

The Galactic Underworld

The Milky Way's dormant black holes and neutron stars

Kareem El-Badry
Caltech

*What is essential is
invisible to the eye.*

- Antoine de Saint-Exupéry,
The Little Prince





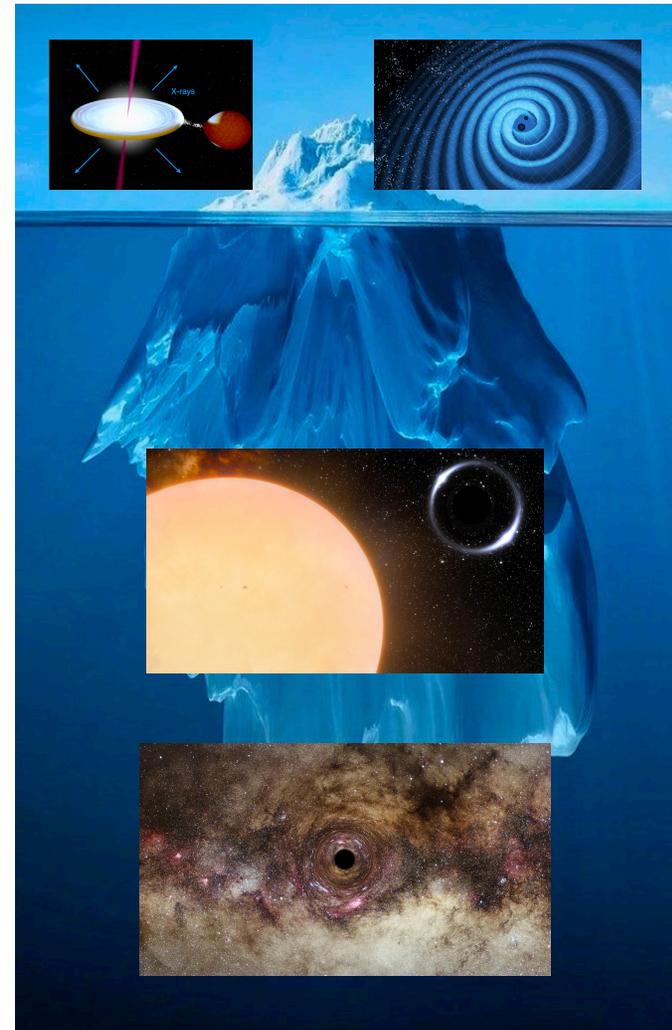
Kareem El-Badry (Caltech)

X-ray binaries and
gravitational wave events:
“easy” to find, but rare



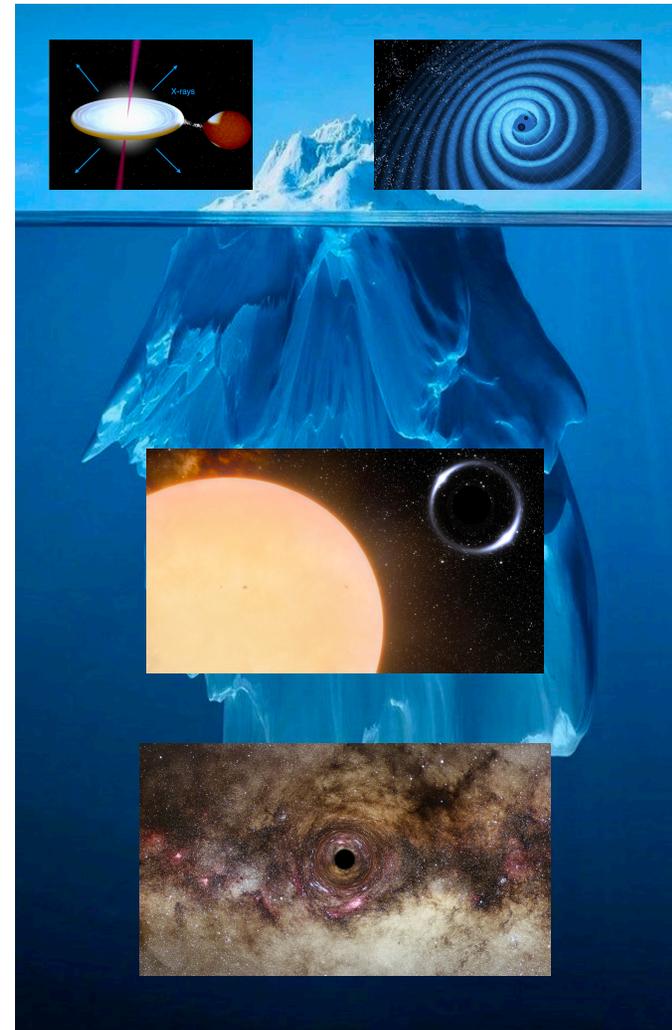
X-ray binaries and
gravitational wave events:
“easy” to find, but rare

BHs in wide binaries +
isolated BHs:
hard to find, but common



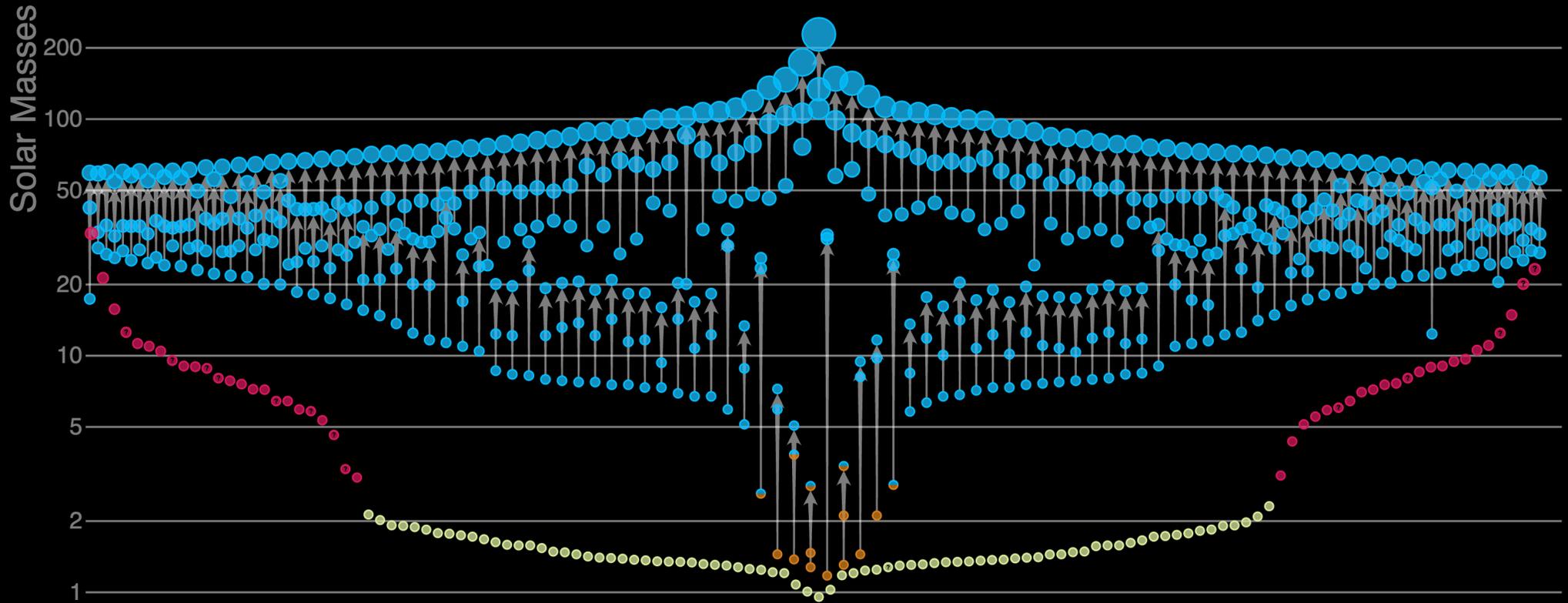
*Time present and time past
Are both perhaps present in time future,
And time future contained in time past.*

T.S. Eliot, Four Quartets



Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars

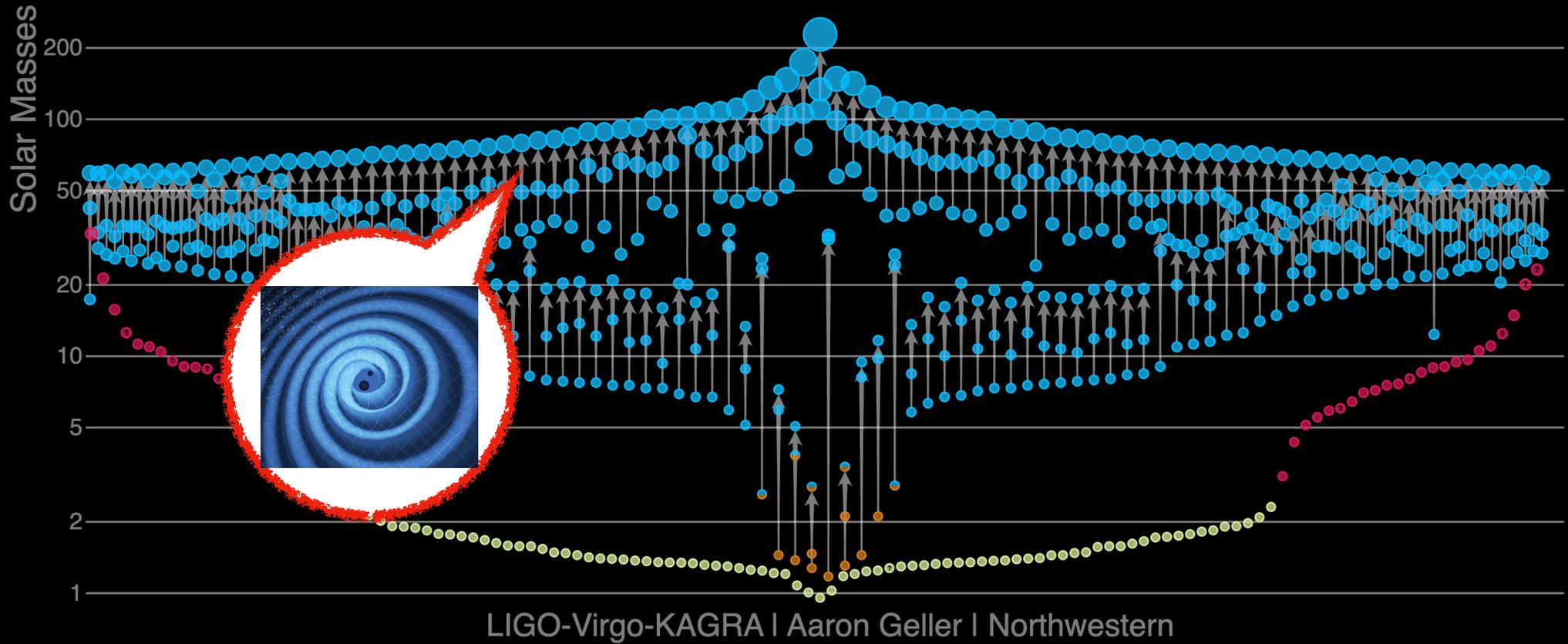


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Kareem El-Badry (Caltech)

Masses in the Stellar Graveyard

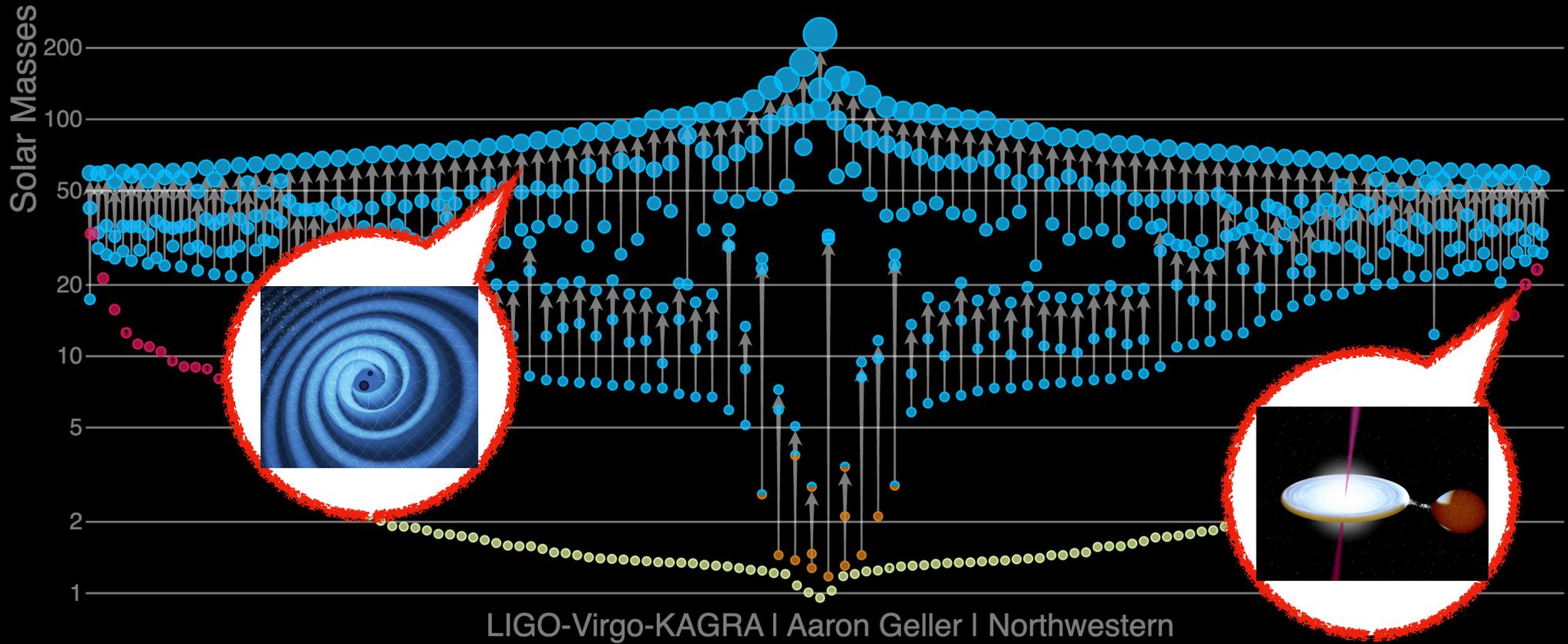
LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*



Kareem El-Badry (Caltech)

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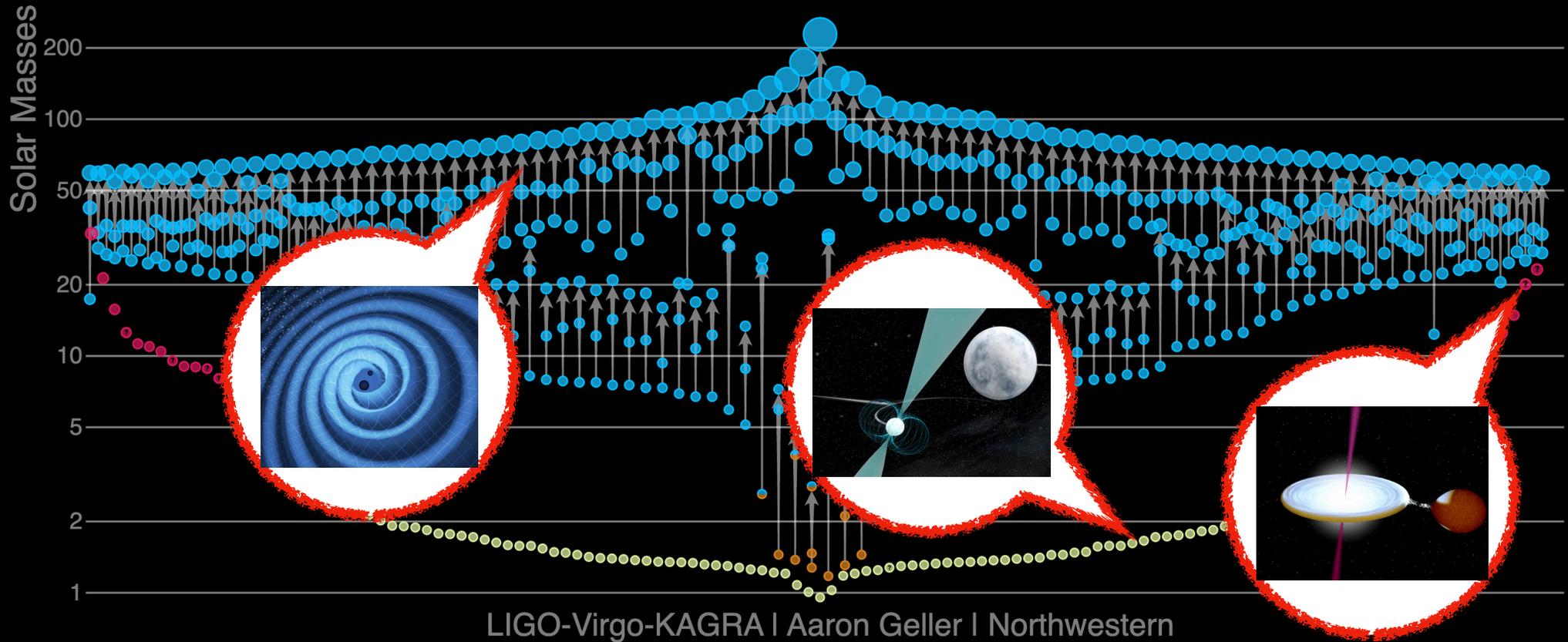
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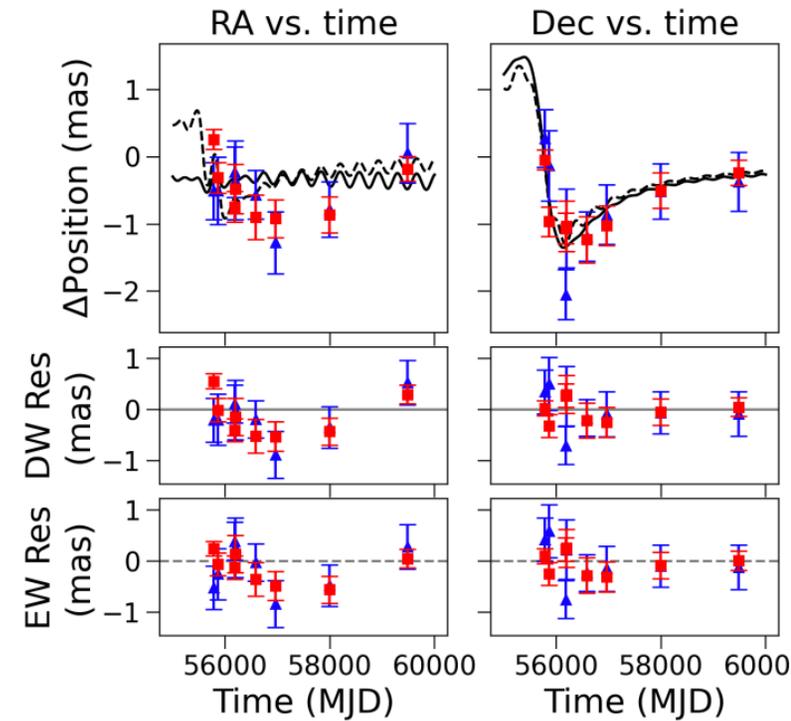
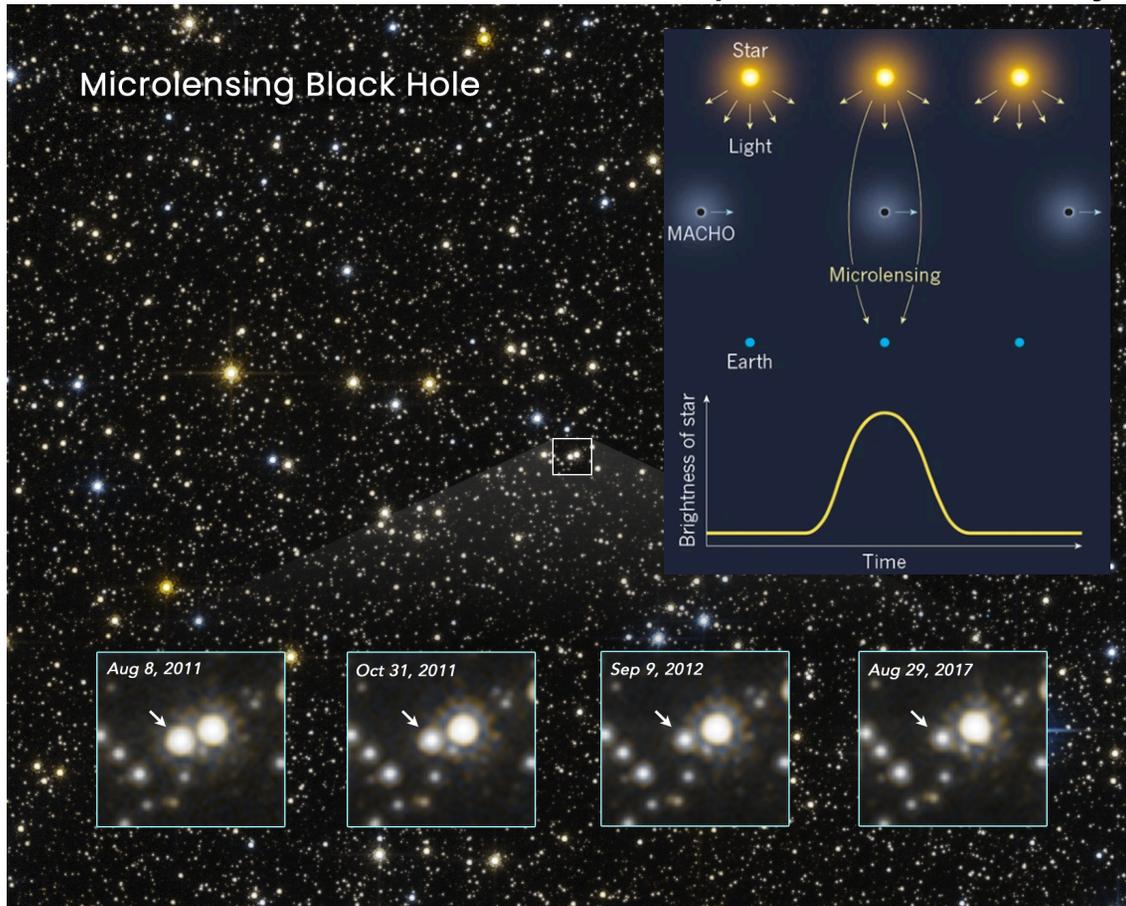
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LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

