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A 33 solar mass black hole discovered in GAIA!

Letter to the Editor

Discovery of a dormant 33 solar-mass black hole in pre-release Gaia astrometry★

Gaia Collaboration: P. Panuzzo[1**], T. Mazeh[2], F. Arenou[1], B. Holl[3,4], E. Caffau[1], A. Jorissen[5], C. Babusiaux[6], P. Gavras[7], J. Sahlmann[7], U. Bastian[8], Ł. Wyrzykowski[9], L. Eyer[3], N. Leclerc[1], N. Bauchet[1], A. Bombrun[10], N. Mowlavi[3], G.M. Seabroke[11], D. Teyssier[12], E. Balbinot[13,14], A. Helmi[13], A.G.A. Brown[14], A. Vallenari[15], T. Prusti[16], J.H.J. de Bruijne[16], A. Barbier[17], M. Biermann[8], O.L. Creevey[18], C. Ducourant[19], D.W. Evans[20], R. Guerra[21], A. Hutton[22], C. Jordi[23,24], S.A. Klioner[25], U. Lammers[21], L. Lindegren[26], X. Luri[23,27,24], F. Mignard[18], C. Nicolas[17], S. Randich[28], P. Sartoretti[1], R. Smiljanic[29], P. Tanga[18], N.A. Walton[20], C. Aerts[30,31,32], C.A.L. Bailer-Jones[32], M. Cropper[11], R. Drimmel[33], F. Jansen[34], D. Katz[1], M.G. Lattanzi[33,35], C. Soubiran[19], F. Thévenin[18], F. van Leeuwen[20], R. Andrae[32], M. Audard[3], J. Bakker[21], R. Blomme[36], J. Castañeda[37,23,24], F. De Angeli[20], C. Fabricius[24,23,27], M. Fouesneau[32], Y. Frémat[36], L. Galluccio[18], A. Guerrier[17], U. Heiter[38], E. Masana[24,23,27], R. Messineo[39], K. Nienartowicz[40,4], F. Pailler[17], F. Riclet[17], W. Roux[17], R. Sordo[15], G.

ESA Press release: https://www.esa.int/Science_Exploration/Space_Science/Gaia/Sleeping_giant_surprises_Gaia_scientists

These are some of the summary conclusions/findings of Gaia BH3. Some of the most interesting highlights: that the system has a high eccentricity of ~ 0.7 (this is thought to be unlikely for systems that went through common envelope evolution). And that the [Fe/H] fraction is low: -2.6 which is a metallicity of Z= 10^-2.6 x Z_sun = 0.00003!!

$32.70 \pm 0.82\ M_\odot$ BH   **11.6 yr** period

the visible component is an old, very metal-poor giant (G-star, climbing the giant-branch) of the Galactic halo, at a distance of **590 pc**

Conclusions:

1. Gaia BH3 system is most massive Galactic stellar-origin BH known thus far! (2nd: Cyg X-1; MILLER-JONES 2021; ~20 MSUN)
2. The low metallicity of Gaia BH3 star (Z~0.00003) supports theory that metal-poor massive stars are progenitors of the high-mass BHs detected by gravitational-waves.
3. The Galactic orbit of the system and its metallicity indicate that it might belong to the Sequoia halo substructure.
4. Alternatively, and more plausibly, it could belong to the ED-2 stream, which likely originated from a globular cluster that had been disrupted by the Milky Way :)

We inspected ASAS-SN, ZTF, and TESS photometry, finding that the source does not present any significant periodic variability. The source was not observed with XMM-Newton, Chandra nor GALEX, nor it is present in the RAVE, APOGEE, LAMOST, or GALAH spectroscopic surveys. No eROSITA data have been made available yet for Gaia BH3, which belongs to the eastern Galactic hemisphere

Table 2. Campbell orbital elements of the *Gaia* BH3 system and the astrometric parameters of its barycentre.

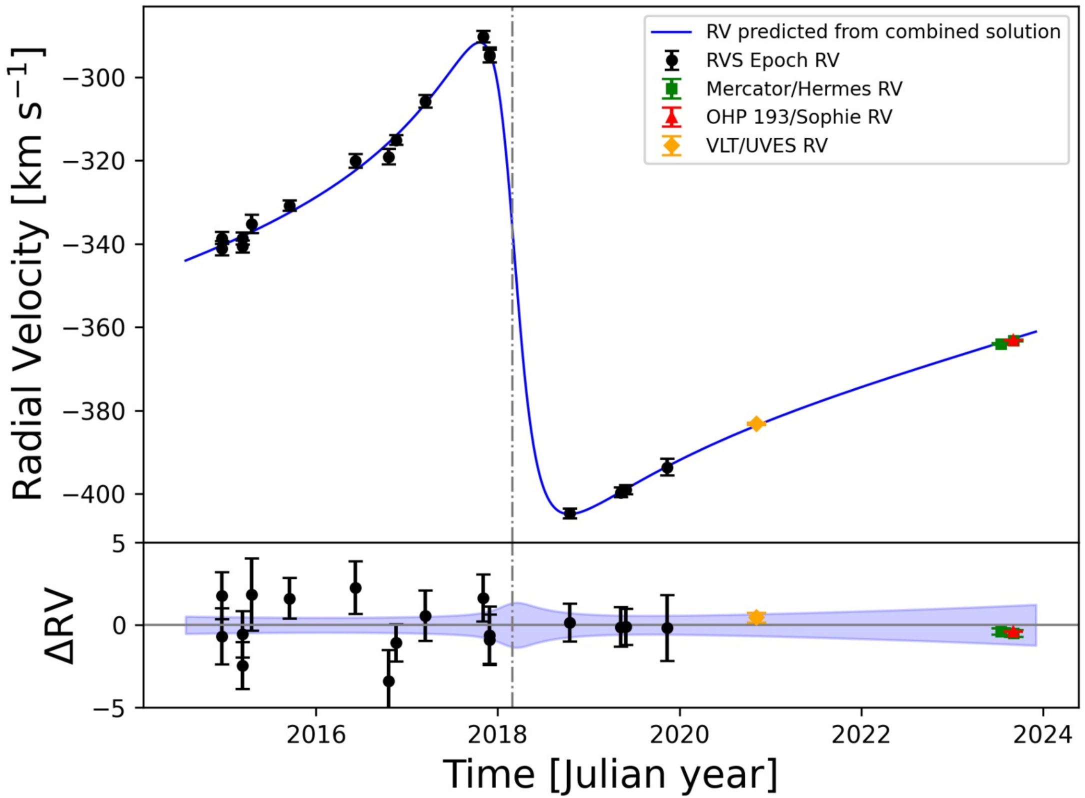
Parameter	Astrometric solution	Combined solution
α [deg]	294.8278502411[a]	294.8278502301[a]
σ_{α^*} [mas]	0.060	0.054
δ [deg]	14.9309190720[a]	14.9309190869[a]
σ_δ [mas]	0.086	0.074
ϖ [mas]	1.6747 ± 0.0094	1.6933 ± 0.0164[b]
μ^*_α [mas yr^{-1}]	-28.372 ± 0.077	-28.317 ± 0.067
μ_δ [mas yr^{-1}]	-155.150 ± 0.129	-155.221 ± 0.111
P [days]	4194.7 ± 112.3	4253.1 ± 98.5
e	0.7262 ± 0.0056	0.7291 ± 0.0048
a_0 [mas]	27.07 ± 0.56	27.39 ± 0.49
i [deg]	110.659 ± 0.107	110.580 ± 0.095
T_p [JD, TCB]	2458177.28 ± 0.98	2458177.39 ± 0.88
Ω [deg]	136.200 ± 0.147	136.236 ± 0.128
ω [deg]	77.77 ± 0.66	77.34 ± 0.76
a_1 [AU]	...	16.17 ± 0.27
γ [km s^{-1}]	...	-357.31 ± 0.44
f_M [$M_\odot$]	32.03 ± 0.64	31.23 ± 0.81
GoF	2.17	−0.53

Notes. [(a)] The reference epoch of DR4 coordinates is J2017.5 (JD 2457936.875). [(b)] Derived as a_0/a_1, see text.

