VIRGO Status and Prospects

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On behalf of the Virgo Collaboration – VIR-0993A-22

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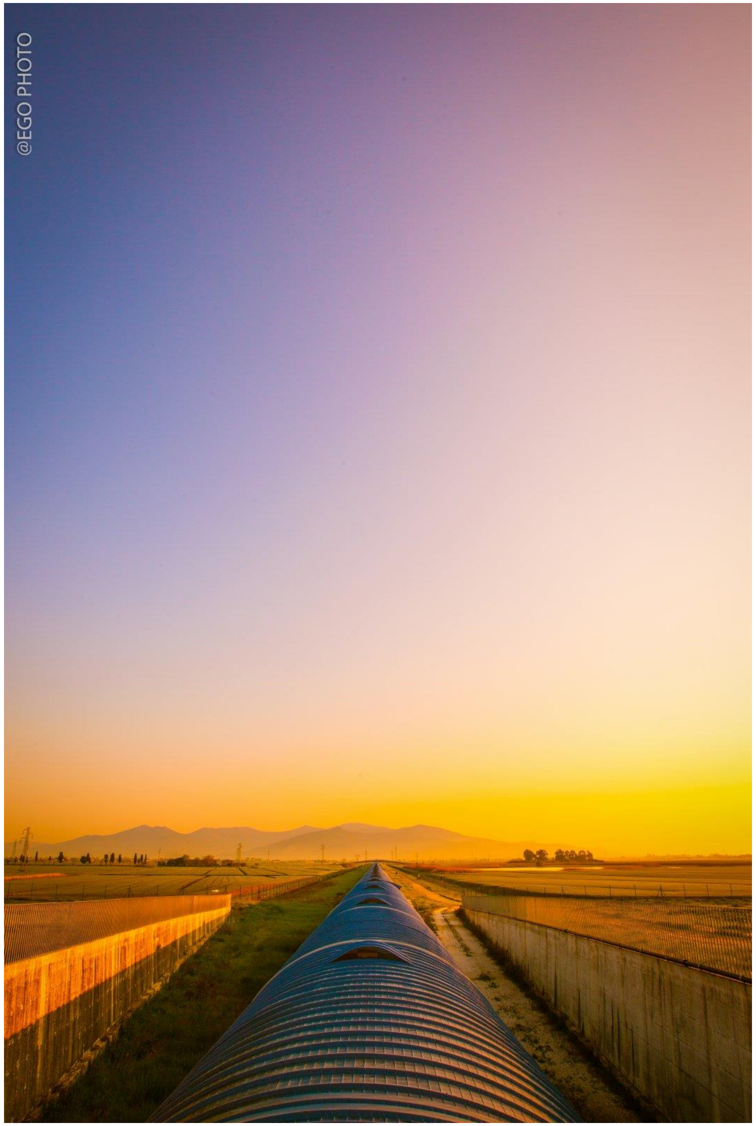
https://twitter.com/ego_virgo
https://www.facebook.com/EGOVirgoCollaboration
https://www.instagram.com/ligo_virgo
https://www.youtube.com/c/EGOtheVirgoCollaboration

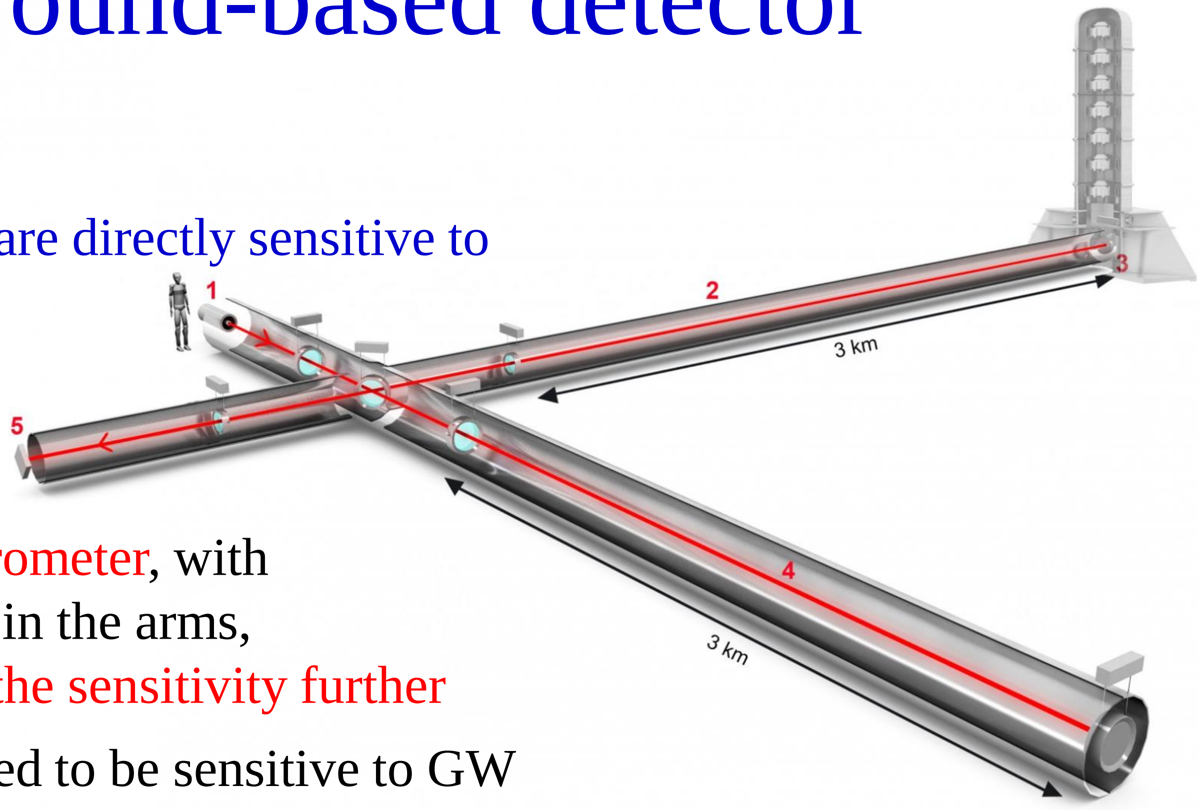
Outline

- Detecting gravitational waves (GWs) with ground-based interferometric detectors
- Virgo, EGO and the LIGO-Virgo-KAGRA network
- Setting the stage
  - Detector performance
  - Network planning
- Virgo during the O3 run
- Detector upgrades
  - Sensitivity and noises
  - The Advanced Virgo+ project
    - Phase I: now
    - Phase II: future
  - Virgo_nEXT
  - Einstein Telescope
- Conclusions



GW & ground-based detector

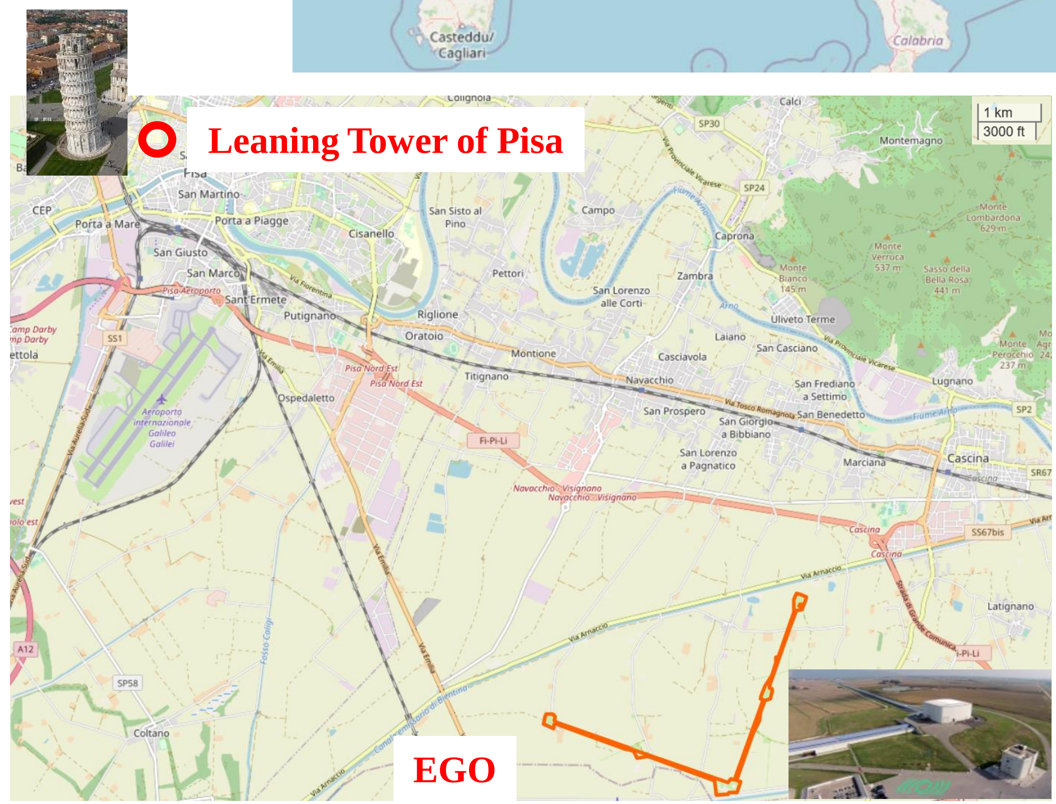
- GW strain h(t)
  - The quantity GW detectors are directly sensitive to
  - Dimensionless
  - Scales like 1/distance

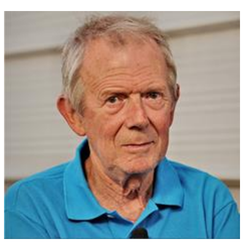


- Suspended Michelson interferometer, with km-long Fabry-Perot cavities in the arms, recycling mirrors to enhance the sensitivity further
- Specific working point required to be sensitive to GW
  → Active feedback control systems
    - Bring the detector to its global working point and maintain it
- GW passing through the detector
  - Differential effect on arm optical paths
  → Interference condition changes at interferometer output
  → Variation of the detected power
  → GW strain channel h(t)
    - Reconstructed from raw data

