Observations of Compact Binary Coalescences by LIGO-Virgo-Kagra Collaboration

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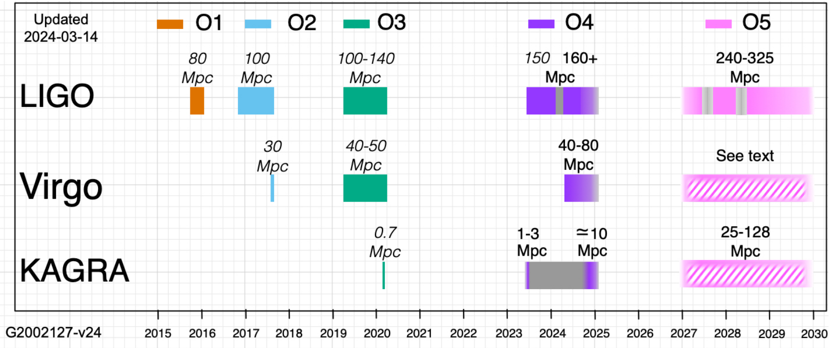
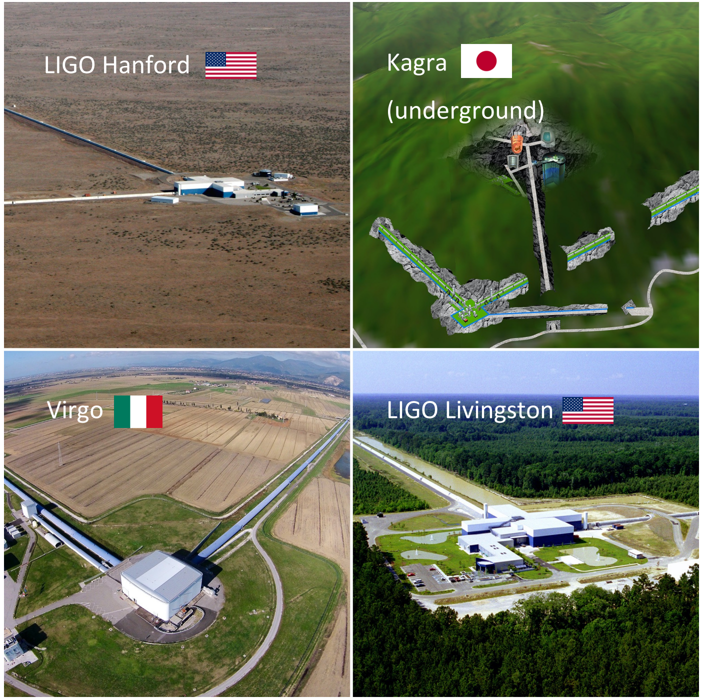
LIGO-Virgo-KAGRA Collaboration

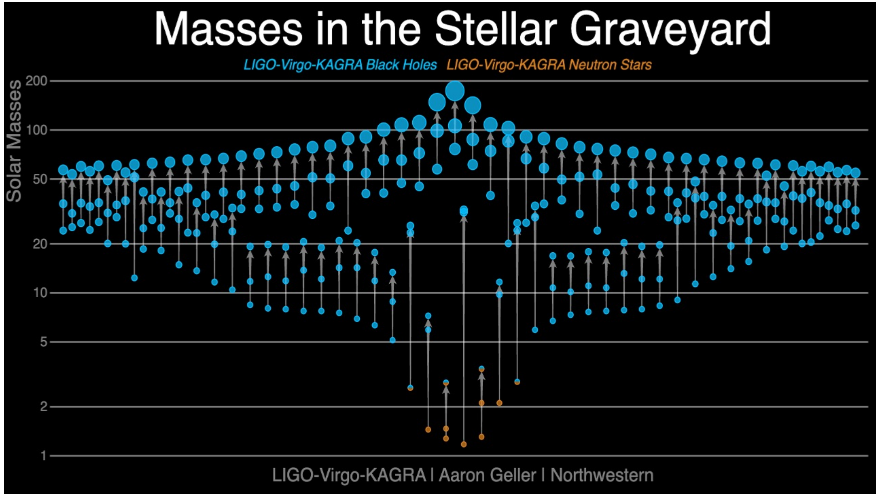
- **Detector Type:** Advanced Michelson interferometers
- **GW Frequency Range:** Sensitive to ~ 10 Hz – several kHz, ideal for detecting compact binary coalescences (CBCs):
  - Binary Black Holes (BBH)
  - Binary Neutron Stars (BNS)
  - Neutron Star-Black Hole (NSBH)





