Results from the O3 run of LIGO-Virgo-KAGRA and prospects for O4

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Recap of gravitational-wave astronomy

Gravitational-wave theory

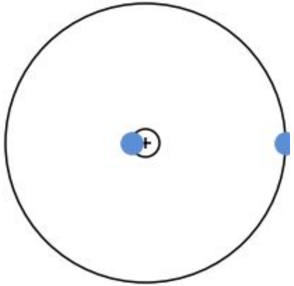
Einstein field equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Linearization

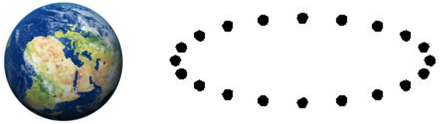
Flat spacetime　　Small perturbation

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$



r ~ 1 Gpc

Redshift, lensing, new physics…

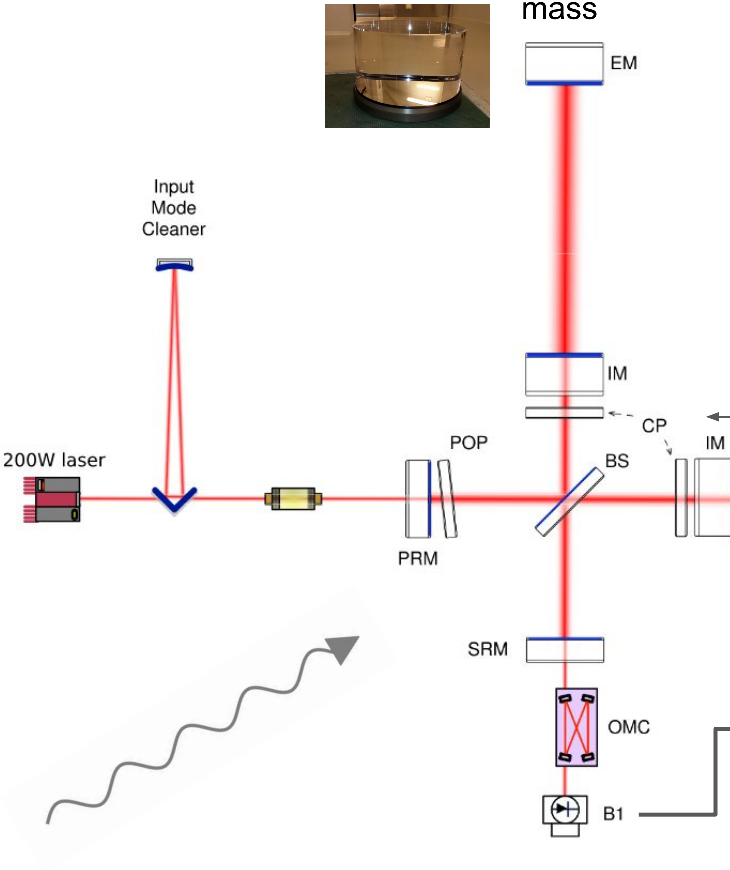


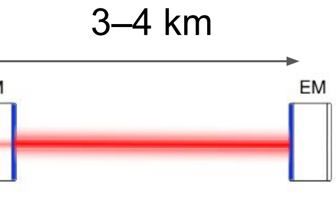
Astrophysical source
Mass ~ 10 M_{Sun}
Velocity ~ c
Mass quadrupole Q

$$h_{ij} \sim \frac{G}{c^4}\frac{\ddot{Q}}{r} \sim \Delta L/L \sim 10^{-22}$$

Experimental measurement of gravitational waves

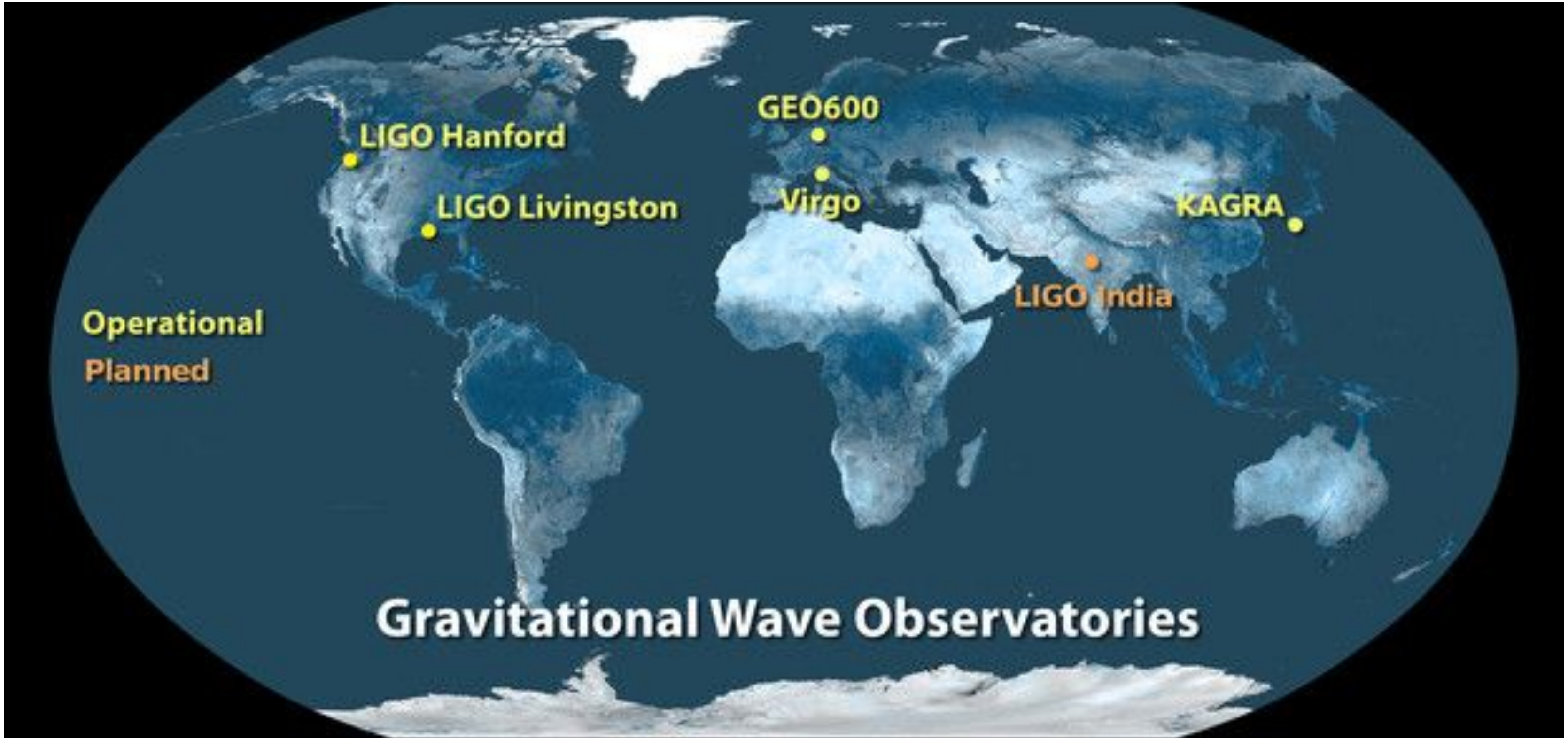
Test mass





Data acquisition system → Calibration Cleaning … → GW strain time series $h(t)$ → Astrophysical analyses

Experimental measurement of gravitational waves



Gravitational-wave data

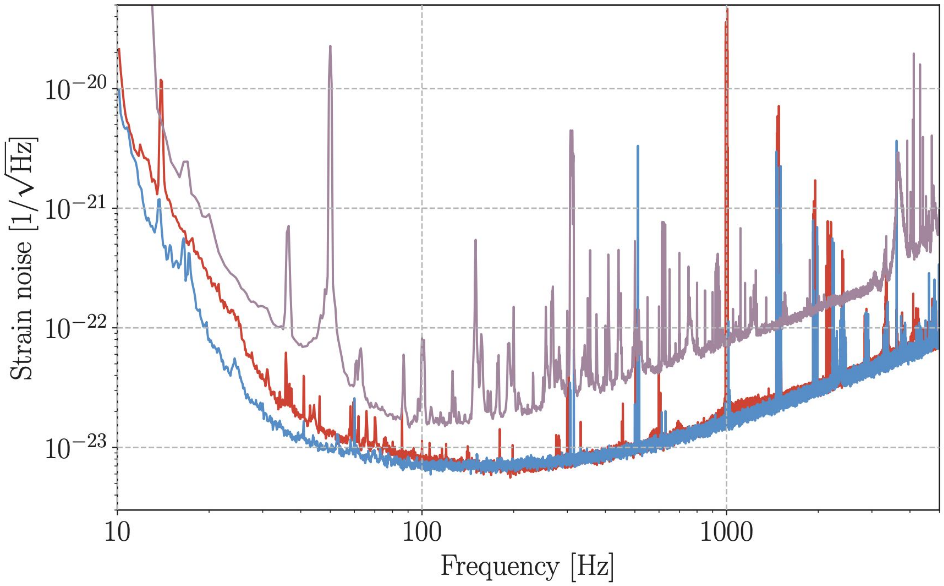
https://www.gw-openscience.org/

First component:

Quasi-stationary, quasi-Gaussian detector noise

Described via the spectral density of its variance/power/amplitude.

