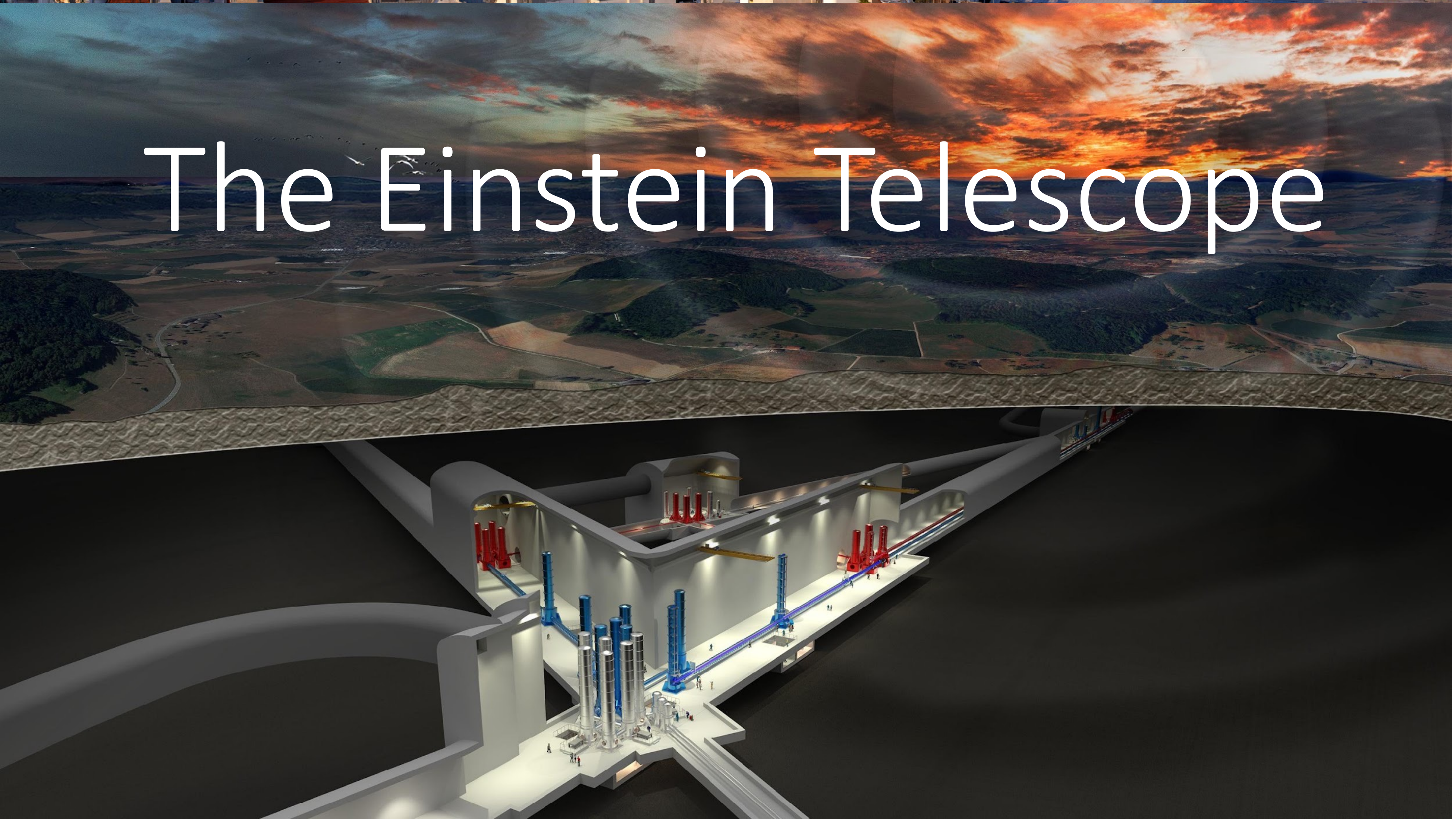
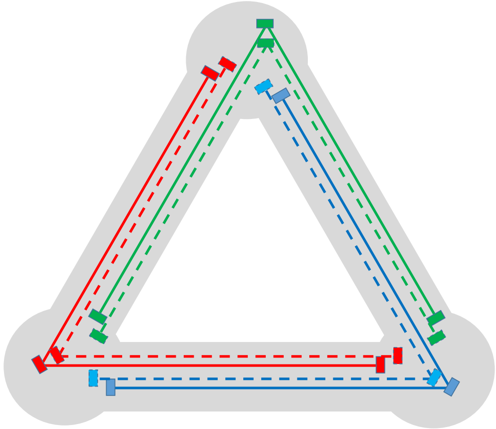
The Einstein Telescope





