STUDYING THE POPULATION OF GALACTIC BLACK HOLES WITH MICROLENSING

Łukasz Wyrzykowski

(pron. Woo-cash Vi-zhi-kov-ski)

Astronomical Observatory,
University of Warsaw, Poland

Polish-German WE-Heraeus-Seminar

7-10.Nov 2022, Kraków, PL

WILHELM UND ELSE HERAEUS-STIFTUNG

GAIA.ASTROUW.EDU.PL

BHTOM.SPACE

LW @ASTROUW.EDU.PL

TEAM

https://gaia.astrouw.edu.pl

Warsaw University Astronomical Observatory

Łukasz Wyrzykowski
(staff)

Monika Sitek
(staff)

Mariusz Gromadzki
(postdoc)

Milena Ratajczak
(postdoc)

Przemek Mikołajczyk
(staff)

Barbara Kubiak
(staff)

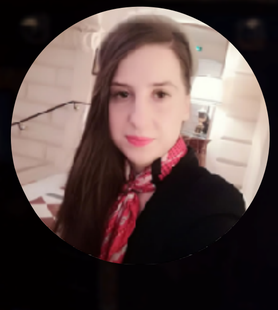
UMK Toruń

Paweł Zieliński
(postdoc)

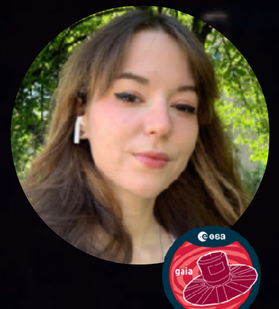
Kris A. Rybicki
(PhD student)

Katarzyna Kruszyńska
(PhD student)

Nada Ihanec
(PhD student)



Algita Stankevičiūtė
(PhD student)



Maja Jabłońska
(PhD student)

Kornel Howil
(BSc student)

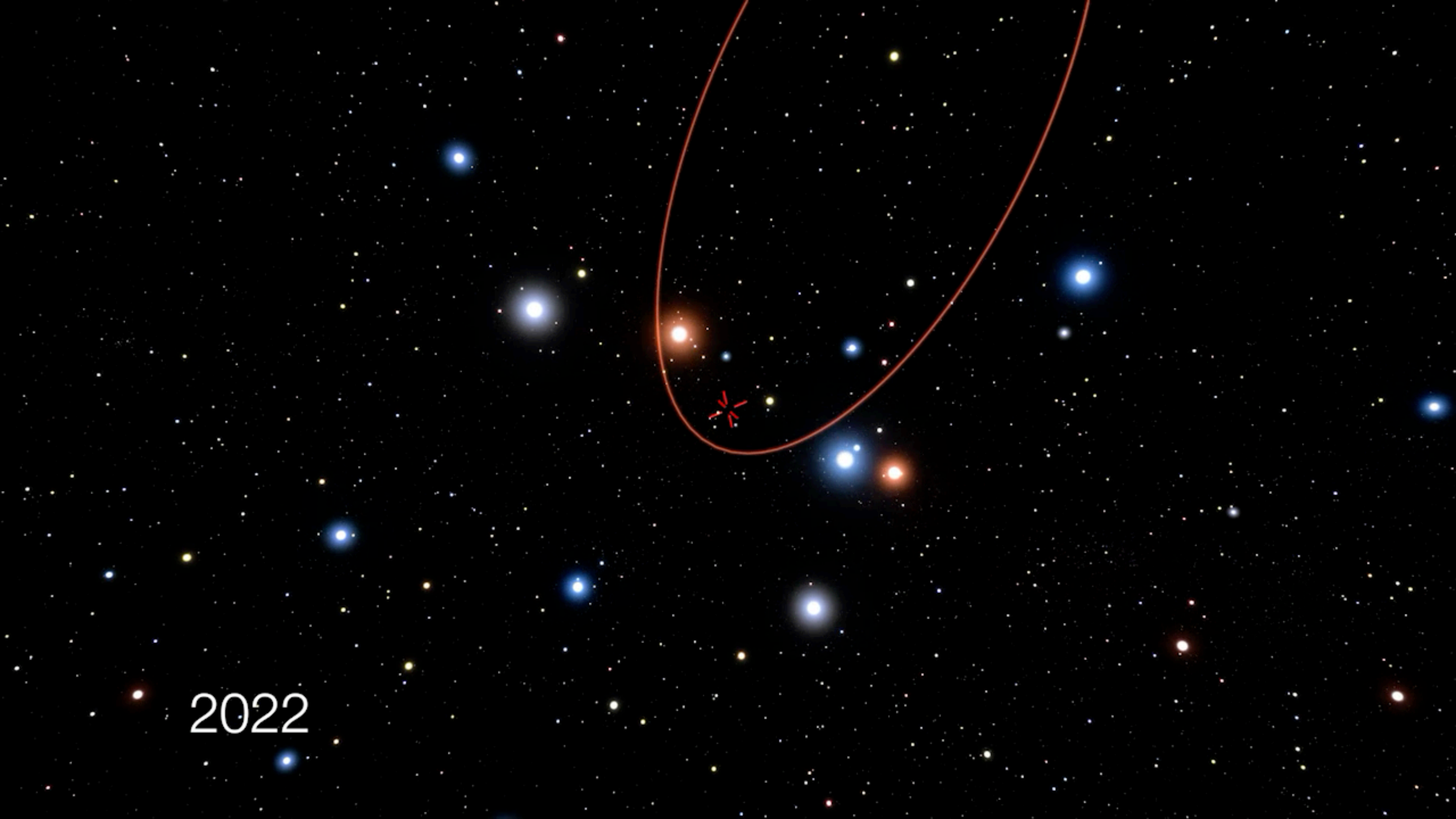
Uliana Pylypenko
MSc student

Heidelberg

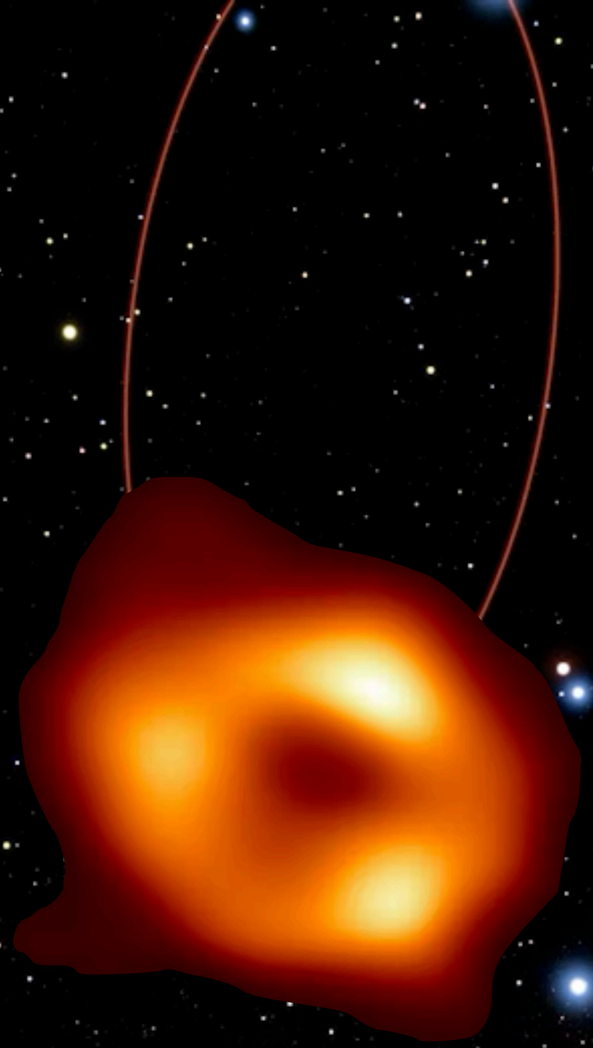
Zofia Kaczmarek
(PhD student)

Collaborators::
Patrik Sivak Iwetta Achkar Piotr Trzcionkowski Zuzanna Kostrzewa-Rutkowska
University of Cambridge, University of Heidelberg, Weizmann Institute, Geneva Observatory, Vilnius University, Nicolaus Copernicus University, University of Nova Gorica, Tel Aviv University, Caltech, UAM Madrid, Las Cumbres Observatory, Science Now

Funding:

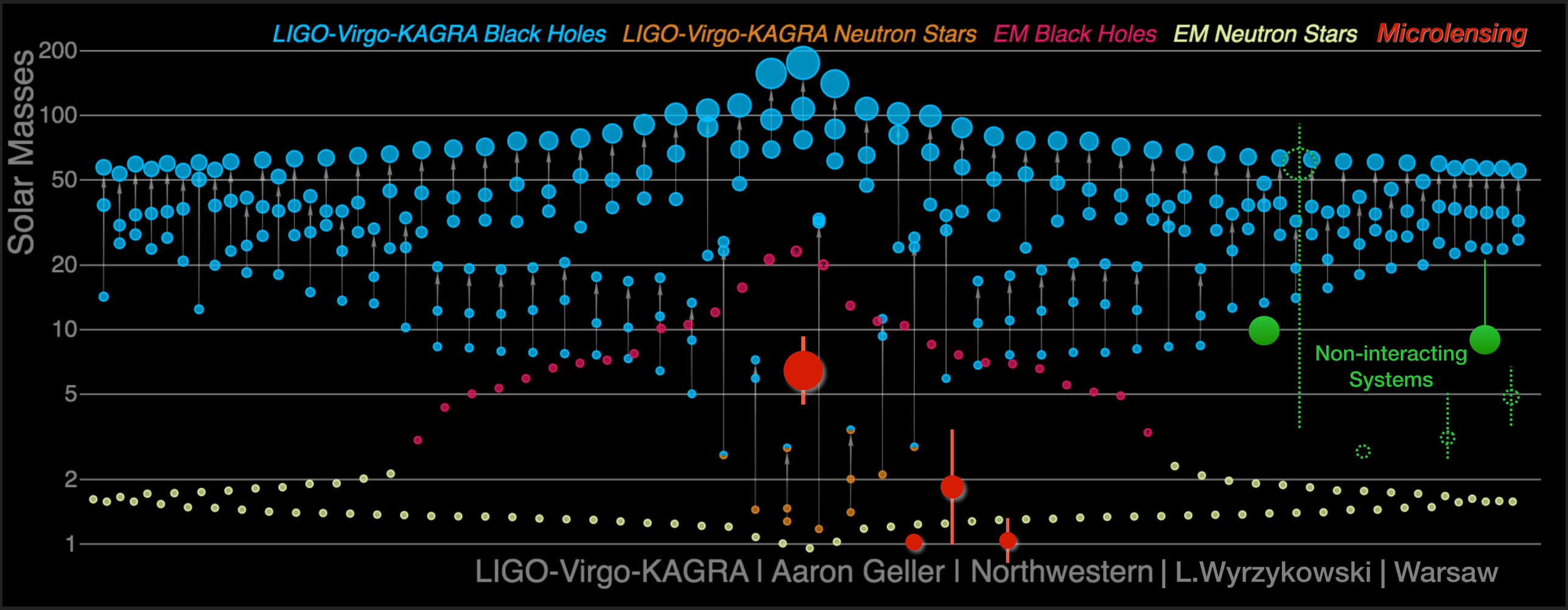

2022

Nobel Prize
in Physics 2020



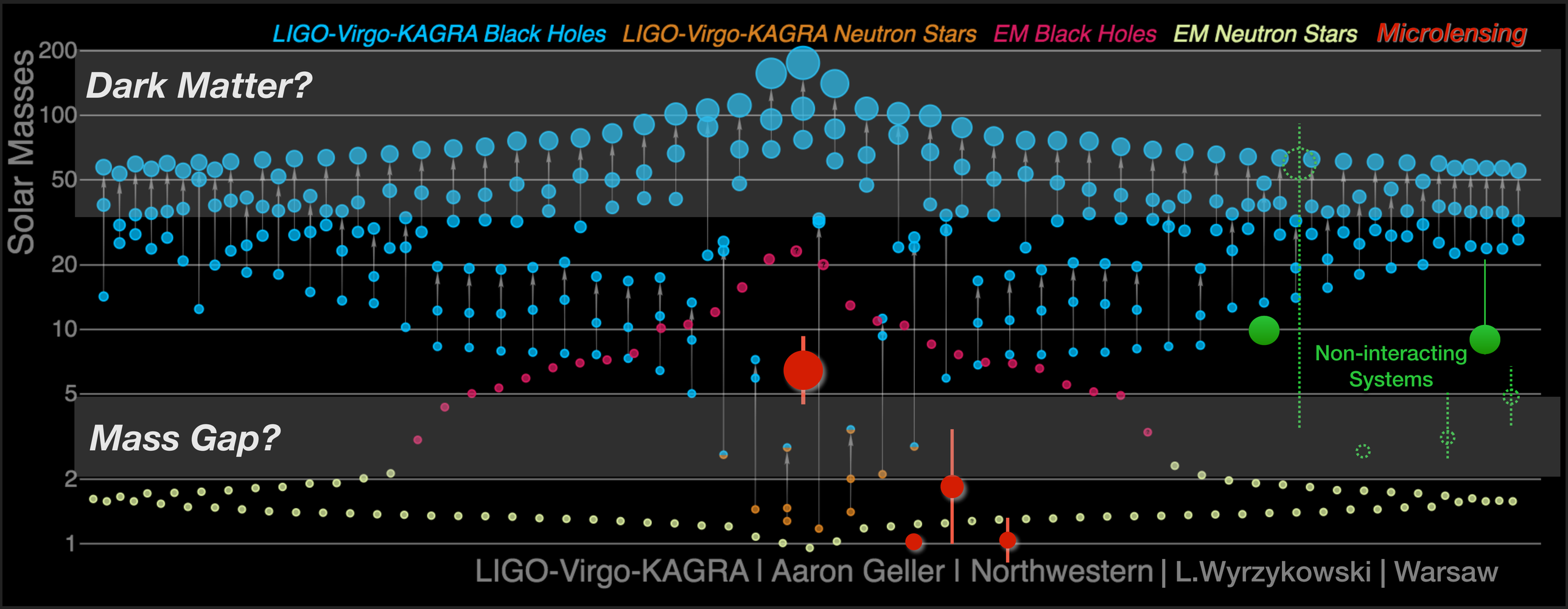
2013

MULTI-MESSENGER TIME-DOMAIN VIEW ON MASSES OF BLACK HOLES AND NEUTRON STARS



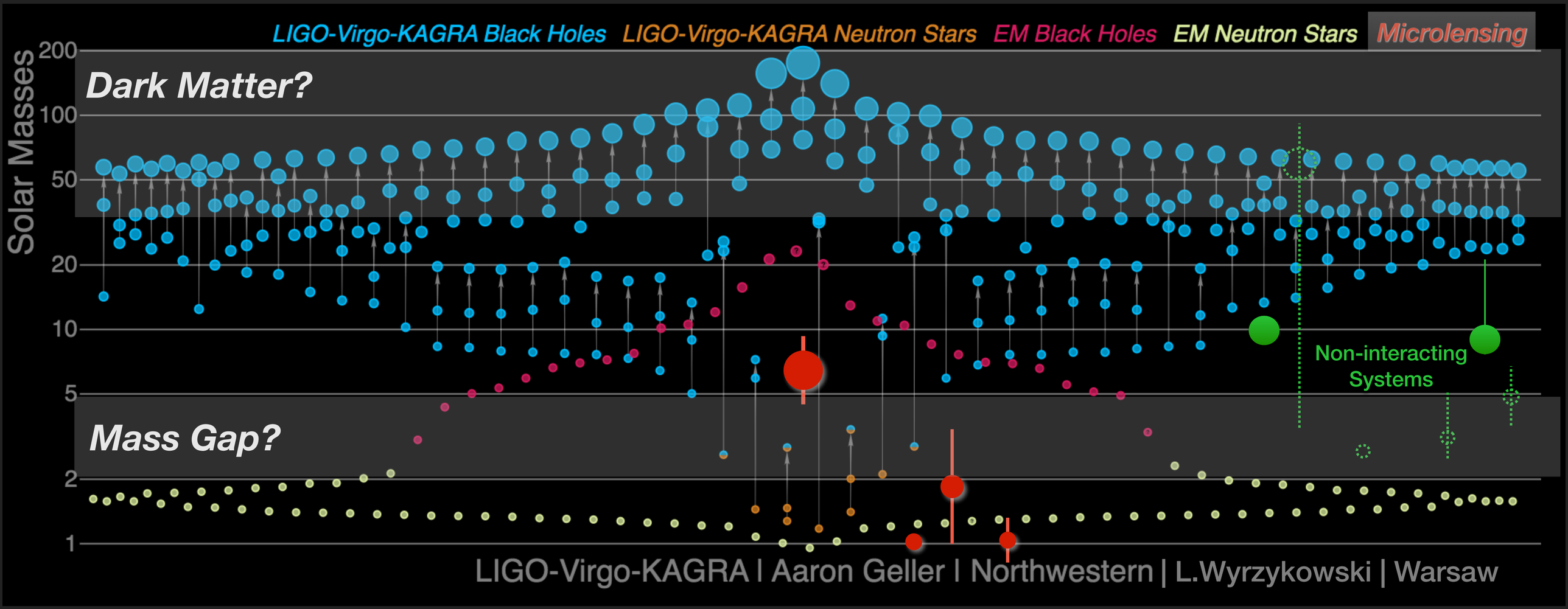
Abbott+2021 *Thompson et al. 2019, Liu+2020, Shenar+2022* *Sahu+2022* *Rybicki+2022, Kruszynska+2022*
Corral Santana+2016 *Rivinius+2020, Jayasinghe+2021, El Badry+2022* *Lam+2022, Mróz+2022* *Jablonska+2022*

