Detection of Gravitational Waves Signals in LIGO-Virgo data

PhD day – October 4, 2022
Nitoglia Elisa

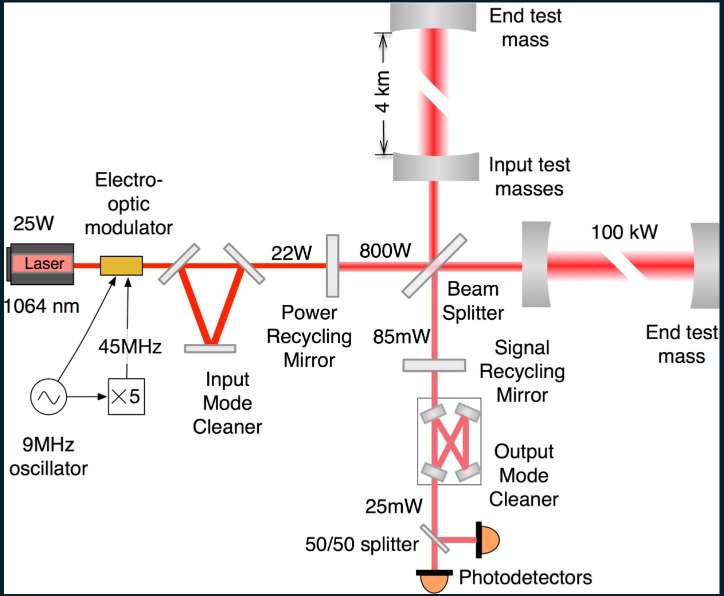
Gravitational Waves in General Relativity

- Predicted by Einstein in 1915 in his theory of General Relativity
- Directly observed for the first time in 2015 with GW150914[1]
- Ripples in the curvature of the spacetime generated by the acceleration of masses
- Propagating at the speed of light
- Gravitational Waves (GW) create a deformation in the spacetime with a time dependence $h(t)$

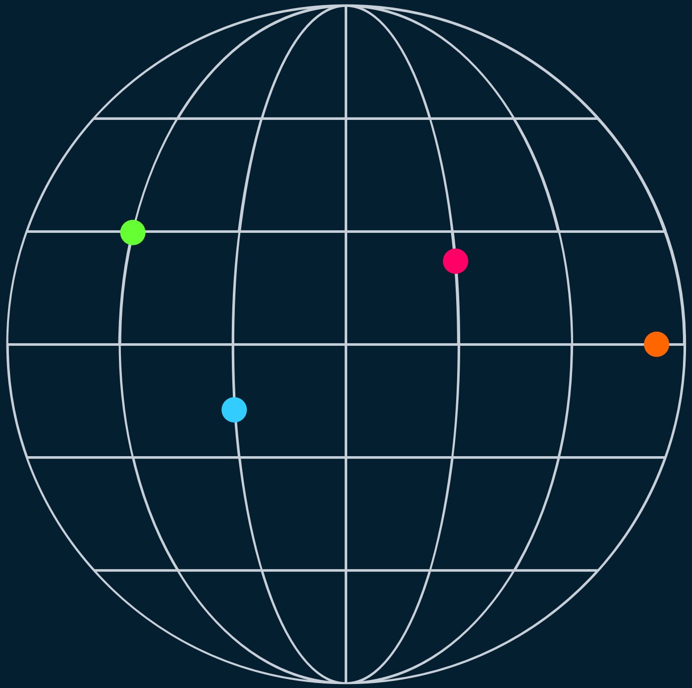
[1] B.P. Abbott et al (The LIGO Scientific Collaboration and The Virgo Collaboration) Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102, Feb 2016

Measurement Technique

- The instruments used to detect the passage of a GW are kilometer-scale Michelson interferometers equipped with Fabry-Pérot cavities
- GWs stretch the space in one direction and simultaneously compress in another direction
- They produce a modulation of the distance between the end test mass optics and the beam splitter
- If no GWs are passing, the pattern fringes is in total destructive interference



