Recent results from
Advanced LIGO and Advanced Virgo

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Istituto Nazionale Fisica Nucleare Sezione di Pisa

SCUOLA NORMALE SUPERIORE

on behalf of
the LIGO Scientific Collaboration
and the Virgo Collaboration

LIGO Scientific Collaboration

Outline

O1: Advanced LIGO's first observing run

The beginning of GW astronomy

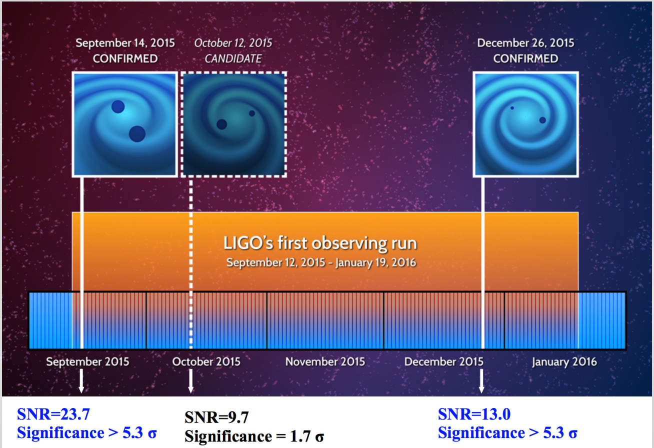
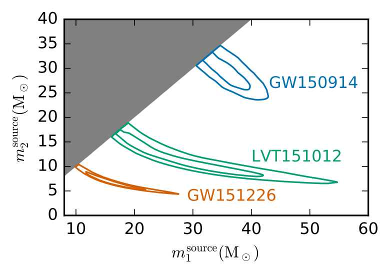


Image credit: LIGO
Abbott et al. 2016, Phys. Rev. X, 6, 041015

Physical parameters of O1 BBH systems



Event	GW150914	GW151226	LVT151012
m_1 ($M_\odot$)	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
m_2 ($M_\odot$)	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}

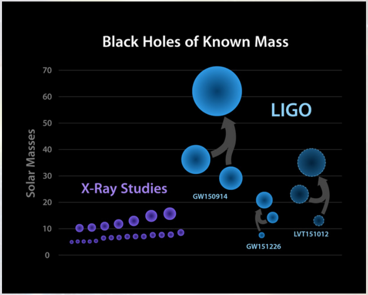


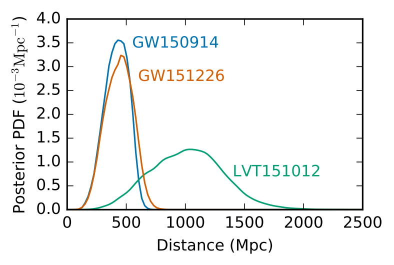
Image credit: LIGO

- First direct evidences for "heavy" stellar mass BHs (> 25 $M_\odot$)
- Heavy stellar mass BBHs most likely formed in low-metallicity environment (≤ 0.5 $Z_\odot$)

Abbott et al. 2016, Phys. Rev. X, 6, 041015
Abbott et al. 2016, ApJL 818, 22

Where did the BBH mergers occur?

Luminosity distance



Event	GW150914	GW151226	LVT151012
D_L (Mpc)	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}

Abbott et al. 2016, Phys. Rev. X, 6, 041015

Final sky localization

Event	GW150914	GW151226	LVT151012
$\Delta\Omega$ (deg^2)	230	850	1600

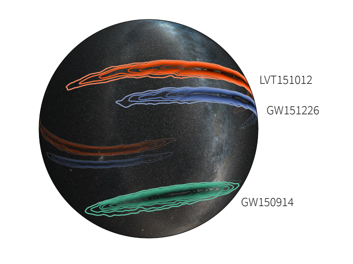


Image credit: LIGO/L. Singer/A. Mellinger

O2: the second observing run

November 30, 2016 - August 25, 2017

Other BBH mergers detected by Advanced LIGO...

