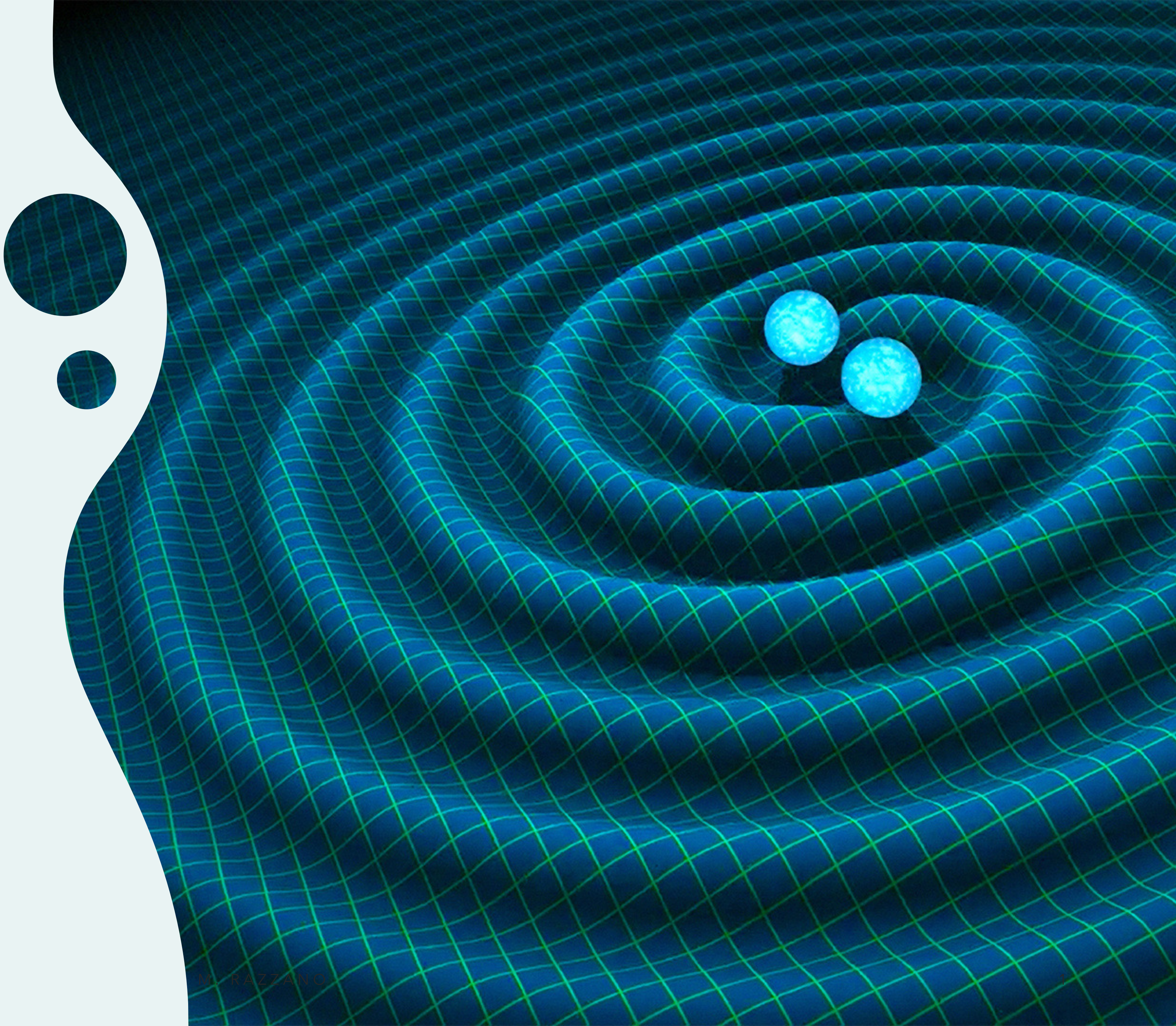
The Universe with Gravitational Waves

status & observational results



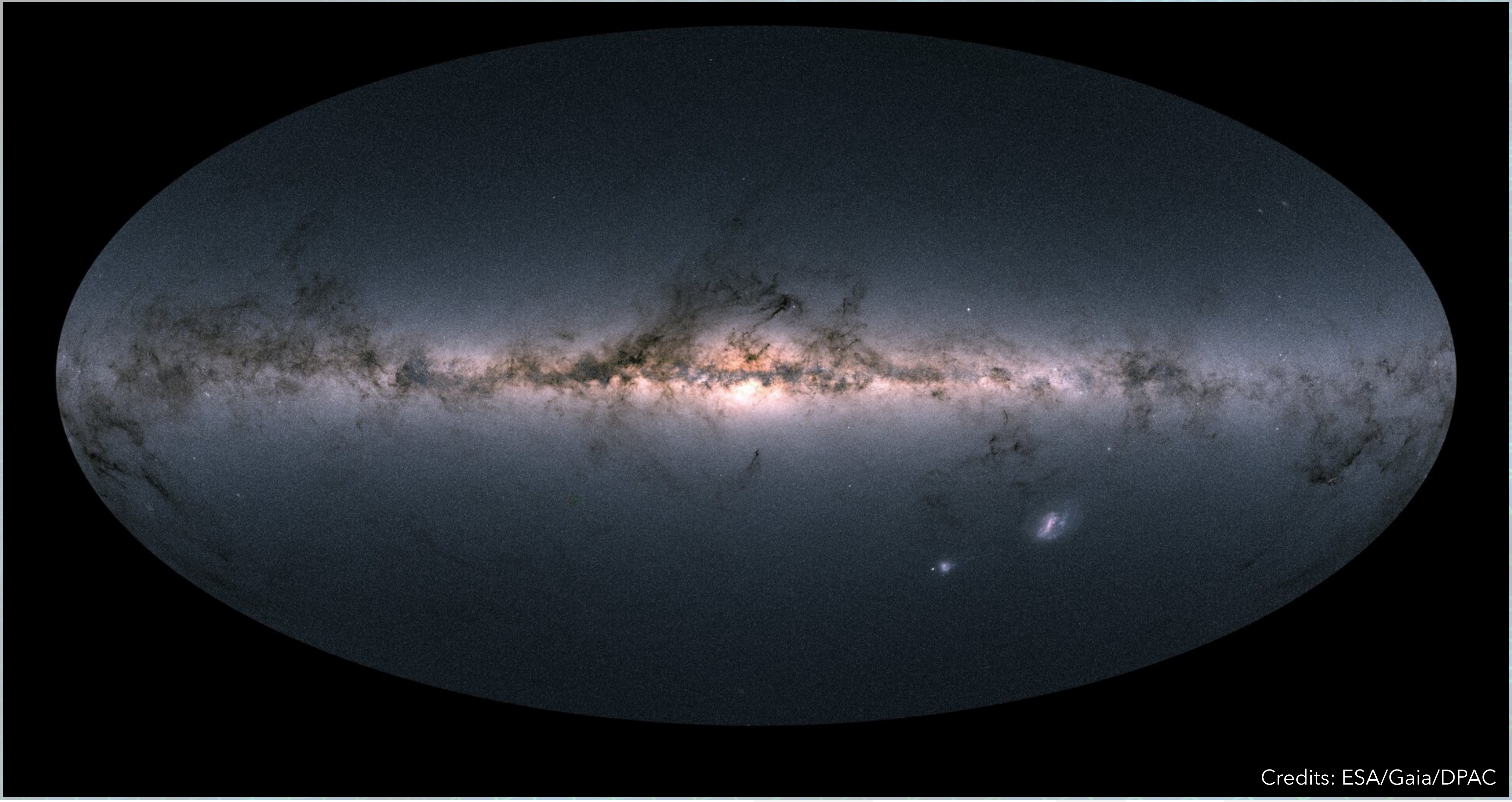
Massimiliano Razzano

(University of Pisa and INFN-Pisa)

On behalf of the LIGO-Virgo-KAGRA Collaboration

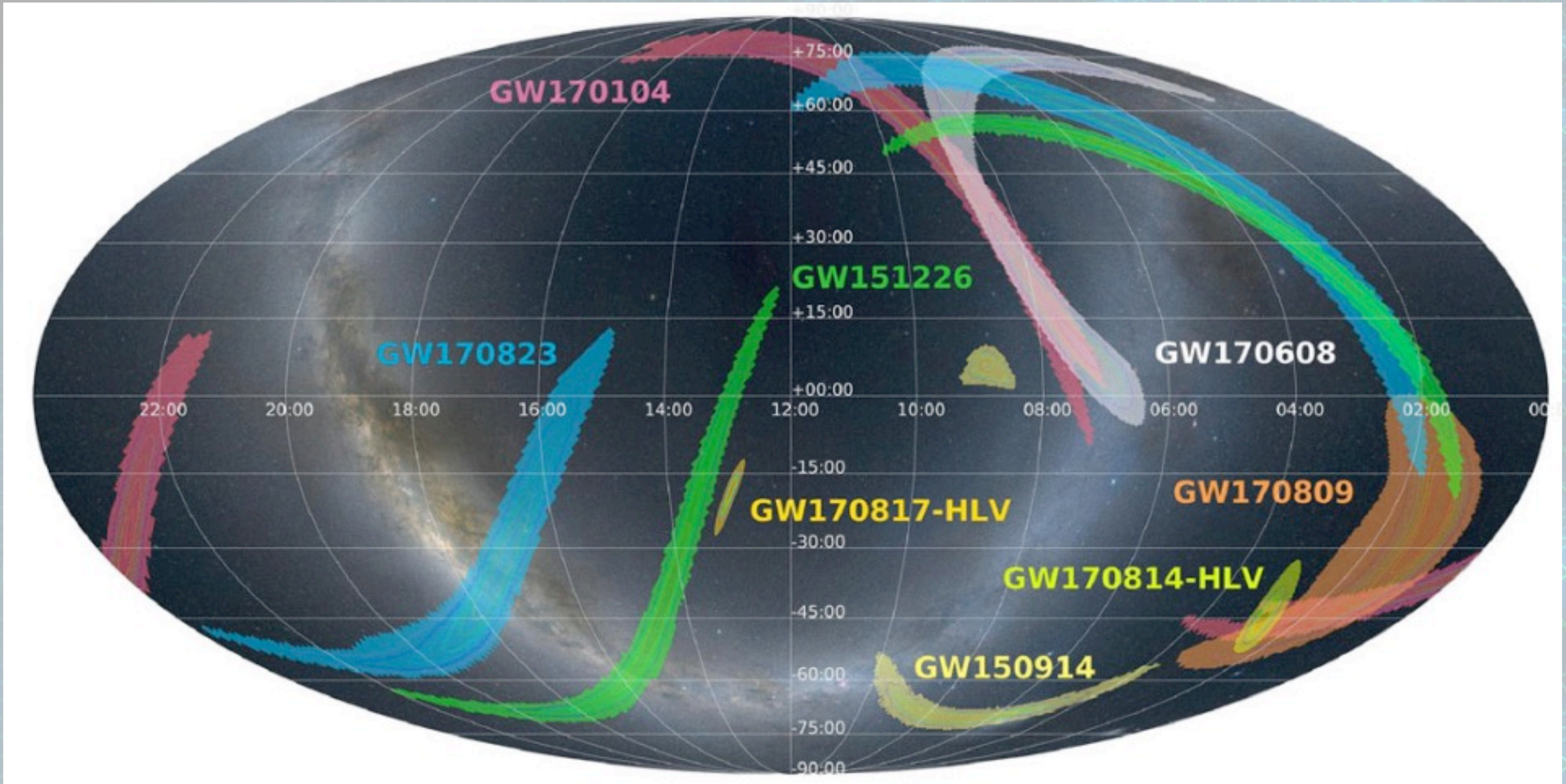
INFN-Bari 8 October 2024

From here…



Credits: ESA/Gaia/DPAC

..to here (and beyond)



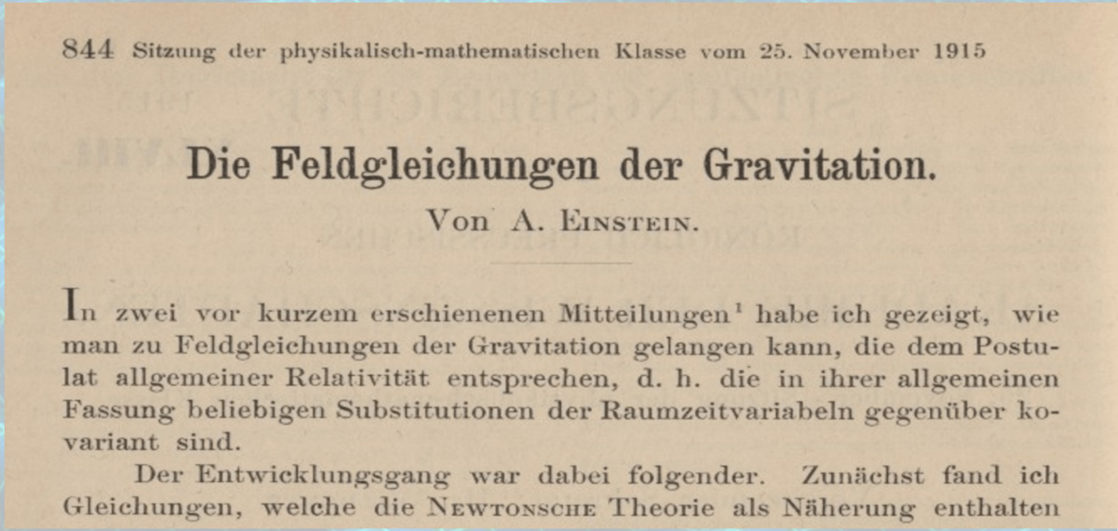
Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

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

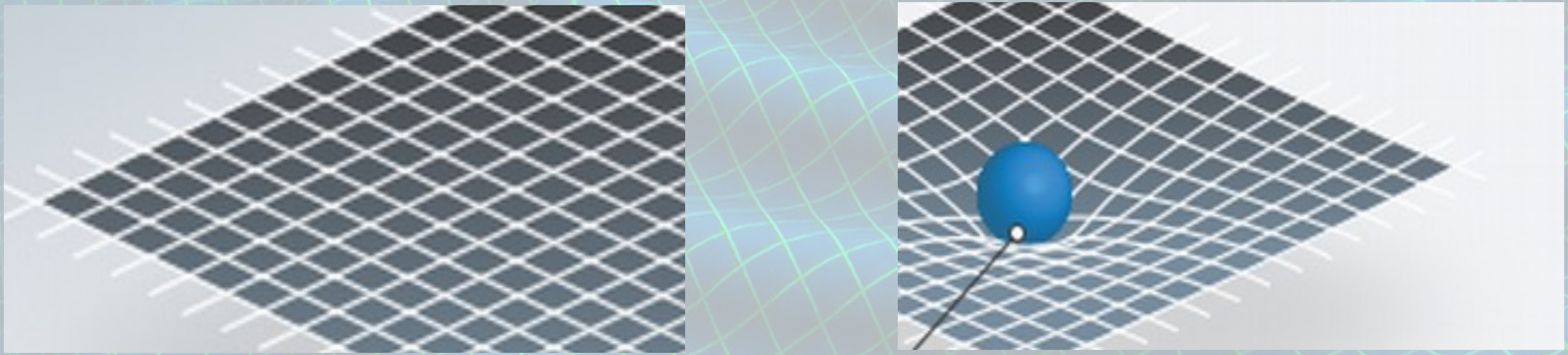
Die Feldgleichungen der Gravitation.

Von A. Einstein.

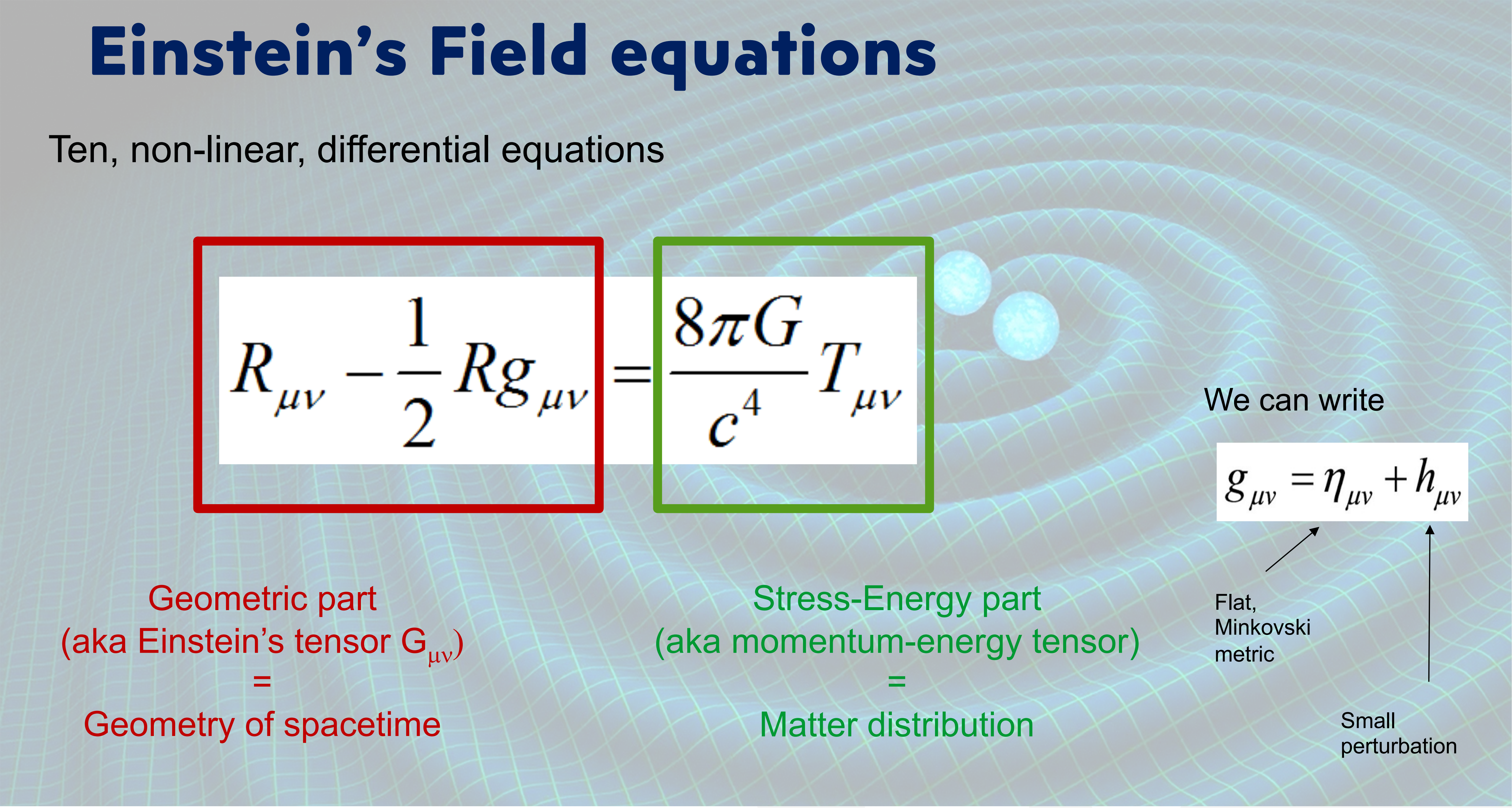
In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

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

Credits: Preussische Akademie der Wissenschaften, Sitzungsberichte, 1915



Einstein’s Field equations



Ten, non-linear, differential equations

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

Geometric part
(aka Einstein’s tensor $G_{\mu\nu}$)
=
Geometry of spacetime

Stress-Energy part
(aka momentum-energy tensor)
=
Matter distribution

We can write

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

Flat,
Minkovski
metric

Small
perturbation

Properties of Gravitational Waves

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

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

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

GW travels 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)
- Generated by non-vanishing quadrupole moment (e.g. accelerating masses, asysimmetric rotating stars & explosions)

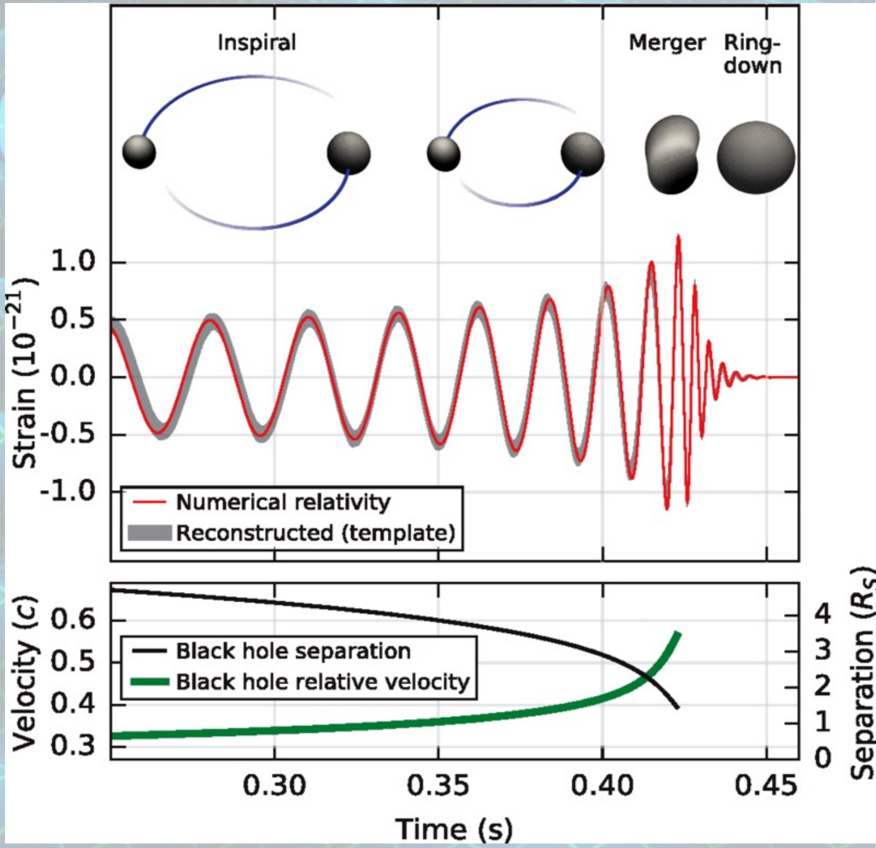
Expected sources of Gravitational Waves

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

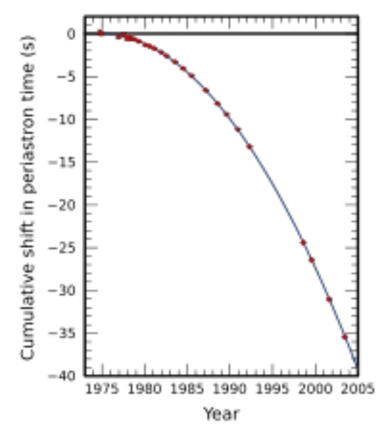


Abbott et al 2016, PRL, 116, 101103

The challenge of detecting GWs

1960's
J. Weber work
resonant bars

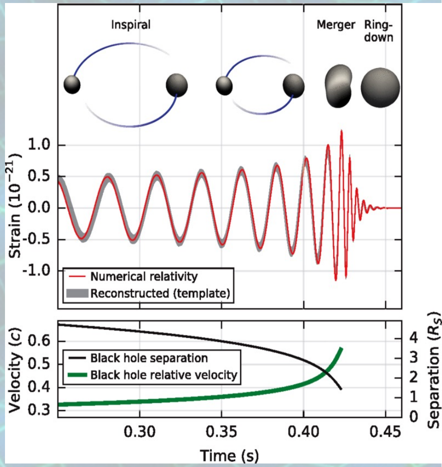
1974
Hulse-Taylor binary pulsar
Indirect evidence of GWs



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!

