Status and performance of the Advanced Virgo Detector during the LIGO-Virgo Observation Run 3

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Nicolas Arnaud (narnaud@lal.in2p3.fr)
Laboratoire de l'Accélérateur Linéaire (CNRS/IN2P3 & Université Paris-Sud)
European Gravitational Observatory (Consortium, CNRS & INFN)
On behalf of the Virgo Collaboration

VIR-0249A-19

EGO EUROPEAN GRAVITATIONAL OBSERVATORY

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LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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Outline

- Introduction
  - Virgo collaboration
  - Virgo detector
  - Global network of gravitational-wave detectors

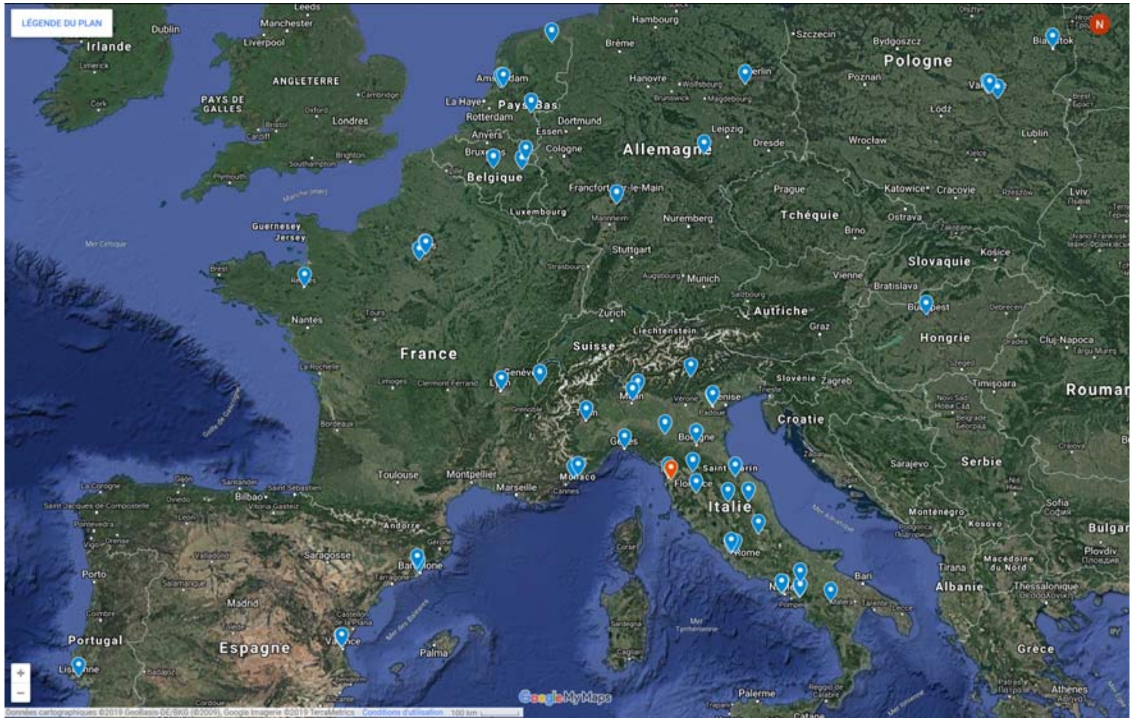
- From O2 to O3
  - Status at the end of O2
  - Post-O2 commissioning period
  - O2-O3 upgrades
  - Noise hunting and pre-O3 commissioning

- O3
  - Performance 3 months onto the run
  - Plans

- Conclusion
  - Beyond O3: Advanced Virgo Plus

Introduction

The Virgo collaboration



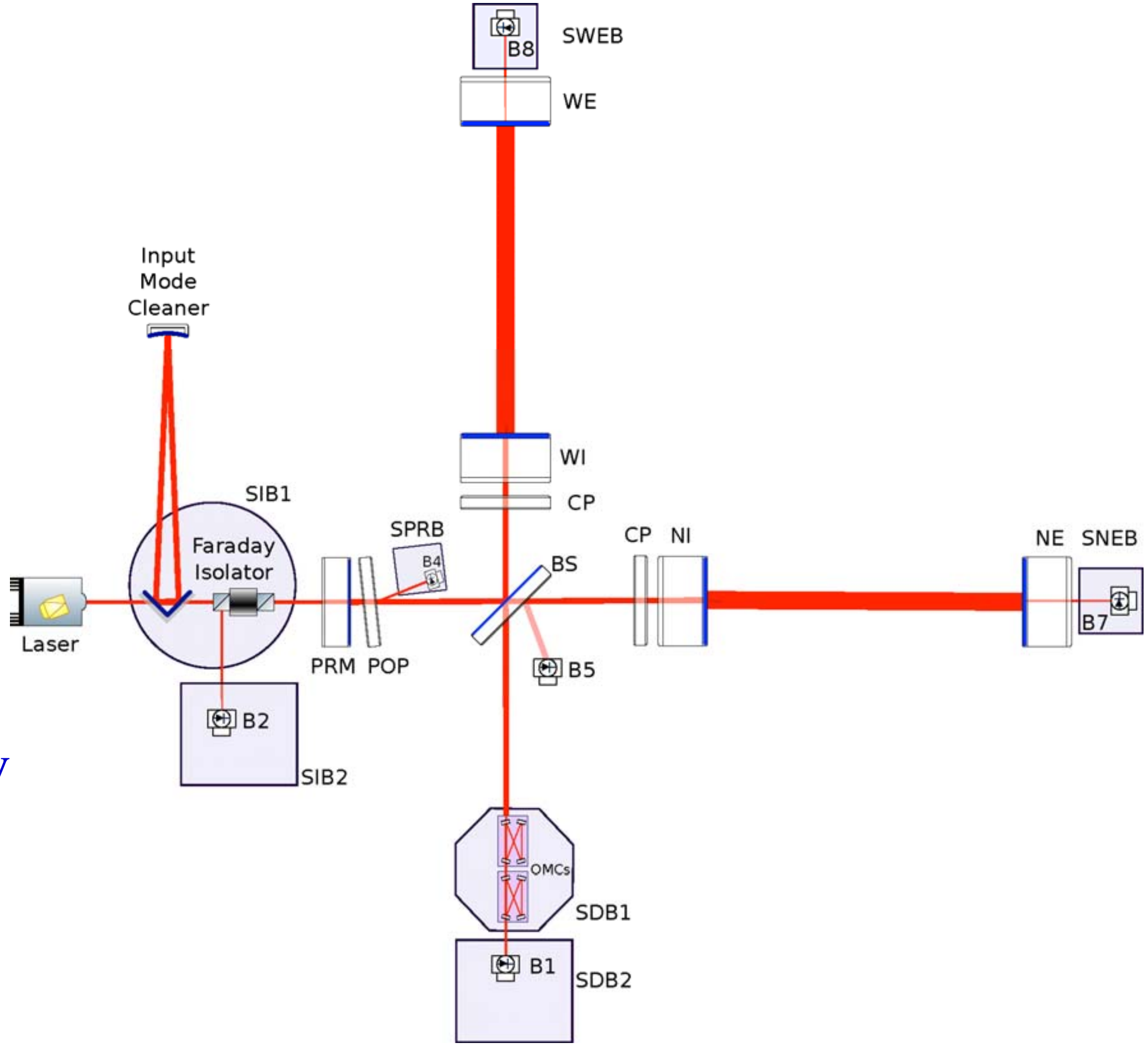
- 8 European countries
  - France
  - Italy
  - The Netherlands
  - Poland
  - Hungary
  - Spain
  - Belgium
  - Germany

→ About 80 institutes
  - About 400 members

- Project started more than 20 years ago

The Virgo detector

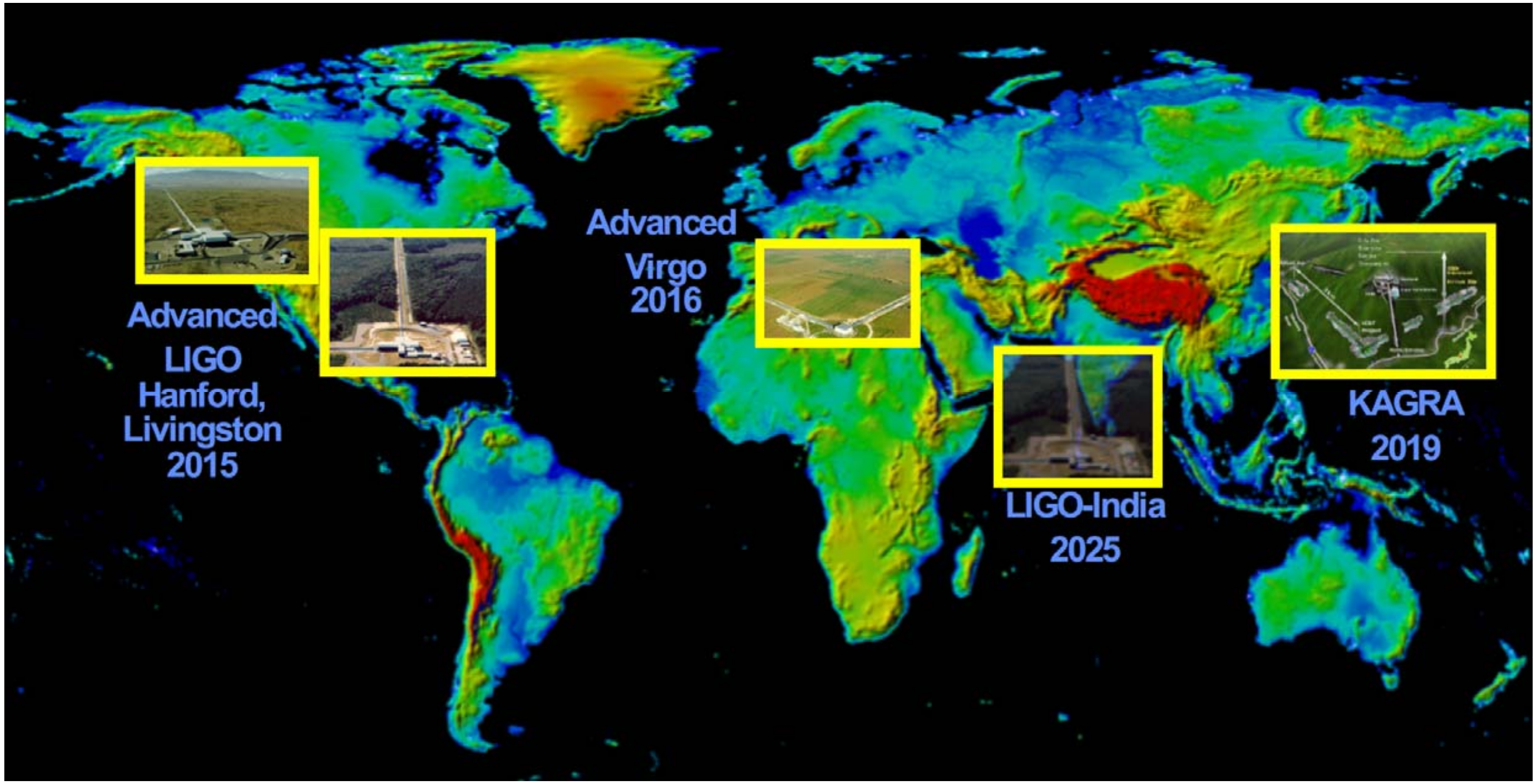
- Suspended, power-recycled Michelson interferometer with 3-km long Fabry-Perot cavities in the arms
  - No signal recycling yet



- Located at the European Gravitational Observatory (EGO) in Cascina – near Pisa, Italy

Global network of gravitational-wave detectors

- Currently: a 3-2nd generation detector network
  - Ligo Hanford (WA state) and LIGO Livingston (LA state)
  - Virgo
- KAGRA (Japan) should join the network before the end of O3
- 3rd LIGO interferometer planned in India for the next decade



- MoUs ruling the joint effort of the LIGO Scientific Collaboration and the Virgo Collaboration to detect and study gravitational-wave signals