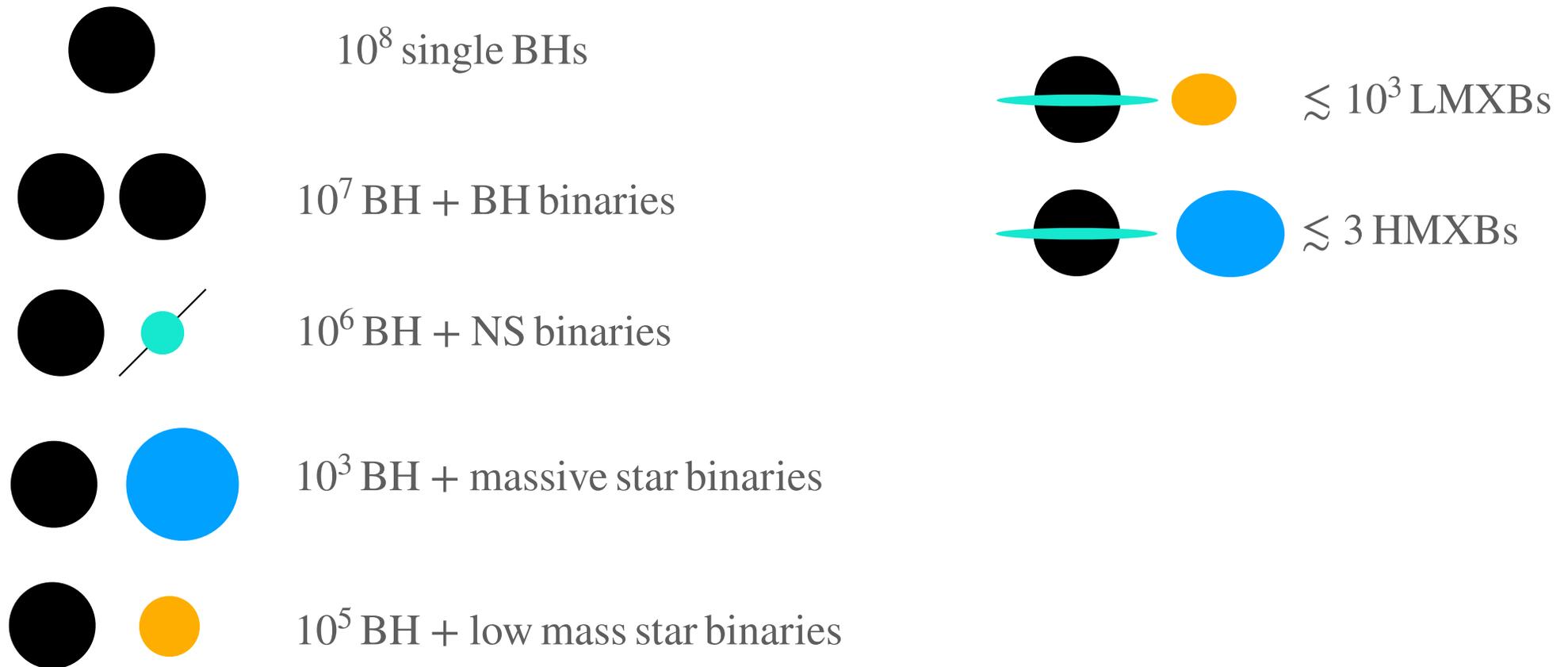
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Microlensing: probably the only way to find isolated BHs requires astrometry (so far)

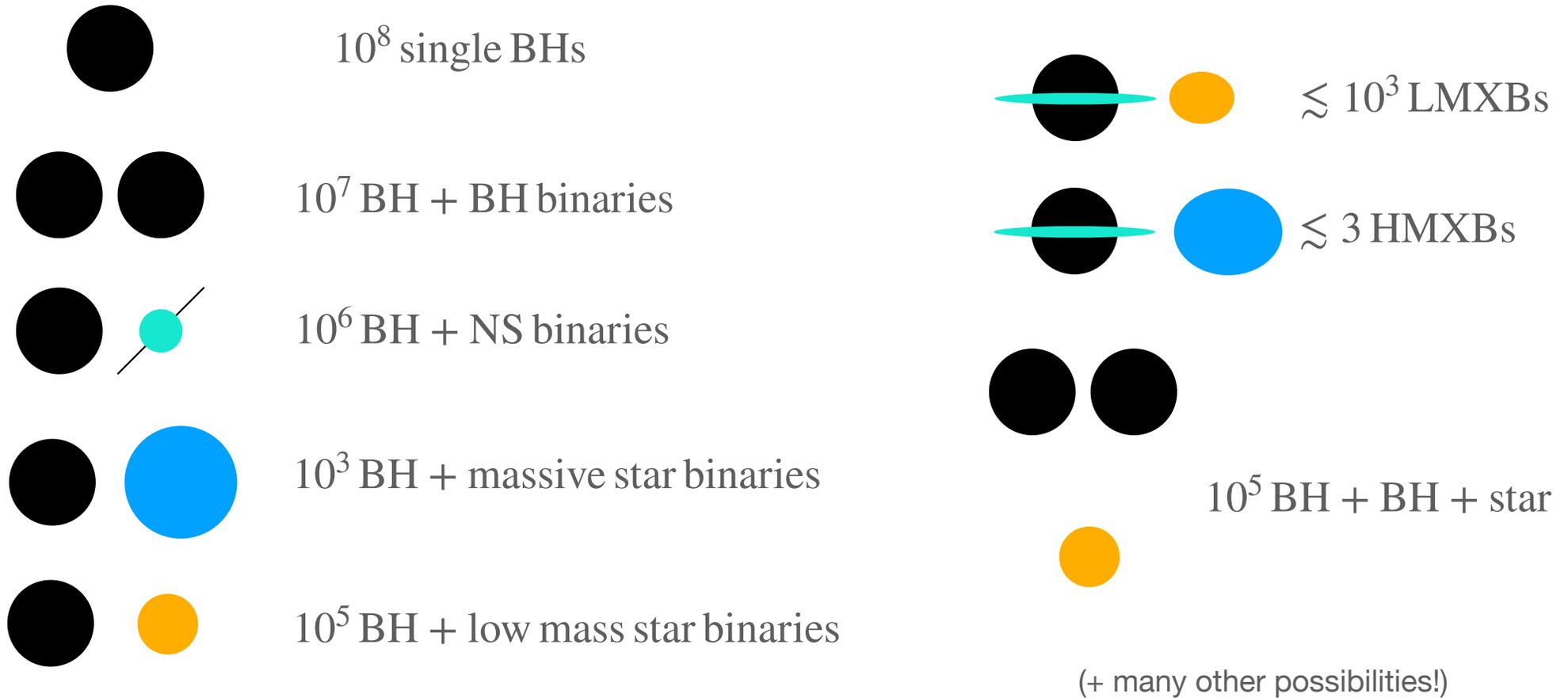


Lam+2022
Sahu+2022
Mroz+2022
Lu, Lam 2023

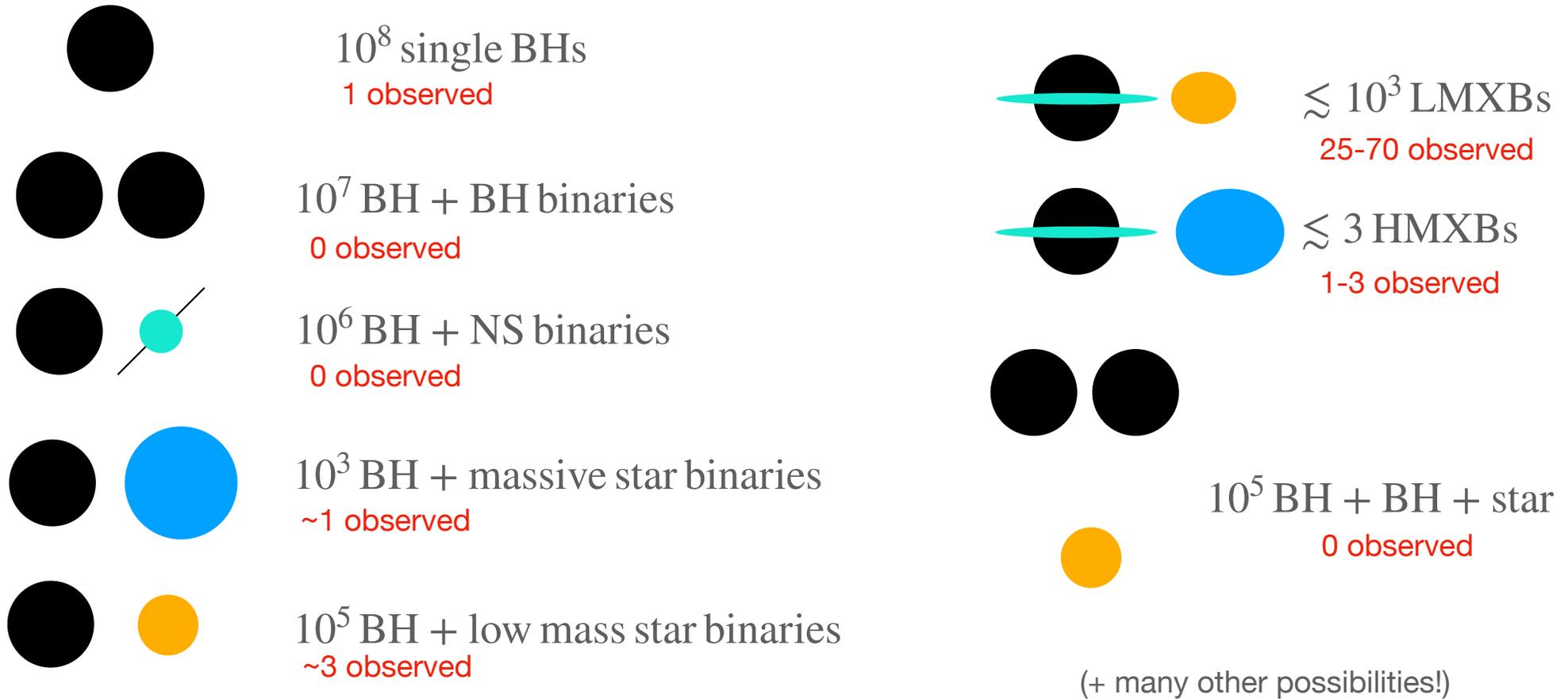
Population demographics of Galactic BHs (KE guesstimates)



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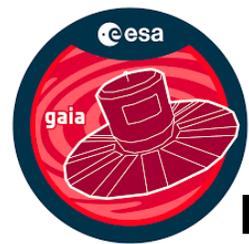
Population demographics of Galactic BHs (KE guesstimates)



Open questions

- What are the masses, spins, and natal kicks of BHs and NSs?
- How do these quantities depend on properties of the progenitor stars?
- How do BH/NS binaries form, evolve, and survive?
- What else lurks in the dark?

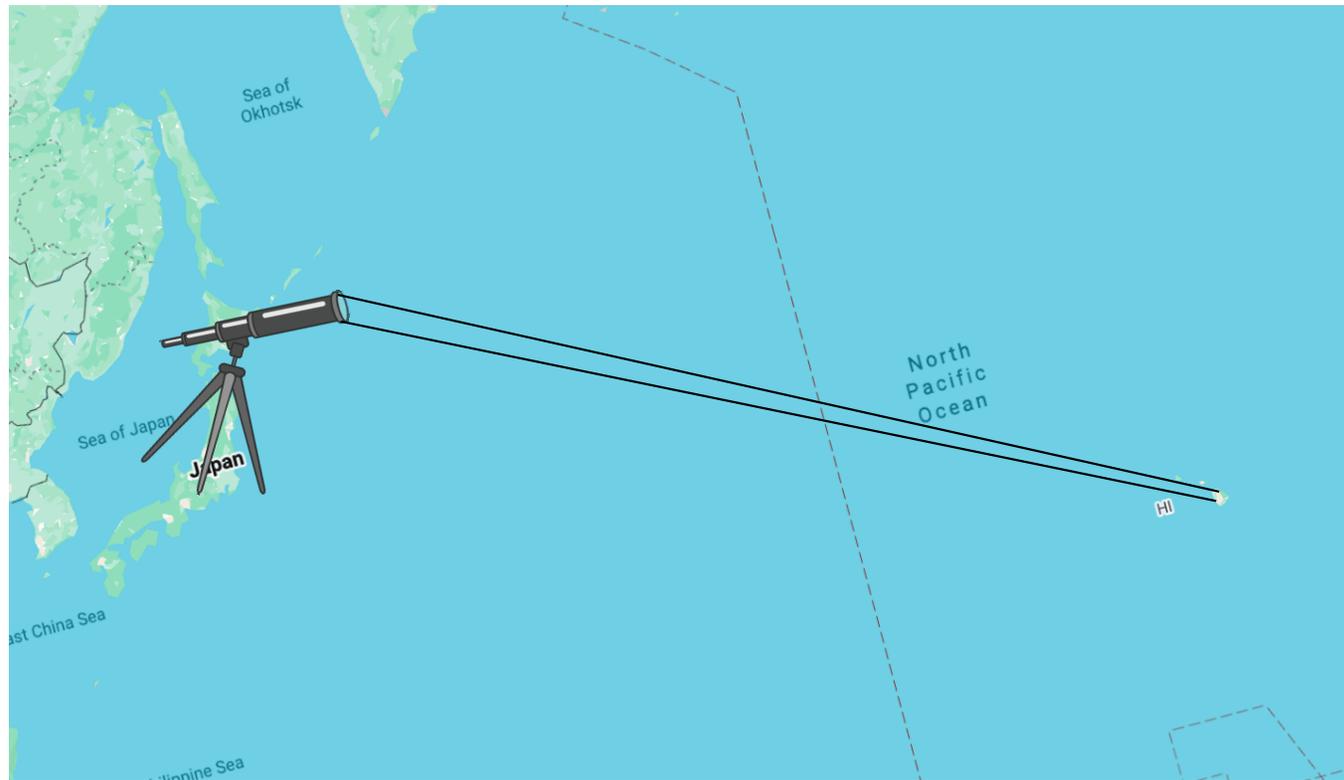
The *Gaia* mission: precise positions for 2 billion stars



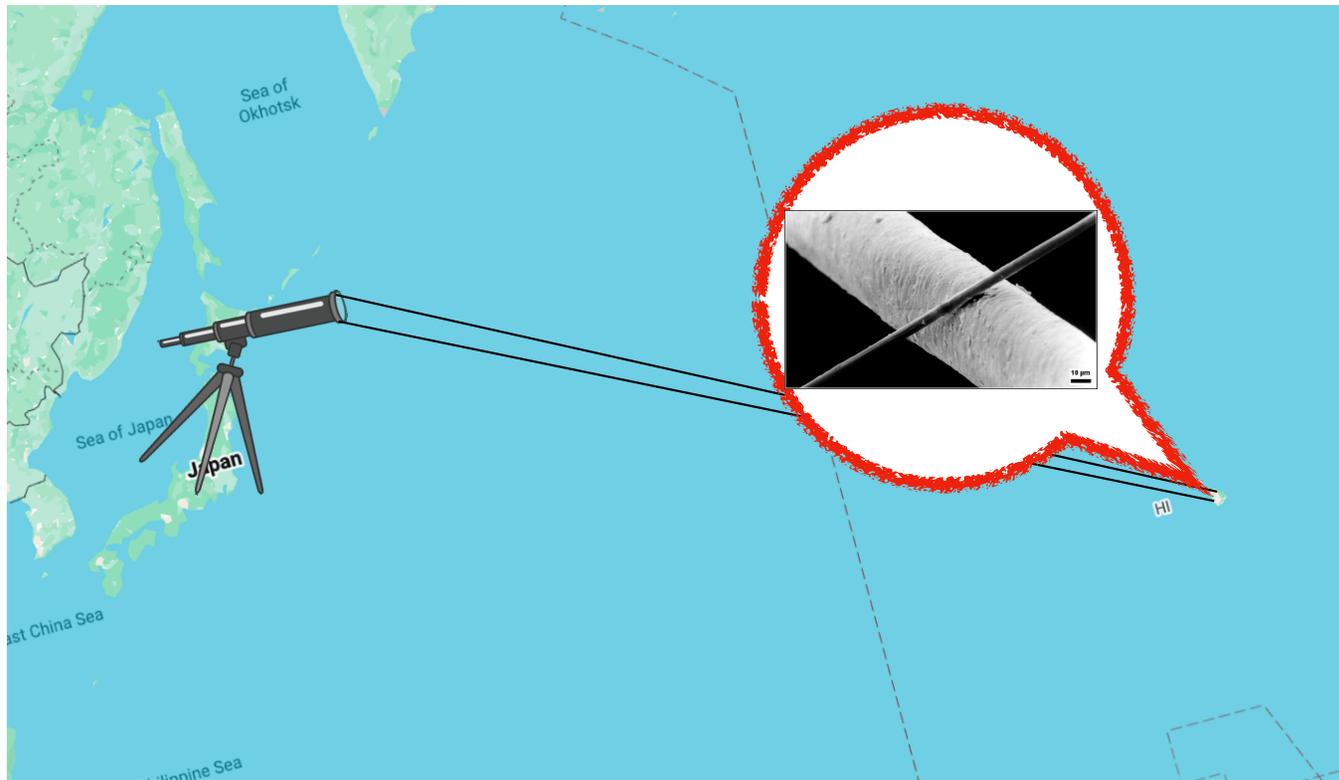
Gaia scans the whole sky every ~30 days, for 11 years

Records astrometry with ~0.01 milliarcsecond precision (at bright end)

0.01 milliarcsecond precision

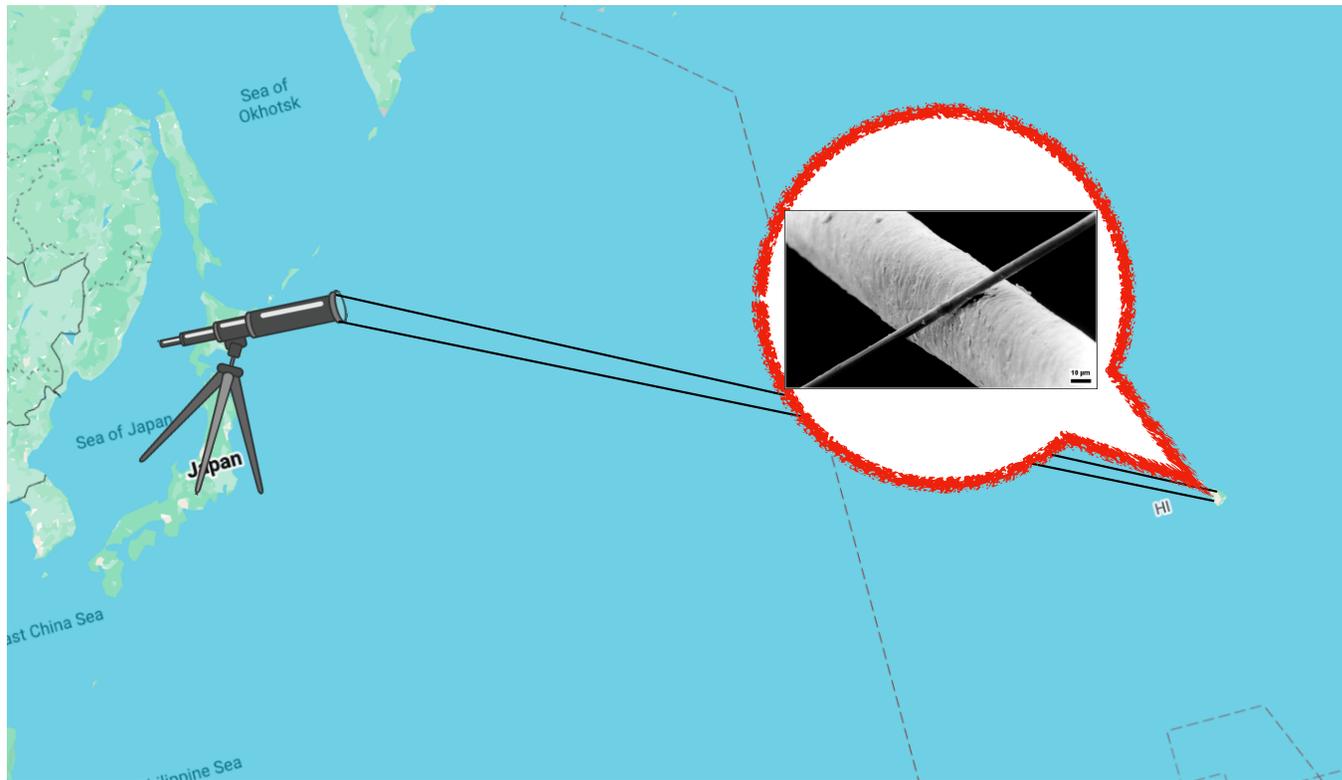


0.01 milliarcsecond precision



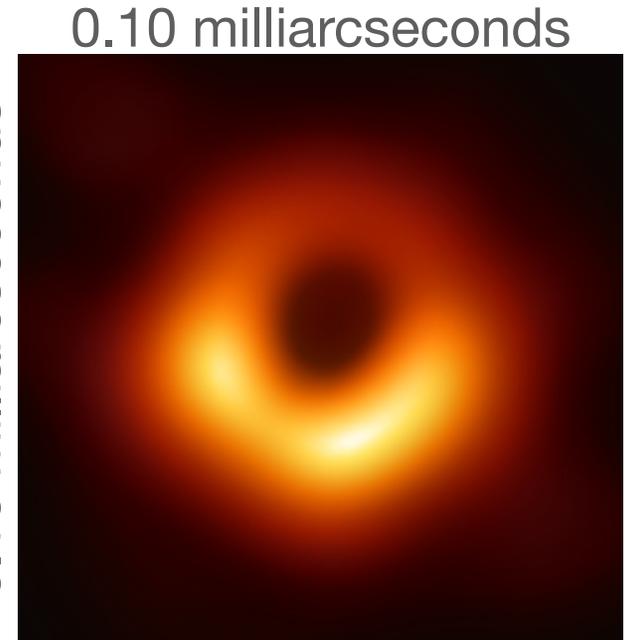
$$\frac{0.2 \text{ mm}}{5000 \text{ km}} = 0.01 \text{ milliarcseconds}$$

0.01 milliarcsecond precision

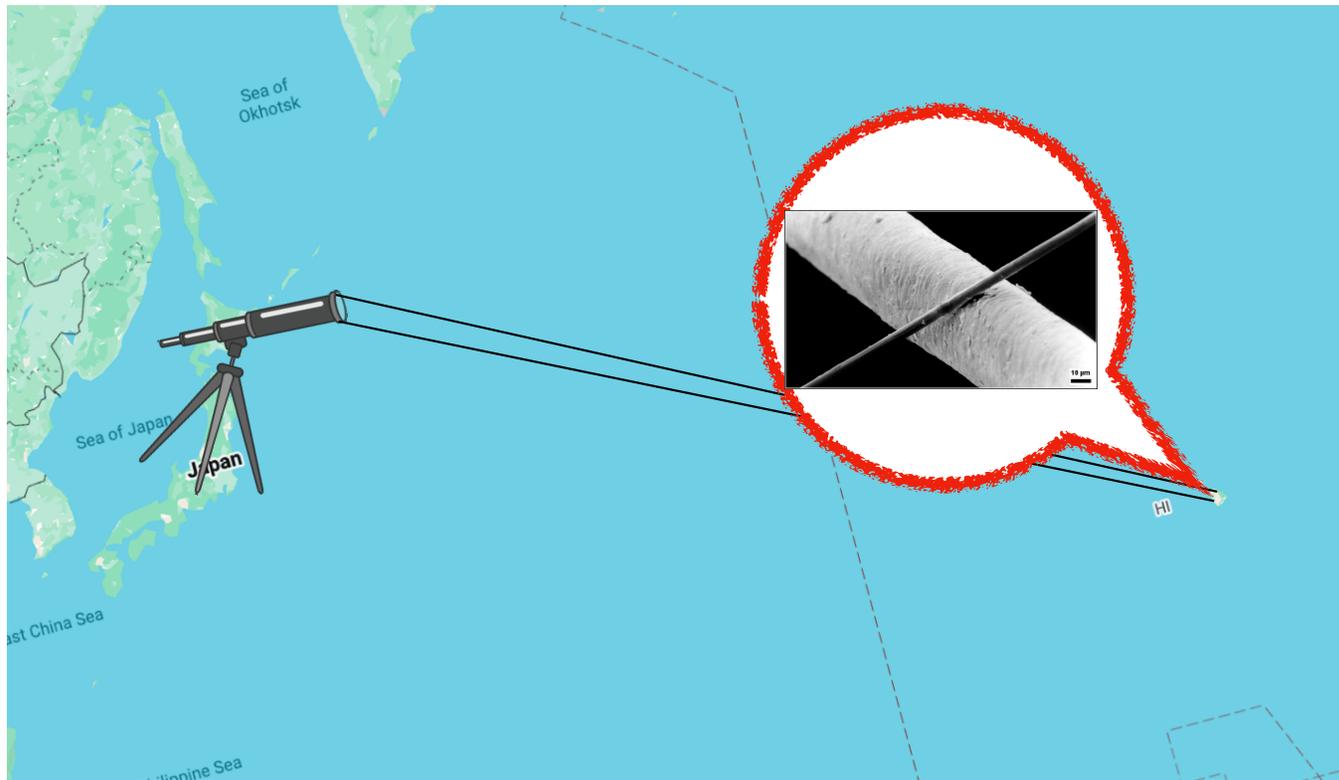


$$\frac{0.2 \text{ mm}}{5000 \text{ km}} = 0.01 \text{ milliarcseconds}$$

0.10 milliarcseconds

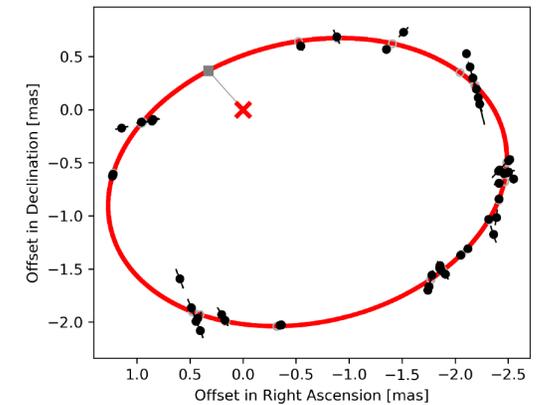


0.01 milliarcsecond precision



$$\frac{0.2 \text{ mm}}{5000 \text{ km}} = 0.01 \text{ milliarcseconds}$$

Gaia observes a binary



(Observations over 3 years)



