The Effect of Primordial Binaries and Cluster Dynamics on Binary Black Hole Mergers

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MODEST-24

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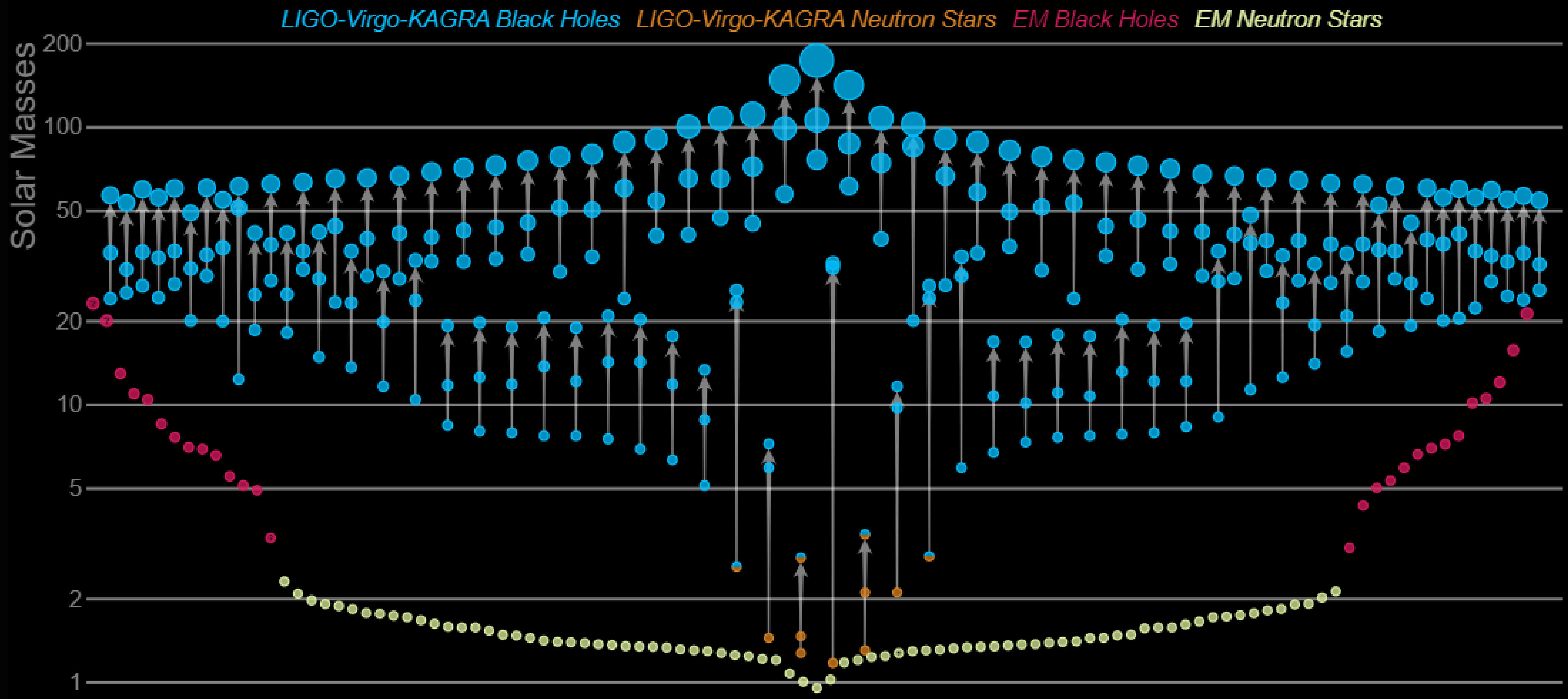
Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Motivation

- 90 Detections from O1, O2 and O3.
- LVK has found > 100 BBH detections from the O4 run alone.

LIGO/Virgo/KAGRA Public Alerts

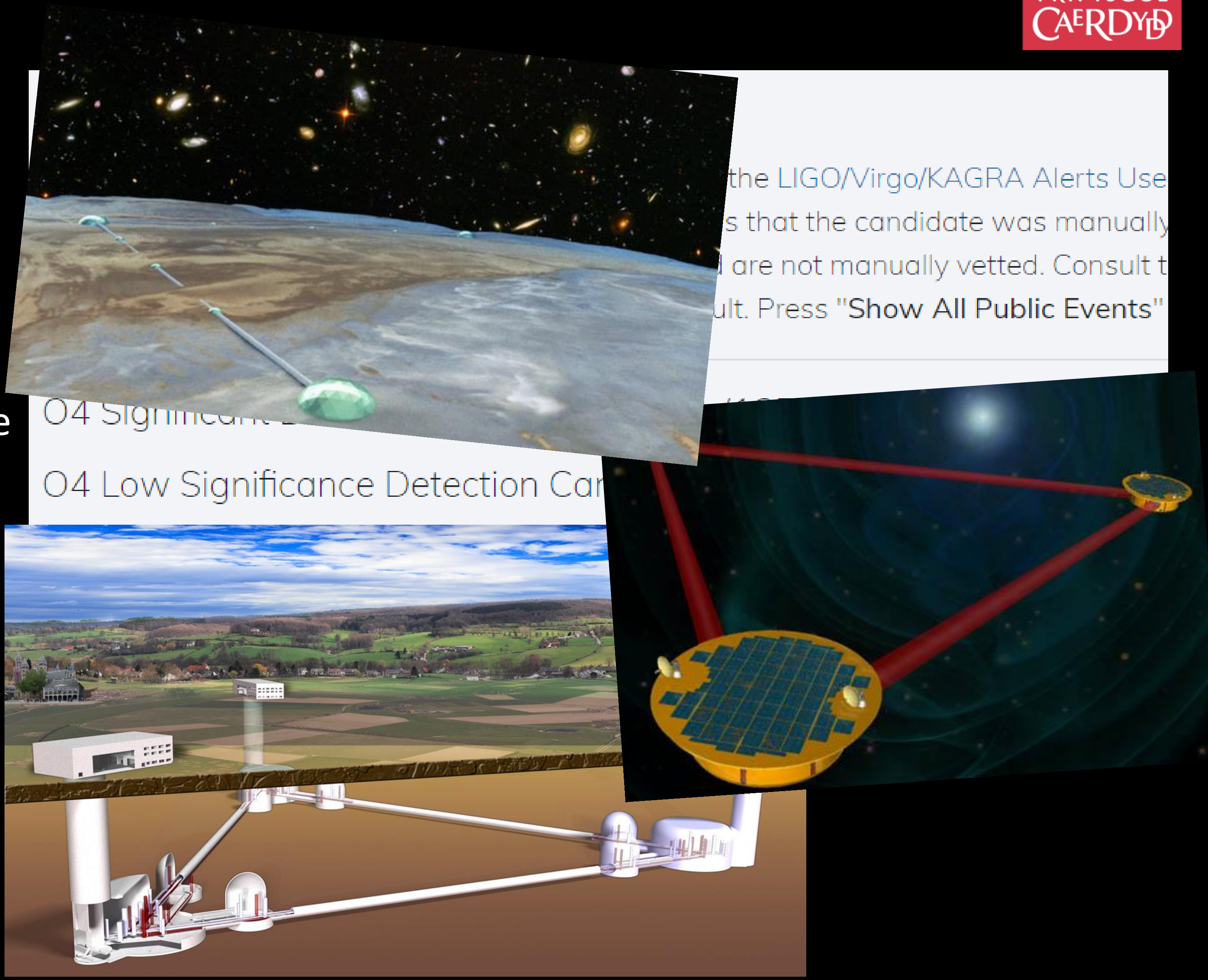
- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts Use
- Retractions are marked in red. Retraction means that the candidate was manually
- Less-significant events are marked in grey, and are not manually vetted. Consult t
- Less-significant events are not shown by default. Press "Show All Public Events"

O4 Significant Detection Candidates: **121** (137 Total - 16 Retracted)

O4 Low Significance Detection Candidates: **2195** (Total)

Motivation

- 90 Detections from O1, O2 and O3.
- LVK has found > 100 BBH detections from the O4 run alone.
- With future detectors (ET, CE, LISA) will be detecting ~1 event per day.
- LISA observing in milli-hertz regime → Looking at very different systems.
- Formation of these merging BBHs is still a mystery!



Formation Channels:
A Quick Refresher

BBH Formation Channels

Isolated binary evolution

- Two massive stars form together and co-evolve.
- Relatively open environment (e.g., galactic field) → Little/no external influence.
- Stars undergo some form of common envelope evolution. → Shrinks core separation.
- Both stars explode forming a tight BBH → Merges in Hubble time.
- GW Signatures → Low/no eccentricity, aligned spins, maximum mass $\approx 60\ \mathrm{M}_{\odot}$.

