The Einstein Telescope Timing issues: picosecond resolution for a billion years journey back in time

Presented at the
LLRF Topical Workshop - Timing, Synchronization, Measurements and Calibration
on
29 Oct 2024

Speaker: Riccardo Travaglini
INFN - Sezione di Bologna

Outline
A glance at Gravitational Wave detectors

✳ Gravitational Waves (GW) and detection with Interferometers

✳ The Einstein Telescope (ET) project: a 3rd generation GW detector

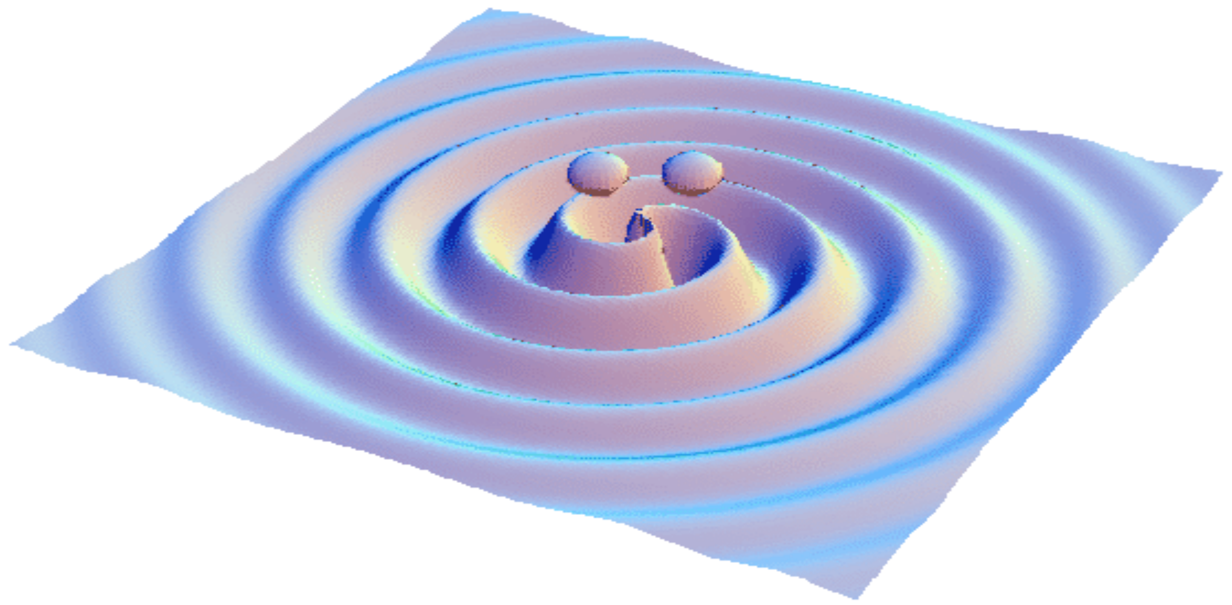
✳ Timing and synchronization issues for GW detectors and ET

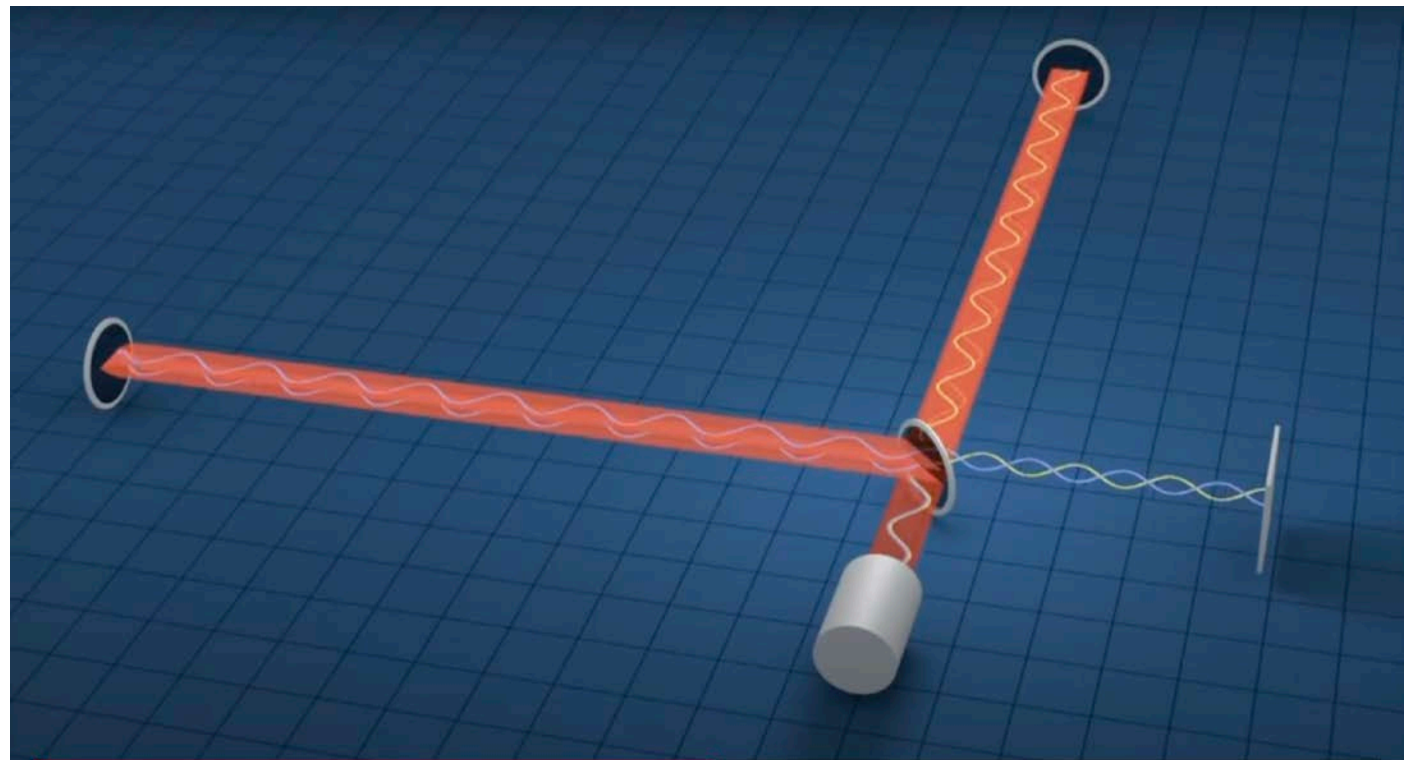
A long time ago in a galaxy far, far away....

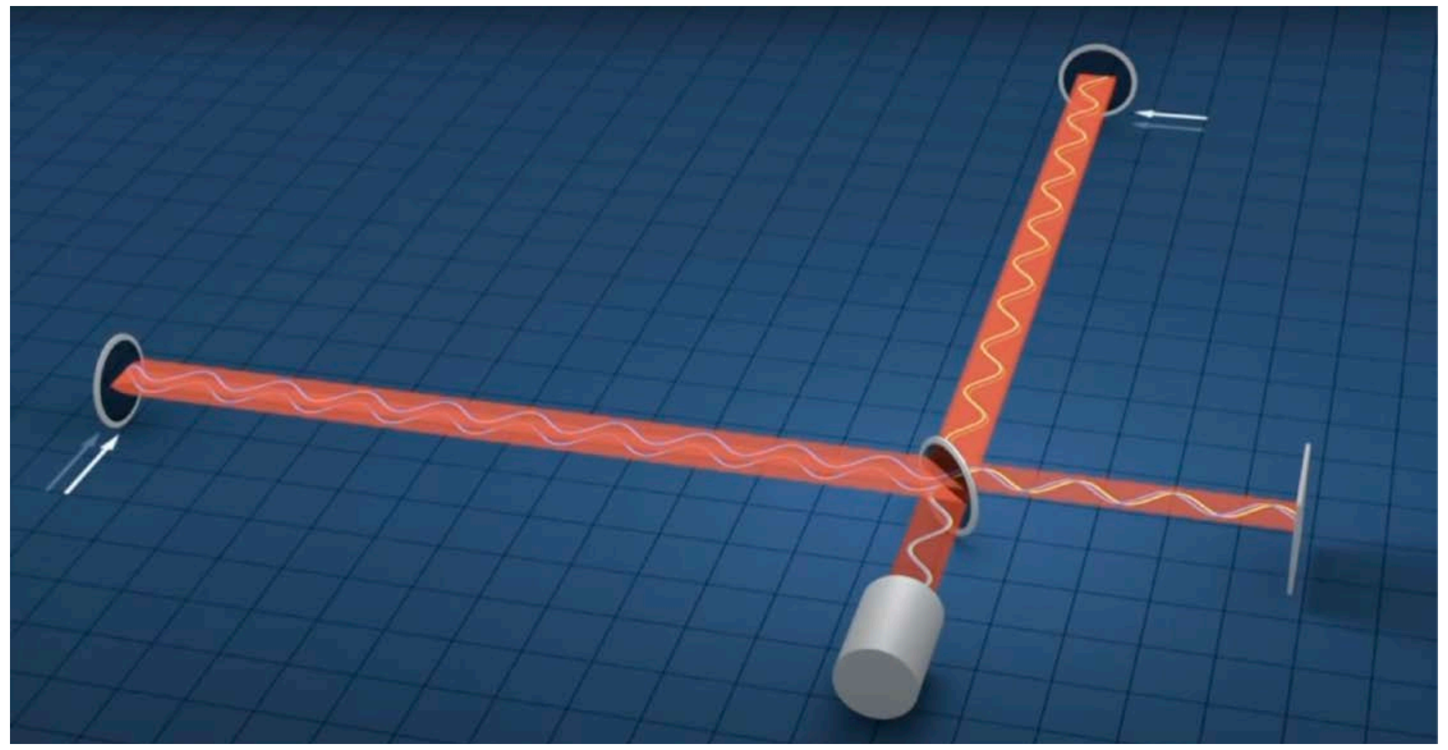
Image Credit: SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)

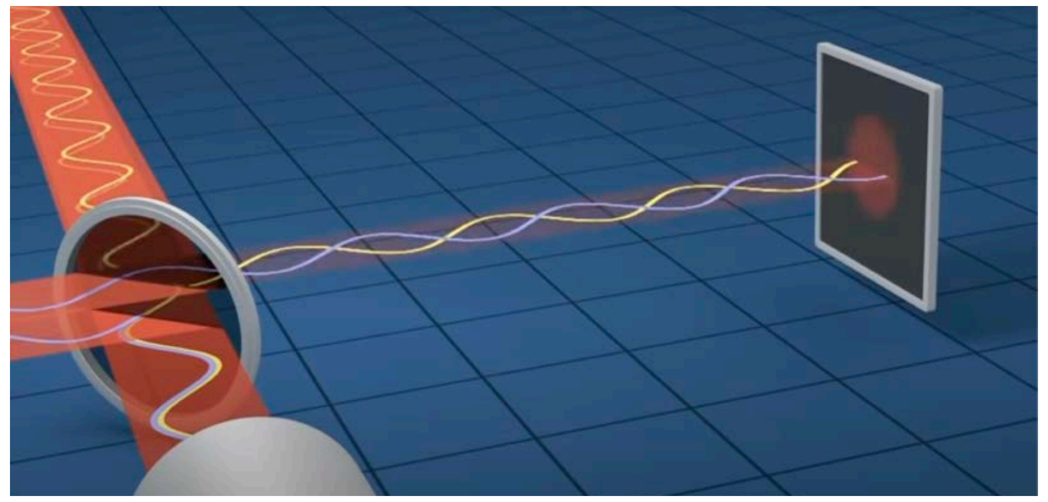
GW detection with interferometer

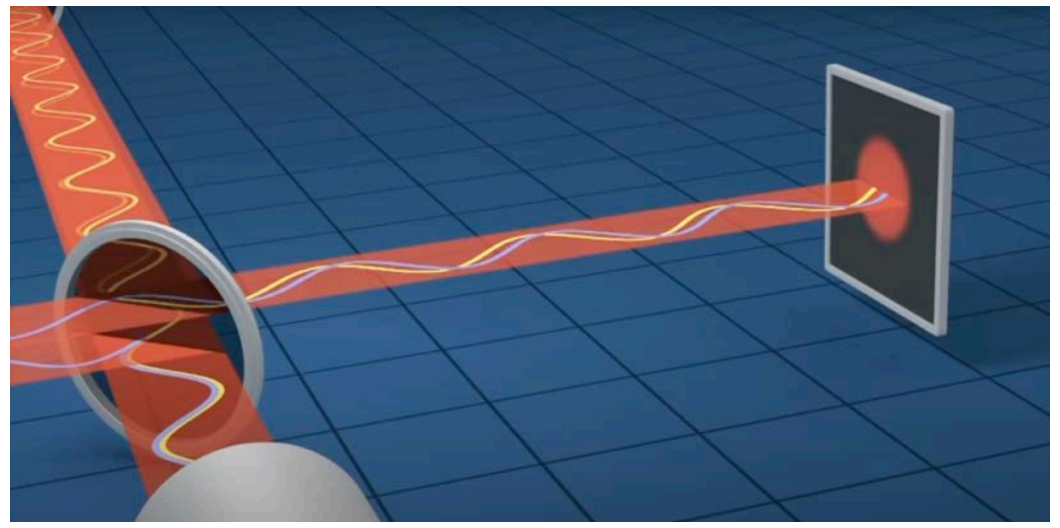
The principle







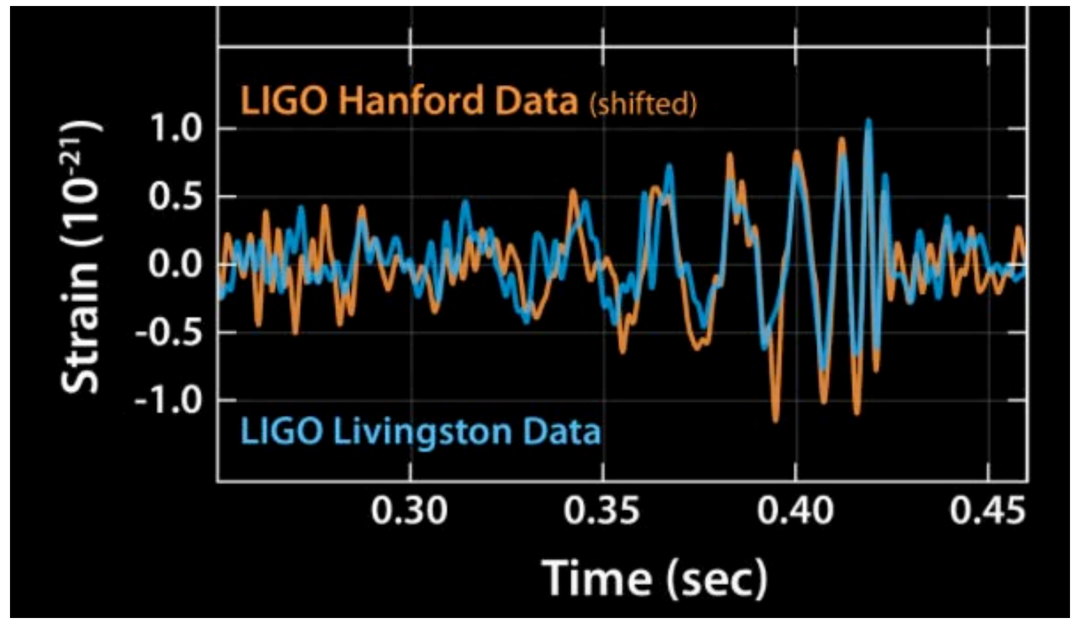




Gravitational waves are ripples in spacetime: Albert Einstein predicted them in 1916, as a consequence of his theory of General Relativity.

Gravity is a consequence of spacetime curvature generated by the presence of mass-energy.

