Three Decades of the OGLE Survey

Andrzej Udalski

Astronomical Observatory
University of Warsaw

OGLE Headquarters – Astronomical Observatory, University od Warsaw (Founded 1825)

~1840

~1910

1939

1945

Pop Ivan – 1938

Pop Ivan – 1990s

OGLE

Headquarters – Astronomical Observatory, University od Warsaw (Founded 1825)

OGLE – PEOPLE

Modern astrophysics at Warsaw University Observatory after WWII

- Nestors: Profs. **Stefan Piotrowski, Włodzimierz Zonn**: 1950s – 1970s
- Warsaw School of Astronomy (1960s – on): Profs: **Krzysztof Serkowski, Andrzej Kruszewski, Józef Smak, Wojtek Krzemiński, Martin Kubiak, Kazik Stępień, Wojtek Dziembowski, Bohdan Paczyński, Slavek Ruciński** and many more
- Theory but great observing experience as well
- 1980s – new generation of young astronomers: **Janusz Kałużny, Michał Szymański, Grzegorz Pojmański, AU**
- Permanent contacts with leading western astronomical institutions: USA, Western Europe, Chile
- Good scientific background for new challenges of 1990s when the new opportunities opened!

OGLE – Early History

- **Last months of 1990** – first discussions on large observing program: BP (Princeton) – Toronto (AU) – Warsaw (JK, MK, MSz). Ideas: SNe, Microlenses, Variable Stars
- **1991** – intensive discussions. Final decision on the main science driver – microlensing. Collaboration with Carnegie Institution of Washington: George Preston, Mario Mateo.
- **October 1991** – Las Campanas Observatory 1-m Swope telescope time application for large number of nights
- **February 1992** – ~80 observing nights granted in April—September period. Intensive hardware/software preparations for the first observing run in **April 1992**

OGLE – Science Drivers

THE ASTROPHYSICAL JOURNAL, **304**: 1–5, 1986 May 1

GRAVITATIONAL MICROLENSING BY THE GALACTIC HALO

BOHDAN PACZYŃSKI[1]
Princeton University Observatory
Received 1985 August 1; accepted 1985 October 23

ABSTRACT

The massive halo of our Galaxy has an optical depth to gravitational microlensing $\tau \approx 10^{-6}$. If the halo is made of objects more massive than $\sim 10^{-8}\ M_\odot$, then any star in a nearby galaxy has a probability of 10^{-6} to be strongly microlensed at any time. The lensing events last ~ 2 hr if a typical "dark halo" object has a mass of $10^{-6}\ M_\odot$, and they last ~ 2 yr for objects of $100\ M_\odot$. Monitoring the brightness of a few million stars in the Magellanic Clouds over a time scale between 2 hr and 2 yr may lead to a discovery of "dark halo" objects in the mass range 10^{-6}–$10^2\ M_\odot$ or it may put strong upper limits on the number of such objects.

Subject headings: galaxies: Magellanic Clouds — gravitation — stars: variables

I. INTRODUCTION

The possibility of gravitational microlensing by stars in distant galaxies has been suggested and studied by many authors (Liebes 1964; Refsdal 1964; Chang and Refsdal 1979, 1984; Gott 1981, Young 1981; Vietri and Ostriker 1983; Nityananda and Ostriker 1984; Subramanian, Chitre, and Narasimaha 1985; Paczyński 1985). Unfortunately, in most cases the time scale of intensity changes of a distant quasar subject to microlensing by a solar mass star located at a cosmological distance is very long, and therefore it is not likely to be observed unless many lensed quasars are monitored for many years. If we want to make the time scale much shorter, we have to consider stars which are much closer to us, such as those in the halo of our own Galaxy. The price we pay for the shortened time scale is rather high: optical depth to gravitational lensing on known stars in the halo of our Galaxy is very small. However, most of the halo mass is believed to be, not in stars, but in some unknown form of "dark matter;" possibly black holes, Jupiters, snowballs, or some elementary particles. If the "dark matter" is made of massive objects, then it may give rise to gravitational lensing with an optical depth of $\sim 10^{-6}$, which is substantially higher than the optical depth for the known halo stars.

The aim of this paper is to present a simple model of microlensing by massive objects that might be present in the halo of our Galaxy. We calculate the probability of the effect, and we discuss some possible observations that may lead to a discovery of the effect or put interesting limits on the masses of individual objects that contribute to the mass of the halo.

written in the deflector's plane as

$$r^2 - r_0 r - R_0^2 = 0\,, \qquad (1)$$

where the coordinate system is centered on the lensing point mass, the source is at r_0, the image is at r, and

$$R_0^2 = \frac{4GMD}{c^2}\,, \quad D = \frac{D_d D_{ds}}{D_s}\,, \qquad (2)$$

and all symbols have their usual meaning. The quantity R_0 is the radius of the annular image that is formed when the source and the point mass are perfectly aligned.

The equation (1) has two solutions corresponding to the positions of two images:

$$r_{1,2} = [r_0 \pm (r_0^2 + 4R_0^2)^{1/2}]/2\,. \qquad (3)$$

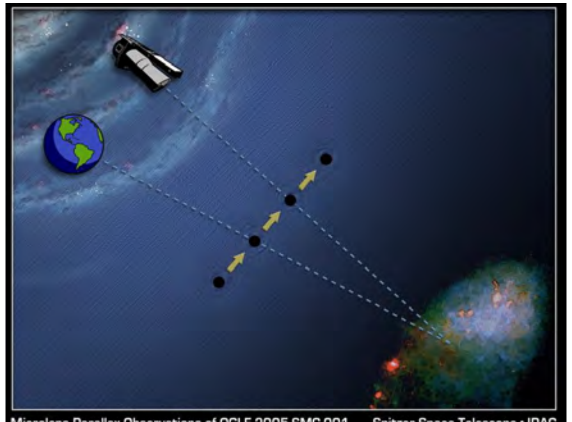
Their amplifications are given by

$$A_{1,2} = \mathrm{abs}\left(\frac{r_{1,2}}{r_0}\frac{dr_{1,2}}{dr_0}\right) = \mathrm{abs}\left(\frac{r_{1,2}^4}{r_{1,2}^4 - R_0^4}\right), \qquad (4)$$

and their combined amplification is

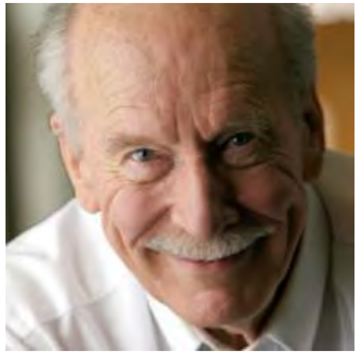
$$A \equiv A_1 + A_2 = \frac{u^2+2}{u(u^2+4)^{1/2}}\,, \quad u \equiv \frac{r_0}{R_0}\,. \qquad (5)$$

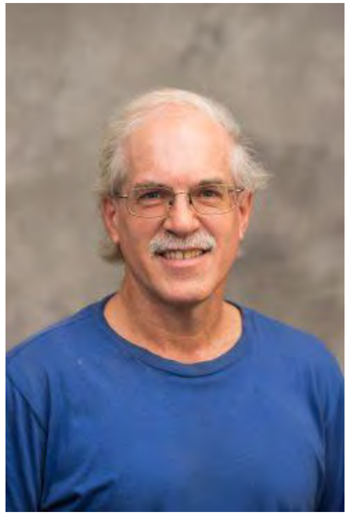
If the optical depth is τ, then the probability that the source is found within a radius R_0 of some point mass is also τ. According to equation (5) the combined amplification of the two images is, in that case, larger than 1.34. Of course, the



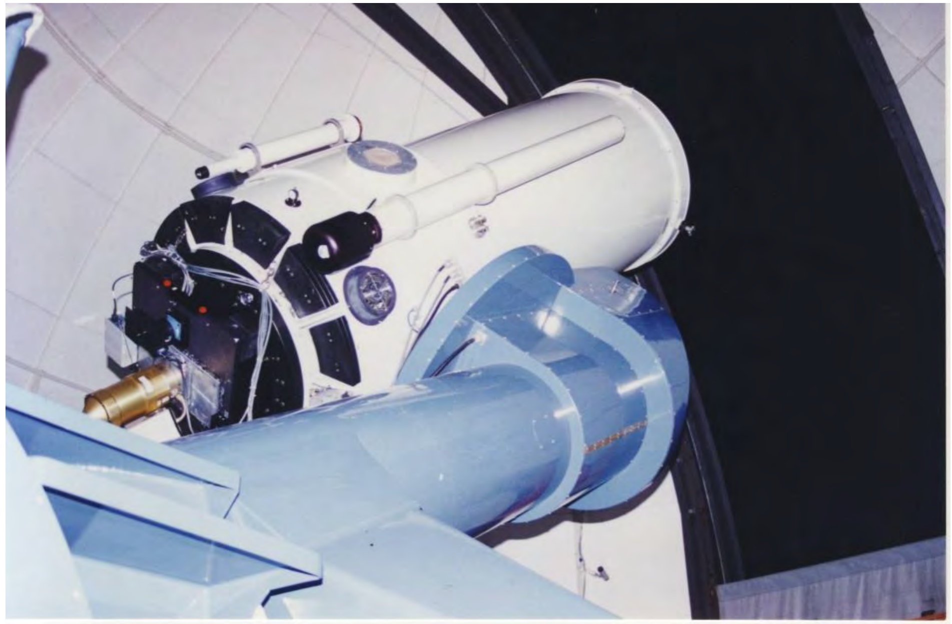
Microlens Parallax Observations of OGLE-2005-SMC-001 Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / S. Dong (Ohio State University) ssc2007-XX