Terrestrial Network



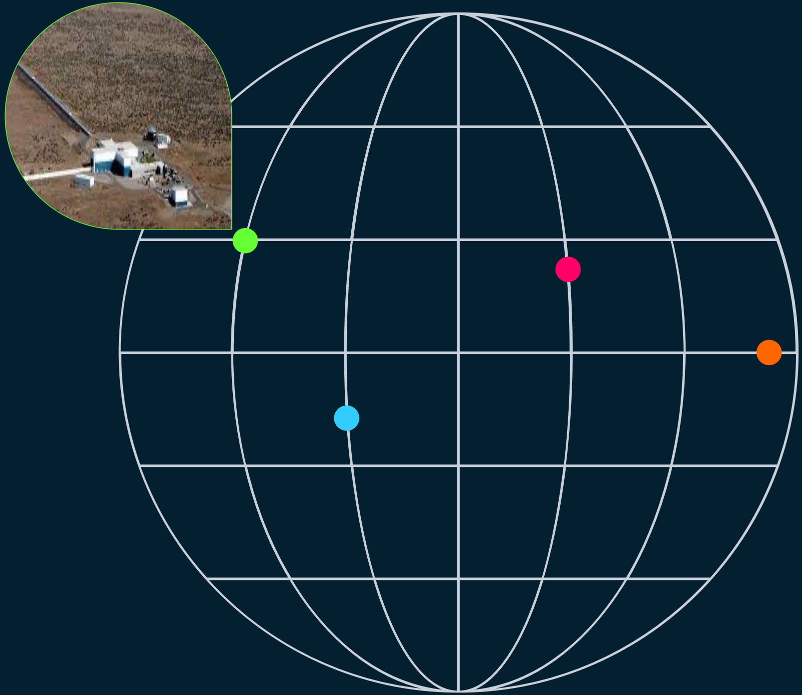
LIGO Hanford
Washington, US
4kms

LIGO Livingston
Louisiana, US
4kms

Virgo
Cascina, IT
3kms

Kagra
Gifu Prefecture, JP
3 kms, cryogenics

Terrestrial Network



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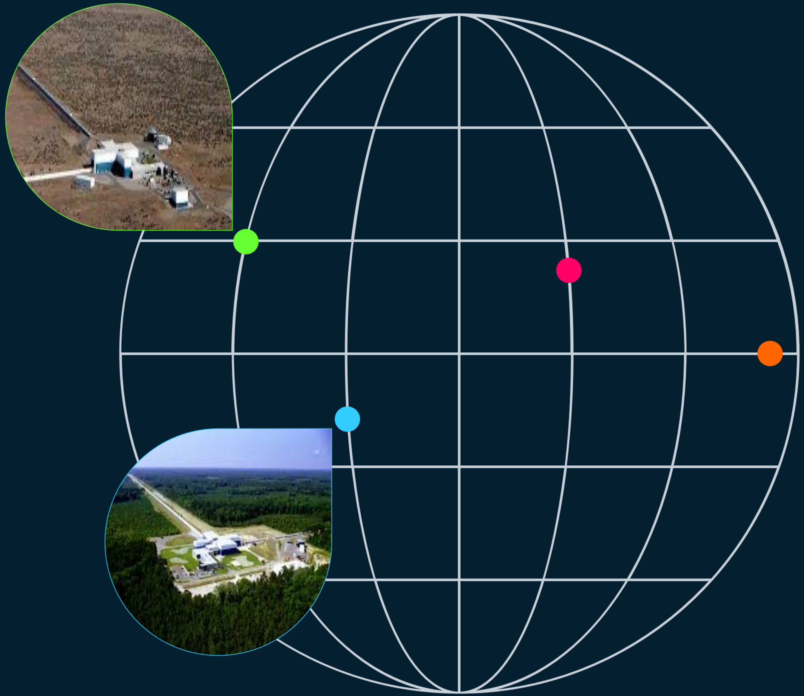

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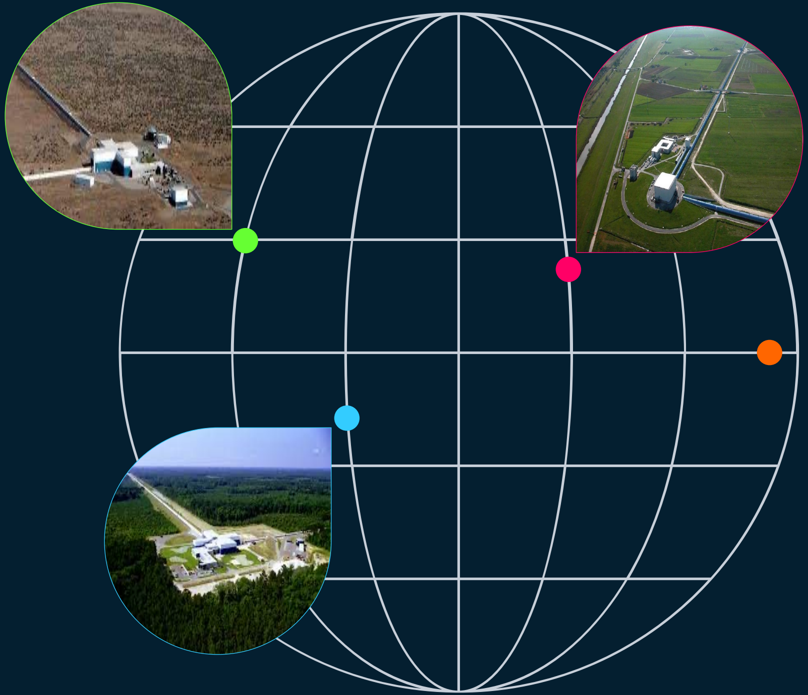

