Advanced LIGO and VIRGO next science runs

M.Branchesi (Gran Sasso Science Institute)
on behalf of the LIGO and Virgo collaborations

O1-O2 Multi-Messenger Searches with GWs

LIGO & Virgo have signed MOUs with 95 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 EM triggered / joint search MOUs

O1 and O2 MoU

Collaborative effort but the MoU clearly splits LVC and EM follow-up works

Memorandum of Understanding between XXXXX and LIGO and VIRGO

regarding follow-up observations of gravitational wave event candidates

This Memorandum of Understanding (MOU) establishes a collaborative effort among the Laser Interferometer Gravitational-Wave Observatory (LIGO) and LIGO Scientific Collaboration (LSC), the European Gravitational Observatory and Virgo Collaboration (EGO/Virgo), and Full-name-of-XXXXX-Collaboration (XXXXX) in order to participate in a program to perform follow-up observations of gravitational wave (GW) candidate events with the sharing of proprietary information (see LIGO-M1300550 and VIR-0494#-13 for an overview)

E Data and information sharing

1. All parties will share information with all PARTNERS in the follow-up program through a dedicated communication network. LIGO and VIRGO will communicate the detected GW candidate events in the form of alerts. For each follow-up observation made by XXXXX, XXXXX will share the coordinates of the observations that have been made as soon as practical and within 12 hours of the observing time. For shared and space facilities, the intended coordinates should be shared as soon as practical and within 12 hours of the intended observing time. XXXXX is encouraged to share data analysis results in the form of a list of plausible candidates, or other relevant findings, or a non-detection statement as promptly as possible. The notices communicated by LIGO, VIRGO and all PARTNERS will include an author field, a reference number and a date to make them citable. All notices pertaining to a given event will be made publicly available when the publication of the event is released.
2. LIGO, VIRGO and XXXXX will share relevant updated information about event candidates as it becomes available.

No request of information sharing except the time and coordinate of the observations → however many results in the GCNs

The embargo worked well and allowed LVC to publish with a "reasonable" timeline

F Publications and Presentations

General rules

1. Any apparent counterpart to the GW event candidate, that was identified due to the GW candidate alert, is strictly *embargoed*: it may not be published or presented prior to the public announcement or publication of the GW event candidate by LIGO and VIRGO. LIGO and VIRGO will share detailed information with all partners who observed the counterpart prior to publishing or presenting the GW event results.

Publication Cases

Results from searches of GW and presence or absence of counterparts can be published together or separately, as follows:

Publication Case 1: Separate publication of GW results and follow-up results

Publication Case 2: Joint publication of GW results and follow-up results

Possibility of joint analysis and paper but not requested

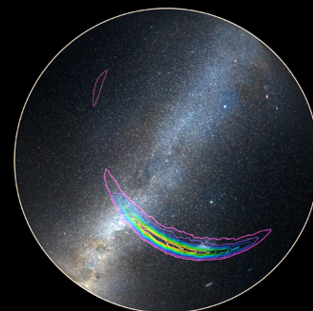
O1 and O2 low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alerts

LSC VIRGO

GW candidates — Sky Localization — EM facilities

LIGO-H LIGO-L

Virgo

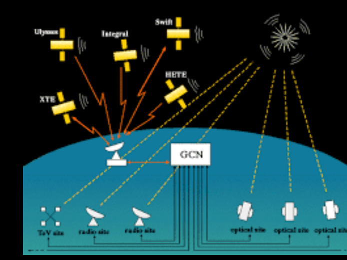


Event validation

Low-latency search
to identify the GW-candidates

Software to

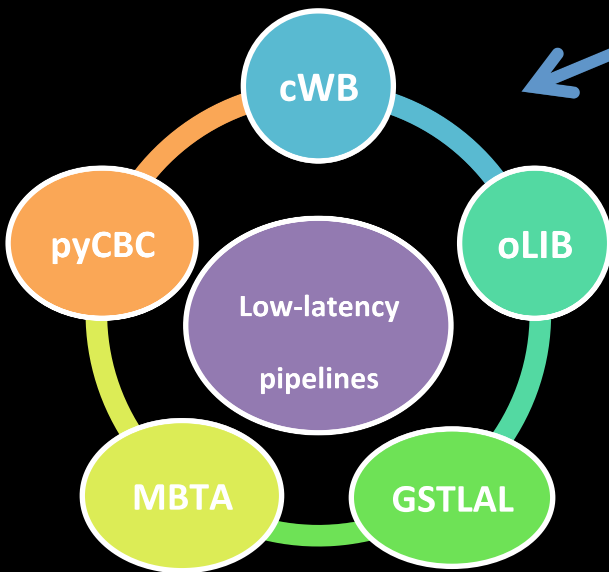
- select statistically significant triggers wrt background
- check detector sanity and data quality
- determine source localization



→ a few min → 30 min

Parameter estimation codes → Hours,days → GW candidate updates

Online and offline GW data analysis pipelines



Low-latency online pipelines:

- *All five low-latency pipelines detect candidates within < 1min of data acquisition*
- *Quick estimate of significance, candidate may not be real GW events*

Offline pipelines:

- *Optmized results within 1-2 weeks*
- *~5 days of coincident data for background estimation*
- *final significance to distinguish real GW events*

Nitz et al., arXiv:1705.01513; Usman et al. 2016, CQG 33, 215004 [pyCBC]

Adams et al. 2015 CQG 33, 175012 [MBTA]

