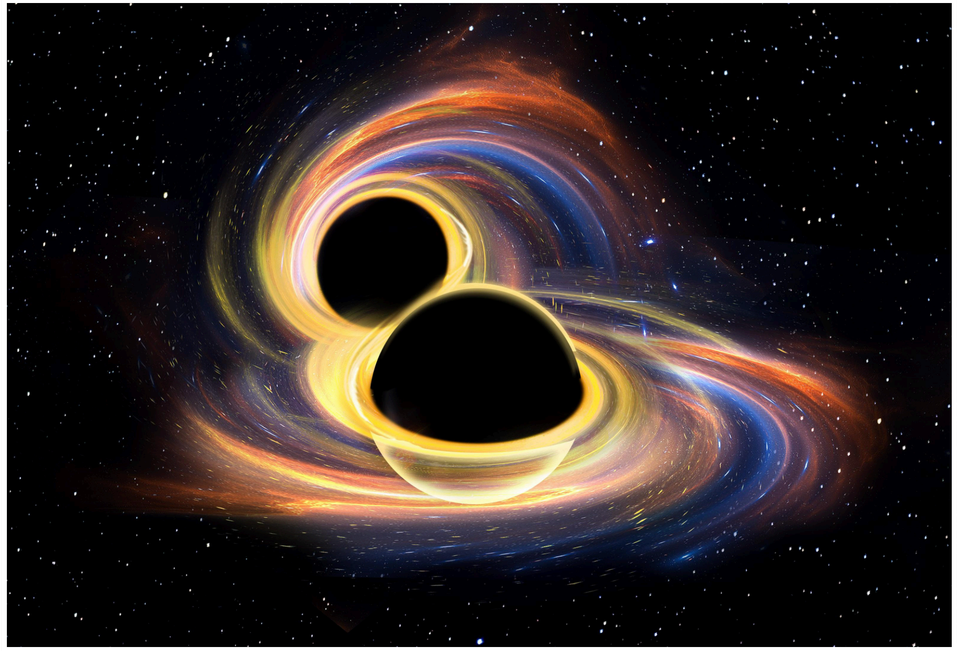
# Hierarchical mergers as tracers of globular cluster formation history



credit: X-ray: NASA / CXC / SAO;
Optical: NASA / ESA / STScI;
IR: NASA / ESA / CSA / STScI; Processing:
NASA / CXC / SAO / L. Frattare



credit: Raul Perez and Davis Newell, Georgia Tech



Messier 13, credit: ESA/Hubble and NASA

**Andris Dorozsmai**
National Astronomical Observatory of Japan

**AGWM, Chiang Mai, 2026**

# Outline

Goal:

- To show how accurately we can infer **cluster formation history** with detections of **hierarchical mergers** with **3rd generation GW detectors**.

# Outline

Goal:

- To show how accurately we can infer **cluster formation history** with detections of **hierarchical mergers** with **3rd generation GW detectors**.

How:

- By combining numerical models with Bayesian inference models.

# Outline

Goal:

- To show how accurately we can infer **cluster formation history** with **detections of hierarchical mergers** with **3rd generation GW detectors**.

How:

- By combining numerical models with Bayesian inference models.

Outline:

- A little bit about globular clusters.

# Outline

Goal:

- To show how accurately we can infer cluster formation history with detections of hierarchical mergers 3rd generation GW detectors.

How:

- By combining numerical models with Bayesian inference models.

Outline:

- A little bit about globular clusters.
- Formation of GW sources in globular clusters.

# Outline

Goal:

- To show how accurately we can infer cluster formation history with detections of hierarchical mergers 3rd generation GW detectors.

How:

- By combining numerical models with Bayesian inference models.

Outline:

- A little bit about globular clusters.
- Formation of GW sources in globular clusters.
- Why hierarchical mergers are good tracers of cluster formation efficiency.

# Outline

Goal:

- To show how accurately we can infer cluster formation history with detections of hierarchical mergers 3rd generation GW detectors

How:

- By combining numerical models with Bayesian inference models

Outline:

- A little bit about globular clusters
- Formation of GW sources in globular clusters
- Why hierarchical mergers are good tracers of cluster formation efficiency.
- Details of method.

# Outline

Goal:

- To show how accurately we can infer cluster formation history with detections of hierarchical mergers 3rd generation GW detectors

How:

- By combining numerical models with Bayesian inference models

Outline:

- A little bit about globular clusters
- Formation of GW sources in globular clusters
- Why hierarchical mergers are good tracers of cluster formation efficiency.
- Details of method.
- Results + Conclusion.

# What are globular clusters ?

- Dense, gravitationally bound stellar systems.



Messier 13, credit: ESA/Hubble and NASA

# What are globular clusters ?

- Dense, gravitationally bound stellar systems.
- $10^4$-$10^6$ stars.



Messier 13, credit: ESA/Hubble and NASA

# What are globular clusters ?

- Dense, gravitationally bound stellar systems.
- $10^4$-$10^6$ stars.
- Typically very old and low metallicity (not always).



Messier 13, credit: ESA/Hubble and NASA

# What are globular clusters ?

- Dense, gravitationally bound stellar systems.
- $10^4$-$10^6$ stars.
- Typically very old and low metallicity (not always).
- Evolution defined by (strong) stellar dynamics.



Messier 13, credit: ESA/Hubble and NASA

# What are globular clusters ?

- Dense, gravitationally bound stellar systems.
- $10^4$-$10^6$ stars.
- Typically very old and low metallicity (not always).
- Evolution defined by (strong) stellar dynamics.
- Ideal environment of formation of GW sources.



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**

- Still an open question.



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**

- Still an open question.
- Likely the extreme end of normal star formation in high-pressure, gas-rich environments (i.e. high redshift).



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**

- Still an open question.
- Likely the extreme end of normal star formation in high-pressure, gas-rich environments (i.e. high redshift).
- Only the most massive, tightly bound clusters survive to become today's globular clusters.



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**

- Still an open question.
- Likely the extreme end of normal star formation in high-pressure, gas-rich environments (i.e. high redshift).
- Only the most massive, tightly bound clusters survive to become today's globular clusters.

**The key uncertainties are:**



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**

- Still an open question.
- Likely the extreme end of normal star formation in high-pressure, gas-rich environments (i.e. high redshift).
- Only the most massive, tightly bound clusters survive to become today's globular clusters.

**The key uncertainties are:**

- Cluster formation efficiency as a function of star forming conditions is poorly understood,



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**

- Still an open question.
- Likely the extreme end of normal star formation in high-pressure, gas-rich environments (i.e. high redshift).
- Only the most massive, tightly bound clusters survive to become today's globular clusters.

**The key uncertainties are:**

- Cluster formation efficiency as a function of star forming conditions is poorly understood,
- which clusters survive and form GCs.



Messier 13, credit: ESA/Hubble and NASA

# Formation of globular clusters

**How do GCs form?**

- Still an open question.
- Likely the extreme end of normal star formation in high-pressure, gas-rich environments (i.e. high redshift).
- Only the most massive, tightly bound clusters survive to become today's globular clusters.

**The key uncertainties are:**

- **Cluster formation efficiency as a function of star forming conditions is poorly understood,**
- which clusters survive and form GCs.



Messier 13, credit: ESA/Hubble and NASA

# BHs as messengers of clusters

- Merging binary black holes probably form efficiently in globular clusters.



*Young massive cluster*

credit: X-ray: NASA / CXC / SAO;
Optical: NASA / ESA / STScI;
IR: NASA / ESA / CSA / STScI; Processing: NASA / CXC / SAO / L. Frattare

# BHs as messengers of clusters

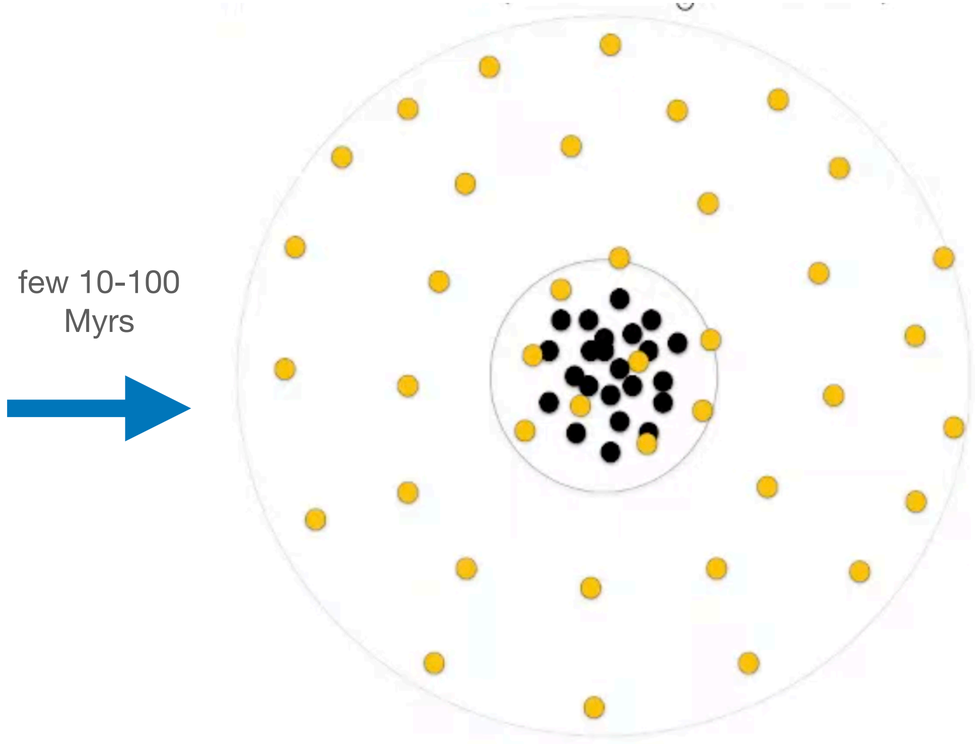
- Merging binary black holes probably form efficiently in globular clusters.



*Young massive cluster*

credit: X-ray: NASA / CXC / SAO;
Optical: NASA / ESA / STScI;
IR: NASA / ESA / CSA / STScI; Processing: NASA / CXC / SAO / L. Frattare

few 10-100 Myrs



credit: Kyle Kremer

credit: Mandel & Farmer 2018

# BHs as messengers of clusters

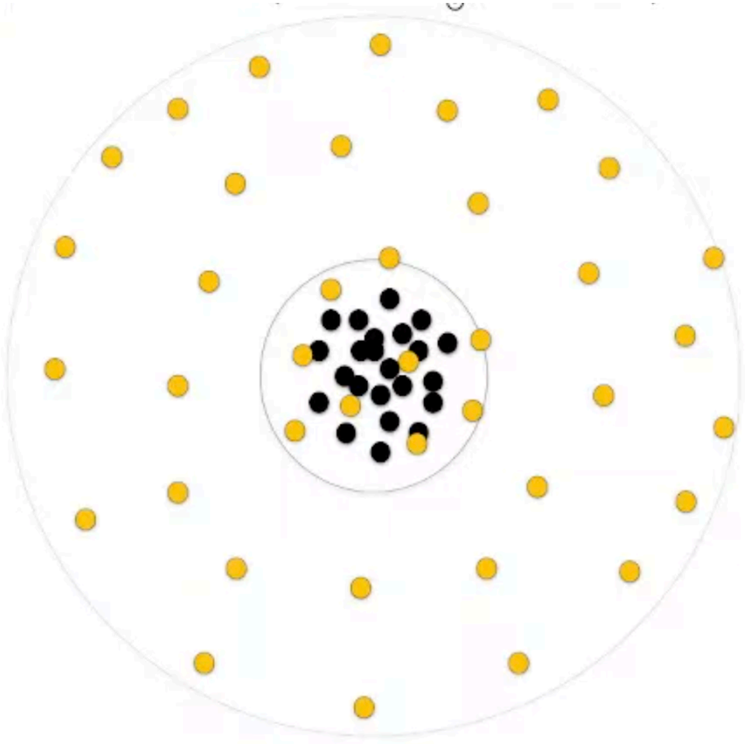
- Merging binary black holes probably form efficiently in globular clusters.