Related to fundamental physics: laser shot noise, thermal noise, radiation pressure…



Gravitational-wave data

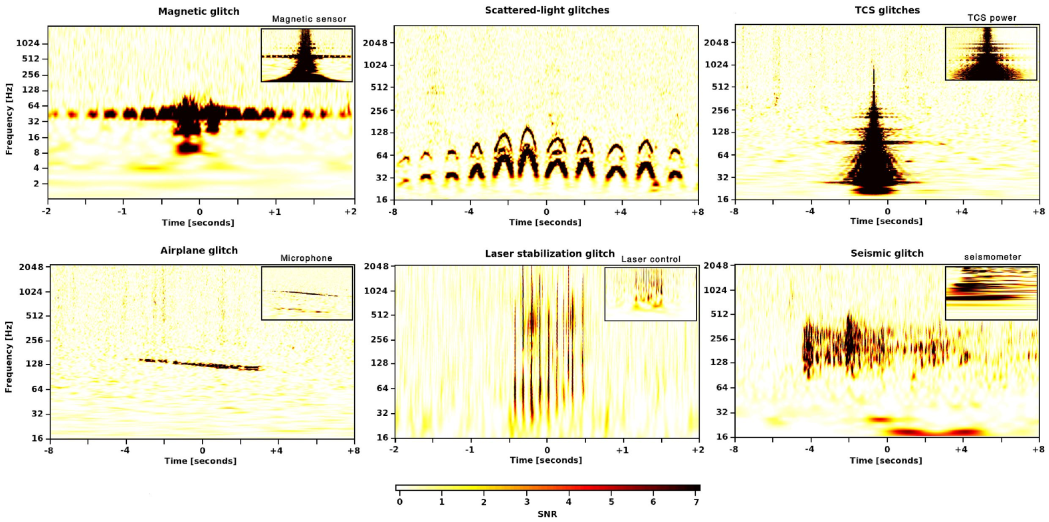
https://www.gw-openscience.org/

Second component:

Transient detector noise, “glitches”, spectral lines

Often very hard to model, predict or eliminate. Investigated and characterized via time-frequency decompositions.

Related to imperfect isolation of the detector, imperfect behavior of its various components, human activity, weather, earthquakes, etc.



Gravitational-wave data

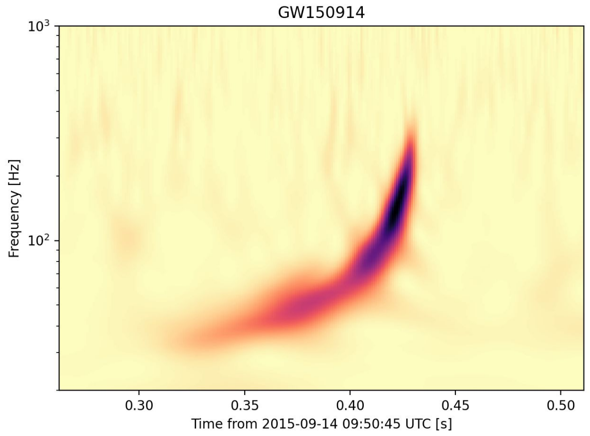
https://www.gw-openscience.org/

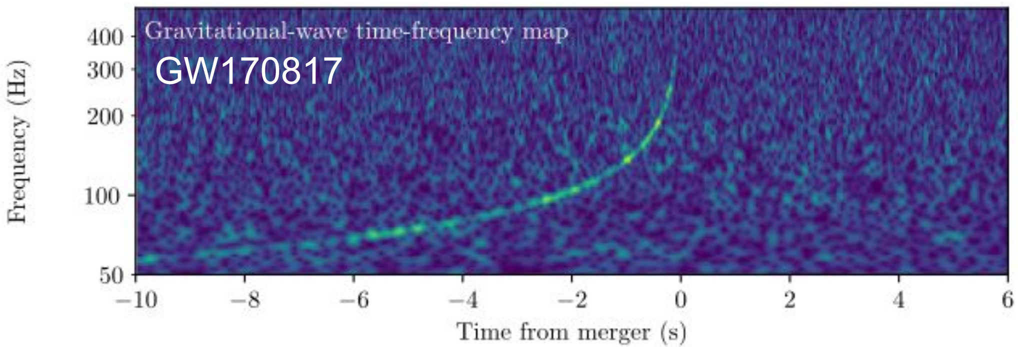
Third component:

Superposition of astrophysical signals

Short-lived / persistent
Narrow-band / wide-band
Strongly-modeled / weakly-modeled

Compact binary mergers
Core-collapse supernovae
Rotating neutron stars
Cosmic string bursts
Stochastic background
…





Data analysis and dissemination of results

Detector characterization, noise removal, data visualization

Identification of astrophysical signals

Characterization of individual signals

“Hyperanalyses”

Low-latency results
Seconds to hours.
Significance, timing, rough spatial localization, rough source classification.

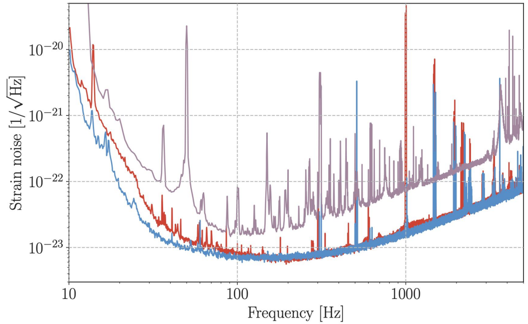
Medium-latency results
Hours to days.
Improved localization and classification.

“Offline” results – Event catalogs
Months to years.
Full event-by-event characterization, hyperanalyses, MMA…

A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals
LIGO & Virgo collaborations, arXiv:1908.11170

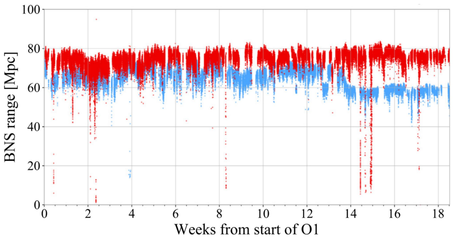
Results from the O3 run (2019-2020)

Sensitivity evolution for binary neutron star mergers

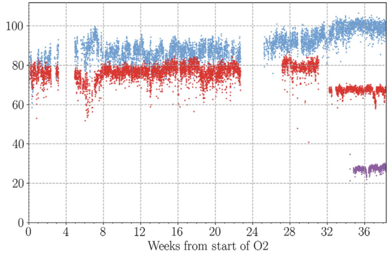


BNS range: average lum. distance at which we can "see" a NS-NS binary, taking m_{NS} = 1.4 M_{Sun} as a reference.

