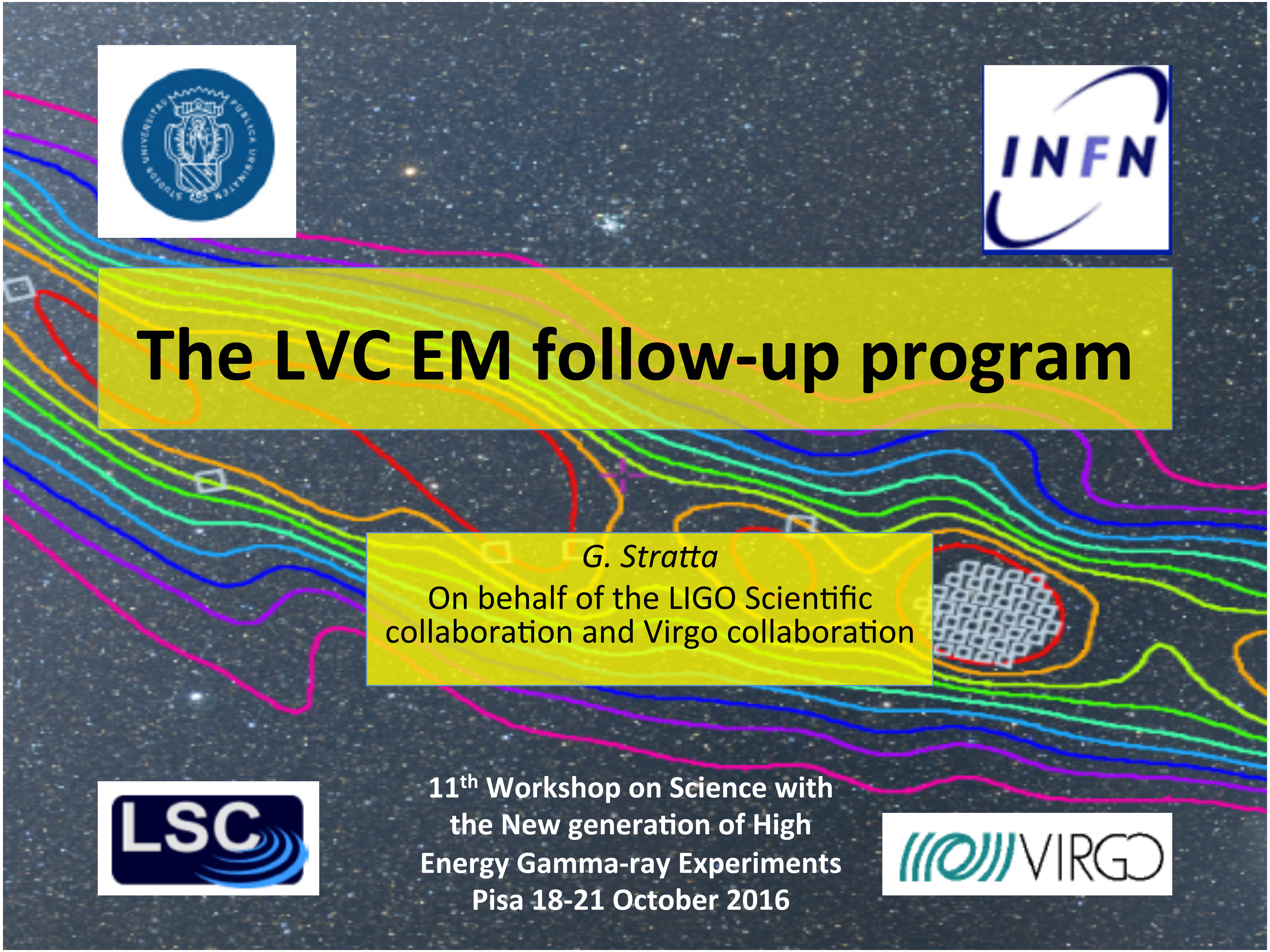


The LVC EM follow-up program

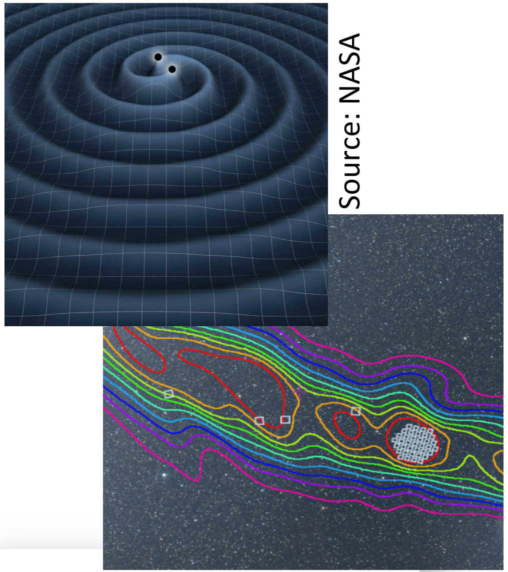
G. Stratta

On behalf of the LIGO Scientific collaboration and Virgo collaboration

11th Workshop on Science with the New generation of High Energy Gamma-ray Experiments
Pisa 18-21 October 2016

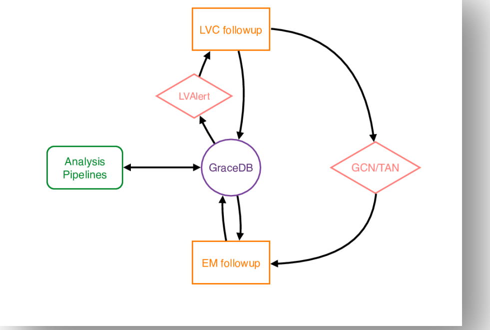
Outline

- *EM counterparts of GW sources: what do we expect and why are important*
- *Past and current LVC EM follow-up programs*
- *EM follow-up campaign of GW150914*
- *Future plans*



Source: NASA

Skymap Viewer



https://gracedb.ligo.org/documentation/general.html

High Frequency (10 – 10000 Hz) Gravitational Wave detectors

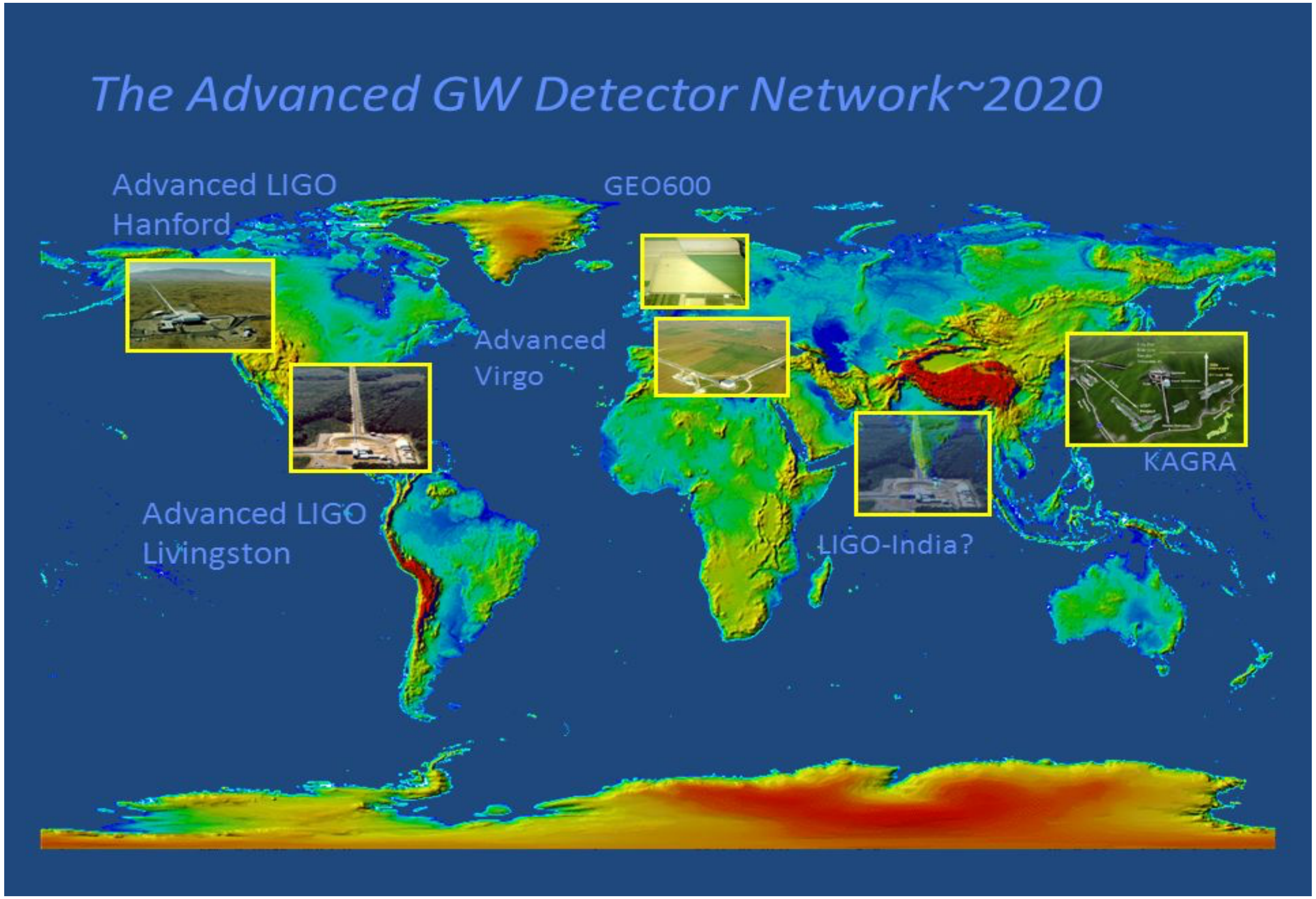
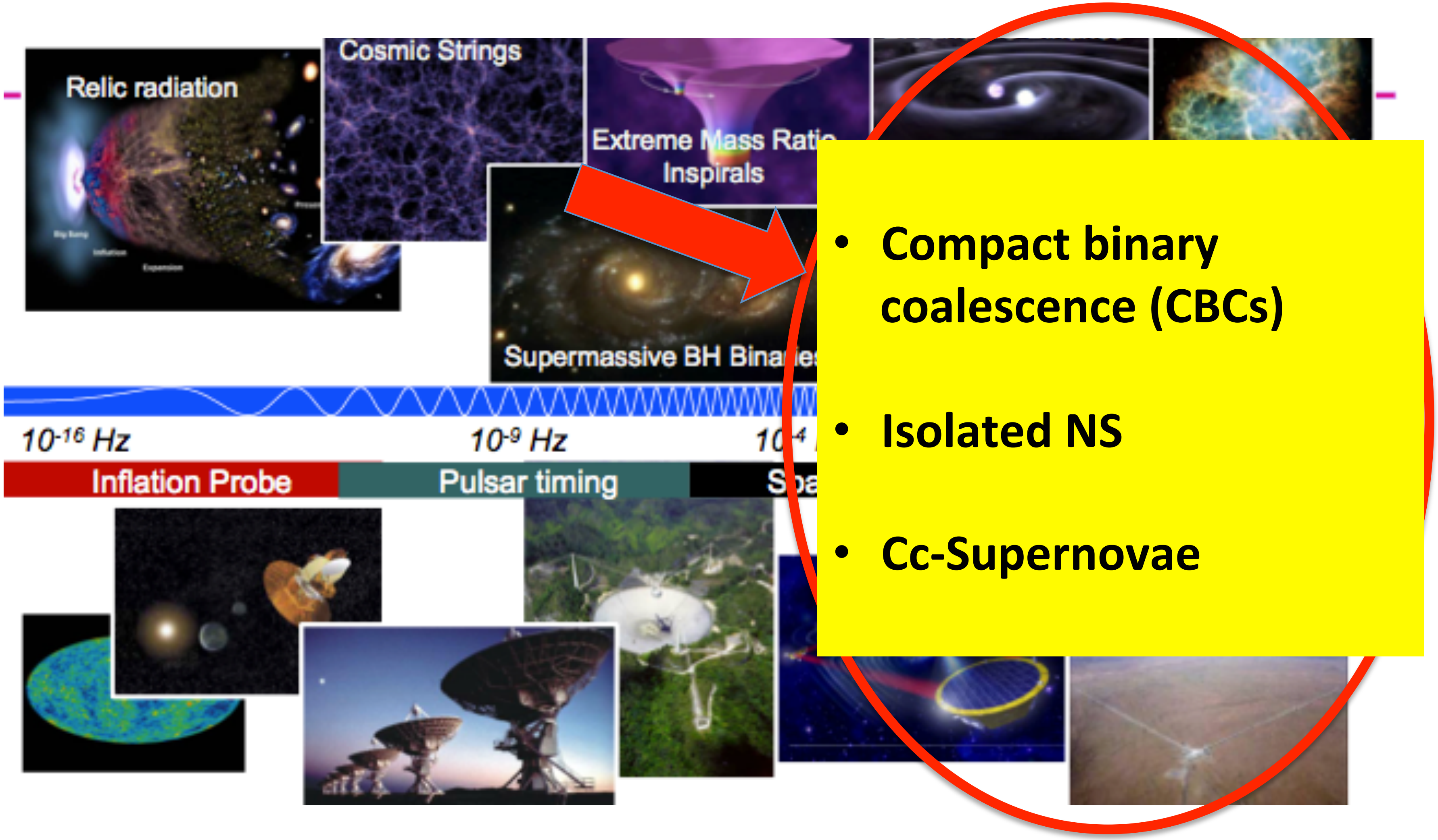


Image credit: Tarun Souradeep

GW sources



- **Compact binary coalescence (CBCs)**
- **Isolated NS**
- **Cc-Supernovae**

(from A. Weinstein NYU lecture, 2015)