Virgo @ EGO

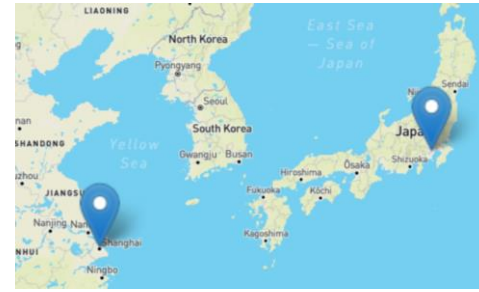
- European Gravitational Observatory (EGO): the lab hosting the Virgo detector
  - Located in Cascina, about 10 km South-East of Pisa (Italy)
- Virgo timeline
  - End of 80's: proposal
  - Mid-90's: funding
  - 00's: first-generation (initial) detector
  - 10's-now: second-generation (advanced) detector





- Virgo founding fathers
  - Alain Brillet (CNRS)
  - Adalberto Giazotto (INFN, 1940-2017)

The Virgo Collaboration



- ~800 members
  - ~530 authors

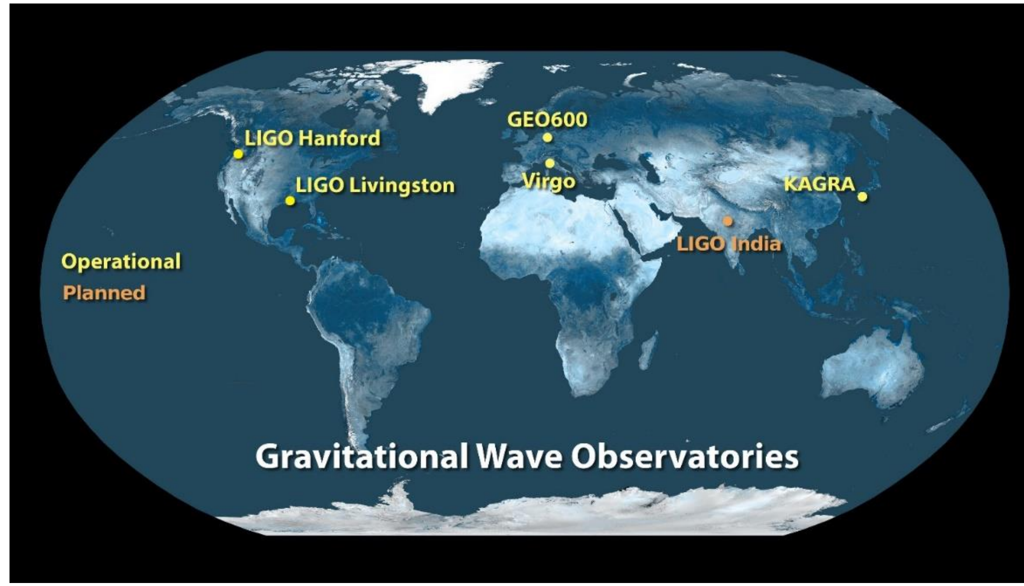
→ Strong growth since first detections
  - GW150914: ~230 Virgo authors
  - GW170817: ~260 "

- ~140 participating institutions from 15 countries
  - Gathered in ~35 groups from 9 countries

- Websites
  - Virgo: https://www.virgo-gw.eu [New]
  - EGO: https://www.ego-gw.it
  - Public: http://public.virgo-gw.eu [To be moved elsewhere]

Virgo within LIGO-Virgo-KAGRA (LVK)

- A worldwide network of ground-based GW interferometric detectors
  - Joint data analyses & publications
    → Detection confidence
    → Sky localization
    → Polarization determination
    → Source parameters inference



- GEO600 [Germany]
  - Astrowatch, R&D
- LIGO Hanford [WA, USA]
  LIGO Livingston [LA, USA]
  - Advanced detectors online since September 2015
- Advanced Virgo : since August 2017
- KAGRA [Japan]
  - Underground and cryogenic
- Gravitational Wave Open Science Center (GWOSC): https://www.gw-openscience.org




Detector performance: figures of merit

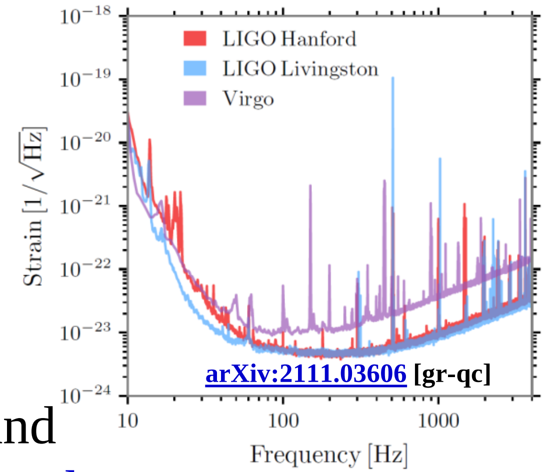
- Sensitivity
  - Amplitude spectral density
  - Unit: $1/\sqrt{\text{Hz}}$

→ Range
  - Average distance [Mpc]…
    - Sky location-averaged and source orientation-averaged
  - … up to which a given source…
    - Typically BNS mergers Binary Neutron Star ($1.4\ M_\odot$) merger
  - … is detected
    - Signal-to-noise ratio (SNR) ≥ 8

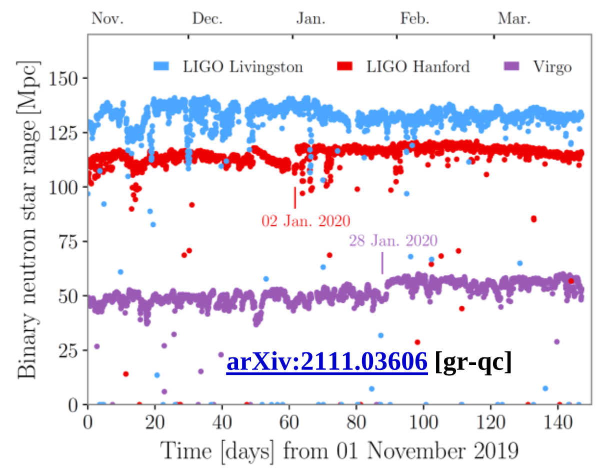
- Duty cycle
  - Fraction of time a detector or a network configuration takes good data

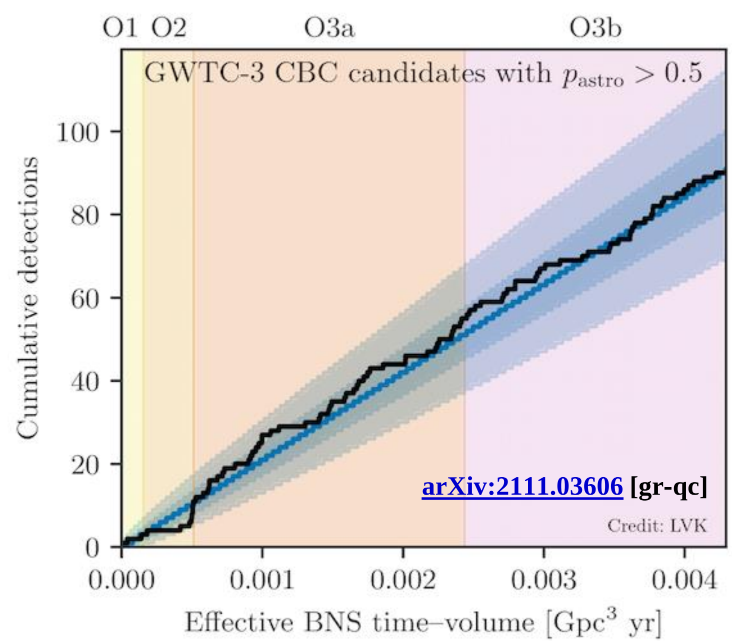
→ Number of transient GW detections
$\propto$ (Volume probed) × (Time of observation)