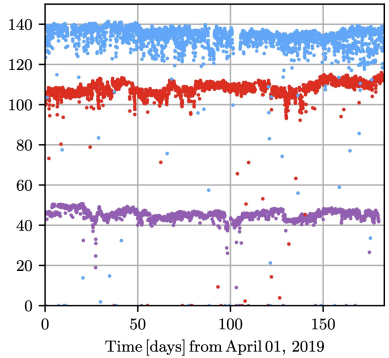
O1



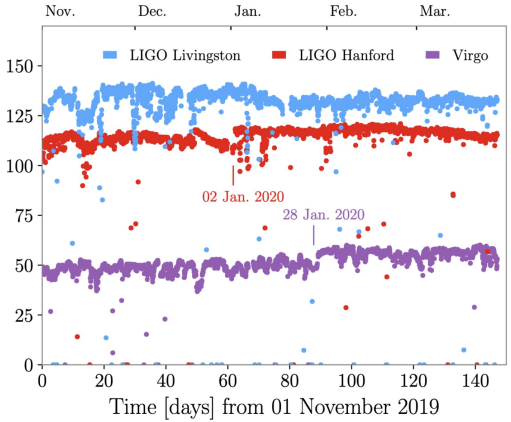
O2



O3a



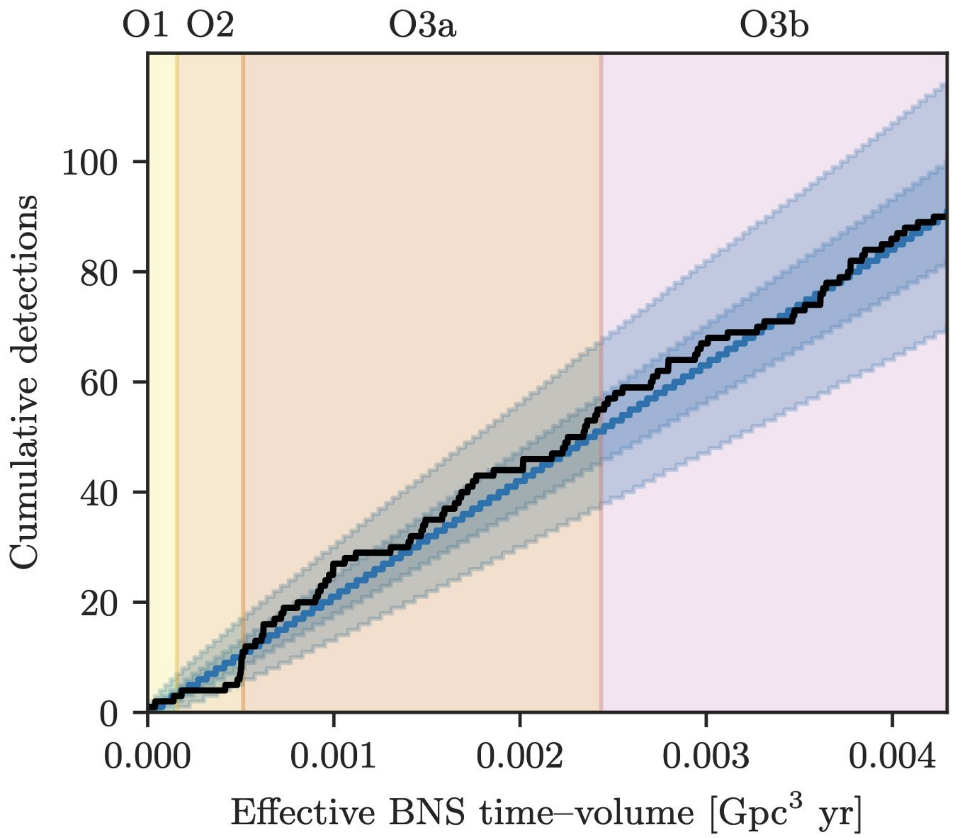
O3b



Detection rate ~ range^3 for $z \lesssim 1$, then cosmology.

Range grows with mass up to ~100 M_{Sun} then drops back to zero.

Catalog of gravitational-wave transients - GWTC



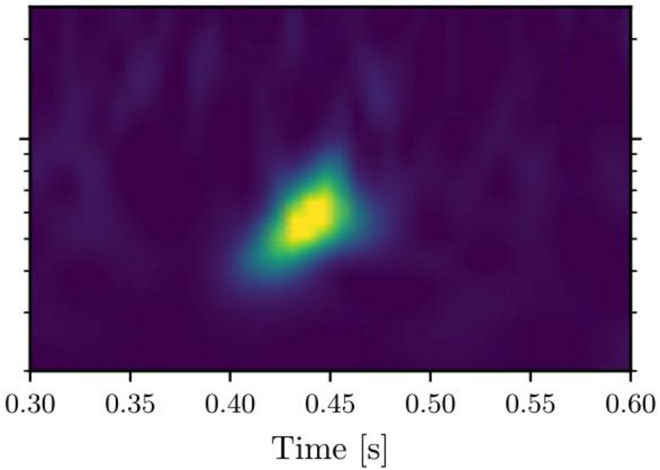
~90 transients at the end of O3.

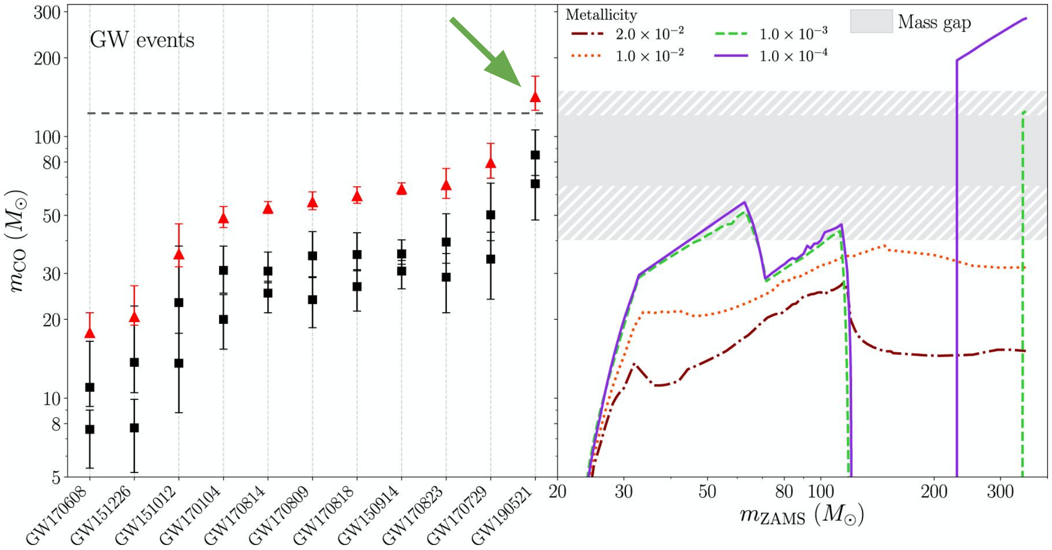
All consistent with the coalescence of compact binary systems in quasicircular orbits.

Available online on the GWOSC web site: https://www.gw-openscience.org/eventapi/html/GWTC/

Publications:
arXiv:2010.14527 (superseded)
arXiv:2108.01045
arXiv:2111.03606

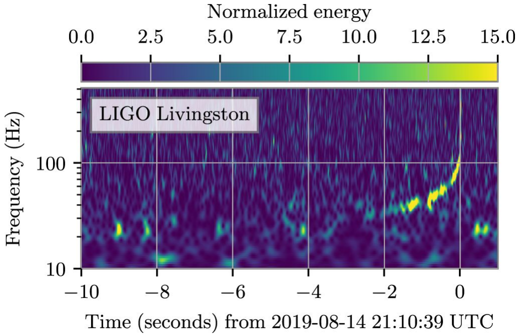
GW190521: a particularly massive black hole merger

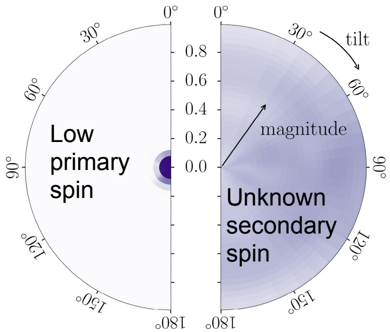




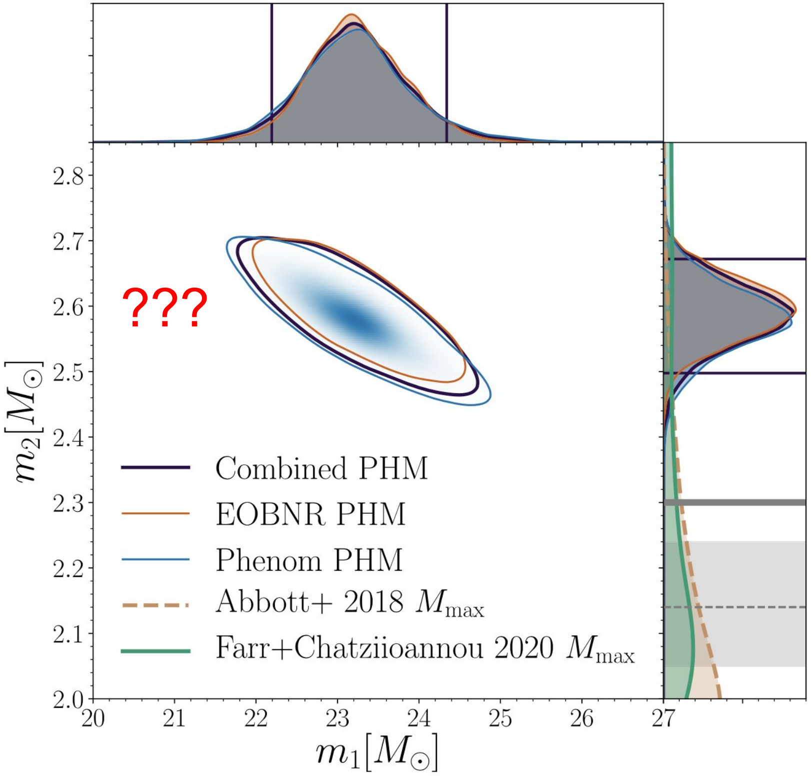
- Shortest transient confidently detected.
  LIGO/Virgo, arXiv:2009.01075
- Various astrophysical interpretations possible.
  LIGO/Virgo, arXiv:2009.01190
- Simplest one: BH-BH merger of total mass ~150 $M_{\rm Sun}$ at redshift ~0.6 → “tail” of BBH population.