BBH Formation Channels

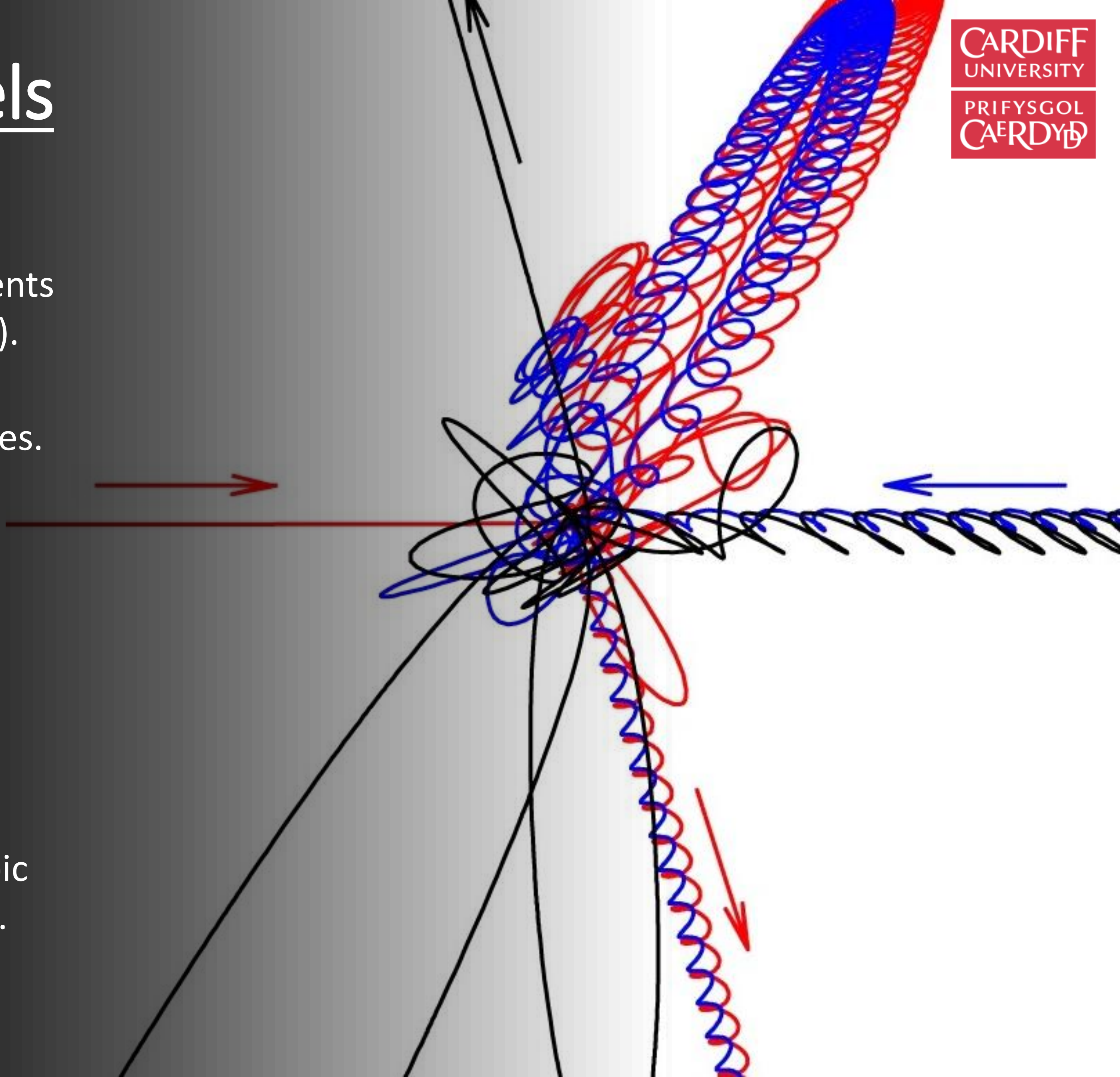
Dynamical binary formation

- Typically occurs within dense environments (e.g., Nuclear clusters, Globular Clusters).

- Dynamical interaction between > 2 bodies.
  - Evolution triple BH systems (higher multiple systems)
  - Encounters between BH systems

- BBHs formed through → GW captures, binary exchange, binary hardening

- GW Signatures → Likely somewhat eccentric(very for GW captures), Isotropic spin distribution, BH masses $> 100\ \mathrm{M}_{\odot}$.



BBH Formation Channels

Star Clusters

- Young clusters born with lots of massive stellar binaries (>70 %) (Sana et al. 2012) – "primordial binaries".

- Short evolution time for these massive stars $\approx 10^6$ yrs → form BBHs early in cluster lifetime.

- Primordially binaries form BBHs → subsequently experience encounters within the cluster. → Alter their orbital properties.

- Combination of Isolated and Dynamical formation channels.

Simulations using PeTar

Wang et al. 2020

Initial Conditions

Clusters initialized with updated MCLUSTER (Küpper et al. 2011)

- King cluster model $W_0 = 7$
- $M_{\rm cl} = 10^4\ \mathrm{M}_\odot \rightarrow 10^6\ \mathrm{M}_\odot$
- $\rho_{\rm h} = 1200\ \mathrm{M}_\odot\ \mathrm{pc}^{-3} \rightarrow 10^5\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$
- $Z = 0.01, 0.001, 0.0001$

Primordial binary variations

1. All stars with $M > 20\ \mathrm{M}_\odot$ in binaries.
2. No primordial binaries.

Stellar evolution from BSE & SSE (Hurley et al. 2002)

Model	Metallicity	Total Mass $\mathrm{M}_\odot$	Density $\mathrm{M}_\odot\ \mathrm{pc}^{-3}$	Half-Mass Relaxation Time Myrs	Binary Fraction	End Time Myrs	Binary Period Dist
Z1-M1-D3		10,000	1200	11.5	0, 0.0025	1000	Sana
Z1-M5-D3	0.01	50,000	1200	47.0	0, 0.0025	1000	Sana
Z1-M10-D3		100,000	1200	86.2	0, 0.0026	1000	Sana
Z1-M50-D3		500,000	1200	253.7	0	608	Sana
Z1-M100-D3		1,000,000	1200	506.8	0	632	Sana
Z2-M1-D3		10,000	1200	11.3	0, 0.0025	1000	Sana
Z2-M5-D3		50,000	1200	49.4	0, 0.0025	1000	Sana
Z2-M5-D3-L		50,000	1200	49.4	0, 0.0025	3000	Sana
Z2-M10-D3		100,000	1200	86.2	0, 0.0026	1000	Sana
Z2-M10-D3-L	0.001	100,000	1200	86.2	0, 0.0026	3000	Sana
Z2-M10-D3-L*		100,000	1200	86.2	0, 0.0026	3000	Duquennoy & Mayor
Z2-M10-D4		100,00	10,000	24.4	0, 0.0025	1000	Sana
Z2-M1-D5		10,000	100,000	0.561	0, 0.0025	1000	Sana
Z2-M5-D5		50,000	100,000	2.78	0, 0.0025	1000	Sana
Z3-M1-D3		10,000	1200	11.2	0, 0.0025	1000	Sana
Z3-M5-D3	0.0001	50,000	1200	47.7	0, 0.0025	1000	Sana
Z3-M10-D3		100,000	1200	86.7	0, 0.0025	1000	Sana
Z3-M50-D3		500,000	1200	253.7	0	568	Sana
Z3-M100-D3		1,000,000	1200	506.8	0	280	Sana

BBH Mergers

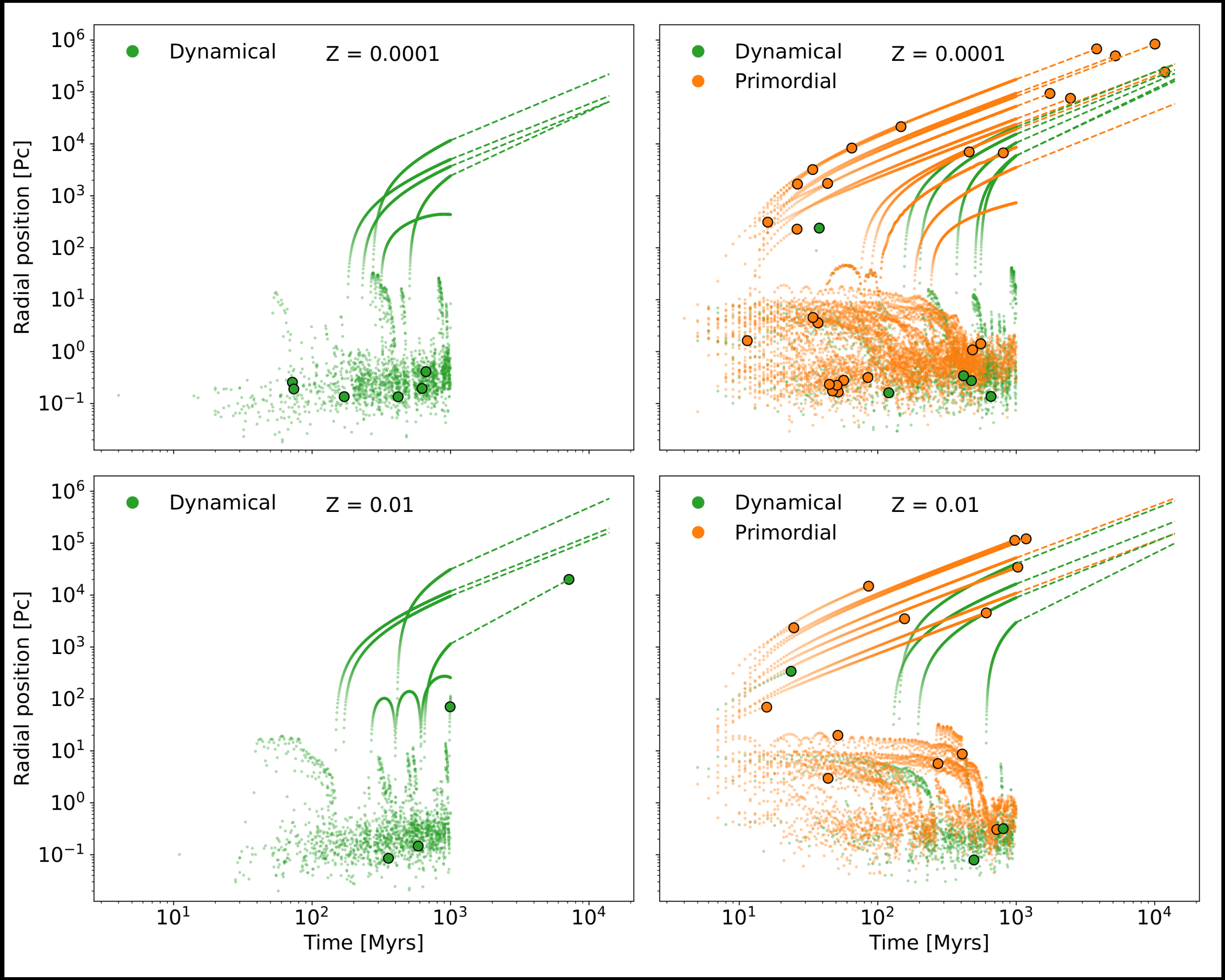
Example Cluster

- $M_{\text{cl}} = 10^5\ M_{\odot}$, $\rho_h = 1200\ M_{\odot} pc^{-3}$

- Predominately BBH mergers from the primordial binary population.

