Time Allocation Committee for
MPG time at the ESO 2.2m-telescope
c/o MPI für Astronomie
Königstuhl 17
D-69117 Heidelberg / Germany

Application No.
Observing period April - September 2023
Received

APPLICATION FOR OBSERVING TIME

from [X] MPIA [ ] MPG institute [ ] other

2.1 Applicant

Kareem **El-Badry**	MPIA
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2.2 Collaborators

R. Seeburger; H.-W. Rix; E., Zari	MPIA; MPIA; MPIA
name(s)	institute(s)
name(s)	institute(s)

2.3 Observers

service	
name	name

By specifying the names under item 2.3 it is obligatory to also send out these observers to La Silla, if required. Correspondence on the rating of this application will be sent to the applicant (P.I.) as quoted under 2.1 above.

3. Observing programme: Category: [E]

Title : **A search for solar-type orbiting black holes and neutron stars**

Abstract : We propose FEROS spectroscopy to measure multi-epoch radial velocities (RVs) for a sample of 50 astrometric binaries suspected to contain black holes (BHs) and neutron stars (NSs). Our targets are selected from the recent 3rd data release of the *Gaia* mission, which provides a factor-of-100 increase in sample size over all previous samples of binary star orbits. We have identified 50 binaries whose *Gaia* solutions suggest they contain dormant NSs and BHs as companions to solar-type stars. Multi-epoch spectra are required to validate and refine the *Gaia* orbital solutions, ultimately providing constraints on the masses of the unseen companions and on the stellar parameters and abundances of the luminous stars. The program will characterize a majority of all good candidates for BH/NS binaries in *Gaia* DR3.

4. Instrument: [ ] WFI [X] FEROS [ ] GROND

5. Brightness range of objects to be observed: from 10 to 15.0 *Gaia* G mag

6. Number of hours:

applied for			already awarded	still needed
165			140	70
no restriction	grey	dark		

7. Optimum date range for the observations: .... 04.01.2023 – 09.31.2023
Usable range in local sideral time LST: .... 0:00h – 24:00h

Astrophysical context

The Milky Way is thought to contain of order 10^8 stellar-mass BHs and 10^9 NSs [1, 2, 3]. However, only $\sim$20 BHs are dynamically confirmed [4, 5]. Almost all of the known stellar-mass BHs are accreting from a companion and were discovered via X-rays; almost all known neutron stars were discovered via radio emission (in young pulsars) or X-rays (in accreting binaries). Many theoretical models predict that wider binaries containing non-accreting BHs and NSs should vastly outnumber accreting systems [6, 7], which are likely a very rare outcome of binary evolution. The truth is that we have no idea how common detached BH/NS + normal star binaries are, because there are no robust observational constraints.

Basic open questions include the magnitude of natal kicks for BHs, the fraction of BHs formed by direct collapse rather than supernovae, the initial-final mass relation for massive stars, and the evolutionary pathways through which X-ray binaries form. Theoretical predictions for BH and NS binary population statistics disagree considerably between models. For example, varying the fraction of a binary's orbital energy that is coupled to the envelope of the BH/NS progenitor during common envelope evolution (the "α" parameter) changes the number of predicted close BH/NS-main sequence binaries by orders of magnitude [13, 3]. The discovery of *any* detached BH companions to low-mass stars ($M < 3\,M_{\odot}$) rules out some models, which predict that binaries cannot survive when the mass ratio is large [6].

The recent 3rd *Gaia* data release opens a completely new window on the binary population. For the first time, the *Gaia* collaboration has fit its astrometric data with a model that allows for "wobble" due to binary motion, in addition to parallax and proper motion [14]. These data constrain the Keplerian orbits of $\sim 200,000$ astrometric binaries – including the orbital inclination, which is typically unknown for spectroscopic binaries – making it possible to measure component masses directly. We select BH and NS binary candidates from this sample.

Our FEROS follow-up in 2022B already resulted in the discovery and characterization of a $10\,M_{\odot}$ BH orbited by a solar-type star [17], the first object of its kind. We have one additional strong candidate for a dormant BH (described in [17] and [15]) and a few dozen strong candidates of NS + normal-star binaries.

