SCIENCE FROM TIME-DOMAIN OPTICAL ASTRONOMY

- SUBJECTIVE OVERVIEW

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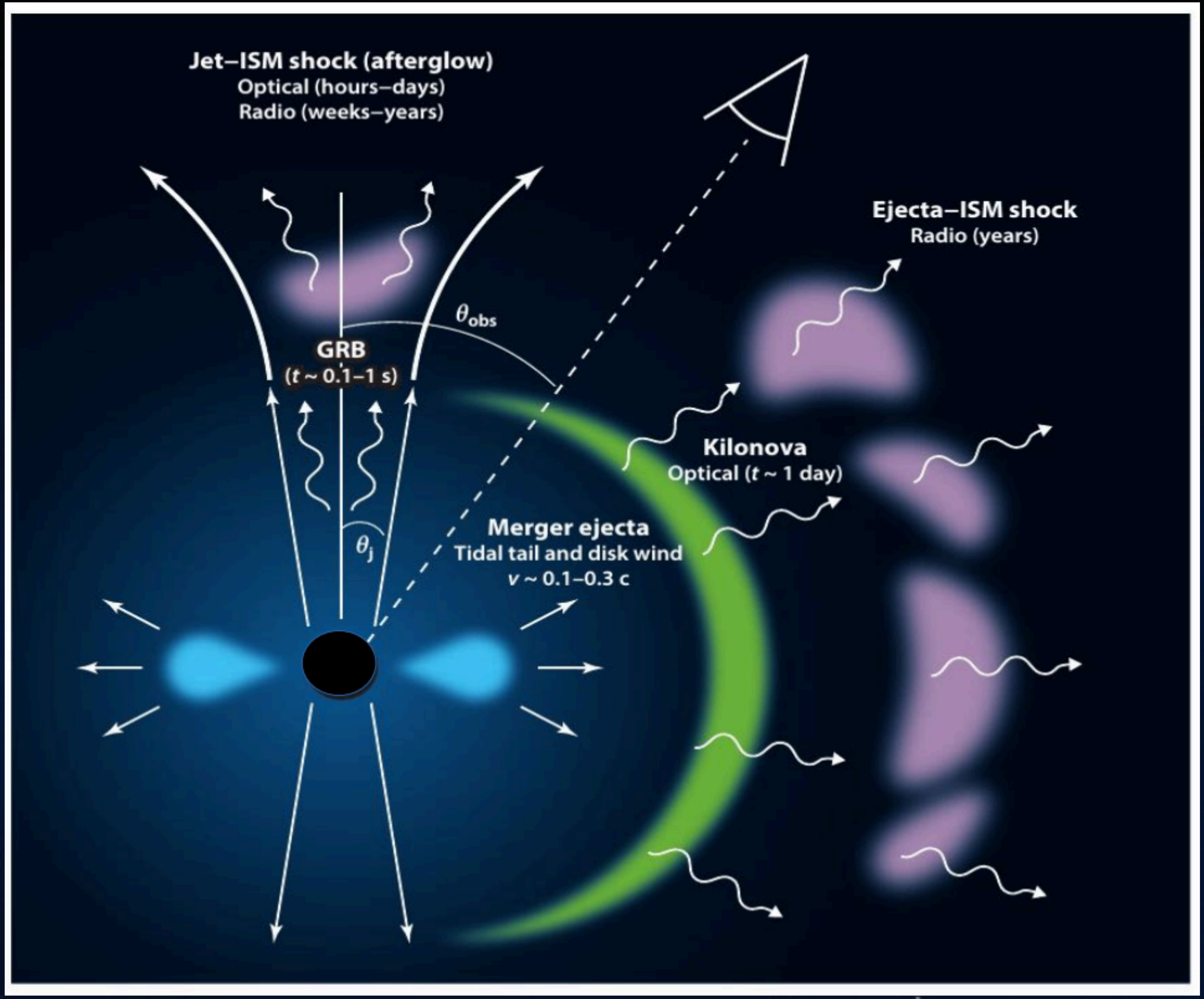
ACME KickOff Meeting

16 September 2024

Horizon Europe ACME

KILONOVA

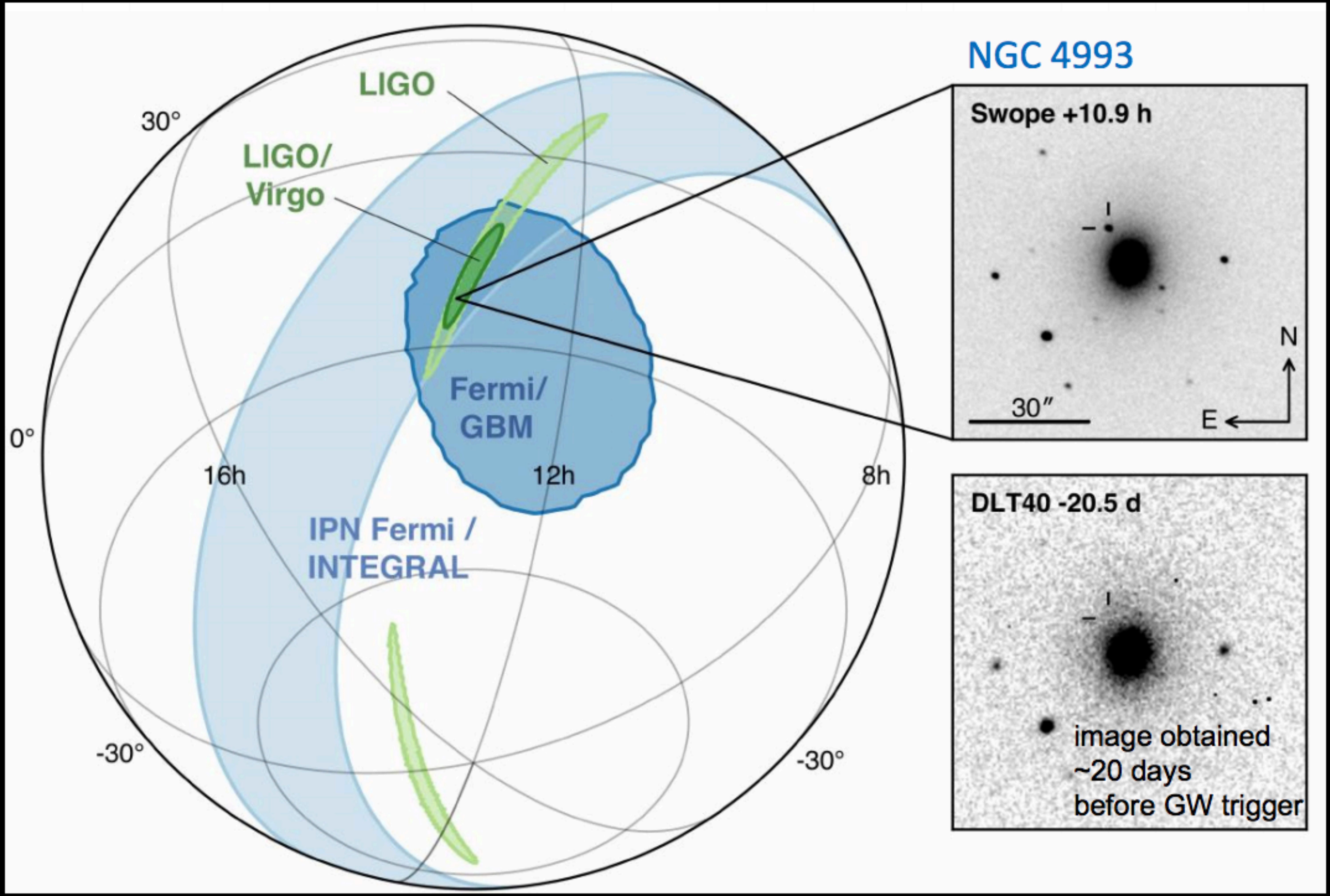


Li&Paczyński 1998, Metzger 2014

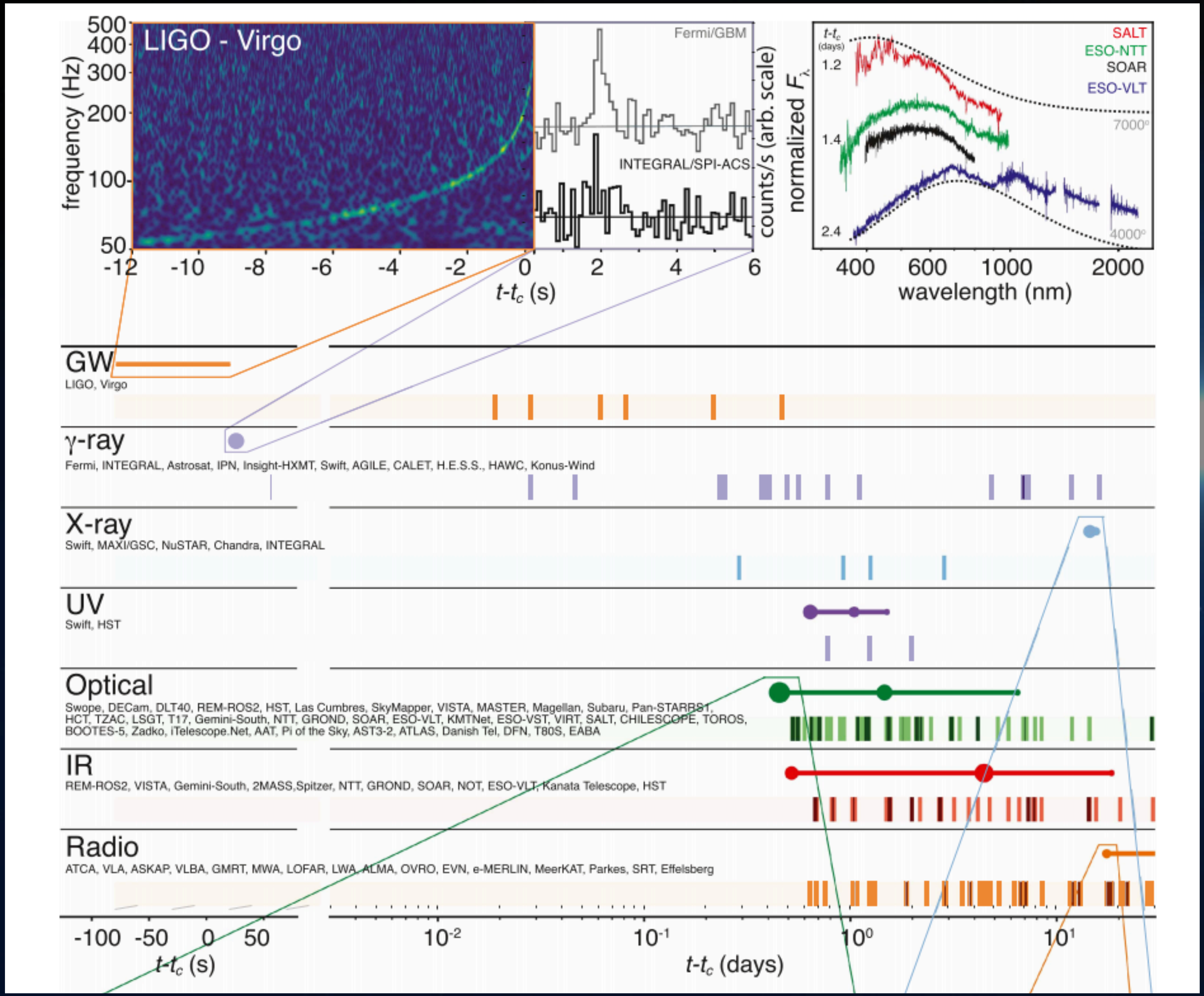
GW170417

Kilonova from merging neutron stars (GW170817)

OPTICAL counterpart detection ~ 11 hours after GW trigger

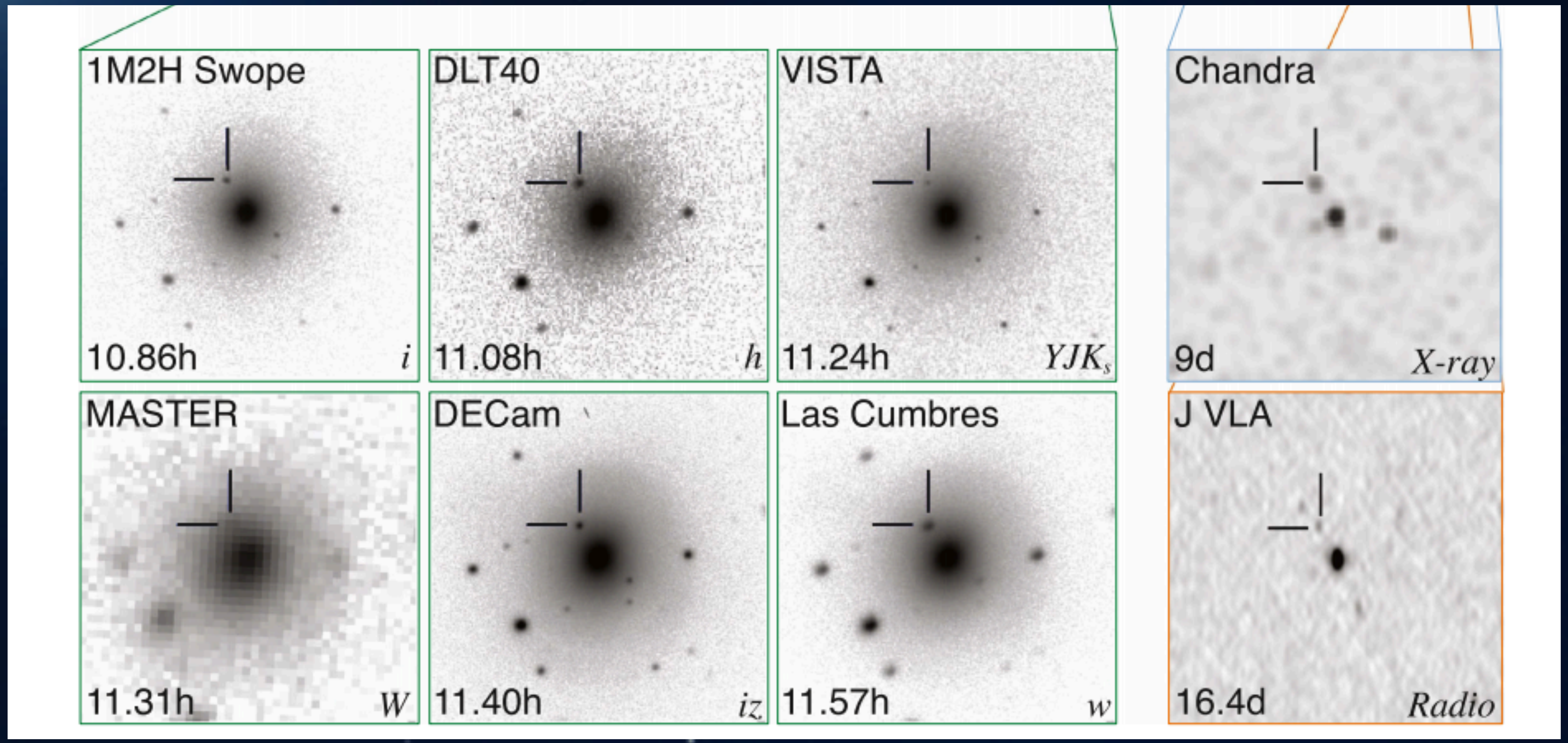


MW FOLLOW-UP



Smartt et al. 2017 (Nature)

- Optical (imaging) follow-up still the easiest
- Numerous telescopes on any hemisphere
- Continous monitoring, fast reactions
- Extensive archives



MASSES OF STELLAR REMNANTS

Abbott+2021
Corral Santana+2016

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MASSES OF STELLAR REMNANTS

Abbott+2021 *Gaia Col.,Panuzzo+2024, Shenar+2022* *Sahu+2022, Lam+2022, Mróz+2022,*
Corral Santana+2016 *El Badry+2022,2023,* *Rybicki+2022, Jablonska+2022, Howil+2024*

MASSES OF STELLAR REMNANTS

Abbott+2021
Corral Santana+2016

THE MOST MASSIVE GALACTIC BLACK HOLE - GAIA BH3

- ➔Mass = 33 $M_\odot$, distance = 590 pc
- ➔Companion: old giant (0.76 $M_\odot$) very low metallicity [Fe/H] = –2.56 ± 0.11
- ➔Possibly part of *Sequoia* halo structure: median [Fe/H] ~ –1.7
- ➔or more probable ED-2 stream: [Fe/H] = –2.6 ± 0.2

Panuzzo+2024

Video credit: ESA/Gaia/DPAC, Stefan Jordan, Toni Sagristá

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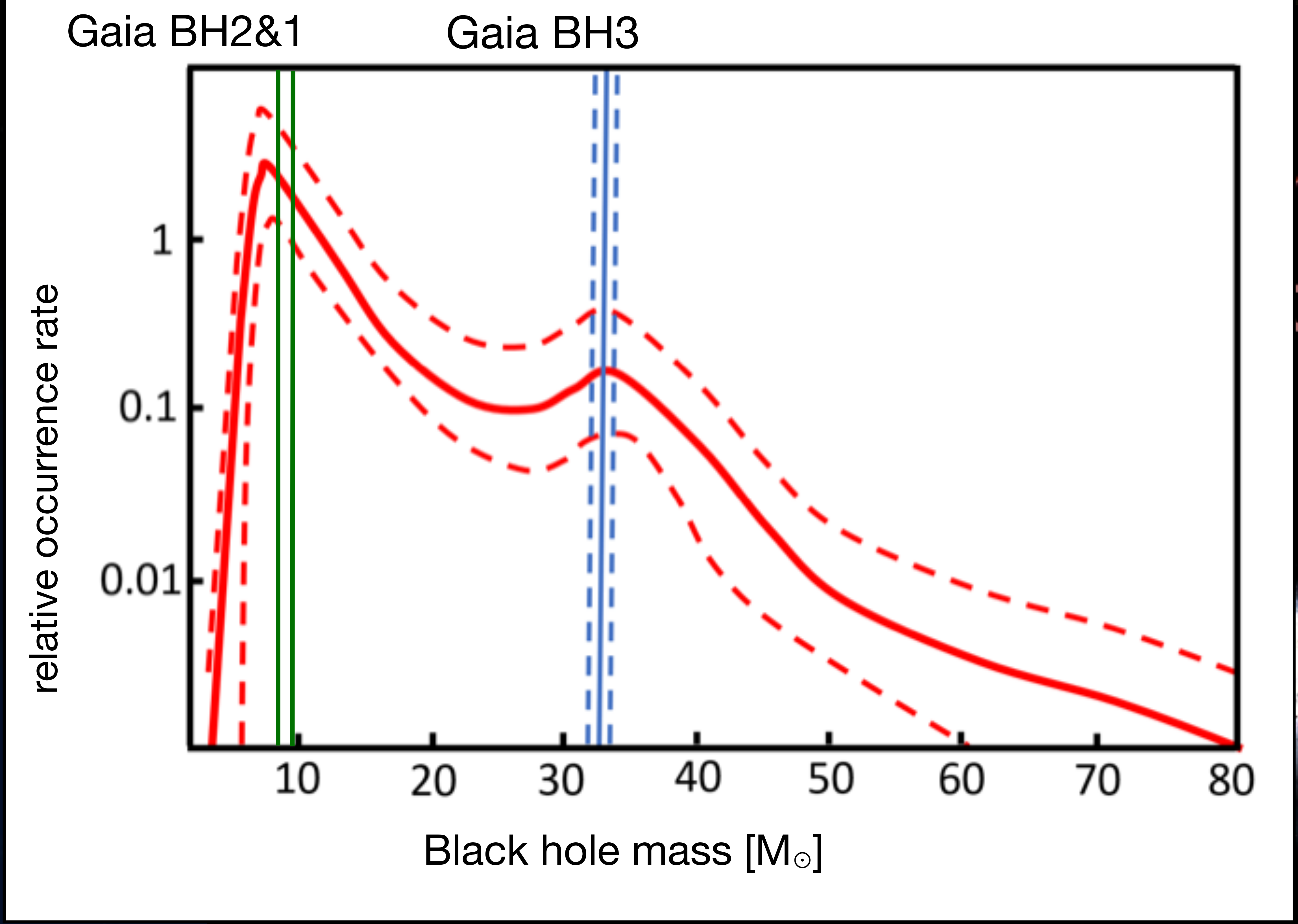

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Panuzzo+2024

, Stefan Jordan, Toni Sagristá

MASSES OF STELLAR REMNANTS

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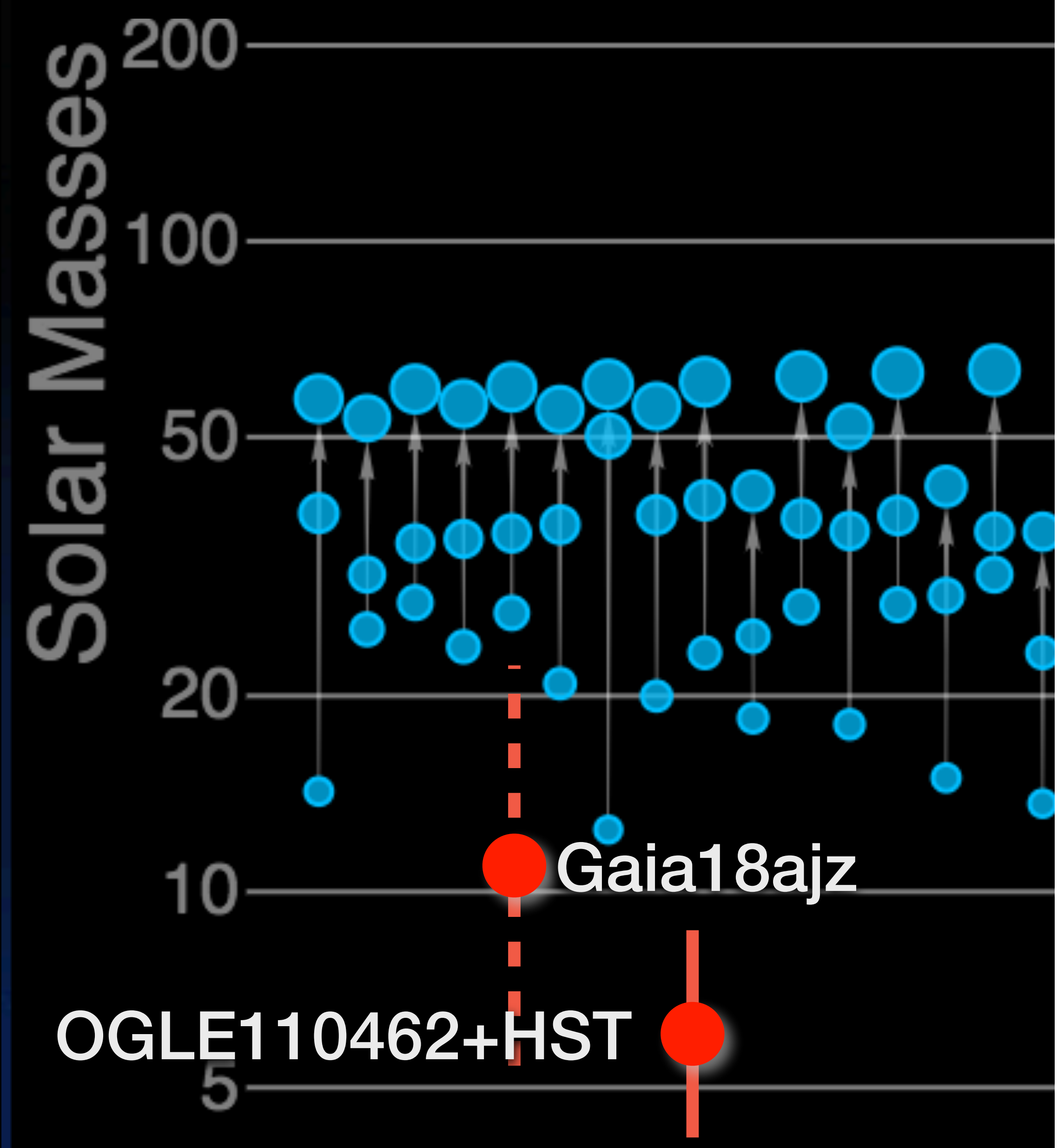
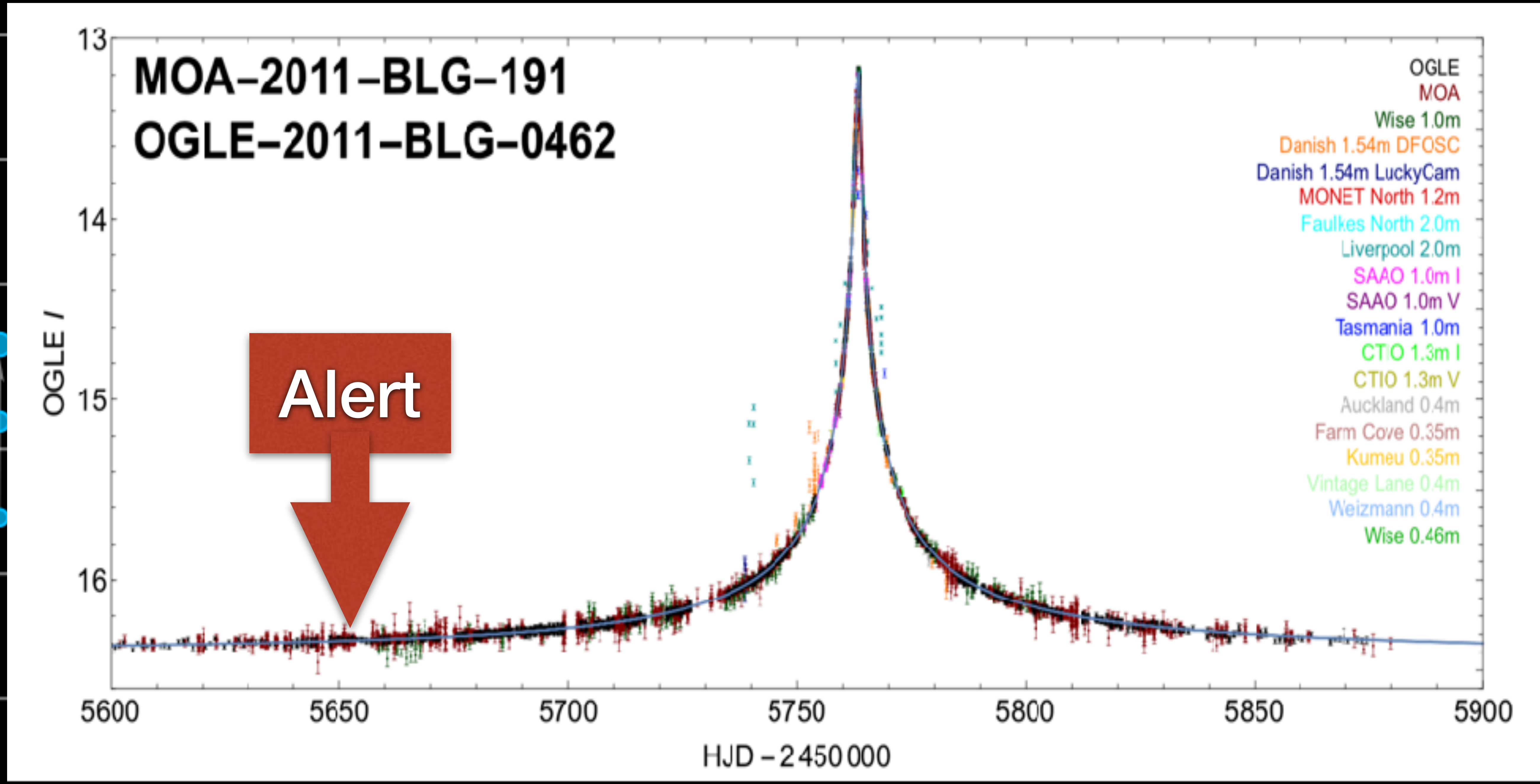
Gaia Col.,Panuzzo+2024, Shenar+2022
El Badry+2022,2023,
Sahu+2022, Lam+2022, Mróz+2022,
Rybicki+2022, Jablonska+2022, Howil+2024

