MODEST-24: Exploring Dense Stellar Systems Across Cosmic Time

Decoding binary evolution: insights from detached black hole-star systems

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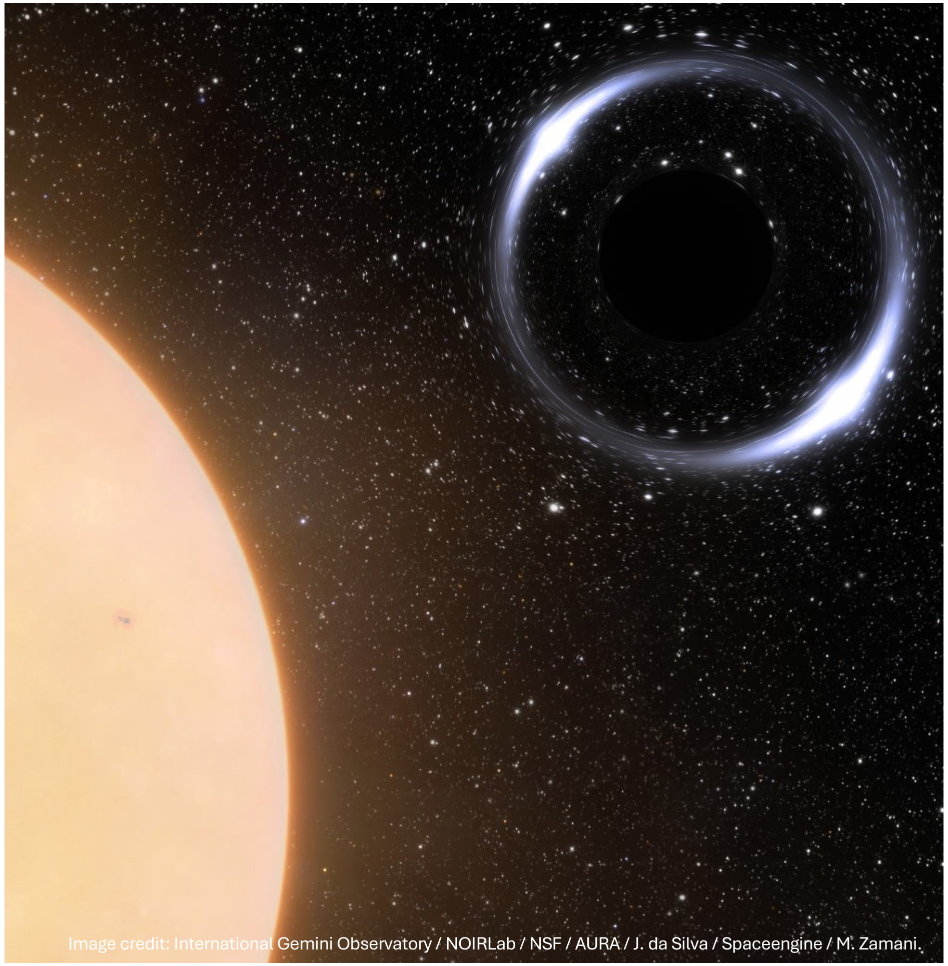

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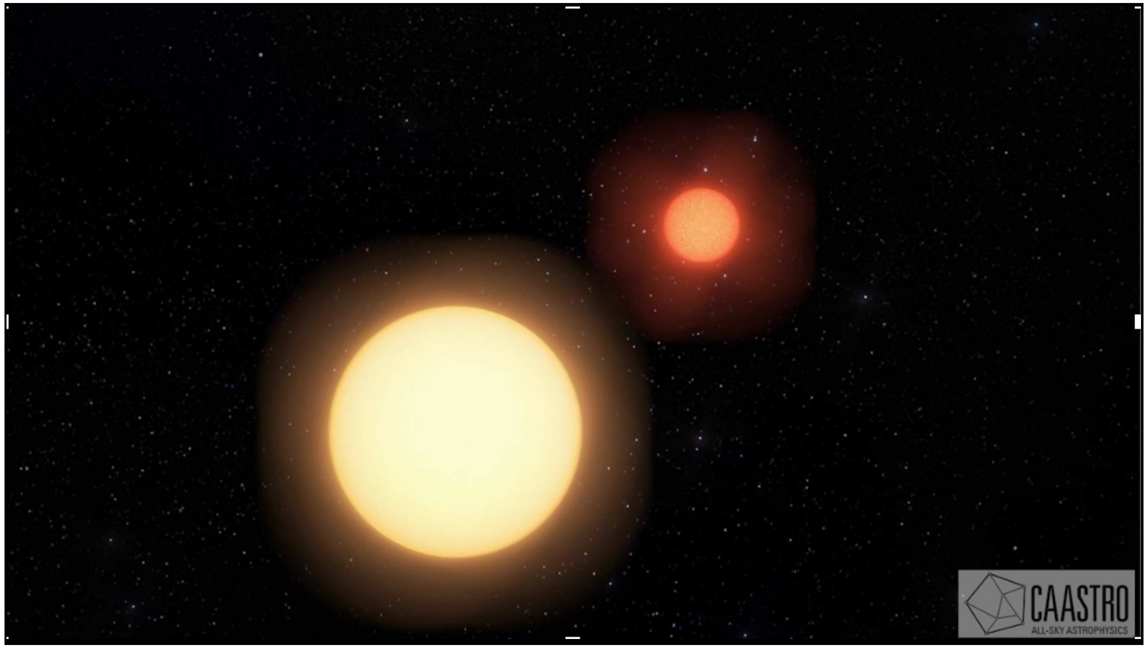
Binary evolution: important yet enigmatic

