# A Sun-like star orbiting a black hole

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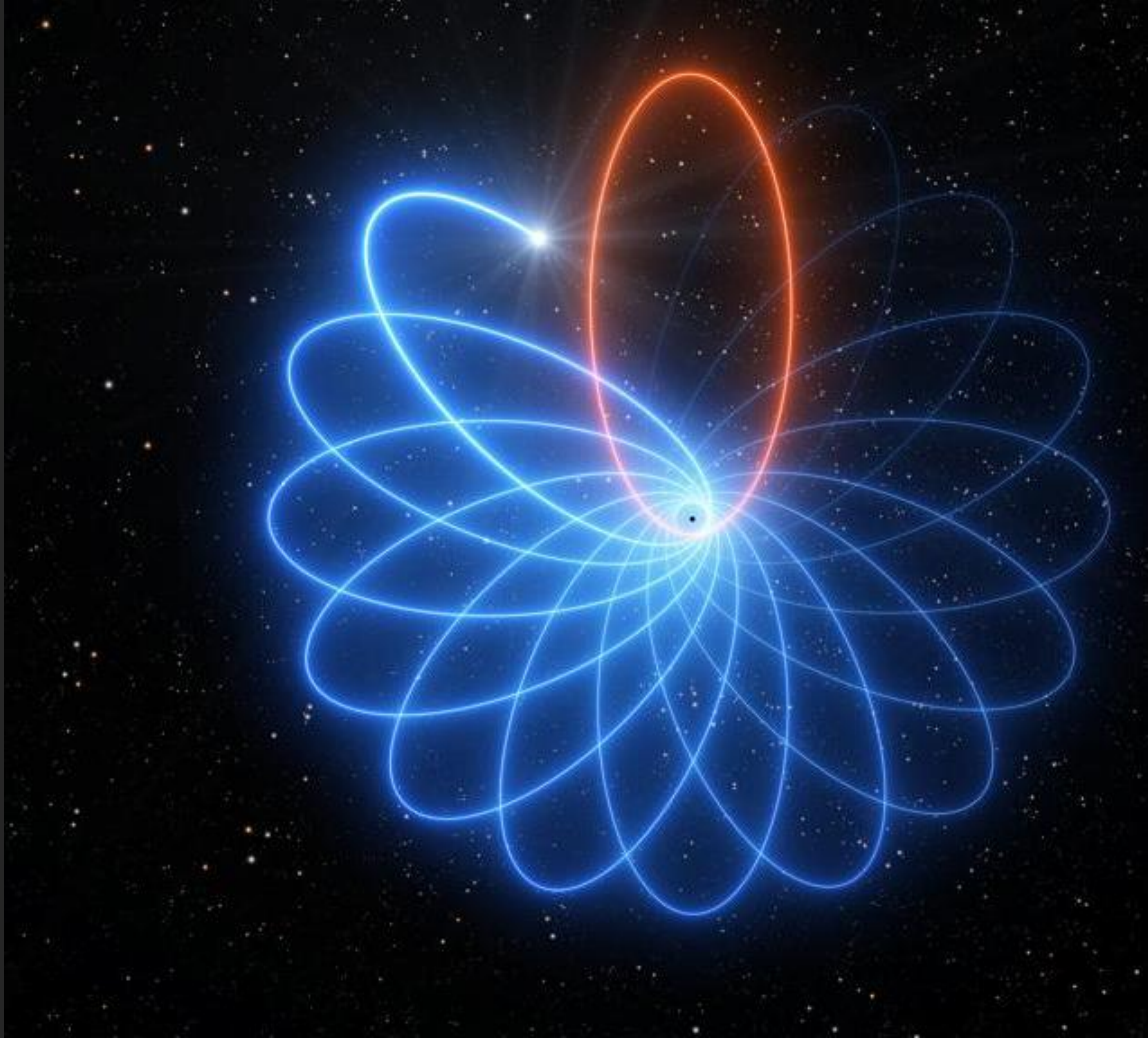


# Brief overview of the paper:

1. Discovery of a bright, nearby ($G$ = 13.8; $d$ = 480 pc /1467.7 Ly) Sun-like star orbiting a dark object. Companion mass is 9.8 +/-0.2 M_s

2. Identified as a black hole candidate using GAIA mission astrometry solutions.

3. The LAMOST spectra revealed a main-sequence G star with reported $T_{eff}$ = 5863, log $g$ = 4.36.

4. Gaia BH1 is different in several ways from other known BHs in binaries. It is nearby ($d$ = 480 pc) and bright ($G$ = 13.8). Together with the lack of contamination from an accretion disk and the fact that the luminous star is cool and slowly rotating, this makes it possible to study the system in greater detail in the optical than is possible for other known BH X-ray binaries.

