Multimessenger observations with gravitational waves from ground-based interferometers

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Overview

Recap of gravitational-wave astronomy and cosmology

Present cosmology results

Expectations for the future

Gravitational waves

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 → $h_{\mu\nu}$

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

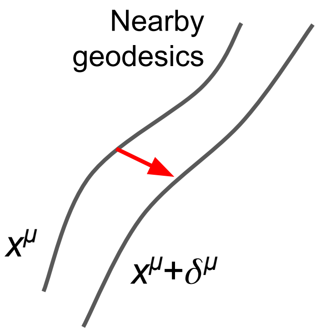
Radiation from a source

Mass quadrupole moment → $\ddot{Q}$

$$h_{ij} \sim \frac{G}{c^4} \frac{\ddot{Q}}{r}$$

Luminosity distance → r

Observable effects



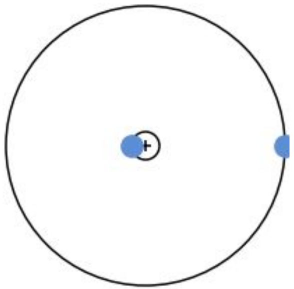
Time-dependent source

↓

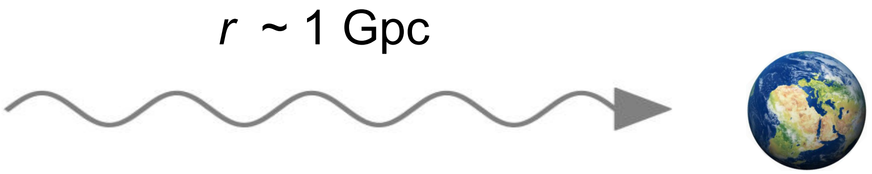
Change in proper length along direction u^i

$$\frac{\delta L}{L} \approx \frac{1}{2} h_{ij} u^i u^j$$

Gravitational-wave astronomy



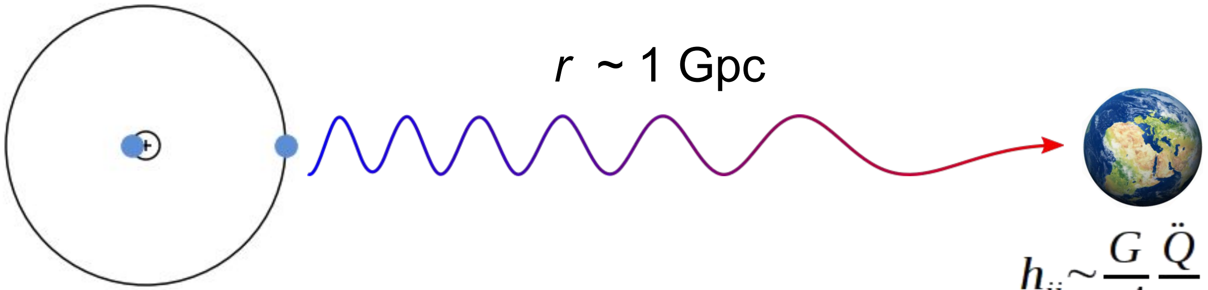
Astrophysical source
Mass ~ 10 M_{Sun}
Velocity ~ c
Mass quadrupole Q



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

Waveform directly driven by the bulk motion at the source

Gravitational-wave ~~astronomy~~ cosmology

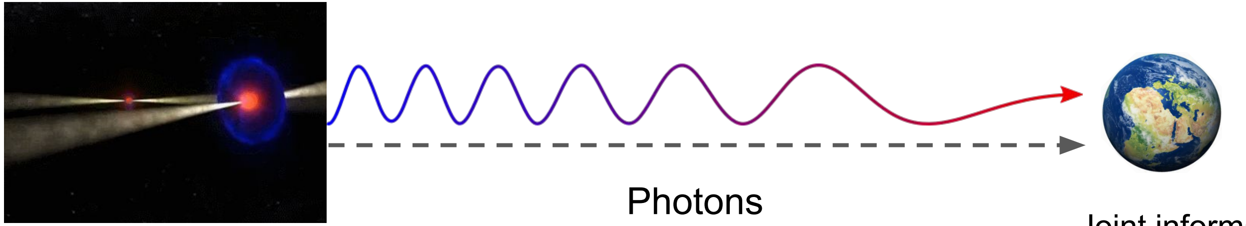


Astrophysical source
Mass ~ 10 M_{Sun}
Velocity ~ c
Mass quadrupole Q

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

Waveform directly driven by the redshifted bulk motion at the source

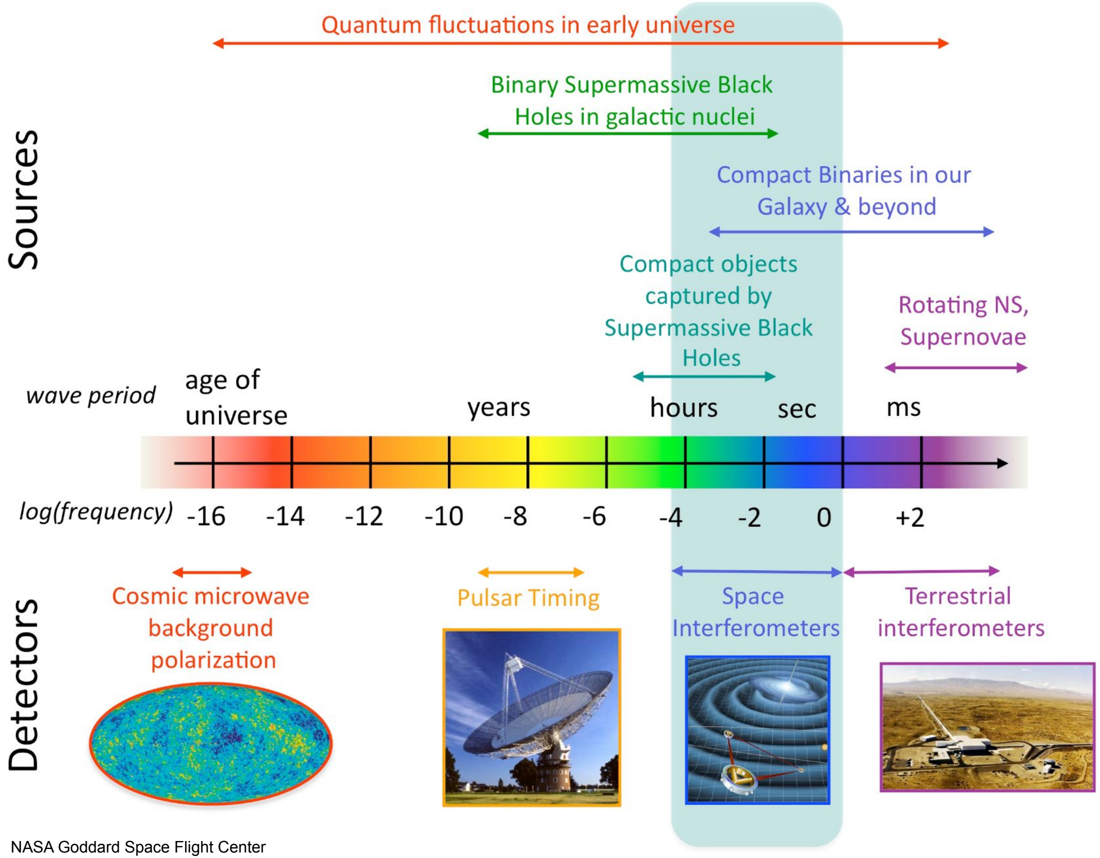
Multimessenger astronomy



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

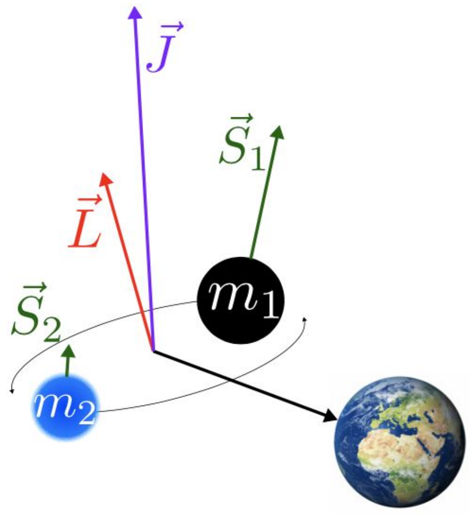
Joint information about bulk motion, circum-source environment, matter, temperature, redshift…

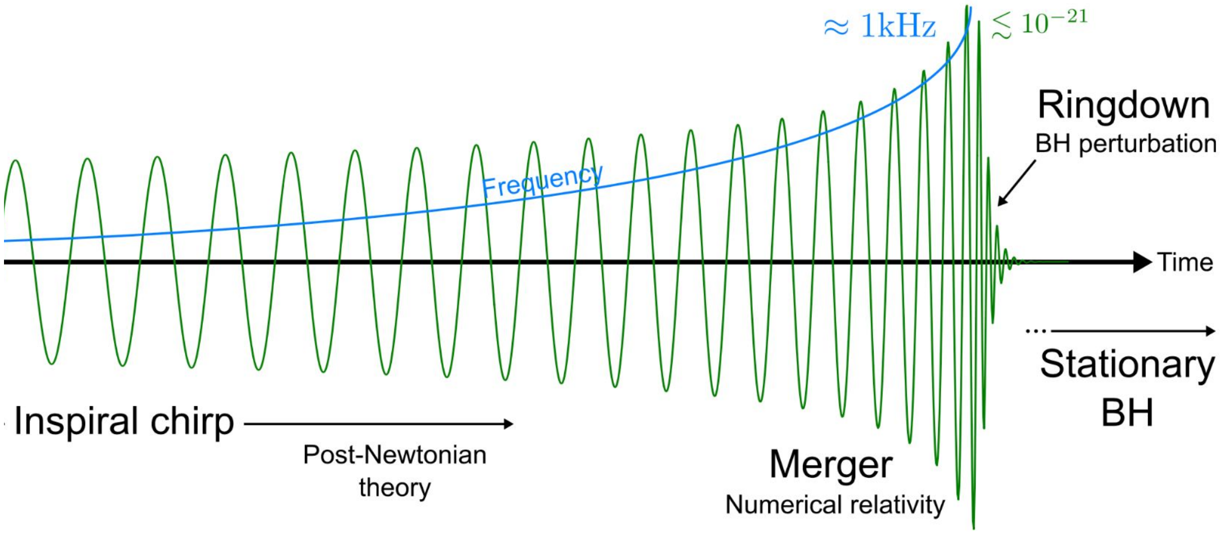
Sources across the gravitational-wave spectrum



