

GW detection and em follow up

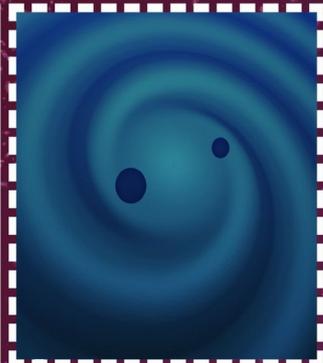
Fulvio Ricci

O1 : the first Science run of the advanced detectors

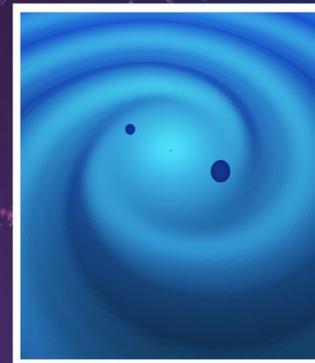
September 14, 2015
CONFIRMED



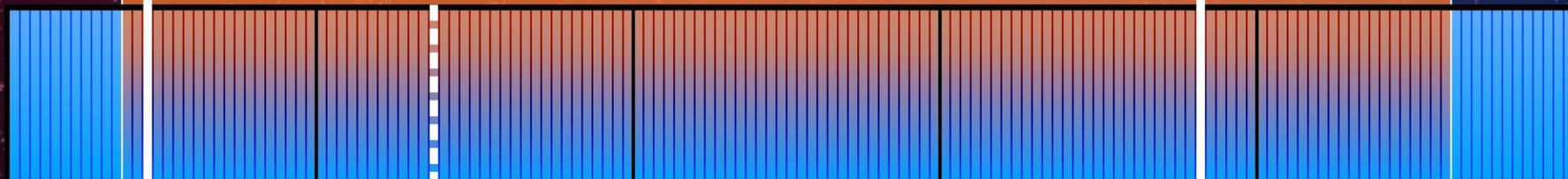
October 12, 2015
CANDIDATE



December 26, 2015
CONFIRMED



LIGO's first observing run
September 12, 2015 - January 19, 2016



September 2015

October 2015

November 2015

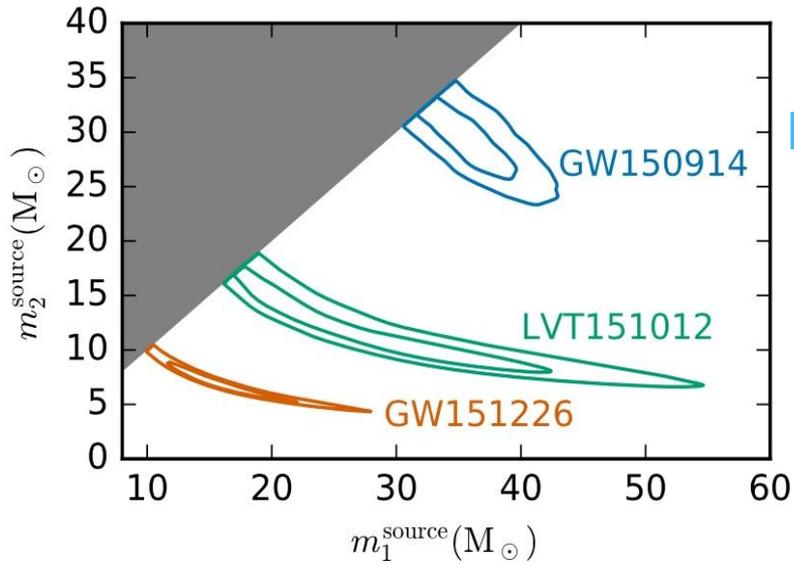
December 2015

January 2016

SNR=24

SNR=9

SNR=13



Mass Contour Plot

Event	Final Masses
GW150914	$62.3^{+3.7} M_{\odot}$
GW151226	$20.8^{+5.9}_{-3.1} M_{\odot}$
LVT151012	$35^{+14}_{-4} M_{\odot}$

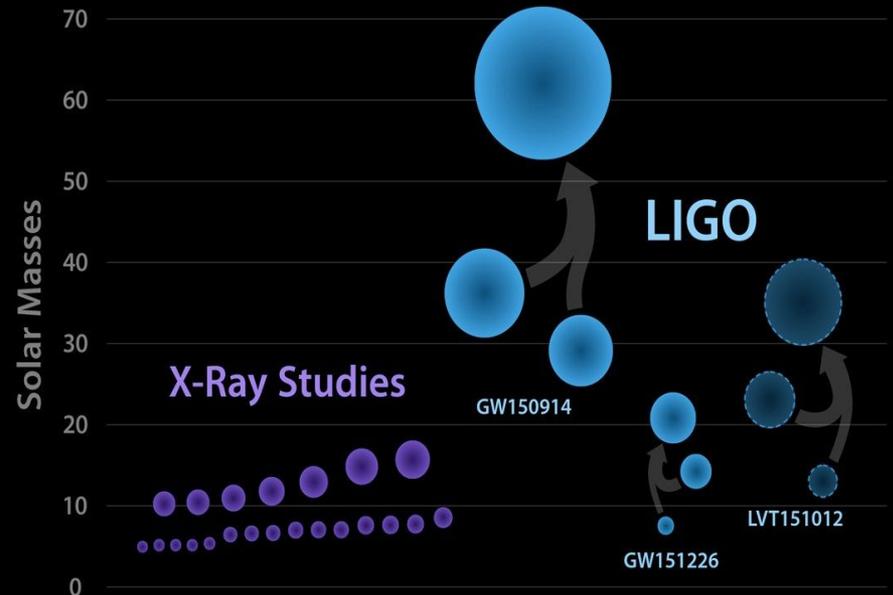
Event	GW150914	GW151226	LVT151012
Primary mass $m_1^{\text{source}} / M_{\odot}$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\text{source}} / M_{\odot}$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}

