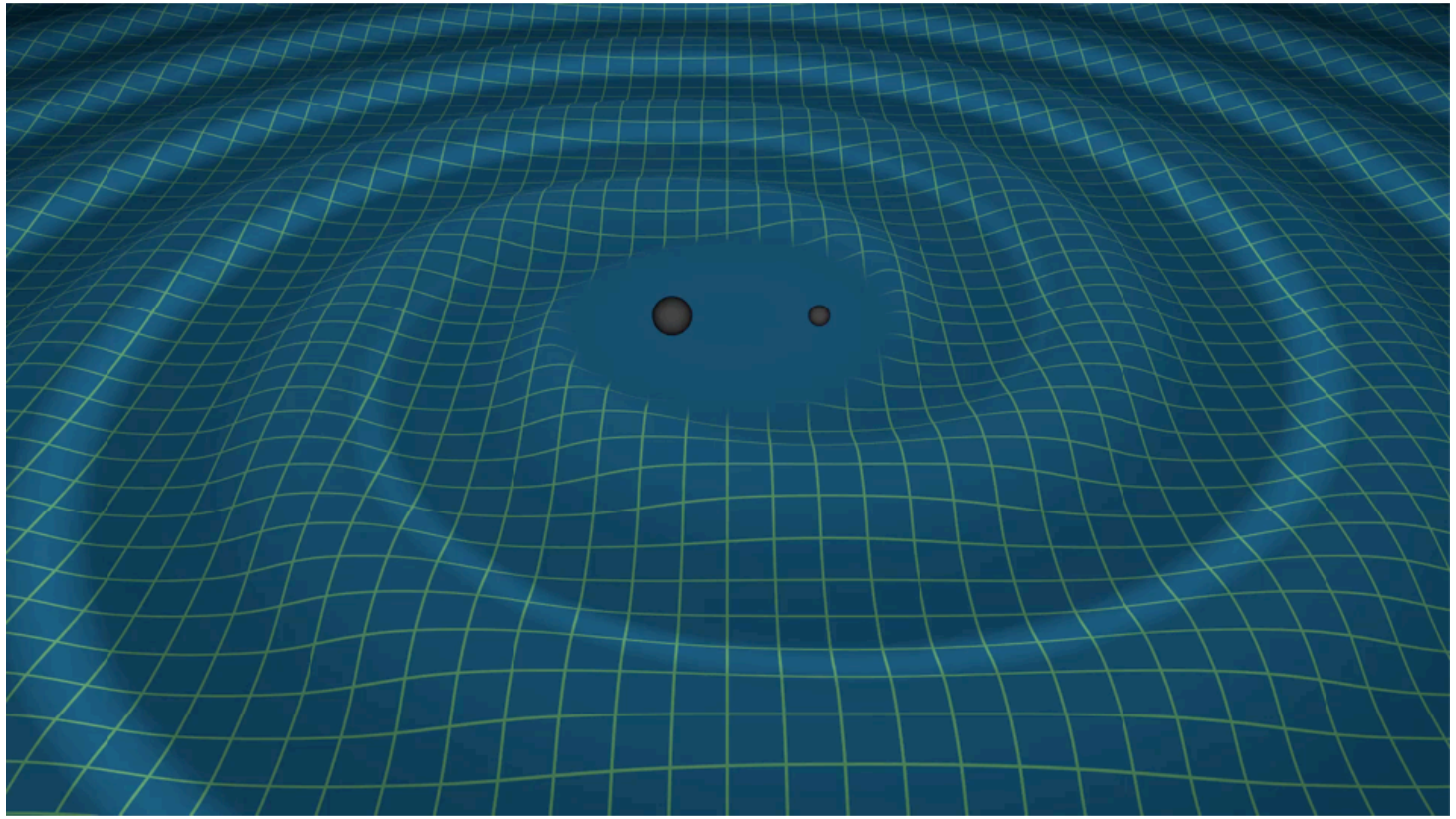
Listening to Black Holes with Gravitational Waves



Maya Fishbach (she/her)

fishbach@cita.utoronto.ca

KICP 20th Anniversary

June 8 2024

CITA | ICAT

Canadian Institute for Theoretical Astrophysics L'Institut Canadien d'astrophysique théorique

UNIVERSITY OF TORONTO

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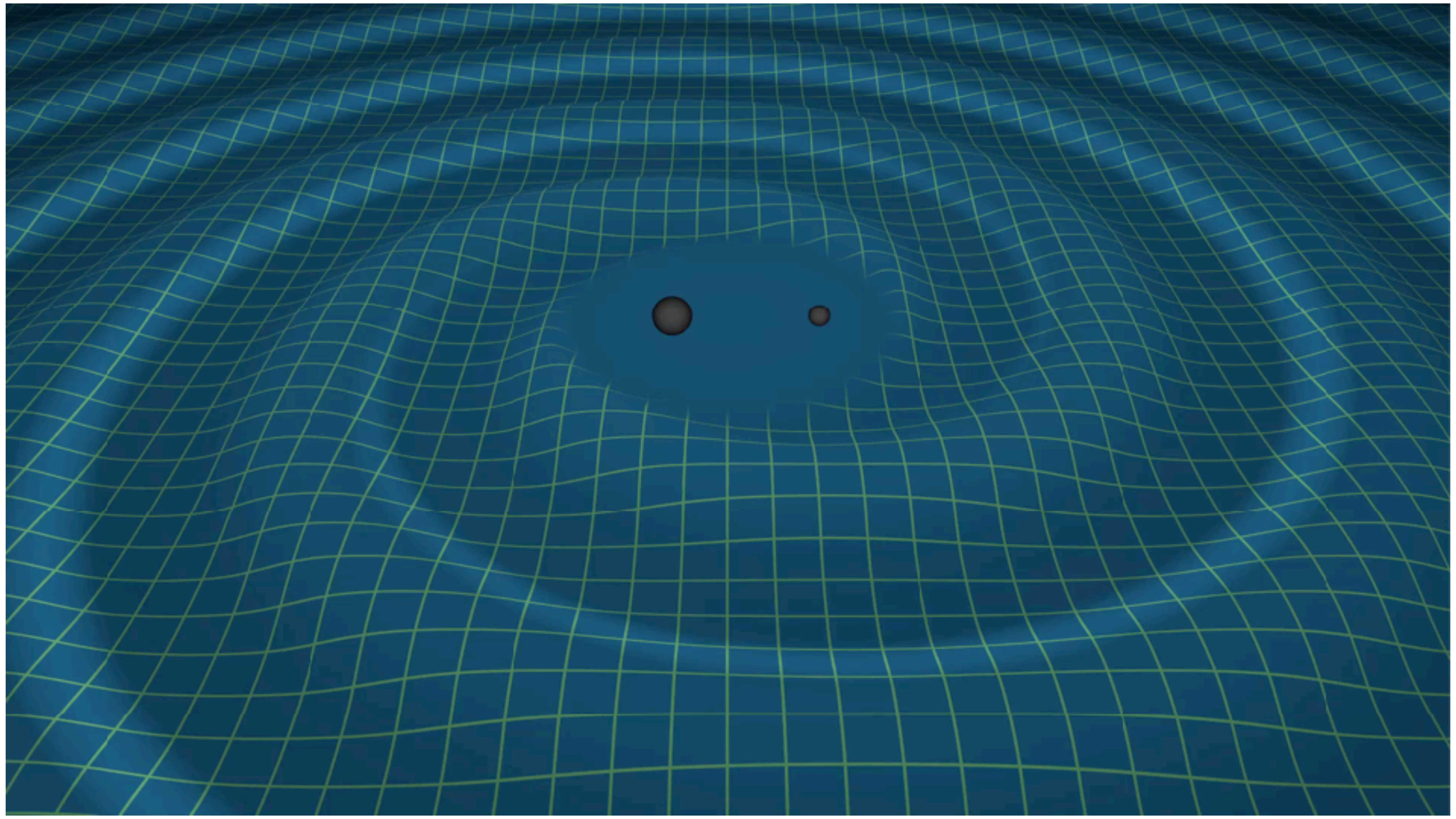

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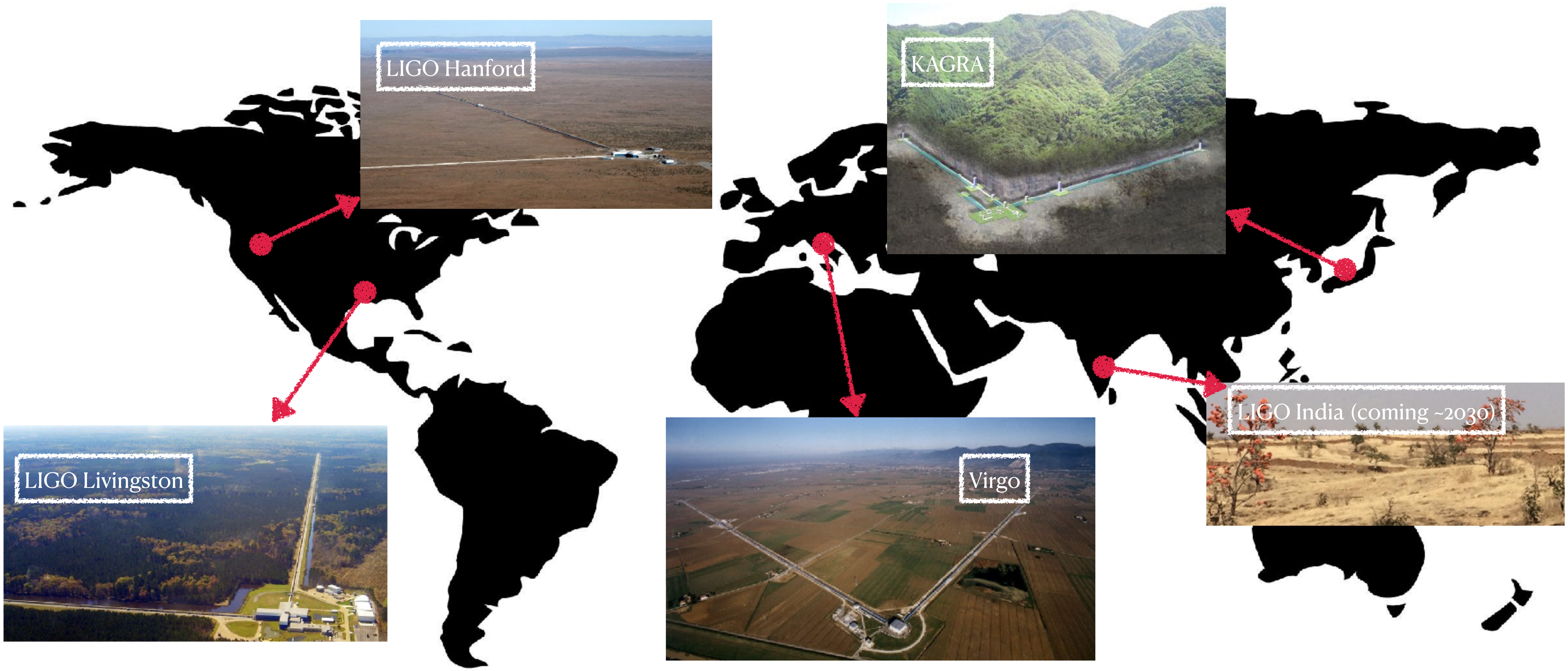
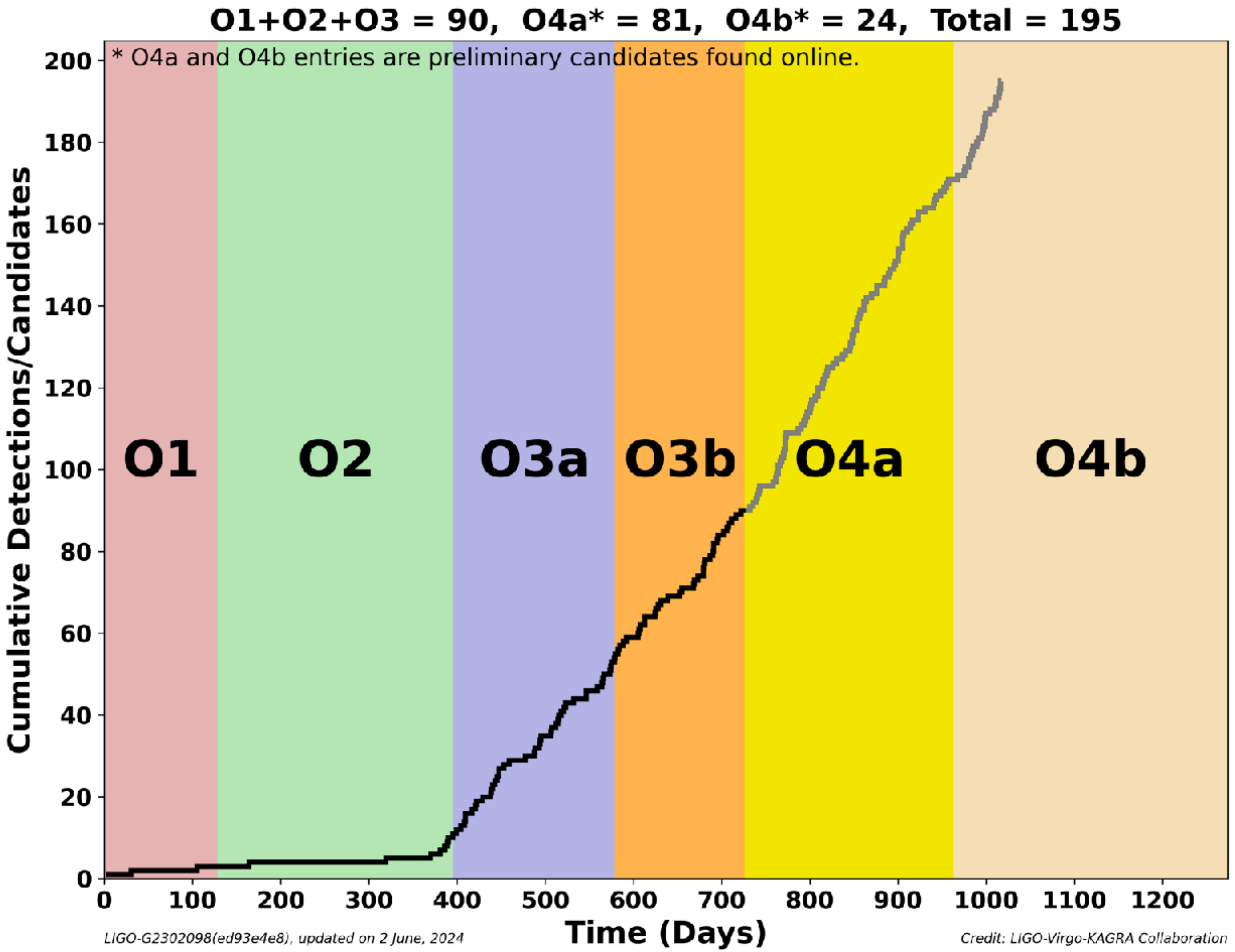
Gravitational-wave observatories