GW 170104

- *Primary BH mass* m_1*:* $31.2^{+8.4}_{-6.0}$ $M_\odot$
- *Secondary BH mass* m_2*:* $19.4^{+5.3}_{-5.9}$ $M_\odot$
- *Final BH mass* M_f*:* $48.7^{+5.7}_{-4.6}$ $M_\odot$
- *Radiated energy* $E_{\rm rad}$*:* $2.0^{+0.6}_{-0.7}$ $M_\odot\ c^2$
- *Luminosity distance* D_L*:* 880^{+450}_{-390} *Mpc*

Abbott et al. 2017, PRL, 118, 221101

GW170608

- *Primary BH mass* m_1*:* 12^{+7}_{-2} $M_\odot$
- *Secondary BH mass* m_2*:* 7^{+2}_{-2} $M_\odot$
- *Final BH mass* M_f*:* $18.0^{+4.8}_{-0.9}$ $M_\odot$
- *Radiated energy* $E_{\rm rad}$*:* $0.85^{+0.07}_{-0.17}$ $M_\odot\ c^2$
- *Luminosity distance* D_L*:* 340^{+140}_{-140} *Mpc*

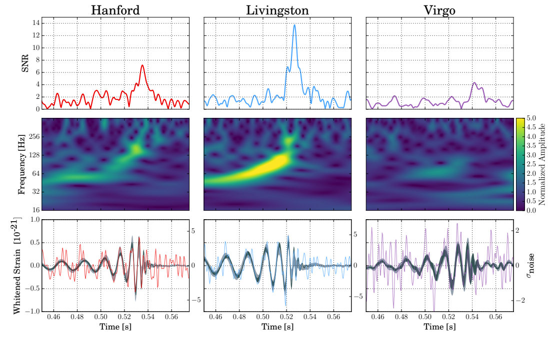
Abbott et al. 2017, ApJL, 851, 35

BBH merger rate (O1 + GW170104): 12 - 213 Gpc^{-3} yr^{-1}

GW170814

On August 1st, 2017 Virgo joined Advanced LIGO.

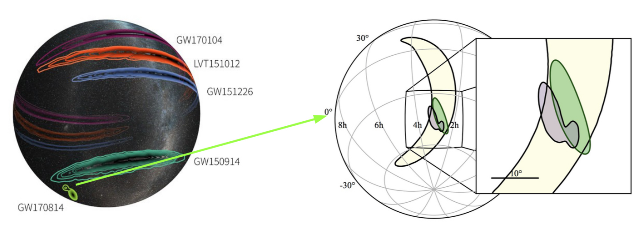
On August 14: **the first three-detector observation** of a GW signal!



- Combined SNR: 18
- $D_L = 540^{+130}_{-210}$ Mpc
- $m_1 = 30.5^{+5.7}_{-3.0}$ $M_\odot$;
  $m_2 = 25.3^{+2.8}_{-4.2}$ $M_\odot$;
- $M_f = 53.2^{+3.2}_{-2.5}$ $M_\odot$
- $E_{rad} = 2.7^{+0.4}_{-0.3}$ $M_\odot$ c^2

Abbott et al., PRL, 119, 141101 (2017)

GW170814: sky localization



Sky localization:

rapid loc., HL: 1160 deg^2

rapid loc., HLV: 100 deg^2

final loc., HLV: 60 deg^2

Image credit:

LIGO/CALTECH/MIT/L. Singer/A. Mellinger
Abbott et al., PRL, 119, 141101 (2017)

Virgo significantly improved the sky localization!