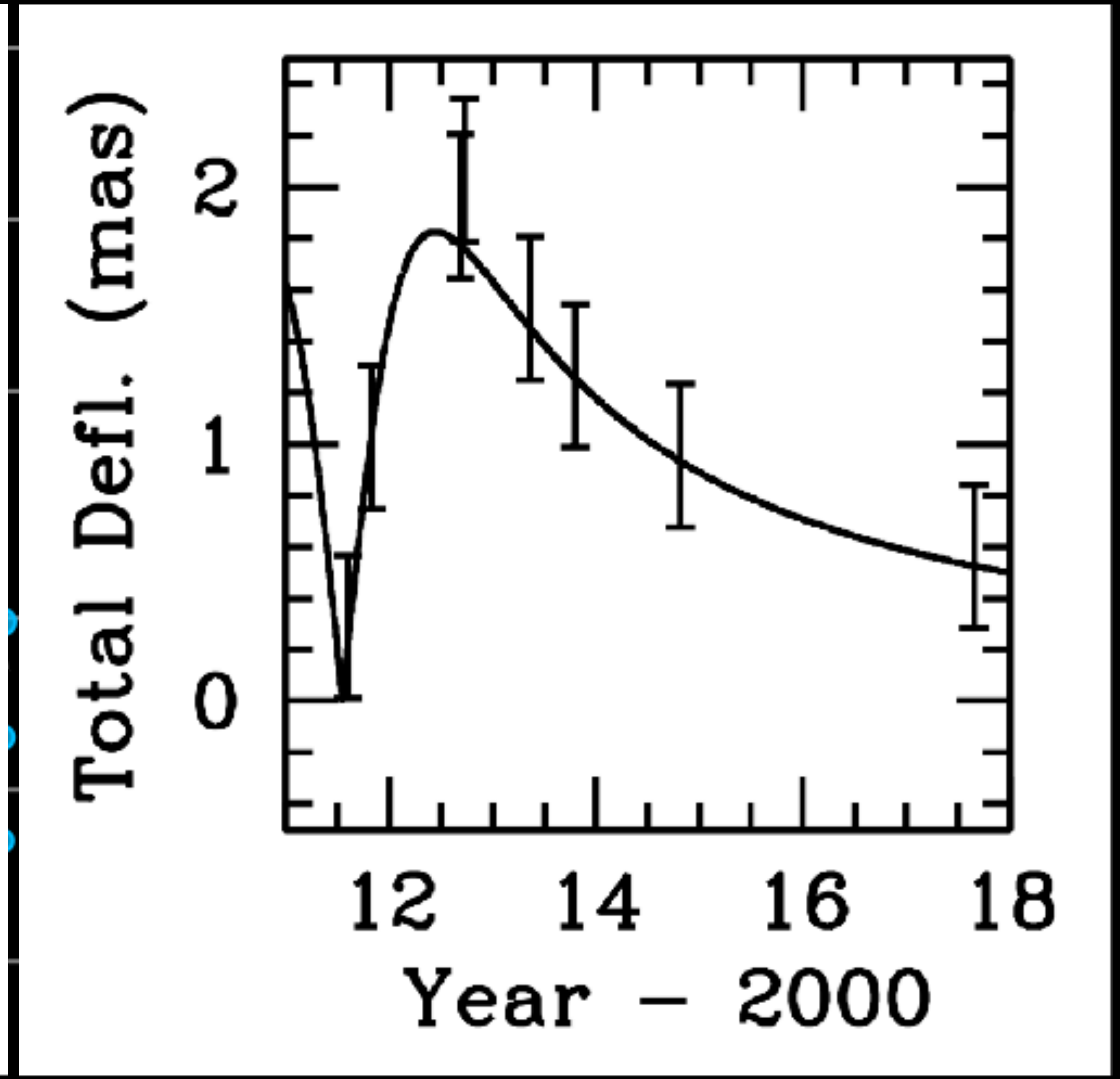
THE FIRST SINGLE BLACK HOLE - MICROLENSING EVENT OGLE110462



photometric time-series



astrometric time-series



OGLE

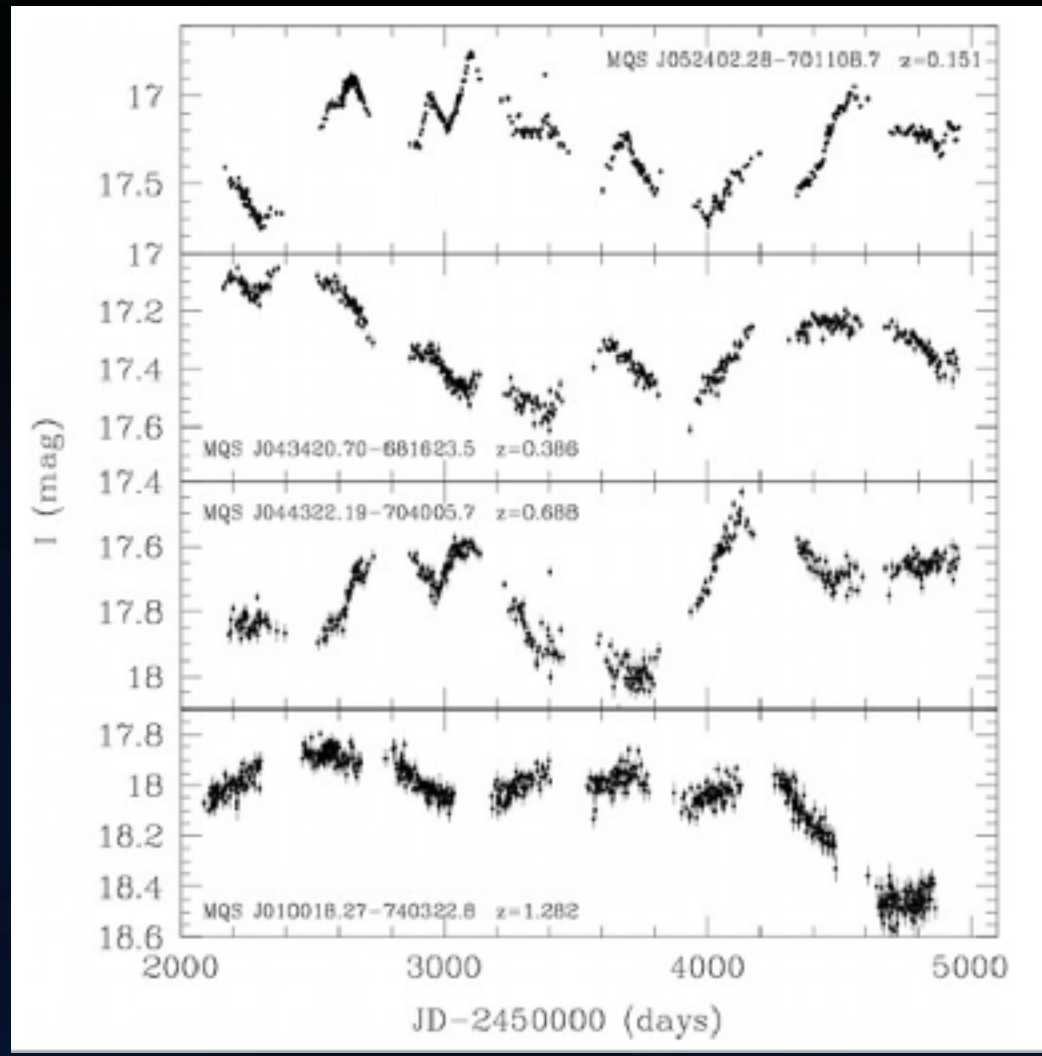
Mass=7.9+-0.8 M☉
Distance=1.5+-0.1 kpc

Sahu+2022, Lam+2022, Mróz+2022

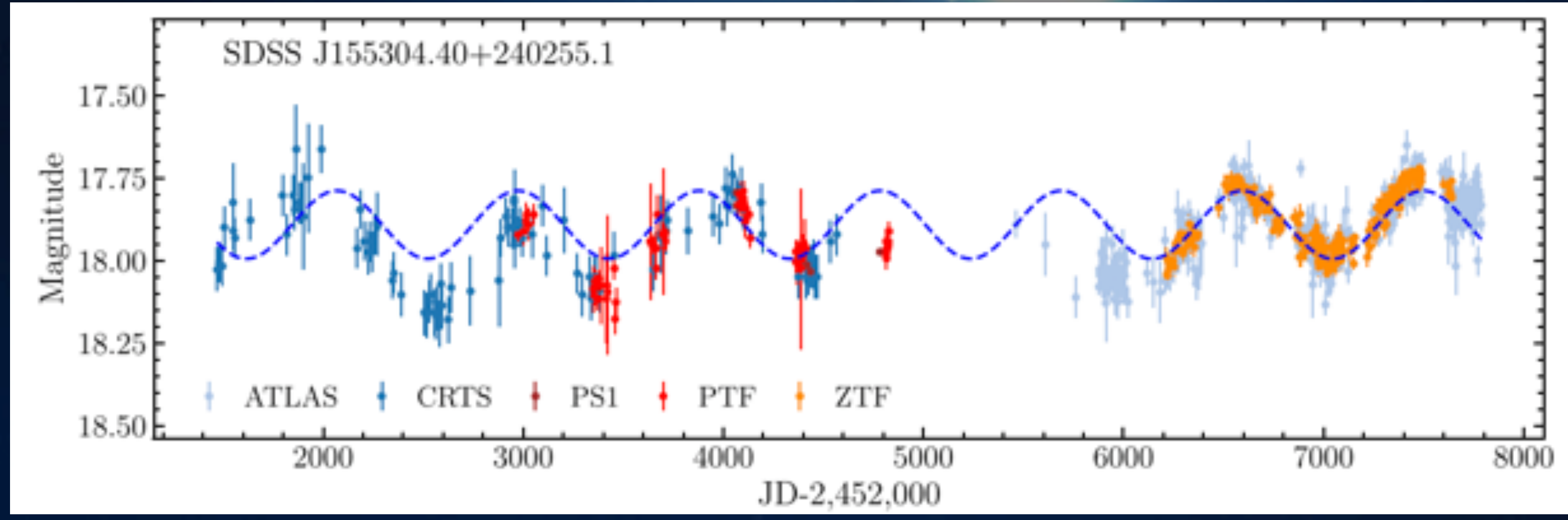
Hubble Space Telescope

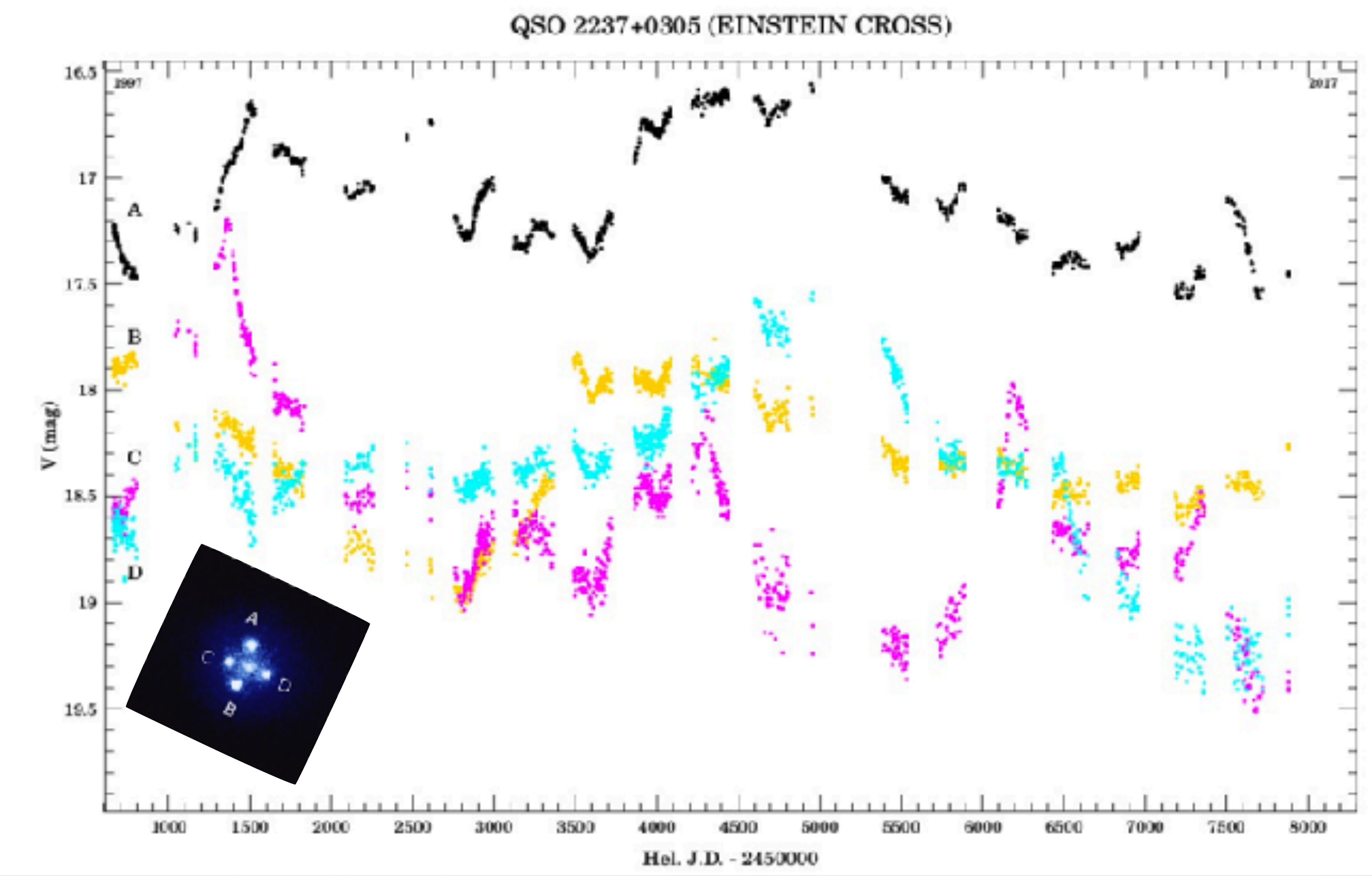
QUASAR MONITORING

- AGN studies: reverberation mapping, sizes, masses of BHs
- Lensed QSOs - sizes, dark matter
- Binary SMBHs



Kozlowski et al. 2013, 2021

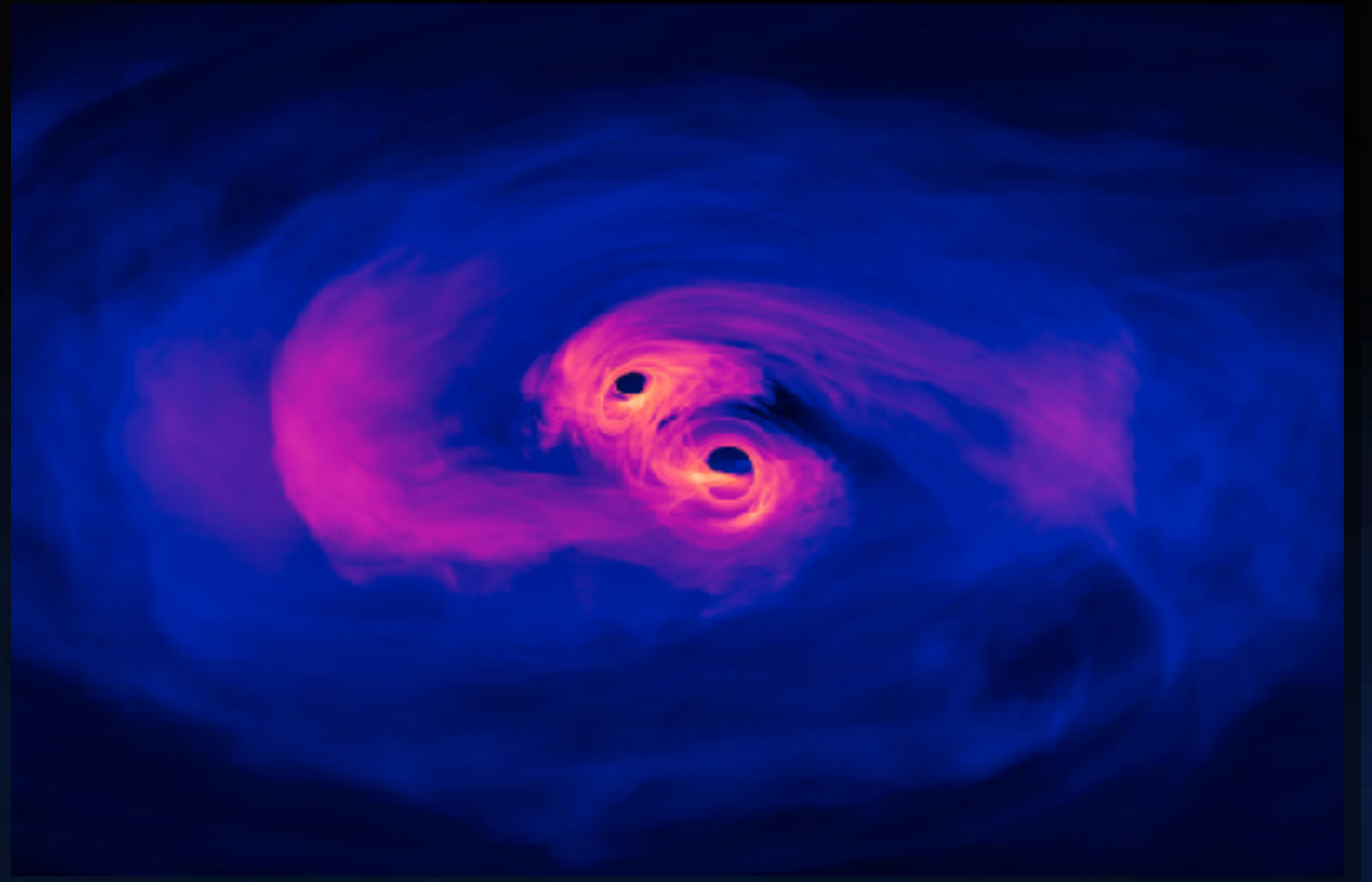




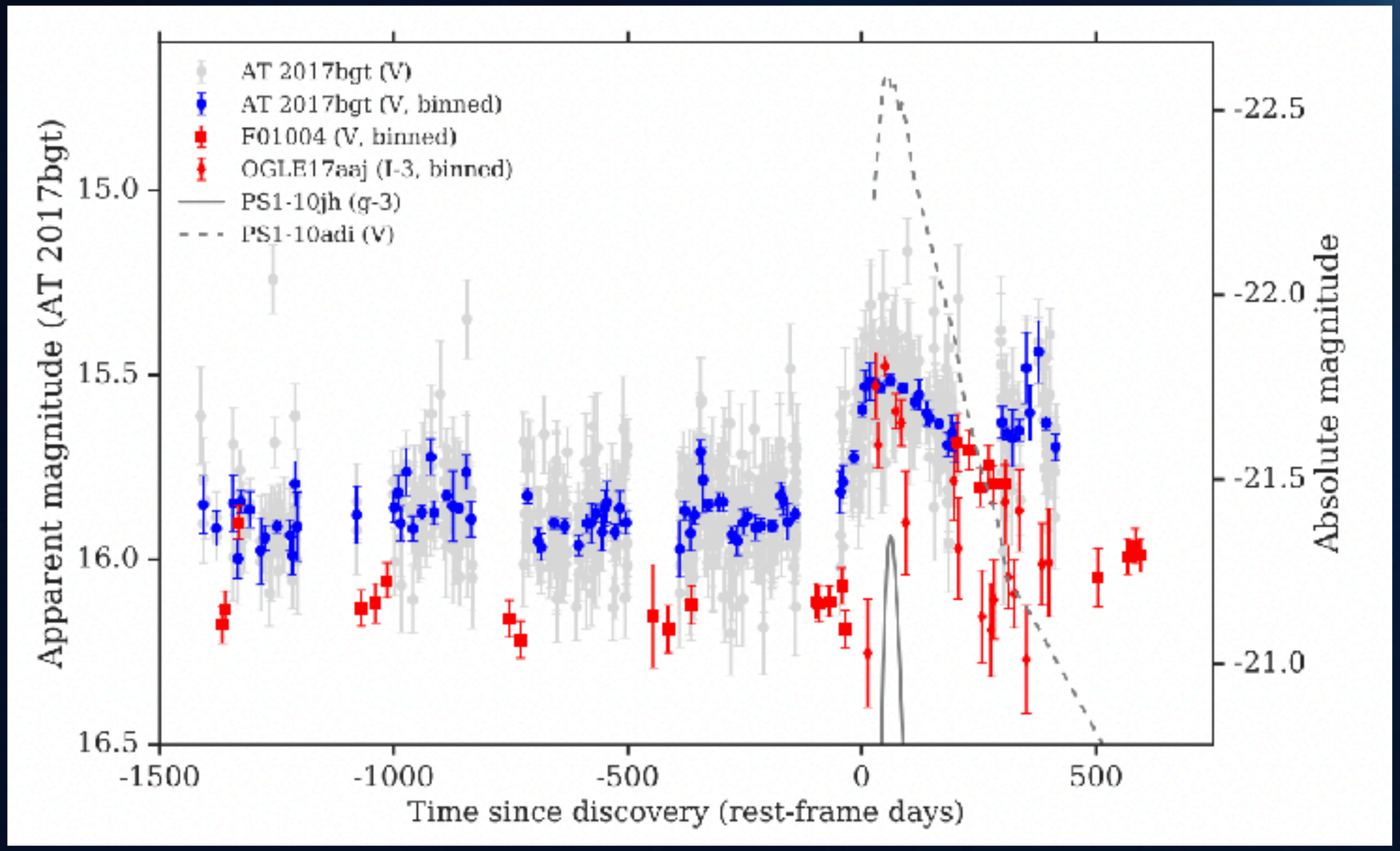
e.g. Charisi et al. 2022, Yong-Jie et al. 2024

