Advanced Virgo
status & prospects

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DIECI ANNI DI ONDE GRAVITAZIONALI

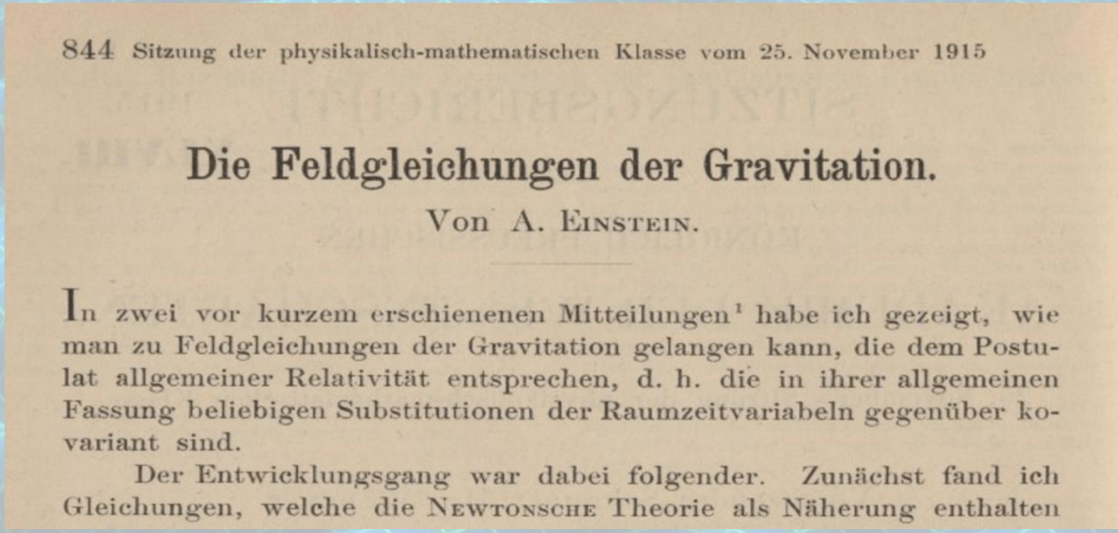
24 September 2025

What are Gravitational Waves?

- A consequence of Einstein's General Relativity
  - Gravity as a manifestation of the geometry of the spacetime

"Spacetime tells matter how to move; matter tells spacetime how to curve"

(J. Wheeler)



844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

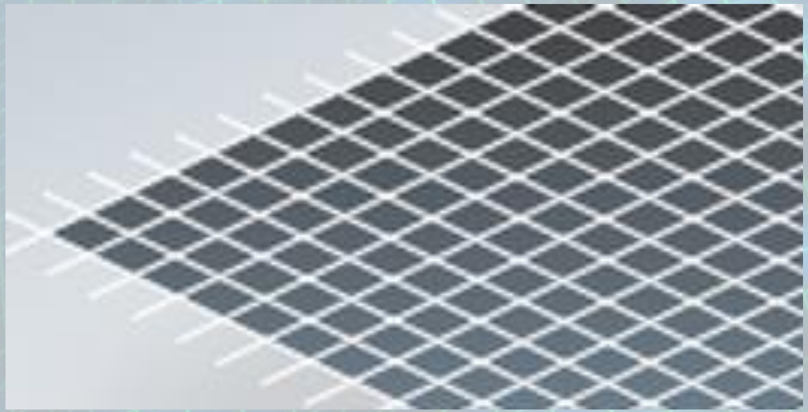
Die Feldgleichungen der Gravitation.

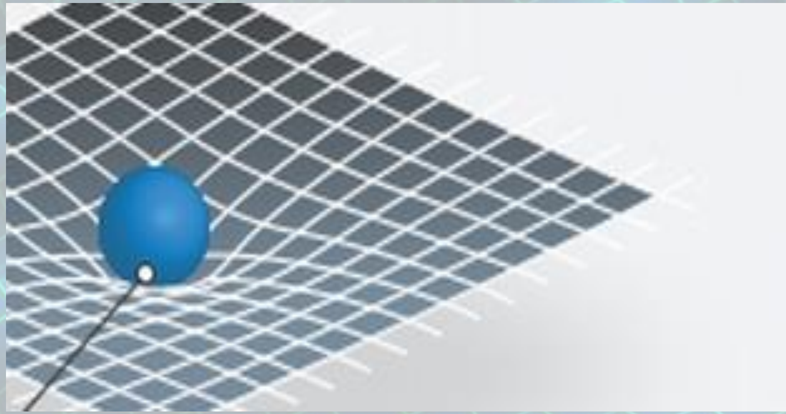
Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten

Credits: Preussische Akademie der Wissenschaften, Sitzungsberichte, 1915





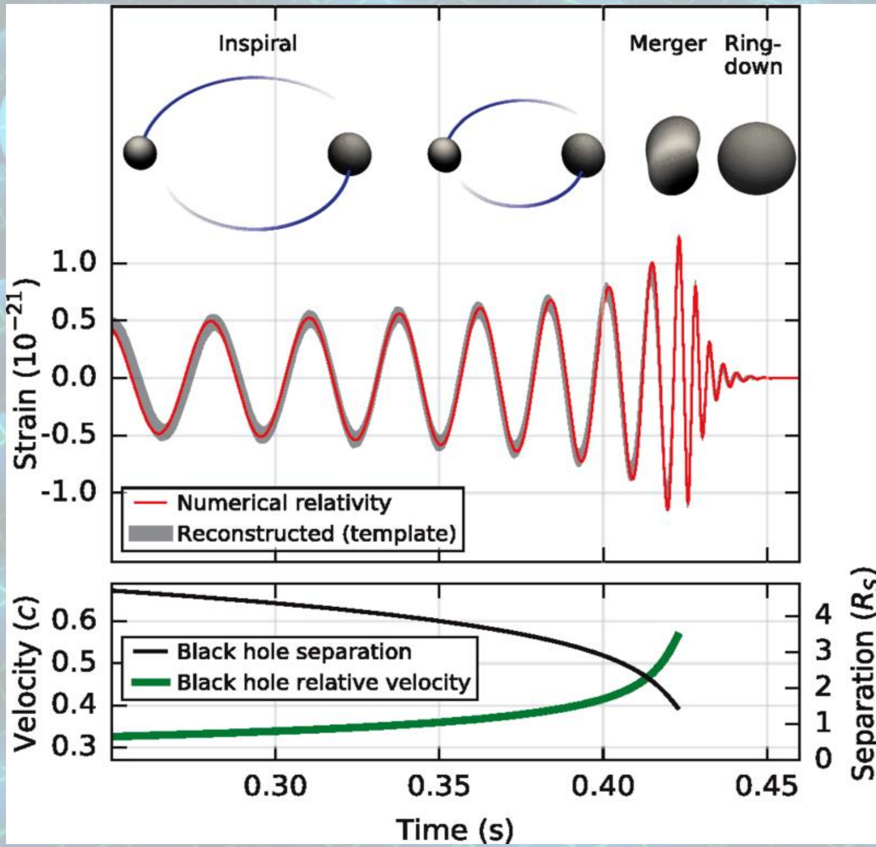
Expected sources of Gravitational Waves

Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (matched filter with template banks)
  - Only source class detected so far
- **Core-collapse of massive stars**
  - Uncertain waveforms
  - Unmodeled searches less sensitive than matched filter

Non transients

- **Rotating neutron stars**
  - Quadrupole emission from stellar asymmetry
  - Continuous and periodic
- **Stochastic background**
  - Continuous, due to unresolved sources/Big Bang relics

