COMPACT BINARY MERGERS IN THE FIRST AND SECOND OBSERVING RUNS OF LIGO AND VIRGO*

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GWTC-1:** *A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs
arXiv:1811.12907 [astro-ph.HE]
Science summary: GWTC-1: A new catalog of gravitational-wave detections

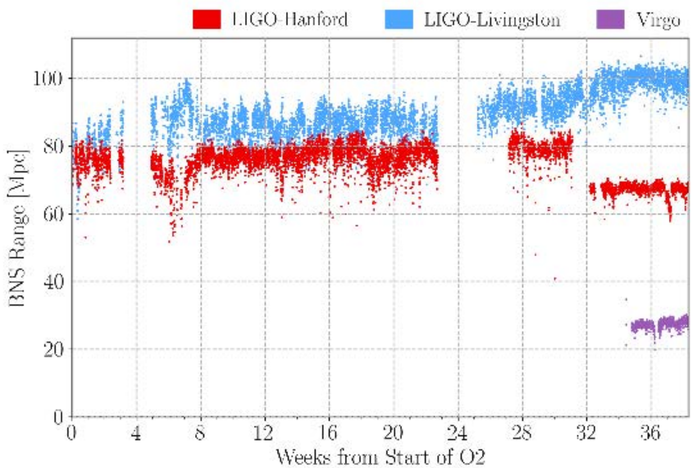
GRAVITATIONAL DETECTOR NETWORK

Scientific runs

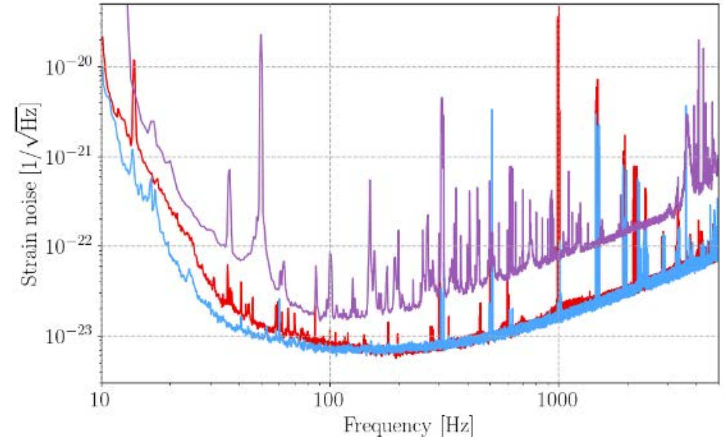
- O1: 12 Sep 2015 → 19 Jan 2016
- O2: 30 Nov 2017 → 25 Aug 2017 (Virgo: 1 Aug 2017 → 25 Aug 2017)
- Total observation time: 0.46 y; 118 days double coincidence; 15 days triple coincidence

LIGO-Virgo

INSTRUMENT AND DATA



BNS range for each instrument during O2



Representative amplitude spectral density of the total strain noise

O2 data were recalibrated (post run) and cleaned (available ~march 2018)

+20% sensitivity in LHO (arXiv:1806:00532)

Final calibration benefited from post-run measurements and lines removal

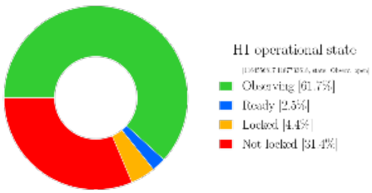
LIGO calibration error: ~3% in amplitude; ~2 deg in phase

Virgo calibration error: ~5% in amplitude; ~2 deg in phase

Duty cicle:

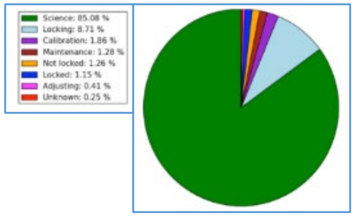
LIGO detectors: ~60%

Virgo: ~80%



H1

L1



V1

GRAVITATIONAL WAVE OPEN SCIENCE CENTER
(GWOSC - HTTPS://WWW.GW-OPENSCIENCE.ORG)

Gravitational Wave Open Science Center

- Getting Started
- Data
  - Catalogs
  - Bulk Data
- Tutorials
- Software
- Detector Status
- Timelines
- My Sources
- GPS ↔ UTC
- About the detectors
- Projects
- Acknowledge GWOSC

LIGO Hanford Observatory, Washington
(Credits: C. Gray)

LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

Virgo detector, Italy
(Credits: Virgo Collaboration)

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

Get started!

Download data

GWTC-1: Catalog of Compact Binary Mergers

Join the email list

Explore the open data web course

LIGO and Virgo's portal for

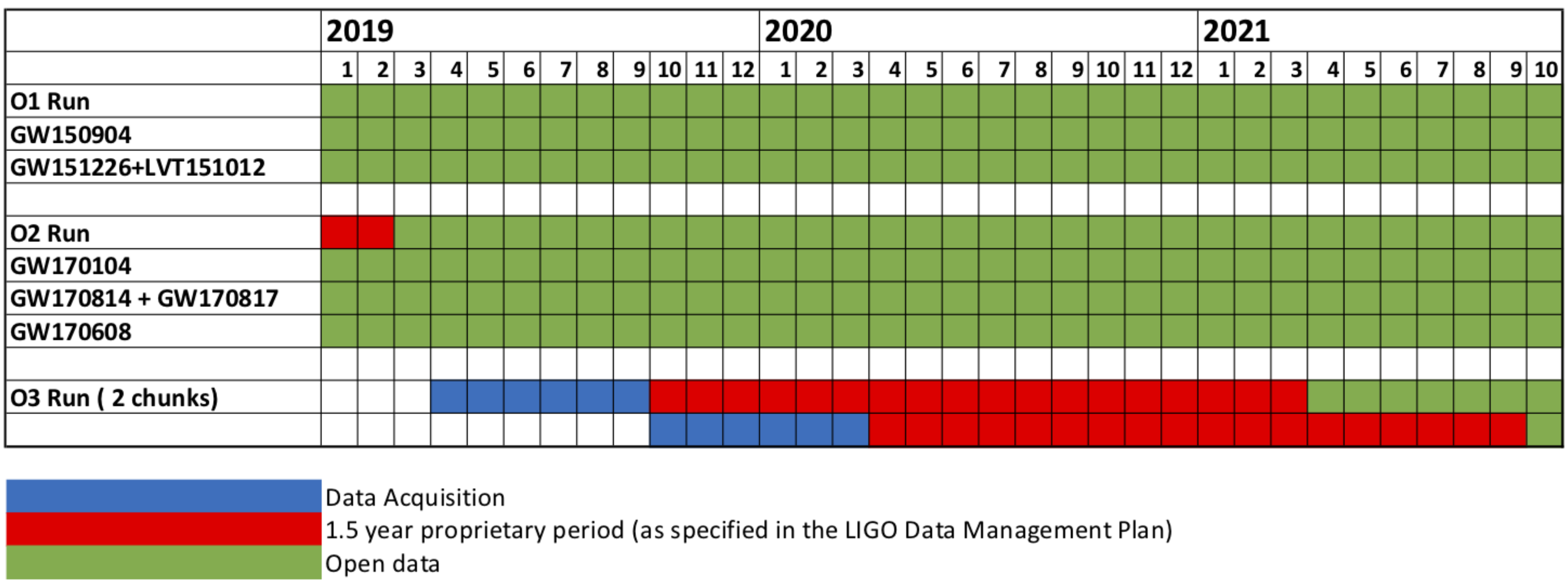
- Bulk data
- Event 1-hour time-series data, etc.
- Pointers to papers, data behind figures, posterior samples
- Pointers to analysis codes
- Pointers to Workshop materials

DATA RELEASE POLICY

- O1 data are public since end of January 2018 (24 months after end of run)
- O2 data will be public end of February 2019 (24 months after end of run)

- Future bulk releases are planned to be (no later than) **18 months after the end of a 6-month data acquisition period**

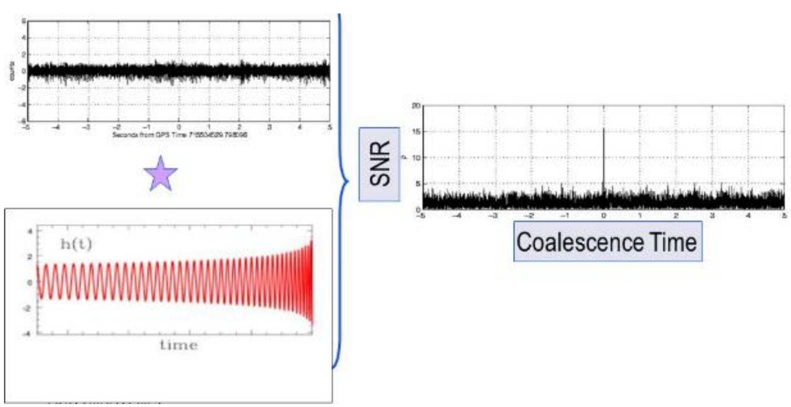
  e.g., if O3 starts in April 2019, the first planned bulk data release would be **April 2021**

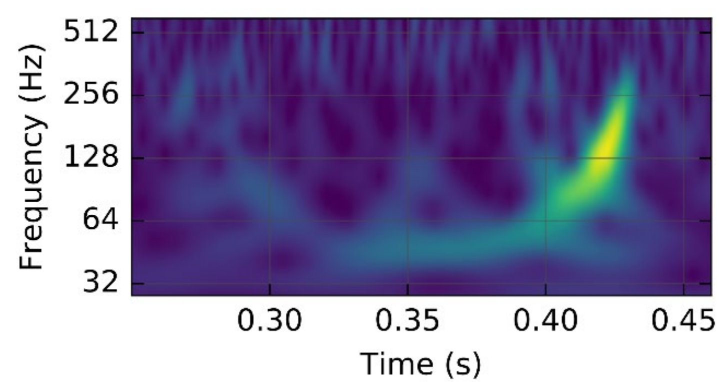


THE SEARCHES

- **Three search algorithms**:
  A. two matched-filter searches (**GstLAL** and **PyCBC**) compare a bank of templates (GW) to the data to look for matches
  Total mass range: 2-500$M_{\odot}$ (PyCBC) and 2-400$M_{\odot}$ (GstLAL)
  B. coherentWaveBurst (**cWB**), searches for generic short signals, “chirping” in the time-frequency plane; total mass range: <100$M_{\odot}$
  more flexible, less sensitive → it gives us confidence that we’re not missing things…
- **Search strategy**:
  A. Identify and rank single detector triggers using a statistic that depends on **SNR**; **look for temporal coincidence** of triggers between detectors; **assign statistical significance** wrt background (time shifts) → False Alarm Rate (**FAR)**
  B. Find events that are coherent in multiple detectors; assign statistical significance wrt background (time shifts) → **FAR**

Improvements in search pipelines since O1
(extended parameter space, vetoes, signal-consistency tests, …)





EVENT SELECTION CRITERIA

Identify all events that are **confidently astrophysical in origin**, and additionally provide a manageable set of **marginal triggers** that may include some true signals, but certainly also includes noise triggers

- **Threshold I: estimated FAR < 1 per 30 days** (~12.2 per year)
- **Threshold II: probability of astrophysical origin greater than 50%**