The deformations of spacetime can become waves, the gravitational waves, which travel at the speed of light, propagating through the universe.



https://www.youtube.com/watch?v=UA1qG7Fjc2A

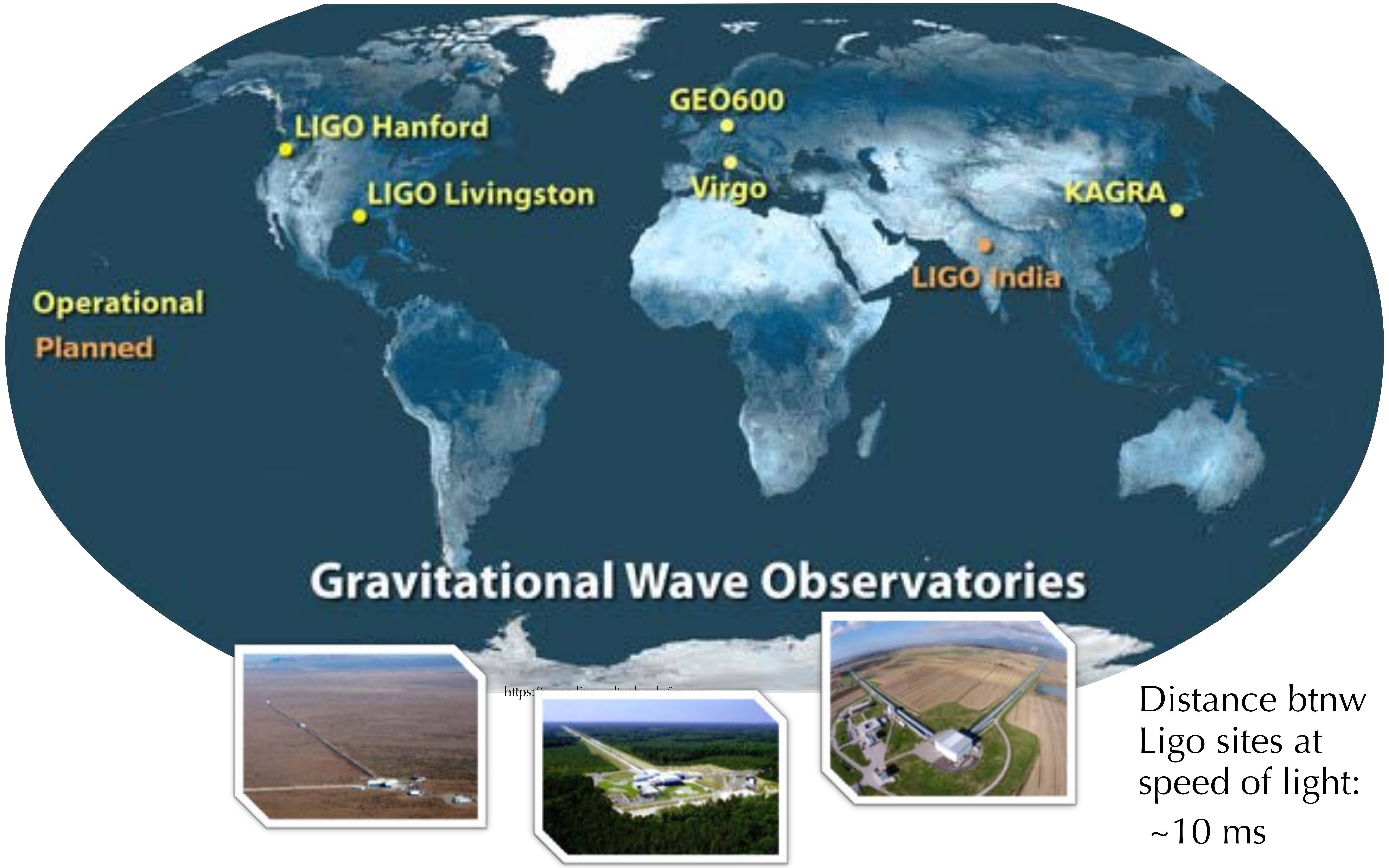
GW150914

2 black holes of ~30 solar mass at 1.3B light years

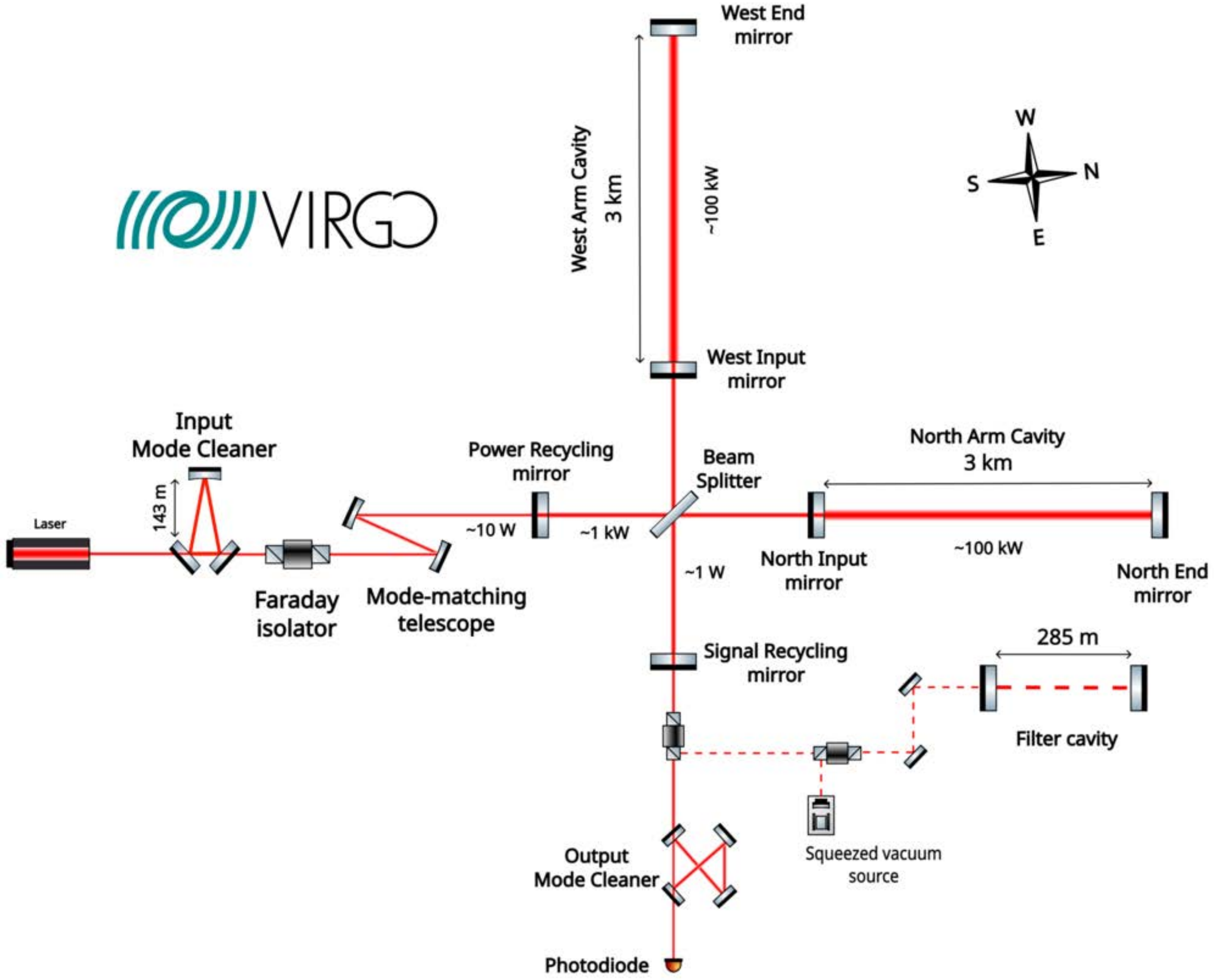
Strain ($\Delta L/L$) of ~10^{-21}

Current GW experiments

Advanced 2nd generation Detectors

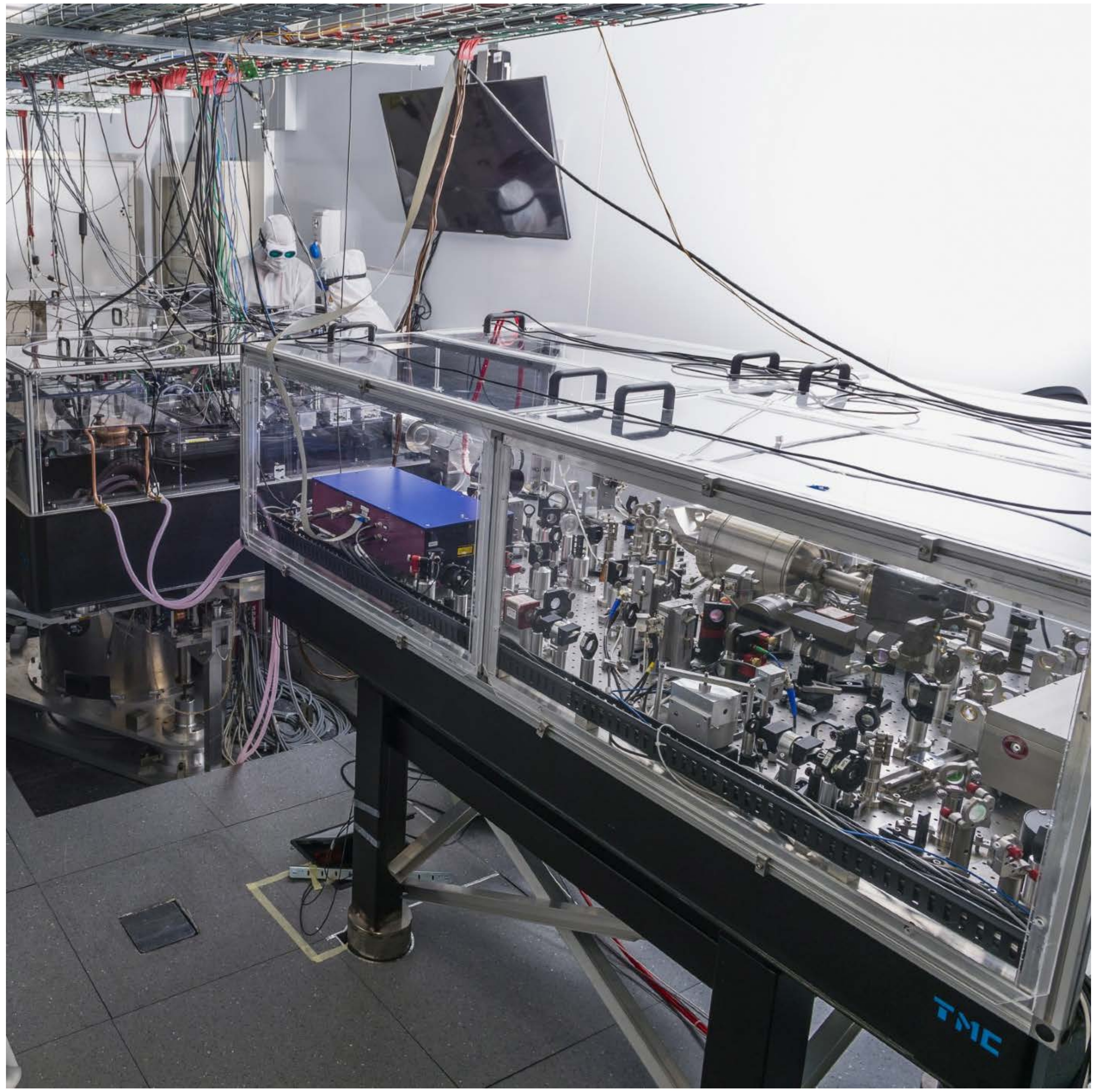


Distance btnw Ligo sites at speed of light:
~10 ms

