The LIGO-Virgo Observation Run 3 (O3): April 2019 – March 2020

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On behalf of the Virgo Collaboration and the LIGO Scientific Collaboration

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LIGO Scientific Collaboration

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VIRGO

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Outline

- Detecting gravitational waves with the global LIGO-Virgo network

- LIGO-Virgo Observing Runs

- The third Observing Run: O3
  - Schedule
  - Performance

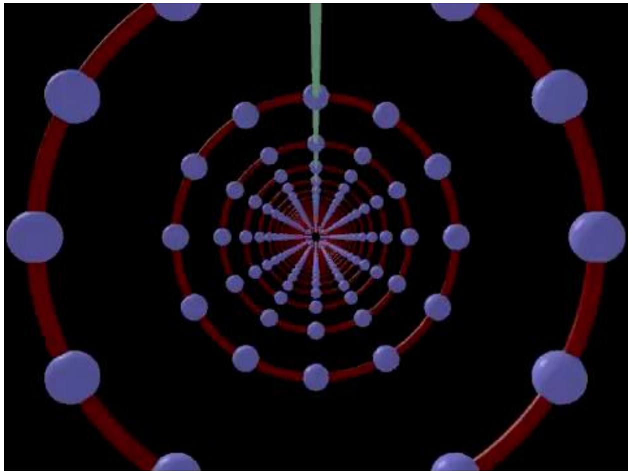
- Public alerts
  - Motivation and dataflow
  - O3 Summary

- First O3 published detections
  - GW190425, GW1901412 & GW190814

- Outlook
  - More O3 publications to come
  - The path to O4: the « Advanced Plus » detectors

Gravitational waves (GW) in a nutshell

- One of the first predictions of general relativity (GR, 1916)
  - Accelerated masses induce perturbations of the fabric of the spacetime, propagating at the speed of light – ‘speed of gravity’



- Traceless and transverse (tensor) waves
  - 2 polarizations in GR: « + » and « × »
  - Quadrupolar radiation
    → Deviation from axisymmetry to emit GW

- GW strain h
  - Dimensionless, scales like 1/distance

- Detectors directly sensitive to h
  → Small sensitivity gains can lead to large improvements in event rate

- Rough classification
  - Signal duration
  - Frequency range

  } Detectable by the instruments
  - Known/unknown waveform
  - Any/no counterpart (electromagnetic spectrum, neutrinos, etc.) expected

Example (*): the Advanced Virgo detector

- Suspended, power-recycled Michelson interferometer
  with 3-km long Fabry-Perot cavities in the arms

- Working point
  - Michelson on the dark fringe
  - All Fabry-Perot cavities resonant

  → Feedback control systems acting on
  the mirror positions and on the laser

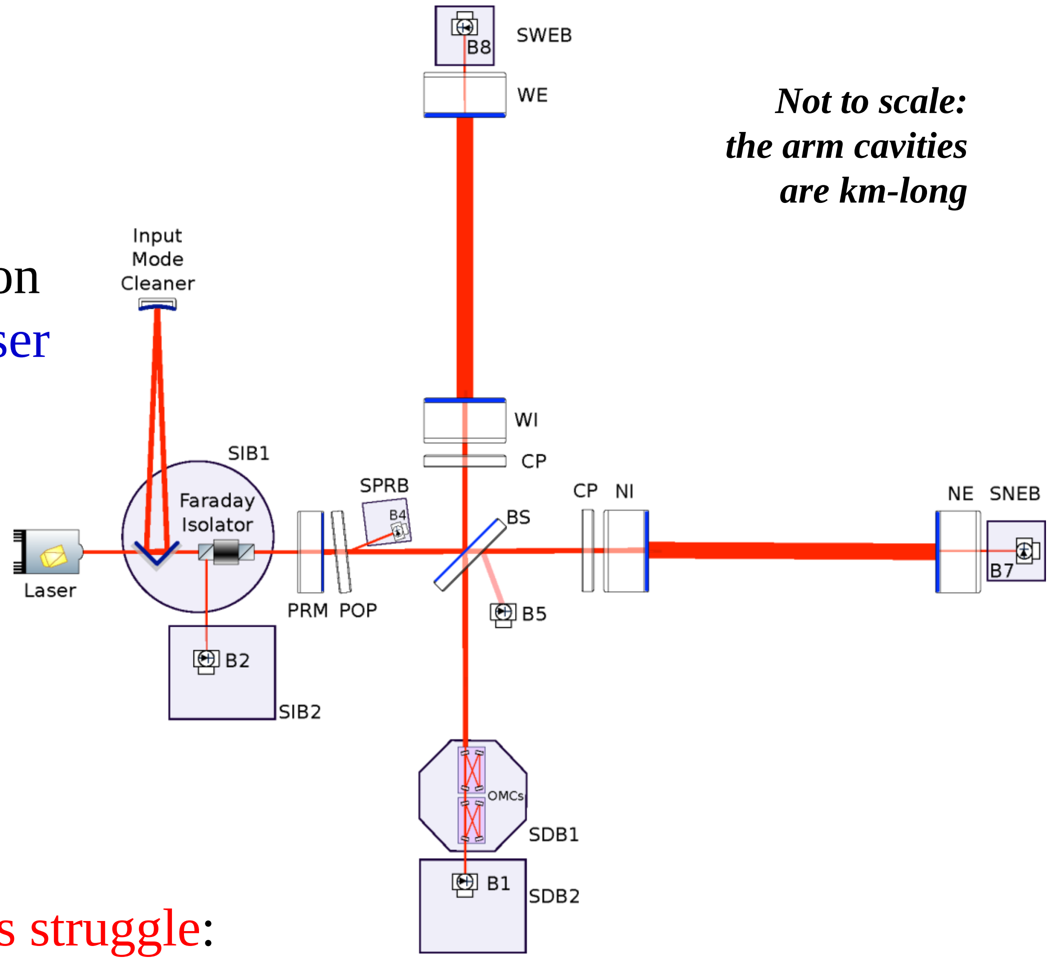
- GW passing through
  - Differential effect on
    the arm optical paths

  → Change of interference condition
  at the detector output

  → Variation of the detected power

- Sensitivity limited by noises
  - Fundamental
  - Technical
  - Environmental

  } Continuous struggle: design, improvement, noise hunting, mitigation



Not to scale: the arm cavities are km-long

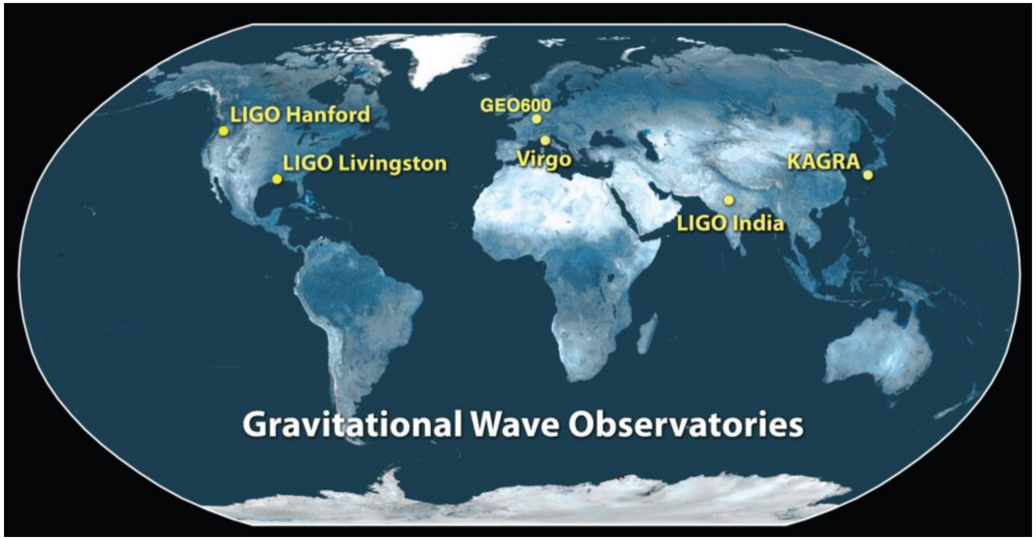
(*) *LIGO detectors are conceptually the same*

