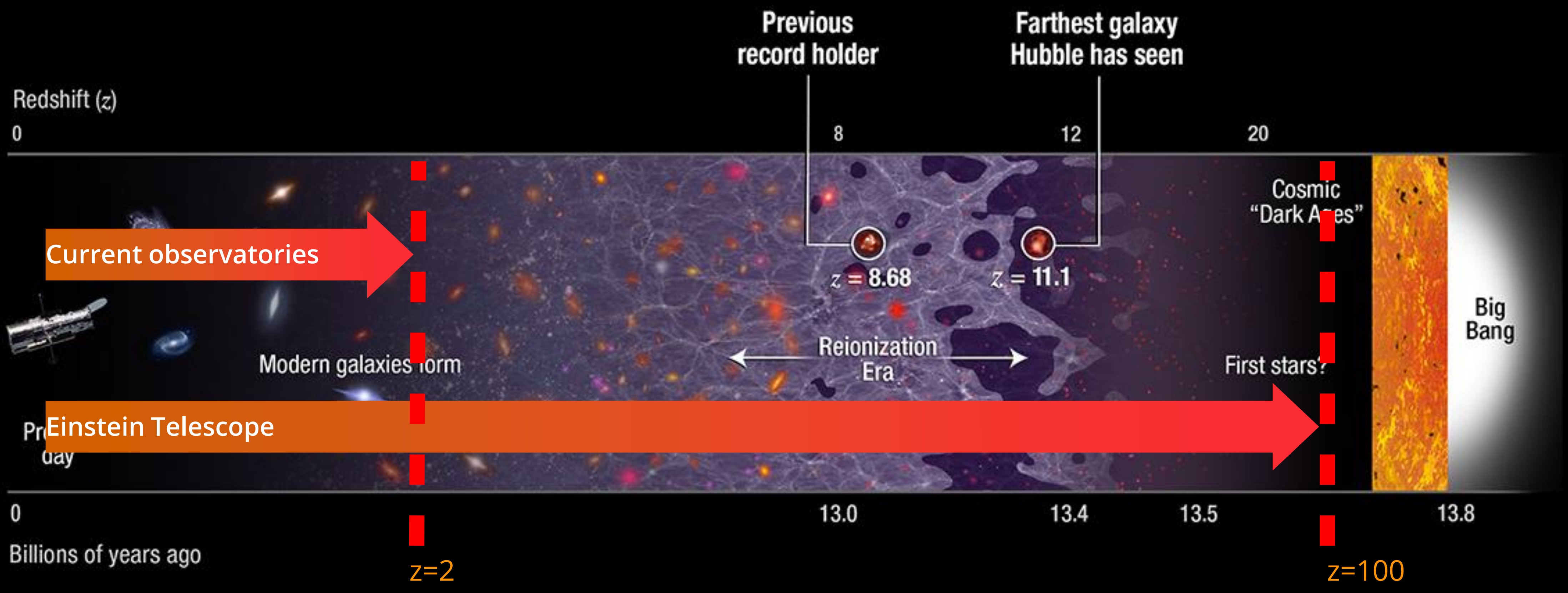
# The Einstein Telescope:

## a next-generation Gravitational Wave observatory in Europe

Patrick Werneke (Nikhef & ETO)
p.Werneke@nikhef.nl
CERN Accelerator School
St Michelsgestel, 07.06.2024

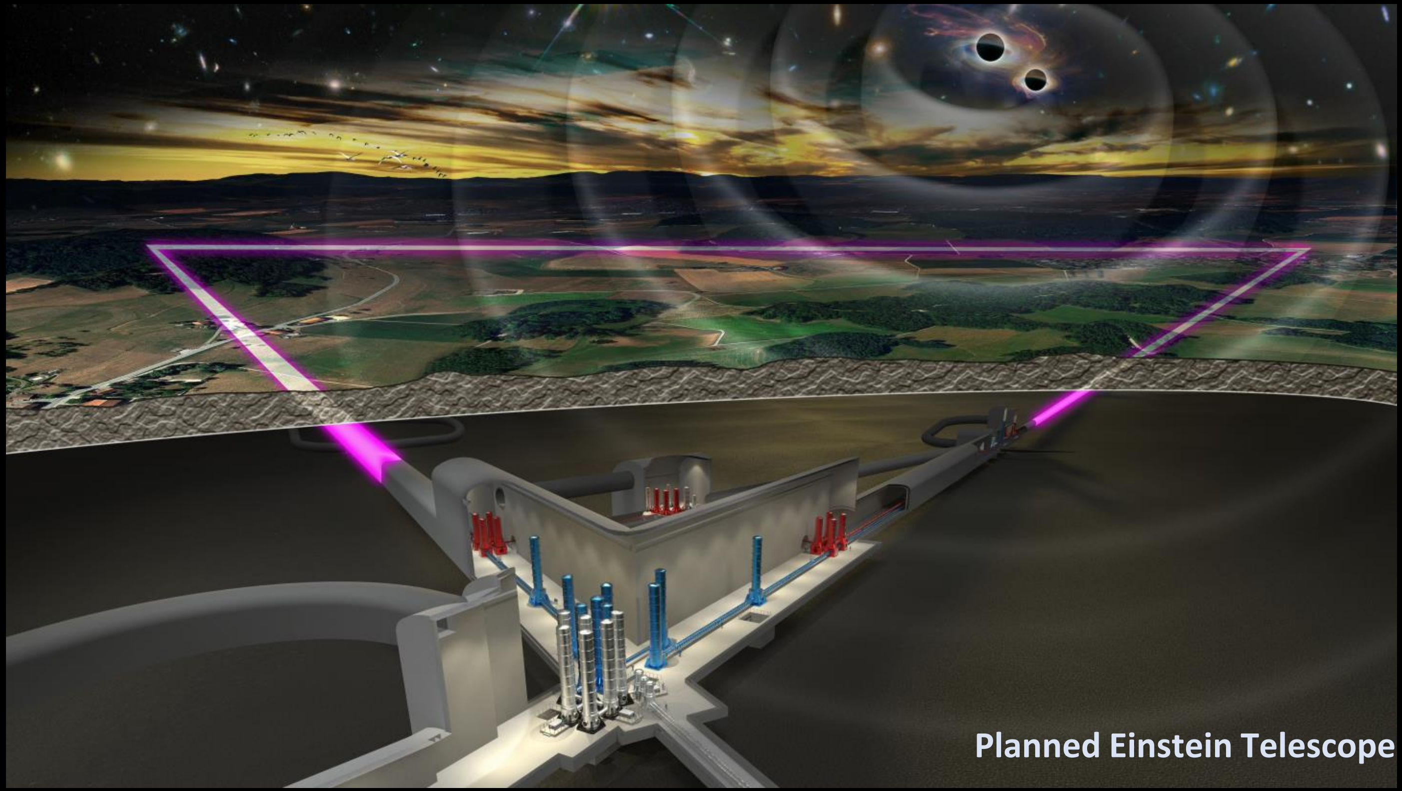
# From the science case for ET




[slide courtesy of A. Freise]

# From current detectors to ET




Current detectors observe about one signal per week.

ET will observe about 100.000 to 1.000.000 binary black hole mergers per year! And many other new sources!

[slide courtesy of A. Freise]

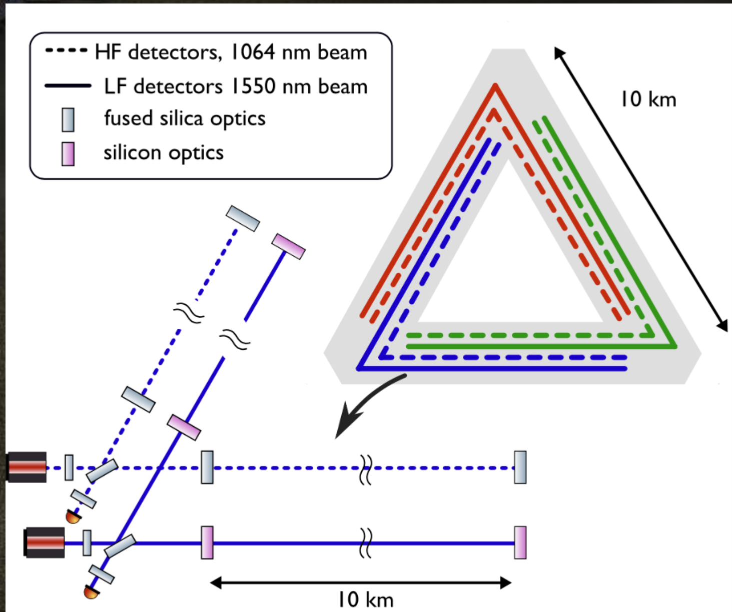
# From current detectors to …




# The Einstein Telescope

10 km

- 3rd generation GW detector
- ~ 250 m underground
- Laser beams
- Super-polished optics
- Ultra-high vacuum
- Cryogenics

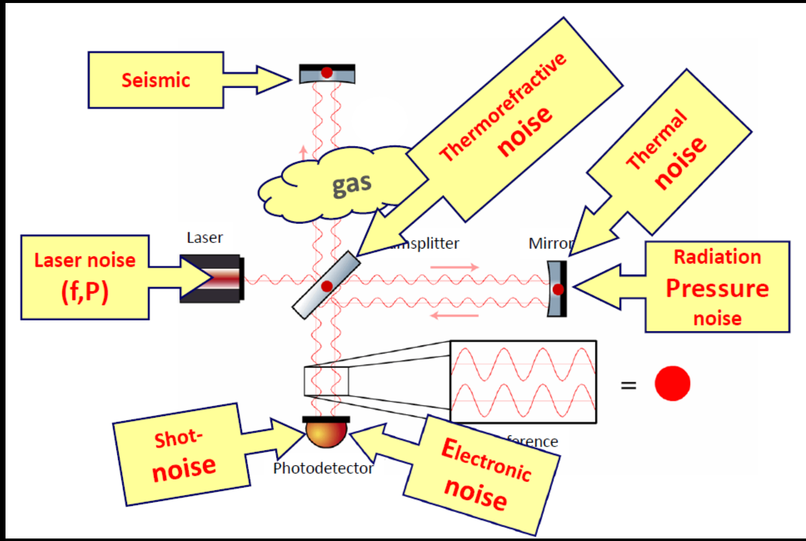



[slide courtesy of A. Freise]