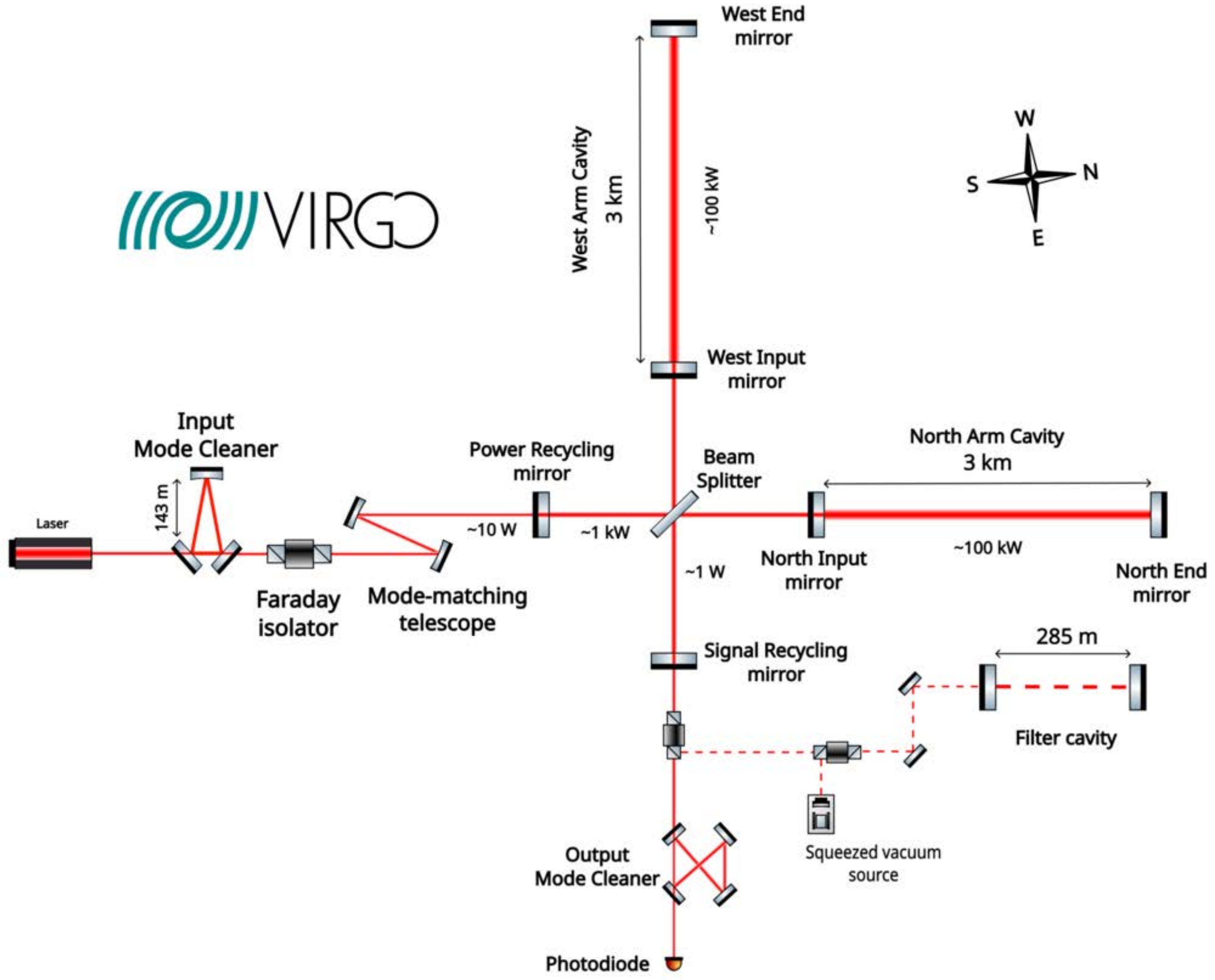


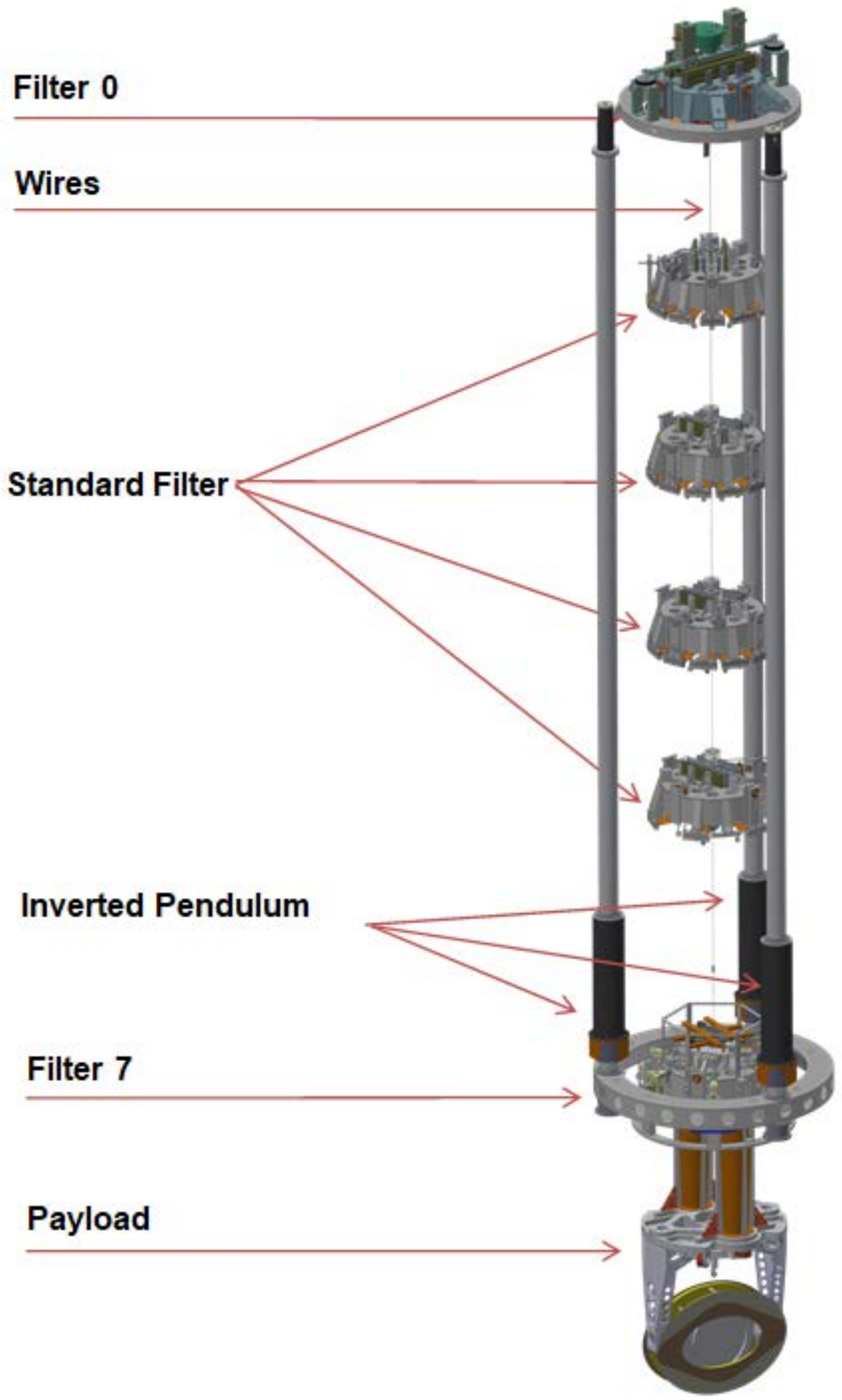
Arms : ~3 km
Laser power in arms : 100 kW
Arms mirrors weight: 42 kg
Vacuum operates at about 10^{-7} mbar

There's more complexity



Optical benches where the Virgo laser beam is generated
© Cyril Frésillon/Virgo/Photothèque CNRS

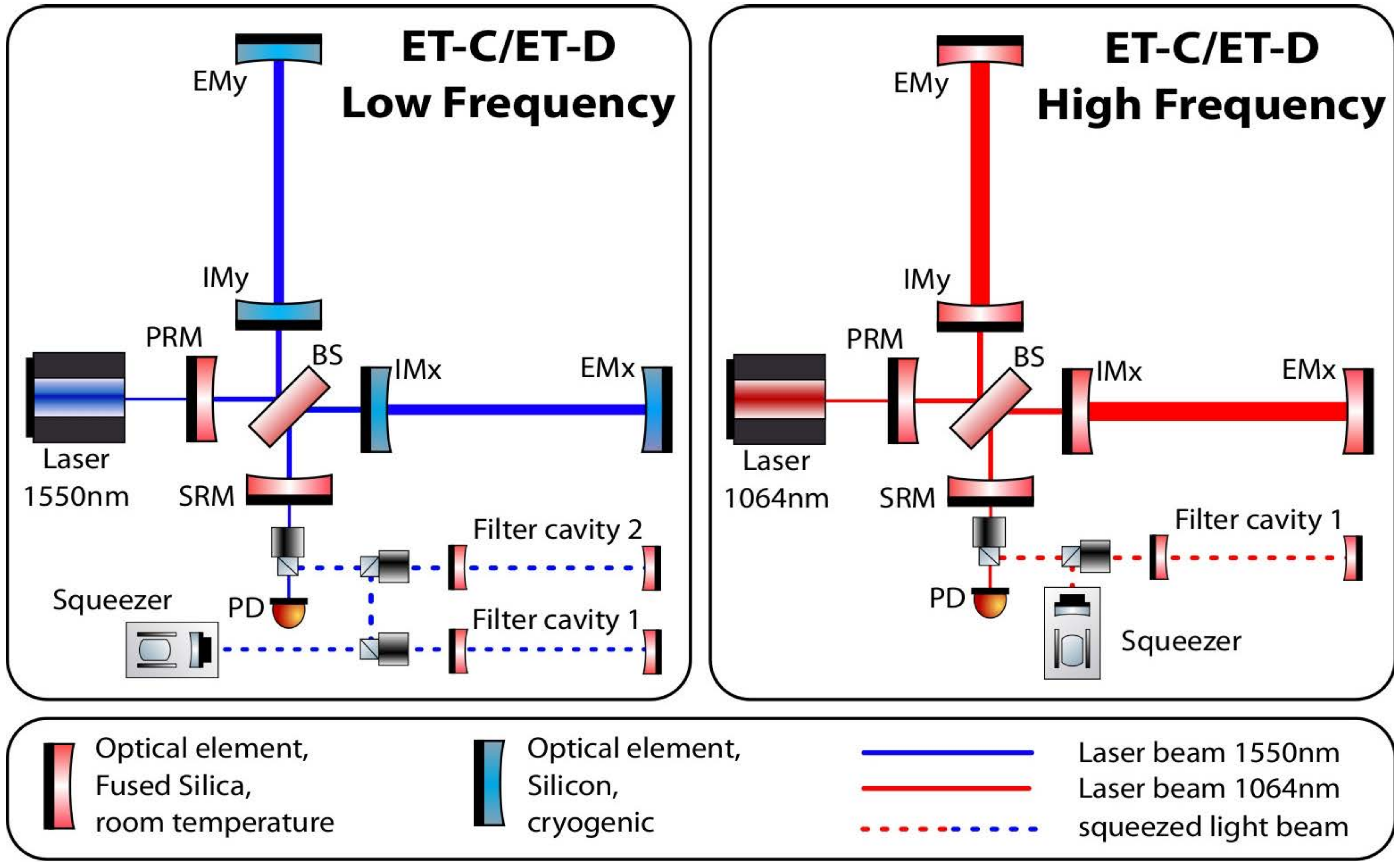


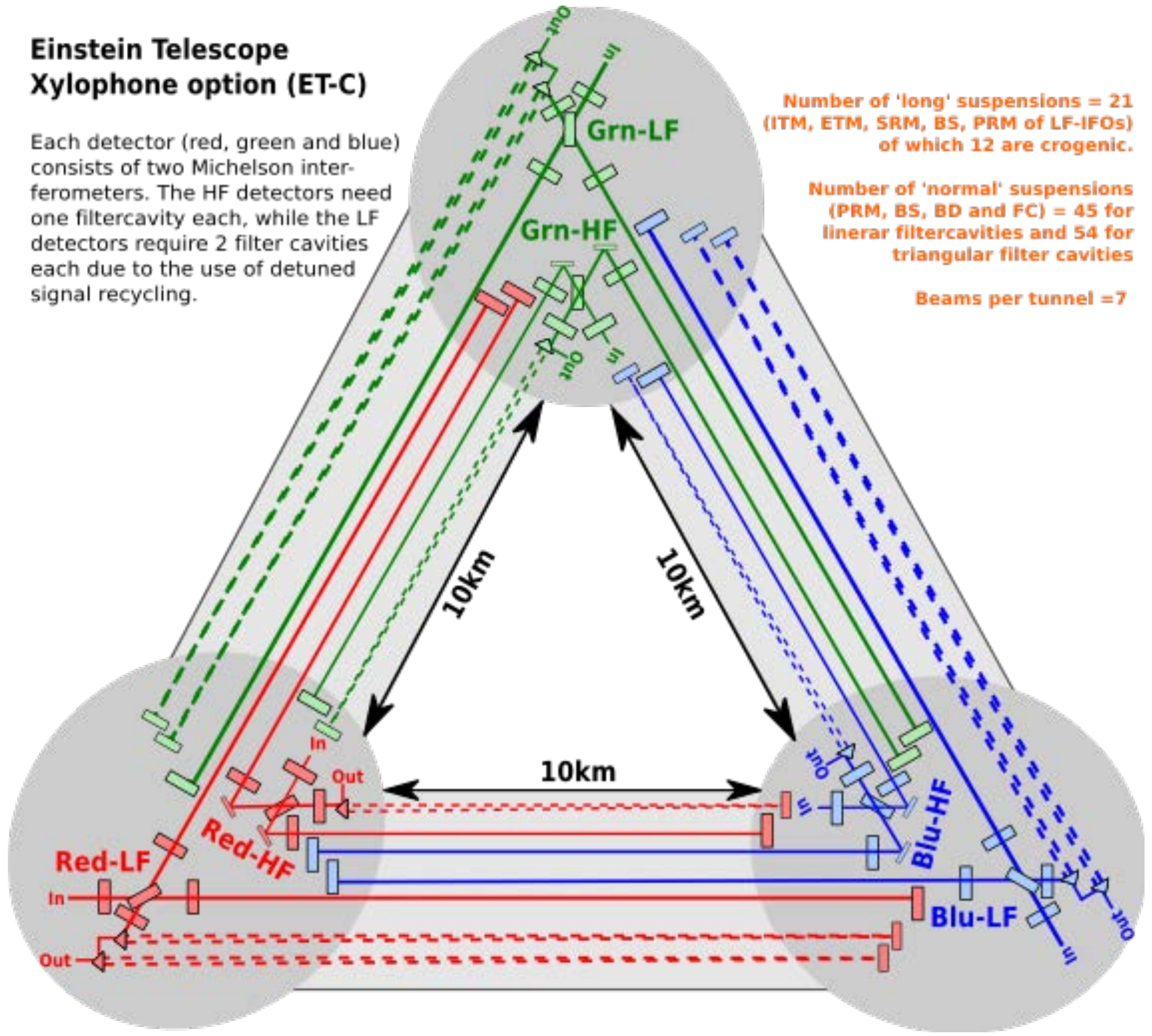


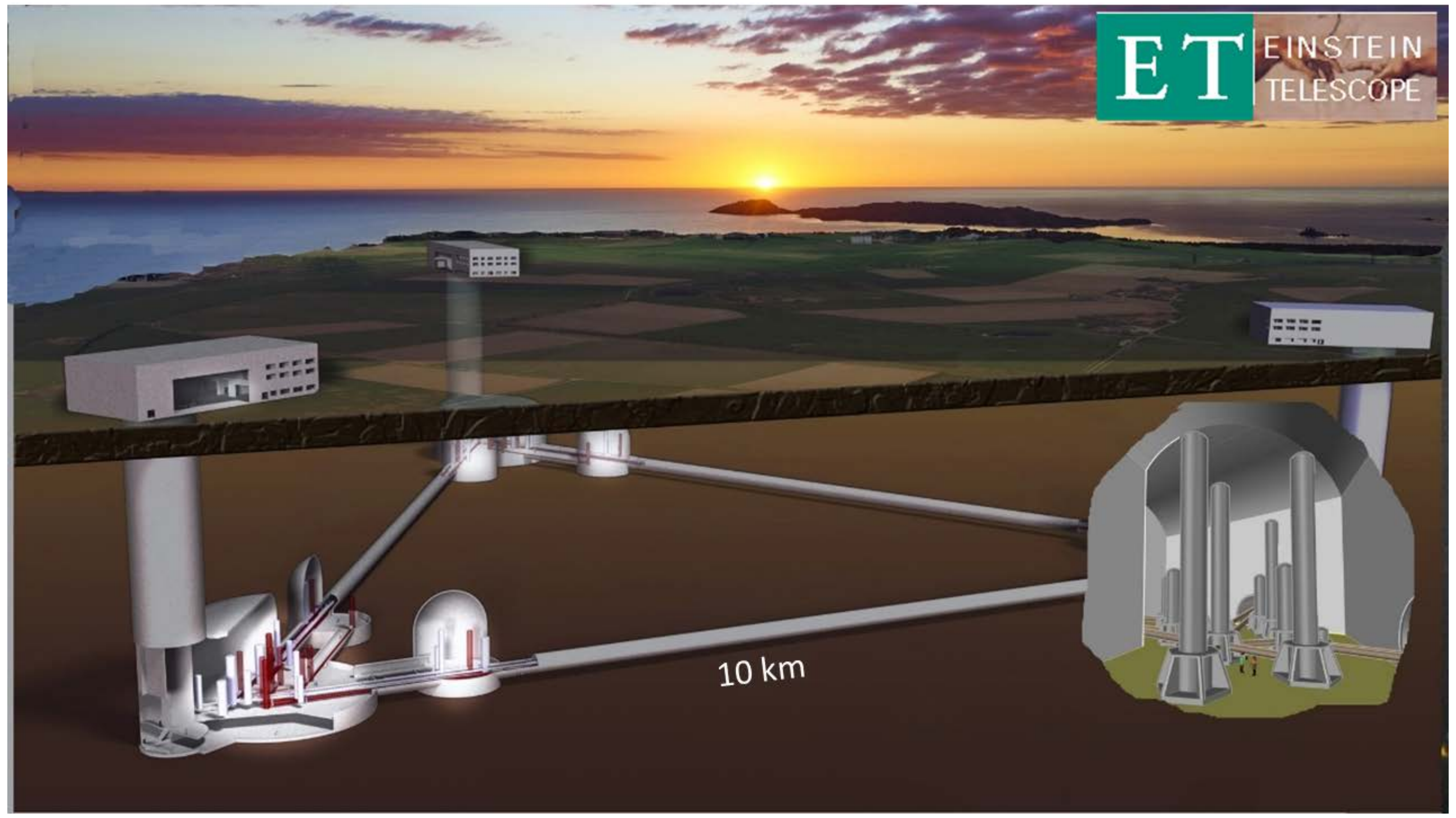
Advanced Virgo Superattenuator
(7 as in picture - 6.88m height- , 3 shorter)