O3b Sensitivities



O3b Ranges

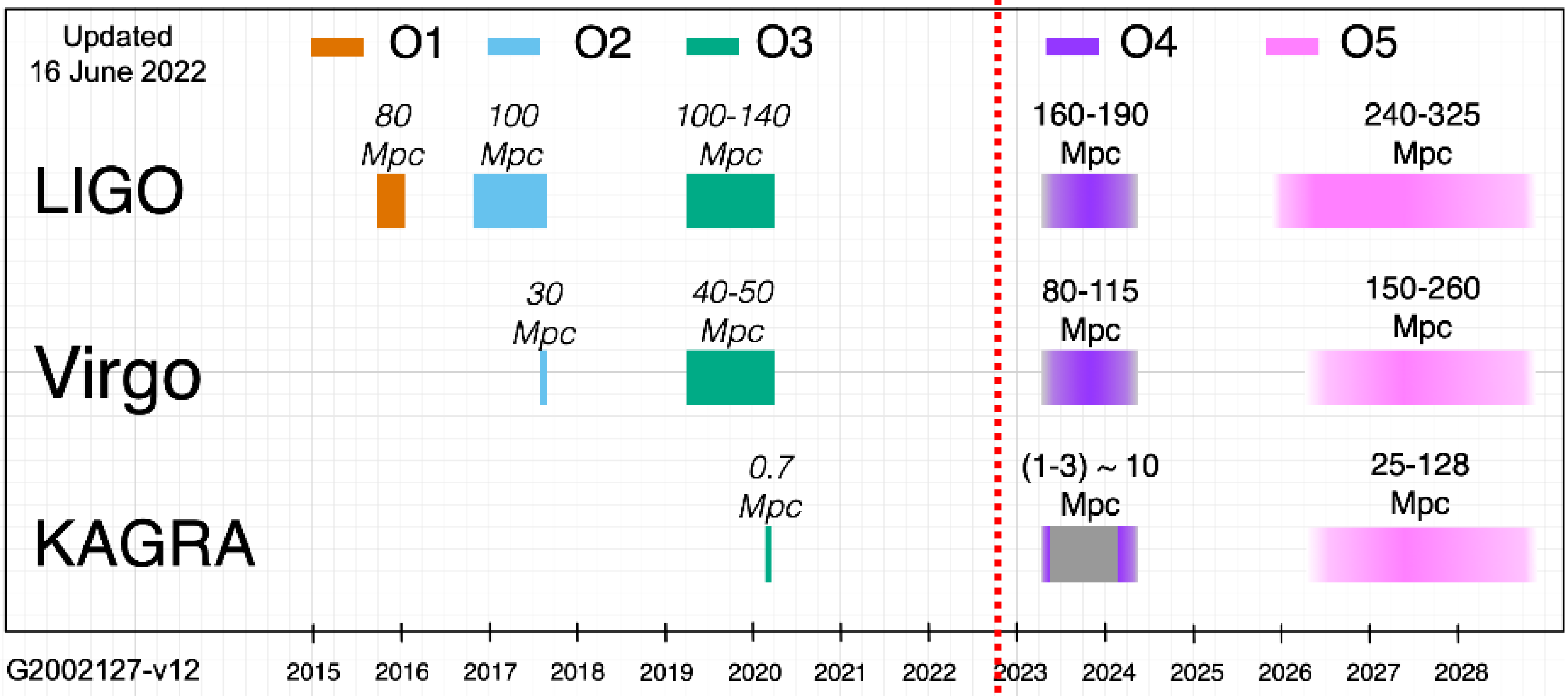




Of data taking periods and upgrades

- LVK is a meta-collaboration aiming at optimizing the global yield of the network
  - Joint strategy
    - → Data taking periods:
      Observing Runs (O*n*) Past: *n=1,2,3* Future: *n=4,5,etc.*
    - → Upgrades

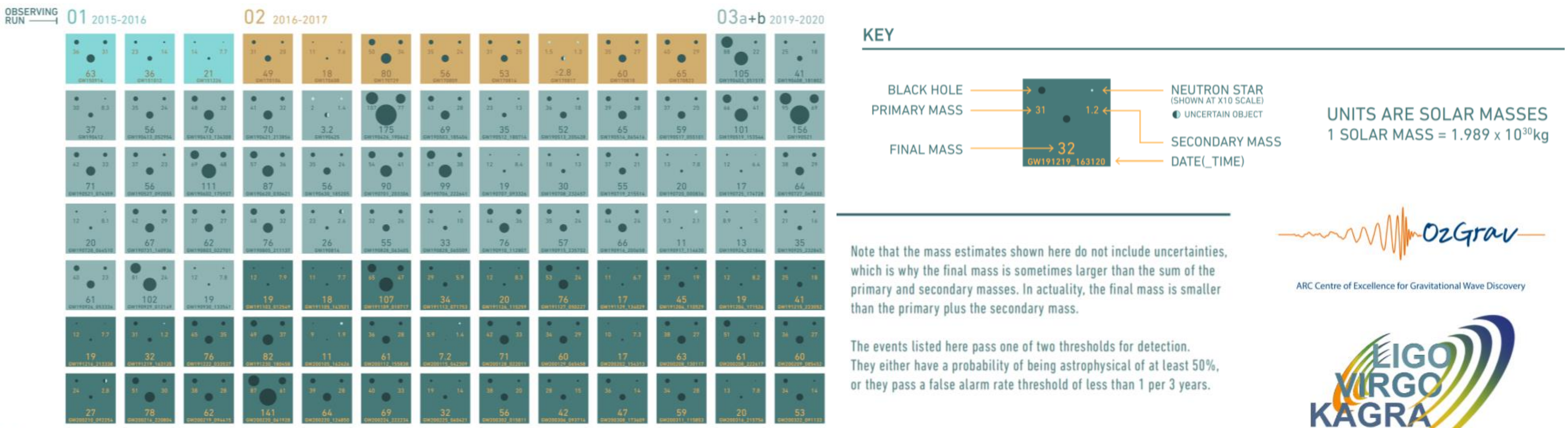
Today



Advanced Virgo | Advanced Virgo+ Phase I | Advanced Virgo+ Phase II

The O3 run

- All 3 detectors (the two LIGO + Virgo) taking data for the whole run
  - O3a: 6 months – 2019/04/01 → 2019/10/01
  - 1-month commissioning break: 2019/10
  - O3b: 5 months – 2019/11/01 → 2020/03/27, shortened by covid-19 pandemic

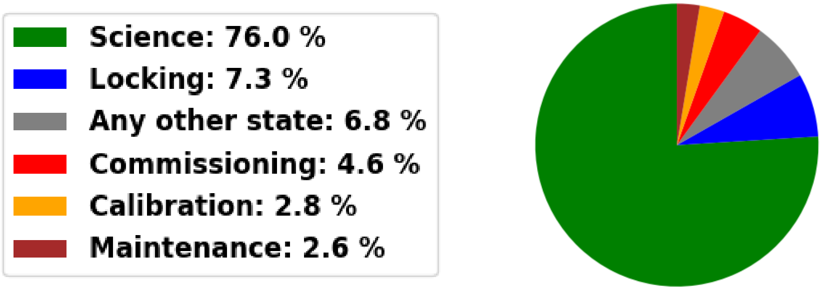


- O3: 79 new GW signals – 90 total, all transient
  → GWTC-3 (3rd issue of our GW transient catalog): arXiv:2111.03606 [gr-qc]
  - All 3 types of compact binary mergers detected / no multi-messenger observation
  - Rates and populations studies, tests of General Relativity
  - Targeted searches: GRBs, FRBs, type-II supernovae, etc.
  - Searches for continuous signals

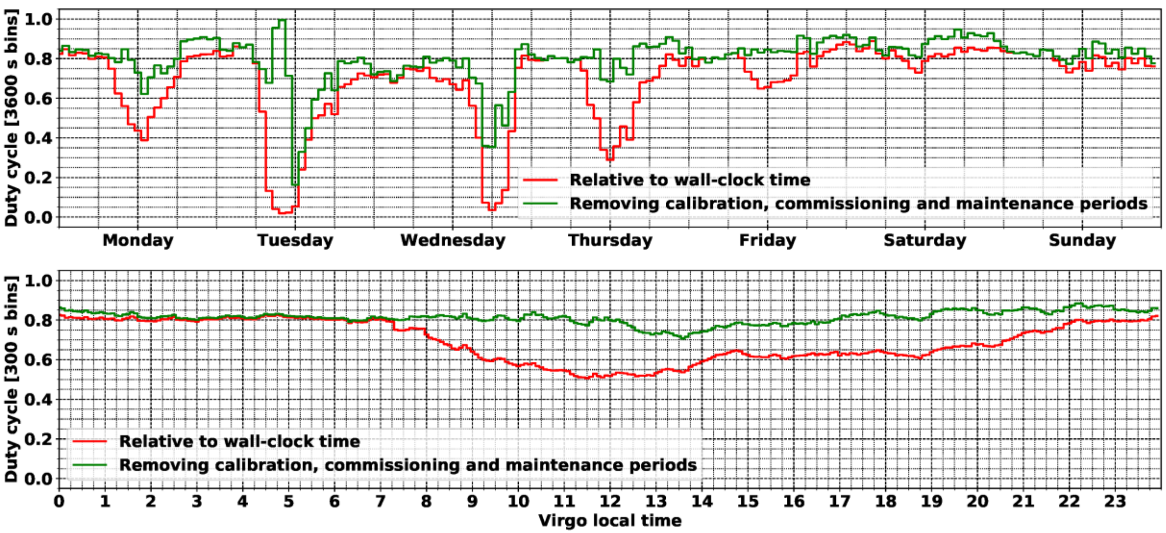
} companion and related articles

Duty cycle of the Virgo detector during O3

arXiv:2210.15633 [gr-qc]



