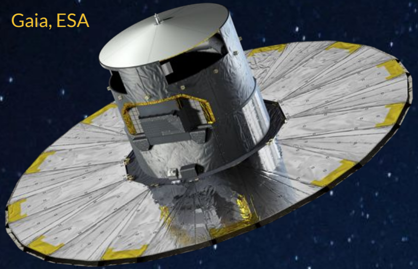
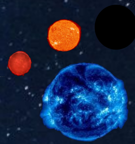
Gaia, ESA





Hunting for black holes around massive stars with Gaia

Soetkin Janssens

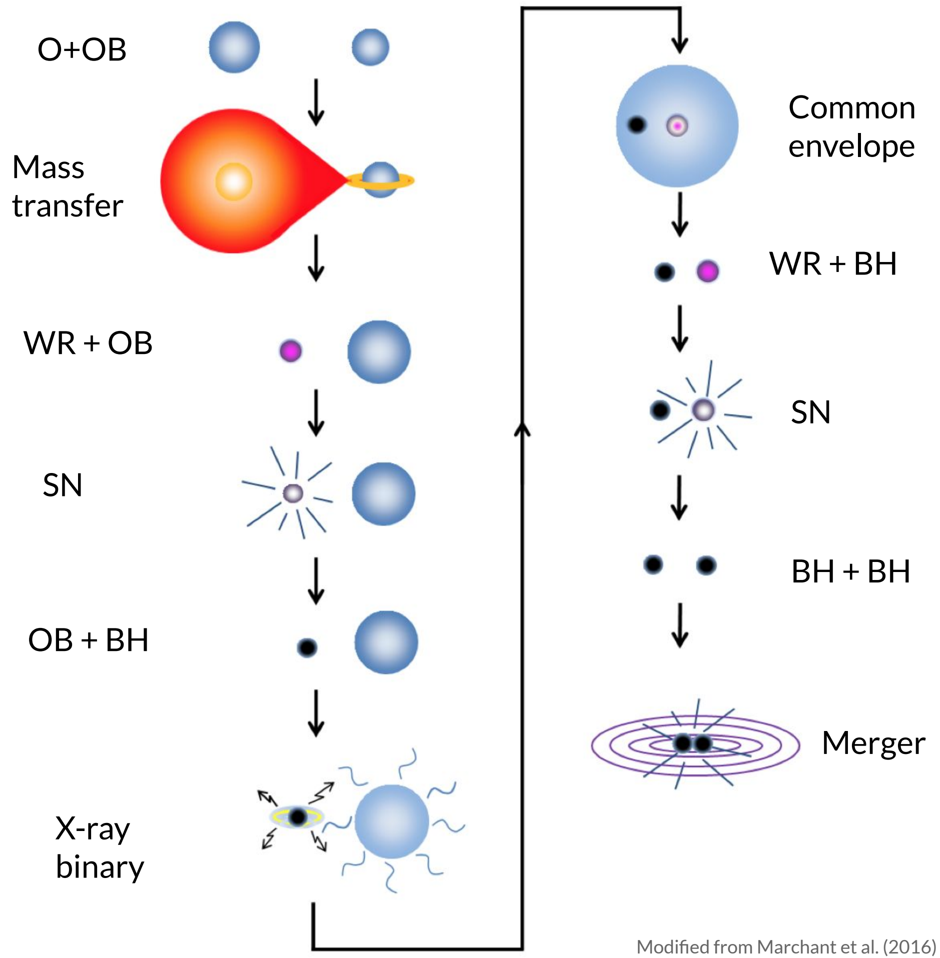
in collaboration with Prof. Hugues Sana
Dr. Tomer Shenar

Naples - Sept. 2022

Research Foundation Flanders
Opening new horizons

KU LEUVEN

Evolution towards compact object merger



Modified from Marchant et al. (2016)

OB = massive main-sequence star ($M_{\rm i} > 8 M_\odot$)

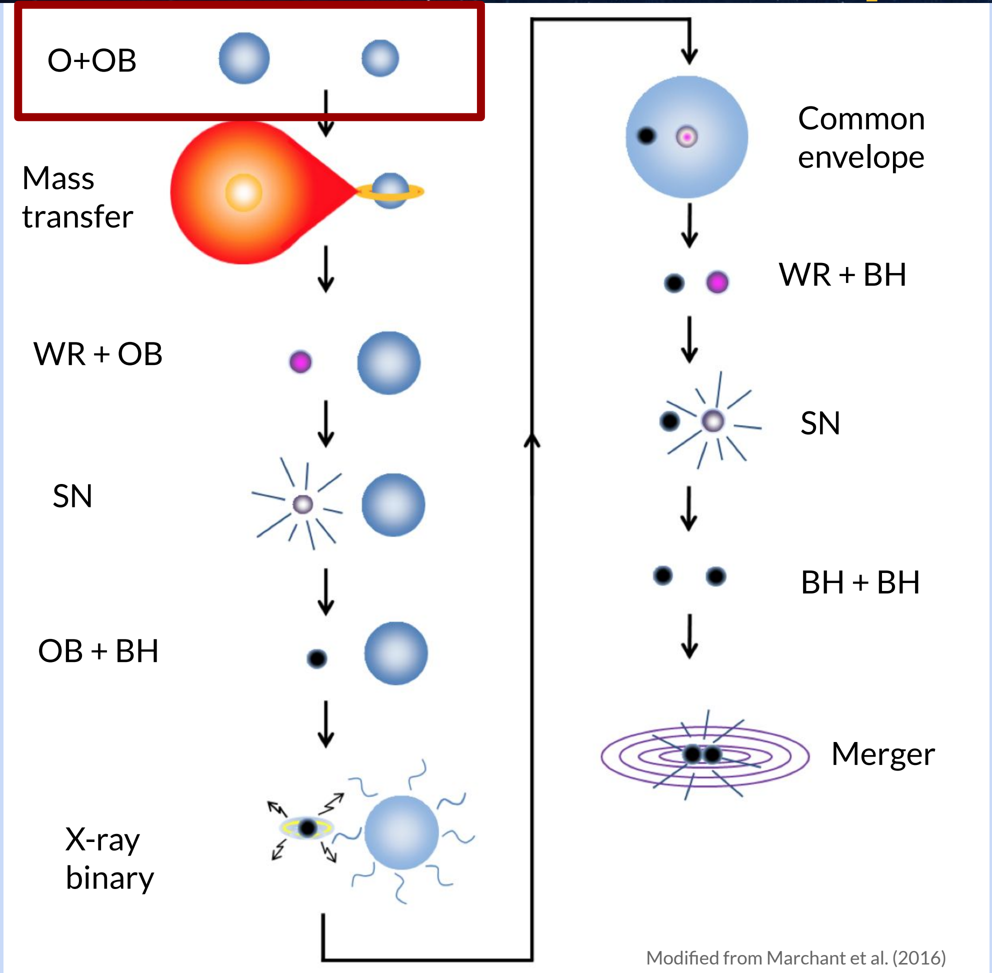
WR = Wolf Rayet

SN = supernova

BH = black hole

Merger = gravitational wave source

Evolution towards compact object merger



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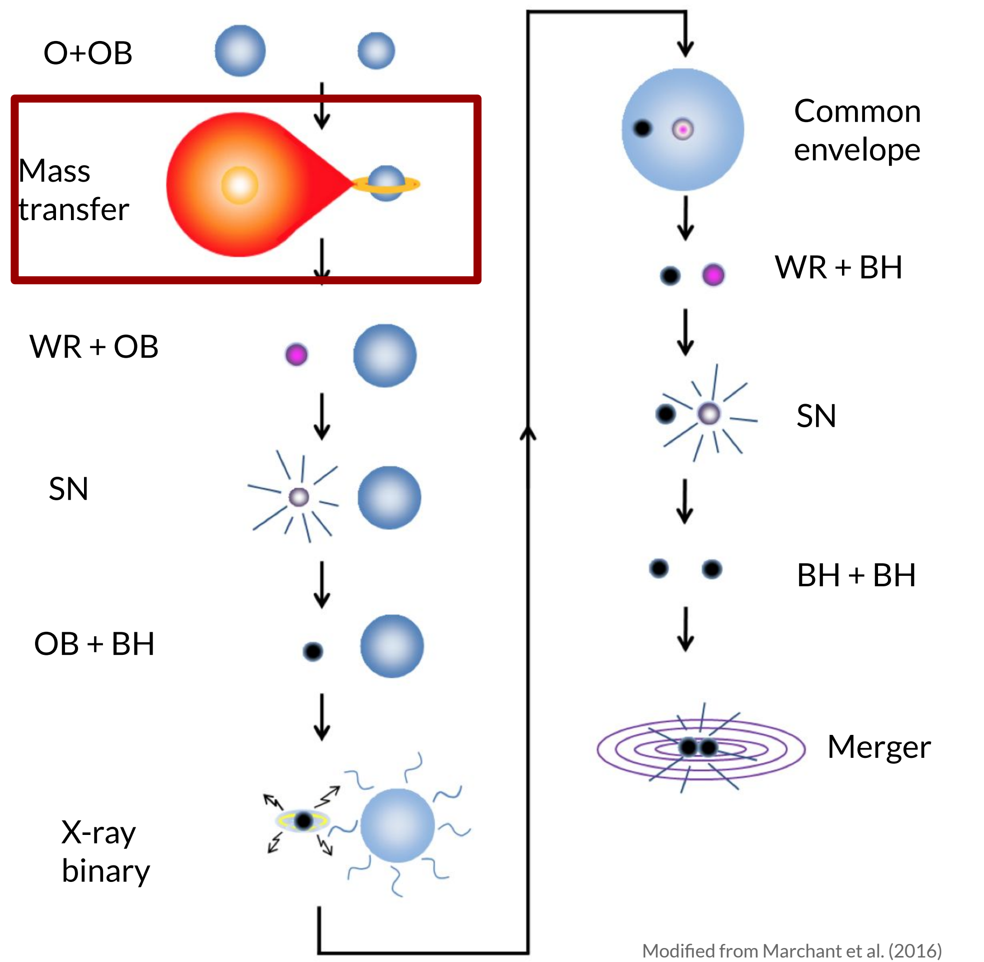

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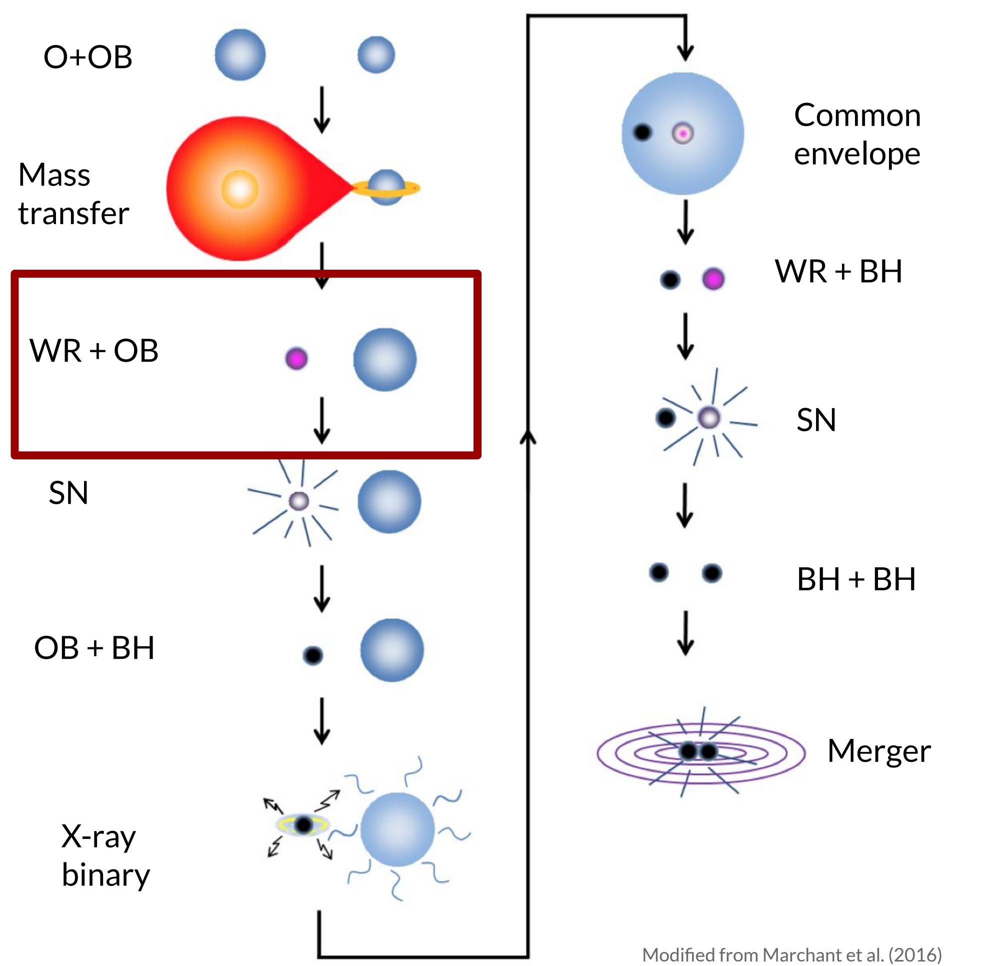

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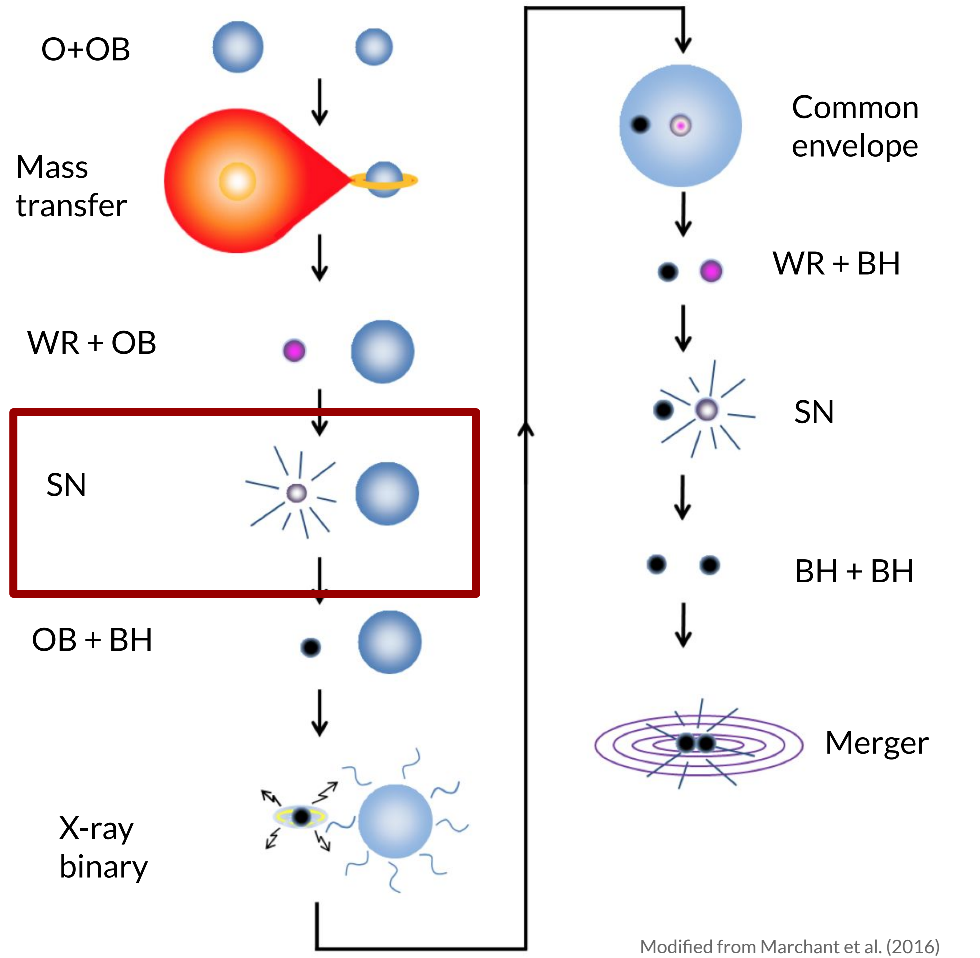