Immediate aim

We will obtain 3-10 RV epochs for each target, with follow-up timed such that we probe a majority of the dynamic range in RV predicted by the *Gaia* solution. We have already observed most of our targets in P109 and will observe them again in P110. Because the *Gaia* orbital period distribution peaks near 1000 days, observations over several semesters are required to cover a full orbit. Nevertheless, between our in-hand data obtained in P109 and P110, and our proposed observations in P111, we will be able to validate the *Gaia* orbital solutions for most of our targets. For the longest-period targets, we will apply again in P112 to continue RV monitoring.

Once a few RVs are obtained, it becomes straightforward to determine whether the *Gaia* orbital solution is reliable (see Figure 1). Although a large majority of all published *Gaia* astrometric solutions are robust, this is not necessarily the case for solutions that imply NS/BH-mass companions. Since these are astrophysically rare, a small number of false-positives can easily dominate over the true population. Given the RVs we have already obtained and the orbital solutions of our targets, we expect that it will be possible to validate or reject the *Gaia* solutions for a majority of our sample by the end of P111. Future RV monitoring will only refine these solutions of long-period binaries.

Previous work

Despite decades of effort and many interesting candidates [9, 10, 11, 12], most previous searches for dormant BHs and NSs in binaries have turned up only imposters [18, 19, 20]. The tide has recently begun to turn after the advent of binary solutions from *Gaia* DR3.

We vetted the *Gaia* DR3 sample in [16] and started RV follow-up of promising systems in P109, as described by [17]. We have obtained at least one RV for all good dormant BH/NS candidates. The long periods of most of the binaries in our sample demand follow-up over a multi-semester time baseline.

Layout of observations

Our targets are distributed across the southern sky; on any given night in P111, about 60% are observable from La Silla at some point in the night. To maximize the number of targets we can observe, we request that our observations are spread out into 4 blocks (e.g., blocks of several days in April, June, July, and August). In most cases, 3 epochs are sufficient to determine whether the astrometric solution is spurious. In cases where it is reliable, we will obtain $\sim$ 10 RV epochs spread over a significant fraction of the orbit. Together with the *Gaia* astrometric constraints, these will fully constrain the orbit and companion mass.

Strategic importance for MPIA

MPIA has invested in several upcoming spectroscopic surveys that aim to discover stellar remnants in binaries (SDSS-V, 4MOST, WEAVE, *Gaia*). Analysis of this data set will be a component of the PhD thesis of CO-I Seeburger. These observations are also an important element of Co-I Rix's just approved ERC Advanced Grant, *Hunting for Dormant Black Holes.*