The LIGO-Virgo global network

- A single interferometer is not enough to detect GW with certainty
  - Difficult to separate confidently a potential signal from noise

→ Need to use a network of interferometers

- 2nd generation: « Advanced »
  - LIGO Hanford: 2015
  - LIGO Livingston: 2015
  - Virgo: 2017
- GEO-600: « Astrowatch » + R&D
- KAGRA: 2020+
- LIGO-India: coming decade

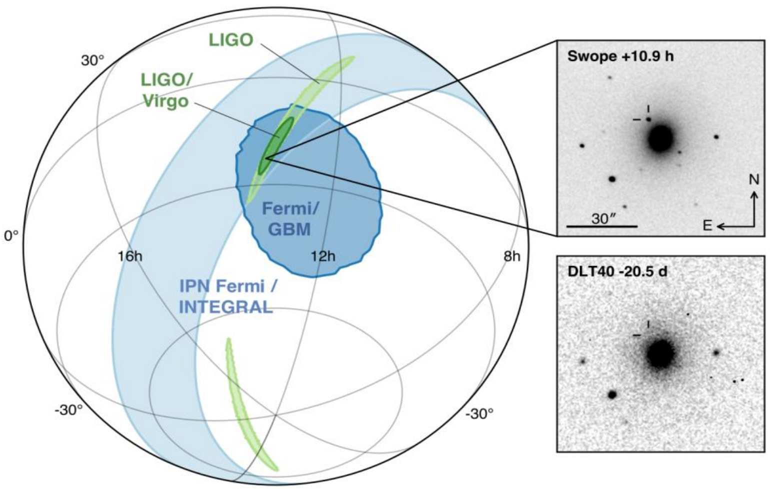


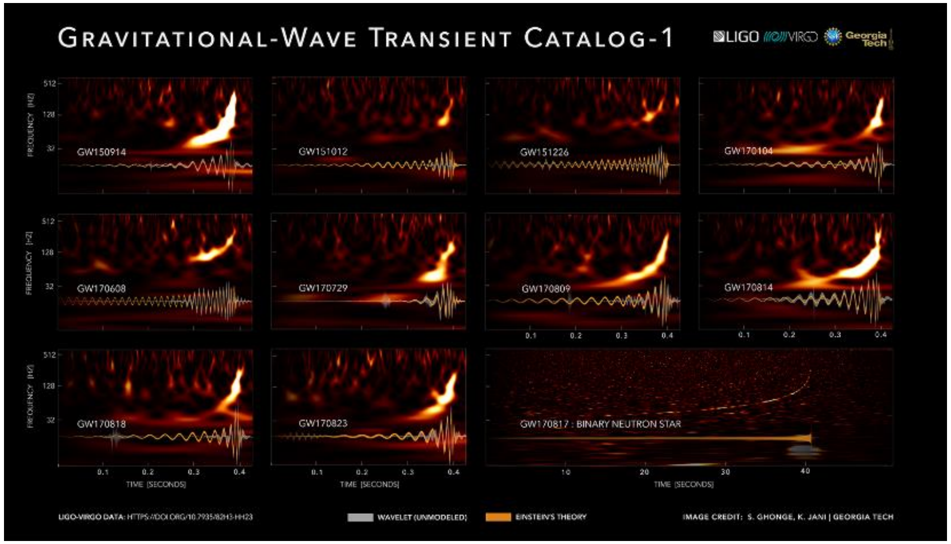
- Agreements (MOUs) between the different projects – Virgo/LIGO: since 2007
  - Share data, common analysis, publish together Virgo-LIGO/KAGRA: 2019
- Interferometers are non-directional detectors
  - Sensitive to a significant fraction of the sky but non-uniform response
  - Time delays for the signal arrival in the different instruments: O(few ms)

    → Threefold detection: reconstruct source location in the sky

Observation runs O1 and O2

- O1: September 2015 – January 2016
  - LIGO only
  - GW150914: first direct detection of GWs – binary black hole merger





- O2: December 2016 – August 2017
  - First LIGO only, Virgo from August 1st onwards
  - GW170814: first triple-detector GW detection
  - GW170817: first binary neutron star merger detection
    birth of multi-messenger astronomy with GW
  - GWTC-1: first LIGO-Virgo catalog of transient GW sources

Towards the Observation Run 3: O3

- End of O2: August 25, 2017
- Beginning of O3: April 1, 2019

→ In between: 19 months, with alternating phases of
  - Commissioning
  - Upgrade
  - Noise hunting
  - Engineering run

} Joint LIGO-Virgo planning
→ Common goals: improve sensitivity & duty cycle

- Example of Virgo
  - Mirror suspension wires upgraded + vacuum improvement
  - Increase of the laser power injected in the interferometer
  - « Squeezer » to lower shot noise limiting above a few hundreds Hz

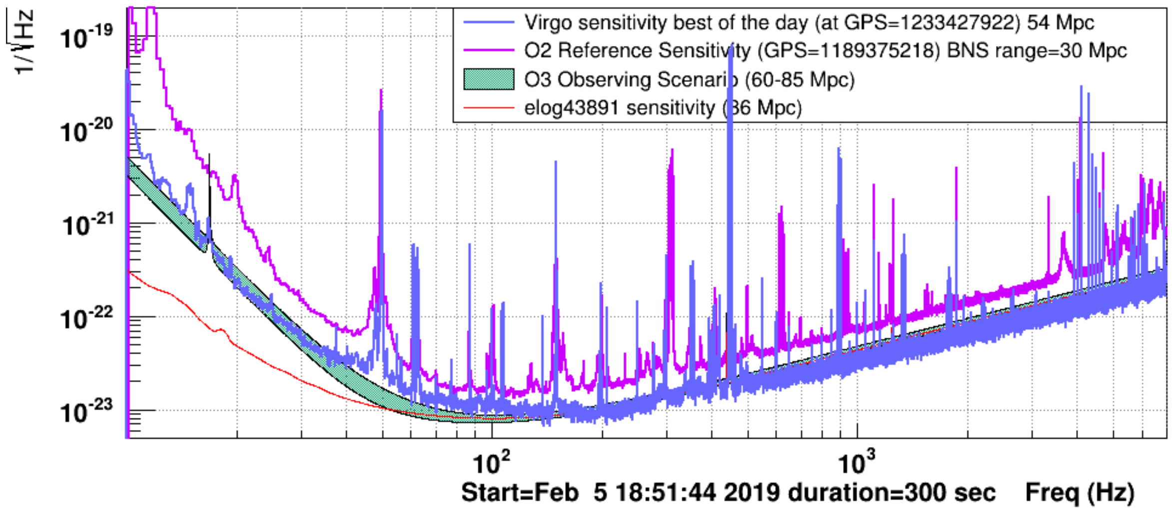
  \+ software improvements & better understanding of the upgraded instrument

