PHYSICS with CURRENT and FUTURE GW EXPERIMENTS

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O1: 12 Sep 2015 → 19 Jan 2016
Information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms.

<table>
<thead>
<tr>
<th>Event</th>
<th>$m_1/M_\odot$</th>
<th>$m_2/M_\odot$</th>
<th>$M/M_\odot$</th>
<th>$\chi_{\text{eff}}$</th>
<th>$M_1/M_\odot$</th>
<th>$a_\text{f}$</th>
<th>$E_{\text{rad}}/(M_\odot c^2)$</th>
<th>$\ell_{\text{peak}}/(\text{erg s}^{-1})$</th>
<th>$D_L/\text{Mpc}$</th>
<th>$z$</th>
<th>$\Delta \Omega/\text{deg}^2$</th>
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</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>35.6$^{+4.8}_{-3.0}$</td>
<td>30.6$^{+3.0}_{-4.4}$</td>
<td>28.6$^{+1.6}_{-1.2}$</td>
<td>-0.01$^{+0.12}_{-0.13}$</td>
<td>63.1$^{+3.3}_{-3.0}$</td>
<td>0.69$^{+0.05}_{-0.04}$</td>
<td>3.1$^{+0.4}_{-0.3}$</td>
<td>3.6$^{+0.4}_{-0.3}$ $\times 10^{56}$</td>
<td>430$^{+150}_{-170}$</td>
<td>0.09$^{+0.03}_{-0.03}$</td>
<td>194</td>
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<tr>
<td>GW151012</td>
<td>23.2$^{+14.0}_{-5.4}$</td>
<td>13.6$^{+4.1}_{-4.8}$</td>
<td>15.2$^{+2.0}_{-1.2}$</td>
<td>0.04$^{+0.28}_{-0.19}$</td>
<td>35.7$^{+9.9}_{-3.7}$</td>
<td>0.67$^{+0.13}_{-0.11}$</td>
<td>1.5$^{+0.5}_{-0.5}$</td>
<td>3.2$^{+0.8}_{-0.7}$ $\times 10^{56}$</td>
<td>1060$^{+540}_{-480}$</td>
<td>0.21$^{+0.09}_{-0.09}$</td>
<td>1491</td>
</tr>
<tr>
<td>GW151226</td>
<td>13.7$^{+8.8}_{-3.2}$</td>
<td>7.7$^{+2.2}_{-2.6}$</td>
<td>8.9$^{+0.3}_{-0.3}$</td>
<td>0.18$^{+0.20}_{-0.12}$</td>
<td>20.5$^{+6.4}_{-1.5}$</td>
<td>0.74$^{+0.07}_{-0.05}$</td>
<td>1.0$^{+0.1}_{-0.2}$</td>
<td>3.4$^{+0.7}_{-0.7}$ $\times 10^{56}$</td>
<td>440$^{+180}_{-190}$</td>
<td>0.09$^{+0.04}_{-0.04}$</td>
<td>1075</td>
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<td>GW170104</td>
<td>31.0$^{+7.2}_{-5.6}$</td>
<td>20.1$^{+4.9}_{-4.5}$</td>
<td>21.5$^{+2.1}_{-1.7}$</td>
<td>-0.04$^{+0.17}_{-0.20}$</td>
<td>49.4$^{+5.2}_{-3.9}$</td>
<td>0.66$^{+0.09}_{-0.11}$</td>
<td>2.2$^{+0.5}_{-0.5}$</td>
<td>3.2$^{+0.7}_{-0.7}$ $\times 10^{56}$</td>
<td>960$^{+420}_{-410}$</td>
<td>0.19$^{+0.07}_{-0.08}$</td>
<td>912</td>
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<td>GW170608</td>
<td>11.2$^{+5.4}_{-1.9}$</td>
<td>7.5$^{+1.5}_{-2.1}$</td>
<td>7.9$^{+0.2}_{-0.2}$</td>
<td>0.04$^{+0.19}_{-0.06}$</td>
<td>17.9$^{+3.4}_{-0.7}$</td>
<td>0.69$^{+0.04}_{-0.03}$</td>
<td>0.8$^{+0.1}_{-0.1}$</td>
<td>3.4$^{+0.5}_{-0.5}$ $\times 10^{56}$</td>
<td>320$^{+120}_{-110}$</td>
<td>0.07$^{+0.02}_{-0.02}$</td>
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<tr>
