Status of the Advanced LIGO and Advanced Virgo detectors

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On behalf of the LIGO Scientific Collaboration and of the VIRGO Collaboration



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Outline

- Introduction
  - Gravitational waves
  - Giant interferometric gravitational-wave detectors
  - A network of detectors

- Looking back: a quick summary of Advanced LIGO Observation Run 1 (O1)

- Advanced LIGO Observation Run 2 (O2)
  - GEO600

- Advanced Virgo commissioning

- Looking at the future
  - Virgo's goal is to join O2
  - O2/O3 break
  - O3 and beyond

Gravitational Waves @ EPS-HEP 2017

- This parallel session

	Status of the Advanced LIGO and Advanced Virgo Detectors *Room Martinelli, Palazzo del Casinò*	*Nicolas Arnaud* 16:30 - 16:45
	Results of transient GW searches with Advanced LIGO *Room Martinelli, Palazzo del Casinò*	*Ed Porter* 16:45 - 17:00
17:00	**Testing the strong-field dynamics of general relativity with gravitational wave signals from compact binary coalescences**	*Archisman Ghosh*
	Astrophysical and cosmological results from compact binary coalescences *Room Martinelli, Palazzo del Casinò*	*Dr. Vivien Raymond* 17:15 - 17:30
	GW transient searches to probe Neutron star physics *Room Martinelli, Palazzo del Casinò*	*Dr. Claudia Lazzaro* 17:30 - 17:45
	Low latency gravitational wave searches for prompt multimessenger followups *Room Martinelli, Palazzo del Casinò*	*Marco Drago* 17:45 - 18:00
18:00	**Stochastic GW searches and Cosmology with GWs** *Room Martinelli, Palazzo del Casinò*	*Giancarlo Cella* 18:00 - 18:15
	The search for continuous gravitational waves with LIGO and Virgo detectors *Room Martinelli, Palazzo del Casinò*	*Dr. Cristiano Palomba* 18:15 - 18:30
	Extending the gravitational waves searches for black holes with intermediate masses and residual eccentricity at merger	*Shubhanshu Tiwari*

Data analysis

- Plenary talk on Monday afternoon

Gravitational Wave observations: status and perspectives *Sala Grande, Palazzo del Cinema*	*Michele Punturo* 14:30 - 15:00

Gravitational waves in a nutshell

$$P = \frac{c^5}{G} \epsilon^2 \left(\frac{v}{c}\right)^6 \left(\frac{R_s}{R}\right)^2$$

- Gravitational waves (GW)
  - Ripples in the fabric of the spacetime
  - Emitted by accelerated masses
  - Propagate at the speed of light
  - Time-varying quadrupolar moment of the mass distribution required

  → No emission if spherical or cylindrical symmetry

$$R_s = \frac{2GM}{c^2}$$

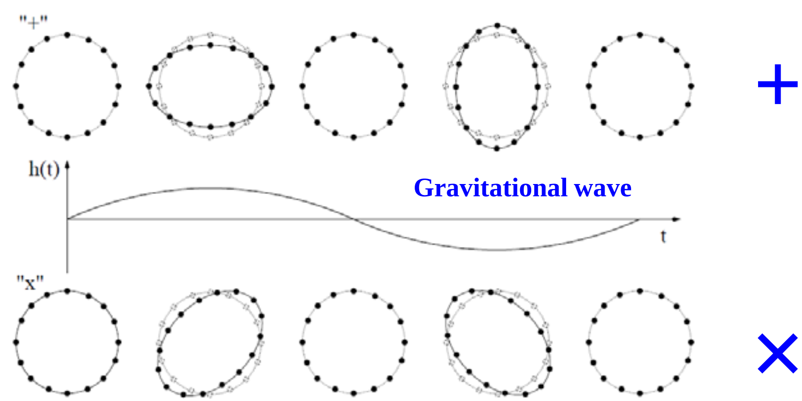
R_S: Schwartzschild radius
- **3 km for the Sun**

- One of the first predictions of General Relativity (GR) – Einstein 1916
- GW characterized by its dimensionless strain h
  - h ∝ 1 / (distance from the source)

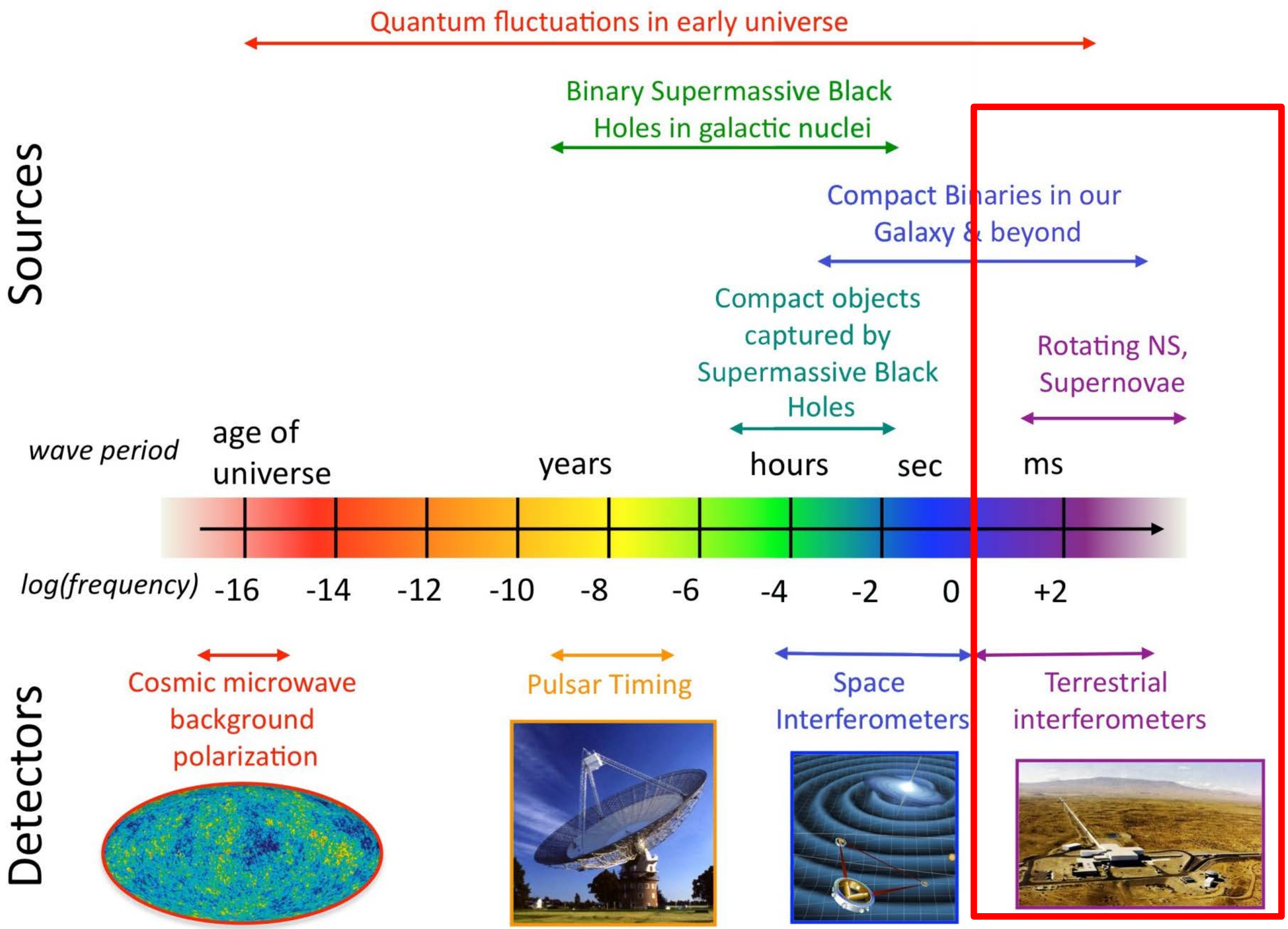
$$\mathbf{h}(t) = \frac{2\,\Delta\mathbf{L}(t)}{\mathbf{L}}$$

