THE DES GRAVITATIONAL WAVE EVENT FOLLOW-UP PROGRAM

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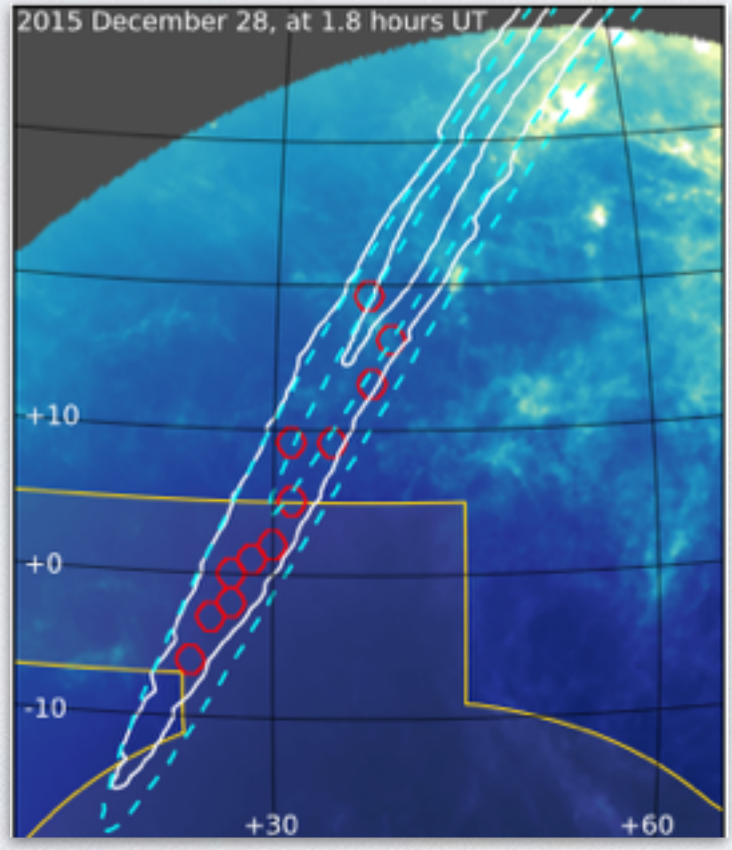
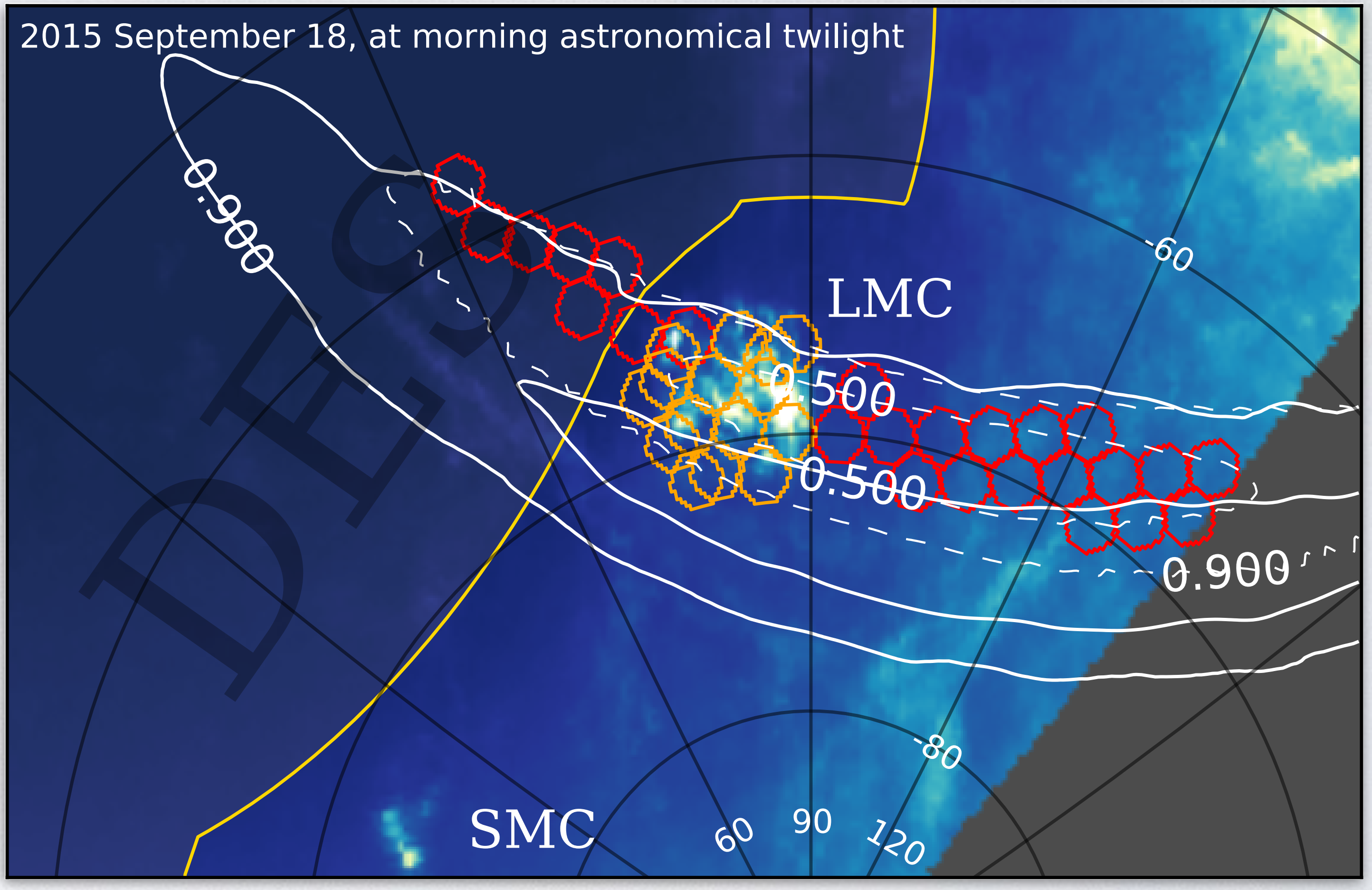