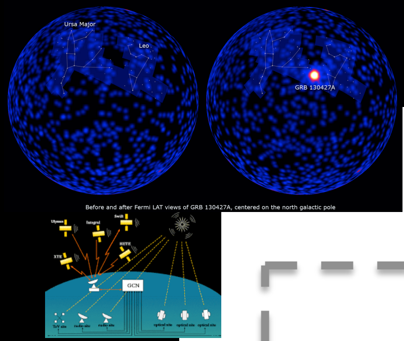
Messick et al. 2017 Phys. Rev. D 95, 042001 [gstlal]

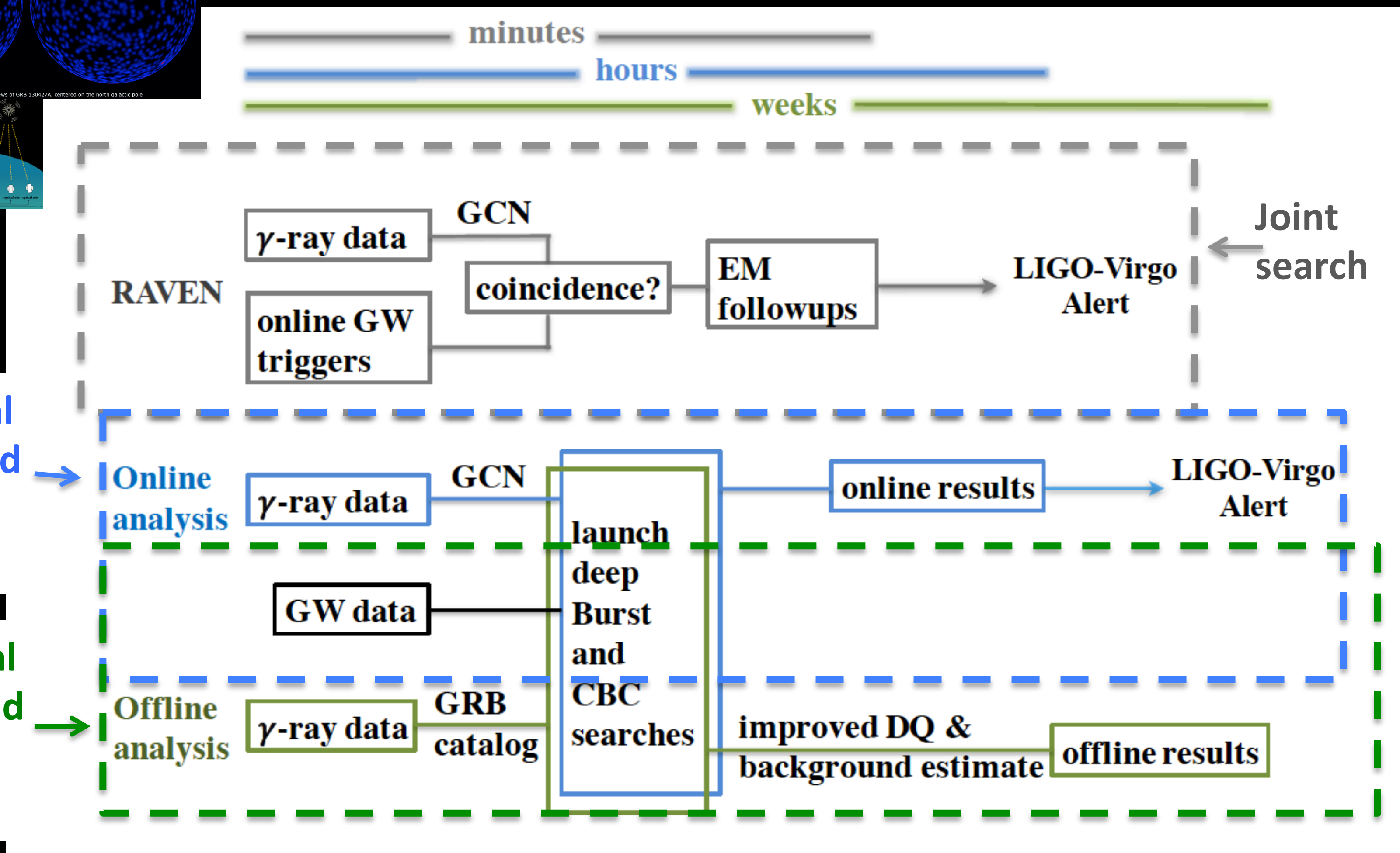
Lynch et al, arXiv:1511.05955 [oLIB]

Klimenko et al. 2016 Physical Review D, 93; Drago 2015, arXiv:1511.05999 [cWB]

Veitch et al. 2015, PRD 91, 042003 [LALInference]

Low-latency joint/external triggered search





Credit: Pannarale

GCN Alerts contents to support observing strategy

- Event **time** and **probability sky localization 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 compact binary candidates:

- ***"EM bright" indicators:***

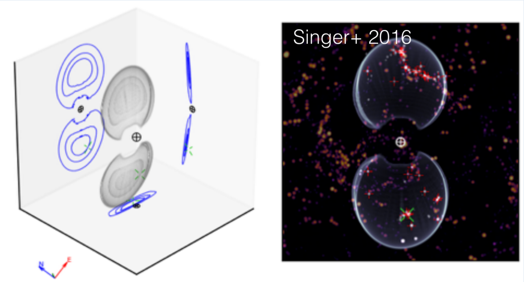
  - **Source classifier** → Probability of **presence of a NS** in the binary (object m< 3 solar mass)

  - **Remnant mass classifier** → 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)