- Most dynamical formed BBHs merge inside the cluster.
  - Primordial binaries merge $\approx 50/50$ inside/outside.

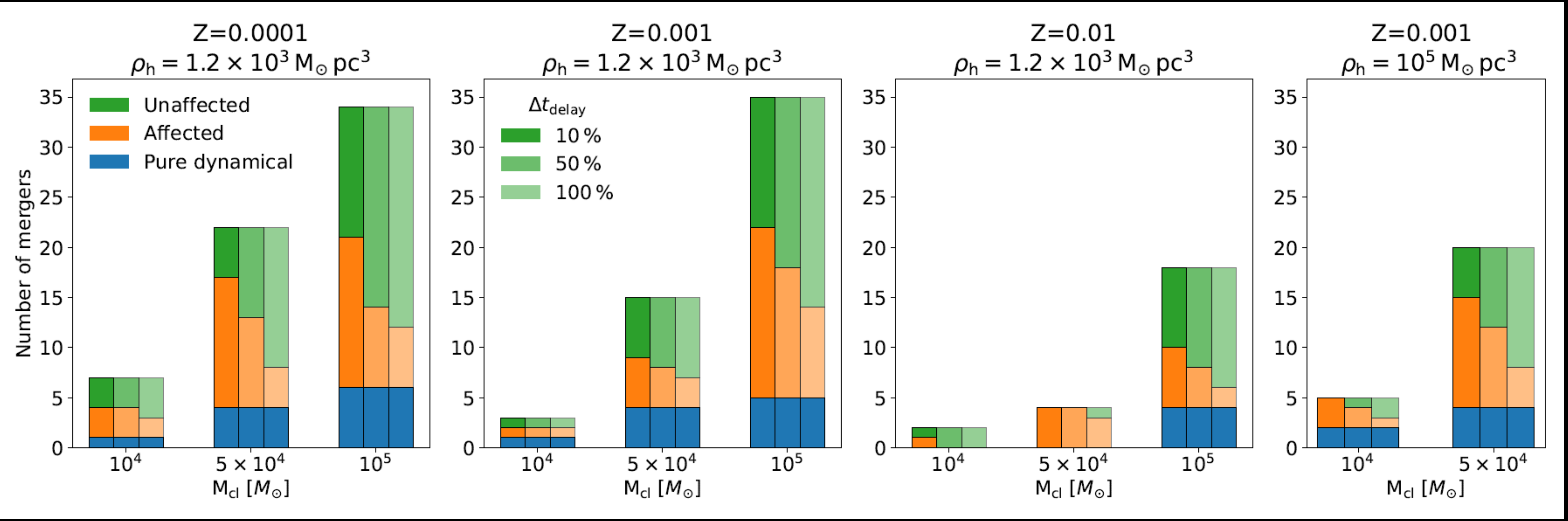
No Primordial Binaries | With Primordial Binaries



Are primordial binaries affected by cluster dynamics before merger?

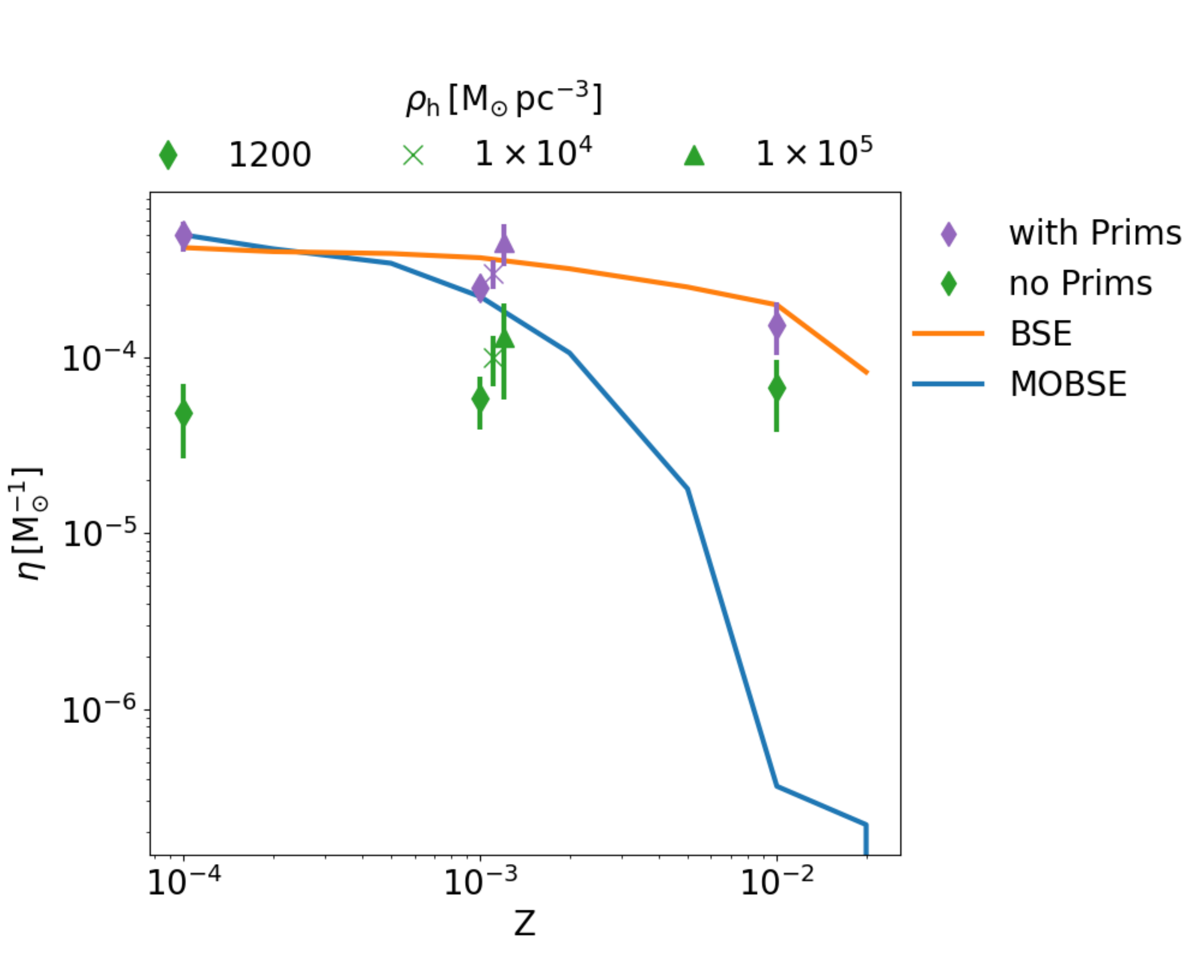
- Run same initial stellar binaries with isolated binary code *BSE* with same stellar prescriptions.
- Compare time of merger to same binary from *PeTar* Simulations. → How much has cluster altered this?

$$\Delta t_{\text{delay}} = \frac{\left|t_{\text{isolated}} - t_{\text{N-body}}\right|}{t_{\text{isolated}}}$$



Merger Efficiency

Clusters with a primordial binary population (**purple points**) → Consistent with Isolated evolution. → Cluster dynamics have had little effect.



