Image: Carl Knox, OzGrav-Swinburne University of Technology

Status and plans of A02

Soichiro Morisaki

ICRR/University of Tokyo

November 18, 2024.

The second annual conference, Hotel Matsunoi Minakami.

A02 members

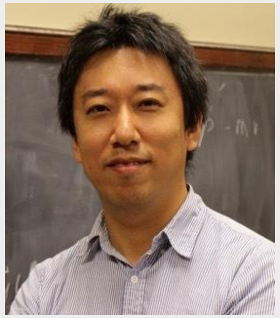
ICRR/UTokyo

Soichiro Morisaki

Hideyuki Tagoshi

RESCEU/UTokyo

Kipp Cannon

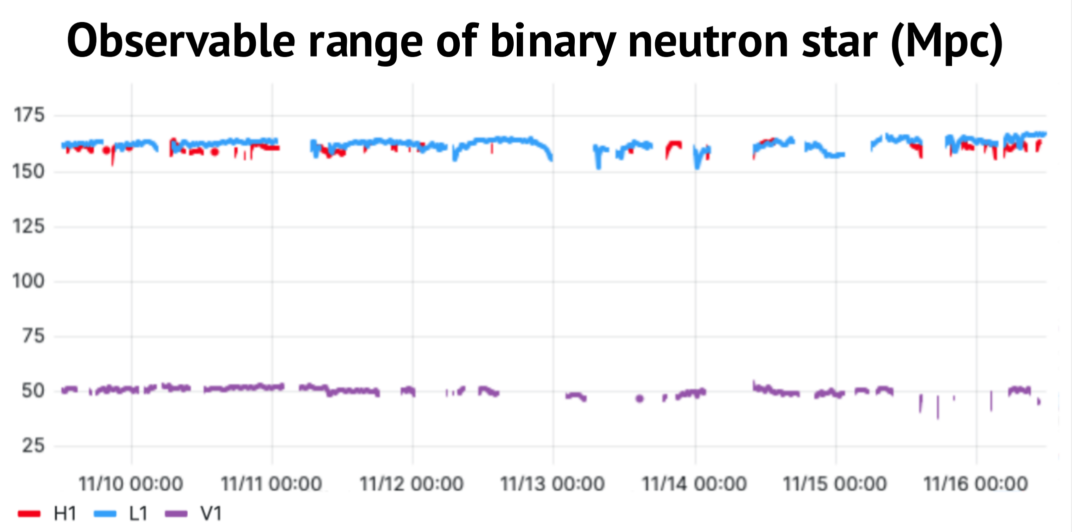


Atsushi Nishizawa

Moved to Hiroshima U.

O4 is ongoing!

- Observable range of binary neutron star: 160−165Mpc (LIGO), 50−55Mpc (Virgo).
- 159 significant events (as of 16 November 2024)
- Planned end date: 9 June 2025.
- KAGRA will rejoin the observation with the target sensitivity ~ 10Mpc.



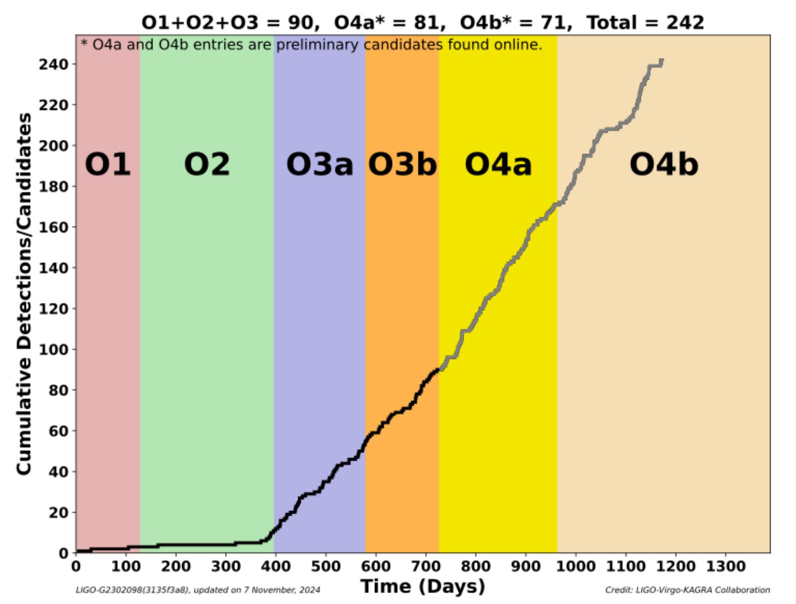


Figure: Cumulative number of detections

GW230529 – Another NSBH candidate from O4

- Likely the most symmetric NSBH event with the primary in the mass gap: $m_1 = 3.6^{+0.8}_{-1.2} M_\odot$, $m_2 = 1.4^{+0.6}_{-0.2} M_\odot$.
- Single-detector event with SNR ~ 11 → No EM counterparts detected, no tidal imprints on GWs detected.