GW170814: GW polarization

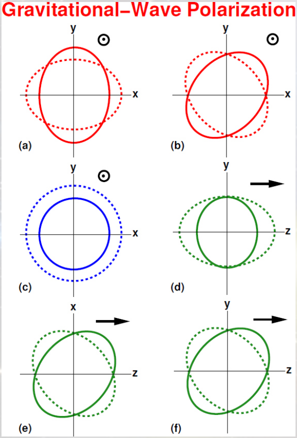


Image credit: Will 2014, LLR, 17, 117

- General Relavitity: two tensor polarizations only
- generic metric theories: allow up to six polarization states

LIGO-Hanford and Livingston have similar orientations $\rightarrow$ little information about GW polarizations

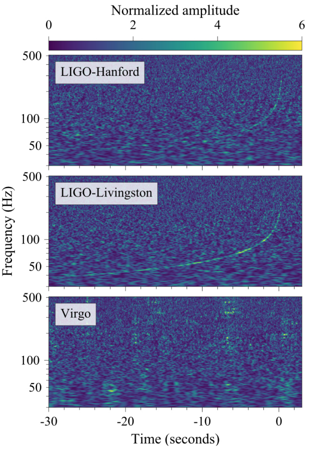
With Virgo we can project the GW amplitude onto the 3 detectors $\rightarrow$ probe the nature of GW polarizations

Only models with "pure" polarization states (tensor, vector or scalar) have been considered.
Result: purely tensor polarization is strongly favored over purely scalar or vector polarizations

Abbott et al. 2017, PRL, 119, 141101

GW170817

On August 17, 2017 at 12:41:04 UTC Advanced LIGO and Advanced Virgo made their **first observation of a binary neutron star (BNS) inspiral!**



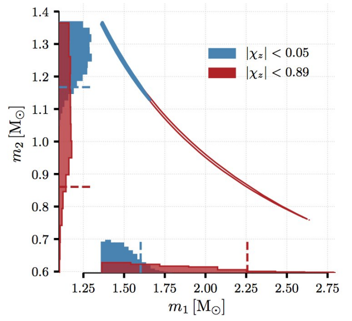
- GW170817 swept through the detectors' sensitive band for ~ 100 s ($f_{start} = 24$ Hz)
- The SNR is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

  the combined SNR is 32.4

  $\Rightarrow$ This is the loudest signal yet observed!

Abbott et al., PRL, 119, 161101 (2017)

BNS detection: component masses



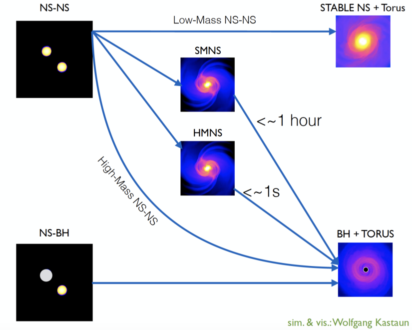
	low-spin ($|\chi| \lesssim 0.05$)	high-spin ($|\chi| \lesssim 0.89$)
m_1	1.36 - 1.60 $M_\odot$	1.36 - 2.26 $M_\odot$
m_2	1.17- 1.36 $M_\odot$	0.86 - 1.36 $M_\odot$
M_{chirp}	$1.188^{+0.004}_{-0.002}$ $M_\odot$	$1.188^{+0.004}_{-0.002}$ $M_\odot$
M_{Tot}	$2.74^{+0.04}_{-0.01}$ $M_\odot$	$2.82^{+0.47}_{-0.09}$ $M_\odot$

Estimated masses (m_1 and m_2) within the range of known NS masses and below those of known BHs $\Rightarrow$ this suggests the source was composed of two NSs

Abbott et al., PRL, 119, 161101 (2017)

BNS detection: the compact remnant

The outcome of a BNS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state of nuclear matter.