Wozniak et al. 2000

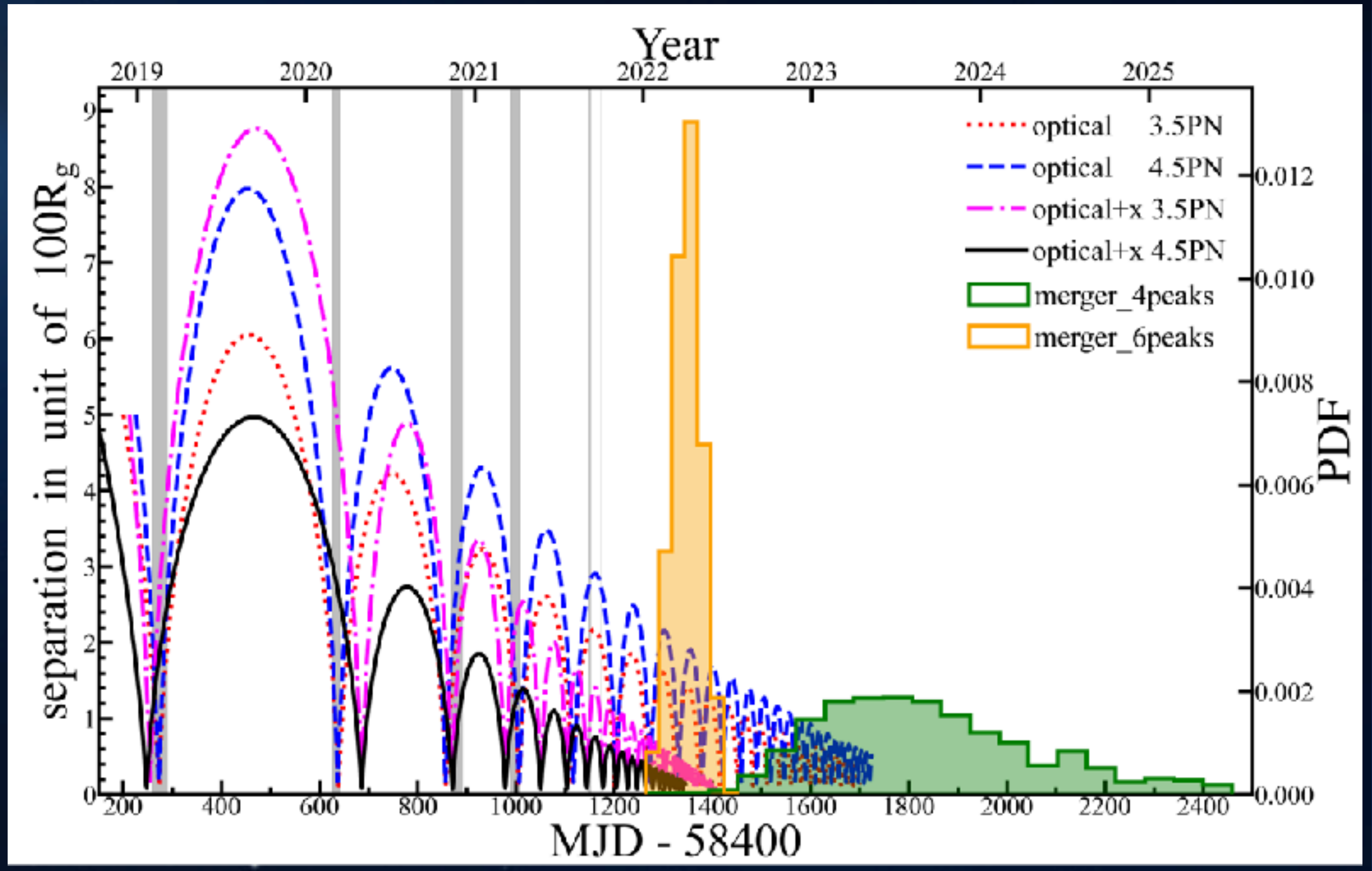
SMBH TRANSIENTS



- Mergers in binary SMBHs (Tic-Toc candidate)
- Changing Look QSOs (MacLeod+2012)
- Bowen Fluorescence Flares (Trahtenbrot+2019)
- Tidal Disruption Events (Van Veltzen+2011)

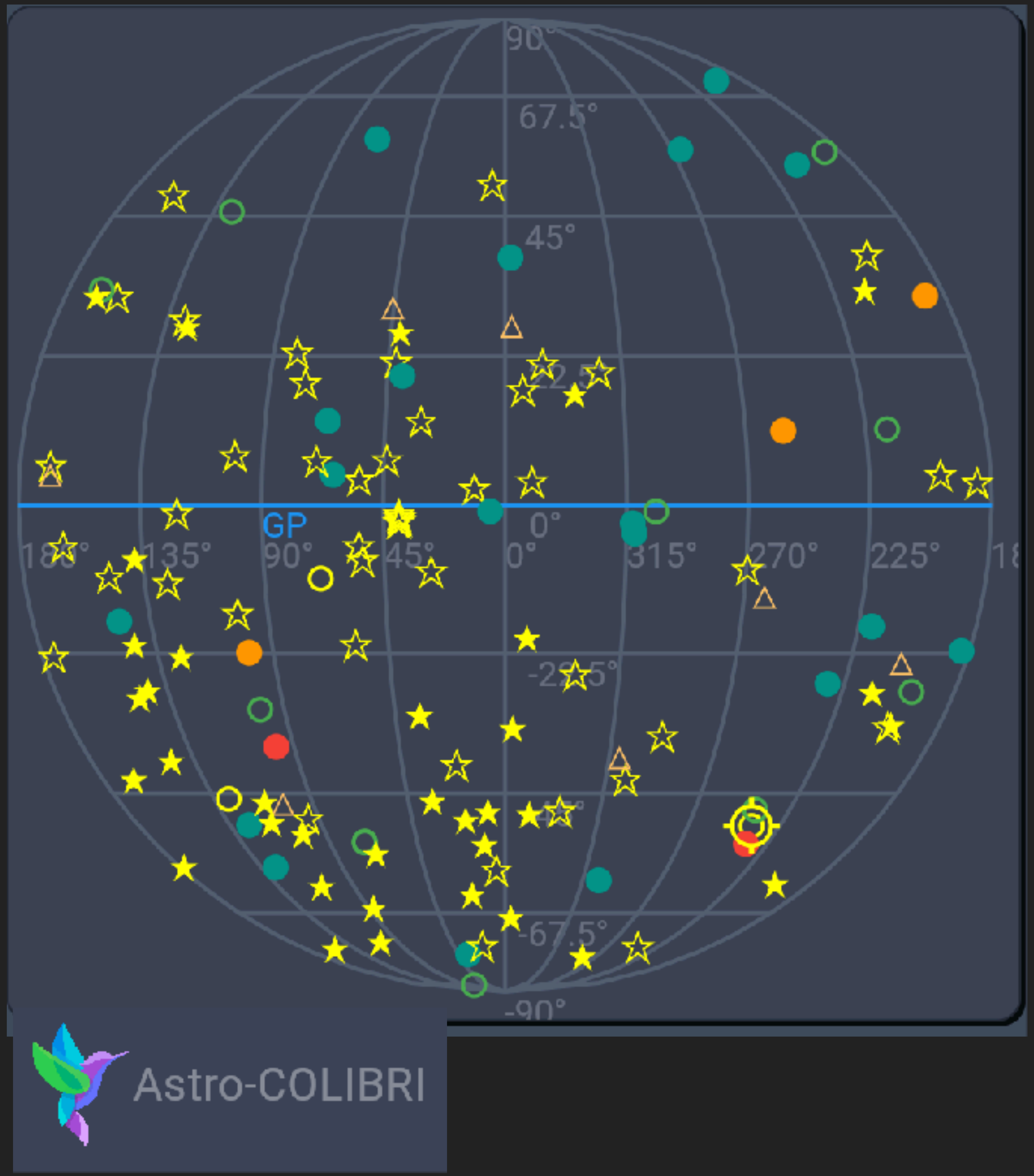


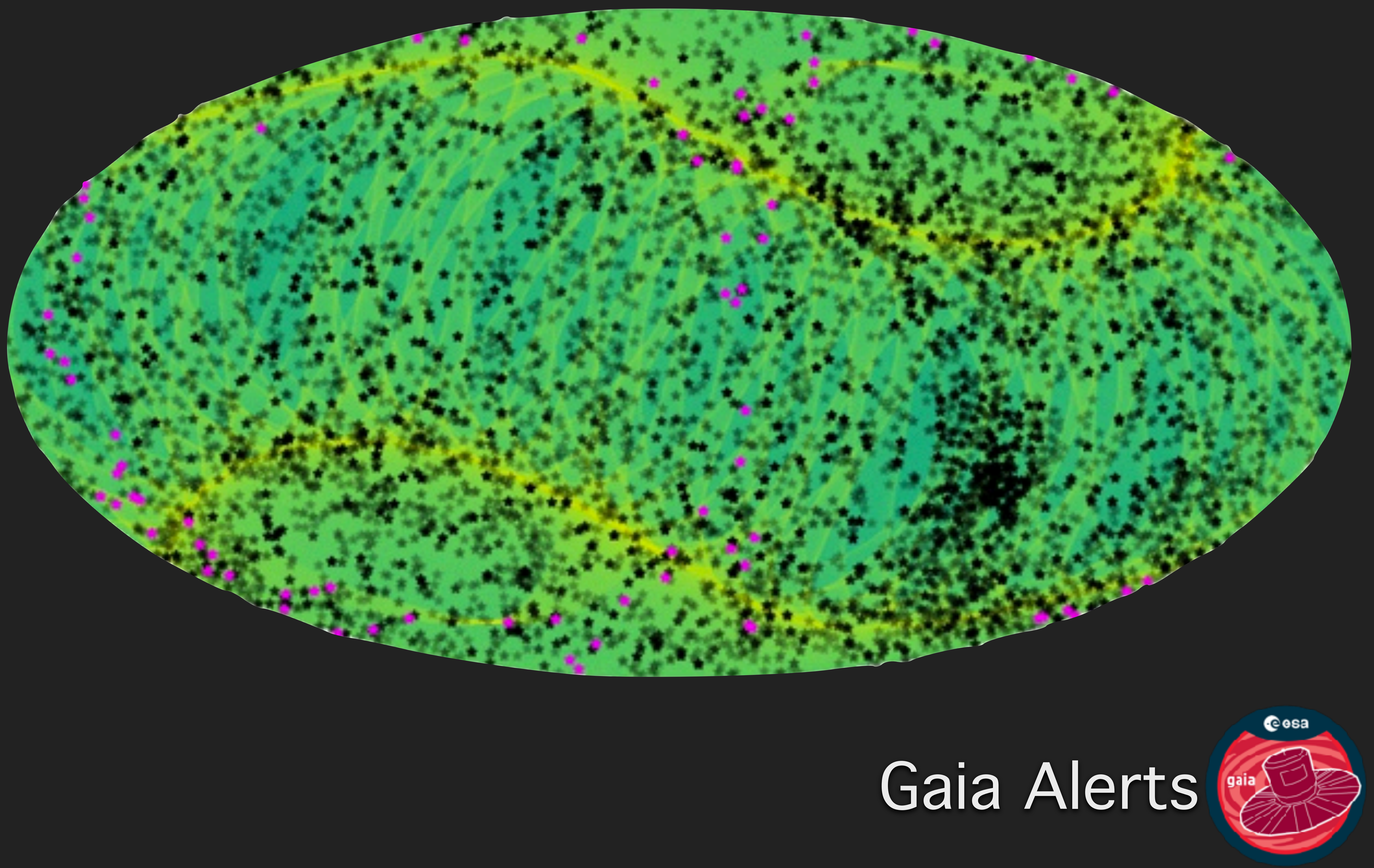
Trahtenbrot+2019, NatAst



Jiang et al. (2022)

THERE IS ALWAYS A TIME-DOMAIN INTERESTING OBJECT VISIBLE ON THE SKY

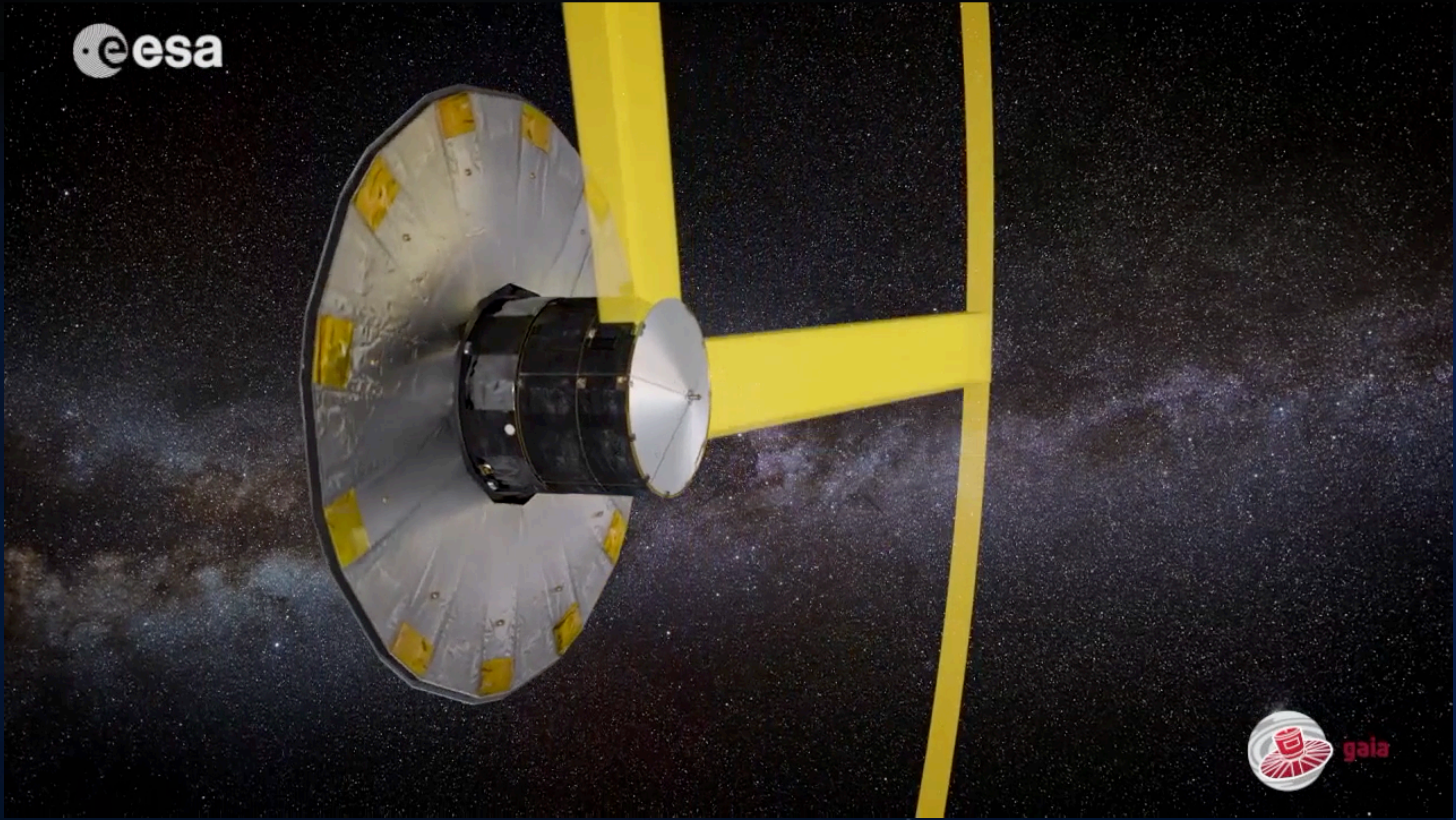




extra slides

GAIA - ALL SKY - PERFECT OPTICAL SURVEY

- ESA mission since 2013
- located in L2
- 10m in diameter
- two 1.4m mirrors
- depth: G~20.5mag
- positional accuracy: <1 mas
- 2 billion sources
- simultaneous brightness, position and spectral observations
- typical cadence: 30 days



GAIA ALERTS

- in operation from 2014
- ~20,000 alerts
- ALL types of transients:
  - supernovae
  - tidal disruption events
  - super-luminous SNe
  - cataclysmic variables
  - dimming stars (RCrB)
  - young stellar objects
  - Be-type outbursts
  - microlensing events
  - quasars
- human-vetted,
  but automation is coming
- typical latency: 1-2 days

UNIVERSITY OF CAMBRIDGE

Gaia Alerts | Alerts Index | All-Sky | Alerts Search | GaiaX Test | Surveys-ATels | Tools | Documentation | About

ioa **Gaia Photometric Science Alerts**

Index to Gaia Photometric Alerts

If you publish any results based on these Gaia discoveries, we would appreciate an acknowledgement along the lines of: "*We acknowledge ESA Gaia, DPAC and the Photometric Science Alerts Team (http://gsaweb.ast.cam.ac.uk/alerts)*"

These are all the alerts raised to date. You might wish to view or download these as a table in CSV or pipe-delimited formats or using the tools described in this page.

See here for an explanation of the columns.

Show 10 entries Search:

Name	TNS	Observed	RA (deg.)	Dec. (deg.)	Mag.	Historic mag.	Historic scatter	Class	Published	Comment	RVS
Gaia22edj	AT2022xat	2022-10-02 05:42:25	305.25649	0.85987	18.74	19.09	0.03	unknown	2022-10-08 10:41:05	0.3 mag flare on red Gaia source	
Gaia22edi	AT2022vkz	2022-10-03 01:06:20	22.29503	53.49412	18.91	20.45	0.18	unknown	2022-10-08 09:09:38	2 mag outburst in Gaia source	
Gaia22edh	AT2022xas	2022-10-02 05:50:27	309.36226	7.12995	17.40	18.95	0.61	unknown	2022-10-08 09:09:30	2 mag outburst in candidate CV	
Gaia22edg	AT2022xar	2022-08-24 06:48:57	221.06185	-56.24877	17.30	18.46	0.42	unknown	2022-10-08 09:09:20	Outburst in erratic Gaia source	
Gaia22edf	AT2022xaq	2022-10-02 10:54:37	276.67349	-33.62638	14.57	14.95	0.06	unknown	2022-10-08 09:09:13	bright gal.plane source candidate microlensing event or Be-type outburst rises by 0.4 mag	
Gaia22ede	SN2022wbh	2022-10-02 02:06:43	107.38830	24.53159	18.58			SN Ia	2022-10-08 09:09:08	confirmed SN Ia	
Gaia22edd	SN2022vqx	2022-10-02 08:14:44	112.17797	17.25046	17.86			SN Ia-pec	2022-10-08 09:09:02	confirmed SN Ia-pec	
Gaia22edc	AT2022vsw	2022-10-03 02:25:22	116.13491	7.04804	18.85			unknown	2022-10-08 09:08:56	candidate SN near PanSTARRS source	
Gaia22edb	AT2022xap	2022-10-02 16:52:57	274.42710	-34.06443	18.86			unknown	2022-10-08 09:08:49	Apparently hostless transient	
Gaia22eda	AT2022xao	2022-10-02 20:05:06	102.69372	25.04992	16.48	15.20	0.26	unknown	2022-10-08 09:08:41	fading in known blazar QSO B0647+250	

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

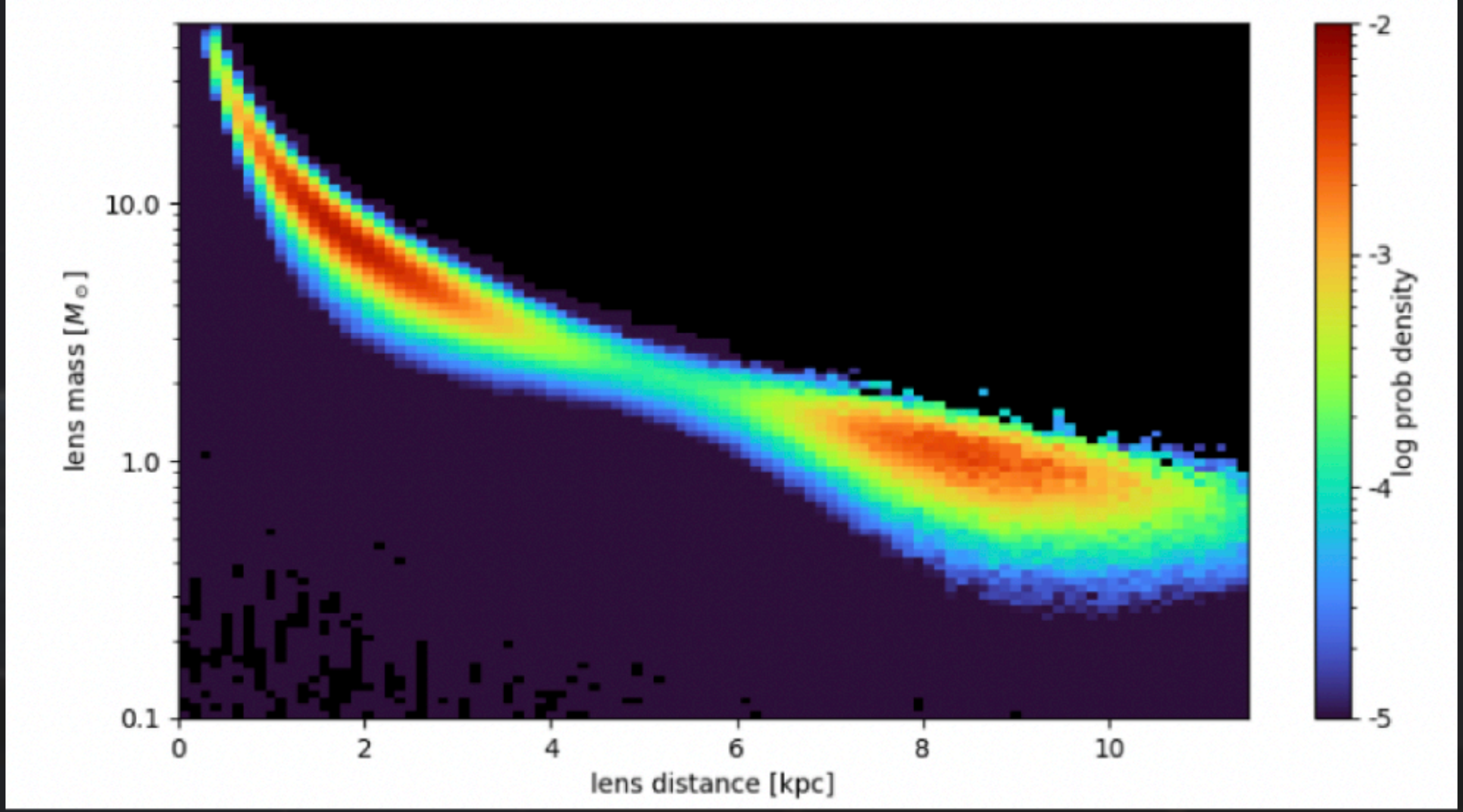
GAIA18AJZ ALERT

- one of the longest events ever (te~450d) at *gal_l*=+23 deg
- dark lens, most likely ~12 MSun at ~2kpc
- hint for microlensing signal in astrometry in elevated RUWE (=1.5)

