Present Status and Future Prospects of the Advanced Virgo Gravitational-Wave Detector

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13 September 2021

1. The Virgo Collaboration & The International GW Network
2. The Advanced Virgo Detector in *O3*
3. Advanced Virgo Performance in the *O3* Observing Run
4. The Advanced Virgo Plus Era

Background Image Credit: *University of Warwick* and *Mark Garlick*

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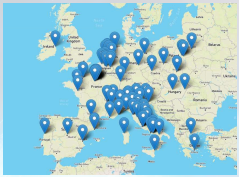
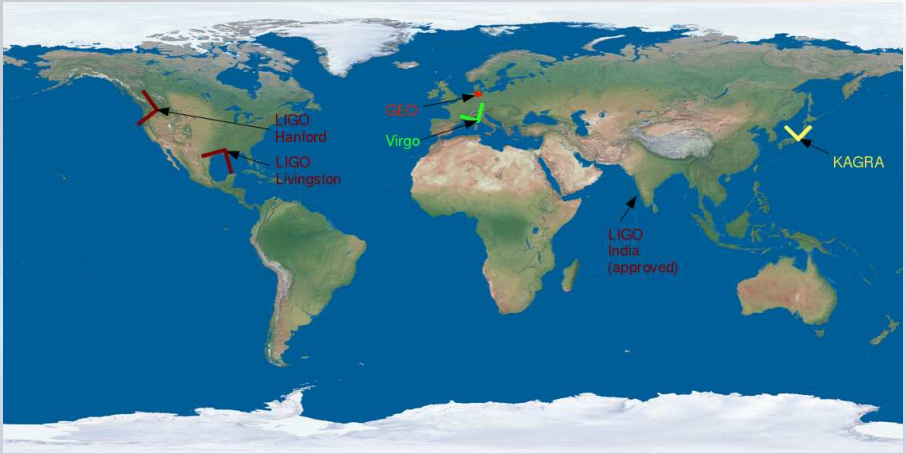
The Virgo Collaboration

- $\sim$ 700 members, $\sim$ 480 authors
- 30 groups from 130 institutions
- 15 countries contributing
- 9 countries represented in the Virgo Steering Committee



The International Gravitational-Wave Network (IGWN)



http://public.virgo-gw.eu/a-worldwide-network/

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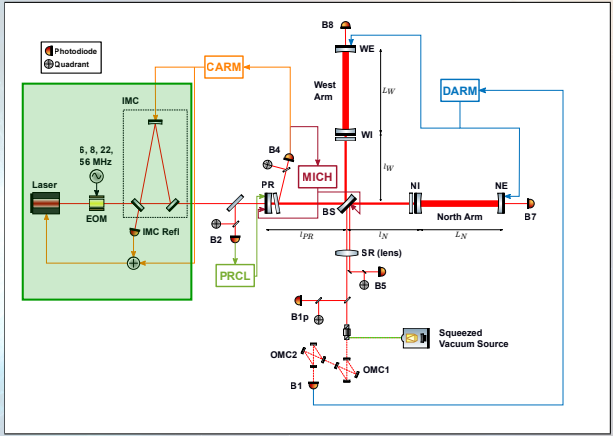
Optical Layout (1) – Injection System

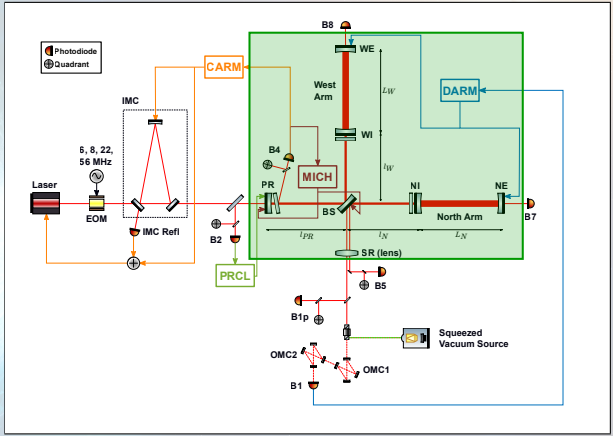
- Main laser beam from a 1064 nm Nd:YAG source, pre-stabilized in amplitude and frequency
- An Electro-Optic-Modulator generates radio-frequency sidebands used for the controls
- A triangular resonant cavity (Input Mode Cleaner) removes high-order modes and allows only TEM00 mode propagation



https://doi.org/10.3390/universe7090322

Optical Layout (2) – Main Interferometer (1)