  → Sensitivity improved by roughly a factor 2

- Large improvements on the LIGO side as well
  - See O3 performance in later slides

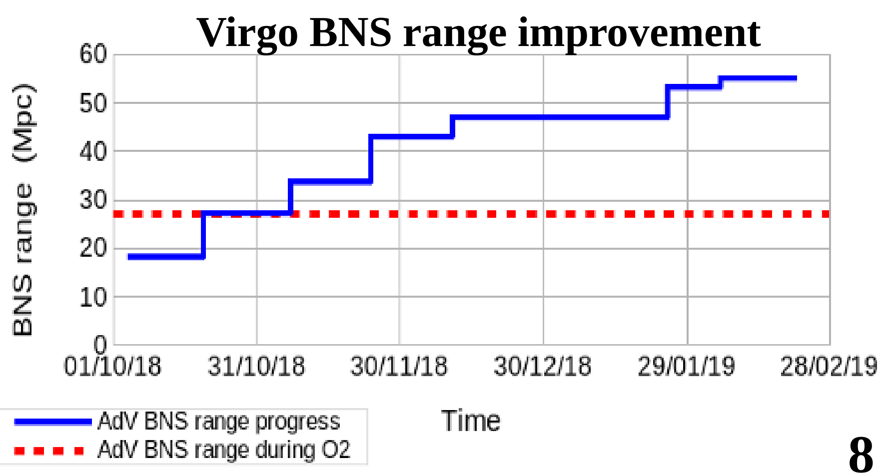
Detector sensitivity and BNS range

- Sensitivity: noise amplitude spectrum density [Unit: 1/√Hz] vs. frequency
  - Complex curve full of features, summing up contributions from many noise sources



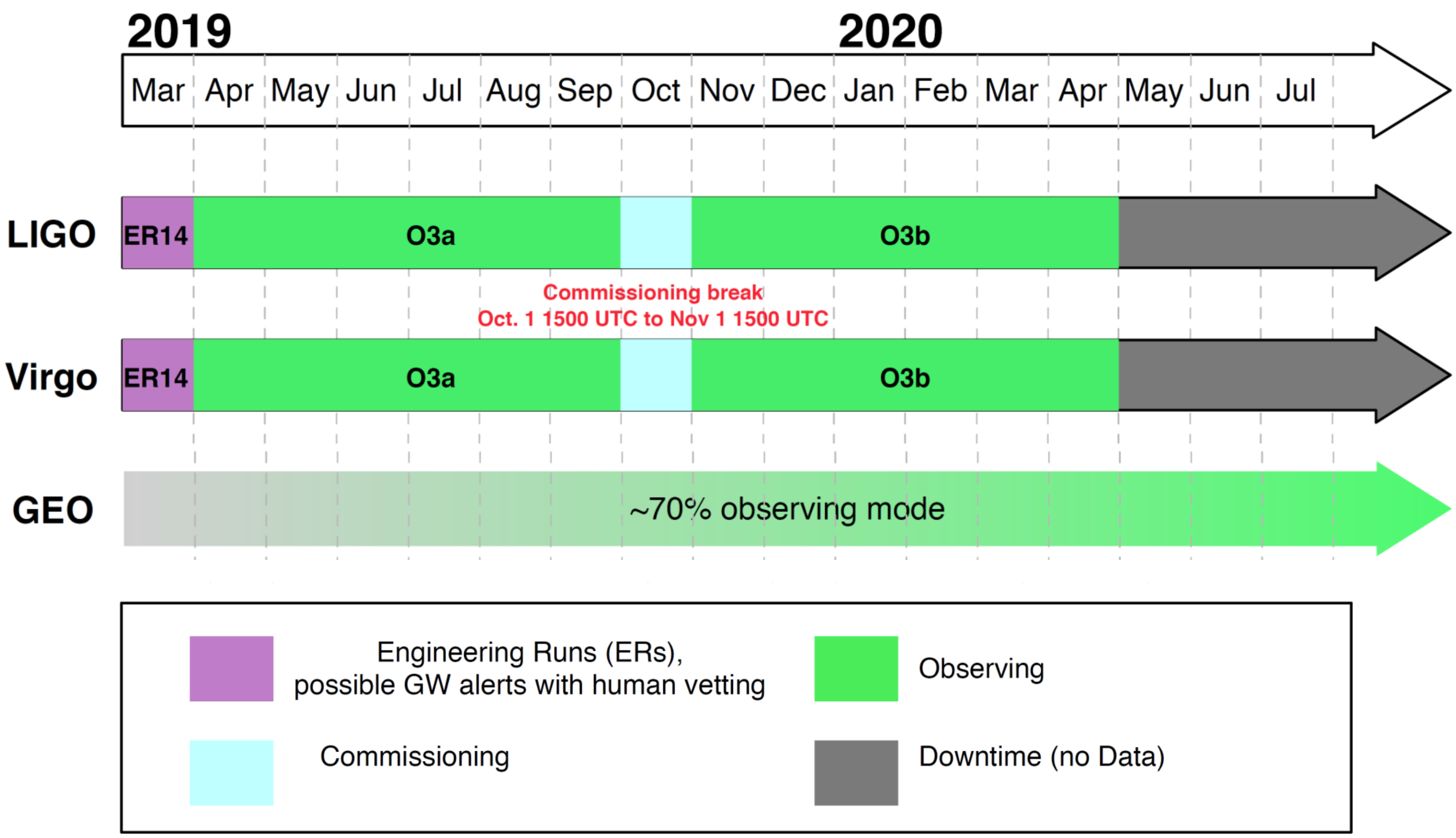
→ Useful (simplifying) figure of merit:
the BNS range

- Averaged (sky and binary inclination) distance [in Mpc] at which a « standard » merging binary neutron star system can be detected (signal-to-noise ratio of 8)



