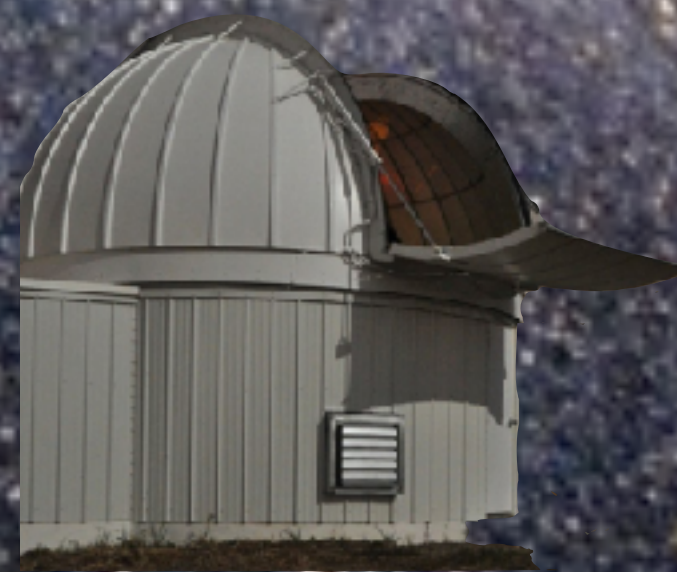


HOW TO FIND A BLACK HOLE WITH GAIA AND YOUR HOME TELESCOPE

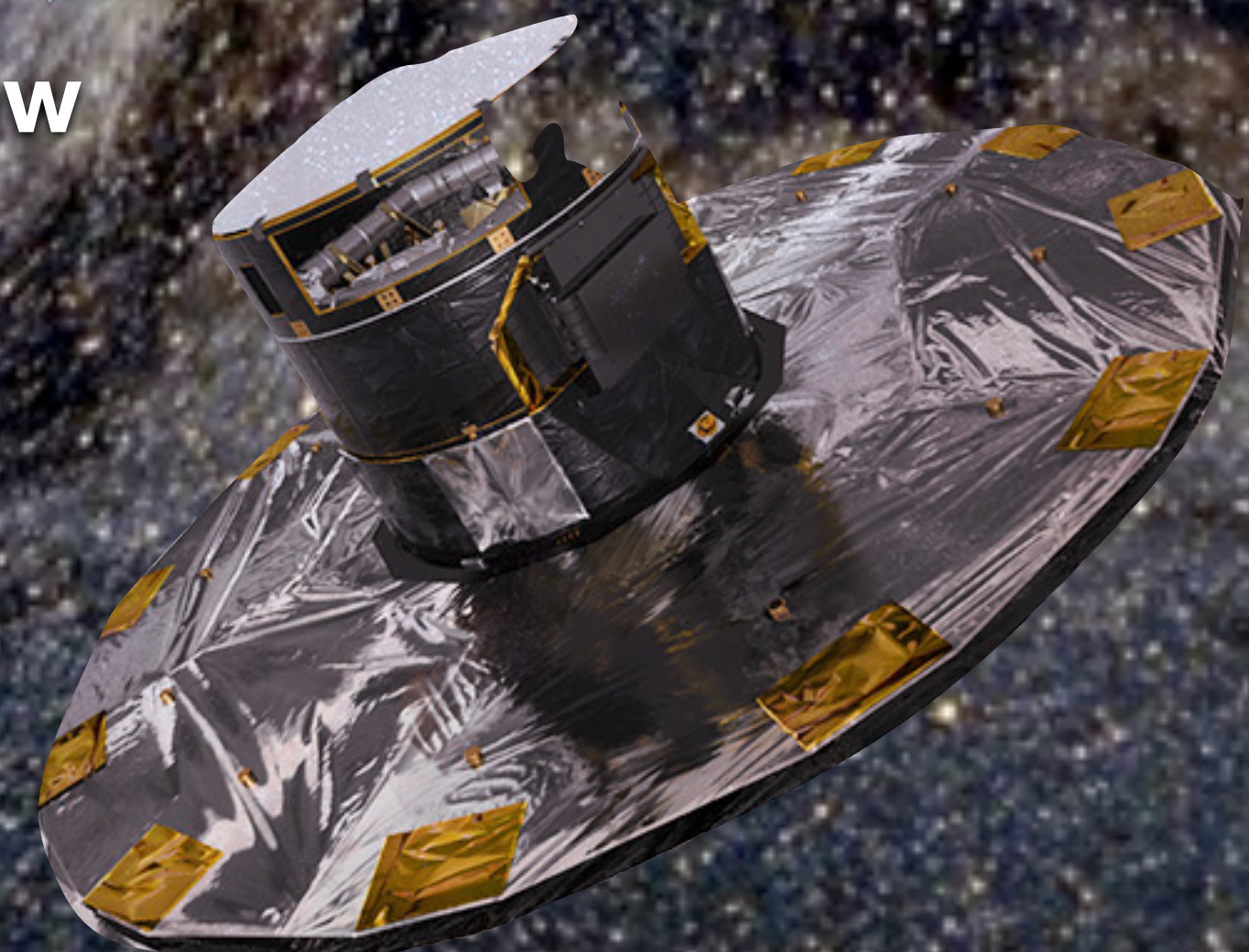


Łukasz Wyrzykowski
(pron. Woo-cash Vi-zhi-kov-ski)

Astronomical Observatory, University of Warsaw
Poland



RAPAS - IAP Paris 8.Oct.2022



TEAM



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(postdoc)



Przemek Mikołajczyk
(staff)



Barbara Kubiak
(staff)



Paweł Zieliński
(postdoc)



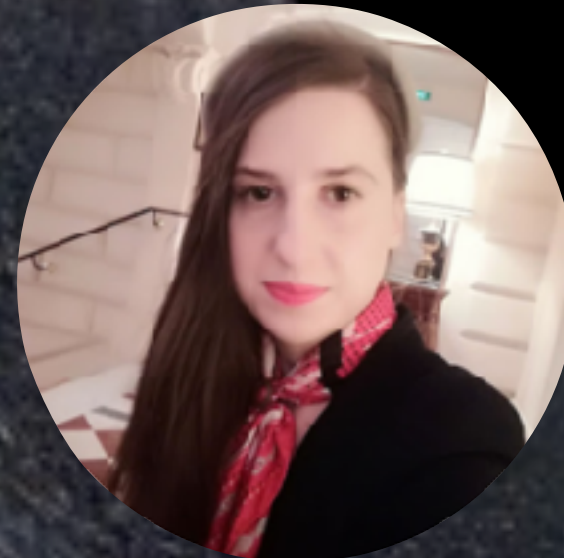
Kris A. Rybicki
(PhD student)



Katarzyna Kruszyńska
(PhD student)



Nada Ihanec
(PhD student)



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Kornel Howil
(BSc student)



Uliana Pylypenko
MSc student



Zofia Kaczmarek
(PhD student)

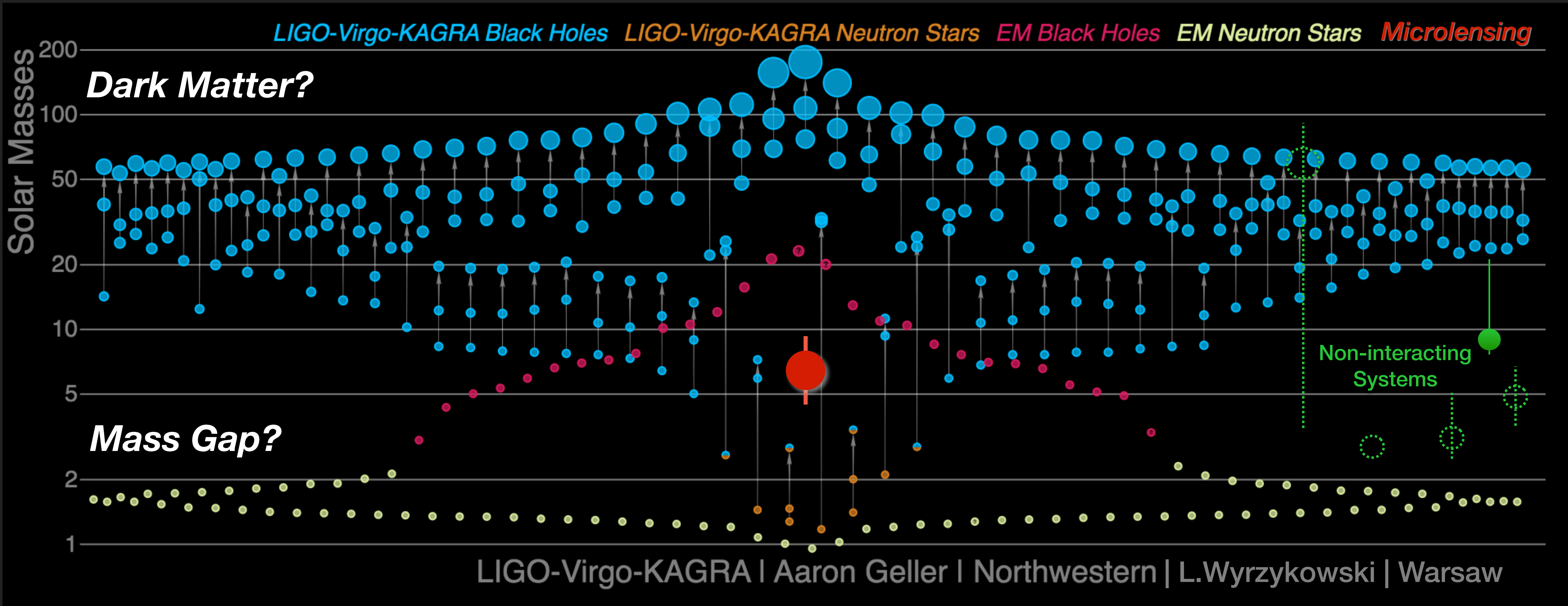


<https://gaia.astrow.edu.pl>

Funding:



MASSES OF BLACK HOLES AND NEUTRON STARS



Abbott+2021

Thompson et al. 2019, Liu+2020, Shenar+2022

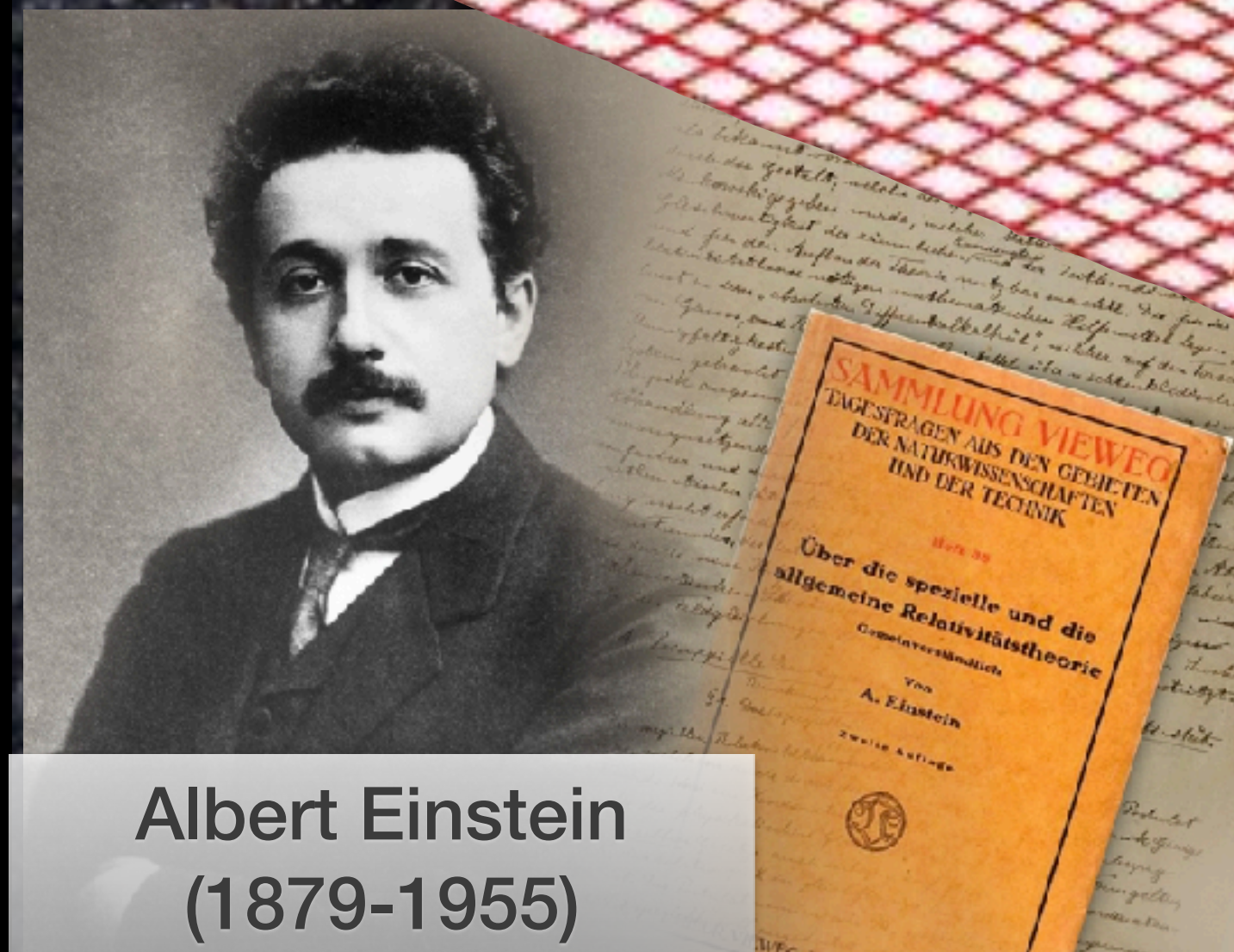
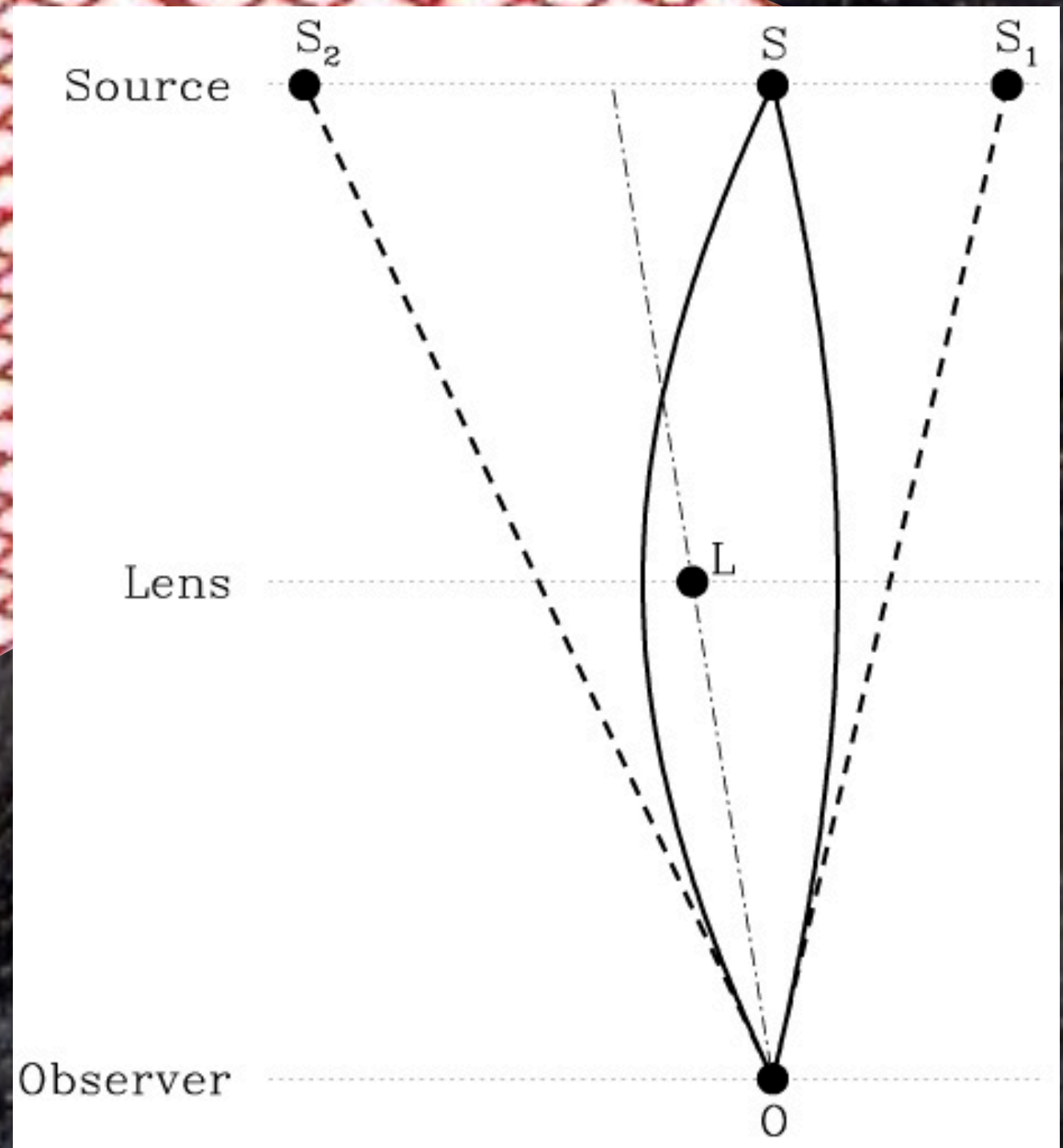
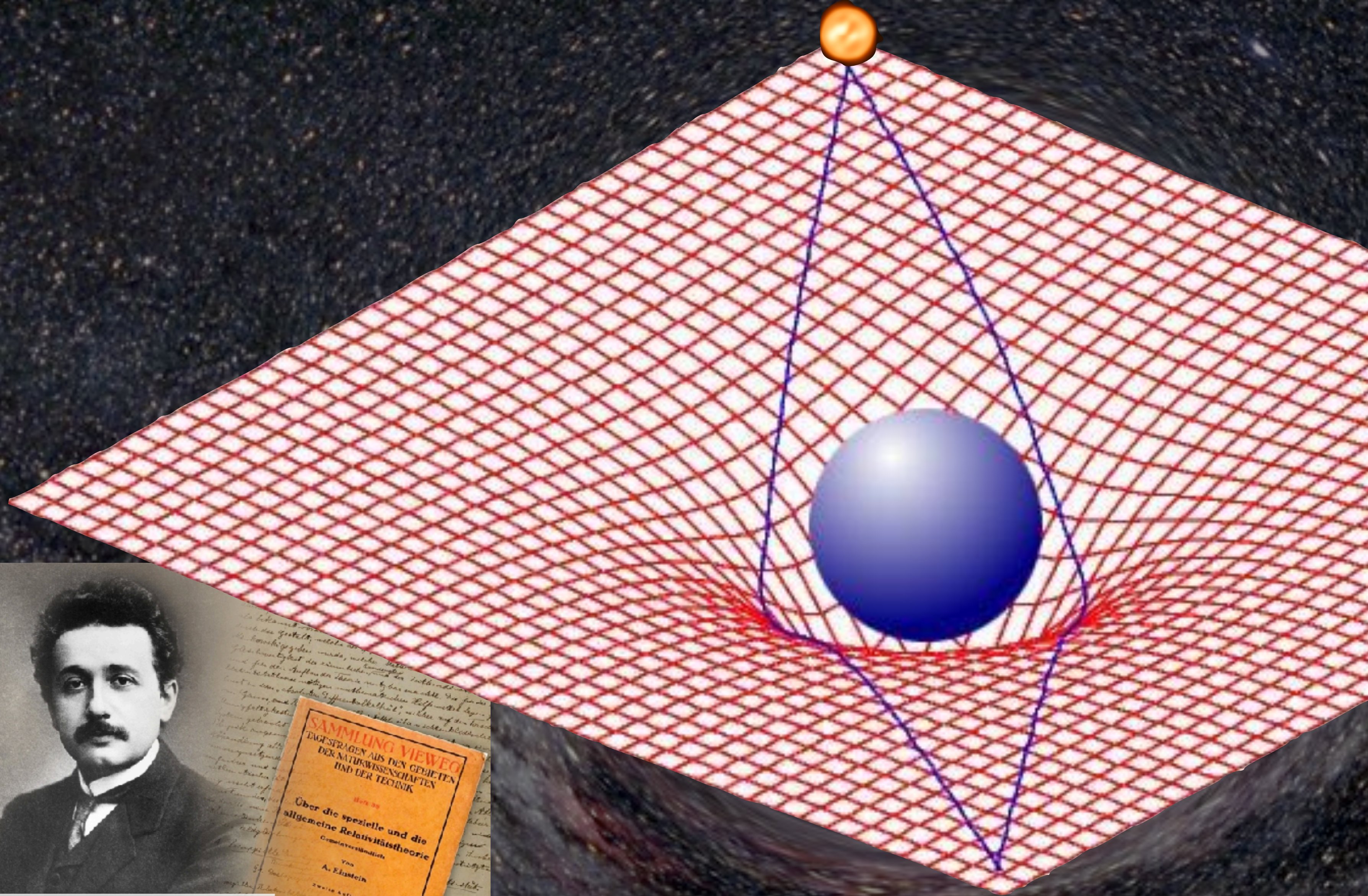
Sahu+2022

Corral Santana+2016

Rivinius+2020, Jayasinghe+2021

Lam+2022, Mróz+2022

GRAVITATIONAL MICROLENSING



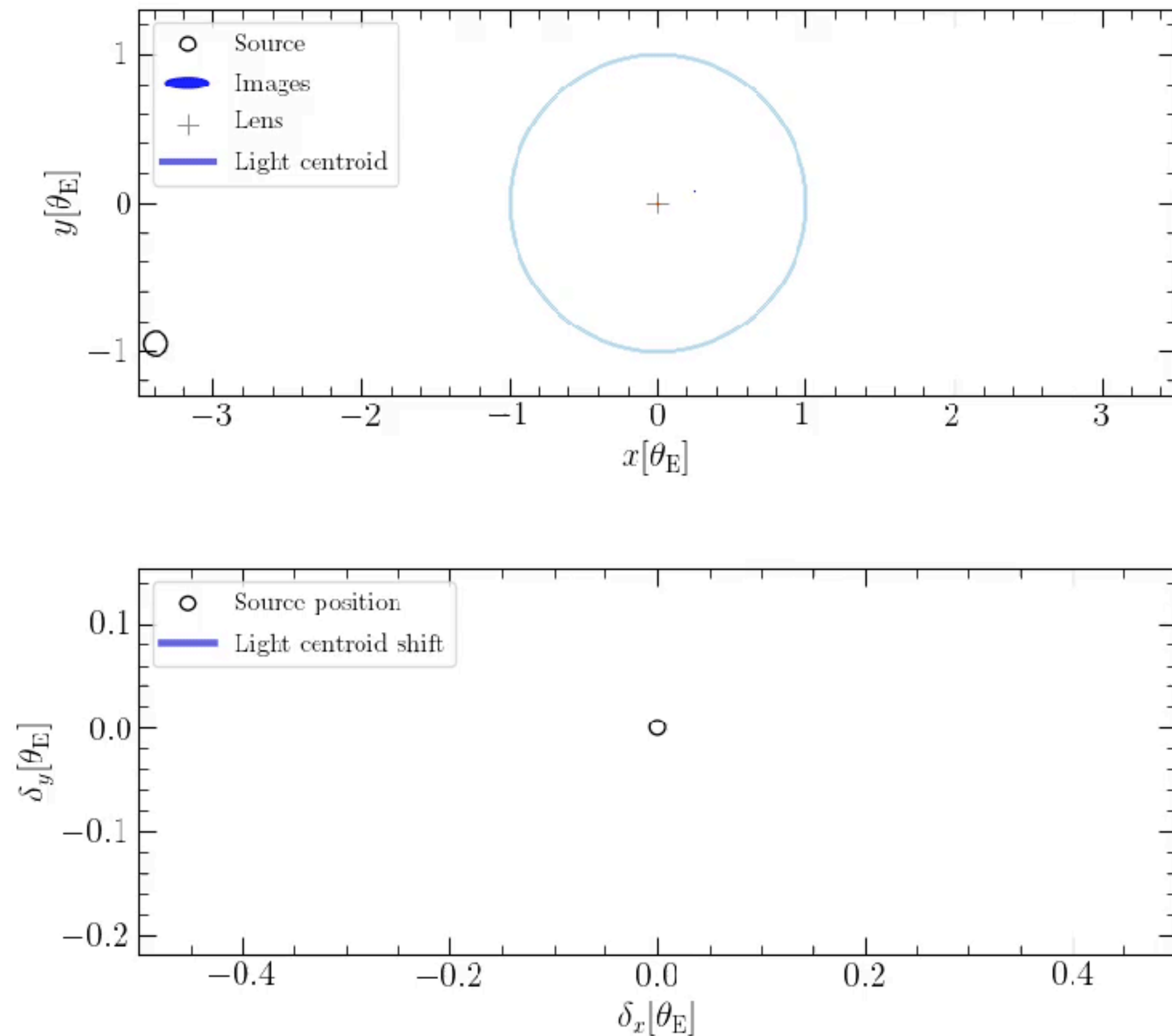
Albert Einstein
(1879-1955)

1915

GRAVITATIONAL MICROLENSING

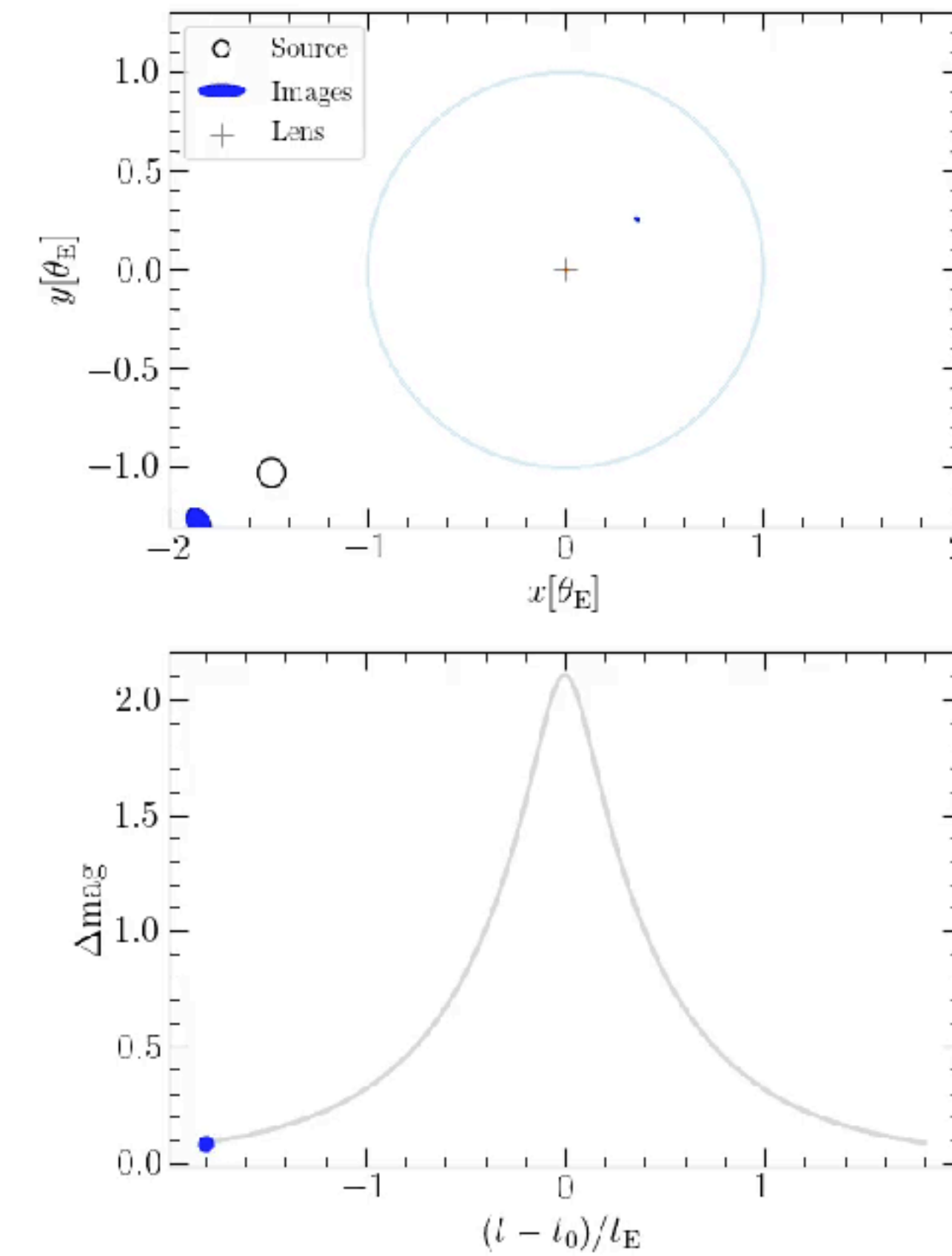
- Sources: background stars (chance: 10^{-6} in the Bulge, 10^{-8} in the LMC)
- Appearance of two images makes the source brighter and shifted