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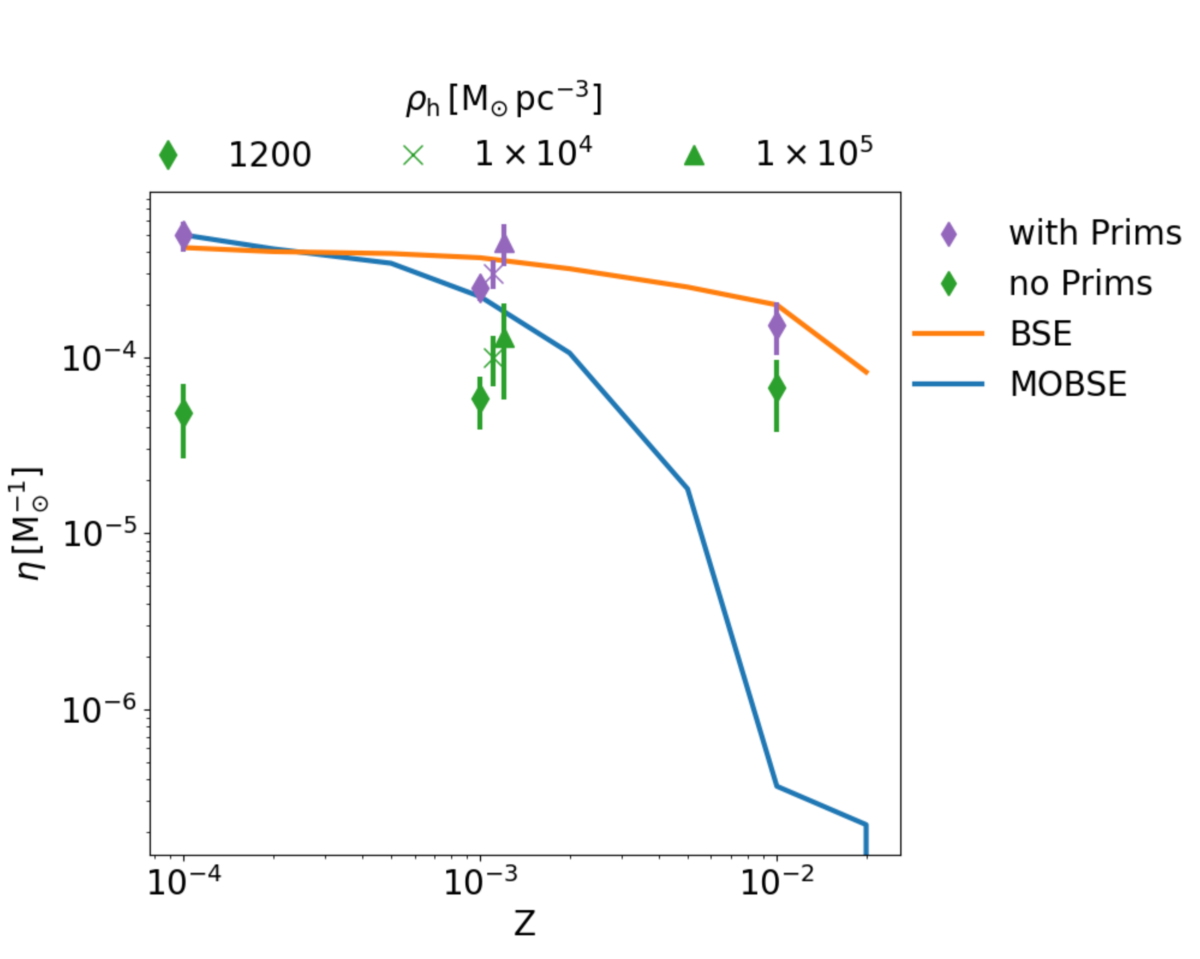


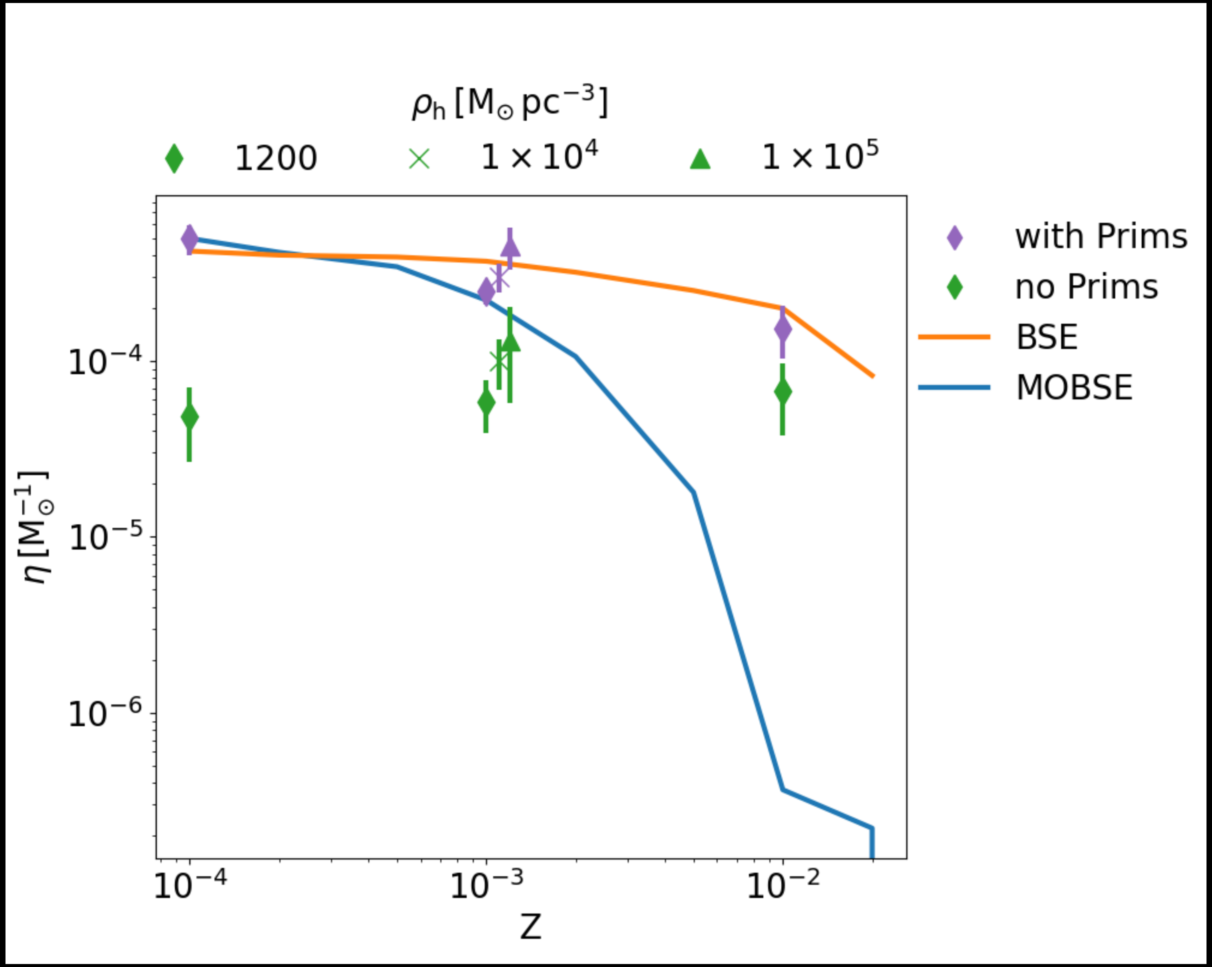
Why do MOBSE and BSE differ so much?

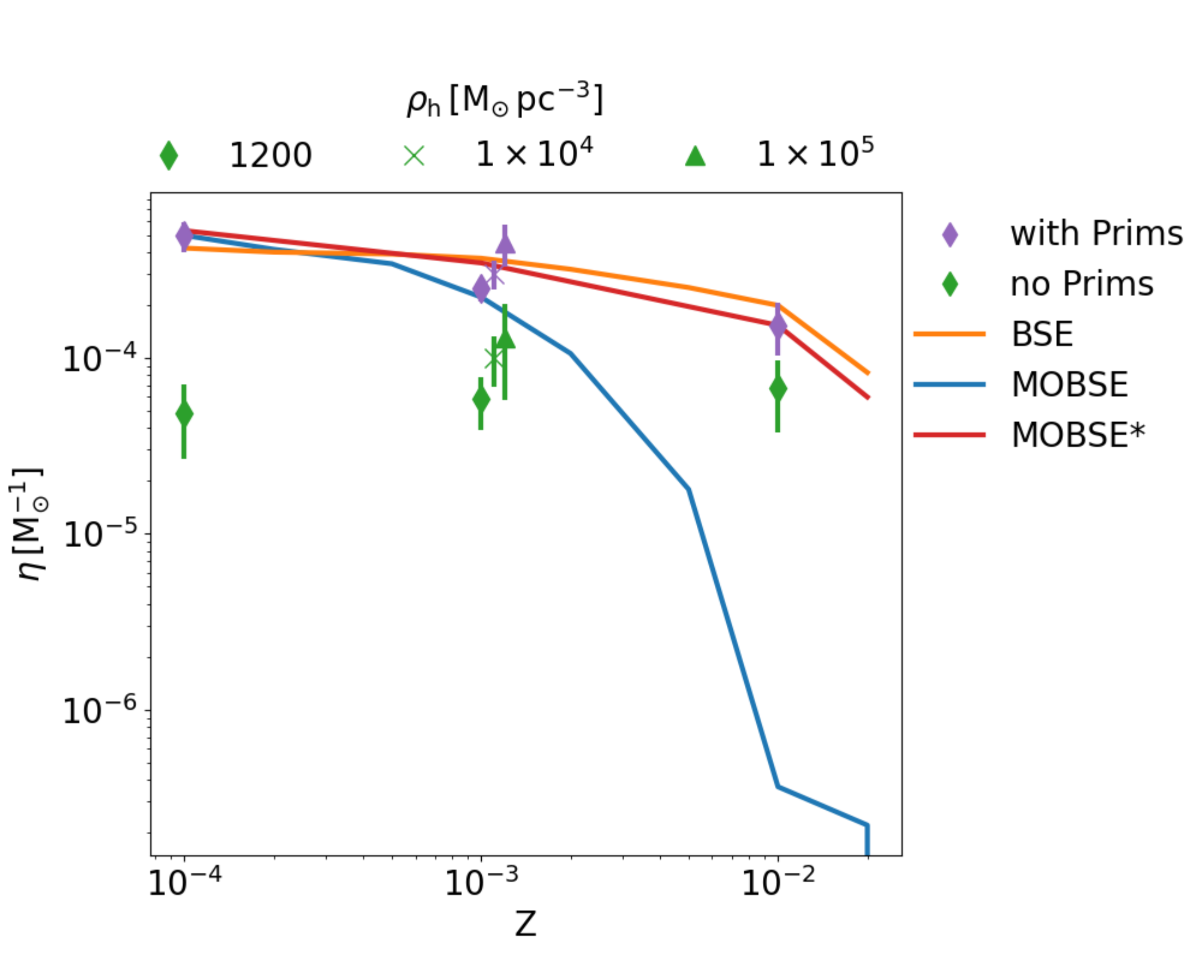
Merger Efficiency

BSE vs MOBSE difference due to treatment of HG donor stars during common envelope evolution.