NASA Goddard Space Flight Center

Compact binary mergers





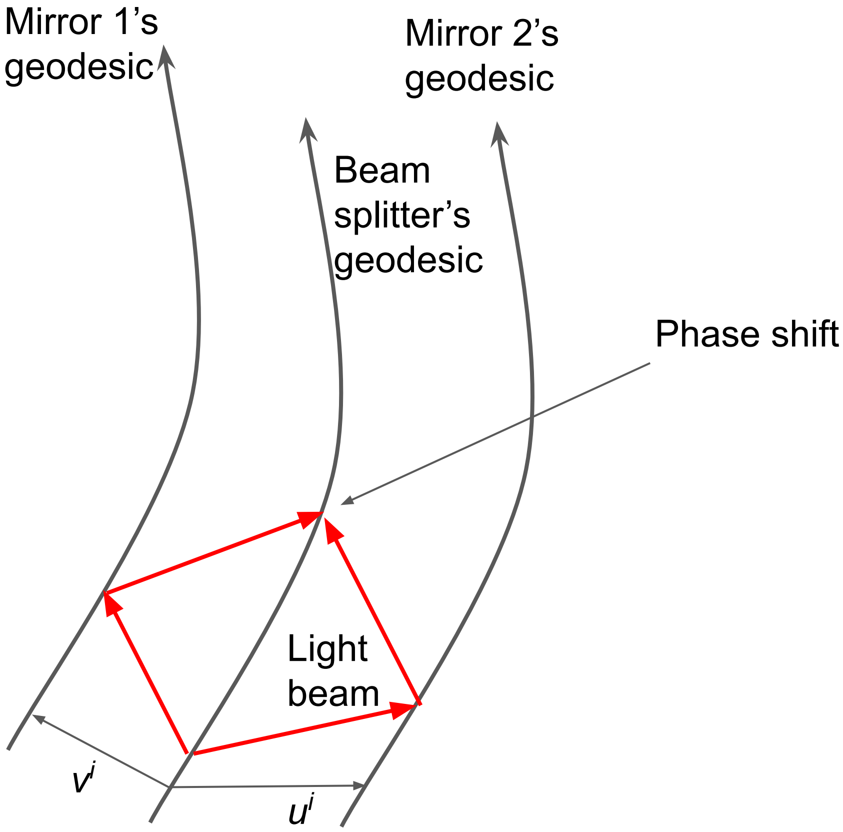
"Standard siren" for cosmology: if we see such a signal, we can infer

- The luminosity distance
- The redshifted masses

independently from cosmological assumptions.

Potentially "EM-bright" if neutron stars are involved.

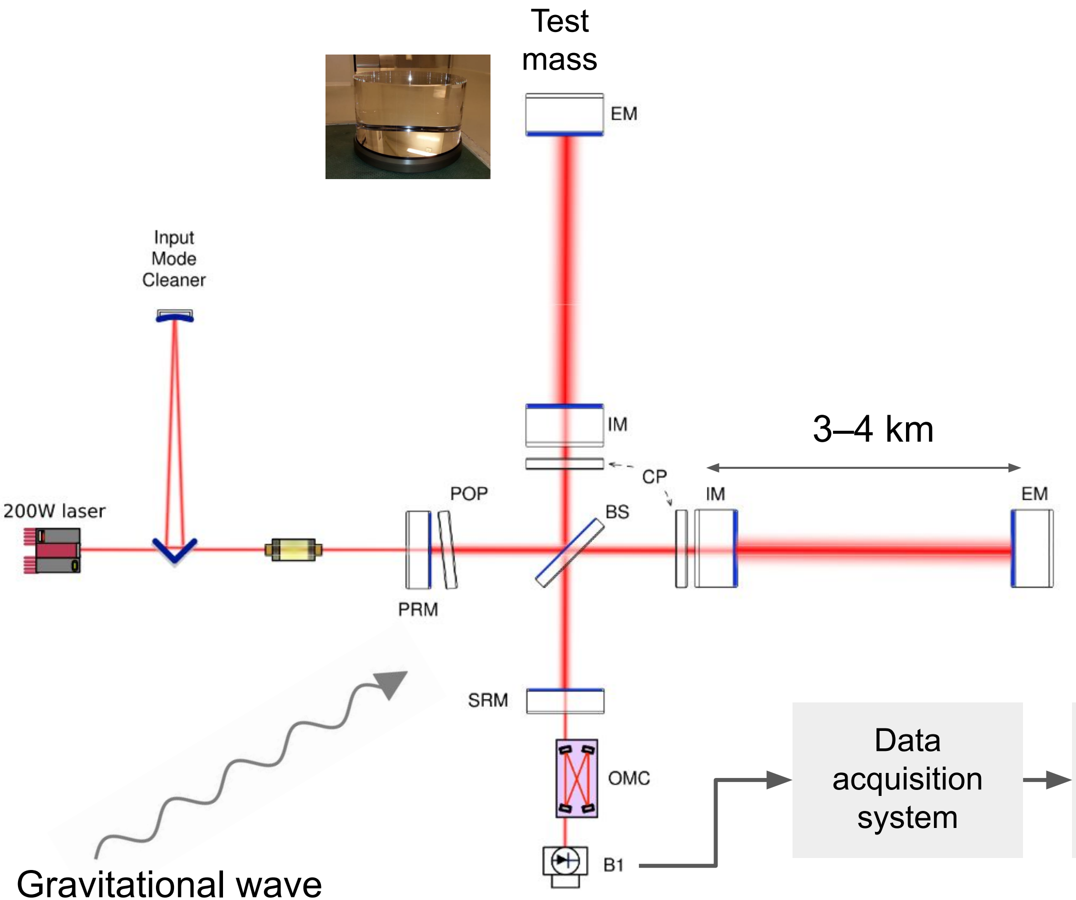
Interferometric gravitational-wave detectors

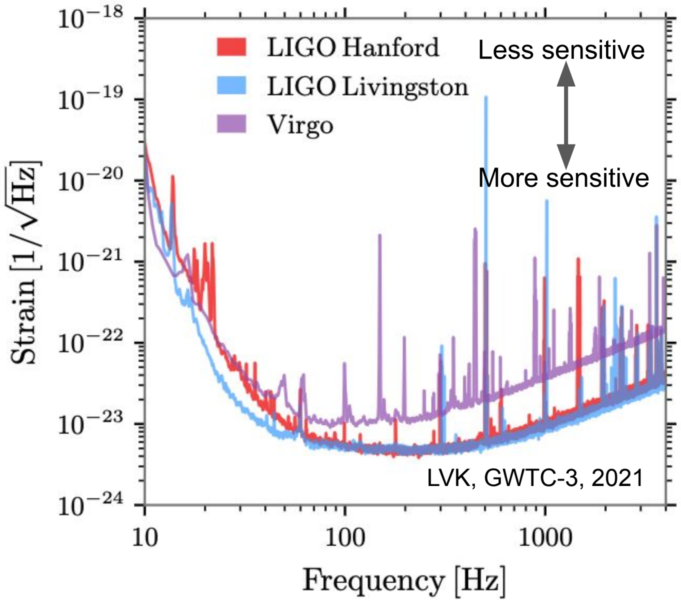


$$\delta\phi = \frac{4\pi f_{\mathrm{light}}}{c}(\delta L_1 - \delta L_2)$$

$$\propto L(u^i u^j - v^i v^j)h_{ij}$$

Interferometric gravitational-wave detectors

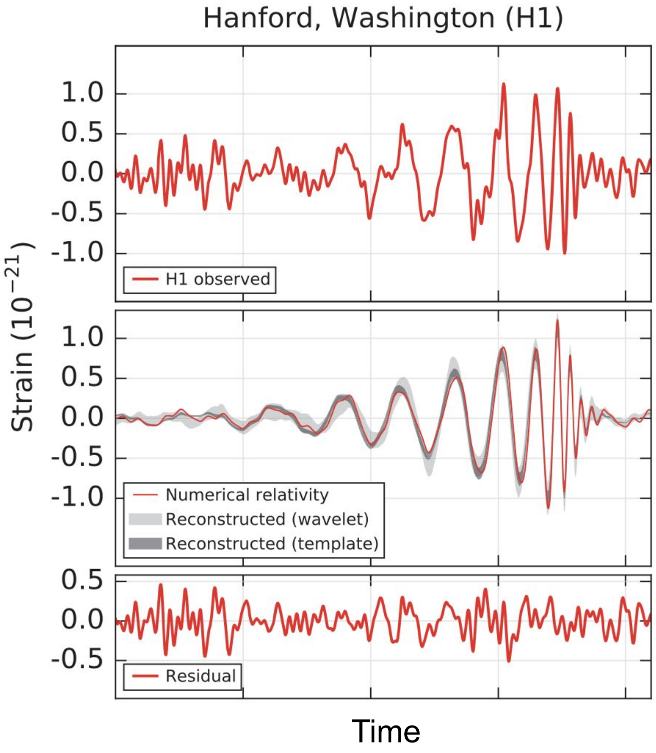




Data acquisition system → Calibration Cleaning … → GW strain time series $h(t)$ → Astrophysical analyses

Analysis of gravitational-wave data

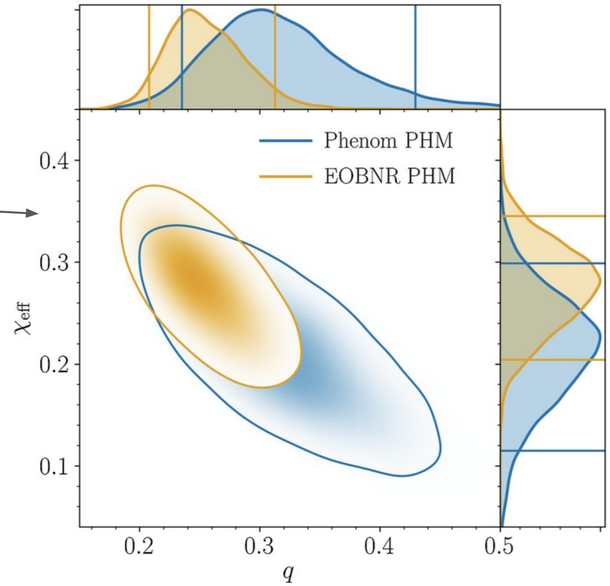
1) Find the signals in the data 2) Interpret the signals based on available models 3) Population analyses