The Einstein Telescope project

A 3rd generation GW detector



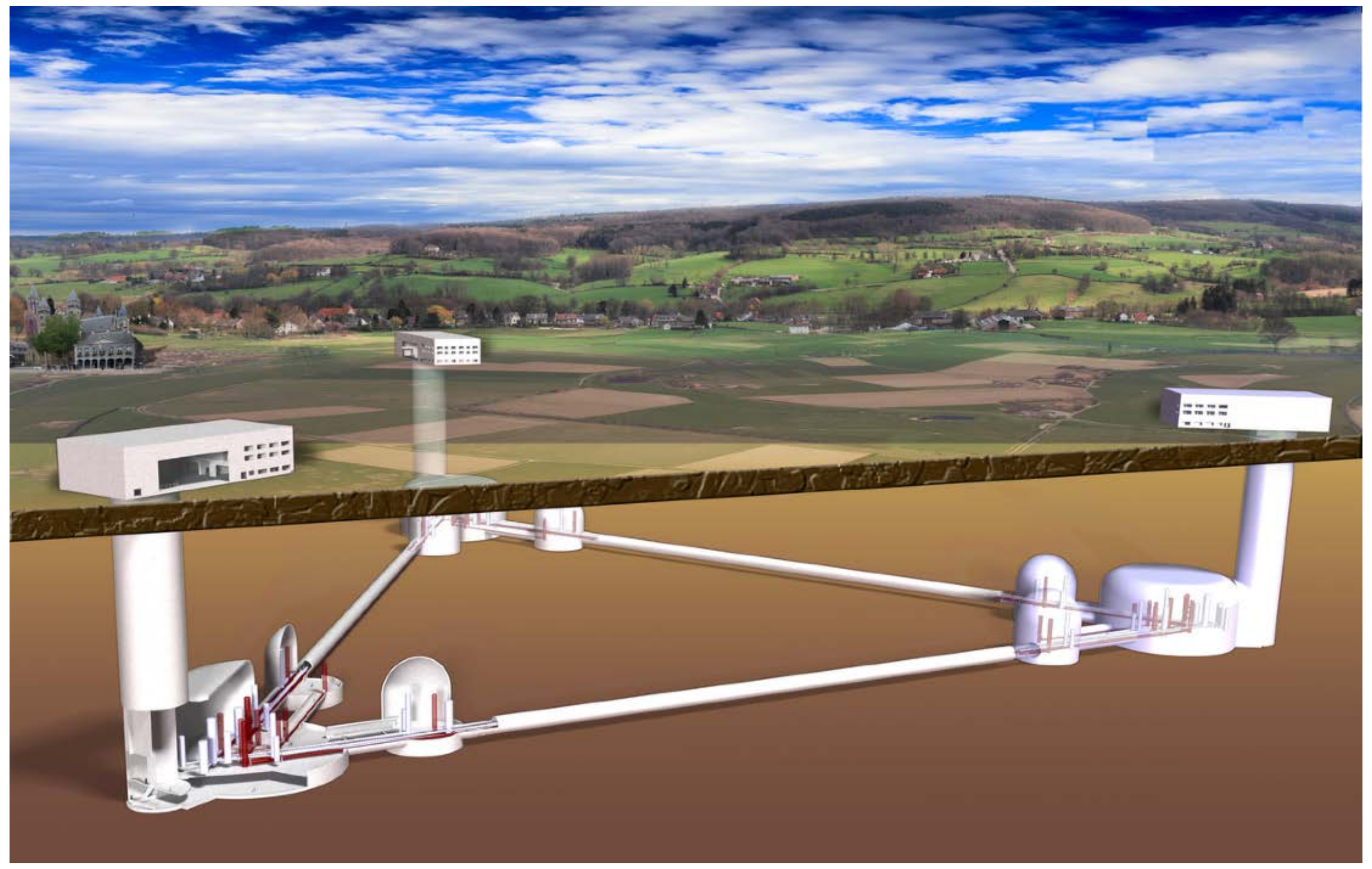


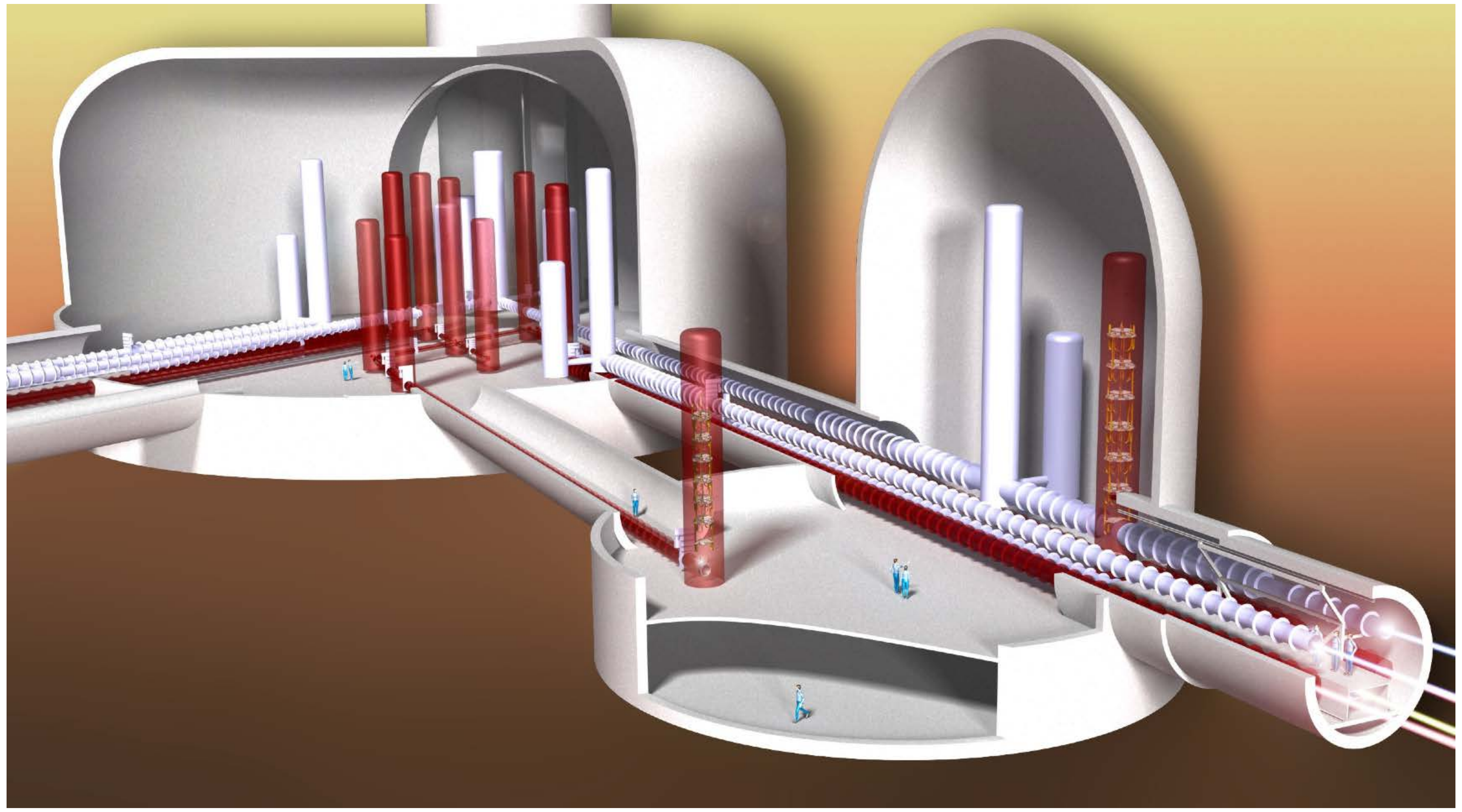


A technological challenge

- Underground (~ 200 m deep, ~ 30 km tunnels in baseline configuration)
- Cryogenics (LF) - mirrors at about 10 K
- Arms > ~10 km (in vacuum)
- Larger test masses - f.i. mirrors
  (new materials like silicon and sapphire)
- New coatings
- High power laser: ~1 kW

Top view of Virgo © Nicola Baldocchi/EGO





ET Artistic views: https://www.et-gw.eu/index.php/etimages

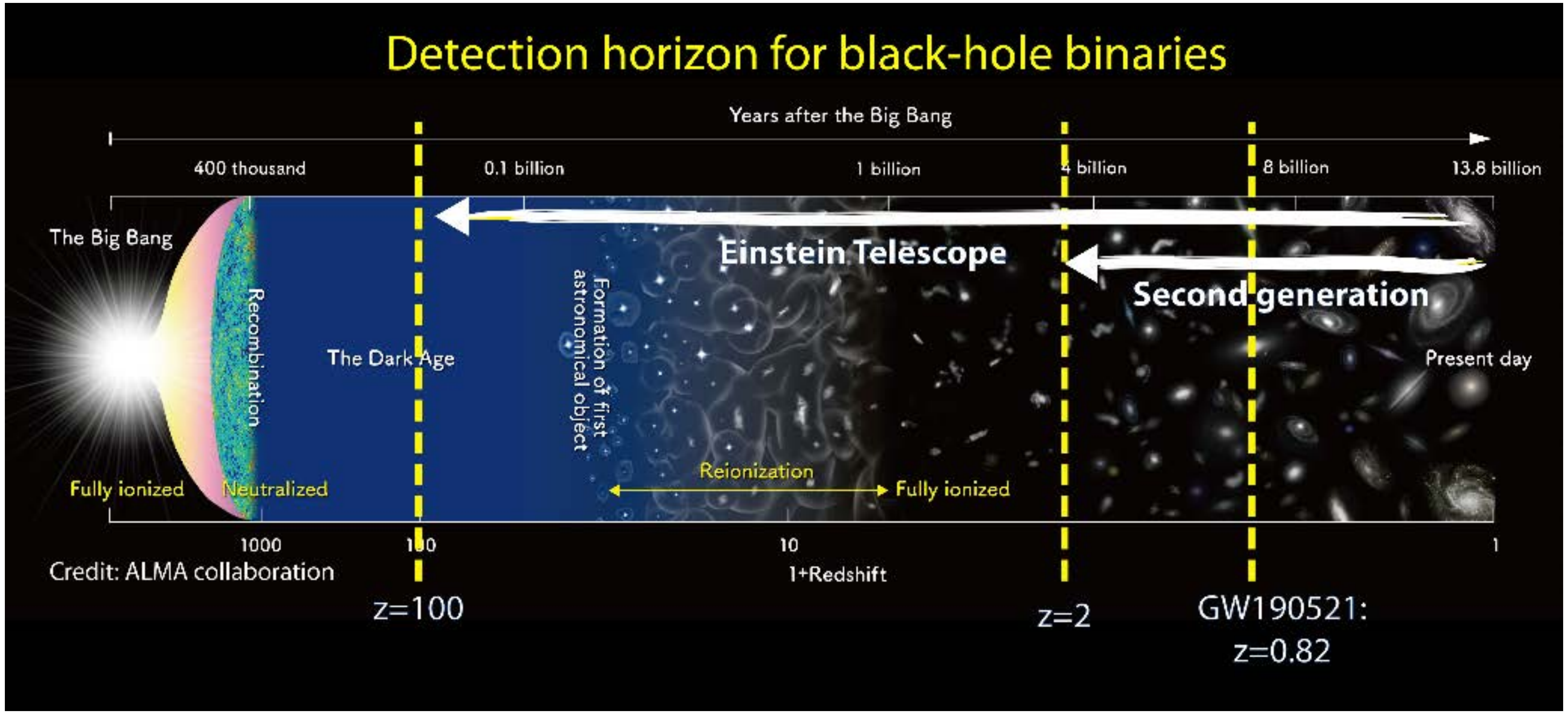
Up to the cosmological dark ages
And closer to the black-hole horizon

ASTROPHYSICS

- Black hole properties
- Neutron star properties
- Multi-band and -messenger astronomy
- Detection of new astrophysical sources

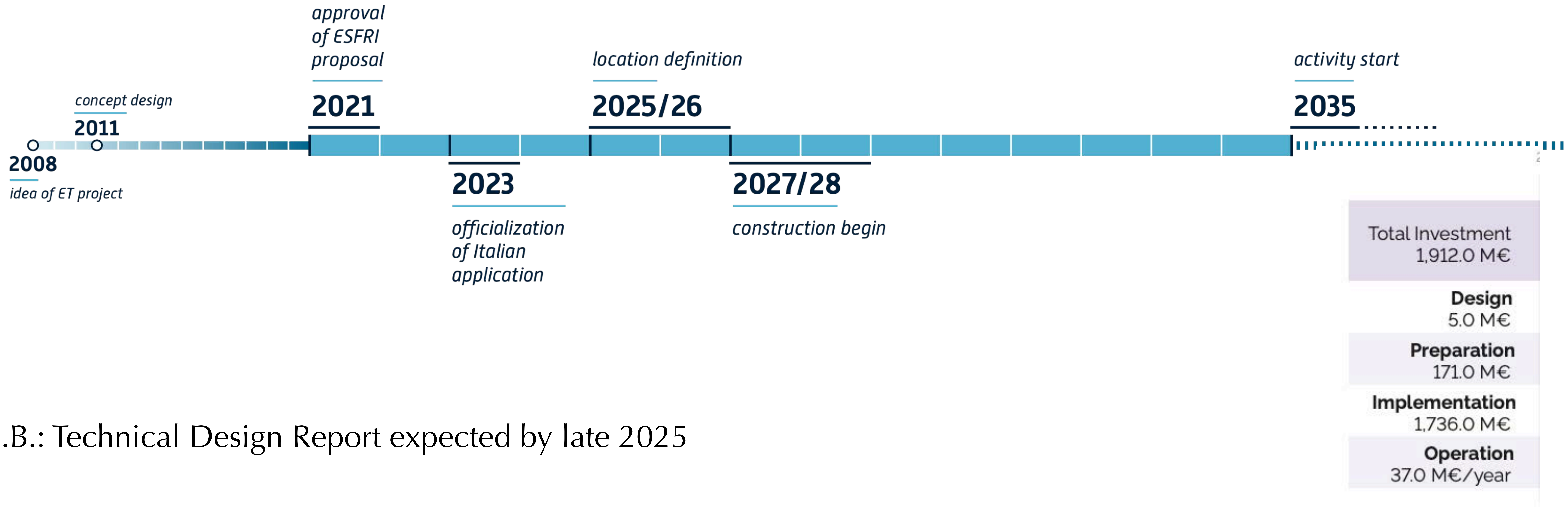
FUNDAMENTAL PHYSICS AND COSMOLOGY

- The nature of compact objects
- Tests of General Relativity
- Dark matter
- Dark energy and modifications of gravity on cosmological scales
- Stochastic backgrounds of cosmological origin



ET Timeline and estimated costs

Entered in the ESFRI Roadmap 2021



N.B.: Technical Design Report expected by late 2025

https://roadmap2021.esfri.eu/projects-and-landmarks/browse-the-catalogue/et/

The Scientific Collaboration

But there are more actors …

XII ET Symposium in Budapest (Hungary)

