Summary of Data Analysis activities by Virgo Italia in 2016

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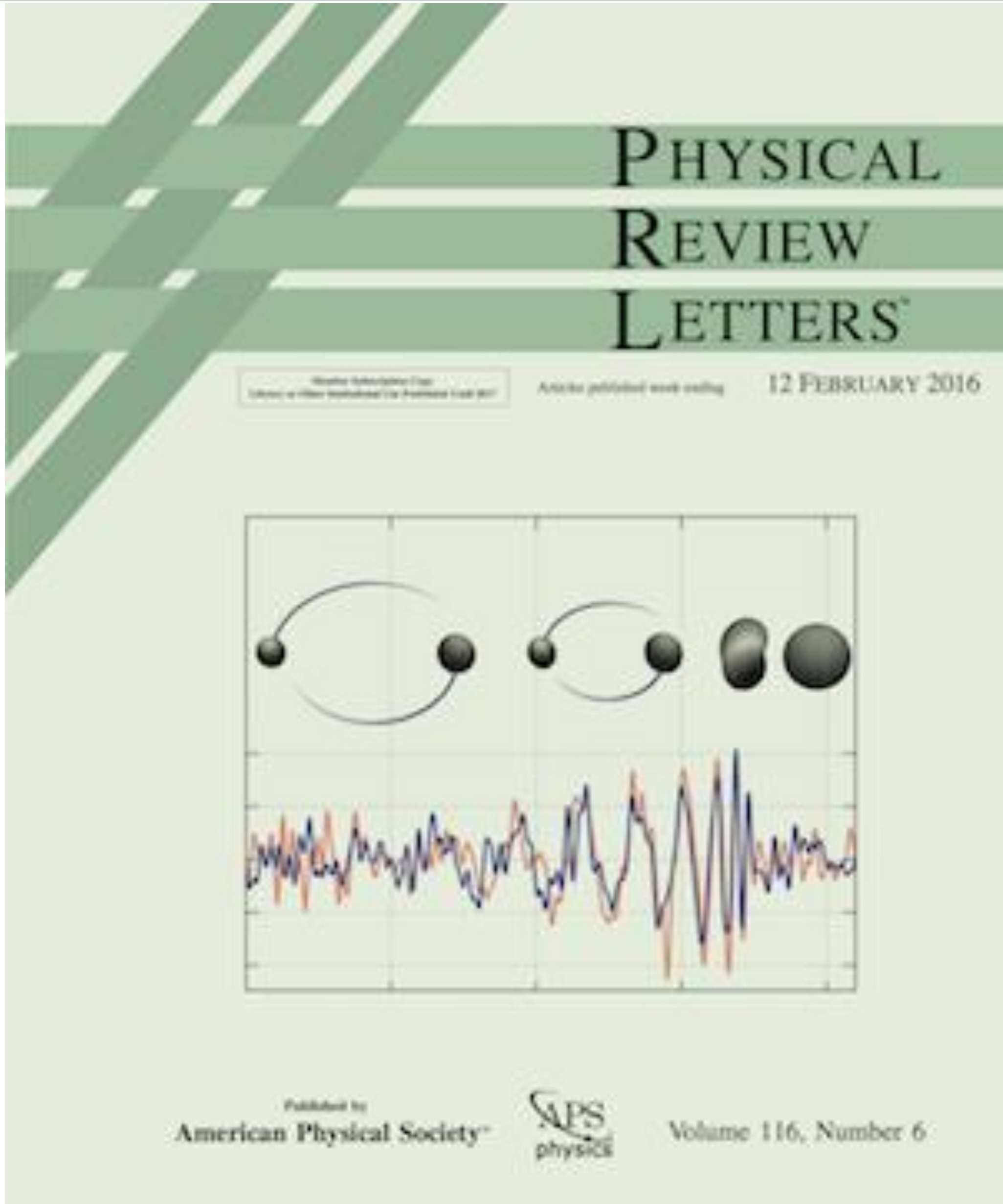
for Virgo Italia

credits to M.Branchesi, G.Cella, E.Cuoco, G.Guidi, P.Leaci, G.Vedovato

Incontro con i referees INFN Virgo, EGO 8 Sett. 2016

Outline

- general framework
- activities on
  - Detchar and Data Quality assessment
  - GW searches
    - Transient signal searches: generic bursts, Compact Binary Coalescences
    - Continuous waves
    - Stochastic
  - Multimessenger searches
- perspectives and remarks



LIGO-Virgo data analysis papers, 1

- **Detection paper, GW150914:**

Observation of Gravitational Waves from a Binary Black Hole Merger, PRL 116, 061102, Feb 11 2016

- **"Companion papers" to GW150914:**

1. Tests of general relativity with GW150914, PRL 116, 221101
2. Properties of the Binary Black Hole Merger GW150914, PRL 116, 241102
3. Astrophysical Implications of the Binary Black-Hole Merger GW150914, ApJ 818, L22
4. The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914, arXiv:1602.03842, submitted to ApJL,
5. Localization and broadband follow-up of the gravitational-wave transient GW150914, ApJ 826, L13
6. GW150914: Implications for the stochastic gravitational wave background from binary black holes, PRL 116 131102 (40 cit.)
7. GW150914: First results from the search for binary black hole coalescence with Advanced LIGO PRD93, 122003 (38 cit.)
8. Observing gravitational-wave transient GW150914 with minimal assumptions, PRD93, 122004
9. High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES, PRD93, 122010
10. Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914, CQG 33, 134001
11. An improved analysis of GW150914 using a fully spin-precessing waveform model, arXiv:1606.01210, submitted to PRX
12. Directly comparing GW150914 with numerical solutions of Einstein's equations for binary black hole coalescence, arXiv:1606.01262, in press PRD
13. The basic physics of the binary black hole merger GW150914, arXiv:1608.01940, submitted to Annalen der Physik

LIGO-Virgo data analysis papers, 2

- **O1 results papers:**
  - GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence, Phys. Rev. Lett. 116, 241103 (2016)
  - Binary Black Hole Mergers in the first Advanced LIGO Observing Run, arXiv:1606.04856, submitted to PRX
  - Upper limits on the rates of binary neutron star and black-hole neutron-star mergers from Advanced LIGOs first observing, arxiv:1607.07456, submitted to ApJL
  - Close to be released:
    - All-sky search for short gravitational-wave bursts in the first Advanced LIGO run
    - Assessing accuracy of waveform models to best interpret GW150914
    - Inferring the Mass Function of Merging Binary Black Holes from GW150914, LVT151012, and GW151226
    - Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO's First Observing Run
    - Directional limits on persistent gravitational waves from Advanced LIGO’s first observing run

- Most recent papers on **past observation runs** (S5-6, VSR2-3):
  - Search for Transient Gravitational Waves in Coincidence with Short Duration Radio Transients, arXiv:1605.01707
  - Comprehensive All-sky Search for Periodic Gravitational Waves in the Sixth Science Run LIGO Data, arXiv:1605.03233
  - A First Targeted Search for Gravitational-Wave Bursts from Core-Collapse Supernovae in Data of First-Generation Laser
  - Interferometer Detectors, arXiv:1605.01785
  - Results of the deepest all-sky survey for continuous gravitational waves on LIGO S6 data running on the Einstein@Home volunteer distributed computing project, arXiv:1606.09619
  - Search for continuous gravitational waves from neutron stars in globular cluster NGC 6544, arXiv:1607.02216