Data

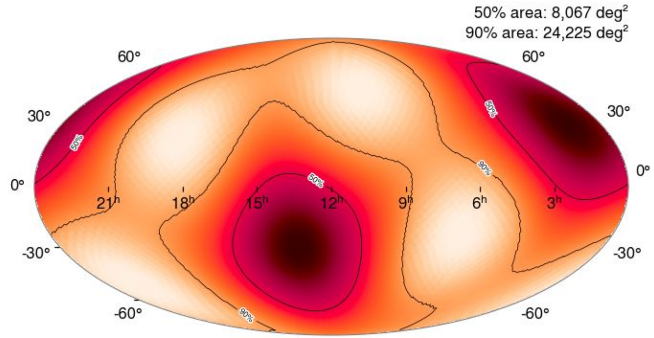
Inference

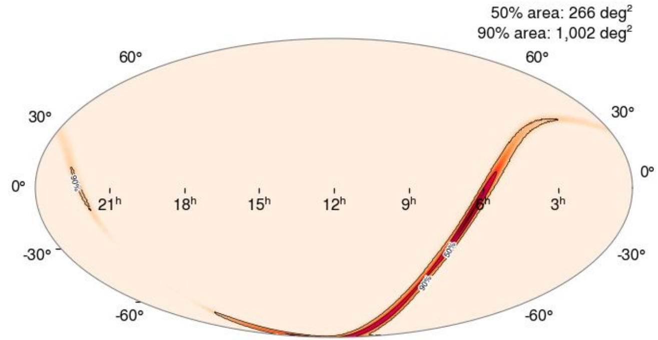
Model



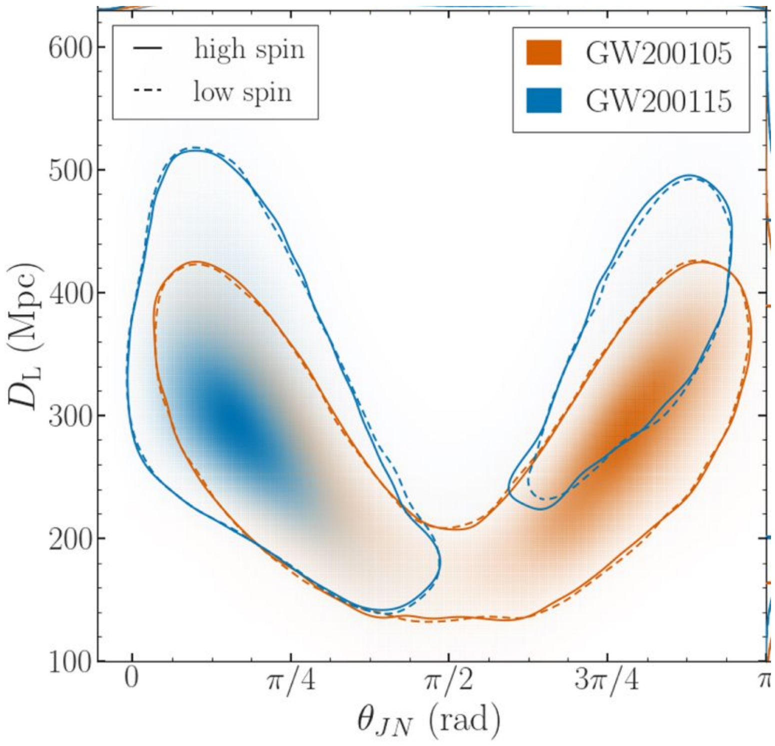
Analysis of gravitational-wave data: degeneracies

Sky localization





Distance - orbital inclination



Measuring H_0 with gravitational waves: bright sirens method

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3 \Omega_M + \Omega_\Lambda}}$$

Small redshift

Gravitational-wave observation

Electromagnetic observation of the GW source

$$d_L \approx \frac{cz}{H_0}$$

Challenges:

- Low rate of EM-bright transient GW sources
- Uncertainties in their spatial localizations
- EM signals rapidly-fading and relatively faint.

Measuring H_0 with gravitational waves: dark sirens + catalog

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3\Omega_M + \Omega_\Lambda}}$$

Small redshift

Gravitational-wave observation

$$d_L \approx \frac{cz}{H_0}$$

Electromagnetic observation of galaxies spatially compatible with the GW source

Challenges:

- Completeness of the galaxy catalogs
- Uncertainties in spatial localization of GW sources.

Measuring H_0 with gravitational waves: dark sirens alone

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3\Omega_M + \Omega_\Lambda}}$$

Small redshift

Prior knowledge of source-frame mass

Gravitational-wave observation

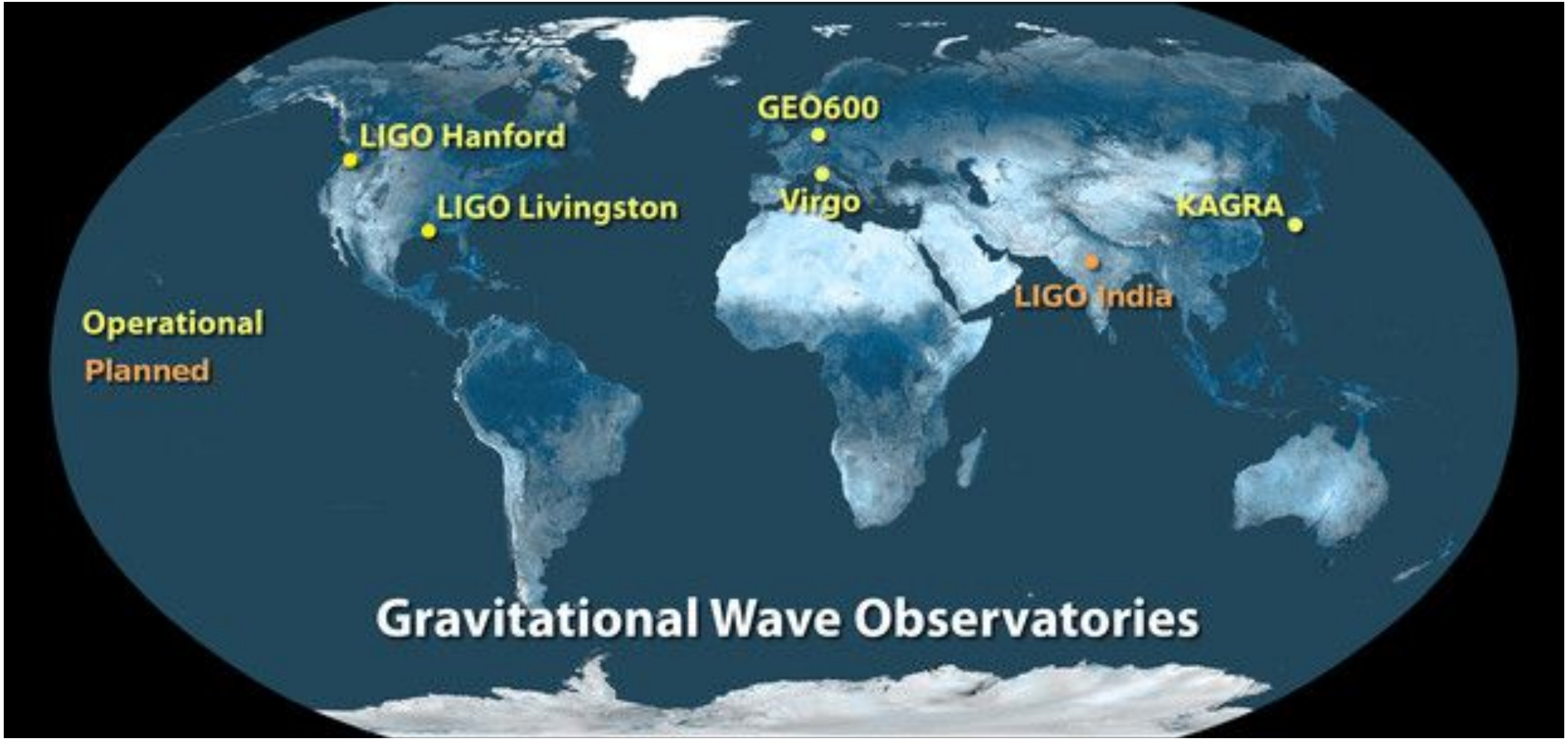
$$m_{\rm obs} = (1+z) m_{\rm src}$$

$$d_L \approx \frac{cz}{H_0}$$

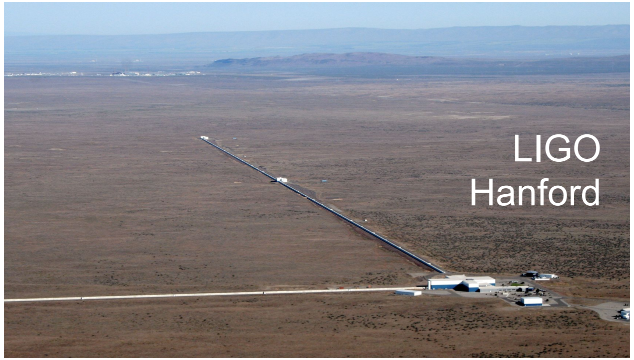
Challenges:

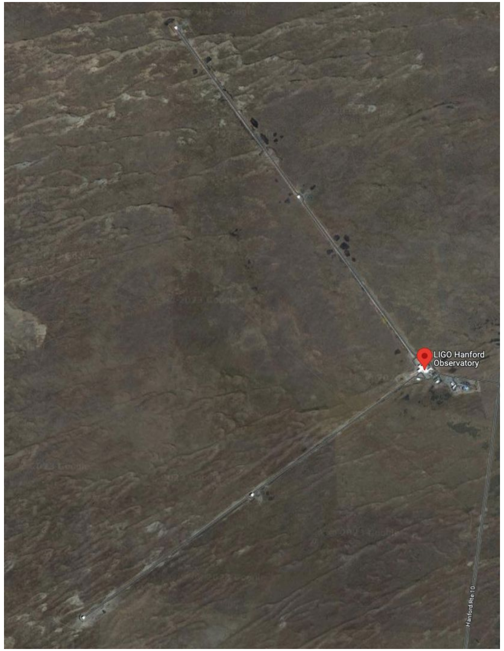
- Need “sharp” features in the intrinsic mass distribution
- Results depend on the chosen population model.

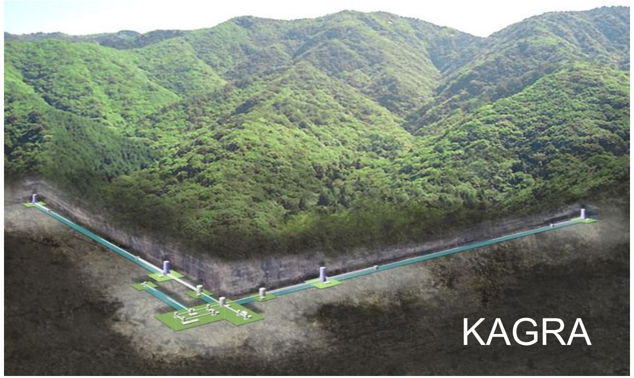
Present network of ground-based detectors



