Gravitational Wave observations
status & prospects

Massimiliano Razzano

(University of Pisa and INFN-Pisa)

On behalf of the LIGO-Virgo-KAGRA Collaboration

ADVANCES IN MODELING HIGH-ENERGY ASTROPHYSICAL SOURCES: INSIGHTS FROM RECENT MULTIMESSENGER DISCOVERIES

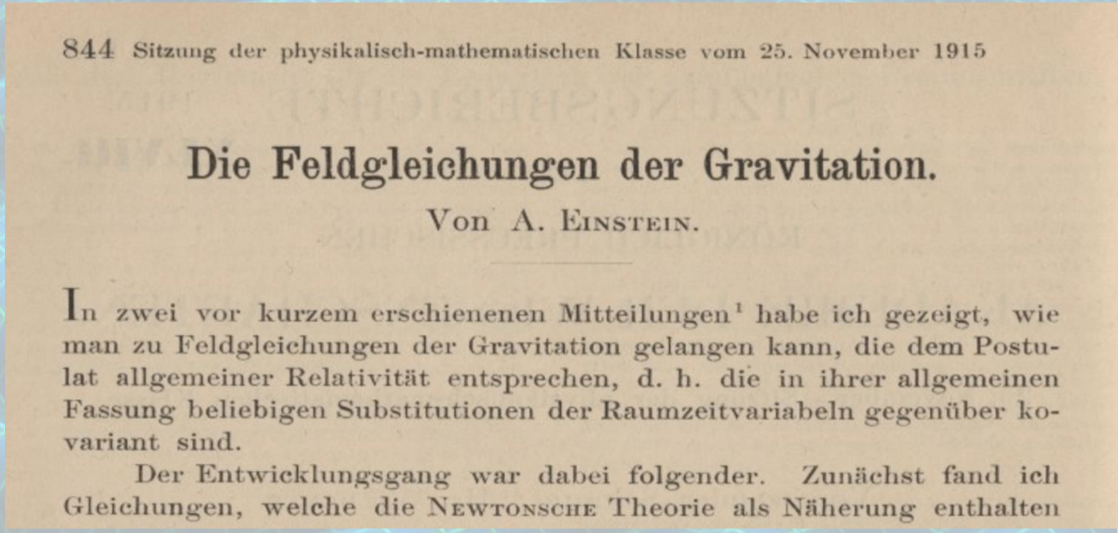
Sexten Center for Astrophysics, 2 July 2025

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

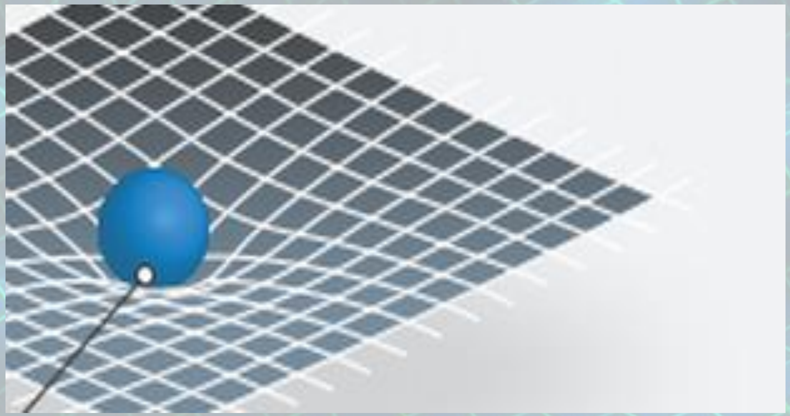
Die Feldgleichungen der Gravitation.

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



Properties of Gravitational Waves

- From Einstein equations produce wave equation in h(t) → wave solution (gravitational waves)
- Fixing the gauge (Transverse-traceless, TT)

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

$$\Box = -(1/c^2)\partial_t^2 + \nabla^2$$

GWs travel at speed of light (consequence of field equations and confirmed by observations)

$$h_{\mu\nu}^{TT}(t,z) = \begin{pmatrix} h_+ & h_x & 0 \\ h_x & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}_{\mu\nu} \cos[\omega(t - z/c)]$$

- Two polarizations (Plus and Cross)
- Produced by non-vanishing quadrupole moment (e.g. accelerating masses, asysimmetric rotating stars, explosions)

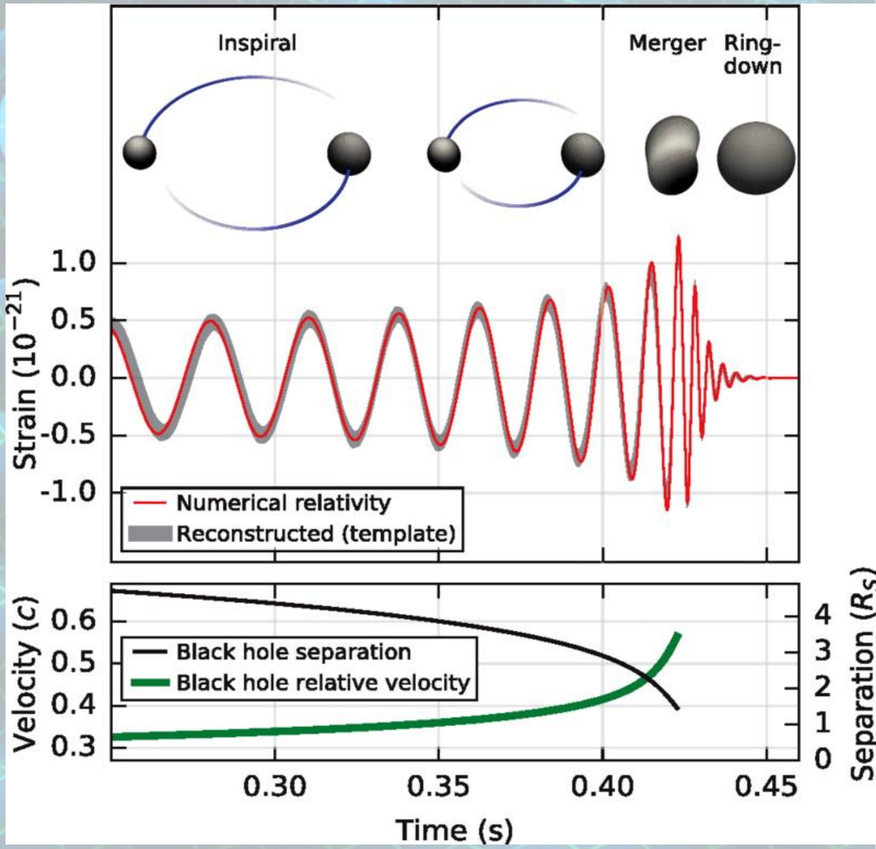
Expected sources of Gravitational Waves

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

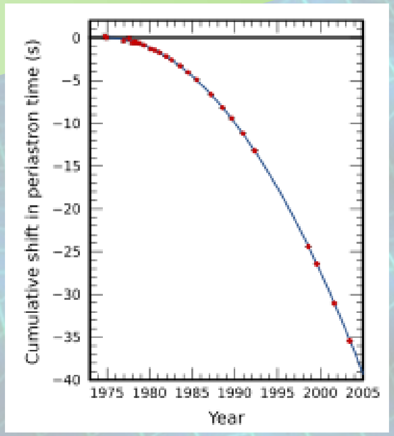
2000s
First generation
(e.g. LIGO/Virgo/GEO600)
No detection ☹

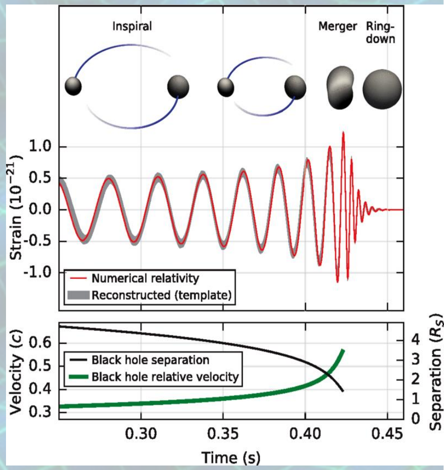
1980s-1990s
First works on laser interferometers
(LIGO,Virgo)

1974
Hulse-Taylor binary pulsar
Indirect evidence of GWs

1960's
J. Weber works
on resonant bars

2010s
Second «Advanced»generation
→ First detection!



