gaia

Search for black holes using gravitational microlensig events observed by Gaia

Katarzyna Kruszyńska, Łukasz Wyrzykowski, P. Zieliński, K. A. Rybicki, M. Gromadzki, M. Jabłońska, K. Howil, N. Ihanec et al. (Astronomical Observatory, University of Warsaw)

Seminarium Ogólne, UMK, Toruń, 30.05.2022

Outline

1) Black holes – known and unknown

2) Gravitational microlensing – history, use, surveys and future

3) Gaia and Gaia Science Alerts

4) Gaia and Microlensing

5) Constraning mass and distance to the lens explained on Gaia18cbf

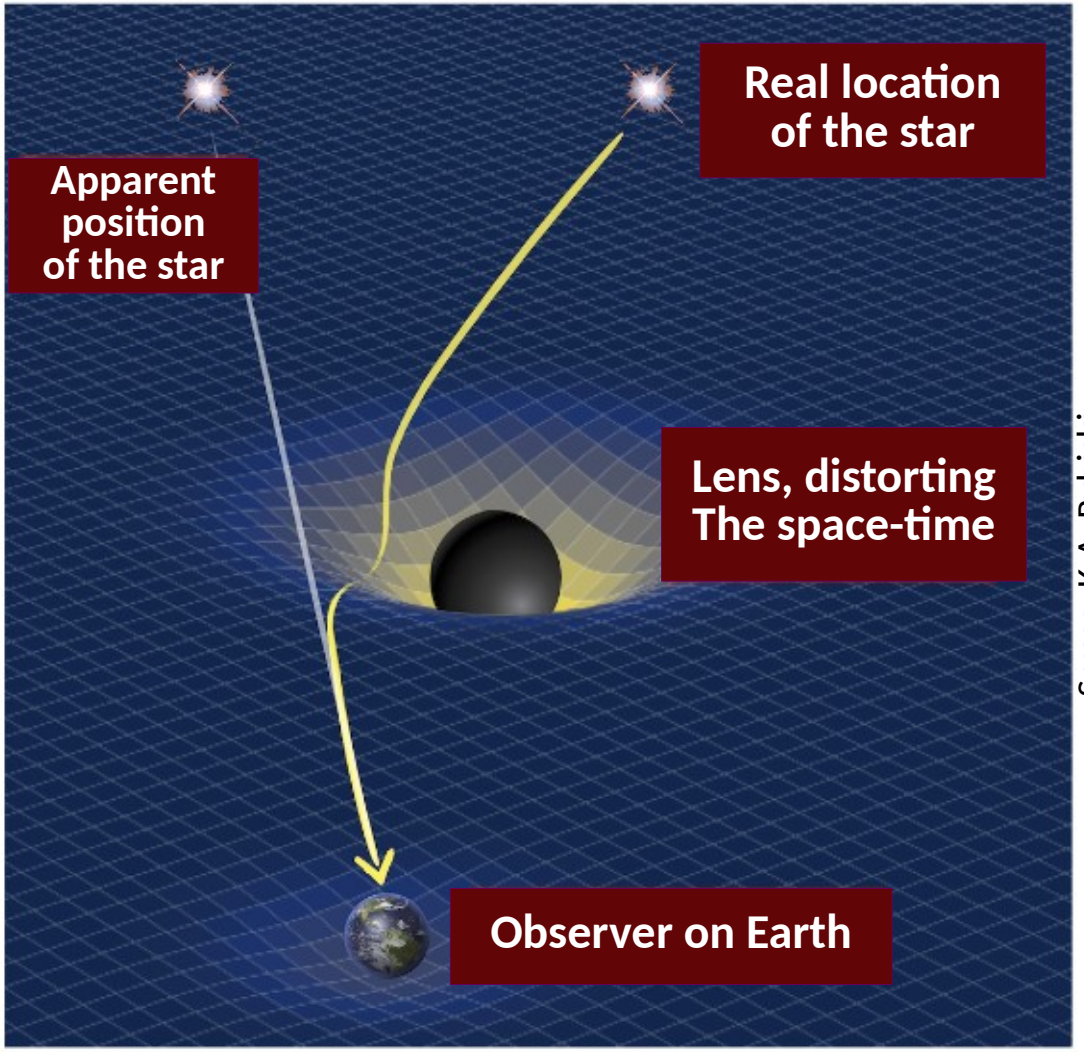
6) The Future

Black holes (and other dark remnant): What Do We Know? Do We Know Things?? Let's Find Out!

- **Distribution of remnants: where are they? Are BHs in Galactic bulge or disk or halo?**
- **How massive are the remnants and what is their mass distribution?**
- **Mass gap: does it exist or not?**
- **Natal kick velocity of remnants? Is it large or small?**
- **Source of knowledge:**
  - LIGO-VIRGO merger rates <= binary systems of two remnants
  - X ray binary systems with Bhs <= binary systems with one remnant
  - Non-interacting: Thompson et al. 2019 (mass-gap object)

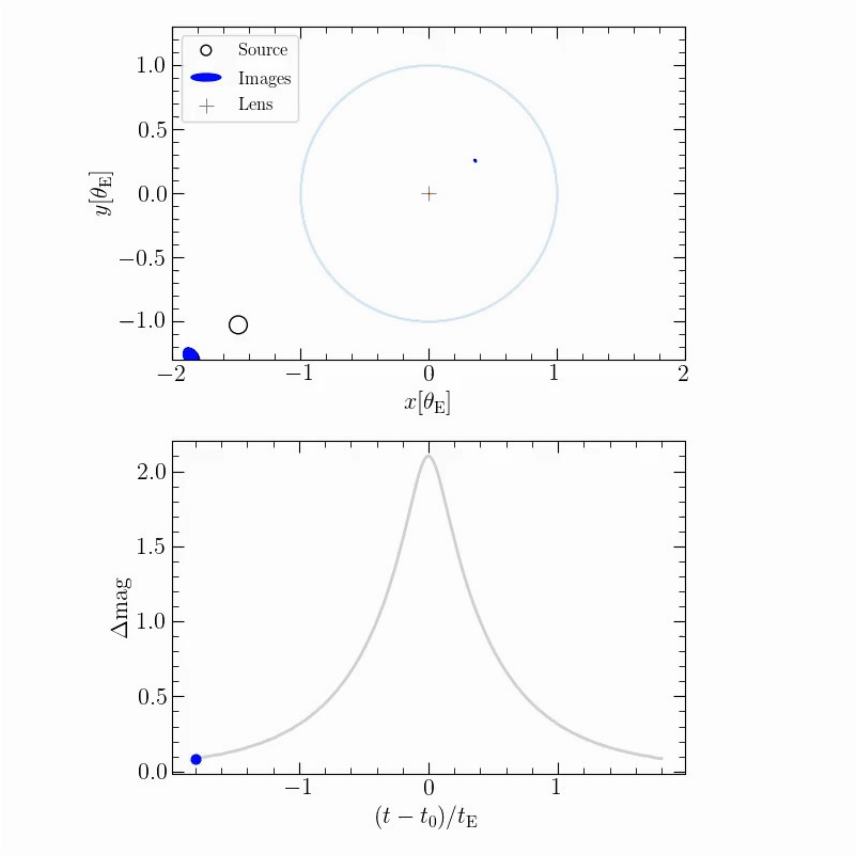
Gravitational Microlensing

- Change in brightness of a background source star due to gravitational field bending light by a foreground lens
- Can detect massive objects which don't emit light:
- Planets, white dwarfs, neutron stars, **black holes**
- Can be used to study the structure of the Milky Way (optical depth for microlensing)



Souce: K.A. Rybicki

Gravitational Microlensing



Source: https://www.astrouw.edu.pl/~krybicki/animations.php

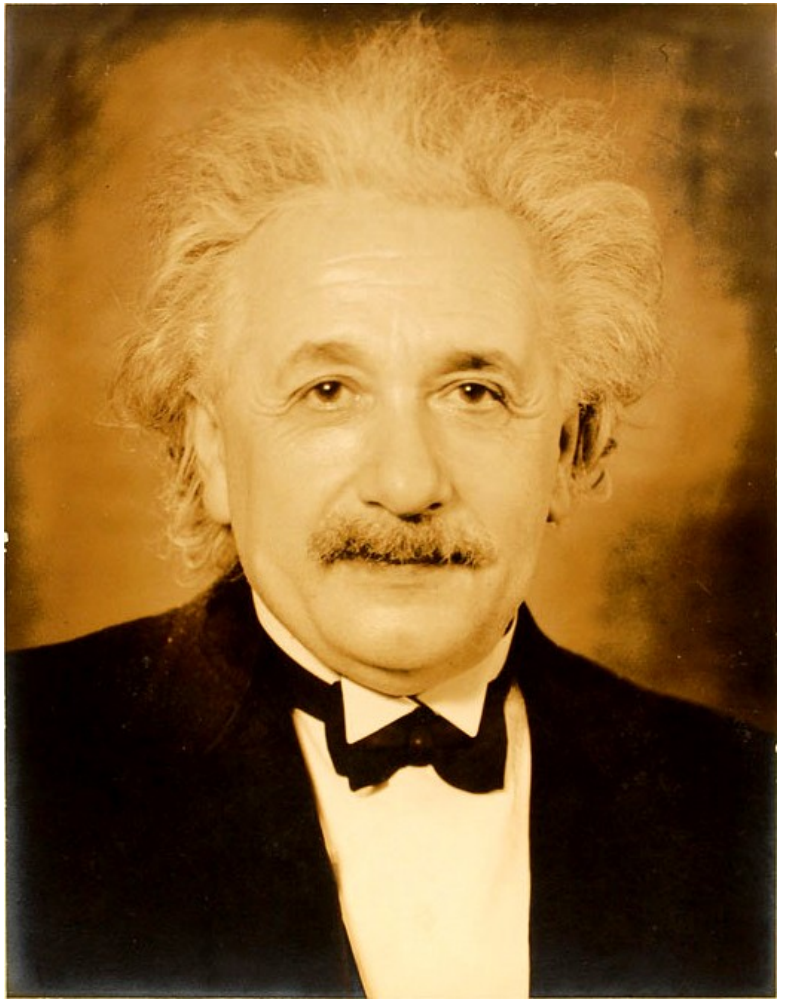
Gravitational Microlensing

- First by Einstein (1936),

  by suggestion of R. W. Mandl

  https://www.mpiwg-berlin.mpg.de/Preprints/P160.PDF

  https://www.sciencenews.org/blog/context/amateur-who-helped-einstein-see-light
- Theoretical ground-work:Liebes (1964), Refsdal (1964)
- Revival: Paczynski (1986)



Einstein in 1935, Princeton,
Source: https://en.wikipedia.org/wiki/Albert_Einstein

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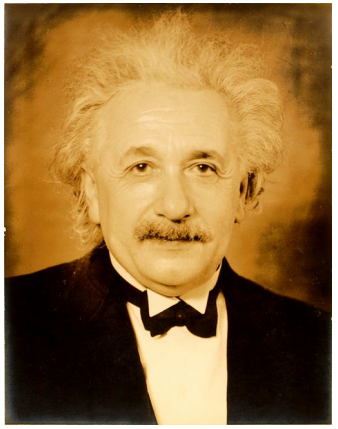

PROPOSES EINSTEIN TEST

Rudi W. Mandl, as he washed dishes in a restaurant, worked out an astronomical test of the relativity theory that won the approval of Professor Einstein and was published by him.

Source: https://www.sciencenews.org/archive/attic-genius-wins-einsteins-approval-relativity-test

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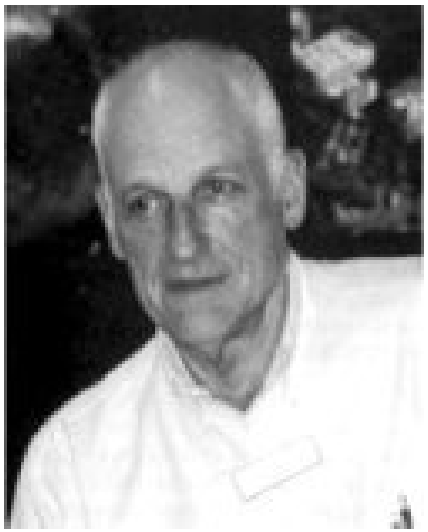

Sidney Liebes

Sjur Refsdal

Source:
https://www.globalcommunity.org/wtt/walk_bio.shtml
https://en.wikipedia.org/wiki/Sjur_Refsdal

PHYSICAL REVIEW JOURNALS ARCHIVE
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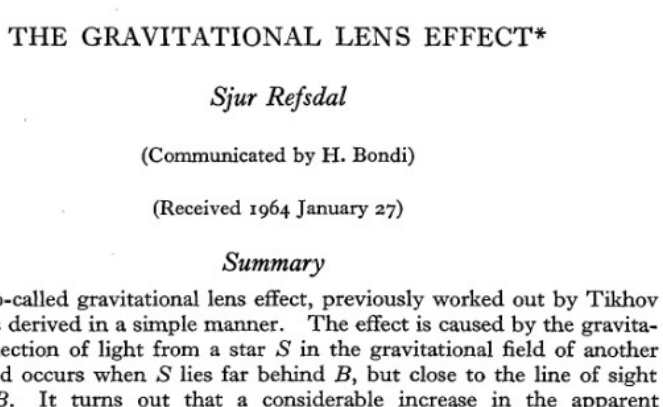
Gravitational Lenses

Sidney Liebes, Jr.
Phys. Rev. **133**, B835 – Published 10 February 1964

Article References Citing Articles (195) PDF Export Citation

ABSTRACT

A stellar gravitational lens has the capacity to intensify by a factor in excess of 1000 the image of



THE GRAVITATIONAL LENS EFFECT*

Sjur Refsdal

(Communicated by H. Bondi)

(Received 1964 January 27)

Summary

The so-called gravitational lens effect, previously worked out by Tikhov in 1937, is derived in a simple manner. The effect is caused by the gravitational deflection of light from a star S in the gravitational field of another star B, and occurs when S lies far behind B, but close to the line of sight through B. It turns out that a considerable increase in the apparent

