Gravitational wave cosmology with large galaxy surveys

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GWADW @ Elba
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GW170814 $H_0$ in collaboration with: M. Soares-Santos, J. Annis, Z. Doctor, W. Farr, M. Fishbach, J. Gair, J. Garcia-Bellido, D. Holz, O. Lahav, H. Lin, W. Hartley, & many more (DES & LVC)
Synergy between GW experiments and galaxy surveys allows **cosmology**, other than counterpart discovery and GW astrophysics.

**Introduction**

- **Motivation**
  - Dark Energy Survey (DES, KiDS/HSC)
  - Standard sirens

- **Current GW detectors**
- **Current galaxy surveys**

**Results**

- **Impact on cosmology**
  - Identify limits/systematics

**Ways forward**

- **Cosmology with next generation GW detectors & galaxy surveys**
Dark Energy Survey (DES)

- First/last light: 12-12-12 / 01-08-19
- Main goal: multi-probe cosmology
  DESCam currently **premier instrument** for GW optical follow up in the Southern hemisphere

DECam

- **3 sq deg FOV**, 570 Mpix optical CCD camera
- CTIO Blanco 4-m telescope (Chile)

DES programs

- **Wide**: 5000 sq deg grizY
- **SNe**: 30 sq deg SNe survey
- **Neutrinos**: followup of Icecube events
- **GW**: followup of LIGO/Virgo events

DECam follow-up continues

Public data

- [https://des.ncsa.illinois.edu/home](https://des.ncsa.illinois.edu/home)
- DR1 (Y3) - 400M objects (r~24)
Motivation for GW cosmology
Is the Universe boring?

- 70% of the mass-energy of the Universe is an unknown substance, Dark Energy (DE). Universe well described by flat ΛCDM

- DE equation of state parameter $w$: $P = w\rho$

- **Cosmological constant** $\Lambda$: energy density constant in time, $w=-1$.

- Current results consistent with $w=-1$

- Dynamical DE (CPL): $w(z) = w_0 + w_a(1 - a)$

- No evidence for dynamical DE

$w = -1.00^{+0.05}_{-0.04}$ (DES+Plank+JLA+BAO, DES 2019 1708.01530)
Hubble constant tension

- **4.4 sigma discrepancy** between early and late time Universe measurements.

- Systematics or new physics?

- Need for an independent measurement. If from late Universe: ideally independent of distance ladder.

Riess+2019
Hubble constant tension

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Riess+2019
Standard sirens

- Similar to SN cosmology:
Standard sirens

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$\mathcal{L}$

GW experiment

Schutz 1986
Holz & Hughes 2005
MacLeod & Hogan 2008
Nissanke+2010
Del Pozzo 2012
Standard sirens

• Similar to SN cosmology:

GW experiment

$dl$

EM experiment - host galaxy redshift

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- Similar to SN cosmology:
  - $d_L$
  - GW experiment
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- Similar to SN cosmology:

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

Local Universe:

\[ H_0 d_L \approx c z \]

EM experiment - host galaxy redshift

GW experiment

\[ z \gtrsim 0.1 : \]

\[ E(z) = \sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda} \]

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*Other methods use GW only (Assumptions on NS MF, EOS, tidal distortions...)

Markovic 1993, Taylor & Gair 2012...

Schutz 1986
Holz & Hughes 2005
MacLeod & Hogan 2008
Nissanke+2010
Del Pozzo 2012
GW+EM standard siren methods

Unique host galaxy

No EM counterpart: potential host galaxies

Bright standard sirens

Dark standard sirens / statistical method
GW170817 as bright standard siren

- NGC 4993 (z~0.01)

\[ H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

- Ideal to solve the Hubble constant tension:
  1. Self-calibrating: Independent of distance ladder
  2. Cosmological model independent
GW170817 as bright standard siren

- Limitations:
  - Peculiar velocity
  - Inclination angle is correlated with $D$
- Can break degeneracy by constraining $i$ from EM
- Improve precision by factor 2-3 (Guidorzi+17, Hotokezaka+18)


Dark sirens
Standard sirens with no EM counterpart

Proposed by Schutz in 1986
Del Pozzo 2012
Chen, Fishbach & Holz (2018)

Machine learning / A.I.

H₀ inference

Prior on H₀

Value of H₀

BBH position (D_L, R.A., Dec)

Priors on BBH parameters

DES galaxy properties (z, M*, Z, τ, μ, σ, R.A.₉₀₀, Dec₉₀₀)

Priors on properties of BBH host galaxies

GW strain signal

LIGO / VIRGO

Prior distribution

Random variables

Observed data

Theoretical data

Proposed by Schutz in 1986
Del Pozzo 2012
Chen, Fishbach & Holz (2018)
Dark sirens
Standard sirens with no EM counterpart

• Factor ~10 more BBH events
• Will miss some EM counterparts to BNS
• Further away - can do more than $H_0$

Proposed by Schutz in 1986
Del Pozzo 2012
Chen, Fishbach & Holz (2018)
Simulations

- Single events: posterior expected to have peaks corresponding to large scale structure along the los
- Peaks are broadened and blended if $d$ or $z$ uncertainty increases.
- Converge to the input value of $H_0$ from combining enough events

DES & LVC (2019) arxiv:1901.01540
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Disclaimer

We are not doing precision cosmology from one event!