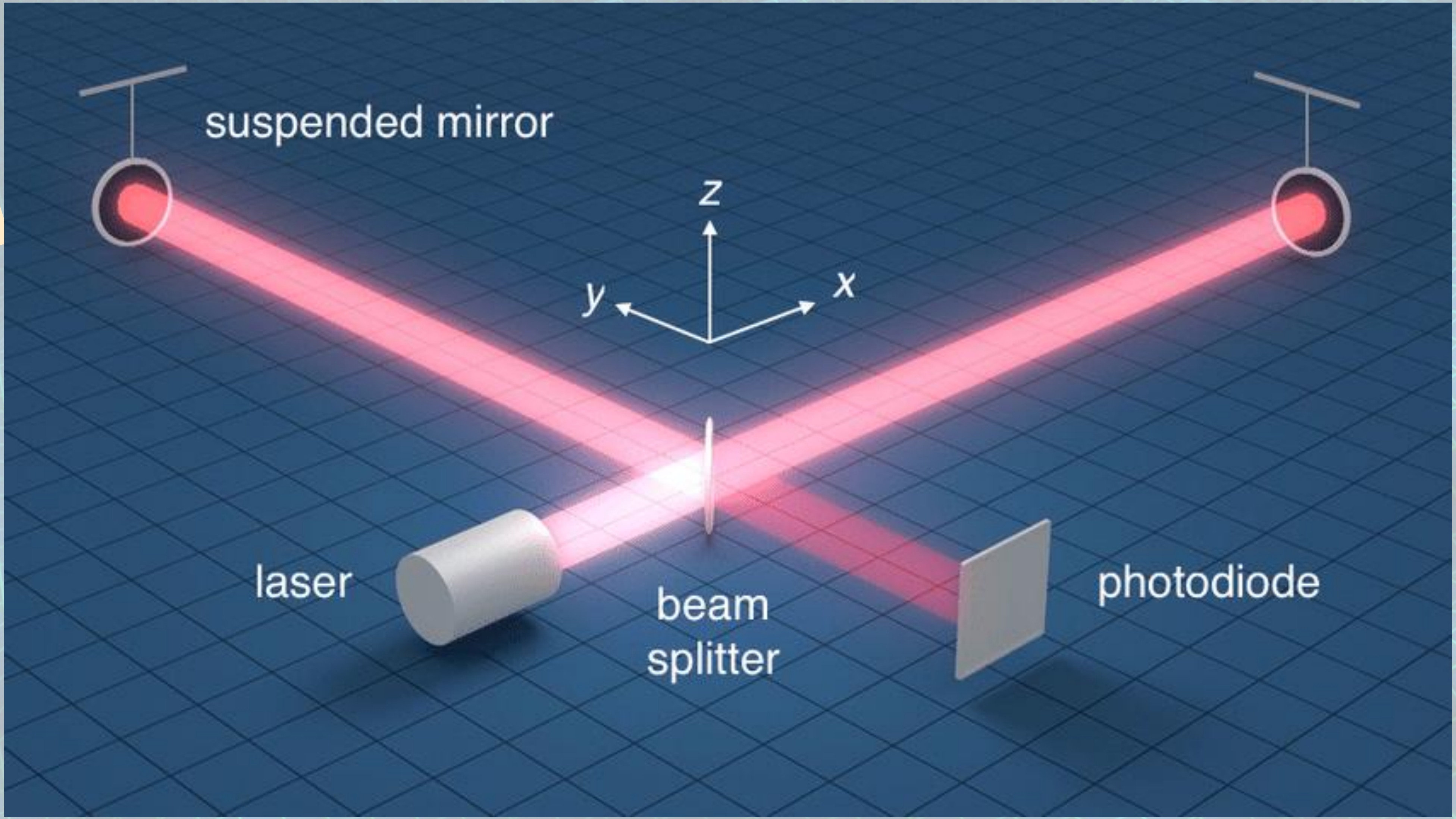


How to detect Gravitational Waves

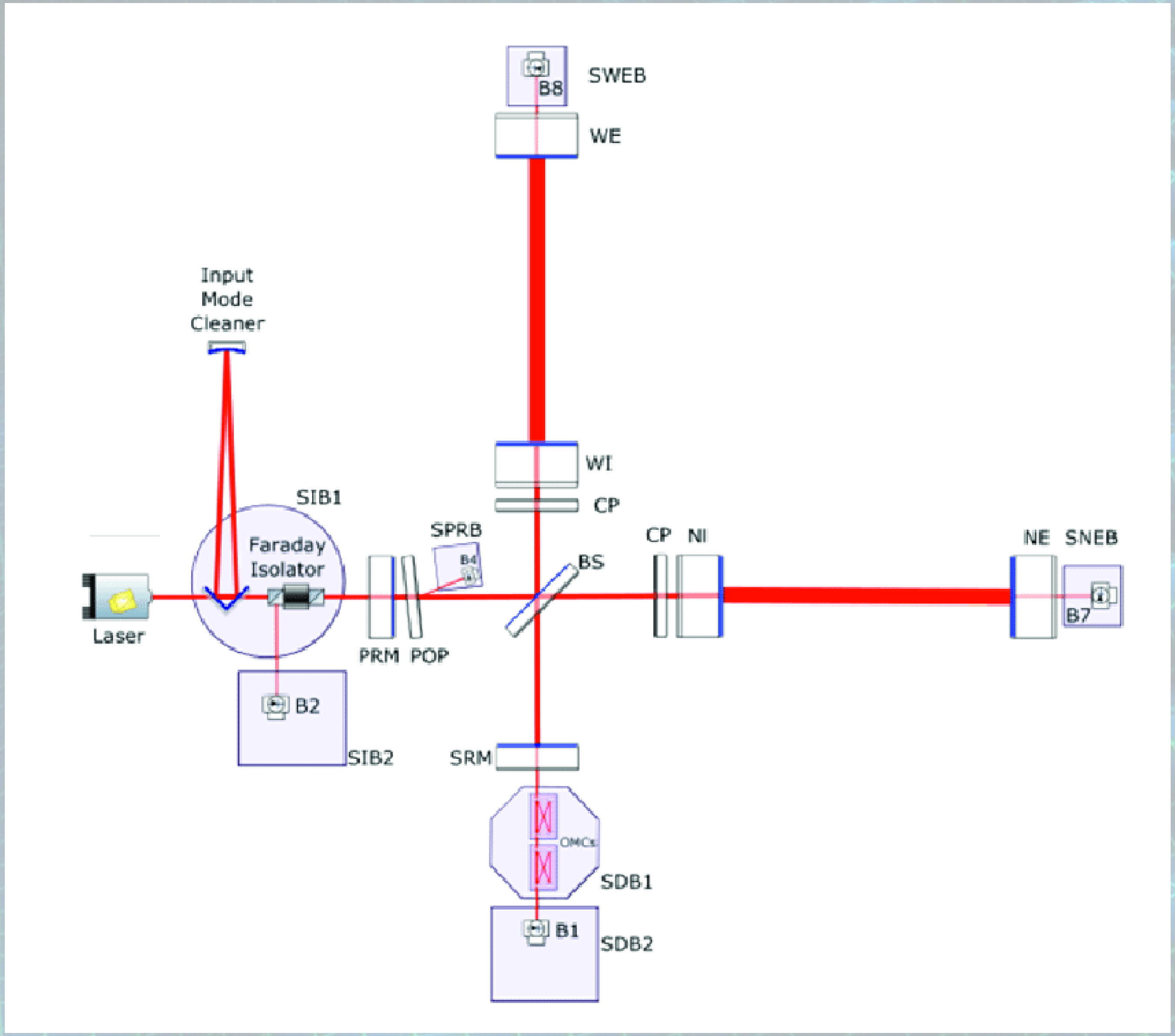
Expected h(t) ~ 10^{-21}

Since h(t) ~ dL/L

→ dL ~10^{-18} m

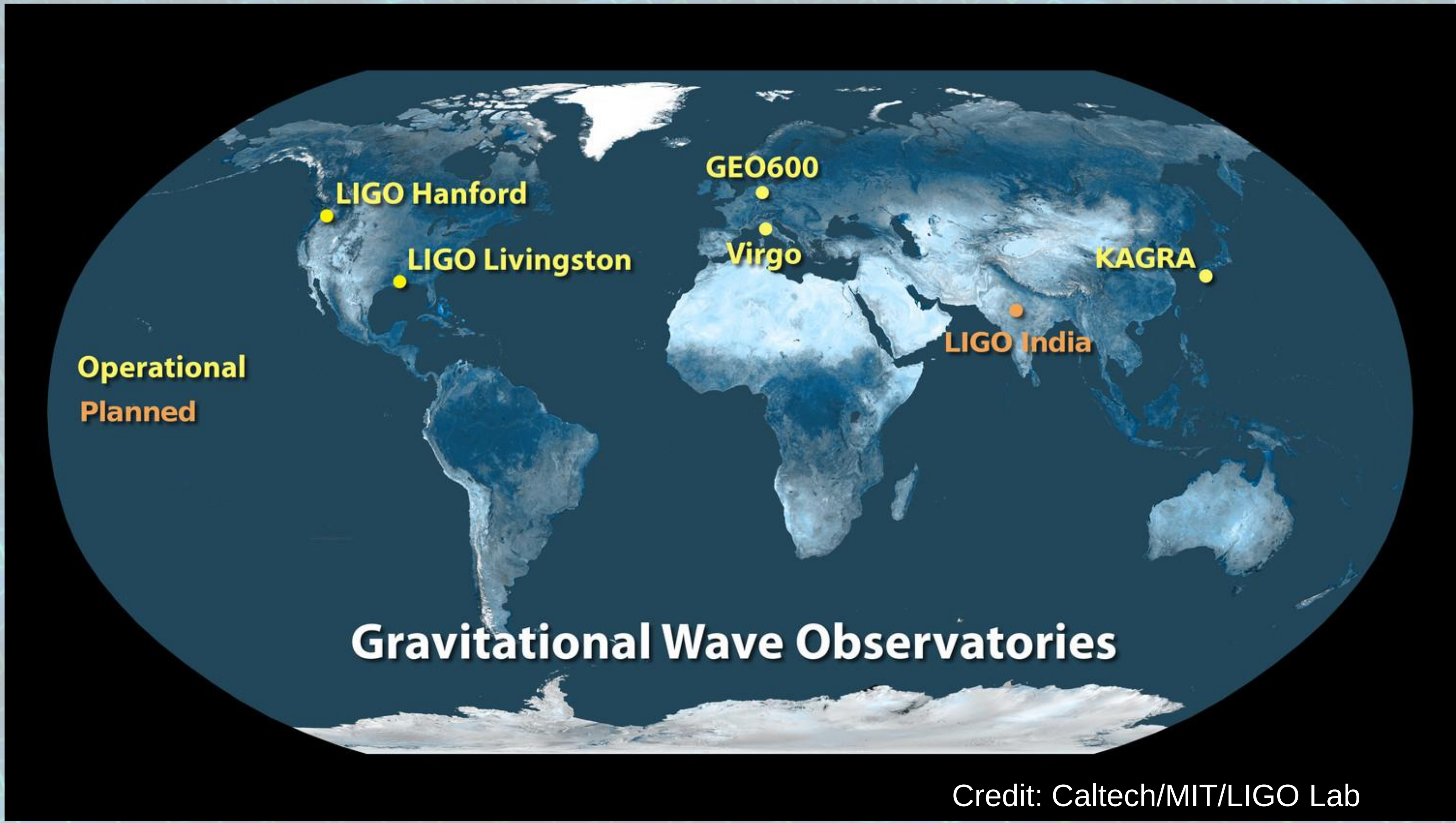


A more complex interferometer layout



Advanced Virgo
Acernese et al., 2018, EPJC, 182

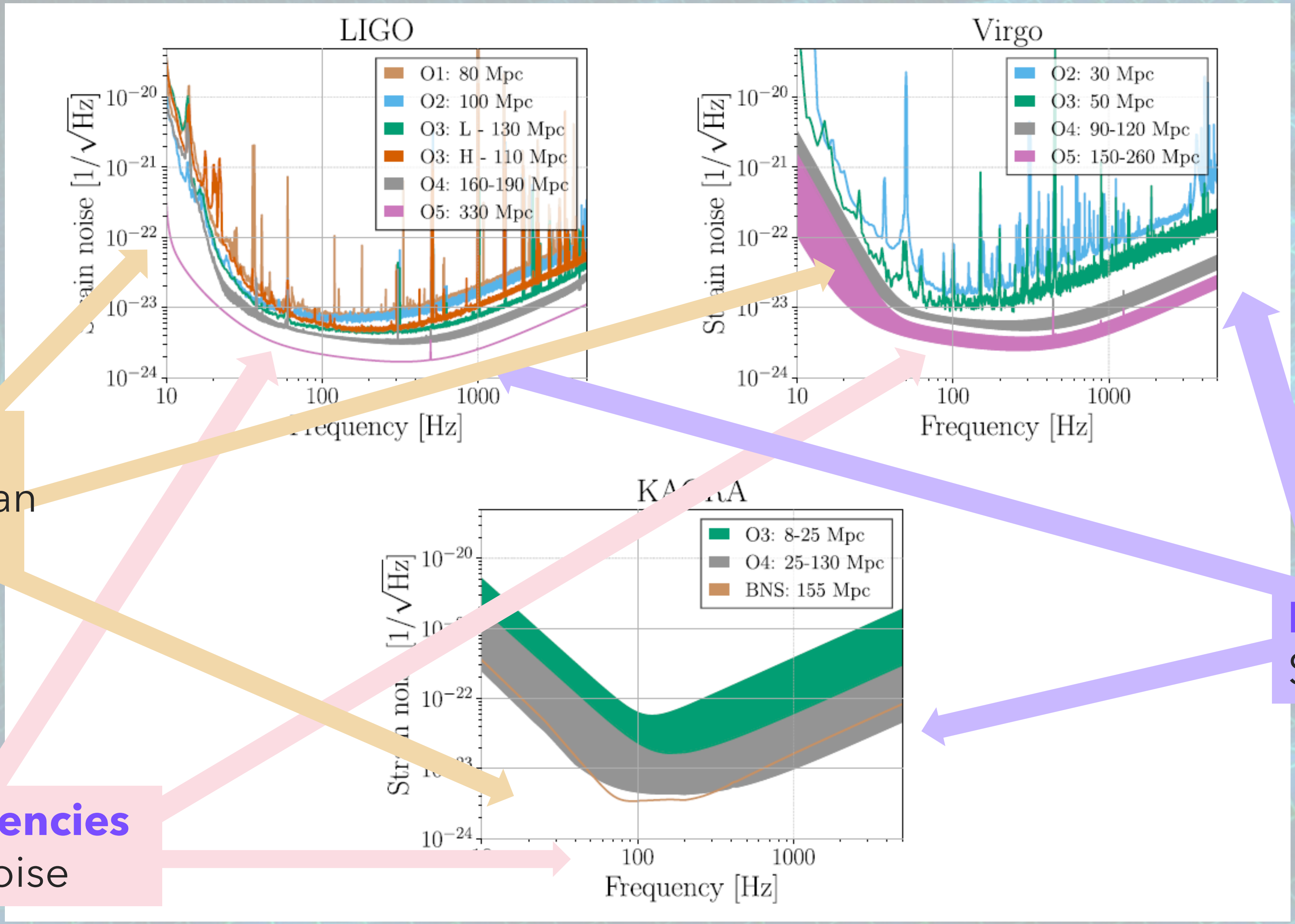
An international Network



Better sensitivity

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

Sensitivity Curves



Low Frequencies
Seismic & Newtonian Noise

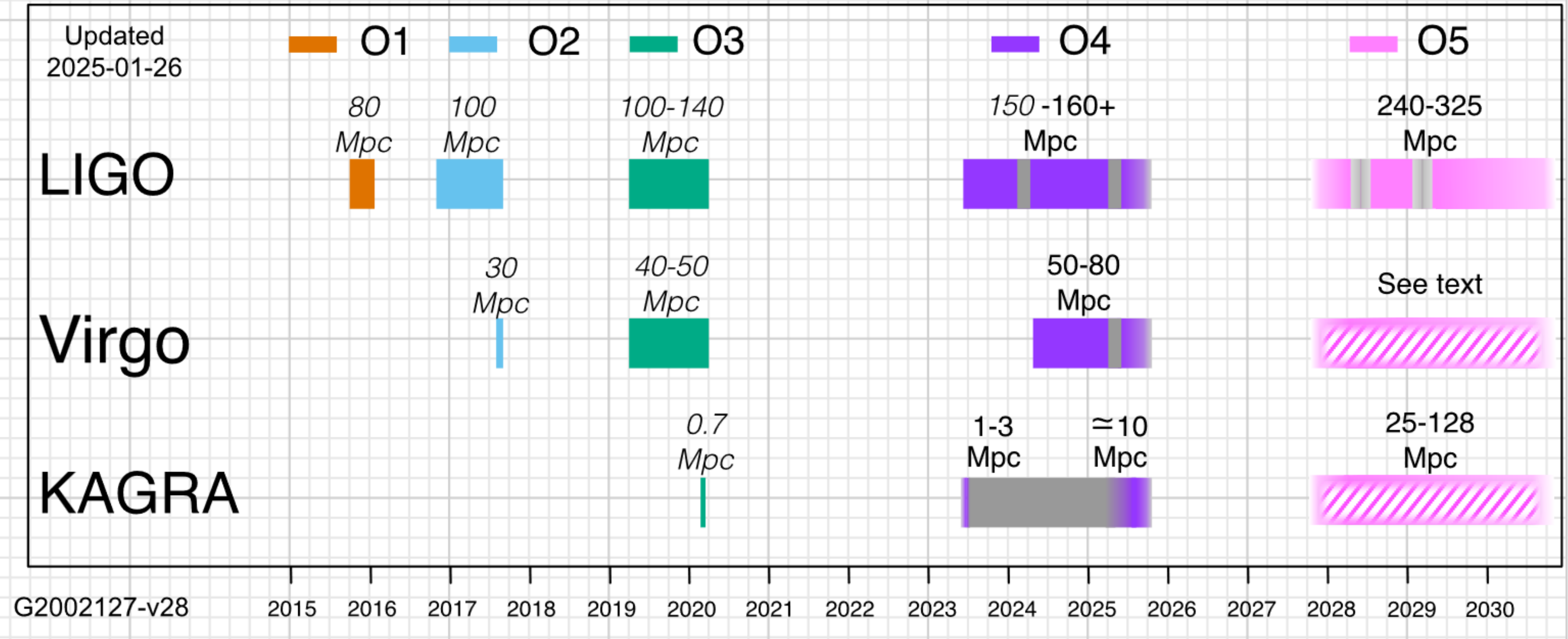
Mid Frequencies
Thermal Noise

High Frequencies
Shot Noise

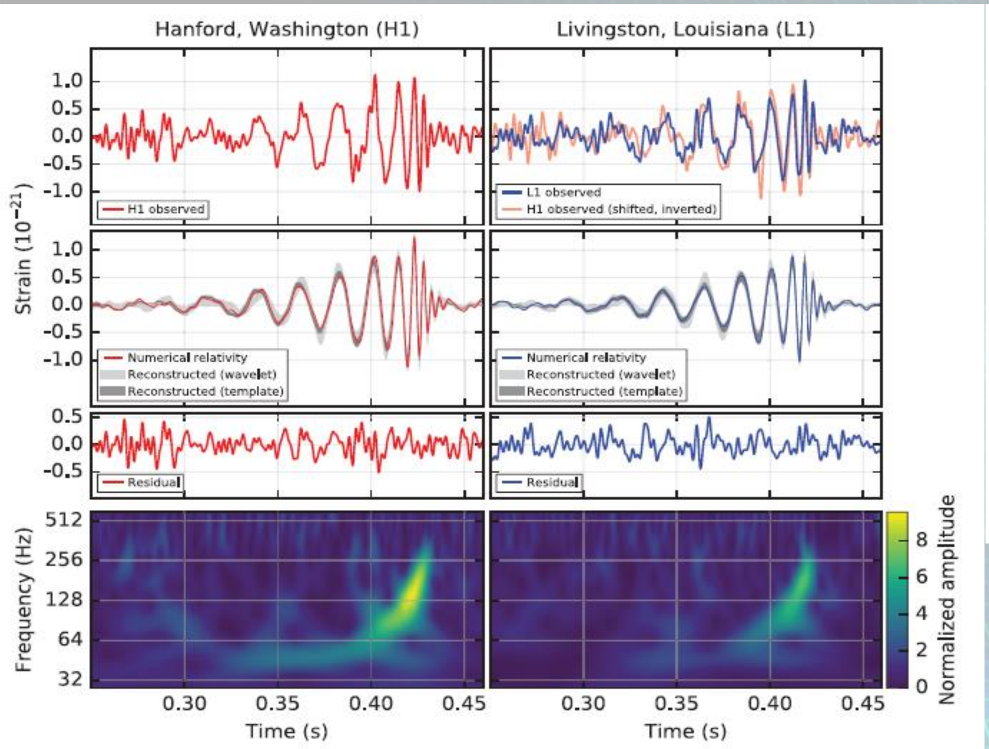
Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

