

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](#)



Outline

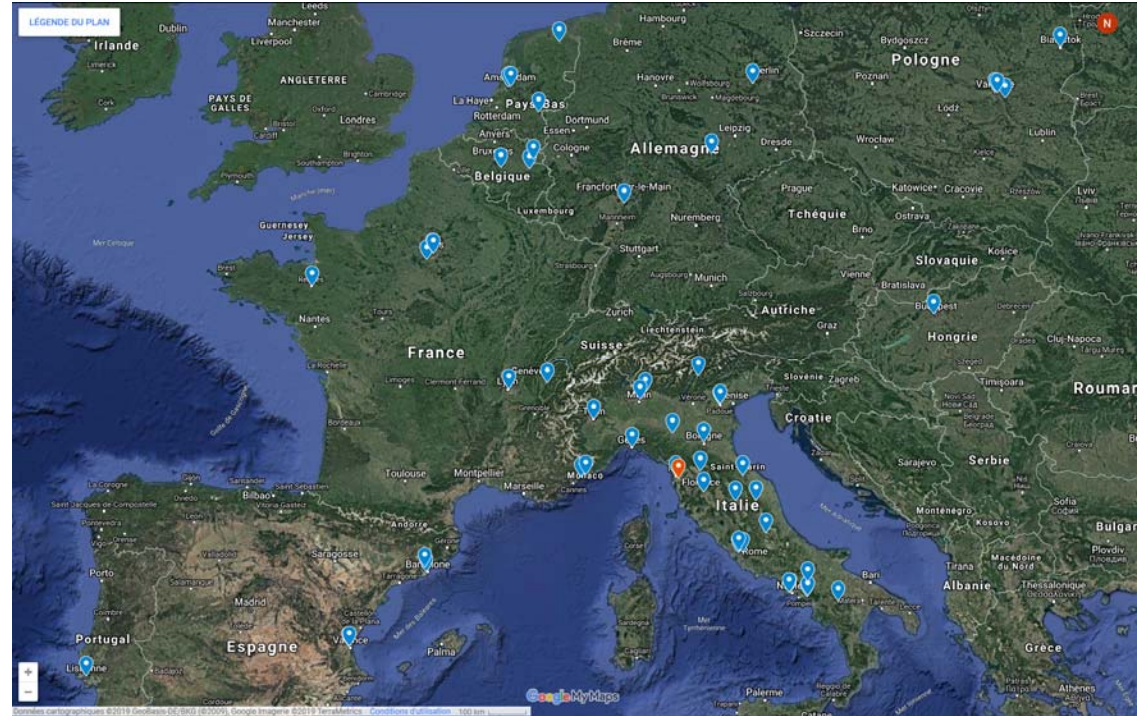
- **Introduction**
 - Virgo collaboration
 - Virgo detector
 - Global network of gravitational-wave detectors
- **From O2 to O3**
 - Status at the end of O2
 - Post-O2 commissioning period
 - O2-O3 upgrades
 - Noise hunting and pre-O3 commissioning
- **O3**
 - Performance 3 months onto the run
 - Plans
- **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

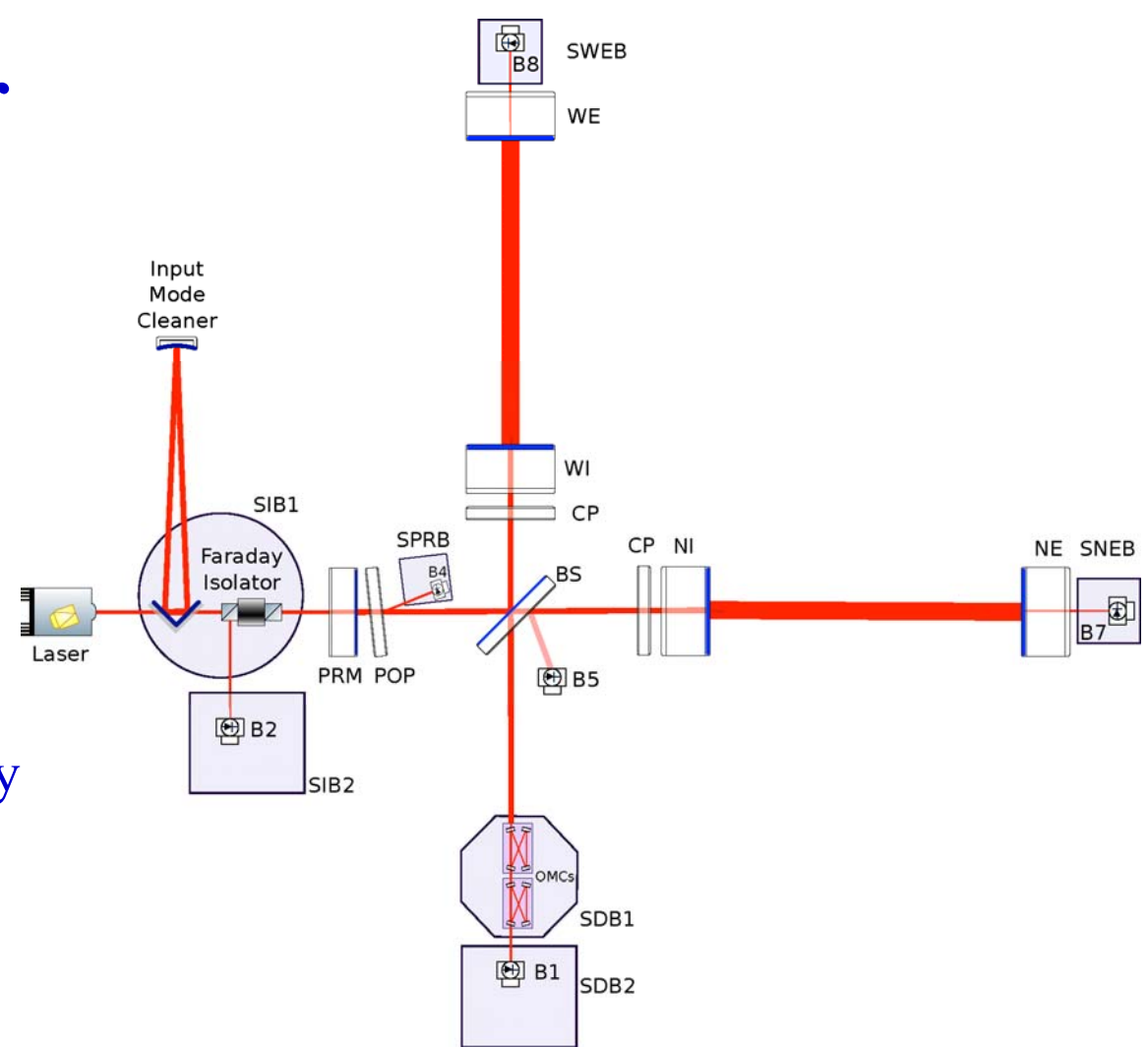
- About 400 members

● 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

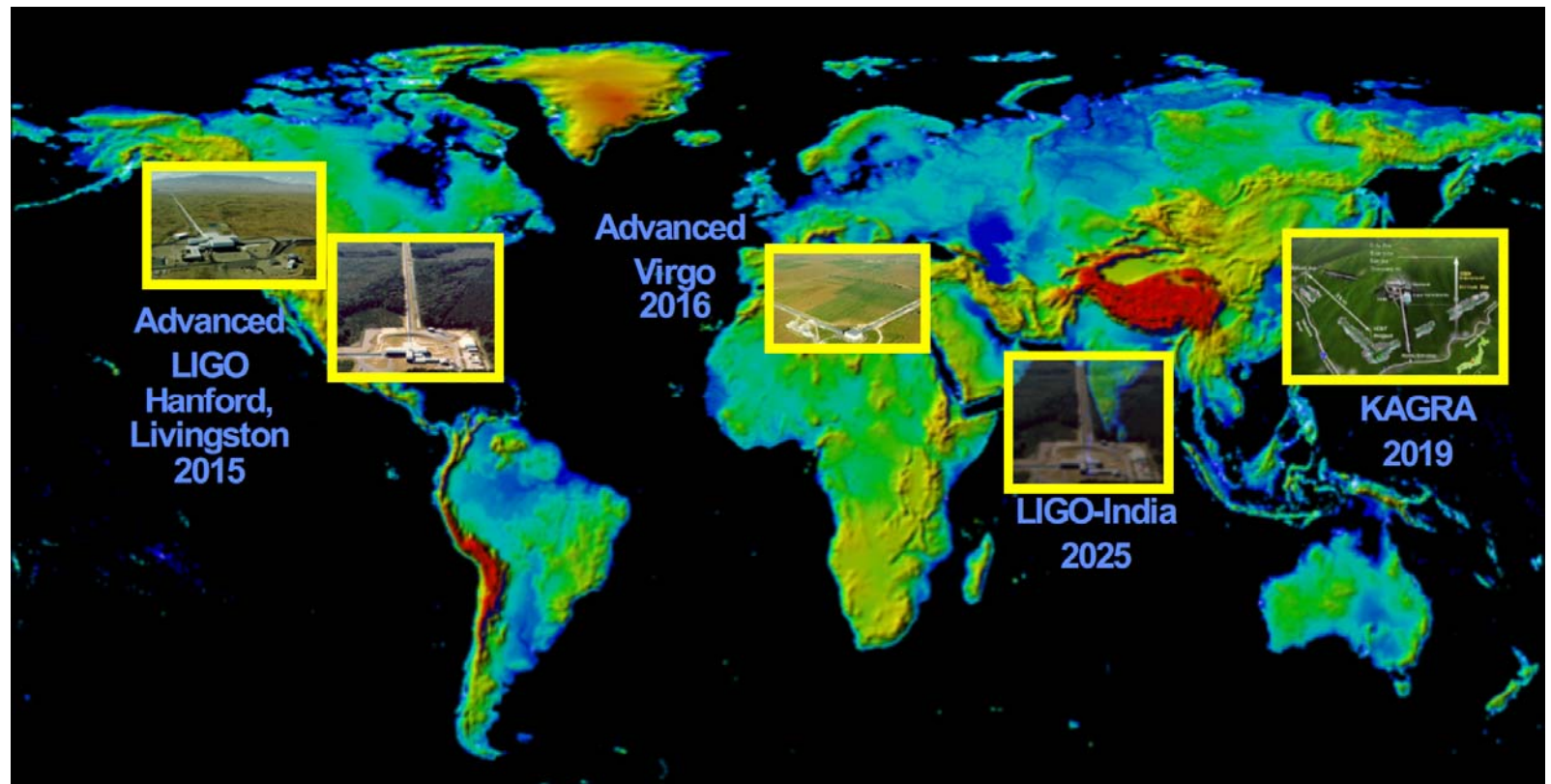


Global network of gravitational-wave detectors

- 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



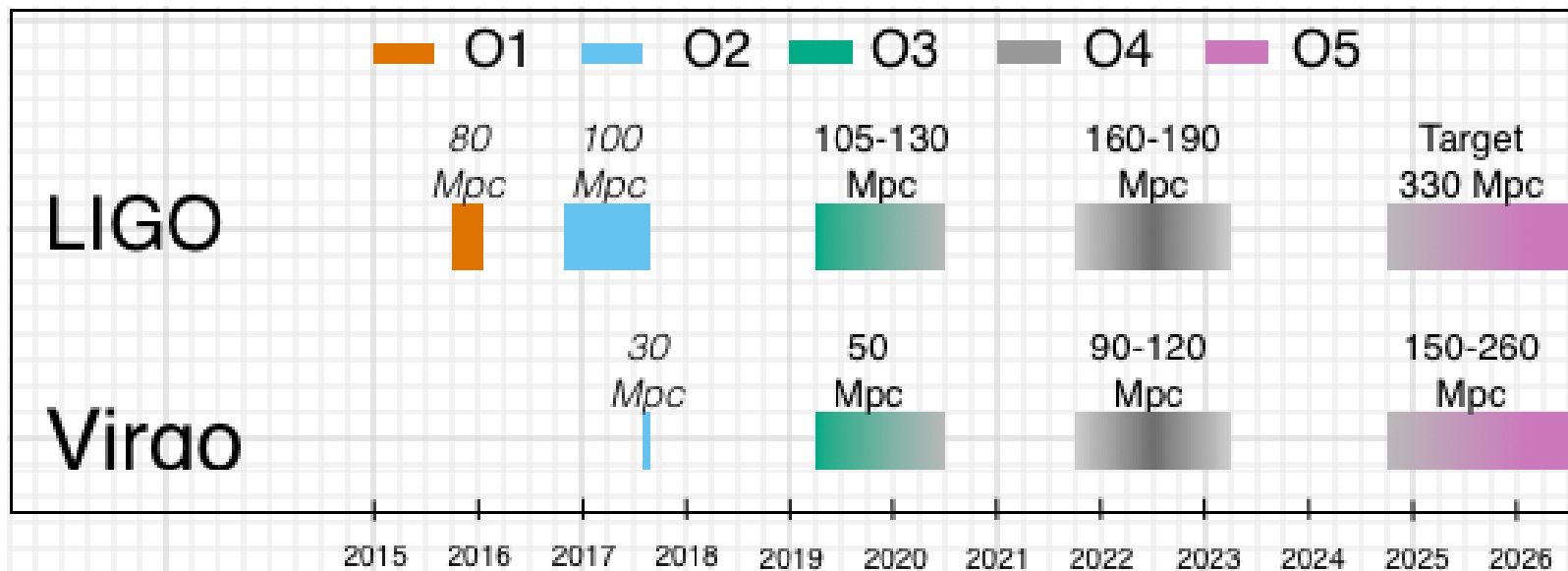
- **MoUs** ruling the joint effort of the **LIGO Scientific Collaboration** and the **Virgo Collaboration** to detect and study gravitational-wave signals