astrometry - shift



milliseconds

photometry - brightening



weeks-months

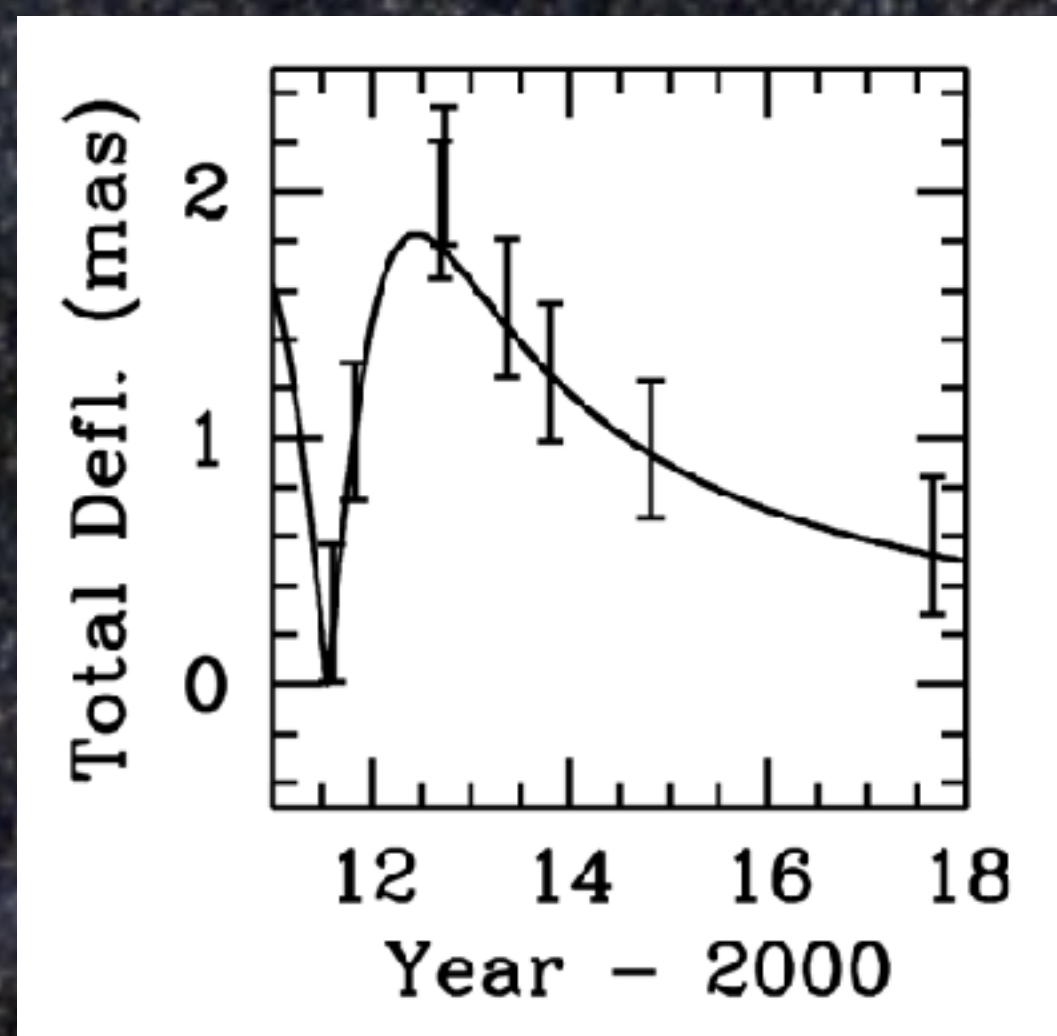
FIRST ISOLATED BLACK HOLE FROM MICROLENSING

EINSTEIN RADIUS FROM ASTROMETRY

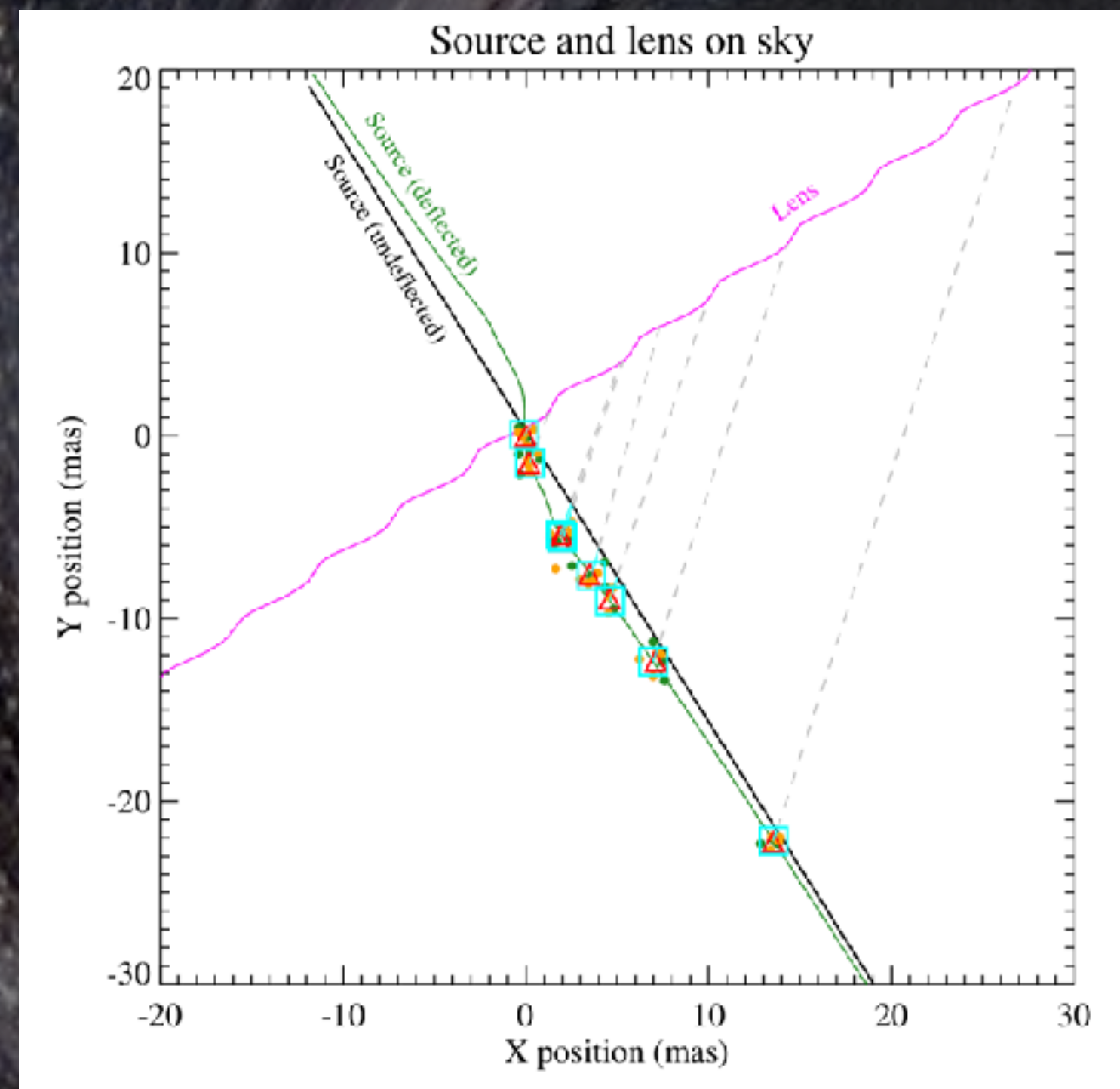
MICROLENSING PARALLAX

$$M = \frac{\theta_E}{\kappa \pi_E} = 7.9 \text{ M}_{\text{Sun}}$$

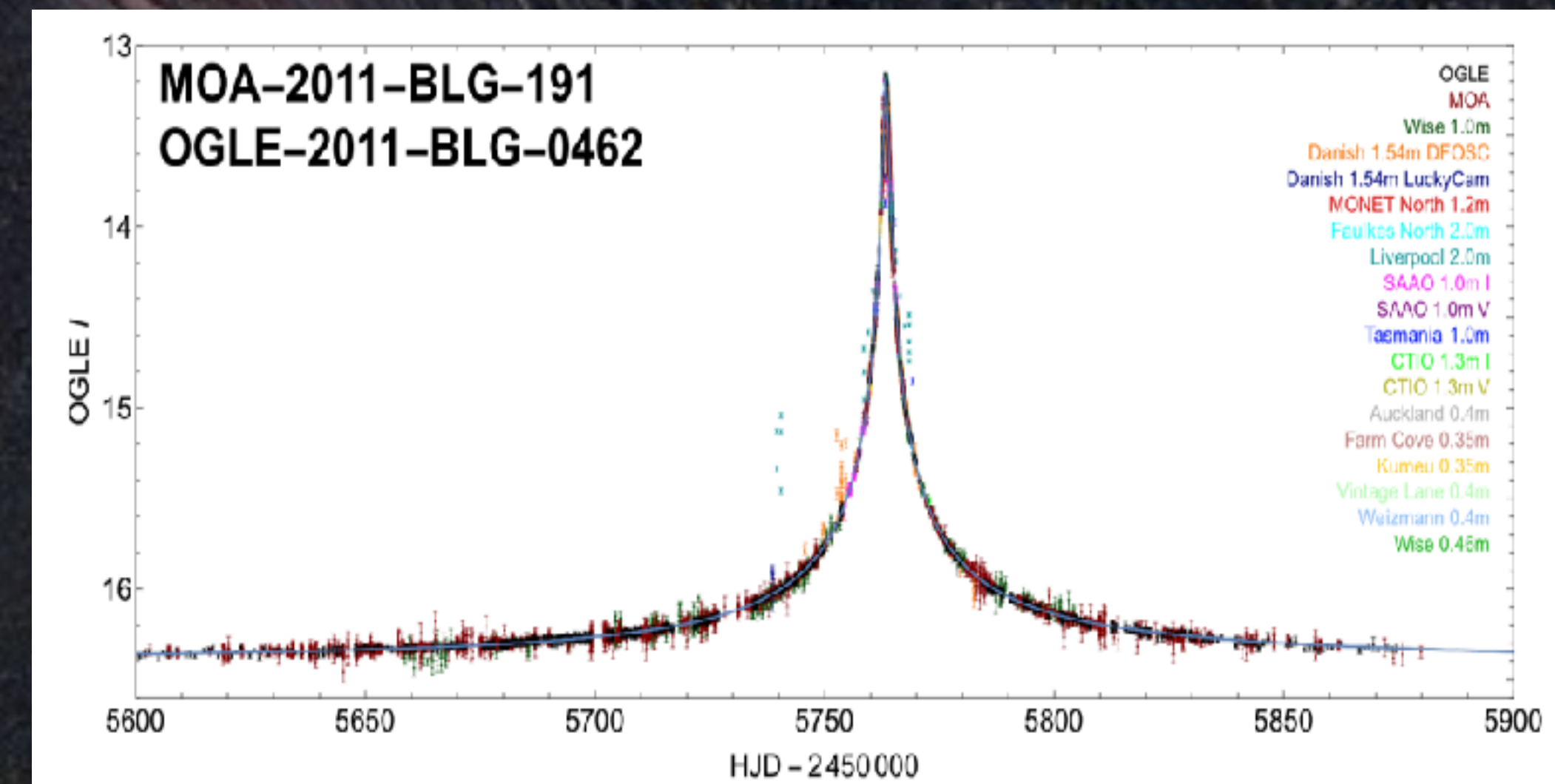
EINSTEIN RADIUS FROM ASTROMETRY



astrometric time-series



MICROLENSING PARALLAX



photometric time-series

OGLE



Sahu+OGLE, 2022
Lam+OGLE, 2022
Mróz et al. 2022



GAIA SPACE MISSION



GAIA SPACE MISSION

- ▶ ESA mission
- ▶ launched in 2013
- ▶ located in L2
- ▶ 10m in diameter
- ▶ two 1.4m mirrors
- ▶ depth: $G \sim 20.5$ mag
- ▶ 2 billion sources