*Young massive cluster*

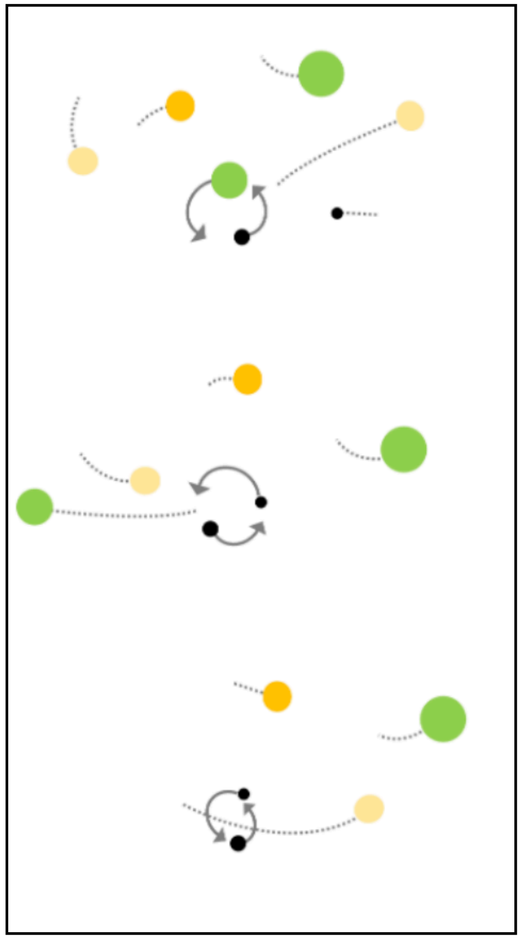
credit: X-ray: NASA / CXC / SAO;
Optical: NASA / ESA / STScI;
IR: NASA / ESA / CSA / STScI; Processing: NASA / CXC / SAO / L. Frattare

few 10-100 Myrs



credit: Kyle Kremer

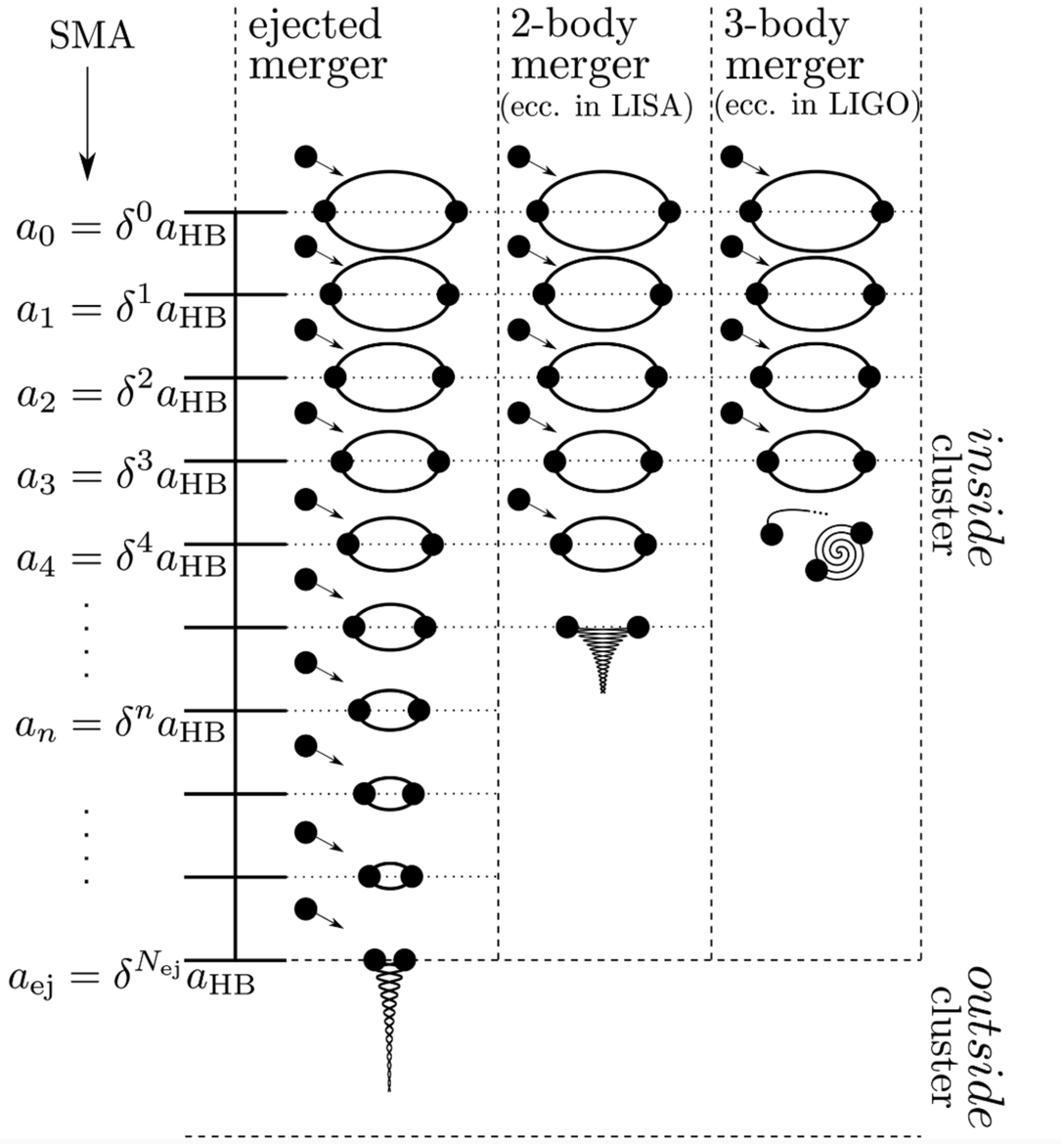
inside the GC



credit: Mandel & Farmer 2018

# Hierarchical mergers

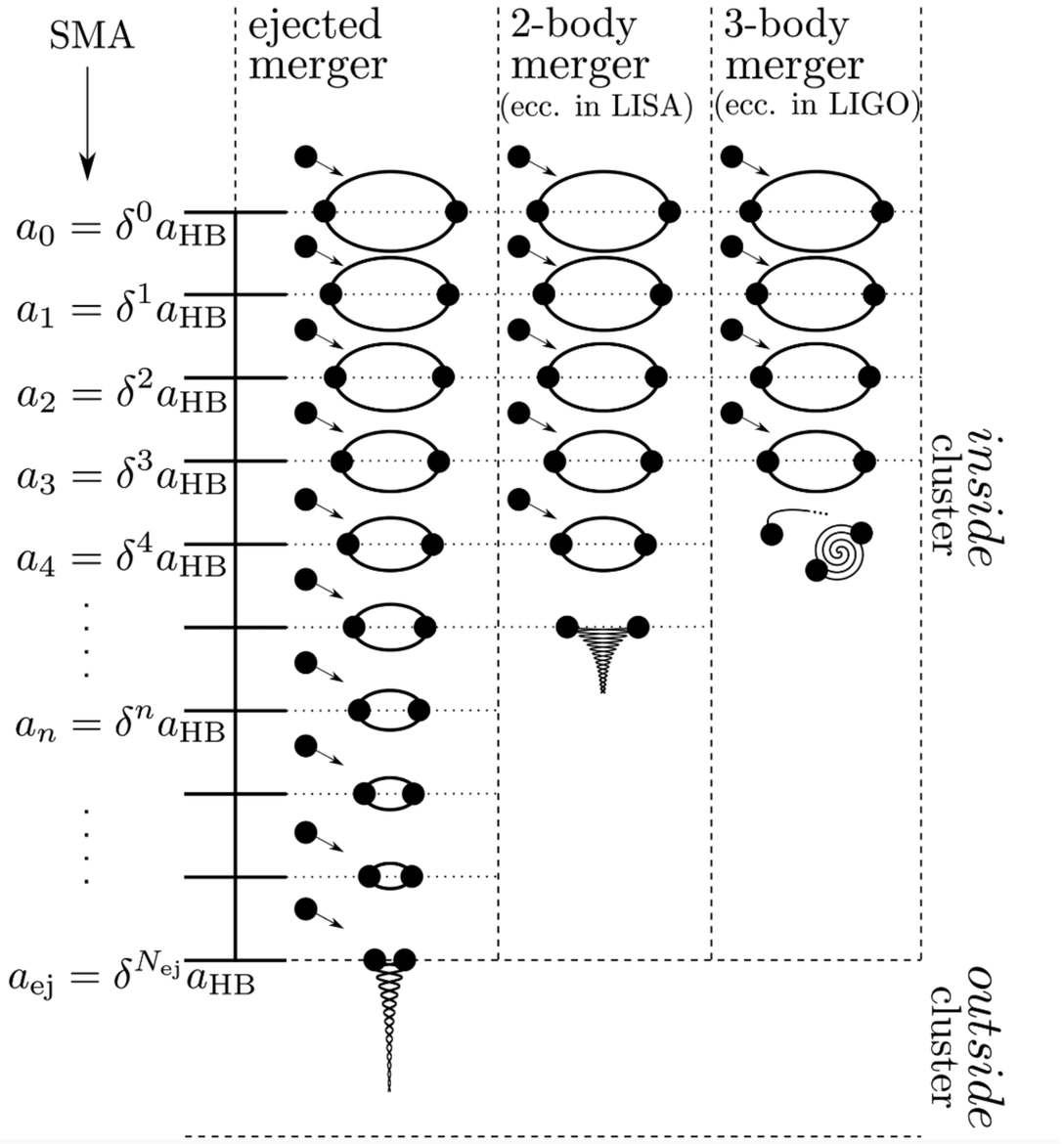
- Typically three main formation pathways are distinguished:



# Hierarchical mergers

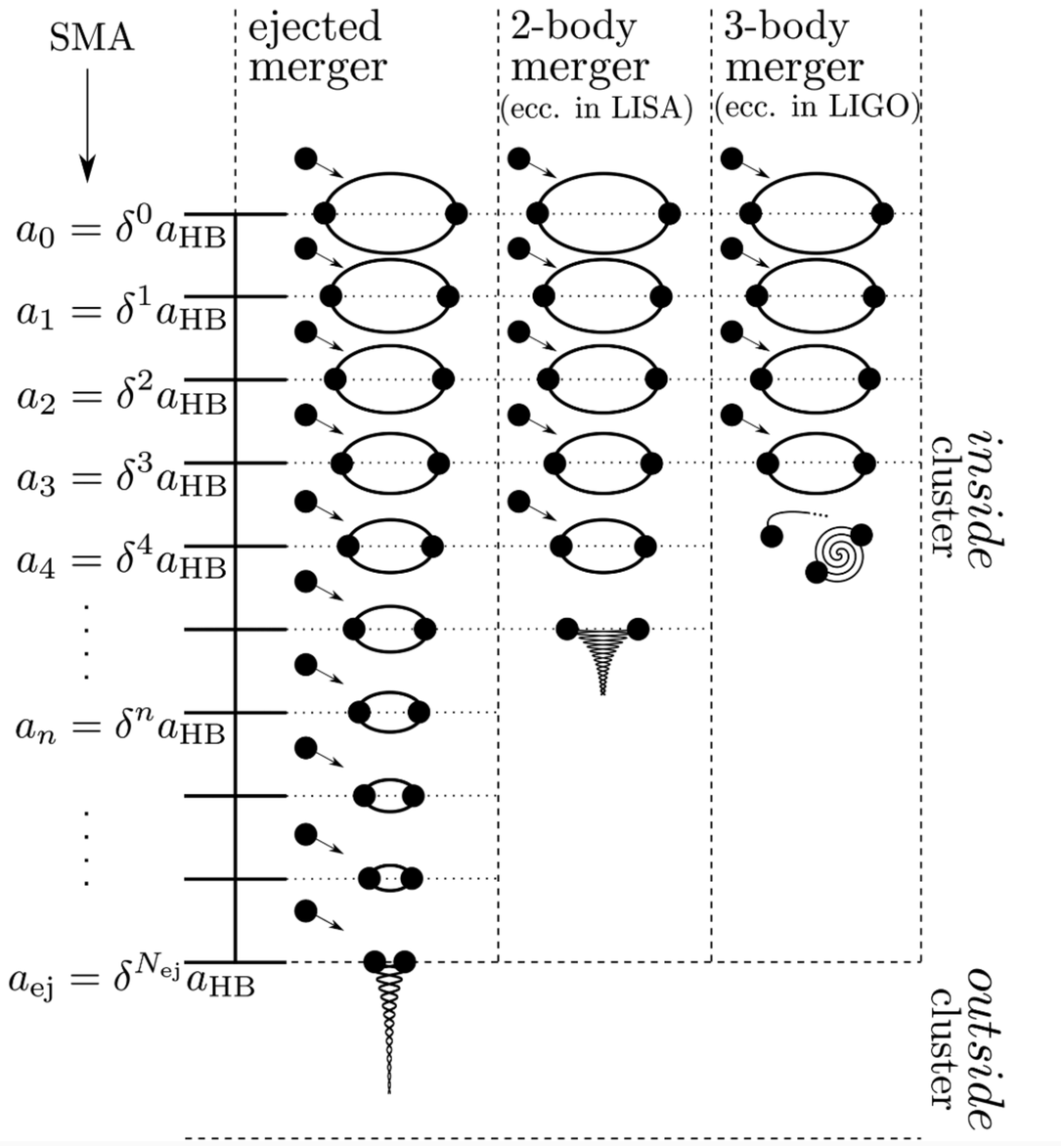
- Typically three main formation pathways are distinguished:

- A sizeable fraction is expected to be inside the cluster.