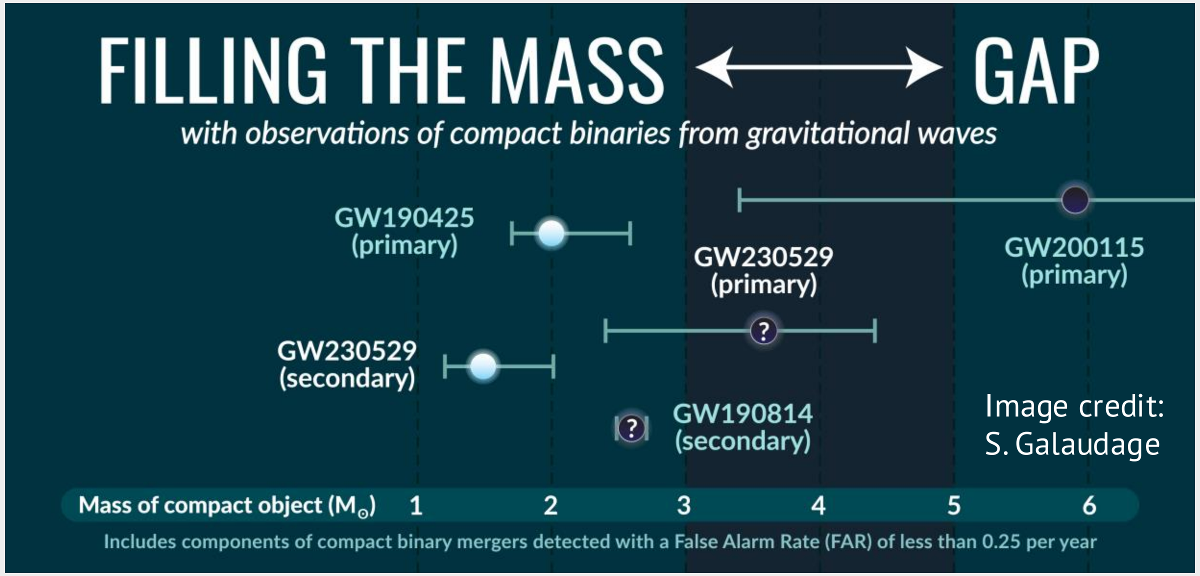


Image credit: S. Galaudage

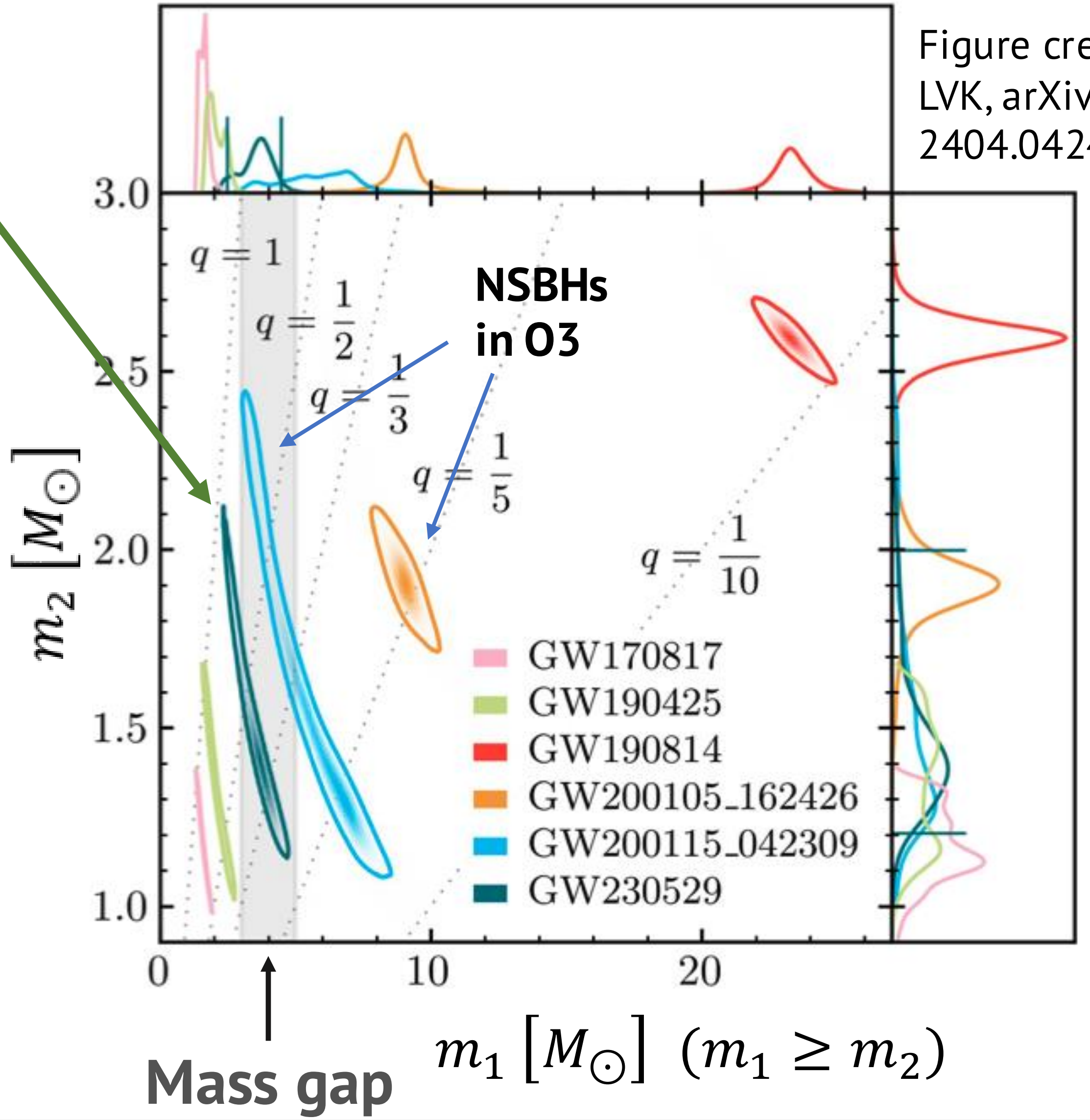


Figure credit: LVK, arXiv: 2404.04248.

Leveraging O4 BBHs: Formation History

~90 binary black holes (BBHs) in O1–O3
+ ~150 additional BBHs in O4 so far.

Their masses, spins, and redshifts provide clues to their formation history.