From O2 to O3

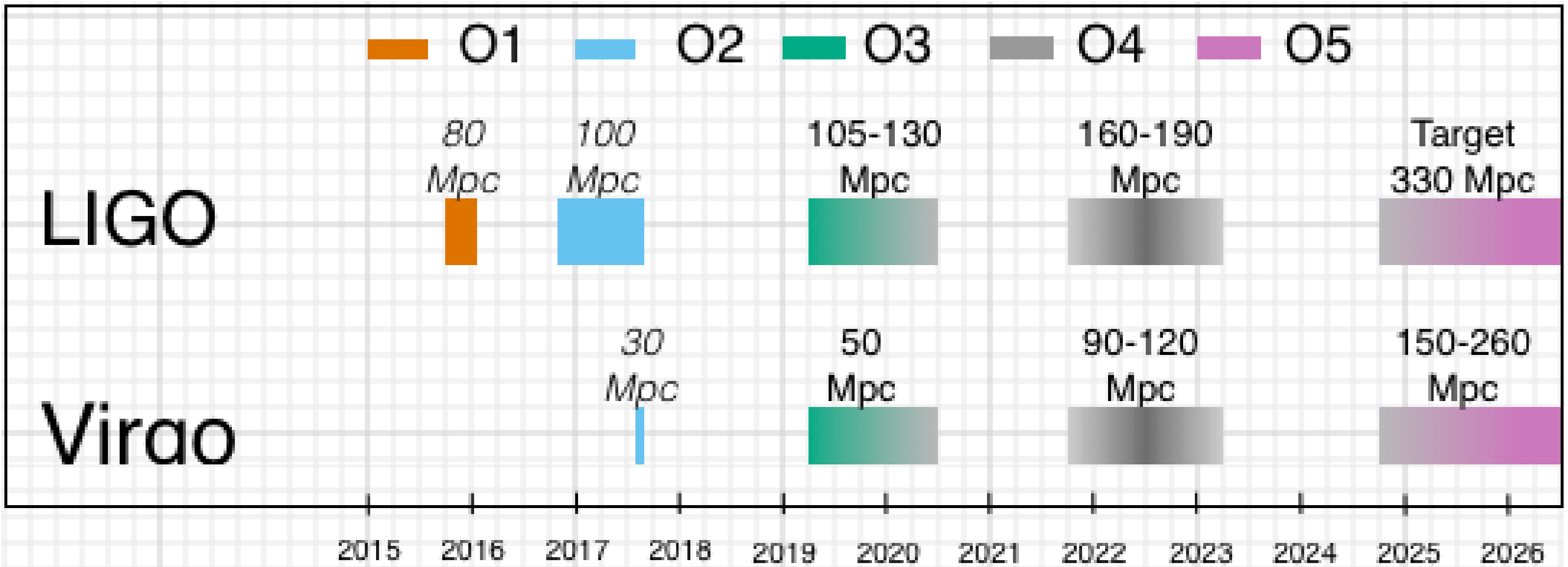
LIGO-Virgo observation runs

- O1: September 2015 → January 2016
  - Only LIGO Hanford and LIGO Livingston
    - Virgo still being upgraded
  - GW150914: first direct detection of gravitational waves

- O2: November 2016 → August 2017
  - Virgo joined on August 1st, 2017

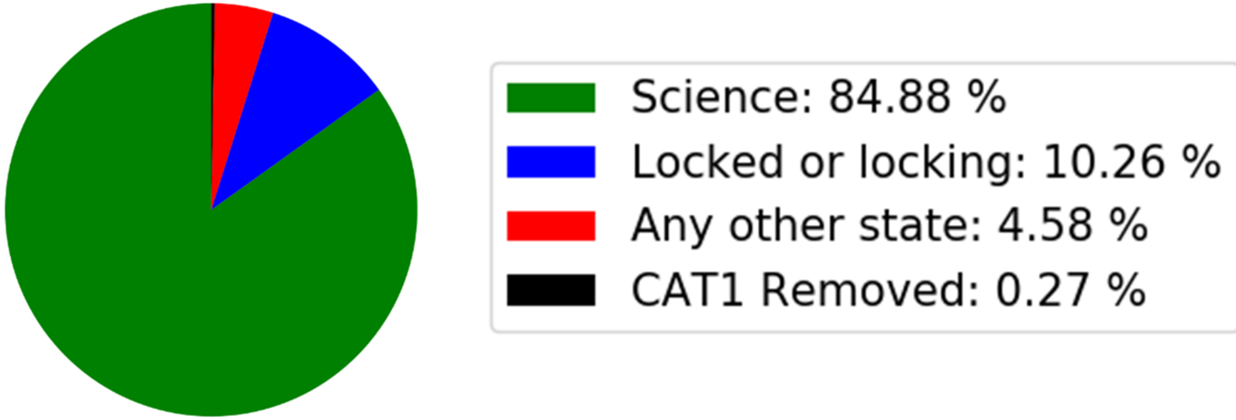
- O3: April 1st, 2019 → *ongoing*
  - Joint LIGO-Virgo data taking

- Future
  - O4, O5

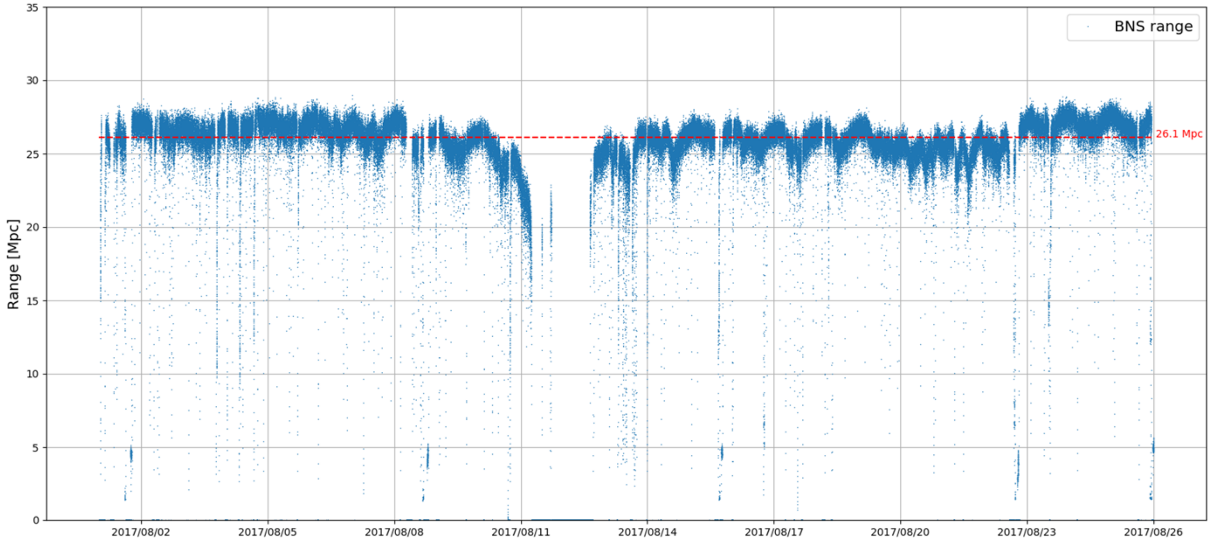


Virgo O2 performance and results

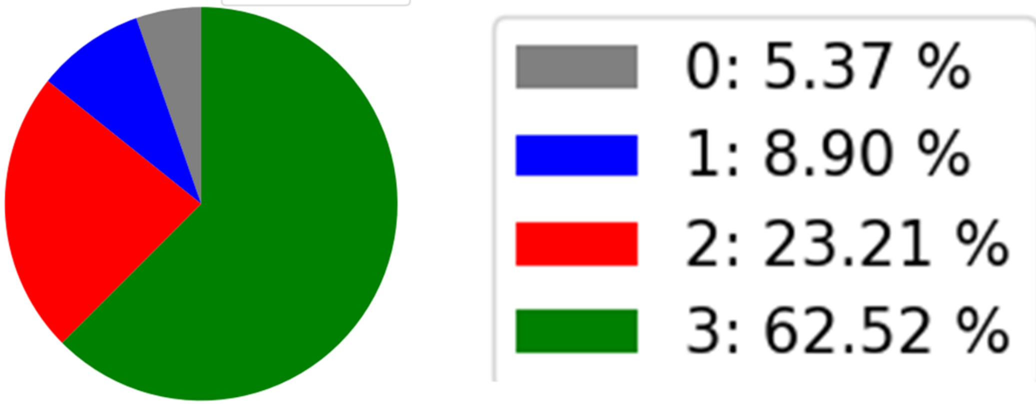
- Virgo duty cycle



- Virgo BNS range
  - ~26 Mpc

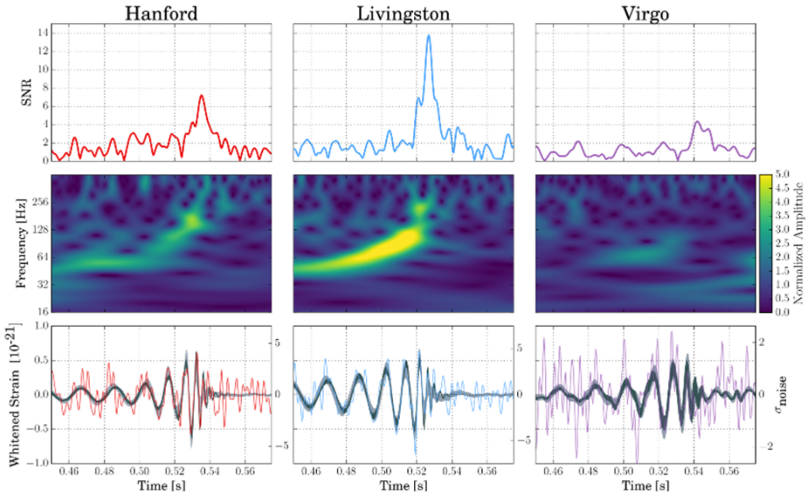


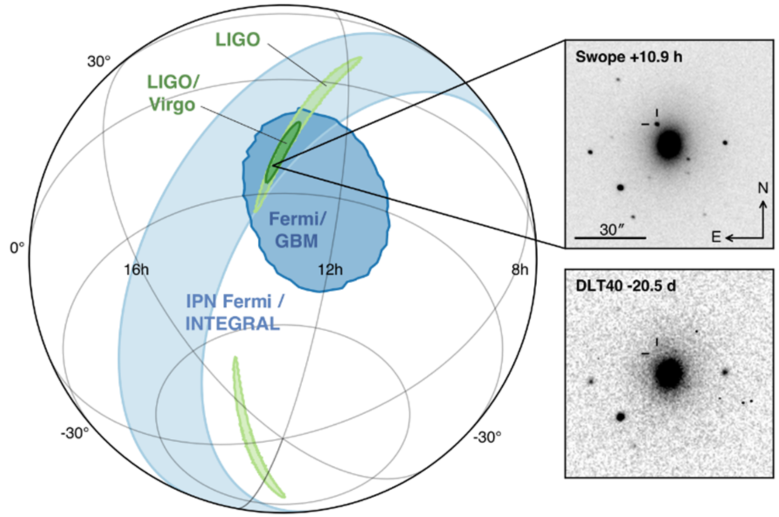
- LIGO-Virgo network duty cycle



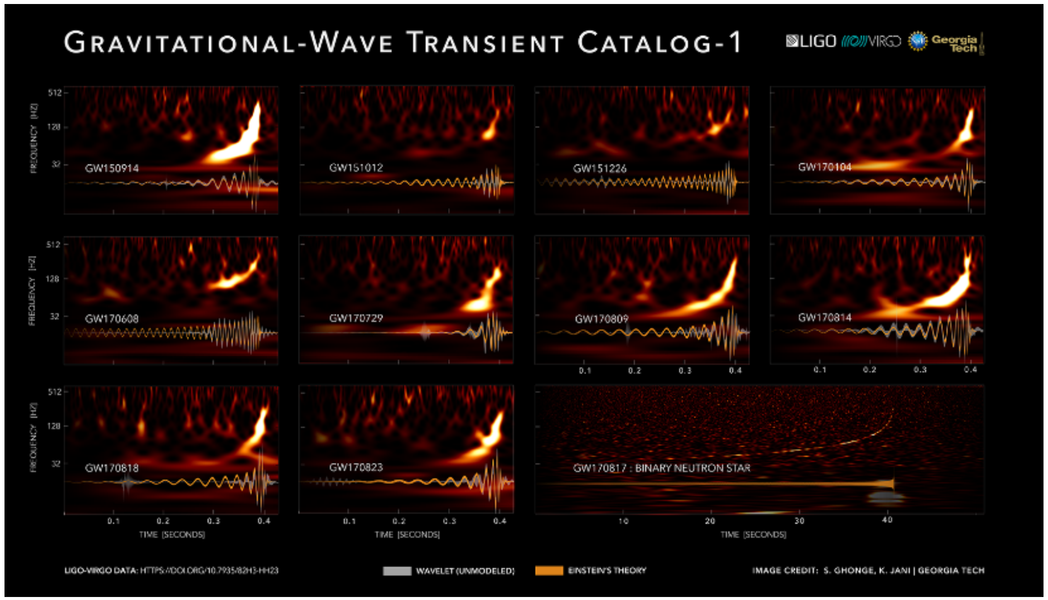
Scientific highlights

- GW170814
  - First 3-detector detection





- GW170817
  - First binary neutron star fusion
  - Multi-messenger astronomy with gravitational waves