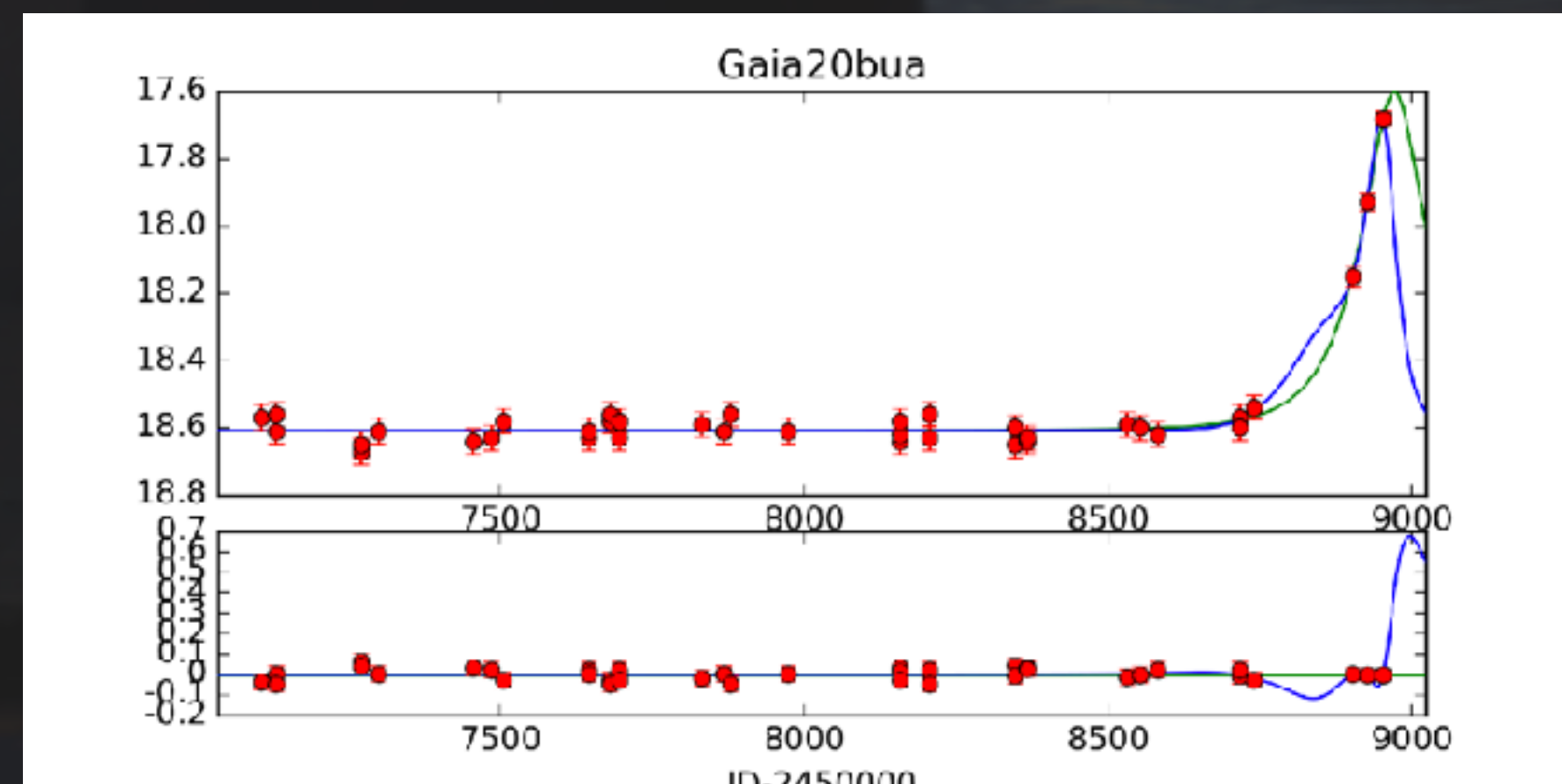
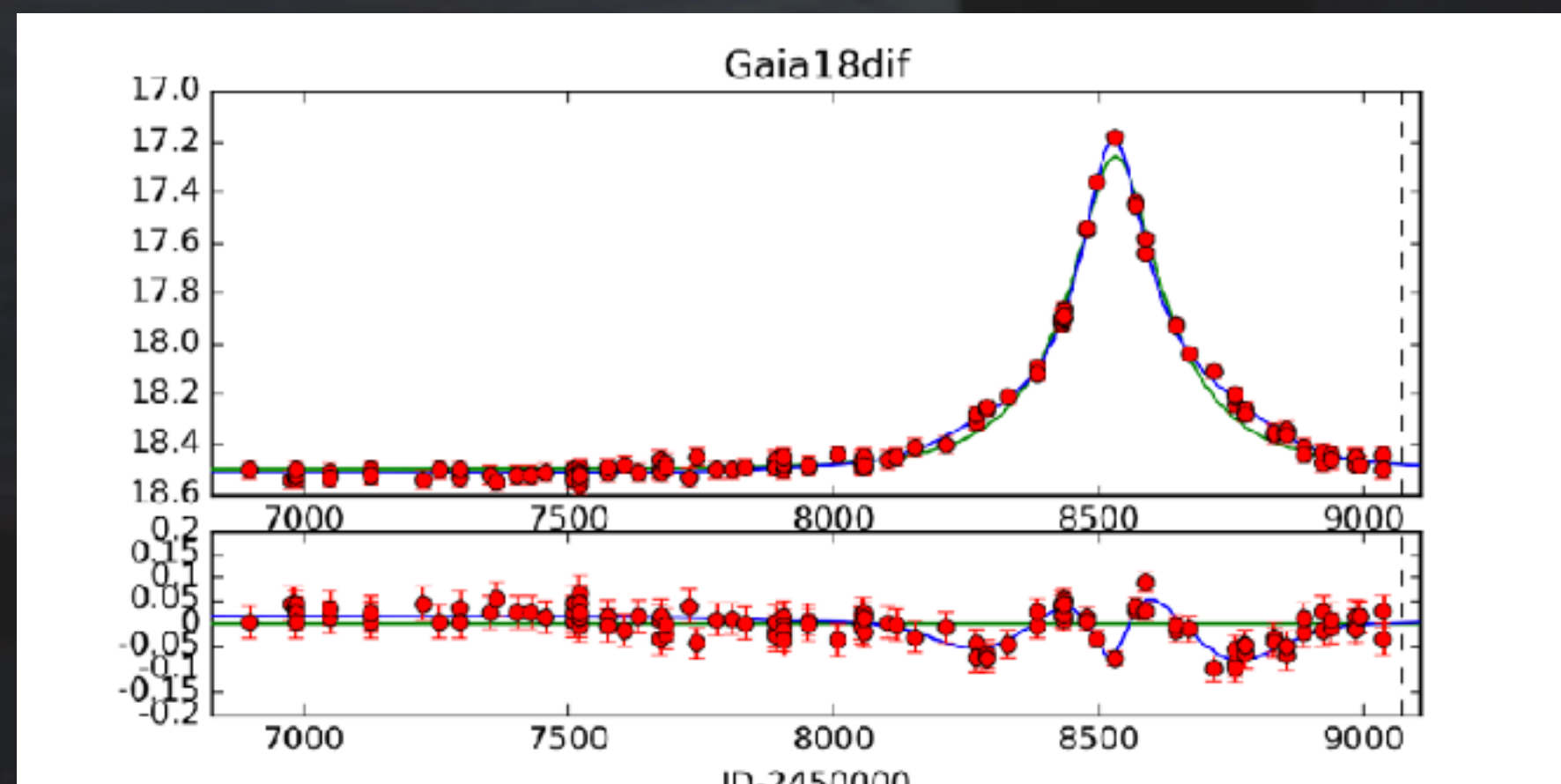
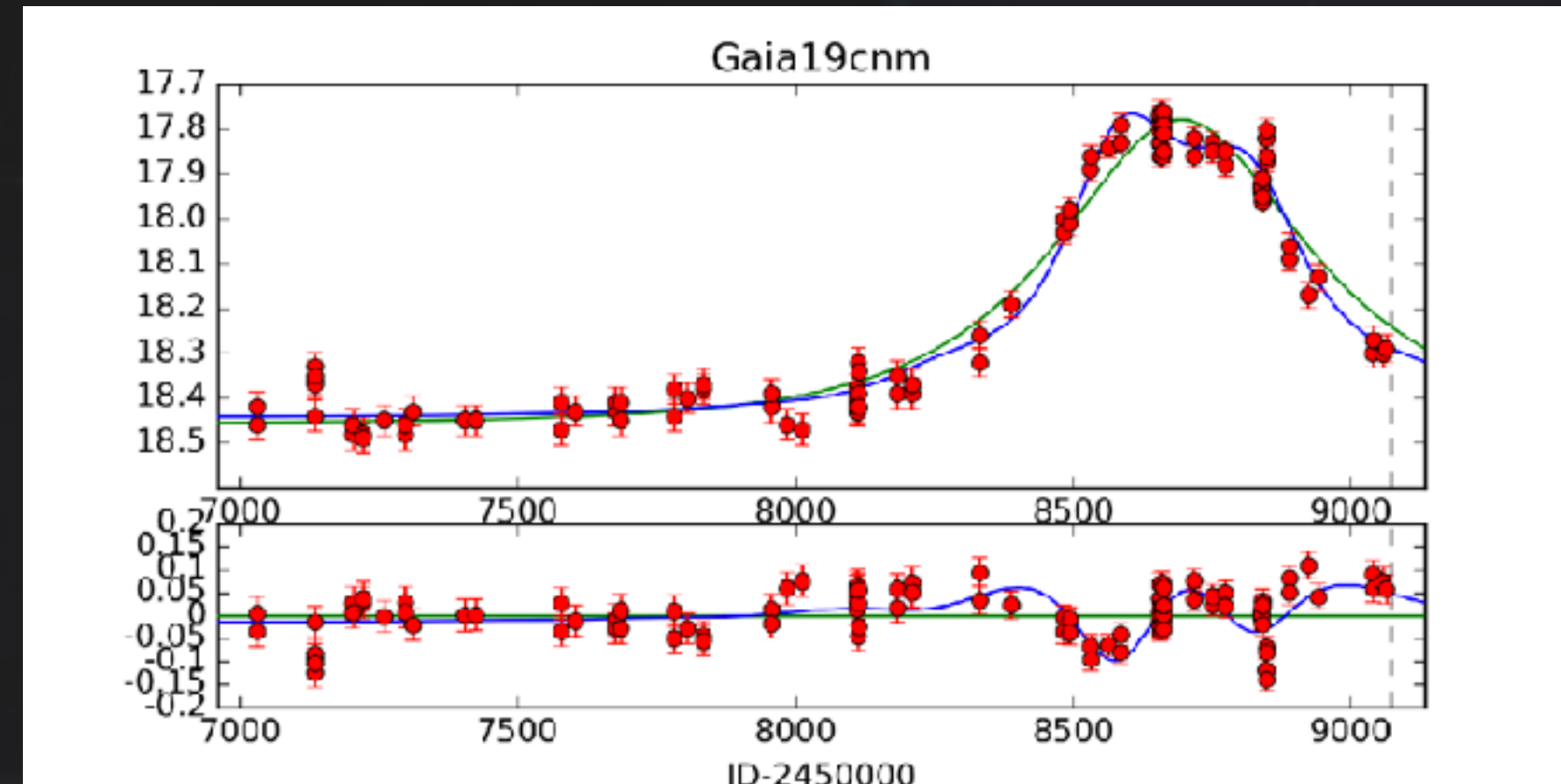
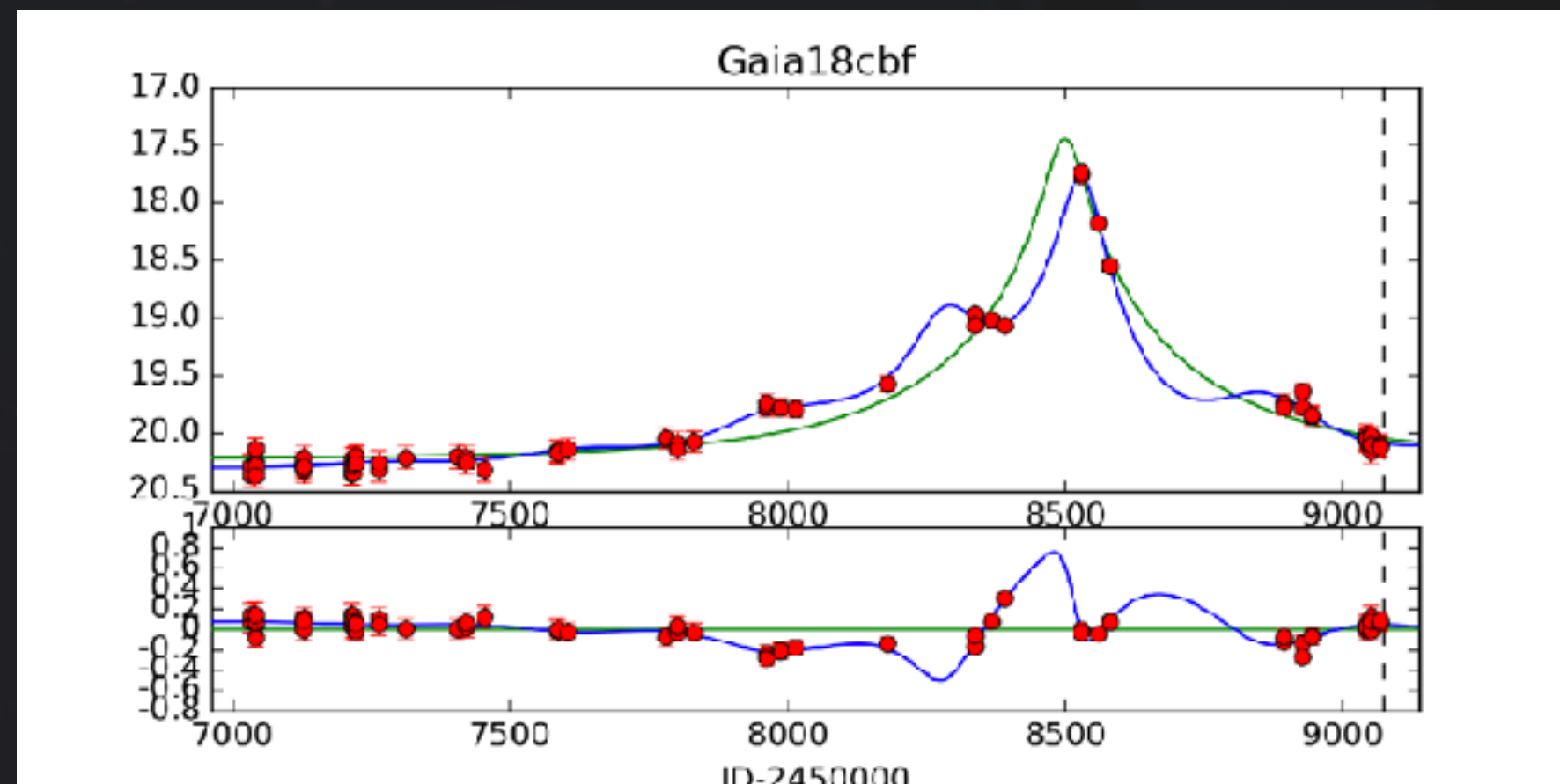


MICROLENSING EVENTS IN GAIA ALERTS

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



- ▶ 400 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*

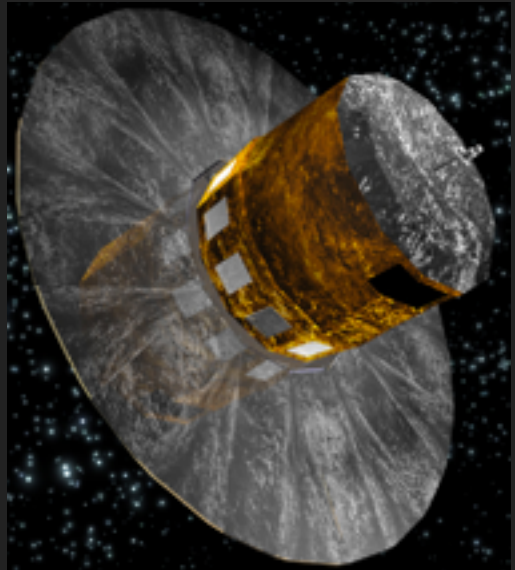


*Gaia alerts on ALL types of transients: supernovae, TDE, Novae, CVs, RCrB, etc.