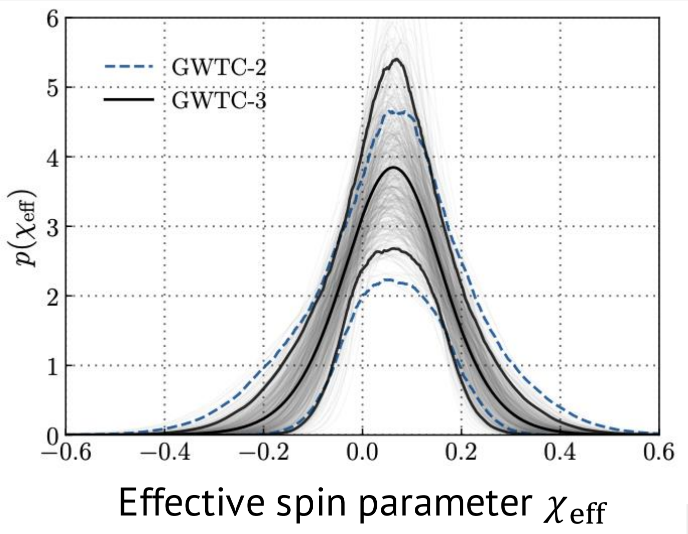


Figure credit:
R. Abbott *et al.*, PRX **13**, 011048 (2023),
A. Hussain *et al.*,
arXiv: 2411.02252.

Figure:
Distribution of effective spin χ_{eff}

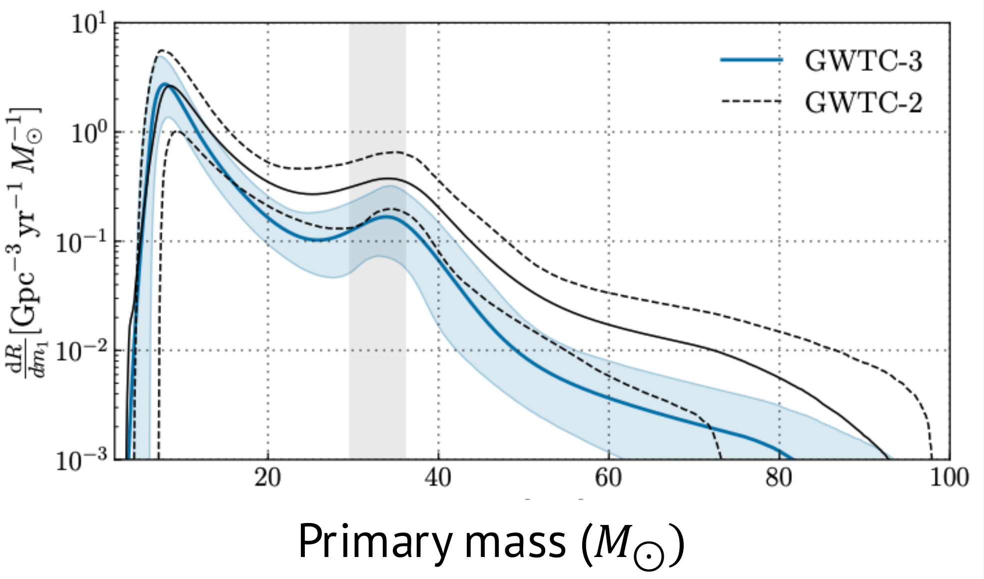


Figure:
Distribution of primary masses

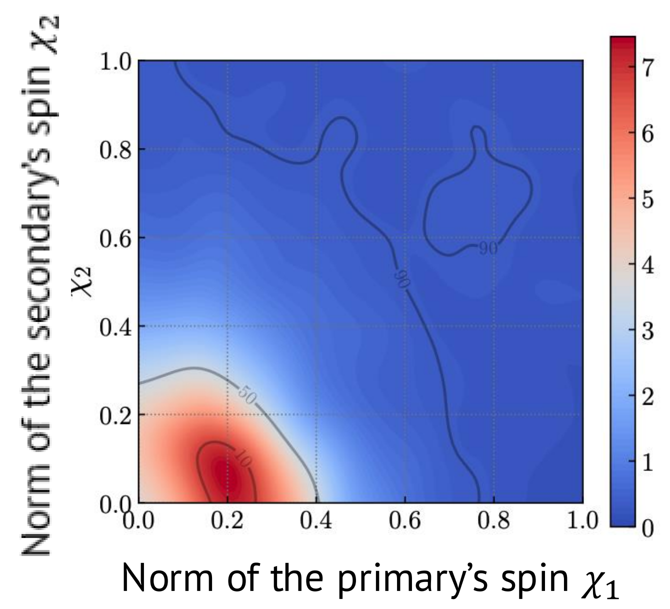


Figure:
Distribution of spin norms

Leveraging O4 BBHs: Formation History

Recovering the distribution of source parameters from data is challenging.

- Need to incorporate selection effects (e.g., heavier ones are easier to observe).

  e.g., I. Mandel, W. Farr, and J. R. Gair (2019).

- Some of the results are not robust against the choice of model distribution.

  e.g., J. Roulet *et al*. (2021), S. Galaudage *et al*. (2021).

- Many error sources in likelihood evaluations, with some of them growing as the number of events increases.

  e.g., R. Essick and W. Farr (2022), C. Talbot and J. Golomb (2023).

Leveraging O4 BBHs: Formation History

We are improving the analysis framework for O4 analyses, in collaboration with the C02 group.

- We investigate potential error sources in likelihood evaluations (See the next talk).

  M. Iwaya, K. Kobayashi, *SM*, K. Hotokezaka, T. Kinugawa in preparation
  (manuscript being reviewed by LVK).

- We examine potential biases from the choice of prior **(See the poster by Kazuya Kobayashi)**.

