LIGO-Virgo-KAGRA 第4期重力波観測運転の現状と将来の展望

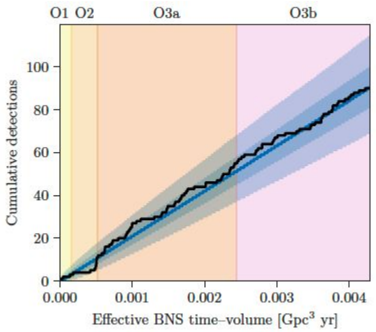
塚田怜央
ペンシルベニア州立大学

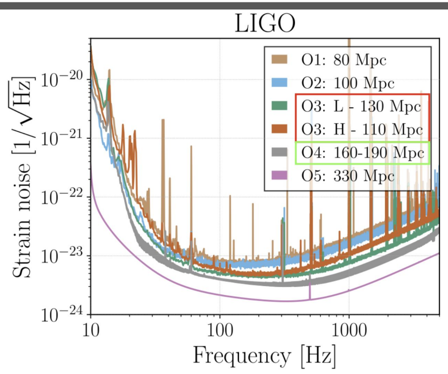
日本天文学会 2023年秋季年会
「マルチメッセンジャー宇宙物理学」

重力波観測の変遷

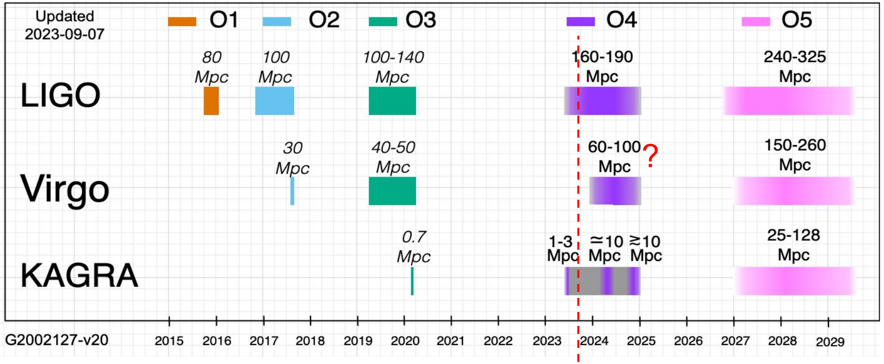
- 過去3回の観測運転 (O1 - O3)
  - コンパクト連星系起源の重力波信号を計90発検出
  - 各観測ごとに検出器感度を向上
    LIGO : 80 Mpc ⇨ 130 Mpc (BNS range)

- 第4期観測運転 (O4)
  - 当初の予定(2022年夏)から遅れて開始
  - 現時点ではLIGO2台での観測
  - 目標感度　LIGO : 160 - 190 Mpc
    Virgo : ?? Mpc
    KAGRA : 10 Mpc
  - 予想レート BNS : ~ 1発/ 3 - 6ヶ月 ?





R. Abbott *et al.*



https://www.ligo.org/scientists/GWEMalerts.php

第4期重力波観測運転

LIGO Ready to Explore Secrets of the Universe

News Release • May 24, 2023

Global network of gravitational-wave detectors starts next observing run

Today, the LIGO-Virgo-KAGRA (LVK) collaboration begins a new observing run with upgraded instruments and other improvements to boost the search for gravitational waves, or ripples in space-time, generated by colliding black holes and other extreme cosmic events. The LVK collaboration consists of scientists across the globe who use a network of gravitational-wave observatories—**LIGO** in the United States, **Virgo** in Europe, and **KAGRA** in Japan.

This observing run, the fourth since the National Science Foundation-funded **LIGO made history in 2015** by making the first direct detection of gravitational waves, will be the most sensitive yet. Called 04, the run begins on May 24, 2023, and will last 20 months, including up to two months of commissioning breaks, during which work will be undertaken to further improve instrument performance. The observing run will begin with the twin LIGO observatories resuming operations May 24; Virgo will join later in the year. KAGRA will join for one month beginning on May 24, then rejoin later in the run after some upgrades.

https://www.ligo.caltech.edu/news/ligo20230524

Virgo O4参加計画

LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS ¶

(15 September 2023 update; next update 15 October 2023 or sooner)

We started the O4 Observing run on 24 May 2023. The observing run will last 20 calendar months including up to 2 months of commissioning breaks for maintenance.