BSE → HG stars always survive.

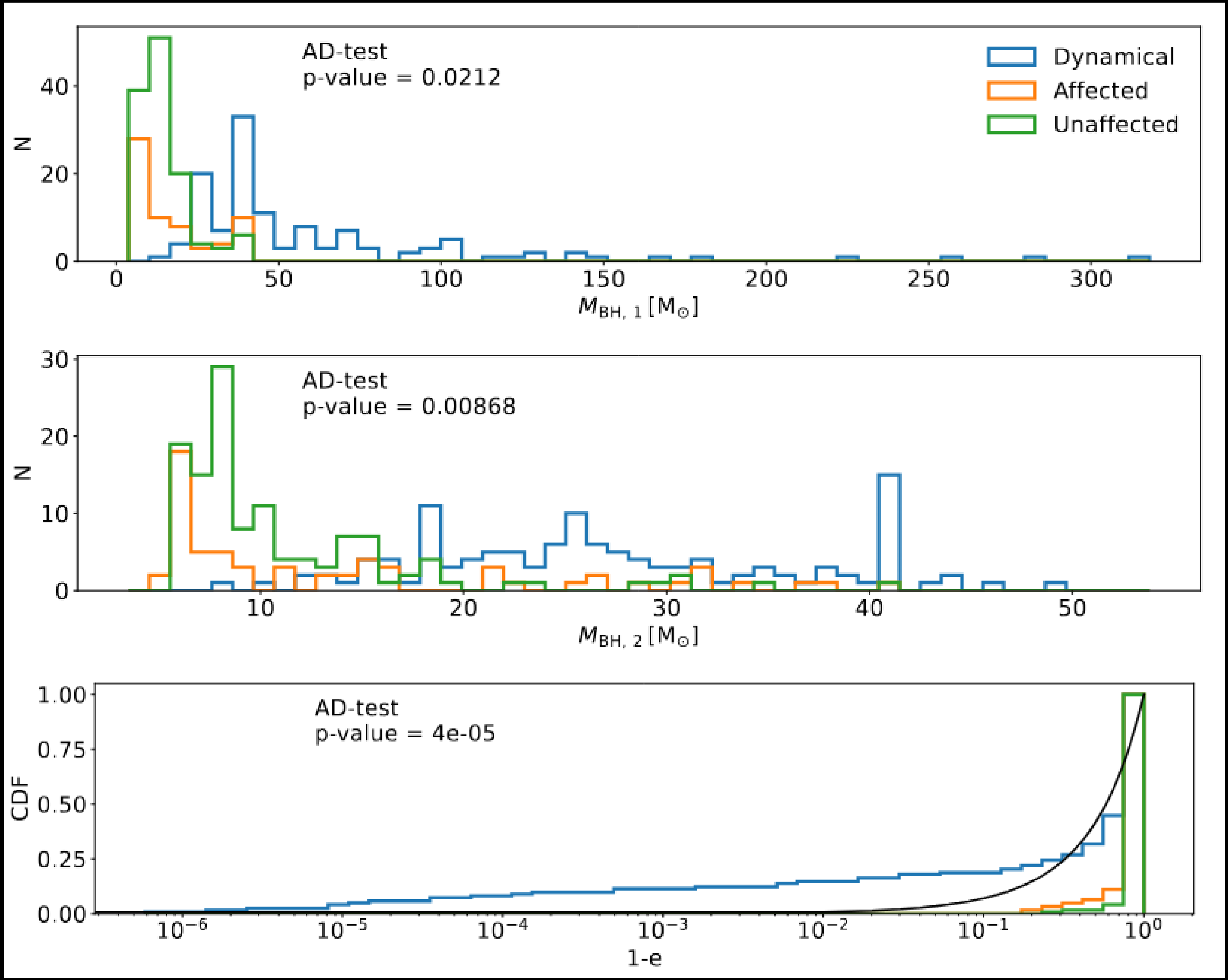
MOBSE → HG stars allowed to merge.





Merging BBH Distributions

- Anderson-Darling K-sample test (Unaffected vs Affected BBHs).
- Drawn from different distributions at 5% level.



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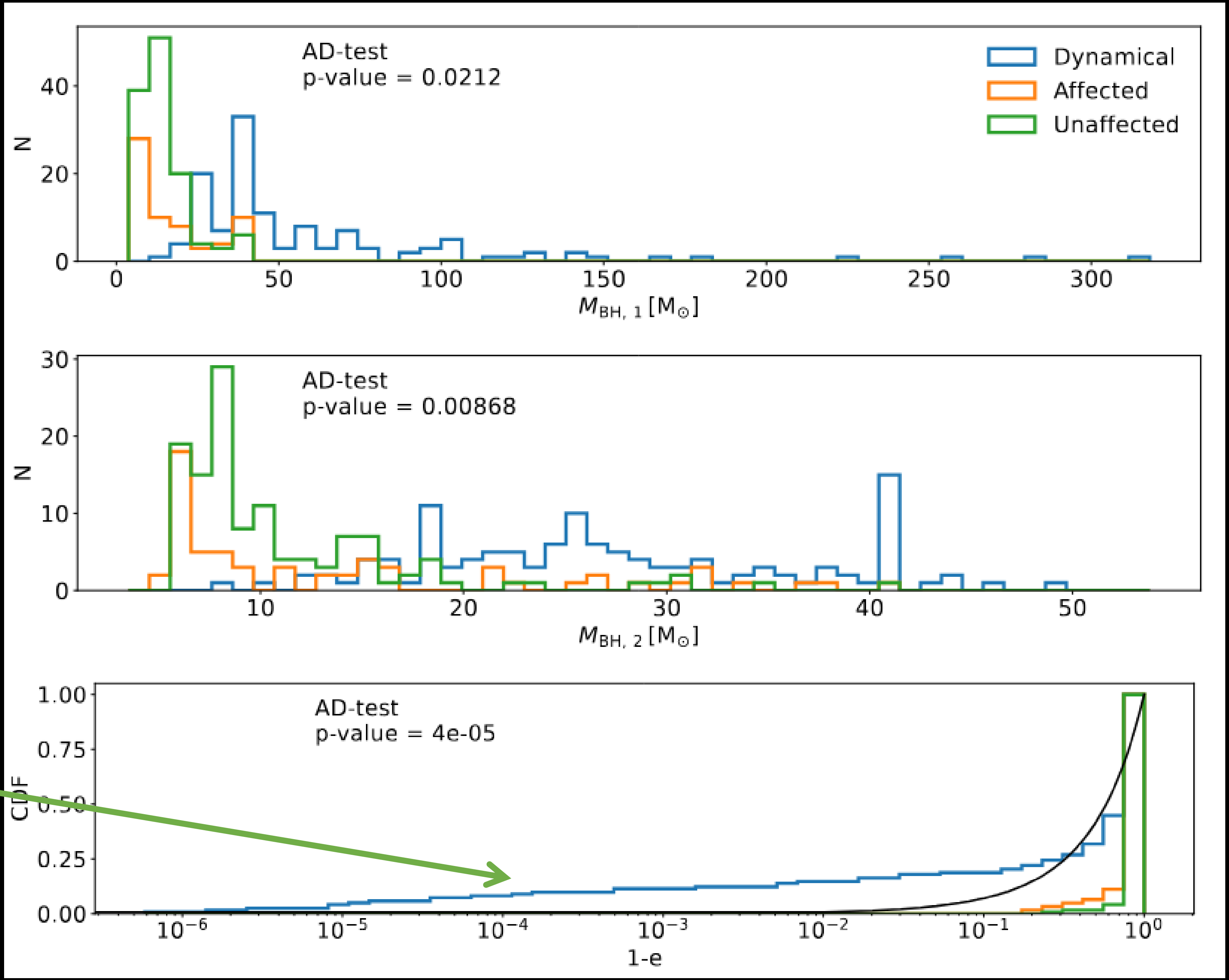
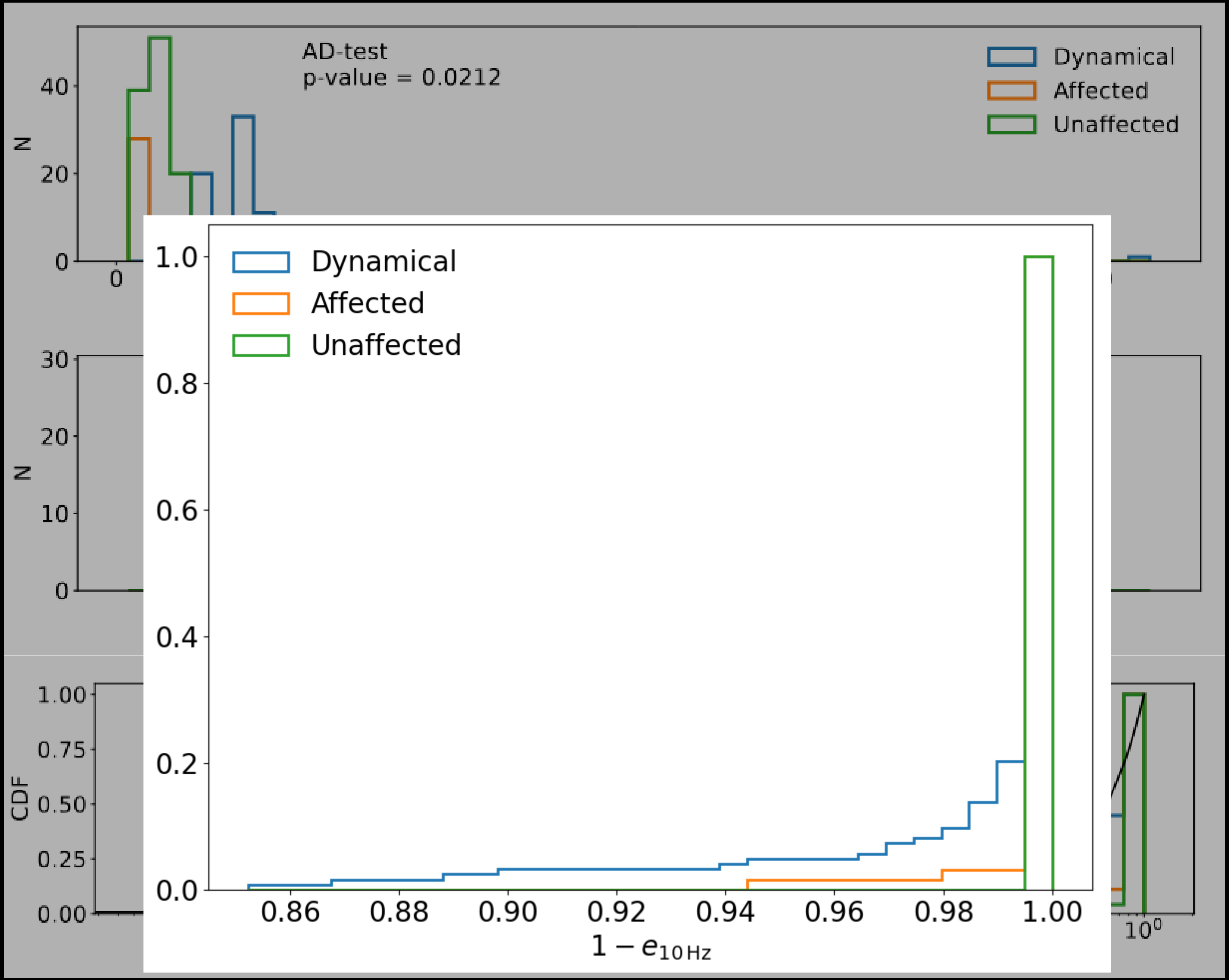


