12th Cosmic Ray International Seminar - CRIS 2022

Overview and status of gravitational-wave astronomy

Tito Dal Canton
Université Paris-Saclay, CNRS/IN2P3, IJCLab

Gravitational-wave theory

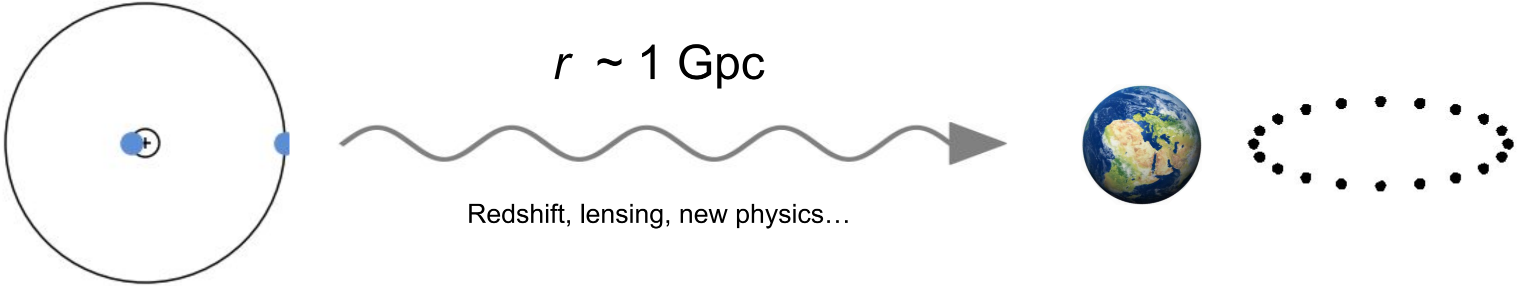
Einstein field equations

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

Linearization

Flat spacetime → $\eta_{\mu\nu}$; Small perturbation → $h_{\mu\nu}$

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



Astrophysical source

Mass ~ 10 M_{Sun}

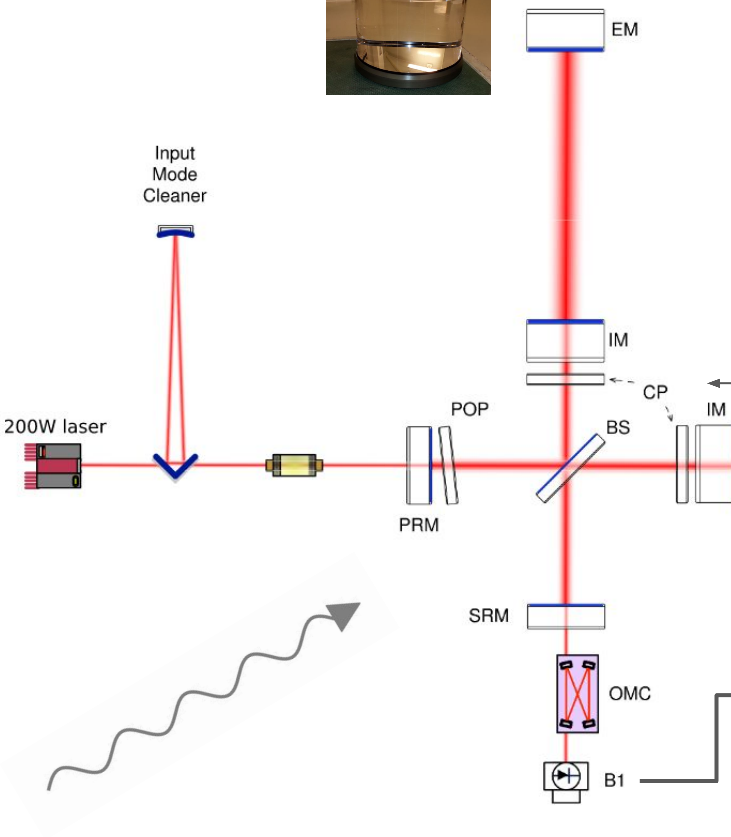
Velocity ~ c

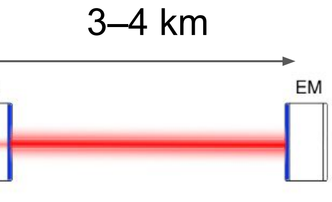
Mass quadrupole Q

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

Experimental measurement of gravitational waves

Test mass



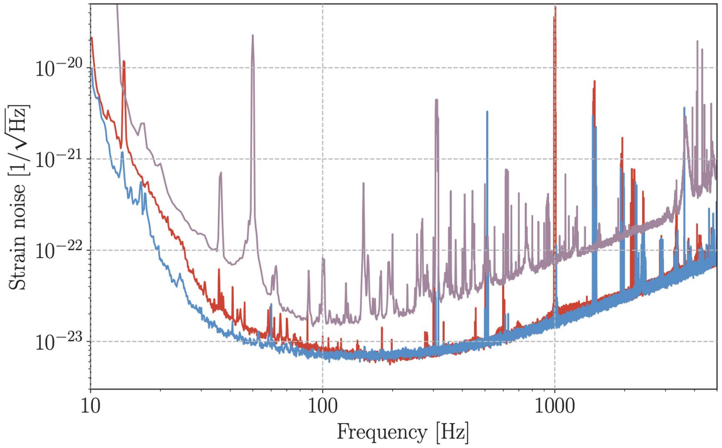


Data acquisition system → Calibration Cleaning … → GW strain time series $h(t)$ → Astrophysical analyses

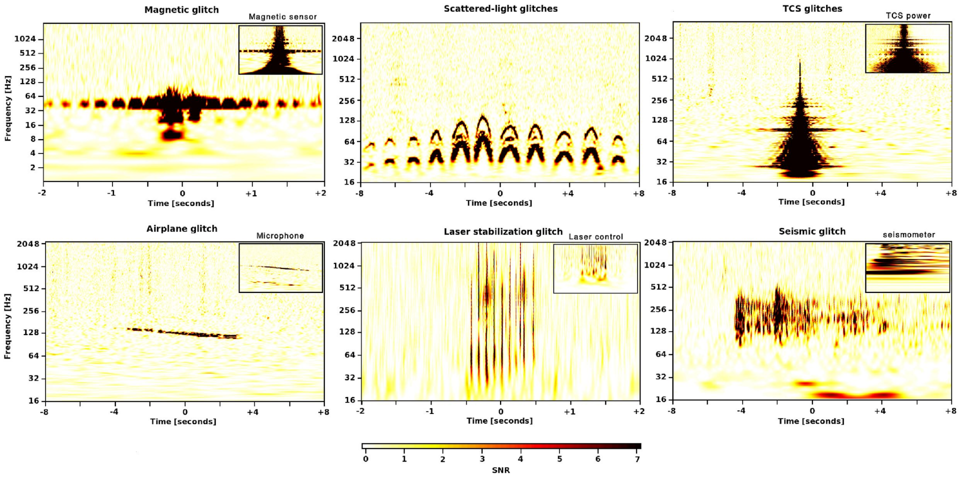
Gravitational-wave data

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

Quasi-stationary quasi-Gaussian noise



Transient noise, "glitches"