MULTI-MESSENGER TIME-DOMAIN VIEW ON MASSES OF BLACK HOLES AND NEUTRON STARS



Abbott+2021
Corral Santana+2016
Thompson et al. 2019, Liu+2020, Shenar+2022
Rivinius+2020, Jayasinghe+2021, El Badry+2022
Sahu+2022
Lam+2022, Mróz+2022
Rybicki+2022, Kruszynska+2022
Jablonska+2022

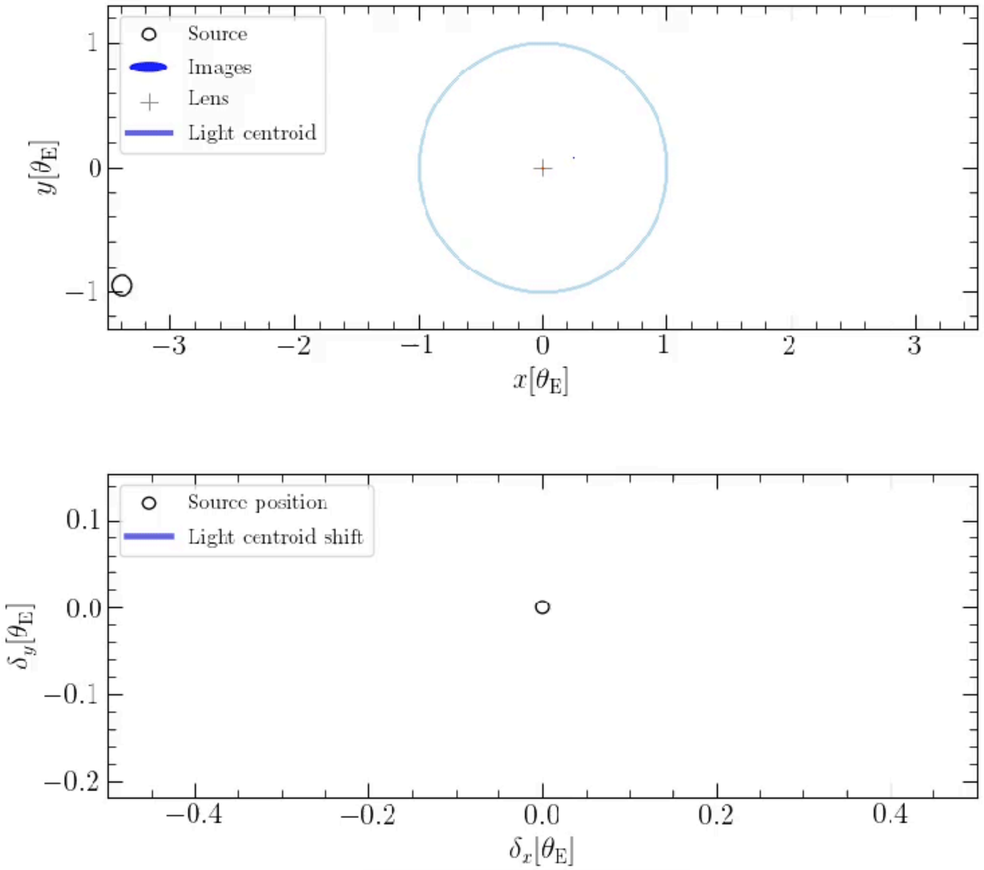
MULTI-MESSENGER TIME-DOMAIN VIEW ON MASSES OF BLACK HOLES AND NEUTRON STARS



Abbott+2021 Thompson et al. 2019, Liu+2020, Shenar+2022 Sahu+2022 Rybicki+2022, Kruszynska+2022
Corral Santana+2016 Rivinius+2020, Jayasinghe+2021, El Badry+2022 Lam+2022, Mróz+2022 Jablonska+2022

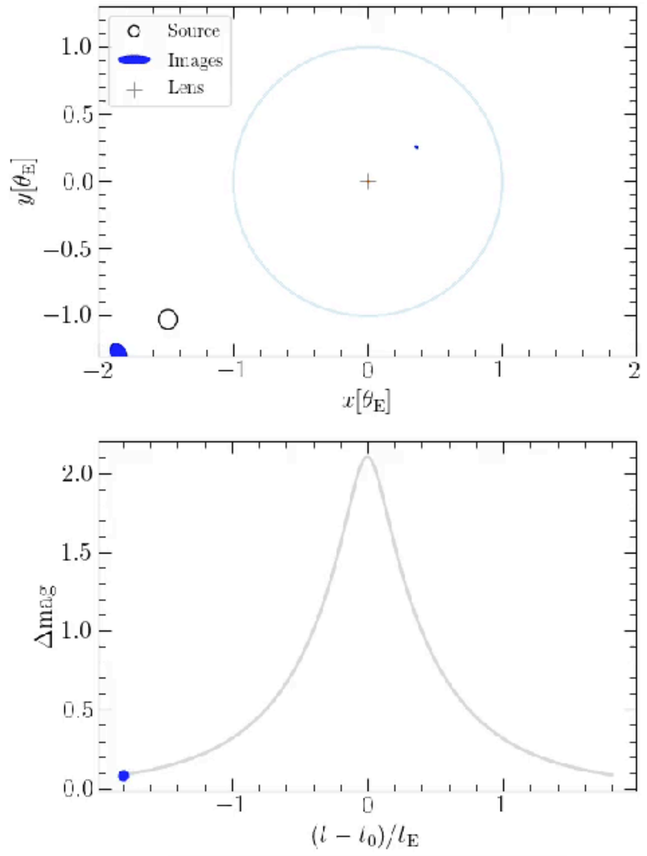
GRAVITATIONAL MICROLENSING – IN 1 IN A MILLION STARS!

astrometry - shift



miliseconds

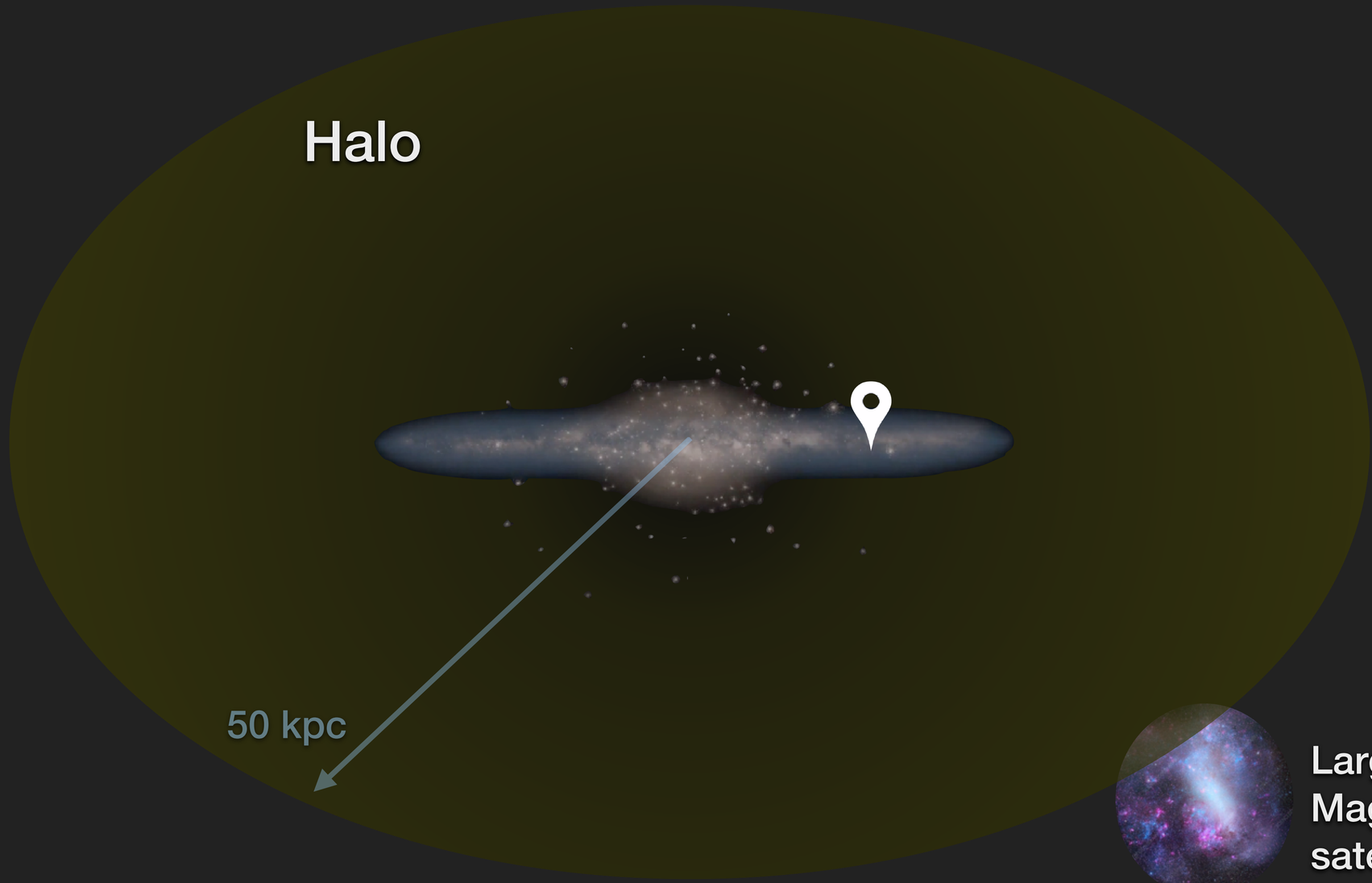
photometry - brightening



weeks-months

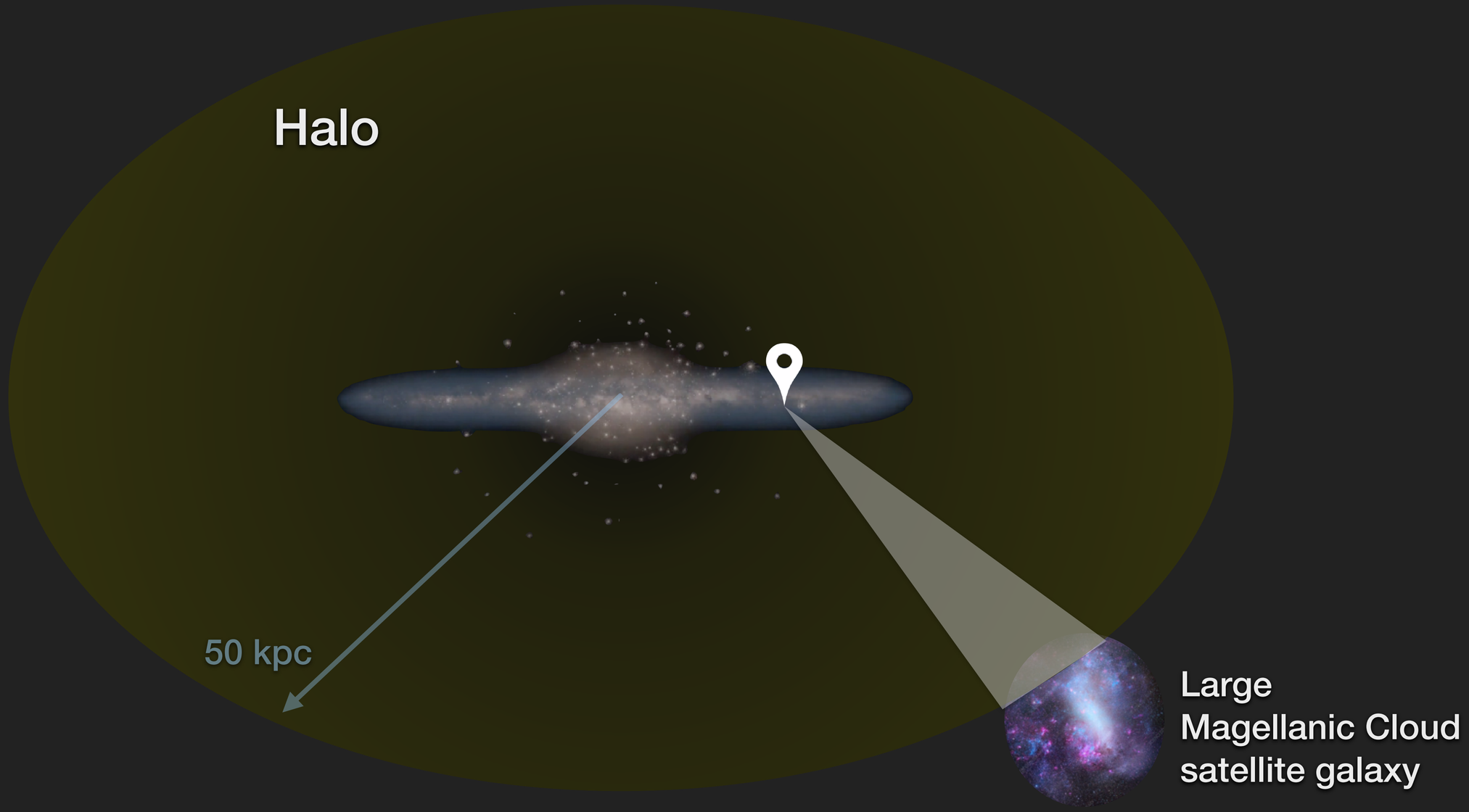
animations by K.Rybicki

HOW TO FIND DARK MATTER WITH MICROLENSING?



Large
Magellanic Cloud
satellite galaxy

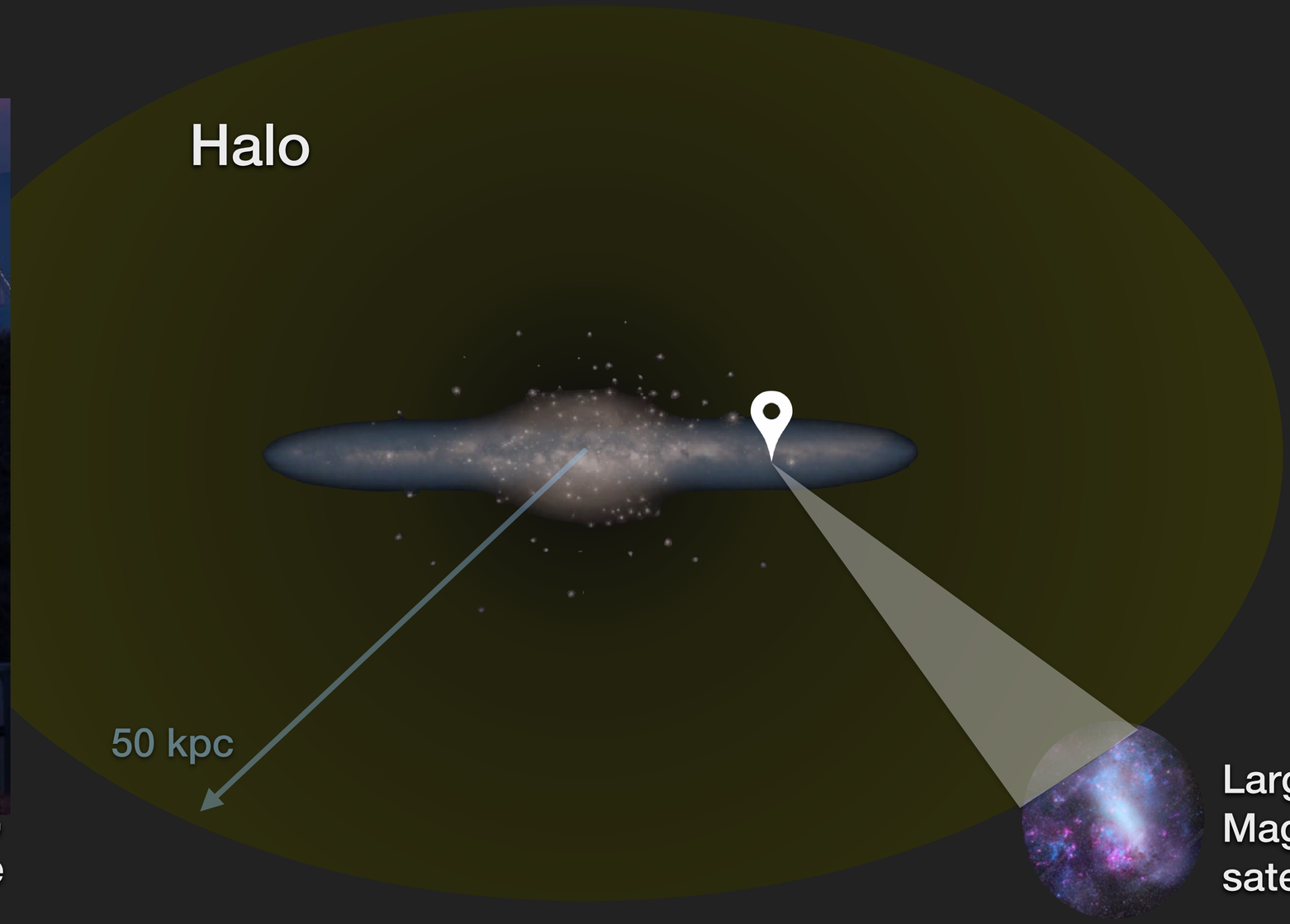
HOW TO FIND DARK MATTER WITH MICROLENSING?