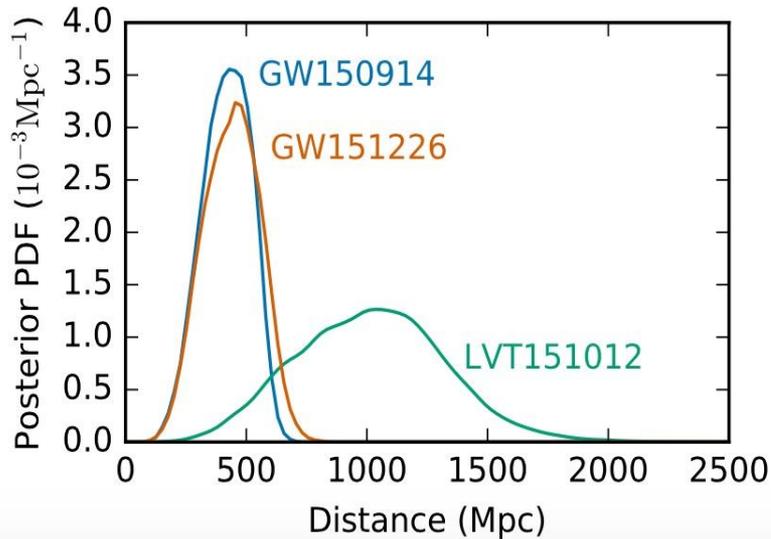
LVC 2016 Phys. Rev. Lett. 116, 061102

LVC 2016 ApJL, 818, 22

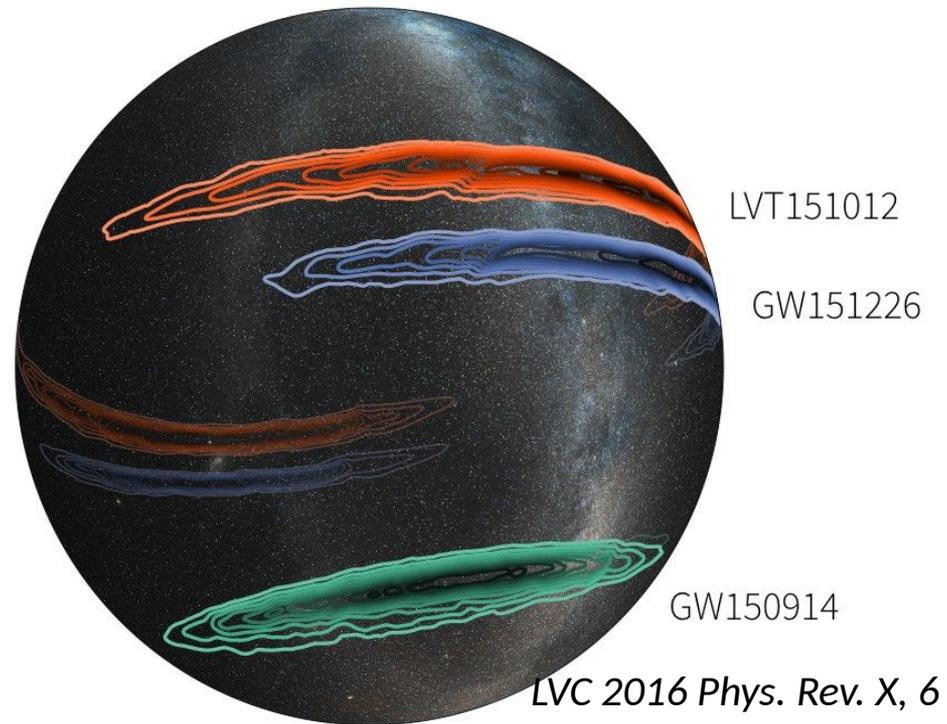
LVC 2016 Phys. Rev. Lett. 116,

Black Holes of Known Mass





Event	GW150914	GW151226	LVT151012
Luminosity distance D_L /Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}



LVC 2016 Phys. Rev. X, 6

Sky Localization 90% credible areas

- ✓ GW150914 600 deg²
- ✓ LVT 151012 1600 deg²
- ✓ GW151226 1000 deg²

In the volume of the Universe corresponding to GW150914, LVT151012, GW151226 there are 10^5 - 10^6 galaxies

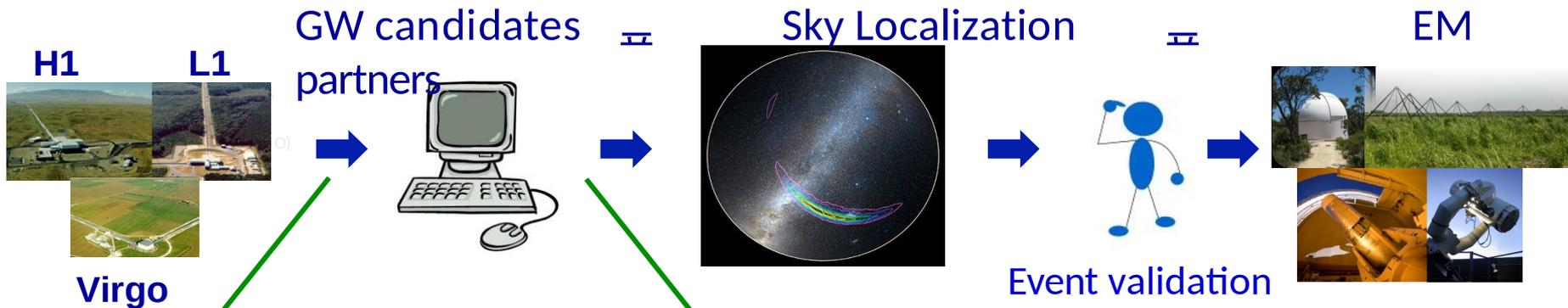
LIGO & Virgo have signed MOUs with **92 groups** for rapid EM/neutrino follow-up of GW candidate events found in low-latency

INVOLVED:

- **About 200 EM instruments** - satellites and ground based telescopes covering the full spectrum from radio to very high-energy gamma-rays
- ***Worldwide astronomical institutions, agencies and large/small teams of astronomers***

+ In addition a number of triggered / joint search MOUs

Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alert to obtain EM observations