- Transverse with two polarizations
  - « + » and « × »
  - Effect on a ring of test masses (free-falling)

  → Length variations in ⊥ directions



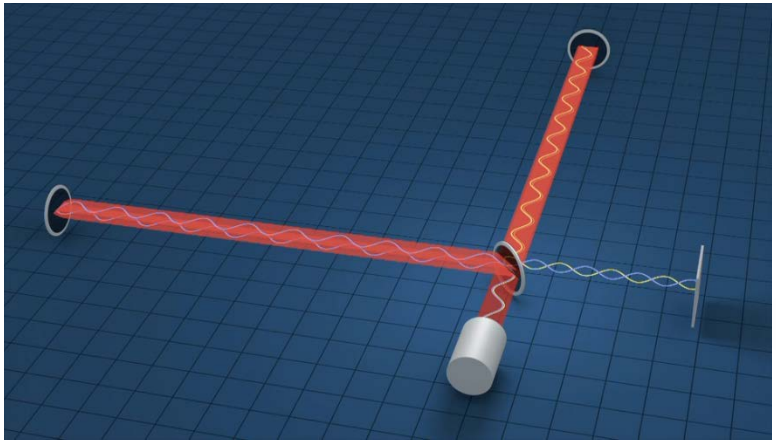
Gravitational-wave spectrum

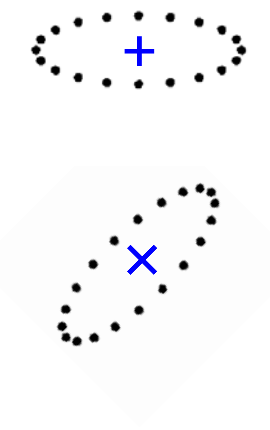


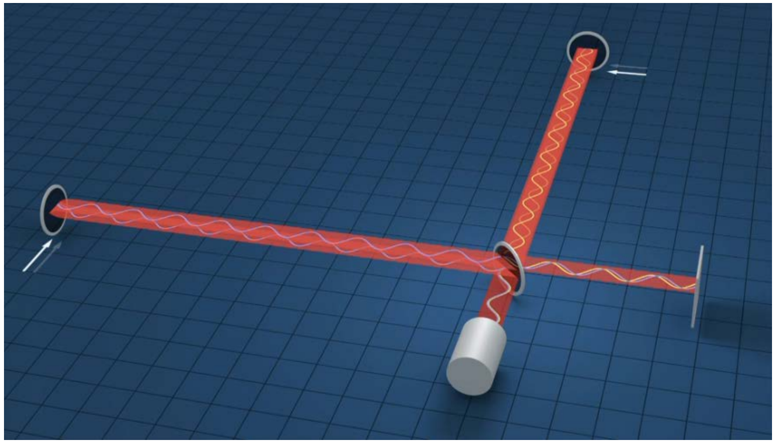
Earth-based giant interferometers: LIGO, Virgo …

Gravitational-wave interferometric detection

- Michelson interferometer
  → Compare light travel time in the arms
  - Best sensitivity around dark fringe