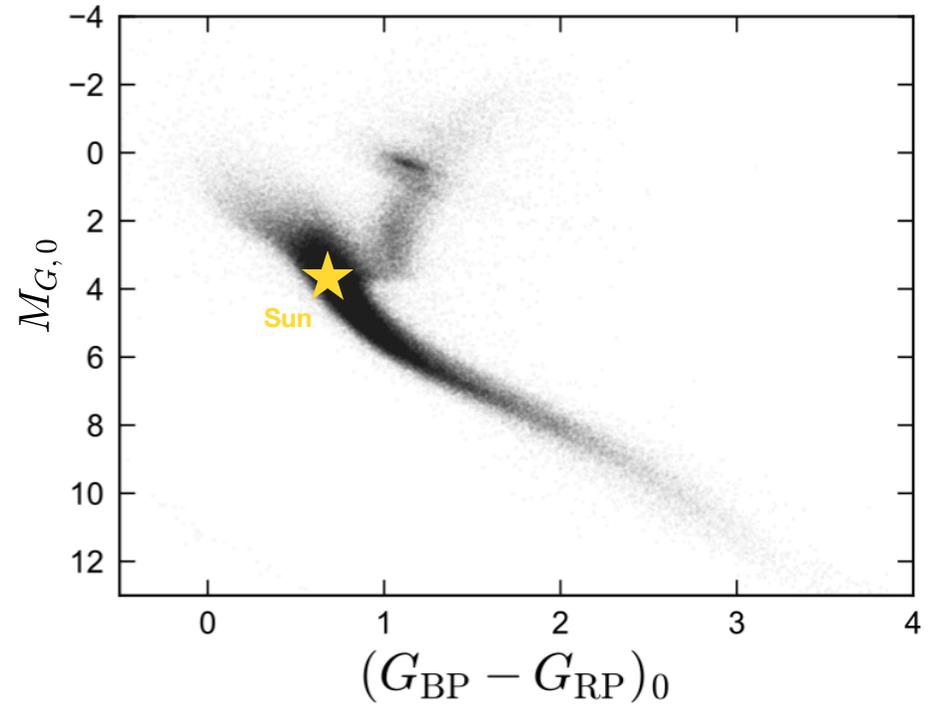
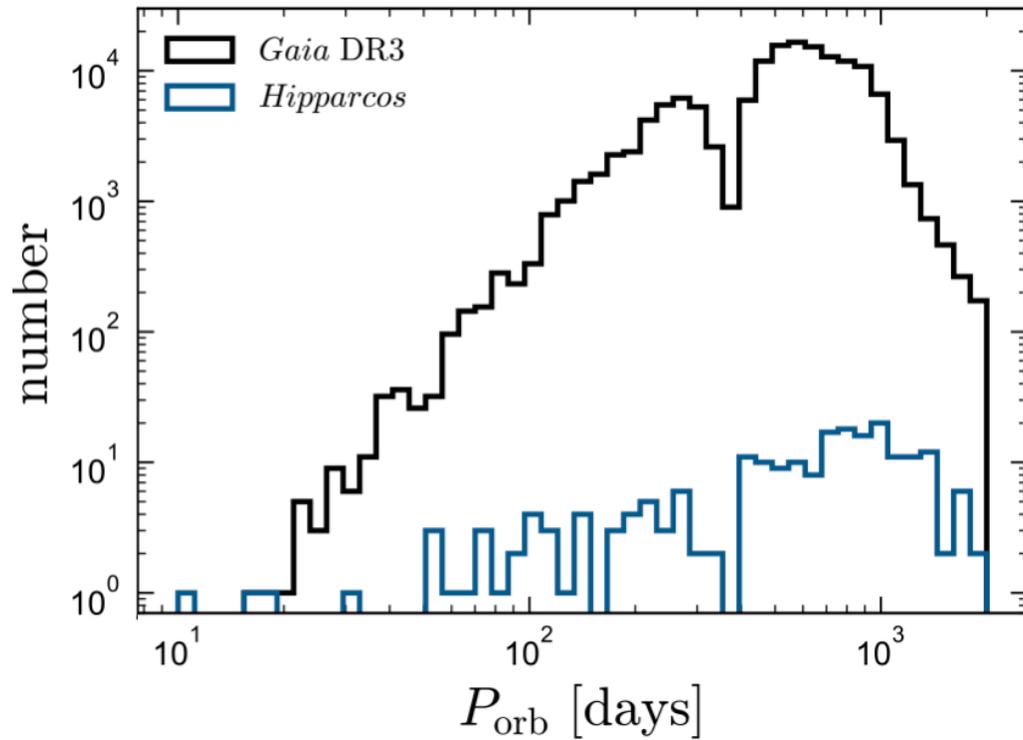
RIP *Gaia* (2014-2025)

11 year baseline: sensitive to orbits up to ~20 years
~120 astrometric measurements per source on average

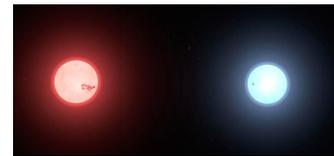
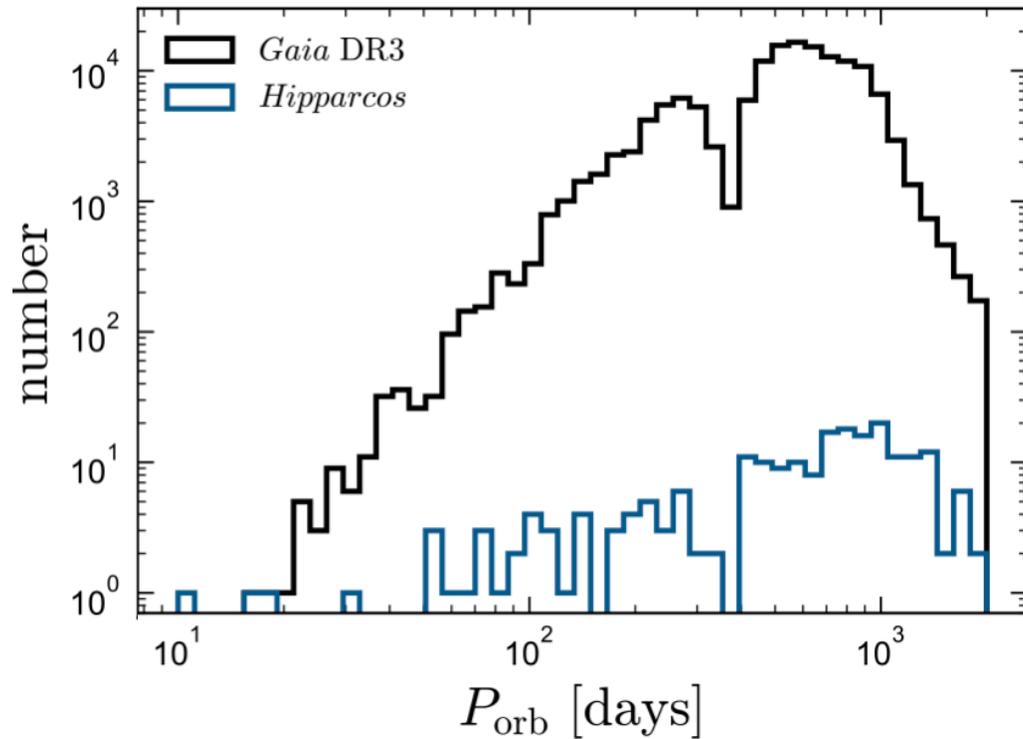
Only the first 3 years of data are processed so far.

DR4 this December. The best is yet to come!

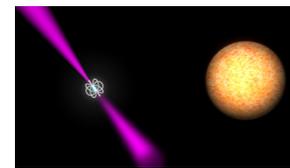
Gaia DR3: 170,000 astrometric binary solutions
factor of ~ 50 increase over all previous literature



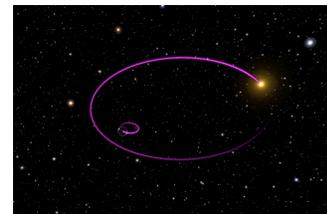
Gaia DR3: 170,000 astrometric binary solutions
factor of ~50 increase over all previous literature



5000 WD candidates
~5000 robust

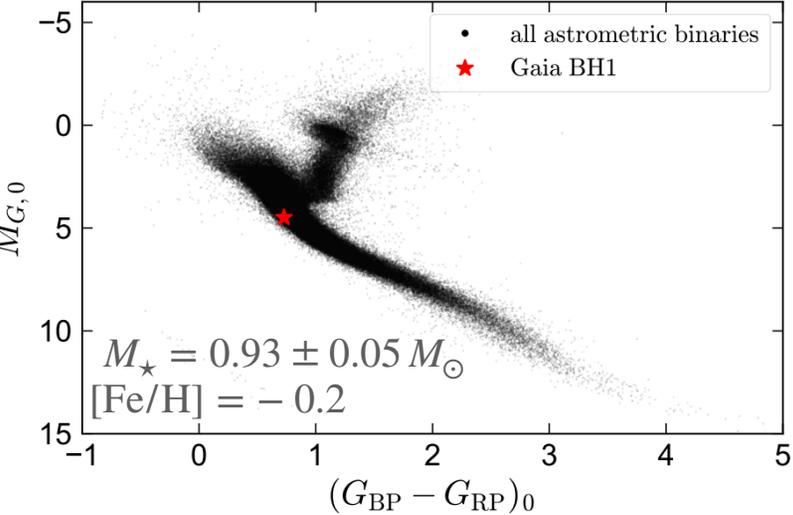


50 NS candidates
~25 confirmed

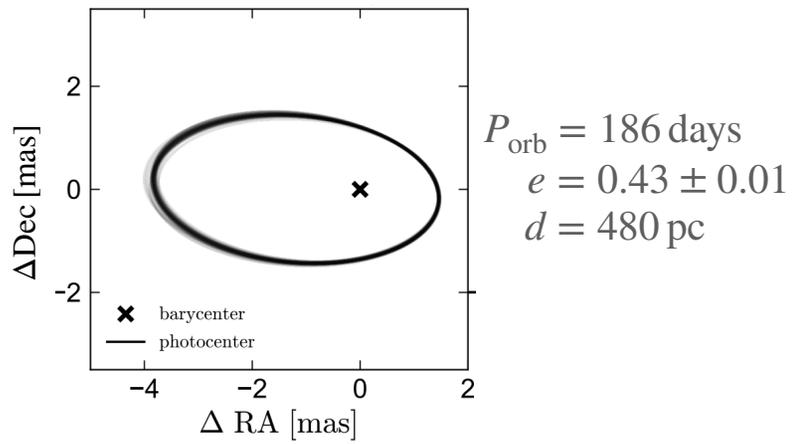
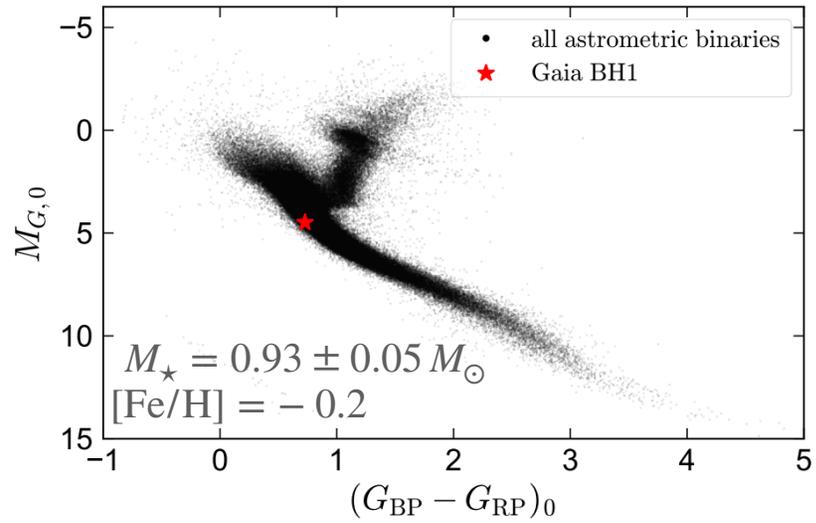


5 BH candidates
2 confirmed

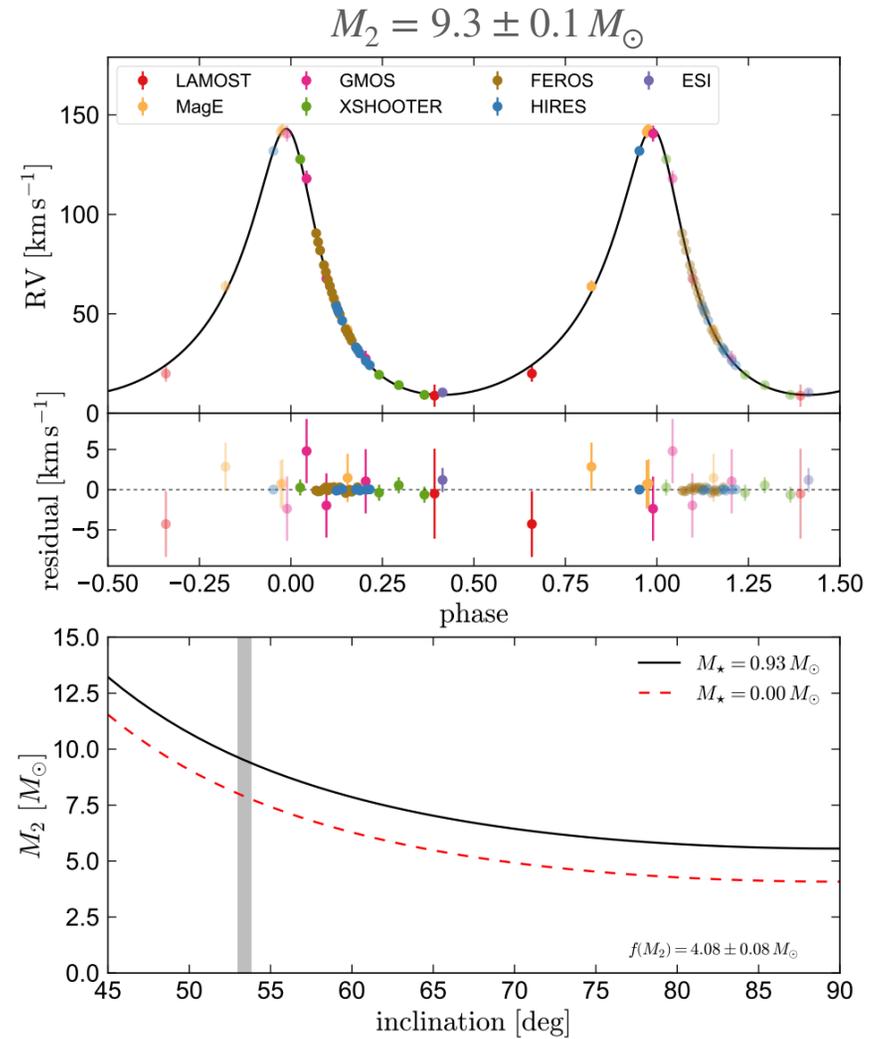
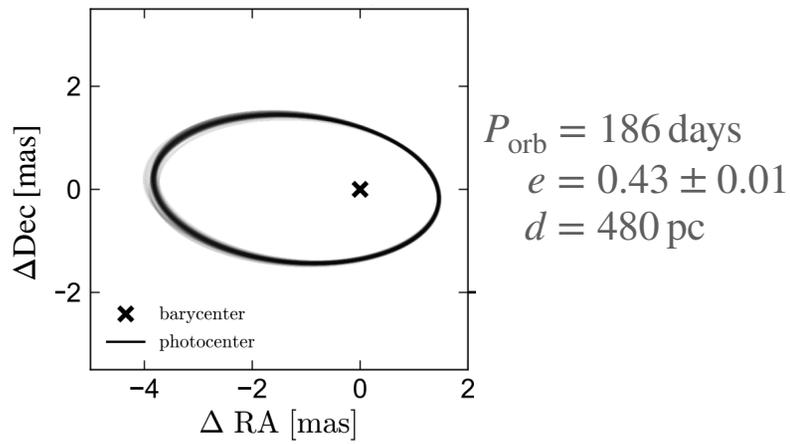
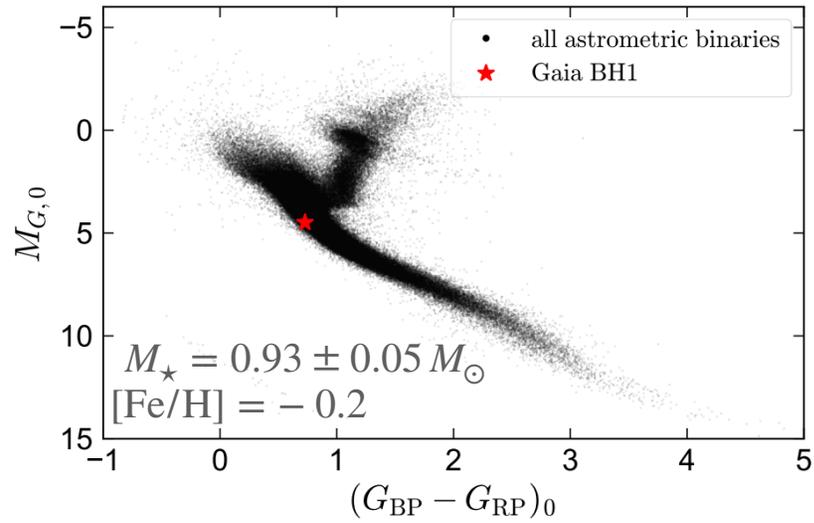
Gaia BH1



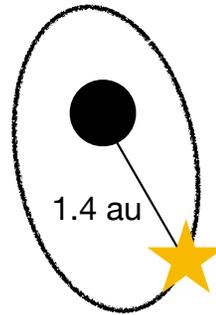
Gaia BH1



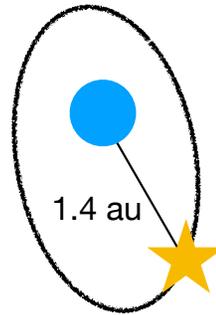
Gaia BH1



How to form this?



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$10 M_{\text{sun}} \text{ BH} = \sim 40 M_{\text{sun}} \text{ progenitor?}$

How to form this?



$10 M_{\text{sun}}$ BH = $\sim 40 M_{\text{sun}}$ progenitor?



If systems survives a common envelope, final separation should be very tight

There are currently *significantly* more models than Gaia BHs

Isolated binary evolution (+ strong winds): Gilkis & Mazeh 2024, Iorio+2024, Kotko+2024, Kruckow+2024, Chawla+2025, Olejak+2025

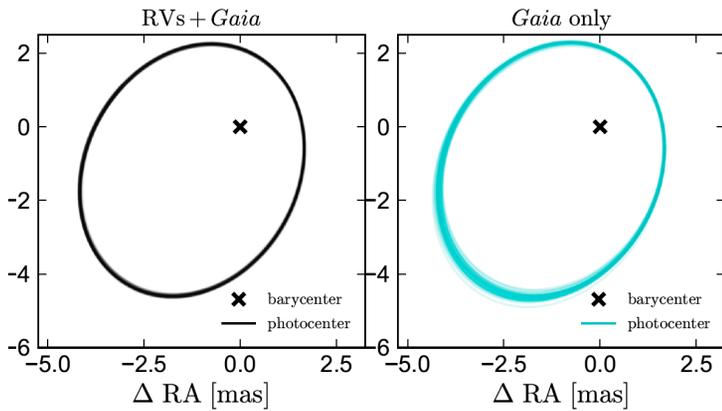
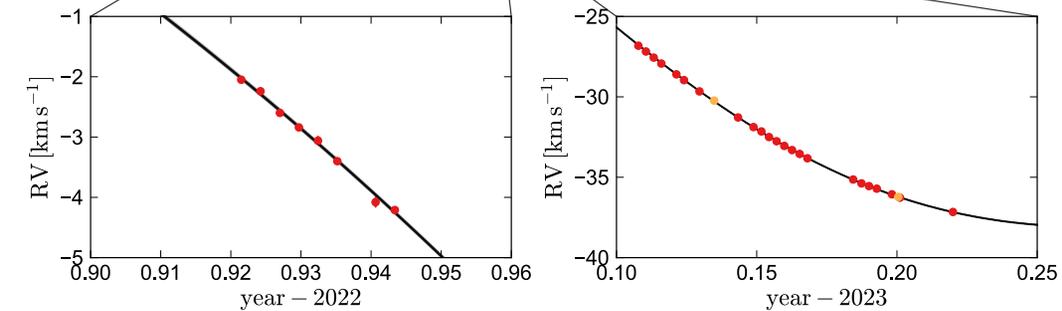
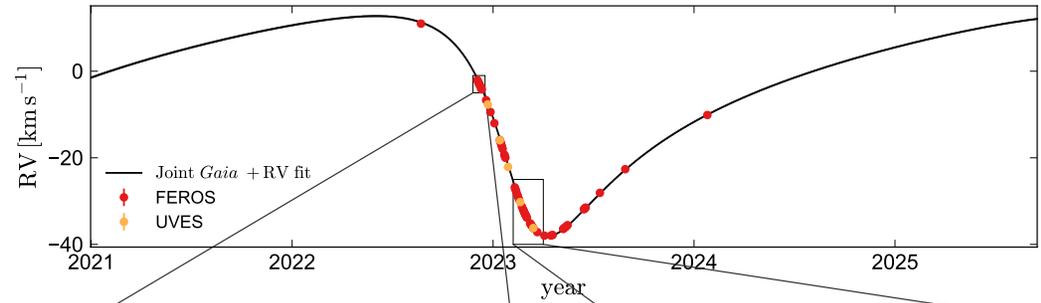
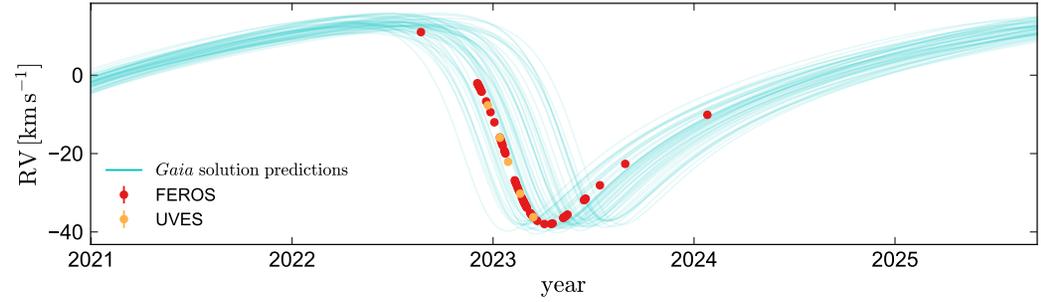
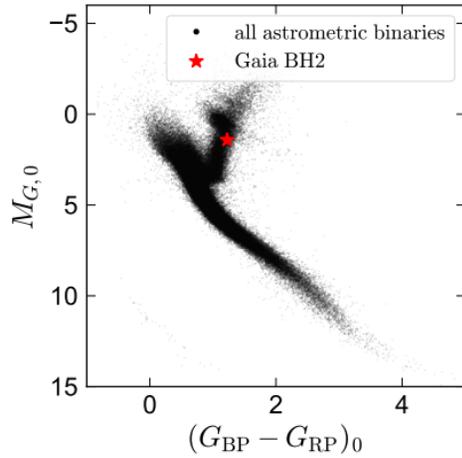
Triples: Li+2024, Generozov & Perets 2024, Nagarajan+2024, Naoz+2025, Hu+2025, Li+2026