Data Analysis Agreements

- Data Analysis is a joint business of LSC and Virgo
  - Astrophysical observations are joint collaboration business
  - Collaboration open data available for methodological studies by “small” groups of collaboration members.
  - Open data policy:
    - the data around the detected signals and the trigger are publicly available (at the time of the related LIGO Virgo publication)
    - after the first bunch of GW detections, LSC will make the entire data set publicly available as traditionally done for astronomical observatories. On what date LIGO O1 data will be released is not yet decided, but 2017 is likely.
    - *This will deeply affect the science goals and internal organization of LIGO Scientific Collaboration and Virgo*
- Data Analysis agreement with Kagra is being finalized:
  - reciprocal open access to future data, plans for joint observations
  - participation of KAGRA members to LIGO-Virgo R&D
- Multimessenger
  - Em follow-up program of GW alarms with selected astronomical partners
  - Agreements with neutrino detectors (e.g. Antares, IceCube, SNEWS) and cosmic rays detectors (e.g. Auger under negotiation)
- Involvement of Theory groups for the interpretation of results is becoming urgent
  - Numerical Relativity expertise in absence of matter (urgent for BBH) and in presence of Neutron Stars
  - expertise in General Relativity and theoretical astrophysics

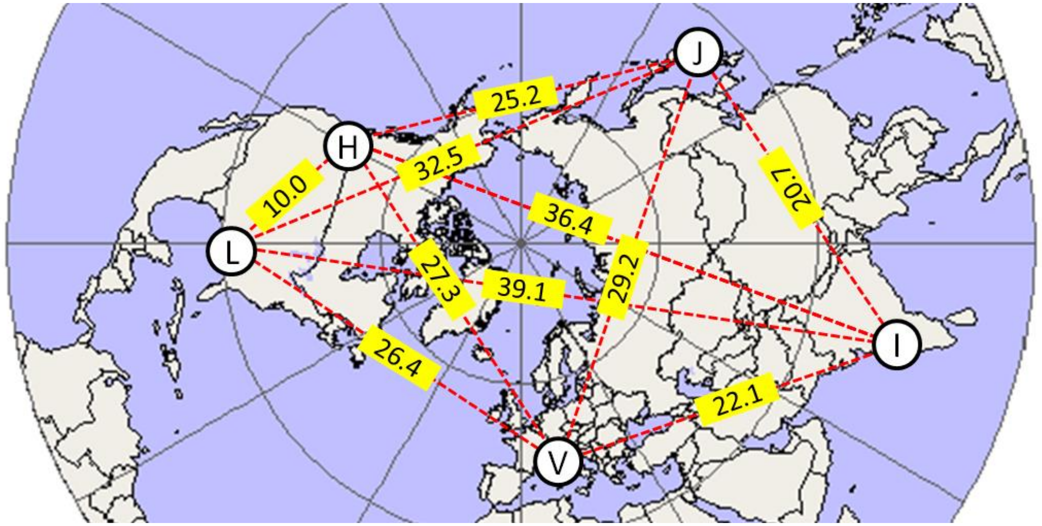
In 2012, **LIGO Virgo agreed on the policy on releasing GW alerts**

*"Initially, **triggers** (partially-validated event candidates) will be **shared promptly only with astronomy partners who have signed a Memorandum of Understanding** (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting.*

***After four GW events have been published**, further event candidates with high confidence will be **shared immediately with the entire astronomy community**, while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU."*

- open calls for participation in GW-EM follow-up program have been a success:
  - ✓ **80 MoUs signed, including astronomical institutions/agencies and large/small teams of astronomers**
  - ✓ **170 instruments participating covering all the EM spectral range**
  - ✓ **65 groups have been ready for O1**

Gravitational Wave Surveys



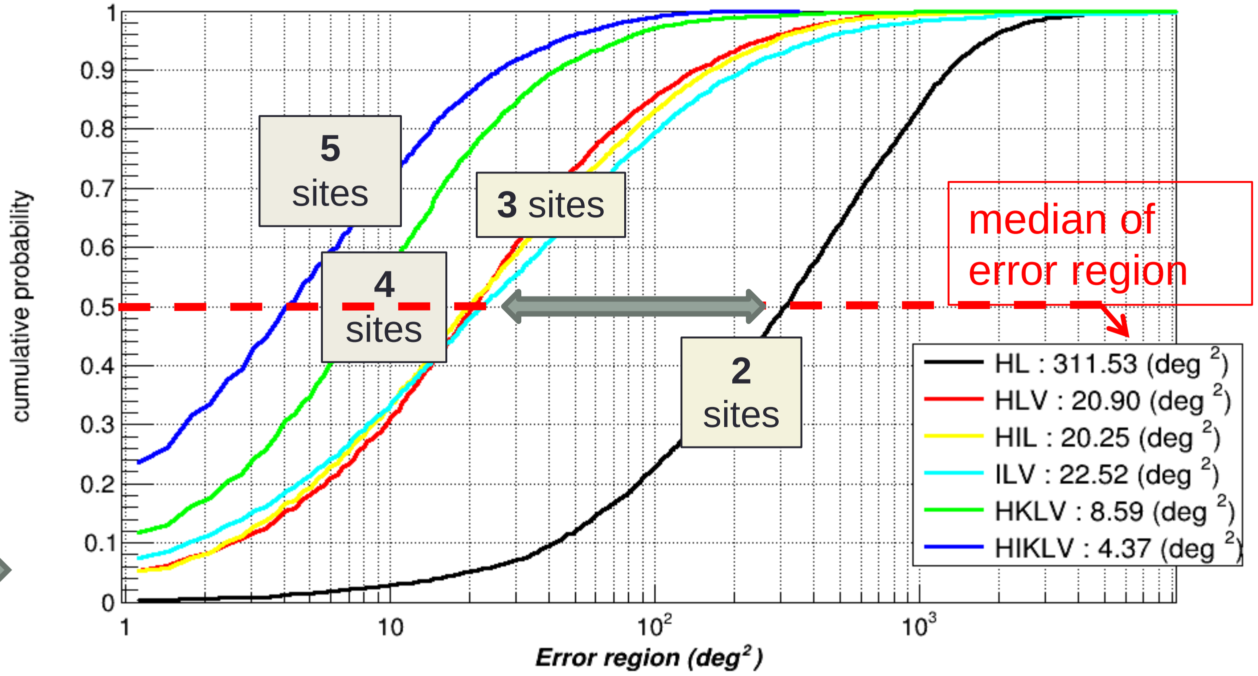
A network of detectors is required

Sky survey plans by Advanced LIGO and Virgo are being updated together with Kagra (Japan) (updating Living Rev. Relativity 19 (2016) 1, arXiv:1304.0670)

