The Status of Virgo
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The 5th KAGRA International Workshop, Perugia, February 14, 2019
## Contents

Virgo Collaboration is growing and new groups are being integrated into Virgo

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status of Virgo</td>
<td>3</td>
</tr>
<tr>
<td>Scientific highlights</td>
<td>7</td>
</tr>
<tr>
<td>Commissioning</td>
<td>19</td>
</tr>
<tr>
<td>Computing and Data Processing</td>
<td>31</td>
</tr>
<tr>
<td>Upgrade project AdV+</td>
<td>35</td>
</tr>
<tr>
<td>Path towards Einstein Telescope</td>
<td>47</td>
</tr>
<tr>
<td>Summary and outlook</td>
<td>57</td>
</tr>
</tbody>
</table>
Virgo Collaboration

Virgo is a European collaboration with more than 300 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

- 24 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - IFAE Barcelona
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI
  - LAPP Annecy
  - LMA Lyon
  - LKB Paris
  - Nikhef Amsterdam
  - POLGRAW (Poland)
  - RADBOUD Uni.
  - RMKI Budapest
  - UCLouvain
  - ULiege
  - Univ. of Barcelona
  - Univ. of Valencia
  - University of Jena

Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

8 European countries
Advanced Virgo

Most infrastructure installed for Advanced Virgo. It features many improvements with respect to Virgo and Virgo+. However the absence of Signal Recycling has great impact

Instrumentation improvements for Observing run 2

- Larger beam: 2.5x larger at ITMs
- Heavier mirrors: 2x heavier
- Higher quality optics: residual roughness < 0.5 nm
- Improved coatings for lower losses: absorption < 0.5 ppm, scattering < 10 ppm
- Reducing shot noise: arm finesse of cavities are 3 x larger than in Virgo+
- Thermal control of aberrations: compensate for cold and hot defects on the core optics:
  - ring heaters
  - double axicon CO2 actuators
  - CO2 central heating
  - diagnostics: Hartmann sensors & phase cameras
- Stray light control: suspended optical benches in vacuum, and new set of baffles and diaphragms to catch diffuse light
- Improved vacuum: 10^{-9} mbar instead of 10^{-7} mbar
2018: IFAE and UBarcelona, ULiège and UCLouvain

New groups strengthen Virgo in areas as Computing and Stray Light Mitigation

Groups from UTorino, UMaastricht, USannio, USardinia joined Virgo indirectly
LVC scientific output
LIGO-Virgo analyses for sources of gravitational waves

Sources can be transient or of continuous nature, and can be modeled or unmodeled

**Burst**
- Coalescence of Compact Sources
  - Colliding binary systems (e.g. black holes, neutron stars)
- Asymmetric core collapse supernovae (and other poorly modeled events)

**Continuous Waves**
- Rapidly rotating neutron stars (with lumps on them)

**Stochastic**
- A stochastic, unresolvable background (from the Big Bang, or all of the above)
Scientific achievements: properties of black holes

Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

LVC reported on 10 BBH mergers (and 1 BNS)

Chirp mass is well inferred

Merger dynamics more sensitive to total mass

Properties of black holes

Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms.

Table of O1 and O2 triggers with source properties
See https://dcc.ligo.org/LIGO-G1801864

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Virgo data contributed to Parameter Estimation of 5 events

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First triple detection by Virgo and LIGO

August 14, 2017 three detectors observed BBH. Initial black holes were 31 and 25 solar mass, while the final black hole featured 53 solar masses. About 3 solar mass radiated as pure GWs.
Polarization of gravitational waves

Polarization is a fundamental property of spacetime. It determined how spacetime can be deformed. General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations

GR only allows (T) polarizations

General metric theories also know vector (V) and scalar (S) polarizations

First test of polarizations of gravitational waves

According to Einstein’s General Relativity there exist only two polarizations. General metric theories of gravity allow six polarizations. GW170814 confirms Einstein’s prediction.

Angular dependence (antenna-pattern) differs for T, V, S.

LIGO and Virgo have different antenna-patterns.
This allows for a fundamental of the polarizations of spacetime.
First test of polarizations of gravitational waves

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Angular dependence (antenna-pattern) differs for T, V, S

LIGO and Virgo have different antenna-patterns
This allows for a fundamental of the polarizations of spacetime

Our analysis favors tensor polarizations in support of General Relativity

Our data favor tensor structure over vector by about a (Bayes) factor 200
And tensor over scalar by about a factor 1000

This is a first test, and for BBH we do not know the source position very well
Virgo allowed source location via triangulation

GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it.
Distributed skymaps
See https://dcc.ligo.org/LIGO-G1801864
Scientific impact of gravitational wave science