Over the past few weeks, the Virgo sensitivity reached a BNS range of up to 31 Mpc. On the other hand, the detector has also experienced control instabilities, which prevented us from doing systematic noise hunting and making further progress. An additional commissioning period, estimated to be at least three months, is needed for Virgo to achieve acceptable sensitivity to join O4. Given the current situation and the planned actions, Virgo anticipates joining not earlier than mid December.

https://observing.docs.ligo.org/plan/

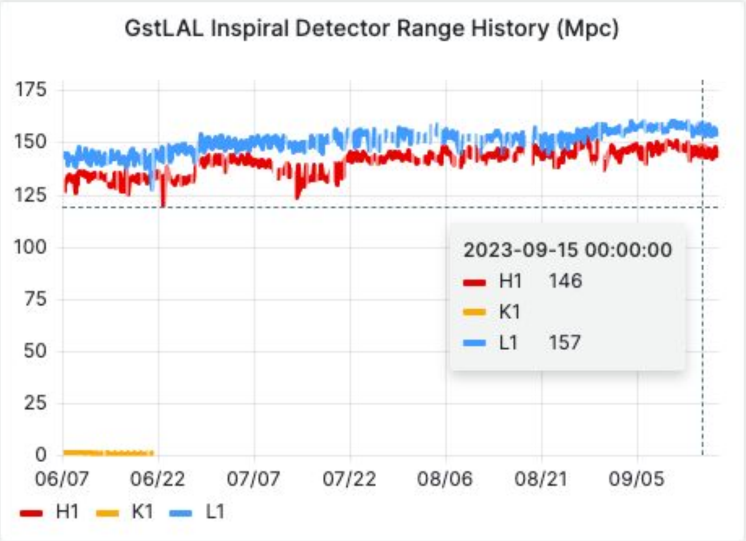
観測状況のモニタリング

➢ online.ligo.org で稼働状況と感度をリアルタイムで表示

Gravitational Wave Detector Network

Operational Snapshot as of Sept. 17, 2023 04:45:21 UTC

Detector	Status	Duration [hh:mm]	Latency [s]
GEO600	Observing	00:08	90
LIGO Hanford	Observing	00:53	80
LIGO Livingston	Observing	01:15	107
Virgo	Down	>99:00	82
KAGRA	Info too old	49:40	



GraceDB

- ➢ 計40イベント(誤検出率 FAR<1/month)が検出
  - 1イベント / 3 日
  - 38 BBH + 1 NSBH + 1 NSBH or BBH
  - BNSは未検出

LIGO/Virgo/KAGRA Public Alerts

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

O4 Significant Detection Candidates: **40** (49 Total - 9 Retracted) ← FAR < 1/month

O4 Low Significance Detection Candidates: **827** (Total) ← FAR < 14/day

https://gracedb.ligo.org/superevents/public/O4/

イベントページ(例:S230914ax)

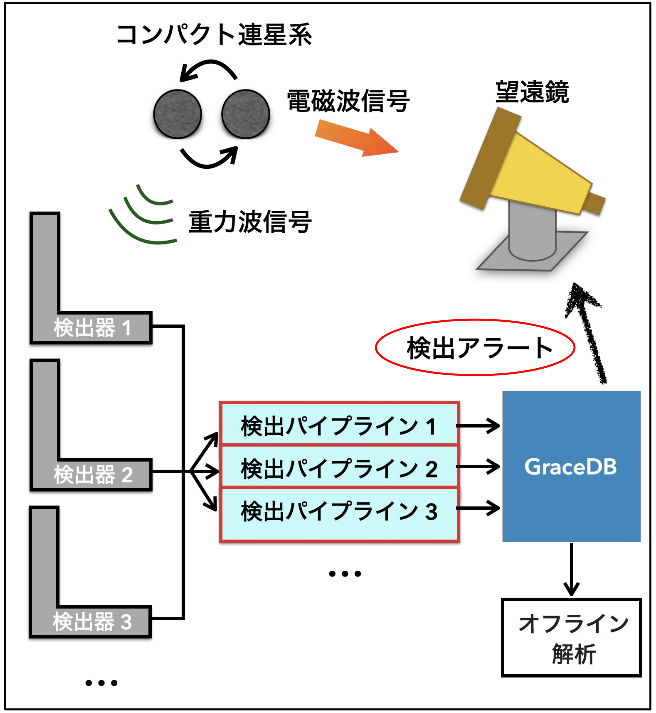
S230819ax
日付　a,b,c -> aa, ab

Superevent Information	
Superevent ID	S230819ax
Category	Production
FAR (Hz)	8.842e-09
FAR (yr^{-1})	1 per 3.5837 years
t_0	1376500768.45
t_{end}	1376500769.48
Submitted ▾	2023-08-19 17:19:24 UTC
Links	Data