- O1 + O2 : 11 events total
- "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", The LIGO Virgo Collaboration, arXiv:1811.12907, accepted for publication in PRX

Post-O2 commissioning period

- 3 months between the end of O2 and the start of the hardware upgrades
  - Starting point: the good (best at the time) O2 sensitivity

- Goals
  - Improve the detector configuration
    - Frozen during the August data-taking period
  - Get ready for upgrades and post-upgrade commissioning
    - Example: thermal compensation system (TCS)
  - Mitigate known noise sources, more noise hunting
    - Example: scattering light, spectral lines (mains, etc.)
  - Increase input power (~12 W in O2)

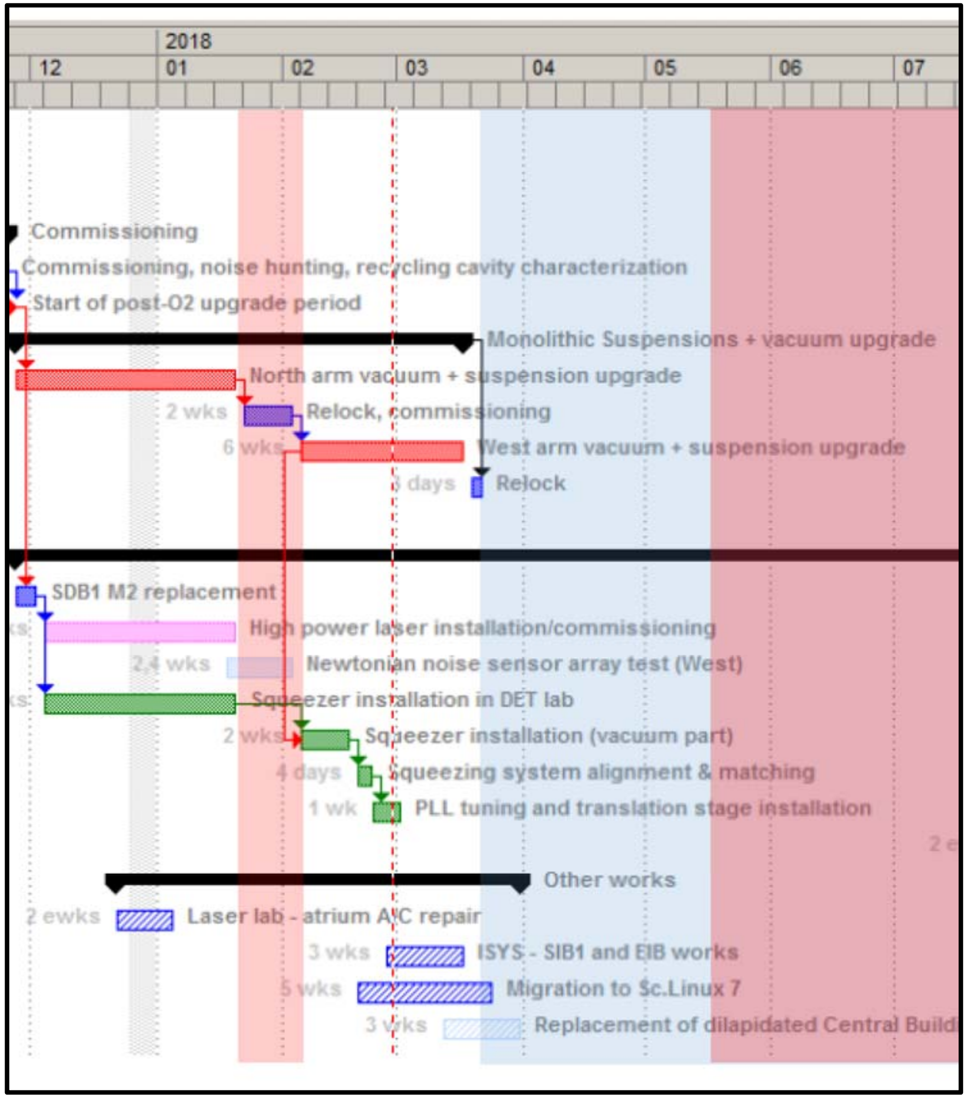
- Sequential activities
  - 2017/09: commissioning
  - 2017/10: noise hunting activities
  - 2017/11: TCS work and input power increase
    - Input power lowered after successul test – up to ~22 W

O2-O3 upgrades

- December 2017 → March 2018
- Fabry-Perot cavity test masses suspended again on fused silica fibers
  - In parallel: vacuum system improvement
- Installation of the AEI Hannover squeezer
  - Frequency-independent squeezing
- Injection system improvements
  - New amplifier allowing for the delivery of up to 60 W after input mode-cleaner
- Upgrades split into two periods
  - 3-week commissioning break in between
    - Control acquisition sequence
    - Calibration ↔ sensitivity
    - New noise sources

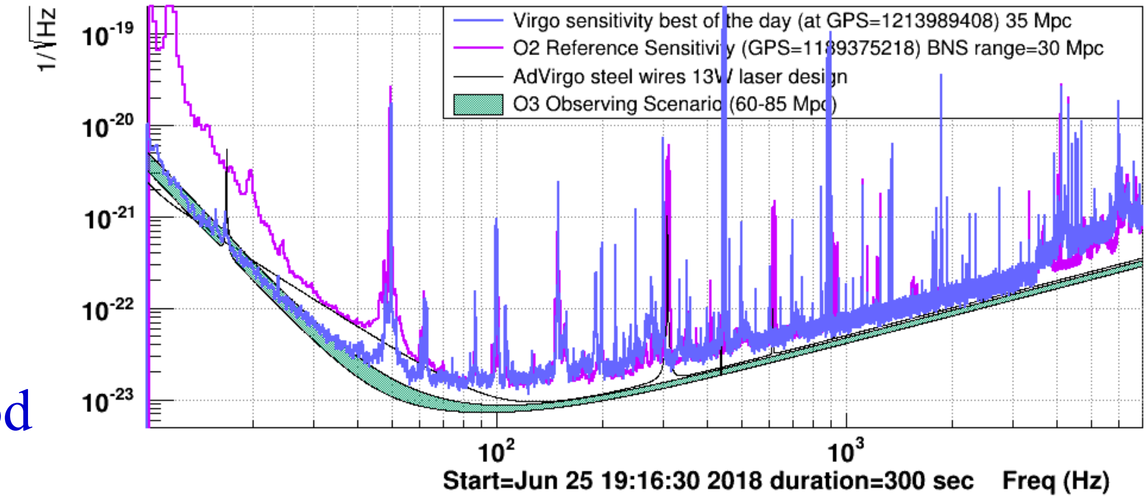
  } Checks

→ Successful: quick recovery, decent sensitivity restored in two weeks



O2-O3 upgrades

- Pre-O3 commissioning started mid-March 2018
  - O3 start planning at the time: Fall 2018
    → 6-7 months of commissioning foreseen
  - Then O3 start postponed to end of Winter 2018-2019



- Record sensibility end of June
  → BNS range ~35 Mpc
    - 12 W input power
    - Low frequency range quite good
  - Despite some delays / difficulties

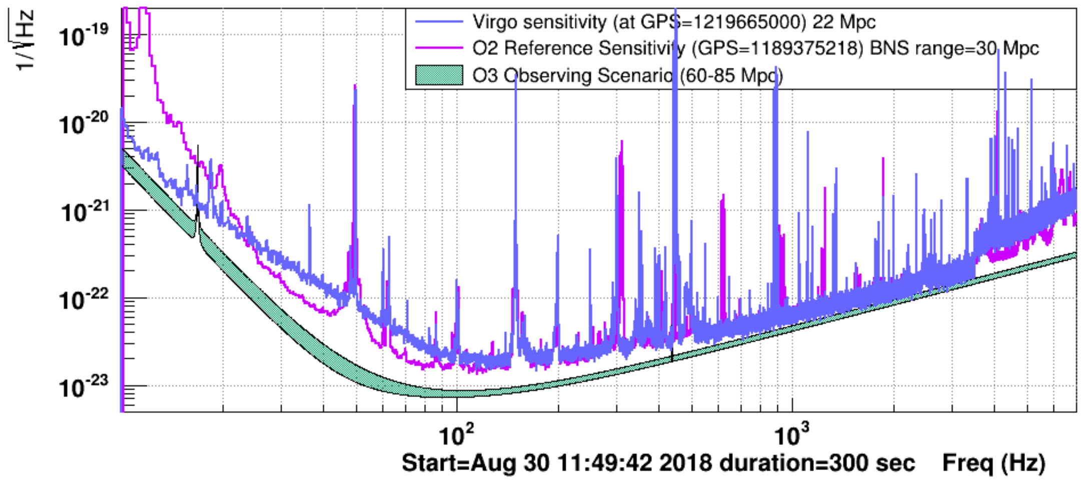
- Next in the plan: increase laser power up to 25 W
  - Similar power increase successfully tested the previous fall

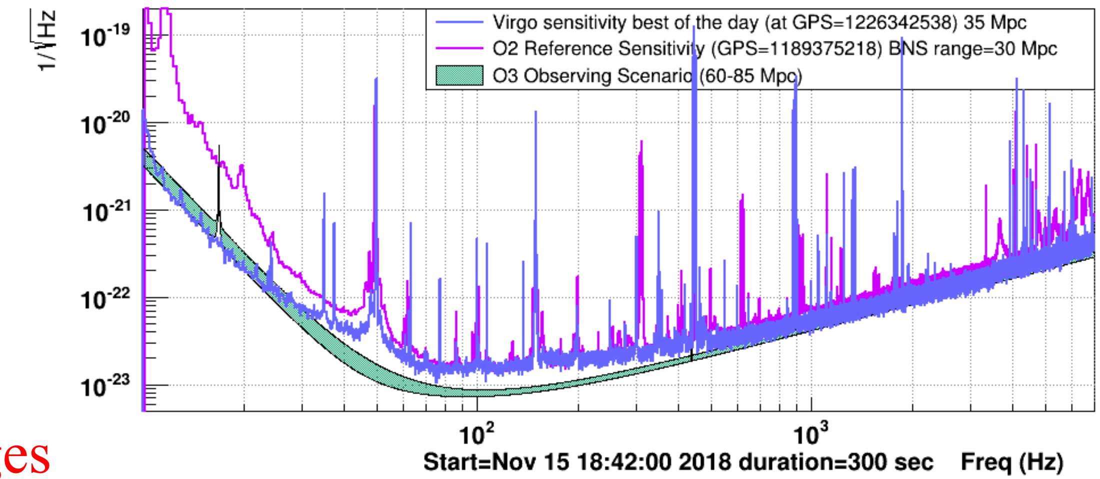
- Yet: many problems
  - Clearly a different detector: longer recovery / tuning periods
  - Hardware issues: scattering light needed mitigation, laser amplifier power failure, burning of the surface of the first output mode-cleaner, etc.