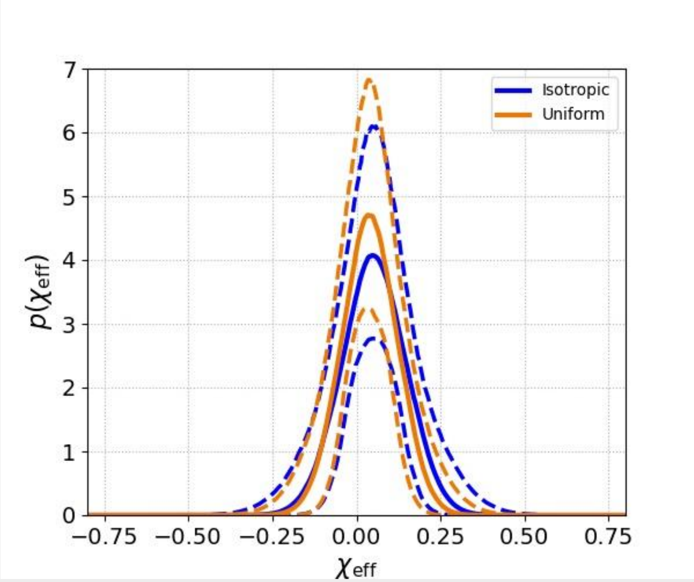


Figure: Recovered distribution of $\chi_{\rm eff}$ with different spin prior (isotropic vs uniform-in-$\chi_{\rm eff}$)

Population Analysis of Binary Black Holes Estimated with Uniform Effective Spin Prior

Kazuya Kobayashi [1](kazuya@icrr.u-tokyo.ac.jp), Masaki Iwaya[1],
Soichiro Morisaki[1], Tomoya Kinugawa[2], Kenta Hotokezaka[3]
ICRR University of Tokyo[1], Faculty of Engineering Shinshu University[2],
RESCEU University of Tokyo[3]

Leveraging O4 BBHs: Ringdown

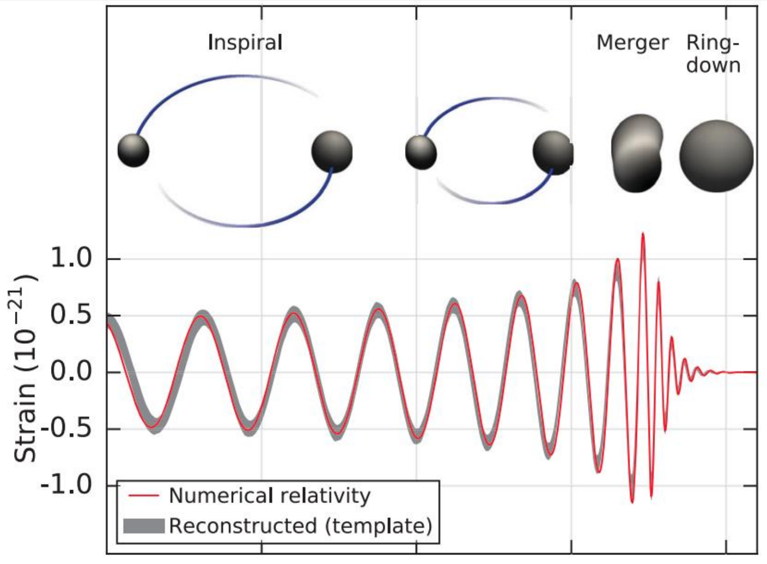


Figure credit:
B. P. Abbott *et al.*, PRL **116**, 061102 (2016).

The ringdown signal is a superposition of damped sinusoids:

$$h(t) = \sum_n A_n e^{-\frac{t}{\tau_n(M_f, a_f)}} \sin(\omega_n(M_f, a_f)t + \phi_n).$$

M_f, a_f: Mass and spin of the remnant BH

Tests of General Relativity with ringdown signals:

- Consistency between ringdown and inspiral parts.
- Consistency between different sinusoids (possible detection of overtones by M. Isi *et al.* (2019)).

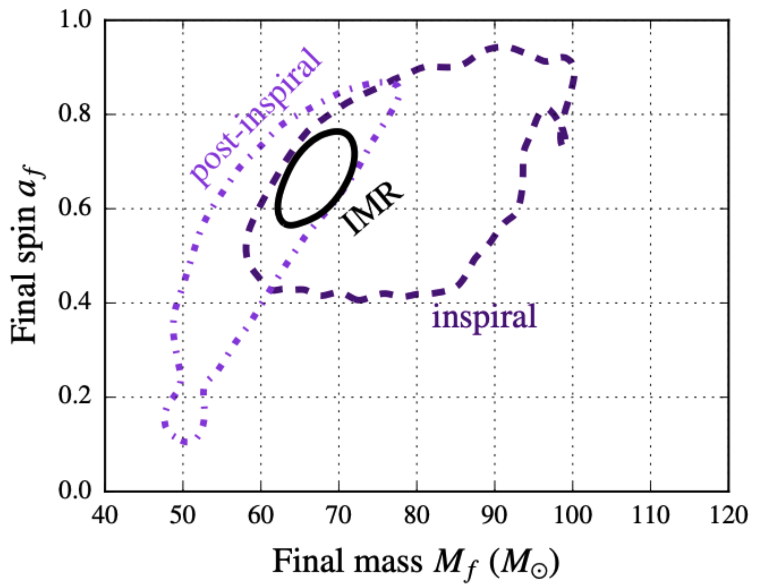
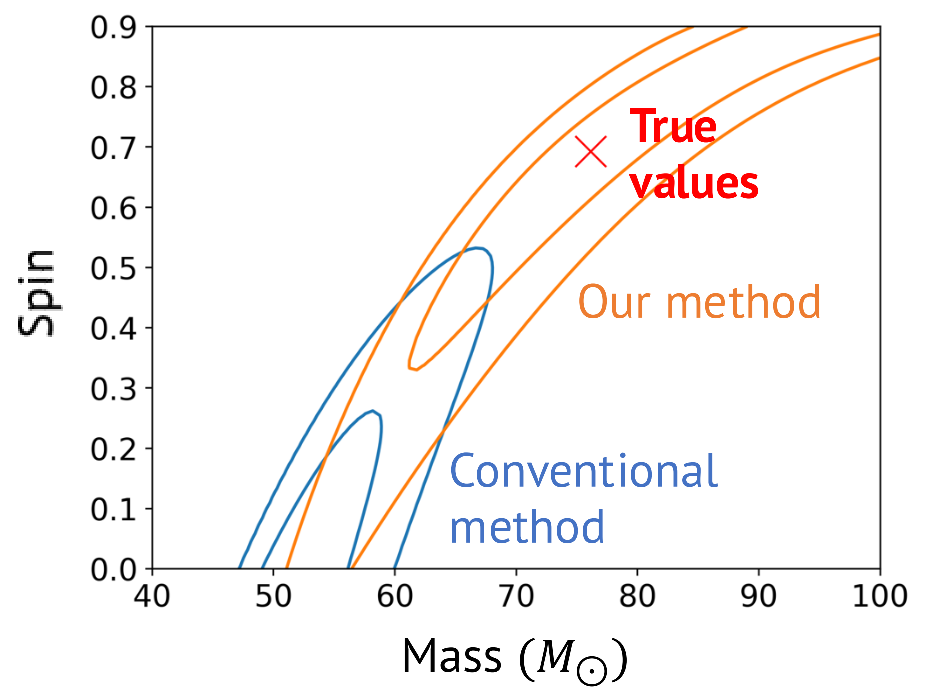