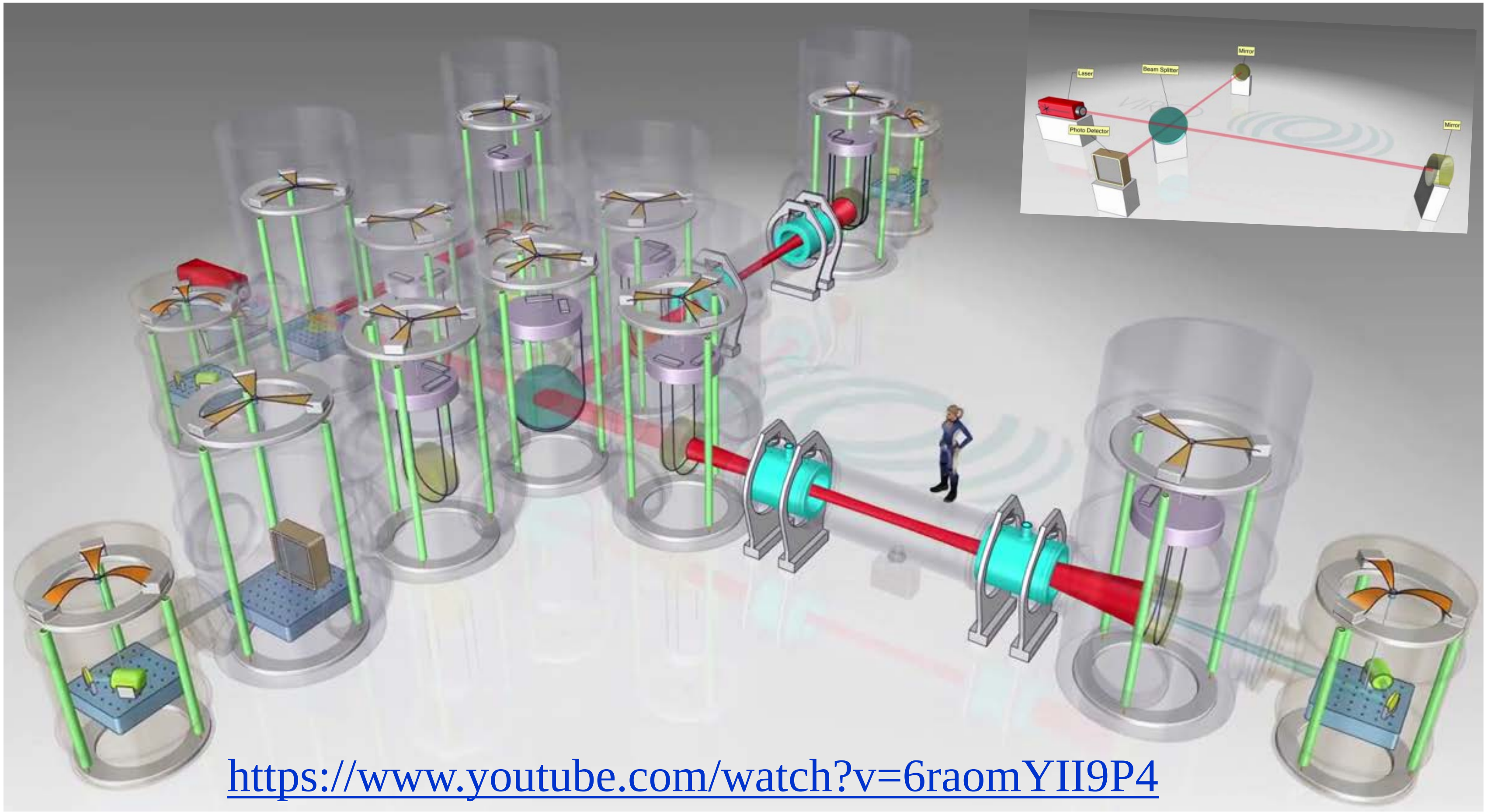
GW effect vastly exagerated

- Incident GW
  → Optical path changes
  → Output power variation

- Snapshots from https://www.ligo.caltech.edu/video/ligo20160211v6

From the concept to a real detector

- Example of Advanced Virgo – design similar for Advanced LIGO



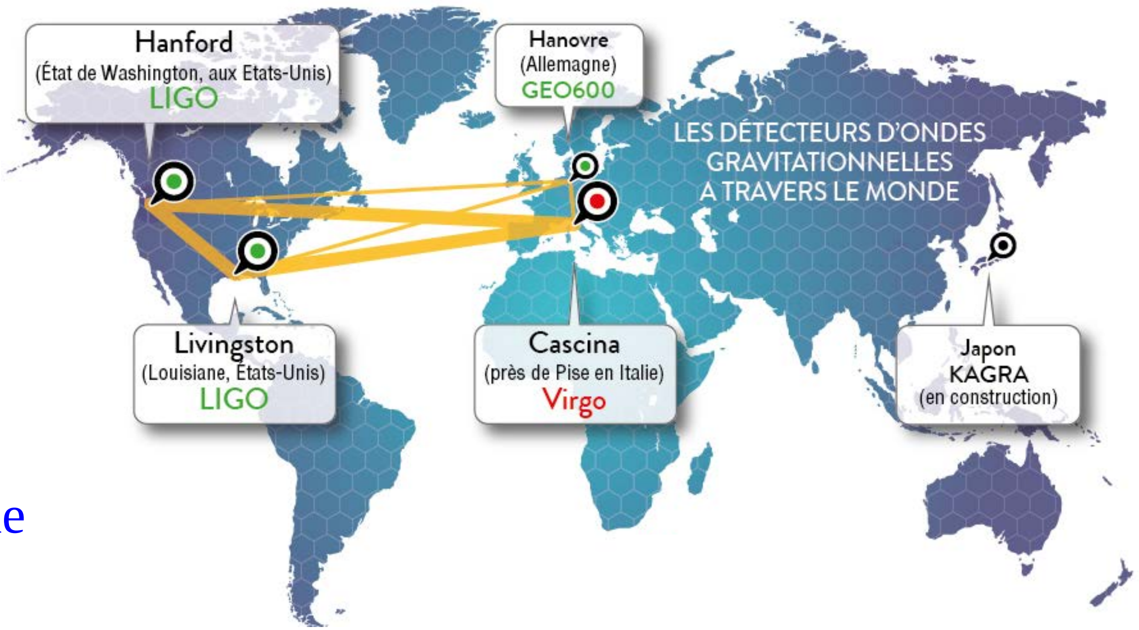
https://www.youtube.com/watch?v=6raomYII9P4

- More complex optical configuration
- Suspended mirrors and benches
- Ultra-high vacuum
- Active control
- Noise mitigation
- Km-long arms

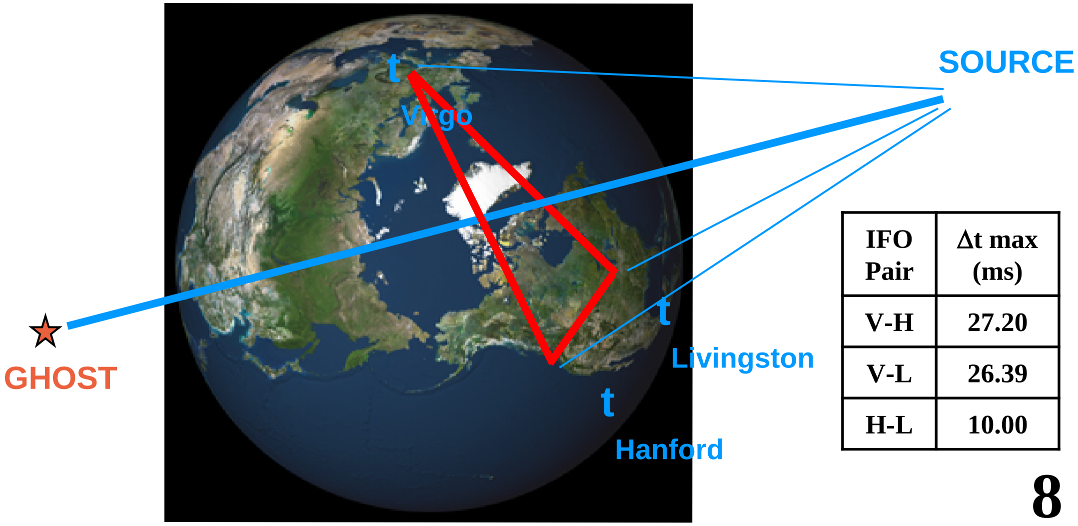
A worldwide network of detectors

- Single interferometer unable to detect GW alone
  - Difficult to separate a signal from noise confidently

→ Need to use a network of interferometers



- Agreements (MOUs) between the different projects
  - Virgo/LIGO: 2007
  - Share data, common analysis, publish together
- Non-directional detectors → non-uniform response in the sky
- Threefold detection: reconstruct source location in the sky



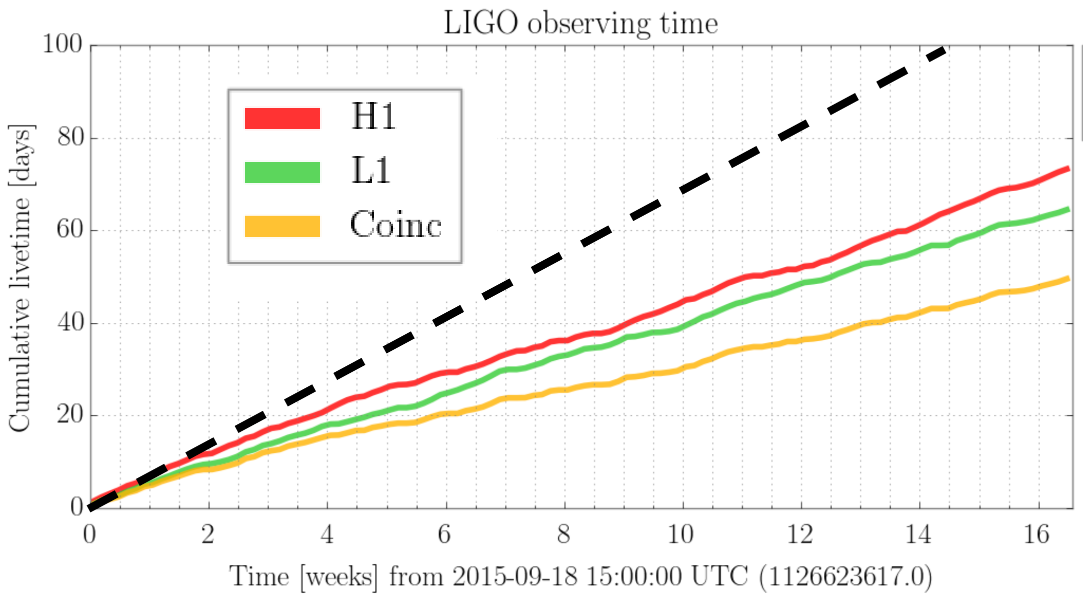
IFO Pair	Δt max (ms)
V-H	27.20
V-L	26.39
H-L	10.00

