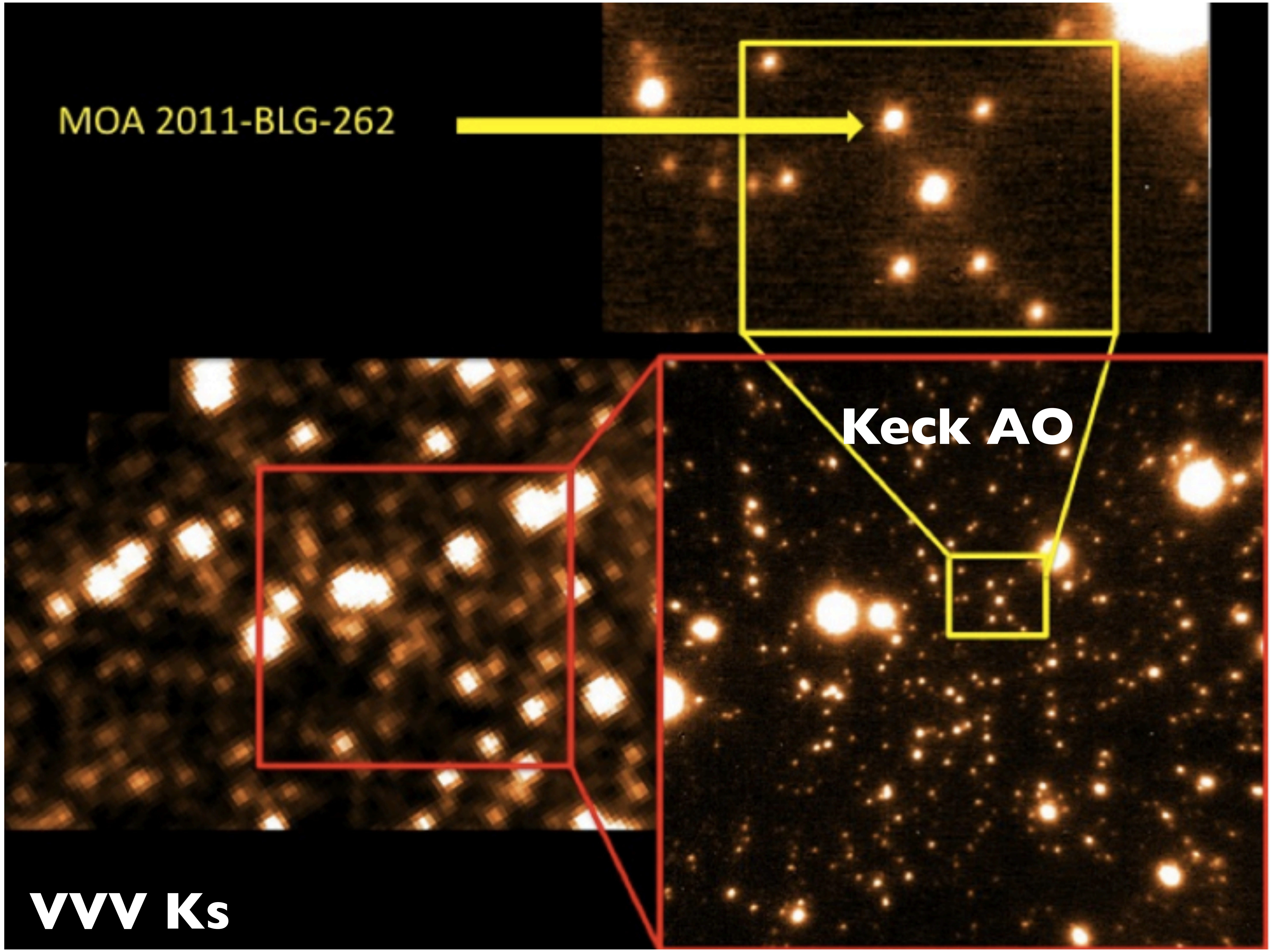
Two possible fits:

MOA-2011-BLG-262Lb:
A Sub-Earth-Mass Moon
Orbiting a Gas Giant
Primary
or
A High Velocity Planetary
System in the Galactic
Bulge



D. Bennett et al. (2014, ApJ, 785, 155)

MOA-2011-BLG-262Lb: A Sub-Earth-Mass Moon Orbiting a Gas Giant Primary or A High Velocity Planetary System in the Galactic Bulge



The VVV data was used to calibrate the Keck AO photometry in order to constrain the lens parameters.