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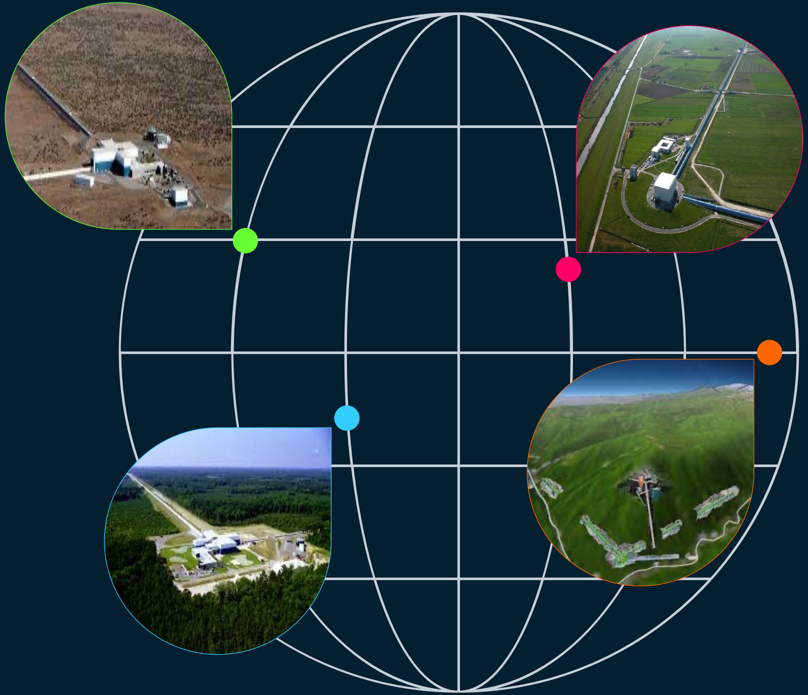

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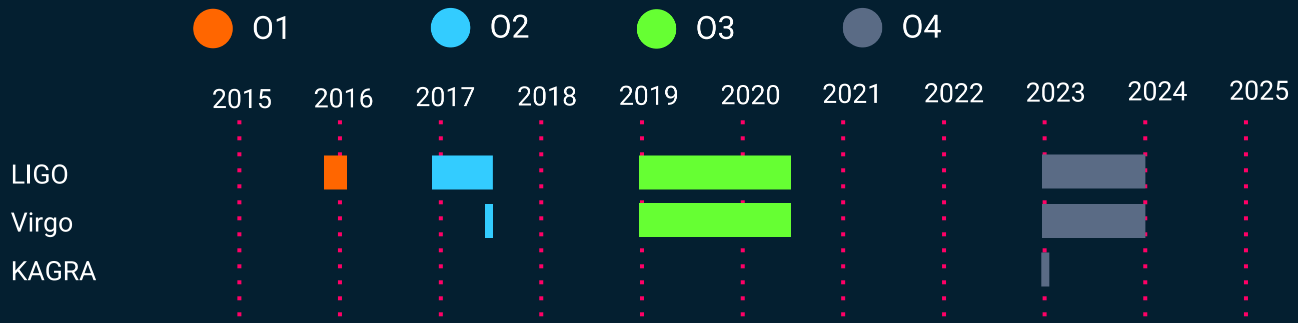
Observing Runs



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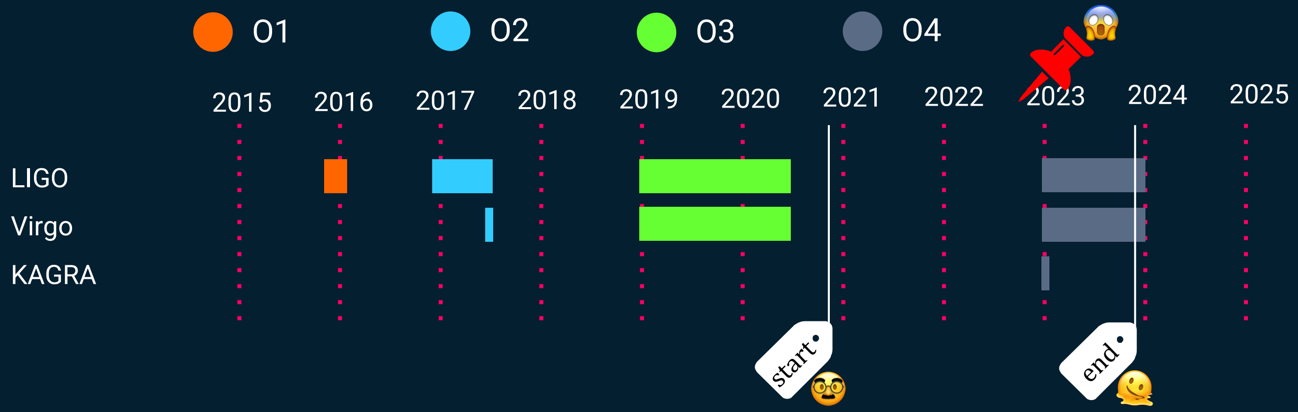
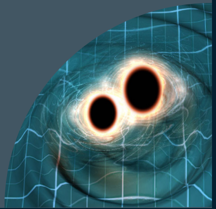