A worldwide network of detectors

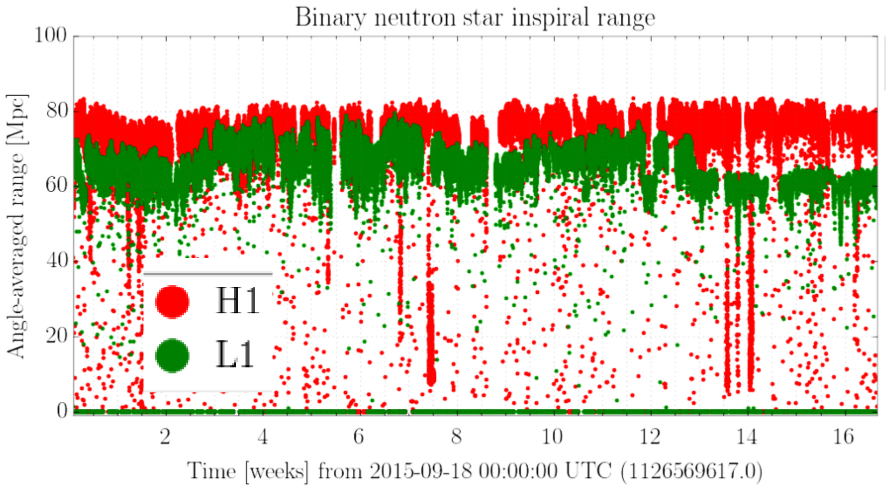
Advanced LIGO Observation Run 1

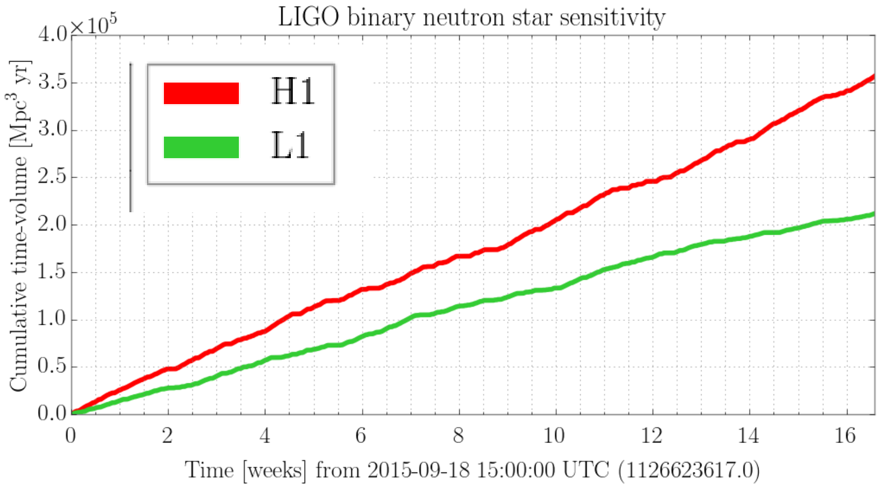
- September 2015 → January 2016
  - 2 confirmed detections: GW150914 & GW151226
  - 1 candidate: LVT151012

→ All 3 stellar mass binary black hole mergers
  - No other source detected



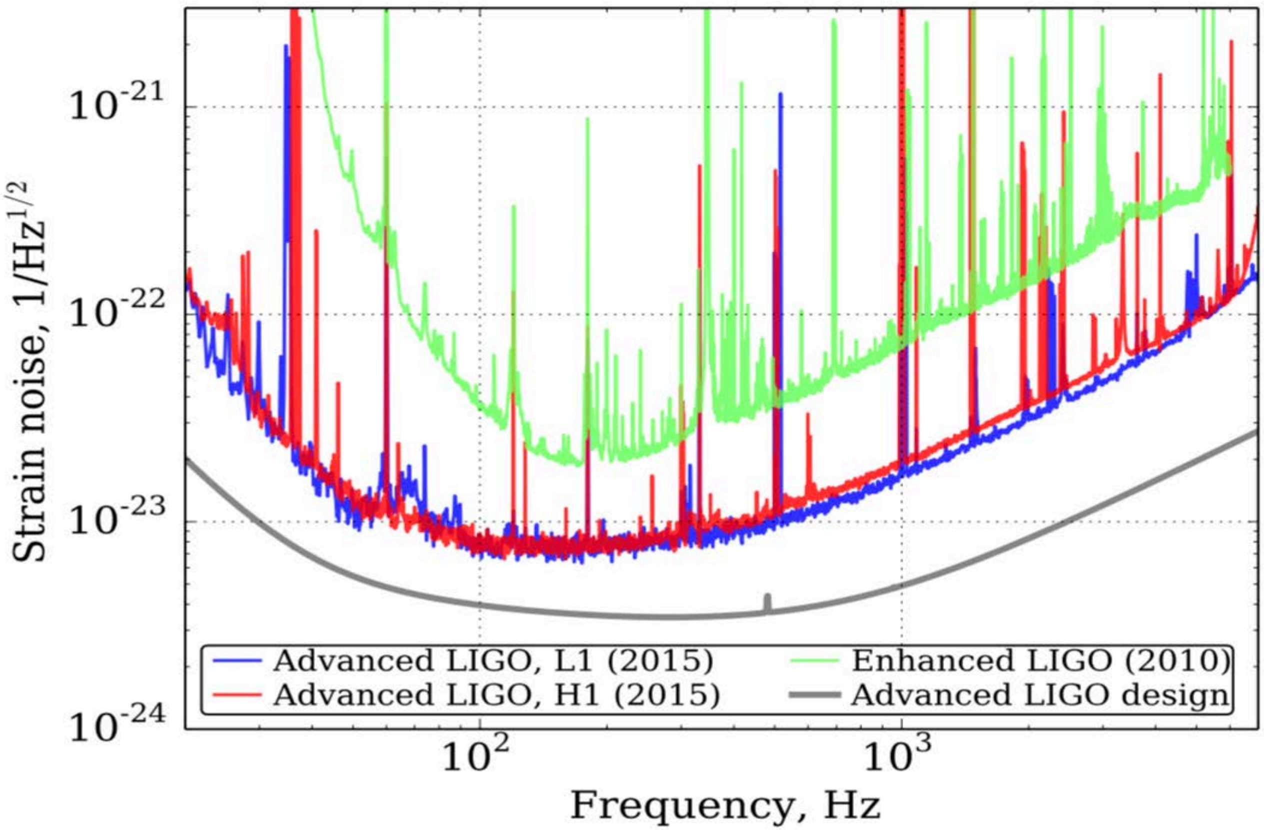
- 94% of coincidence data passed data quality cuts for physics analysis





Advanced LIGO Observation Run 1

- Typical sensitivity curves



- With respect to the 1rst generation LIGO detectors
  - Factor 3 improvement broadband
  - 2 orders of magnitude gain around 40 Hz

- Room for improvement to reach the design sensitivity
  - By the end of the decade

Advanced LIGO O1/O2 commissioning break

- 10 months: January → October 2016

- Threefold goals
  - Reduce noise
  - Improve duty cycle
  - Improve data quality

- Main activities
  - Hanford: laser power increase
  - Livingston: mitigation of scattering noise, duty cycle

→ Successful activities but limited performance improvement overall

- Engineering run in November 2016

- Official start of « Observation Run 2 » (O2) on November 30th 2016

- Ongoing until end of August 2017

Advanced LIGO Observation Run 2

- From http://www.ligo.org/news.php
  - June 2017 update on LIGO's second observing run

- 1 June 2017 – The second Advanced LIGO run began on November 30, 2016. It was suspended on May 8, 2017 for some in-vacuum commissioning activities and is resuming at the end of May. Prior to the May break, approximately 74 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%.