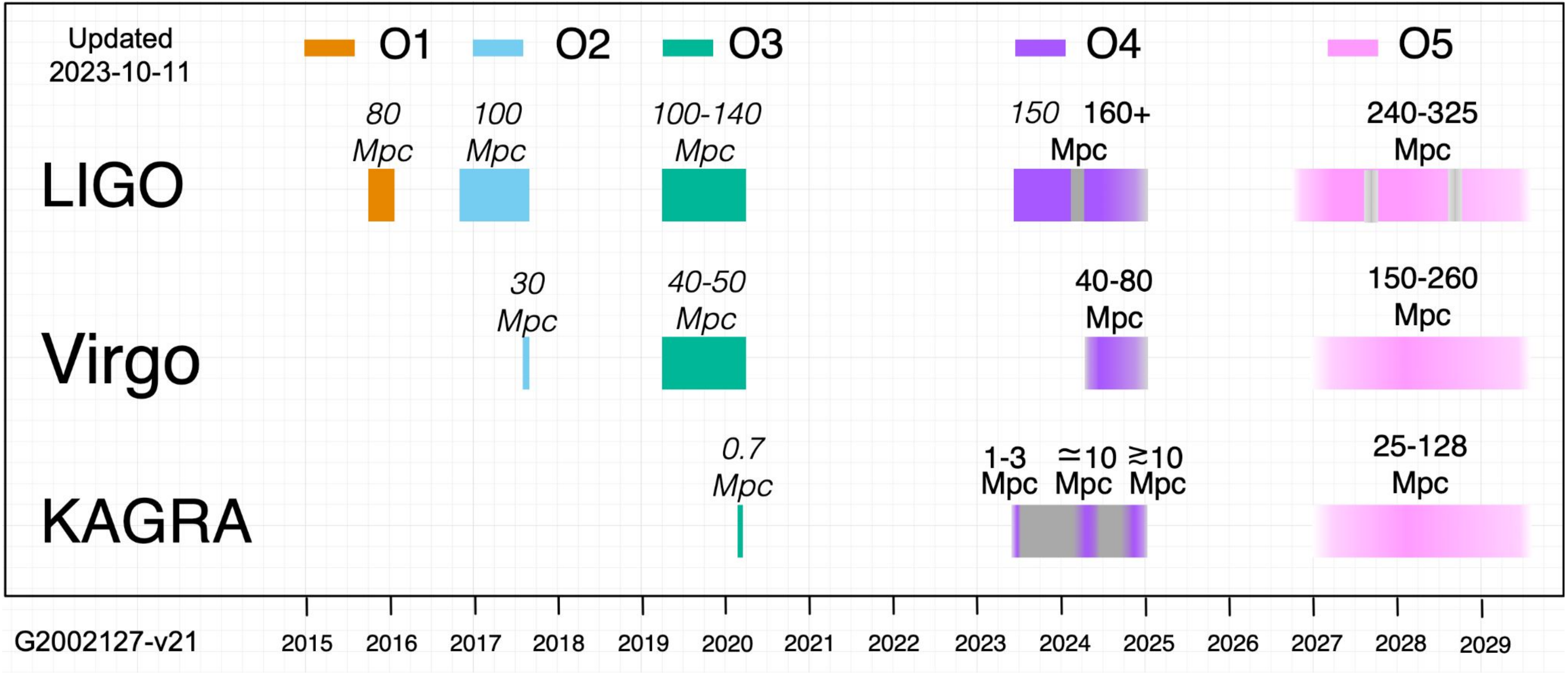
Present network of ground-based detectors





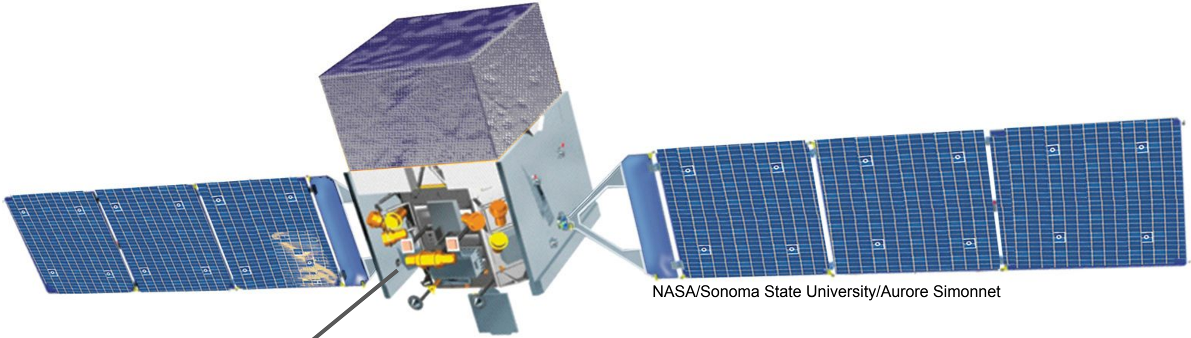


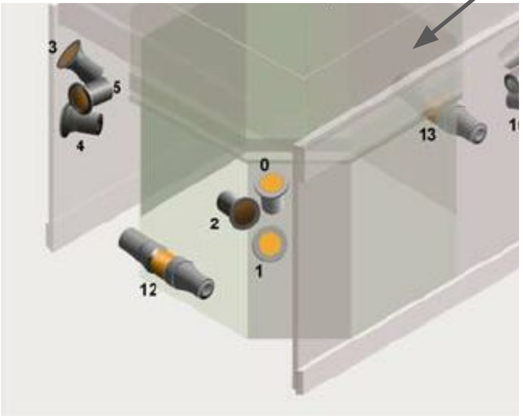
Timeline of LIGO-Virgo-KAGRA observations



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

The Gamma-ray Burst Monitor on the Fermi satellite



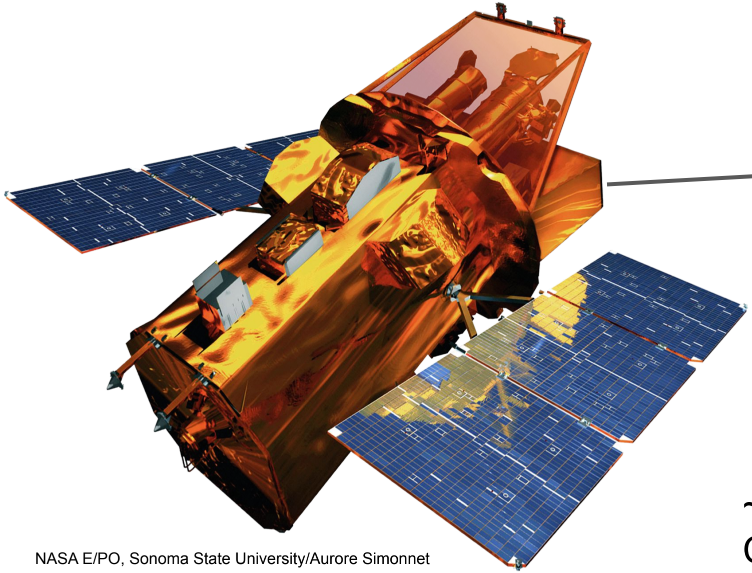


All-sky (except for Earth occulted sources, ~70%)
All-time (except for South Atlantic Anomaly passages)
12 NaI, 2 BGO scintillators + photomultipliers
Energy range 8 keV - 40 MeV, 128 energy channels

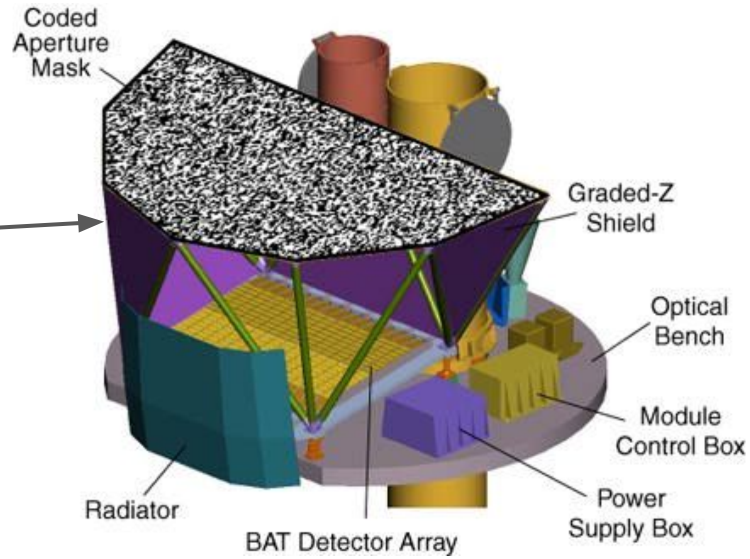
Onboard triggering
Continuous Time Tagged Event data downlink, ~5 μs timing

Source localization to ~1–20 deg

The Burst Alert Telescope on the Neil Gehrels Swift satellite



NASA E/PO, Sonoma State University/Aurore Simonnet

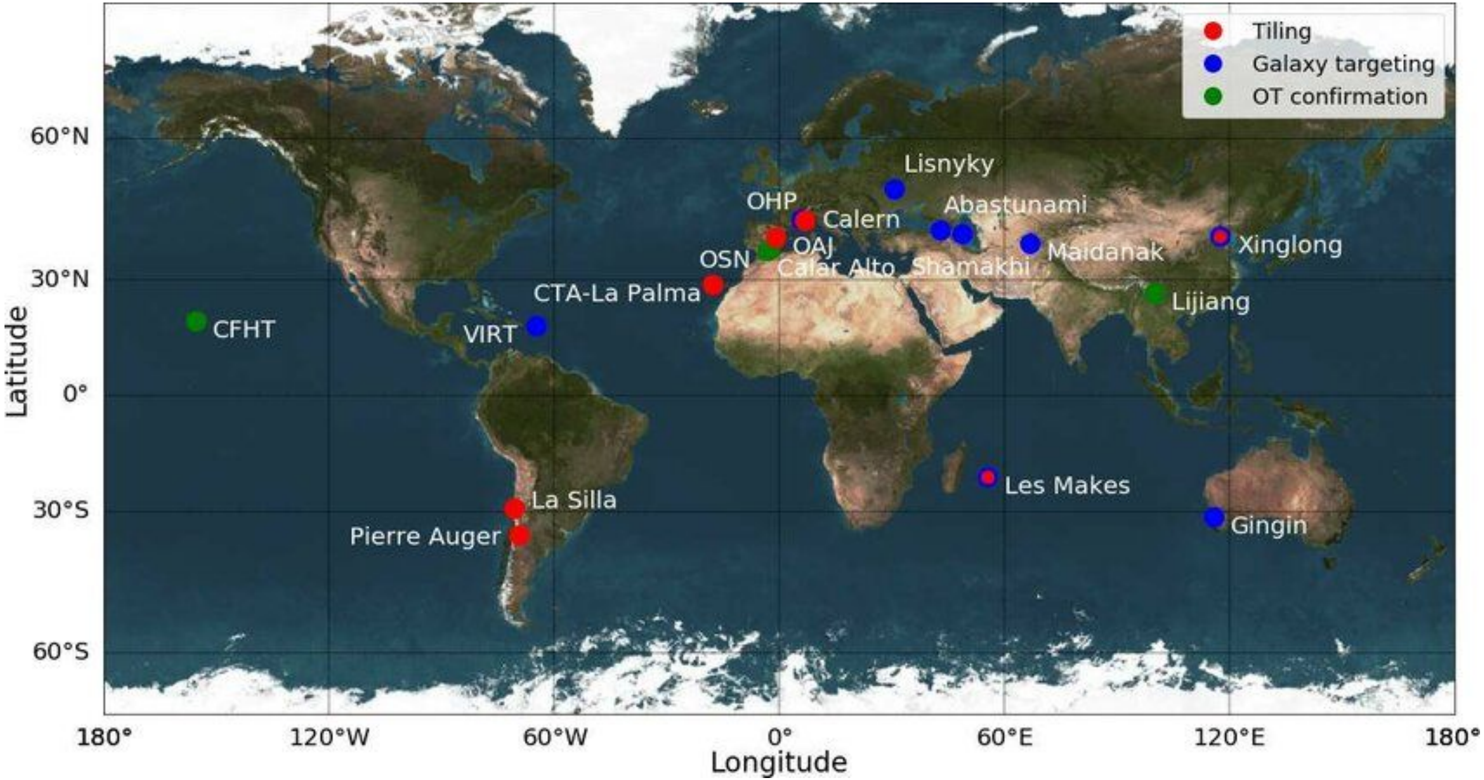


~2 sr FoV
Coded mask telescope
Energy range 15-150 keV in 4096 channels
Source localization to ~arcminutes