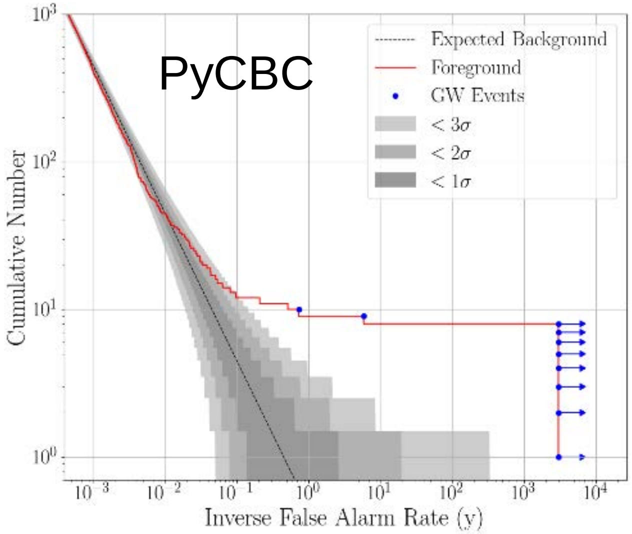
Events satisfying thresholds I & II: **'GW' designation**

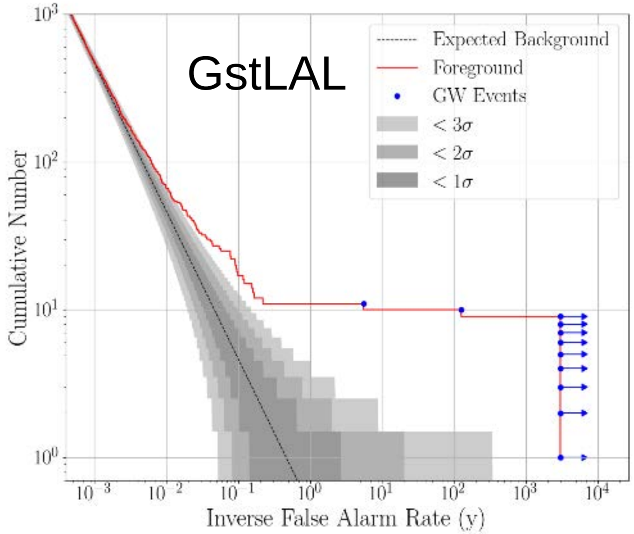
Events satisfying threshold I, but failing II designated as **"marginal"**

For O1 & O2, any sample of events all of whose measured FARs are > 1 per 30 days is expected to consist of ~50% noise triggers

Thresholds to be satisfied in *at least one* of the two matched-filter searches

SEARCH RESULTS VS IFAR

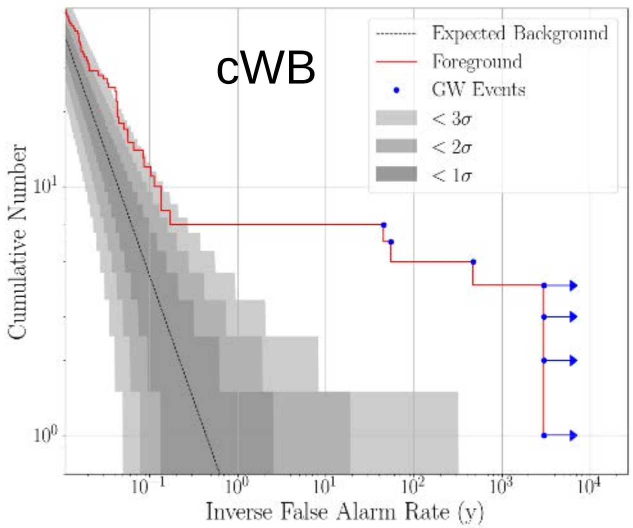




FAR indicates how often you would expect to find something at least as “signal-like” if you were to analyze a stretch of data with the same statistical properties as the data considered, assuming that they is only noise in the data

FAR does not fold in the probability that there are real gravitational waves occurring at some average rate

Since we have now confident detections, we can work out the probability that something flagged by a search pipeline is a real signal vs noise



EVENT CLASSIFICATION

	GstLAL					PyCBC					cWB	
	terrestrial	BNS	NSBH	BBH	astrophysical	terrestrial	BNS	NSBH	BBH	astrophysical	terrestrial	BBH
GW150914	0	0	0.0064	0.99	1	0	–	–	1	1	0	1
151008 [a]	–	–	–	–	–	0.73	–	–	0.27	0.27	–	–
151012A	0.98	0.022	0.0012	0	0.023	–	–	–	–	–	–	–
GW151012	0.001	0	0.031	0.97	1	0.04	–	–	0.96	0.96	–	–
151116 [b]	–	–	–	–	–	~ 1	$\ll 0.5$	–	–	$\ll 0.5$	–	–
GW151226	0	0	0.12	0.88	1	0	–	–	1	1	0.05	0.95
161202	0.97	0.034	0	0	0.034	–	–	–	–	–	–	–
161217	0.98	0	0.011	0.0078	0.018	–	–	–	–	–	–	–
GW170104	0	0	0.0028	1	1	0	–	–	1	1	0	1
170208	0.98	0	0.011	0.0088	0.02	–	–	–	–	–	–	–
170219	0.98	0.019	0	0	0.02	–	–	–	–	–	–	–
170405	1	0.004	0	0	0.004	–	–	–	–	–	–	–
170412	0.94	0	0.029	0.032	0.06	–	–	–	–	–	–	–
170423	0.91	0.086	0	0	0.086	–	–	–	–	–	–	–
GW170608	0	0	0.084	0.92	1	0	–	–	1	1	0	1
170616 [b]	–	–	–	–	–	~ 1	–	$\ll 0.5$	–	$\ll 0.5$	–	–
170630	0.98	0.02	0	0	0.02	–	–	–	–	–	–	–
170705	0.99	0	0.006	0.0061	0.012	–	–	–	–	–	–	–
170720	0.99	0	0.0077	0.002	0.0097	–	–	–	–	–	–	–
GW170729	0.018	0	0	0.98	0.98	0.48	–	–	0.52	0.52	0.057	0.94
GW170809	0	0	0.0064	0.99	1	0	–	–	1	1	–	–
GW170814	0	0	0.0024	1	1	0	–	–	1	1	0	1
GW170817	0	1	0	0	1	0	1	–	–	1	–	–
GW170818	0	0	0.0053	0.99	1	–	–	–	–	–	–	–
GW170823	0	0	0.0059	0.99	1	0	–	–	1	1	0.0043	1

CONFIDENT DETECTIONS

O1 data: 151012 designated as a GW event
(higher significance because of improved detection pipelines)

O2 data: found **four new binary black hole merger** events:
GW170729, GW170809, GW170818, GW170823

Not *all* events found with *all* searches

Event	UTC Time	FAR $[y^{-1}]$ PyCBC	FAR $[y^{-1}]$ GstLAL	FAR $[y^{-1}]$ cWB	Network SNR PyCBC	Network SNR GstLAL	Network SNR cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
GW170823	13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

COMMENTS

Former LVT151022 now meets the criteria (FAR 7.92 x 10^{-3} yr^{-1}) and is relabeled GW151012

No new discoveries in O1 data

GW170729 lowest FAR event (PyCBC: 1.36 yr^{-1}; GstLAL: 0.18 yr^{-1}; cWB: 0.02 yr^{-1}) observed difference in FAR consistent with noise fluctuation

GW170818 third triple detection (after GW170814 and GW170817)
SNR: V1=4.2; H1=4.1; L1=9.7

identified in low-latency as a LLO-Virgo double trigger

GW170729 and GW170809 low SNR in Virgo

GW170823 Virgo data not used due to ongoing detector aactivity

MARGINAL EVENTS

Event candidates with an estimated FAR > 1 per 30 days

Some of these marginal triggers **may be of astrophysical origin**, we cannot then determine which

For 4 marginal events, an observed **instrumental artifact** overlaps the signal region, and may account for the strain amplitude of the marginal trigger

Date	UTC	Search	FAR [y^{-1}]	Network SNR	$\mathcal{M}^{det}$ [$M_\odot$]	Data Quality
151008	14:09:17.5	PyCBC	10.17	8.8	5.12	No artifacts
151012A	06:30:45.2	GstLAL	8.56	9.6	2.01	Artifacts present
151116	22:41:48.7	PyCBC	4.77	9.0	1.24	No artifacts
161202	03:53:44.9	GstLAL	6.00	10.5	1.54	Artifacts can account for
161217	07:16:24.4	GstLAL	10.12	10.7	7.86	Artifacts can account for
170208	10:39:25.8	GstLAL	11.18	10.0	7.39	Artifacts present
170219	14:04:09.0	GstLAL	6.26	9.6	1.53	No artifacts
170405	11:04:52.7	GstLAL	4.55	9.3	1.44	Artifacts present
170412	15:56:39.0	GstLAL	8.22	9.7	4.36	Artifacts can account for
170423	12:10:45.0	GstLAL	6.47	8.9	1.17	No artifacts
170616	19:47:20.8	PyCBC	1.94	9.1	2.75	Artifacts present
170630	16:17:07.8	GstLAL	10.46	9.7	0.90	Artifacts present
170705	08:45:16.3	GstLAL	10.97	9.3	3.40	No artifacts
170720	22:44:31.8	GstLAL	10.75	13.0	5.96	Artifacts can account for

SOURCE PROPERTIES- WAVEFORM MODELS

Complete description of waveform **for all stages of the coalescence**

LIGO/Virgo needs waveform models which are

- **accurate** (to extract maximum physics)
- **fast** (detailed analyses)

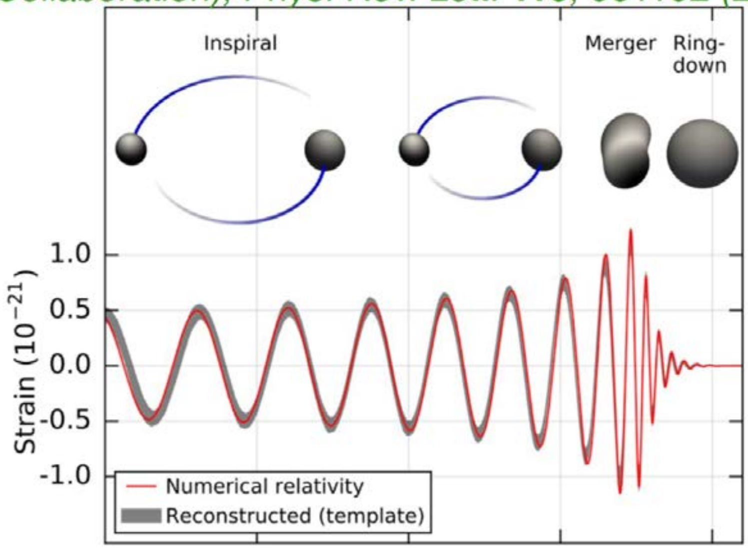
BBH waveform models:

- **Fully-precessing EOB model** (SEOBNRv3)
- **Effective precessing phenomenological model** (IMRPhenomPv2)
- Tuned to numerical relativity in aligned spin sector

BNS waveform models:

- Frequency-domain BBH models with phase correction from fit to NR (IMRPhenomPv2NRT, SEOBNRv4NRT, TaylorF2)
- Time-domain EOB models including tidal effects: (SEOBNRv4T, **TEOBResumS**)