The Birth of the ET Collaboration on 7th of July, 2022

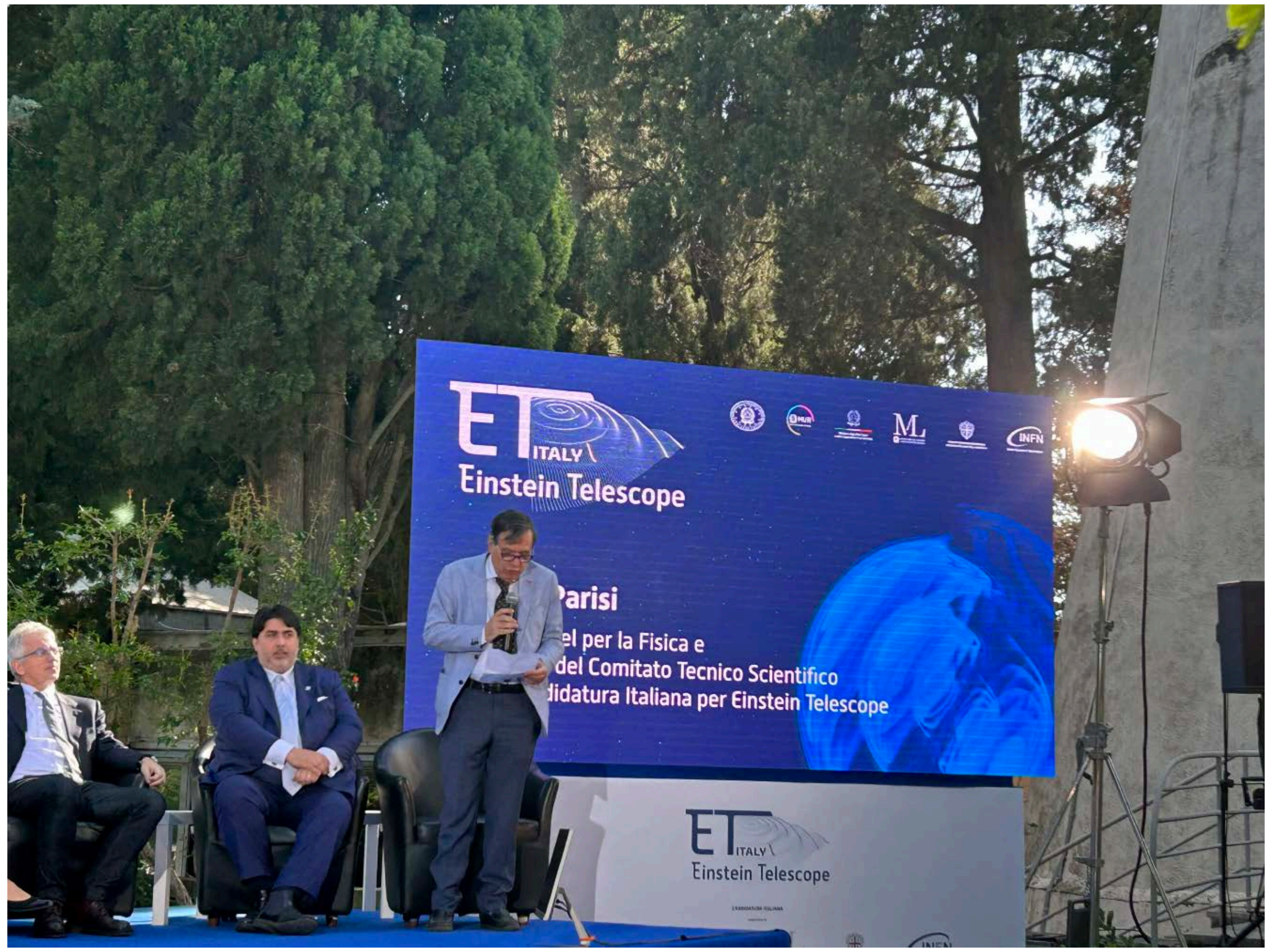
On 1st of October 2024:

> 1,700 members,

~253 institutions across 30 countries.

M.Punturo (INFN-PG) Spokeperson

Supporting actors : funding agencies, ET Organization, National governments, site committees and projects supporting site candidates, …



Location

Two official site candidates

https://www.einsteintelescope-emr.eu

https://www.einstein-telescope.it/

Drilling site in the 2024 drilling campaign for Einstein Telescope EMR. Photo: ET-EMR

Einstein Telescope Infrastructure Consortium

ETIC

Next Generation EU (PNRR)

Investment focused on

ET enabling technology and
Sardinian site candidature support

Leaded by INFN,
Partners:
11 Universities
INAF and Italian Space Agency

Budget 50 M€

Start of the project:
1st January 2023

Timing and synchronization issues for GW detectors and ET

Timing distribution system
Tasks

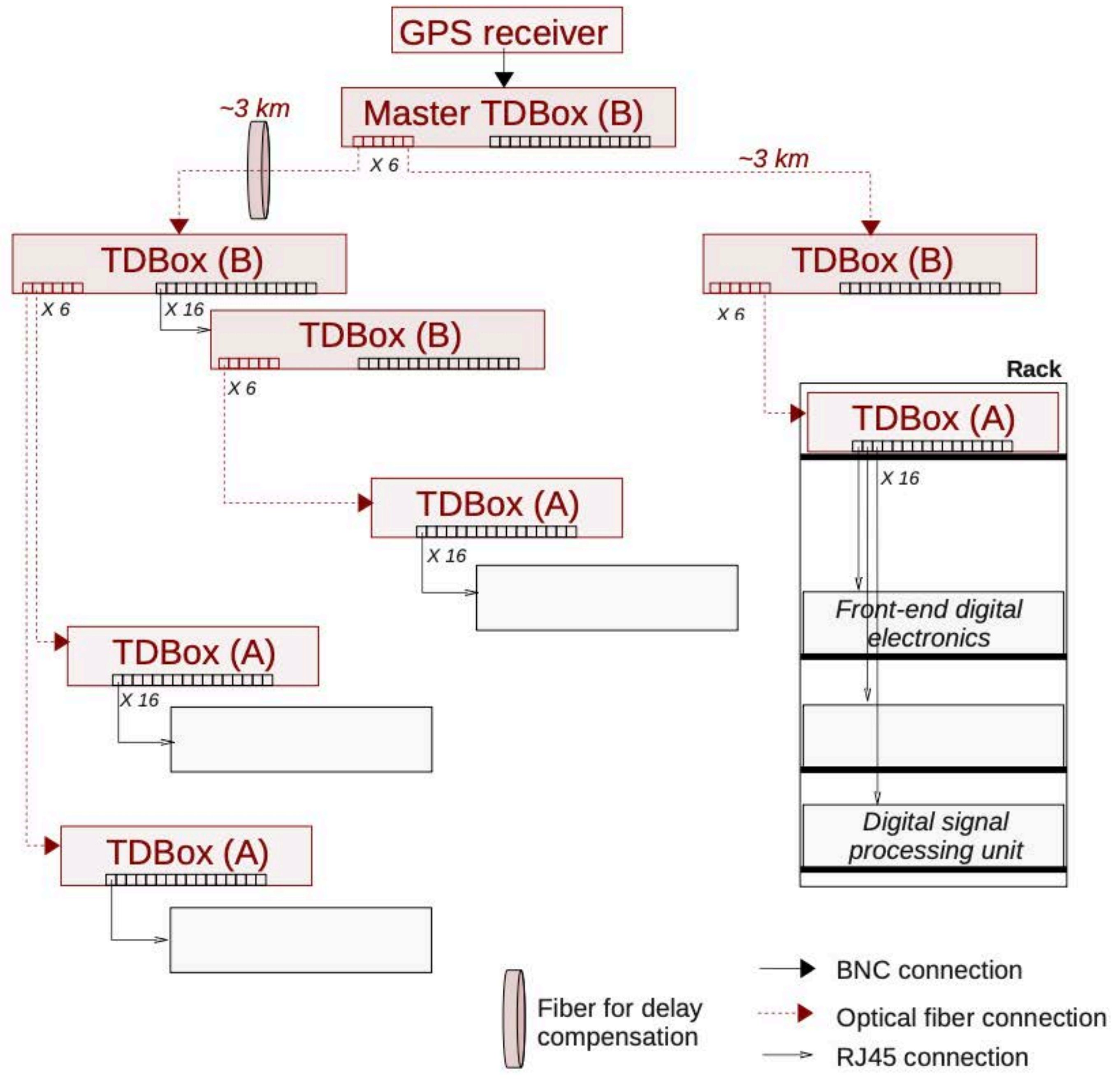
- Distribute timing information and high-precision clock(s)

- Delivered to:
  - interferometer controls (relative timing accuracy)
  - servoloops (low phase noise clock)
  - readout system (absolute timing and low jitter/phase noise clock)

Timing distribution system

Present solutions

- Virgo: custom solution based on distributing IRIG-B + 10/100 MHz signals
- LIGO: 'Duotone' + custom time stamp (measured PPS sync btwn nodes of about 15 ns *))
- Both separated from DAQ and Control system:
  - Virgo uses propriety TOLM format (2.5 Gbps link over optical fiber)
  - LIGO uses 'reflective memory' for fast communication (commercial solution from Dolphin) and EtherCat for slower (<= 1 kHz) communication



*) Imre Bartos et al 2010 Class. Quantum Grav. 27 084025 - DOI 10.1088/0264-9381/27/8/084025

Absolute synchronization
Requirements

- Timing accuracy in reconstructing GWs is important for sky localization of sources (astrophysical studies and multi-messenger detection)

- Timing error contributes to SNR for reconstructed GW
  - Events due to binary massive objects have effective bandwidth of ~O(100 Hz)
  - If it was the only source of error => timing error for 3 detectors~ O(100 μs) @ SNR = 10

- Approach: allocate a timing error budget (feasible) so that the contribute to SNR is small (compared to fundamental noise sources)
  - Advanced Virgo : ≤ 10 μs
  - ET guess: O(1μs)

Absolute timing distribution
Approach for ET

- Use of commercial high-quality GPS
- Accurate choice of off-the-shelf components for clock distribution (OCXO, …)
- Move to standard solution
- Monitoring the latency of the distribution network and accuracy

Control loops

Active noise suppression and increase stability

- Hard real time

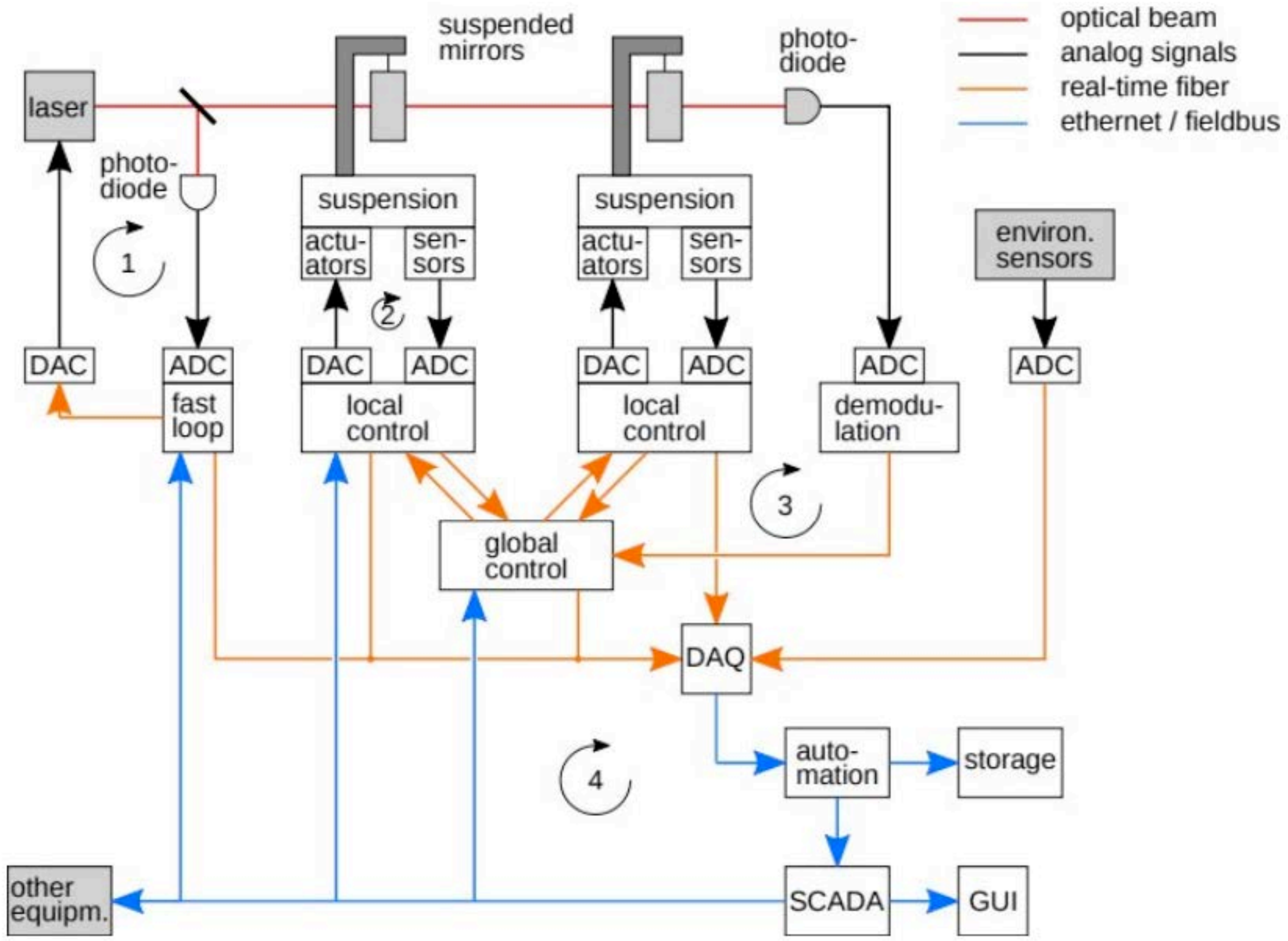
  1) very fast analog/digital loops (~MHz)

  2) fast local control of suspension (~10 kHz)

  3) fast global control of the whole interferometer (~10 kHz)

- Soft real time

  4) slow automation (~ 1 Hz)



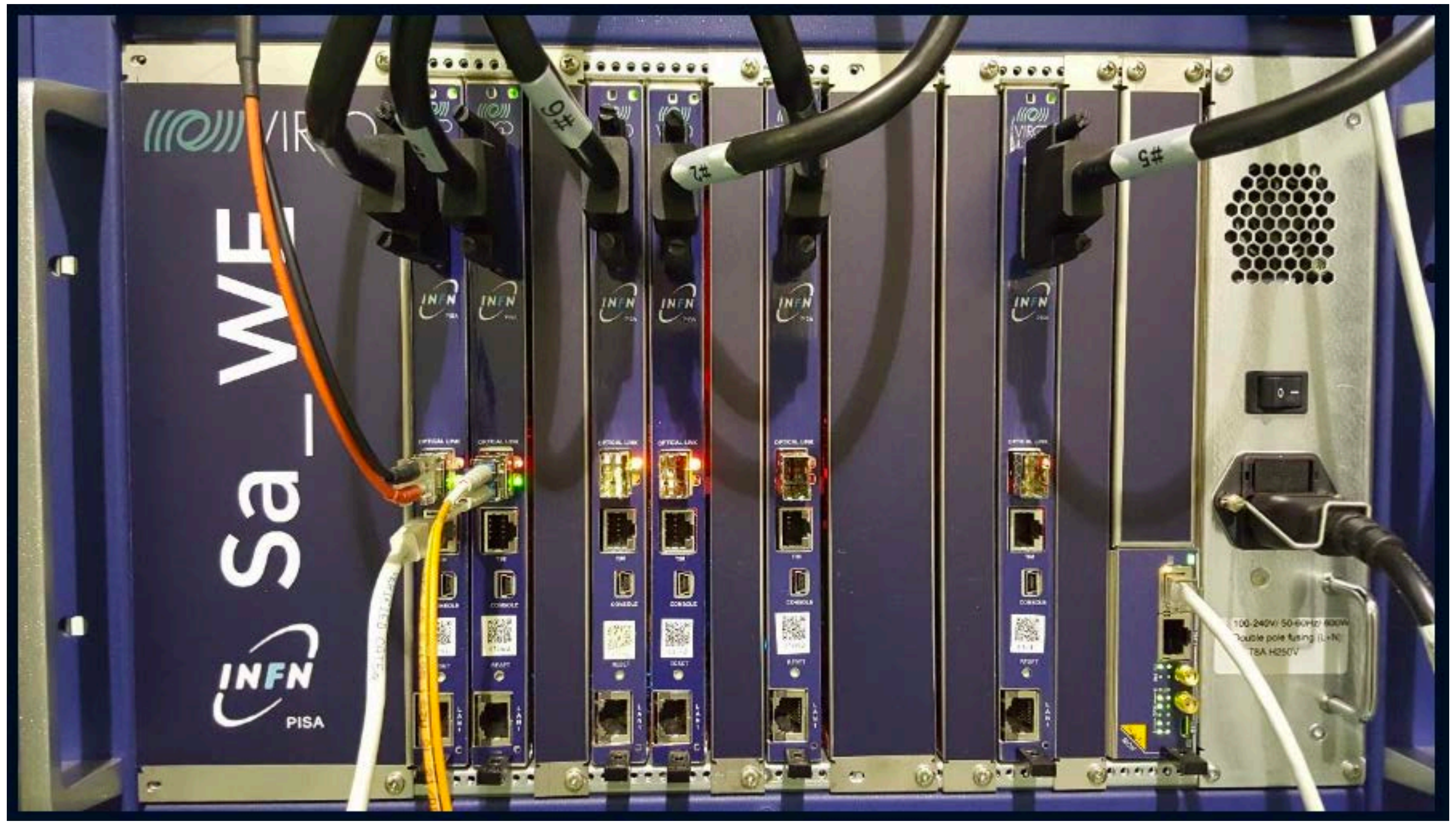
Requirements from control loops

- Relative timing
  - from loop bandwidth (also constrains electronics latency)
- Phase noise/Jitter of the Clock distributed
  - from sampling/actuation rate
  - from precision