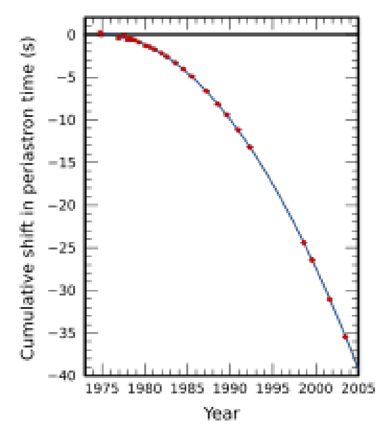


Abbott et al 2016, PRL, 116, 101103

The challenge of detecting GWs

1960's
J. Weber works
on resonant bars

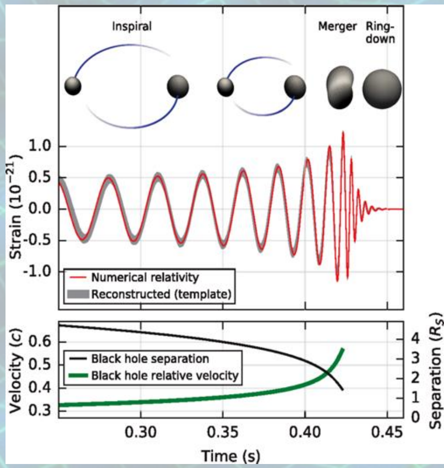
1974
Hulse-Taylor binary pulsar
Indirect evidence of GWs



1980s-1990s
First works on laser interferometers
(LIGO, Virgo)

2000s
First generation
(e.g. LIGO/Virgo/GEO600)
No detection ☹

2010s
Second «Advanced» generation
→ First detection!



LIGO & Virgo : origins

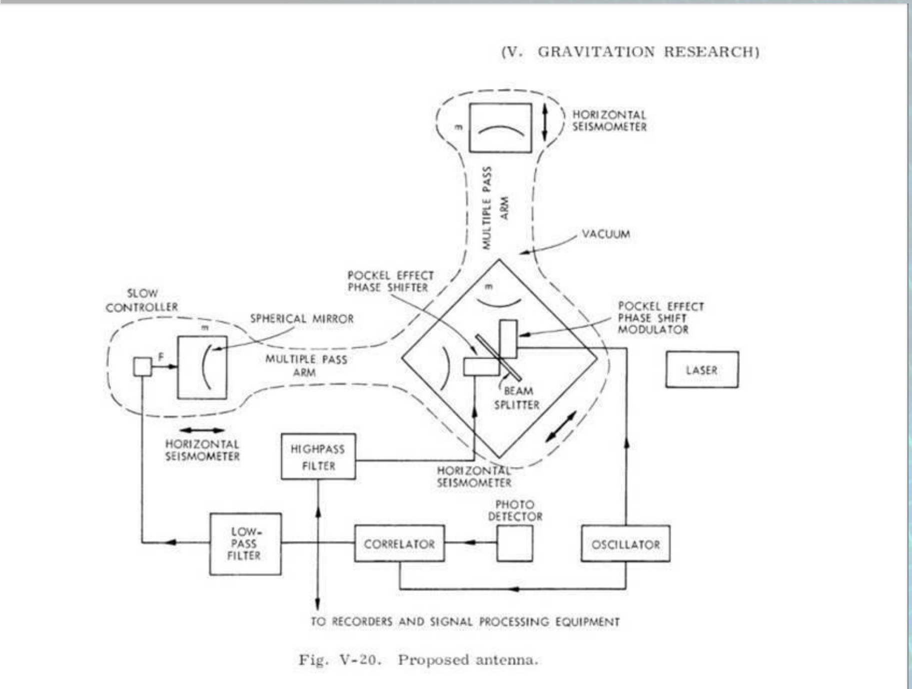
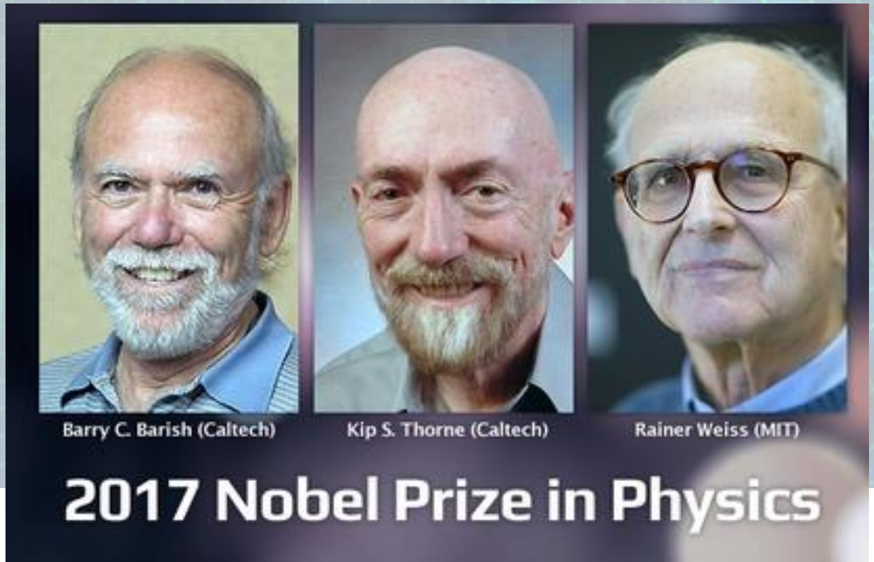


Fig. V-20. Proposed antenna.

In 1972 Rainer Weiss (MIT) proposed a GW detector exploiting interferometry



In mid-80s Giazotto&Brillet discussion on a GW detector focusing on low frequencies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12 Maggio 1987
INFN PI/AE 87/1

Proposta di

Antenna interferometrica a grande base per la ricerca di Onde Gravitazionali

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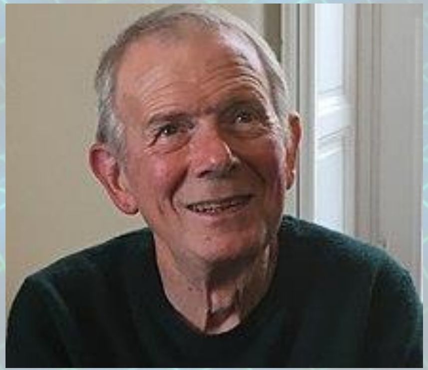
A. Giazotto (1940-2017)