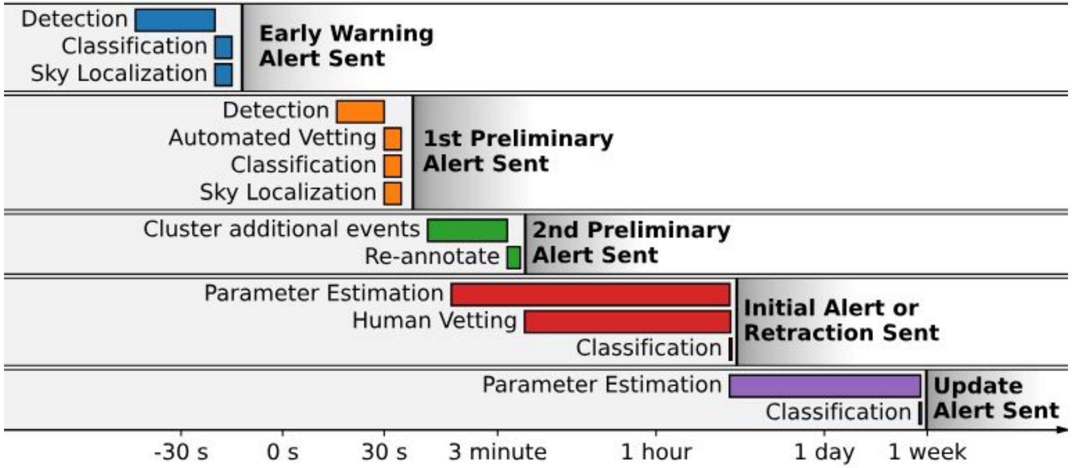
Event Information	
Group	CBC
Pipeline	gstlal
Search	AllSky
Instruments	H1,L1
Event Time ▾	1376500768.455
Submitted ▾	2023-08-19 17:19:27 UTC

重力波検出アラートシステム

アラートシステム概略図



各アラート発出のタイムスケール



https://emfollow.docs.ligo.org/userguide/analysis/index.html

重力波検出アラートシステム

GCN Circular (例:S230807f)

GCN Circular 34360

Subject LIGO/Virgo/KAGRA S230807f: Identification of a GV
Date 2023-08-07T21:46:40Z (a month ago)
From Dripta Bhattacharjee <dripta.bhattacharjee@ligo.(
Submitted By Web form

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

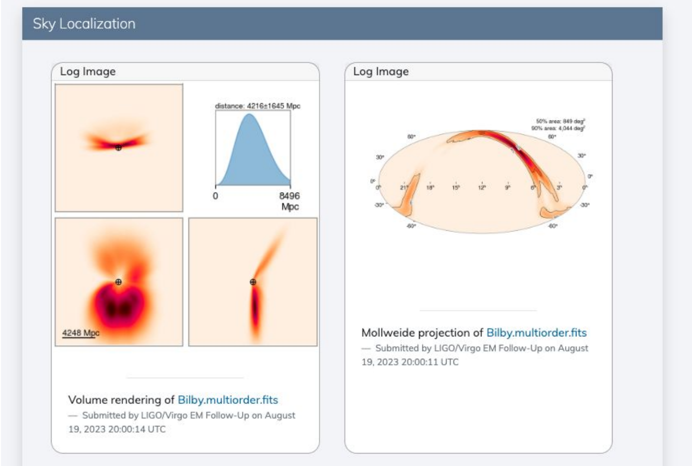
We identified the compact binary merger candidate S230807f during real-time processing of data from LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) at 2023-08-07 20:50:45.416 UTC (GPS time: 1375476663.416). The candidate was found by the CWB [1], GstLAL [2], MBTA [3], PyCBC Live [4], and SPIIR [5] analysis pipelines.

S230807f is an event of interest because its false alarm rate, as estimated by the online analysis, is 7.1e-08 Hz, or about one in 5 months. The event's properties can be found at this URL:

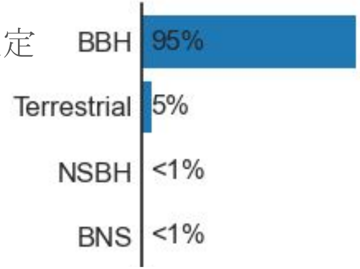
https://gracedb.ligo.org/superevents/S230807f

The classification of the GW signal, in order of descending probability, is BBH (86%), Terrestrial (14%), NSBH (<1%), or BNS (<1%).