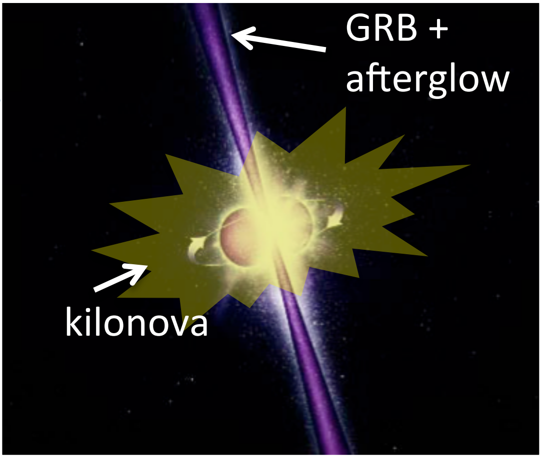
EM counterparts of most promising GW sources (CBCs)

NS-NS or NS-BH*

- **“Short” γ-ray bursts** (GRB, <2 s) (e.g. Eichler et al. 1989, Berger2014)
- **MW Afterglows**: X-rays (<1 day)/opt (<1 week/ radio(<1 month)

→ **well established emission but collimated →only a fraction (1-cosθ) of NS-NS/NS-BH (10°→1%!)**

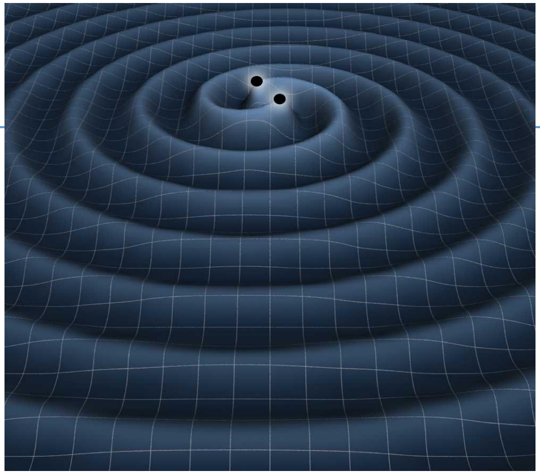
- “**macronova**”: opt/NIR bands, T0+1-10 days (e.g. Lattimer & Schramm 1976)
- **Late radio emission:** T0+1 month (e.g. Piran+2013)
- **X-ray emission:** if NS remnant is formed (e.g. Siegel & Ciolfi 2015)
- MW Off-axis afterglows: T+hours/days



BH-BH*

- No obvious EM counterpart is expected from such systems since no presence of matter is expected around BHBH
- Recent works however propose some possible scenarios where some material may be bound to the system and emit EM radiation (e.g. remnant disk, Perna et al. 2016; third body tidal disruption, Seto& Muto2011)

*stellar-mass black hole (i.e. <100 $M_\odot$)



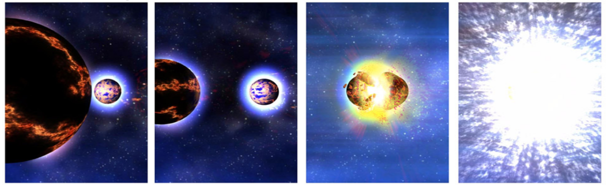
Source: NASA

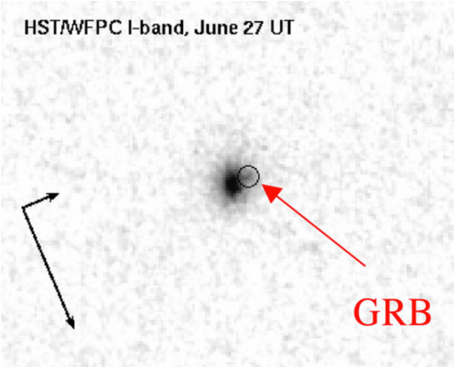
Why searching for EM counterparts?

Some examples:

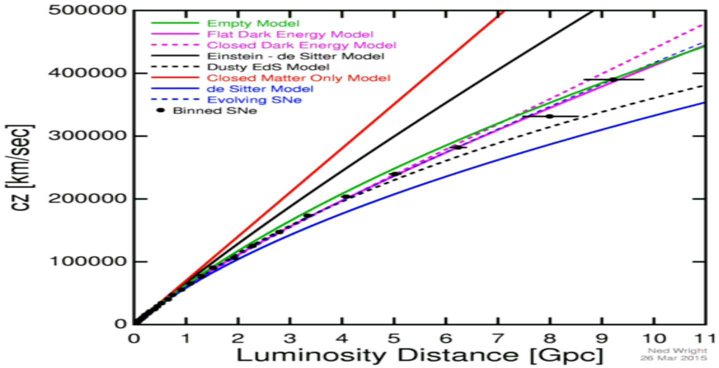
- To gain a more complete phenomenological pictures of astrophysical sources:
  - GW: masses, spins, orientations
  - EM: particle acceleration and emission processes
- For the case of sGRB we will confirm their progenitor nature and possibly distinguish between NS-NS and NS-BH
- Host galaxy identification (if extra-galactic):
  - ISM properties -> formation history of GW source, etc.
  - Independent measure of distance from spectral line systems
- Measuring cosmological z from optical spectra and luminosity distance from GW for large sample of CBC→ constraints on cosmological parameters

Image Credit: NASA / Dana Berry





Credit: A. Gal-Yam (Caltech)



Credit:Ned Wright

Joint GW+EM detection: 2 ways

1. **Triggers from EM sources** → offline GW archival data analysis using EM source position and trigger time as priors for signal search and parameter estimation (e.g. SN, GRB, etc.)

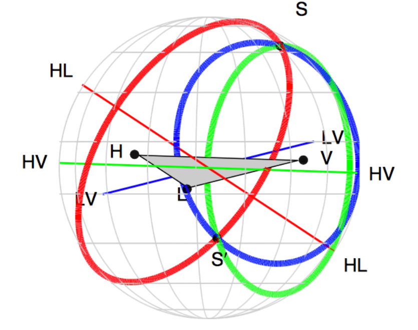
2. **Triggers from GW events** → EM follow-up observations (and archival searches) using GW event time and rough localization (e.g. macronova, off-axis afterglows, NS spindown emission, etc.)

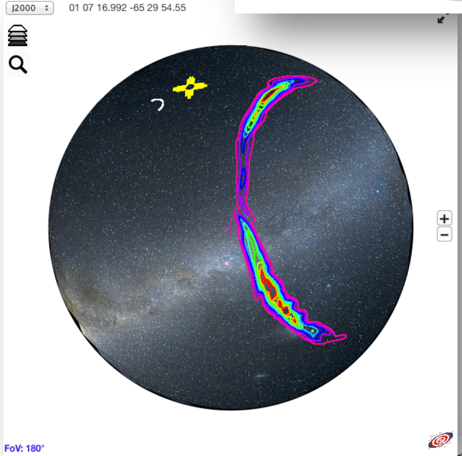
(~~RA, Dec~~) → GW Skymaps

- GW source sky localizations are provided by a network of interferometers via **triangulation**
- Large sky areas are identified depending on the number of GW detectors

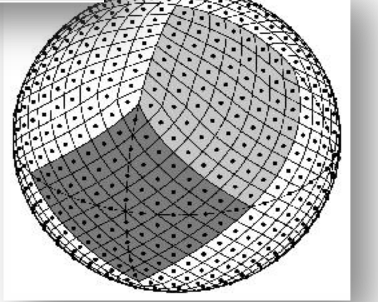
  E.g. with 2 detectors: 100-1000 deg2, with 5 detectors (>2022) ~10 deg2 or less
- Rather than a pair of sky coordinates +uncertainties, GW sources are localized with **sky probability maps**
  - The whole sky is divided in equal area pixels of 0.16 deg2 and to each pixel the probability of finding the GW source is assigned
- Sky probability densities are currently computed by several pipelines based on different algorithms with increasing computational costs

Abbott+2016 LRR19





Skymap of GW150914 Plotted with “Skymap Viewer” on GraceDB



Gorsky et al. 2004

Past LVC GW-EM follow-up program

- First GW-triggered EM follow-up campaigns during initial LIGO and Virgo science runs:
  - Dec 2009 - Jan 2010
  - Sept 2010 - Oct 2010

- Despite no significant GW event was detected, 8 GW candidates* were selected among unmodeled bursts and CBCs signals (FAR<1-0.25 day^{-1})

- GW candidate **inferred sky locations were used to centrally plan follow-up observations**

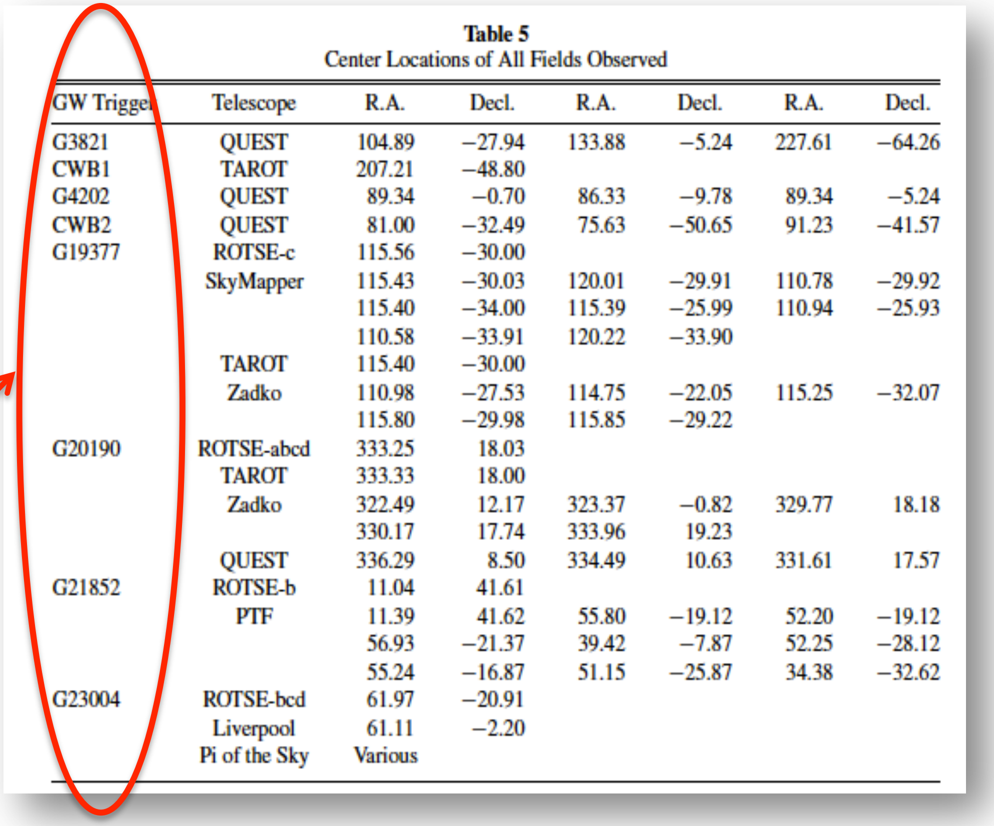


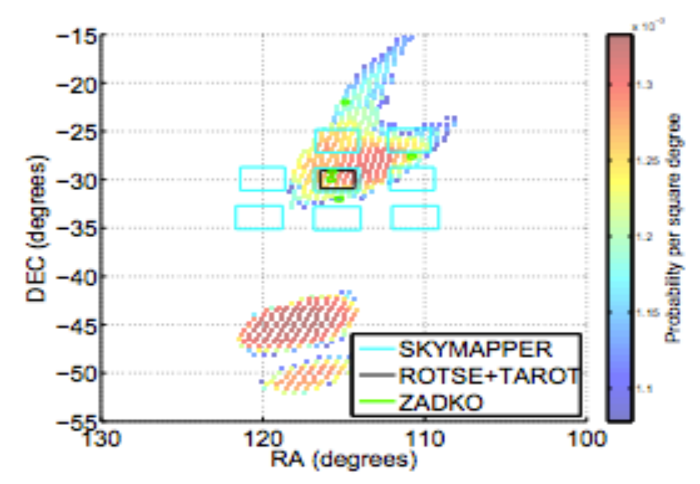
Table 5
Center Locations of All Fields Observed