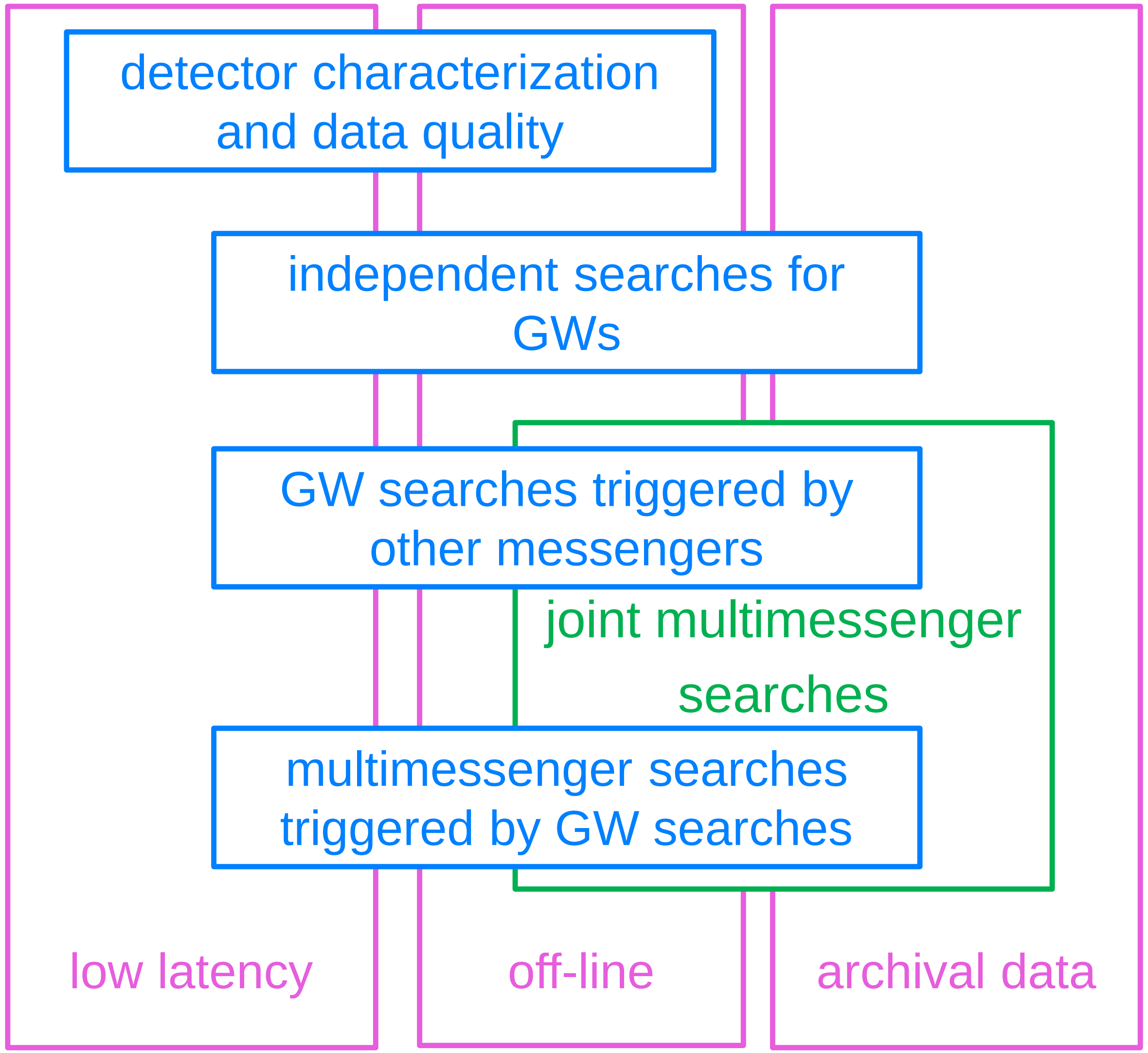
- ✓ **Sept.'15 - Jan.'16**: first advanced LIGO run
- **Oct.'16 - mid '17: second, longer run** two LIGOs & Virgo
- ○ **2017+** improving sensitivity interleaved with observation runs
- ○ 2020 Kagra joining
- ○ **202X+** LIGO India joining

3 detectors network vs 2 detectors network:

- improve time and sky coverage
- increase confidence of detections
- measure both GW polarization components
- O (10) better localization of source (sky area)



Data Analysis Map



DETECTOR CHARACTERIZATION and DATA QUALITY ASSESSMENT

Virgo chair of detector characterization group: Florent Robinet (LAL)

Main Virgo Italia involvement 2016: EGO, Roma1, Fi-Urb

Novità: per O2 sarà distribuita informazione **data quality e veti** assieme al segnale **low-latency**

Commento: in generale le persone si sono focalizzate sulle ricerche di onde gravitazionali ed il progresso in detchar rispetto all'anno scorso ne ha risentito

Fast glitch classification

- automatic classification of noise transients ("glitches")
  - low latency or off-line classification by frequency, SNR and waveform morphology of noise transients
  - noise hunting and disturbance removal
  - data quality assessment, especially for all the transient-signal searches
- methodological development in collaboration with LIGO groups
  - coordinated challenge among 3 different methods by LIGO and Virgo detector characterization groups (simulated noise + glitches)
  - development in Virgo is led by DA group at EGO (E.Cuoco) on Wavelet Detection Filter and machine learning
  - paper published: Class. Quant. Grav., 32 (21), pp. 215012, 2015

Classification methods for noise transients in advanced gravitational-wave detectors

Jade Powell[1], Daniele Trifirò[2 5], Elena Cuoco[3 4], Ik Siong Heng[1] and Marco Cavaglià[5]

- Tested on ER7 data, paper close to be released:

  Classification methods for noise transients in advanced gravitational-wave detectors II: performance tests on Advanced LIGO data.

spectral noise lines: NoEMi tool

- identification and monitor of noise lines in the frequency spectrum
  - low latency or off-line
  - noise hunting and disturbance removal
  - data quality assessment, especially for all the continuous-signal searches
- developed for Virgo and exported to the LIGO detectors
  - restarted in Cascina, smoothly running at the LIGOs
  - under development the daily production of peakmaps for the continuous signal searches
  - development led by the Continuous Wave group at Rome1

noise canceling by decorrelating against auxiliary channels

- Investigation of non-linear couplings of auxiliary channels to dark fringe
  - two methods: by Fi-Urbino group and by Padova-Trento with LSC colleagues.
  - e.g. suppression of side-band noise due to up-conversion
  - extended to suppression of glitches Fi-Urb -> LAPP (pipeline Silente)

GW SEARCHES by LIGO-VIRGO SCIENCE GROUPS

Burst group → transients of more general waveforms (co-chair M.A.Bizouard, LAL)
Compact Binary Coalescences group → transients (co-chair E.Porter, APC)

some joint targets

Continuous Waves group → quasi-periodic signals (co-chair P.Leaci, Roma1)

Stochastic group → stochastic GW "background" from cosmological or unresolved sources (co-chair T.Regimbau, OCA)

Virgo Data Analysis Coordinator: G.A.Prodi, Padova-Trento

Burst searches for GW transients with minimal assumptions

Eyes-wide-open approach for the broadest scope search of transient GWs by coherent WaveBurst 2G, joint project led by Florida, Padova-Trento and AEI Hannover.