KITP Workshop
Santa Barbara
Aug 11, 2016

Soares-Santos et al. 2016, ApJL 823, 33
Annis et al. 2016, ApJL 823, 34
Cowperthwaite et al. 2016 (arXiv:1606.04538)

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

LIGO: arXiv:1304.0670

We are here!

O1

	Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within $5\,deg^2$	$20\,deg^2$
aLigo	2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
aLigo	2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
aVirgo + aLigo	2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
aVirgo + aLigo	2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
	2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

DES observations (Sep-Feb months)

LSST era!

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

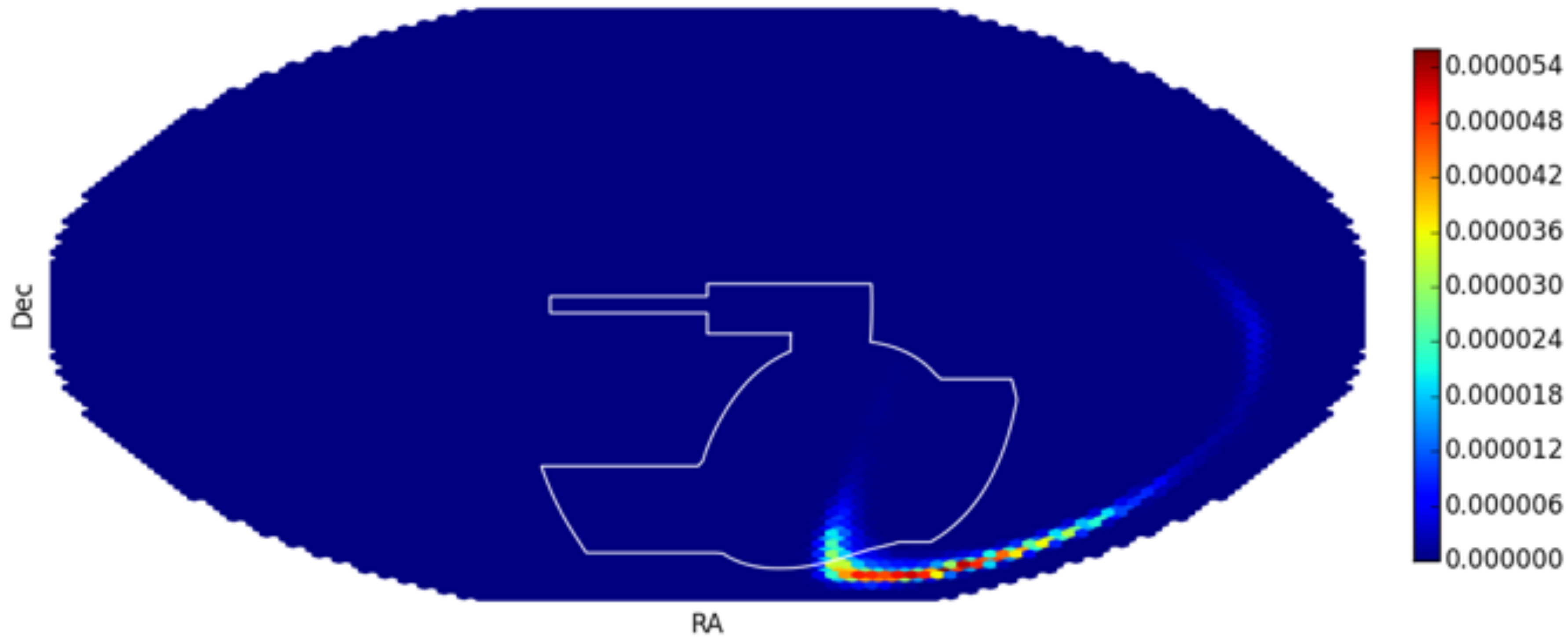
GW151226 **(aka *event #2*):** 5-sigma, high-mass BBH merger

