EINSTEIN TELESCOPE

Einstein Telescope Research Infrastructure: Challenges and Long-Term Sustainability

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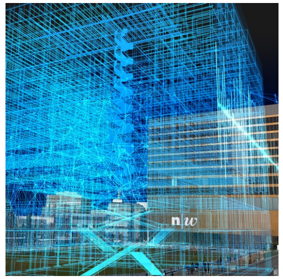

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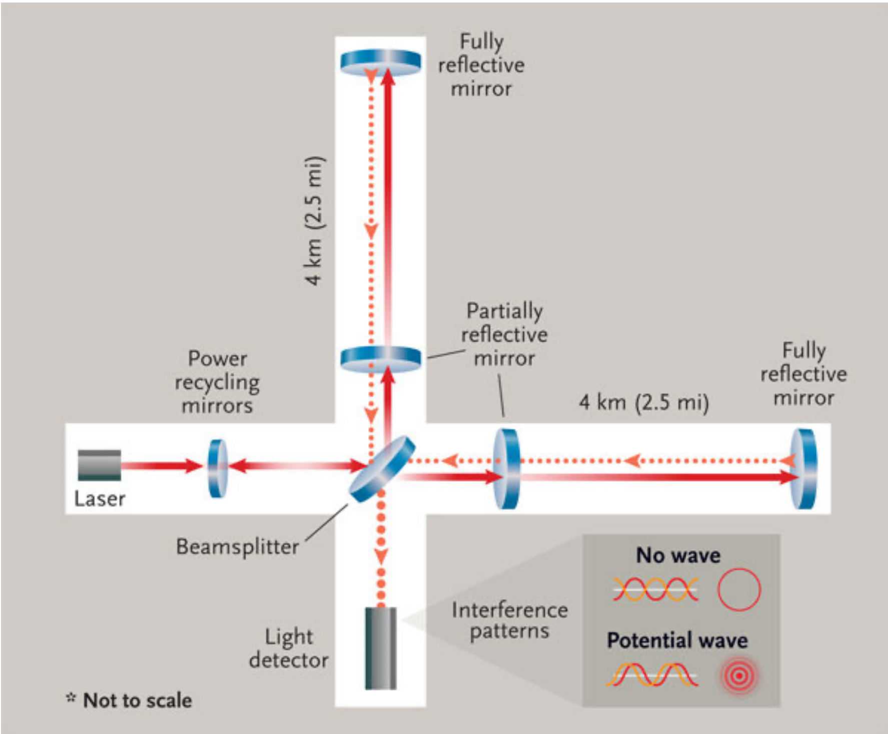
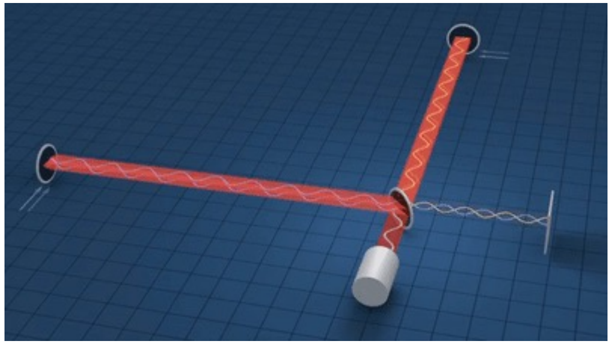
outline

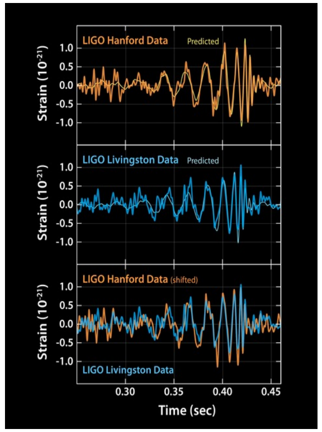
- GW research infrastructure (in the space, extended lenght and underground)
- Geometry and site selection
- Design challenges - noise sources and mitigation, safety, excavated volumes, interface with technological systems and requirements definitions
- Digital Modeling and Data-Driven approach for infrastructure multi-criteria design
- Developing a Sustainable Development Strategy for ET
- Timeline of the ET project

Detection of Gravitational Waves

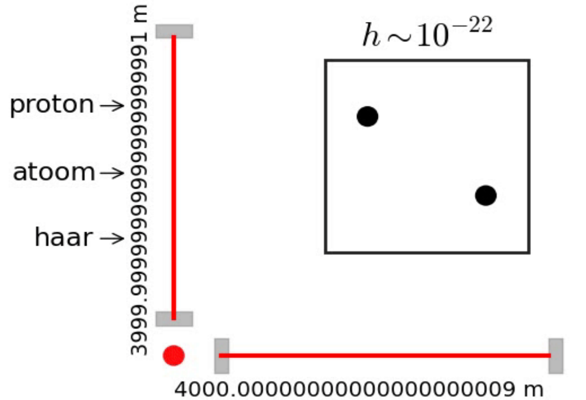




FIRST DECTECTION – GW150914
14 September 2015



$$h = \frac{\Delta L_1 - \Delta L_2}{L}$$



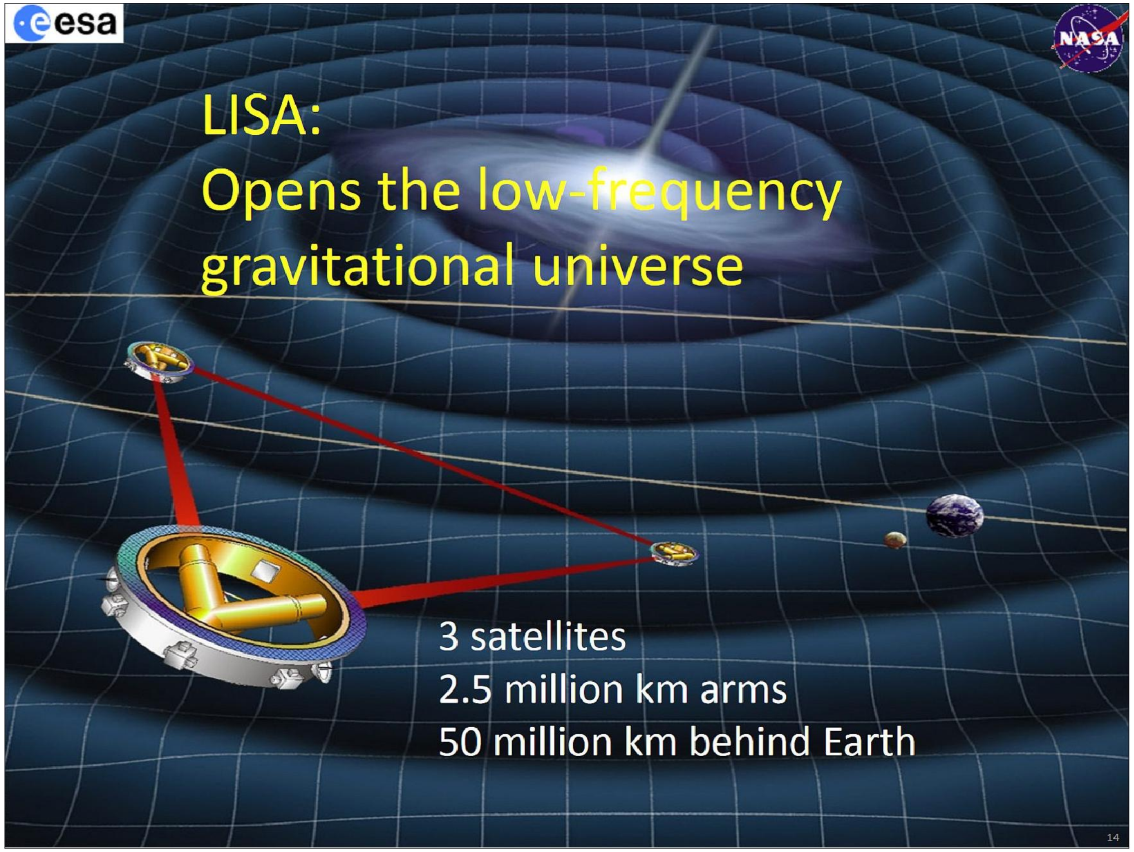
3G Gravitational Wave Detector future infrastructure = increased sensitivity

The mission

ESA's Laser Interferometer Space Antenna (LISA) will be the first space-based observatory dedicated to studying gravitational waves