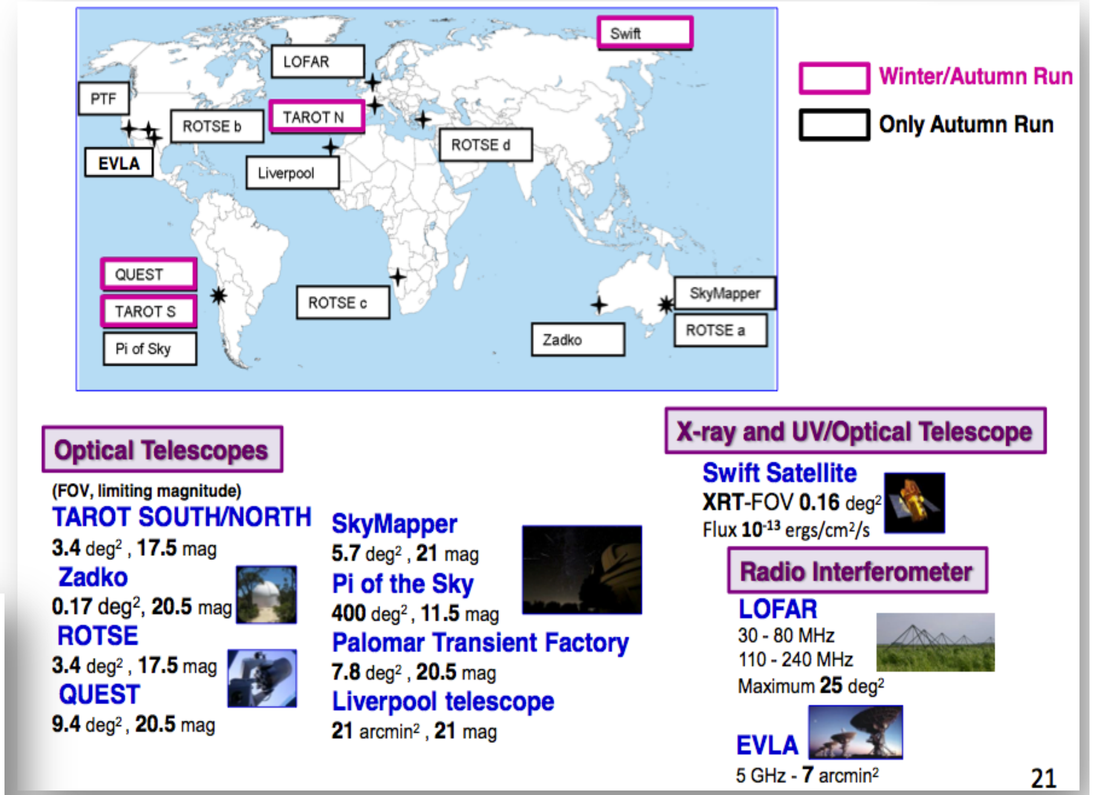
GW Trigge	Telescope	R.A.	Decl.	R.A.	Decl.	R.A.	Decl.
G3821	QUEST	104.89	−27.94	133.88	−5.24	227.61	−64.26
CWB1	TAROT	207.21	−48.80				
G4202	QUEST	89.34	−0.70	86.33	−9.78	89.34	−5.24
CWB2	QUEST	81.00	−32.49	75.63	−50.65	91.23	−41.57
G19377	ROTSE-c	115.56	−30.00				
	SkyMapper	115.43	−30.03	120.01	−29.91	110.78	−29.92
		115.40	−34.00	115.39	−25.99	110.94	−25.93
		110.58	−33.91	120.22	−33.90		
	TAROT	115.40	−30.00				
	Zadko	110.98	−27.53	114.75	−22.05	115.25	−32.07
		115.80	−29.98	115.85	−29.22		
G20190	ROTSE-abcd	333.25	18.03				
	TAROT	333.33	18.00				
	Zadko	322.49	12.17	323.37	−0.82	329.77	18.18
		330.17	17.74	333.96	19.23		
	QUEST	336.29	8.50	334.49	10.63	331.61	17.57
G21852	ROTSE-b	11.04	41.61				
	PTF	11.39	41.62	55.80	−19.12	52.20	−19.12
		56.93	−21.37	39.42	−7.87	52.25	−28.12
		55.24	−16.87	51.15	−25.87	34.38	−32.62
G23004	ROTSE-bcd	61.97	−20.91				
	Liverpool	61.11	−2.20				
	Pi of the Sky	Various					

Aasi+2014 ApJSS, 211,7

Past LVC GW-EM follow-up program

- **Tiles were assigned to individual facilities**
- **10** optical and radio ground-based facilities plus Swift high energy satellite were involved at that time





Winter/Autumn Run

Only Autumn Run

Optical Telescopes

(FOV, limiting magnitude)

TAROT SOUTH/NORTH
3.4 deg^2 , **17.5** mag

Zadko
0.17 deg^2, **20.5** mag

ROTSE
3.4 deg^2 , **17.5** mag

QUEST
9.4 deg^2 , **20.5** mag

SkyMapper
5.7 deg^2 , **21** mag

Pi of the Sky
400 deg^2 , **11.5** mag

Palomar Transient Factory
7.8 deg^2 , **20.5** mag

Liverpool telescope
21 arcmin^2 , **21** mag

X-ray and UV/Optical Telescope

Swift Satellite
XRT-FOV **0.16** deg^2
Flux **10^{-13}** ergs/cm^2/s

Radio Interferometer

LOFAR
30 - 80 MHz
110 - 240 MHz
Maximum **25** deg^2

EVLA
5 GHz - **7** arcmin^2

21

* off-line analysis confirmed the non-astrophysical origin of GW candidates

Aasi+2014 ApJSS, 211,7

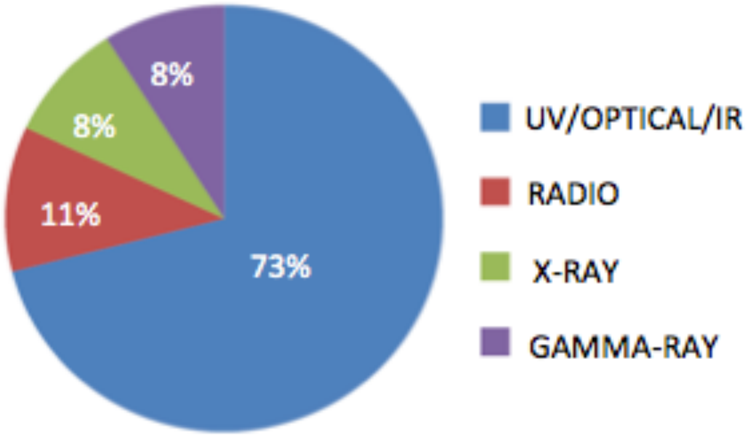
Current LVC GW-EM follow-up program

- **Today there are about 83 teams that have signed the LVC MoU!**

- **~170 instruments**

(satellites/world-wide ground-based)
covering the full spectrum
from radio to
very high-energy gamma-rays!

- **Astronomical institutions, agencies and large/small groups of astronomers** from 19 countries



Credit: Branchesi

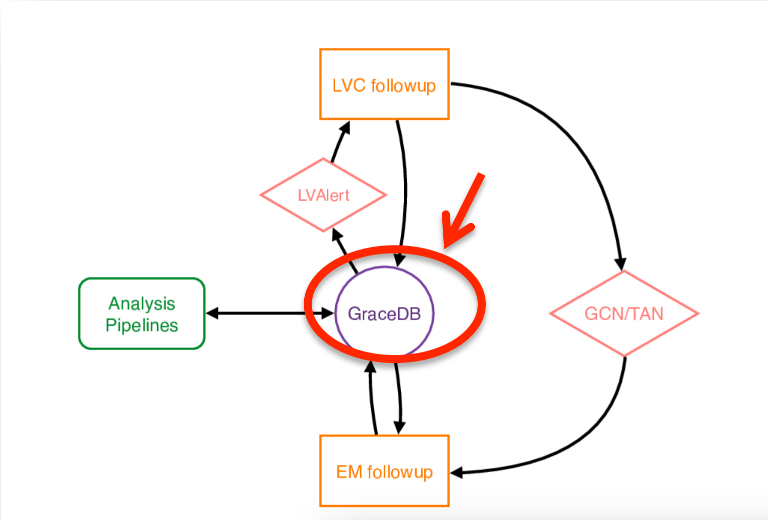
Some of them
https://gw-astronomy.org/wiki/LV_EM/PublicParticipatingGroups

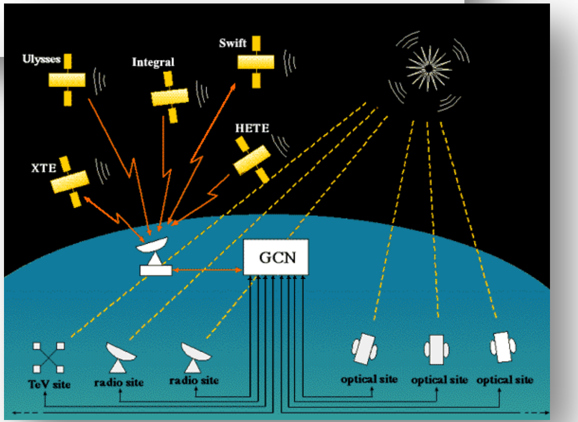
Current LVC GW-EM follow-up program

Rather than centrally planning assignments of tiles to each facility:

- **Skymaps** of GW events are distributed to MoU partners with the **Gamma-ray Coordinates Network (GCN*)** system:
  1. machine-readable Notices
  2. Short bullettins/circulars with descriptions of results and observations
- A **common EM bulletin board** has being created to coordinate observations by:
  - Announcing planned or performed observations providing sky coordinates and wavelength
- The main interface between low-latency GW data analysis and EM follow-up observations is the **Gravitational wave Candidate Data Base (GraceDB)** webpage

https://gracedb.ligo.org/documentation/general.html





http://gcn.gsfc.nasa.gov

***GCN are currently restricted to MoU parnters until the event has been published**

Localization and Broadband Follow-up of GW150914 *(Abbott+2016 ApJL 826,13)*

On 14-09-2015 an interesting GW event was detected

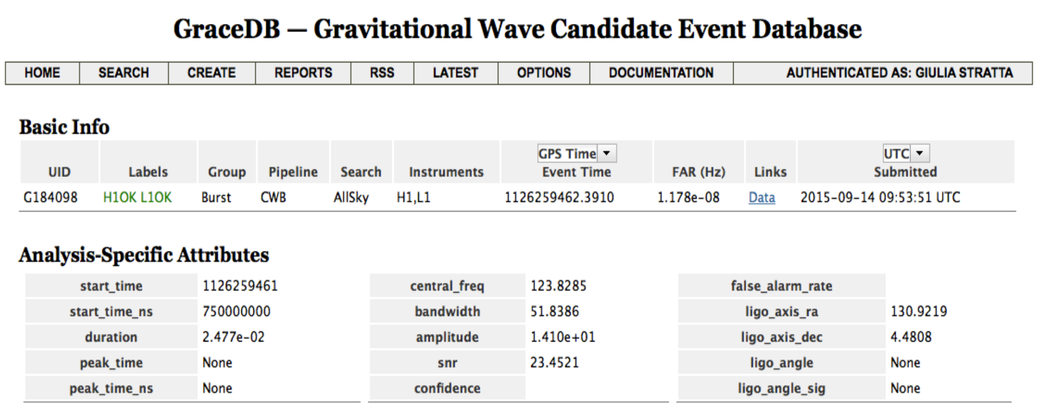
SNR=23.4

FAR<0.3/yr

→ below predefined threshold of 1/month

→ skymaps sent via GCN together with the link to the GraceDB page to 63 teams

https://gracedb.ligo.org/events/G184098



GraceDB — Gravitational Wave Candidate Event Database

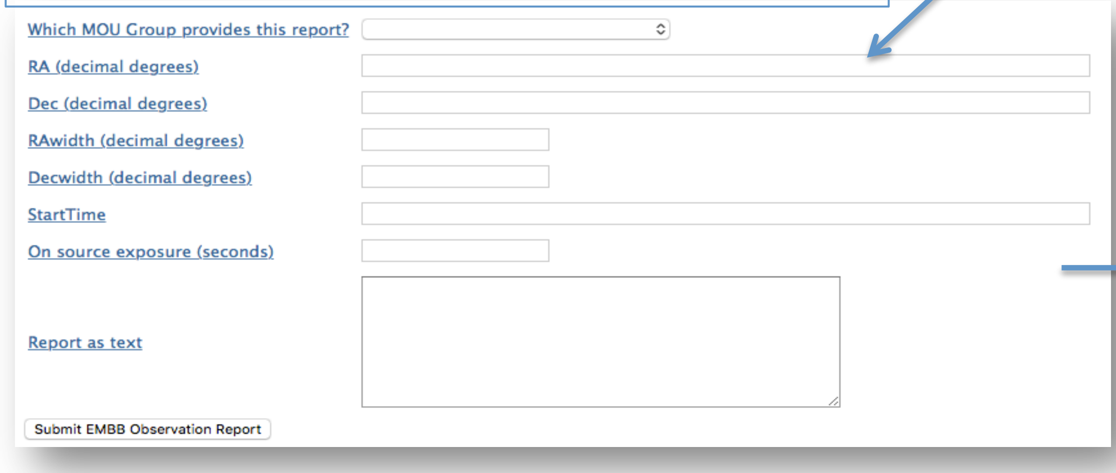
Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G184098	H1OK L1OK	Burst	CWB	AllSky	H1,L1	1126259462.3910	1.178e-08	Data	2015-09-14 09:53:51 UTC

Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

EM Observations (RA, Dec, λ, Tstart, etc.)



Which MOU Group provides this report?

RA (decimal degrees)

Dec (decimal degrees)

RAwidth (decimal degrees)

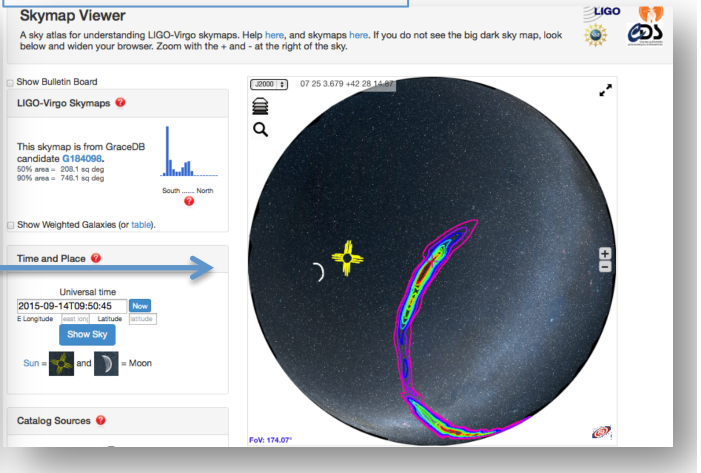
Decwidth (decimal degrees)

StartTime

On source exposure (seconds)

Report as text

Skymap Viewer



Skymap Viewer

A sky atlas for understanding LIGO-Virgo skymaps. Help here, and skymaps here. If you do not see the big dark sky map, look below and widen your browser. Zoom with the + and - at the right of the sky.

☐ Show Bulletin Board

LIGO-Virgo Skymaps

This skymap is from GraceDB candidate G184098.
50% area = 208.1 sq deg
90% area = 746.1 sq deg

☐ Show Weighted Galaxies (or table).