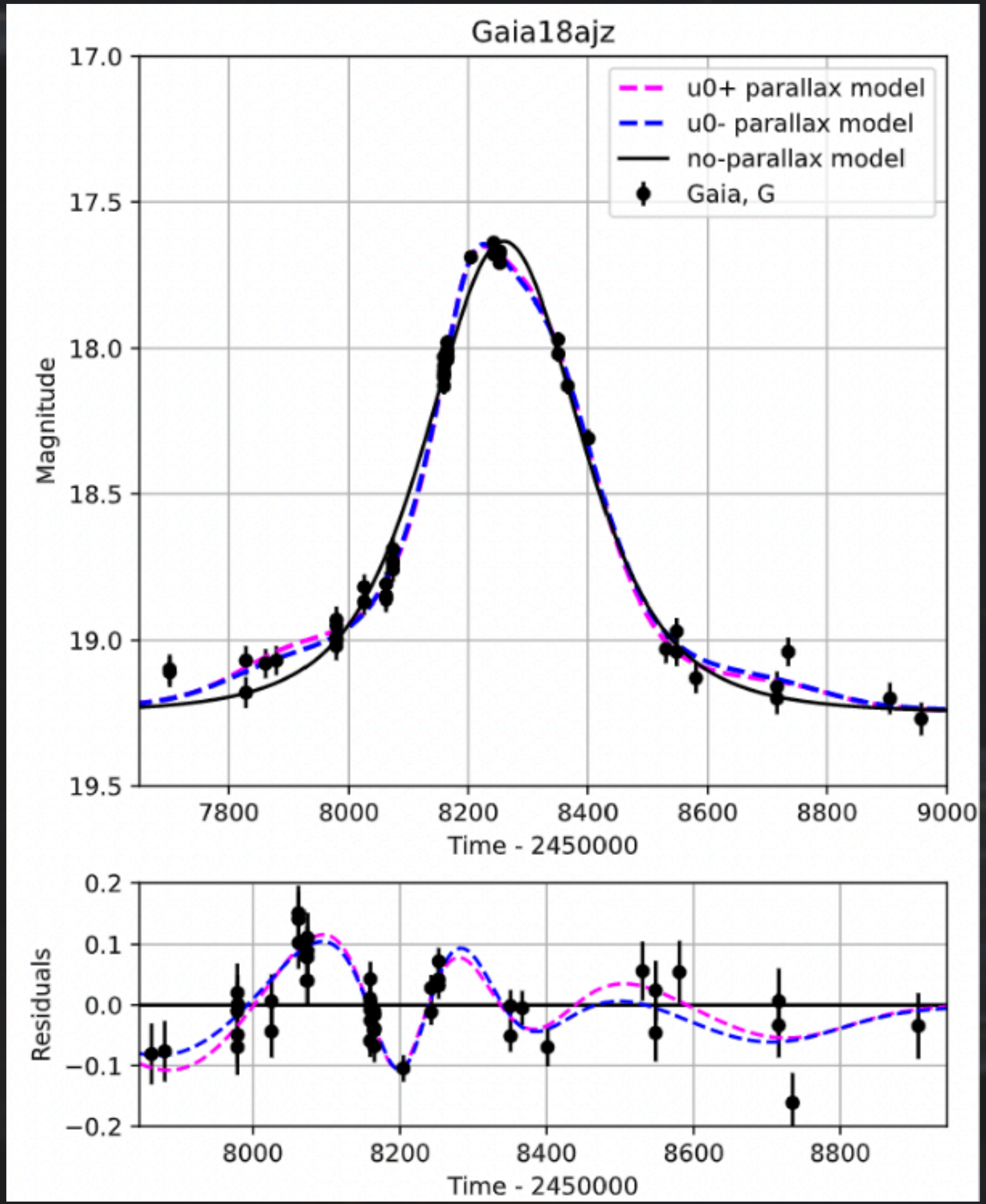
$$M = \frac{\theta_E}{\kappa \pi_E}$$

EINSTEIN RADIUS FROM GALAXY MODEL

MICROLENSING PARALLAX



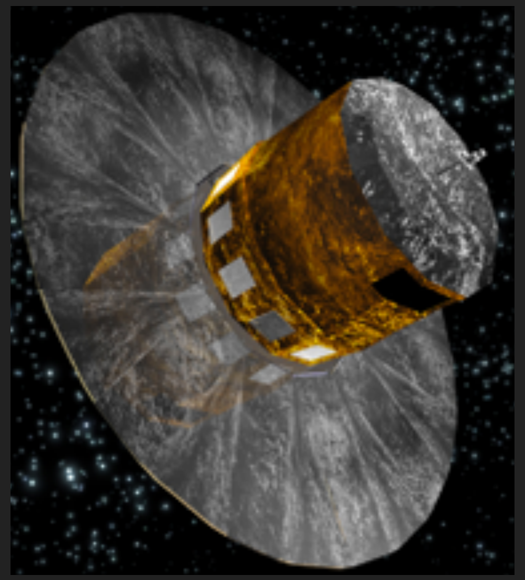
Howil et al. 2024

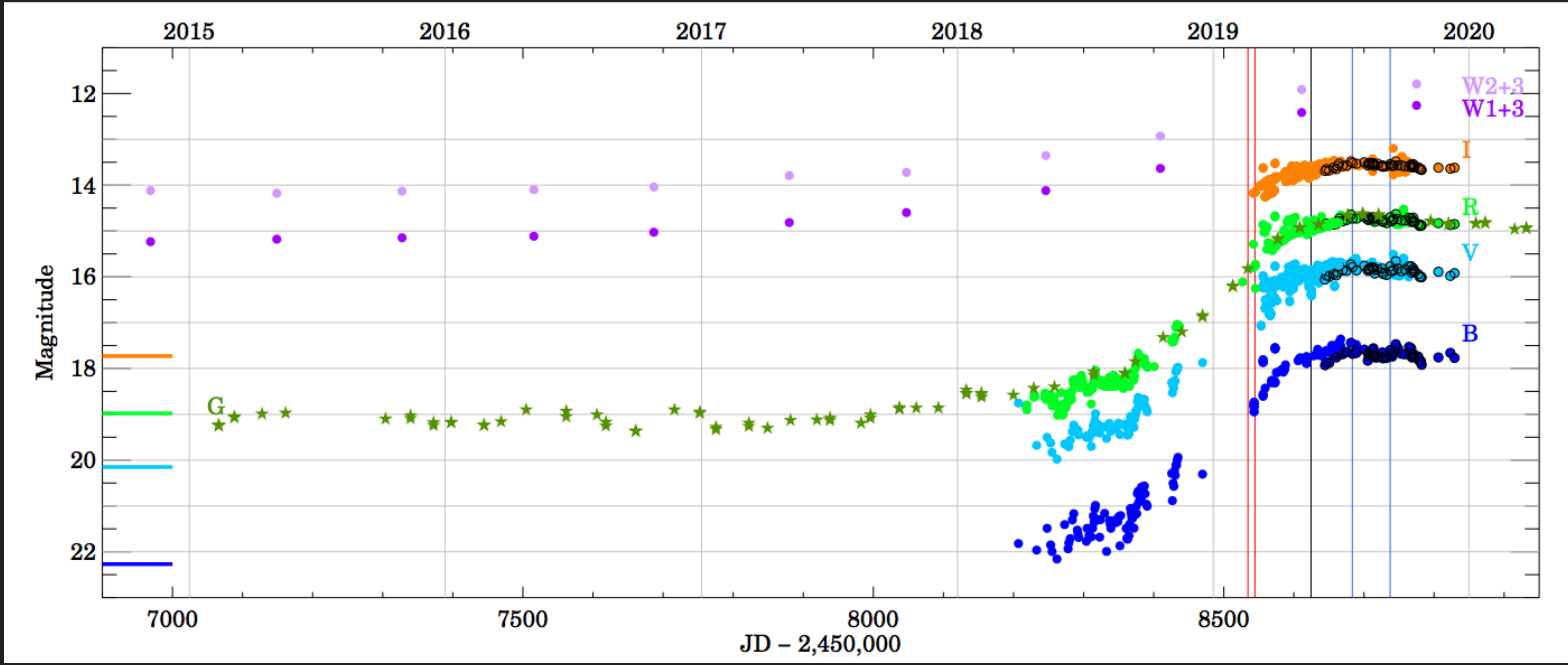


by Kornel Howil with MulensModel

GAIA18DVY ALERT

- New example of rare FU Ori young stellar object in outburst
- Optical + Infrared time-series

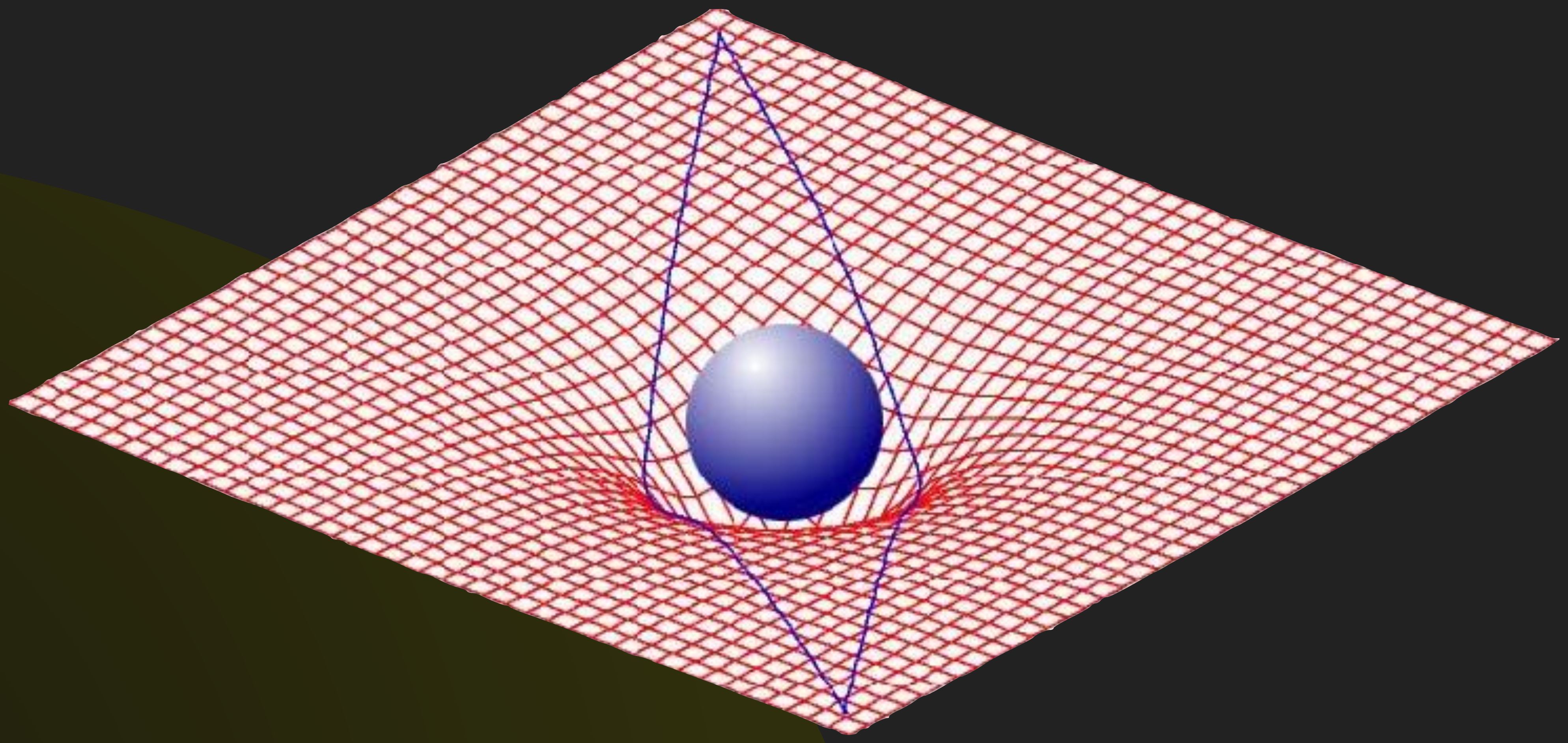


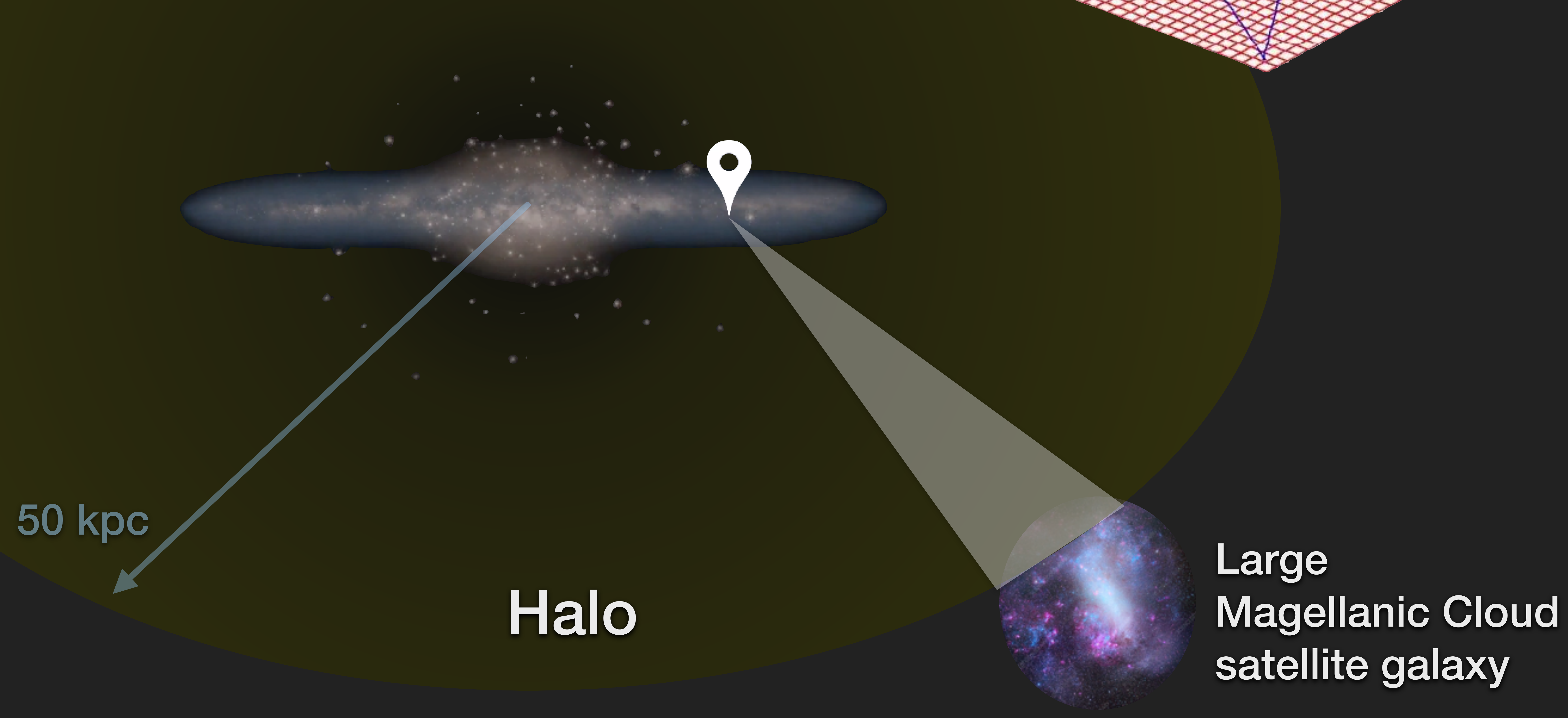


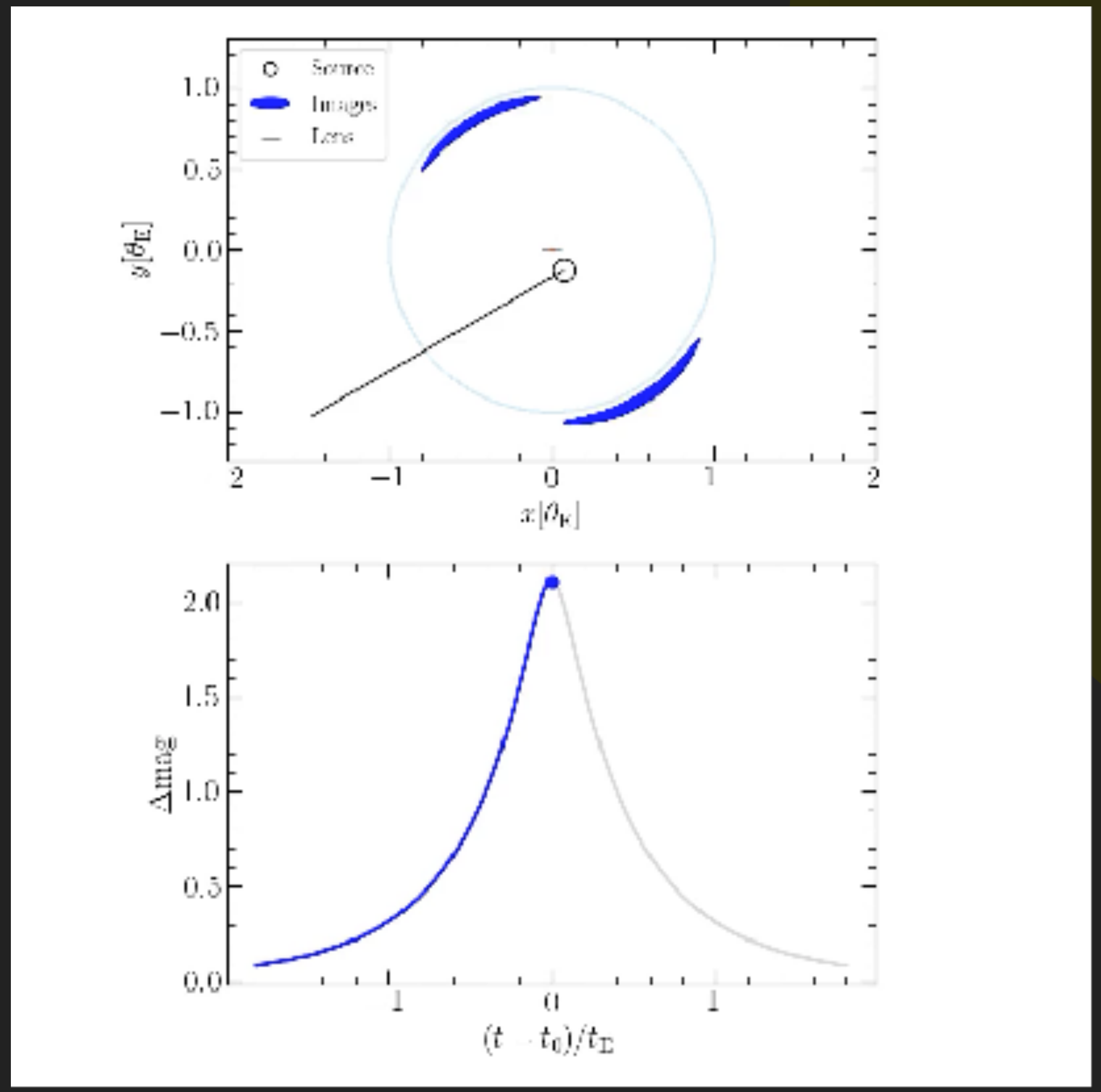
Szegedi-Elek et al. 2020

HOW TO FIND DARK MATTER WITH MICROLENSING?

- Massive Astrophysical Compact Halo Objects (MACHOs) if dominant in the Galaxy Halo could cause temporal lensing (brightenning) events on background stars