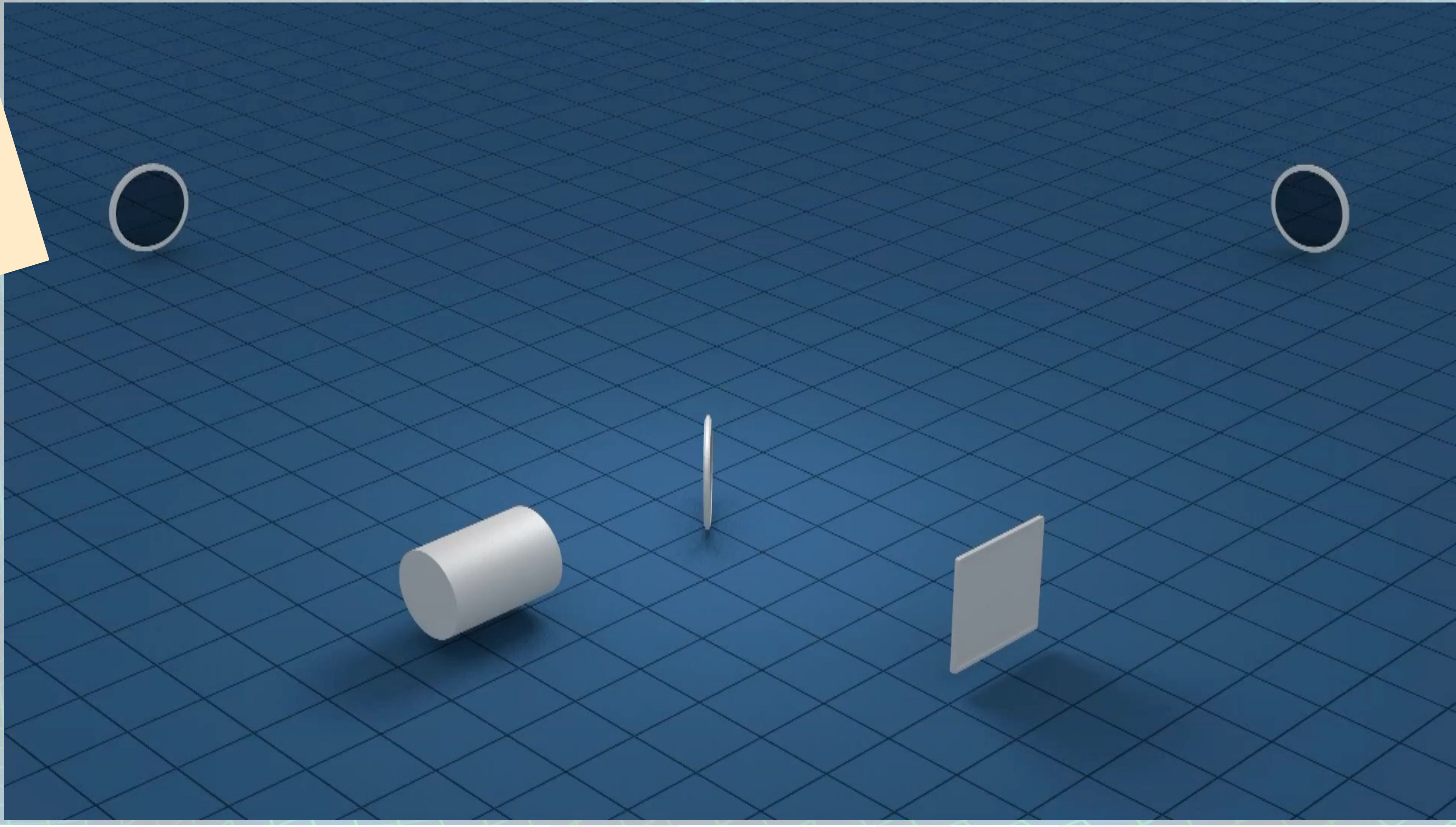


How to detect Gravitational Waves

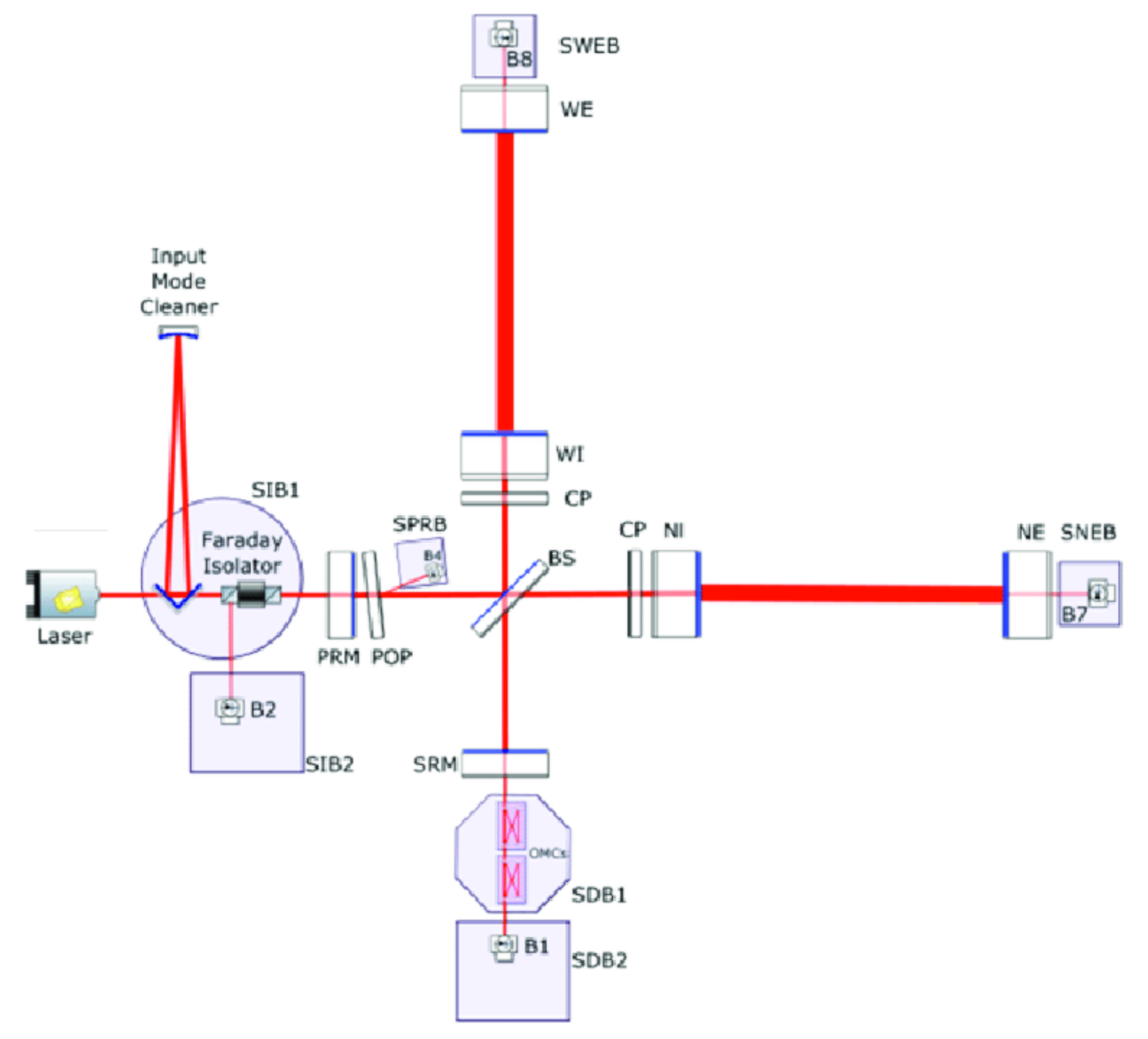
Expected h(t) ~ 10^{-21}

Since h(t) ~ dL/L

→ dL ~10^{-18} m

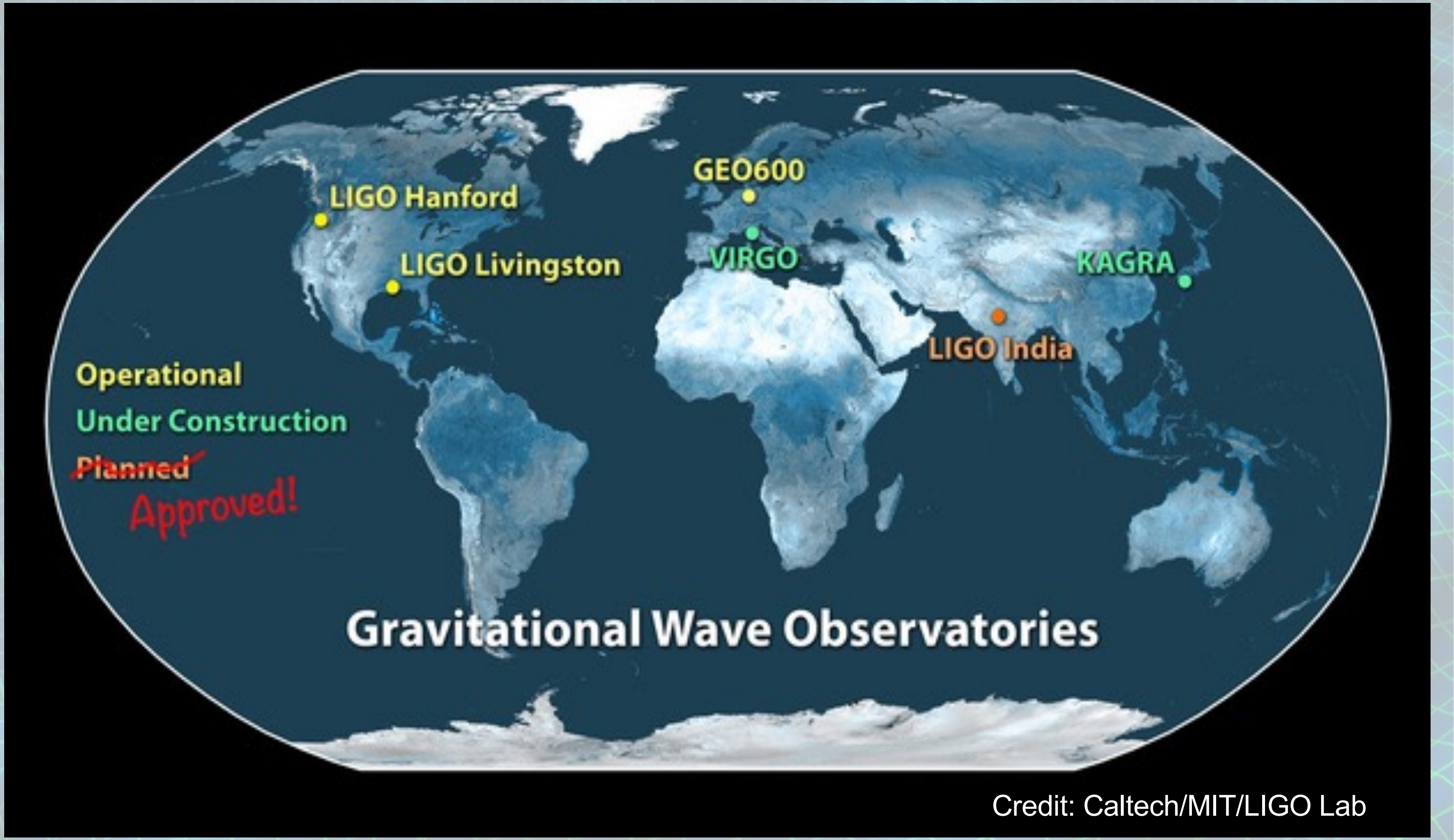


A slightly more complex picture



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

An international Network

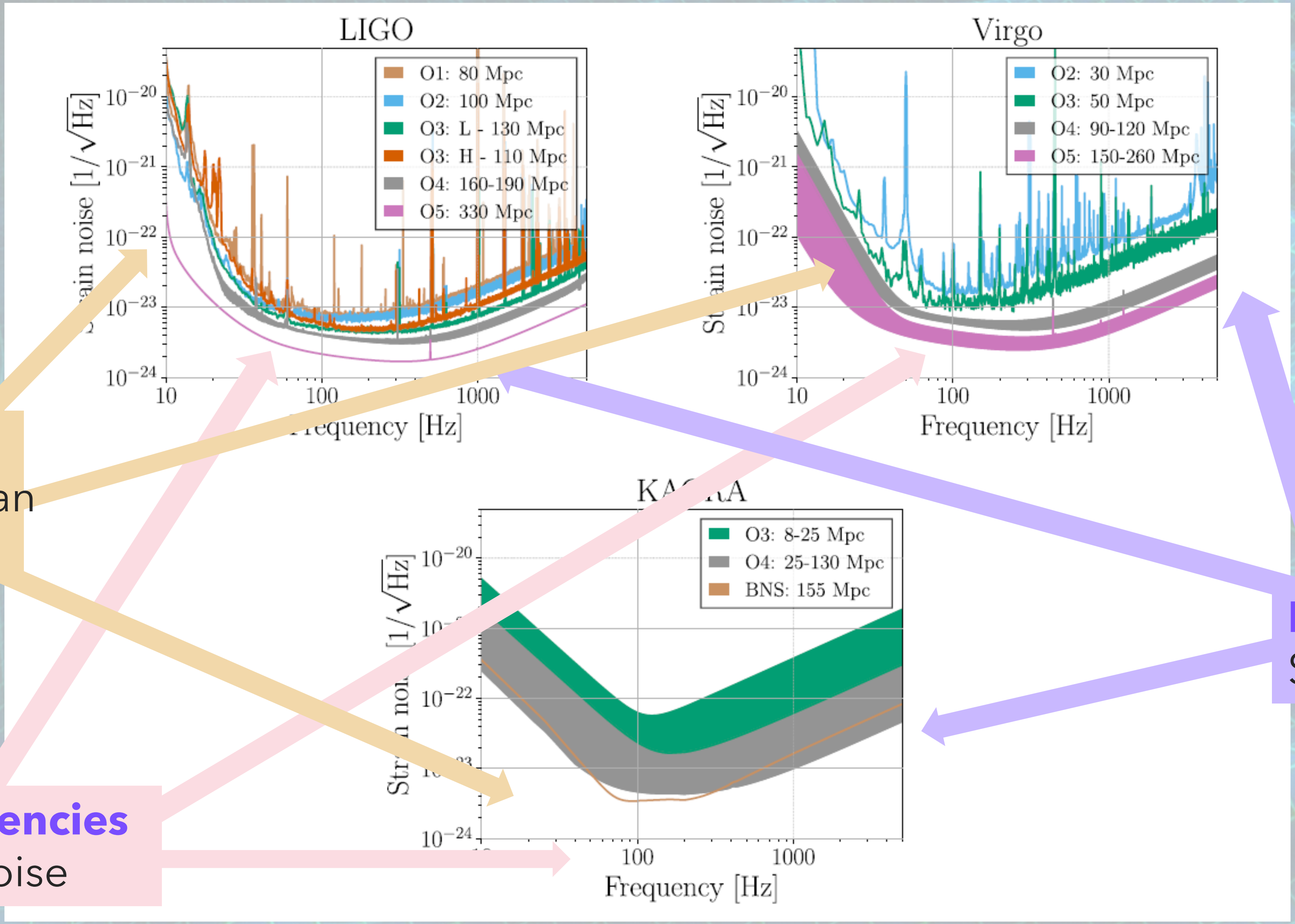


Credit: Caltech/MIT/LIGO Lab

Better sensitivity

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

Sensitivity Curves



Low Frequencies
Seismic & Newtonian Noise

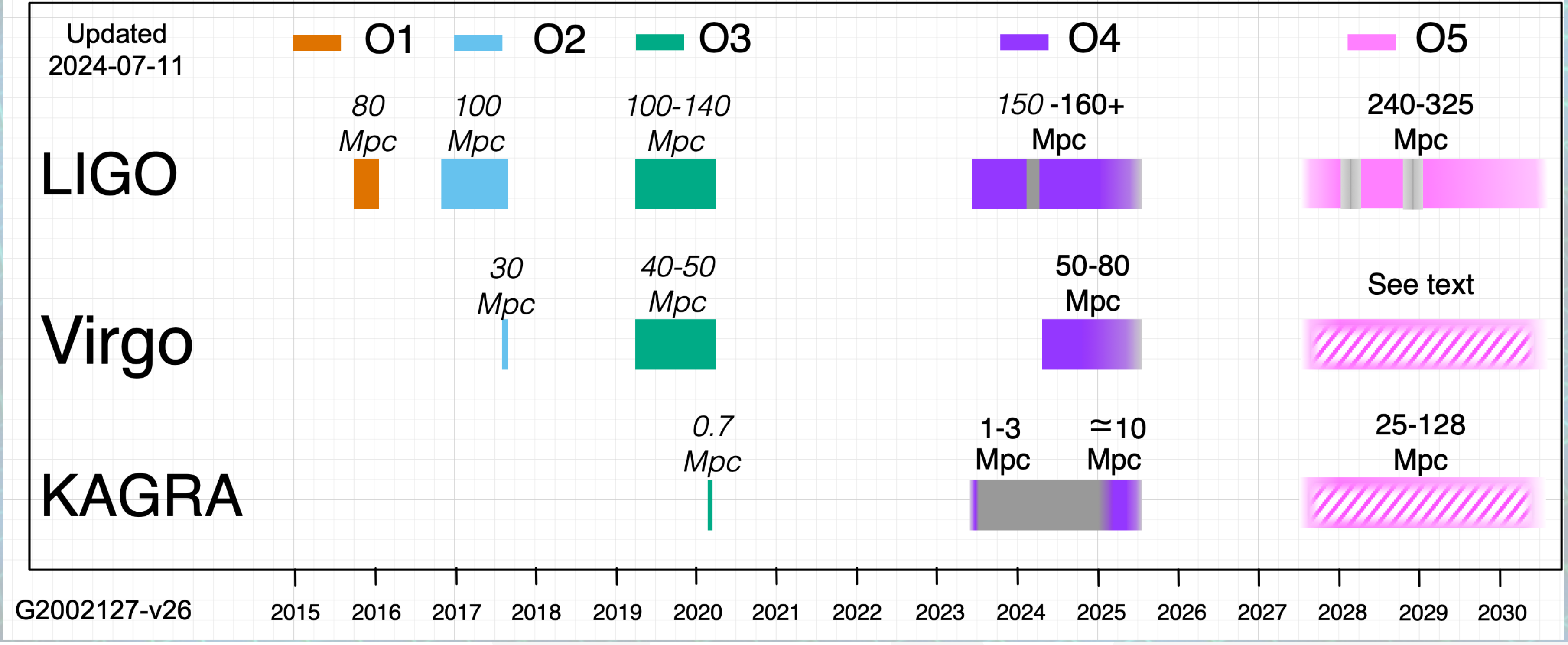
High Frequencies
Shot Noise

Mid Frequencies
Thermal Noise

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

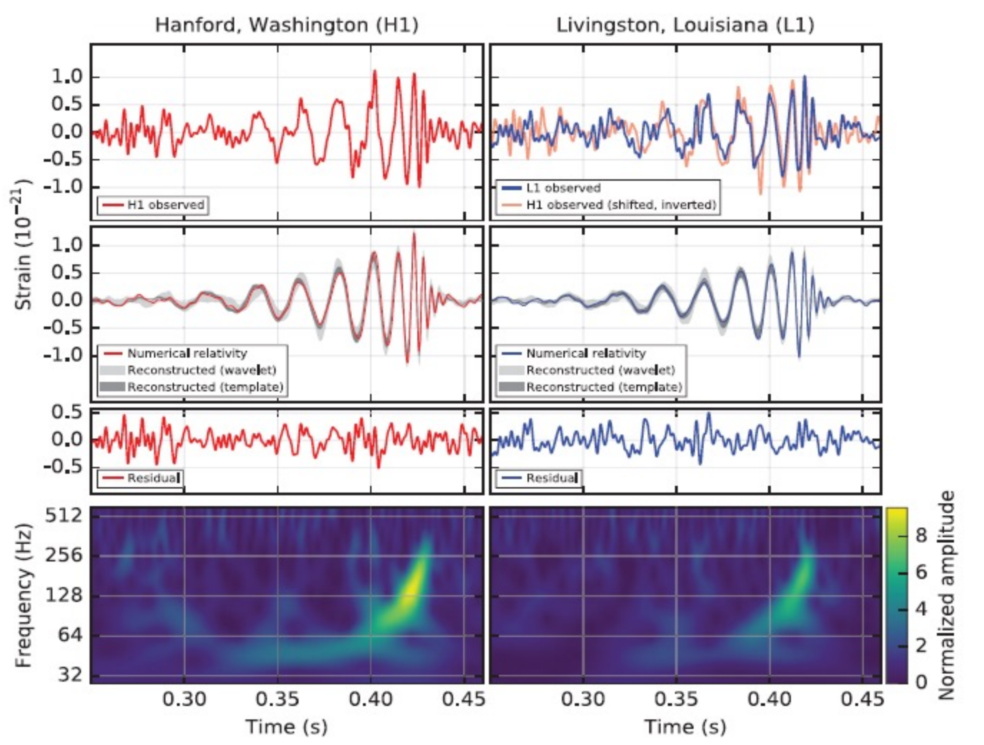
The story so far

- **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 9 2025