Gravitation Wave Transient Catalog - 3

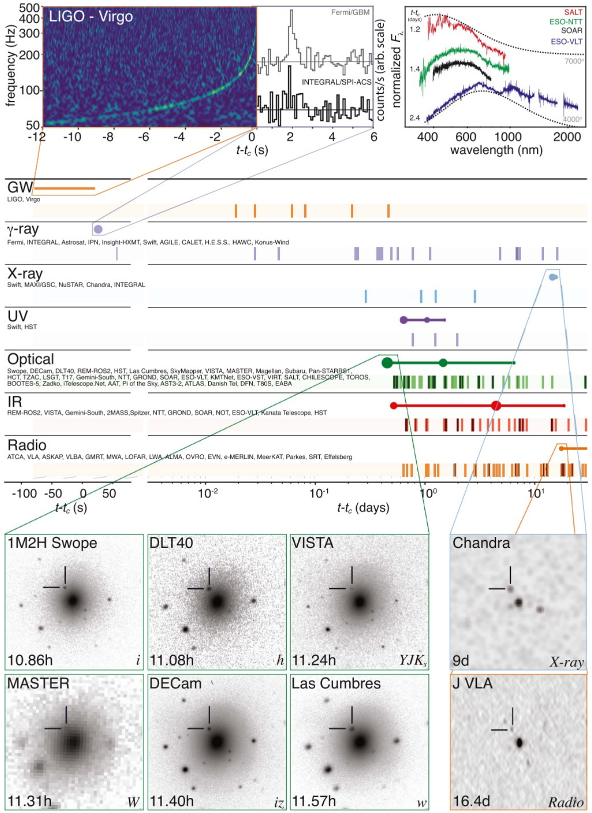
- **GW150914:** The first direct detection of gravitational waves, observed on Sept. 14th 2015 from a binary black hole merger
- **GWTC-3:** 90 events from the O1 to O3 run (arxiv)
- **O4 run:** started in 24th May 2023, divided into O4a/O4b
- O4a data release (**GWTC-4**) expected in August 2025.
- **81 public low-latency alerts** sent during O4a to astronomy community for EM follow-up (+11 retracted alerts after human noise vetting)



R. Weiss, K. S. Thorne, B. C. Barish

GW170817: first multi-messenger event!

- **First BNS Detection:** GW170817 was the first detection of a binary neutron star merger, observed on August 17th 2017
- **Host Galaxy:** NGC 4993, identification allowed for precise localization and study of the progenitor's environment
- **Multi-messenger Astronomy:** This event was also observed across the electromagnetic spectrum, providing comprehensive data:
    - A short gamma-ray burst GRB 150101B was associated to this event
    - **Kilonova:** The bright electromagnetic radiation confirmed the production of heavy elements through r-process nucleosynthesis in BNS mergers

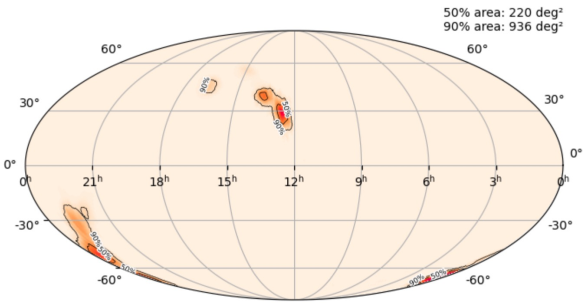


(arxiv)

Some notorious GW observations

GW190521

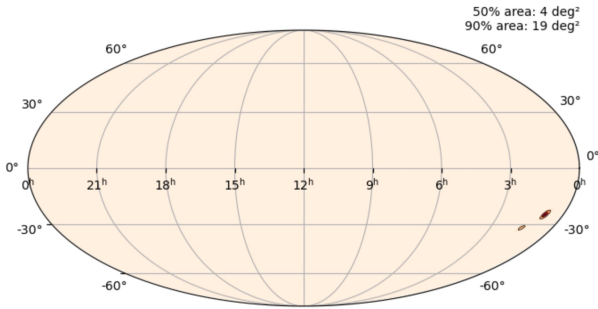
A merger of two black holes with masses of approximately 85 and 66 solar masses, resulting in a final black hole of around 142 solar masses. This event is significant because it falls in the predicted pair-instability mass gap.



