TOROS: The Transient Optical Robotic Observatory of the South

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Outline

LIGO outlook

EM counterparts
    The Kilonova model

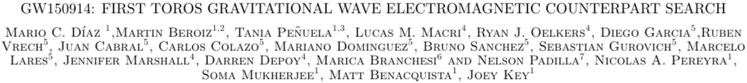
O1 ALIGO Run
    GW150914

TOROS follow-up

The bigger picture

The TOROS Team and Partnerships

- The CGWA at the UTRGV (USA)
- OAC - IATE (Argentina)
- Texas A&M (USA)
- California State University Fullerton (USA)
- Pontificia Universidad Católica (Chile)
- Universitá di Urbino (Italy)
- Observatory of Rome (Italy)
- And the LIGO-VIRGO Consortium



GW150914: FIRST TOROS GRAVITATIONAL WAVE ELECTROMAGNETIC COUNTERPART SEARCH

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LIGO outlook

- LIGO's limiting sensitivity has improved (by $>$ than a factor of 10) over the entire initial LIGO frequency band and in bandwidth to lower freqs. (from ~ 40 Hz to ~ 10 Hz)

- The most likely objects are BH binaries, NS binaries and BH-NS binaries:

- Inspiraling NS binaries to a distance of 200 Mpc.

- NS-BH binaries will be detected out to 650 Mpc

- Coalescing BH-BH systems out to $z \sim 0.4$

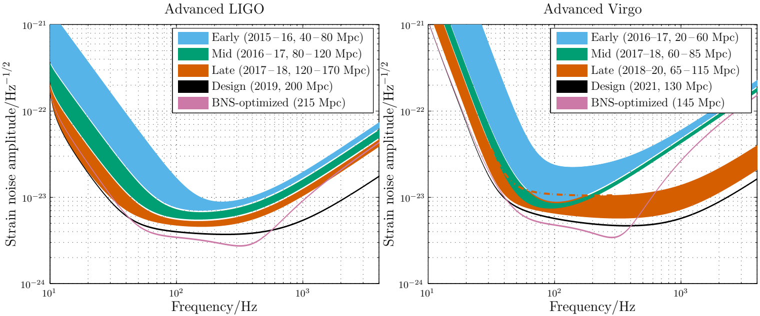
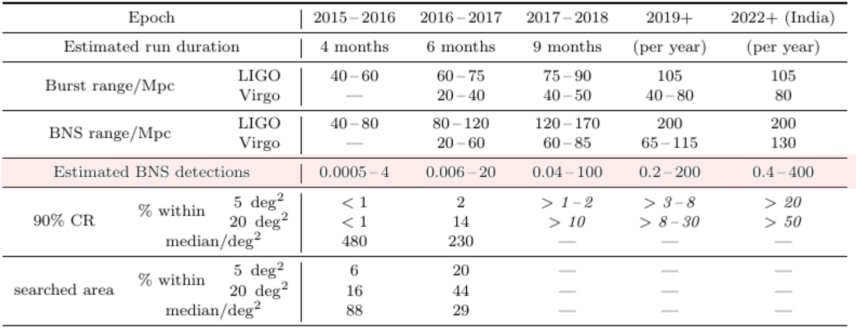


Figure 1: LIGO-VIRGO Projected limiting sensitivity, Abbott et al. and the LVC, 2016



Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	$> 1-2$	$> 3-8$	> 20
		20 deg^2	< 1	14	> 10	$> 8-30$	> 50
	median/deg^2		480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
	median/deg^2		88	29	—	—	—

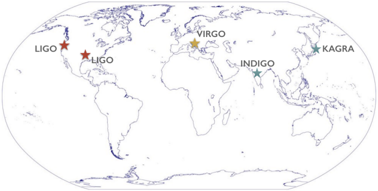
BNs rates, Abbott et al. and the LVC, 2016

Localization

- Posterior probability distributions for the sky position are constructed following a Bayesian framework *(Veitch, J. et al. 2015; Cornish et al. 2015, Singer & Price 2016.)*