- Two 3 km-long Fabry-Pérot resonant cavities as interferometer arms (Finesse $\mathcal{F} \approx 460$)
- Power Recycling mirror to re-inject reflected beam and increase the circulating power (additional resonant cavity)
- Signal Recycling mirror to improve and shape the frequency response (*not installed for O3*)



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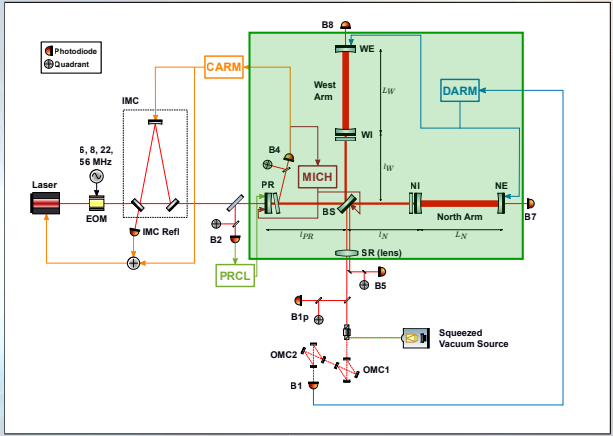
Optical Layout (3) – Main Interferometer (2)

- Resonant cavities need to be controlled with high precision
- Several longitudinal Degrees of Freedom:
  - MICH = $l_N - l_W$, length difference of the short arms of the Michelson
  - PRCL = $l_{PR} + \frac{l_N + l_W}{2}$, Power Recycling cavity length
  - CARM = $\frac{L_N + L_W}{2}$, common arm length of the long arms
  - DARM = $L_N - L_W$, differential arm length of the long arms, sensitive to the strain induced by GWs



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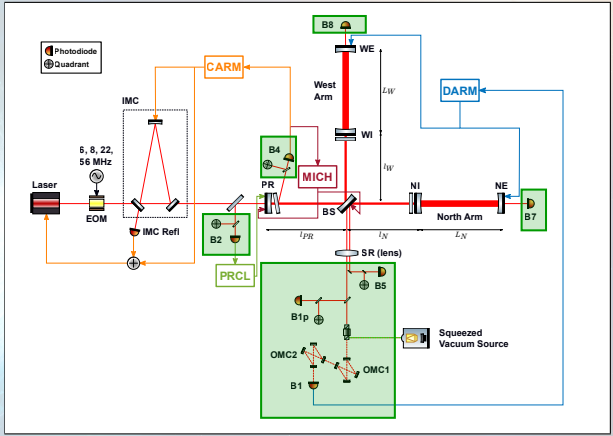
Optical Layout (4) – Detection System

- Distributed system, composed by photodiodes and quadrant photodiodes at the several ports of the interferometer
- Two Output Mode Cleaners reduce HOMs and clean the beam from the sidebands fields before the dark port
- Interaction with the Squeezing system
- B1 is the detection photodiode



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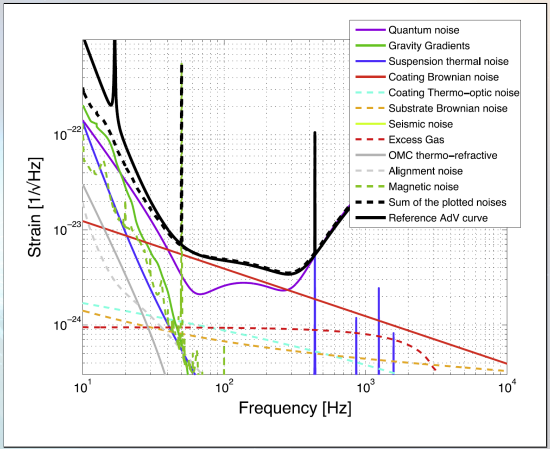
Sensitivity Curve & Noise Budget