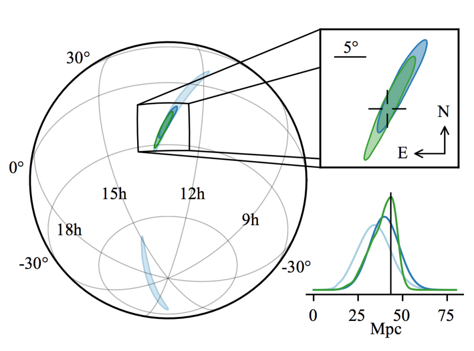


- Stable NS
  (continuous-wave GW signal)
- Supramassive NS (SMNS) collapsing to a BH in 10 - 10^4 s
  (long-transient GW signal)
- Hypermassive NS (HMNS) collapsing to a BH in < 1 s
  (burst-like GW signal)
- BH prompt formation
  (high frequency quasi normal mode ringdown GW signal)

Searches for short (<1 s) and medium (< 500 s) duration transients have not found any post-merger signals (Abbott et al. 2017, ApJL, 851, 16).

Searches for long-duration transients are currently ongoing

Where did the BNS merger occur?



Sky localization:

- rapid loc., HL: 190 deg^2
- rapid loc., HLV: 31 deg^2
- final loc., HLV: 28 deg^2

Luminosity distance:

40^{+8}_{-14} Mpc

This is the closest and most precisely localized gravitational-wave signal!

Abbott et al., PRL, 119, 161101 (2017)

Which were the expected EM counterparts?

- Short GRBs:
  - *Prompt* γ-ray emission (< 2 s).
  - Multiwavelegth *afterglow* emission: X-ray, optical and radio (minutes, hours, days, months).
- Kilonova: optical and NIR (days-weeks).
- Late blast wave emission: radio ($\sim$ months, years).

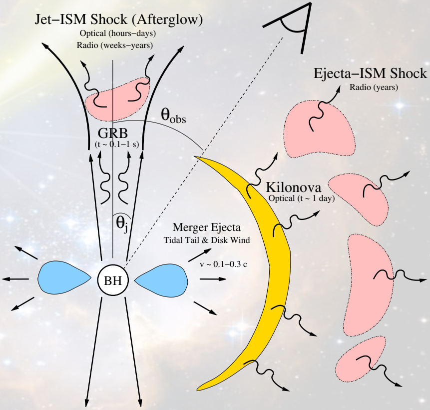
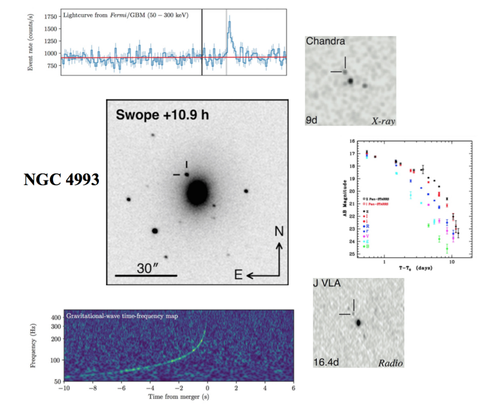


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

What did we observe?



- coincident short GRBs detected in gamma rays

  ⇒ first direct evidence that at least some **BNS mergers are progenitors of short GRBs**

- the **host galaxy** has been identified: NGC 4993

- an optical/infrared/UV counterpart has been detected

  ⇒ first spectroscopic **identification of a kilonova**

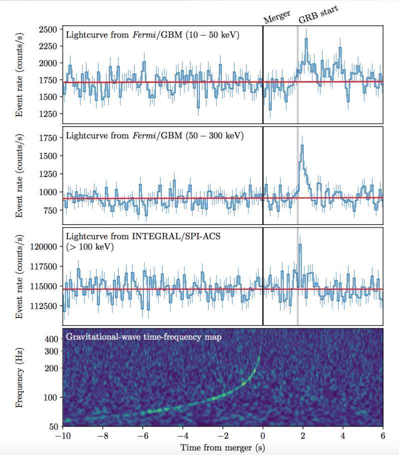
- An X-ray and a radio counterparts have been identified

  ⇒ off-axis afterglow? cocoon emission?