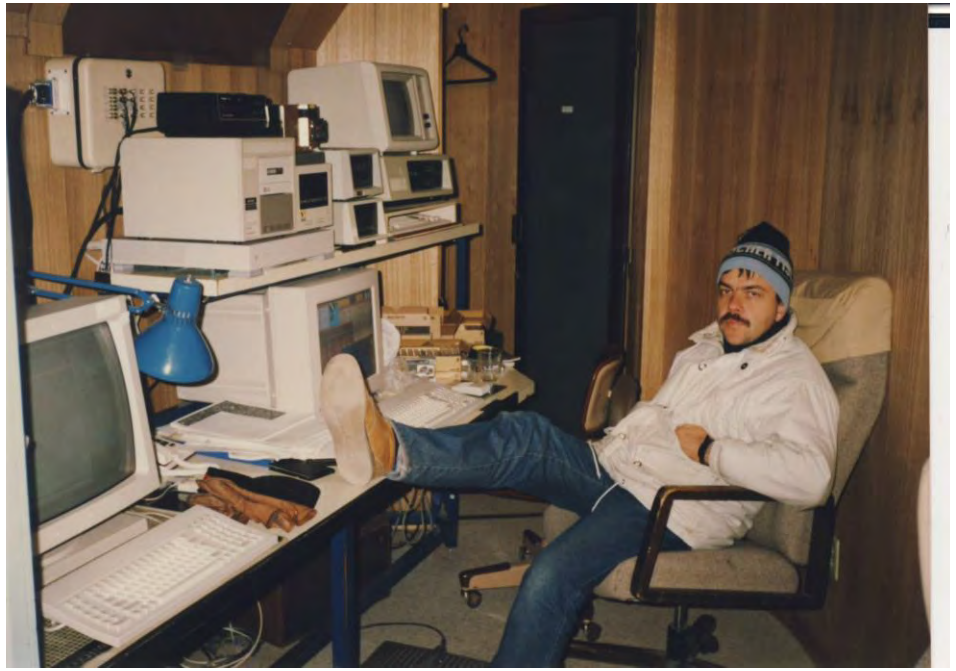
OGLE – I TEAM



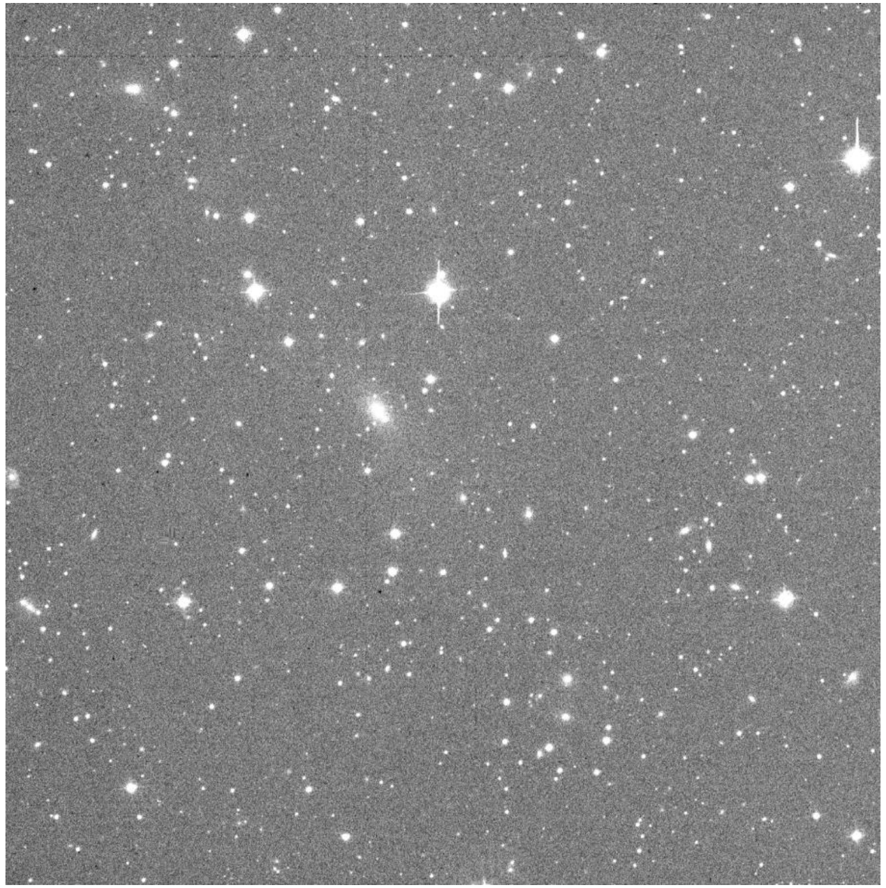


OGLE – I Observations

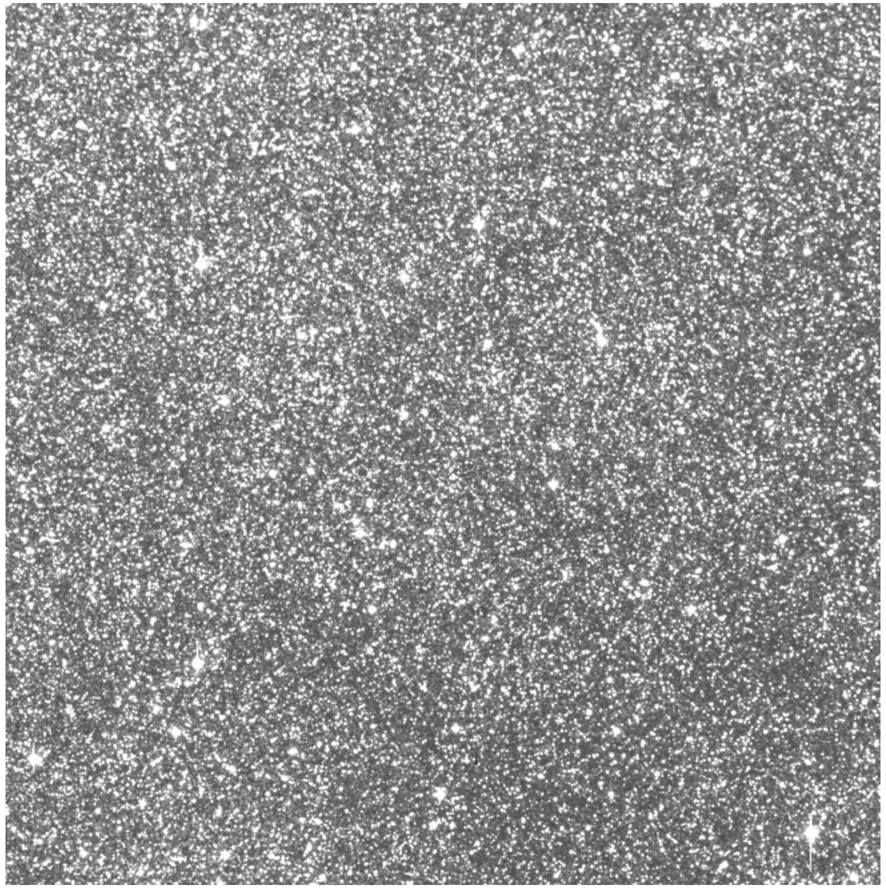




First Images
April 12, 1992

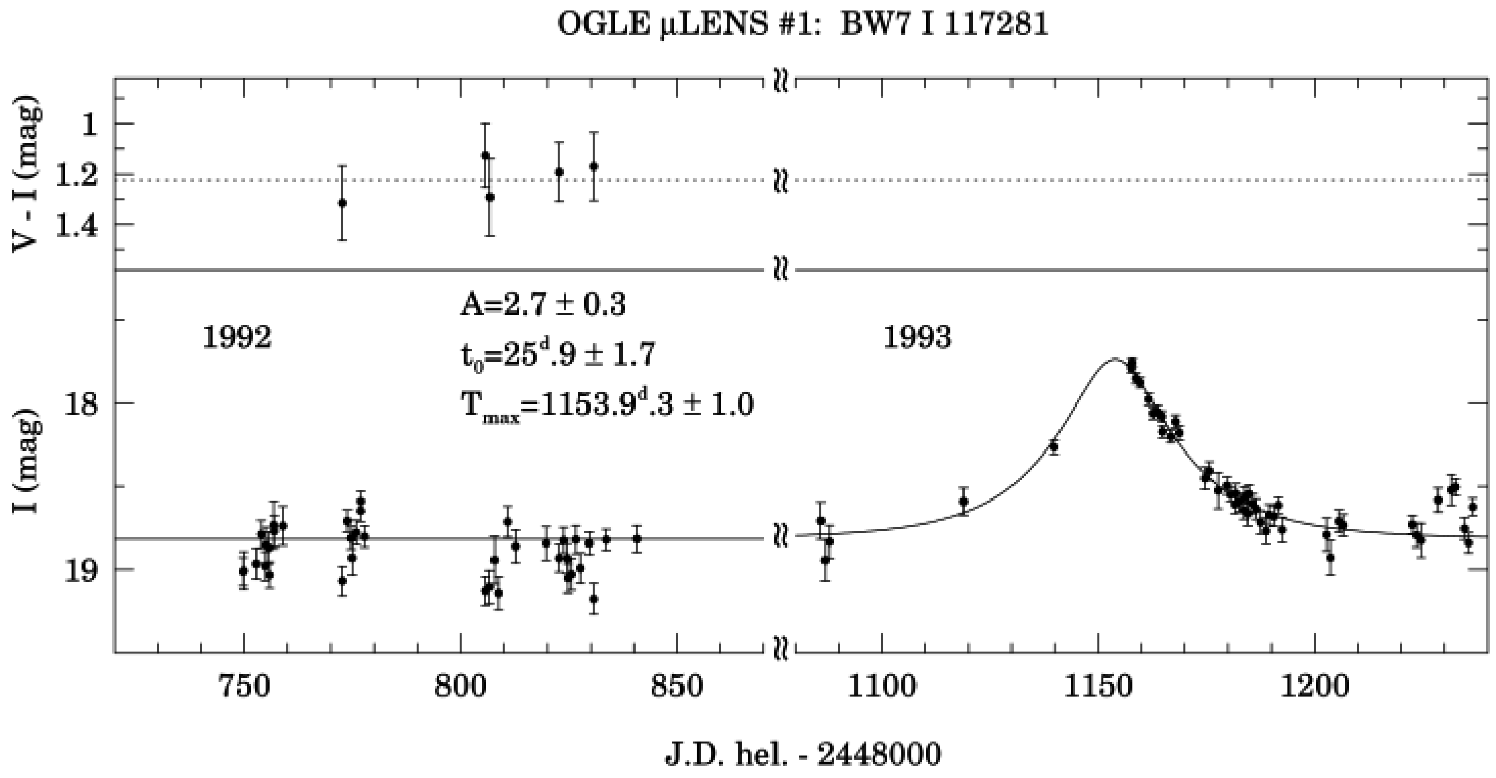


One of the Abell galaxy clusters



Galactic center: Baade's Window

Discovery of the First Microlensing Events September 1993



LETTER to the EDITORS

ACTA ASTRONOMICA
Vol. 43 (1993) pp. 289–294

The Optical Gravitational Lensing Experiment. Discovery of the First Candidate Microlensing Event in the Direction of the Galactic Bulge[1]

by

A. Udalski, M. Szymański, J. Kałużny, M. Kubiak,

Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

W. Krzemiński, M. Mateo[2], G.W. Preston,

The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101 USA

and

B. Paczyński

Princeton University Observatory, Princeton, NJ 08544 USA

Received September 29, 1993

ABSTRACT

We report the discovery of the first candidate microlensing event to be discovered in the direction of the Galactic Bulge. The peak brightness of the candidate event occurred on June 15, 1993. The event had time scale (R_0/V, R_0 – the Einstein radius, V – the transverse velocity of the lens) equal to 23.8 ± 0.9 day and amplification $A = 2.4 \pm 0.1$. The lensed star is at the turn-off point in the Galactic Bulge. The lensing object is likely to be a disk M-dwarf of about 0.3 $M_\odot$.

Key words: *gravitational lensing – Galaxy: halo – Stars: low mass, brown dwarfs*

The possibility of use gravitational microlensing as a probe of the dark, unseen matter in our Galaxy was originally proposed by Paczyński (1986, 1991) and further developed by Griest (1991) and Griest *et al.* (1991). Because the probability of a star being microlensed at any given moment turns out to be very small, only a large-scale photometric survey in dense stellar fields is suitable to search for microlensing events. Candidate regions of the sky include dense fields in the directions of the Magellanic Clouds and the Galactic Bulge where lensing events by halo objects can be potentially detected. Lensing events due to disk objects can also be expected in

[1] Based on observations obtained at the Las Campanas Observatory of the Carnegie Institution of Washington.

[2] Current address: Department of Astronomy, University of Michigan, 821 Dennison Bldg., Ann Arbor, MI 48109-1090 USA.

OGLE

Discovery of the first events toward the GB (1993).

Discovery of the First Microlensing Events
September 1993

LETTERS TO NATURE

Possible gravitational microlensing of a star in the Large Magellanic Cloud

C. Alcock*†, C. W. Akerlof†¶, R. A. Allsman*, T. S. Axelrod*, D. P. Bennett*†, S. Chan‡, K. H. Cook*†, K. C. Freeman‡, K. Griest†||, S. L. Marshall†§, H-S. Park*, S. Perlmutter†, B. A. Peterson‡, M. R. Pratt†§, P. J. Quinn‡, A. W. Rodgers‡, C. W. Stubbs†§ & W. Sutherland†

* Lawrence Livermore National Laboratory, Livermore, California 94550, USA
† Center for Particle Astrophysics, University of California, Berkeley, California 94720, USA
‡ Mt Stromlo and Siding Spring Observatories, Australian National University, Weston, ACT 2611, Australia
§ Department of Physics, University of California, Santa Barbara, California 93106, USA
|| Department of Physics, University of California, San Diego, California 92039, USA
¶ Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA

THERE is now abundant evidence for the presence of large quantities of unseen matter surrounding normal galaxies, including our own[1,2]. The nature of this 'dark matter' is unknown, except that it cannot be made of normal stars, dust or gas, as they would be easily detected. Exotic particles such as axions, massive neutrinos or other weakly interacting massive particles (collectively known as WIMPs) have been proposed[3,4], but have yet to be detected. A less exotic alternative is normal matter in the form of bodies with masses ranging from that of a large planet to a few solar masses. Such objects, known collectively as massive compact halo objects[5] (MACHOs), might be brown dwarfs or 'jupiters' (bodies too small to produce their own energy by fusion), neutron stars, old white dwarfs or black holes. Paczynski[6] suggested that MACHOs might act as gravitational microlenses, temporarily amplifying the apparent brightness of background stars in nearby galaxies. We are conducting a microlensing experiment to determine whether the dark matter halo of our Galaxy is made up of MACHOs. Here we report a candidate for such a microlensing event, detected by monitoring the light curves of 1.8 million stars in the Large Magellanic Cloud for one year. The light curve shows no variation for most of the year of data taking, and an upward excursion lasting over 1 month, with a maximum increase of ~2 mag. The most probable lens mass, inferred from the duration of the candidate lensing event, is ~0.1 solar mass.

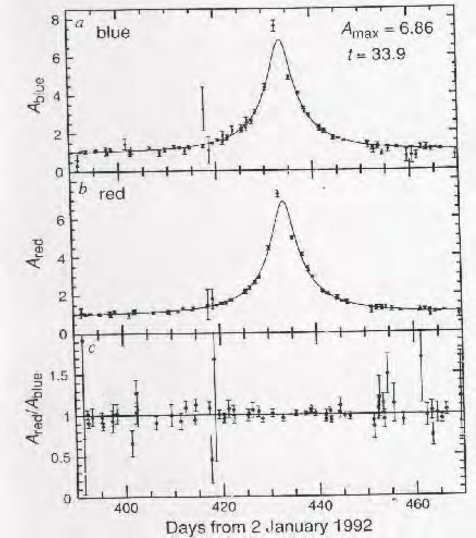
large, but these events are extremely rare; for this reason our survey was designed to follow >ten million stars over several years.

The survey employs a dedicated 1.27-m telescope at Mount Stromlo. A field-of-view of 0.5 square degrees is achieved by operating at the prime focus. The optics include a dichroic beam-splitter which allows simultaneous imaging in a 'red' beam (6,300–7,600 Å) and a 'blue' beam (4,500–6,300 Å). Two large charge-coupled device (CCD) cameras[11] are employed at the two foci; each contain a 2×2 mosaic of 2,048×2,048 pixel Loral CCD imagers. The 15-μm pixel size corresponds to 0.63 arcsec on the sky. The images are read out through a 16-channel system, and written into dual ported memory in the data acquisition computer. Our primary target stars are in the LMC. We also monitor stars in the Galactic bulge and the Small Magellanic Cloud. As of 15 September 1993, over 12,000 images have been taken with the system.

The data are reduced with a crowded-field photometry routine known as Sodophot, derived from Dophot[12]. First, one image of each field that was obtained in good seeing is reduced in a manner similar to Dophot to produce a 'template' catalogue of star positions and magnitudes. Normally, bright stars are matched with the template and used to determine an analytic point spread function (PSF) and a coordinate transformation. Photometric fitting is then performed on each template star in descending order of brightness, with the PSF for all other stars subtracted from the frame. When a star is found to vary significantly, it and its neighbours undergo a second iteration of fitting. The output consists of magnitudes and errors for the two colours, and six additional useful parameters (such as the χ^2 of the PSF fit and crowding information). These are used to flag questionable measurements, that arise from cosmic ray events in the CCDs, bad pixels and so on.

These photometric data are subjected to an automatic time-series analysis which uses a set of optimal filters to search for microlensing candidates and variable stars (which we have detected in abundance[13]). For each microlensing candidate a light curve is fitted, and the final selection is done automatically using criteria (for example, signal-to-noise, quality of fit, wavelength independence of the light curve and colour of the star) that were established empirically using Monte Carlo addition of fake events into real light curves.