<td>GW170729</td>
<td>50.7$^{+16.3}_{-10.8}$</td>
<td>34.4$^{+8.9}_{-10.2}$</td>
<td>35.8$^{+6.3}_{-4.9}$</td>
<td>0.37$^{+0.21}_{-0.26}$</td>
<td>80.3$^{+14.5}_{-10.3}$</td>
<td>0.81$^{+0.07}_{-0.13}$</td>
<td>4.9$^{+1.6}_{-1.7}$</td>
<td>4.2$^{+0.8}_{-1.5}$ $\times 10^{56}$</td>
<td>2760$^{+1290}_{-1350}$</td>
<td>0.48$^{+0.18}_{-0.21}$</td>
<td>1069</td>
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<tr>
<td>GW170809</td>
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<td>23.8$^{+5.2}_{-5.1}$</td>
<td>25.0$^{+2.1}_{-1.6}$</td>
<td>0.07$^{+0.17}_{-0.16}$</td>
<td>56.4$^{+5.2}_{-3.7}$</td>
<td>0.70$^{+0.08}_{-0.09}$</td>
<td>2.7$^{+0.6}_{-0.6}$</td>
<td>3.5$^{+0.6}_{-0.5}$ $\times 10^{56}$</td>
<td>990$^{+320}_{-380}$</td>
<td>0.20$^{+0.05}_{-0.07}$</td>
<td>310</td>
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<tr>
<td>GW170814</td>
<td>30.7$^{+5.5}_{-2.9}$</td>
<td>25.6$^{+2.8}_{-4.0}$</td>
<td>24.3$^{+1.4}_{-1.1}$</td>
<td>0.07$^{+0.12}_{-0.11}$</td>
<td>53.6$^{+3.2}_{-2.5}$</td>
<td>0.73$^{+0.07}_{-0.03}$</td>
<td>2.8$^{+0.4}_{-0.3}$</td>
<td>3.4$^{+0.5}_{-0.5}$ $\times 10^{56}$</td>
<td>560$^{+140}_{-210}$</td>
<td>0.12$^{+0.03}_{-0.04}$</td>
<td>99</td>
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<tr>
<td>GW170817</td>
<td>1.46$^{+0.12}_{-0.10}$</td>
<td>1.27$^{+0.09}_{-0.09}$</td>
<td>1.186$^{+0.01}_{-0.01}$</td>
<td>0.00$^{+0.02}_{-0.01}$</td>
<td>2.8$^{+0.8}_{-0.8}$</td>
<td>$\leq 0.89$</td>
<td>$\geq 0.04$</td>
<td>$\geq 0.1 \times 10^{56}$</td>
<td>40$^{+10}_{-10}$</td>
<td>0.01$^{+0.00}_{-0.00}$</td>
<td>22</td>
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<tr>
<td>GW170818</td>
<td>35.5$^{+7.5}_{-4.7}$</td>
<td>26.9$^{+4.4}_{-5.2}$</td>
<td>26.7$^{+2.1}_{-1.7}$</td>
<td>-0.09$^{+0.18}_{-0.21}$</td>
<td>59.8$^{+4.8}_{-3.7}$</td>
<td>0.67$^{+0.07}_{-0.08}$</td>
<td>2.7$^{+0.5}_{-0.5}$</td>
<td>3.4$^{+0.5}_{-0.7}$ $\times 10^{56}$</td>
<td>1020$^{+430}_{-370}$</td>
<td>0.20$^{+0.07}_{-0.07}$</td>
<td>35</td>
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<td>GW170823</td>
<td>39.5$^{+10.1}_{-6.6}$</td>
<td>29.4$^{+6.5}_{-7.1}$</td>
<td>29.3$^{+4.2}_{-3.1}$</td>
<td>0.08$^{+0.19}_{-0.22}$</td>
<td>65.6$^{+9.3}_{-6.5}$</td>
<td>0.71$^{+0.08}_{-0.09}$</td>
<td>3.3$^{+0.9}_{-0.8}$</td>
<td>3.6$^{+0.6}_{-0.5}$ $\times 10^{56}$</td>
<td>1860$^{+840}_{-840}$</td>
<td>0.34$^{+0.13}_{-0.14}$</td>
<td>1780</td>
</tr>
</tbody>
</table>
Masses

- Wide range of BH masses
  - More BBH towards the heavy end, none in either mass gaps
  - GW170729: heaviest (~80 M⊙) and furthest (z~0.5)
- BNS remnant in the mass gap
BH Spins