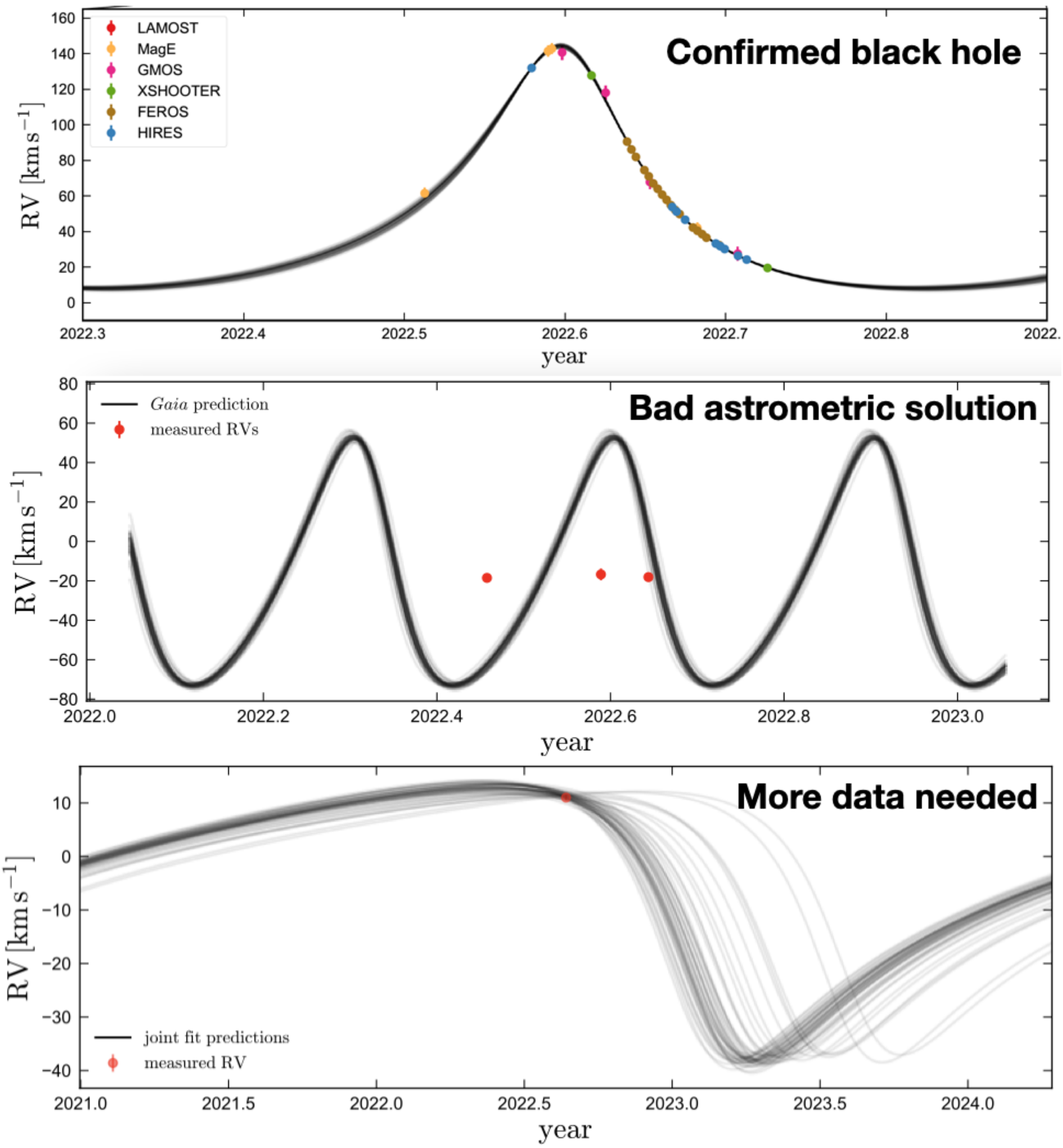

Figure 1: Range of possible outcomes in our RV follow-up so far. Top panel shows Gaia BH1, which our follow-up found to be a Sun-like star orbiting a $9.8\,M_\odot$ BH [**?**]. Middle panel shows a case where the *Gaia* astrometric solution implies a $4\,M_\odot$ BH, but RV follow-up shows the solution to be spurious. Bottom panel shows a case where the first-epoch of RV follow-up is consistent with the *Gaia* solution (which implies a $9\,M_\odot$ BH companion to $\sim 1\,M_\odot$ giant), but more RVs are needed to test the astrometric solution.

9. Objects to be observed

(Objects to be observed with high priority should be marked in last column)