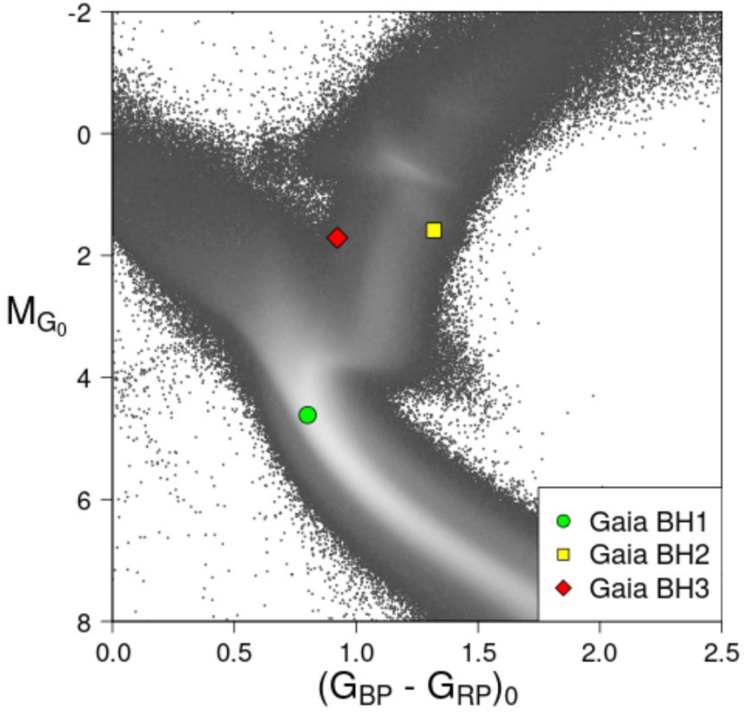
- Progenitors of a wide range of astrophysical transients
- Source of chemical enrichment
- Shapers of dynamics in star clusters *

Several uncertainties in their evolution: mass transfer processes, evolution of progenitor stars, evolution inside a common envelope



* See talk by Sara Saracino

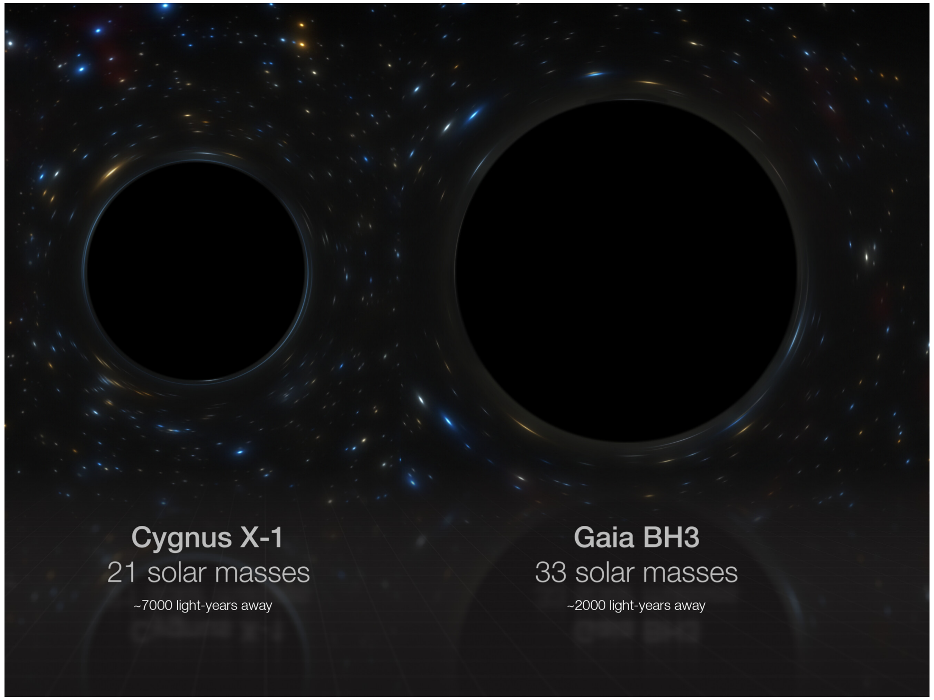
Detached BH-star systems detected with Gaia



System Name	Black Hole Mass ($M_\odot$)	Companion Star Mass ($M_\odot$)	Orbital Period (days)	Orbital Eccentricity
Gaia BH1	9.62	0.93	185	0.45
Gaia BH2	8.94	1.07	1276	0.51
Gaia BH3	32.7	0.76	4253	0.73

(El-Badry et al. 2023b,a,
Gaia Collaboration 2024)

Debatable origin Gaia BH3



Dynamical origin (Balbinot et al. 2024, Marín Pina et al. 2024)?

- The metallicity is very subsolar ([Fe/H~-2.56])
- It is in the middle of the ED2 stream - a disrupted globular cluster?

Isolated binary evolution cannot be ruled out either (El-Badry 2024, Iorio et al. 2024)

Uncovering its origin is valuable for both stellar and binary evolution!