- **Mission accomplished !**
- **Sentinel:** pointed at the first event in real time (3 min), included the prompt identification of the main characteristics of the source, which were unexpected. Triggered the LIGO Virgo collaboration and stimulated the extension of the targeted parameter space by template searches.
- **Detection confidence**: assessed high confidence to GW150914 even in the framework of a generic transient search (off-line)
- Fundamental contributions to the discovery paper, central contribution to the companion paper "Observing gravitational-wave transient GW150914 with minimal assumptions, PRD93, 122004". Sky map of source location passed to partner astronomers.
- cWB methods paper:

Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors, S. Klimenko et al. Phys.Rev. D93 (2016) no.4, 042004

Burst searches for GW transients with minimal assumptions

- Continue the commitment for **all-sky burst searches for O2** (low latency and off-line)

- **Upgrading cWB 2G pipeline for O2**
  - different signal decomposition dictionary: packets of WDM wavelets instead of single wavelet pixels
  - better signal reconstruction capabilities (sky localization, burst parameter estimation, waveform error estimation, studies on parameter estimation of the black hole ring down, low latency parameter estimation)
  - wider signal parameter space searched: longer duration signals, better detection efficiency to generic compact binary coalescence sources
  - computationally optimized code (AVX instructions)
  - ready to run on Open Science Grid (US grid standard) and CNAF

- **Follow up of Post Merger signals after Binary Neutron Star coalescences**
  - Development of methodology to estimate quantities of astrophysical interest (post merger neutron star) with cWB 2G.
  - Collaboration with numerical relativity groups to test this procedure on a large bank of numerical relativity waveforms; estimation of detectability in Adv noise and O1 (Trento PhD Thesis)

- **Eccentric Binary Black Holes [1 FTE]**
  - tune a targeted cWB 2G search (including development of specific quantities/estimators to characterize eccentric source).
  - Analysis of the O1 and O2 data for a combined O1+O2 paper (GSSI - Trento PhD thesis).
  - Method paper: "Proposed search for the detection of gravitational waves from eccentric binary black holes", V. Tiwari et al., Phys. Rev. D 93, 043007 (2016)

Compact Binary Coalescence searches with signal template banks

The BBH detections are expected to give a catalog of new sources in O2

The activity is concentrated in the development of the on-line analysis **Virgo pipeline MBTA (Multi Band Template Analysis)**

- has already run in the previous scientific runs S6-VSR2_3 and O1.
- will run in ER10 and O2.

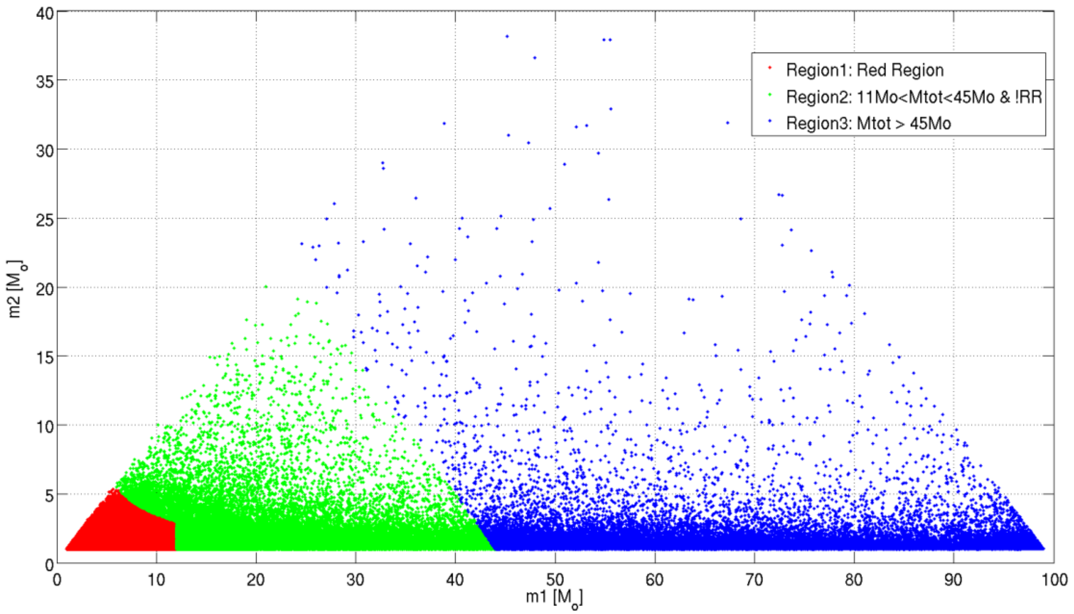
Several question have been faced:

- Is the parameter space of the search appropriate ?
- Is the configuration sane ?
  - Waveform models used for templates in various parts of the parameter space
  - 2 bands with metric / 2 bands without metric / 1 band
  - Low frequency cutoff, Frequency division between low frequency and high frequency bands
- Is the tuning efficient to detect signals ?
  - Gating of noise glitches
  - Signal based vetoes: Chi2, MFO shape cut, autochi2
  - Binning of templates for False Alarm Rate estimate
- Does the online implementation behave ?

Compact Binary Coalescence searches with signal template banks

One of the main change and challenge with respect O1 MBTA analysis configuration has been the deployment of a new search space for on-line analysis: 2 solar masses < Mtot < 100 solar masses

This new search space will include systems of BHBH like the two detected in O1: GW150914 and GW151229
The space will be devided in 3 region analysed with three different configurations.



O1 replays

- To validate MBTA behavior in this new configuration the analysis on O1 (O1 replay) is currently on-going.

Continuous-Wave (CW) searches

- SEARCHES FOR ISOLATED PULSARS
  - All-sky (PRD 90, 042002, 2014)
  - Targeted (APJ 737, 93, 2011)
  - Narrow-band (PRD 89, 062008, 2014)
- NEW SEARCHES FOR PULSARS IN BINARY SYSTEMS
  - Directed/all-sky (arXiV:1607.08751)
  - Targeted/Narrow-band (work in progress)
- NEW HETERODYNE-BASED METHOD TO BE APPLIED ON TOP OF SEMI-COHERENT CW SEARCHES (work in progress)
- NEW SEARCHES FOR TRANSIENT CW SIGNALS (work in progress)

Rome group

- NEW DATABASE VERSION WHERE STORING EPHEMERIDES TO BE USED IN CW SEARCHES (work in progress)
- REBOOT OF THE RESAMPLING PIPELINE (work in progress)
  - (PRD 83, 044033, 2011)