5. The orbital period, $P_{orb}$ = 185.6 days, is longer than that of any known stellar-mass black hole binary

# Why is this discovery important?

1. The inventory of known and suspected BHs consists of about 20 dynamically confirmed BHs in X-ray binaries, an additional ~ 50 Xray sources suspected to contain a BH based on their X-ray properties. **Binary black holes are the primary endpoint of massive stars. Their properties provide a unique opportunity to constrain binary evolution, which remains poorly understood.**

2. This paper presents detailed follow-up of one astrometric BH binary candidate, which was found to be the most compelling candidate published in Gaia DR3 data release.

3. This is the nearest known black hole to our Solar system by a factor of 3, and its discovery suggests the existence of a sizable population of dormant black holes in binaries.

4. The paper suggests that wide BH binaries like Gaia BH1, while being harder to detect, are significantly more common than BHs in close binaries with ongoing accretion.

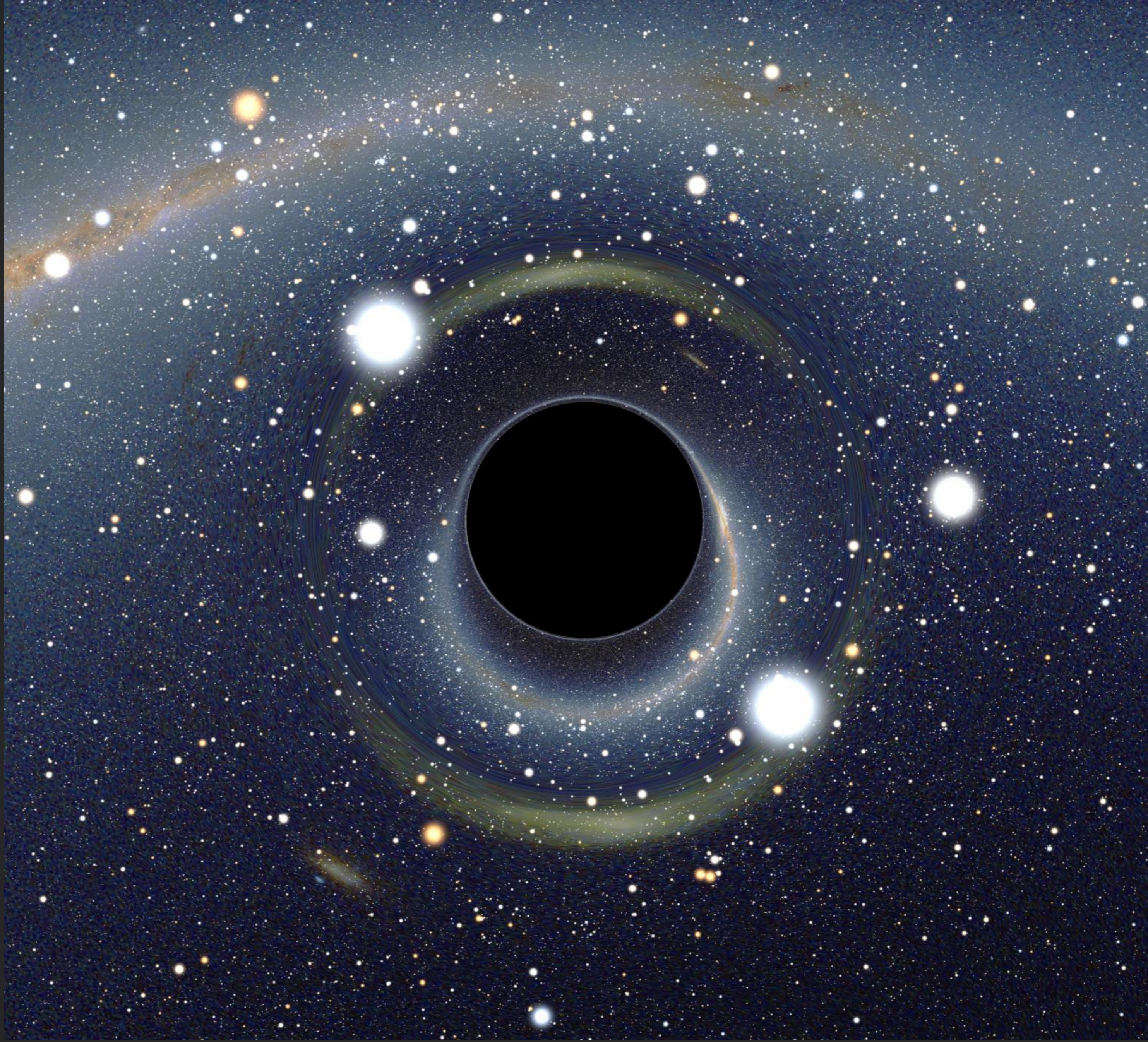
# What is a black hole (BH) and BH binary?