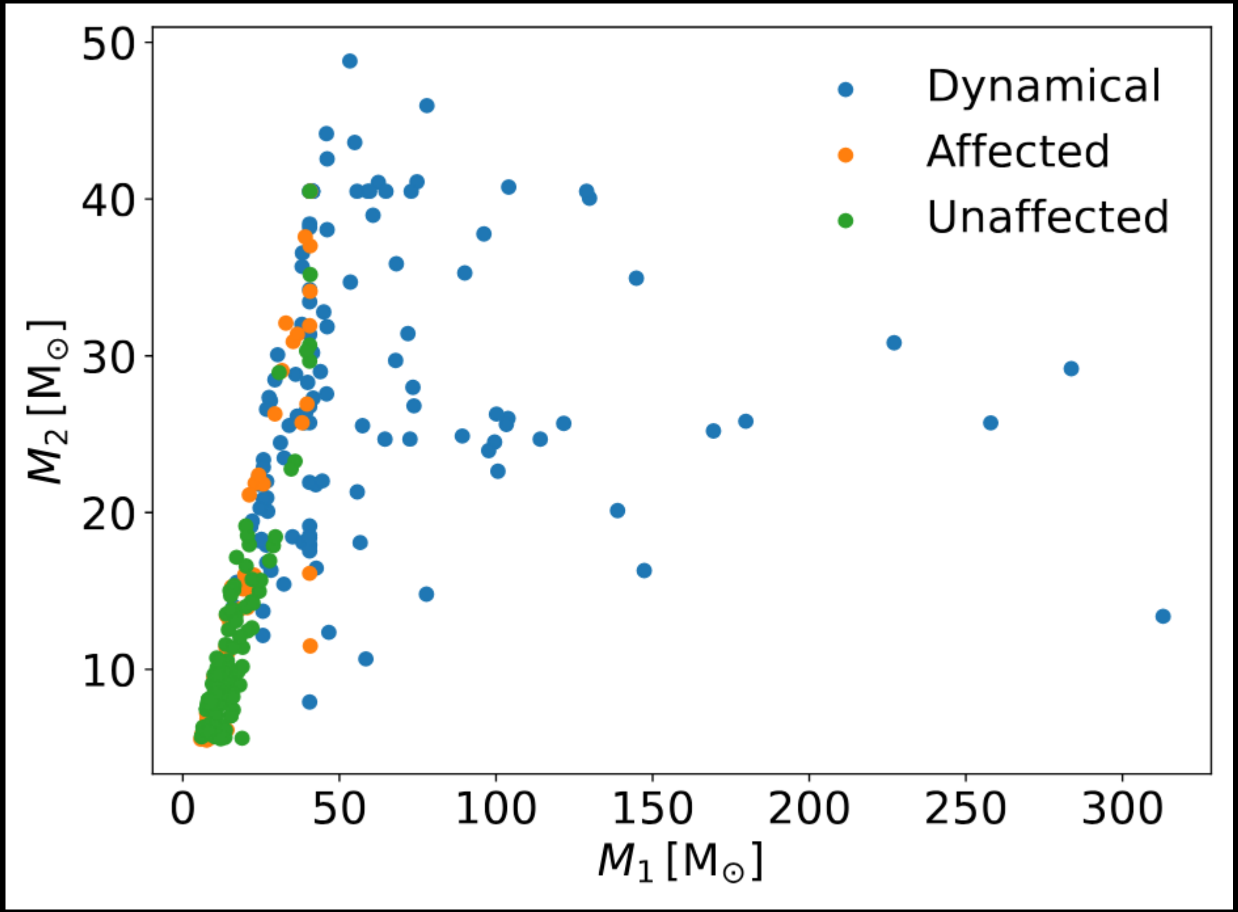
Merging BBH Distributions

- Anderson-Darling K-sample test (Unaffected vs Affected BBHs).
- Drawn from different distributions at 5% level.
- Appears to have very high eccentricity in dynamical BBHs.
- Evolved to 10 Hz → 2% have $e > 0.1$ in LIGO band