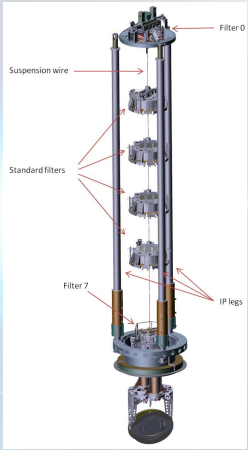
- It is the frequency response of the detector to GW-induced strain
- It is a calibrated, reconstructed DARM spectrum
- Many fundamental and technical noises limit it
- Different technological solutions to improve it in different frequency ranges

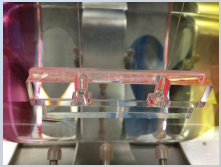


http://doi.org/10.1051/epjconf/201818202003

Low Frequency: Gravity Gradients, Seismic Motion, Thermal Noise

- Superattenuator: N multi-stage pendulum from which a double pendulum system (*payload*) is hanged, the mirror is the last stage
- $1/f^{2N}$ seismic noise attenuation factor
- System connected to ground through a 3-legs inverted pendulum, for further noise suppression at very low frequency
- The payload holds the mirror, actuators, thermal compensation elements and scattered light mitigations
- Fused silica fibers hold the mirrors, for low mechanical losses and thermo-elastic dissipation





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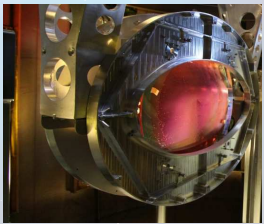
Intermediate Frequency: Thermal Noise of the Optics

- In the $40 \div 300\,\mathrm{Hz}$ range sensitivity is limited by the thermal noise of the coating layers on the mirror surfaces (needed for reflectivity requirements)
- Core mirrors are cylinders of ultra-pure fused silica (Suprasil™ 3002 and 312), $0.3\,\mathrm{ppm/cm}$ absorption and $\phi \approx 10^{-9}$ loss angle
- Coatings: stack of alternate layers (Bragg reflector) of SiO_2 and TiO_2:Ta_2O_5
- Thermal treating (annealing) lowers optical absorption and internal stress



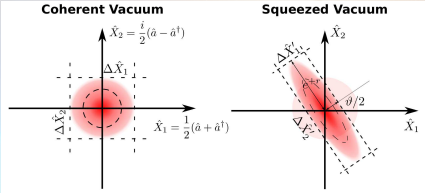
Credit: M. Perciballi

High Frequency: Photon Shot Noise

- Quantum noise: radiation pressure at low frequency (hidden by technical noises in *O3*) and photon shot noise at high frequency, which is limiting
- Noise mitigated by the increase of the circulating power (main laser)
- Additional reduction via the injection of squeezed vacuum states:

$$\Delta X_1 \Delta X_2 \geq 1$$

  - Reduction of the uncertainty of one quadrature but increase on the other
  - Squeezed vacuum source at the dark port
  - AEI squeezer integrated in Advanced Virgo: squeezing produced in a standalone breadboard and injected through the dark port



https://doi.org/10.3390/galaxies8040079

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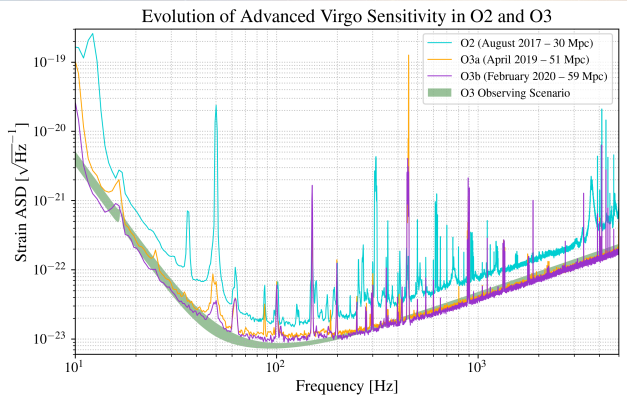
Sensitivity Curve of Advanced Virgo in *O3*