Low-latency Search

to identify the GW-candidates

Unmodeled GW burst search

Matched filter with waveforms of compact binary coalescence

Evaluation of

- the statistical significance of triggers (background n.)
- check detector sanity and data quality
- determine source localization

a few min

15/30 min

Parameter estimation codes

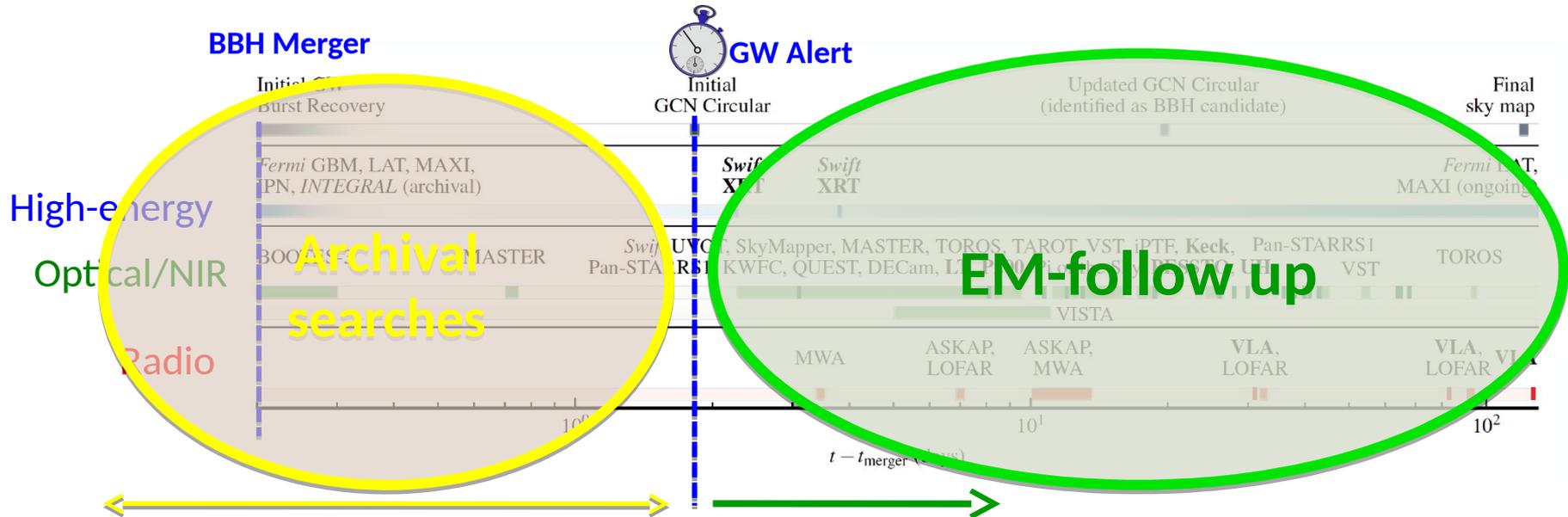
Hours, days

GW candidate updates



EM follow up observations and archival searches

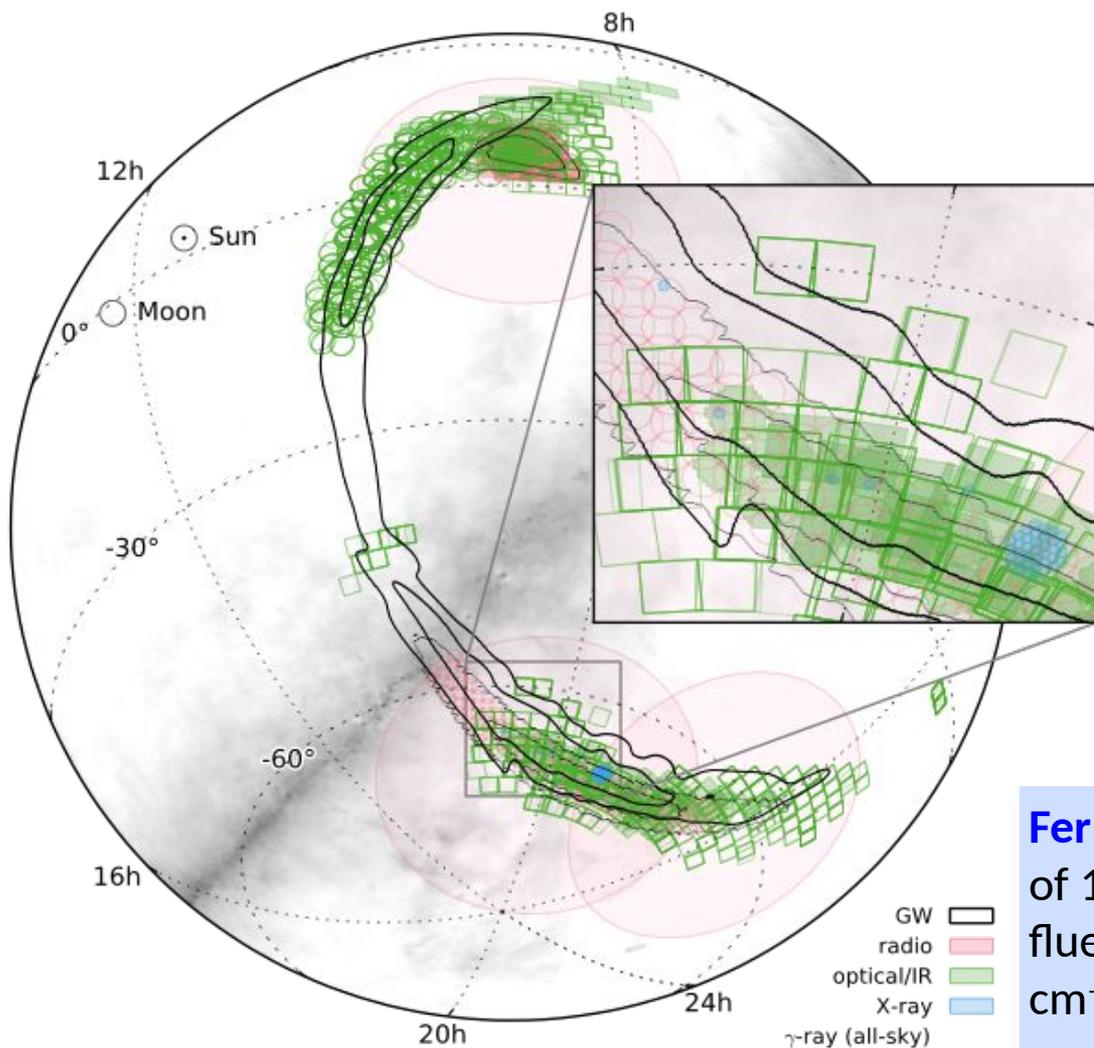
- **Twenty-five teams** of observers responded to the GW alert
- The EM observations involved **satellites and ground-based telescopes** around the globe spanning 19 orders of magnitude in frequency across the EM spectrum



LVC+astronomers, ApJL, 826, 13
 LVC+astronomers ApJS, 225,8
 Connaughton et al. ApJL, 826, 6
 Savchenko et al. 2016 ApJL 820, 36
 Fermi-LAT collaboration ApJL, 823,2
 Hurley et al. ApJL, 829, 12

Evans et al. MNRAS 460, L40
 Morokuma et al. PASJL, 68, 9
 Lipunov et al. arXiv:1605.01607
 Soares-Santos et al. ApJL, 823, 33
 Annis et al. ApJL, 823, 34
 Smartt et al. MNRAS, 462, 4094