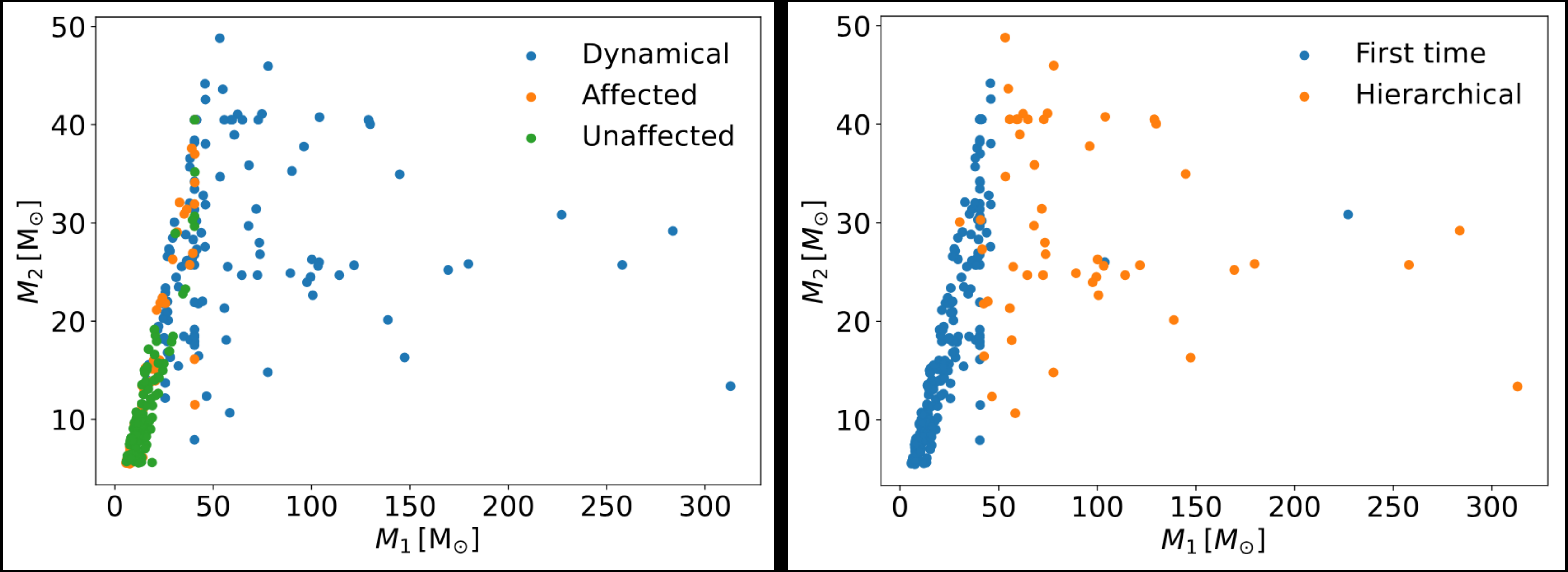
Hierarchical BBH mergers

Many dynamical BBH mergers with very massive primary mass



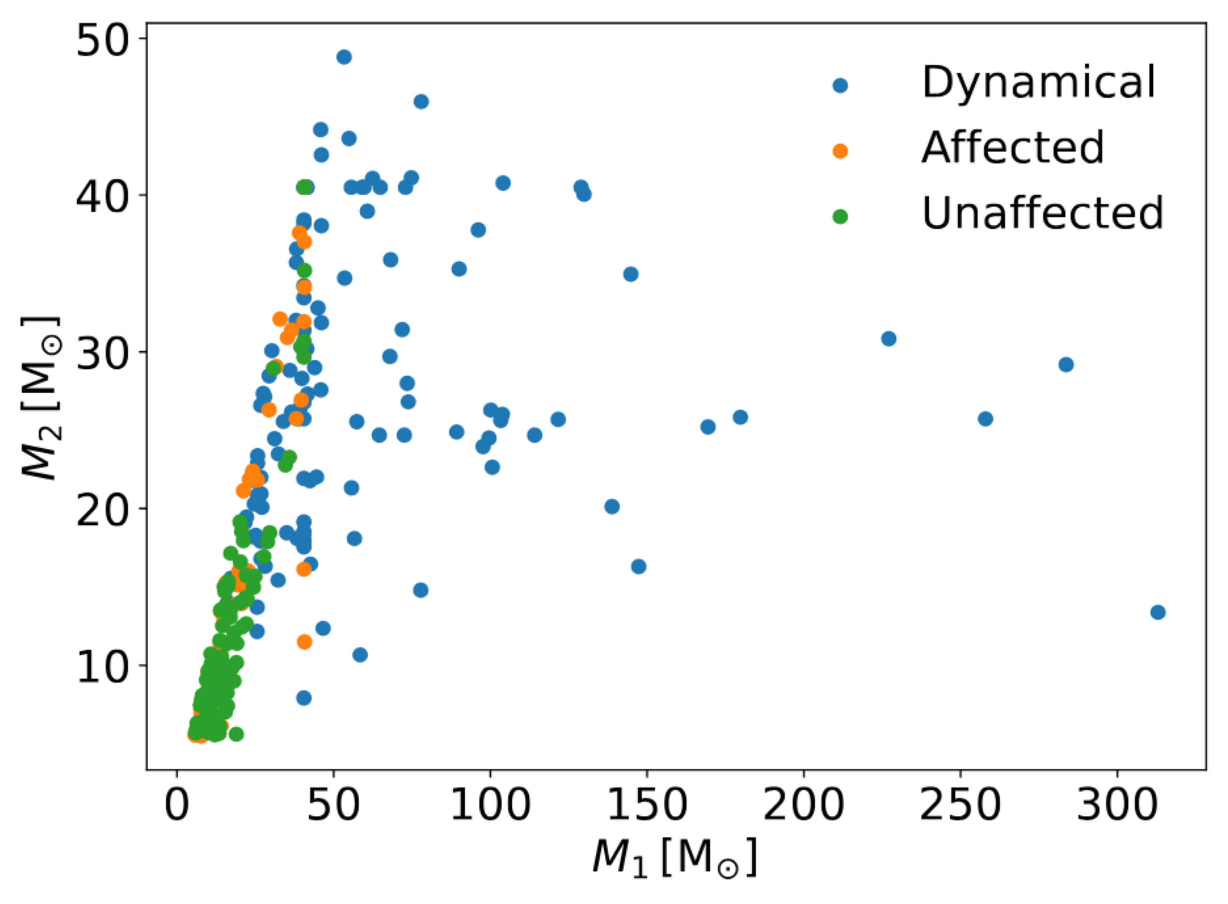
Hierarchical BBH mergers

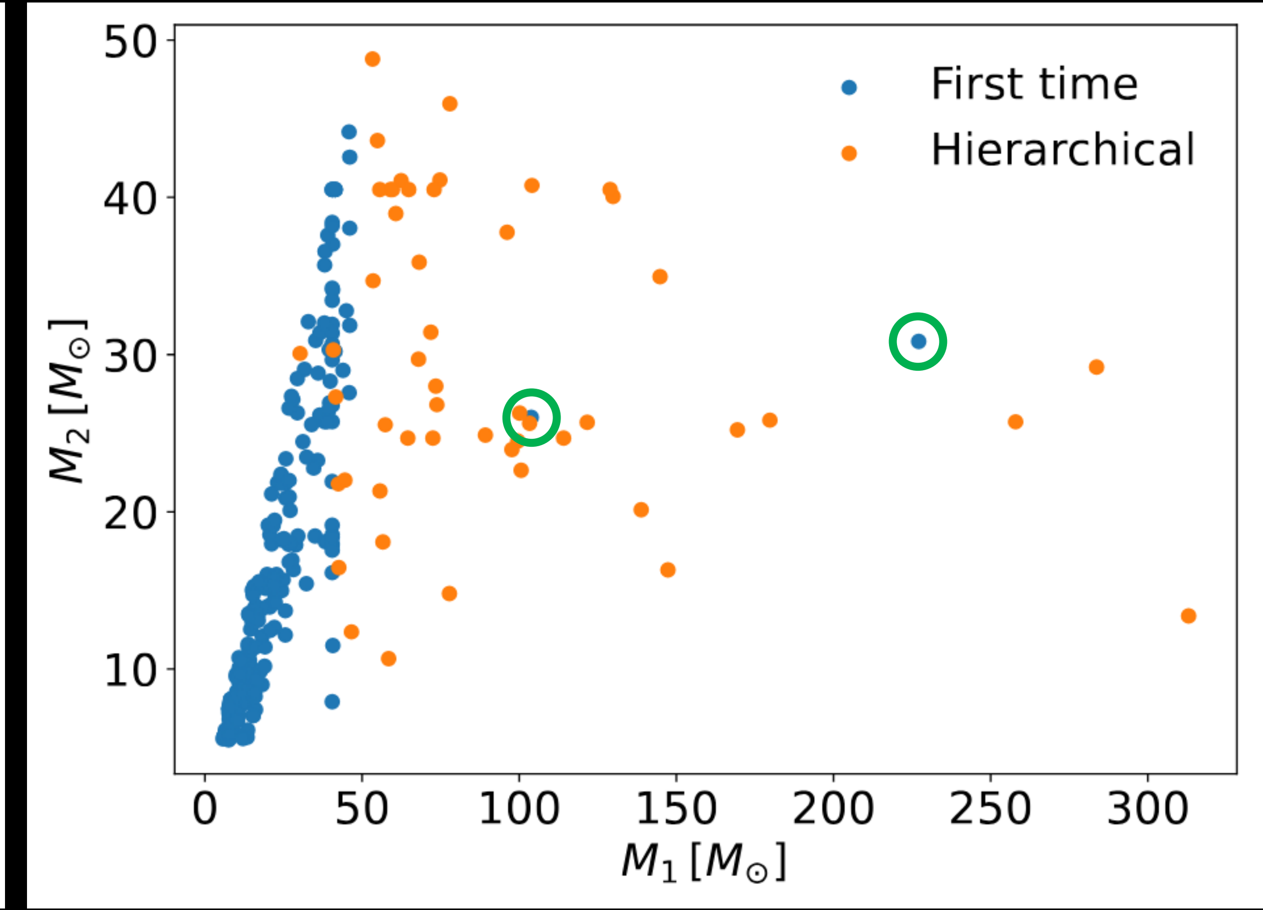
Many dynamical BBH mergers with very massive primary mass → Most Hierarchical mergers → Note lacks PN terms, doesn't account for GW kick



Hierarchical BBH mergers

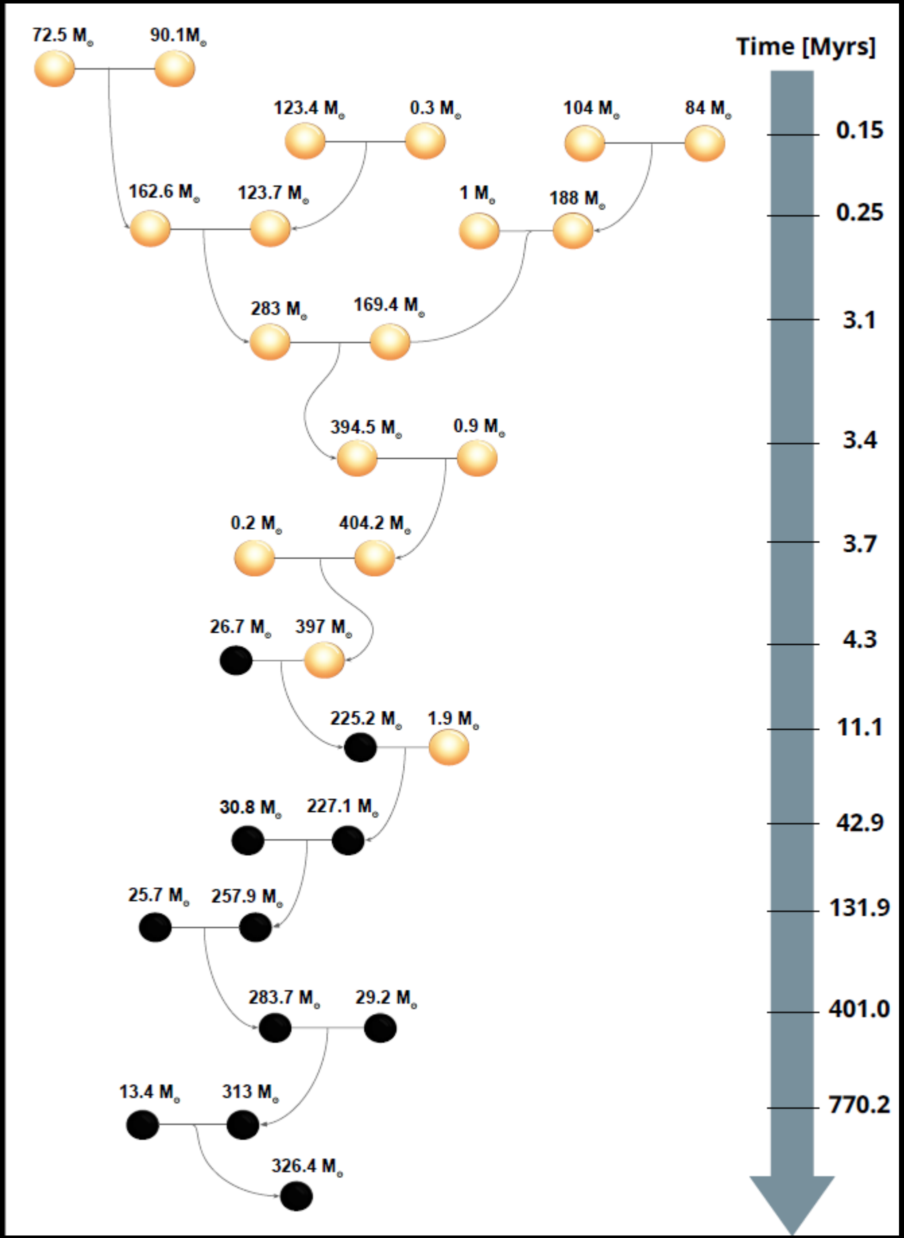
Many dynamical BBH mergers with very massive primary mass → Most Hierarchical mergers → Note lacks PN terms, doesn't account for GW kick → A couple notable first-time mergers