Onboard triggering
Very fast repointing

The GRANDMA telescope network

[Agayeva et al 2020]



LIGO-Virgo-KAGRA discoveries to date

LVK, GWTC-3, 2021

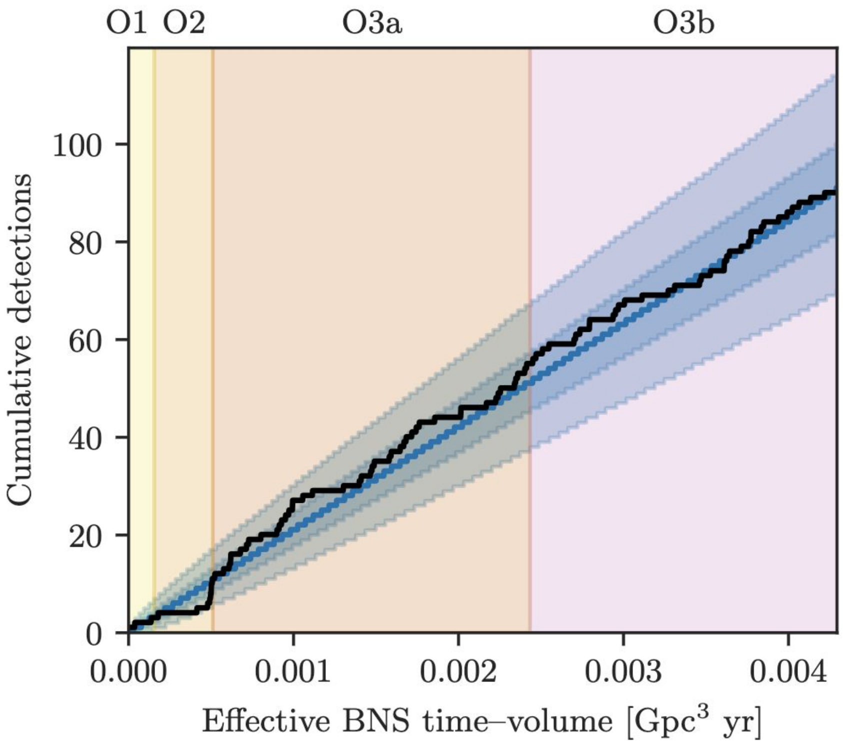
~100 mergers of compact binaries
(mostly binary black holes)

Routine discoveries at present,
rate ~few / week.

Automated EM followup observations.

Live public results on https://gracedb.ligo.org

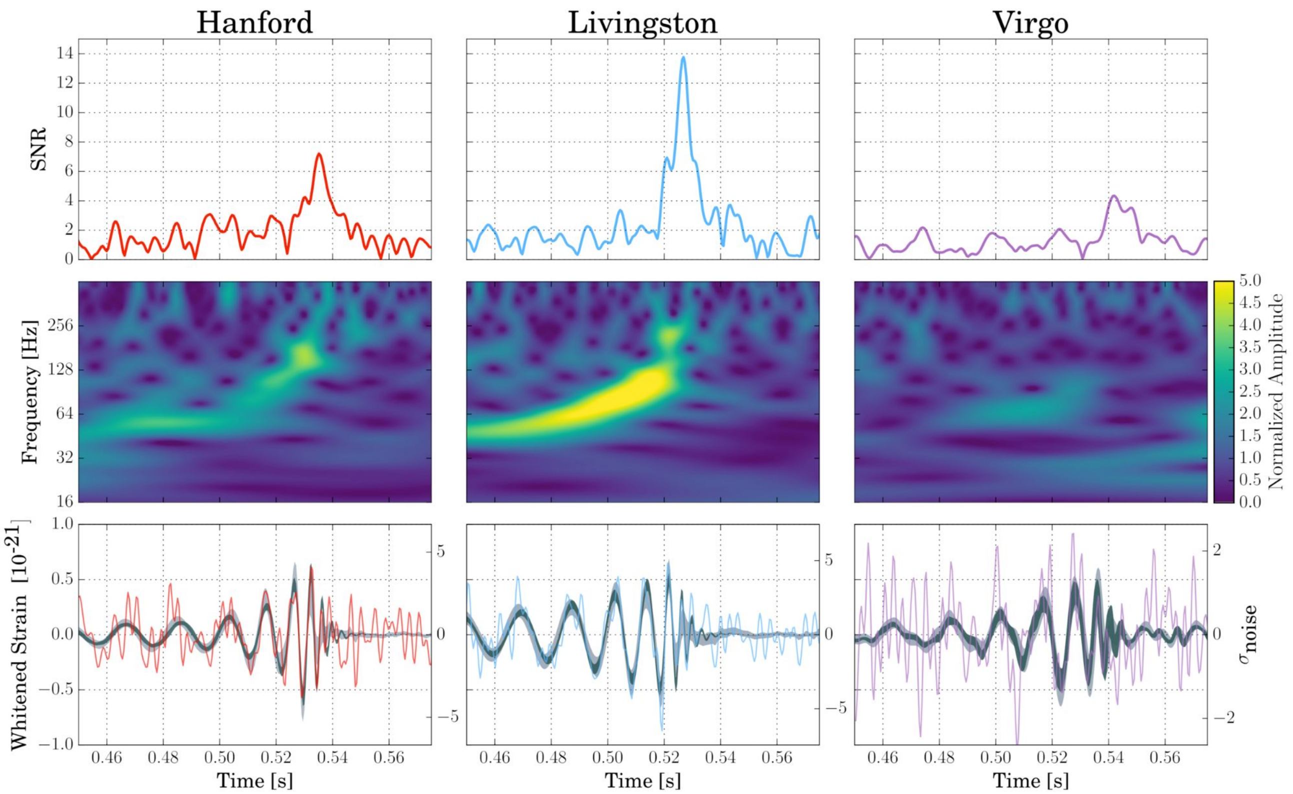
Catalog events on https://gwosc.org



LIGO-Virgo-KAGRA discoveries to date: BBH

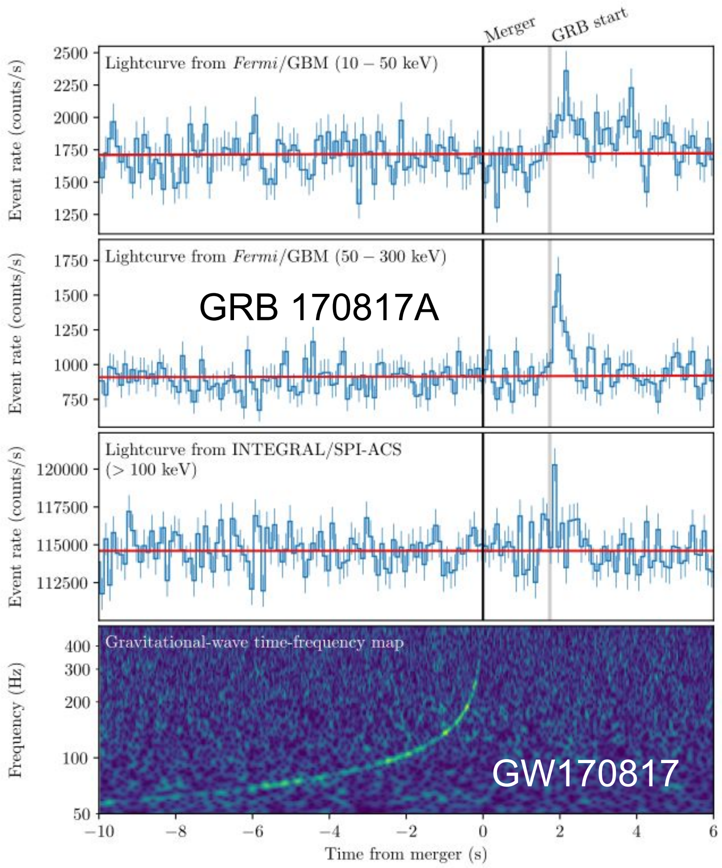
[LVK, GWTC-3, 2021]

GW190814, BBH merger observed by the entire network

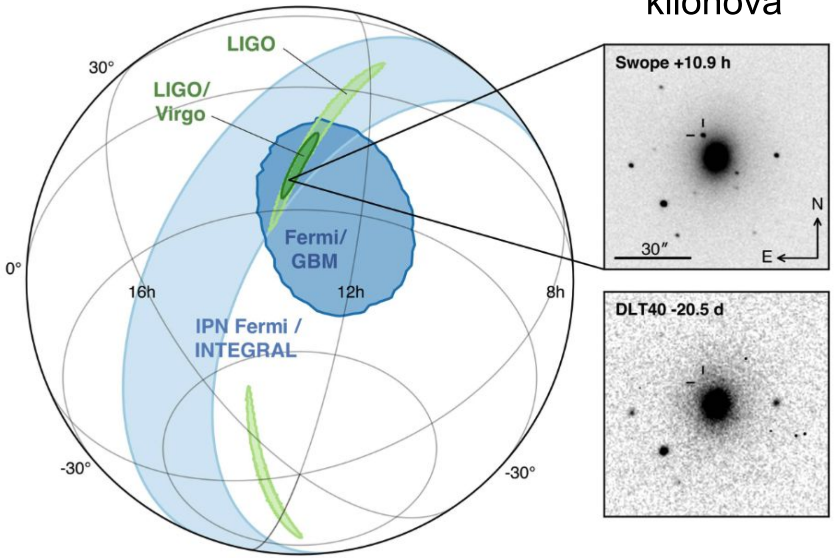


LIGO-Virgo-KAGRA discoveries to date: BNS

LVK, GWTC-3, 2021



AT2017gfo kilonova

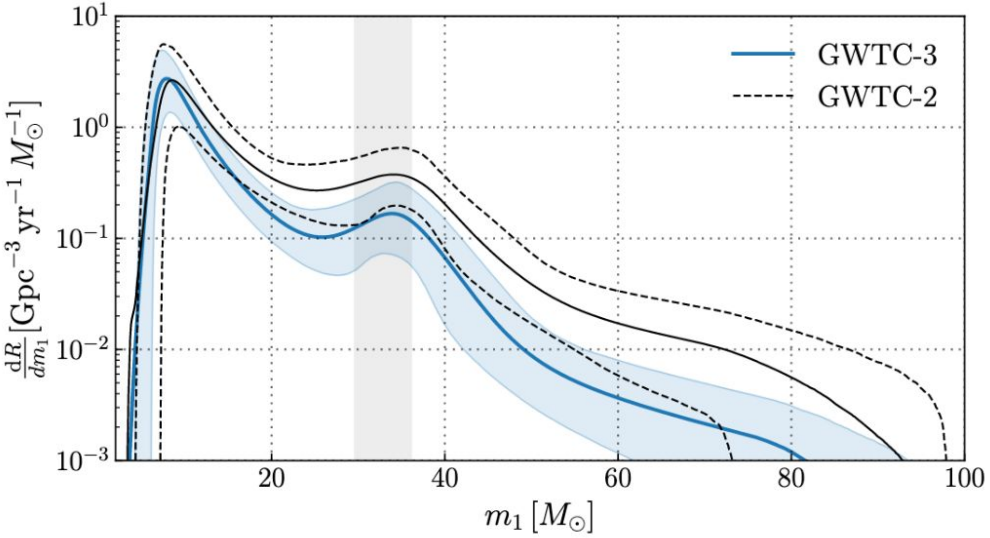


At present this remains the only robust observation of a GW signal with EM counterparts.