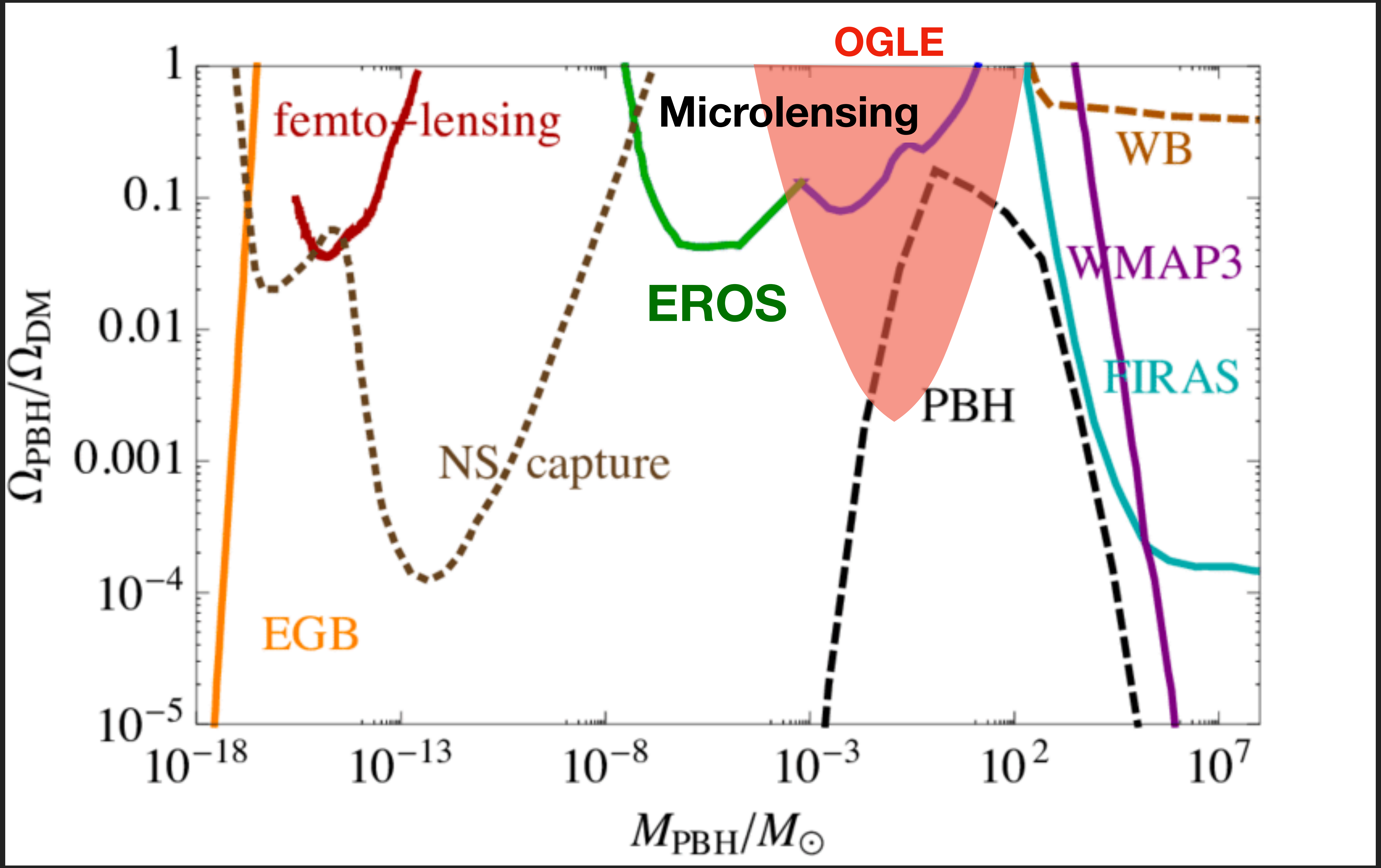


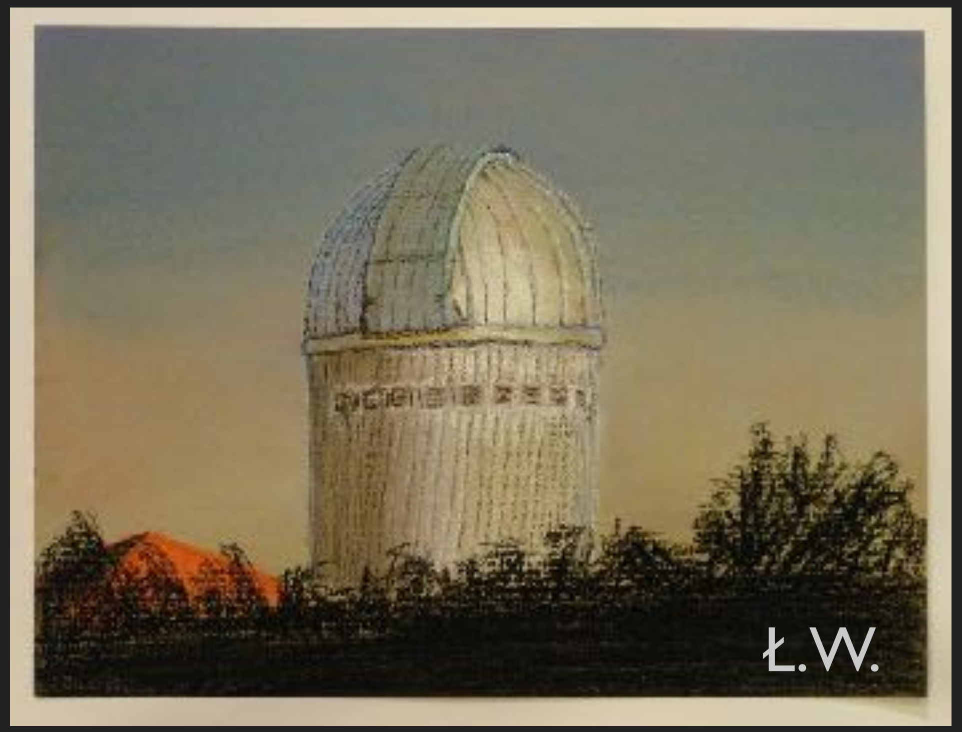


Paczyński curve

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



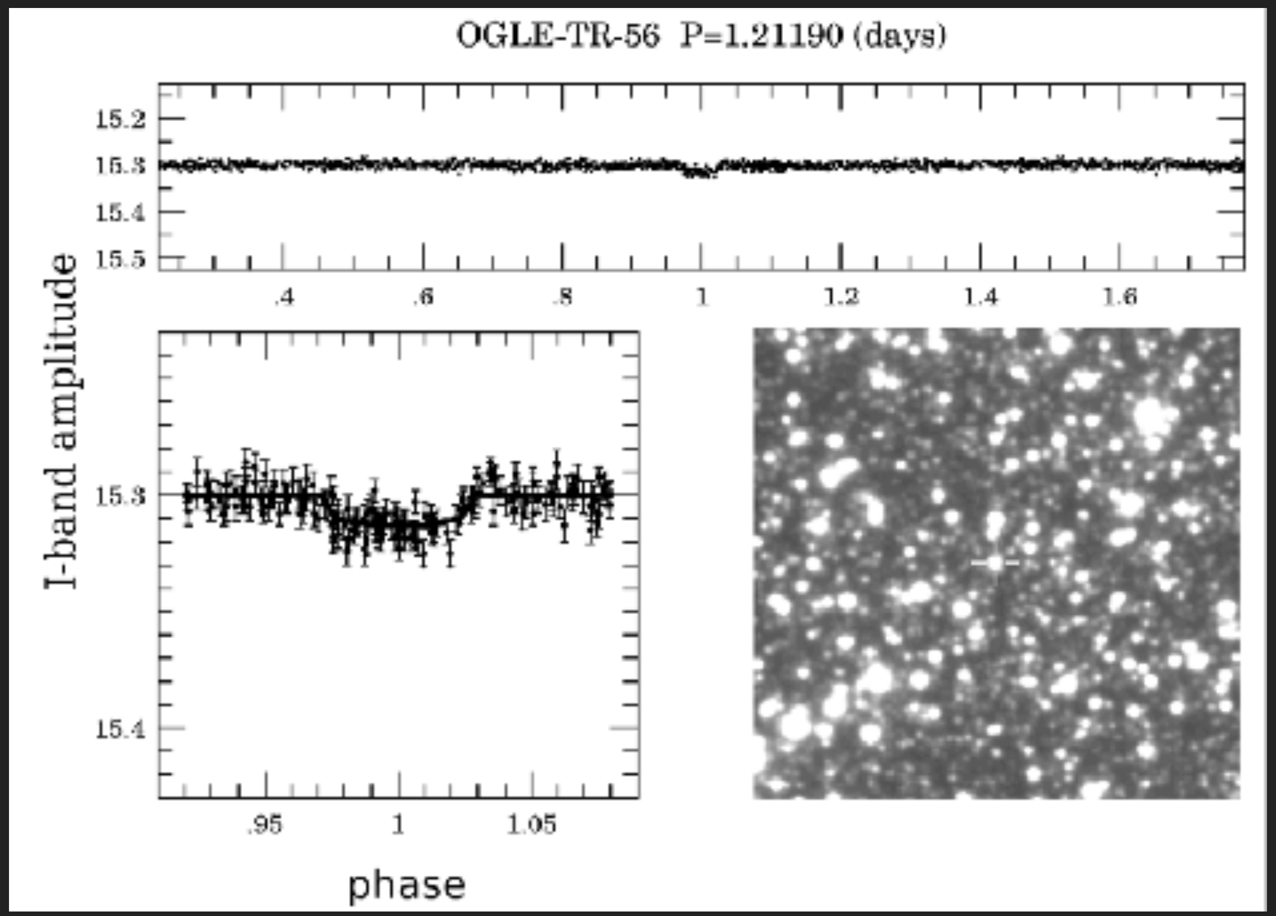


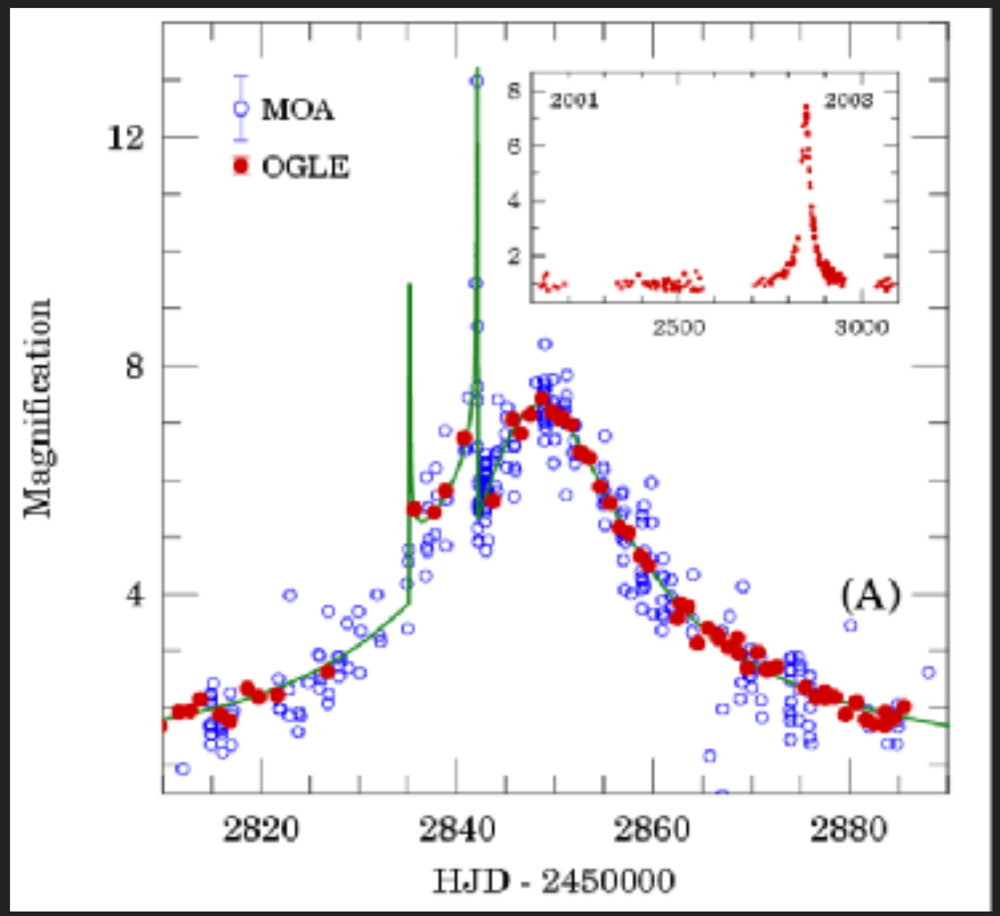
Garcia-Bellido & Clesse 2017

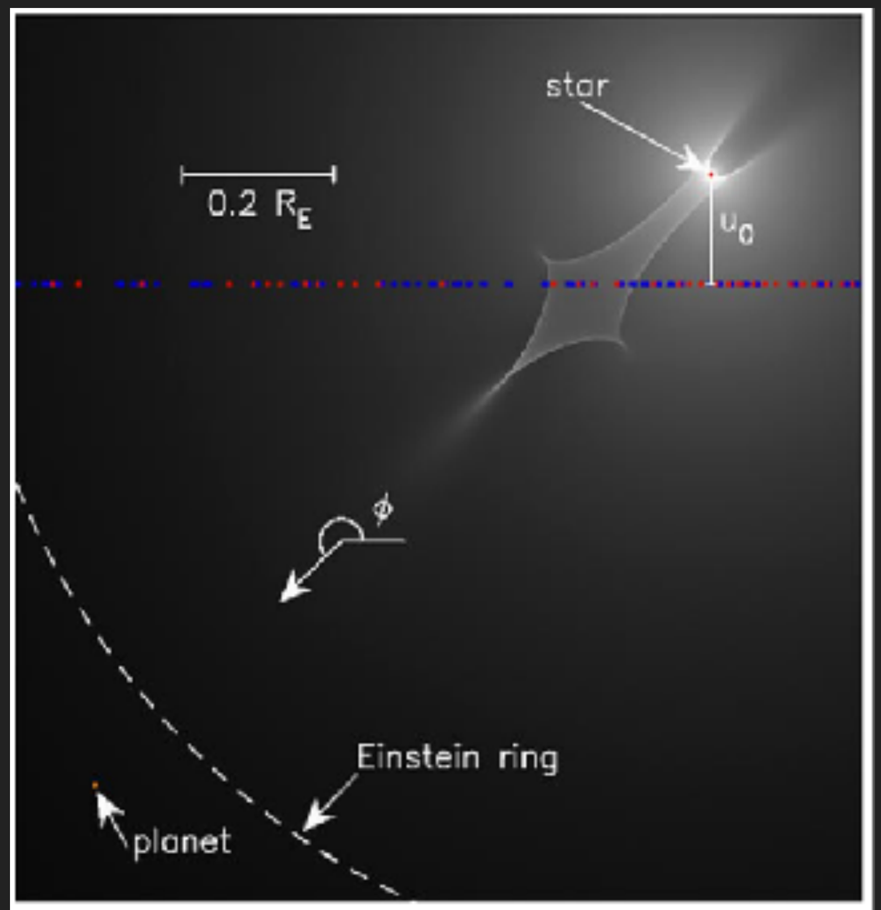
Wyrzykowski+ 2009,2010,2011a,2011b; Mroz+2024

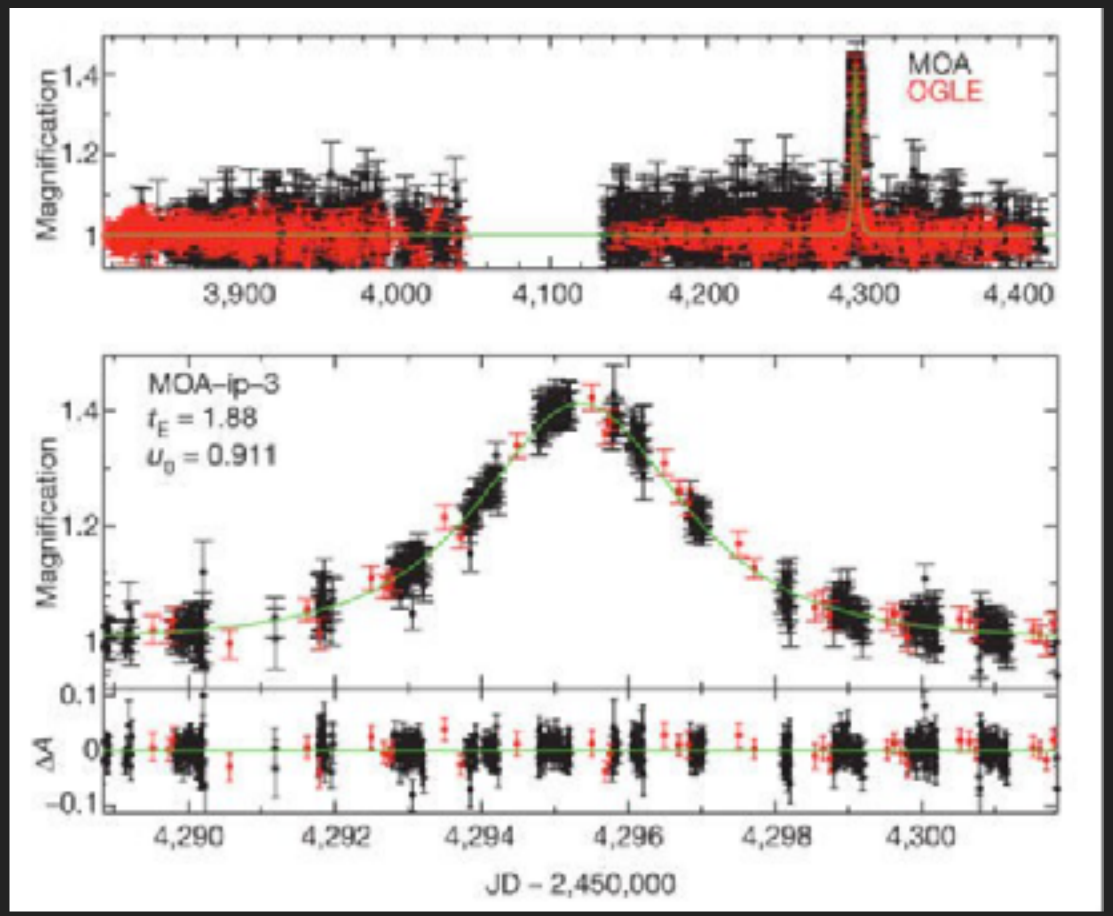
PLANETS

- Planet abundance: 17% Jupiters, 52% Neptunes, 62% Super-Earths
- Free-floating planets (no stellar host) - challenge for planet formation theory
- Different methods:
  - microlensing (short perturbations to Paczynski curve, ~hours)
  - transits (dimming of the host star)



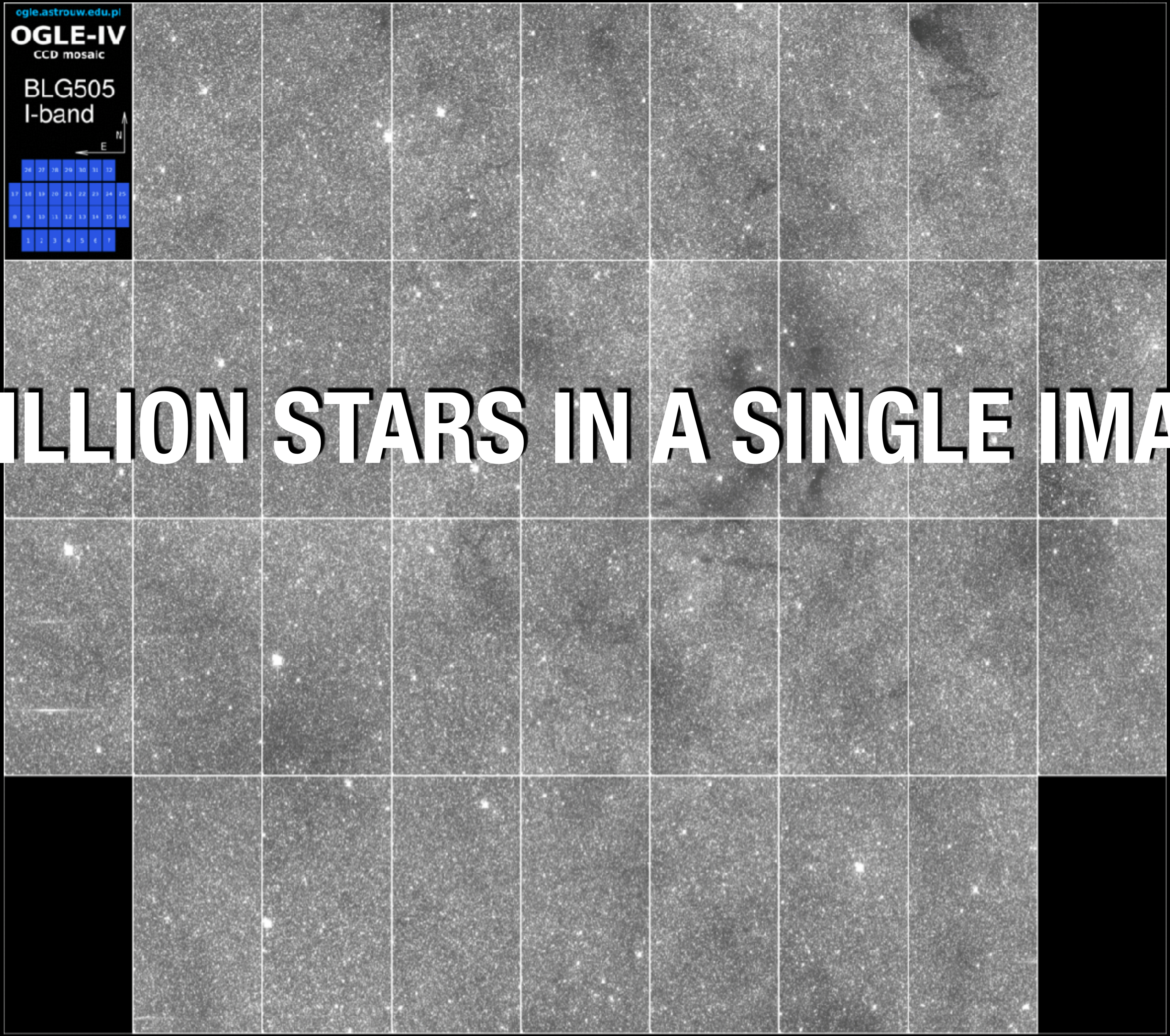






Udalski et al. 2002, Bond et al. 2004, Cassan et al. 2012, Sumi et al. 2011, Mroz et al. 2017

5 MILLION STARS IN A SINGLE IMAGE!



Black hole detection

Astrometry

Orbit usually smaller than instrument resolution: model photo-centre of the system.

Credit: ESA, link to video

Black hole detection

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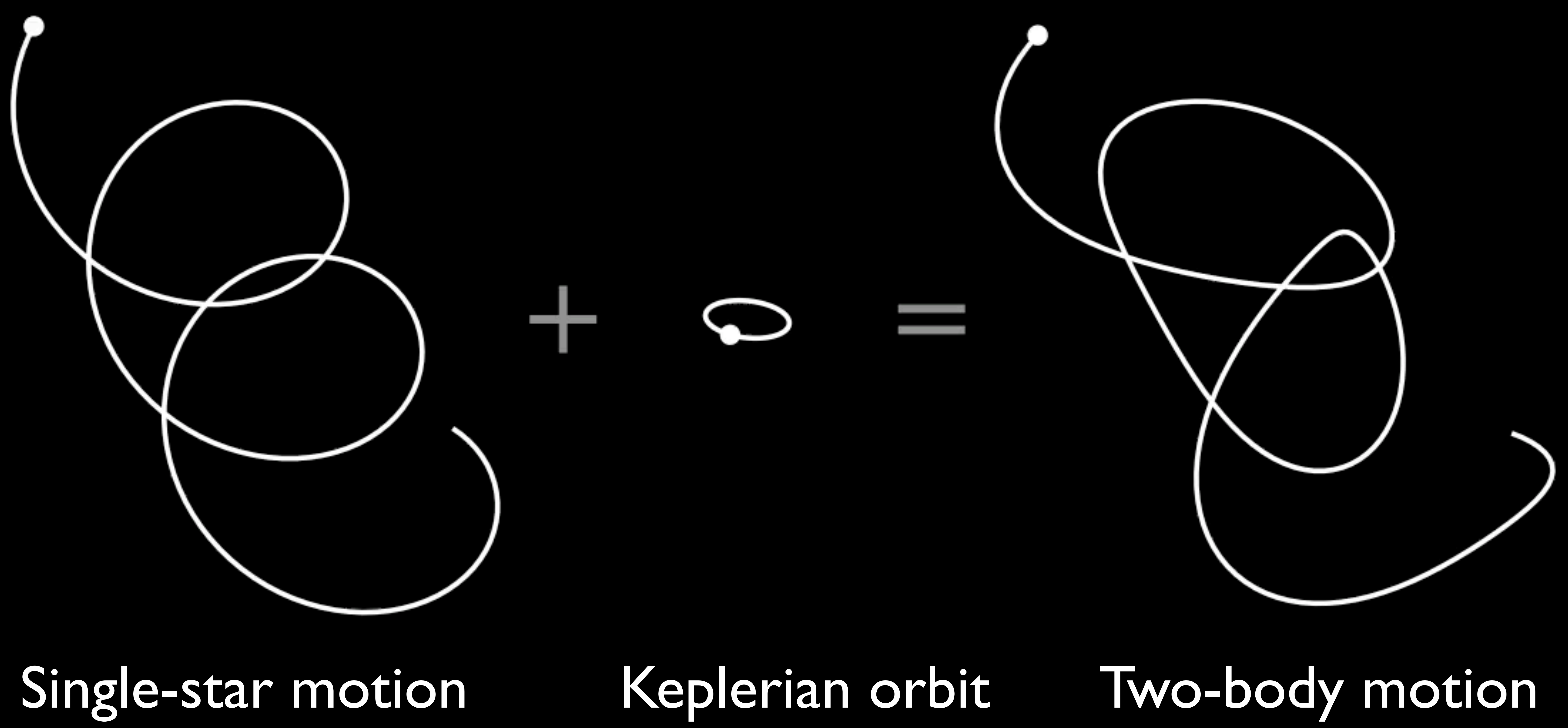


Orbit usually smaller than instrument resolution: model photo-centre of the system.

Credit: ESA/Gaia/DPAC/Johannes Sahlmann, link to video

Black hole detection

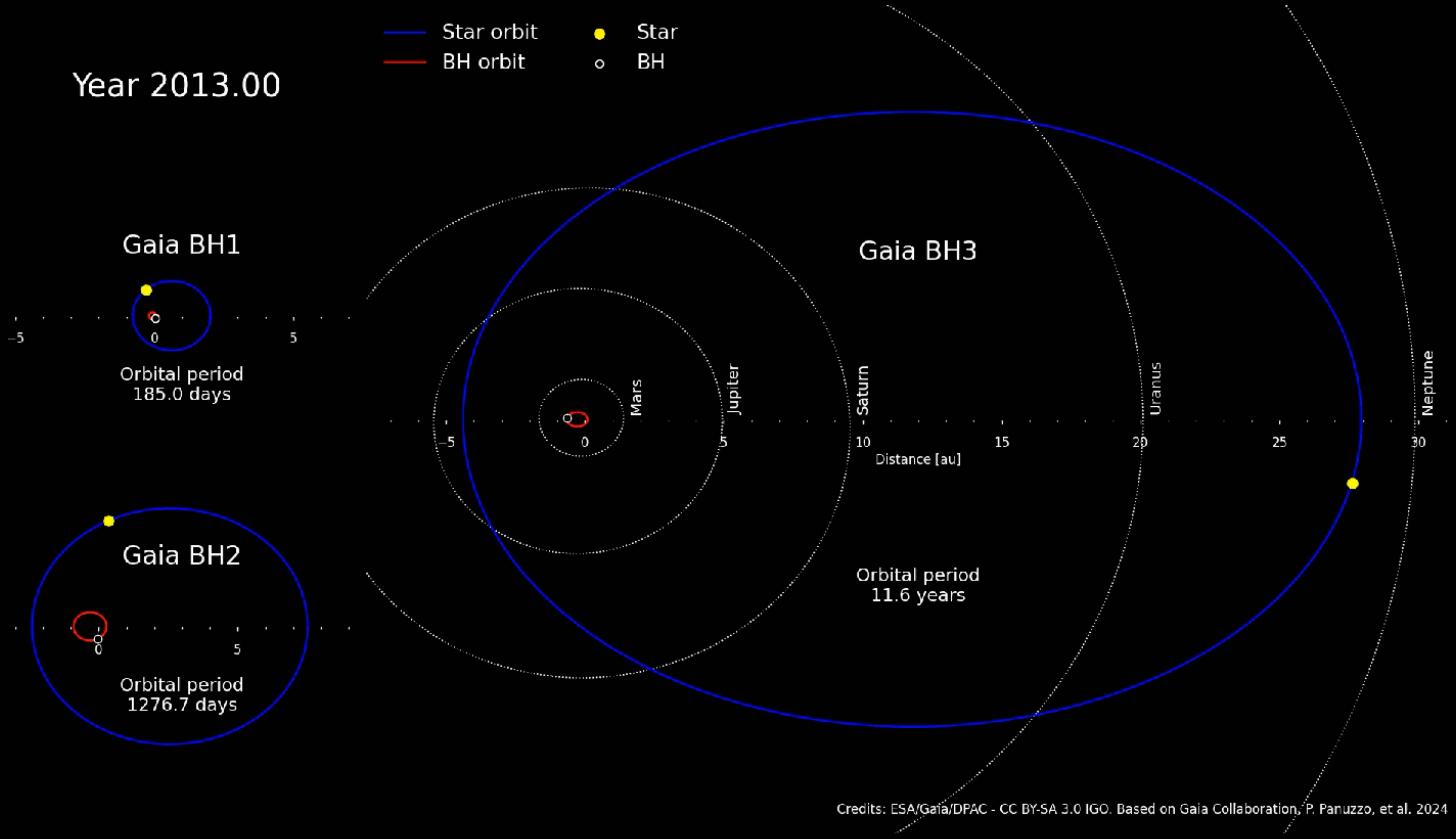
Astrometry orbit

$$\alpha = \left(\frac{M_{\rm BH}}{M_*}\right)\left(\frac{a}{1\ \rm au}\right)\left(\frac{1\ \rm pc}{d}\right)\ \rm arcsec$$

Large signal when $M_{\rm BH} \gg M_*$: typical BH system!

