Gravitational Wave Archival Search

Unveil Stellar-mass Binary Black Hole Formation Using Eccentricity

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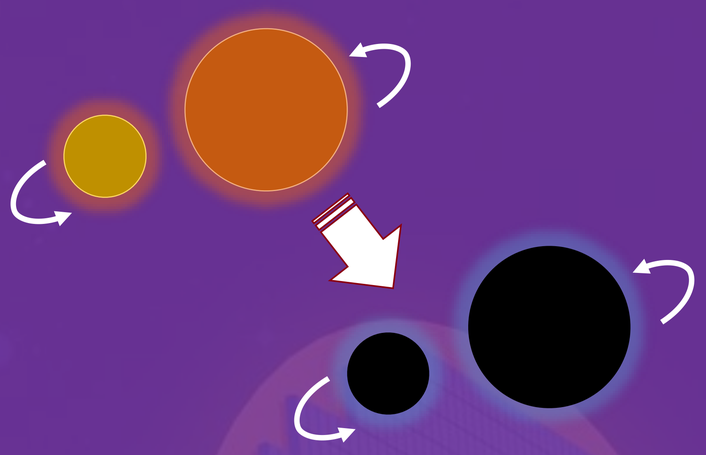
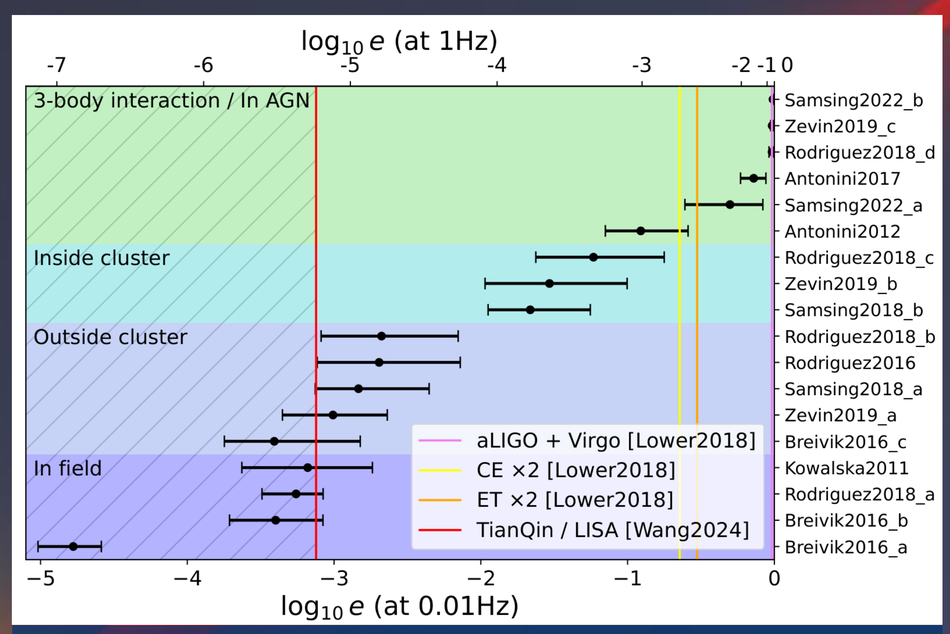
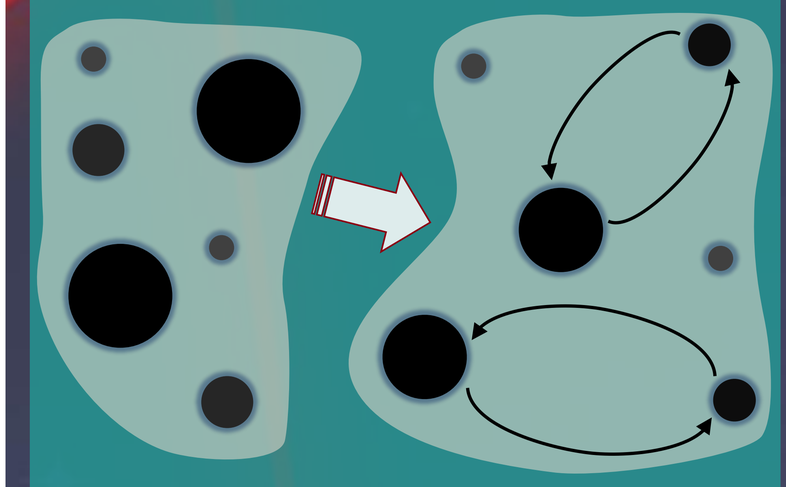


A sMBBH formed by the **co-evolution** process from an isolated pair of massive stars in (galactic) fields, whose orbit is expected to be almost **circular**



The orbital eccentricity of a stellar-mass binary black hole (sMBBH) system can be a key probe to unveil its origin



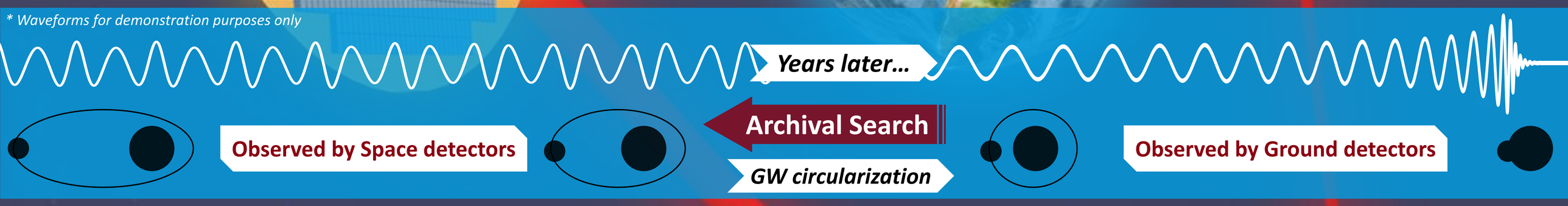
sMBBHs formed by **dynamical interaction** in a dense environment like globular clusters, which are expected to have **non-negligible eccentricities**