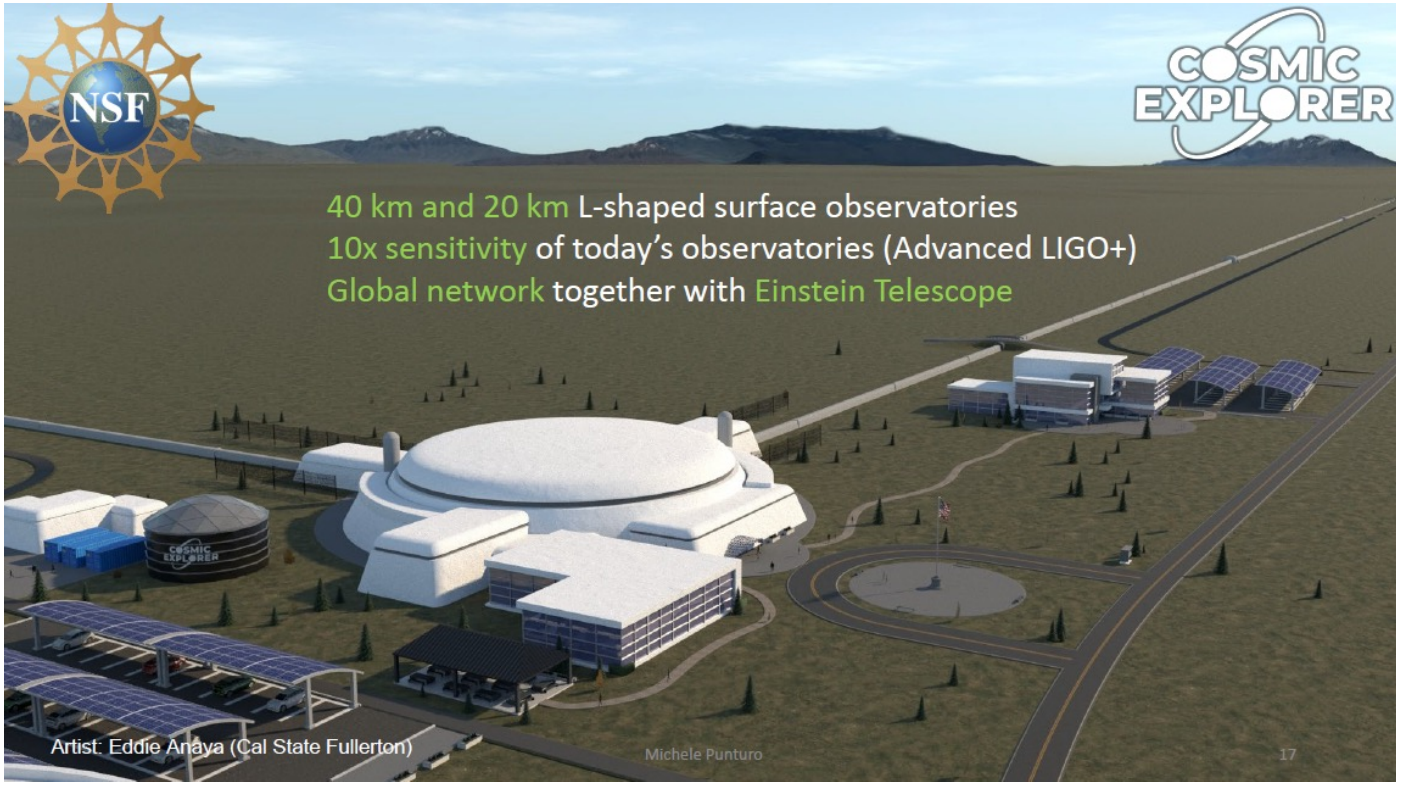
The launch

Launch: planned for 2035
Launch location: Europe's Spaceport in French Guiana
Launch vehicle: Ariane 6
Orbit: heliocentric: trailing or leading Earth



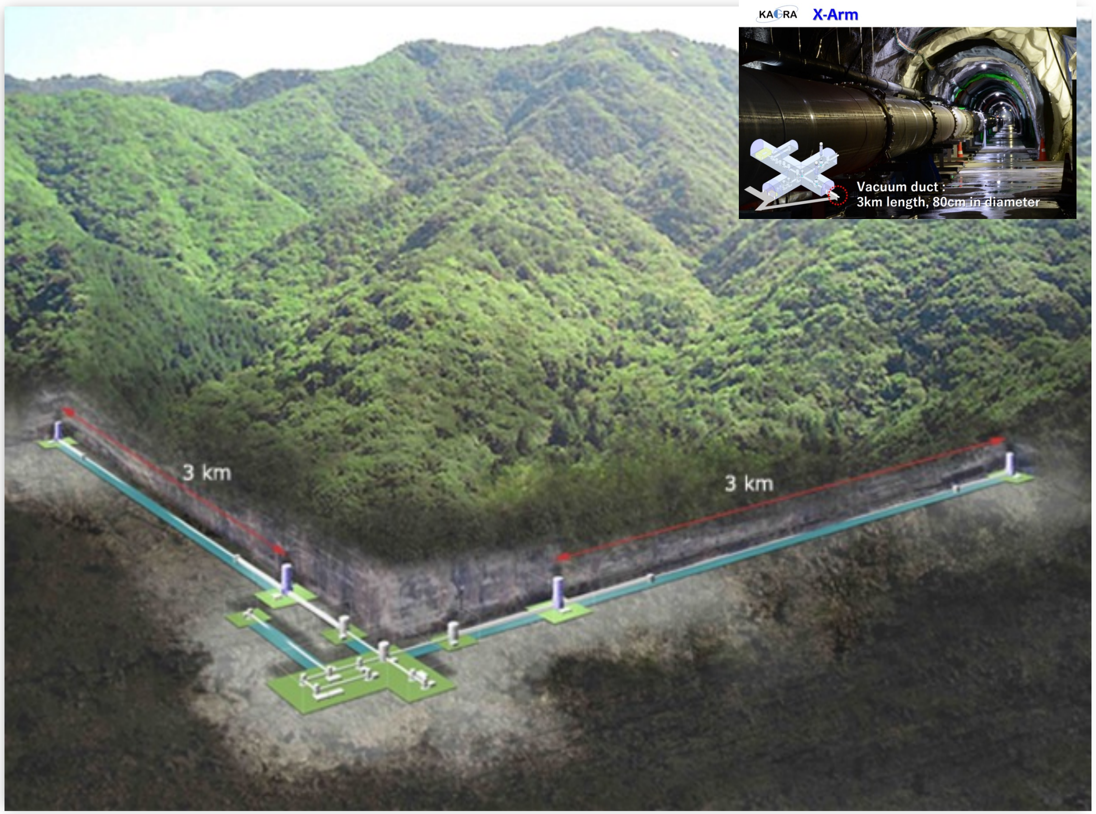
3G Gravitational Wave Detector future infrastructure = increased sensitivity

- Surface (proximal)
- Length off arms
- New technology (squeezing, cryogeny, environmental condition, monitoring, noise reduction, etc.

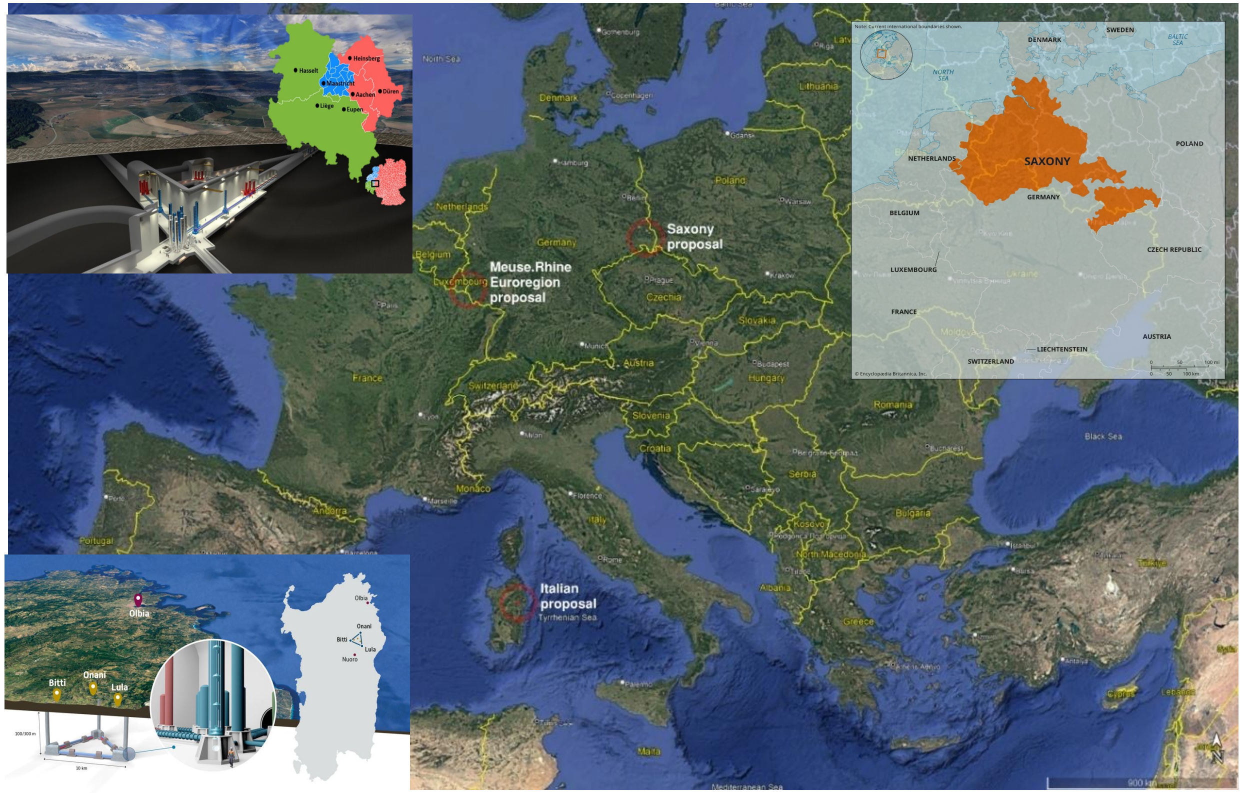


KAGRA (Kamioka Gravitational Wave Detector)

- **Overview of KAGRA Observatory**
  - Located in Japan, KAGRA is the fourth major gravitational wave detector globally, collaborating with LIGO (USA) and Virgo (Italy/Europe).
  - It is the first underground gravitational wave detector and utilizes cryogenic mirrors for enhanced performance.
- **Location and Infrastructure**
  - **Site**: Situated within the Kamioka mine, Gifu Prefecture, beneath Mount Ikenoyama.
  - **Underground Design**: Built over 200 meters below ground to minimize seismic interference.
  - **Structure**: Features a **3 km** long Michelson laser interferometer.
- **Technological Features**
  - **Cryogenics**: Sapphire test masses cooled to -250°C (20 Kelvin) to reduce thermal noise and improve sensitivity.
  - **Suspension Systems**: Advanced mechanisms to isolate mirrors from ground vibrations.
  - **Interferometer Design**: Incorporates a "dual-recycling Fabry-Perot Michelson" configuration for precision detection.



The 3 candidate sites for ET in Europe – 1 Triangle or 2L scenario



- The Italian government supports the candidacy of the area surrounding **Sos Enattos mine**, an existing minerary site in Sardinia, located in the Province of Nuoro between the municipalities of Bitti, Lula and Onanì.
- **Meuse-Rhine Euroregion (EMR)** a rural area between Maastricht, Liège and Aachen is the second candidate. For this proposal, the area being analysed as a potential site lies between the three Belgian localities of Asse, Hoof and Beusdael.
- The government of Saxony (Germany) has proposed the third candidate site in **the Lusatia region of Saxony** a rural zone between the localities of Wittichenau, Kamenz, Crostwitz and Doberschütz.