波源の位置推定マップ



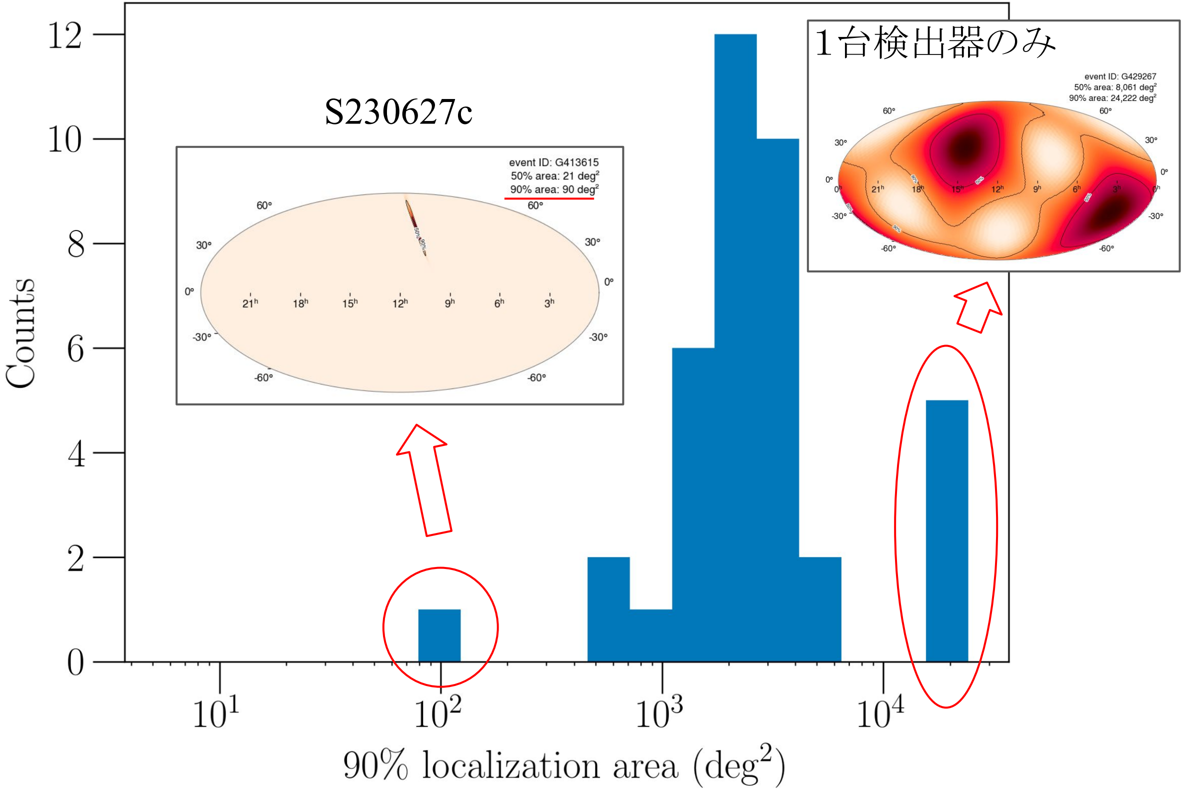
波源天体のカテゴリ推定



到来方向の推定精度

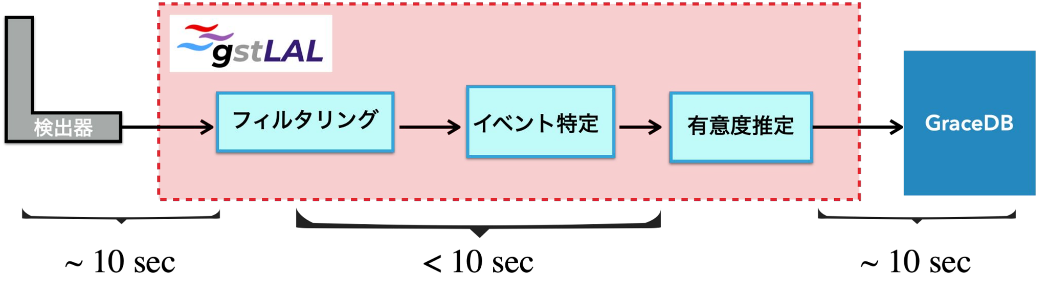
- LIGO2台のみ稼働
  - 多くがO(1000) deg^2
  - 5イベントが1台検出器
  - S230627cが現時点での位置推定の最高精度