Gravitational Microlensing

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Source: https://www.nature.com/articles/4471064a

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

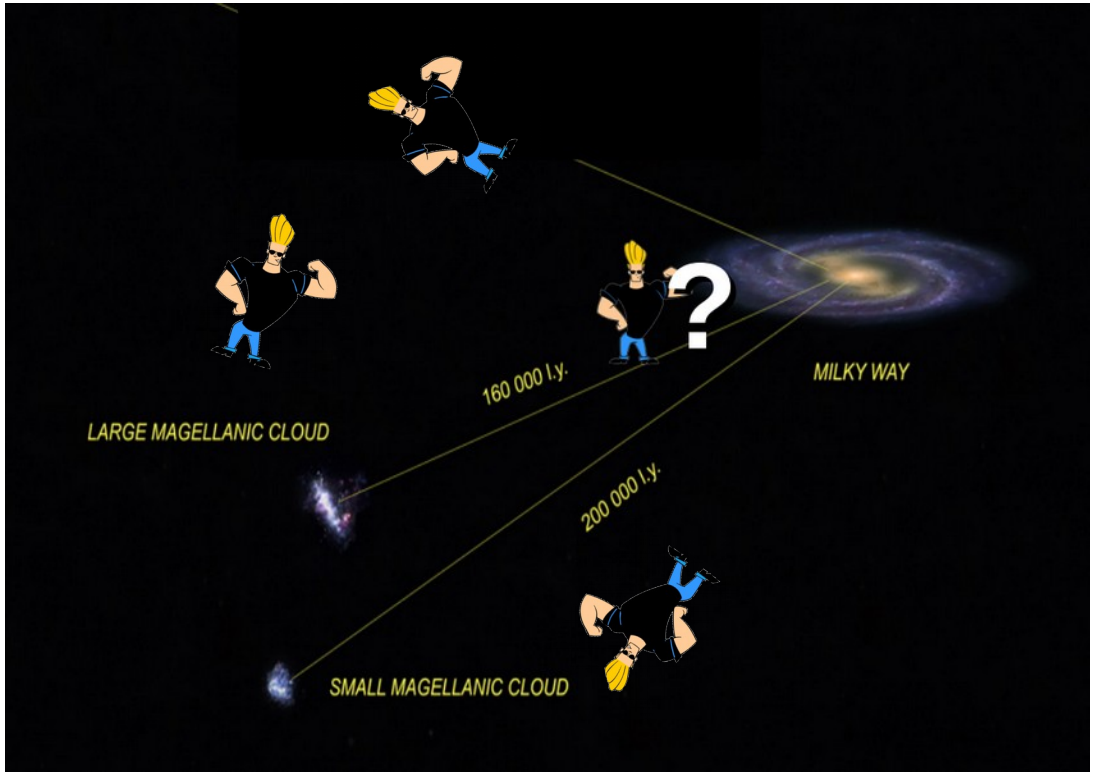
ABSTRACT

Gravitational Microlensing

- **Bohdan Paczyński → observing LMC (MACHOs)**

WIMP
Weakly
Interacting
Massive
Particle

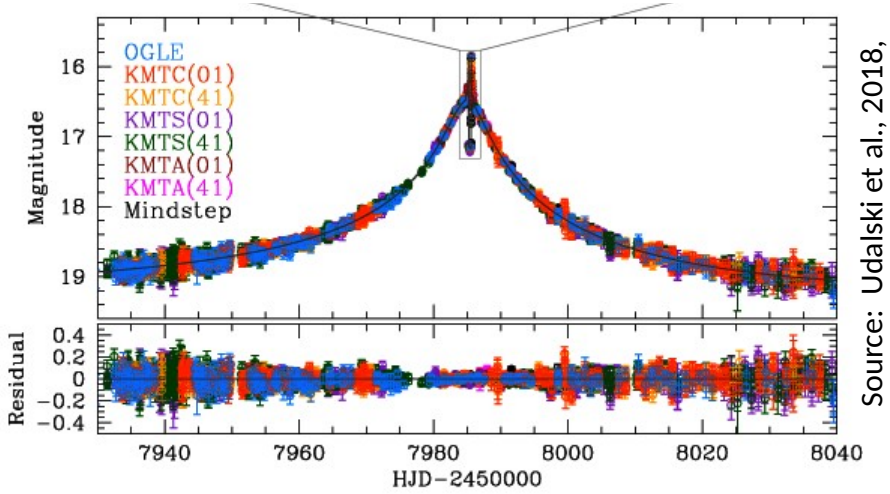
MACHO
Massive
Compact
Halo
Object



Gravitational Microlensing

- **Surveys:** MACHO, OGLE, EROS, MOA, KMTNet, ZTF
- **MACHOs →** initially proven to exist by MACHO survey (Alcock+ 1997, Bennett+ 2005), but soon ruled out by EROS (Tisserand+ 2007) and OGLE (Wyrzykowski+ 2009, 2010, 2011a,b)
- **Modern uses:**
  - Search for planets

Source: OGLE/KU-ŁW



Source: Udalski et al., 2018, Acta Astron., 68, 1

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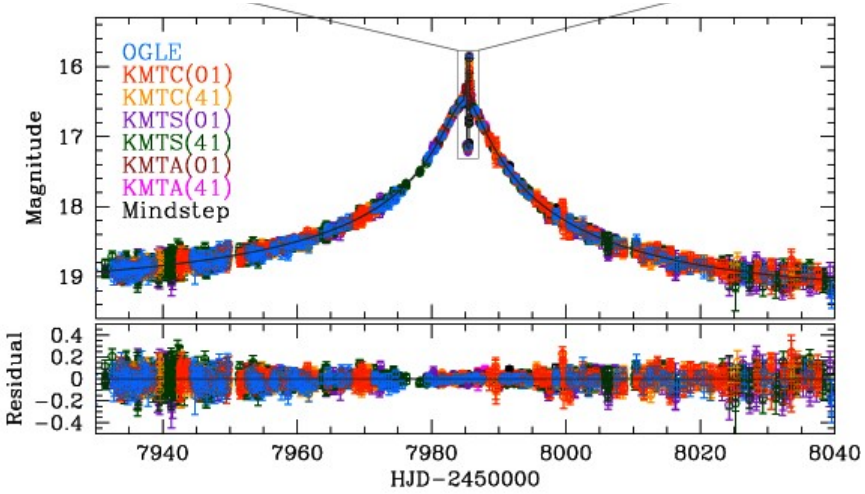
  - Search for planets
  - Future: Nancy Grace Roman Space Telescope

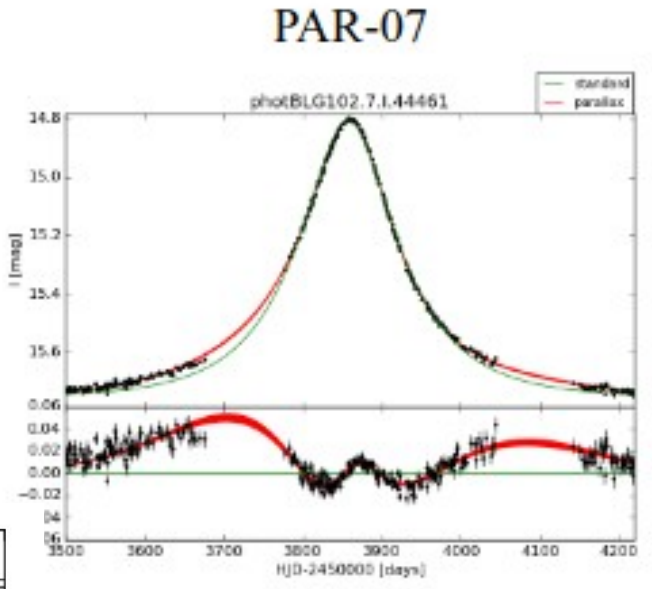


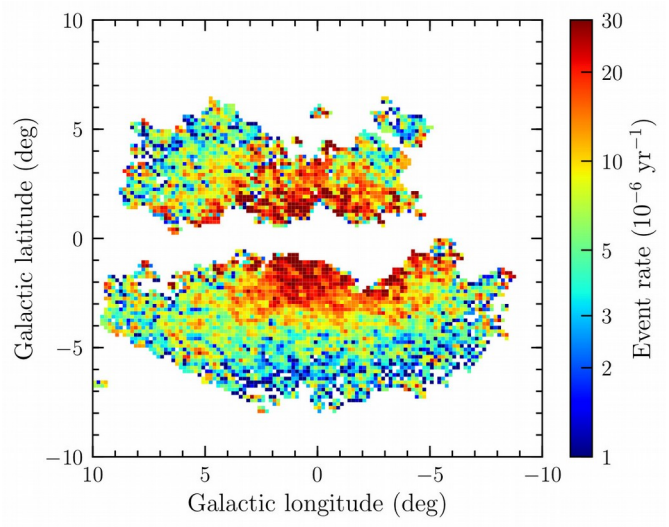
Source: Udalski et al., 2018, Acta Astron., 68, 1

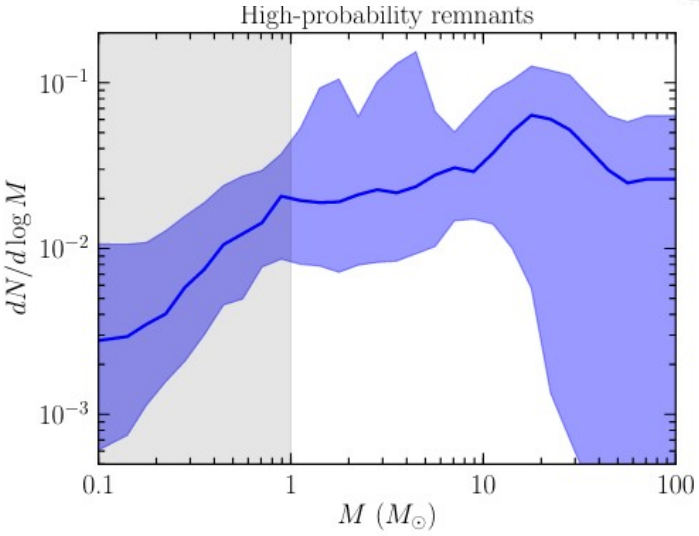
Source: NASA

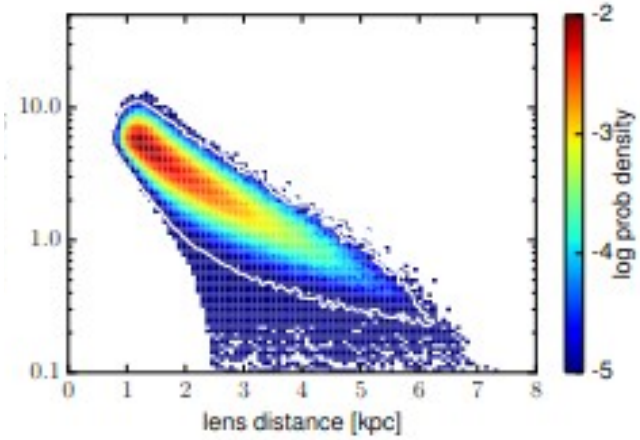
Gravitational Microlensing - history

- **Other uses:**
  - Dark remnants (Wyrzykowski et al. 2016, Wyrzykowski&Mandel 2020, Mróz et al. 2021)
  - Structure of the Galaxy (Wyrzykowski et al. 2015, Mróz et al. 2020a,b)