GW190814: a compact object with an unexpected mass





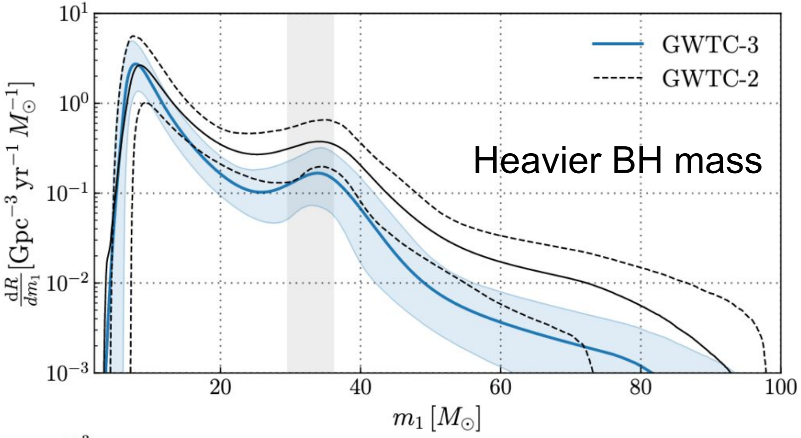
- Ambiguous nature of the secondary object: either a **very light BH** or a **very massive NS**.
- Estimates of max possible NS mass favor the first hypothesis.
- The combination of masses, mass ratio, and rate is challenging to explain.

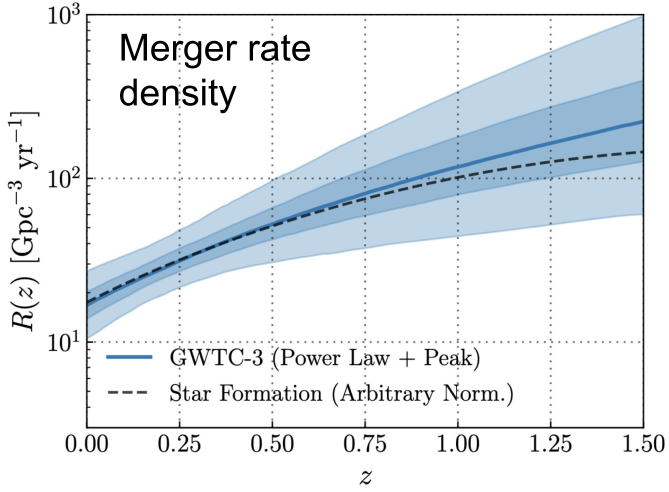


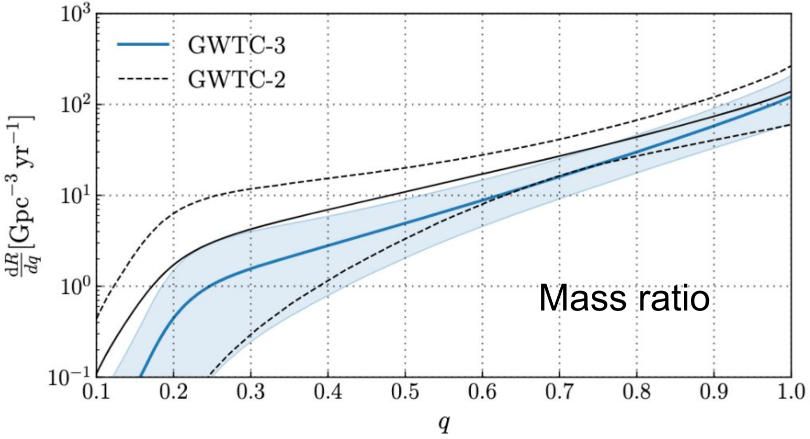
ApJ Letters, 896:L44 (20pp), 2020

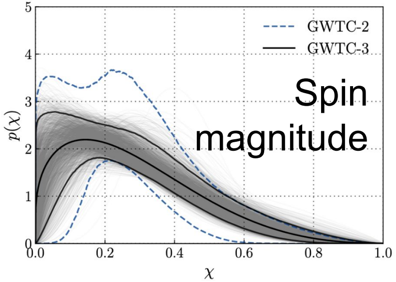
Population of binary black hole mergers

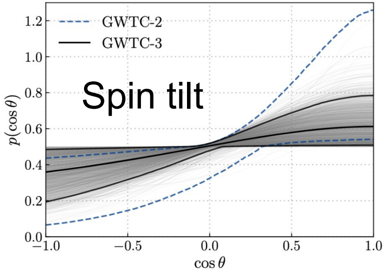
LIGO/Virgo/KAGRA, arXiv:2111.03634



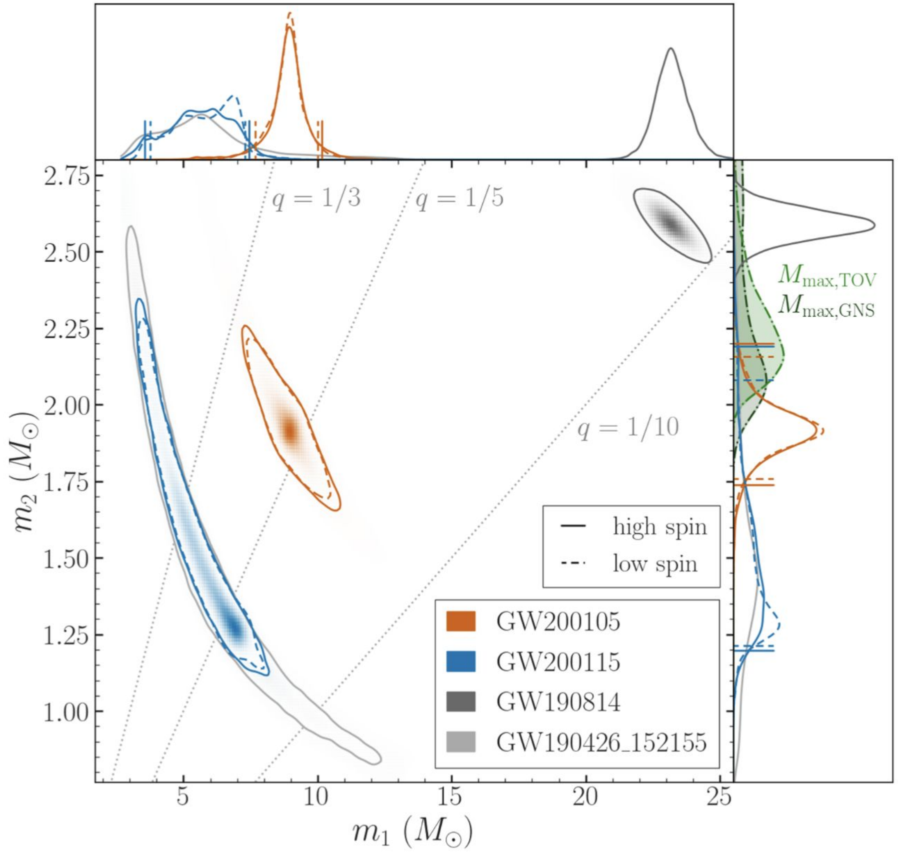








GW200105 and GW200115: first evidence of NS-BH mergers



- Most likely NS-BH mergers based on secondary mass. LVK, arXiv:2106.15163
- However, no robust EM counterparts found so far…
- …and too weak to infer the nature of the least massive object from tidal effects.