*** 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.

GW150914

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

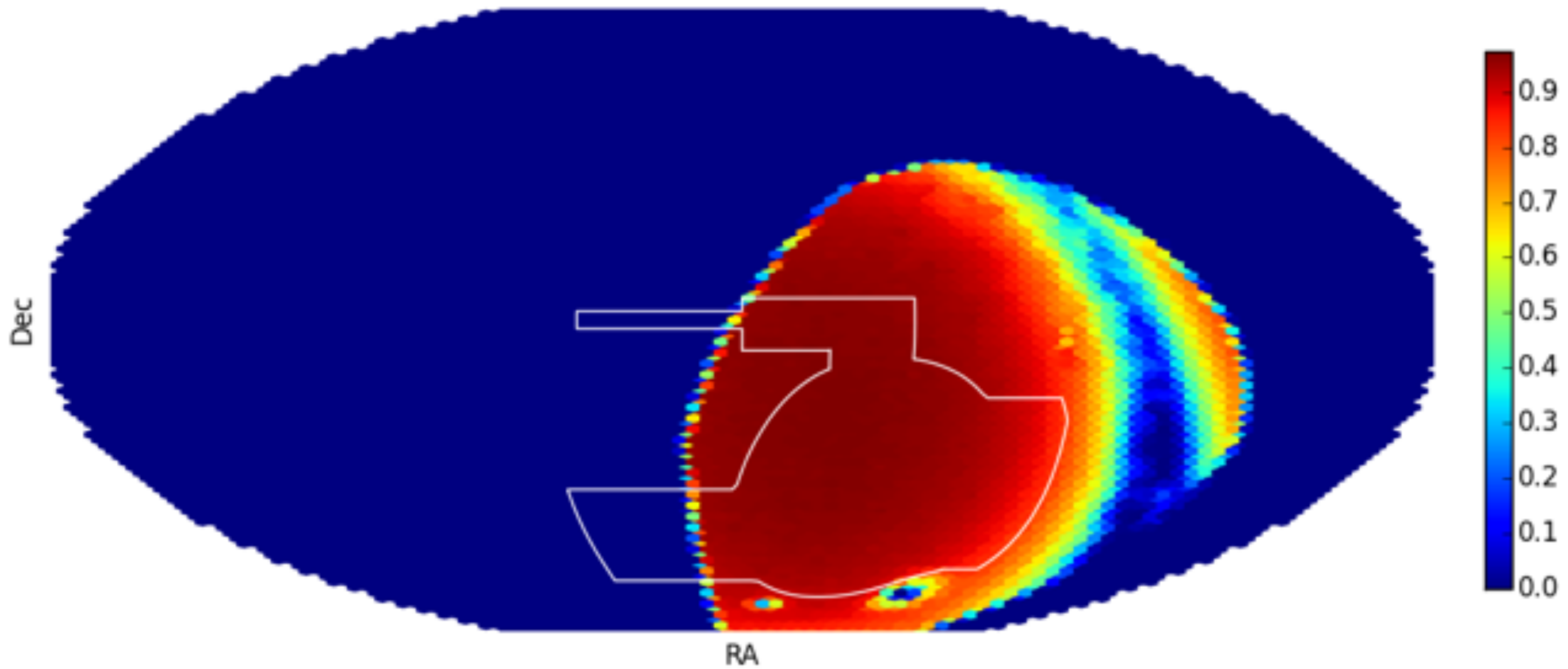


LVC sky localization probability map (final)