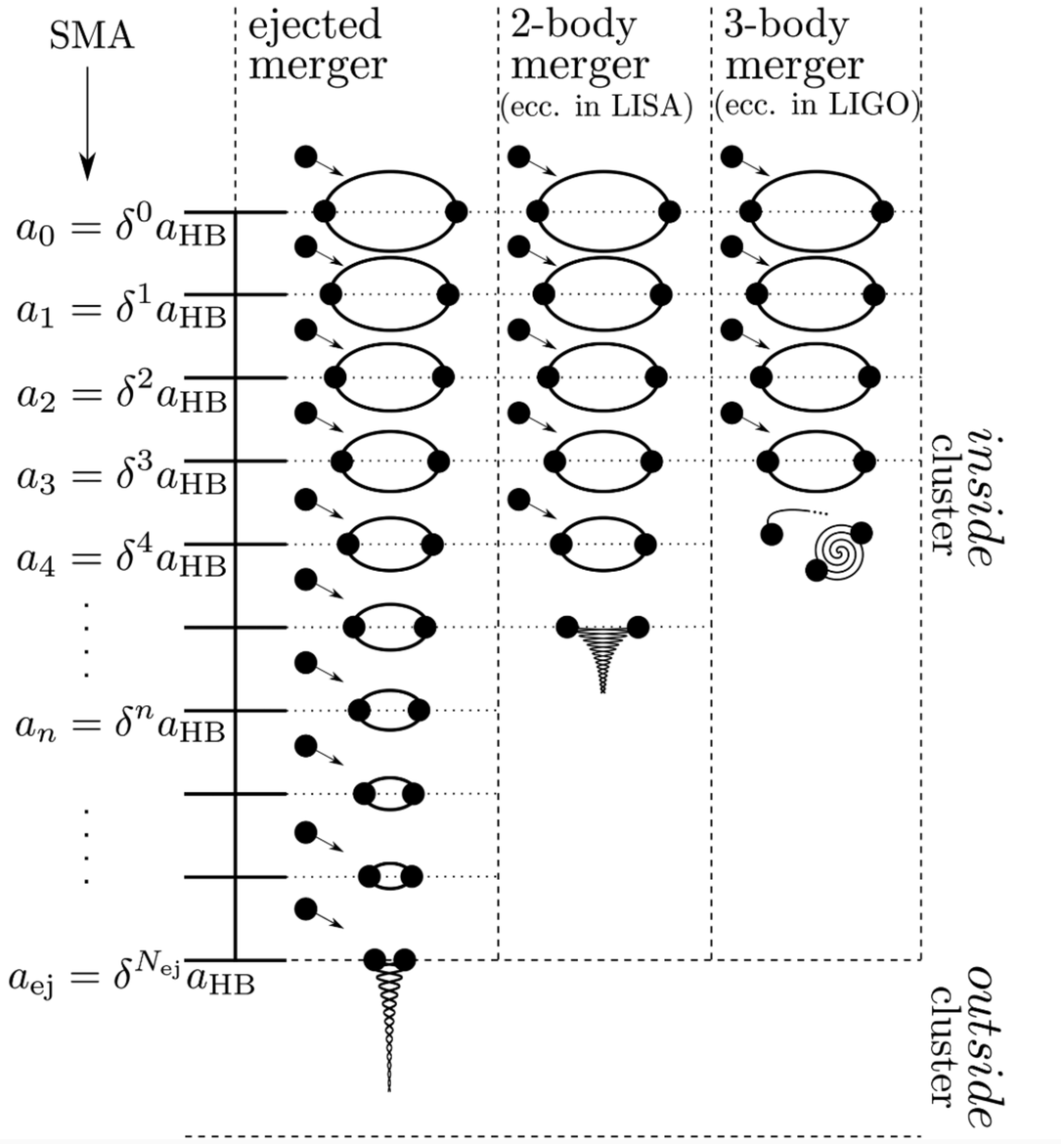
# Hierarchical mergers

- Typically three main formation pathways are distinguished:
- A sizeable fraction is expected to be inside the cluster.
- The merger product may be retained (especially for more massive clusters.



# Hierarchical mergers

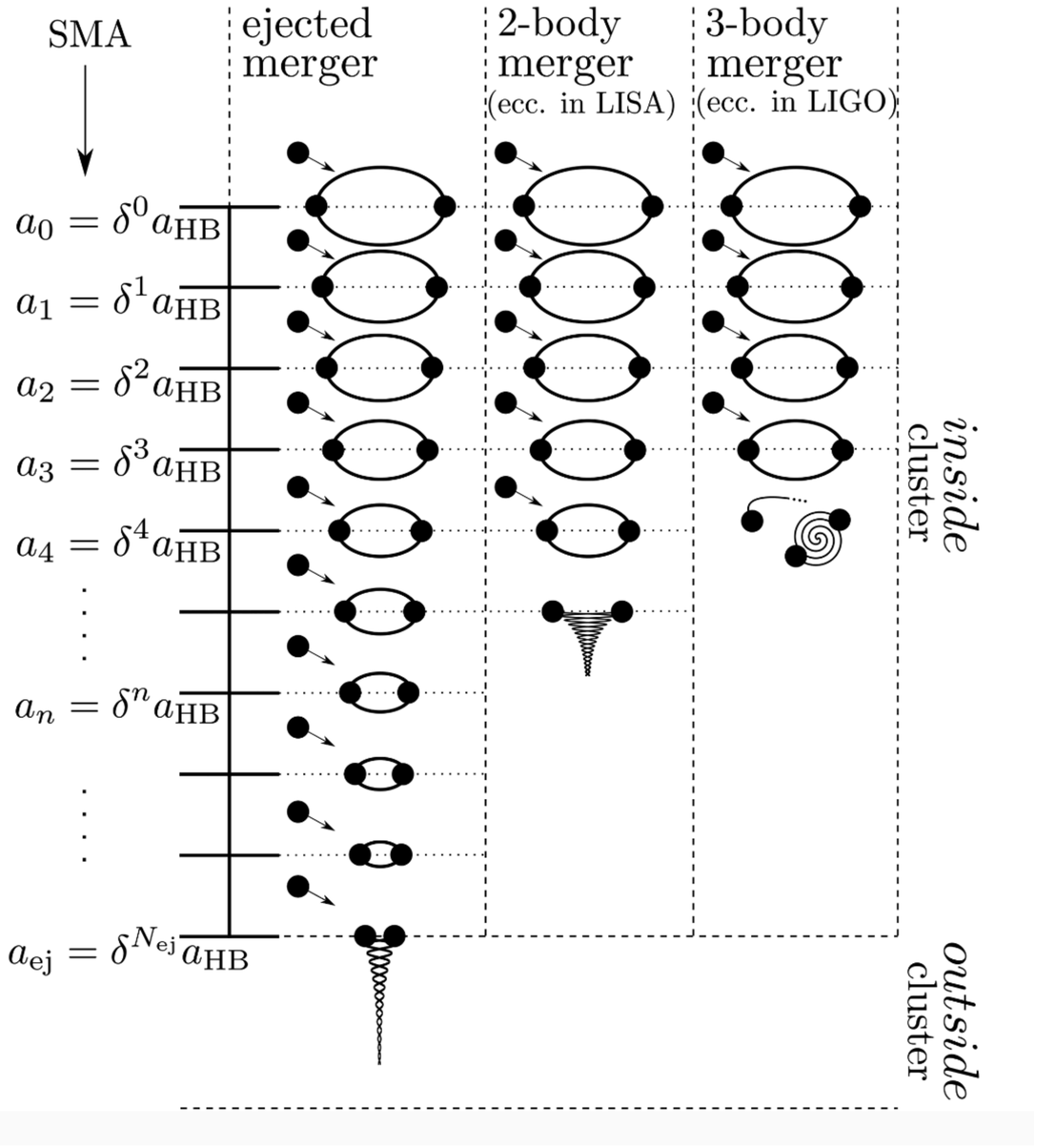
- Typically three main formation pathways are distinguished:
- A sizeable fraction is expected to be inside the cluster.
- The merger product may be retained (especially for more massive clusters.
- The merger product may merge with another BH again -> *Hierarchical BH mergers.*



# Hierarchical mergers

- Typically three main formation pathways are distinguished:
- A sizeable fraction is expected to be inside the cluster.
- The merger product may be retained (especially for more massive clusters.
- The merger product may merge with another BH again -> *Hierarchical BH mergers.*

…but do these mergers actually exist?



# Hierarchical mergers

## Do they exist?

- We don’t know yet, but there are strong indications!

# Hierarchical mergers

## Do they exist?

- We don’t know yet, but there are strong indications!

- Many detections so far consistent with being in the mass gap…

Abac et al. 2025

# Hierarchical mergers

## Do they exist?

- We don’t know yet, but there are strong indications!

- Many detections so far consistent with being in the mass gap…
- with unequal mass ratios

Abac et al. 2025

# Hierarchical mergers

## Do they exist?

- We don’t know yet, but there are strong indications!

- Many detections so far consistent with being in the mass gap…
- with unequal mass ratios,
- and spins consistent with hierarchical mergers.

Abac et al. 2025

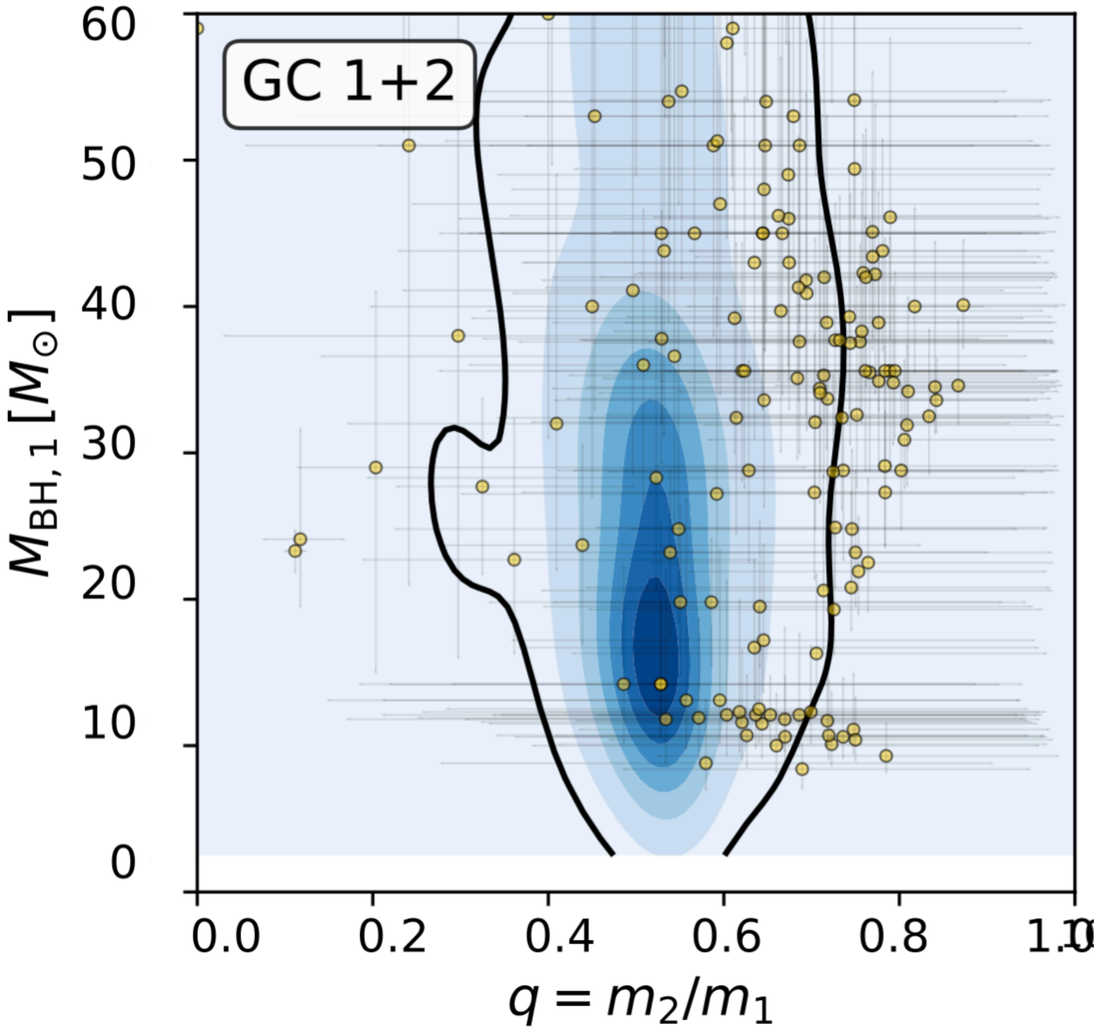
# Hierarchical mergers

## Do they exist?

- We don’t know yet, but there are strong indications

- Many detections so far consistent with being in the mass gap…
- with unequal mass ratios,
- and spins consistent with hierarchical mergers.

Dorozsmai et al. 2026 in prep.