see Abbott et al., ApJ Letters, 848, 2 (2017) and refs. therein

Constraints on fundamental physics

The observed time delay between GRB170817A and GW170817 ($\sim$1.7 s) can be used to put constraints on fundamental physics:



- **Speed of gravity vs speed of light**

$$-3 \times 10^{-15} \leq \frac{\Delta\nu}{\nu_{\rm EM}} \leq 7 \times 10^{-16}$$

- **Test of Equivalence Principle**
  - Shapiro delay δt_S: time difference travelling in a curved spacetime relative to a flat one
  - Effects of curvature quantified with the parameter $\gamma \rightarrow \delta t_S \propto (1+\gamma)$
  - Weak equivalence principle:

    Shapiro delay affects both GW and EM waves in the same manner ($\gamma_{\rm GW}{=}\gamma_{\rm EM}$)

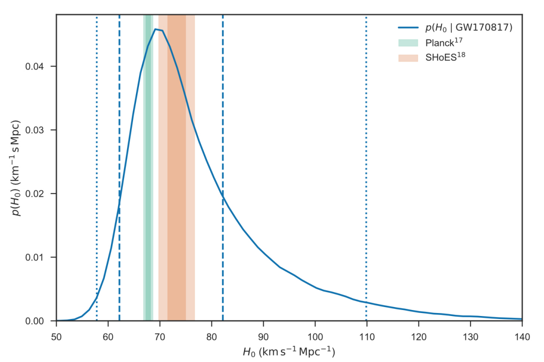
$$-2.6 \times 10^{-7} \leq \gamma_{\rm GW} - \gamma_{\rm EM} \leq 1.2 \times 10^{-6}$$

Abbott et al. 2017, ApJL, 848, 13

Implications for Cosmology

GW170817 as a standard siren:
the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**

$$\mathrm{H}_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1}$$



Abbott et al., Nature, 551, 85 (2017)

The LVC GW-EM/neutrino follow-up program: Towards O3

GW Alerts: from O1 to O2

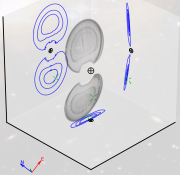
Informations about GW triggers shared through GCN alerts

GCN Alerts content:

- Event time
- Probability sky localization map
- Estimate of the False Alarm Rate of the event candidate (FAR < 1/1month)
- Basic source classification (pipeline that found the event: CBC, Burst or both)

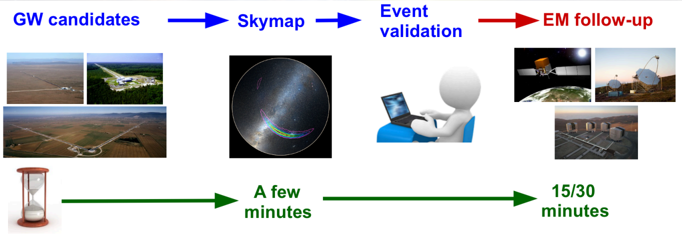
From O2, for CBC events

- "EM bright" indicators:
  - Source classifier: probability of presence of a NS in the binary ($m < 3\ M_{\odot}$)
  - Remnant mass classifier: probability of presence of any NS tidally disrupted mass left outside the BH (Foucart 2012; Pannarale & Ohme 2014)
- Luminosity distance
- 3D skymaps with direction-dependent distance (Singer et al. 2016, ApJL 829, L15)



GW Alerts in O2

Typical latency of tens of minutes (longer in some cases due to technical issues)

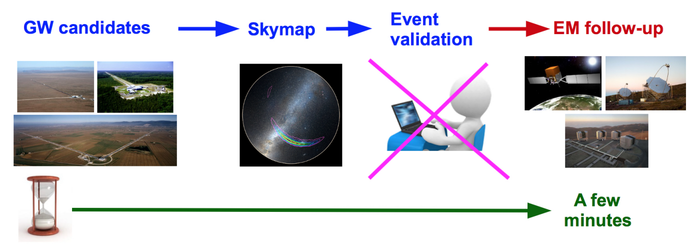


GCN alerts shared with MoU partners for rapid EM/neutrino follow-up of GW candidates found in low latency

95 MoUs involving $\sim$ 200 instruments (satellites and ground-based telescopes) covering the full spectrum from radio to very high-energy γ-rays

From O2 to O3

Aim at sending automatic alerts without human vetting, eventually followed by retraction notices/circulars $\Rightarrow$ latency of minutes!