Open clusters: Rastello+2023, Marín Pina+2024, Di Carlo+2024, Tanikawa+2024, Zhou 2025

Massive clusters: Fantoccoli+2025, Souvatzis+2025, Banerjee 2025, 2026

Gaia BH2

$M_{\star} = 1.07 \pm 0.19 M_{\odot}$
[Fe/H] = -0.2
 $M_2 = 9.0 \pm 0.3 M_{\odot}$
 $P_{\text{orb}} = 1277$ days
 $a = 4.9$ au
 $e = 0.52$
 $d = 1.16$ kpc



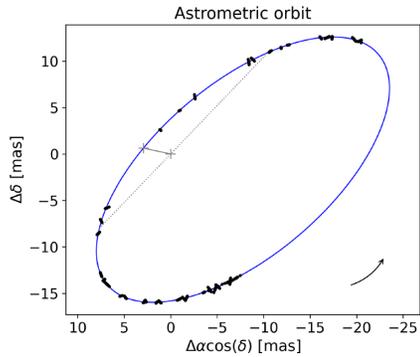
El-Badry et al. 2023; Tanikawa+2023

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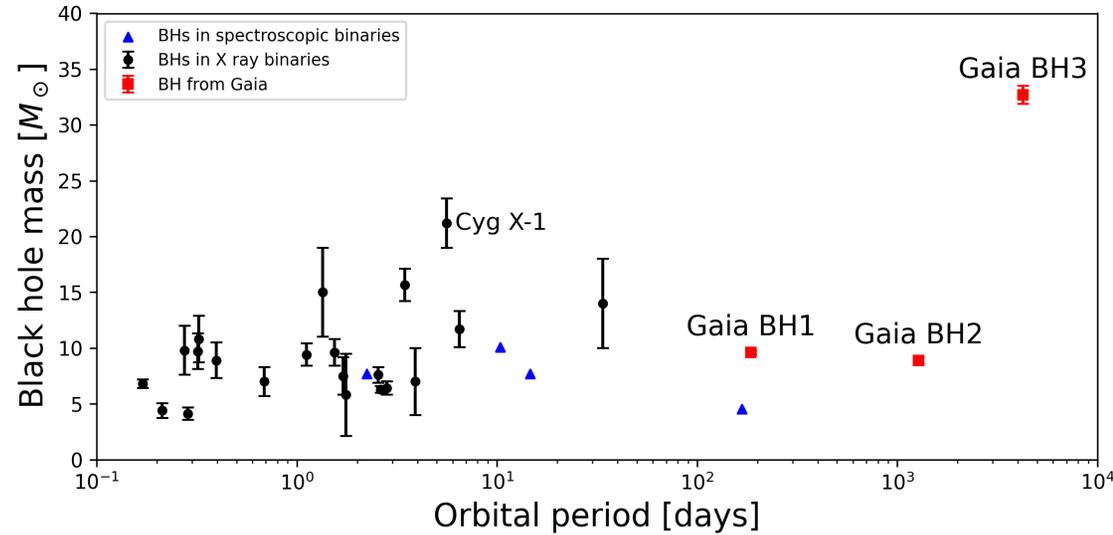
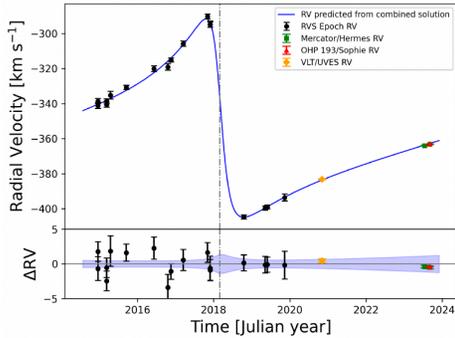
But wait, there's more!

Gaia BH3

(From pre-release DR4 astrometry)



$M_{\star} = 0.76 \pm 0.04 M_{\odot}$
 $[\text{Fe}/\text{H}] = -2.5$
 $M_2 = 33 \pm 1 M_{\odot}$
 $P_{\text{orb}} = 4250 \text{ days}$
 $a = 16.5 \text{ au}$
 $e = 0.73$
 $d = 0.59 \text{ kpc}$
 $[\text{Fe}/\text{H}] = -2.5$

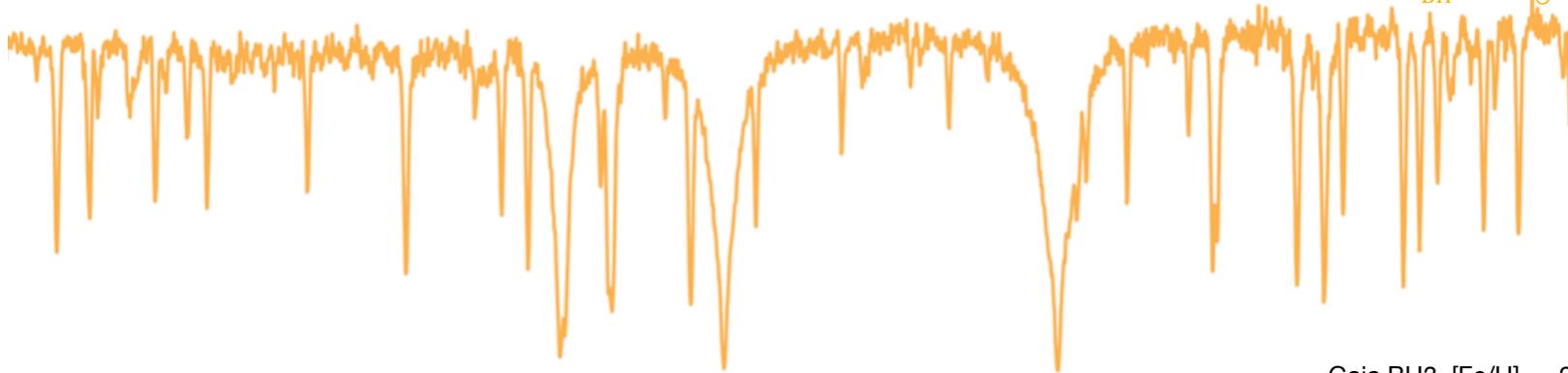


Gaia Collaboration, 2024

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We have metallicities!

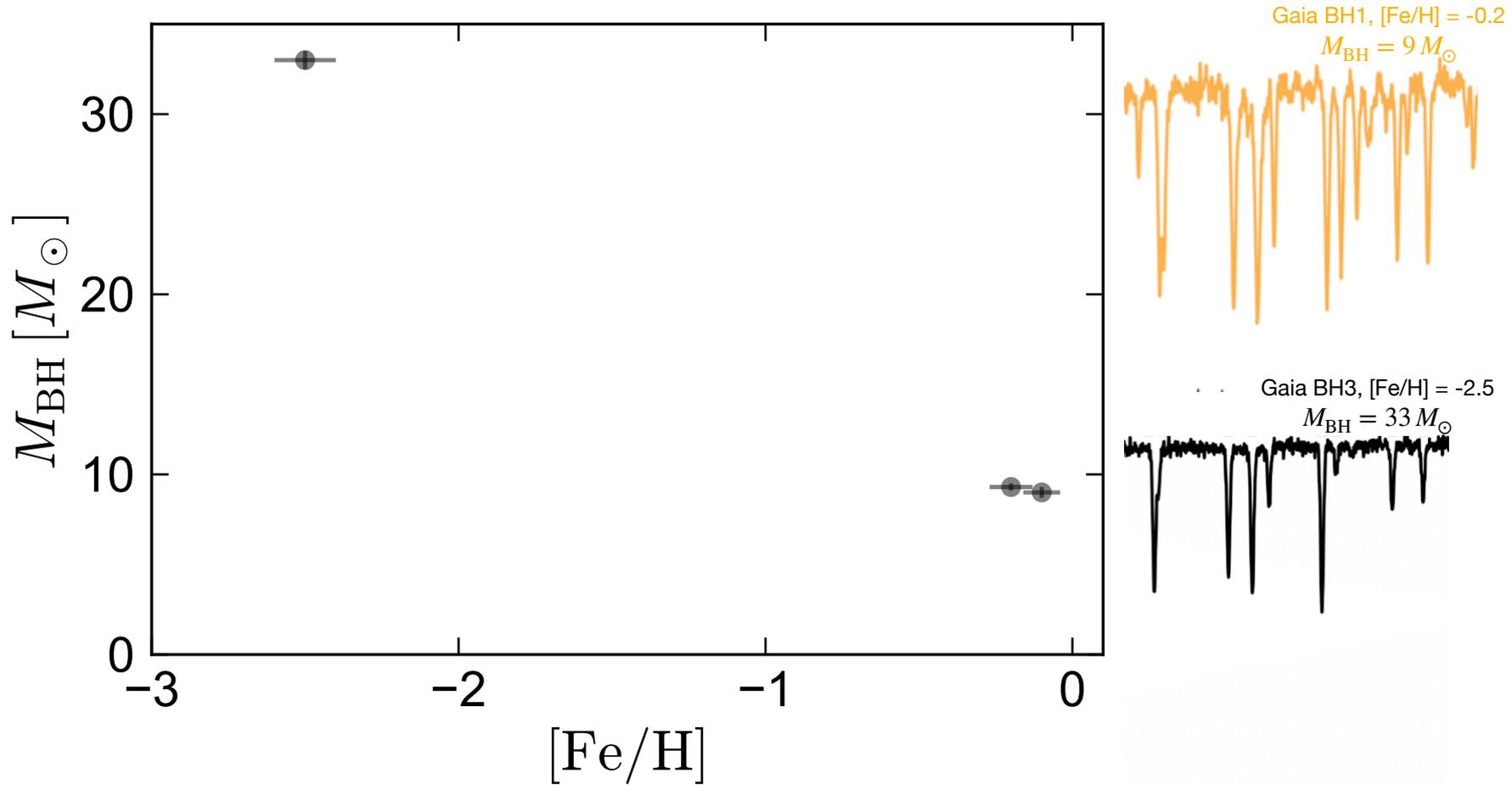
Gaia BH1, [Fe/H] = -0.2
 $M_{\text{BH}} = 9 M_{\odot}$



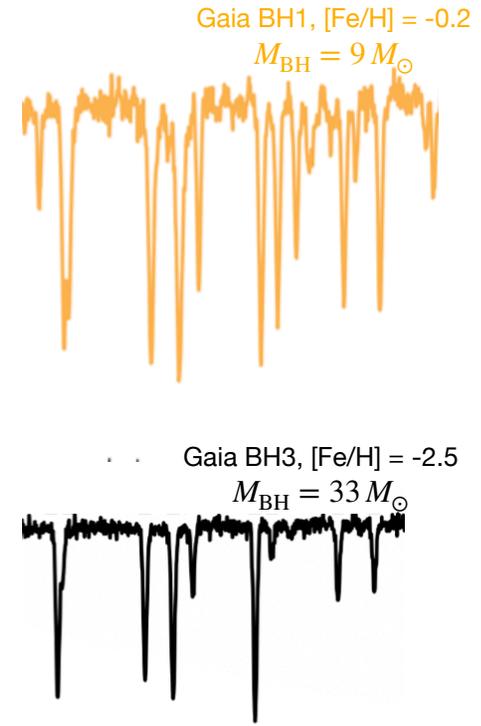
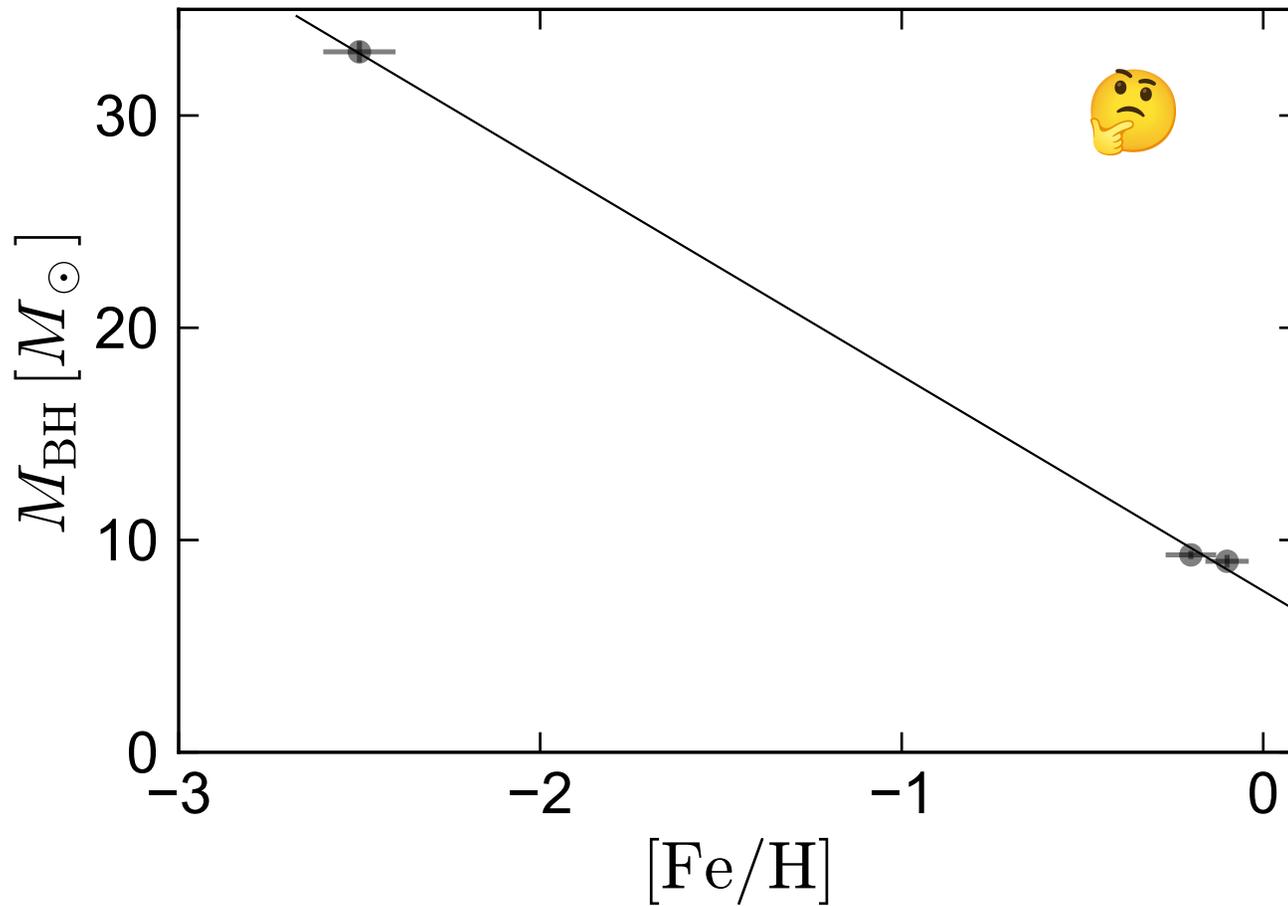
Gaia BH3, [Fe/H] = -2.5
 $M_{\text{BH}} = 33 M_{\odot}$



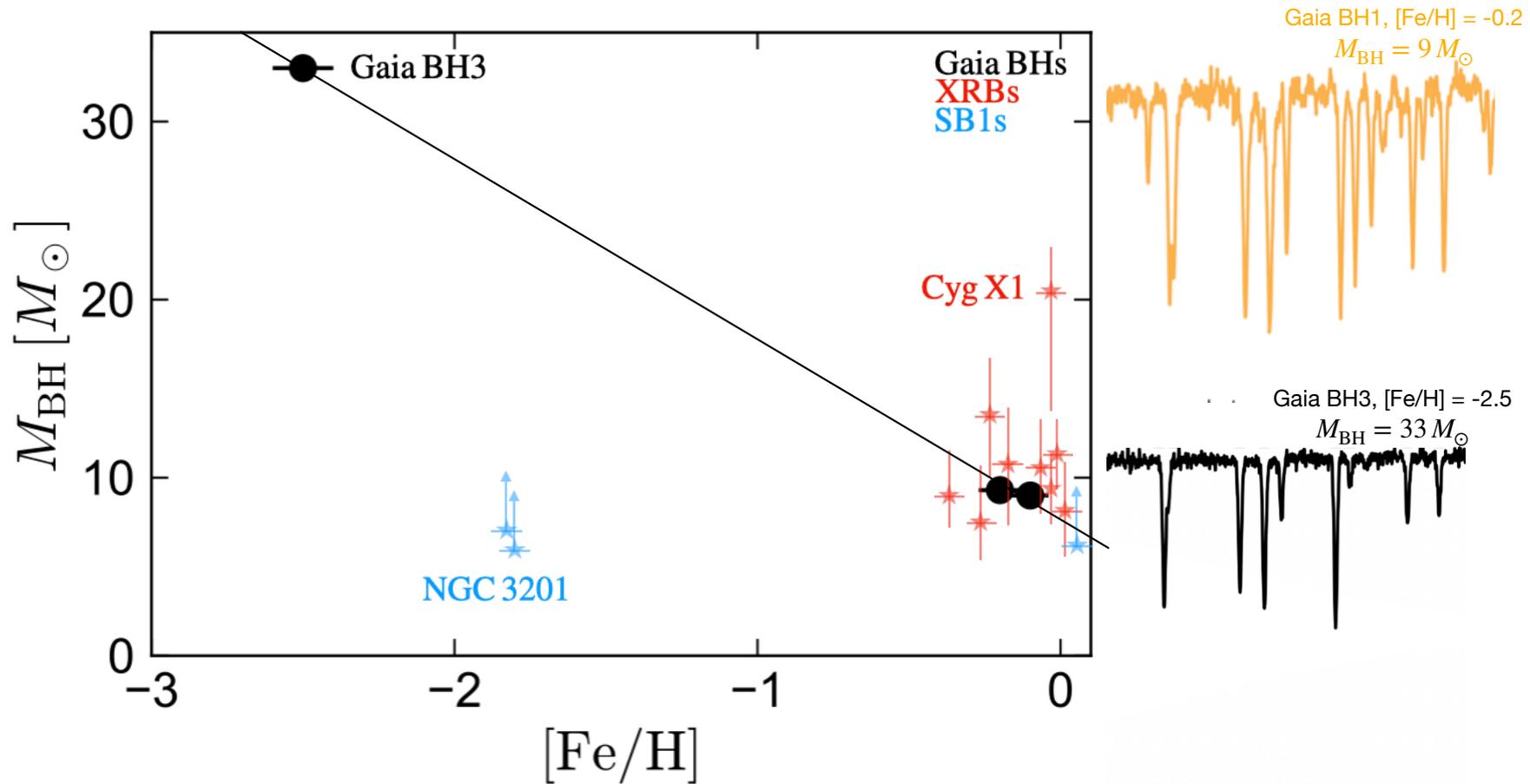
We have metallicities!



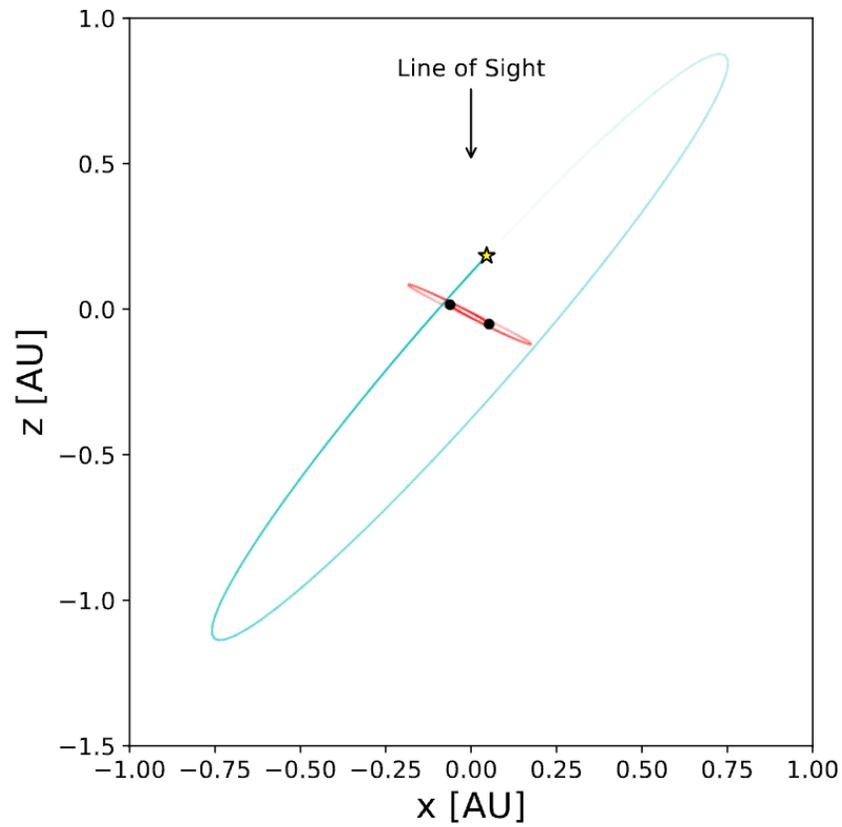
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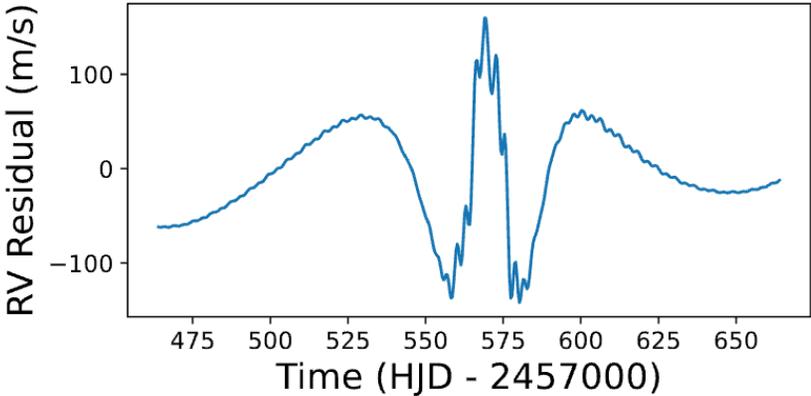
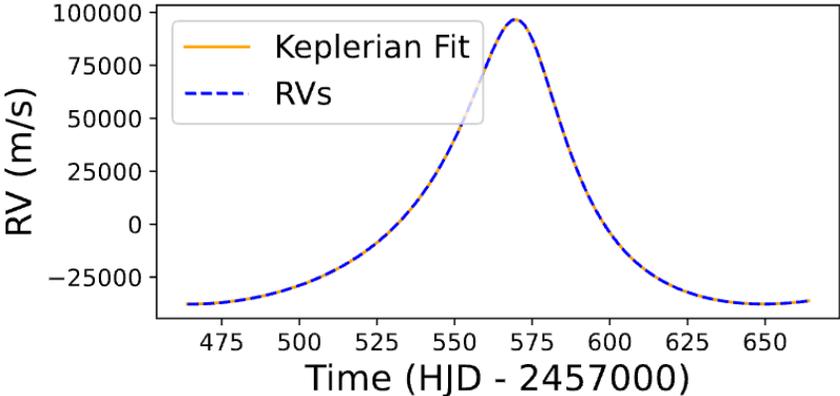
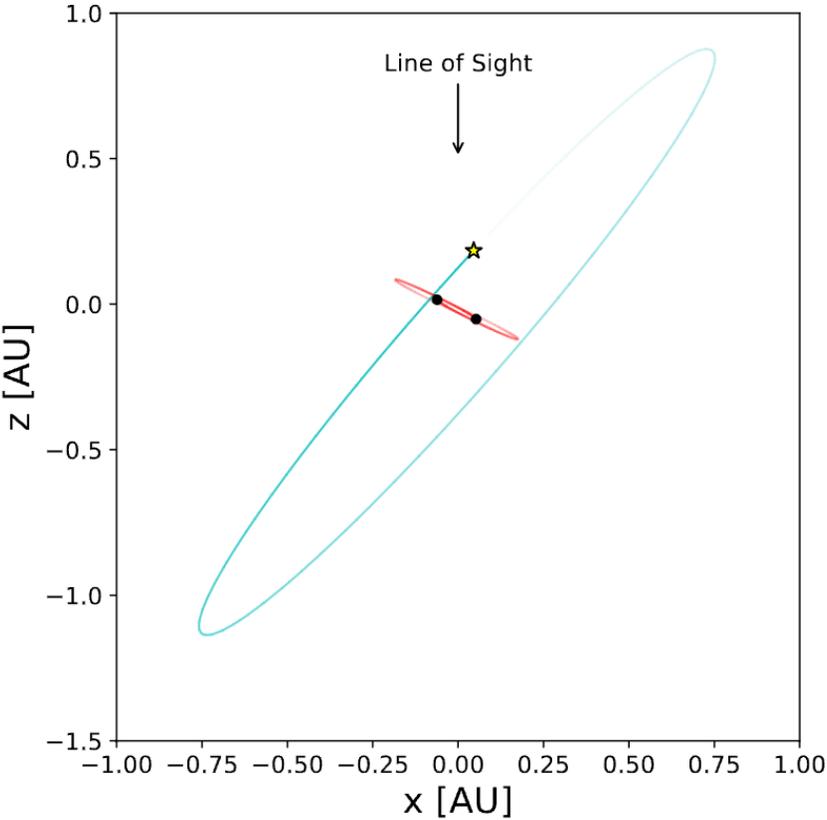
We have metallicities!