DES & LVC (2019) arxiv:1901.01540
GW170814: the golden event (for DES)

- First BBH event from LIGO+Virgo: 90% probability in 60 sq deg
- 90%+ covered by DES-GW follow up (no counterpart - Doctor et al. 2019)
- Falls in the DES footprint
Define a complete volume limited galaxy sample down to $4 \times 10^8 \, M_\odot$ (77\% of total stellar mass) using **Year 3 data**

- ~77,000 galaxies
Results

\[ H_0 = 75.2^{+39.5}_{-32.4} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

DES & LVC (2019) arxiv:1901.01540
GW170817 as a dark siren

- Localization **volume** is crucial!

- Ignore counterpart and use GW170817 as a dark siren

- 1.7x more precise than GW170814

- 2x less precise than bright siren

Prospects for current GW detectors & 3G
Prospects for current detectors

- Few % measurement in ~2022 from **bright sirens**: enough to **solve** $H_0$ **tension**

- **Dark sirens from BBH worse.** Need more well-localized events

- **NSBHs** can provide competitive constraints, if rate $>1/10$ BNS (Vitale & Chen 2019, PRL)

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Chen, Fishbach & Holz 2018, Nature
Dark sirens precision

4-5% statistical precision with DES-like data and ~100 GW170814-like events

Ansatz, systematics to be understood before precision cosmology is allowed:

- Impact of galaxy bias
- Photo-z systematics or spec-z greater incompleteness?
- Clustering of typical host galaxies
Impact on full cosmology

- Combining upcoming GW $H_0$ constraints + future CMB + BAO significantly improves constraints beyond $\Lambda$CDM

- Breaks geometrical degeneracies between parameters from CMB

- Factor 1.6-2.8 improvement on dynamical DE parameters
Host galaxy of GW170817

Synergy GW-large galaxy survey extends to astrophysics of GW sources

Unlikely the binary formed as isolated binary in this type of galaxy
• Position of the transient lies on a shell, remnant of galaxy merger
• Galaxy merging activity may relate sGRB hosts

Suggest that galaxy mergers can boost the BNS formation/merging by boosting dynamical interactions

Alternative: assume isolated binary + SFH → constrain time delay (Blanchard+2017)

Larger statistics of GW hosts will shed light on formation channels of GW sources

Palmese+DES (2017) arxiv:1710.06748
For tens of nearby bright events, small telescopes are enough.

In the era of hundreds-thousands of distant BNSs and for dark sirens, synergy GW experiments-upcoming galaxy surveys is crucial
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Deep imaging and spectroscopy needed.
**DESI** (Wide field spec surveys - Taipan, 4MOST, SDSSV)

*Dark Energy Spectroscopic Instrument*

- 5000 fibers spectrograph at Kitt Peak (AZ)
- ~7 sq. deg. FoV
- 5 years, first light 2019

The **Bright Galaxy Survey (BGS)**
- 14,000 sq deg
- Magnitude limited (r=19.5) out to z~0.4 (median 0.2)
- Great host galaxy catalog for GW science

![DESI Survey Map](image)
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Prospects for standard sirens:
- **Bright sirens:**
  Quick counterpart classification
  Galaxy redshift and peculiar velocities
  \[ \sigma_H \simeq \frac{1}{D} \sqrt{c^2 \sigma_z^2 + \sigma_v^2 + H_0^2 \sigma_D^2} \]
- **Dark sirens:**
  Photo-z systematics suppressed

Palmese+2019, arxiv:1903.04730
LSST & other imaging surveys

- 3.5 deg FoV
- Deepest and widest
- Entire Southern sky
- Every few nights

- Serendipitous discoveries of KNe

**KN Redshift reach** of different experiments

- Potentially detect most KNe at A+ sensitivity: no need to rely on GRB only

- LSST & WFIRST ongoing activities for potential GW follow-up

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**Expected number of KNe found in each sample.**