D. D’Urso

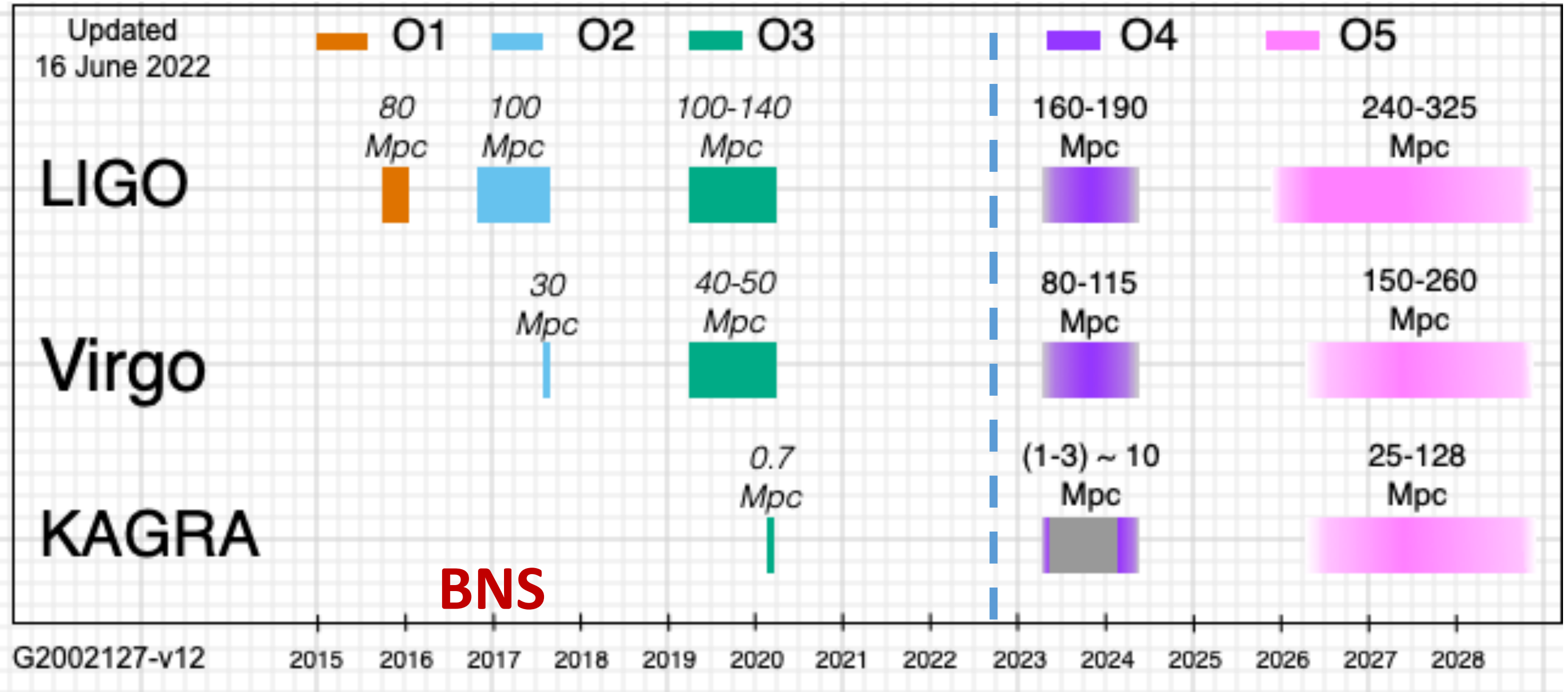
University of Sassari

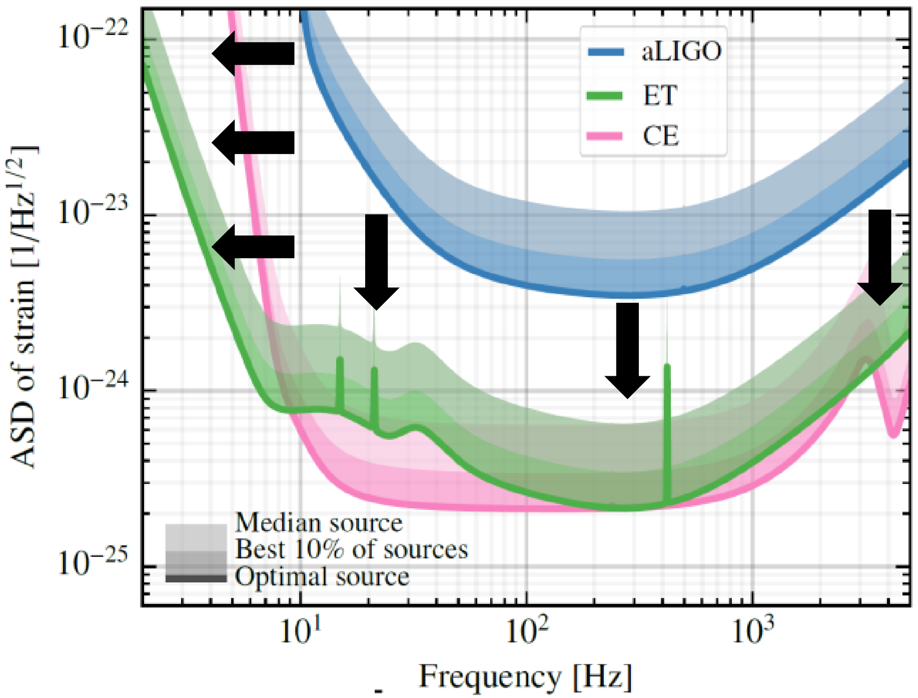
and INFN-LNS

On behalf and with the contribution of the ET Collaboration

Introduction

- Advanced LIGO and Advanced Virgo have completed the third observing run and are being upgraded toward LIGO A+ and AdV+ operations (O4: ~2023-2024 – O5: ~2026-2028)
- Further upgrades are being planned for post-O5

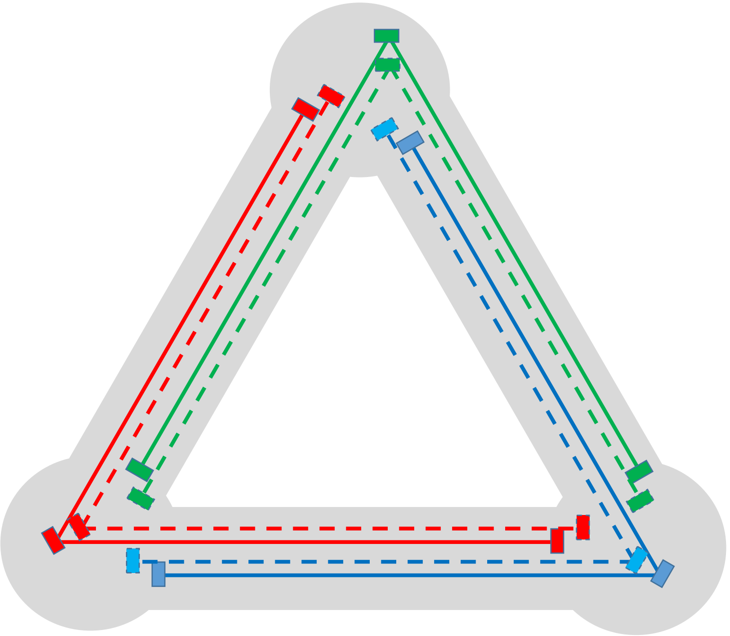




What's the Einstein Telescope (ET)

- **3rd generation GW observatory** Sensitivity aims at least one order of magnitude better with respect to the nominal sensitivity of advanced detectors in all the detection frequency band
- **Precision measurement and a new discovery project.** A wide frequency band observatory
- **Special focus on massive (or intermediate mass) black holes.** Extraordinary sensitivity at low frequency (few Hz)
- **High reliability.** High observation duty cycle
- **Lifetime of several decades,** (50 years in the ET proposal). Capable to host the evolution of the detectors, without limiting their sensitivity

ET Design: key elements

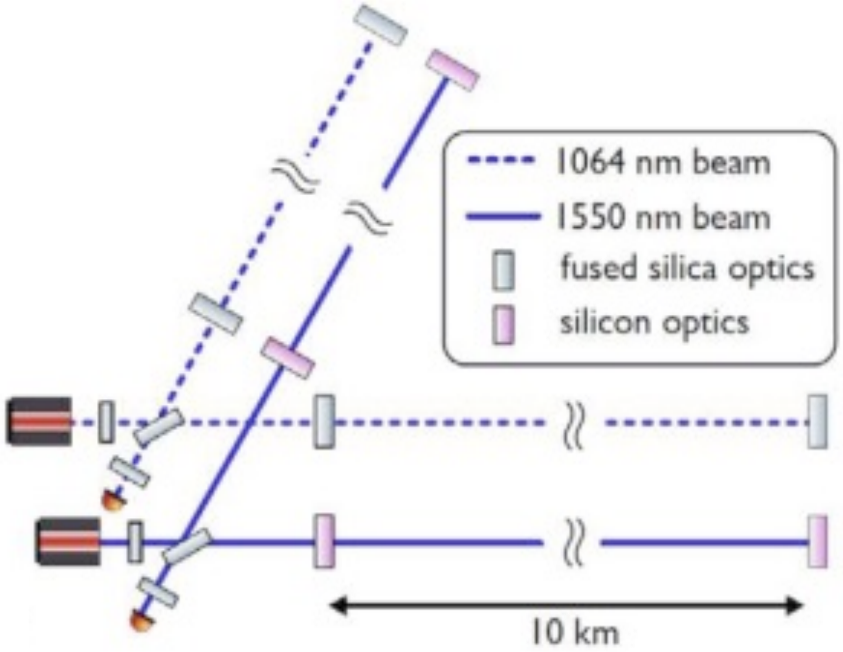


Requirements

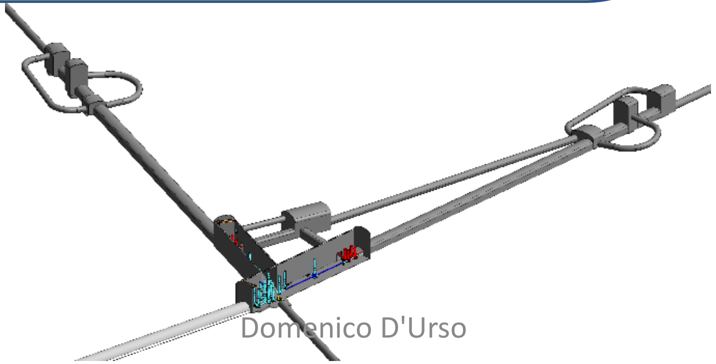
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape
- Multi-detector design
- Longer arms



ET EINSTEIN TELESCOPE



ET Science Case in a nutshell

EINSTEIN TELESCOPE

ASTROPHYSICS

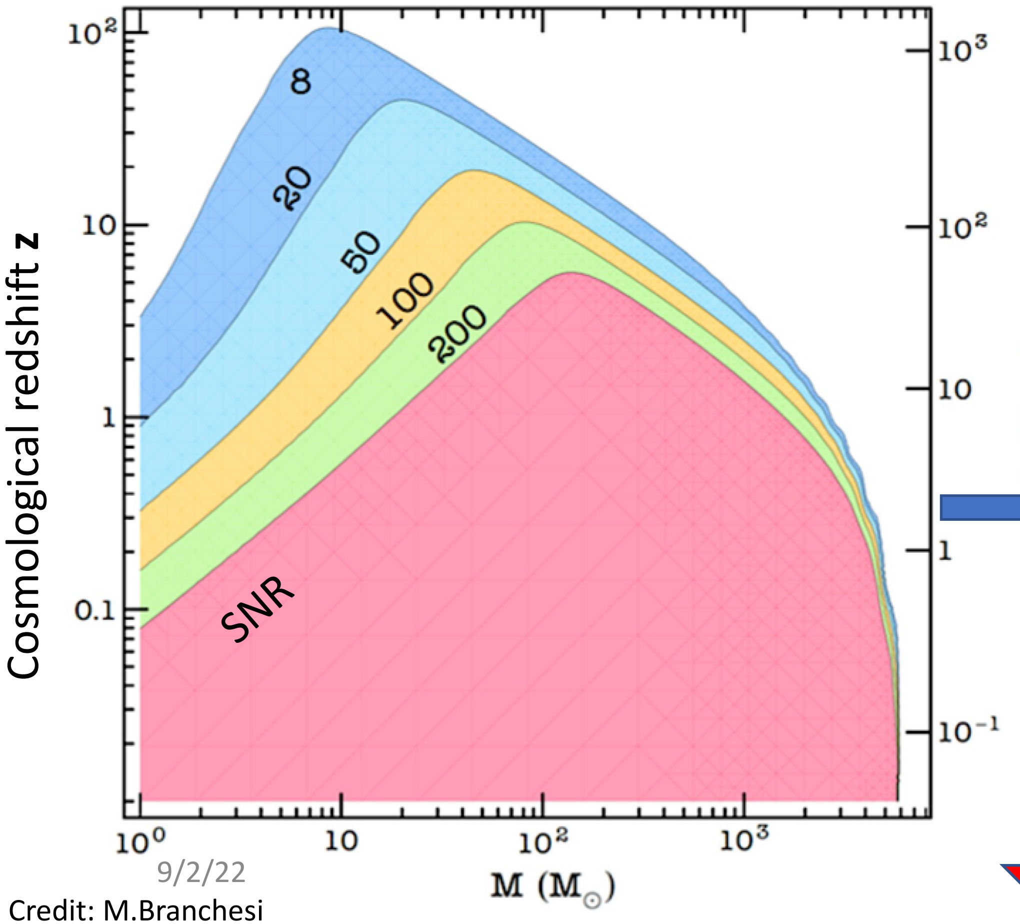
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