  → 2 months needed to partially recover low-noise operation

O2-O3 upgrades

- Significant sensitivity degradation at low frequency
  - Complete mystery at first
    → Collaboration-wide rallying



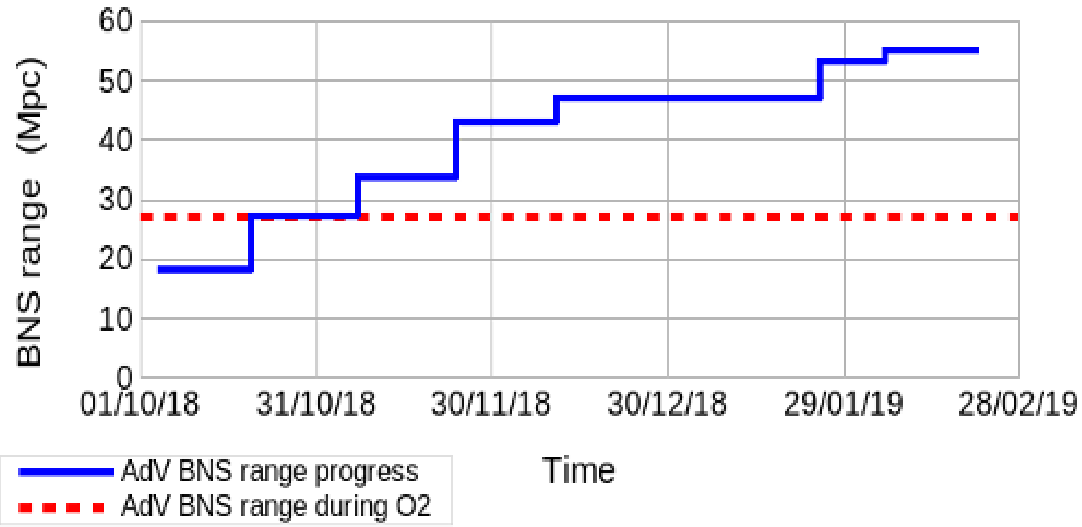


- Explanation found after ~1.5 month
  - Test masses are charged
  - Modified suspension coil drivers introduced common mode noise
    → Electrostatic actuation on top of expected coil-magnet driving

→ New electronics board design fixed the problem
  - Low-frequency sensitivity back

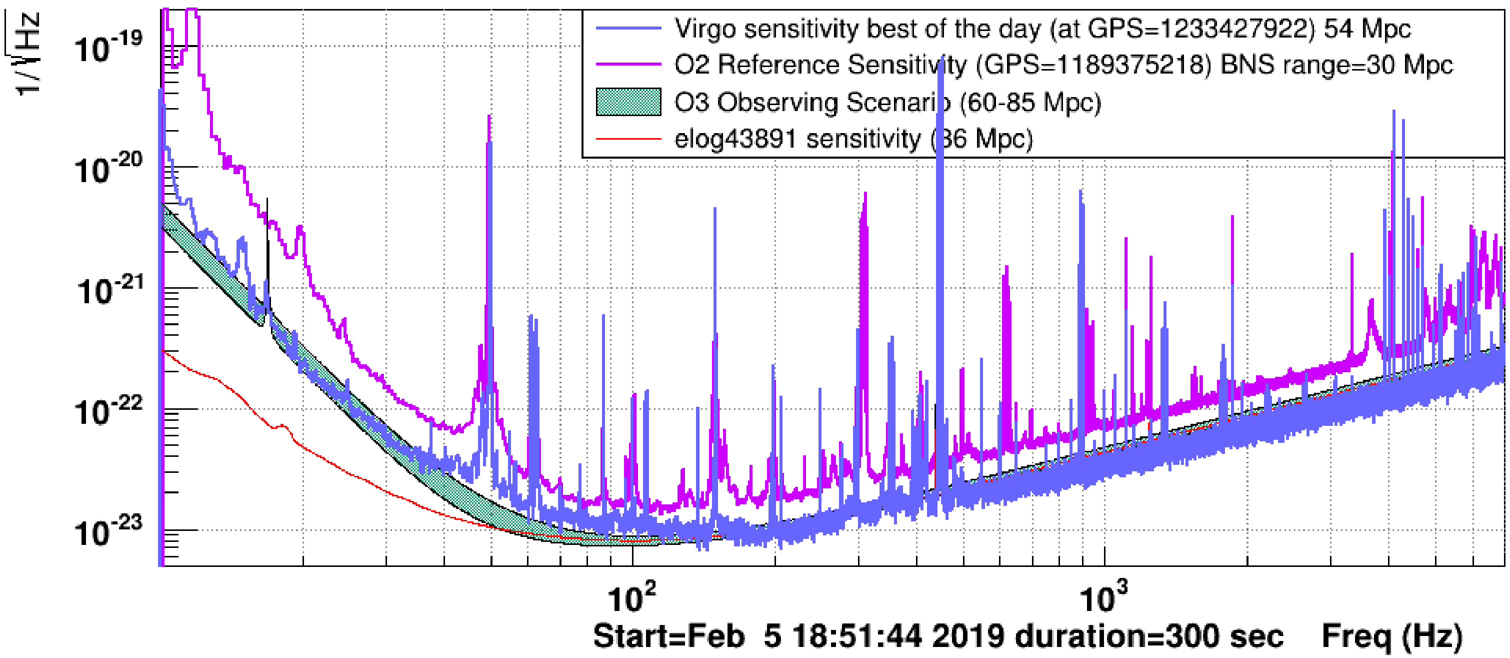
- Activities in progress
  - To understand the origin of the charges
    - Ion pumps!? First contact peeling off the mirror!?
  - To mitigate or discharge test masses
    - Ion gun studies in progress

O2-O3 upgrades



- Significant progress of the sensitivity over the next few months
  - Record BNS range [in Mpc] vs. time

- Best sensitivity achieved in early February
  - Input power: 18 W
  - Squeezing: 3 dB
    → See next slide



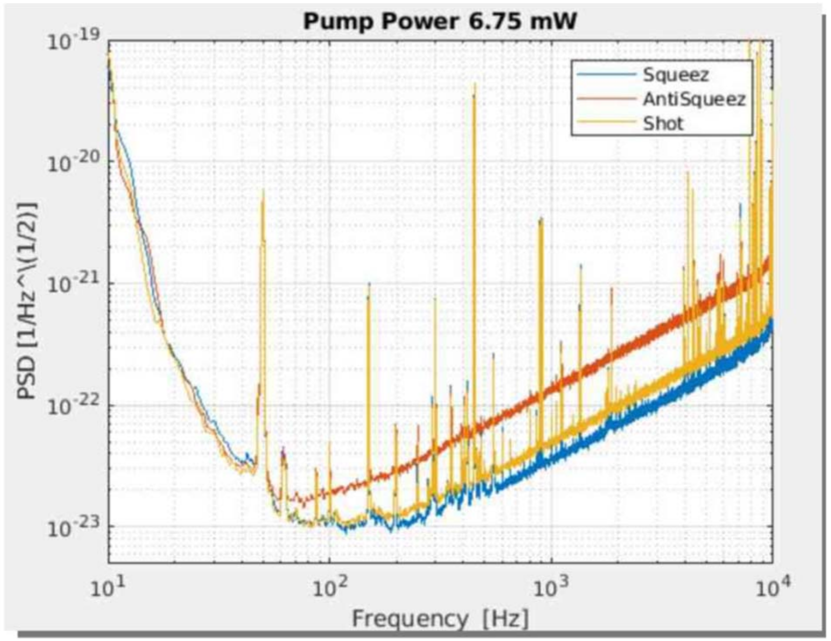
- Time for final tuning before start of data taking
  - Engineering Run 14: 1 month-long
  - Start of O3 on April 1st [!] 2019 @ 15:00 UTC

Squeezing

- Quantum noise due to vacuum state entering through the dark port

- Vacuum fluctuations follow Heisenberg uncertainty principle
  - Squeezed state of light currently used in Virgo: smaller uncertainty in phase w.r.t. amplitude, compared to coherent state of light
    - Generated by non-linear optics

→ Quantum noise limit beaten at high frequency
  - Shot noise



- AEI squeezer installed at EGO delivers about 3dB of squeezing
  - 2-3 Mpc gain for the BNS range

  → Laser power ~doubled
  - No impact at low-frequency
    - Other noises are dominant

- Quantum noise due t … port
- Vacuum fluctuations
  - Squeezed state of l … oherent state of light
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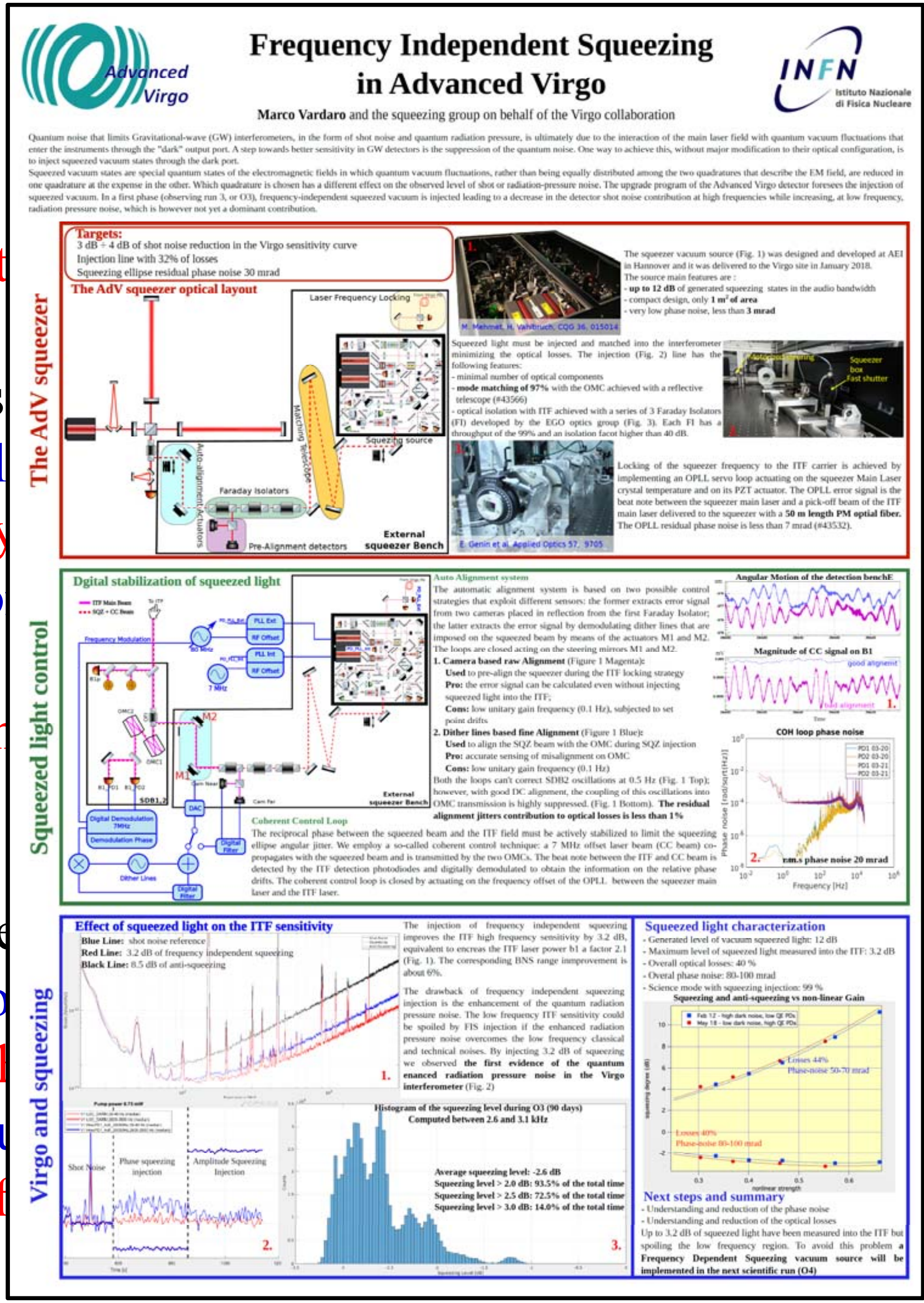
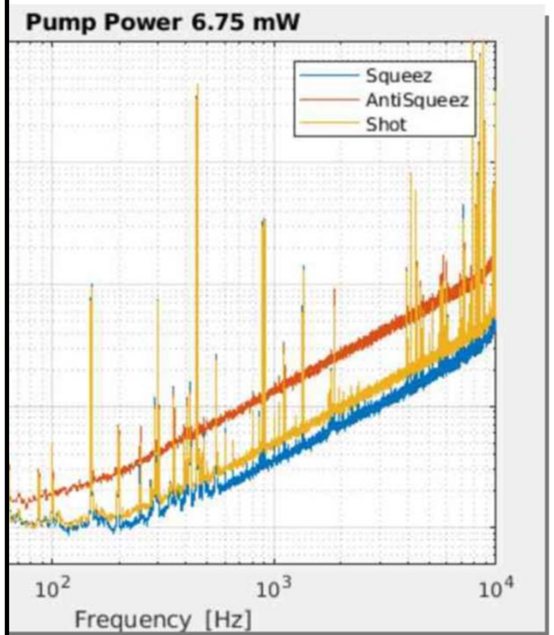


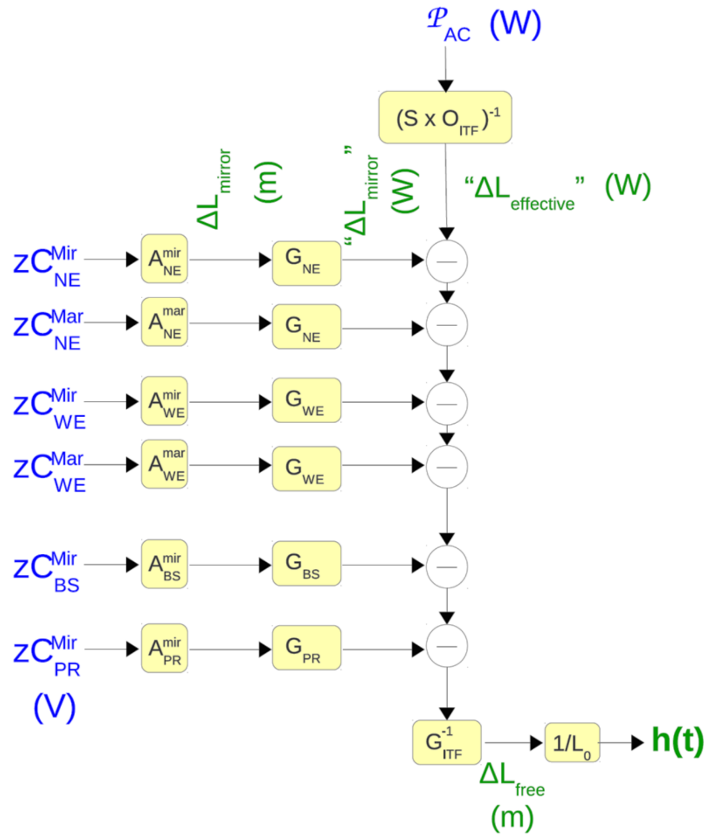


See Marco Vardaro's poster
"Frequency Independent Squeezing in Adv-Virgo"

