Gravitational wave astrophysics and cosmology with (DES)* galaxies

Antonella Palmese
Midwest workshop on SN and transients @ KICP
25 February 2019


*DECam+other surveys
DECam currently one of the best instrument for GW optical follow up in the Southern hemisphere

4 DES studies on GW170817 → DECam analysis of host galaxy

By studying the host galaxy → binary formation

Synergy between GW experiments and galaxy surveys also allows cosmology

First measurement of $H_0$ from a dark siren using GW170814 (DES+LVC)

Outline:
- What we learned from DES/DECam galaxies
- Science with future surveys (DELVE, DESI, LSST)
Dark Energy Survey (DES)

DECam
- 3 sq deg FOV, 570 Mpix optical CCD camera
  CTIO Blanco 4-m telescope (Chile)
- First/last light: 12-12-12 / 01-08-19

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

Public data
https://des.ncsa.illinois.edu/home
- DR1 (Y3) - 400M objects (r~24)
- Value added Y1 catalogs
- Y3 Supernovae
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Part I

Bright events

Astrophysics  Cosmology
GW170817 host galaxy - SED analysis

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

Stellar mass map from pixel SED fit

Palmese et al. (2017) 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:

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

Expected observable events for BNS in LIGO O1+O2
- Early type galaxies: 0.04
- All galaxies: \(\sim0.5\)

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

Vangioni et al. 2016
NGC 4993: a normal elliptical?

- DECam $ugrizY + HST \ F606W + VHS + WISE$
- Extensive morphology study
- A disturbed galaxy (extended stellar halo, some asymmetry, 2 superimposed stellar populations...)
NGC 4993: a shell galaxy

- Residual images from DECam and HST
- At least 4 shell structures
- HST: inner shell on which the transient seem to lie and dust lanes
- Signs of a recent galaxy merger
NGC 4993: a recent galaxy merger

Shells are arcs of enhanced surface brightness corresponding to higher stellar densities, relics of a galaxy merger

http://hubblesite.org/video/558/news/4-galaxies
Galaxy merger and environment

Distribution of shells can constrain the time of the galaxy merger
Survival time of the innermost shell: \( t_{\text{mer}} < t_{\text{dyn}} < 200 \text{ Myr} \)

- Unlikely the binary formed as isolated binary
- Position of the transient lies on a shell
- Galaxy merging activity may relate sGRB hosts

- Suggest that galaxy mergers can boost the BNS formation/merging by boosting dynamical interactions
- More likely to be observed in galaxy groups
- For this group:
  \[ t_{\text{cr}} \sim \frac{R_v}{\sqrt{2.5} \sigma_v} \sim 1.6 \text{ Gyr} \]
Standard sirens

- Similar to SN cosmology:

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

Done for GW170817 in Abbott et al. 2017
Part II

Dark events

Astrophysics

Cosmology
Dark sirens

Standard sirens with no EM counterpart

GW strain signal

Synthetic stellar population library (FSPS)

Training sample galaxy properties ($z, M^*, Z, \tau, \mu, \sigma$)

Priors on galaxy properties

Synthetic photometry

DES galaxy properties ($z, M^*, Z, \tau, \mu, \sigma, R.A._{\text{gal}}, \text{Dec}_{\text{gal}}$)

Value of $H_0$

Priors on BBH host galaxies

BBH position ($D_L, R.A., \text{Dec}$)

Prior on $H_0$

Priors on BBH parameters

LIGO / VIRGO

Machine learning / A.I.

Prior distribution

Random variables

Observed data

Theoretical data

DES galaxy properties

Priors on population model parameters

Priors on properties of BBH host galaxies

Trained galaxy population model

$H_0$ inference

Value of $H_0$

BBH position ($D_L, R.A., \text{Dec}$)

Prior on $H_0$

Priors on BBH parameters

DES galaxy properties ($z, M^*, Z, \tau, \mu, \sigma, R.A._{\text{gal}}, \text{Dec}_{\text{gal}}$)

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Theoretical data
Dark sirens
Standard sirens with no EM counterpart

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

Proposed by Schutz in 1986

Selection effects

LIGO/Virgo

DES

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
Simulations

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• Peaks are broadened and blended if $d$ or $z$ uncertainty increases.

• Converge to the input value of $H_0$ from combining enough events.

Disclaimer

We are not doing precision cosmology from one event!
GW170814: the golden event (for DES)

- LIGO+Virgo: 90% probability in 60 sq deg
- 90%+ covered by DES-GW follow up (see Zhoeyr Doctor talk tomorrow)
- Falls in the DES footprint
GW170814: the golden event (for DES)

- 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]
Part III

(Near) future galaxy surveys

Astrophysics

Cosmology
DESI

- 5000 fibers spectrograph at Kitt Peak (AZ)
- 5 years, first light 2019

The Bright Galaxy Survey (BGS)
- 14,000 sq deg
- Magnitude limited survey \((r=19.5)\) out to \(z \sim 0.4\) (median 0.2)
- 10M galaxies
- Precision \(\sigma_z \sim 0.0005\)
BLISS+DELVE PI: Alex Drlica-Wagner

While we wait for LSST…
Conclusions

• Synergies between GW experiments and large galaxy surveys allow studies of both the formation of GW sources and cosmological parameter inference, other than transient discovery

• Lessons from DES+LIGO/Virgo:
  • Indication for **BNS formation different from isolated binary scenario**
  • **First measurement** of $H_0$ with GW170814+DES galaxies
  • Proof of concept and identification of sources of systematics/ansatz

Future work

• Systematics of dark sirens
• Similar method for dark events host galaxy properties
• DESI and LSST GW science
• Full sky galaxy catalog for dark siren cosmology & follow-up (DES+BLISS+public catalogs)
Back-up slides
Shell galaxies in DES Year 1

~15% of selected early-type galaxies present shells

Public morphological catalog:
No strong conclusions about BNS formation from one event, but the coincidence of a recent merger in a galaxy for which a BNS event was otherwise improbable is compelling.

- Belczynski et al. 2018 follows similar motivation to suggest alternative formation scenario.
- 50% of mass formed by ~11 Gyr ago -> median delay timescale.
Results from simulations

- 4-5% statistical precision with DES-like data and ~100 GW170814-like events
Host galaxy - Comparison to sGRB hosts

- **Asymmetry and concentration** consistent with early-type galaxies but **unusual** for sGRB hosts
- **Clear major galaxy mergers** are unusual amongst sGRB hosts
- Other sGRBs are at **cosmological distances** and thus are mostly undergoing extensive galaxy formation through star formation or merging
- **Common feature:** merging activity
- **Minor merger** such that the bulk morphology is still elliptical

→ Is the BNS formation or evolution related to a recent galaxy merger history?
Host galaxy - pCMD

- Well represented by a pixel “main sequence” that is bluer at fainter levels, typical of early-type galaxy color gradients
- Supports scenario in which BNS is not related to local SF events

Evidence for a recent **dry** minor galaxy merger (no SF)
A star cluster?

- $r$-band absolute magnitude from a 4 sq.arcsec region around the transient location in the galaxy-subtracted image is $-10.65$
- Dynamical interactions are more likely within star clusters and in galaxy nucleus (higher stellar density in ellipticals), where infalling stars may have passed
- Cannot exclude kicks