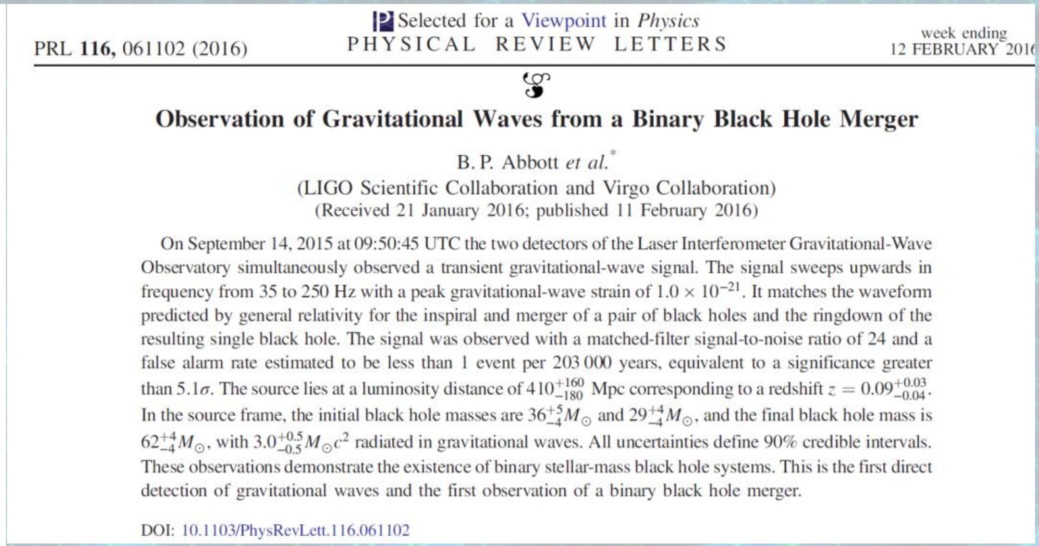
The story so far

- **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)



First detections





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)

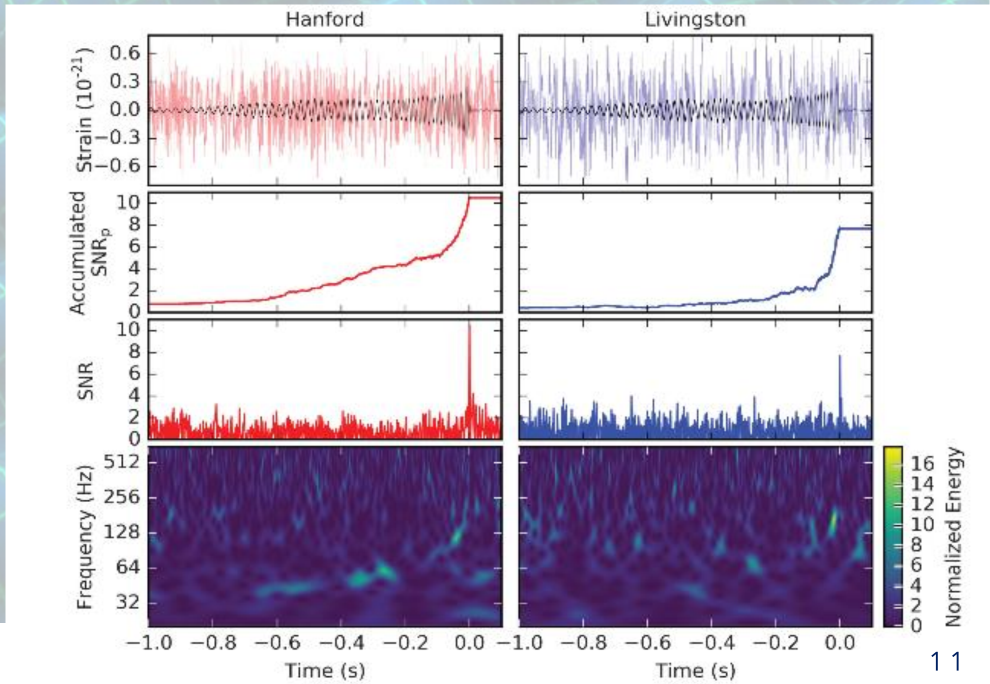
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches 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

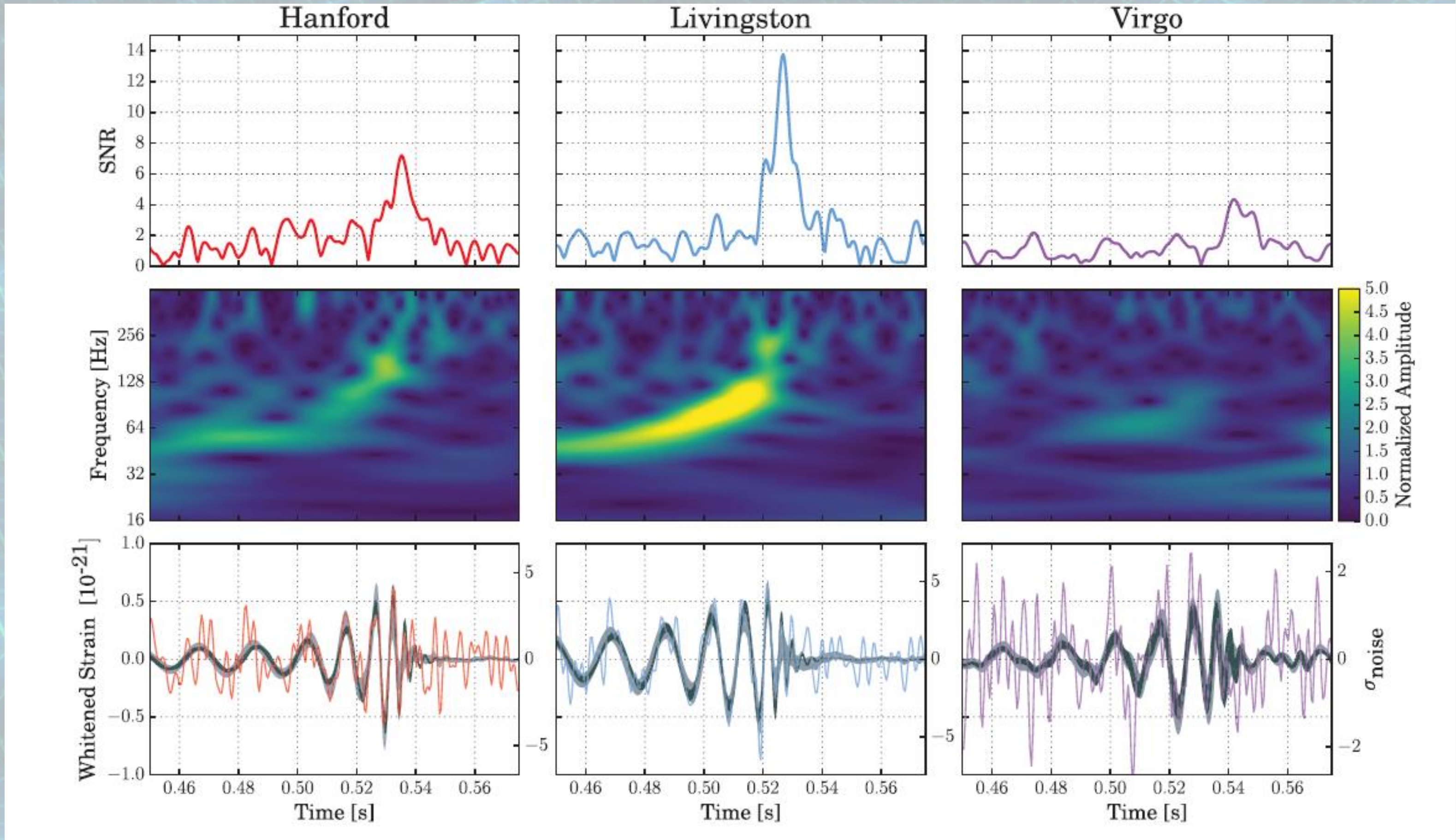
Modeled as coalescence of two black holes
(see B. Patricelli's talk for more details)

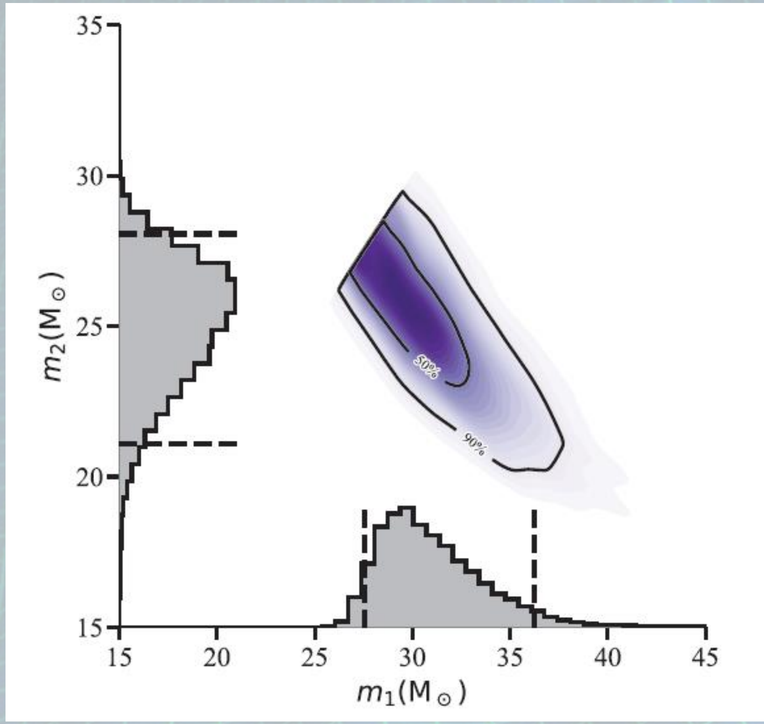
GW151226
Abbott+16, PRL116,24



GW170814: the first «triple» event

- 2017 August 14, 10:40 UTC
- BBH 30 + 25 Msun
- Distance 540 Mpc



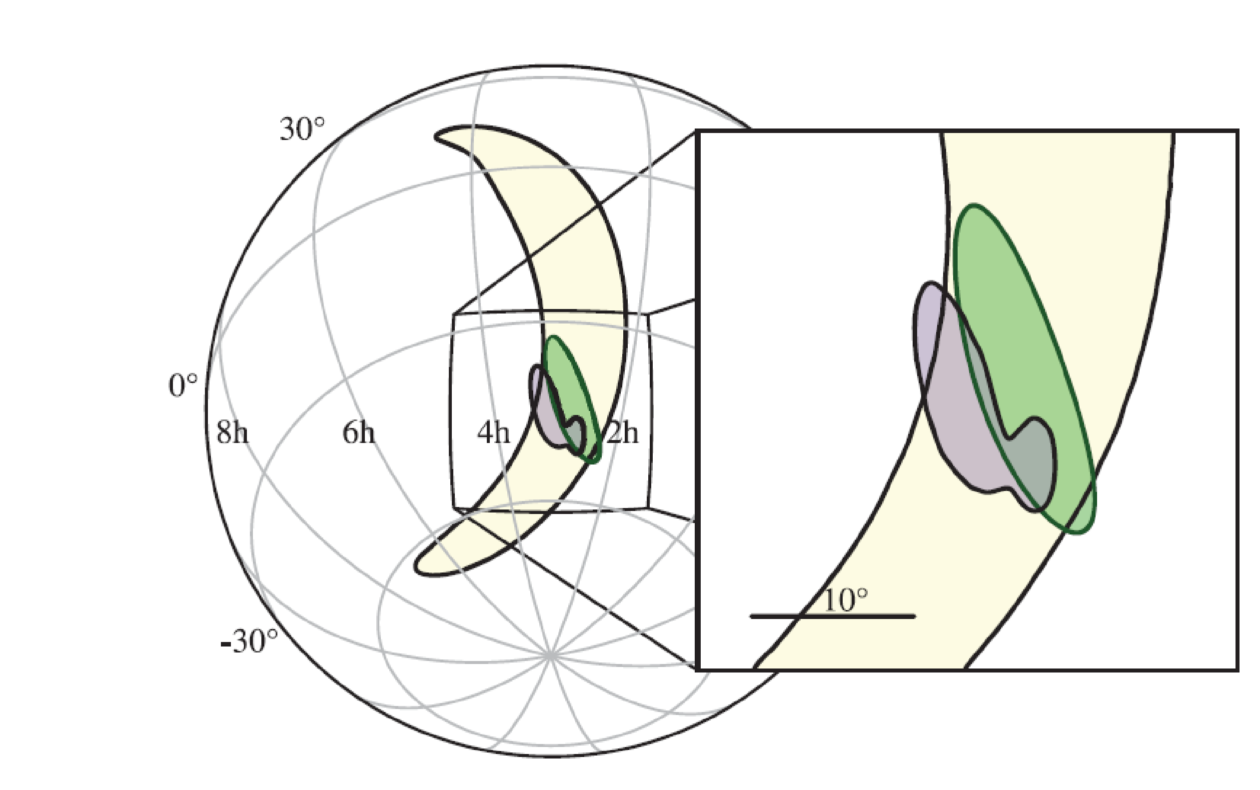


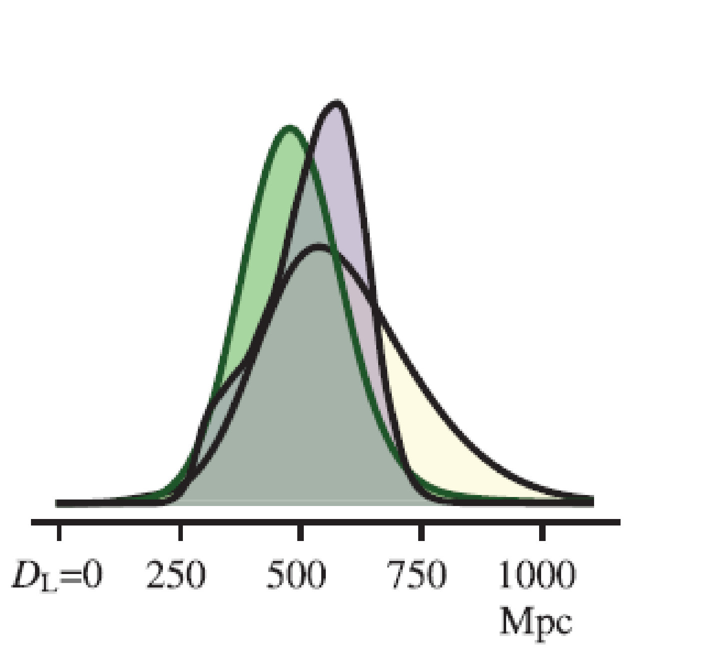
Abbott et al 2017, PRL, 119, 141101

The key to localization

- 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)