Designation	α (2000)	δ (2000)	magnitude in spectral range to be observed	priority
4922744974687373440	$00^h\,03^m\,25.84^s$	$-56^\circ\,04'\,31.99''$	14.48	1
2429401251156528384	$00^h\,13^m\,19.37^s$	$-07^\circ\,59'\,33.50''$	13.98	1
2426116249713980416	$00^h\,36^m\,11.78^s$	$-09^\circ\,32'\,38.11''$	13.02	1
2581557958039687296	$01^h\,02^m\,21.12^s$	$+09^\circ\,48'\,54.19''$	13.40	1
5039979680444075392	$01^h\,19^m\,09.55^s$	$-25^\circ\,26'\,39.06''$	12.72	1
5136025521527939072	$01^h\,52^m\,50.89^s$	$-20^\circ\,49'\,05.64''$	12.05	1
2574867704662509568	$01^h\,56^m\,35.41^s$	$+12^\circ\,28'\,02.66''$	10.40	1
4638295715945158144	$02^h\,02^m\,39.50^s$	$-74^\circ\,18'\,59.30''$	12.93	1
4637171465304969216	$02^h\,17^m\,51.41^s$	$-75^\circ\,41'\,53.40''$	14.01	1
3263804373319076480	$03^h\,34^m\,55.36^s$	$+00^\circ\,09'\,10.24''$	12.67	1
41408333753757056	$03^h\,36^m\,30.37^s$	$+14^\circ\,19'\,04.95''$	14.87	1
3253873309421802624	$04^h\,17^m\,54.30^s$	$-02^\circ\,06'\,31.41''$	13.61	1
3184078579032750464	$04^h\,41^m\,25.70^s$	$-11^\circ\,29'\,33.87''$	13.73	1
3389767036738482432	$05^h\,33^m\,15.72^s$	$+14^\circ\,42'\,22.82''$	14.72	1
2995961897685517312	$05^h\,53^m\,53.15^s$	$-13^\circ\,49'\,55.26''$	13.00	1
2912474227443068544	$06^h\,16^m\,11.10^s$	$-24^\circ\,29'\,10.32''$	13.81	1
5283631903842076032	$06^h\,32^m\,40.35^s$	$-66^\circ\,14'\,26.69''$	13.31	1
5580526947012630912	$06^h\,39^m\,47.80^s$	$-36^\circ\,55'\,51.51''$	13.36	1
2919995917769953408	$06^h\,40^m\,07.83^s$	$-26^\circ\,21'\,31.89''$	14.97	1
3047635233349460736	$07^h\,21^m\,34.96^s$	$-09^\circ\,33'\,48.29''$	14.42	1
5530442371304582912	$07^h\,42^m\,15.70^s$	$-47^\circ\,49'\,26.65''$	14.60	1
3072288654854260864	$08^h\,45^m\,07.03^s$	$-02^\circ\,03'\,46.33''$	14.26	1
5327240562221030528	$09^h\,14^m\,47.10^s$	$-47^\circ\,28'\,37.08''$	13.05	1
613025599896017152	$09^h\,45^m\,00.49^s$	$+11^\circ\,39'\,46.50''$	14.02	1
5446310318525312768	$10^h\,12^m\,24.71^s$	$-35^\circ\,37'\,13.17''$	10.37	1
5355633933885075328	$10^h\,21^m\,00.83^s$	$-54^\circ\,49'\,26.40''$	13.73	1
3869650535947137920	$10^h\,46^m\,05.95^s$	$+10^\circ\,02'\,58.33''$	12.94	1
3494029910469026432	$11^h\,50^m\,52.82^s$	$-22^\circ\,03'\,50.52''$	12.66	1
3509370326763016704	$13^h\,01^m\,17.03^s$	$-18^\circ\,52'\,08.92''$	12.47	1
3619399009406031360	$14^h\,01^m\,42.33^s$	$-07^\circ\,17'\,18.34''$	13.90	1
6092954989675820416	$14^h\,25^m\,22.70^s$	$-47^\circ\,06'\,27.19''$	13.67	1
6328149636482597888	$14^h\,32^m\,20.68^s$	$-10^\circ\,21'\,58.85''$	13.34	1
6281177228434199296	$14^h\,52^m\,50.33^s$	$-19^\circ\,22'\,25.03''$	11.26	1
4429564978284010624	$15^h\,47^m\,46.70^s$	$+06^\circ\,24'\,04.09''$	14.65	1
5820382041374661888	$15^h\,53^m\,34.49^s$	$-68^\circ\,46'\,43.21''$	14.19	1
4466767229088016256	$16^h\,22^m\,31.73^s$	$+16^\circ\,47'\,48.15''$	13.78	1
6037767138131854592	$16^h\,23^m\,13.61^s$	$-30^\circ\,20'\,29.80''$	14.28	1
4373465352415301632	$17^h\,28^m\,41.08^s$	$-00^\circ\,34'\,51.93''$	13.77	1
4065778224715865344	$18^h\,09^m\,25.09^s$	$-24^\circ\,55'\,37.41''$	14.95	1
4482912934572480384	$18^h\,14^m\,02.45^s$	$+10^\circ\,17'\,42.29''$	12.35	1
4526711950202650240	$18^h\,16^m\,44.75^s$	$+18^\circ\,39'\,42.79''$	14.61	1
4320637632685061248	$19^h\,12^m\,40.28^s$	$+15^\circ\,32'\,16.38''$	14.48	1
4212627137946990336	$19^h\,17^m\,39.46^s$	$-04^\circ\,23'\,22.40''$	14.83	1
4240540718818313984	$19^h\,49^m\,42.67^s$	$+01^\circ\,29'\,31.14''$	14.61	1
6481502062263141504	$20^h\,57^m\,58.39^s$	$-47^\circ\,42'\,02.18''$	13.58	1
6802561484797464832	$21^h\,00^m\,25.70^s$	$-25^\circ\,35'\,08.48''$	12.88	1
6588211521163024640	$21^h\,56^m\,05.59^s$	$-35^\circ\,22'\,40.57''$	14.19	1
6601396177408279040	$22^h\,25^m\,52.42^s$	$-32^\circ\,31'\,07.68''$	14.07	1
6593763230249162112	$22^h\,28^m\,51.34^s$	$-39^\circ\,43'\,18.89''$	13.54	1

