The Einstein Telescope
status and challenges

Andreas Freise, CERN ECFA meeting, 17.11.2023, ET-0457A-23
Exploring the dark side of the Universe

- By detecting space-time vibrations on Earth, we can measure dark cosmic objects, such as black holes.
- 100 years from prediction to first detection: 2017 Nobel Prize.
- New window to the Universe and fundamental physics: discovery space!
Next generation detectors

- Large laboratories and three 10 km long tunnels, more than 200m underground.
- 10 times better than design sensitivity of current detectors, providing GW data for astronomy and fundamental physics for at least 50 years.
Cosmic Explorer
The US Vision for Gravitational-Wave Astrophysics

- Next-Generation Gravitational-Wave Observatory
  - 40 km and 20 km L-shaped surface observatories
  - 10x sensitivity of today’s observatories
  - Global network together with European Einstein Telescope

- Enables access to
  - Stellar to intermediate mass mergers throughout Cosmic Time
  - Dynamics of Dense Matter
  - Extreme Gravity

https://cosmicexplorer.org
The GW spectrum

You are here!
The GW spectrum

10 times improved sensitivity in a broad band

Shifting the `seismic wall’ to lower frequencies

http://gwplotter.com/
The science case for ET

**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

Andreas Freise, 17.11.2023
A leap into the past

Current observatories

Einstein Telescope

Redshift
0

0 Present day

Farthest galaxy confirmed to date
8

Newly-identified farthest galaxy candidate
12

Cosmic “Dark Ages”
30

Big Bang

13.8 Billions of years ago

z=2

z=11.0

z=13.3

z=100

Andreas Freise, 17.11.2023
Neutron star detection rates

**Table 2.1: Expected number of binary NS detections per year $N$; localized with a resolution of $<1$, $<10$ and $<100$ square degrees, $N_1$, $N_{10}$ and $N_{100}$, respectively, and median localization error $M$, in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV, KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).**

<table>
<thead>
<tr>
<th>Network</th>
<th>$N$</th>
<th>$N_1$</th>
<th>$N_{10}$</th>
<th>$N_{100}$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLV</td>
<td>48</td>
<td>0</td>
<td>16</td>
<td>48</td>
<td>19</td>
</tr>
<tr>
<td>HLVKI</td>
<td>48</td>
<td>0</td>
<td>48</td>
<td>48</td>
<td>7</td>
</tr>
<tr>
<td>1ET+2CE</td>
<td>990k</td>
<td>14k</td>
<td>410k</td>
<td>970k</td>
<td>12</td>
</tr>
</tbody>
</table>
Difference between the speed of gravity and the speed of light: $-3 \times 10^{-15}$ to $+7 \times 10^{-16}$ times the speed of light!
Neutron star detections can provide a unique window to explore strong interactions under extreme conditions. 

Illustration: Alan Stonebraker

Orsaria et al. 2019
Constraining neutron-star matter with microscopic and macroscopic collisions

Interpreting high-energy, astrophysical phenomena, such as supernova explosions or neutron-star collisions, requires a robust understanding of matter at supranuclear densities. However, our knowledge about dense matter explored in the cores of neutron stars remains limited. Fortunately, dense matter is not probed only in astrophysical observations, but also in terrestrial heavy-ion collision experiments. Here we use Bayesian inference to combine data from astrophysical multi-messenger observations of neutron stars\(^1\) and from heavy-ion collisions of gold nuclei at relativistic energies\(^2\), with microscopic nuclear theory calculations\(^3\) to improve our understanding of dense matter. We find that the inclusion of heavy-ion collision data indicates an increase in the pressure in dense matter relative to previous analyses, shifting neutron-star radii towards larger values, consistent with recent observations by the Neutron Star Interior Composition Explorer mission\(^4\). Our findings show that constraints from heavy-ion collision experiments show a remarkable consistency with multi-messenger observations and provide complementary information on nuclear matter at intermediate densities. This work combines nuclear theory, nuclear experiment and astrophysical observations, and shows how joint analyses can shed light on the properties of neutron-rich supranuclear matter over the density range probed in neutron stars.

How to build the Einstein Telescope?