Table 3. Stellar parameters of *Gaia* BH3 derived in this work.

Parameter	Value
$T_{\rm eff}$ [K]	5212 ± 80
$\log g$	2.929 ± 0.003
[Fe/H]	-2.56 ± 0.11
[α/Fe]	0.43 ± 0.12
[M/H]	-2.21 ± 0.15
$\log(L_\star/L_\odot)$	1.208 ± 0.030
$M_\star$ [$M_\odot$]	0.76 ± 0.05
$R_\star$ [$R_\odot$]	4.936 ± 0.016
$M_{G,0}$ [mag]	1.778 ± 0.082
$(G_{BP} - G_{RP})_0$ [mag]	0.921 ± 0.031

Could Gaia BH3 be mis-identified?



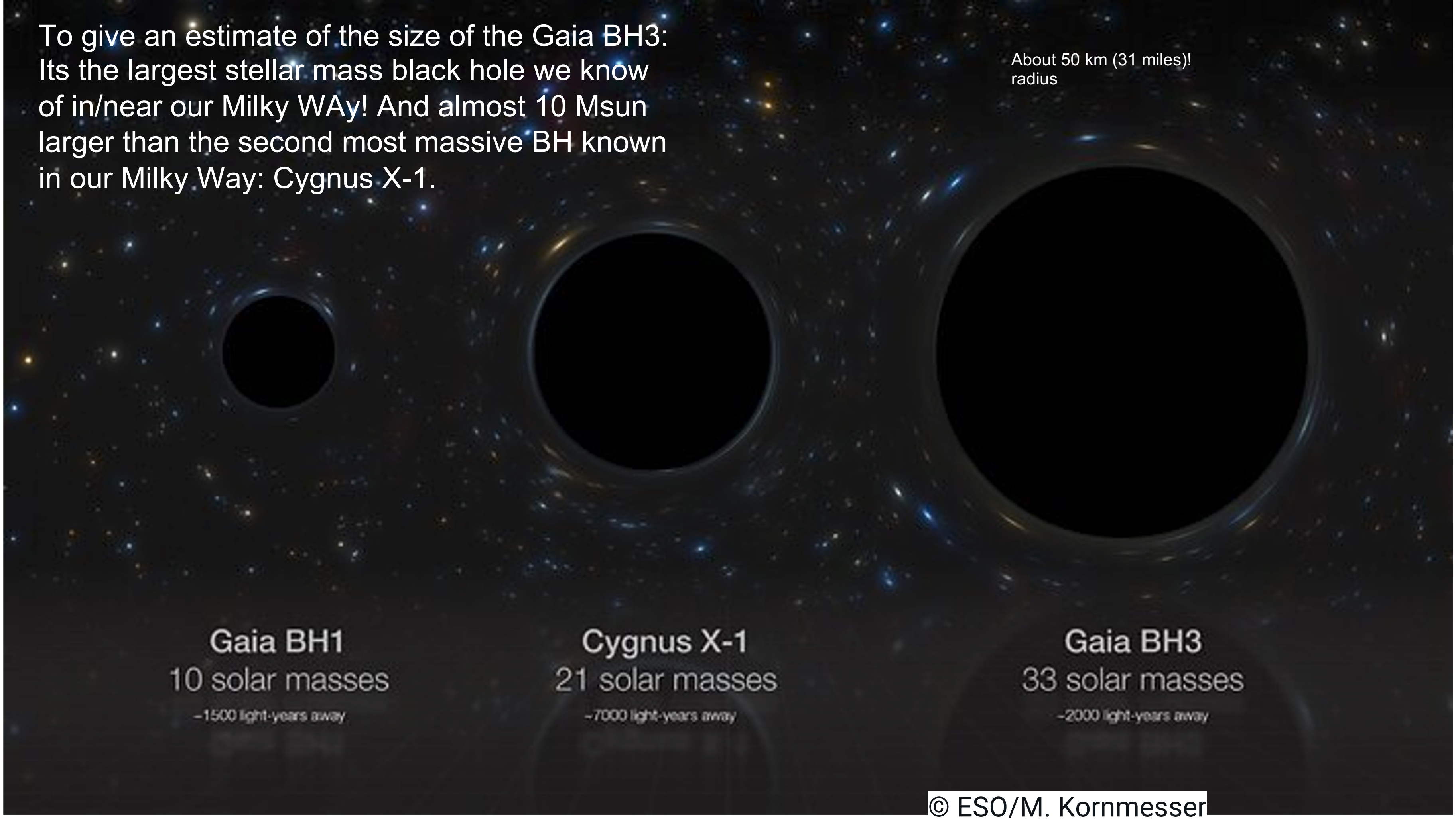
From the residuals here it is very clear that its really challenging to hide anything else than some kind of dark object. Could either be one black hole, or a binary black hole ! Gaia doesn't have the resolution (yet) to fully rule out the latter scenario. But follow-up observations could help clear this up! (Cool scenario: if it is an inner black hole binary, it might be visible with space-based gravitational-wave observatory *LISA* when *LISA* starts observing.. !

Fig. 3. Radial-velocity evolution of *Gaia* BH3. Top panel: Comparison between the radial-velocity evolution predicted from the combined *Gaia* astrometric-spectroscopic binary model (blue solid line) and the epoch radial velocities measured with the *Gaia* RVS instrument (black filled circles), and ground-based measurements for *Gaia* BH3. Bottom panel: Radial-velocity residuals with respect to the binary solution compared with the 1-σ uncertainty of the predicted radial-velocity evolution (blue shaded area). The vertical dot-dashed line in both panels marks the time of the periastron passage.

"It's a real unicorn! It's like nothing we've ever seen." says Pasquale Panuzzo of CNRS, Observatoire de Paris, in France and lead author of the paper.

To give an estimate of the size of the Gaia BH3: Its the largest stellar mass black hole we know of in/near our Milky WAy! And almost 10 Msun larger than the second most massive BH known in our Milky Way: Cygnus X-1.