But what if it's two black holes?

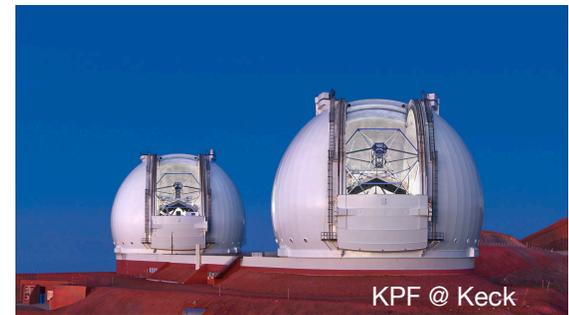
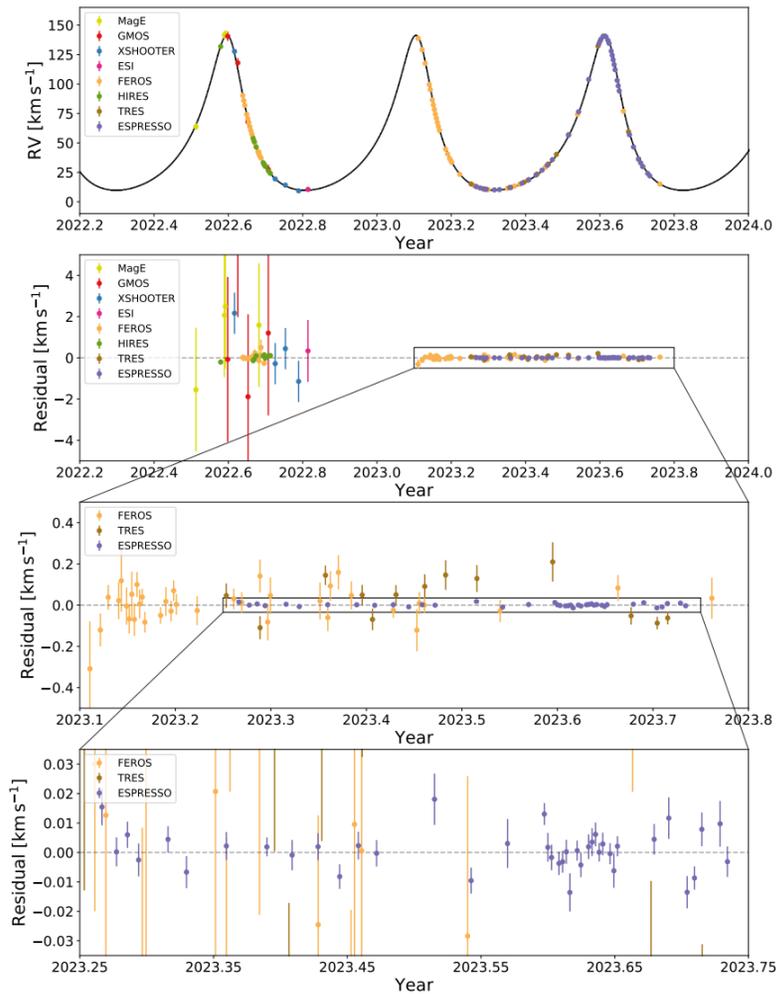


But what if it's two black holes?



Pranav Nagarajan

But what if it's two black holes?



3 m/s at $G = 14$ in 900s
~60 epochs over 1 orbit

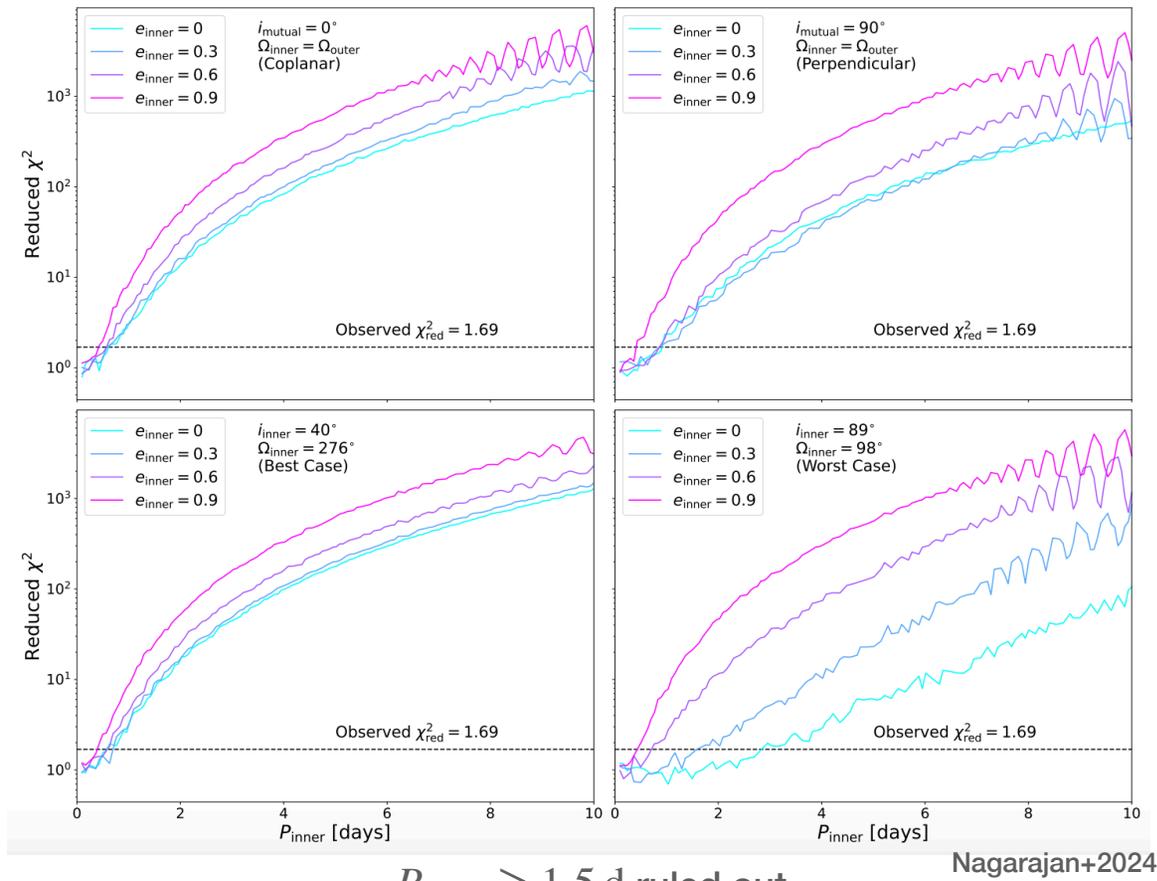
$$f(M_2) = 3.9358 \pm 0.0002$$

No evidence for non-Keplerian motion

with Pranav Nagarajan

Kareem El-Badry (Caltech)

But what if it's two black holes?

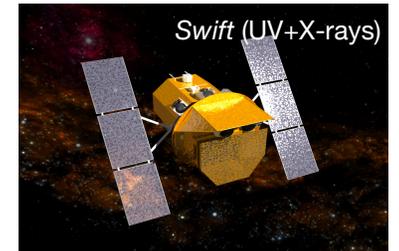
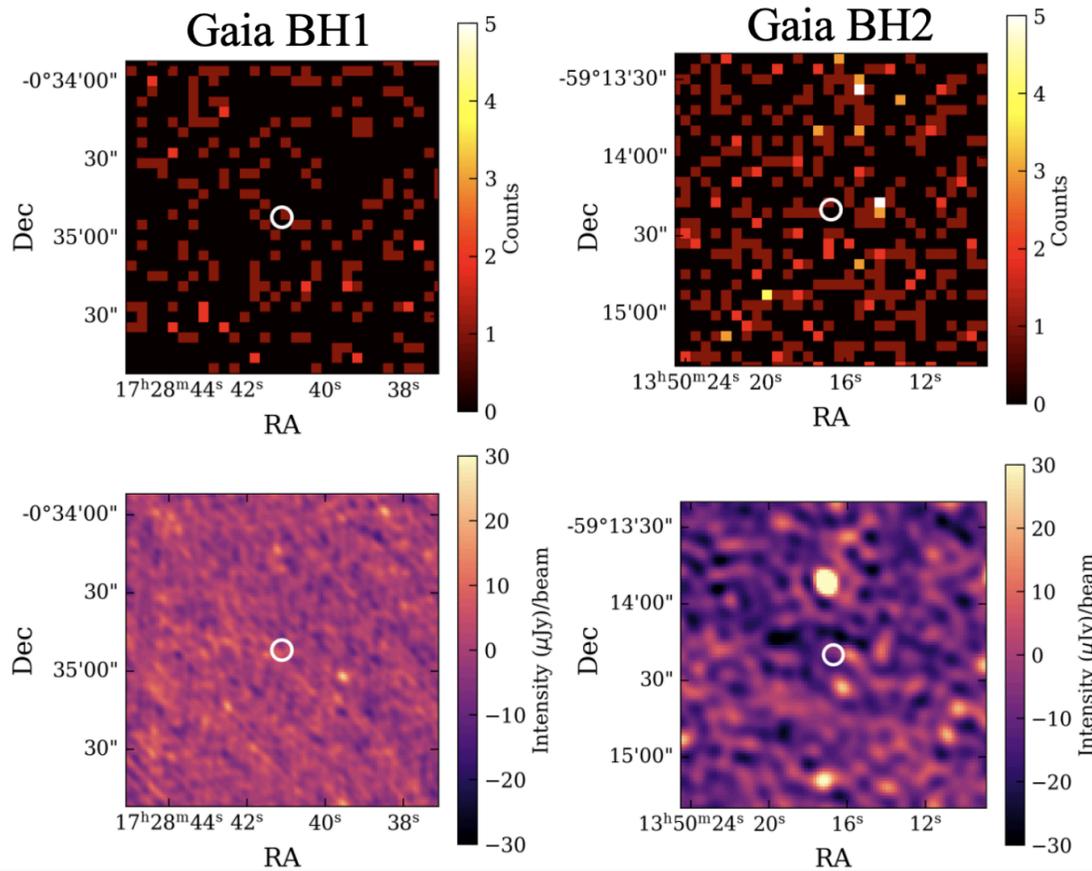


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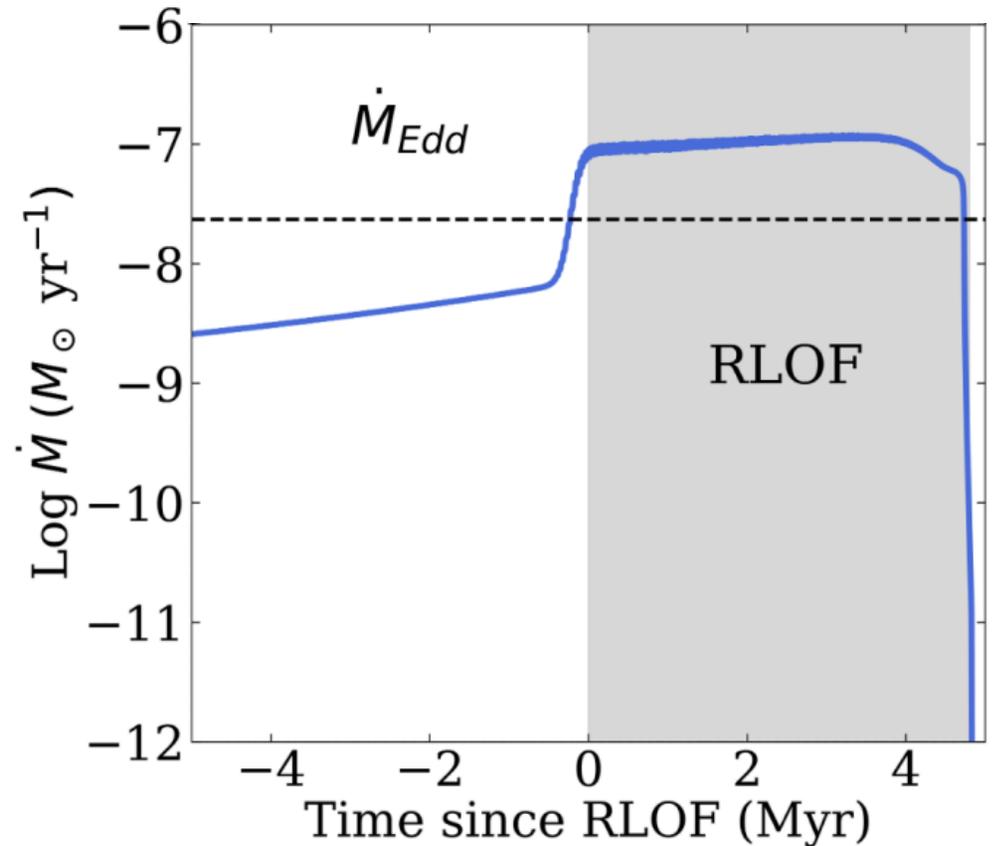
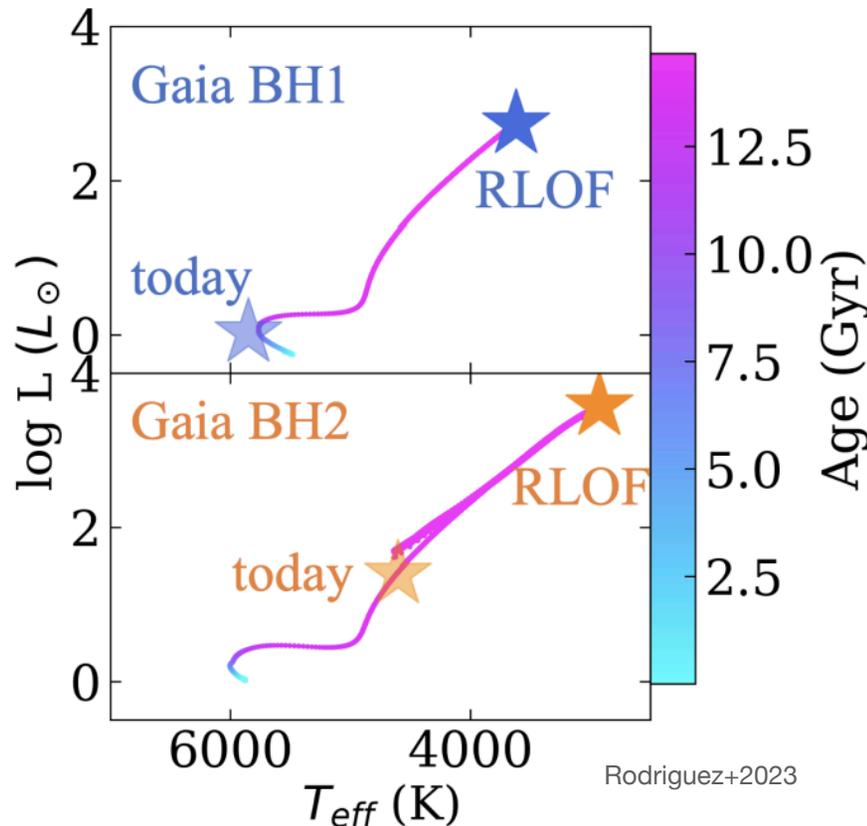
X-ray and radio: zero photons



Tony Rodriguez

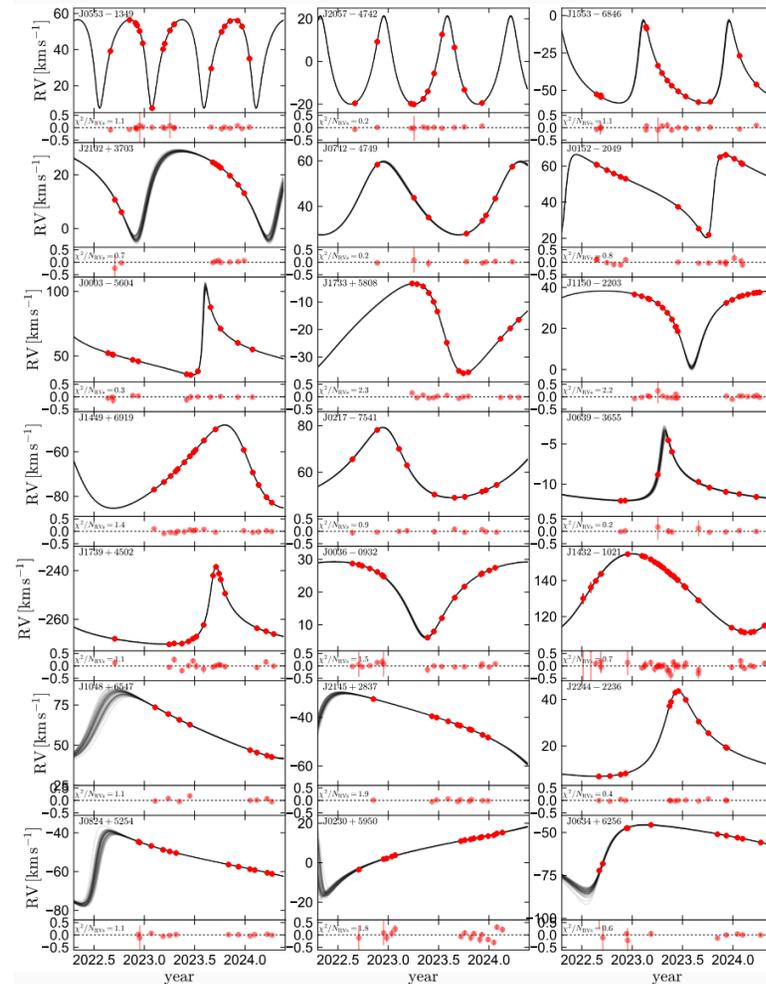
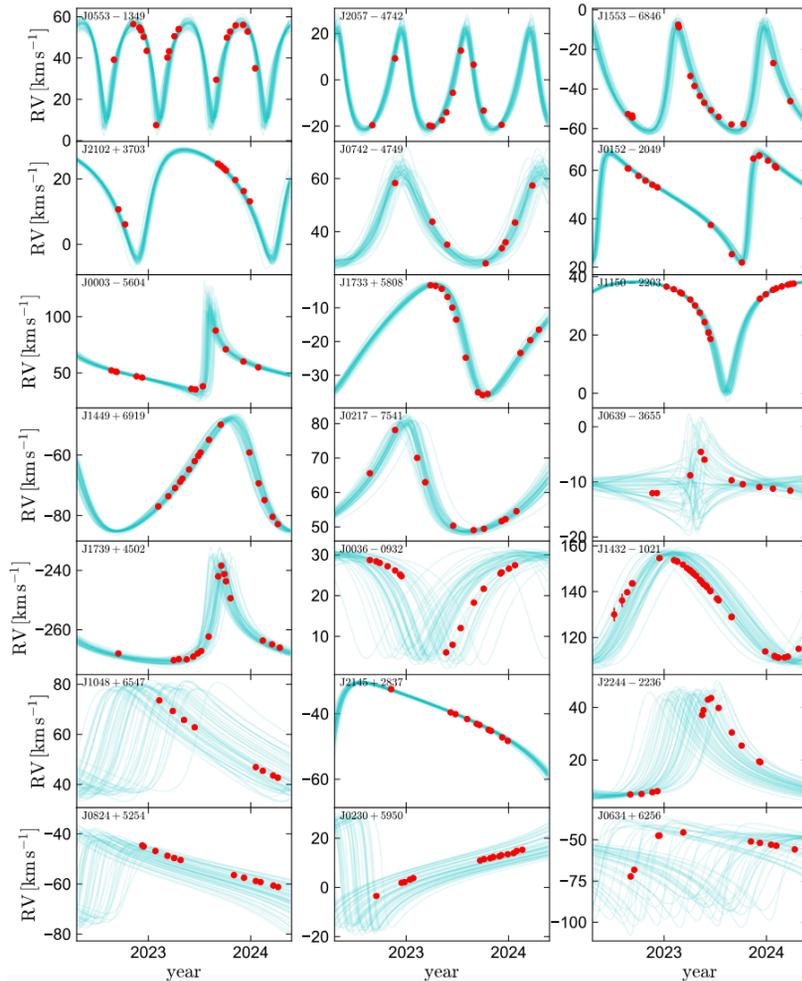
Kareem El-Badry (Caltech)

X-rays and radio: come back in a few Gyr



$\tau_{\text{X-rays}} / \tau_{\text{Dormant}} \gtrsim 0.001 \Rightarrow$ **BH+giant symbiotic XRBs yet to be discovered**