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

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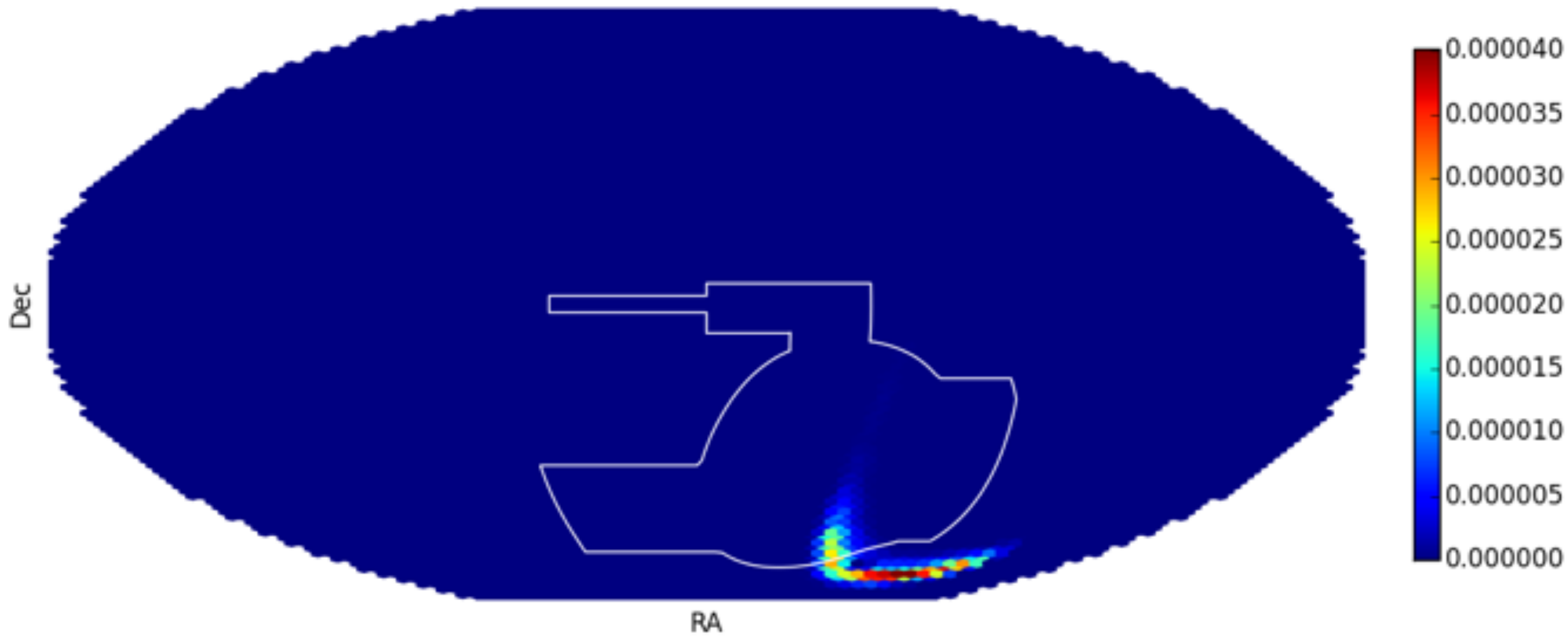
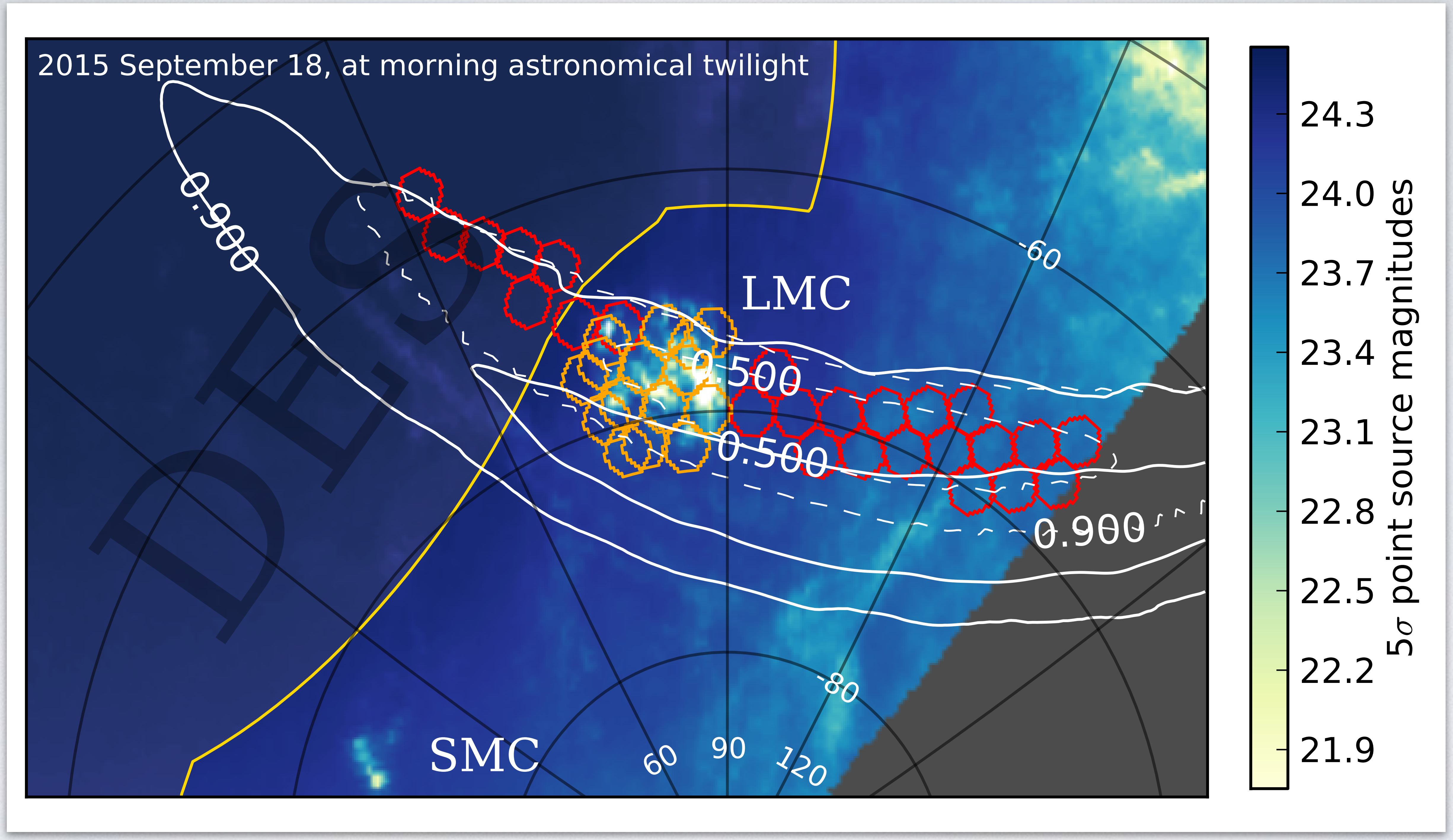
Obs time: 2015 Sep 18
(end of the night)