This analysis has been done on four fields near the centre of the LMC, containing 1.8 million stars, with approximately 250 observations for each star. The candidate event reported here occurs in the light curve of a star at coordinates α = 05 h 14 min 44.5 s, δ = −68° 48′ 00″ (J2000). (A finding chart is available on request from C.A.). The star has median magnitudes V ~19.6, R ~19.0, consistent with a clump giant (metal-rich helium core burning star) in the LMC. These magnitudes are estimated using colour transformations from our filters to V and R that have been derived from observations of standard



LETTERS TO NATURE

Evidence for gravitational microlensing by dark objects in the Galactic halo

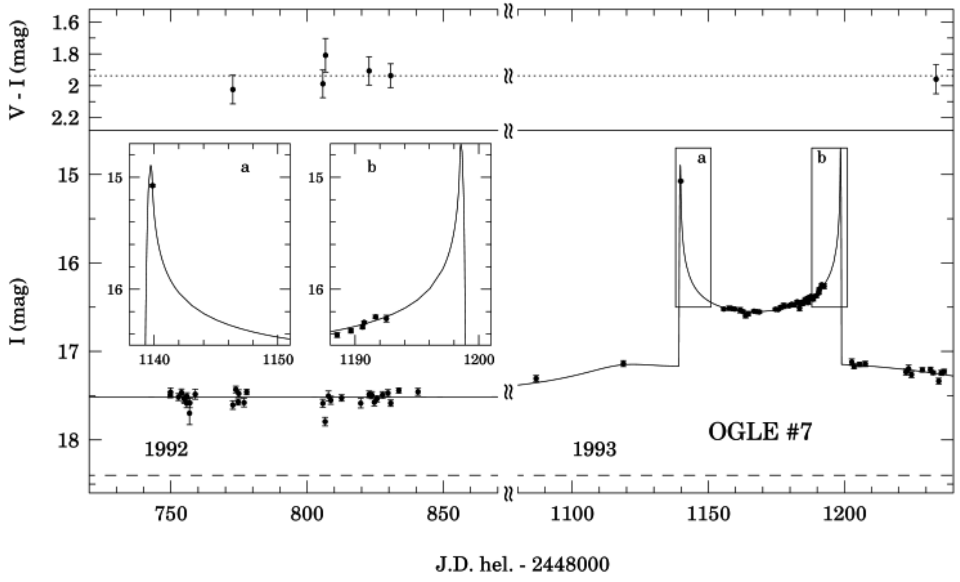
E. Aubourg*, P. Bareyre*, S. Bréhin*, M. Gros*, M. Lachièze-Rey*, B. Laurent*, E. Lesquoy*, C. Magneville*, A. Milsztajn*, L. Moscoso*, F. Queinnec*, J. Rich*, M. Spiro*, L. Vigroux*, S. Zylberajch*, R. Ansari†, F. Cavalier†, M. Moniez†, J.-P. Beaulieu‡, R. Ferlet‡, Ph. Grison‡, A. Vidal-Madjar‡, J. Guibert§, O. Moreau§, F. Tajahmady§, E. Maurice||, L. Prévôt|| & C. Gry¶

* DAPNIA, Centre d'Études de Saclay, 91191 Gif-sur-Yvette, France
† Laboratoire de l'Accélérateur Linéaire, Centre d'Orsay, 91405 Orsay, France
‡ Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France
§ Centre d'Analyse des Images de l'Institut National des Sciences de l'Univers, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France
|| Observatoire de Marseille, 2 place Le Verrier, 13248 Marseille 04, France
¶ Laboratoire d'Astronomie Spatiale de Marseille, Traverse du Siphon, Les Trois Lucs, 13120 Marseille, France

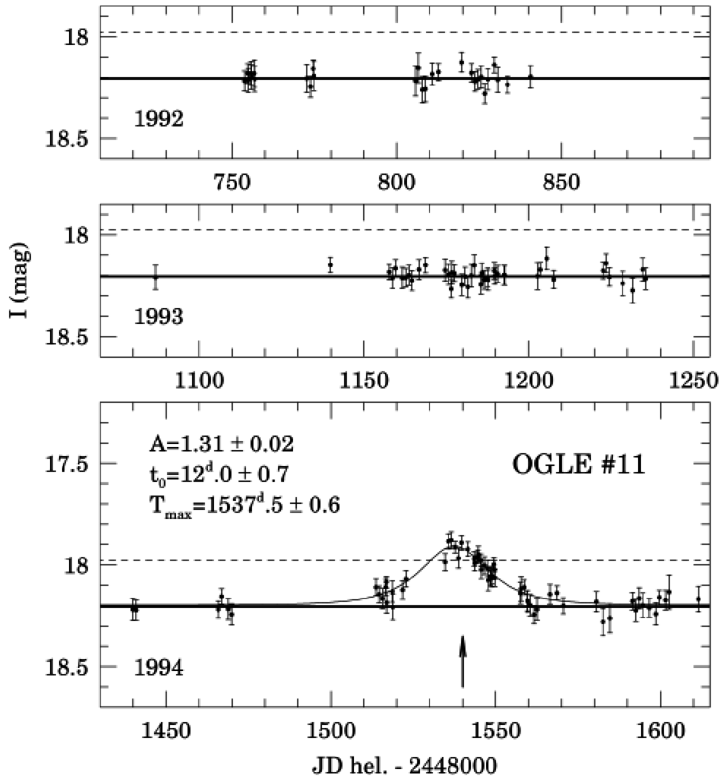
THE flat rotation curves of spiral galaxies, including our own, indicate that they are surrounded by unseen haloes of 'dark matter'[1,2]. In the absence of a massive halo, stars and gas in the outer portions of a galaxy would orbit the centre more slowly, just as the outer planets in the Solar System circle the Sun more slowly than the inner ones. So far, however, there has been no direct observational evidence for the dark matter, or its characteristics. Paczyński[3] suggested that dark bodies in the halo of our Galaxy can be detected when they act as gravitational 'microlenses', amplifying the light from stars in nearby galaxies. The duration of such an event depends on the mass, distance and velocity of the dark object. We have been monitoring the brightness of three million stars in the Large Magellanic Cloud for over three years, and here report the detection of two possible microlensing events. The brightening of the stars was symmetrical in time, achromatic and not repeated during the monitoring period. The timescales of the two events are about thirty days and imply that the masses of the lensing objects lie between a few hundredths and one solar mass. The number of events observed is consistent with the number expected if the halo is dominated by objects with masses in this range.

The 'EROS' (Expérience de Recherche d'Objets Sombres) col-

OGLE – I Main Results: μLensing



First Binary Microlensing (1994)

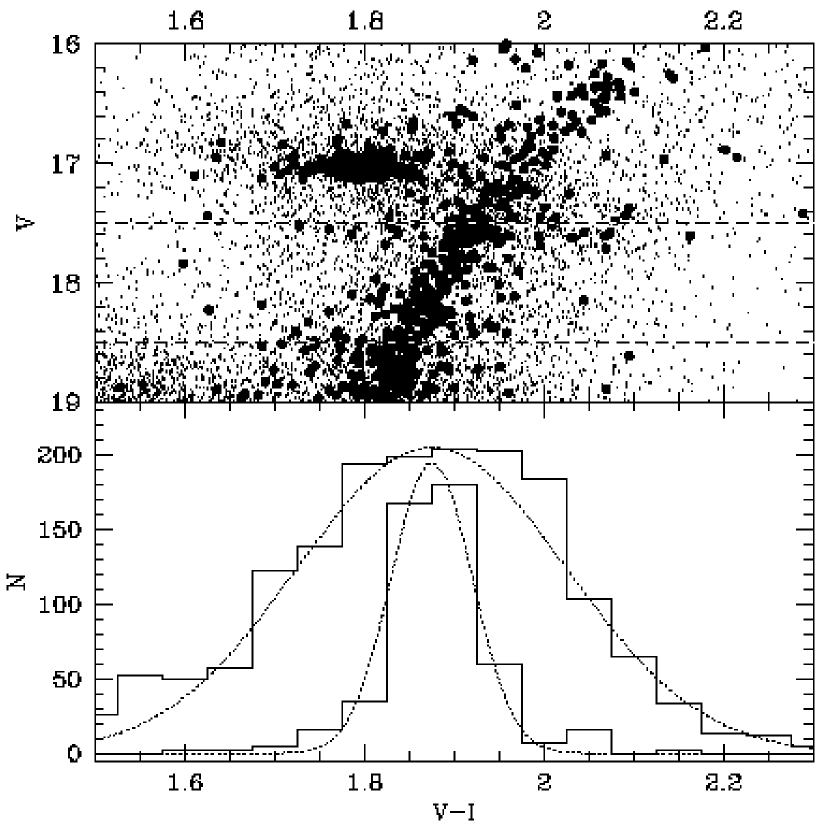


Early Warning System (EWS – 1994)

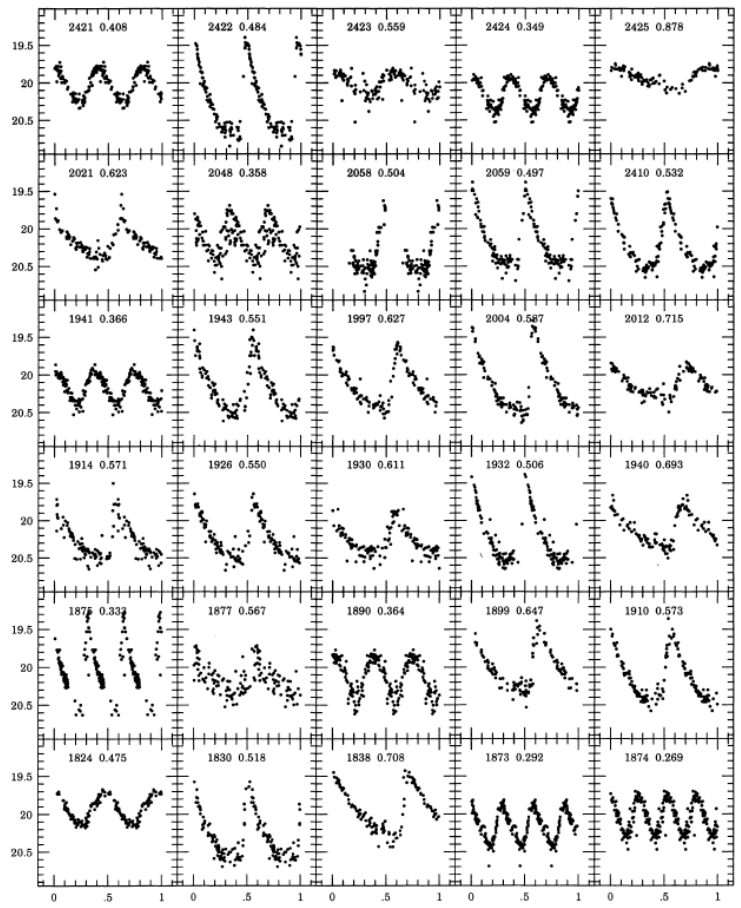
Microlensing Optical Depth: First empirical determination (1994)

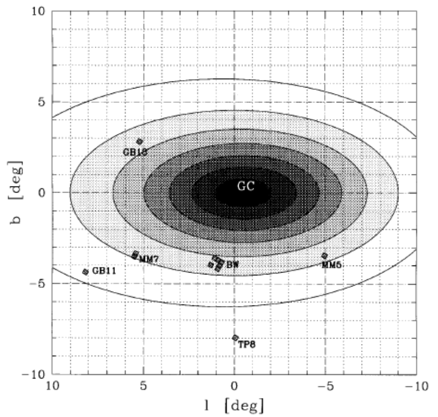
$\tau = 3.3 \times 10^{-6}$

OGLE – I Main Results: misc



Variable Stars:
- Variables in the Galactic bulge
- Variables in Globular Clusters (ω Cen, 47 Tuc)
- Variables in Dwarf Galaxies: Sculptor, Sagittarius





Modeling the Galactic Bar

First Microlensing Conference – Livermore 1995

OGLE 1.3-m Warsaw Telescope

DFM Engineering Inc.
Manufacturing

Tinsley Labs
Optics

Las Campanas Observatory
Site – July 1995

OGLE

1.3-m Warsaw Telescope

1.3-m Warsaw Telescope
First light: February 9, 1996
Full operation: January 1, 1997

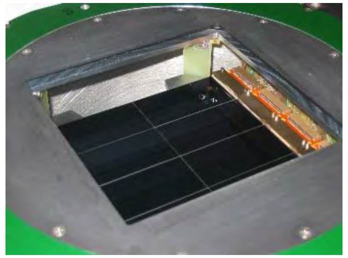
Visit of BP at Las Campanas
February 1998

The Optical Gravitational Lensing Experiment (1992 - ….)

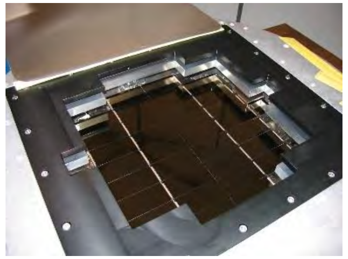
Phases of the OGLE Survey:

OGLE-I (1992 – 1995). 1 m Swope telescope at Las Campanas Observatory, Chile. ~2 million stars observed. Microlensing

OGLE-II (1997 – 2000). 1.3 m Warsaw telescope. ~40 million stars observed. Variable and non-Variable Stars in GB, MC



OGLE-III (2001– 2009). 8k x 8k mosaic CCD. ~200 million stars observed (GB, GD, MC). Extrasolar Planets, Microlensing



OGLE-IV (2010 – ….). 32-chip 256 Mpixel mosaic CCD. >Two billion stars regularly monitored

(March 17, 2020 – August 12, 2022: CoViD-19 pandemic stopped observations)

http://ogle.astrouw.edu.pl

OGLE TEAM & Guests

30th Anniversary

Bohdan Paczyński (1940 – 2007)

Wojtek Krzemiński (1933 – 2017)

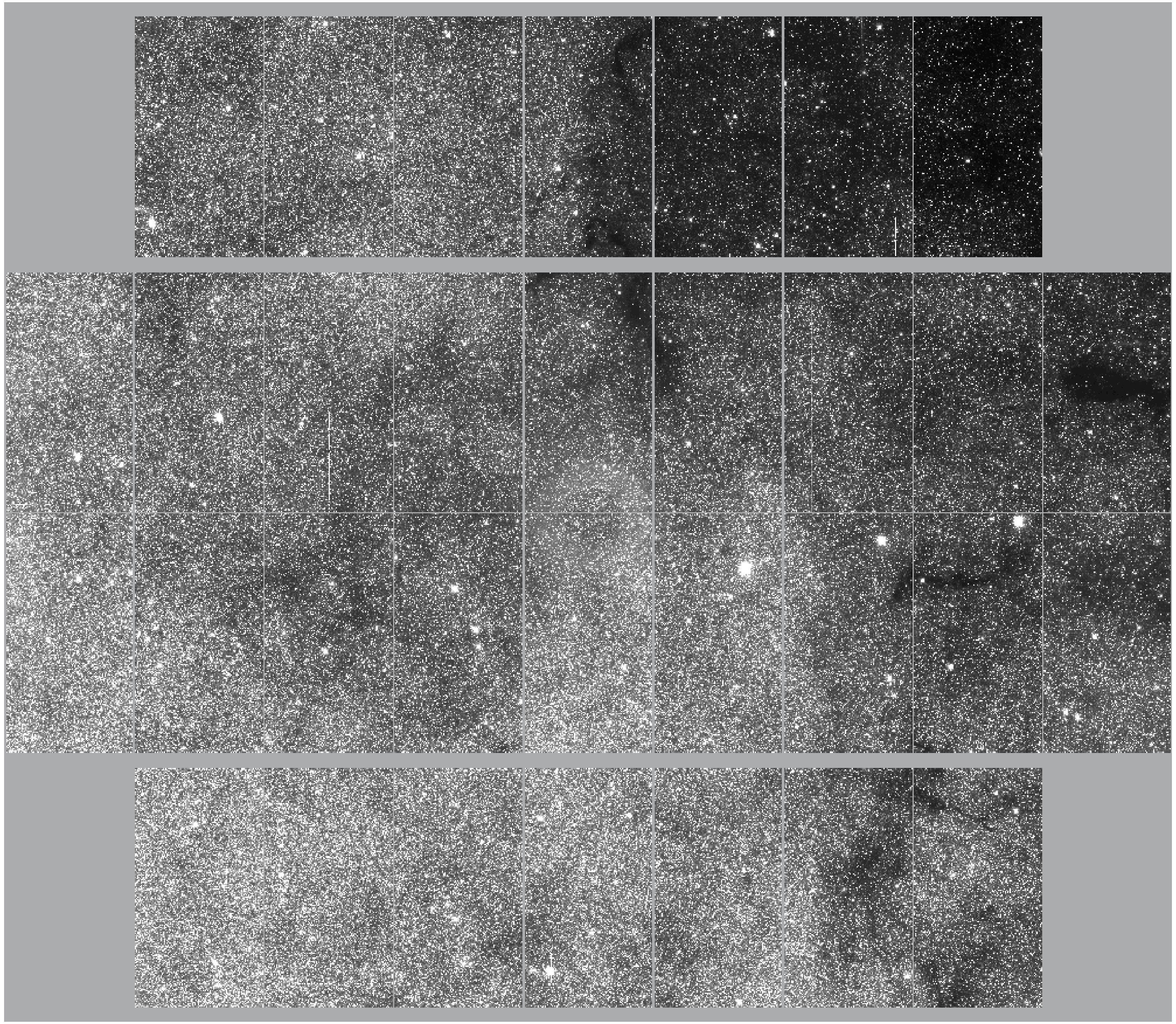
Janusz Kałużny (1955 – 2015)