O1+O2+O3 = 90, O4a* = 81, O4b* = 24, Total = 195
* O4a and O4b entries are preliminary candidates found online.
O1
O2
O3a
O3b
O4a
O4b
Cumulative Detections/Candidates
Time (Days)
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
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700
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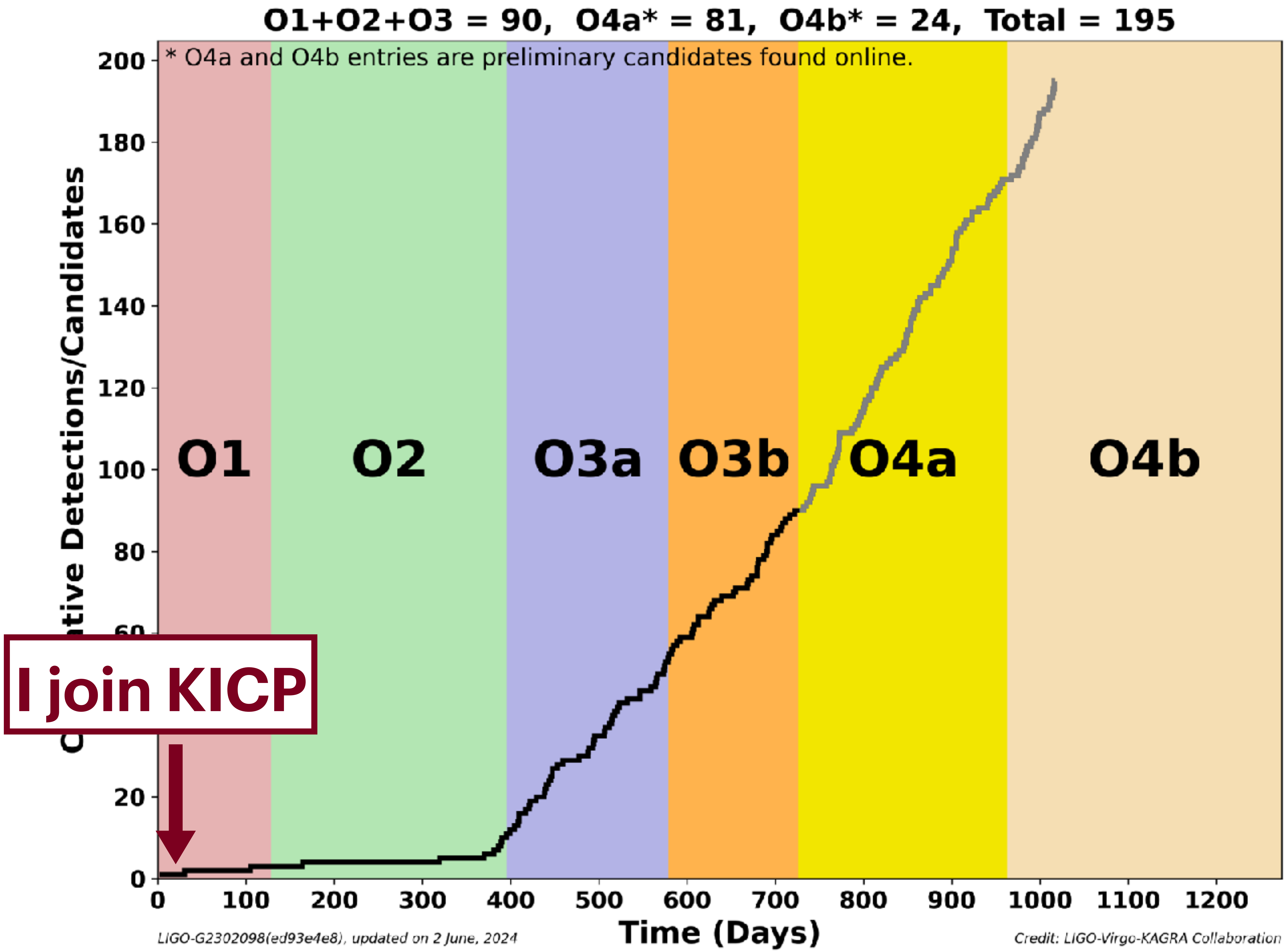
1100
1200
LIGO-G2302098(ed93e4e8), updated on 2 June, 2024
Credit: LIGO-Virgo-KAGRA Collaboration



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O2
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O4a
O4b
I join KICP
Time (Days)
LIGO-G2302098(ed93e4e8), updated on 2 June, 2024
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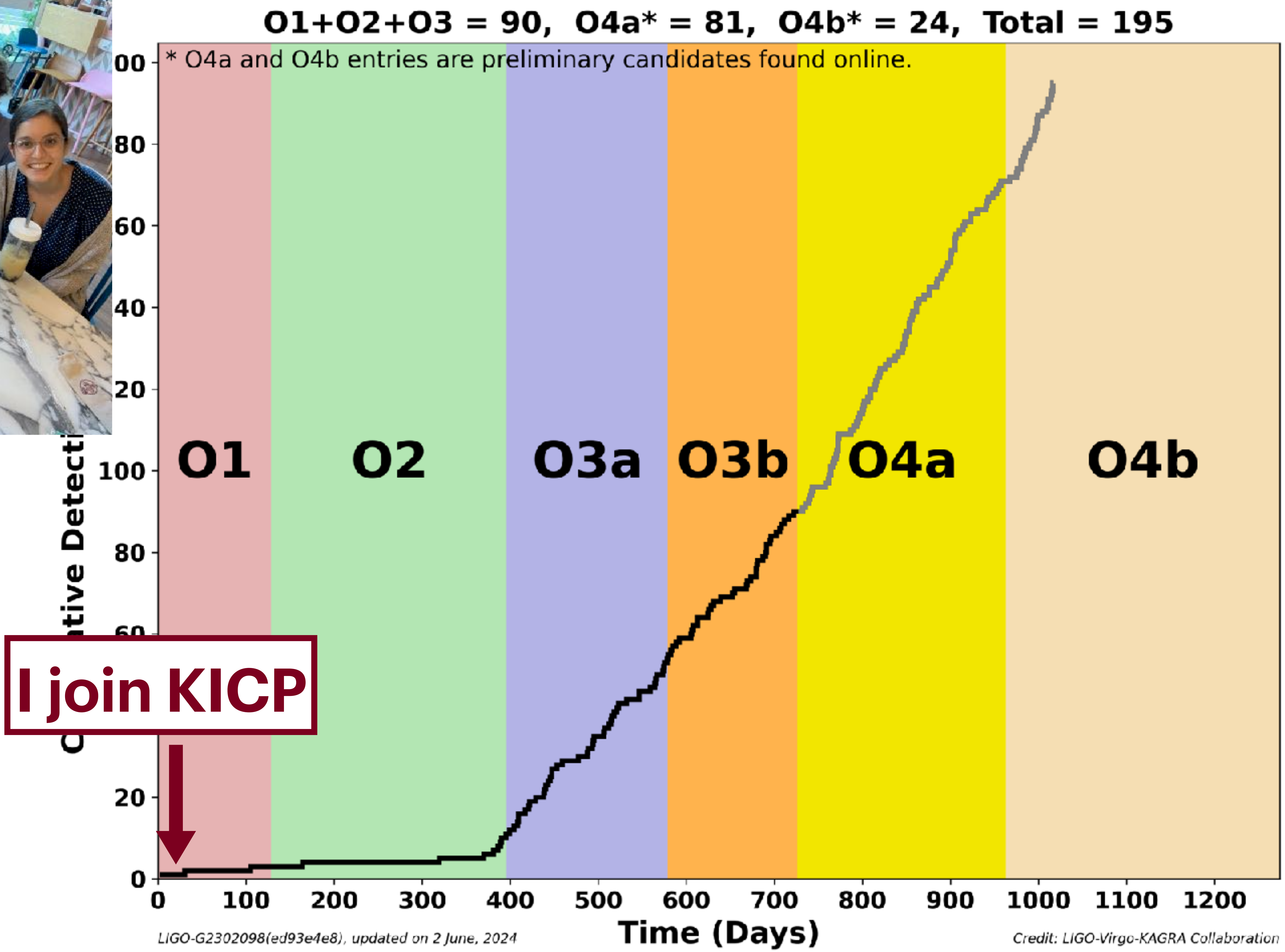

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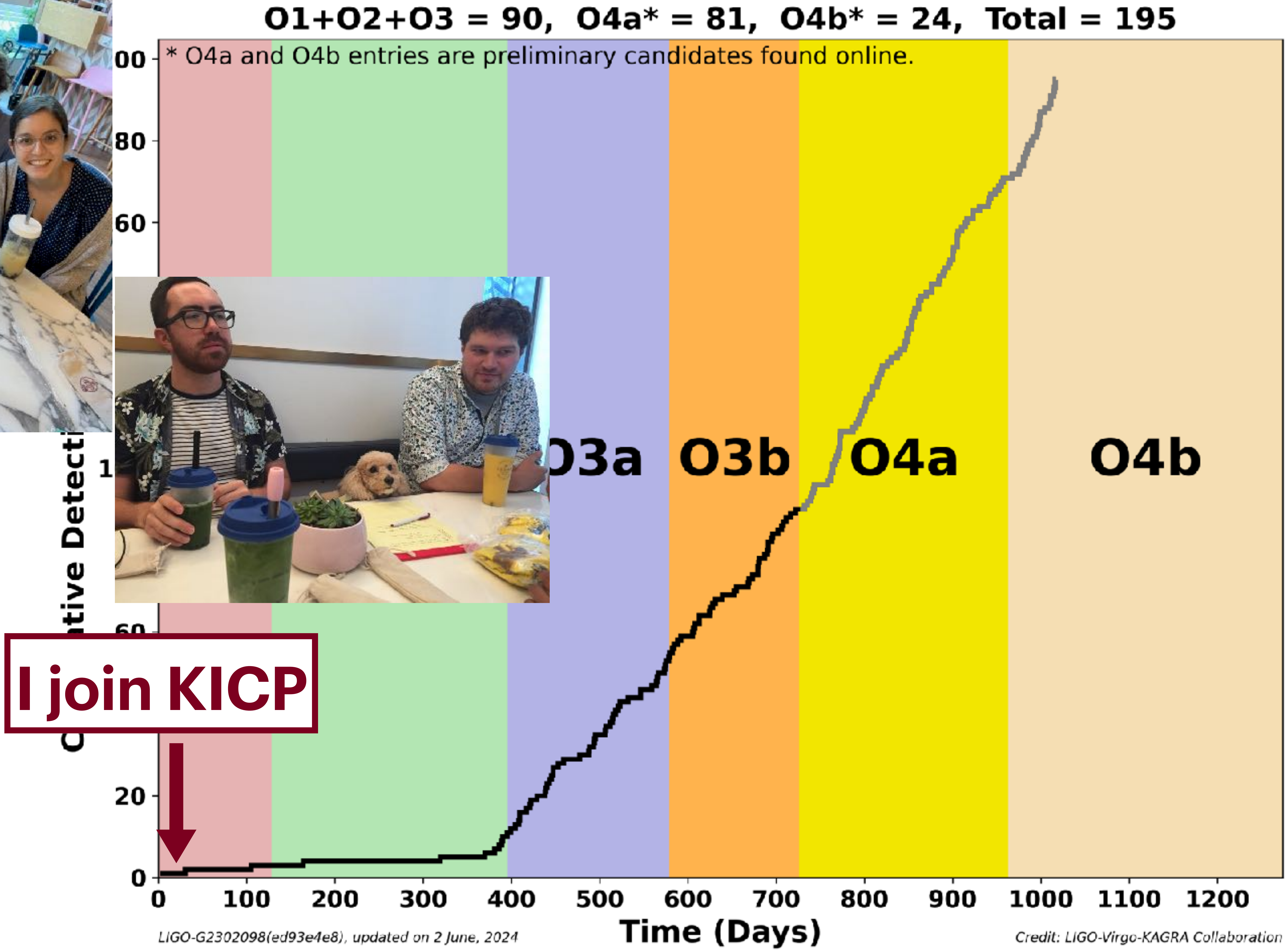