21 neutron stars in wide binaries

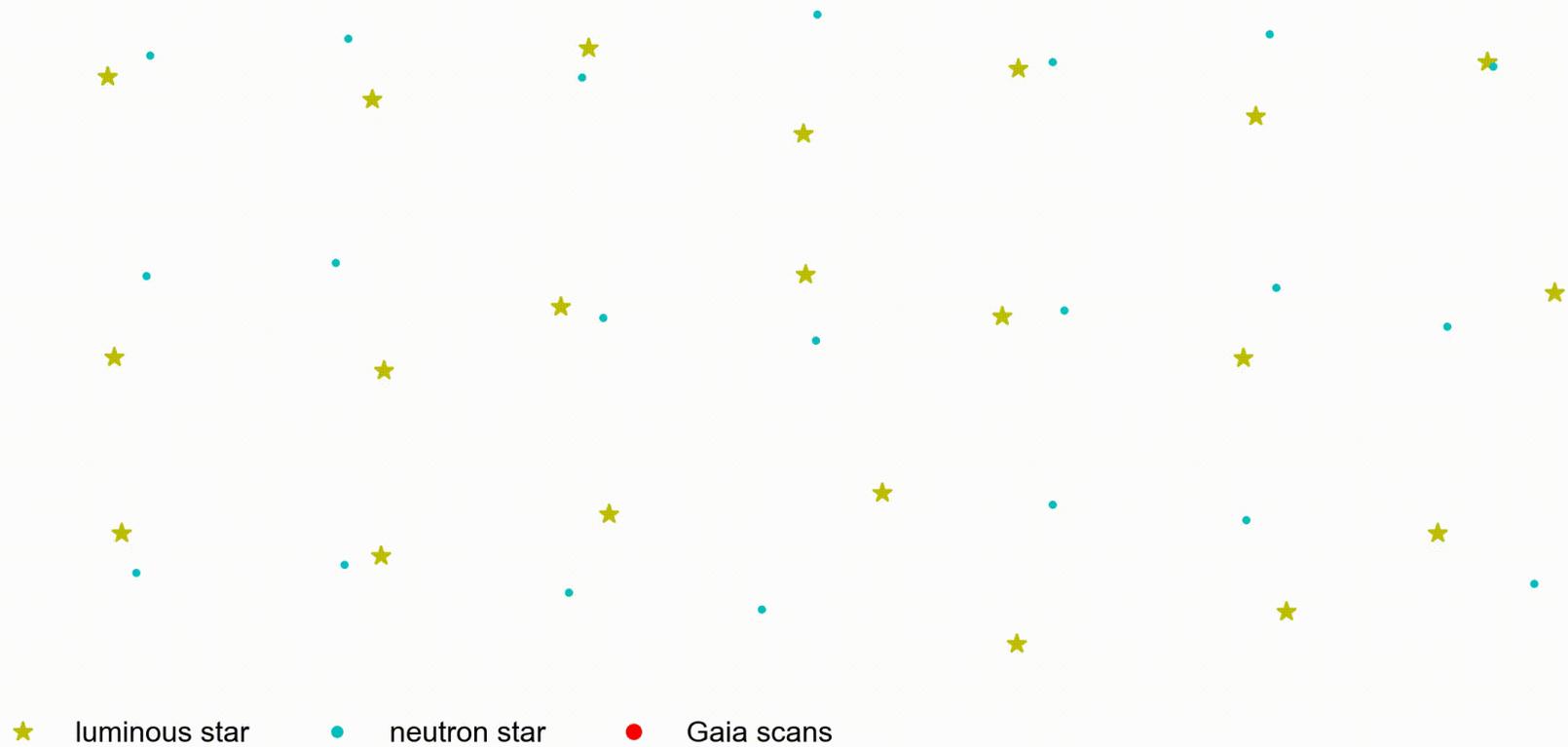


El-Badry+2024

Kareem El-Badry (Caltech)

21 neutron stars in wide binaries

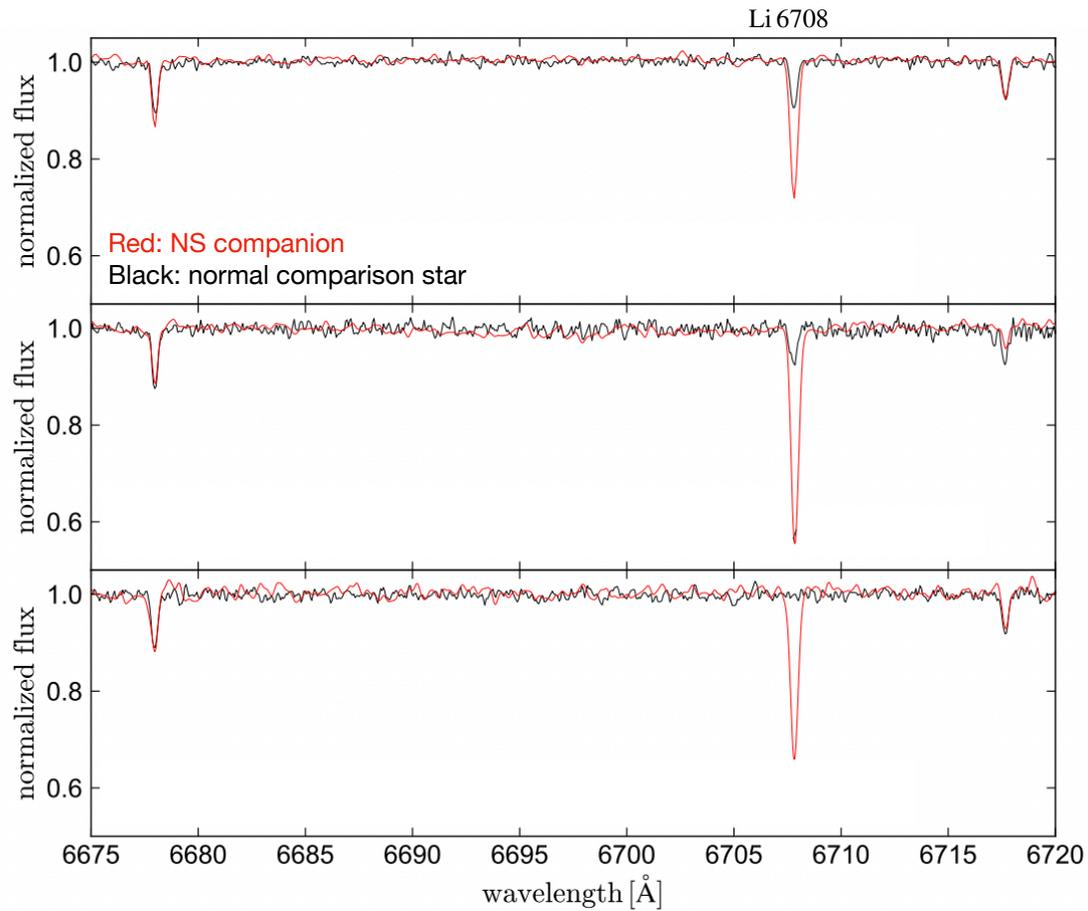
2014.5



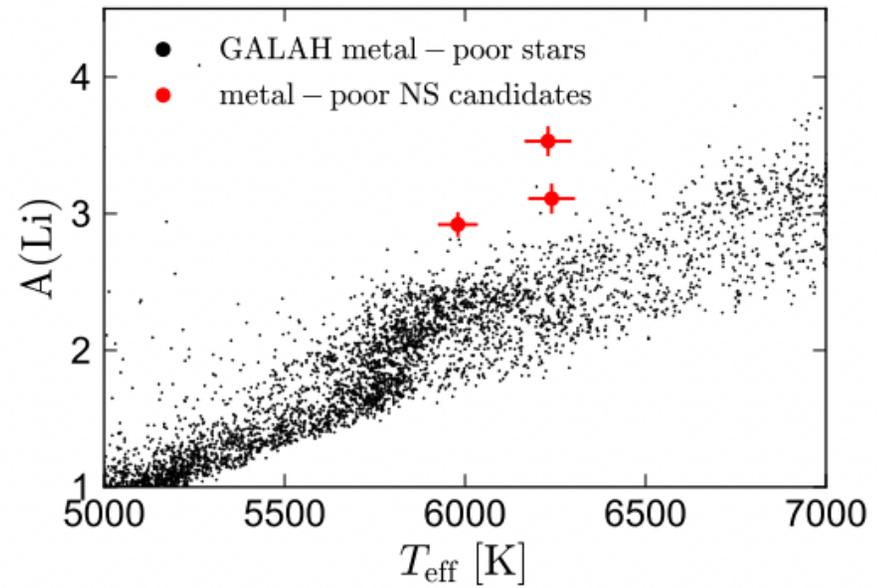
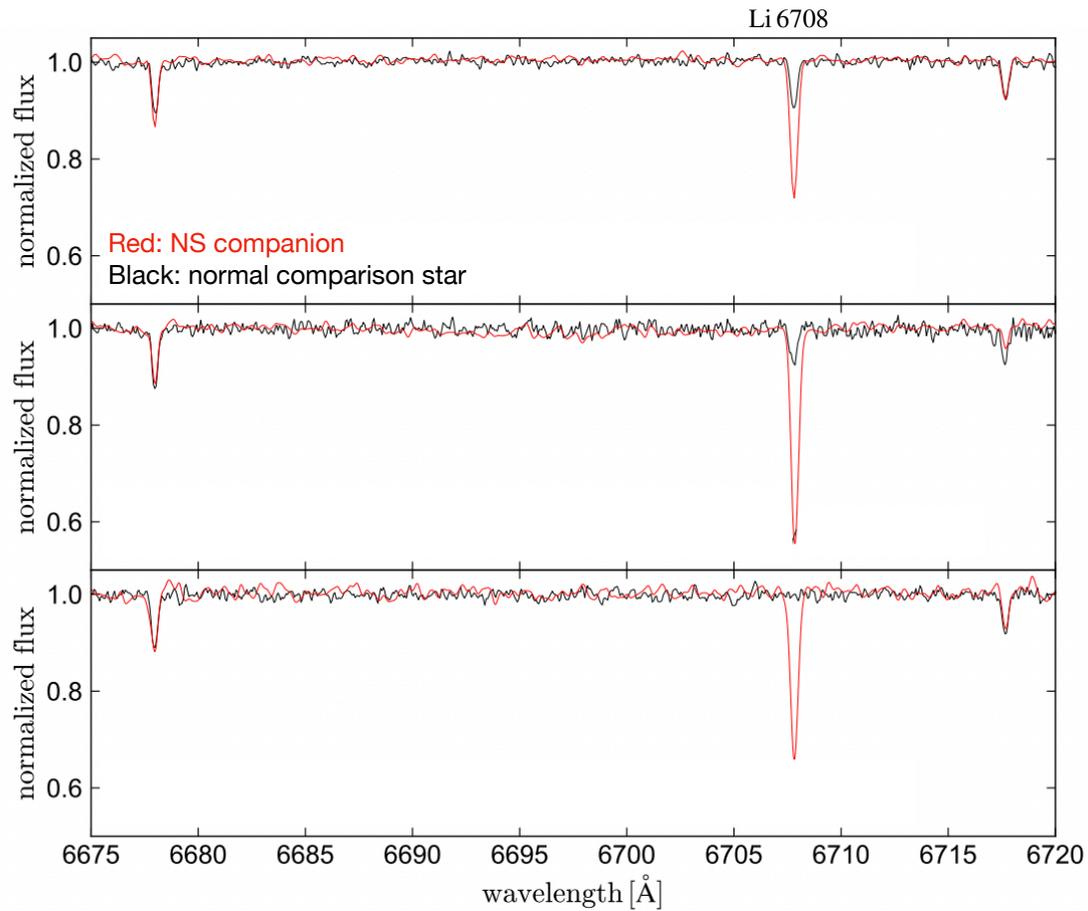
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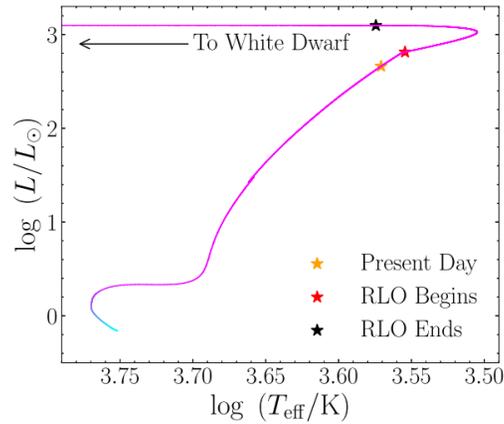
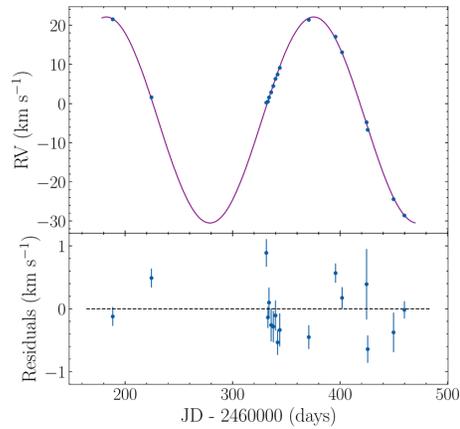
Unexpected Li enhancement in NS companions



Unexpected Li enhancement in NS companions

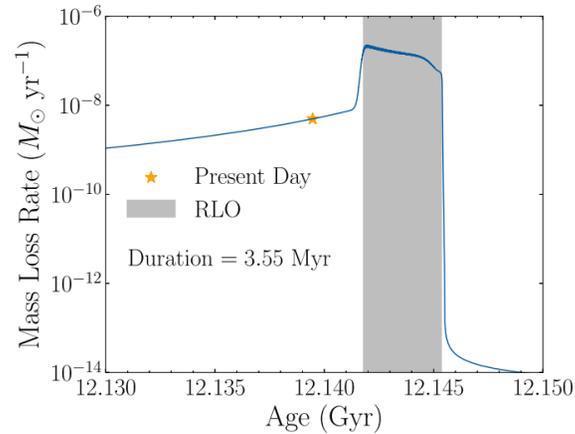
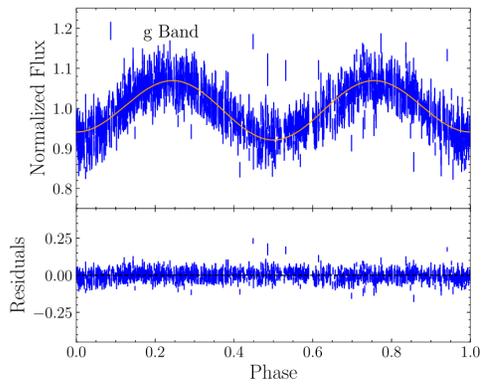


Gaia NSs as future X-ray binaries



IGR J16194-2810

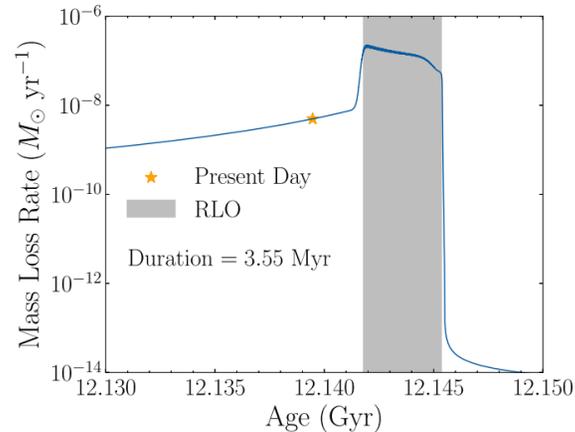
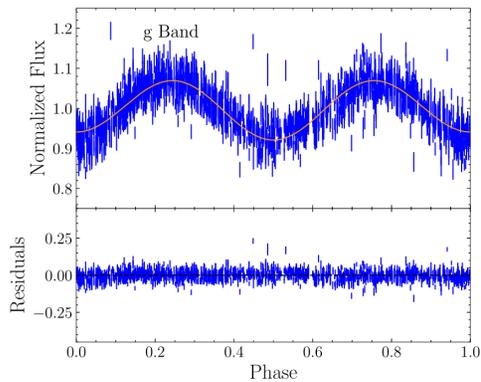
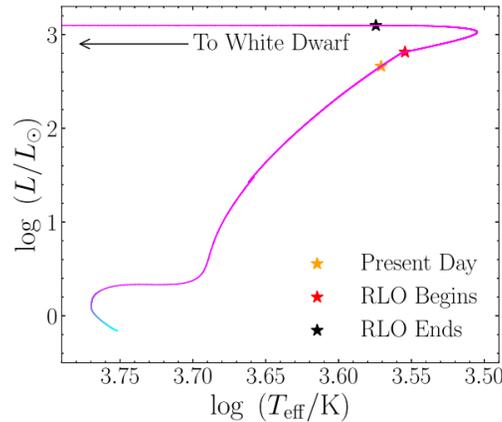
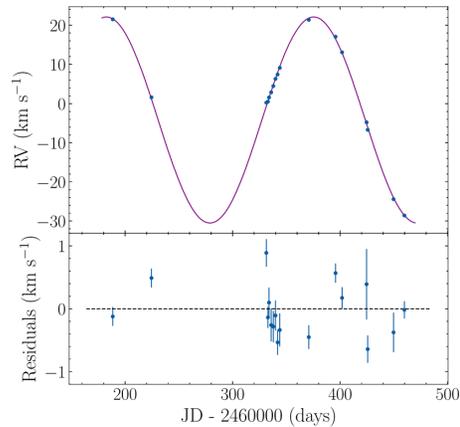
Nearest X-ray bright red giant + NS binary



Pranav Nagarajan

Kareem El-Badry (Caltech)

Gaia NSs as future X-ray binaries



IGR J16194-2810

Nearest X-ray bright red giant + NS binary

$d = 2.1$ kpc (10 times farther than nearest Gaia NS)

$\tau_{\text{X-rays}} \approx 10$ Myr (1000 times shorter than Gaia NSs)

Gaia NSs are the progenitors of SyXBs

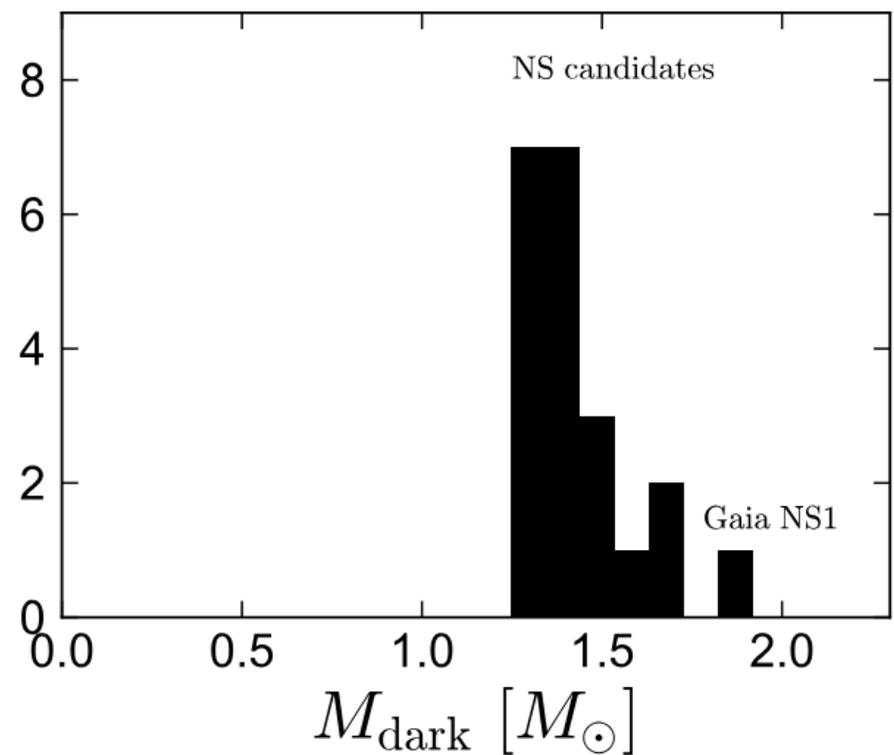
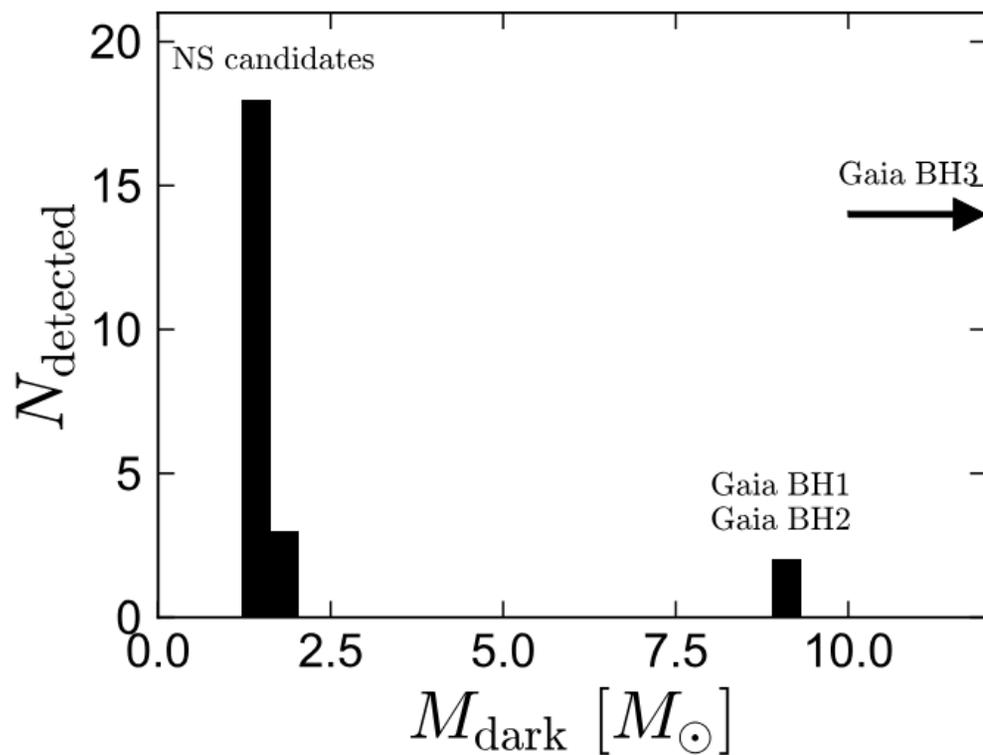


Pranav Nagarajan

Kareem El-Badry (Caltech)

We are sensitive to low-mass BHs. We do not detect them.