<table>
<thead>
<tr>
<th>Survey</th>
<th># KNe</th>
<th>Survey Years</th>
<th>KN Redshift Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS</td>
<td>0.13</td>
<td>2</td>
<td>0.02 – 0.05</td>
</tr>
<tr>
<td>SNLS</td>
<td>0.11</td>
<td>4</td>
<td>0.05 – 0.20</td>
</tr>
<tr>
<td>PS1</td>
<td>0.22</td>
<td>4</td>
<td>0.03 – 0.11</td>
</tr>
<tr>
<td>DES</td>
<td>0.26</td>
<td>5</td>
<td>0.05 – 0.20</td>
</tr>
<tr>
<td>ASAS-SN</td>
<td>&lt; 0.001</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>SMT</td>
<td>0.001</td>
<td>5</td>
<td>0.01 – 0.01</td>
</tr>
<tr>
<td>ATLAS</td>
<td>8.3</td>
<td>5</td>
<td>0.01 – 0.03</td>
</tr>
<tr>
<td>ZTF</td>
<td>10.6</td>
<td>5</td>
<td>0.01 – 0.04</td>
</tr>
<tr>
<td>LSST WFD</td>
<td>69</td>
<td>10</td>
<td>0.02 – 0.25</td>
</tr>
<tr>
<td>LSST DDF</td>
<td>5.5</td>
<td>10</td>
<td>0.05 – 0.25</td>
</tr>
<tr>
<td>WFIRST</td>
<td>16.0</td>
<td>2</td>
<td>0.1 – 0.8</td>
</tr>
</tbody>
</table>

Scolnic+DES 2017
Prospects for 3G detectors

- Direct impact on cosmological parameters beyond $H_0$ because of higher $D$ reach

- $D$-z relation sensitive to: $H_0, \Omega_m, \Omega_k, w_0, w_a$

- ET + sGRB: $\sim 1000$ events. Still needs host galaxies. Improve with KNe?

- Cannot constrain all parameters competitively with current DE experiments by itself (Sathyaprakash+09, Zhao+11)

- Combination with experiments that constrain some parameters (e.g. Planck) will lead to DE constraints competitive with DE experiments (in particular Taylor & Gair 2012, no EM)

Zhao+11
Conclusions

• Current GW detectors + current/near future galaxy surveys have the potential to help understanding:
  ★ $H_0$ tension
  ★ LCDM extensions (indirectly)
• 3G: Dark Energy
• Improved localization volume will be crucial for cosmology with 3G, potentially allowing interesting dark siren cosmology constraints

To dos:
• More uniformly sampled, complete, galaxy catalogs for dark siren cosmology & follow-up
• Forecasts for 3G + galaxy surveys
• Impact on target selection + GW follow-up for 2030s DE experiments (DESI2, LSST spectroscopy…)
Back-up slides
Method

- Bayes’ theorem:

\[ p(H_0|d_{GW}, d_{EM}) \propto p(d_{GW}, d_{EM}|H_0)p(H_0) \]

- Source position assumption: it lives in galaxies \( i \)
- Marginalize over all galaxies

\[ p(H_0|d_{GW}, d_{EM}) \propto \frac{p(H_0)}{\beta(H_0)} \sum_i w_i \int dz_i \ p(d_{GW}|d_L(z_i, H_0), \Omega_i) \ p(d_{EM}|z_i) \frac{r^2(z_i)}{H(z_i)} \]

Proposed by Schutz in 1986

LIGO data (source position & distance)

DES data (galaxies’ positions & redshifts)

Selection effects

LIGO/Virgo Skymap

DES photo-zs

Del Pozzo 2012
Chen, Fishbach & Holz (2018)
BLISS+DELVE

PI: Drlica-Wagner

While we wait for LSST...

Important for:
- Template images
- Complete galaxy catalogs
- Pan-STARRS in the North
GW170817 host galaxy - SED analysis

- Spectral (6dF) and photometric (DECam+VHS) SED fit
- \( M^* = (3.8 \pm 0.20) \times 10^{10} \, M_\odot, \) Age\(~11\) Gyr
- Weak \textbf{ionized gas emission lines by AGN}
- \textbf{Pixel SED fit}, also allowing late SF bursts
- \textbf{No evidence for recent star formation}
- \textbf{Surprising for isolated binary scenario}

Palmese et al. (2017) \texttt{arxiv:1710.06748}
Expected rate in early type galaxies

- Assuming BNSs are formed as isolated binaries

\[ R_{NSM}(t) = \alpha R_{NS}(t') \]

\[ t' = t - \Delta t_{NSM} \]

\[ R_{NS}(t') = \int dM_\star \Phi(M_\star) \Psi(t_\star) \Theta_{NS}(M_\star) \]

- Assume SMF + cosmic SFR density:

\[ R_{NSM}^{\text{early}} = 23^{+2}_{-14} \text{ yr}^{-1} \text{ Gpc}^{-3}; \quad R_{NSM}^{\text{all}} \approx 270 \text{ yr}^{-1} \text{ Gpc}^{-3} \]

Expected observable events for BNS in LIGO O1+O2

Early type galaxies: 0.04
All galaxies: \(\sim 0.5\)

Observing a merger of isolated binary in this type of galaxy unlikely

Palmese et al. (2017) [arxiv:1710.06748]