HOW TO FIND DARK MATTER WITH MICROLENSING?

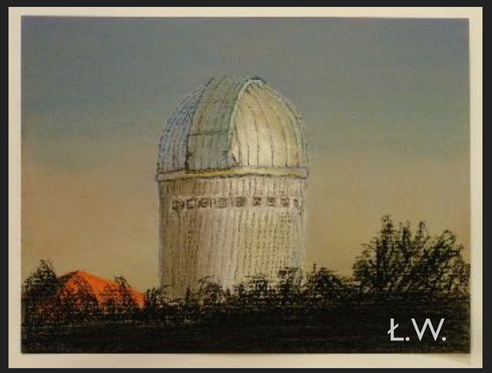
OGLE

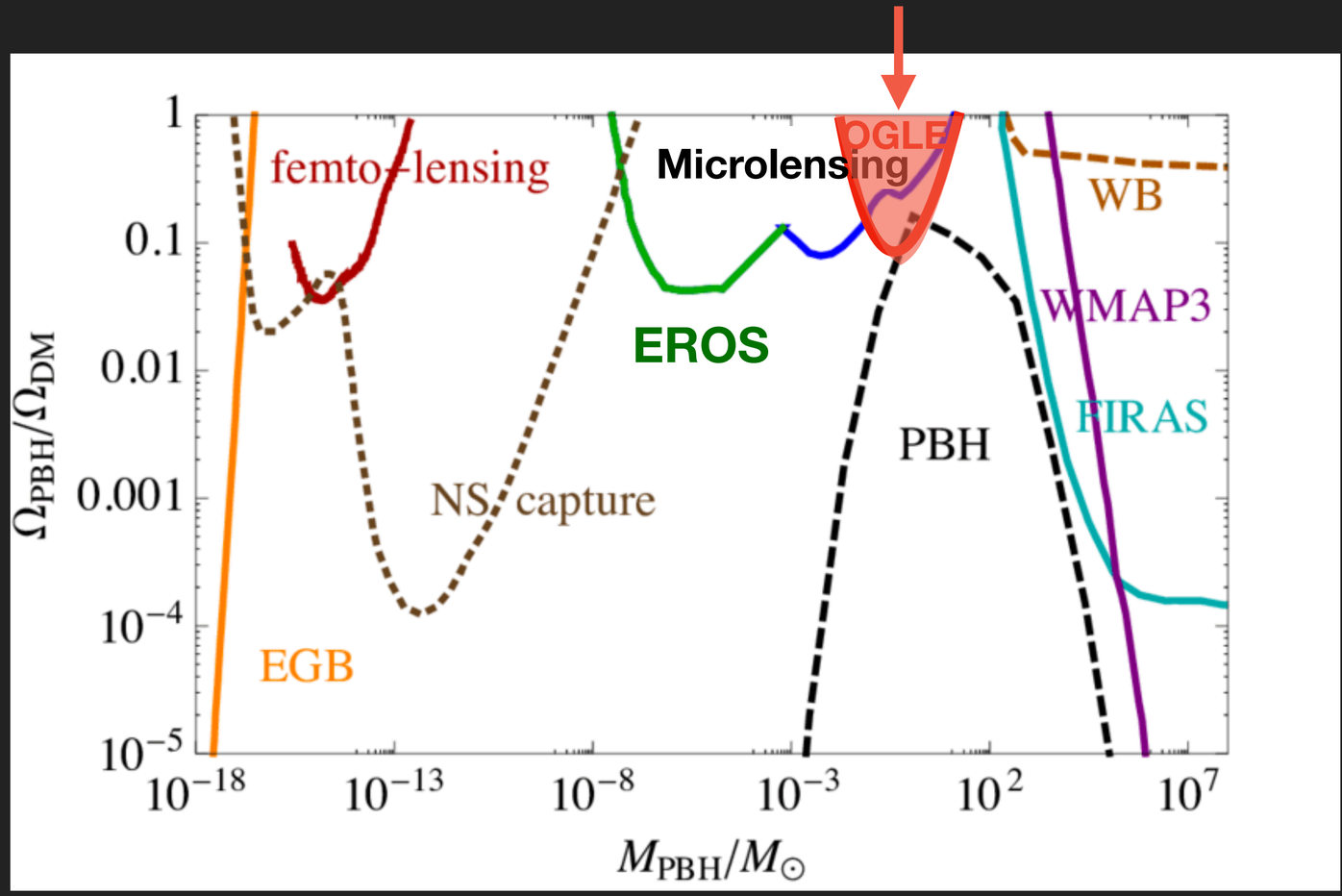
OGLE started in 1992, Polish 1.3m telescope built in Chile in 1996



MICROLENSING CONSTRAINS ON THE HALO DARK MATTER (MACHO)

- OGLE data (1996-2009) was searched for time-varying changes in stars
- Dark Matter in form of primordial black holes (PBH) with monochromatic mass spectrum was ruled out to <~10 Solar Mass



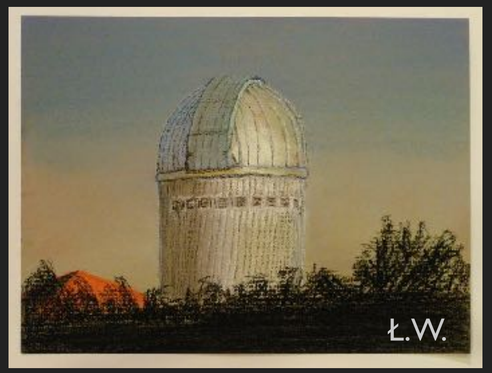


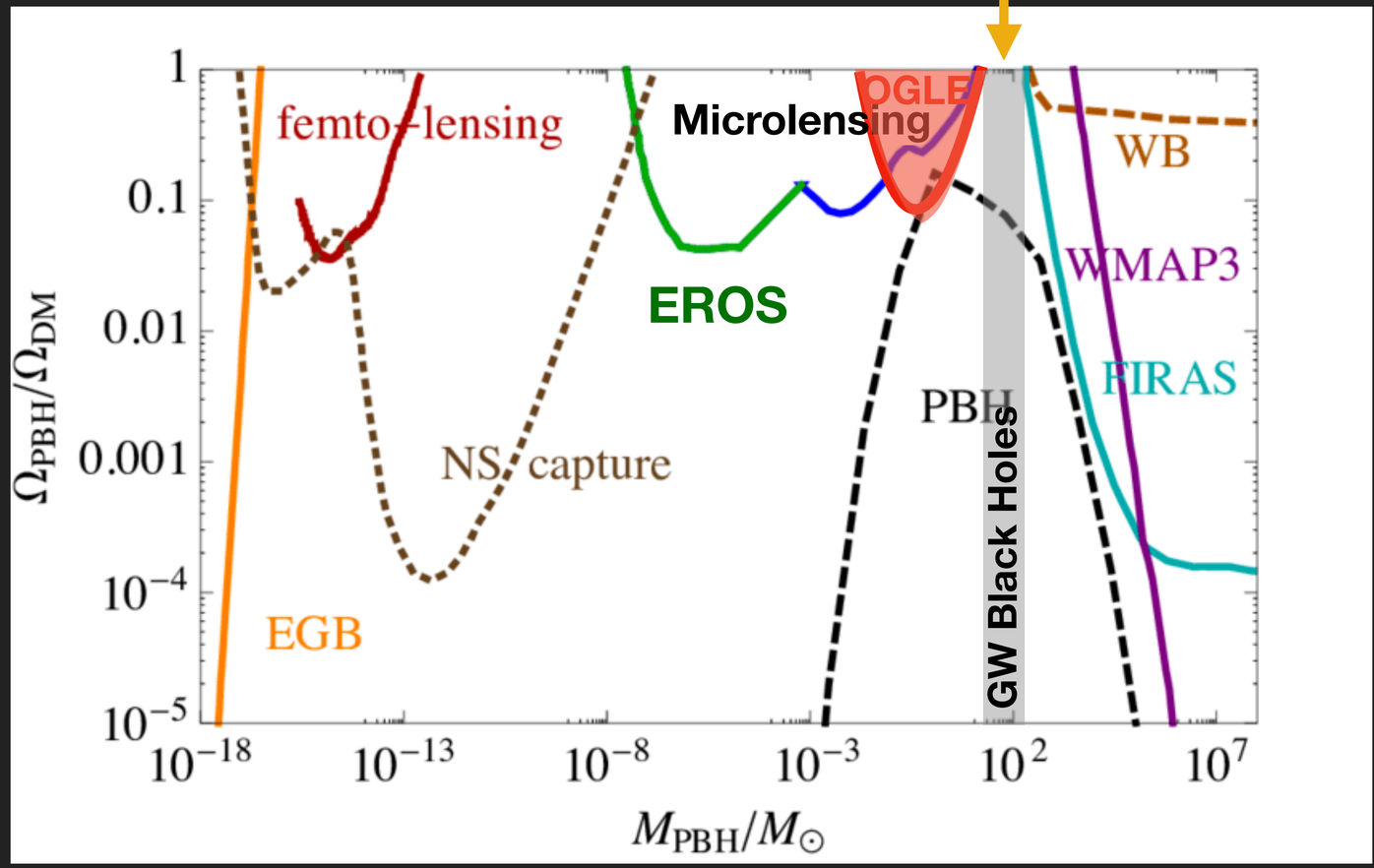
Garcia-Bellido & Clesse 2017
Wyrzykowski+ 2009,2010,2011a,2011b

MICROLENSING CONSTRAINS ON THE HALO DARK MATTER (MACHO)

The only window for Primordial Black Holes coincides with the GW black holes!

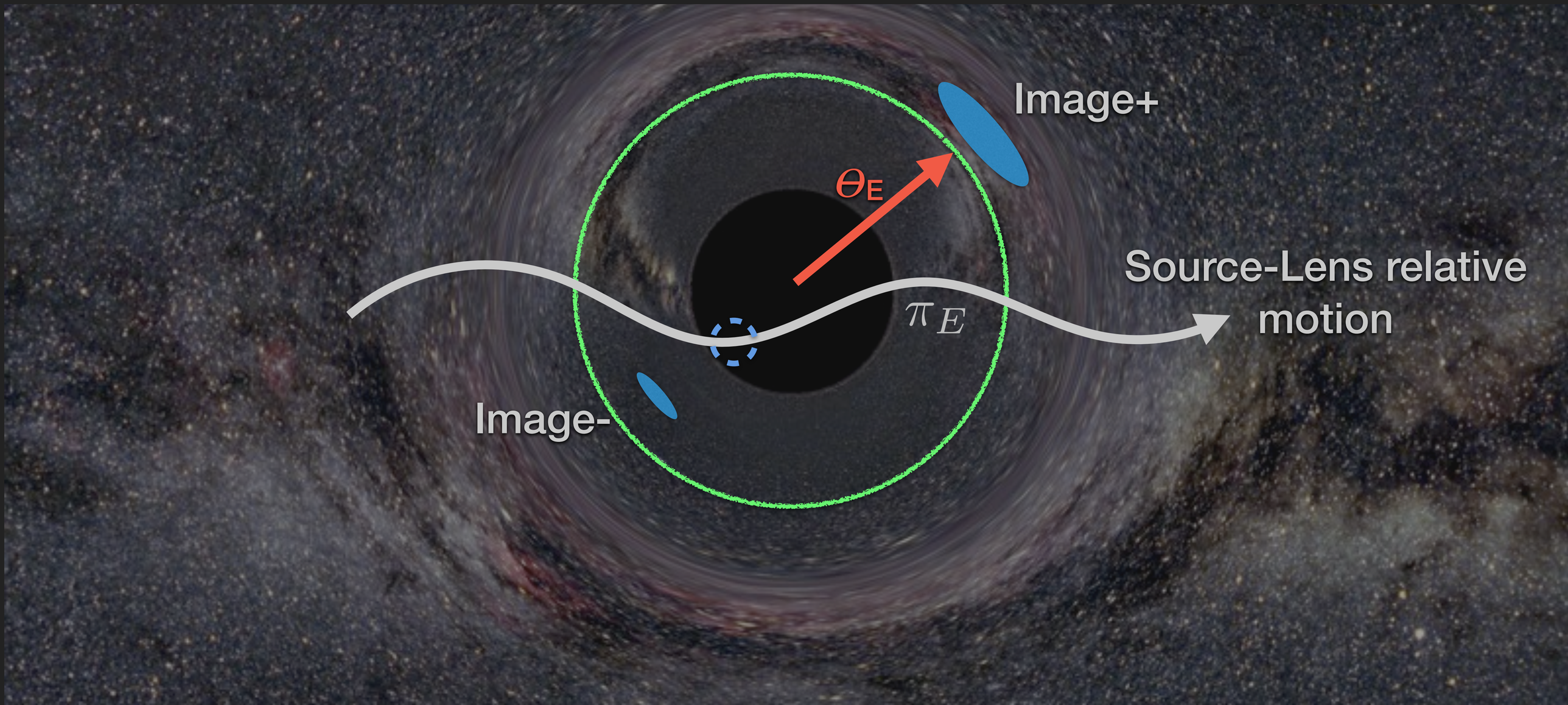
- OGLE data (1996-2009) was searched for time-varying changes in stars
- Dark Matter in form of primordial black holes (PBH) with monochromatic mass spectrum was ruled out to <~10 Solar Mass





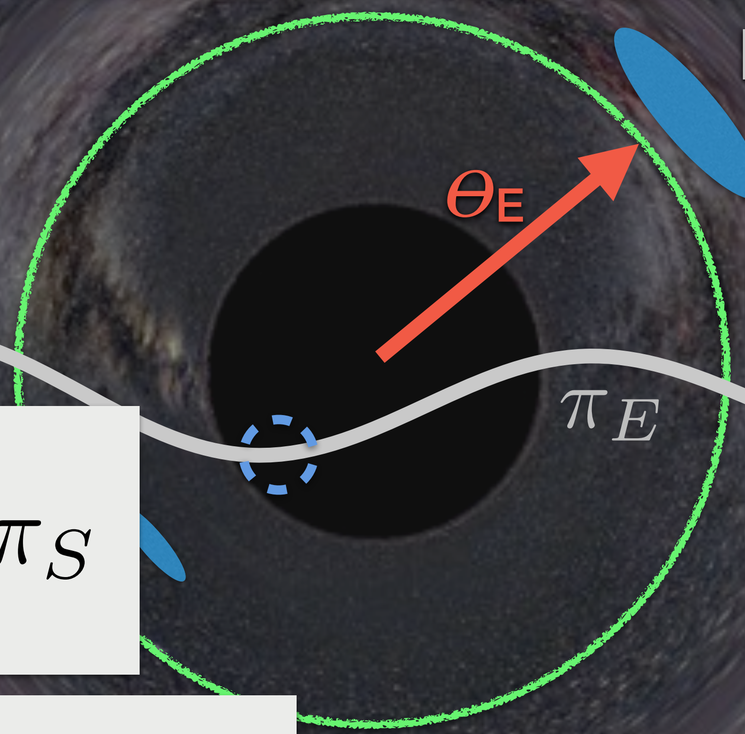
Garcia-Bellido & Clesse 2017
Wyrzykowski+ 2009,2010,2011a,2011b

HOW TO FIND A GALACTIC BLACK HOLE WITH MICROLENSING?



HOW TO FIND A GALACTIC BLACK HOLE WITH MICROLENSING?

Black hole = large mass + dark object



mass

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

distance

$$\pi_L = \theta_E \pi_E + \pi_S$$

flux (luminosity)

$$F_L = F_{obs}(t) - A(t) F_S$$

HOW TO FIND A GALACTIC BLACK HOLE WITH MICROLENSING?

Black hole = large mass + dark object

Photometry | Astrometry | Spectroscopy

mass

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

distance

$$\pi_L = \theta_E \pi_E + \pi_S$$

flux (luminosity)

$$F_L = F_{obs}(t) - A(t) F_S$$

HOW TO FIND A GALACTIC BLACK HOLE WITH MICROLENSING?