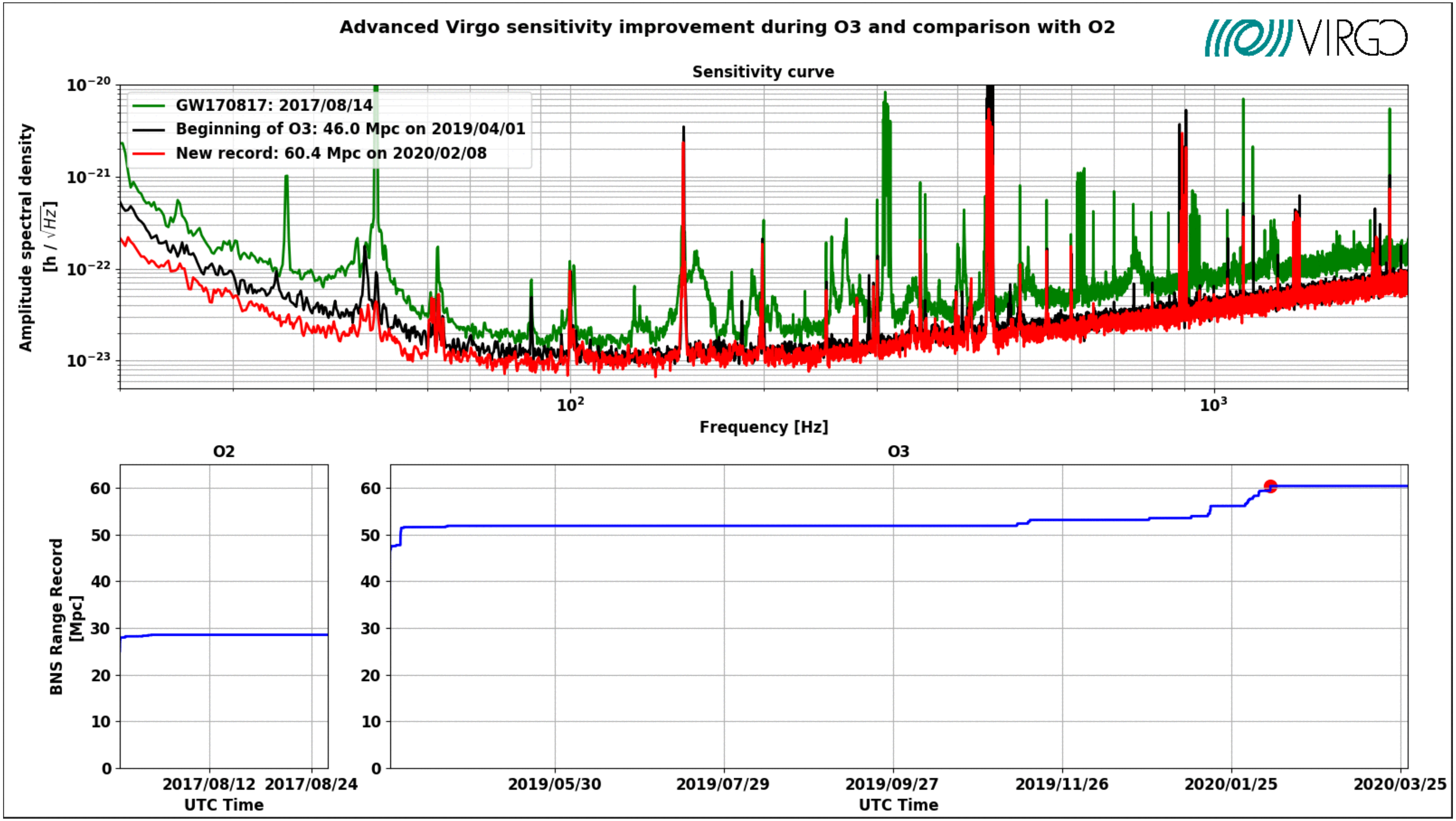
- O3 overall duty cycle: 76.0%
  → Stable over time
  - O3a (Spring + Summer): 76.3%
  - O3b (Fall + Winter): 75.6%
- Remaining time divided almost equally among three categories
  - Working point control / Maintenance + Calibration + Commissioning / Problems
- Projecting the duty cycle onto a fictious week (top) or day (bottom) by averaging data from the whole O3 run shows that the duty cycle variations are mainly due to detector crew activities (**red** → **green** curves)



arXiv:2203.04014 [gr-qc]

Virgo sensitivity improvement

- O2-O3 (2017-2020) sensitivity and BNS range evolution

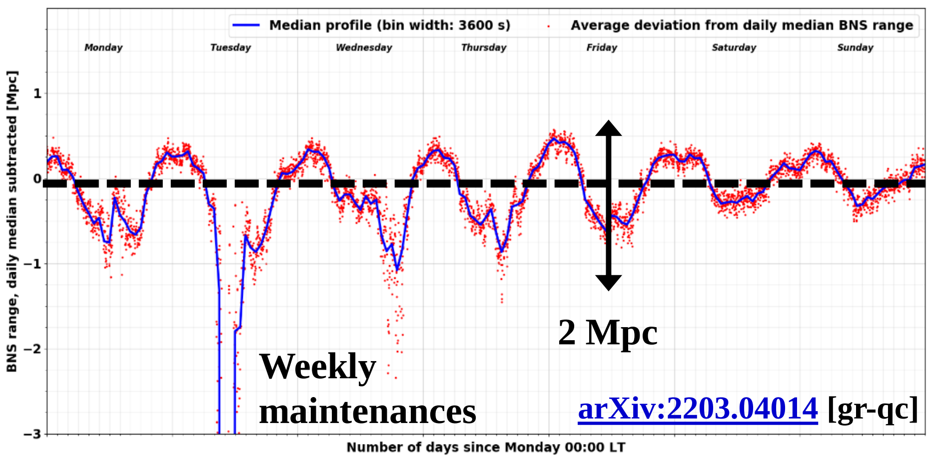


Virgo sensitivity robustness

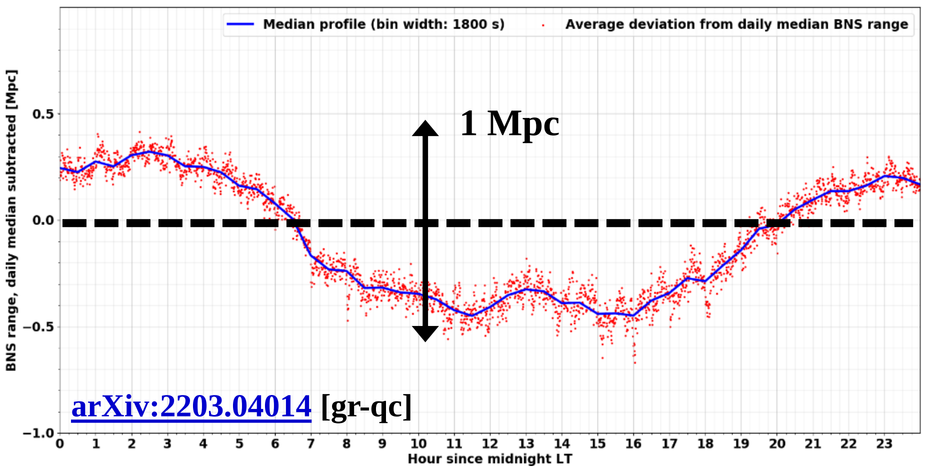
- Input: the BNS range
  - "Raw" value subject to variations from multiple (and changing) sources
    - Control accuracy, detector global status, transient problems, environment, etc.
  - → Thus not suitable for such study
    - Instead: use the BNS range variations around its daily median level

- O3-averaged variations

Over a week baseline



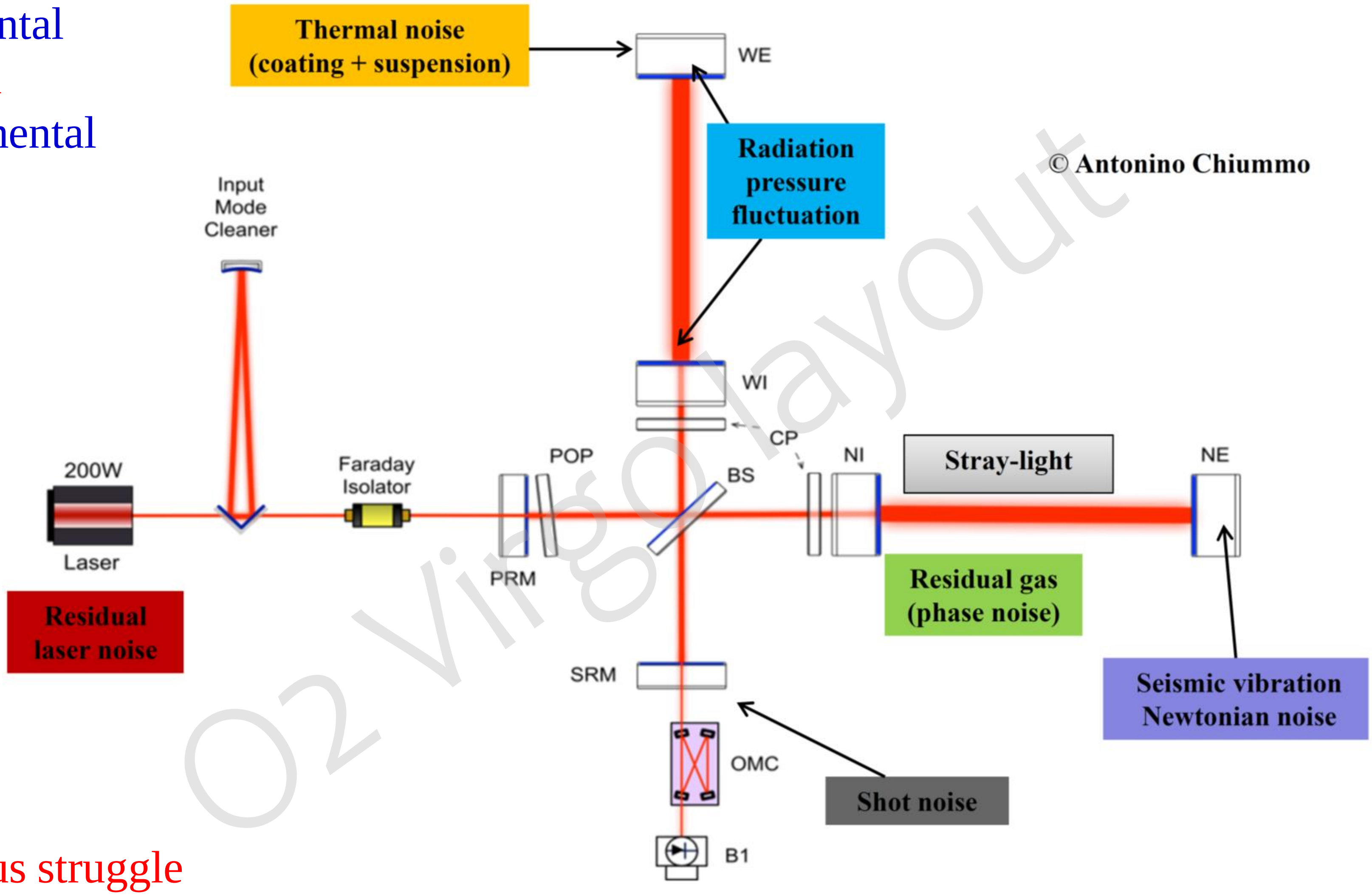
Over a 24-hour baseline



→ Modulation similar to anthropogenic noise
- Limited amplitude: a few percents at most – Virgo O3 BNS range: 45-60 Mpc