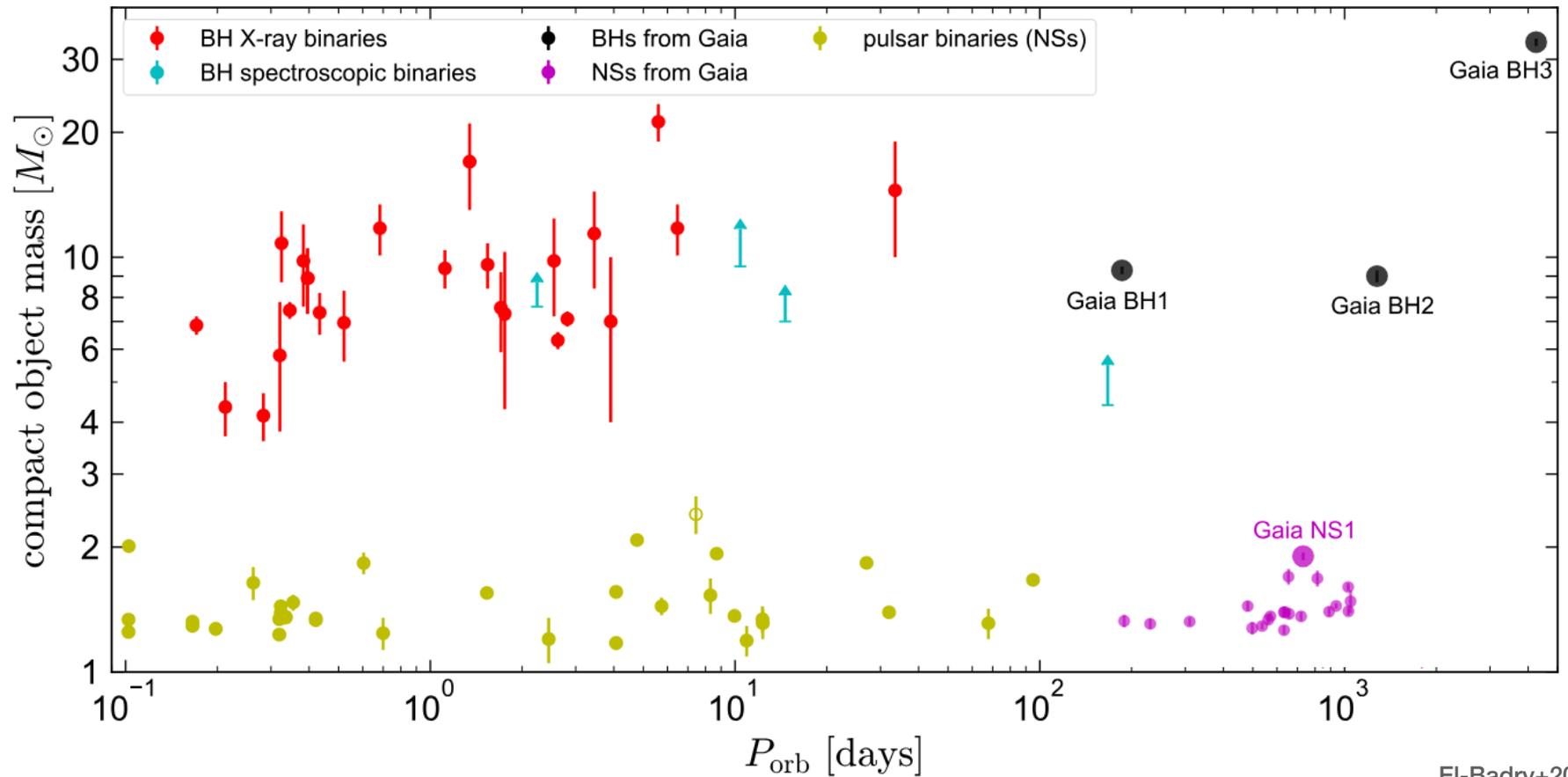
We can measure the mass distribution of pristine NSs



El-Badry+2024

Kareem El-Badry (Caltech)

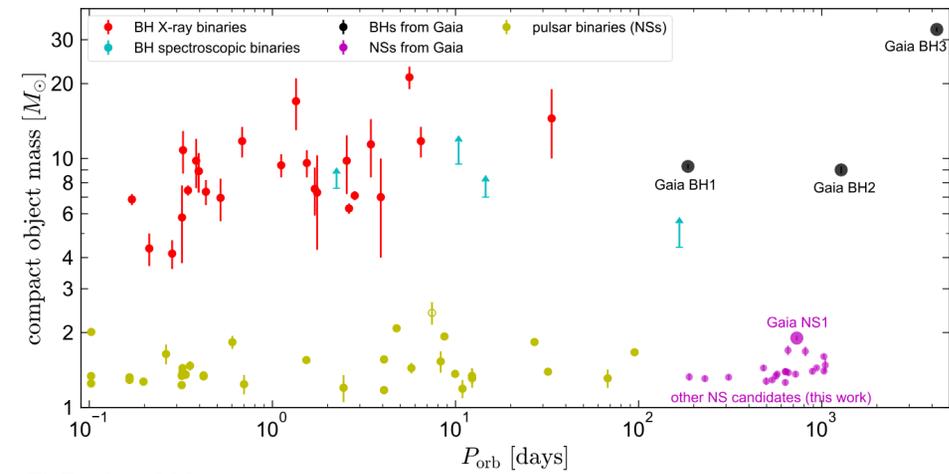
A mass gap over 4 orders of magnitude in orbital period



El-Badry+2024

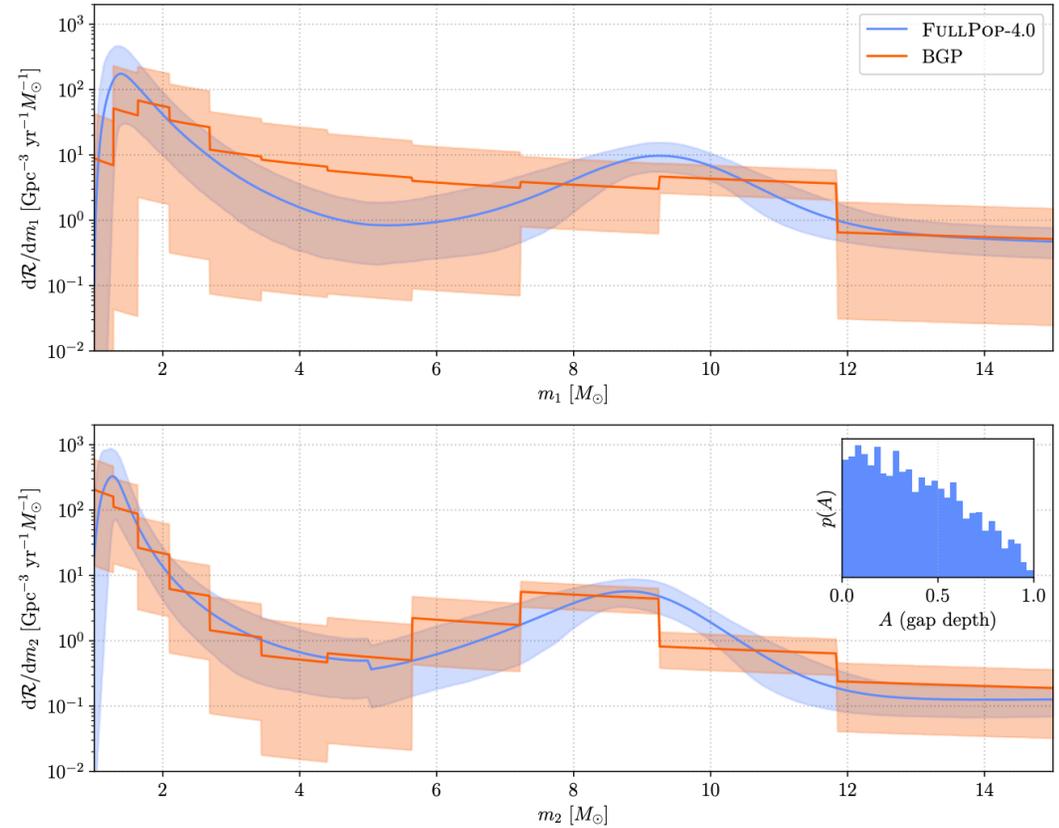
Kareem El-Badry (Caltech)

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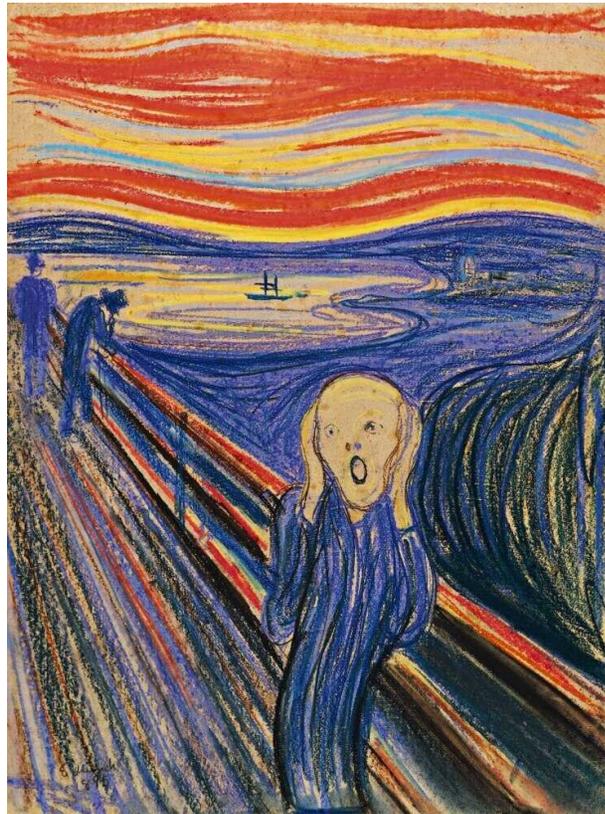


El-Badry+2024

GWTC-4 (talk by S. Vitale)

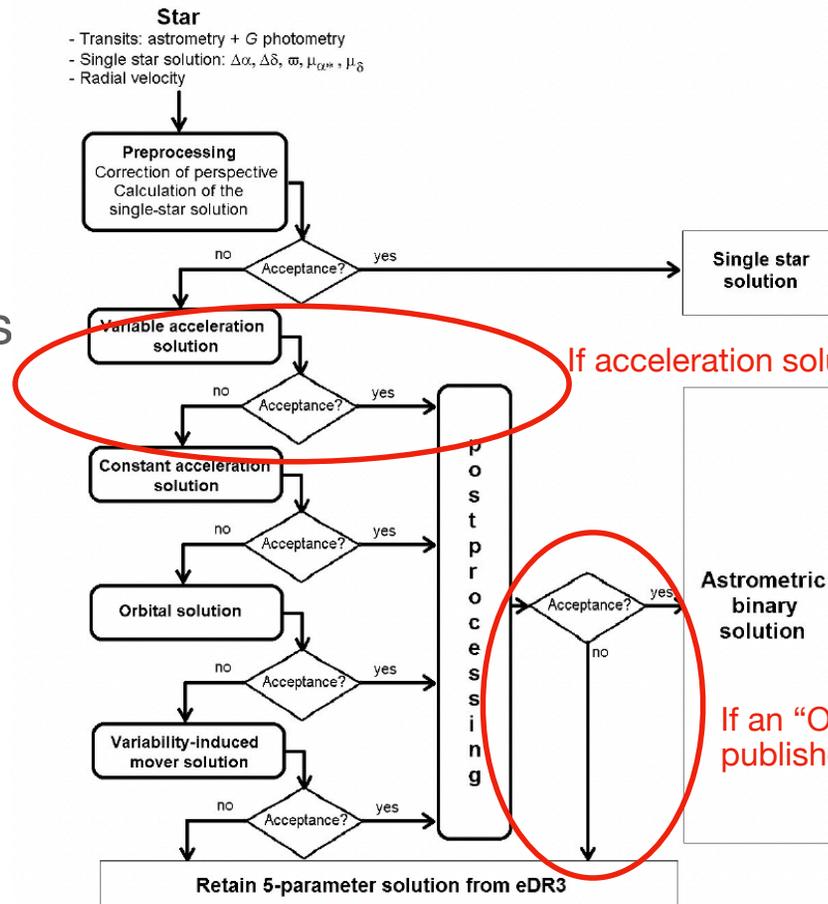


Selection functions and population inference with *Gaia* data



Population inference with *Gaia* data

Gaia astrometric catalogs are made with a complicated cascade cascade of astrometric models

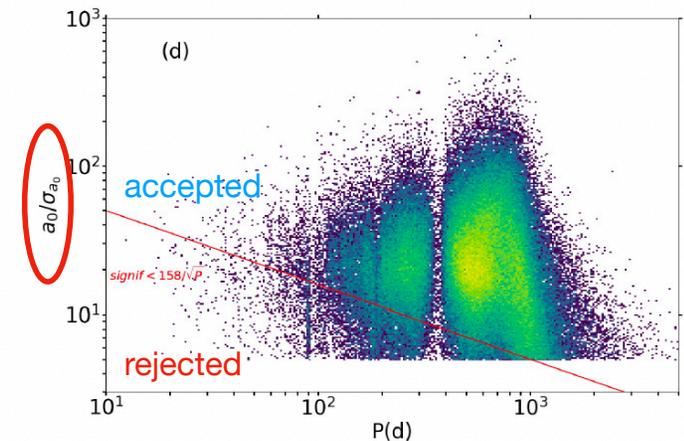
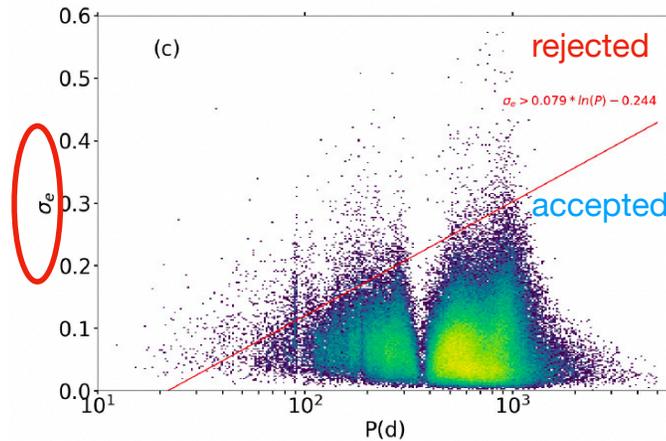
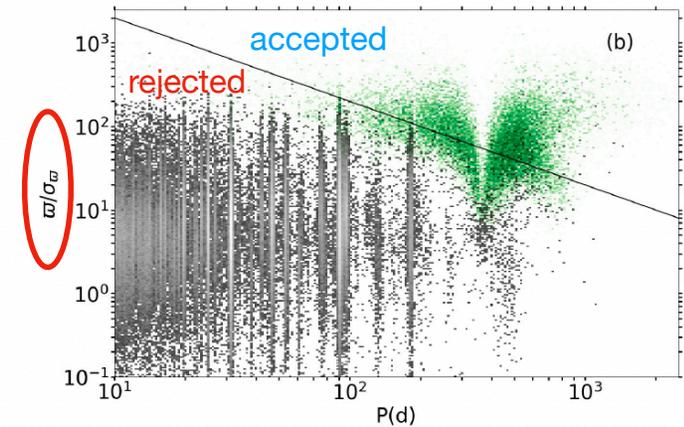
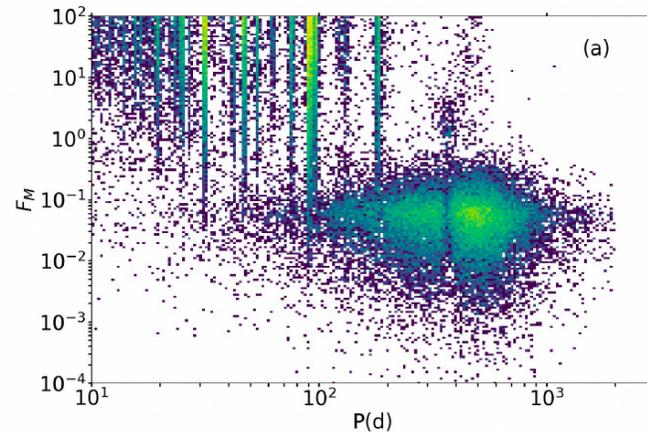


If acceleration solution is “OK”, don’t try an orbital solution

If an “OK” solution is not good enough to be published, don’t try anything else

Population inference with *Gaia* data

And there are many complicated cuts



Halbwachs+2023

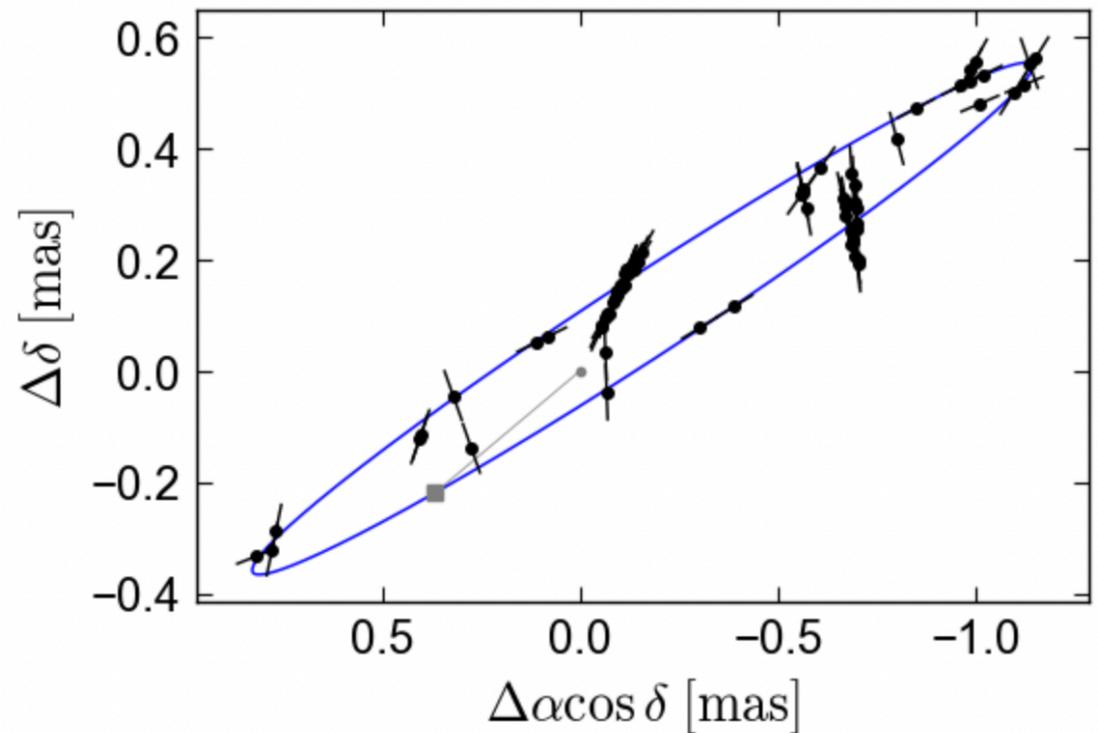
Need to be able to predict things like eccentricity error to know completeness

Population inference with *Gaia* data

But even so, *Gaia* observations are easy to simulate

Signal depends only on flux ratio and orbit

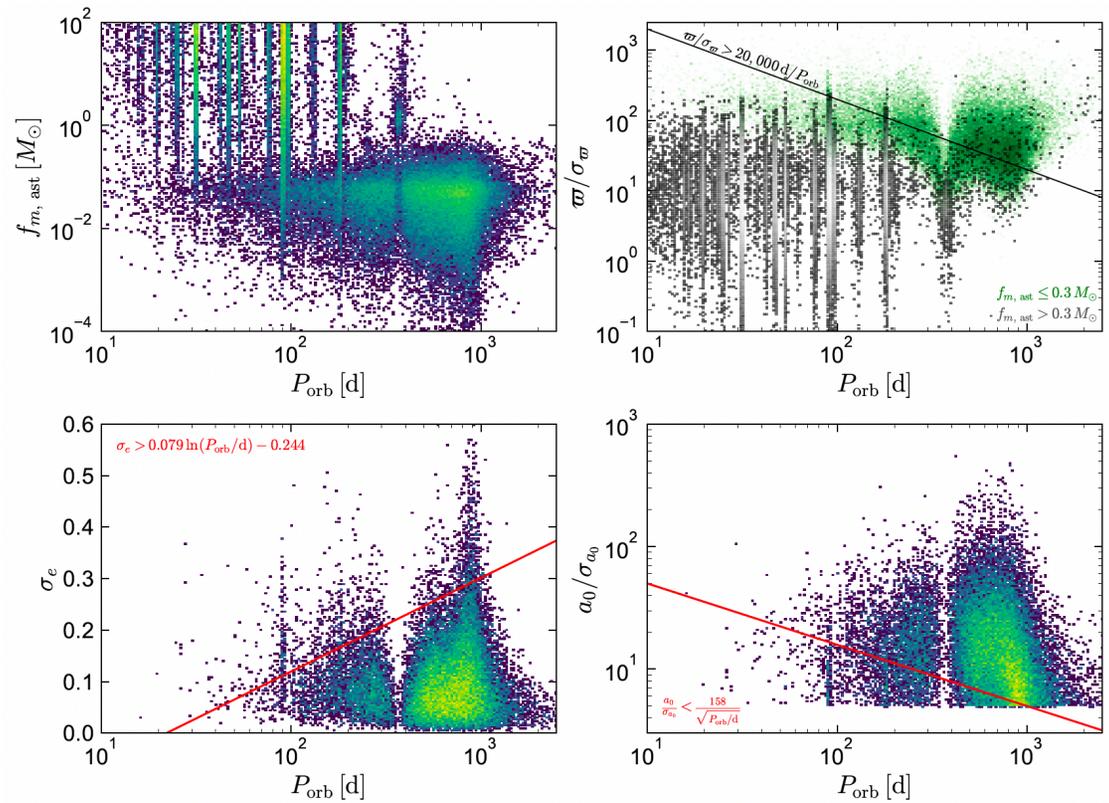
So: let's forward-model everything



El-Badry+2024

Population inference with *Gaia* data

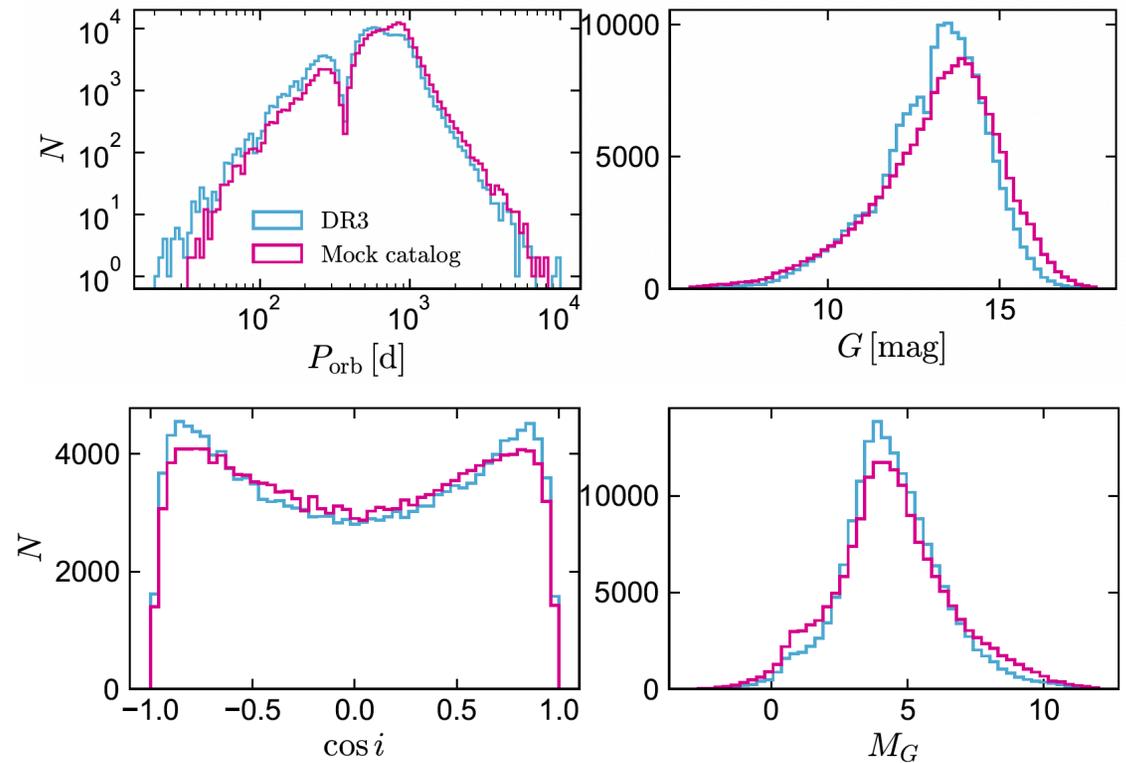
Astrometric model cascade and quality cuts are also easy to simulate



El-Badry+2024

Population inference with *Gaia* data

It works pretty well!
(but not perfect)



El-Badry+2024

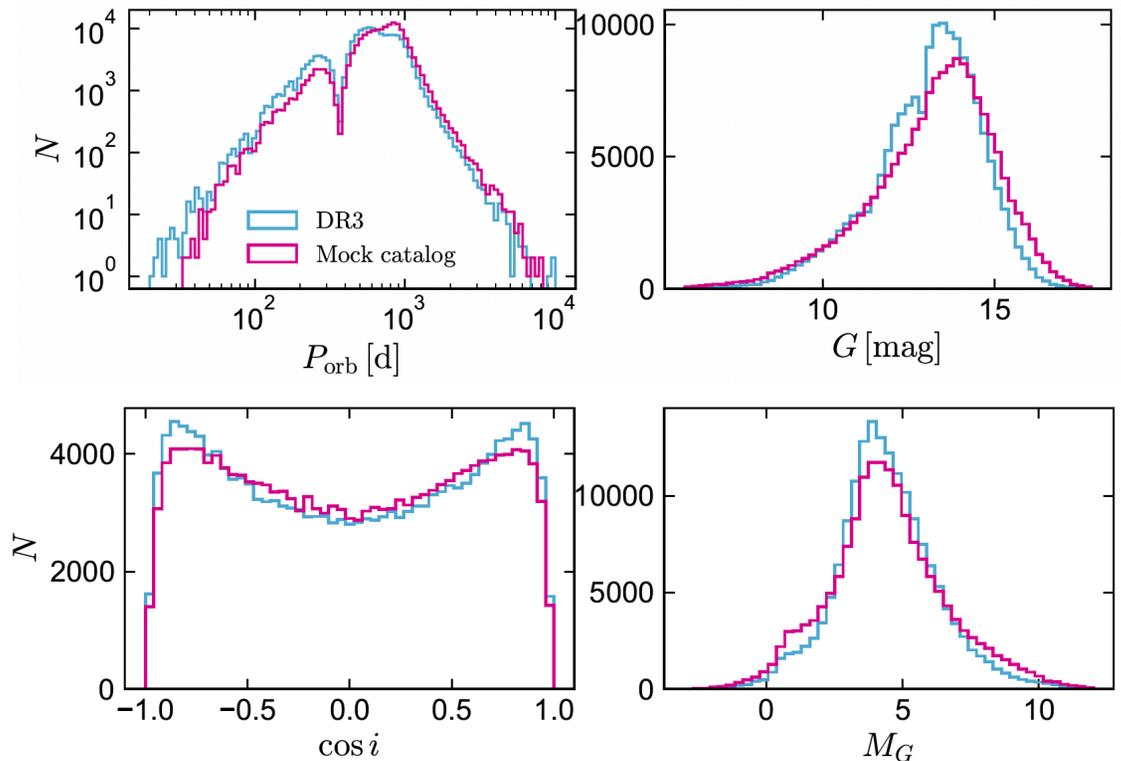
Population inference with *Gaia* data

It works pretty well!
(but not perfect)

Gaia is not **complete** anywhere

But, we understand the completeness remarkably well!