D. Bennett et al. (2014, ApJ, 785, 155)

Two possible fits:

A free-floating exoplanet-exomoon system:
ML = 3.2MJup orbited by a moon of Mm = 0.47M⊕ separated by a = 0.13AU, with the lens system at a distance of DL = 0.56kpc.

or

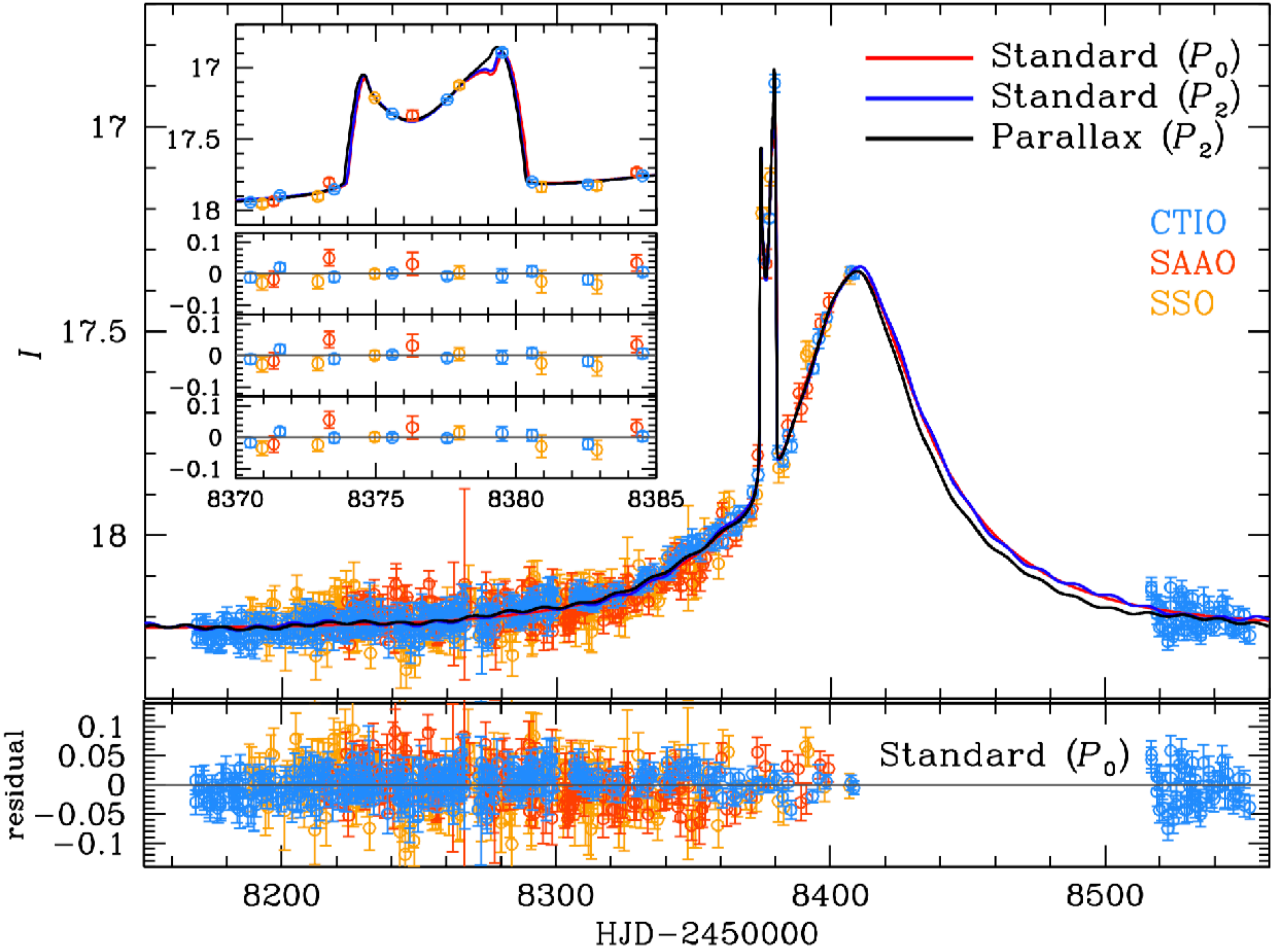
A high velocity planetary system in the bulge:
A star with ML = 0.11+0.21M⊙ orbited by a planet of mass Mp = 17+28M⊕ separated by a = 0.95 AU at a distance of DL = 7.2 kpc.

