Optical follow-up of gravitational wave events with DECam

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Gravitational Waves can come from sources other than black hole mergers, e.g. stellar core collapse, neutron star merger, BH-NS merger, etc.

LIGO/Virgo collaboration has several community partners for optical followup, searching for EM signatures
- DES-GW group consists of both DES and GW community members; uses DECam (4m Blanco telescope at CTIO in Chile) for optical followup

DECam currently premier instrument for followup in the Southern Hemisphere
GW EM Followup

LIGO/Virgo

- Trigger: probability map, distance, etc.

Gamma-Ray Coordinates Network (GCN)

- Trigger information to partners; partners' results shared

Other EM followup partners

- Trigger information from LIGO

DES-GW group

- Combine trigger information from LIGO, source detection probability maps

Process Images, Analyze results

- Provide details of any candidates for spectroscopic followup by other partners

Formulate plan, take observations

- Report area(s) observed

Observe? Formulate observing plan: wait for the next one

- Inform DES management of desire to follow up; take final decision with them

- Provide details of any candidates for spectroscopic followup by other partners
GW EM Followup

Light from NS merger events expected to fade in ~days. For early spectroscopic followup, imperative to complete analysis and report findings through GCN within 24 hours.
Observing Strategy and Economics Calculation

- Given imperfect localization, must decide where to observe each night
- Ideally three passes over region: immediately, a few days later, and 2-3 weeks later
  - Want to observe decline in flux for NS merger candidates
- Observing plan formulation:
  - Compute source detection probability assuming source at LIGO distance (conditions change throughout the night)
  - Multiply source detection probability with LIGO probability map to create detection probability
  - Apply algorithm to maximize detection probability over the course of the night taking into account observing conditions
Detecting EM counterparts

• Detect candidates via "difference imaging (diffimg)": subtract template images (previous images of same region of sky) from search images, scan for "new" objects
• Machine learning algorithms applied to candidates
• Detection efficiencies calculated by overlaying fake candidates on search images
• Diffimg pipeline described in Kessler et al. 2016, AJ 150, 172
Putting the plan in action

- As soon as observing plan ready, begin preprocessing template images; do as much as possible before beginning observation (done in grid jobs; few hours per image)
- Engage "listener" which looks for new images once observations have commenced
- Listener calculates needed template images, checks for incomplete template preprocessings, automatically submits preprocessing and difference imaging jobs via HTCondor DAG for each new exposure
  - Listeners will submit jobs for new images every ~4 minutes during observations

2-24 hours before first image
(varies depending on when trigger arrives)

Continuous throughout observing time
Job Processing

- Each search and template image first goes through “single epoch” processing (few hours per image). About 10 templates per image on average (some overlap of course).
- Once done, run difference imaging (template subtraction) on each CCD individually (around 1 hour per job; 60 CCDs) Total: 5-10K CPU-hours for diffimg runs needed per night, depending on # of images. To stay on schedule, must provision CPUs rapidly!
- For initial processing, expect to use mix of FNAL CPUs, opportunistic OSG resources, and commercial cloud resources if necessary (successfully tested on AWS). Tests demonstrate needed rate is achievable
- Use fifebatch job submission infrastructure (GlideinWMS) to seamlessly go between FNAL and remote resources (see FIFE talk, abstract 551)
- Additional campus resources available for subsequent processing on slower timescales
Results from Season 1

- Followup of GW150914 (discovery event) with two analyses
  - Search for disappearing stars in LMC to check for stellar core-collapse (all present and accounted for) Annis et al. 2016, ApJL 823, 2:L34
- Followup of GW151226 (2\textsuperscript{nd} event)
  - Final analysis used Harvard computing resources; 4 candidates but none consistent with GW event Cowperthwaite et al. 2016, ApJL 826, 2:L29
Plans for Season 2

• General cleanup and streamlining of code
  – Preprocessing now using multiple cores, reduced memory and disk footprint

• Additional tests to ensure < 24 hr turnaround

• Re-indexing of databases to promote faster DB response

• Expect many more triggers during second season (~1 per month)
  – Finite amount of observing time. Have to decide whether to observe a given trigger or wait for a better one to (maybe) come along
  – This is a deliberative process involving DES and LIGO members. Must consider several inputs: type of event (BH or NS), sky location, time of trigger (how soon can we start observing?), detection probability, time remaining in season, observing time remaining
  – Final decision also involves DES operations and considers other priorities for telescope time