From O2 to O3

LIGO-Virgo observation runs

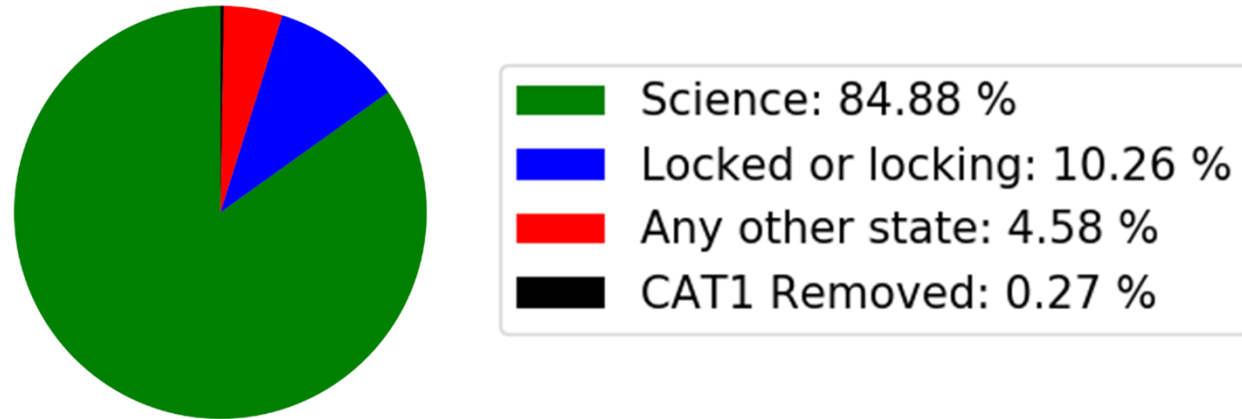
- **O1**: September 2015 → January 2016
 - Only LIGO Hanford and LIGO Livingston
 - ◆ Virgo still being upgraded
 - **GW150914**: first direct detection of gravitational waves
- **O2**: November 2016 → August 2017
 - Virgo joined on August 1st, 2017
- **O3**: April 1st, 2019 → *ongoing*
 - Joint LIGO-Virgo data taking

- **Future**
 - **O4, O5**



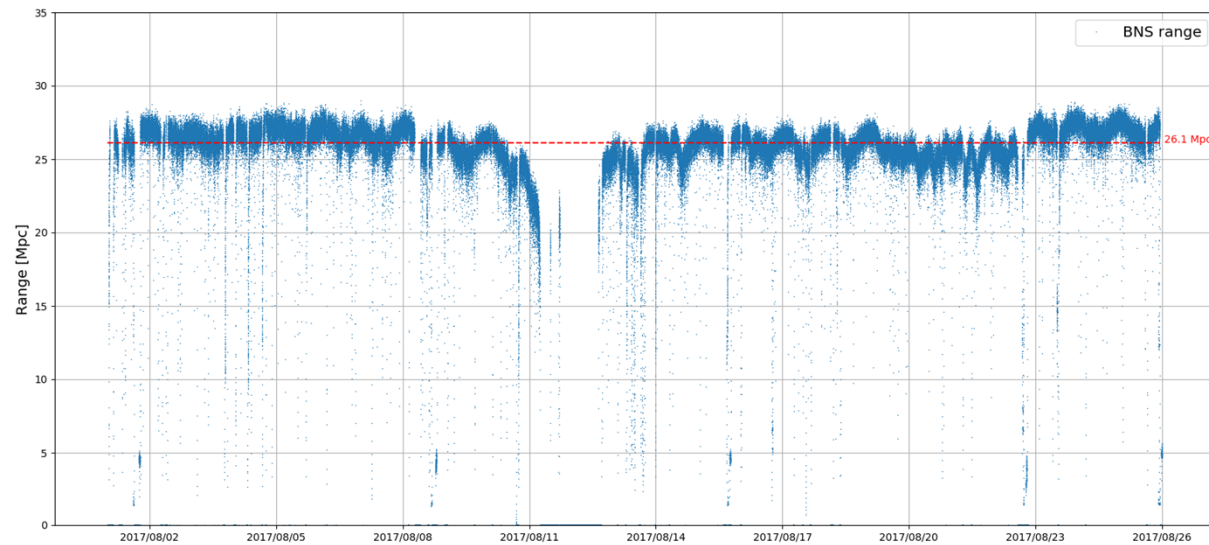
Virgo O2 performance and results

- Virgo duty cycle

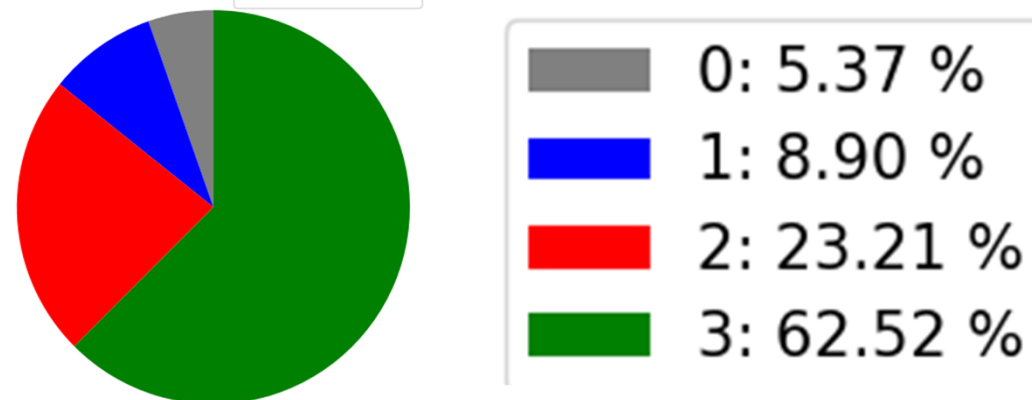


- Virgo BNS range

- ~26 Mpc

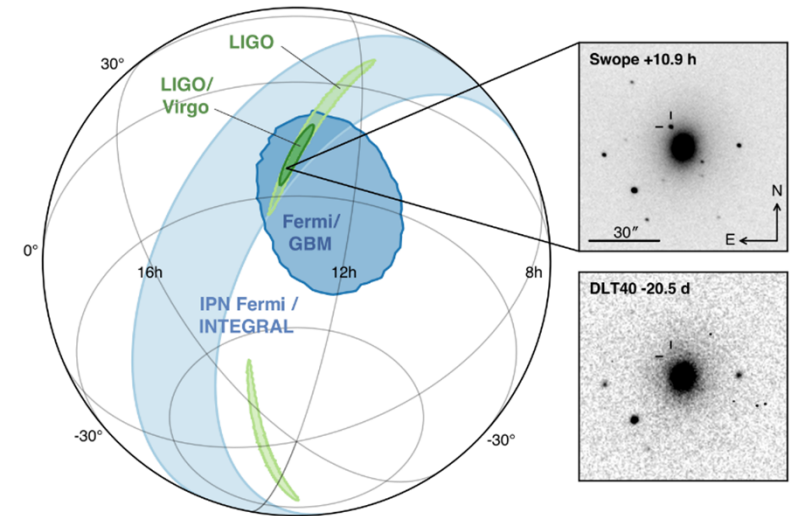
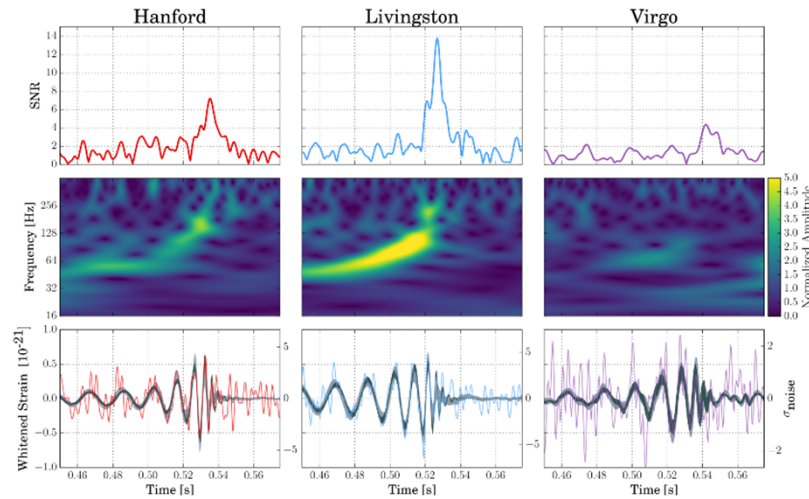


- LIGO-Virgo network duty cycle

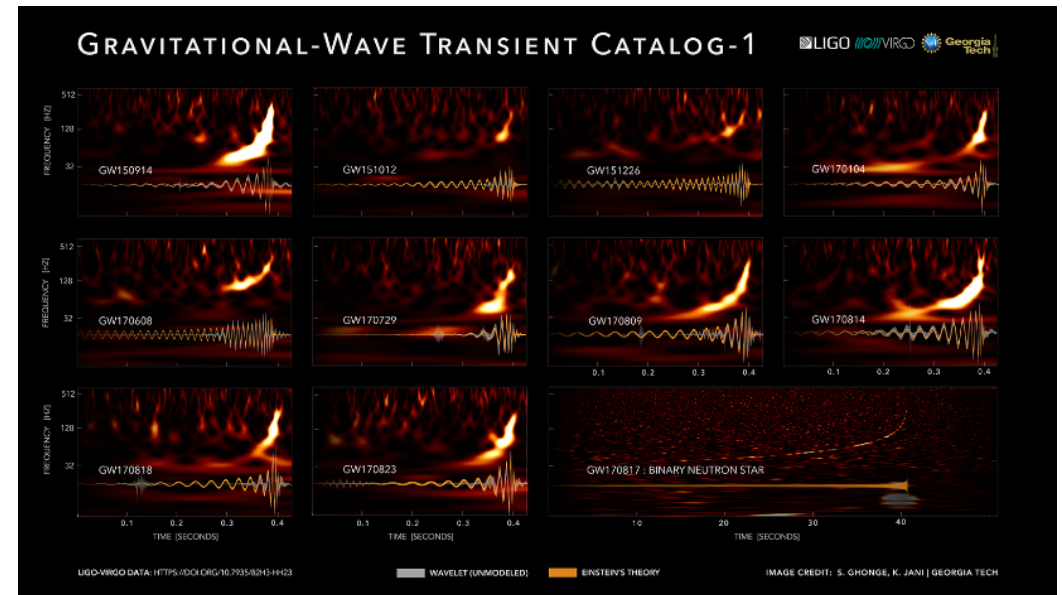


Scientific highlights

- **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](https://arxiv.org/abs/1811.12907), accepted for publication in [PRX](https://arxiv.org/abs/1811.12907)