Key signatures to discriminate BH populations: shed light on formation mechanism

GW170729 has a clear indication of a net positive \( \chi_{\text{eff}} \)

Precession remains unconstrained for all events

\[
\chi_{\text{eff}} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \cdot \hat{L}_N}{M}
\]
GW170817

Aug 17, 2017
GW from BNS detected by LIGO/Virgo
Fermi GBM detects sGRB after 1.7 s

GCN sent after ~27'
Event localized within ~30° sq
Optical counterpart first observed by SWOPE after ~11h

Multiwavelength observation of the source: kilonova

ApJL 2017 and ref. therein

GW170817
INTERNAL STRUCTURE AND COMPOSITION (LARGELY UNKNOWN) ENCODED IN THE EQUATION OF STATE

Each NS is deformed by the tidal field of the companion. Deformations leave an imprint on the GW emission.
LIGO/VIRGO are measuring the NS radius/mass. Improving the accuracy (better SNR, more events) will allow to determine the EOS.

LVC, PRL 121, 161101 (2018)
From GW: redshifted mass and luminosity distance

\[ \Psi(f) \propto 2\pi ft_c \Phi_c \frac{\pi}{4} + \frac{3}{128} (\pi M_z f)^{-5/3} [1 + \ldots] \]

\[ \tilde{h}_+ (f) \propto A_0 \frac{M_z^{5/6}}{D_L} \left[ 1 + \cos^2 \iota \right] f^{-7/6} e^{i\Psi(f)} \]

Inclination angle introduces degeneracy, which will be removed by measuring the 2 polarizations.
New measurement of $H_0$ using the O1+O2 detections and galaxy catalogs

$H_0 = 68^{+14}_{-7}$ km s$^{-1}$ Mpc$^{-1}$
GW170817: FUNDAMENTAL PHYSICS

- GW170817 provides a stringent test of the speed of gravitational waves

\[
\frac{v_{GW} - c}{c} \approx \frac{c}{D} (\Delta t_{obs} - \Delta t_{start})
\]

- \(\Delta t = 1.7 \pm 0.5\) s over \(\sim 130\) Myrs

\[-3 \cdot 10^{-15} \leq \frac{v_{GW} - c}{c} \leq 7 \cdot 10^{-16}\]

Assuming \(D = 26\) Mpc (lowest value)

Assuming sGRB emitted 10 s after GW

More science from O1-O2

- **Updated merger rates:**
  - BNS: $[110,3840] \text{Gpc}^3 \text{y}^{-1}$
  - BBH: $[9.7,101] \text{Gpc}^3 \text{y}^{-1}$
  - NSBH merger rate 90% upper limit of 610 Gpc$^3$ y$^{-1}$

- **Propagation of GW (dispersion):** $m_g \leq 4.7 \times 10^{-23} \text{eV}/c^2$

- **Polarization tests**

- **Tests of the nature of the BNS remnant**

- **Data available:** [https://www.gw-openscience.org/catalog](https://www.gw-openscience.org/catalog)

LVC, GWTC-1, PRX 2019
LVC, arXiv 1903.04467
LVC, PRL 2017
LVC, arXiv 1908.01012
The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

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
The O3 run

O3a: Apr 1 2019 → Oct 1 2019
O3b: Nov 1 2019 → May 1 2020 (with KAGRA)
Open Public Alerts

LIGO-Virgo will issue Open Public Alerts during the O3 run

Time since gravitational-wave signal

In minutes: automatic preliminary notice with rapid localization

Within 24 hrs: retraction or updated localization, source classification

Significant updates

Original Detection
Set Preferred Event
Automated Vetting
Classification
Rapid Localization

Parameter Estimation
Human Vetting
Classification

Initial Alert or Retraction Sent

Update Alert Sent

10 second 1 minute 1 hour 1 day 1 week
Open Public Alerts

- **Localization**: 3D map for follow-up
- **Classification**: Five numbers, summing to unity, giving probability that the source belongs to five categories
  - This assumes that terrestrial and astrophysical events occur as independent Poisson processes

[Diagram showing classification and mass distribution]

arXiv:1903.06881
Network duty factor

[123816018-129190618]

- Triple interferometer [44.1%]
- Double interferometer [37.7%]
- Single interferometer [15.1%]
- No interferometer [3.2%]
O3a - Summary of public alerts

Mass Gap

Retracted

https://arxiv.org/abs/1304.0670
- 33 public alerts (excluding retractions) in O3a
- Most interesting:
  - 3 NSBH (p>50%)
  - 4 BNS (p\geq 50%)
  - 1 system with a star in the "mass gap"
  - 1 BBH at z \geq 1
- Extensive follow-up but no e.m. counterpart in O3a

https://gracedb.ligo.org/latest/
In just 4 years...