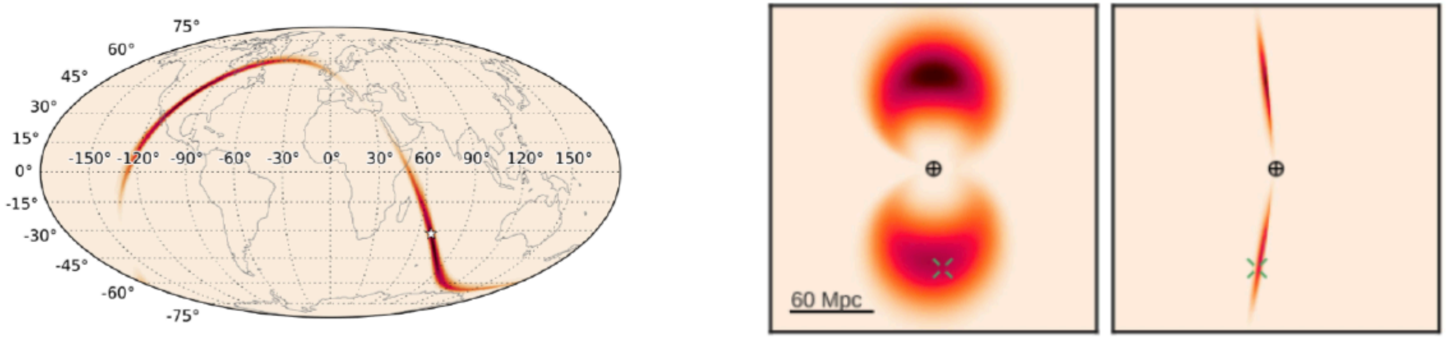


CBC Sky localization map

Arrival time
Amplitudes
Phase

→ sky location
→ distance to the source

Sky location also in 3 D



Sky direction

Projections of 3d location

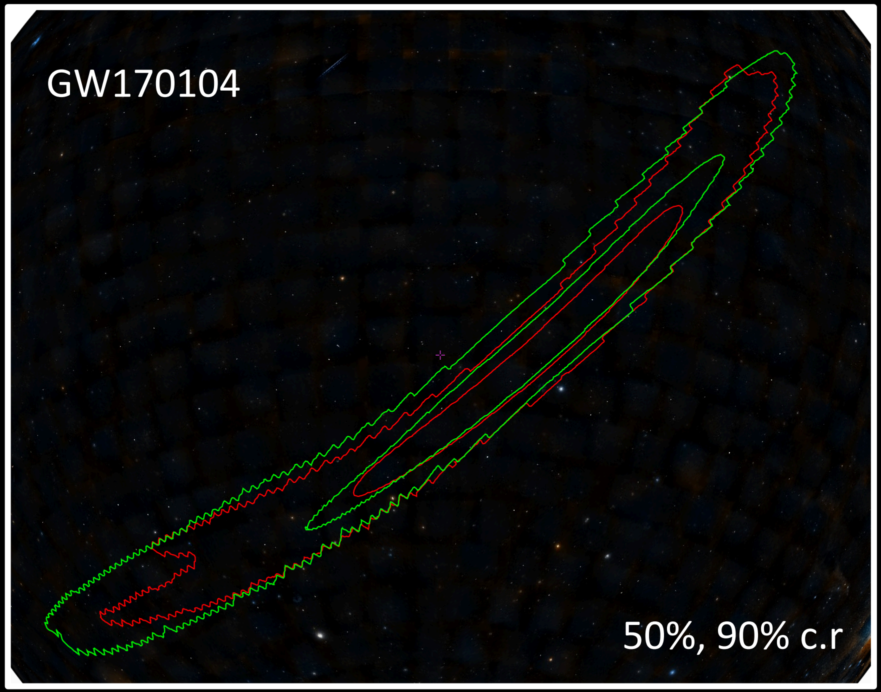
Online pipelines estimate → arrival time, phase, signal amplitude at each detector

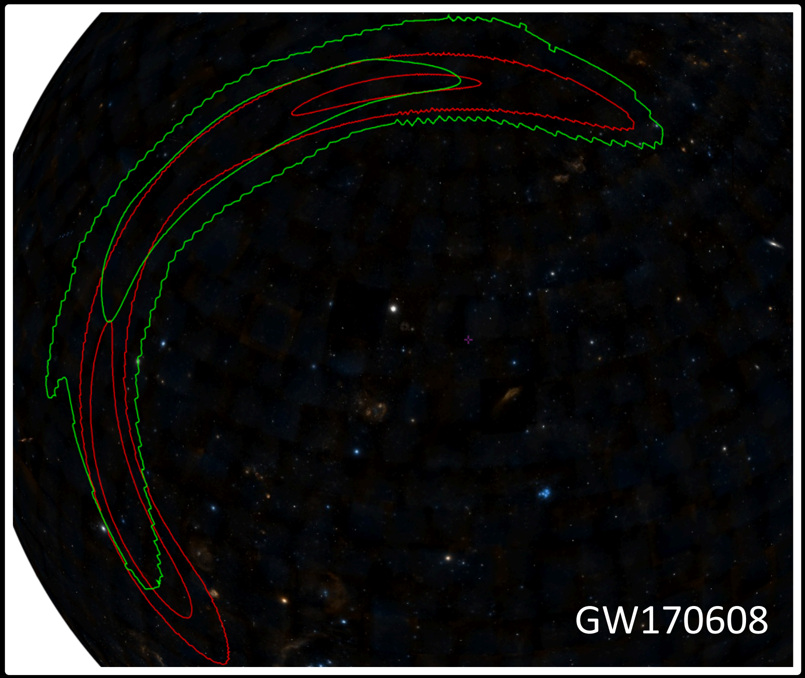
These estimates + template masses constrain direction of GW arrival and distance to the source

→ **BAYESTAR (Singer et al 2014, ApJ, 795, 2016 ApJL, 829)**: estimate 3D location in <1 minute

→ **LALInference**, **full PE Bayesian MCMC** **(Veitch 2015; Berry et al. 2015)**, modeling the inspiral-merger-ring down phase and taking into account the calibration uncertainty

Initial skymaps: BAYESTAR → LALinference (RAPID PE)





→ Median latency BAYESTAR/LALinference 5 days, for GW170817 6 hours!