Pisa group

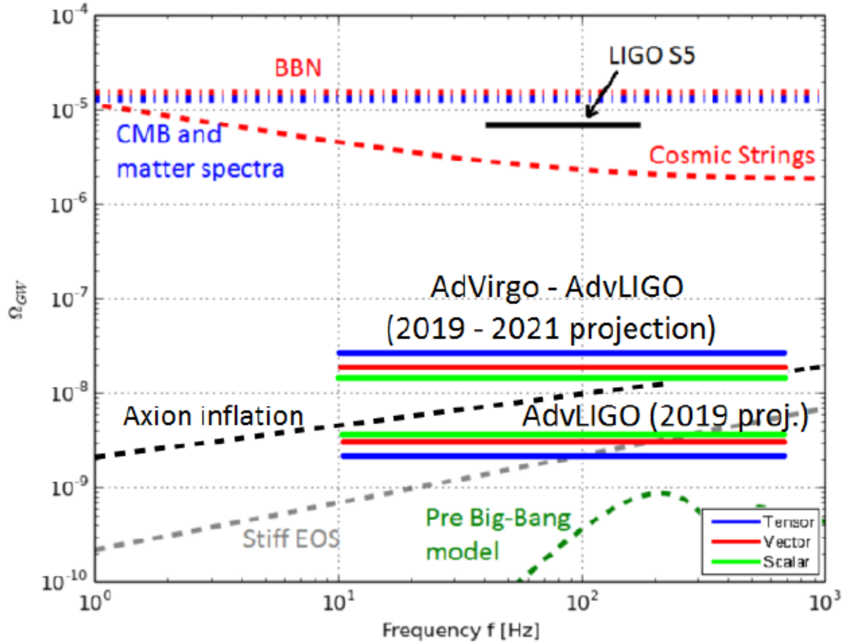
Advanced Virgo

Continuous-Wave searches

- Several LVC observational papers have been delivered so far!
- Upcoming LVC observational papers:
  - O1 all-sky wideband search for isolated pulsars employing an optimized (sped up) Hough-Transform method (RM)
  - O1 targeted 5-vector search for high-value targets (i.e. isolated pulsars for which the spin-down limit can be approached/beaten) (RM)
  - O1 narrow-band search for O(10) isolated pulsars (for which no updated EM ephemerides exist) with the generalized 5-vector method (RM)
  - O1 targeted search for Vela Jr. using the revised resampling method (PI)

Stochastic backgound searches

- In generale
- Gruppo numericamente ridotto: Pisa piu' interesse da parte di Genova
- Volontà nell'immediato futuro di utilizzare maggiormente le risorse di calcolo italiane (migrazione pipeline)

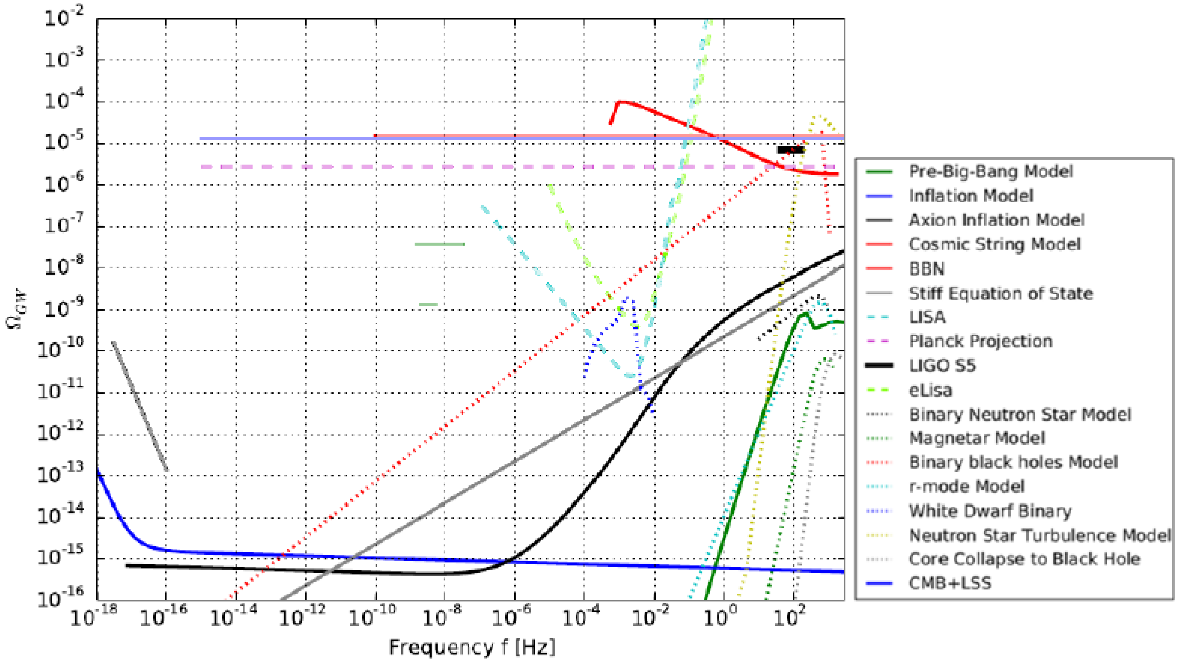


Progetto 1: Fondi stocastici e violazioni della Relatività Generale

- Ricerca di polarizzazioni non standard
- Segnatura di violazioni della relatività generale
- Attività previste: ricerca su dati reali Advanced Virgo/LIGO

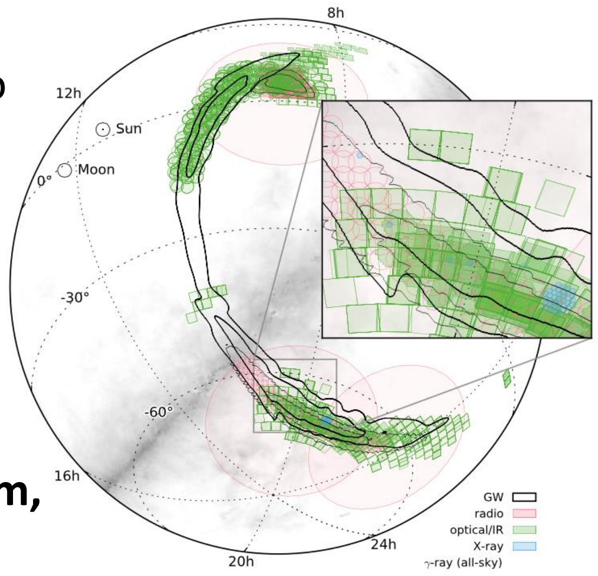
Progetto 2: Fondi stocastici non Gaussiani

- Di origine astrofisica o cosmologica
- Pongono speciali problemi per una rivelazione ottimale
- Attività previste: studio della detection e ricerca su dati reali Advanced Virgo/LIGO



Multimessenger observations of GW transients

- Participation in the **LVC infrastructure development for the EM follow-up program:**
  - Development and testing of database and software to send low-latency GW alerts and storage and visualize GW and EM properties of GW candidate alerts: graceDB, SkymapViewer, GCNs;
  - Development of software to manage the HEALPix GW sky map interacting with astronomical tools, data and environment (e.g. SAMP+Aladin, GWsky, MOC);
- Participation in the **managment of gw-astronomy forum, communications and MoUs with the astronomers**;



EM-follow up of GW150914

- Participation in the follow-up advocate team **shifts to validate GW alerts**;
- Participation in the **writing of the 2 O1 follow-up papers** and the review of the astronomers' papers;
- Studies of galaxies of the local Universe to estimate GW detection rate for binary systems and supernovae and optimize the EM follow-up observational strategies (In collaboration with external astronomers, mainly INAF);
- Studies on combined GW/EM emissions (in collaboration with external astronomers and involving PhD students);

Multimessenger observations of GW transients

Short term plans:

- Participate in the software development and tools implementation to validate and send GW alerts during O2;
- Development of new software able to manage 3D skymaps (with direction-dependent distance info) and new GW alert content;
- Organize and participate in the shifts for the human GW candidate alert validation;
- Organize the communications with astronomers and GW/EM info flow;
- Continue studies on GW/EM observational strategies and data analysis;
- Continue collaboration and networking activity with astronomers;
- Participate in the organization of a one-day workshop at ESO to discuss the EM-follow-up project, and GW-related IAU and EWASS symposia.