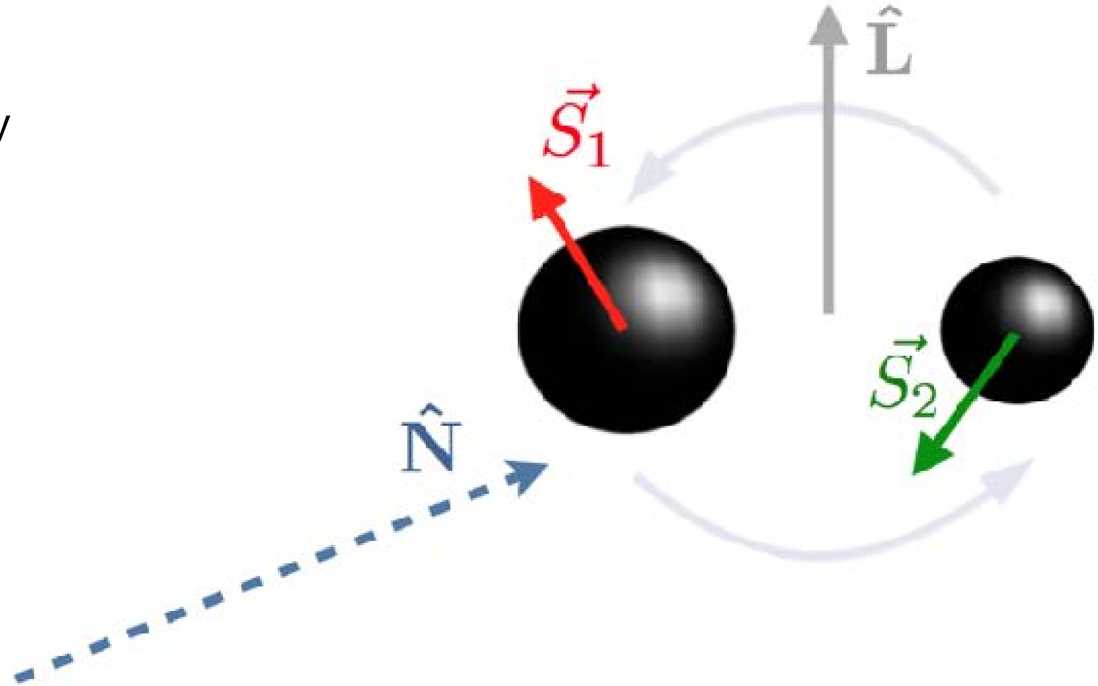
Abbott et al. (LIGO Collaboration, Virgo Collaboration), Phys. Rev. Lett. ***116****, 061102 (2016)*

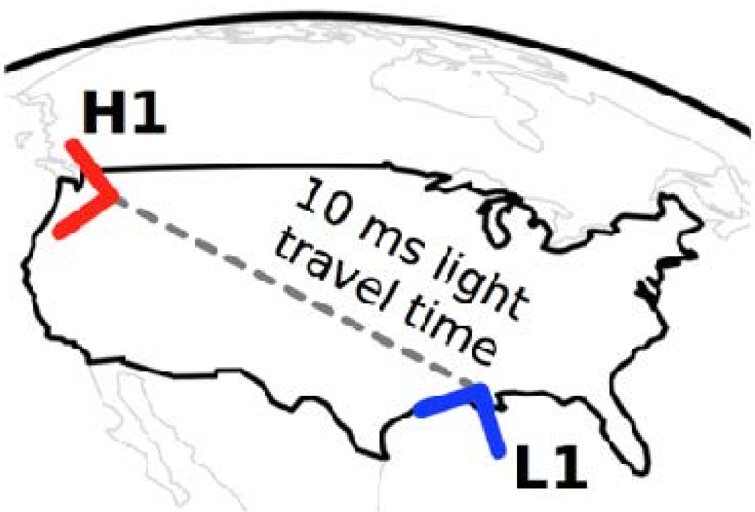


Waveforms are **implemented** in https://wiki.ligo.org/Computing/DASWG/WebHome

SOURCE PROPERTIES - MODEL PARAMETERS

Intrinsic parameters (8):
masses, spins, tidal deformability
(eccentricity $\simeq$ 0)





Extrinsic parameters (7):
sky location (right ascension, declination)
distance, orbital inclination and polarization angle, time and phase at coalescence

Credit: LIGO/Virgo

INTRINSIC PARAMETERS

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \left[\frac{q}{(1+q)^2}\right]^{3/5} (m_1+m_2)$$

Chirp mass – leading order PN expansion

$$q = \frac{m_2}{m_1} \leq 1$$

Total mass 1PN but accessible through

$$f_{GW,max} = \frac{1}{6\sqrt{6}\,(2\pi)} \frac{c^3}{GM} \simeq 2.2\,\mathrm{kHz} \left(\frac{M_\odot}{M}\right)$$

$$\vec{\chi}_i = \frac{c\,\vec{S}_i}{G\,m_i^2} \qquad a_i = |\vec{\chi}_i| = \frac{c\,|\vec{S}_i|}{G\,m_i^2}$$

Dimensionless spin (spin-spin coupling 2PN)

$$\chi_{eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot\vec{L}_N}{m_1+m_2}$$

Effective aligned spin (spin-orbit coupling 1.5PN)

$$\chi_p = \frac{1}{B_1 m_1^2}\max(B_1 S_{1\perp}, B_2 S_{2\perp})$$

$$B_1 = 2 + \frac{3q}{2} \qquad B_2 = 2 + \frac{3}{2q}$$

Effective precession spin parameter (2PN)
arXiv:1308.3271

BNS only

$$\Lambda = \frac{2}{3} k_2 \left(\frac{c^2}{G}\frac{R}{m}\right)$$

Dimensionless tidal deformability

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{M^5}$$

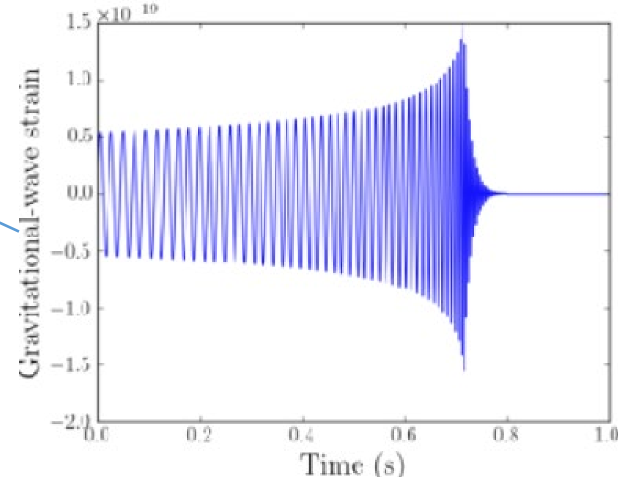
Effective tidal deformability parameter (5PN)

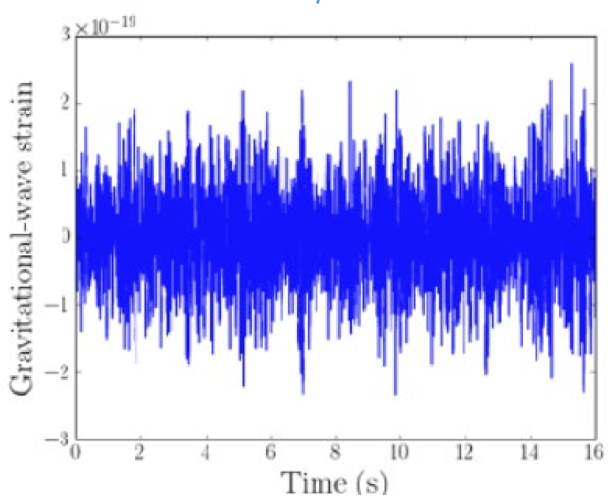
PARAMETER ESTIMATION

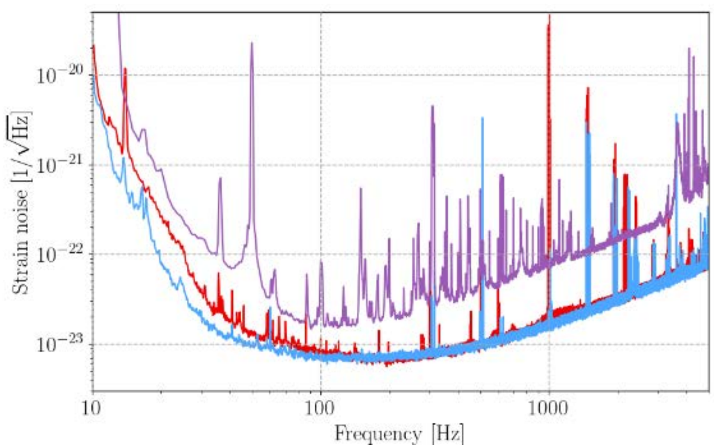
Coherent Bayesian inference: $p(\vec{\theta}|\vec{d}) \propto p(\vec{d}|\vec{\theta}) \cdot p(\vec{\theta})$

The likelihood $p(\vec{d}|\vec{\theta})$ depends on

$$\langle d|h \rangle = 4\,\mathrm{Re} \int_0^\infty \frac{\tilde{s}(f)\,\tilde{h}^*(f)}{S_n(f)} df$$







PARAMETER ESTIMATION RESULTS

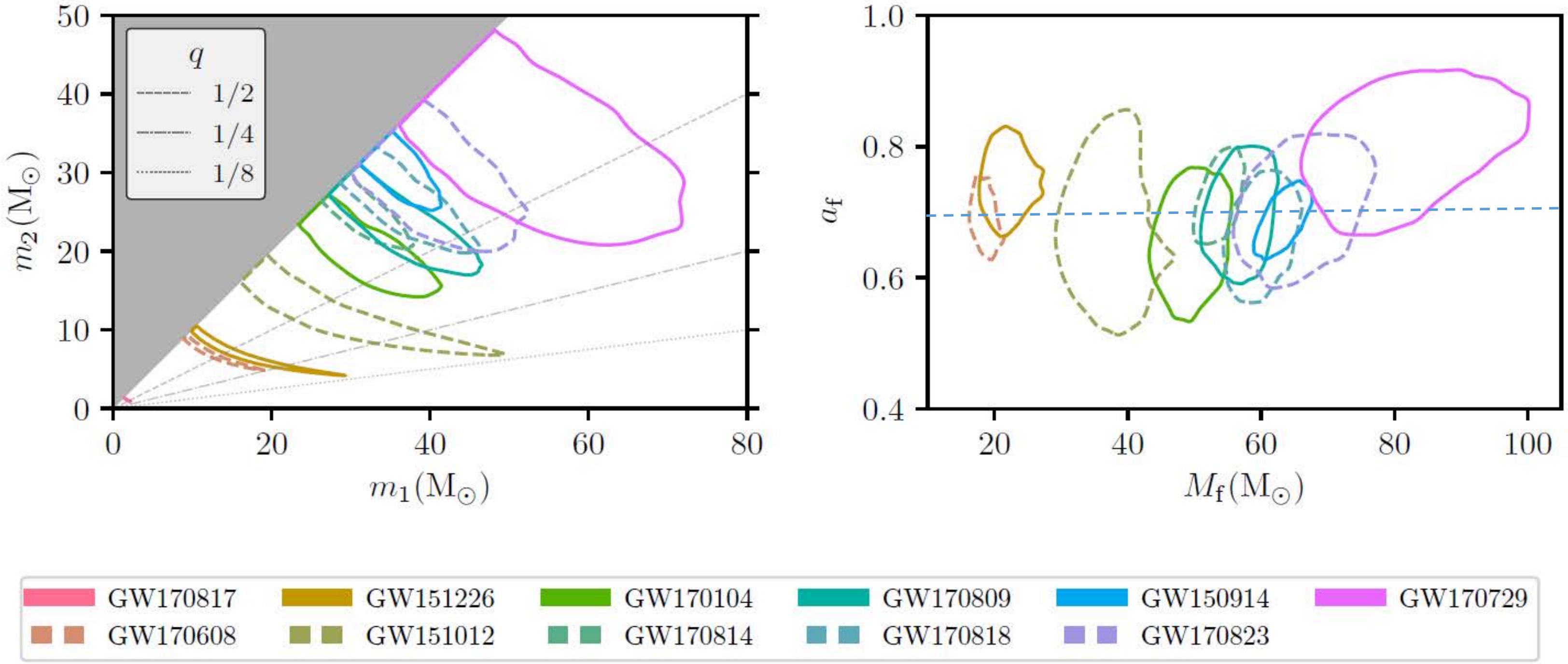
Medians and 90% credible intervals for selected source parameters.