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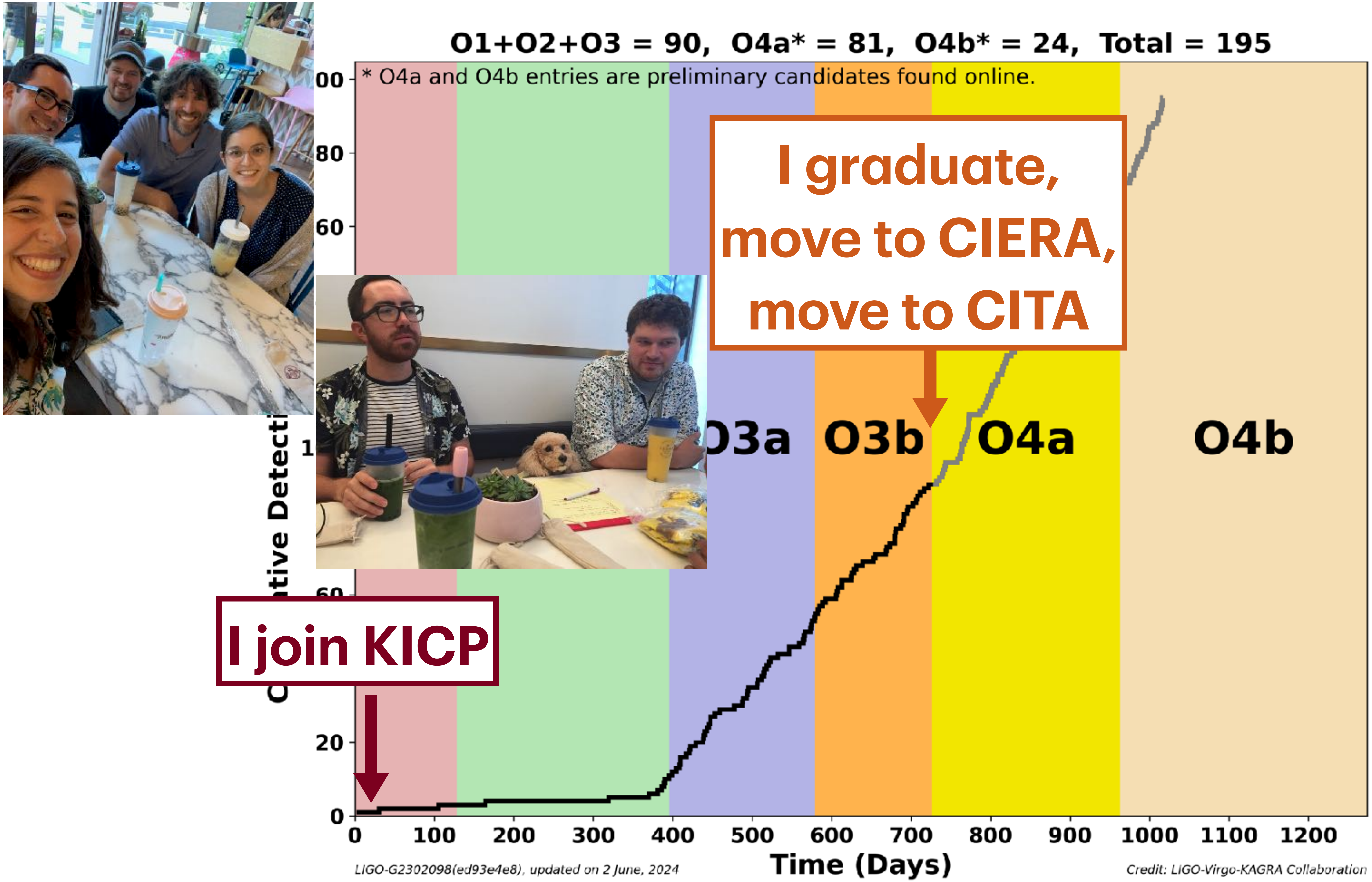
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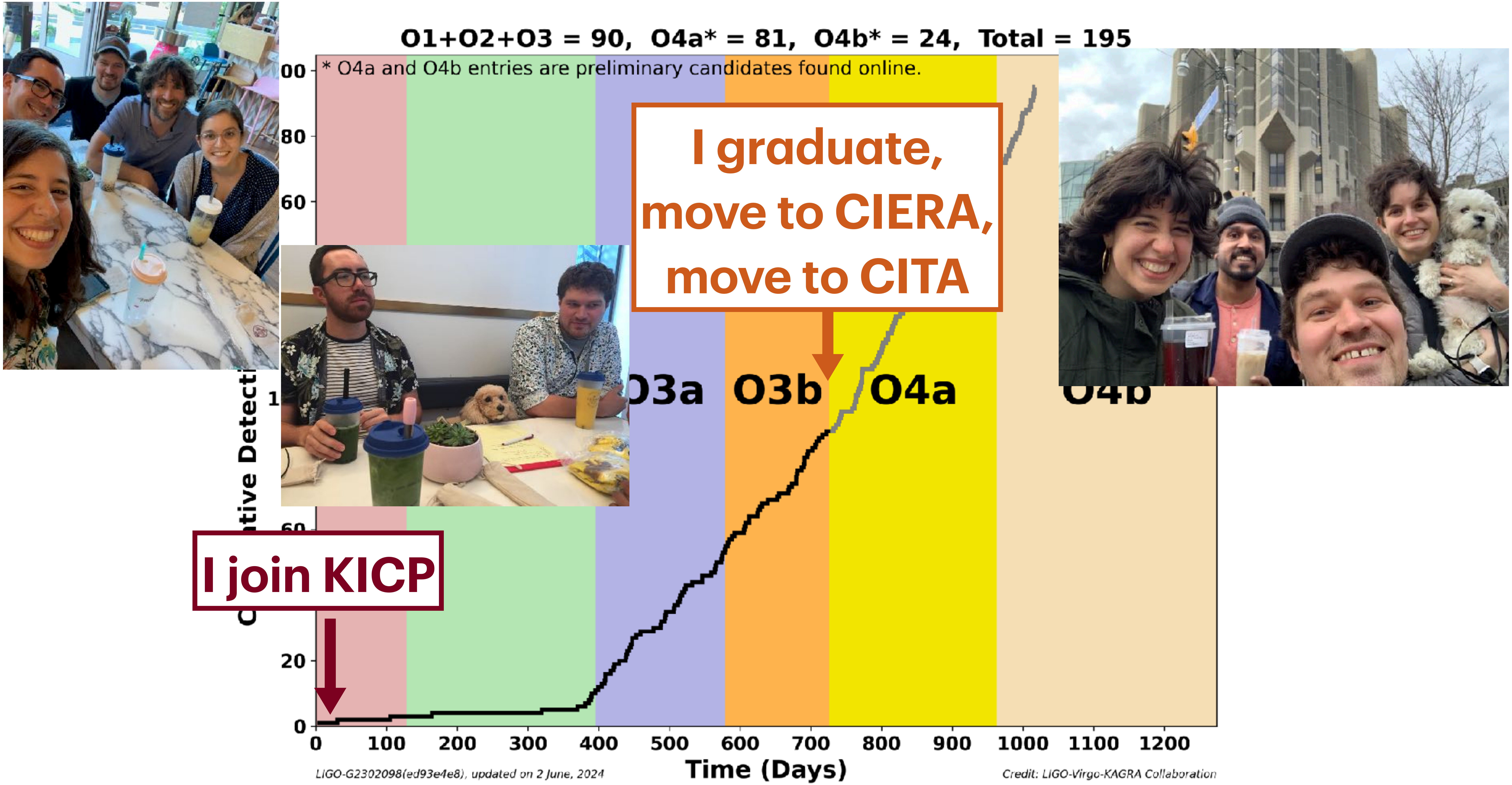
Credit: LIGO-Virgo-KAGRA Collaboration
I graduate,
move to CIERA,
move to CITA
I join KICP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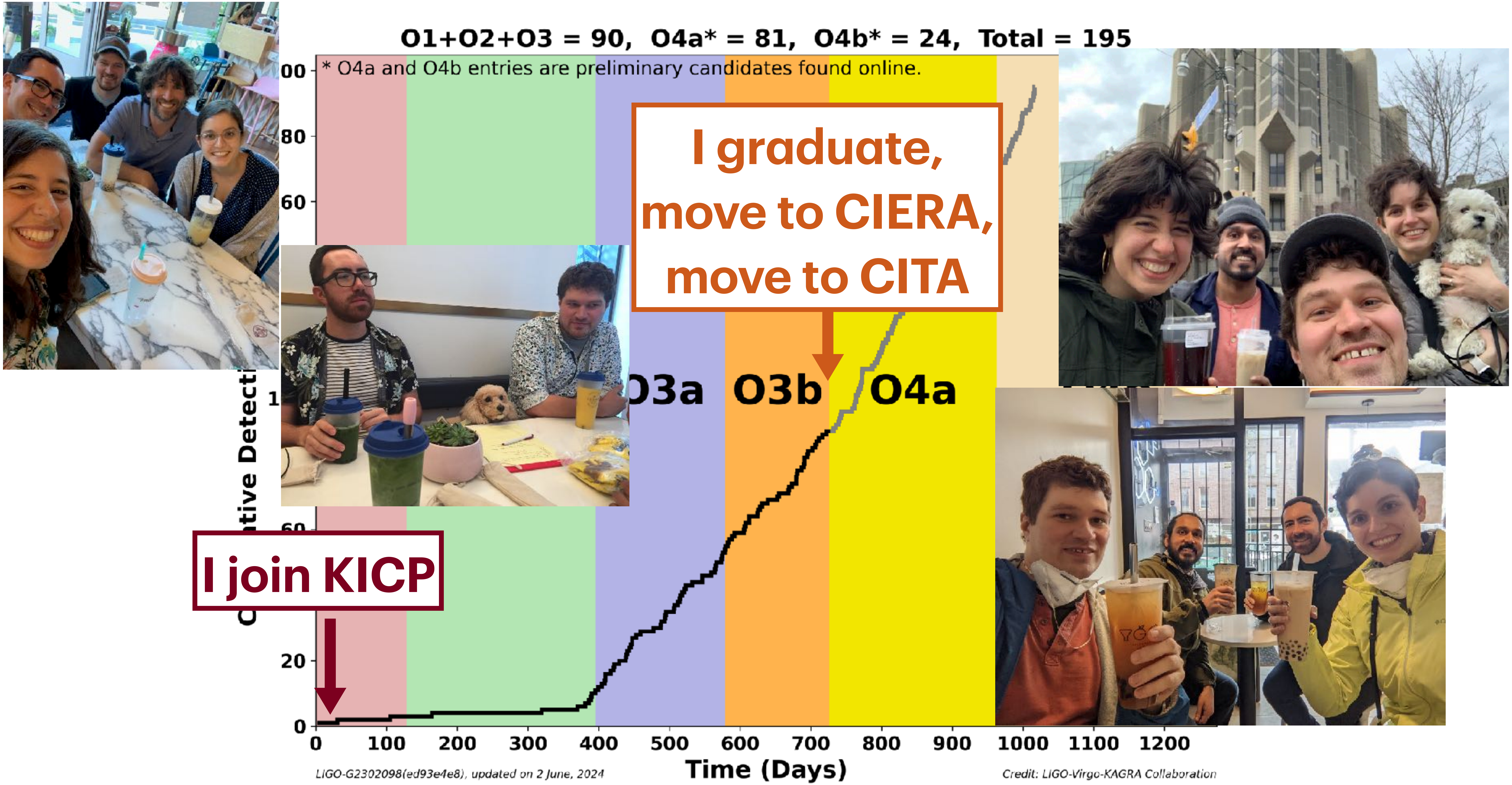
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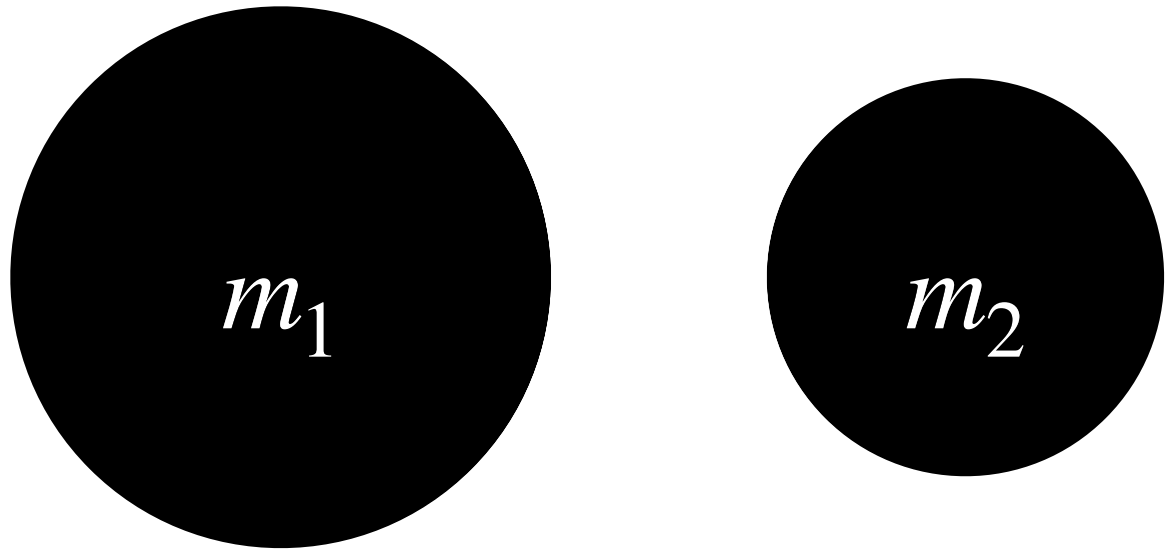
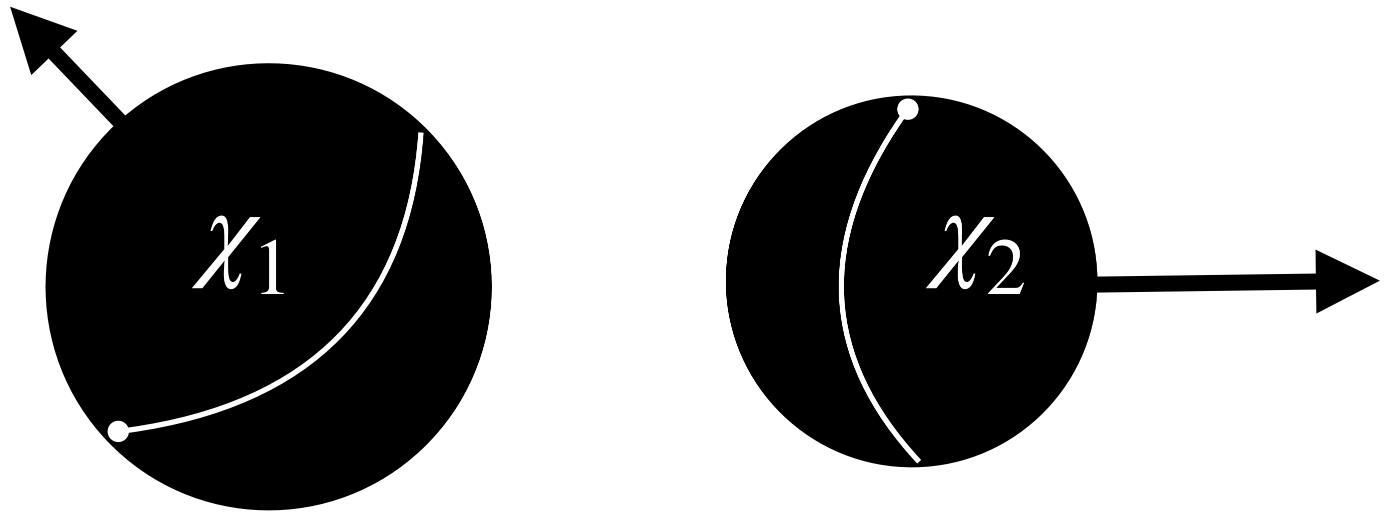
Masses in the Stellar Graveyard

Observing Binary Black Holes

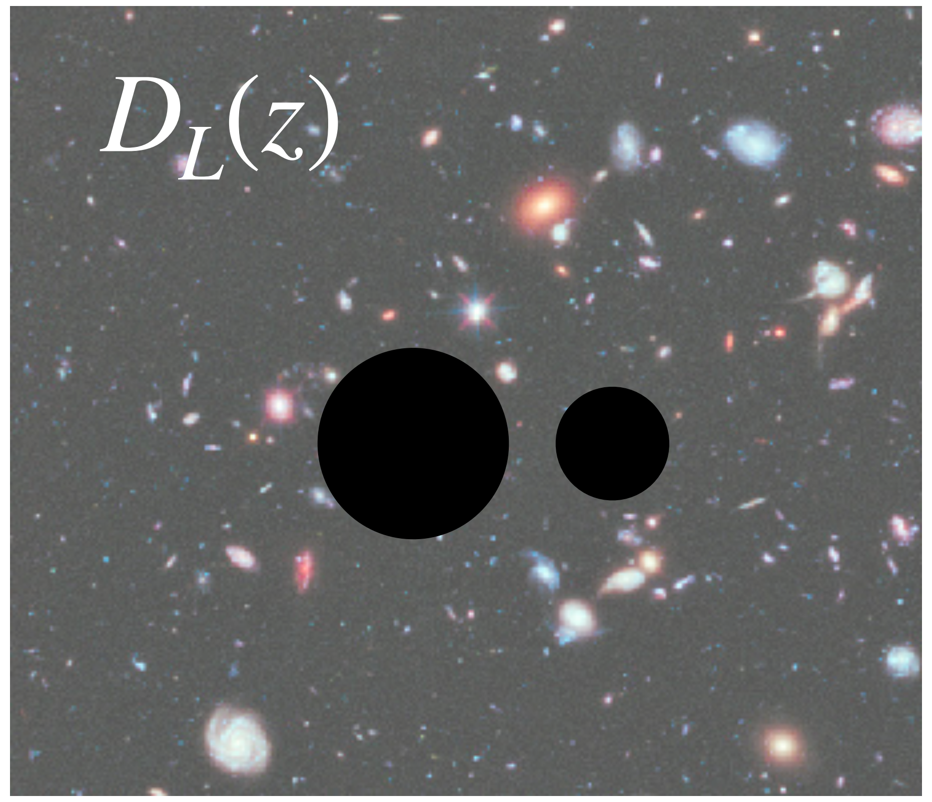
How *big* is each black hole?