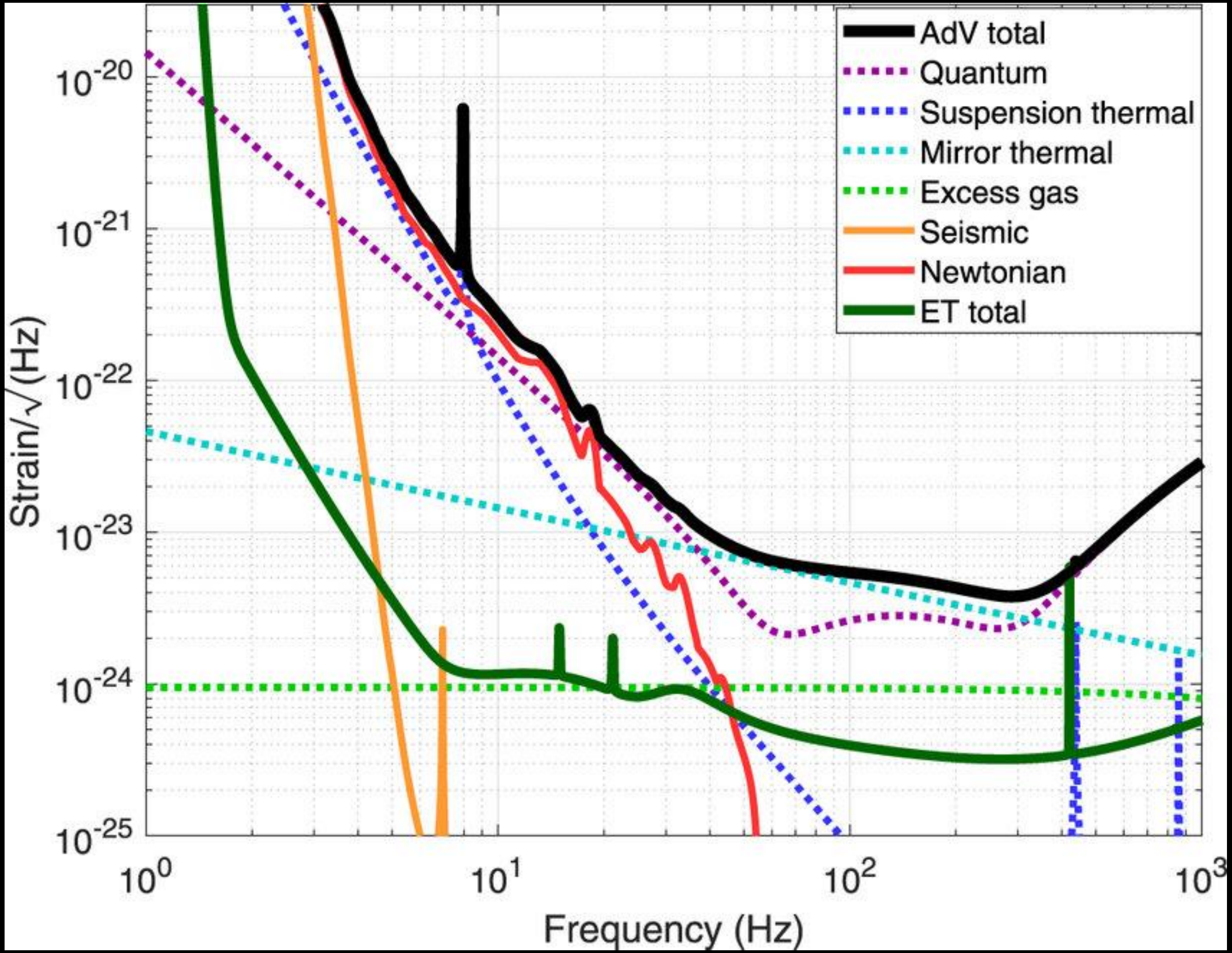
# Interferometer: noise sources

## Fundamental and technical noise sources limit the sensitivity of our instruments

- Shot noise: a light beam consists of a stream of photons and some seconds there arrive more and in other seconds fewer photons at the photodiode
- Radiation pressure noise: photons carry momentum and exert a mechanical pressure on the mirrors
- Seismic noise: earth crust moves relentlessly in a wide frequency range for nHz to hundreds of Hz – tectonic movements, lunar tides, ocean waves, wind induced noise
- Thermal noise: noise which arises from the expansion coefficient of the material
- Phase noise: due to residual gas fluctuations
- ……………



# ET Design Sensitivity



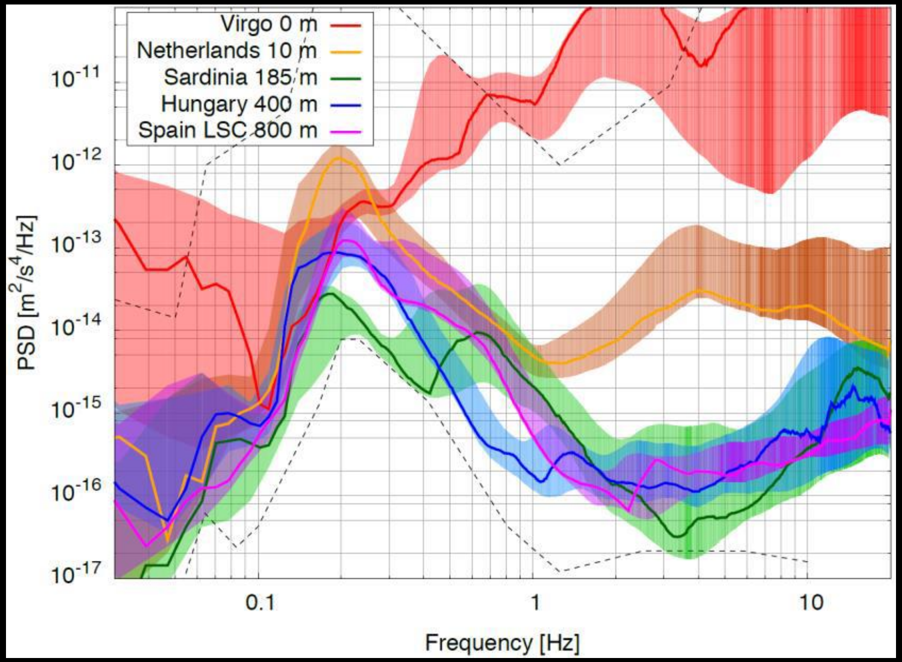

- Increase arm length
- Going underground
- Cryogenics for LF suspension thermal noise
- Better vacuum
- .........

# Interferometer: noise sources

## Underground infrastructure:

- Active and passive vibration isolation systems are used to suppress seismic noise.
- Newtonian noise (gravity gradients) acts directly on test masses
- Newtonian noise limits sensitivity at low frequency
- We need a site with low ambient seismic noise:
  **at ~ 250 m depth we can reach our sensitivity**
- Decrease noise by a factor 20

Mark Beker et al.




[slide courtesy of J. vd Brand]

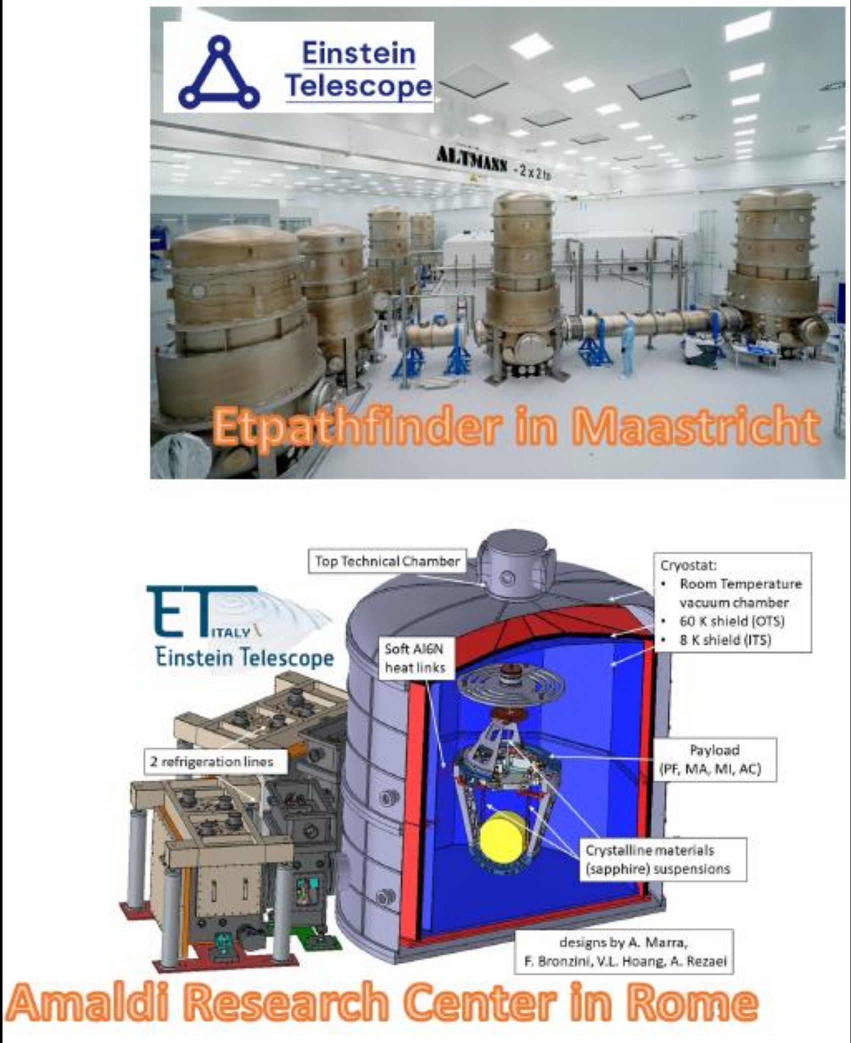
# Interferometer: noise sources

## Suspension thermal noise:

- Caused by thermal fluctuations of the suspension system and of the test mass
- Solution for LF: cool the mirror to **cryogenic** temperatures: 10 – 20 k

## Challenges:

- Acoustic and vibration noises
- Laser absorption and heat extraction
- Cleanliness
- Cooling time
- Materials




[slide courtesy of M. Punturo]

# Interferometer: noise sources

Beampipe vacuum:

- Main specifications:
  - The phase noise due to the residual gas molecules should not affect the sensitivity by more than 10%
  - $P(H_2) < 10^{-10}$ mbar
  - $P(H_2O) < 5x10^{-11}$ mbar
  - $P(C_XH_Y) < 10^{-14}$ mbar (M > 100 amu)

- 1 m inner diameter and total length of 120 km
- UHV volume beampipe = 94000 $m^3$
- Beampipe inner surface = 380000 $m^2$