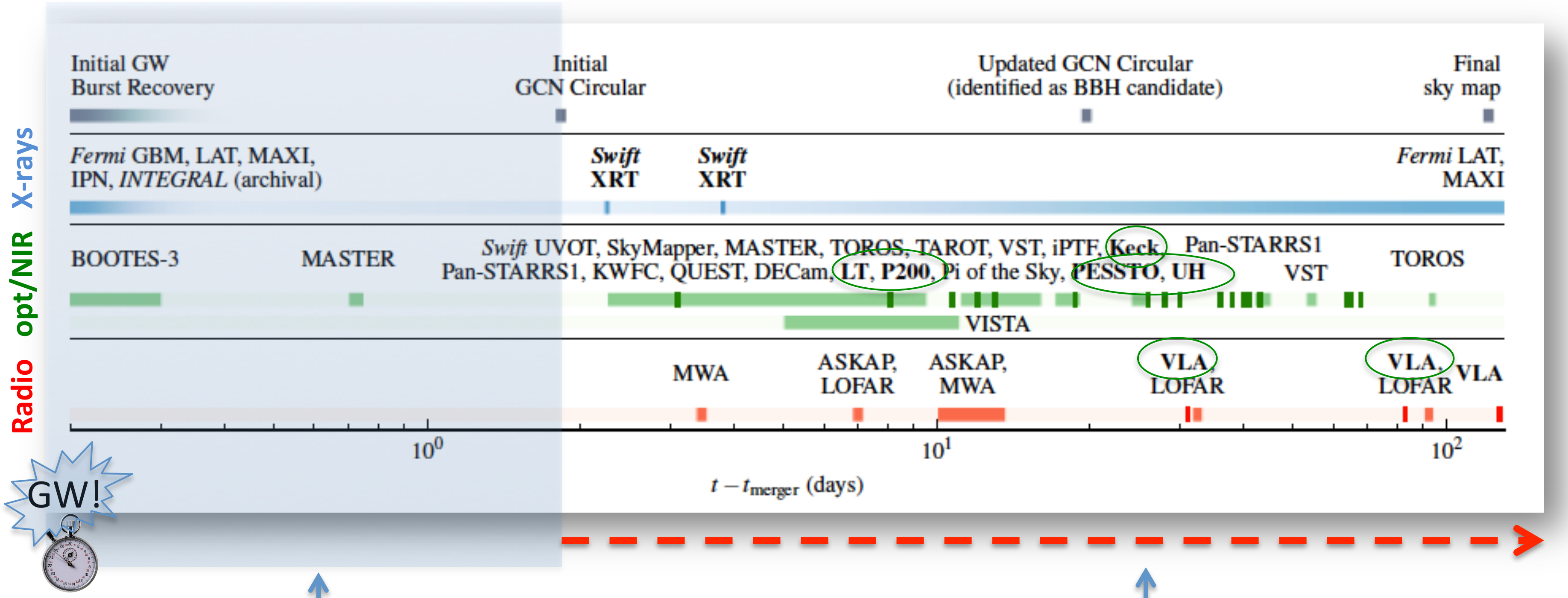
Time and Place

Universal time: 2015-09-14T09:50:45

Sun = and = Moon

Catalog Sources

Localization and Broadband Follow-up of GW150914 *(Abbott+2016 ApJL 826,13)*



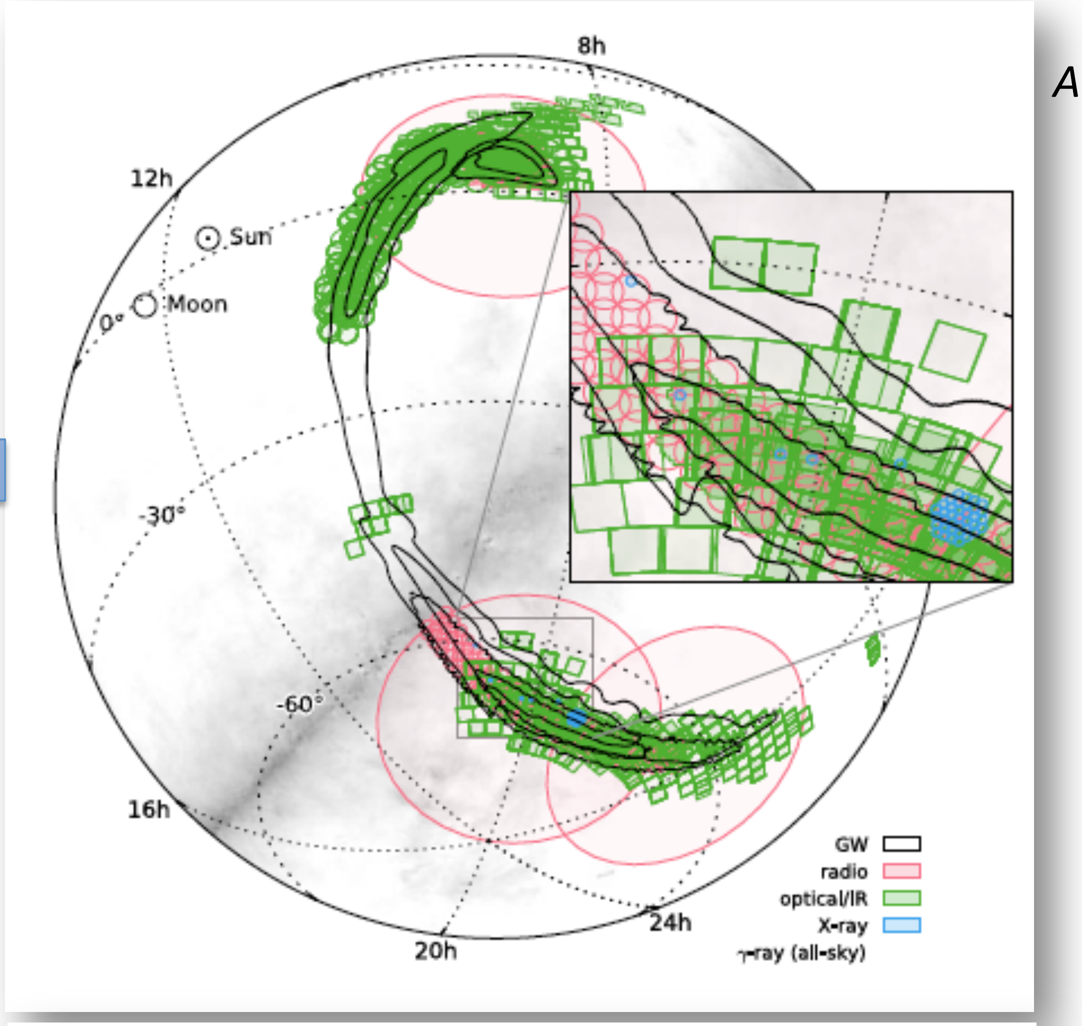
Archival searches

Follow-up observations

Large FOV telescopes

List of best candidates

50% and 90% confidence levels of the initially distributed GW skymaps

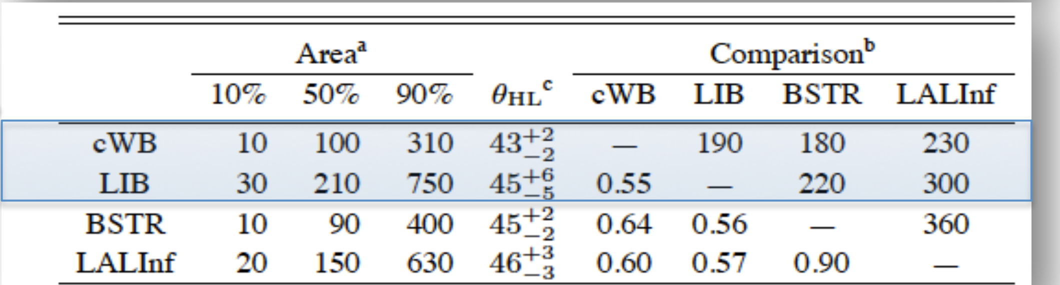


Abbott+2016 ApJL 826,13

~600 deg^2 from GW data

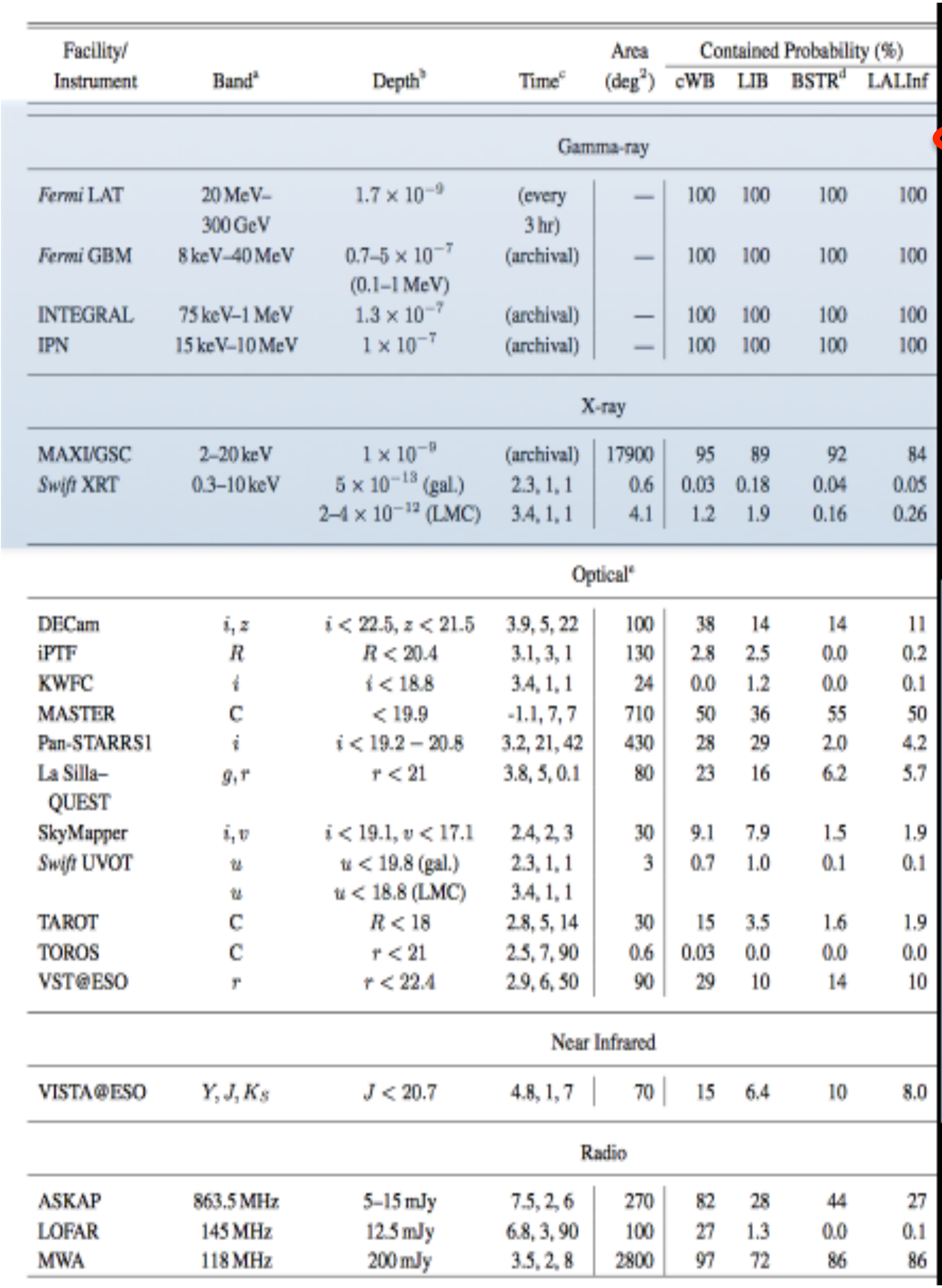
Contained probability:

- 100% gamma-rays
- 86% radio
- 50% optical



	Area[a]				Comparison[b]			
	10%	50%	90%	θ_{HL}[c]	cWB	LIB	BSTR	LALInf
cWB	10	100	310	43^{+2}_{-2}	—	190	180	230
LIB	30	210	750	45^{+6}_{-5}	0.55	—	220	300
BSTR	10	90	400	45^{+2}_{-2}	0.64	0.56	—	360
LALInf	20	150	630	46^{+3}_{-3}	0.60	0.57	0.90	—

4 skymaps were released (computed with different algorithms and increasing computational costs)



Facility/ Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained Probability (%) cWB	LIB	BSTR[d]	LALInf
			Gamma-ray					
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100
Fermi GBM	8 keV–40 MeV	$0.7\text{–}5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100
IPN	15 keV–10 MeV	1×10^{-7}	(archival)	—	100	100	100	100
			X-ray					
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05
		$2\text{–}4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26
			Optical[e]					
DECam	i, z	$i < 22.5, z < 21.5$	3.9, 5, 22	100	38	14	14	11
iPTF	R	$R < 20.4$	3.1, 3, 1	130	2.8	2.5	0.0	0.2
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1
MASTER	C	< 19.9	-1.1, 7, 7	710	50	36	55	50
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7
SkyMapper	i, v	$i < 19.1, v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1
	u	$u < 18.8$ (LMC)	3.4, 1, 1					
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0
VST@ESO	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10
			Near Infrared					
VISTA@ESO	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0
			Radio					
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86

Abbott+2016 ApJL 826,13

Most complete coverage in the **gamma-ray down to 10^{-7} erg cm^{-2} s^{-1}**

X-rays coverage complete down to 10^{-9} erg cm^{-2} s^{-1} (MAXI), relatively **sparse at fainter flux** with the Swift XRT

Ex: X-rays from sGRB @70 Mpc: 10^{-9}-10^{-7} cgs at 11hr

Fermi-GBM sub-threshold search → **weak signal** of 1 sec 0.4 s after GW15014 fluence(1 keV-10 MeV) = 2.4×10^{-7} erg cm^{-2} FAR 4.79×10^{-4} Hz, FAP 0.0022