BBH events: combined samples between two precessing waveform models (IMRPhenomPv2, SEOBNRv3)

Reanalysis of published events: overall consistent results

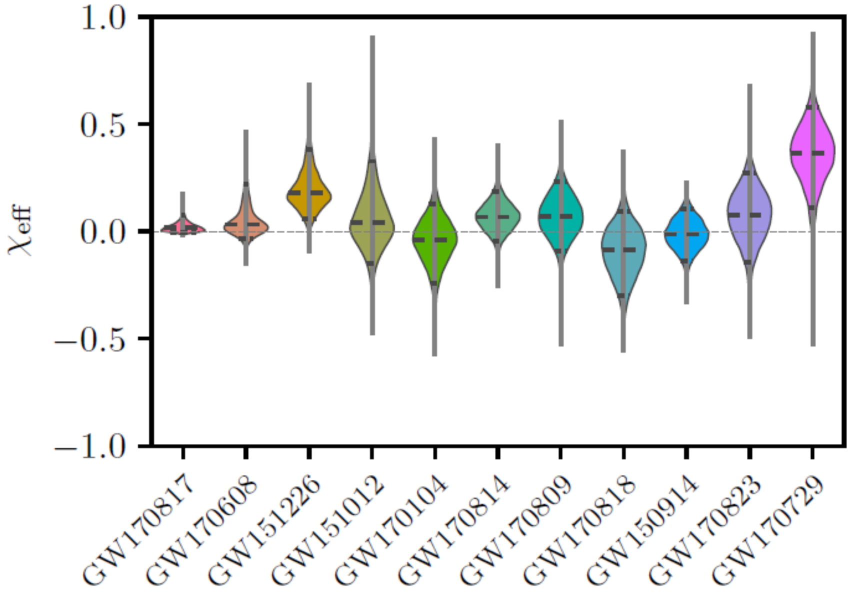
Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_eff	$M_\mathrm{f}/\mathrm{M}_\odot$	a_f	$E_\mathrm{rad}/(\mathrm{M}_\odot c^2)$	$\ell_\mathrm{peak}/(\mathrm{erg\,s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

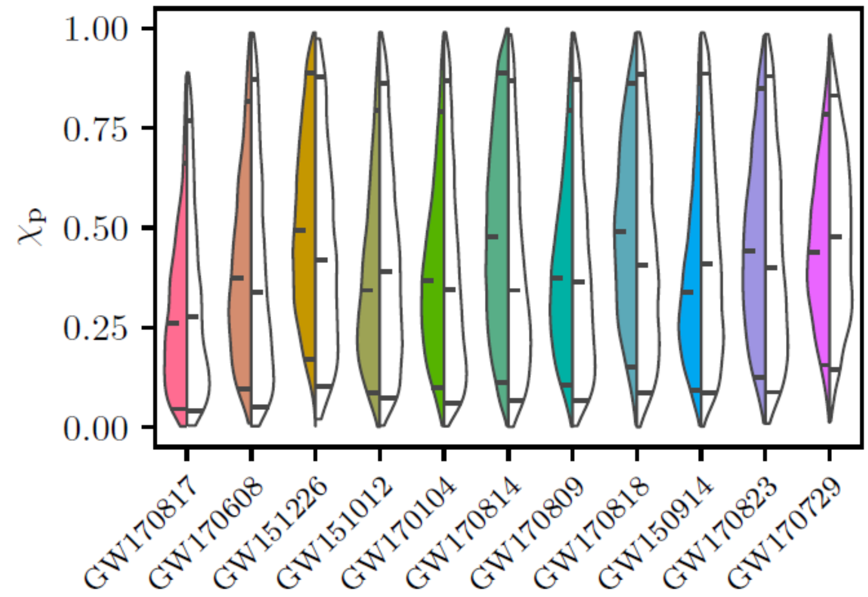
COMPONENT MASSES AND FINAL MASS AND SPIN



- Component masses from ~5$M_\odot$ to ~70$M_\odot$
- Heavier component in GW170729 ~lower boundary of the possible mass gap expected from pulsational pair instability and pair instability supernovae at ~60–120$M_\odot$
- Lowest-mass BBH, GW151226 and GW170608, have 90% credible lower bounds on $m_2 > 5M_\odot$ above the proposed BH mass gap region of 2–5$M_\odot$
- Only a small fraction (0.02–0.07) of the binary's total mass is radiated away in GWs (scales with total mass; ~4.8$M_\odot$ for GW170829)
- Peak luminosity depends on *q* and spin
  GW170729 has the highest value ℓ_{peak} ~4 x 10^{56} erg s^{-1} because of its relatively high spin

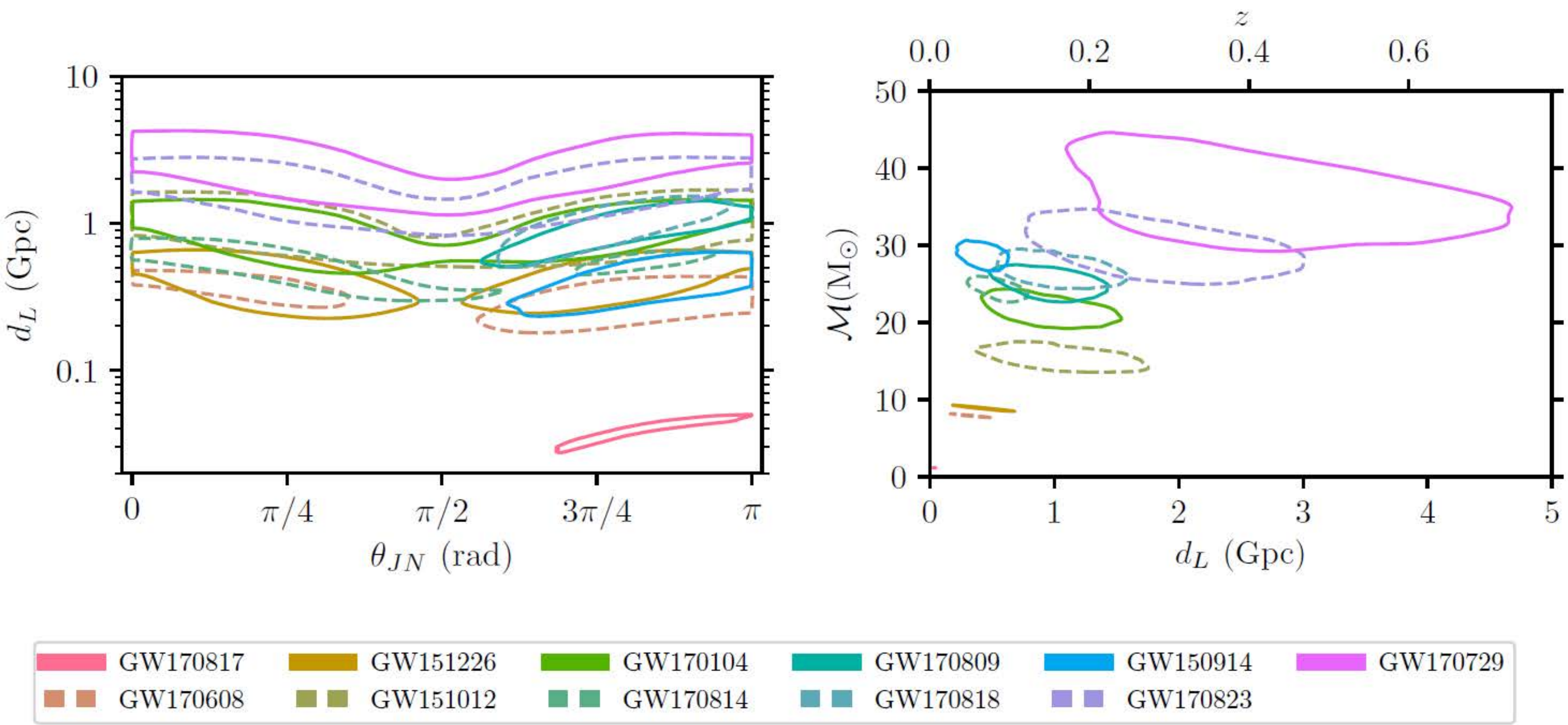
EFFECTIVE SPINS





- Posteriors of χ_{eff} peak around zero
- The posteriors for GW151226 and GW170829 exclude χ_{eff} = 0 at 90% confidence
- The remaining spin degrees of freedom are due to a misalignment of the spin vectors with the normal to the orbital plane and give rise to precession of the orbital plane and spin vectors around the total angular momentum of the binary
- The χ_p posteriors are broad, covering the entire domain from 0 to 1, and are overall similar to the priors conditioned on the χ_{eff} posterior distribution