Credit: ESA/Gaia/DPAC/Johannes Sahlmann, link to video

Gaia BH 1, 2, 3 orbits



Stellar remnant black holes

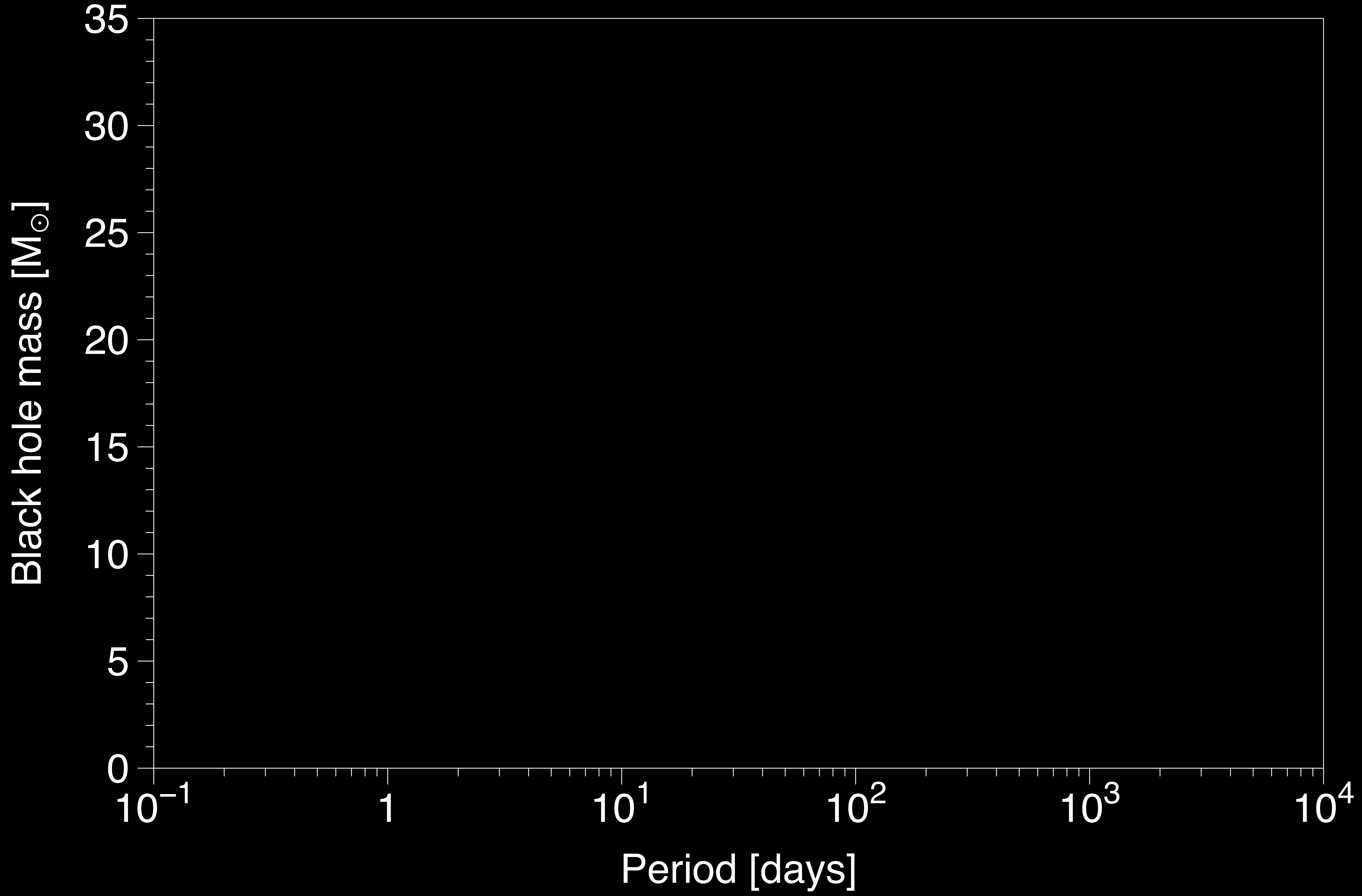
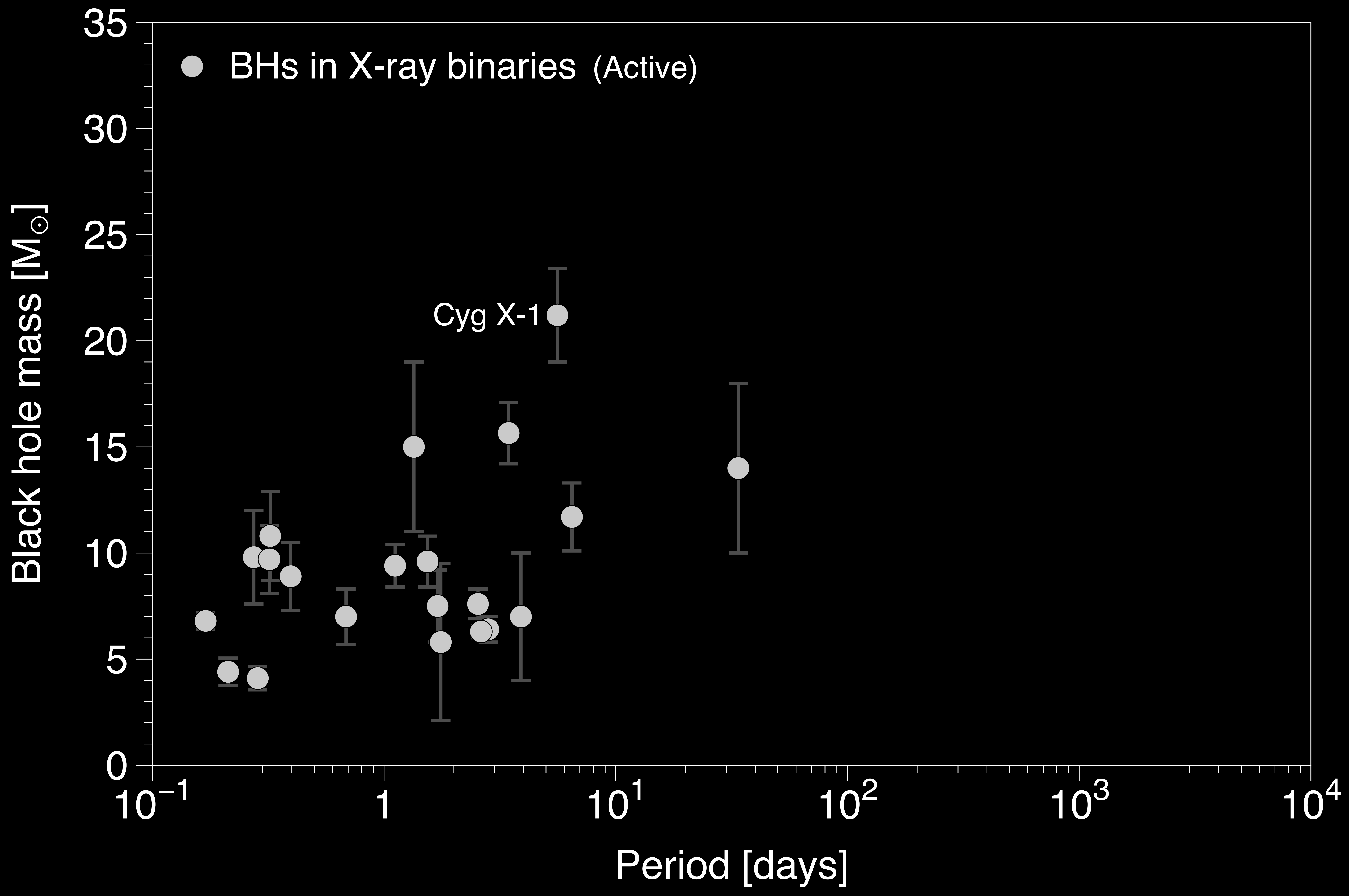


Figure adapted from Pasquale Panuzzo and Tsevi Mazeh

Stellar remnant black holes



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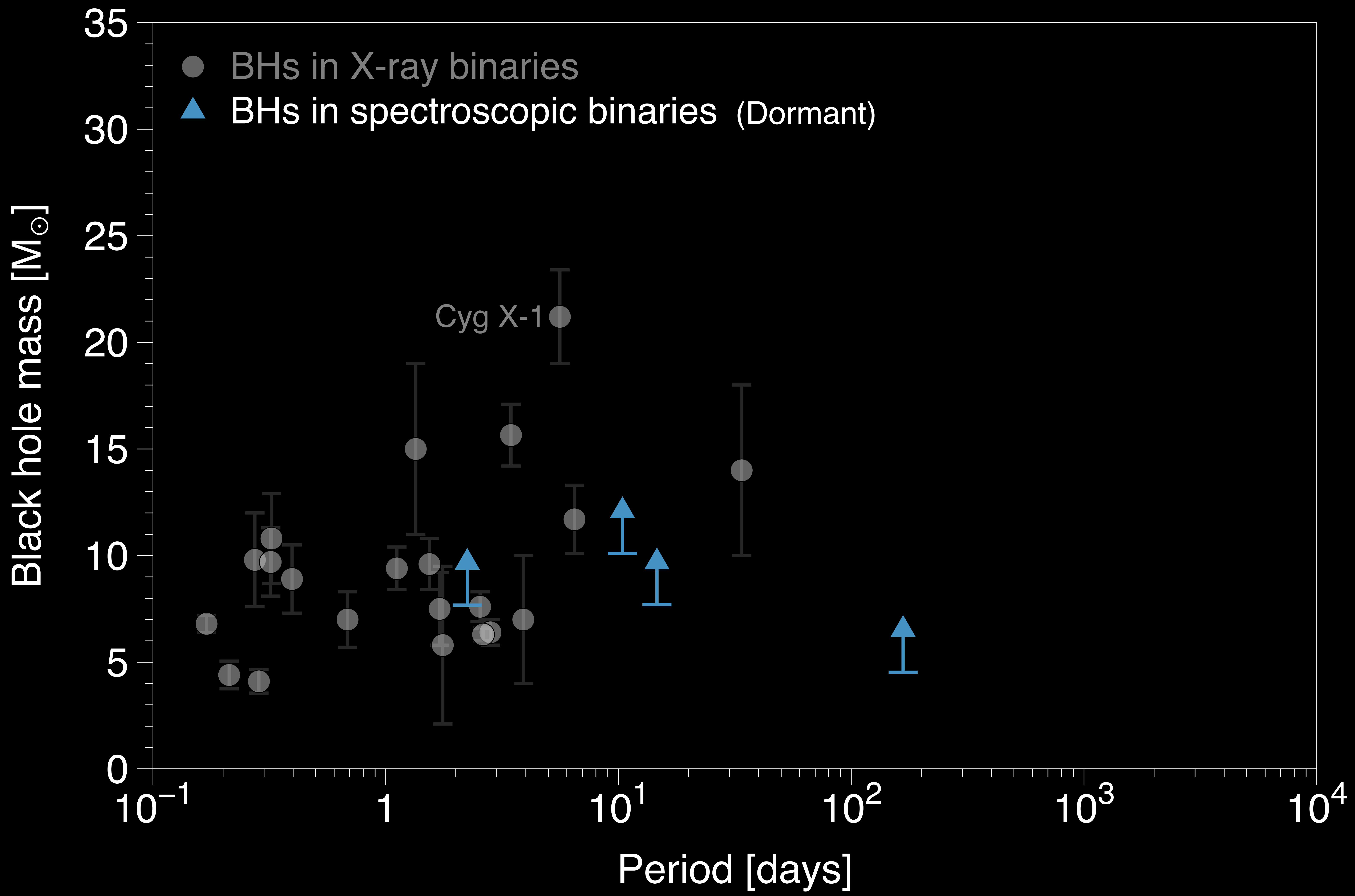

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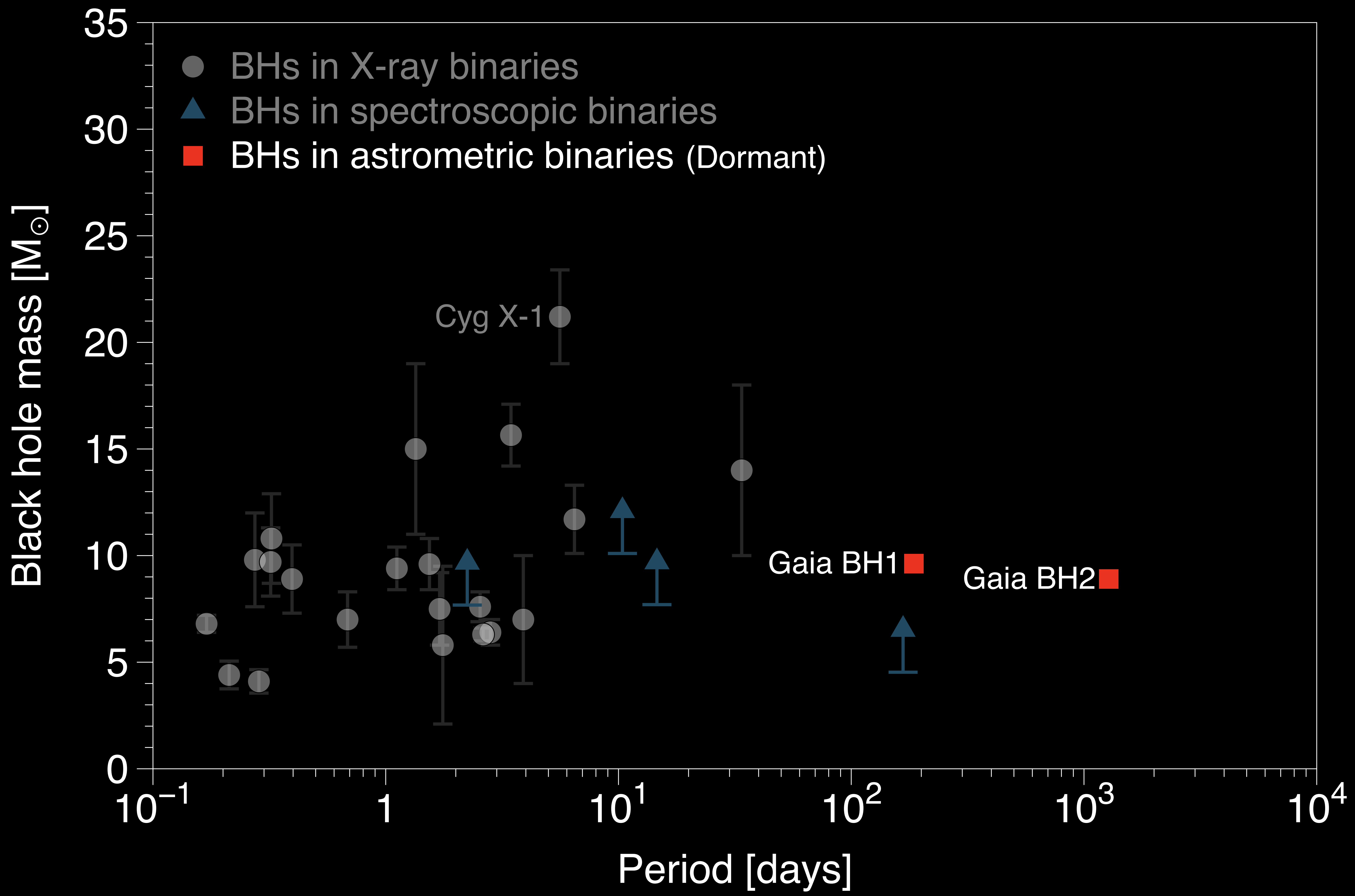

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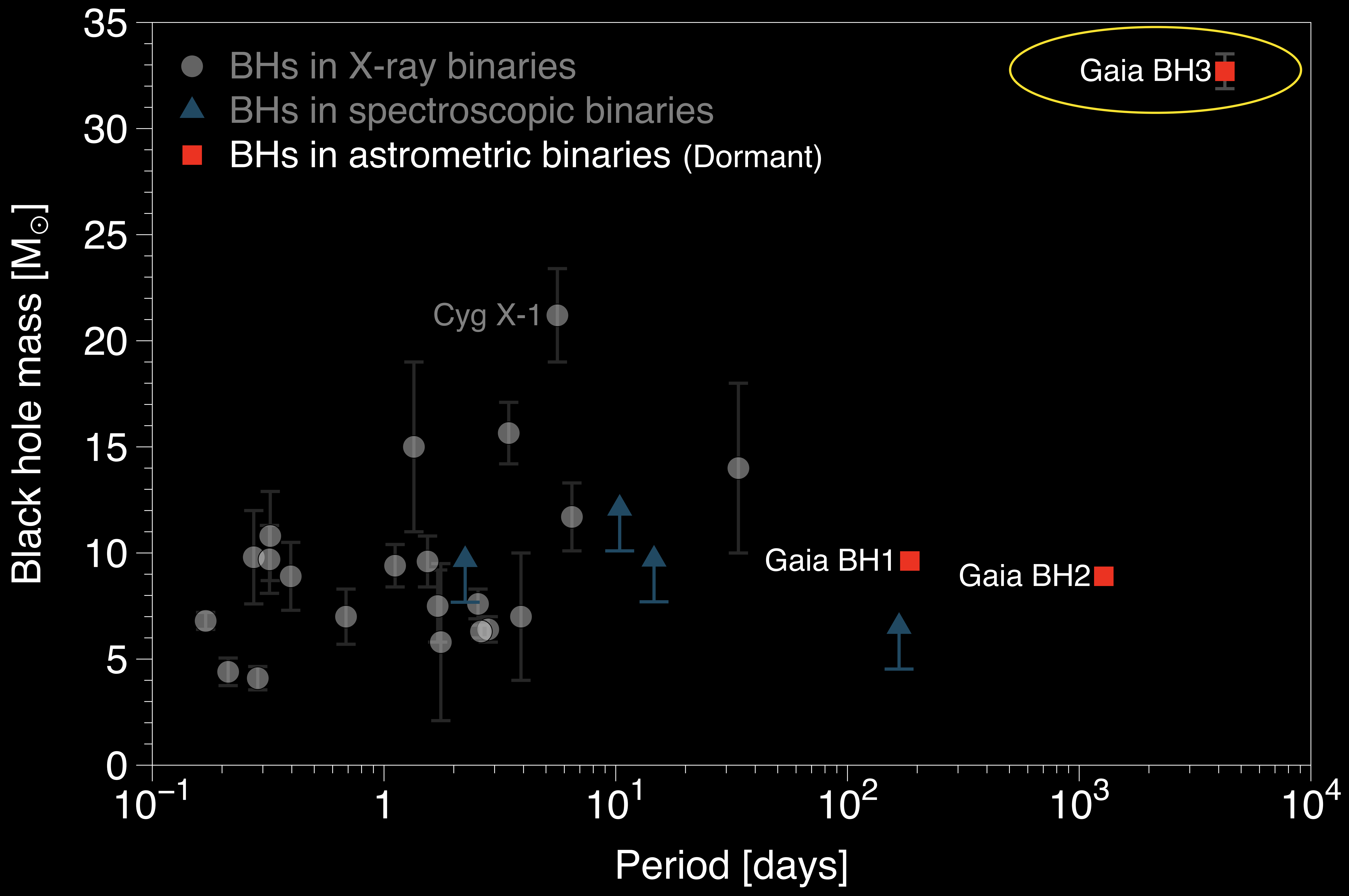

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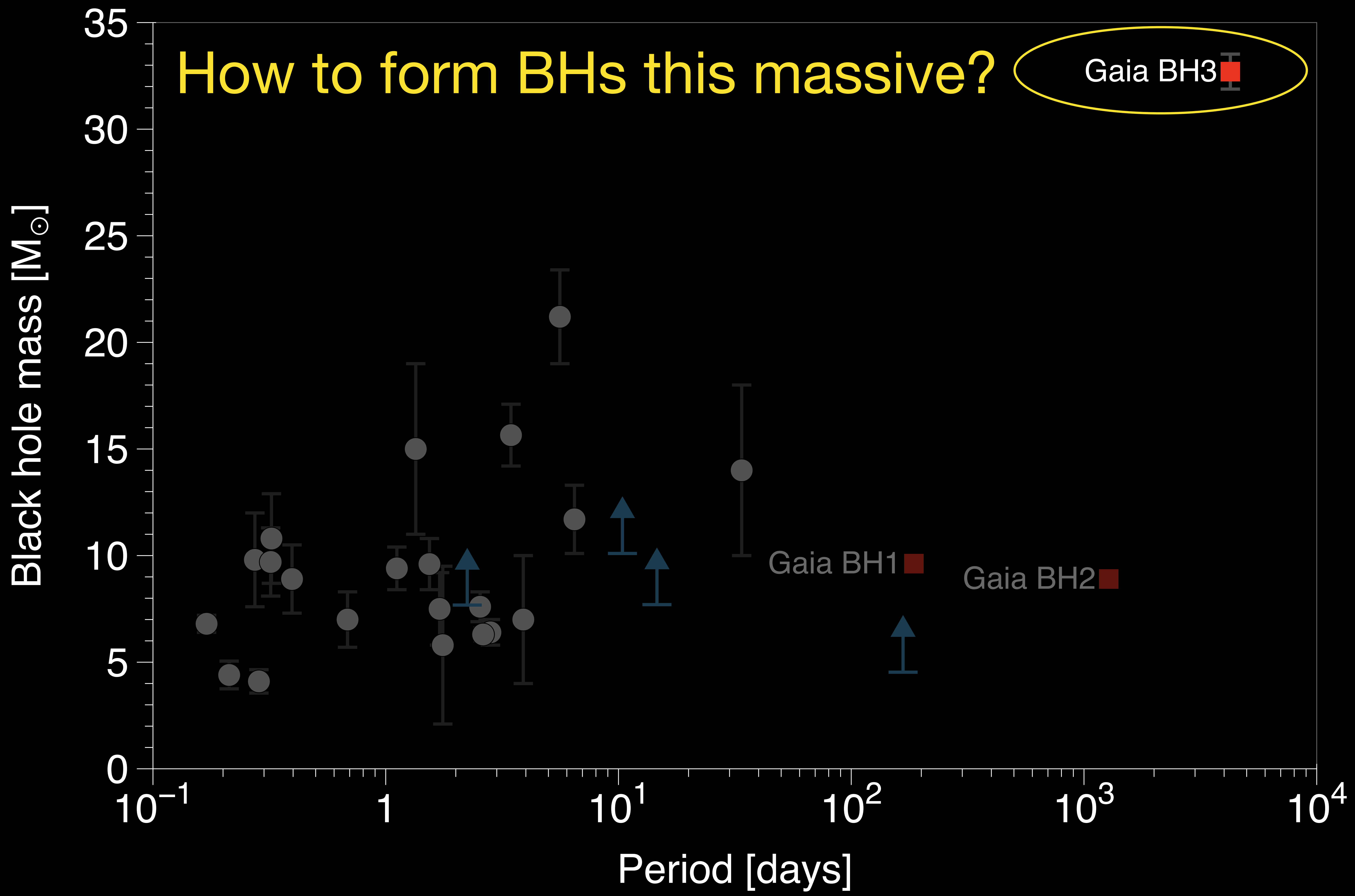
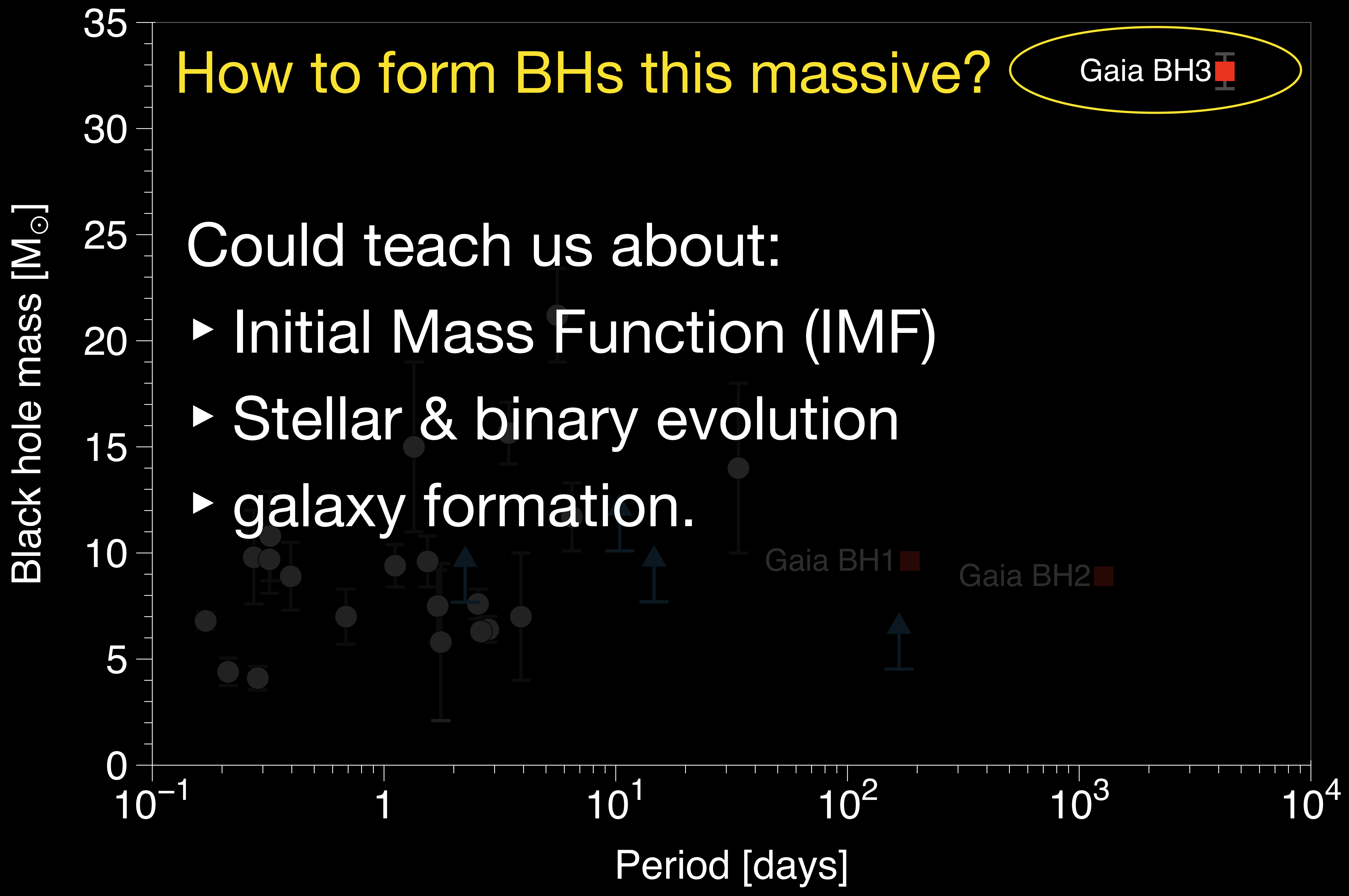


How to form BHs this massive?
Gaia BH3
Gaia BH1
Gaia BH2
Black hole mass [$M_\odot$]
Period [days]
0
5
10
15
20
25
30
35
10^{-1}
1
10^1
10^2
10^3
10^4


How to form BHs this massive?
Gaia BH3
Could teach us about:
▸ Initial Mass Function (IMF)
▸ Stellar & binary evolution
▸ galaxy formation.
Gaia BH1
Gaia BH2
Black hole mass [M$_\odot$]
35
30
25
20
15
10
5
0
10^{-1}
1
10^1
10^2
10^3
10^4
Period [days]

Multiple BH mass regimes

Do we expect a high mass regime?
➜ Gravitation wave data suggests yes!