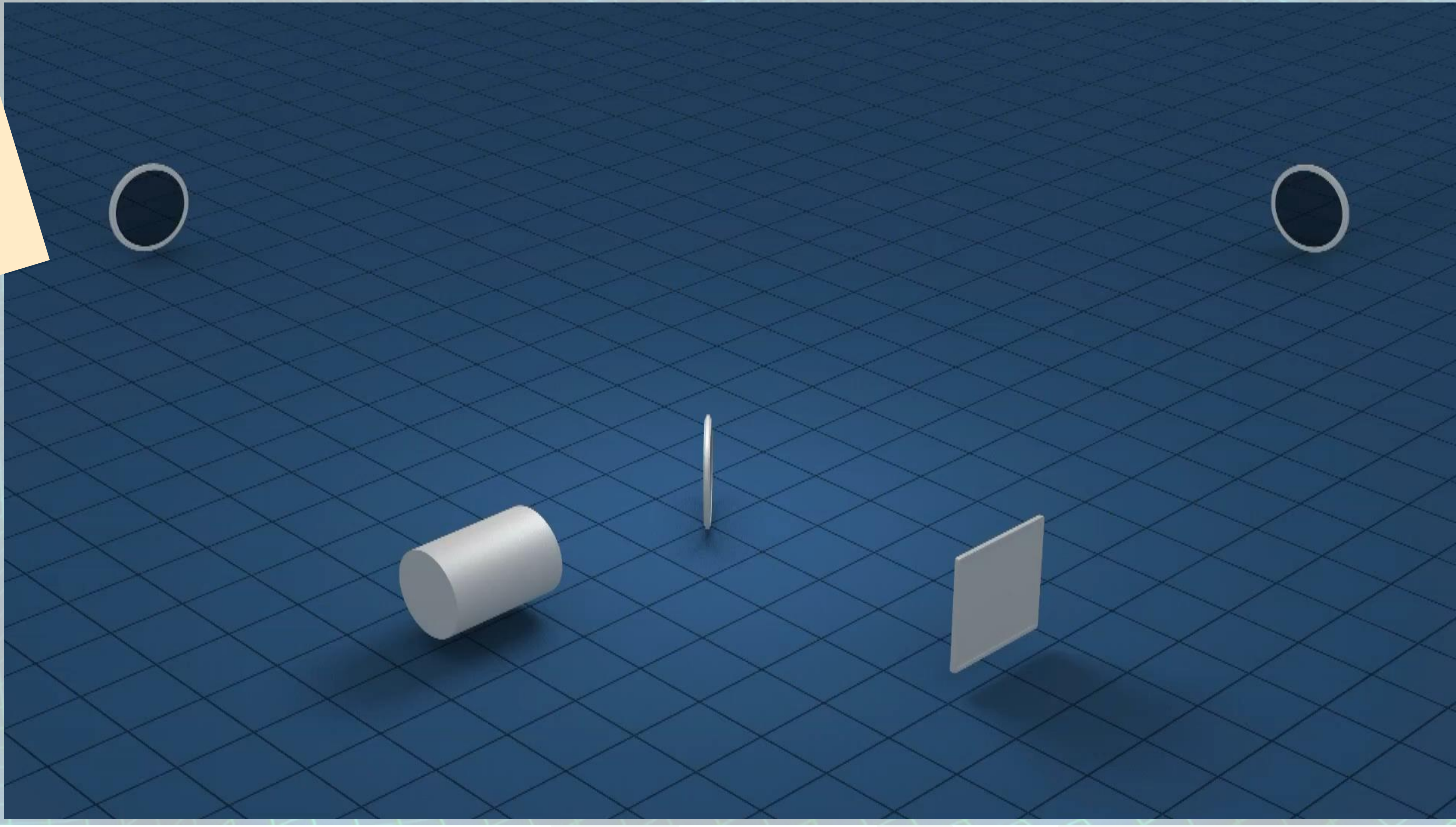

A. Brillet (1947-)

How to detect Gravitational Waves

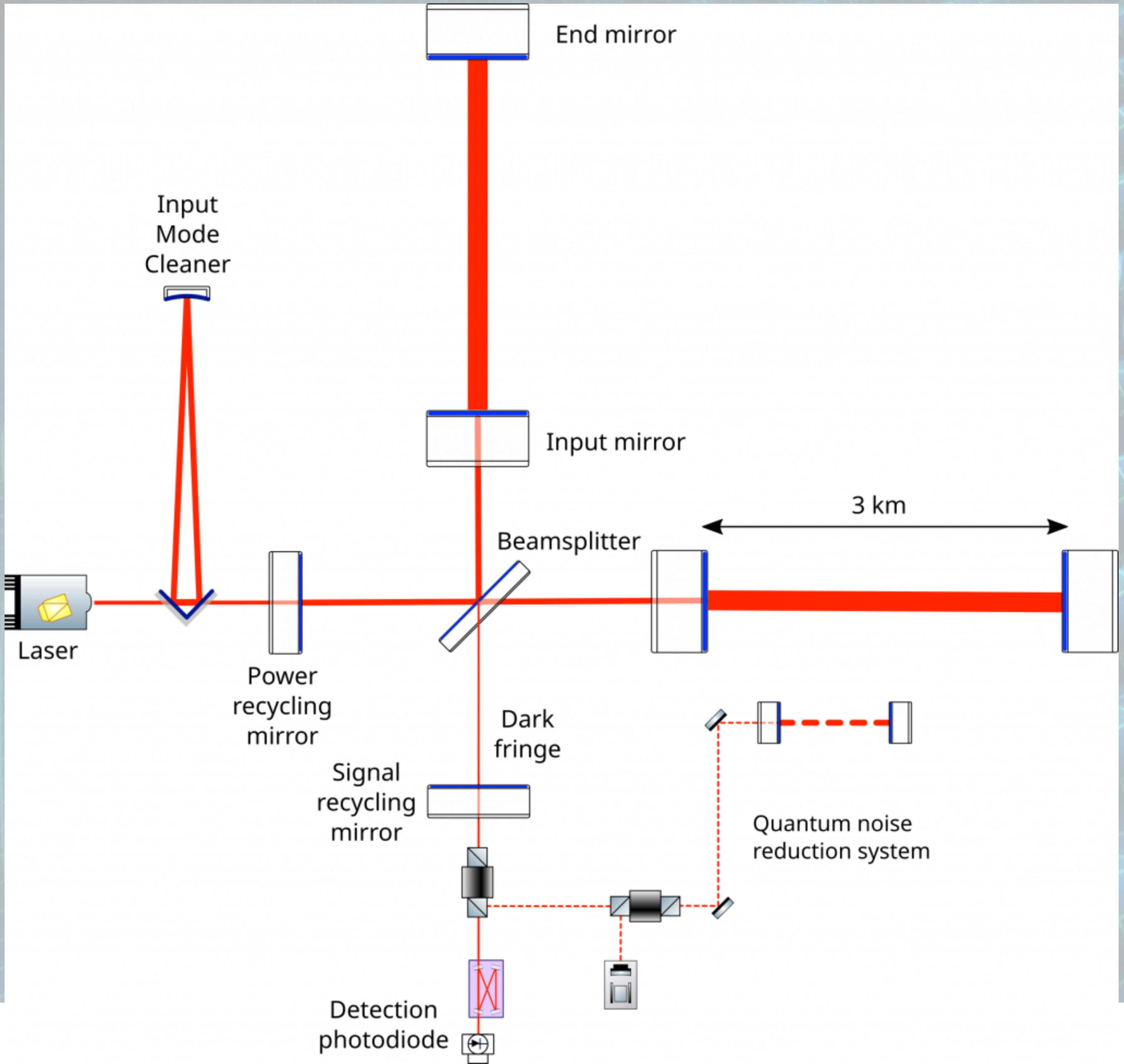
Expected h(t) ~ 10^{-21}

Since h(t) ~ dL/L

→ dL ~10^{-18} m

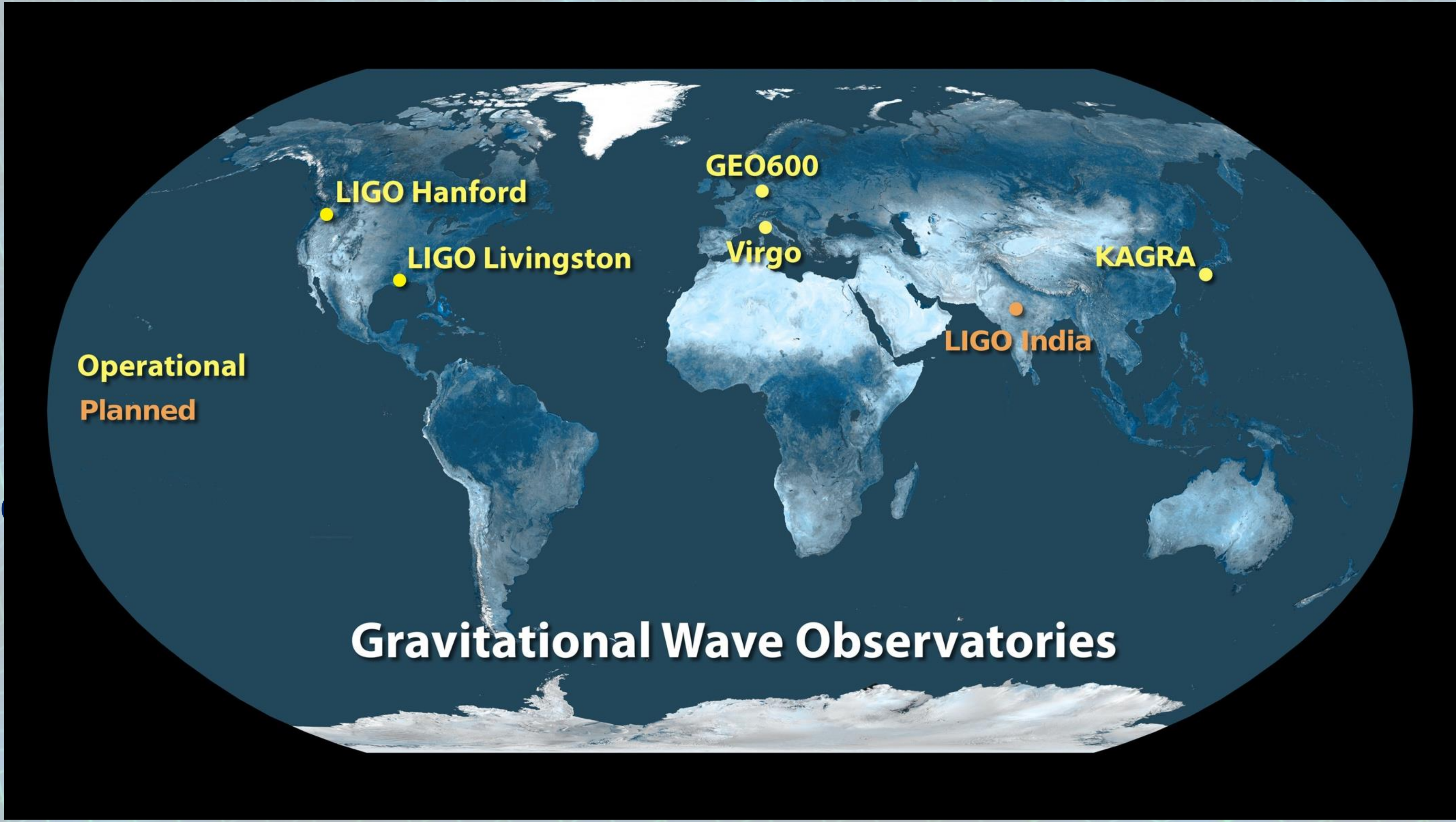


A more complex interferometer layout



Advanced Virgo