A black hole is a region of spacetime where gravity is so strong that nothing – no particles or even electromagnetic radiation such as light – can escape from it.

On 11 February 2016, the LIGO Scientific Collaboration and the Virgo collaboration announced the first direct detection of gravitational waves, representing the first observation of a black hole merger.

On 10 April 2019, the first direct image of a black hole and its vicinity was published, following observations by the Event Horizon Telescope (EHT) in 2017 of the supermassive black hole in Messier 87's galactic center.

Since black holes by their very definition cannot be directly observed, proving their existence is difficult. The strongest evidence for black holes comes from binary systems in which a visible star can be shown to be orbiting a massive but unseen companion in a system called the Black hole binary.



# Why is Gaia BH1 special?

Most often, scientists discover stellar-mass black holes in close X-ray binaries, where a compact object actively pulls the matter of a companion star onto itself, however, models of the evolution of binary systems predict that many black holes can be part of wide binary systems, where there is no significant transport masses from a star to a compact object, which makes it difficult to search for them in the X-ray range.

However, the black hole in this case can be detected due to its gravitational influence on the companion star even without actively accreting matter from the companion star.

The star in the BH1 system is a slowly rotating, bright yellow dwarf, with a mass of 0.93 solar masses, located 1555 light years from the Sun in the constellation of Ophiuchus. Its invisible companion has an estimated mass of about 9.8±0.2 solar masses, or at least more than five times the mass of the Sun, placing it in the black hole category.

