Optical follow-up of gravitational wave events with DECam

Ken Herner for the DES-GW group

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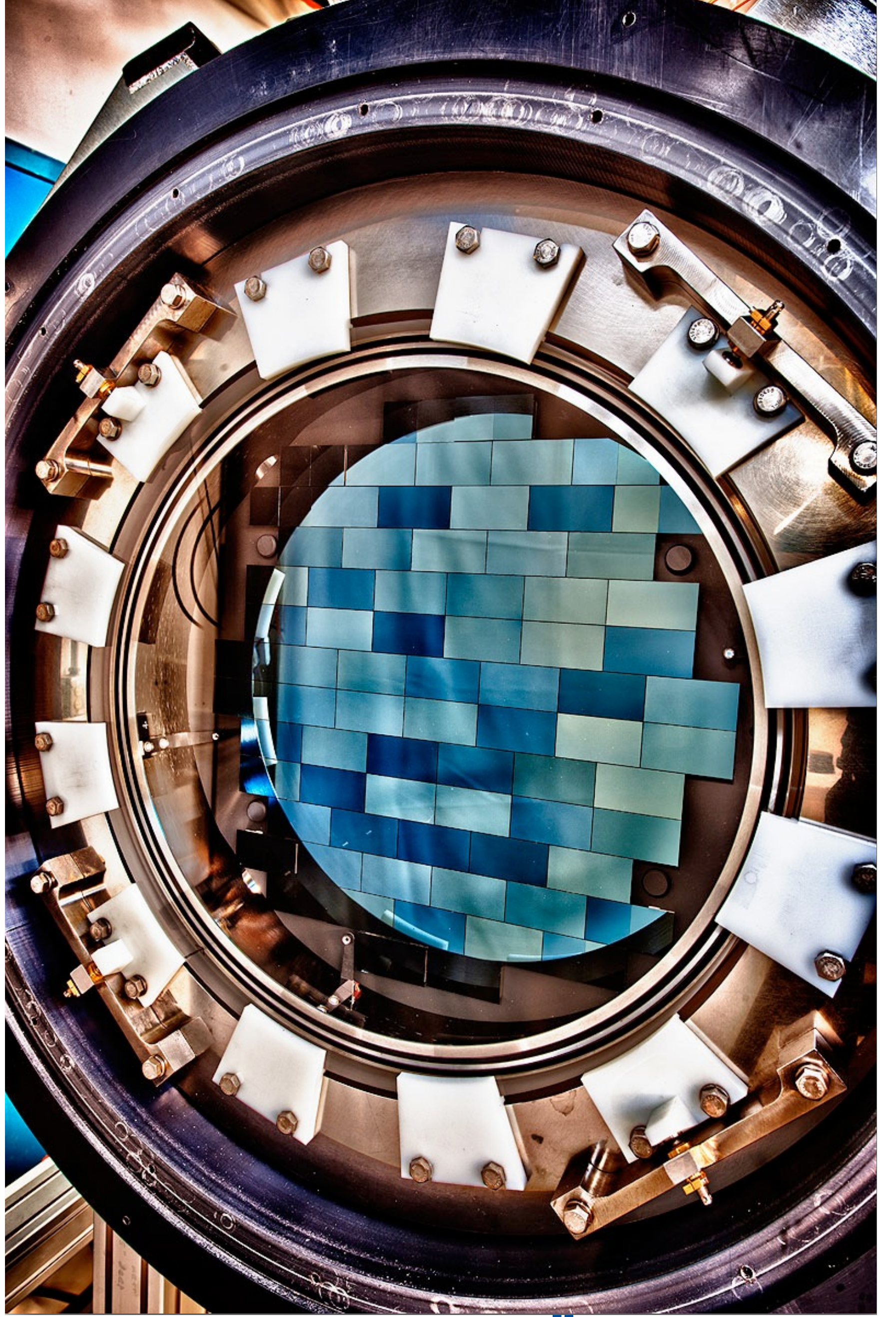
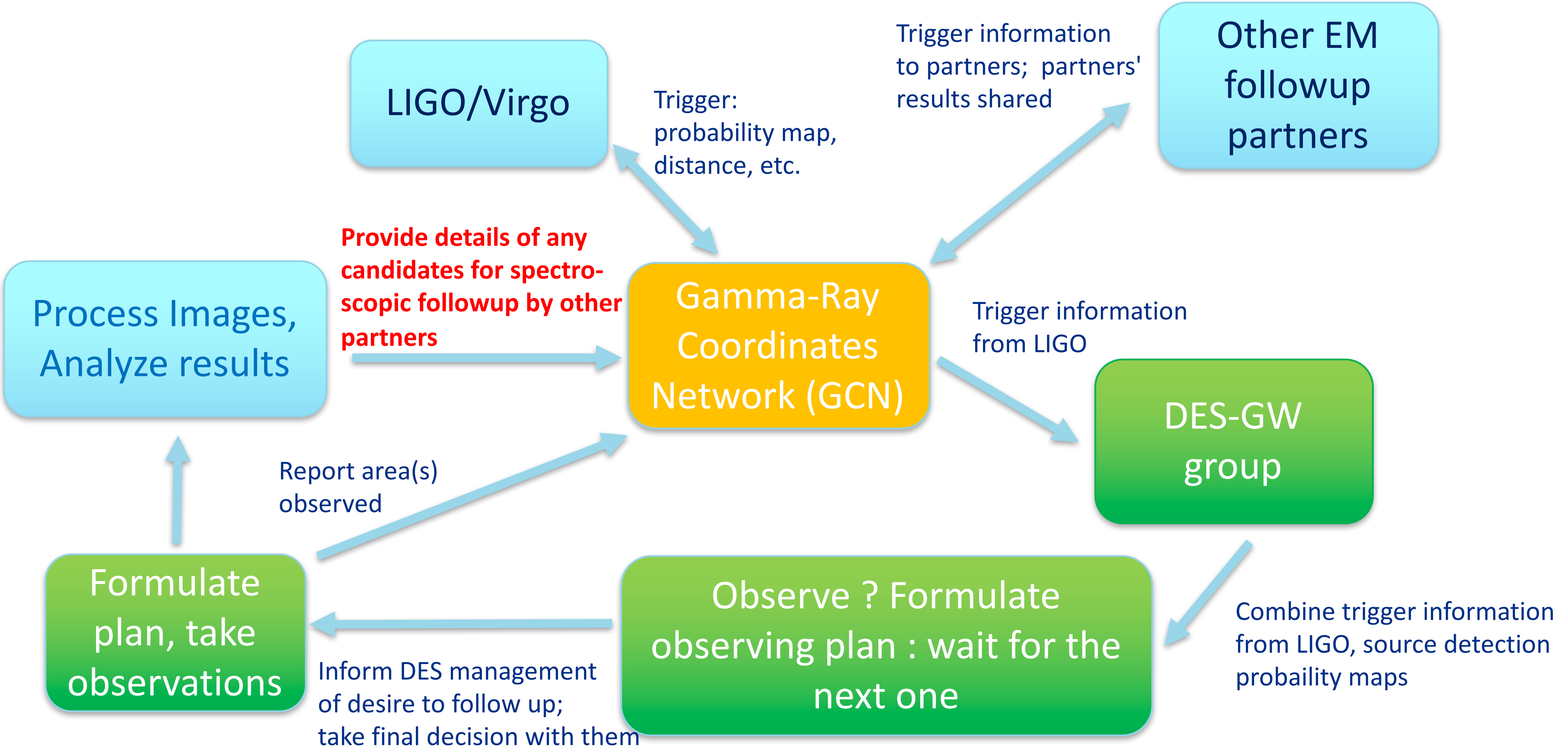
DES-GW Introduction