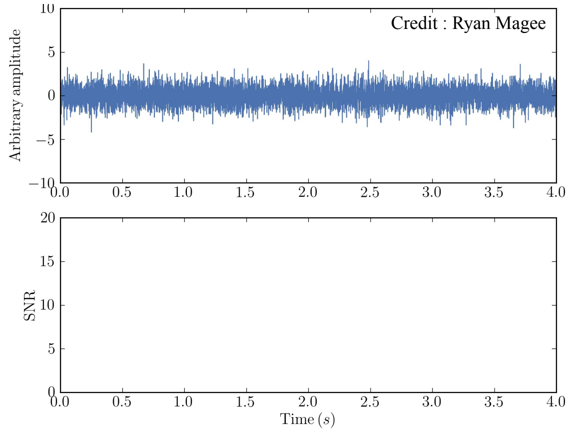
- S230627c
  - LIGO2台で同時検出
  - 光度距離 ~ 291Mpc
  - 90% 位置推定：90 deg^2
    cf. GW170817 : 28 deg^2
  - NSBH 49%, BBH 48%
  - 対応天体の報告なし



低遅延検出パイプライン

➢ 例: GstLAL

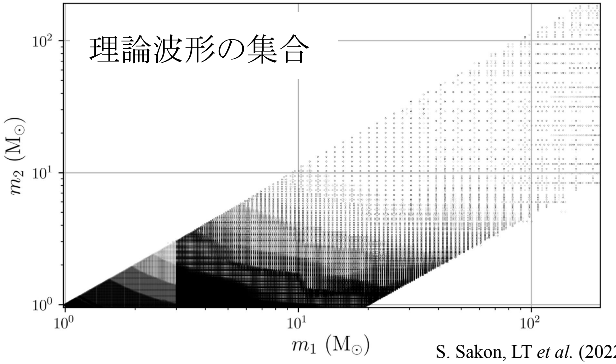




➢ マッチドフィルター

理論波形

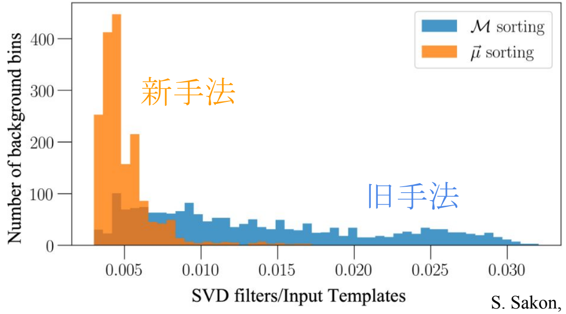
$$\mathrm{SNR}(t) = 4\int_0^\infty \frac{\tilde{h}^*(f)\tilde{s}(f,t)}{S_n(f)}df$$