GAIA20FNR

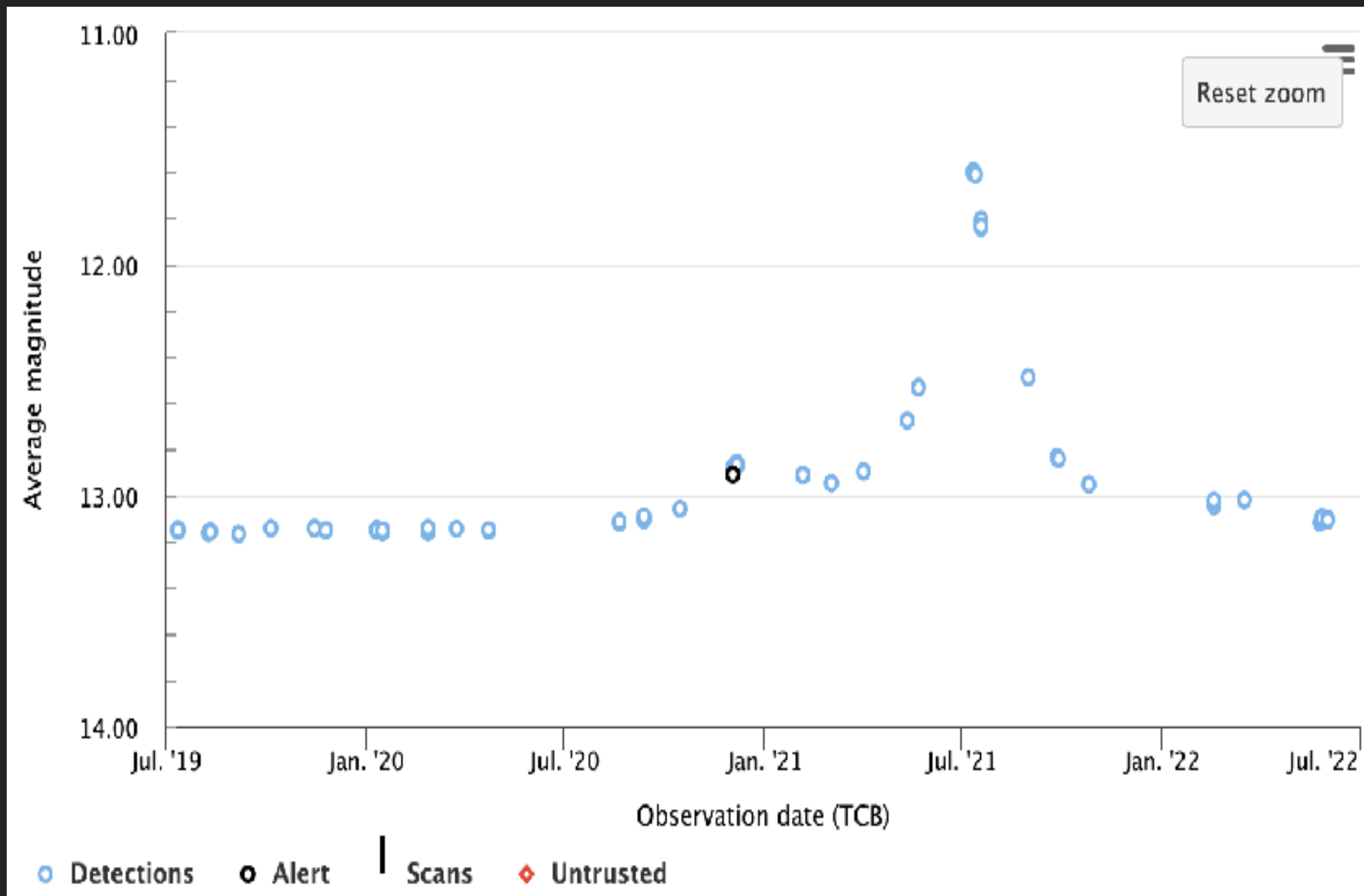
still on-going!

<http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia20fnr>



- ▶ long-term bright southern event
- ▶ possibly a fast rotating binary lens

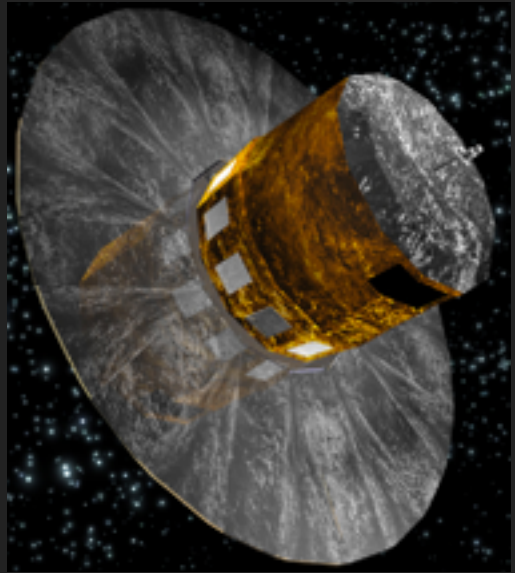
Gaia alone



GAIA20FNR

still on-going!

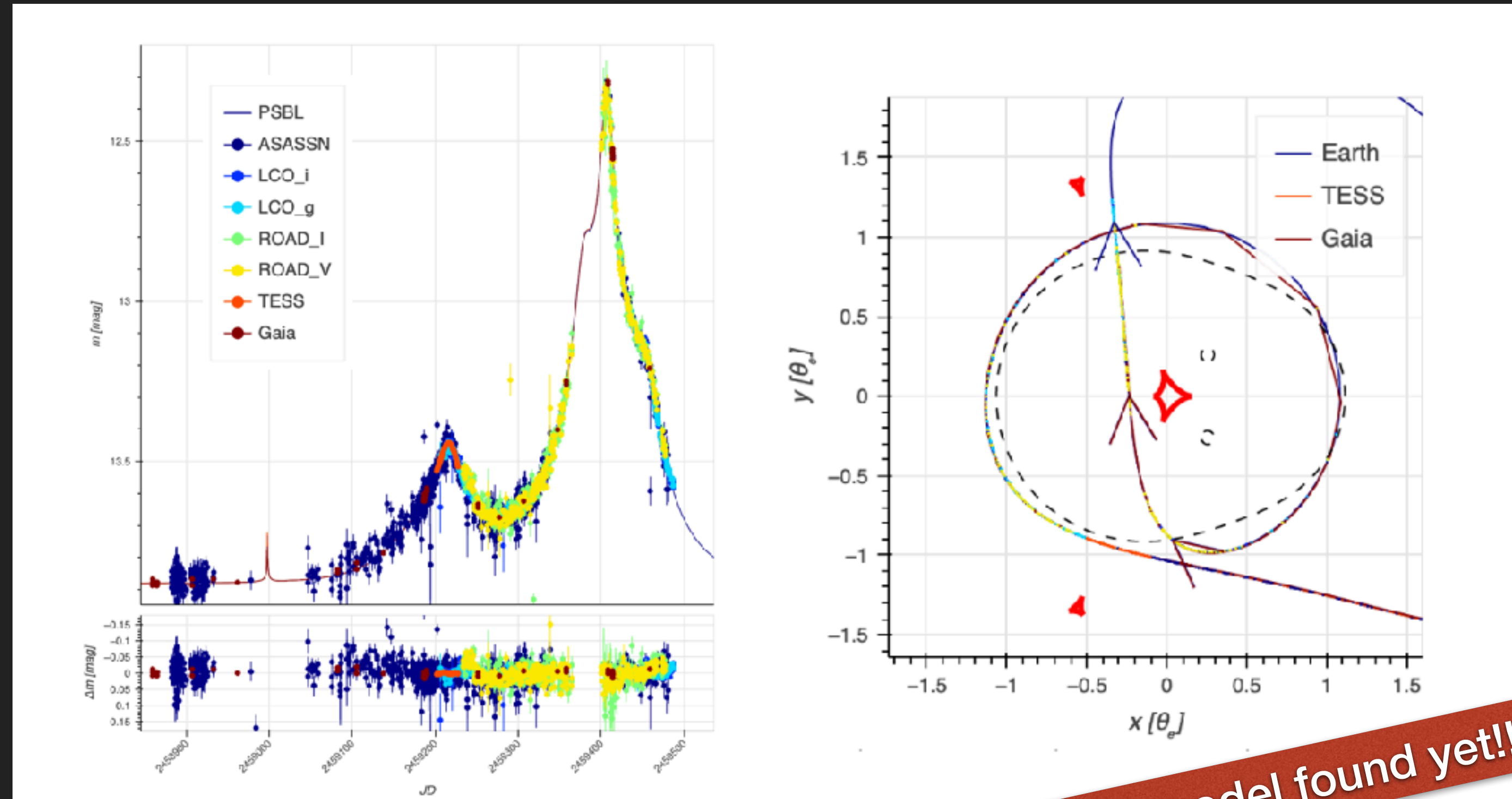
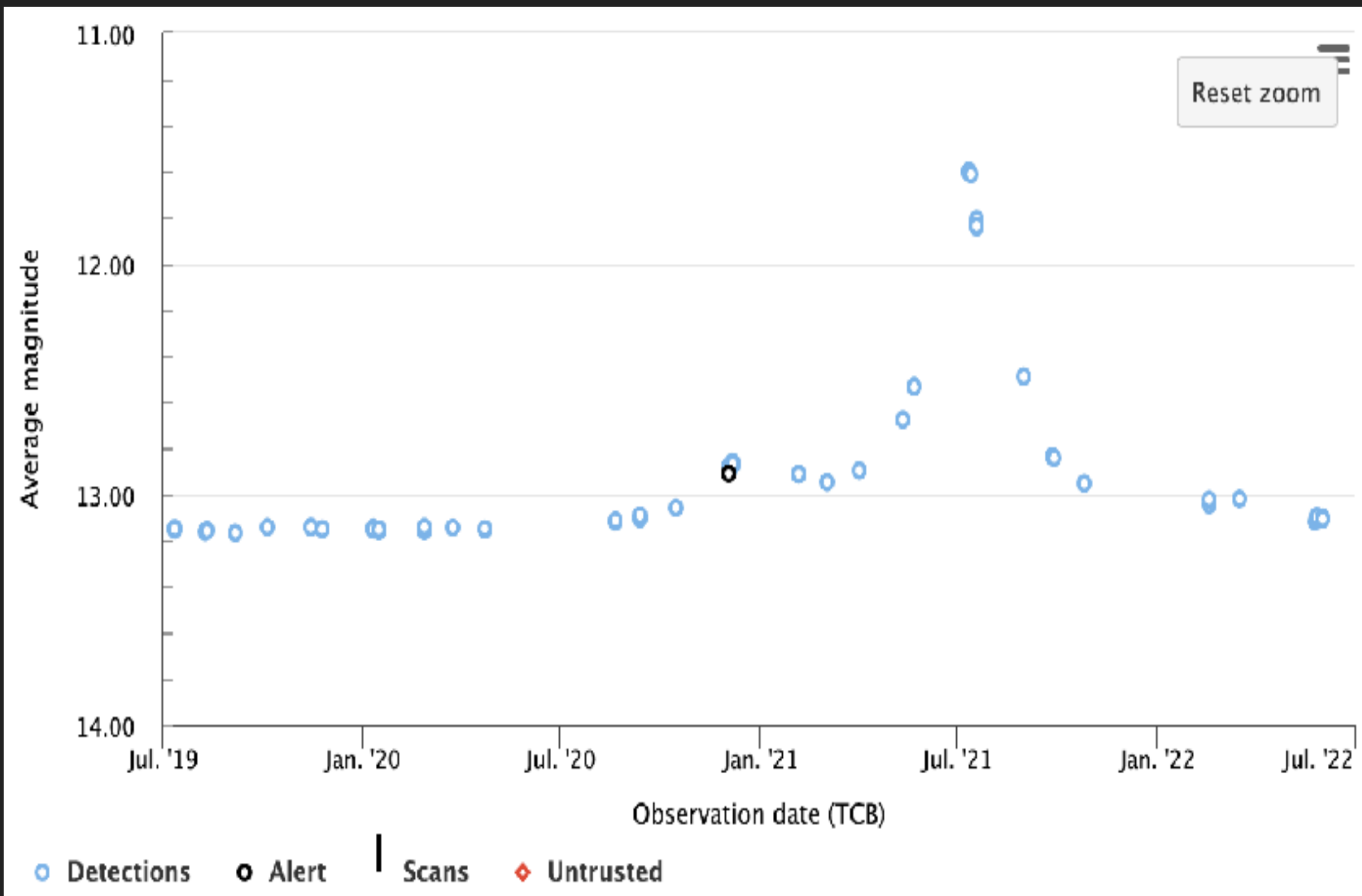
<http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia20fnr>



- ▶ long-term bright southern event
- ▶ possibly a fast rotating binary lens

Gaia alone

with follow-up observations + TESS



no good model found yet!!