- Frequency-dependent response to GW-induced strain
- Factor 2 increase with respect to *O2*
- Improvement during the 1 month Commissioning break between *O3a* and *O3b*
- In line with Observing Scenario, exception at intermediate frequency



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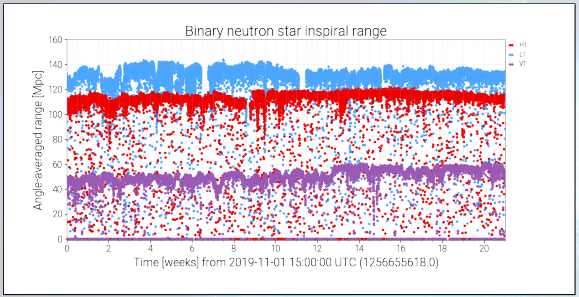
BNS Range of Advanced Virgo in *O3*

- Binary Neutron Star Range: figure of merit based on benchmark source

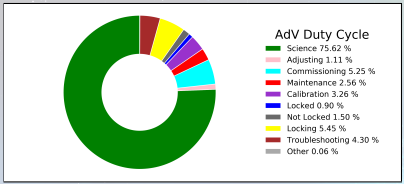


https://www.gw-openscience.org/detector_status/O3b/

https://emfollow.docs.ligo.org/userguide/glossary.html

- BNS Range peaked at 60 Mpc in *O3*
- Improvement in *O3b*, in value and stability
- Still a gap with respect to LIGOs, but progressively smaller (2 year gap in detector operation)

Duty Cycle of Advanced Virgo in *O3*



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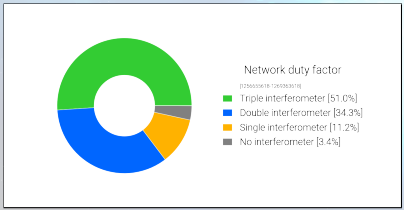
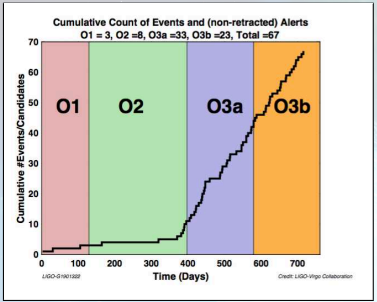


https://www.gw-openscience.org/detector_status/O3b/

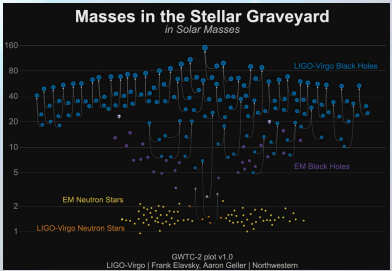
- High duty cycle in Science Mode
- Mandatory Maintenance, Calibration and Commissioning activities sum up for the major part of the offline time
- High three-detector simultaneous operation during *O3*, and usually only one detector down at a given time
- Coincidence detection is of paramount importance for source localization and parameter estimation

Alerts & Events in *O3*



- Number of alerts and events dramatically increased with three detectors online
- 56 non-retracted alerts in *O3*

- *O3a* data and GWTC-2 catalog already released, *O3b* data and GWTC-3 in preparation
- See presentations by A. Rocchi and W. Del Pozzo for detailed information