→ BAYESTAR/LALinference typically consistent, except in the case of calibration/glitch issues

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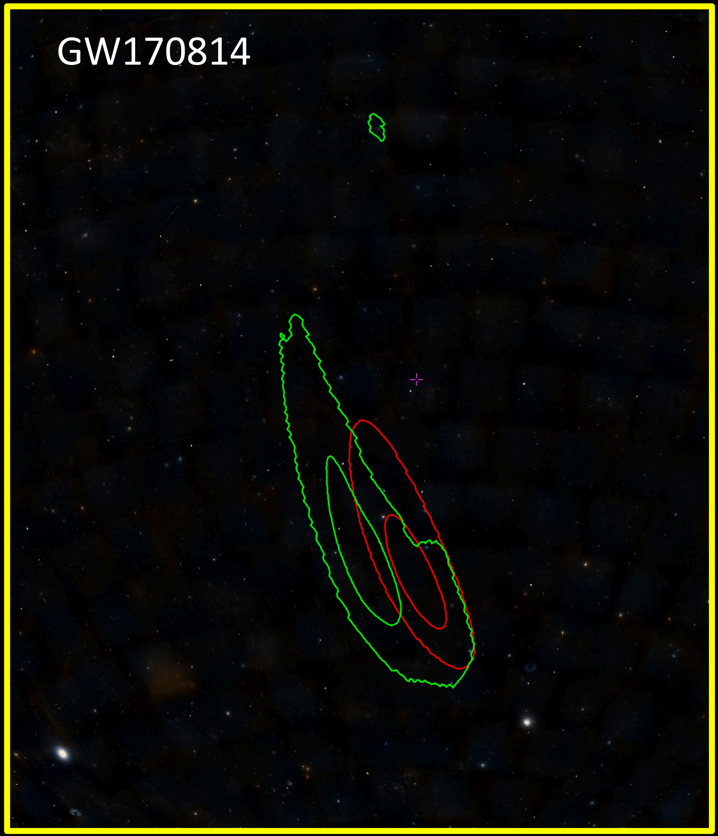
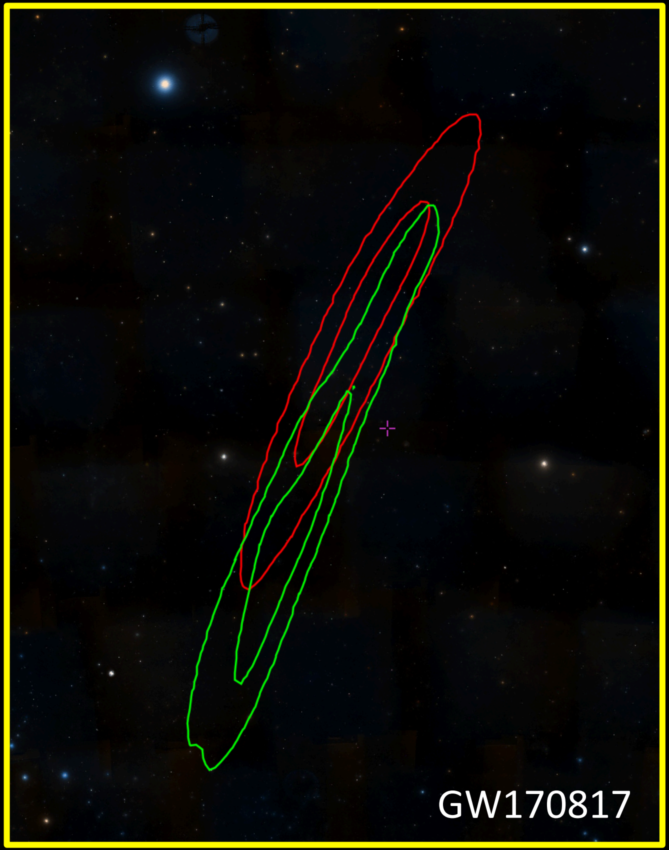




O3 Warning: data quality flag? OBs flexibility?

Providing error ellipses for sufficiently well-localized events?

