Gravitational waves
Advanced Virgo and Einstein Telescope

Jo van den Brand
Nikhef SAC, Amsterdam, 8 July 2019; jo@nikhef.nl
LIGO and Virgo

Establishing Virgo as a partner in the global GW network was a major accomplishment

LIGO and Virgo have coordinated data taking and analysis, and release joint publications. LIGO and Virgo work under an MOU already for more than a decade. KAGRA may join in 2019.
Virgo Collaboration has invested in Advanced Virgo

Virgo is a European collaboration with about 400 members from about 80 institutes

Advanced Virgo (AdV) and AdV+: upgrades of the Virgo interferometric detector

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

- Institutes in Virgo Steering Committee
  - APC Paris
  - ARTEMIS Nice
  - 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 Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW (Poland)
  - RADBOUD Uni.
  - Nijmegen
  - RMKI Budapest
  - UCLouvain, ULiege
  - Univ. of Barcelona
  - University of Sannio
  - 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

LIGO and Virgo running of O3

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

2018: IFAE and UBarcelona, ULiège and UCLouvain

2019: USannio/UniSA, Jena University, Maastricht University, and request for membership by Antwerp University

Groups from UTorino, USardinia, joined Virgo indirectly

ULBrussels, UAntwerp, UGhent, UUtrecht, KULeuven, KIT, … in discussion
Advanced LIGO’s Second Observing Run

January 4, 2017

June 6, 2017

August 1, 2017

Virgo turns on
Scientific achievements: properties of binary systems

Table of O1 and O2 triggers with source properties

See arXiv:1811.12907

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See arXiv:1811.12907

Virgo data contributed to Parameter Estimation of 5 events

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Properties of black holes

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

Nikhef Gravitation Physics group

Good mix between instrumentation and data analysis. Instrumentation is emphasized at Nikhef and Maastricht University. Composition: 19 seniors, 7 postdocs, 12 PhD students. More to come …

Instrumentation
Alessandro Bertolini  Senior Nikhef
Bas Swinkels       Scientist Nikhef
Matteo Tacca       Scientist Nikhef
Daniela Pascucci   Postdoc Nikhef
Jo van den Brand   Professor VUAmsterdam
Henk Jan Bulten    Senior VUAmsterdam
Soumen Koley       PhD VUAmsterdam
Boris Boom         PhD VUAmsterdam
Laura van der Schaaf PhD VUAmsterdam
Rob Walet          PhD VUAmsterdam
Stefan Hild        Professor UMAastricht
Stefan Danilishin  A. Professor UMAastricht
Jessica Steinlechner A. Professor UMAastricht
Sebastian Steinlechner A. Professor UMAastricht
Ayatri Singha      PhD UMAastricht
Andrei Utina       PhD UMAastricht
Frank Linde        Professor UAmsterdam

Data analysis
Sarah Caudill      Scientist Nikhef
Chris Van Den Broeck Professor UUtrecht
Tim Dietrich       Postdoc UUtrecht
Ka Wa Tsang        PhD UUtrecht
Tsun Ho Pang (Peter) PhD UUtrecht
Anuradha Samajdar  Postdoc UUtrecht
Archisman Ghosh    Postdoc UUtrecht
Gideon Koekoek     A. Professor UMAastricht

Astrophysics
Gijs Nelemans      Professor UNijmegen
Paul Groot         Professor UNijmegen
Steven Bloemen     Senior UNijmegen

Grappa
Samaja Nissanke    Professor UAmsterdam
Tanja Hinderer     Postdoc UAmsterdam
David Nichols      Postdoc UAmsterdam
Andrew Williamson  Postdoc UAmsterdam
Geert Raaijmakers  PhD UAmsterdam

Detector R&D
Niels van Bakel    Senior Nikhef
Martin van Beuzekom Senior Nikhef
Maria Bader        PhD VUAmsterdam
Yuefan Guo         PhD UAmsterdam
Maastricht University is partner in Nikhef
Admitted for Virgo Collaboration membership on July 4, 2019

Group is active in LIGO and has various responsibilities. For reasons of continuity there will be a 10% LSC membership (approved by LSC Council)

- S. Danilishin: LSC Quantum Noise Working Group chair
- J. Steinlechner: LSC Optics Working Group co-chair
- J. Steinlechner: LSC LAAC co-chair
- S. Hild: LSC AIC Working Group chair
- S. Hild: LSC Publications and Presentations Committee co-chair
- S. Hild: LSC Excomm member
- S. Hild: LSC technical advisor to the LIGO Oversight Committee
- G. Koekoek: Main organiser of 2018 LVC meeting in Maastricht
Gravitational wave science at Nikhef

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

Searches for binary coalescences
GstLAL is one of the main search pipelines that led to the detections in O1, O2, O3
Sub-solar mass (primordial?) black holes

Inferring the structure of neutron stars
State-of-the art inspiral waveform modeling
For the future: post-merger

Testing the dynamics of general relativity
Inspiral-merger-ringdown process
Gravitational wave propagation