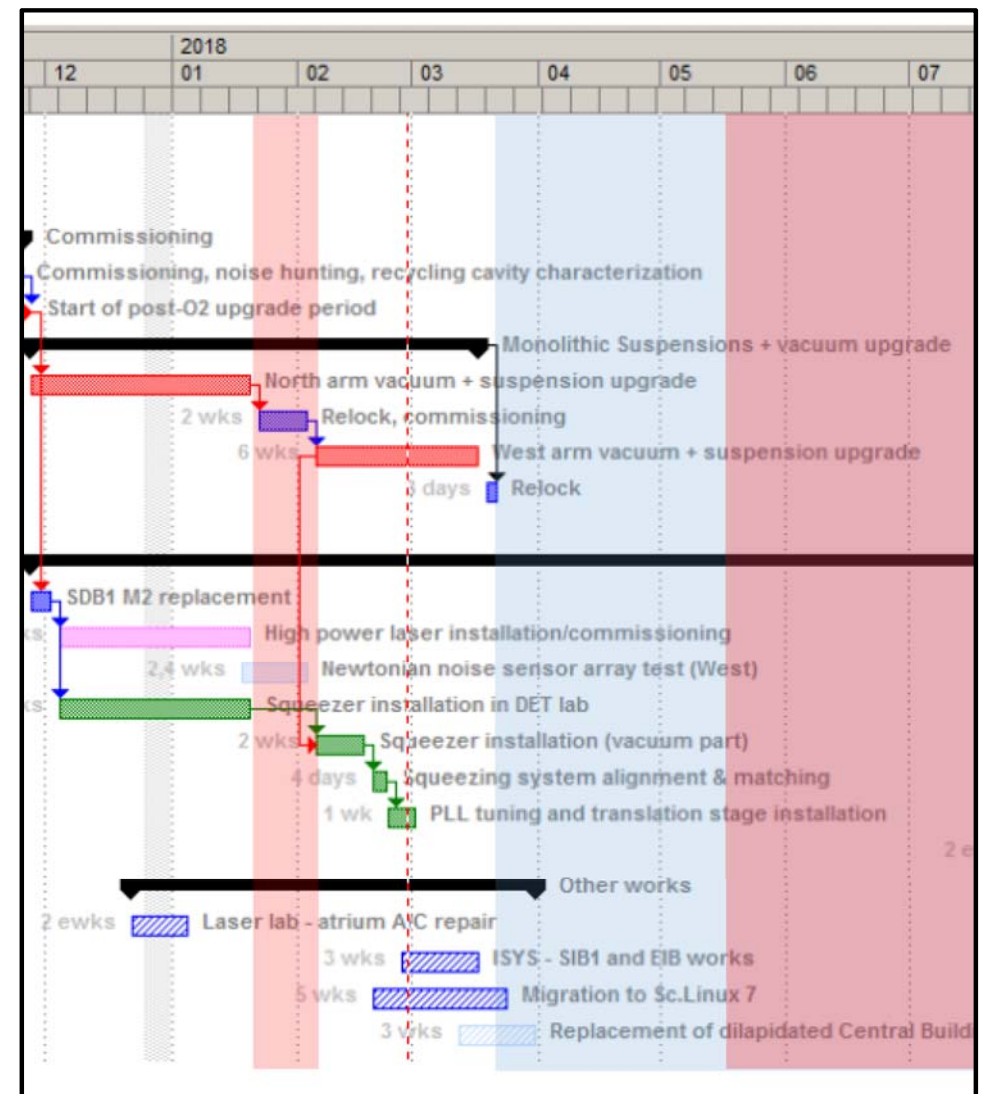


Post-O2 commissioning period

- **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 successful 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



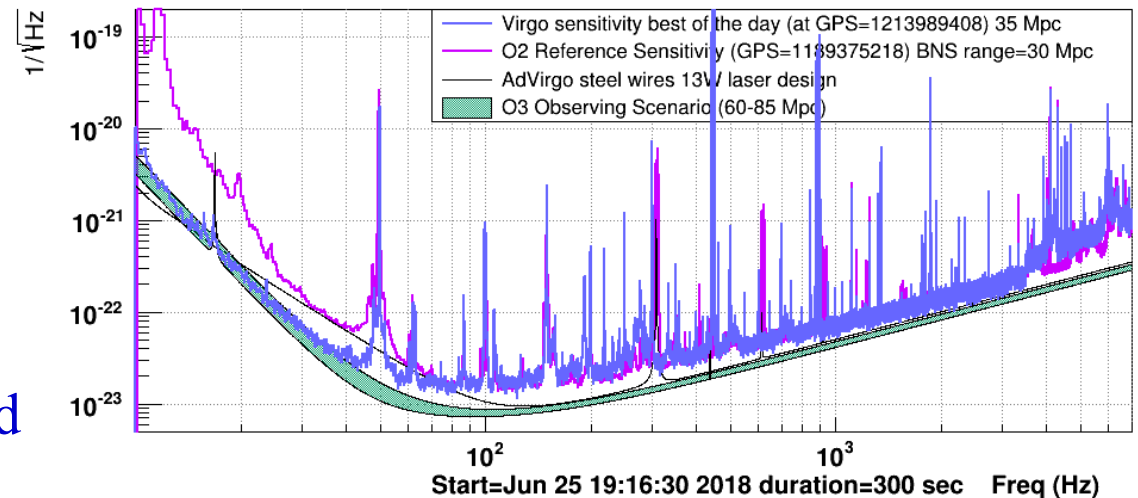
O2-O3 upgrades

- **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

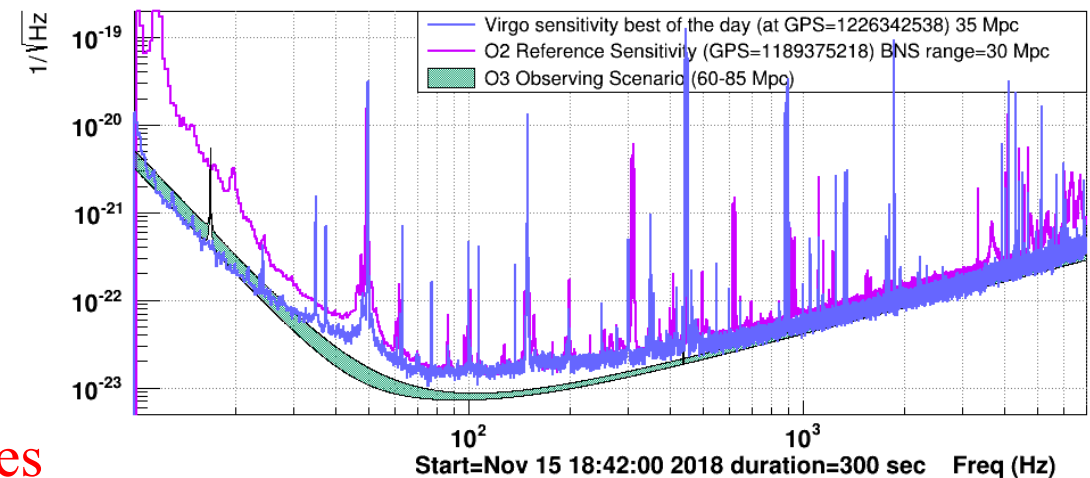
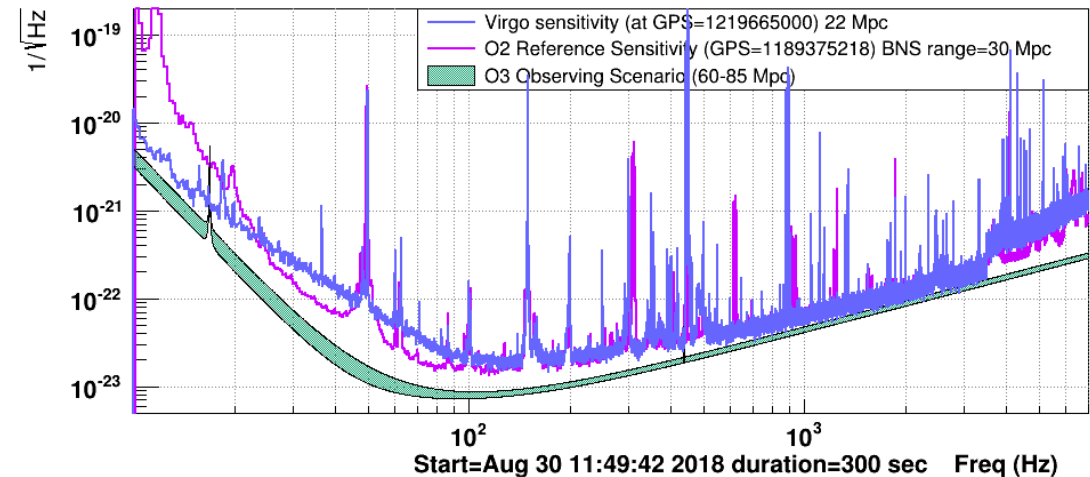
- Activities in progress

- To understand the origin of the charges

- ◆ Ion pumps!? First contact peeling off the mirror!?