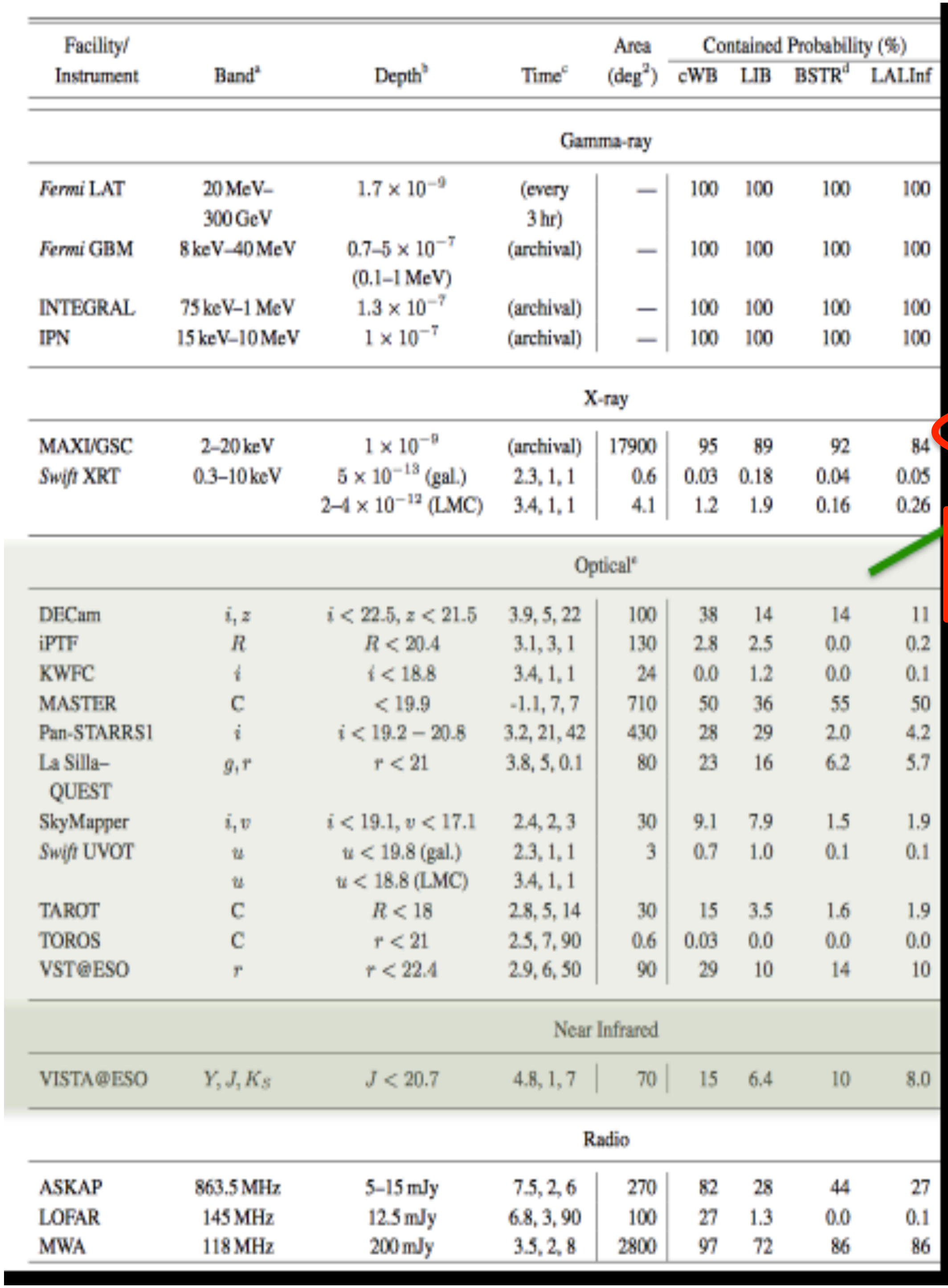
(**Connaughton et al. arXiv:1602.03920**)

INTEGRAL → no signal but **stringent upper limit**

(**Savchenko et al. 2016 ApJL, 820**)

AGILE → no signal (Tavani+2016)

Credit: Branchesi



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INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100
IPN	15 keV–10 MeV	1×10^{-7}	(archival)	—	100	100	100	100
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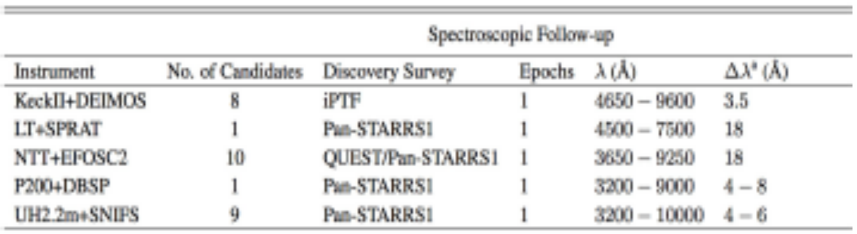
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7
SkyMapper	i, v	$i < 19.1, v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1
	u	$u < 18.8$ (LMC)	3.4, 1, 1					
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0
VST@ESO	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10
				Near Infrared				
VISTA@ESO	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0
				Radio				
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86

Optical facilities tiled together about **900 deg^2** with a **contained probability of over 50% of the initial sky map** and slightly less **of the refined sky map**

The **depth varies widely** among the different facilities

DES and **VST** deepest surveys **22.5**

Ex: Macronova@70 Mpc :
R ~ 17-24 mag at 1-2 weeks



Spectroscopic Follow-up

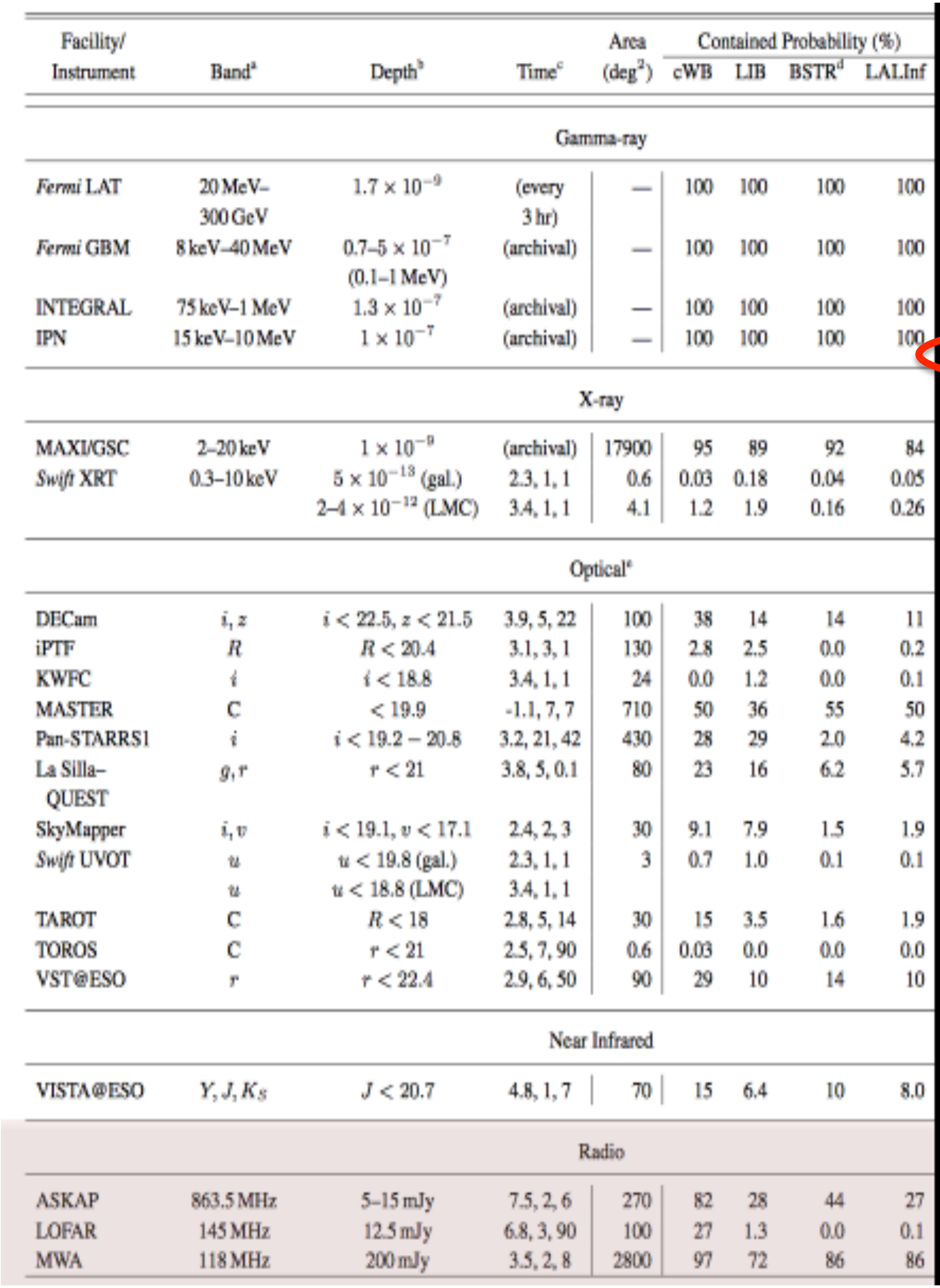
Instrument	No. of Candidates	Discovery Survey	Epochs	λ (Å)	Δλ[a] (Å)
KeckII+DEIMOS	8	iPTF	1	4650 – 9600	3.5
LT+SPRAT	1	Pan-STARRS1	1	4500 – 7500	18
NTT+EFOSC2	10	QUEST/Pan-STARRS1	1	3650 – 9250	18
P200+DBSP	1	Pan-STARRS1	1	3200 – 9000	4 – 8
UH2.2m+SNIFS	9	Pan-STARRS1	1	3200 – 10000	4 – 6

Abbott+2016 ApJL 826,13

Deep photometry, broadband observations and spectroscopy → candidates are normal population type Ia type II SNe, dwarf novae, active galactic nuclei, all unrelated to GW150914

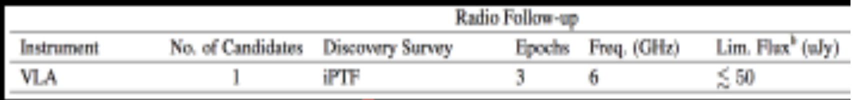
Credit: Branchesi

Abbott+2016 ApJL 826,13



Facility/ Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	cWB	LIB	BSTR[d]	LALInf
			Gamma-ray					
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100
Fermi GBM	8 keV–40 MeV	$0.7–5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100
IPN	15 keV–10 MeV	1×10^{-7}	(archival)	—	100	100	100	100
			X-ray					
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05
		$2–4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26
			Optical[e]					
DECam	i, z	$i < 22.5, z < 21.5$	3.9, 5, 22	100	38	14	14	11
iPTF	R	$R < 20.4$	3.1, 3, 1	130	2.8	2.5	0.0	0.2
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1
MASTER	C	< 19.9	-1.1, 7, 7	710	50	36	55	50
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7
SkyMapper	i, v	$i < 19.1, v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1
	u	$u < 18.8$ (LMC)	3.4, 1, 1					
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0
VST@ESO	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10
			Near Infrared					
VISTA@ESO	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0
			Radio					
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86

Radio coverage at low frequencies extensive, with the contained probability of about **90%** down to **5-200 mJy flux densities**



Radio Follow-up

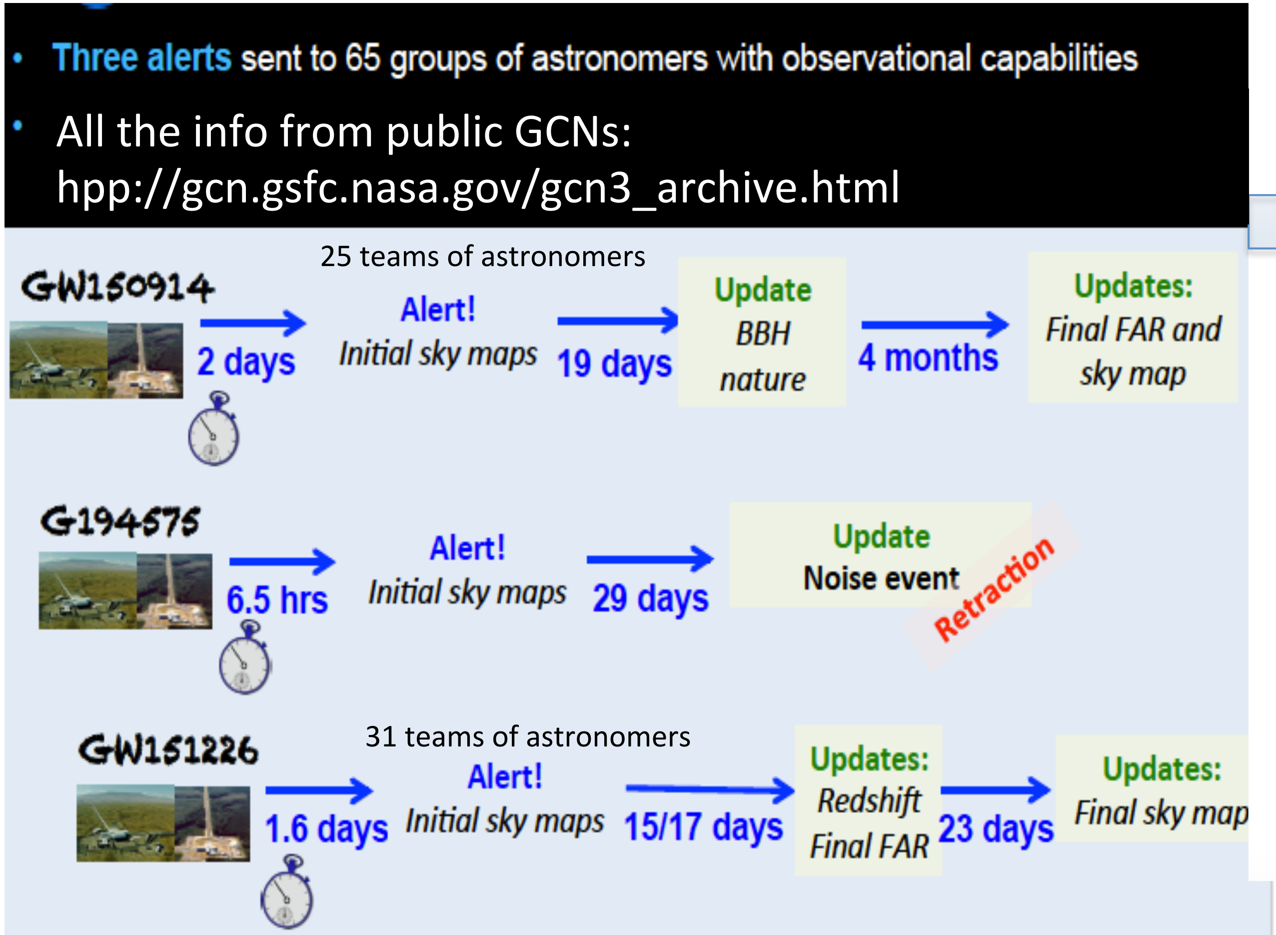
Instrument	No. of Candidates	Discovery Survey	Epochs	Freq. (GHz)	Lim. Flux[b] (μJy)
VLA	1	iPTF	3	6	$\lesssim 50$