About 50 km (31 miles)!
radius



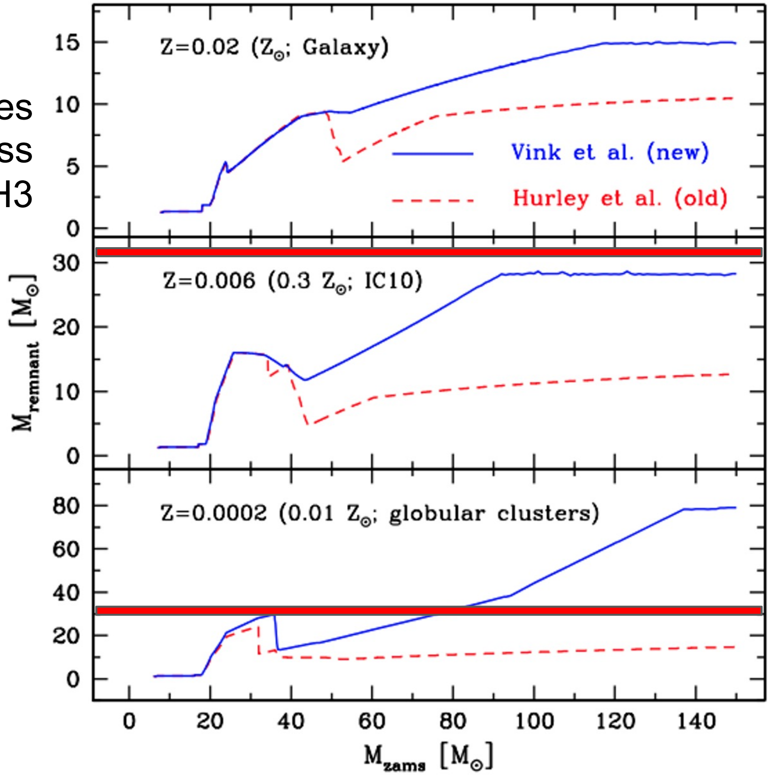
Fun fact: the size of Gaia BH3 is so large that it could completely swallow all the Astro departments in New York City (including CCA and the Simons Foundation, Columbia) and Princeton

Stellar evolution theory expects only low metallicity to form > 30Msun BHs, as stong metallicity driven stellar winds lead to significant mass loss (and low mass black holes) at higher metallicity

Belczysnki 2010

The lack of metals substantially decreases the mass loss during the stellar lifetime (Vink 2008) and reduces the radius of the evolving progenitors (Hurley et al. 2000; Belczynski et al. 2010a), the latter effect decreasing the probability of merging during the common envelope phase (Belczynski et al. 2007) in binary systems. Finally, the higher mass of the BHs produced by low-metallicity progenitors is expected to decrease substantially or eliminate the natal kick strength at the birth of the BHs, preserving the binary as a bound system (Belczynski et al. 2010b)

Red lines indicate mass of Gaia BH3



And interestingly enough, the companion of Gaia BH3 is extremely metal-poor, hinting that Gaia BH3 likely also formed from an extremely metal-poor progenitor star. This suggests that our theory might be right: maybe only metal-poor stars can form BHs > 30 Msun…

But… What metallicities of stars can produce > 30 Msun BHs is still very active debate:

These differences are understood in terms of the updated wind mass loss prescriptions and of the internal mixing prescription (see Appendix B for more details on the role of overshooting and rotational velocity). Note that we have not only adopted different wind mass loss prescriptions but we have also proposed transition criteria among prescriptions that are more complex than traditionally adopted in the modeling of massive stars

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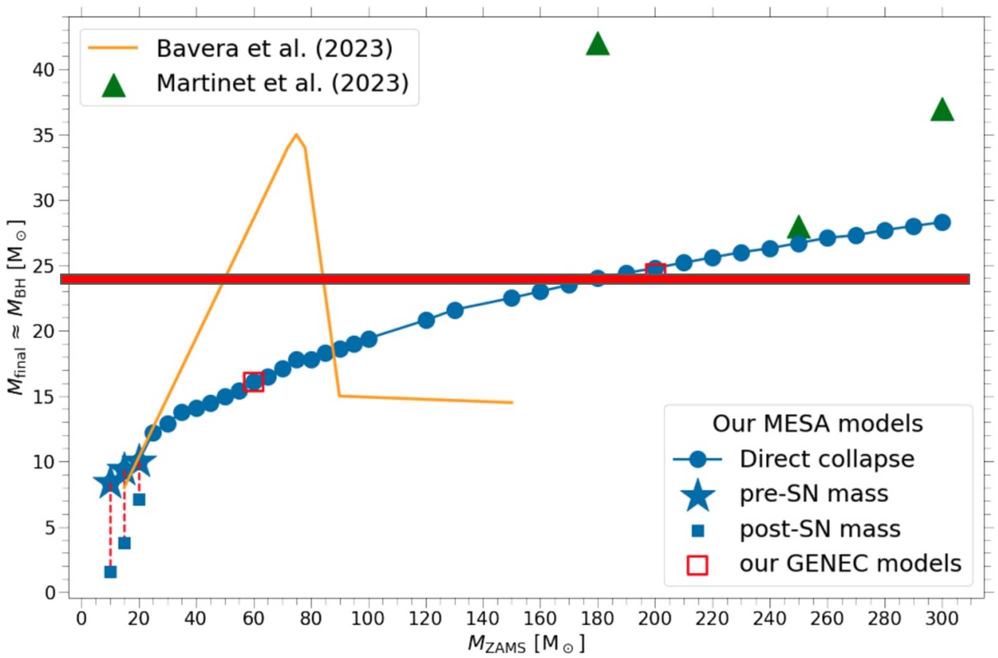
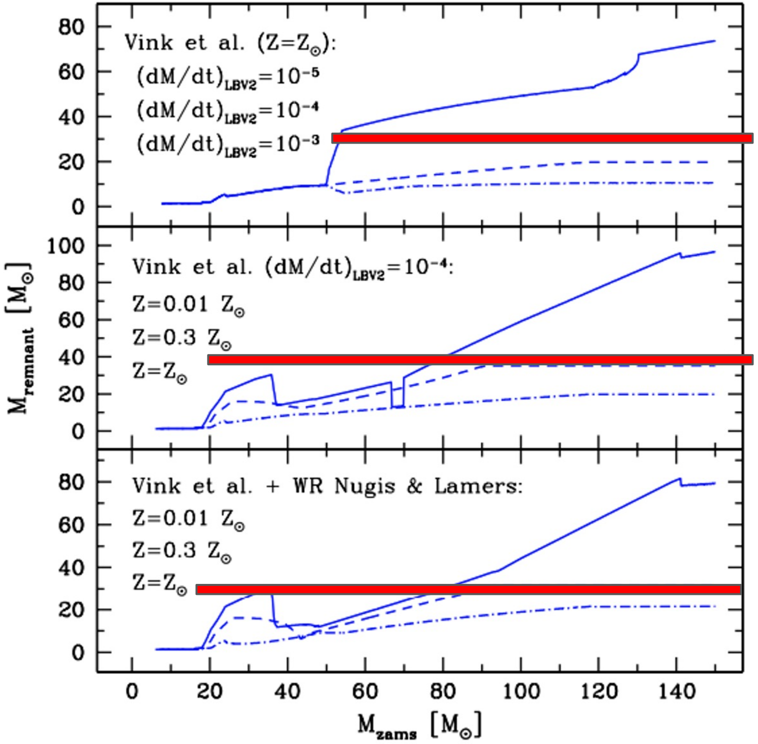
Romagnolo (2023), Bavera (2023), Martinet (2023) all ~ solar Z = 0.014



Belczysnki 2010



Already work such as Belczynski+2010 mentioned that different assumptions (especially in the LBV winds) can lead to also solar metallicity stars forming > 30 Msun BHs. And recent results (left plot) show that simulations disagree whether solar metallicity stars can form > 30 Msun stars, and if so, which range of initial stellar masses (ZAMS masses) lead to > 30 Msun stars. For now we think that it is no problem to form the 33 Msun Gaia BH3, as it likely came from a very metal poor progenitor star. But it is still an open question whether we should expect in the future to detect BHs like Gaia BH3 (with > 30 Msun masses) with solar metallicity companions. On the other hand, systems like Gaia BH3 can inform us about wind-loss and mass loss of low metallicity massive stars, something that is extremely challenging to observe in any other way! (we only have observations of LMC/SMC that have metallicities of at lowest ~Z_sun/5. Gaia BH is 0.003 * Z_sun!!