Figure credit:
B. P. Abbott *et al.*, PRL **116**, 221101 (2016).

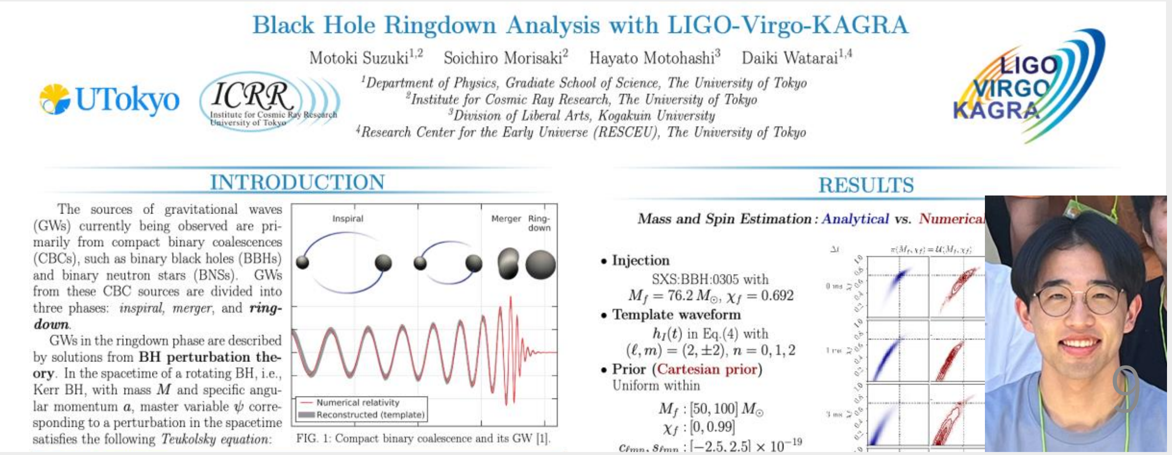
Leveraging O4 BBHs: Ringdown

We are analyzing O1–O3 BBHs and improving the analysis method for O4 BBHs.

- We found that the conventional method tends to underestimate remnant masses.
- We developed a semi-analytic method using the Gram-Schmidt orthogonalization.



See the poster by Motoki Suzuki.



Black Hole Ringdown Analysis with LIGO-Virgo-KAGRA

Motoki Suzuki[1,2] Soichiro Morisaki[2] Hayato Motohashi[3] Daiki Watarai[1,4]

[1]*Department of Physics, Graduate School of Science, The University of Tokyo*
[2]*Institute for Cosmic Ray Research, The University of Tokyo*
[3]*Division of Liberal Arts, Kogakuin University*
[4]*Research Center for the Early Universe (RESCEU), The University of Tokyo*

INTRODUCTION

The sources of gravitational waves (GWs) currently being observed are primarily from compact binary coalescences (CBCs), such as binary black holes (BBHs) and binary neutron stars (BNSs). GWs from these CBC sources are divided into three phases: *inspiral*, *merger*, and ***ringdown***.

GWs in the ringdown phase are described by solutions from **BH perturbation theory**. In the spacetime of a rotating BH, i.e., Kerr BH, with mass M and specific angular momentum $\boldsymbol{a}$, master variable ψ corresponding to a perturbation in the spacetime satisfies the following *Teukolsky equation*:

FIG. 1: Compact binary coalescence and its GW [1].

RESULTS

Mass and Spin Estimation : Analytical vs. Numerical

- **Injection**
  SXS:BBH:0305 with
  $M_f = 76.2\,M_\odot,\ \chi_f = 0.692$
- **Template waveform**
  $h_I(t)$ in Eq.(4) with
  $(\ell, m) = (2, \pm 2),\ n = 0, 1, 2$
- **Prior (Cartesian prior)**
  Uniform within
  $M_f : [50, 100]\,M_\odot$
  $\chi_f : [0, 0.99]$
  $c_{\ell mn}, s_{\ell mn} : [-2.5, 2.5] \times 10^{-19}$

Seeking New Discoveries: Sub-Solar Mass

- Merging sub-solar-mass binaries may exist, e.g., in the scenario of primordial BHs.
- Lower masses → longer duration
  ex) Duration~ 1 day for $0.1M_{\odot}$ - $0.1M_{\odot}$.
- We are developing an efficient search method that incorporates Earth's rotation **(See the poster by Yasuhiro Murakami)**.