Kasliwal et al. ApJL, 824, 24
 Diaz et al. ApL 828, 16
 Greiner et al. ApJL, 827, 38
 Tavani et al. ApJL, 825, 4
 Troja et al. ApJL, 827, 102



- Covered sky map contained probability:
 - 100% gamma-ray**
 - 86% radio**
 - 50% optical
- **In the optical**, candidate counterparts rapidly characterized and identified to be normal population SNe, dwarf novae and AGN

Fermi-GBM = **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. 2016 ApJL, 826)

INTEGRAL = no signal but

stringent upper limit

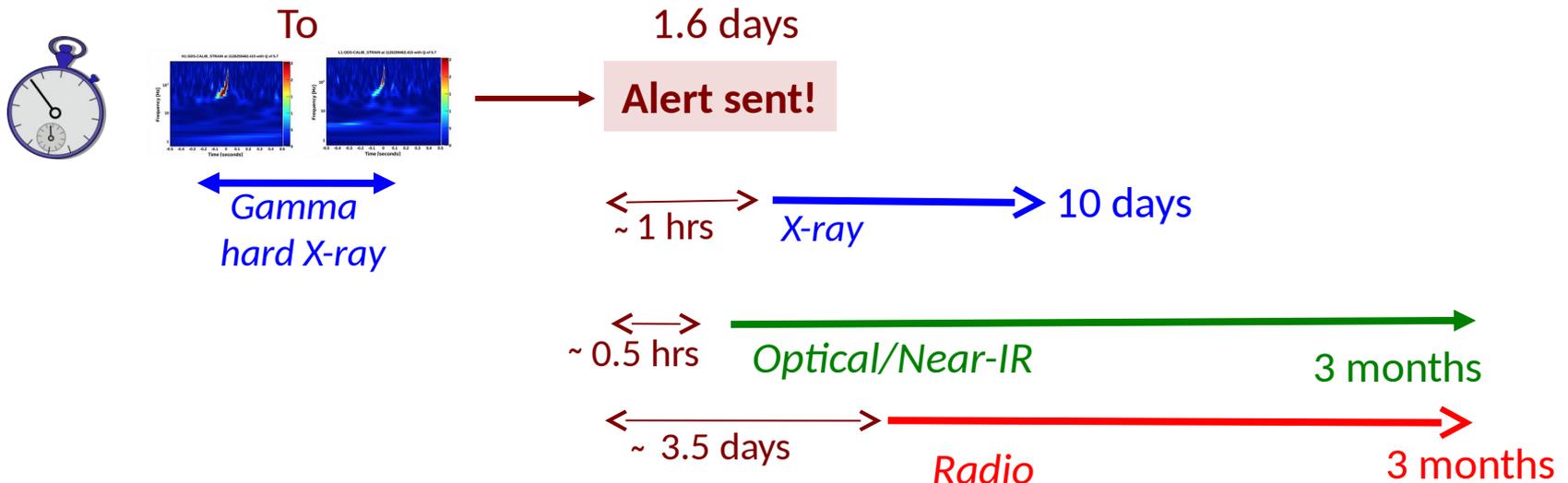
(Savchenko et al. 2016 ApJL, 820)

Thirty-one groups responded to the GW alert:

High-energy and Very high-energy \equiv **Swift, XMM-Slew, MAXI, AGILE, Fermi, CALET, CZTI, IPN, MAGIC, HAWC**

Optical-NIR \equiv **MASTER, GRAWITA, GOTO, Pan-STARRS1, J-GEM, DES, La Silla-QUEST, iPTF, Mini-GWAC SVOM, LBT-Garnavich, Liverpool Telescope, PESSTO, VISTA-Leicester, Pi of the Sky observations, LCOGT/UCSB, CSS/CRTS, GTC**