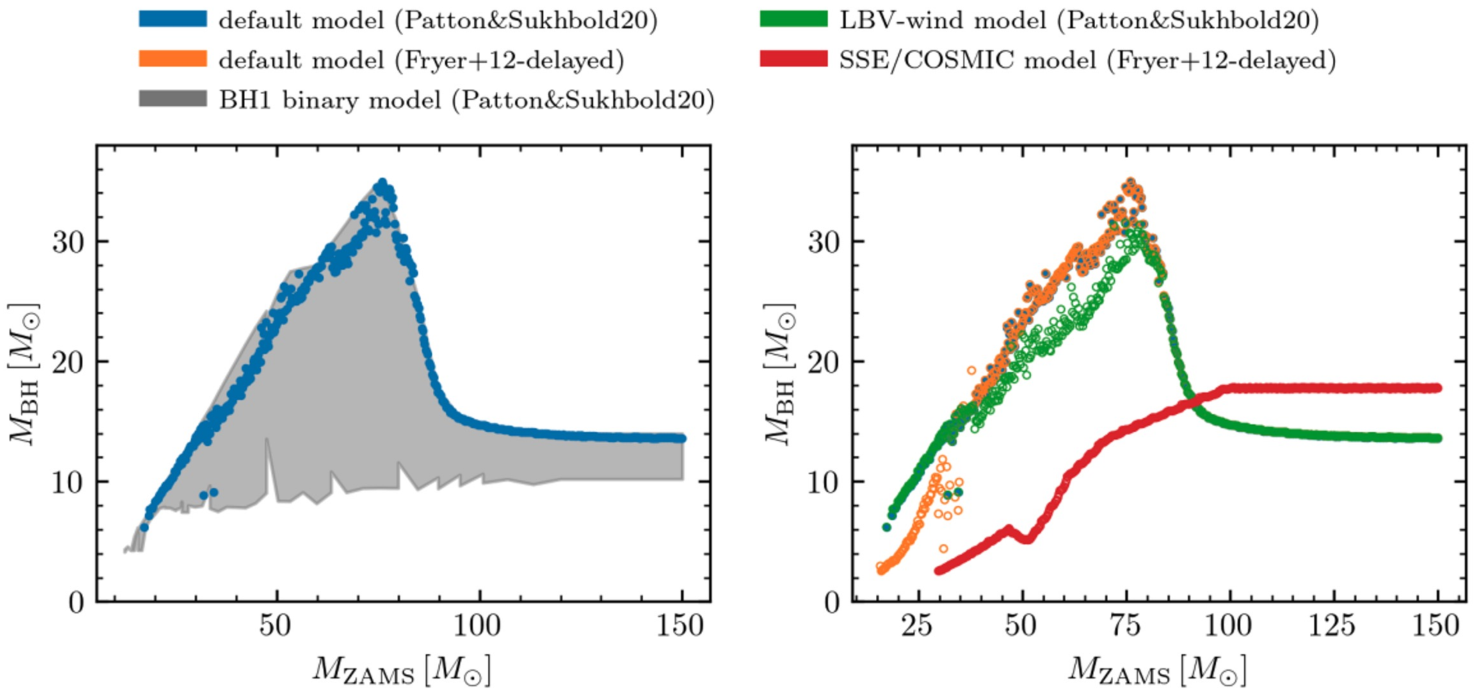
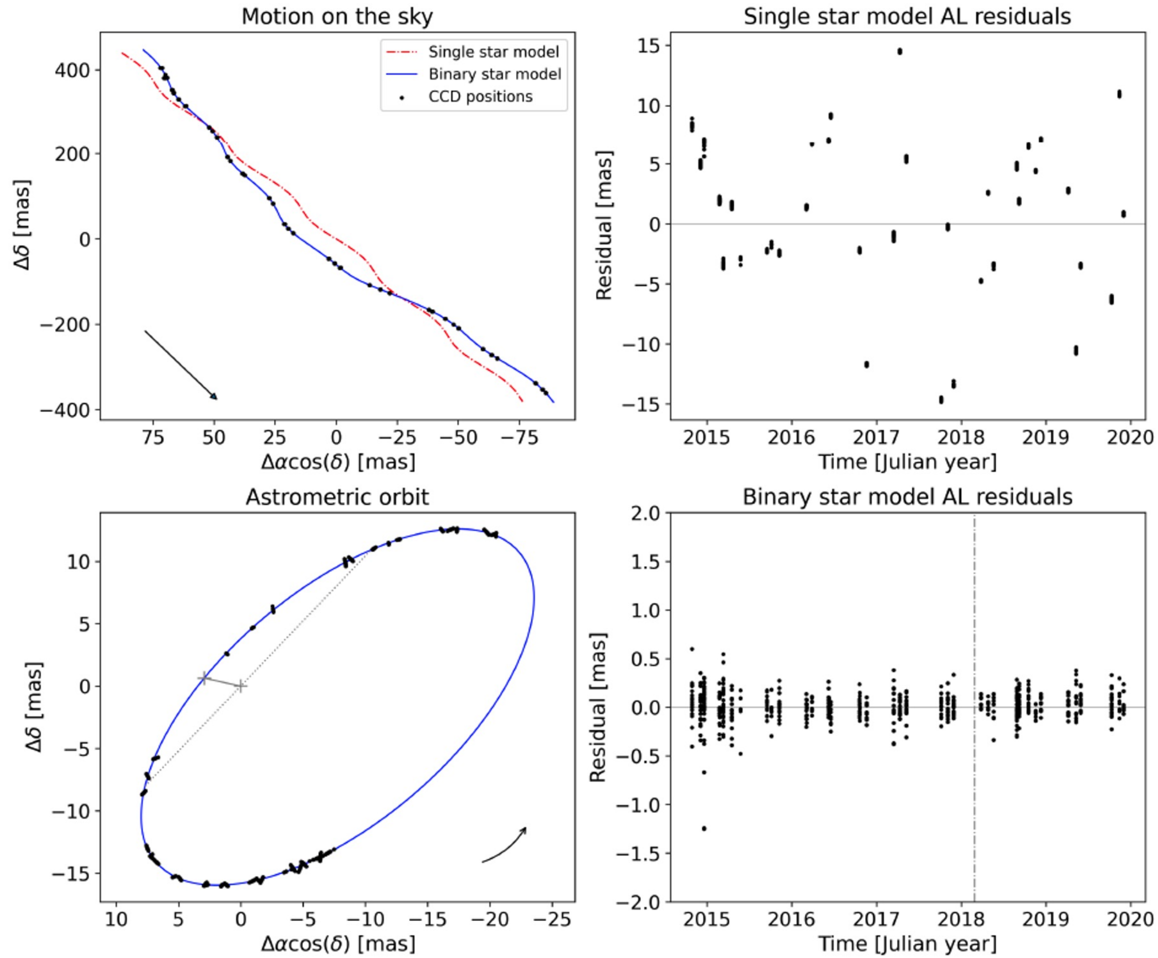


Figure 3. (*Left*) BH mass from single stellar evolution for a given ZAMS stellar mass at solar metallicity (markers) and the first-born BH mass of binary systems (gray area), with the extend of the grey area caused by the diversity of binary interactions starting at different orbital periods covered in POSYDON's binary grids. (*Right*) We show the BH mass, resulting from single stars, given two different core-collapse assumptions for our default model according to the legend and the model variation including LBV-like winds. For comparison, we show BH masses as predicted by the SSE stellar models as implemented in COSMIC[28] given one of the considered core-collapse prescriptions.

From Bavera 2023



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Orbits from Gaia BH3 paper!