Sensitivity and noises

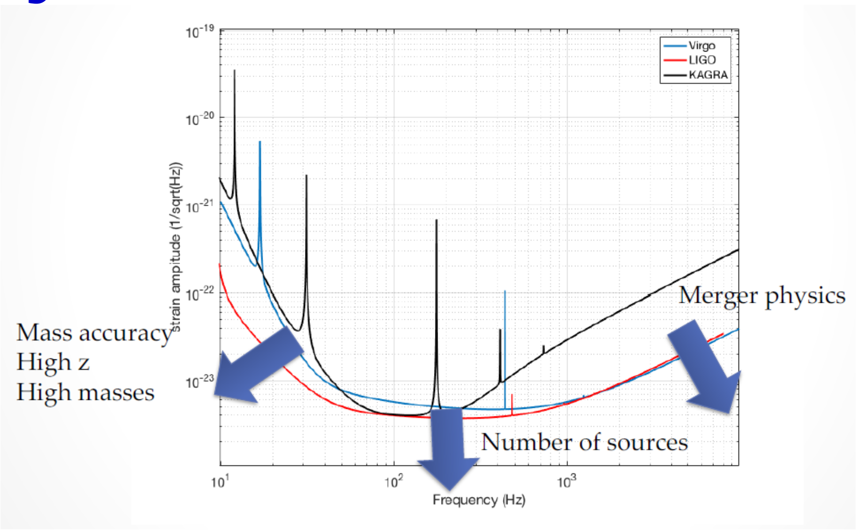
- Sensitivity limited by many noises
  - Fundamental
  - Technical
  - Environmental



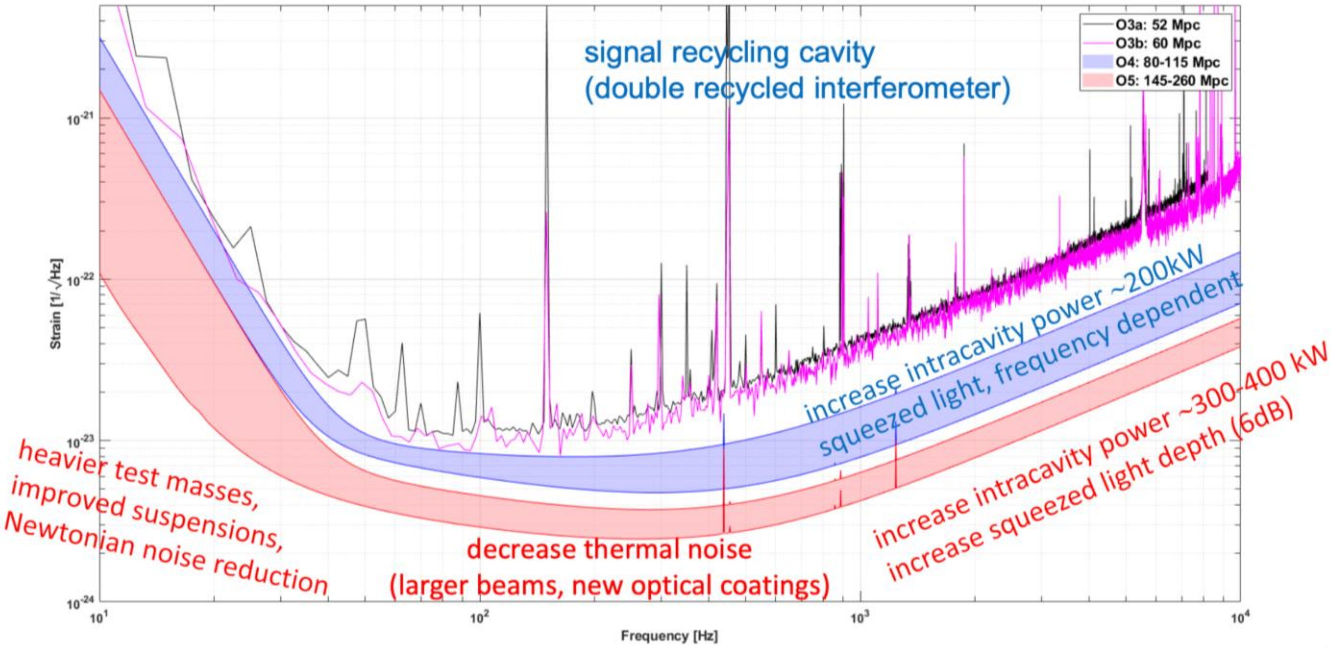
→ Continuous struggle
- Design, construction, improvement, noise hunting, noise mitigation

Sensitivity and noises

- Physics improvements
  depend on the frequency band
  in which sensitivity is improved



→ Impact of noise improvements on the GW detector sensitivity



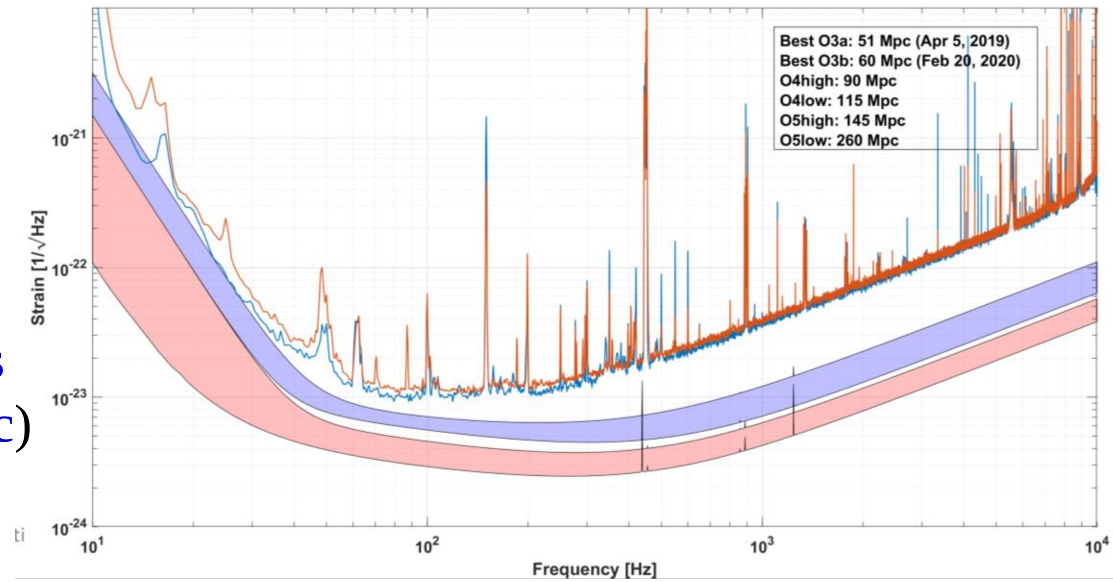
Upgrading Virgo: Advanced Virgo+

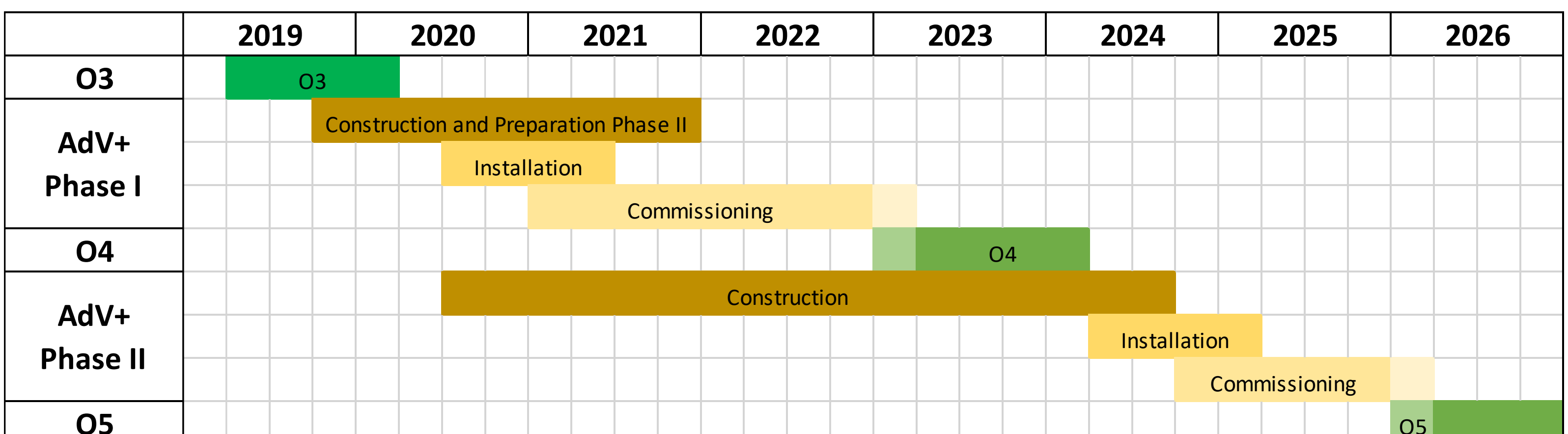
- Project proposed in 2017
- Two phases
  - Phase I: O3/O4 (2023-2024)
    - Main target: quantum noise
    - Reduction of technical noises

    → BNS range goal: O(100 Mpc)
  - Phase II: O4/O5 (2026-2027)
    - Main target: thermal noise

      → More invasive upgrade: mirrors to be changed

    → BNS range goal: O(200 Mpc)