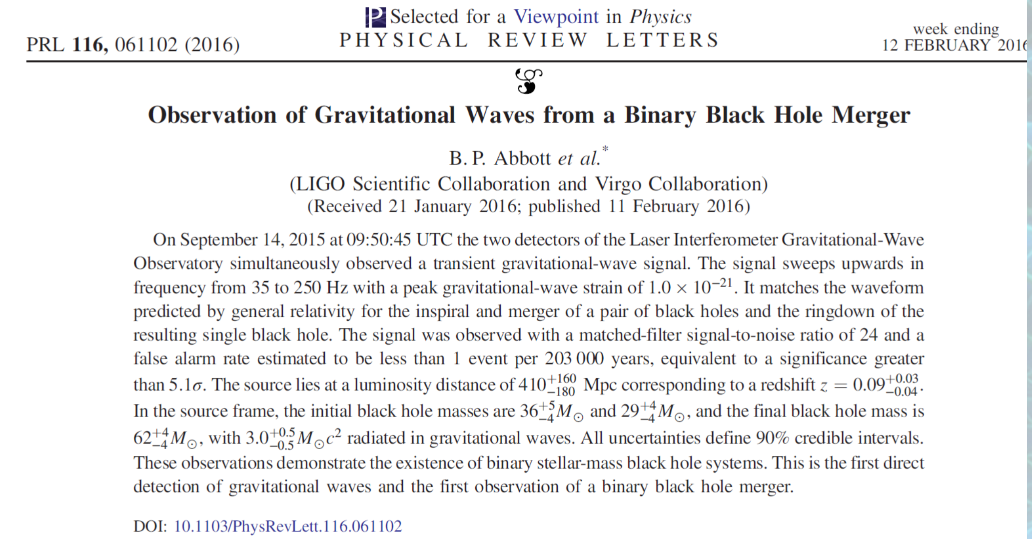


https://observing.docs.ligo.org/plan/

The First detections



GW150914
Abbott+16, PRL116,6



PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

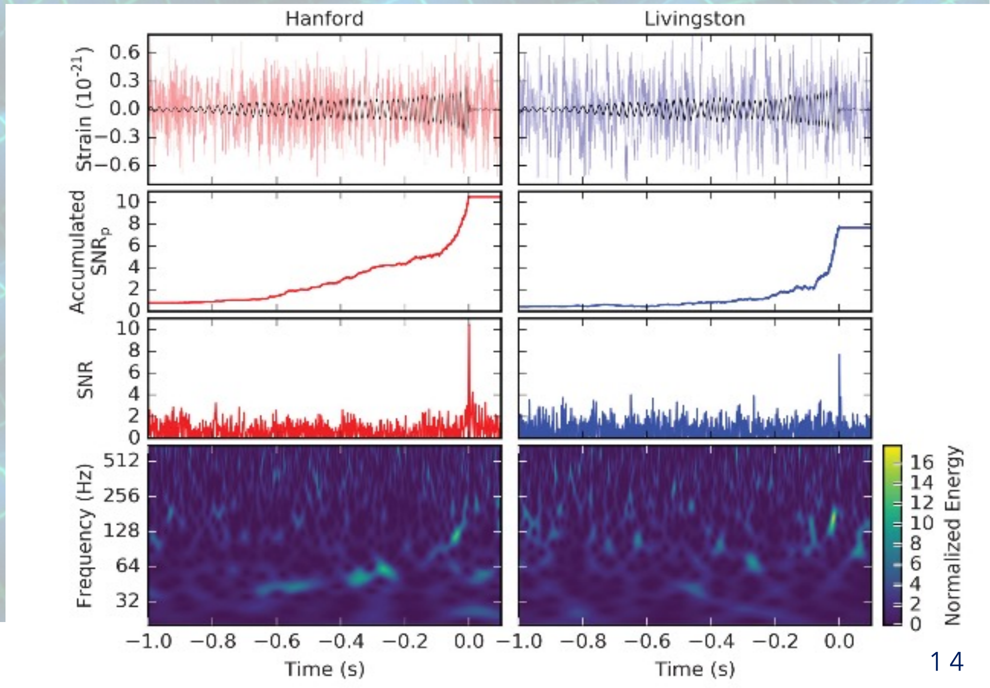
B. P. Abbott *et al.*[*]

(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.

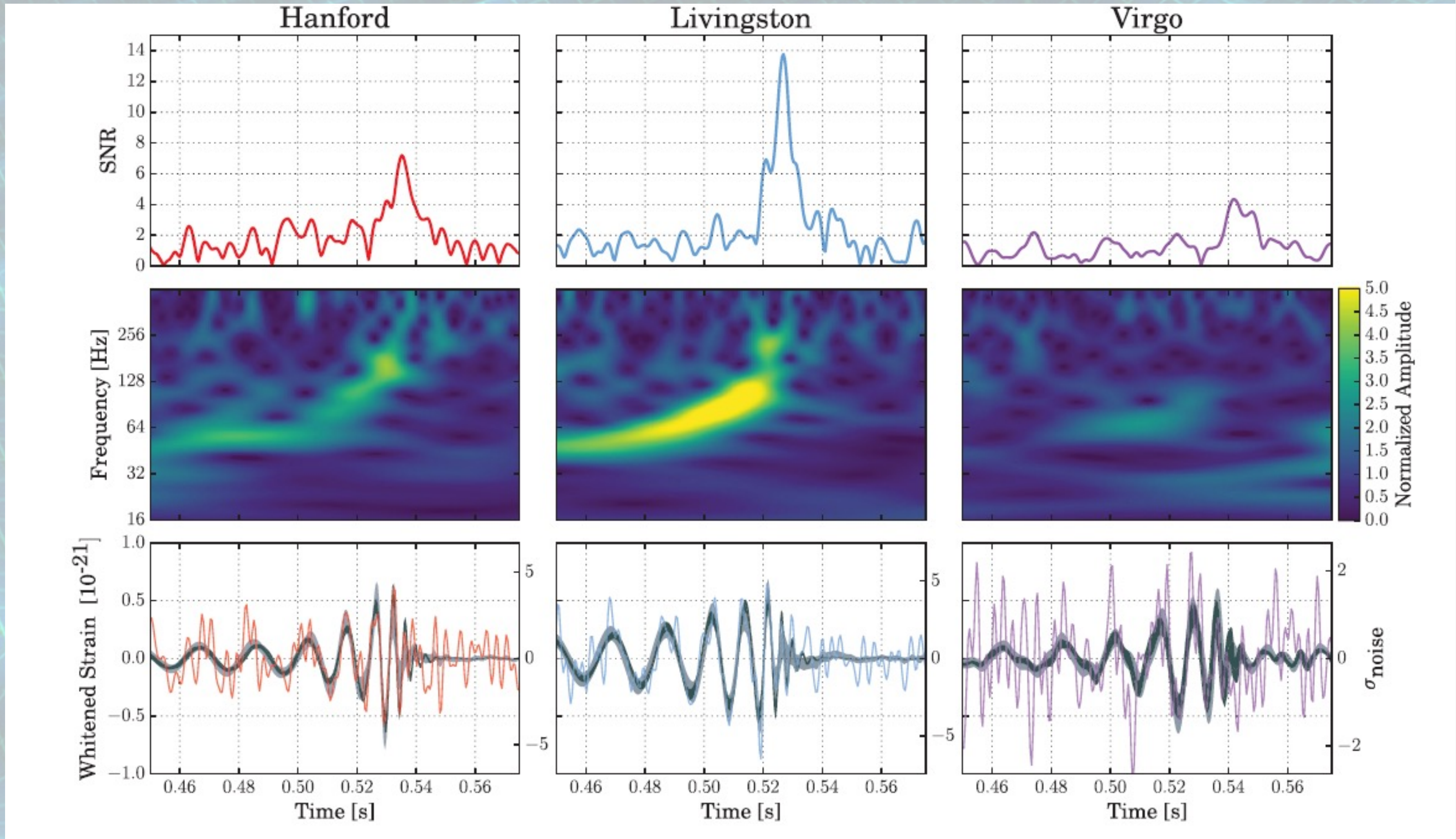
DOI: 10.1103/PhysRevLett.116.061102

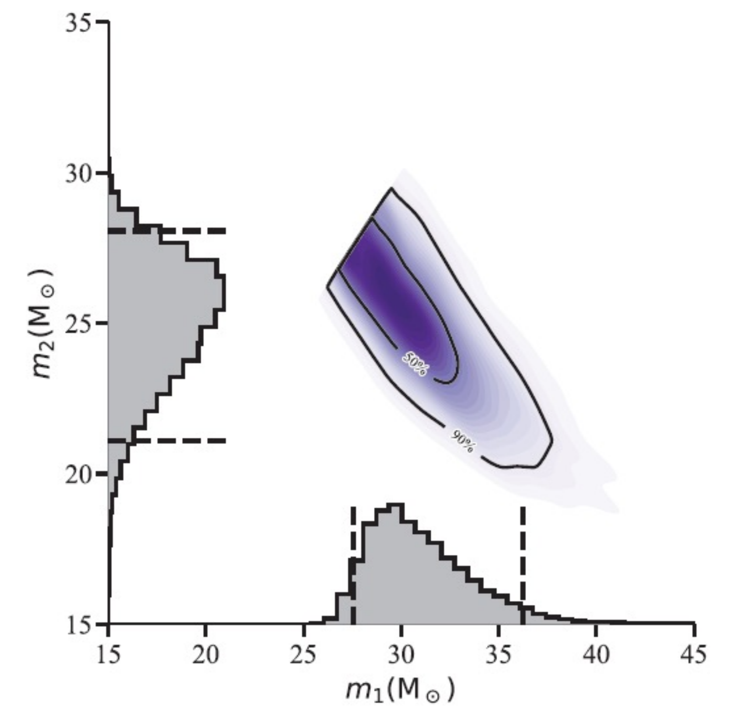


GW151226
Abbott+16, PRL116,24

GW170814: the first «triple» event

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



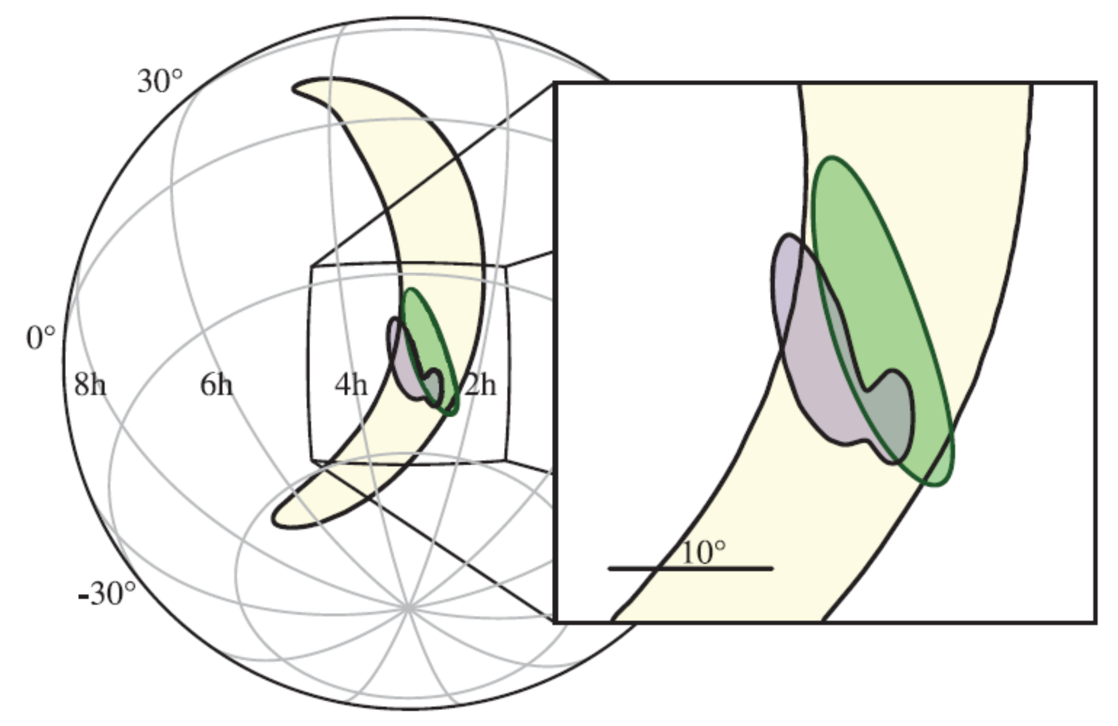


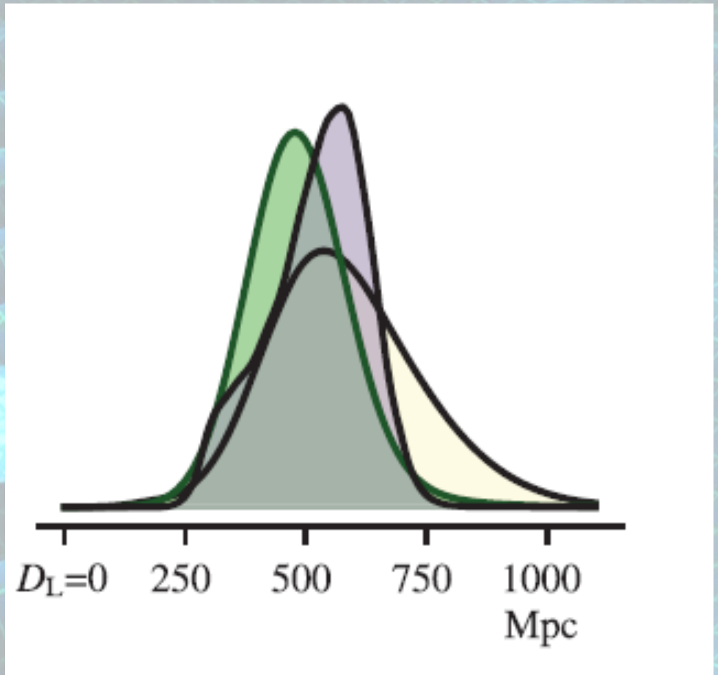
Abbott et al 2017, PRL, 119, 141101

The key to localization

- Using only LIGO detectors → 1160 deg2
- Adding Virgo → 100 deg2
- Full analysis → 60 deg2

- Credible volume (and # of galaxies
$71x10^6$ Mpc^3 → $2.1x10^6$ Mpc^3)