Fig. 2. Astrometric data of *Gaia* BH3. Top-left panel: Motion on the sky of the photocentre of the source, as seen by *Gaia* in the different CCD transits (dots), compared with the best fitting single-star solution from AGIS and the astrometric-binary solution from the NSS pipeline; the arrow indicates the direction of the proper motion. Bottom-left panel: Derived astrometric orbit of the photocentre, after a subtraction of parallax and

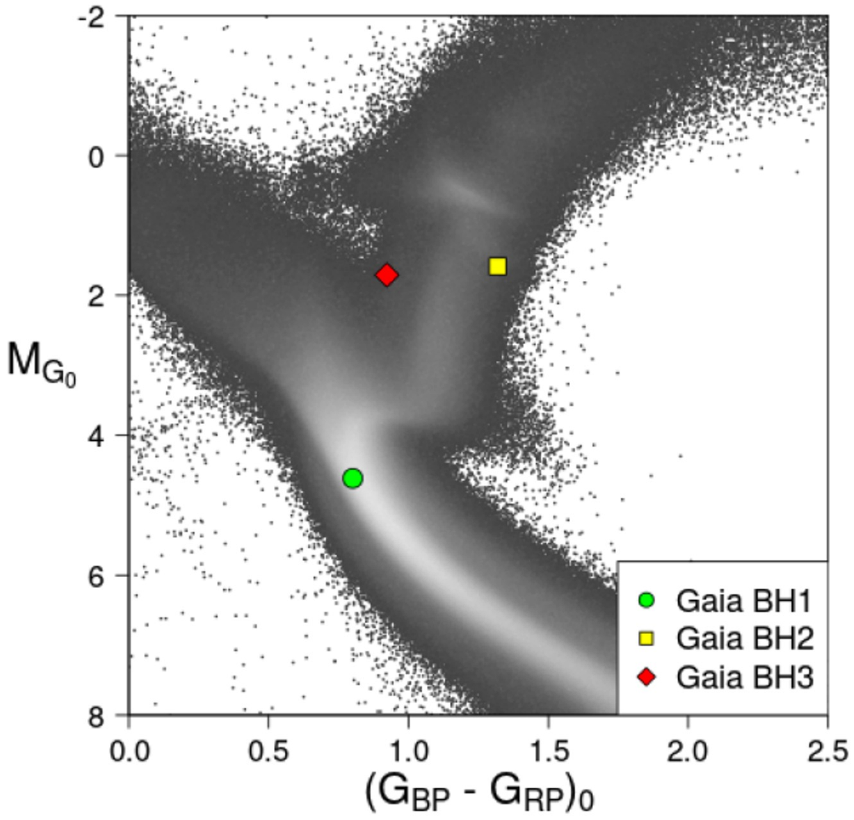


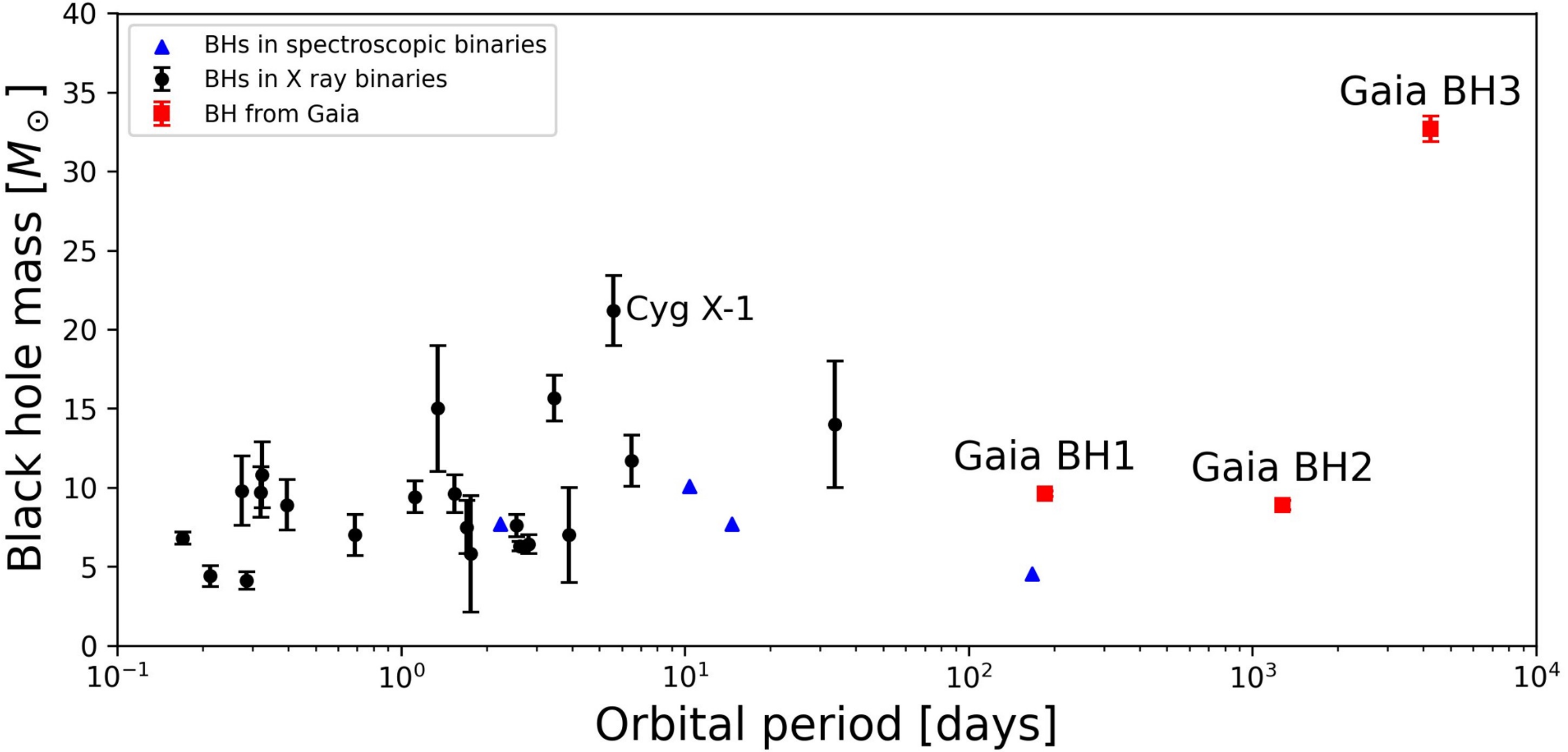
Fig. 1. *Gaia* BH3 position in the *Gaia* color-magnitude diagram, compared with the position of Gaia BH1, BH2 and the low extinction ($A_0 < 0.05$ mag) *Gaia* DR3 color-magnitude diagram. All extinctions are estimated through the Lallement et al. (2022) extinction map.