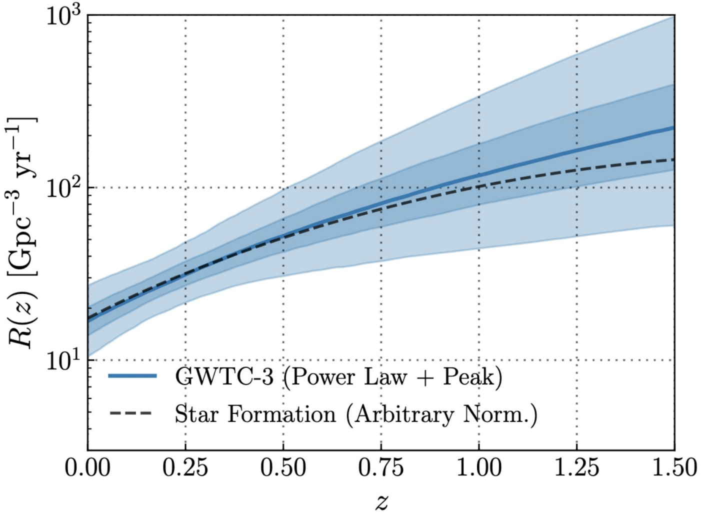
Population of binary black hole mergers

LIGO/Virgo/KAGRA, arXiv:2111.03634

Mass of the heaviest component of the binary



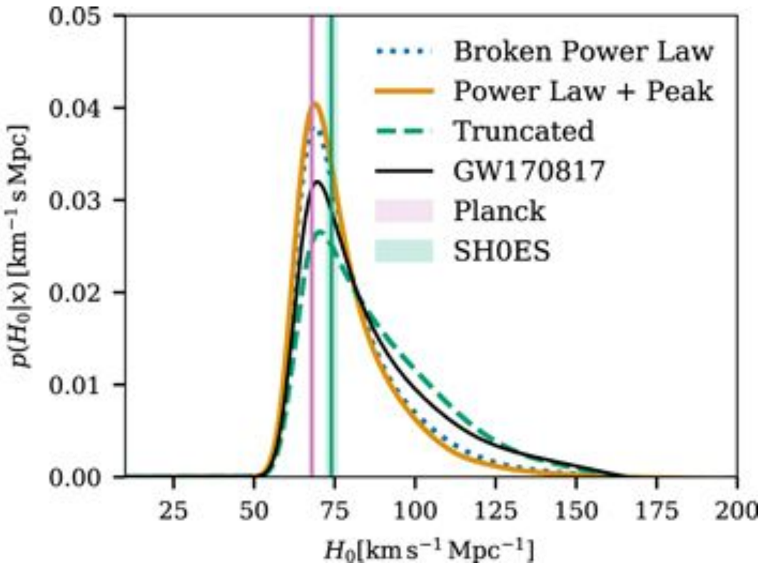
Merger rate density evolution with redshift

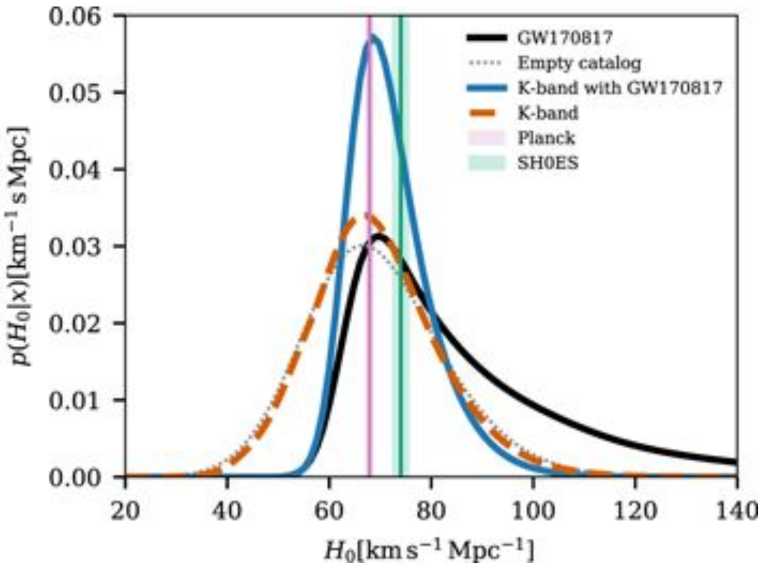


H_0 measurements to date

R. Abbott *et al* 2023 *ApJ* **949** 76

One bright siren + tens of dark sirens available

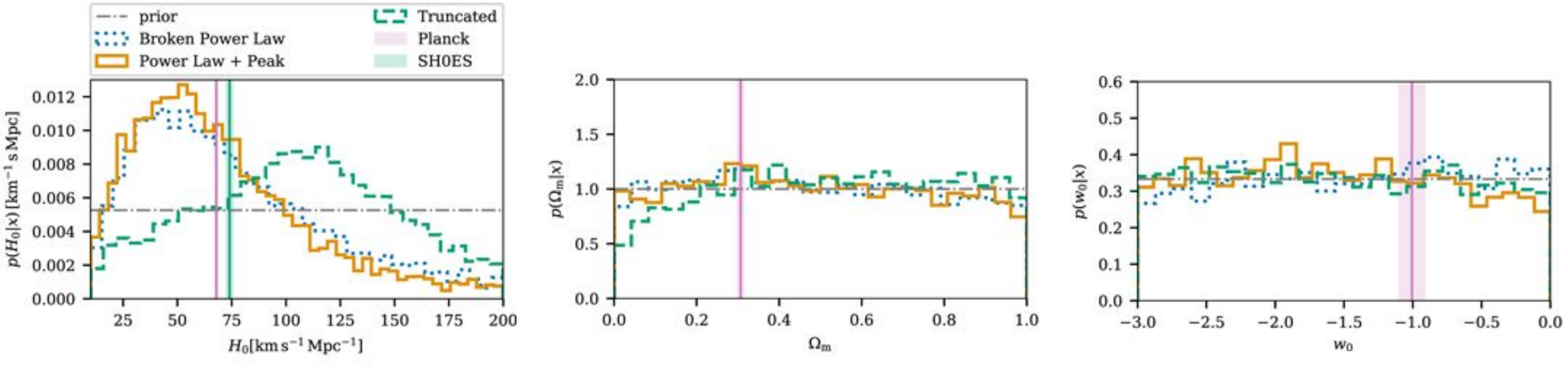




Constraints on other parameters

R. Abbott *et al* 2023 *ApJ* **949** 76

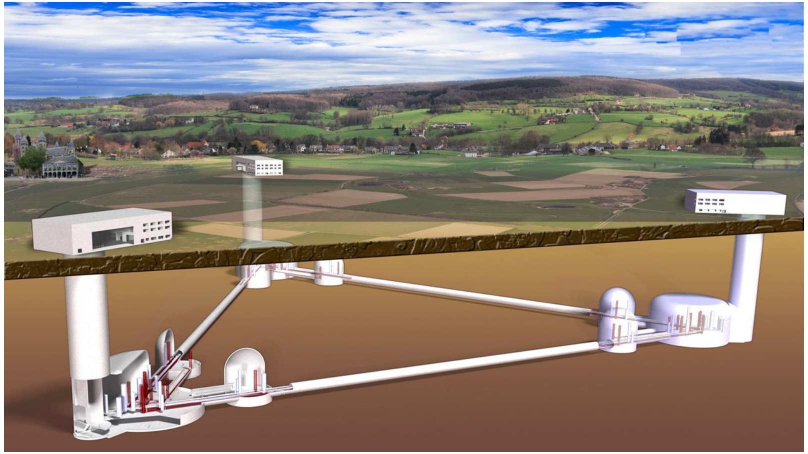
Trying a wider cosmological model, and excluding GW170817

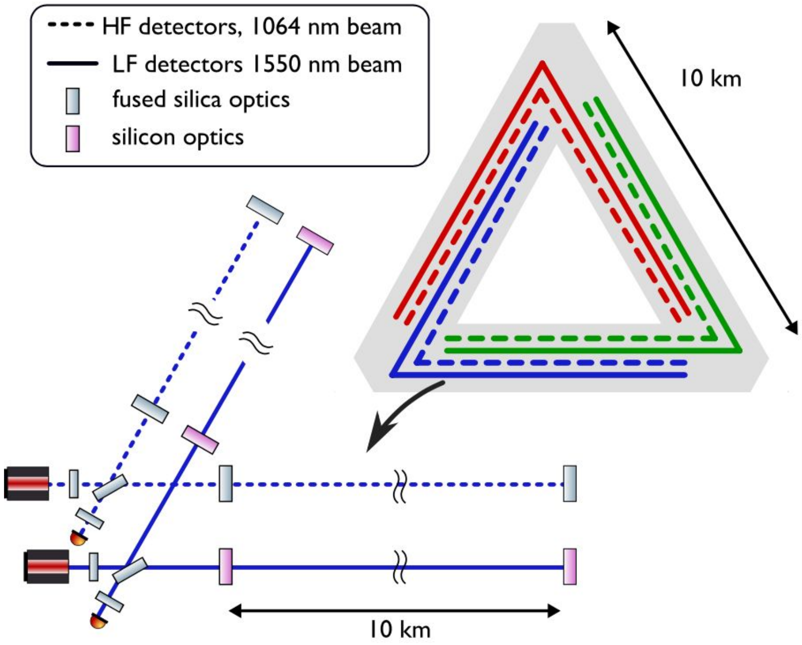


No statistical power so far to constrain the additional parameters.