OGLE

Science Factory

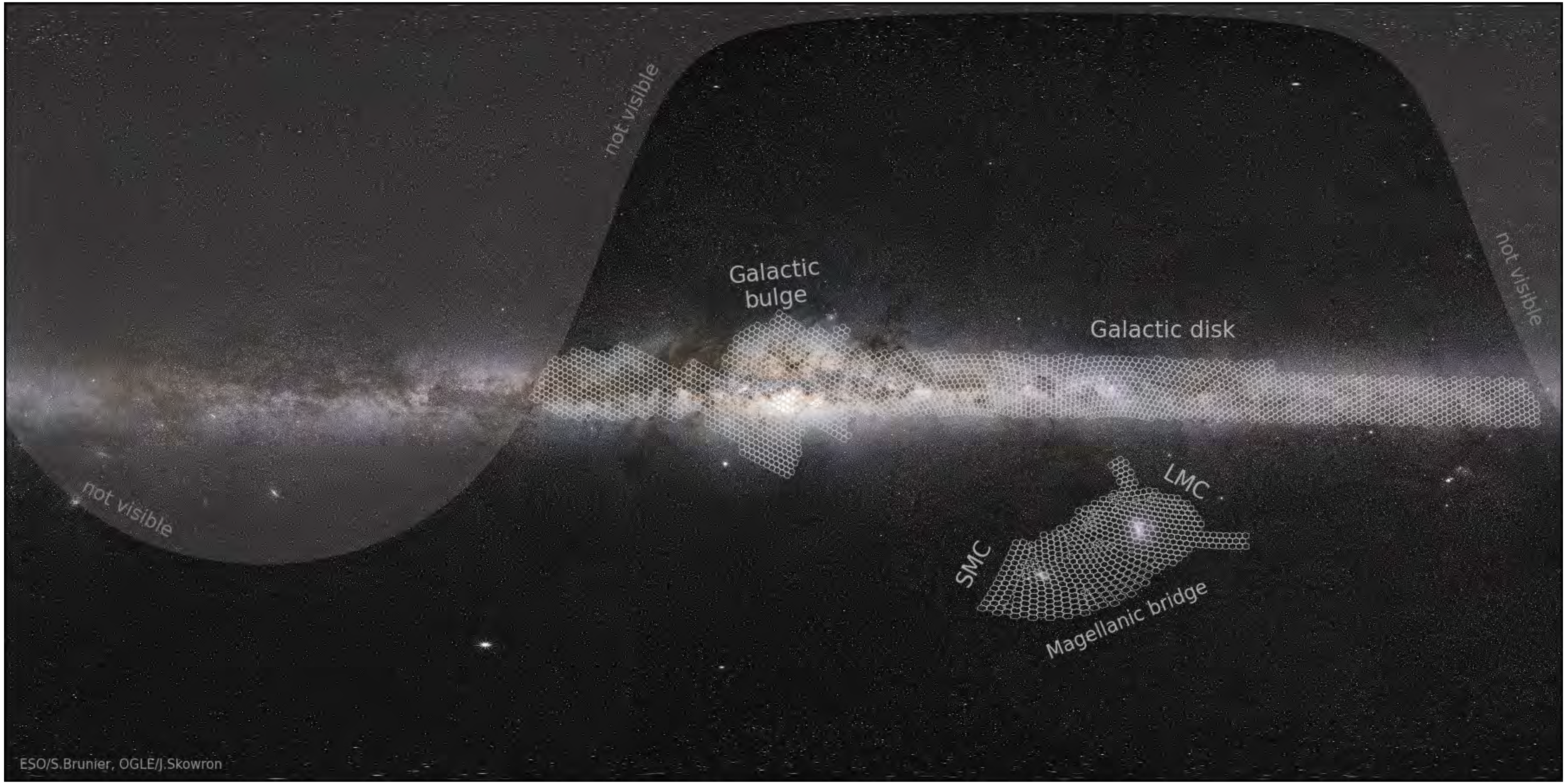
Main Milestones

OGLE-IV SKY: 1.4 deg^2 FOV, I~21mag



~6 million stars in this picture!

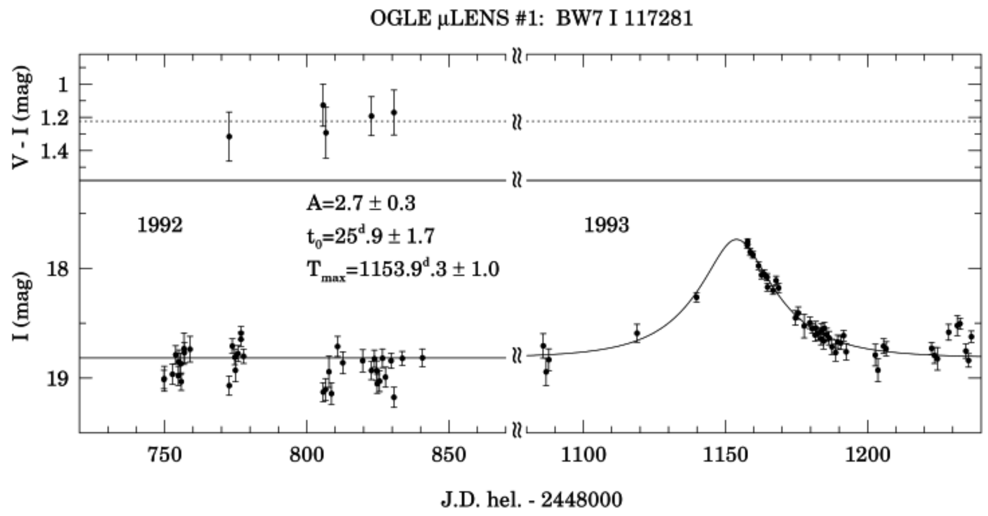
OGLE SKY

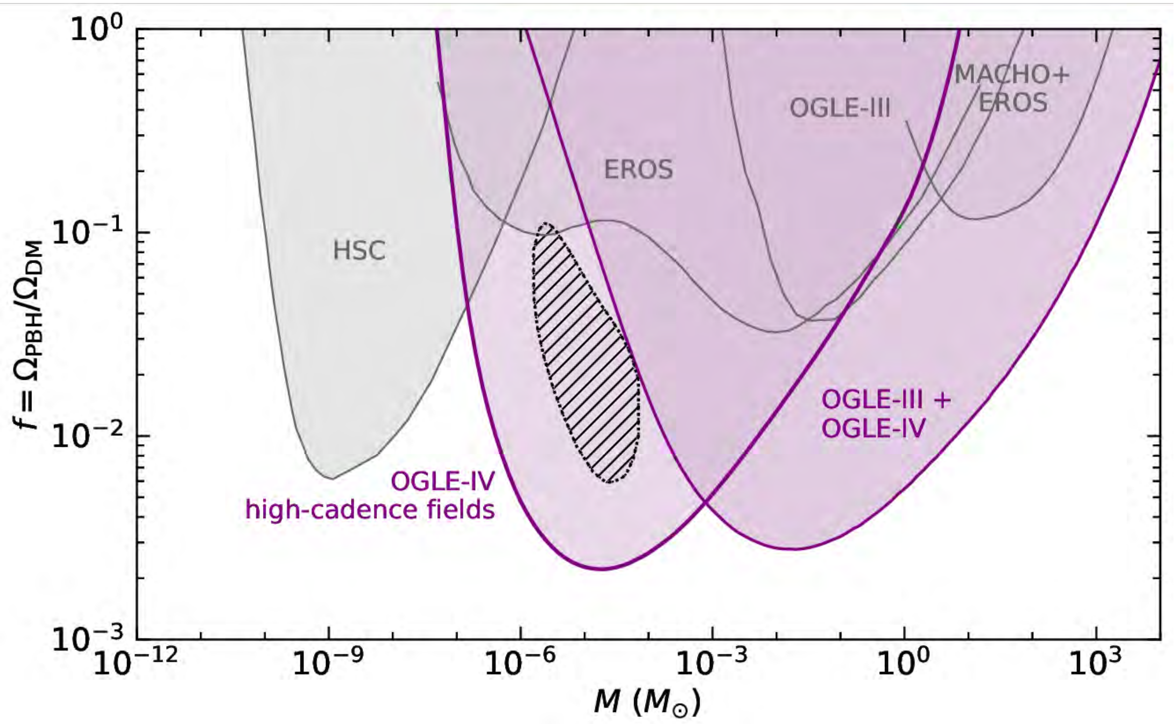


not visible
not visible
Galactic bulge
Galactic disk
not visible
LMC
SMC
Magellanic bridge
ESO/S.Brunier, OGLE/J.Skowron

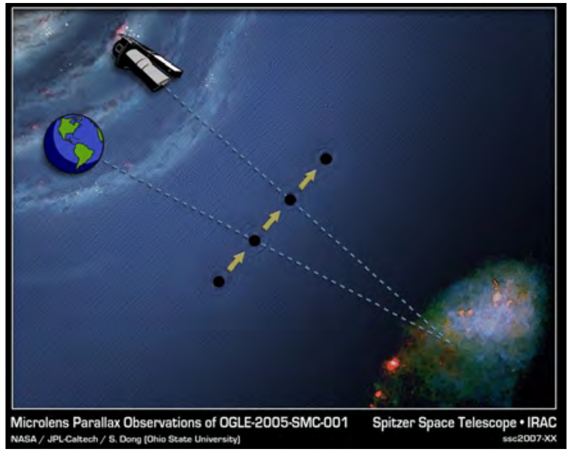
OGLE Microlensing

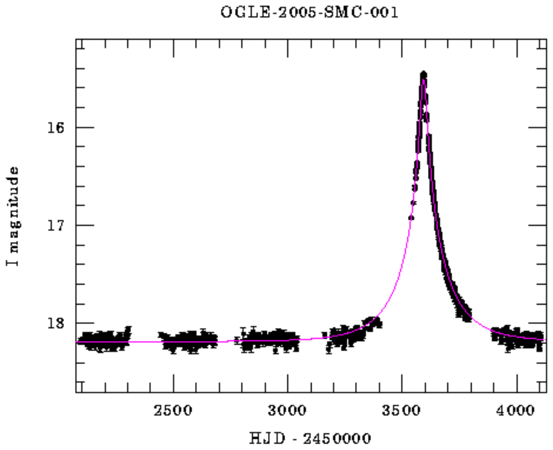
- **Discovery: 1993**





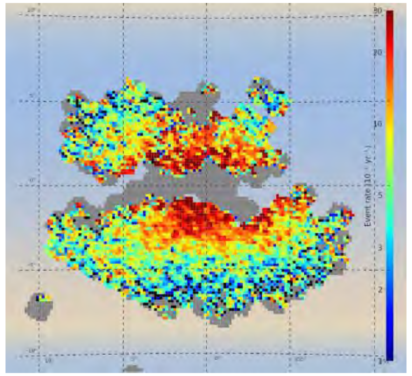
- **Search for Dark Matter (1992 – 2024)**



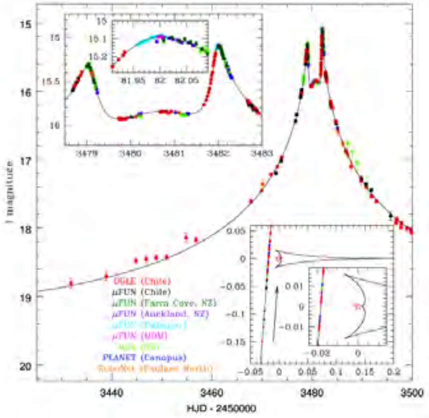


Final result: tightest limits on DM

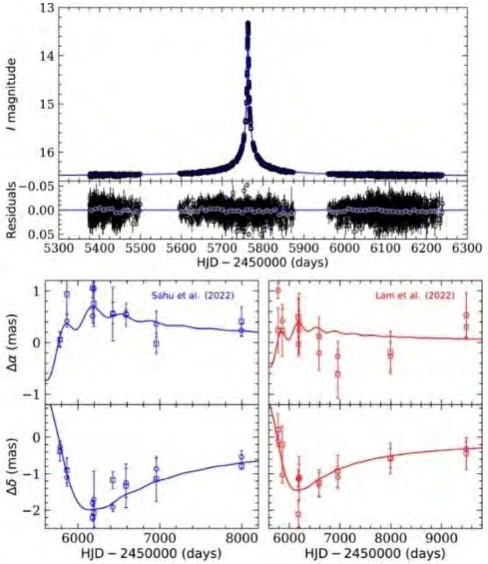
OGLE Microlensing



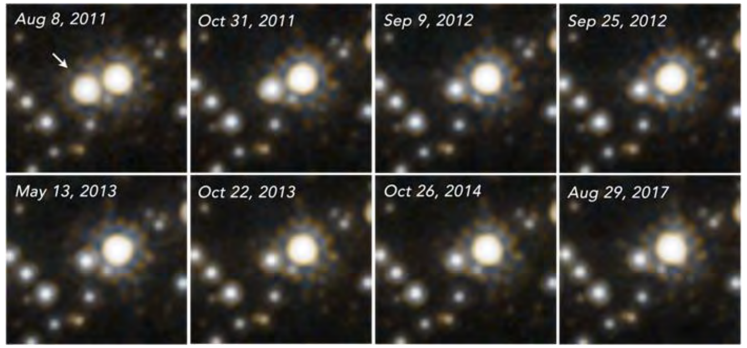
- **Galactic Structure Studies (1994 – 2020)**
  (optical depth: Galactic center & disk)