Population of neutron star mergers

LIGO/Virgo/KAGRA, arXiv:2111.03634

Second confident BNS discovery:

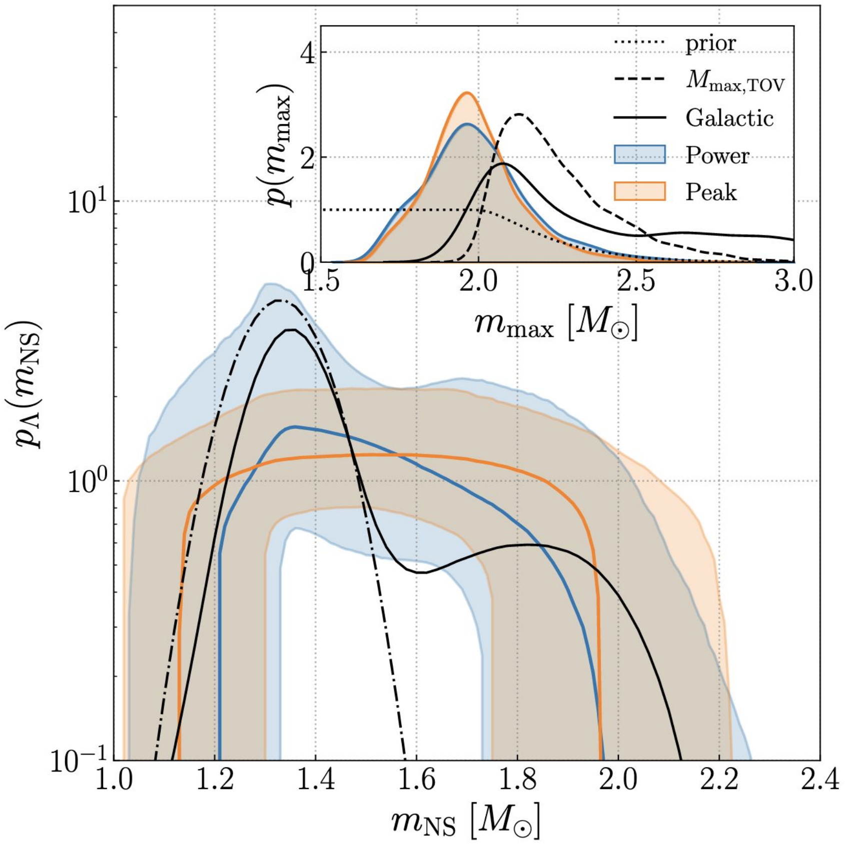
GW190425

Inferred merger rate densities:

NS-NS
10–1700 Gpc^{-3} yr^{-1}

NS-BH
7.8–140 Gpc^{-3} yr^{-1}

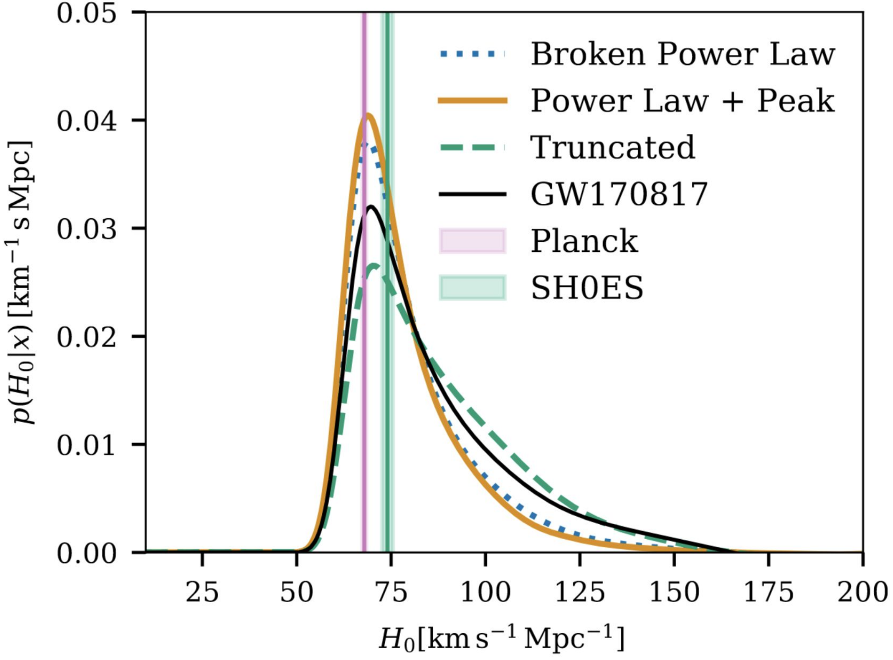
Compare with BH-BH
17.9–44 Gpc^{-3} yr^{-1}



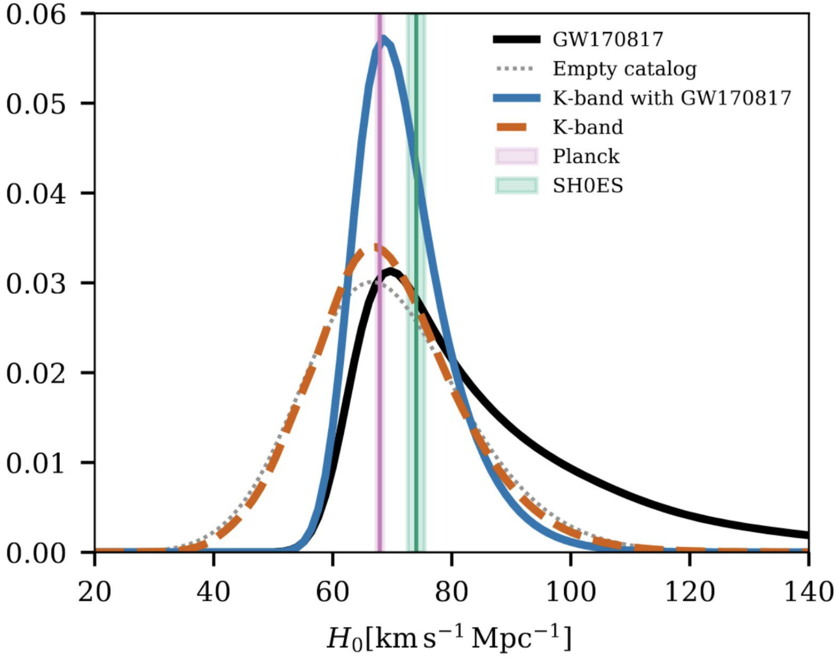
Cosmological constraints

LIGO/Virgo/KAGRA 2021, arXiv:2111.03604

Variable BH mass model

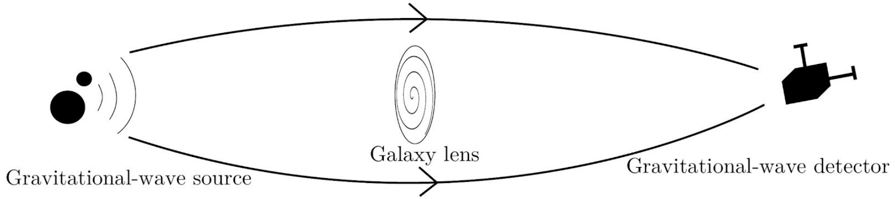


Fixed BH mass model + galaxy catalog

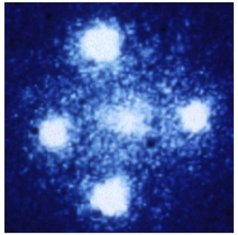


Search for lensing effects

Abbott et al 2021 ApJ 923 14



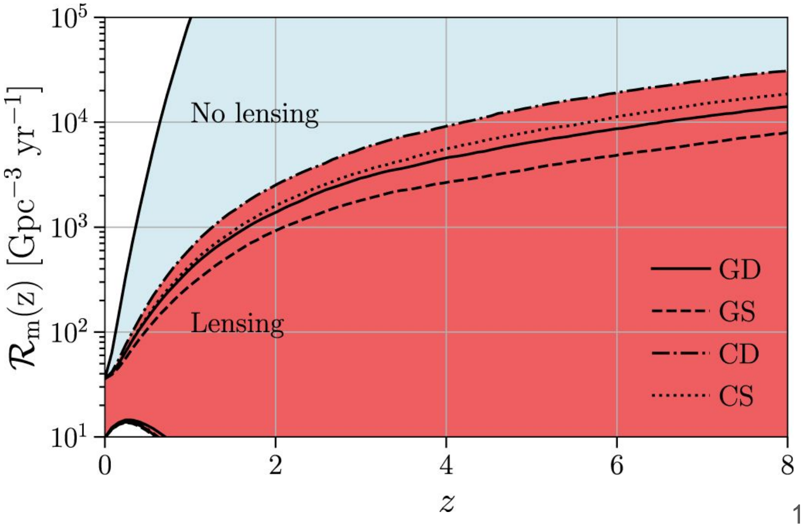
ESA/Hubble & NASA



NASA, ESA, and STScI

NASA, ESA, Hubble SM4 ERO Team, ST-ECF

- Magnification of individual events; distortion of individual waveforms; repeated events.
- A priori expected rate very small, $\lesssim 10^{-3}$.
- Multiple searches performed using 2019 data → No evidence for lensing effects so far. O3b analysis to be released soon.
- Assuming no lensing, we can constrain the compact binary merger rate at high redshift.