- 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



GW EM Followup

LIGO/Virgo

Trigger: probability map, distance, etc.

Trigger information to partners; partners' results shared

Other EM followup partners

Process Images, Analyze results

Provide details of any candidates for spectro-scopic followup by other partners

Gamma-Ray Coordinates Network (GCN)

Trigger information from LIGO

DES-GW group

Report area(s) observed

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.

Formulate plan, take observations

Inform DES ma
of desire to foll
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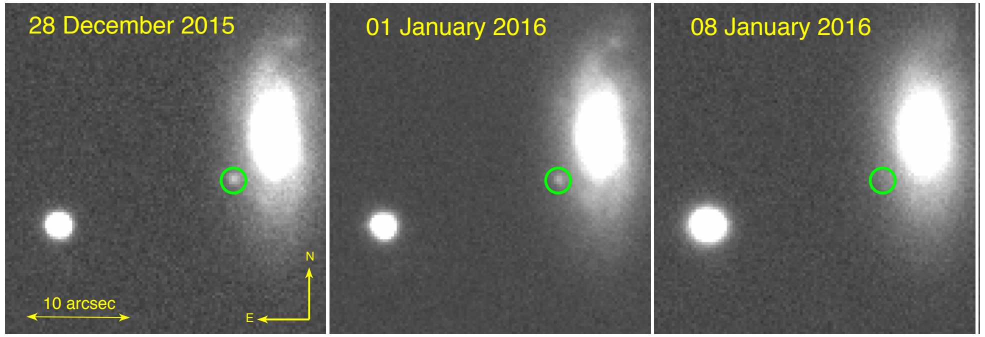
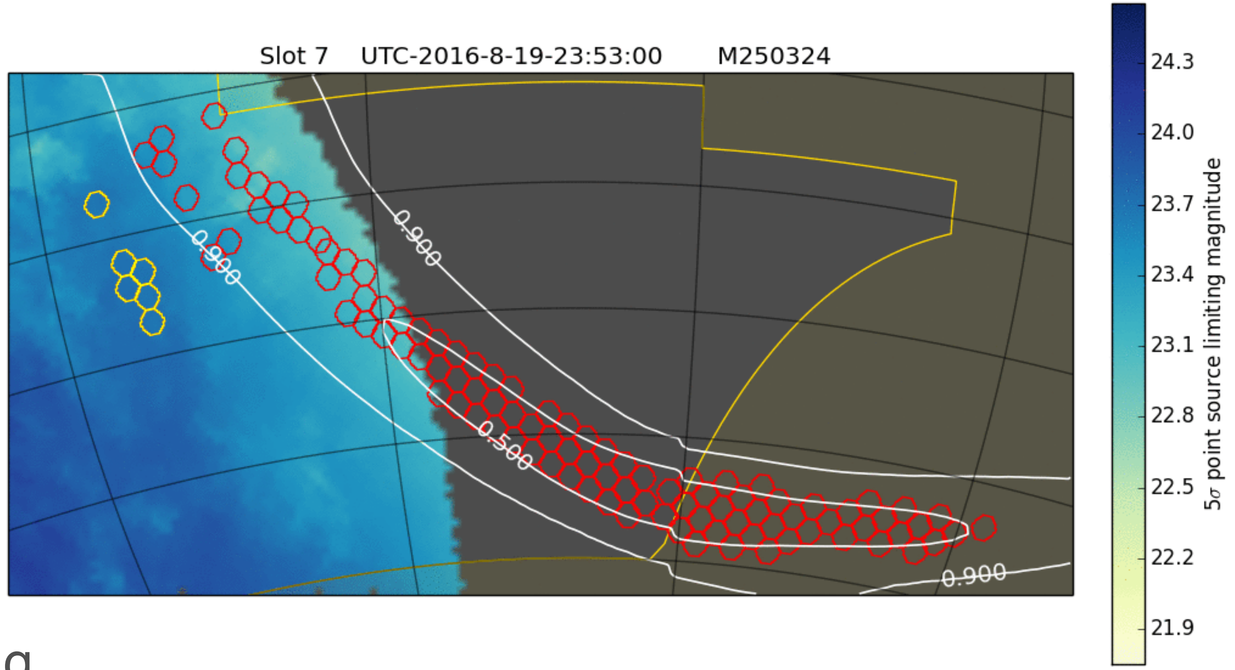
Combine trigger information from LIGO, source detection probaility maps