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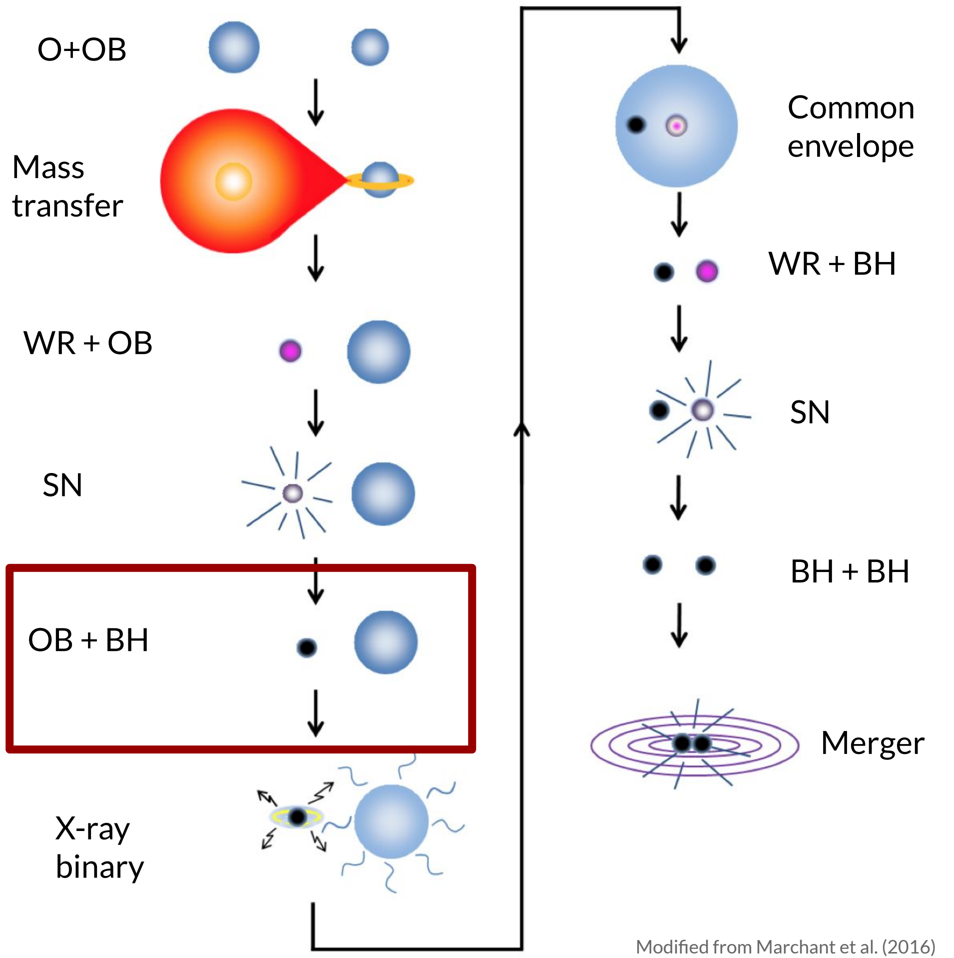

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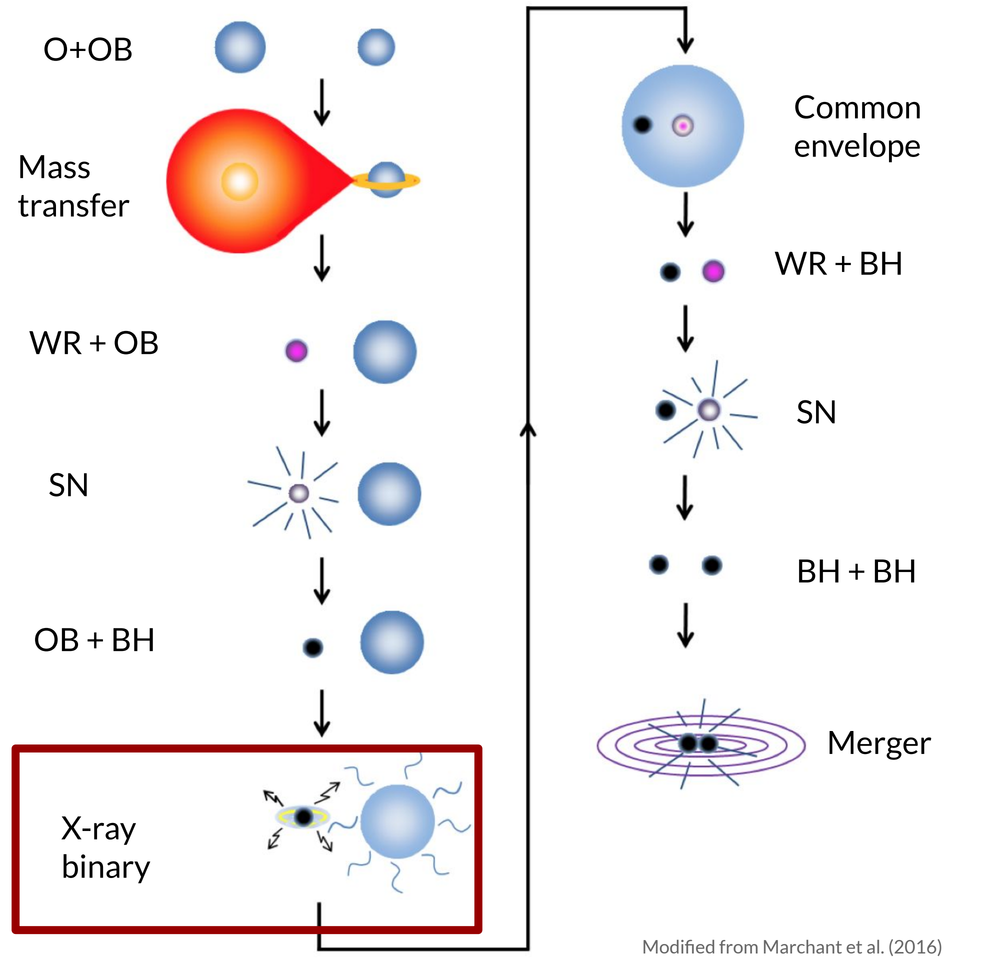

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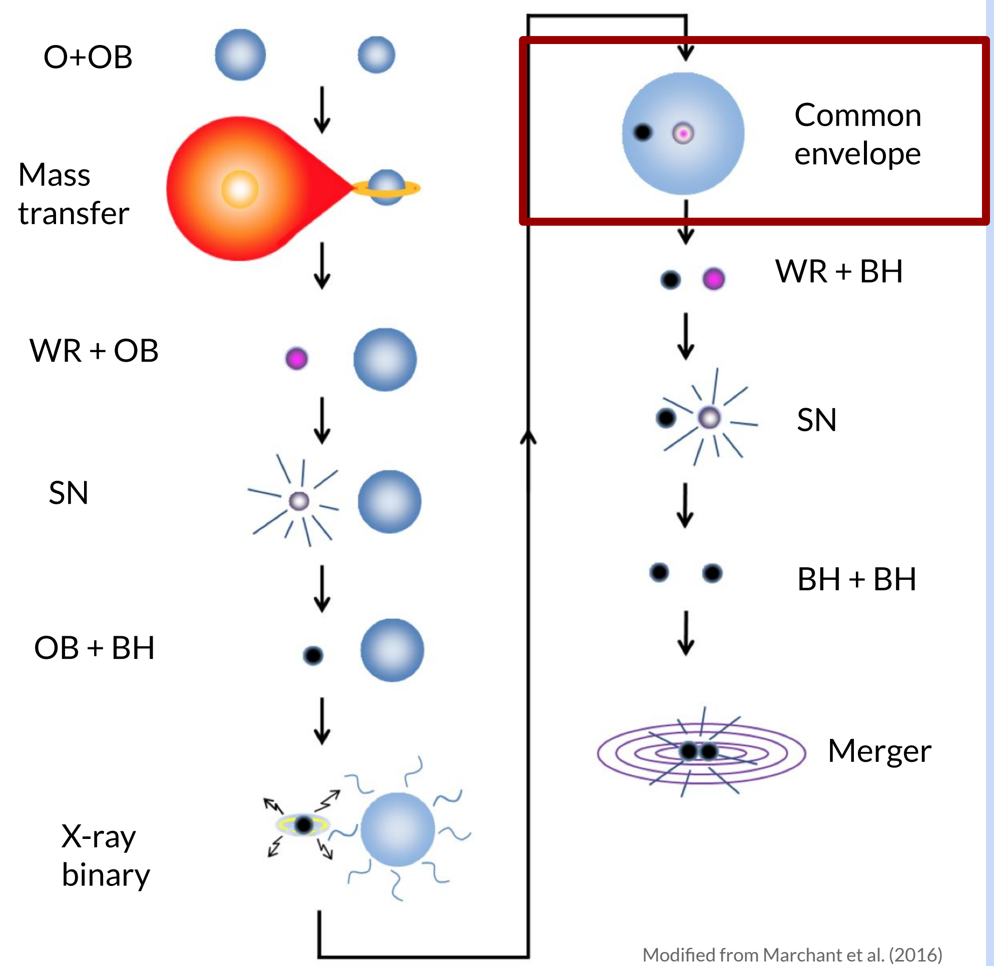

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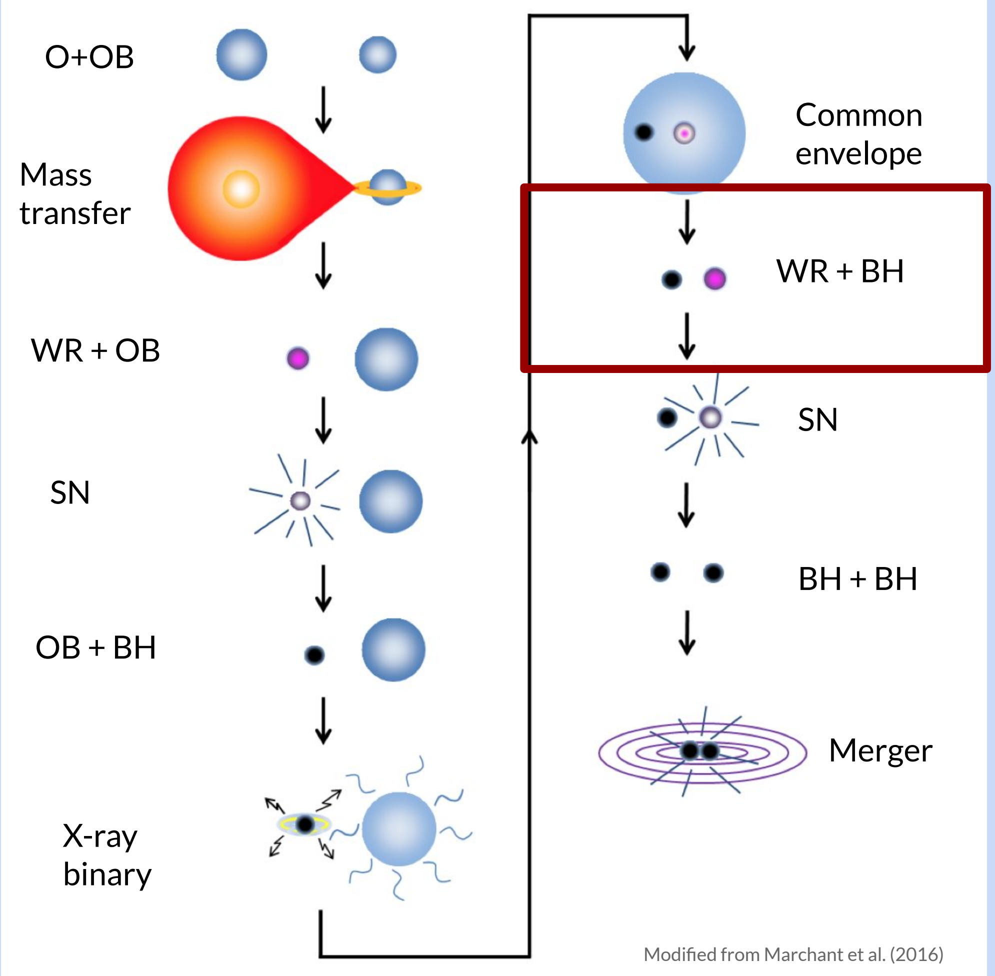

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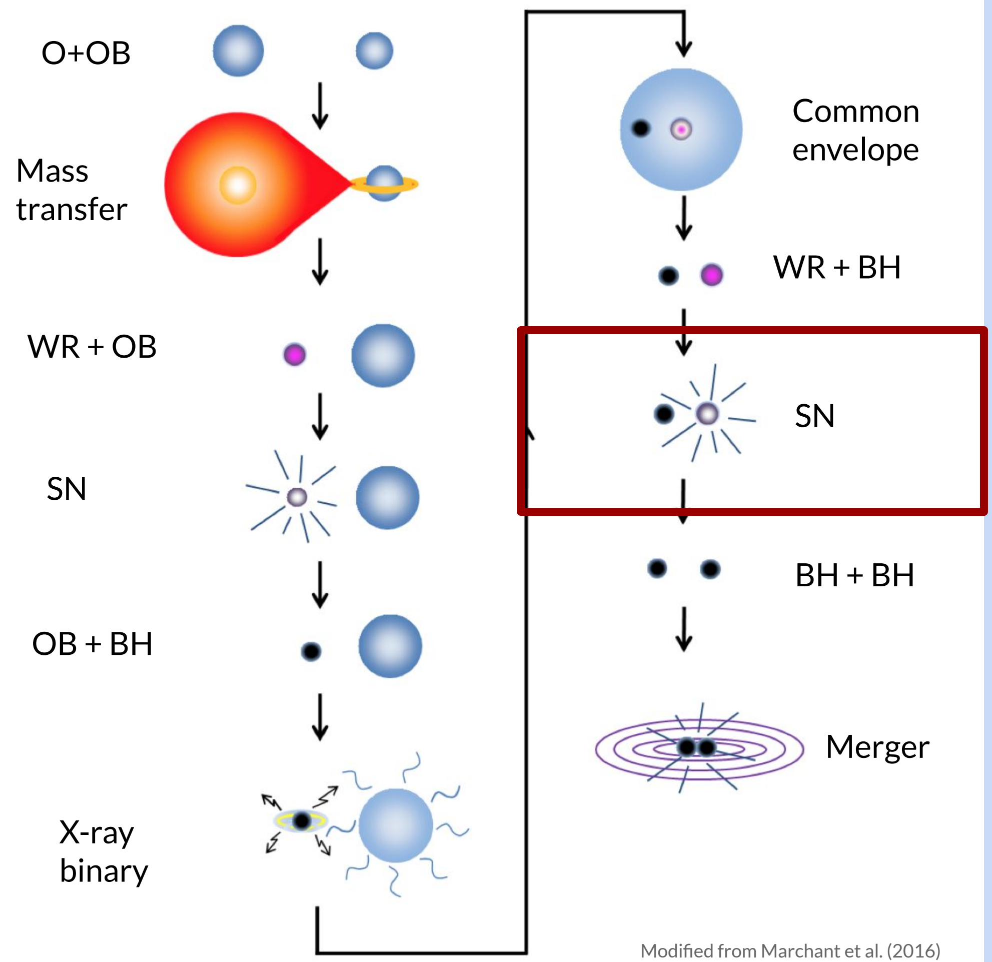

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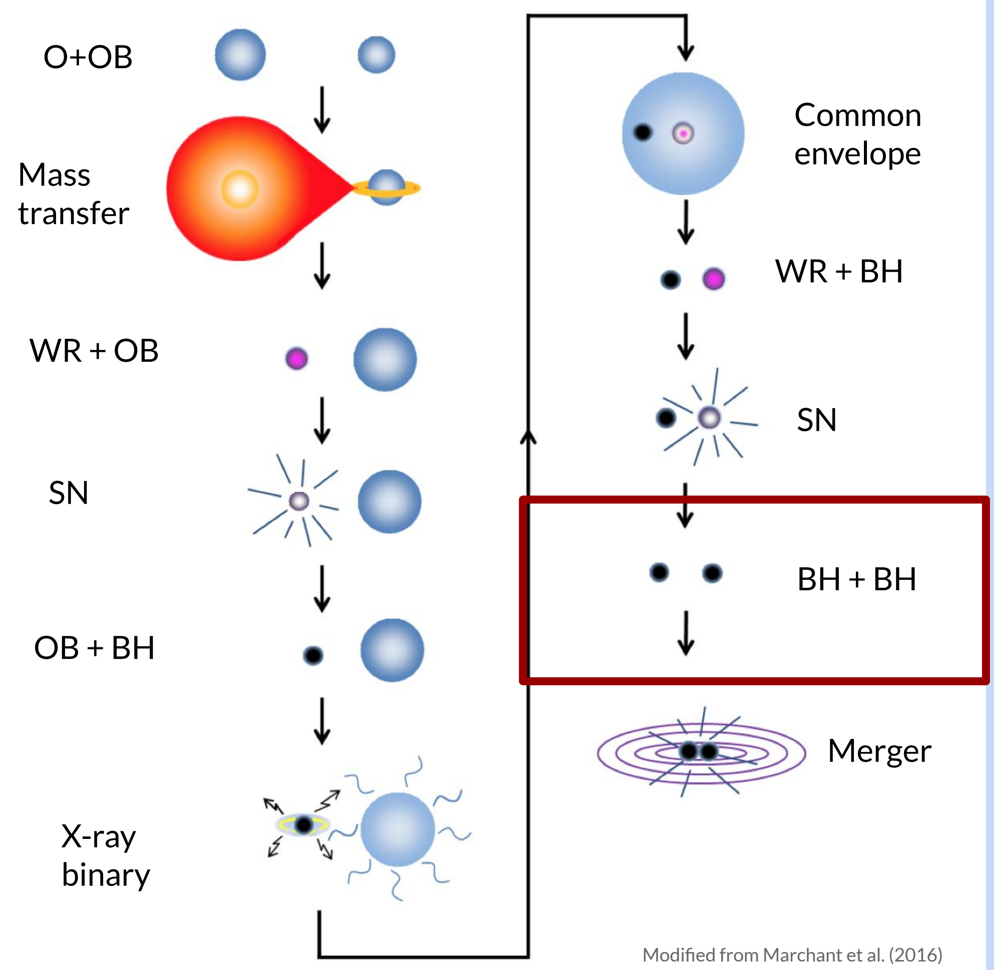