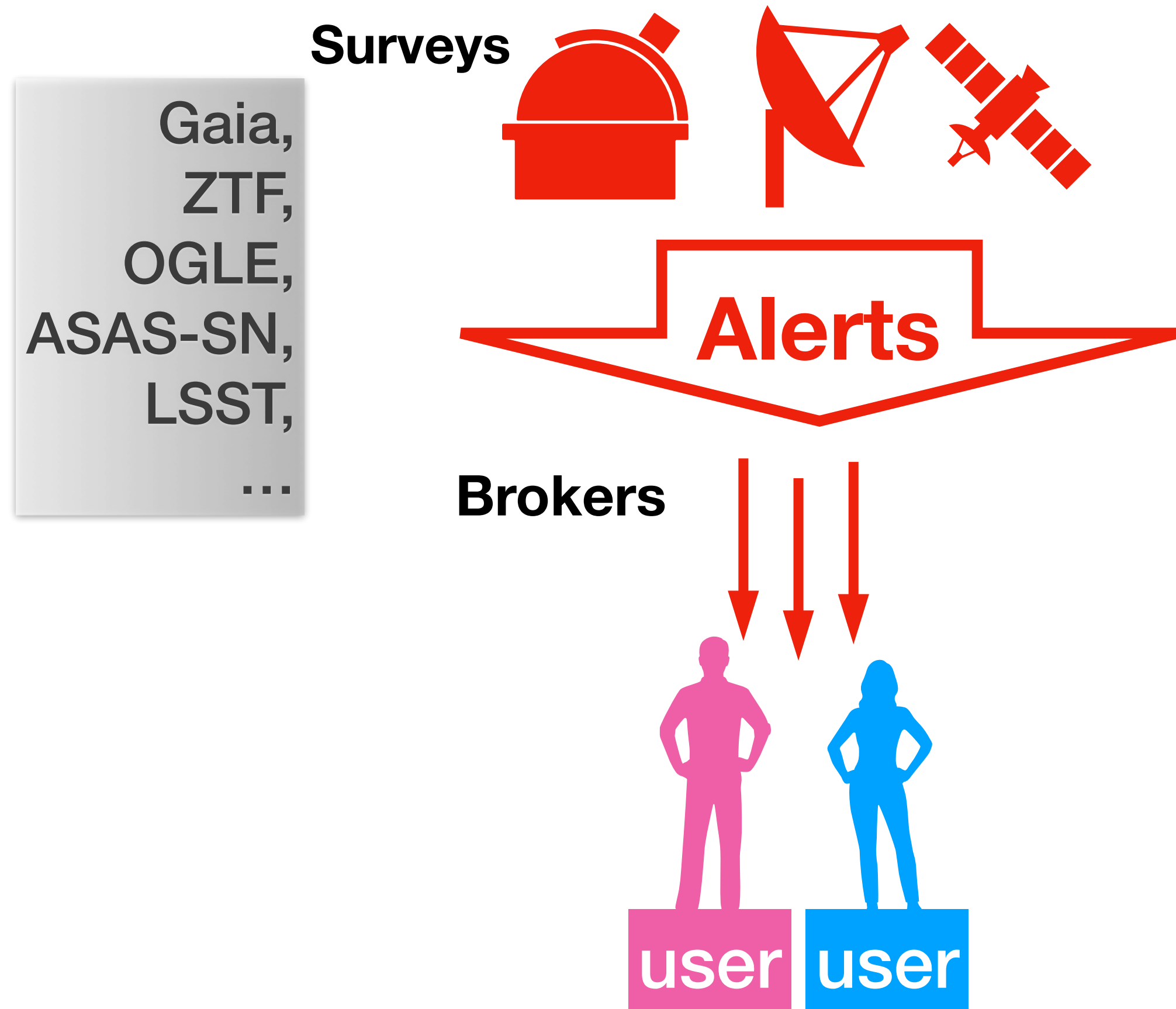
LUKASZ WYRZYKOWSKI - HOW TO FIND BLACK HOLES WITH GAIA AND YOUR HOME TELESCOPE



Surveys

Gaia,
ZTF,
OGLE,
ASAS-SN,
LSST,
...





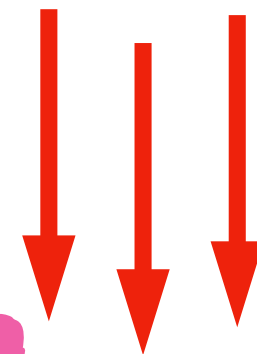
Surveys



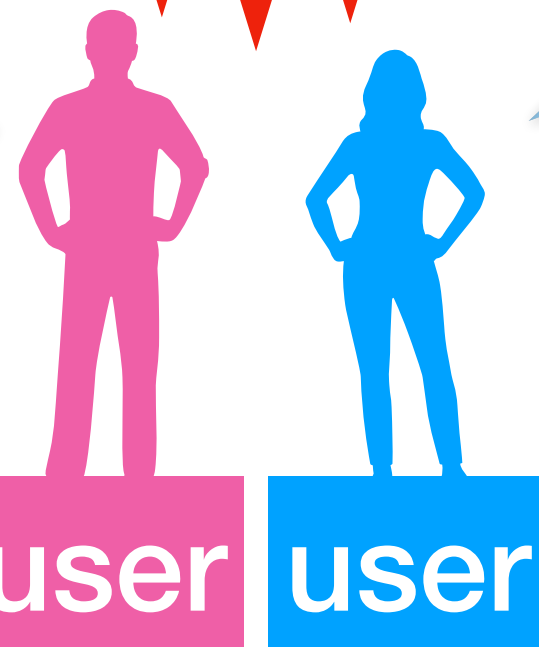
Gaia,
ZTF,
OGLE,
ASAS-SN,
LSST,
...



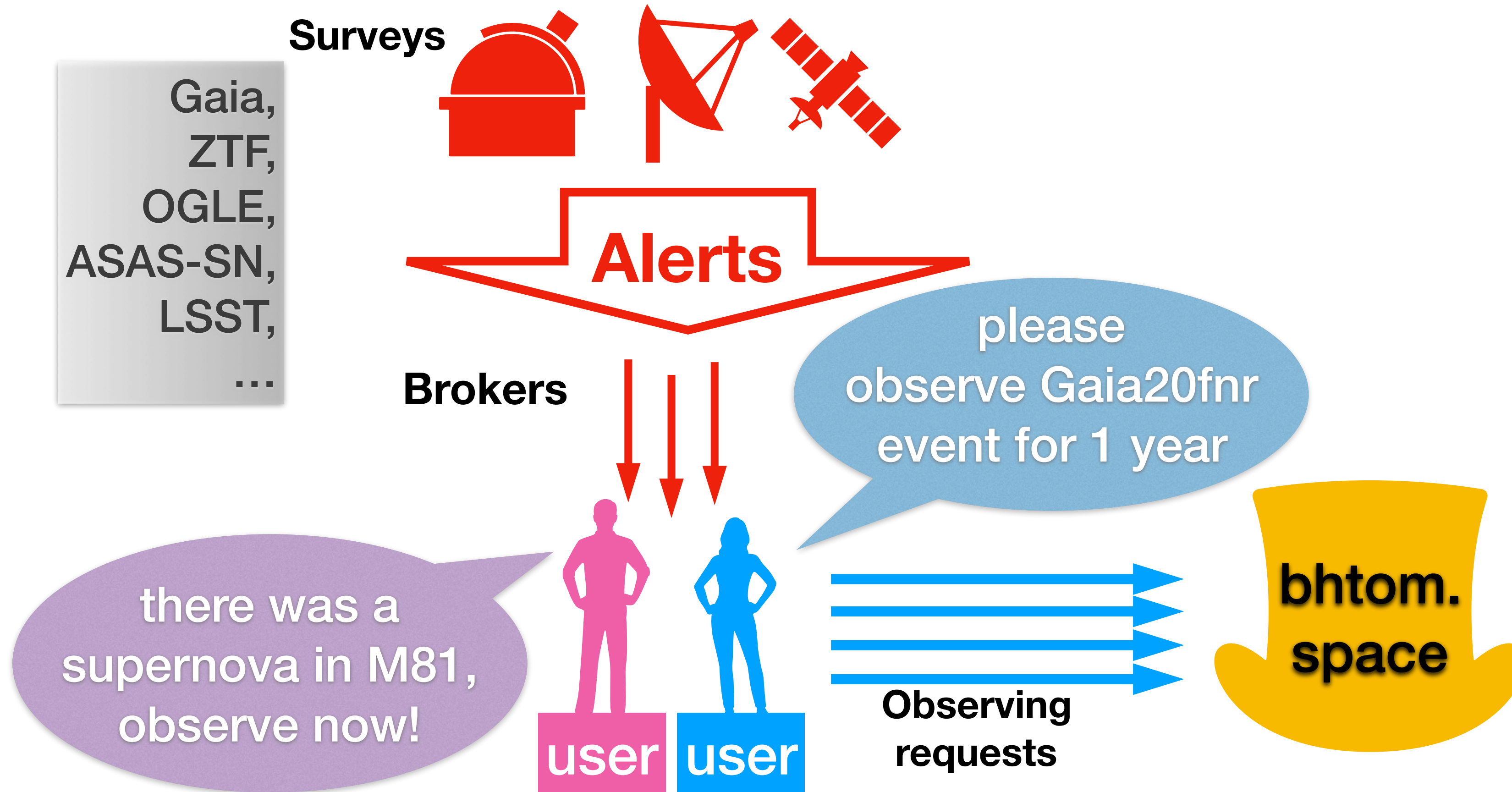
Brokers

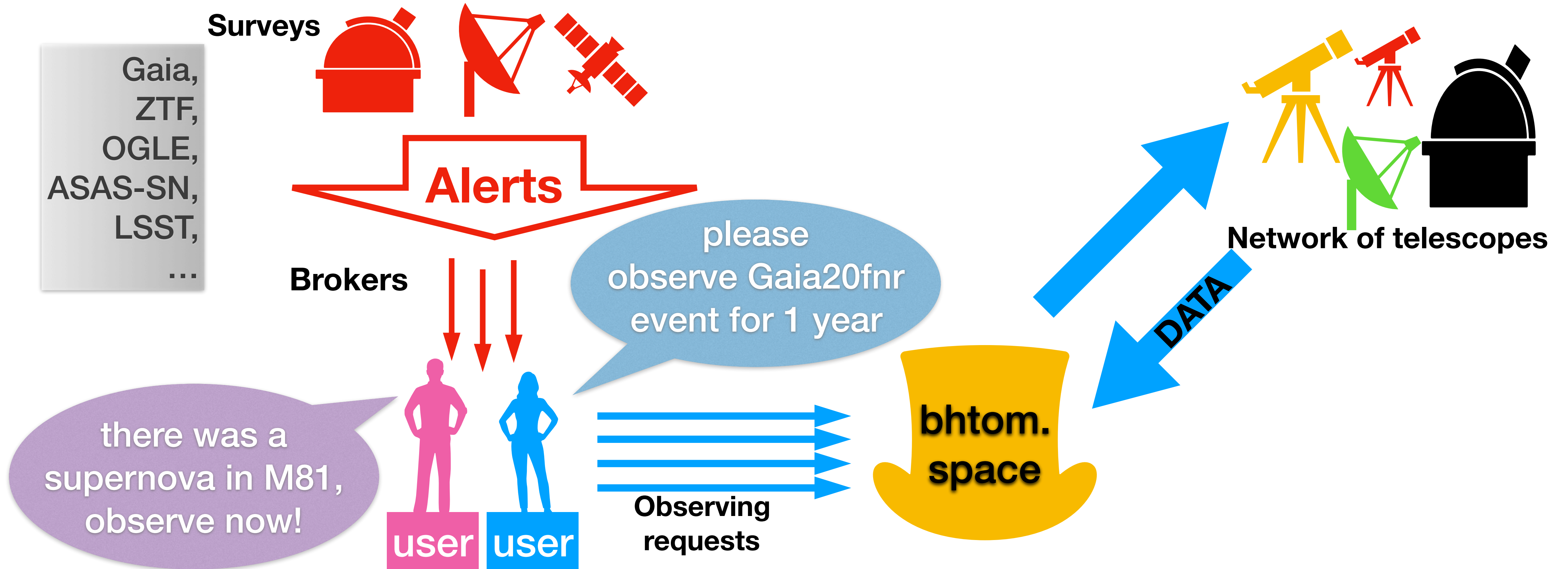


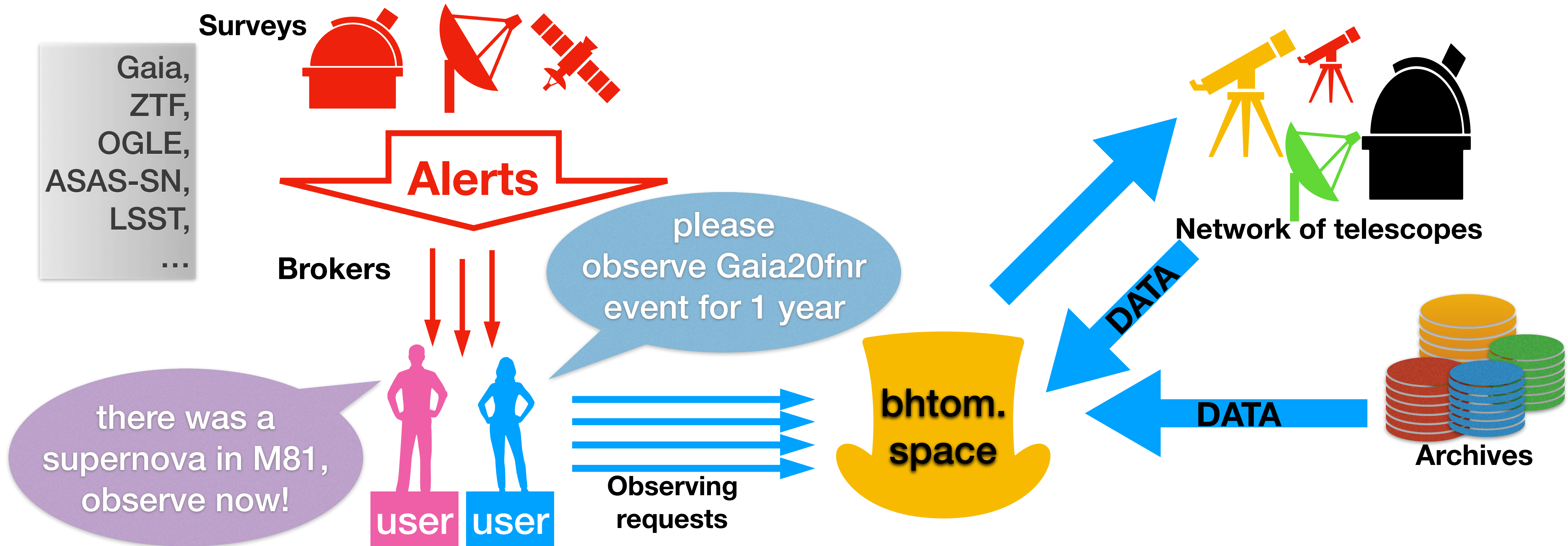
please
observe Gaia20fnr
event for 1 year

