Cosmology from combining GW events with optical surveys

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with DES-GW

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https://arxiv.org/abs/1710.06748
https://arxiv.org/abs/1901.01540
The age of Gravitational Wave astronomy

**O1 + O2**

11 confident detections

GW170104
LVT151012
GW151226
GW170817
GW150914

DARK ENERGY SURVEY

LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)
Multi-messenger astronomy: DES+LIGO/Virgo

- DECam on the Blanco is (currently) the premier instrument for rapid optical follow-up of Gravitational Wave events*.

- Achieve a depth of $i \approx 22.5$ in a 90s exposure, across a 3 deg$^2$ field.

- Allows us to cover wide regions of sky in a single night – before short-lived transients fade.

- In preparation for the advanced-LIGO GW detector runs, we began a collaboration: DES-GW, involving DES, LIGO and external participants.
Early Binary Black Hole follow-up

Searches for optical counterparts from the first two events: GW150914, GW151226 → nothing (as expected)

Similarly for GW170814, though we were able to cover the whole localisation region.
GW170817 – the event of 2017

- Observations started: 10.53h post merger
- 70.4 deg$^2$, 93.4% initial sky map, 80.7% new
- Visual inspection and comparison with Pan-STARRS: discovery of the KN in NGC 4993 (40 Mpc away)
- Independently discovered by 5 groups
- Candidate selection:
  1. At least 1 detection in i and z
  2. ML score >0.7 in all detections
  3. Significantly faded in the last observations
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- **Bluer bands:** fading below detection limit quickly
- **Redder bands:** slow decline 1.5 d+shoulder at 4d+decline
- KN models with 2 ejecta components are a good fit:
  - lanthanide poor (blue)+ lanthanide rich (red)
- Consistent with estimated r-process production from MW abundances.
What caused the GW170817 event?

- NGC 4993 appears to be a pretty normal early-type galaxy.
- Spectral (6dF) and photometric (DECam+VHS) SED fit:
  \[ M^* = (3.8 \pm 0.20) \times 10^{10} \, M_\odot, \text{ Age} \sim 11 \, \text{Gyr} \]

→ No evidence for recent (last few Gyr) star-formation.
What caused the GW170817 event?

- From modelling binaries and chemical evolution arguments, BNS coalescence is expected to occur within ~ Gyr of formation.

- Expected observable events for BNS in LIGO O1+O2:
  - Early type galaxies: 0.04
  - All galaxies: ~0.5
What caused the GW170817 event?

- From modelling binaries and chemical evolution arguments, BNS coalescence is expect to occur within ~ Gyr of formation.

- Expected observable events for BNS in LIGO O1+O2:
  Early type galaxies: 0.04
  All galaxies: ~0.5

- Clear evidence of a recent galaxy merger.
  → Perhaps some dynamical process was responsible?
What caused the GW170817 event?

If the BNS formation was triggered by the galaxy merger, then delay time = $t_{\text{formation}} - t_{\text{coalescence}} < 200 \text{ Myr}$
Cosmology with GW events

- Emerging tension in the value of $H_0$ derived by different probes:

  Reiss et al. (2019) – $4.4\sigma$ tension between SNe (SHOES), Planck. As high as $6.1\sigma$ inferred through combining late-universe probes.
Cosmology with GW events

- Rate of change in GW frequency → system mass, separation
- GR then tells us the GW luminosity (signal amplitude).
  → “Standard Siren” analogous to type 1a SNe

\[ d_L(z) = (1 + z) \int_0^z \frac{dz'}{H_0 E(z')} \]

\[ [\ c z = H_0 d_L \ ] \]

- If we can obtain a redshift for the event
  → Direct measure of \( H_0 \)!
Cosmology with GW170817

\[ D_L = 43.8 \pm 2.9, \pm 6.9 \text{ Mpc} \]
\[ v_H = 3017 \pm 166 \text{ km s}^{-1} \]

Main uncertainties: Orbital inclination; peculiar velocity.

→ Can obtain a competitive measurement of \( H_0 \) with \(~20\) events
Constraining luminosity distance

- Expected GW strain depends on orbital inclination of the merging binary.
- Produces degeneracy between inclination and distance (hence $H_0$).
Constraining luminosity distance

Super-luminal radio jet emission from KN breaks degeneracy!

Uncertainty reduced by factor ~2.
Peculiar velocities being a nuisance
Peculiar velocities being a nuisance

- Parameterisation of peculiar velocity in Abbott et al. results in bias.
- Possible bias as large as difference between Planck and SH0ES.
Peculiar velocities being a nuisance

Smoothing scale input as a nuisance param.

Nicolaou et al. (subm.)
Howlett & Davis (subm.)
Current LIGO run (O3)

## Current LIGO run (O3)

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<thead>
<tr>
<th>Event ID</th>
<th>Possible Source (Probability)</th>
<th>UTC</th>
<th>GCN</th>
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Current LIGO run (O3)
Cosmology with “Dark Sirens”
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H₀ = 73
Cosmology with “Dark Sirens”
Cosmology with “Dark Sirens”
- GW170814: the first H0 measurement with a BBH

- Measurement is effectively density contrast along l.o.s., w.r.t. flat in volume (weighted by localisation prob.).
- Spectroscopic samples incomplete and not deep enough → photo-z
- Smears out structure, weakening signal.
Cosmology with “Dark Sirens”
- GW170814: the first $H_0$ measurement with a BBH

Soares-Santos, Palmeese, Hartley et al. (2019)

Very little signal in one event
Cosmology with “Dark Sirens”
- limiting factors

- Sky localisation area
  - Cosmic structure diluted on large scales

- LIGO/VIRGO distance estimate
  - Will improve in future with additional stations

- Redshift precision (+ accuracy)
  - Use spectroscopic redshifts where available
    → Main systematic error: photo-z
Cosmology with “Dark Sirens”

- Bayesian formalism to measure $P(H_0 \mid \text{data}_{GW}, \text{data}_{\text{DES}})$ (similar to Chen et al. 2017)
- Blinded analysis tested on realistic simulation data.