Tracking formation of Massive BH

- Period of repeated stellar mergers → Leads to Very massive star formed.
- Massive star merges with much smaller black hole → Yields very massive BH!



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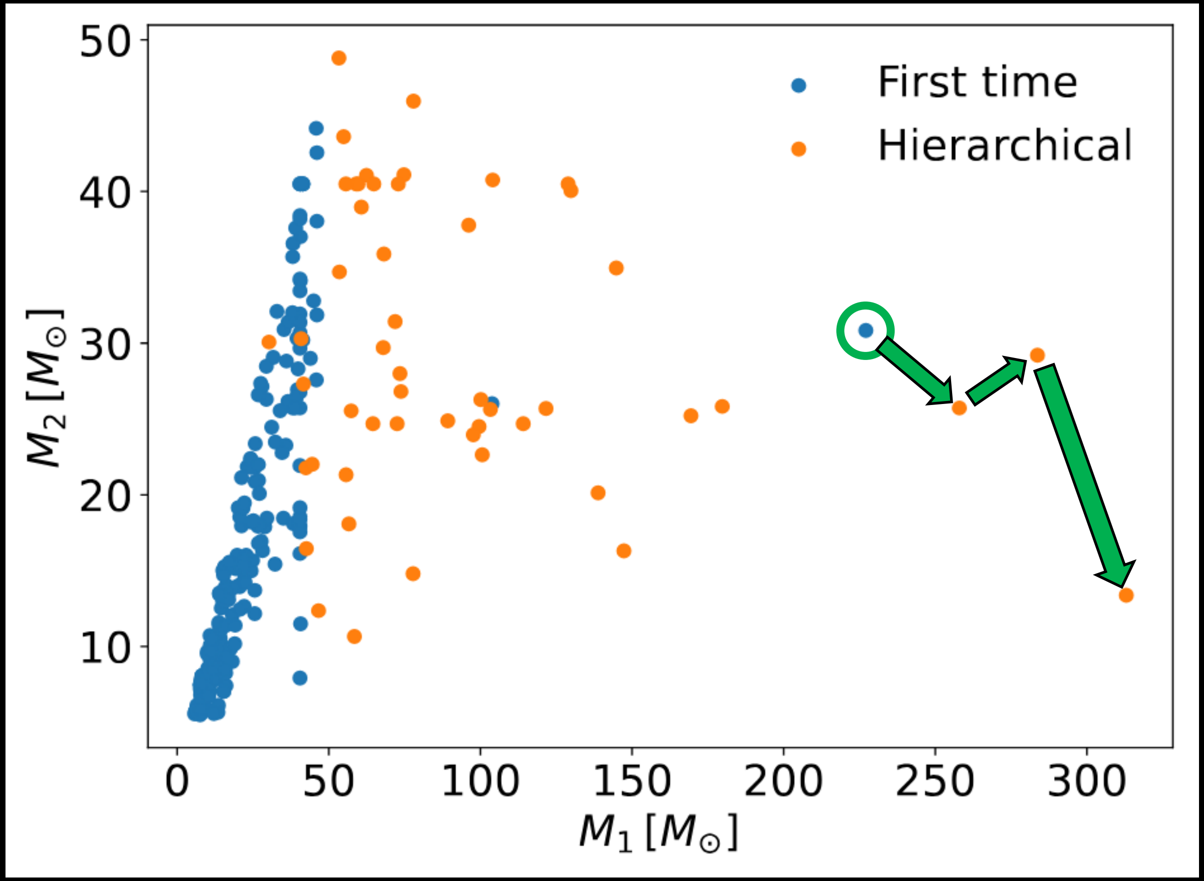

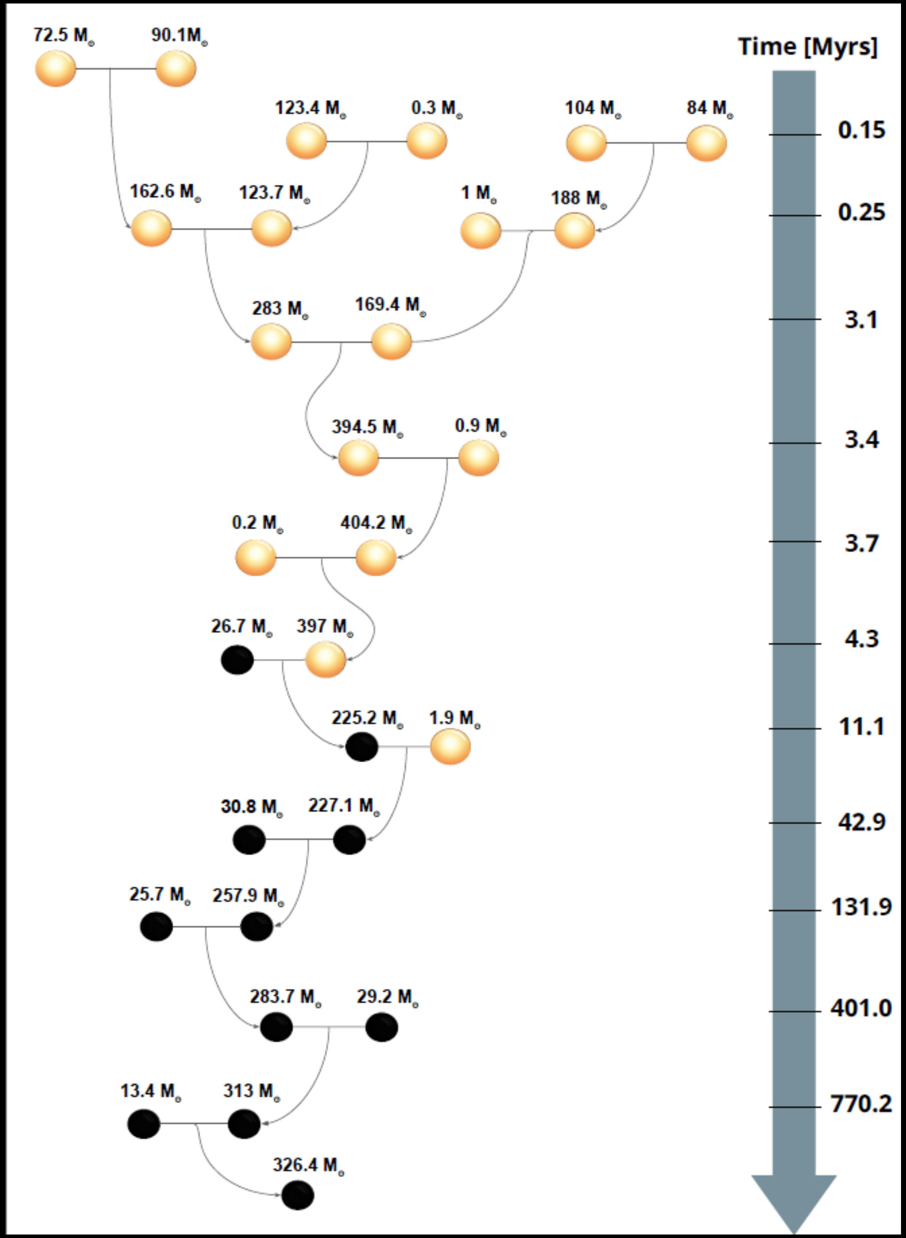

Summary

We have used PeTar to model star clusters with and without primordial binaries, across a range of initial cluster masses, densities and metallicity.

Key Results

- Primordial binaries are contributing the most to the merging BBH population in low mass($< 10^5\ \mathrm{M}_\odot$) stellar clusters.
- Only about half of the primordial binary mergers are affected by the dynamics of the cluster.
- Clusters with primordial binaries → merger efficiency is mostly unaffected by the cluster dynamics.
- 2% of dynamical BBHs merge with “measurable” eccentricity in LIGO band.

Full results to be discussed in Barber et al. 2024 (in prep)

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Multiplicity of Merging BBH Systems