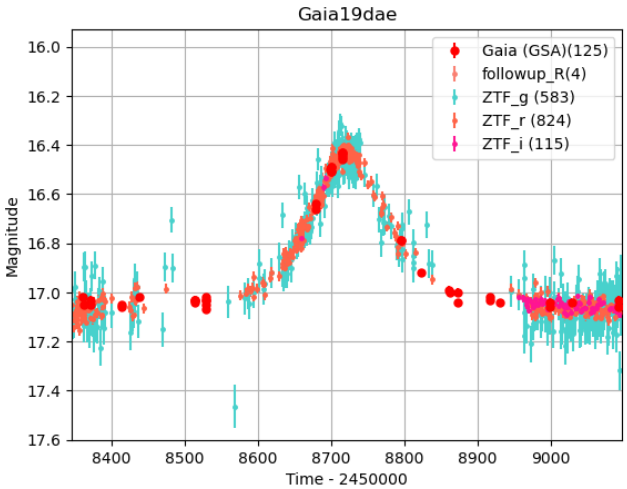








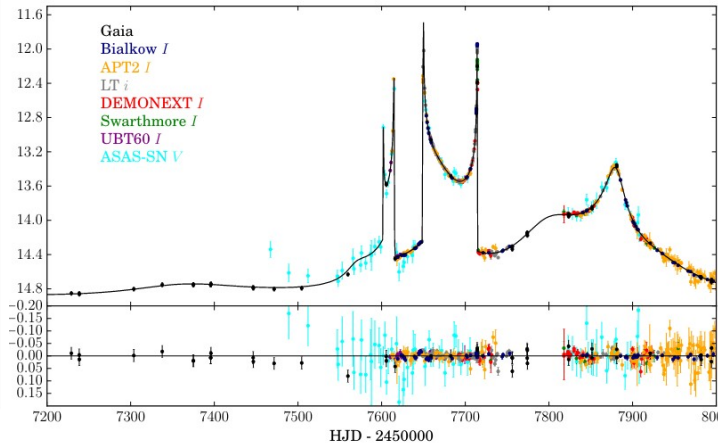
Microlensing events zoo



Single lens event

Planetary event

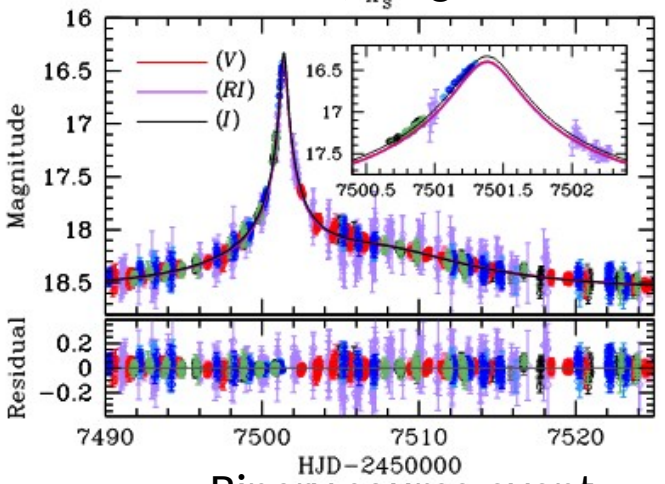
Gaia16aye, Wyrzykowski+ 2020



Binary lens event

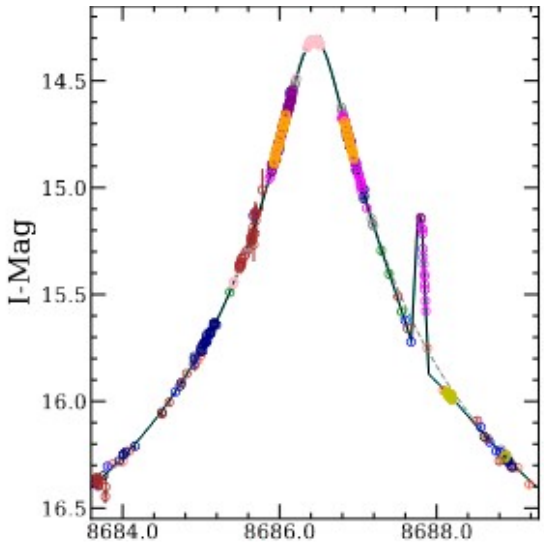
Parallax effect

OB160733, Jung+ 2017

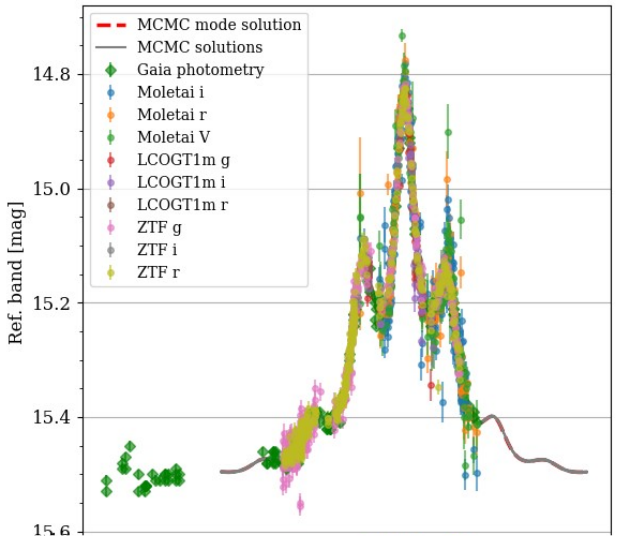


Binary source event

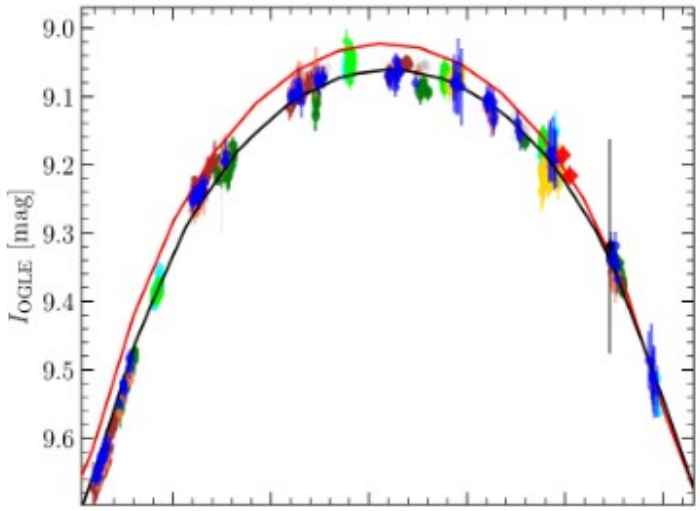
Finite-source effect



OB190960, Yee+ 2021



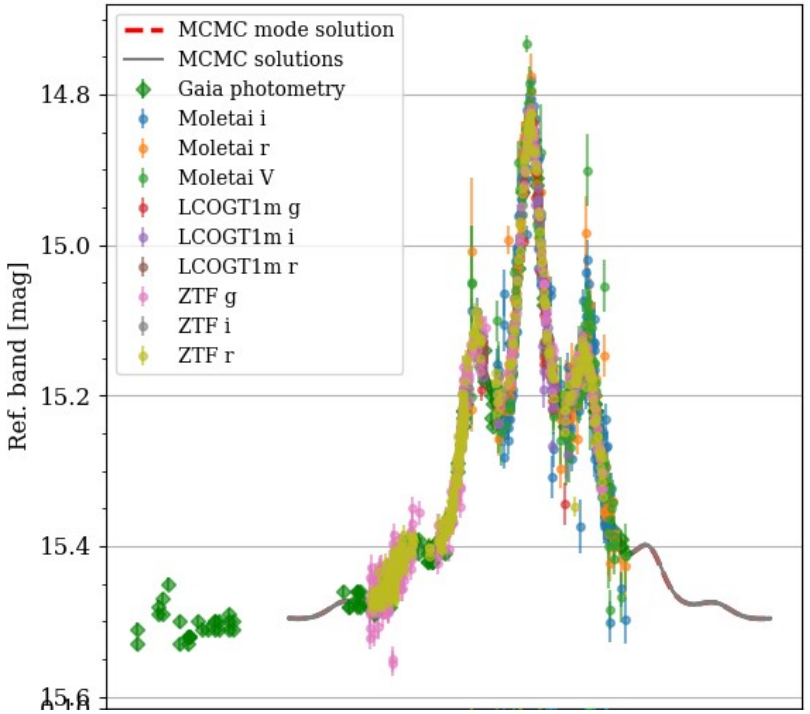
Gaia19dke, Maskoliunas+ in prep.



Gaia19bld, Rybicki+ 2022

Parallax effect

- **Movement of earth starts to be reflected in the light-curve**
- **For longer events → the lens might be massive (or moves slowly…)**



Gaia19dke, Maskoliunas+ in prep.

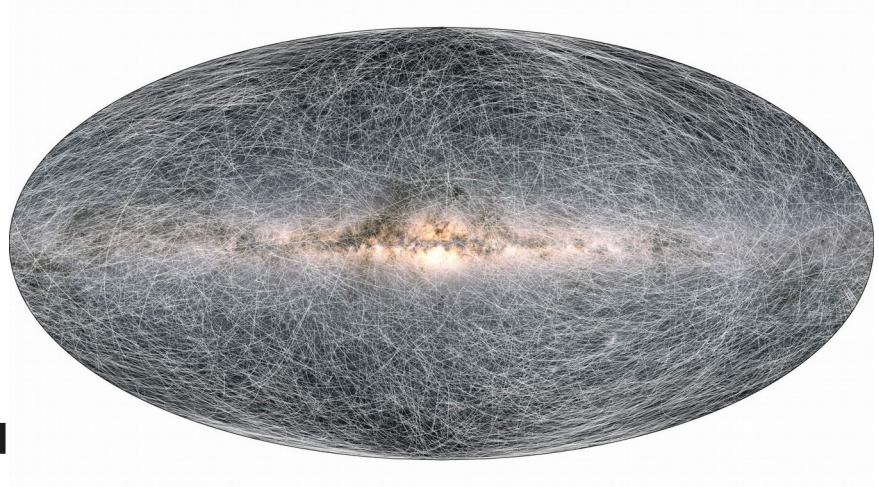
$$M_L = \frac{\theta_E}{\kappa \pi_E}$$

Einstein ring radius

Microlensing parallax

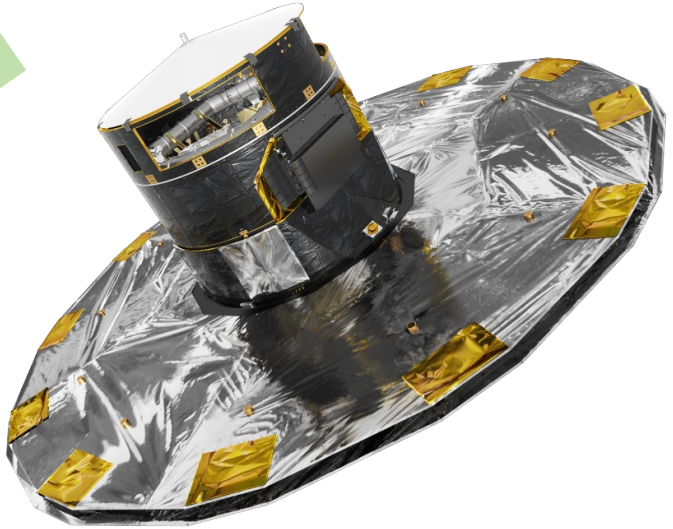
Gaia

- Launched on 19th Dec 2013 from French Guiana
- Space satellite in L2 point (distance = 1% au)
- Main goal: astrometry for 1 billion sou MW with precision down to 24 mas
- Whole sky covered 40-200 times over 5 years, cadence: 9x4s - 106min - 30 days
- Astrometric time-series!
- Data Release 2 => over 2000 papers
- Data Release 3 coming very soon!



Source: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO.

DONE!

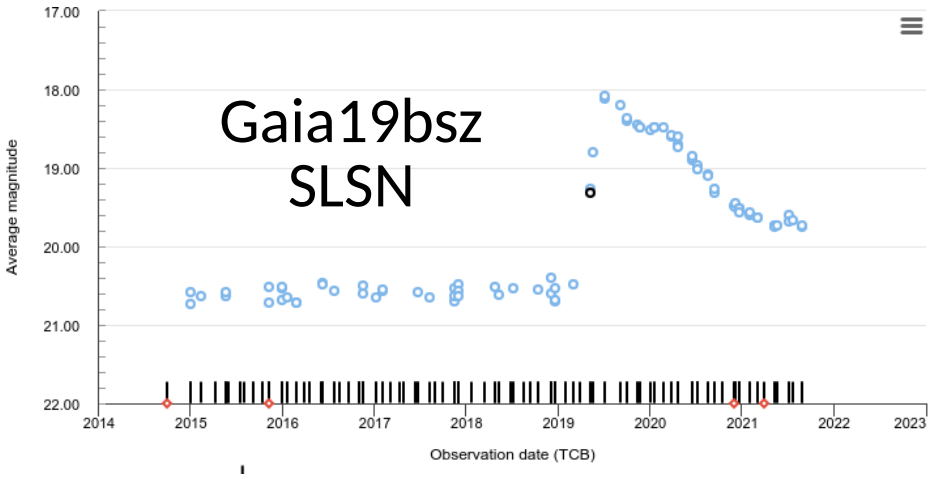


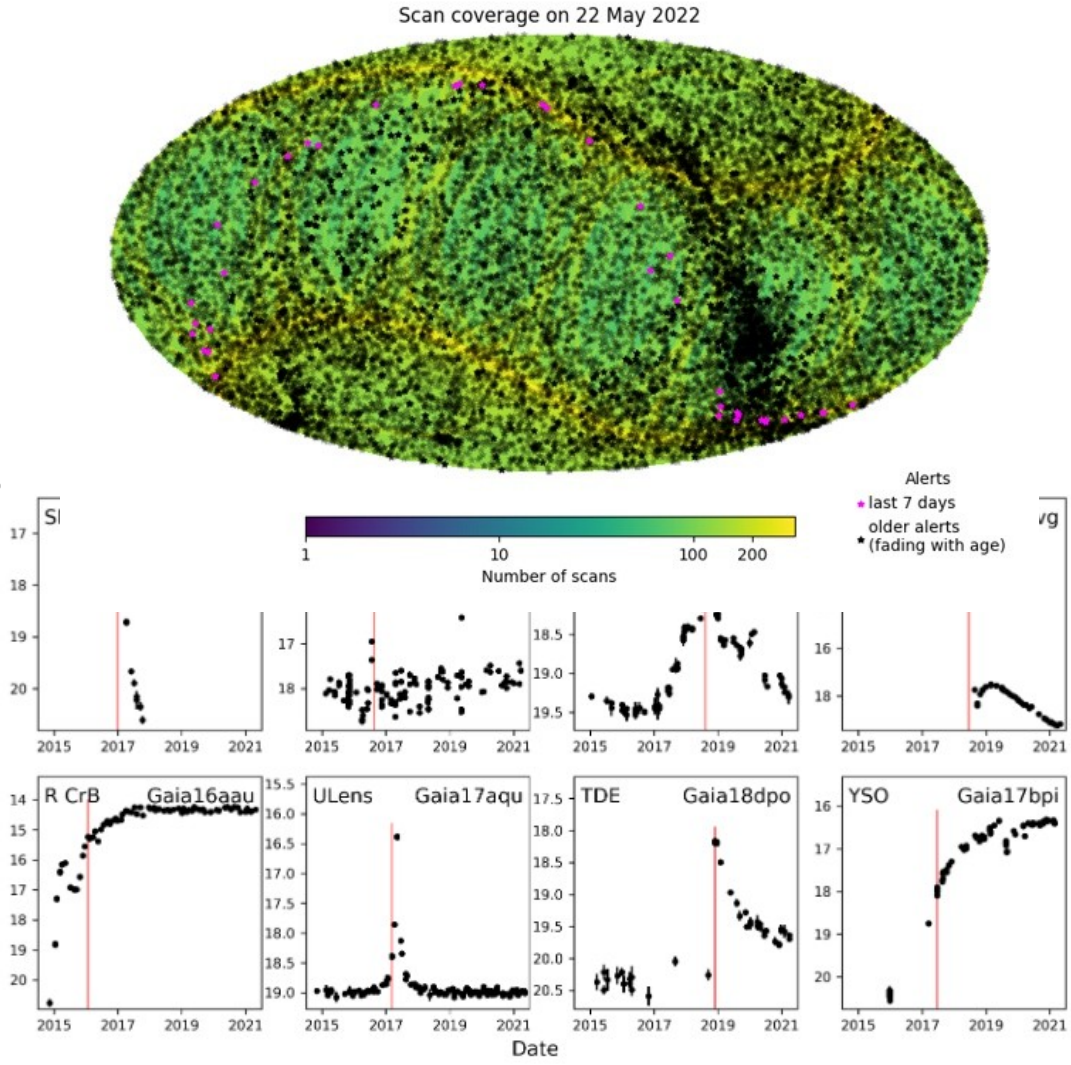
Source: ESA/Gaia/DPAC

Gaia Science Alerts

- Publishing since 2015
- 19 000+ Alerts on transients
- Mostly SNs, novae, CVs, YSOs…