Multi-messenger astronomy started: a broad community is relying on detection of gravitational waves

**Fundamental physics**
Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo’s, primordial, no-hair
Black hole mimickers, Lorentz-invariance, equivalence principle, polarization, parity violation, axions

**Astrophysics**
First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

**Astronomy**
Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

**Cosmology**
Binary neutron stars can be used as standard “sirens”
Dark Matter and Dark Energy, stochastic background

**Nuclear physics**
Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state, phase transitions

LVC will be back with improved instruments to start the next observation run (O3) early this year
Commissioning
Projected sensitivity evolution for Virgo

From the 2013 “Observing Scenario”, arXiv:1304.0670. We projected at least 60 Mpc for O3. Note that LIGO aims at > 120 Mpc.
Virgo sensitivity: significant improvement wrt O2

Comparison to the best sensitivity obtained in O2. Monolithic suspensions are now installed. Flat noise contribution in mid-frequency range, and significant 50 Hz noise.
Engineering runs and next observation run

LIGO and Virgo scheduled ER13 and ER14 engineering runs to prepare for observation run O3

ITF input power 18 W

- ER13 (4 days) just completed
- ER14 (4 weeks) starts around March 1, 2019
- O3 begins in April 2019
Engineering run ER13
ER13 lasted from December 14 – 18, 2018

Goals of ER13

• End-to-end test of the Open Public Alert (OPA) software
• Rapid Response Team (RRT) exercise
• Test of new Data Quality Reporting on online data
Engineering run ER13
Comparison to the best sensitivity obtained in O2
Engineering run ER13
Comparison to goals set for O3

Virgo aims at BNS range > 60 Mpc
- Commissioning in progress. Also at LIGO
Virgo will implemented signal recycling after O3

Comparison to L1 and H1

Virgo’s strain sensitivity

- Effect of no signal recycling is apparent. Also injected laser power 18 W, no squeezing, 3 km, …
Virgo’s best sensitivity so far

Sensitivity (BNS range) has now reached 55 Mpc. Further improvements are explored: implement squeezing, reduce 50 Hz noise, and/or reduce “flat” noise contribution.
Squeezing
The AEI squeezer installed in Virgo’s DET lab. Squeezer can deliver up to 14 dB of squeezed light

Squeezer connected with electronics, and operating: same squeezing level obtained as in Hannover
Set up external bench (telescopes,...), replaced in-vacuum Faraday isolator, alignment and commissioning
Implementation of frequency independent squeezing is underway

**Main activities**

Significant priority since October 2018

Completed hardware installation: injection 10 dB and expected losses = 40% (see VIR-0745A-18) +10% (technical noise) = 50%

Set up and optimize control loops: coherent control and automatic alignment

Mitigation of back-scattered light

**Preliminary results**

Measured a peak SQZ injection of almost 2 dB (3 dB is our O3 target)

BNS range improvement of 2-3 Mpc to 55 Mpc

Inferred losses 60-70%

Need to improve stability
Commissioning has the highest priority

**Main objective**
Identify technical noise contributions at mid frequency

Carry out a *systematic* study to identify technical performance. Identify tests, interpret test results, generate ideas for new tests. Rapid turn around with help of PhD students, postdocs

Current candidate: working point of ITF

Full priority over all other ITF activities: CC sets priority

Meetings: dedicated discussions tagged on to weekly Commissioning and Detchar meetings

Wiki to list status and progress: [https://wiki.virgo-gw.eu/Commissioning/FlatNoise](https://wiki.virgo-gw.eu/Commissioning/FlatNoise)

**Parallel activities**
Electronics to achieve improved 50 Hz robustness is under preparation

System to discharge mirrors is under investigation

Focus on stability

Reliability and risk reduction
Virgo Computing and Data Processing
Virgo Computing and offline Data processing

Recent developments and boundary conditions

Computing situation for LVC is becoming a bottleneck
• Virgo is making an effort to increase its contribution to LVC computing resources for DA
• Recent focus on LV Continuous Wave analysis
• Note that all O2 data will become public in February 2019
Virgo Computing and Data Processing

VSC agreed (August 29, 2018) to implement a new Virgo CDP subsystem (supersede VDAS). New structure is also recommended by ECC

New organization
• Local computing and low latency computing
• Offline computing management

Management
• DPI: EGO-Virgo Data Processing Infrastructure coordinator
• CDP: Virgo Computing and Data Processing coordinator

Scope
• DPI and CDP will work closely with other coordinators (DAQ and DA)
• Report to EGO Director and Virgo Spokesperson
Project deliverables

WBS and Projects with clear deliverables have been defined. Resources have been allocated.