Main group involved: Urbino/INFN-Firenze, Trento-Padova, Pisa and Genova

M. Branchesi liaison of the EM-follow up team

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

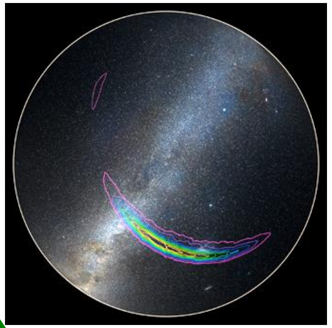
GW candidates

Sky Localization

EM facilities

LIGO-H **LIGO-L**

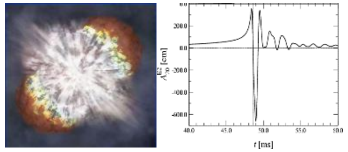
Virgo



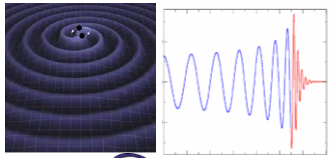
Event validation

Low-latency Search

to identify the GW-candidates



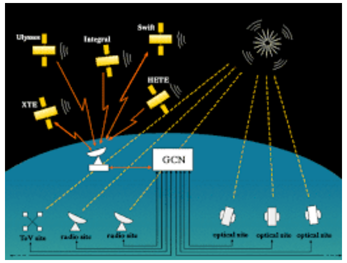
Unmodeled GW burst search



Matched filter with waveforms of compact binary coalescence

Software to

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



a few min

15/30 min

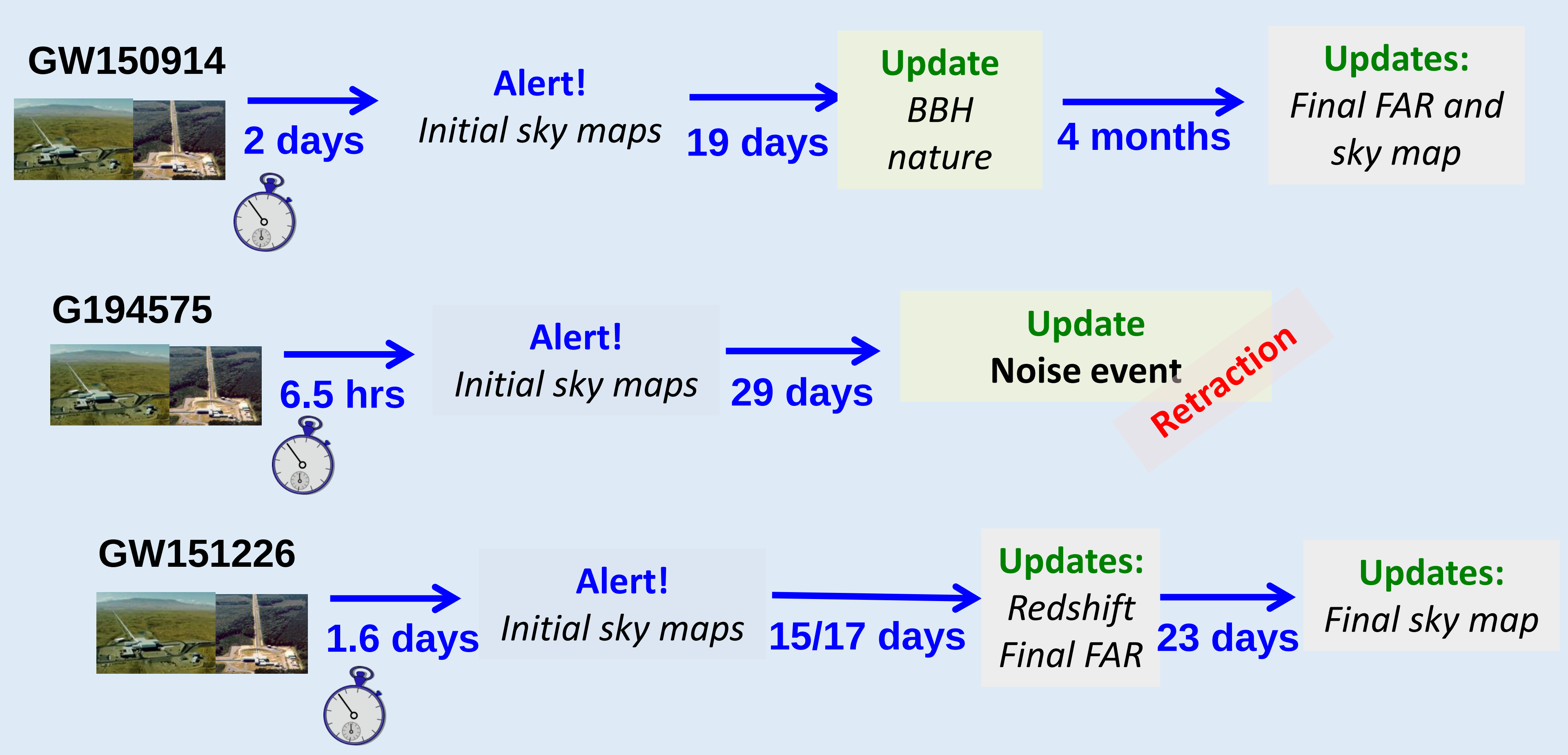
Parameter estimation codes

Hours,days

GW candidate updates

EM follow-up program - O1 run

- **Three alerts** sent to 65 groups of astronomers with observational capabilities
- **About 40 groups followed-up at least one alert** giving a broadband coverage of the sky maps and the rapid characterization of the candidate counterparts