From discovery...

...to population studies
MID-TERM OUTLOOK

- KAGRA to join the network in O3b
- Ligo/Virgo to be further upgraded (A+/AdV+) after O3
- Ligo India to join the network in ~2024
1st GW detection

1st BNS Multi-messenger

arXiv:1304.0670 (v8 Sept 2019)

~20% in 20 sq deg  
HLV 2019

~60% in 10 sq deg  
HIKLV 2024

Credit: S Fairhurst
LONG-TERM OUTLOOK
From here to 3G - GWIC

- 2016: subcommittee to look at the 3G in a coordinated way
  - D Reitze, M Punturo co-chairs
- 2019: report of actions/recommendations to be delivered
  - Science drivers for 3G detectors
  - Coordination of the ground-based GW community
  - Networking
  - Funding agencies interfacing and advocacy
  - Investigate 3G detectors governance schemes
  - Computing

The GW community is engaged in a coherent effort to develop 3G
EINSTEIN TELESCOPE
EINSTEIN TELESCOPE

ET Design Study, 2011

HIGH MASS/HIGH Z

ET

Advanced Virgo

MERGER PHYSICS LOCALIZATION

NUMBER of SOURCES

JENAS2019, Orsay, Oct 16, 2019

G Losurdo - INFN Pisa
COSMIC EXPLORER

- 3rd generation observatory in the US
- Above ground, L shaped, 40 km
- NSF funded design study under way (www.cosmicexplorer.org)
The combination of distances and masses explored, sheer number of detections, and detections with very high SNR will provide a wealth of data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics.
A 3G detector is needed to measure which EOS is the right one.

Takami, Rezzolla, Baiotti (2014)
GW170817 has already demonstrated the possibility to measure $H_0$ with GW standard sirens

Multi-messenger observations at high redshift with 3G will make possible to measure $\rho_{DE}(z)$

Possibility to explore models beyond $\Lambda$CDM
Galileo, 1610
WE HAVE THE RIGHT INSTRUMENT.
NOW WE NEED TO MAKE IT BETTER AND BETTER AND BETTER…

Galileo, 1610

Galileo, 1616

HST, 400 yrs later
ET: the big investment for the next decade (recommendation...
THE POSSIBLE ROLE OF CERN

- The GW community looks at CERN as a model to many extents
- We have a lot to learn from CERN:
  - Model of governance
  - Management of big projects
  - Technology: underground infrastructure, vacuum, cryogenics, computing
- A commitment of CERN on ET (in some form) might be a game changer
The future generation of GW ground-based detectors, which in Europe is the Einstein Telescope project, has the unique potential to strengthen the synergy between cosmology, particle, nuclear, astroparticle physics and astrophysics science domains since: 1) It tests the nature of gravity (…) 2) It explores the nature of dark matter in a complementary way to colliders and underground direct search experiments (…); 3) It provides an independent measure of the Hubble constant either solving the current tension between its far and near determinations or alternatively opening a portal to new physics (…); 4) It reveals phase transition from nucleons to free quarks giving insight into the QCD phase diagram, explores the state of ultra-dense nucleons and the origin of heavy elements (…); 5) It studies the primordial Universe, through primordial stochastic backgrounds, early-Universe phase transitions, cosmic strings (…); 6) It probes the nature of space-time at the interface with quantum mechanics, through the study of alternative gravity and quantum gravity theories.

ET science not only reflects CERN’s own pursuit of fundamental physics, but strong synergies exist concerning the precision engineering that was required to build and operate the LHC.
CONCLUDING REMARKS

- A new field of research has been opened promising access to fundamental physics, nuclear physics, astrophysics, cosmology, dark sector, …
- Time to invest on the development of 3G technologies, infrastructure, detectors
- Einstein Telescope: a EU project for a 3G detector of GW
  - Very strong science case
  - Cost ~1.5 G€
  - Timeline >2030
- A great chance to ensure EU leadership in the field