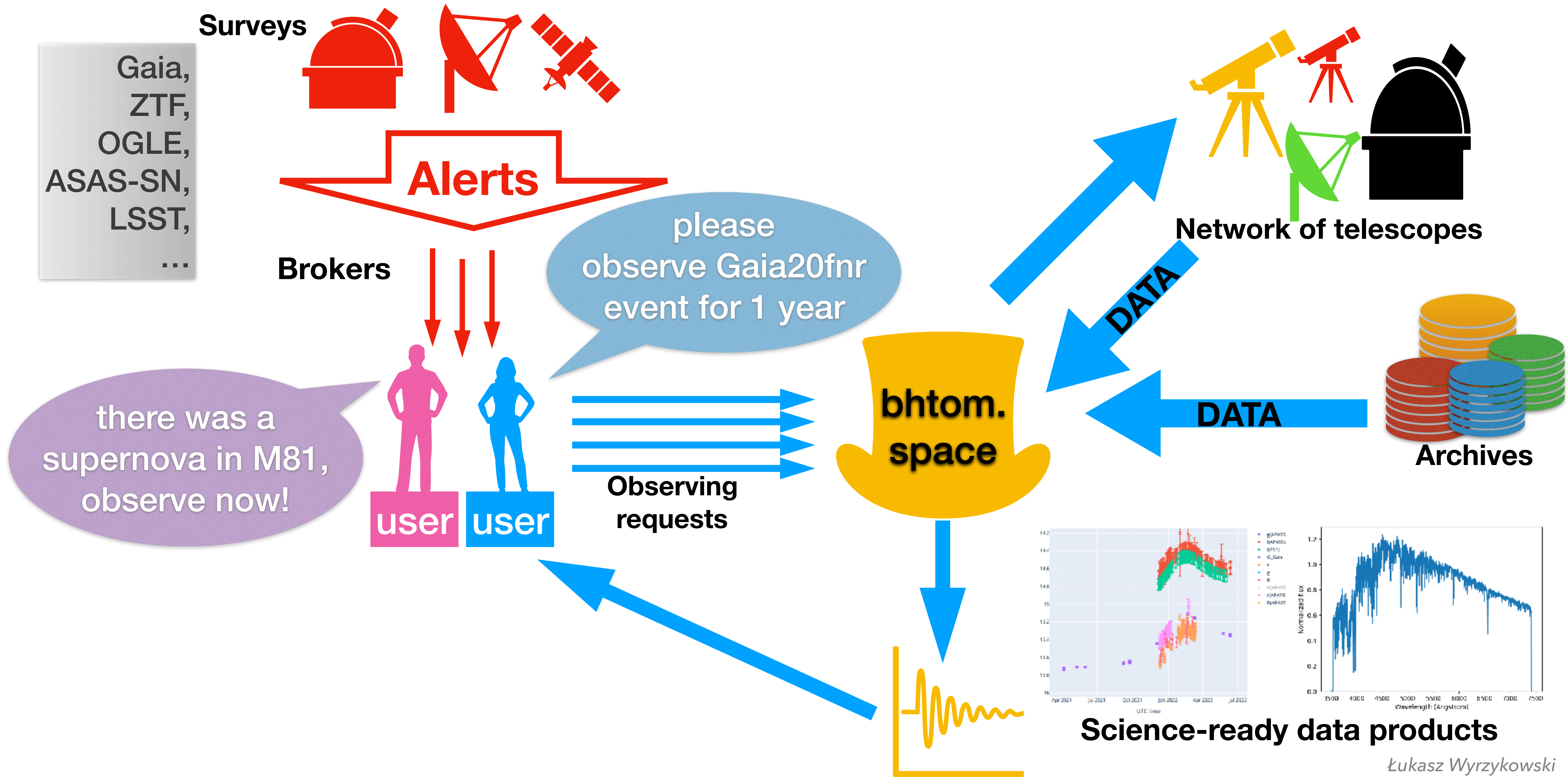


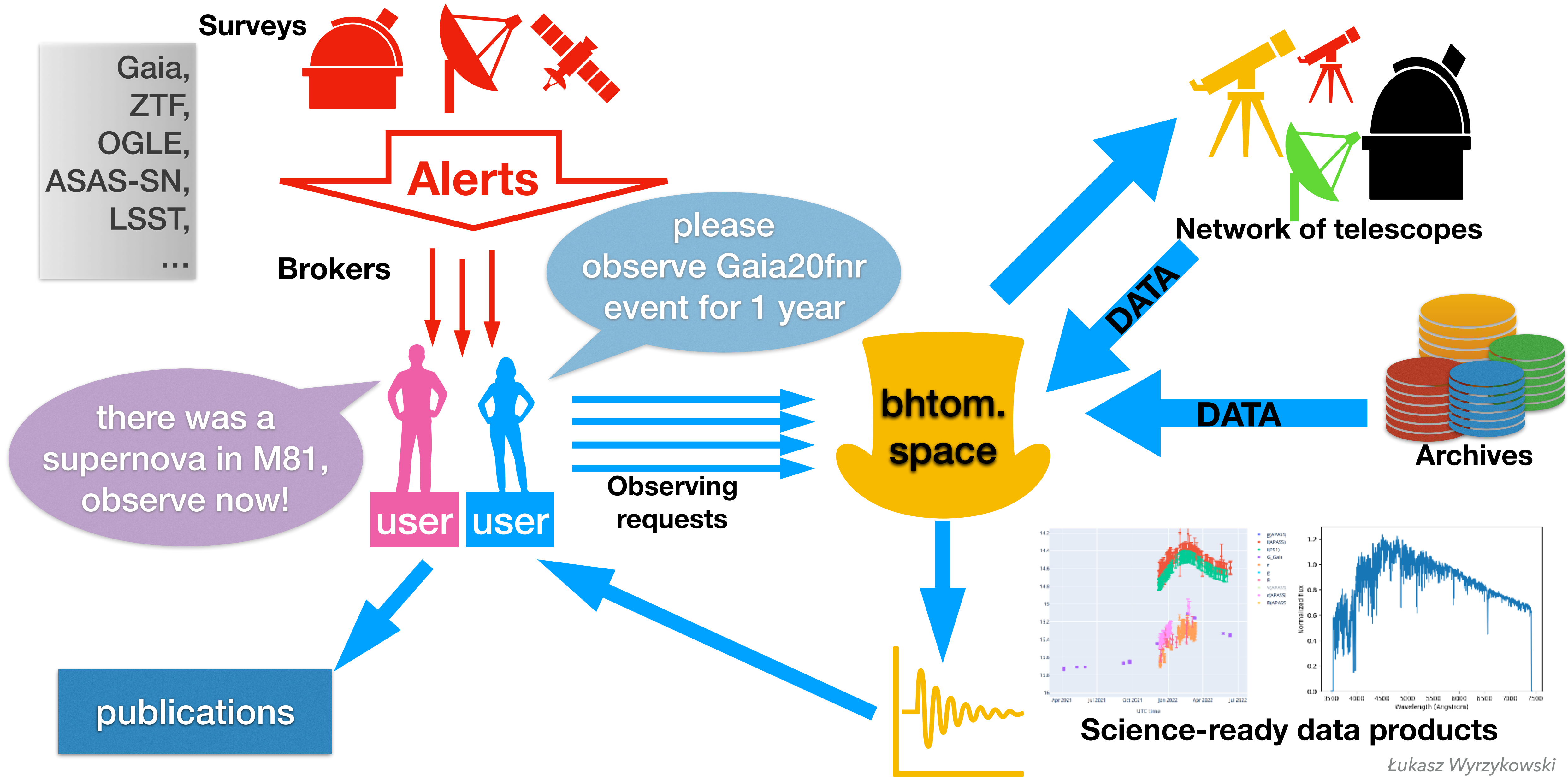
there was a
supernova in M81,
observe now!











BLACK HOLE TOM

<https://bhtom.space>

Gaia20azc

Update Delete List Fits

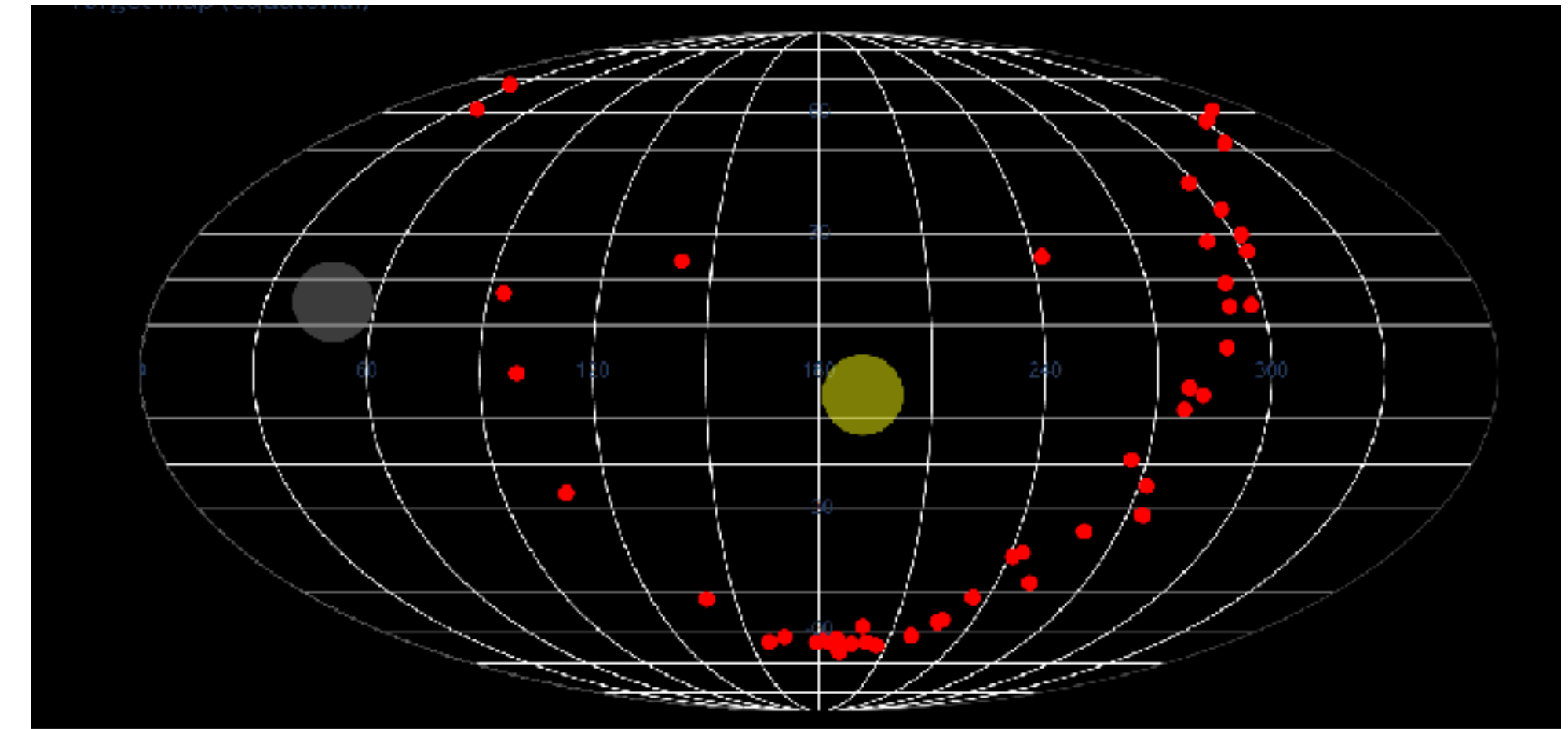
Names: Gaia20azc
 Target Type: SIDEREAL
 Right Ascension: 242.75086
 Declination: 25.00718
 Epoch: 2000.0

gala_alert_name: Gaia20azc
 calib_server_name: Ivo://Gaia20azc
 ztf_alert_name: ZTF18abjndpj
 galadr2_id: rapidly changing blazar/quasar
 tweet: False
 jdlastobs: 2459073.7281134
 maglast: 20.83
 priority: 5.0
 discovery_date: 1.0
 cadence: 1.0
 Sun_separation: 62.112924142328666

Photometry Spectroscopy Upload Observe Observations Data

Manage Groups

Photometry Check for new data



Event Name/Aliases	RA	Dec	Number of Observations	Last Gala [mag]	Target Importance	Time from last obs [days]	Required Cadence [days]	Observing Priority	Sun distance [deg]
Gaia' 8cbf	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
Gaia' 9dak	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	64
Gaia' 9cmm	227.93683	-57.0571	5396	18.03	10.0	9.4	1.0	94.3	65

Photometry Spectroscopy Upload Observe Observations Data

Manage Groups

Upload a data product

Here you can upload your photometric and spectroscopic observations for this target. Please refer to the BHTOM manual for details.

Example CSV formats for [photometry](#) and [spectroscopy](#). SExtractor format is required for instrumental photometry. FITS is supported for spectra.

For photometric FITS processing choose the observatory from the list. You can add a new instrument [here](#).

Files

Choose Files No file chosen

Data product type

- Instrumental photometry file (SExtractor format)
- Fits image for photometric processing
- Spectrum as ASCII
- Photometric time-series (CSV)

Submit an observation to LT

Names: Gaia20ga
 Target Type: SIDEREAL
 Right Ascension: 3.7096
 Declination: 64.4929

IOO IOI SPAT PRODOSpec

Proposal*: OPTICON 2020B Zielinski

Constraints*

Access < 2
 Delay < 1.2
 Access

Start Date*: dd/mm/yyyy Time*: 12:00



BLACK HOLE TOM

<https://bhtom.space>

Photometry Spectroscopy Upload Observe Observations Manage Groups **Publication** Data

Download photometry stats latex table Download photometry stats

THE ASTROPHYSICAL JOURNAL, 899:130 (8pp), 2020 August 20
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<https://doi.org/10.3847/1538-4357/aba129>



Gaia 18dvy: A New FUor in the Cygnus OB3 Association

E. Szegedi-Elek¹, P. Abraham^{1,2}, Ł. Wyrzykowski³, M. Kun¹, Á. Kóspál^{1,2,4}, L. Chen¹, G. Marton^{1,2}, A. Moór^{1,2}, C. Kiss^{1,2}, A. Pál^{1,2,5}, L. Szabados¹, J. Varga^{1,6}, E. Varga-Verebélyi¹, C. Andreas⁷, E. Bachelet⁸, R. Bischoff⁷, A. Bódi^{1,9}, E. Breidt¹⁰, U. Burgaz^{11,12}, T. Butterley¹³, J. M. Carrasco¹⁴, V. Čepas¹⁵, G. Damjanovic¹⁶, I. Gezer³, V. Godunova¹⁷, M. Gromadzki¹⁸, A. Gurgul³, L. Hardy¹⁸, F. Hildebrandt⁷, S. Hoffmann⁷, M. Hundertmark¹⁹, N. Ihanec³, R. Janulis¹⁵, Cs. Kalup¹, Z. Kaczmarek³, R. Könyves-Tóth¹, M. Krezinger¹, K. Kruszyńska³, S. Littlefair¹⁸, M. Maskoliūnas¹⁵, L. Mészáros¹, P. Mikołajczyk²⁰, M. Mugrauer⁷, H. Netzel²¹, A. Ordasi¹, E. Pakštienė¹⁵, K. A. Rybicki³, K. Sárneczky¹, B. Seli¹, A. Simon²², K. Šiškauskaitė¹⁵, Á. Sódor¹, K. V. Sokolovsky^{23,24,25}, W. Stenglein⁷, R. Street⁸, R. Szakáts¹, L. Tomasella²⁶, Y. Tsapras¹⁹, K. Vida^{1,2}, J. Zdanavicius¹⁵, M. Zdzienicka³, D. Zdenek³, and G. Zuercher^{1,3}

Single lens mass measurement in the high magnification microlensing event Gaia19bld located in the Galactic Disk

K. A. Rybicki,¹ Ł. Wyrzykowski,¹ E. Bachelet,² A. Cassan,³ P. Zieliński,¹ A. Gould,^{4,5} S. Calchi Novati,⁶ J.C. Yee,⁷ Y.-H. Ryu,⁸ M. Gromadzki,¹ P. Mikołajczyk,⁹ N. Ihanec,¹ K. Kruszyńska,¹ F.-J. Hambsch,^{10,11} S. Zola,¹² S. J. Fossey,¹³ S. Awiphan,¹⁴ N. Nakharutai,¹⁵ F. Lewis,^{16,17} F. Olivares E.,¹⁸ S. Hodgkin,¹⁹ A. Delgado,¹⁹ E. Breidt,¹⁹ D. L. Harrison,^{19,20} M. van Leeuwen,¹⁹ G. Rixon,¹⁹ T. Wevers,¹⁹ A. Yoldas,¹⁹ A. Udalski,¹ M. K. Szymański,¹ I.