O3

O3 sensitivity

- Gravitational-wave channel h(t) computed in frequency domain by subtracting calibrated correction signals from output port photodiode
  - Calibration: optical transfert function measurements
  - Laser wavelength used as benchmark
  - Gain evolution measured using calibration lines
  - Online subtraction of clearly identified noise sources for which witness channels exist

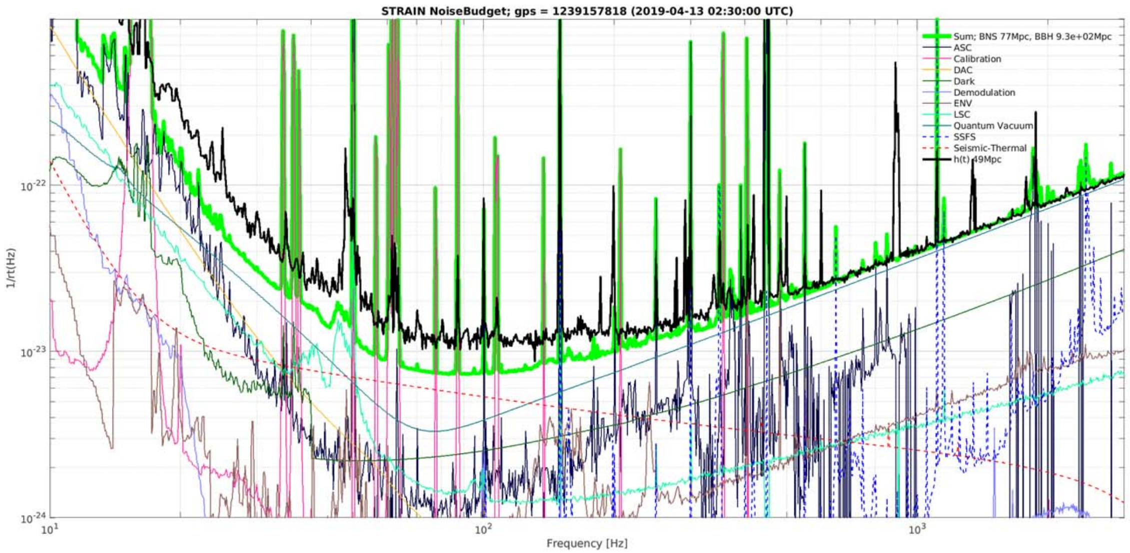


→ Uncertainties for O3 online reconstruction
  - ±5% in amplitude
  - ± 35 mrad ⊕ ± 10 μs in phase
  - Over a wide frequency band: 20 Hz → 2 kHz

See Dimitri Estevez's talk
“Intercalibration Of Advanced Ligo And Advanced Virgo For The Third Observing Run O3”
in the C2 parallel session

O3 sensitivity

- A complementary approach: the noise budget
  - Quadrature sum of modelled individual noise contributions
  - Transfer function measurements to get couplings



→ BNS range: ~30 Mpc difference between noise budget and actual sensitivity

- High frequency range: good match between prediction and measurements
- Low frequency range: commissioning stopped when reaching O3 goals
  - ◆ Thermal noise may be higher due to damaged mirror anchors
- Medium frequency range: empirical “flat” noise contribution added
  - ◆ Origin unknown in spite of several hypothesis / tests

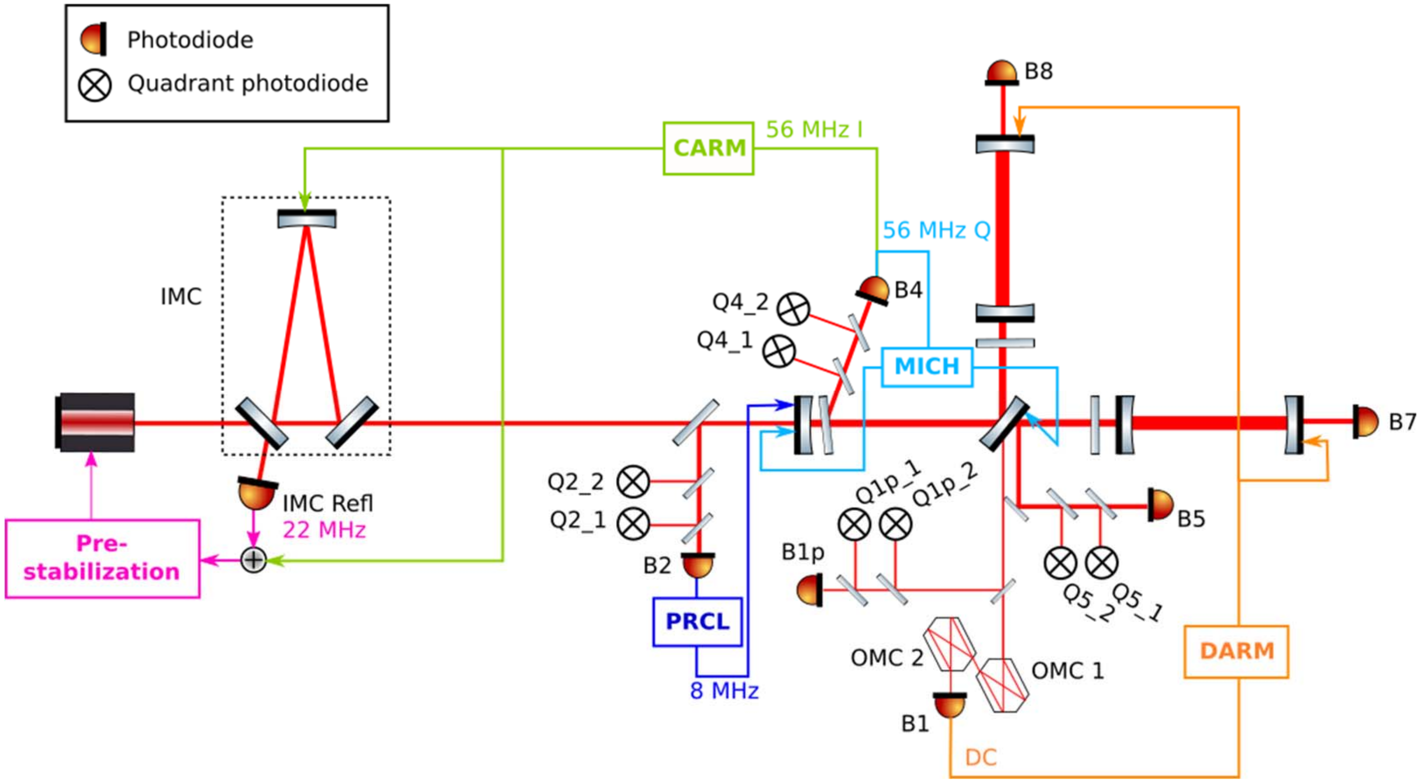
  → Mandatory to address and fix before switching to Advanced Virgo Plus

Locking Virgo

- Control acquisition ('locking') and conservation ('lock') over long periods
  - Photodiodes: sensing
  - Filtering
  - Actuation

- 4 Longitudinal degrees of freedom

- Angular control
  - Key to stability and duty cycle

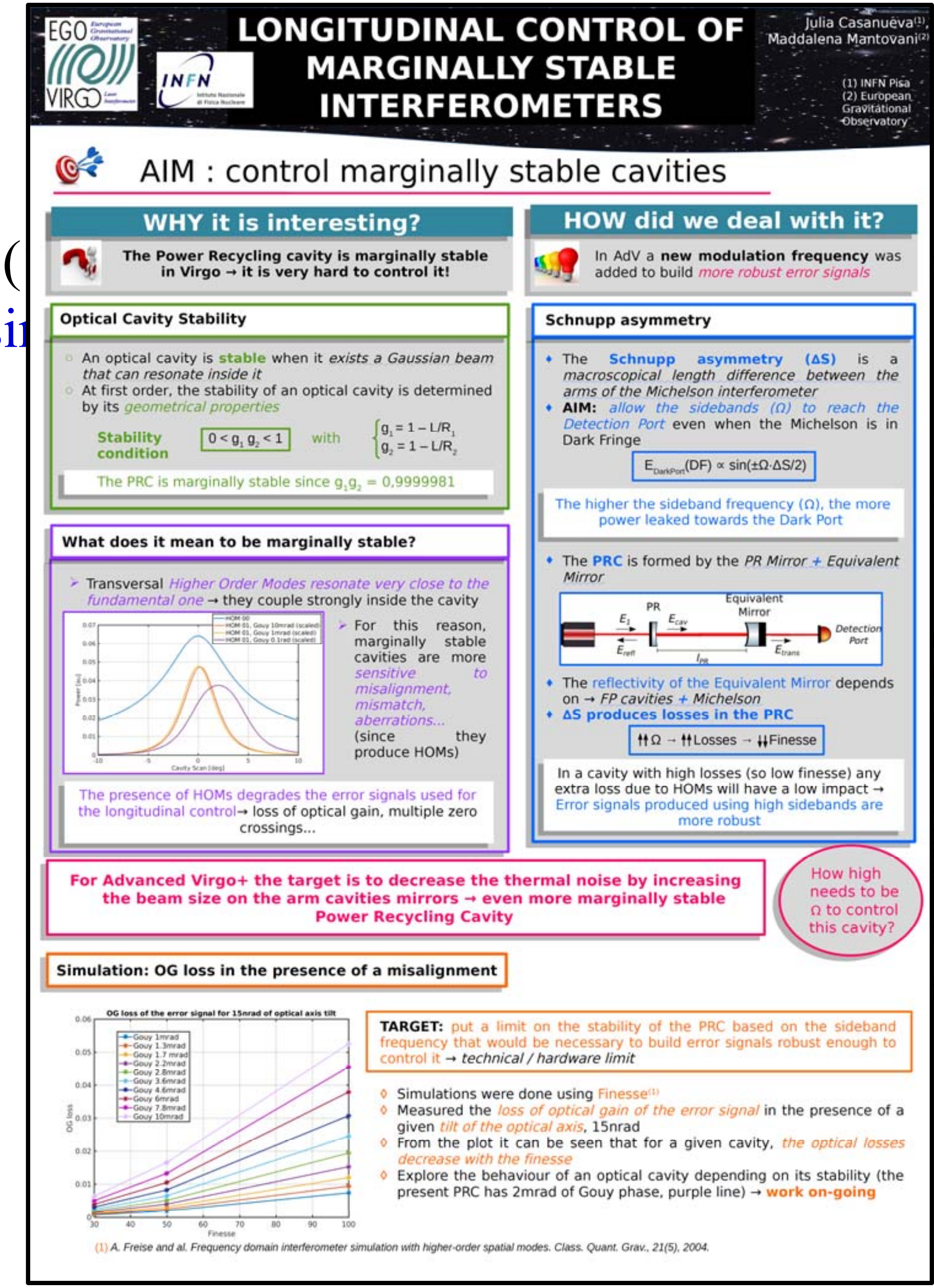


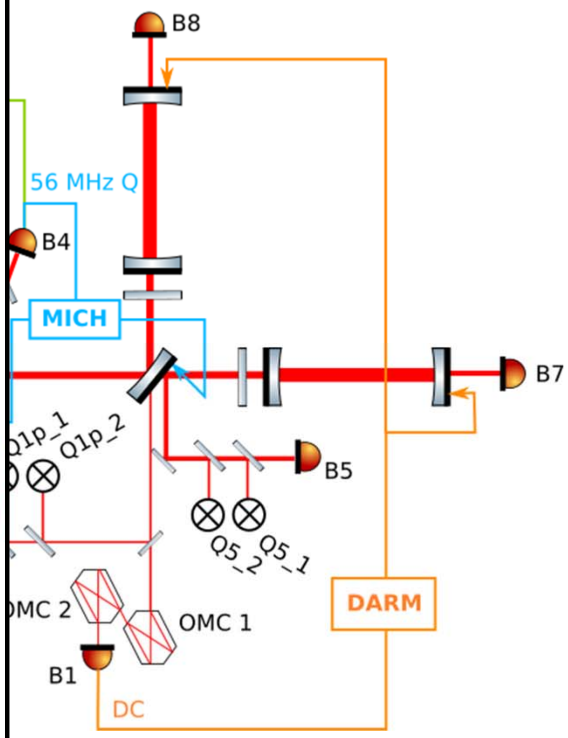
See Maddalena Mantovani's talk
"The Advanced Virgo Interferometer Sensing And Control For The O3 Scientific Run"