Radio \equiv **VLA-Corsi, LOFAR, MWA**



All the info from public GCNs: http://gcn.gsfc.nasa.gov/gcn3_archive.html

Racusin et al. arXiv:1606.04901

Cowperthwaite et al., ApJL, 826, 29

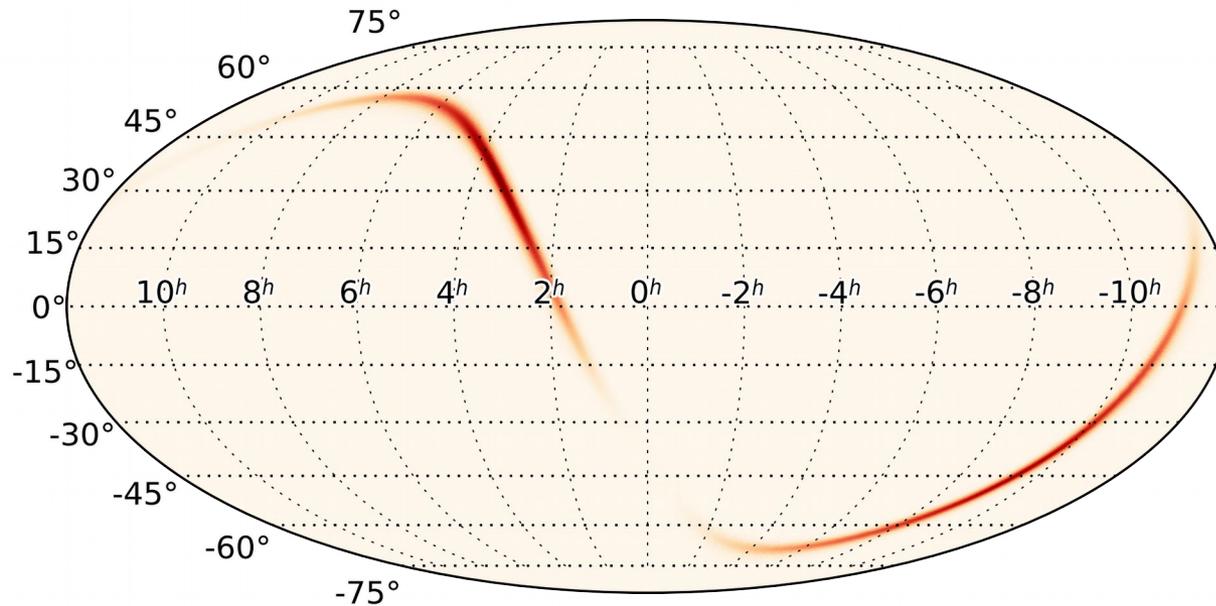
Smartt et al. arXiv:1606.04795

Evans et al. MNRAS, 462, 1591

Palliyaguru et al. ApJL, 829, 28

Copperwheat et al. MNRAS, 462, 3528

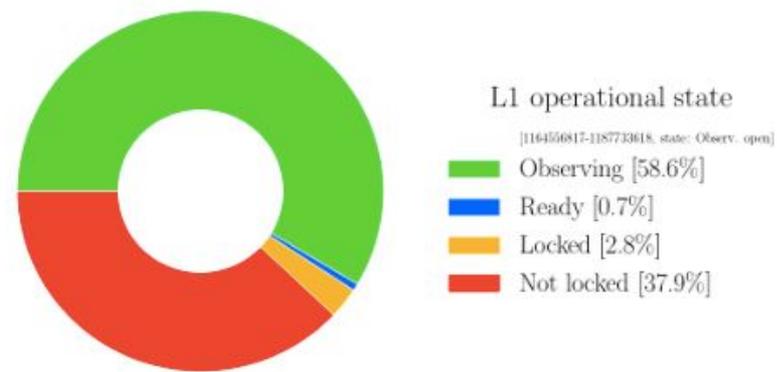
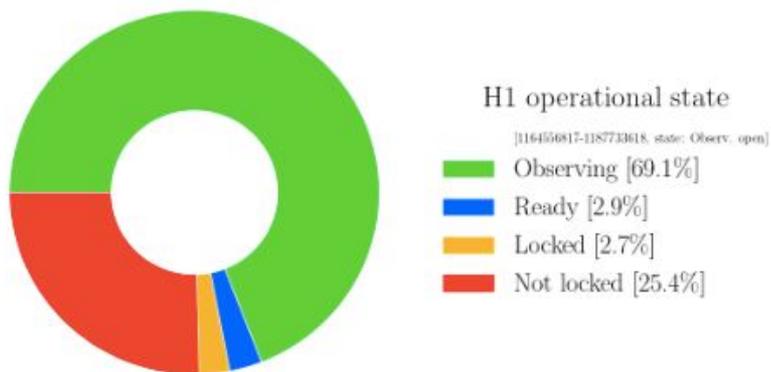
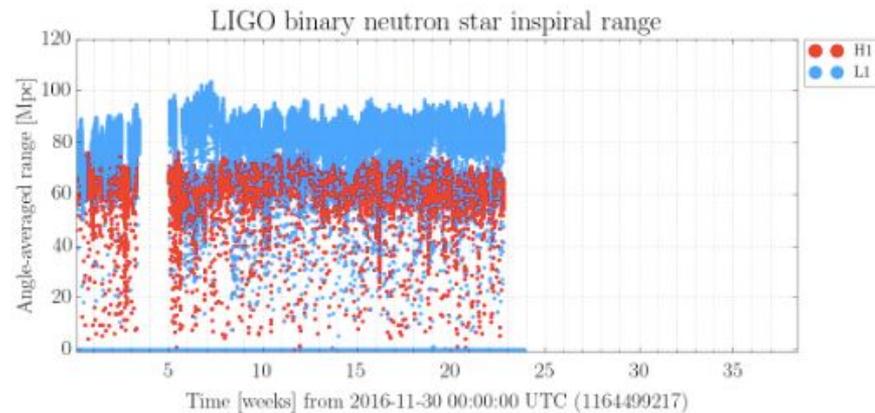
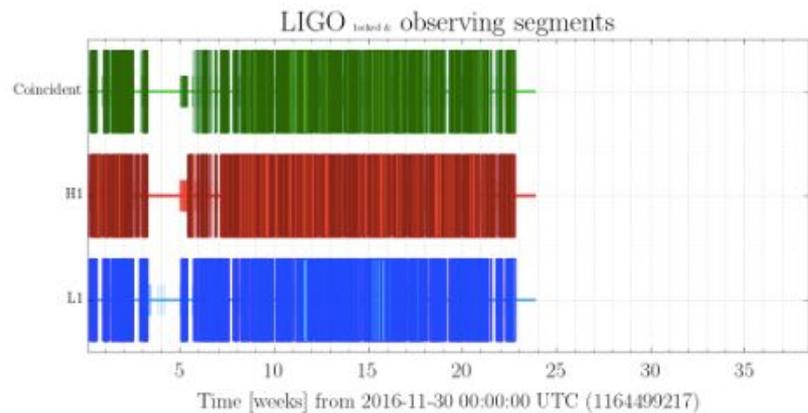
Adriani et al. ApJL, 829, 20