*Credit: Alexander Voytyuk*

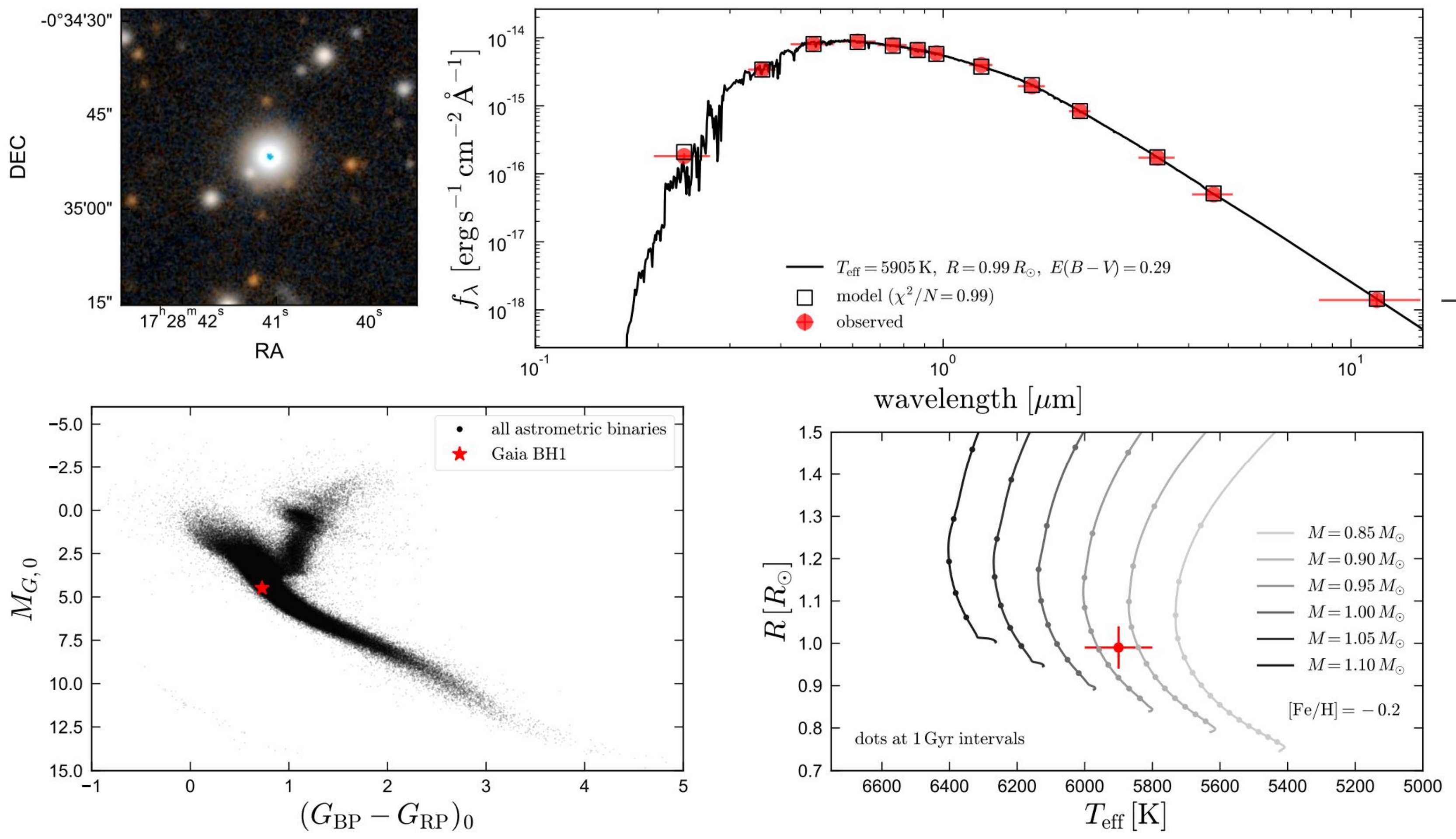



**Figure 1.** Properties of the luminous star. Upper left shows a 45 arcsecond wide *z*/*g* PanSTARRS postage stamp centered on the source. Upper right shows the broadband SED and a single-star fit. Red points show observed photometry; open black squares show the integrated fluxes predicted for the model spectrum (black line). Lower left compares the source to the rest of the *Gaia* astrometric binary sample on the color-magnitude diagram. Lower right compares the temperature and radius measured from the SED to single-star MIST evolutionary models with [Fe/H] = -0.2 (as measured from spectroscopy), which suggest a mass of $M_\star \approx 0.93\, M_\odot$.

# Figure 1: Properties of the luminous star.

Upper left shows a 45 arcsecond wide ***z*/*g*** PanSTARRS postage stamp centered on the source.

Upper right shows the broadband SED and a single-star fit.

Lower left compares the source to the rest of the Gaia astrometric binary sample on the color-magnitude diagram.

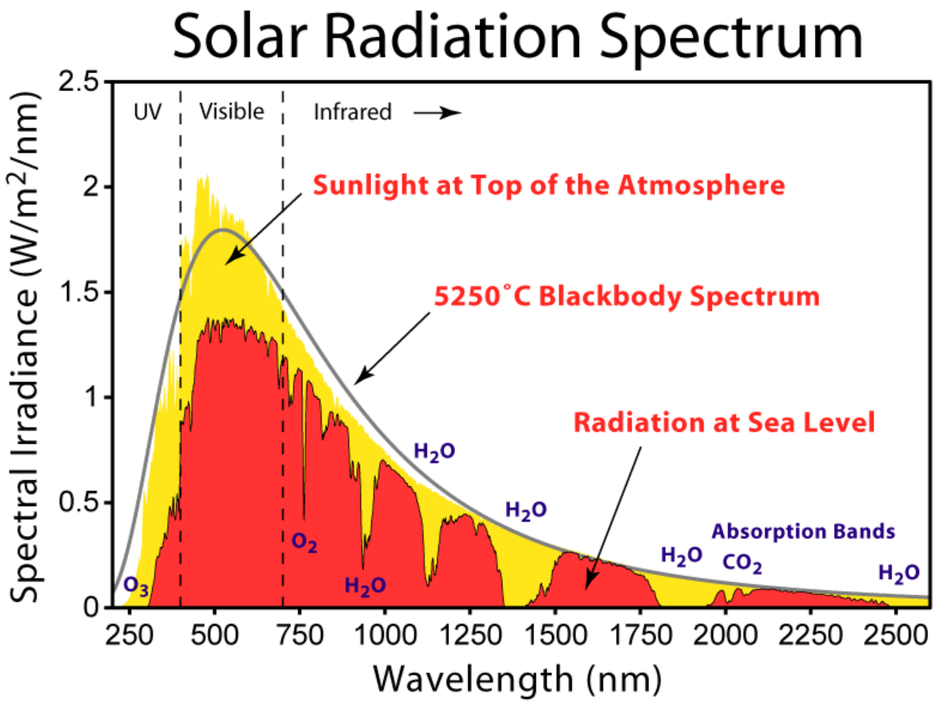
Lower right compares the temperature and radius measured from the SED to single-star MIST evolutionary models with [Fe/H] = -0.2 (as measured from spectroscopy), which suggest a mass of ***M*★ ≈** 0.93 ***M***.