Sky localization
(arxiv)

GW190814

A merger involving a 23 solar mass black hole and a 2.6 solar mass object, potentially the lightest black hole or the heaviest neutron star ever observed.

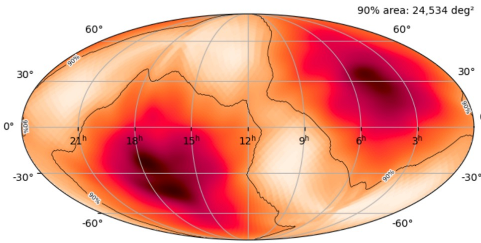


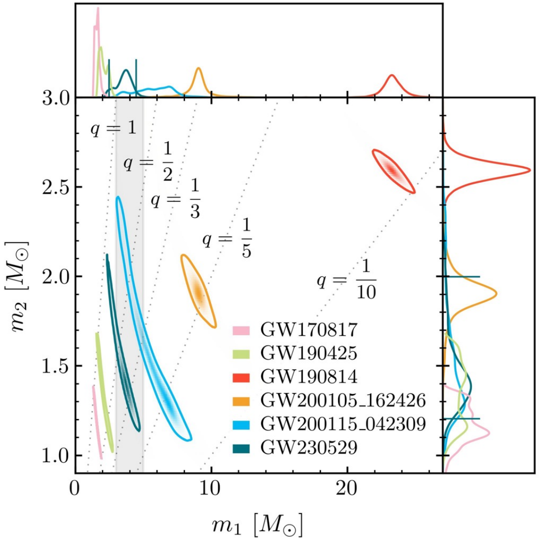
Sky localization
(arxiv)

GW230529: A particular O4a event

- One discovery from O4a is now public (arxiv)
- Coalescence of a 2.5-4.5 $M_\odot$ Compact Object and a NS (90% confidence)
- X-ray binary systems within the Milky Way suggests a mass gap in the 3-5 $M_\odot$ region (lower mass gap)
- Discovery provides further evidence for compact objects existing within it
- Cannot determine if the 2nd object is BH or NS considering the GW alone

CBC analysis pipelines	GstLAL	MBTA	PyCBC
Online S/N	11.3	11.4	11.6
Online inverse FAR (yr)	1.1	1.1	160.4
Offline inverse FAR (yr)	60.3	>1000	>1000

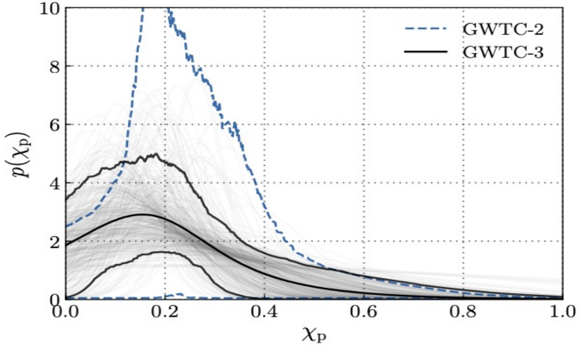


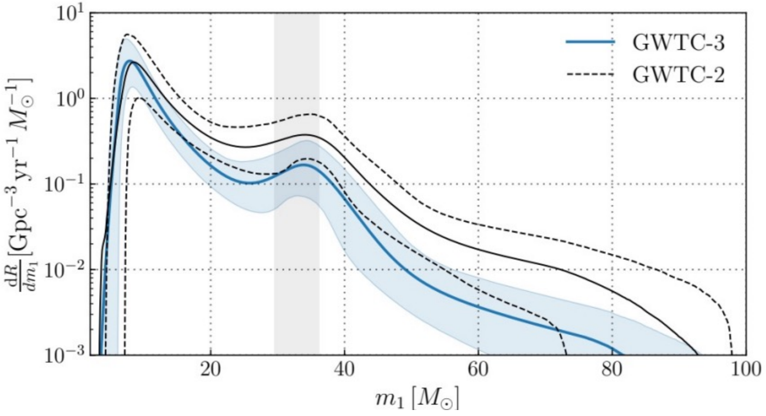


Rates & Populations

- BH mass distribution fits with a power-law + a Gaussian peak, indicating a possible substructure
- Current observations suggest that the mass distribution of black holes does not significantly depend on redshift
- Evidence of spin-induced precession, smoking gun for dynamical formation channel of BBH!
- NS in binaries slightly heavier than galactic NS