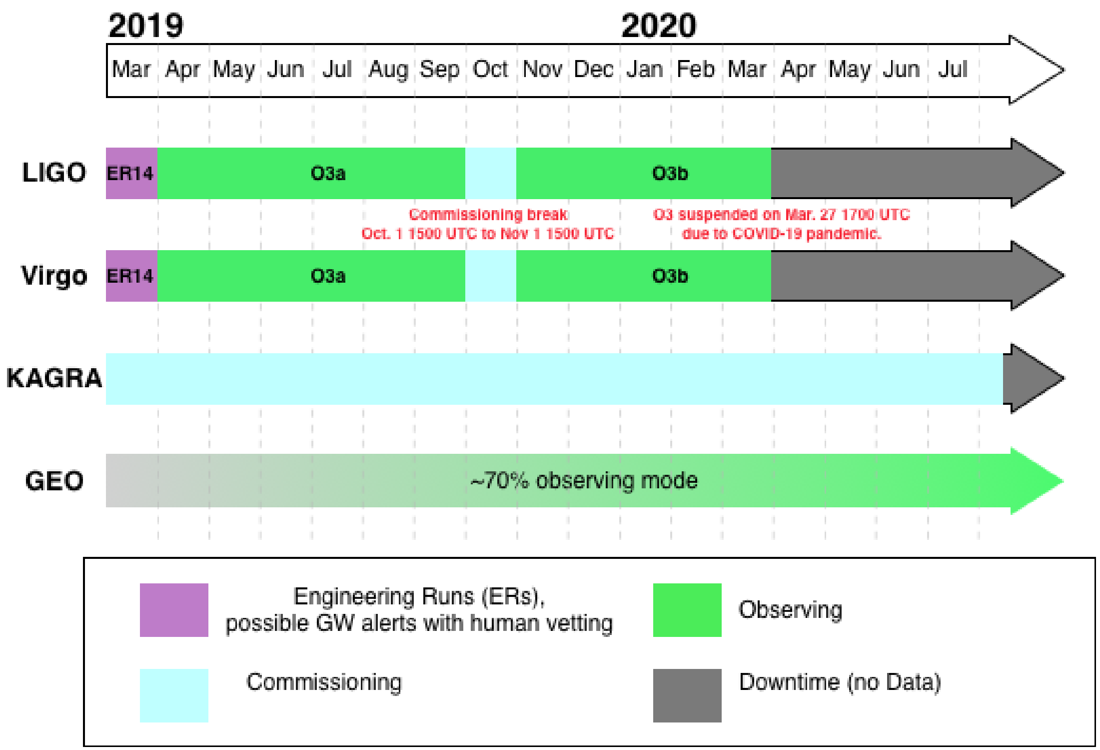
The O3 schedule

- Early plan
  - 12 months of data taking: 2019/04 → 2020/04
  - 2 chunks of 6 months (O3a and O3b), with a 1-month commissioning break (2019/10) in between



The O3 schedule

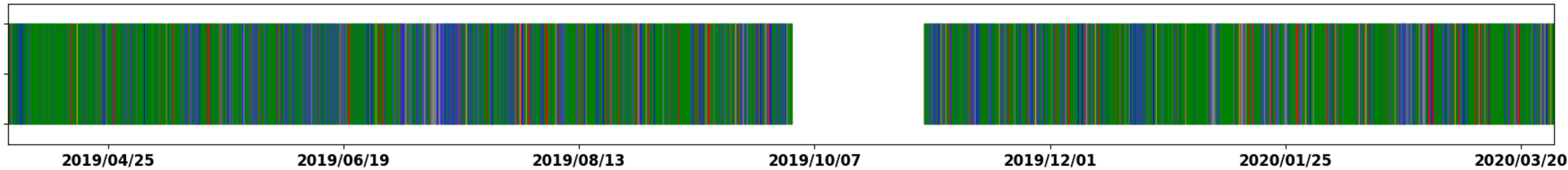
- Then came the pandemic…
  - O3 run globally suspended on March 27
  - Later decision not to start an « O3c » and to focus on the O3-O4 upgrades

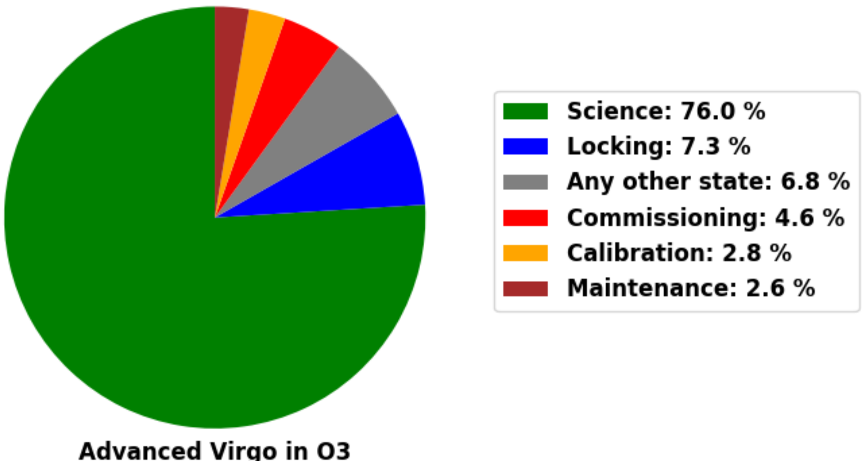


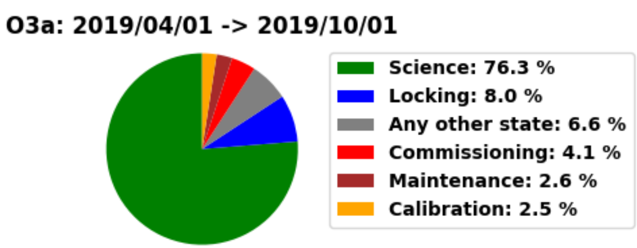
- 2 weeks (7-21 April) of joint GEO-KAGRA data taking: run « O3GK »
  - KAGRA switched from commissioning to data taking end of February
    → Sensitivity still low but improving

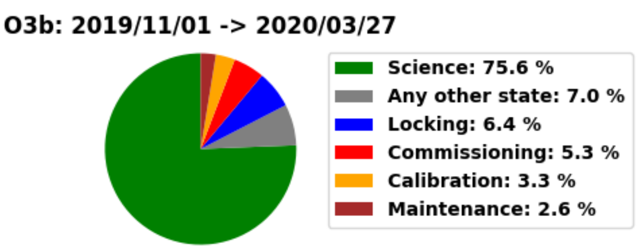
O3 performance: duty cycle

- Single detector: example of Virgo
  - Science ↔ good data used for physics analysis
    - Online data quality; fraction of a percent removed offline









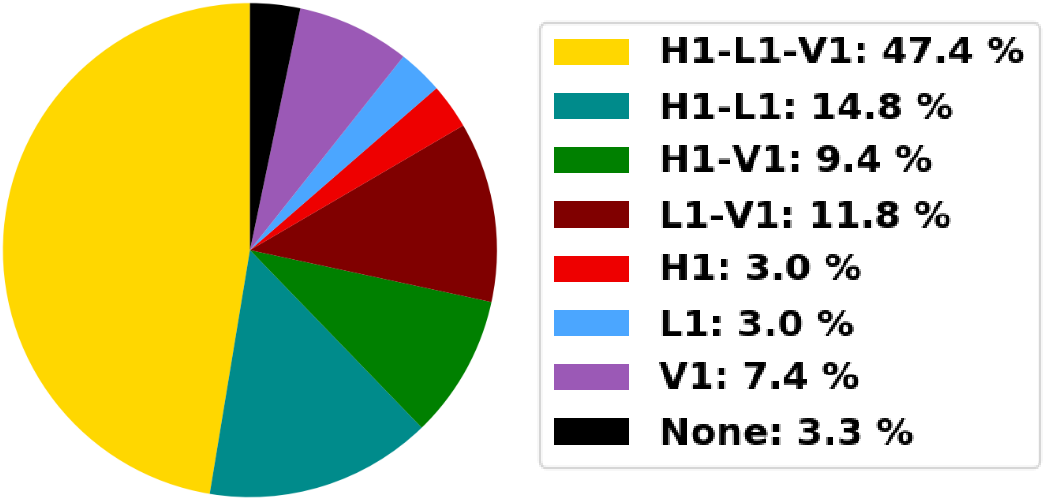
→ More information: https://www.virgo-gw.eu/status.html