O1 O2 low-latency triggers and multi-messenger campaign

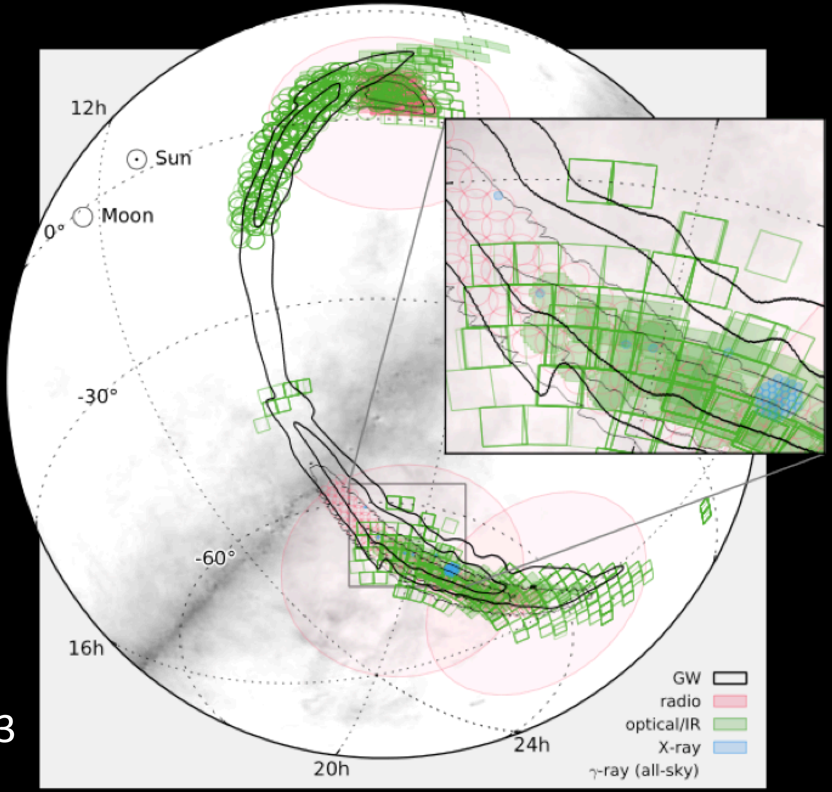
O1 run

- 4 months of Advanced LIGO network
- total coincident time 50 days
- BNS distance range 75 Mpc

Three alerts → BBH GW150914 and GW151226
and one retracted

About 30 papers on the EM follow-up

2 joint LVC+astronomers papers



LVC+astronomers ApJL, 826, 13
LVC+astronomers ApJS, 225, 8

O1 O2 low-latency triggers and multi-messenger campaign

O2 run

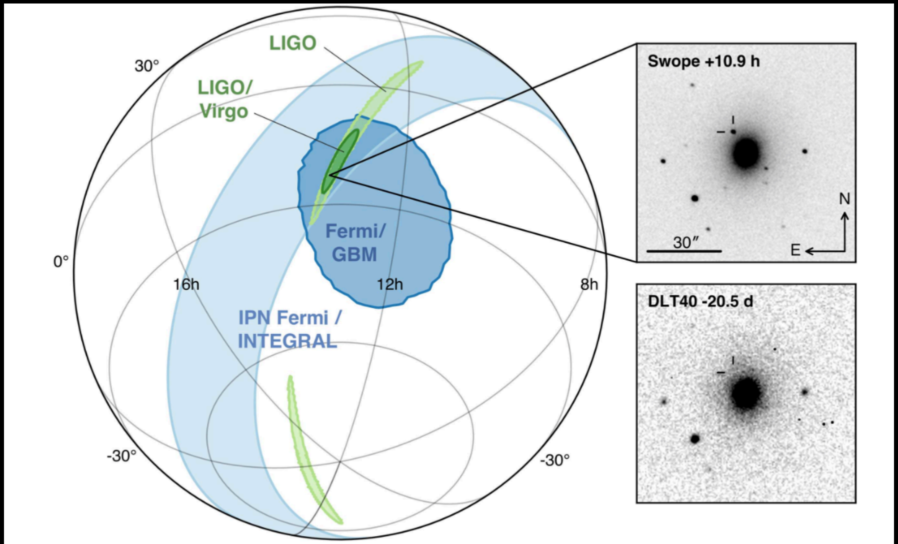
- 7 months of Advanced LIGO network
  total LIGO-detector coincident time 117 days
  BNS distance range 78.5 Mpc

- 25 days Advanced LIGO and Virgo network
  Virgo BNS distance range: 25 Mpc

14 alerts → BBH GW170104, GW170608, GW170814, BNS GW170817
and others waiting for the final off-line analysis
Loose FAR threshold (< 1/month) → not all real events!

GW170817: about 150 published papers
Four joint LVC+astronomers paper

LVC 2017 PhRvL,119, 161101
LVC+astronomers 2017, ApJL, 848, 12



O2 LVC EM follow-up → O3

LIGO/Virgo policy statement (May 2012)

Public alerts for high-confidence event candidates

- ➢ LSC and Virgo will **release significant (< 1/100 yrs) triggers** promptly **to the entire scientific community after** the Collaborations have **published papers about 4 GW events**
- ➢ Possibility of **MoU** for **lower significance threshold and/or lower latency** in order to carry out a more systematic joint observing campaign and combined interpretation of the results

LIGO/Virgo will release confident events publicly during the upcoming O3 observing run, planned to begin in late 2018

- *Extensive discussion within LVC on the details of the implementation of Open Public Alert (OPA), both on policy and on technical requirements*
- *Development of infrastructures to send OPA. Data quality and vetting automation to reduce the latency and deal with an increasing rate of astrophysical events*

GW OPA in the time domain astronomy

Goals of OPA

To maximize the science the entire scientific community can do with the GW detections

To minimize the chance of missing EM/neutrino counterparts

- how to maximize the chance to detect neutrino/em counterparts and maximize the science of astronomers?
- how to maximize the LVC core science (LIGO and Virgo are not only user-facilities)?
- how to maximize science which requires combined GW/EM analysis?

What constitutes an Open Public Alert?

1) Selection criteria for OPAs
2) OPA transmission and latency
3) GW event information in OPA

ALL under discussion within LVC…

we welcome feedback/suggestions from astronomers

What constitutes an Open Public Alert?

1) **Selection criteria for OPAs**
2) OPA transmission and latency
3) GW event information in OPA

Should all type of systems (including unmodelled bursts) be eligible to produce OPAs?

What is the target of "purity" for OPA acceptable by astronomers and LVC (90%/99%)? FAR/contamination/impurity "budget" different among event types?

'p_astro' - probability that a given event is astrophysical (e.g. BBH)

What constitutes an Open Public Alert?

1) Selection criteria for OPAs
2) **OPA transmission and latency**
3) GW event information in OPA

Lowest latency achievable: minute scale. Aim at automatic vetting and alerting through GCN notices → unvetted candidate

What is the acceptable latency for confirmation/retraction?

Providing lowest latency candidate could be affected by failures of automatic vetting procedures!

What constitutes an Open Public Alert?