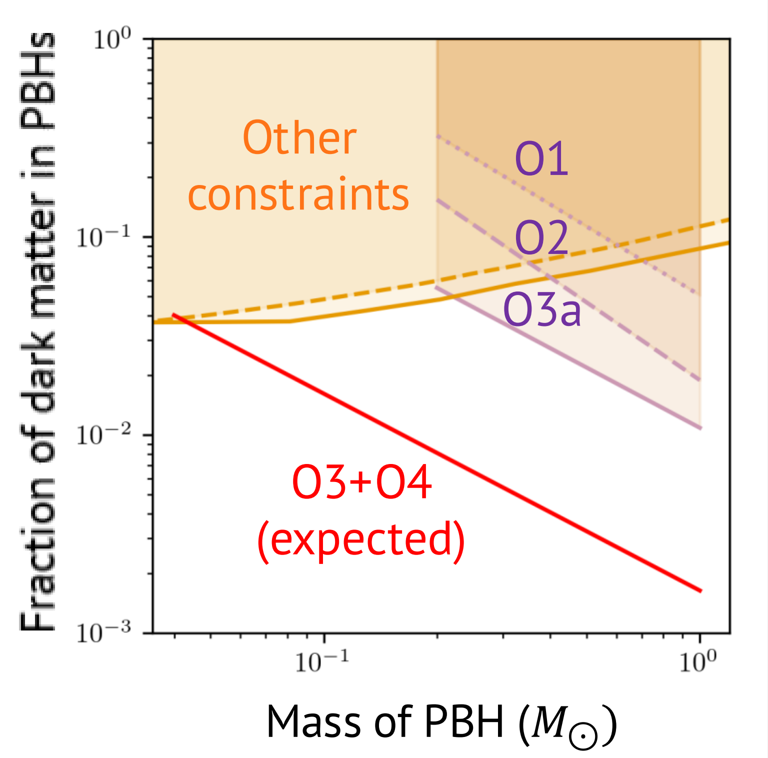
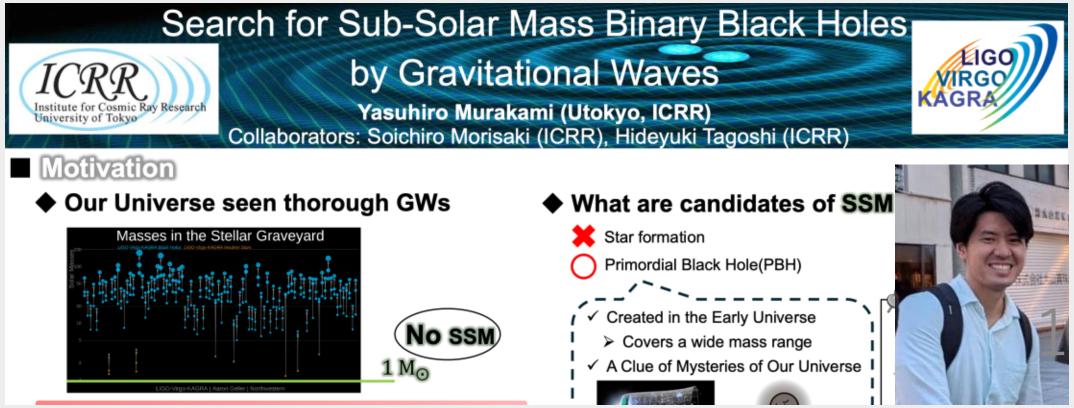


Figure: Constraints on PBH abundance



Search for Sub-Solar Mass Binary Black Holes by Gravitational Waves

ICRR Institute for Cosmic Ray Research University of Tokyo

LIGO VIRGO KAGRA

Yasuhiro Murakami (Utokyo, ICRR)

Collaborators: Soichiro Morisaki (ICRR), Hideyuki Tagoshi (ICRR)

■ **Motivation**

◆ **Our Universe seen thorough GWs**

Masses in the Stellar Graveyard

No SSM

1 $M_{\odot}$

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

◆ **What are candidates of SSM**

✖ Star formation

○ Primordial Black Hole(PBH)

✓ Created in the Early Universe

➢ Covers a wide mass range

✓ A Clue of Mysteries of Our Universe

Seeking New Discoveries: Ultralight Dark Matter

GW detectors are sensitive to **ultralight bosonic dark matter** (dark photon, axion, dilaton etc.) as well as GWs.

- We conducted a search for dark photon with KAGRA O3 data and obtained upper bounds on its coupling constant.

  LIGO-Virgo-KAGRA (including *SM*),
  PRD **110**, 042001 (2024).

- We developed an optimal analysis method for O4 searches.

  SM et al. in preparation.