S. Sakon, LT *et al.* (2022)

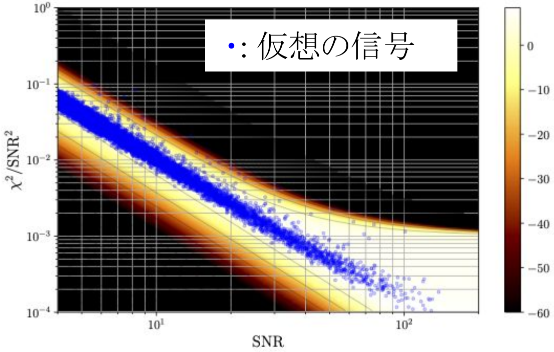
O4に向けたGstLALの感度向上

➢ 特異値分解を用いた理論波形データの圧縮率向上

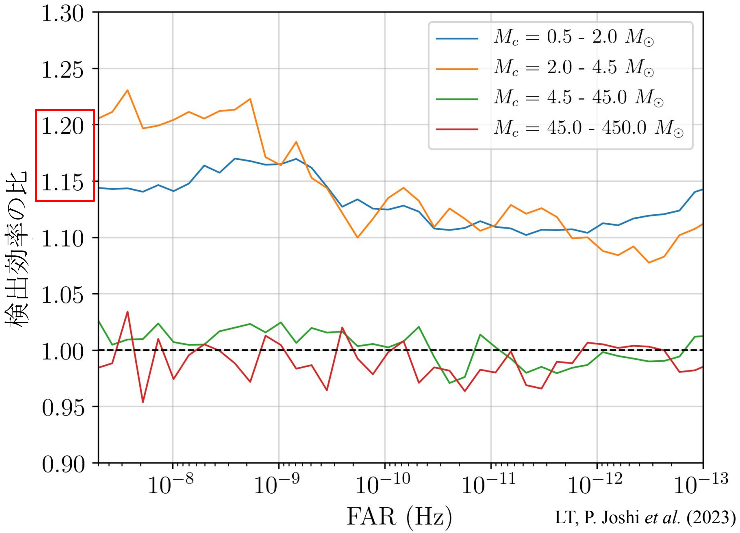


S. Sakon, LT *et al.* (2022)

➢ SNR-χ^2 の信号モデルを解析的に導出



➢ 検出感度がO3と比べ、15-20% の向上が示された

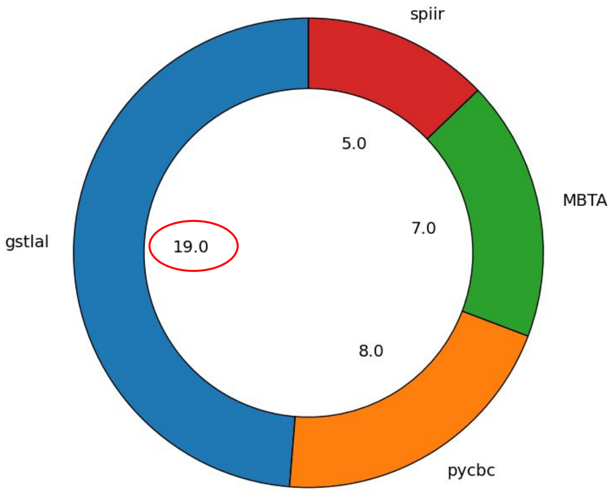


LT, P. Joshi *et al.* (2023)