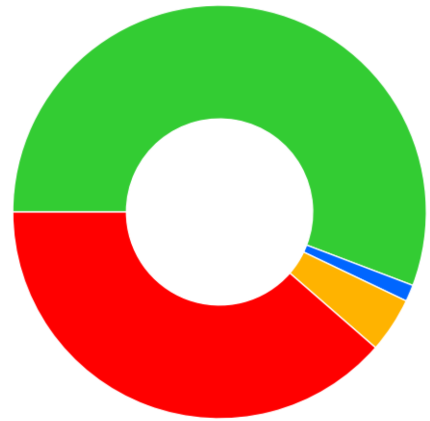
- Prior to the May commissioning break, 7 triggers, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.
  - GW170104 is one of these 7 triggers

Advanced LIGO Observation Run 2 (cont'd)

- Duty cycles
  - Single interferometers and coincidence

Hanford

- **Observing: 61.3%**
- **Ready: 2.4%**
- **Locked: 3.1%**
- **Not locked: 33.3%**



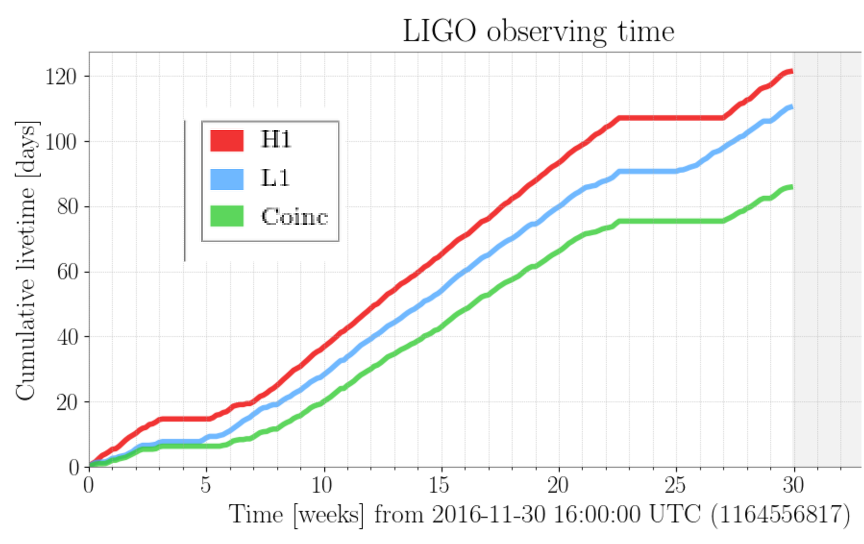
Livingston

- **Observing: 55.8%**
- **Ready: 1.3%**
- **Locked: 4.3%**
- **Not locked: 38.6%**

LIGO network

L

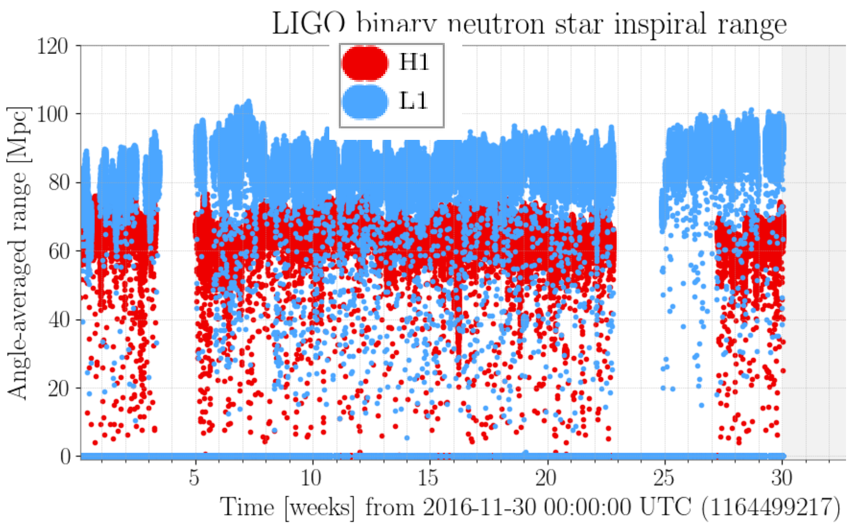
- **Double IFO: 43.4%**
- **Single IFO: 30.4%**
- **No IFO: 26.3%**



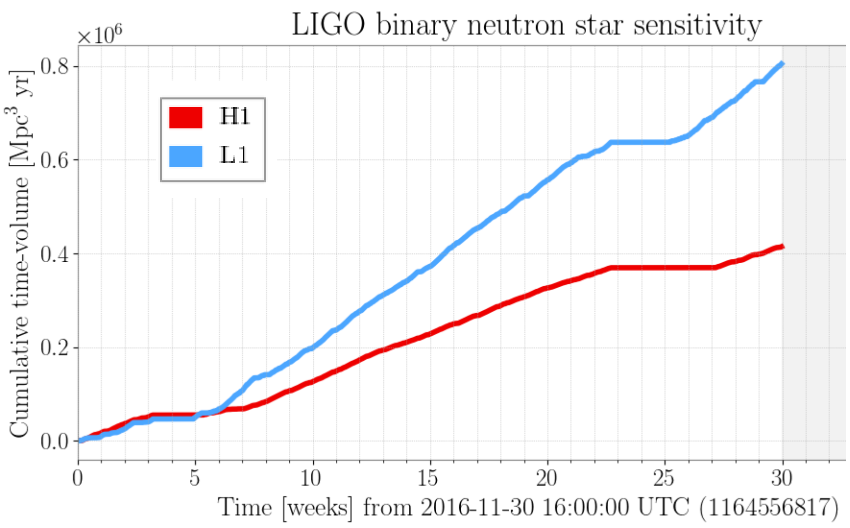
→ Values very similar to O1

Advanced LIGO Observation Run 2 (cont'd)