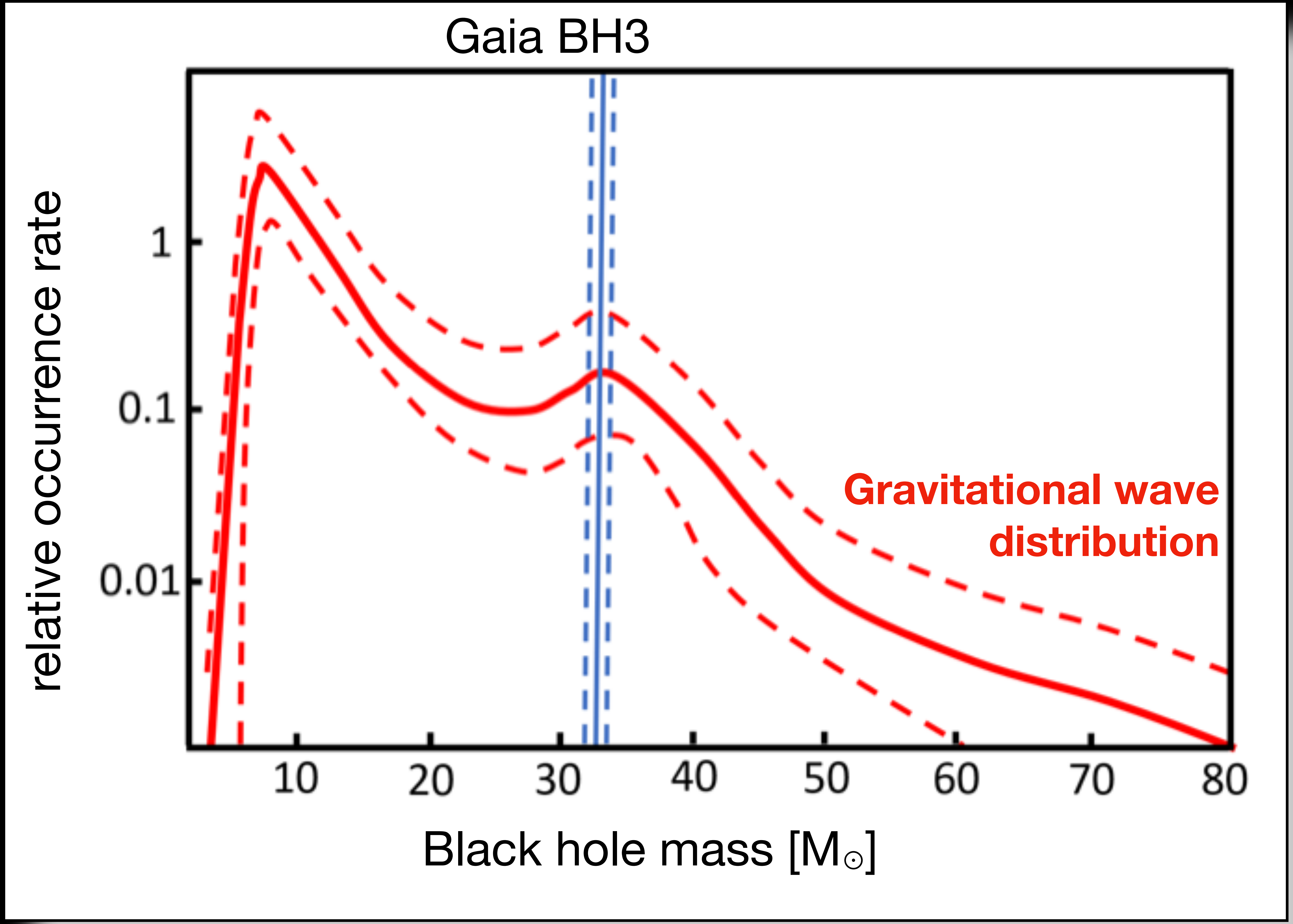


Figure credits: Adapted from Abott et al. Phys. Rev. 2023 by Uli Bastian, ESA/Gaia/DPAC.

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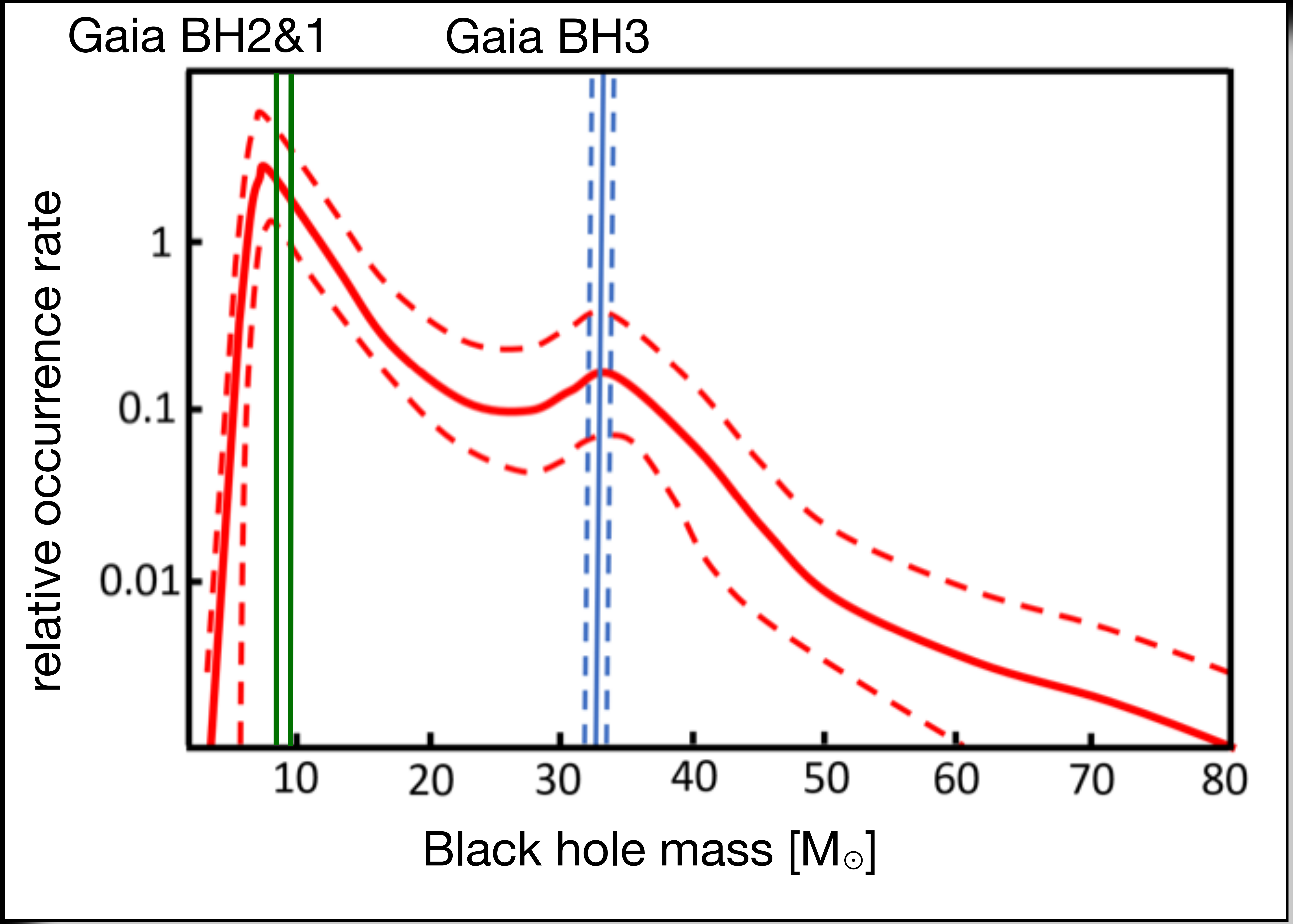

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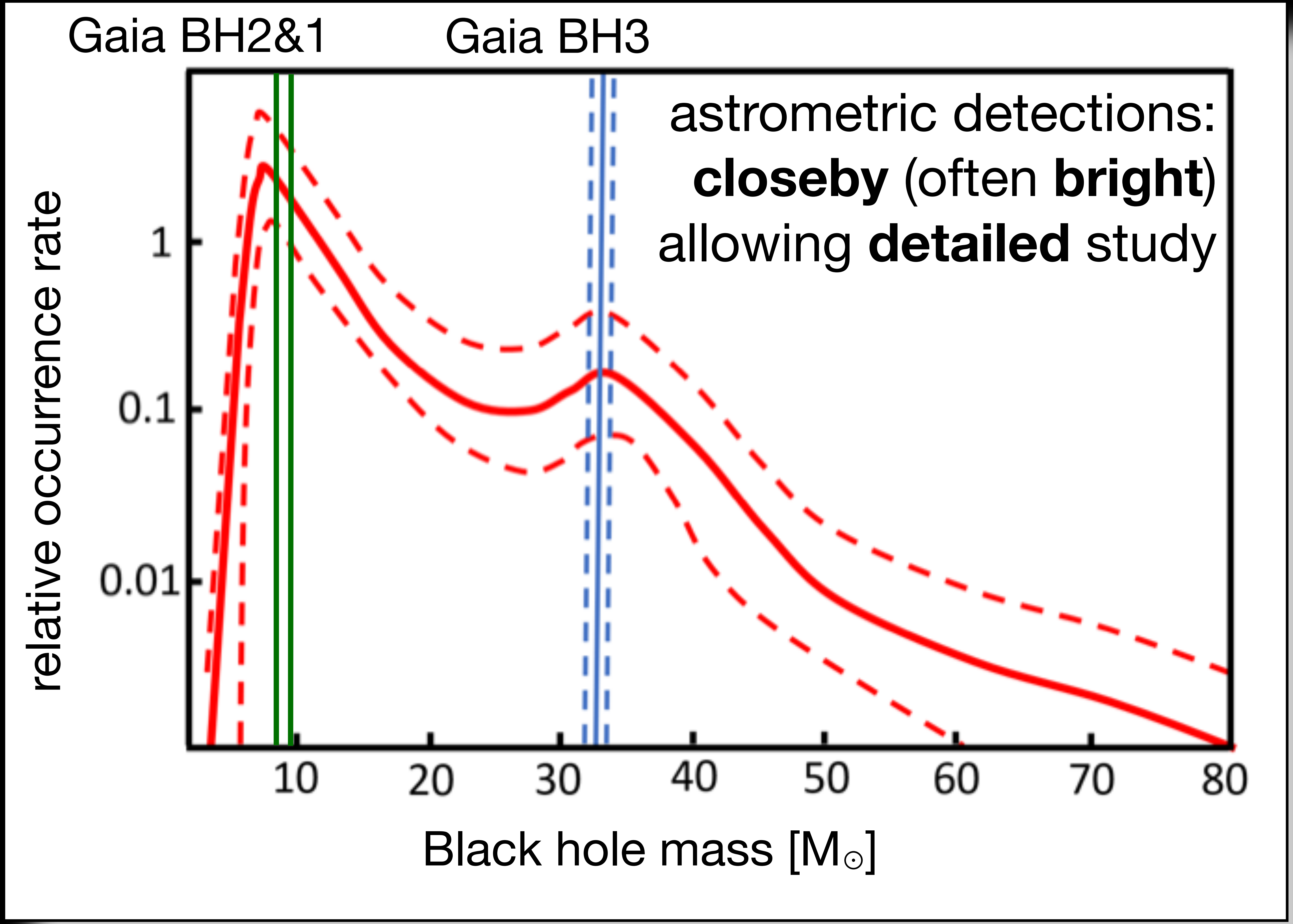

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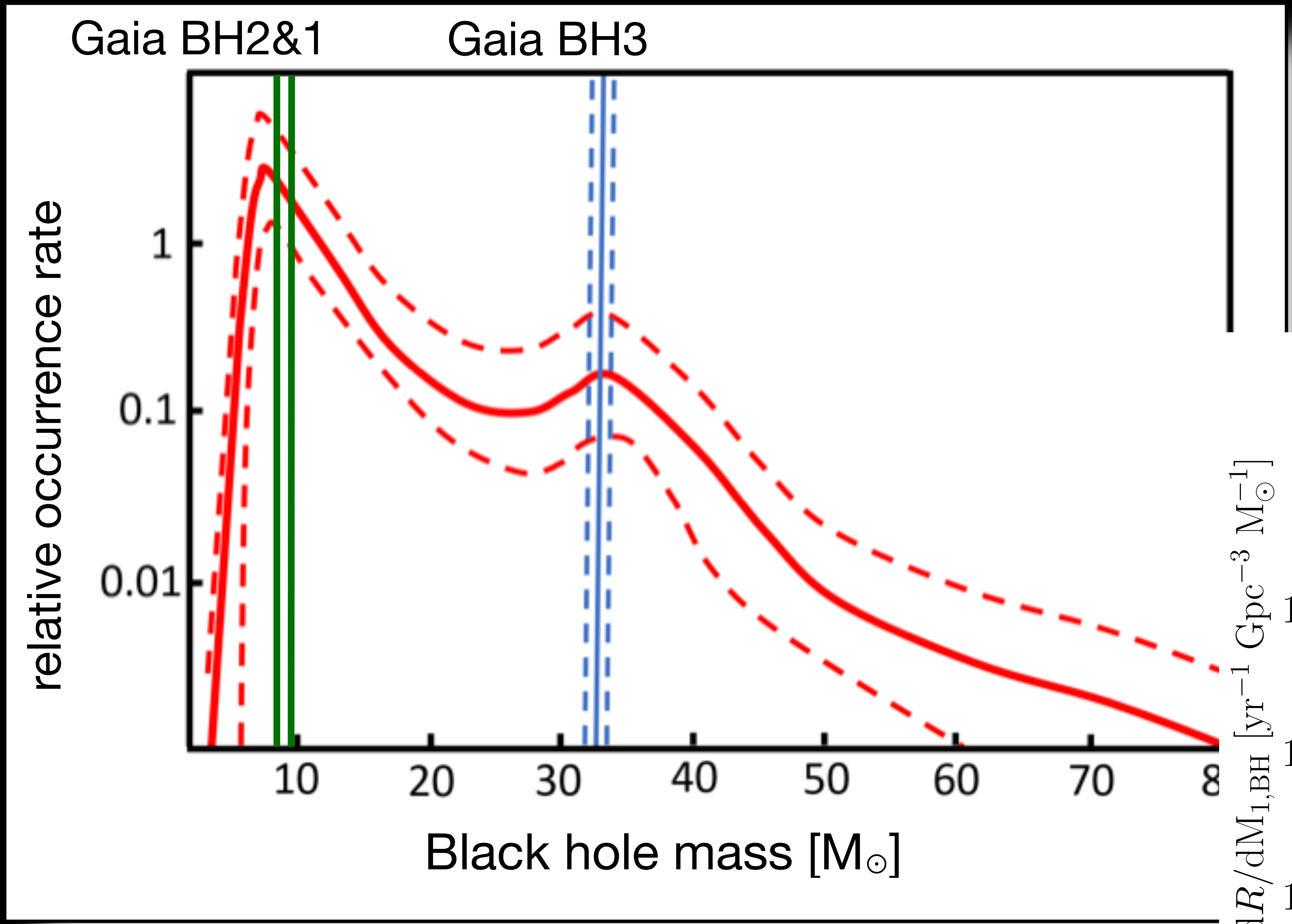
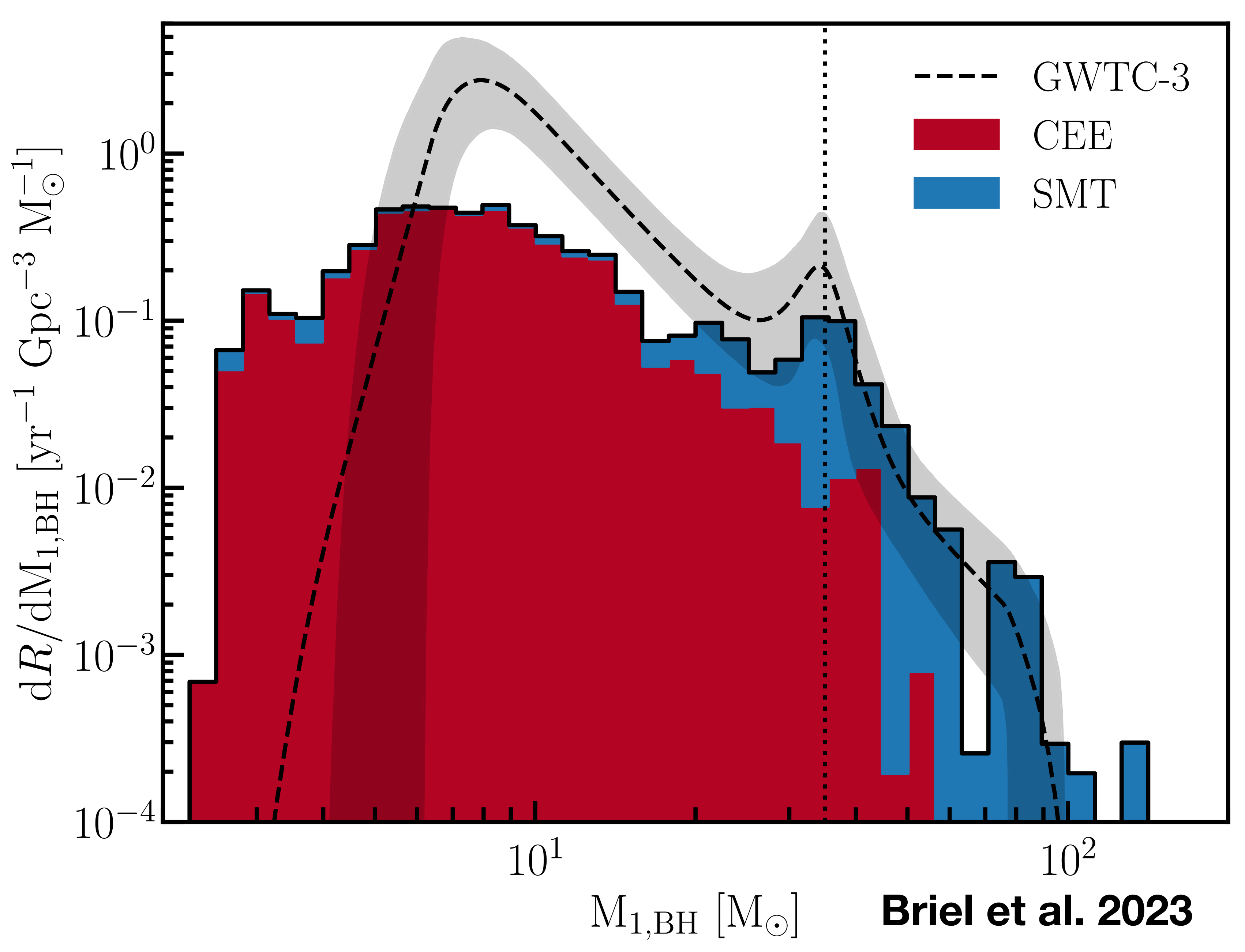
Gaia BH3: binary evolution models

Binary evolution

Can BH3 teach us something about binary evolution?



Second peak:
Accretion onto lower mass BHs could perhaps do the trick!



Briel et al. 2023

Slide credit Anastasios Fragkos

Gaia BH3

One possible story...

1. Gaia BH3 formed from single massive very metal poor star,

2. Interacted heavily with others in a globular cluster
   and/or was in 3-body system,

3. finally paired up with a 0.76 $M_\odot$ companion
   having no chemical enrichment.

Slide credit Anastasios Fragkos & Sylvia Ekström

Gaia BH3: binary evolution models

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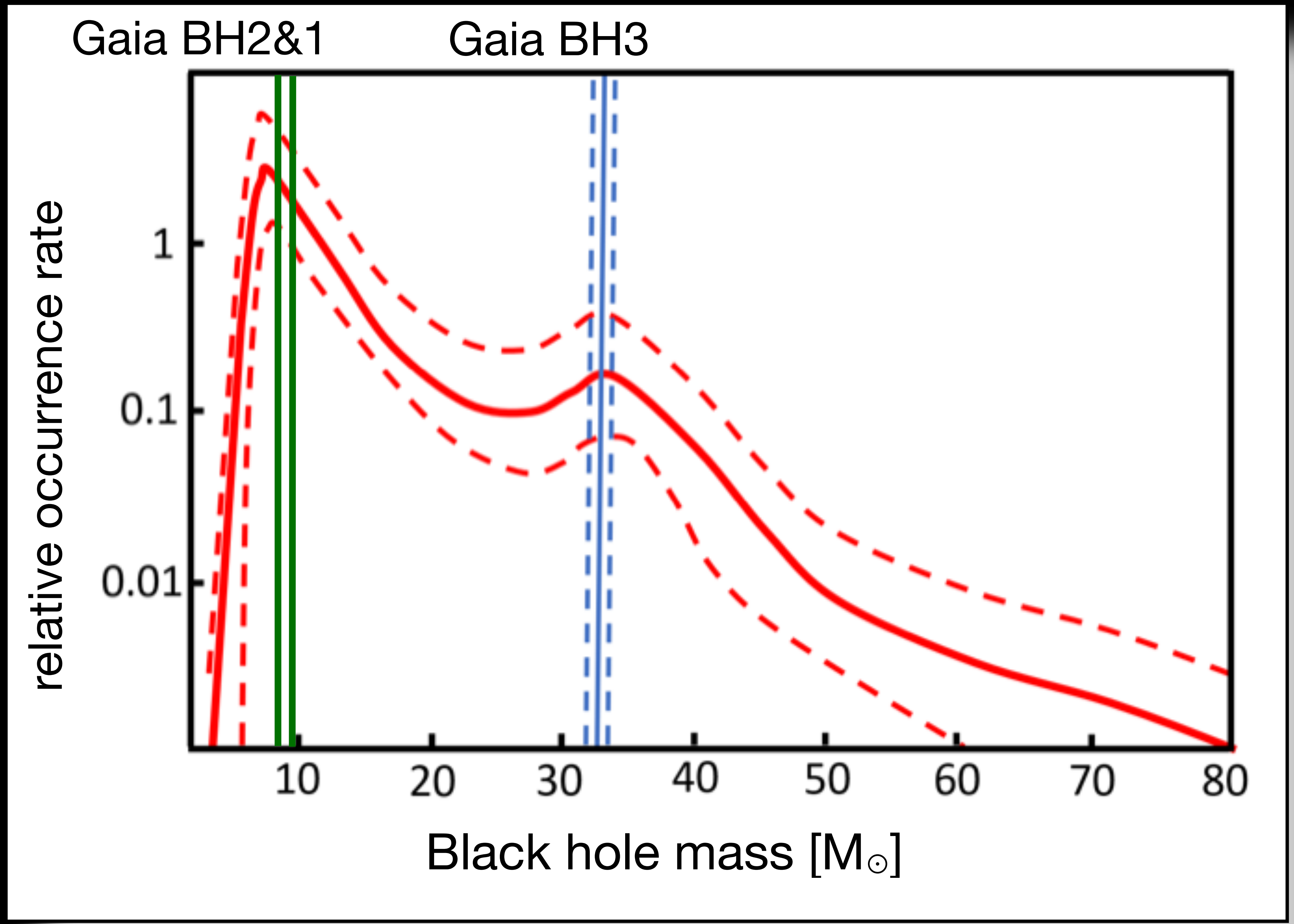

Origin of BH1 and 2:
Stars above 80 $M_\odot$
(at solar metallicity)
skip giant phase and
become WR:
losing lots of mass.