https://www.virgo-gw.eu/science/detector/optical-layo

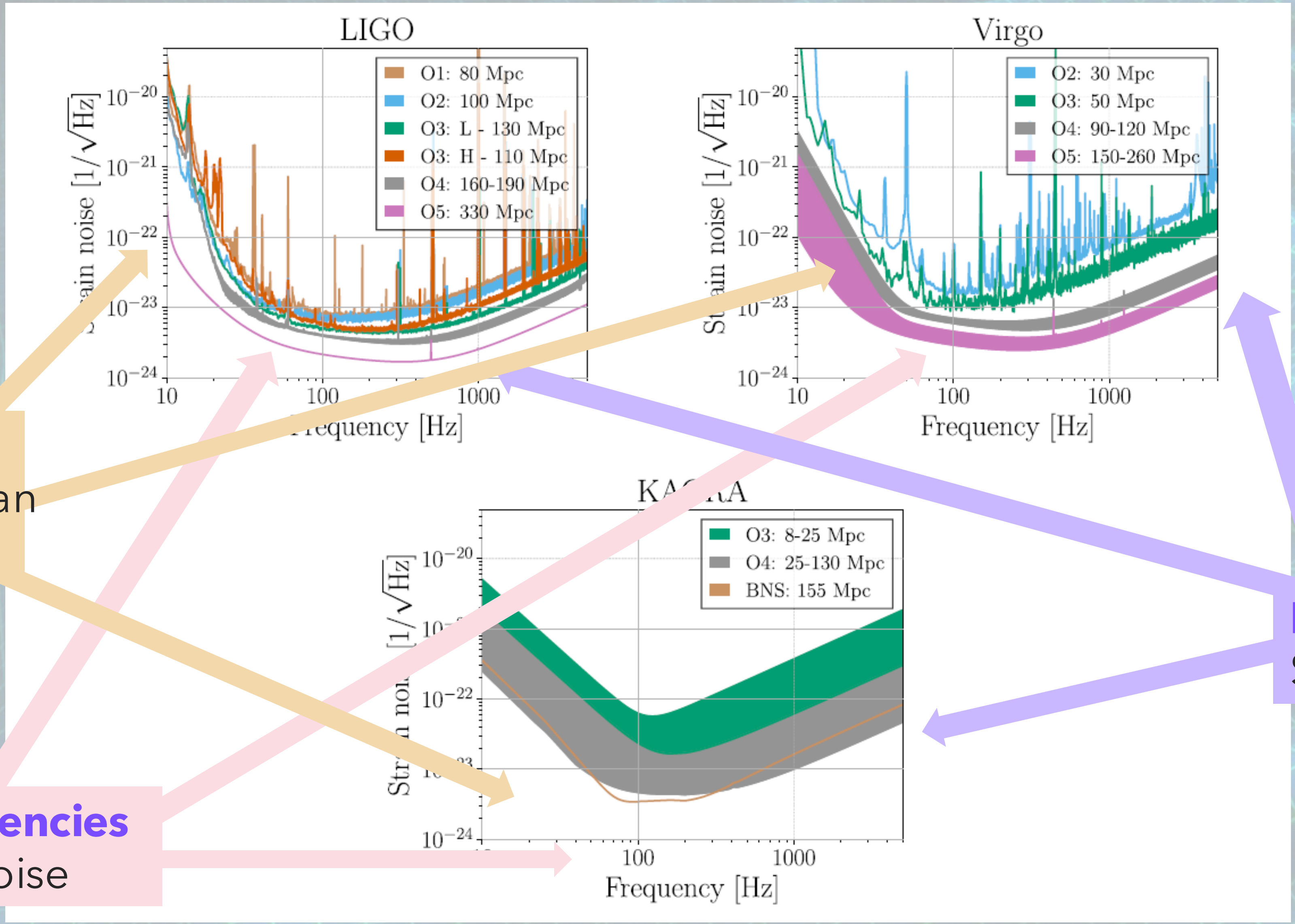
An international Network



Better sensitivity

- ~10x wrt previous generation (2002-2011)
- ~1000x more volume → ~100(
higher rates

Sensitivity Curves



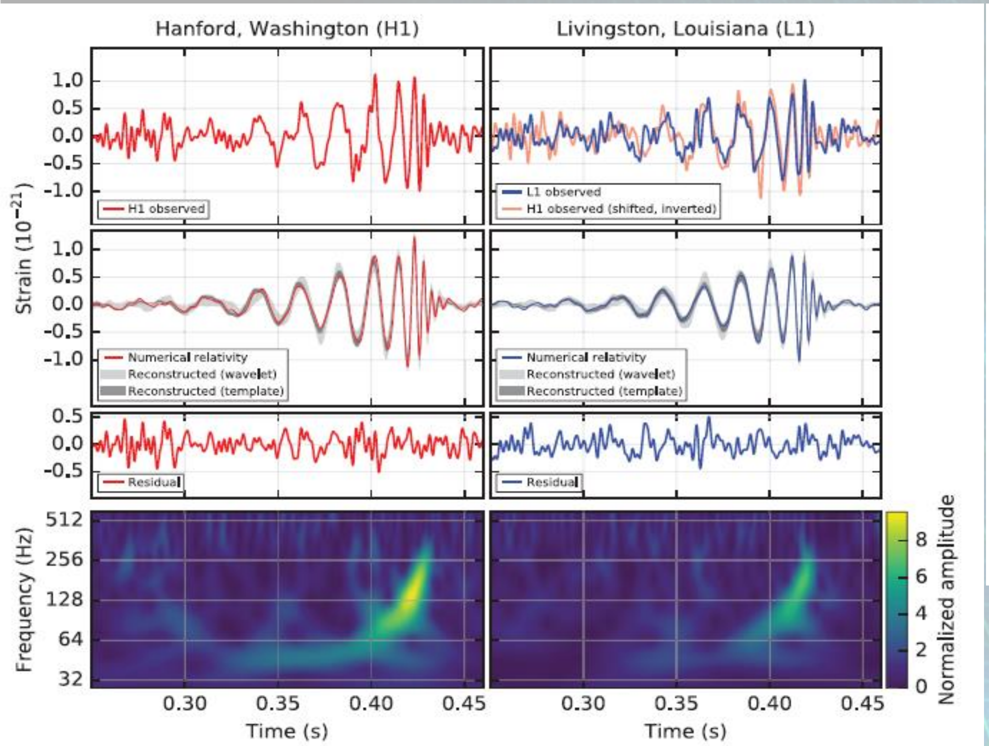
Low Frequencies
Seismic & Newtonian Noise