  http://gsaweb.ast.cam.ac.uk/alerts
- 500+ microlensing events since 2016

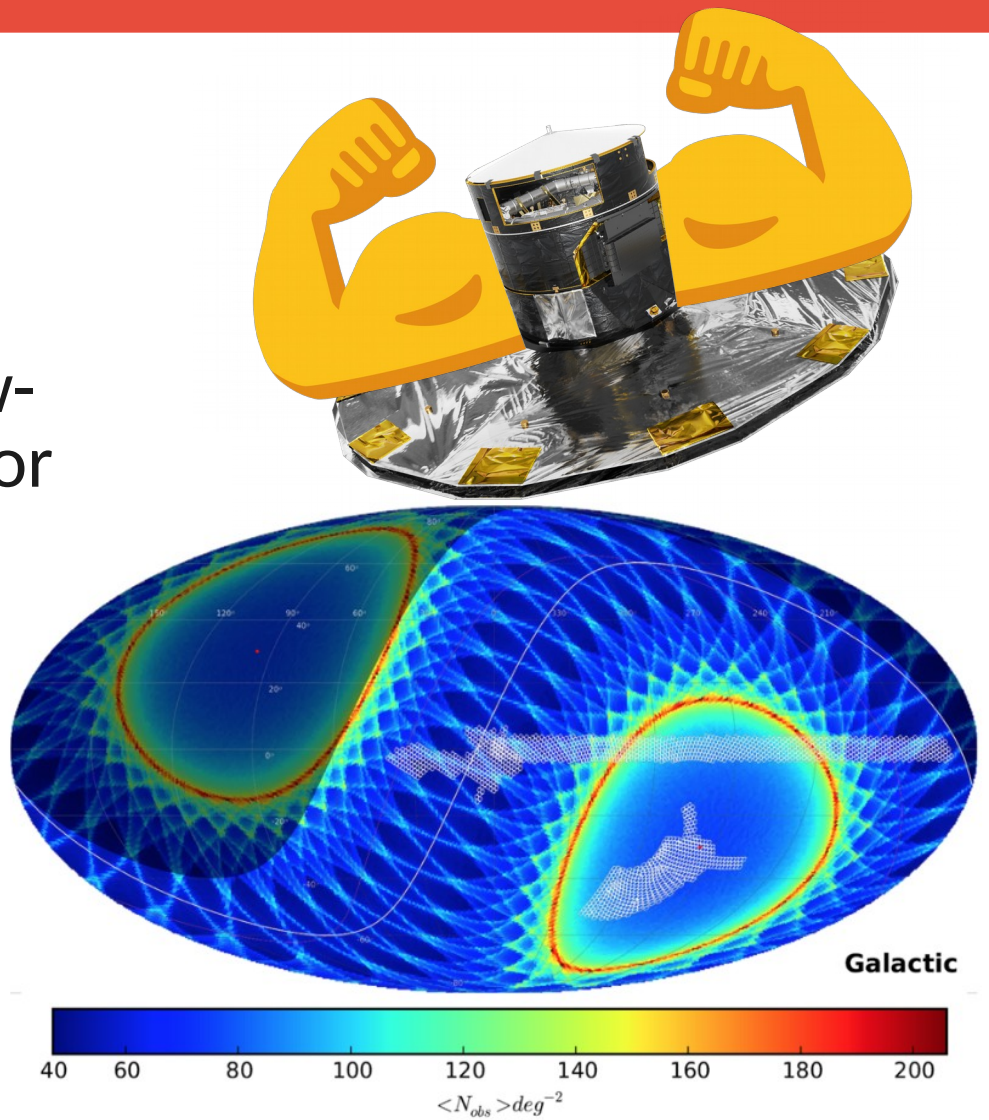




Source: Hodgkin et al. 2021

Gaia and microlensing

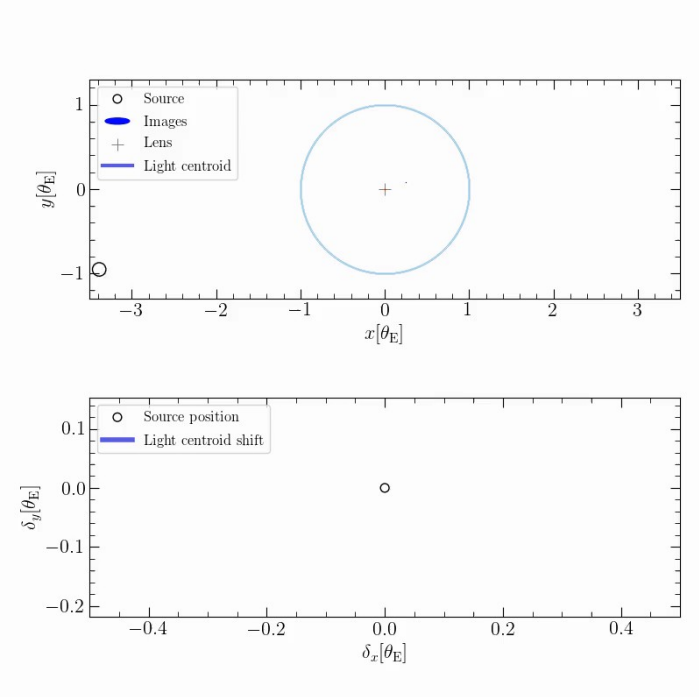
- **Strengths**
  - Observes entire Galaxy
  - Three band photometry, low-resolution spectra – useful for classification
  - Astrometric time-series!
- **Weaknesses**
  - Low-cadence (especially in Galactic Bulge)



Gaia figure by Nadia Blagorodnova, OGLE fields by Jan Skowron

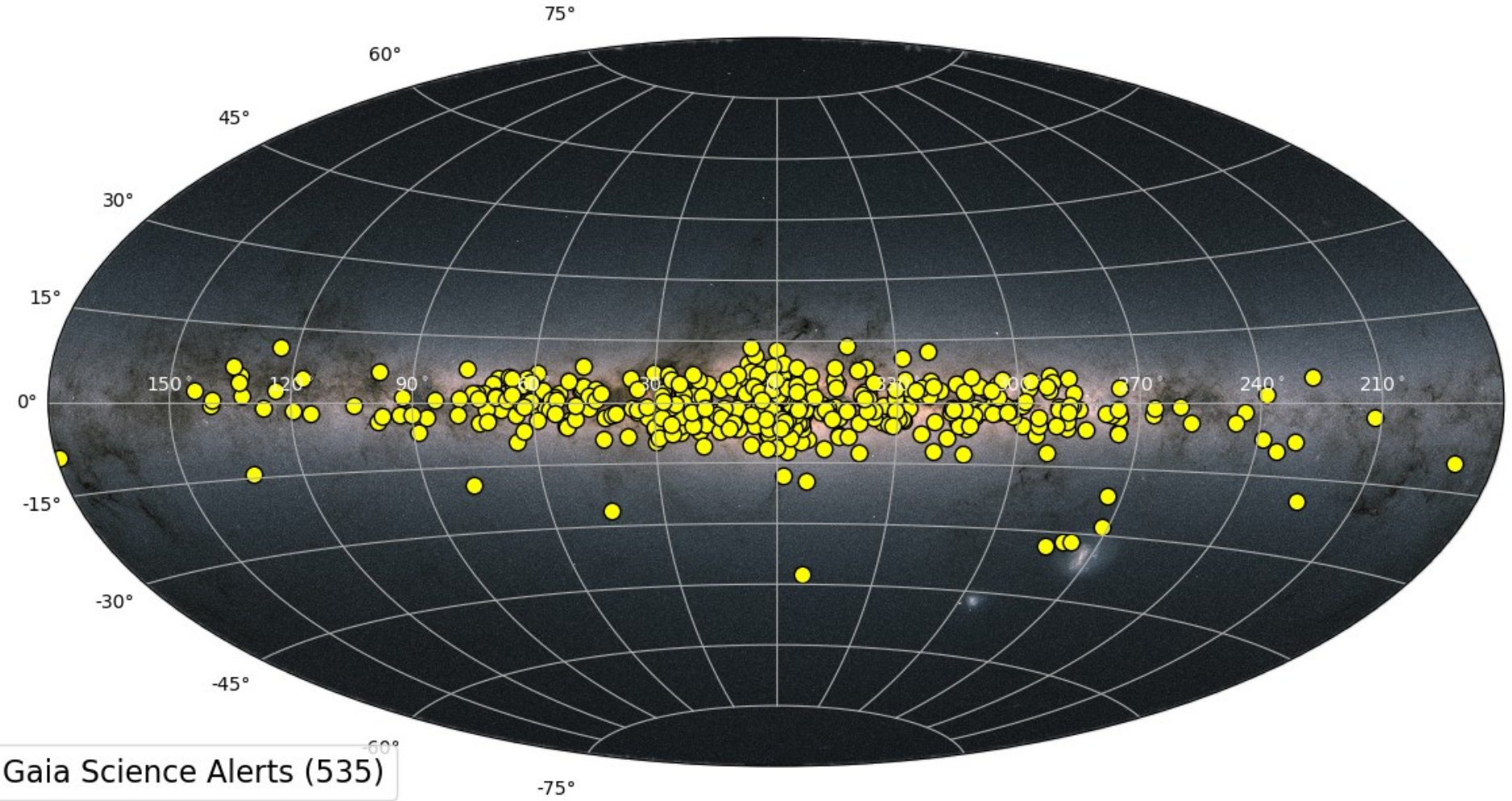
Gaia and microlensing

- **Astrometric and photometric microlensing**



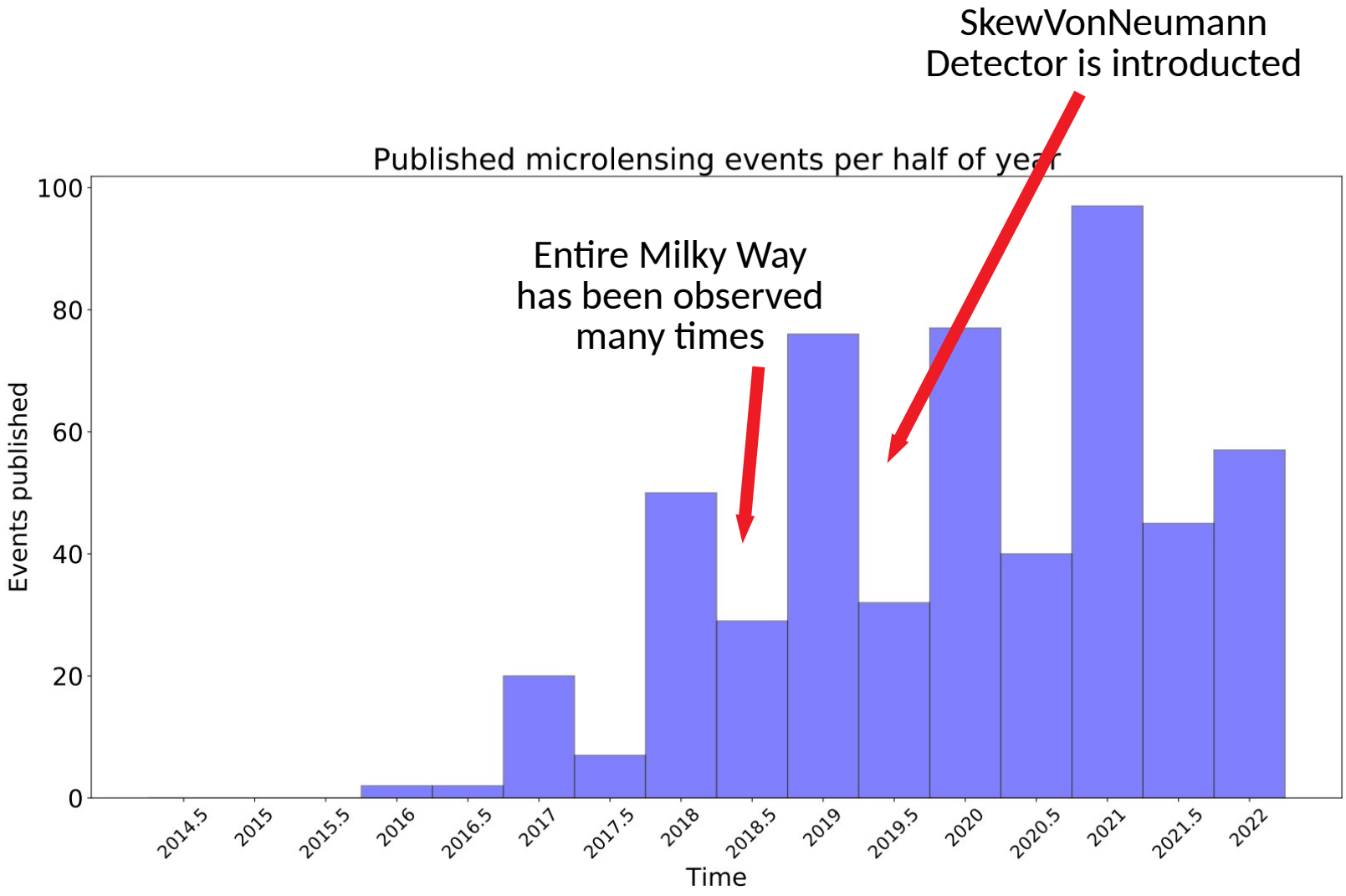
Source: https://www.astrouw.edu.pl/~krybicki/animations.php