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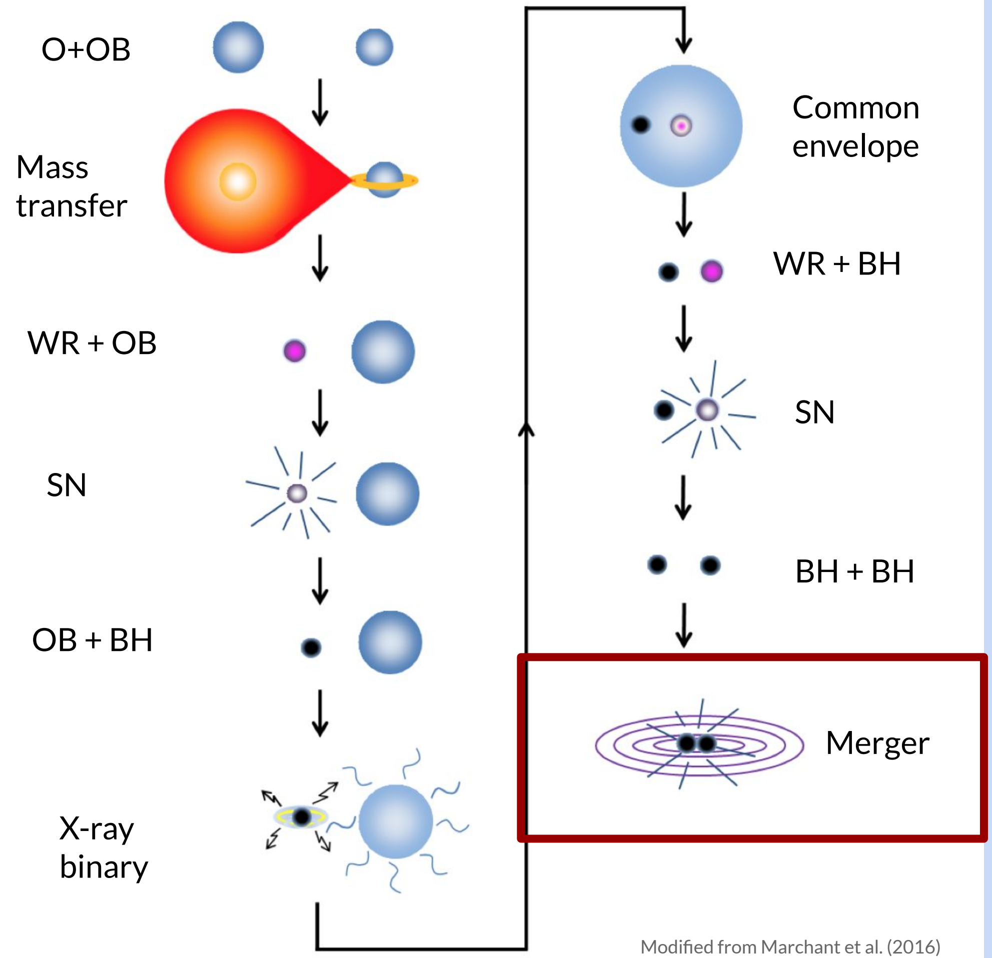

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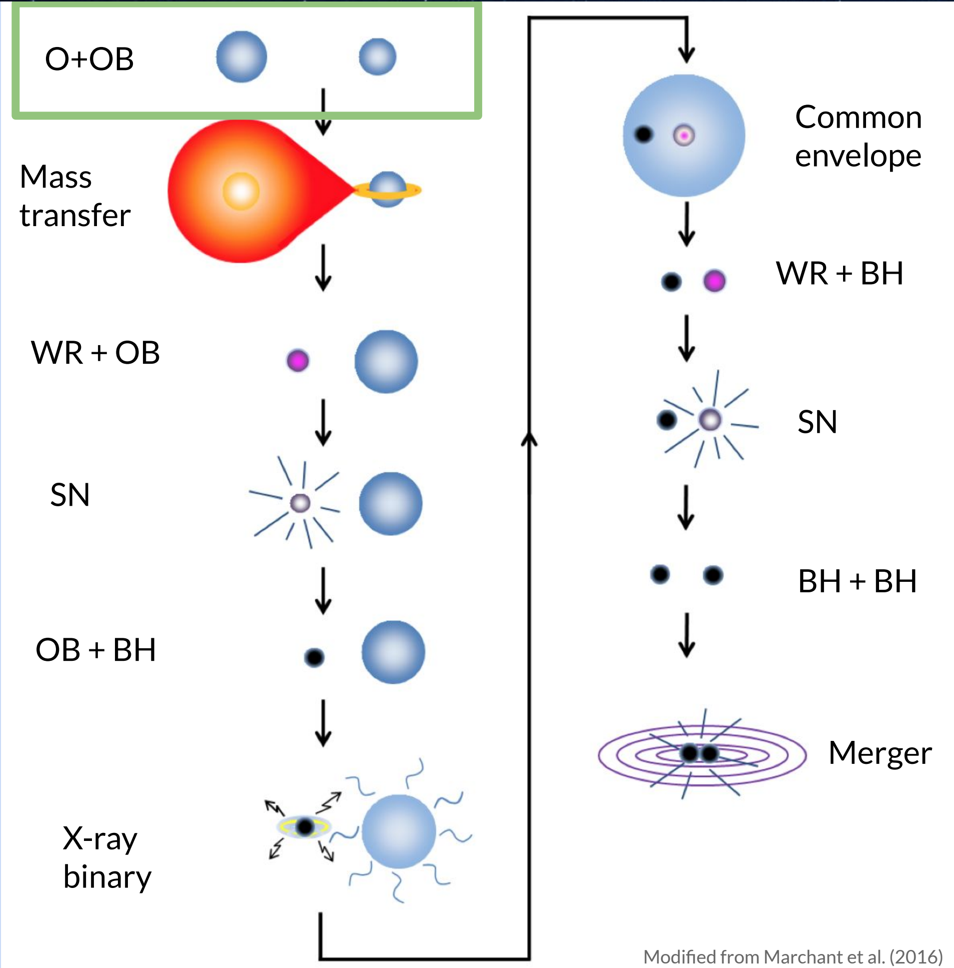
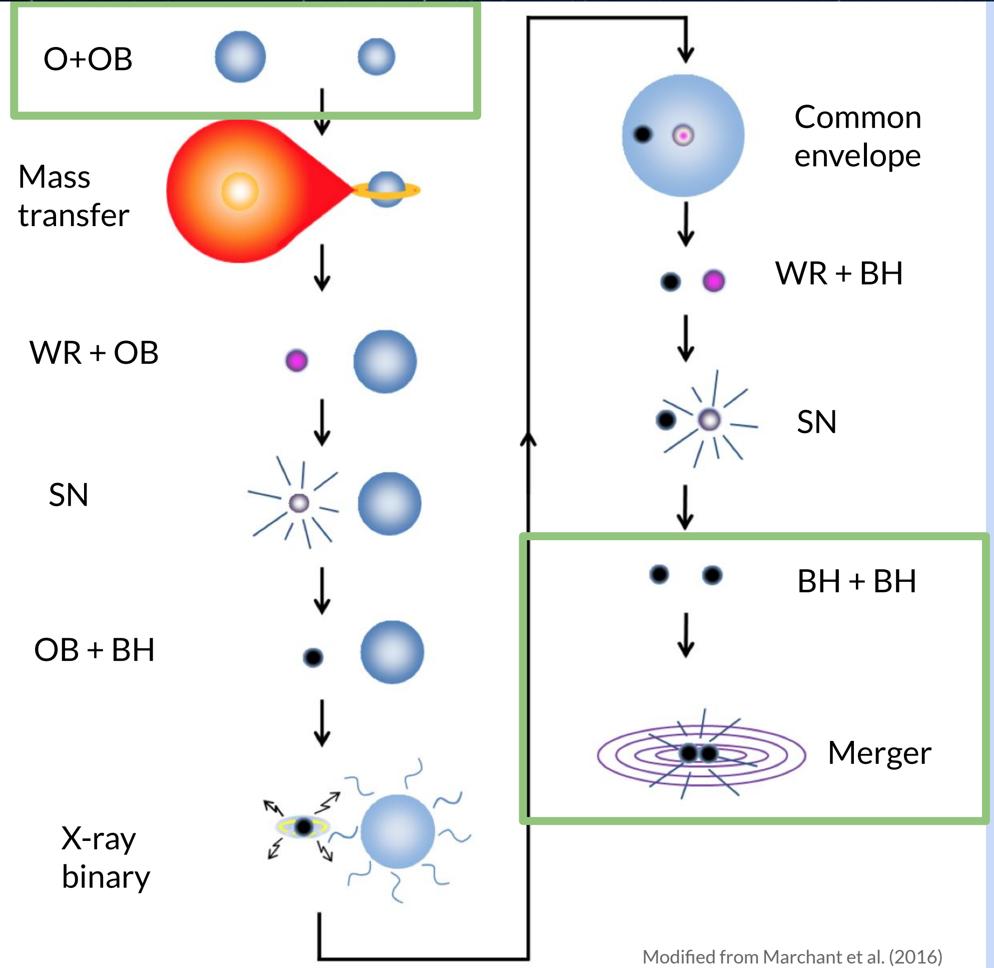


Modified from Marchant et al. (2016)

: Observed

Evolution towards compact object merger



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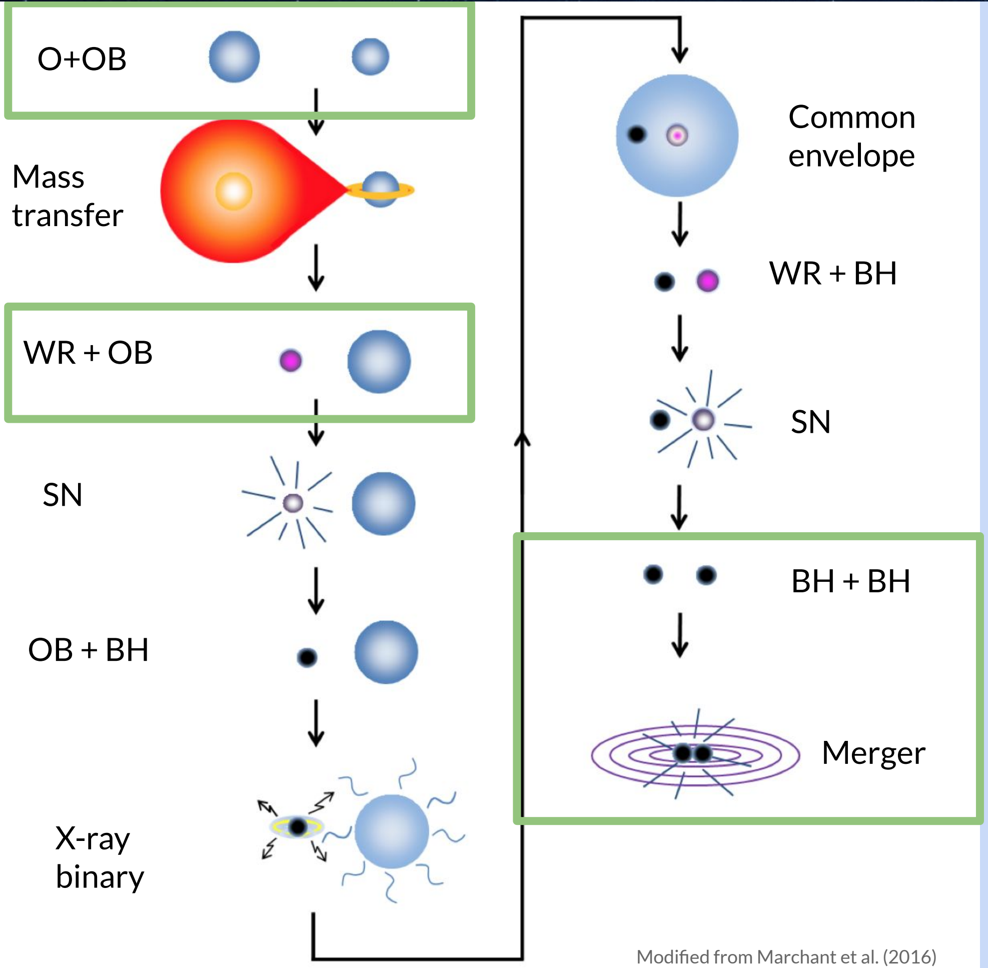

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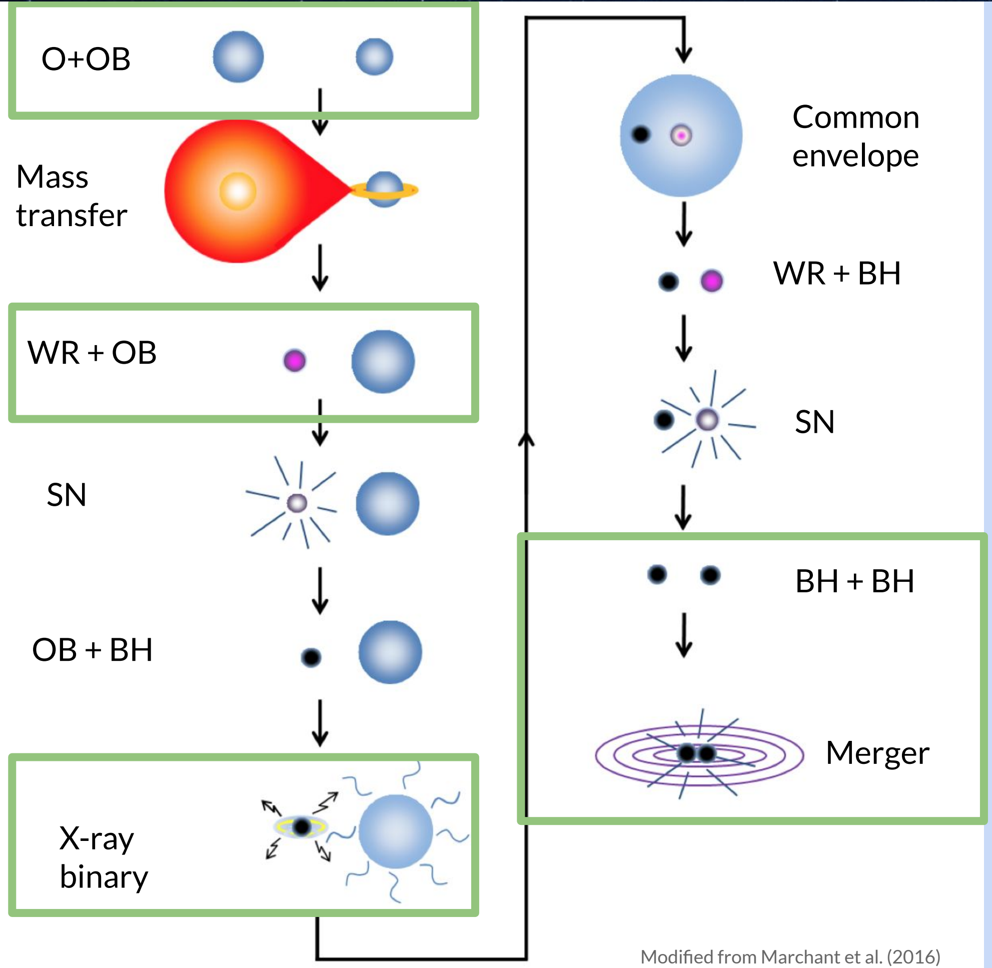

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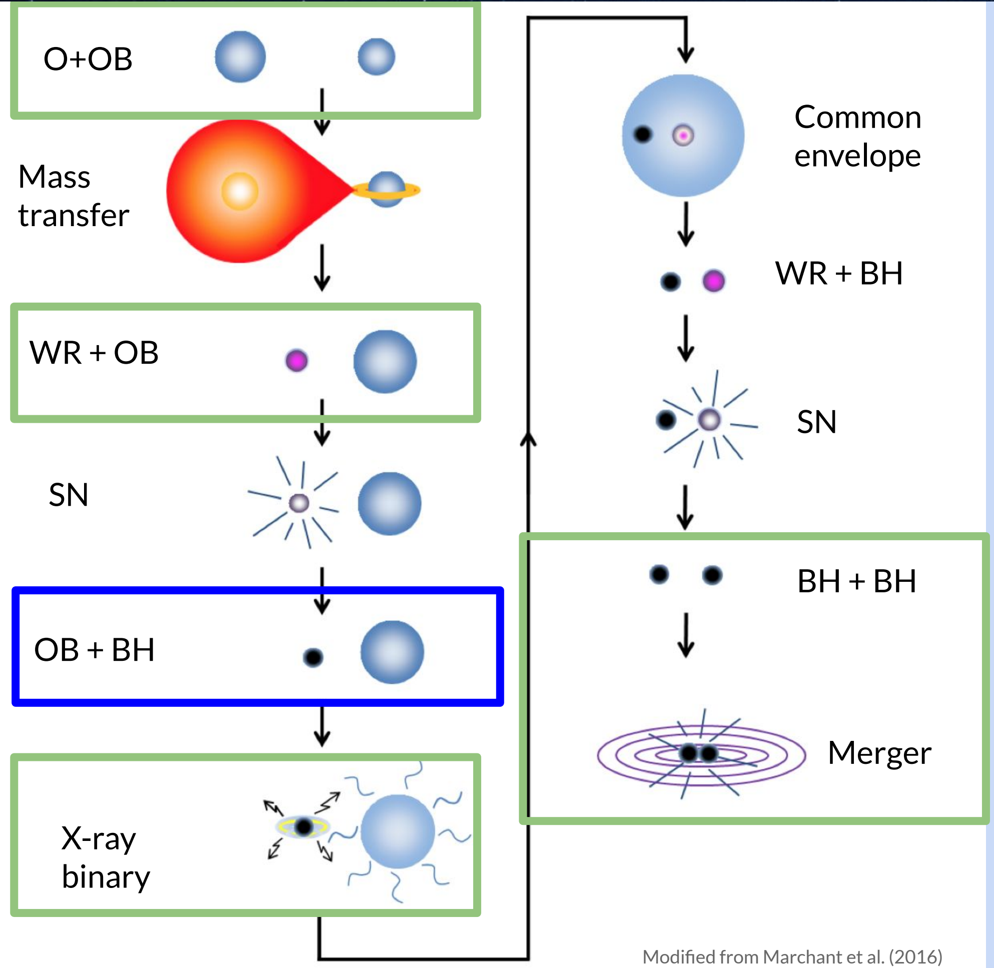
Evolution towards compact object merger