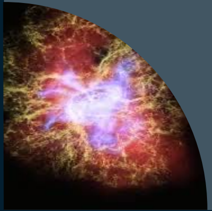
Sources of Gravitational Waves

- Massive and compact objects
- Events violent enough to induce a sufficiently strong gravitational deformation of the spacetime
- Necessarily of astrophysical origin

Compact Binary Coalescences (CBCs)



Burst



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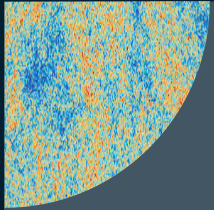

Stochastic Background

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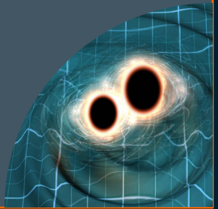

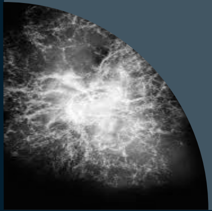

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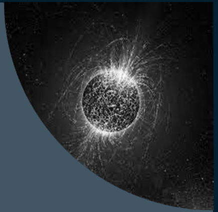

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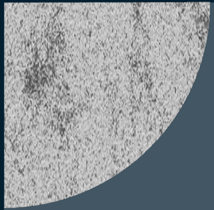

Stochastic Background

Compact Binary Coalescences

- CBCs are a class of GW sources composed by two compact objects spiraling towards each other due to the loss of energy and angular momentum of the system, caused by the emission of GWs
- Binary systems capable of generating signals potentially detectable on Earth are Binary Black Holes (BBHs), Binary Neutron Stars (BNs) and Neutron Star-Black Hole binaries (NSBHs)

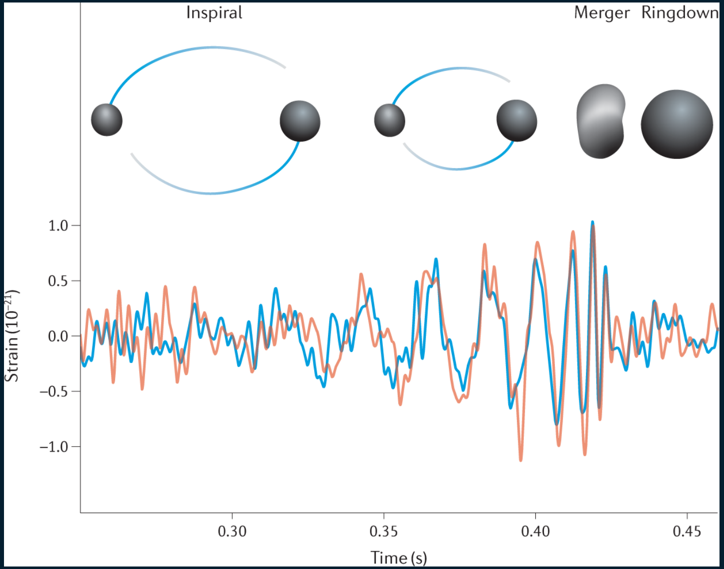

Illustration of the evolution of GW150914. The waveforms are shifted and inverted to compensate for the slightly different arrival times and different orientations of the detectors (red: LIGO Hanford, blue: LIGO Livingston).