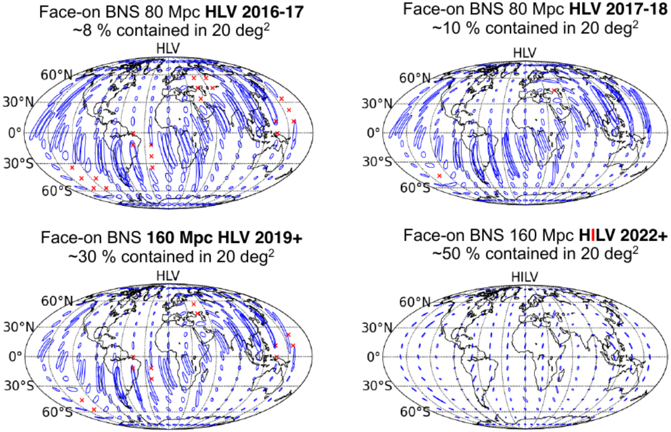
- Information comes from the time of arrival, plus the phase and amplitude of the GW.

- One can understand localization through triangulation by using the observed time delays between sites *(Fairhurst,et al. 2009; Fairhurst et al., 2011)*.



Detectors around the world

$$\sigma_t = 1/2\pi\rho\delta_f \sim 10^{-4}s \tag{1}$$



Face-on BNS 80 Mpc **HLV 2016-17**
~8 % contained in 20 deg^2

Face-on BNS 80 Mpc **HLV 2017-18**
~10 % contained in 20 deg^2

Face-on BNS **160 Mpc HLV 2019+**
~30 % contained in 20 deg^2

Face-on BNS 160 Mpc **HILV 2022+**
~50 % contained in 20 deg^2

Figure 4: Abbott et al. and LVC, 2016

EM counterparts

The Kilonova model

- EM counterparts of GWs are expected *(Schutz et al. 1986, Sylvestre et al. 2003, Sttubs et al. 2008, Stamatikos et al. 2009, Metzger and Berger 2012).*

- In the case of face on activity we expect SGRBs to be coincident with the GW alarms.

- sGRBs are rare (0.3 yr^-1) within 200 Mpc (mean observable distance of LV).

- NIR peak? –depth and area for IR detectors needed–> optical follow up is the best alternative and the most inexpensive way to go!

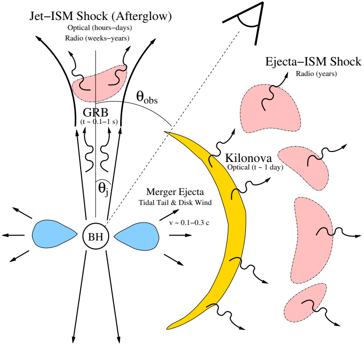


Figure 5: Potential EM counterparts of a GW (Metzger & Berger, 2012)

They are important because:

1. They could add precision to the inferred binary parameters (Hughes & Holz 2003)
2. They will Improve significantly the localization of the putative source (for a determination of $\sim$ arcsecond sky positions)
3. Identify the merger redshift, and therefore the energy scale of the sources.

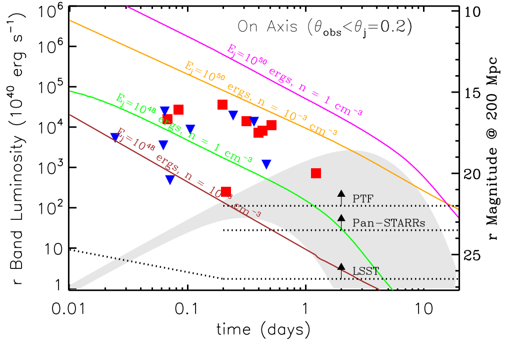


Figure 6: On axis sGRB and Kilonova (Metzger & Berger 2012)

O1 ALIGO Run

- 74 groups, ground and space based facilities, MOU with the LVC.
- Only 25 were able to perform follow up for the first detection.
- The program for EM follow up is based on a system that has been established for broad-band follow up of GRBs. it distributes times and locations through the Gamma-ray coordinate network (GCN). The results of each of the teams are published back through the same system in the form of small bulletins i.e. GCN circulars.
- LIGO data now is restricted now to MOU partners, but after the 4th high confidence published detection, data will be open to the public.