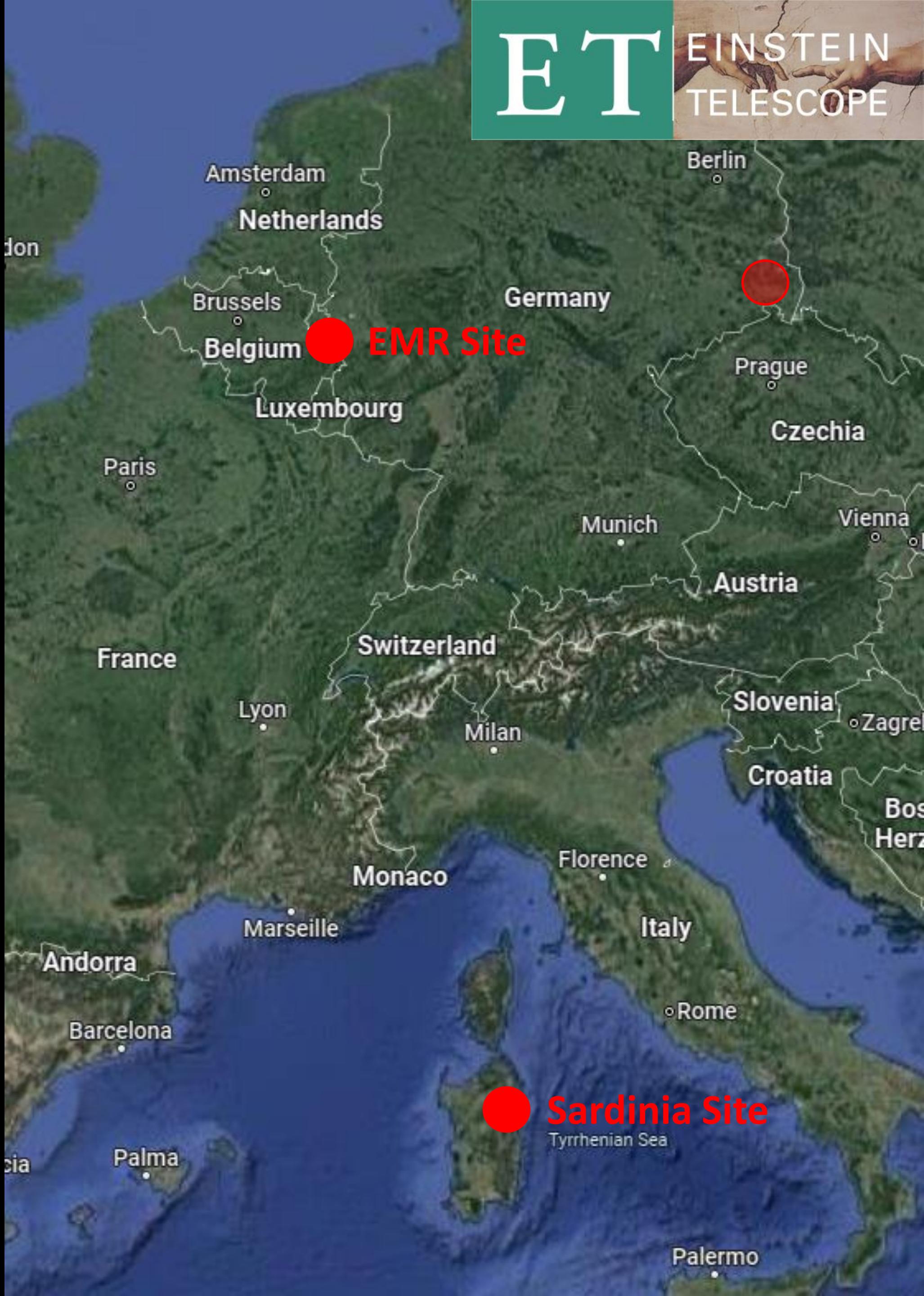
Kagra

# Possible ET Sites

Currently there are two official candidate sites to host the Einstein Telescope:

1. The Sardinia site, close to the Sos Enattos mine
2. The Euroregion Meuse-Rhine site close to the NL-B-D border

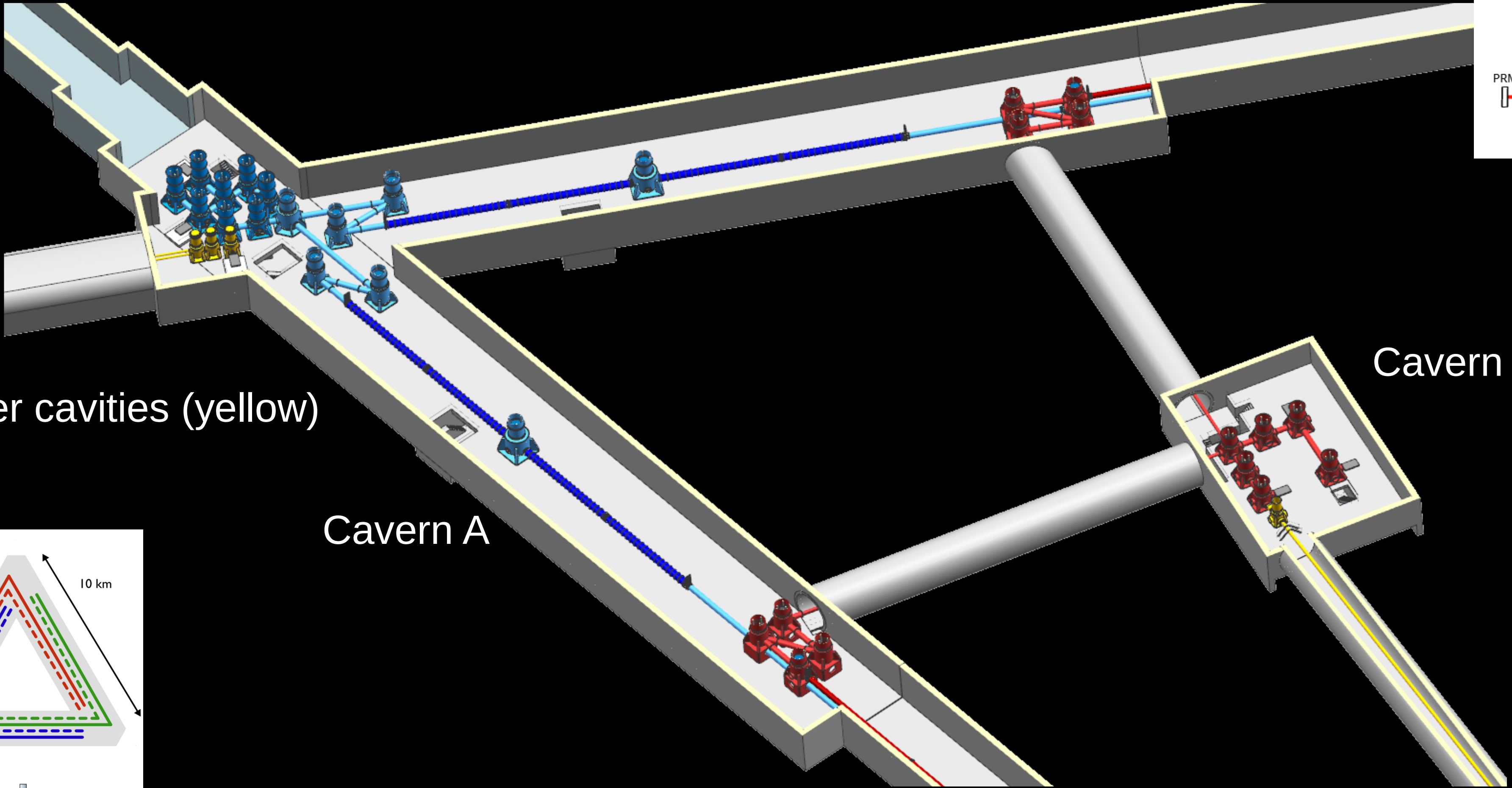
3. A third option in Saxony (Germany) is under discussion, but  still too preliminary to be a candidate.

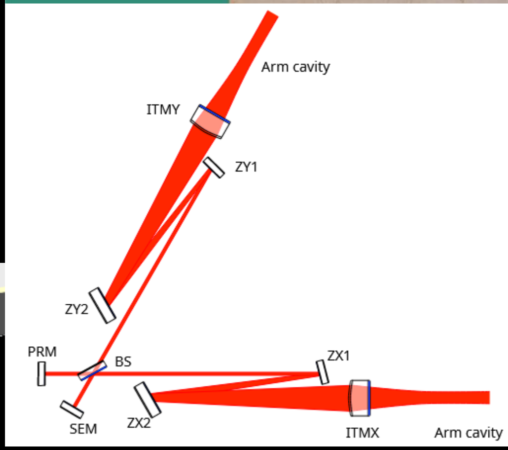


# Einstein Telescope: corner station

Low frequency towers (blue): height = 20 m

High frequency towers (red): height = 10 m

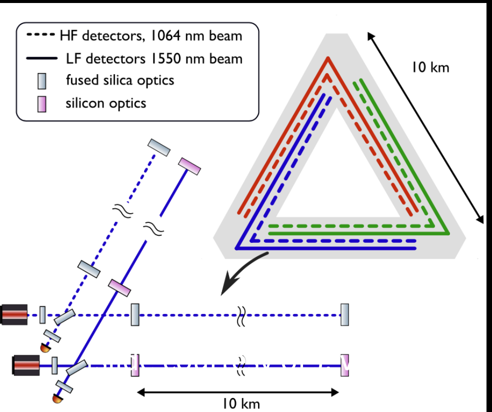




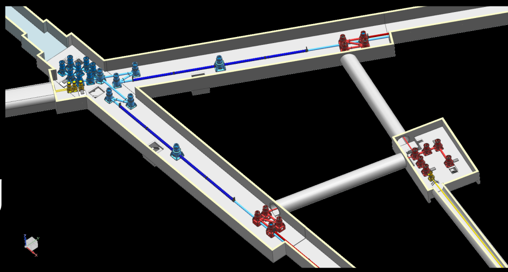

Cavern B

Towers for filter cavities (yellow)

