THE DES GRAVITATIONAL WAVE EVENT FOLLOW-UP PROGRAM

Marcelle Soares-Santos
The DES Collaboration
Fermilab

THE DECAM/DESGW PROGRAM

Can we take advantage of this new way to observe the universe, with Gravitational Waves, in combination with traditional astronomical, data to study new Astrophysics and Cosmology?

With this goal in mind, we launched the DESGW program in 2013.

We developed an analysis that is sensitive to NS-NS, BH-NS mergers out to 200Mpc — and didn’t see an optical counterpart for the first event. It turned out the event did not have a NS in it, but prospects for future are good!

This effort is done in partnership with LIGO members and non-DES users of DECam. It is supported by Fermilab’s LDRD grant program in FY15 & FY16, and by the Chicago SCI grant in FY17.
THE PROGRAM

**GW trigger**
- time stamp
- sky region
- distance
- event type

~24h

**DECam search system**
- prepare template images
- schedule observations
- take new images
- perform image subtraction
- detect, model counterpart

---

**We are here!**

<table>
<thead>
<tr>
<th>O1</th>
<th>DES observations (Sep-Feb months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aLigo</td>
<td>2015</td>
</tr>
<tr>
<td>aLigo</td>
<td>2016-17</td>
</tr>
<tr>
<td>aVirgo + aLigo</td>
<td>2017-18</td>
</tr>
<tr>
<td>aVirgo + aLigo</td>
<td>2019+</td>
</tr>
<tr>
<td>aVirgo + aLigo</td>
<td>2022+ (India)</td>
</tr>
</tbody>
</table>

**LIGO:** arXiv:1304.0670

---

Marcelle Soares-Santos ◆ DESGW ◆ KITP Workshop, Santa Barbara ◆ Aug 11, 2016
SUMMARY OF O1

Events:

GW150914 (aka event #1): 5-sigma detection, high-mass BBH

LVT151012 (aka, the one that didn’t trigger): 2-sigma event, high-mass BBH

GW151226 (aka event #2): 5-sigma, high-mass BBH merger

* We followed-up on events #1 and #2.

Various groups also did follow-up observations, covering most of the EM spectrum. See Abbott et al. 2016 (arXiv:1602.08492) for a summary of all groups involved.
Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

LVC sky localization probability map (final)
GW150914

Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

Obs time: 2015 Sep 18
(end of the night)

DES source detection probability map
GW150914

Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

Obs time: 2015 Sep 18
(end of the night)

DES source detection probability map
## DATA

28 fields, izz bands, 90 sec (11 in footprint, 17 outside)  
20 fields, izz bands, 5 sec (LMC area)

<table>
<thead>
<tr>
<th>Program</th>
<th>Night</th>
<th>MJD</th>
<th>$\Delta t^a$ (days)</th>
<th>$\langle$PSF(FWHM$_i$)$\rangle$ (arcsec)</th>
<th>$\langle$airmass$\rangle$</th>
<th>$\langle$depth$_i$$\rangle$ (mag)</th>
<th>$\langle$depth$_z$$\rangle$ (mag)</th>
<th>$A_{\text{eff}}^b$ (deg$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main, 1$^{\text{st}}$ epoch</td>
<td>2015-09-17</td>
<td>57383</td>
<td>3.88</td>
<td>1.38</td>
<td>1.50</td>
<td>22.71</td>
<td>22.00</td>
<td>52.8</td>
</tr>
<tr>
<td></td>
<td>2015-09-18</td>
<td>57384</td>
<td>4.97</td>
<td>1.35</td>
<td>1.46</td>
<td>22.82</td>
<td>22.12</td>
<td>14.4</td>
</tr>
<tr>
<td>Main, 2$^{\text{nd}}$ epoch</td>
<td>2015-09-20</td>
<td>57286</td>
<td>6.86</td>
<td>2.17</td>
<td>1.51</td>
<td>22.18</td>
<td>21.48</td>
<td>67.2</td>
</tr>
<tr>
<td>Main, 3$^{\text{rd}}$ epoch</td>
<td>2015-10-07</td>
<td>57303</td>
<td>23.84</td>
<td>1.46</td>
<td>1.40</td>
<td>22.33</td>
<td>21.63</td>
<td>67.2</td>
</tr>
<tr>
<td>LMC, initial</td>
<td>2015-09-17</td>
<td>57383</td>
<td>3.98</td>
<td>1.14</td>
<td>1.30</td>
<td>21.32</td>
<td>20.62</td>
<td>14.4</td>
</tr>
<tr>
<td>LMC, extension</td>
<td>2015-09-26</td>
<td>57292</td>
<td>12.96</td>
<td>1.21</td>
<td>1.28</td>
<td>20.91</td>
<td>20.21</td>
<td>33.6</td>
</tr>
</tbody>
</table>
ANALYSIS 1