GW150914

- September 14, 2015 at 09:50:45 UTC Both detectors simultaneously observed a gravitational wave signal.
- A 35 to 250 Hz jump was observed with a peak gravitational strain of 1.0×10^{-21}
- The signal was observed with a matched filter S/N of 24 and a significance of $> 5.1\sigma$.
- It matches a wave-form predicted by general relativity for the inspiral and merger of BBH. With masses of ~ 36 and ~ 29 and the final BH mass is $\sim 62\ M_{\odot}$.
- The source lies at a $z \sim 0.1$ (or $\sim 410 Mpc$)
- It is the first time we detect directly GWs and the first observation of BBH merger.

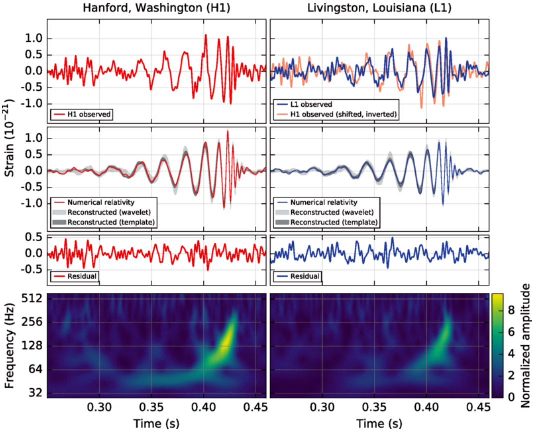


Figure 7: LVC 2016

Pipelines

For O1, four low-latency pipelines were prepared to receive and process signals from GWs.

Un-modeled GW burst search:

- The coherent Wave Burst (cWB; Klimenko et al. 2015)
- Omicron+LALInference Burst (LIB; Lynch et al. 2015)

NS binary mergers using matched filtering:

- GSTAL (Cannon et al. 2015)
- Multi-band Template Analysis (MBTA; Adams et al. 2015)

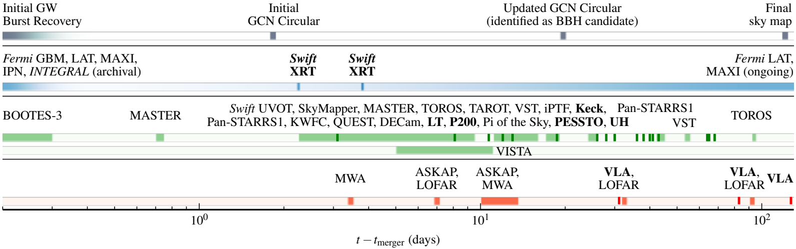
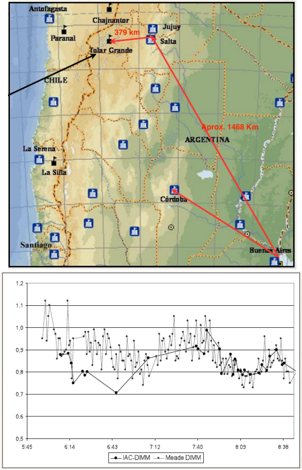


Figure 8: Time-line of the observations of GW150914.

TOROS follow-up

The observatory

- At Cerro Macón, 4600m above the see level
- Conditions are great, very low cloud activity and 93% of photometric nights per year.
- This site has been tested and it was pre-selected for the E-ELT
- First observatory fully dedicated to the search of GW optical counterparts.