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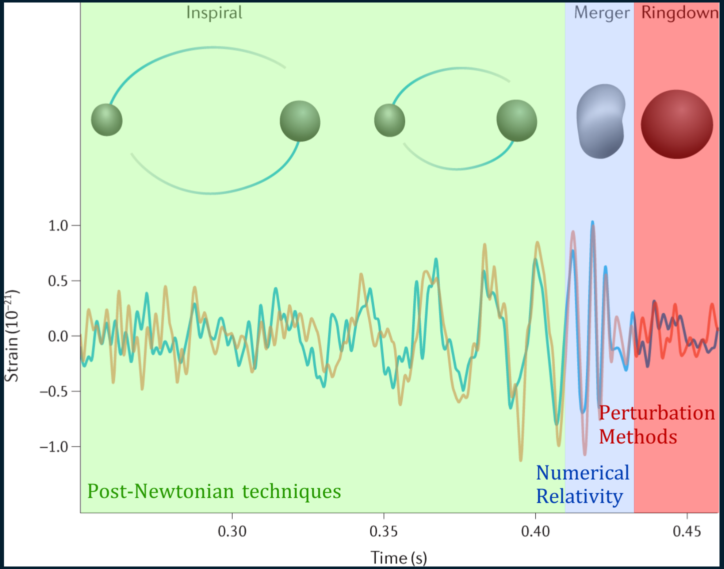
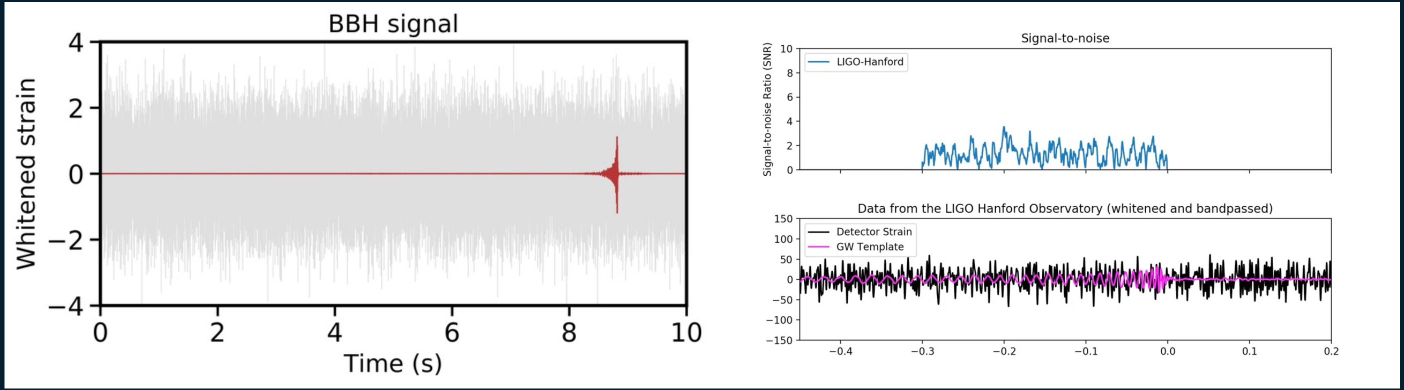


Illustration of the evolution of GW150914. The waveforms are shifted and inverted to compensate for the slightly different arrival times and different orientations of the detectors (red: LIGO Hanford, blue: LIGO Livingston).

The Search Method

We use a technique called matched filtering to extract CBC signals from the GW channel data of each detector in the network independently which computes the correlation between the hypothetical signal and the interferometer output signal



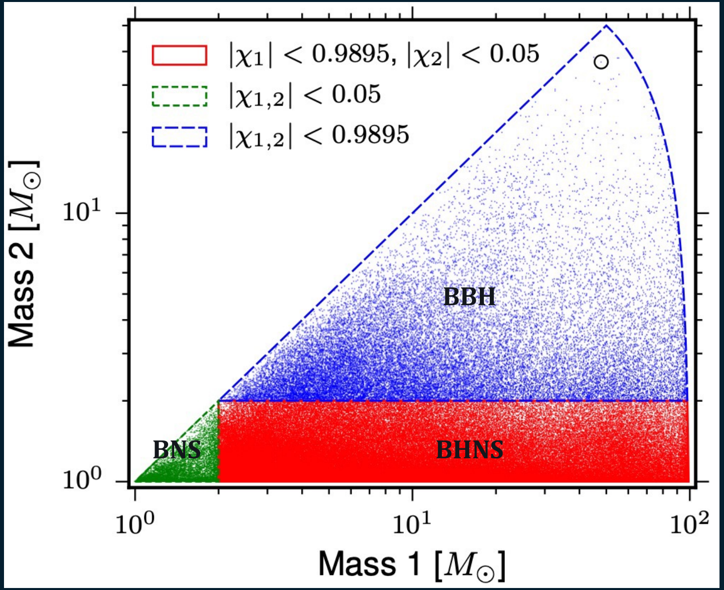
Task: to find out which filter maximize the signal-to-noise ratio (SNR)

Template Bank

- Need to know the shape of the signal we are looking for → waveform modeling
- Optimize the filter for a particular signal → use source parameters
- Deal with many possible signal shapes → generate template banks