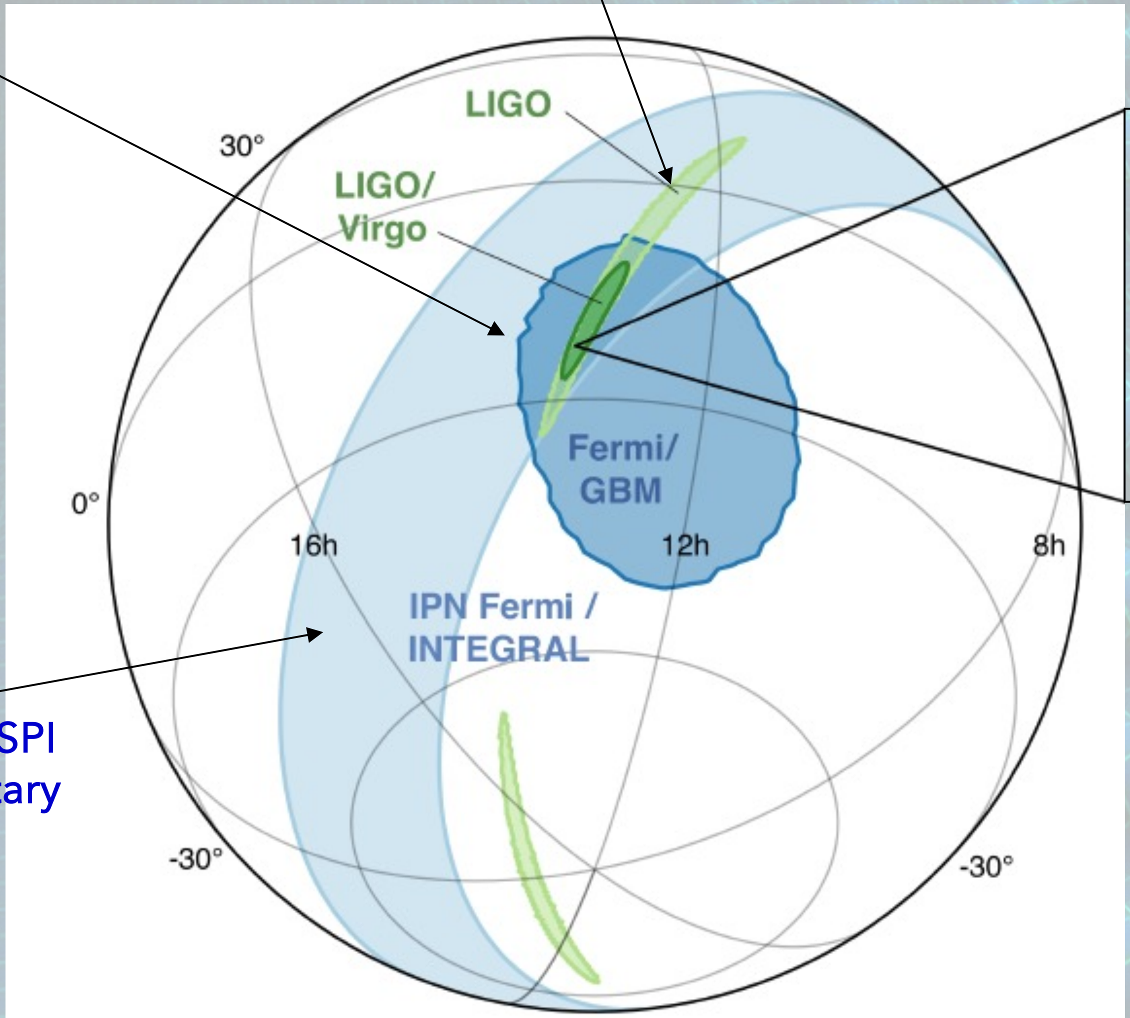


Abbott et al 2017, PRL, 119, 141101

The GW170817 event

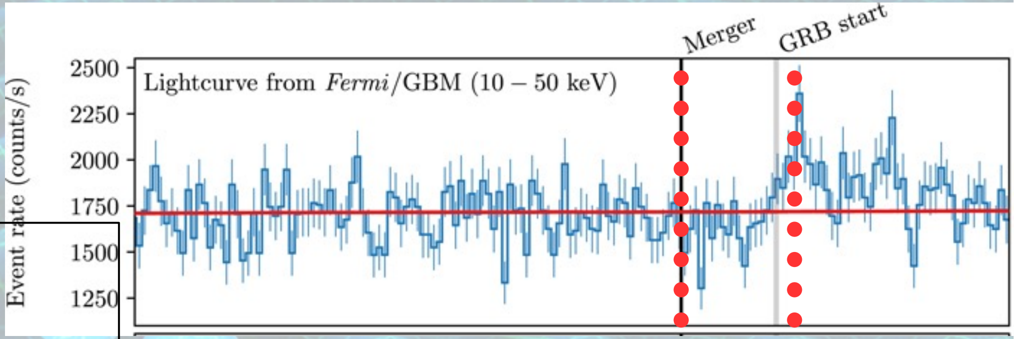
LIGO: 190 deg^2

Fermi GBM: 1100 deg^2

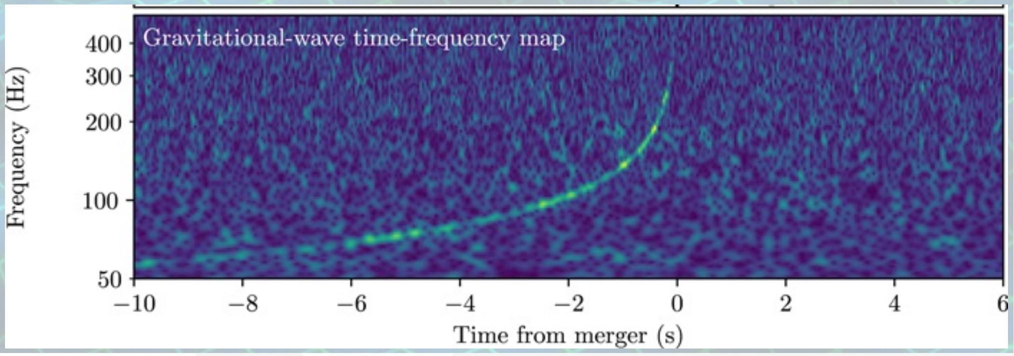


Fermi GBM
+
INTEGRAL SPI
(Interplanetary Network)
Additional constraints

LIGO
+
Virgo
=
31 deg^2

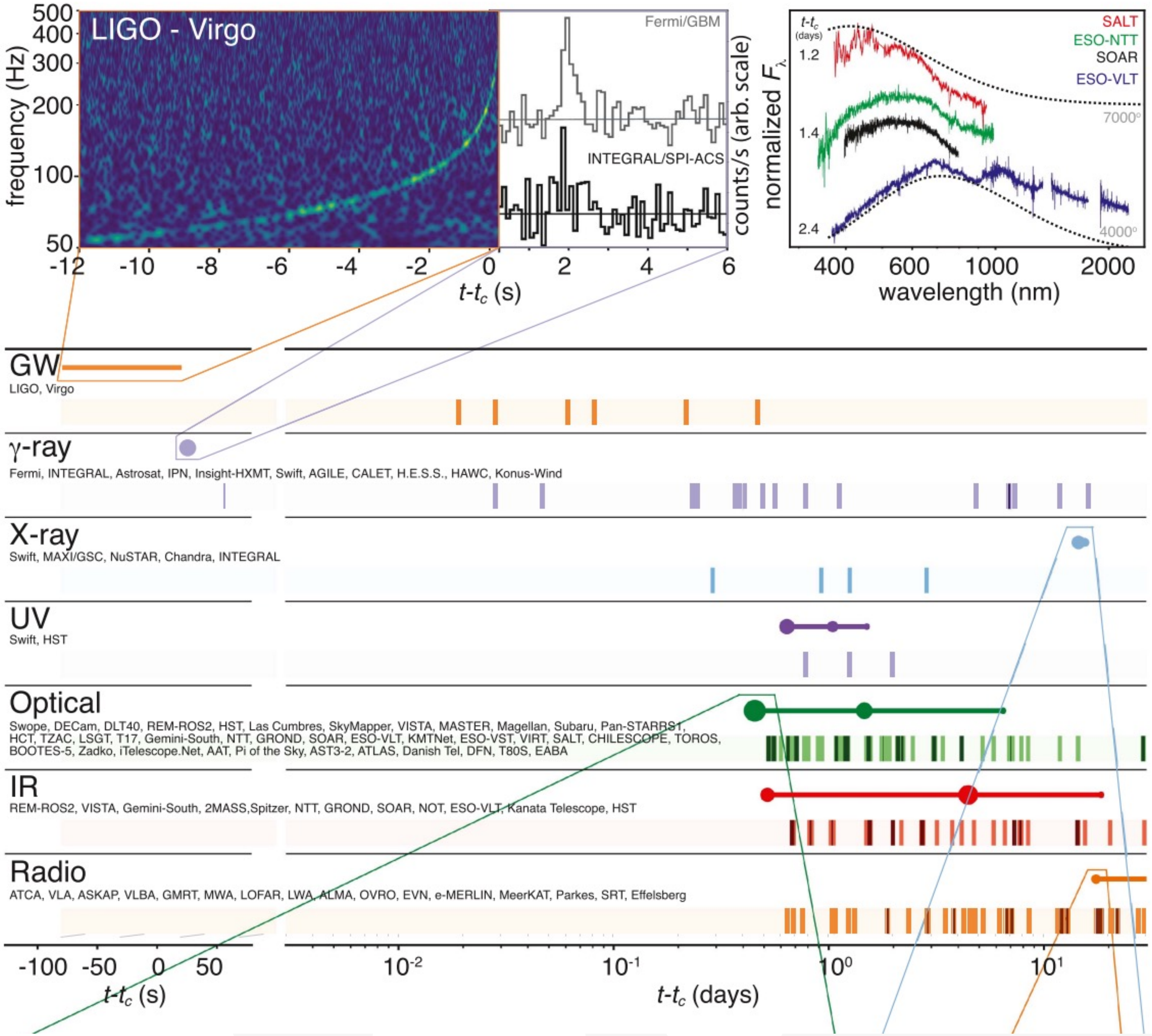


- ΔT ~ 1.7 sec



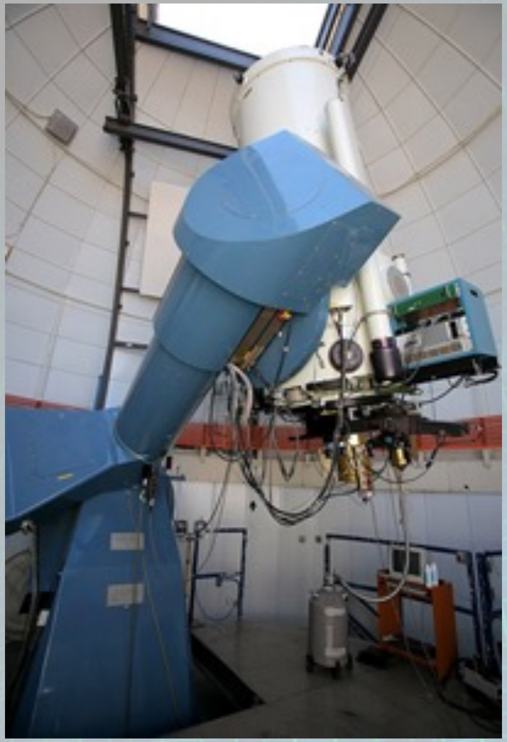
Abbott et al 2017, PRL, 119, 161101

GW170817:
the EM follow-up

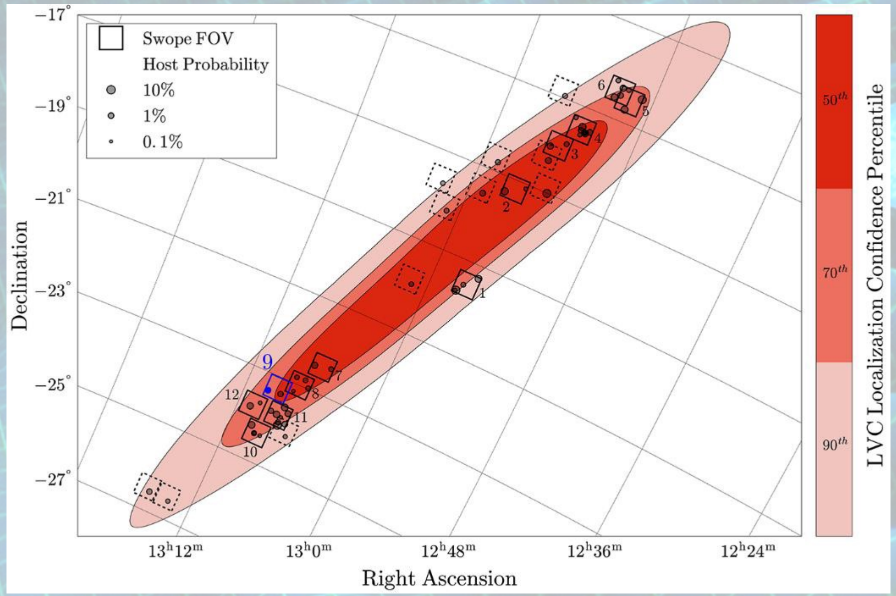


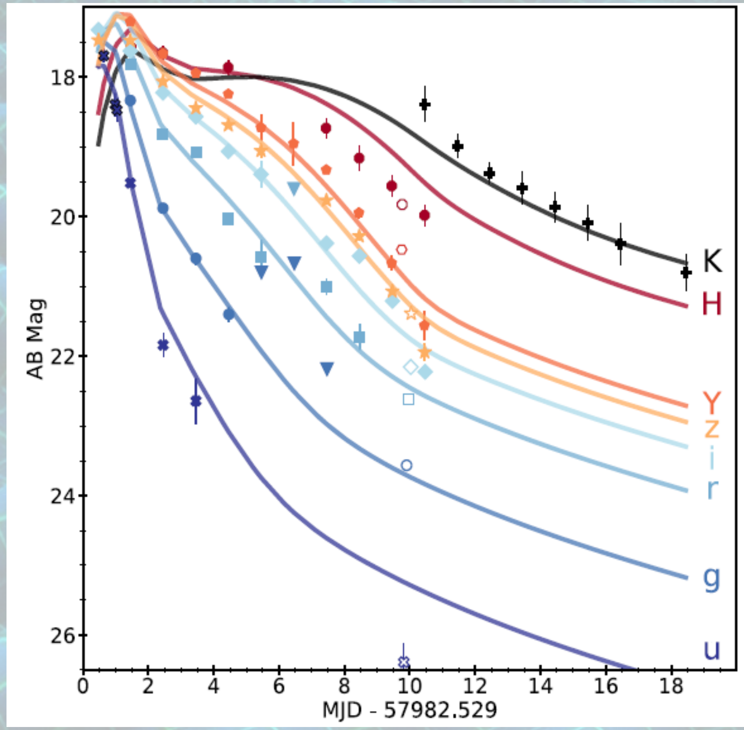
Abbott et al 2017, ApJL 848, 12

GW170817: the optical transient



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

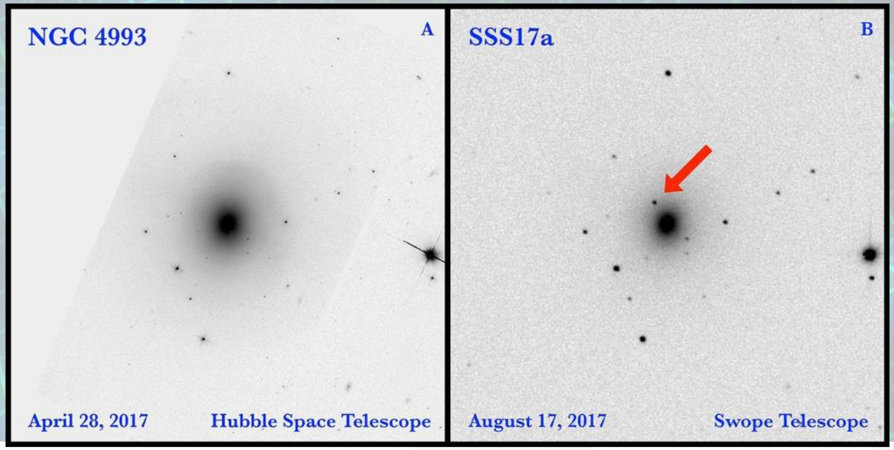




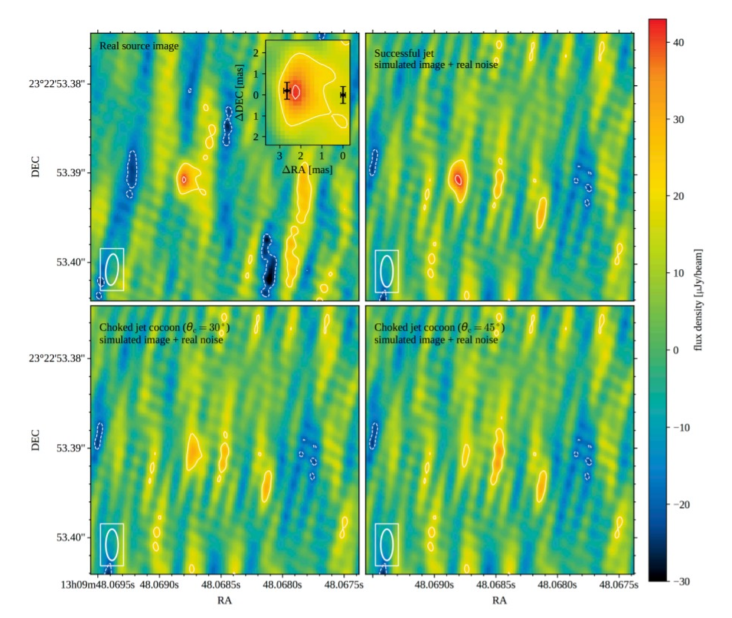
Cowperthwaite et al. 2017

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

- *(Coulter et al. 2017)*

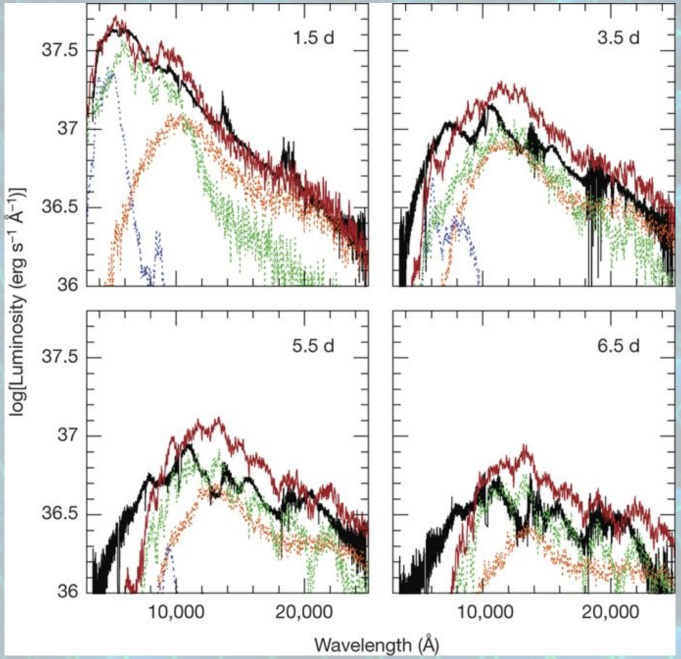


GW170817: (some) lesson learned



GRB Physics

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



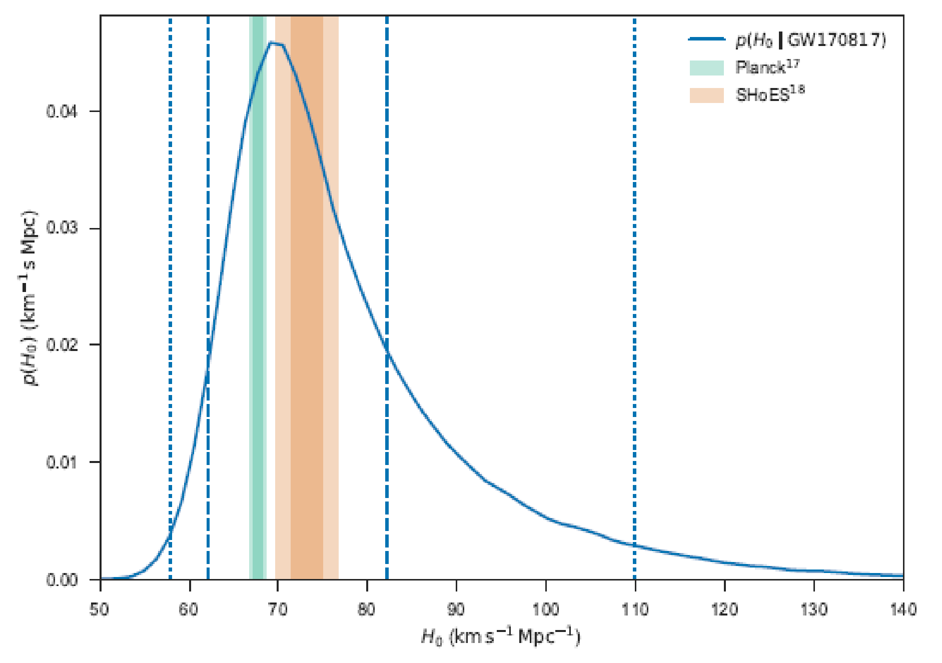
R-process nucleosynthesis

e.g. Pian et al. 2017, Nature, 551,67

GW as standard sirens

e.g. Abbott et al, Nature, 551,85

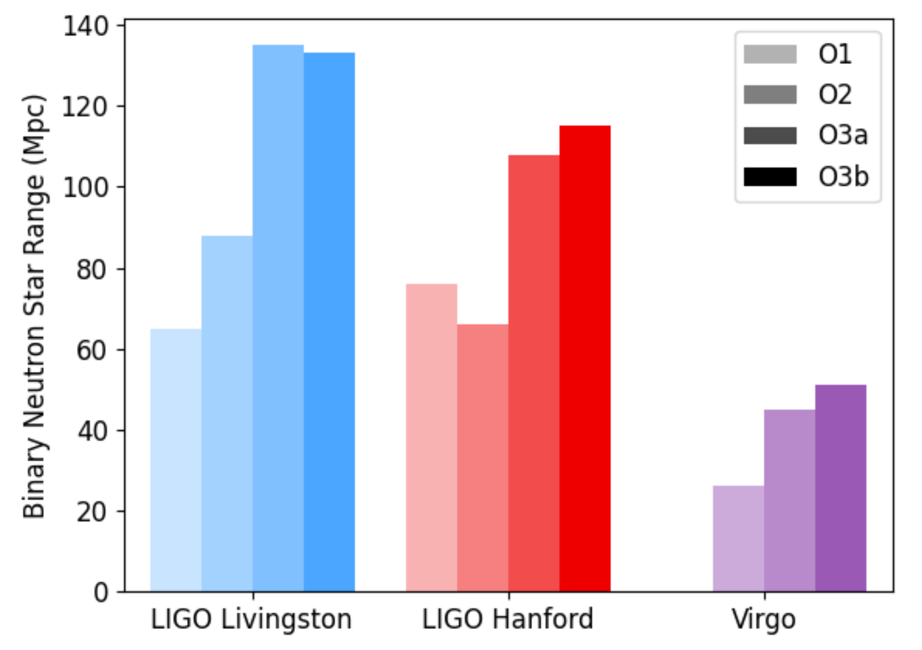
$H_0 = 70^{+12}_{-8}$ Km s^{-1} Mpc^{-1}