# Hierarchical mergers

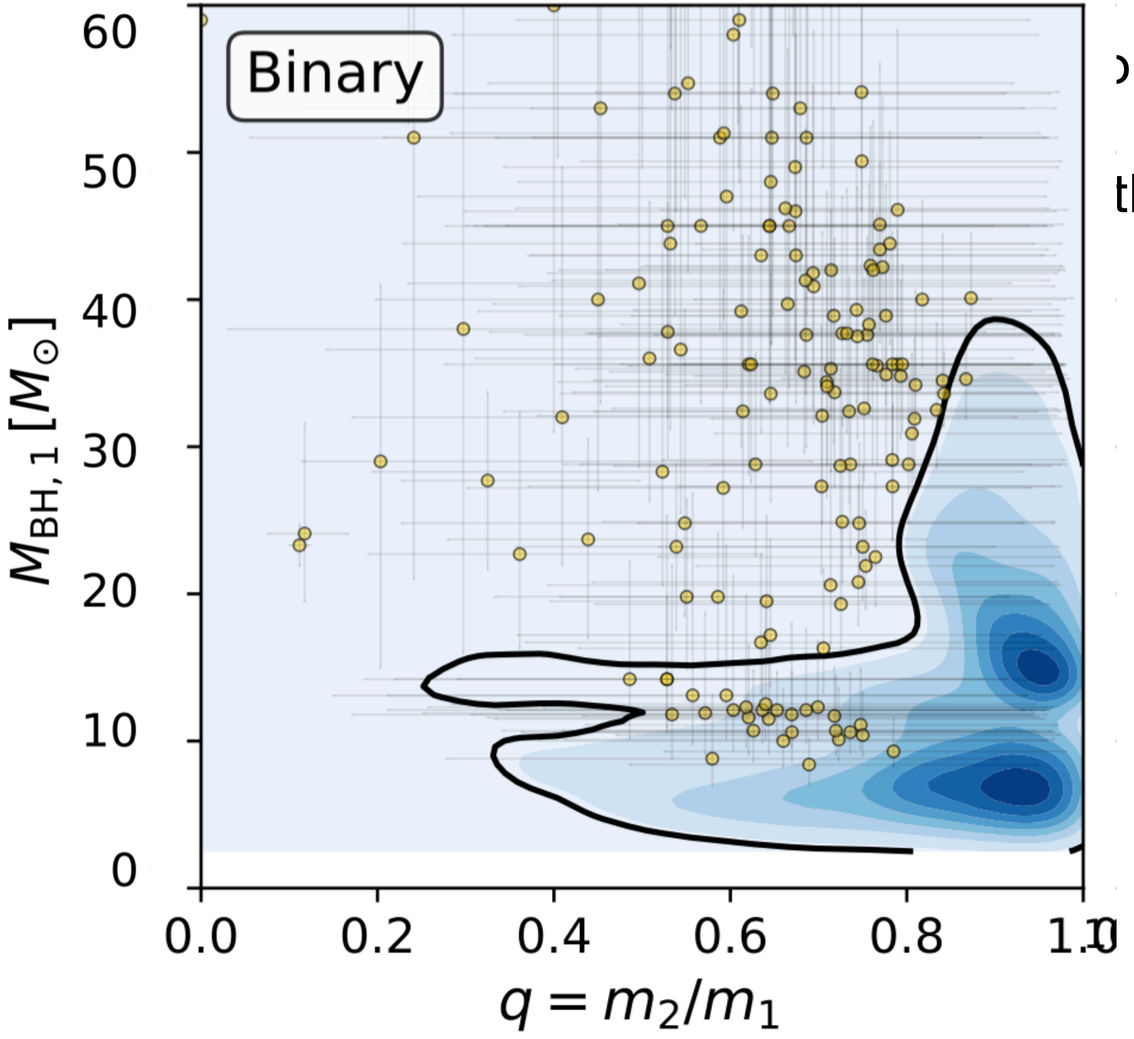
## Do they exist?

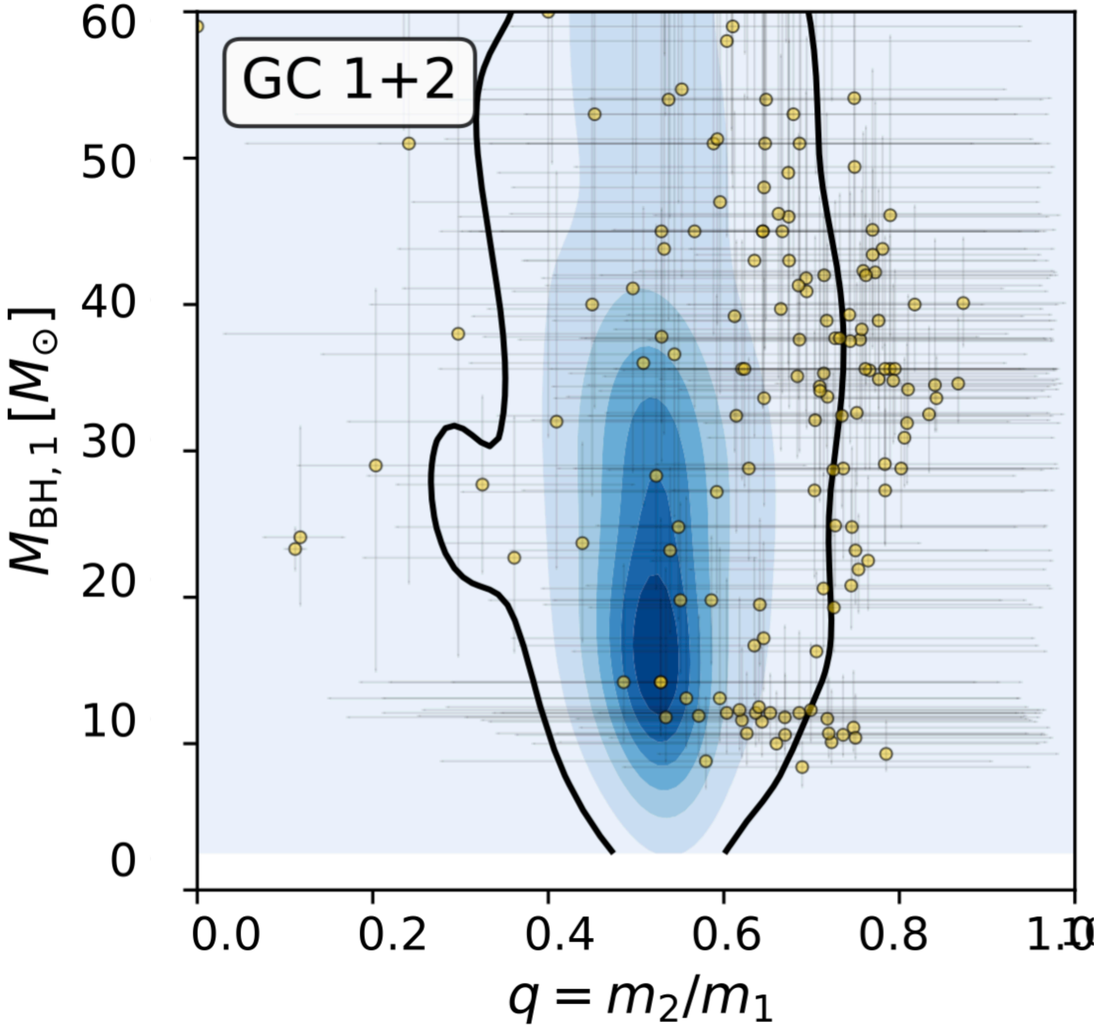
- V
- N
  n
- v
- a

ons

the

Dorozsmai et al. 2026 in prep.



# Hierarchical mergers

## Do they exist?

- We don’t know yet, but there are strong indications!

- Many detections so far consistent with being in the mass gap…
- with unequal mass ratios,
- and spins consistent with hierarchical mergers.
- **GW241011: a particularly strong candidate!**

| Event | $m_1\ (M_\odot)$ | $m_2\ (M_\odot)$ | $q$ | $\mathcal{M}\ [M_\odot]$ | $D_\mathrm{L}$ (Mpc) | $\chi_1$ | $\theta_1$ (deg) |
|---|---|---|---|---|---|---|---|
| GW241011 | $19.6^{+3.6}_{-2.5}$ | $5.9^{+0.8}_{-0.8}$ | $0.30^{+0.09}_{-0.08}$ | $9.1^{+0.1}_{-0.1}$ | $214^{+44}_{-48}$ | $0.78^{+0.09}_{-0.09}$ | $31^{+11}_{-14}$ |

Abac et al. 2025

# Hierarchical mergers

Hierarchical mergers are ideal candidates for GC formation tracers:

- Have unique characteristics => very unlikely to form in non-dense environments.

# Hierarchical mergers

Hierarchical mergers are ideal candidates for GC formation tracers:

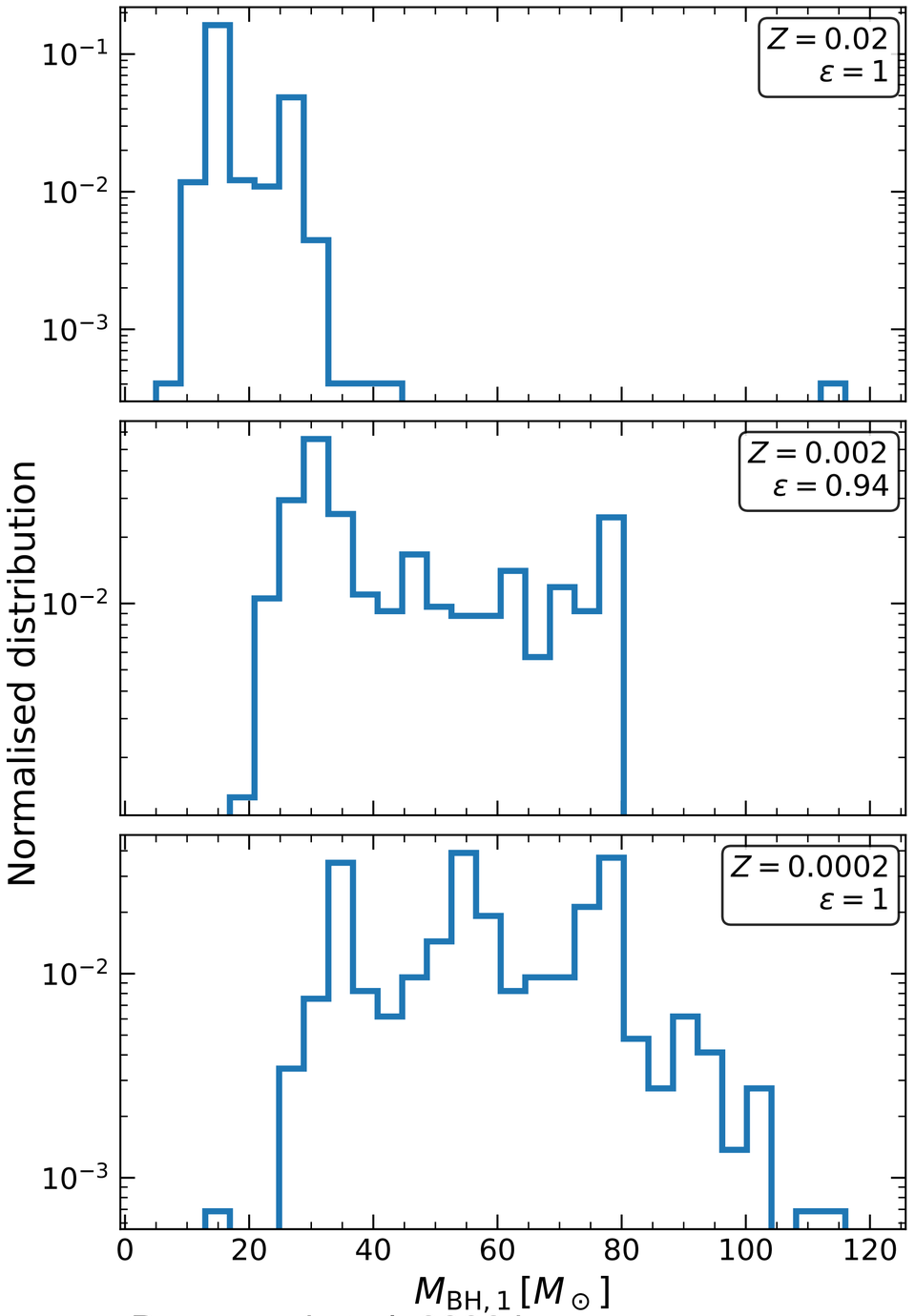
- Have unique characteristics => very unlikely to form in non-dense environments.
- Merger efficiency is weakly dependent on metallicity.

Dorozsmai et al. 2026 in prep.

# Hierarchical mergers

Hierarchical mergers are ideal candidates for GC formation tracers:

- Have unique characteristics => very unlikely to form in non-dense environments.
- Merger efficiency is weakly dependent on metallicity.