Observing Strategy and Economics Calculation

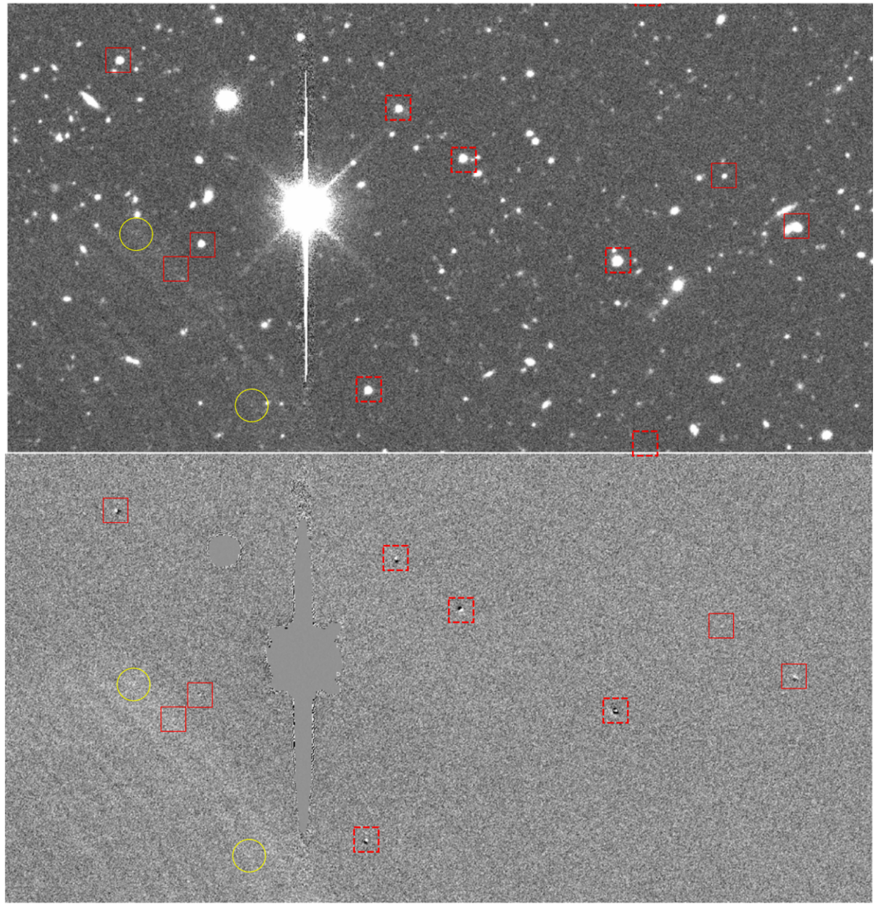
- Given imperfect localization, must decide where to observe each night
- Ideally three passes over region: immediately, a few days later, and 2-3 weeks later
  - Want to observe decline in flux for NS merger candidates
- Observing plan formulation:
  - Compute source detection probability assuming source 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

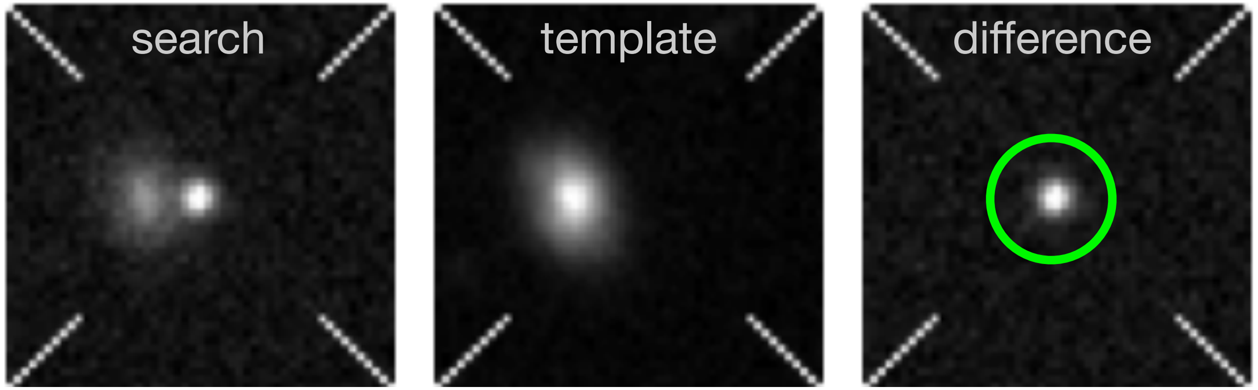




Detecting EM counterparts

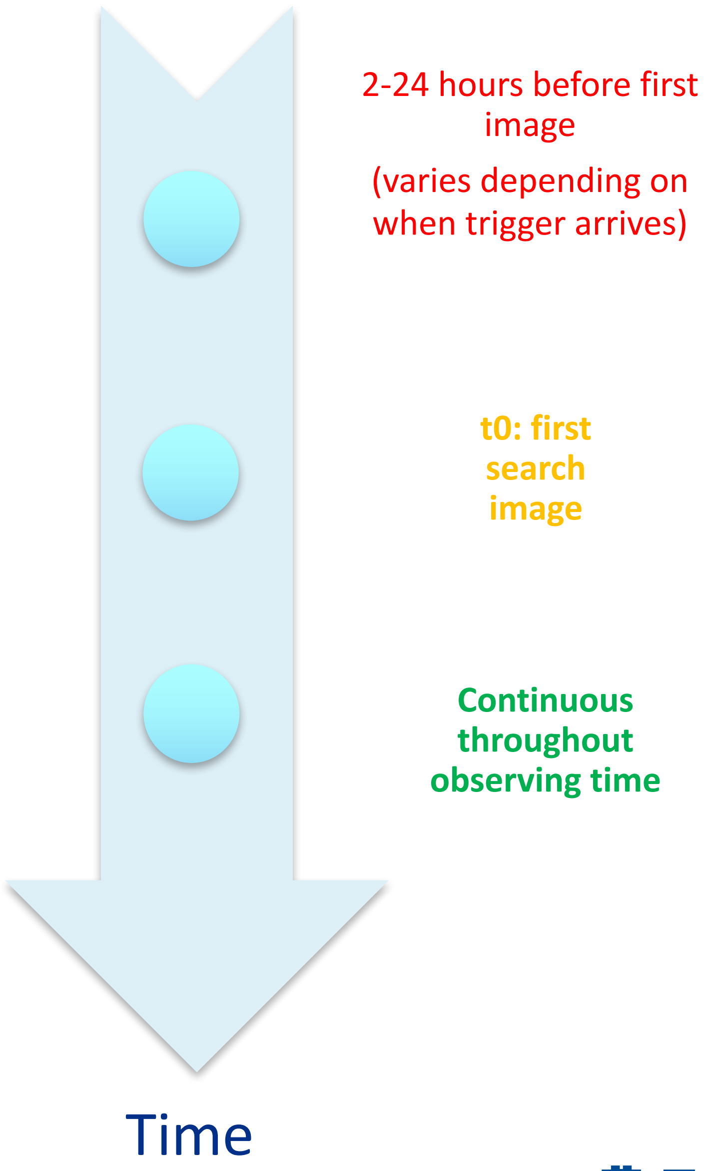
- Detect candidates via "difference imaging (diffimg)": subtract template images (previous images of same region of sky) from search images, scan for "new" objects
- Machine learning algorithms applied to candidates
- Detection efficiencies calculated by overlaying fake candidates on search images
-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