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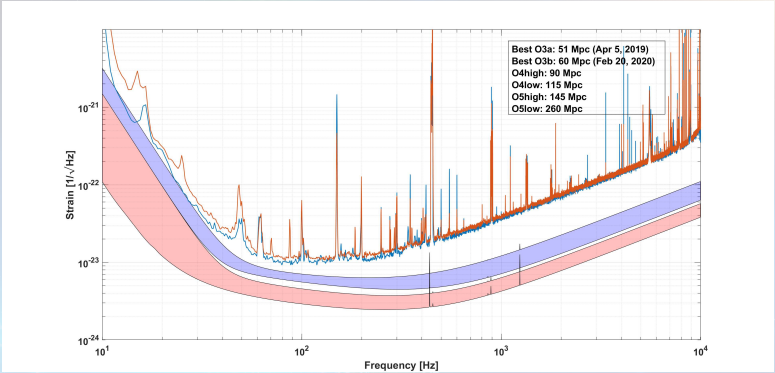
Advanced Virgo Plus: An Upgrade in Two Phases

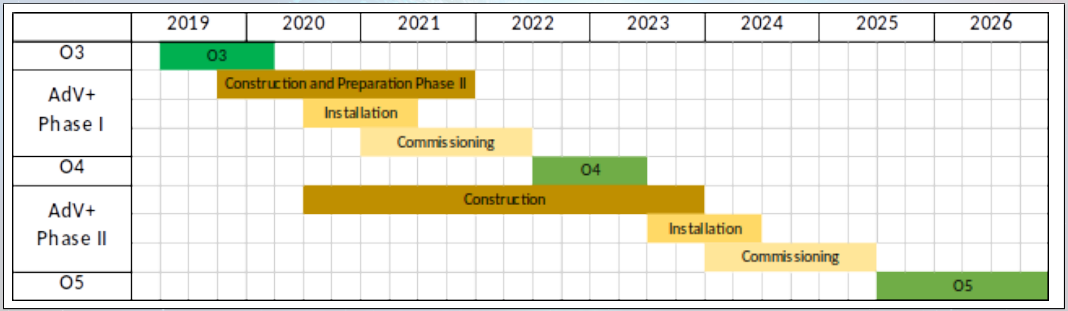


- Phase 1 (*O4*): reduce the quantum noise & hit the thermal noise wall
- BNS Range $\approx$ 100 Mpc

- Phase 2 (*O5*): new mirrors to lower the thermal noise wall
- BNS Range $\approx$ 200 Mpc

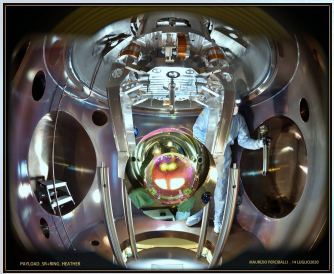
Advanced Virgo Plus: The Timeline

- Phase 1:
  - Signal Recycling Mirror
  - Auxiliary Laser System
  - Frequency Dependent Squeezing
- Phase 2:
  - Heavier End Masses
  - Modified Payloads



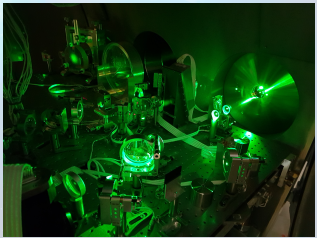
Advanced Virgo Plus Phase 1: Signal Recycling & Auxiliary Lasers

- Signal Recycling Mirror installed
- Lock Acquisition completely revisited, additional resonant cavity and new SRCL longitudinal degree of freedom