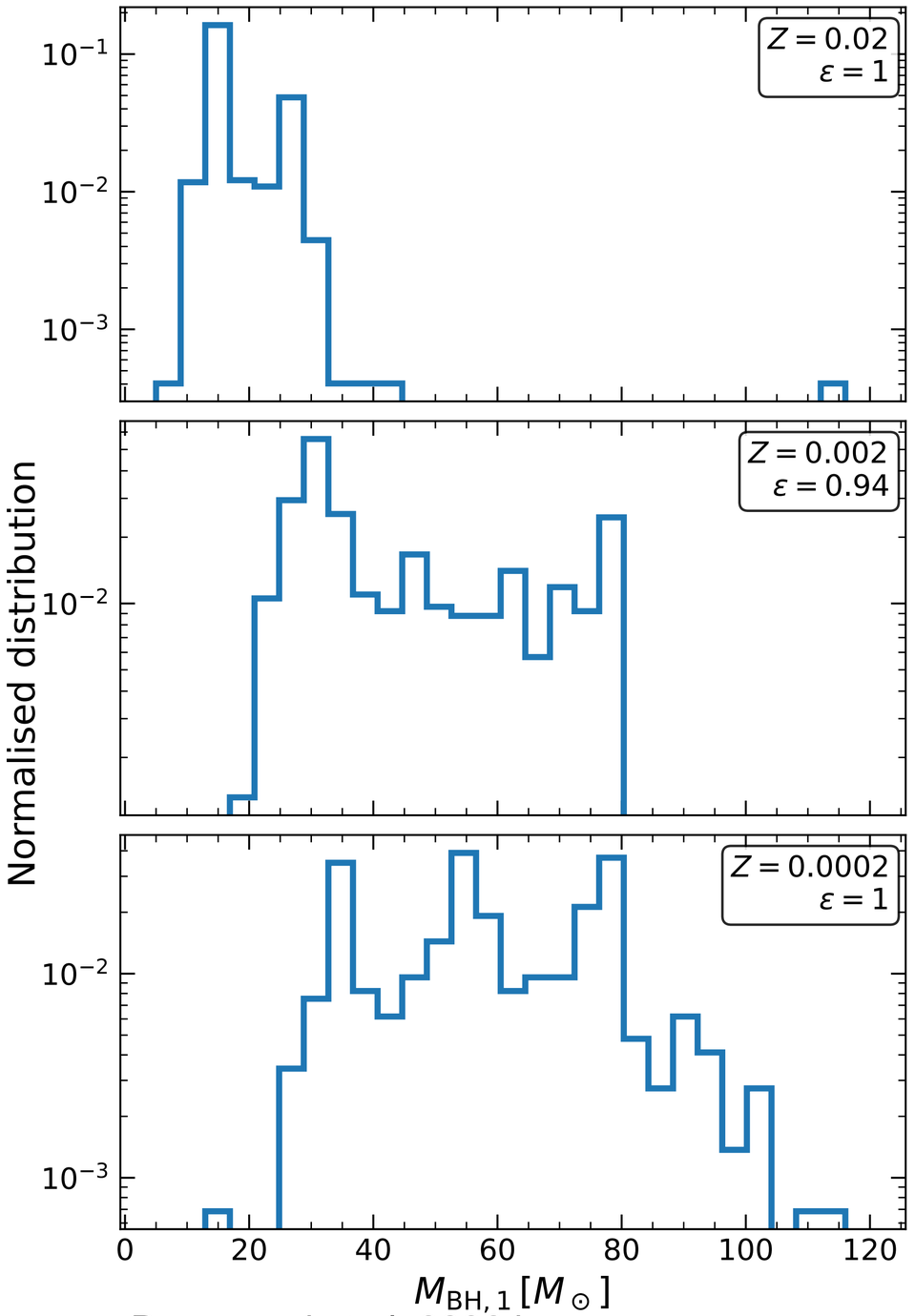



Dorozsmai et al. 2026 in prep.

# Hierarchical mergers

Hierarchical mergers are ideal candidates for GC formation tracers:

- Have unique characteristics => very unlikely to form in non-dense environments.
- Merger efficiency is weakly dependent on metallicity.
- Which implies that merger rate evolution over redshift tracks the cluster formation history (with some time delay).



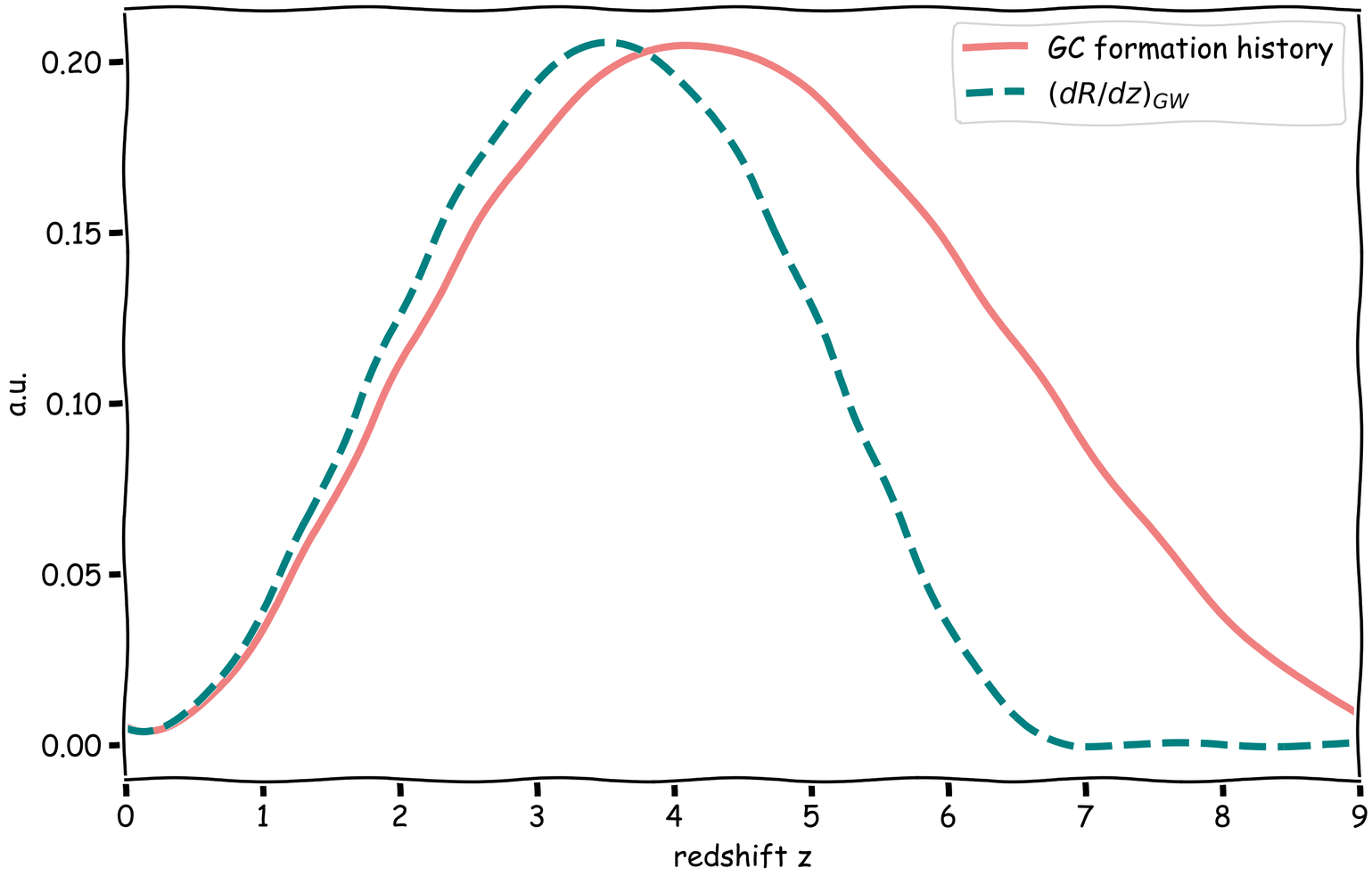

Dorozsmai et al. 2026 in prep.

# Hierarchical mergers

If we can infer the merger rate distribution over redshift for these sources and have a reasonable model for time delay, then…

**…We can reconstruct the GC formation history!**

Schematic Figure




Dorozsmai et al. 2026 in prep.

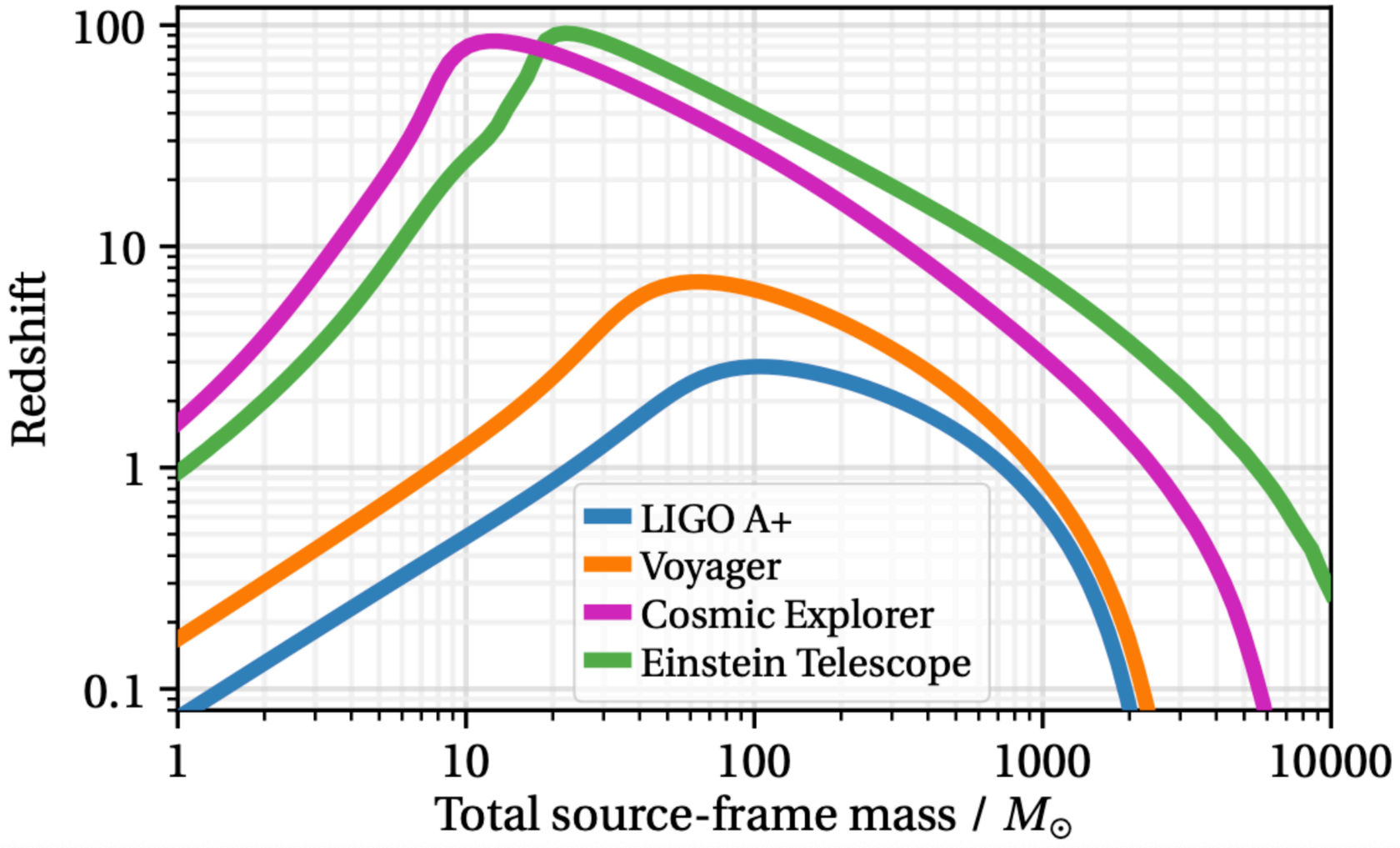
# Third-generation detectors

But how do we infer $dR/dz$ up to $z \sim$ 6-8?

- By using 3rd generation detectors!

Planned detectors:

- Einstein telescope built in Europe.
- Cosmic Explorer built in USA (or Australia).




https://cosmicexplorer.org/sensitivity.html

Dorozsmai et al. 2026 in prep.

# CMC simulation

In order to model the population of hierarchical mergers in the Universe, we make use of:

- CMC dataset from Kremer et al. 2020.
- A large grid of globular cluster simulation, characterised by:

- Initial number of particles $\mathrm{N} = [2 \times 10^5, 4 \times 10^5, 8 \times 10^5, 1.6 \times 10^5]$
- Virial radii $R_v$ = [0.5, 1, 2, 4] pc
- Galactrocentric radius $R_{gc}$ = [2, 8, 20] kpc
- Metallicity Z = [0.02, 0.002, 0.0002]

Among many other things these models:

- Reproduce the observed properties of MW GCs.
- Make predictions of demographics of merging binary black holes.