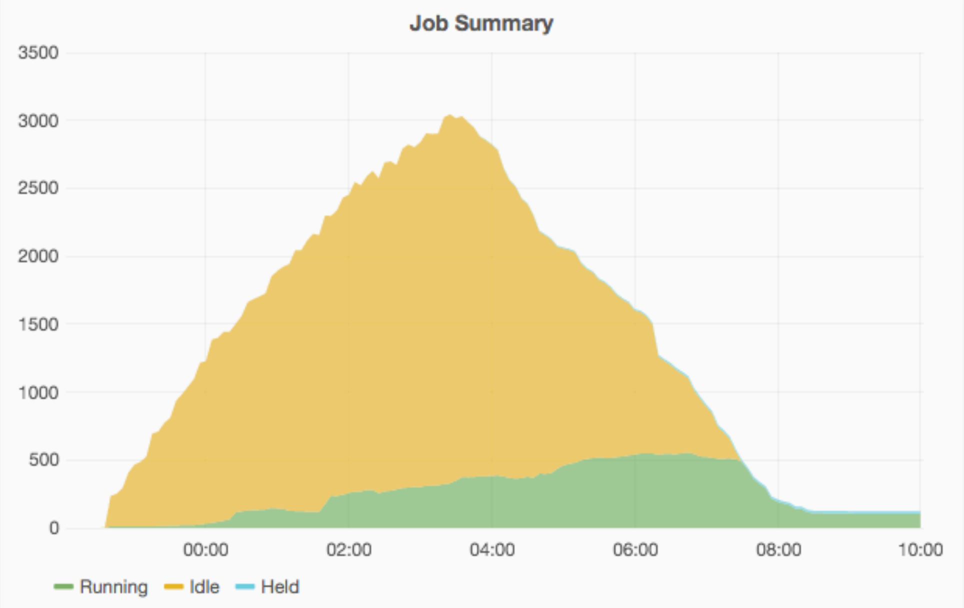
Putting the plan in action

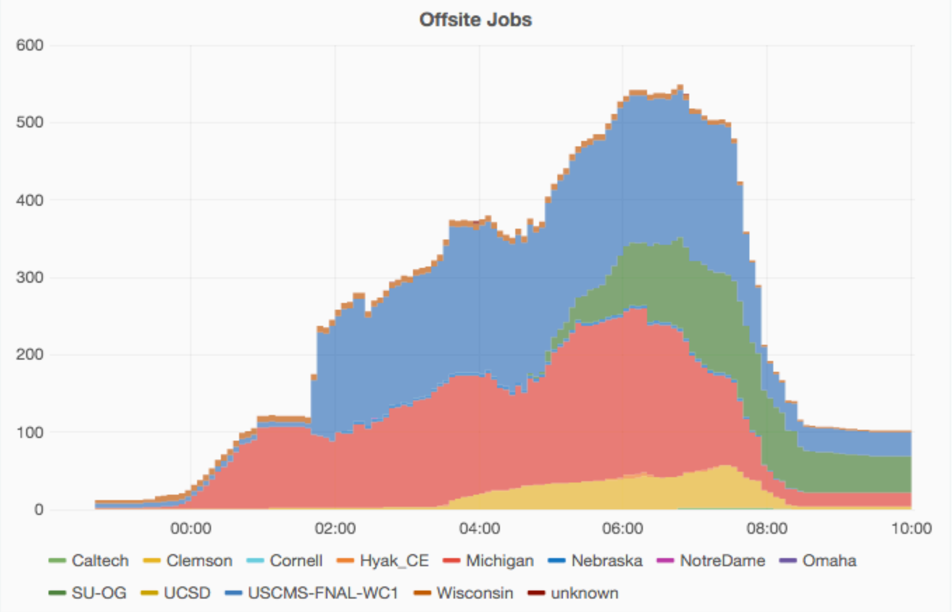
- *As soon as observing plan ready, begin preprocessing template images*; do as much as possible before beginning observation (done in grid jobs; few hours per image)
- Engage "listener" which looks for new images once observations have commenced
- Listener calculates needed template images, checks for 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