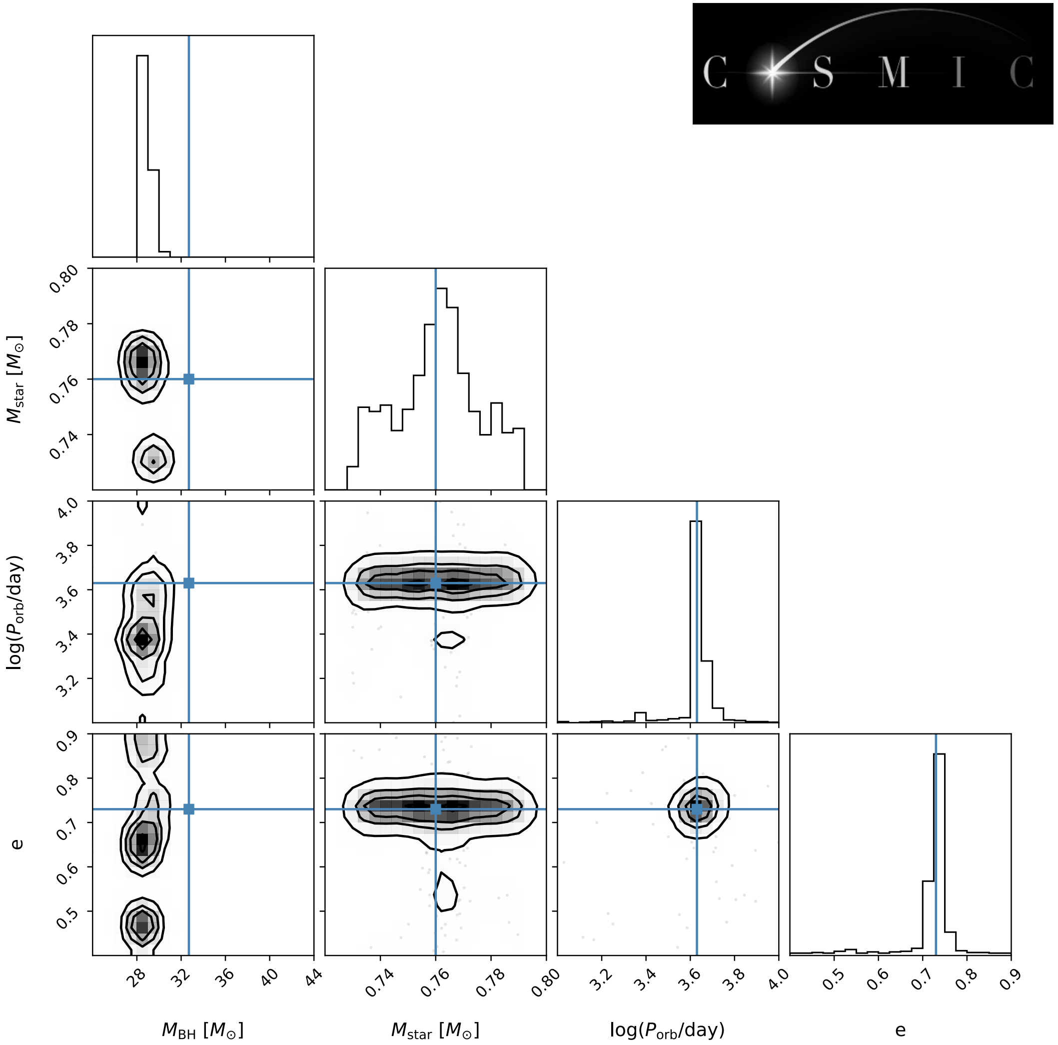
For other Gaia BHs, see, e. Di Carlo, Agrawal et al. 2023, El-Badry et al. 2023a,b , Rastello et al. 2023, Tanikawa et al. 2023, Banerjee et al. 2024

Using COSMIC to get initial conditions for Gaia BH3

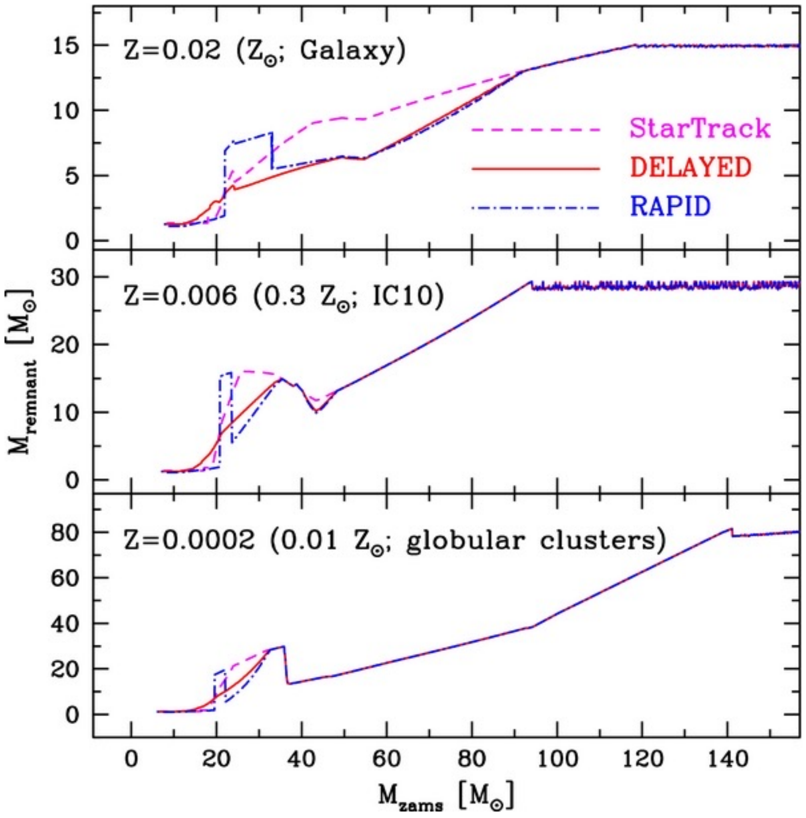
Python based binary population synthesis code (Breivik et al. 2020) based on BSE (Hurley et al. 2002)

”Backward modelling” (Wong et al., 2023) to explore combinations of binary assumptions and infer initial parameters required to reproduce Gaia BH3