How fast are they *spinning*? Where are the spin axes pointing?

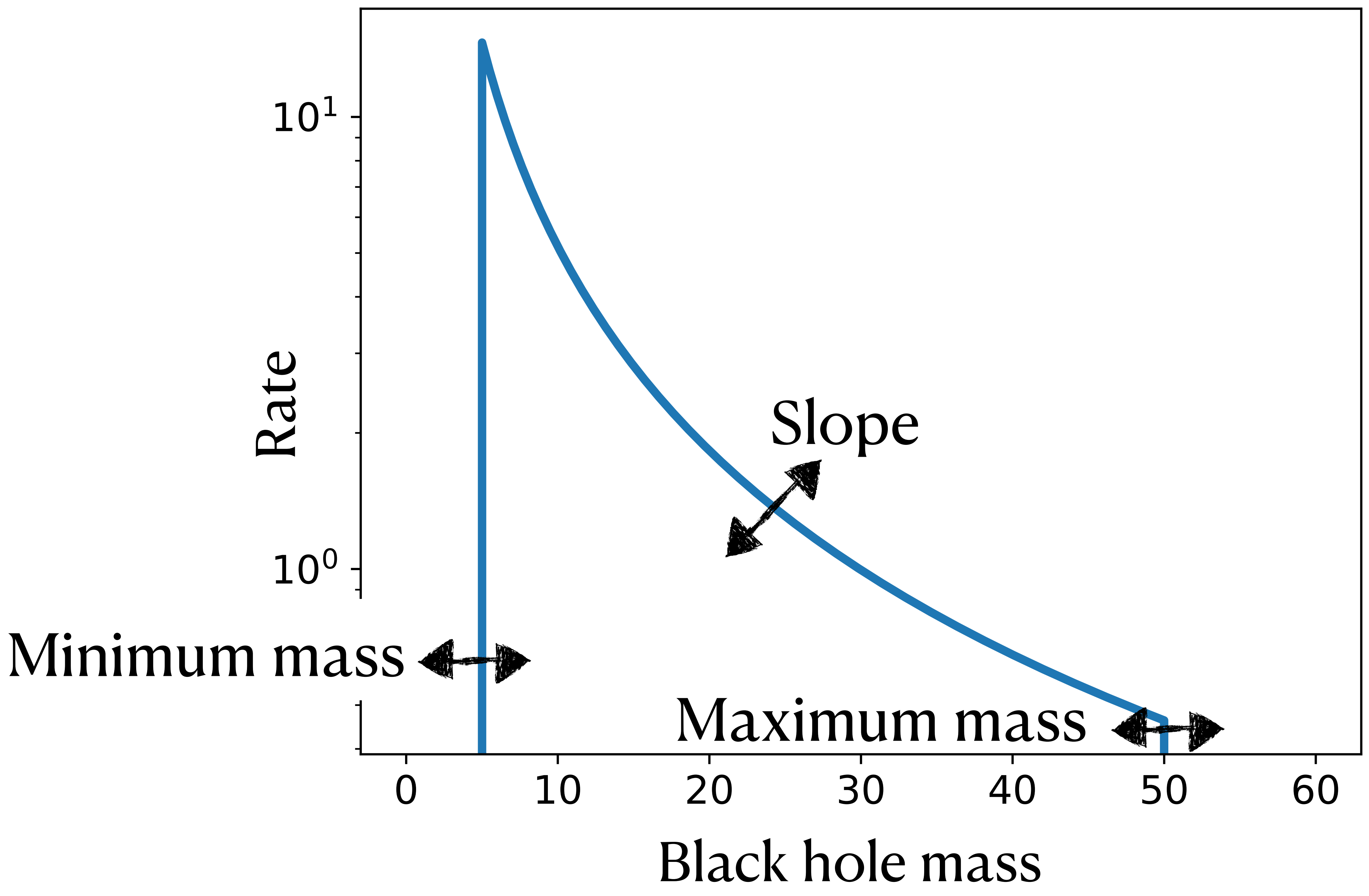


How *far away* and *long ago* did they merge?



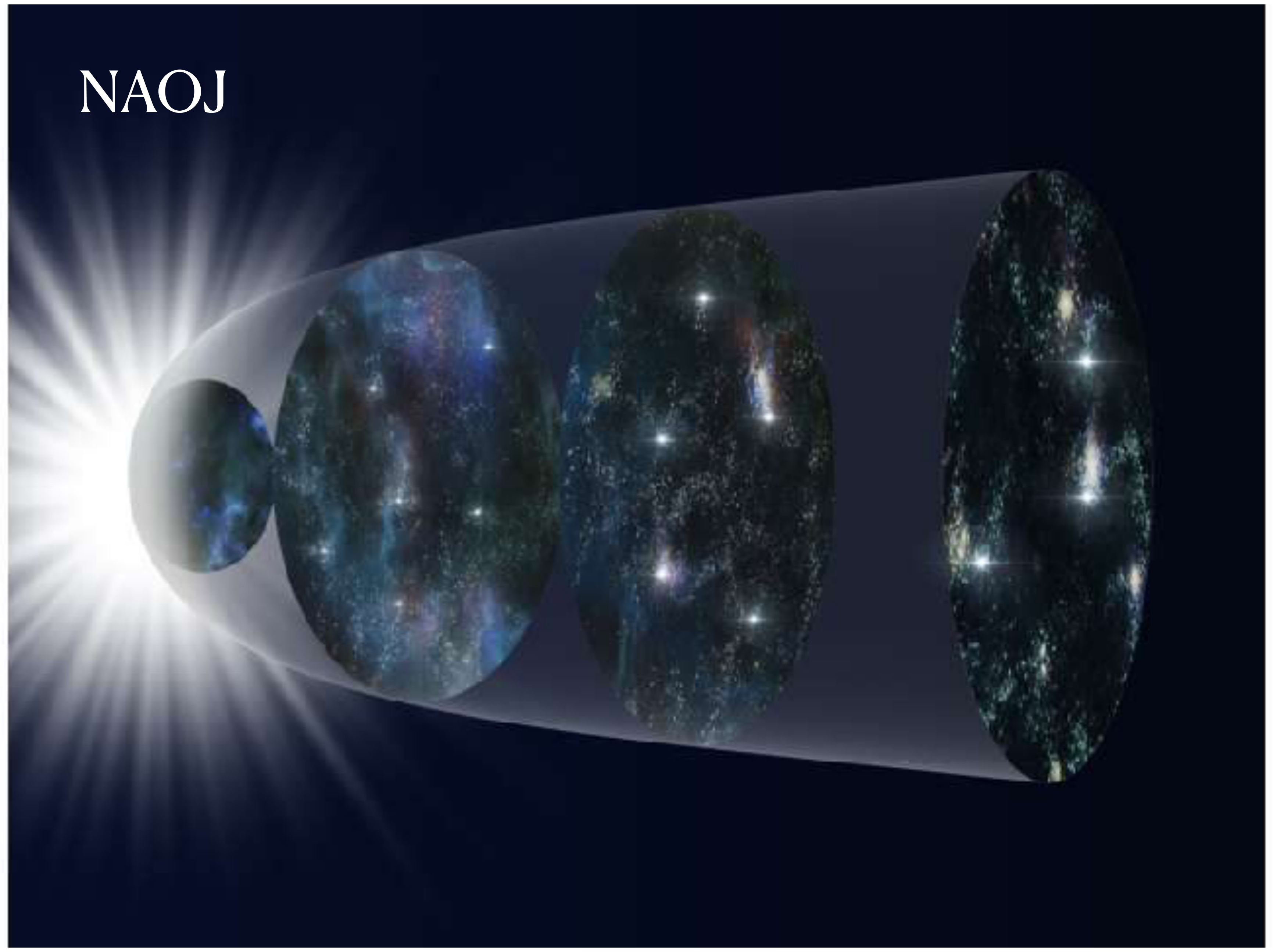
From Single Events to a Population: Hierarchical Bayesian Inference

- Introduce a population model that describes the **distributions** of masses, spins, redshifts across **multiple events**.
- Example: Fit a power law to black hole masses.
- Take into account **measurement uncertainty** and **selection effects**.
    - Don't just fit the "detected distribution!" (Essick & MF 2024)

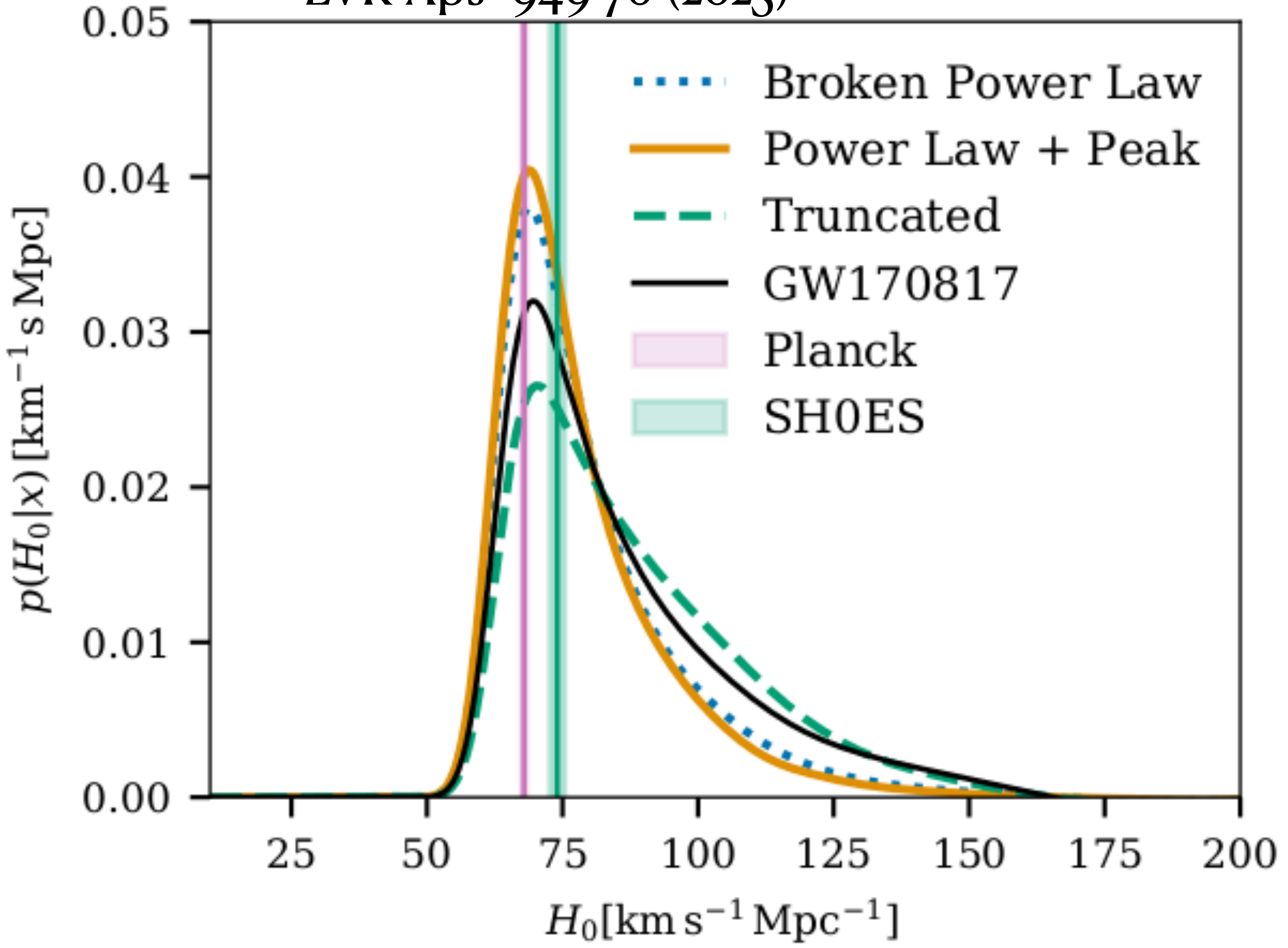


Cosmology with binary black hole (and neutron star) mergers

- Standard siren cosmography
- Evolution of stars and their environments across cosmic time
- Chemical enrichment history