- Control acquisition (… long periods
  - Photodiodes: sensi…
  - Filtering
  - Actuation

- 4 Longitudinal degrees of freedom

- Angular control
  - Key to stability and duty cycle



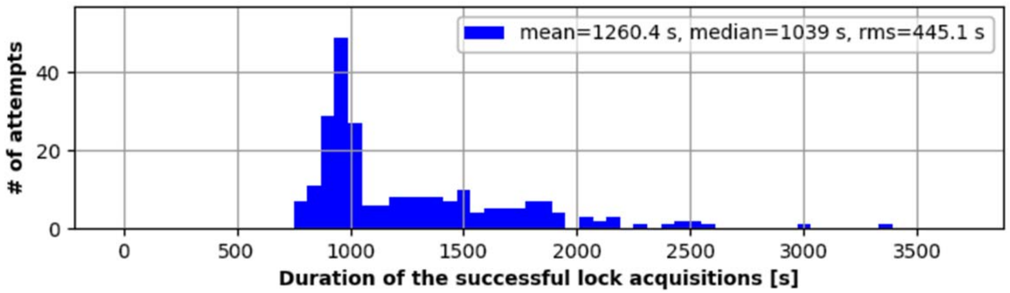


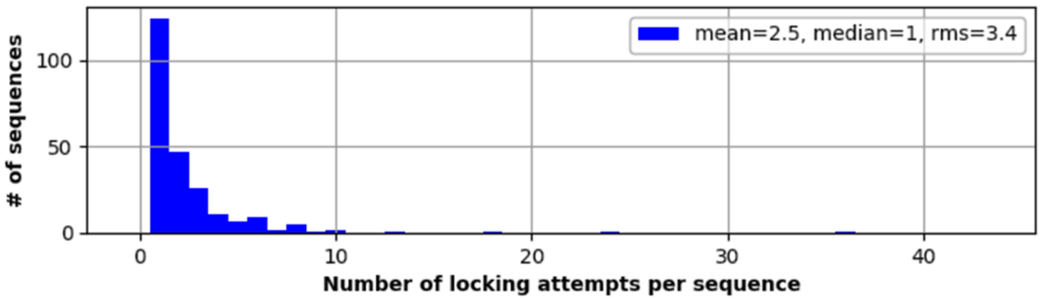
See Julia Casanueva's poster
"Longitudinal Control Of Marginally Stable Interferometers"

Locking Virgo

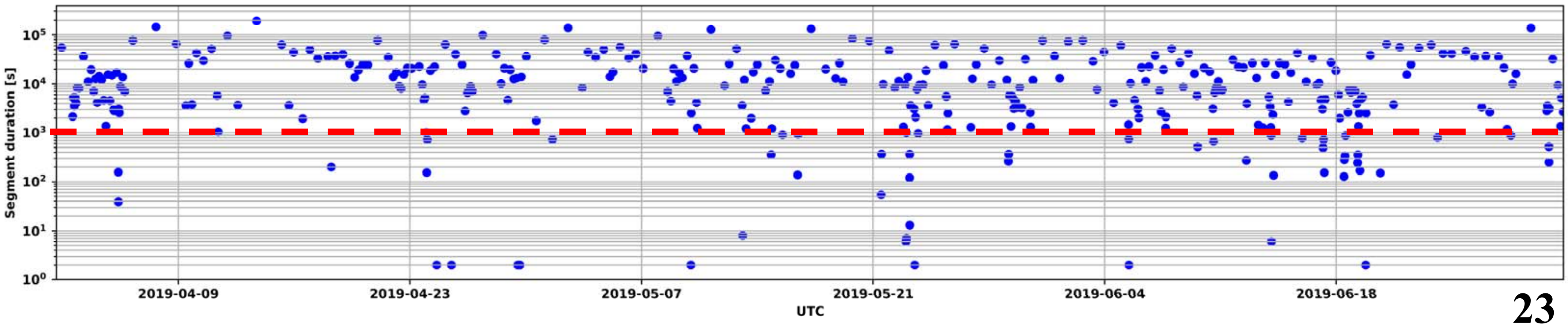
- Locking performance
  - ~20 minutes to acquire full control of the detector
  - 1-2 attempts to achieve that control

  → Rather quick and efficient



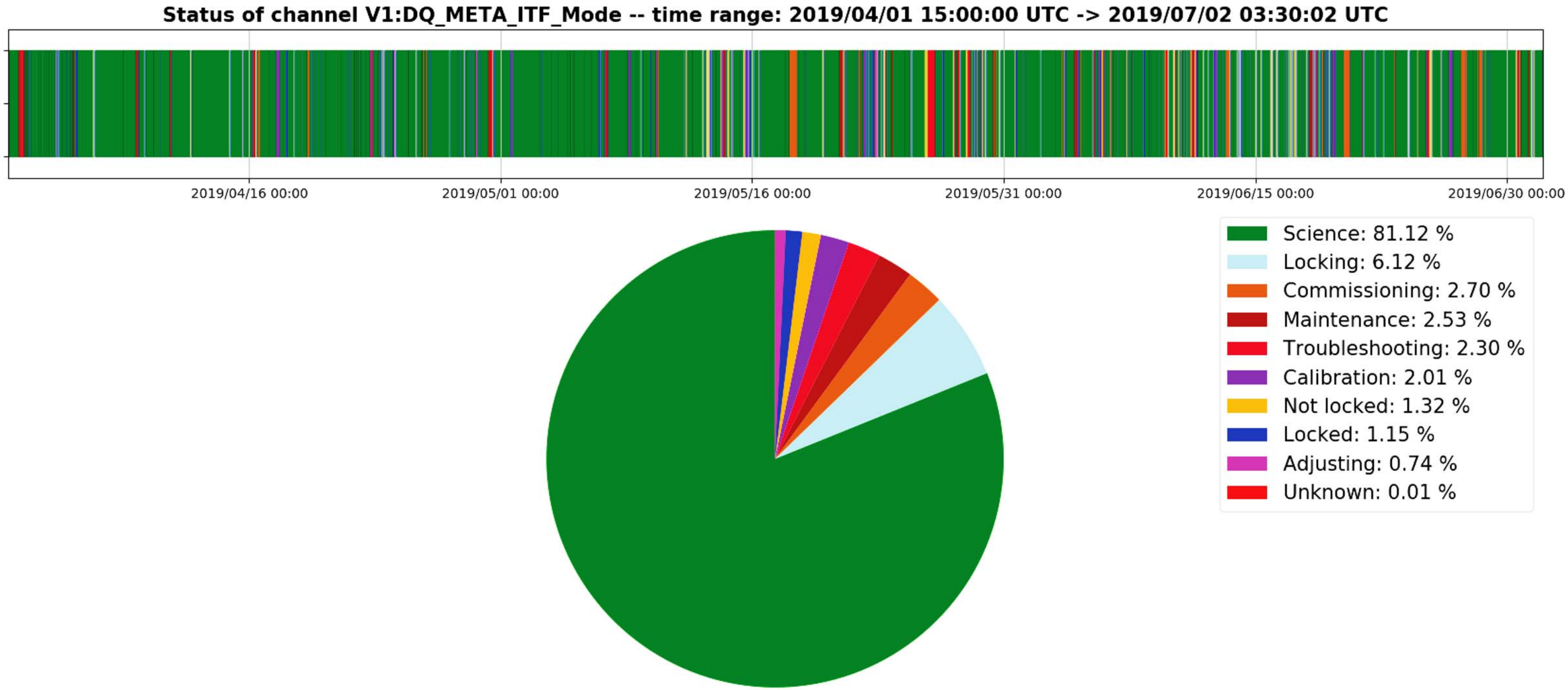


- Lock stability
  - Lock segments lasting several hours
    - Up to a couple days



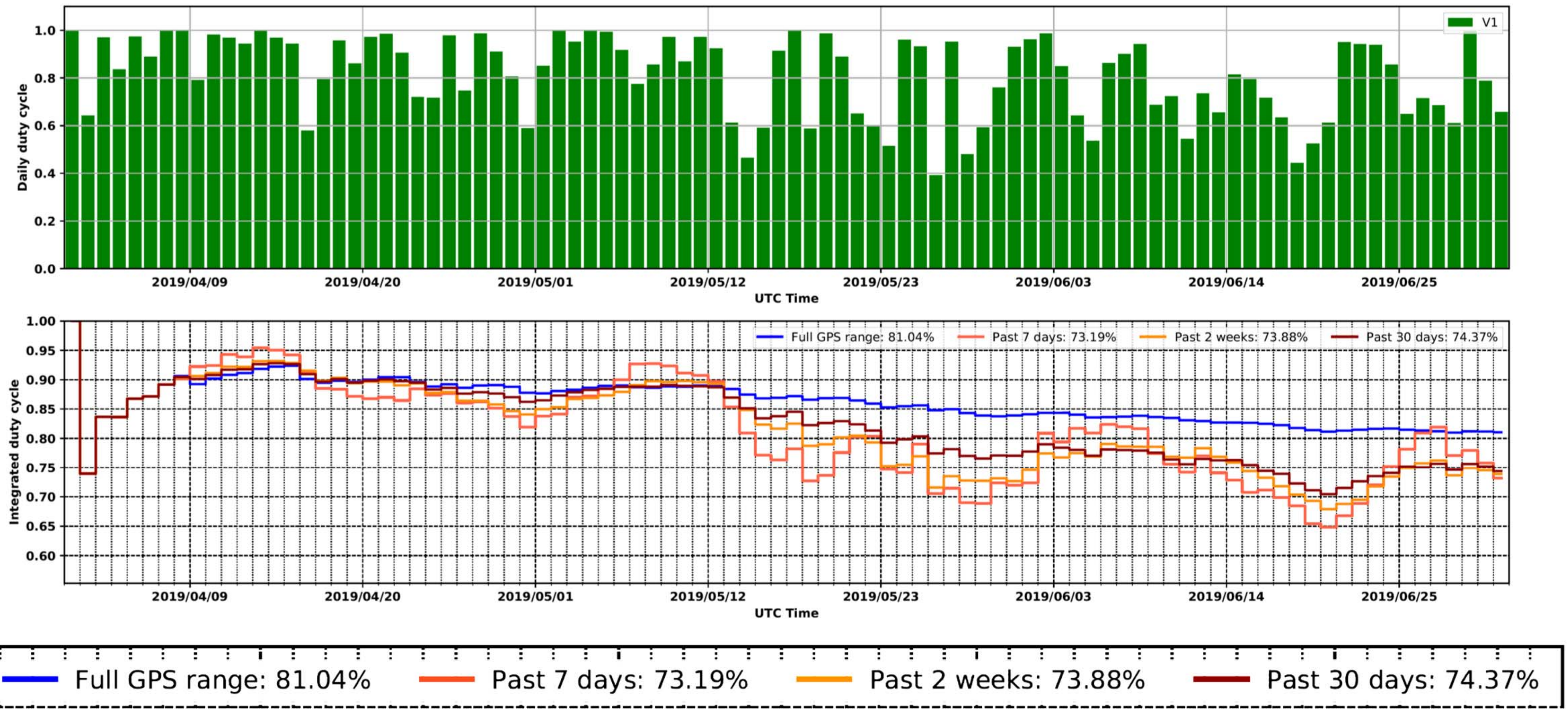
Virgo performance, 3 months onto the O3 run

- Duty cycle
  - Based on data from the Virgo automation system
    - 'Metatron' based on LIGO's Guardian framework
  - Duty cycle averaged over 3+ months