- Research and Technology
- Organisation and Governance
- Infrastructure and Engineering
Einstein Telescope: from idea to project

- **2000**: ESF exploratory workshop in Perugia on 3G GW detectors
- **2005**: ILIAS (FP6) Networking activity of future GW
- **2005**: ET conceptual design study (FP7)
- **2010**: ET R&D funded by ASPERA-2
- **2015**: ELITES (FP7) Project (KAGRA-ET synergies)
- **2020**: Project Organisation
- **2020**: ESFRI status
- **2020**: Scientific Collaboration

[Timeline: Michele Punturo]
The Einstein Telescope in an international framework

ET is a project that will be carried out within the framework of the European Strategy Forum for Research Infrastructures (ESFRI). INFN and Nikhef leading a consortium of 41 European institutions.

This ESFRI timeline and budget are out of date. We are starting the process of defining a new, robust schedule, based on a technical designs and a full definition of the Product and Work Breakdown Structures.
Two international pillars of ET:
1) project management and 2) scientific collaboration

ET Collaboration

- Collaboration board
- Executive board
- Specific boards: ISB, OSB, EIB, SCB, SSB, ...

ETO (ET Organisation)

- Board of governmental representatives
- Board of Scientific representatives
- Coordinators
- ET Directorate
- Project office
- Engineering department
- Administrative office
- ET-PP

ET-PP
ETO: an organisation for realising ET

Temporary groups, working towards becoming the ET governing body, such as a Council. **Our most important link to governments and funding agencies** (Austria, Belgium, France, Italy, Netherlands, Poland, Spain, UK are members with Germany as observer).

An small but active organisation with the formal responsibility to realise of ET. **A future legal entity for ET would be based on this structure.**
ETO: an organisation for realising ET

EU-funded support for the preparation phase, led by Mario Martinez IFEA, Spain.
Where to build ET?

Currently there are two candidate sites to host ET:

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

Preparing the ground for a large infrastructure, this will take several years.
Success factors, so far

- ET Collaboration:
  - Officially established 09.06.2022
  - **1559 members, 222 institutions, 24 countries and 84 research units**

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

- International coordination:
  - Established a structure to form and evolve international partnership
  - **Active group of ministry delegates meets regularly**
How to build the Einstein Telescope?

- Research and Technology
- Organisation and Governance
- Infrastructure and Engineering
Research and technology, the strength of our collaboration

https://indico.ijclab.in2p3.fr/event/9686/
Example: Seismic isolation, from Virgo towards ET

Vibration isolation for cryogenic mirrors in ETpathfinder
How to build the Einstein Telescope?

• Research and Technology
• Organisation and Governance
• Infrastructure and Engineering
We need to connect two disciplines: Civil Engineering and Geoscience
• Civil Engineering for minimum requirements on safe and robust construction
• Geophysics for subsurface mapping of layered structure and water flow
• Jointly determine the construction risk
Towards an ETO engineering department

- We are working with CERN to get support from their team for these topics.
- The first project started in 2022 and will deliver the Technical Design Report (TDR) for the vacuum pipe in 2025.
- A second project has been approved to support delivering a preliminary TDR for the underground infrastructure in 2026.
The CERN collaboration with ET

Deliberation Document

on the 2020 update of the European Strategy for Particle Physics

The European Strategy Group
(prepared by the Strategy Secretariat)

5. Synergies with neighbouring fields

There are many synergies between particle physics and other fields of research. Clear examples are nuclear and astroparticle physics, which address common fundamental questions and use common tools.

b) Astroparticle physics, coordinated by APPEC in Europe, also addresses questions about the fundamental physics of particles and their interactions. The ground-breaking discovery of gravitational waves has occurred since the last Strategy update, and this has contributed to burgeoning multi-messenger observations of the universe. Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.

CERN's “Recognised Experiment” status allows collaborations whose experiments do not take place at CERN but are in fields relevant to its scientific goals, to make use of CERN's infrastructure, e.g. to hold meetings, use offices or receive administrative support. It would be appropriate to establish a new procedure for such collaborations seeking CERN's technical support, which should be limited to providing technical expertise and infrastructure services in a cost-neutral way for CERN.
CERN vacuum project: rapid progress

Modelling

Design

Simulation

Material test

Welding test

Planning
GWs in the CERN Courier

12.05.2023

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 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. $10^{-23}$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 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 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 surfacetreatment basis-

https://cerncourier.com/a/cern-shares-beampipe-know-how-for-gravitational-wave-observatories/
Summary

• Gravitational wave science is an exciting new method to answer fundamental questions.

• The Einstein Telescope has changed from an idea into a project.

• We are setting up professional structures in order to address the challenges of the next phase: building a robust case (science, design, costing, schedule, ...) to capture the interest of a large community and the trust of governments of partner states.

• ET is now a recognised experiment at CERN. We benefit strongly from several active collaborations with the CERN technical teams.