Example 1

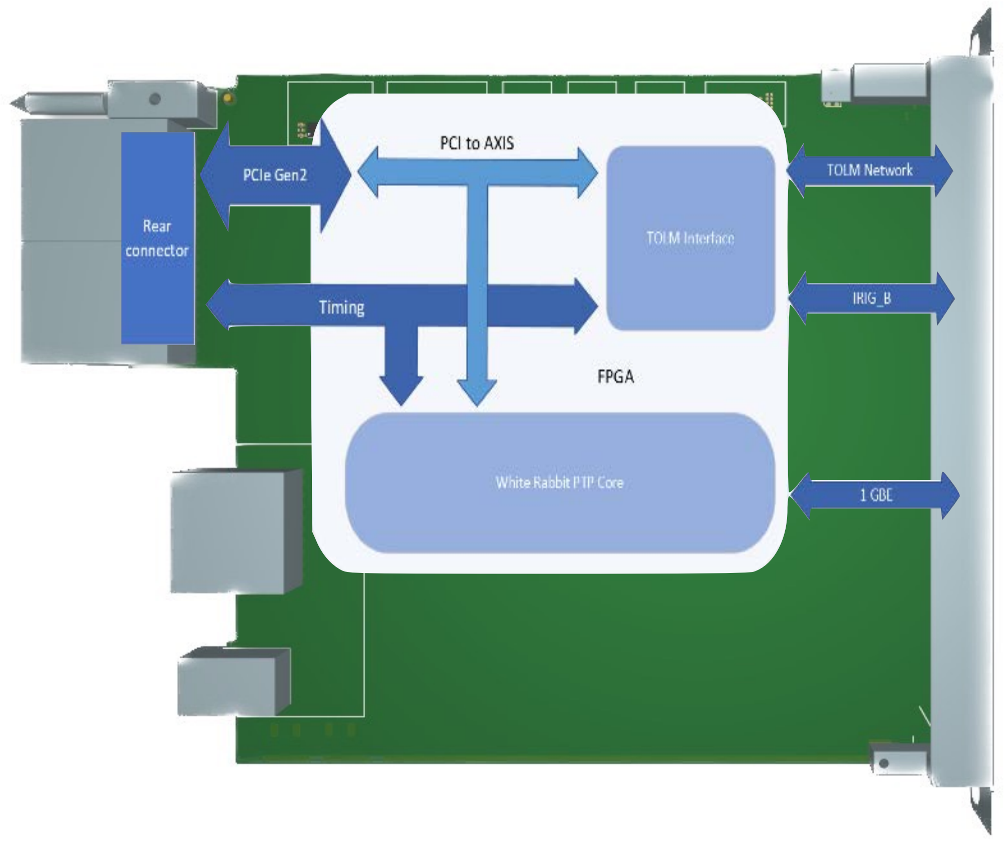
Advanced Virgo fast local control of suspension (~10 kHz)

- MicroTCA.4 (customized)
- Up to 12 boards (usually 6-8) per crate - 2 crates x suspension
- Each board equipped with:
  6chADC(24bit,3.84MSPS)
  6ch DAC (24bit 320 kSPS)
  8 core DSP TMS3206678
  Analog electronics
- Clock Jitter < 100 ps
- 60 GFLOPS per board (about 10 TFLOPS available in VIRGO)



UDSP control board

Designed by INFN-Pisa



A new version design is on going

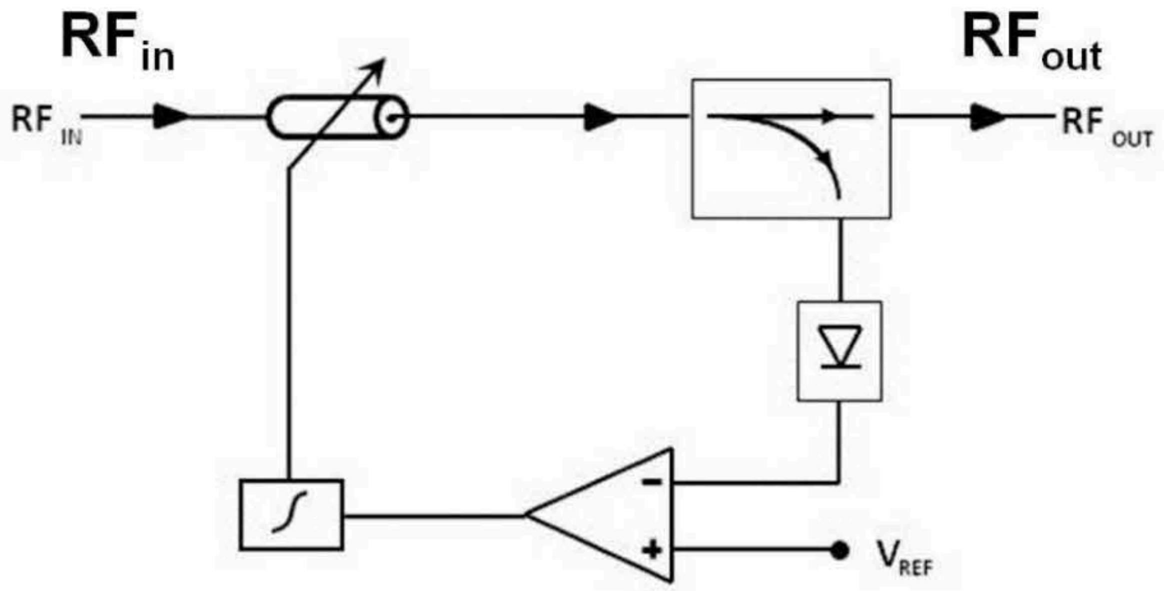
Joint project INFN (Pisa-Bologna_perugia)

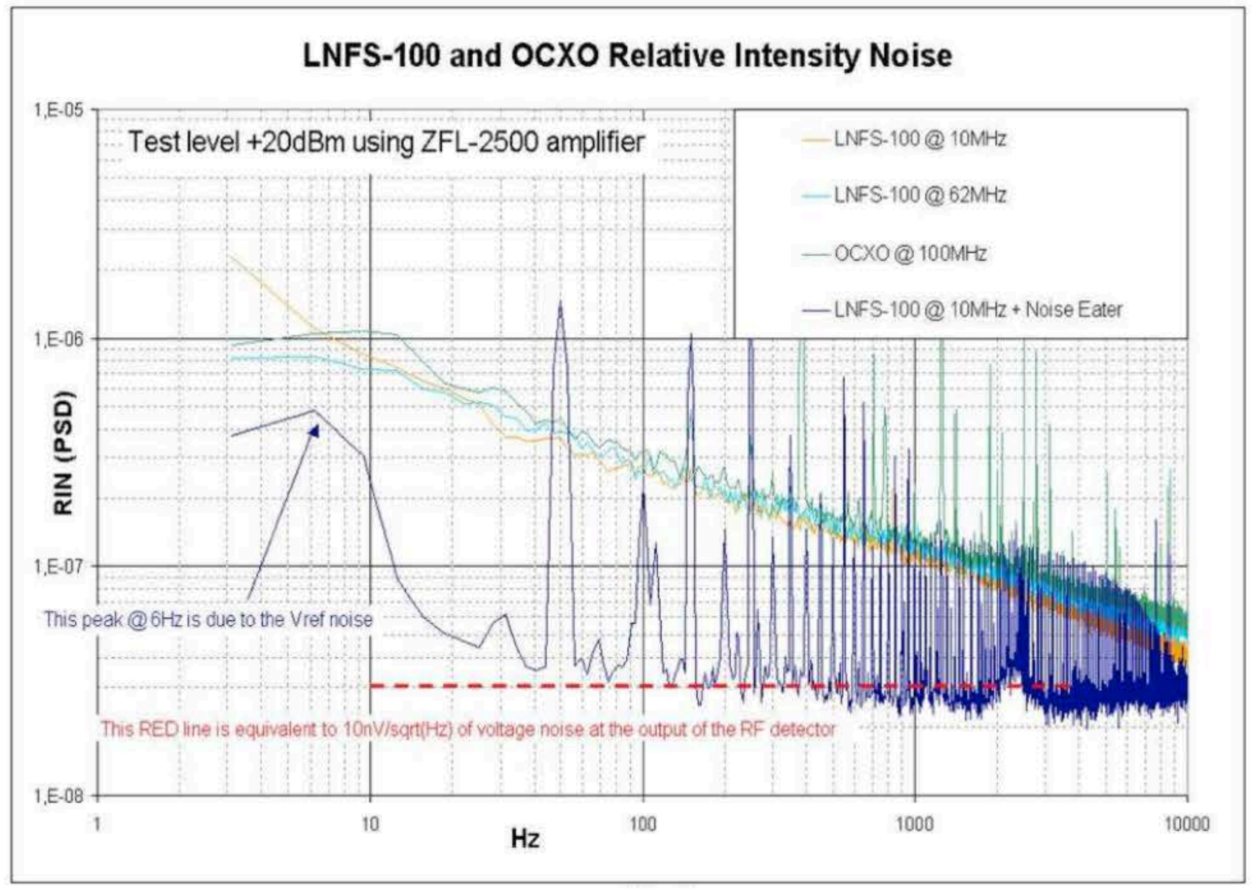
Example 2

Advanced Virgo very fast analog/digital loops (~MHz)

- To measure test masses displacement, the laser is modulated with several RF (this generates sidebands which are measured)
- Generated by a LNFS-100 low noise synthesizer

  - 48 bit frequency resolution, 14 bit phase resolution and 12 bit amplitude control
- Cleaned with servoloop (500 kHz)
  - low noise RF amplifier (ZHL-3A)
  - need stable V_{ref}
- ET will move to high rate digital loops?

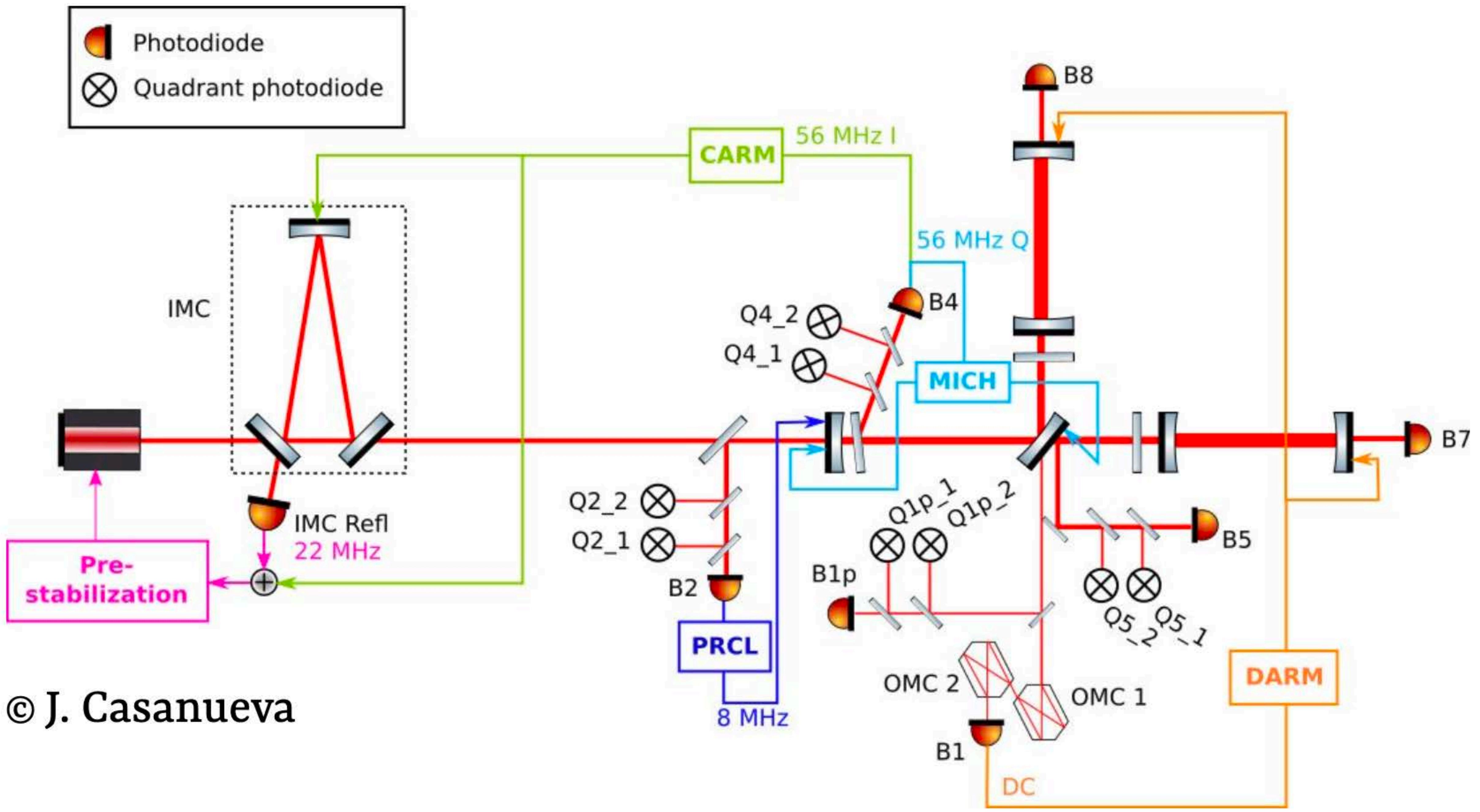




Example 3

Advanced Virgo fast global control of the whole interferometer (~10 kHz)

- Measure Photodiode power in quadrature to extract variation of modulation RF
- Global timing error < 120 ns
- Digital demodulation of the photodiode signals at frequencies between 6 MHz and 132 MHz (boards designed by LAPP*)
  - ADCs sampling at 400-500 Msps with Renesas ISLA214S50 14-Bit, 500/350 MSPS JESD204B
  - LMK04800 Low-Noise Clock Jitter Cleaner (< 200 fs)
- Control photodiode demodulated signals are affected by phase noise -> timing distribution system is critical



© J. Casanueva

*Laboratoire d'Annecy de Physique des Particules

Data acquisition in GW experiments

Bandwidth and latency

- Data produced not a big issue

  Virgo: ~1 PB/year (w. raw data) - ET: expected ~10x (LHC experiments are ~100x!)