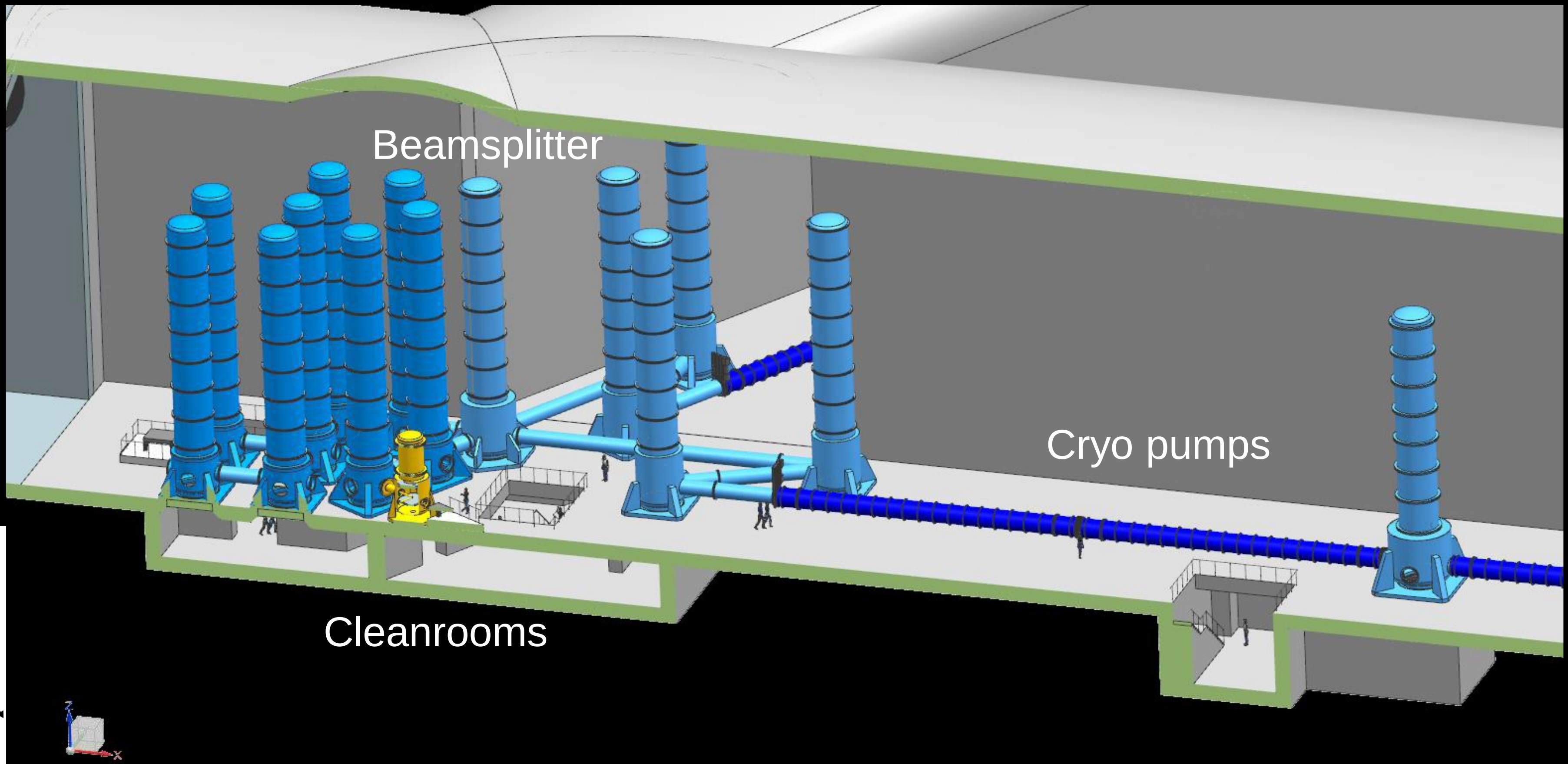
Cavern A

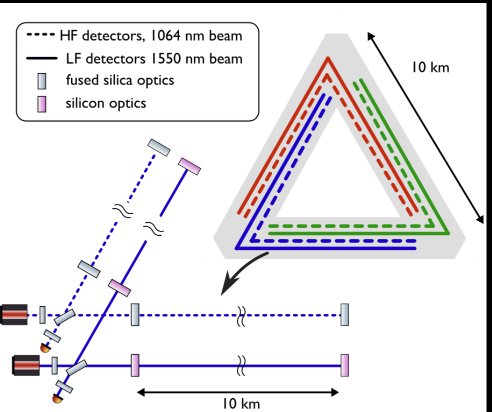


# Einstein Telescope: cavern A



Houses the beamsplitter of the cryogenic low frequency interferometer
Towers are ~20 m high. Cavern A dimensions are 20 m wide, 30 m high, 175 m long

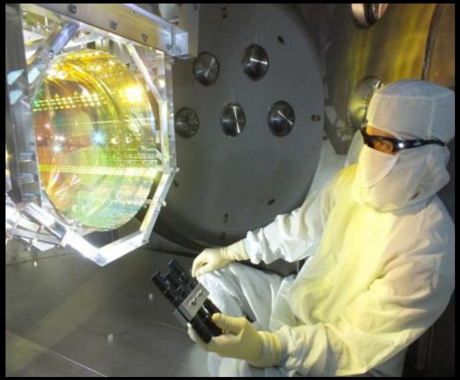


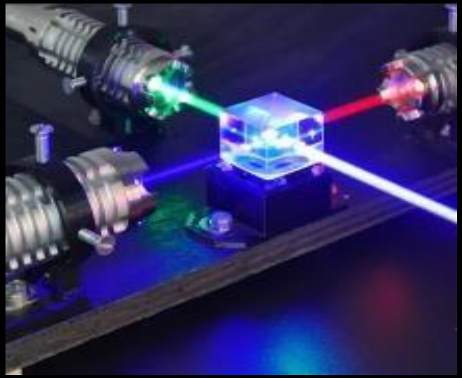
# Development and testing of new technologies

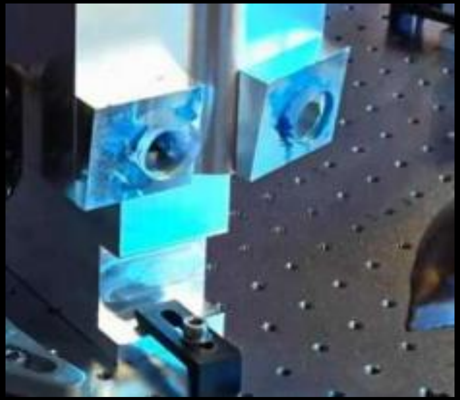
**controls**

**(quantum) optics**

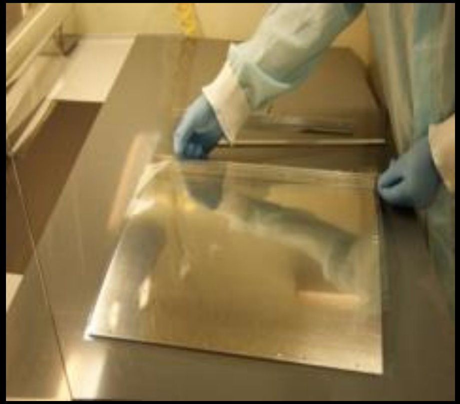


**lasers**

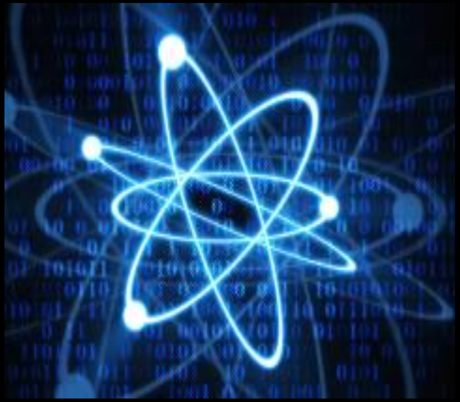




**sensors**



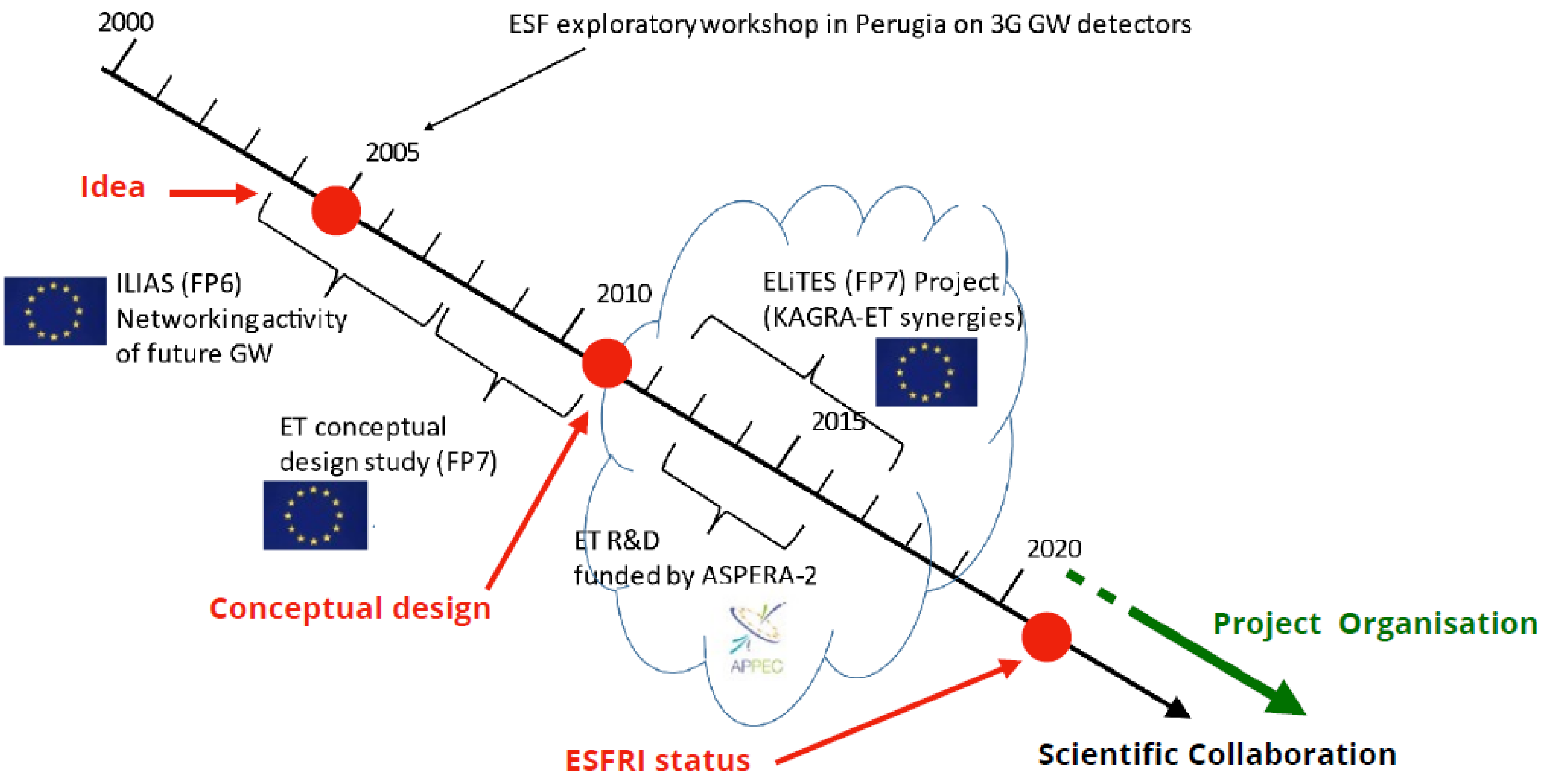
**materials**



**algoritms**


[slide courtesy of G. Koekoek]