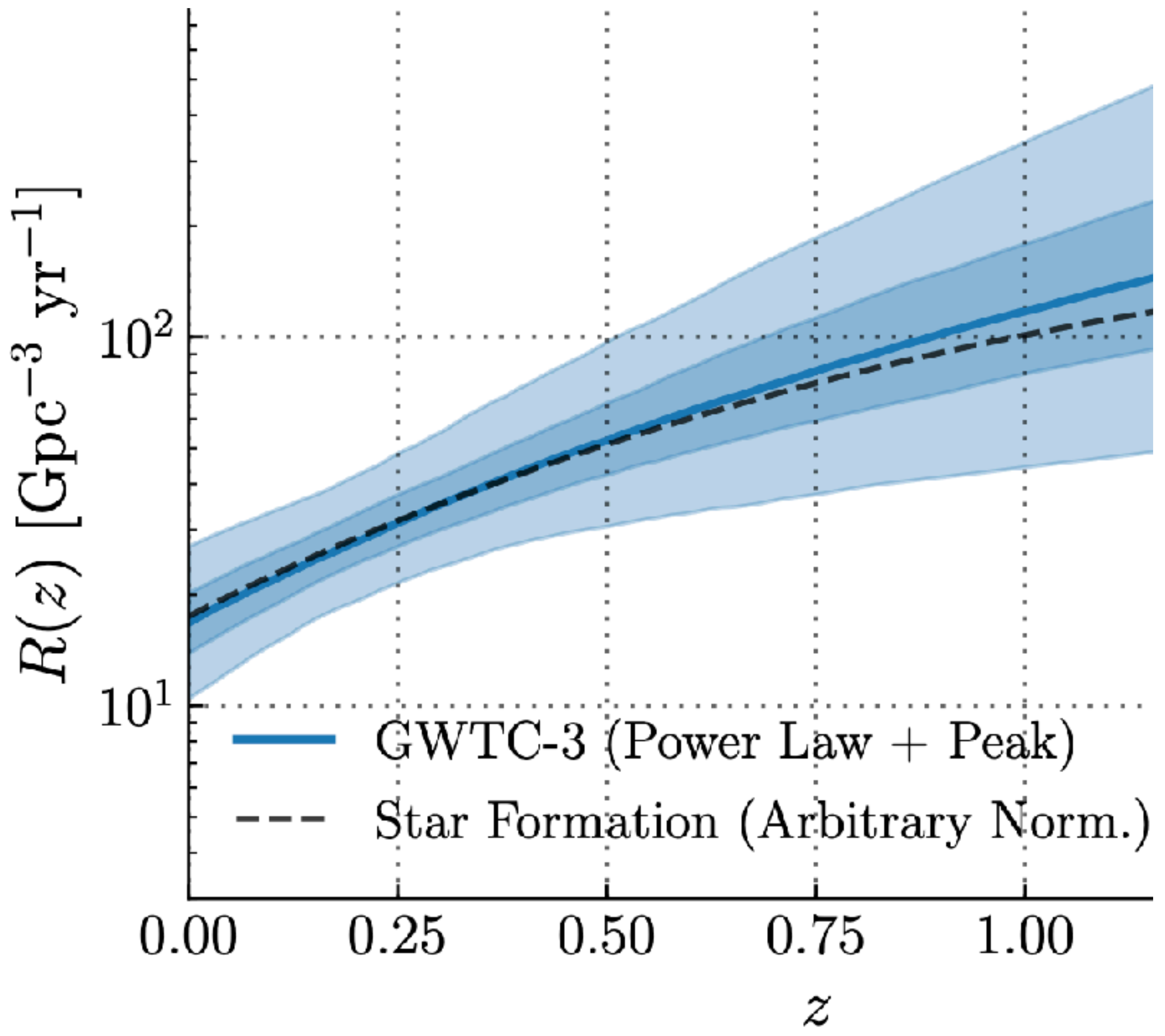


LVK ApJ 949 76 (2023)



Probing cosmic history with gravitational waves

Merger rate density

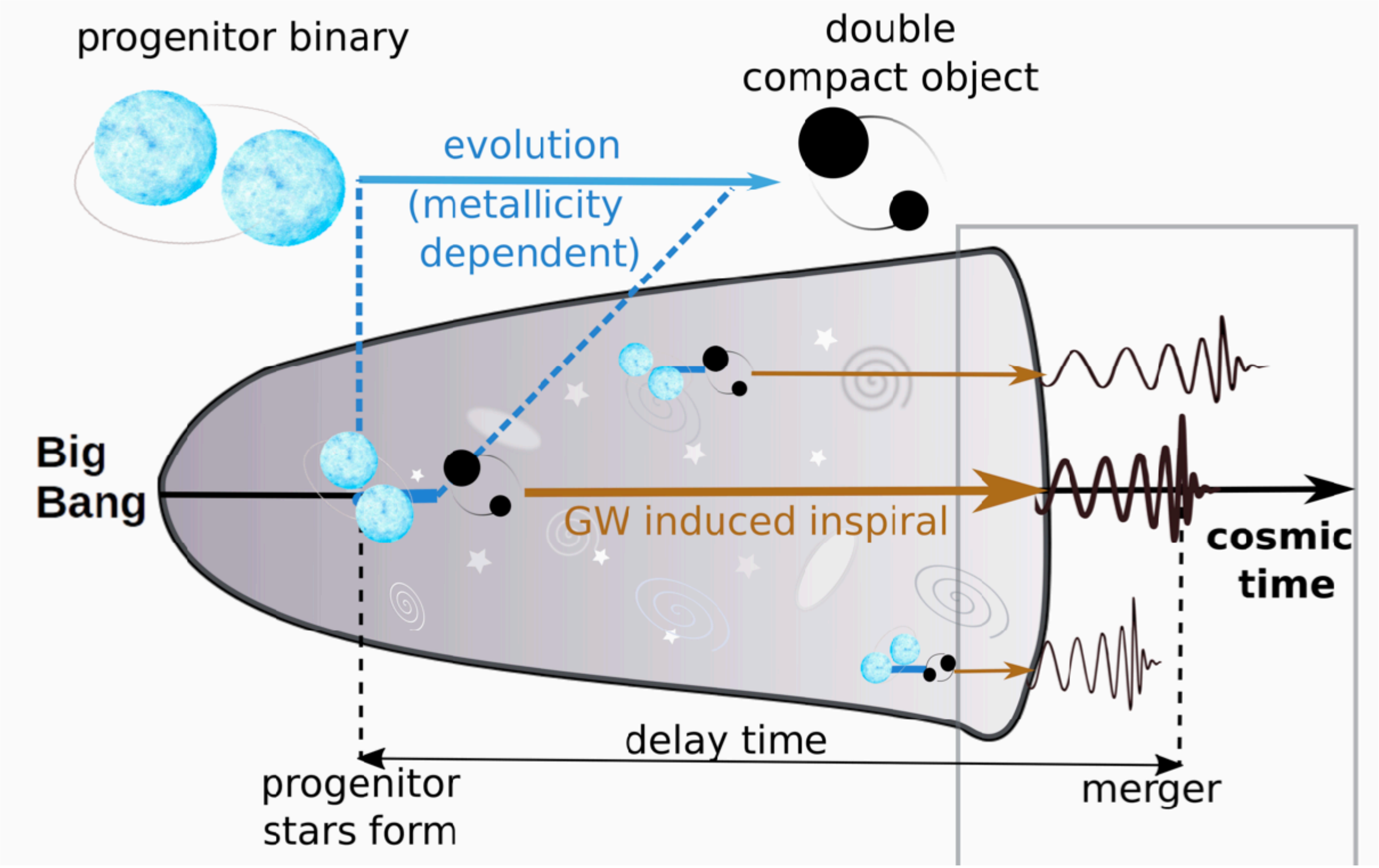


Redshift

LVK PRX 13 011048 (2023)

Method based on MF, Farr & Holz 2018 ApJL 863 L41

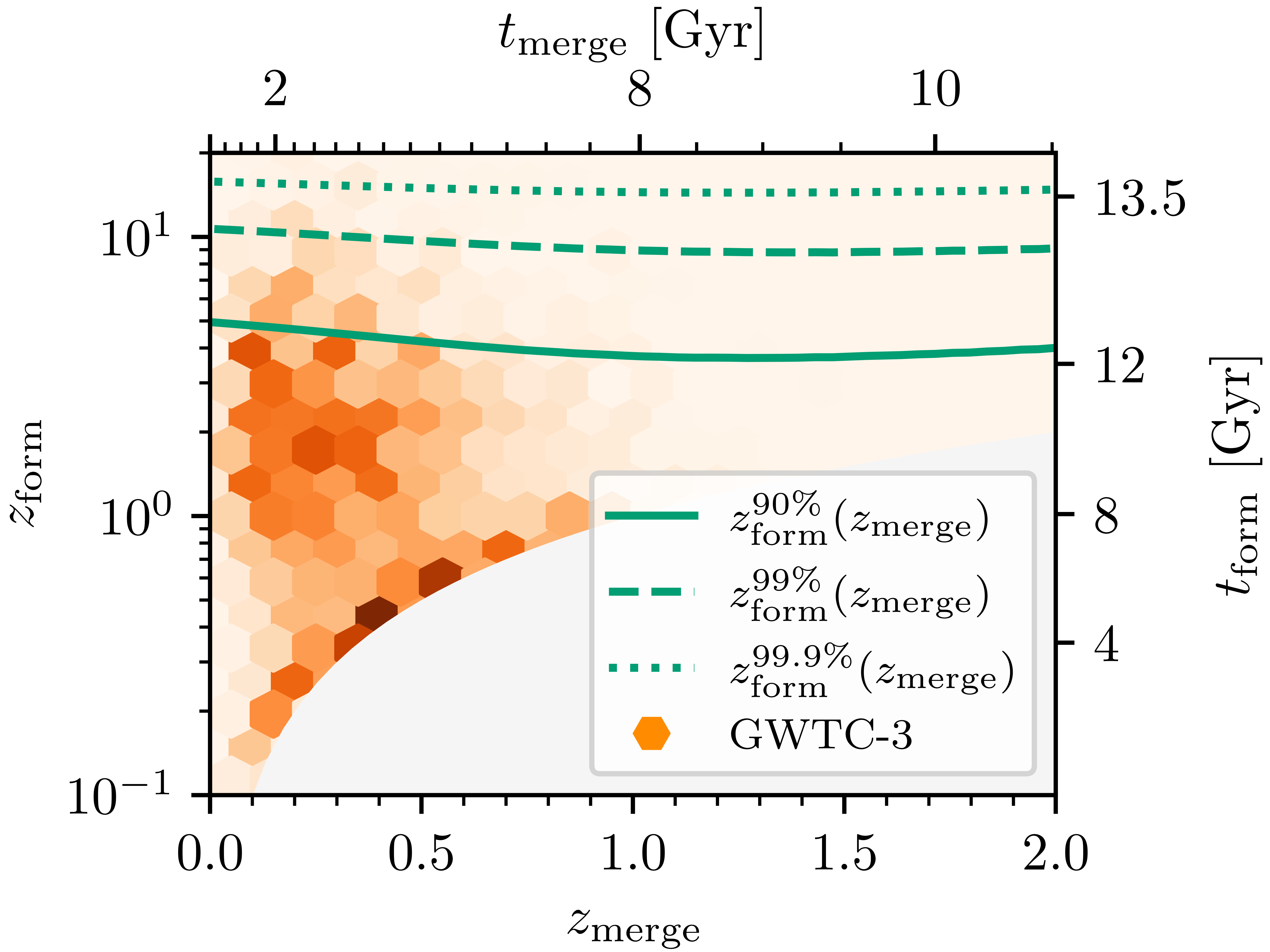
Merger rate follows progenitor formation rate with a *delay time*



Chruslinska, Annalen der Physik 536 2 2200170

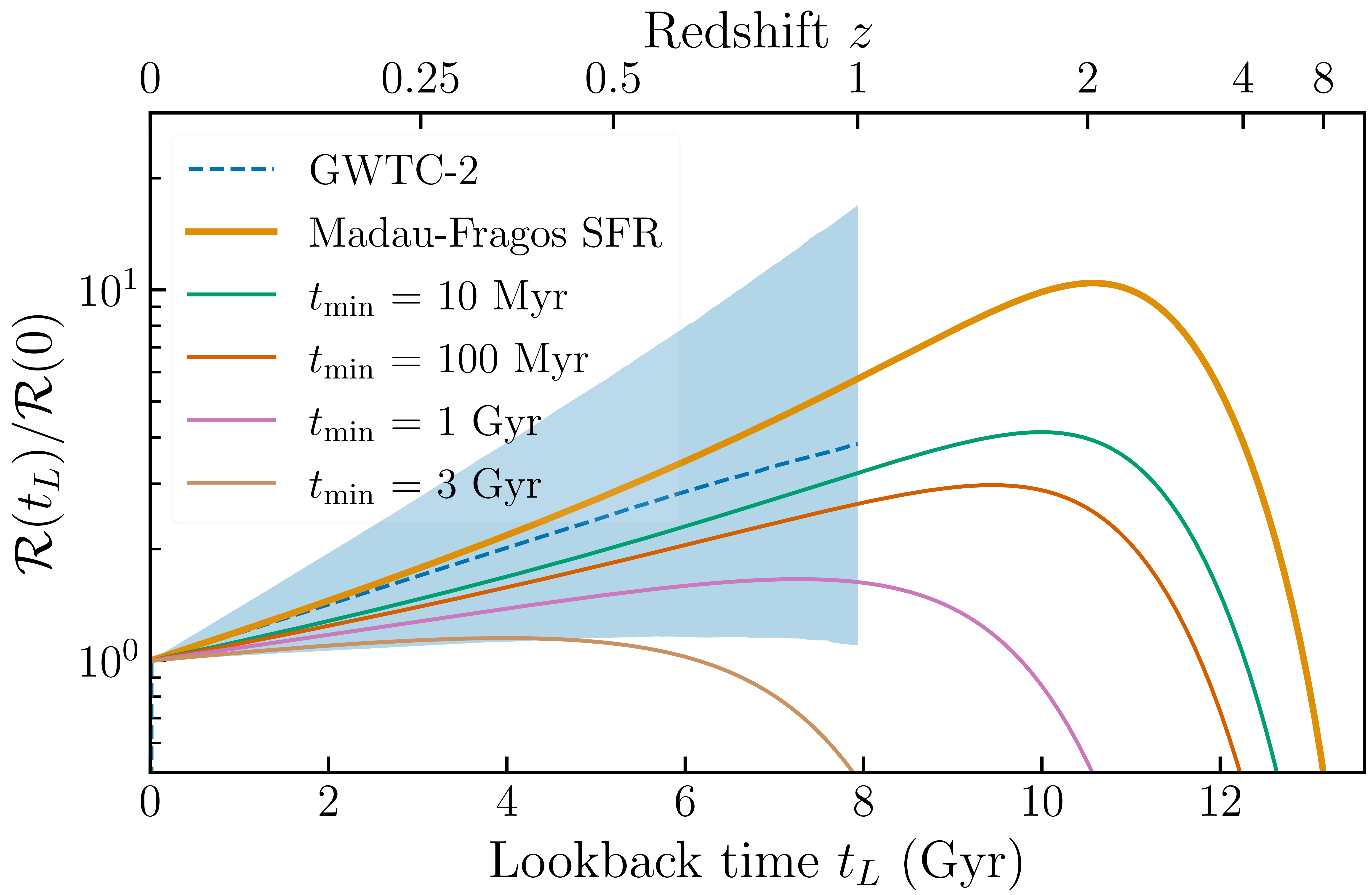
LIGO-Virgo-KAGRA's Oldest Black Holes

We have probably observed black holes that formed in the Universe's first billion years
(Even though they all merged within the last 8 billion years)