- Bandwidth could be dominated by peak data rate

  Virgo DAQ uses 1.6 Gb/s link - update to 2.5 Gb/s is ongoing

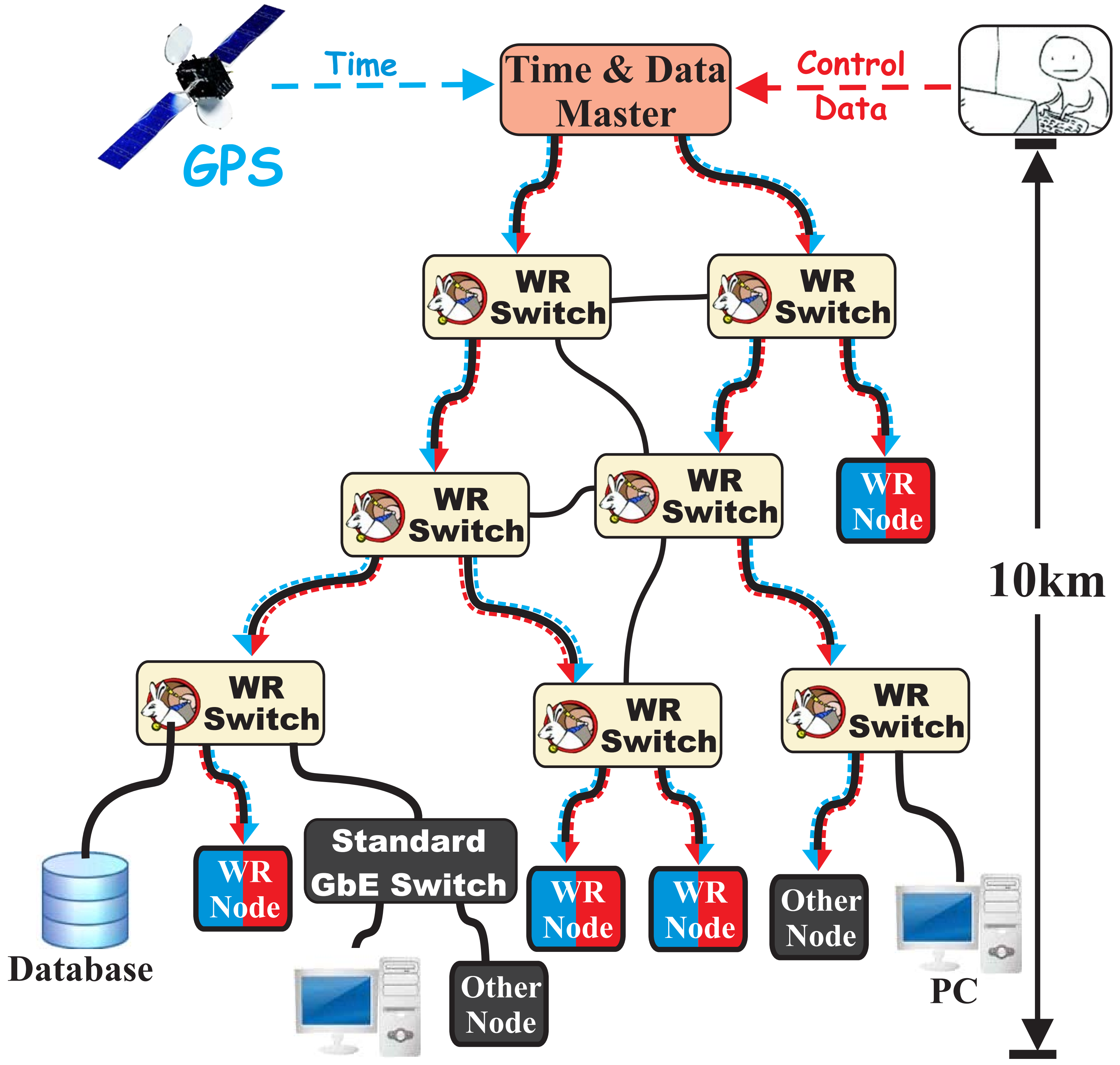
- Latency: ~us

=> ~10 Gb/s links for DAQ

White Rabbit

A potential solution for ET

- Satisfactory timing performance and clock distribution
- Interest in 10 Gb/s implementation (participation in Infra-Tech calls)
- Plan to install WR between buildings in Virgo (under test)
- New boards for the Virgo Superattenuator control will have WR interface as an option



Bologna ET Integrated Facility

An ETIC-WP5 infrastructure based on FPGA, White Rabbit, GPU

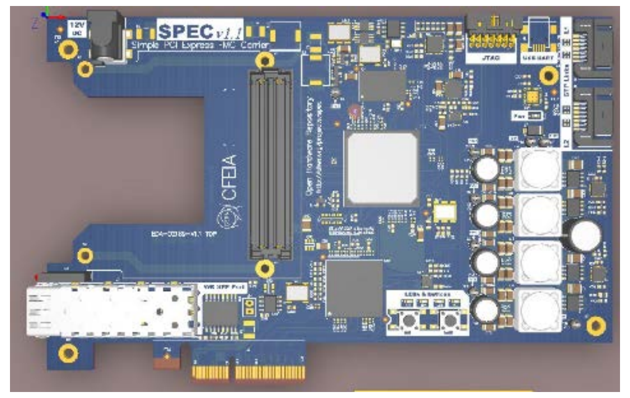
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani | INFN

ALVEO U55C, ALVEO V70, **ALVEO X3**, ALVEO U250, **ALVEO U45N**

1 Server dedicated
to White Rabbit (WR) and DAQ

1x WR Switch

2x SPEC



1x GPS

What we could have in common

100% my opinion!

- GPS calibration and monitoring
- Off the shelf: PLLs, clock buffers, oscillators, voltage references, ADCs, DACs, …
- High precision/ low noise RF instruments
- Real time “processors”: PCs, DSPs, FPGAs
- White Rabbit
- High speed and low latency links
- Standards: μTCA, …

Summary

- Einstein Telescope will be the 3rd generation detector for Gravitational Waves
- A big scientific project
- Vast technological effort and R&D are foreseen and already on going
- Timing will be a critical aspect for
    - Scientific performance
    - Operation of the detector
- I see several points of contact with the community of LLRF

Bibliography

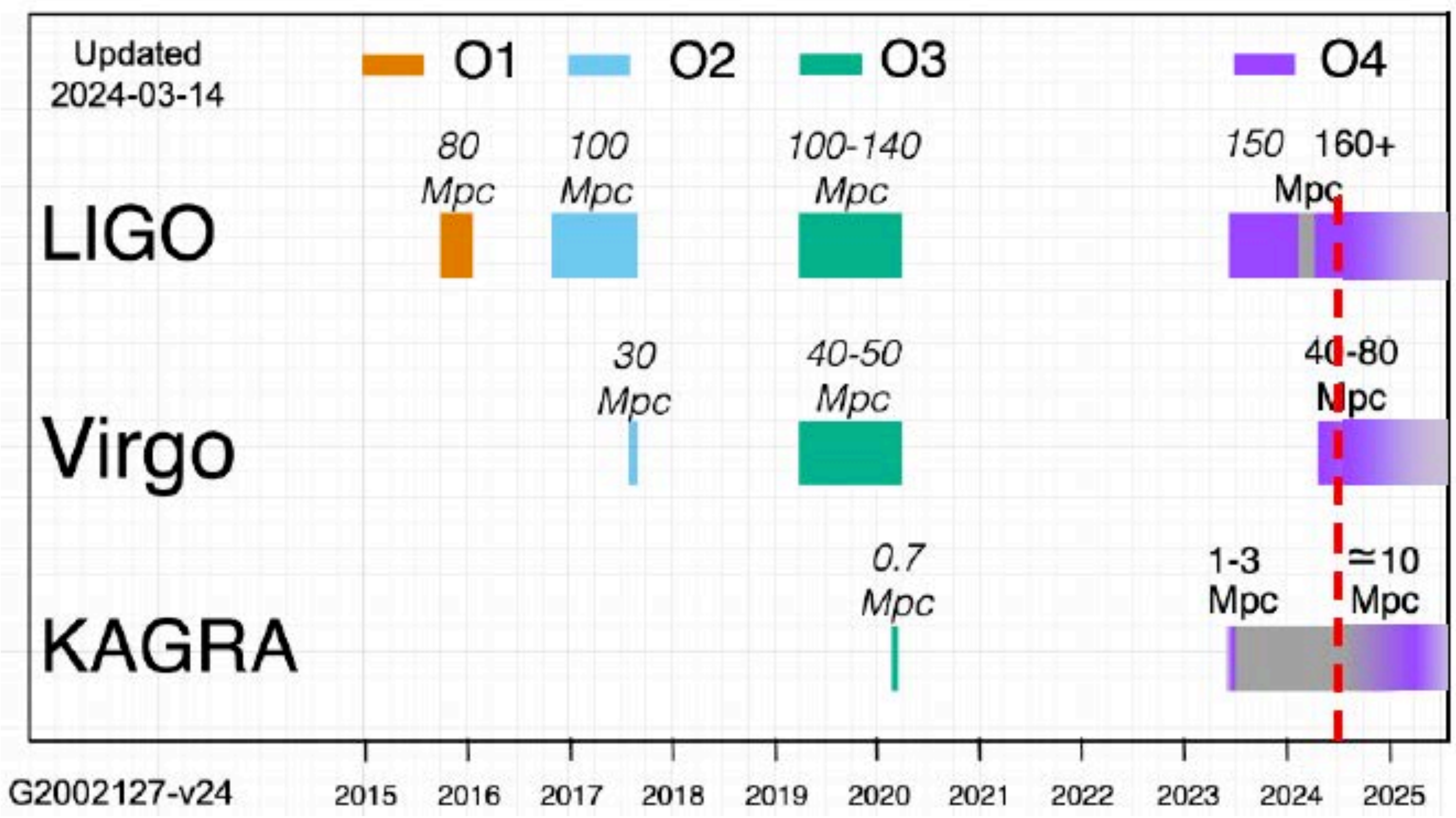
- The Virgo collaboration, Advanced Virgo Technical Design Report. Virgo Internal Document VIR-0128A-12. Available online: https://tds.virgo-gw.eu/ql/?c=8940 (accessed on 23 October 2024).

- ET Data acquisition & real time control (ISB division) - kick-off meeting - presentation from B. Swinkels, L. Rolland - ET-0020A-24 - https://apps.et-gw.eu/tds/ql/?c=17038

- An Introduction to the Virgo Suspension System. In: Bassan, M. (eds) Advanced Interferometers and the Search for Gravitational Waves. Astrophysics and Space Science Library, vol 404. Springer Cham https://doi.org/10.1007/978-3-319-03792-9

Additional Material

Observing Runs



Absolute synchronization
Timestamping

- Timing accuracy in reconstructing GWs is important for sky localization of sources (astrophysical studies and multi-messenger detection)

Uncertainty in reconstruction due to timing inaccuracy

$$SNR = \frac{1}{2\pi\sigma_t\sigma_f}$$

- Looks like the formula for ADC errors due to clock jitter
- σ_t = timing uncertainty in strain reconstruction
- σ_f = effective bandwidth of a GW signal: for binary massive objects ~O(100 Hz) => σ_t ~ O(100 μs) @ SNR = 10

Stephen Fairhurst 2011 New J. Phys. 13 069602 DOI 10.1088/1367-2630/13/6/069602

Timing in GW experiments

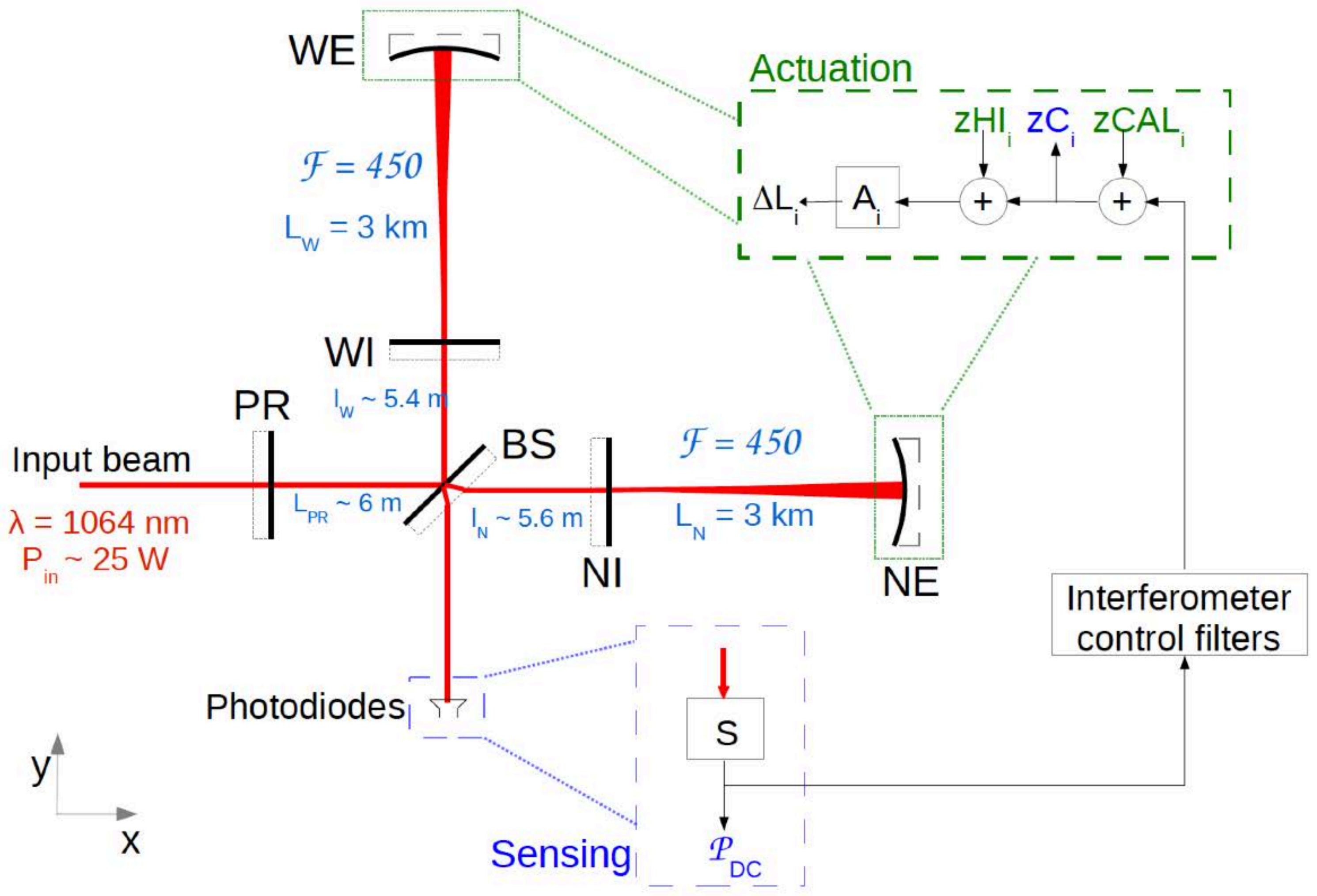
Absolute, for control loops and for fast sampling