Mid Frequencies
Thermal Noise

High Frequencies
Shot Noise

Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

10 years ago



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

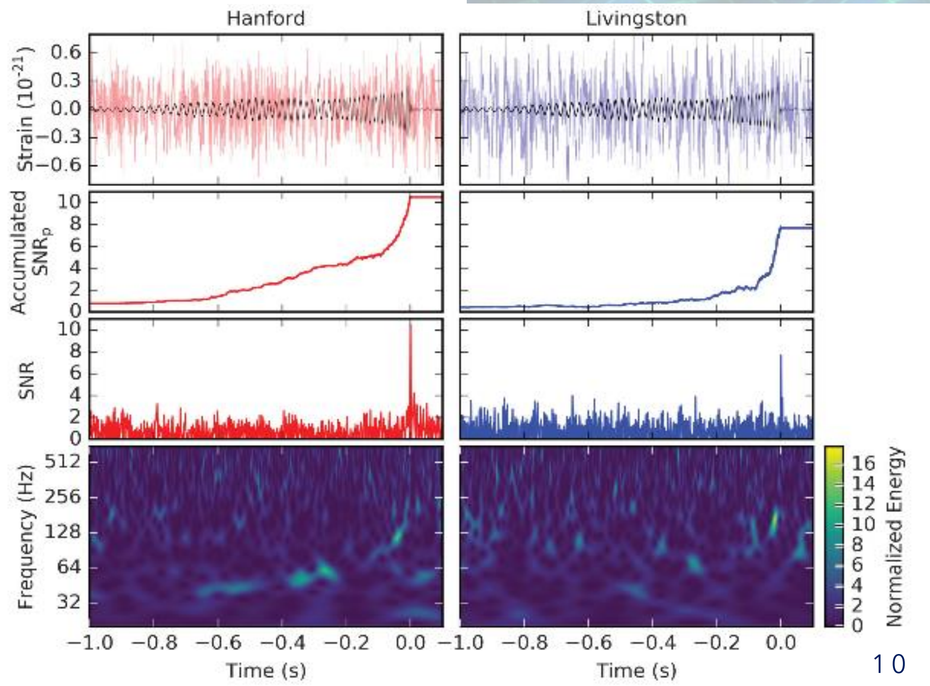
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

GW150914
Abbott+16, PRL116,6

Modeled as coalescence of two black holes

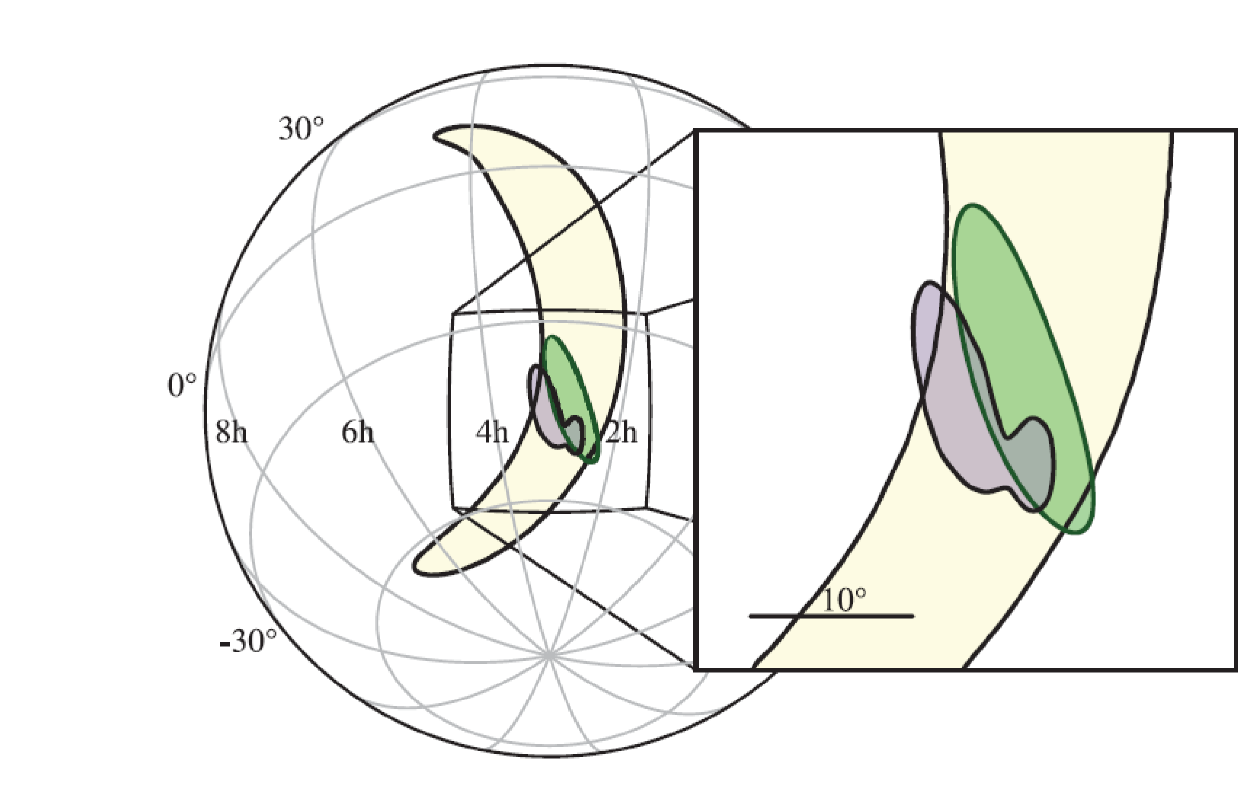


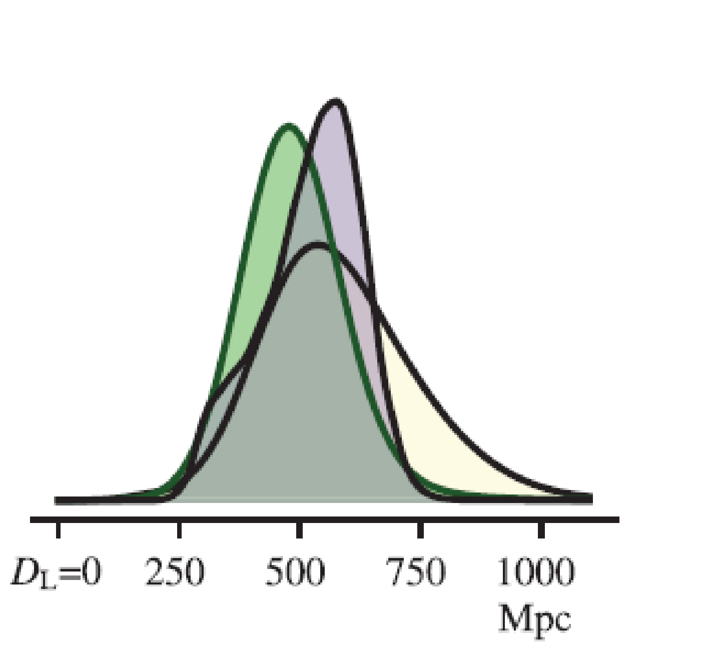
GW151226
Abbott+16, PRL116,24

GW170814: the first «triple» detection

- Using only LIGO detectors → 1160 deg^2
- Adding Virgo → 100 deg^2
- Full analysis → 60 deg^2