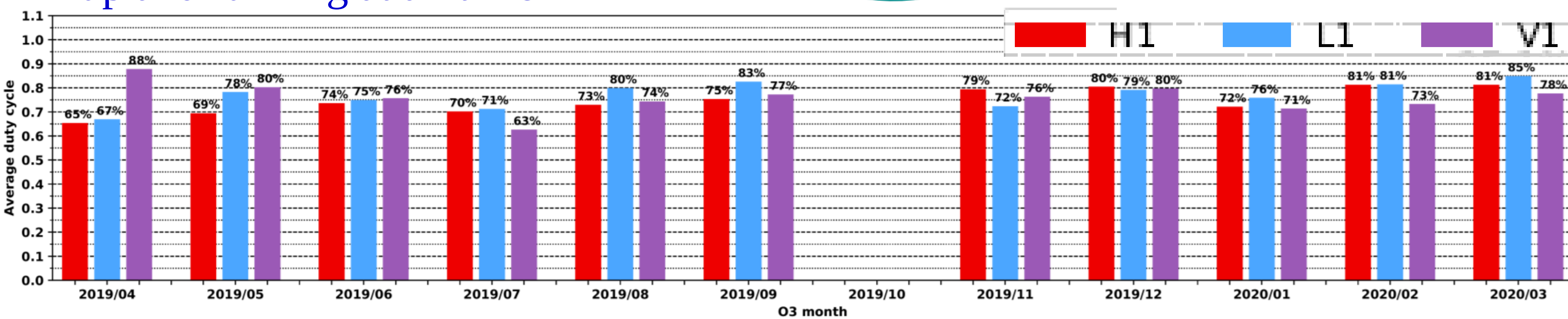
O3 performance: duty cycle

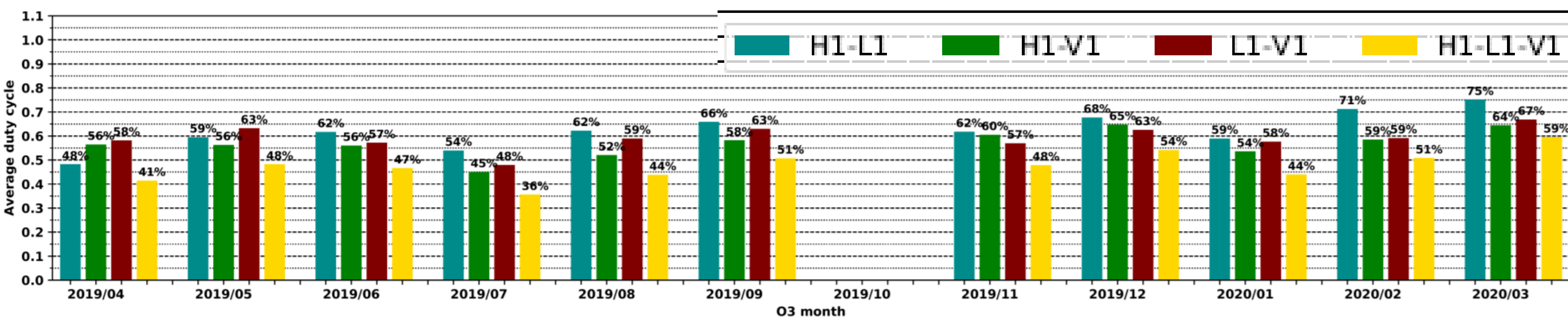
- 3-Detector network

→ Maximize triple coincindent observation
  - Maintenance / time difference

→ Ensure at least one detector up and running at all time

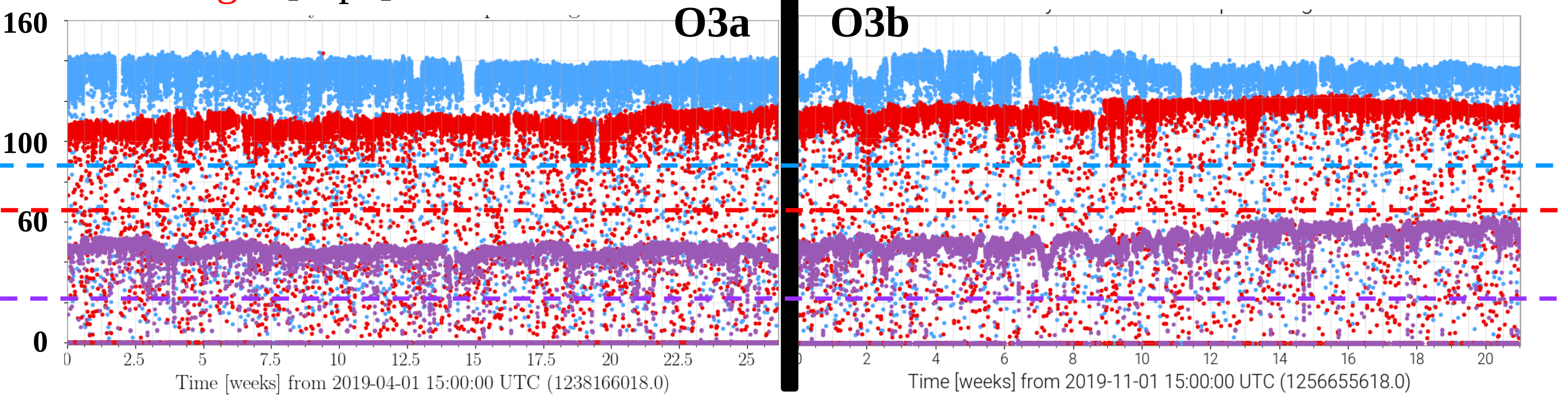






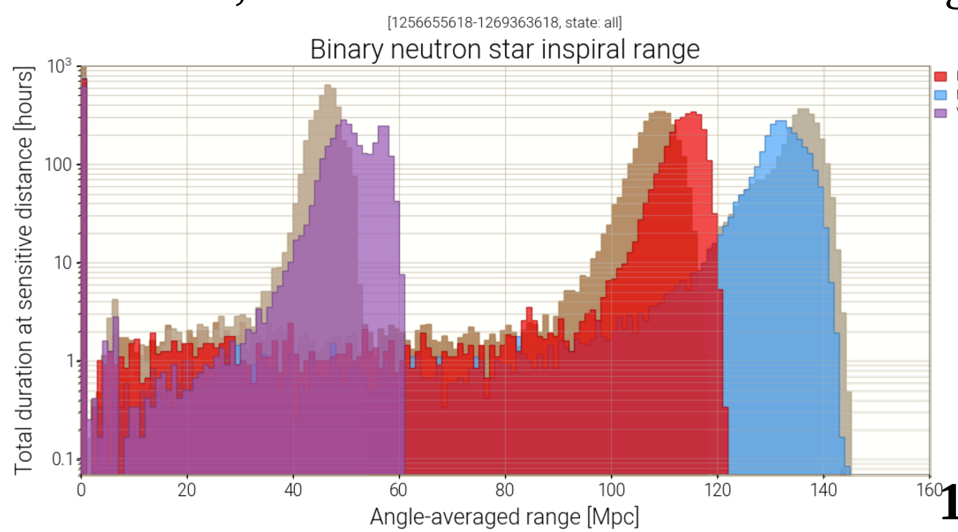
O3 performance: sensitivity

- BNS ranges [Mpc]