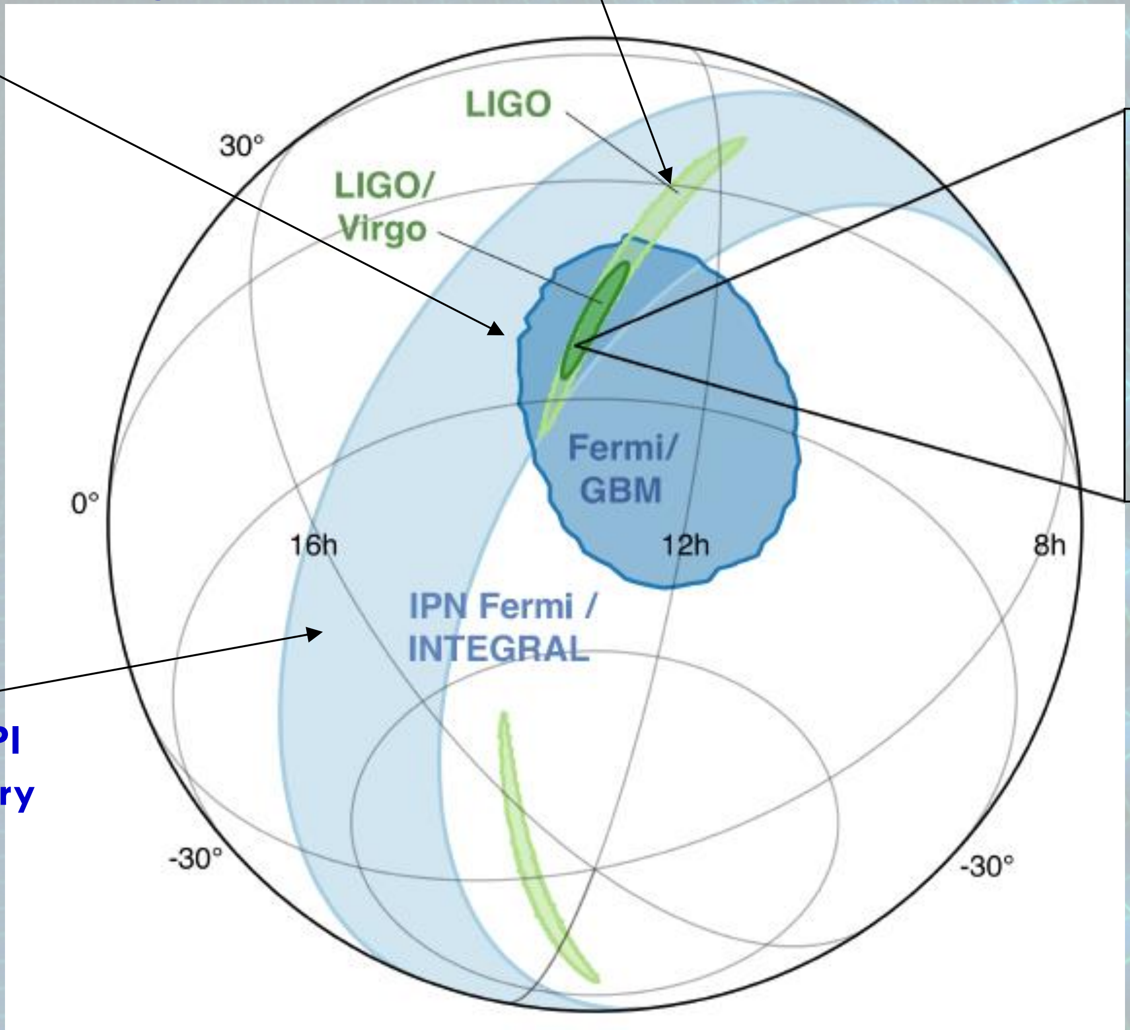


Abbott et al 2017, PRL, 119, 141101

The GW170817 event

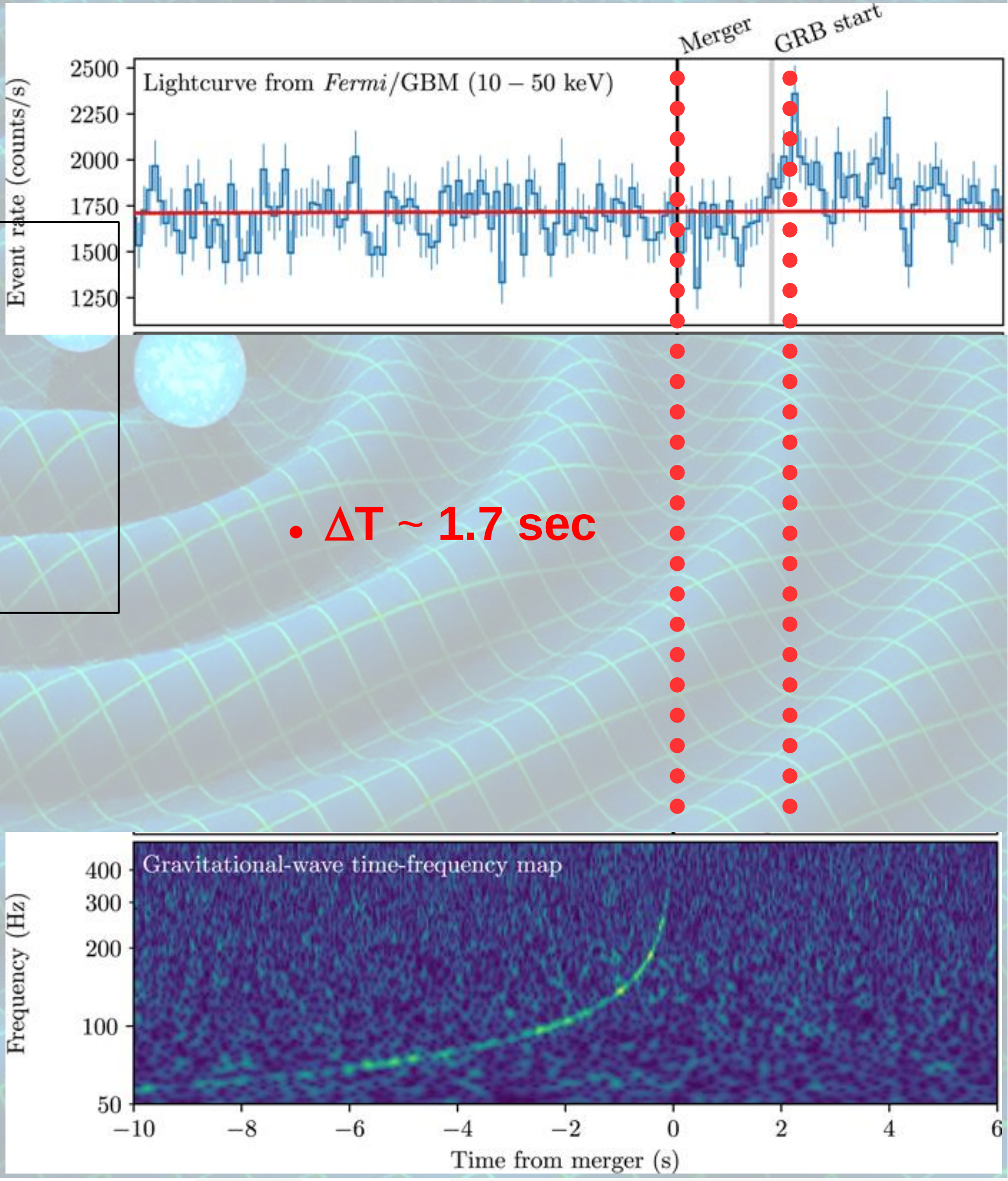
LIGO: 190 deg^2

Fermi GBM: 1100 deg^2



Fermi GBM
+
INTEGRAL SPI
(Interplanetary
Network)
Additional
constraints

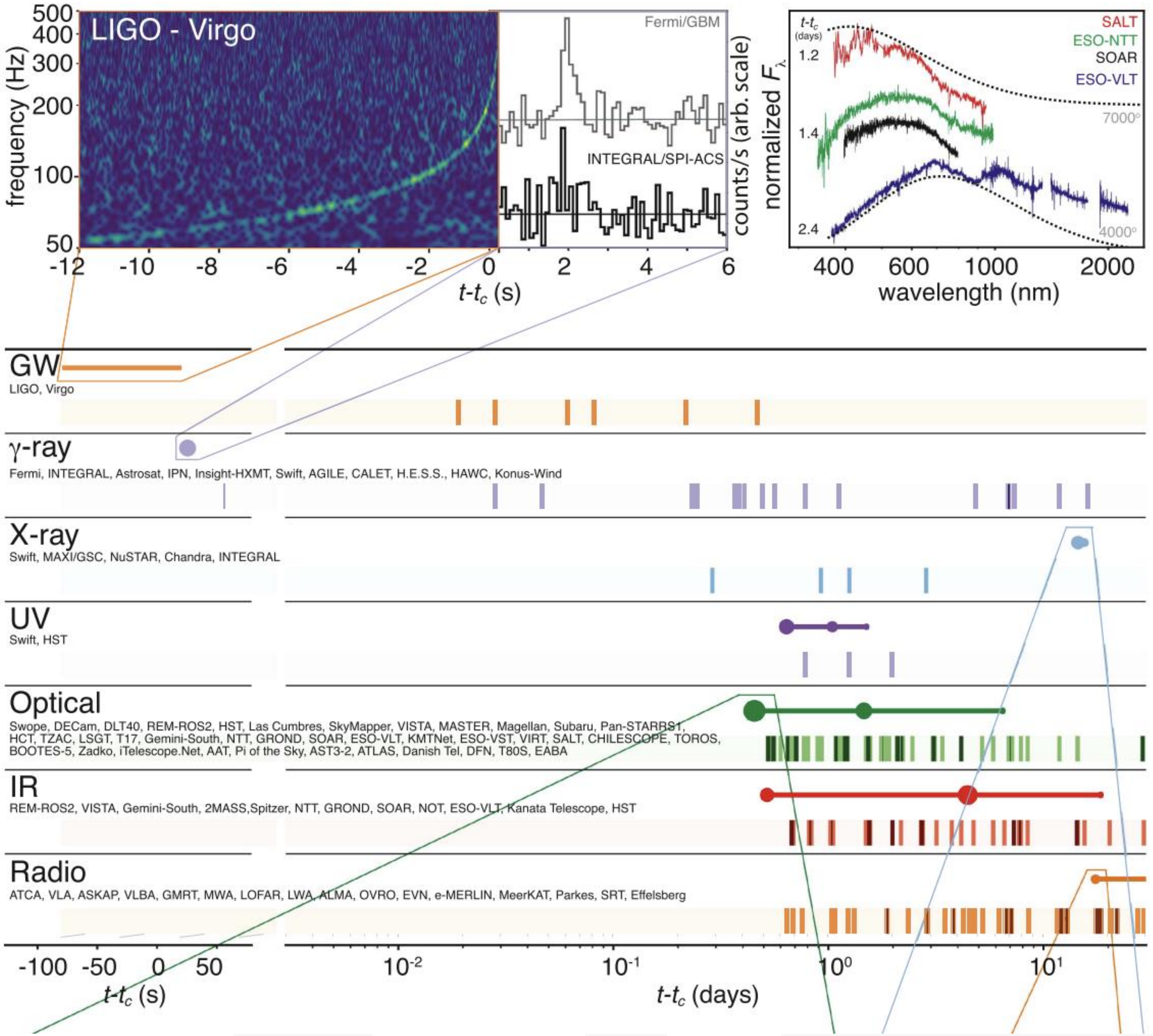
LIGO
+
Virgo
=
31 deg^2



- ΔT ~ 1.7 sec

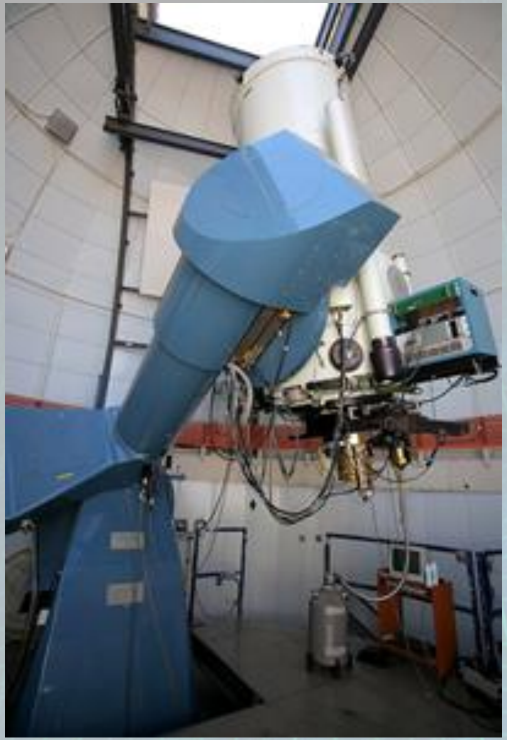
Abbott et al 2017, PRL, 119, 161101

GW170817:
the EM follow-up campaign

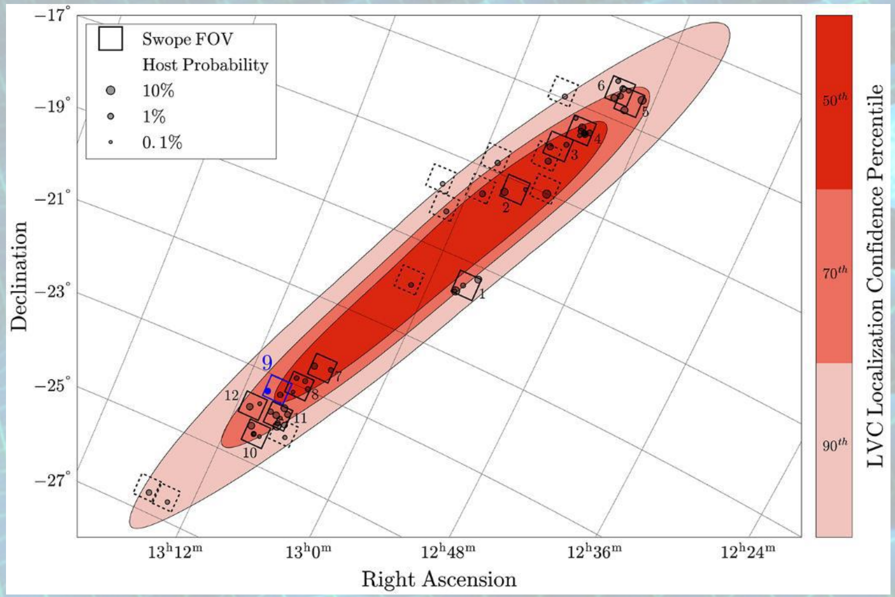


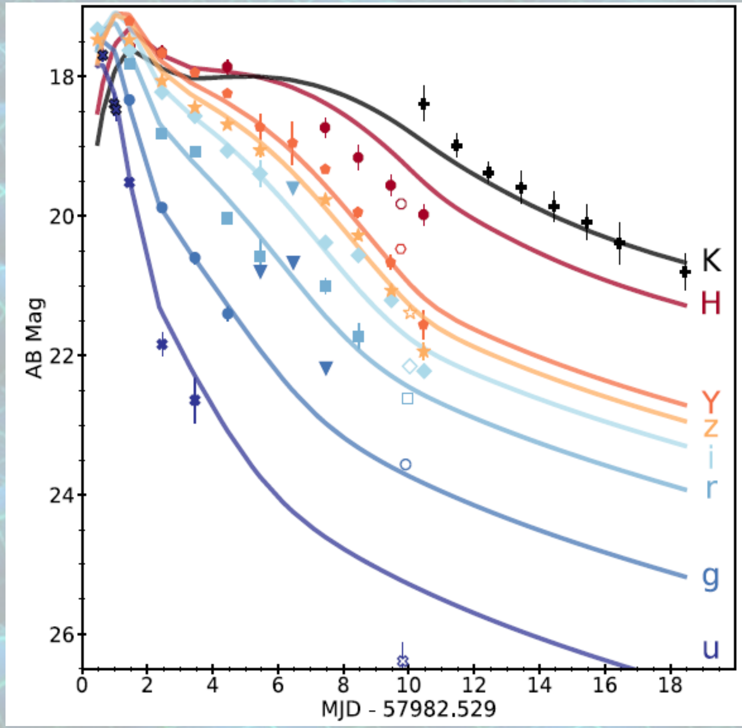
Abbott et al 2017, ApJL 848, 12

GW170817: the optical transient



One-Meter, Two-Hemisphere (1M2H) team