# Einstein Telescope: from idea to project




[Timeline: Michele Punturo]

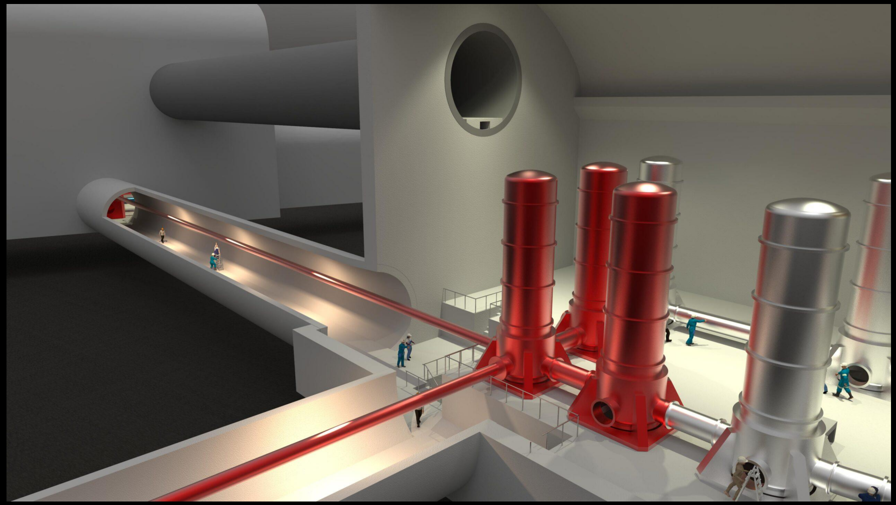
# The next steps for ET

- Design and Preparation **Phase 1:**
  Preparing preliminary technical design documents for the the detector and the infrastructure. Providing all the necessary documents for an approval of ET and a decision of the site(s).

- Design and Preparation Phase 2:
  Adapt the preliminary designs to the chosen site(s) and complete the site preparation work. Create legal entity to oversee construction and operation.

- Implementation Phase:
  Construction of the infrastructure and the detectors

- Operation Phase



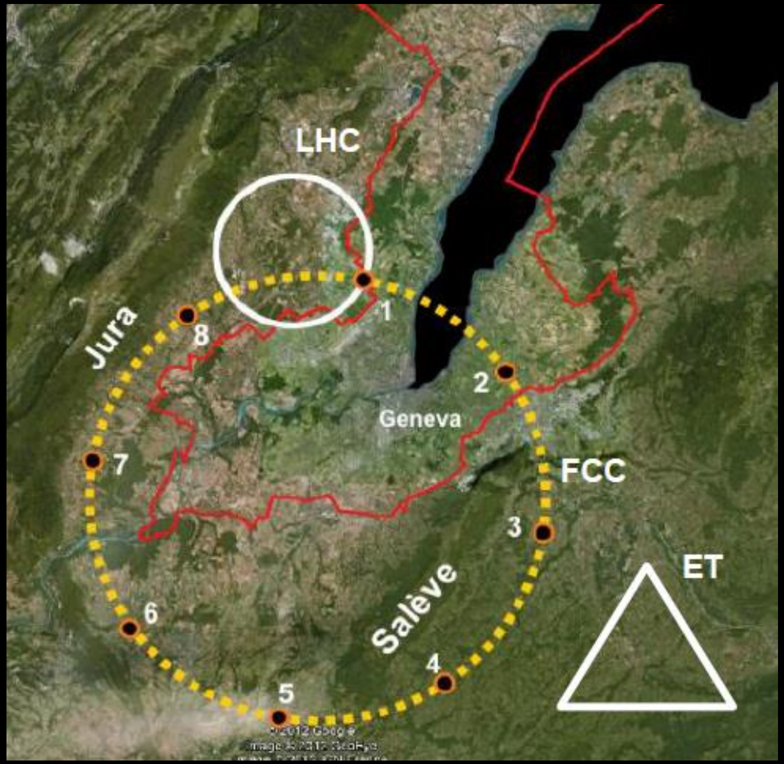
[slide courtesy of A. Freise]

# Einstein Telescope and CERN

**Interesting is the CERN role in the development of the Einstein Telescope. There are several similarities between ET and CERN projects:**

J. vd Brand

- Underground civil infrastructure
- Large ultra-high vacuum infrastructure
- Cryogenics
- Materials
- Controls
- Managing a large and complex scientific project
- Strong scientific interest from particle physicists



# Einstein Telescope and CERN

**We have an MoU with CERN for their support on technical topics:**

CERN Courier

- Civil Engineering
- **Vacuum Beampipe**

Under discussion:

- Technical Infrastructure
- Occupational Health and Safety
- Integration
- Planning
- Information Management
- Support for costing
- Cryogenic infrastructure
- Survey

BEAMPIPES FOR GRAVITATIONAL WAVE TELESCOPES 2023

## Beampipe know-how for GW observatories

The direct detection of gravitational waves (GWs) in 2015 opened a new window to the universe, allowing researchers to study the cosmos by merging data from multiple sources. There are currently four gravitational wave telescopes (GWTs) in operation: LIGO at two sites in the US, Virgo in Italy, KAGRA in Japan and GEO600 in Germany. Discussions are ongoing to establish an additional site in India. The detection of GWs is based on Michelson laser interferometry with Fabry–Perot cavities, which reveals the expansion and contraction of space at the level of ten-thousandths of the size of an atomic nucleus, i.e. $10^{-19}$ m. Despite the extremely low strain that needs to be detected, an average of one GW is measured per week of measurement by studying and minimising all possible noise sources, including seismic vibration and residual gas scattering. The latter is reduced

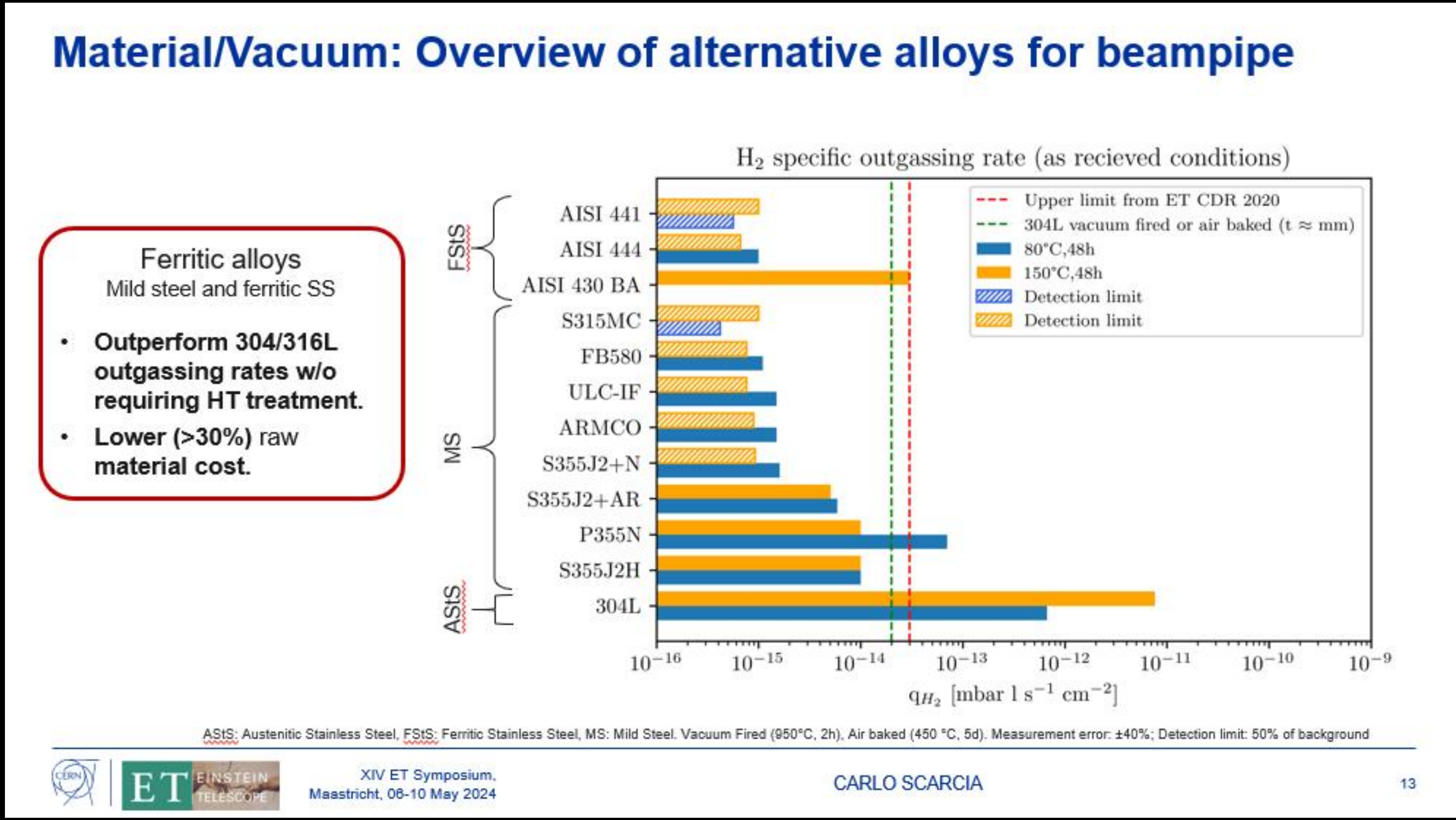
**Beam me up**
*The participants of the March workshop that was dedicated to vacuum technologies for beampipes of next-generation gravitational-wave telescopes.*