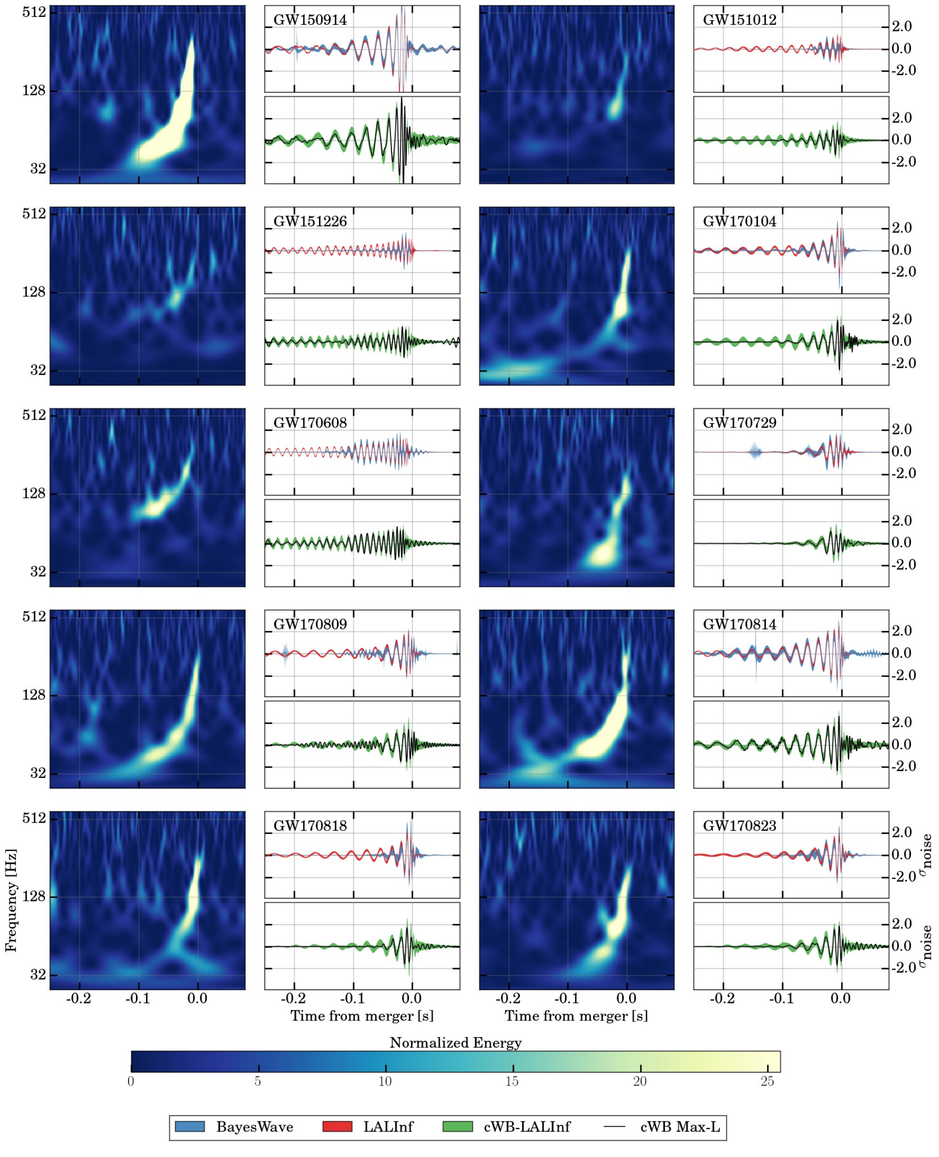
From single events to catalogs

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

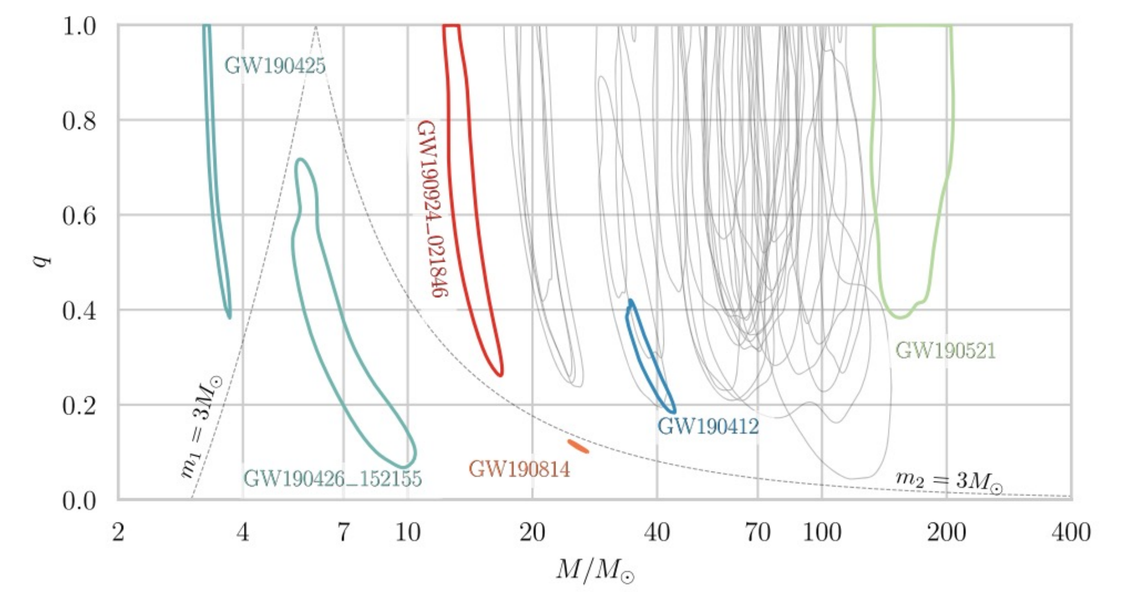
GWTC-2

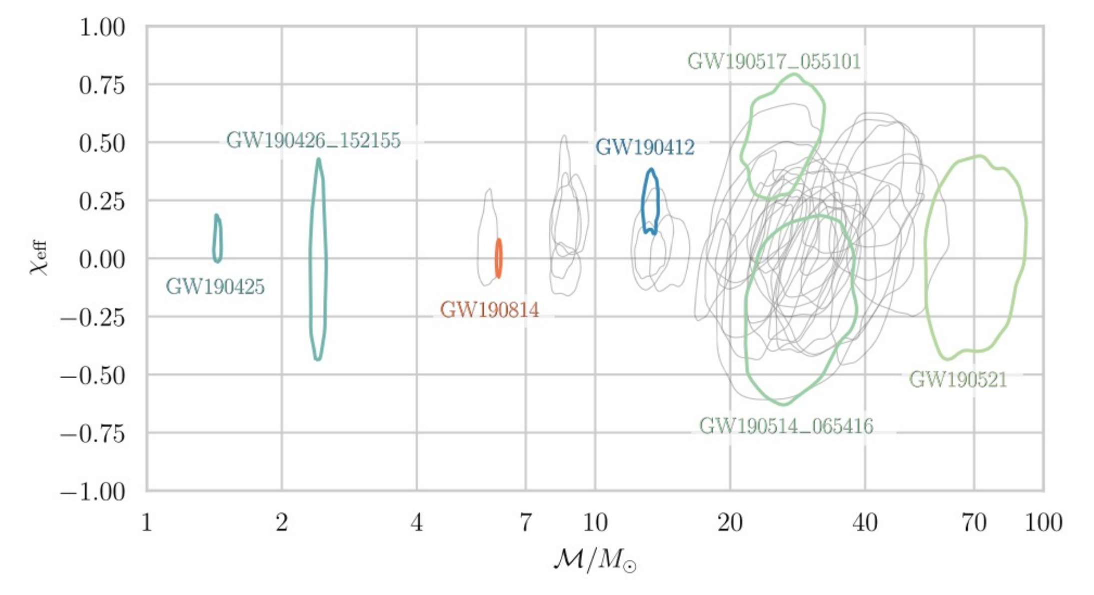
Gravitational Wave Transient Catalog 2 (GWTC-2)

- +39 events
- O1+O2+O3a detections
- Abbott et al 2020,
- (arxiv2010.14527)

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

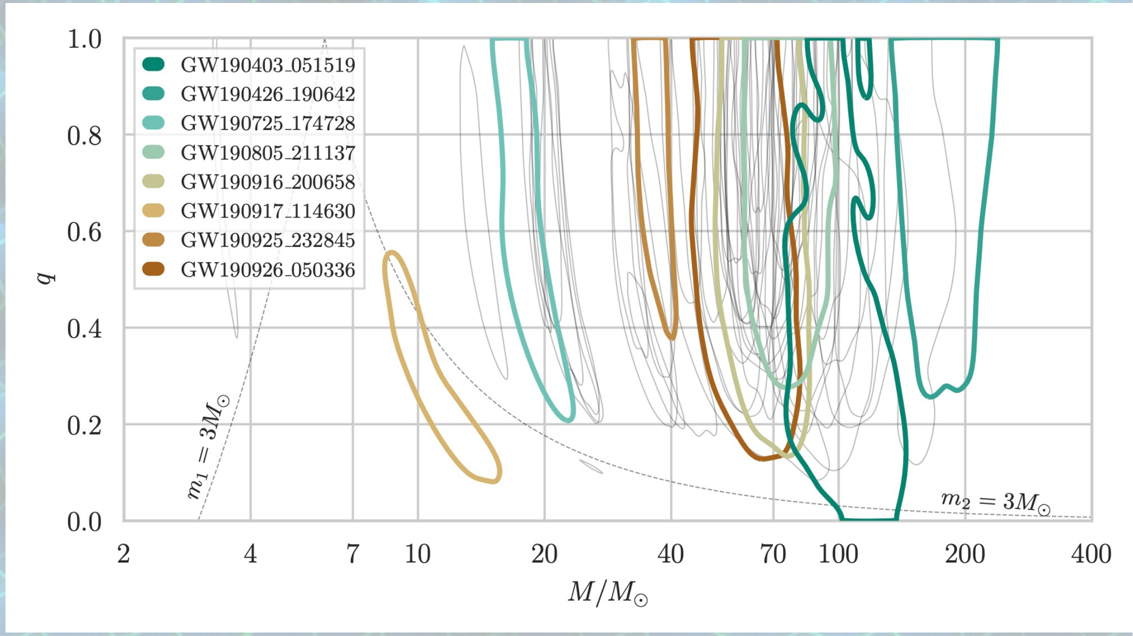
GWTC-2.1

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

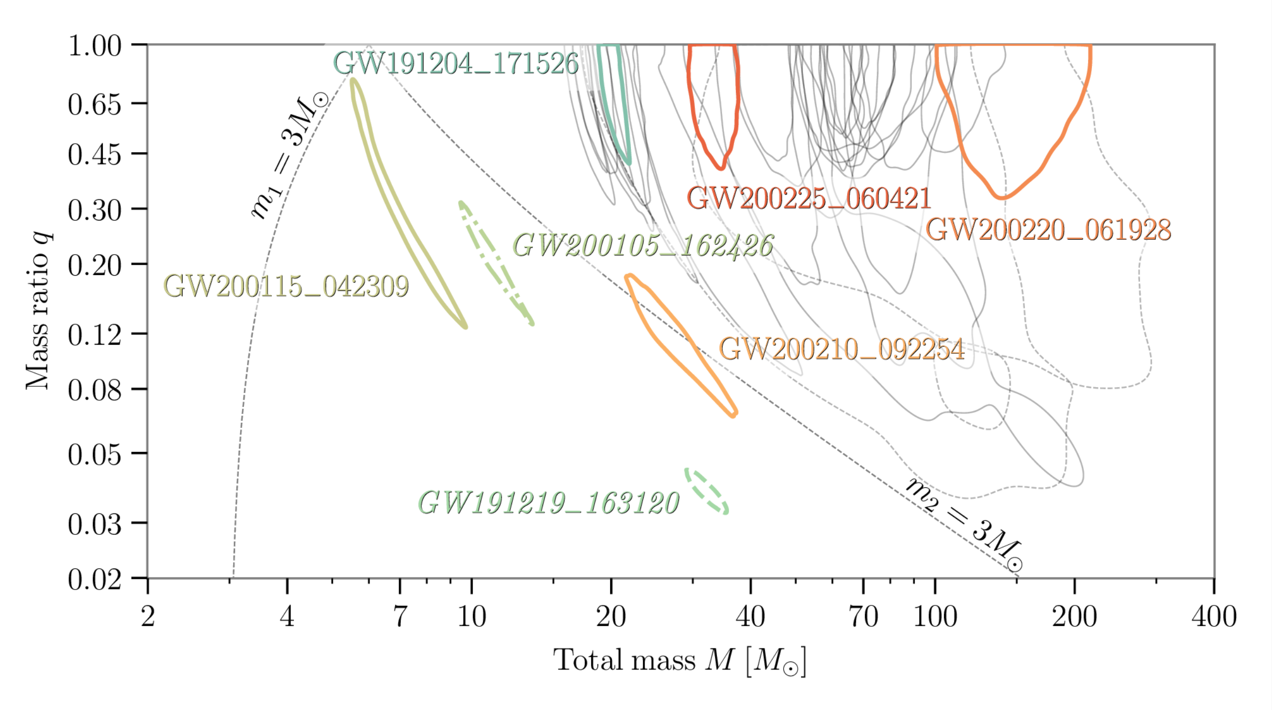
From single events to catalogs

Gravitational Wave Transient Catalog 3 (GWTC-3)

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

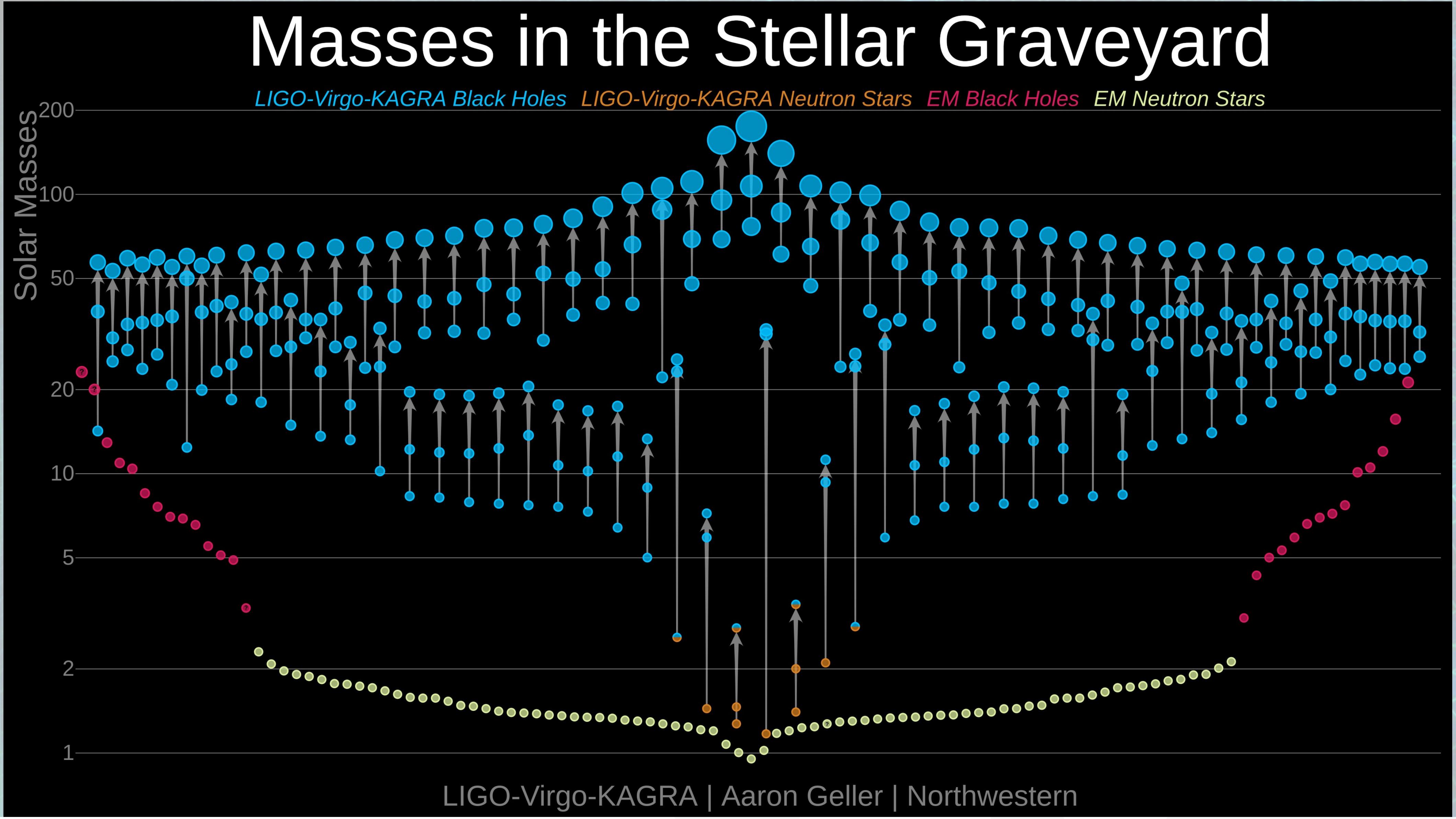
Highlights

- **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

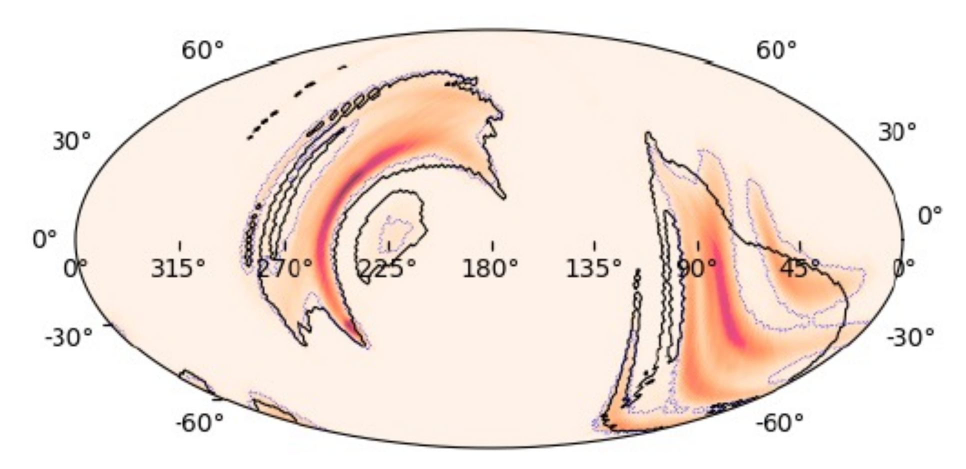
Masses in GWTC-3

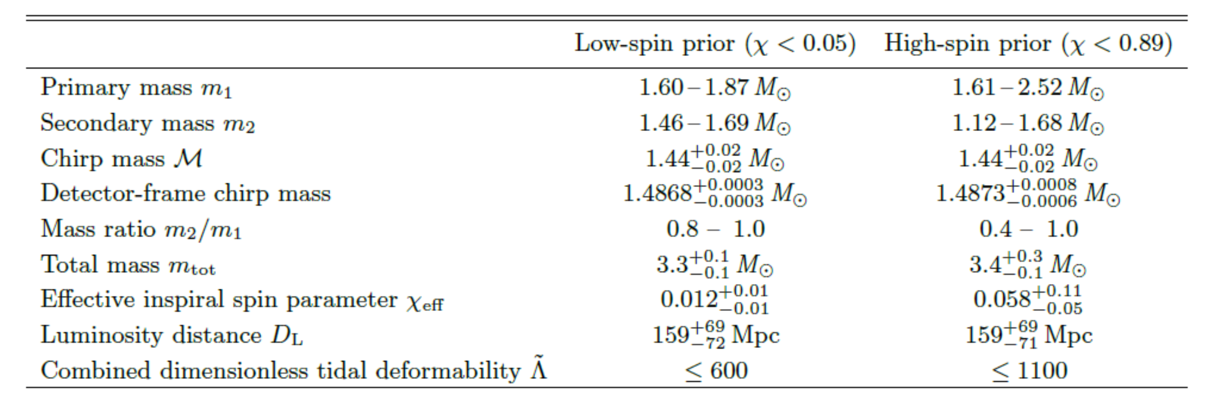


GW190425, the other BNS

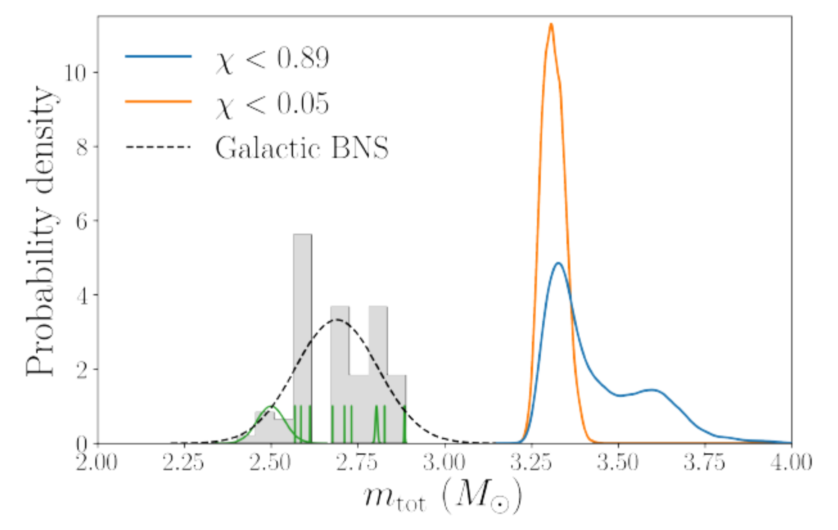
- Detected by LIGO L1 only at 8:18 (H1 offline, V1 SNR low)
- 1 detector-→ poor localization ($10000 deg^2$ → $8200 deg^2$)

- 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



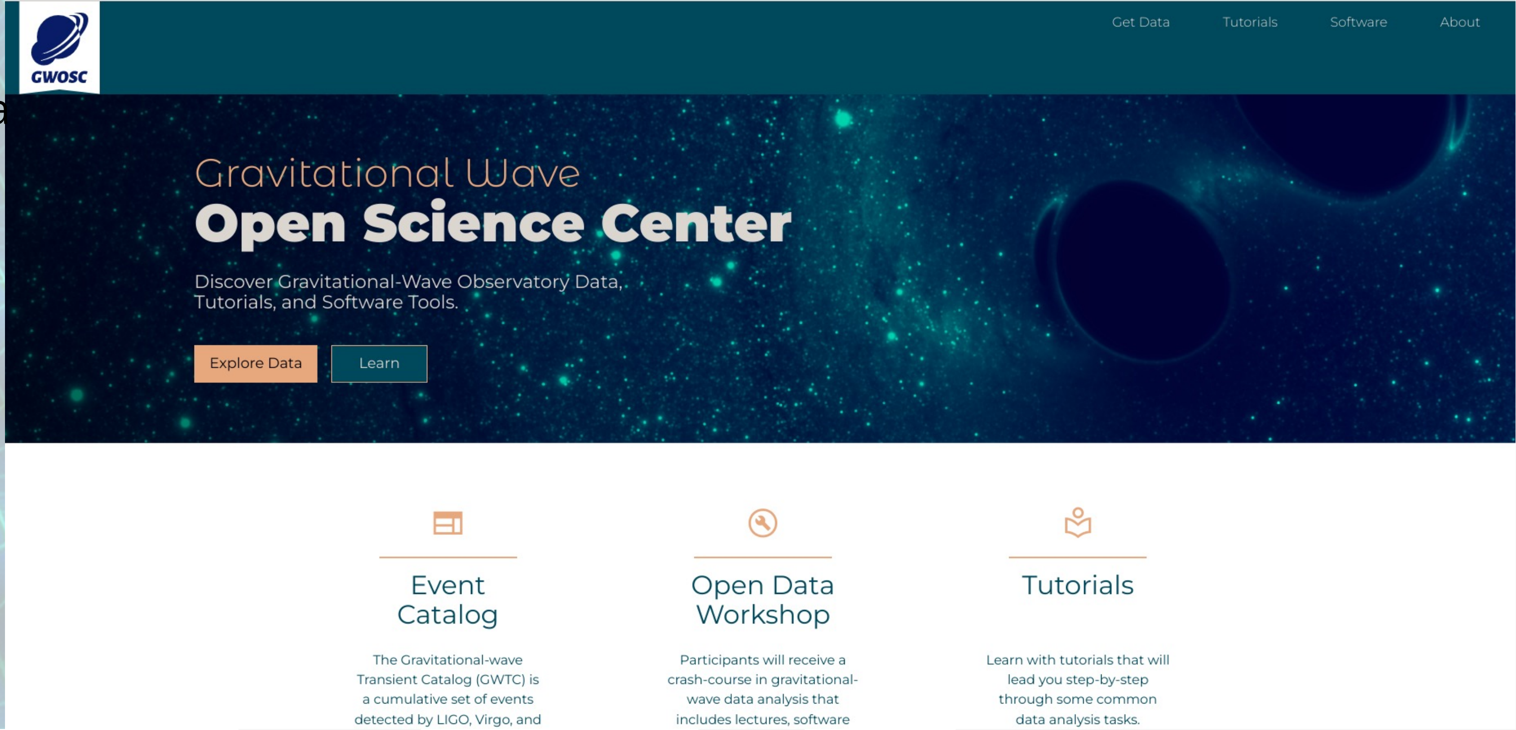
Abbott et al, 2020, ApJL, 892,1

Where to get the data?