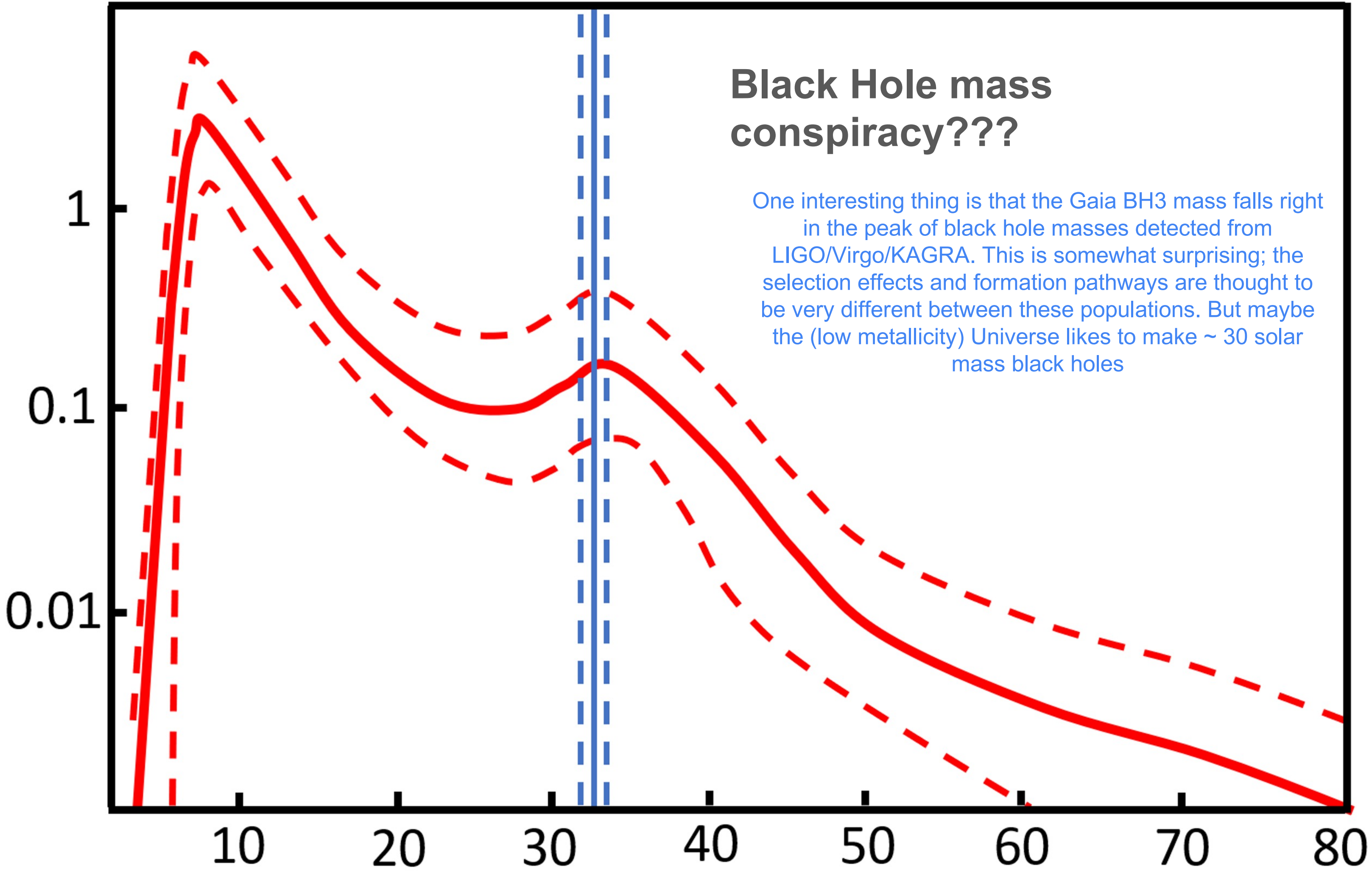
The companion star is 0.76, but already climbing to the Giant Branch… (see plot on left). This sounds confusing at first: a 0.8 star should have a lifetime on the main sequence that well exceeds the Hubble time (see the related BH2 discussion on this below). But! At low metallicity these stars have much shorter lifetimes as they are much brighter and run faster through their fuel/hydrogen. The observation of the star climbing the gian branch (RGB star) together with calculating the lifetime actually puts strong constraints on the mass of the companion star of Gaia BH3: if it was much less massive it wouldnt have evolved yet, if it was more massive it would be a white dwarf already. This provides extra confidence that it must be a ~0.75 msun star

From El-badry (BH2)
https://arxiv.org/pdf/2302.07880.pdf

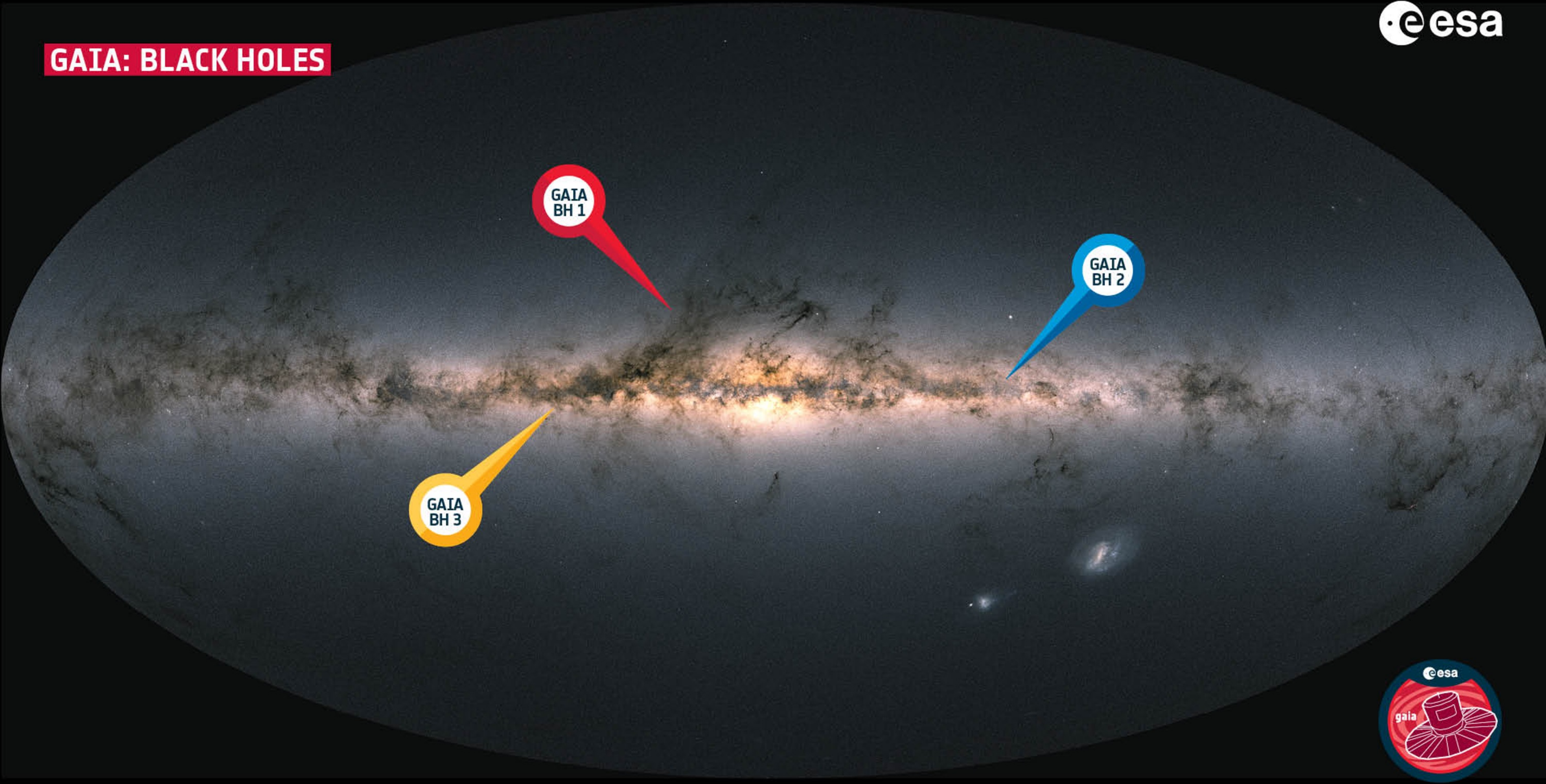
Fitting the measured temperature and radius implies a luminous star mass of $1.07 \pm 0.19\, M_{\odot}$. The uncertainty is dominated by uncertainty in the observed effective temperature, though uncertainties in the stellar models likely contribute at a similar level (e.g. Joyce et al. 2022). The corresponding age range is about 5-13 Gyr. In all plausible models, the star is on the lower red giant branch and has recently begun to expand following core hydrogen exhaustion; it is *not* a core helium burning red clump star that has already reached the tip of the giant branch and experienced a helium flash.