# Summary of methodology

# Summary of methodology

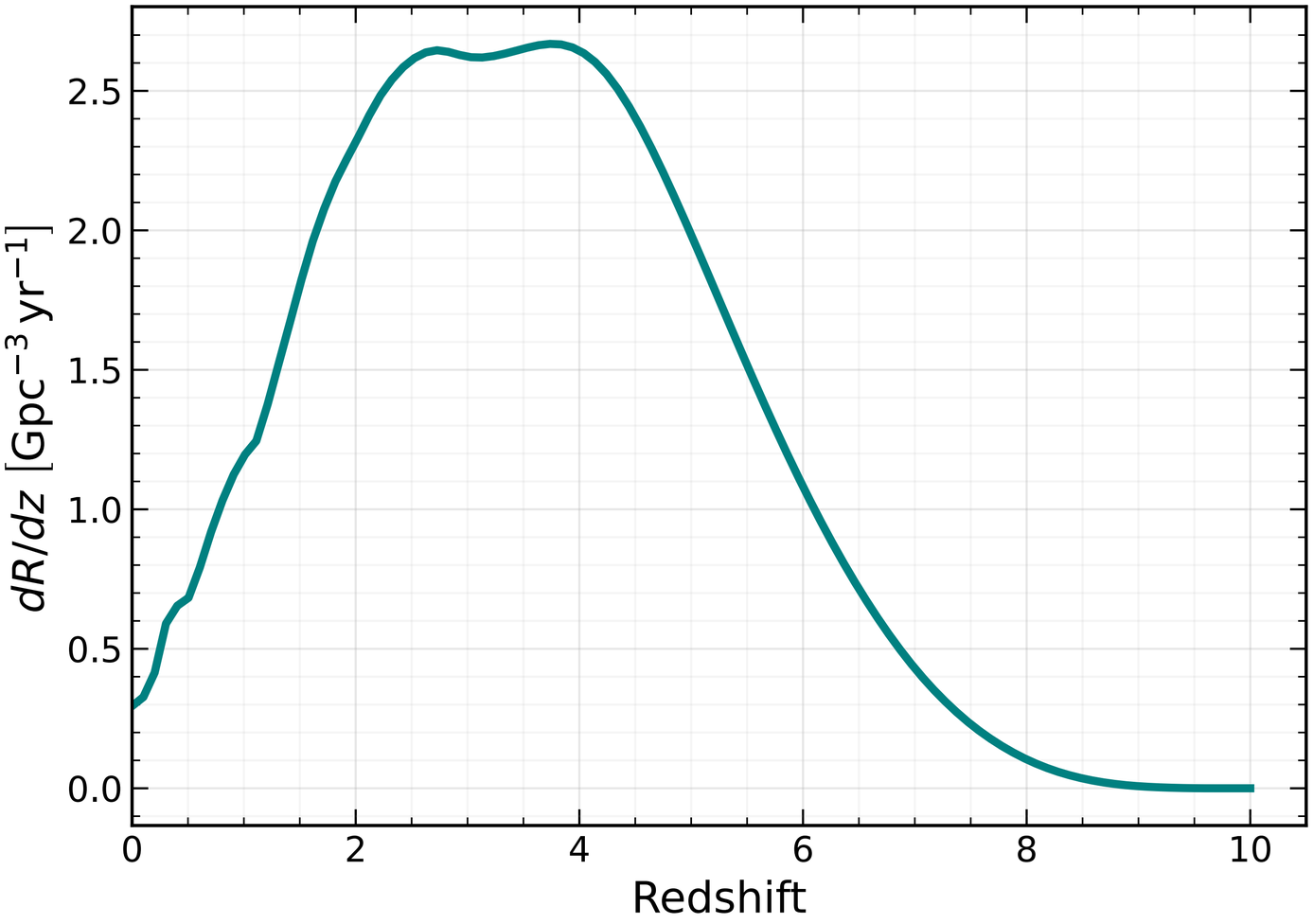
# Summary of methodology

# Summary of methodology

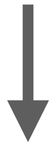


# Summary of methodology

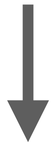
Dorozsmai et al. 2026 in prep.



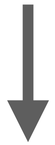
# Summary of methodology



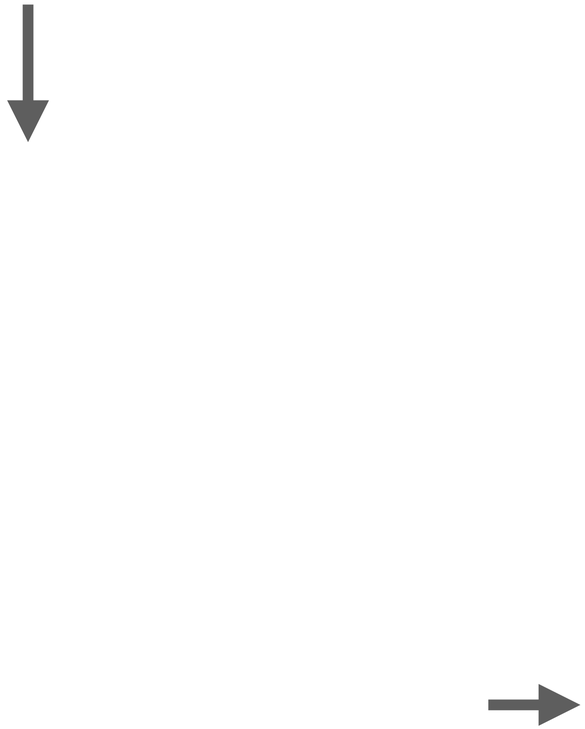
# Summary of methodology



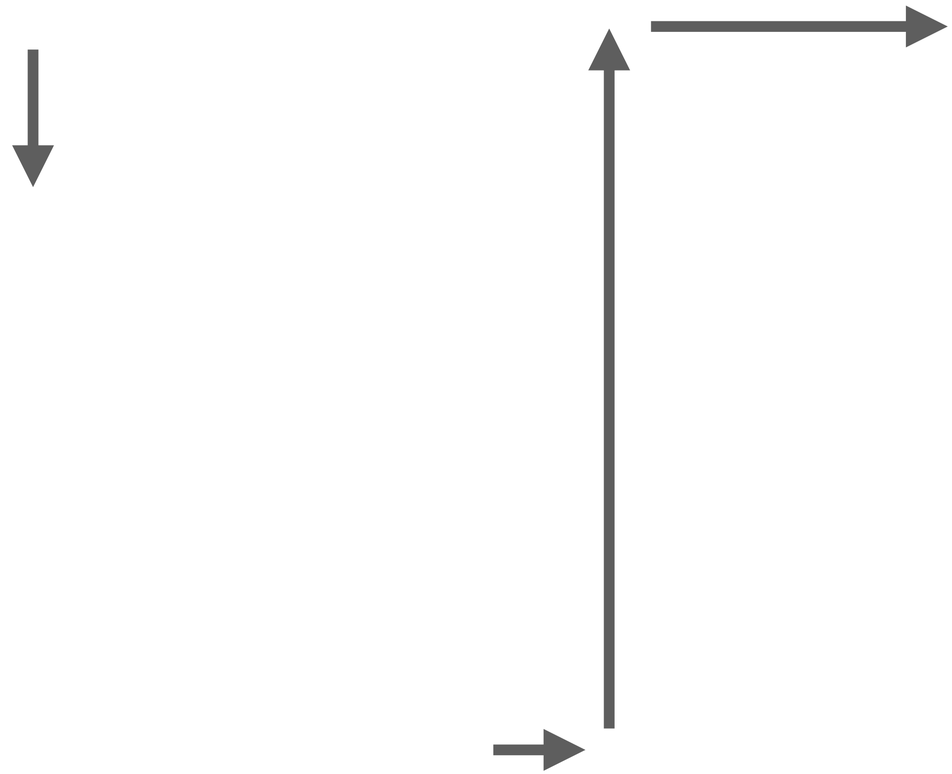
# Summary of methodology



# Summary of methodology

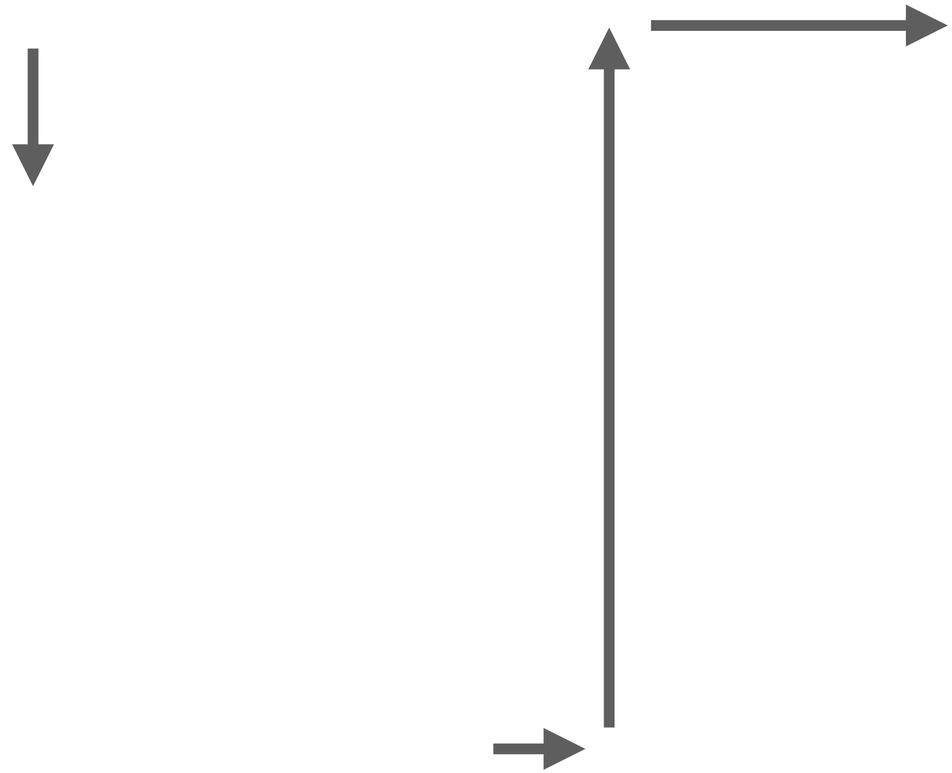


# Summary of methodology



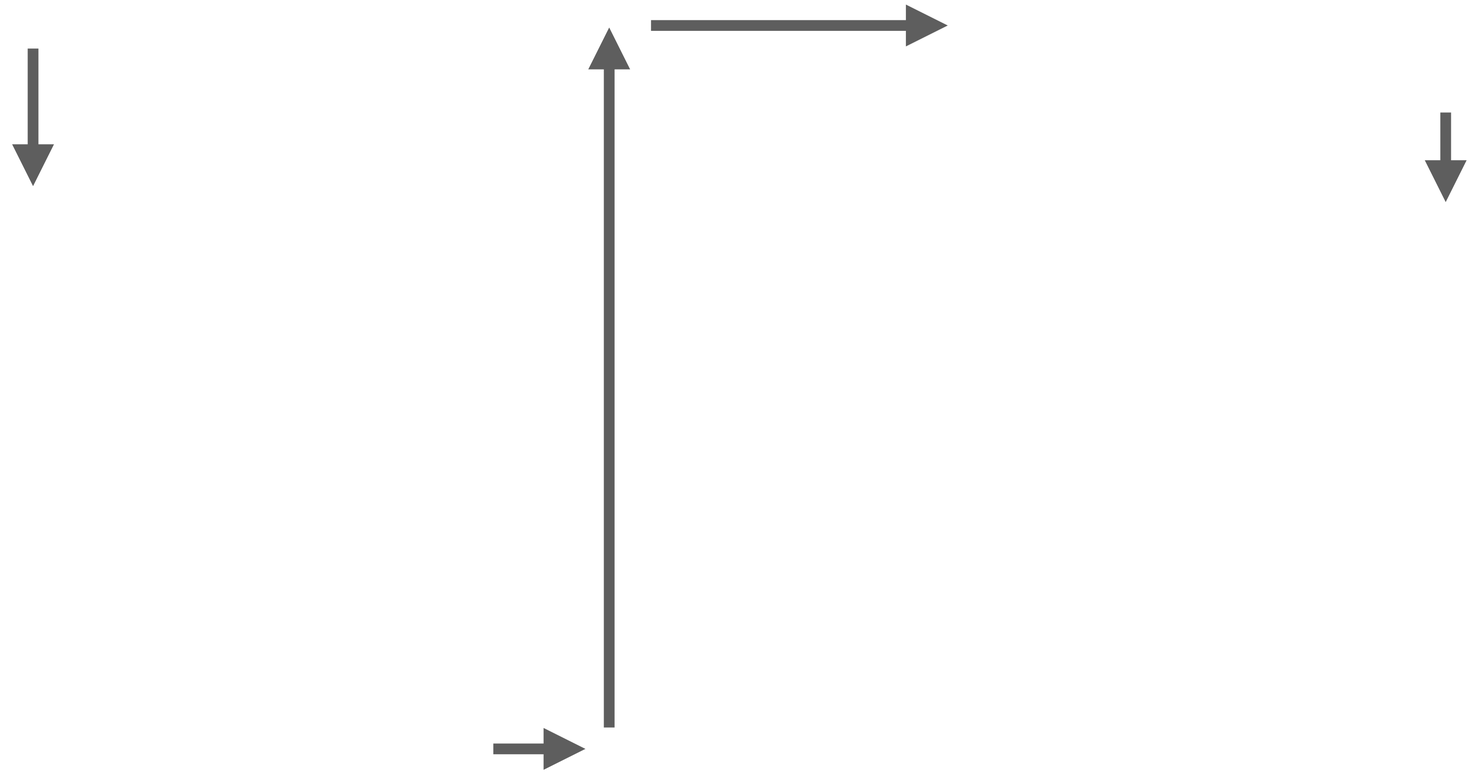
# Summary of methodology

*Mass dependent delay time distribution:*
*More massive BHs merge faster:*
- *Shorter mass segregation timescale*
- *Larger cross section*