→ GW data hosted at Gravitational wave Open Science Center

- GW related to events
- GW "bulk" data
  - Bulk datasets of observing runs
  - Publicly releases after 18 months from the end of the run
  - Full O3 data published

- Supporting documentation and tools
  - Help the external community in using data
  - Lots of tutorials
  - Open Data Workshops



Gravitational Wave
Open Science Center

Discover Gravitational-Wave Observatory Data, Tutorials, and Software Tools.

Event Catalog

The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of events detected by LIGO, Virgo, and

Open Data Workshop

Participants will receive a crash-course in gravitational-wave data analysis that includes lectures, software

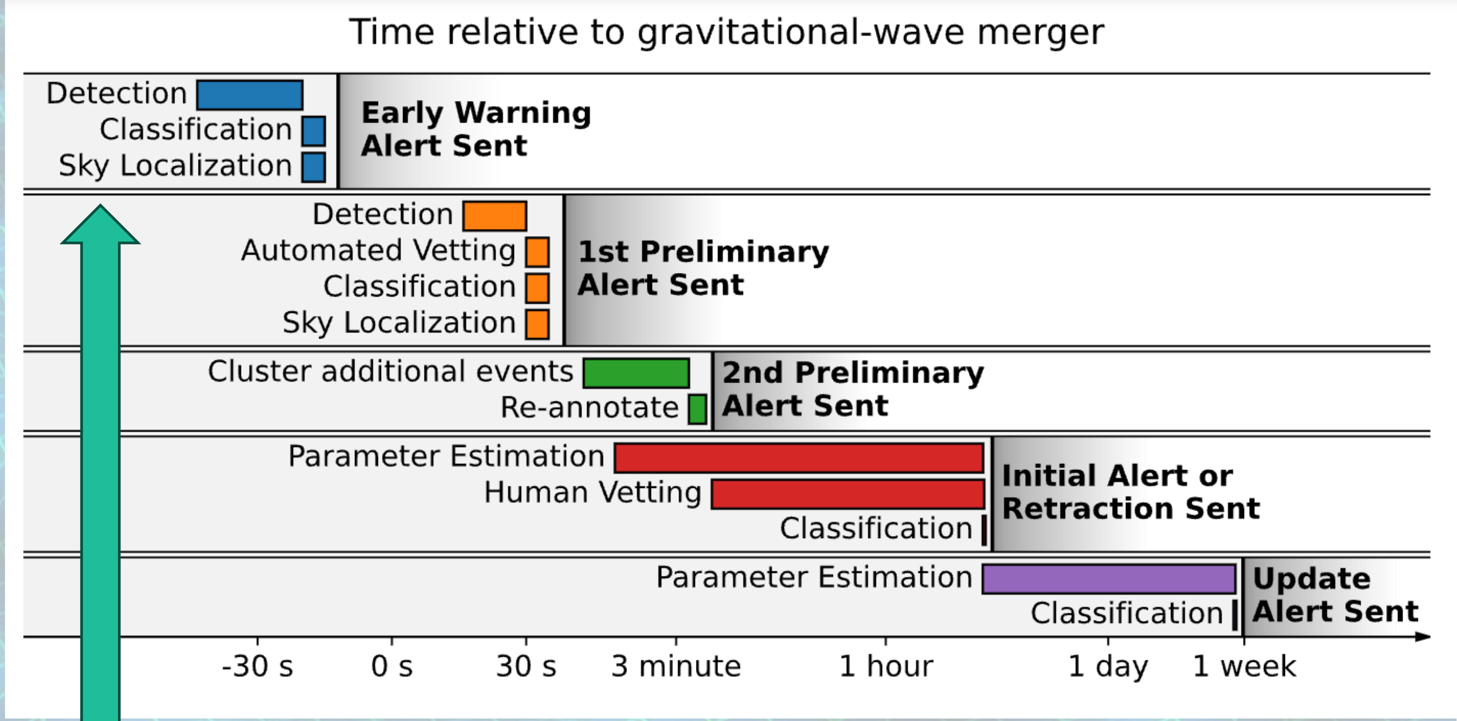
Tutorials

Learn with tutorials that will lead you step-by-step through some common data analysis tasks.

https://gwosc.org/

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)



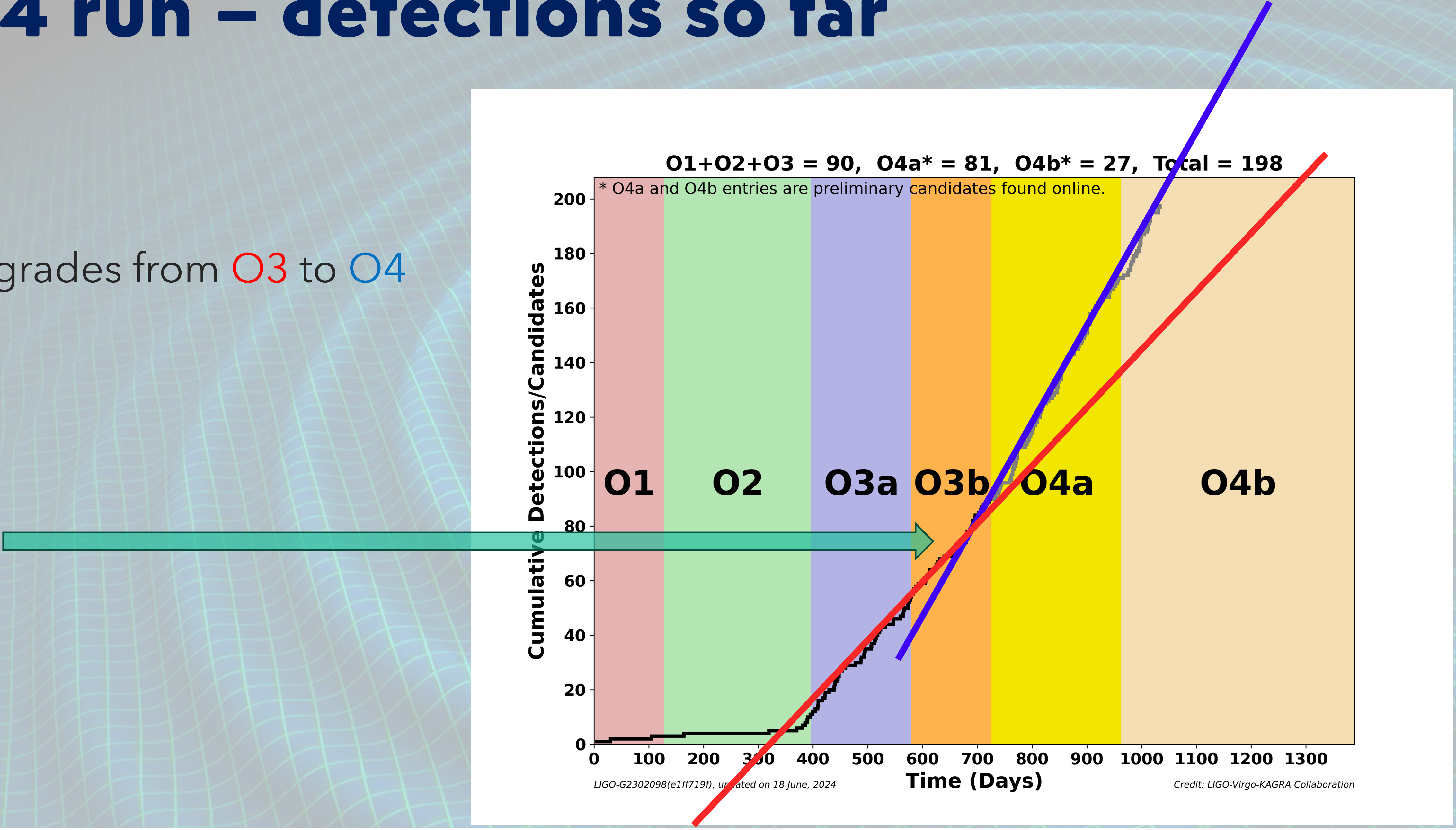
- From O3: public alerts
  - Preliminary GCN Notice within minutes
  - Rapid Response Team confirms or retracts
  - More details in following GCNs
  - Available at the Gravitational Wave Event Database (GraceDB) website (https://graced.ligo.org)

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



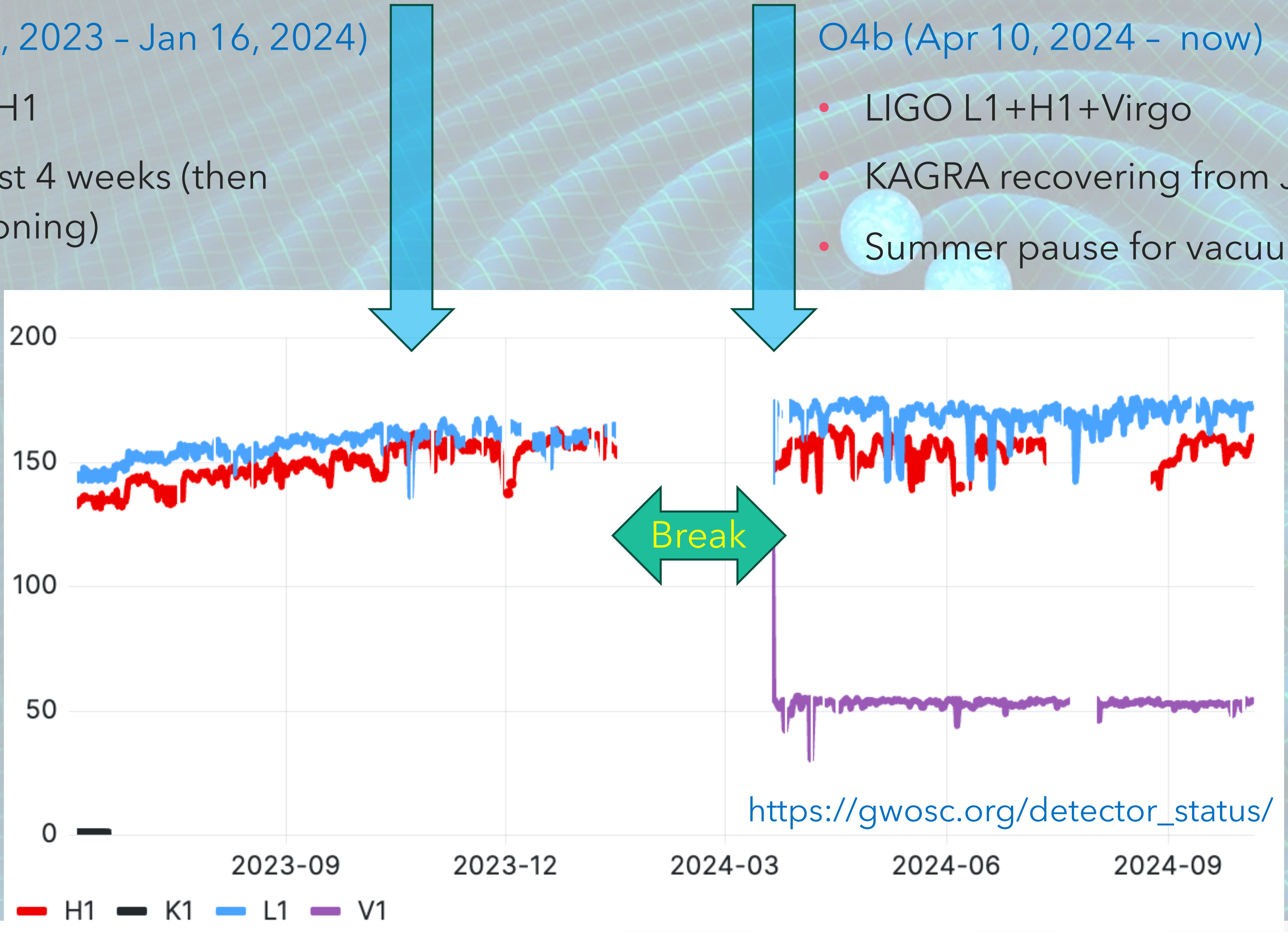
O4 run Timeline (so far)

O4a (May 24, 2023 – Jan 16, 2024)

- LIGO L1+H1
- KAGRA first 4 weeks (then commissioning)

O4b (Apr 10, 2024 – now)

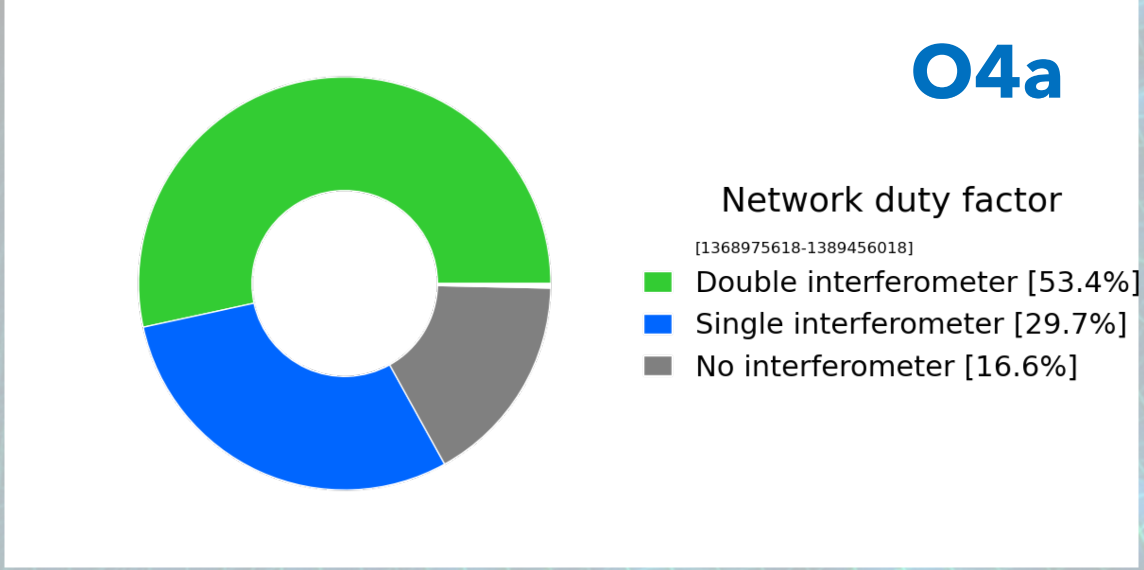
- LIGO L1+H1+Virgo
- KAGRA recovering from Jan 1 Earthquake
- Summer pause for vacuum intervention

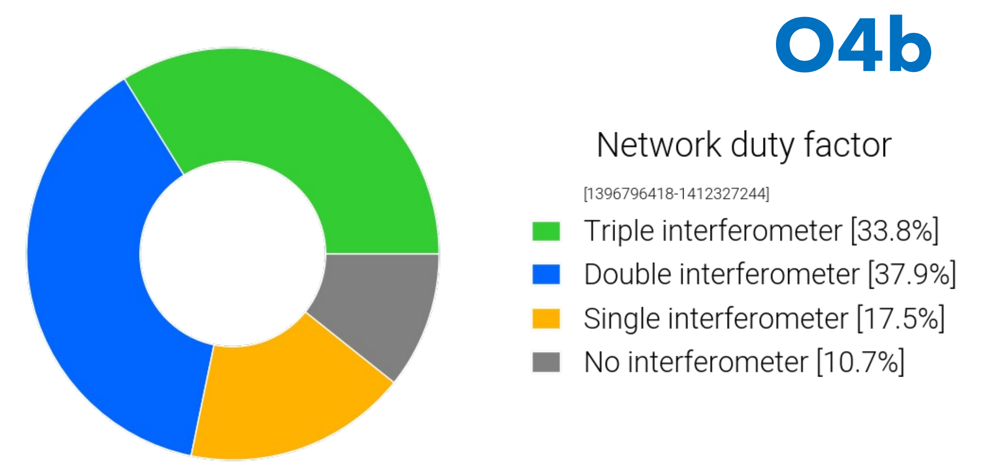


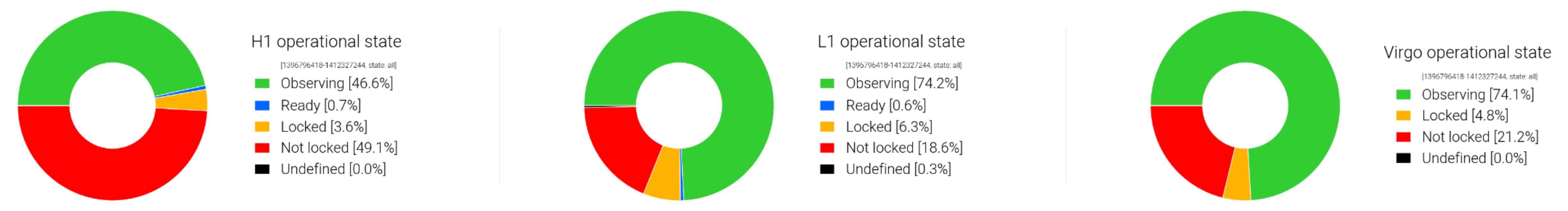
https://gwosc.org/detector_status/

O4 extended to June 2025

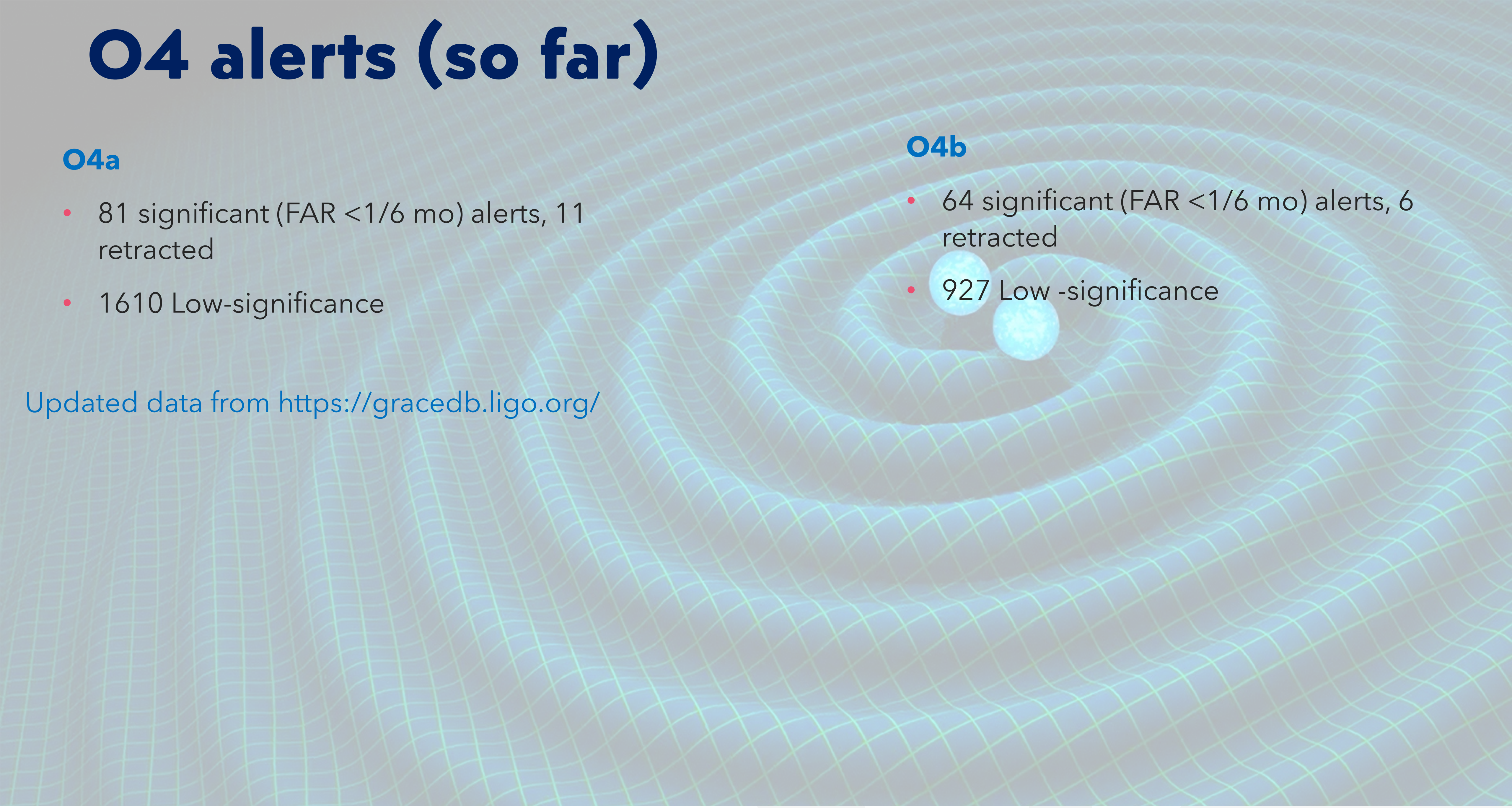
O4 Duty cycle


O4a


O4b



O4 alerts (so far)