Location and seeing, Cerro Macón

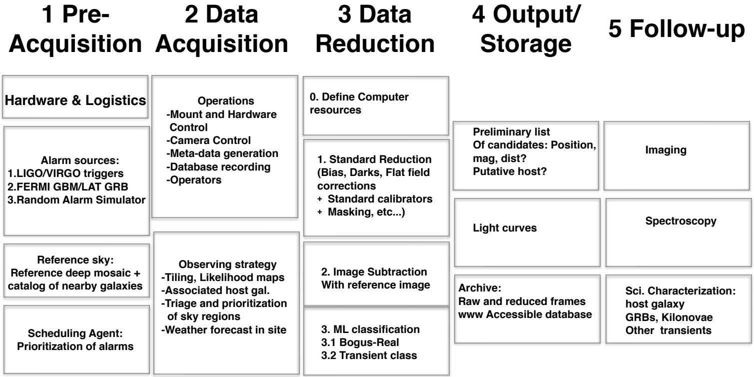
The telescope:

- 0.6m telescope
- 10k x 10k CCD camera
- Focal length of 1815mm
- FoV: 9 deg^2
- Pixel scale $\sim 1''/px$
- White light (mainly, covering a $0.4-0.9\mu m$ window)
- We estimate to be able to cover around 200 deg^2 per night down to $I_{AB} \sim 22mag$

Toritos: The Pilot project

- TOROS will not be operational before 2017
- Small (0.45m) Schmidt Cassegrain telescope
- FoV: 0.25deg^2
- pixel scale: 0.45 $''/px$
- Reduced area, but it can survey up to 8 deg^2 per night down to $I_{AB} \sim 19mag$.

Figure 10: Construction of TOROS at cerro Macón.



1 Pre-Acquisition

Hardware & Logistics

Alarm sources:
1.LIGO/VIRGO triggers
2.FERMI GBM/LAT GRB
3.Random Alarm Simulator

Reference sky:
Reference deep mosaic +
catalog of nearby galaxies

Scheduling Agent:
Prioritization of alarms

2 Data Acquisition

Operations
-Mount and Hardware Control
-Camera Control
-Meta-data generation
-Database recording
-Operators

Observing strategy
-Tiling, Likelihood maps
-Associated host gal.
-Triage and prioritization of sky regions
-Weather forecast in site

3 Data Reduction

0. Define Computer resources

1. Standard Reduction
(Bias, Darks, Flat field corrections
+ Standard calibrators
+ Masking, etc...)

2. Image Subtraction
With reference image

3. ML classification
3.1 Bogus-Real
3.2 Transient class

4 Output/ Storage

Preliminary list
Of candidates: Position,
mag, dist?
Putative host?

Light curves

Archive:
Raw and reduced frames
www Accessible database

5 Follow-up

Imaging

Spectroscopy

Sci. Characterization:
host galaxy
GRBs, Kilonovae
Other transients

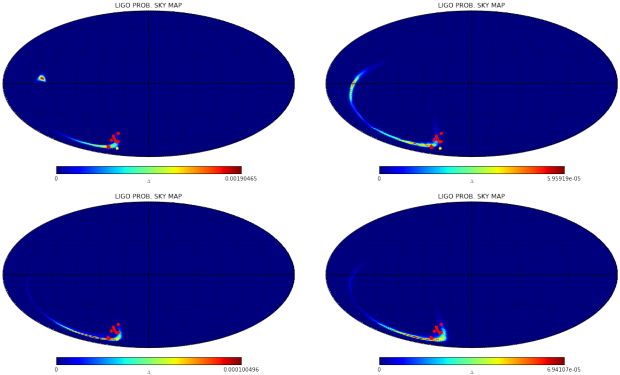
Figure 11: TOROS strategy

Estación Astrofísica de Bosque Alegre (EABA)

- 1.54m telescope
- 1024 × 682 px CCD camera
- FoV: 12.7 × 8.5 $arcmin^2$
- Pixel scale $\sim 0.75''/px$

- White-light $(0.35 - 1.\mu m)$
- Area: 0.6 deg^2
- Limiting mag $r_{AB} = 21.7 \pm 0.3 mag$ with $\sim 10 - 20 min$ exposures (see observations).