Challenges for a sustainable Implementation of ET

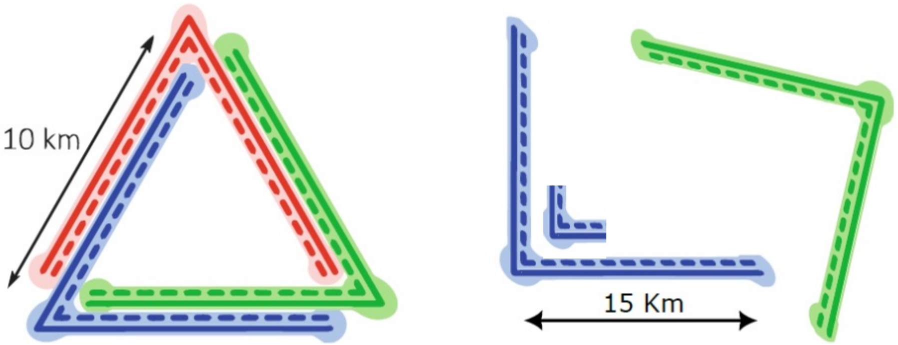
It is an underground infrastructure (second only to KAGRA in Japan).

Geometry and characteristics are still under definition, with many assumptions currently in place.

Ongoing activity include site selection and geometry definition, with a strong focus on sustainability considerations.

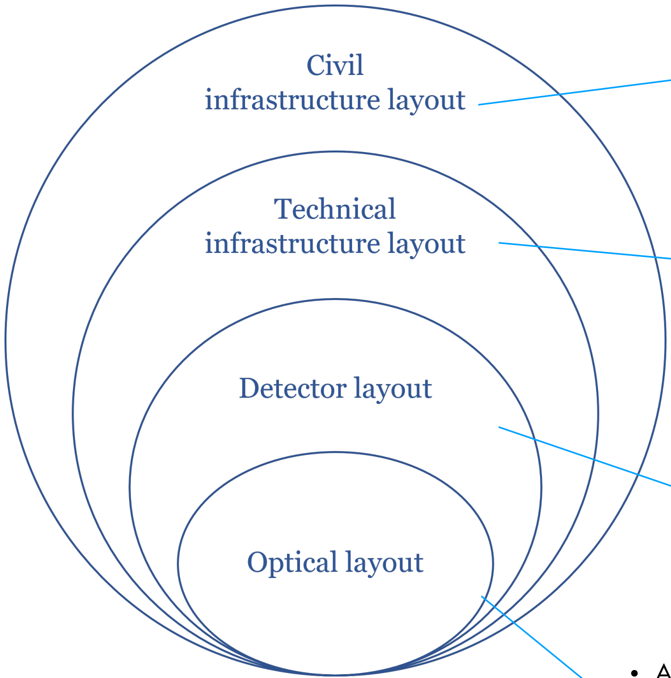
Preparatory phase of ESFRI roadmap - pre-feasibility studies managed by candidate sites to prepare technical and economic proposal for candidacy(Bid)

VIRGO GW Site – Cascina (Pisa) – EGO



Breakdown of ET underground research infrastructure

a collaborative effort between ETC, ETO-ED,CERN

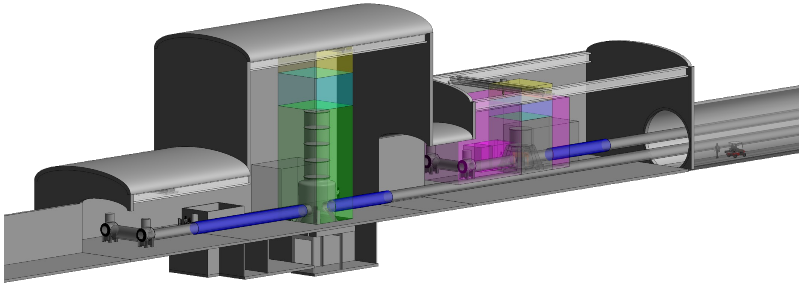


- TBM Tunnel (main arms)
- Caverns
- Access shafts/tunnels
- Emergency exits, etc.

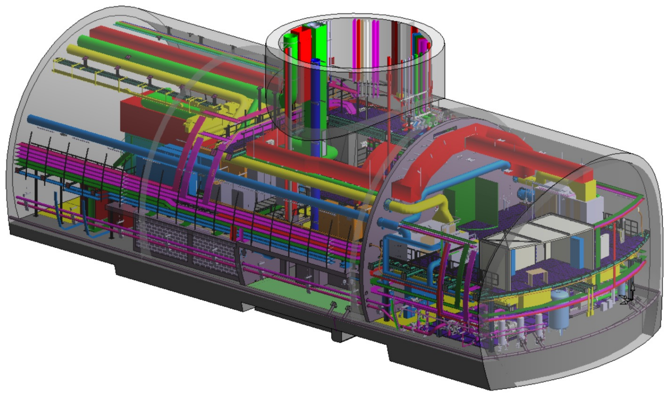
- Mechanical systems
- Cooling & ventilation,
- Electrical systems,
- Safety systems,
- Logistics

- Tower base, suspensions, tower envelopes,
- Scaffolding,
- Clean rooms,
- Auxiliary benches,
- Beampipes
- Logistics

- Arm cavities + recycling cavities
- Laser, injection, detection, squeezing



"caverns" and "tunnels" not final



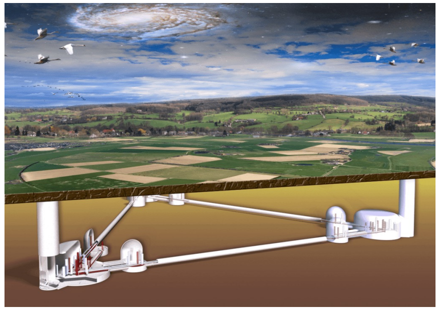
See Talk Sorrentino-Rocchi– Session IV)

Note: Conceptual drawing. Dimensions subject to change
Volumes estimated using simplified civil engineering criteria

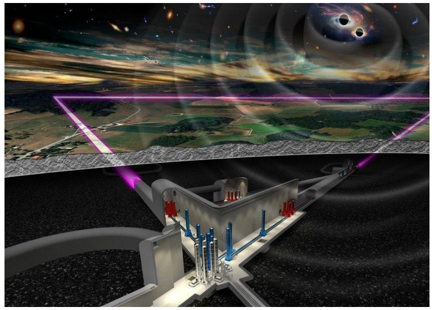
Source ED-ETO (J. Bratanata) -Web viewable 3D Detector Layout(s): https://wiki.et-gw.eu/ED/WebHome

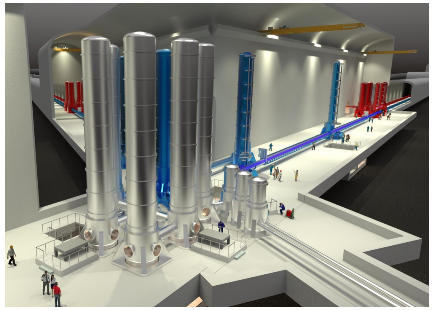
ET design implementation history

2011

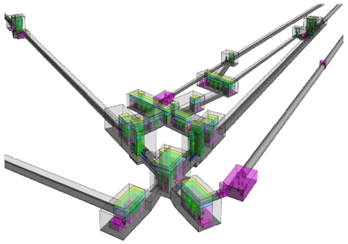


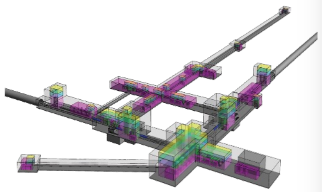
2019 - ESFRI Roadmap



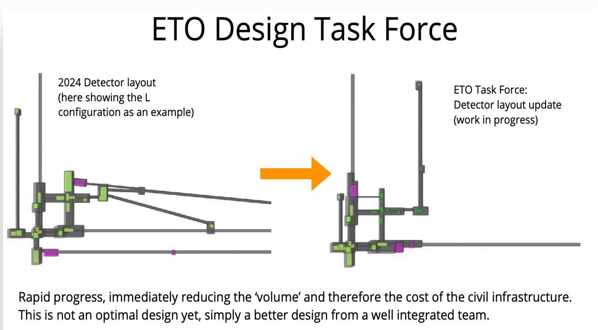


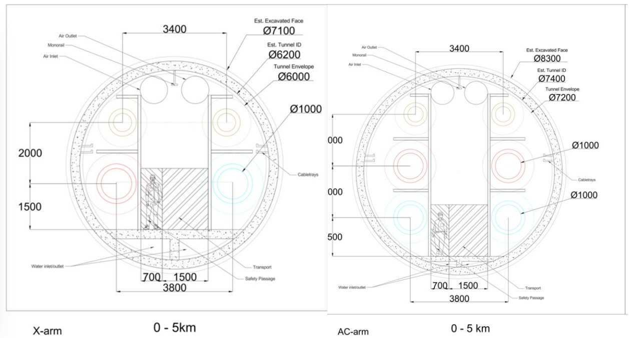
2025 Design Task Force optical & detector baseline layout update