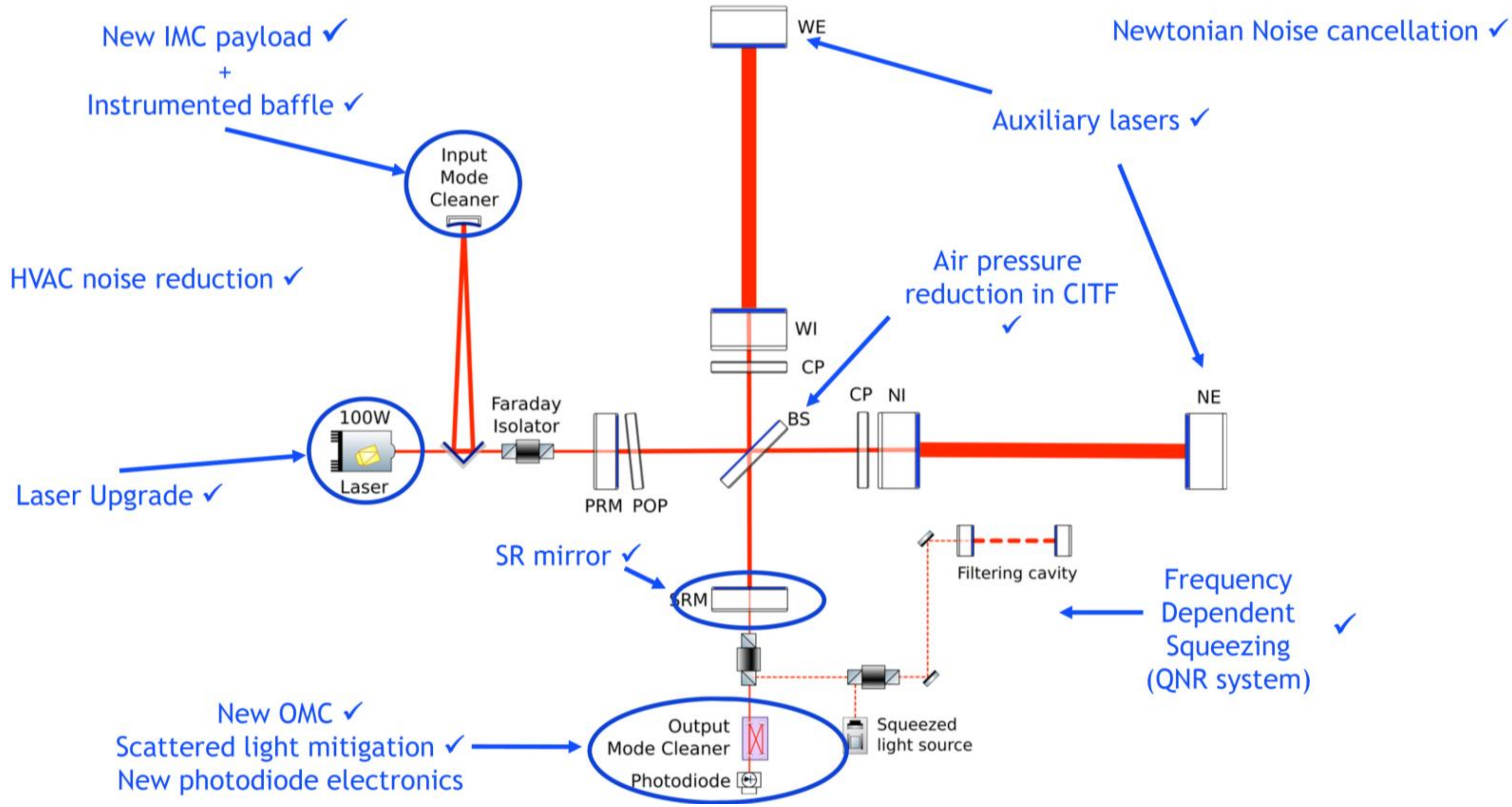




→ Global pandemic impact: significant delays – O4 planned to start end of 2021!

AdV+ Phase I: the path towards O4

- Several improvements



- Installation phase
  - Completed in December 2021 for main interferometer
  - in April 2021 for the quantum noise reduction system

→ Commissioning started immediately after installation completed

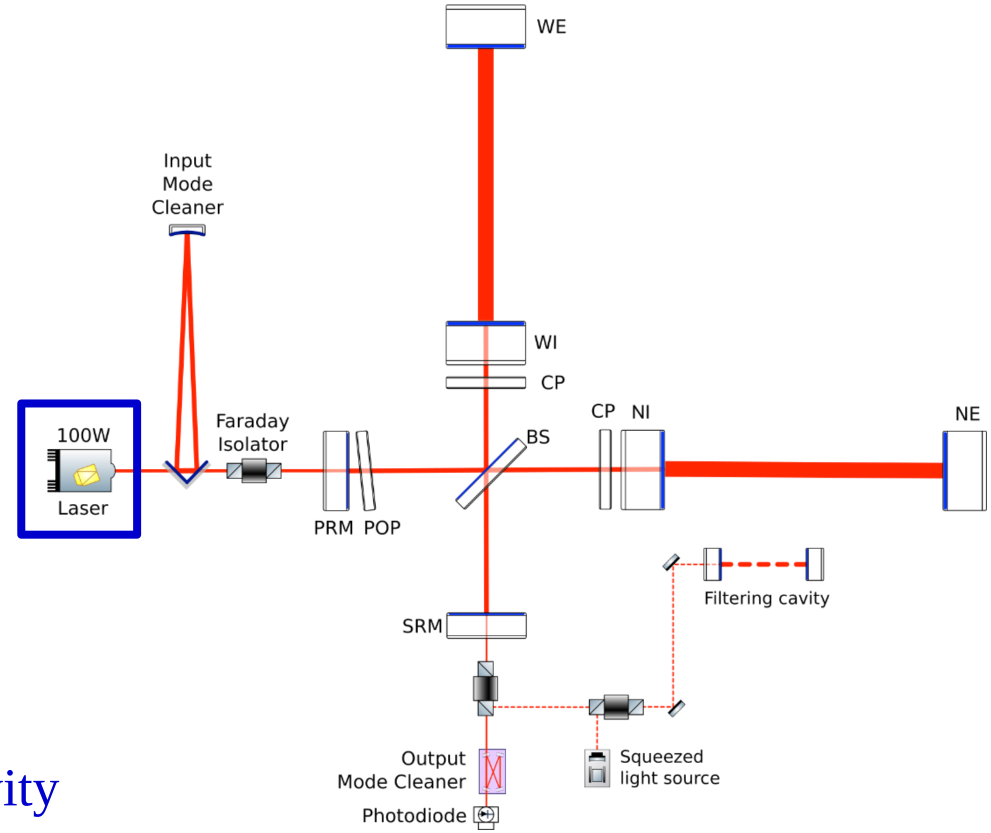
Progress and difficulties

- Shot noise improvement
  - Input laser power increase
    sensitivity ∝ 1/√(laser power)

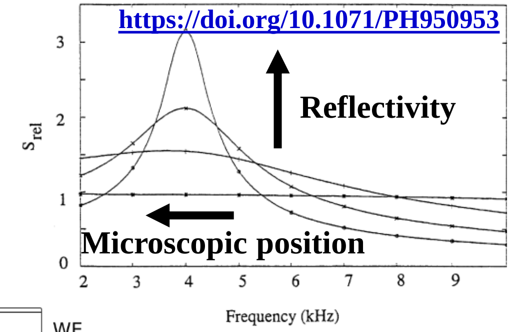
→ Higher radiation pressure impacts detector control

→ Stronger thermal effects impact both control and optical performance

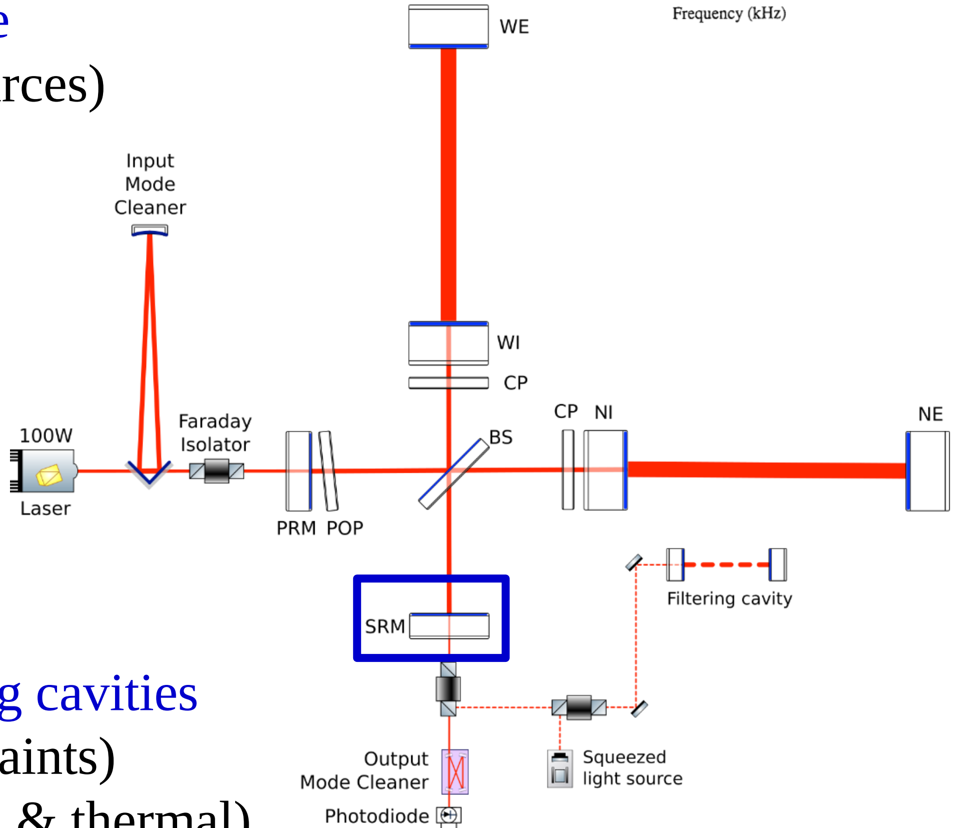
→ Limited power increase:
25W → 33W, instead of 40W
  - Not limiting the planned O4 sensitivity