Black hole = large mass + dark object

mass

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

distance

$$\pi_L = \theta_E \pi_E + \pi_S$$

flux (luminosity)

$$F_L = F_{obs}(t) - A(t) F_S$$

Photometry	Astrometry	Spectroscopy
Gaia, OGLE, Spitzer, LCO, **Rubin/LSST*	Gaia, VLTI/GRAVITY, VLTI/PIONIER, AO, JWST, **ELT*, *Roman/*WFIRST*	Gaia, VLT, Gemini, SOAR, SALT, **ELT*

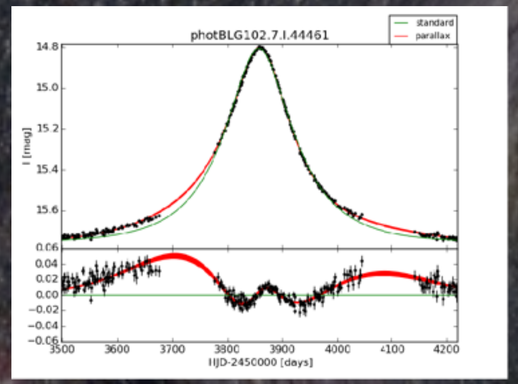
DARK LENSES FROM PHOTOMETRY

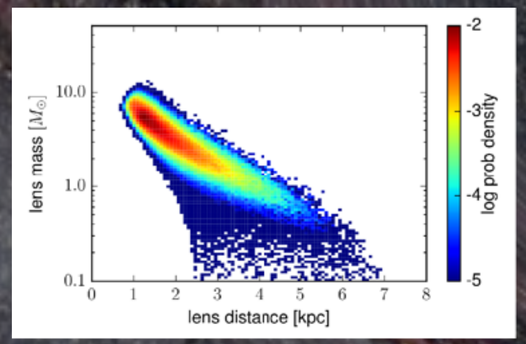
$$M = \frac{\theta_E}{\kappa \pi_E}$$

OGLE-III 2001-2009 Bulge 150 million stars

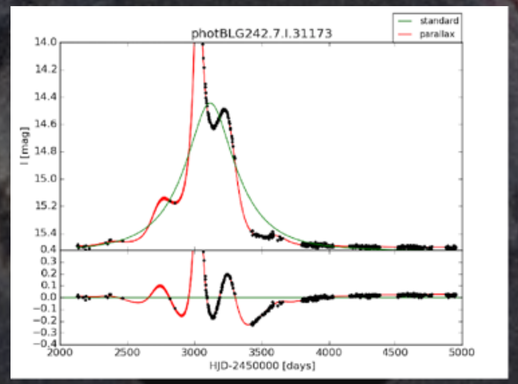
OGLE

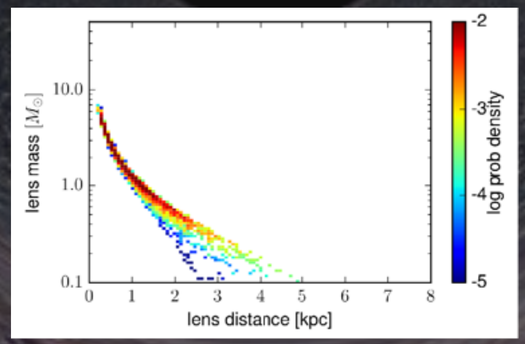
PAR-07 (Notec)



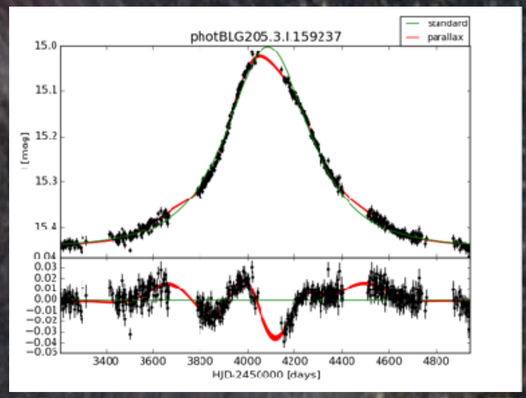


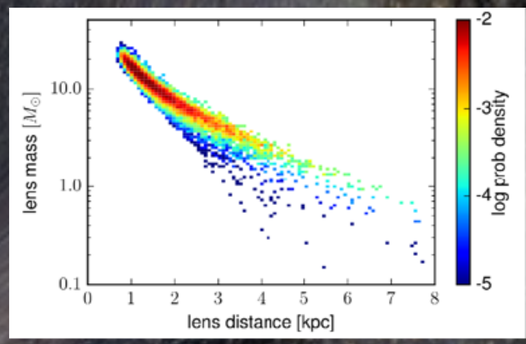
PAR-03 (Warta)





PAR-02 (Odra)





Masses of lenses estimated using Galactic model (guessing thetaE)

Wyrzykowski+2016, Wyrzykowski&Mandel 2020
Mróz&Wyrzykowski 2021

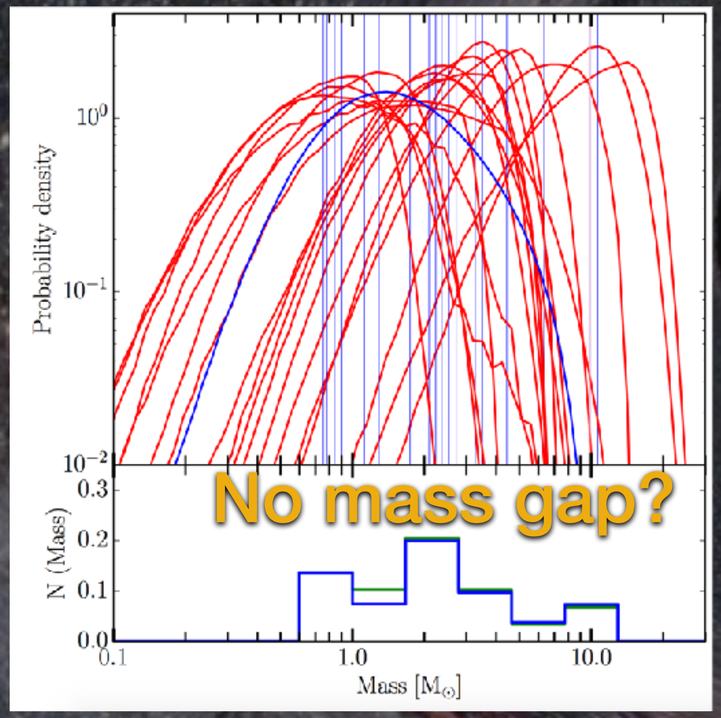
DARK LENSES FROM PHOTOMETRY

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

OGLE-III 2001-2009 Bulge 150 million stars

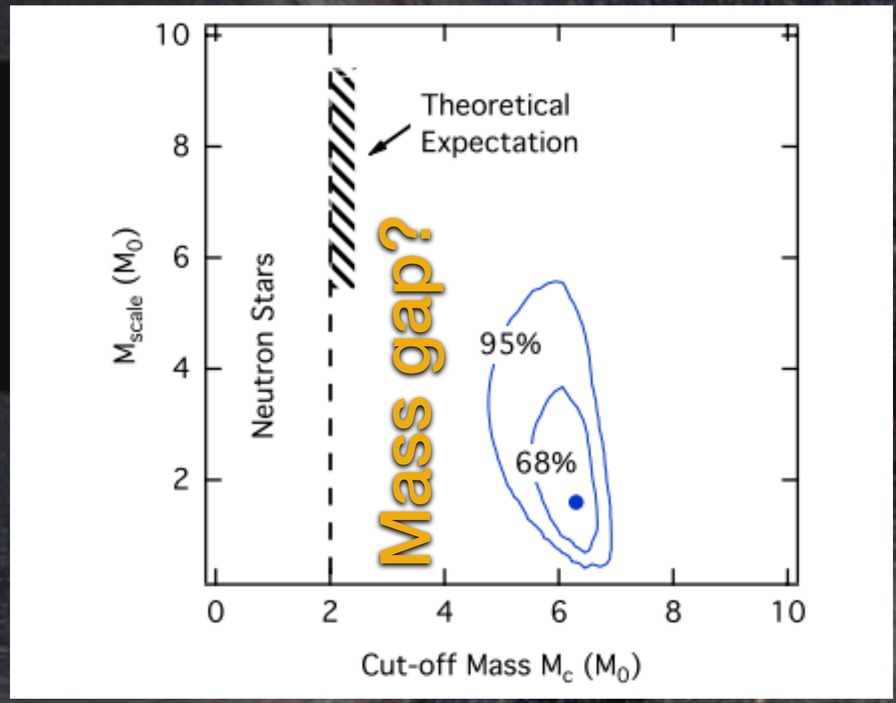
OGLE

microlensing



Wyrzykowski+2016, Wyrzykowski & Mandel 2020, Mróz & Wyrzykowski 2021

X-ray binary systems



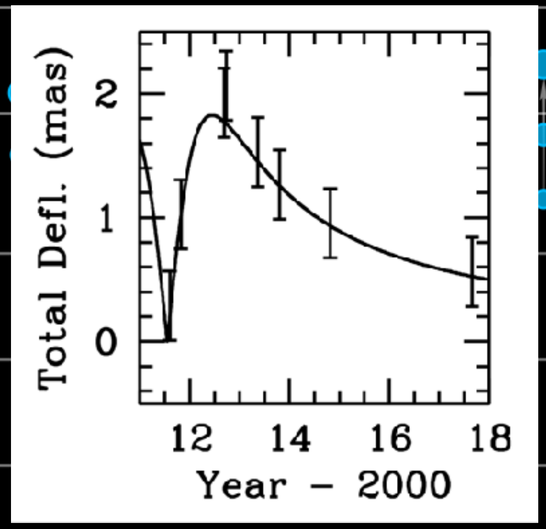
Ozel+2010

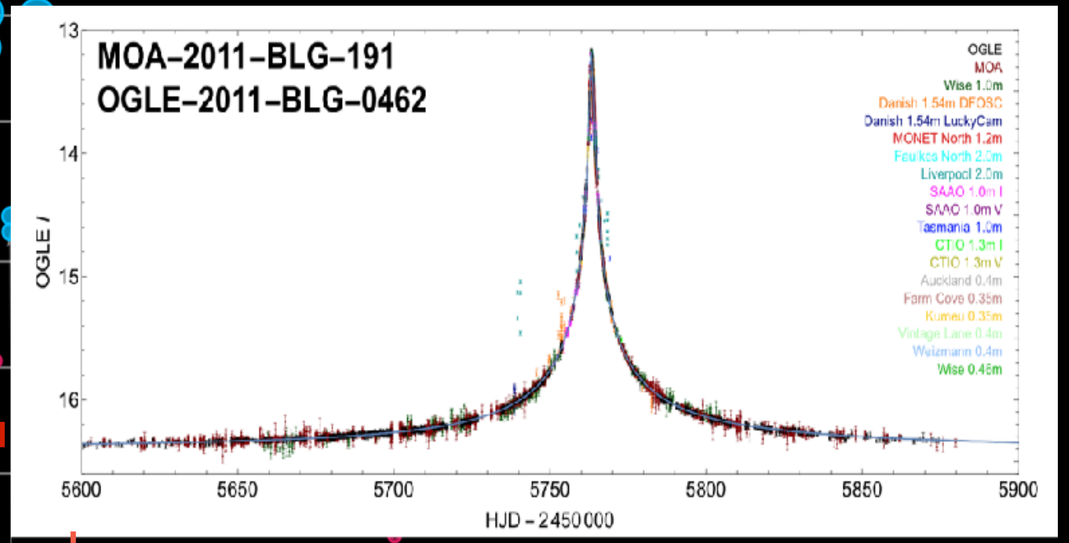
FIRST ISOLATED BLACK HOLE FROM MICROLENSING

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

LIGO-Virgo-KAGRA Black Holes | LIGO-Virgo-KAGRA Neutron Stars | EM Black Holes | EM Neutron Stars | Microlensing

Solar Masses





astrometric time-series

photometric time-series

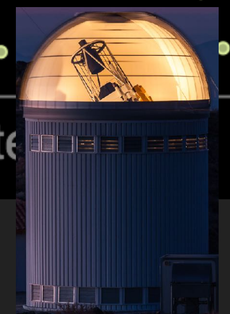
200
100
50
20
10
5
2
1

Hubble Space Telescope

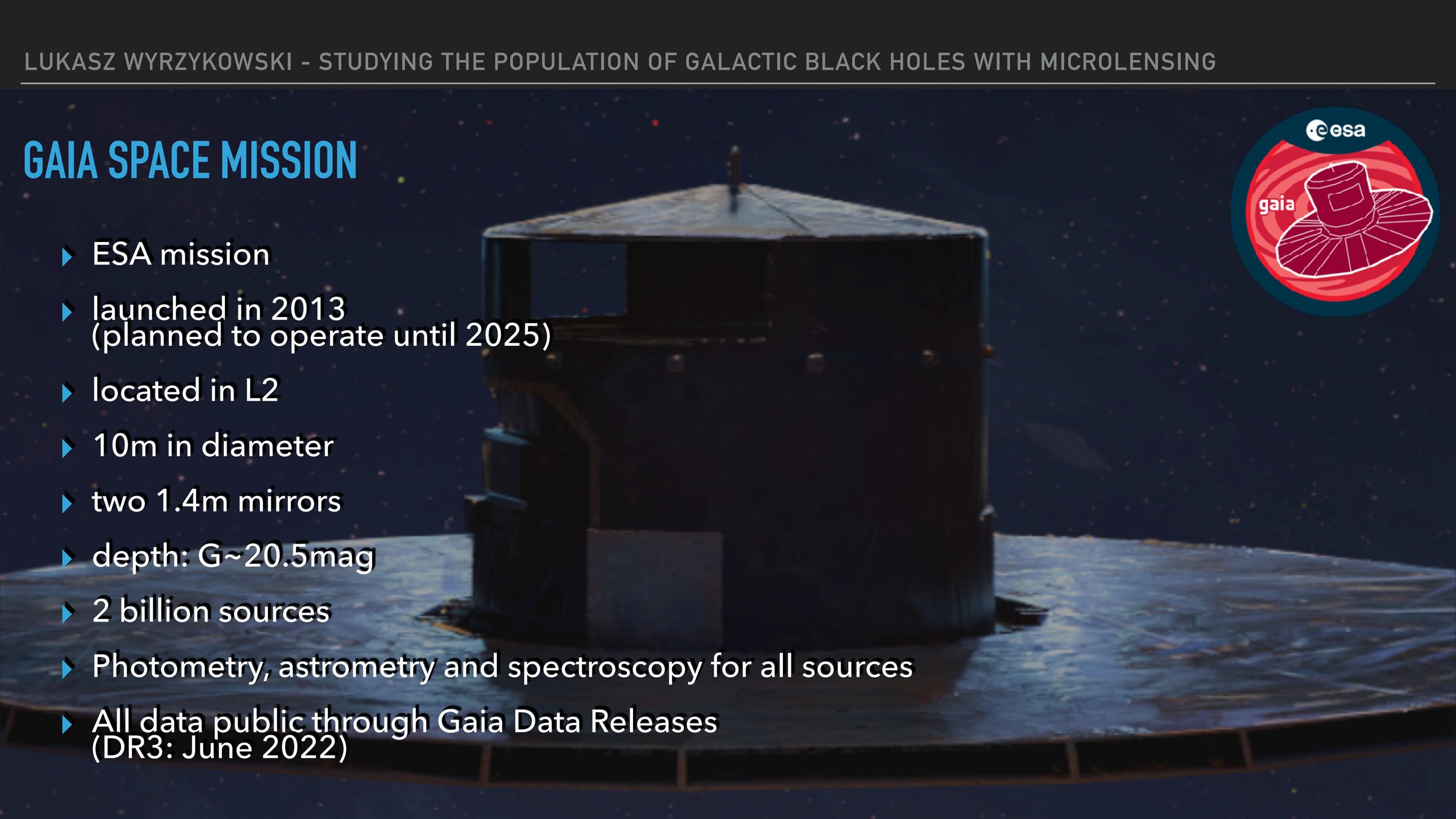
LIGO-Virgo-KAGRA | Aaron Geller | Northweste