Black Holes in the Milky Way!!! And this is just the beginning as Gaia will soon see many more (~10-100) expected – see Chawla et al. 2022 for some predictions : https://ui.adsabs.harvard.edu/abs/2022ApJ...931..107C/abstract...





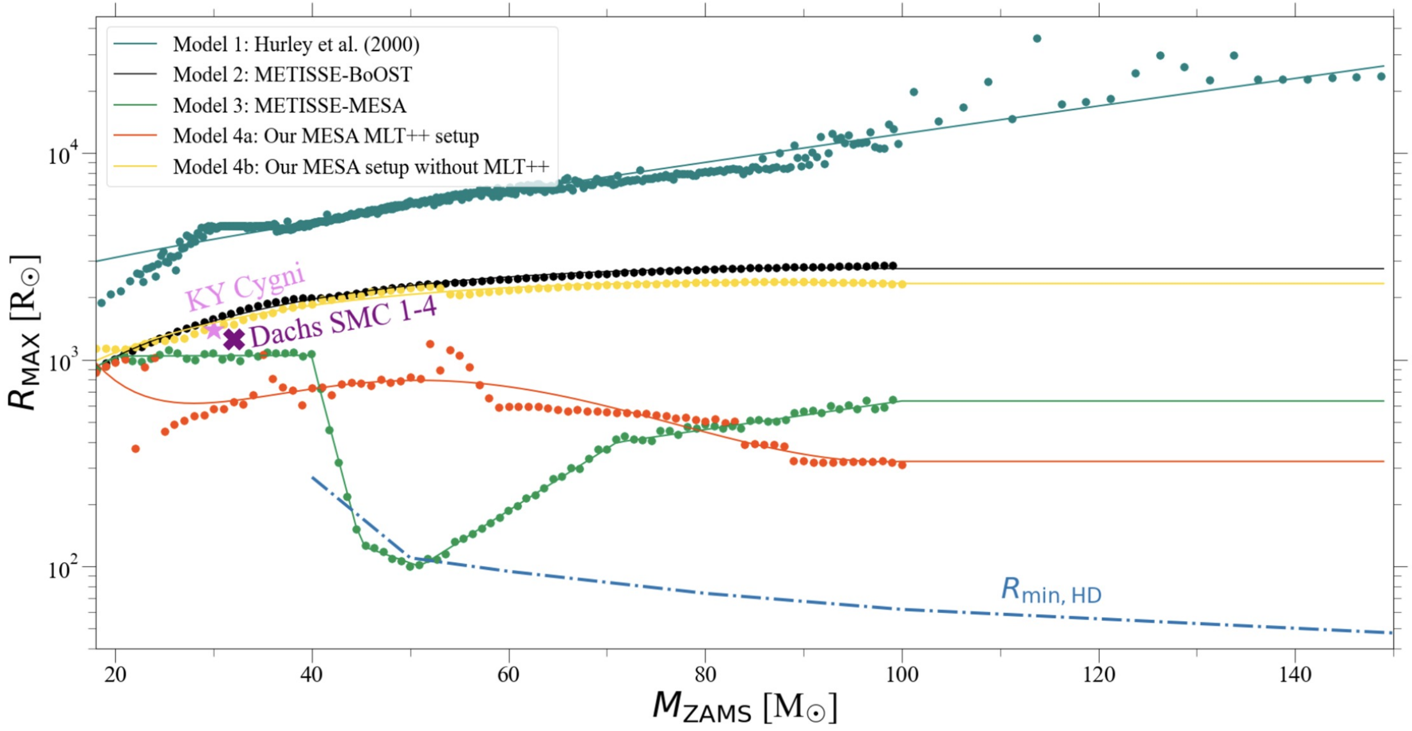
Black Hole mass conspiracy???
One interesting thing is that the Gaia BH3 mass falls right in the peak of black hole masses detected from LIGO/Virgo/KAGRA. This is somewhat surprising; the selection effects and formation pathways are thought to be very different between these populations. But maybe the (low metallicity) Universe likes to make ~ 30 solar mass black holes
1
0.1
0.01
10
20
30
40
50
60
70
80


GAIA: BLACK HOLES
GAIA BH 1
GAIA BH 2
GAIA BH 3
esa
gaia

The estimated mass of the BH in *Gaia* BH3 makes it the most massive BH of stellar origin discovered in our Galaxy. It is striking that the only BH with a mass larger than 20 $M_{\odot}$ found in the *Gaia* data so far is in orbit with a very metal-poor star, while such stars make up only a tiny fraction of the stars analysed in the NSS pipeline run (0.4% of sources which produced a binary solution have [M/H] < -2 from DR3 GSP-Phot). Such stars also make up a small fraction of our Galactic halo (less than 5% according to Bonifacio et al. 2021) where this star and the majority of metal-poor stars are located. Although we can not exclude that this BH is the result of the merger of two less massive BHs, this discovery strongly supports the scenario where high-mass BHs are remnants of low-metallicity stars. The above considerations also raise the question of the maximum metallicity value for the formation of high-mass BHs, which in Belczynski et al. (2016) is identified at [M/H] $= -1$. The much lower metallicity of *Gaia* BH3 may be an indication that high-mass BHs form only at very low metallicities rather than at moderately low ones.

theless, a few aspects ought to be highlighted. As discussed in El-Badry et al. (2023b,a), the formation of the *Gaia* BH1 and BH2 systems as isolated binaries is unlikely. This is also true for the recently discovered *Gaia* NS1 system (El-Badry et al. 2024), composed of a high-mass neutron star and a low-metallicity star. Given the size of their orbits, these systems should have experienced a common-envelope phase and then a mass transfer toward the light companion, which would then have resulted in much closer orbits than the observed ones. For *Gaia* BH2, the common-envelope phase could have been avoided if the BH progenitor was more massive than 65 $M_\odot$. In the case of *Gaia* BH3, the present-day minimum separation is of the order of 1000 $R_\odot$ and the common-envelope phase could not have been avoided because models predict that the BH progenitor becomes a red supergiant even at 150 $M_\odot$ (Chen et al. 2015). Similarly to *Gaia* BH1 and BH2, the chemical composition of the luminous component does not show any unusual abundance; in particular, the absence of ^{13}C and the observed [Ba/Fe] point toward a lack of contamination by the BH progenitor during its evolution. The observed enhanced Eu abundance could be due to the contamination from the SN at the birth of the BH, but also due to the medium in which the star formed. An alternative formation scenario, proposed to explain the *Gaia* BH1 and BH2 systems, is that the BH acquired the low-mass companion via dynamical exchange in a dense environment (see for example Rastello et al. 2023; Tanikawa et al. 2024). Such a scenario might be supported by the probable association of *Gaia* BH3 with the ED-2 stream, which could be a remnant of a globular cluster (Dodd et al. 2023; Balbinot et al. 2023).