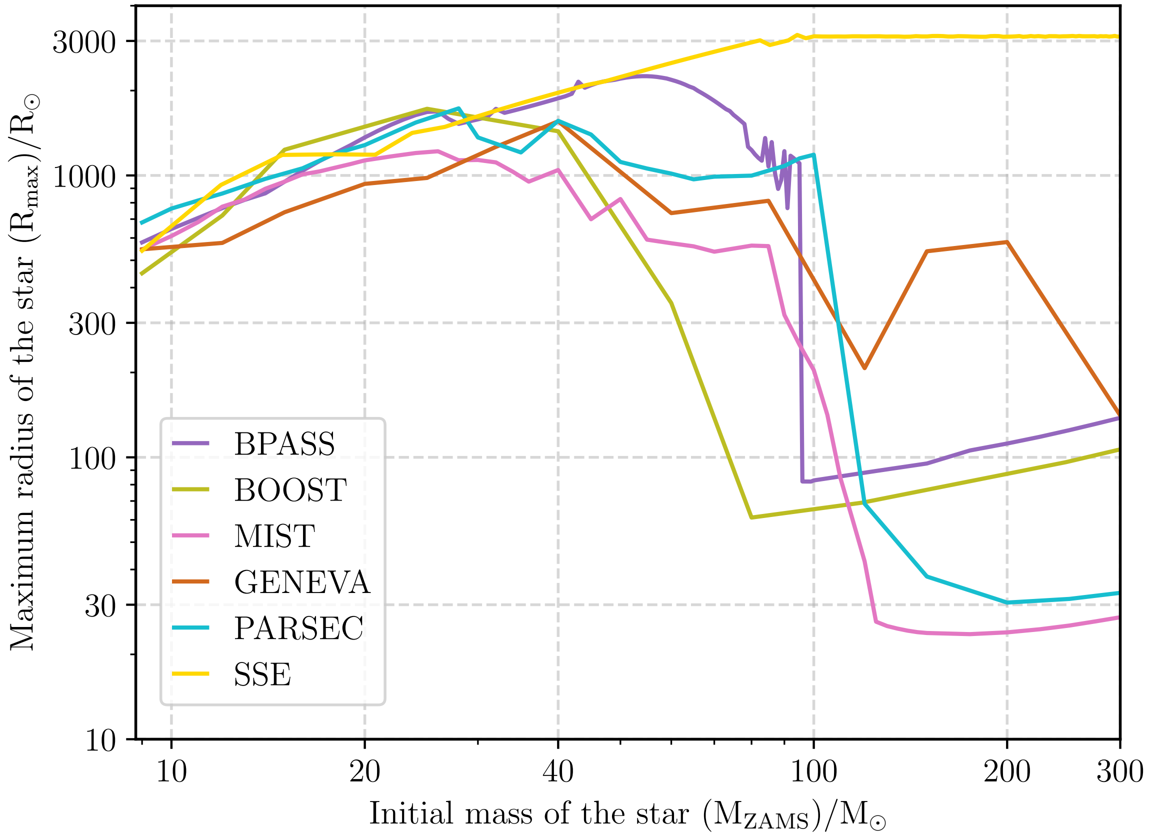
Stellar evolution from SSE fitting formulae (Hurley et al. 2000) uses stellar models as described in Pols et al. (1998)



SSE and uncertainties in stellar evolution



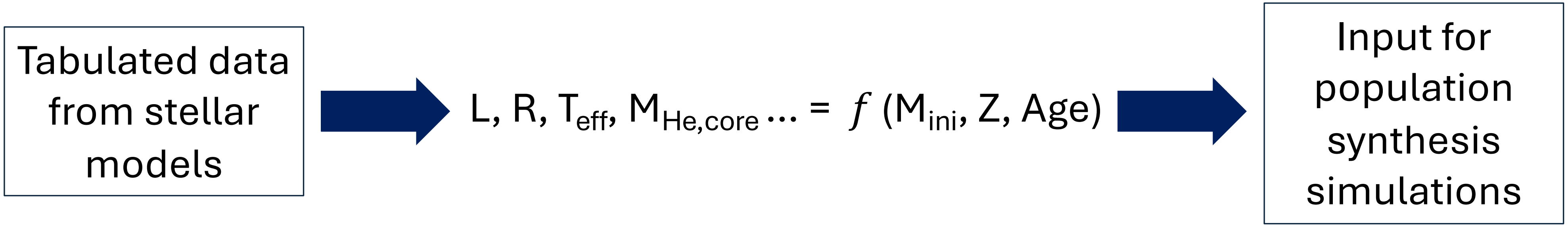
Fryer et al. 2012



Agrawal et al. 2022a

Varying Stellar Parameters with METISSE

(**MET**hod of **I**nterpolation for **S**ingle **S**tar **E**volution)