Sahu+2022
Lam+2022, Mróz+2022

OGLE



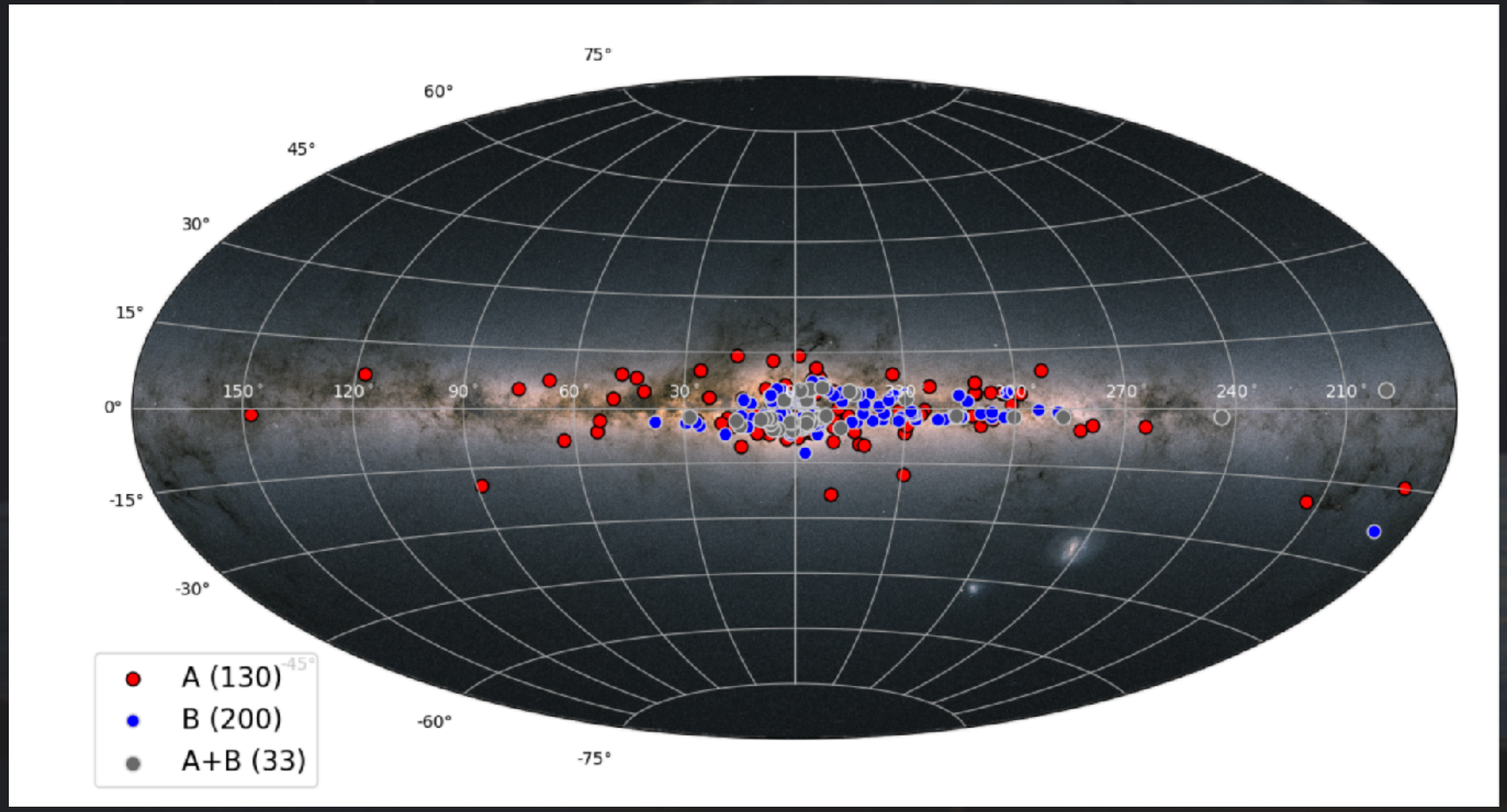
GAIA SPACE MISSION

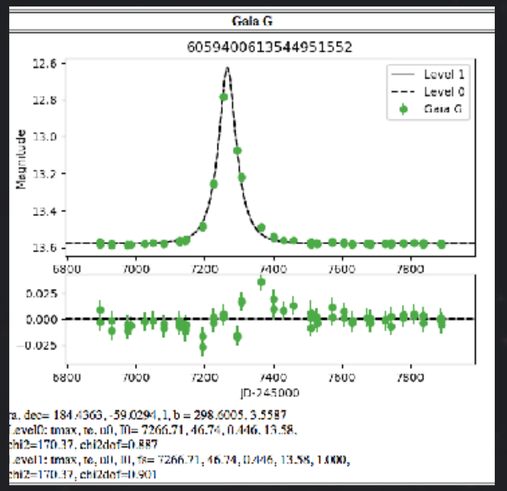


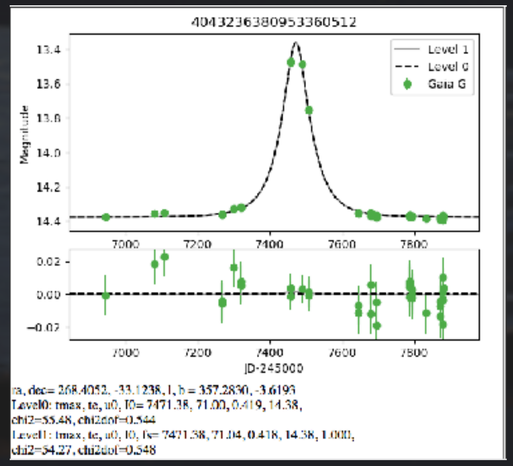
- ESA mission
- launched in 2013
  (planned to operate until 2025)
- located in L2
- 10m in diameter
- two 1.4m mirrors
- depth: G~20.5mag
- 2 billion sources
- Photometry, astrometry and spectroscopy for all sources
- All data public through Gaia Data Releases
  (DR3: June 2022)

MICROLENSING EVENTS IN GAIA

- 363 archival events from 2014-2017 in Gaia DR3 *(Wyrzykowski+2022)*





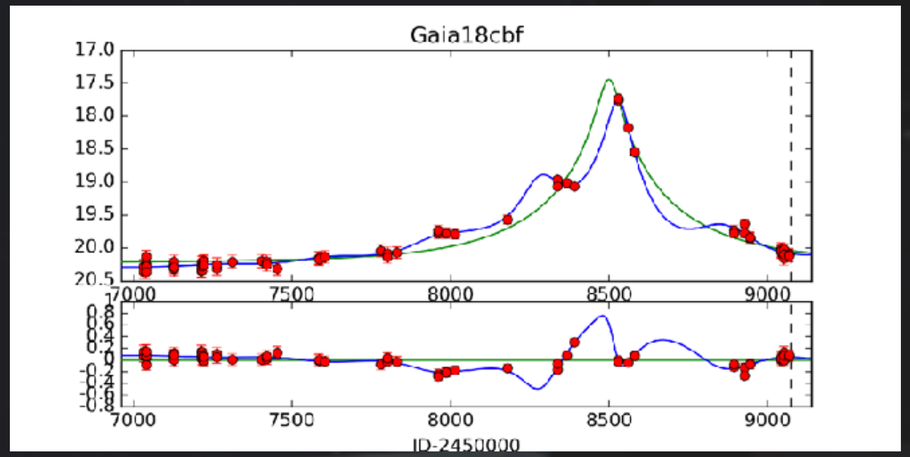


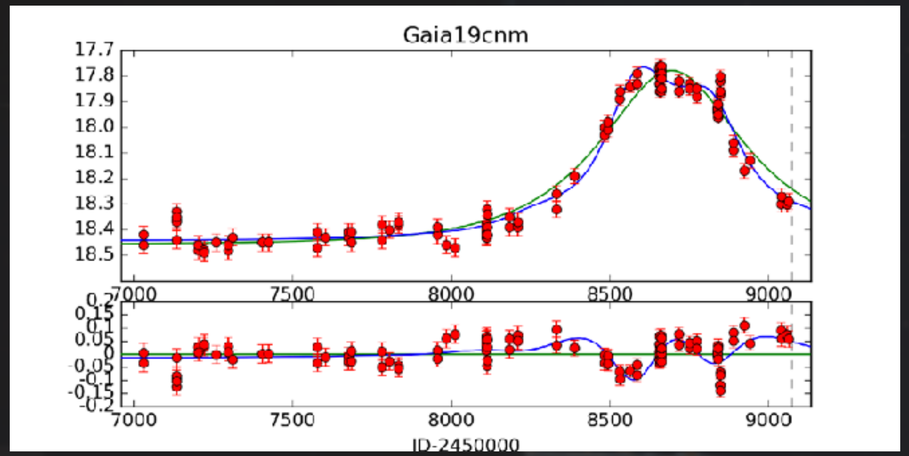
MICROLENSING EVENTS IN GAIA ALERTS

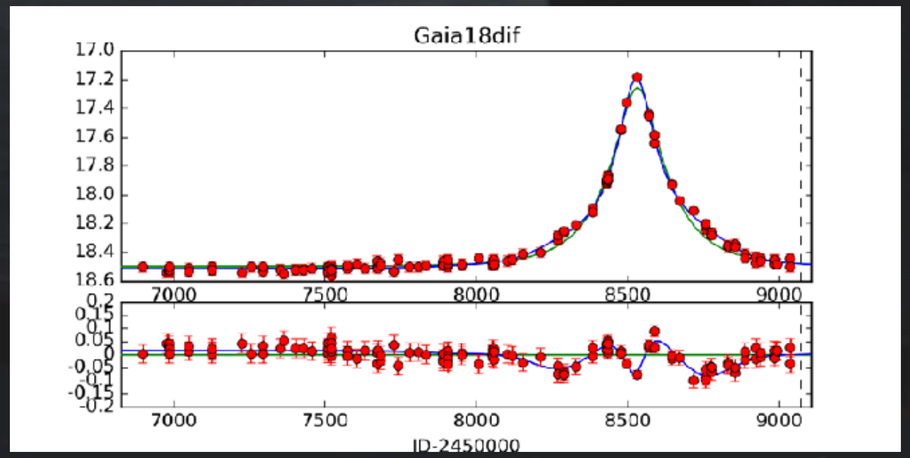
http://gsaweb.ast.cam.ac.uk/alerts/

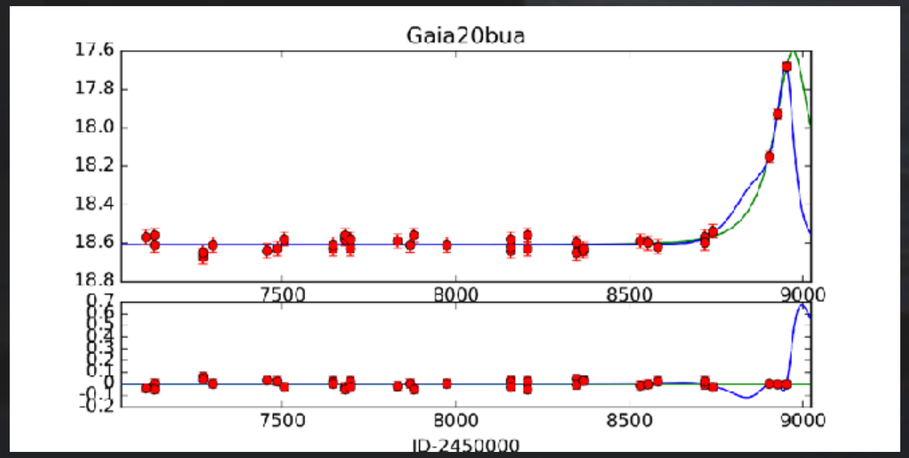
UNIVERSITY OF CAMBRIDGE

- 343 events from 2016-2021 found by Gaia Science Alerts *(Hodgkin+2021)*
- 1-5 new events found every week in real-time by Gaia Science Alerts*





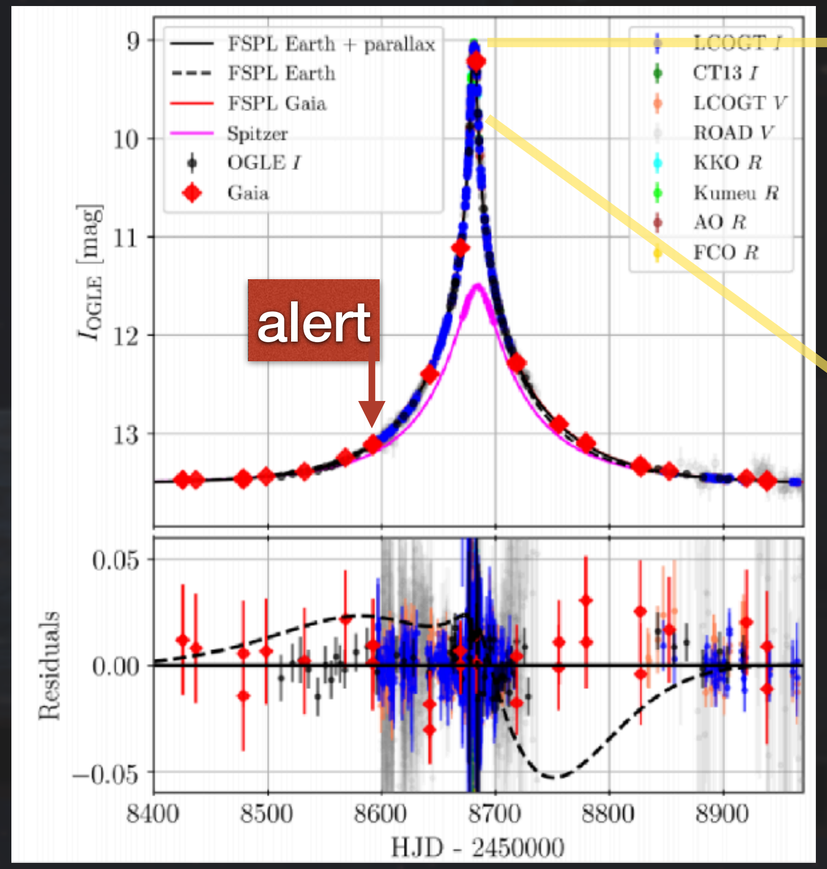


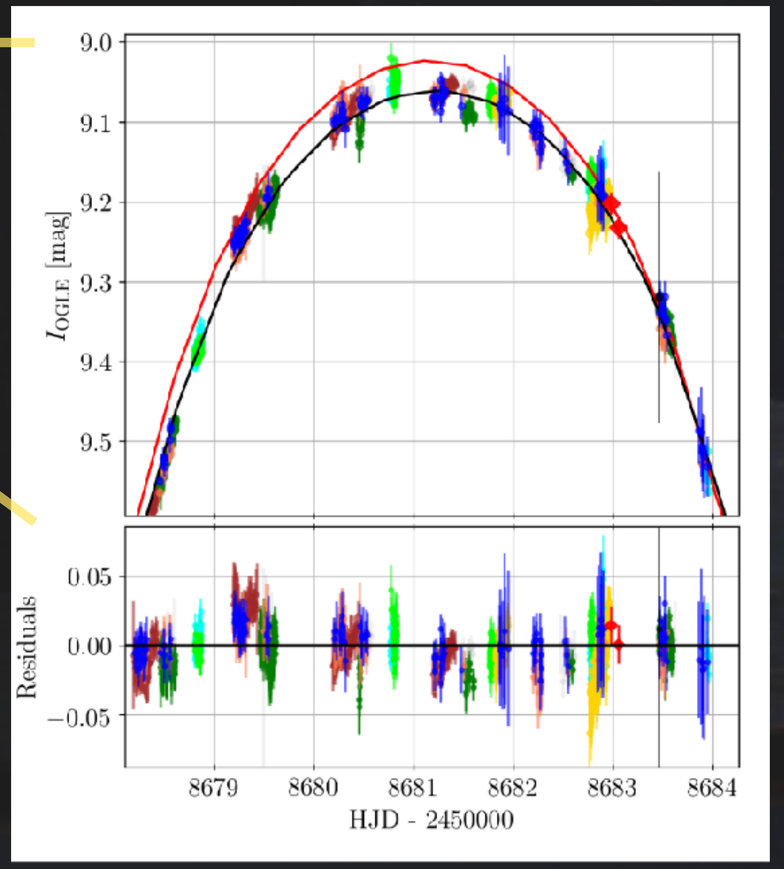


*Gaia alerts on ALL types of transients: supernovae, TDE, Novae, CVs, RCrB, etc.