Probing the nature of massive compact objects
Testing the no-hair conjecture
Gravitational wave echoes

Cosmology
Measuring the Hubble constant with or without electromagnetic counterparts
Embedding in LIGO Virgo data analysis

Chris Van Den Broeck
Co-chair, Testing GR group
Chair of the paper writing team, “Tests of general relativity with GW170817”

Sarah Caudill
Co-chair, All-sky searches for compact binary coalescences
Member of the paper writing team, “Search for sub-solar mass ultra-compact binaries in Advanced LIGO’s second observing run”

Tim Dietrich (postdoc)
Member of the paper writing team, “Properties of the binary neutron star merger GW170817”

Archisman Ghosh (postdoc)
Co-chair, Cosmology group
Member of the paper writing team, “A gravitational-wave standard siren measurement of the Hubble constant”

Anuradha Samajdar (postdoc)
Member of the paper writing team, “Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1”

PhD students: Pawan Gupta, Peter Pang, Ka Wa Tsang
April 1, 2019: LIGO and Virgo started Observation run O3
Joining O3 is another big step for Virgo
Virgo sensitivity: typically around 50 Mpc

Significant improvement (> 90%) with respect to the average sensitivity (26 Mpc) obtained in O2. We see a flat noise contribution at mid-frequencies, and significant 50 Hz noise. Power amounts to 18 W Efficiency around 90%
Commissioning of Virgo
Commissioning encompasses many responsibilities. Coordinator must assemble a team and define roles and responsibilities

Main objectives of Commissioning
Identify and study current limitations: technical noise contributions at low and mid frequency
Integrate new systems to discharge mirrors, signal recycling, high power laser, squeezing, …

Commissioning and Operations

Commissioning Coordinator must form a ROTA for Run Coordinator, be present in the Rapid Response Team, and be part of the LIGO Virgo Joint Run Planning Committee
Virgo Computing and offline Data processing

Recent developments and boundary conditions

Computing situation for LVC is a bottleneck
- Virgo is making an effort to increase its contribution to LVC computing resources for Data Analysis

Management
- EGO-Virgo Data Processing Infrastructure coordinator
- Virgo Computing and Data Processing Coordinator
Virgo Computing and Offline Data Processing

Virgo has implemented a new structure and has defined several projects

**CW:** Complete LV data analyses on Continuous Waves

**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
O3 is here! See [https://gracedb.ligo.org/latest/](https://gracedb.ligo.org/latest/)

Public alerts in the 3rd science run: already more candidate events than O1 and O2 combined

**Latest — as of 8 July 2019 09:03:46 UTC**

Test and MCC events and supernovae are not included in the search results by default; see the [query help](https://gracedb.ligo.org/latest/) for information on how to search for events and supernovae in these categories.

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Virgo's low latency computing is working as designed. Automatic public alerts not so “automatic” (yet)

Three events were retracted by the LVC after more detailed analysis

A new **binary neutron star** event: only LIGO Livingston and Virgo were operational, thus large uncertainty in sky position. A **neutron star-black hole** event: LIGO Livingston, LIGO Hanford, and Virgo operational, but no EM counterpart found
Public alerts in the 3\textsuperscript{rd} science run: already more candidate events than O1 and O2 combined

Virgo's low latency computing is working as designed. Automatic public alerts not so “automatic” (yet)

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A new binary neutron star event: only LIGO Livingston and Virgo were operational, thus large uncertainty in sky position. A neutron star-black hole event: LIGO Livingston, LIGO Hanford, and Virgo operational, but no EM counterpart found
Science harvesting with the global GW detector network

Multi-messenger astronomy started: a broad community is relying of 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 back with improved instruments for observation run (O3) that started in April this year
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
Virgo will implemented signal recycling after O3

Signal recycling will improve Virgo’s sensitivity at medium to high frequency

Virgo’s strain sensitivity

- Effect of no signal recycling is apparent. Also injected laser power 18 W, no squeezing, 3 km, …
Frequency dependent squeezing

Nikhef has important responsibilities in the AdV+ upgrade project

Nikhef contributes to

a) Optical system design
b) High-finesse 300 m long filter cavity
c) Vibration isolation of in-vacuum squeezer bench and beam matching microtowers
Newtonian Noise Cancellation

Nikhef contributes arrays of seismic sensors will be used to subtract Newtonian noise in AdV+

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
Phase 1: reaching the thermal noise wall

Increase laser power, implement signal recycling, frequency dependent squeezing and Newtonian noise suppression.
Phase 2: pushing the thermal noise wall down
Implement larger ETMs and employ better coatings
Even better sensitivity can be obtained by replacing all mirrors, but this would be too invasive.
Scheduling of science runs, AdV+ installation and commissioning

Five year plan for observational runs, commissioning and upgrades

<table>
<thead>
<tr>
<th>Year</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
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</table>