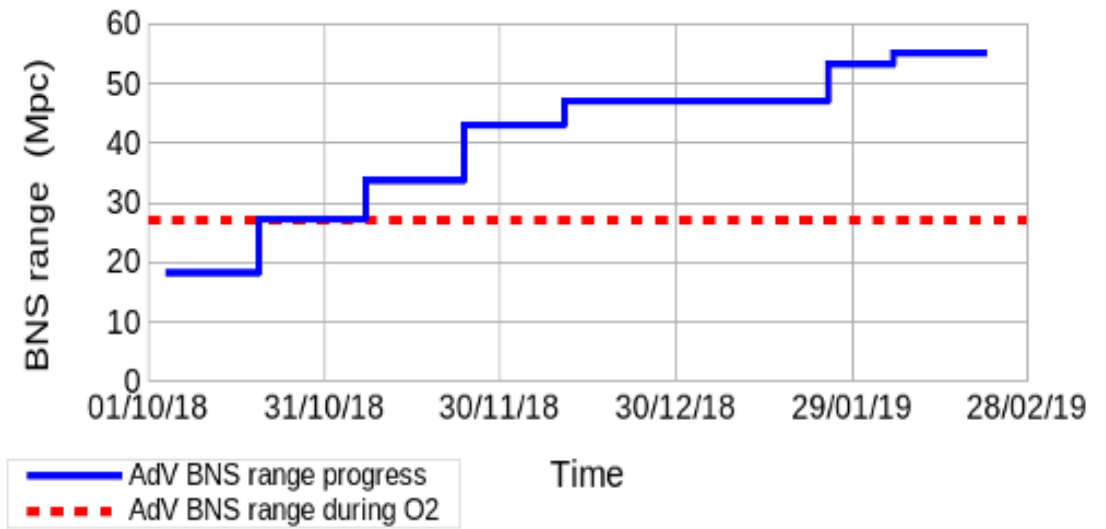
- To mitigate or discharge test masses

- ◆ Ion gun studies in progress



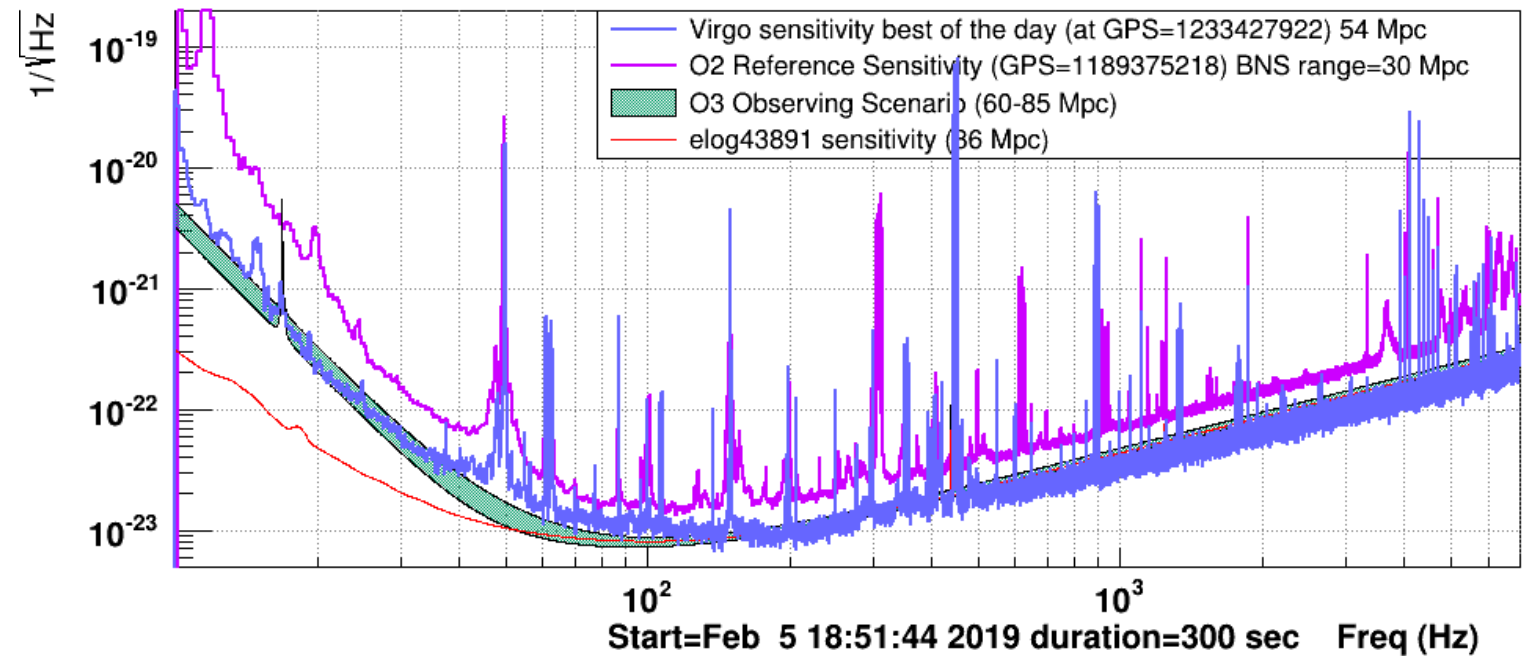
O2-O3 upgrades

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



- Best sensitivity achieved in early February

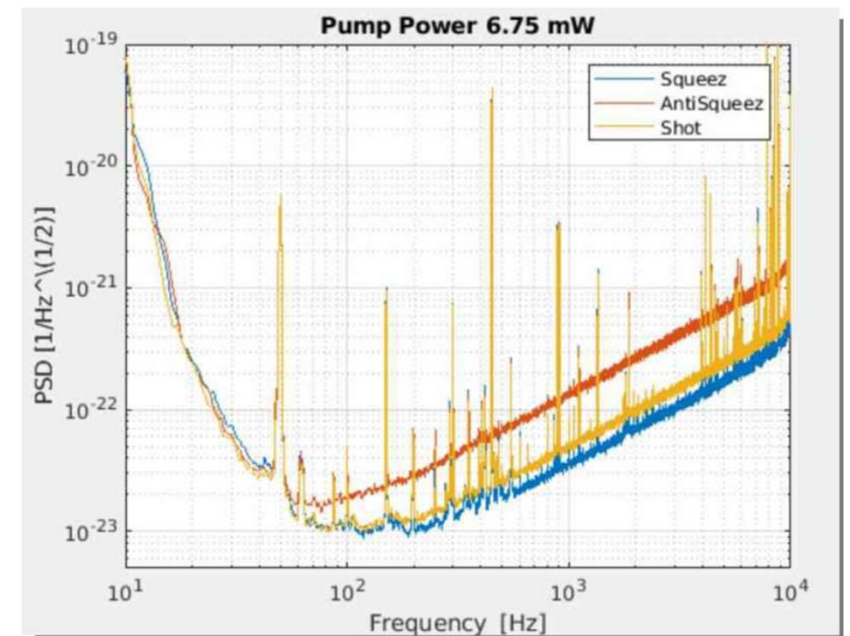
- Input power:
18 W
- Squeezing:
3 dB
→ See next slide




- 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 to
- Vacuum fluctuations
 - Squeezed state of light
 - smaller uncertainty
 - ♦ Generated by noise
- Quantum noise limit
 - Shot noise
- AEI squeezer installed
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 - 2-3 Mpc gain for the detector
 - Laser power ~double
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Frequency Independent Squeezing in Advanced Virgo

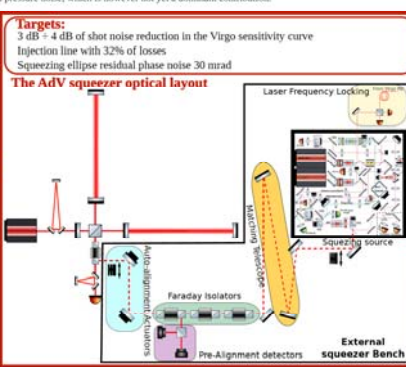


Marco Vardaro and the squeezing group on behalf of the Virgo collaboration

Quantum noise that limits Gravitational-wave (GW) interferometers, in the form of shot noise and quantum radiation pressure, is ultimately due to the interaction of the main laser field with quantum vacuum fluctuations that enter the instruments through the "dark" output port. A step towards better sensitivity in GW detectors is the suppression of the quantum noise. One way to achieve this, without major modification to their optical configuration, is to inject squeezed vacuum states through the dark port.

Squeezed vacuum states are special quantum states of the electromagnetic fields in which quantum vacuum fluctuations, rather than being equally distributed among the two quadratures that describe the EM field, are reduced in one quadrature at the expense of the other. Which quadrature is chosen has a different effect on the observed level of shot or radiation-pressure noise. The upgrade program of the Advanced Virgo detector foresees the injection of squeezed vacuum. In a first phase (observing run 3, or O3), frequency-independent squeezed vacuum is injected leading to a decrease in the detector shot noise contribution at high frequencies while increasing, at low frequency, radiation pressure noise, which is however not yet a dominant contribution.

The Adv squeezer



Targets:
 3 dB + 4 dB of shot noise reduction in the Virgo sensitivity curve
 Injection line with 32% of losses
 Squeezing ellipse residual phase noise 30 mrad

The Adv squeezer optical layout

The squeezer vacuum source (Fig. 1) was designed and developed at AEI in Hannover and it was delivered to the Virgo site in January 2018. The source main features are:

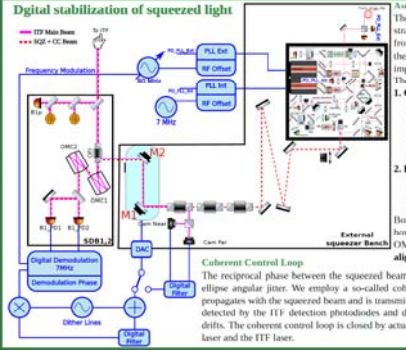
- up to 12 dB of generated squeezing states in the audio bandwidth
- compact design, only 1 m² of area
- very low phase noise, less than 3 mrad

Squeezed light must be injected and matched into the interferometer minimizing the optical losses. The injection (Fig. 2) line has the following features:

- minimal number of optical components
- mode matching of 97% with the OMC achieved with a reflective telescope (#43566)
- optical isolation with ITF achieved with a series of 3 Faraday Isolators (FI) developed by the EGO optics group (Fig. 3). Each FI has a throughput of the 99%, and an isolation factor higher than 40 dB.

Locking of the squeezer frequency to the ITF carrier is achieved by implementing an OPLL servo loop actuating on the squeezer Main Laser crystal temperature and on its PZT actuator. The OPLL error signal is the beat note between the squeezer main laser and a pick-off beam of the ITF main laser delivered to the squeezer with a 50 m length PM optical fiber. The OPLL residual phase noise is less than 7 mrad (#43532).

Squeezed light control



Digital stabilization of squeezed light

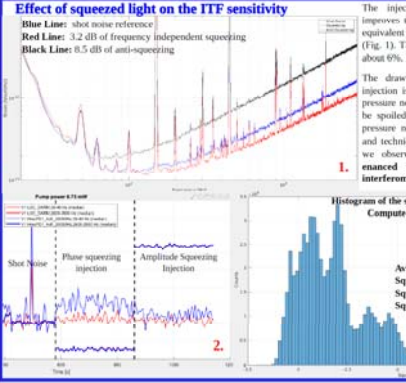
The automatic alignment system is based on two possible control strategies that employ different sensors: the former extracts error signal from two cameras placed in reflection from the first Faraday Isolator; the latter extracts the error signal by demodulating other lines that are imposed on the squeezed beam by means of the actuators M1 and M2. The loops are closed acting on the coating mirrors M1 and M2.

1. Camera based raw Alignment (Figure 1 Magenta):
 Used to pre-align the squeezer during the ITF locking strategy.
 Proc: the error signal can be calculated even without injecting squeezed light into the ITF.
 Cons: low unitary gain frequency (0.1 Hz), subjected to set point drifts.

2. Dither lines based fine Alignment (Figure 1 Blue):
 Used to align the SQZ beam with the OMC during SQZ injection.
 Proc: accurate sensing of misalignment on OMC.
 Cons: low unitary gain frequency (0.1 Hz).
 Both the loops can't correct NDH2 oscillations at 0.5 Hz (Fig. 1 Top); however, with good DC alignment, the coupling of this oscillations into OMC transmission is highly suppressed (Fig. 1 Bottom). The residual alignment jitter contribution to optical losses is less than 1%.

Coherent Control Loop
 The reciprocal phase between the squeezed beam and the ITF field must be actively stabilized to limit the squeezing ellipse angular jitter. We employ a so-called coherent control technique: a 7 MHz offset laser beam (CC beam) co-propagates with the squeezed beam and is transmitted by the two OMCs. The beat note between the ITF and CC beam is detected by the ITF detection photodiodes and digitally demodulated to obtain the information on the relative phase drifts. The coherent control loop is closed by actuating on the frequency offset of the OPLL between the squeezer main laser and the ITF laser.

Virgo and squeezing



Effect of squeezed light on the ITF sensitivity

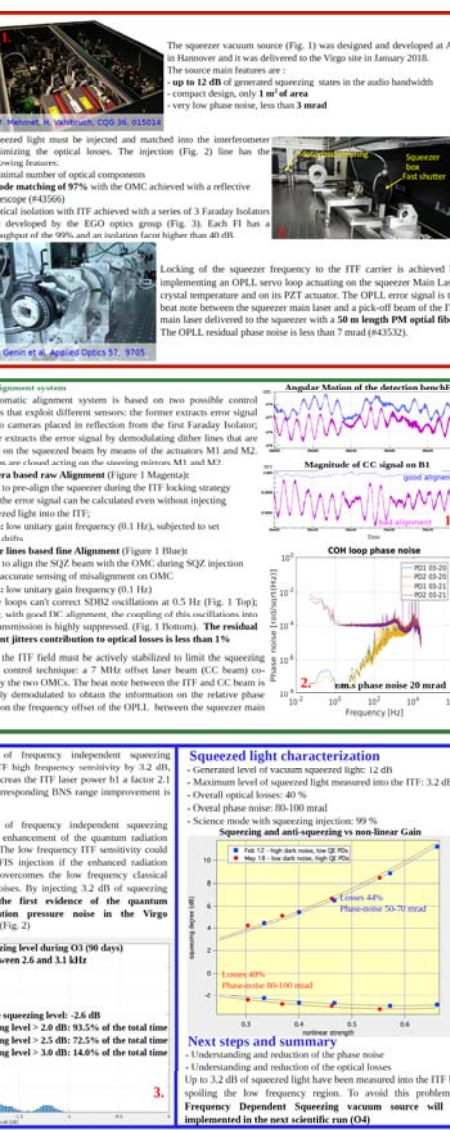
Blue Line: shot noise reference
 Red Line: 3.2 dB of frequency independent squeezing
 Black Line: 0.5 dB of anti-squeezing

The drawback of frequency independent squeezing injection is the enhancement of the quantum radiation pressure noise. The low frequency ITF sensitivity could be spoiled by FIS injection if the enhanced radiation pressure noise overcomes the low frequency classical and technical noises. By injecting 3.2 dB of squeezing we observed the first evidence of the quantum enhanced radiation pressure noise in the Virgo interferometer (Fig. 2).