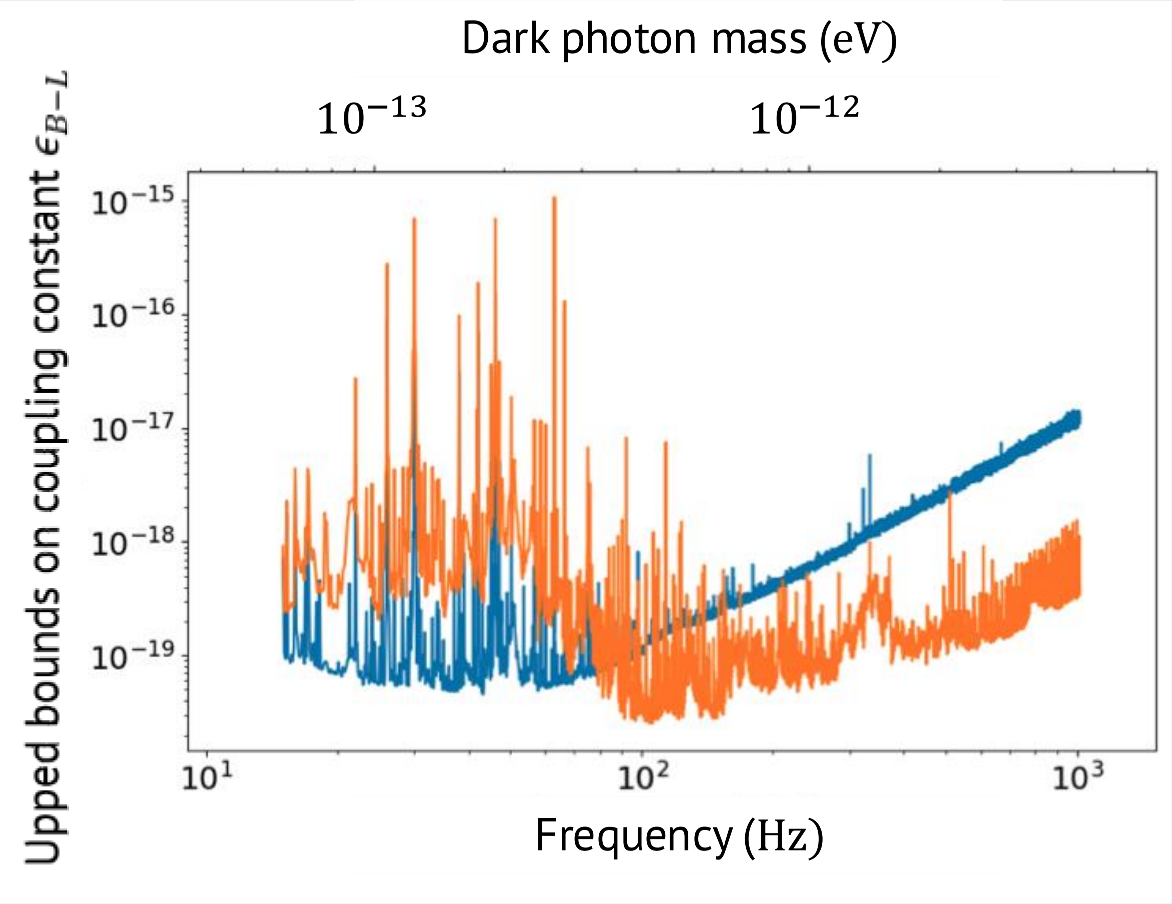
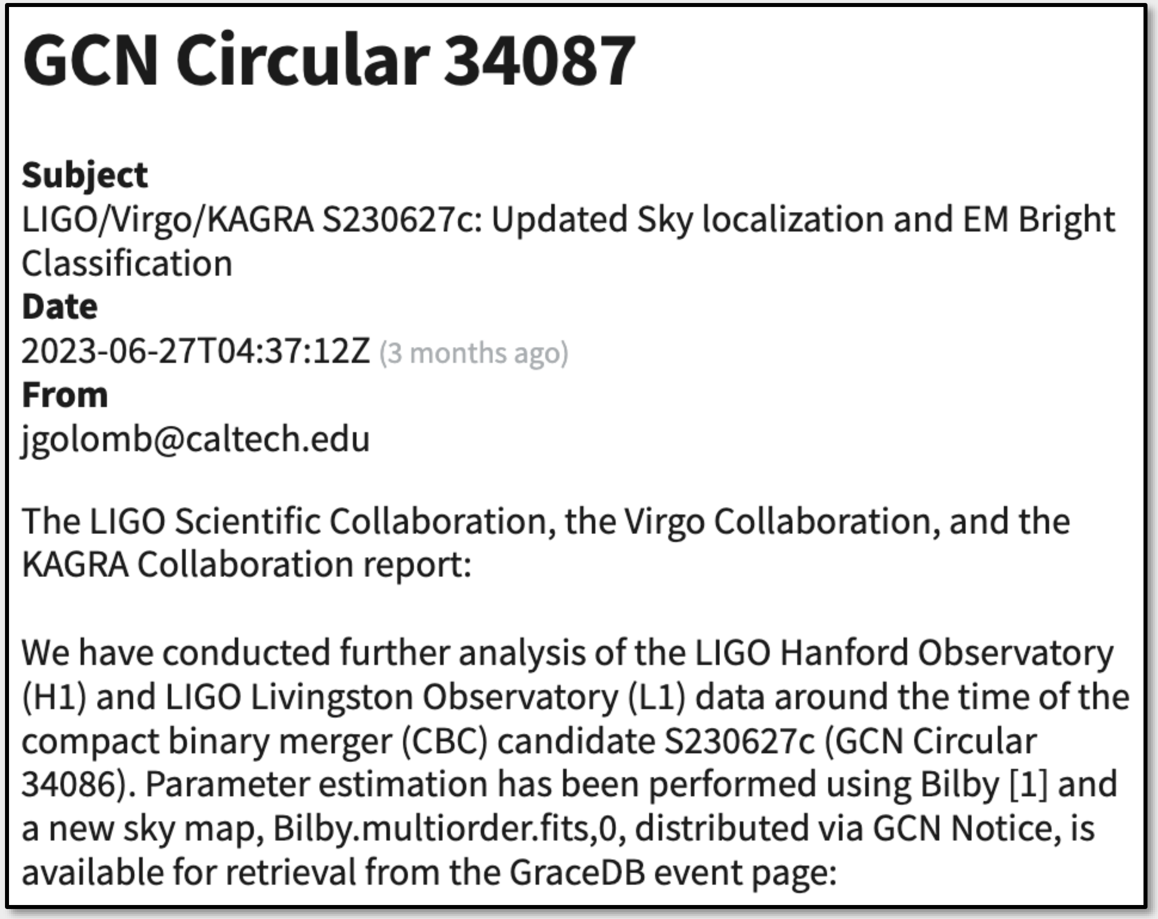


Figure: Upper bounds obtained from KAGRA O3 data

Low-Latency Parameter Estimation in O4 and toward O5



GCN Circular 34087

Subject
LIGO/Virgo/KAGRA S230627c: Updated Sky localization and EM Bright Classification
Date
2023-06-27T04:37:12Z (3 months ago)
From
jgolomb@caltech.edu

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration report:

We have conducted further analysis of the LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) data around the time of the compact binary merger (CBC) candidate S230627c (GCN Circular 34086). Parameter estimation has been performed using Bilby [1] and a new sky map, Bilby.multiorder.fits,0, distributed via GCN Notice, is available for retrieval from the GraceDB event page:

Update GCN circular for S230627c
https://gcn.nasa.gov/circulars/34087

Latencies of parameter-estimation updates were ~days in O3.