Envisioned evolution of present gravitational-wave detectors

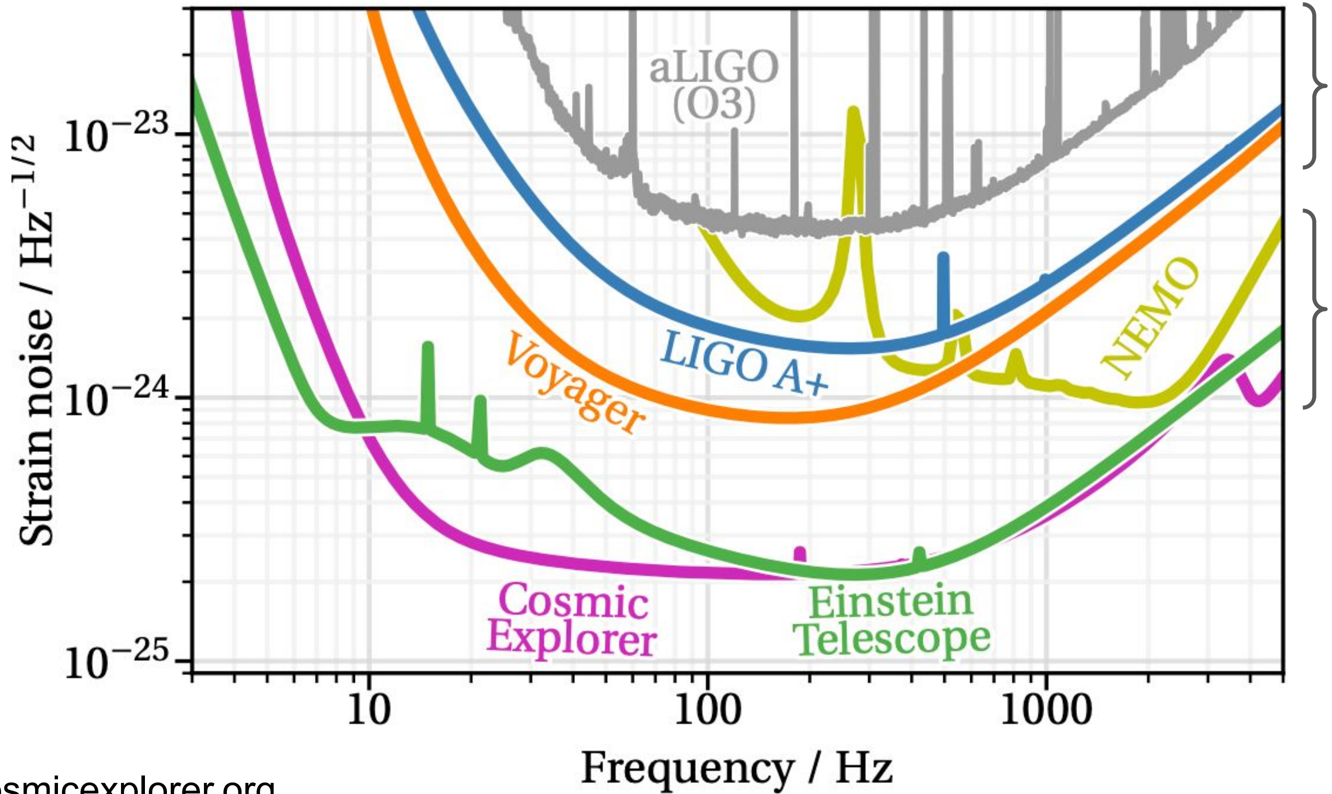
Einstein Telescope: underground triangle-shaped combination of six interferometers in the EU.





Cosmic Explorer: 40 km L-shaped interferometer in the US.