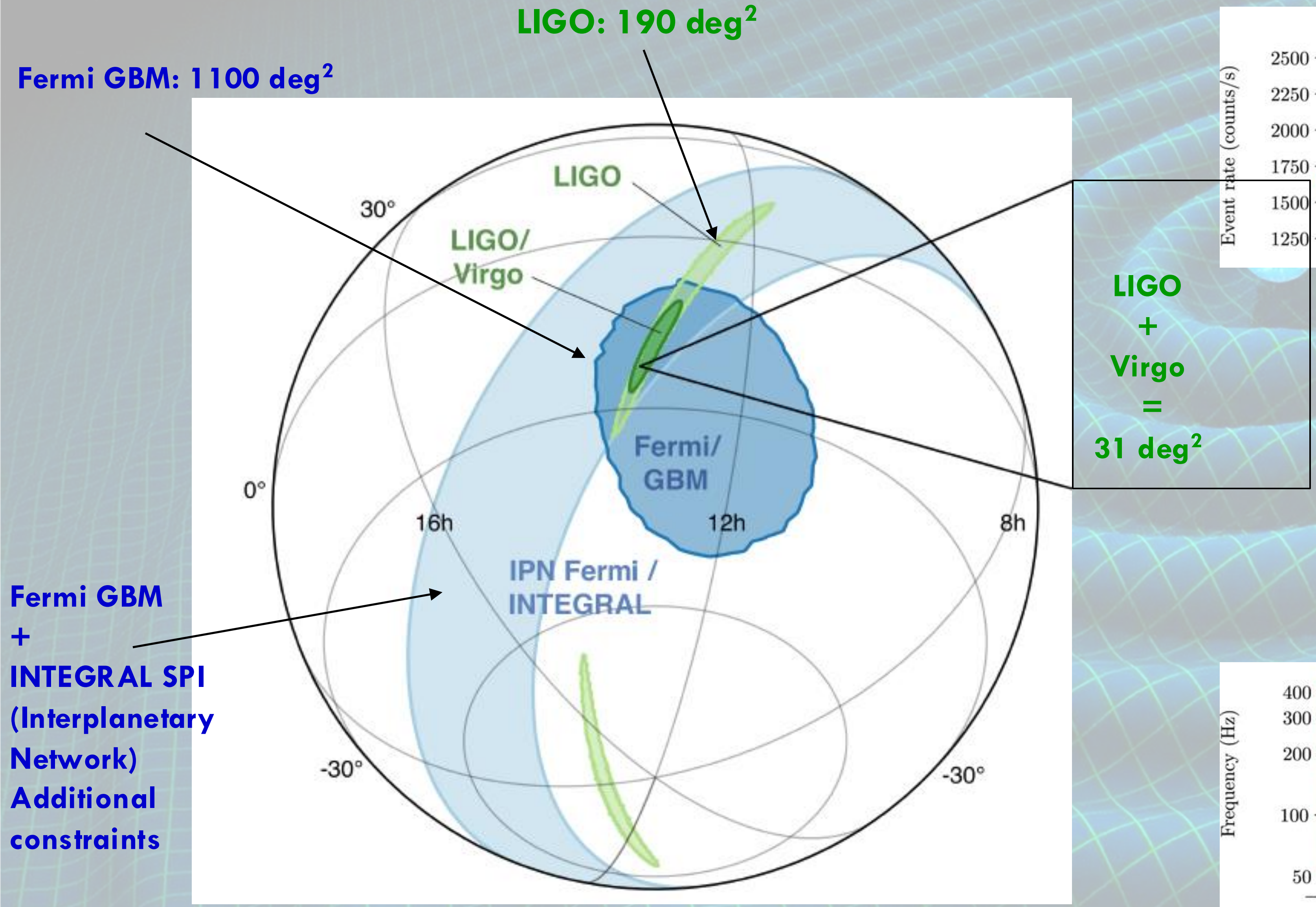
- Credible volume (and # of galaxies
71×10^6 Mpc^3 → 2.1×10^6 Mpc^3)