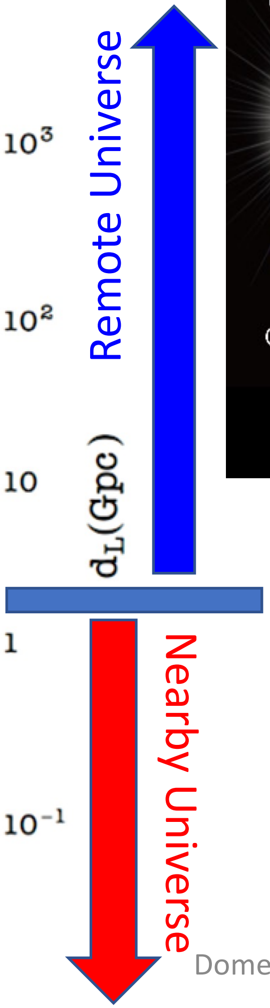
- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

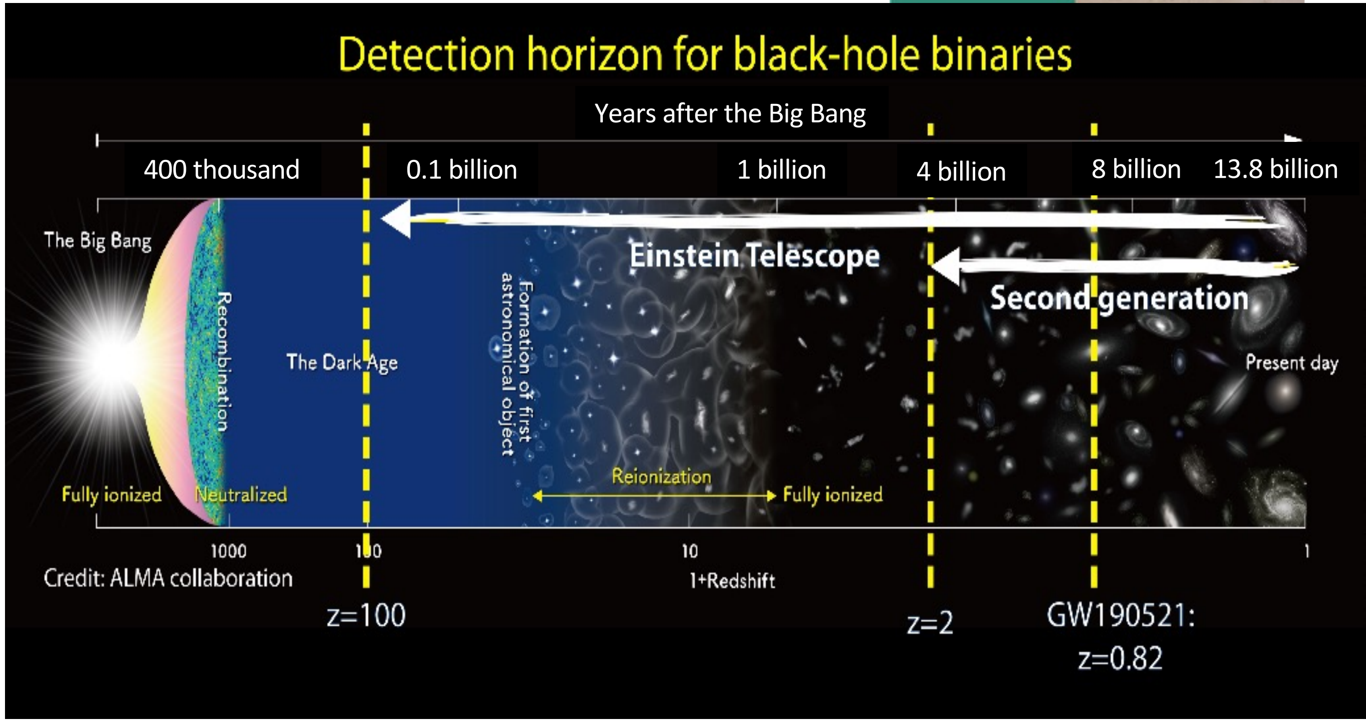
ET Science in a nutshell: double nature

- ET will be a new discovery machine:
  - ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang



Credit: M.Branchesi

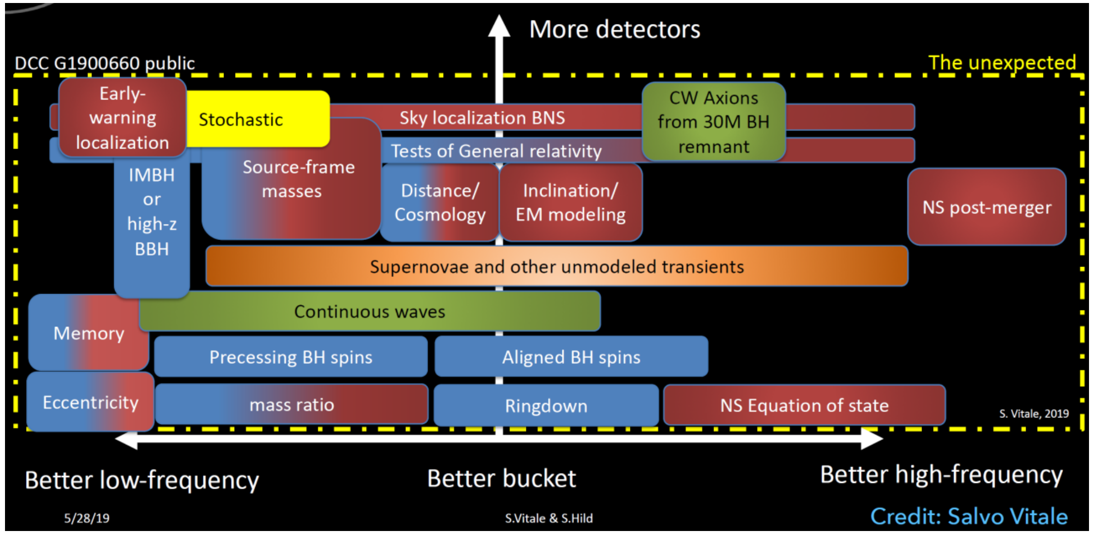




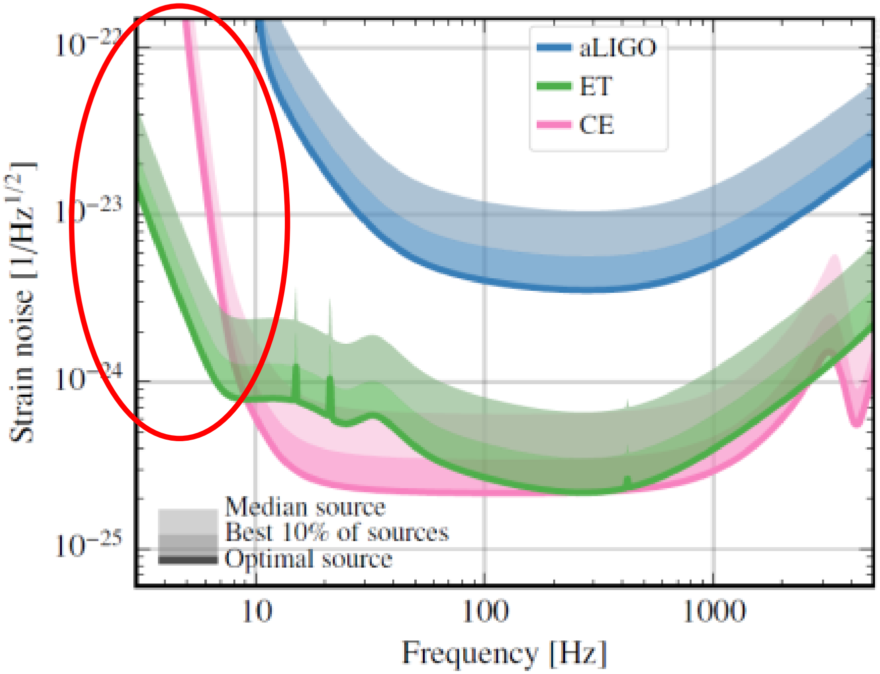
- ET will be a precision measurement observatory:
  - ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei

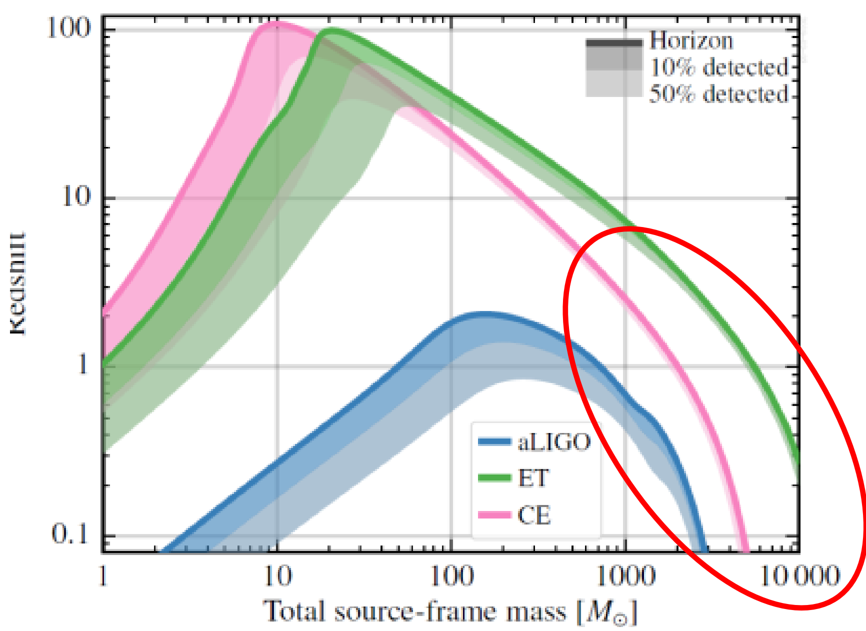
ET Science in a nutshell: double nature

- GW science targets are almost equally distributed in the frequency range accessible by terrestrial GW detectors (but technical difficulties aren't)
- We want to have access both to low and high frequency targets



- ET will be a wide band observatory with a special focus on (intermediate) massive compact object:
  - **Low frequency!**





ET TECHNOLOGY (MAIN) CHALLENGES

Challenging engineering

New technology in cryo-cooling

New technology in optics

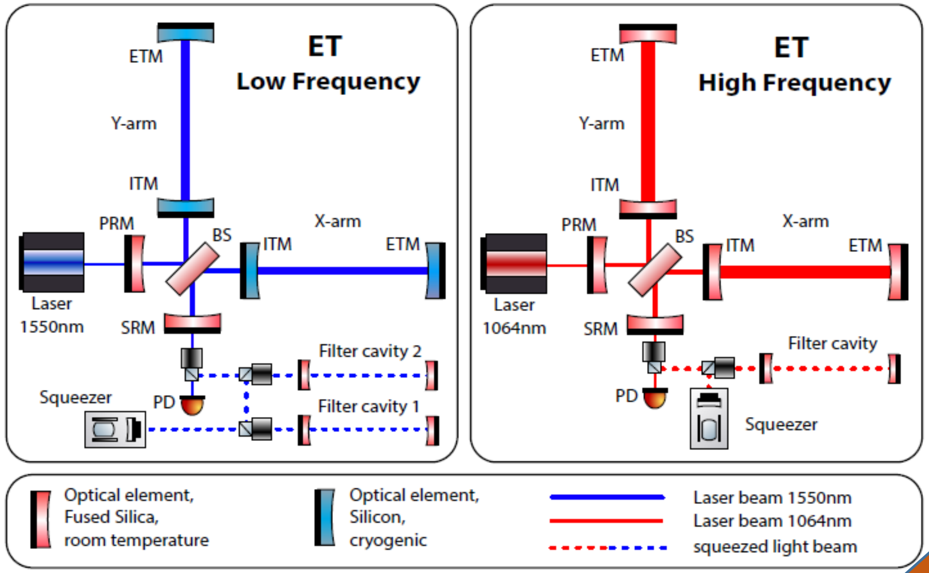
New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

- The multi-interferometer approach asks for **two parallel technology developments**

- ET-LF
  - Underground
  - Cryogenics
  - Silicon (Sapphire) test masses
  - Large test masses
  - New coatings
  - New laser wavelength
  - Seismic suspensions
  - Frequency dependent squeezing



- ET-HF
  - High power laser
  - Large test masses
  - New coatings
  - Thermal compensation
  - Frequency dependent squeezing