GAIA19BLD ALERT

- High-magnification microlensing event with ~10,000 observations
- Dark lens identified, mass 1.13 MSun





Rybicki et al. 2022
Bachelet et al. 2022
Cassan et al. 2022

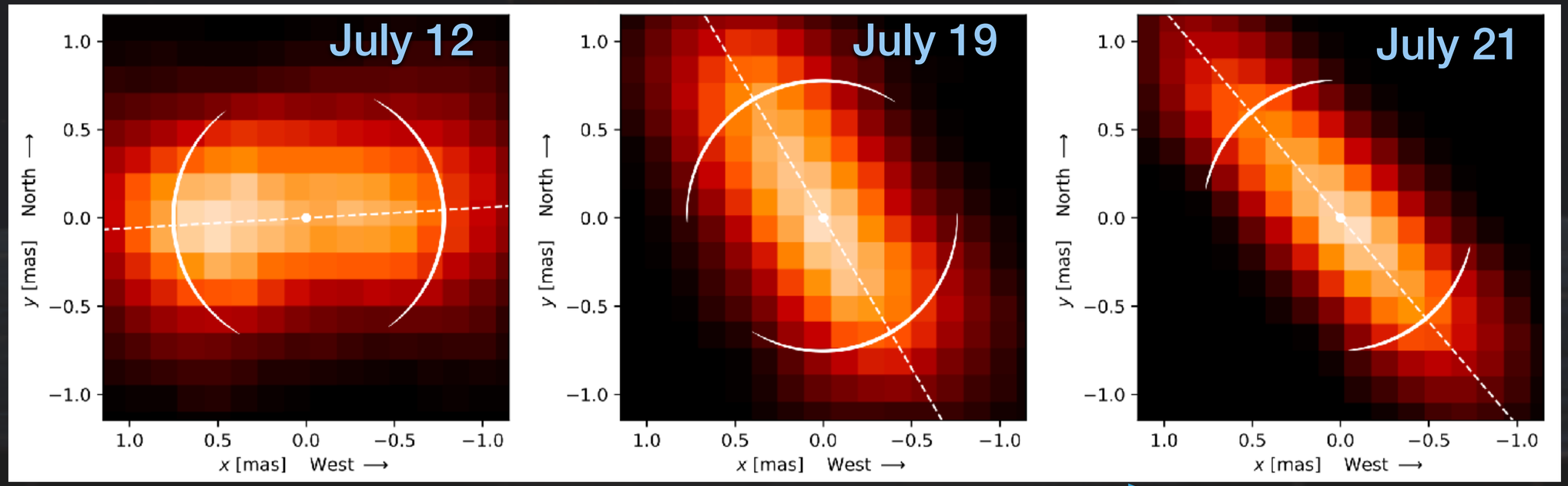
EINSTEIN RADIUS FROM OPTICAL INTERFEROMETRY

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

GAIA19BLD ALERT

- bright enough for optical interferometry (second case ever)
- smallest Einstein Radius measured (0.7 mas) and rotation of images detected

ESO/VLTI/PIONIER



Cassan et al. 2022
(Nature Astronomy)

GAIA-DR3-ULENS-001

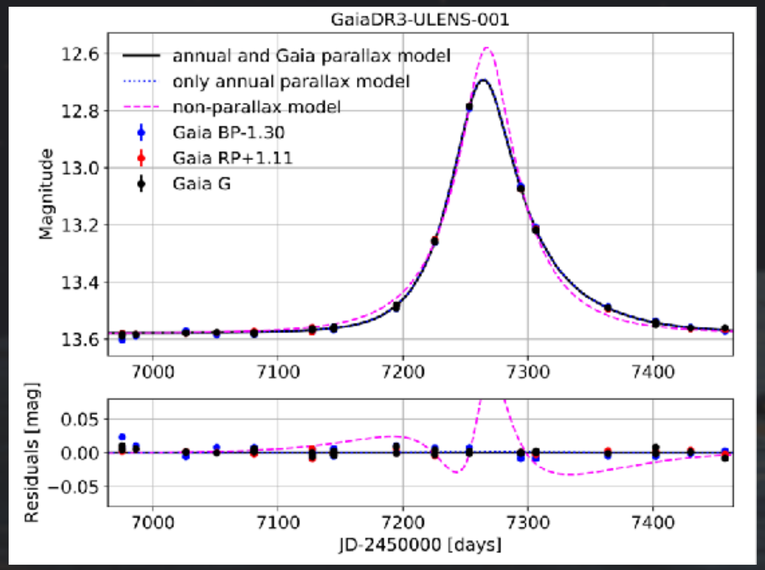
EINSTEIN RADIUS FROM ~ASTROMETRY

MICROLENSING PARALLAX

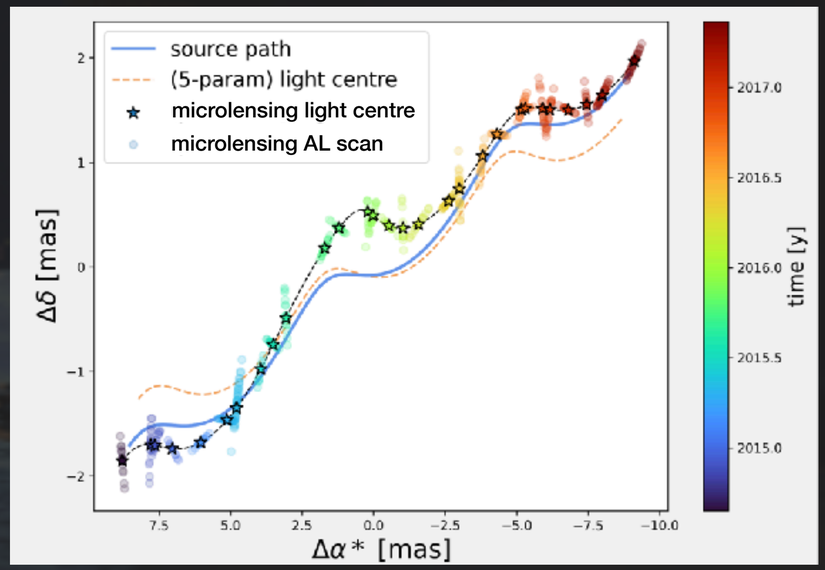
$$M = \frac{\theta_E}{\kappa \pi_E}$$

- Gaia astrometric measurements anomalous - can be explained with microlensing
- dark lens mass measured (~1 MSun) at 1 kpc towards the Galactic Disk

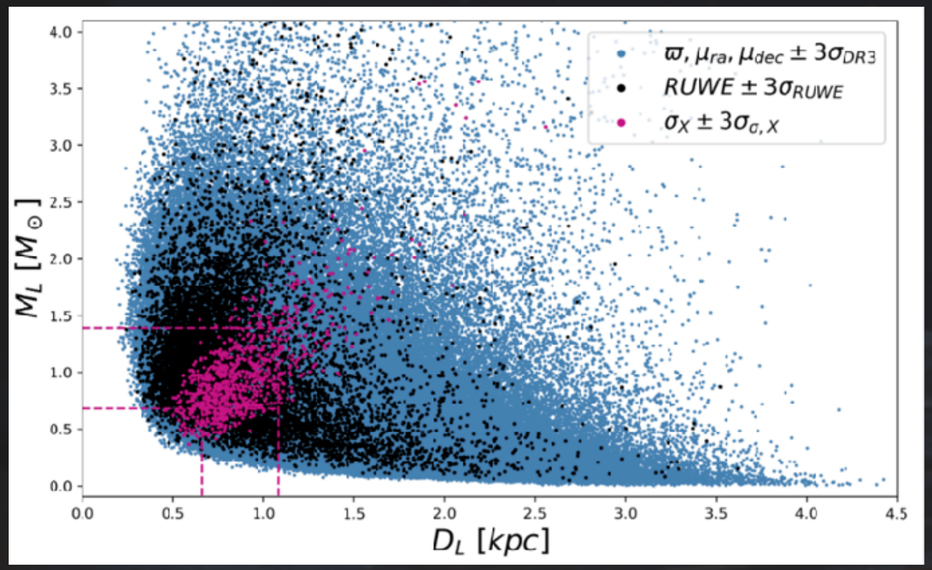
Gaia photometry



Gaia astrometry (sim)



lens mass/distance

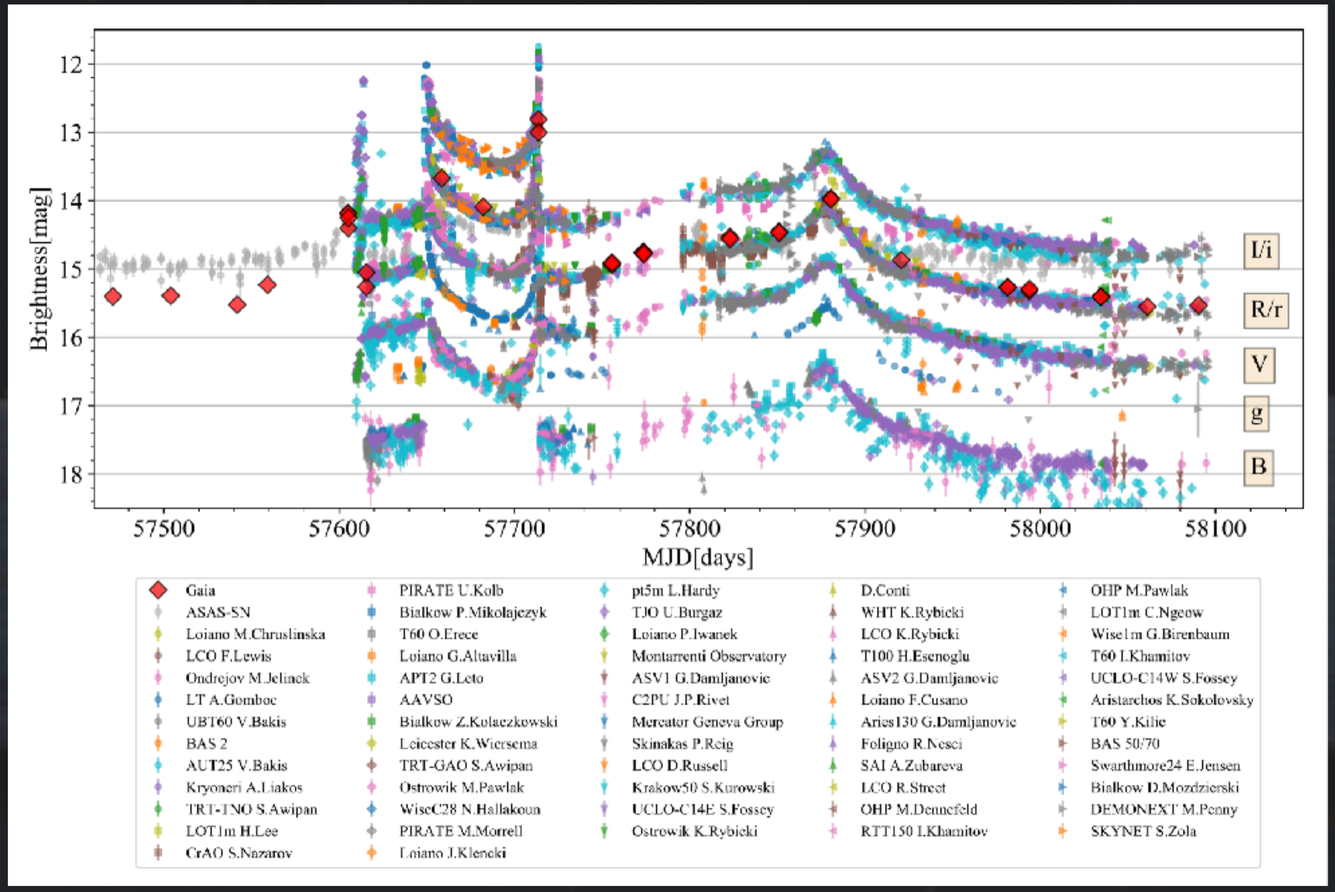


Simulated astrometry to reproduce Gaia DR3 statistics and error-bars

Jabłońska et al. (2022)

GAIA16AYE ALERT – THE MOST COMPLEX BINARY MICROLENSING EVENT!

- 20,000 ground-based follow-up observations from 51 observatories
- full-orbital solution found for the invisible MS star binary system (0.6+0.4 MSun) at 800pc