Astrophysical signal

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

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

Data analysis tasks, tools and publication of results

Detector characterization, noise removal, data visualization

BayesWave, GWPy, iDQ, Omicron…

Identification of astrophysical signals

Compact binary mergers: GstLAL, MBTA, PyCBC, SPIIR
Short transients: Coherent WaveBurst, X-pipeline
Long transients: STAMPAS
Quasi-monochromatic signals: FrequencyHough, SkyHough, SOAP, TD F-stat
Stochastic background: PyStoch
Multimessenger events: PyGRB, RAVEN, X-pipeline
…

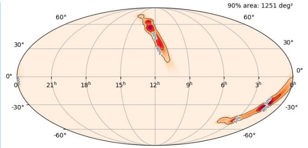
Characterization of individual signals

BAYESTAR, BayesWave, LALInference/Bilby, PyCBC, pyRing, RIFT…

"Hyperanalyses"

Cosmology: gwcosmo, ICAROGW
Population properties
Lensing of gravitational waves
Tests of General Relativity
…

Low-latency results



Latency: seconds to hours.
Content: significance, timing, rough spatial localization, rough source classification.
Distributed via GCN notices and circulars, stored in GraceDB.

Medium-latency results

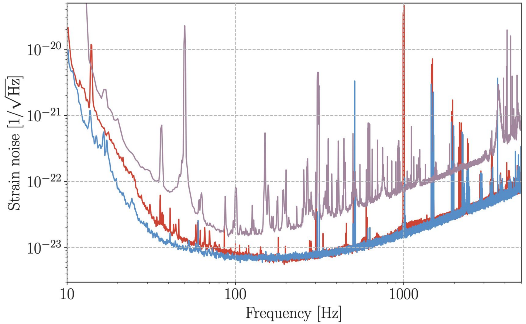
Latency: hours to days.
Content: improved localization and classification.
Distributed via GCN notices and circulars.

"Offline" results – Event catalogs

Latency: months to years.
Content: full event-by-event characterization.
LIGO/Virgo/KAGRA: GWTC, GWOSC.
AEI Hannover: OGC.

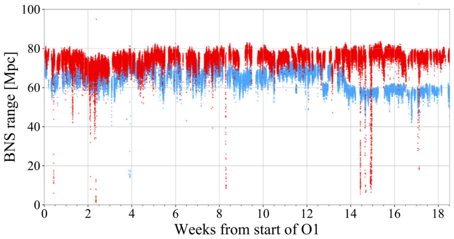
A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals
LIGO & Virgo collaborations; arXiv:1908.11170

Sensitivity improvement over the years

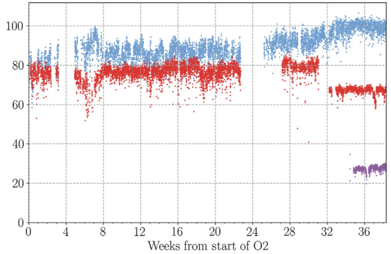


BNS range: average lum. distance at which we can "see" a NS-NS binary, taking $m_{NS} = 1.4\ M_{Sun}$ as a reference.