Consistency with General Relativity

LIGO/Virgo/KAGRA, arXiv:2112.06861

Residual tests

Inspiral-merger-ringdown consistency

Post-Newtonian

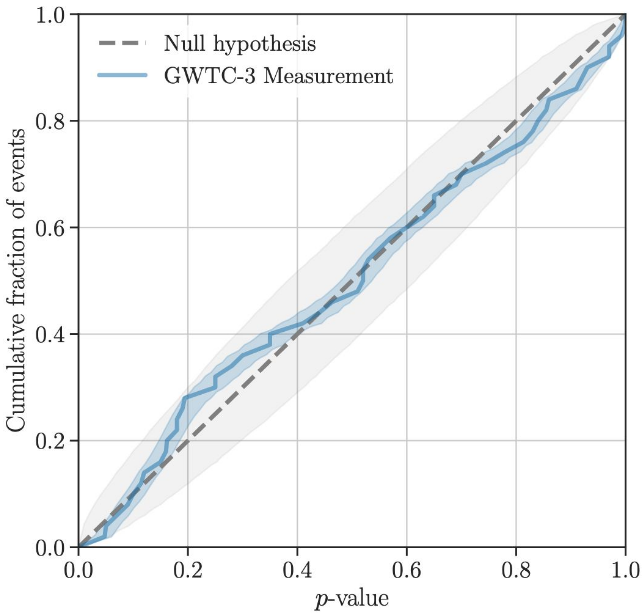
GW dispersion relation

GW polarization

Spin-induced quadrupole moment
of compact objects

Remnant object properties / quasi-normal modes

Post-merger echoes



No evidence for any new physics here.
Improved limit on graviton mass:

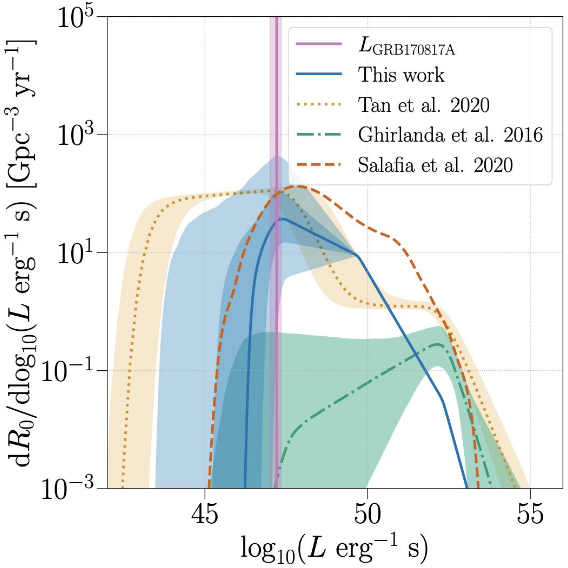
$$m_g \leq 1.27 \times 10^{-23} \mathrm{eV}/c^2$$

Archival multimessenger transient searches

Gamma-ray bursts from Fermi and Swift

LIGO/Virgo/KAGRA, arXiv:2111.03608

No evidence of new joint detections after GW170817 + GRB 170817A.

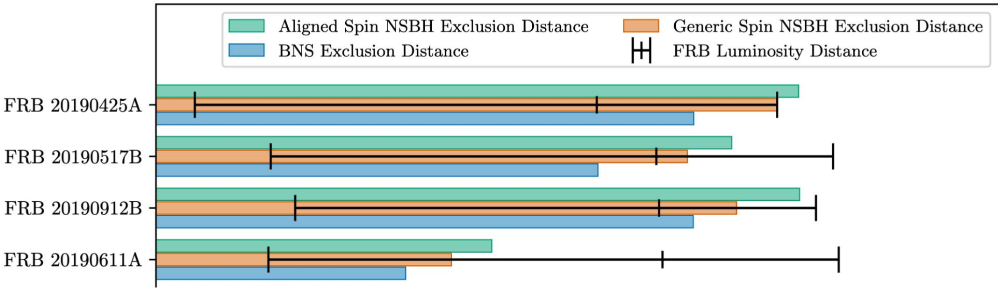


Fast radio bursts from CHIME

LIGO/Virgo/KAGRA, arXiv:2203.12038

No evidence of joint detections.

Nearby FRBs unlikely to come from compact binary mergers.



More results coming…

Searches for continuous gravitational waves

Known galactic pulsars
arXiv:2111.13106

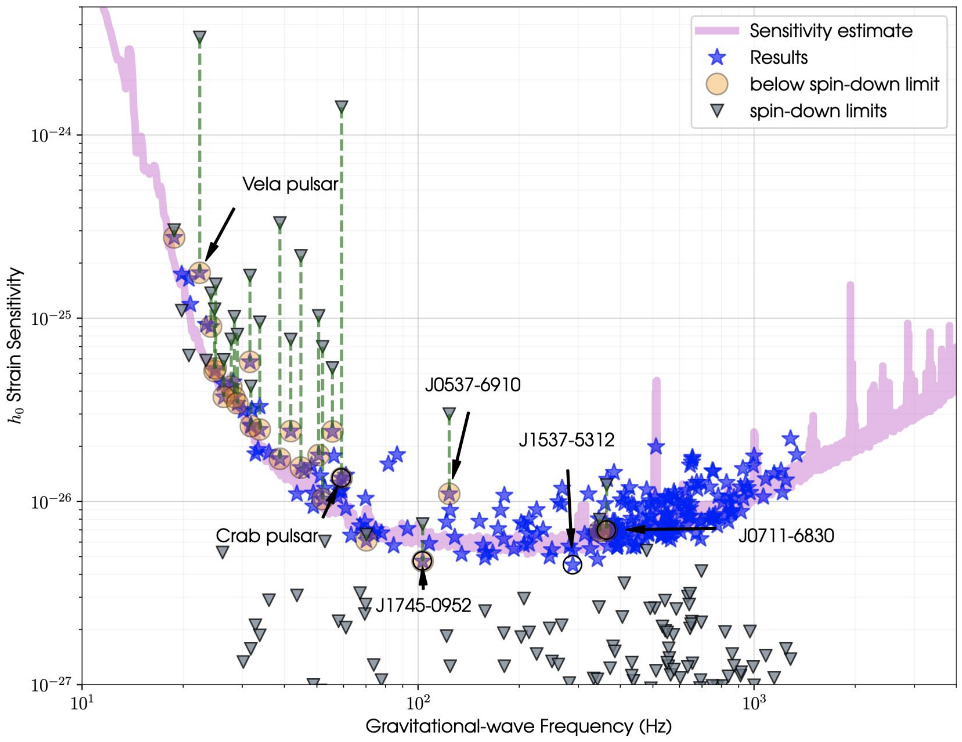
Unknown isolated NSs
arXiv:2201.00697

Supernova remnants Cas A & Vela Jr.
arXiv:2111.15116

Sco X-1
arXiv:2201.10104

Scalar boson clouds around BHs
arXiv:2111.15507

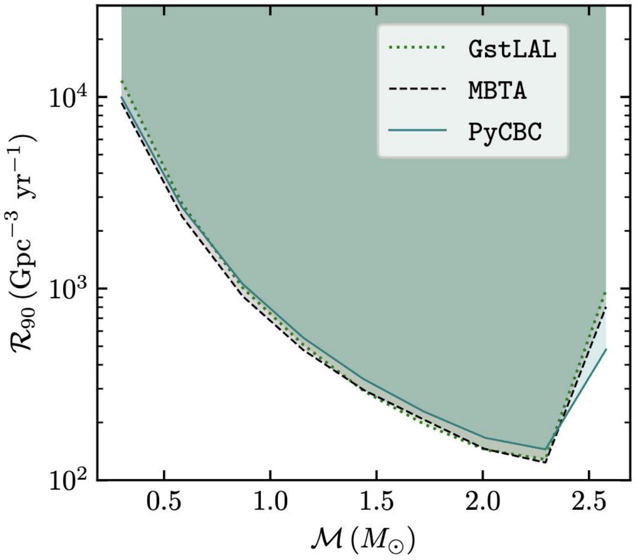
No detections yet, but upper limits keep improving. Well under the spin-down limit in a few cases.