- **Microlensing Exoplanets (2003 – …)**



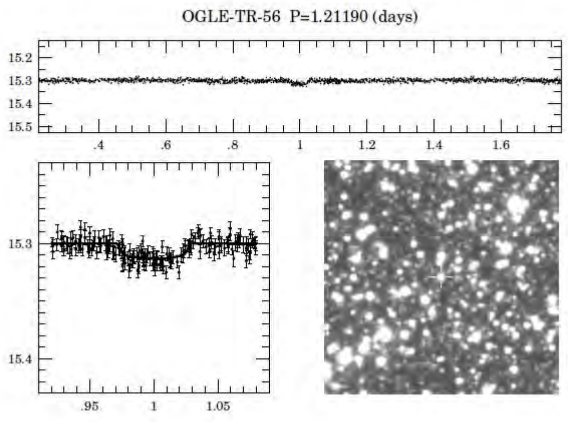
- **Free Floating Black Holes (2022 – …)**

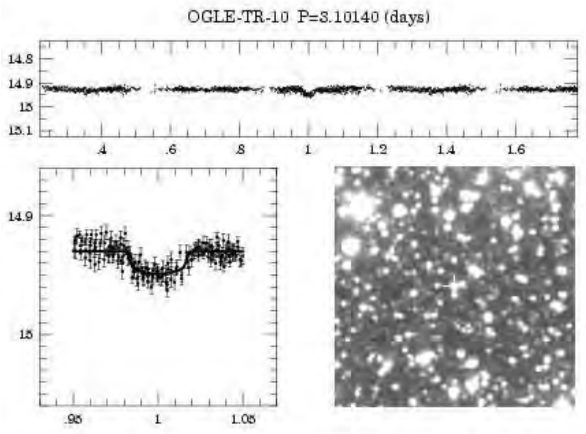


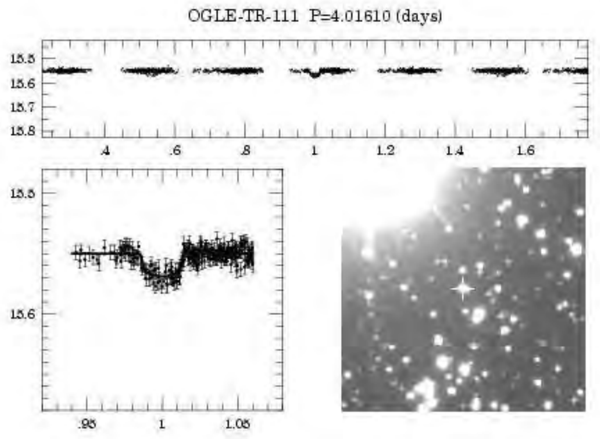
OGLE Exoplanets:
Two New Photometric Methods of Exoplanet Detection

- **Microlensing technique**: First detection of microlensing exoplanet (2004)
- **Transit technique**: First transiting exoplanets detected with classical transit approach

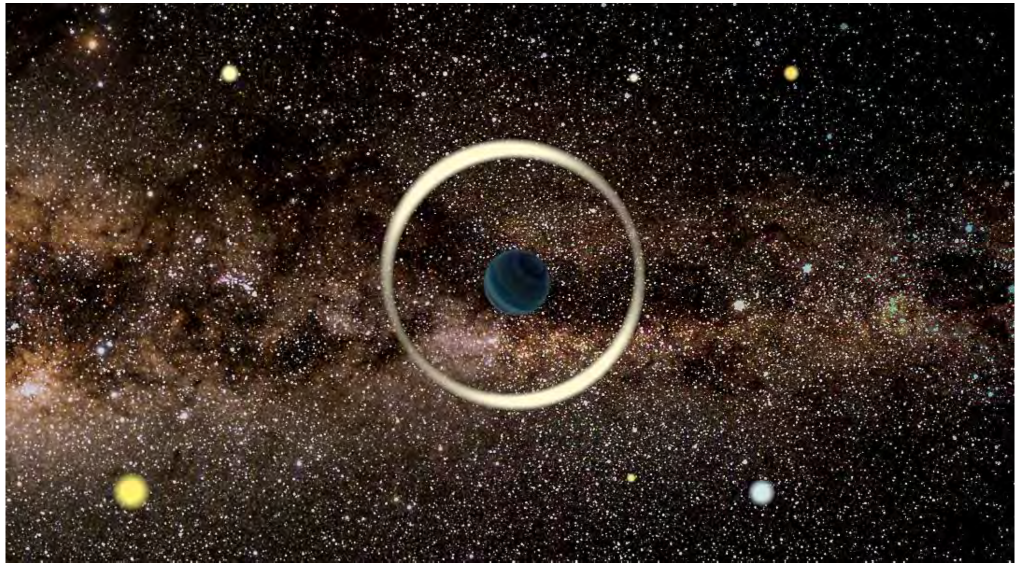
OGLE Transiting Planets (2001 — 2006)

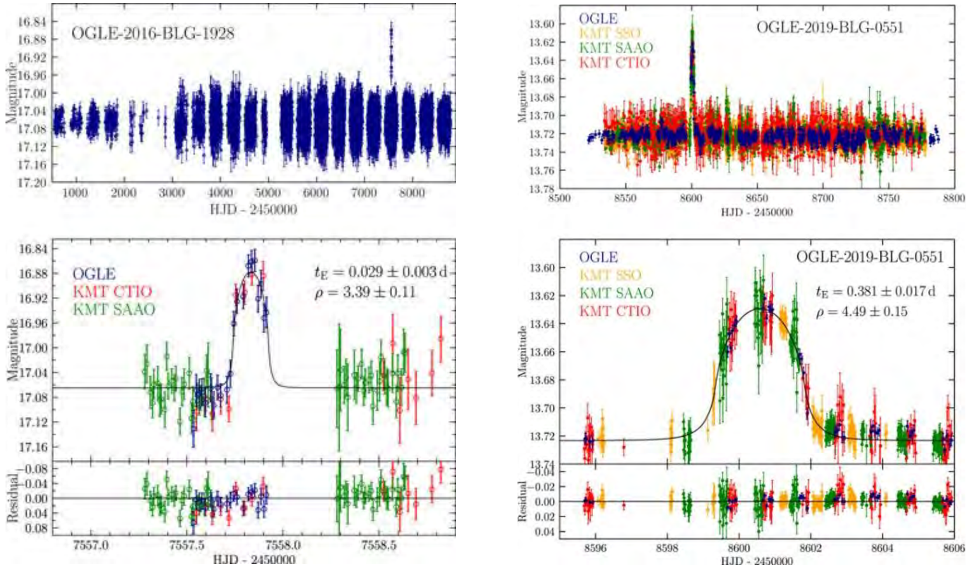






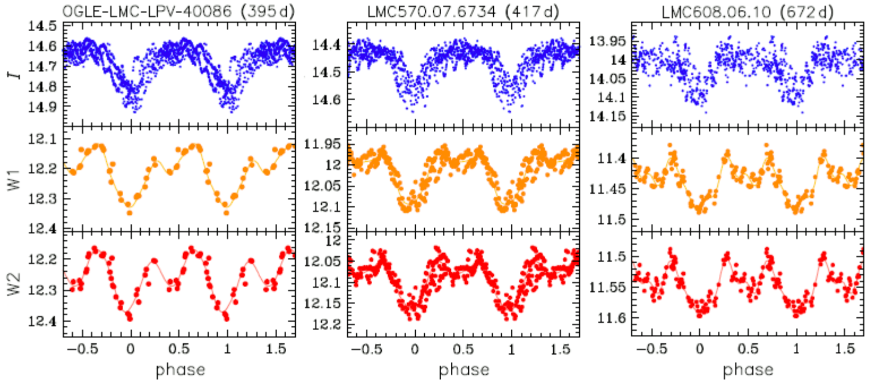
OGLE Free Floating Planets





Series of papers on FFPs – Przemek Mróz *et al*.

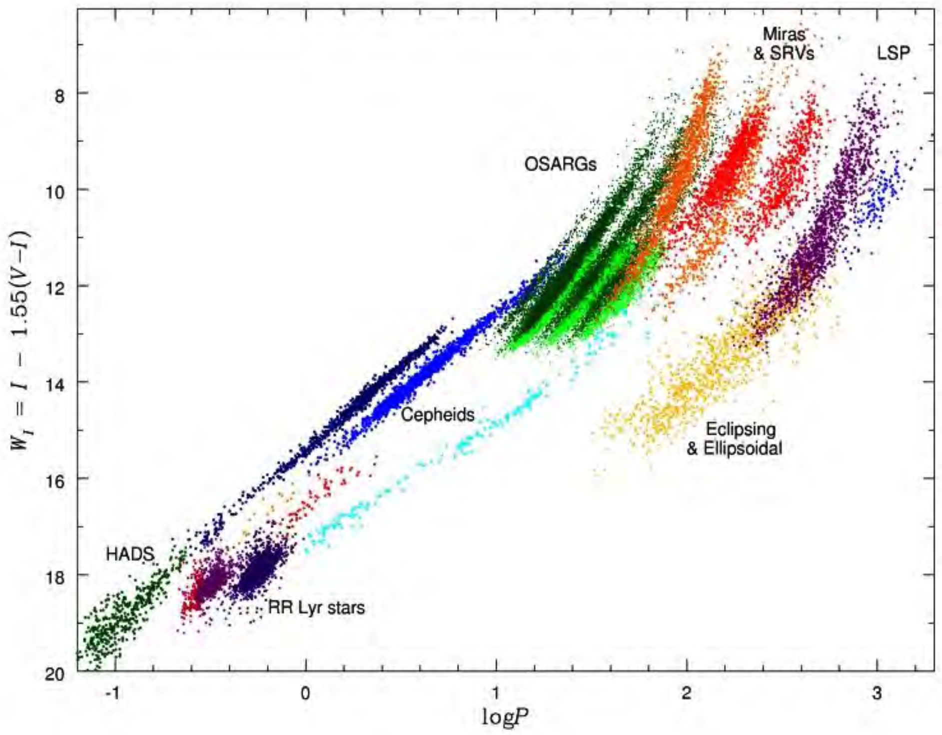
OGLE LSP – Traces of exoplanets?



ERC Starting Grant 2021 – Dorota Skowron

OGLE Collection of Variable Stars

- ~30 years time span, very precise photometry
- High completeness (>90%) and classification purity
- Over one million OGLE periodic variable stars
- Gold sample of all type variables for other surveys



P–L relations

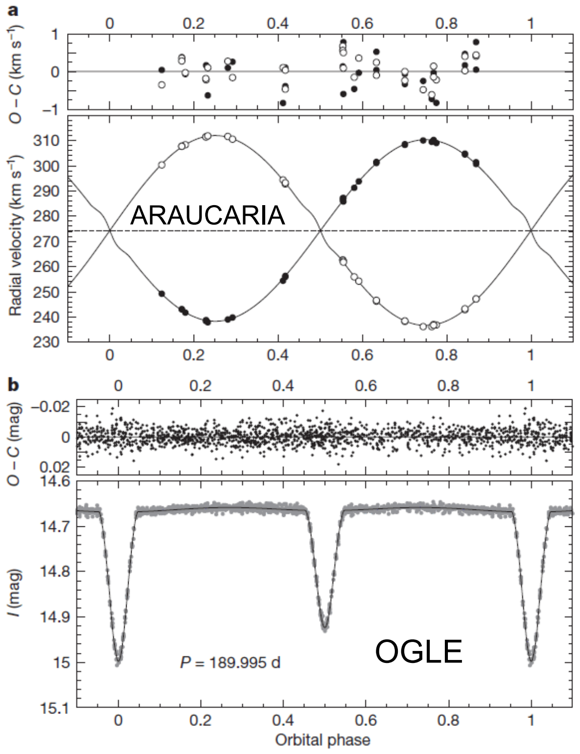


Figure 1 | Change of the brightness of the binary system OGLE-LMC-ECL-06575 and the orbital motion of its components. a, The main panel shows the

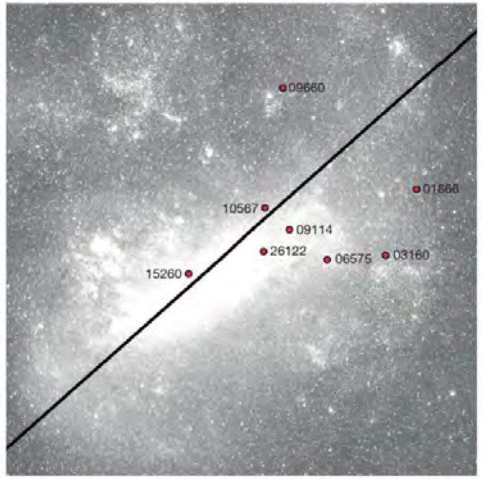
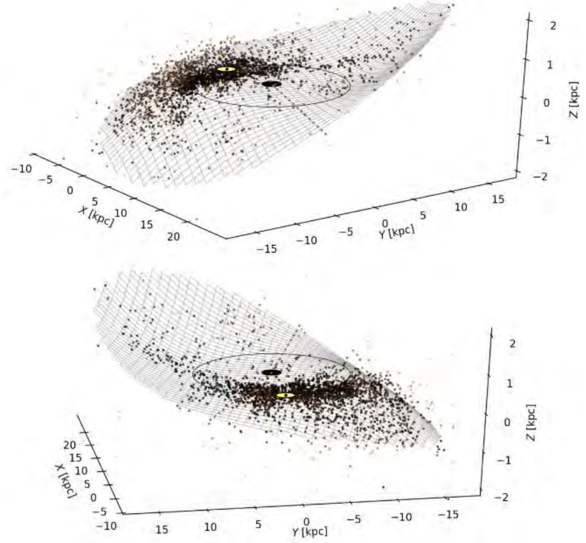


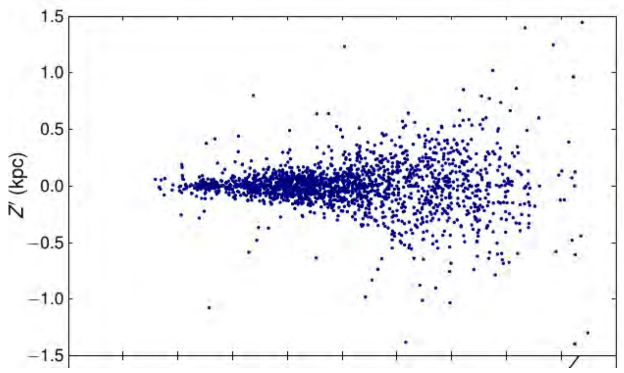
Figure 3 | Location of the observed eclipsing systems in the LMC. Most of