Web accessible 2D (.dwg) 3D (.rvt) Detector Layouts

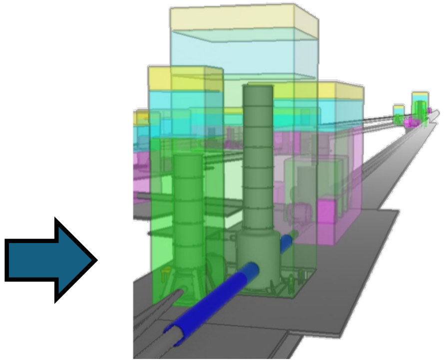


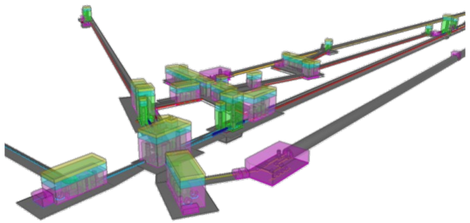


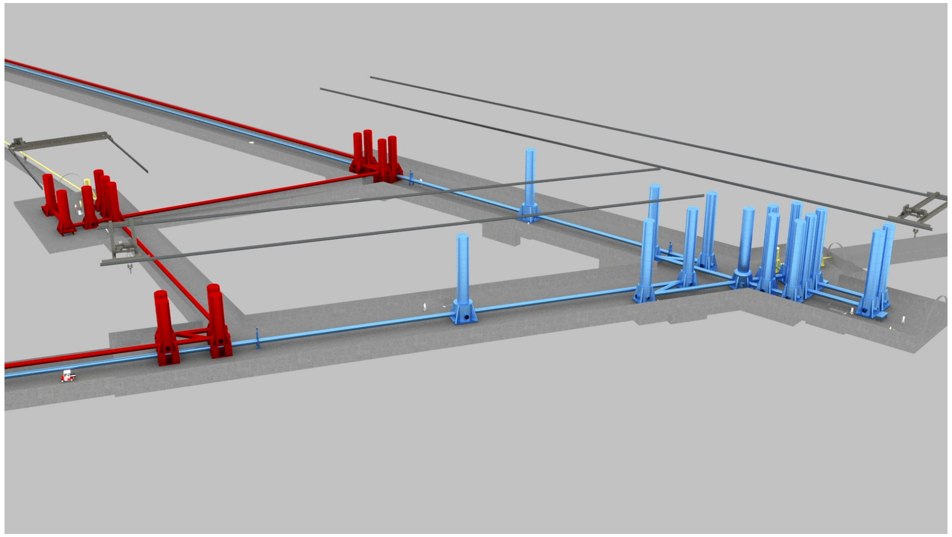
Source ETO- ED

ETO-Civil Engineering activity in support of taskforce

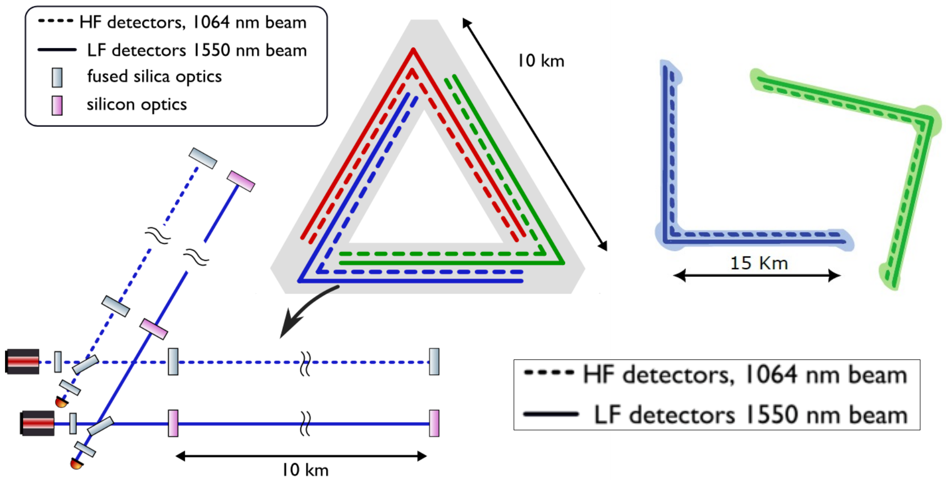
- Organize the discussion on alternative detector layout regarding civil engineering specifications
- Support the consideration on non-site dependent design and cost assessment to be agreed among the stakeholders
- Provide tools for sharing the 3model and analyzed following the criteria identified



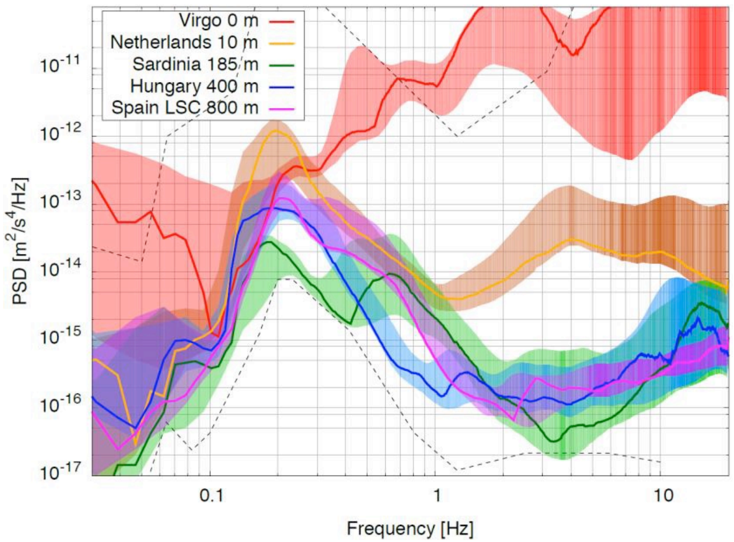




Challenges for underground 3G infrastructure - noise sources and mitigation



Xylophone: 2 different systems working together



- **Arm length** is the first improving factor for improving detection
- Sensitivity would be limited by **Newtonian noise** below about 40 Hz if built on the Earth's surface in a seismic virgo-like noise environment
- **NN** produced by fluctuating gravitational forces caused by moving masses (natural, anthropic sources)
- hundreds of design and material parameters contribute to the sensitivity curves
- **Quantum noise** is a matter of the optical system (squeezing, buffer, cleaner etc.) NN of infrastructure design

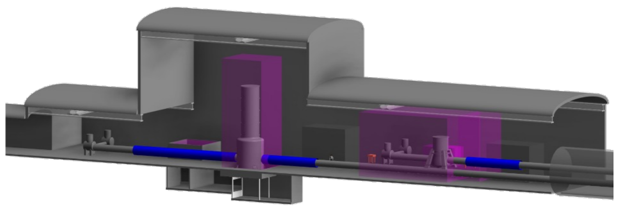
Source ETO- ED

Challenges for underground 3G infrastructure - noise sources and mitigation

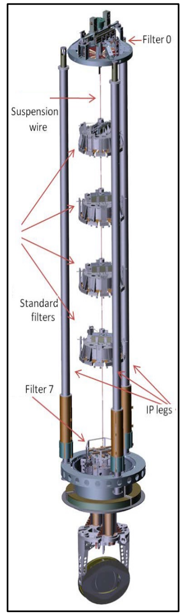
- Active and passive vibration isolation systems are used to suppress seismic noise
- Newtonian noise (gravity gradients) acts directly on test masses (main mirrors) and limits sensitivity at low frequency
- ~250 m depth to reach sensitivity (geology/site dependent)

Seismic isolation system, ETpathfinder (Maastricht)

VIRGO (Pisa; surface)



Passive vibration isolation system → Inverted pendulum concept



Source ETO- ED

Challenges for underground 3G infrastructure - safety strategy (preliminary)

The safety concept will be designed for the high-occupancy detector installation phase, not the low-occupancy maintenance phase (CERN and ETO)

Corner Stations:
- Specialized teams: 10 x 4p = 40 persons for each corner station
- Dedicated ET personnel: 10 persons
- Cleaning personnel: 10 persons
- Visitors: optional – not a priority

Total: 60p * 1.5 = **90 persons**

End Stations:
- Specialized teams: 1 x 4p = 4 persons for each end station
- Dedicated ET personnel: 2 persons
- Cleaning personnel: 2 persons

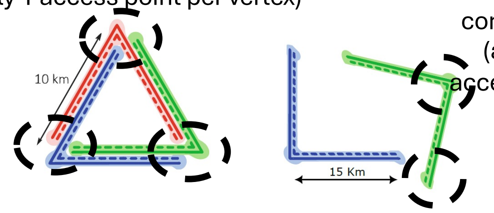
Total: 8p * 1.5 = **12 persons**

10-15km Tunnels:
- Specialized teams: 2 x 4p = 8 persons **
- Dedicated ET personnel: 2 persons
- Cleaning personnel: 2 persons

Total: 12p * 1.5 = **18 persons for each tunnel halve**

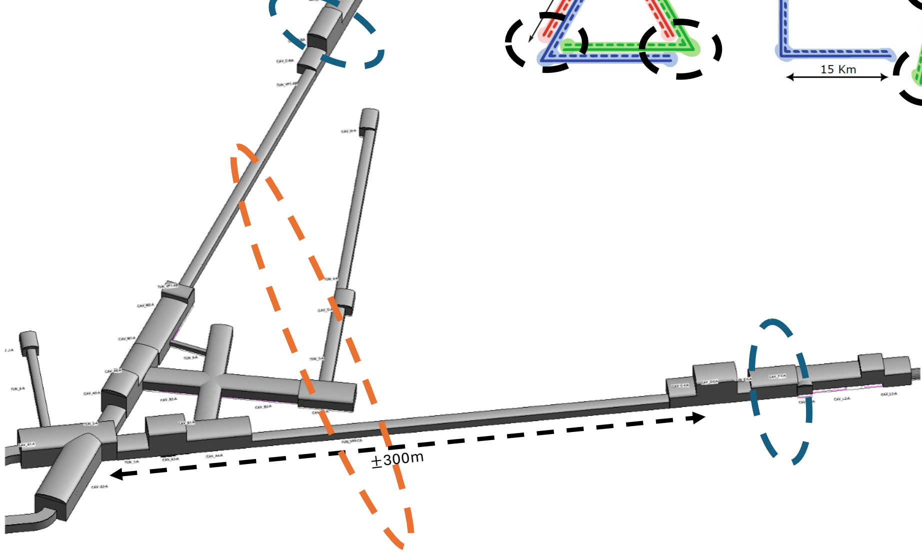
Total personnel in worst case evacuation scenario:

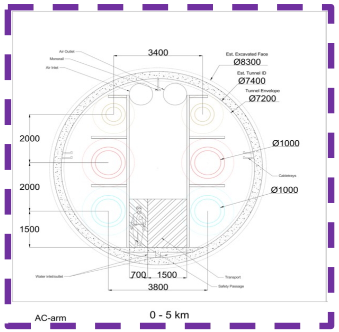
Triangle: 150 personnel per vertex of the triangle (assuming only 1 access point per vertex)



2L: 126 personnel at corner of the triangle (assuming only 1 access point per point)