MF & van Son, ApJL 957 L31 (2023)

If we know the progenitor formation rate, we can measure *delay time distribution*

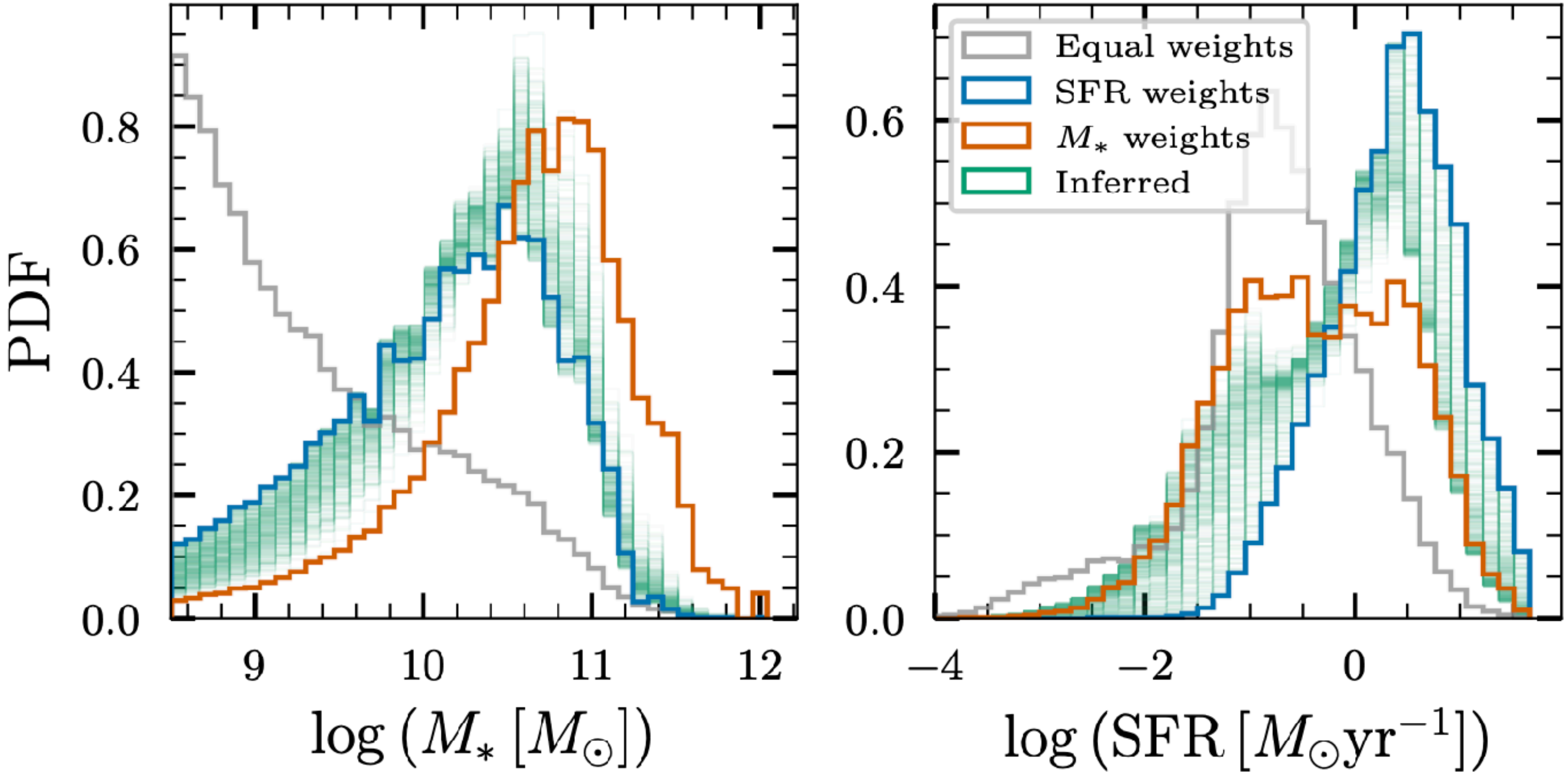


Blue: Inference of the black hole merger rate as a function of cosmic time

Solid lines: Predicted merger rate evolution from different delay time distributions

MF & Kalogera 2021, ApJL 914 L30

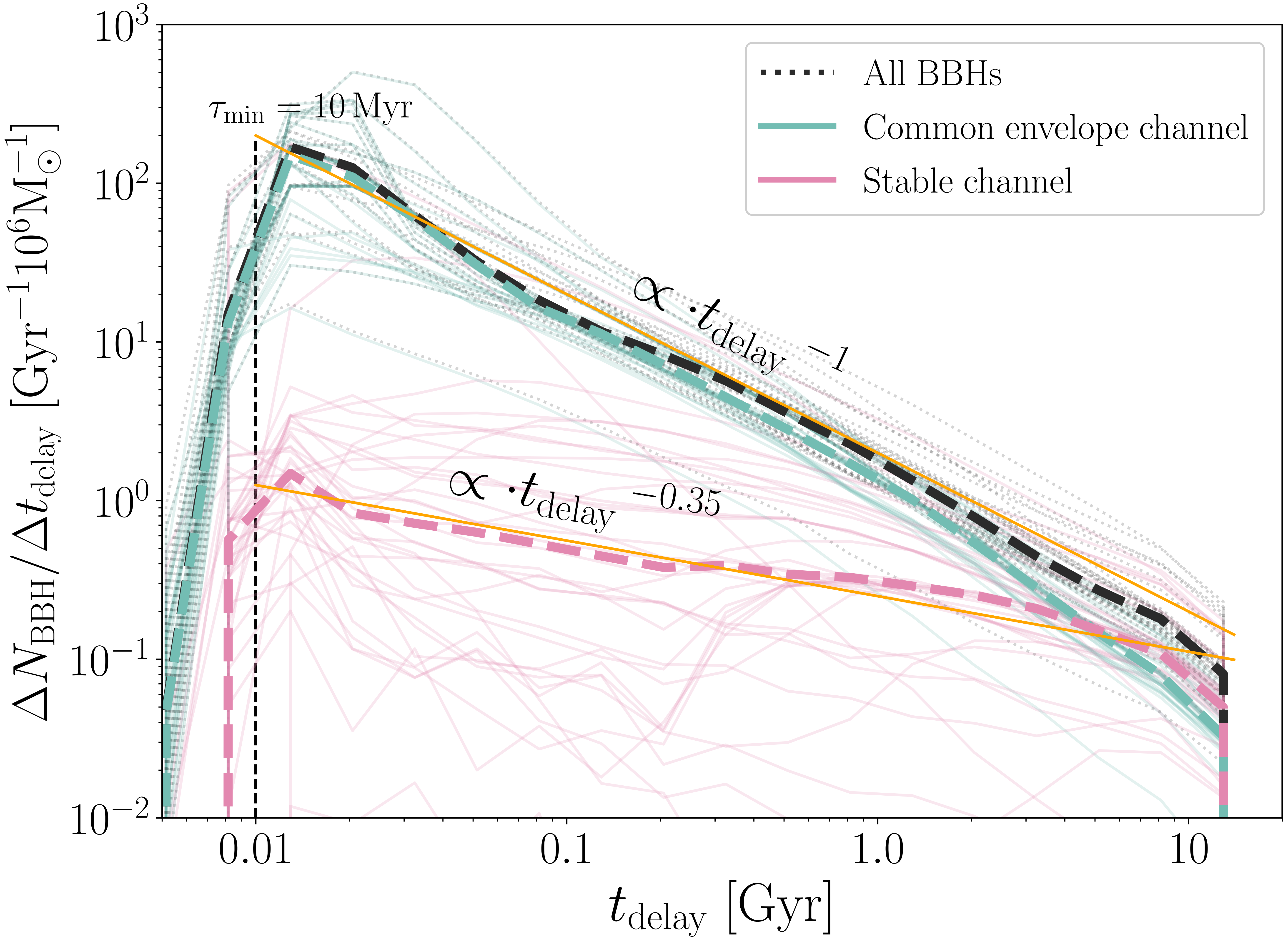
Delay time distribution informs the population of mergers' host galaxies



Vijaykumar, MF, Adhikari & Holz arXiv:2312.03316

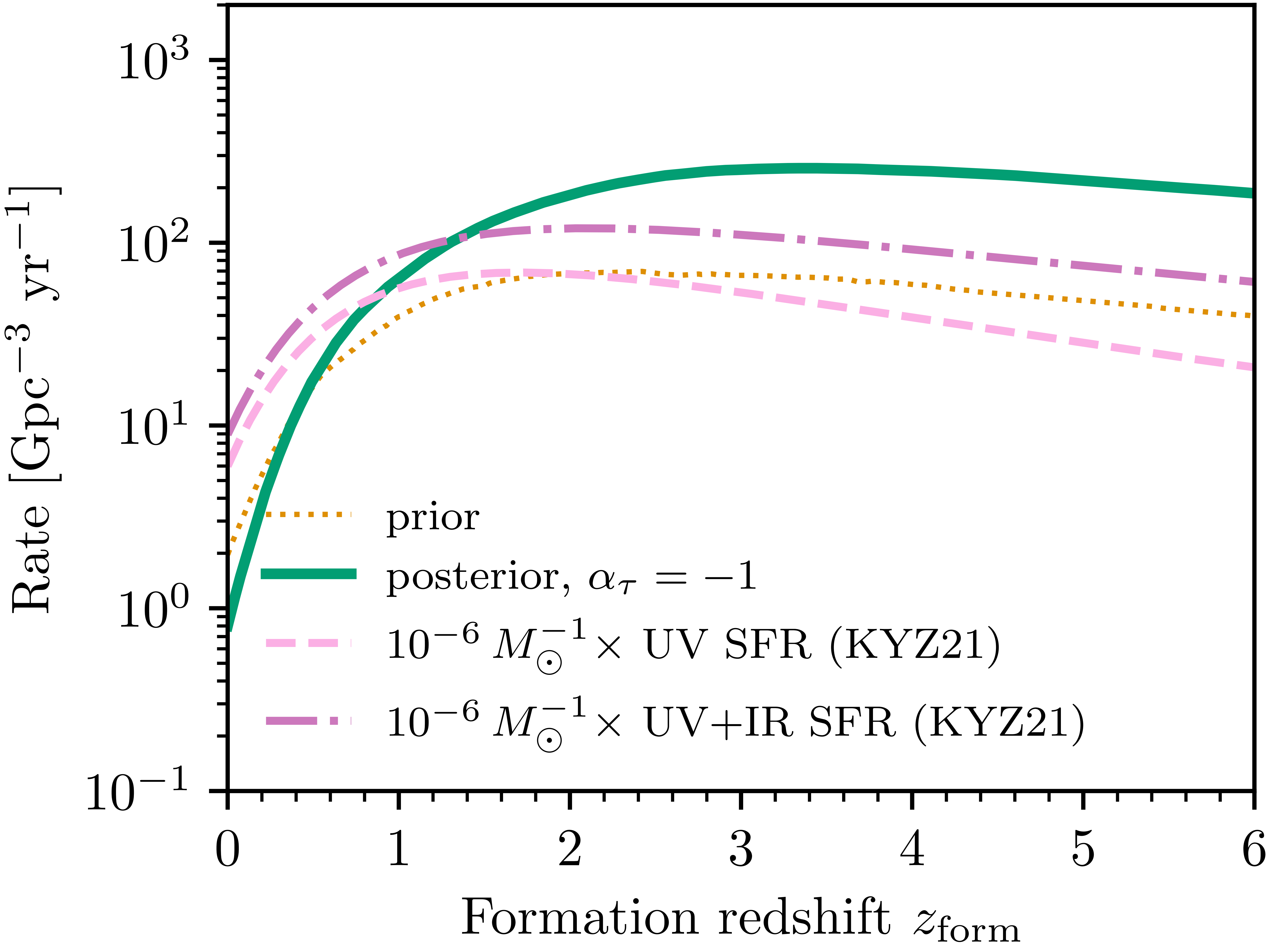
See also Adhikari, MF, Holz, Wechsler & Fang 2020

Compare against theoretical predictions for delay time distribution



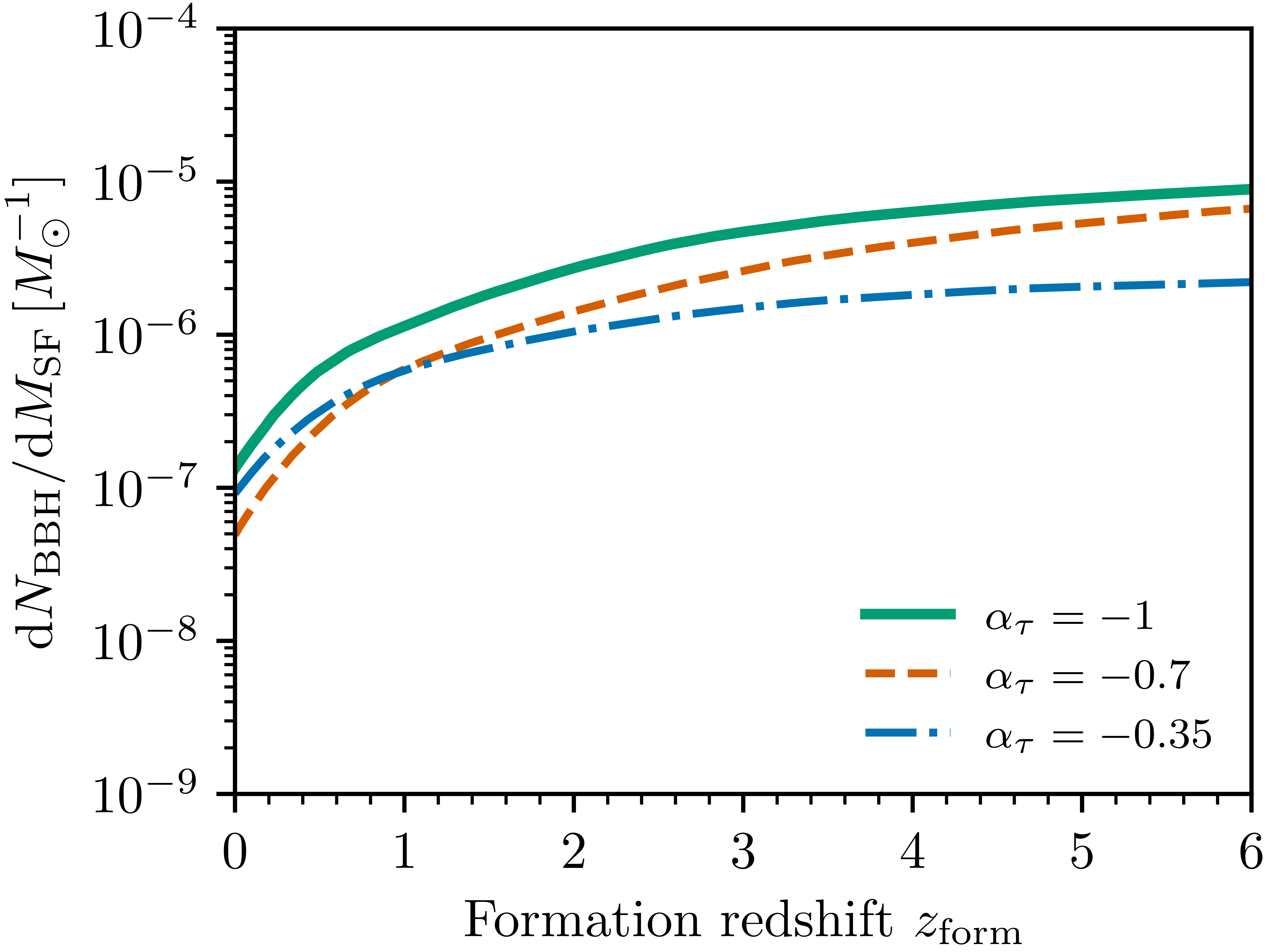
MF & van Son (2023)