For many applications, this is **as good** as being complete



EI-Badry+2024

Two models for the Galactic BH population



Pranav Nagarajan

Isolated binary evolution

THE ASTROPHYSICAL JOURNAL, 931:107 (19pp), 2022 June 1
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<https://doi.org/10.3847/1538-4357/ac60a5>

OPEN ACCESS



Gaia May Detect Hundreds of Well-characterized Stellar Black Holes

Chirag Chawla¹, Sourav Chatterjee¹, Katelyn Breivik², Chaithanya Krishna Moorthy³, Jeff J. Andrews⁴, and Robyn E. Sanderson^{2,5}

Dynamical formation

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Young Star Clusters Dominate the Production of Detached Black Hole–Star Binaries

Ugo Niccolò Di Carlo^{1,2,3}, Poojan Agrawal^{2,3}, Carl L. Rodriguez^{2,3}, and Katelyn Breivik⁴

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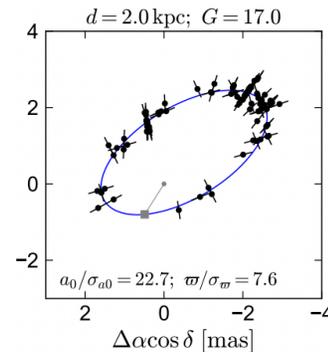
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Mock Gaia observations



Mock catalog

Dynamical formation

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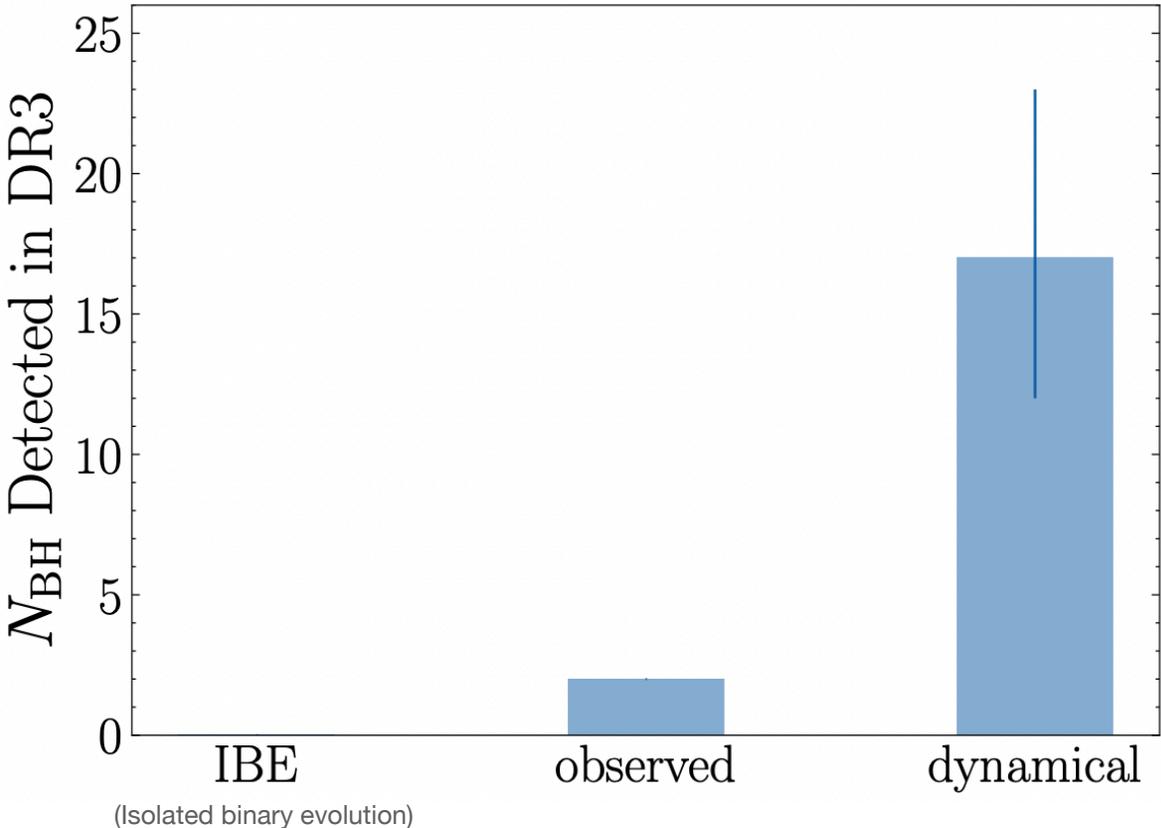
Nagarajan+2025

Kareem El-Badry (Caltech)

Two models for the Galactic BH population



Pranav Nagarajan



Nagarajan+2025

Commercial break

We understand the selection function of Gaia astrometric catalogs remarkably well.

Apply it to your favorite simulated binary population today!

gaiamock Public



What's next?

Many more binaries coming:

- DR4 (2000 day baseline): December
- DR5 (4000 day baseline): 2030

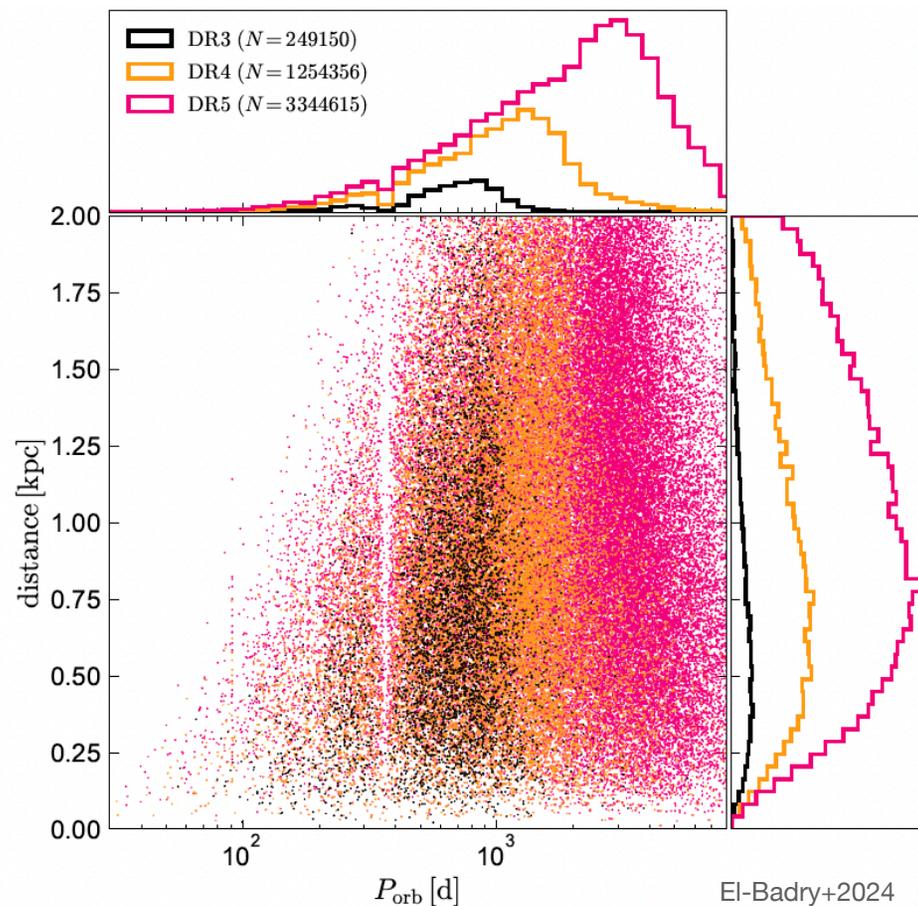
Longer observing baseline \rightarrow larger orbits \rightarrow larger search volume

DR4 will include:

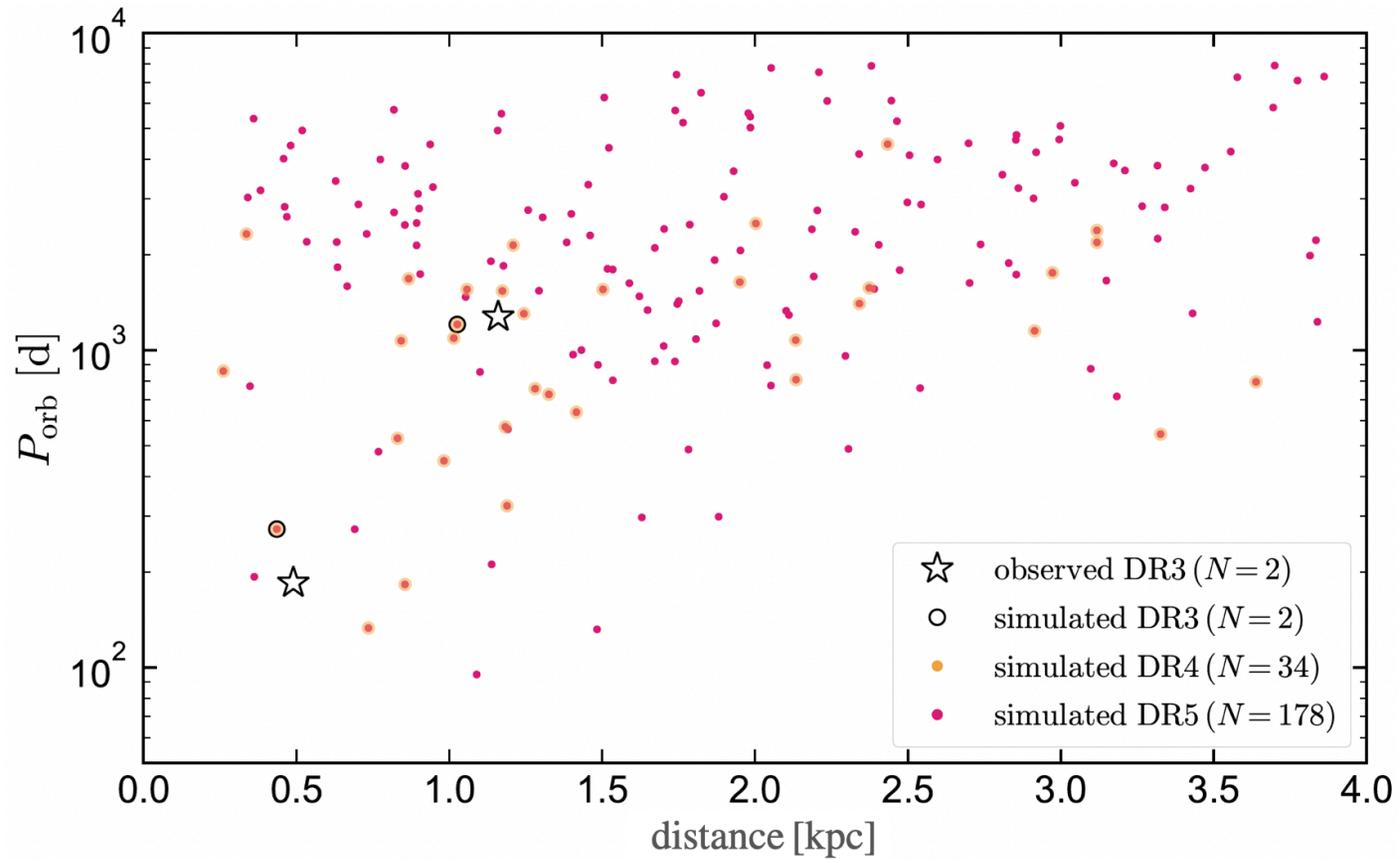
- epoch astrometry for all sources.
- epoch RVS spectra for 30M sources with $G_RVS < 14$
- epoch light curves for all sources

These data will be transformational for BHs, exoplanets, and basically all kinds of binaries

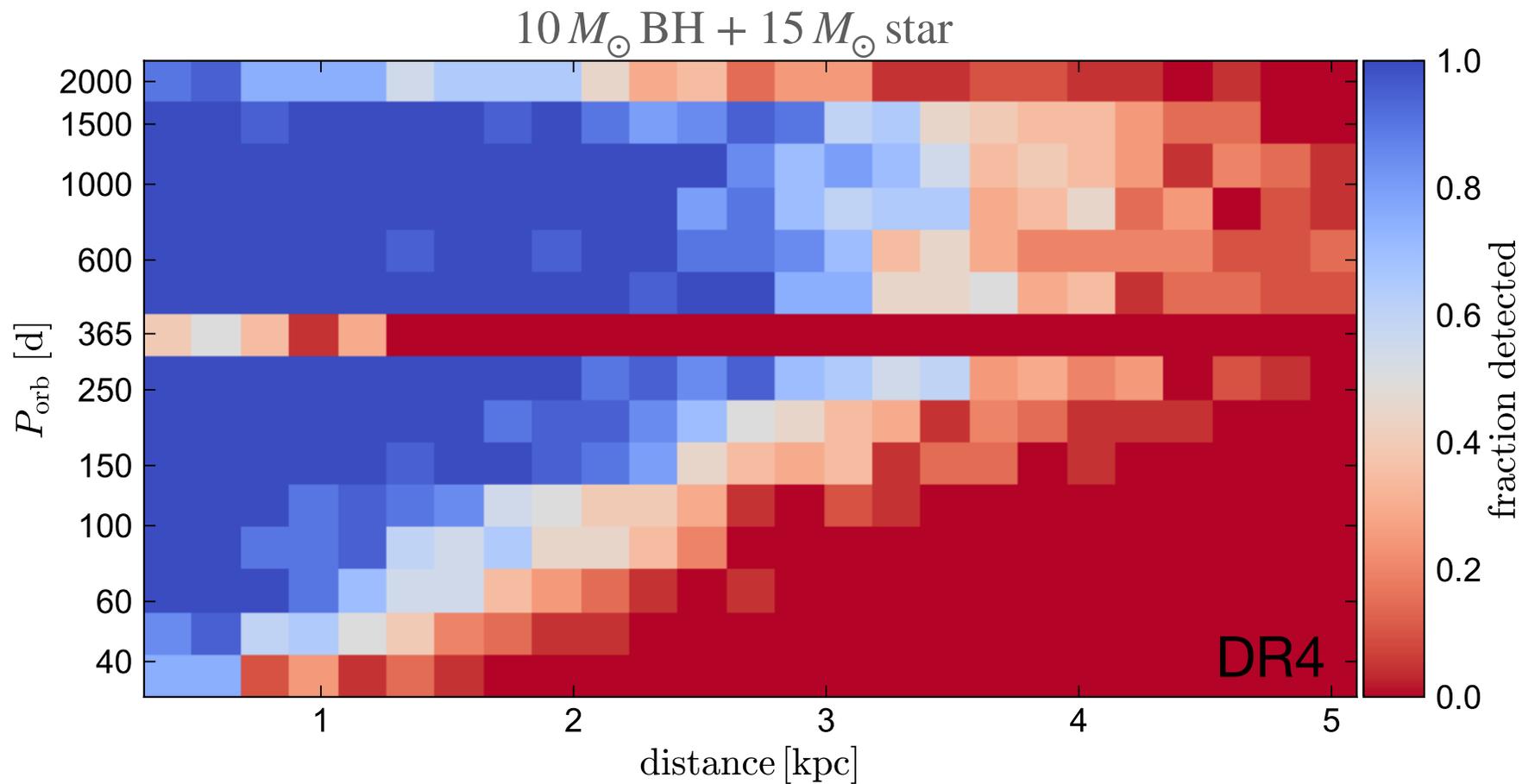
Simulated astrometric binaries in future *Gaia* releases



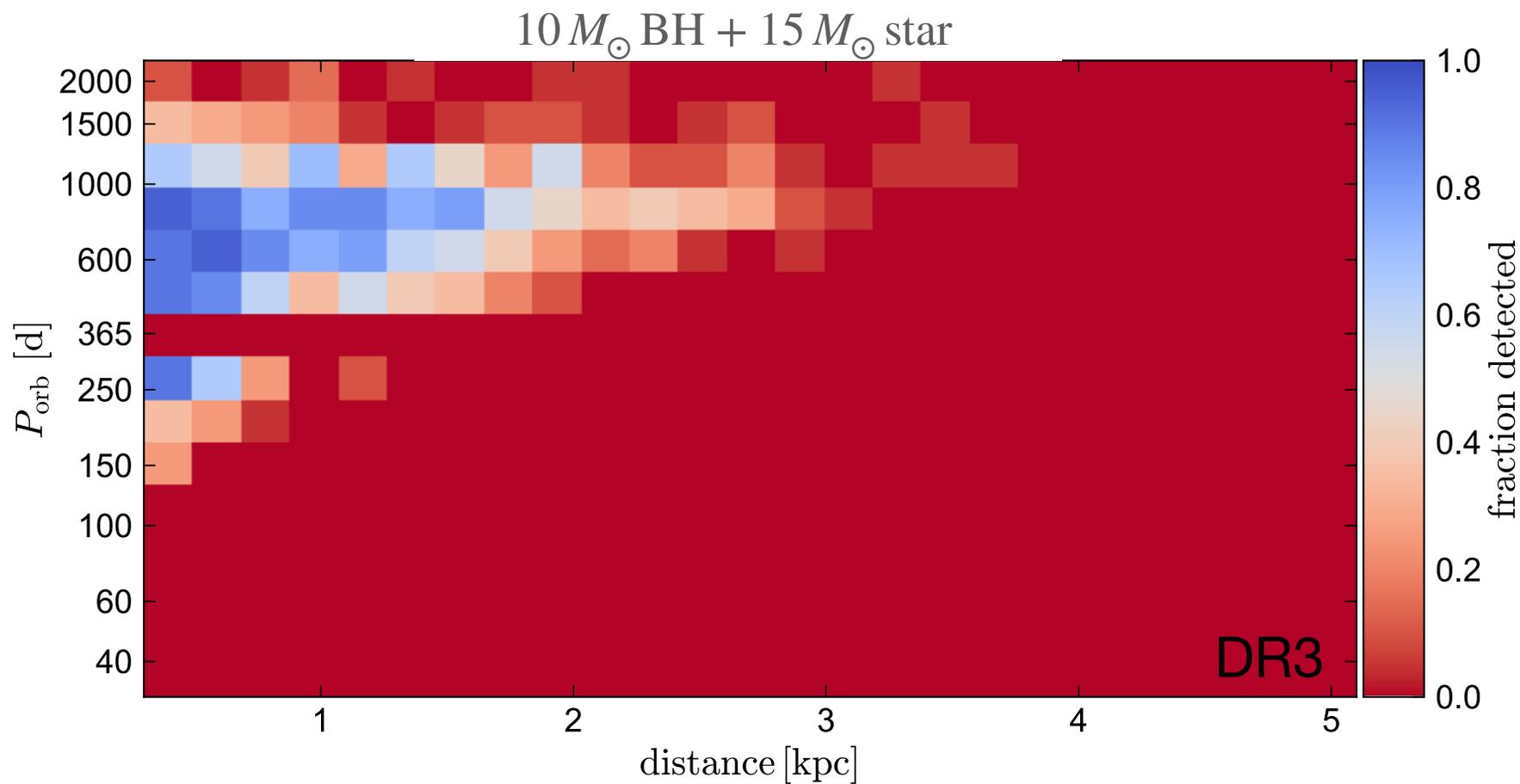
Simulated BH+low mass star detections in Gaia DR4/DR5



What about BHs with massive star companions?



What about BHs with massive star companions?



DR4 will require a lot of follow-up

- **Multi-epoch, high-resolution spectra**
 - To vet and refine orbits
 - To rule out luminous companions
 - To measure metallicities, rotation, atmospheric parameters...
 - To look for pollution from SN ejecta
- **High-resolution imaging**
 - To search for tertiaries + rule out blending
- **X-ray + radio**
 - To detect accretion

Follow-up will be more challenging than DR3: more targets, fainter sources, more false-positives

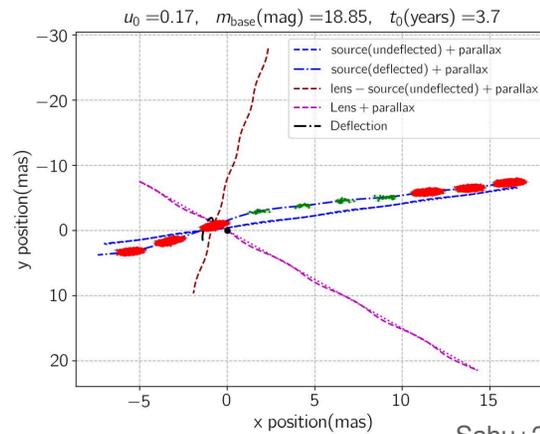
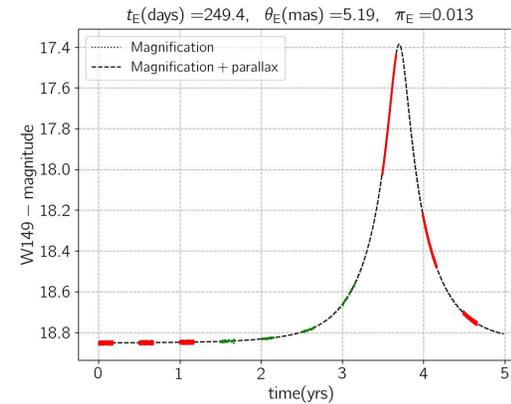
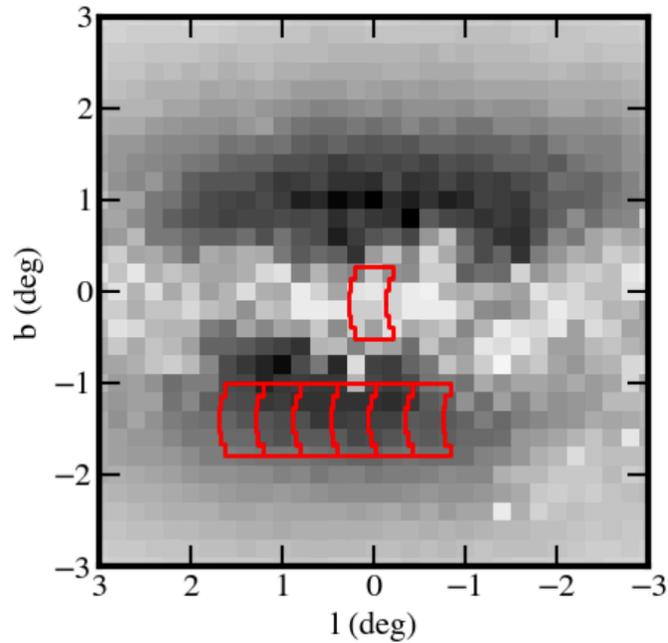
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Isolated BH searches with Roman: beginning next year!



Sahu+2023

Roman will measure light curves and astrometry *simultaneously*, yielding solid masses and velocities for 10-100 BHs

The search is on for stellar-mass black holes

Astrometric and spectroscopic surveys have made the first discoveries, with more to come; microlensing detections will accelerate with Roman

Gaia is just getting warmed up

Sensitivity improves *dramatically* with increasing observing baseline, and we have only analyzed the first 30% of the data

Binaries are key to most open & interesting problems in stellar physics

We do not yet understand how most detected BHs (in X-ray binaries, wide binaries, GW sources...) formed.