Skymaps



cWB, LIB, BYST, LALinf Sky-maps. 90% of the credible localization area for cWB: 310 deg^2, LIB : 750 deg^2, and the LALinf: 620 deg^2

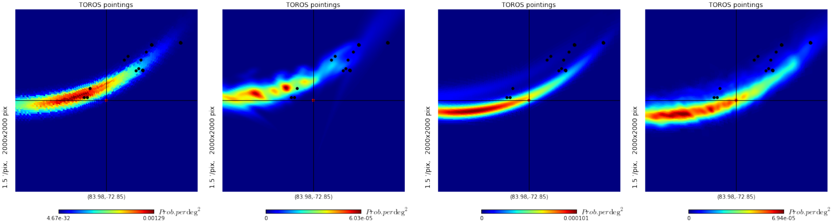


Figure 12: cWB, LIB, BYST, LALinf Sky-maps. Black points are our pointings.

Galaxy Ranking Approach

1. Galaxy Catalogs: We use GWGC (White et al. 2010) $\sim 53,000$ galaxies within 100 Mpc with reliable distances, blue magnitudes.

2. We used a built in-house "scheduler" with the following criteria:
   -**Observability** at location and time.
   -**Luminosity:** $B_{Abs} \geq -21$ Mag (AB). The distribution of BNS (in the nearby univ.) is expected to follow star formation due to short merger timescales *(Phinney et al. 1991, Belczynski et al. 2002).*
   -**Distance:** ≤ 60 Mpc (99.99 of completeness of catalog is reached at 40 Mpc).

3. We **cross-match** galaxies with the skymaps, and rank galaxies by assigning a probability $P_{g,i}$

4. We map host galaxies and its surroundings out to ~ 5kpc *(Berger et al. 2014, Fong & Berger 2013, Church 2011 and etc...)*

Observations

Date	ID	RA	DEC	t_{exp}	$Tile$	$dist$
	–	(deg)	(deg)	(s)	–	(Mpc)
2015-09-16	IC1933	51.416101	-52.78547	600	1,2,3,4	17.45
2015-09-16	NGC1529	61.833301	-62.89993	600	5,6,7,8	54.76
2015-09-16	IC2038	62.225246	-55.99074	600	9,10,11,12	7.00
2015-09-16	IC2039	62.259901	-56.01172	600	9,10,11,12	7.63
2015-09-17	ESO058-018	102.59385	-71.03123	1020	13	52.23
2015-09-17	ESO084-015	65.550449	-63.61097	1140	14	14.99
2015-09-17	ESO119-005	72.072451	-60.29376	1080	15	9.73
2015-09-17	NGC1559	64.398901	-62.78358	900	16	12.59
2015-09-17	PGC016318	73.728898	-61.56747	1020	17	9.54
2015-09-17	PGC269445	100.20915	-71.33026	1140	18	54.83
2015-09-17	PGC280995	96.382499	-69.15257	1140	19	55.08
2015-09-17	PGC128075	64.859998	-60.53844	720	20	63.71
2015-09-17	PGC381152	63.584547	-58.20726	1200	21	13.26
2015-09-17	PGC075108	63.670349	-58.13199	1200	21	13.29

Table 1: Targeted host galaxies.

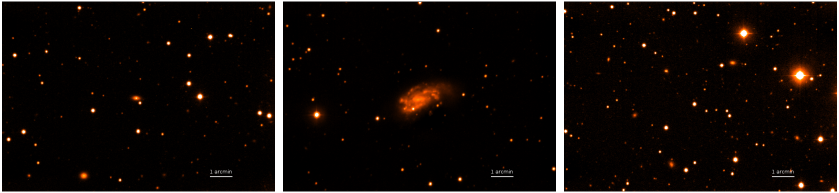


Figure 13: Some of the images taken with the EABA telescope (PGC128075, NGC1559 and PGC381152)

Image differencing methods and Results!!!