- LIGO/Virgo will release **confident events publicly** during the upcoming O3 observing run
- LIGO/Virgo will still offer to share less significant candidates with observers through MOUs

Conclusions

- We observed for the first time GWs from merging binary BH and NS systems
- We had the first multi-messenger (GWs+photons) observation of a binary system
- Other sources still to be detected (supernovae, pulsars...)
- Plans are under way to improve LIGO and Virgo sensitivity for O3 and beyond (see A. Allocca's talk)

Many other discoveries are expected in the near future... stay tuned!

Backup slides

BH and NS masses

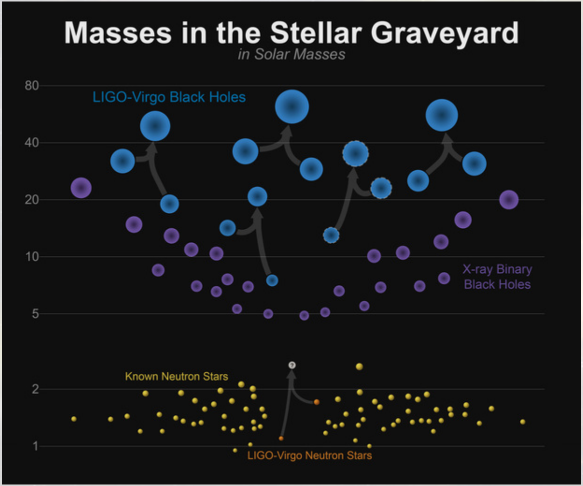
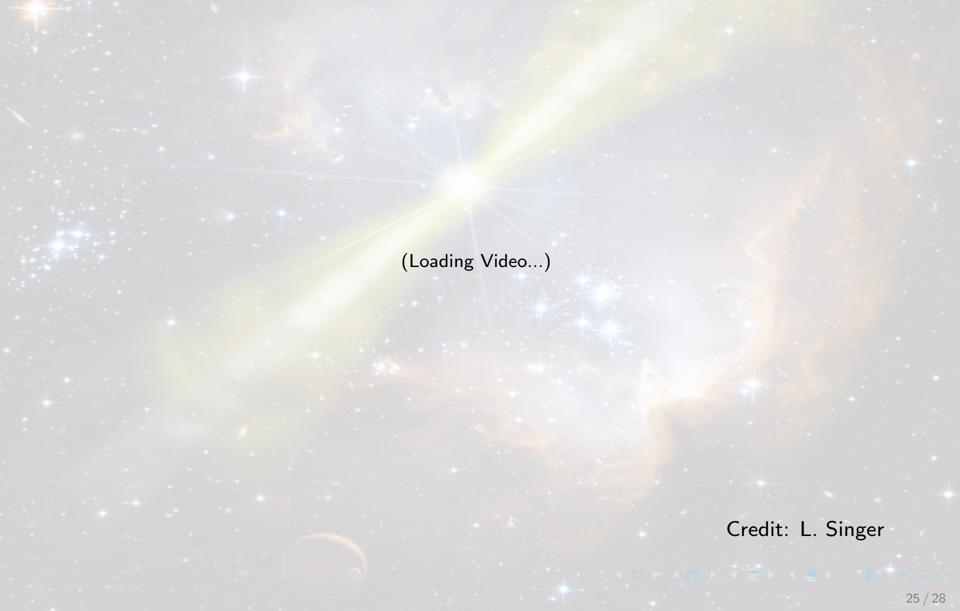


Image credit: LIGO-Virgo/Frank Elavsky/Northwestern University

LIGO and Virgo antenna patterns



(Loading Video...)