Job Processing

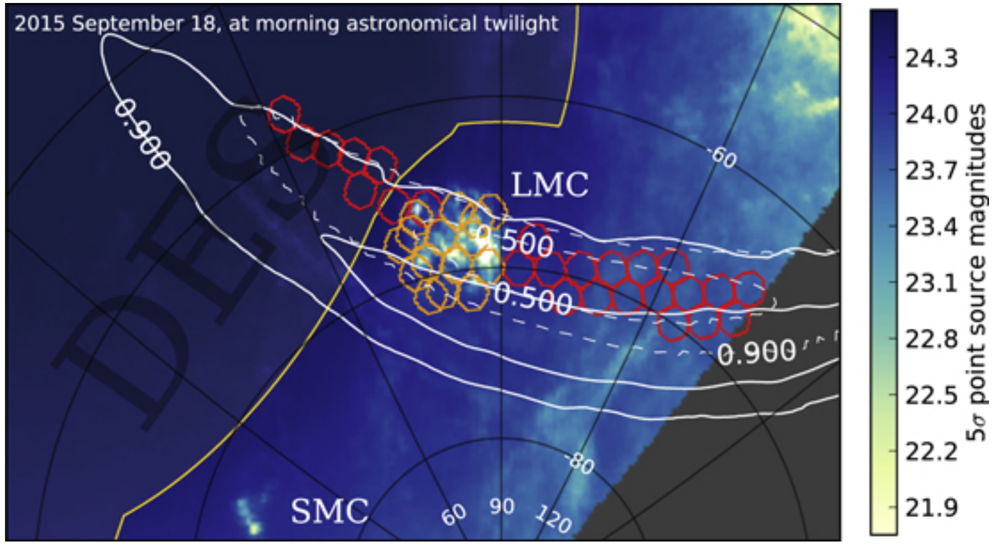
- Each search and template image first goes through “single epoch” processing (few hours per image). About 10 templates per image on average (some overlap of course)
- Once done, run difference imaging (template subtraction) on each CCD individually (around 1 hour per job; 60 CCDs) Total: 5-10K CPU-hours 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

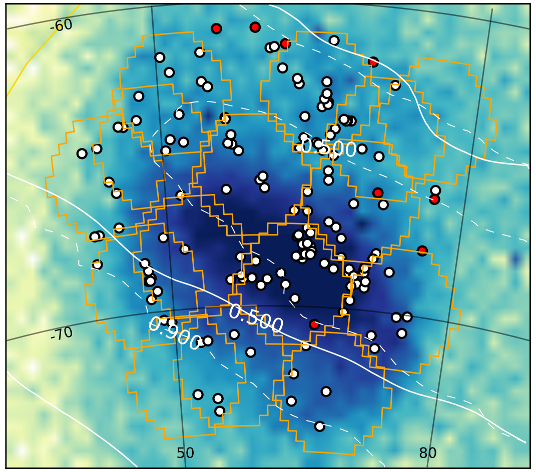


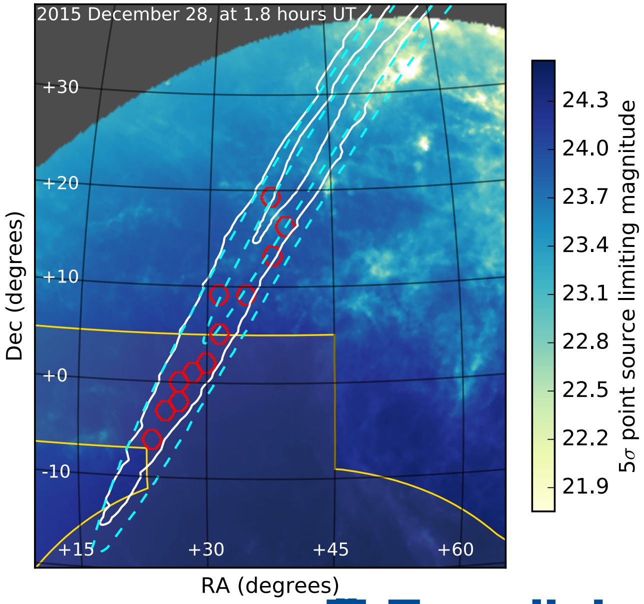


Results from Season 1

- Followup of GW150914 (discovery event) with two analyses
  - Standard followup of event, no EM candidates seen (as expected in BBH merger) [Soares-Santos et al. 2016, ApJL 823, 2:L33]
  - 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 (2nd 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: $\boldsymbol{P_{t,i} = P_{SM}(\vec{C}) + P_{\leq i}(A_{left} - \vec{C}) \cdot \vec{N}_{BH,i}}$
- $P_{SM}(\vec{C})$ 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/nights 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 $\boldsymbol{P_{t,i}}$** (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

Credit: T. Abbott and NOAO/AURA/NSF

BACKUP

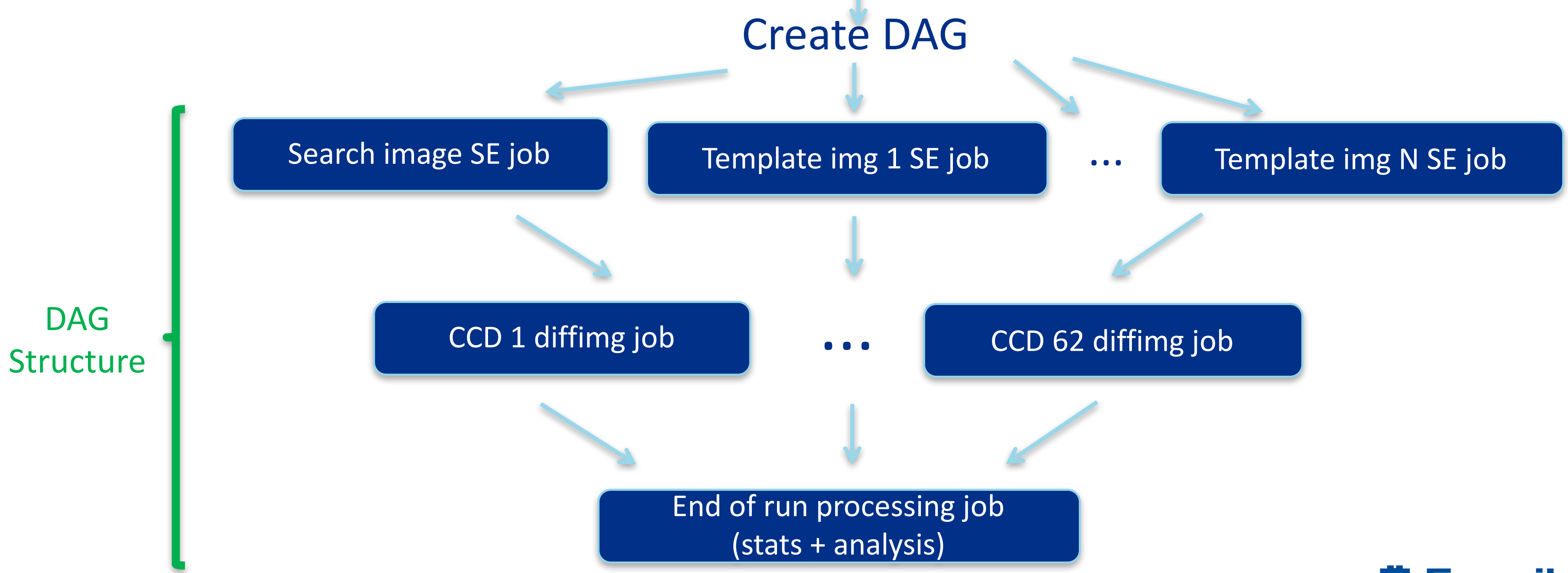
Imagine listener steps and HTCondor DAG Generation