Histogram of the squeezing level during O3 (90 days)
 Computed between 2.6 and 3.1 kHz

Average squeezing level: -2.6 dB
 Squeezing level > 2.0 dB: 93.5% of the total time
 Squeezing level > 2.5 dB: 72.5% of the total time
 Squeezing level > 3.0 dB: 14.0% of the total time

Squeezed light characterization



Generated level of vacuum squeezed light: 12 dB
 Maximum level of squeezed light measured into the ITF: 3.2 dB
 Overall optical losses: 40%
 Overall phase noise: 80-100 mrad
 Science mode with squeezing injection: 99%

Squeezing and anti-squeezing vs non-linear gain

• Eries 44%
 • Phase-noise 50-70 mrad

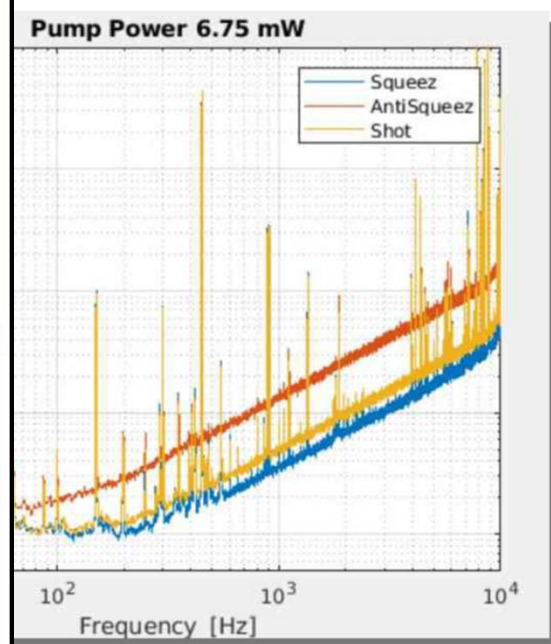
Next steps and summary

- Understanding and reduction of the phase noise
- Understanding and reduction of the optical losses

Up to 3.2 dB of squeezed light have been measured into the ITF but spoiling the low frequency region. To avoid this problem a Frequency Dependent Squeezing vacuum source will be implemented in the next scientific run (O4).

port

coherent state of light

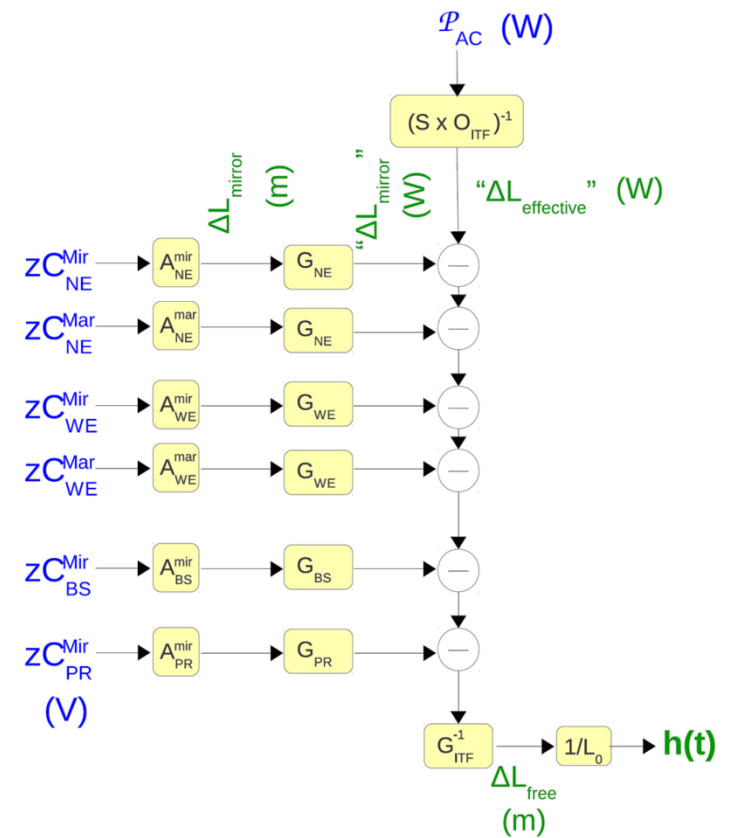


See Marco Vardaro's poster
 "Frequency Independent Squeezing in Adv-Virgo"

03

O3 sensitivity

- **Gravitational-wave channel $h(t)$** computed in frequency domain by subtracting calibrated correction signals from output port photodiode
 - Calibration: optical transfer 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



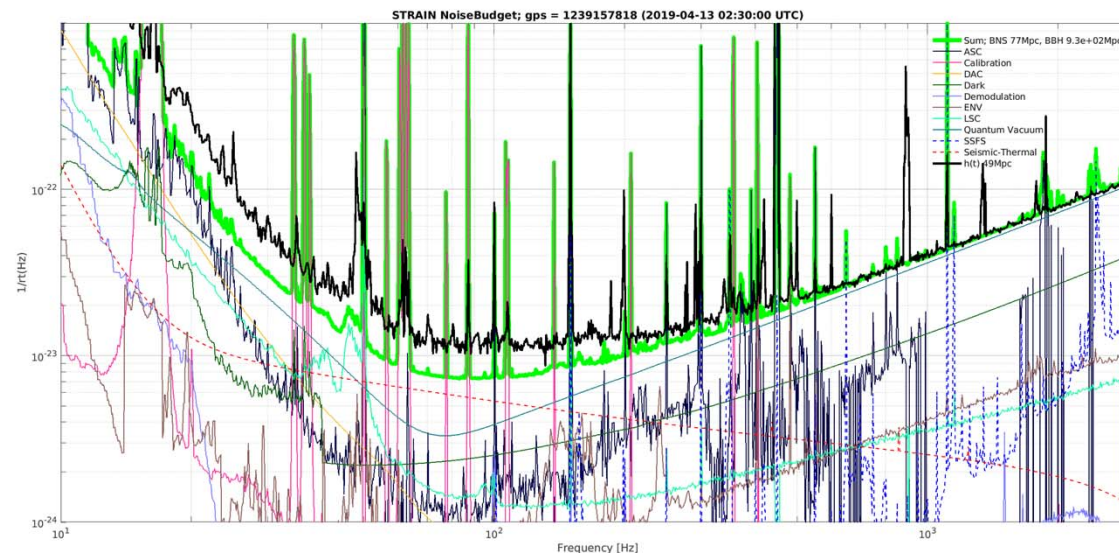
→ Uncertainties for O3 online reconstruction

- $\pm 5\%$ in amplitude
- $\pm 35 \text{ mrad} \oplus \pm 10 \mu\text{s}$ in phase
- Over a wide frequency band: 20 Hz \rightarrow 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

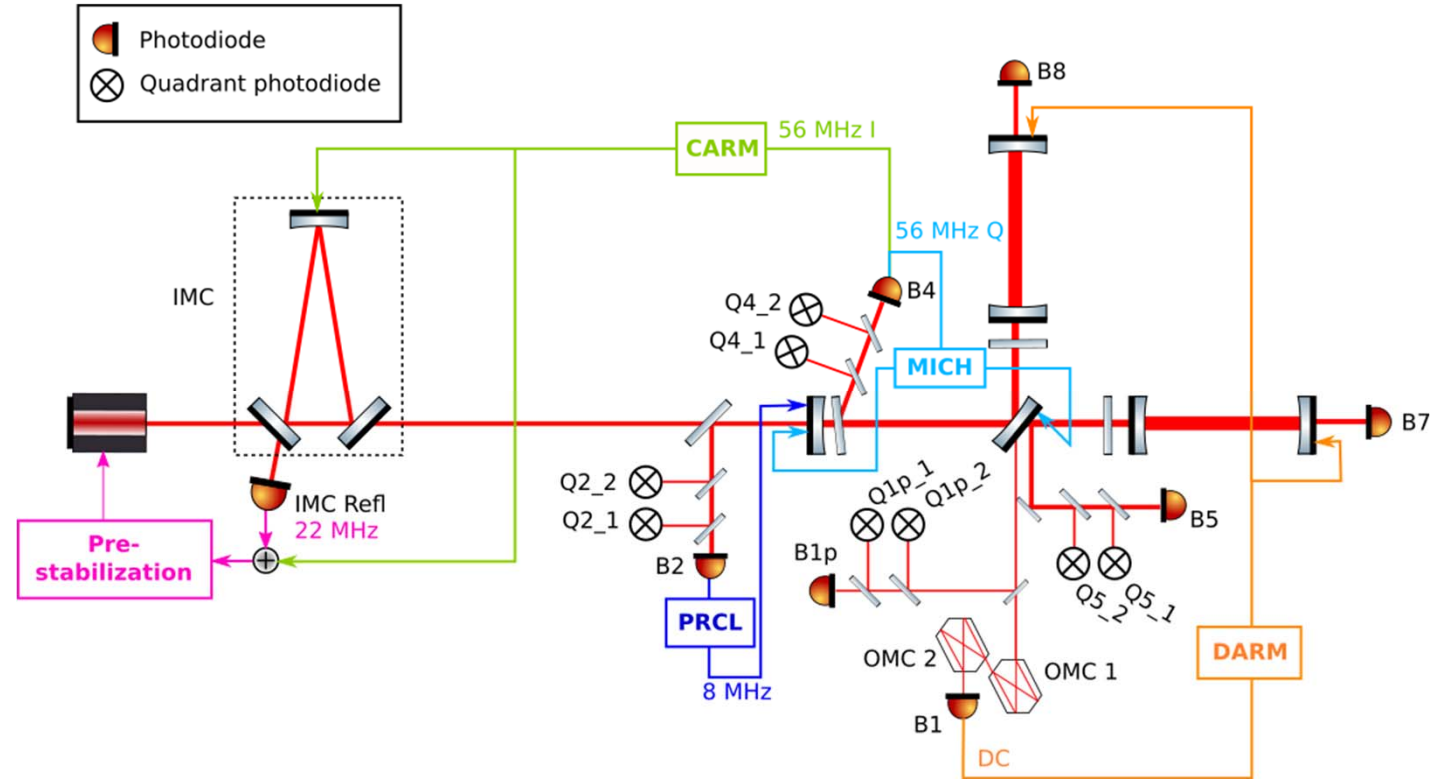
- A complementary approach: the noise budget
 - Quadrature sum of modelled individual noise contributions
 - Transfer function measurements to get couplings



- 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"](#)

LONGITUDINAL CONTROL OF MARGINALLY STABLE INTERFEROMETERS

Julia Casanueva⁽¹⁾, Maddalena Mantovani⁽²⁾
 (1) INFN Pisa
 (2) European Gravitational Observatory

AIM : control marginally stable cavities

WHY it is interesting?

The Power Recycling cavity is marginally stable in Virgo → it is very hard to control it!

Optical Cavity Stability

- An optical cavity is **stable** when it exists a Gaussian beam that can resonate inside it
- At first order, the stability of an optical cavity is determined by its **geometrical properties**

Stability condition $0 < g_1, g_2 < 1$ with $\begin{cases} g_1 = 1 - L/R_1 \\ g_2 = 1 - L/R_2 \end{cases}$

The PRC is marginally stable since $g_1, g_2 = 0,9999981$

What does it mean to be marginally stable?

Transversal Higher Order Modes resonate very close to the fundamental one → they couple strongly inside the cavity

For this reason, marginally stable cavities are more sensitive to misalignment, mismatch, aberrations... (since they produce HOMs)

The presence of HOMs degrades the error signals used for the longitudinal control → loss of optical gain, multiple zero crossings...

HOW did we deal with it?

In AdV a new modulation frequency was added to build **more robust error signals**

Schnupp asymmetry

- The **Schnupp asymmetry (ΔS)** is a macroscopical length difference between the arms of the Michelson interferometer
- AIM: allow the sidebands (Ω) to reach the Detection Port** even when the Michelson is in Dark Fringe

$E_{\text{DarkPort}}(\text{DF}) \propto \sin(\pm\Omega\Delta S/2)$

The higher the sideband frequency (Ω), the more power leaked towards the Dark Port

- The **PRC** is formed by the PR Mirror + Equivalent Mirror

- The reflectivity of the Equivalent Mirror depends on → FP cavities + Michelson
- ΔS produces losses in the PRC

$\uparrow\uparrow \Omega \rightarrow \uparrow\uparrow \text{Losses} \rightarrow \downarrow\downarrow \text{Finesse}$

In a cavity with high losses (so low finesse) any extra loss due to HOMs will have a low impact → Error signals produced using high sidebands are more robust

For Advanced Virgo+ the target is to decrease the thermal noise by increasing the beam size on the arm cavities mirrors → even more marginally stable Power Recycling Cavity

How high needs to be Ω to control this cavity?

Simulation: OG loss in the presence of a misalignment

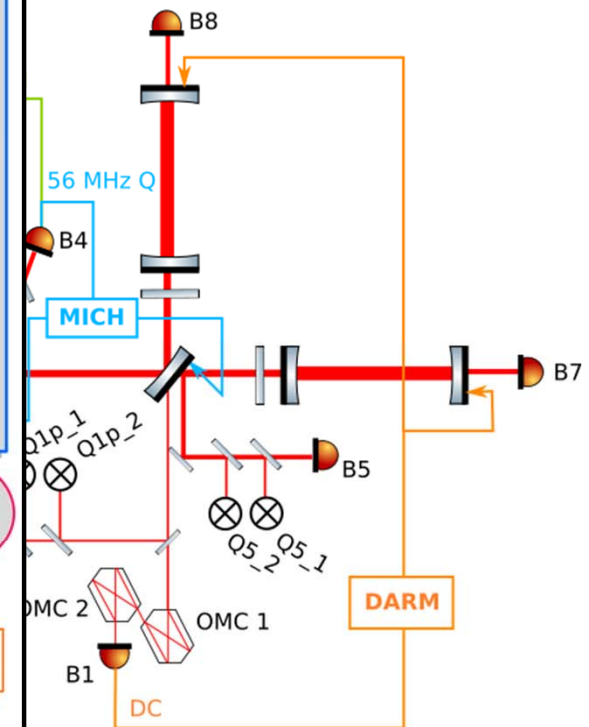
TARGET: put a limit on the stability of the PRC based on the sideband frequency that would be necessary to build error signals robust enough to control it → **technical / hardware limit**

- Simulations were done using Finesse⁽¹⁾
- Measured the **loss of optical gain of the error signal** in the presence of a given **tilt of the optical axis, 15mrad**
- From the plot it can be seen that for a given cavity, **the optical losses decrease with the finesse**
- Explore the behaviour of an optical cavity depending on its stability (the present PRC has 2mrad of Gouy phase, purple line) → **work on-going**

(1) A. Freise and al. Frequency domain interferometer simulation with higher-order spatial modes. Class. Quant. Grav., 21(5), 2004.