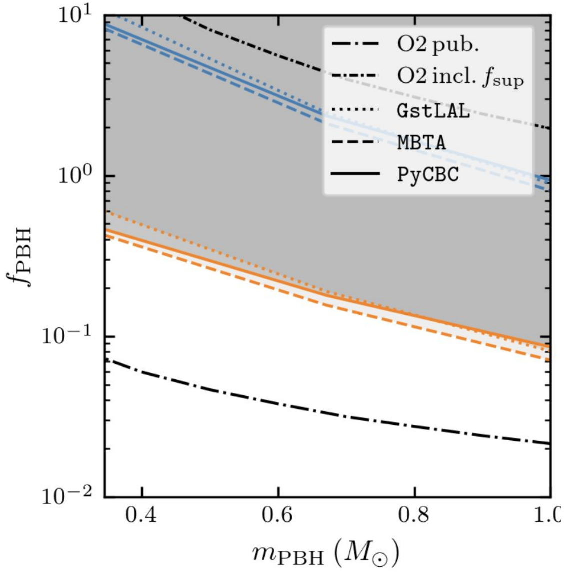


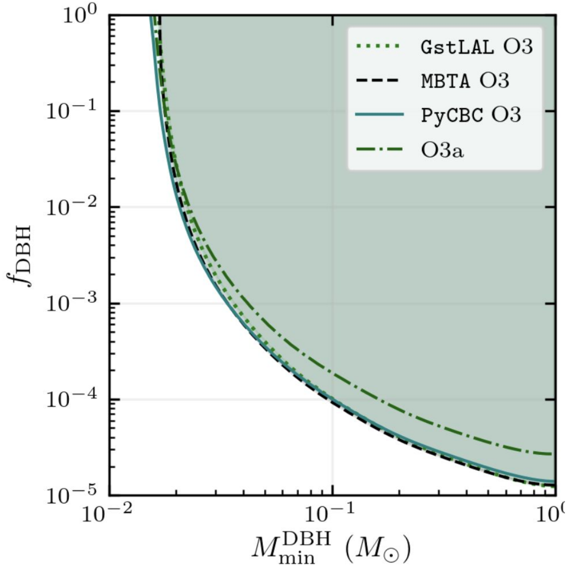
Searches for inspirals of sub-M_{Sun} binaries

LVK, arXiv:2212.01477

No detections yet. Starting to constrain some DM models



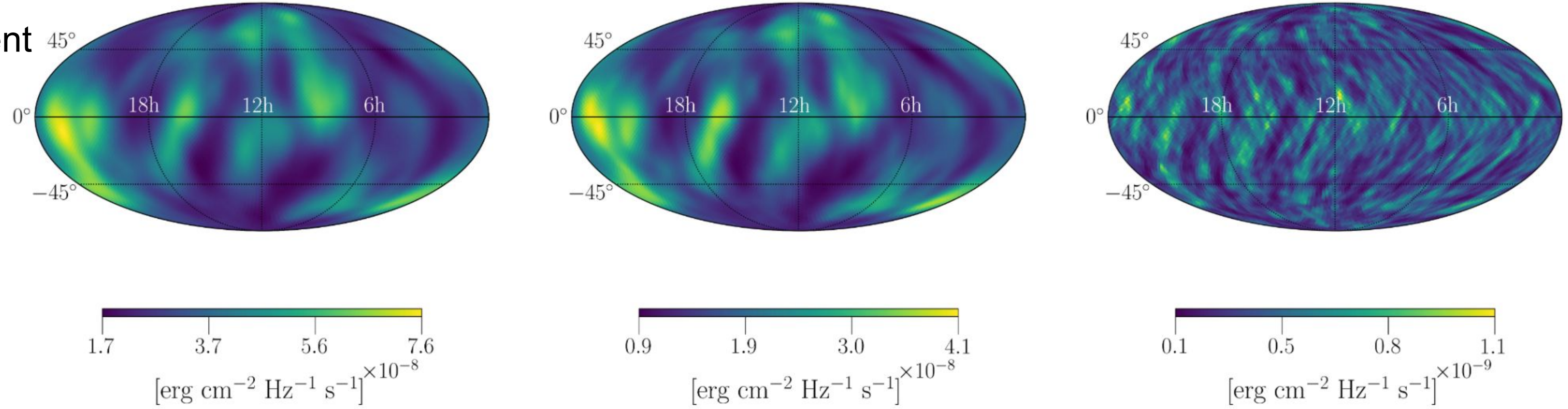




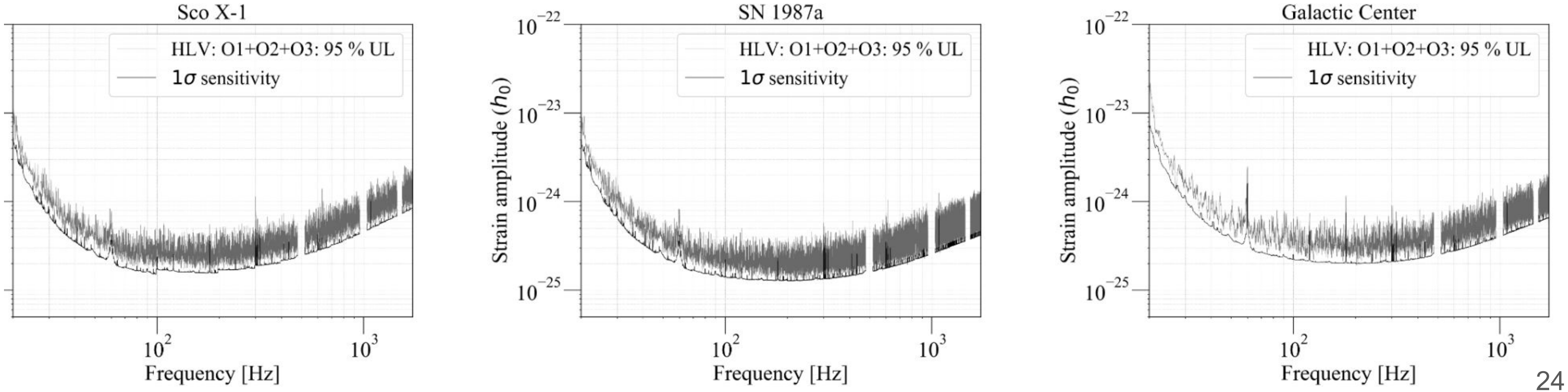
Stochastic gravitational-wave background

LVK, arXiv:2103.08520

Sky-dependent upper limits for different power-law spectra



Frequency-dependent upper limits for specific targets



Expectations for the O4 run

Detector upgrades

LIGO

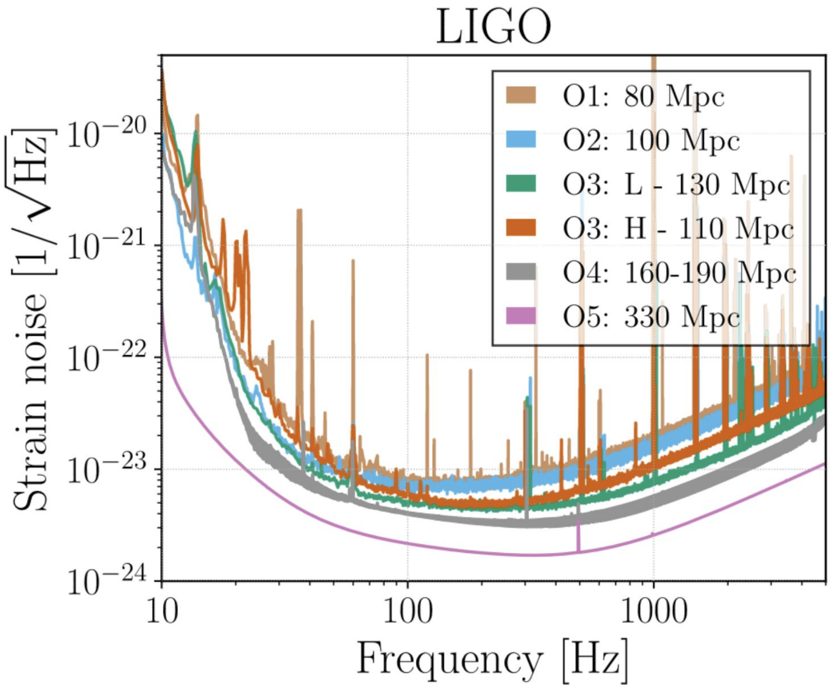
- 2x power
- Frequency-dependent squeezing
- Improvements in technical noise (scattered light, control noise…)

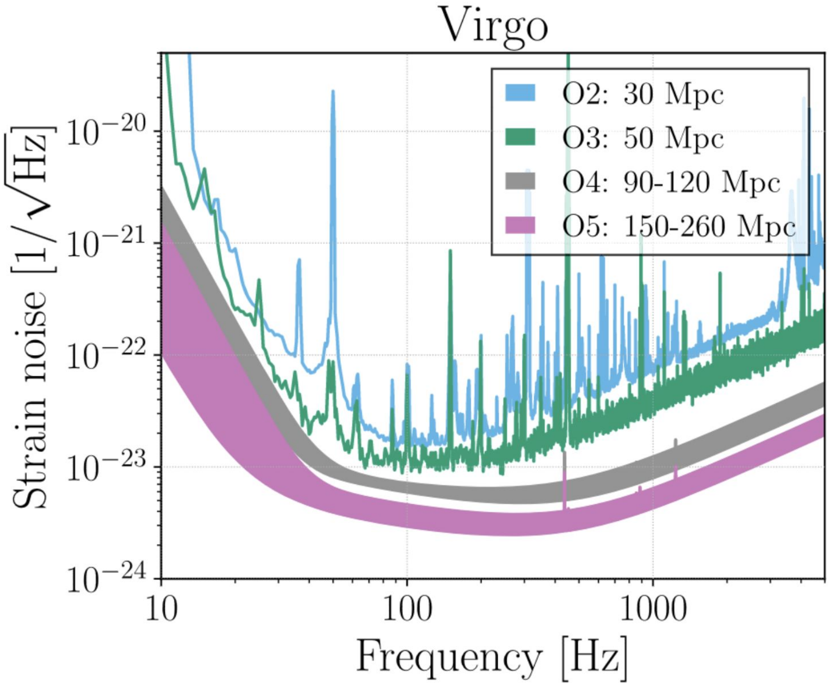
Virgo

- Higher power
- Signal recycling
- Frequency-dependent squeezing
- Improvement in technical noise