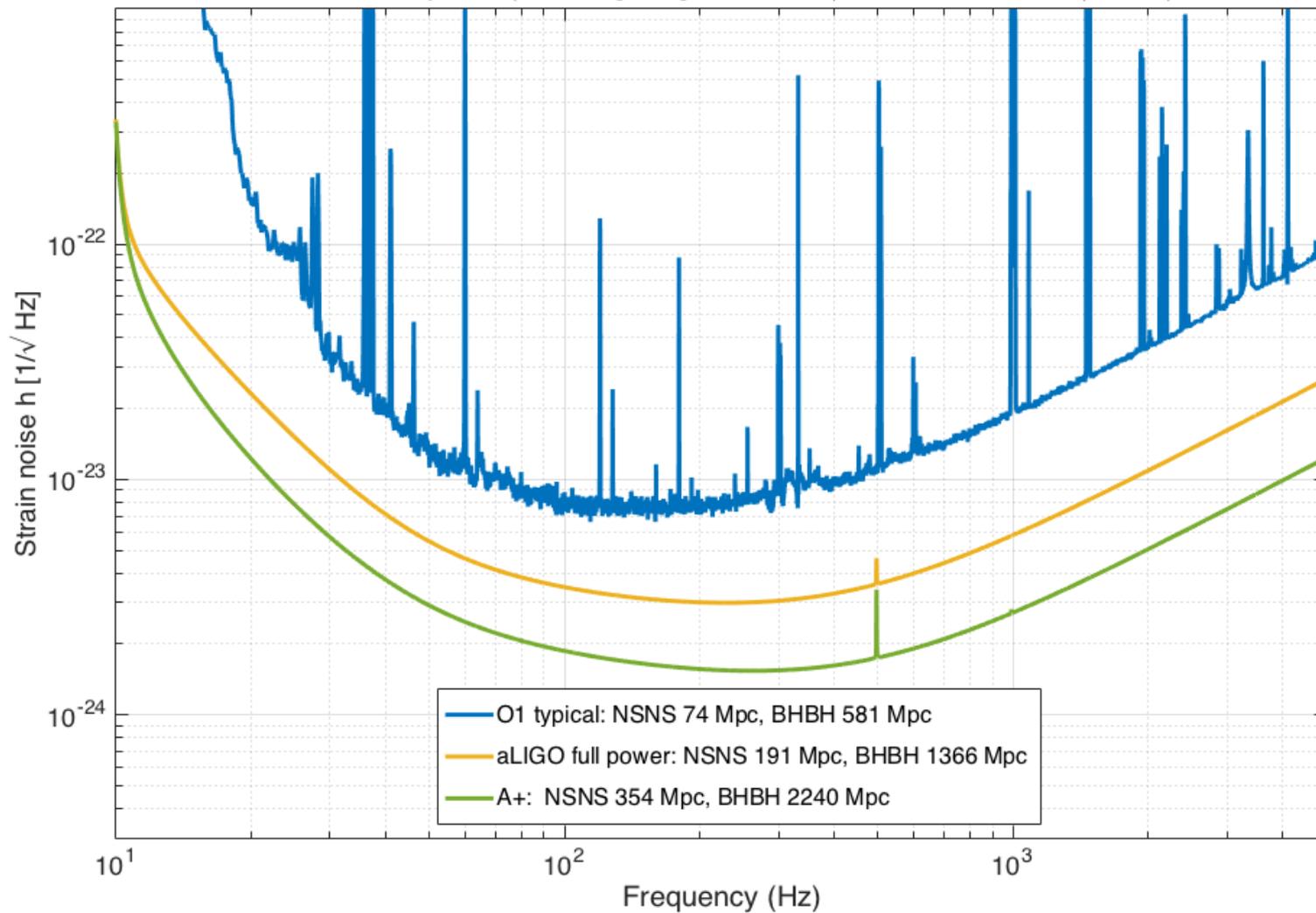
Bayestar
Software code

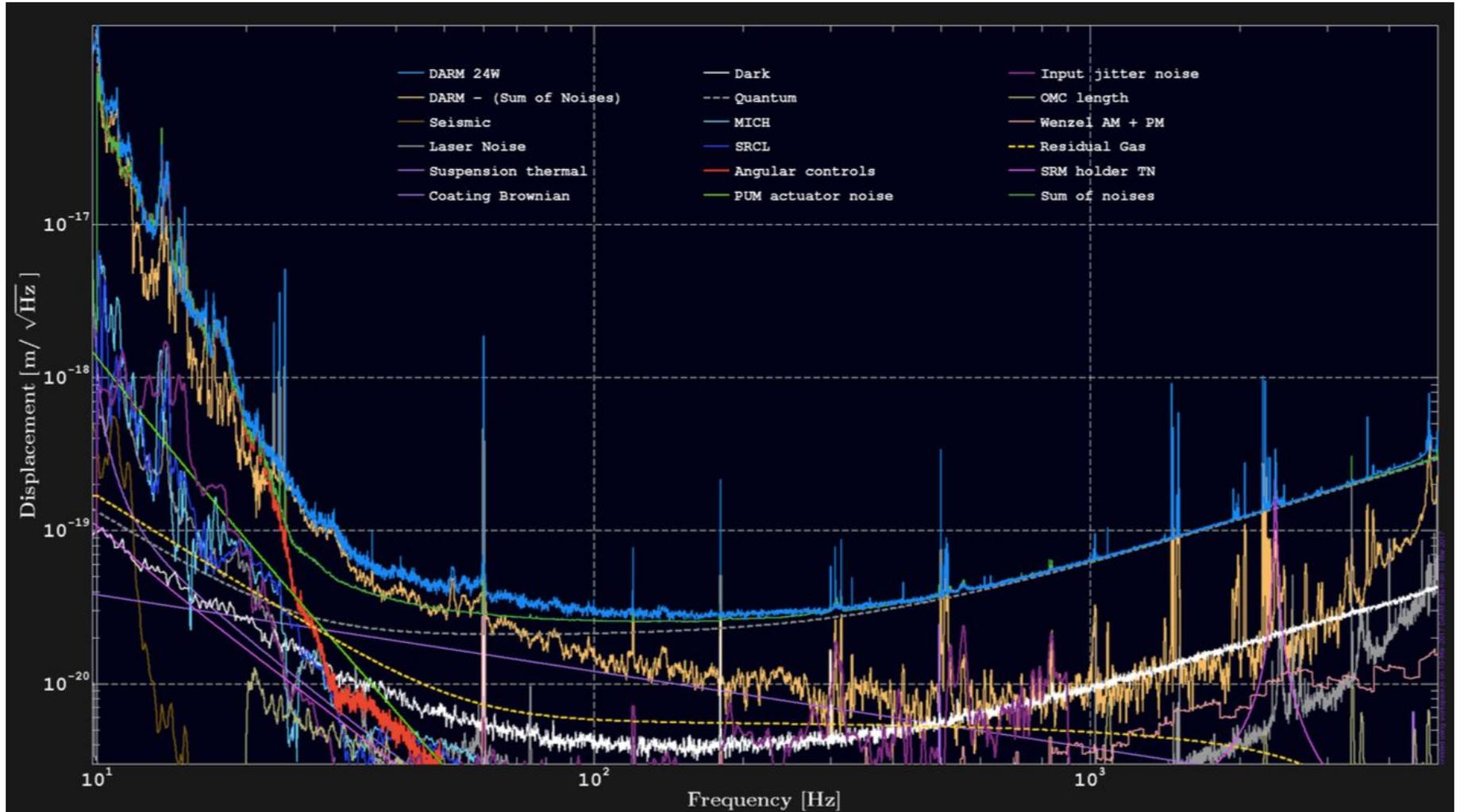
- Large portions of the GW sky map observed
- Candidate counterparts rapidly characterized
- In the optical, candidate counterparts identified to be normal population SNe, dwarf novae and AGN
- **No EM counterpart reported**

O2 science run



A+ Strain Projection (Comoving Ranges: NSNS 1.4/1.4 M_{\odot} and BHBH 20/20 M_{\odot})





NEWS

MAY 2017 UPDATE ON LIGO'S SECOND OBSERVING RUN

3 May 2017 -- The second Advanced LIGO run began on November 30, 2016 and is currently in progress. As of April 23 approximately 67 days of Hanford-Livingston coincident science data have been collected. The average reach of the LIGO network for binary merger events has been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.