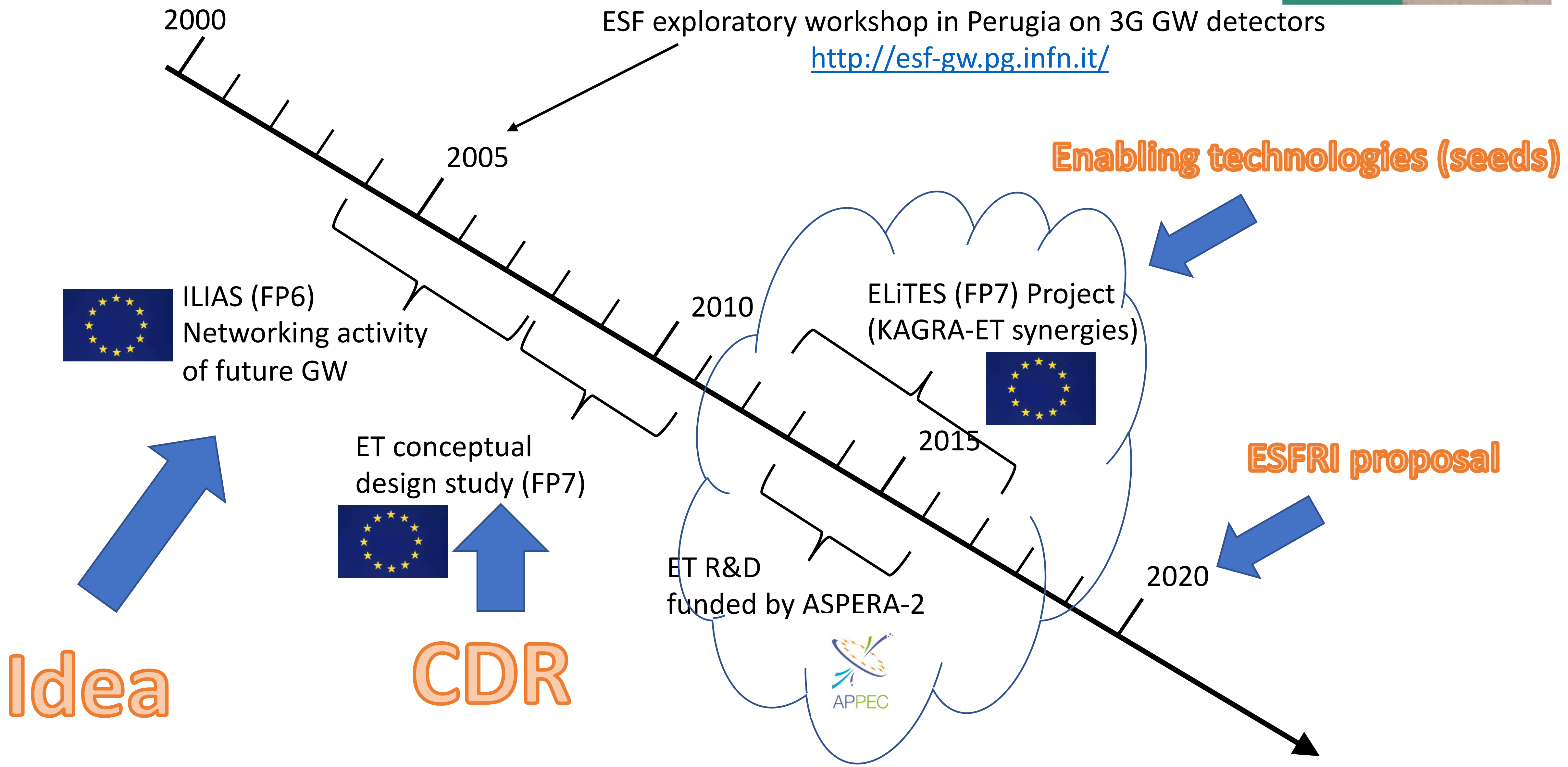
Evolved laser technology

Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

ET long path

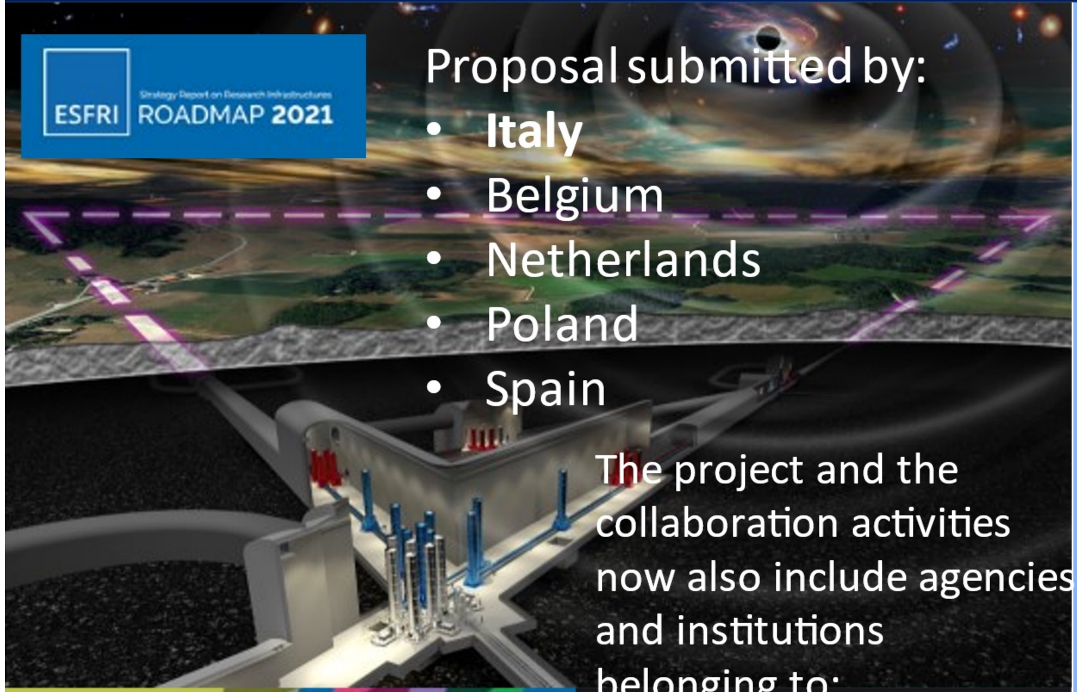

2000
ESF exploratory workshop in Perugia on 3G GW detectors
http://esf-gw.pg.infn.it/
2005
Enabling technologies (seeds)
ILIAS (FP6)
Networking activity
of future GW
2010
ELiTES (FP7) Project
(KAGRA-ET synergies)
2015
ESFRI proposal
ET conceptual
design study (FP7)
ET R&D
funded by ASPERA-2
APPEC
2020
Idea
CDR

ET in the ESFRI Roadmap (2021)

European Strategy Forum on Research Infrastructures

ET in the ESFRI Roadmap

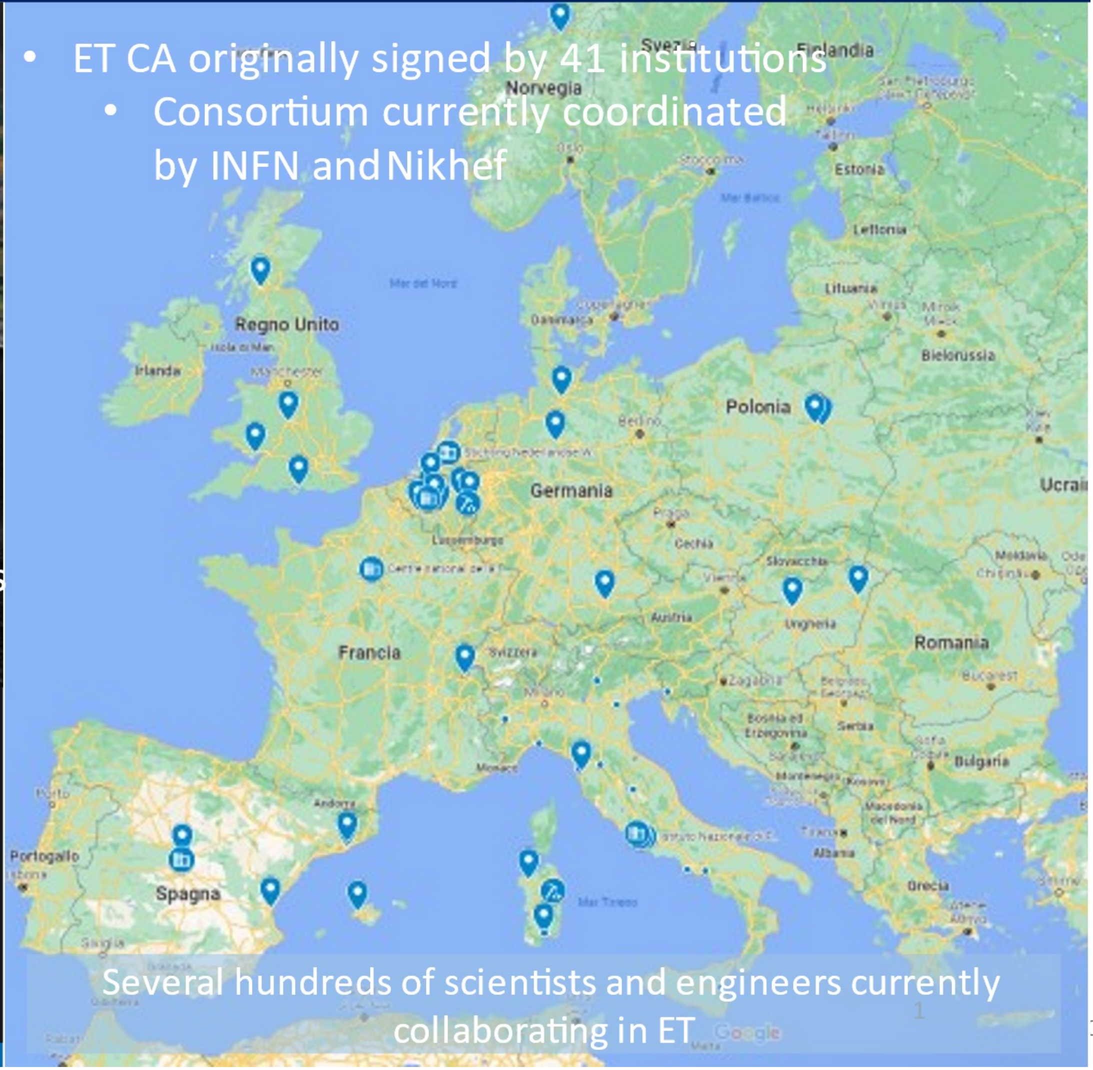
ESFRI ROADMAP 2021



Proposal submitted by:
- **Italy**
- Belgium
- Netherlands
- Poland
- Spain

The project and the collaboration activities now also include agencies and institutions belonging to:
- **Austria**
- **France**
- **Germany**
- **Hungary**
- **Switzerland**
- **UK**

Preparatory funds available in some country (IT, NL, …); an EU INFRA-DEV proposal approved with a grant of 3.45M€ starts the 1 st of September;