Microlensing in Gaia Science Alerts



Background image: ESA/DPAC

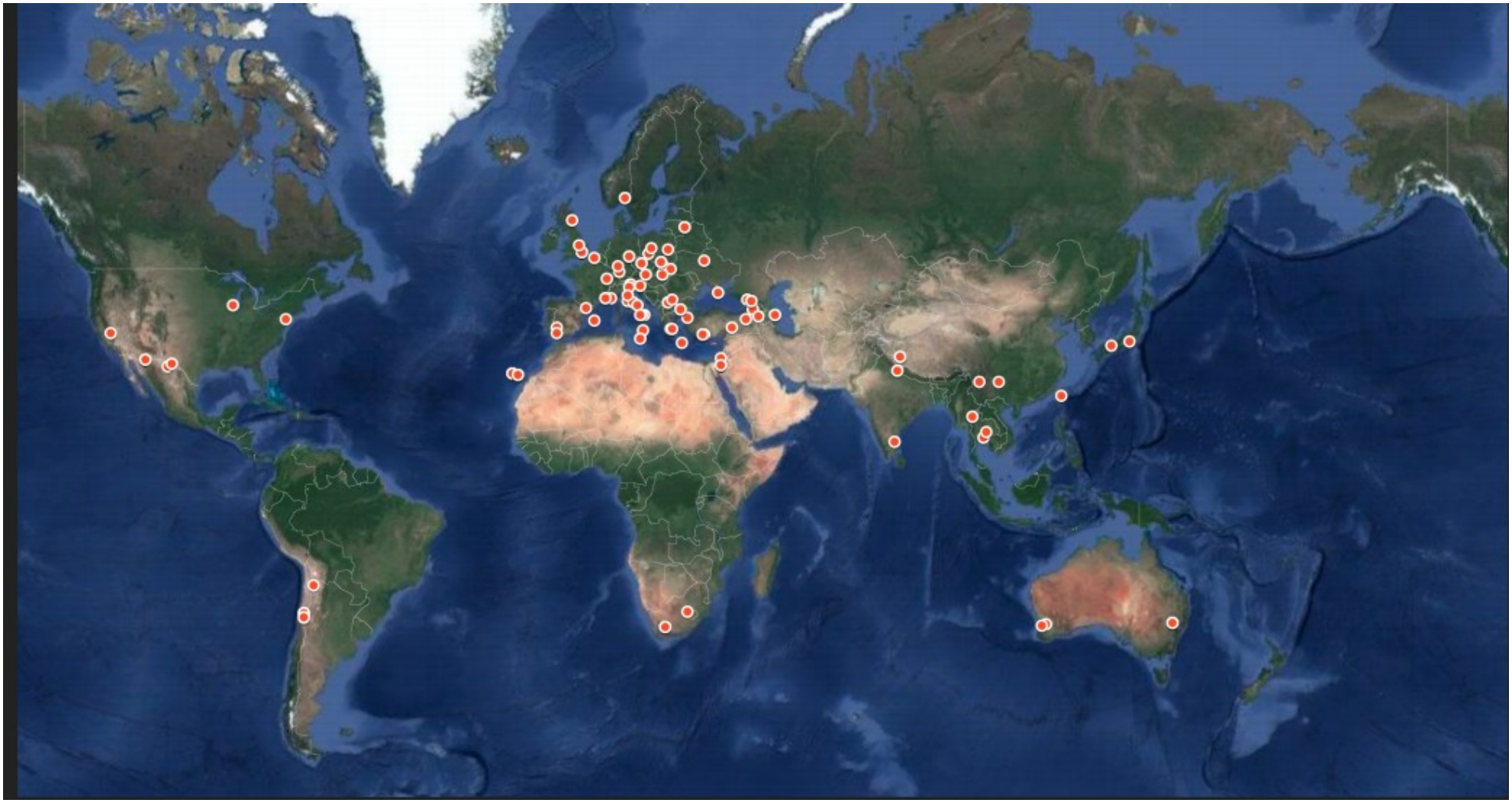
Microlensing in Gaia Science Alerts over the years



How to get better data?

- **Follow-up network! → Black Hole TOM**
- **… and applying for time with various observatories (LCO, REM, SMARTS…)**

Follow-up network



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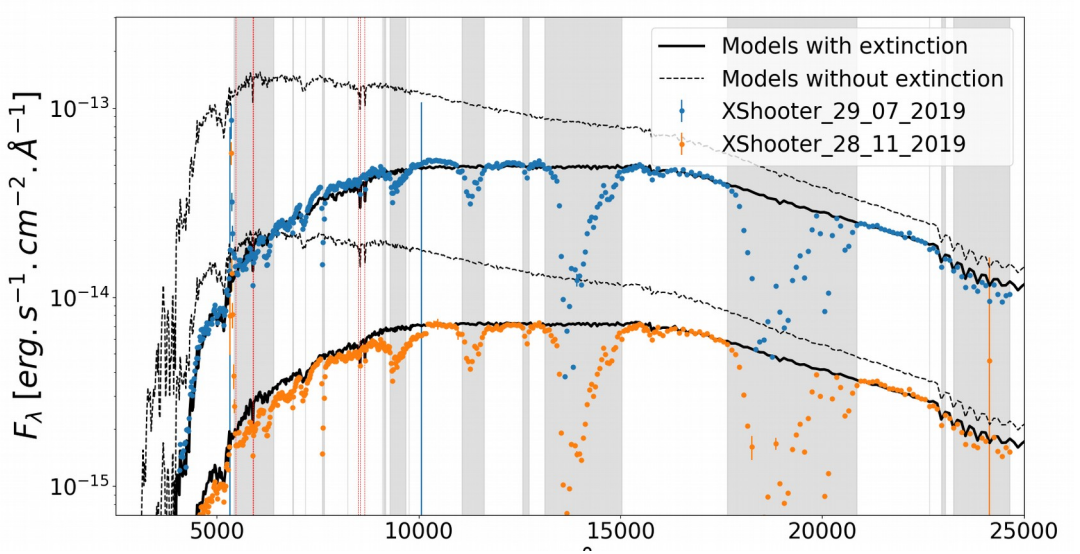
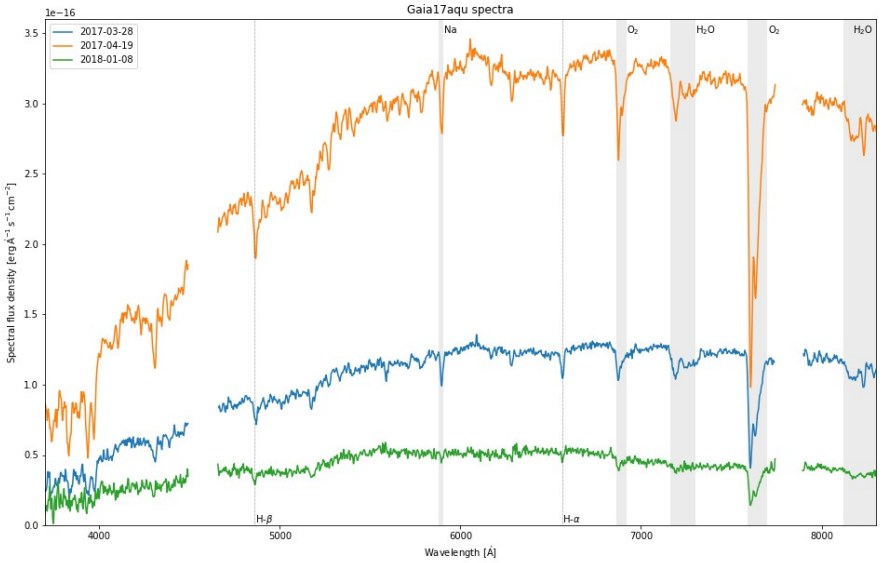
  - Low res specrosopy on LT/SPRAT… → classification
  - High res spectroscopy on RSS/SALT, VLT/XSHOOTER → source star parameters determination

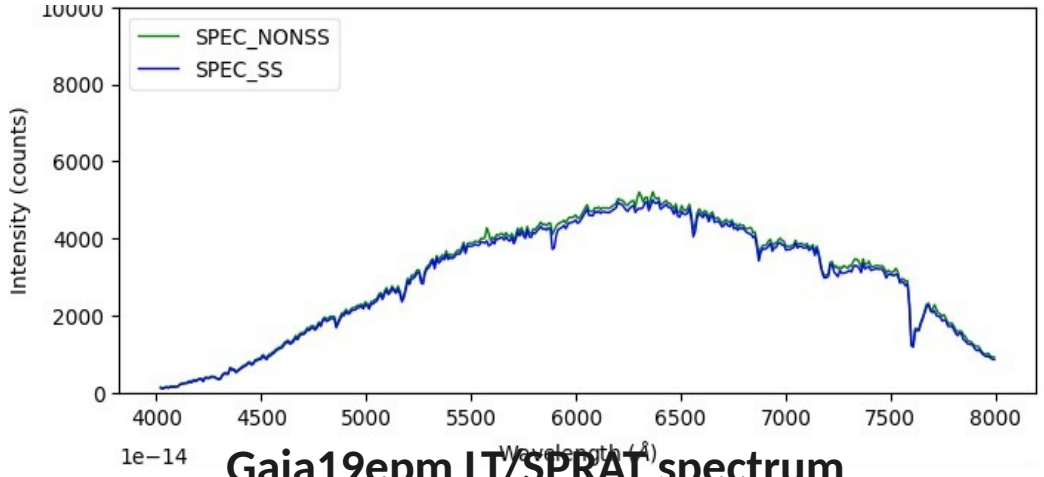
Highlights



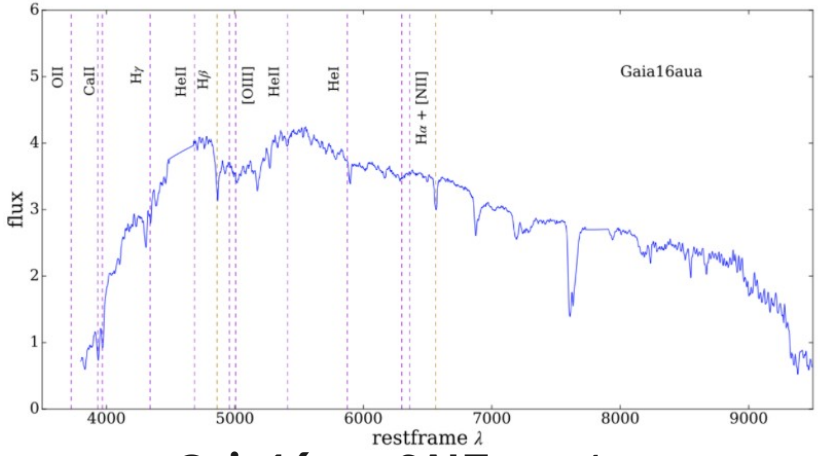
Gaia19bld VLT/X-SHOOTER spectra



Gaia17aqu SALT spectra



Gaia19epm LT/SPRAT spectrum



Gaia16aua SALT spectrum

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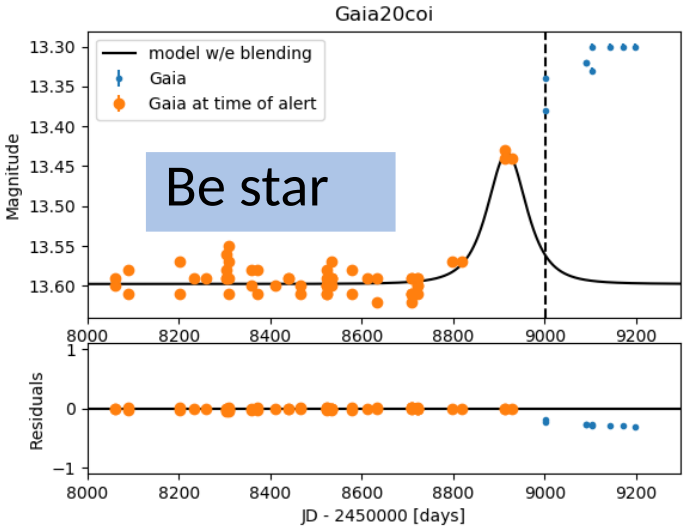
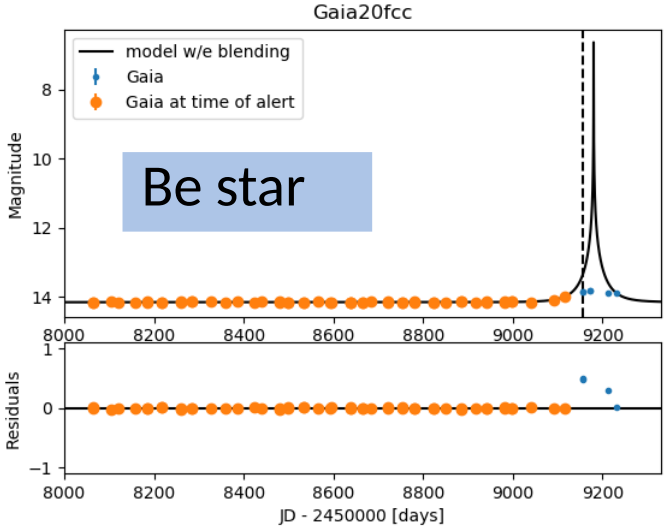
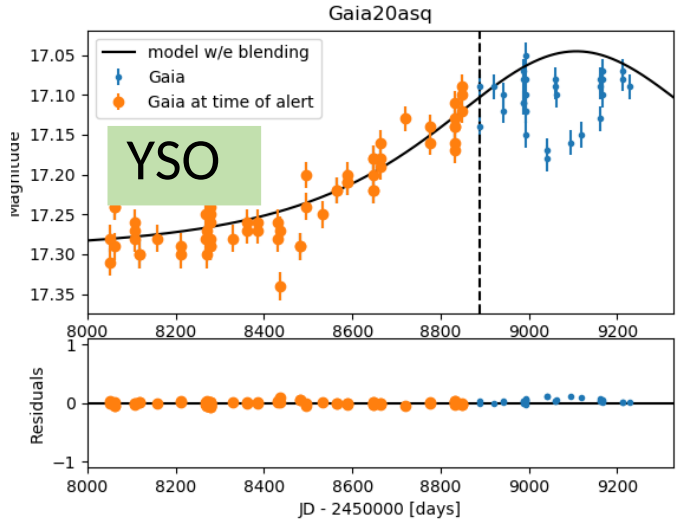
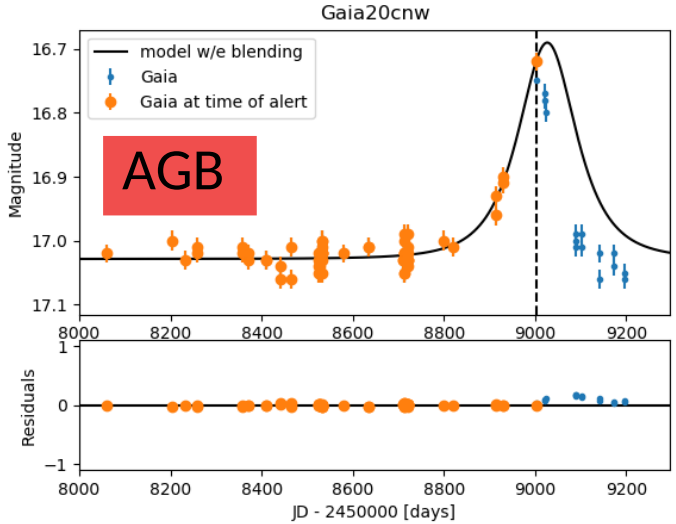
- **Early classification based on archival data**