Virgo performance, 3 months onto the O3 run

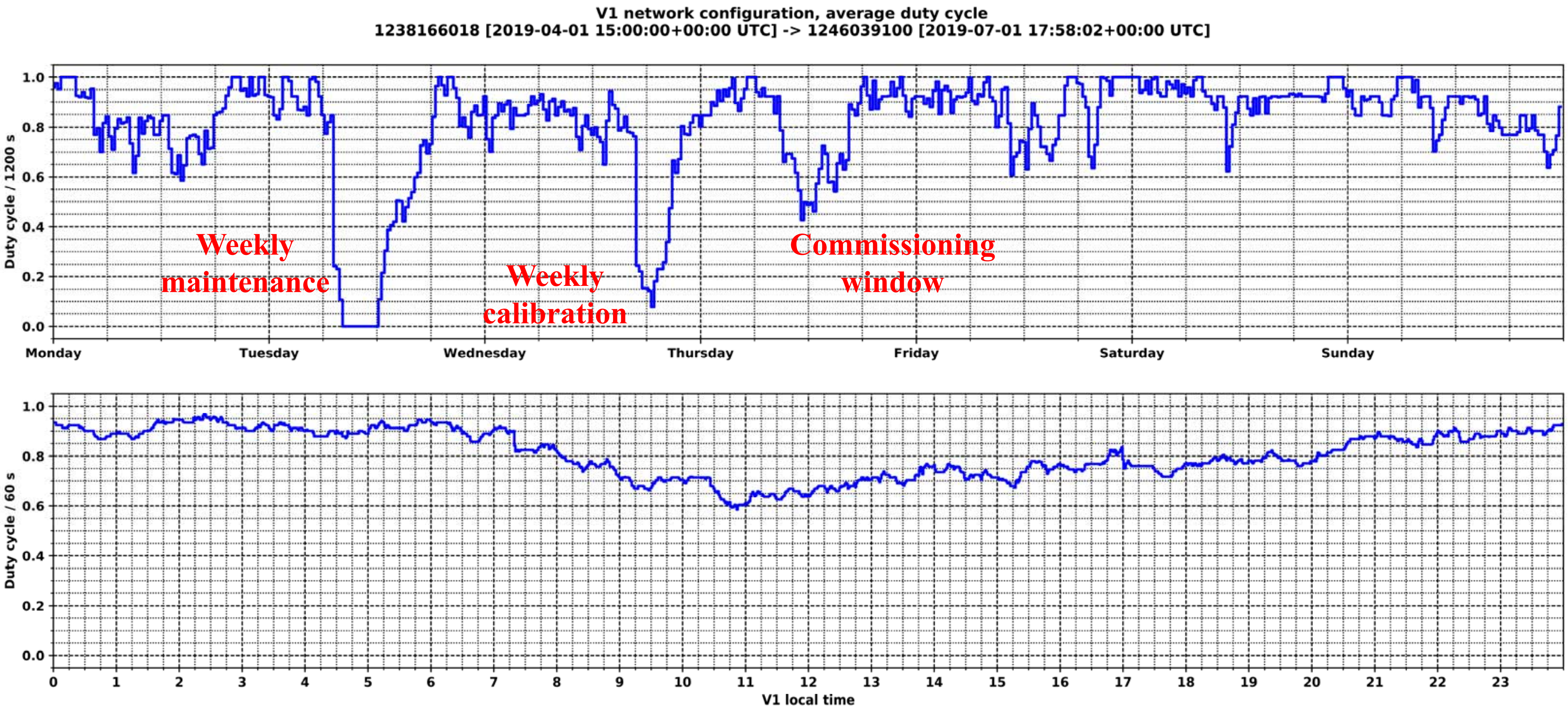
- Duty cycle evolution
  - Top histogram: daily duty cycle
  - Bottom plot: integrated duty cycles over the past N days



→ Slow but steady decrease over time
  - Restoring beginning of the run performance is a goal for the coming weeks

Virgo performance, 3 months onto the O3 run

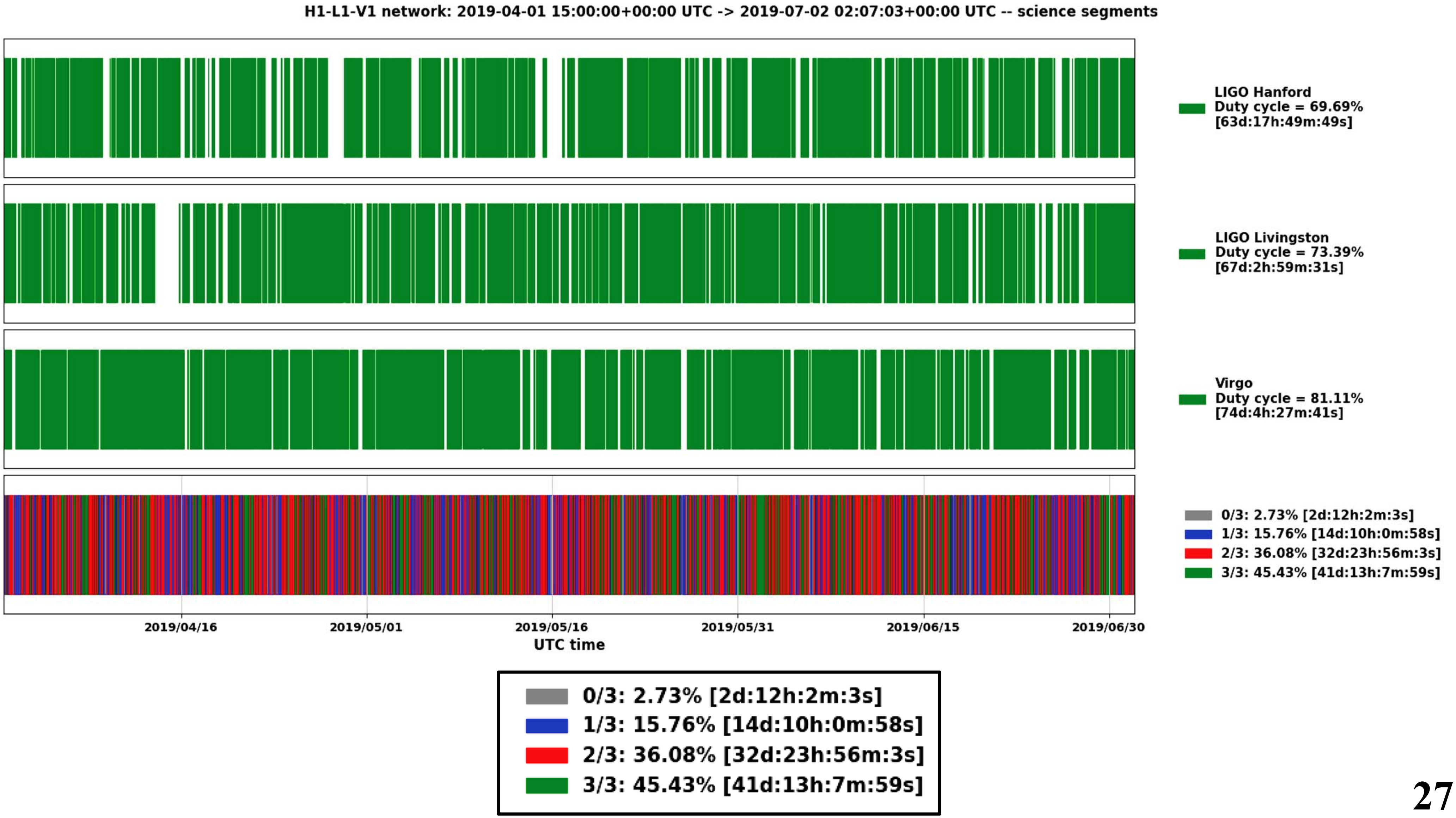
- Virgo: ‘wrapped’ duty cycle on a day or a calendar week
  - Top plot: calendar week
  - Botton plot: a day



- Averaged over the whole data taking period

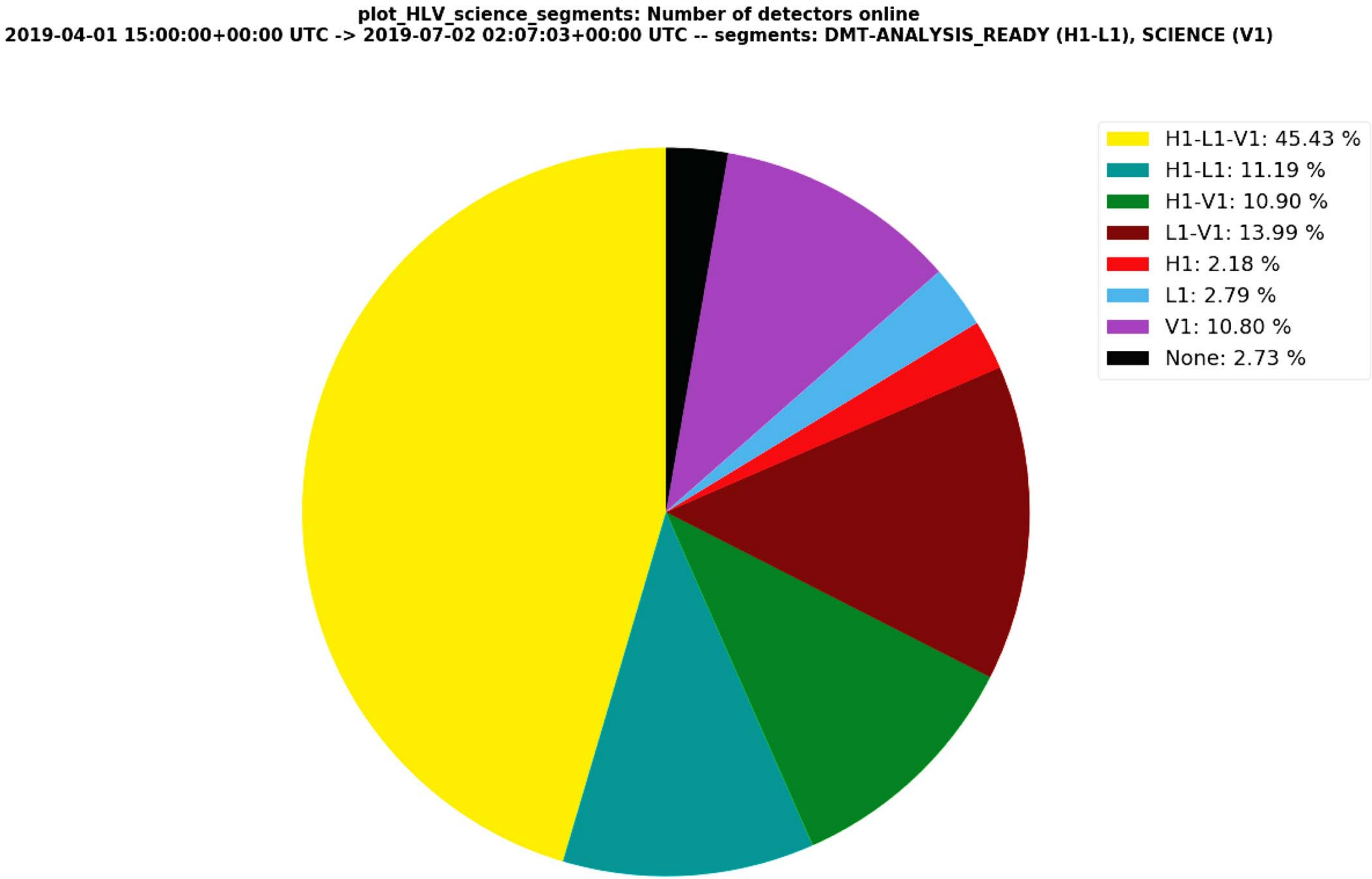
Virgo within the LIGO-Virgo 3-detector network