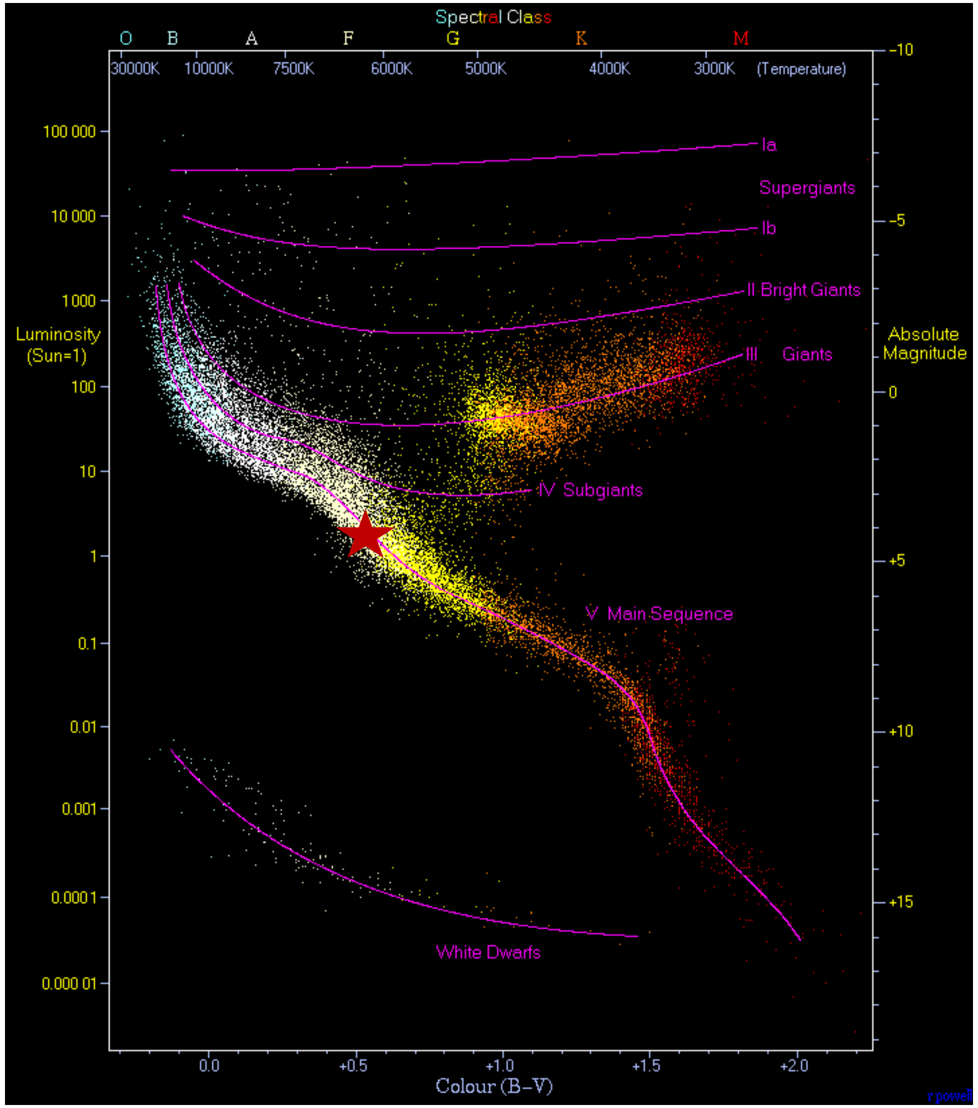
# Spectral Energy Distribution (SED)

The SED, or Spectral Energy Distribution, is a description of how the flux of light from an object (in this case the Black Hole), depends on the frequency of light that is observed. By analyzing an SED, one can obtain information about an objects's geometry, inclination, and constituents.

For our source, the SED was fit using GALEX NUV band, SDSS $\boldsymbol{u}$ band, PanSTARRS $\boldsymbol{grizy}$ bands, 2MASS $\boldsymbol{JHK}$ bands and WISE $\boldsymbol{W}1$ $\boldsymbol{W}2$ $\boldsymbol{W}3$ bands.

The inferred temperature and radius correspond to a solar-type star near the main sequence, and evolutionary models then predict a mass of $\boldsymbol{M}\star \approx 0.93 \pm 0.05$ $\boldsymbol{M}$.






In the color-magnitude diagram, the source appears as a solar-type main sequence star.

# Metallicity

For the Sun, the total amount of metals by mass, is about $Z_{\odot} = 0.02$ , or 2 per cent of the mass in the solar system is *not* hydrogen or helium. This is inferred not just from observations of the Sun, but also from the composition of comets.
For other stars, one usually compares the metallicity in units of the solar value, on a logarithmic scale,

$$[Fe/H] \equiv log_{10}\left[(Fe/H)/(Fe/H)_{\odot}\right] .$$

So if a star has [Fe/H]=0, it has the same Iron abundance as the Sun, for [Fe/H]=-1, it has one tenth the solar value.