DES source detection probability map

DATA



2015 September 18, at morning astronomical twilight
0.900
DES
LMC
0.500
0.500
0.900
-60
-80
SMC
60
90
120
24.3
24.0
23.7
23.4
23.1
22.8
22.5
22.2
21.9
5σ point source magnitudes

DATA

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

Program	Night	MJD	Δt^{a} (days)	$\langle PSF(FWHM_i)\rangle$ (arcsec)	$\langle$airmass$\rangle$	$\langle depth_i\rangle$ (mag)	$\langle depth_z\rangle$ (mag)	$A_{eff}{}^{b}$ (deg^2)
Main, 1^{st} epoch	2015-09-17	57383	3.88	1.38	1.50	22.71	22.00	52.8
	2015-09-18	57384	4.97	1.35	1.46	22.82	22.12	14.4
Main, 2^{nd} epoch	2015-09-20	57286	6.86	2.17	1.51	22.18	21.48	67.2
Main, 3^{rd} epoch	2015-10-07	57303	23.84	1.46	1.40	22.33	21.63	67.2
LMC, initial	2015-09-17	57383	3.98	1.14	1.30	21.32	20.62	14.4
LMC, extension	2015-09-26	57292	12.96	1.21	1.28	20.91	20.21	33.6

ANALYSIS I

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

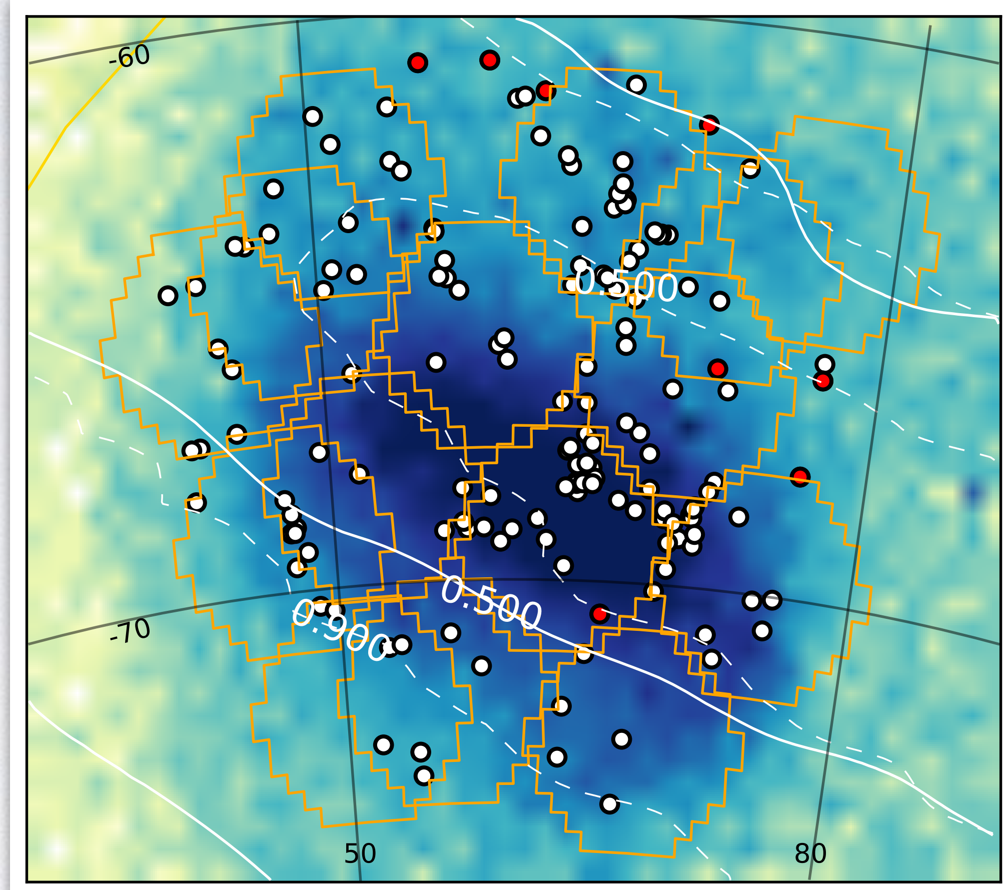
Efficiency estimates from simulated events
decay rate: 0.3 mag/day
50% recovery rate depth:

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.