1-m Swope telescope, Las Campanas (Chile)

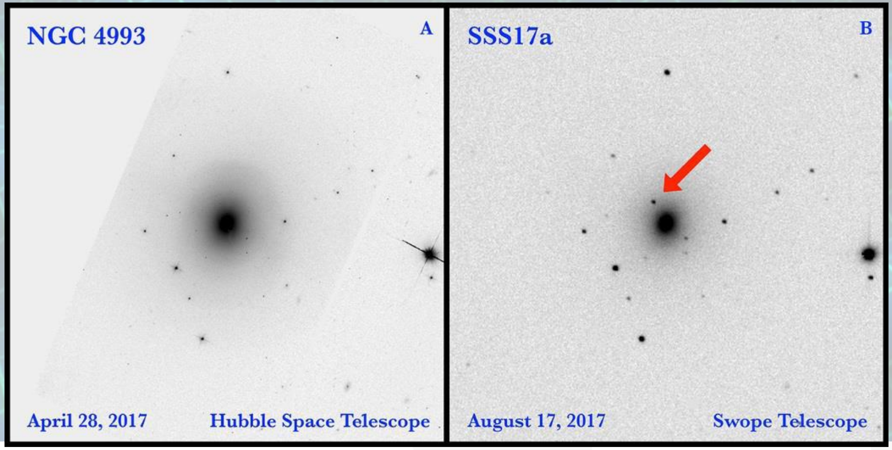




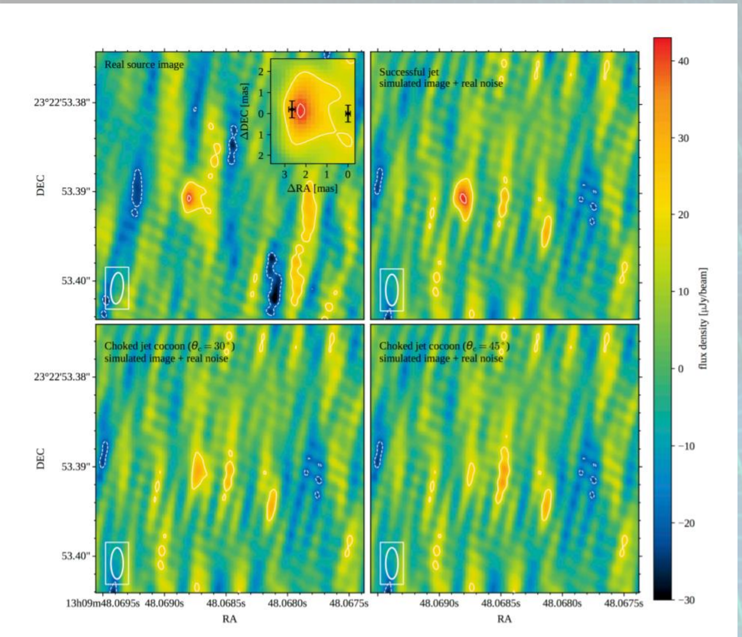
Cowperthwaite et al. 2017

- Observation at t_0+10.8 hr
- mag(i) ~17
- Names SSS17a
- later AT2017gfo
- ESO 508 cluster at 40 Mpc

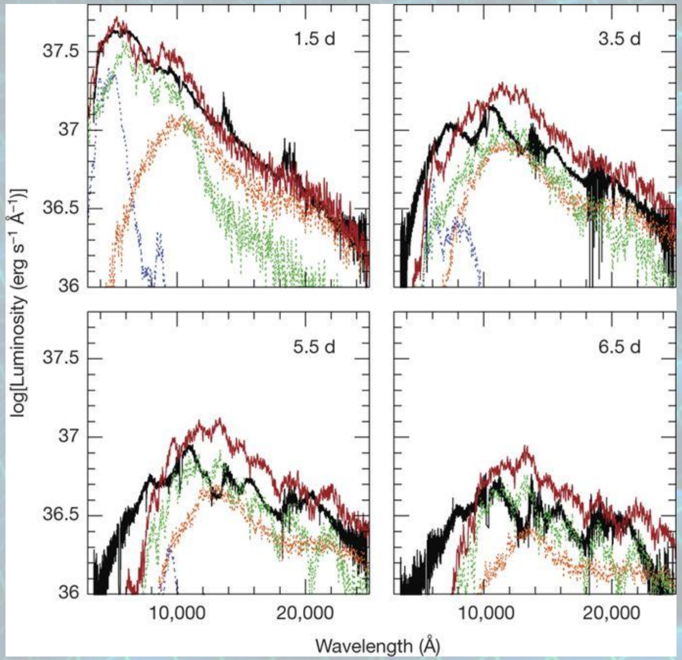
- *(Coulter et al. 2017)*



GW170817: (some) lesson learned



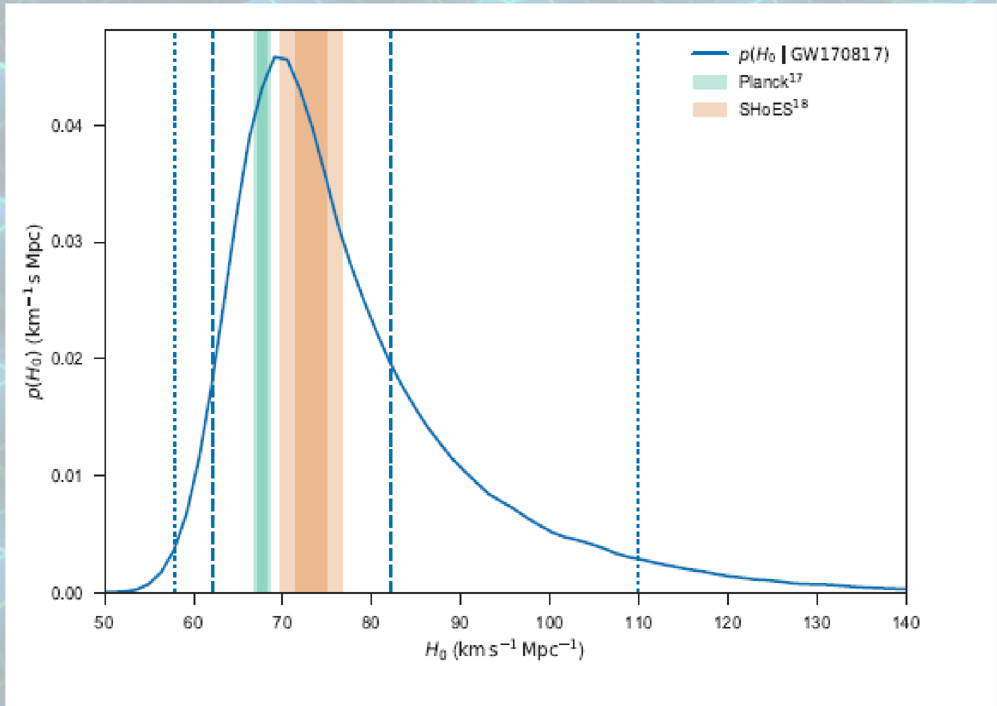
GRB Physics
e.g. Ghirlanda et al. 2018, Science, 363, 6430



R-process nucleosynthesis
e.g. Pian et al. 2017, Nature, 551,67

Cosmology:
GW as standard sirens
e.g. Abbott et al, Nature, 551,85

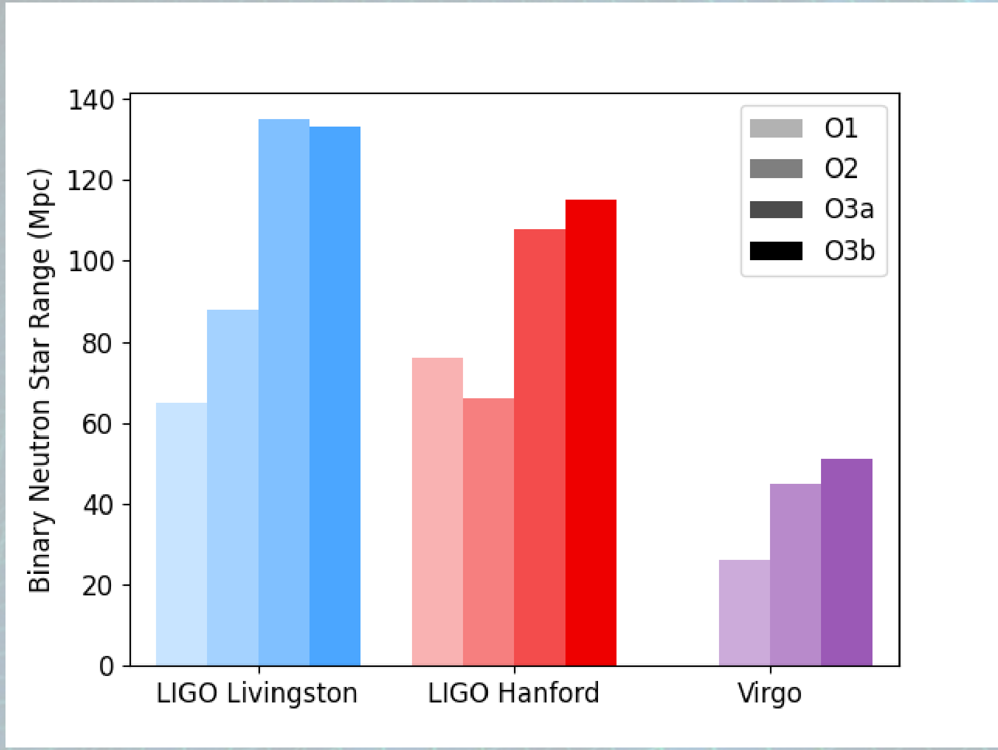
$H_0 = 70^{+12}_{-8}$ Km s^{-1} Mpc^{-1}