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

SE = "Single Epoch" (image preprocessing)



OSG-only Grid test

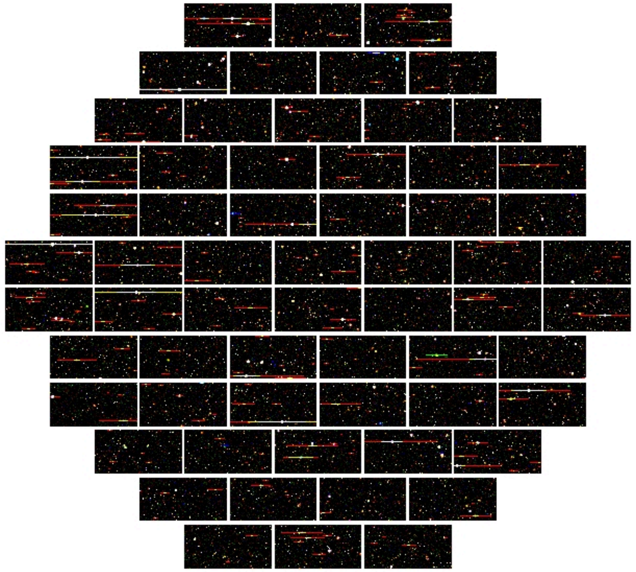
- Decided to take about one night's worth of images and process at a "real-time" rate (new images every 4 minutes)
- Central question: if dedicated resources were unavailable what kind of turnaround time could one expect?
  - Important in evaluating need for commercial cloud resources
  - Caveat: jobs 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**