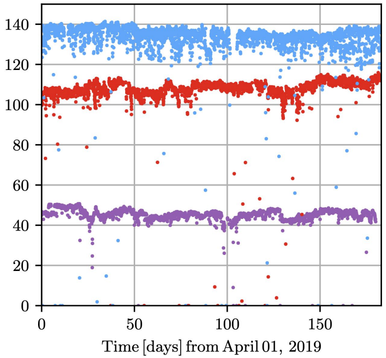
O1



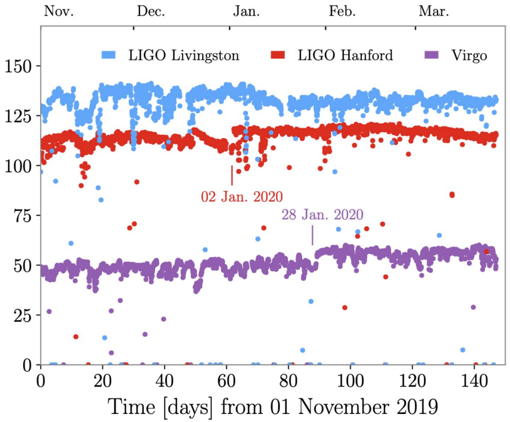
O2



O3a



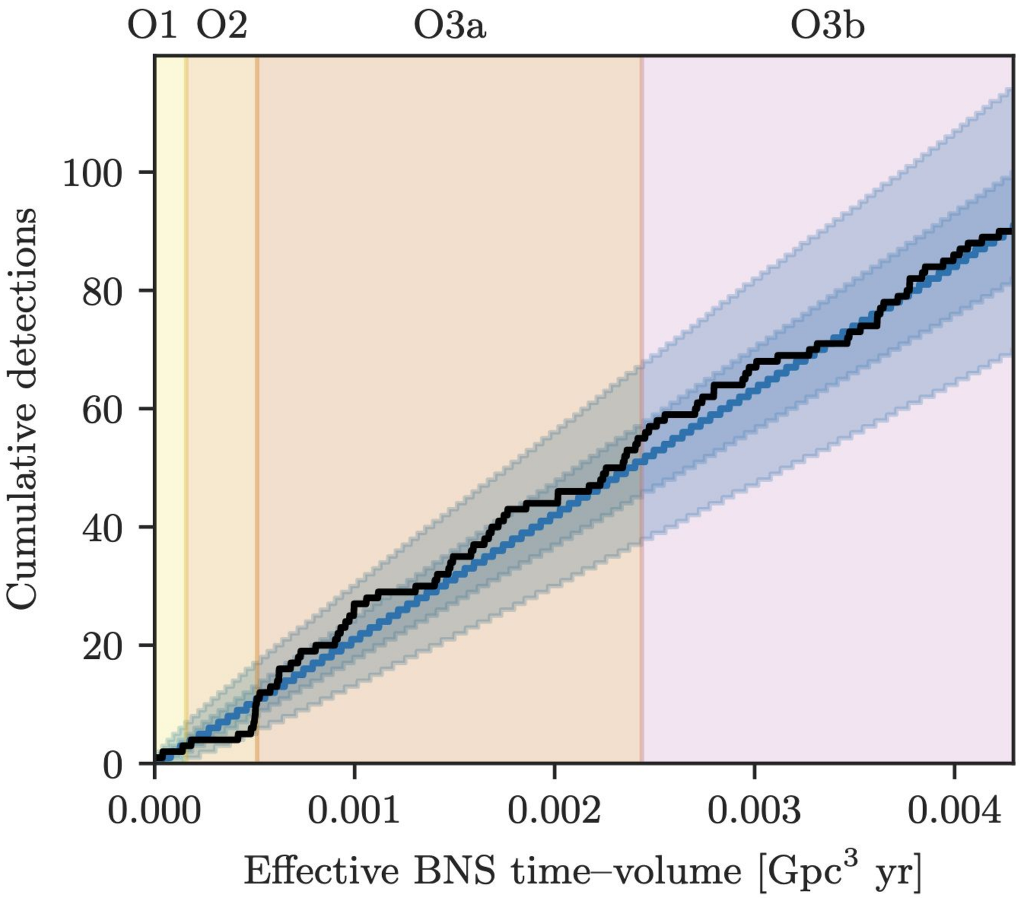
O3b



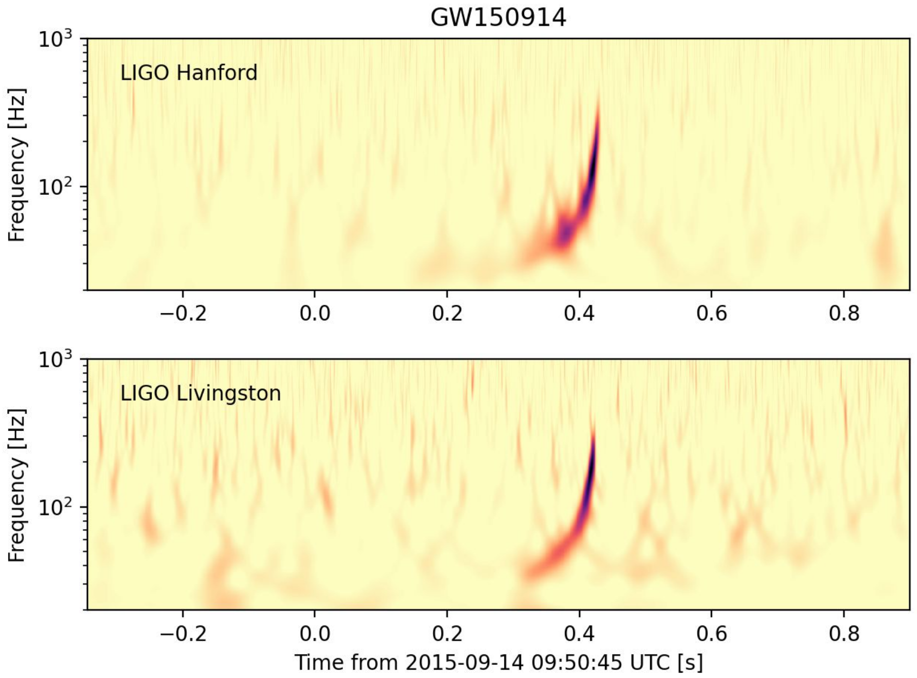
Detection rate ~ range^3
for $z \lesssim 1$, then cosmology.

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

Evolution of detections with sensitivity



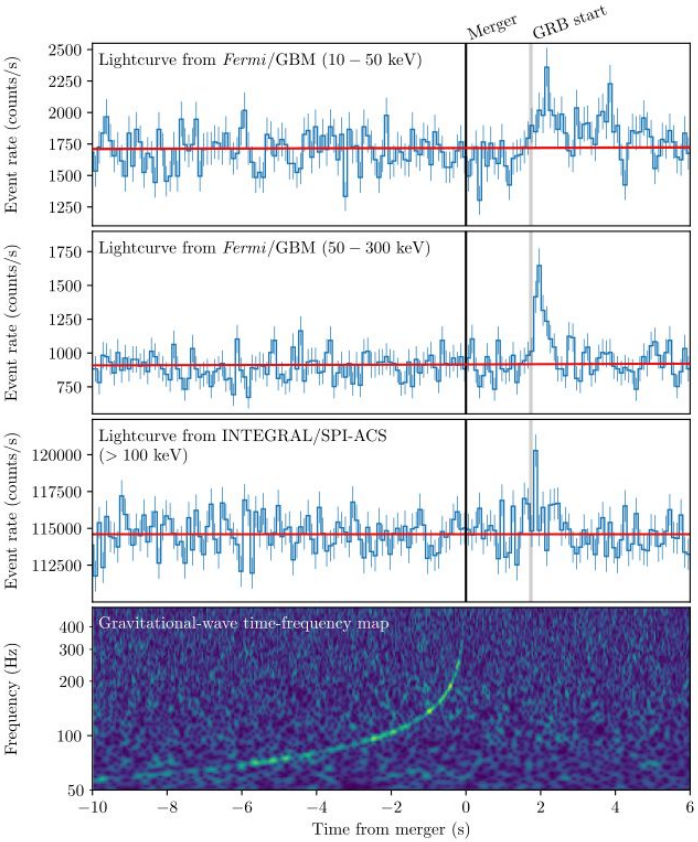
GW150914

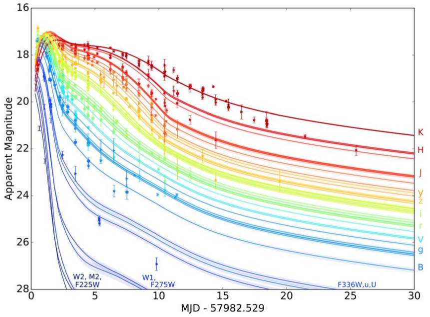


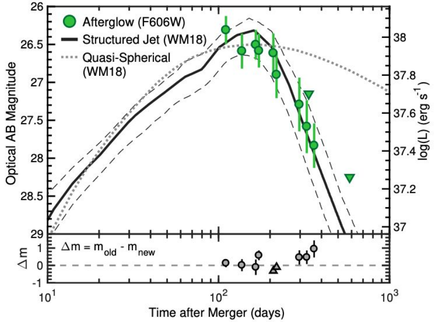
Total mass ~65 M_{Sun}
redshift ~0.1

- Direct detection of GWs.
  LIGO/Virgo, arXiv:1602.03837
- Unambiguous observation of a black hole merger.
  LIGO/Virgo, arXiv:1608.01940
- Measurement of merger rate density.
- Establish GW astronomy.