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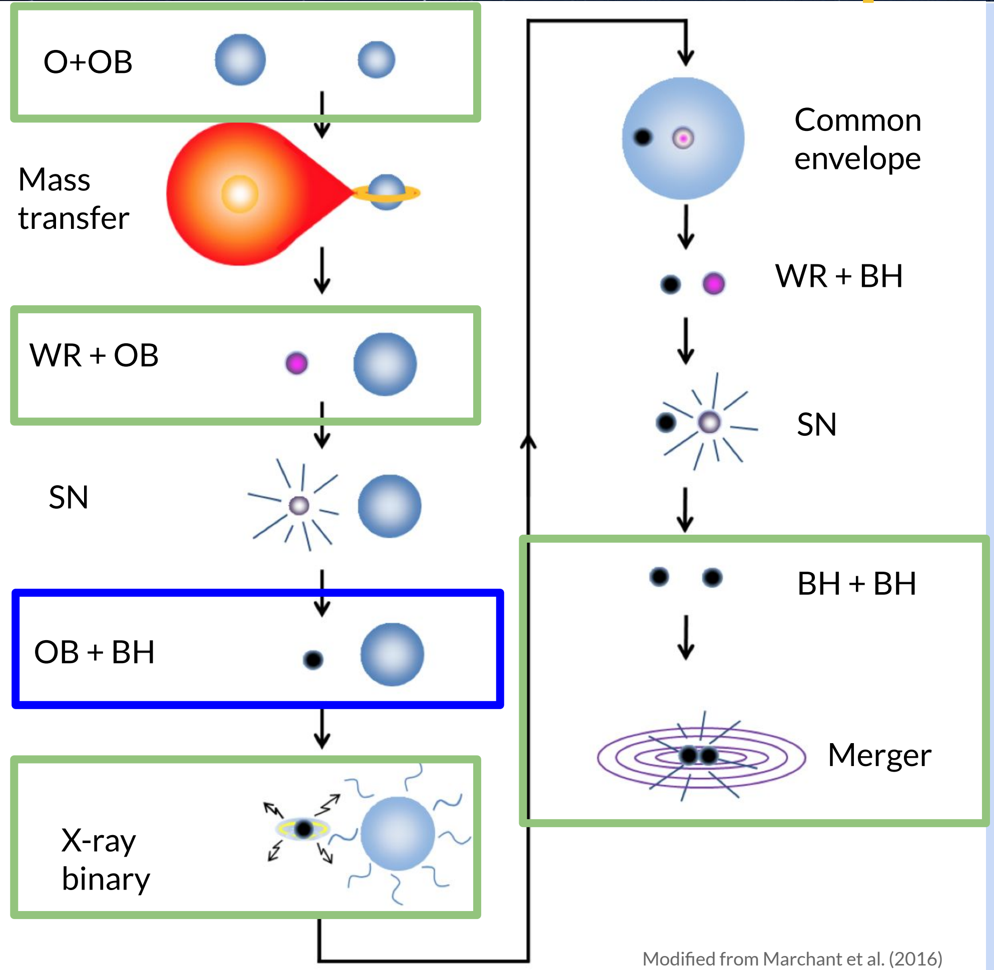
Direct collapse (no mass loss) and no kick:

predicted ~ 3% of OB binaries have BH companion (Langer et al. 2020, ~1200 OB+BH in Milky Way)

Evolution towards compact object merger



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Direct collapse (no mass loss) and no kick:

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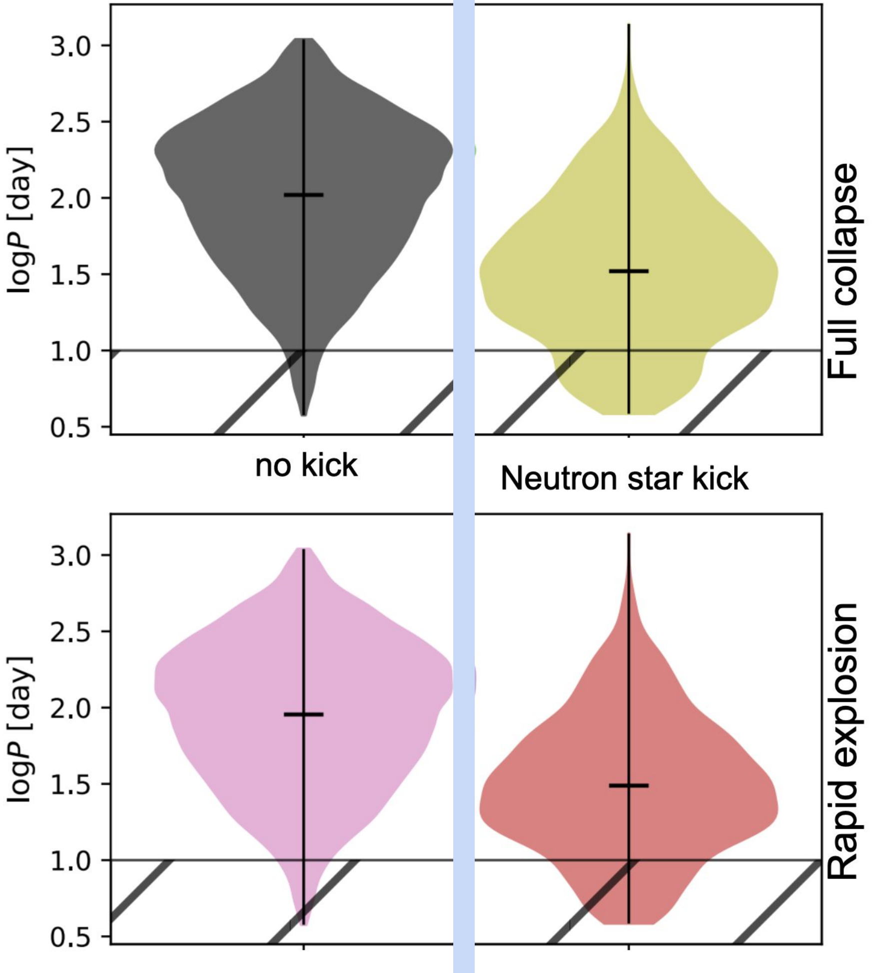
Currently: handful of candidates of dormant OB+BHs

(e.g. Mahy et al. 2022, Shenar et al. 2022 → LMC)

??? Where are the dormant BHs ???

Uncertain BH-formation physics



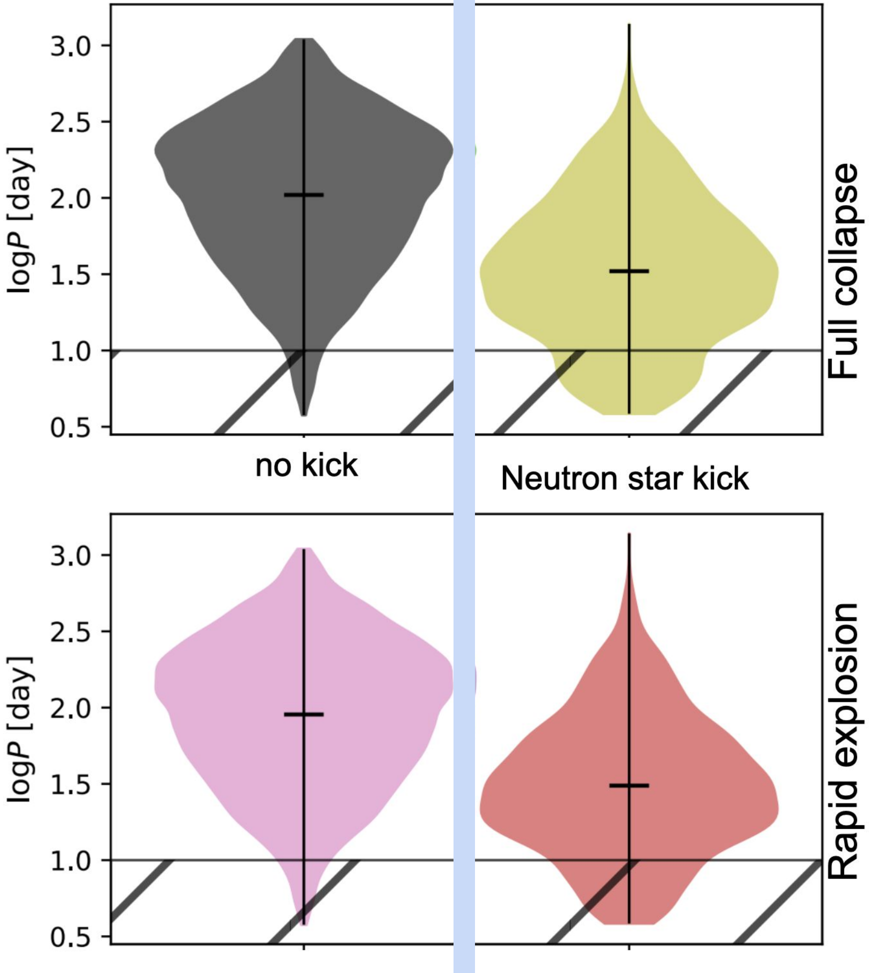
Different BH-formation scenarios

↓

Different distributions in e.g. P

Janssens et al. (2022)

Uncertain BH-formation physics



Different BH-formation scenarios

↓

Different distributions in e.g. P

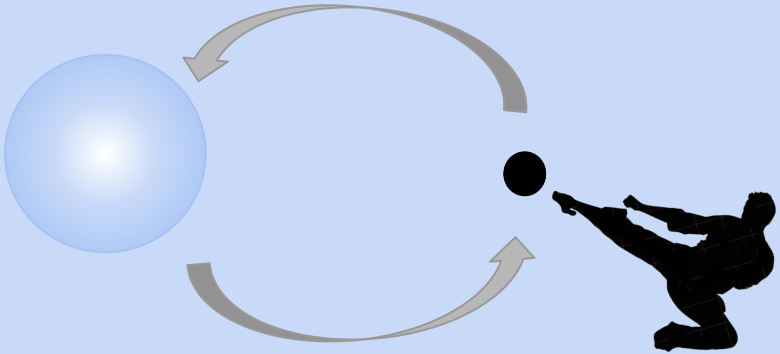
but also in eccentricity and mass of black hole

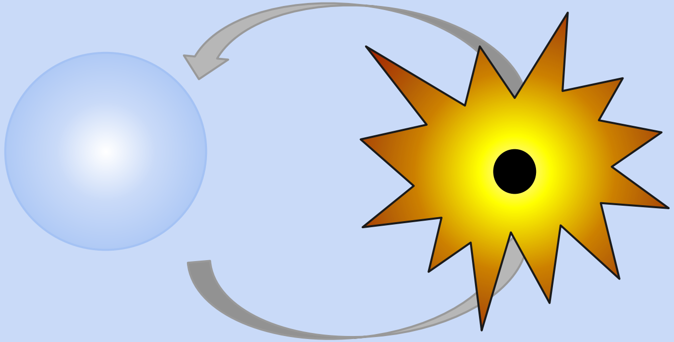
+ different number of systems
(e.g. stronger kick → easier disrupted)

Janssens et al. (2022)

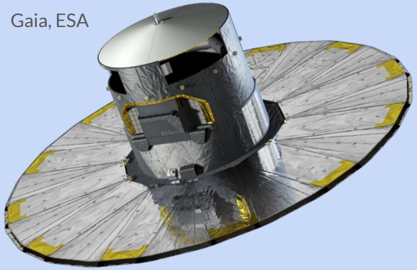
Where are the dormant BHs?

- Do BHs receive kicks? → OB+BH systems disrupted
- Mass loss during BH-formation? → supernovae
- Other detection methods? → spectroscopy is challenging





Not on scale



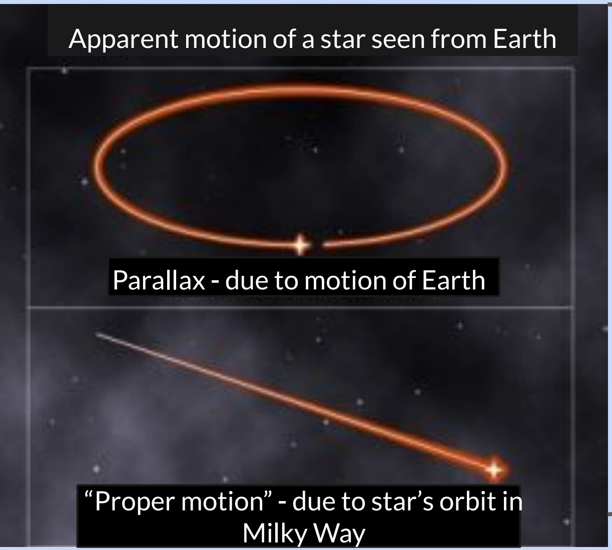
Gaia, ESA

ESA

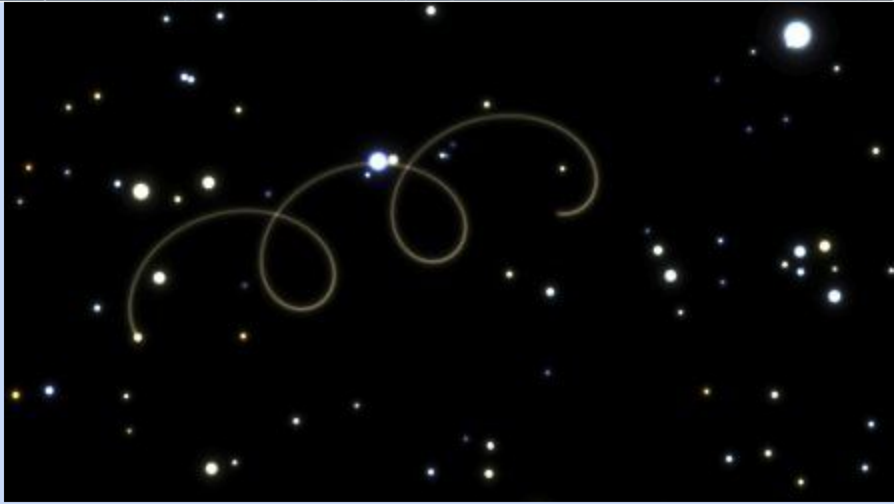
Gaia astrometry bringing new opportunities

What does Gaia see?

https://www.open.edu/openlearn/science-maths-technology/science/physics-and-astronomy/gaia-taking-the-galactic-census



single star



ESA

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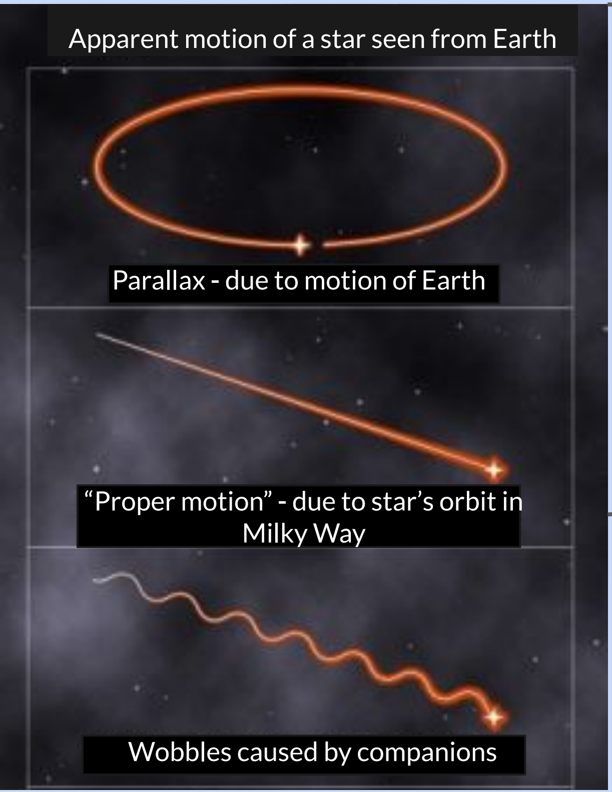

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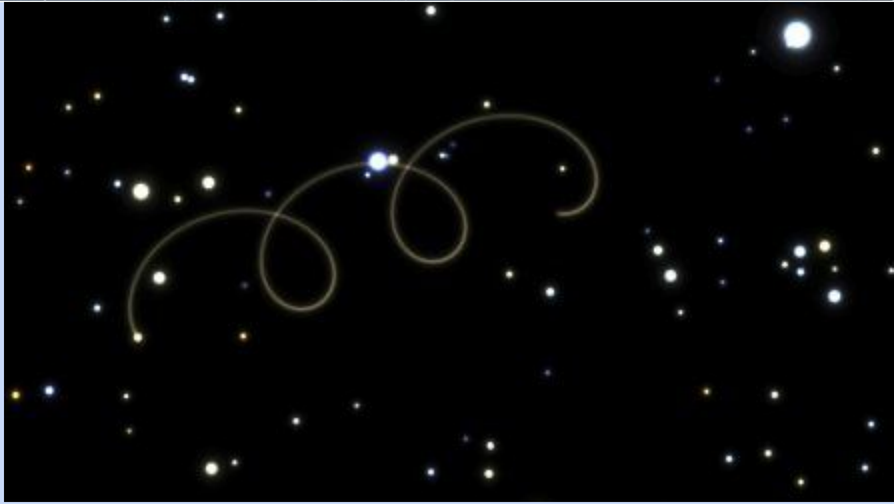