At **high-frequency** (GHz) the narrow-field VLA followed localized transients down to **μJy flux densities**

BNS@70Mpc: 0.01-10 mJy (months)

Credit: Branchesi

EM follow-up program in O1



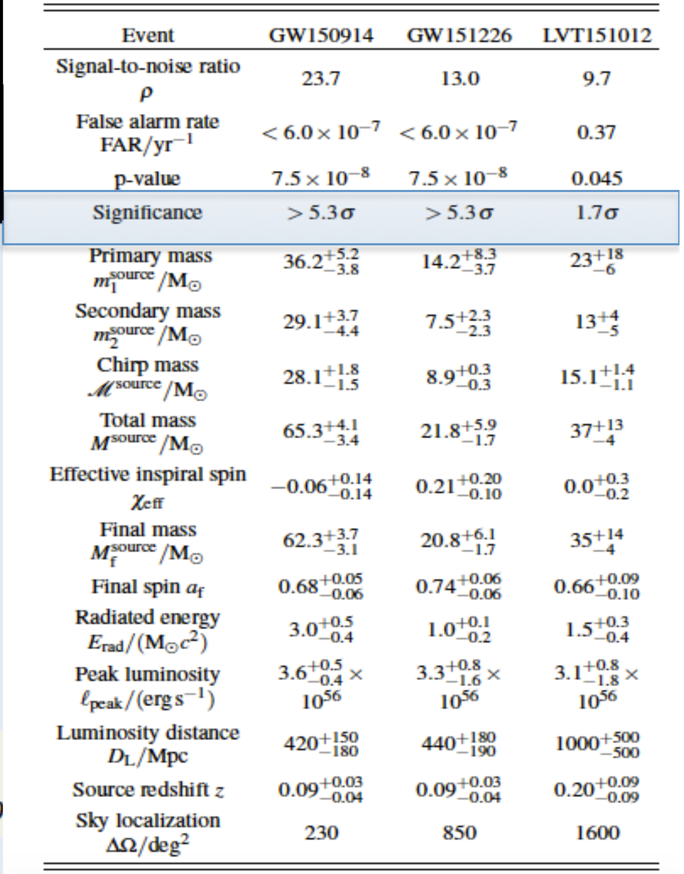
- **Three alerts** sent to 65 groups of astronomers with observational capabilities
- All the info from public GCNs: hpp://gcn.gsfc.nasa.gov/gcn3_archive.html

GW150914
25 teams of astronomers
2 days → **Alert!** *Initial sky maps* → 19 days → **Update** *BBH nature* → 4 months → **Updates:** *Final FAR and sky map*

G194575
6.5 hrs → **Alert!** *Initial sky maps* → 29 days → **Update** Noise event
Retraction

GW151226
31 teams of astronomers
1.6 days → **Alert!** *Initial sky maps* → 15/17 days → **Updates:** *Redshift* *Final FAR* → 23 days → **Updates:** *Final sky map*

Credit: Branchesi



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

"Binary Black Hole Mergers in the first Advanced LIGO Observing Run" Abbott+1606.04856

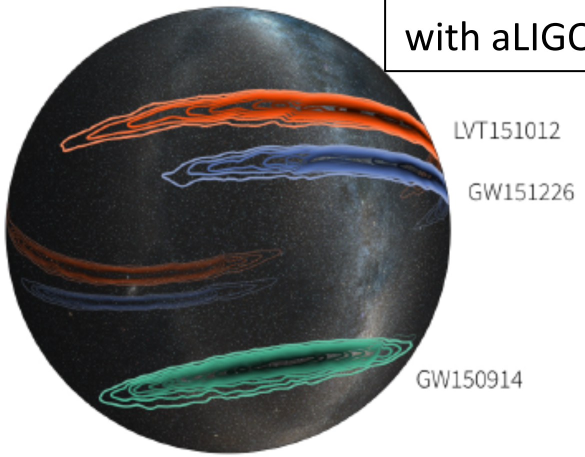
Future program for O2

- Next run (O2) starting in November
- Future alerts will provide **<u>within minutes:</u>**
  - Date & time of the GW event
  - skymap (only the preferred skymap at time of sending)

  If CBC:
  - **source distance**
  - **signal type (e.g. if a NS is present →EM-bright flag)**

  If burst:
  - **duration, central frequency (?)**
- **Virgo will significantly improve the sky localization** (estimates for GW 150914 indicates more than a factor of 10!)

Current localizations with aLIGO



Localizations with aLIGO+AdV

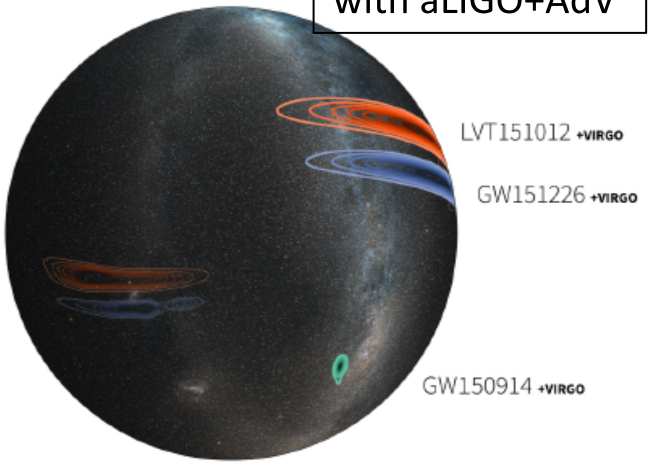
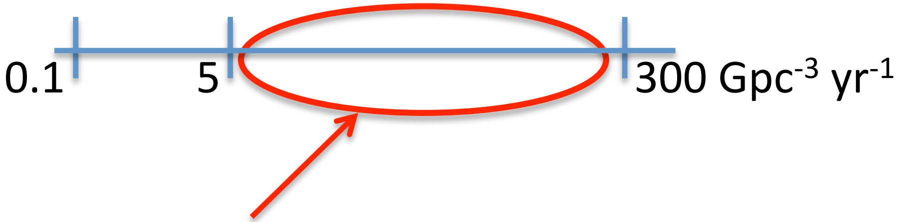


Image Credit: LIGO/L.Singer/A. Mellinger

Future program for O2

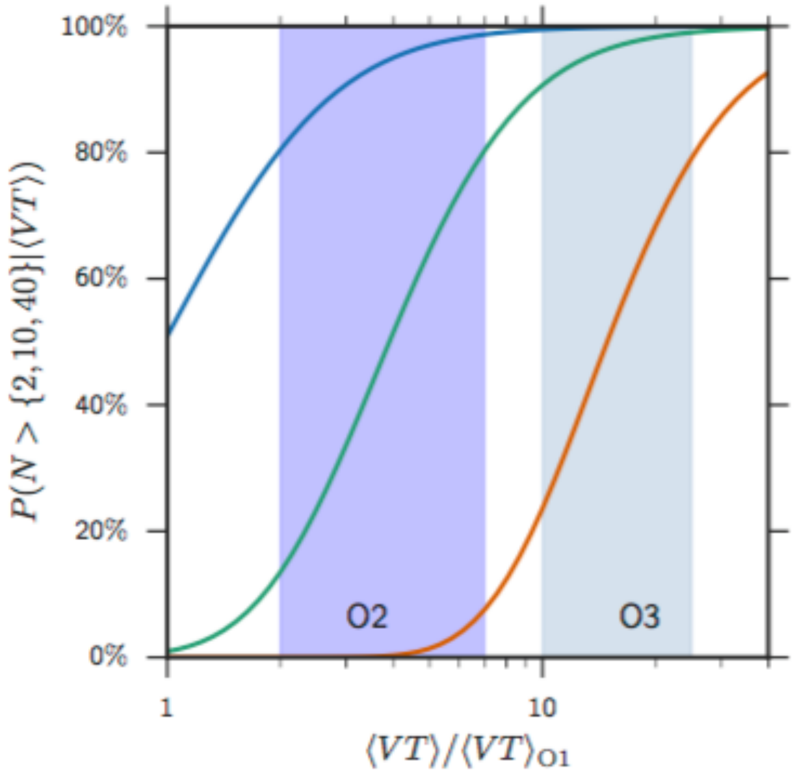
BBH rate from Abadie+2010



New constraints from O1 for BBH population are: **9-240 Gpc^{-3} yr^{-1}**

High significance BBH detections:

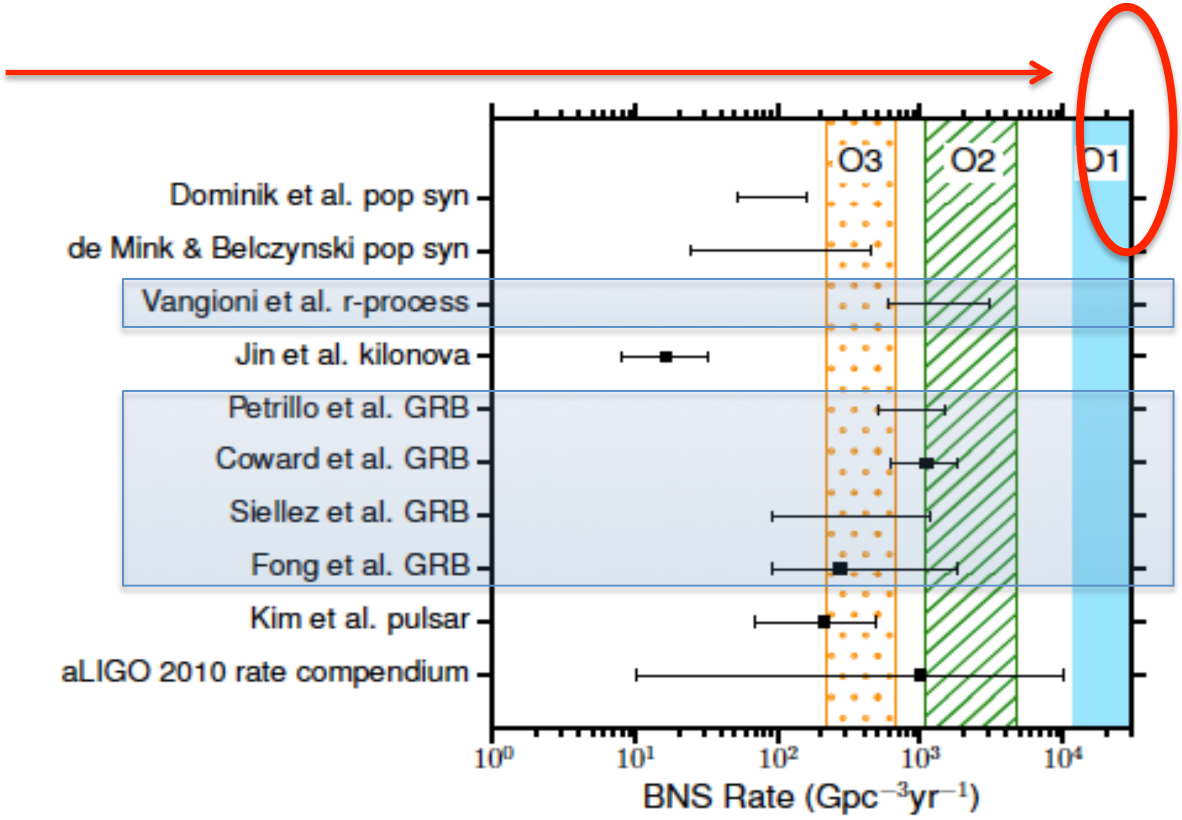
- **O2:**
  - ~90% probability to see >2 BBH
  - ~50% to see >10 BBH
- **O3:**
  - ~90% of probability to see > 10 BBH
  - ~60% of probability to see >40 BBH



“BBH Mergers in the first aLIGO observing run” Abbott+2016, ApJL in press

Future program for O2

- **O1 no BNS detections still consistent with expectations**
  - R_BNS < 12600 Gpc^{-3} yr^{-1}
- **O2 expected number of BNS is: 0.006-20** (Abbott +2016 LRR, for 6 months of LIGO+Virgo)
- **Non detections in O2 will start to provide constraints on estimated upper limits**



"Upper limits on the rates of BNS and NSBH from aLIGO first observing run" Abbott+2016 arXiv: 1607.07456v1

Summary

- EM counterparts are expected from gamma-rays to radio, and are fundamental to obtain a complete phenomenological picture of several GW sources
- EM follow-up observations are challenging due to the poor localization of GW detectors and uncertainties on expected emission
- Current EM follow-up program has being successfully tested in O1 managing optimal coordinations of >30 astronomical facilities
- For O2, sky probability maps will be released in tens of min, with additional information as e.g. source distance, EM expected brightness flag – if CBC -
- The join of Virgo to the network will significantly improve sky localizations **enhancing the probability to find the EM counterparts!**