GW170817, GRB 170817A and AT 2017gfo

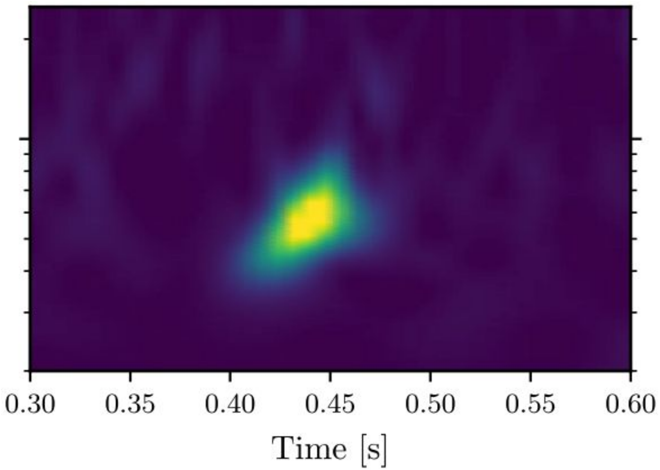


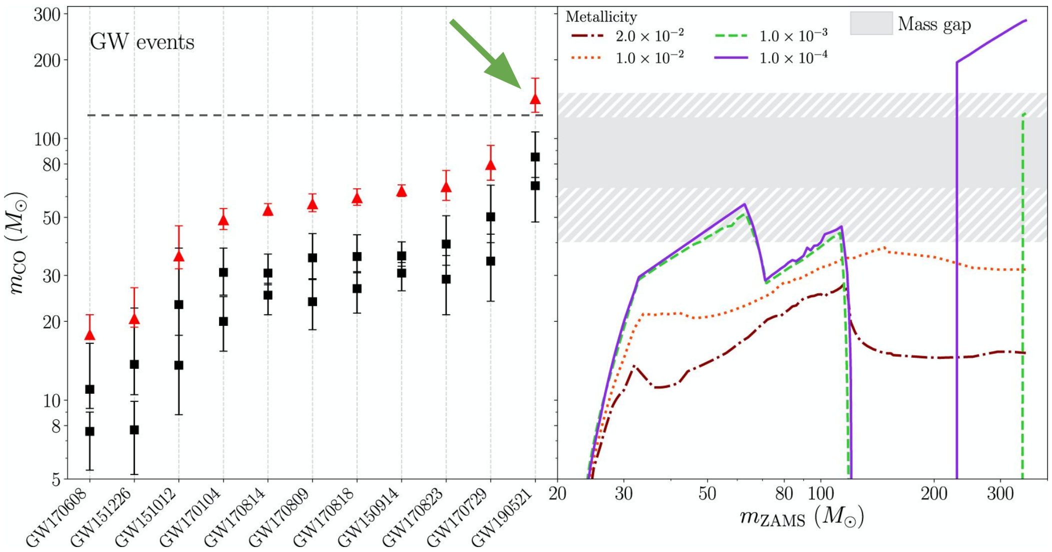




- Unambiguous observation of a neutron star merger.
  LIGO/Virgo, arXiv:1710.05832
- Measurement of NS-NS merger rate density.
- Link NS mergers and short GRBs.
  LIGO/Virgo/Fermi-GBM/INTEGRAL, arXiv:1710.05834
- Unambiguous observation of a kilonova.
- Equation of state of dense nuclear matter.
- Establish multimessenger astronomy with GWs.
  LIGO/Virgo/others, arXiv:1710.05833

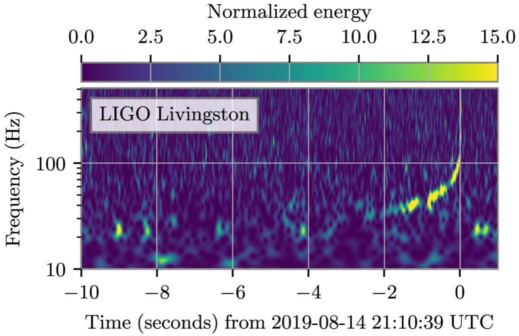
GW190521

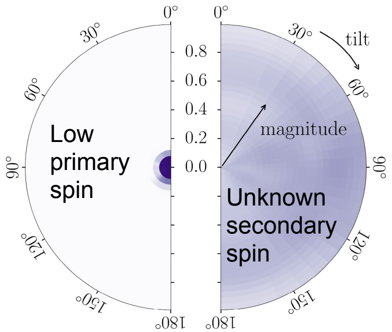


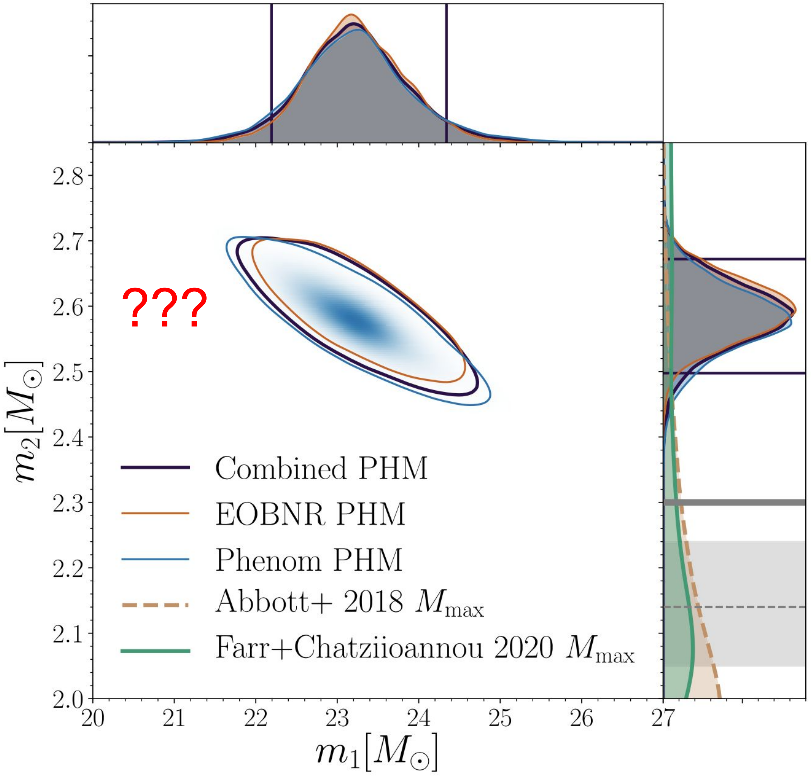


- Shortest transient confidently detected.
  LIGO/Virgo, arXiv:2009.01075
- Various astrophysical interpretations possible.
  LIGO/Virgo, arXiv:2009.01190
- Simplest one: BH-BH merger of total mass ~150 M_{Sun} at redshift ~0.6, e.g. “tail” of population.