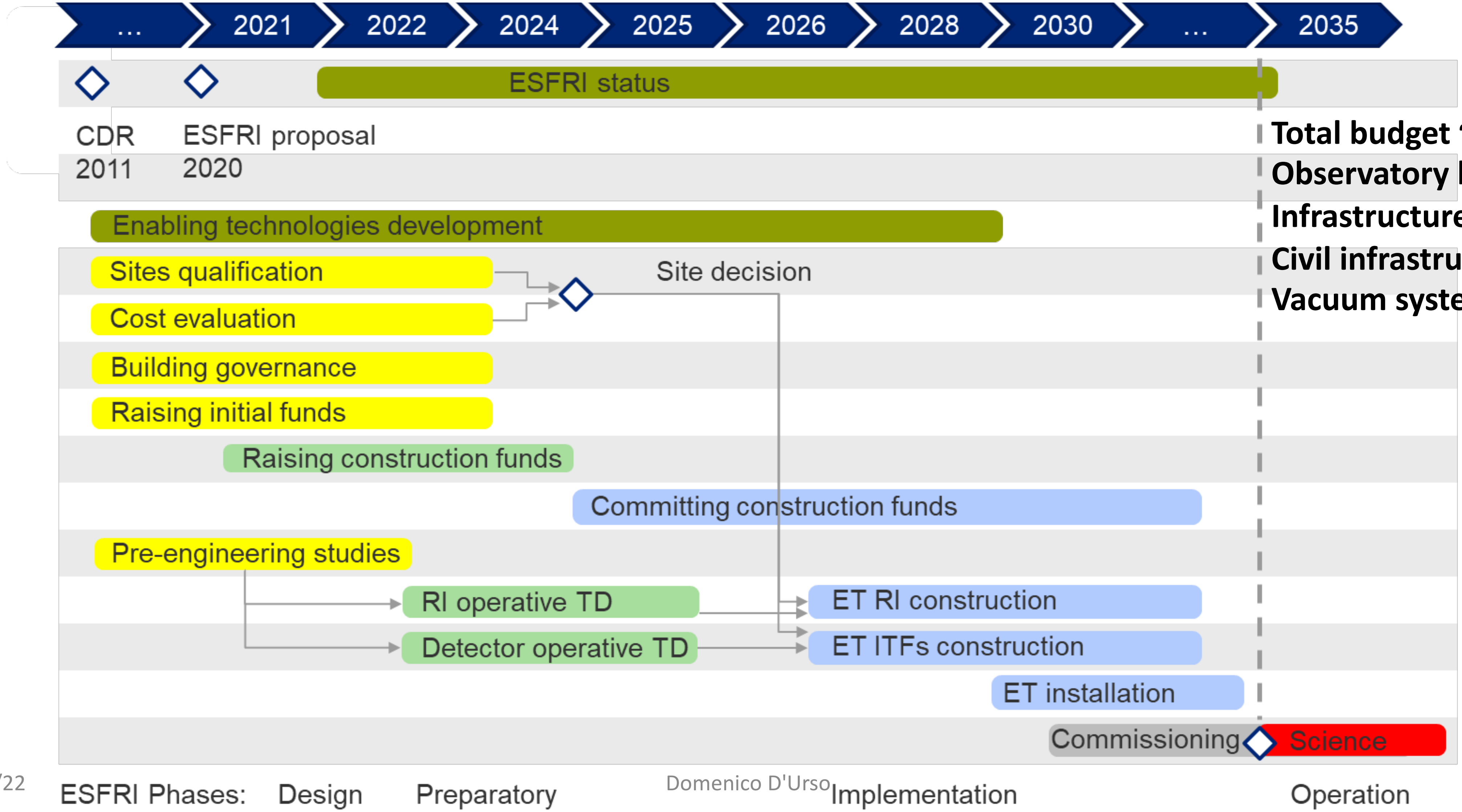


- ET CA originally signed by 41 institutions
  - Consortium currently coordinated by INFN and Nikhef

Several hundreds of scientists and engineers currently collaborating in ET

ET time scale (ESFRI proposal)

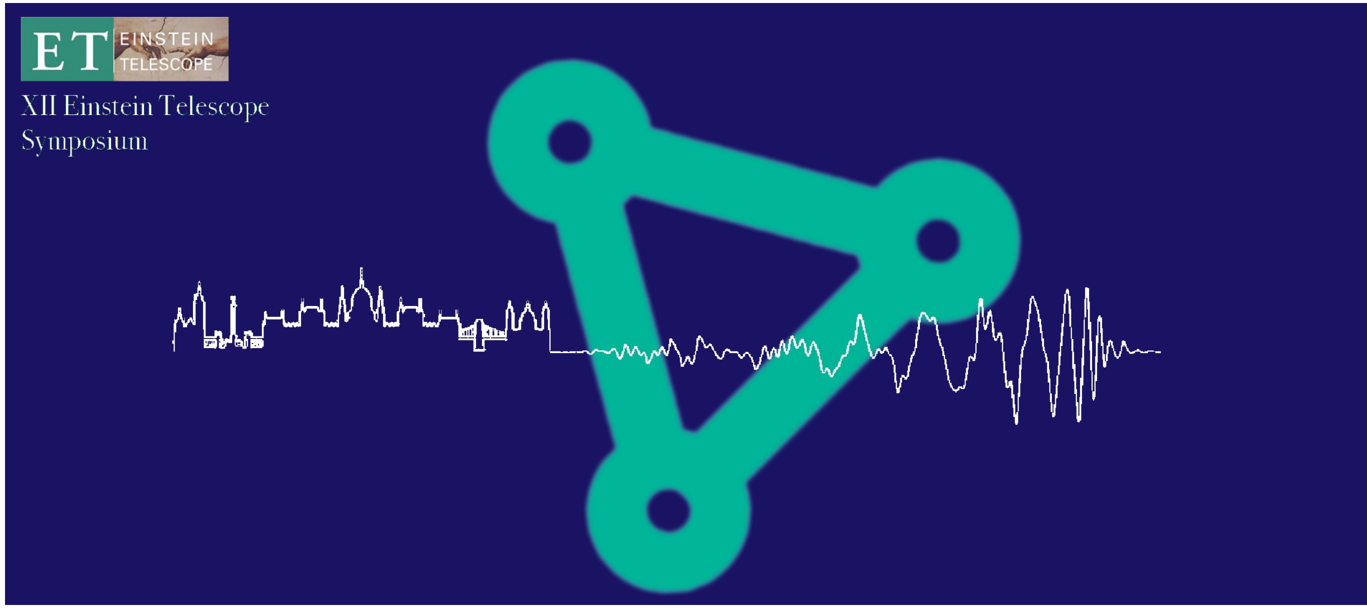
The ESFRI approval boosted the activities at all the levels: scientists, agencies and governments



Total budget ~ 2G€
Observatory budget ~ 1.7G€
Infrastructure Budget:
Civil infrastructure: ~930M€
Vacuum system: ~570M€

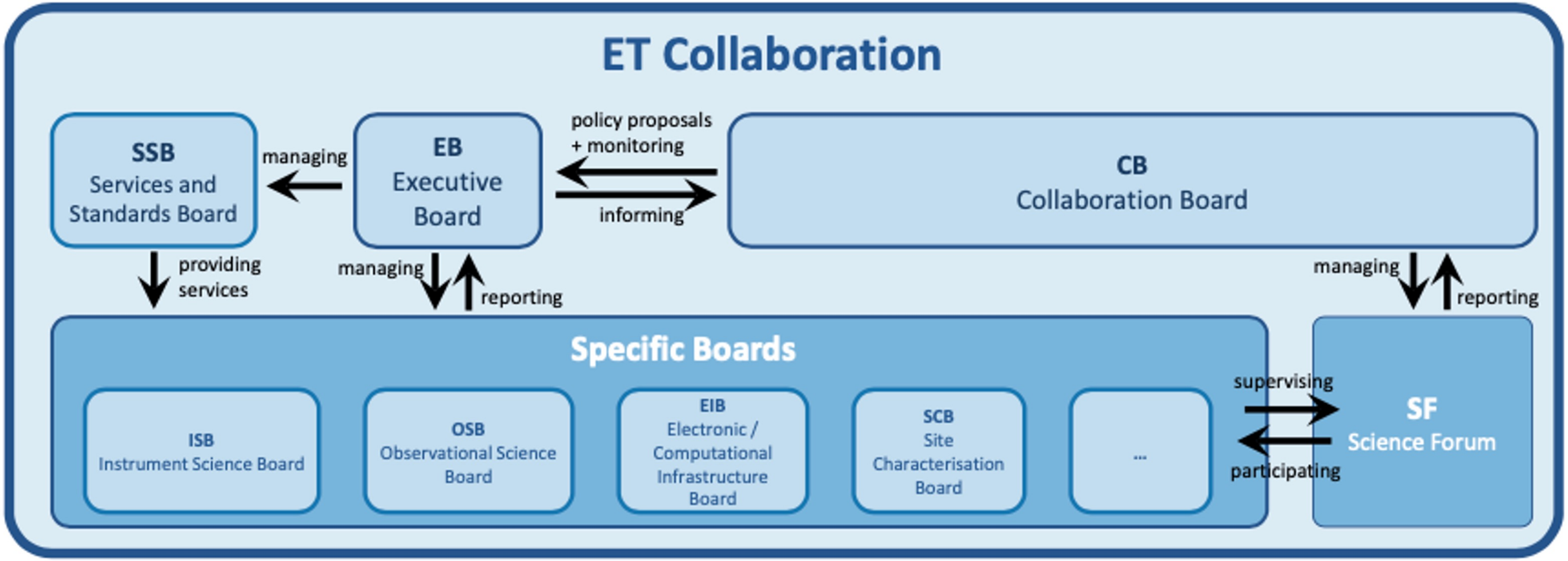
Birth of ET Collaboration

- **Official Birth of the ET Collaboration** XII ET Symposium, Budapest on June 7th - 8th
- More than 400 scientists, out of more than 1200 members of the Collaboration, participated in the meeting in person or remotely.