Resulting remnants:
10-12 $M_\odot$ BH

Slide credit Anastasios Fragkos

Gaia BH3: binary evolution models

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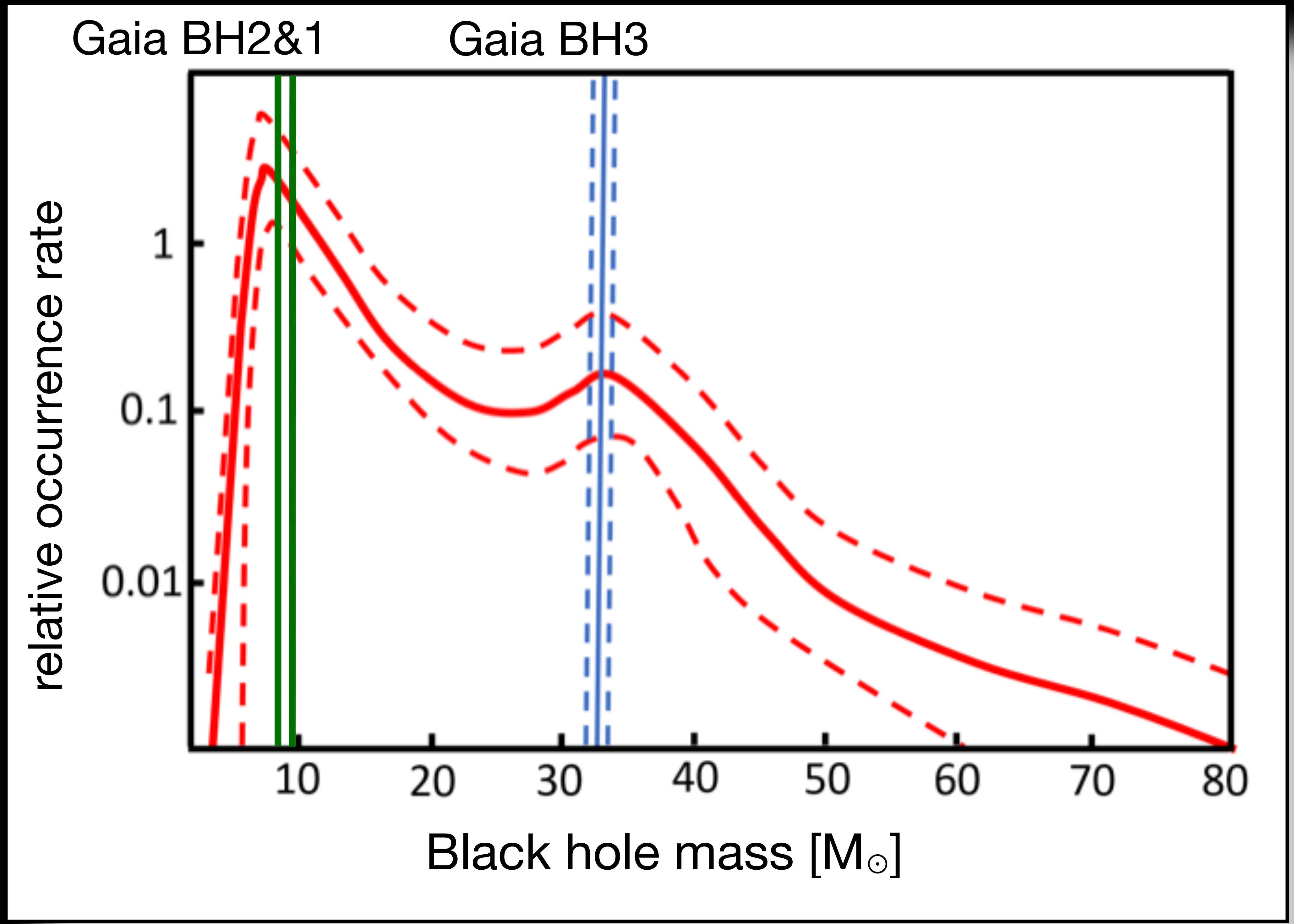


Second peak:
Pulsational pair instability disrupts stars when they are too massive

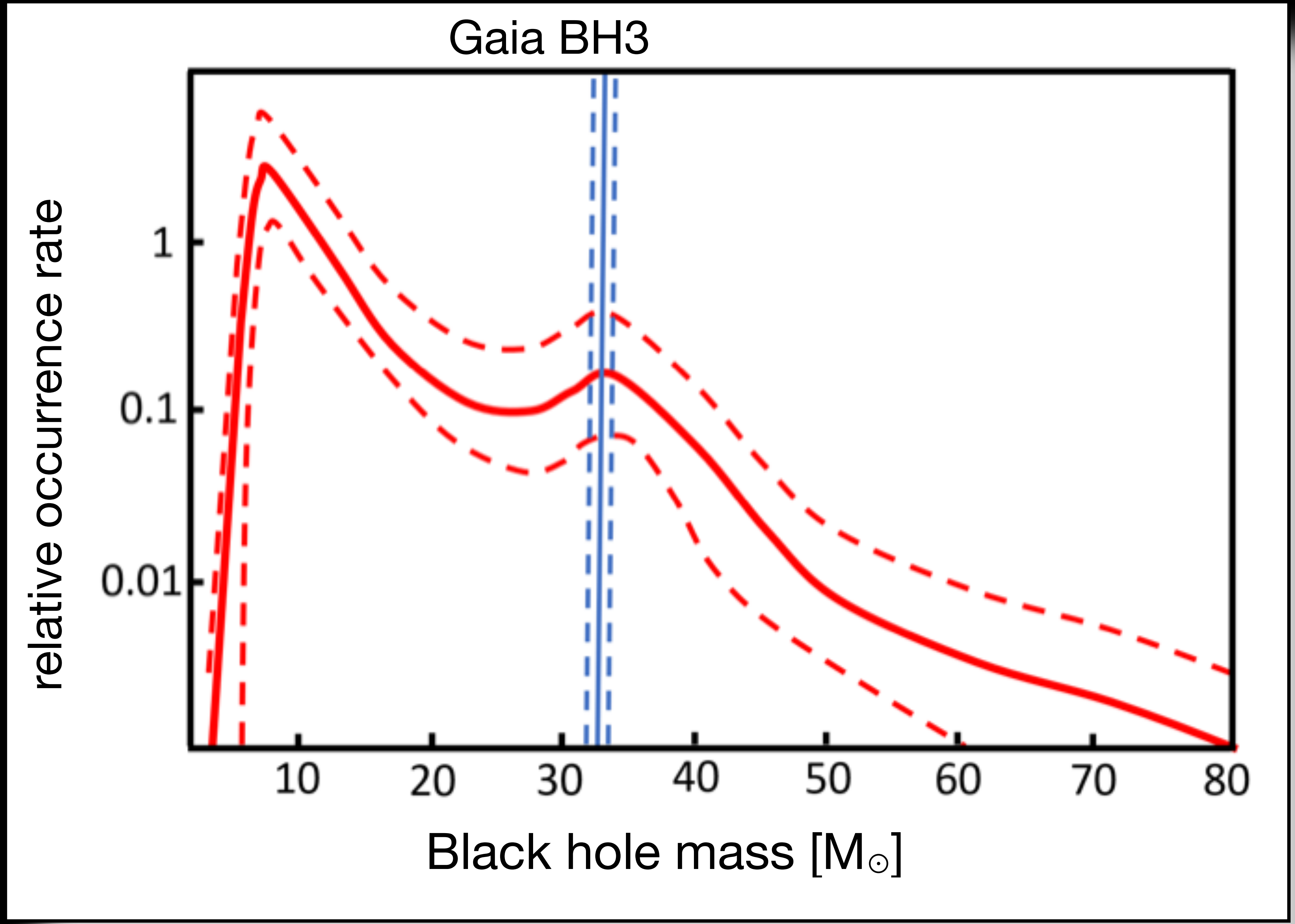
Resulting remnants:
<45 $M_{\odot}$ BH

But not though to really be responsible for this peak.

Gaia BH3: binary evolution models

Binary evolution

Question: could second (GW) peak come primarily from mergers of sources from those in the lower peak?



Answer:
probably not, as in GW data you can deduce spin information, and the second peak would have then usually very high spin as it absorbs the angular orbital momentum of the merging binary, and this is not observed in general for second peak GW sources.

Slide credit Anastasios Fragkos

Gaia BH3: clues for its origin

From the companion:

- Galactic orbit in **halo**
- moving in **opposite direction to Galactic disk stars** (high-energy retrograde orbit)
- **very low metallicity** ([Fe/H] = −2.56 ± 0.11)
- **very old** (>12Gyr)
- **normal chemical abundances** (→ no pollution from a companion)

It supports, for the first time, the idea that the high-mass black holes observed by gravitational wave experiments were produced by the collapse of primaeval massive stars that are poor in heavy elements.

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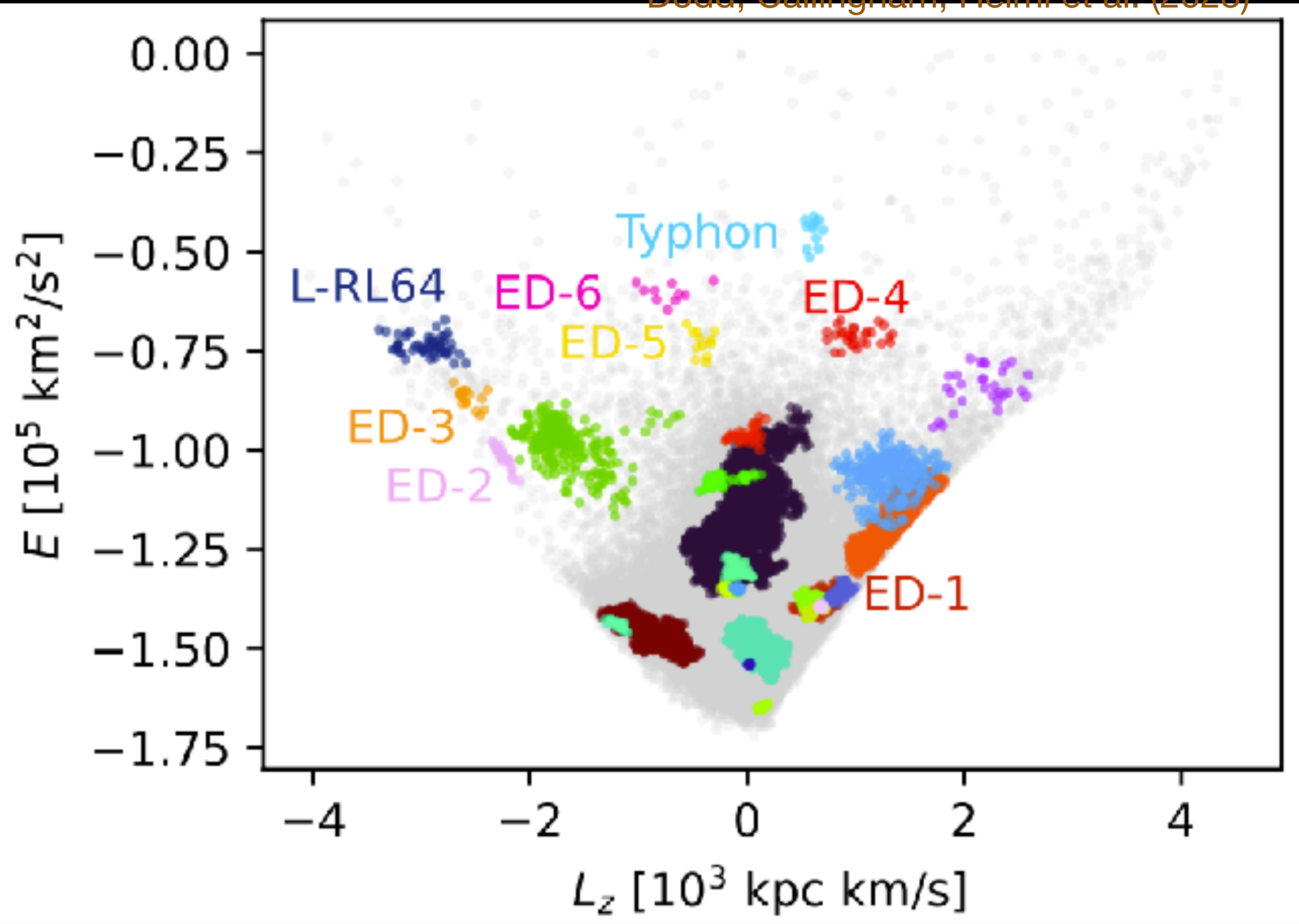
Galactic substructures

Dodd, Callingham, Helmi et al. (2023)



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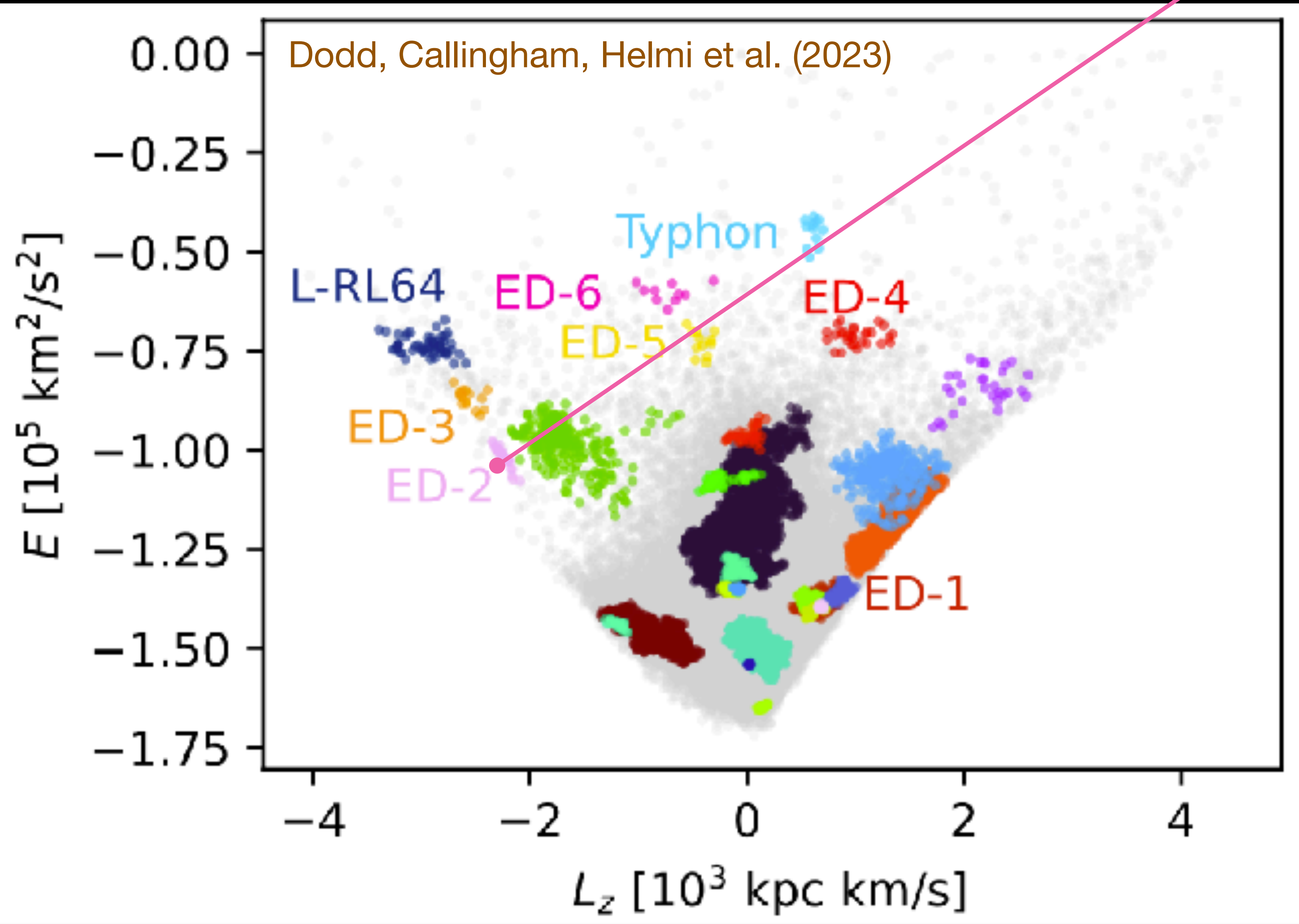
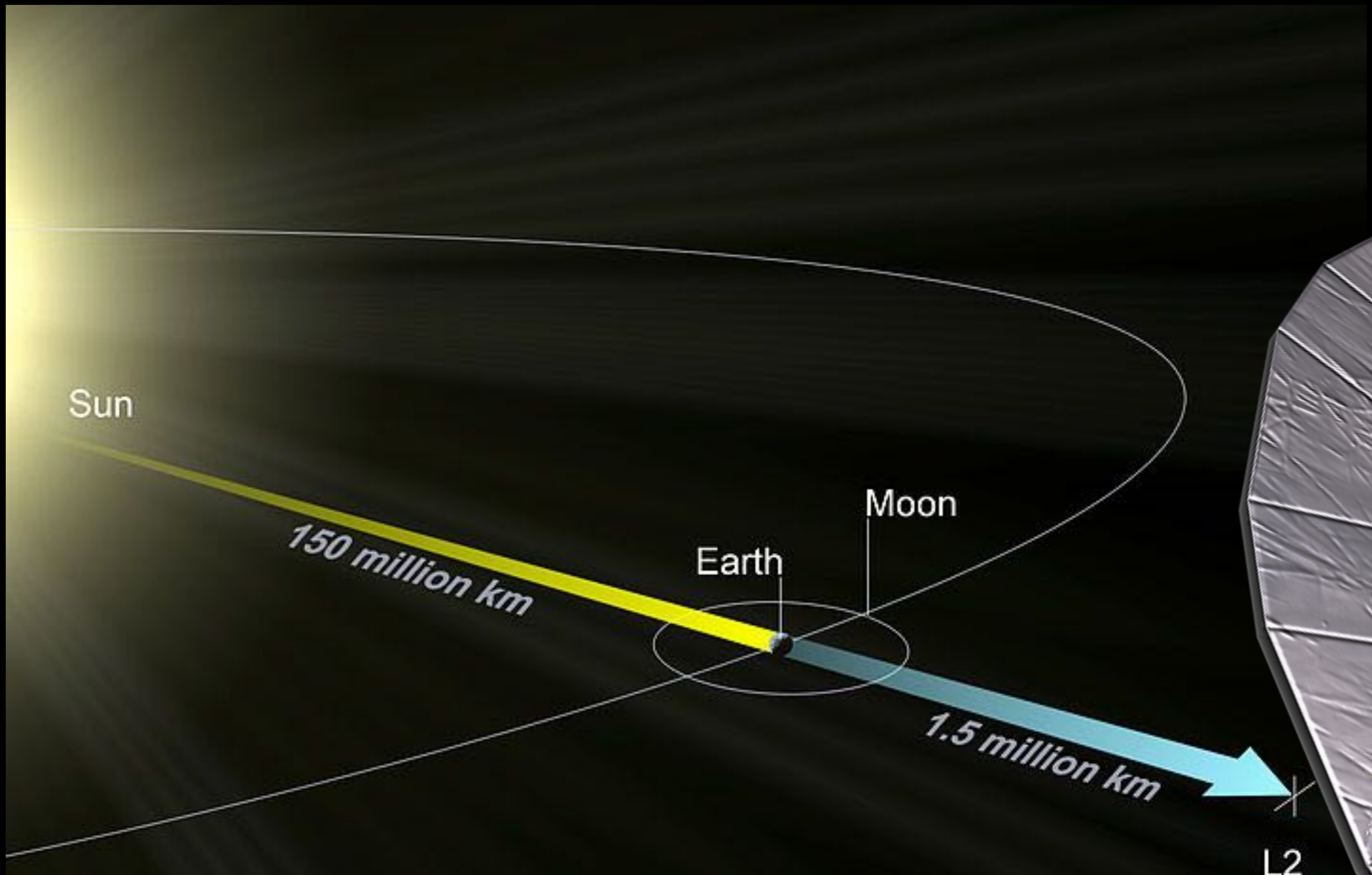


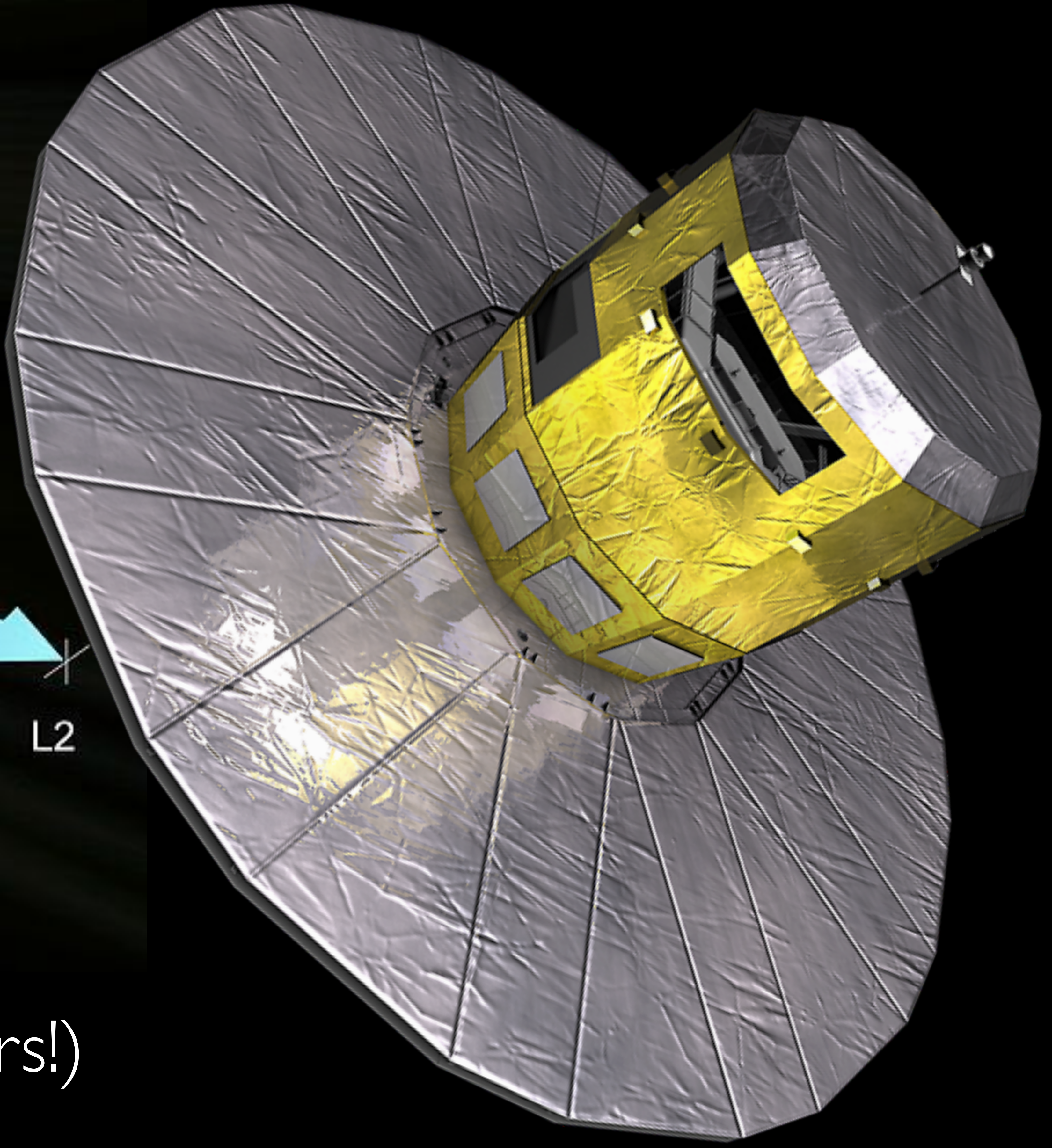
Compatible with ED-2 halo stream
(which also has median [Fe/H] = –2.6 ± 0.2 !)

ED-2 is the **remnant of a Globular Cluster**

→ Has Gaia BH3 been accreted in a binary system due to cluster dynamics?

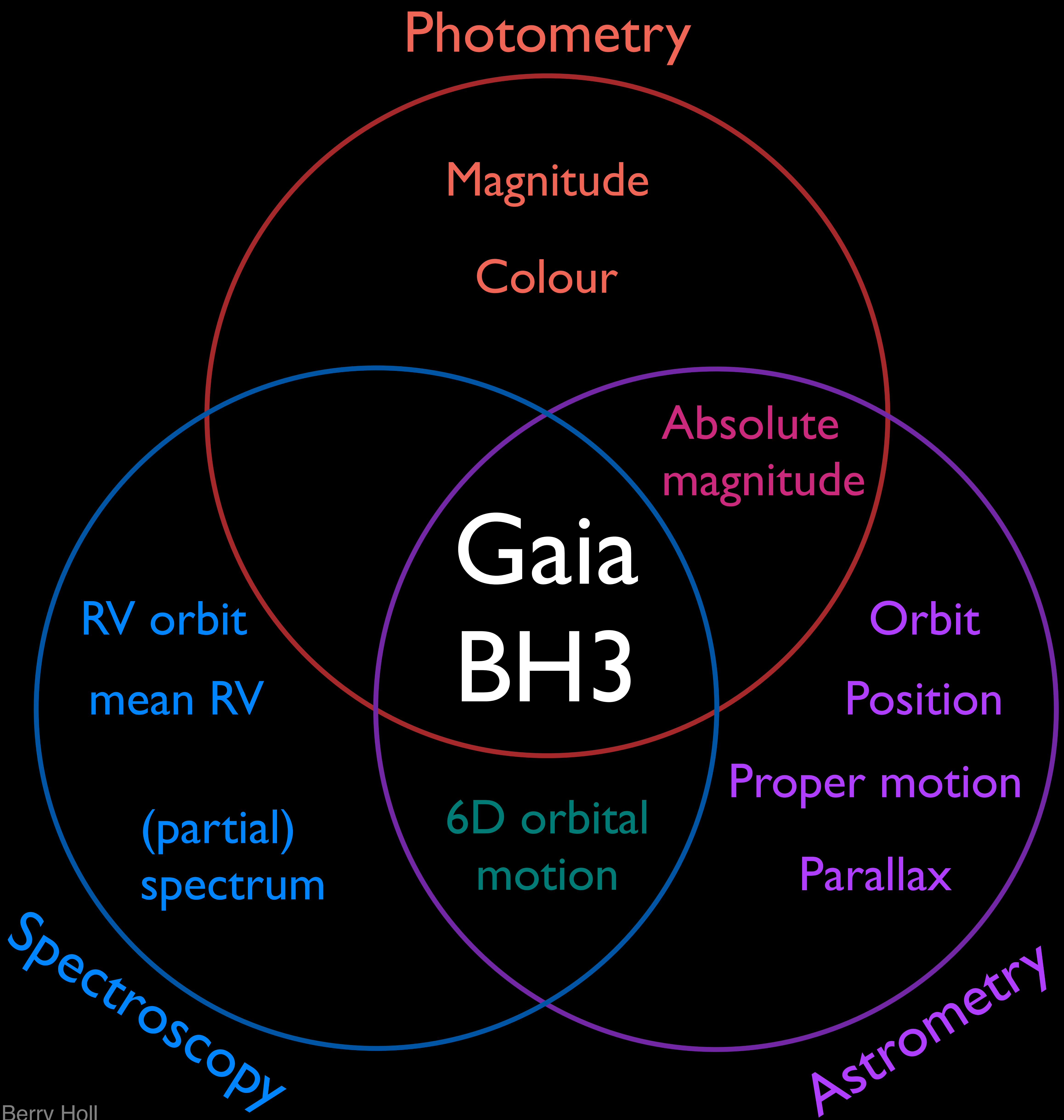
Two billion star mission





- Launched: 19 Dec 2013
- Orbit: around L2 Lagrange point
- Operations: Jul 2014 - Jan 2025 (10+ years!)

Multi-domain measurements



Gaia BH3 observations