GW190814



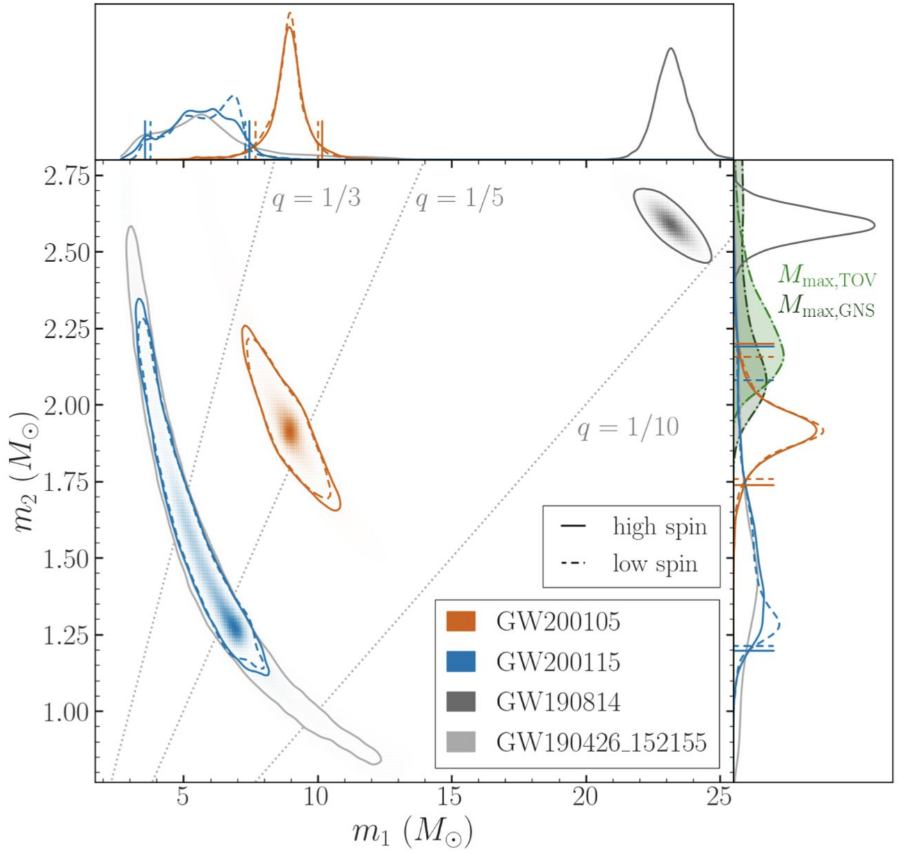




- Ambiguous nature of the secondary object: either a **very light BH** or a **very massive NS**.
- Estimates of max possible NS mass favor the first hypothesis.
- The combination of masses, mass ratio, and rate is challenging to explain.

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

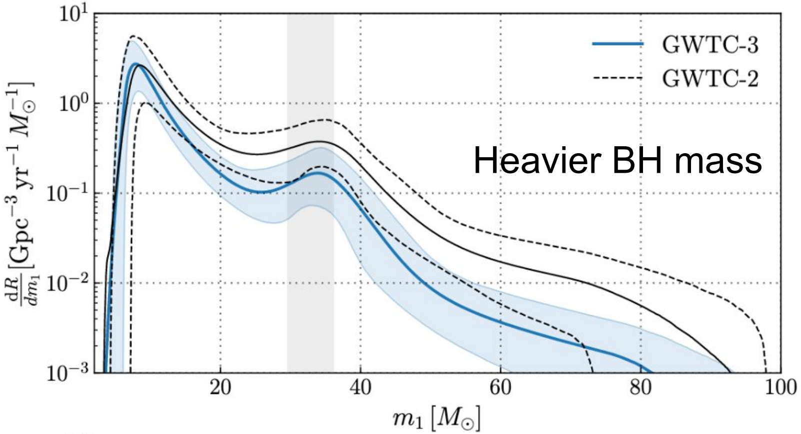
GW200115

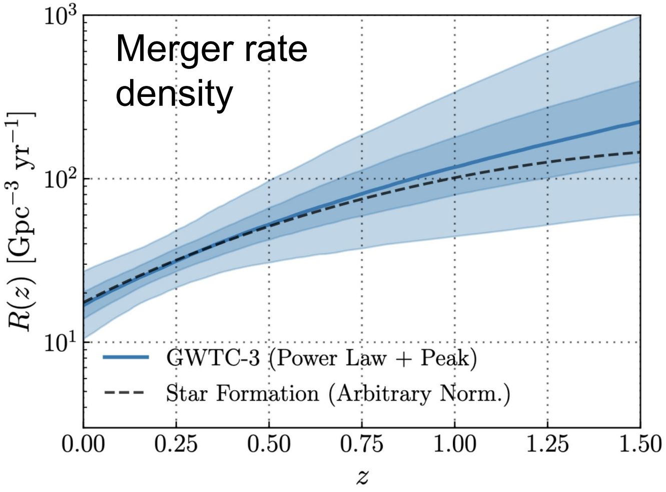


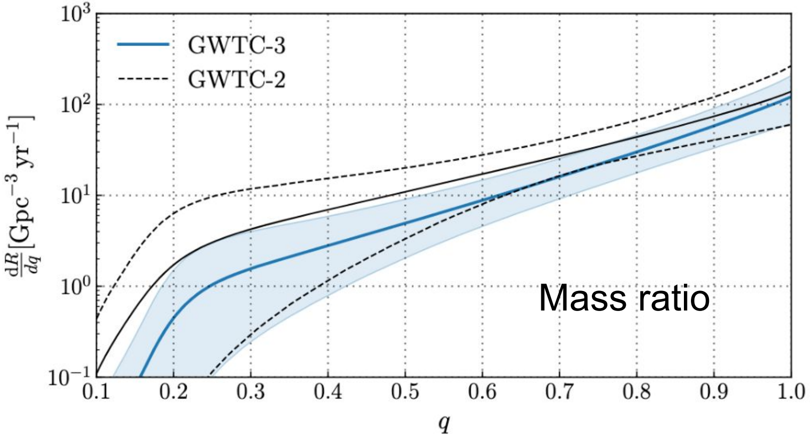
- Most likely a NS-BH merger. LIGO/Virgo/KAGRA, arXiv:2106.15163
- However, no robust EM counterparts found so far…
- …and signal too weak to infer the nature of the least massive object.