Tabulated data from stellar models

$L, R, T_{eff}, M_{He,core} \ldots = f\,(M_{ini}, Z, Age)$

Input for population synthesis simulations

Designed to mimic the structure of SSE fitting formulae

Optimized to use few computational resources

Can use a range of stellar models, including multi-dimensional models

Agrawal et al. 2020, 2023
Also see: https://metisse.readthedocs.io

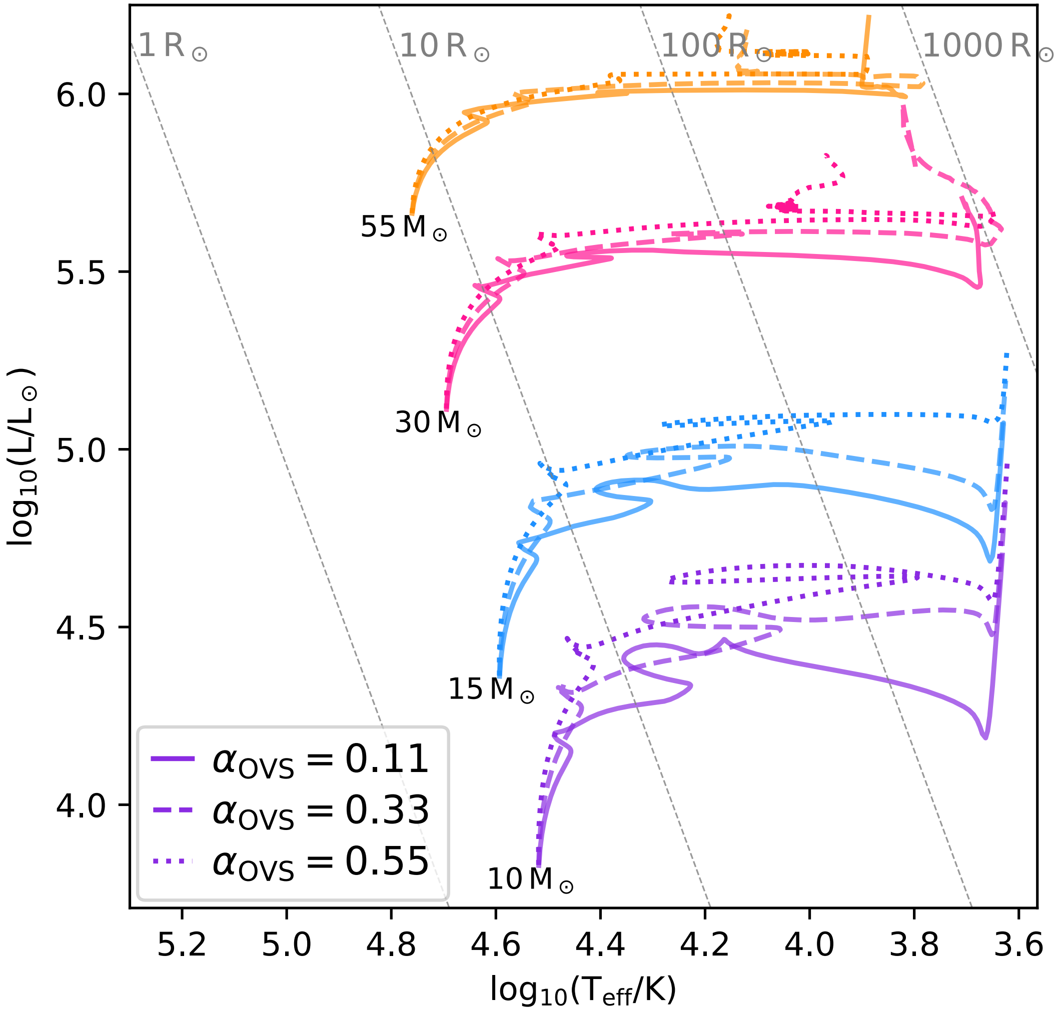
Varying internal mixing parameters

Use MESA to calculate stellar models with different core overshooting

Step overshooting prescription

Overshooting parameter, α_{OVS}

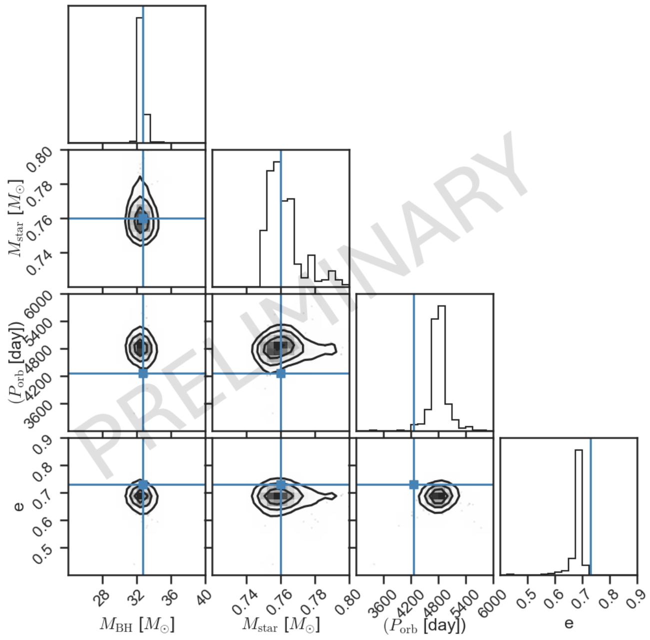
- 0.33 (standard - Brott et al. 2011)
- 0.11 (low overshooting)
- 0.55 (high overshooting)



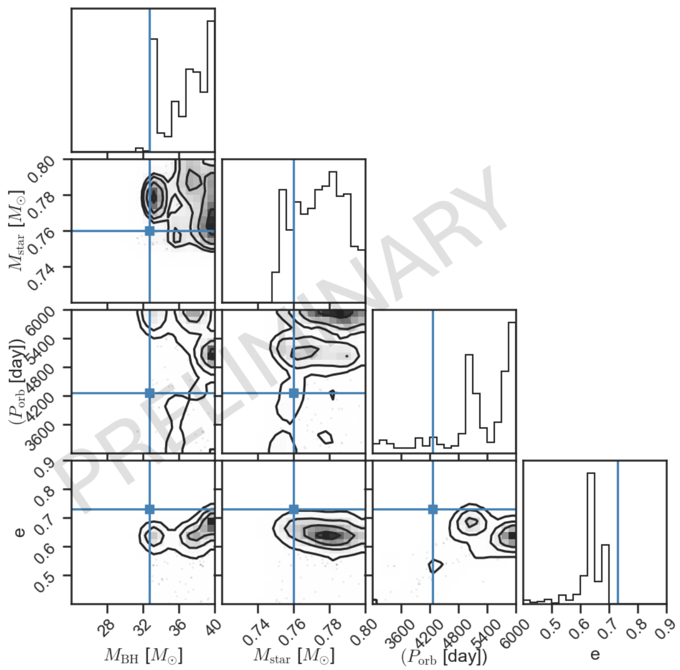
See e.g., Gilkis et al. 2019, Agrawal et al. 2023