2L: 30 personnel at end of the 15km arms





Source ETO- ED

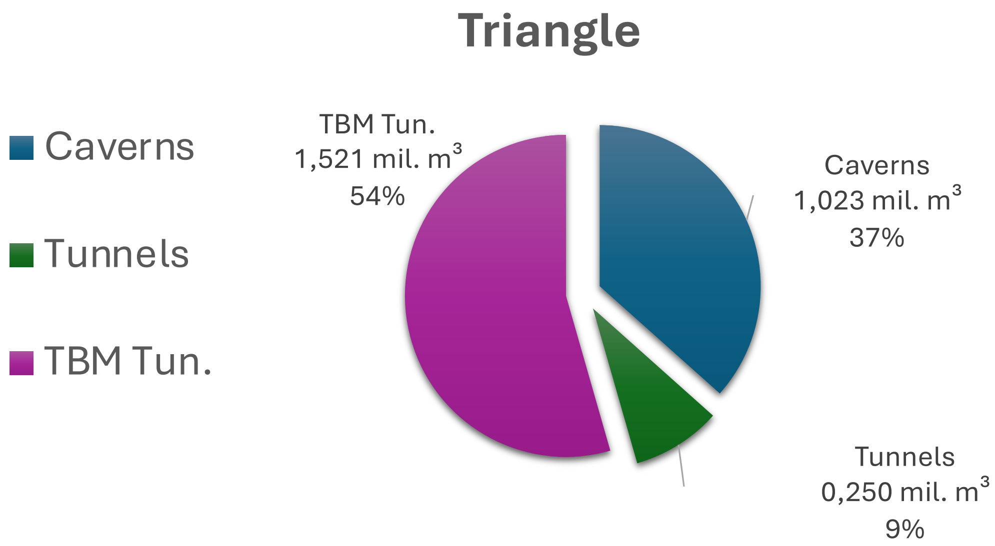
Estimated Excavation Volumes – 2025 Layout (main caverns & tunnels only)

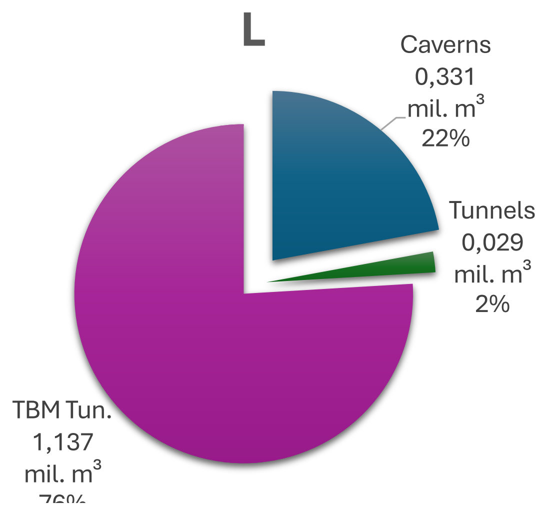
Triangle Configuration

- TBM tunnels: ~54.4% of total excavation volume→ Large component, but proportionally smaller than in L configuration
- Caverns: ~36.6% of total→ ~3× larger than L layout due to 6 interferometers (vs. 2)

L Configuration

- TBM tunnels: ~75.9% of total volume→ Indicates a tunnel-dominant layout, focused on 15 km arms (x2 for 2 sites)
- Caverns: ~22.1%→ Simpler/compact central infrastructure→ But still requires 3 feasible geological sites for corner station & end stations
- Non-TBM tunnels: ~2.0%→ Minimal auxiliary connections; simpler layout



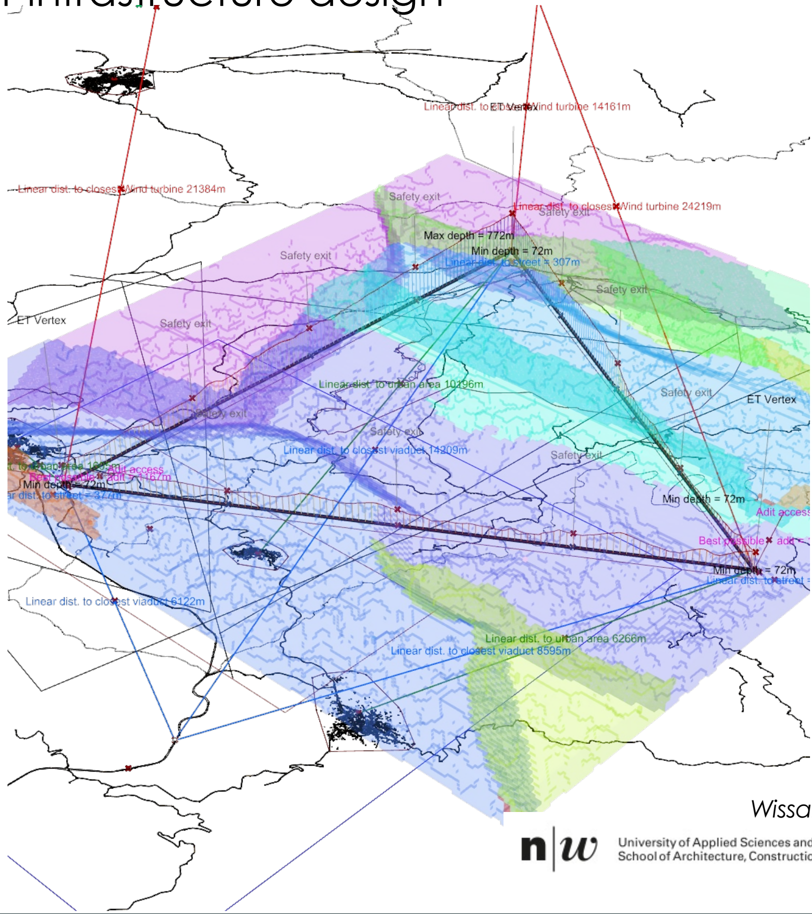


Courtesy of J. Bratanata - ETO Task Force Doc

Source ETO- ED

Digital Modeling and Data-Driven approach for infrastructure design

- A data-driven methodology uses **measured, simulated, and historical data** to:
- Define objective functions (cost, carbon, risk, resilience, energy use)
- Quantify constraints (geology, regulations, land use, capacity)
- Evaluate multiple design scenarios
- Select optimal solutions based on measurable criteria
- Rather than optimizing only for cost, modern infrastructure optimization integrates:
- Economic performance
- Environmental impact (CO_2, material use, water impact)
- Social and operational resilience



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University of Applied Sciences and Arts Northwestern Switzerland
School of Architecture, Construction and Geomatics

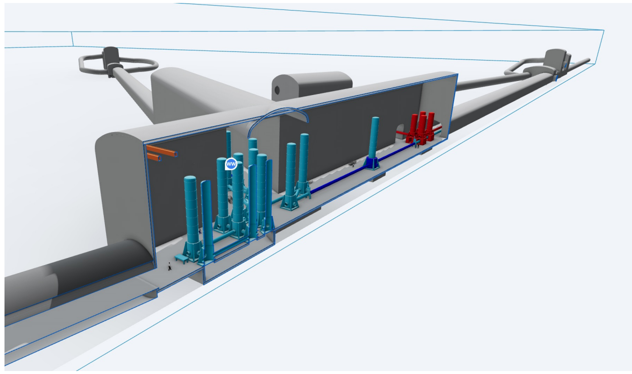
Digital Modeling and Data-Driven approach for infrastructure design

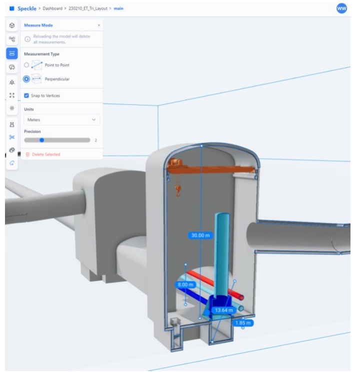
Types of Data

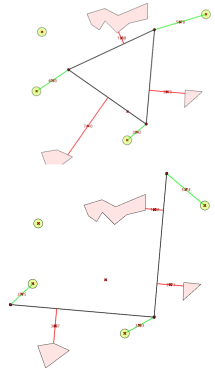
Design & Planning
Construction
Monitoring & Operational
Environmental Data

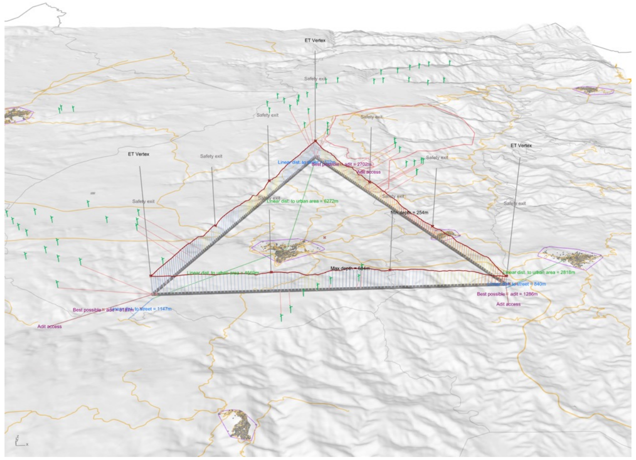
Methodological Approaches

Parametric Optimization
Probabilistic & Risk-Based Models
BIM–GIS Integration
Multi-Criteria Decision Analysis (MCDA)
Digital Twins

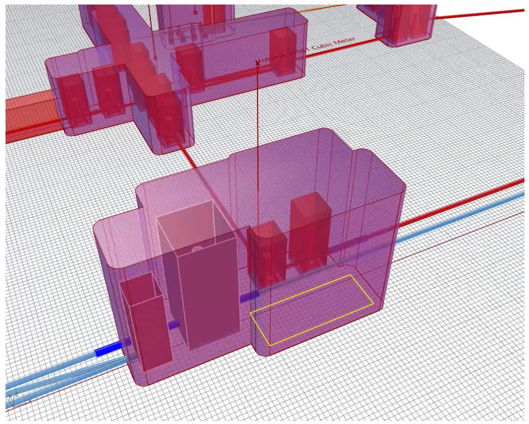








assessments of placement situations

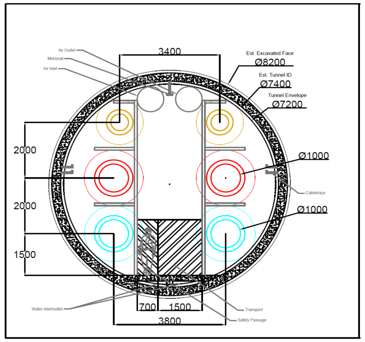


Estimating quantiites /costs layout variables.