Geometric distance to the LMC

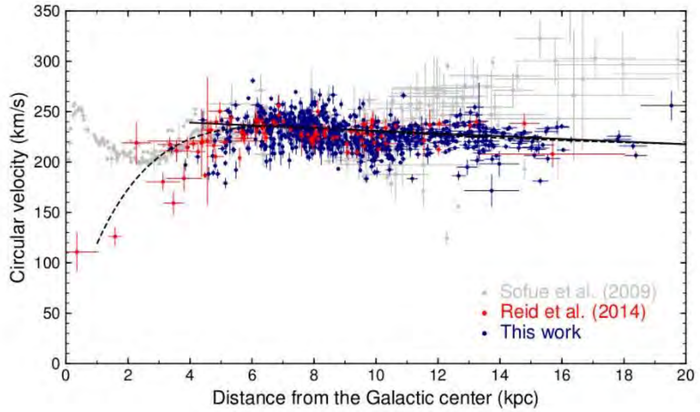
Milky Way and MCs Structure



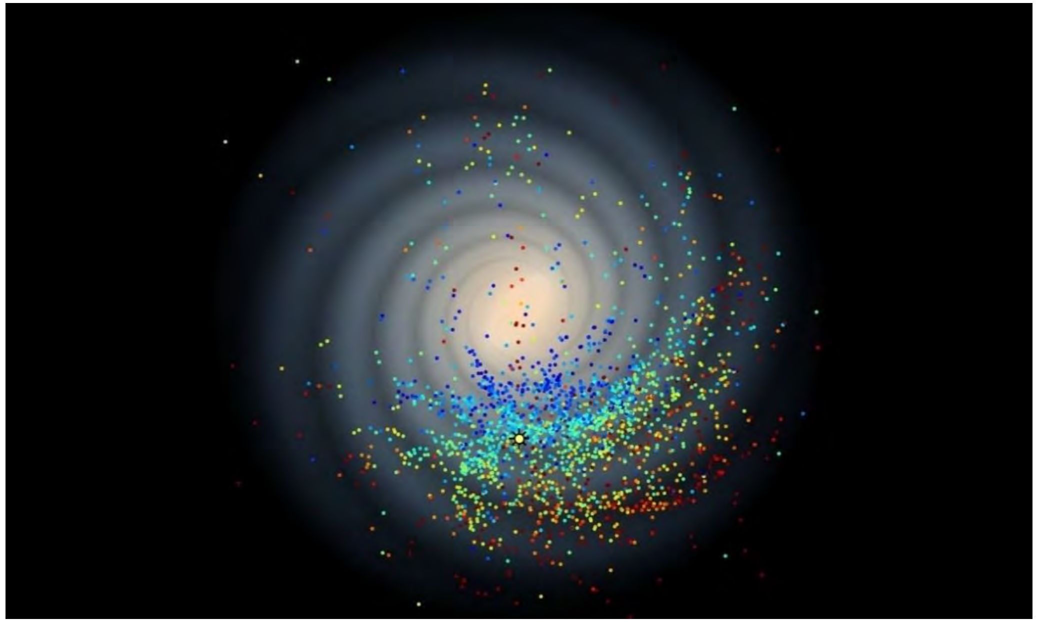
Galactic disk warp



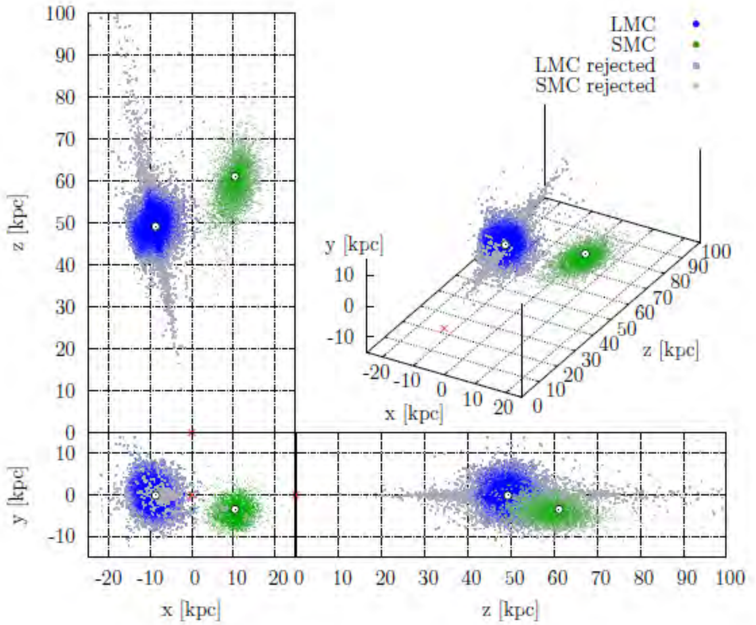
Galactic disk flaring



Galactic rotation curve



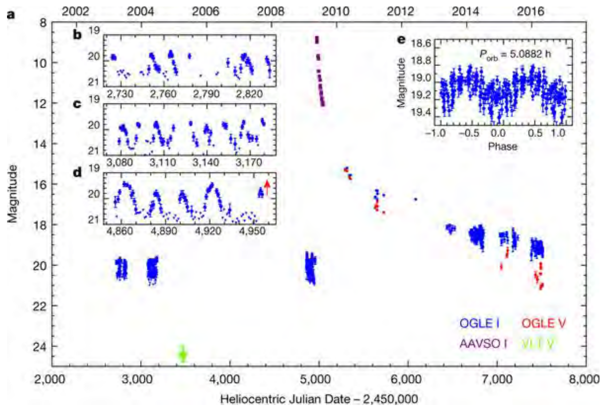
Milky Way top view and age tomography

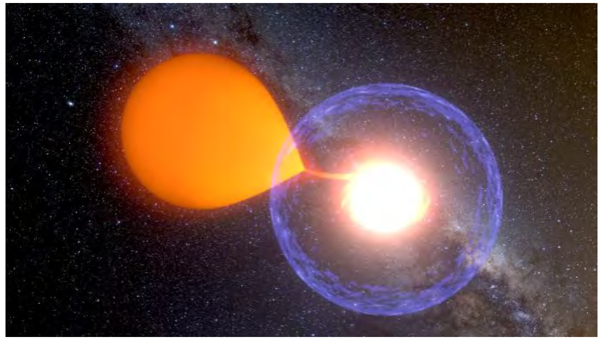


Magellanic Clouds 3D structure

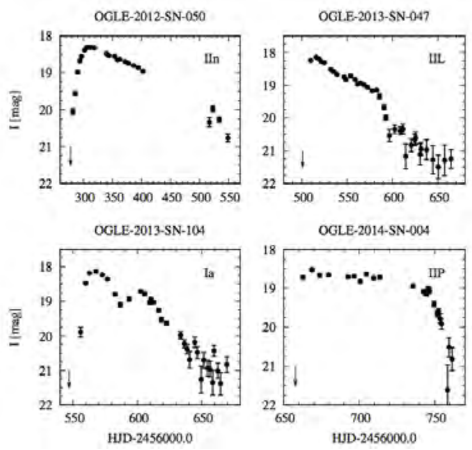
OGLE Transients

- ~2000 Microlensing Events / Season
- ~150 Novae
- >1000 Dwarf Novae
- >1000 SNe

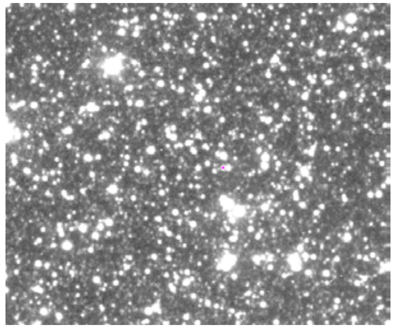


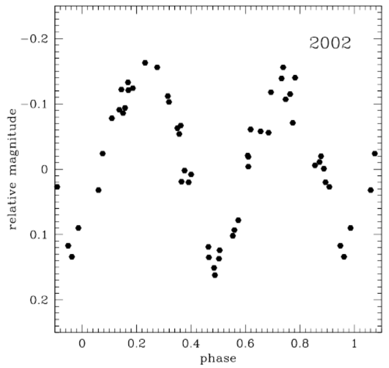


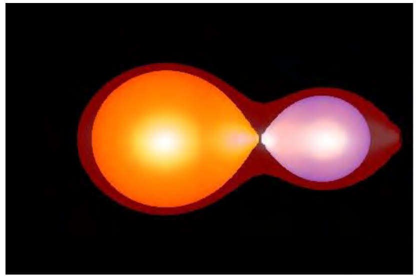
Novae (**Nova Centauri 2009**)

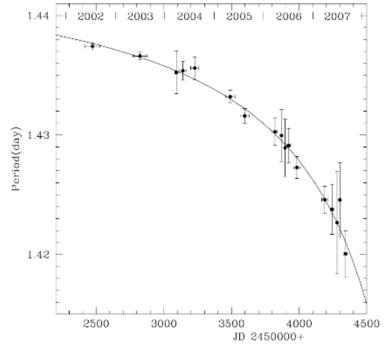


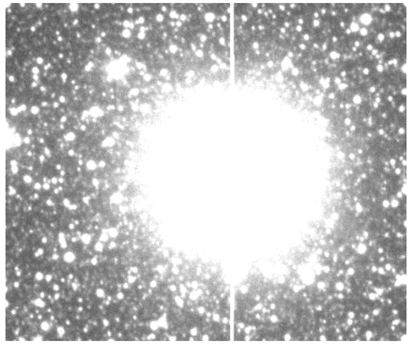
SNe

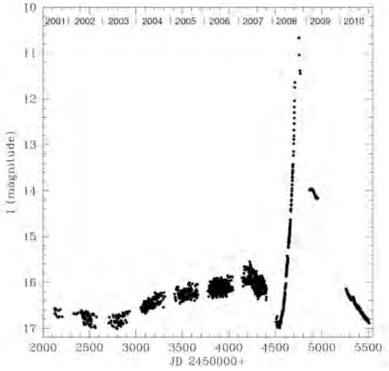










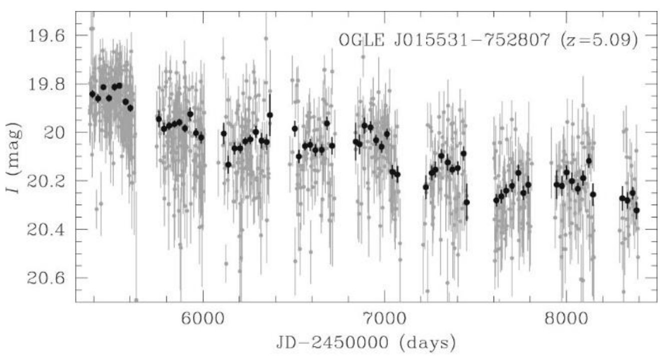


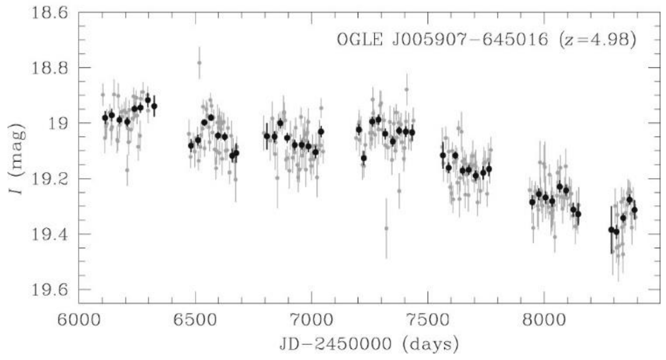
V1309 Sco Red Nova – the first well documented stellar merger

Covering the Whole Universe:

OGLE

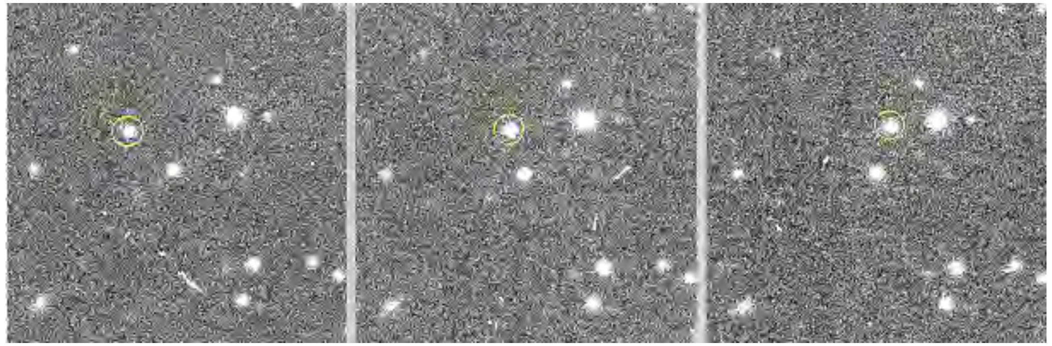
z ~ 5 quasars





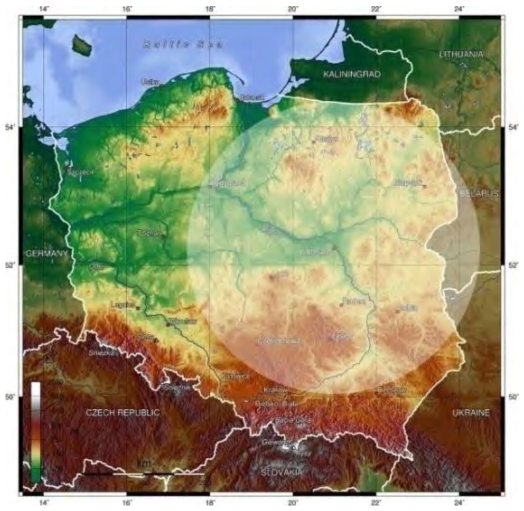
OGLE

Trans Neptunian Objects



DZIEWANNA (2010 EK 139)

April 15, 2018

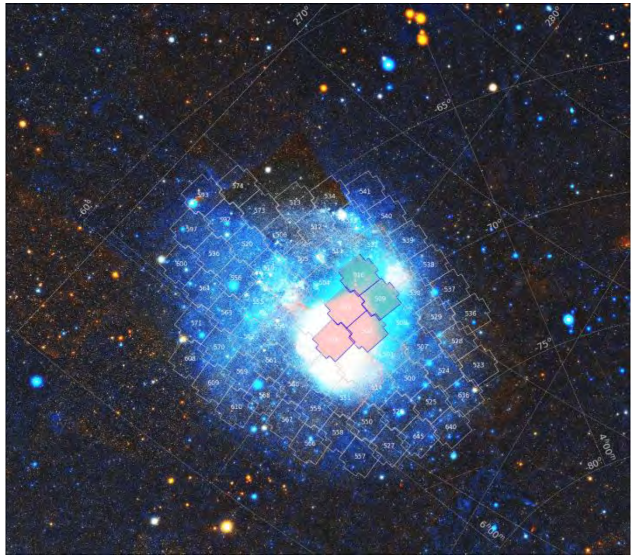


D ~ 500 km
(*Herschel*)