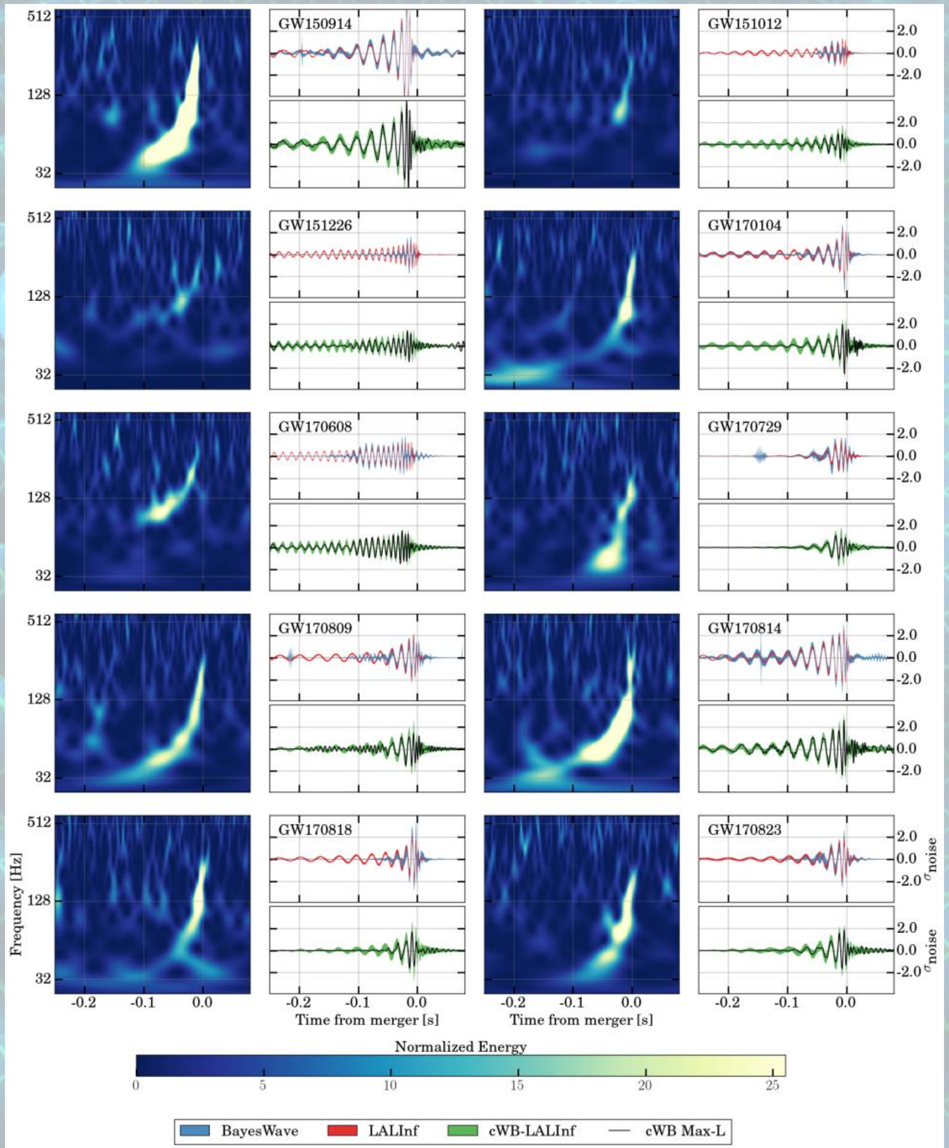
From single events to catalogs

Gravitational Wave Transient Catalog 1 (GWTC-1)

- 10 BBH+1 BNS + marginal events
- O1+O2 detections
- Abbott et al 2019, PRX, 9, 031040



Credits: LIGO-Virgo-KAGRA Collaborations/Hannah Middleton/OzGrav.



Adapted from Abbott et al 2019, PRX, 9, 031040

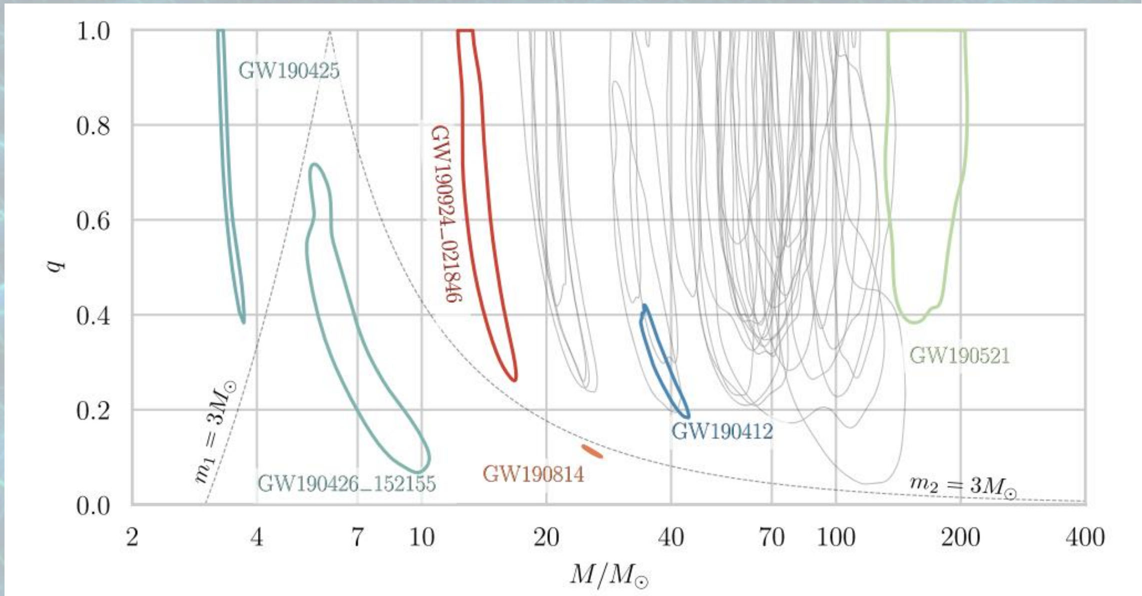
GWTC-2

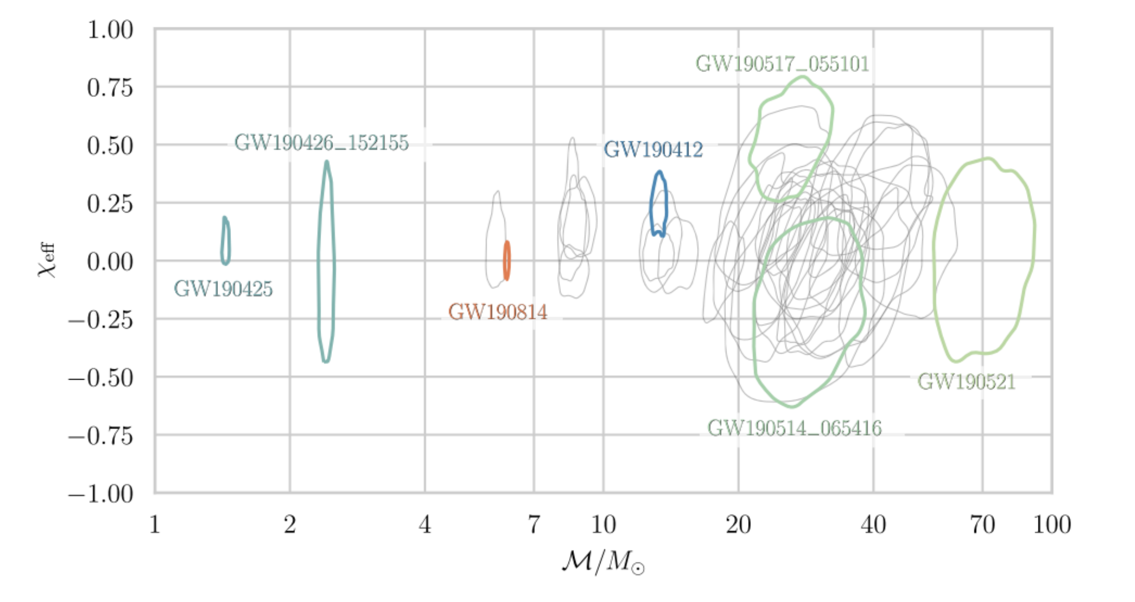
Gravitational Wave Transient Catalog 2 (GWTC-2)

- +39 events
- O1+O2+O3a detections
- Abbott et al 2020,

Highlights

- **GW190412 & GW190814**: asymmetric component masses (e.g. 2.6 + 23 M_{sun} for GW190814, low-mass BH or high-mass NS)
- **GW190425**: second BNS
- **GW190521**: BBHS with total mass over 150Msun (IMBH? Other cases e.g. GW190519_153544)
- **GW190514_065416**: BBH with smallest effective aligned spin (hints to formation in GC?)
- **GW190517_055101**: BBH with largest aligned effective spin
- **GW190924_021846**: lowest-mass BBH (2.5-5 Msun lower mass gap object?)





Abbott et al 2021, PRX, 11,021053

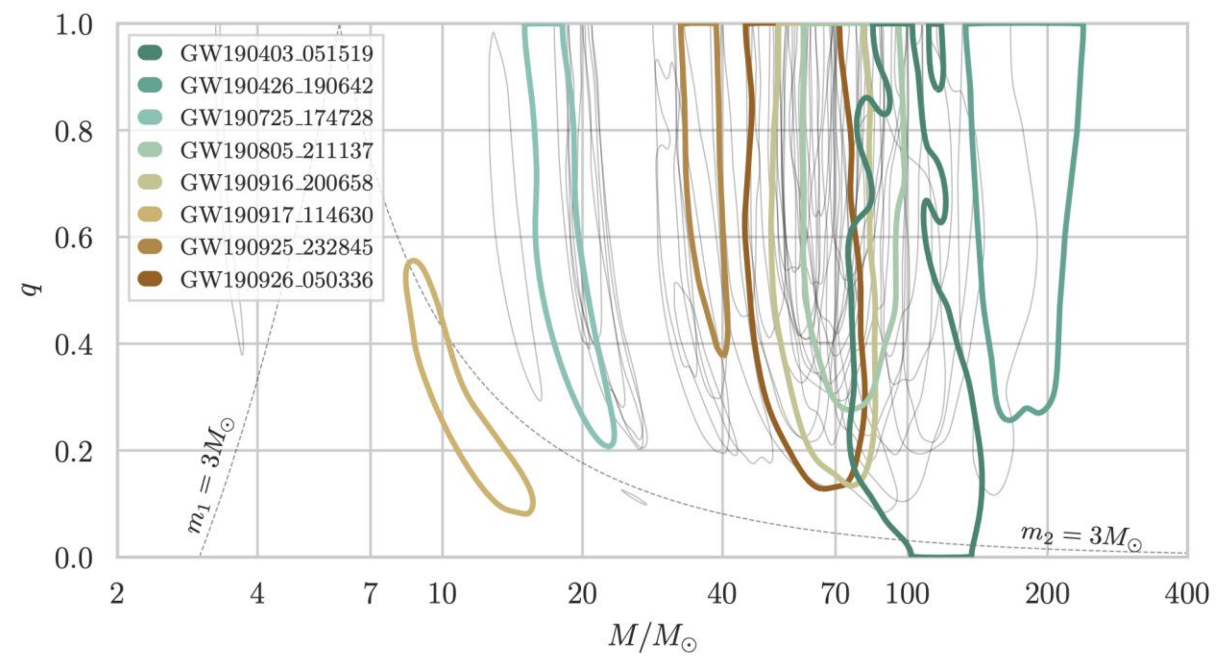
GWTC-2.1

Gravitational Wave Transient Catalog 2.1 (GWTC-2.1)

- Revision of GWTC-2 with higher FAR (2/day instead of 2/year of GWTC-2)
- 1201 candidates
- 44 with P>50% of astrophysical origin
- 8 new events

Highlights

- **GW190917_114630**: potential NSBH
- **GW190426_190642** (185Msun, higher than GW190521. 65-120 Msun pair instability gap of primary object
- **GW190403_051519** and **GW190805_21137**, non-zero spin of a BBH



Abbott et al 2023, arXiv :210.80104

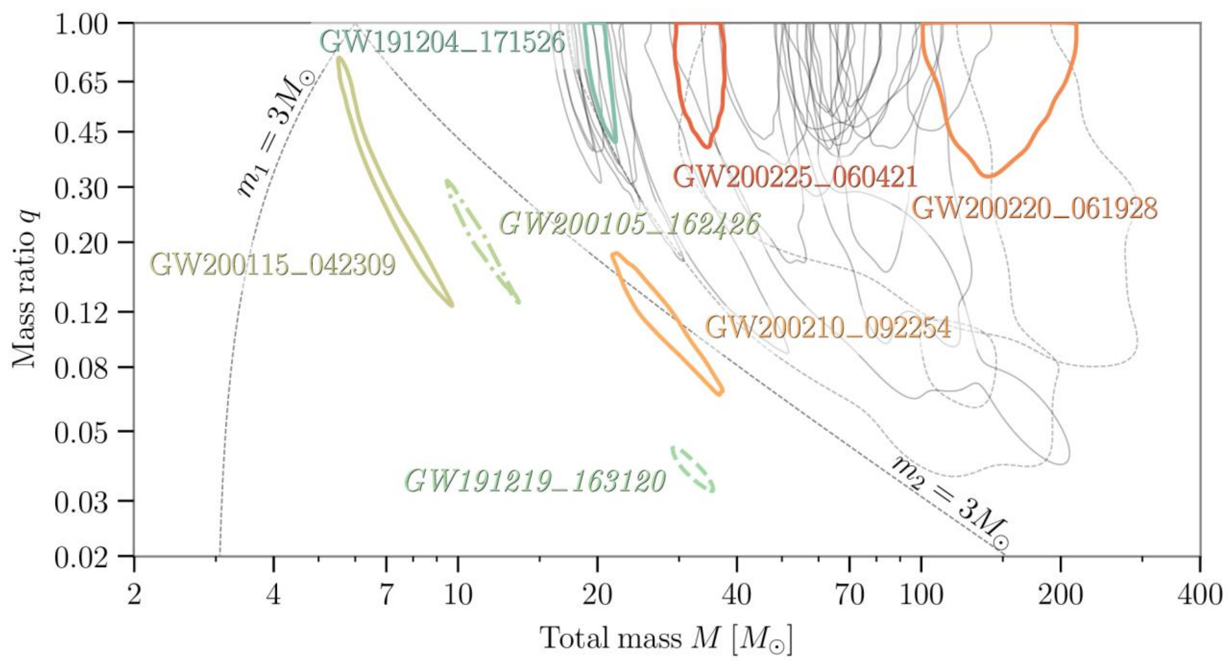
GWTC-3

Gravitational Wave Transient Catalog 3 (GWTC-3)