Using COSMIC-METISSE to reproduce Gaia BH3

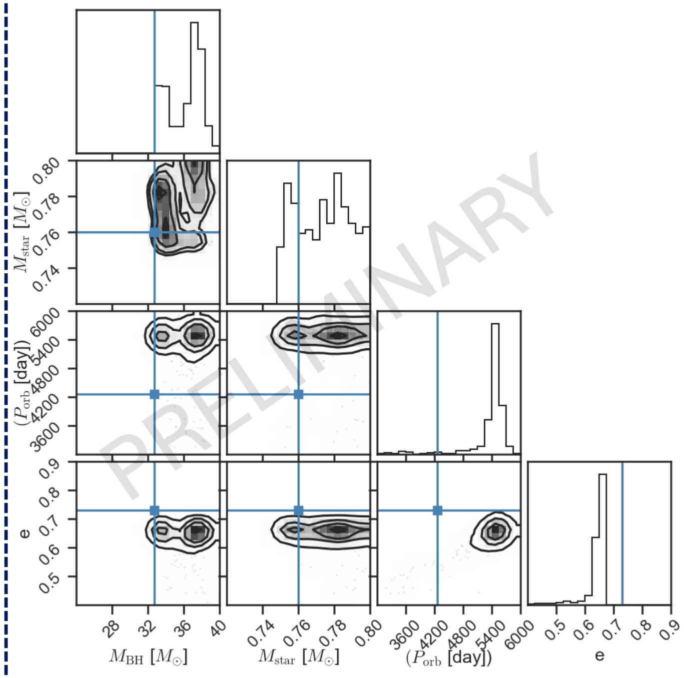
Low overshooting



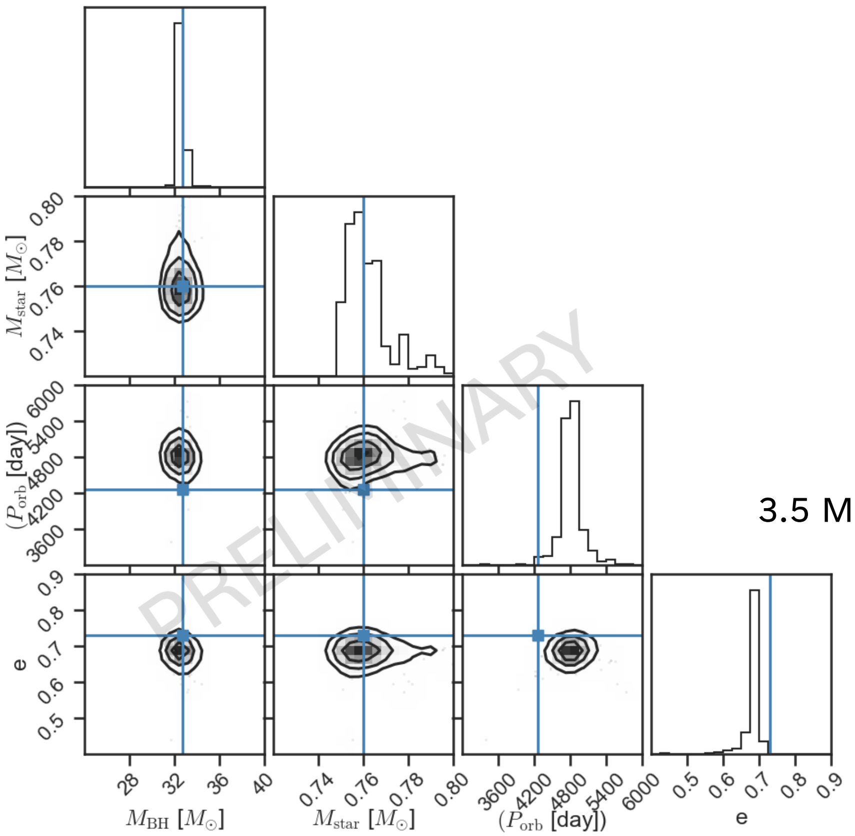
Standard overshooting



High overshooting



Low overshooting



Time

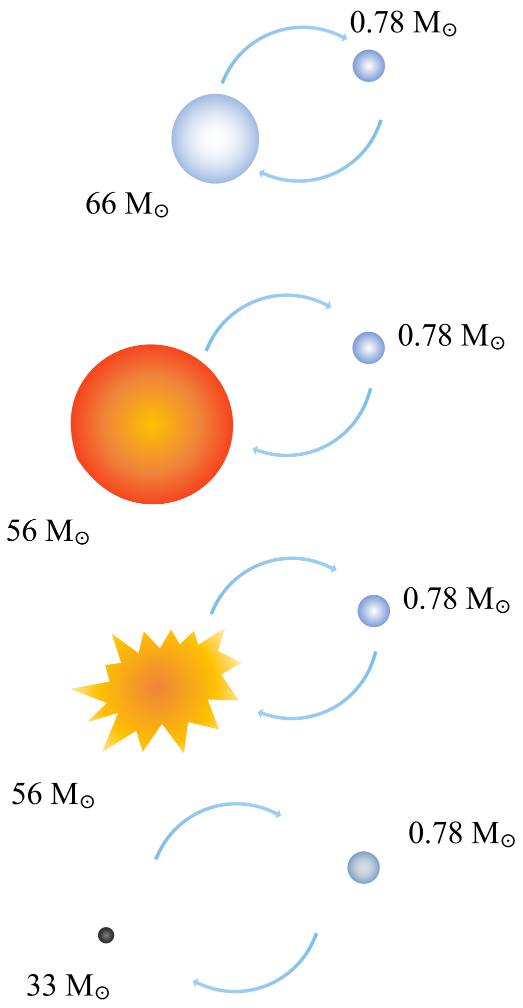
3.5 Myrs

Initial State
(462 days, 0.002)

Wind fed accretion
(633 days, 0.002)

Pulsational pair instability and collapse of primary
(633 days,0.002)

Final State
(5142 days, 0.7)



Varying $^{12}C\,(\alpha, \gamma)^{16}O$ reaction rate

Nuclear reaction rates from STARLIB
(Sallaska et al. 2013)

Three reaction rates,

- Median rate $\sigma_{C12} = 0.0$
- Standard deviation of $\sigma_{C12} = -1.5$ (low rate)
- Standard deviation of $\sigma_{C12} = +1.5$ (high rate)