**CW:** Complete LV data analyses on Continuous Waves and secure LVC publications

**GstLAL:** Allow most important CBC pipelines to run on European grid-computing resources. Start with GstLAL, but expand to other LV pipelines

**LVC:** I. Update VCDP Computing Model, Implementation Plan, and Management Plan (involve DA and CDP coordinators), and II. Prepare a strategy in collaboration with LSC and Computing Centers
What’s next?
Towards a global network
KAGRA expected to join LIGO and Virgo in Observation run 3
Planned observing timeline

One-year O3 planned to start in April 2019 with about twice the sensitivity in O3 (thus about $2^3$ in rate). In O3 LIGO and Virgo will release Open Public Alerts.

**Observation run O3**

Three detectors and perhaps 1 event per week

KAGRA expected to join at the end of O3

Contribute to sky localization and PE

AdV+ as the next incremental step forward in sensitivity

AdV+ is the plan to maximize Virgo’s sensitivity within the constrains of the EGO site. It has the potential to increase Virgo’s detection rate by up to an order of magnitude

AdV+ features

Maximize science
Secure Virgo’s scientific relevance
Safeguard investments by scientists and funding agencies
Implement new innovative technologies
De-risk technologies needed for third generation observatories
Attractive for groups wanting to enter the field

Upgrade activities

Tuned signal recycling and HPL: 120 Mpc
Frequency dependent squeezing: 150 Mpc
Newtonian noise cancellation: 160 Mpc
Larger mirrors (105 kg): 200-230 Mpc
Improved coatings: 260-300 Mpc
Phase I
Quantum noise will be tackled after the O3 science run in Phase 1: **installation in 2020**

**Power increase**
All in-fiber 200 W laser system for 125 W after the IMC
Foreseen as part of AdV

**Tuned signal recycling: 120 Mpc**
Install SR mirror
Control additional DOF (auxiliary lasers?)

**Frequency dependent squeezing: 150 Mpc**
Squeezed light source and filter cavity

**Newtonian noise cancellation: 160 Mpc**
Seismic sensor networks
Phase II

Reduce thermal noise: modify optical design of the Fabry-Perot arms to accommodate larger beams and heavier test masses

Larger mirrors
Diameter: 550 mm, thickness: 200 mm, mass: 105 kg
Scenario 1: ETM-only → 200 Mpc
Scenario 2: full upgrade → 230 Mpc

Coating research
Factor three reduction in CTN
Scenario 1: ETM-only → 260 Mpc
Scenario 2: full upgrade → 300 Mpc

Grand Coater upgrade

Many activities
Vacuum, infrastructure
Payloads and superattenuators
Aberration control
The AdV – AEI Squeezing Working Group prepared a Conceptual Design (transverse activity)

Optical loss, injection losses, noise tolerances
  Technical noise and phase noise
  Filter cavity: cavity length and finesse
  Stray light considerations

Infrastructure
  Overall layout
  Minitower and control microtower locations
  Cavity mirrors locations

Suspensions
  Optical benches and mirrors suspensions

Optics, optical layout, filter cavity mirrors
  OPO location
  Filter cavity control schemes
  Suspended bench optical links
  General layout
  In-air squeezed light source operation
  In-vacuum squeezed light source operation

Frequency dependent squeezing in the post-O4 era: EPR-entanglement
FDS Project Breakdown Structure

PBS follows the hardware components (not a WBS)

Responsibilities for construction of items for AdV+ have been allocated
   a) Optical design and preparations for FDS ongoing
   b) Smart infrastructure (HVAC) for NNC: under discussion
Improvements to the infrastructure are expected to have a large impact

Noise at Central Building is about an order of magnitude higher than the noise in the vicinity of Virgo

Need for emphasis on smart infrastructure for gravitational wave observatories
- Smart infrastructure design
- Newtonian noise modeling of infrastructure noise
- HVAC modification
AdV+ upgrade and extreme mirror technology

Laboratoire des Matériaux Avancés LMA at Lyon produced the coatings used on the main mirrors of the two working gravitational wave detectors: Advanced LIGO and Virgo. These coatings feature low losses, low absorption, and low scattering properties.