As of April 23, 6 triggers have been identified by the online analysis, using a loose false-alarm-rate threshold of one per month, and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

<http://ligo.org/news/index.php>

- ❖ About 67 days of coincident Handford and Livingston science data
- ❖ Range: BNS 70 Mpc,
BBH (M=10+10 Mo) 300 Mpc,
BBH (M=30+30 Mo) 700 Mpc
- ❖ 6 triggers (FAR < 1/month) sent to astronomers

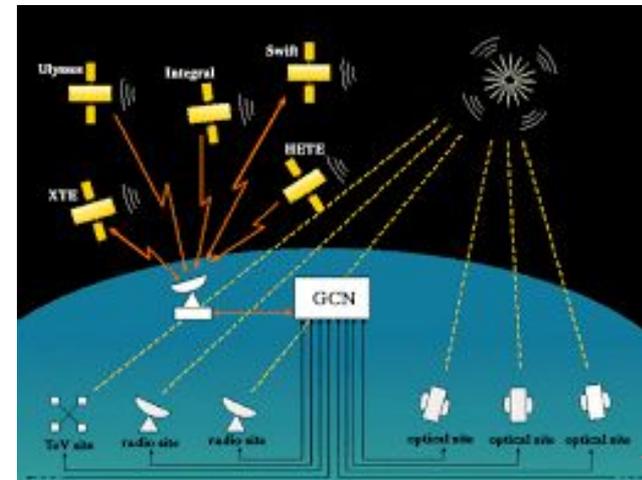
Loose FAR threshold \Rightarrow these are not all real events!

Astronomers expressed interest before and after O1 to receive marginal candidates and be free to set their own stringent False Alarm Rate (FAR) thresholds

- There was extensive follow-up for the O2 marginal candidates. FAR was used as a criterion to make these decisions, for example some expensive facilities didn't run
- Complaint from a few groups *“LVC does the community a disservice by presenting these triggers in a manner that leads observers to believe that they are significant”*



Update to our EM alert policy on the way



- Event **time** and **probability sky map** (HEALPix FITS file)
- Estimate of **False Alarm Rate** of event candidate (FAR < 1/1month)
- **Basic source classification**: found by CBC, Burst, or both pipelines;

For CBC candidates LVC GCN will have:

- **“EM bright” indicators**:
 - **Source classifier** \Rightarrow Probability of **presence of a NS** in the binary (object $m < 3.0$ solar mass)
 - **Remnant mass classifier** \Rightarrow Probability of **presence of any NS tidally disrupted mass left outside the BH**
(Foucart 2012, PhRvD, Pannarale & Ohme, 2014,

ApJ)

- **Luminosity distance** marginalized over whole sky
(mean+/-standard deviation)
- **3D sky maps**
with direction-dependent distance

(e.g. Singer et al. 2016, ApJL 829, L15)

Increase the amount of information in the circular and better explain the significance of some numbers

- Specify if event looks as
 - ✓ unstructured burst,
 - ✓ E.E. bright event
 - ✓ BBH event
- Statistical significance:
 - ✓ Low significance \square FAR > 1/yr
 - ✓ Significant \square 1/yr > FAR > 1/100 yr
 - ✓ Highly significant \square FAR < 1/100 yr

- ✓ Specify if multiple pipelines see the candidates
- ✓ Update circulars with information on the detector status
- ✓ Retract candidate if necessary as soon as possible