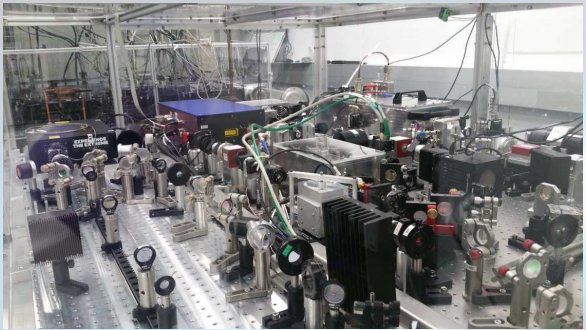
Credit: M. Perciballi

- Lock acquisition of arms and central interferometer initially decoupled
- Auxiliary Laser System ($\lambda = 532\,\mathrm{nm}$), injected from the End Benches, provides additional control system for the arms



https://doi.org/10.3390/galaxies8040087

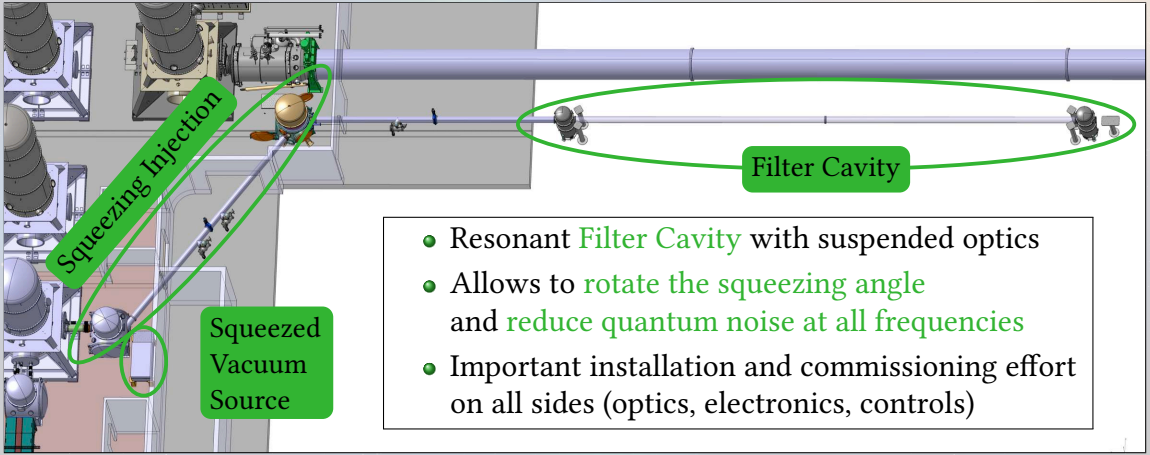
Advanced Virgo Plus Phase 1: Injection & Detection Systems



- New laser:
  - Increased power, from 25 W to 40 W
  - Fiber amplifier

- New high-Finesse Output Mode Cleaner
- Scattered light mitigation in the Detection system

Advanced Virgo Plus Phase 1: Frequency Dependent Squeezing

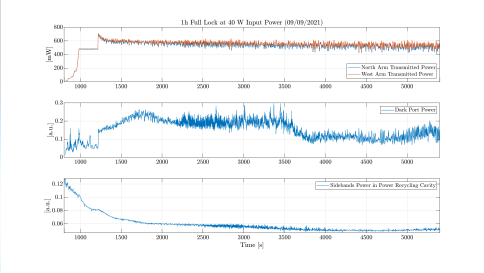


- Resonant Filter Cavity with suspended optics
- Allows to rotate the squeezing angle and reduce quantum noise at all frequencies
- Important installation and commissioning effort on all sides (optics, electronics, controls)

Advanced Virgo Plus Phase 1: Commissioning Status

Current status:

- Installation completed in December 2020 (interferometer) and April 2021 (squeezing)
- Commissioning started in January 2021 (interferometer) and May 2021 (squeezing)
- Milestones:
  - Arm cavities locked with Auxiliary Lasers
  - Central interferometer locked with infrared beam
  - Full interferometer locked on infrared beam
  - Filter cavity aligned and locked on the green laser
  - One hour of full lock at design input power (40 W) achieved on 09/09/2021