Most Common Contaminants









Gezer et al. 2022 (submitted)

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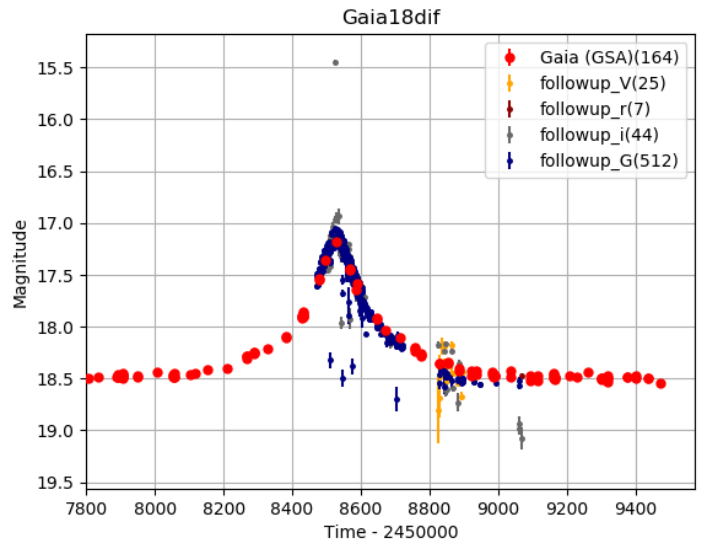
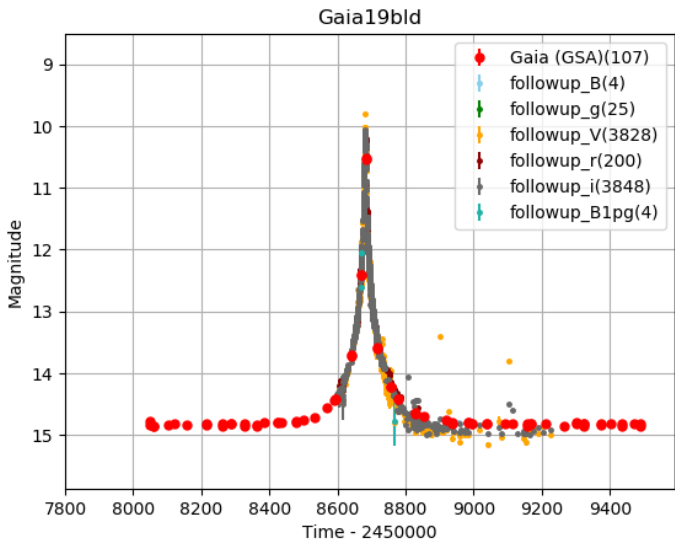
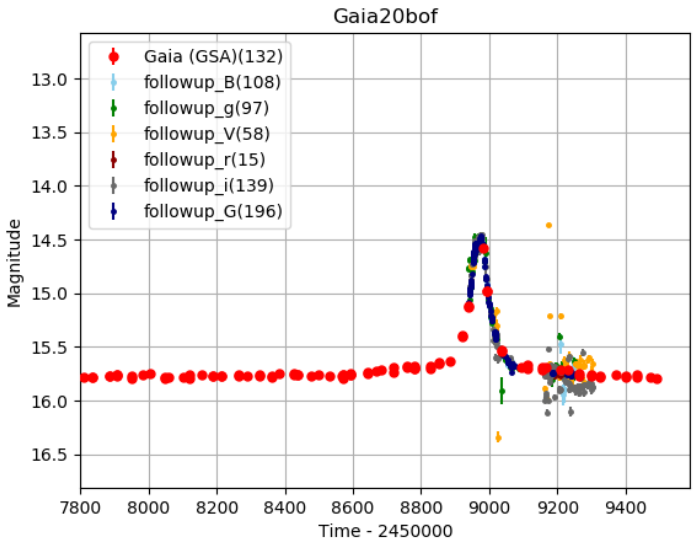
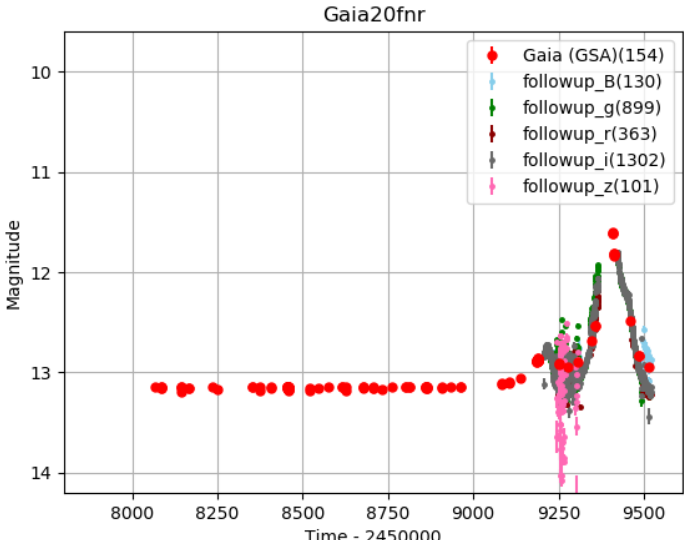
- **Early classification based on archival data**
- **The outcomes → catching interesting events!**

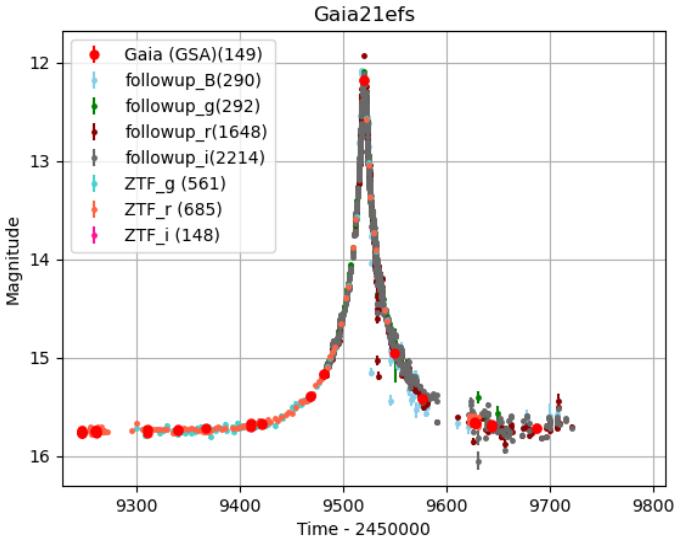
Microlensing highlights – with follow-up