Progress and difficulties



- Signal recycling mirror
  - Improve and shape the sensitivity curve in a given frequency band (specific sources)
    - Mirror reflectivity ↔ Bandwidth
    - Position ↔ Resonance frequency



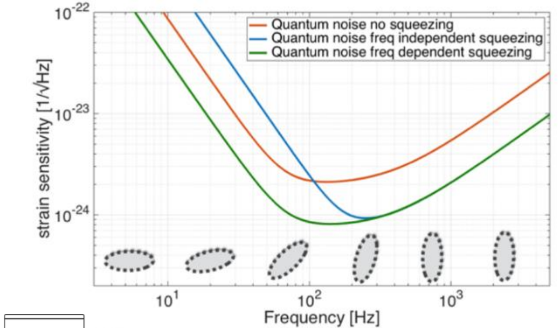
→ Additional cavity to control
  - Longitudinal and angular degrees of freedom

→ Need to redesign the procedure leading to the global control of the full detector

→ Additional difficulty: the Virgo recycling cavities are only marginally stable (space constraints)
  - More sensitive to optical defects (cold & thermal)
  - Mirror radius of curvature tuned for high power: more instabilities at lower power

→ A lot of control and stability issues
  - Months of measurements and simulations to understand the new detector

Progress and difficulties



- Frequency-dependent squeezing
  - Inject squeezed vacuum states into the interferometer output

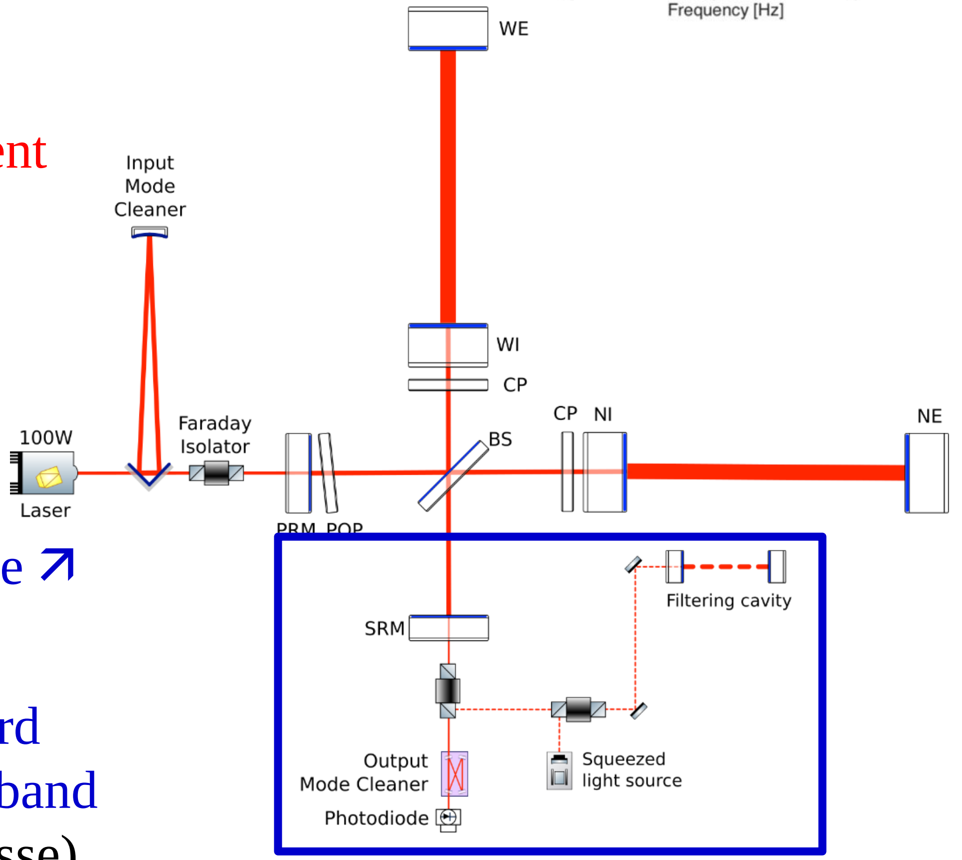
  → Broadband quantum noise improvement
    - Radiation pressure at low frequency
    - Shot noise at high frequency

- Built on O3 experience (LIGO + Virgo)
  - Frequency-independent squeezing PhysRevLett.123.231108

  → Shot noise ↘ but radiation pressure ↗
    - Not a concern: subdominant

- Different approach needed to beat standard quantum limit over the whole frequency band
  - Filter cavity (300 meter-long, high finesse)

    → Amplitude squeezing at low frequency and phase squeezing at high frequency



→ Squeezed light produced, filter cavity controlled and squeezing measured below 20 Hz; standalone system up to now

Advanced Virgo current status

- Global control is now stable and reproducible

- First calibration recently performed
  - Sensitivity limited by control noise
  - Key optical component at the interferometer output found damaged by light flashes
    - Output mode-cleaner

    → To be replaced in the coming weeks

    → Automated safety procedure recently improved

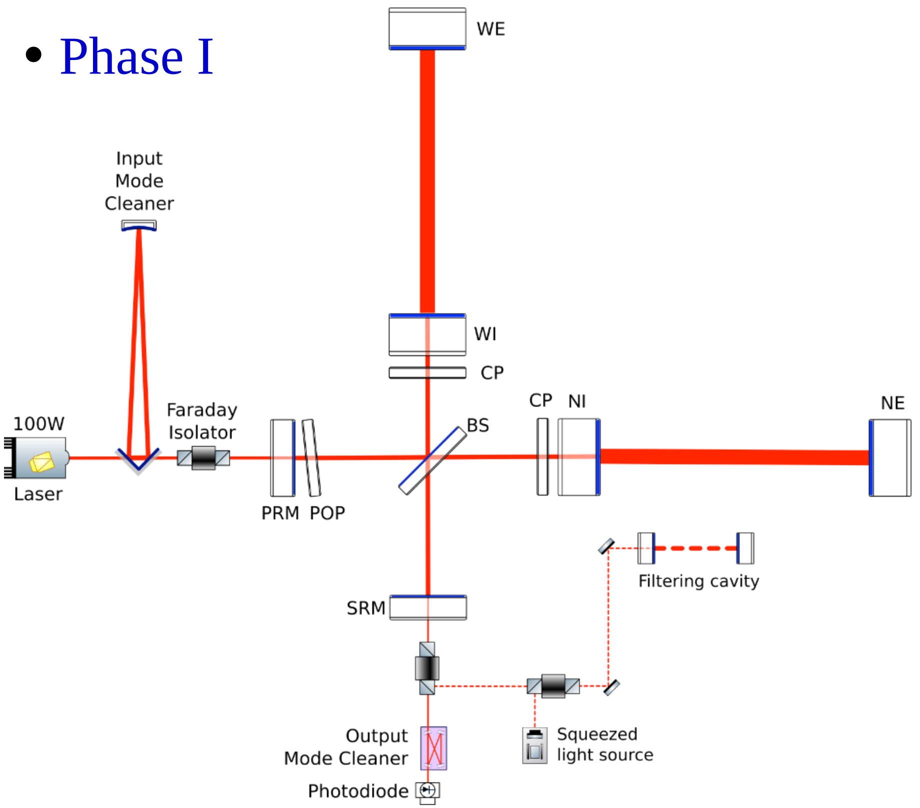
- Next steps
  - Noise hunting, stability improvement, injection of frequency-dependent squeezing

→ But still a lot of work ahead before the start of O4!

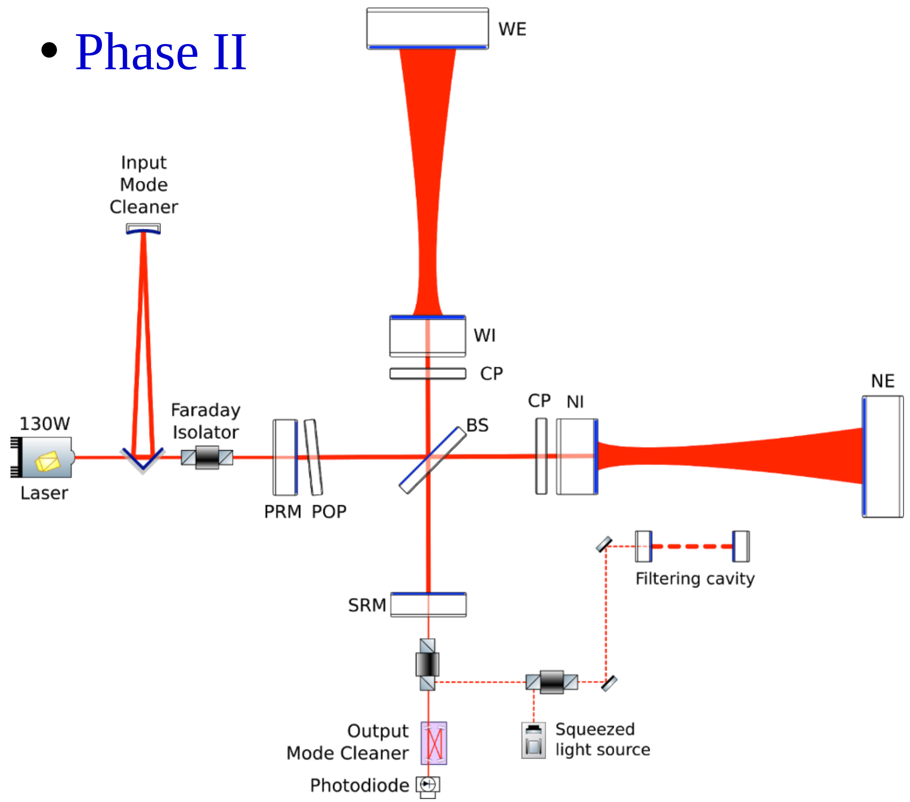
AdV+ Phase II: from O4 to O5

- Tackle thermal noise: reduce its source and mitigate its impact

- Phase I



- Phase II



- Larger beams on end test masses: radius 6 cm → 10 cm
- Larger end mirrors: diameter 35 cm (40 kg) → 55 cm (100 kg)
- Better mirror coatings: lower mechanical losses, less point defects, better uniformity
- New suspensions/seismic isolators for large mirrors
- Further increase of input laser power: up to 80 W