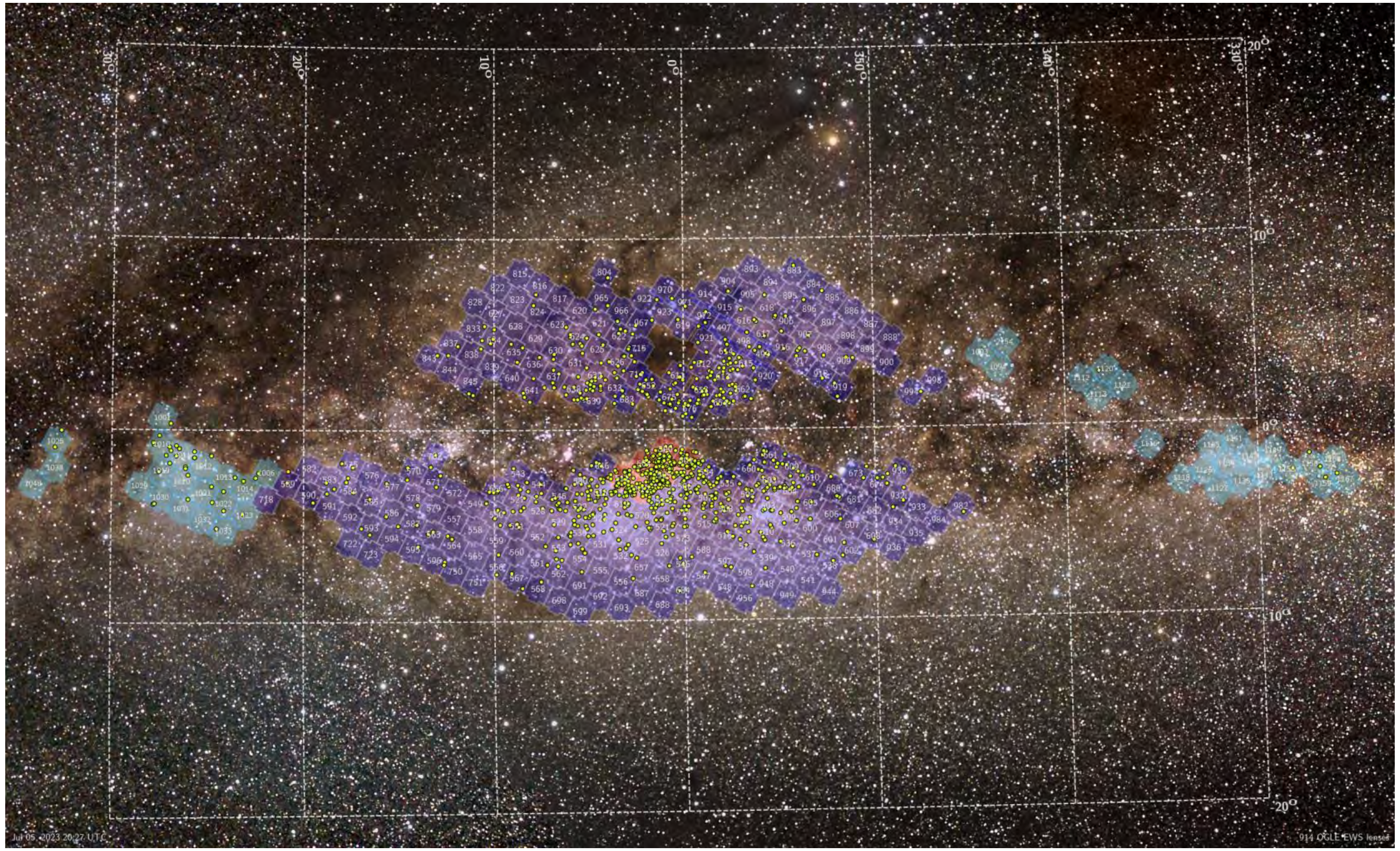
Slavic Goddess of the wild nature

Post-CoViD OGLE

- Regular observations resumed on August 12, 2022
- New observing strategies:



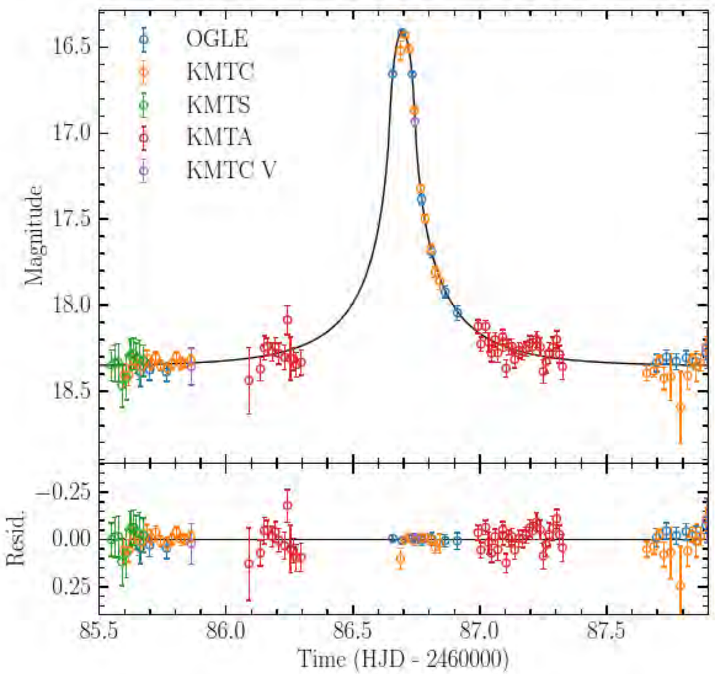
MCs (LMC)



BIG Galactic BULGE

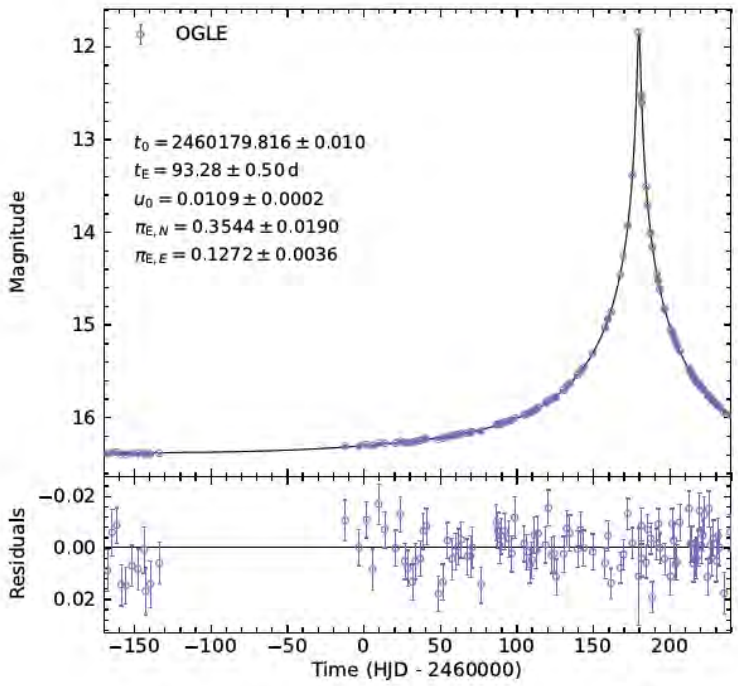
OGLE Nowadays

μLensing



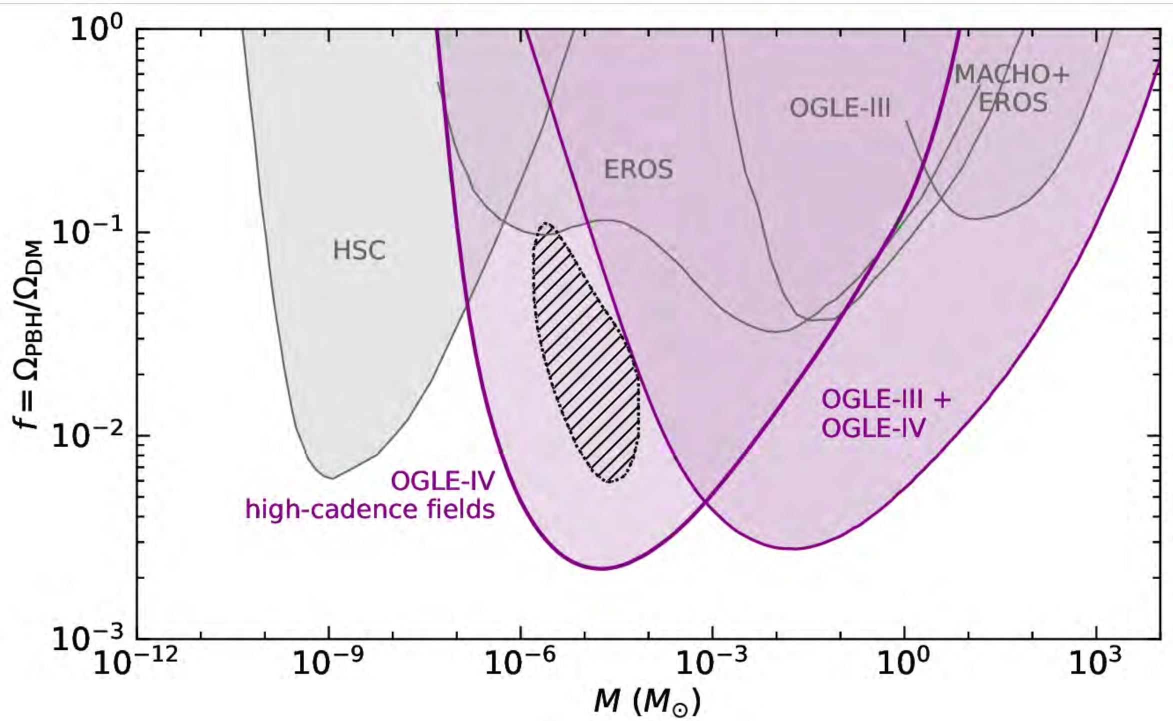
FFP

OGLE-2023-BLG-0524



Interferometry

OGLE-2023-BLG-0061

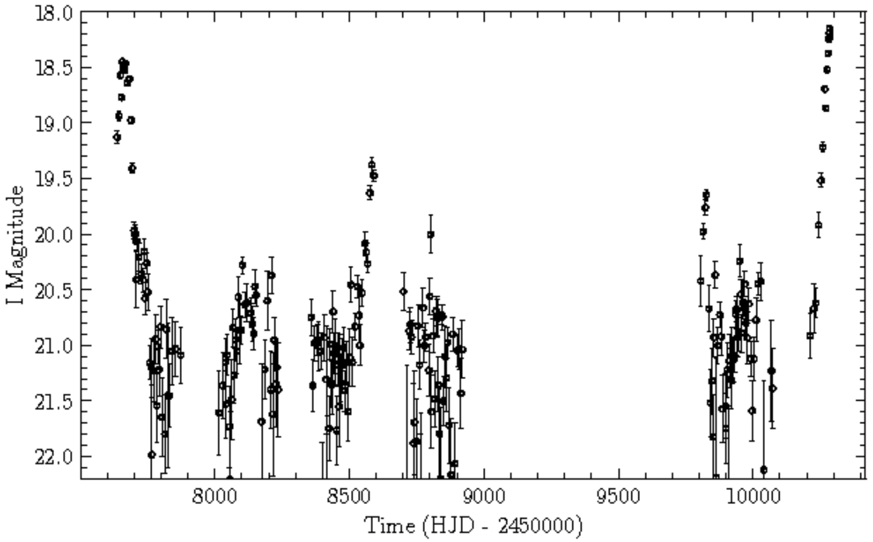


Final limits on DM

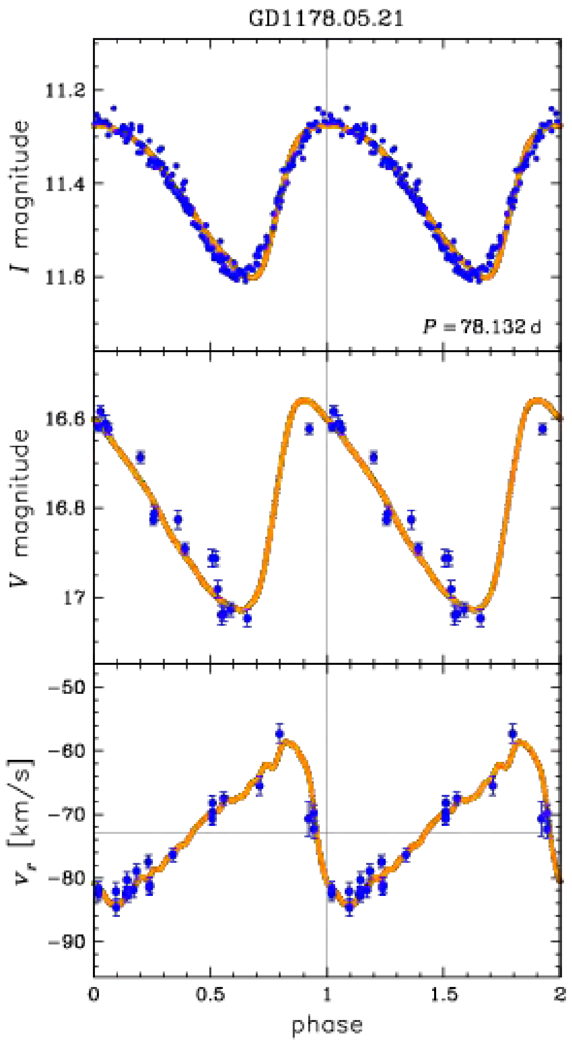
EWS: Real time μLensing (~1300 events in 2023)