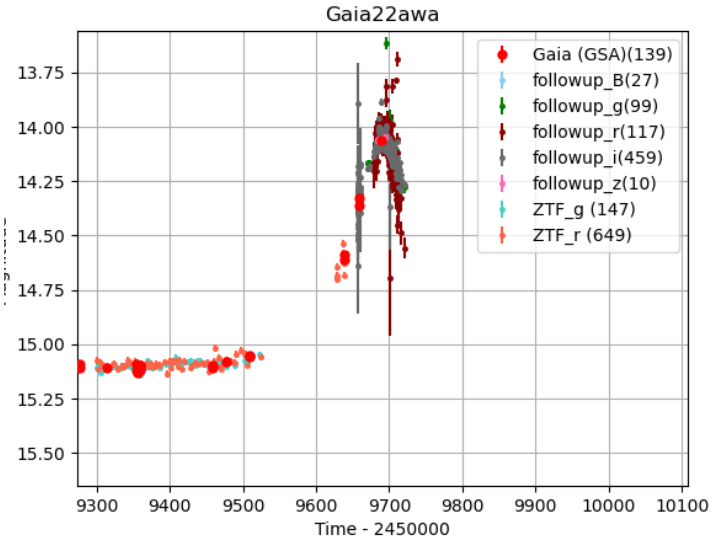




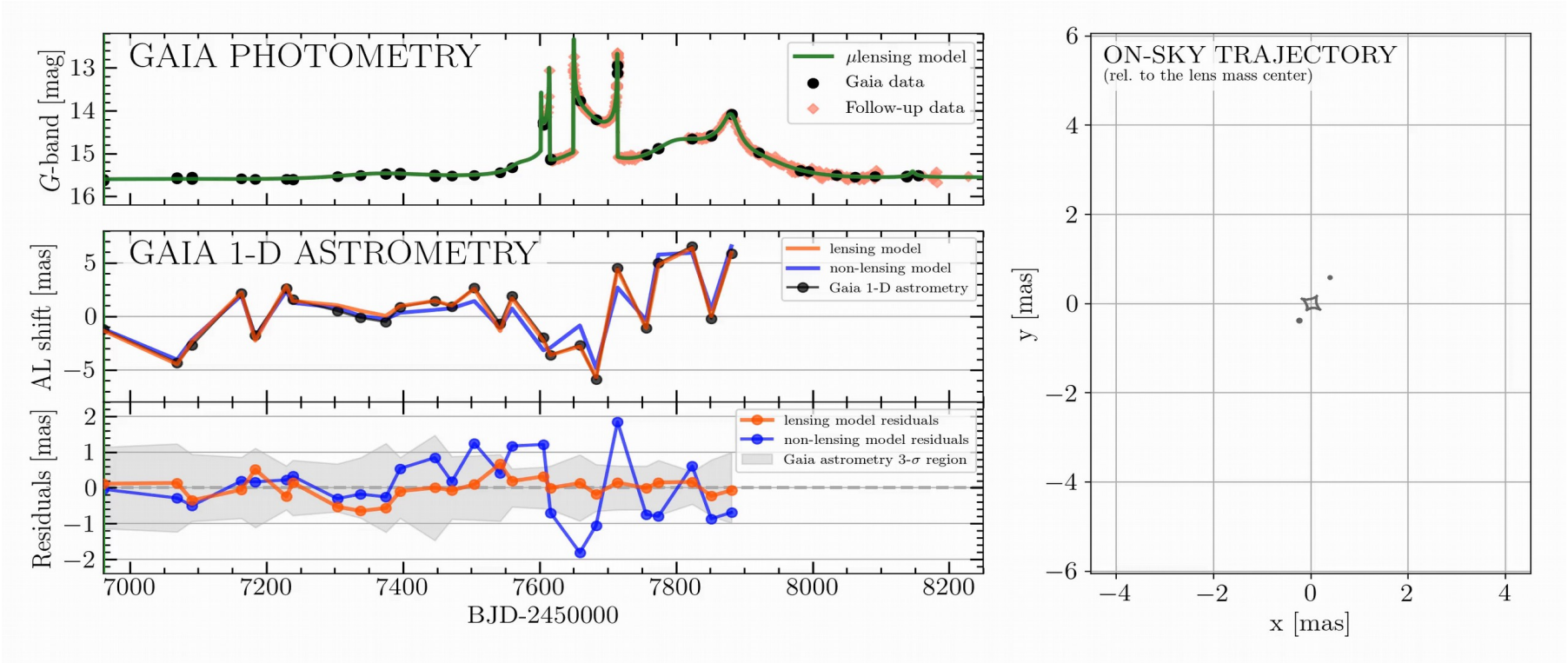








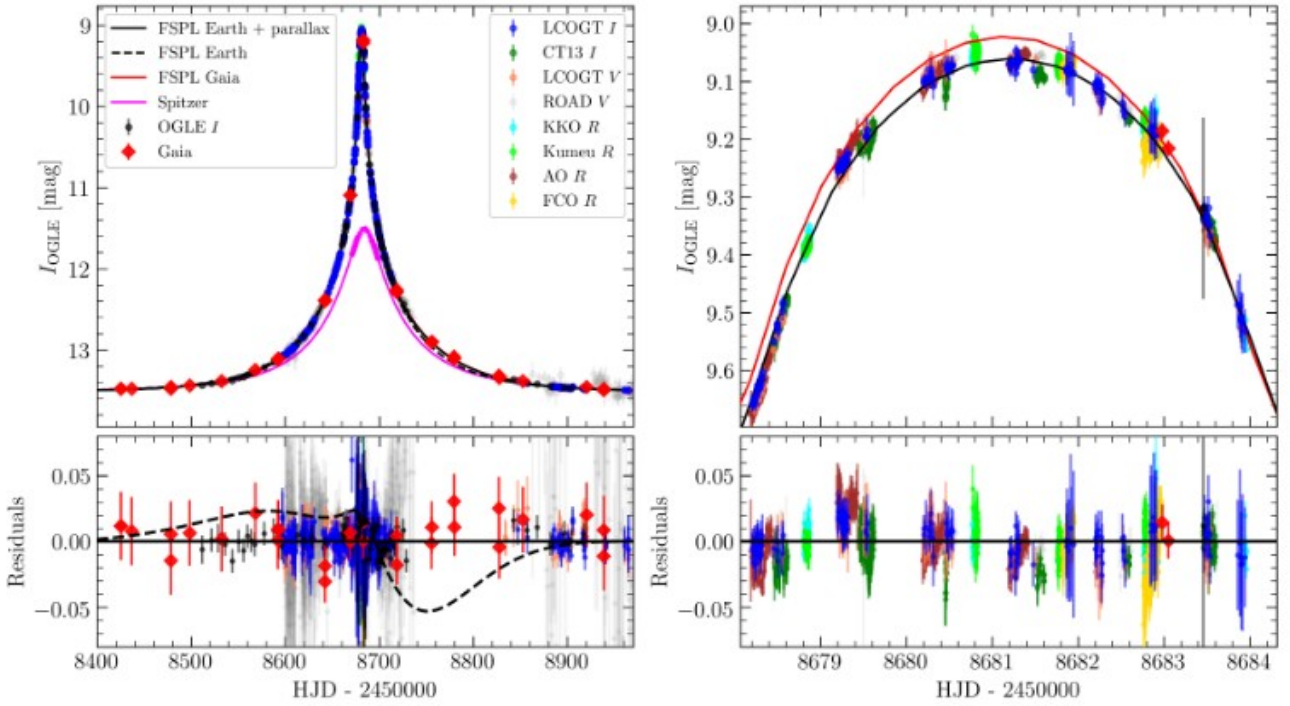
Gaia16aye



Source: https://www.astrouw.edu.pl/~krybicki/animations.php
https://www.cosmos.esa.int/web/gaia/iow_20210924

Gaia19bld

- **Microlensing event in the Galactic disc**
- **Observed (among others) by Spitzer and VLTI/PIONIER**
- **Also spectroscopic follow-up**



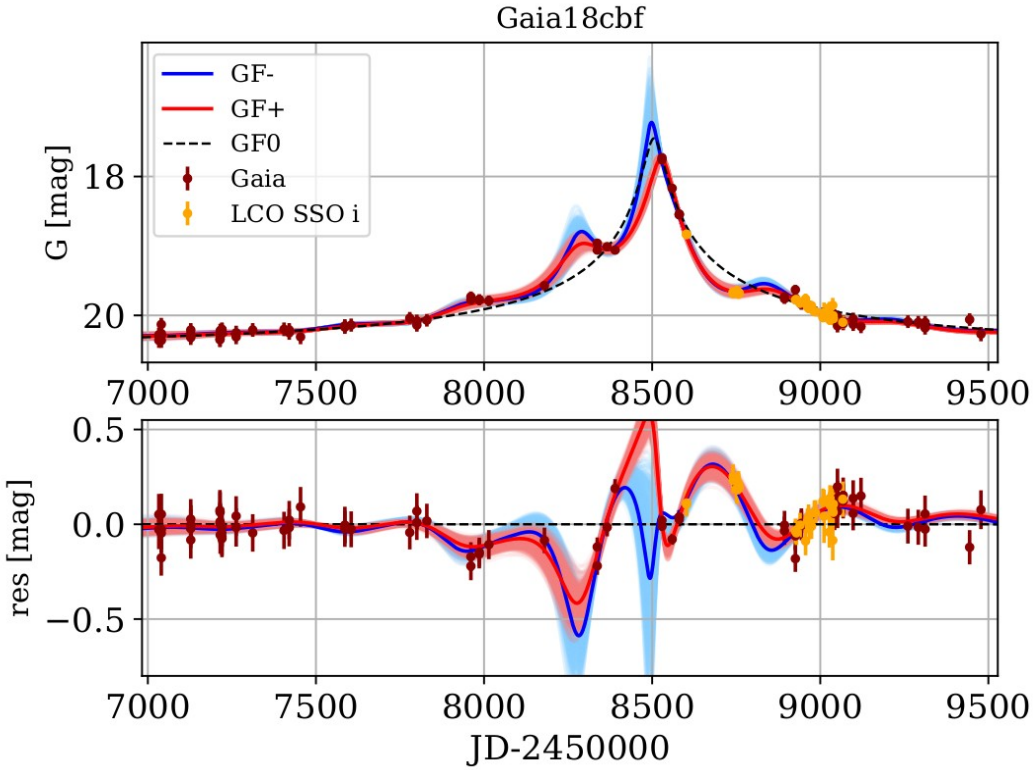
Rybicki+ 2021

Animation: https://www.astrouw.edu.pl/~krybicki/animations.php

Gaia18cbf

- 2nd longest microlensing event ever observed in terms of t_E
- time span of the whole event of ~1900 days
- Very dim (baseline at G~20.5mag)

Parameter	GF0	GF+	GF-
$t_{0,par} - 245000.$ [days]	–	8529.00	
$t_0 - 2450000.$ [days]	$8505.34^{+2.04}_{-2.00}$	$8524.76^{+4.33}_{-4.57}$	$8513.14^{+4.68}_{-3487}$
u_0	$0.0133^{+0.0086}_{-0.0065}$	$0.0825^{+0.0231}_{-0.0208}$	$-0.0567^{+0.0162}_{-0.0169}$
t_E [days]	$2058.40^{+1956.82}_{-781.12}$	$491.41^{+128.31}_{-84.94}$	$453.74^{+178.69}_{-105.74}$
π_{EN}	–	$-0.1192^{+0.0273}_{-0.0285}$	$-0.1697^{+0.0516}_{-0.0577}$
π_{EE}	–	$-0.0442^{+0.0077}_{-0.0084}$	$-0.0257^{+0.0054}_{-0.0057}$
G_0 [mag]	$20.44^{+0.07}_{-0.07}$	$20.34^{+0.03}_{-0.03}$	$20.34^{+0.04}_{-0.03}$
$f_{S,G}$	$0.198^{+0.109}_{-0.090}$	$0.894^{+0.263}_{-0.226}$	$0.717^{+0.294}_{-0.233}$
i_0 [mag]	$20.06^{+0.07}_{-0.07}$	$20.01^{+0.06}_{-0.05}$	$20.00^{+0.07}_{-0.06}$
$f_{S,i}$	$0.157^{+0.084}_{-0.072}$	$0.996^{+0.250}_{-0.219}$	$0.746^{+0.253}_{-0.208}$
χ^2	143.98	40.87	46.69
$\frac{\chi^2}{dof}$	1.40	0.40	0.46



- Two solutions:
  - GF+ t_E = 491.41days, $f_{s,G}$ = 0.894
  - GF- t_E = 453.74days, $f_{s,G}$ = 0.717
- Follow-up data from LCO network (2m at Siding Springs Observatory)

Kruszynska+ 2022, A&A in press

Gaia18cbf

How can we constrain mass and rule out star scenario?

Microlensing parallax

+

Proper motions from Gaia

+

Estimate of the distance to the source

+

Galactic model

+

Mass-function of remnants

???

Method described in: Wyrzykowski+ 2016, Wyrzykowski&Mandl 2020, Mróz&Wyrzykowski 2021…

Gaia18cbf

How can we constrain mass and rule out star scenario?

Microlensing parallax

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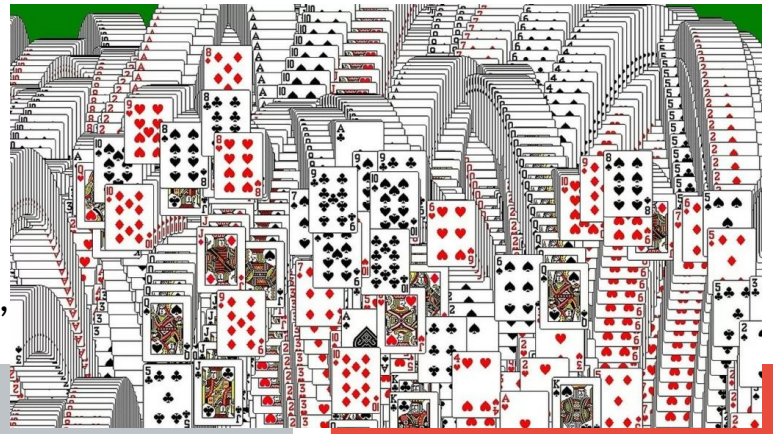
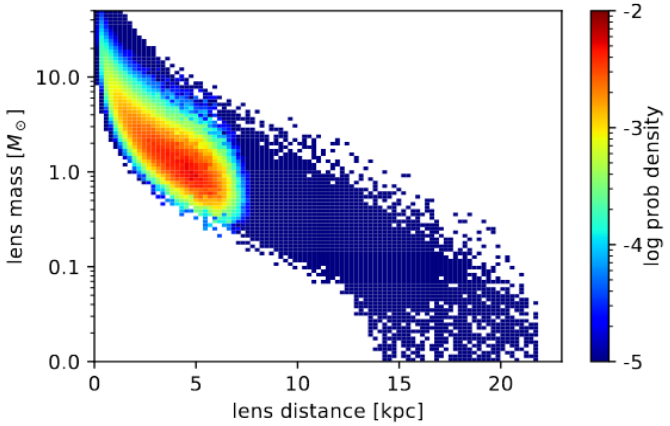
Estimate of the distance to the source

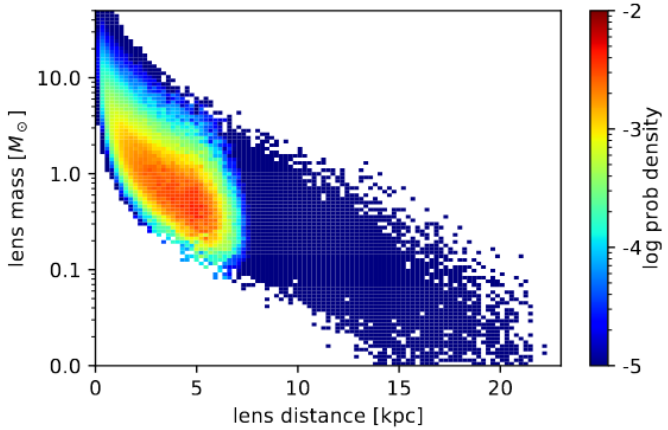
PROFIT

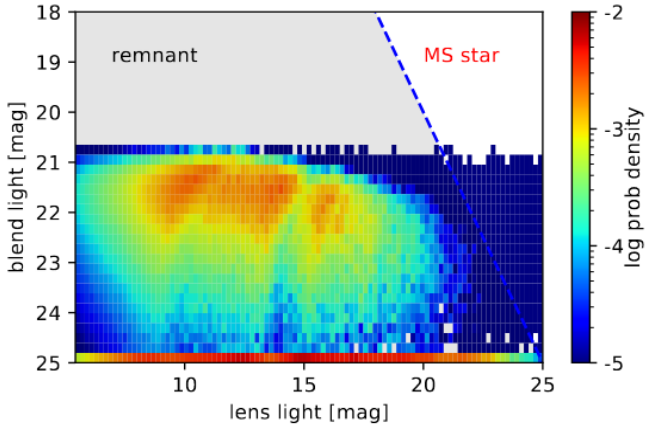


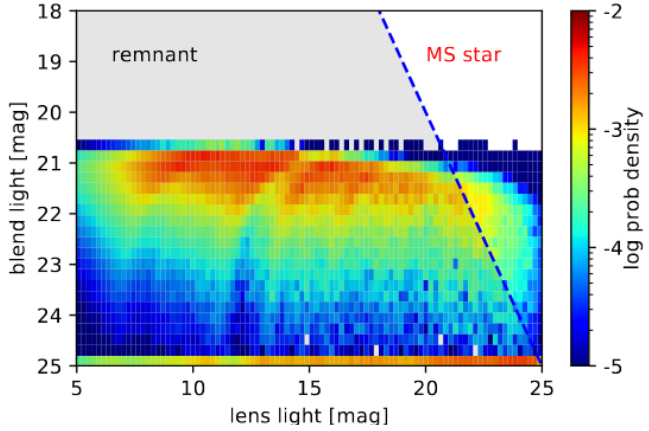
Method described in: Wyrzykowski+ 2016, Wyrzykowski&Mandl 2020, Mróz&Wyrzykowski 2021… and still being refined

Gaia18cbf









Kruszynska+ 2022, A&A in press

GF+ lens is

$M_L\ [M_\odot]$	$2.65^{+5.09}_{-1.48}$
D_L [kpc]	$2.84^{+1.94}_{-1.67}$

GF- lens is

$M_L\ [M_\odot]$	$1.71^{+3.78}_{-1.06}$
D_L [kpc]	$2.66^{+1.97}_{-1.56}$

Gaia18cbf – different scenarios

- **There was a number of assumptions done – let's play around with them:**
  - Remnant mass function: could be less steep…
  - or more steep
  - Assumed distance to the source derived using archival photometric data…
  - but maybe Bailer-Jones distances are correct? (Despite negative parallax)

https://arxiv.org/abs/2111.08337

Parameter	GF+	GF-
$G_{\rm blend}$ [mag]	$21.31^{+\rm inf}_{-0.47}$	$20.89^{+\rm inf}_{-0.23}$
Mass function $\propto M^{-1.00}$, 14.5 kpc $< D_{\rm S} <$ 23.0 kpc		
$M_{\rm L}$ [$M_\odot$]	$6.17^{+14.79}_{-4.09}$	$4.83^{+13.30}_{-3.41}$
$D_{\rm L}$ [kpc]	$1.55^{+2.08}_{-1.02}$	$1.45^{+2.00}_{-0.97}$
$G_{\rm MS}$ [mag]	<10.76 (B2.5V)	10.95 (B5V)
Mass function $\propto M^{-3.00}$, 14.5 kpc $< D_{\rm S} <$ 23.0 kpc		
$M_{\rm L}$ [$M_\odot$]	$1.23^{+1.32}_{-0.53}$	$0.62^{+0.80}_{-0.30}$
$D_{\rm L}$ [kpc]	$4.34^{+1.27}_{-1.74}$	$4.14^{+1.35}_{-1.67}$
$G_{\rm MS}$ [mag]	17.81 (F6V)	21.89 (K8V)
Mass function $\propto M^{-1.75}$, 6.4 kpc $< D_{\rm S} <$ 9.8 kpc (B-J distance)		
$M_{\rm L}$ [$M_\odot$]	$3.78^{+7.78}_{-2.41}$	$2.38^{+5.73}_{-1.60}$
$D_{\rm L}$ [kpc]	$1.76^{+1.51}_{-1.01}$	$1.67^{+1.47}_{-0.97}$
$G_{\rm MS}$ [mag]	-0.39 (B7V)	13.13 (A0V)