To be discussed in the LVC collaboration

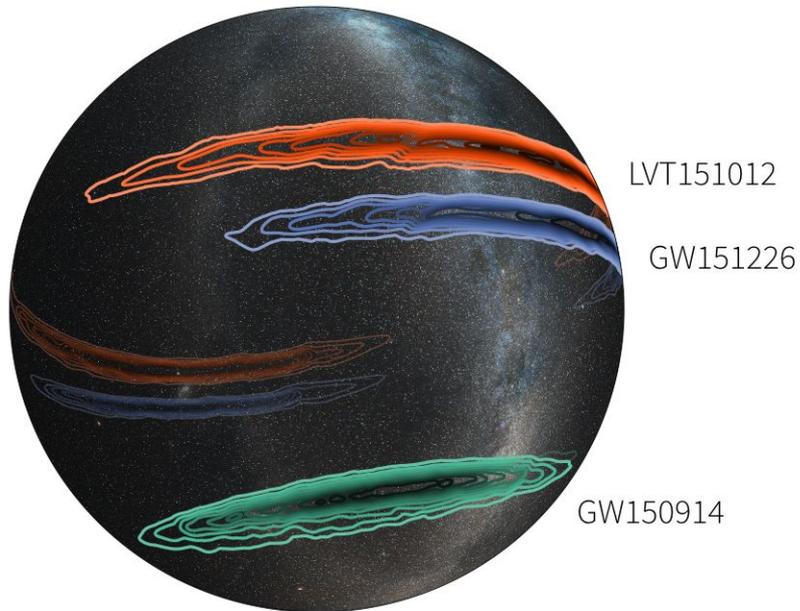
1/month = $3.858e-7$ Hz

1/yr = $3.171e-8$ Hz

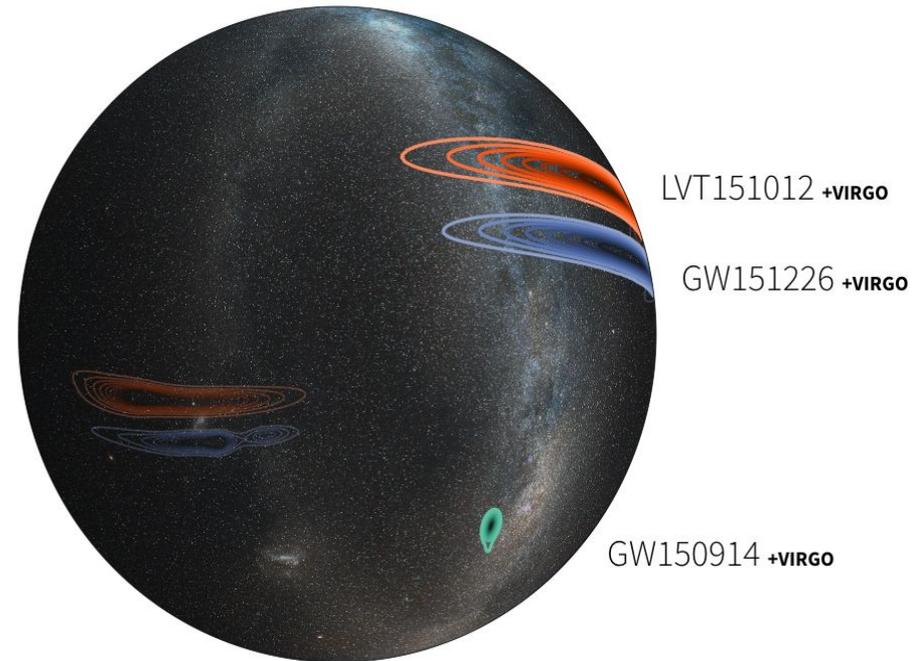
1/100yr = $3.171e-10$ Hz

Virgo will join soon

Actual estimates

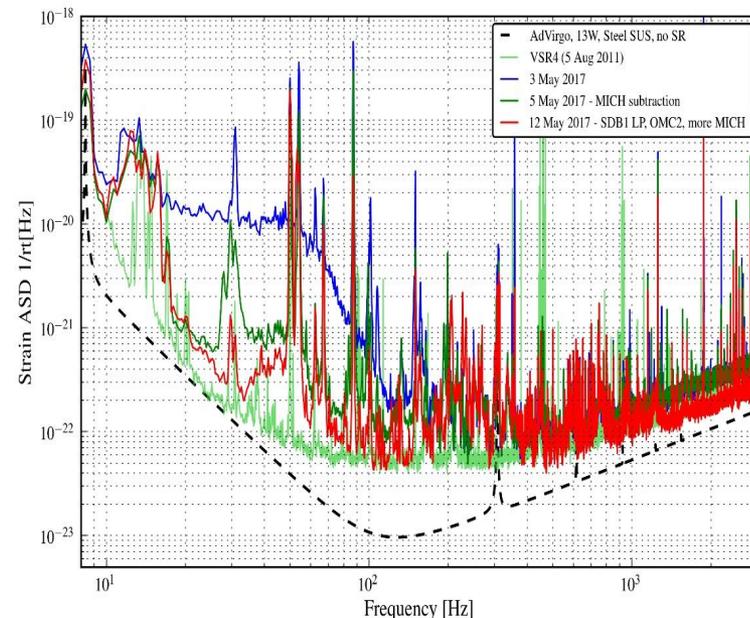
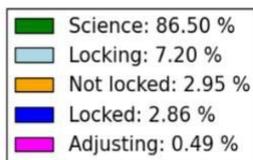
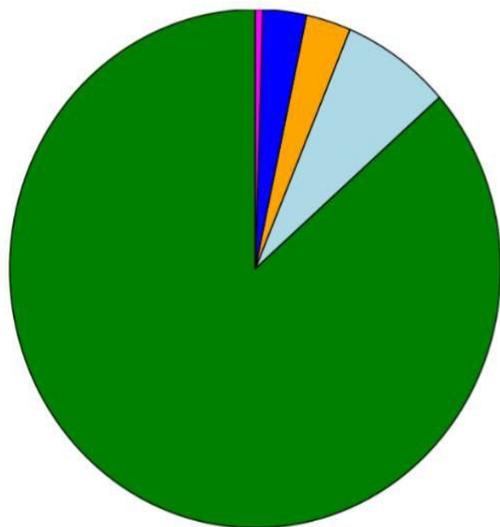


Simulated estimates with Virgo



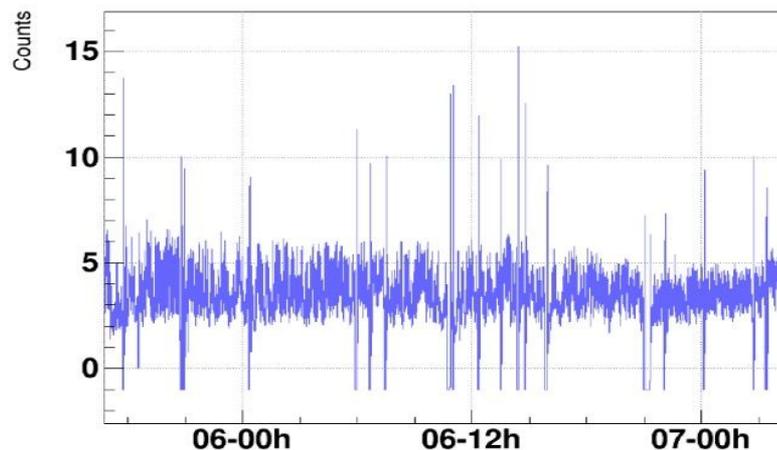
Virgo is expected to join
O2 run soon!

- From May 5th to May 8th (morning)
- Operators in shift 24 hours/day
- Important commissioning (and project) milestone
- Some numbers:
 - Longest lock stretch about 6 hours
 - BNS range ~ 6 Mpc
 - Duty cycle about 85%
- Production of “science data” restarted after 5 years of desert...



dataDisplay v10r8 : started by rocchi on May 7 2017 04:48:51 UTC

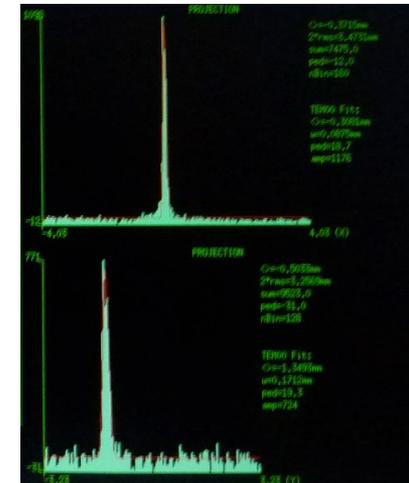
V1:CAL_RANGE_NSNS__TIME



1178038020.0000 : May 5 2017 16:46:42 UTC

- Next milestone: join ER11 in a month from now
- Work to be done:
 - Improve the stability of the Power Recycling Cavity stability
 - Upgrade the Second Stage Frequency Stabilization from 500 kHz sampling time to 1 MHz
 - Noise hunting: Environmental noise +diffused light+ beam clipping
 - Strength the detector characterization
 - Calibratio (two independent methods

Photo-calibrator



- Option being considered
 - ITF input power to 25 W (now 13 W)
 - More commissioning: noise hunting, parametric instabilities and thermal lensing

- O2 run started at the end of November 2016
- Two stops : Christmas break, end of April (two weeks)
 - mirror vacuum chamber vented for mirror inspection
 - run will continue until middle of June
 - middle of June joint engineering run with 3 detectors
- At present LIGO is restarting LIGO after the two weeks of stand-by
- VIRGO in full commissioning phase.
 - The commissioning run C8 done during the long week end of May 1st achieved the 85 % duty cycle,
 - Next joint engineering run with LIGO in the middle of June