Space-based Detection

- Space-based gravitational wave (GW) detectors like TianQin and LISA will be launched in the next decade
- Longer baselines allow them observe lower-frequency GWs, preserve physical characteristics of sMBBHs like **eccentricity** from their long early inspirals
- $\mathcal{O}(10)$ sMBBHs with signal-to-noise ratio (SNR) $\rho > 8$ are expected to be detected every year
- Hard to accumulate high SNR though long observation
- Require unreachable computational cost for years of observation

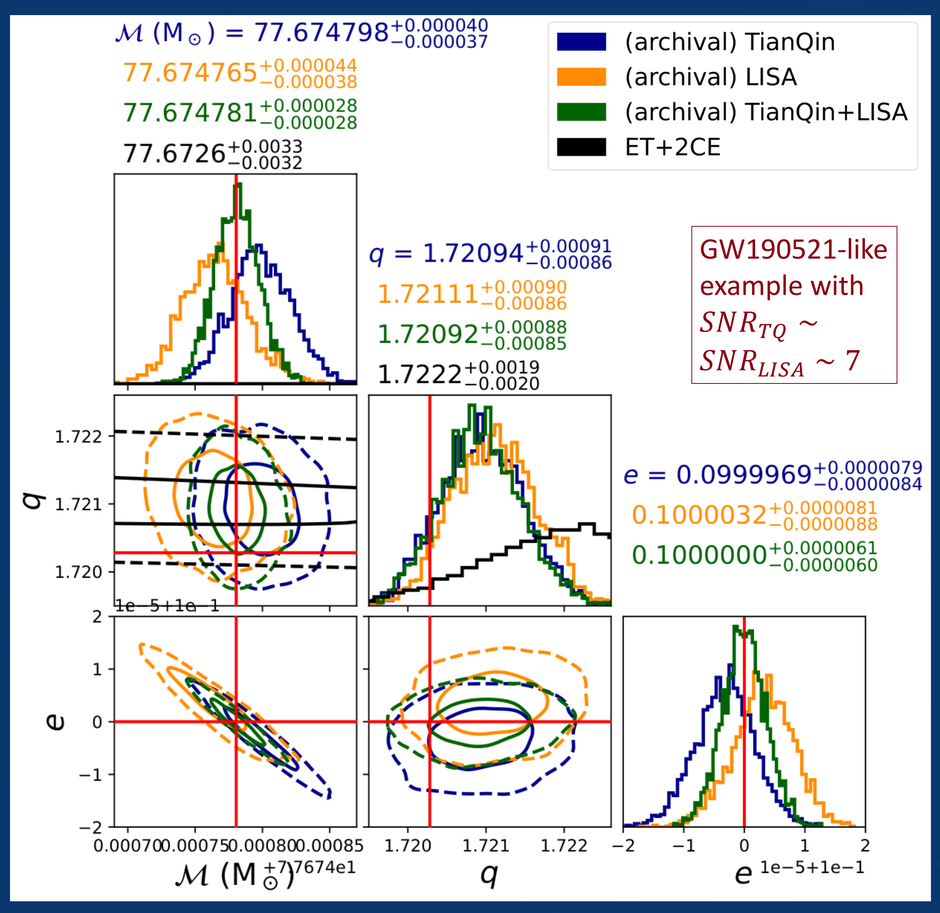
Ground-based Detection

- Next-generation ground-based detectors like Cosmic Explorer and Einstein Telescope observe sMBBHs with high SNR: $\mathcal{O}(10^3)$
- Measure most of the physical parameters with high precision, e.g. uncertainty of chirp mass $\Delta\mathcal{M} \sim 10^{-6}$
- However, highly sensitive frequency range leads to a short observation time (around the merger)
- GW emission **circularizes** binary's orbit
- Information of how **eccentricity** evolves will be easily lost in data of ground detectors



Multiband Detection via Archival Search: "Embrace Both Sides"

- A search of archival data from space detectors, triggered by detection with ground counterparts
- Most of the parameters are constrained by ground, so that we can focus on only *masses* and ***eccentricity*** that space can improve better



GW190521-like example with $SNR_{TQ} \sim SNR_{LISA} \sim 7$

Search and Inference

- Matched-filtering search: Requires a suitable set of waveform filters, or "template bank"
- Bayesian inference: Posterior from the ground as the prior of space-based inference

gwastro/sbank
gwastro/pycbc

- We made both work for
  - Space detectors, by considering their noises and antenna responses
  - And the eccentric GW waveform, by adding the impact of **eccentric harmonics** for the responses

TianQinSYSU/GWSpace
HumphreyWang/pyEccentricFD

Conclusions

- We constructed the first end-to-end data analysis pipeline for archival searches that include orbital eccentricity
- Eccentricities can be constrained to $\mathcal{O}(10^{-5})$ at $e_{0.01\mathrm{Hz}} = 0.1$ for a GW190521-like source with SNR∼7
- Which suggests the capability of space detectors for distinguishing sMBBHs formed by different channels

Wang+2024 | Wang+2025

References

1. Liu, et al. PRD 101.10 (2020): 103027
2. Moore, et al. MNRAS: Letters, 2019, 488(1): L94-L98
3. Wong, et al. PRL 121.25 (2018): 251102
4. Ewing, et al. PRD 103.2 (2021): 023025
5. Sesana. PRL 116.23 (2016): 231102

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