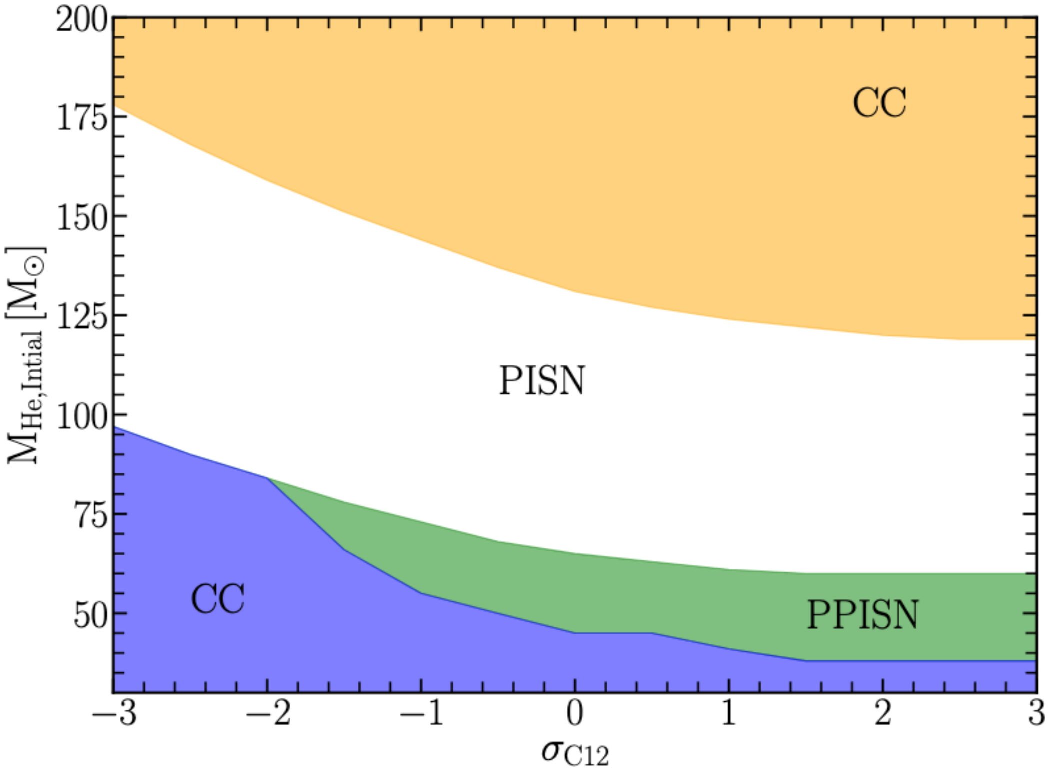
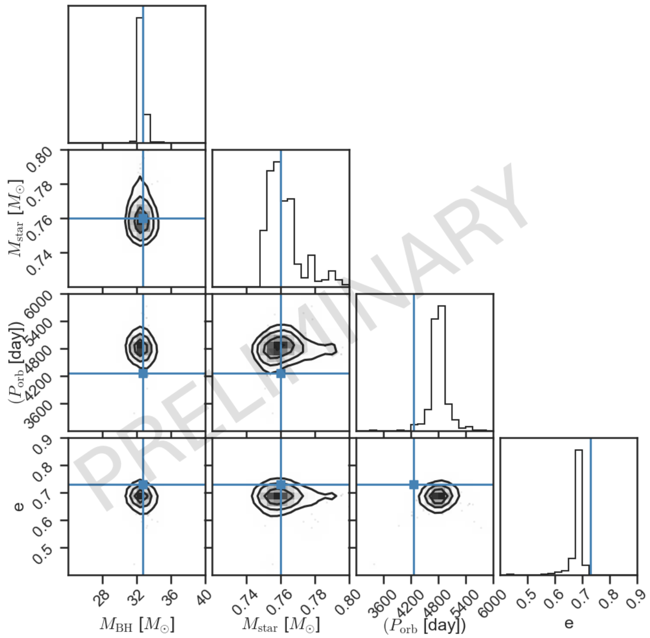


Image Credit: Farmer et al. 2020

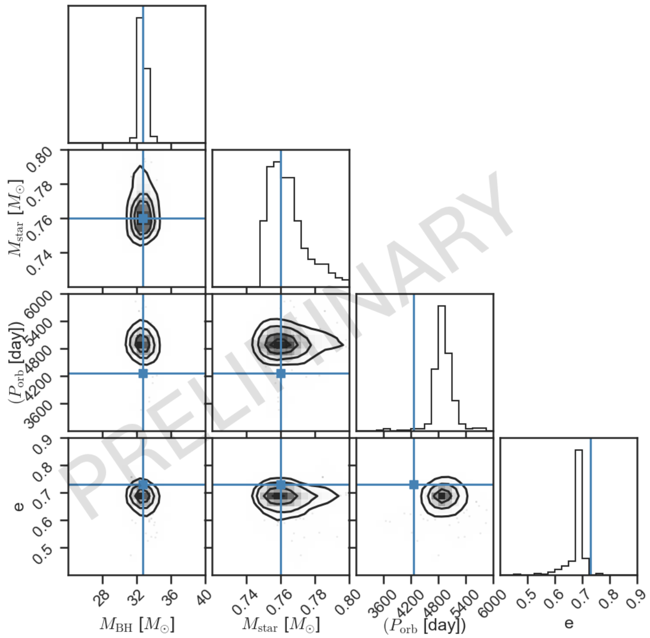
See e.g., Farmer et al. 2020, Fields et al. 2018, Tanikawa et al. 2020