- Covers the target parameters space
- Discrete and limited
- Should not over-cover the parameters space

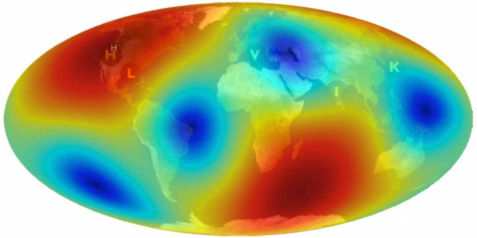
- For O3 we used ~O(10^6) of templates over the entire parameters space
- The BHNS parameters space is the most populated



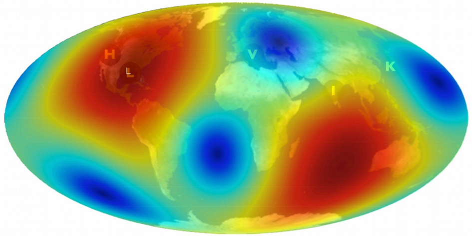
The LIGO Scientific Collaboration and the Virgo Collaboration. GW150914: First results from the search for binary black hole coalescence with Advanced LIGO - 2016

Detector Coincidences

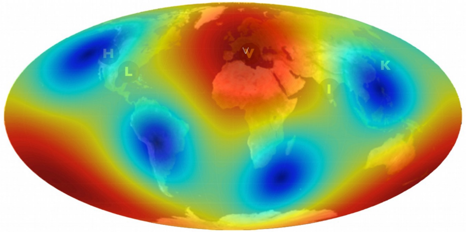
LIGO Hanford



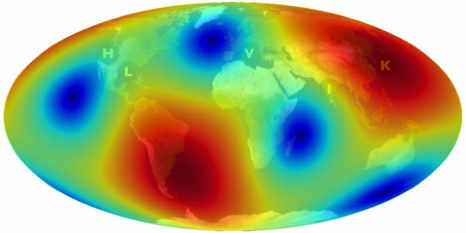
LIGO Livingston

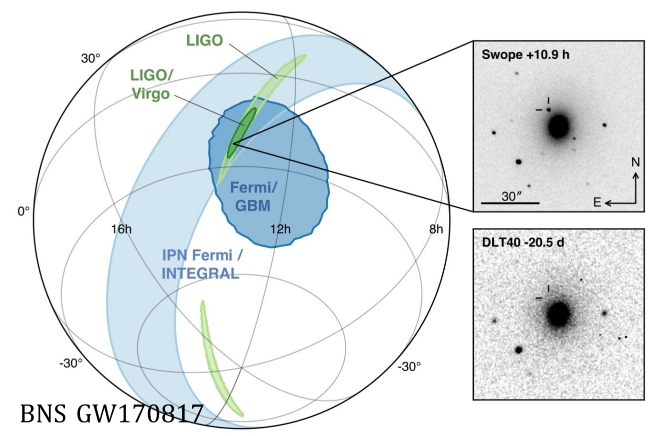


Virgo



Kagra





BNS GW170817

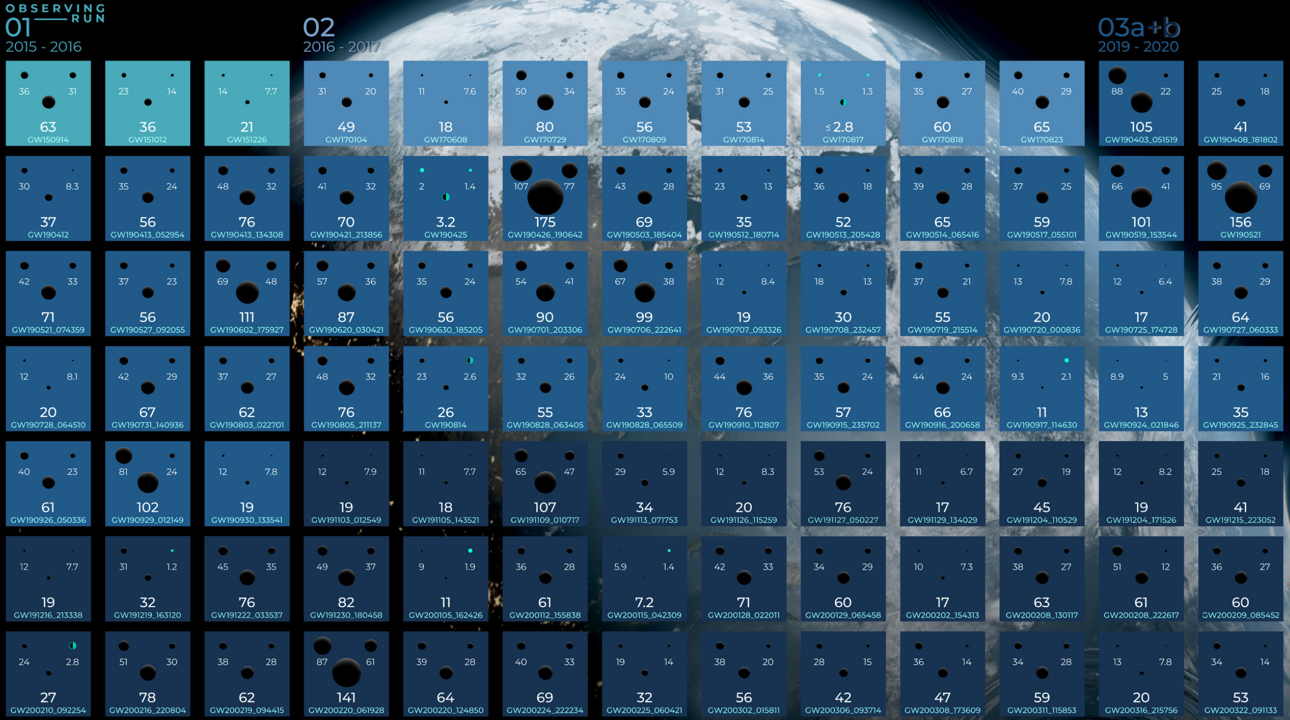
Apparent host galaxy NGC4993
(10.9h after the merger)