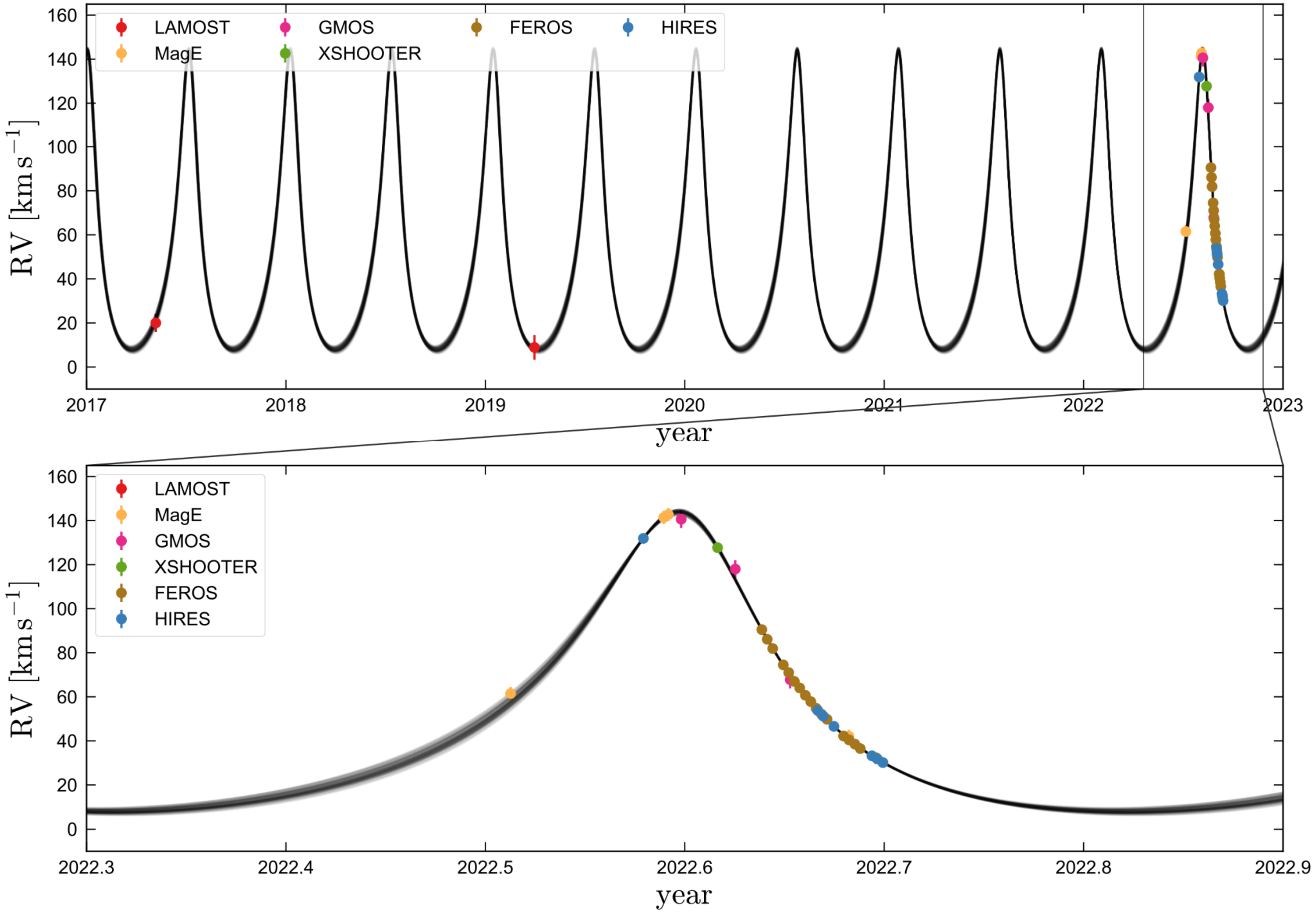
Similarly, In case of the star in BH1 binary, [Fe/H] = -0.2 measures the Iron abundance relative to our Sun.

# Figure 2: Radial velocities(RV)

Top panel shows all available RVs, including observations by the LAMOST survey in 2017 and 2019;

Bottom panel highlights the follow-up in 2022. The best-fit solution has a period of 186 days, eccentricity 0.45, and RV semi-amplitude of 68 km s−1 .