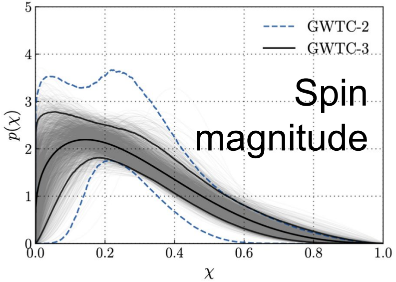
Population of binary-black-hole mergers

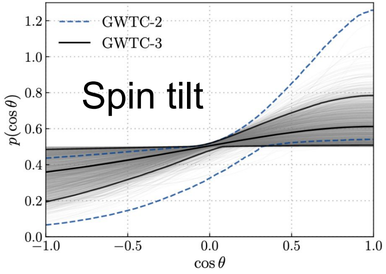
LIGO/Virgo/KAGRA, arXiv:2111.03634











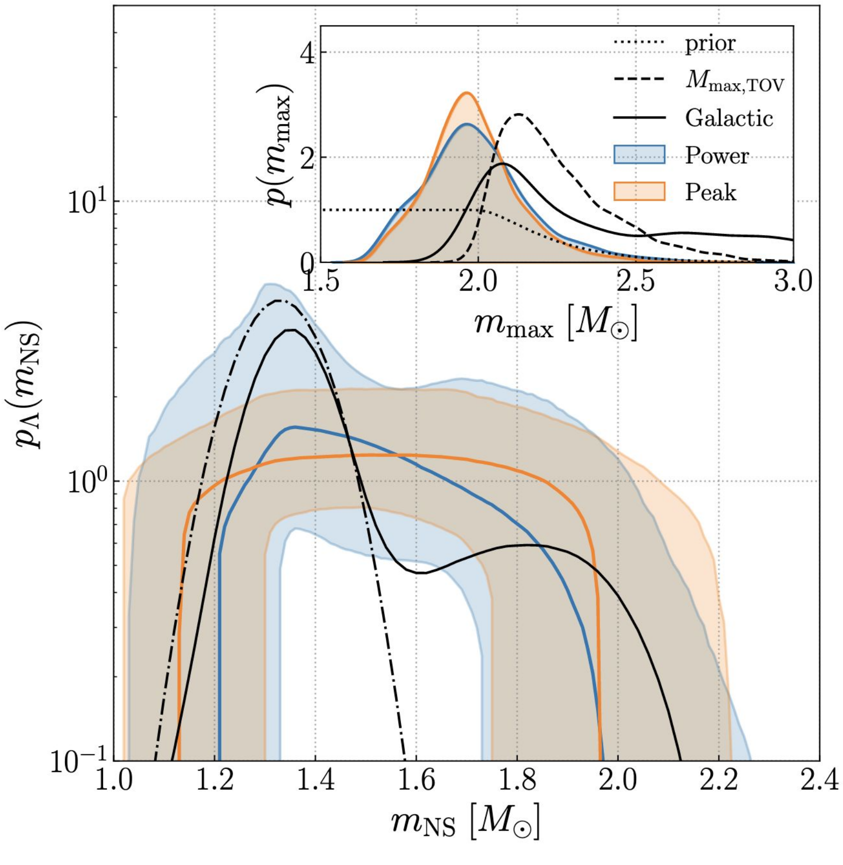
Population of neutron-star mergers

LIGO/Virgo/KAGRA, arXiv:2111.03634

Inferred merger rate densities:

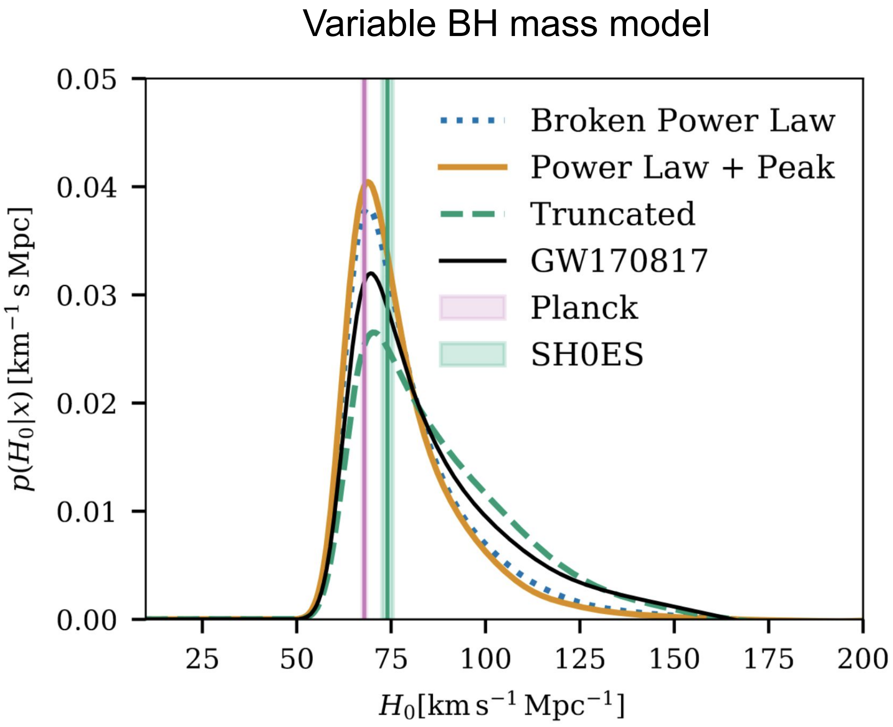
NS-NS
10-1700 Gpc^{-3} yr^{-1}

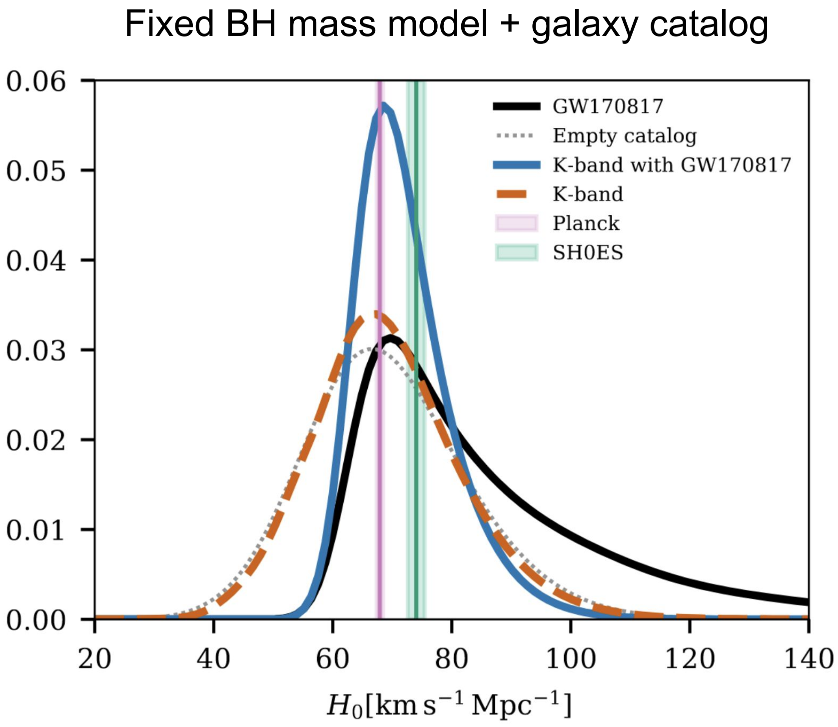
NS-BH
7.8-140 Gpc^{-3} yr^{-1}



Cosmological inference

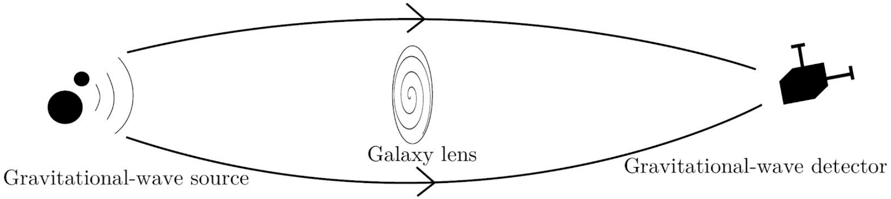
LIGO/Virgo/KAGRA 2021, arXiv:2111.03604



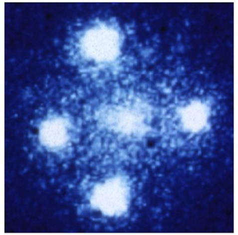


Lensing effects

Abbott et al 2021 ApJ 923 14

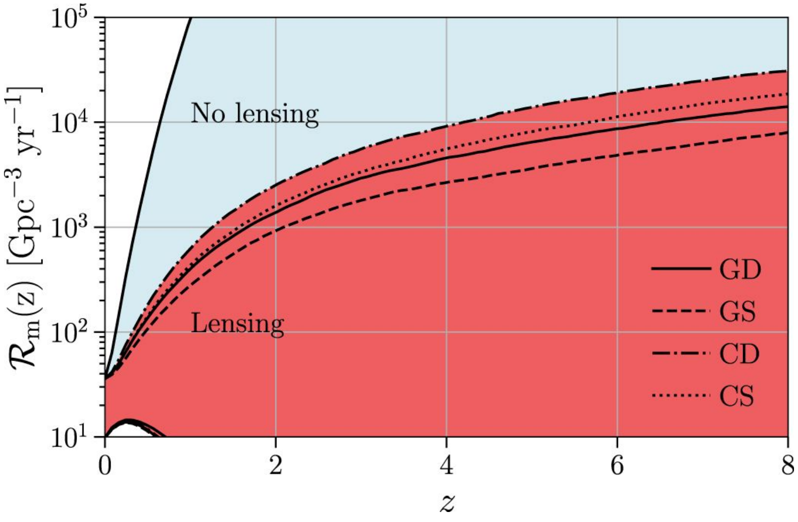



ESA/Hubble & NASA


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.
- 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

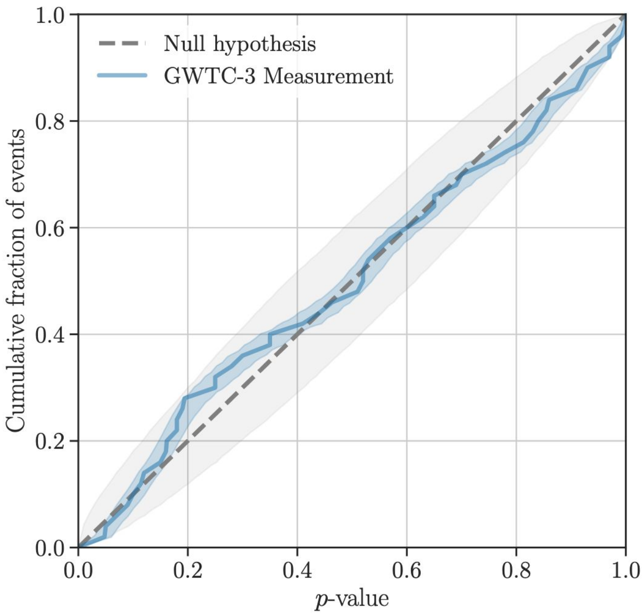
GW dispersion relation

GW polarization

Spin-induced quadrupole moment of compact objects

Remnant object properties / quasi-normal modes

Post-merger echoes



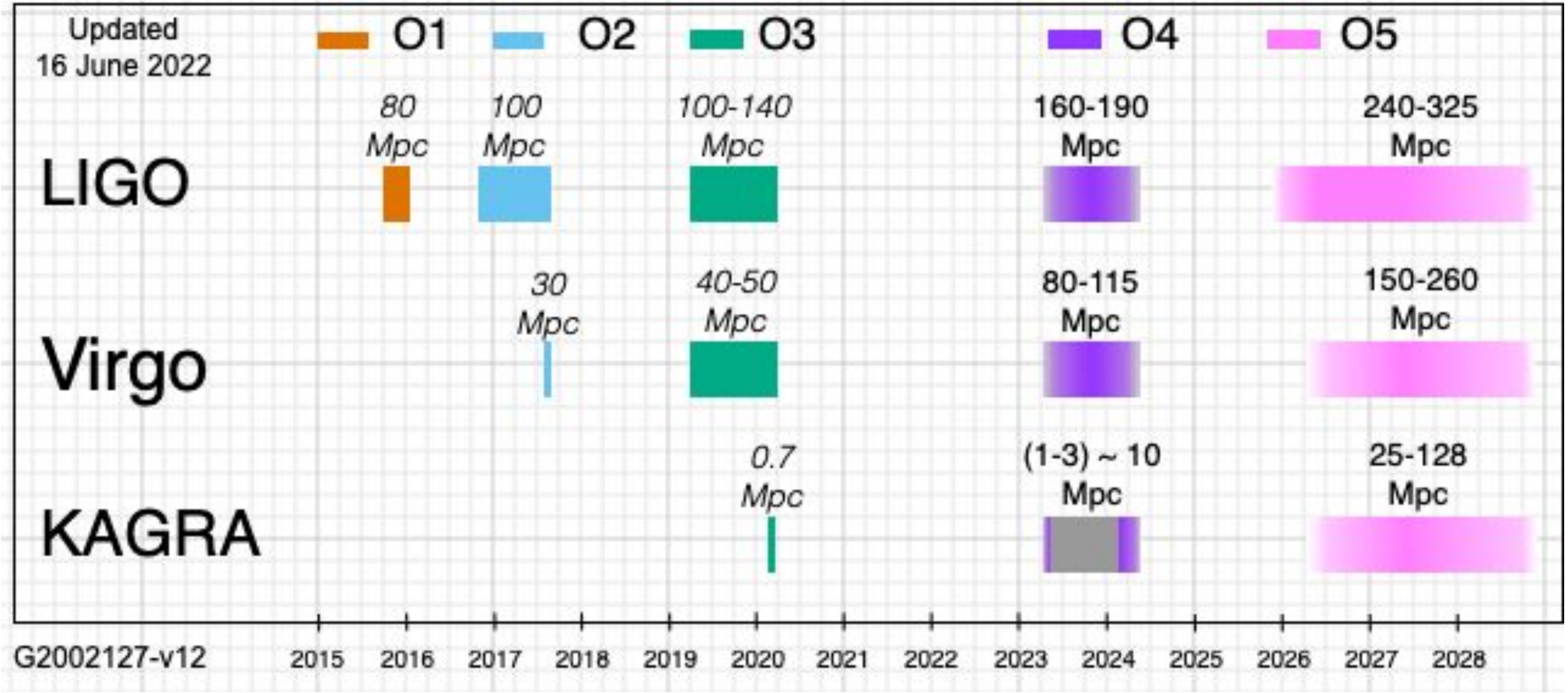
No evidence for any new physics here.