1) Selection criteria for OPAs
2) OPA transmission and latency
3) **GW event information in OPA**

What is the **minimal set of information** to maximize the success of EM observations?

Time, initial distance, initial 3D skymap, source-classifier?

Anything else?

*Some information will be promptly available, even though with **significant errors** and very likely to change over the course of hours, days and months with the ultimate result becoming available (most likely) when offline analyses complete*

O3 MoU?

~~To make available **lower latency GW candidate alerts**~~? (if unvetted notice sent!)

To make available **lower significance GW candidate alerts**?

- *GW transient events with a FAR at, say, 1/month don't meet the requirements (at least of the LVC) to be announced as GW detections; what is the science payoff in pursuing such alerts in EM/neutrinos: more BBHs/BNSs detections? Statistical studies?*
- *Low-confidence candidates may later be rejected, while others may remain indeterminate*

Science-focused MOUs which target specific science goals jointly with astronomers? Call for joint scientific projects?

- *specific science-focused MoU which enable joint analyses/interpretation, exchange of more information (both-ways) on the candidate events and to regulate joint/separate publication (e.g. cosmology, NS physics)*

TOWN HALLS

Two Town Hall meetings of 1 day, one in the US and one in Europe, will be organized to present, discuss and collect feedback from the astronomical and neutrino communities about the policy for Open Alert Era, possible MoUs, joint scientific projects.

Europe: Cascina, EGO site
USA: Boston, Atlanta

Period: **March/April**
Possible options:
Boston or Atlanta (16-17 March or 29-30 March)
Cascina (March 27-30 and April 11-13)
Doodle to maximize participation

Plans towards O3

Overall O3 picture

- Goal: run O3 for approximately **1 calendar year** with both **LIGO** detectors at (at least) **120 Mpc**, and **Virgo** at (at least) **65 Mpc**

- Given current progress at the three sites, we believe that the sensitivity goals will be achieved by the end of 2018

Plausible O3 scenario

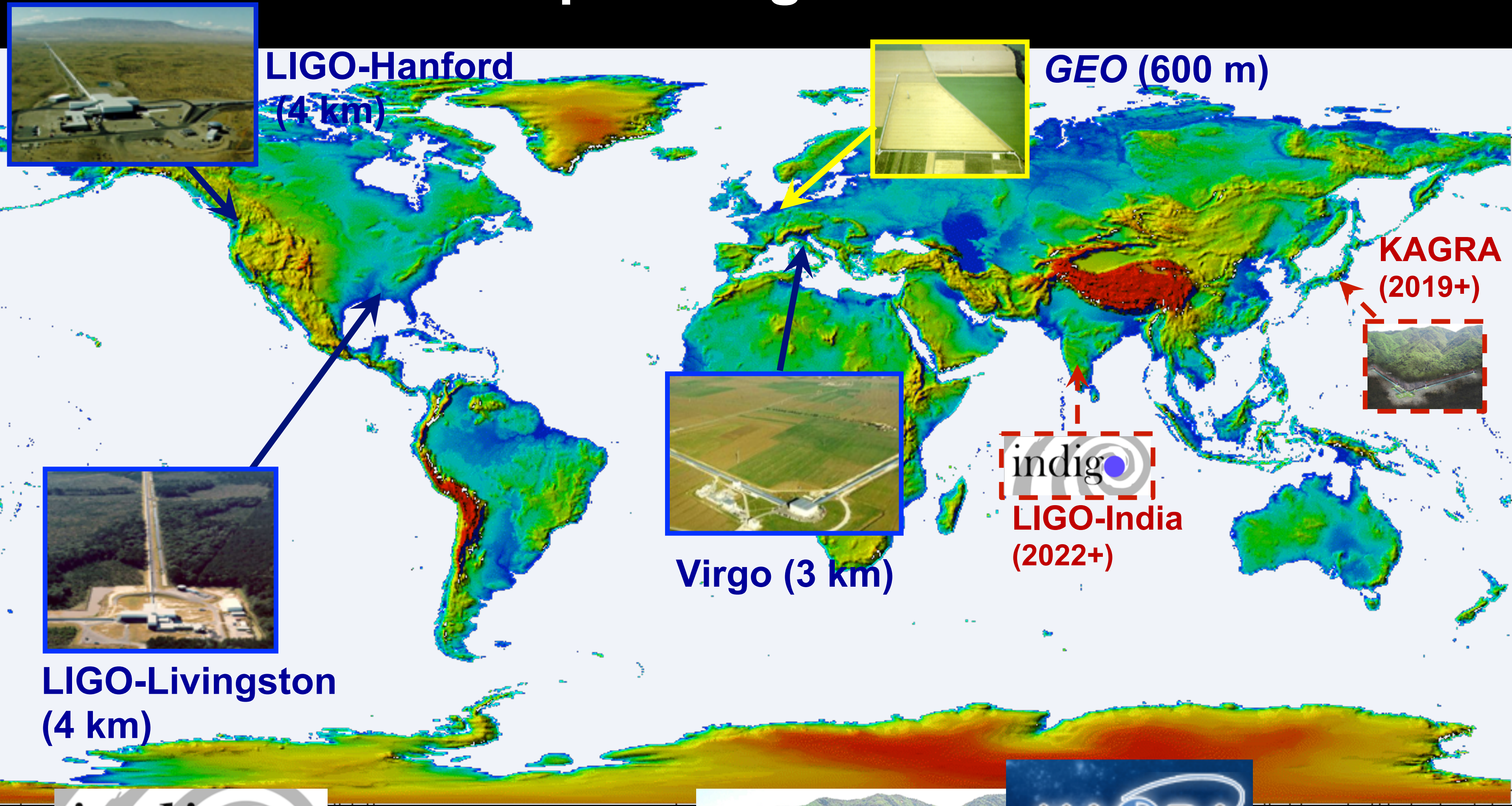
- **1 month long Engineering Run** (ER) with three detectors, right before O3, starting in **October/November 2018**
  – Main goal is to test on-line analysis infrastructure – O3 to follow