GGW150914

EM follow up observations and archival searches

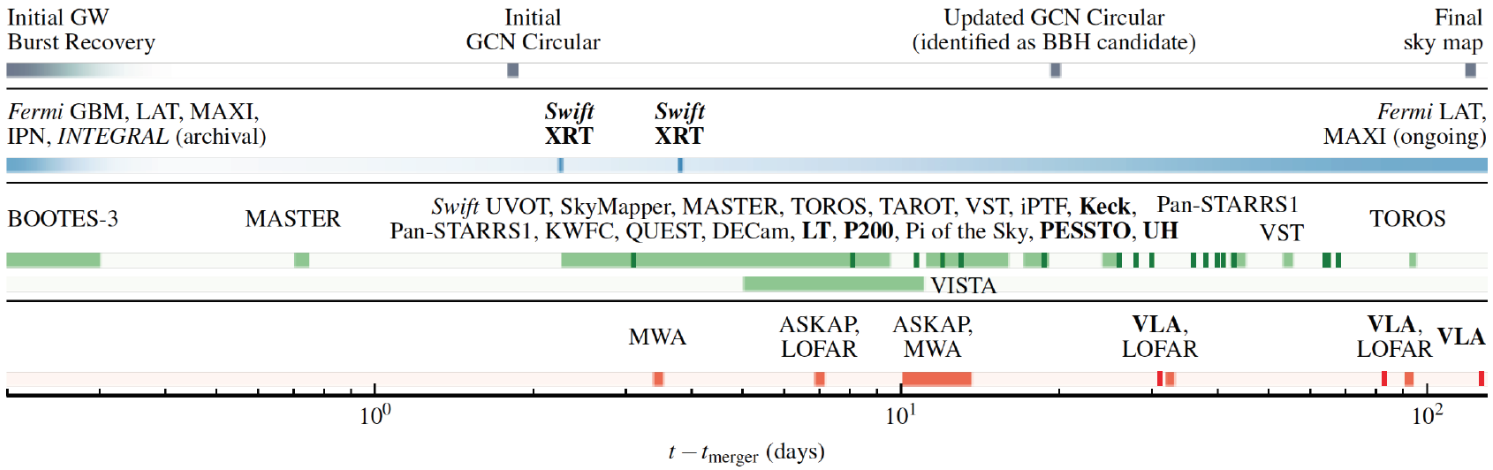
- ***Twenty-five teams*** *of observers responded to the GW alert*

- *The EM observations involved* ***satellites and ground-based telescopes*** *around the globe spanning 19 orders of magnitude in frequency across the EM spectrum*

High-energy

Optical/NIR

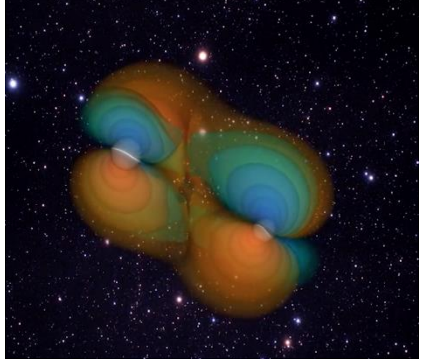
Radio



LVC+astronomers arXiv1602.08492
LVC+astronomers arXiv1604.07864
Connaughton et al. arXiv:1602.03920
Savchenko et al. 2016 ApJL 820, 36

Smartt et al. arXiv160204156S
Evans et al. MNRAS 460, L40
Annis et al. arXiv:1602.04199
Kasliwal et al. arXiv:1602.08764

Morokuma et al. arXiv:1605.03216
Fermi-LAT collaboration APJL, 823,2
Lipunov et al. arXiv:1605.01607
Soares-Santos et al. arXiv:1602.04198



*EM follow-up of GW150914 and GW151226 demonstrates the **capability to cover large area**, to **identify candidates**, and to rapidly **activate larger telescopes***

No stellar-BBH EM emission due to the absence of the accreting material
…but some mechanisms that could produce unusual presence of matter around BHs recently discussed
Loeb 2016 ; Perna et al. 2016 ; Zhang et al. 2016

Future EM follow-ups of GW will shed light on the presence or absence of firm EM counterparts for BBH

The follow-up campaign sensitive to emission expected from BNS mergers at 70 Mpc range
The widely variable sensitivity across the sky localization is a challenge for the EM counterpart search

extra

LIGO-Virgo observing scenario

Living Rev. Relativity, 19, (2016), 1
DOI 10.1007/lrr-2016-1

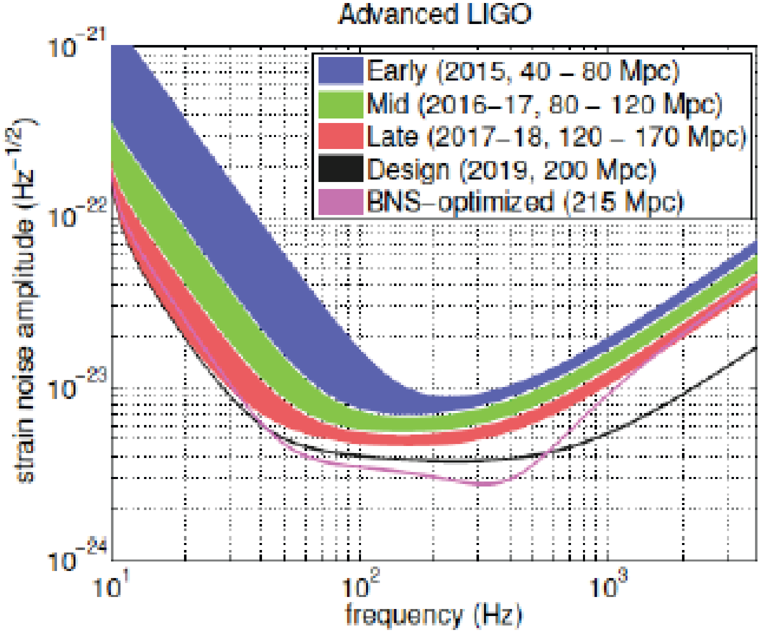
LIVING REVIEWS in relativity

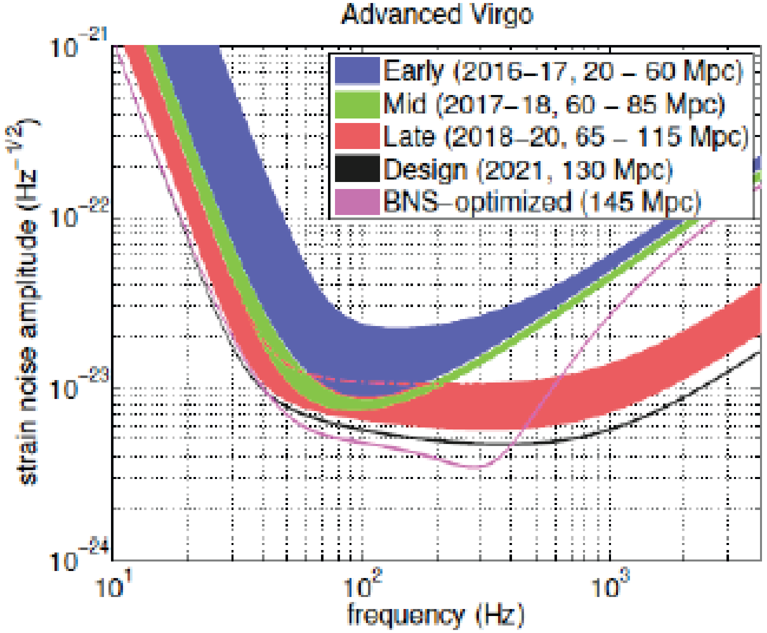
Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