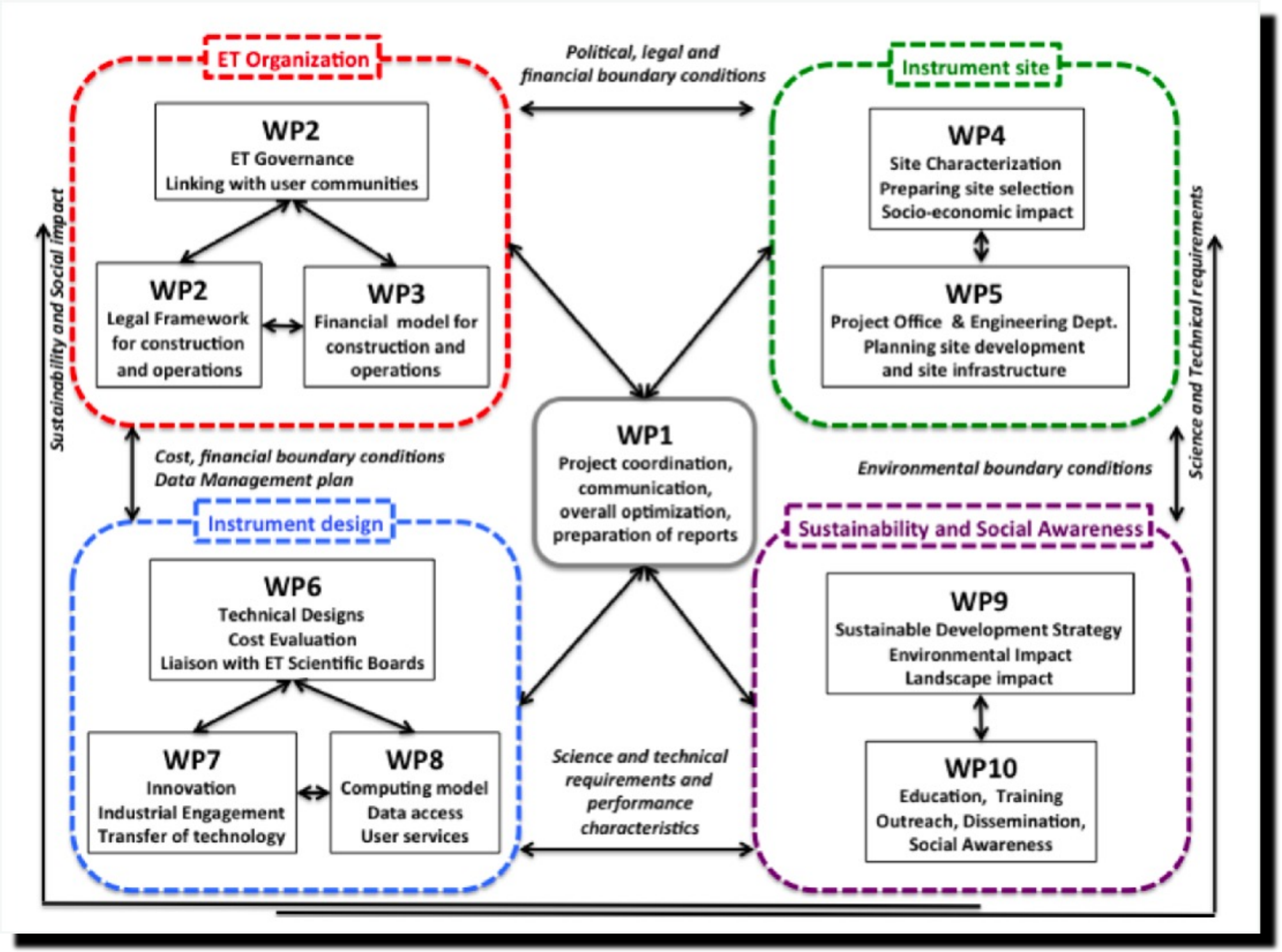
ET Collaboration: Structure

- ➢ Executive Board (EB)
- ➢ Collaboration Board (CB)
- ➢ Science Forum (SF)
- ➢ Specific Collaboration Boards
- ➢ Service and Standards Boards and Committees



INFRADEV: ET-PREPARATORY PHASE

- ET governance
  - Legal framework
- Site characterisation
  - Project Office & engineering
- Technical design
  - Innovation, computing
- Environmental impact
  - Sustainability, outreach



ET site(s)

- ➢Currently there are two sites, in Europe, candidate to host ET:
  - ❑The Sardinia site, close to the Sos Enattos mine
  - ❑The EU Regio Rhine-Meusse (EMR) site, close to the NL-B-D border
- ➢A third option in Saxony (Germany) is under discussion

ET sites under characterisation

Euregio Meuse-Rhine

- A 250-m deep borehole has been excavated and equipped
  - Seismic data under acquisition and analysis
- A set of other boreholes will be completed in 2022
- Extensive active and passive site characterisation with sensor arrays in 2021
- Large active seismic campaign on going
- Good seismic noise attenuation given by the particular geological structure
- Characterisation funded through Interreg grants
- Large proposal for qualifying the site approved to the Dutch government

Sardinia

- Long standing characterisation of the mine in one of the corners continuing
  - Seismic, magnetic and acoustic noise characterisation ongoing at different depth in the mine
- Underground laboratory under preparation (SarGrav)
- Two ~290m boreholes have been excavated, equipped and data taking is ongoing
- Active and passive seismic campaign at ET verteces
- Intense surface investigations programme ongoing
- Characterisation funded on regional and national funds
- Large proposal for technology development and engineering design submitted to the Italian government

Next Steps

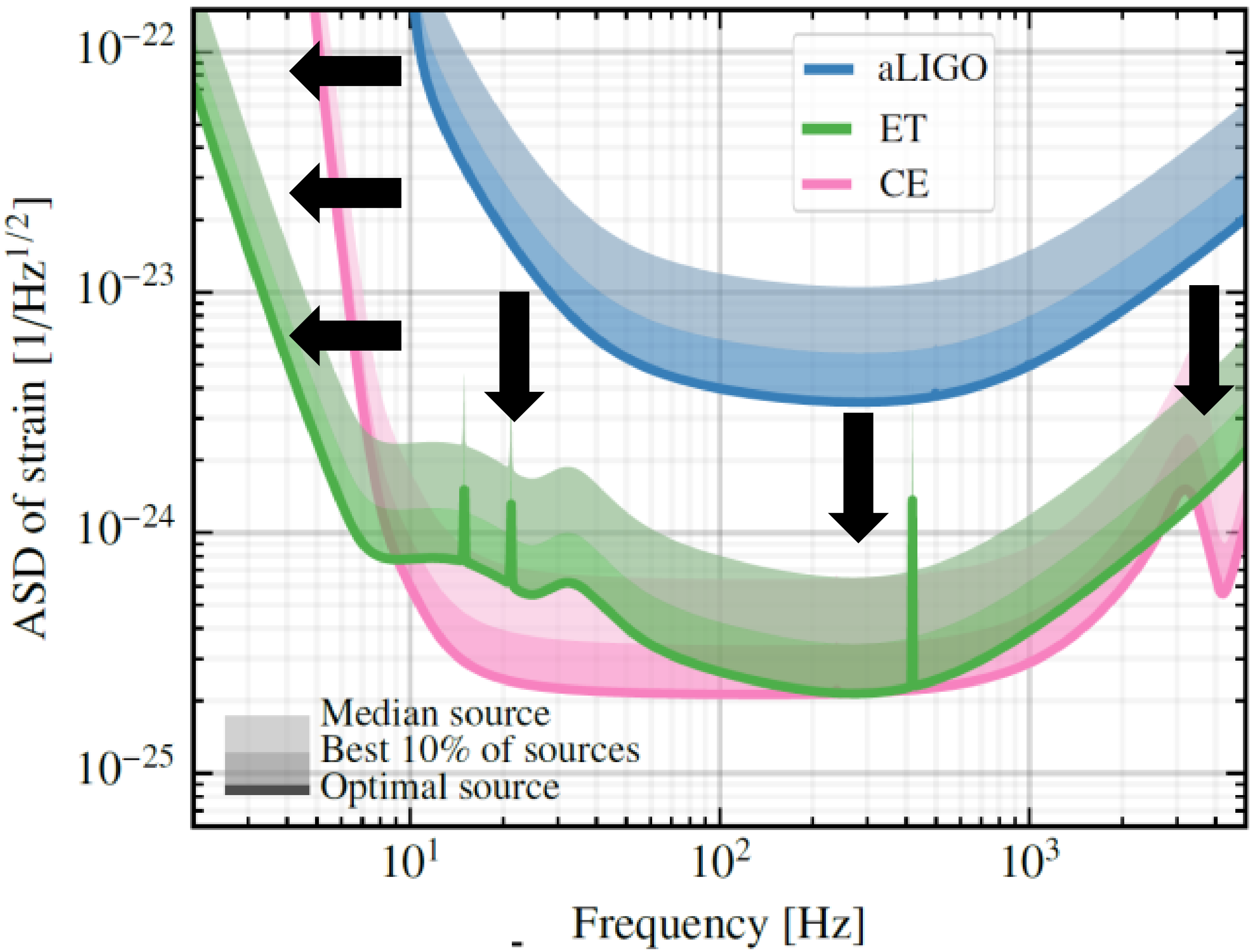
Einstein Telescope is a complex enterprise. ET Collaboration has been just formed. Funding agencies and governments are setting up structures to manage the project

- ➢Finalize formation of the Collaboration and operating bodies
- ➢Site selection
- ➢Evolve the 2011 CDR into a TDRs

The Science Case of ET

- The Science Case of ET is broad, and addresses crucial problems in astrophysics, in cosmology and in fundamental physics

- ET will be a discovery machine: GW detection has literally opened a new window on the Universe.