- Plausible **O3 starting date: November / December 2018**
  – Plans will be consolidated over the Summer

+Possible additional ER before the end of the Summer but heavily depends on commissioning progress

Joint Run Planning Committee (chairs L. Barsotti, N. Leroy)

Upcoming network

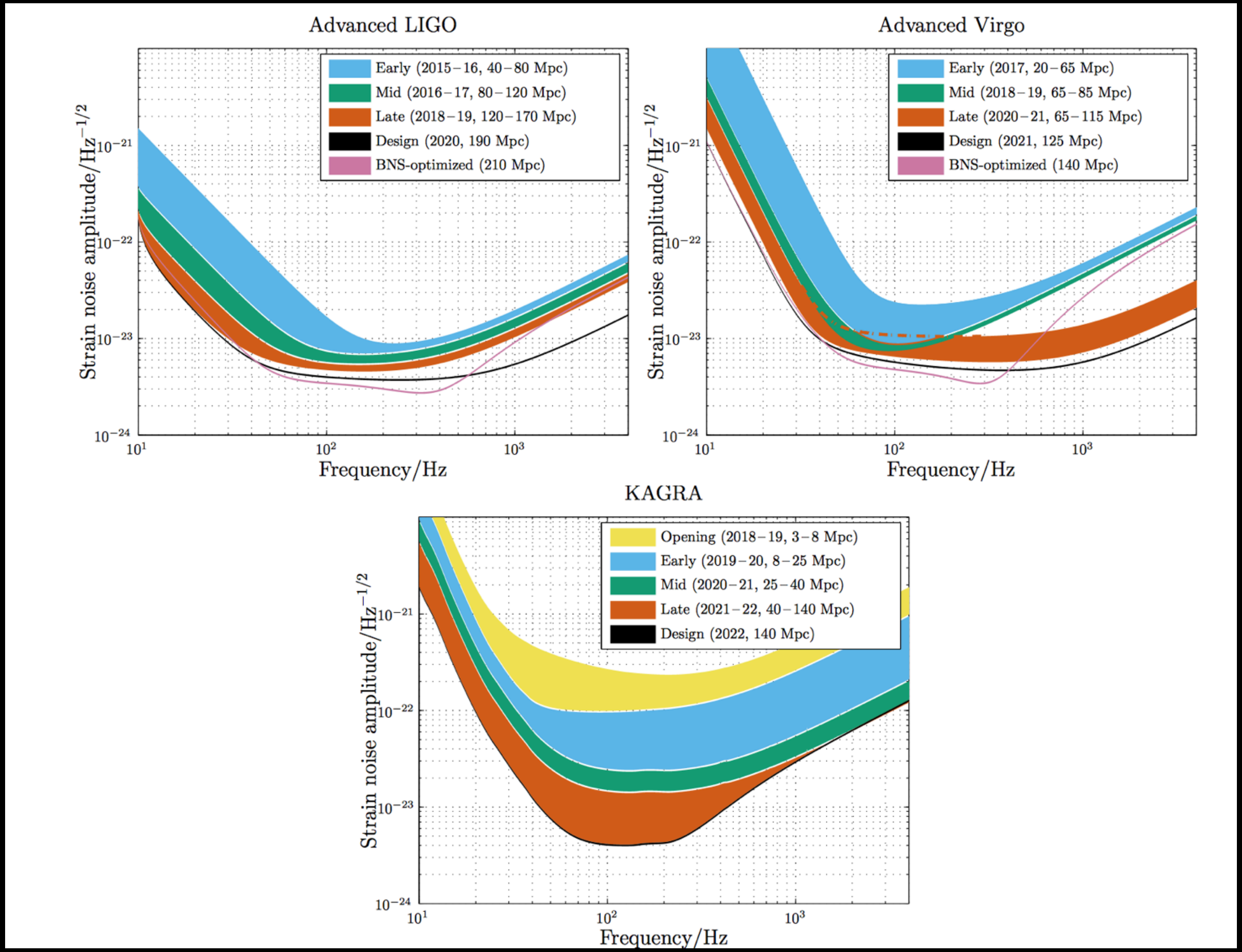


LIGO detector in India
(4 km)

Underground detector in Kamioka mine (3km)

Advanced Detector Era Observing Scenario

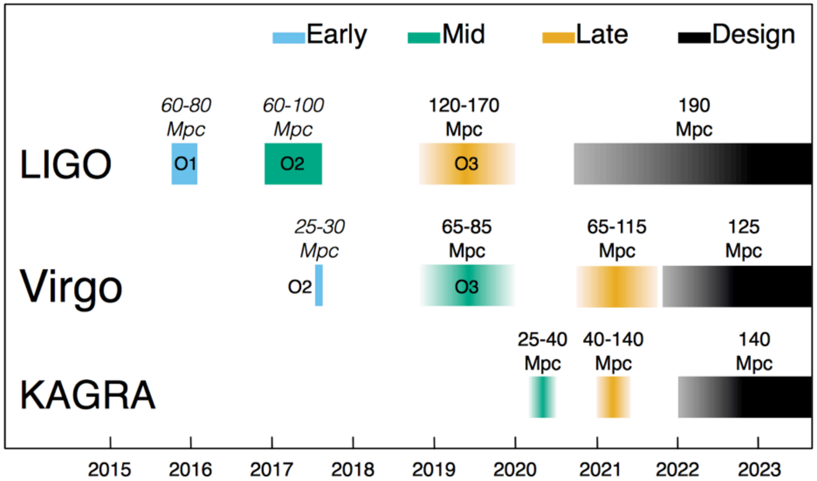
LSC & Virgo Collaborations, arXiv:1304.0670