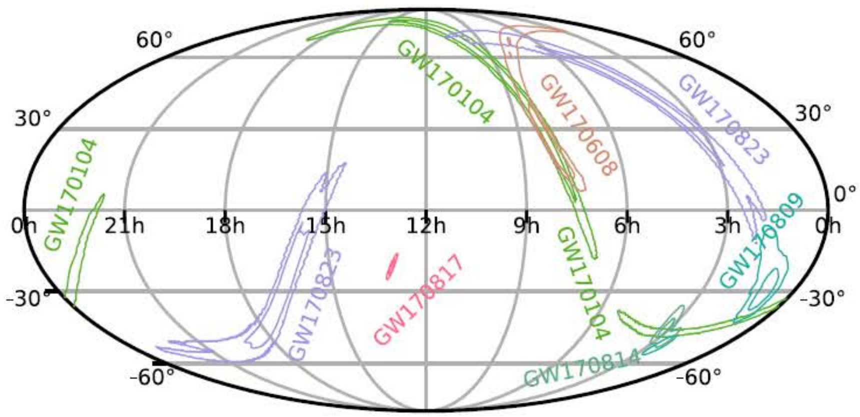
DISTANCE AND INCLINATION



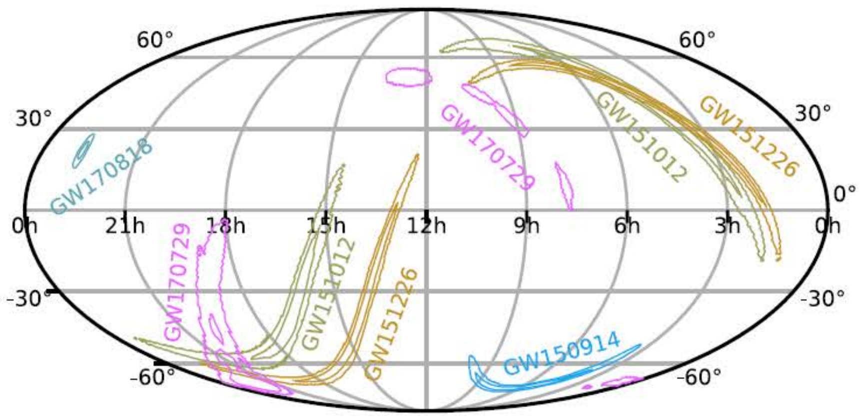
- Most distant BBH is GW170829 at d_L ~2.75 Gpc (~9 x 10^9 ly; z = 0.48)
  Closest is GW170608 at d_L ~320 Mpc
- Large errors because of degeneracy between distance d_L and inclination θ_{JN}

- Analysis assume that emitted GW signal is not affected by gravitational lensing
- Overall, luminosity distance and chirp mass are positively correlated, as expected for unlensed BBHs observations

SKY LOCATION



O2 GW events for which alerts were sent to EM observers

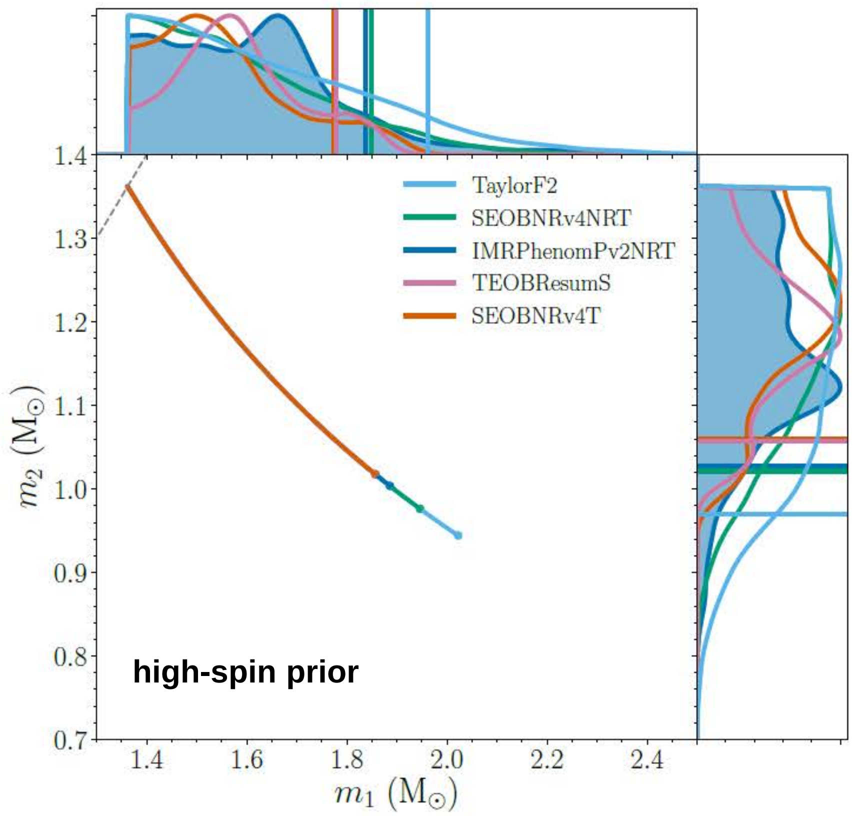


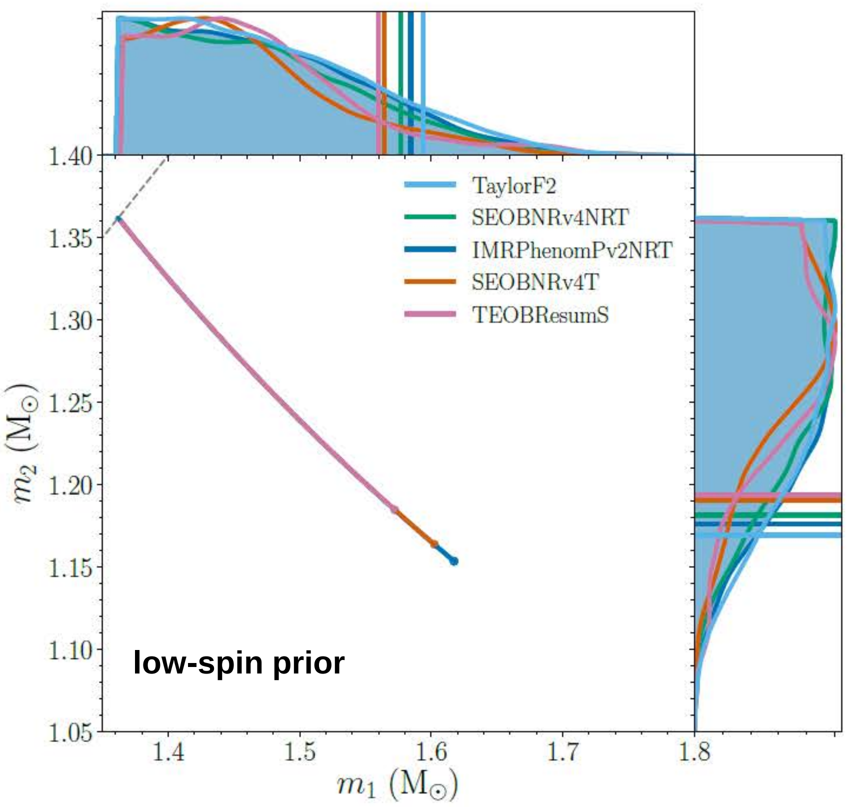
O1 events along with O2 events (GW170729, GW170818) not previously released to EM observers

- Sky areas scale inversely with SNR^2
- **Inclusion of Virgo improves sky localization**: importance of a *global GW detector network* for accurately localizing GW sources

- GW170818 is best localized BBH to date: with a 90% area of 39 deg^2

GW170817 UPDATE – COMPONENT MASSES

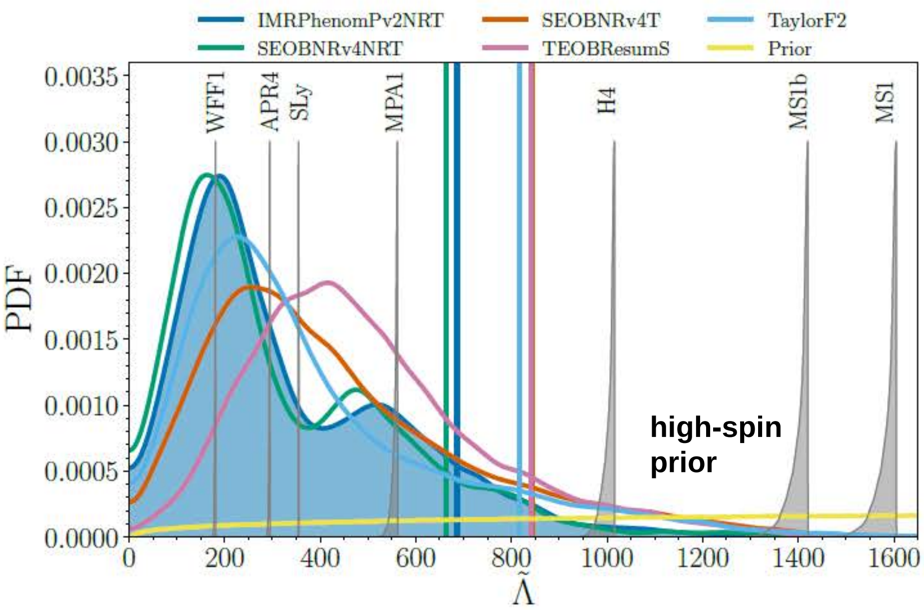


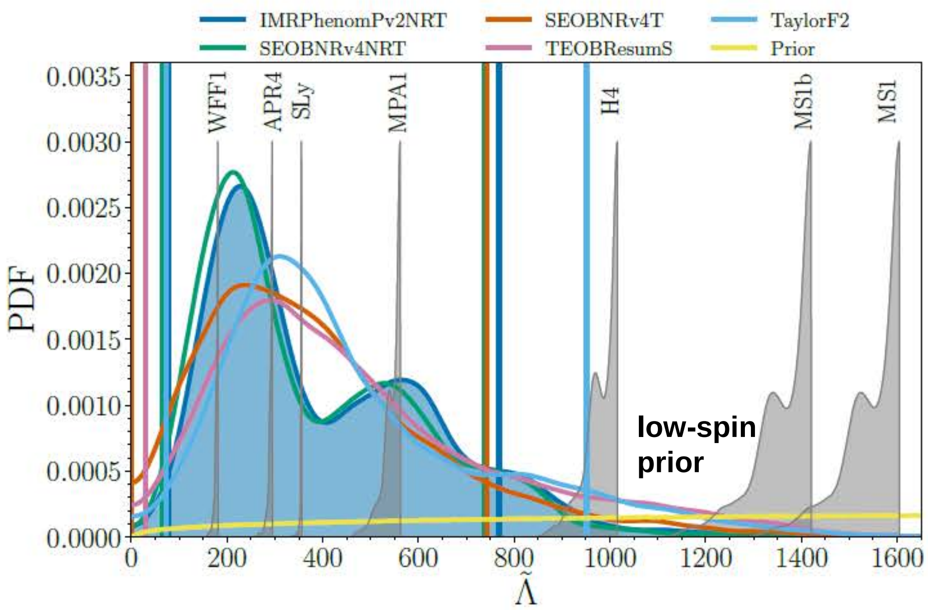


- Reanalysis of BNS including two time-domain EOB models and using recalibrated O2 data: results consistent with previous analysis

- mass of the larger NS in [1.36,1.84] $M_\odot$ ([1.36,1.58] $M_\odot$) @90% confidence
- Mass of the smaller NS in [1.03,1.36] $M_\odot$ ([1.18,1.36] $M_\odot$) @90% confidence