O4a

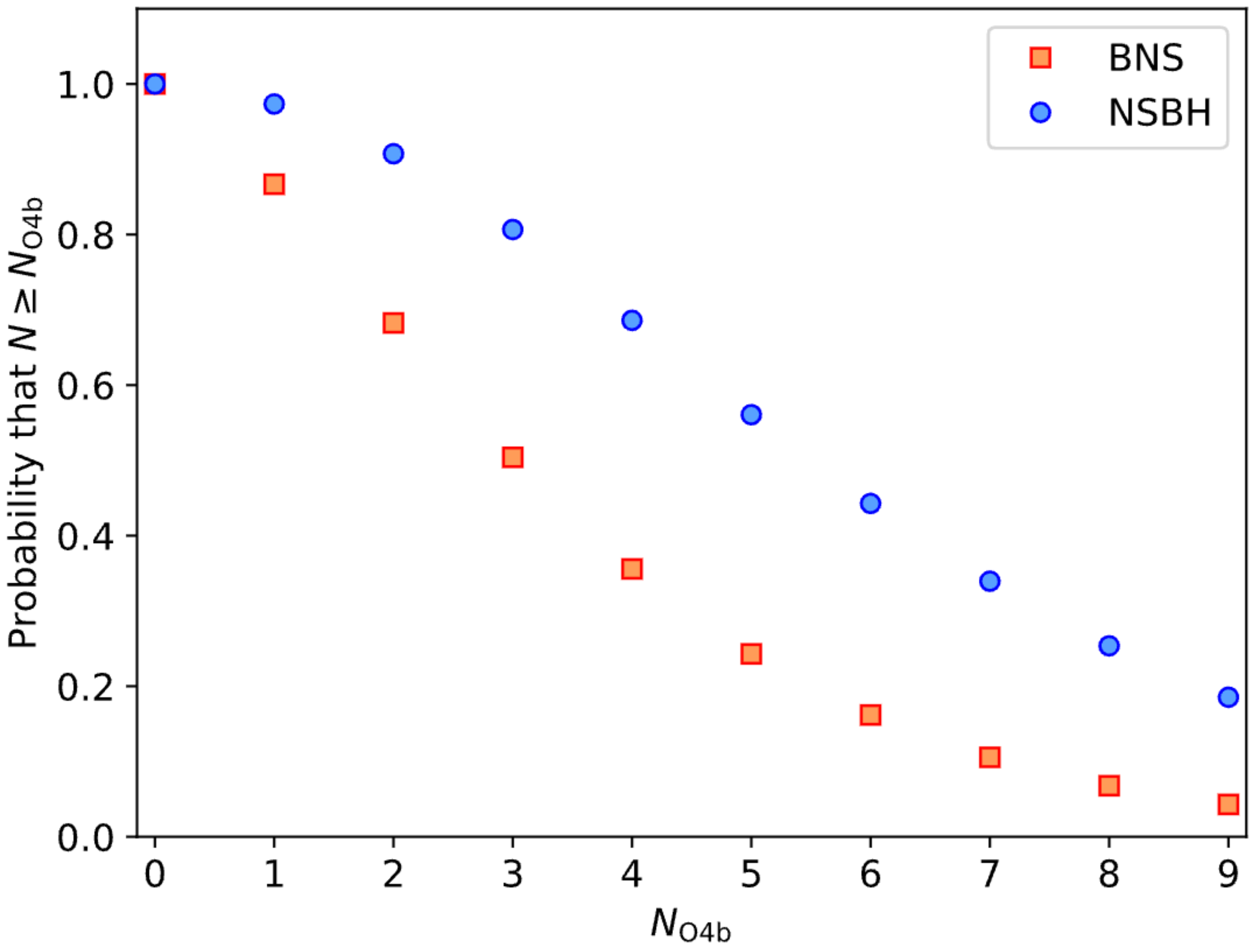
- 81 significant (FAR <1/6 mo) alerts, 11 retracted
- 1610 Low-significance

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

O4b

- 64 significant (FAR <1/6 mo) alerts, 6 retracted
- 927 Low -significance

O4 expectations



https://emfollow.docs.ligo.org/userguide/capabilities.html

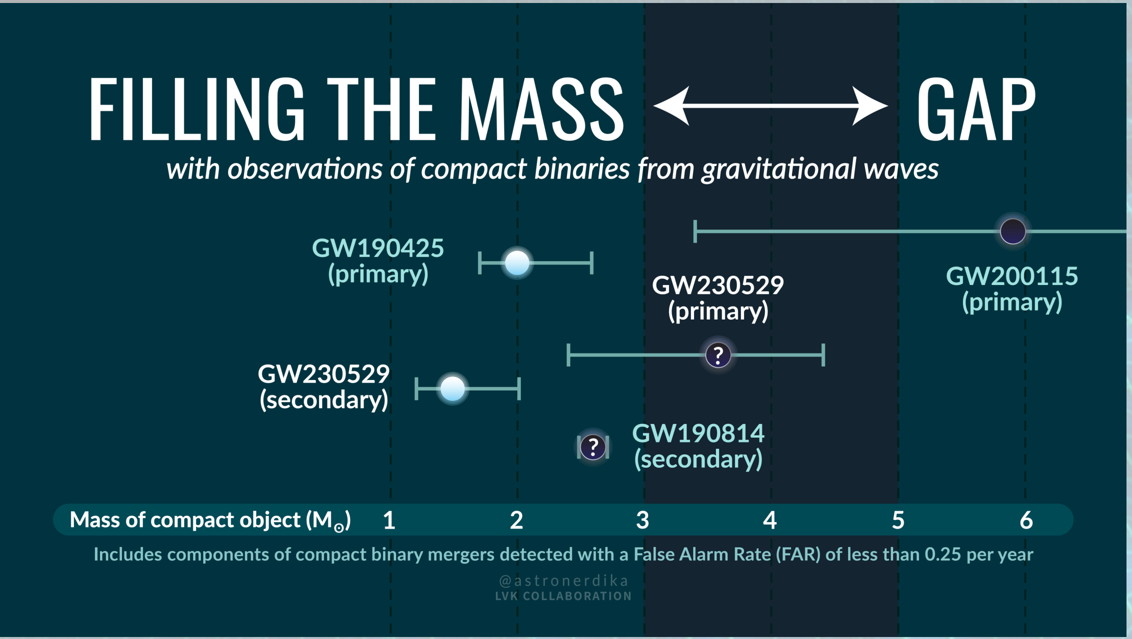
BNS

- 80% of observing at least 1 BNS
- BNS rate: 5 - 920 Gpc^{-3} yr^{-1}

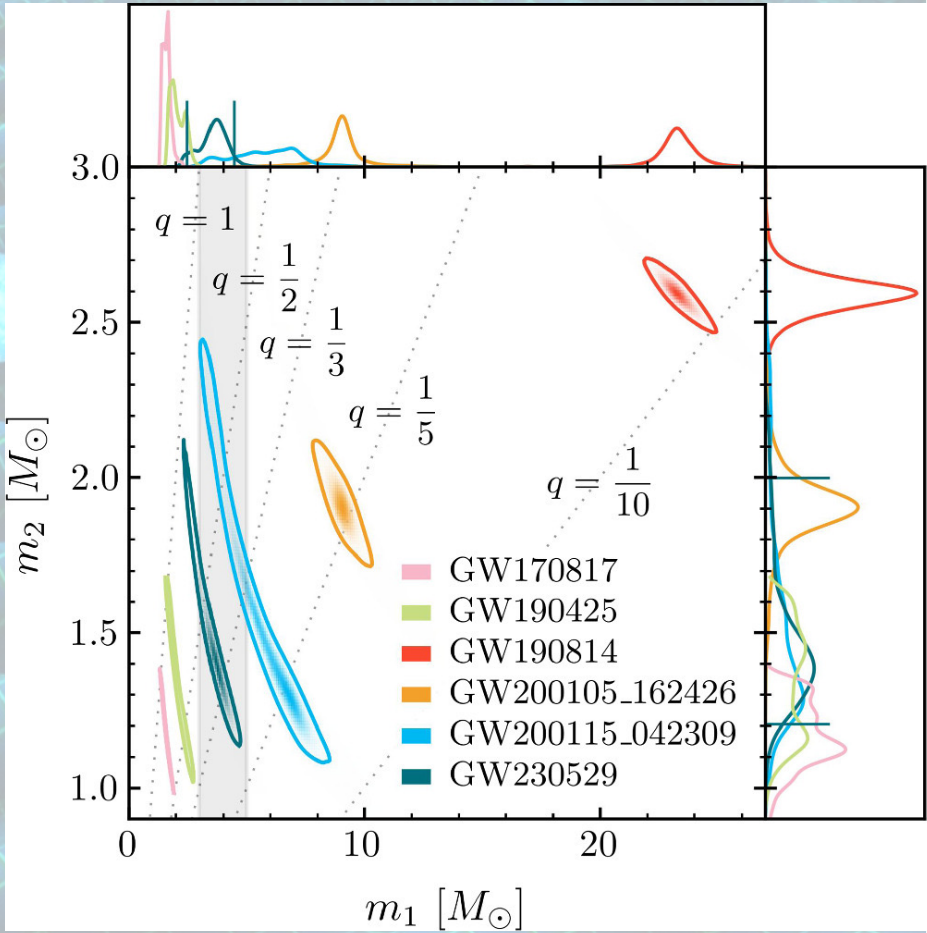
NSBH

- 94% of observing at least 1 BNS

O4 results: GW230529_181500



Credits: S. Gaudalage



Abac et al 2024, ApJL 970, 34

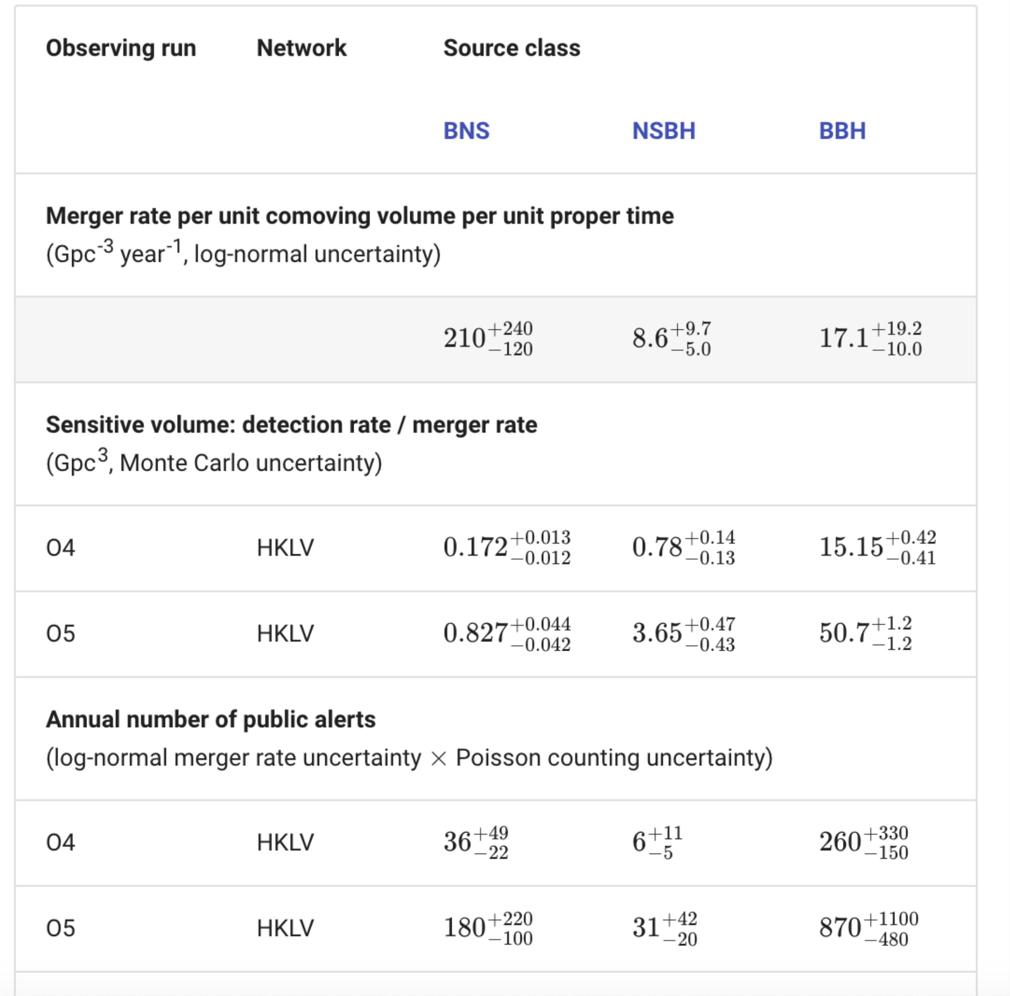
Highlights

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

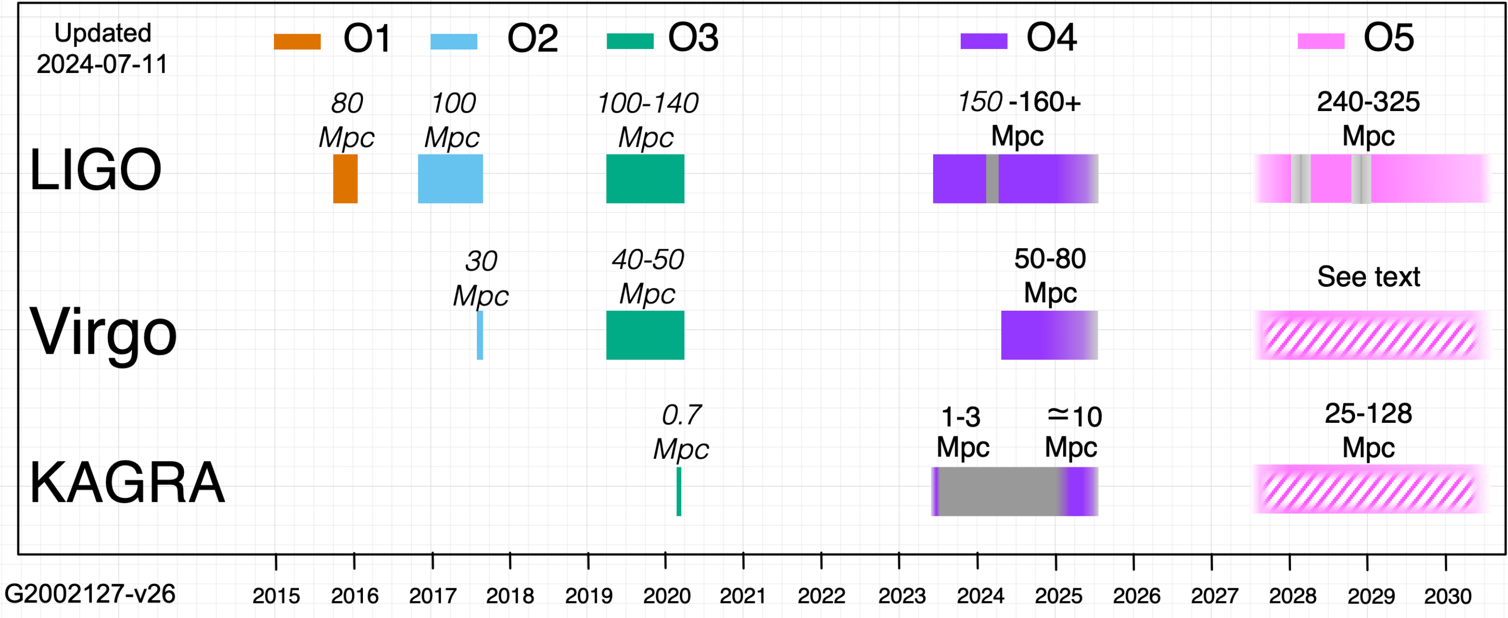
Formation & implication

- Isolated binary evolution
- Hierarchical formation

O5 expectations



Observing run	Network	Source class		
		BNS	NSBH	BBH
Merger rate per unit comoving volume per unit proper time (Gpc^{-3} year^{-1}, log-normal uncertainty)				
		210^{+240}_{-120}	$8.6^{+9.7}_{-5.0}$	$17.1^{+19.2}_{-10.0}$
Sensitive volume: detection rate / merger rate (Gpc^{3}, Monte Carlo uncertainty)				
O4	HKLV	$0.172^{+0.013}_{-0.012}$	$0.78^{+0.14}_{-0.13}$	$15.15^{+0.42}_{-0.41}$
O5	HKLV	$0.827^{+0.044}_{-0.042}$	$3.65^{+0.47}_{-0.43}$	$50.7^{+1.2}_{-1.2}$
Annual number of public alerts (log-normal merger rate uncertainty × Poisson counting uncertainty)				
O4	HKLV	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	HKLV	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}