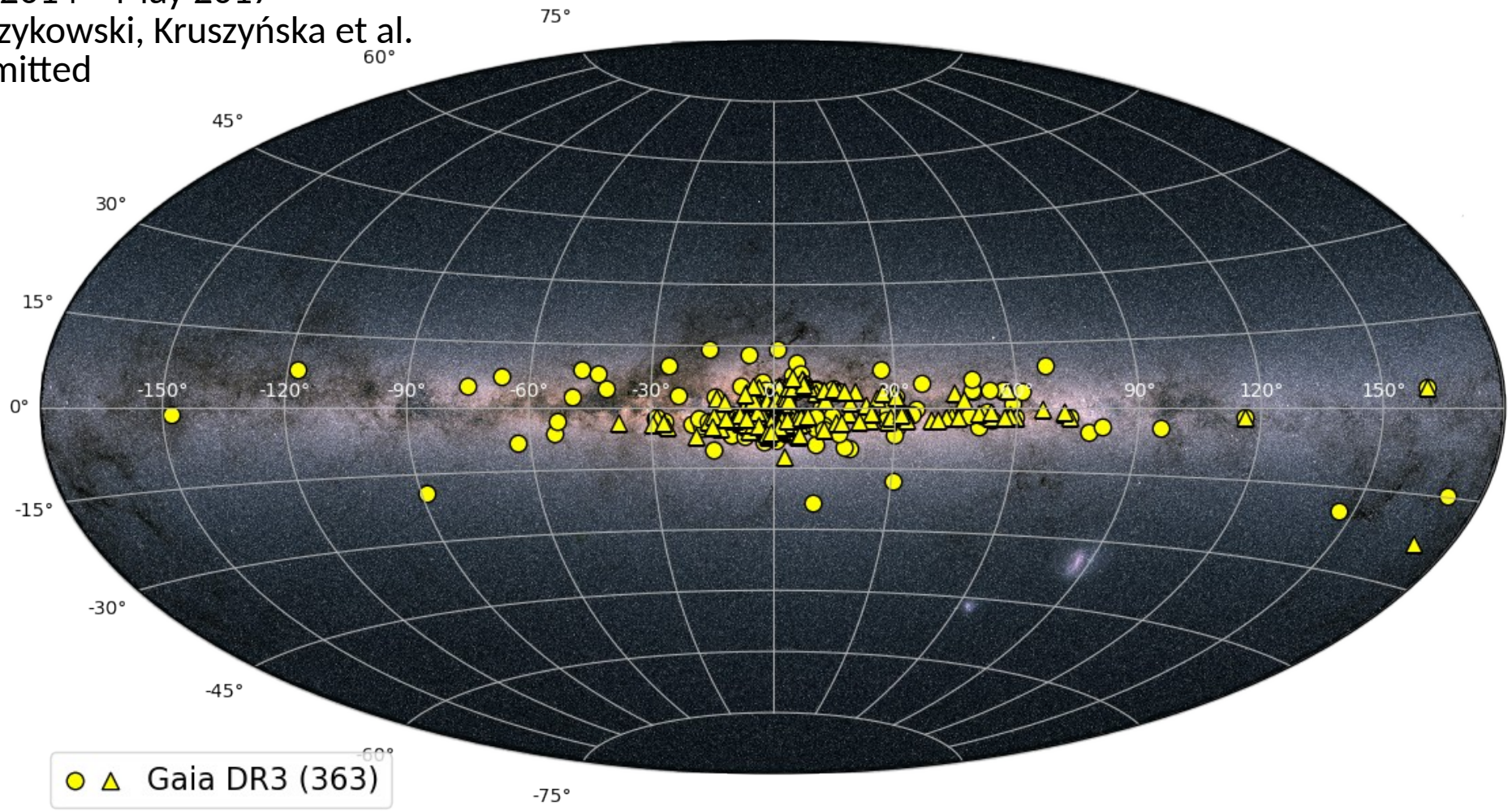
Kruszynska+ 2022, A&A in press

The future

- Gaia DR3 microlensing catalogue

Gaia Data Release 3 – 13th June 2022

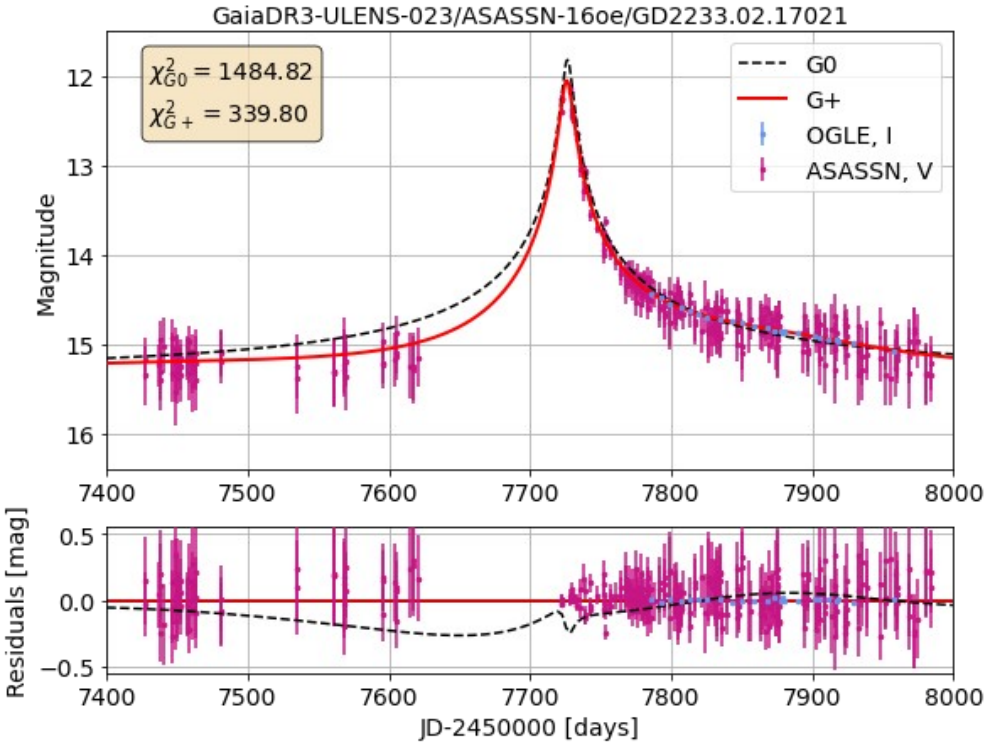
Candidate events from
July 2014 – May 2017
Wyrzykowski, Kruszyńska et al.
submitted



Background image: ESA/DPAC

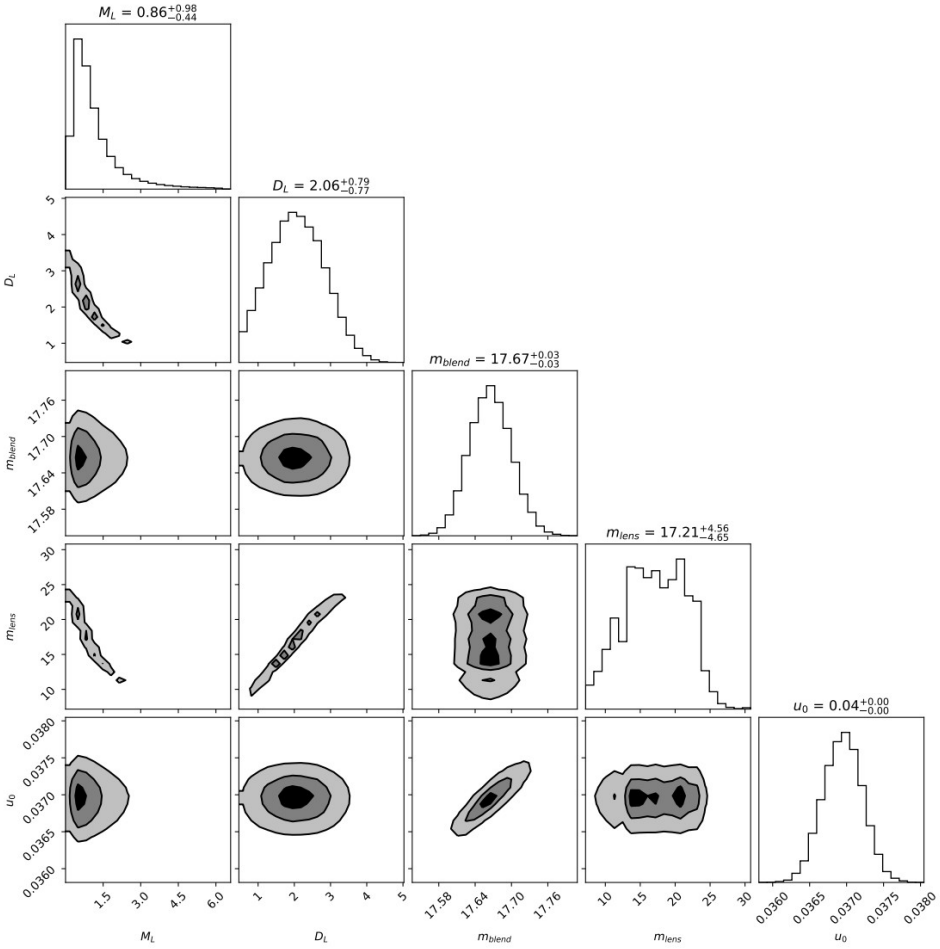
The future

- Gaia DR3 microlensing catalogue
- Applying the same method of mass and distance determination to all events from Gaia DR3...



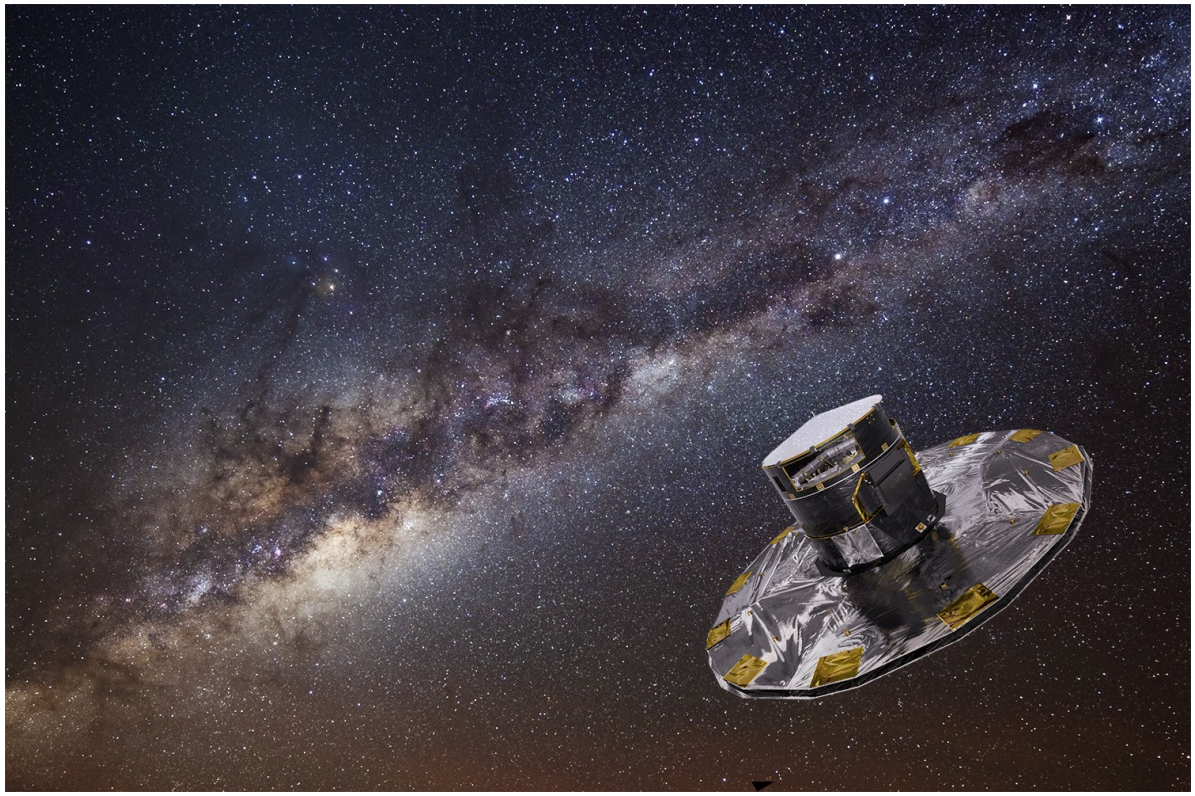
The future

- Gaia DR3 microlensing catalogue
- Applying the same method of mass and distance determination to all events from Gaia DR3...



The future

- Gaia DR3 microlensing catalogue
- Applying the same method of mass and distance determination to all events from Gaia DR3...
- And to events found in GSA
- Stay tuned!
- Also enjoy DR3~



Source: ESA/DPAC