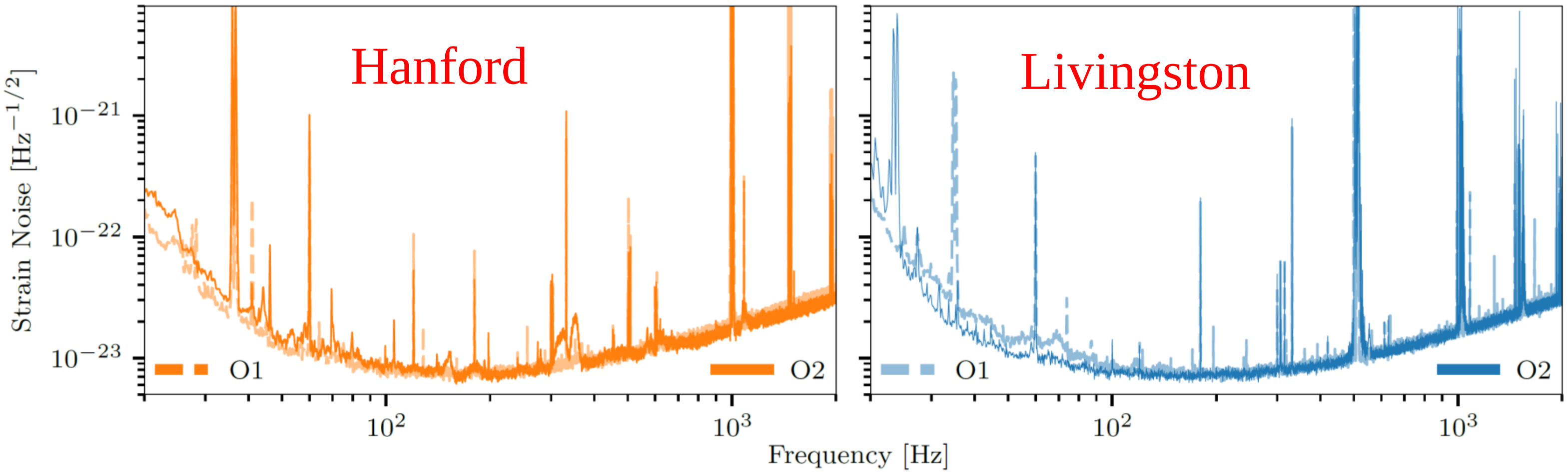
- Range



- Volume



- Sensitivity



GEO

- Detector built in Germany near Hannover
  - Arms 600 m-long

    → Reduced sensitivity
  - Test and R&D facility

    → The GEO collaboration is a member of the LIGO Scientific Collaboration

- Astrowatch mode

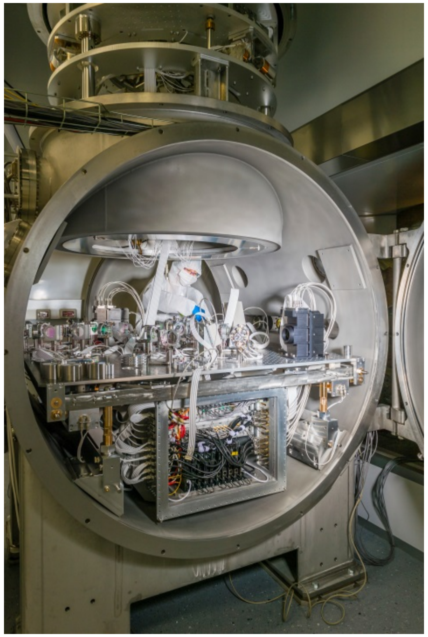
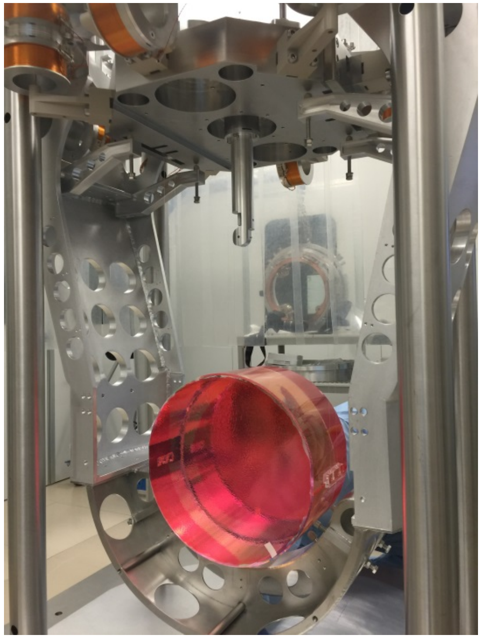
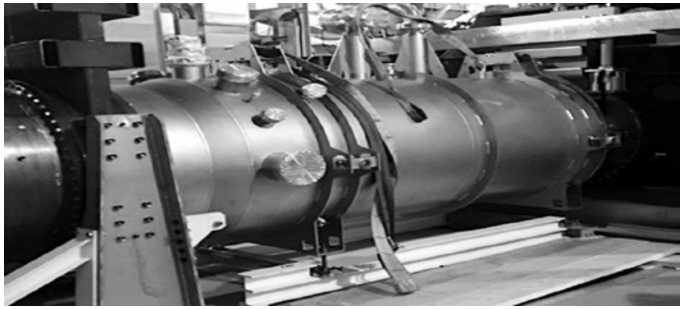
  → Don’t miss a large / nearby GW event

- Instrument science activities require a working detector
  - Science mode during nights and weekends
  - Goal: duty cycle > 70%

Advanced Virgo commissioning

- August 2016: Full interferometer in vacuum for the first time
  $\rightarrow$ Real start of commissioning phase

- A brand new detector
  - Modification of the optical cavity parameters
  - Mirrors bigger and twice heavier
  - Benches suspended and under vacuum
  - Hardware/software upgrades
  - Monolithic suspensions
  - Cryotraps

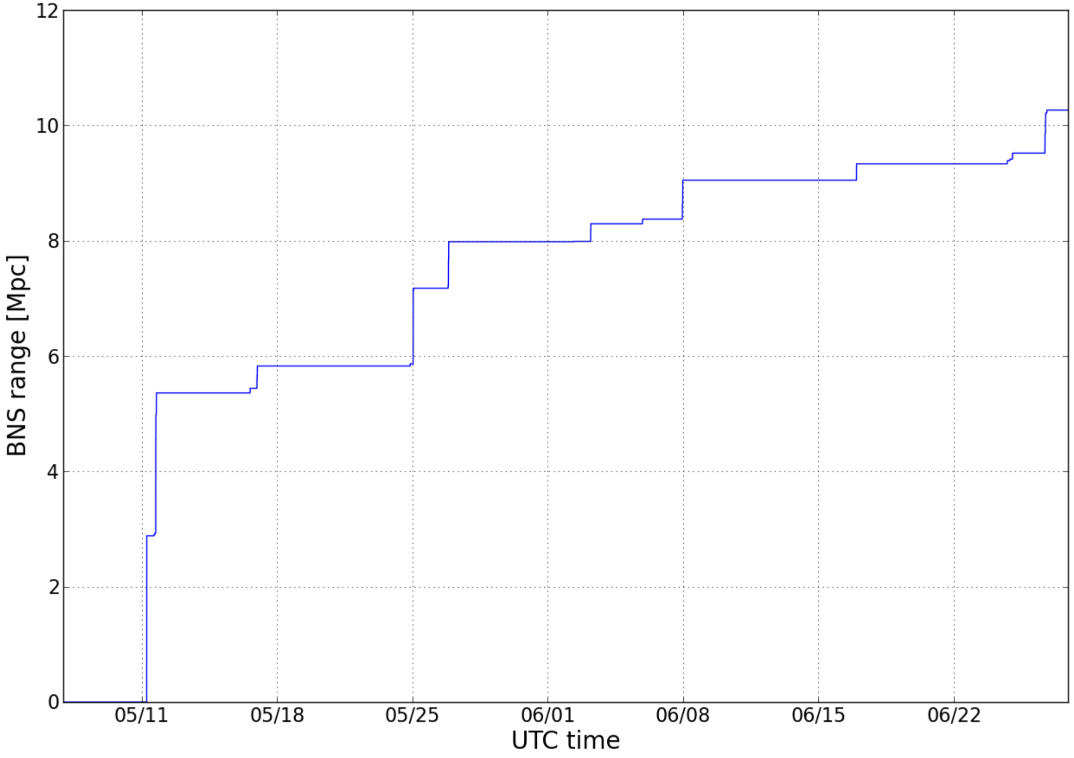

Advanced Virgo commissioning

- Long-standing issue involving the monolithic (fused silica) mirror suspensions
  - All monolithic suspensions installed under vacuum broke one after the other
    → Initially w/o any clear pattern
  - Fall: decision taken to move back to steel wires
    → Impact on target sensitivity for O2 – not a limiting factor so far
  - Significant collaboration-wide effort to understand the source of the problem
    → Vacuum contamination by dust particles accelerated during venting operation and hitting the glass wires – strong but fragile
    → Solution for O3:
      - Upgrade of the vacuum system to get rid of contamination problem: new piping, removal of scroll pumps
      - Additional safety: fiber guards added on the payload

- Milestones achieved in the following weeks
  → First 1-hour long control of the full detector in March 2017

Advanced Virgo commissioning (cont’d)

- Evolution of the best binary neutron star (BNS) range [in Mpc]