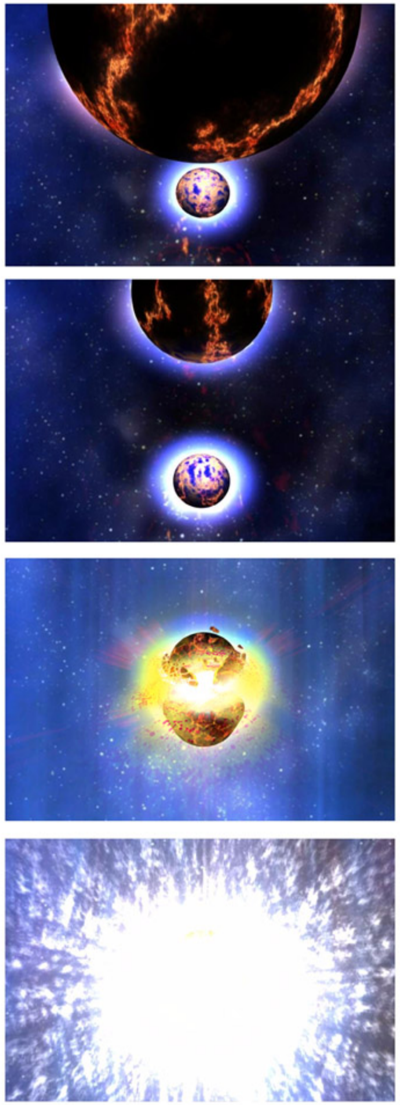
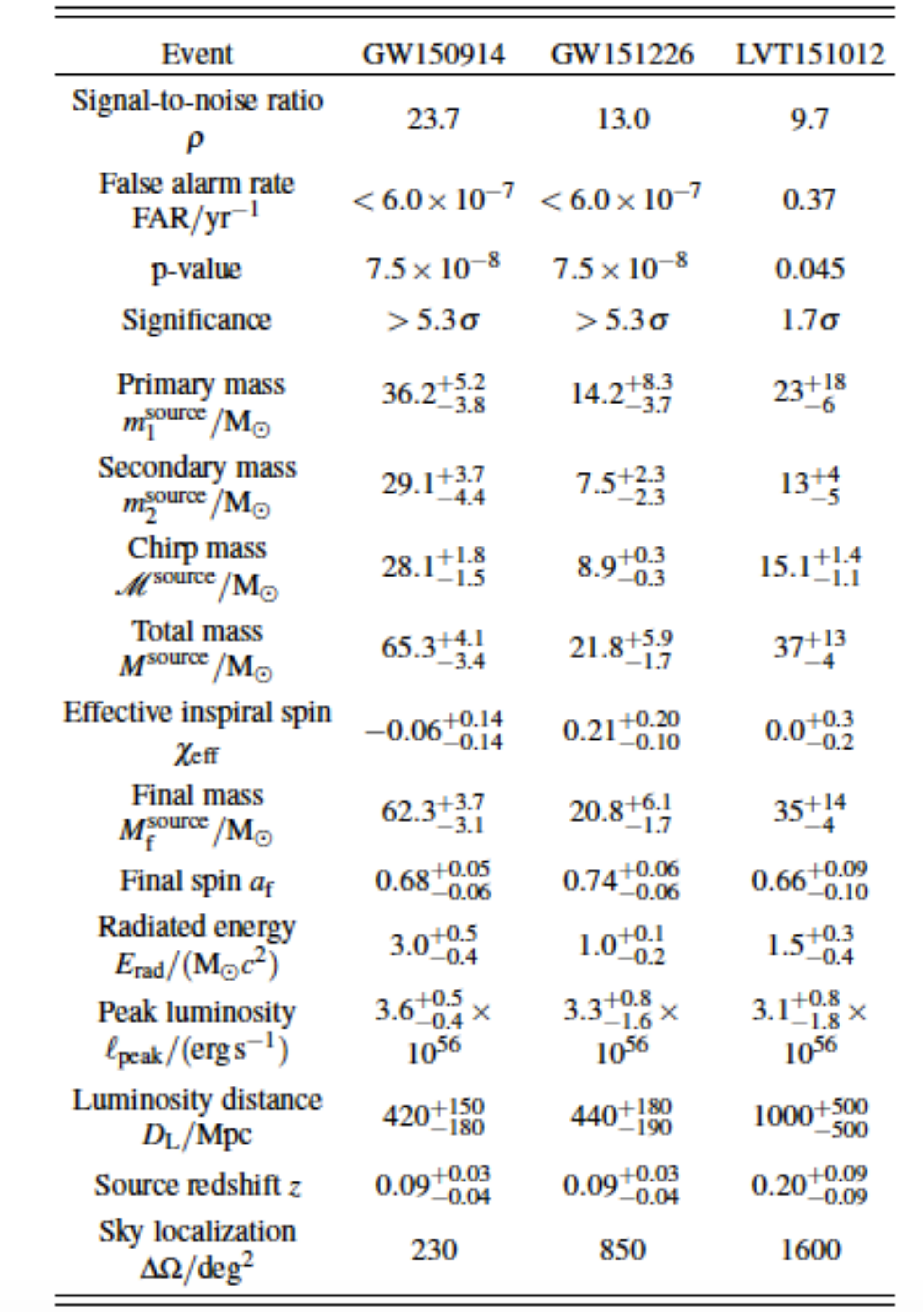


Image Credit: NASA / Dana Berry

Extra slides



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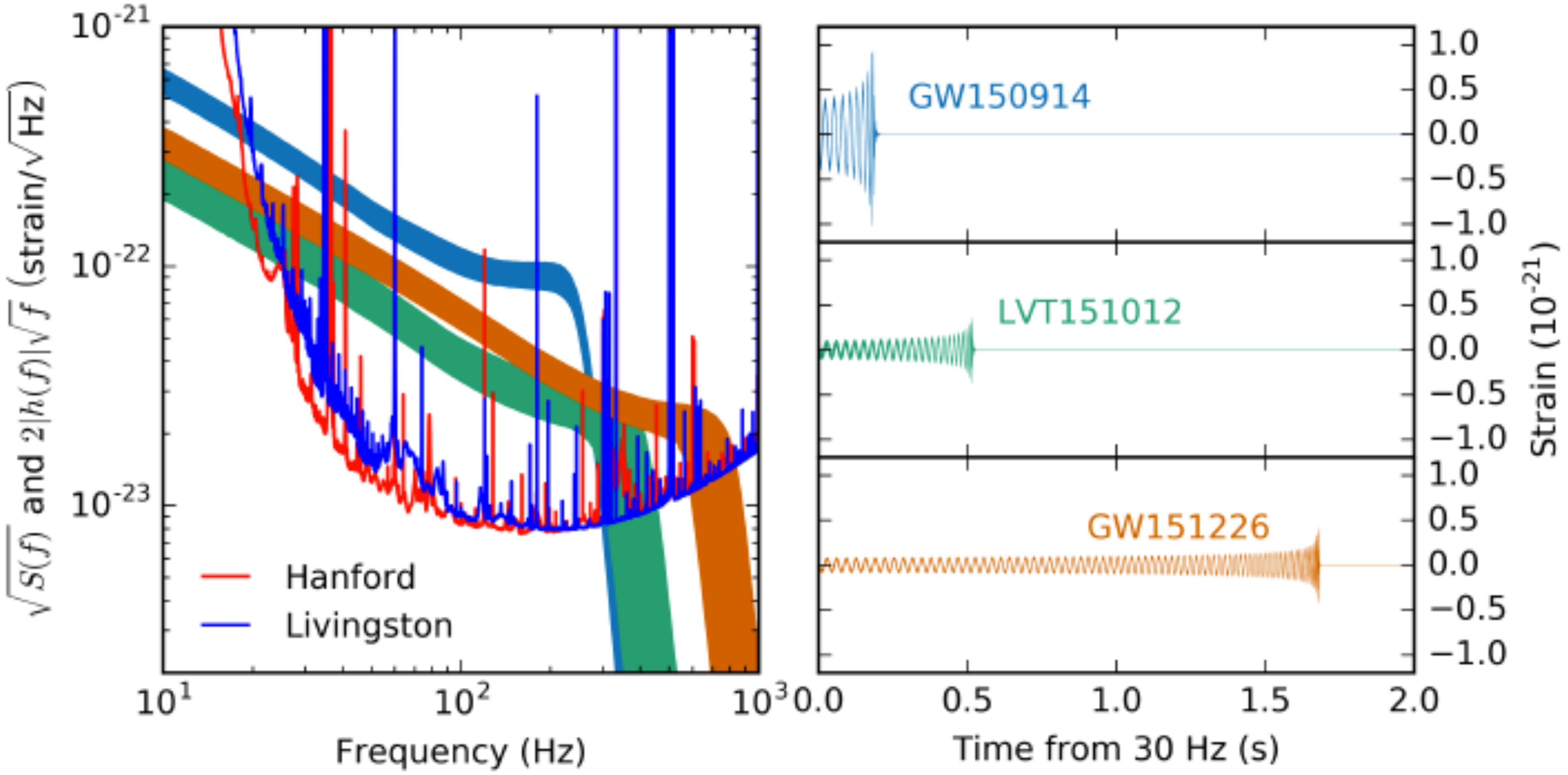
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

1606.04856



10^{-21}
10^{-22}
10^{-23}
$\sqrt{S(f)}$ and $2|\tilde{h}(f)|\sqrt{f}$ (strain/$\sqrt{\text{Hz}}$)
Hanford
Livingston
10^1
10^2
10^3
Frequency (Hz)
GW150914
LVT151012
GW151226
1.0
0.5
0.0
−0.5
−1.0
Strain (10^{-21})
0.0
0.5
1.0
1.5
2.0
Time from 30 Hz (s)

1606.04856

Localization and Broadband Follow-up of GW150914 *(Abbott+2016 ApJL 826,13)*

- aLIGO ER8: 17-08-2015 → 17-09-2015

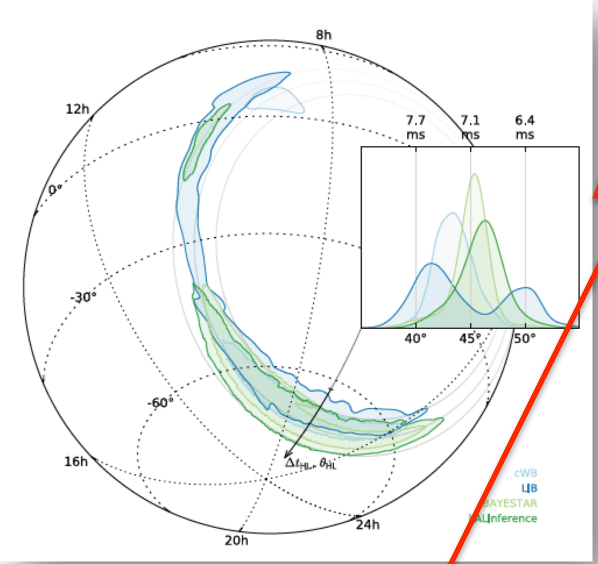
  aLIGO O1 start: 18-09-2015

- **On 14-09-2015 cWB detected a GW event, SNR=23.4, FAR<0.3/yr → below predefined threshold of 1/month → OK!**

- T0+2 days: first skymaps
  - cWB (17 min)
  - LALInference Burst (LIB, 14h)

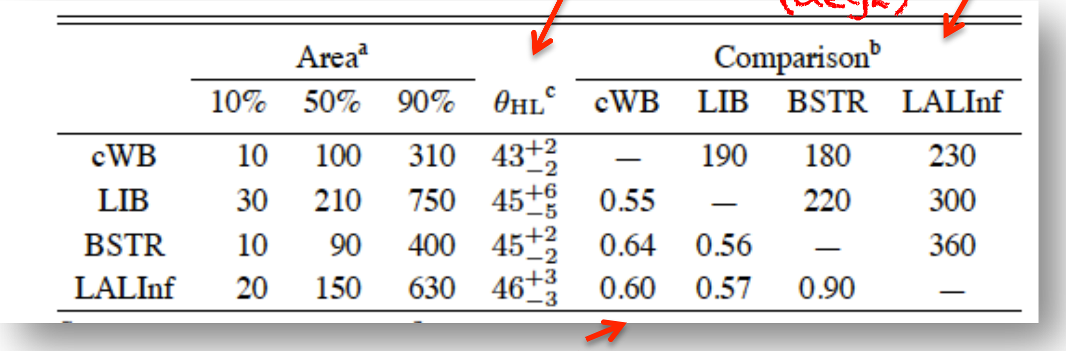
- T0+4months: refined skymaps
  - BAYESTAR
  - LALInference

  based on CBC pipeline output



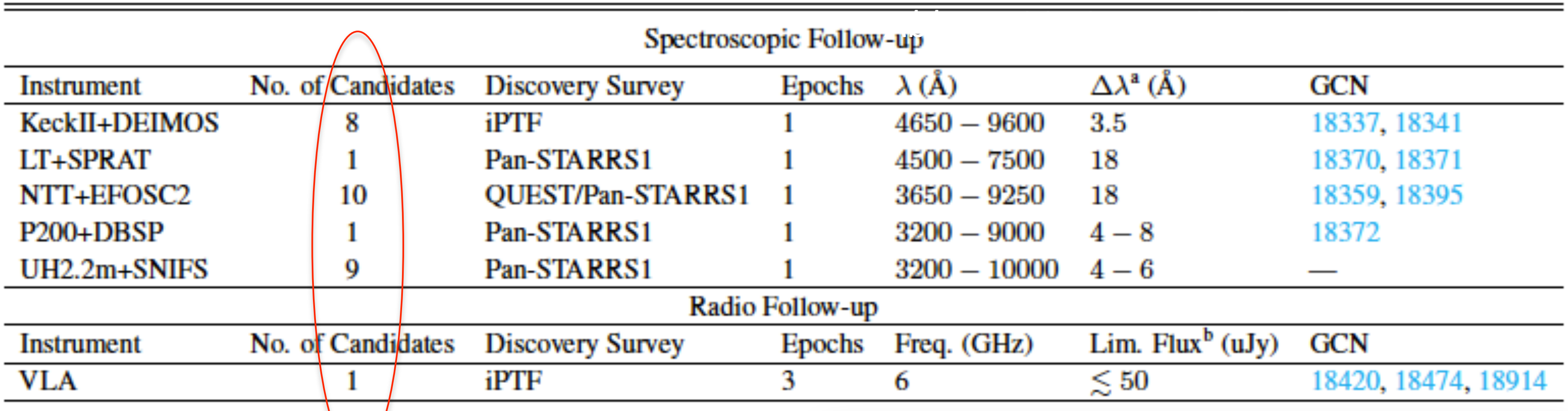
Polar angle

Intersection (deg2)