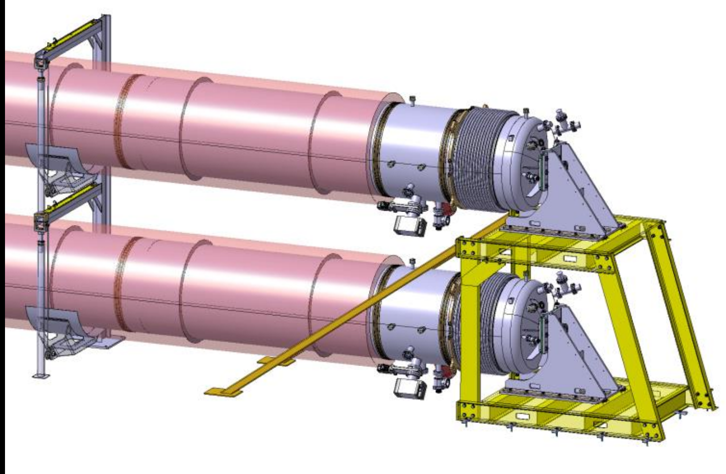
solutions were adopted, then the vacuum pipe system would amount to half the estimated cost of the CE and almost one-third of the ET, with underground civil engineering the dominant amount. Reducing the cost of vacuum systems requires the development of different technical approaches with respect to previous-generation facilities. Developing cheaper technologies is also a key subject

vacuum systems provided a starting point for the presentations of ongoing developments. To conduct an effective cost analysis and reduction, the entire process must be taken into account – including raw-material production and treatment, manufacturing, surface treatment, logistics, installation and commissioning in the tunnel. Additionally, the interfaces with the experimental areas and other services

EINSTEIN TELESCOPE

# Einstein Telescope and CERN



# Einstein Telescope and CERN

## ET Civil Eng. workshop at CERN 29-30th April 2024

- Successful workshop at CERN, hosting colleagues from ETO,  INFN, Nikhef, IFAE, Local Teams, Amberg, Tractebel, Rocksoil.
- Seed questions from the local teams addressed, and hosted a lively discussion
- Identified challenges and considered next steps together
- Decided that a baseline report addressing some of the design complexities of the project would be a positive next step

# Einstein Telescope and CERN


# ET Dual Organizational Structure

1) project organization (towards legal entity) and 2) scientific collaboration

## ETO (ET Organization)

- Board of Governmental Representatives
- Coordinators
- Board of Scientific representatives
- ET Directorate
- INFRA-DEV ET-PP
  - EU project coordination
  - WP1:
  - WP2:
  - WP3:
  - …
- Project Office
- Engineering Department
- Communication

## ETC (ET Collaboration)

- Collaboration Board
- Executive Board
- Specific Boards
  - ISB
  - OSB
  - EIB
  - SPB
  - SSB
  - …

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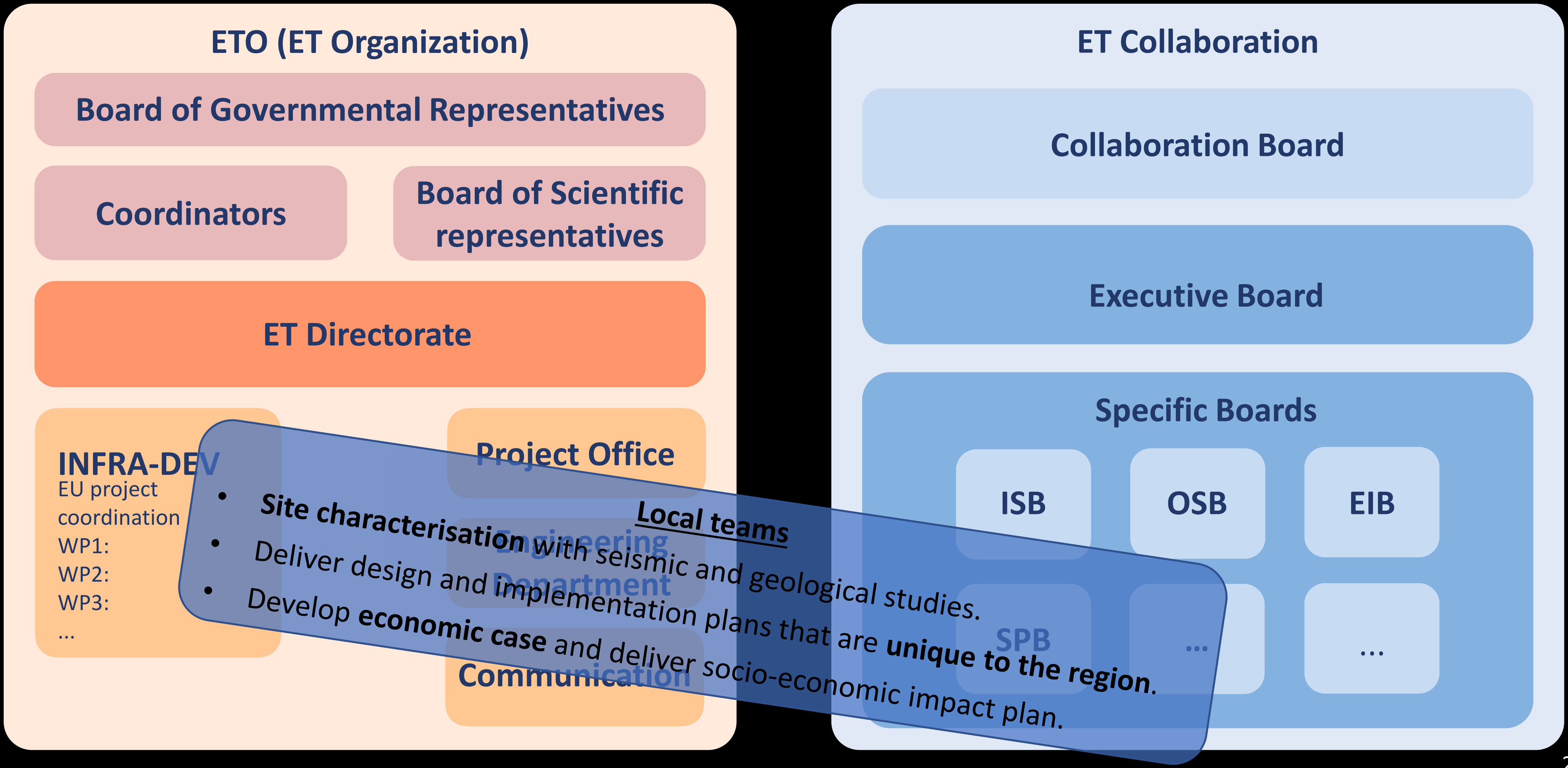
1) project organization (towards legal entity) and 2) scientific collaboration



# Einstein Telescope so far


<u>ET Collaboration:</u>

- Officially established 9 June 2022
- **1500+ members, 220+ institutions, 24 countries**

<u>Project funding:</u>

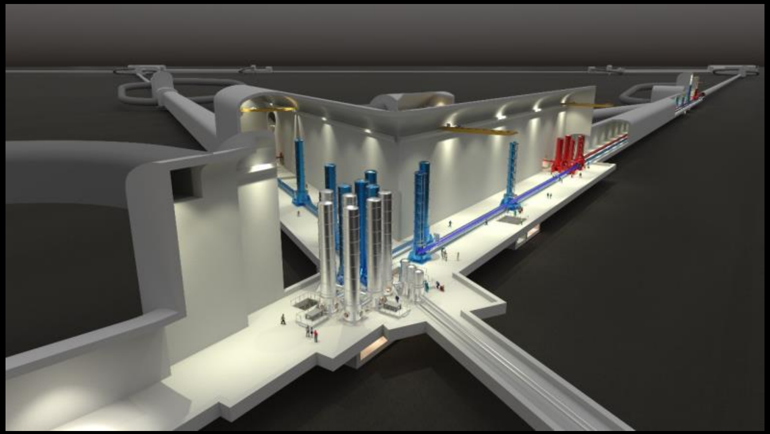
- Large amounts of funding per preparing bids to host ET: 50 M€ ETIC project (Italy), 42 M€ National Growth fund (Netherlands)
- EU funded preparation phase project ‘ET-PP’, total value 12 M€

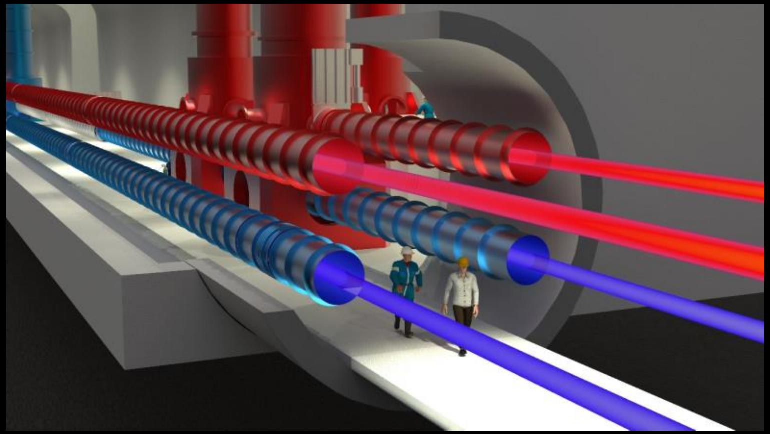
<u>International coordination:</u>

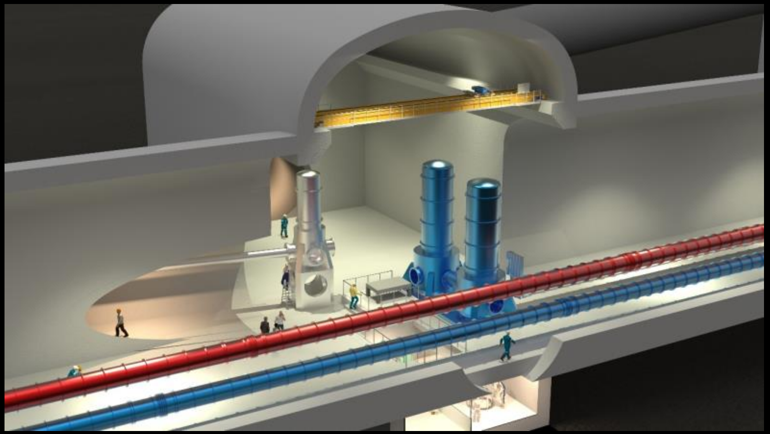
- Established a structure to form and evolve international partnership
- Active group of ministry delegates meet regularly

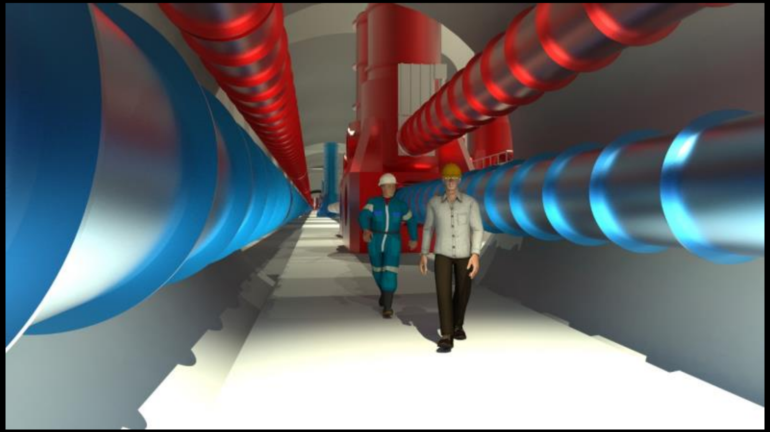
[slide courtesy of A. Freise]