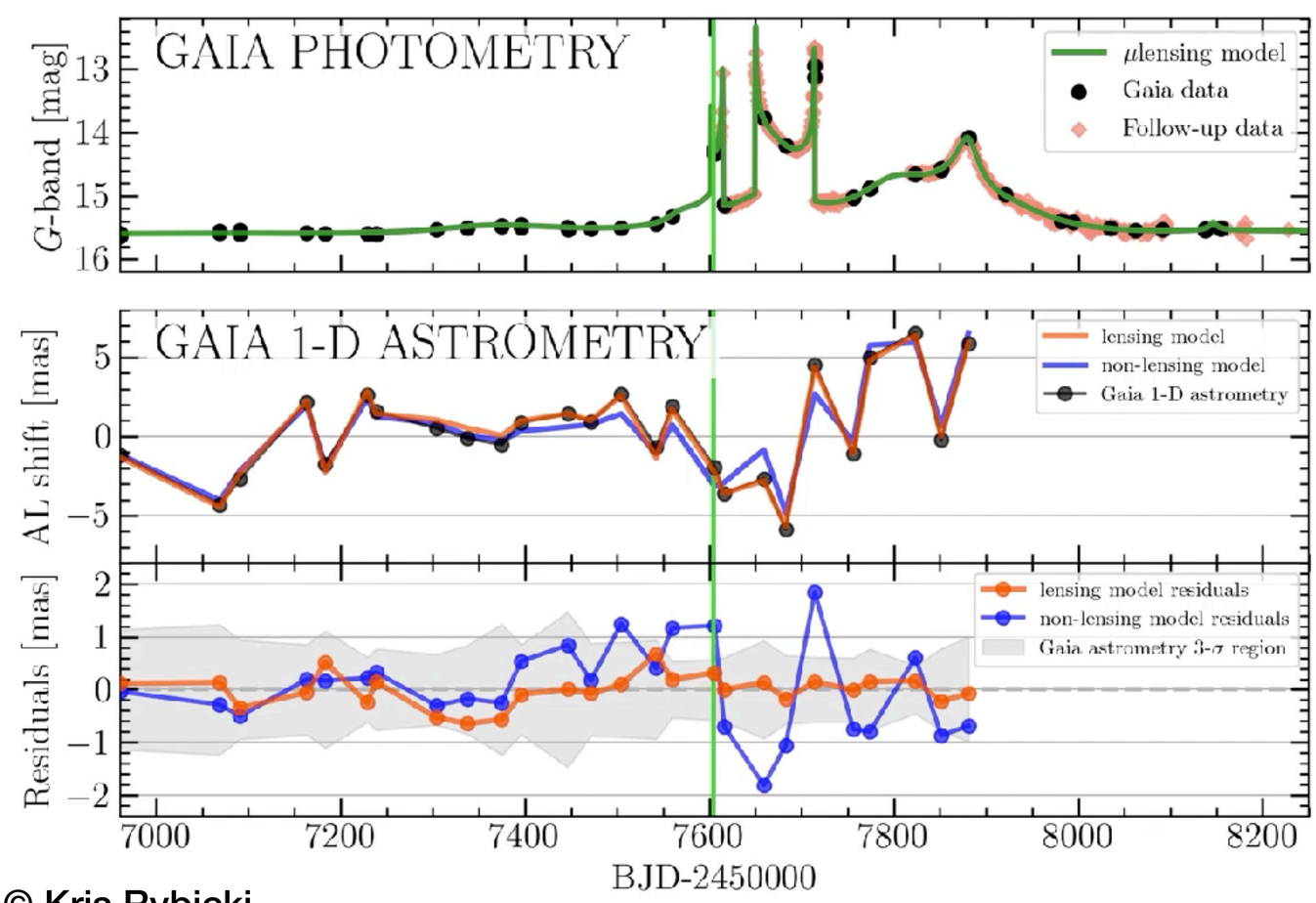


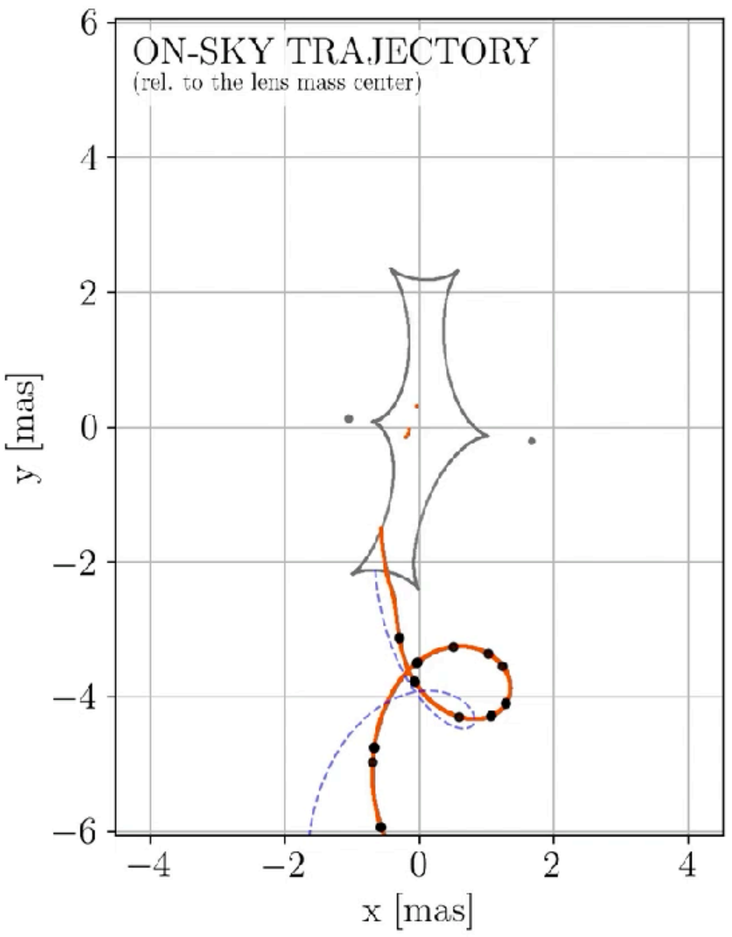
#gaia16aye

Wyrzykowski et al. 2020

GAIA16AYE ALERT AND GAIA ASTROMETRIC TIME-SERIES

- Gaia astrometric time-series reveal microlensing signal





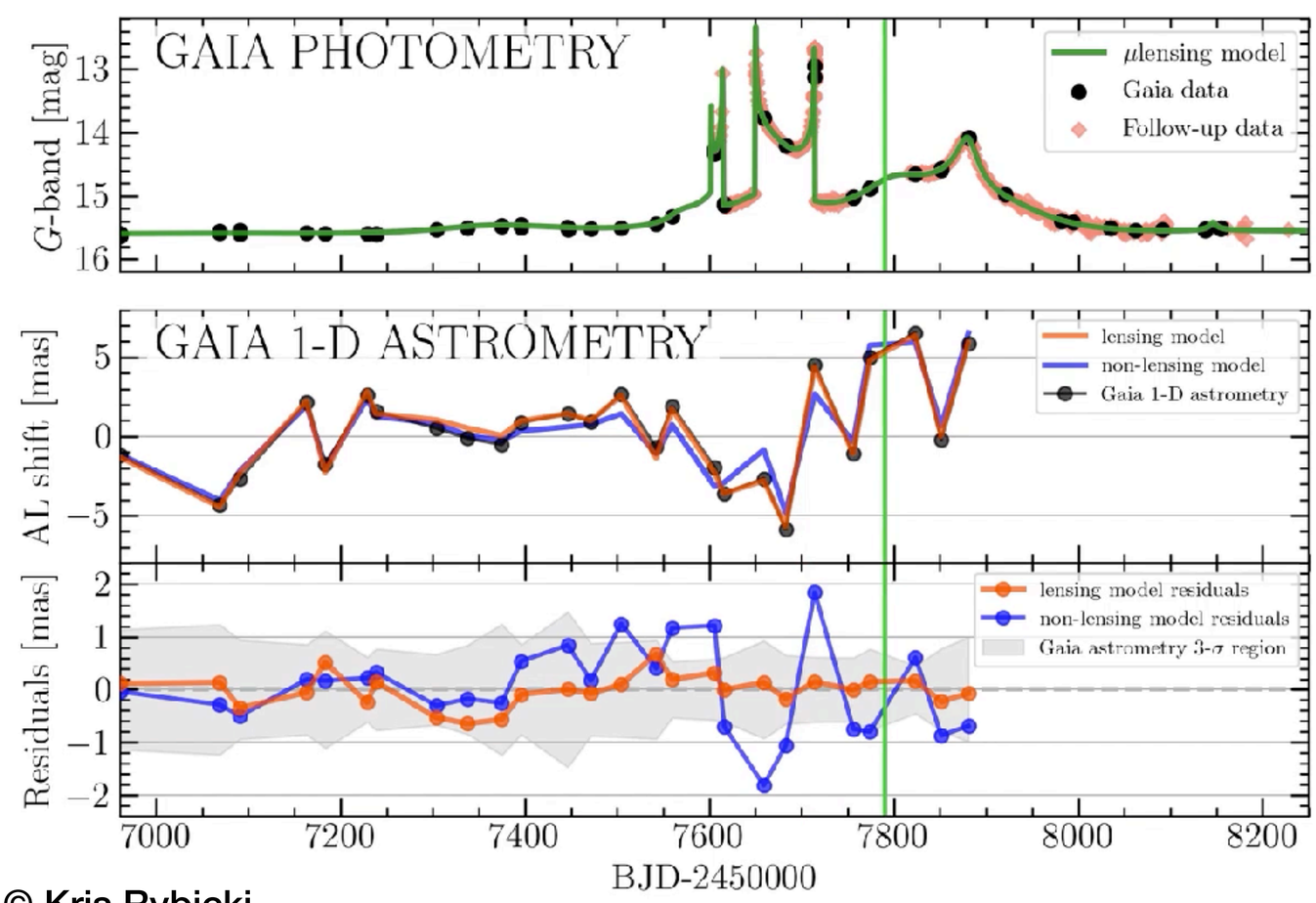
© Kris Rybicki

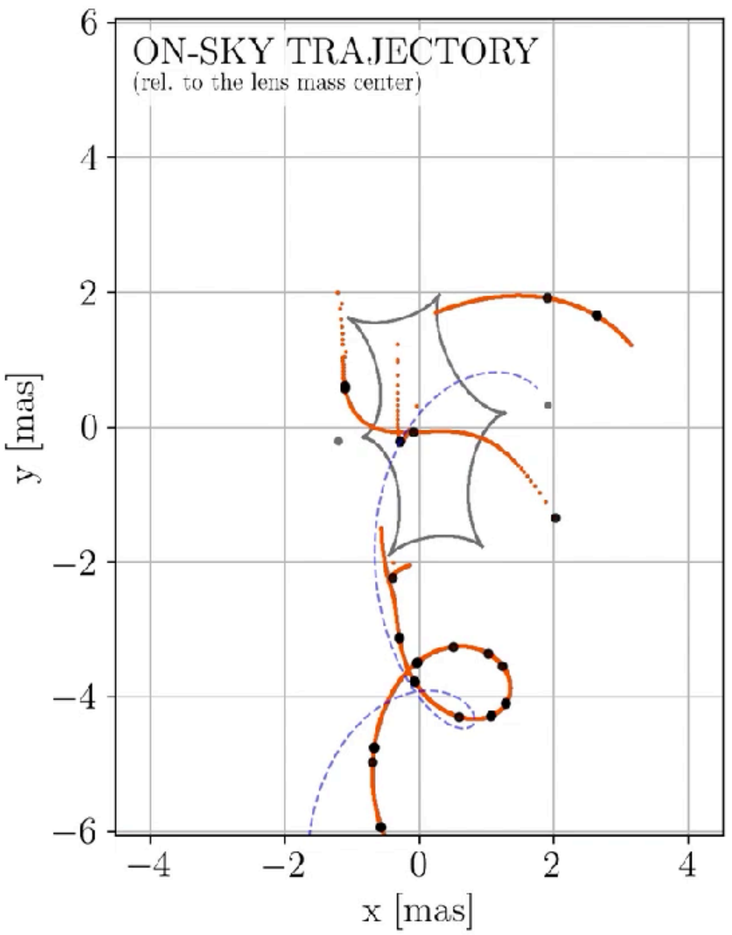
https://www.cosmos.esa.int/web/gaia/iow_20210924

Gaia
Image of the Week
24 Sep.2021

GAIA16AYE ALERT AND GAIA ASTROMETRIC TIME-SERIES

- Gaia astrometric time-series reveal microlensing signal





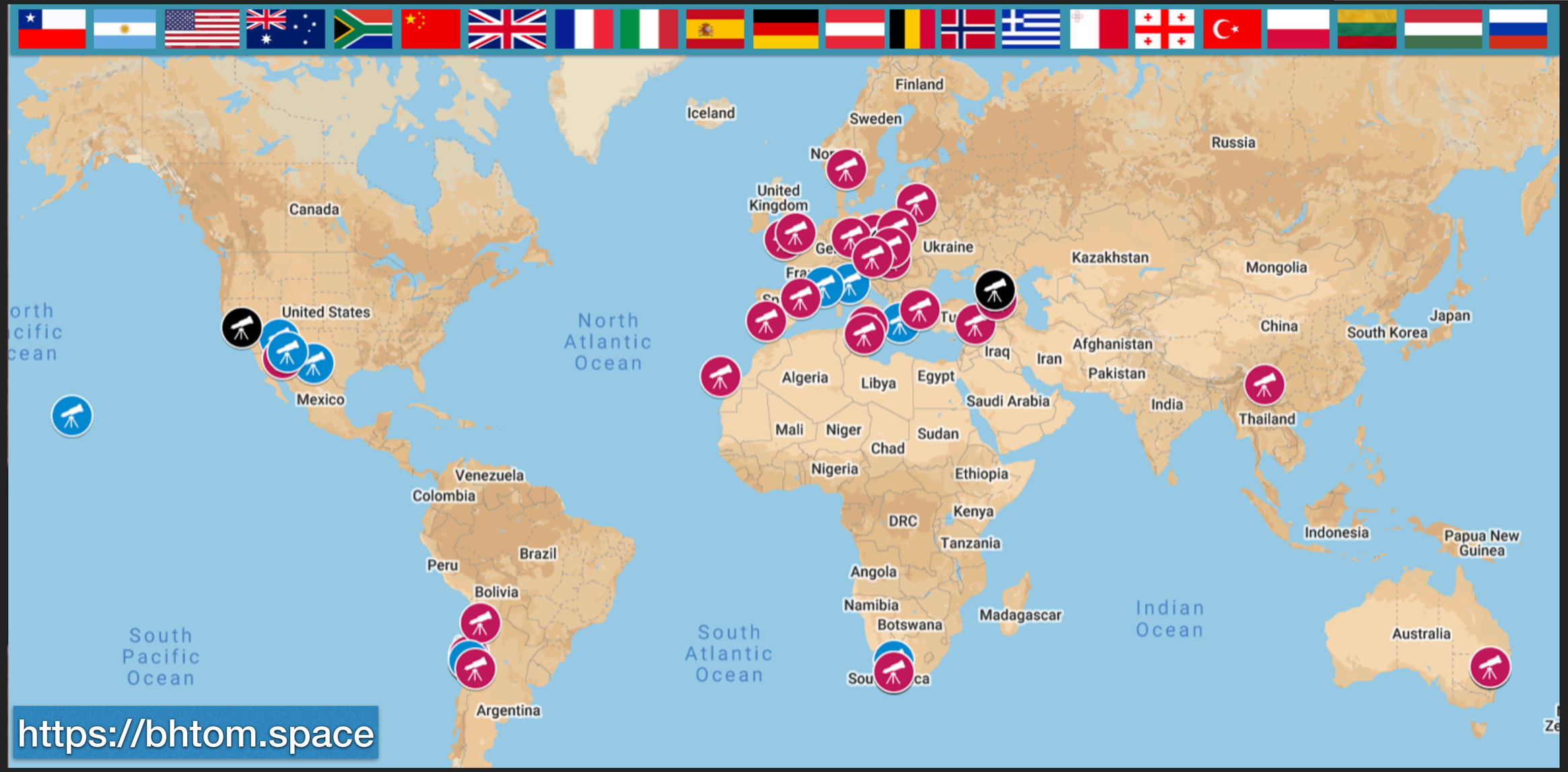
© Kris Rybicki

https://www.cosmos.esa.int/web/gaia/iow_20210924

Gaia
Image of the Week
24 Sep.2021

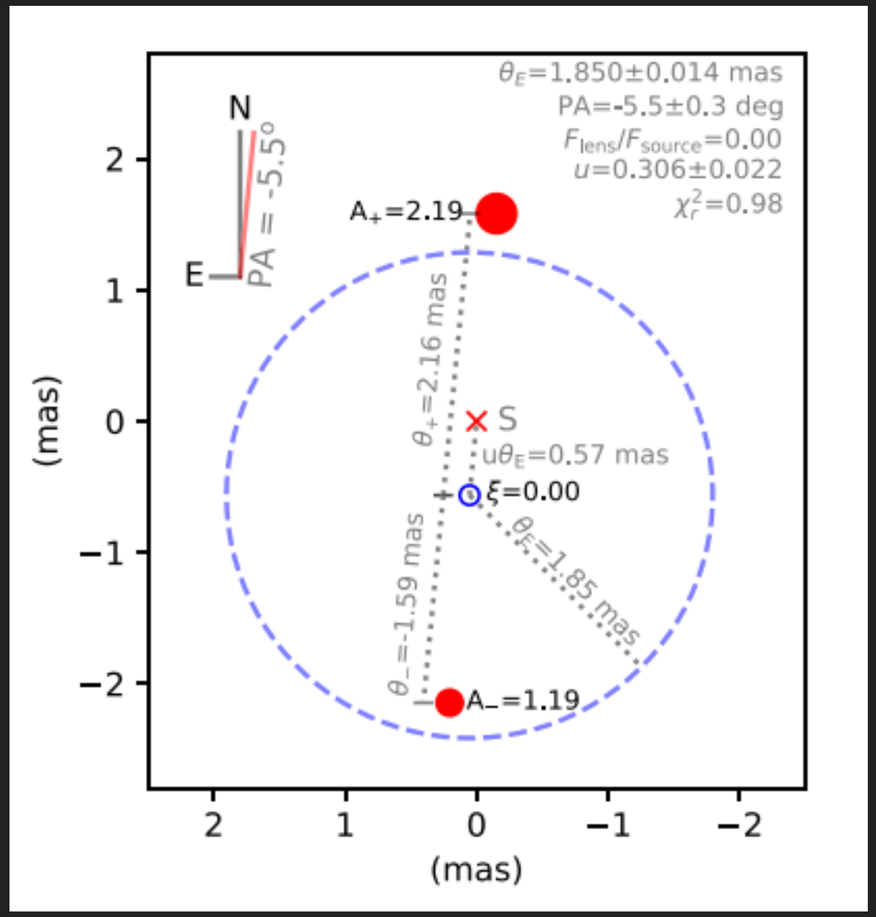
GLOBAL TELESCOPE NETWORK FOR TIME-DOMAIN OBSERVATIONS

OPTICON RadioNet Pilot



ASTROMETRIC FOLLOW-UP OF MICROLENSING EVENTS

- GRAVITY/VLTI/ESO - optical interferometry can resolve images in microlensing events (~1mas)
- Targets often in very dense parts of the sky
- Advent of routine ground-based astrometric measurements of microlensing events



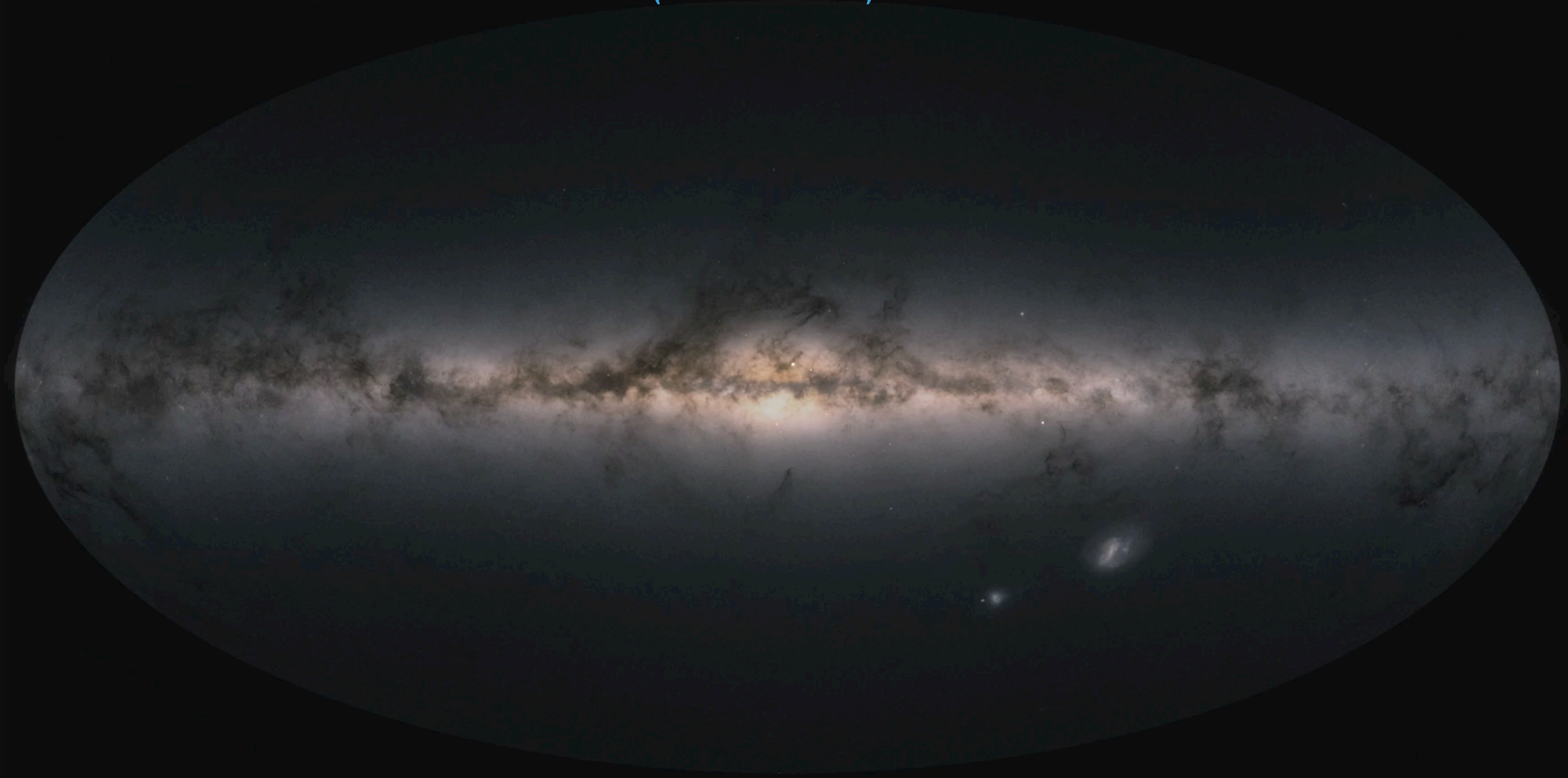
First resolution of two images in microlensing (GRAVITY, Dong+2019)