Merger Rate $[\mathrm{Gpc}^3.\mathrm{year}^{-1}]$
Binary Black Holes ~ 17.9 to 44
Neutron Star-Black Hole ~ 1.8 to 140
Binary Neutron Stars ~ 10 to 1700





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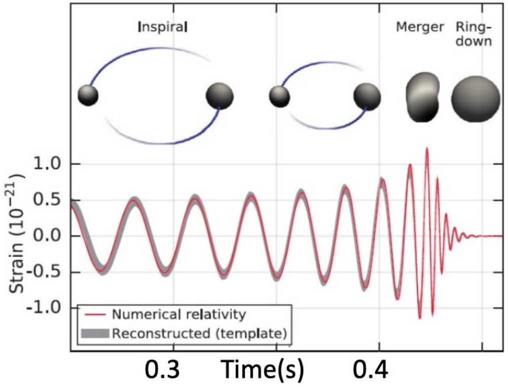
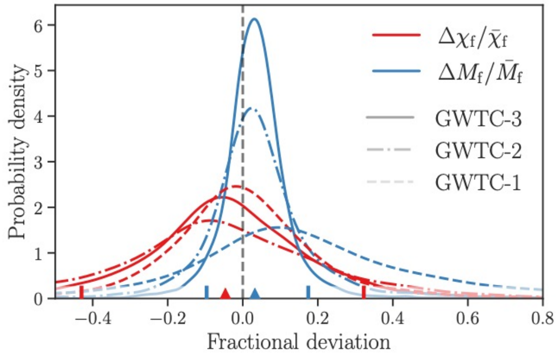
Tests of General Relativity

- Residual tests measure the coherent residual SNR after subtracting the best-fit GR waveform, no deviation identified
- Checks the post-Newtonian coefficients to be consistent with the predictions from GR
- Consistency checks of low and high-frequency parts of the GW signal
- Bound on the mass of the graviton, at 90% credibility $m_g \leq 1.27 \times 10 - 23\ eV/c^2$





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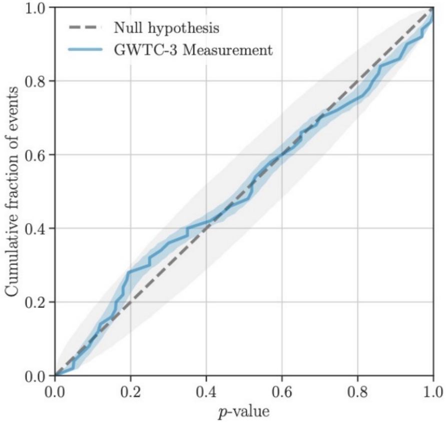
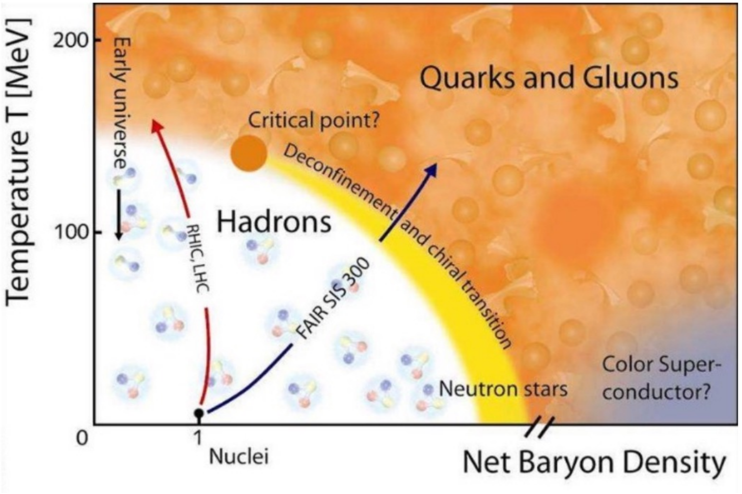