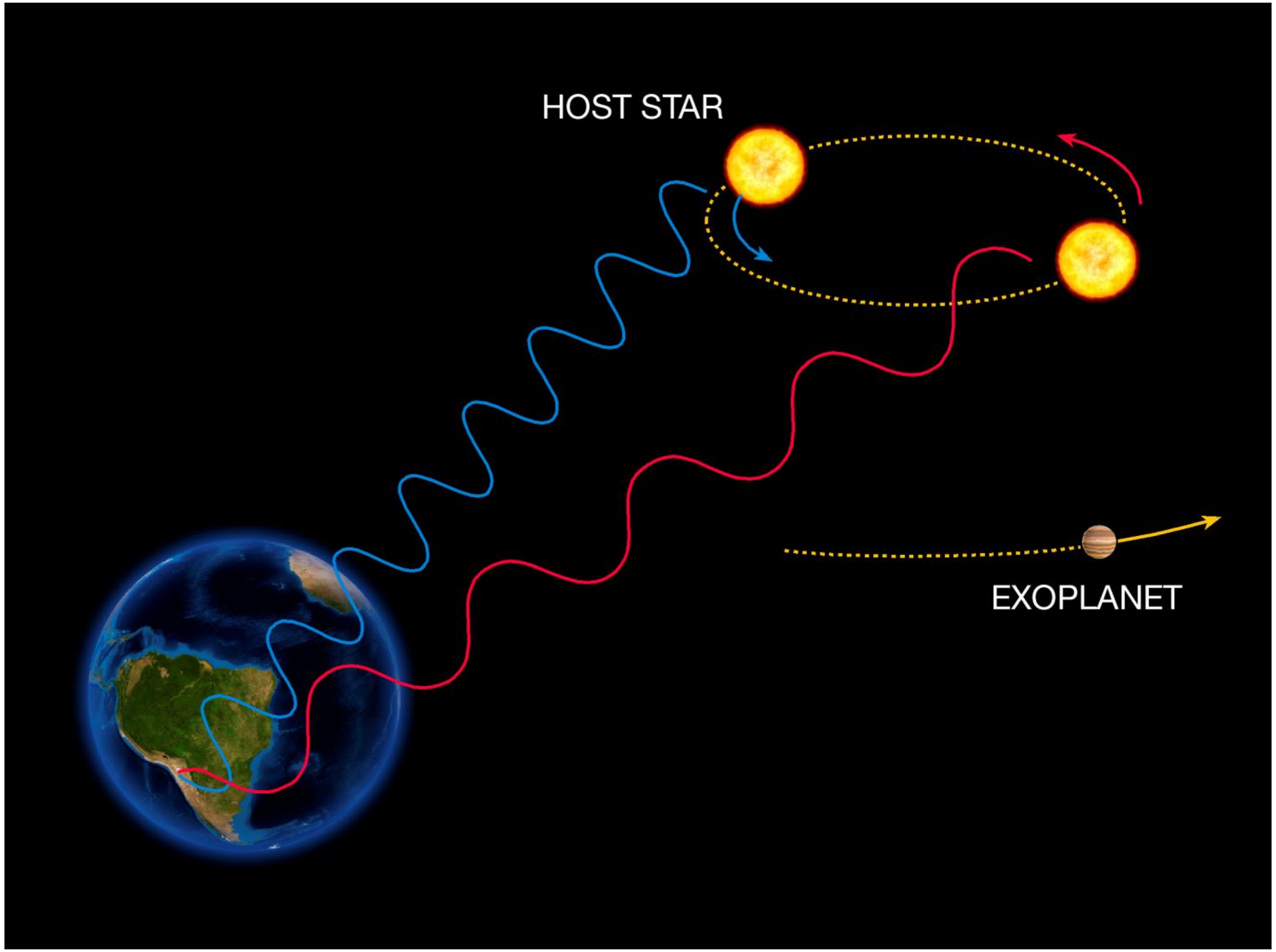
Together with the inclination constraint from astrometry, this implies a companion mass of 9.8 ± 0.2 ***M***



# Radial Velocity explained

RV of a target with respect to an observer is the rate of change of the distance or range between the two points. Radial velocity can be used to estimate the ratio of the masses of the stars, and some orbital elements, such as eccentricity and semimajor axis.

The same method has also been used to detect planets around stars, in the way that the movement's measurement determines the planet's orbital period, while the resulting radial-velocity amplitude allows the calculation of the lower bound on a planet's mass using the binary mass function.