- O3 duty cycles
  - Exclusive categories



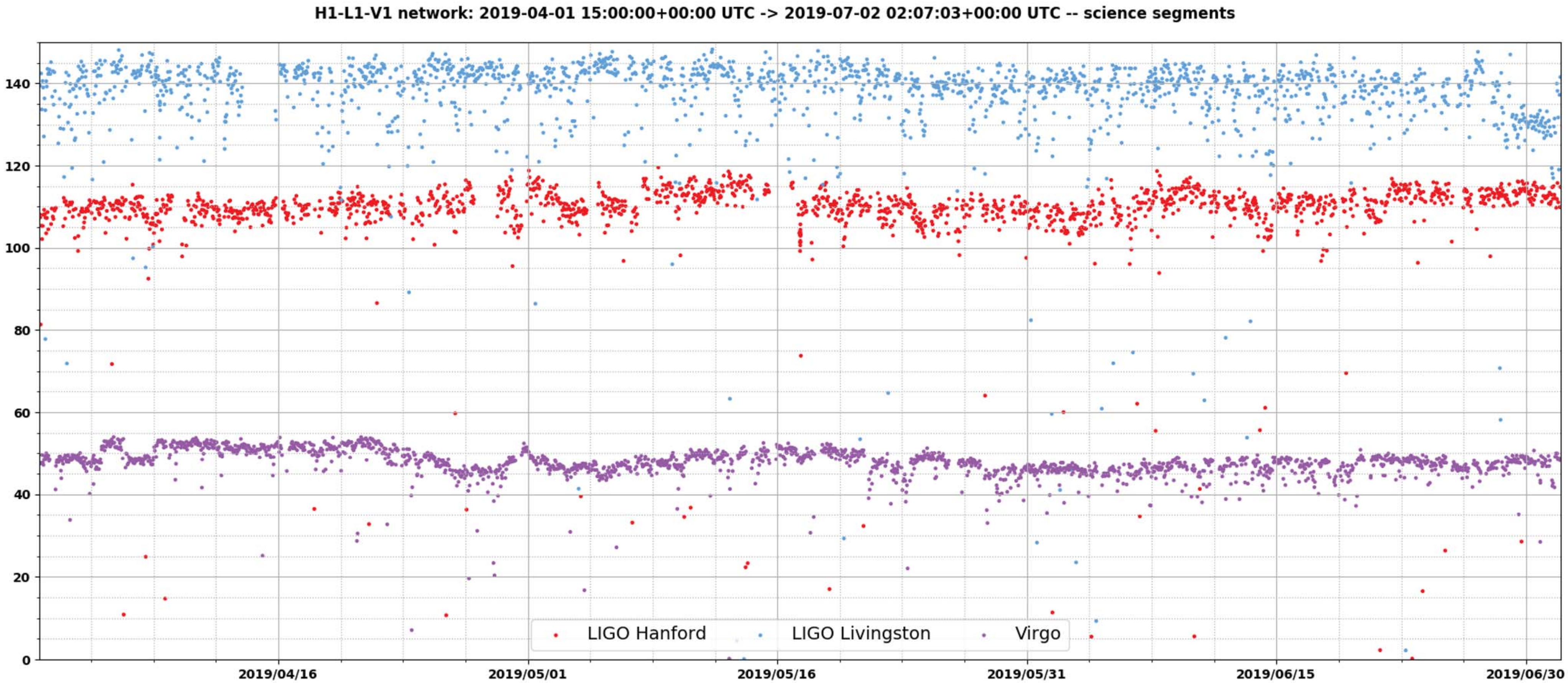
Virgo within the LIGO-Virgo 3-detector network

- Pie chart covering the whole O3 run – mutually exclusive categories



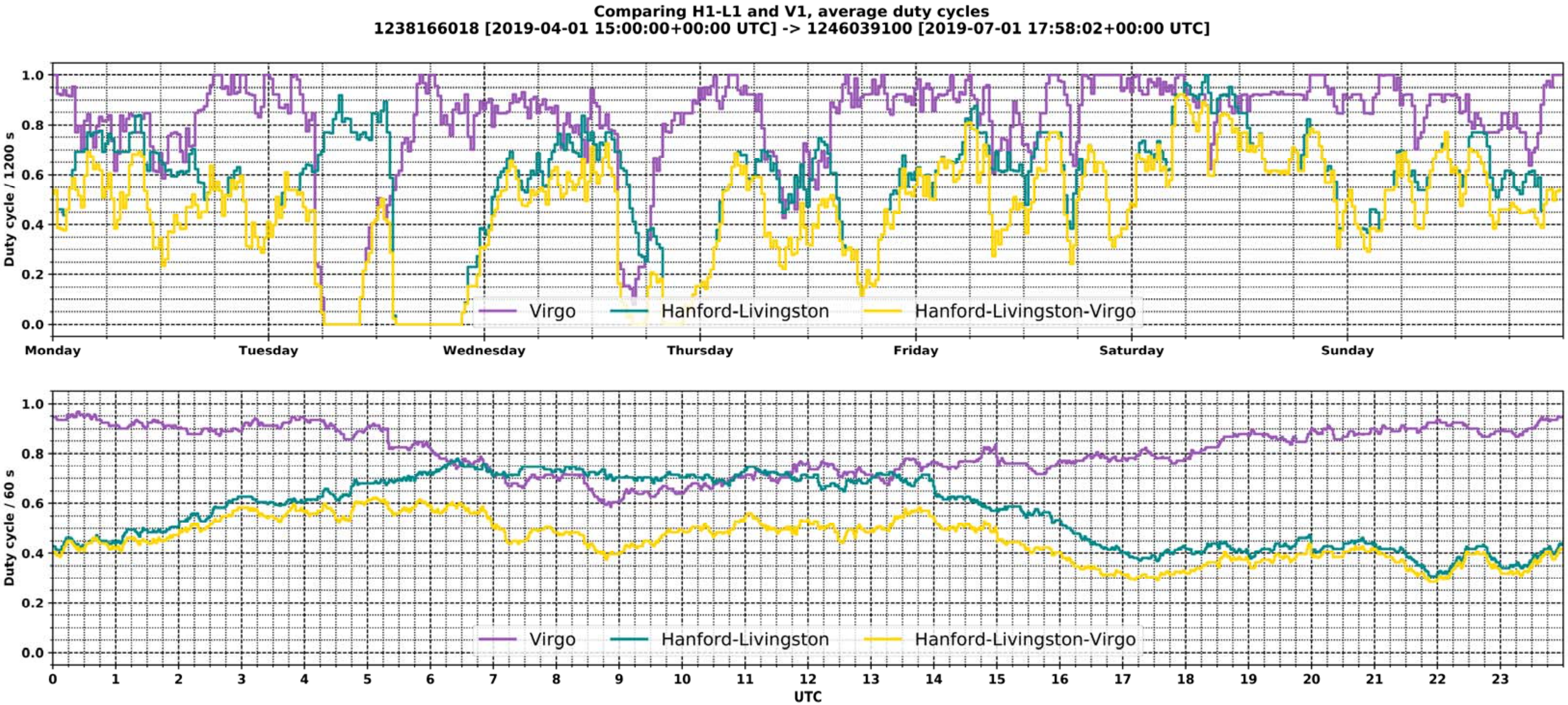
Virgo within the LIGO-Virgo 3-detector network

- BNS range comparison
  - Quite good long-term stability



Virgo within the LIGO-Virgo 3-detector network

- Time difference does matter!
  - The two LIGOs and Virgo are all more efficient at (local) night



Public alerts

- Reference: GraceDB – https://gracedb.ligo.org/latest

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
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S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
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S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
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S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
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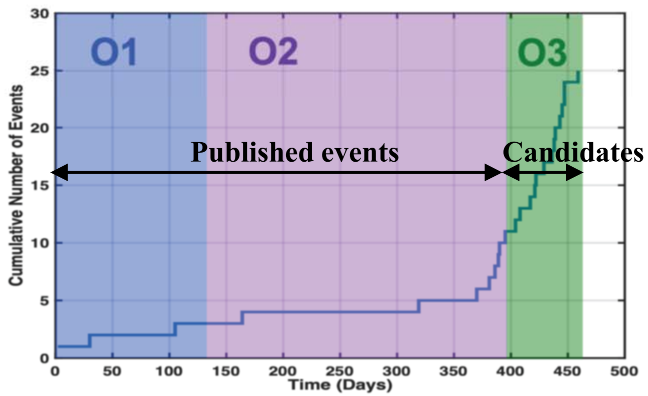
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

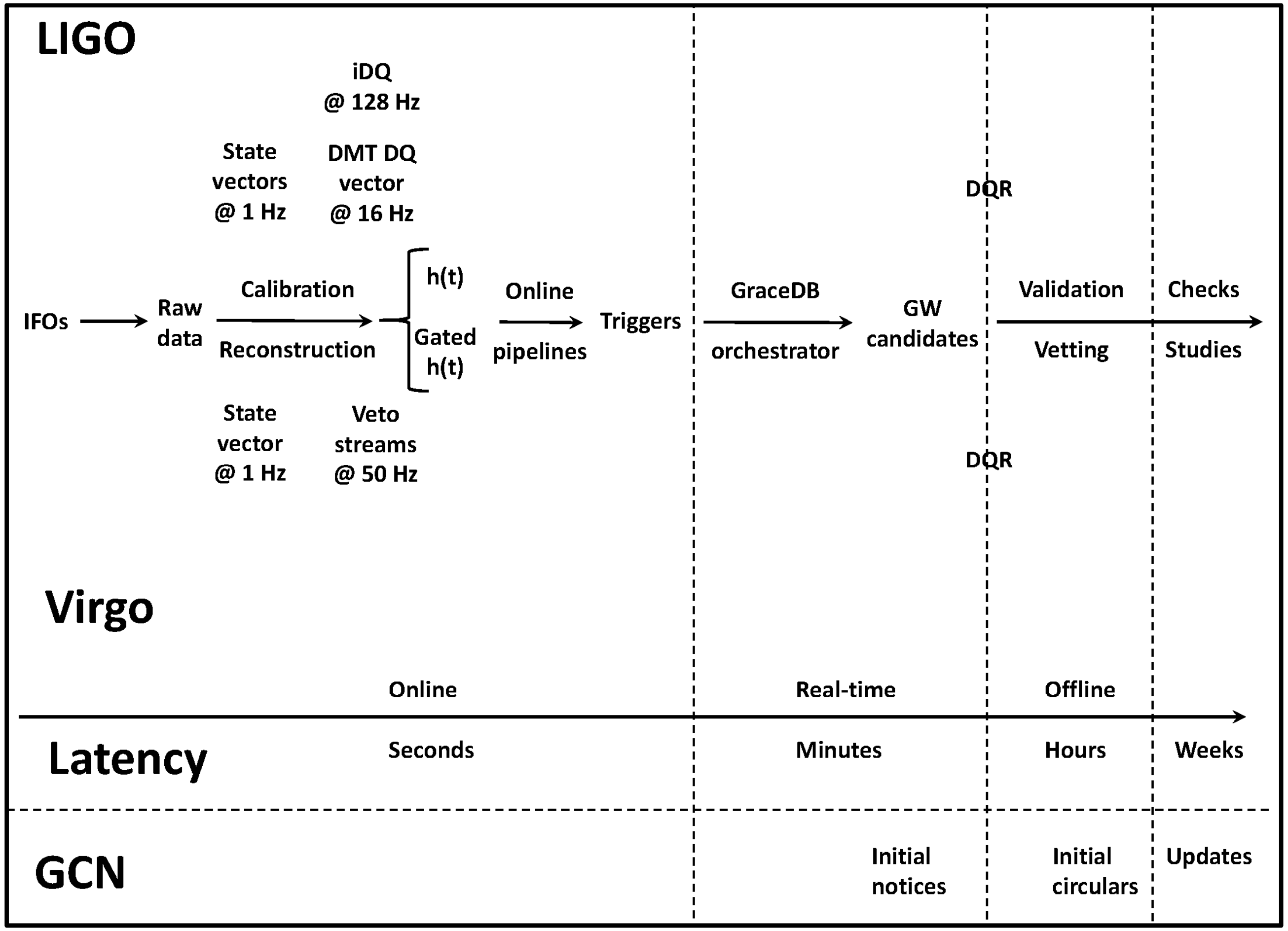
LIGO VIRGO LSC

- 19 public triggers as of July 4th, 2019
  - 3 retracted
- Mainly binary black hole merger candidates
  - Some may involve lighter components
- Offline analysis in progress



Data quality

- LIGO-Virgo dataflow
  - From the detectors to the validation of offline datasets and of individual events
  - Low-latency component significantly improved for O3 in order to deal with open public alerts



See NA's talk
"Virgo Detector Characterization Activities During The O3 Run: From Latency To Gravitational-Wave Event Validation"
in the C2 parallel session last Monday

O3 planning

- Initial plan: 12 months running
  - April 2019 → March 2020

- Announcement at the last LV-EM Open Forum Telecon
  - Potential 1-month commissioning break
  - Starting late September – early October

→ Updated planning to be announced soon

Conclusion

Beyond O3: Advanced Virgo Plus

- Next major upgrades for Virgo
  - Goal: to increase the BNS range well above 100 Mpc
    - Long term: above 200 Mpc
- Two phase-project
  - Phase 1: in between O3 and O4 runs
    - Quantum noise reduction + preparation for phase 2
      - → Signal recycling mirror installation
      - → Frequency-dependent squeezing
      - → Higher laser power
      - → Newtonian noise cancellation
      - \+ Additional works
  - Phase 2: in between O4 and O5 runs
    - Switch to larger test masses with improved coating + higher laser power
- 110+ FTEs, several M€ project
- International committee review well-advanced
  - Project ready to start upon approval

See Raffaele Flaminio's talk
"Towards Advanced Virgo Plus"


Advanced Virgo Plus (AdV+)

Design Report

07 June 2019

The Virgo Collaboration

Outlook

- O3 run well underway
  - Virgo taking data since day 1
  - Significant improvement of BNS range w.r.t. O2
  - High duty cycle

→ Challenge: keep and even try to increase performance over a 1 year-long run

- Future already being prepared
  - Advanced Virgo Plus project
    - 2-phase upgrade
    - O4 & O5 data taking periods
  - Third-generation detector
    - Einstein telescope

→ Ultimate goal: get the best sensitivity achievable on the EGO site