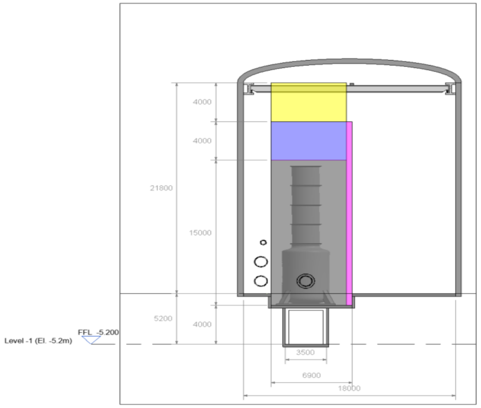
Wissam Wahbeh

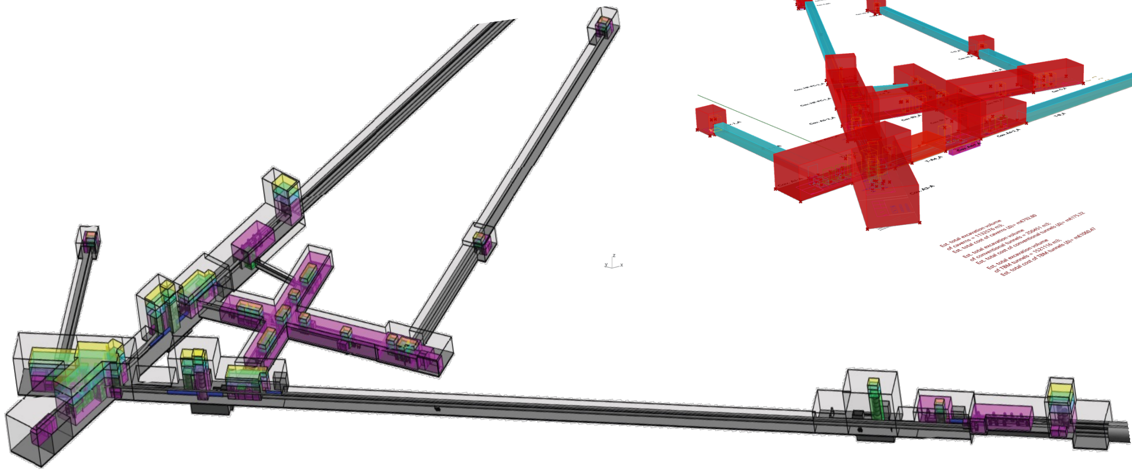
n|w University of Applied Sciences and Arts Northwestern Switzerland
School of Architecture, Construction and Geomatics

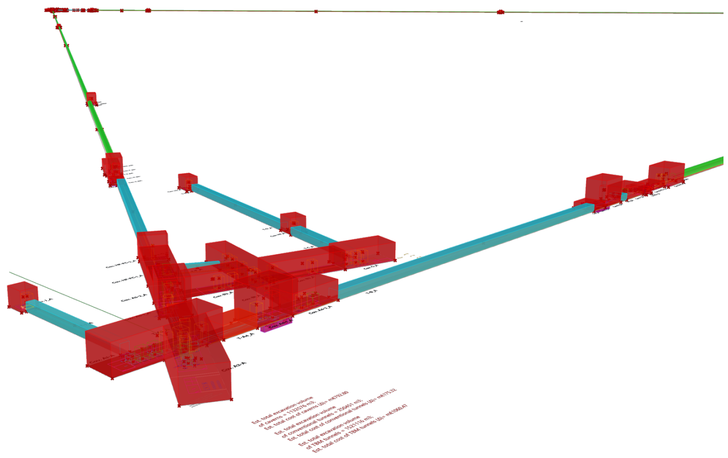
Functional Volumes and multi-criteria approach



AC-arm 0 - 5 km







See Talk Sorrentino-Rocchi– Session IV)

Note: Conceptual drawing. Dimensions subject to change
Volumes estimated using simplified civil engineering criteria

Source ED-ETO (J. Bratanata) -Web viewable 3D Detector Layout(s): https://wiki.et-gw.eu/ED/WebHome

Next steps for ET ESFRI roadmap – Focus on Engineering targets

Design and Preparation- Phase 1

- Preparing preliminary design documents for the detector and the infrastructure.
- Providing all the necessary documents for an approval of ET and a decision of the site(s).
- Engineering preparation for Phase 2

End of 2027

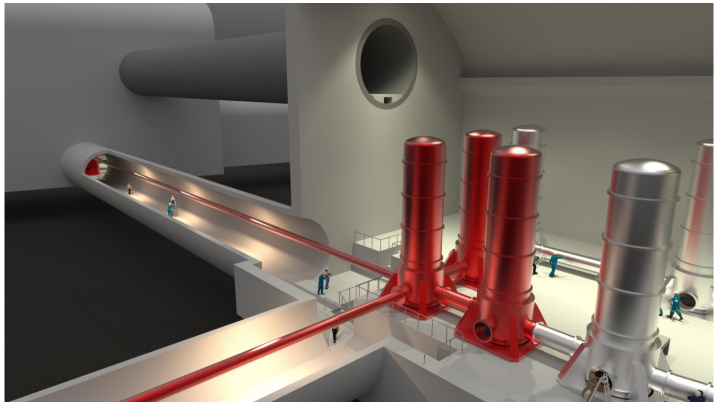
Design and Preparation Phase 2

- Mature preliminary designs of the chosen site(s), complete the site preparation work, and detailed design
- Create legal entity to oversee construction and operation.

Implementation Phase

- Construction of the infrastructure and installation + commissioning of the detectors

Operation Phase



The Geometry Comparison Report (GCR) – ETO mandate

- ET Technical Design Reports for the detector, the technical infrastructures and civil engineering;
- costing and financial methodologies towards the bid books;
- cost estimate of the instrument for both geometries;
- manage stakeholder interfaces with the ET Collaboration and the Host Consortia,
- support the ET Coordinators and the BGR for external communication and relations.

ETO is asked to provide, for September 2026, a report on the geometry comparison, considering five site independent drivers. This report is based on five main topics:

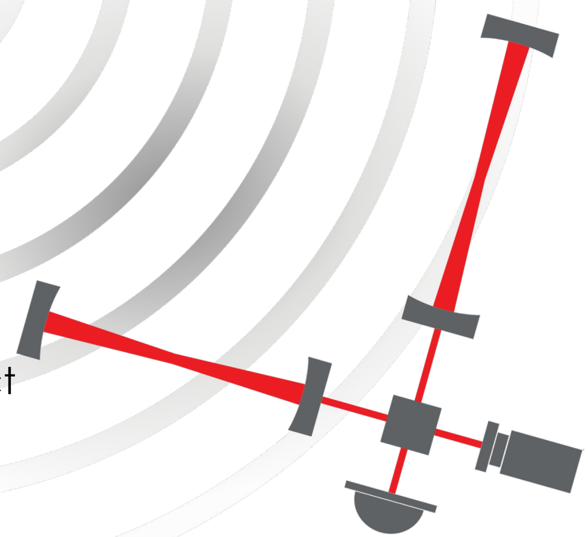
1) The scientific added value

2) The cost estimate

3) The risks assessment

4) The governance

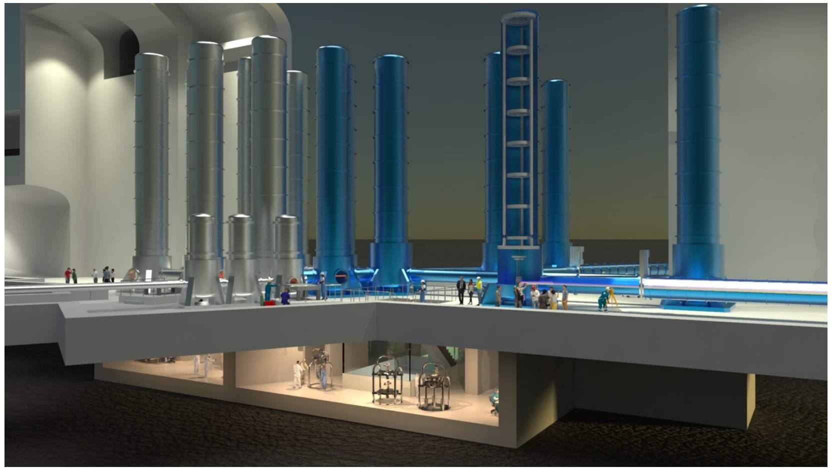
5) The socio-economic impact



Developing a Sustainable Development Strategy for ET

The Einstein Telescope (ET) is a proposed underground gravitational wave observatory that aims to detect gravitational waves with unprecedented sensitivity. While the project holds great promise for advancing our understanding of the universe, it faces several sustainability challenges:

- Environmental Impact Assessment
- Efficient Resource Management
- Waste Generation
- Community Engagement
- Long-term Sustainability Planning
- Climate Change Resilience



The development of comprehensive sustainability strategy is a priority for ET to contribute to scientific advancements while minimizing its environmental and carbon footprint.

Sustainable Development Implementation Strategy - Opportunities

Addressing the path toward sustainability is crucial and can be prioritized proactively rather than reactively.

It can serve as a guide for decision-making in various areas.

An iterative process is being conducted to determine the technologies to be used, sizing, geometry, financial aspects, and environmental impact.

We are in a preparatory phase (ESFRI roadmap), which involves pre-feasibility studies managed by candidate sites as part of the preparation of the technical and economic proposal for candidacy.

ET Sustainable Development Strategy - Reports

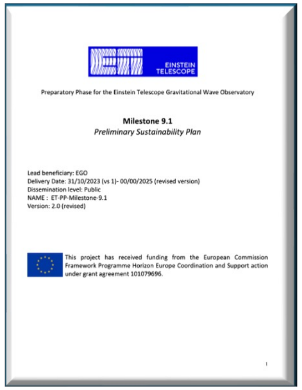
ET Environmental impact assessment and mitigation strategy

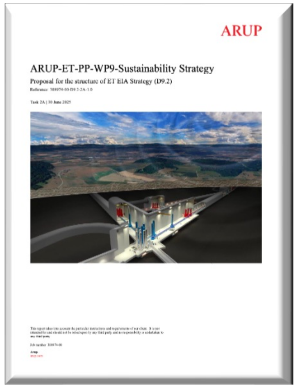
- Scoping and Baseline Assessment
- Alternatives and Mitigation
- Public Participation and Transparency
- Monitoring and follow-up

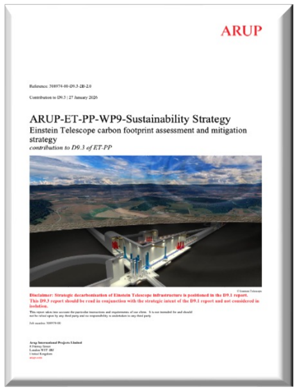
ET CO2 footprint ET assessment and mitigation strategy

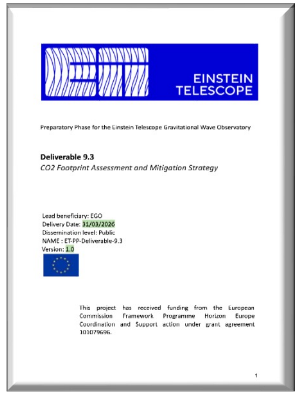
- Compute the key Carbon and Environmental Impacts
- Findings and Mitigation Strategies
- Highlight the most critical insights and recommendations for decision-makers

ET-PP WP9 Sustainable Development Strategy team









Environmental Impact Assessment (EIA) - Workplan

Define Sustainability Strategy with environmental, social, and economic themes

Establish **Baseline conditions** using site-specific data (air, water, soil, noise, biodiversity, etc.)