- **Control acquisition** (
 - Photodiodes: **sensitive**
 - **Filtering**
 - **Actuation**
- **4 Longitudinal degrees of freedom**
- **Angular control**
 - **Key to stability and duty cycle**

... long periods

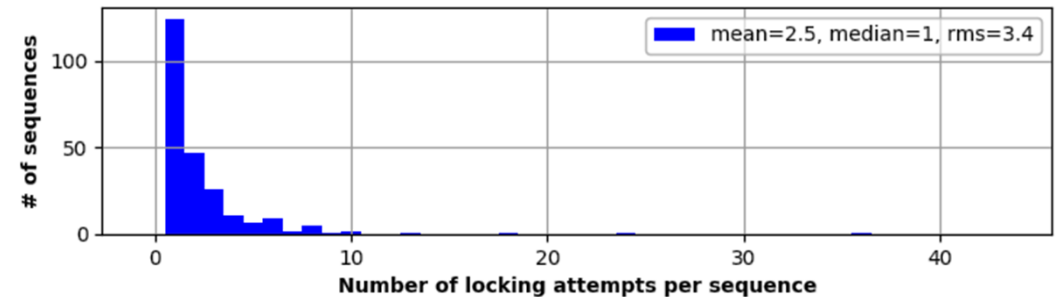
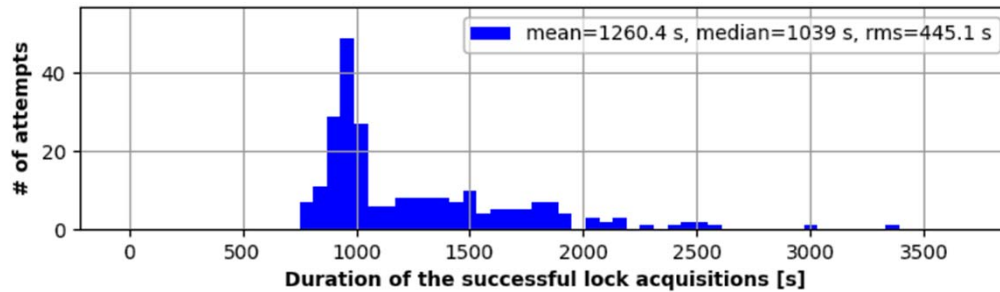


See **Julia Casanueva's** poster
 “**Longitudinal Control Of Marginally Stable Interferometers**”

Locking Virgo

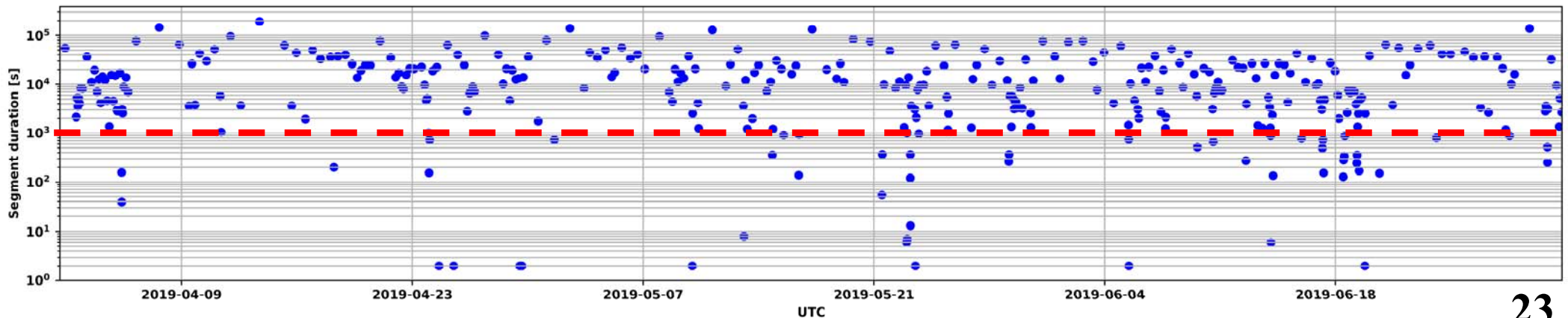
- Locking performance

- ~20 minutes to acquire full control of the detector
 - 1-2 attempts to achieve that control
- Rather quick and efficient



- Lock stability

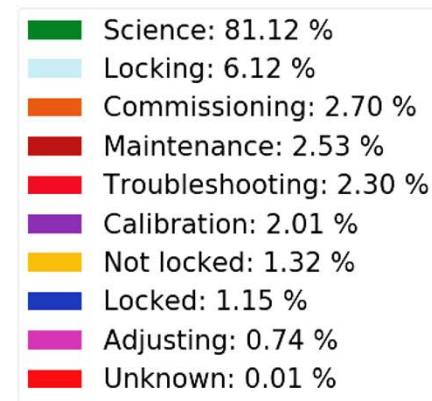
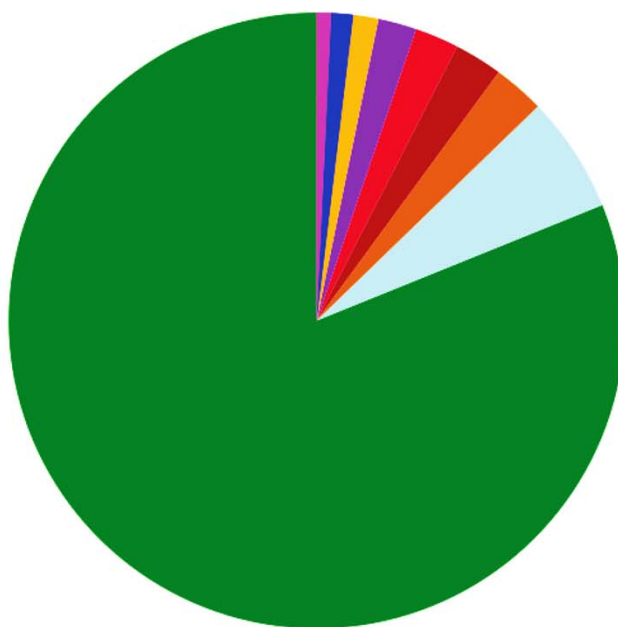
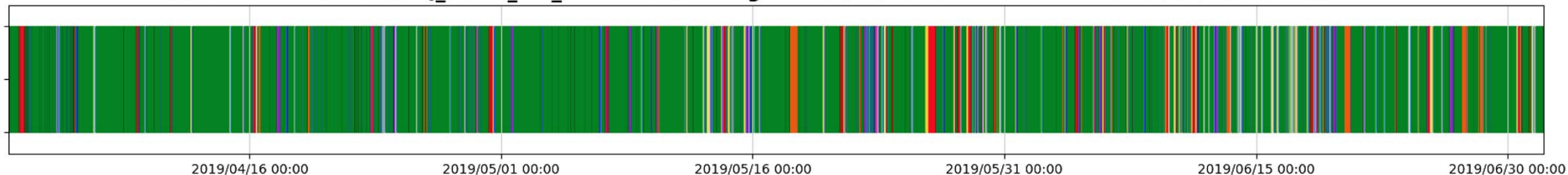
- Lock segments lasting several hours
- ◆ Up to a couple days



Virgo performance, 3 months onto the O3 run

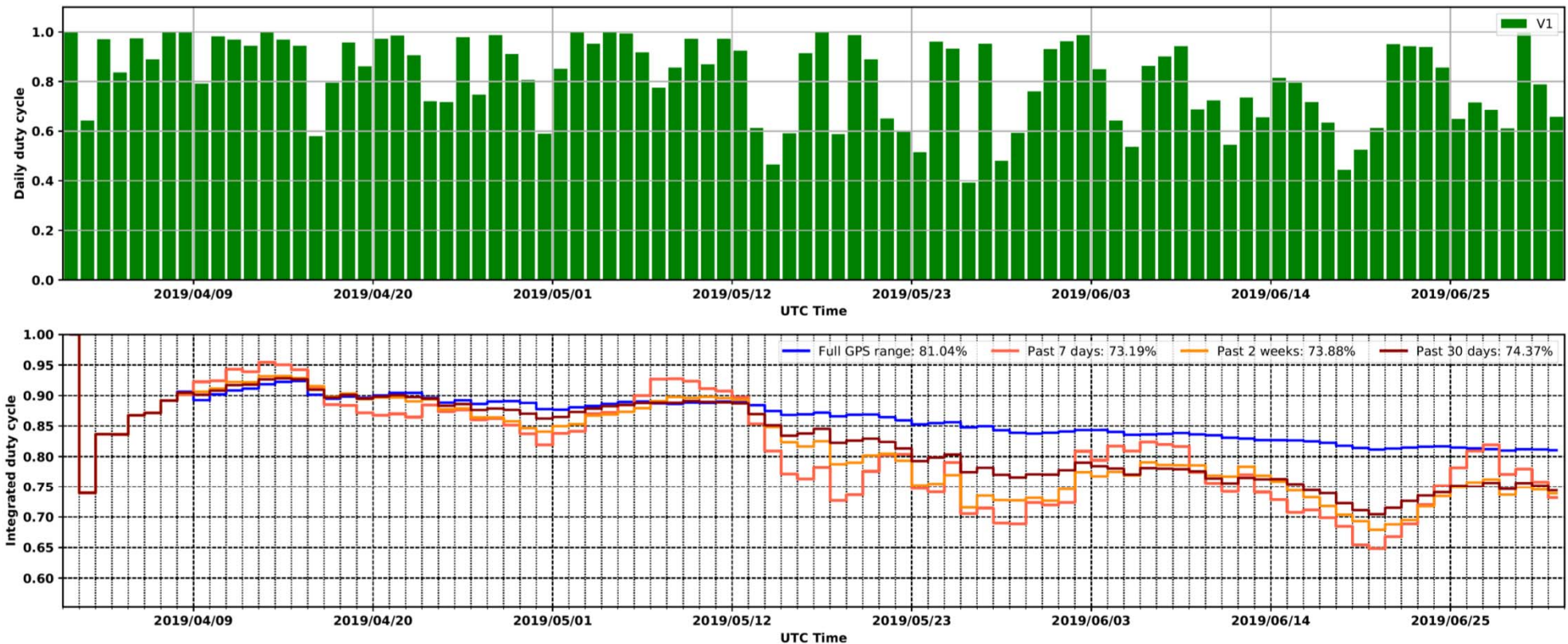
- **Duty cycle**
 - Based on data from the Virgo automation system
 - ◆ ‘**Metatron**’ based on LIGO’s Guardian framework
 - Duty cycle averaged over 3+ months

Status of channel V1:DQ_META_ITF_Mode -- time range: 2019/04/01 15:00:00 UTC -> 2019/07/02 03:30:02 UTC