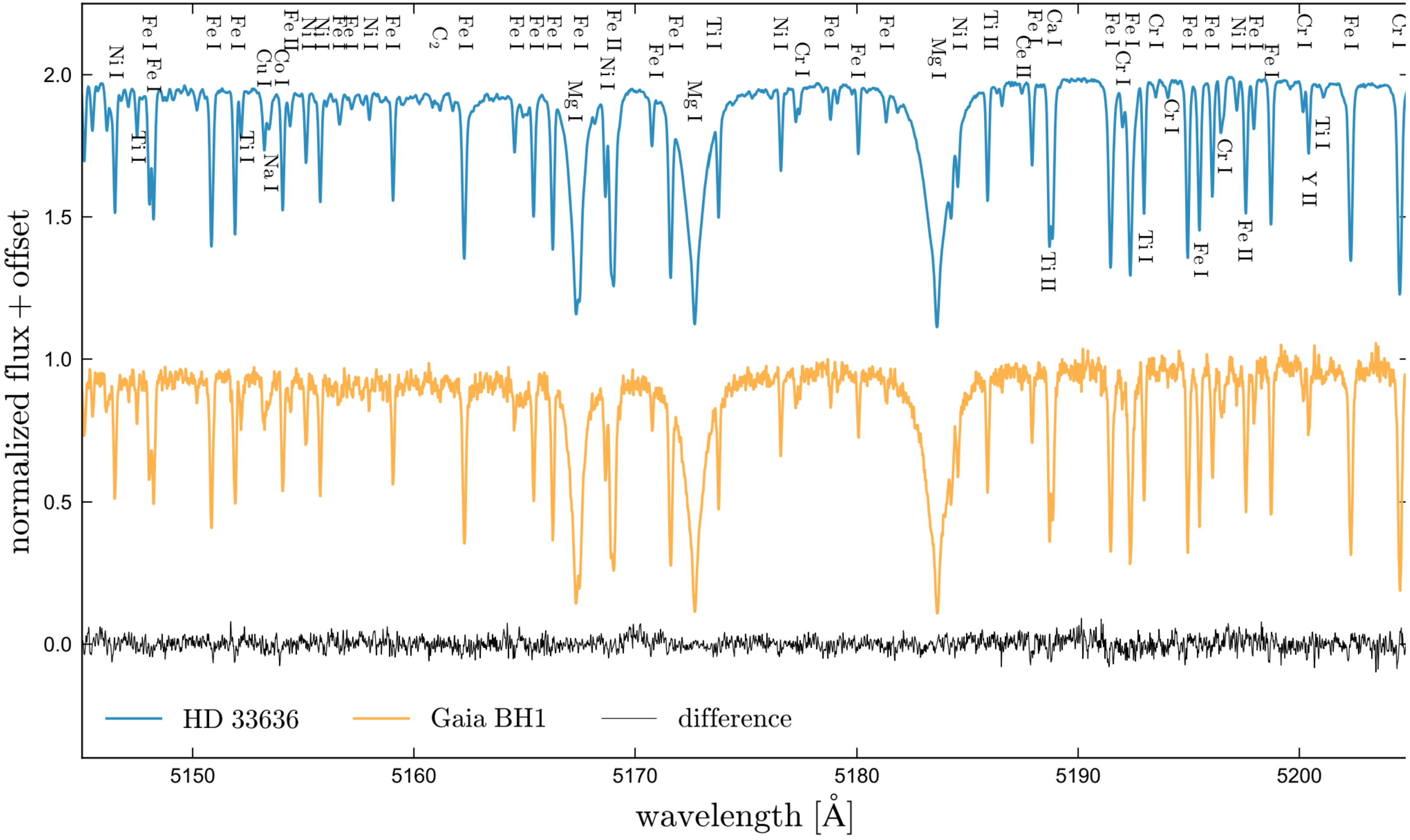



**Figure 5.** Comparison of the HIRES spectrum of Gaia BH1 (gold) and the standard star HD 33636 (blue). Black line shows the difference between the tw spectra. Cutout is centered on the Mg I b triplet; other identifiable lines are labeled. The two spectra are very similar, indicating that the surface properties ar abundances of the G star are normal for thin-disk stars in the solar neighborhood.

# Figure 3: BH1 spectrum

Comparison between the HIRES spectrum of Gaia BH1 to that of its closest match in the library, HD 33636.

The parameters of that star, as measured by Valenti & Fischer (2005) from the HIRES spectrum and synthetic spectral models, are $T$eff = 5904 K, log $g$ = 4.43, $v$ sin $i$ = 3.1 km s−1 , and [Fe/H] = −0.13.

The two spectra are strikingly similar. This simple comparison suggests that the luminous star in Gaia BH1 is a rather unremarkable solar-type star.

# Conclusions and follow up

The paper presented the discovery of Gaia BH1, a new binary system consisting of a $\sim 10\ \boldsymbol{M}$ dark object orbited by an otherwise unremarkable Sun-like star.

It was assumed a BH candidate by Gaia astrometry solutions but even without that consideration, the Radial Velocities imply a companion mass that can only be attributed to a BH. Scenarios not involving a BH are firmly ruled out by the object's large mass and stringent limits on the light contributions of a luminous companion.

Gaia BH1 is different than other known BHs in binaries. It is nearby ($\boldsymbol{d}$ = 480 pc) and bright ($\boldsymbol{G}$ = 13.8). Without an accretion disk and the fact that the luminous star is cool and slowly rotating, this makes it possible to study the system in greater detail in the optical than is possible for BH X-ray binaries.

Because of its long orbital period and close distance, the angular size of Gaia BH1's orbit on the sky is more than 10 times larger than any other known BH binary. This makes the system an excellent target for interferometric follow-up.

Gaia BH1 provides a unique opportunity to test imperfectly-understood models of accretion flows at very low accretion rates