Conduct detailed **Impact assessments** for both construction and operational phases

Develop and implement **Strategic KPIs** (for site comparison) and **Specific KPIs** (for mitigation & performance tracking)

Identify and evaluate **Alternatives and Mitigation Measures** across EIA themes

Analyse and define an overall strategy for reclamation, reuse and recycling of excavated materials

Strategic Priorities:

- Early identification of sensitive receptors (ecological, human)
- Alignment with EU/ISO guidelines (e.g., ISO 14001, WFD, Natura 2000)

Key Priorities

Energy (demand, supply, efficiency, renewables)

Air Quality (pollutants, receptors, modelling)

Climate Change (mitigation, adaptation, emissions)

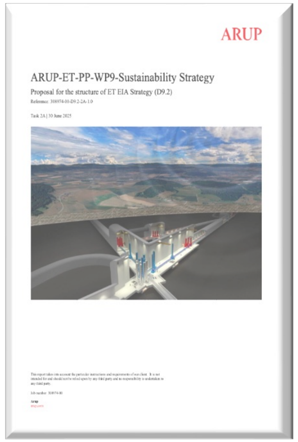
Soil & Land Use

Water (use, quality)

Biodiversity (habitats, species, connectivity)

Materials & Waste

Human Health and Socio-Economic Factors


ARUP

ARUP-ET-PP-WP9-Sustainability Strategy

Proposal for the structure of ET EIA Strategy (D9.2)

Excavation technologies

- geometric, hydrogeological and geotechnical characteristics
- assessment of the risks and mitigation solutions
- performance vs technologies

Mechanized excavation: TBM tunnel and RB shafts

- Open or Shielded tunnel boring machine
- Number of boring machine (time and cost estimation)
- Study the interference with local tunnel enlargement (service cavern, emergency exit)

Drilling and blasting (D&B) works (tunnels, accesses, cavern)

- Preliminary geotechnical stability
- Excavation
- Supports system (bolts, shotcrete, etc.)
- Concrete and reinforcements
- Waterproof system
- Finishing

Reclamation, Reuse and Recycling of the excavated rocks&soils

Technical

Tunnel advance method, -length, -diameter
Site organisation
Material yield parameters
Material analysis
Processing technology

Geological

Geological situation
Chemistry/ mineralogy/ strength properties of excavated materials
Customer specifications
Processability

Legal

Ownership
Waste law
End of waste character

Economic

Supply and demand
Raw material price vs. landfilling costs
Transport route/ -range to customers / landfills


EINSTEIN TELESCOPE

Preparatory Phase for the Einstein Telescope Gravitational Wave Observatory

Deliverable 9.2. Annex I

Management of Excavated Materials

Lead beneficiary: Montanuniversität Leoben (MUL)
Delivery Date: Nov. 2025
Dissemination level: internal
NAME : ET-PP-Deliverable-D9.2. Annex 1
Version: 1.2

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ET High-level carbon assessment of civil engineering components

Goal

- Determine a high-level whole life carbon assessment for the major components of the civil infrastructure of 2 ET configurations (triangle and L-shape).
- The carbon footprints will be used as a baseline before more granular and site-specific carbon assessments are undertaken by the design teams.

Scope and system boundaries

- Top-down carbon assessment of the civil infrastructure of 2 configurations (triangle and L-shape)
- The carbon benchmarks/factors/LCA assumptions are not site specific.
- Whole life carbon assessment including construction, maintenance, operation, and end of life.

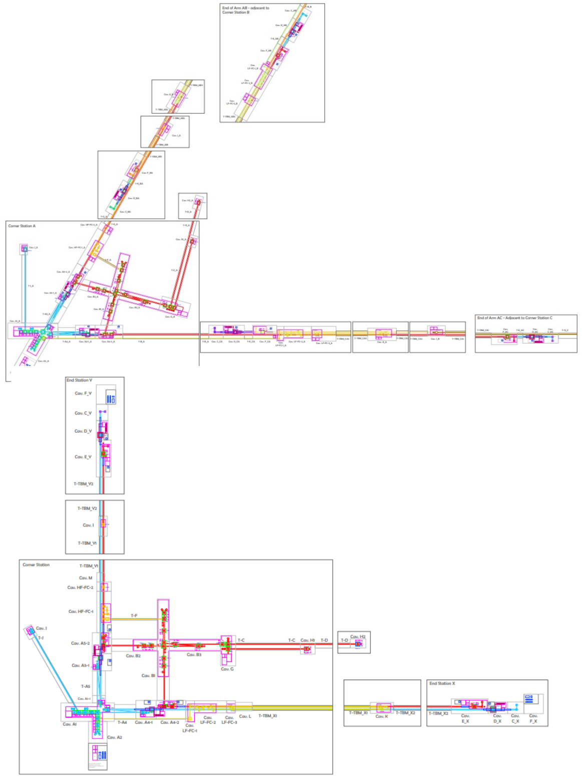
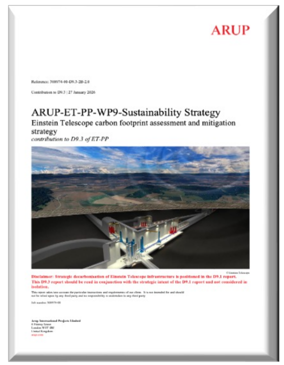


Figure 61: Element Names - L (retrieved from **TD.2**)



Carbon Footprint Assessment Data Needs & Importance (preliminary)

- ✓ Baseline Data Requirements
- ✓ Importance of High-Quality Data
- ✓ Data Collection Gaps

Civil engineering components of the ET infrastructure (for both the triangular and 2L-shaped layouts):

- Conventional tunnels
- TBM (tunnel boring machine) tunnels
- Shafts (access tunnels)
- Caverns
- Excavated material from construction of underground infrastructure
- Surface buildings, including basic MEP (Mechanical, Electrical, Plumbing) services
- Operational energy use of the whole ET facility
- Operational water use of the whole ET facility

Scientific infrastructure components of the ET infrastructure (for both the triangular and 2L-shaped layouts):

- Interferometer (including Optics)
- Noise Mitigation (including Sensors)
- Suspension Systems
- Vacuum Systems
- Cryogenics Systems

ET CO2 footprint ET assessment and mitigation strategy - Workplan

TASKS

1. CARBON ASSESSMENT AND MITIGATION STRATEGY

2. HIGH-LEVEL CARBON ASSESSMENT OF CIVIL ENGINEERING COMPONENTS

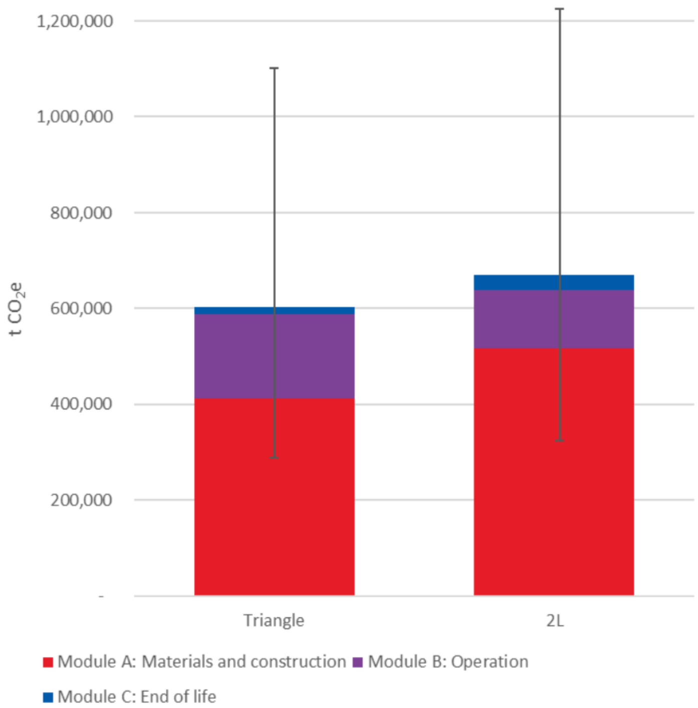
KEY OUTCOMES

1. Carbon assessment and mitigation strategy	2. High-level carbon assessment of civil engineering components
Methodology for carbon assessment	Carbon quantification for major civil infrastructure components
Carbon management and governance in the project	Main carbon hotspots
List of options for mitigation opportunities	Main mitigation opportunities

Typical KPIs for baseline pre-assessment related to energy.
With available benchmarks from EU standards and best practices or comparable projects.

KPI	Unit	Purpose	Benchmark
Presence of energy infrastructure	Yes/No	Assess site readiness	N.A.
Accessibility of power lines	Distance	Assess site readiness	N.A.
Available connection capacity	MW	Assess site readiness	N.A.
Share of renewable energy in grid mix	%	Evaluate sustainability of supply	CERN uses French grid (low-carbon mix)
Possibility of local production from renewables (PV, wind, on-site cogeneration)	Yes/No	Identify on-site generation potential	N.A.
Energy reuse potential (e.g., heat recovery)	% of waste heat	Identify circular opportunities	CERN reuses LHC cooling water for district heating
Proximity of the site to centres of thermal demand	Yes/No	Identify circular opportunities	N.A.
Capacity of the local network to absorb recovered heat	Yes/No	Assess site readiness	N.A.