Alternatively, if we know the delay time distribution, we can infer the *progenitor formation rate*



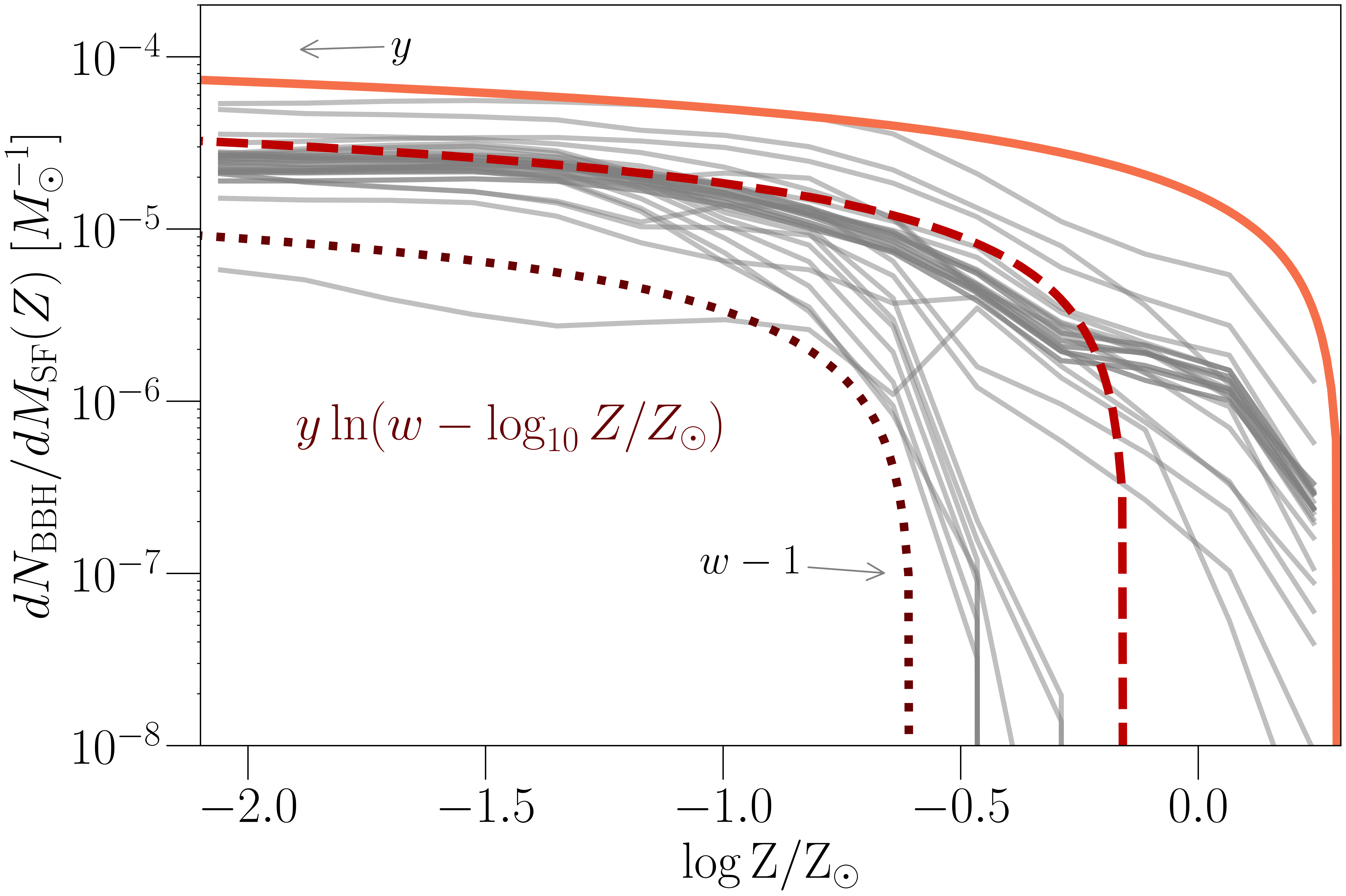
MF & van Son (2023)

Progenitor formation rate divided by star formation rate: *Efficiency*



MF & van Son (2023)

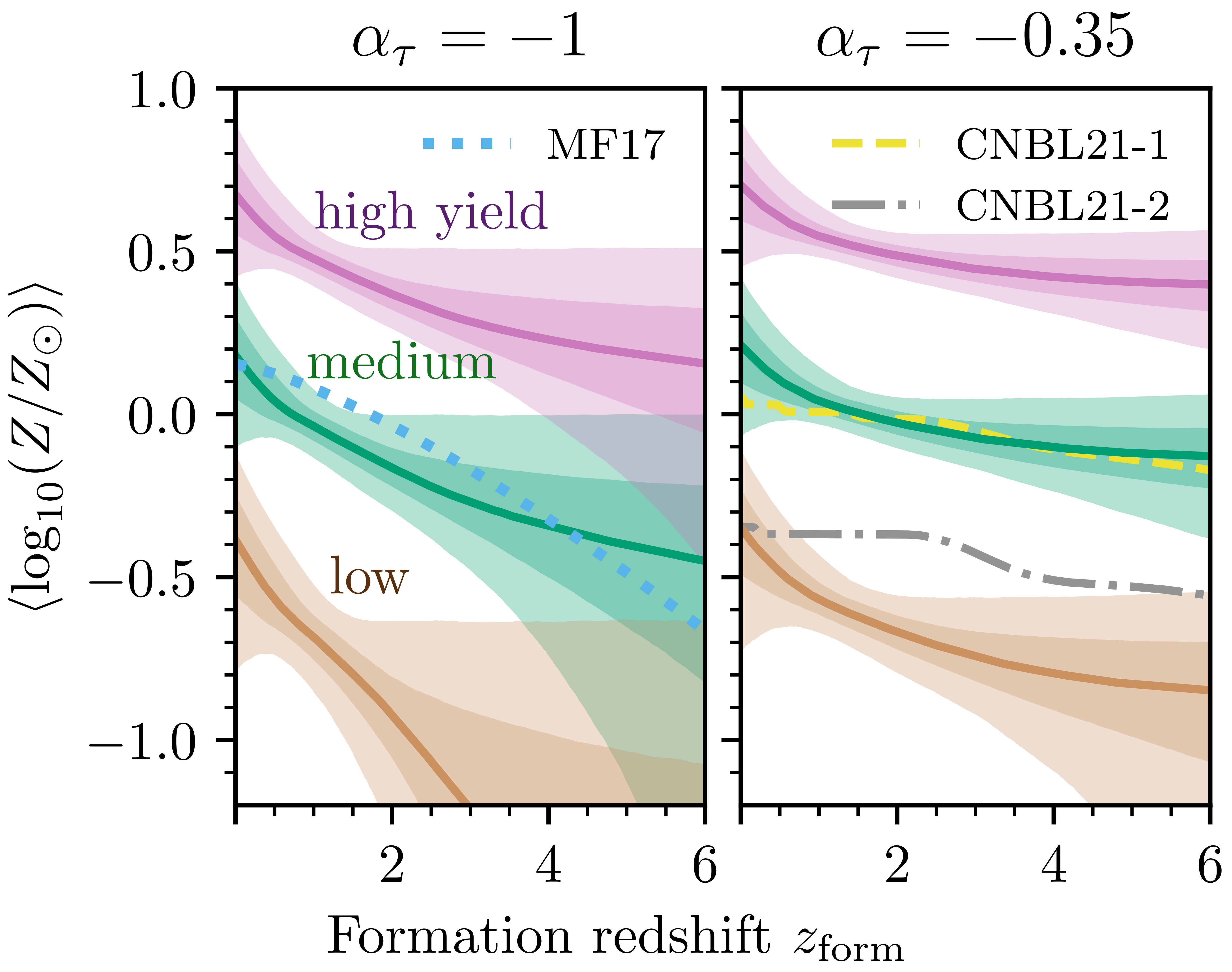
Efficiency depends on metallicity



MF & van Son (2023)

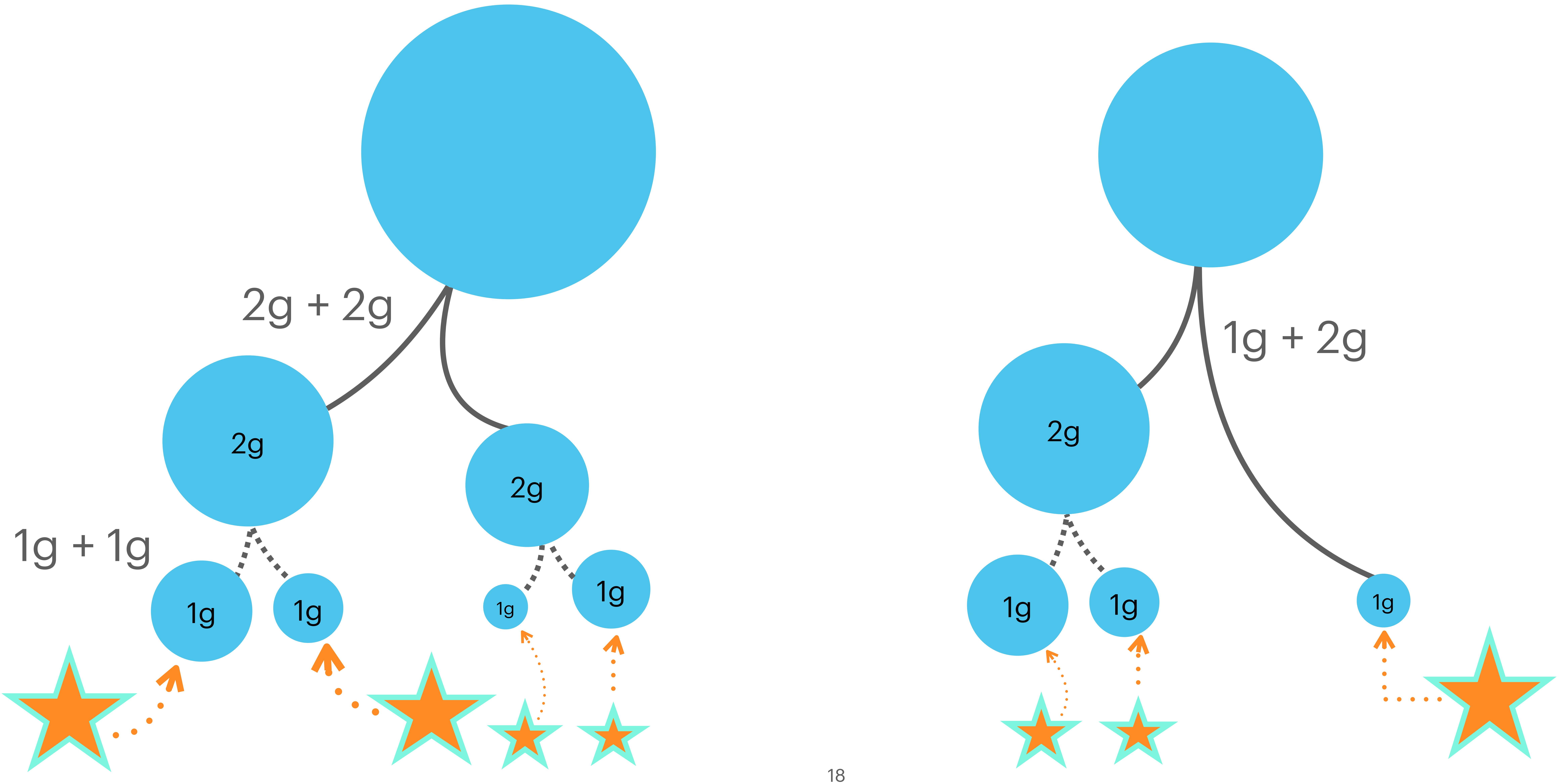
Infer chemical enrichment history

Average metallicity



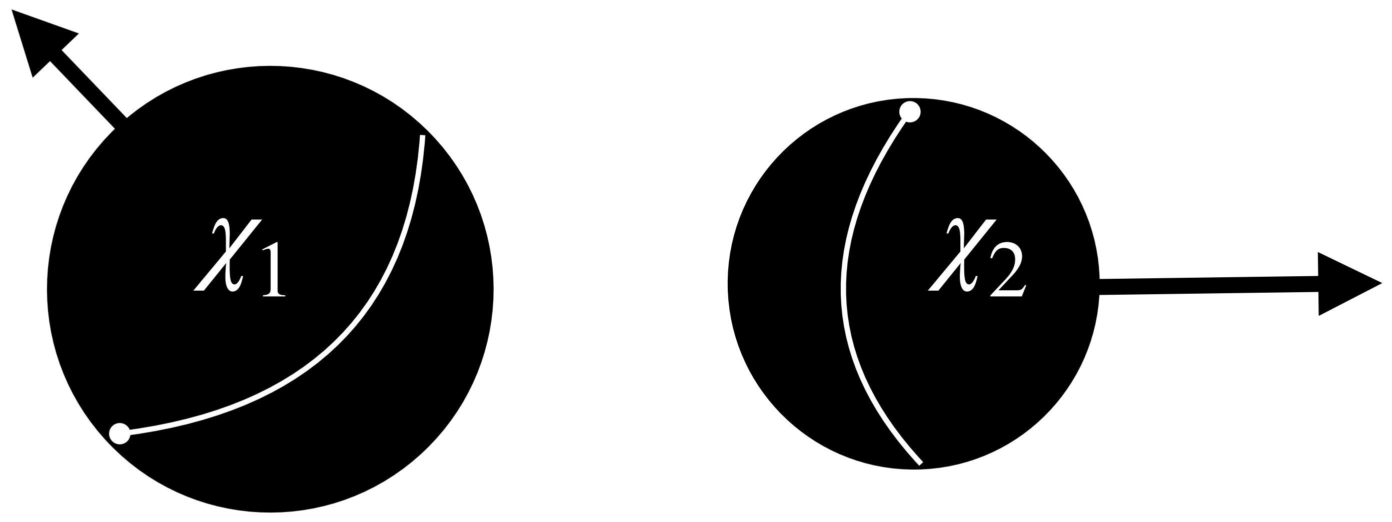
MF & van Son (2023)

Do black holes grow via repeated mergers?