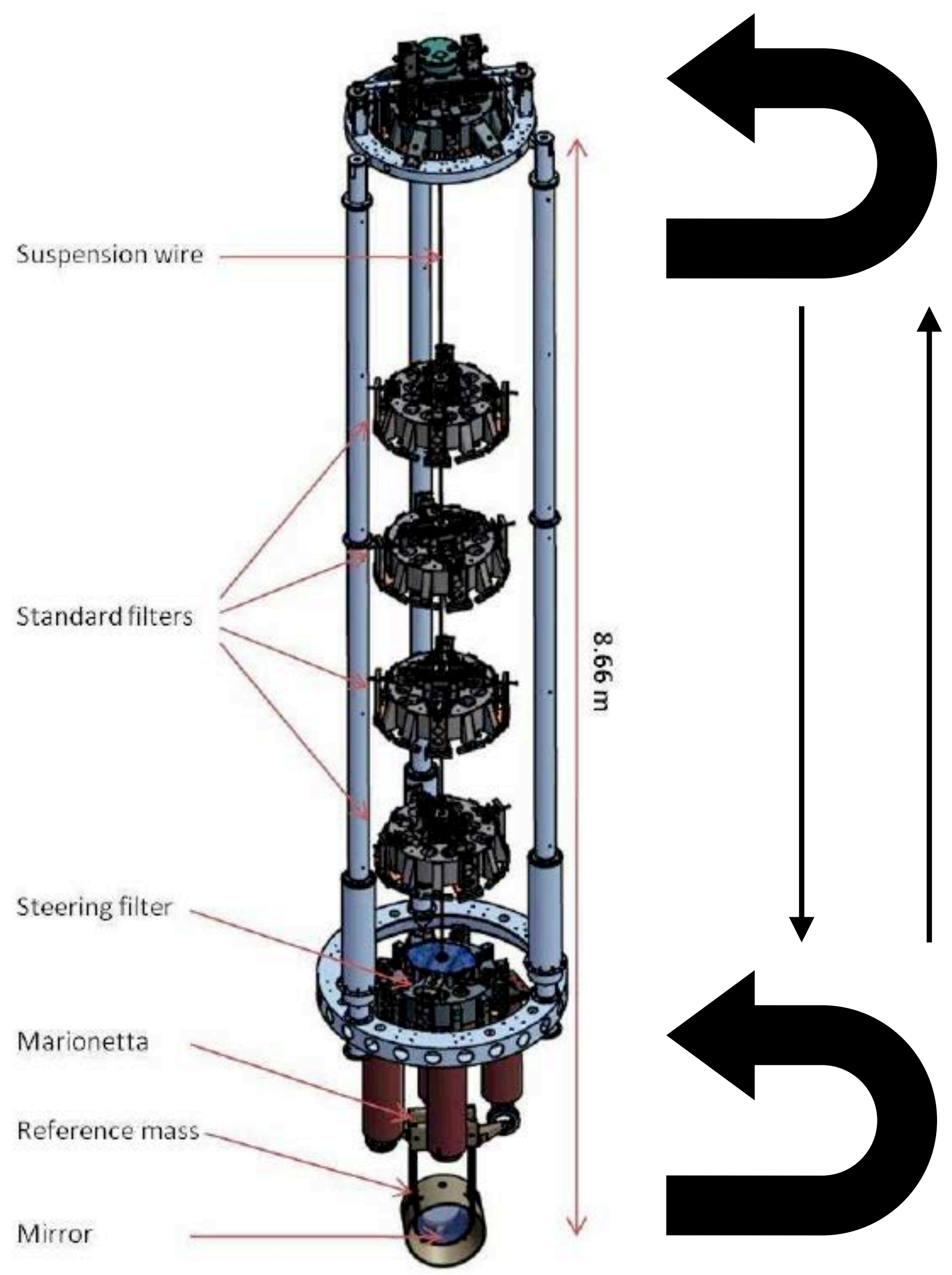
Timing

- Synchronization with others GW observatories (coincidences) and for Multi-messenger analysis require absolute timing of the order of few us

- Control: for Advanced VIRGO the absolute timing precision must be of the order of 0.01 ms or less; ET is expected to be better than 1 us

- Fast sampling: digital demodulation with fast ADCs (~ 500 Msps) with a timing jitter at the level of 1 ps or better

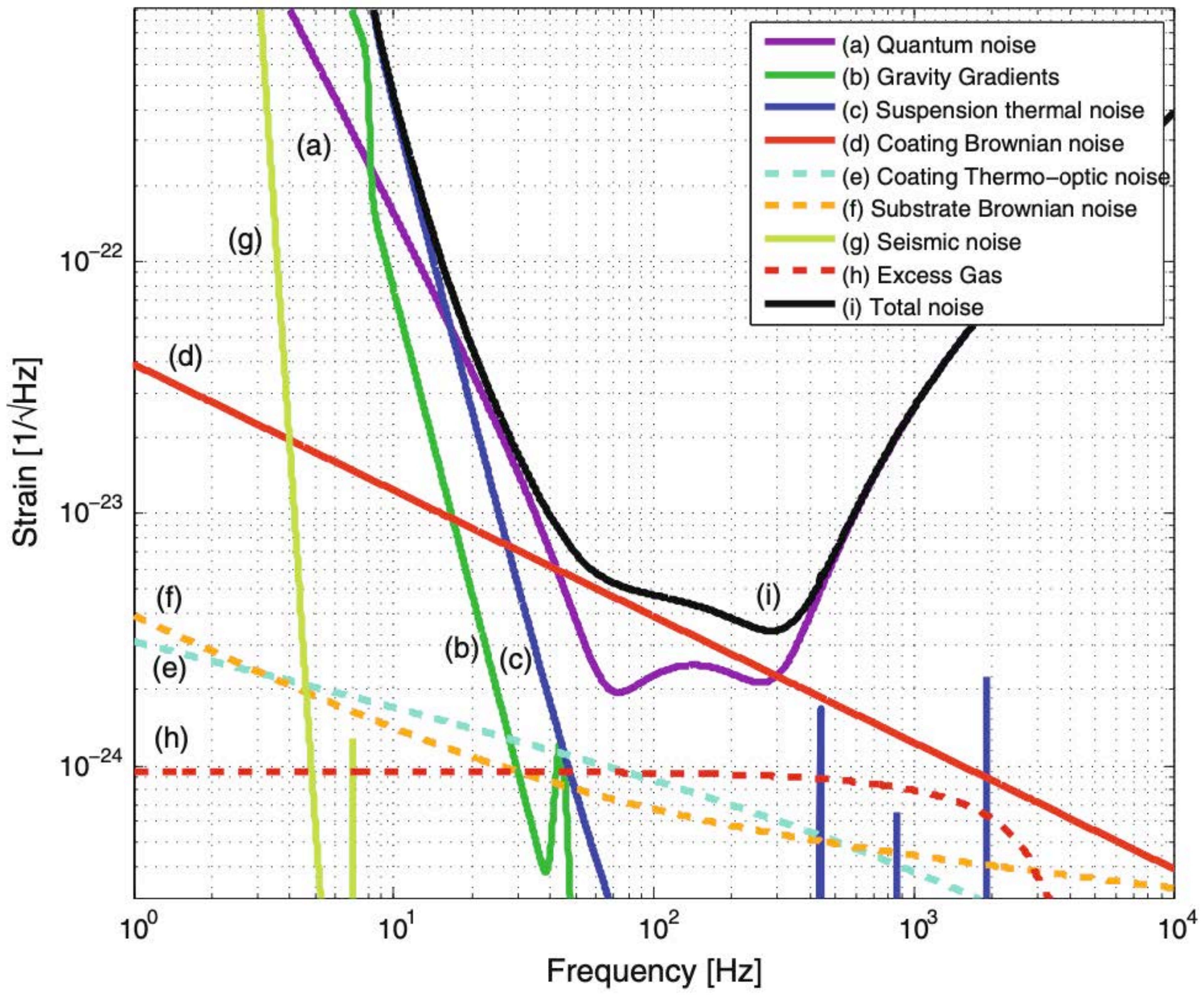




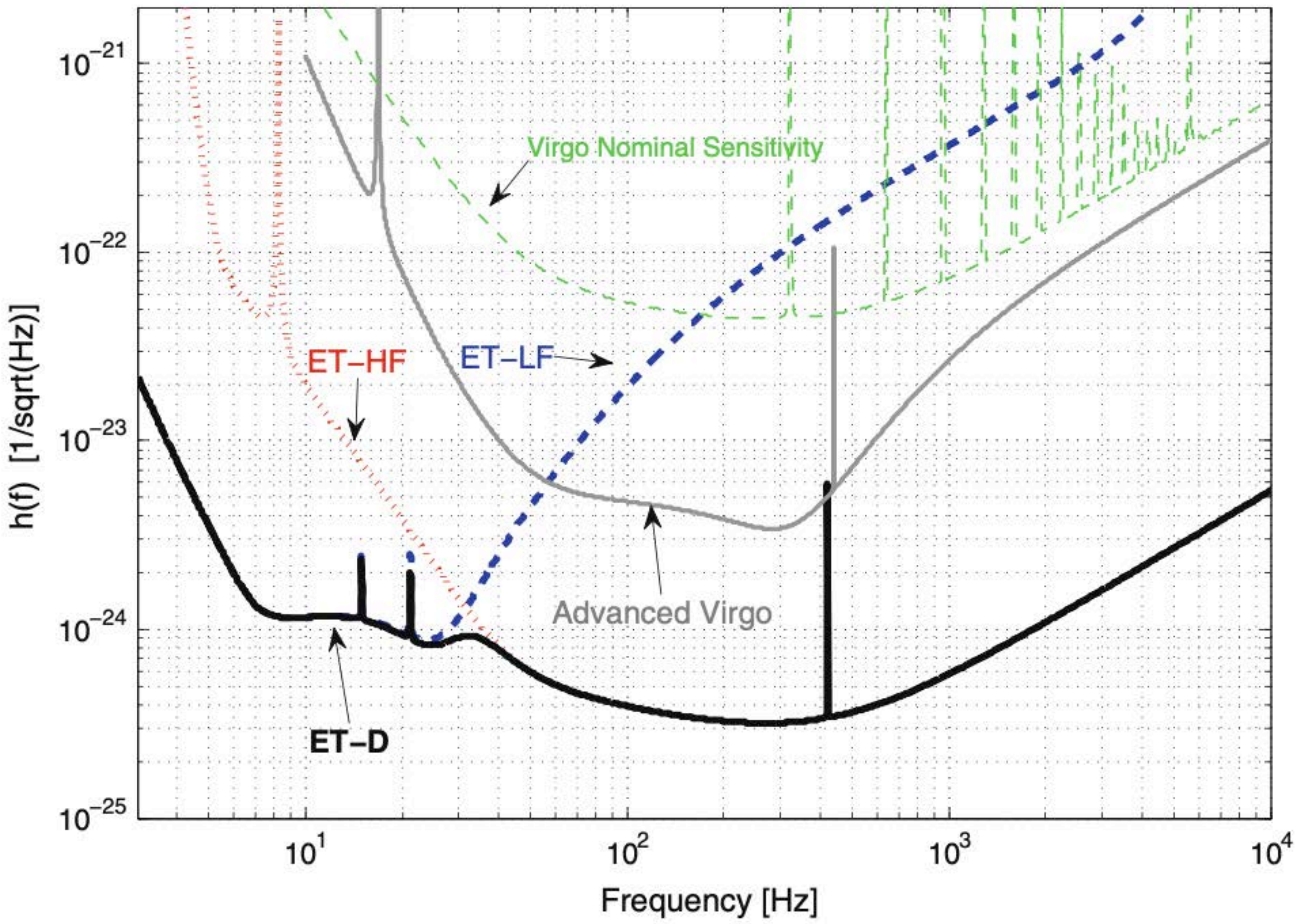
Superattenuator Low-latency fast control loops

Sensitivity and fundamental Noise sources

Interlude



Sensitivity model of an advanced GW detector

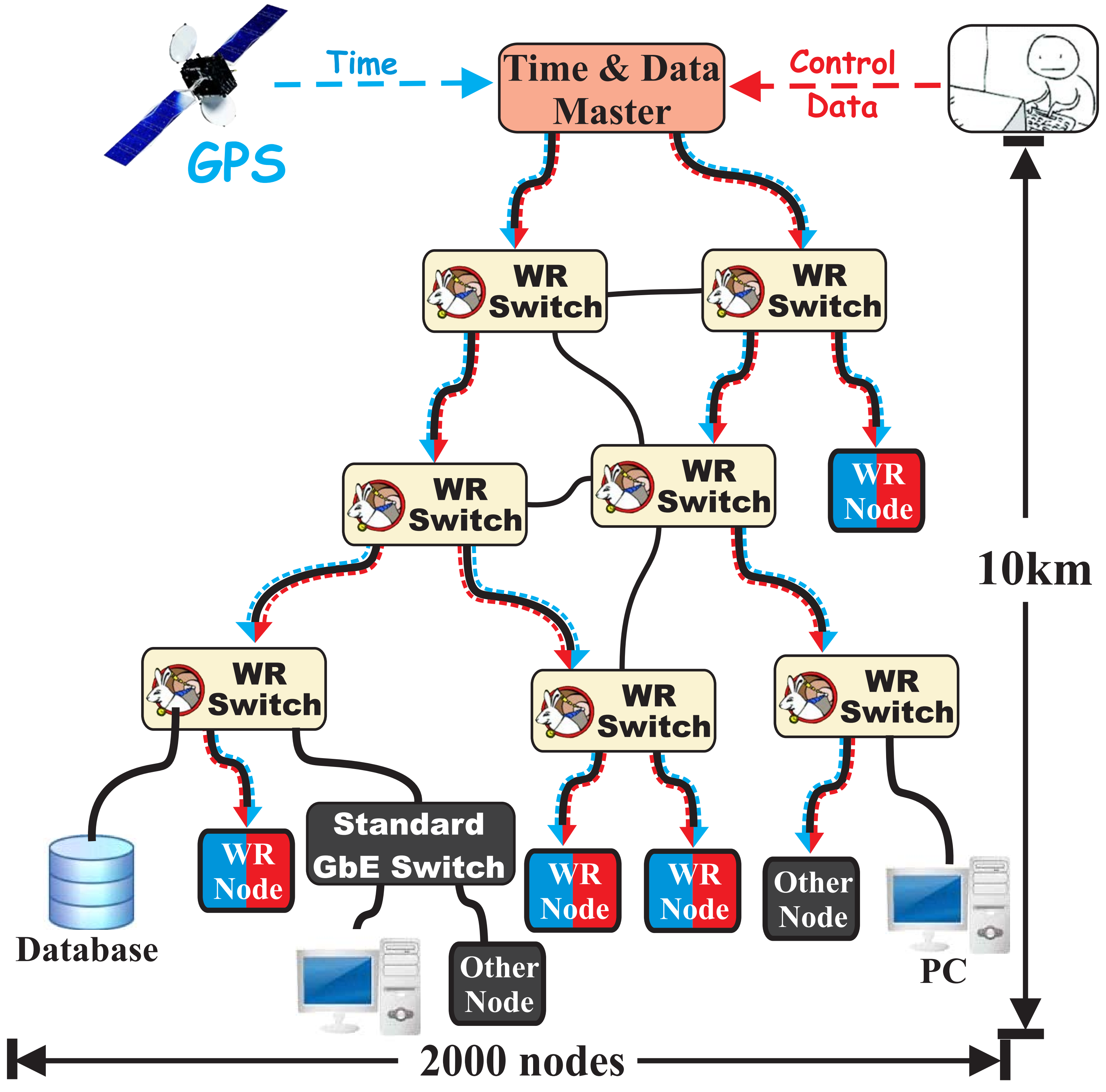


Sensitivity model of a single ET-HF plus ET-LF with 10 km arms (90° opening angle)

White Rabbit

An open source project

- Initially developed by CERN community; recently the WR Collaboration has been established
- Synchronization with sub-nanosecond accuracy and picoseconds precision
- Typical distances of 10 km between network elements
- Gigabit rate of data transfer (data and synch use the same network)
- A set of open-source basic blocks, WR Switches and WR Nodes interconnected, to create a network.



White Rabbit

Current technology (1GbE), next?

Key elements

- Precision Time Protocol (IEEE1588)
- Syntonization (SyncE)
- Phase measurement
- Calibration (link dependent)

Hw-dependent

Need measurements and monitoring of several delays

=> moving to 10 GbE requires new hardware, firmware and software!