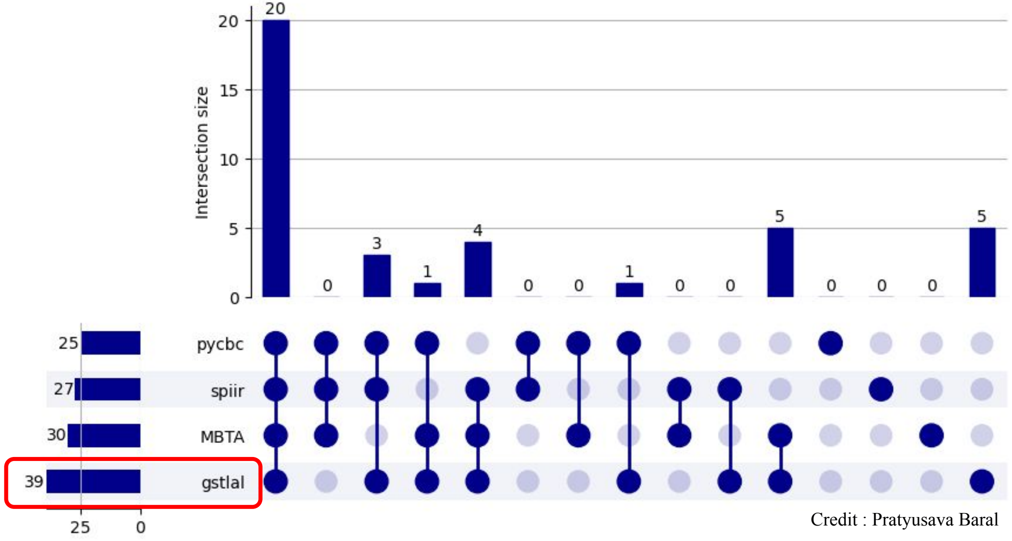
検出器雑音だけでなく、解析パイプラインの感度も非常に重要

検出イベントの内訳

各イベントでSNR最高値を記録した
パイプラインの内訳



各イベントを同時検出した
パイプラインの内訳



Credit : Pratyusava Baral

GstLALはすごい

パラメータ推定

- ベイズの定理

事後分布　尤度関数　事前分布

$$p(\theta|d) = \frac{p(d|\theta)\cdot p(\theta)}{p(d)}$$

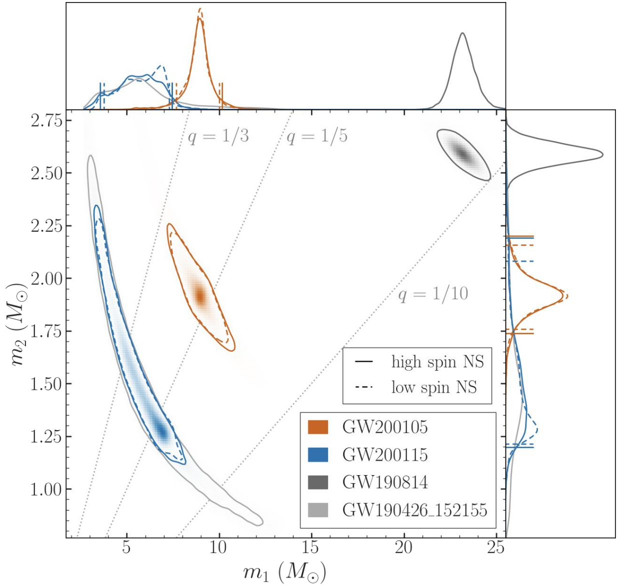
$\theta = \{m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, D, ...\}$ (15次元)

- 確率的に生成したサンプルで事後分布を構築
  - 高次元空間内のサンプリングが必要
  - 波形生成の計算コスト高

⇩

O3までは数日をかけてオフライン解析を行った。

連星系の質量に関する事後分布の例



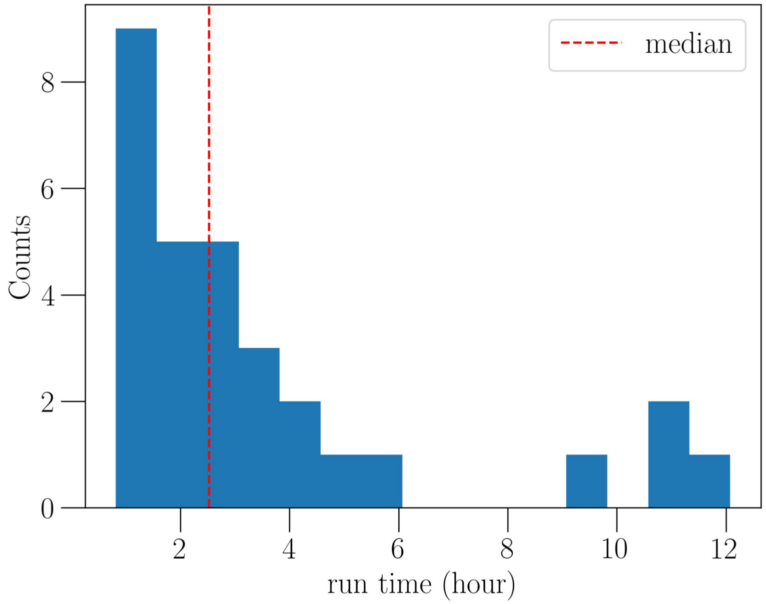
R. Abbott *et al.* (2021)

パラメータ推定

対応天体の観測に向けたO4での改善

- ➢ パラメータ推定の自動化
- ➢ 尤度評価や波形生成の効率化
  - ○ ROQ 基底の活用
    S. Morisaki, LT *et al.* (2023)
  - ○ 各周波数帯域でのサンプル数の低減
    S. Morisaki (2023)
- ➢ 典型的な解析所要時間 2.5時間
  - ○ O3:数日 - 1週間

Credit : Soichiro Morisaki



まとめ

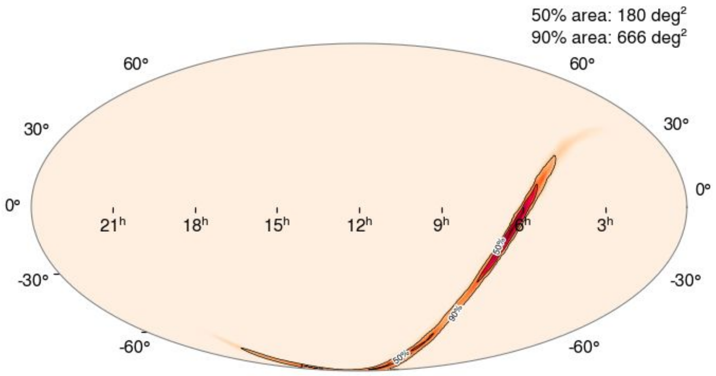
- 2023年5月にLIGO-Virgo-KAGRA コラボレーションがO4を開始
  - 計18ヶ月(+2ヶ月のCommissioning break)の観測を予定している
  - 現在稼働中のLIGO検出器は目標に近い感度に到達
  - Virgo、KAGRAは感度向上後に観測に参加予定
- 9月20日時点で計40発の重力波信号を検出
  - 1つのNSBH候補を除き、全てBBHである可能性が高い
  - LIGO2台での検出のため、位置推定精度は O(1000) deg^2程度に留まる
  - 検出パイプラインやパラメータ推定は性能向上を実現している
- 将来の展望
  - LIGOによる検出レート自体はO3を上回っている
  - 対応天体の観測のためには3台目の検出器が不可欠 (Virgo or KAGRA?)
  - 待望のBNSはいつ検出されてもおかしくはない