- Hanford-Livingston (190 deg^2) - green
- Hanford-Livingston-Virgo (31 deg^2) – dark green
- Triangulation from the time delay between Fermi and INTEGRAL - blue
- Triangulation from the time delay between Fermi-GBM – dark blue

Apparent host galaxy NGC4993
(20.5 days prior the merger)

Analysis Pipelines

- Different analysis pipelines are involved in the CBC search and in the production of catalogues: MBTA (Multi-Band Template Analysis), PyCBC and GstLAL
- The search results from each observing run are reported in the *catalog papers*
- All the information derived from the search are used for other studies:
    - Multimessenger astronomy
    - Sources parameters estimation (within catalogues)
    - Constraint on merger rates
    - Constraints on population properties of compact objects
    - Constraints on cosmological parameters
    - Constraints on nuclear matter inside NSs
    - Test of General Relativity



OBSERVING RUN O1
2015 - 2016

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW150914	36	31	63
GW151012	23	14	36
GW151226	14	7.7	21

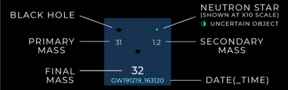
O2
2016 - 2017

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW170104	31	20	49
GW170608	11	7.6	18
GW170729	50	34	80
GW170809	35	24	56
GW170814	31	25	53
GW170817	1.5	1.3	≤ 2.8
GW170818	35	27	60
GW170823	40	29	65

O3a+b
2019 - 2020

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW190403_051519	88	22	105
GW190408_181802	25	18	41
GW190412	30	8.3	37
GW190413_052954	35	24	56
GW190413_134308	48	32	76
GW190421_213856	41	32	70
GW190425	2	1.4	3.2
GW190426_190642	107	77	175
GW190503_185404	43	28	69
GW190512_180714	23	13	35
GW190513_205428	36	18	52
GW190514_065416	39	28	65
GW190517_055101	37	25	59
GW190519_153544	66	41	101
GW190521	95	69	156
GW190521_074359	42	33	71
GW190527_092055	37	23	56
GW190602_175927	69	48	111
GW190620_030421	57	36	87
GW190630_185205	35	24	56
GW190701_203306	54	41	90
GW190706_222641	67	38	99
GW190707_093326	12	8.4	19
GW190708_232457	18	13	30
GW190719_215514	37	21	55
GW190720_000836	13	7.8	20
GW190725_174728	12	6.4	17
GW190727_060333	38	29	64
GW190728_064510	12	8.1	20
GW190731_140936	42	29	67
GW190803_022701	37	27	62
GW190805_211137	48	32	76
GW190814	23	2.6	26
GW190828_063405	32	26	55
GW190828_065509	24	10	33
GW190910_112807	44	36	76
GW190915_235702	35	24	57
GW190916_200658	44	24	66
GW190917_114630	9.3	2.1	11
GW190924_021846	8.9	5	13
GW190925_232845	21	16	35
GW190926_050336	40	23	61
GW190929_012149	81	24	102
GW190930_133541	12	7.8	19
GW191103_012549	12	7.9	19
GW191105_143521	11	7.7	18
GW191109_010717	65	47	107
GW191113_071753	29	5.9	34
GW191126_115259	12	8.3	20
GW191127_050227	53	24	76
GW191129_134029	11	6.7	17
GW191204_110529	27	19	45
GW191204_171526	12	8.2	19
GW191215_223052	25	18	41
GW191216_213338	12	7.7	19
GW191219_163120	31	1.2	32
GW191222_033537	45	35	76
GW191230_180458	49	37	82
GW200105_162426	9	1.9	11
GW200112_155838	36	28	61
GW200115_042309	5.9	1.4	7.2
GW200128_022011	42	33	71
GW200129_065458	34	29	60
GW200202_154313	10	7.3	17
GW200208_130117	38	27	63
GW200208_222617	51	12	61
GW200209_085452	36	27	60
GW200210_092254	24	2.8	27
GW200216_220804	51	30	78
GW200219_094415	38	28	62
GW200220_061928	87	61	141
GW200220_124850	39	28	64
GW200224_222234	40	33	69
GW200225_060421	19	14	32
GW200302_015811	38	20	56
GW200306_093714	28	15	42
GW200308_173609	36	14	47
GW200311_115853	34	28	59
GW200316_215756	13	7.8	20
GW200322_091133	34	14	53