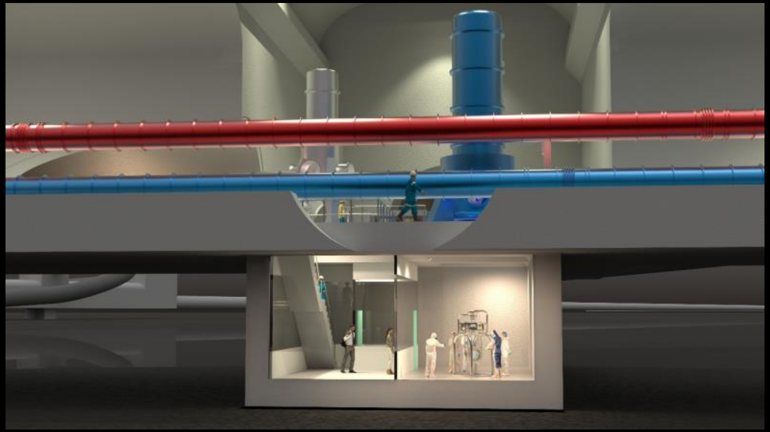
# End



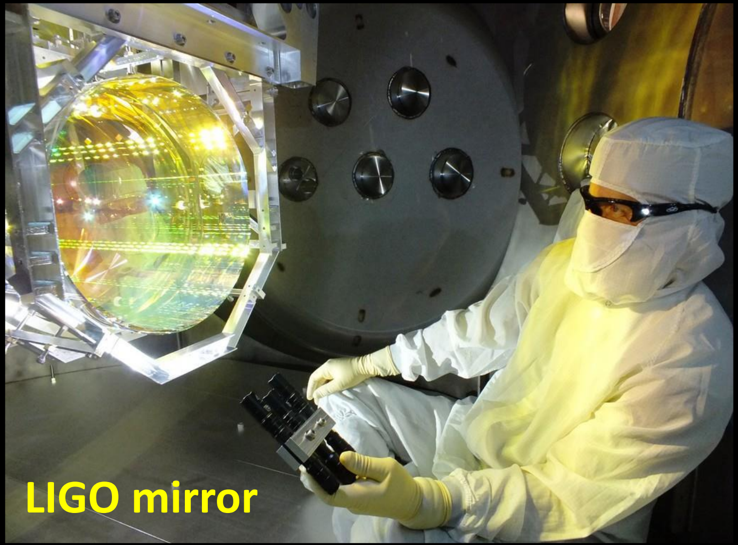


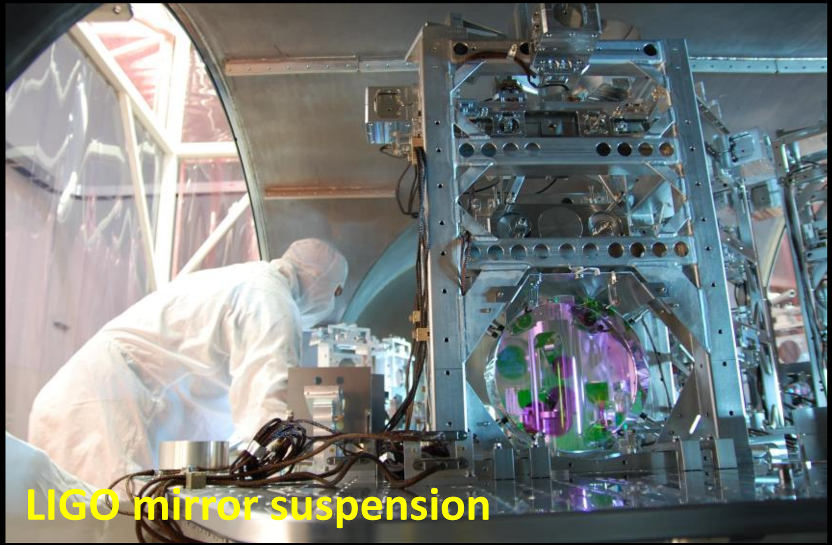






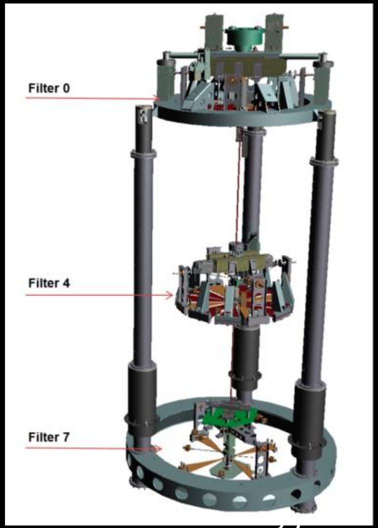
# Development and testing of new technologies









# The Science Case for Einstein Telescope

## ASTROPHYSICS

**Black hole properties**
origin (stellar vs. primordial) evolution, demography

**Neutron star properties**
interior structure (QCD at ultra-high densities, exotic states of matter)
demography

**Multi-band and -messenger astronomy**
joint GW/EM observations (GRB, kilonova,...)
multiband GW detection (with LISA)
neutrinos

**Detection of new astrophysical sources**
core collapse supernovae
isolated neutron stars
stochastic background of astrophysical origin

## FUNDAMENTAL PHYSICS AND COSMOLOGY

**The nature of compact objects**
near-horizon physics
tests of no-hair theorem
exotic compact objects

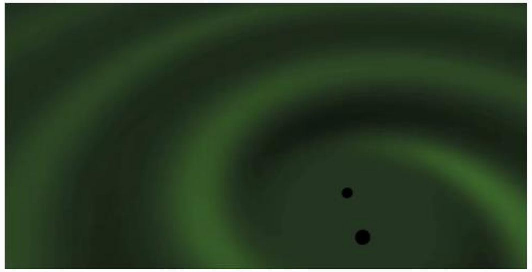
**Tests of General Relativity**
post-Newtonian expansion
strong field regime

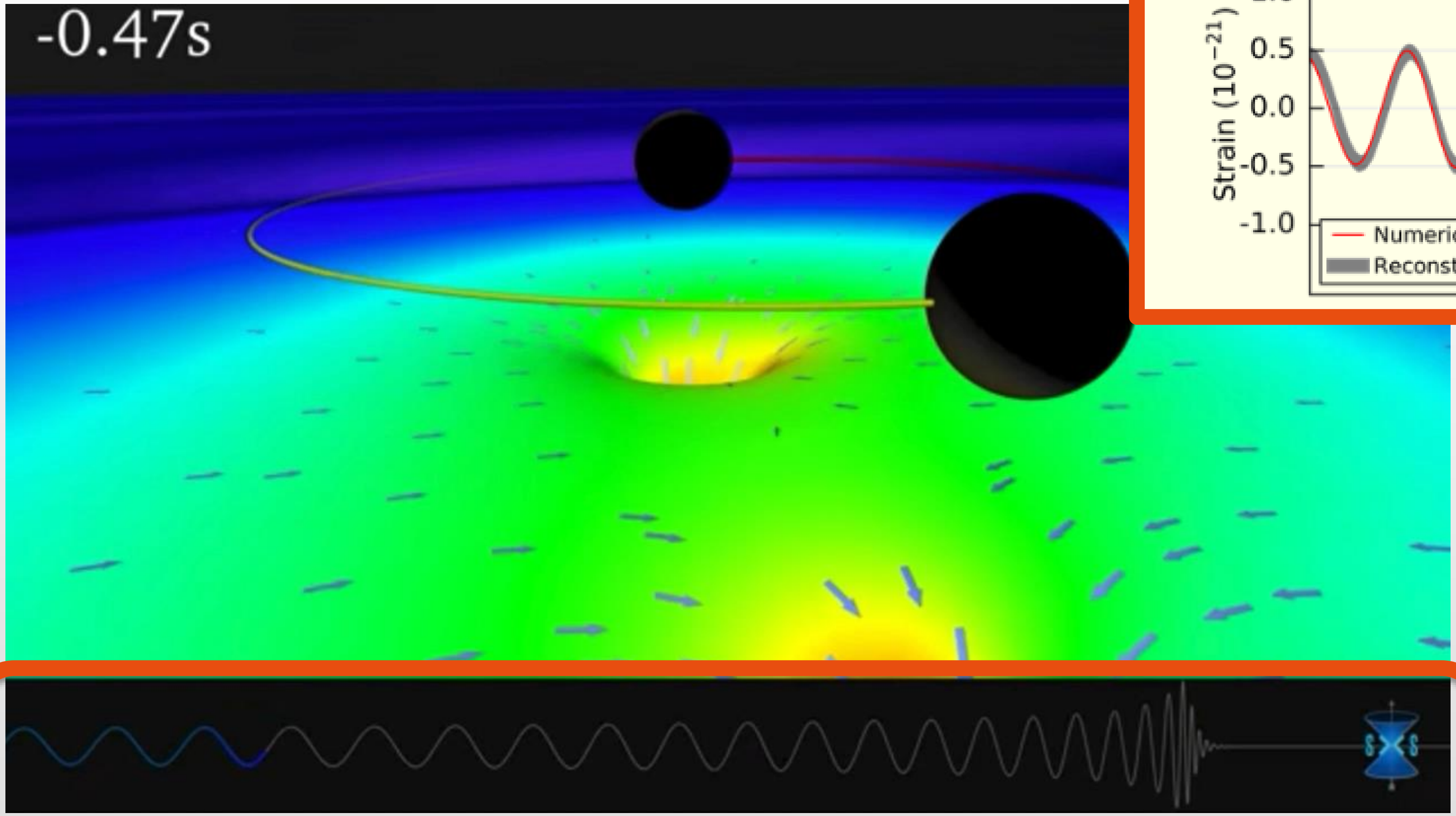
**Dark matter**
primordial BHs
axion clouds, dark matter on compact objects