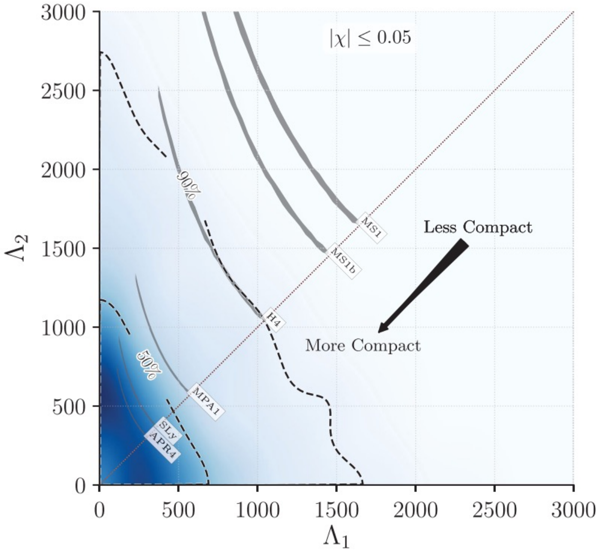
Extreme Matter Physics with BNS!

- Tidal effects before the merge of the 2 neutrons stars tightly linked to their mass, modeled by NS equation of state
- Parameter estimation (Bayesian inference) of the mergers => Tidal deformability Λ, Masses of the BNS components

→ GW detections help to constrain the EoS models of NS!



GW170817



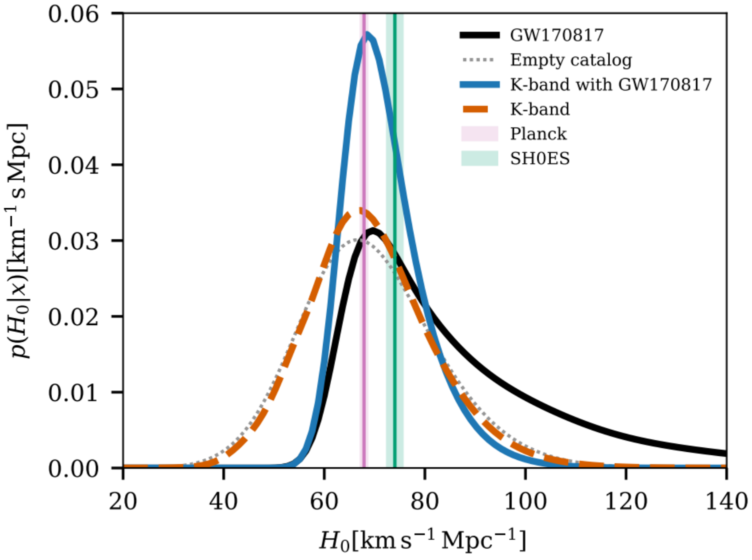
Towards constraining cosmic history!

- GW provides direct measurement of d_L, no calibration needed
- For $z << 1$ redshift event:

$$z = \frac{H_0}{c} d_L$$

Several methods to measure H_0:

- If EM counterpart → Redshift information from EM counterpart (**GW170817**)
- Otherwise:
  - ➢ Statistical inference of redshift using probable galaxy hosts (works well for precisely localised events)
  - ➢ Jointly constrain the cosmological parameters and the source population properties of BBH



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Summary

- Gravitational waves continue to expand our understanding across various fields of physics
- The era of multi-messenger astronomy with GWs has begun!
- Many other search activities within LVK:
  - **Sub-Solar Mass Black Holes:** primordial black holes as potential dark matter candidates
  - **Gravitational Lensing:** Searching for lensing signatures in GW signals to study dark matter
  - Investigating unmodeled GW sources, including bursts (e.g., supernovae), continuous waves, and the stochastic GW background

Thank you for your attention!

LVK Fourth Observation Run (O4)

- Started on **24th May 2023**, divided into O4a and O4b
- 81 public alerts sent to astronomy community (**GCN**) during O4a (11 others retracted after human noise vetting)
- Information made public before data release : sky localization, d_L estimate and some EM emission probabilities
- ~ 2 candidates consistent with containing a NS
- ~ 3 candidates may have an object with masses between 3-5 $M_{\odot}$ (lower mass gap)

Significance	Low-significant	Highly significant
Public events	1624	81