10. `Justification of the amount of observing time requested:`

We want to measure multi-epoch RVs as well as atmospheric parameters, rotation rates, and chemical abundances ($T_{\rm eff}$, $\log g$, $v \sin i$ [Fe/H], [Xe/Fe]). RVs are critical for each epoch; abundances are less essential and can be inferred by co-adding individual epochs for improved SNR.
We use 2x2 binning, which reduces read noise and allows us to reach targets ~ 1 mag fainter than is possible with 1x1. According to the exposure time calculator (and verified in our previous observations), at $G = 11$, we can reach S/N=50 with 10 minute exposures. At $G = 14.0$, we can reach S/N=15 with 40 minute exposures. At $G = 15.0$, we use 60 minute exposures and achieve S/N = 5-10. All of these allow us to measure RVs with our target $\sim 0.3\,{\rm km\,s^{-1}}$ precision; for brighter targets, we reach $\sim 0.1\,{\rm km\,s^{-1}}$ precision.
We expect to observe targets an average of ~ 5 times: 3 times for astrometric solutions that end up being spurious, and ~ 10 times for promising and correct solutions. Our exposure times vary from 10 to 60 minutes, with an average of 40 minutes for targets near $G \approx 14$. 5 epochs at 40 minutes per epoch will take ~ 165 hours, or roughly 16 nights.

11. `Constraints for scheduling observations for this application:`

We want to maximize the time baseline over which we can observe individual targets, and to spread out our observations for well-sampled phase curves. Our targets are distributed approximately uniformly in RA; we will choose which ones to observe on what dates based on the observing dates awarded. Roughly 60% of the targets are observable on any given night in the spring or summer. To maximize phase coverage, we request that our awarded nights be spread out as much as possible. Several blocks of ~4 nights each, spread over the whole semester, would be ideal.

12. `Observational experience of observer(s) named under 2.3:`
`(at least one observer must have sufficient experience)`

We anticipate service observing under the current agreement; with added funds from the GC department for service observing.

13. `Observing runs at the ESO 2.2m-telescope (preferably during the last 3 years)`
`and publications resulting from these`

Telescope	instrument	date	hours	success rate	publications
2.2m	FEROS	Dec 20	60	80%	[19]
2.2m	FEROS	Aug 21	100	50%	[21]
2.2m	FEROS	July 22	140	40%	[17]

14. References for items 8 and 13:

[1] Brown, G. E., & Bethe, H. A. 1994, ApJ, 423, 659

[2] Mashian, N., & Loeb, A. 2017, MNRAS, 470, 2611

[3] Chawla, C., et al. 2022, ApJ, 931, 107

[4] McClintock, J. & Remillard, A., 2006, “Compact stellar X-ray sources”.

[5] Corral-Santana, J., et al., 2016, A&A, 587, 61

[6] Portegies Zwart, S., et al., 1997, A&A, 321, 207.

[7] Breivik, K., et al. 2017, ApJL, 850, 13

[8] Giesers, B., et al. 2018, MNRASL, 475, 15

[9] Khokhlov, S. A., et al. 2018, ApJ, 856, 158

[10] Thompson, T., et al. 2018, Science, 366, 637

[11] Rivinius, T., et al. 2020, A&A, 637, L3

[12] Jayasinghe, T., et al. 2021, MNRAS, 504, 2577

[13] Shao, Y., & Li, X.-D. 2019, ApJ, 885, 151

[14] Gaia Collaboration, Arenou, F., et al., 2022, accepted to A&A.

[15] Tanikawa, A., et al., 2022, ArXiv: 2209.05632

[16] El-Badry, K., & Rix, H.-W., 2022, MNRAS, 515, 1266

[17] El-Badry, K., et al., 2022, ArXiv: 2209.06833

[18] El-Badry, K., et al., 2022, MNRAS, 512,5620

[19] El-Badry, K., & Quataert, E., 2021, MNRAS, 502, 3436

[20] El-Badry, K., & Burdge, K., 2022, MNRASL, 511, 24

[21] El-Badry, K., et al., 2022, MNRAS, 516, 3602

Tolerance limits for planned observations:

maximum seeing:	4″	**minimum transparency:**	50%	**maximum airmass:**	2
photometric conditions:	no	**moon: max. phase / ∠ :**	1/20°	**min. / max. lag:**	1/60 nights