I have thoughts…



Romagnolo et al 2022

Radial extensions of stars are uncertain from theory (and sensitive to many assumptions in the models). The radial extension of stars can easily change orders of magnitude depending on these assumptions. Its thus too soon to say that we "know for certain" that the progenitor of Gaia BH3 must have interacted with its companion

Figure 3. Maximum stellar radii as a function of M_{ZAMS} for each presented model. We show the maximum stellar radii obtained with the Hurley et al. 2000 rapid evolutionary formulae used in many codes (e.g. StarTrack, COMPAS, MOCCA), and the ones obtained from Models 2, 3, 4a and 4b. The dots are the data points from the estimates from StarTrack (Model 1) or detailed calculations (Model 2, 3, 4a, 4b). They are the same colour of the lines representing the R_{MAX} prescriptions. As a reference we show the radius of KY Cygni ($\sim 1500\,R_\odot$, for $M_{ZAMS} = 30\,M_\odot$) and Small Magellanic Cloud Dachs 1-4 ($\sim 1300\,R_\odot$ $M_{ZAMS} = 32\,M_\odot$; see Sec. 3.2 for details). We also show with the dotted line the minimum radial expansion as a function of M_{ZAMS} that a star must reach to cross the Humphrey-Davidson limit according to our simulations. With the partial exception of Model 3, all of the proposed R_{MAX} models cross this limit by even orders of magnitude. Maximum stellar radii for the same M_{ZAMS} may differ by more than one order of magnitude depending on which code and input physics is used.

The 33 $M_{\odot}$ black hole *Gaia* BH3 is part of the disrupted ED-2 star cluster

E. Balbinot[1,2], E. Dodd[1], T. Matsuno[3], C. Lardo[4], A. Helmi[1], P. Panuzzo[5], T. Mazeh[6], B. Holl[7,8], E. Caffau[5], A. Jorissen[9], C. Babusiaux[10], P. Gavras[11], Ł. Wyrzykowski[12], L. Eyer[7], N. Leclerc[5], A. Bombrun[13], N. Mowlavi[7], G.M. Seabroke[14], D. Teyssier[15], I. Cabrera-Ziri[3], T. M. Callingham[1], T. Ruiz-Lara[16,17], and E. Starkenburg[1]

(Affiliations can be found after the references)

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ABSTRACT

Context. The *Gaia* Collaboration has recently reported the detection of a 33 $M_{\odot}$ black hole in a wide binary system located in the Solar neighbourhood.

Aims. Here we explore the relationship between this black hole, known as *Gaia* BH3, and the nearby ED-2 halo stellar stream.

Methods. We study the orbital characteristics of the *Gaia* BH3 binary and present measurements of the chemical abundances of ED-2 member stars derived from high-resolution spectra obtained with the VLT.

Results. We find that the Galactic orbit of the *Gaia* BH3 system and its metallicity are entirely consistent with being part of the ED-2 stream. The characteristics of the stream, particularly its negligible spread in metallicity and in other chemical elements as well as its single stellar population, suggest that it originated from a disrupted star cluster of low mass. Its age is comparable to that of the globular cluster M92 that has been estimated to be as old as the Universe.

Conclusions. This is the first black hole unambiguously associated with a disrupted star cluster. We infer a plausible mass range for the cluster to be relatively narrow, between $2 \times 10^{3} M_{\odot}$ and $4.2 \times 10^{4} M_{\odot}$. This implies that the black hole could have formed directly from the collapse of a massive very-metal-poor star, but that the alternative scenario of binary interactions inside the cluster environment also deserves to be explored.

Key words. Stars: black holes – Stars: Population II - Stars: abundances - Galaxy: kinematics and dynamics – Galaxy: halo - globular clusters

In this new paper, one day after the Gaia BH3 release, the authors show support from the velocity, age, and metallicity that Gaia BH3 came from ED-2 stream, which is likely a disrupted star cluster (with low mass, and a narrow spread of stellar metallicities)

Paper Link: https://arxiv.org/pdf/2404.11604.pdf Balbinot et al. 2024

E. Balbinot et al.: *Gaia*-BH3 and the ED-2 star cluster

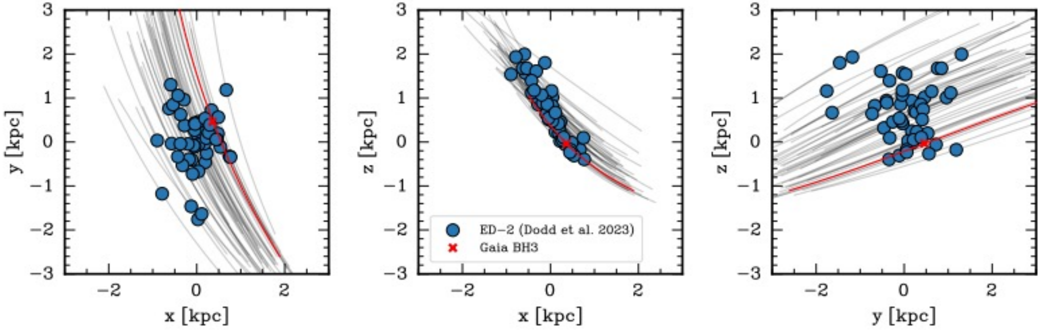
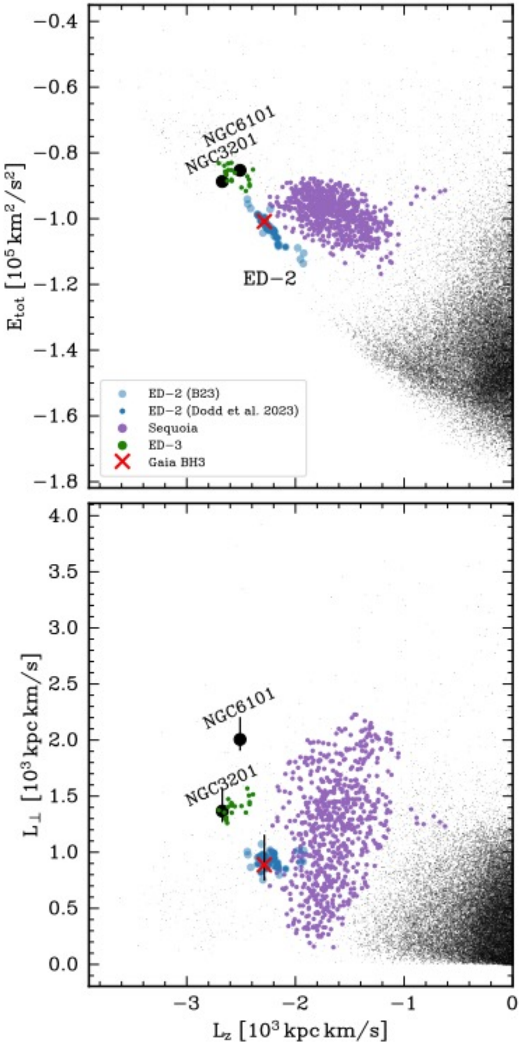


Fig. 3. Cartesian heliocentric projection of the location of ED-2 members and their orbits integrated in the Milky Way potential used in Dodd et al. (2023) for 20 Myr. The red cross and line show the position and orbit of *Gaia* BH3, and is indistinguishable from that of the ED-2 stars.



Outlook: This is Exciting as many more BHs might be discovered soon in Gaia! (DR4) that is measuring with increasing precision the orbits (and accelerations) of stars!

"Gaia is a true black hole detection machine because each of the three instruments can detect them." says Laurent Eyer of Geneva Observatory, member of the Gaia Collaboration.