ANALYSIS 2

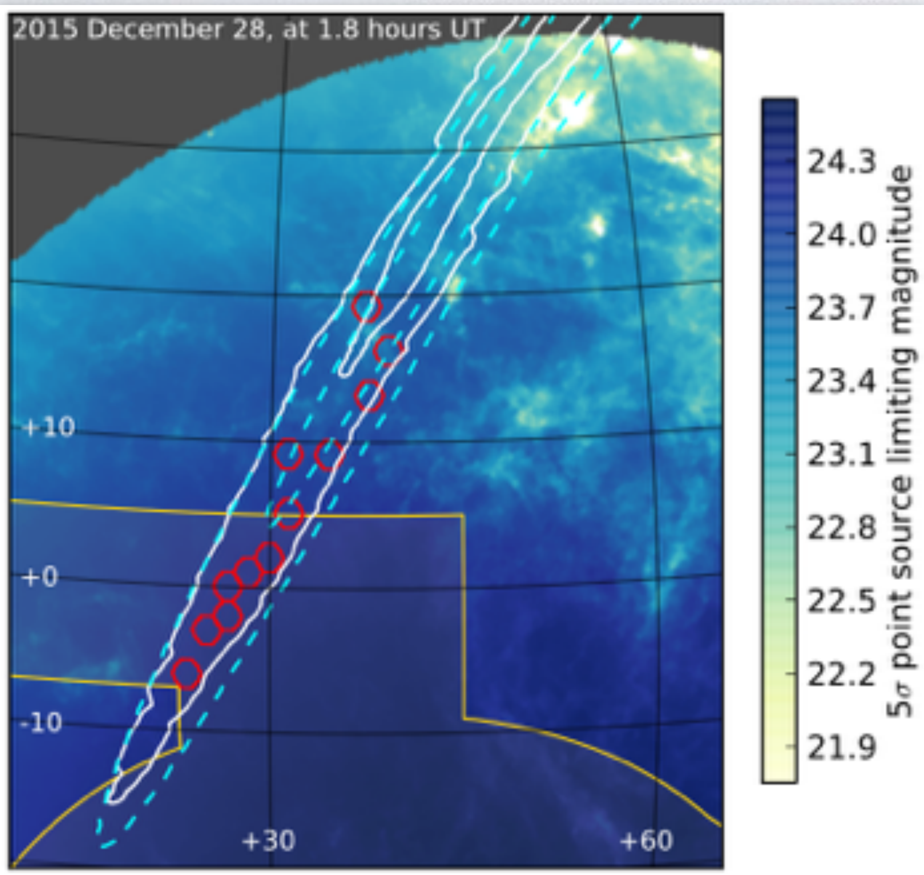
Search for disappearing stars in the LMC (Annis et al. 2016)

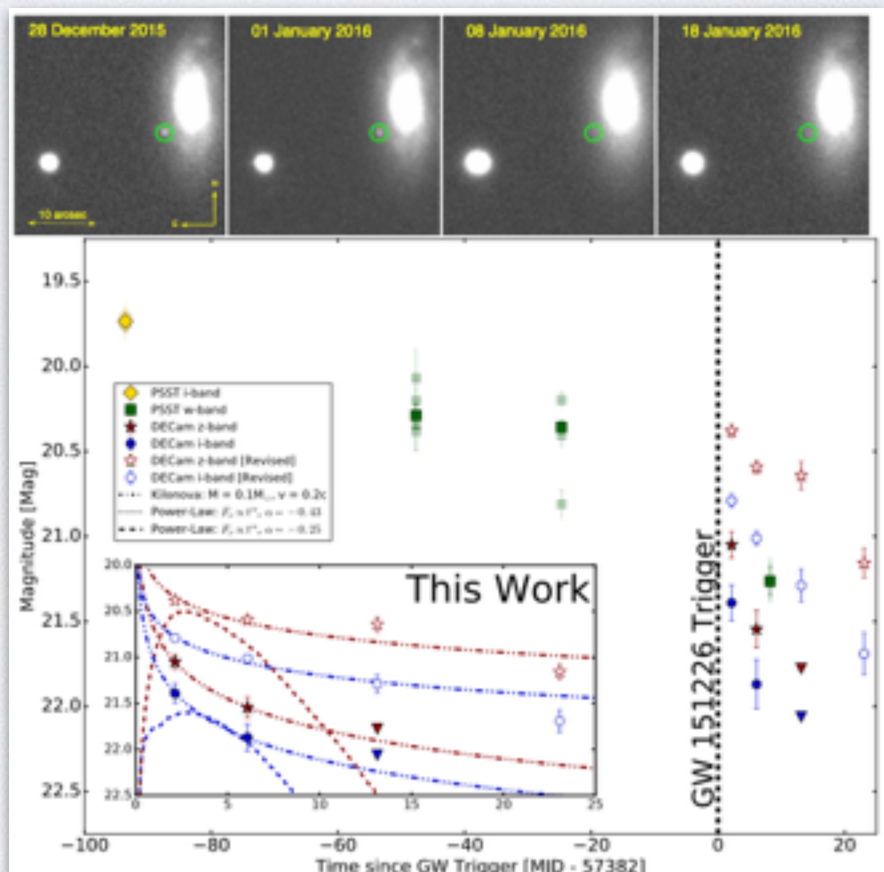


We take possible progenitors (e.g. red supergiants) catalogued in the literature and search for them via visual inspection. 144 were in the observed area; all accounted for.