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



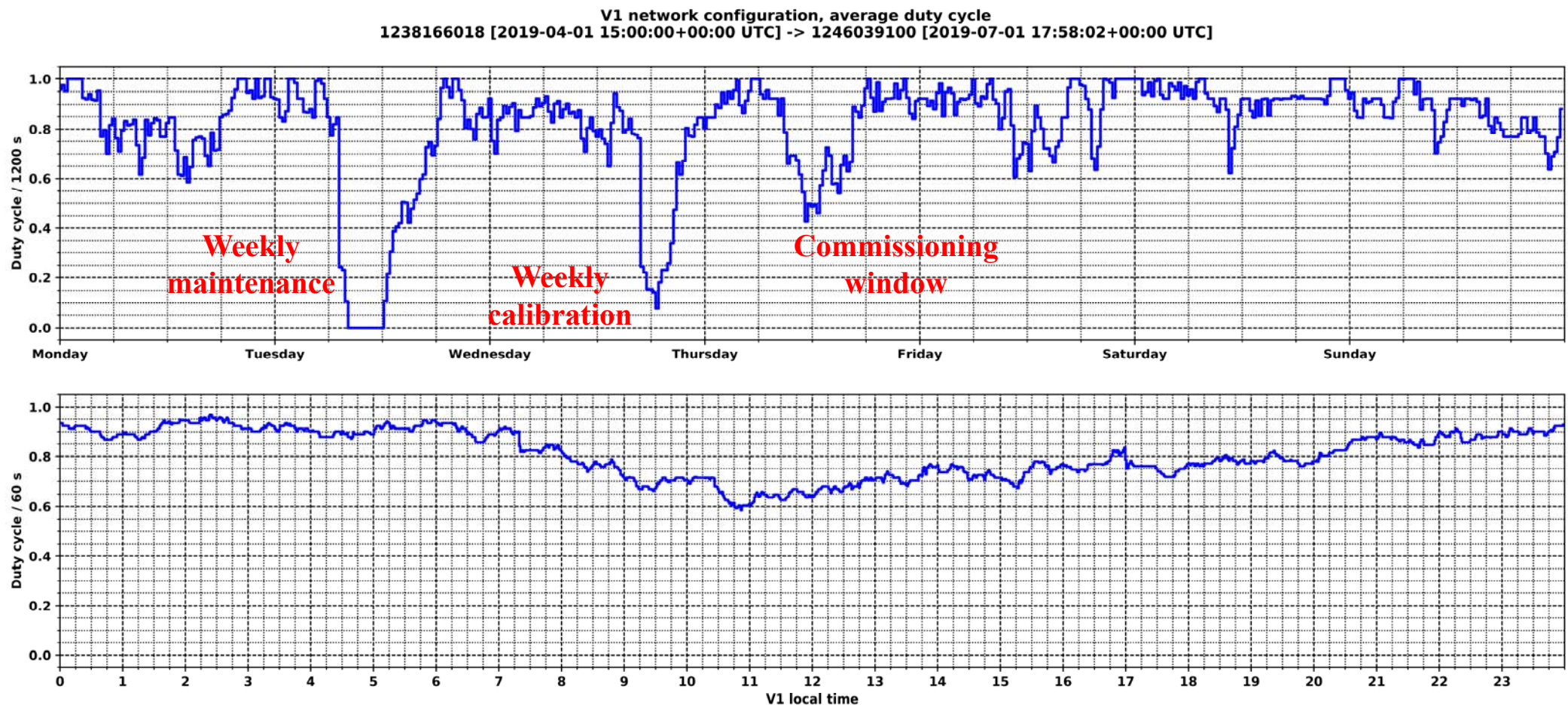
— Full GPS range: 81.04% — Past 7 days: 73.19% — Past 2 weeks: 73.88% — Past 30 days: 74.37%

→ 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
 - Bottom plot: a day

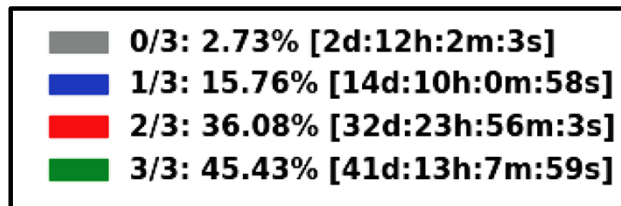
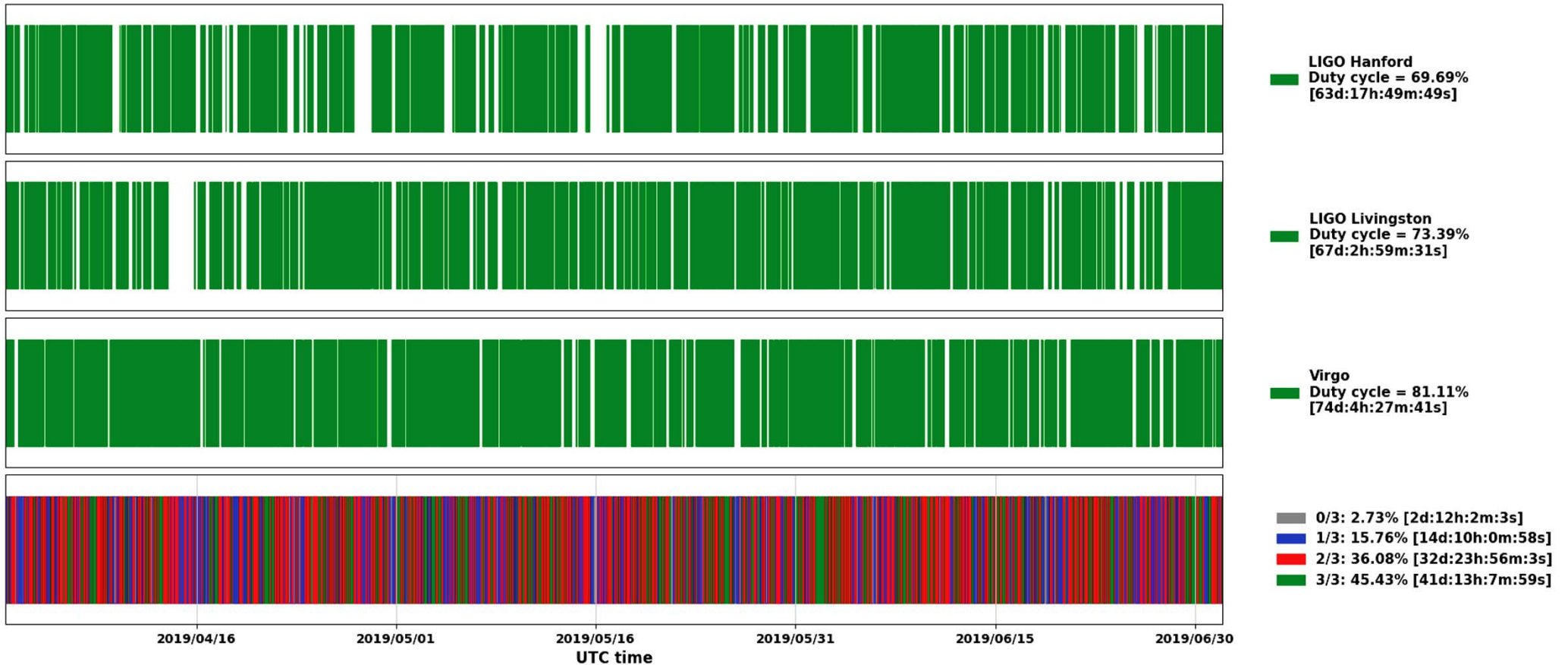


- Averaged over the whole data taking period

Virgo within the LIGO-Virgo 3-detector network

- O3 duty cycles
 - Exclusive categories

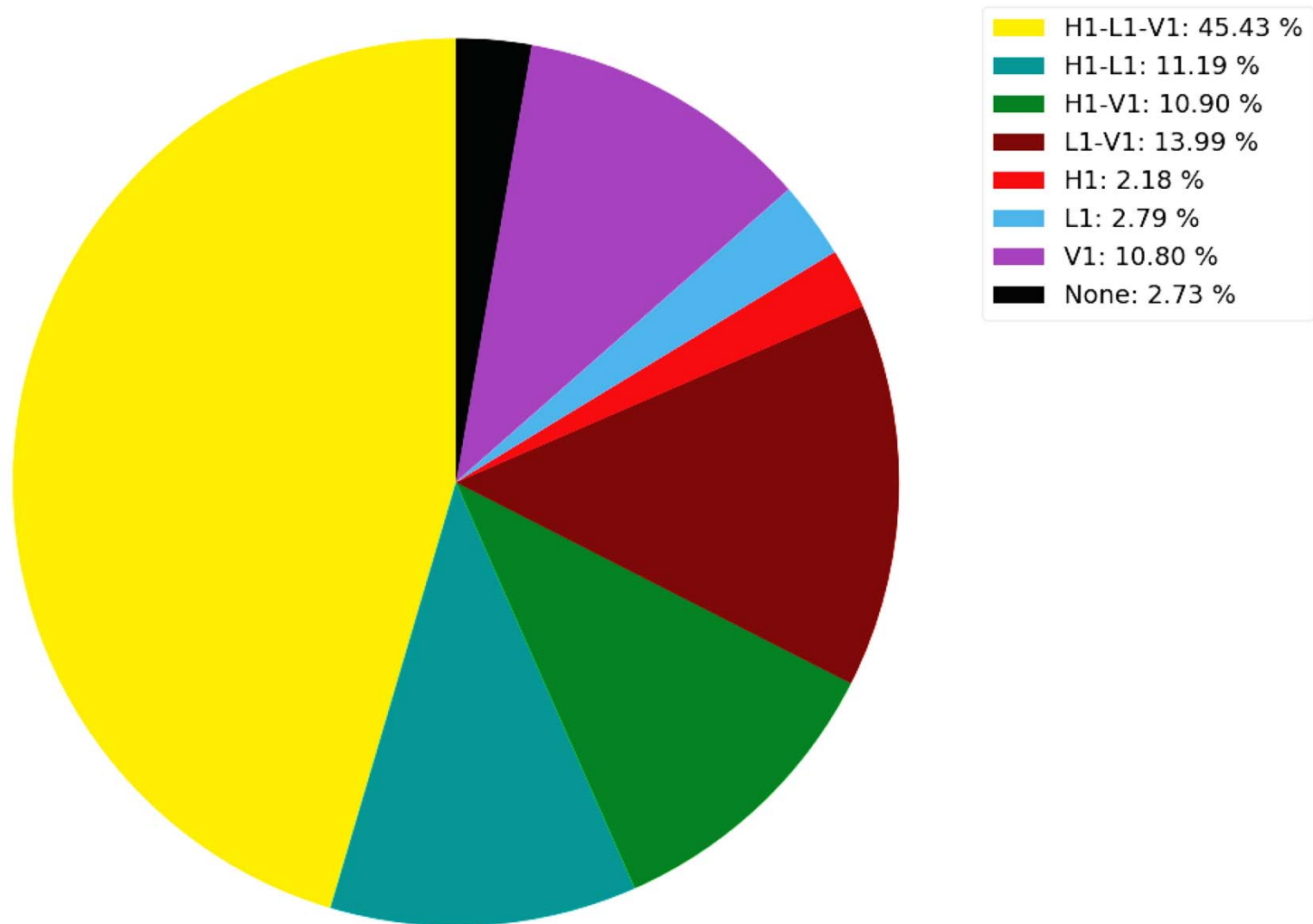
H1-L1-V1 network: 2019-04-01 15:00:00+00:00 UTC -> 2019-07-02 02:07:03+00:00 UTC -- science segments



Virgo within the LIGO-Virgo 3-detector network

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

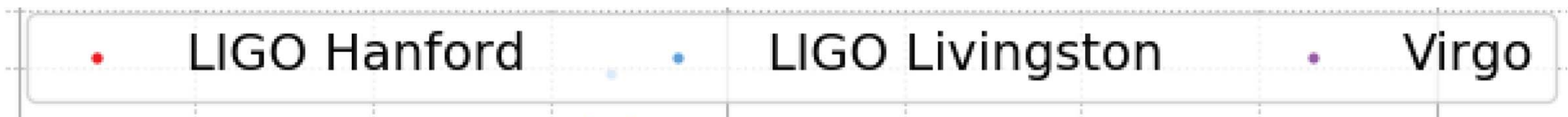
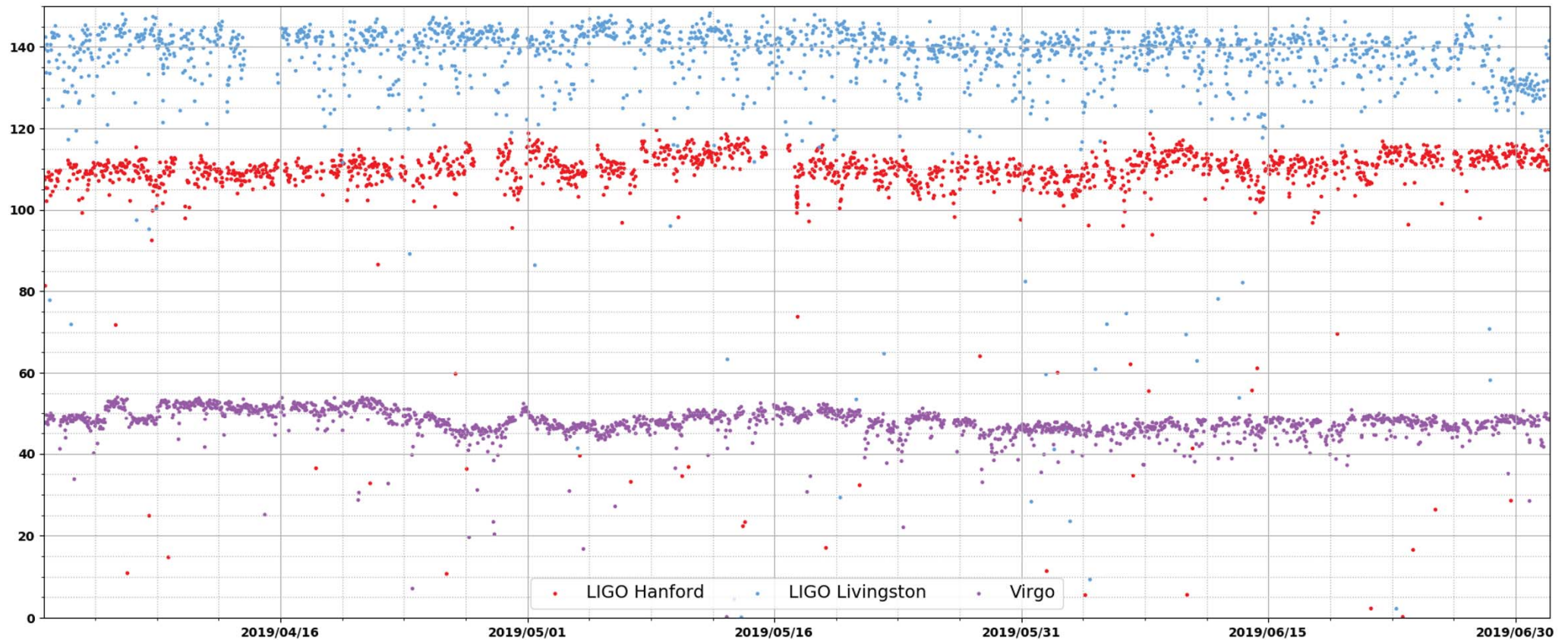
plot_HLV_science_segments: Number of detectors online
2019-04-01 15:00:00+00:00 UTC -> 2019-07-02 02:07:03+00:00 UTC -- segments: DMT-ANALYSIS_READY (H1-L1), SCIENCE (V1)