Search for a decaying transient (Soares-Santos et al. 2016)

Area (square degrees)
Total observed: 102
Excluding LMC: 84
Considering fill-factor: 67
Good after diffimg: 40
(~30% loss due to missing templates)

Sample selection
(all cuts in i and z bands)
0) Good detection in 1st epoch
1) 2nd epoch S/N>2
2) 3+ sigma 1st to 2nd epoch flux decline
3) S/N < 3 sigma in the 3rd epoch

Efficiency estimates from simulated events
 decay rate: 0.3 mag/day
 50% recovery rate depth:
    color: (i-z) ~ 1   i = 21.5
    color: (i-z) ~ 0   i = 21.1
    color: (i-z) ~-1  i = 20.1

Sensitive to typical NS-NS mergers out to 200Mpc.
Search for disappearing stars in the LMC (Annis et al. 2016)

We take possible progenitors (e.g. red supergiants) catalogued in the literature and search for them via visual inspection. 144 were in the observed area; all accounted for.

This particular GW event was a BBH member, but LIGO will be sensitive to nearby core-collapse events, including failed SNe. **This type of search is a template for future GW events, specifically those likely to be a CC event.**
DECAM SEARCH FOR OPTICAL SIGNATURES OF GW151226


36 square degrees observed (28.8 if considering fill-factor)

4 epochs (last one is template)

4 “candidates” (3 AGNs, 1 SN)

Pre-existing templates would have helped reject those. It is really important to have pre-existing templates!

Rising portion of light curve helps too. Try to be on-sky sooner than 48h post-trigger!
IMPROVEMENTS FOR O2

Results of our DECam searches for counterparts to the first two GW events indicate that prospects for a next season are encouraging!

For the upcoming observing campaign, our goals are:

— Optimize observing strategy (we will have multiple events, mostly BBH mergers)
  — New “economics” code dynamically determine time allocation for each event

— Reduce our image processing turnaround time to ~24h
  — Automate job submission, and post processing steps
  — Feedback info from one night to observing strategy for the next night
  — Obtain spectroscopic data for selected candidates

— Improve efficiency of our analysis
  — More sims with more variety of signal and background models
  — Better understanding of efficiency as a function of surface brightness of the host
  — Match candidates to galaxies (reject high-z candidates)
  — Better handling of variability
This talk described our ongoing effort towards astrophysics and cosmology studies with Gravitational Waves, starting with **searches for counterparts to the first two GW events.**

Our results indicate that prospects for a full fledged program in the DES era and beyond are encouraging!

2nd search campaign to begin in Fall 2016. **Stay tuned!**

Marcelle Soares-Santos ◆ DESGW ◆ KITP Workshop, Santa Barbara ◆ Aug 11, 2016
BACKUP SLIDES
Each search image and template run through single epoch processing (few hours each)

Then each CCD in each search image goes through difference imaging pipeline in parallel, copying in needed templates (~1 hr/job)

Challenge: raw images to plots in < 24 hrs

A productive collaboration involving PPD, SCD.

Completely automated job submission immediately after search image available.
Able to run dozens of images in parallel using Fermilab and OSG grid resources, with support from SCD — thank you!

http://fifemon.fnal.gov/
Search for a decaying transient (Soares-Santos et al. 2016)

**Result**
Zero candidates pass our selection criteria. No optical signatures are predicted for BBH events, so this is not surprising.

**Sample selection**
(all cuts in i and z bands)
0) Good detection in 1st epoch
1) 2nd epoch S/N$>2$
2) 3+ sigma 1st to 2nd epoch flux decline
3) S/N $<3$ sigma in the 3rd epoch

<table>
<thead>
<tr>
<th>mag(i)</th>
<th>raw</th>
<th>cut 1</th>
<th>cut 2</th>
<th>cut 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.0–18.5</td>
<td>84</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18.5–19.0</td>
<td>177</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19.0–19.5</td>
<td>291</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19.5–20.0</td>
<td>227</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>20.0–20.5</td>
<td>156</td>
<td>17</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>20.5–21.0</td>
<td>225</td>
<td>42</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>21.0–21.5</td>
<td>334</td>
<td>84</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>21.5–22.0</td>
<td>756</td>
<td>159</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>22.0–22.5</td>
<td>1099</td>
<td>183</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>2349</td>
<td>491</td>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>

This type of search is a starting point for future NS-NS merger searches.