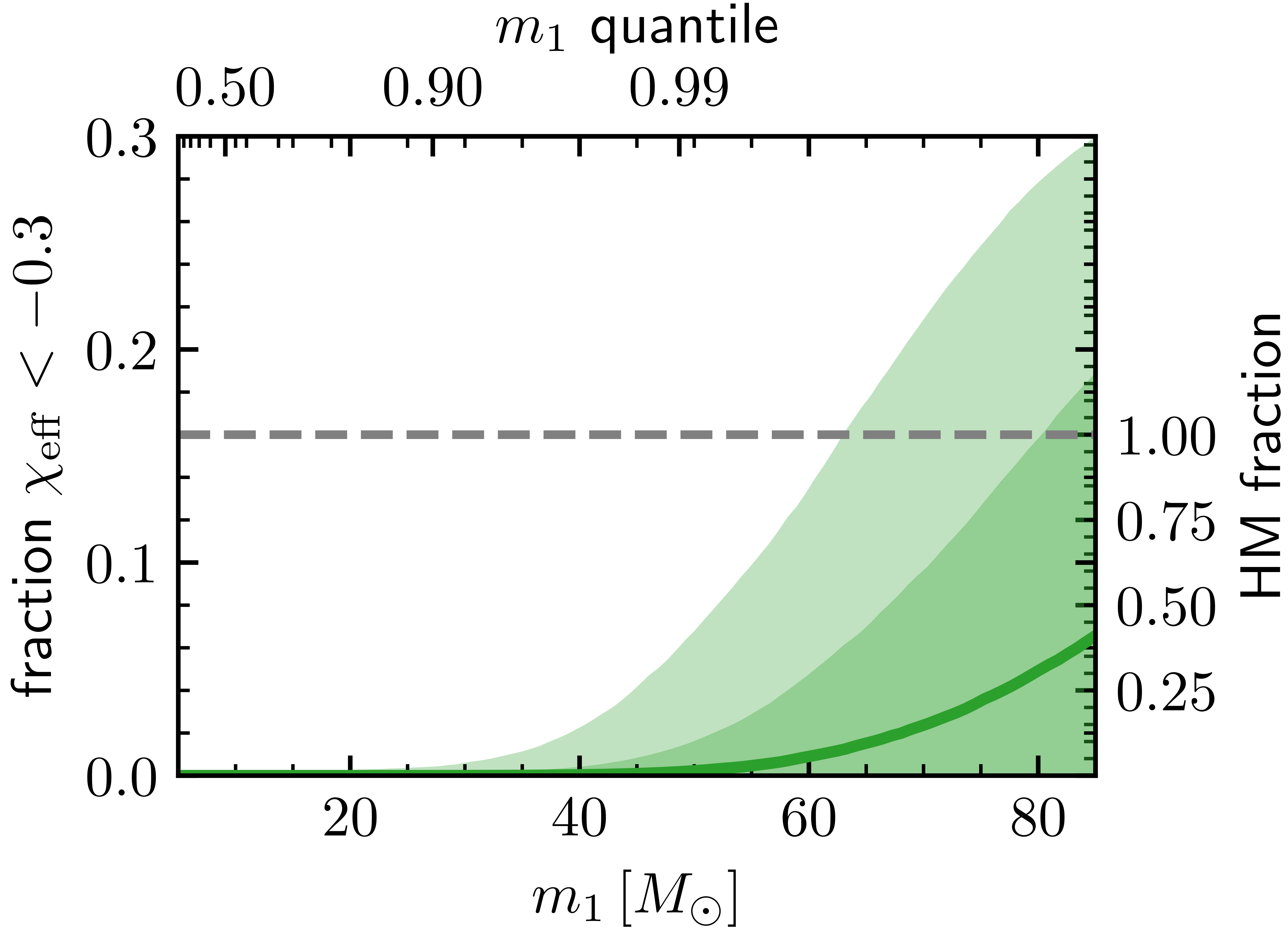
Using spin to distinguish hierarchical mergers

- 2g black holes tend to spin at dimensionless spin magnitude ~0.7 (e.g., MF, Farr & Holz 2017)
- Hierarchical mergers are dynamically assembled, so spin tilts are randomly oriented
- Fixed fraction of hierarchical mergers will have large, misaligned spins



Hierarchical mergers may account for all black holes above $\sim 60\,M_\odot$, but are a very small contribution at lower masses

Fraction of binaries with (moderately) large, misaligned spins



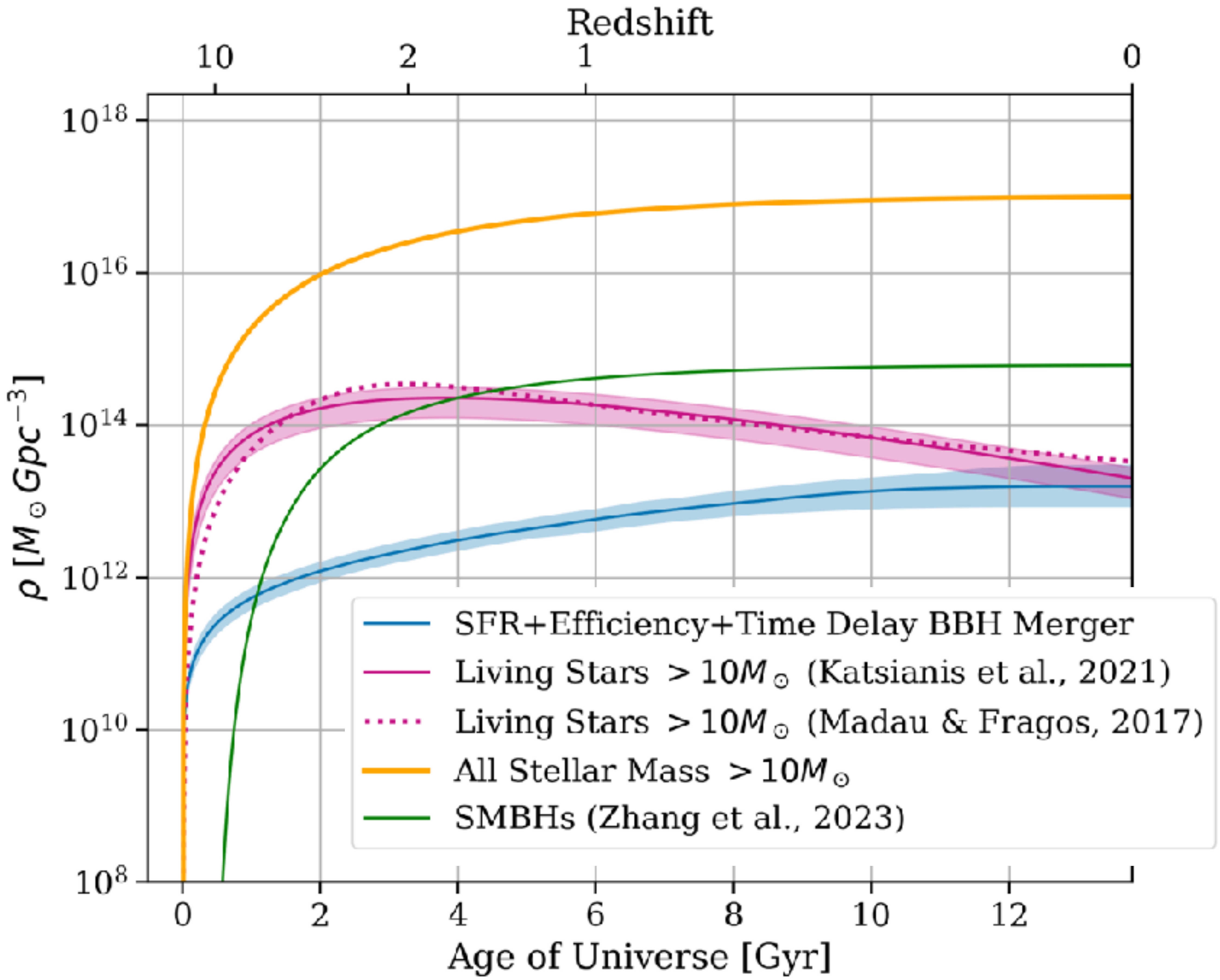
Fraction of hierarchical mergers

MF, Kimball & Kalogera ApJL 935 L26 (2022)

Connection to supermassive black holes?

As a first step, how much mass is available?

Mass density



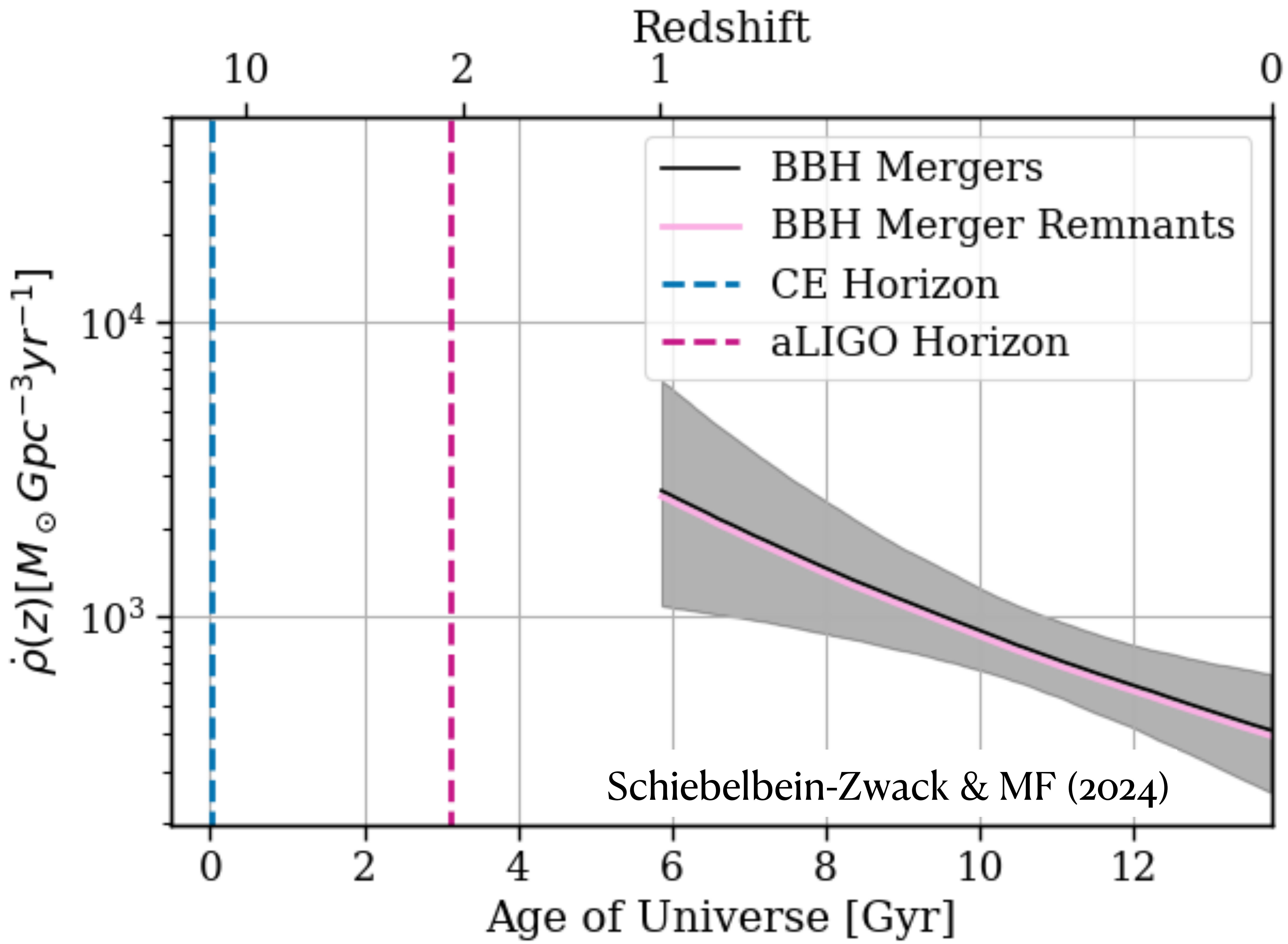
Blue: Extrapolate mass in stellar-mass binary black hole mergers to the early Universe according to star formation rate and delay time model

Green: Mass in supermassive black holes (empirical model TRINITY)

Schiebelbein-Zwack & MF arXiv:2403.17156, ApJ accepted

The next 20 years:
Next generation gravitational-wave detectors

Cosmic Explorer and Einstein Telescope would map the black hole merger rate across *all* of cosmic time, from the very first black holes



Also map the redshift evolution of the mass distribution (e.g. MF+ 2021) and spin distribution (e.g. Bavera, MF+ 2022)

Gravitational-wave probes of the high-redshift Universe

- Gravitational waves probe the metallicity-specific star-formation history:
  - Delay times between progenitor formation and black hole merger imply that we are already probing star formation up to z ~ 6
  - Evolution of the binary black hole merger rate with redshift implies a preference for low-metallicity progenitors
- Do stellar-mass black hole mergers inform the supermassive black hole population?
  - Mergers can produce black holes heavier than 100 solar masses
  - No clear signatures of hierarchical black hole mergers in the LVK band (yet)

Learning from gravitational-wave populations

Learning from gravitational-wave populations

- **How are black holes and neutron stars made?**
  - Where is the **pair-instability mass gap**?
  - Is there a **mass gap between neutron stars and black holes**?
  - What are the **natal spins** of neutron stars and black holes?
  - How do neutron stars and black holes find **merger partners?**

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  - How does the population **evolve across cosmic time**?
  - Does their progenitor rate follow the (low-metallicity?) (globular cluster?) **star formation rate**?
  - What are the **host galaxies** of gravitational-wave sources?

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  - What are the **host galaxies** of gravitational-wave sources?
- **What are the cosmological implications of gravitational-wave sources?**
  - Standard sirens may help arbitrate the **Hubble constant tension**
  - Probe **dark energy** via background expansion and **modified gravitational-wave propagation**
  - Learn about **large scale structure**, gravitational-wave **lensing**