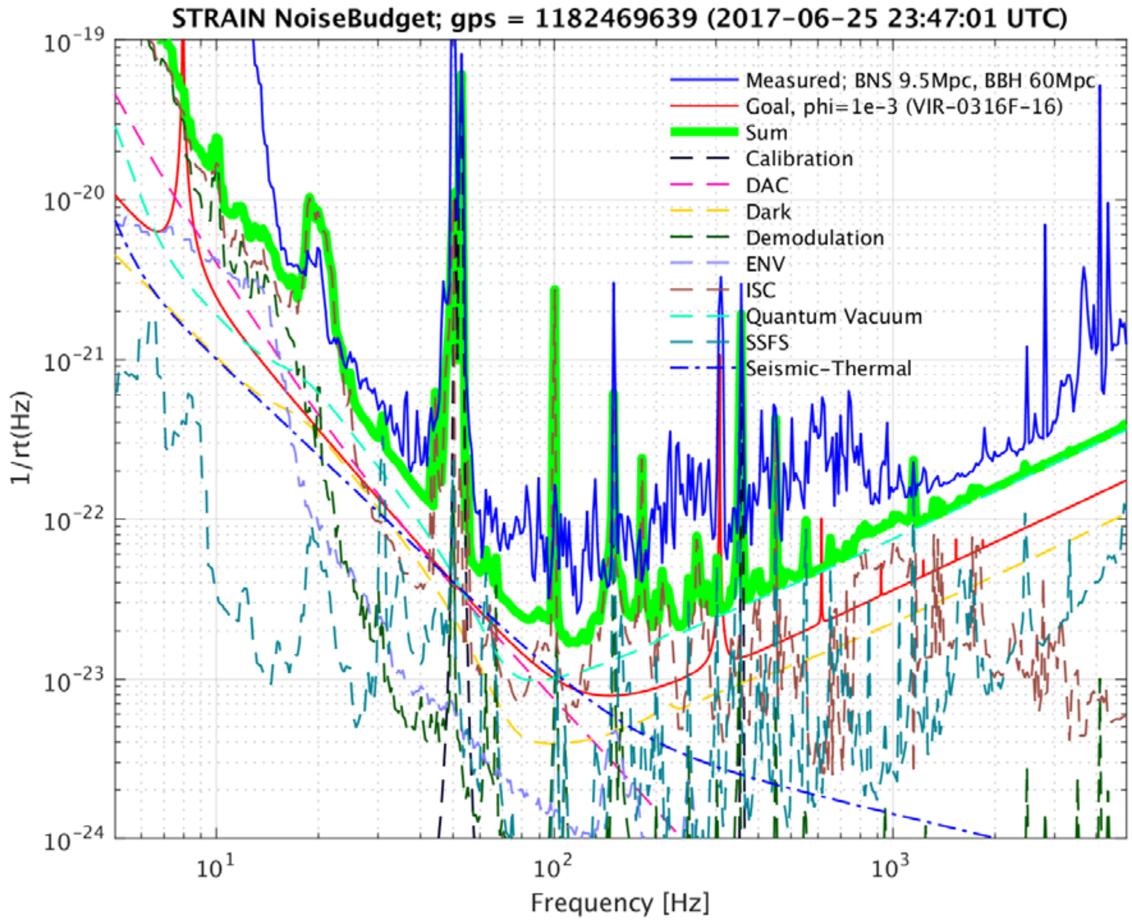


- Took less than 4 months to break the 10 Mpc level – about 5 years for 1rst generation
- Step-wise function
  - Progress is not smooth!

  → Noise hunting phase

Advanced Virgo commissioning (cont'd)

- Noise budget
  - Model all identified sources of noise
  - Compare noise prediction with measurements in the whole frequency range



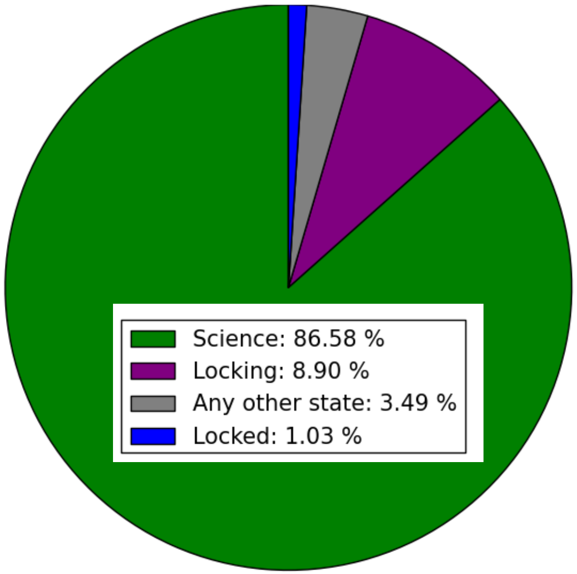
Prediction

Measurement

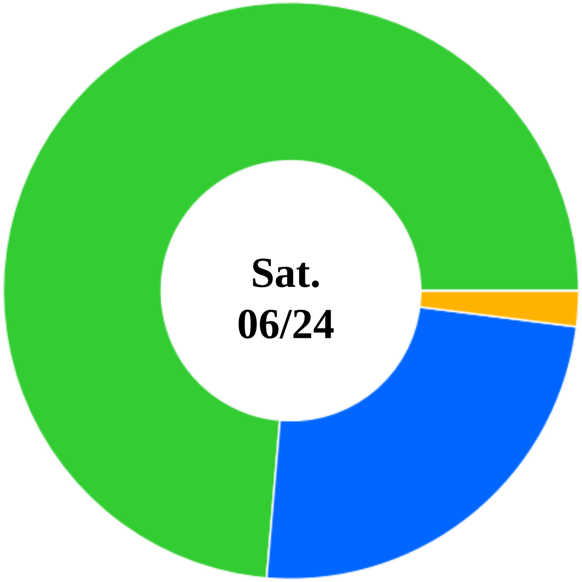
Goal

Towards a 3-advanced detector network

- Common engineering runs with LIGO in May and June
  - During weekends
    → Virgo commissioning in between
  - Maximize data taking efficiency
    → Only fix problems if any
  → High duty cycle after first few hours of tuning
  - Test alert system in case of GW candidate detection
  - Test data analysis pipelines