**Features**
- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:Ta$_2$O$_5$ and SiO$_2$ stacks with optical absorption about 0.3 ppm

**Expand LMA capabilities for next generation**

LMA is the only coating group known to be capable of scaling up.
AdV+ to be carried out in parallel with LIGO’s A+ upgrade

Five year plan for observational runs, commissioning and upgrades

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>Observing Run O3 (&gt; 60 Mpc)</td>
</tr>
<tr>
<td>2020</td>
<td>Design, infrastructure preparation for AdV+</td>
</tr>
<tr>
<td>2021</td>
<td>Install signal recycling (AdV) and frequency dependent squeezing (AdV+)</td>
</tr>
<tr>
<td>2022</td>
<td>?</td>
</tr>
<tr>
<td>2023</td>
<td>Observing Run O4 (&gt; 120 Mpc)</td>
</tr>
<tr>
<td>2024</td>
<td>Install AdV+ large mirror upgrades</td>
</tr>
<tr>
<td>2025</td>
<td>AdV+ commissioning</td>
</tr>
<tr>
<td>2026</td>
<td>Observing Runs</td>
</tr>
</tbody>
</table>

Virgo AdV+ Proposed upgrade plan

LIGO A+ Upgrade plan (see LIGO-G1702134)

A+ fabrication

Install A+ upgrades

A+ integration into chambers

A+ commissioning

Completion AdV+ and A+

Note: duration of O4 has not been decided at this moment

AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope
## Five year plan for observational runs, commissioning and upgrades

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<td>A+ commissioning</td>
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<tr>
<td>2023</td>
<td>Virgo’s coating R&amp;D secures LMA’s relevance in future GW science</td>
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<tr>
<td>2024</td>
<td>Uniformity on selected materials</td>
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<td></td>
<td>Post deposition corrective coatings and optical control</td>
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<tr>
<td>2025</td>
<td>Material selection</td>
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<td></td>
<td>Substrates purchasing and polishing</td>
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<tr>
<td>2026</td>
<td>Mirror production</td>
</tr>
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<td>Completion AdV+ and A+</td>
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**Note:** duration of O4 has not been decided at this moment
3G: observing all mergers in the Universe

This cannot be achieved with existing facilities and requires a new generation of GW observatories.

We want to collect high statistics (*e.g.* millions of BBH events), high SNR, distributed over a large z-range (*z* < 20).

This allows sorting data versus redshift, mass distributions, *etc.* Early warning, IMBH, early Universe, CW, …
ET and CE

Realizing the next gravitational wave observatories is a coordinated effort to create a worldwide 3G network.
Einstein Telescope has excellent sensitivity

Einstein Telescope and Cosmic Explorer can observe the entire universe
Studies of quality at potential sites in Sardinia and B-G-NL

The geology of the B-G-NL Limburg border area: hard rock with on top a layer of soft absorbing and damping soil. In addition the region is free of disturbing (man-made) seismic activities.

Antea borehole

Deltares research

Nikhef simulations
Geologists are actively involved in underground studies

We obtained soil samples up to a depth of 140 m. Picture: Geert-Jan Vis (TNO), Jan Lutgert (EBN), Alessandro Bertolini (Nikhef). Research on samples at CITG in TU-Delft

Plans for detailed geological studies of B-G-NL site are under development in Belgium
Development of a local 3G Excellence Center

Realization of a realistic test facility is under discussion. This will allow de-risking of key technologies such as large scale cryogenic test masses, sensor development, new laser technology, controls, … Also industry will be involved

Opportunity for training on GW instrumentation

Joint B-G-NL Limburg activity
The Einstein Telescope has excellent sensitivity for high mass gravitational waves. The Einstein Telescope and Cosmic Explorer can observe the entire universe.

**Cosmic Epochs**

- **Big Bang**
  - Radiation era
  - ~300,000 years: "Dark ages" begin
- ~400 million years: Stars and nascent galaxies form
- ~1 billion years: Dark ages end
- ~9.2 billion years: Sun, Earth, and solar system have formed
- ~13.7 billion years: Present
Einstein Telescope

Einstein Telescope can observe BBH mergers to a redshift more than 20. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), etc.
Einstein Telescope

Einstein Telescope can observe BBH mergers to a redshift more than 20. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), \textit{etc.}
Dark energy: what is ripping the universe apart?

Einstein Telescope will use CBC events as standard “sirens”. This allows a new type of cosmography. Moreover the equation of state parameter for Dark Energy can be measured.
3G science

Detailed studies of gravity, near black holes. Early warning to EM follow-up community. Precision tests of detailed aspects of CBC. Cross correlation of the largest data sets. Access to early Universe

Signals from early universe?
Bright future for gravitational wave research

LIGO and Virgo are operational. KAGRA in Japan next year, LIGO-India is now under construction. ESA launches LISA in 2034. Einstein Telescope and CE CDRs financed, strong support by APPEC

Gravitational wave research
• LIGO and Virgo operational
• KAGRA to join next year
• LIGO-India under construction (2025)
• ESA selects LISA, NASA rejoins
• Pulsar Timing Arrays, such as EPTA and SKA
• Cosmic Microwave Background radiation

Einstein Telescope and Cosmic Explorer
• CDR ET financed by EU in FP7, CE by NSF
• APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps for 3G
• Organize the community and prepare a credible plan for EU funding agencies
• ESFRI Roadmap (2020)