OGLE Nowadays

Variable sky

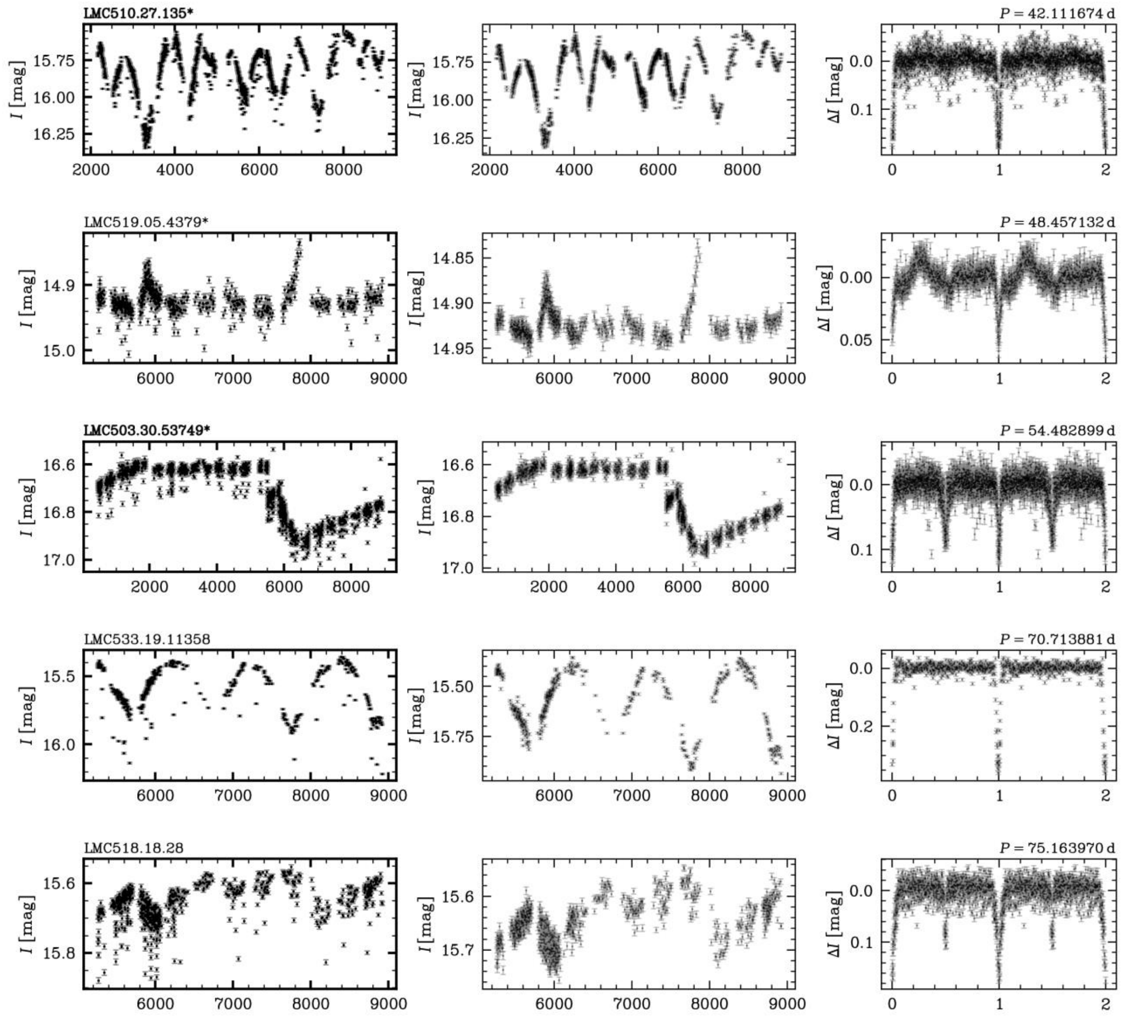


miniNova



Longest P

Cepheid in MW



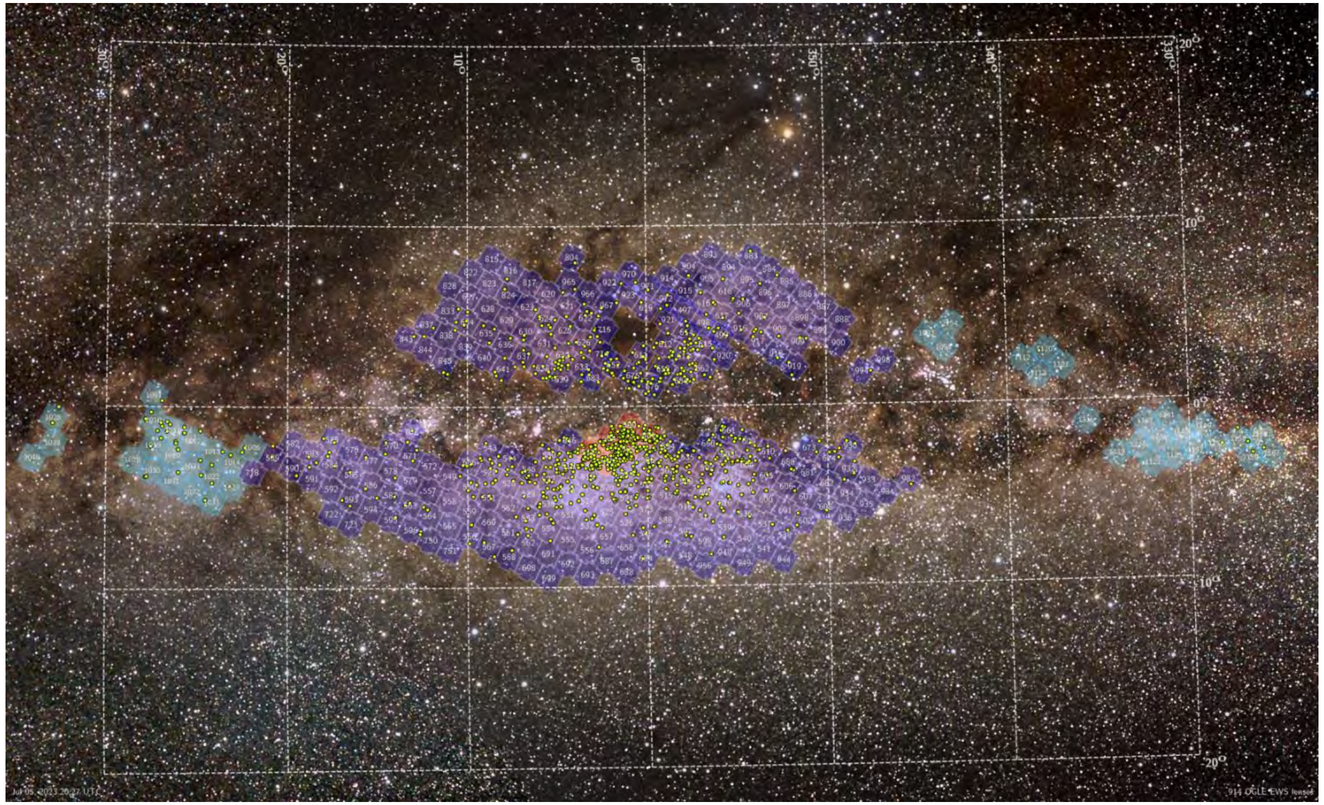
B_e stars in eclipsing systems

OGLE Nowadays

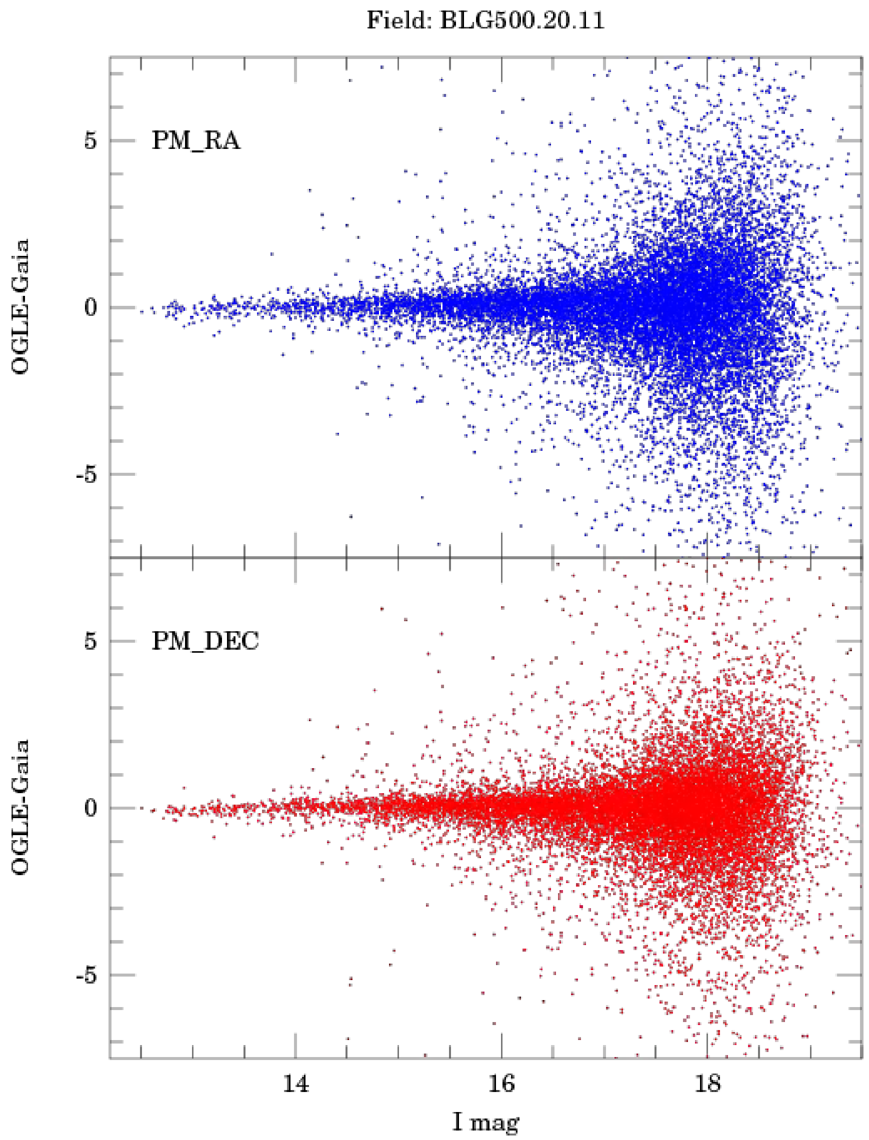
OGLE ASTROMETRY

Uranus – OGLE astrometric database

2024 – first release of the OGLE photometric & astrometric maps



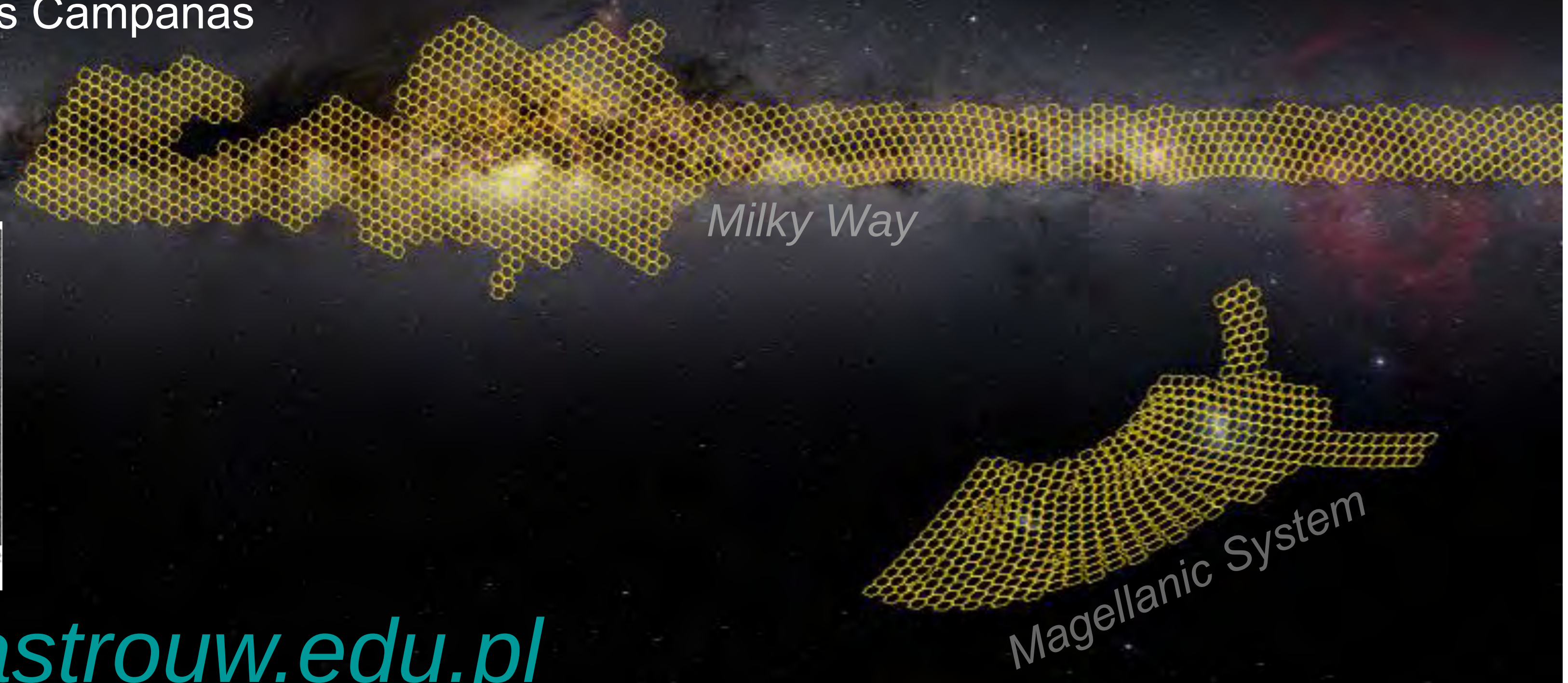
BIG Galactic BULGE

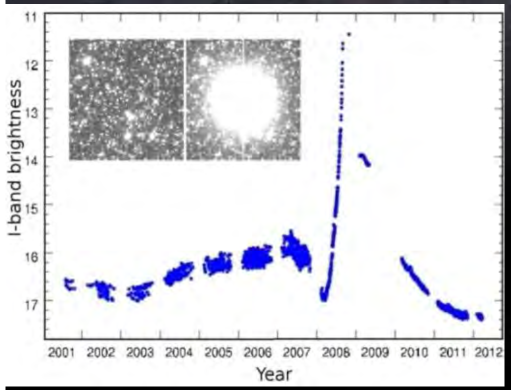


OGLE – an Extremely Large Sky Variability Survey

Warsaw 1.3-m @ Las Campanas

- in operation since 1992
- since 2010 as OGLE-IV (Udalski *et al.* 2015)
- > 4000 deg² sky coverage
- > 2.3 billion sources monitored
- 10^{12} photometric measurements by 2016
- > 22,000 microlensing detections
- > 100 extrasolar planets
- > 1,000,000 new periodic variable stars





http://ogle.astrouw.edu.pl