We developed a rapid parameter estimation technique for O4 (*SM* and V. Raymond 2021, *SM* et al. 2023):

- ~10 mins for a BNS signal
- ~1 hour for a NSBH signal

ex) For S230627c (a NSBH candidate), updated skymap was sent ~2 hours after detection, reducing the 90% credible area: $90\ \mathrm{deg}^2 \rightarrow 82\ \mathrm{deg}^2$.

Low-Latency Parameter Estimation in O4 and toward O5

We are utilizing a machine learning technique known as *Simulation-Based Inference* to achieve prompt parameter-estimation updates in O5.

Future work:

- Accelerating training with multibanding (*SM* (2021)) and relative binning (B. Zackay et al. (2018)).
- Efficient parameterizations of intrinsic and extrinsic parameters (E. Lee, *SM*, and H. Tagoshi (2022), J. Roulet et al. (2022)).

See the poster by Kazuki Takada.

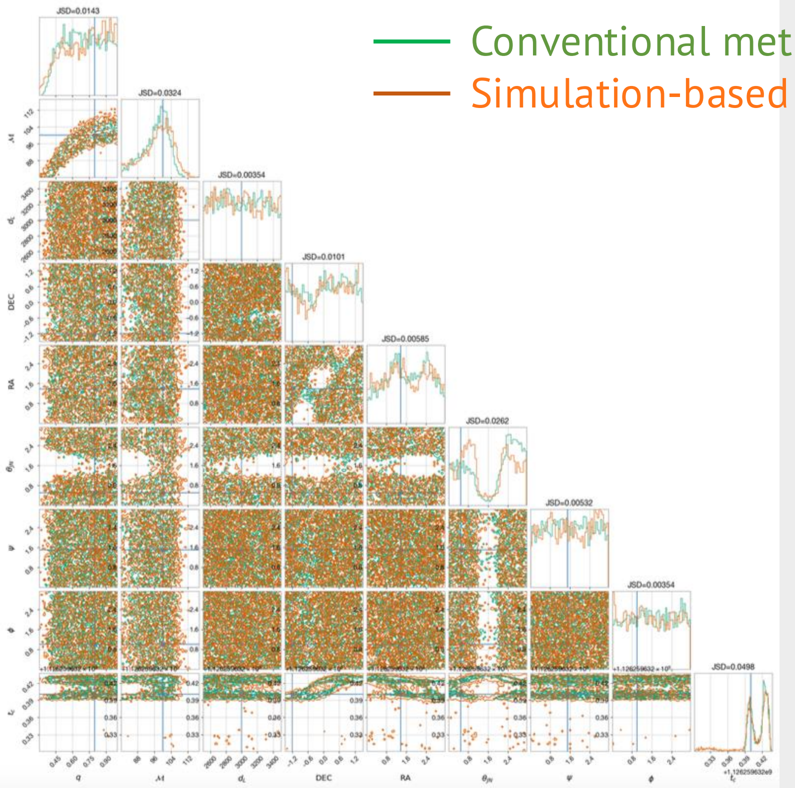
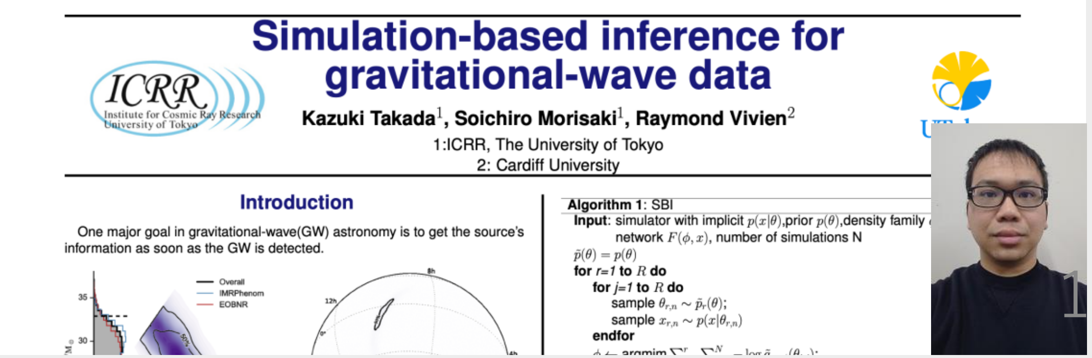


Figure: Posterior for a simulated signal obtained with different inference methods



Simulation-based inference for gravitational-wave data

Kazuki Takada[1], Soichiro Morisaki[1], Raymond Vivien[2]

1:ICRR, The University of Tokyo

2: Cardiff University

Introduction

One major goal in gravitational-wave(GW) astronomy is to get the source's information as soon as the GW is detected.

```
Algorithm 1: SBI
Input: simulator with implicit $p(x|\theta)$,prior $p(\theta)$,density family
        network $F(\phi, x)$, number of simulations N
$\tilde{p}(\theta) = p(\theta)$
for r=1 to $R$ do
    for j=1 to $R$ do
        sample $\theta_{r,n} \sim \tilde{p}_r(\theta)$;
        sample $x_{r,n} \sim p(x|\theta_{r,n})$
    endfor
```

Summary

- O4 is ongoing with LIGO's binary-neutron-star ranges ~ 160Mpc and will end on 9 June 2025.

- Several ongoing projects in preparation for O4 analyses and toward O5.
  - Statistical properties of binary black holes.
  - Tests of General Relativity with ringdown signals.
  - Searching for sub-solar-mass binaries and ultralight dark matter.
  - Low-latency parameter estimation using machine learning techniques.

- TODO:
  - Hopefully, we will detect multimessenger events in the remaining part of O4.
  - What can we do from non-detections? We will obtain better estimates on rates.