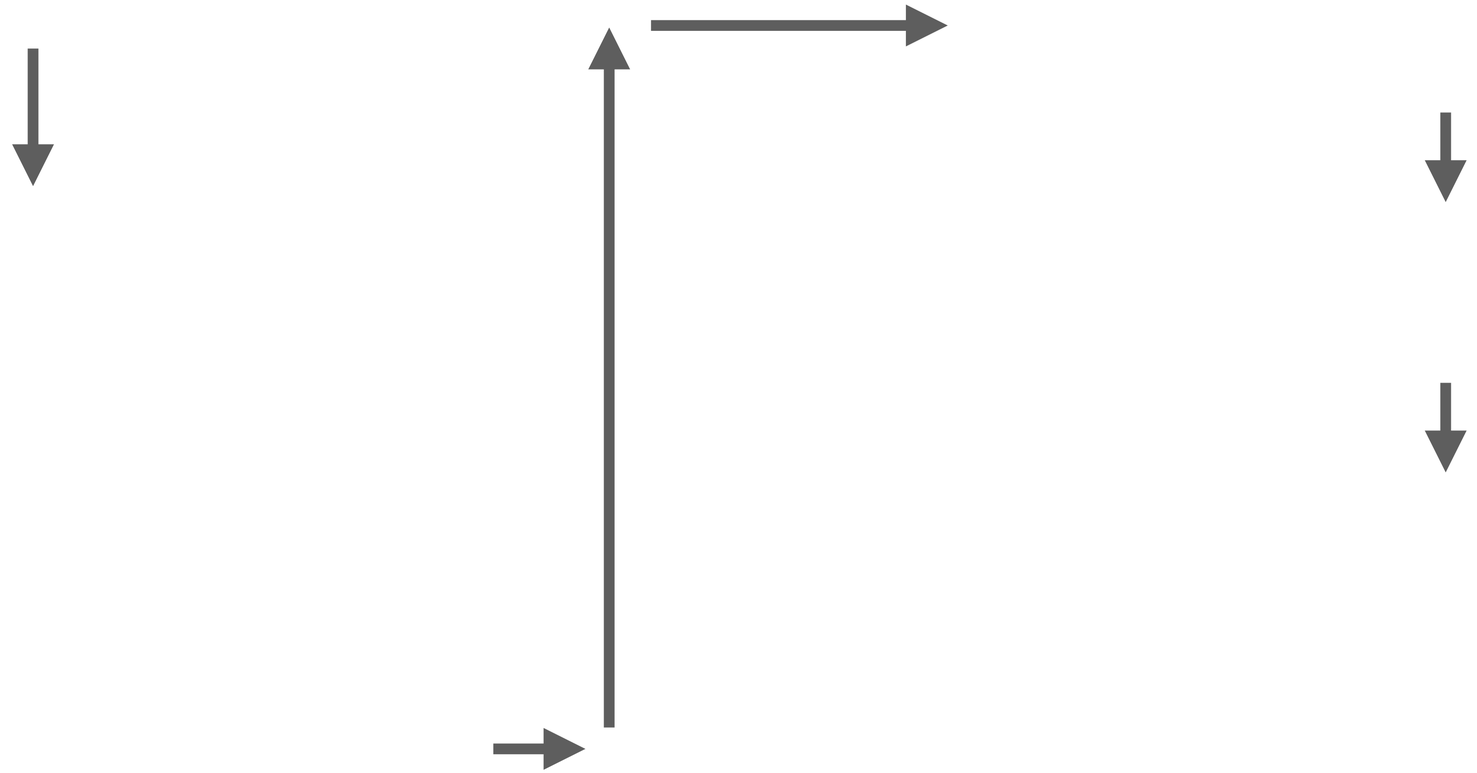
# Summary of methodology

*Mass dependent delay time distribution:*
*More massive BHs merge faster:*
- *Shorter mass segregation timescale*
- *Larger cross section*



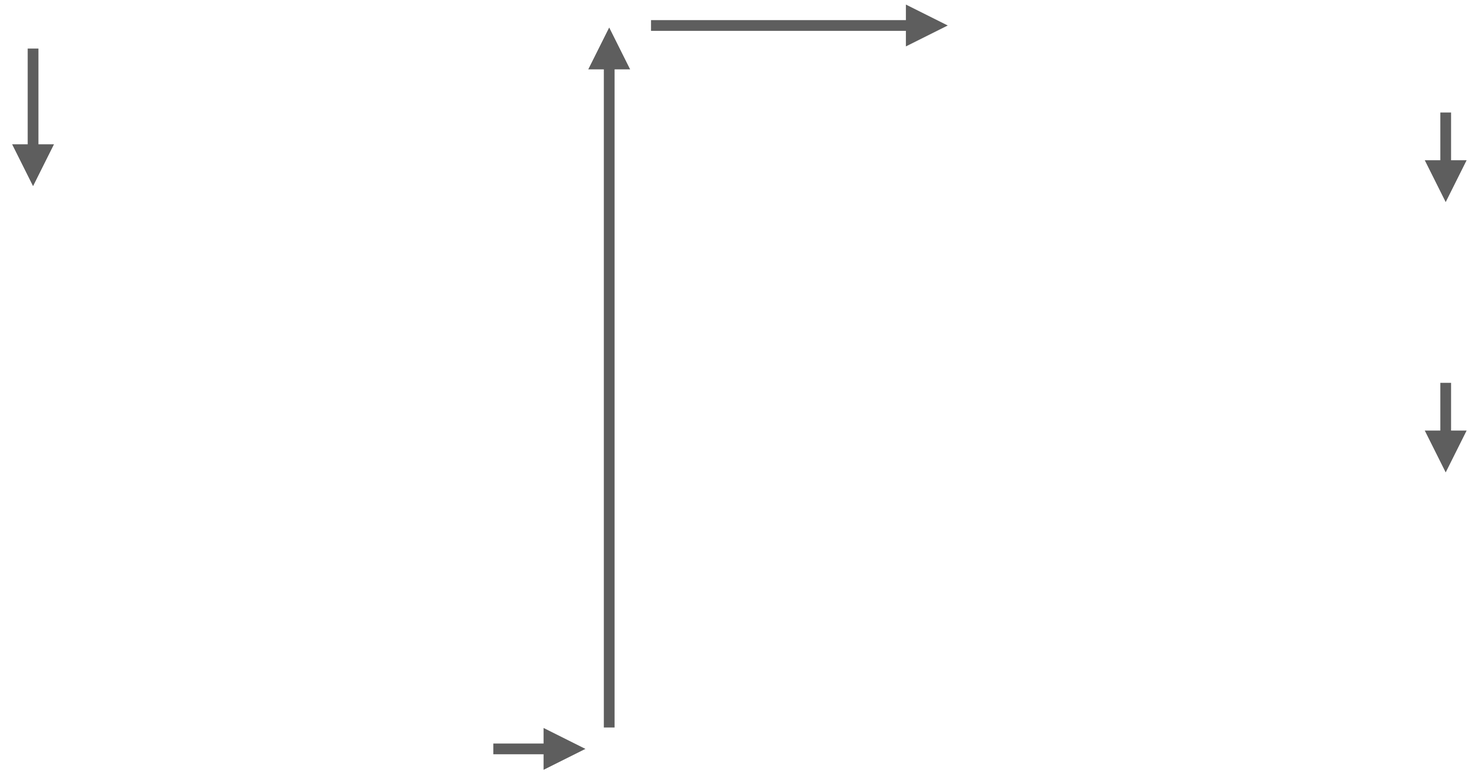
# Summary of methodology

*Mass dependent delay time distribution:*
*More massive BHs merge faster:*
- *Shorter mass segregation timescale*
- *Larger cross section*



# Summary of methodology

*Mass dependent delay time distribution:*
*More massive BHs merge faster:*
- *Shorter mass segregation timescale*
- *Larger cross section*



*This requires to estimate GC evaporation => compare CIMF/GCMF*
*Uncertain, normalisation introduces ~ order of magnitude uncertainty*

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history.

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history.

This is essentially just based on Bayes' theorem

$$p(\theta \mid d) = \frac{p(\theta) p(d \mid \theta))}{p(d)}$$

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history.

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history

- $dN/dtd\lambda$ is detection rate, so dR/dz = $dN/dtd\lambda$ * (1 + z) * dV/dz

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history

- $dN/dtd\lambda$ is detection rate, so dR/dz = $dN/dtd\lambda$ * (1 + z) * dV/dz
- Within the likelihood model dR/dz is expressed as a function of delay time + GC formation history => we thus directly infer GC formation history.

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history

- $dN/dtd\lambda$ is detection rate, so dR/dz = $dN/dtd\lambda$ * (1 + z) * dV/dz
- Within the likelihood model dR/dz is expressed as a function of delay time + GC formation history => we thus directly infer GC formation history.
- Use MCMC sampling.

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history

What is our prior assumption about GC formation history?

- Non-parametric inference: Gaussian process.
- No fixed functional form, only the prior that the function is smooth and nearby points are similar, while distant points can be different.

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history

What is our prior assumption about GC formation history?

- Non-parametric inference: Gaussian process.
- No fixed functional form, only the prior that the function is smooth and nearby points are similar, while distant points can be different.
- i.e. points in the function can be regarded as a sample from a MVN distribution, with a correlation function that predicts high correlation with close points and low with distant ones.

# Hierarchical Bayesian Inference

We infer the GC formation rate using a hierarchical Bayesian framework, i.e.:

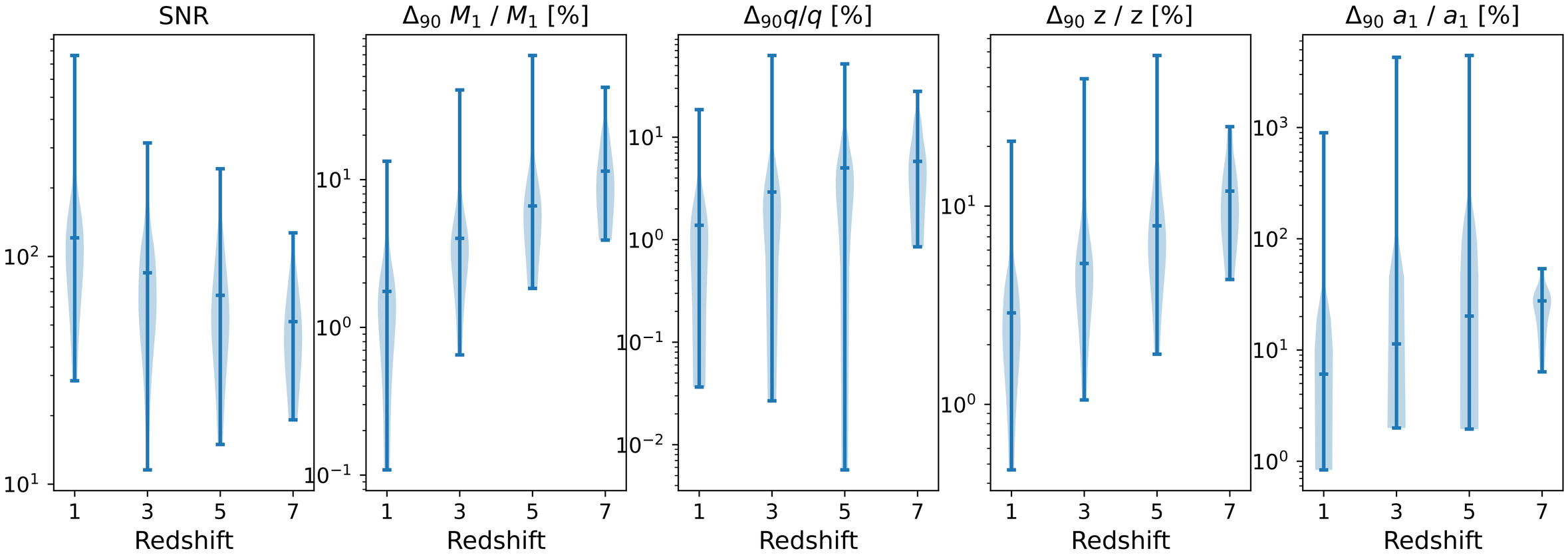
$$p\left(\Lambda \mid \{d_i\}\right) \sim \pi(\Lambda)\, e^{N_{\rm exp}(\Lambda)} \prod_{i=1}^{N_{\rm obs}} \left\langle \frac{1}{\pi_{\rm event}(\lambda)} \frac{dN}{d\lambda\, dt} \right\rangle_{\rm PS}$$

- $\lambda$: binary parameters, $\Lambda$: hyperparameters: essentially this describes the GC formation history

What is our prior assumption about GC formation history?