SUMMARY

- Microlensing is complementing the Multi-Messenger picture of black holes in our Galaxy
- If Dark Matter exists in form of lonely black holes, microlensing should find them
- The mass-gap between neutron stars and black holes is being filled with discoveries from microlensing and other methods
- Gaia is the only tool providing both photometry and astrometry for billion of stars from all over the sky
- Gaia astrometry will be the key to find black holes among Gaia-observed microlensing events
- Ground-based follow-up necessary for selected targets from Gaia, OGLE, LSST in future:
  - photometry from a global network of small telescopes
  - astrometry from GRAVITY+ and ELT in future

GAIA.ASTROUW.EDU.PL
BHTOM.SPACE
LW
@ASTROUW.EDU.PL
Łukasz Wyrzykowski

MICROLENSING EVENTS IN GAIA DR3 (2014–2018)



2014.1

https://youtu.be/o17MoMTbwy0

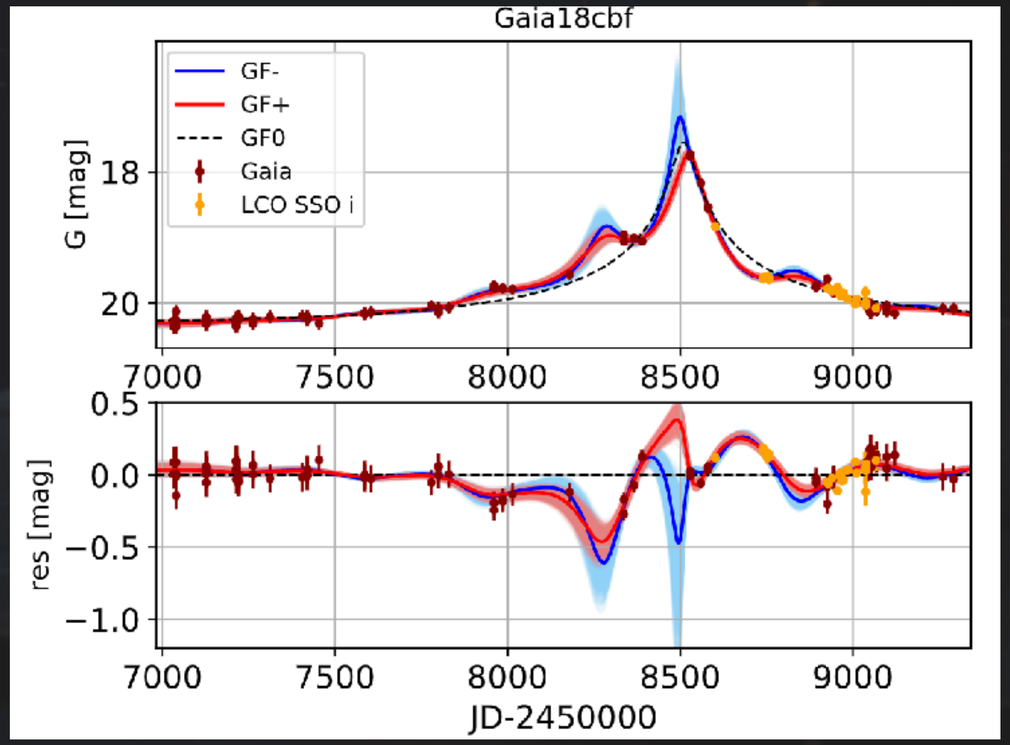
Maja Jabłońska, Andrzej Krupka, LW

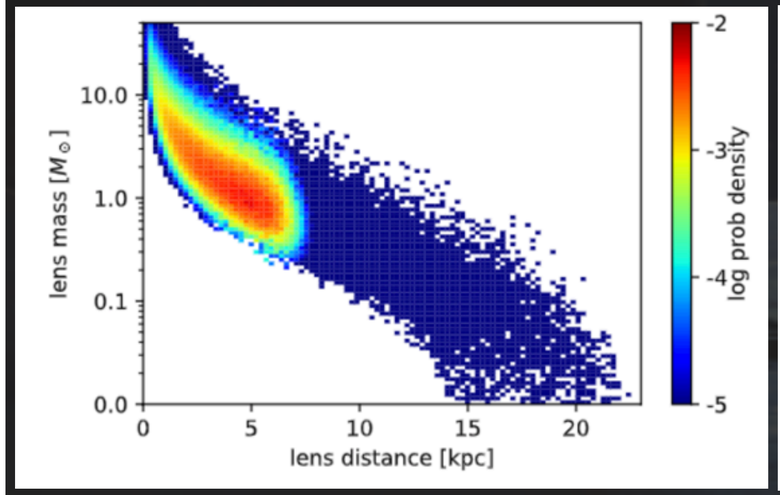
extra slides

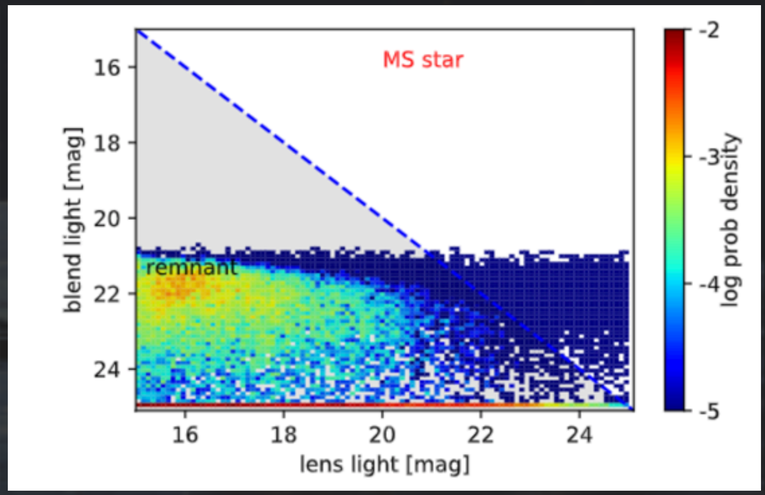
GAIA18CBF

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

- one of the longest events ever studied (time-scale about 500 days), but missed follow-up opportunity
- candidate for a single ~2 MSun dark object at ~4kpc

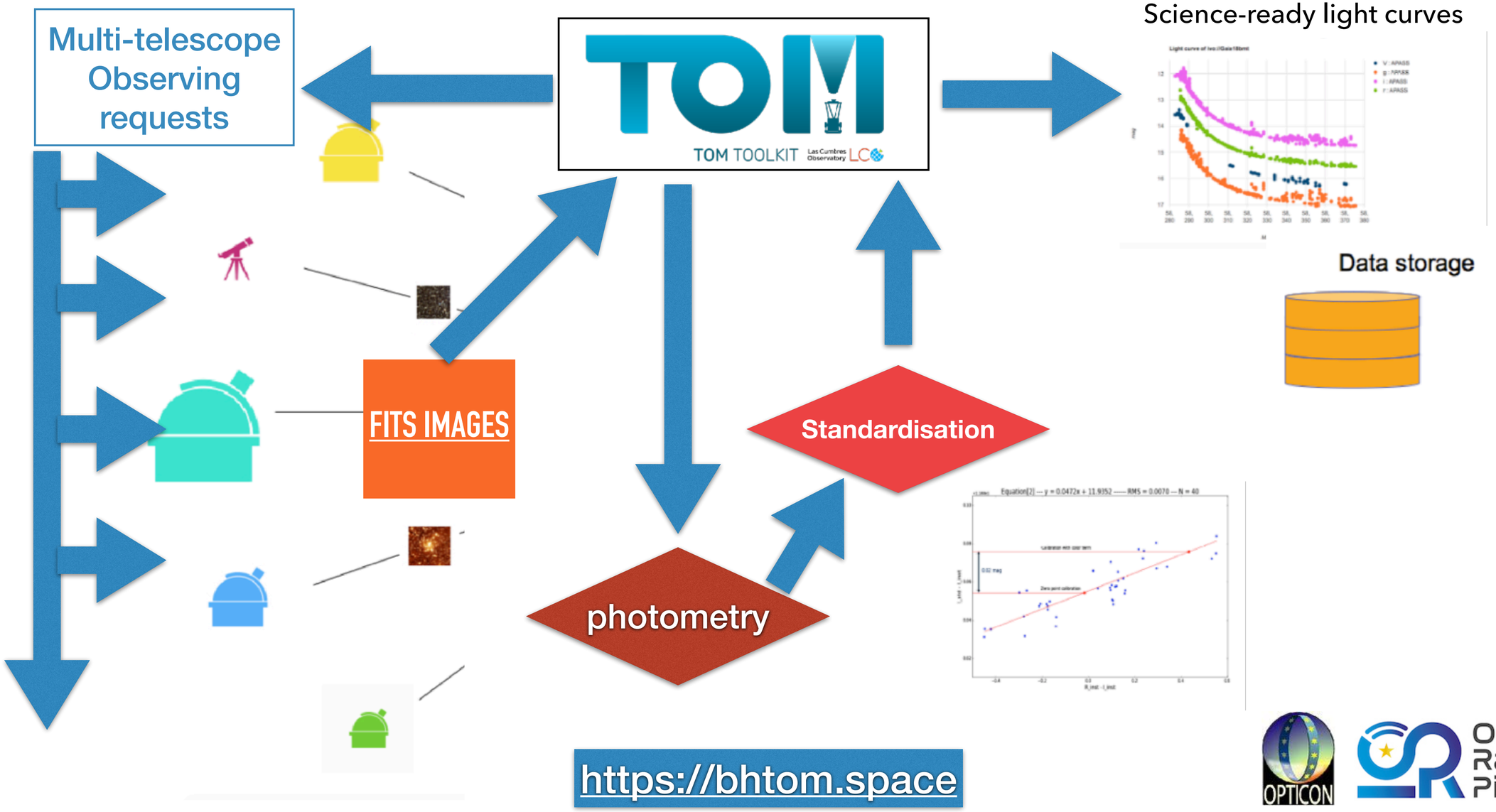






Kruszyńska et al. 2022

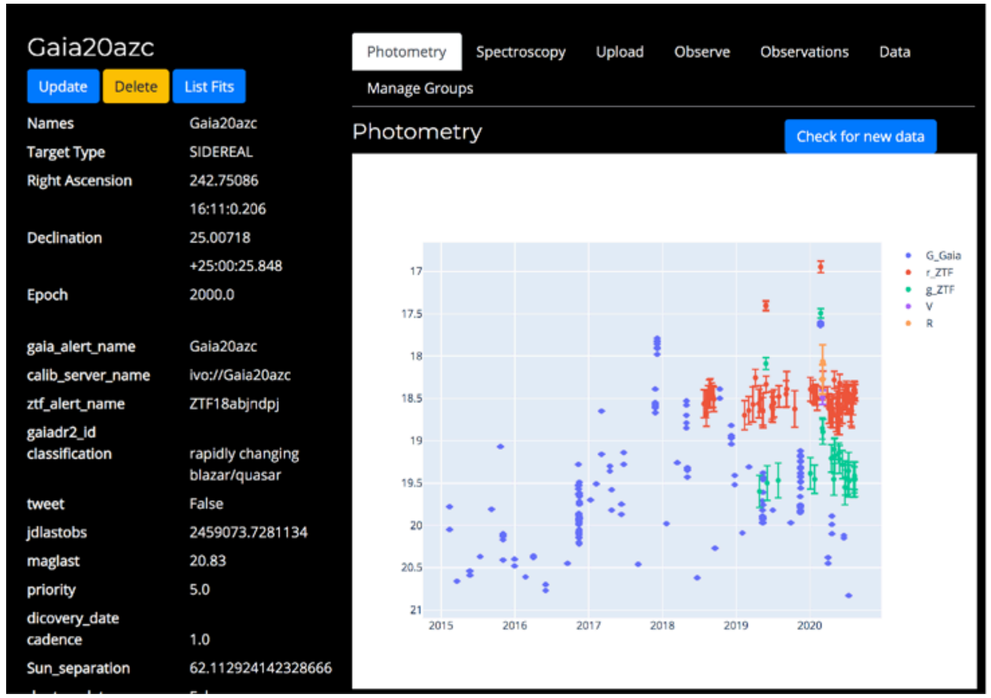
BLACK HOLE TOM ▸ tool for coordination and data processing of time-domain observations

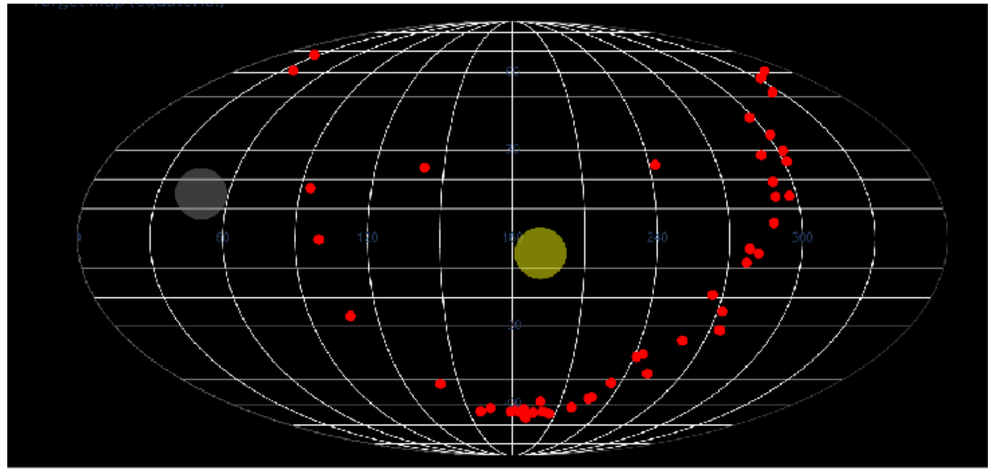


OPTICON RadioNet Pilot

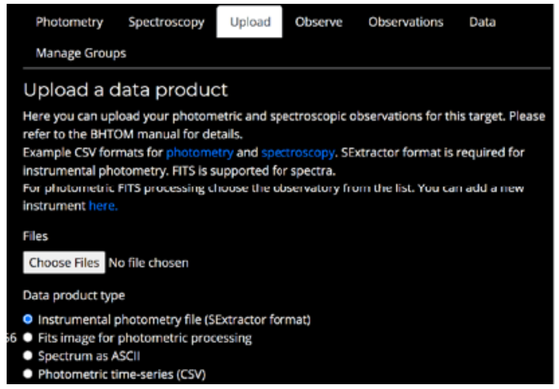
BLACK HOLE TOM

https://bhtom.space





Event Name/Aliases	RA	Dec	Number of Observations	Last Gaia [mag]	Target Importance	Time from last obs [days]	Required Cadence [days]	Observing Priority	Sun distance [deg]
Gaia19bcbf	241.1619	-41.10483	3164	20.13	10.0	29.9	1.0	299.1	64
Gaia20azc	242.75086	25.00718	444	20.83	5.0	54.1	1.0	270.6	62
Gaia20bof	184.61816	-63.49726	10852	15.7	8.0	13.9	0.5	223.0	61
Gaia19dak	302.36516	29.93588	3316	18.98	9.0	24.3	1.0	219.1	115
Gaia20cek	343.03385	60.66898	3333	12.46	10.0	16.1	1.0	160.6	119
Gaia20bgu	205.559	-64.31565	92	16.57	9.0	11.9	1.0	107.4	54
Gaia19cnjm	227.93683	-57.0571	5396	18.03	10.0	9.4	1.0	94.3	65



TOM TOOLKIT Las Cumbres Observatory LCO

///AkondLab.

OPTICON

OPTICON RadioNet Pilot

GAIA VARI

esa

Citizen science project by the European Space Agency supporting Gaia Variable stars classification

- Building community around ESA's Gaia mission through science engagement
- Engaging citizens in classification of the time-series dataset for interesting variable star cases
- Possibility of co-authorship of scientific publications (Data Release 4)
- Collaboration with Zooniverse – the biggest platform for citizen science projects
- Gamification strengthening of the engagement of general public
- Inviting open community to discussion and knowledge sharing
- Attractive storytelling through appealing graphics and illustrations
- New social media channels

sednai

science now.

More to come! Stay tuned!

www.gaiavari.space