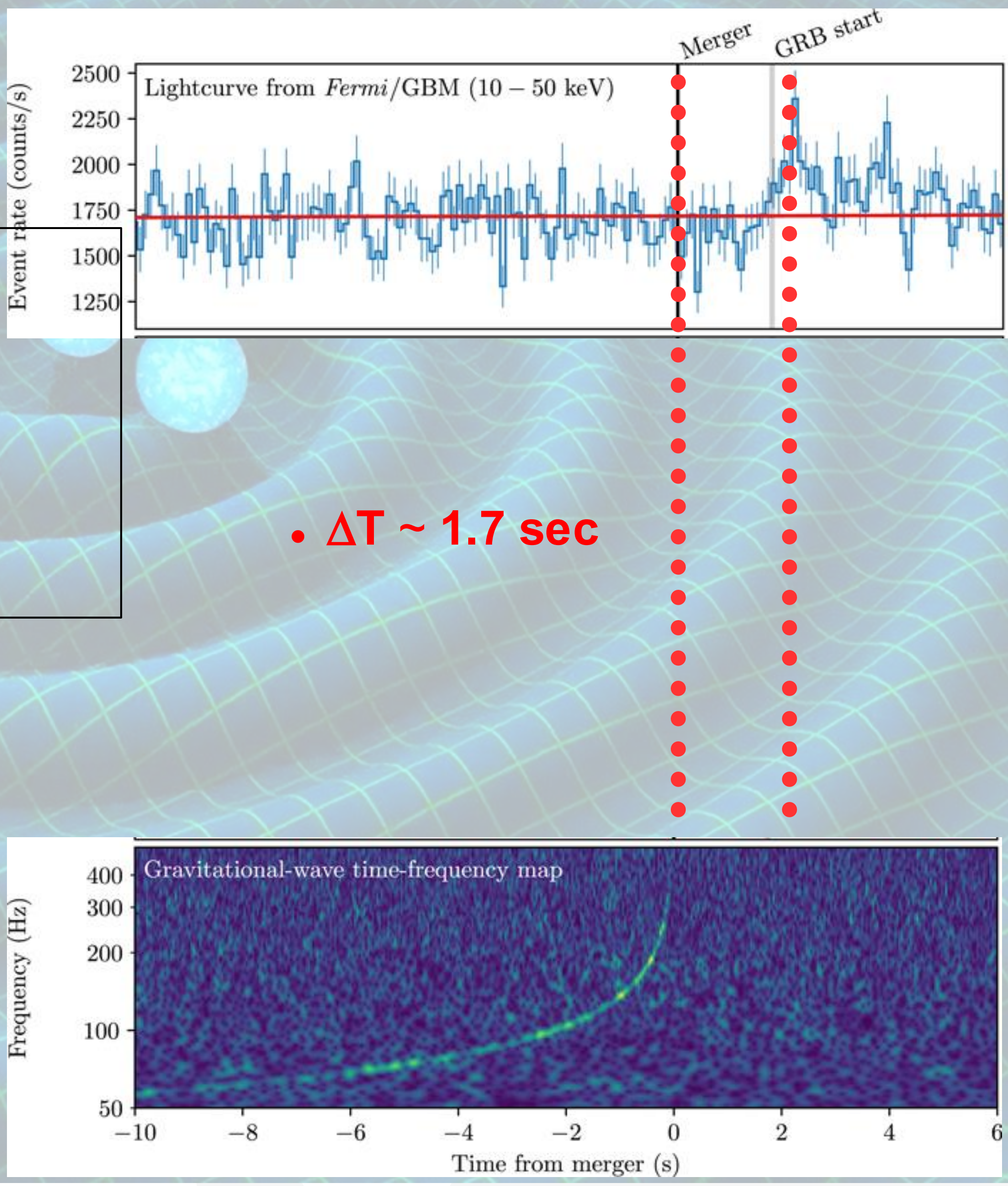




Abbott et al 2017, PRL, 119, 141101

The GW170817 event

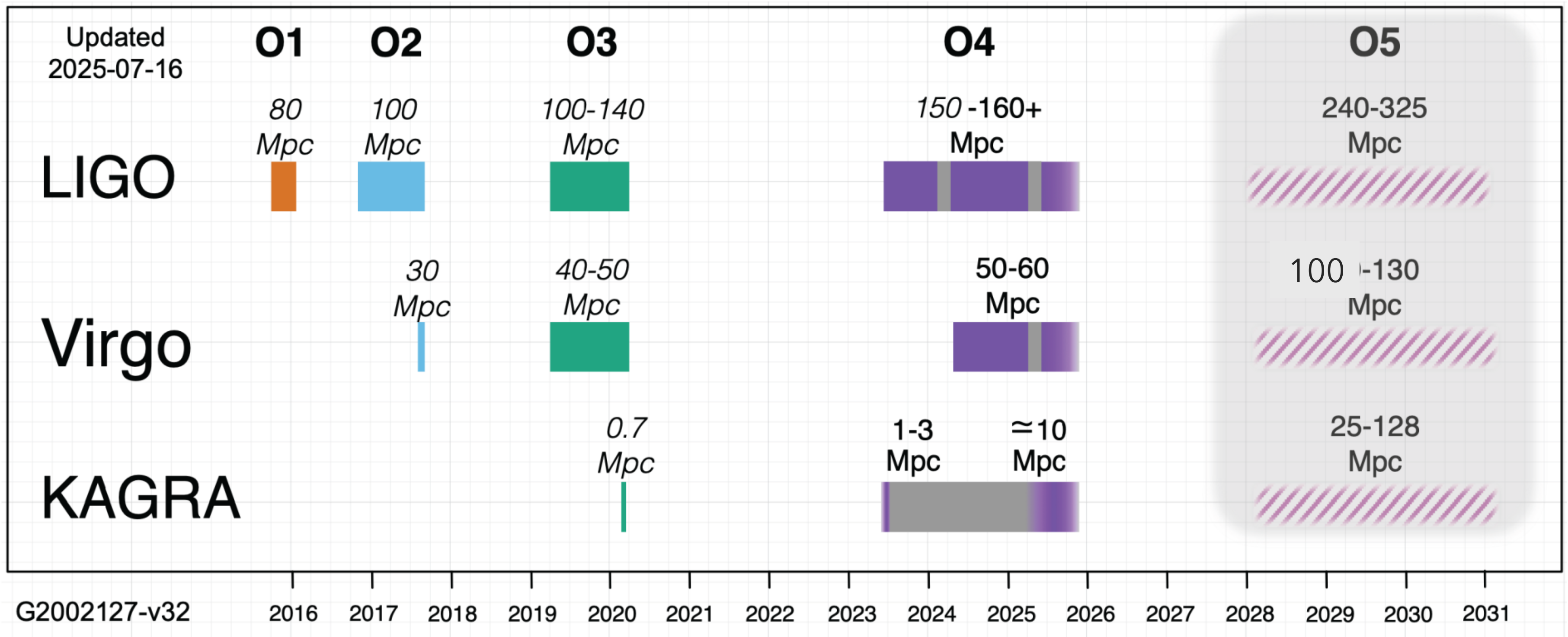




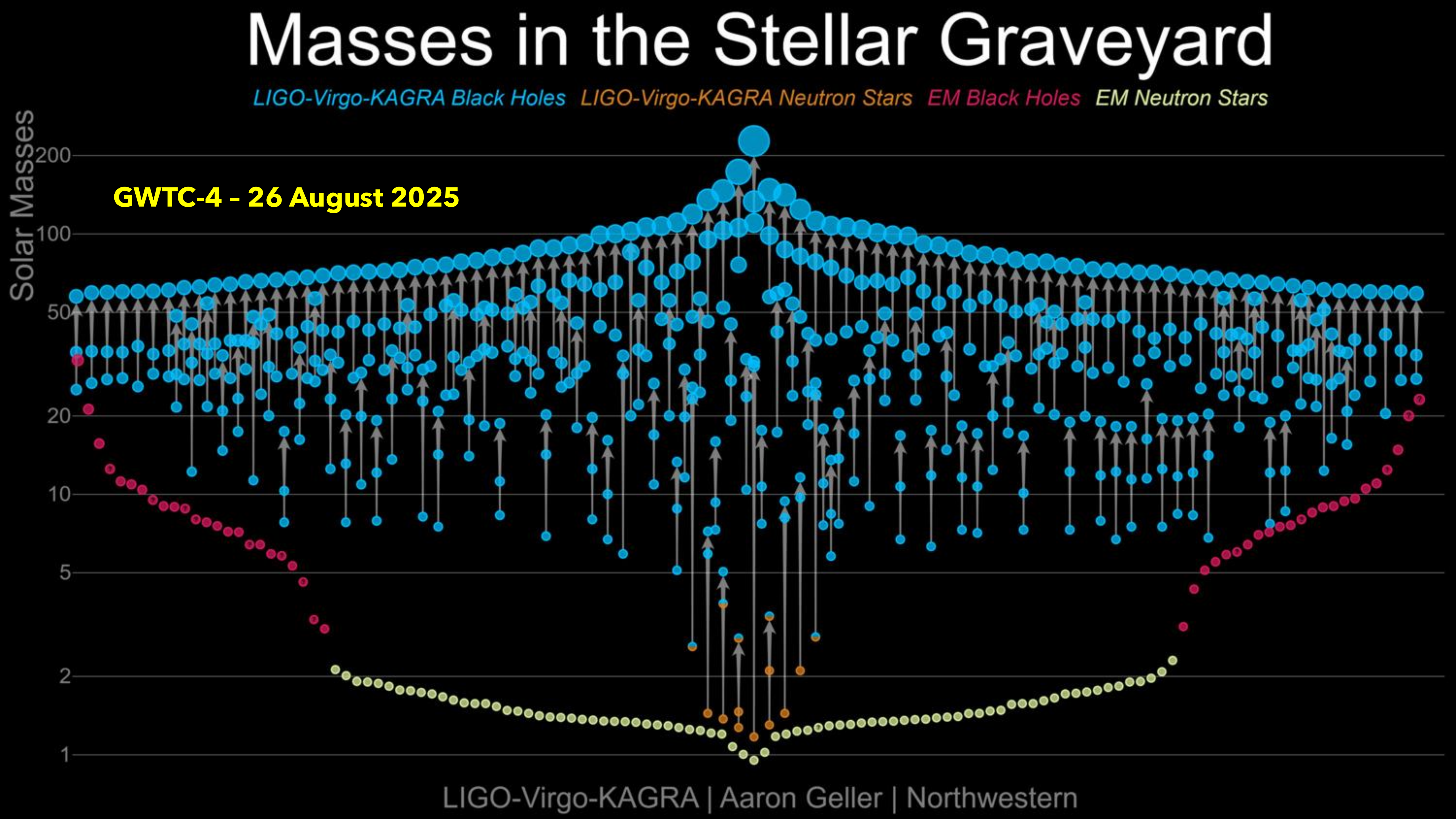
Abbott et al 2017, PRL, 119, 161101

The story so far

- **Joint LIGO-Virgo-KAGRA runs**
- O1 (H1+L1) - Sep 12, 2015 - Jan 19, 2016
- O2 (H1+L1+V1) - Nov 30, 2016 - Aug 25, 2017
- O3a (H1+L1+V1) - Apr 1 - Oct 1, 2019
- O3b (H1+L1+V1) - Nov 1, 2019 - Mar 27, 2020
- O4a (H1+L1) – May 24, 2023 – Jan 16, 2024
- O4b (H1+L1+V+K*) – Apr 10,2024 – Jan 28 2025
- O4c (H1+L1+V1) - Jan 28, 2025 – Nov 18, 2025 (maintenance & commissioning break Apr 1 – Jun 11)