KMT-2018-BLG-1292: A Super-Jovian Microlens Planet in the Galactic Plane

Mp=4.5Mj

RYU, NAVARRO ET AL. 2019 (APJ, 159, 2)

KMT-2018-BLG-1292 fit:
A Super-Jovian planet with
Mplanet = 4.5 ± 1.3 MJ
orbiting a F/G dwarf star
Mhost = 1.5 ± 0.4 M⊙
with period P = 62 days
(not in the habitable zone).



KMT-2018-BLG-1292: A Super-Jovian Microlens Planet in the Galactic Plane

RYU, NAVARRO ET AL. 2019 (APJ, 159, 2)

KMT-2018-BLG-1292
The microlensing extrasolar planet located closest to the Galactic midplane (z~-10pc).

The microlensing planet searches can be extended right to the Galactic plane. Look out for the Nancy Roman Space Telescope (a.k.a. WFIRST)!!!

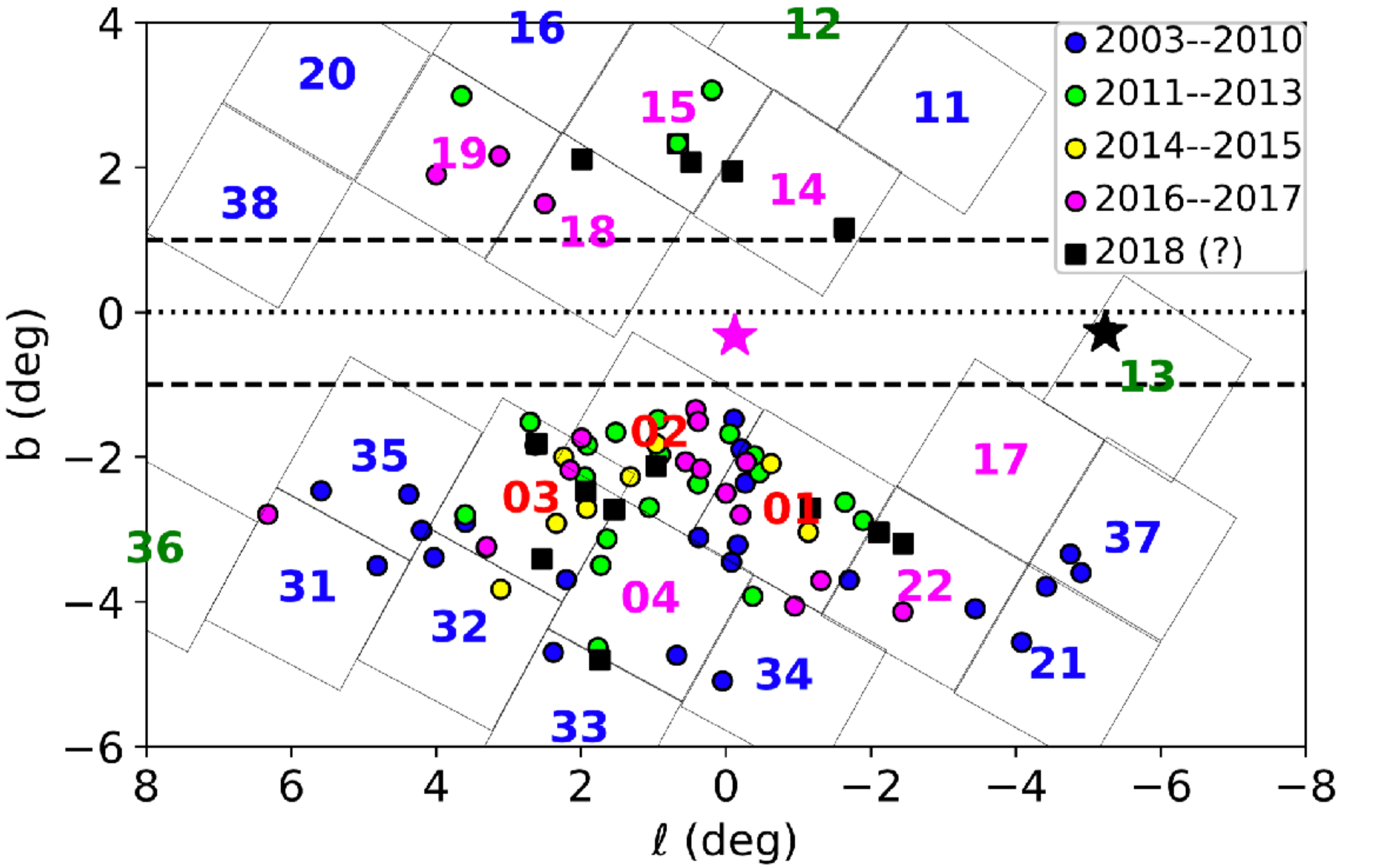
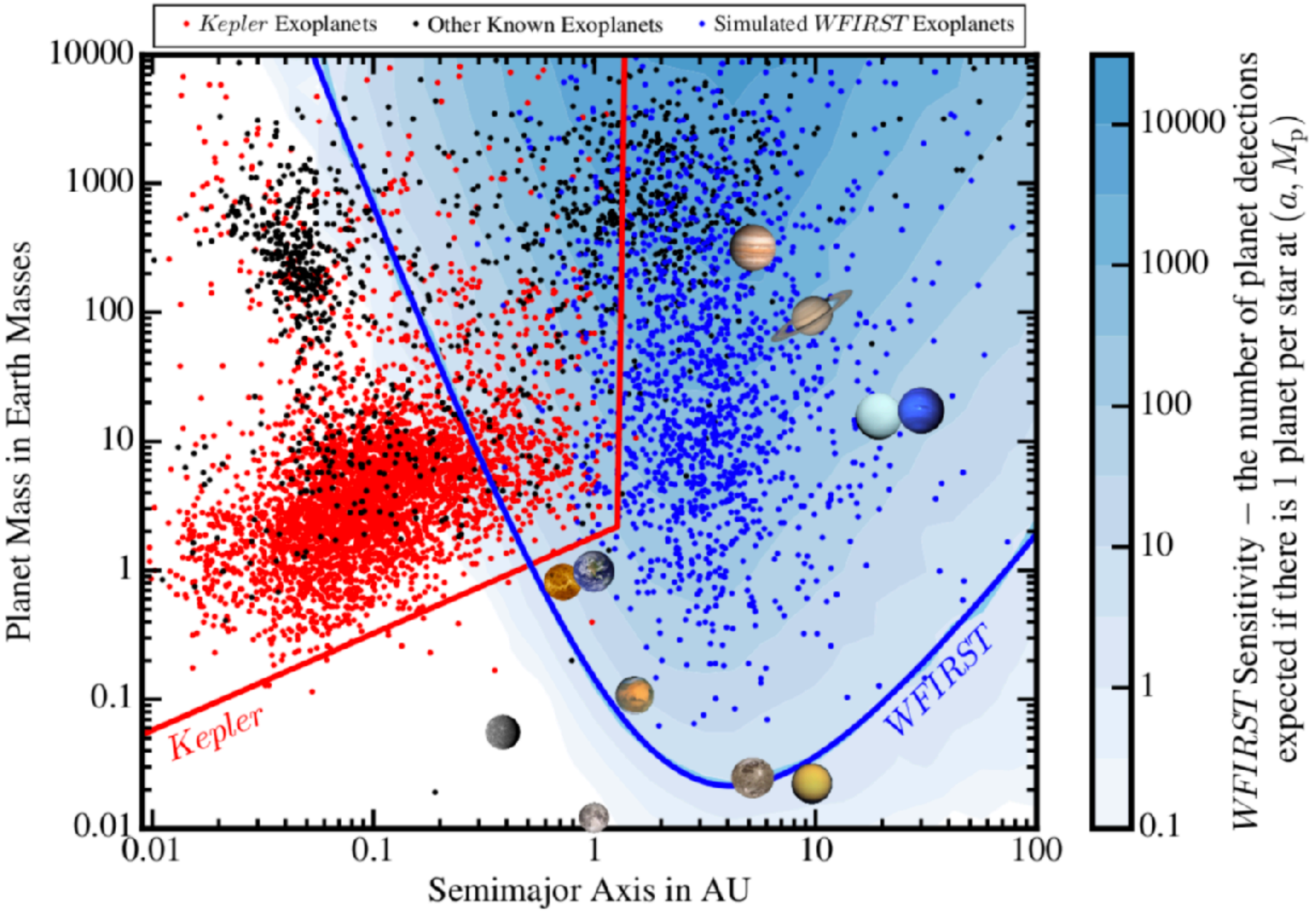