Baseline Whole Life Carbon Assessment – preliminary assessment



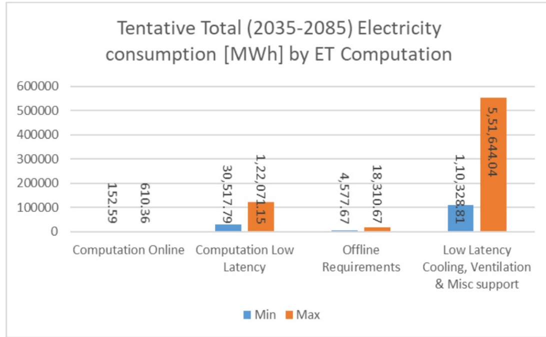
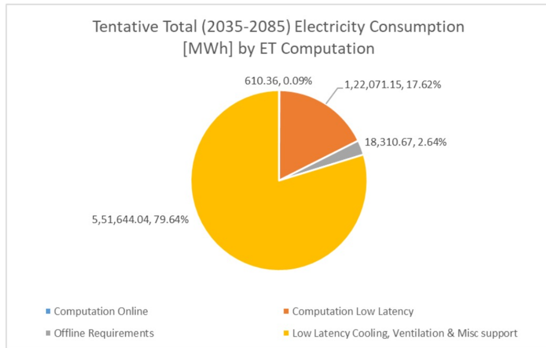


Figure 52: Tentative total (2035-2085) Electricity consumption by ET Computation

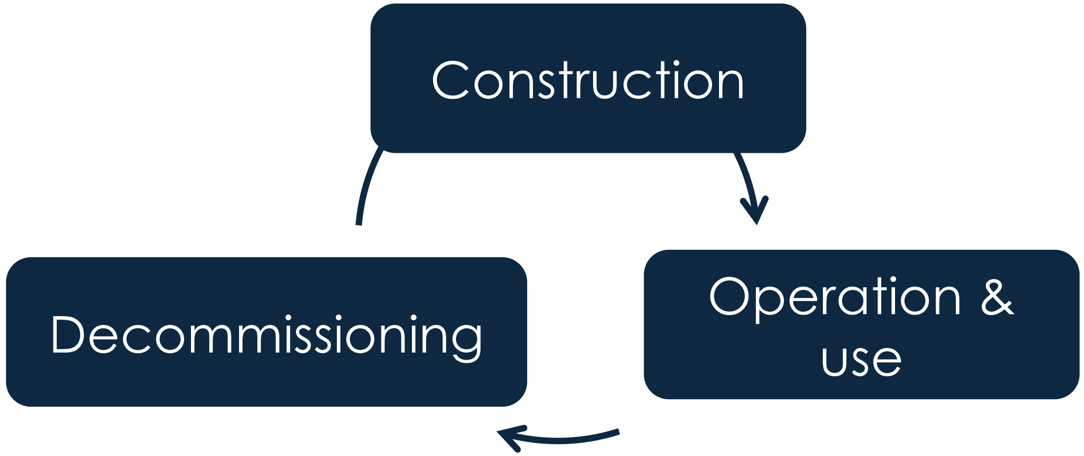


capital and operational carbon impacts of ET underground and surface infrastructure,including uncertainty

Life cycle assessment (LCA)

- LCA in the design phase provides a systematic evaluation of the environmental impacts across entire lifecycle of an infrastructure

- enables project teams to compare proposed construction options, identify critiscis, opportunities and mitigation actions



By integrating this assessment early in the decision-making process, organizations can make more informed, sustainable choices that improve overall performance and support long-term environmental goals.

Key Steps for the Life Cycle Assessment Task during ET Phases

Einstein Telescope`s carbon journey

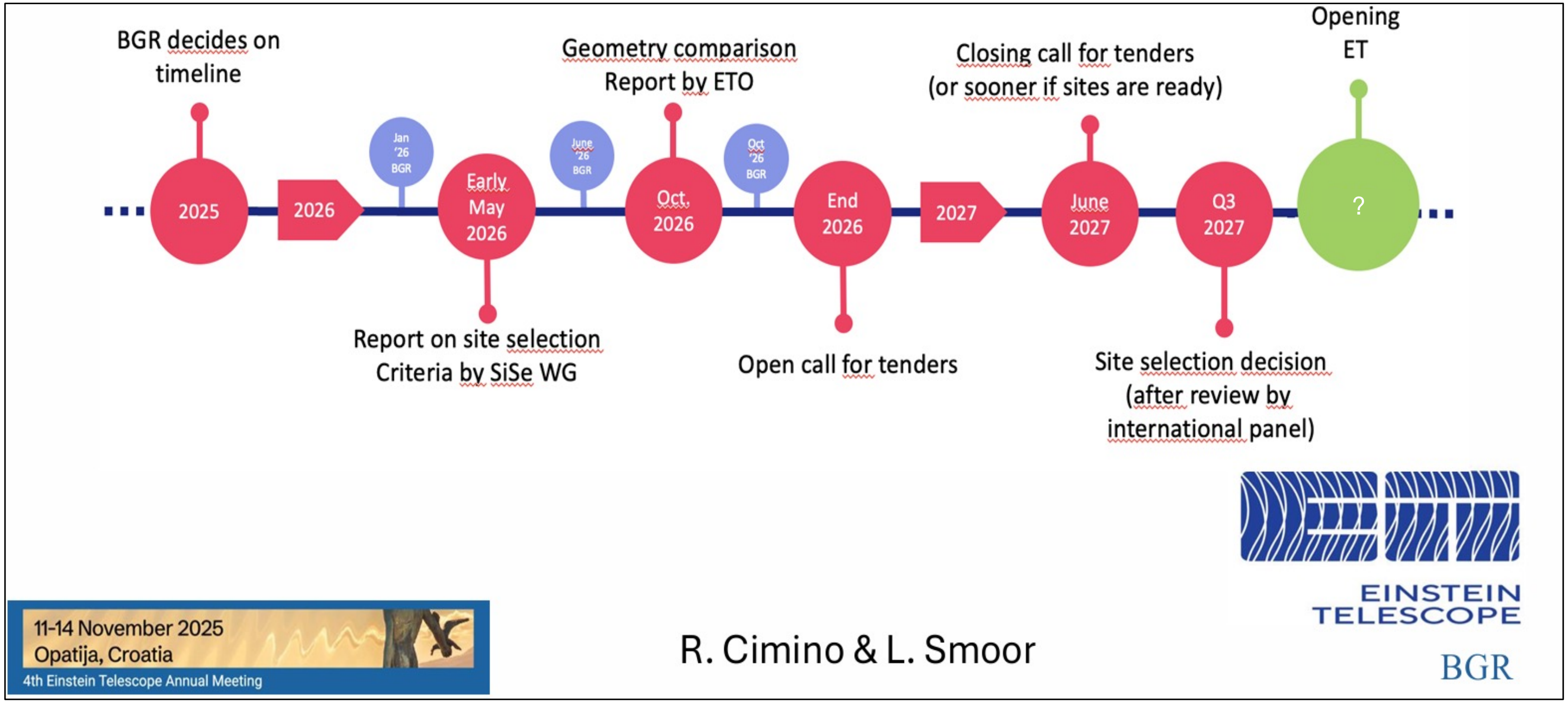
ET Preparatory Phase

1. Define project alternatives
2. Define carbon budget/ targets
3. Define data collection strategy
4. Baseline assessment: quantify carbon on existing design
5. Identify carbon hotspots
6. Benchmark project performance against industry standards and similar projects

ET Construction Phase

7. Identify carbon mitigation strategies
8. Develop scenario analysis
9. Select carbon mitigation solutions
10. Develop project specifications to include carbon mitigation solutions
11. Adopt carbon mitigation strategies and solutions in project construction
12. Update of LCA calculations with as-built data

The "ET project timeline"



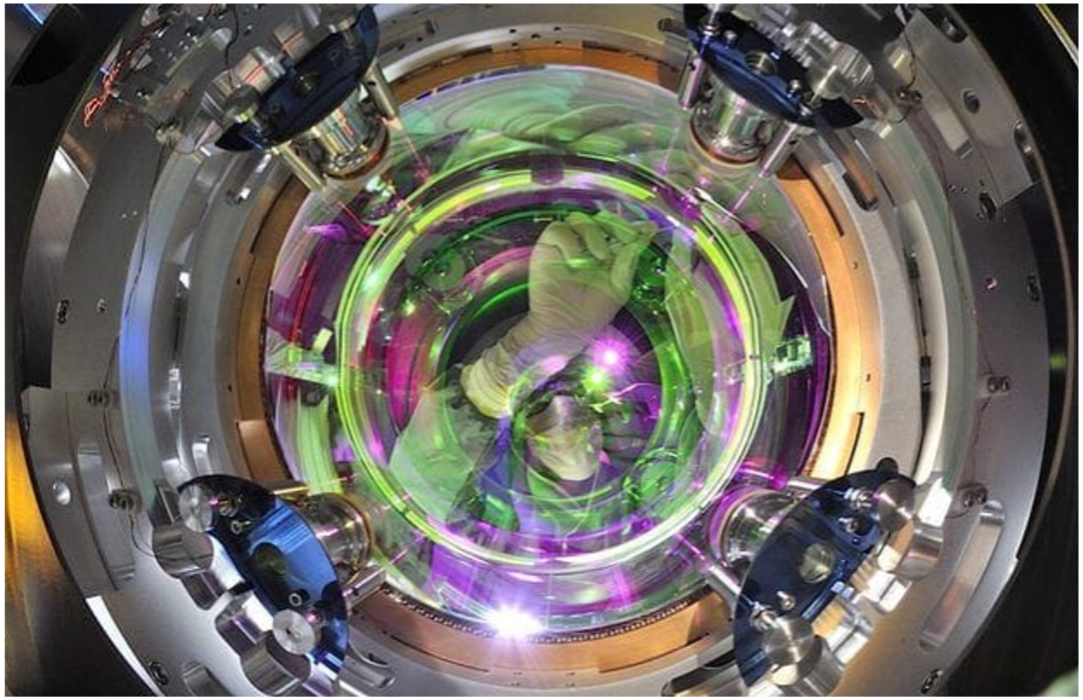
Einstein Telescope (ET): from scientific requirements to research underground infrastructure

- ET is a landmark civil engineering and scientific infrastructure project integrating tunnels, caverns, and advanced systems—optical, cryogenic, vacuum, and mechanical requiring rigorous design and a digital, multi-criteria decision-making approach

- Engineers are engaged with scientist at early and continuously across all domains,

- Sustainability is central to ET's vision, with a stakeholder-driven Life Cycle Assessment framework covering all project phases and prioritizing proactive CO2 mitigation over reactive restoration.

- This commitment is reinforced by a new generation of highly trained professionals ensuring long-term climate resilience is embedded throughout the project's lifecycle.



Thanks for your attention