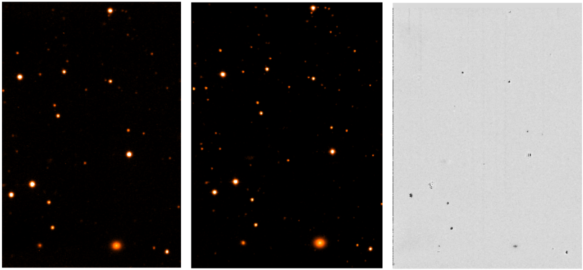


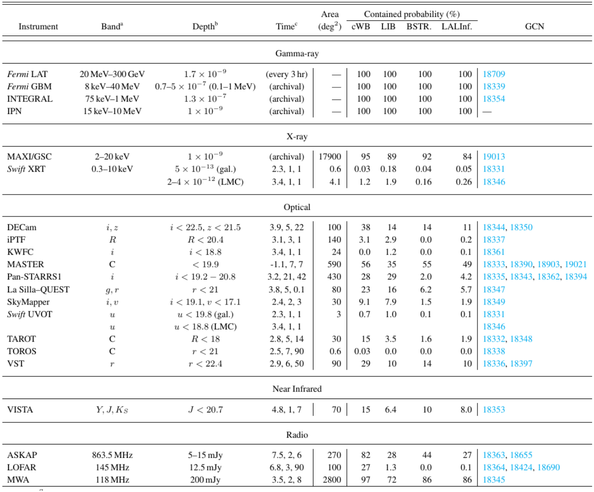
Figure 14: Example of Image differencing on a fraction of field PGC128075. We use Alard & Lupton 1998 and Bramich et al. 2008.

For O1 LIGO Run we have:

- Tested our main Pipeline for transient identification(couple of days)
- Trained our response time to the LIGO alarms (couple of hours)
- Tested our host-galaxy ranking approach (good likelihood and host-galaxy matching for initial and final sky maps)
- We have been successful at producing reference imaging *a posteriori* (There we had some trouble with weather conditions in EABA)

The bigger picture

Figure 15: We are just a little part of a huge project!

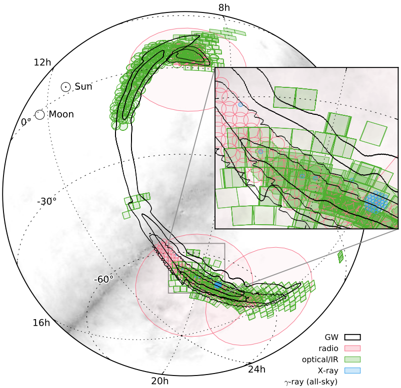


Instrument	Band[a]	Depth[b]	Time[c]	Area	Contained probability (%)				GCN
				(deg^2)	cWB	LIB	BSTR.	LALInf.	
Gamma-ray									
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100	18709
Fermi GBM	8 keV–40 MeV	0.7–5×10^{-7} (0.1–1 MeV)	(archival)	—	100	100	100	100	18339
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100	18354
IPN	15 keV–10 MeV	1×10^{-9}	(archival)	—	100	100	100	100	—
X-ray									
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84	19013
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05	18331
		2–4×10^{-12} (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26	18346
Optical									
DECam	i, z	$i < 22.5$, $z < 21.5$	3.9, 5, 22	100	38	14	14	11	18344, 18350
iPTF	R	$R < 20.4$	3.1, 3, 1	140	3.1	2.9	0.0	0.2	18337
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1	18361
MASTER	C	< 19.9	-1.1, 7, 7	590	56	35	55	49	18333, 18390, 18903, 19021
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2	18335, 18343, 18362, 18394
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7	18347
SkyMapper	i, v	$i < 19.1$, $v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9	18349
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1	18331
	u	$u < 18.8$ (LMC)	3.4, 1, 1						18346
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9	18332, 18348
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0	18338
VST	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10	18336, 18397
Near Infrared									
VISTA	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0	18353
Radio									
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27	18363, 18655
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1	18364, 18424, 18690
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86	18345

Figure 16: Summary of EM efforts, LVC & the astronomers, 2016.

- Gamma-Ray facilities covered 100% of the probability areas.
- Xray coverage is more difficult to quantify, it is relatively sparse at fluxes fainter than $10^{-9} ergcm^{-2}s^{-1}$. E.g. the swift XRT enclosed a probability of 0.3%. Down to the limit, MAXI observations are complete.
- All opt. facilities together tiled $\sim 870deg^2$ covering 57% of the LIB map, and 36% of the final LALinf map.
- Radio coverage was extensive with a contained prob. of 86%.

EM follow up of GW150914, LVC & the astronomers, 2016.



Thank you!