Improved limit on graviton mass:

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

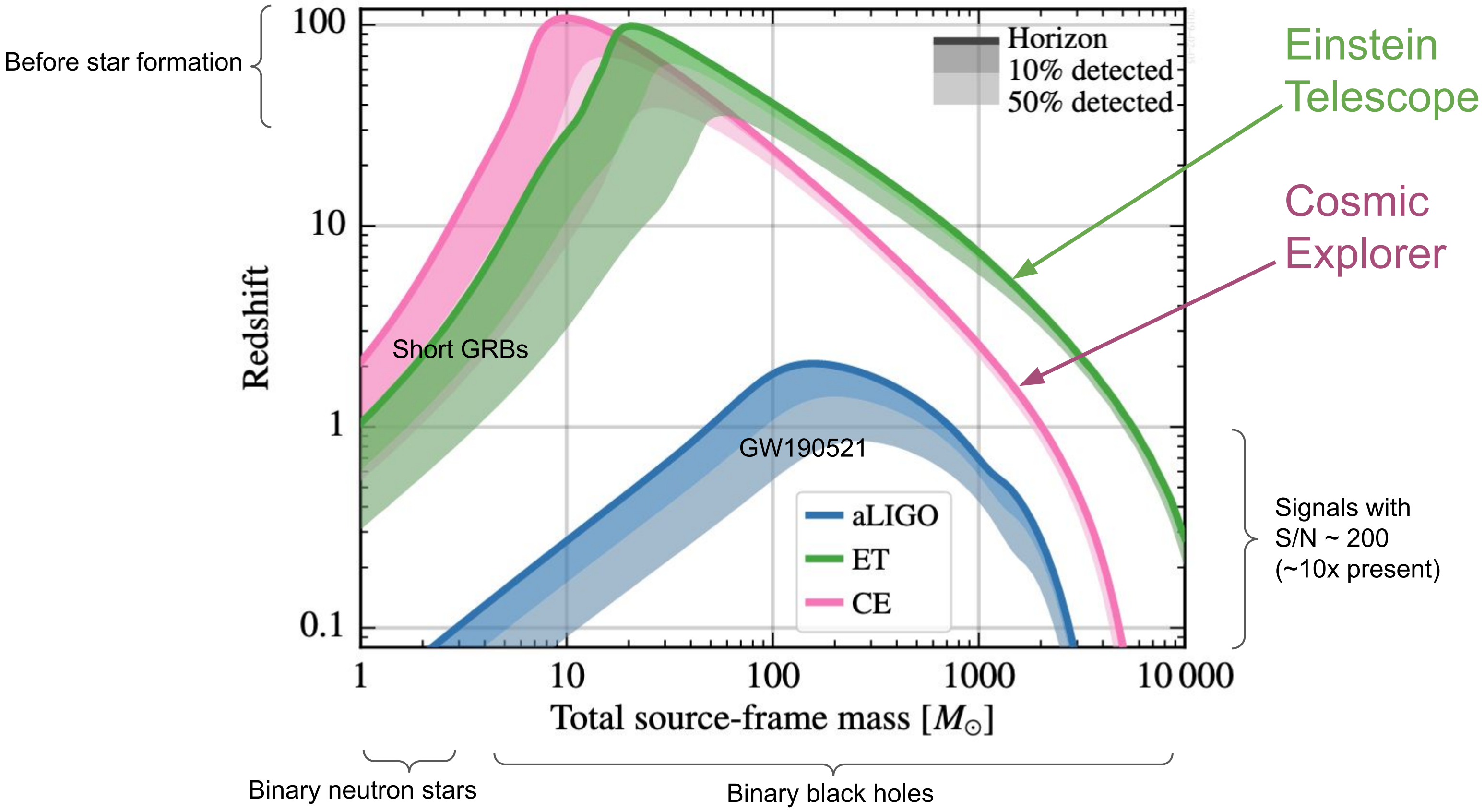
LIGO-Virgo-KAGRA observing plans

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



Next update 15 November

Third-generation ground-based detectors

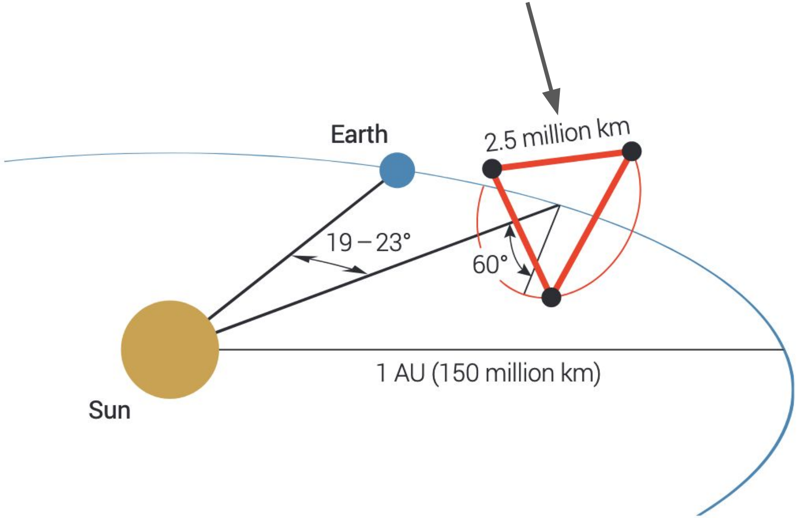


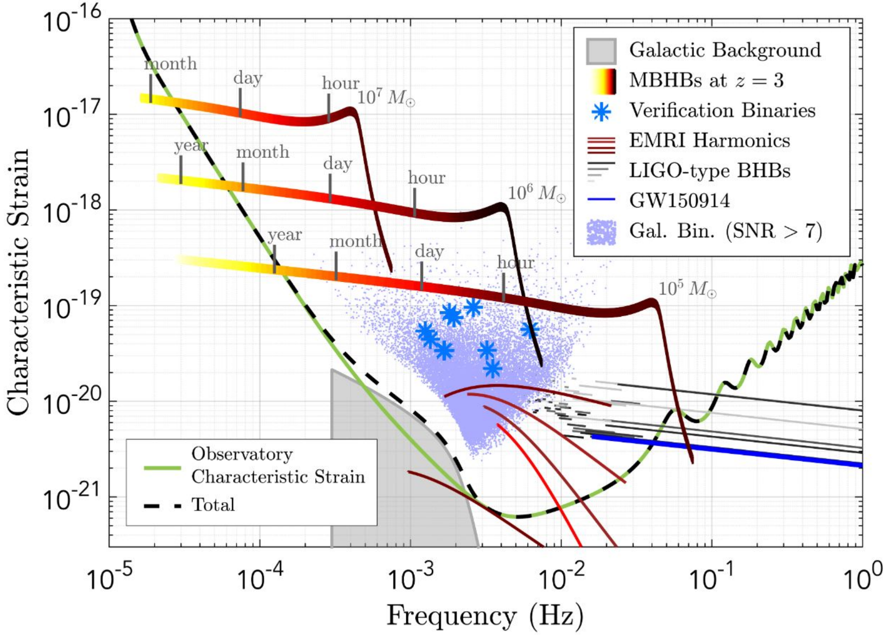
Space detectors

Amaro-Seoane et al. arXiv:1702.00786

LISA

Laser Interferometer Space Antenna





Final thoughts

GW astronomy has been around for 7 years as of this week.

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 will Nature offer *beyond* compact binary mergers?

Next 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!