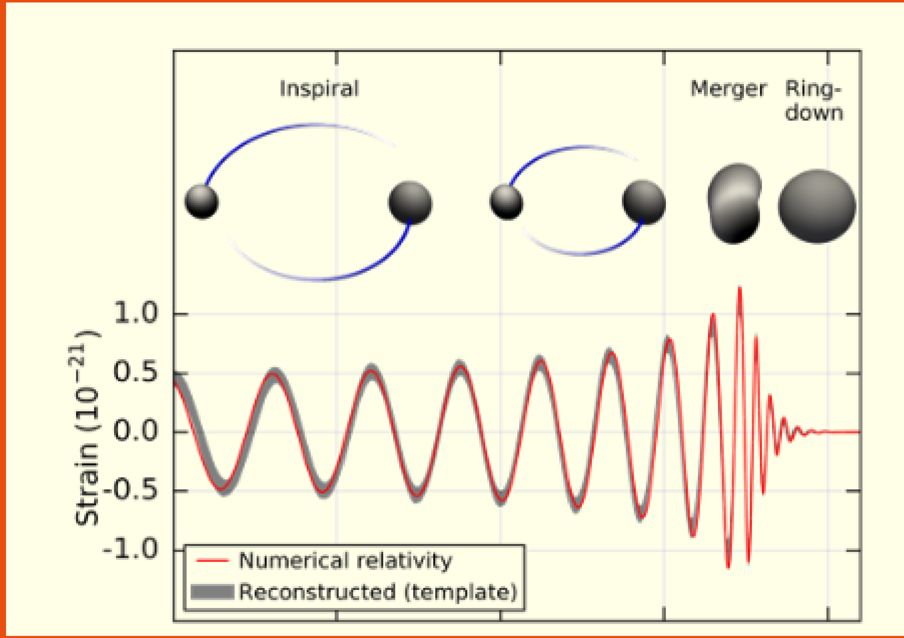
**Dark energy and modifications of gravity**
dark energy equation of state
modified GW propagation

**Stochastic backgrounds of cosmological origin**
inflation, phase transitions, cosmic strings

[see Maggiore et al.; 1912.02622],
also https://www.einsteintelescope.nl/
and https://www.et-gw.eu/]

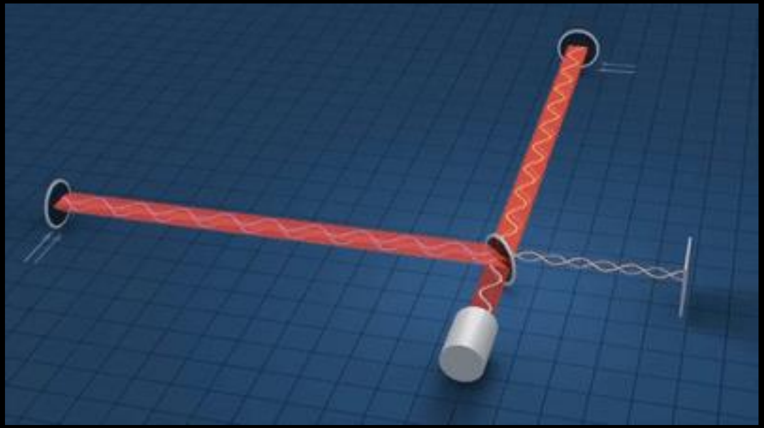


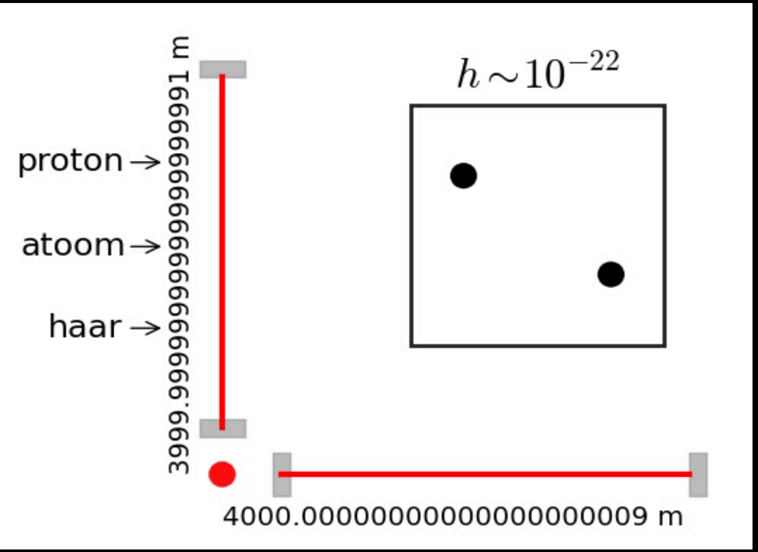


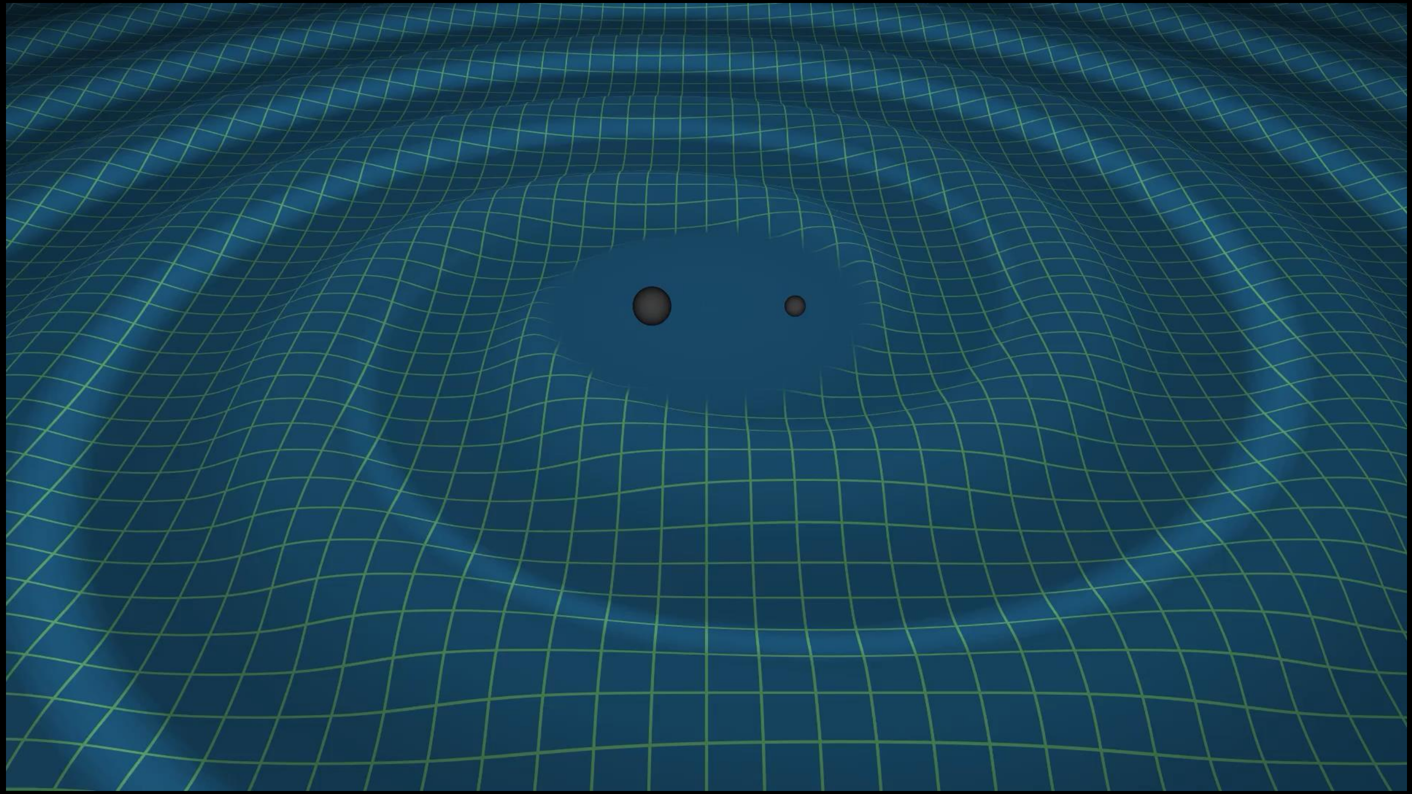




Characteristic shape of a gravitational wave of two colliding black holes

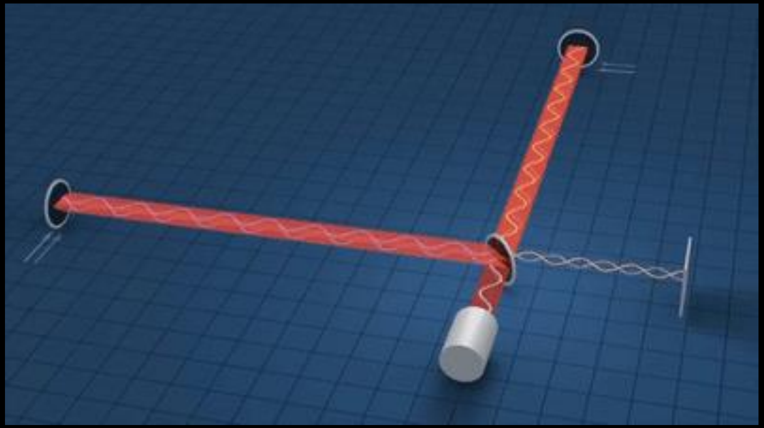
# What is a GW detector?

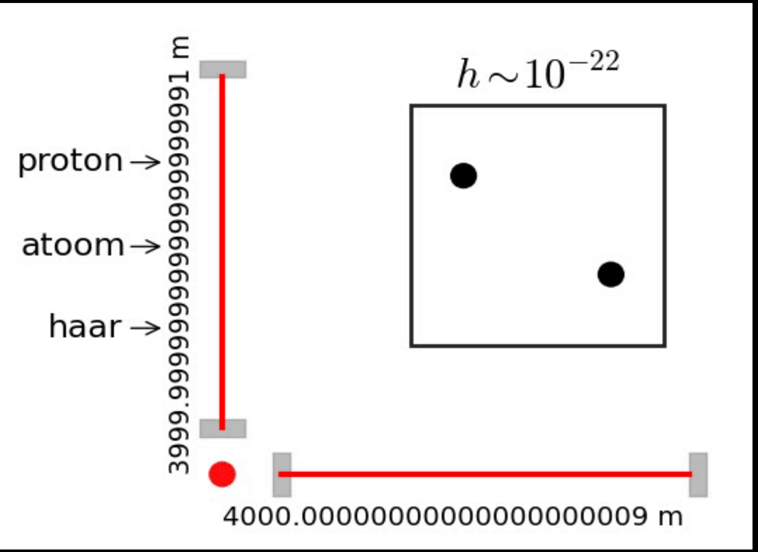




# What is a GW detector?






# ETO Engineering Department – Organisational Chart