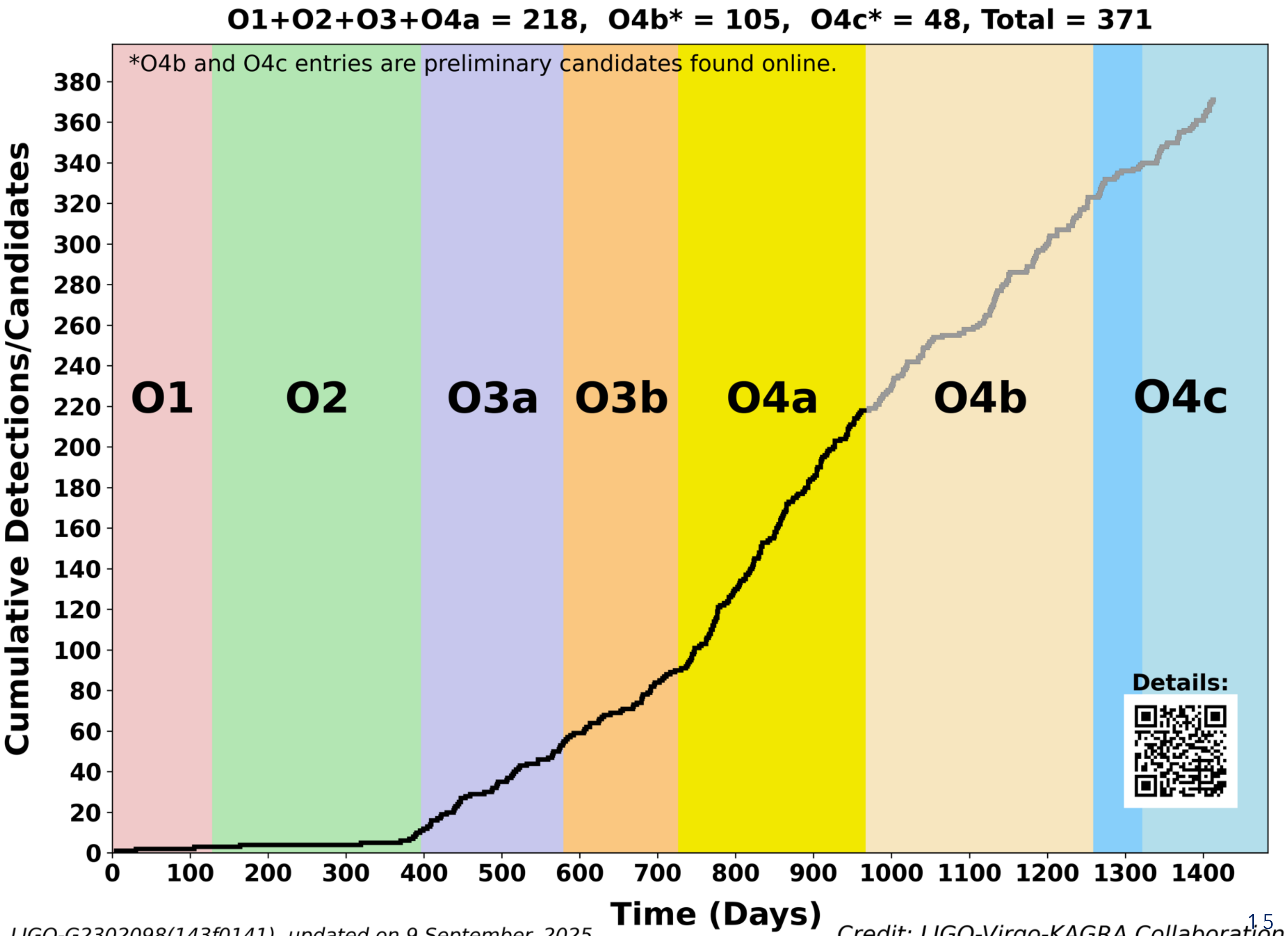


https://observing.docs.ligo.org/plan/


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
GWTC-4 – 26 August 2025
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

O4 run – detections so far

Upgrades from O3 to O4



LIGO-G2302098(143f0141), updated on 9 September, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

Alerts in O4 (so far)

O4a

- 81 significant (FAR < 1/6 mo) alerts, 11 retracted
- 1610 Low-significance

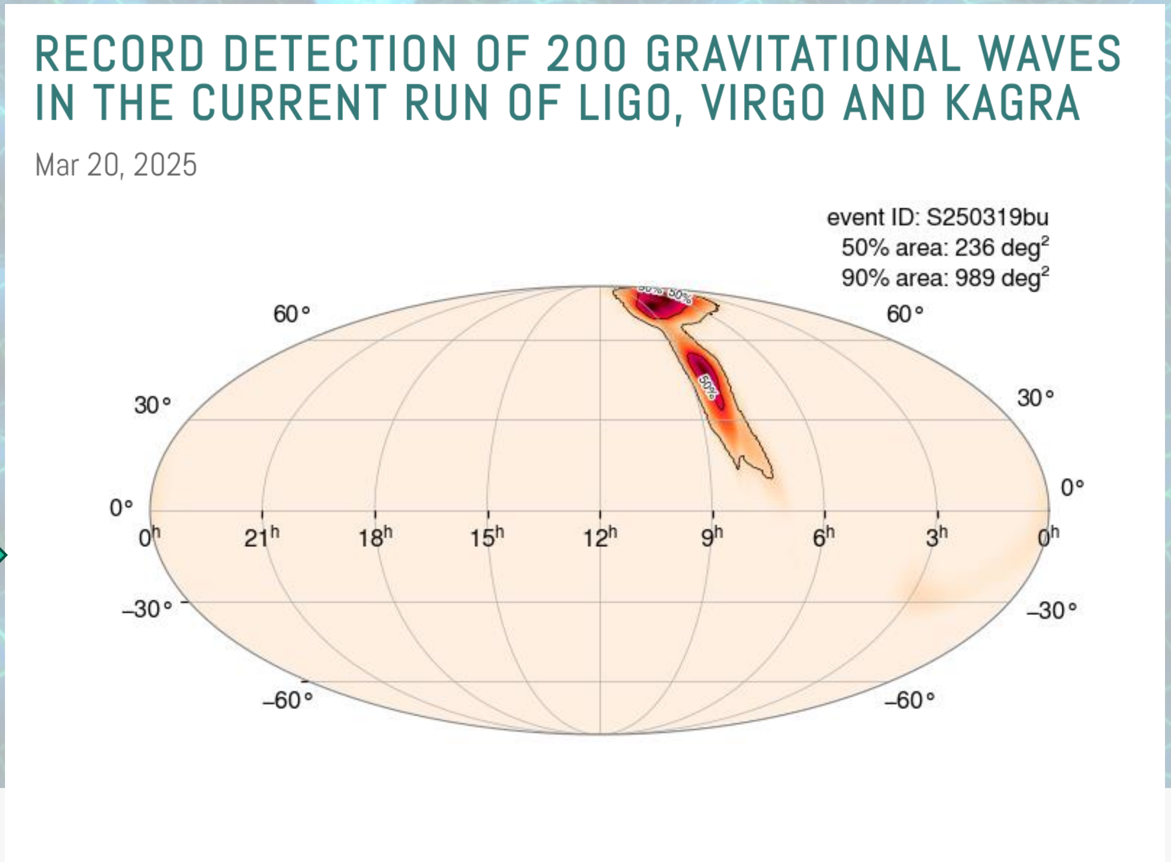
O4b

- 105 significant (FAR < 1/6 mo) alerts, 9 retracted
- 1706 Low -significance

O4c*

- 51 significant (FAR < 1/6 mo) alerts, 7 retracted
- 1394 Low-significance

Updated data from https://gracedb.ligo.org/



*as of Sep 24,2025

Conclusions

- Gravitational waves have opened a new windows on the Universe
- 3 runs successfully concluded
- O4 ongoing, extended until Nov 18, 2025
- Ca 300 detections so far (including O4 alerts)
- Still… lots of open questions
- Plans for future upgrades to further improve sensitivity in O5
- Many years of great science ahead!

Thank you for your attention !