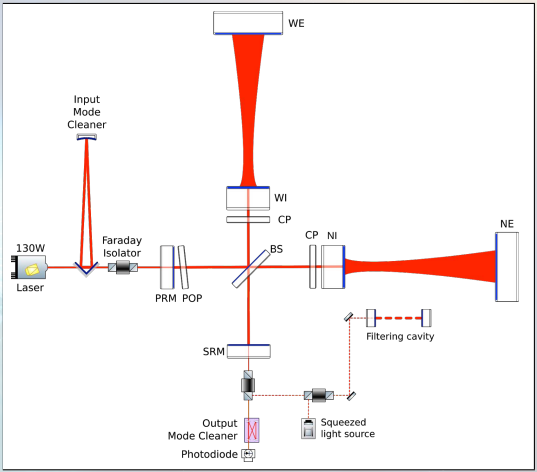


Next steps:

- Optical characterization and tuning
- Frequency dependent squeezing measurement and integration
- Noise hunting

Advanced Virgo Plus: Phase 2

- Larger beam on End Test Masses
  - 6 cm $\Longrightarrow$ 10 cm
- Bigger End mirrors
  - 40 kg $\Longrightarrow$ 100 kg
- Modified suspensions for larger mirrors
  - New redesigned payload
- Improved mirror coatings
  - Lower mechanical losses, reduction of point defects
- Further increase of the laser power
  - 40 W $\Longrightarrow$ 60 W $\Longrightarrow$ 80 W



Towards the Third Generation

ESFRI

Strategy Report on Research Infrastructures
ROADMAP 2021

PRESS RELEASE

ESFRI announces the 11 new Research Infrastructures to be included in its Roadmap 2021

€4.1 billion investment in excellent science contributing to address European challenges

After two years of hard work, following a thorough evaluation and selection procedure, ESFRI proudly announces the **11 proposals** that have been scored high for their science case and maturity for implementation and will be included as new Projects in **the ESFRI 2021 Roadmap Update**.

The new ESFRI Projects are:

EBRAINS - European Brain ReseArch INfrastructureS, a distributed digital infrastructure at the interface of neuroscience, computing and technology, offering scientists and developers advanced tools and services for brain research.

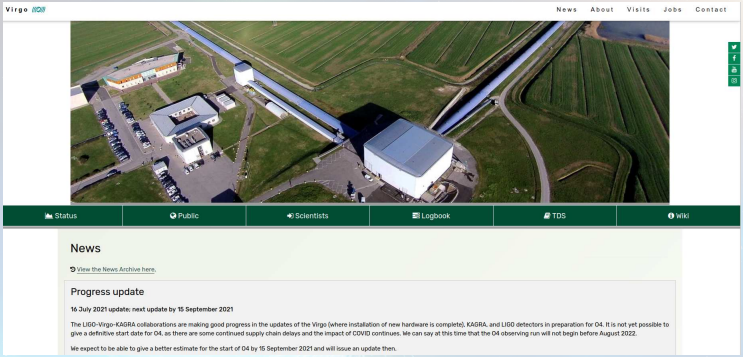
EIRENE RI - Research Infrastructure for EnvIRonmental Exposure assessment in Europe, the first EU infrastructure on human exposome (environmental determinants of health).

ET - Einstein Telescope, the first and most advanced third-generation gravitational-wave observatory, with unprecedented sensitivity that will put Europe at the forefront of the Gravitation Waves research.

EuPRAXIA - European Plasma Research Accelerator with Excellence in Applications, a distributed, compact and innovative accelerator facility based on plasma technology, set to construct an electron-beam-driven plasma accelerator in the

- On 30th June 2021 Einstein Telescope has been included in the 2021 update of the roadmap of the European Strategy Forum on Research Infrastructures (ESFRI)
- ET will not take data before 2036, while *O5* will end in 2026
- Ten years in which Advanced Virgo can go beyond 2nd Generation, up to the limits of technology and infrastructure
- Discussion already ongoing regarding R&D and perspective in view of 3rd Generation

Conclusions



https://www.virgo-gw.eu/

- *O3* has been a very successful run
- *O3b* data release in preparation
- Commissioning for *O4* ongoing
- R&D towards 3rd Gen ongoing

Thank You for the Attention