SN 2018zd: An Unusual Stellar Explosion as Part of the Diverse Type II Supernova Landscape

Jujia Zhang,^{1,2,3,4*} Xiaofeng Wang,^{5,6} József Vinkó,^{7,8,9} Qian Zhai,^{1,2,3,4} Tianmeng Zhang,¹⁰ Alexei V. Filippenko,^{12,13} Thomas G. Brink,¹² WeiKang Zheng,¹² Lukasz Wyrzykowski,¹⁴ Przemysław Mikołajczyk,¹⁴ Fang Huang,¹⁵ Liming Rui,⁵ Jun Mo,⁵ Hanna Sai,⁵ Xinhan Zhang,⁵ Huijuan Wang,^{10,11} James M. DerKacy,¹⁶ Eddie Baron,¹⁶ K. Sárneczky,⁷ A. Bódi,^{7,18} G. Csörnyei,^{7,8} O. Hanyecz,⁷ B. Ignác,⁷ Cs. Kalup,^{7,8,18} L. Kriskovics,^{7,8} R. Könyves-Tóth,^{7,8} A. Ordasi,⁷ A. Pál,^{7,8,17} Á. Sódor,^{7,18} R. Szakáts,⁷ K. Vida,^{7,8,18} G. Zsidi^{7,8,19}

Full orbital solution for the binary system in the northern Galactic disc microlensing event Gaia16aye*

Łukasz Wyrzykowski^{1,11,*}, P. Mróz¹, K. A. Rybicki¹, M. Gromadzki¹, Z. Kolaczek^{1,15,19,20,21,22}, M. Zieliński¹, P. Zieliński¹, N. Britavskiy^{1,3}, A. Gomboc^{3,5}, K. Sokolovsky^{19,21,22}, S.T. Hodgkin⁶, L. Abe^{8,9}, G.F. Aldi^{20,21}, A. AlMannaer^{6,21,100}, G. Altavilla^{22,17}, A. Al Qasbi^{6,21,100}, G.C. Anupama⁸, S. Awiphan¹⁴, E. Bachelet^{6,3}, V. Bakis¹⁰, S. Baker¹⁰⁰, S. Bartlett⁸⁰, P. Bendjoya¹¹, K. Benson¹⁰⁰, I.F. Bikmaev^{76,87}, G. Birenbaum¹², N. Blagorodnova²⁴, S. Blanco-Cuadros^{15,17,4}, S. Boeva¹⁶, A.Z. Bonanos¹⁹, V. Bozza^{20,180}, D.M. Bramich^{6,2}, I. Bruni²⁵, R.A. Burenin^{84,85}, U. Burgaz²¹, T. Butterley²², H. E. Caines³⁴, D. B. Caton⁹¹, S. Calchi Novati⁸³, J.M. Carrasco²³, A. Cassan²⁹, V. Čepas⁵⁶, M. Cropper¹⁰⁰, M. Chruślińska^{1,24}, G. Clementini¹²⁵, A. Clerici³⁵, D. Conti⁹¹, M. Conti⁴⁸, S. Cross⁶³, F. Cusano¹, G. Damjanovic²⁶, A. Dapergolas¹⁹, G. D'Agostini⁸¹, J. H. J. de Bruijne²⁷, M. Dennefeld²⁹, V. S. Dhillon^{30,14}, M. Dominik³¹, J. Dziedzic¹, O. Erece²³, M. V. Eiselevich⁸⁶, H. Esenoglu³³, L. Eyrolle⁷⁴, R. Figueroa Jaimes^{31,53}, S. J. Fossey¹⁴, A. I. Galeev^{26,87}, S. A. Grebenev⁸⁴, A. C. Gupta⁹⁹, A. G. Gutaev⁷⁶, N. Hallakoun¹², A. Hamanowicz^{11,36}, C. Han², B. Handzlik¹⁷, J. B. Haislip⁹⁴, L. Hanlon¹⁰², L. K. Hardy³⁰, D. L. Harrison^{6,88}, H.J. van Heerden¹⁰³, V. L. Hoete⁹⁵, K. Horne³⁴, R. Hudec^{19,76,40}, M. Hundertmark⁴¹, N. Ihanec³⁵, E. N. Irtuganov^{76,87}, R. Itoh⁴³, P. Iwanek¹, M.D. Jovanovic²⁶, R. Janulis¹⁵, M. Jelínek³⁹, E. Jensen⁹², Z. Kaczmarek¹, D. Katz¹⁰¹, I.M. Khamitov^{44,76}, Y. Kilic³², J. Klencik^{11,24}, U. Kolb⁴⁷, G. Kopacki⁴⁵, V. V. Kouprianov⁹⁴, K. Kruszyńska¹, S. Kuroski³², G. Latev¹⁶, C.-H. Lee^{17,18}, S. Leonini⁴⁸, G. Leto⁹⁸, F. Lewis^{50,39}, Z. Li⁶³, A. Liakos¹¹⁹, S. P. Littlefair¹⁴⁰, J. Liu⁵¹, C.J. Manser⁶², S. Mao⁵³, D. Maoz¹², A. Martín-Carrillo¹⁰², J. P. Marais¹⁰³, M. Maskoliūnas⁵⁶, J. R. Maund³⁰, P. J. Meintjes¹⁰³, S. S. Melnikov^{76,87}, K. Ment⁴¹, P. Mikołajczyk⁴⁵, M. Morrell⁴⁷, N. Mowlavi²⁴, D. Moździerski⁴⁵, D. Murphy^{110,1}, S. Nazarov⁹⁰, H. Nataraj¹⁷⁹, R. Neeley⁶⁷, C. C. Neenan⁵⁴, A. J. Norton¹⁴⁷, E. O. Ofek⁵⁵, E. Pakštienė⁵⁶, L. Palaversa^{6,74}, A. Pandey⁸⁹, E. J. Penprase⁵⁸, A. Piascik⁵⁰, J. L. Prieto^{96,97}, J. K. T. Qvam⁹⁸, C. P. Reig^{61,75}, L. Rhodes³⁰, J.-P. Rivet⁸⁹, G. Rixon⁶, D. Roberts⁴⁷, Scarpitta^{20,82}, G. Seabroke¹⁰⁰, B. J. Shappee⁶⁹, R. Schmid⁴¹, Y. Ska^{11,77,79}, C. Snodgrass⁴⁶, P. S. Soares³⁴, B. van Soelen¹⁰³, Z. T. Street⁶³, J. Strobl³⁹, E. Strubbe⁹⁵, H. Szegedi¹⁰³, L. M. Tinjaca¹, S. Villanueva Jr.⁶⁷, O. Vince²⁶, J. Wambsganss^{41,42}, I. P. van der V. Wilson²², A. Yoldas⁶, R. Ya. Zhuchkov^{76,87}, D. G. Zhukov⁷⁶, J. Zola^{67,38}, and A. Zubareva^{73,3}

BLACK HOLE TOM – OPPORTUNITIES

- ▶ for scientists:
 - ▶ virtual tool for long-term monitoring, 24h coverage
 - ▶ global telescope
 - ▶ we will observe your target!
- ▶ for telescopes:
 - ▶ we will tell you which target is of interest for observing
 - ▶ we will process your data
 - ▶ we can even operate your robotic telescope!

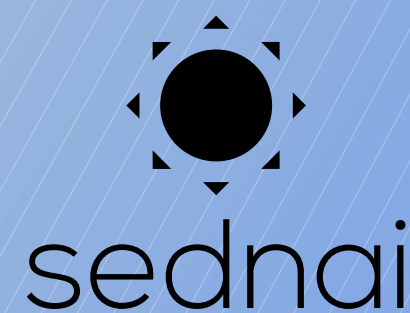
SUMMARY

- ◆ Gaia is the only survey providing time-series of photometry, astrometry and spectroscopy for a billion of stars from all over the sky - perfect for microlensing!
- ◆ Astrometric precision of Gaia < 1 mas - perfect for microlensing!
- ◆ ~1000 events already found in Gaia with more to come
- ◆ Epoch-Astrometric measurements are going to be available for all sources in DR4 (~2025)
- ◆ Events from Gaia Alerts require ground-based follow-up observations:
global telescope network for photometry, large telescopes for spectroscopic source typing



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



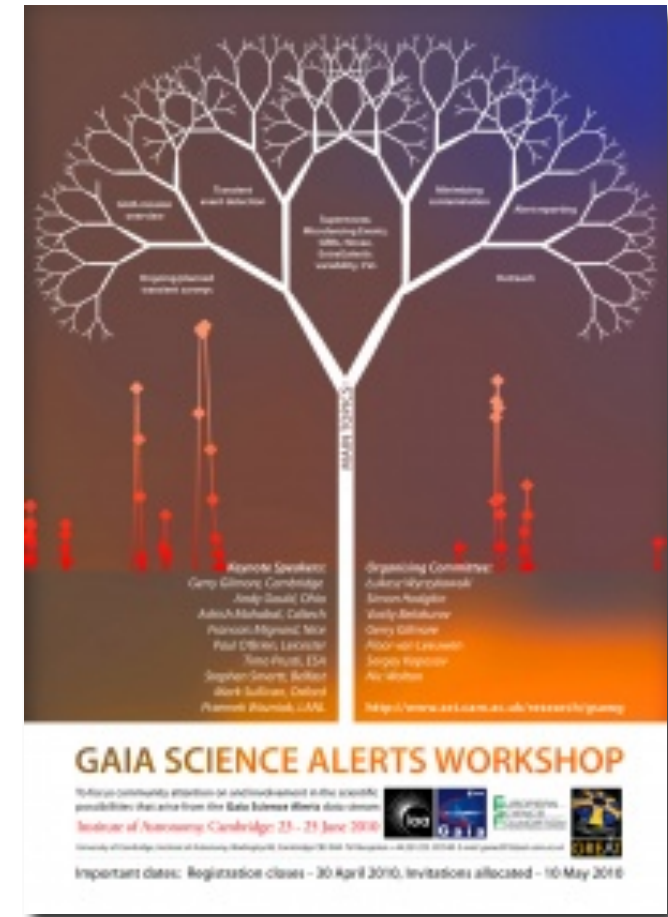
More to come! Stay tuned!

www.gaiavari.space

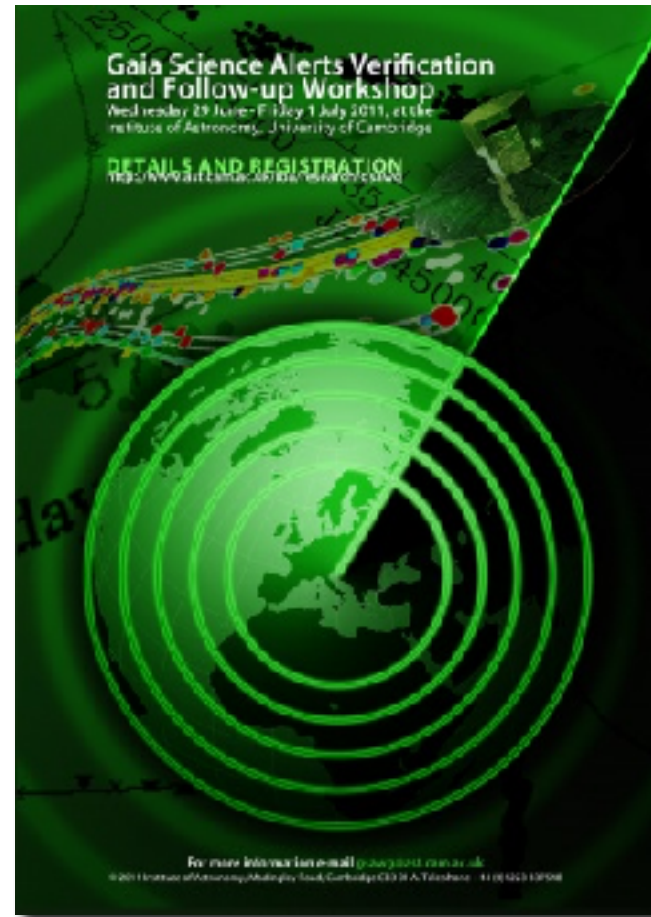
WORKSHOPS SINCE 2010



2010-
Cambridge



2011-
Cambridge



2012-Bologna



2013-Paris



2014-Warsaw



2015-Liverpool



2016-Utrecht



2017-Warsaw



2018-Vipava



2019-Catania



2020 - on-line



2021 - Crete



2022 - Sardinia



2023 - ???



ARCHIVE OF SLIDES AND VIDEOS: [HTTP://WWW.AST.CAM.AC.UK/IOA/WIKIS/GSAWGWIKI](http://www.ast.cam.ac.uk/IOA/WIKIS/GSAWGWIKI)

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