→ Dashed lines show the corresponding O2-averaged BNS ranges

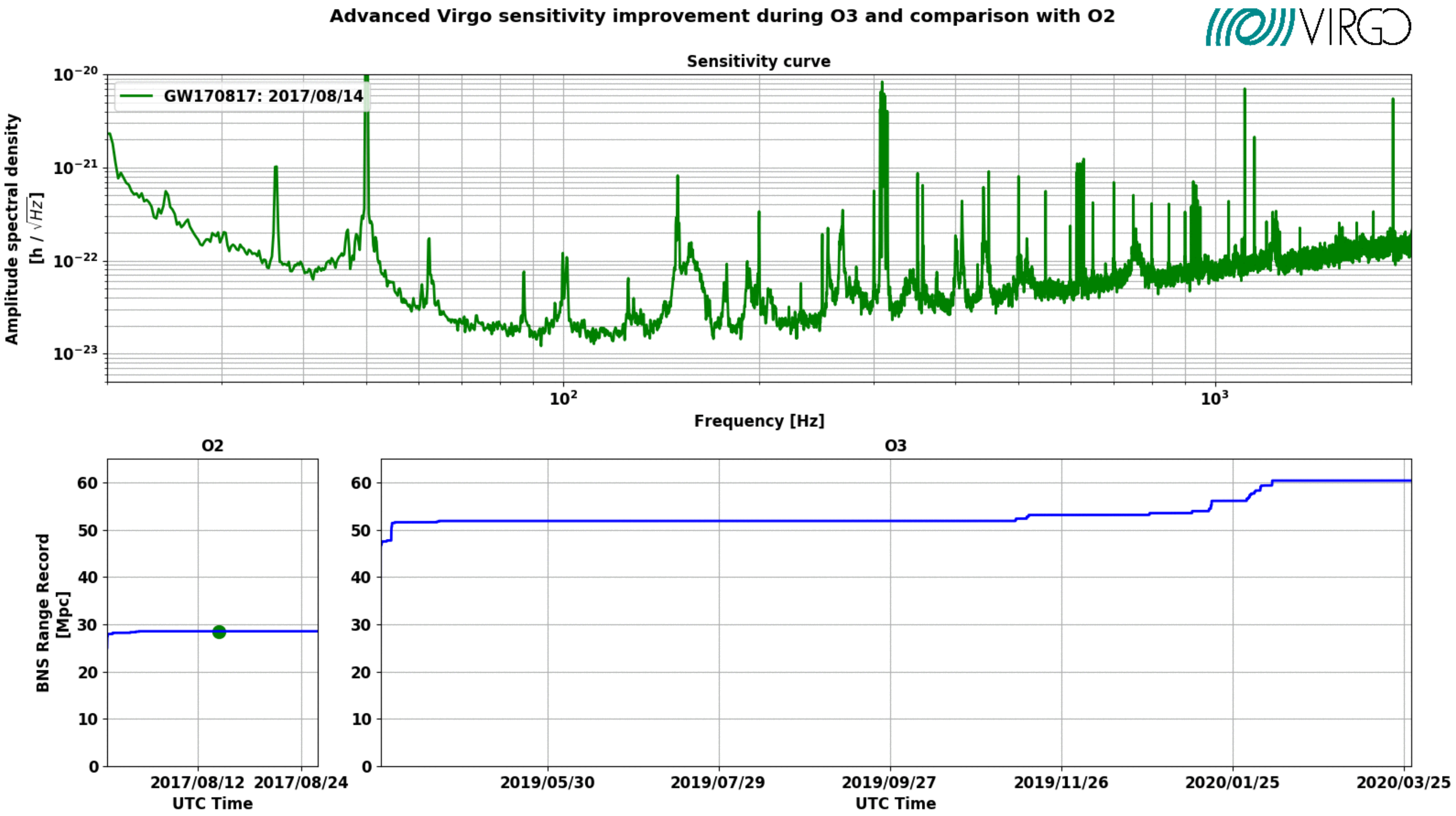
- LIGO Livingston is the most sensitive detector, ahead of LIGO Hanford and Virgo



- Significant progress during the commissioning break for LIGO Hanford and Virgo
  - Point absorbers on optics for LIGO Livingston
    → Part of the lost BNS range recovered by tuning instrument

O3 performance: sensitivity

- O2-O3 sensitivity improvement for Virgo

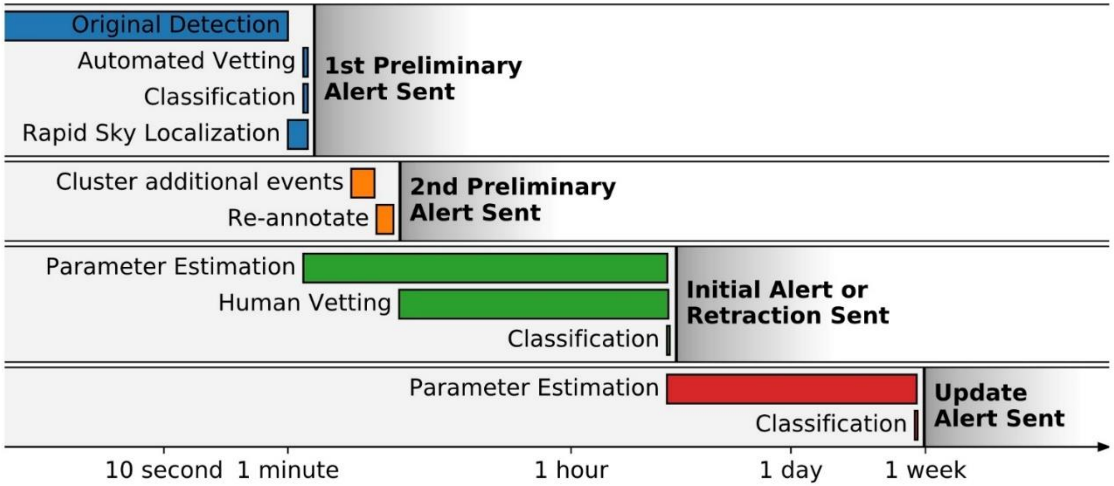


O3 public alerts

- LIGO-Virgo data are jointly analyzed in real-time
  - Modelled (compact binary coalescences) and unmodelled searches (« bursts »)

  → Detect and localize potential transient GW signals
- When a significant-enough candidate is found
  - False-alarm rate lower than 1 / O(few months)

→ Alert sent to astronomers in order to search for counterparts
  - Through NASA's Gamma-ray Coordinates Network (GCN)