- Data from O3a+O3b
- +35 new events
- Total of 90 events

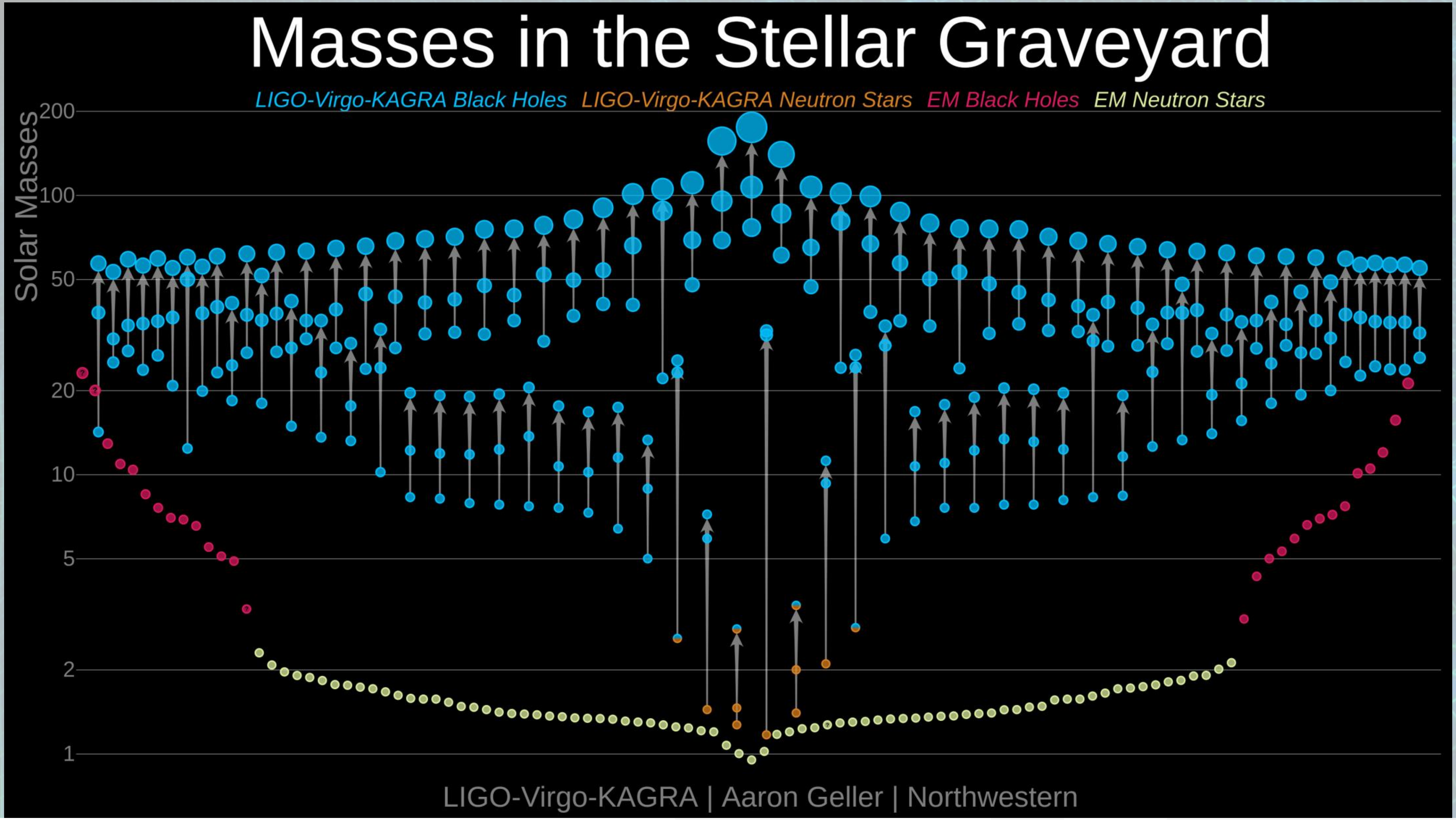
Highlights

- **GW191219_163120**: NSBH with asymmetric members (1.2+31 M_{sun})
- **GW200115_042309**: NSBH (1.4+6 Msun)
- **GW200210_092254** (similar to GW190814): 24+2.8 Msun, probably light BH companion
- **GW200220_061928**: 141 total mass BBH (largest in O3b), surpassing threshold for IMBH
- **GW191204_171526**: effective positive spins (aligned spins)
- **GW191109_134029**: negative effective inspiral spin (aligned in opposite directions)



Abbott et al 2023, PRX, 13, 041039

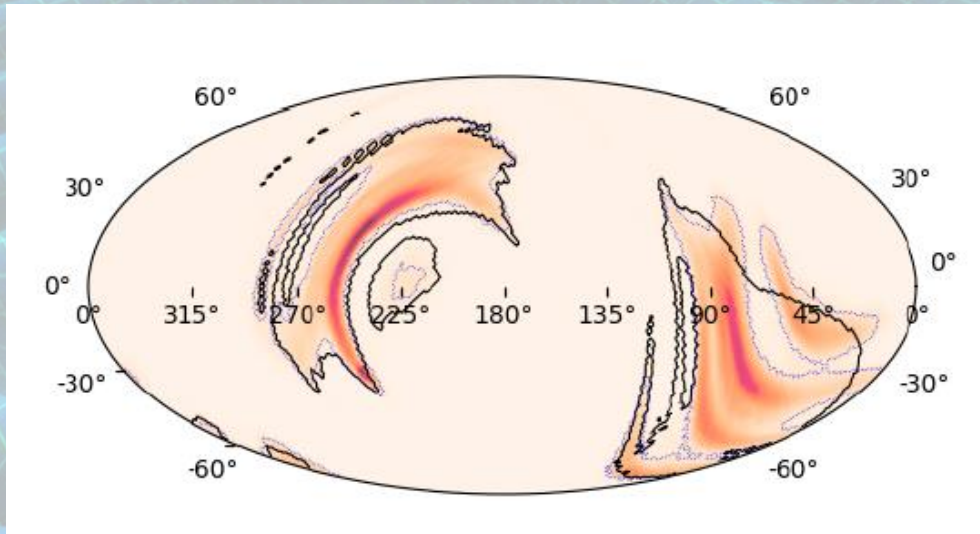
Masses in GWTC-3



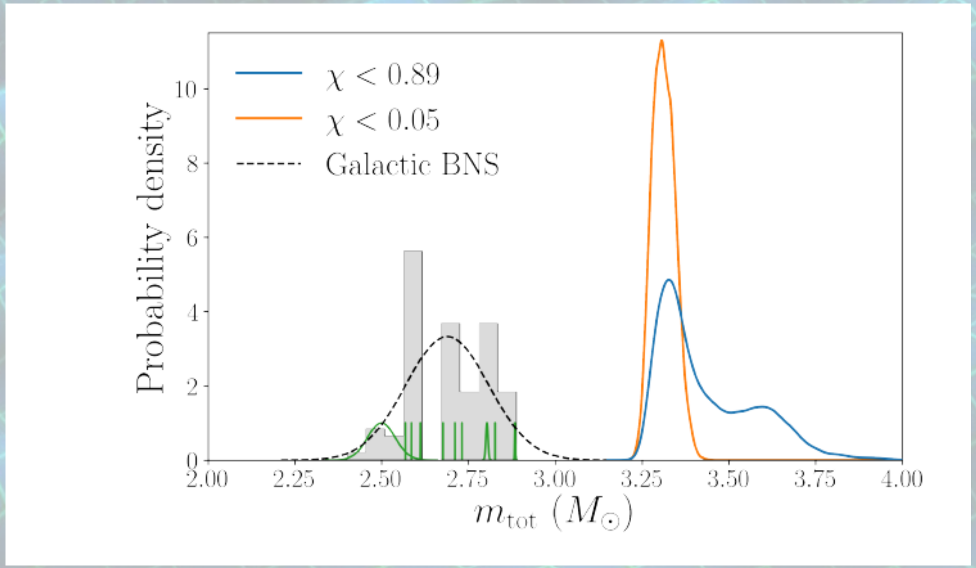
GW190425, the other BNS

- Detected by LIGO L1 only at 8:18 (H1 offline, V1 SNR low)
- 1 detector-→ poor localization ($10000 deg^2 \rightarrow 8200 deg^2$)

- Alert sent, no counterparts
- Total Mass 3.4 Msun : 2 options
  - Binary Neutron Star (different from Galactic popoulation
  - NSBH (no tides), BH in mass gap (or PBH?)
- Updated BNS rate: 250-2810 Gpc-3yr-1



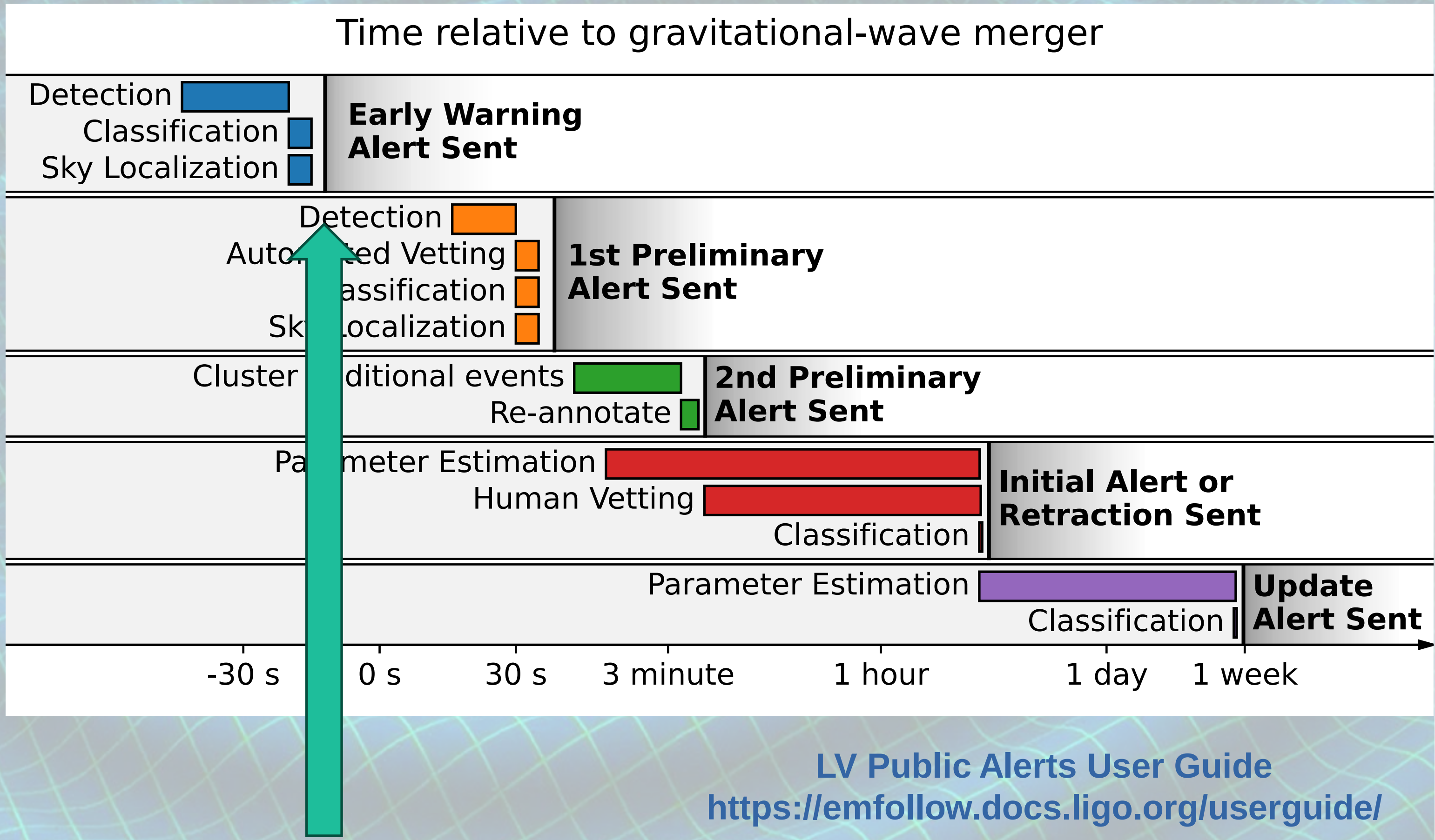
	Low-spin prior ($\chi < 0.05$)	High-spin prior ($\chi < 0.89$)
Primary mass m_1	$1.60 - 1.87\ M_\odot$	$1.61 - 2.52\ M_\odot$
Secondary mass m_2	$1.46 - 1.69\ M_\odot$	$1.12 - 1.68\ M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}\ M_\odot$	$1.44^{+0.02}_{-0.02}\ M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}\ M_\odot$	$1.4873^{+0.0008}_{-0.0006}\ M_\odot$
Mass ratio m_2/m_1	$0.8 - 1.0$	$0.4 - 1.0$
Total mass $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}\ M_\odot$	$3.4^{+0.3}_{-0.1}\ M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.012^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance $D_{\rm L}$	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 600	≤ 1100



Abbott et al, 2020, ApJL, 892,1

Multimessenger Opportunities

- **O1 & O2 follow-up program**
  - Sent privately to groups that signed MoU with LIGO/Virgo
  - 95 groups at the end of O2
  - Alerts sent via GCN for False Alarm Rate <2/month
  - GCN included time, 3D localization, probability of IDs
  - 17 alerts sent, 7BBHS+1BNS (GW170817)



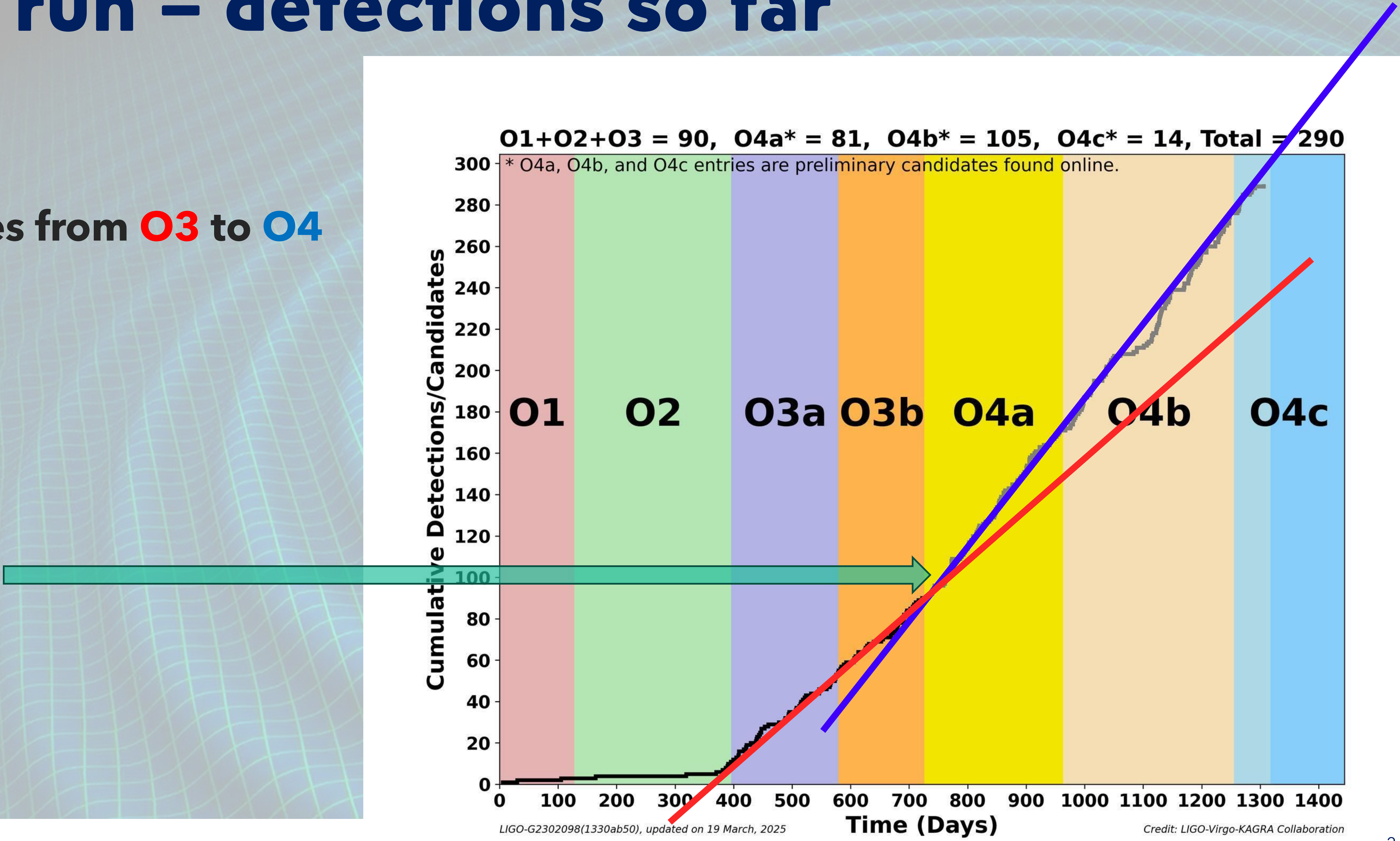
- **From O3: public alerts**
  - Preliminary GCN Notice within minutes
  - Rapid Response Team confirms or retracts
  - More details in following GCNs
  - Available at the Gravitational Wave Event Database (GraceDB) website (https://graced.ligo.org)