Credit: L. Singer

Prospects: a global GW detector network

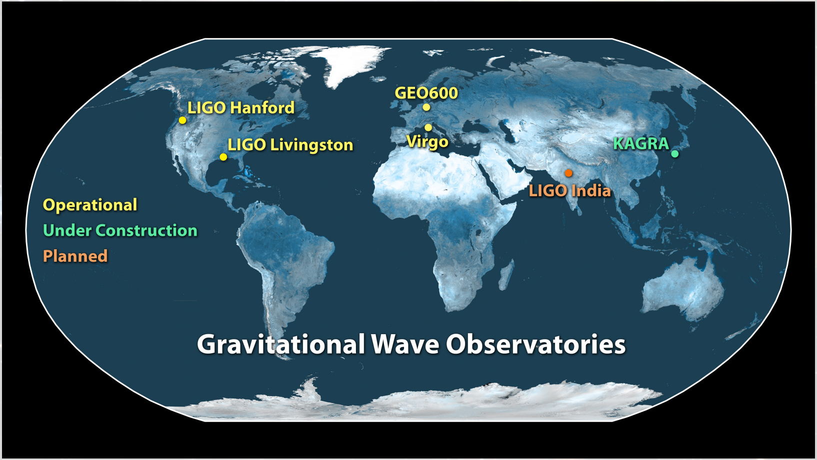
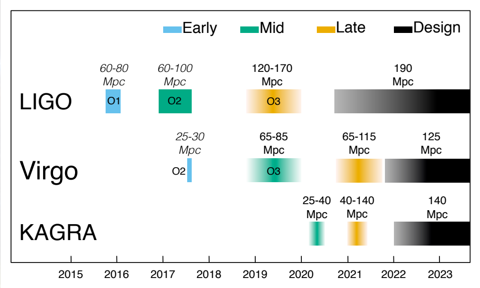


Image credit: Caltech/MIT/LIGO Lab

Prospects: LIGO-Virgo-KAGRA Observing scenario



Epoch	2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration	4 months	9 months	12 months	(per year)	(per year)
Estimated BNS detections*	0.002 – 2	0.007 – 30	0.04 – 100	0.1 – 200	0.4 – 400
% events within 5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
% events within 20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73

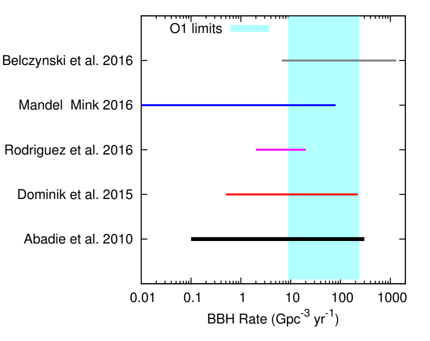
*Assumed BNS merger rate: 10 - 10^4 Gpc^{-3} yr-1

(O2: 320 - 4740 Gpc^{-3} yr-1)

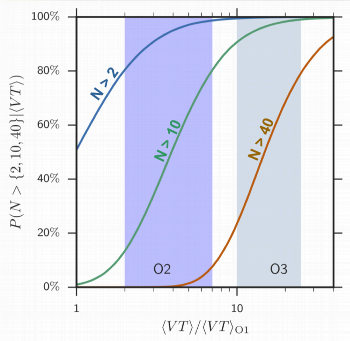
Abbott et al. 2017, arXiv:1304.0670

Expected BBH rate based on O1 observations

O1 BBH merger rate:
9 - 240 Gpc^{-3} yr^{-1}
(O2: 12 - 213 Gpc^{-3} yr^{-1})



BBH highly significant GW detections
(FAR<1/century)



Abbott et al. 2016, PRX, 6, 041015