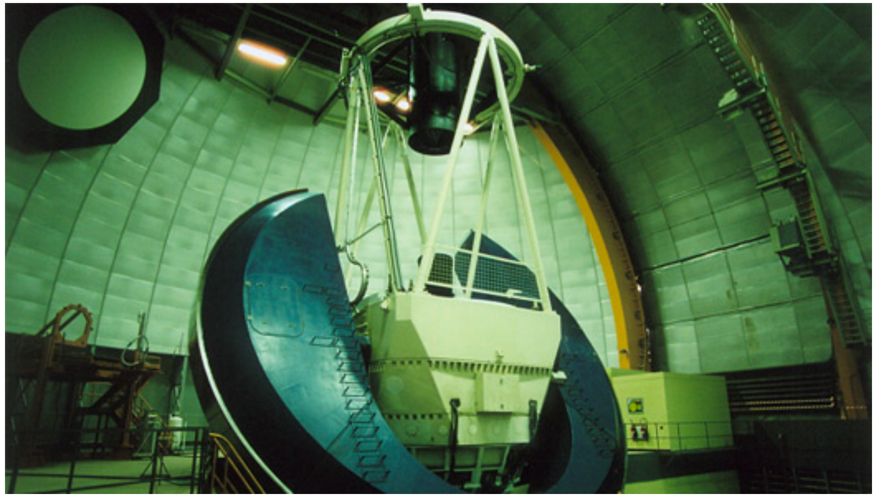
AWS Tests

- 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

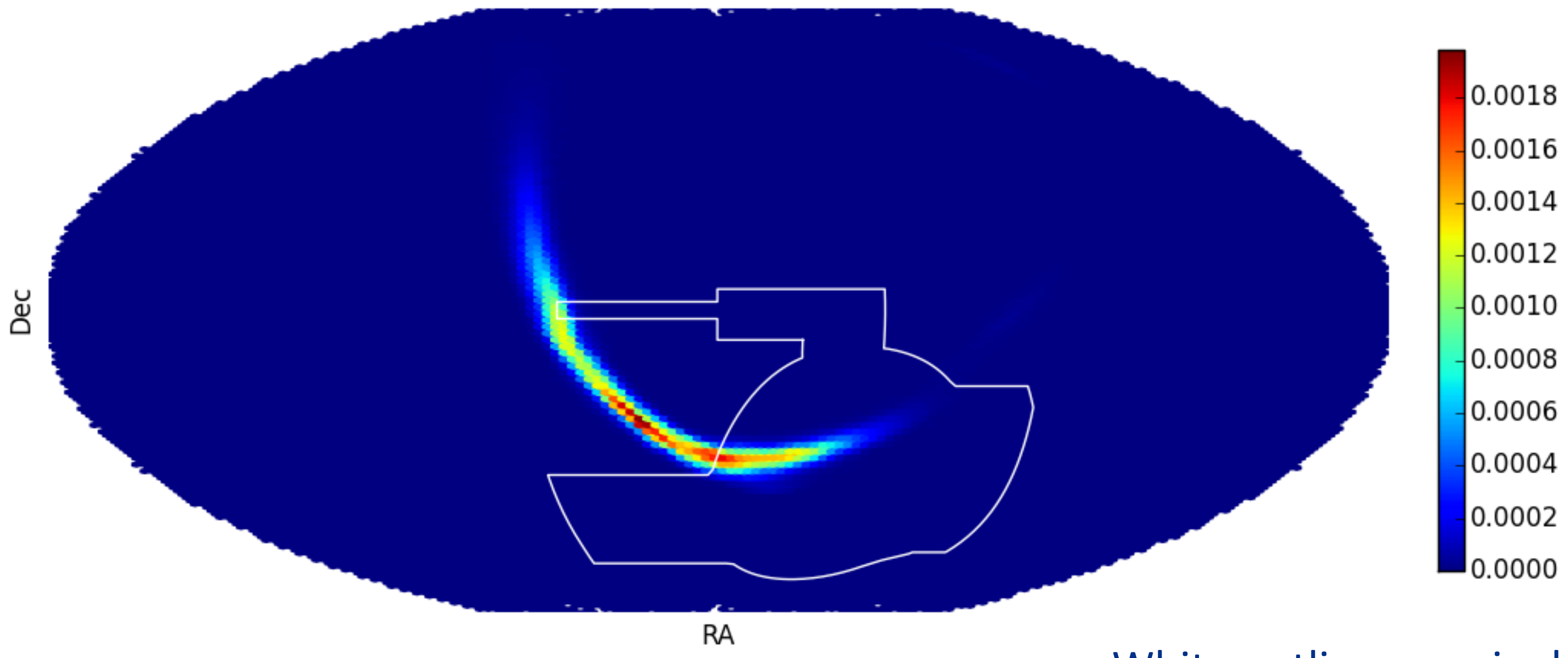
- Collaboration of 400 scientists using the Dark Energy Camera (DECam) mounted on the 4m Blanco telescope at CTIO in Chile
- Currently starting fourth year of 5-year mission
- Main program is four probes of dark energy:
  - Type Ia Supernovae
  - Baryon Acoustic Oscillations
  - Galaxy Clusters
  - Weak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





Formulating an observing plan

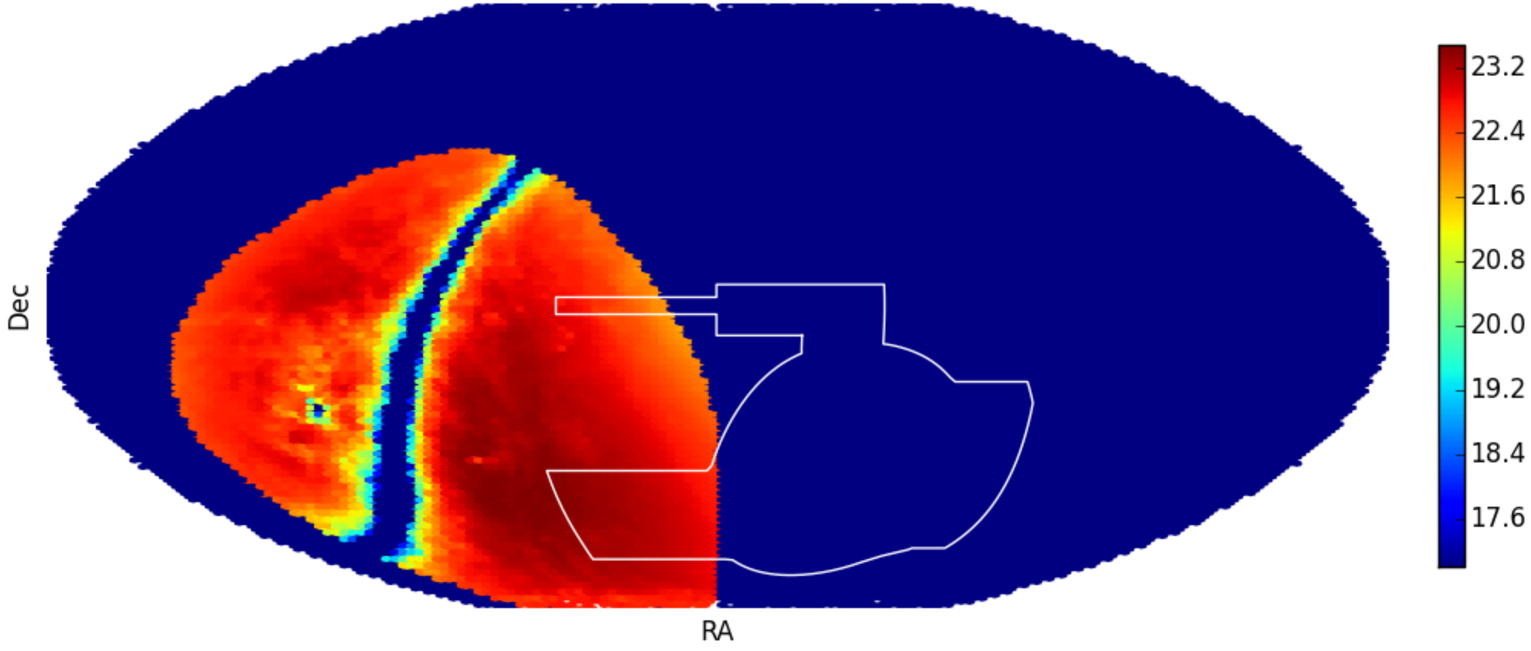
- Receive a location probability map from LIGO, along with distance estimate