Advanced Virgo
Sat. 06/24 + Sun. 06/25



LIGO-Virgo network duty factor

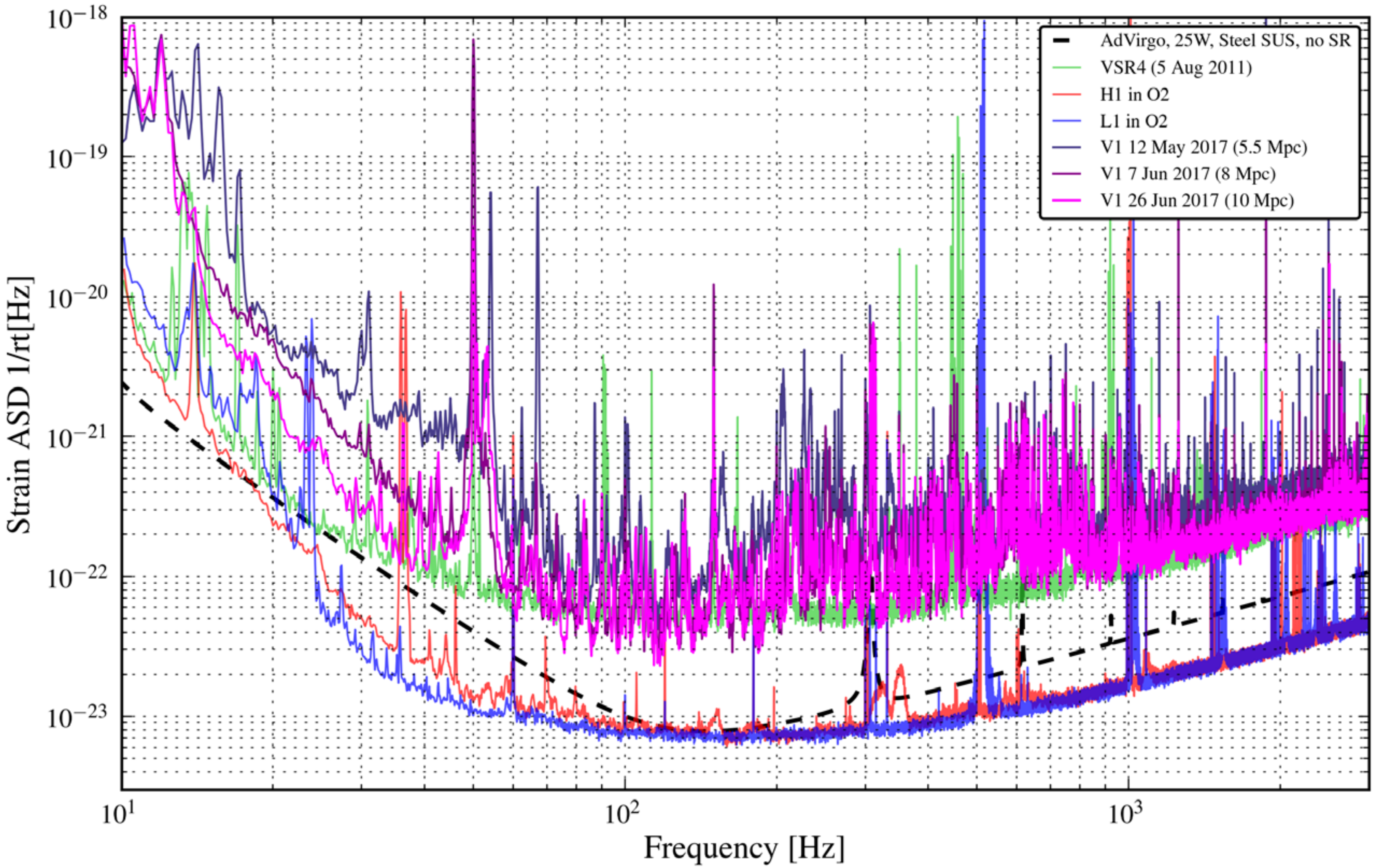
[1182297618-1182384018]

Triple interferometer [73.7%]
Double interferometer [24.4%]
Single interferometer [2.0%]
No interferometer [0.0%]

98%

Towards a 3-advanced detector network

- Sensitivity curves



Upgrades between O2 and O3

- Duration: about a calendar year
  - Start right after O2
  - Could be extended if needed

  → Significant improvement of all detector performances is expected

- LIGO
  - Further reduce scattered light
  - Increase laser power
  - Squeezing activities

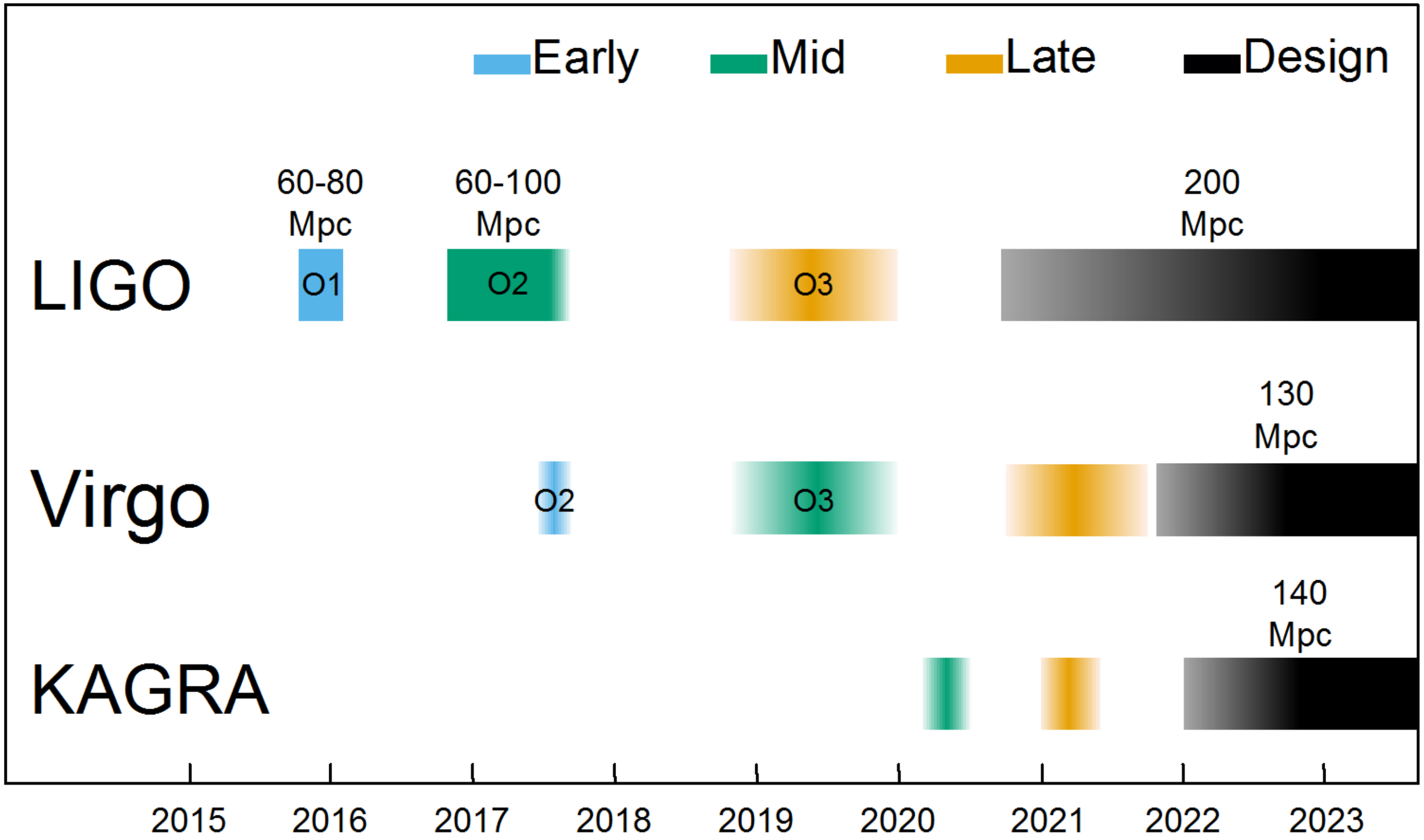
- Virgo
  - Re-install monolithic (fused silica) suspensions
  - Install squeezer provided by GEO (Albert Einstein Institute)
  - Increase laser power

→ For both LIGO and Virgo, all upgrades should be completed early enough to allow a significant commissioning phase before starting O3

- For Virgo, this means delaying the addition of an additional mirror (« Signal Recycling ») after O3

O3 and beyond

- Observing scenario
  - Including KAGRA
    → Being built at Kamiokande (Japan)



Outlook

- LIGO
  - O1: a successful data taking period
  - O2: similar performances
- Virgo
  - Detector fully controlled
  - High duty cycle
  - Sensitivity not good enough yet
    → « Noise hunting » activities in progress
  - Goal is to join O2 asap
- Long break between O2 and O3 for all detectors
  - To improve signficantly their sensitivities
- Rate of merging black hole binary system still poorly known
  - Three events only!
- KAGRA (Japan) to join the network by 2020
- Possibly a 5th detector (INDIGO, India) to be installed in about a decade or so
- ESA (/NASA) LISA mission on the right track for a launch in 2034

When is Virgo going to join O2?

- Virgo targets a sensitivity in excess of 20 Mpc in terms of BNS range
  - Twice the current range

- Several important commissioning actions planned for the next weeks
  - Will likely lead to a sensitivity improvement

→ Virgo is in close and continuous discussion with LIGO