ESA

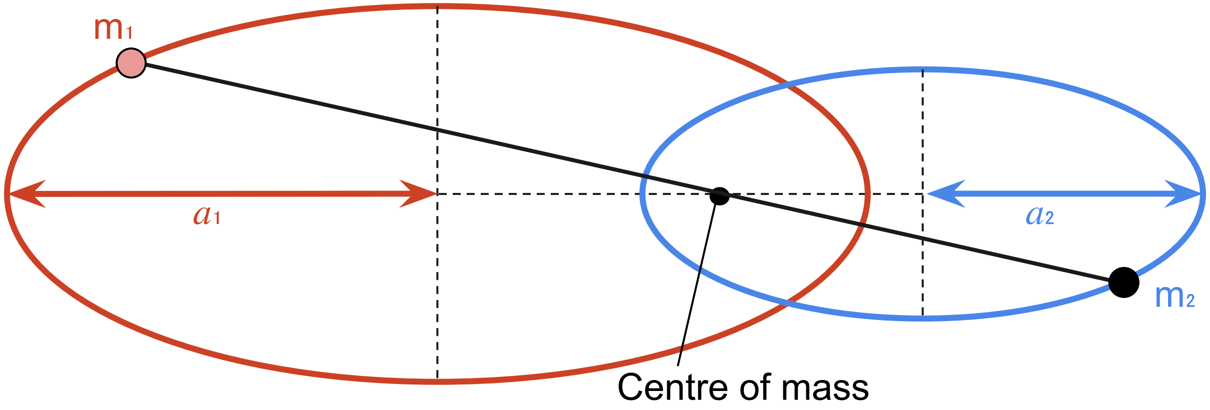
binary

Different kind of binaries

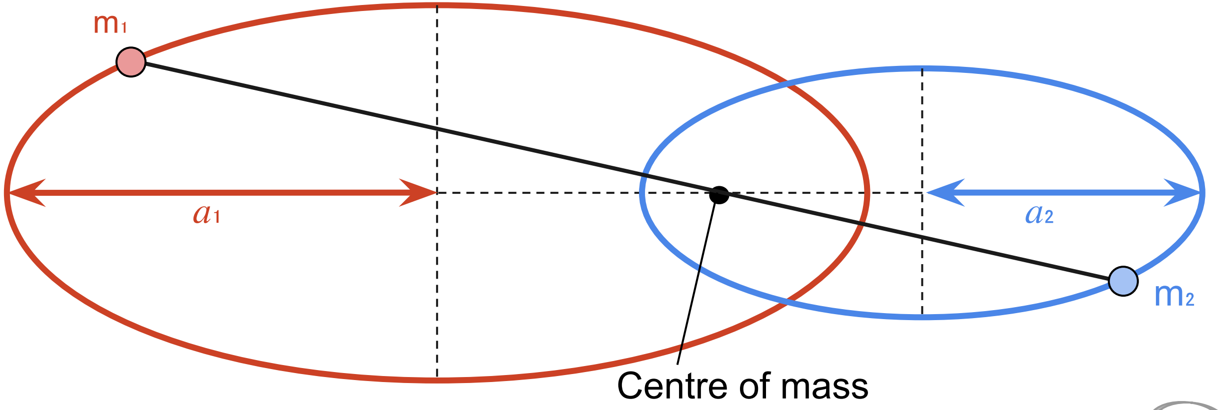
- Gaia (astrometry) can distinguish between single stars and binaries
- Can Gaia see the difference between OB+BH and OB+OB?
  - Unresolved binaries → Measures photocentre motion

Taking a look at the motion of the photocentre

- m_2 = BH

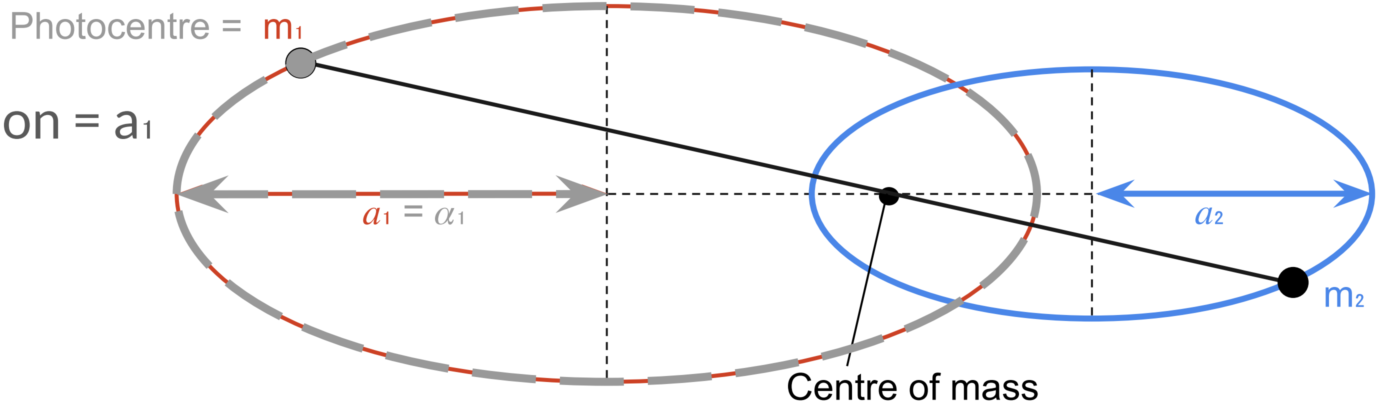


- m_2 = luminous

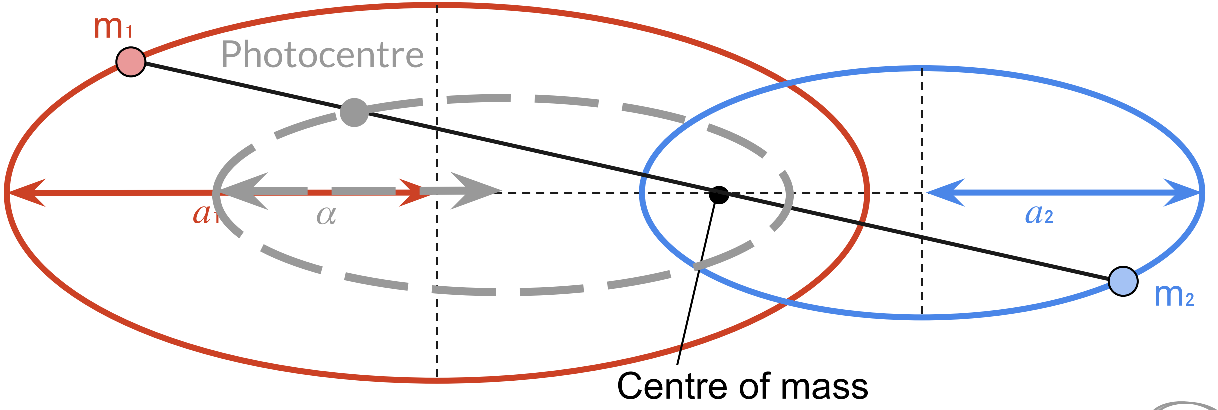


Taking a look at the motion of the photocentre

- m_2 = BH
- Photocentre motion = a_1



- m_2 = luminous
- Photocentre motion ≠ a_1
  - Dependent on mass/intensity ratio



Different kind of binaries

- Gaia (astrometry) can distinguish between single stars and binaries
- Can Gaia see the difference between OB+BH and OB+OB?
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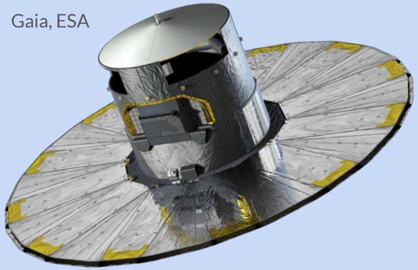
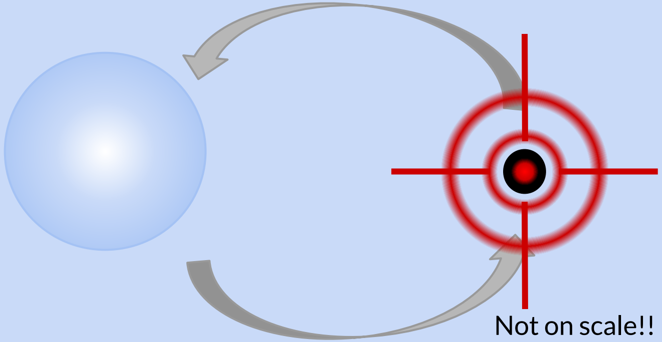
→ Yes! By looking at the size of the photocentre motion

Gaia, ESA



ESA

The identification method



Not on scale!!

The Astrometric Mass-Ratio Function

= AMRF (Shahaf et al. 2019)

Theoretical

Observational

The Astrometric Mass-Ratio Function

= AMRF (Shahaf et al. 2019)

Theoretical

$$\mathcal{A} = \frac{q}{(1+q)^{2/3}} \left(1 - \frac{S(1+q)}{q(1+S)}\right)$$

q = mass ratio =
least luminous / most luminous
S = Intensity ratio (mass dependent)

- predict the maximum photocentre motion for different kinds of systems

Observational

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$$\mathcal{A} = \frac{\alpha}{\varpi}\left(\frac{M_1}{M_\odot}\right)^{-1/3}\left(\frac{P}{\mathrm{yr}}\right)^{-2/3}$$

α = semi-major axis of the ellipse traced by the photocentre motion = astrometric signal
ϖ = parallax
M_1 = mass of the most luminous star
P = period

The Astrometric Mass-Ratio Function

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→ Gaia astrometric binary solutions

The Astrometric Mass-Ratio Function

= AMRF (Shahaf et al. 2019)

Theoretical (non-BH systems)

$$\mathcal{A} = \frac{q}{(1+q)^{2/3}}\left(1 - \frac{S(1+q)}{q(1+S)}\right)$$

q = mass ratio =
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$<$

Observational

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α = semi-major axis of the ellipse traced by the photocentre motion = astrometric signal
ϖ = parallax
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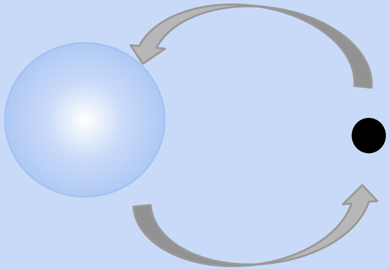
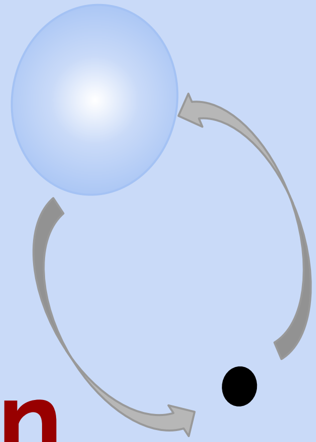
P = period

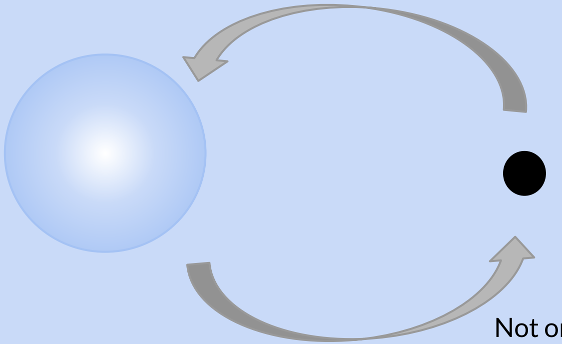
- predict the maximum photocentre motion f… kinds of systems

OB+BH





How many OB+BHs can we find with Gaia?



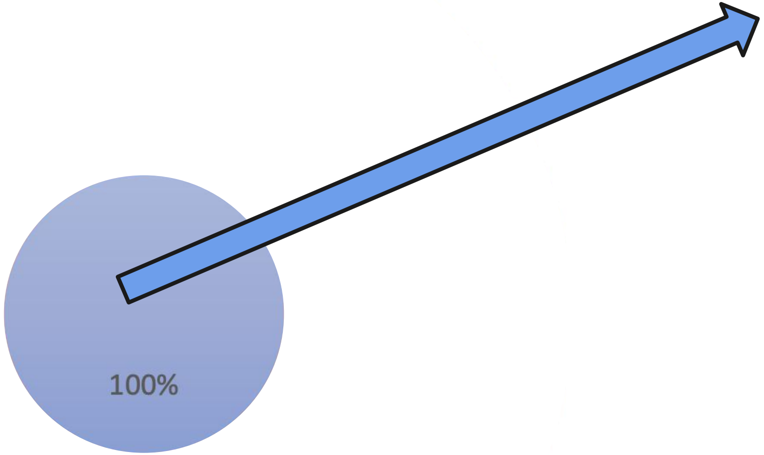
Janssens et al. (2022)

Not on scale!!

Creating an OB+BH population

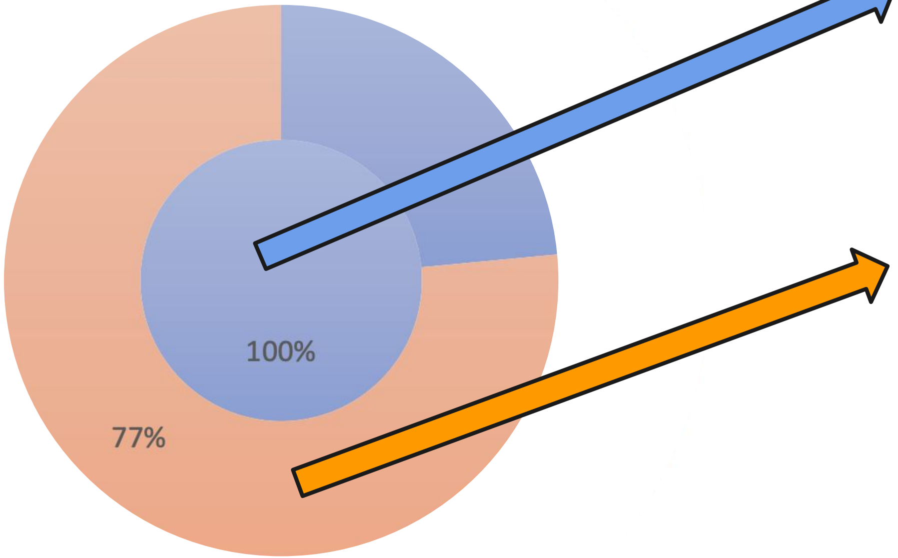
- Sample of OB + BHs from Langer et al. (2020)
  - Direct collapse (no mass loss) and no kick
- Draw distances from known OB catalogue: Alma Luminous Star catalogue II = ALS II (Pantaleoni González et al. 2021)
- Redden $\longrightarrow$ magnitudes

Which are detectable/identifiable?



Total simulated population of OB+BHs = 100%

Which are detectable/identifiable?



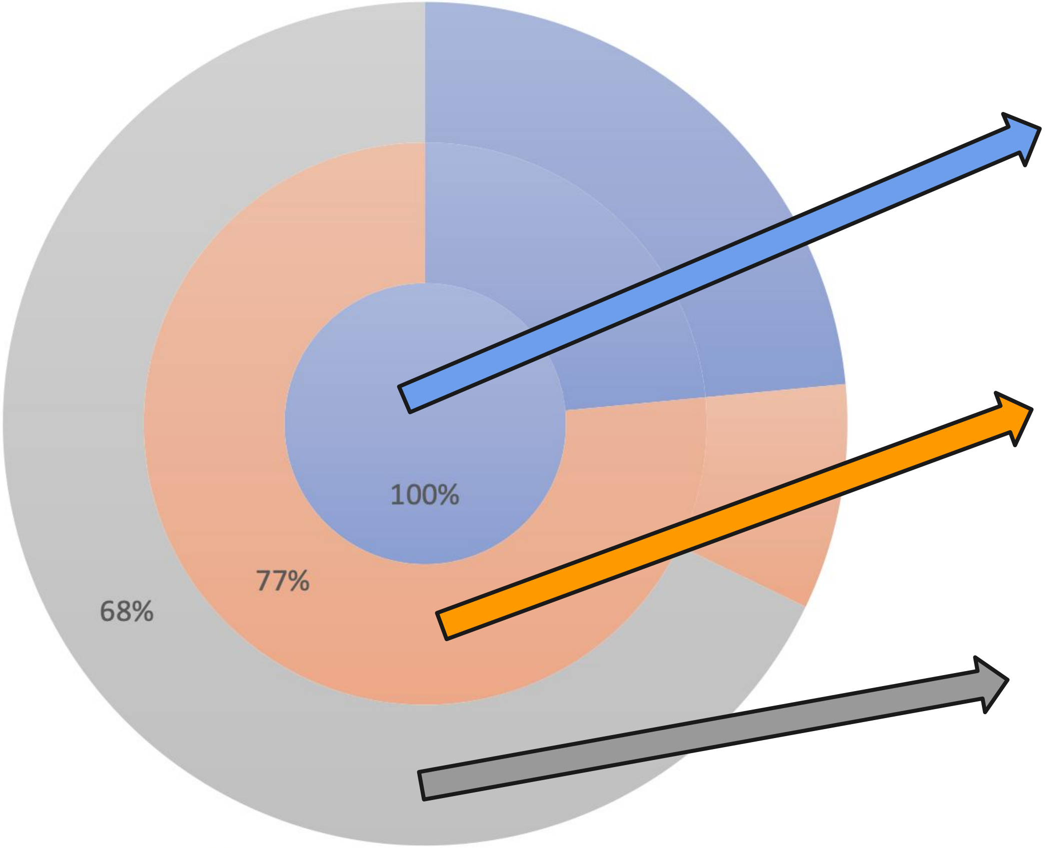
Total simulated population of OB+BHs = 100%

77% detectable: 6<G<20, P<3yr, $\alpha > 3\sigma$

$\alpha =$ astrometric signal

$\sigma =$ Gaia precision

Which are detectable/identifiable?