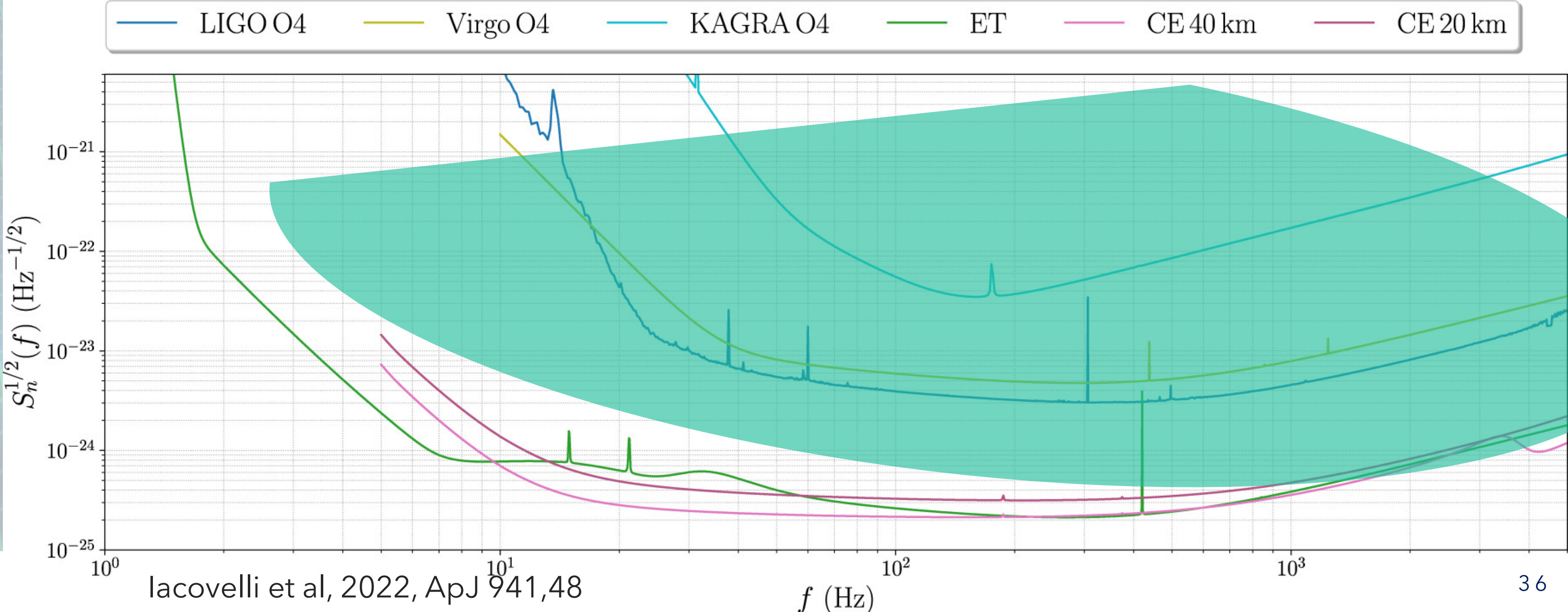


https://emfollow.docs.ligo.org/userguide/capabilities.html

Post-O5: From 2G to 3G

Post O5 upgrade plans

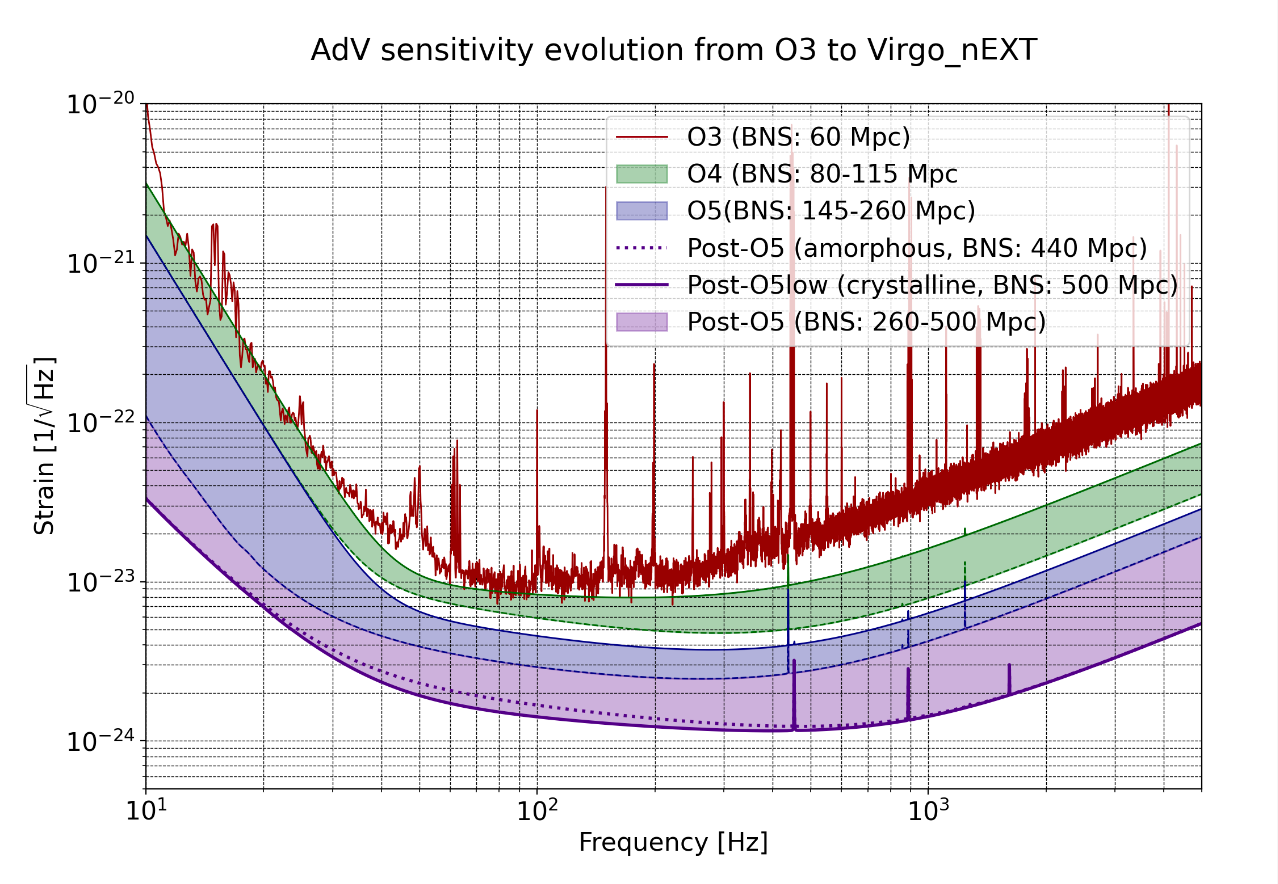
- Bridging the gap between current detectors and 3G
- Continue to observe for a decade after O5
- Reach 2x sensitivity wrt Advanced detectors
- Intermediate technology solution (no cryogeny, same 1064nm laser)
- Current programs: A# (LIGO), Virgo_nEXT



Iacovelli et al, 2022, ApJ 941,48

Virgo_nEXT

- Upgrade within the Advanced Virgo infrastructure
- Laser power O(MW) in cavities
- Reduce Coating Thermal noise
- Larger masses
- Better squeezing
- Better Low Frequency sensitivity (e.g. Newtonian Noise cencellation)
- Installation expected to start in 2028

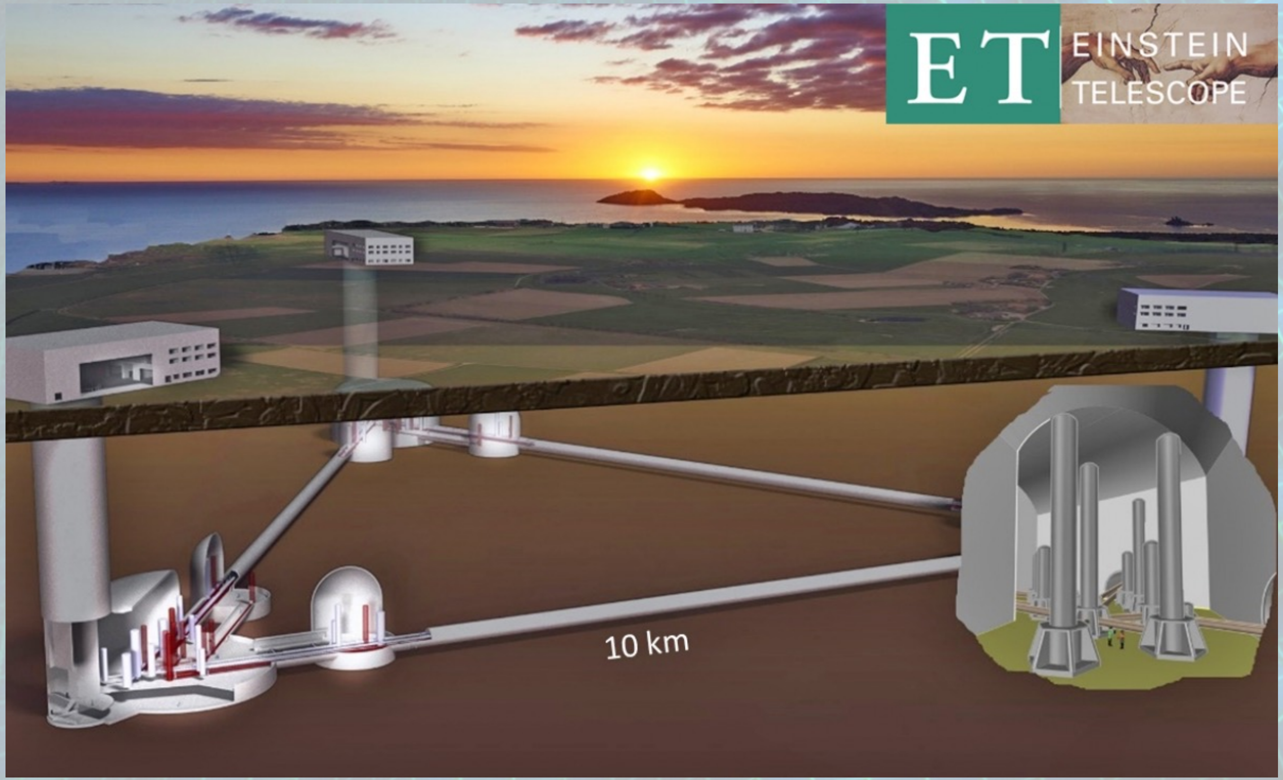


Virgo Collaboration, Post-O5 document (*VIR-0497A-22*)

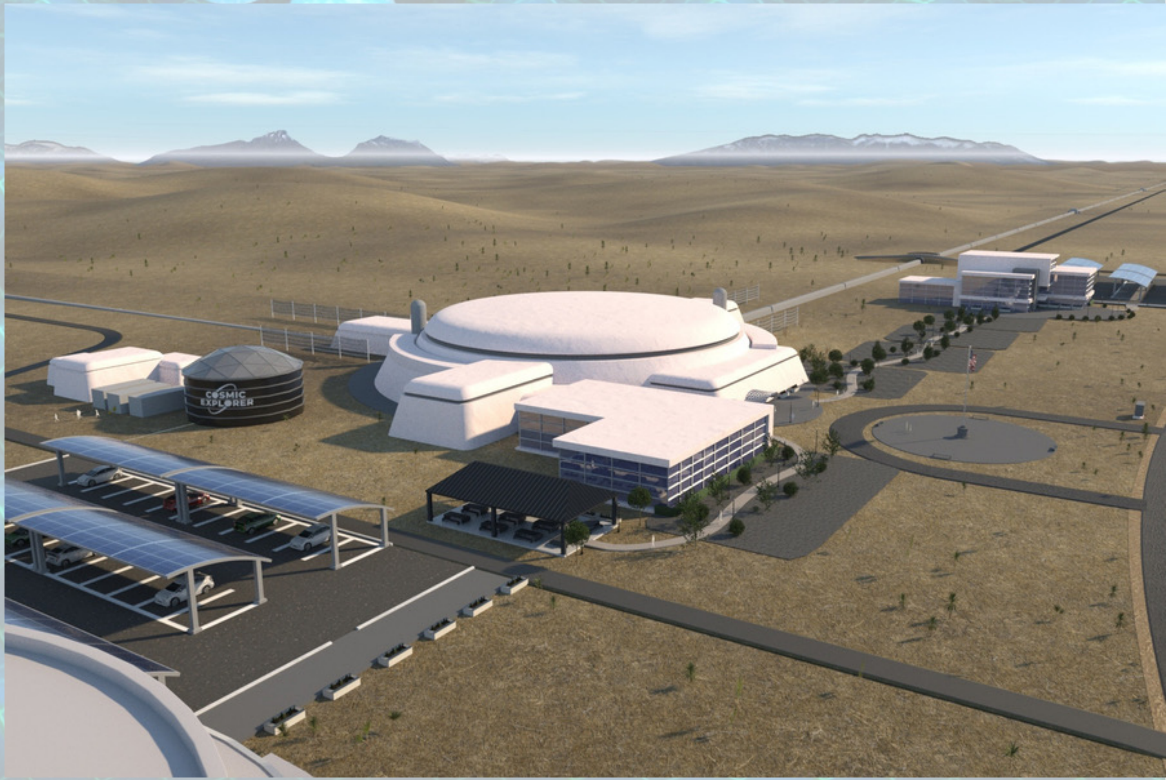
GW: the Third Generation

Einstein Telescope & Cosmic Explorer

- 10x sensitivity wrt LVK
- Extend to lower frequencies
- Built in mid 2030'



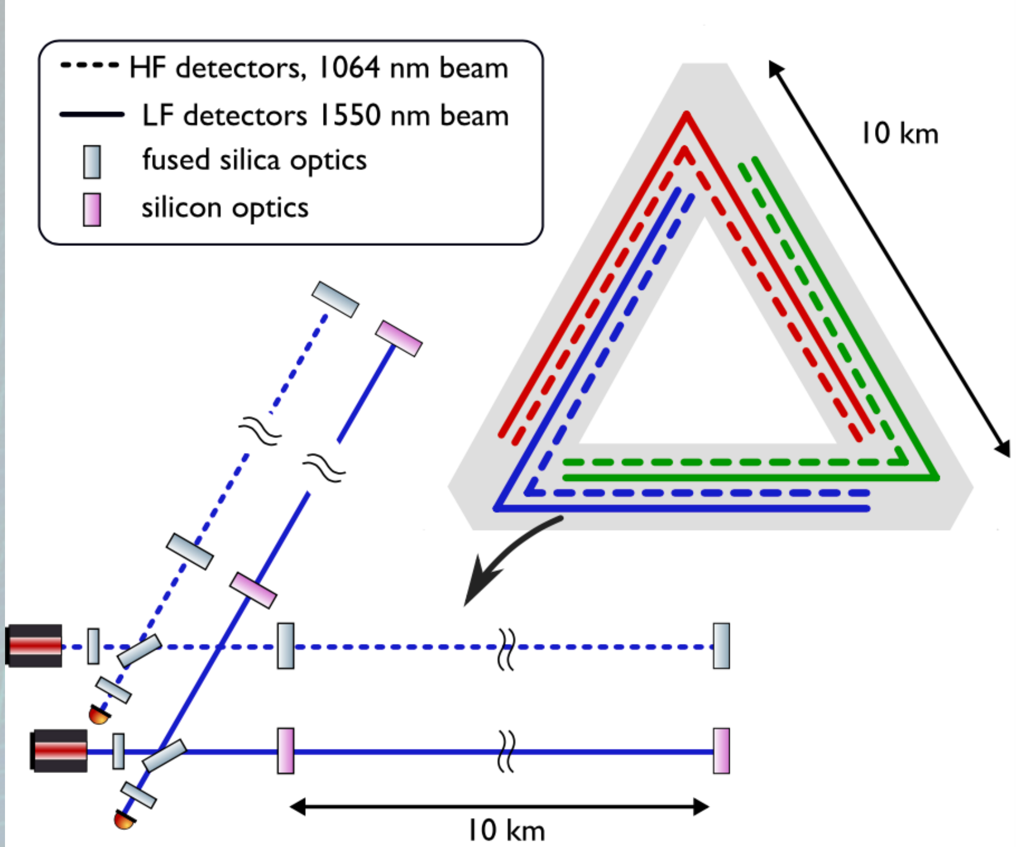
Credits: ET Collaboration



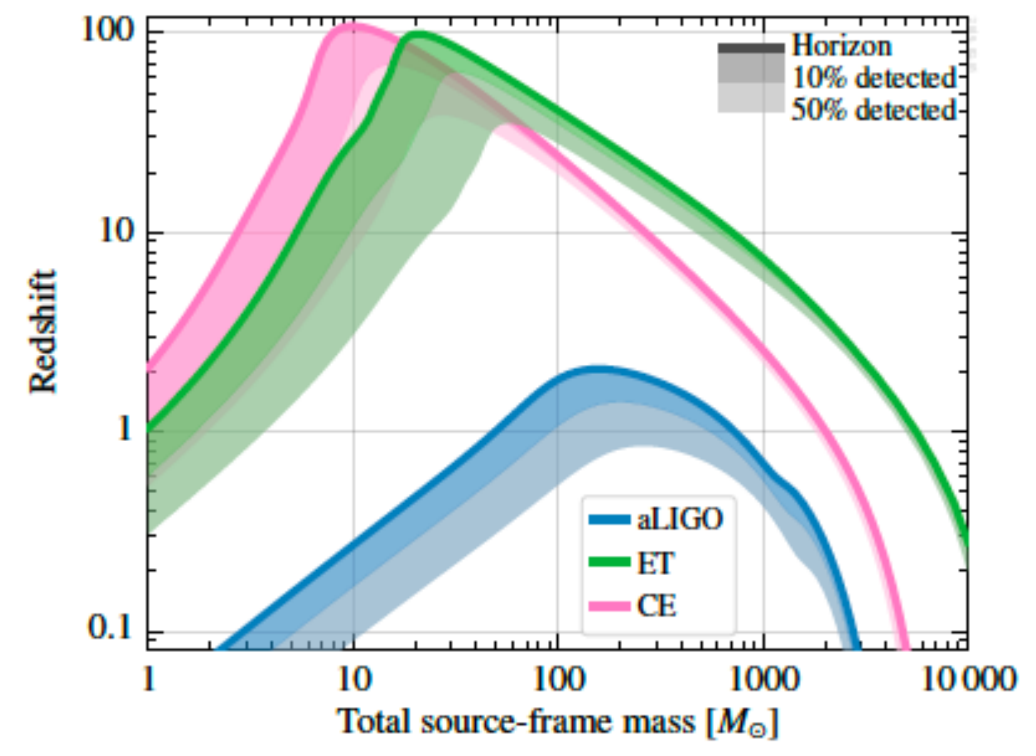
Credits: CE Collaboration

Einstein Telescope

- Xylophone configuration
- Also, 2 L shape under study (e.g. Branchesi et al 2024)

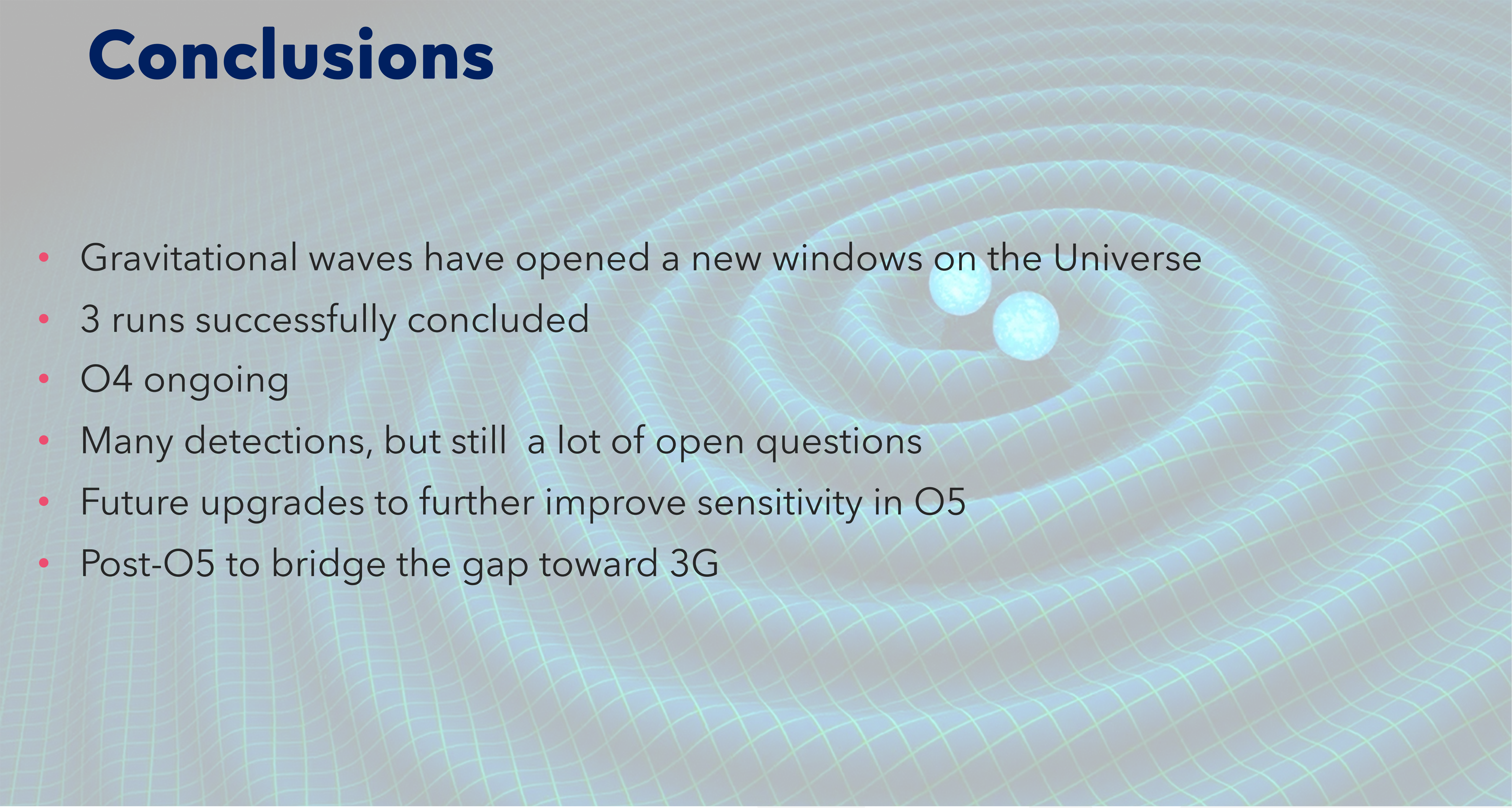


Credits: ET Collaboration



Maggiore et al, 2020, JCAP, 03, 50

Conclusions



- Gravitational waves have opened a new windows on the Universe
- 3 runs successfully concluded
- O4 ongoing
- Many detections, but still a lot of open questions
- Future upgrades to further improve sensitivity in O5
- Post-O5 to bridge the gap toward 3G

Thank you for your attention !