KEY



UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

GRAVITATIONAL WAVE MERGER DETECTIONS
SINCE 2015

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

LIGO VIRGO KAGRA

Publications

- The MBTA pipeline for Detecting Compact Binary coalescences in the Third LIGO-Virgo Observing run – Class. Quantum Gravity 2021
- Catalog paper CBC on O3a – submitted to PRD 2021
- Catalog paper CBC on O3b – submitted to PRX 2021
- NSBH discovery paper – ApJL 2021
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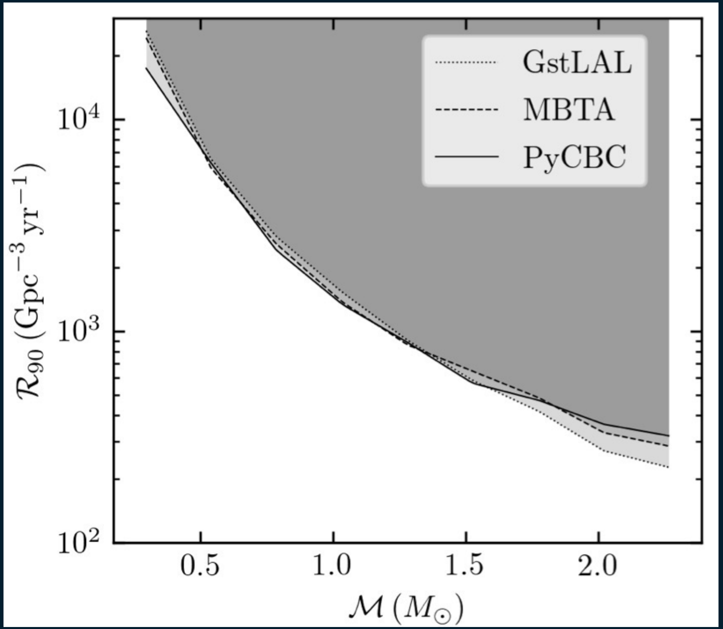
Sub–Solar Mass Search

- The MBTA pipeline is involved in the Sub-Solar Mass (SSM) search in O3 data
- I am the main analyst for this study
- We seek for signals emitted by compact binaries where at least one component has a mass between $0.2M_\odot$ and $1.0M_\odot$
- There is no know mechanism for the formation of objects with a mass below $1.0M_\odot$ within the standard model of stellar evolution
- Several alternative formation channels proposals as Primordial Black Holes (PBHs), collapse of Dark Matter (DM), interaction between DM and standard model particles …
- A detection of such systems would be a clear signal of new physics, a non detection would put upper limits on their merger rate and abundance

Sub–Solar Mass Search – O3a

$$\mathcal{M} = \frac{(m_1 \cdot m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- Search already performed in data from O1 and O2
- No gravitational wave candidates identified so far
- Constraint on the merger rate of such systems



The LIGO Scientific Collaboration and the Virgo Collaboration. Search for sub-solar mass binaries in the first half of the third observing run - 2021

Conclusions

- Gravitational waves is a multidisciplinary field (astrophysics, nuclear physics, cosmology, particle physics…)
- 90 identified CBC candidate events so far (used to study CBC rates, population of compact objects, infer cosmology measures, constrain general relativity …)
- The MBTA group is actively participating to searches and analysis
- What is next?
  - We are looking forward to the next observing run (O4)
  - Kagra will join the data taking (LVC → LVK collaboration)
  - Improved sensitivity during O4 so we expect more detections wrt O3 (factor ~3)
  - We are working on a low-latency version of the SSM search to be performed during O4