- Non-parametric inference: Gaussian process.
- No fixed functional form, only the prior that the function is smooth and nearby points are similar, while distant points can be different.
- i.e. points in the function can be regarded as a sample from a MVN distribution, with a correlation function that predicts high correlation with close points and low with distant ones.
- Why? this allows flexibility so essentially any shape can be inferred as long as we have enough data with sufficiently small uncertainties.

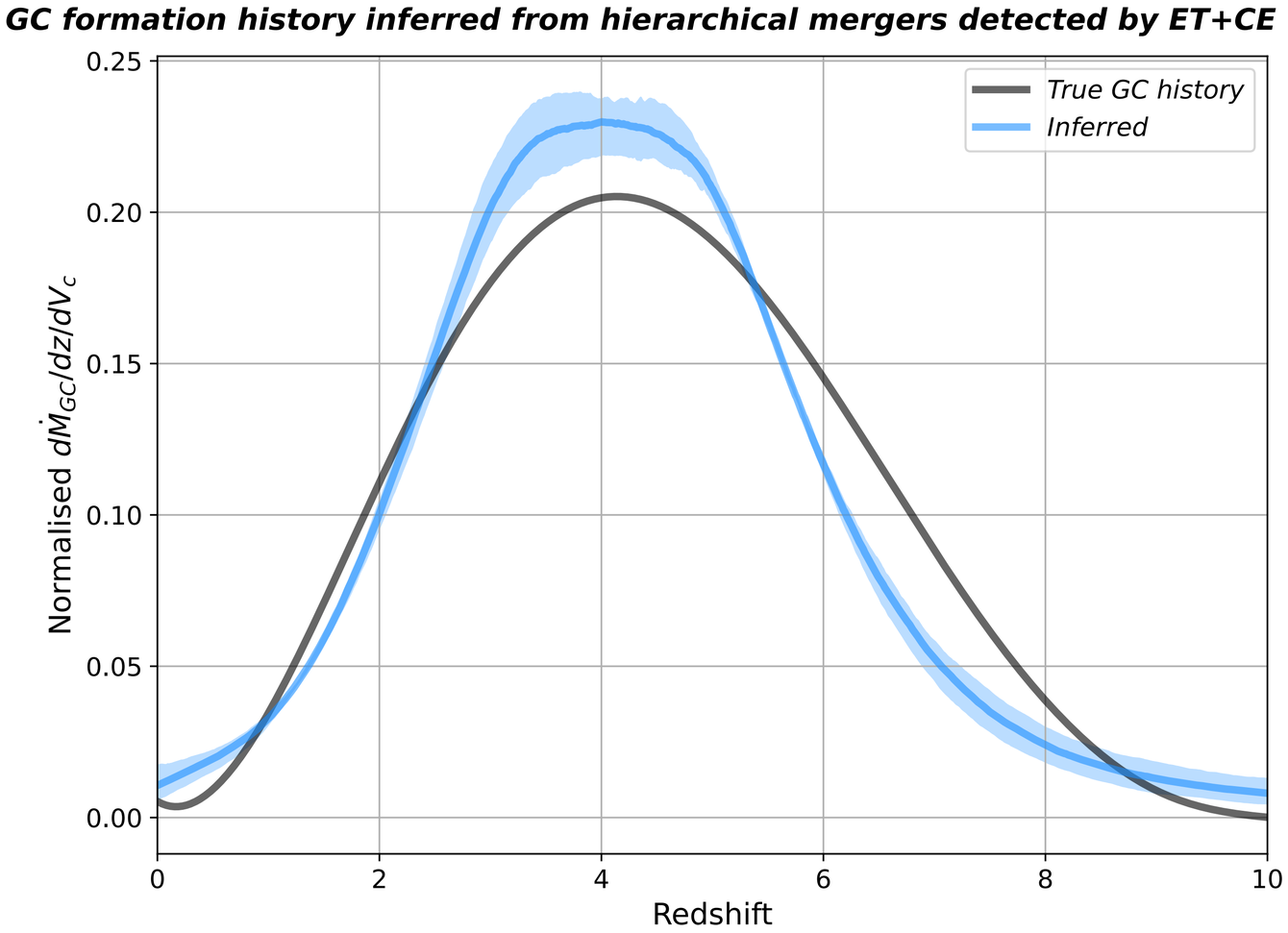
# Predicted uncertainties of detected GW events




Dorozsmai et al. 2026 in prep.

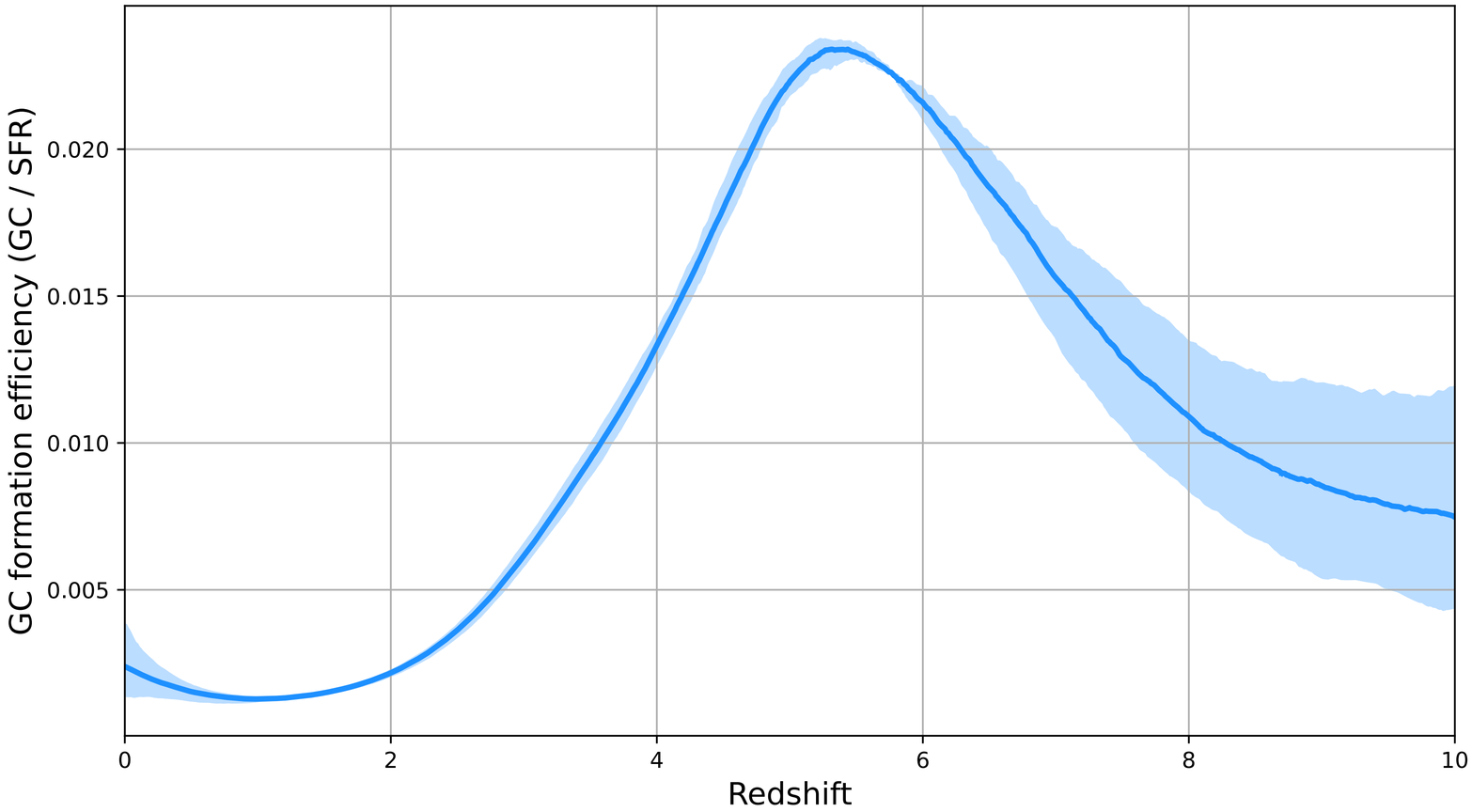
# The recovered cluster formation history

- The shape of the cluster history is broadly recovered.
- Up to z ~ 2 excellent agreement .
- Systematic error due to delay time model dominates.
- Credible intervals are narrow but not very informative.
- Very good results for relative rate, normalisation introduces ~order of magnitude uncertainty.



# Cluster formation efficiency

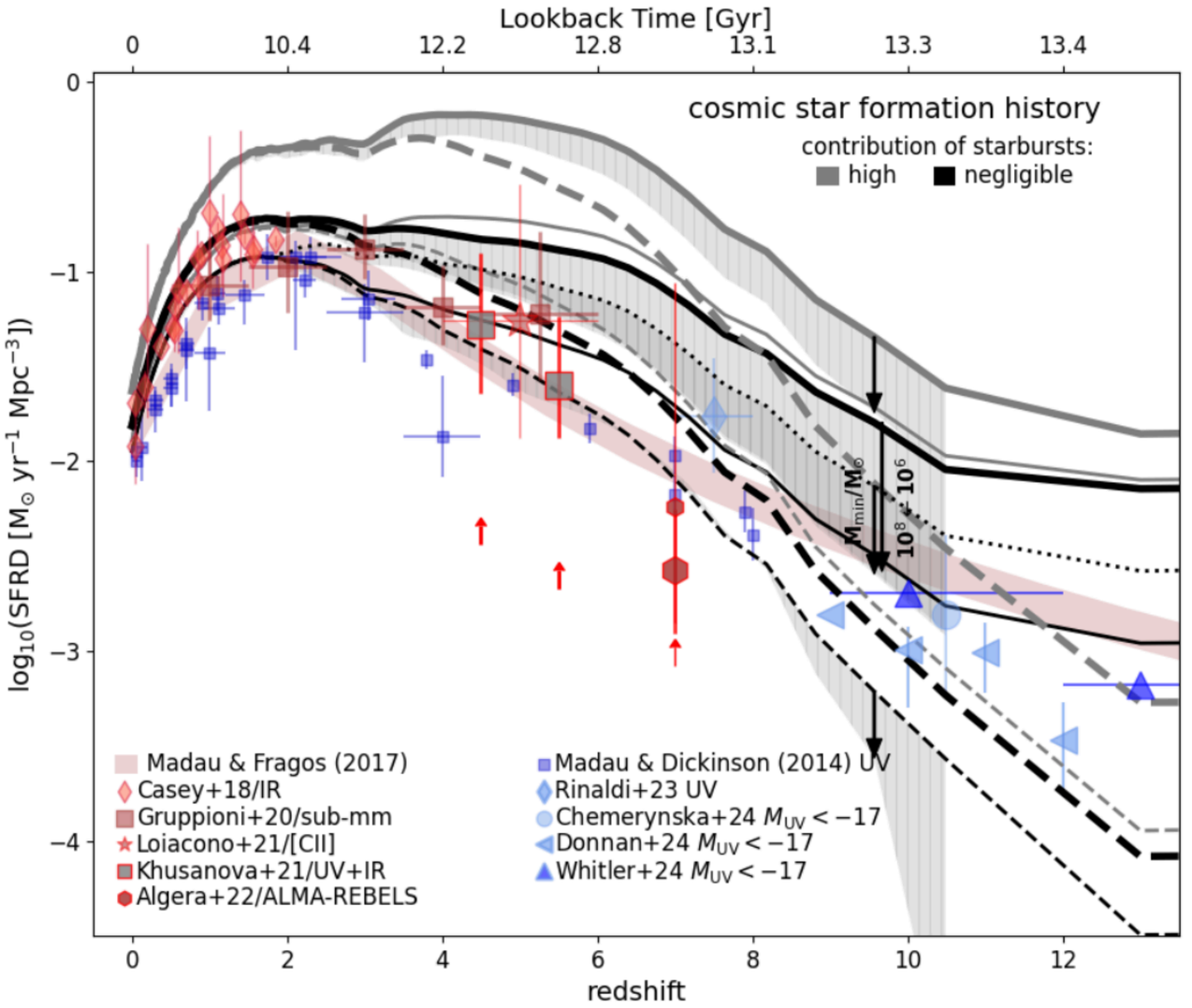
If one knows the total SFR, then one can use the inferred curve the determine the **cluster formation efficiency.**



# Cluster formation efficiency

If one knows the total SFR, then one can use the inferred curve the determine the **cluster formation efficiency.**

Note, that there's about an order of magnitude uncertainty in the total SFR, so our estimate is also an order of magnitude estimate




Chruslinska et al. 2026

# Conclusion

- The relative formation rate of clusters can be inferred to an unprecedented accuracy.
- The absolute rate requires determining the merger efficiency of BBHs per cluster formation. This likely introduces an order of magnitude uncertainty.
- Cluster formation efficiency can be determined to a 1-2 of magnitude accuracy.
- GW astronomy can uniquely help to infer information about cluster formation and high redshift stellar formation.
- Combining JWST/Euclid/ELT with GW detections will maximise science return.

# Thank you for your attention!