White outline: nominal DES observing region

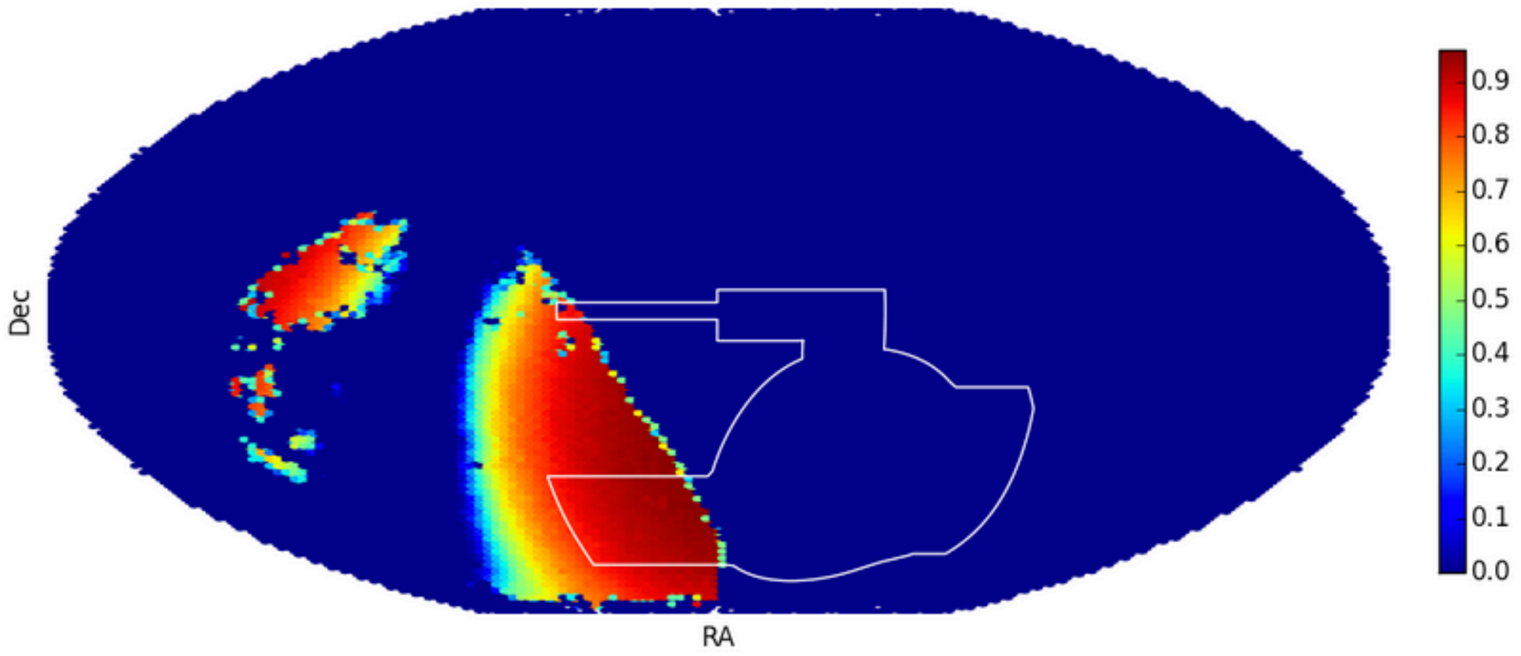
Formulating an observing plan

- 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



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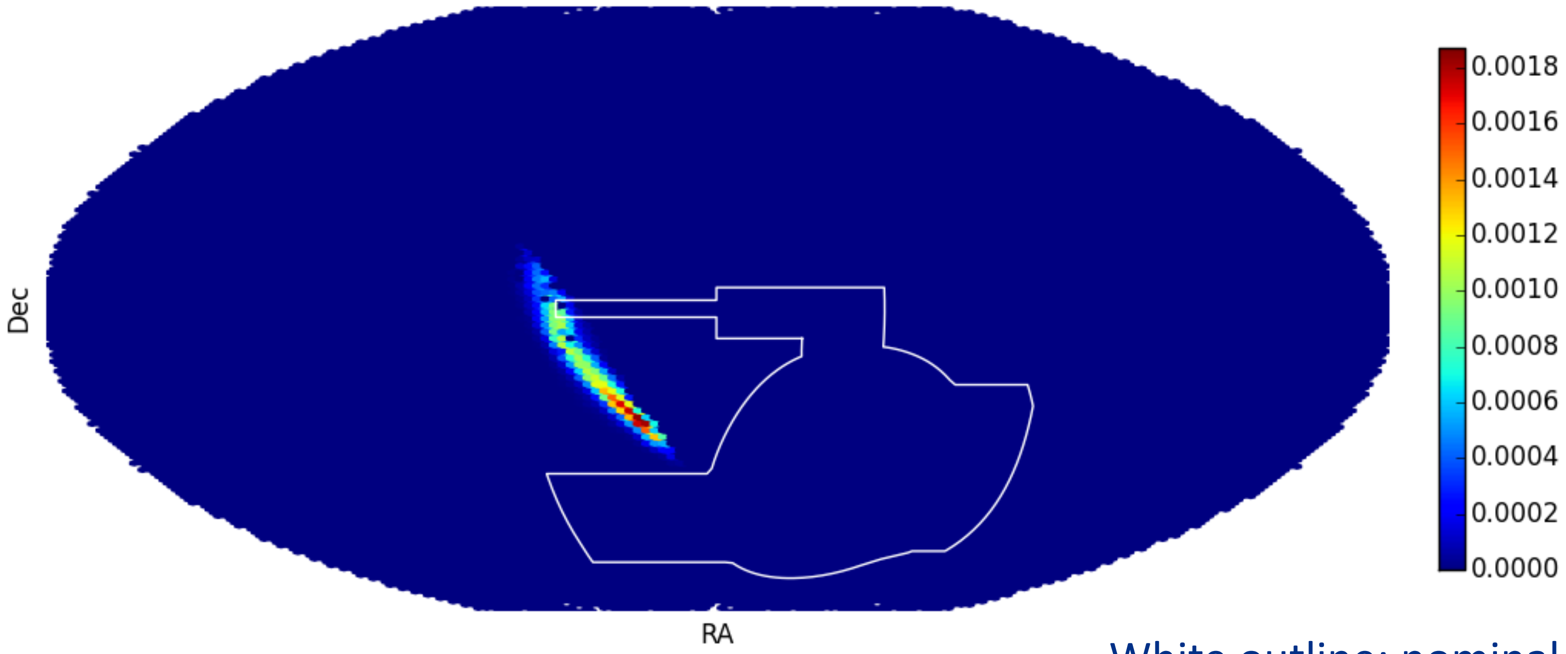
Formulating an observing plan

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



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