GW170817 UPDATE – TIDAL DEFORMABILITY

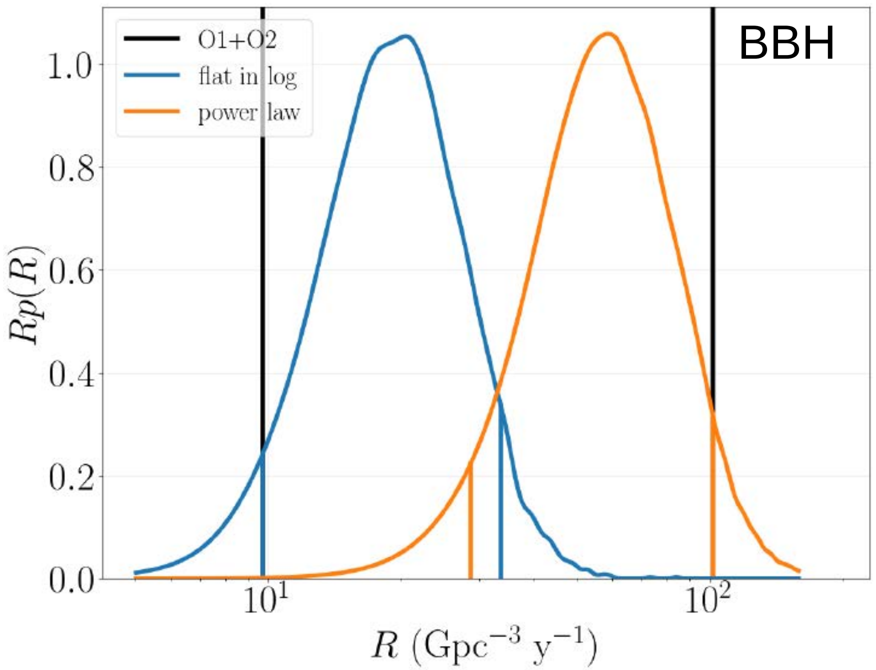


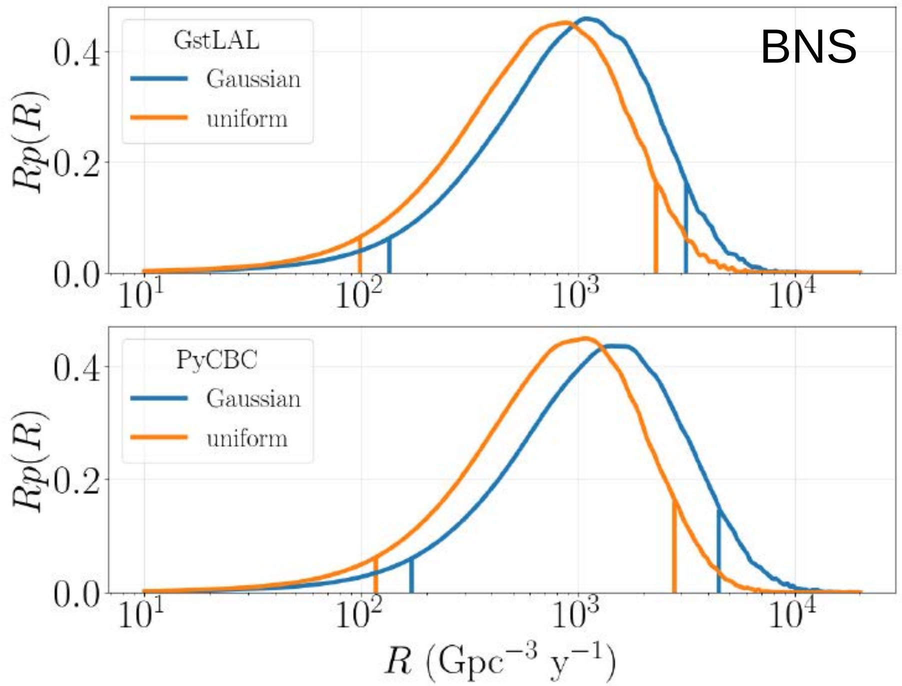


- Bounds on the effective tidal deformability parameter: about 10% wider than previous results $\tilde{\Lambda} \in$ [0,951]

- Some EOS models disfavoured @90% confidence

BBH AND BNS MERGER RATES



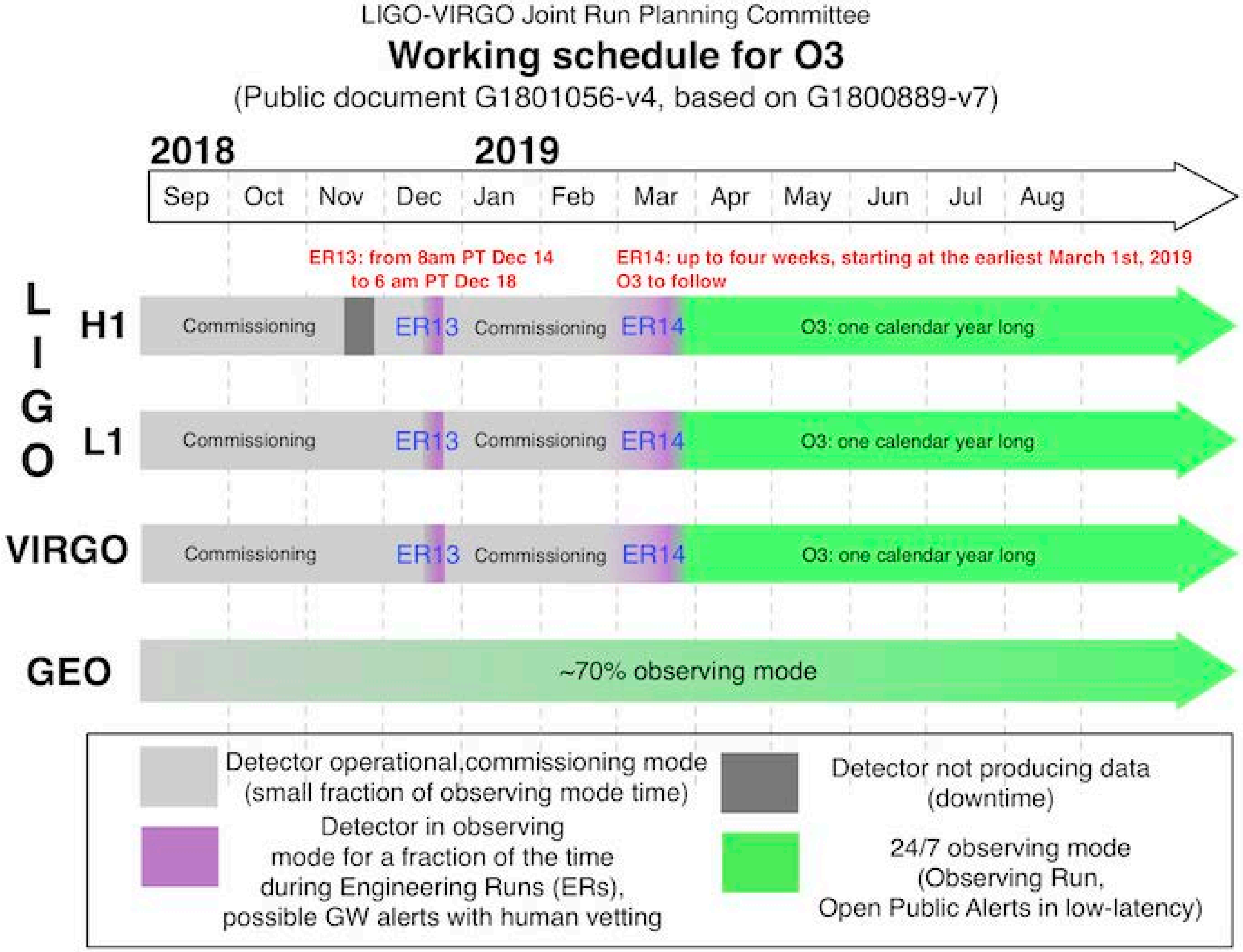


- **BBH event rates:** for the mass distributions of the primary mass m_1 flat in log (blue) and power-law (orange)
  Union of the interval R_{BBH} in [9.7,101] Gpc^{-3} y^{-1}

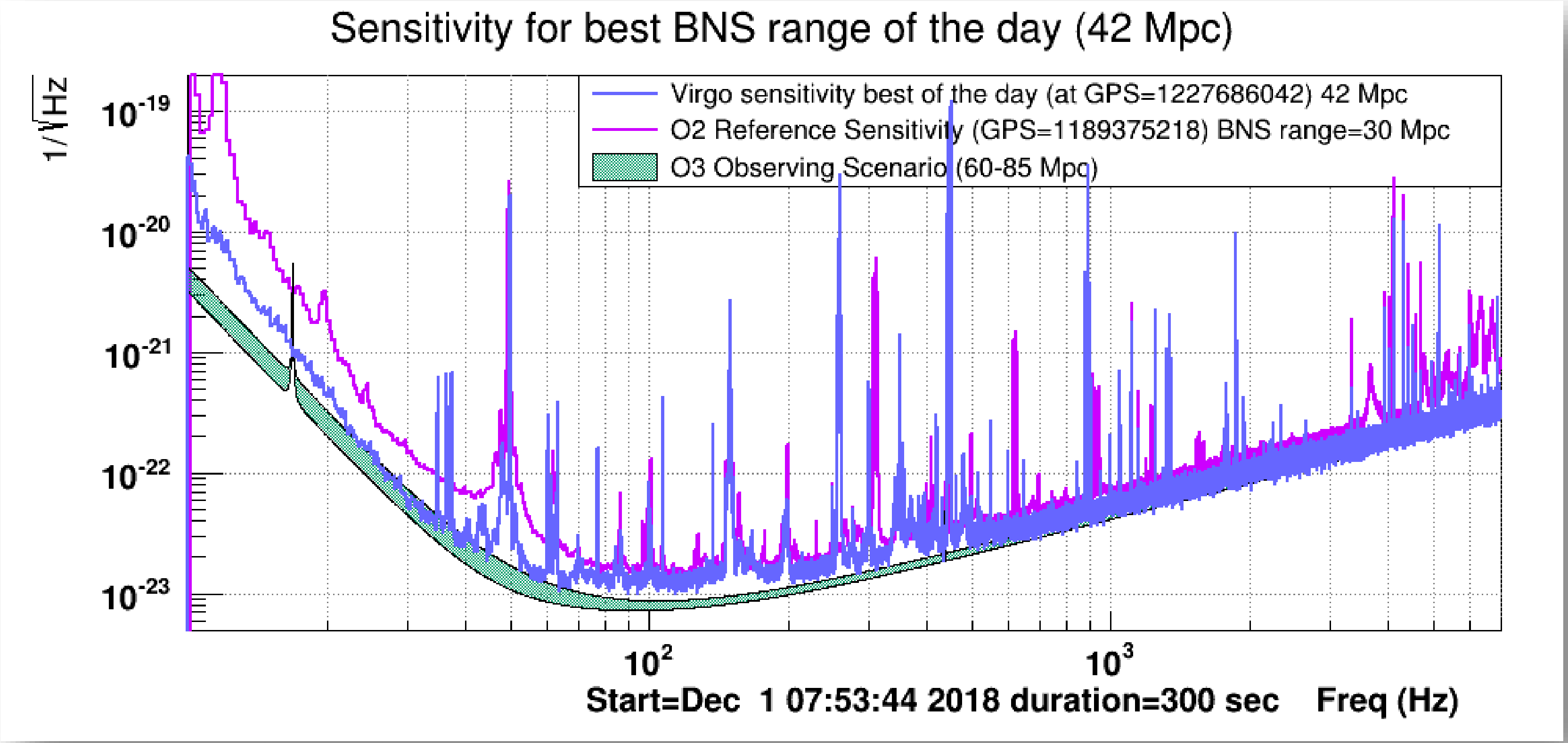
- **BNS event rates:** for uniform or Gaussian component mass distributions
  Union of the interval R_{BNS} in [110,3840] Gpc^{-3} y^{-1}