- Expert vetting

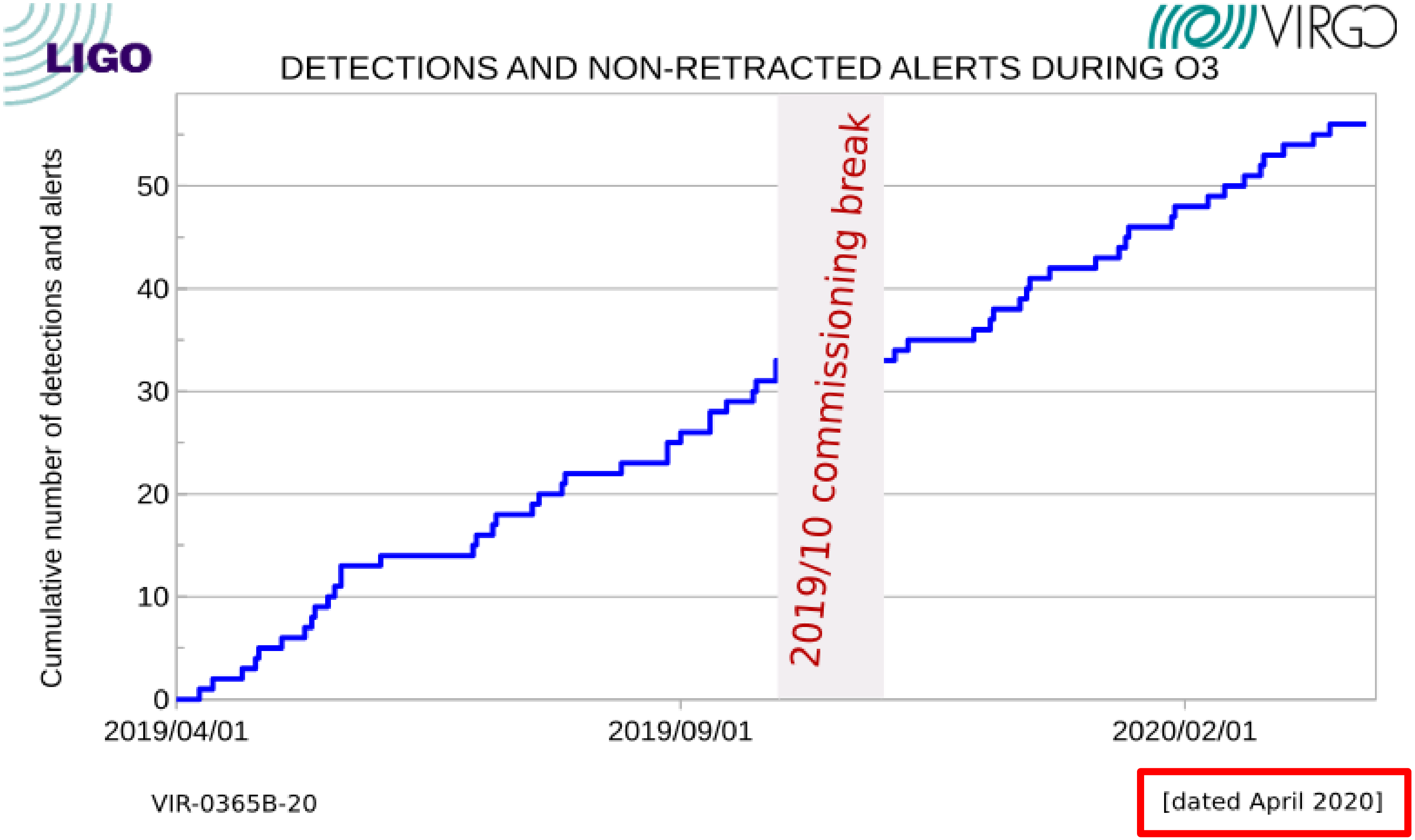
  → Public alerts can be retracted

- More information: https://emfollow.docs.ligo.org/userguide

O3 public alerts

- 80 public alerts in O3
  - 24 retracted

  → 56 not retracted



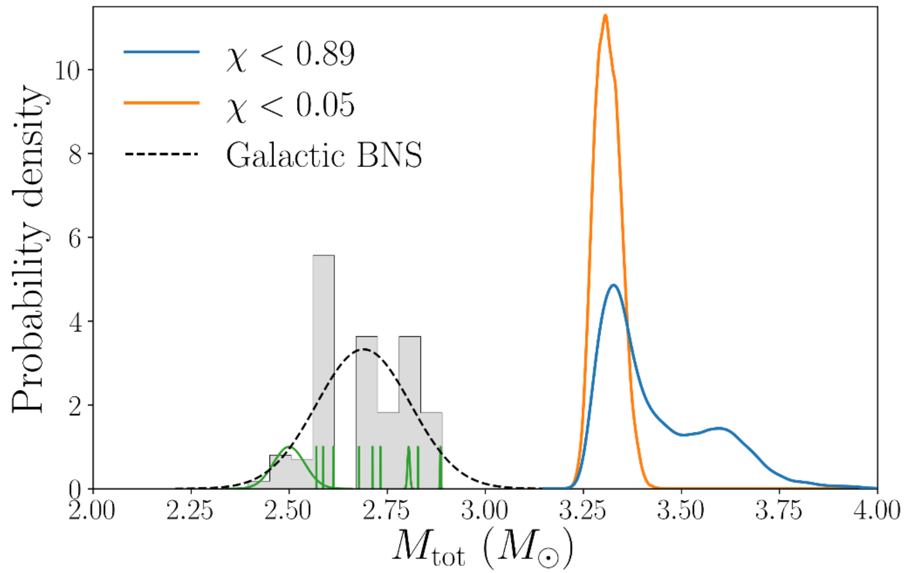
Offline analysis should confirm most of these candidates, and may uncover additional events

First O3 results

- GW190425: Observation of a Compact Binary Coalescence with Total Mass ~3.4 $M_\odot$
  - Astrophys. J. Lett. **892**, L3 (2020)
  - https://iopscience.iop.org/article/10.3847/2041-8213/ab75f5

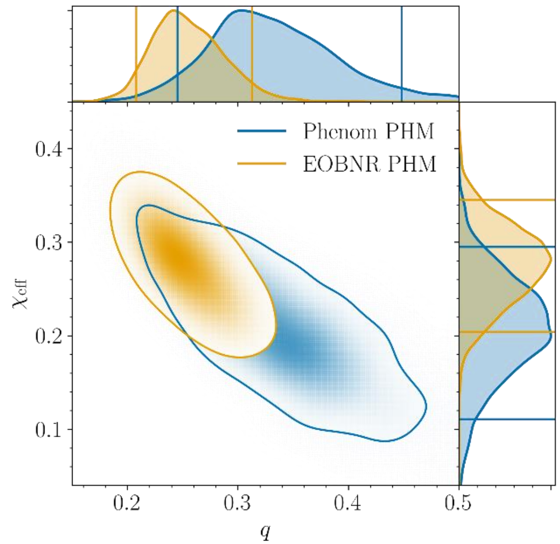
- Likely the second binary neutron star merger detected
  - But no counterpart contrary to GW170817
    $\rightarrow$ More distant source and less well-localized in the sky (L-V detection)

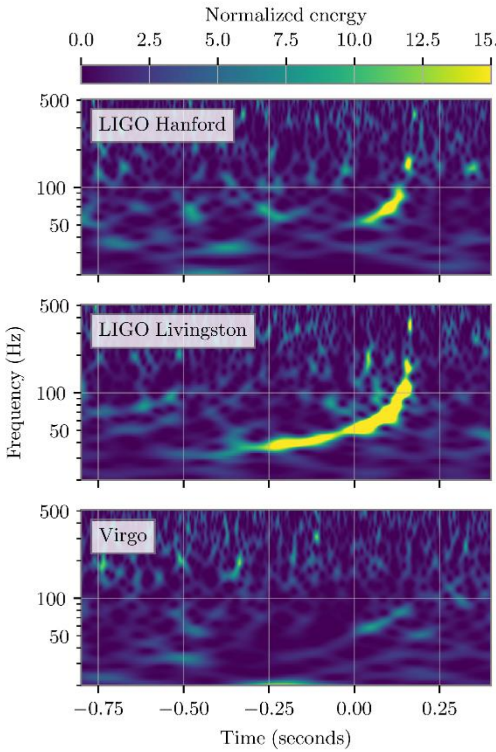
- Total mass larger than any known neutron star
  $\rightarrow$ Hint for a new population?