Envisioned evolution of present gravitational-wave detectors

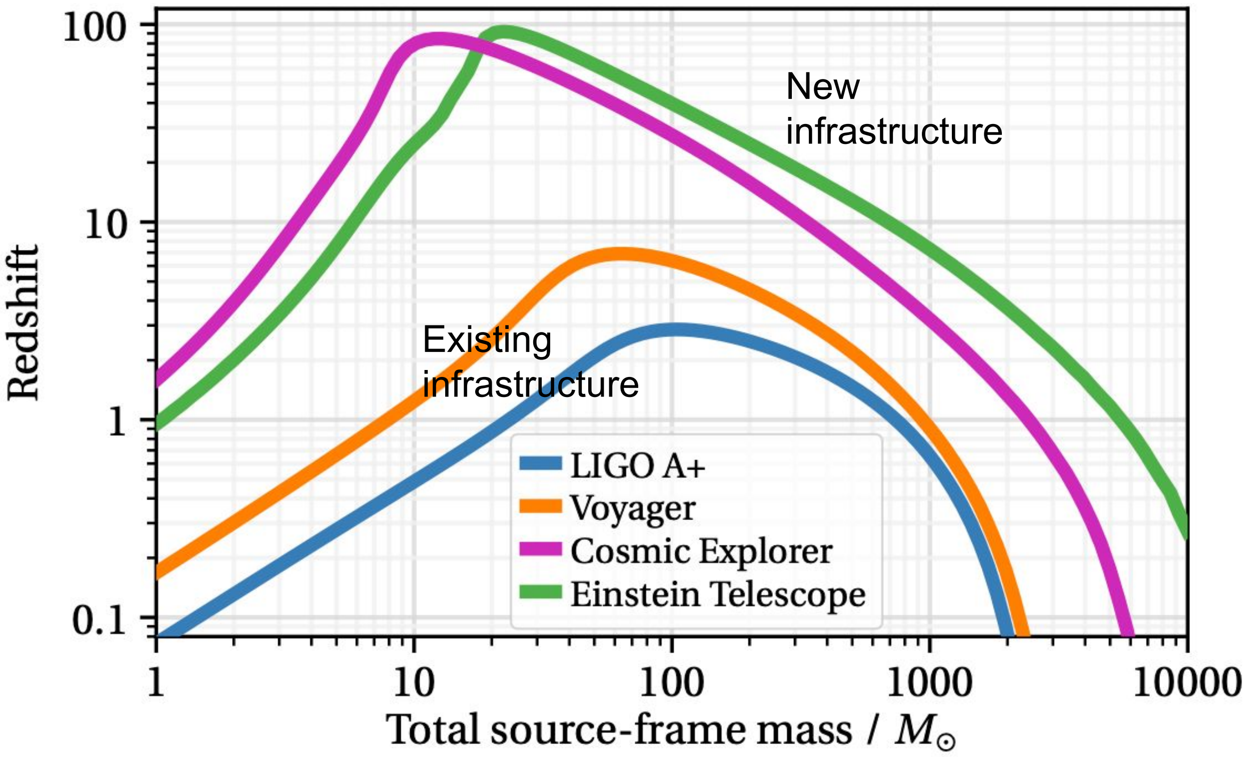


Existing infrastructure

New infrastructure

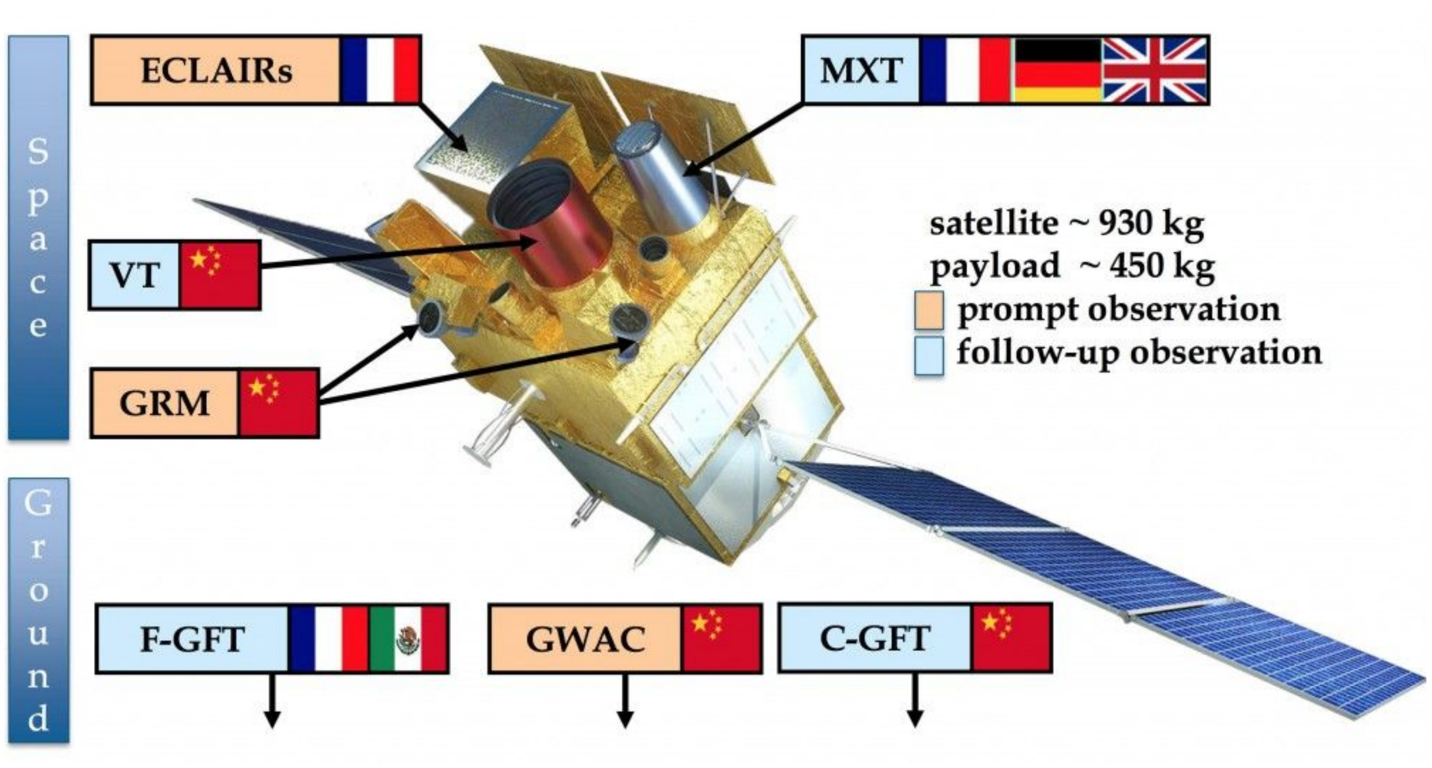
https://cosmicexplorer.org

Envisioned evolution of present gravitational-wave detectors



https://cosmicexplorer.org

Upcoming: the Space Variable Objects Monitor

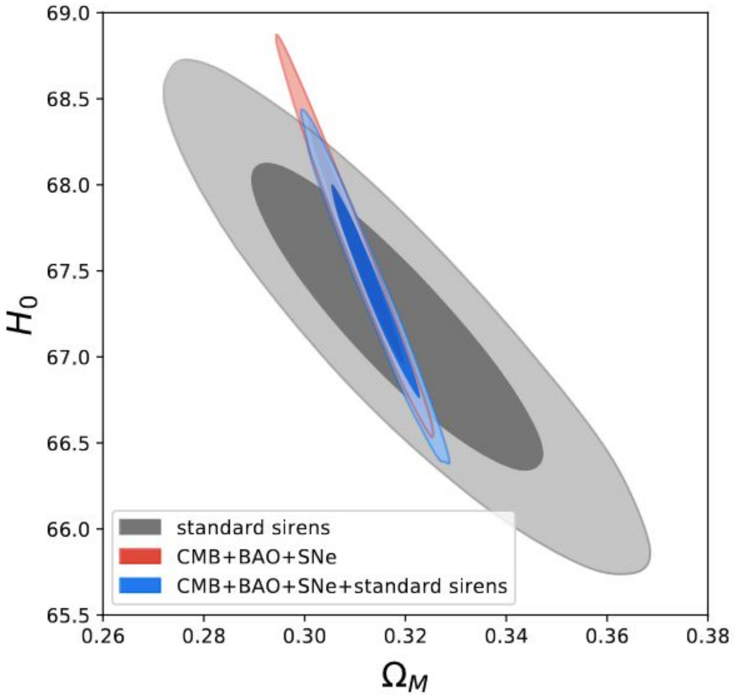


www.svom.eu

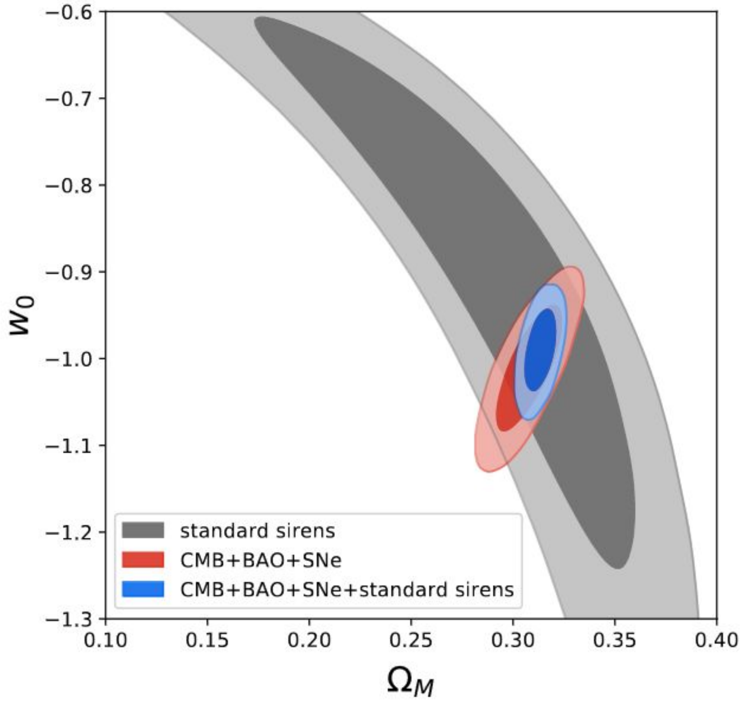
Example of cosmology potential with 3G detectors

Belgacem et al 2018

Lambda-CDM inference with
10^3 standard sirens in ET



wCDM inference
with 10^3 standard sirens in ET



Summary

Black-hole mergers detected routinely. Hundreds expected in the next few years.

Golden multimessenger observations like GW170817 appear to be pretty rare at this point, but we do not necessarily need them!

Cosmological constraints at present limited to local H_0 measurements.
Methods maturing. Precision will slowly improve in the next few years as events accumulate.

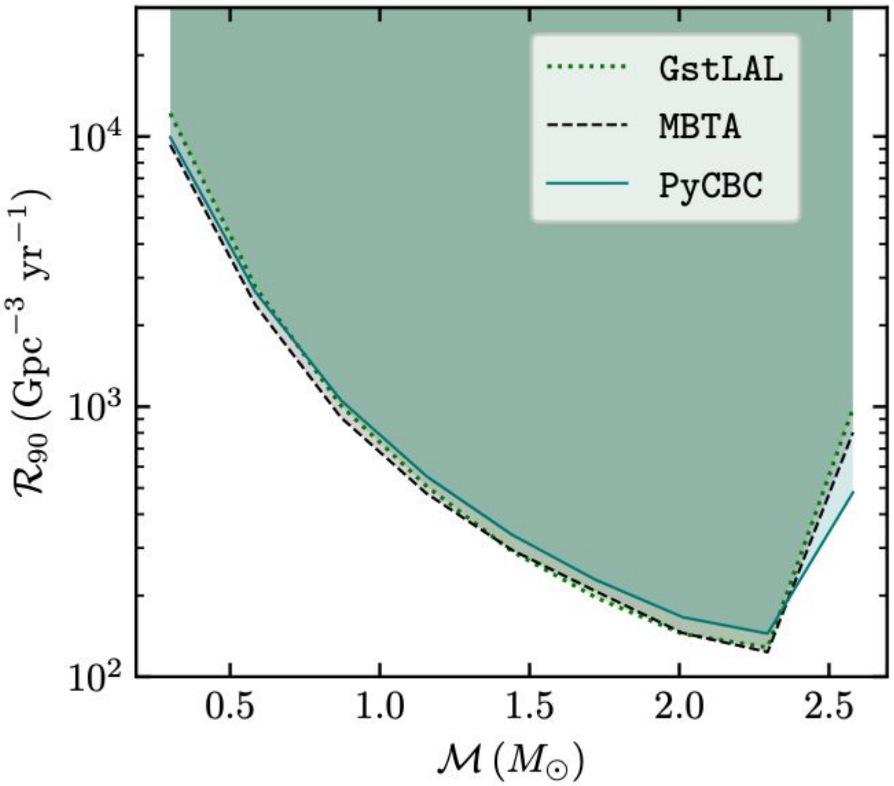
Major improvements expected with detector upgrades, especially third-generation observatories, thanks to much higher detection rates and observations beyond $z = 1$.

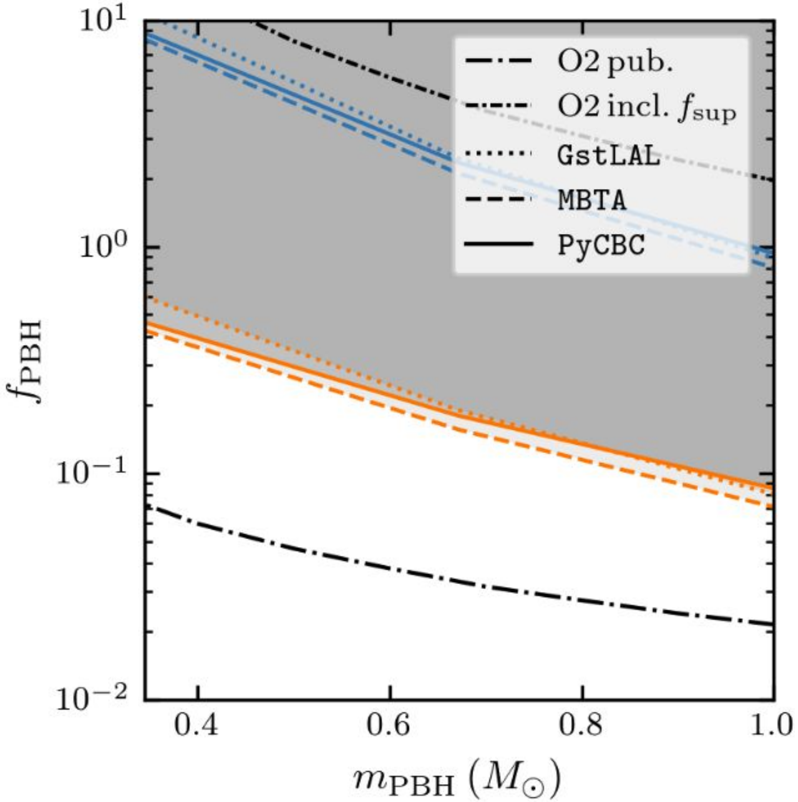
Other cosmological effects might be observable with third-generation detectors as well (e.g. modified GW propagation, cosmic strings, stochastic backgrounds).

Thank you for the attention!

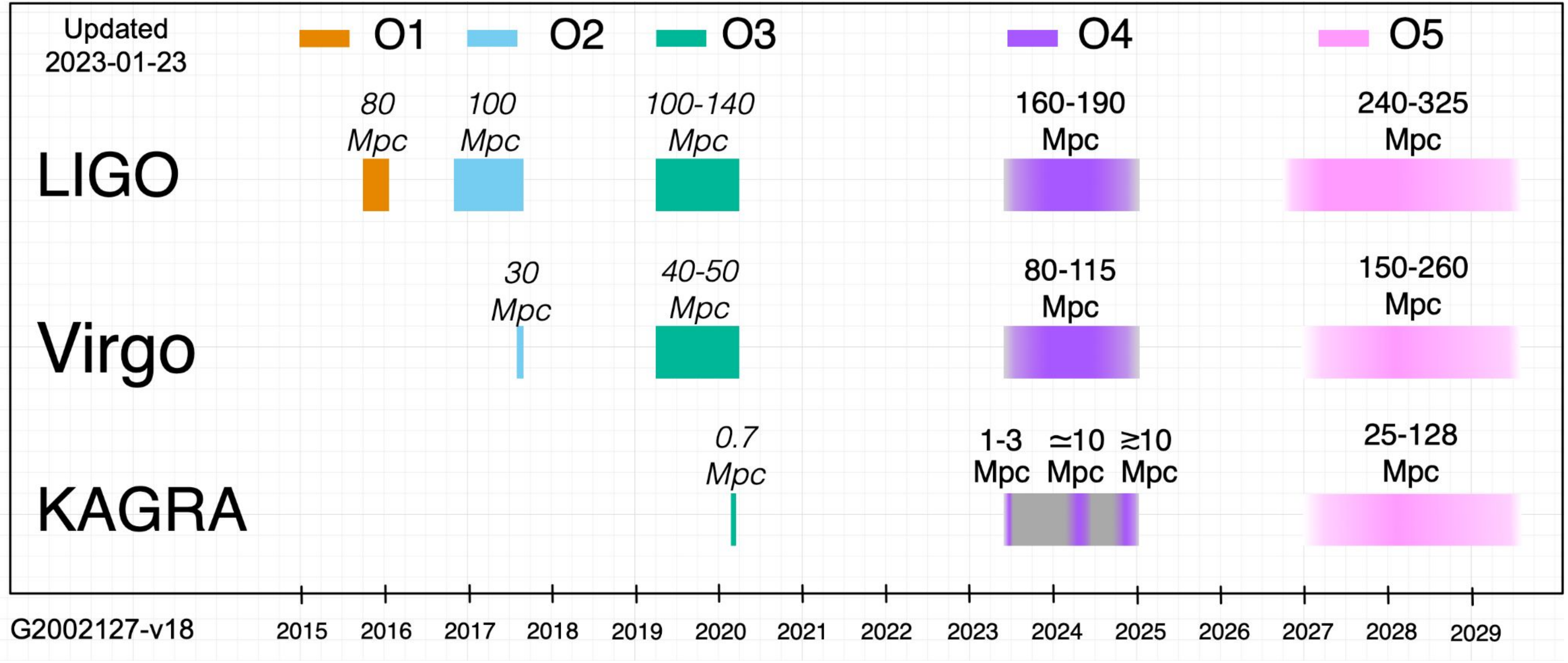
Subsolar-mass compact binary mergers

LVK 2022





Old timeline of LIGO-Virgo-KAGRA observations



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