Total simulated population of OB+BHs = 100%

77% detectable: 6<G<20, P<3yr, $\alpha > 3\sigma$

68% (= 77%*89%) identifiable using AMRF

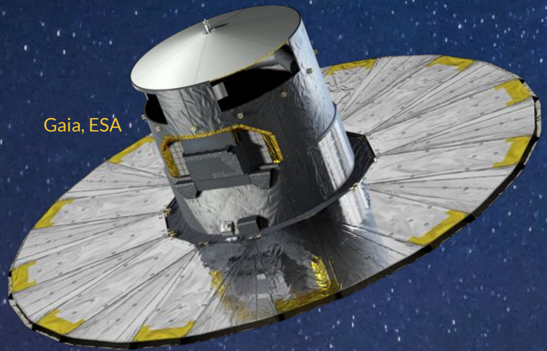
Estimated numbers

- ALS II: >13 000 sources (Pantaleoni González et al. 2021)
- ~ 70% of massive stars in binaries (Sana et al. 2012)
- Of which ~ 3% BH companion (Langer et al. 2020)

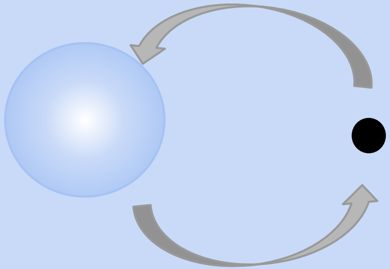
→ ~ 200 OB+BH systems can be identified

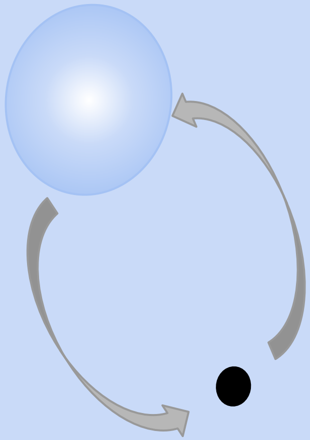
Predictions (Janssens et al. 2022):
With Gaia we can find ~ 200 OB+BH systems
AND
learn about BH-formation scenarios

Gaia, ESA

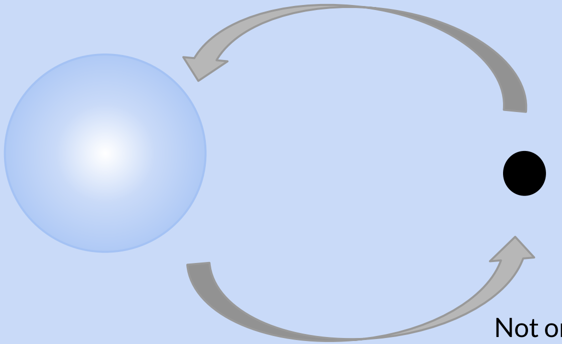


credits to Pablo Marchant





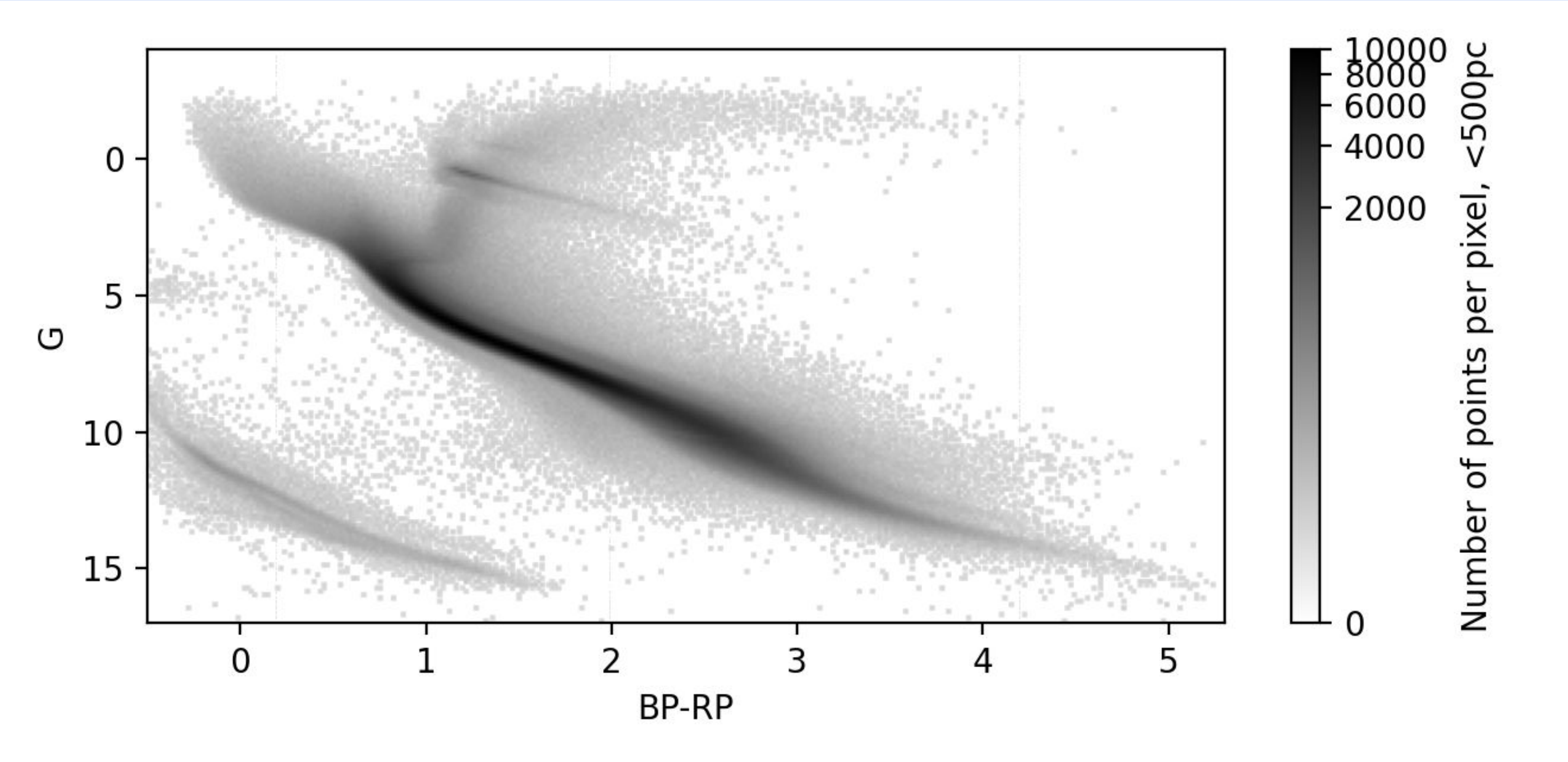
Results from DR3



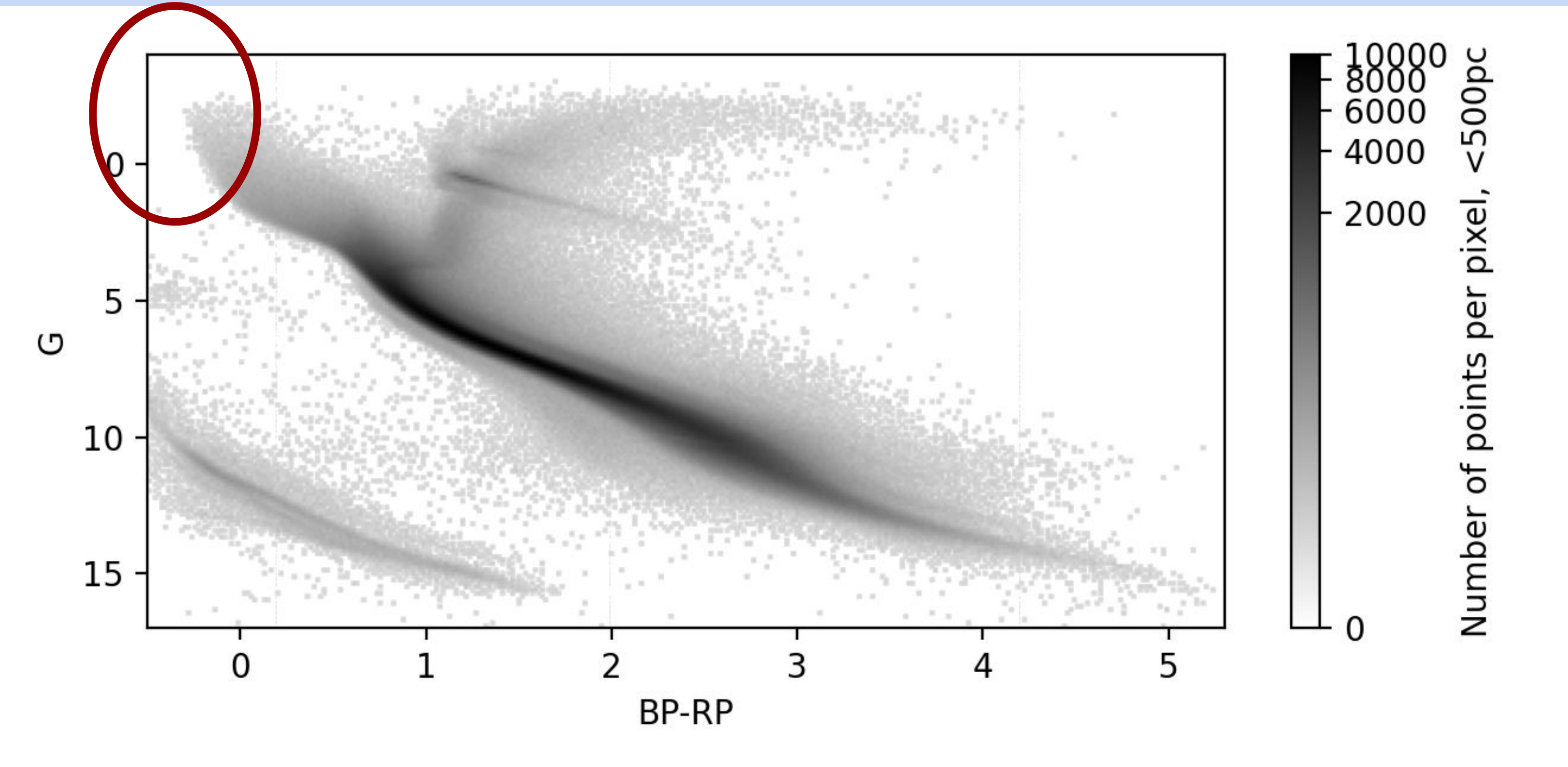
Janssens et al. (subm.)

Not on scale!!