First O3 results

- GW190412: Observation of a binary-black-hole coalescence with asymmetric masses
  - https://arxiv.org/abs/2004.08342 (accepted in PRD)





- First observation of a binary black merger with significantly different component masses: 30 vs. 8 solar masses

→ First observation of GW higher multipoles beyond the leading quadrupolar order
  - Stronger contribution expected from asymmetric systems

- Set of tests consistent with General Relativity

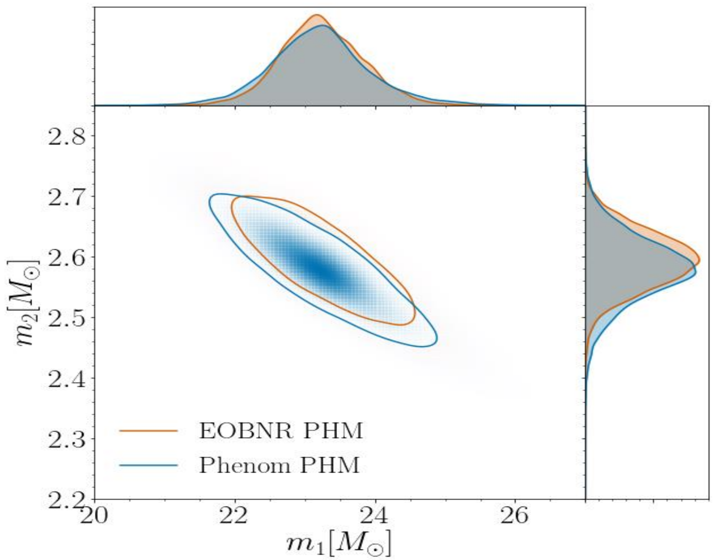
- Inputs for binary black hole population and astrophysical formation channels

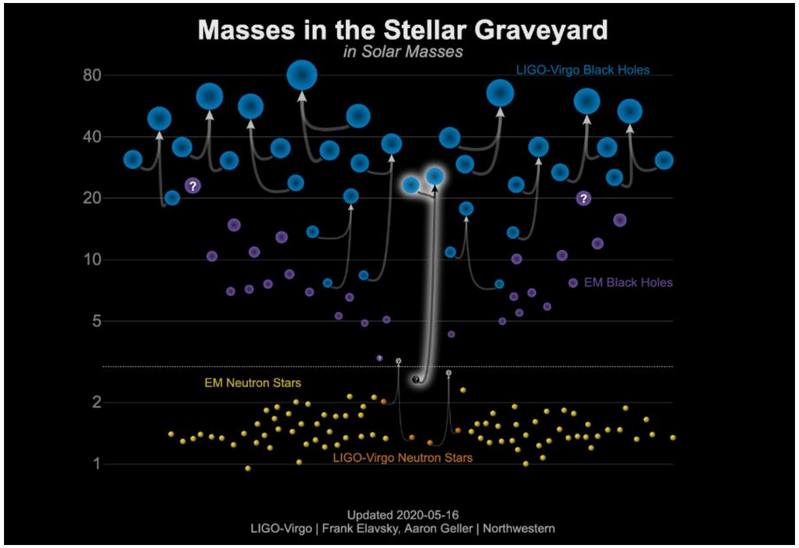
First O3 results

- GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object
  - Astrophys. J. Lett. **896**, L44 (2020)
  - https://iopscience.iop.org/article/10.3847/2041-8213/ab960f

- Uncertain nature of the secondary component
  → Heaviest neutron star in a binary system or lighter black hole
    - Challenge for formation models

- System more asymmetric than GW190412 – 9:1 mass ratio





O3 results: more to come!

- New issue of the GW transient catalog
  - Focus on individual events if they warrant
  - A few companion papers
- Many searches ongoing on the full O3 dataset
- LIGO-Virgo data become public after an initial proprietary period
  - Around an exceptional event, when the associated article is published
  - By chunks of 6 months, 18 months after the end of the data taking

$\rightarrow$ To know more, visit the Gravitational Wave Open Science Center (GWOSC)

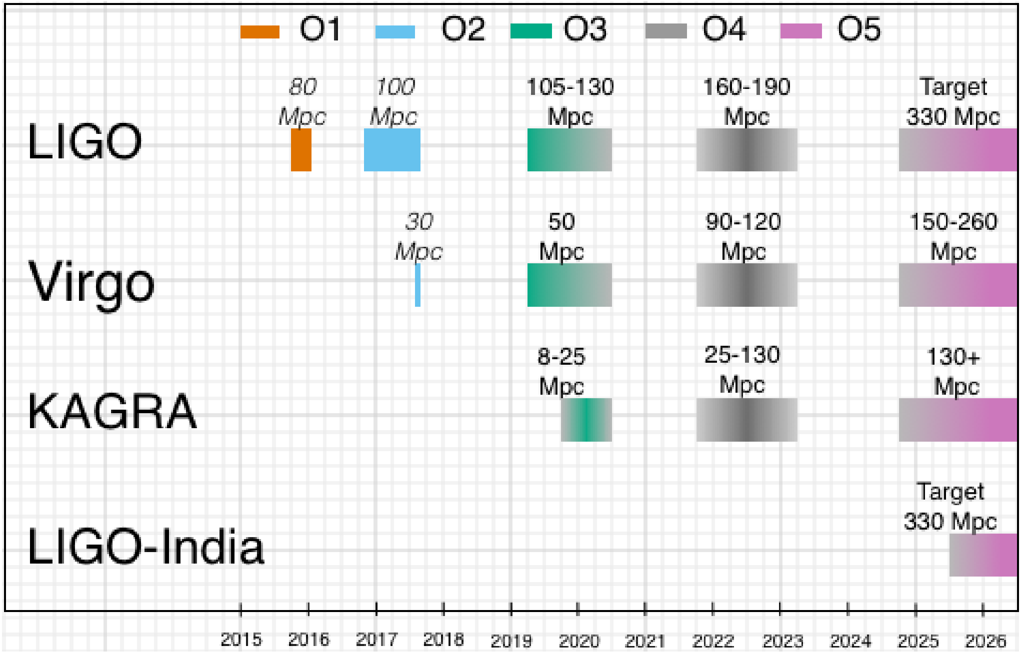
https://www.gw-openscience.org

The path to O4: the « Advanced Plus » detectors

- Shutdown period post-O3 to prepare the 4th Observation Run – O4
  - New series of upgrades: « Advanced detectors » → « Advanced Plus detectors »

- Early, pre-pandemic, planning

"2021/2022 – 2022/2023: 4-detector network with the two LIGO instruments at 160–190 Mpc; Phase 1 of AdV+ at 90–120 Mpc and KAGRA at 25–130 Mpc. The projected sensitivities and precise dates of this run are now being actively planned and remain fluid."



- Impact of the COVID-19 pandemic on the schedule is being actively studied

  → Stay tuned by subscribing to the OpenLVEM forum
  - https://wiki.gw-astronomy.org/OpenLVEM