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





Cowperthwaite et al. 2016 (arXiv:1606.04538)

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

CONCLUSIONS

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.**

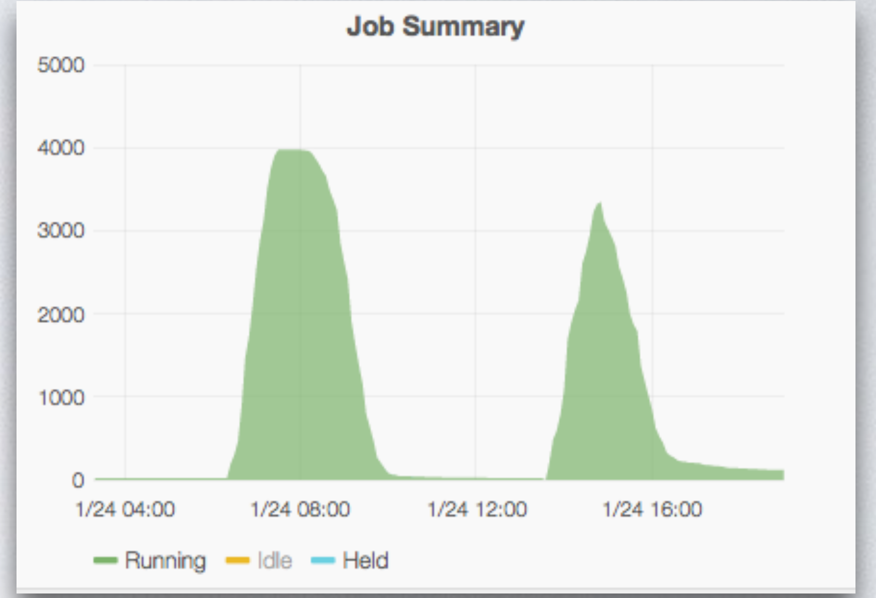
Our results indicate that prospects for a full fledged program in the DES era and beyond are encouraging!

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

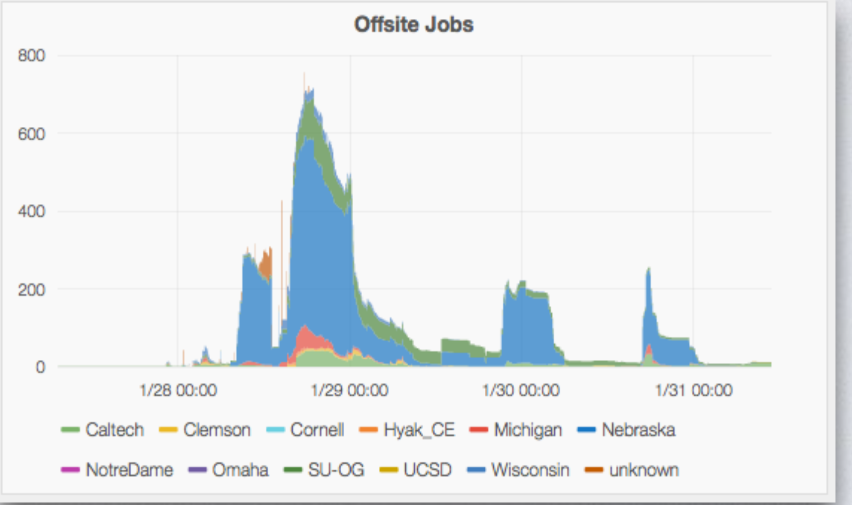
BACKUP SLIDES

IMAGE PROCESSING @FERMILAB

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 (~1hr/job)



Challenge: **raw images to plots in < 24 hrs**

A productive collaboration involving **PPD, SCD**.

http://fifemon.fnal.gov/

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!***

ANALYSIS I

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

NUMBER OF SELECTED EVENTS

mag(i)	raw	cut 1	cut 2	cut 3
18.0–18.5	84	1	0	0
18.5–19.0	177	1	0	0
19.0–19.5	291	2	0	0
19.5–20.0	227	2	1	0
20.0–20.5	156	17	2	0
20.5–21.0	225	42	3	0
21.0–21.5	334	84	2	0
21.5–22.0	756	159	1	0
22.0–22.5	1099	183	0	0
total	2349	491	9	0

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