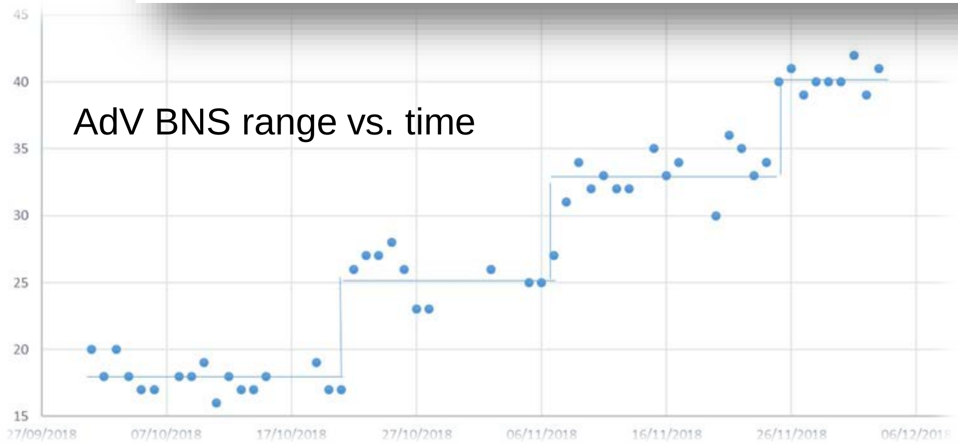
- **NSBH rates** (no detection): **R_{NSBH} < 610 Gpc^{-3} y^{-1} @90% confidence**
  factor of 2 better than O1 results, starts to be interesting

TOWARDS O3…


LIGO-VIRGO Joint Run Planning Committee
Working schedule for O3
(Public document G1801056-v4, based on G1800889-v7)
2018
2019
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
ER13: from 8am PT Dec 14 to 6 am PT Dec 18
ER14: up to four weeks, starting at the earliest March 1st, 2019
O3 to follow
LIGO
H1
Commissioning
ER13
Commissioning
ER14
O3: one calendar year long
L1
Commissioning
ER13
Commissioning
ER14
O3: one calendar year long
VIRGO
Commissioning
ER13
Commissioning
ER14
O3: one calendar year long
GEO
~70% observing mode
Detector operational,commissioning mode (small fraction of observing mode time)
Detector not producing data (downtime)
Detector in observing mode for a fraction of the time during Engineering Runs (ERs), possible GW alerts with human vetting
24/7 observing mode (Observing Run, Open Public Alerts in low-latency)

CURRENT SENSITIVITY





Target sensitivity for O3: 60 Mpc

Theoretical limit: 85 Mpc @ 18 W

FROM AdV TO AdV+

Main motivations for AdV+:

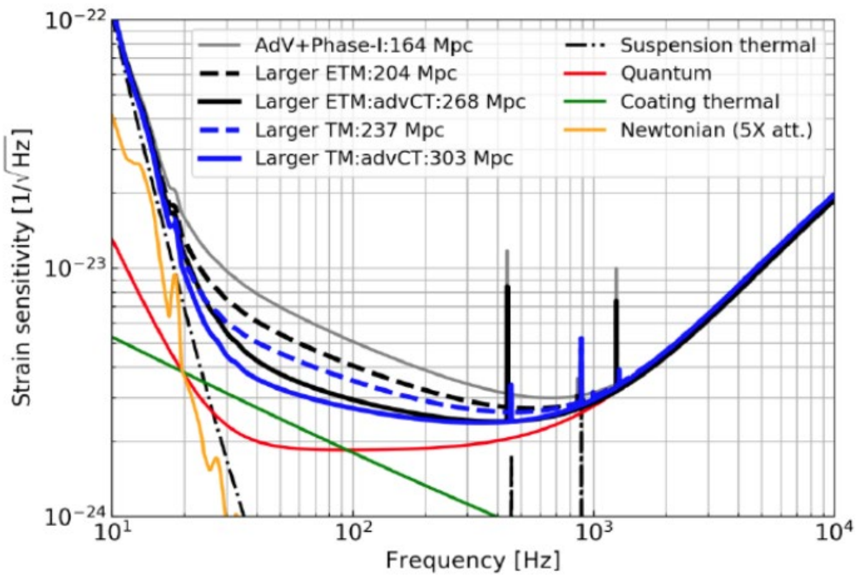
- Maximize Virgo's sensitivity exploiting at best the present infrastructure
- Maximize science
- Secure Virgo's scientific relevance in the global network
- Safeguard investments by scientists and funding agencies
- Explore new innovative technologies also essential for 3rd generation detectors
- De-risk technologies needed for third generation observatories
- Reduce the gap with the Einstein Telescope (time-wise, science-wise and on the technological front)
- Attract new groups wanting to enter the field
- Goal is to be twice more sensitive than AdV (8x event rate)

Phase 1 (2019-2021)

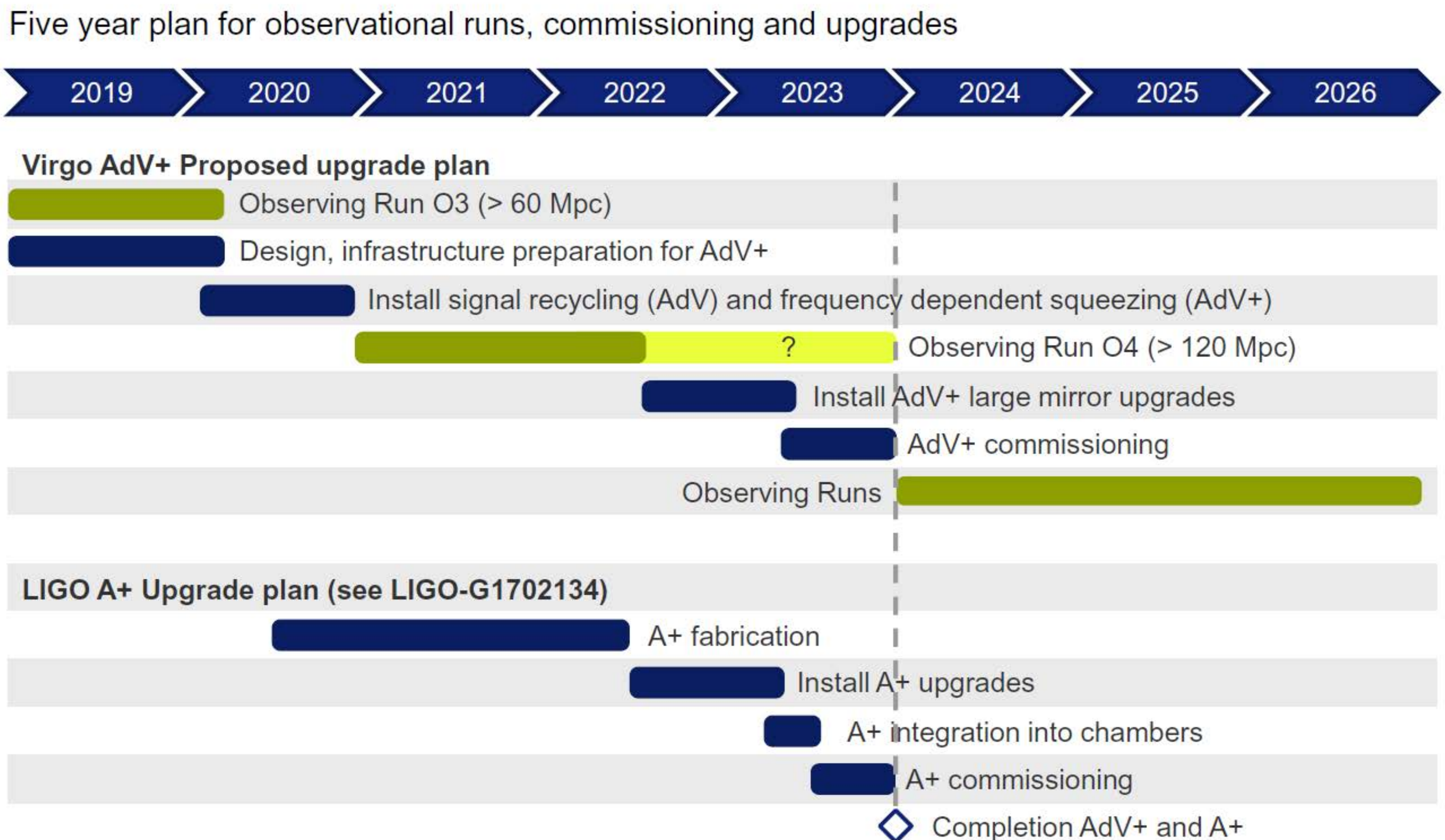
- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc

Phase 2 (2022-2024)

- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc

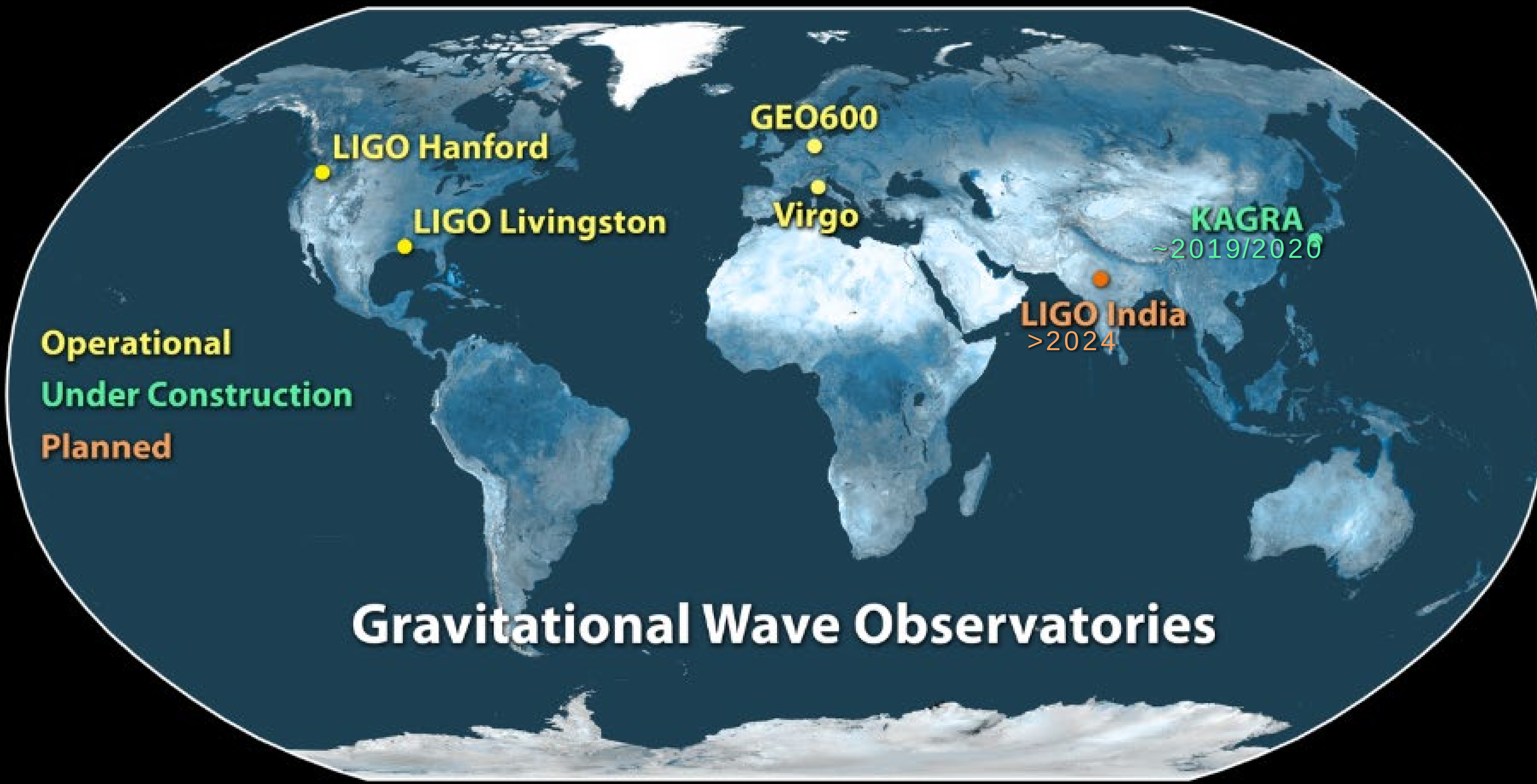


TENTATIVE TIMELINE



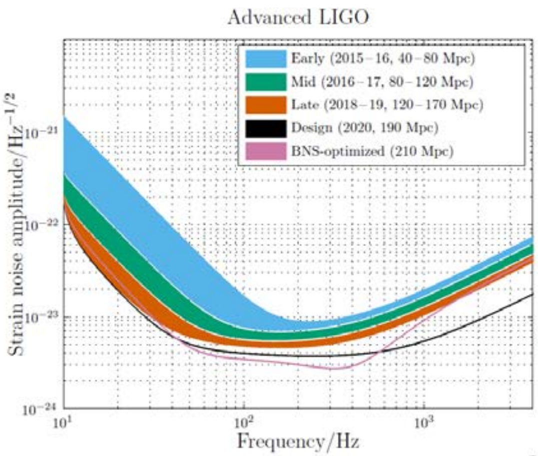
- Incremental approach: Phase1 / Phase2
- In parallel with the LIGO detectors
- The goal is to manage science runs in coincidence

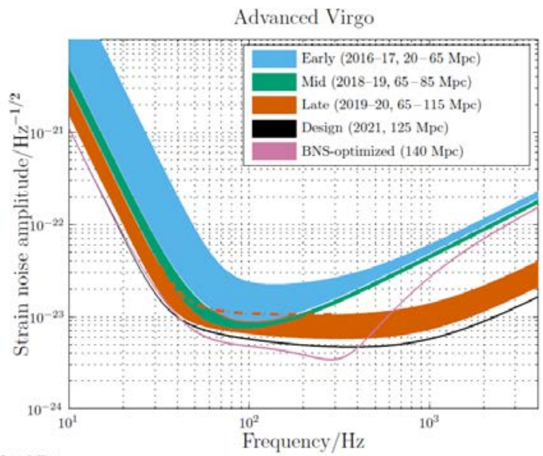
TOWARDS A GLOBAL GW RESEARCH INFRASTRUCTURE

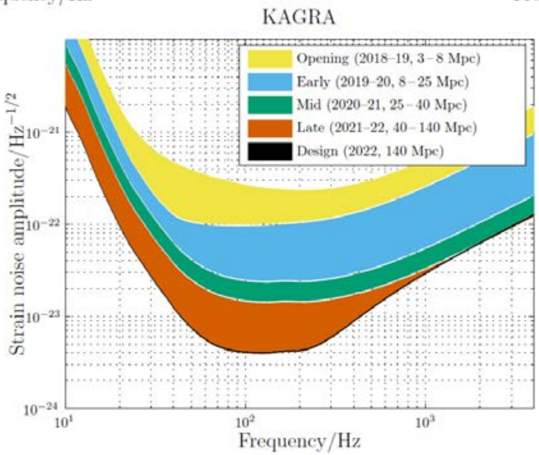


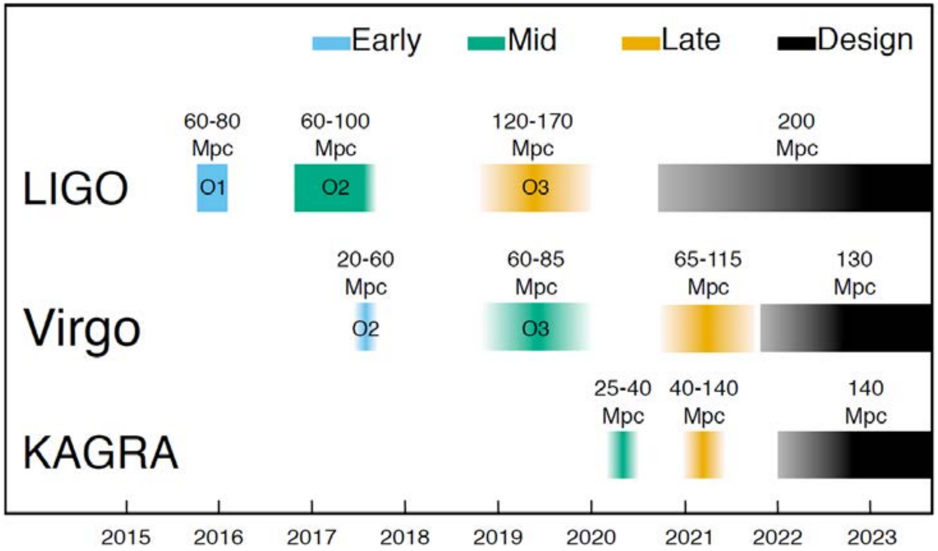
THE NETWORK IS THE DETECTOR

LIGO-VIRGO-KAGRA OBSERVING SCENARIO

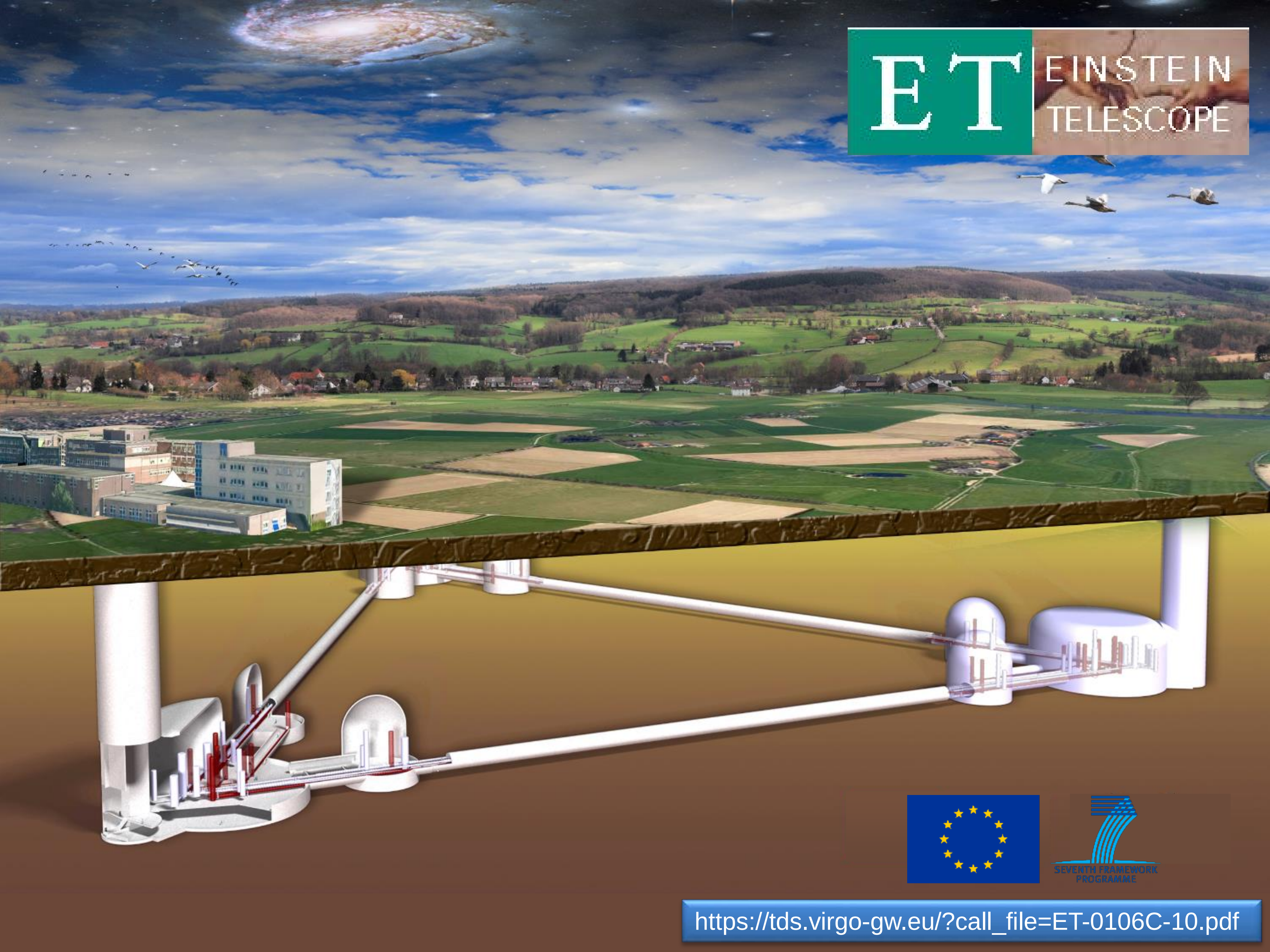








arXiv:1304.0670
Living Rev Relativ (2016) 19



https://tds.virgo-gw.eu/?call_file=ET-0106C-10.pdf

SUMMARY AND OUTLOOK

- In O1 & O2 LIGO/Virgo have made confident observations of GWs from **10 binary black hole coalescences (4 new detections)** and **one binary neutron star**
  - Approximately one GW detection per 15 days of data searched
- **GW170818 is the third triple-coincident LIGO-Virgo event, localized to an area of 39 deg^2, best localised BBH to date**
- We have determined **merger rates** of
  - BNS: [110,3840] Gpc^{-3} y^{-1}
  - BBH: [9.7,101] Gpc^{-3} y^{-1}
  - NSBH merger rate 90% upper limit of 610 Gpc^{-3} y^{-1}
- **No binary components** have been observed in either of the putative **mass gaps** (one between NSs and BHs and the other one due to pair instability supernovae)
- **Component spins**, when measurable, tend to favor **small magnitudes**, in contrast to Galactic X-ray binaries
  - Favors formation scenario in which no spin alignment is present (assembly in globular cluster)
  - Much more details on astrophysical population in **arXiv:1811.12940**
  - Tests of GR coming soon…(seminar of Giulia Pagano on January 17)

- **Third observing run (O3)** of Advanced LIGO and Virgo is planned to start in april 2019, KAGRA hoping to join toward the end of O3

- **Data, samples, codes publicly available** at https://www.gw-openscience.org