et al.
d the Virgo Collaboration
given at the end of paper.)
-spokesperson@ego-gw.it

arXiv:1304.0670v1 [gr-qc] 2 Apr 2013



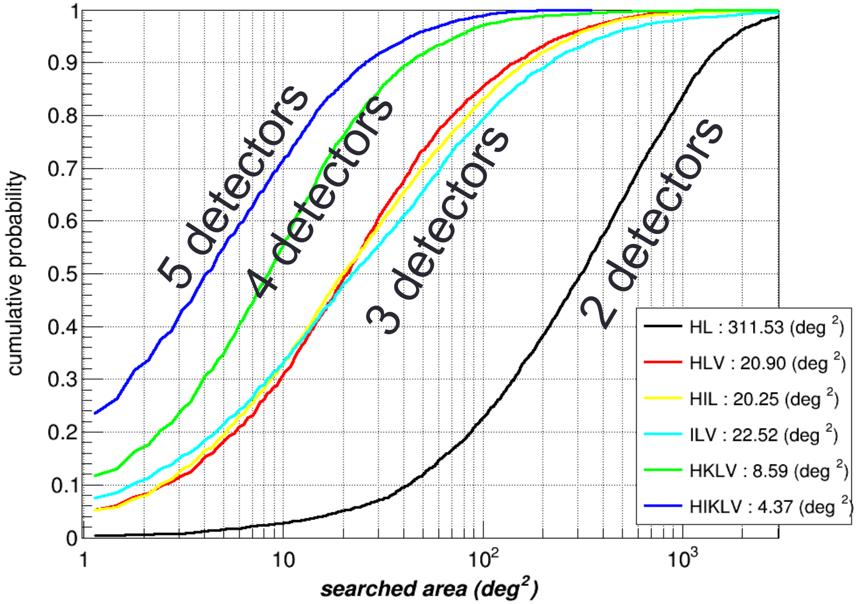


Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
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

Advanced Virgo

Burst searches: astrophysical interpretation

GW source localization:
sample population of BH-BH coalescences
(15-25 solar masses per component)

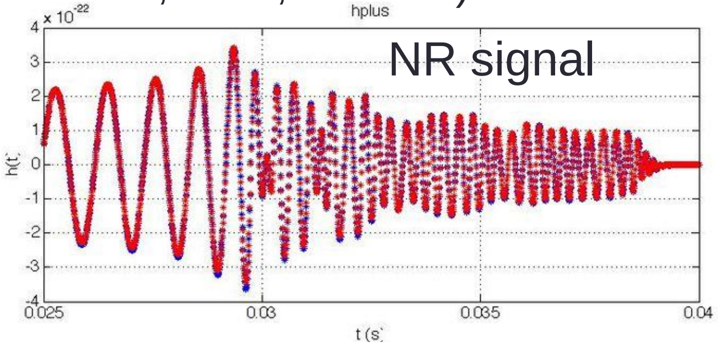


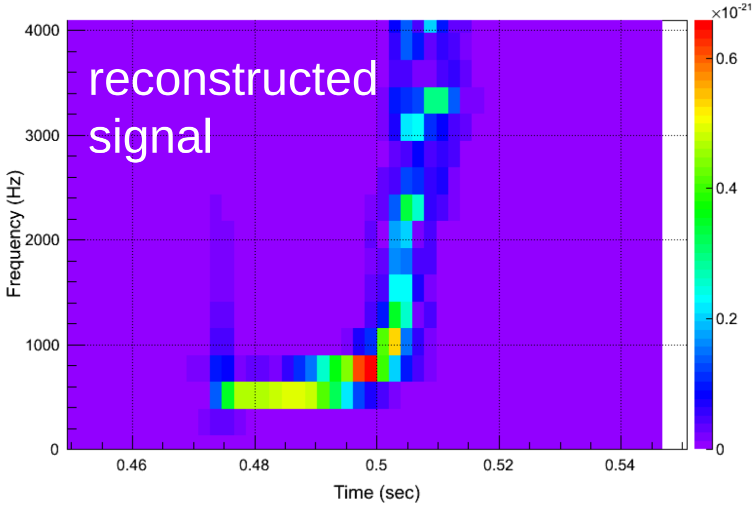
sky error region

make possible **Multimessenger searches:**
fast follow-up as well as archival searches

Next goal: **elliptical polarization angle** or **inclination angle** of the source

Waveform reconstruction:
time frequency reconstruction
e.g. constraining **NS equation of state** from NS-NS post-merger signal in collaboration with **Trento group of Numerical Relativity** (Giacomazzo, Ciolfi, Kastaun)





GW151226

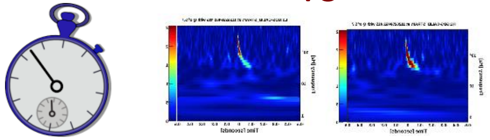
Thirty-one groups *responded to the GW alert:*

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

Optical-NIR → 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 → VLA-Corsi, LOFAR, MWA

To



Gamma
hard X-ray

1.6 days

Alert sent!

~1 hrs
X-ray
10 days

~0.5 hrs
Optical/Near-IR
3 months

~ 3.5 days
Radio
3 months

Racusin et al. arXiv:1606.04901
Smartt et al. arXiv:1606.04795
Copperwheat et al. arXiv:1606.04574

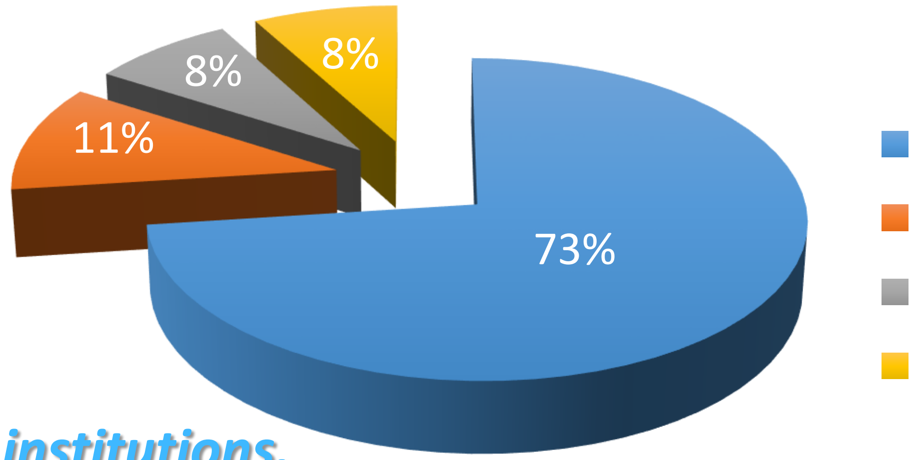
Cowperthwaite et al. arXiv:1606.04538
Evans et al. arXiv:1606.05001

LVC GW-EM follow-up program

80 MoUs involving

- **170 instruments**

covering the full spectrum *from radio to very high-energy gamma-rays!*



- ***Worldwide astronomical institutions, agencies and large/small teams of astronomers***

65 teams of astronomers were ready to observe during O1 (September 2015 – January 2016)!