Virgo within the LIGO-Virgo 3-detector network

- **BNS range comparison**
 - Quite good **long-term stability**

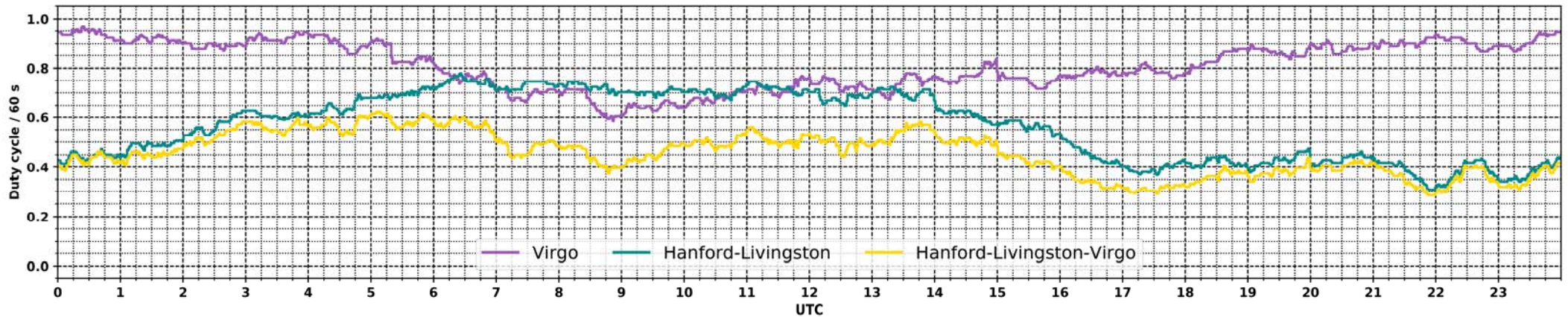
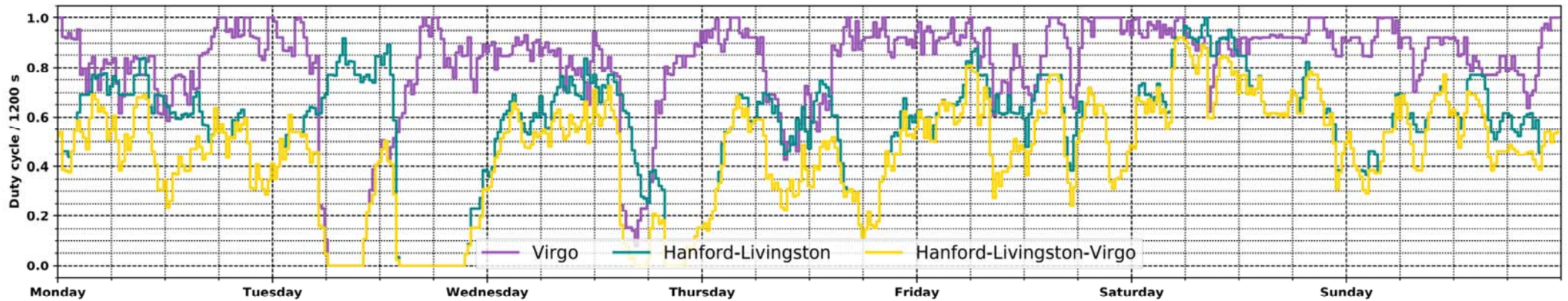
H1-L1-V1 network: 2019-04-01 15:00:00+00:00 UTC -> 2019-07-02 02:07:03+00:00 UTC -- science segments



Virgo within the LIGO-Virgo 3-detector network

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

Comparing H1-L1 and V1, average duty cycles
1238166018 [2019-04-01 15:00:00+00:00 UTC] -> 1246039100 [2019-07-01 17:58:02+00:00 UTC]



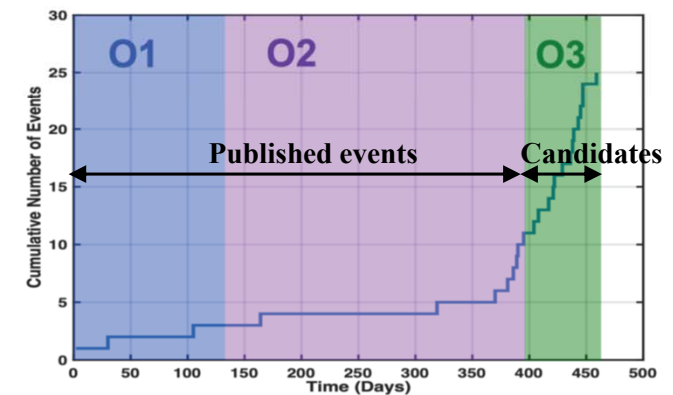
Public alerts

- 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
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
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
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
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
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
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
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
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

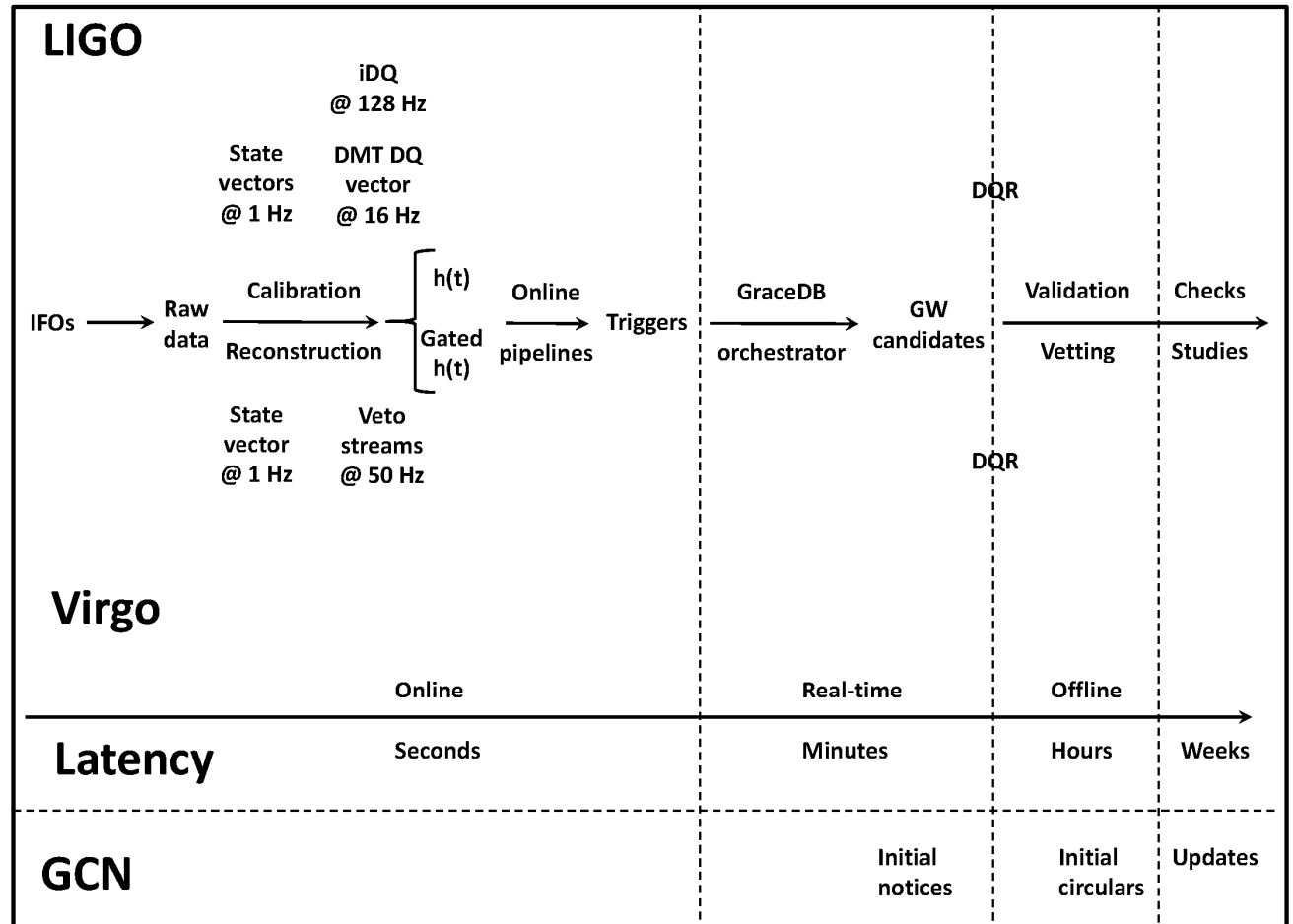


- 19 public triggers as of **July 4th, 2019**
 - 3 retracted
- Mainly **binary black hole merger candidates**
 - Some may involve **lighter components**
- Offline analysis** in progress



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

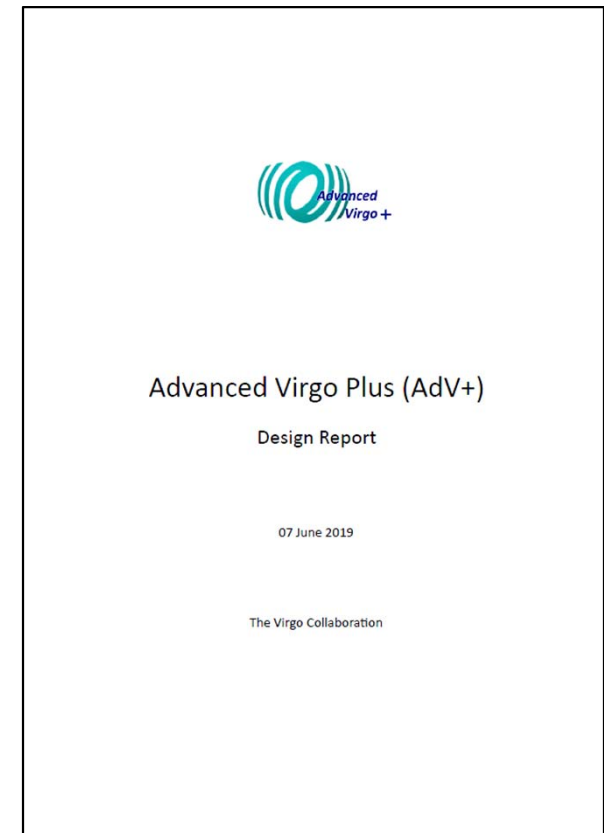
- Initial plan: 12 months running
 - April 2019 → March 2020
 - Announcement at the last [LV-EM Open Forum](#) Telecon
 - Potential 1-month commissioning break
 - Starting late September – early October
- Updated planning to be announced soon

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”](#)



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