Fig. 8.— The positions of published microlensing planets from 2003-2017 (circles) and likely-to-be-published microlensing planets from 2018 (squares) are shown against the KMT

N~30000 microlensing events predicted!

Simulation by
M. Penny et al. 2019, ApJ



The Future of the Galactic Bulge Gravitational Microlensing

Wish List

REFERENCES

MINNITI ET AL. 2015 (APJ, 810, L20)
"VVV SURVEY OBSERVATIONS OF A MICROLENSING STELLAR MASS BLACK HOLE IN THE FIELD OF THE GLOBULAR CLUSTER NGC6553"

NAVARRO ET AL. 2017 (APJ, 851, L13)
"VVV SURVEY MICROLENSING EVENTS IN THE GALACTIC CENTER REGION"

NAVARRO ET AL. 2018 (APJ, 865, L5)
"VVV SURVEY MICROLENSING: THE GALACTIC LONGITUDE DEPENDENCE"

NAVARRO ET AL. 2020A (APJ, 889, 56)
"VVV SURVEY MICROLENSING: THE GALACTIC LATITUDE DEPENDENCE"

NAVARRO ET AL. 2020B (APJ, 893, 1)
"VVV SURVEY MICROLENSING: CATALOG OF BEST AND FORSAKEN EVENTS"

NAVARRO ET AL. 2020C (ACCEPTED IN APJ, ARXIV 2009.06658)
"VVV SURVEY MICROLENSING: EVENTS IN THE FAR SIDE "

SAITO, ET AL. 2019 (MNRAS, 494, 1)
"VVV WIN 1733-3349: A LOW EXTINCTION WINDOW TO PROBE THE FAR SIDE OF THE MILKY WAY BULGE "

RYU, NAVARRO, ET AL. 2019 (APJ, 159, 2)
"KMT-2018-BLG-1292: A SUPER-JOVIAN MICROLENS PLANET IN THE GALACTIC PLANE"

BENNETT, ET AL. 2014 (APJ, 785, 155)
"MOA-2011-BLG-262LB: A SUB-EARTH-MASS MOON ORBITING A GAS GIANT PRIMARY OR A HIGH VELOCITY PLANETARY SYSTEM IN THE GALACTIC BULGE "


That's all Folks!