**Virgo AdV+ tentative upgrade plan**

- **2019**: Design, infrastructure preparation for AdV+
- **2020**: Observing Run O3 (> 60 Mpc)
- **2021**: Install AdV+ signal recycling and frequency dependent squeezing
- **2022**: Observing O4 (> 120 Mpc)
- **2023**: Install AdV+ large mirror upgrades
- **2024**: AdV+ commissioning
- **2025-2026**: Observing Runs
- **2026**: Completion AdV+

Commissioning break in October 2019

Duration of O3: until the end of April 2020 (duration of O4 has not been decided)

Break between O3 and O4 probably around 18 months (allow installation and commissioning)

AdV+ to be carried out in parallel with LIGO’s A+ upgrade

AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope
Virgo’s coating R&D and mirror production are critical

Virgo must have a credible plan for Coating R&D

<table>
<thead>
<tr>
<th>Year</th>
<th>Task</th>
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<td>Uniformity on selected materials</td>
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<td>2020</td>
<td>Design, infrastructure preparation for AdV+</td>
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<tr>
<td></td>
<td>Install signal recycling (AdV) and frequency dependent squeezing (AdV+)</td>
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<tr>
<td></td>
<td>Observing Run O3 (&gt; 60 Mpc)</td>
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<tr>
<td></td>
<td>Install AdV+ large mirror upgrades</td>
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<tr>
<td></td>
<td>AdV+ commissioning</td>
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<tr>
<td>2021</td>
<td>Observation Runs</td>
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<tr>
<td></td>
<td>A+ fabrication</td>
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<td>A+ upgrades</td>
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<td>Integration into chambers</td>
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<td>A+ commissioning</td>
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<td>2022</td>
<td>LIGO A+ Upgrade plan (see LIGO-G1702134)</td>
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<td>A+ upgrades</td>
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<td>Integration into chambers</td>
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<td>A+ commissioning</td>
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<td>2023</td>
<td>Virgo AdV+ Proposed upgrade plan</td>
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<td>AdV+ large mirror upgrades</td>
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<td>AdV+ commissioning</td>
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<td>Observation Run O4 (&gt; 120 Mpc)</td>
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<td>2024</td>
<td>AdV+ and A+</td>
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<tr>
<td>2025</td>
<td>Completion AdV+ and A+</td>
</tr>
</tbody>
</table>

Large mirrors to be installed in Phase 2, but substrates must be acquired in 2020. This has implications for the budget profile.
Einstein Telescope
ET as GW observatory with full sky coverage and high uptime
Einstein Telescope
Excellent low-f sensitivity and great discovery potential

For science case, see https://www.dropbox.com/s/gihpzcue4qd92dt/science-case.pdf?dl=0
Einstein Telescope

Dreaming about a timeline?

2019 2020 2021 2022 2023 2024 2025 2026 … 2032

ESFRI status

Site decision

Construction

Commissioning

* VERY tentative schedule  ⬜ Science
Einstein Telescope
Dreaming about a timeline?

**Reality check**
TDRs, detailed cost scrutiny, realistic exploitation cost estimate, governance structure

Deadline for EU submission: April 2020
Deadline for the national submissions: January 2020

Formal support must be expressed by a consortium of governments wanting to support ET proposal

*We need to organize the global scientific community interested in 3G (and continuously keep them informed)*

*For ESFRI we need to prepare a credible plan for EU funding agencies*
Studies of quality at potential B-G-NL site

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 (human-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. RWTH Aachen involved

Proposal (Intereg) submitted for detailed geological studies of B-G-NL site: E-TEST M€ 14.9
ET studies on civil engineering and vacuum technology
Innovation may lead to cost reduction in main cost drivers of the project
Close collaboration with industry, e.g.

In discussion with Engineering Geology RWTH Aachen, Implenia, Fraunhofer IPT (Institute for Production Technology)

Proposal (Interreg) in preparation for collaborative work with (small to medium-size) industry: M€ 10

ET meets Industry in Antwerp on July 18, 2019
Funding made available for 3G R&D: B-G-NL Limburg

About M€ 14.5 for the realization of a global R&D facility. 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.
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Funding & partners

- Obtained ~14.5 MEuro funding from unconventional sources:
  - InterReg Flanders-South of NL (European fund for cross-border development)
  - Province of Limburg (NL), Dutch and Belgian national ministries
  - Matched contribution by partners
- Partners: Nikhef, universities of Antwerpen, Eindhoven, Ghent, Hasselt, Leuven, Maastricht
- Satellite partners: Aachen, Brussels, Fraunhofer, Liège, Louvain la Neuve, Twente, TNO
- Additional input from Glasgow, AEI, Perugia ...
- 100+ person-years (staff scientists and engineers) committed over the next 5 years
- New collaborators are welcome
Bright future for gravitational wave research and Nikhef is strongly committed

LIGO and Virgo are operational. KAGRA in Japan joins this year, LIGO-India 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 this 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

Points of attention
• Nikhef should increase its focus on data analysis
• Increase the engagement of astro-scientists (OPA)
• Increase role in offline computing
• ET preparation for ESFRI Roadmap is a challenge
Thanks for your attention!!