Stay Tuned!!

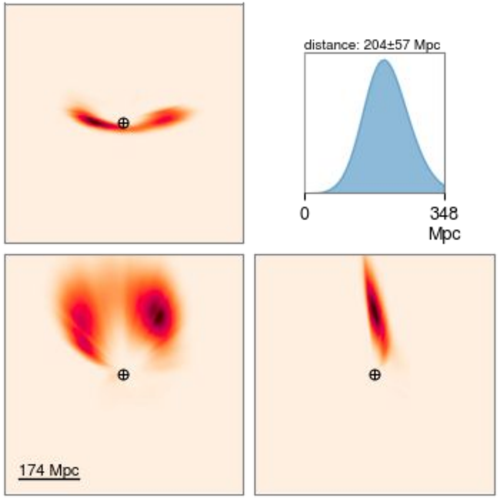
S230518h

O4 開始前(engineering run)での検出
FAR ~ 1 per 98.463 years

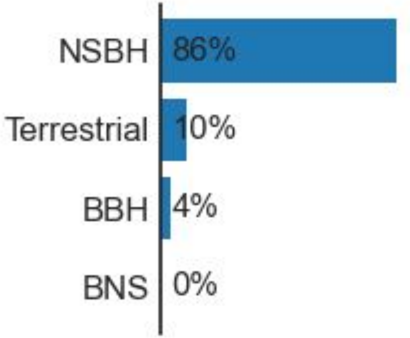
位置推定マップ



光度距離推定



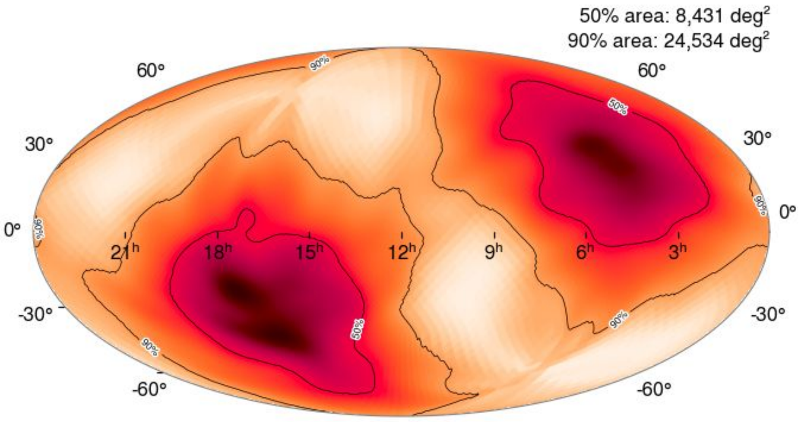
連星系のカテゴリ推定



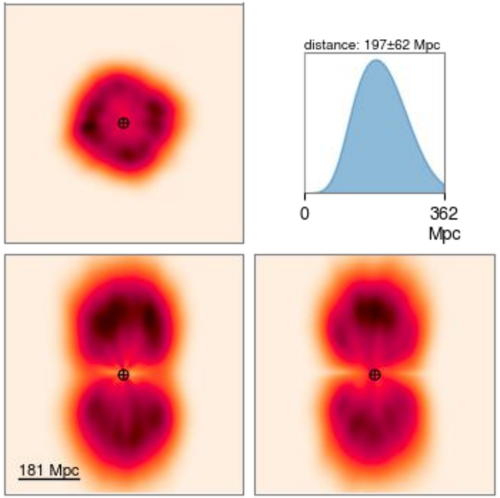
S230529ay

検出器1台のみ(LIGO Livingston)での検出
FAR ~ 1 per 160.44 years

位置推定マップ



光度距離推定



連星系のカテゴリ推定