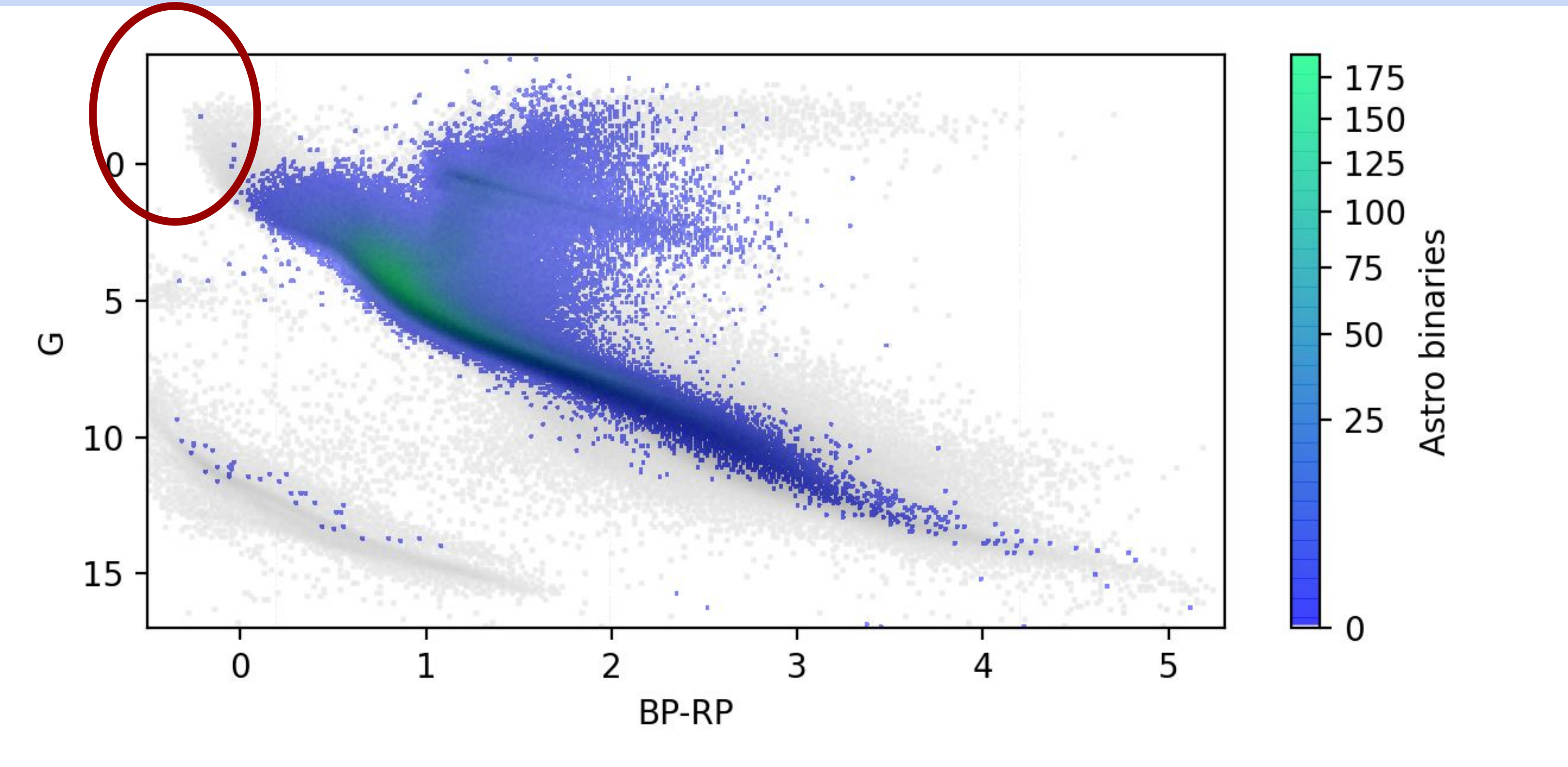
Astrometric DR3 binaries in the HRD



Astrometric DR3 binaries in the HRD

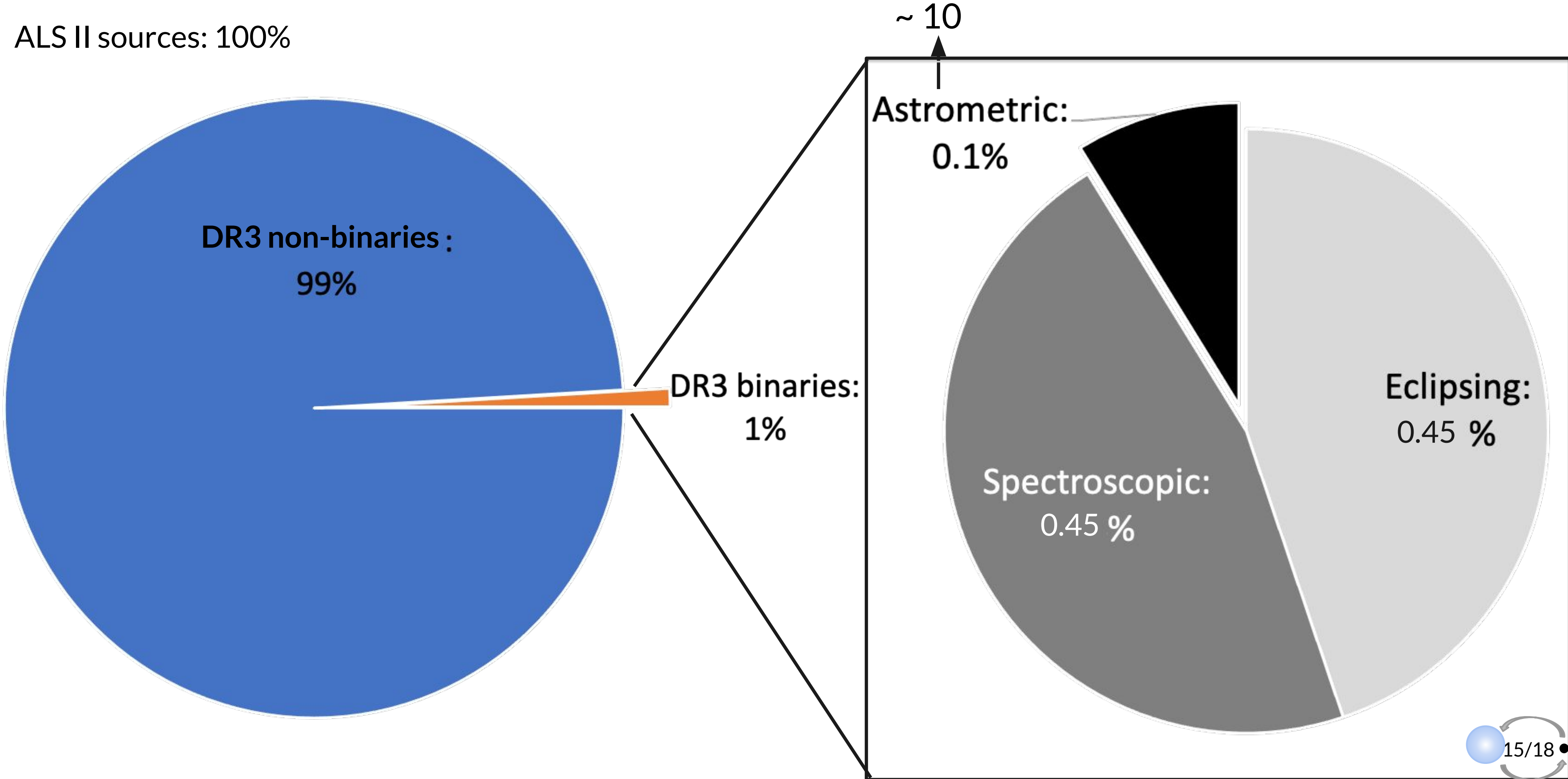


Astrometric DR3 binaries in the HRD



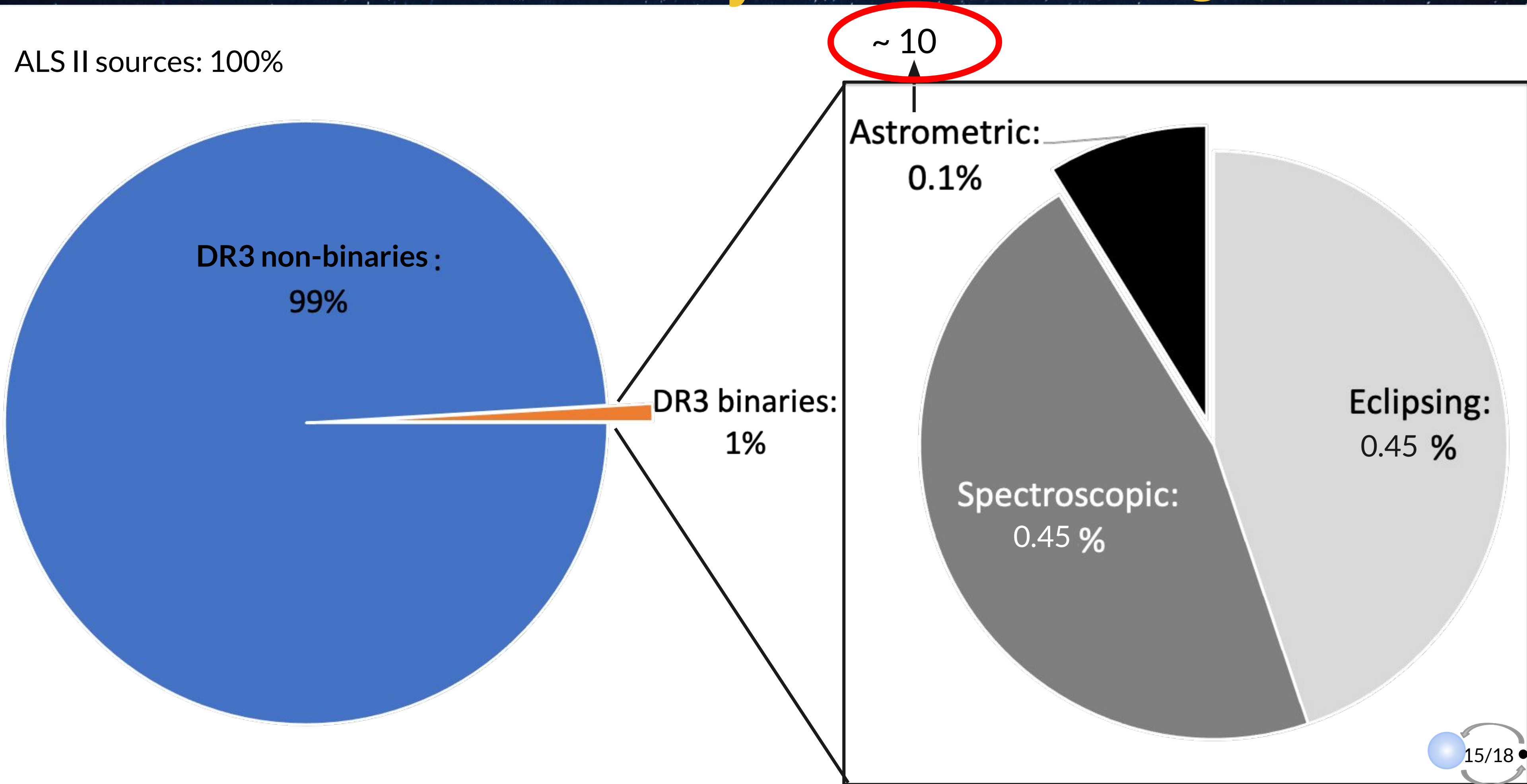
ALS II astrometric binary sources in DR3

ALS II sources: 100%



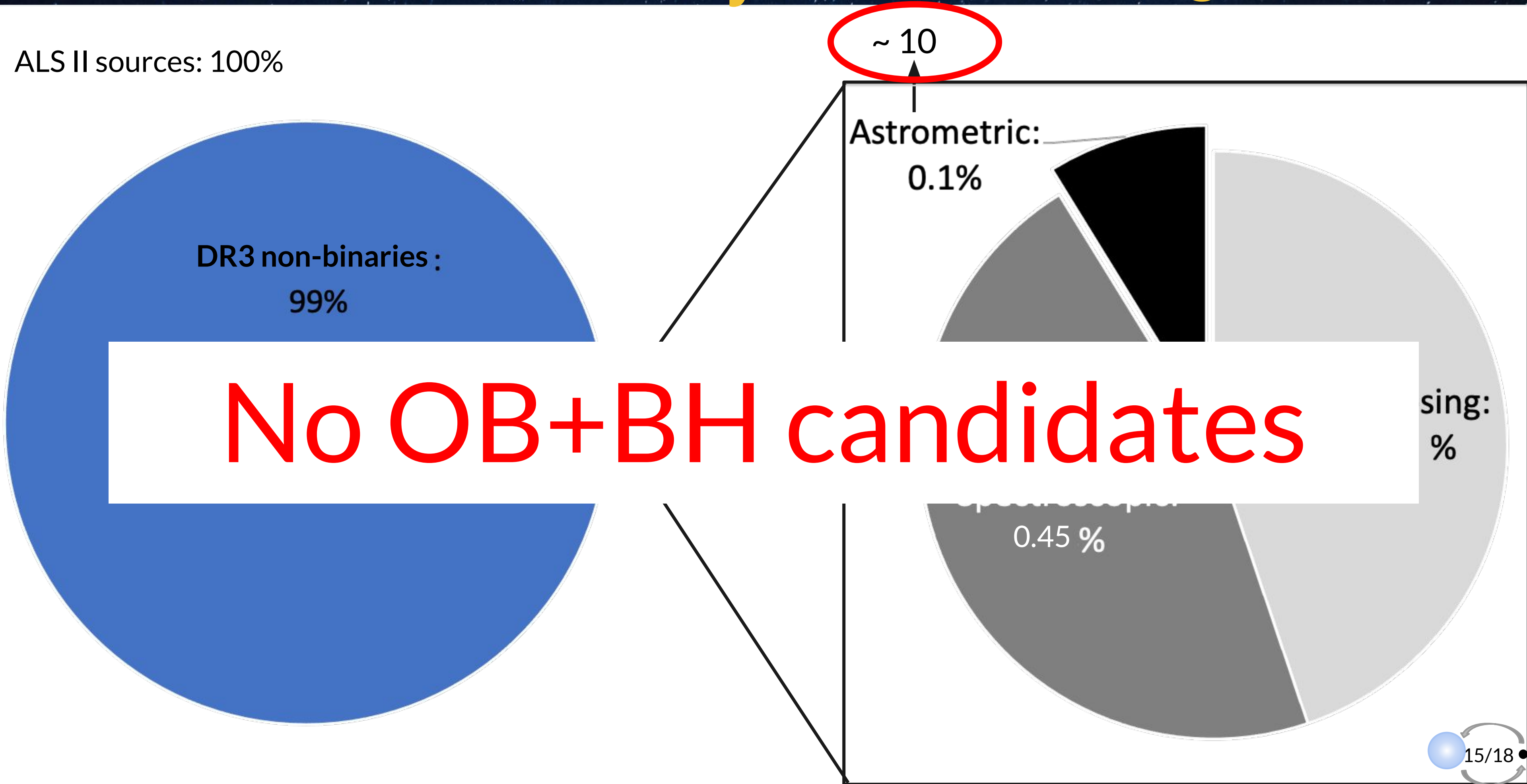
ALS II astrometric binary sources in DR3

ALS II sources: 100%



ALS II astrometric binary sources in DR3

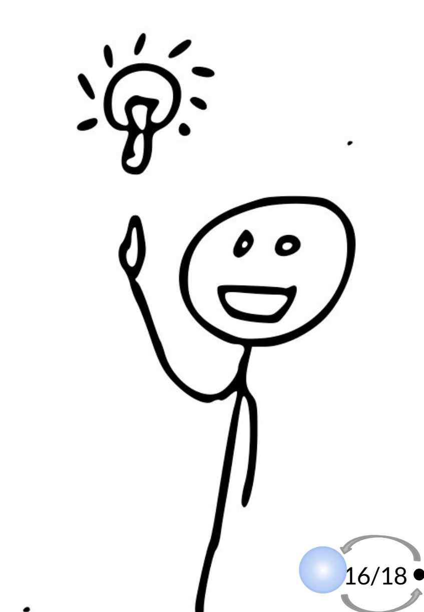
ALS II sources: 100%



No OB+BH candidates

No OB+BH detections

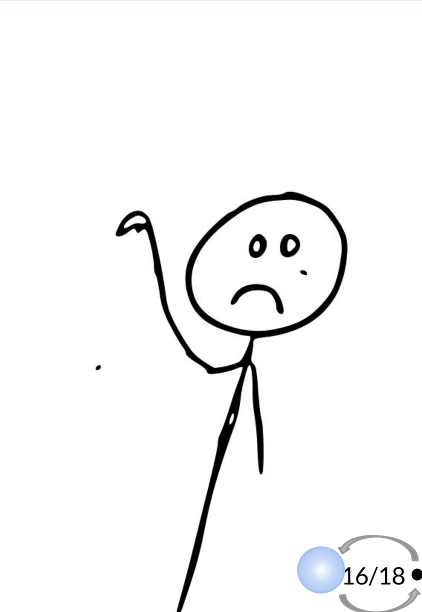
→ information on BH-formation scenario??



No OB+BH detections

→ information on BH-formation scenario??

No



Why no information on BH-formation scenario?

Basic selection criterion for Gaia DR3 astrometric solution:

$$\varpi/\sigma_{\varpi} > 20000/P_{\rm days}$$

https://gea.esac.esa.int/archive/documentation/GDR3/pdf/GaiaDR3_documentation_1.1.pdf

e.g. P = 100d $\rightarrow$ ϖ/σ_{ϖ} = 200 $\rightarrow$ severe restriction in volume

(most of OB+BHs expected with P = 100-300d)

Why no information on BH-formation scenario?

Basic selection criterion for Gaia DR3 astrometric solution:

$$\varpi/\sigma_{\varpi} > 20000/P_{\rm days}$$

https://gea.esac.esa.int/archive/documentation/GDR3/pdf/GaiaDR3_documentation_1.1.pdf

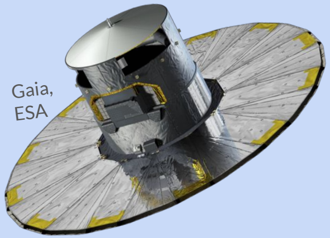
New predictions using ϖ/σ_{ϖ}

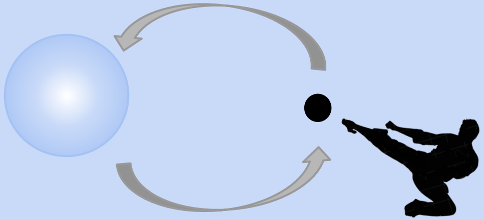
- 0.14% of simulated OB+BHs detected (0-1 OB+BH)
- 0.3% of simulated OB+OB binaries detected (~20 OB+OB)

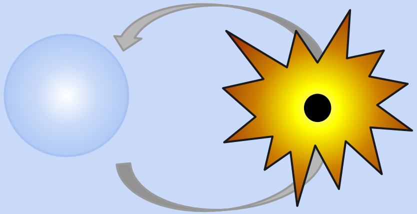
→ In line with ~ 10 ALS II sources having astrometric binary solution...

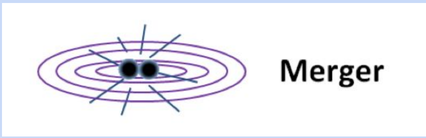
To conclude

- Non-detection of OB+BHs → no information on BH-formation scenario
- Need much less conservative constraint on the actual Gaia data in future data releases to learn about
  - BH-formation physics
  - the formation of BH+BH mergers

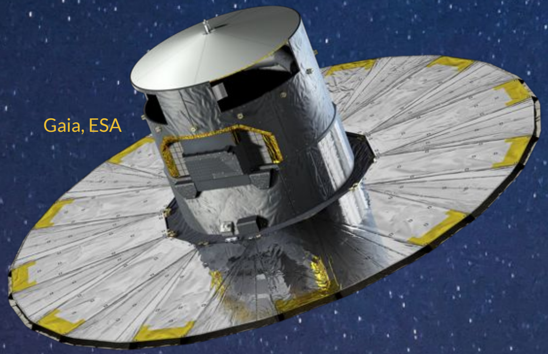








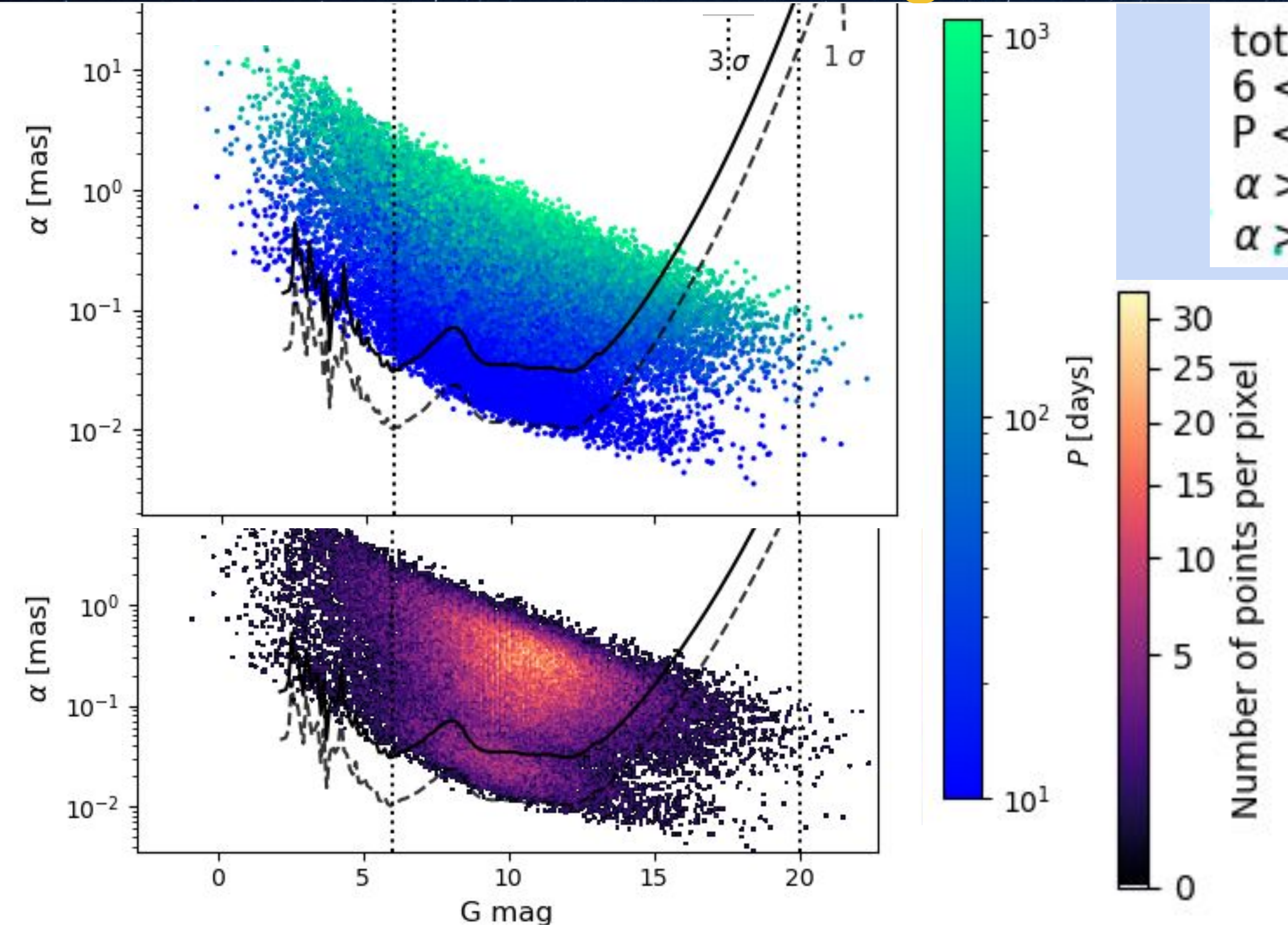
With Gaia we can find ~ 200 OB+BH systems
AND
learn about BH-formation scenarios
IF
constraints are less conservative in future data releases