• Developed an economics calculation to help inform the followup decision for BH events, and formulate the observing plans
Economic Calculation

- Consider maximizing detection probability over the *entire remainder of the season,* not just for *this* event.
- Build repo of simulated probability maps, make tables of sky area needed to reach a given detection probability for a given set of conditions.
- Given your event of interest, construct probability: \( P_{t,i} = P_{SM}(\vec{C}) + P_{\leq i}(A_{left} - \vec{C}) \cdot \vec{N}_{BH,i} \)
  - \( P_{SM}(\vec{C}) \) is the probability from your sky map for a given area, \( A_{left} \) is the remaining area available to observe in the season (prop. to time/night remaining), \( N_{BH} \) is remaining number of events in the season, \( \vec{C} \) is the observing vector (amount of area and direction), \( P_{\leq i} \) is the probability for the mean area if following up on \( i \) events.
- **Choose the \( \vec{C} \) that gives the maximum \( P_{t,i} \)** (i.e. gives the greatest total probability). Prefers smaller observing areas to get same probability; leaves more area/time for "later").
  - Same sky map probability could give a different \( \vec{C} \) at different points in the season.
Summary

- Successful first observing season with proof of concept. DES-GW followup program was the most complete in terms of area covered and magnitude limits.
- Improvements to code and imaging pipeline implemented.
- More robust algorithms available to help inform decisions on whether to follow up on LIGO triggers.
- Eagerly awaiting events during second season and looking forward to sharing results with the GW community.
  - Sensitive to NS mergers out to ~200 Mpc.
  - Excellent discovery potential in the upcoming season.
Imagine listener steps and HTCondor DAG Generation

Separate DAG for each search exposure

New image

Determine overlapping images
Check if SE processing already done for template; if not, add SE job for template to DAG

Create DAG

Search image SE job

Template img 1 SE job

Template img N SE job

CCD 1 diffimg job

CCD 62 diffimg job

End of run processing job (stats + analysis)

SE = "Single Epoch" (image preprocessing)
OSG-only Grid test

- Decided to take about one night’s worth of images and process at a “real-time” rate (new images every 4 minutes)
- Central question: if dedicated resources were unavailable what kind of turnaround time could one expect?
  - Important in evaluating need for commercial cloud resources
  - Caveat: jobs allowed to run opportunistically on FNAL CMS resources
- Took 1-2 hours to ramp up; 90% of jobs completed within 10 hours (tail mostly due to database issues; since fixed)
- This rate would be (barely) sufficient if dedicated FNAL computing resources were unavailable. Can probably get a bit more with optimizing local disk and run time requirements.
  - FNAL dedicated resources typically provide ~3x what we were seeing on OSG alone
AWS Tests

- Considering backup plans in case FNAL and opportunistic OSG resources are unavailable at the time of a trigger
- Commercial clouds are well-suited to this type of "burst" workflow. Can avoid preemption, offer quick provisioning
- Performed tests of diffimg workflow on AWS as part of Femilab HEPCloud evaluation (see B. Holzman's talk); job output stored in S3. All tests successful
- Model would be to perform all phases within AWS to minimize data egress, pulling out only final information about candidates
- Will revisit as we gain more experience and budget considerations clear up
The Dark Energy Survey

- Collaboration of 400 scientists using the Dark Energy Camera (DECam) mounted on the 4m Blanco telescope at CTIO in Chile
- Currently starting fourth year of 5-year mission
- Main program is four probes of dark energy:
  - Type Ia Supernovae
  - Baryon Acoustic Oscillations
  - Galaxy Clusters
  - Weak Lensing
- A number of other projects e.g.:
  - Trans-Neptunian/ moving objects
Formulating an observing plan

- Receive a location probability map from LIGO, along with distance estimate
Formulating an observing plan

- Use observing conditions info, time of day, construct map of faintest objects that can be seen
Formulating an observing plan

• Create source detection probability assuming LIGO distance
Formulating an observing plan

- Multiply LIGO probability with DES detection probability to get source detection probability

White outline: nominal DES observing region