Progression of sensitivity and range for Binary Neutron Stars

Prospects for Observing and Localizing GWs

Observing runs



Observing schedule, sensitivities, and source localization for BNS

Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	*60 – 100*	—	—	—
		Virgo	—	*25 – 30*	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.002 – 2	0.007 – 30	0.04 – 100	0.1 – 200	0.4 – 400
Actual BNS detections			0	—	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	median/deg^2		460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

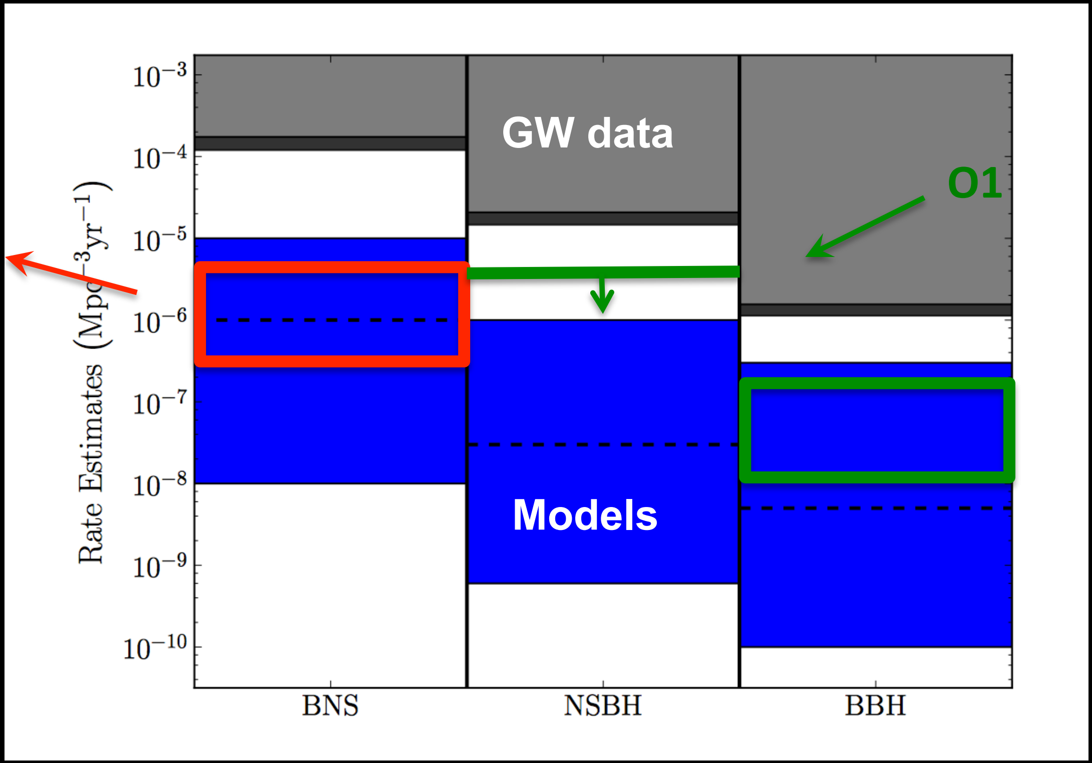
LVC, arXiv:1304.0670

Astrophysical rate

$$R = 1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

LVC 2017 PhRvL,119, 161101

Phys. Rev. D85 (2012) 082002



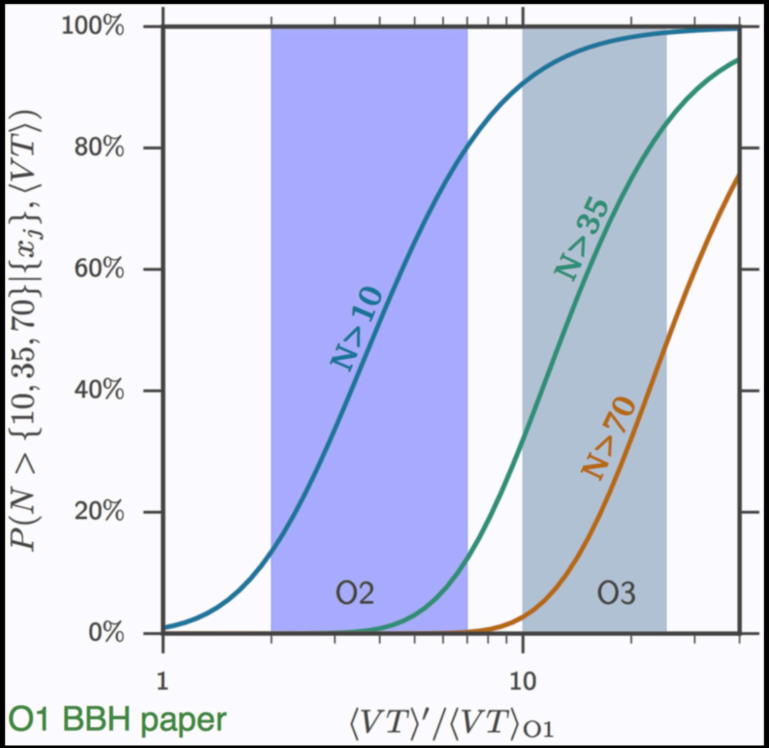
Expected rate	O3	Design-sensitivity
NS-NS	1 – 50	6 – 120 per year

BBH merger rate based on O1 observations

Number of expected highly significant detections (FAR < 1/century)

O1+O2 published BBH

12–213 $Gpc^{-3}\ yr^{-1}$



LVC 2016 Phys. Rev. X, 6