	Area[a]				Comparison[b]			
	10%	50%	90%	θ_{HL}[c]	cWB	LIB	BSTR	LALInf
cWB	10	100	310	43^{+2}_{-2}	—	190	180	230
LIB	30	210	750	45^{+6}_{-5}	0.55	—	220	300
BSTR	10	90	400	45^{+2}_{-2}	0.64	0.56	—	360
LALInf	20	150	630	46^{+3}_{-3}	0.60	0.57	0.90	—

fidelity



Spectroscopic Follow-up

Instrument	No. of Candidates	Discovery Survey	Epochs	λ (Å)	$\Delta\lambda^a$ (Å)	GCN
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LT+SPRAT	1	Pan-STARRS1	1	4500 – 7500	18	18370, 18371
NTT+EFOSC2	10	QUEST/Pan-STARRS1	1	3650 – 9250	18	18359, 18395
P200+DBSP	1	Pan-STARRS1	1	3200 – 9000	4 – 8	18372
UH2.2m+SNIFS	9	Pan-STARRS1	1	3200 – 10000	4 – 6	—

Radio Follow-up

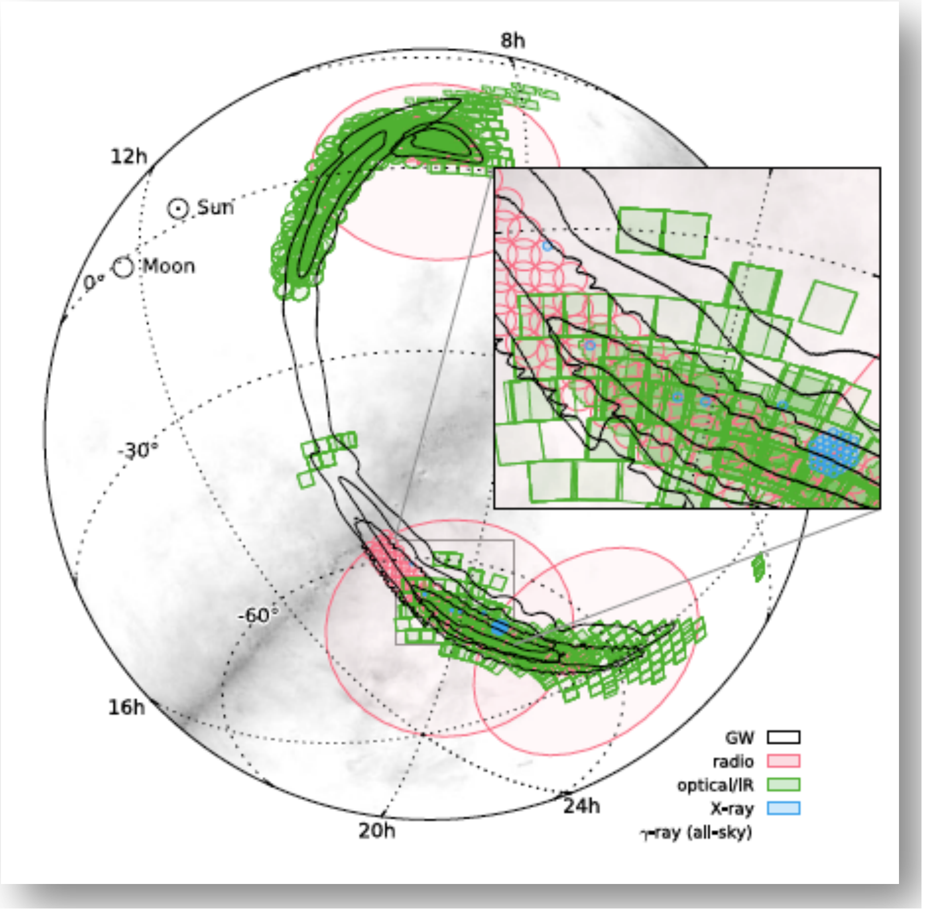
Instrument	No. of Candidates	Discovery Survey	Epochs	Freq. (GHz)	Lim. Flux^b (uJy)	GCN
VLA	1	iPTF	3	6	$\lesssim 50$	18420, 18474, 18914

- Some optical candidate counterparts were followed-up spectroscopically and in radio

- Most candidates were SNIa,SNII, dwarf novae, AGN → not associated with BBH

- Reaction times and sky coverages at all wavelengths successfully demonstrated the new EM-follow up program is overall working well

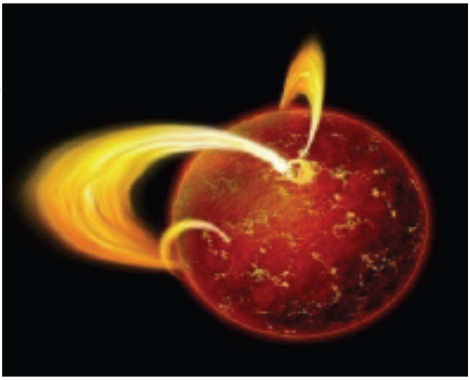
Abbott+2016 ApJL 826,13



EM counterparts of more uncertain GW sources

Isolated NS

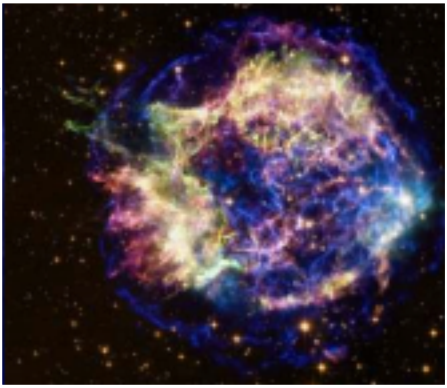
- Seismic activities in NSs with high B ($B>10^{14} - 10^{15}$ G, “magnetar”) are thought to produce GWs
- NS instabilities may originate bursts (0.1-1s, seldom 3-4 min) observed at 40-50 keV -> **Soft Gamma Repeaters, SGR** → Lx ~ 10^{42-47} erg/s



Credit: LIGO

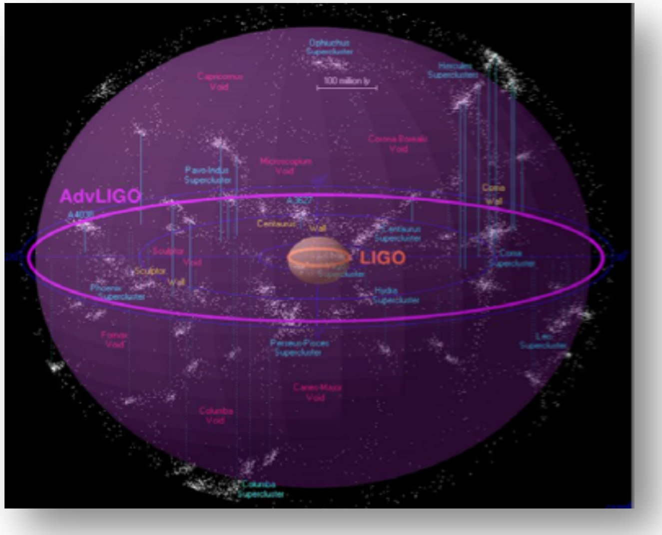
Supernovae

- Gravitational core collapse of massive stars (>8-10 $M_\odot$): SN II, SN Ib/c
- X/UV emission at ~hours after explosion (**Shock Breakout**) and opt emission after tens of days
- Gamma-rays (0.1-100 MeV) → **“long” GRB + afterglow** for a subclass of these SNe (the most energetic ones)



Current GW-triggered EM follow-up

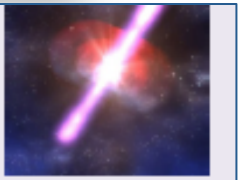
- The **first Advanced LIGO scientific run** started on September 2015 (O1)
- O1 expected to detect a NS-NS up to **70 Mpc**
- in 4 months 0.0005-4 NS-NS were expected (Abbott+2016 LRR 19) (BBH estimates largely uncertain and in the range ~0.006-17 at 400 Mpc)



Compact binary coalescence at nominal sensitivity (2019)

	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

(Abadie et al. 2010, CQG 27)



Mass: NS = 1.4 Mo
BH = 10 Mo

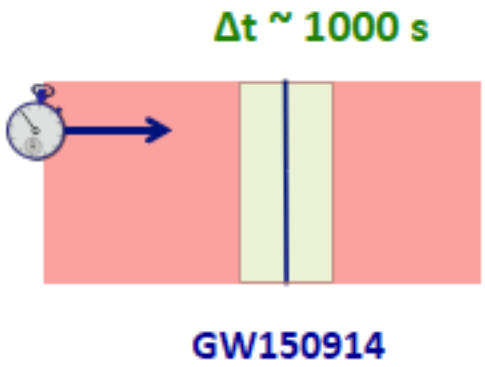
Advanced era

Sky location and orientation averaged range

197 Mpc	for NS-NS
410 Mpc	for NS-BH
968 Mpc	for BH-BH

High-Energy Neutrino Follow-up of GW150914

Search for coincident neutrino candidates within data of **IceCube** and **Antares**



Within ±500 s of GW150914:

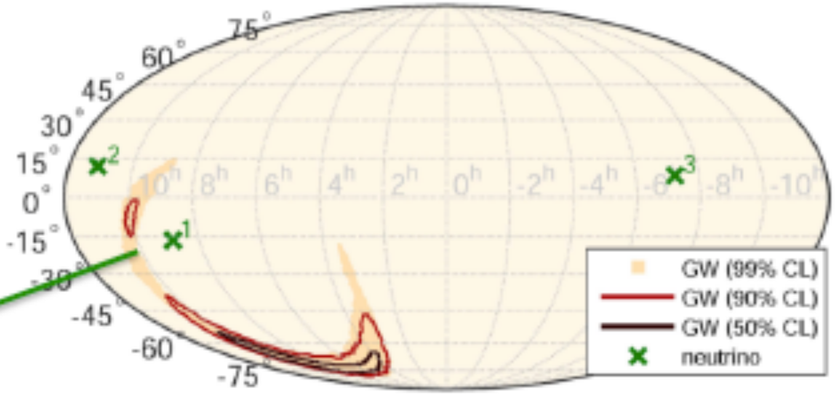
IceCube neutrino candidates **3**

ANTARES neutrino candidate **0**

- Consistent with the expected atmospheric background
- No neutrino candidate directionally coincident with GW150914

#	ΔT [s]	RA [h]	Dec [°]	$\sigma_\mu^{\rm rec}$ [°]	$E_\mu^{\rm rec}$ [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

Small angular uncertainties



No-detection is consistent with our expectati
from a binary black hole merger

A rapid GW/neutrino detection could be used in targeted EM follow-up

Adrián-Martínez et al. PRD, 93, 122010

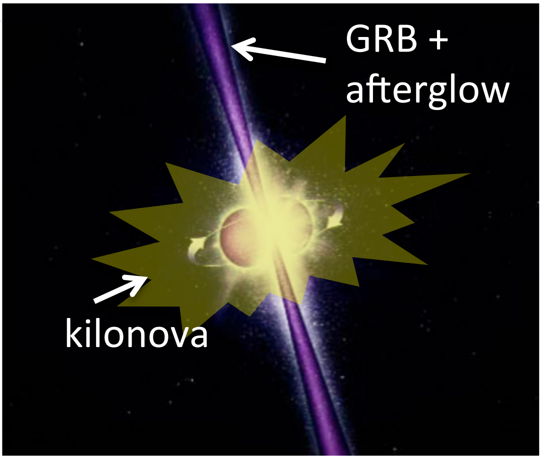
EM counterparts of most promising GW sources (CBCs)

NS-NS or NS-BH*

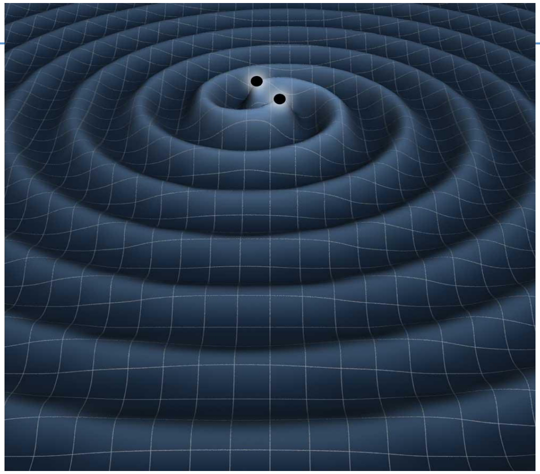
- **Collimated EM emission**: Several indirect evidence associate NS-NS/NS-BH with the progenitors **"Short" γ-ray bursts** (GRB, <2 s) + afterglow progenitors (e.g. Eichler et al. 1989, Berger2014)
- **Isotropic EM emission**: Thermal emission ("**macronova"**) is expected in the opt/NIR bands, 1-10 days after the coalescence (e.g. Lattimer & Schramm 1976). Radio emission at T+1 month is also expected. If a NS is formed, X-ray emission is also predicted (e.g. Siegel & Ciolfi 2015)

BH-BH*

- No obvious EM counterpart is expected from such systems since no presence of matter is expected around BHBH
- Recent works however propose some possible scenarios where some material may be bound to the system and emit EM radiation (e.g. remnant disk, Perna et al. 2016; third body tidal disruption, Seto& Muto2011)



*stellar-mass black hole (i.e. <100 $M_\odot$)



Source: NASA