AdV+ Phase II: from O4 to O5

- Critical path: mirror production
  - Constraints: budget for the substrate, technology for the coating
  - → Very challenging schedule: only 2 years for invasive installation + commissioning
- Mirrors
  - Substrates purchased, being polished
  - Tools and metrology upgrades at Laboratoire des Matériaux Avancés (Lyon, France)
- Coating: a joint LIGO-Virgo effort
  - Pre-selection done: $TiO_2:GeO_2/SiO_2$
  - First mono- and multi-layers being produced and tested
  - → Final decision in a few months
- Additional upgrades
  - Thermal compensation system: more sensors, improved actuators
  - Vacuum and cryogenics: pump vibrations, stray light, dust, electrostatic charging

→ Design report released
  - Costing, personpower, milestones, risks
  - Budget now available

Virgo_nEXT: maximizing facility reach

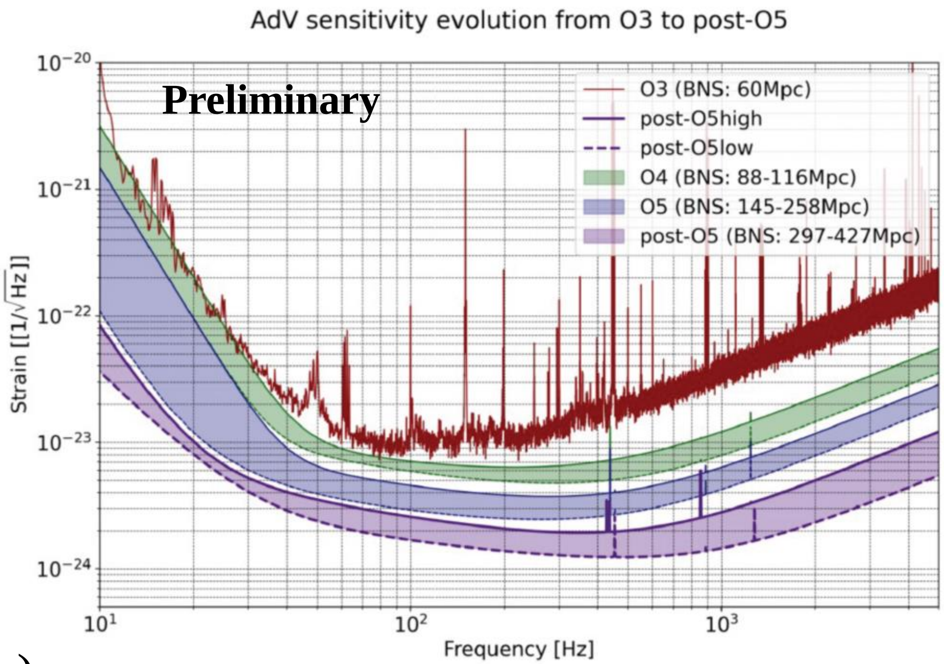
- Bridge the gap between 2nd (‘Advanced’) and 3rd generation detectors
  - Upgrade driven by the fundamental scientific questions in the next decade
  - Test technologies, risk reduction
  - Maintain community of experimentalists, train new generation

- Constraint: keep the existing infrastructure

  → Push it to its limits
    - Suspension thermal noise
    - Newtonian noise subtraction
    - Improved squeezing
    - Lower coating thermal noise

- Data taking vs. upgrades
  - Best strategy with a network of 4 or 5 detectors?
  - Fraction of time for commissioning?

→ Concept study document – O(150 pages)
  - Submitted to funding agencies
  - Baseline design expected in 2023

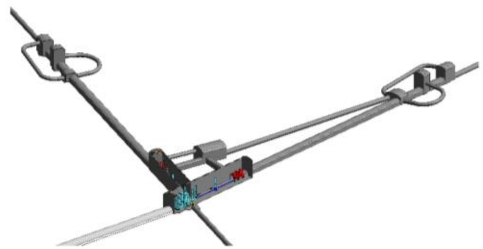


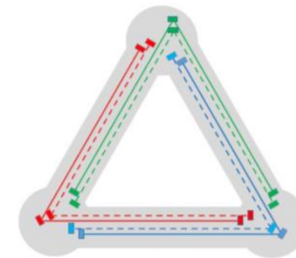
On the even longer term: Einstein Telescope

- Einstein telescope in a nutshell

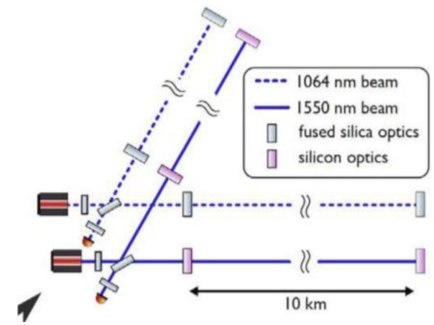
Credit: Alessio Rocchi

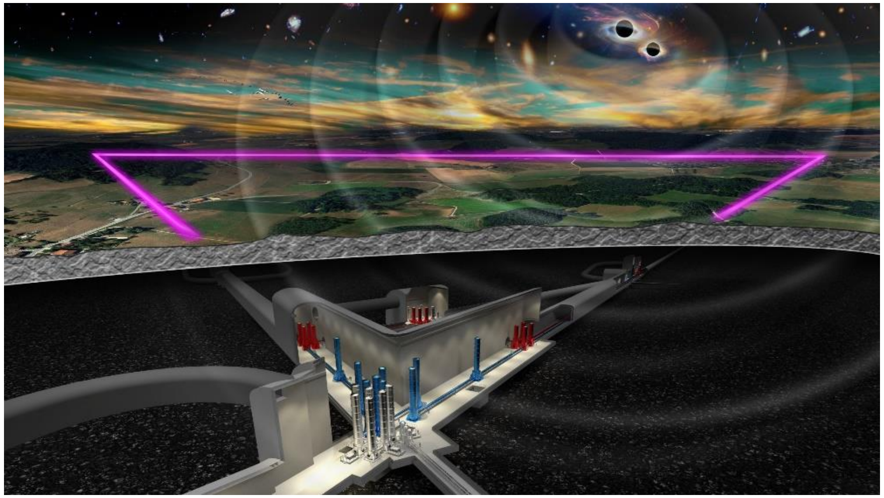
- Xylophone (multi-interferometer) Design
- **Underground**
- **Cryogenic**
- Triangular shape
- Multi-detector design
- Longer arms

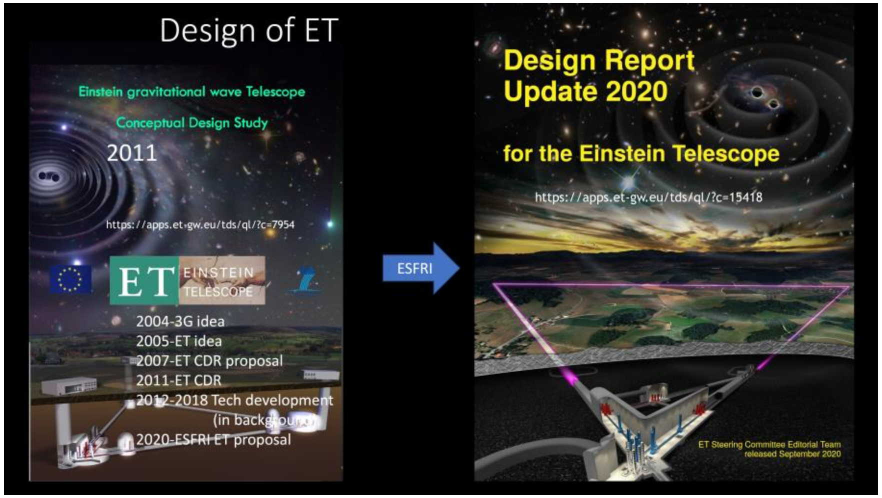




- Wide frequency range
- Massive black holes (LF focus)
- Localization capability
- (more) Uniform sky coverage
- Polarization disentanglement
- High Reliability (high duty cycle)
- High SNR







Outlook

- O1, O2, O3
  - A harvest of scientific results
    - Individual events: GW150914, GW170817, etc.
    - Transient catalog: 90 GW signals in GWTC-3
  - Strenghtening and realization of the LVK network
    → Close coordination for O4 and beyond

- All detectors currently being upgraded
  - Advanced Virgo Plus project: phases I and II

- Longer-term upgrades planned as well

- LVK plans [updated regularly]
  - https://observing.docs.ligo.org/plan
  → Updated regularly

LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS

(15 September 2022 update; next update by 15 November 2022)

LIGO, Virgo, and KAGRA are closely coordinating to start the O4 Observing run together. As a result of the most recent evaluation of the schedule for O4 readiness, we project to start the O4 Observing Run in March 2023, with an Engineering Run to start one month before the observing run begins; low-latency alerts for candidate events identified during engineering time may be released, both to exercise the system and to exploit their scientific value.

The run is planned to start with LIGO Hanford, LIGO Livingston, Virgo, and KAGRA. While the commissioning of the detectors is progressing, the plan towards readiness continues to be reviewed. The updated O4 start date is driven by further unanticipated delays in the detectors' upgrade and commissioning programs. O5 plans are still in formulation; we note that based on experience during previous observing runs, we anticipate the need in O5 for one or more commissioning breaks of a few months duration each to address issues and make improvements based on observing experience.

- Possibility of one or more multi-messenger detections in the coming run!