LV Public Alerts User Guide
https://emfollow.docs.ligo.org/userguide/

Early Warning in O4

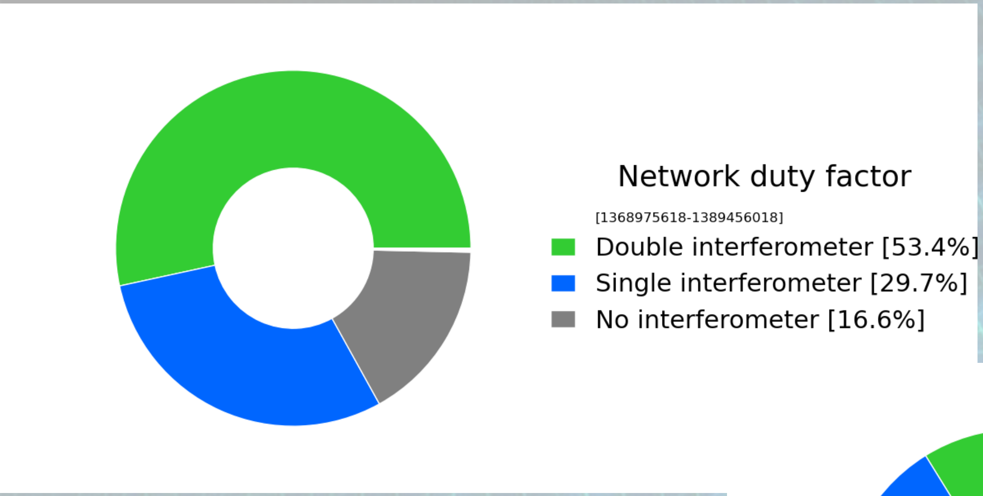
O4 run – detections so far

Upgrades from O3 to O4

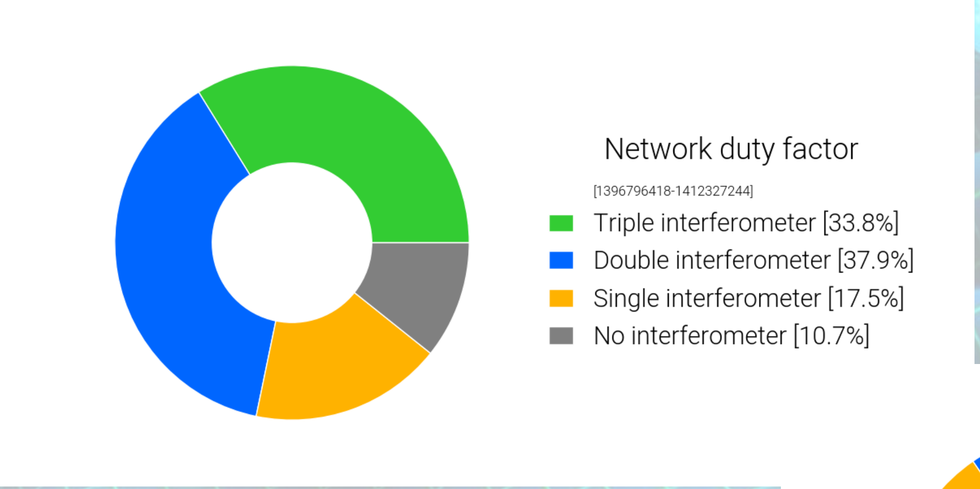


O4 Duty cycle

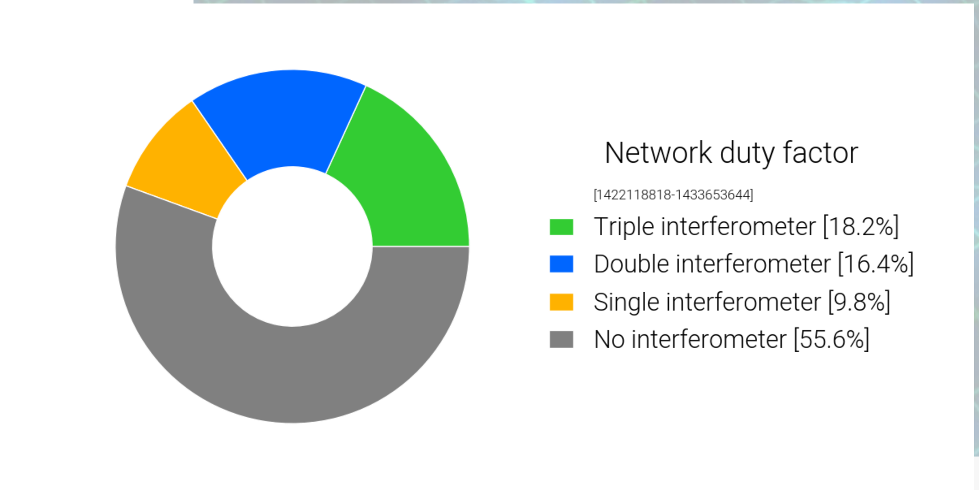
O4a



O4b



O4c*



*as of June 27,2025

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*

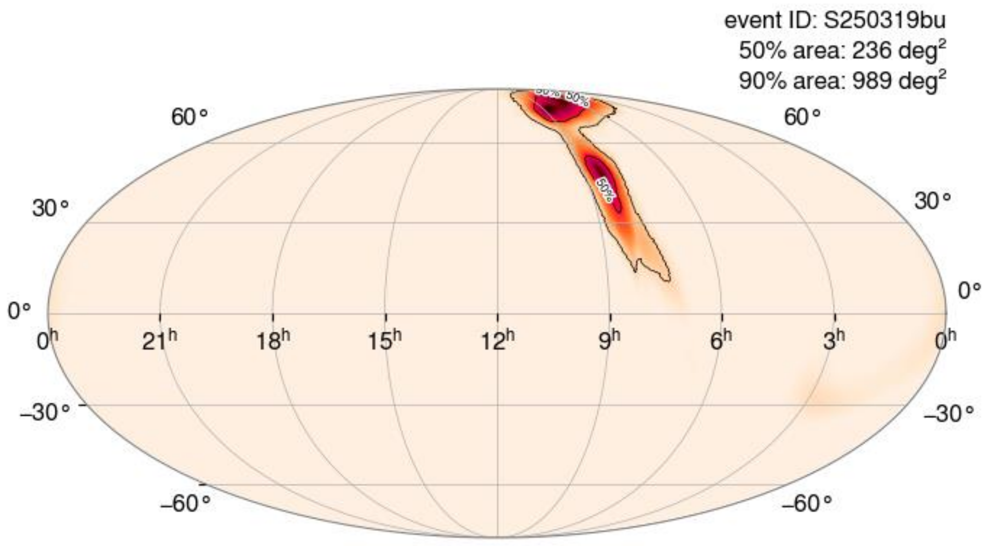
- 17 significant (FAR <1/6 mo) alerts, 5 retracted
- 587 Low-significance

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

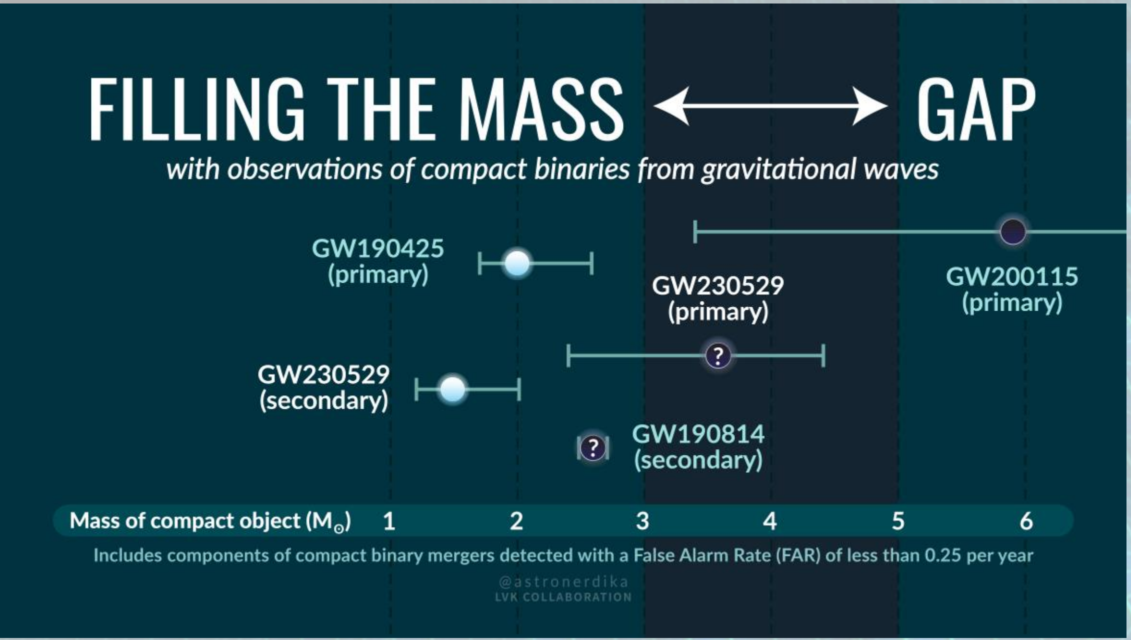
*as of June 27,2025

RECORD DETECTION OF 200 GRAVITATIONAL WAVES IN THE CURRENT RUN OF LIGO, VIRGO AND KAGRA

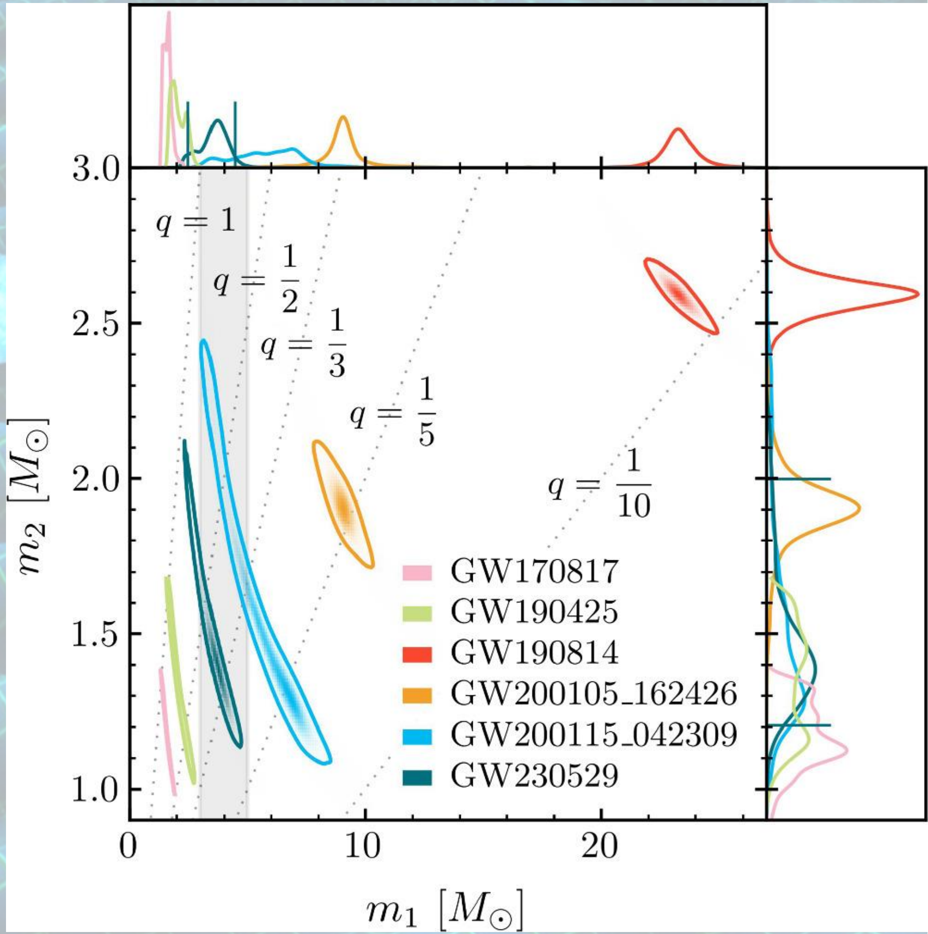
Mar 20, 2025



O4 results: GW230529_181500



Credits: S. Gaudalage



Abac et al 2024, ApJL 970, 34

Highlights

- May 20, 2023
- Observed by LIGOL1 (poor localization, no EM counterpart
- 3.6 Msun with high-significance (mass-gap)

Formation & implication

- Isolated binary evolution
- Hierarchical formation

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 !