Gaia, ESA

credits to Pablo Marchant

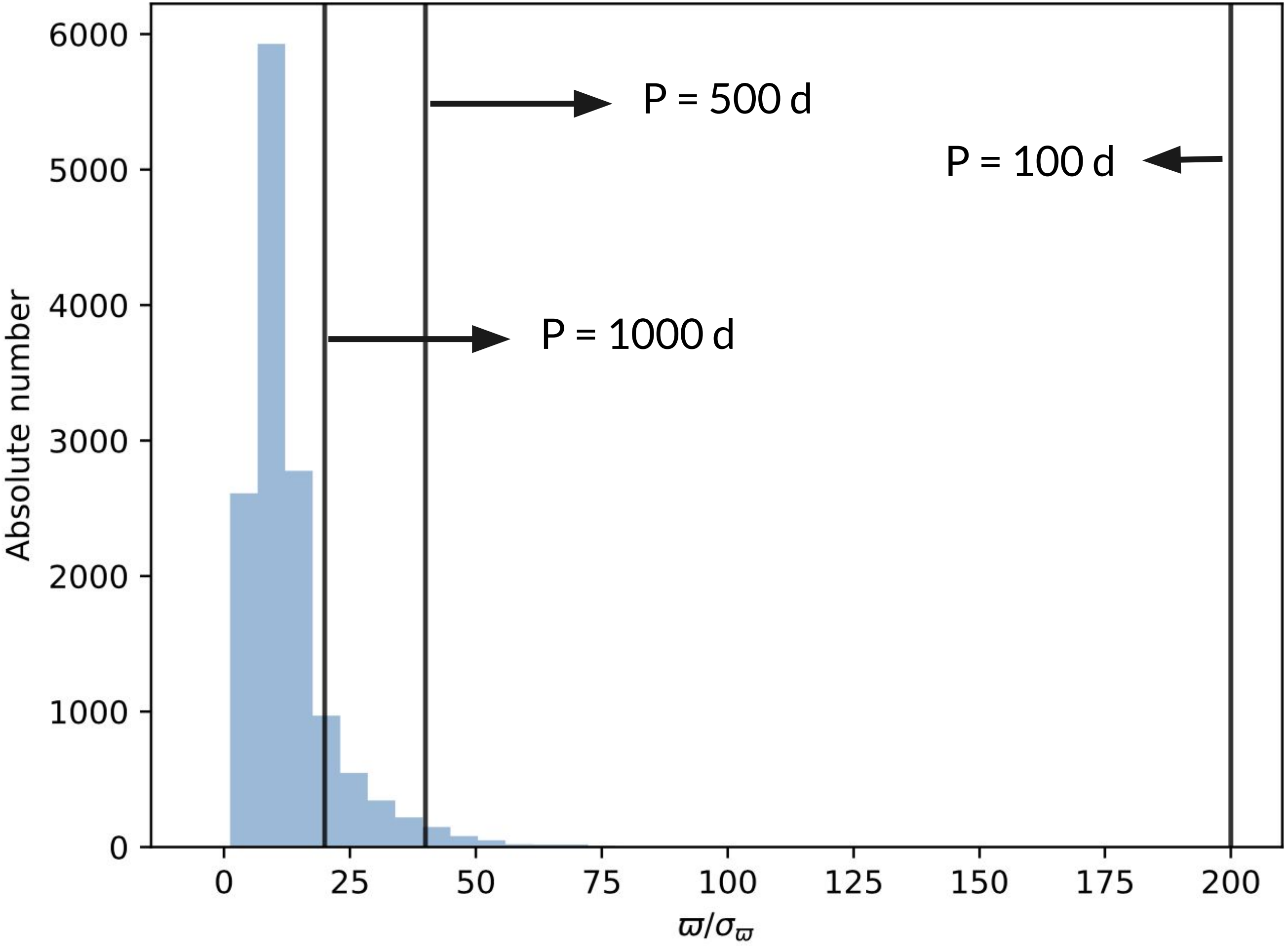
For more info: see Janssens et al. (2022, subm.)

Simulated astrometric signals



total OB+BH:	100.0%
6 < G < 20:	93.1%
P < 3yr:	90.9%
$\alpha > 1\ \sigma$:	87.8%
$\alpha > 3\ \sigma$:	76.5%

Parallax precisions of the ALS II sources

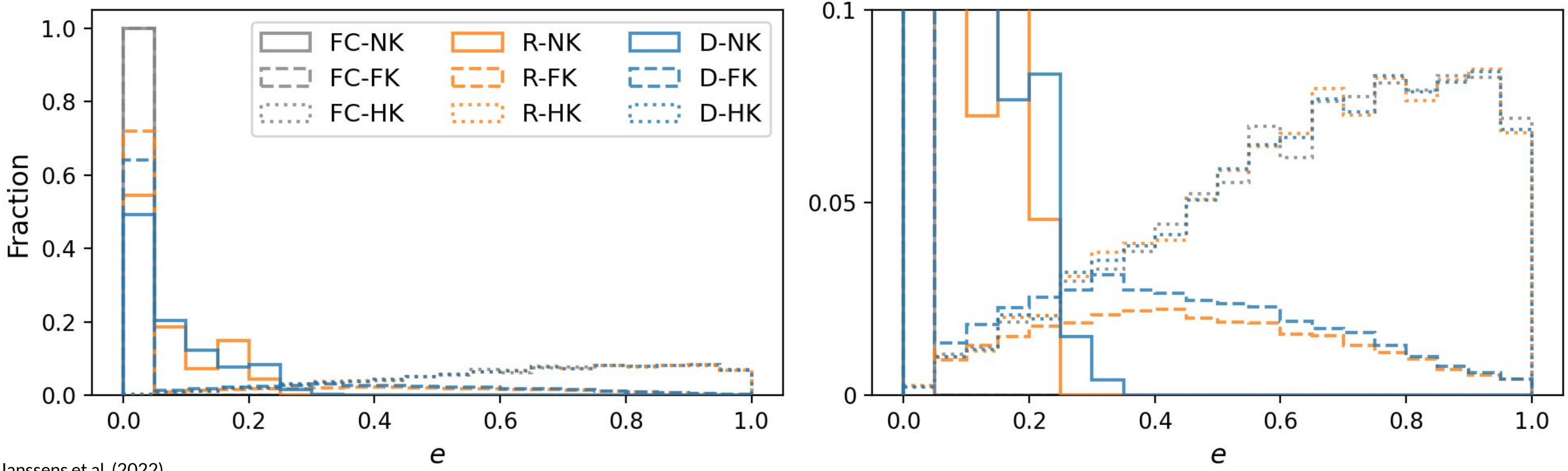


0 with $\varpi/\sigma_\varpi > 200$

~350 with $\varpi/\sigma_\varpi > 40$

Unknown BH-formation physics

- Eccentricity distributions → information about kicks

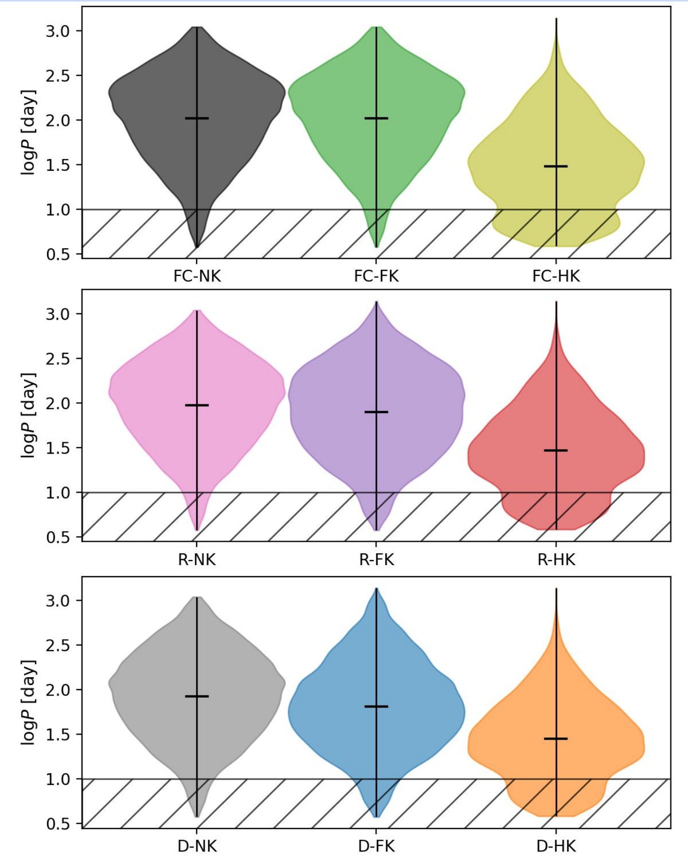


Janssens et al. (2022)

Unknown BH-formation physics

- Period distribution → information about kicks

Different kick mechanism (stronger kicks)

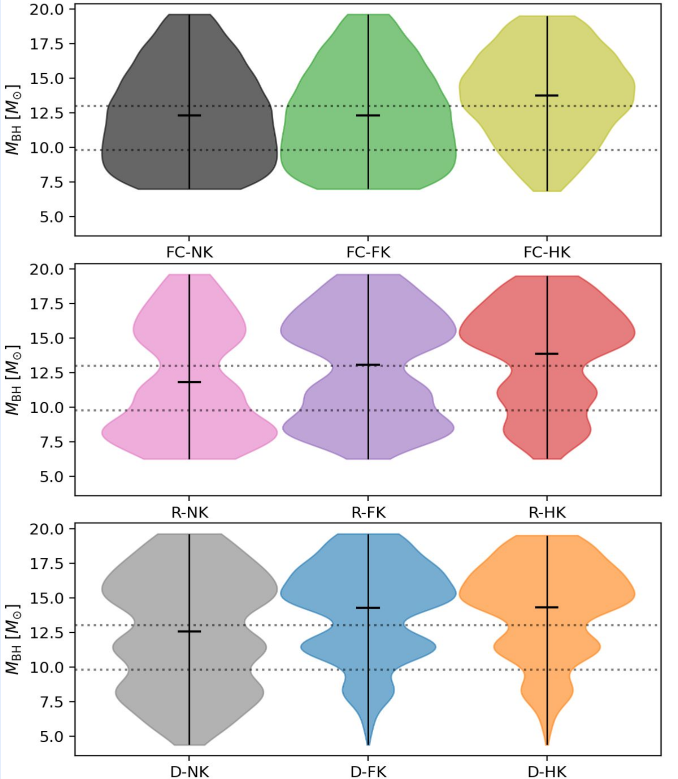


Different explosion mechanism

Janssens et al. (2022)

Unknown BH-formation physics

- Eccentricity distribution → information about kicks
- Period distribution → information about kicks
- Mass of the black hole → information on collapse



Janssens et al. (2022)

The Astrometric Mass-Ratio Function

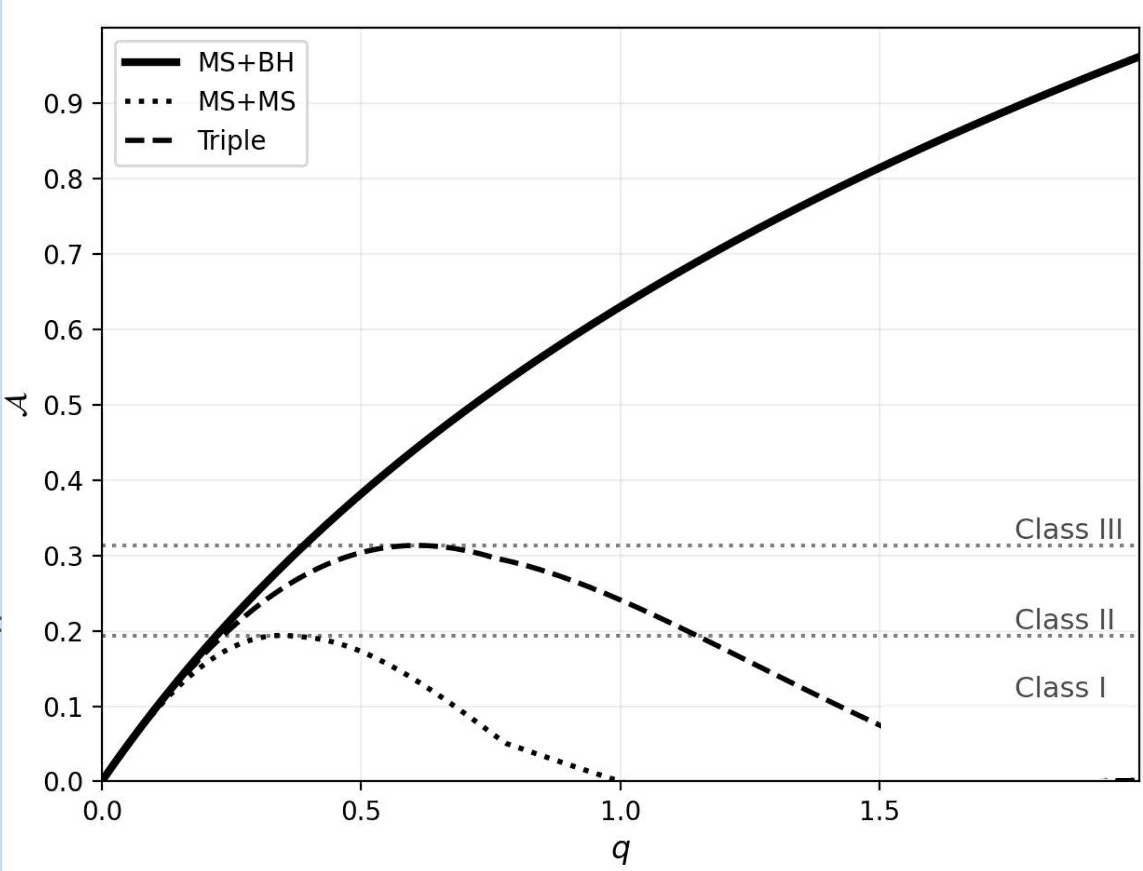
= AMRF (Shahaf et al. 2019)

Theoretical

$$\mathcal{A} = \frac{q}{(1+q)^{2/3}}\left(1 - \frac{S(1+q)}{q(1+S)}\right)$$

q = photometric mass ratio = least luminous / most luminous
S = Intensity ratio (mass dependent)

- predict the maximum photocentre motion for dif kinds of systems



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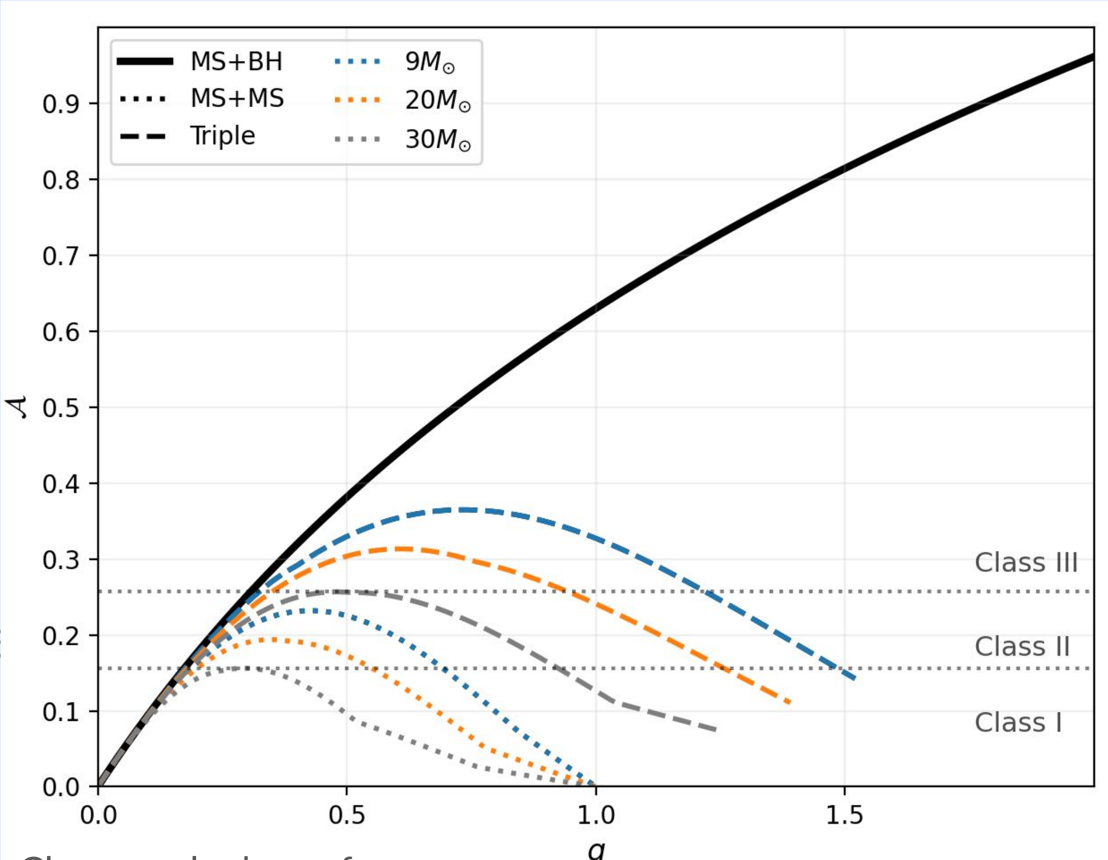

Classes only shown for $30M_\odot$