Using COSMIC-METISSE to reproduce Gaia BH3

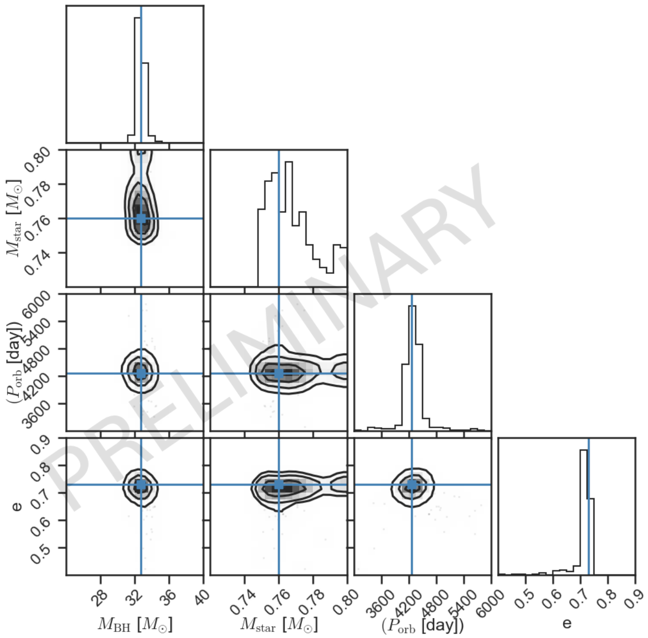
Low rate



Median Rate



High Rate



High Rate-low overshooting

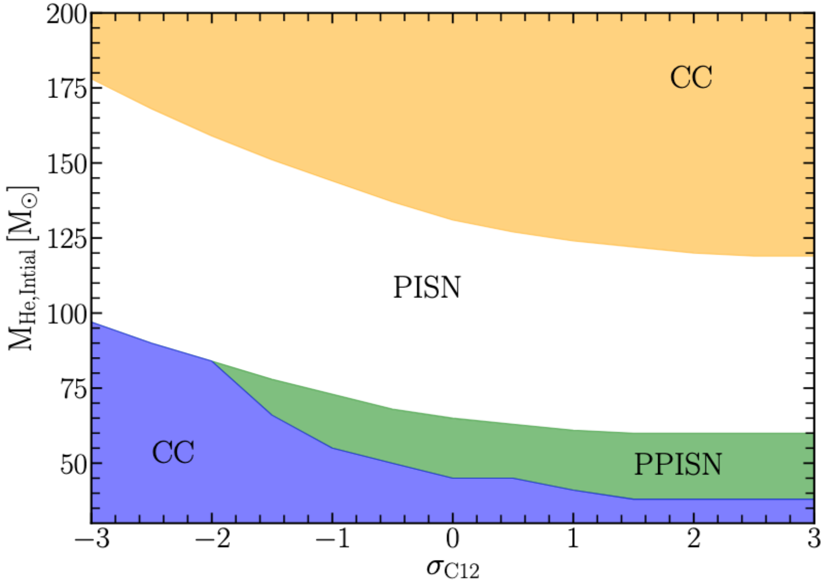
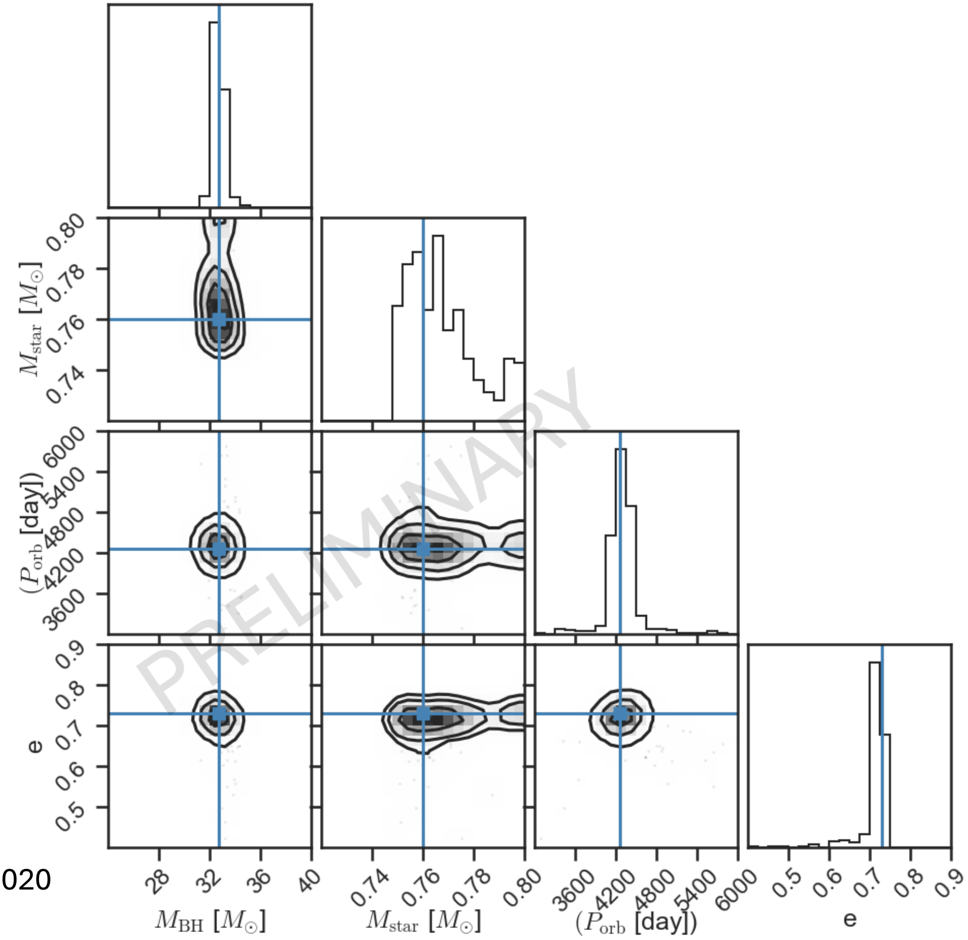


Image Credit: Farmer et al. 2020



Summary

- Newer observations are providing better data for constraining both stellar and binary evolution
- Backward modelling of Gaia BH3 favors low convective core overshooting and high $^{12}C(\alpha,\gamma)^{16}O$ reaction rate.
- How does this change the analysis of progenitors for BH1 and BH2 - Agrawal et al. (in prep)
- What about NS-Star systems (El-Badry et al. 2024) ? - Crow et al. (in prep)
- Stellar evolution parameters do matter!