Detector sensitivity projections from late 2020

LVK, arXiv:1304.0670

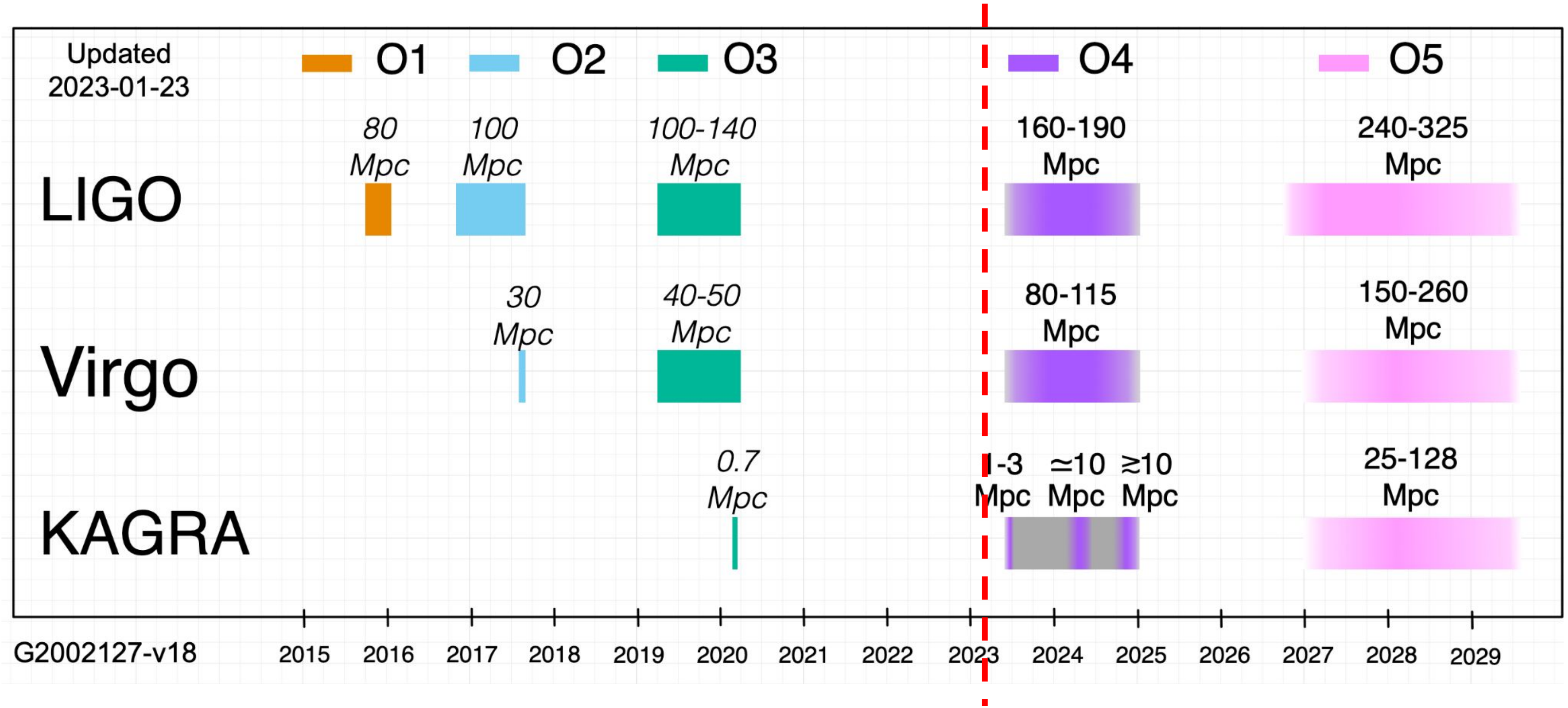




Now somewhat outdated, Virgo O4 and all O5 estimates probably optimistic.

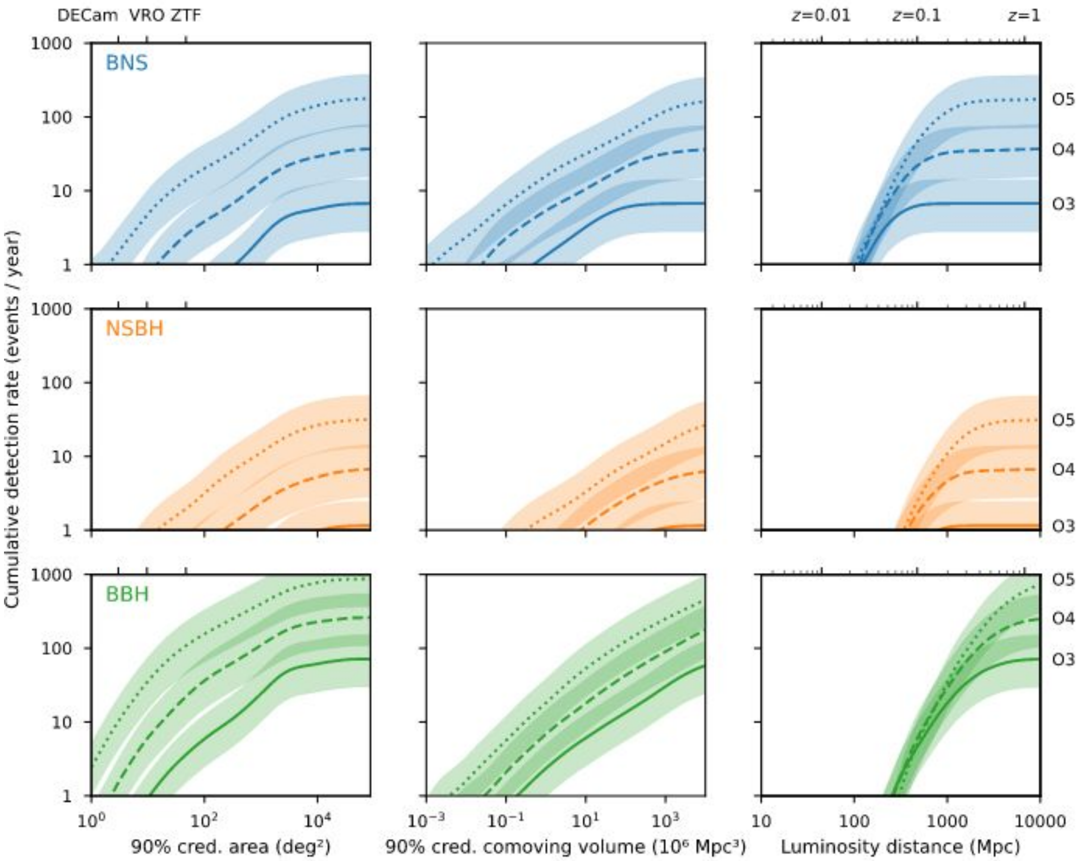
Observing plans

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



Currently planning a 18-month run starting on May 24,
possibly with one or two ~month-long breaks

Projected detection rates for compact binary mergers



Details and assumptions on https://emfollow.docs.ligo.org/userguide/capabilities.html

Mass model based on end-O3 population results.

Sensitivity assumptions are somewhat optimistic, and the uncertainty in sensitivity is not included.

By the end of O4, we expect hundreds of BBH mergers, ~10 NS mergers, and maybe one new joint detection with a GRB.

Conclusion

GW astronomy has been around for more than 7 years.

Discoveries dominated by binary BH mergers, with a few NS mergers.
Starting to see interesting details in the BH population.
More NS mergers needed to really start probing their population.

General Relativity neatly explains all these observations.

Still, many open questions and raised eyebrows in many directions…
E.g. what is the precise shape of the BH mass spectrum? How will the next joint GW-EM discovery look like? What is there to learn *beyond* compact binary mergers?

This year is going to be hectic. Surprises and new questions expected.

We will definitely not answer all the questions with today's observatories.

Thank you for your attention!