GW Ideal Information Carrier (GW Astronomy)

- GW emission: very energetic events but almost no interaction

strong	e.m.	weak	gravity
0.1	1/137	10^{-5}	10^{-39}

- Decoupling after Big Bang
  - GW ~10^{-43} s (T~10^{19} GeV)
  - ν ~ 1s (T~1 MeV)
  - e.m. ~ 10^{12} s (T~0.2 eV)

GW and Cosmic Rays and Neutrinos

- The astrophysical sources of gravitational-wave transient signals associated with gamma-ray bursts, soft gamma-ray repeaters (SGRs), and core-collapse supernovae are expected to emit neutrinos.
  - GWs (produced by the bulk motion of matter) => information on the astrophysical source dynamics
  - neutrinos => information on interactions between accelerated particles with matter and radiation surrounding the sources.
- GWs and neutrinos probe the innermost regions of the source typically opaque to the electromagnetic emission.
- ET, gamma-ray observatories, and neutrino detectors will make it possible to probe the GRB population, their progenitors, and the jet properties and composition.
- The high-energy neutrinos would serve as a powerful probe of cosmic-ray acceleration in GRBs and of the physics of relativistic jets associated with NS-NS and NS-BH mergers.
- GWs + low-energy neutrinos from the core collapse of massive stars may reveal the inner mechanisms of the explosion, the dynamics of the remnant (possibly a newborn neutron star) and the physics of the post-shock region of SuperNova.

see ET Design Report (https://apps.et-gw.eu/tds/?call_file=ET-0007B-20_ETDesignReportUpdate2020.pdf)

GW and Dark Matter

ET has the potential of discovering, or ruling out, several dark-matter candidates that will be inaccessible by any other means.

- **Primordial BH**. Mass range $\sim 0.1{-}100\ M_{\odot}$, seeded by fluctuations generated during the last stages of inflation. Their mass distribution depends on the precise model of inflation and on the epoch when they collapsed. ET will allow us to map the black hole mass distribution and identify an excess of black holes in certain mass intervals.
- **DM particles beyond the Standard Model**. BH could be subject to gravitational drag. joint LISA-ET observations can constrain the parameters of the binary with great accuracy
- DM particles can be captured in astrophysical objects and thermalize with the star. The presence of a dark matter core in a neutron star might again have an imprint upon the GW signal during binary inspiral and merger
- **Ultralight Boson DM**. They can extract rotational kinetic energy from the black hole through “superradiance" to feed the formation of a bosonic “cloud" with mass up to $\sim$ 10% of the black hole. These clouds annihilate over a much longer timescale than their formation, through the emission of nearly monochromatic gravitational waves which could be detected either directly or as a stochastic background from a large number of such objects throughout the Universe.

see ET Design Report (https://apps.et-gw.eu/tds/?call_file=ET-0007B-20_ETDesignReportUpdate2020.pdf)

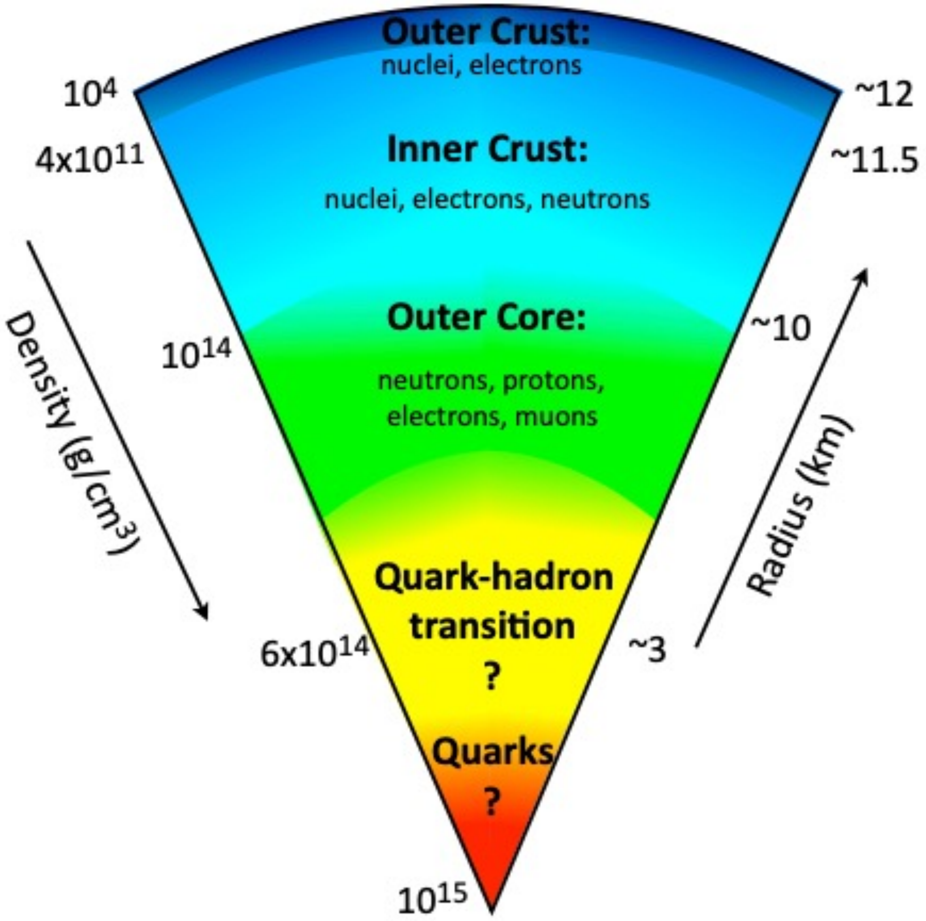
GW and BNS

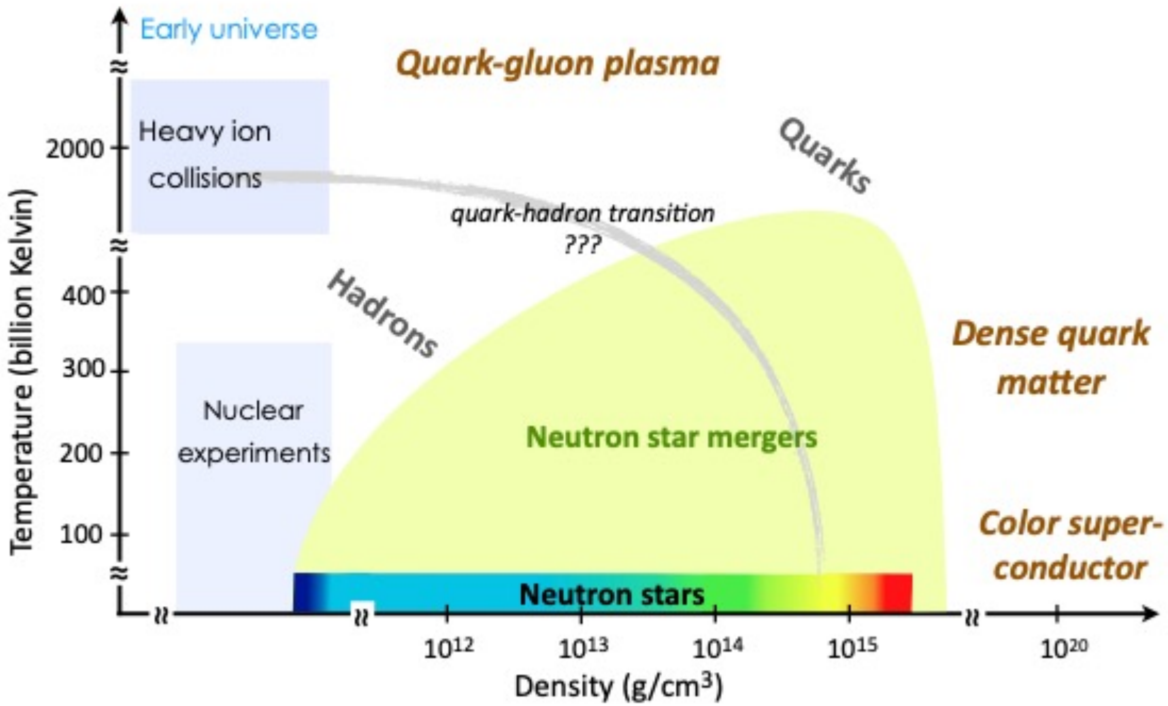
- ET will detect the coalescence of binary neutron stars up to $z \simeq 2-3$, with an estimated rate of about 7×10^4 events per year.
- *The greater sensitivity and larger frequency bandwidth of a detector such as ET will be critical to*
  - *observe a diverse population of NS binaries*
  - *accurately measure GW signatures of matter during the inspiral and probe details of the merger and post-merger phenomena.*
- *These measurements are essential to substantially advance frontiers of subatomic physics by determining*
  - *the properties of cold, dense matter in NSs*
  - *the new physics encountered during the merging, at higher temperatures and more extreme densities*
  - *the formation of heavy elements in the cosmos from synergies with electromagnetic observations.*

see ET Design Report (https://apps.et-gw.eu/tds/?call_file=ET-0007B-20_ETDesignReportUpdate2020.pdf)

GW and BNS

Study of QCD at ultra-high density, including the possibility of phase transitions in the NS core involving deconfined quarks or exotic states of matter.



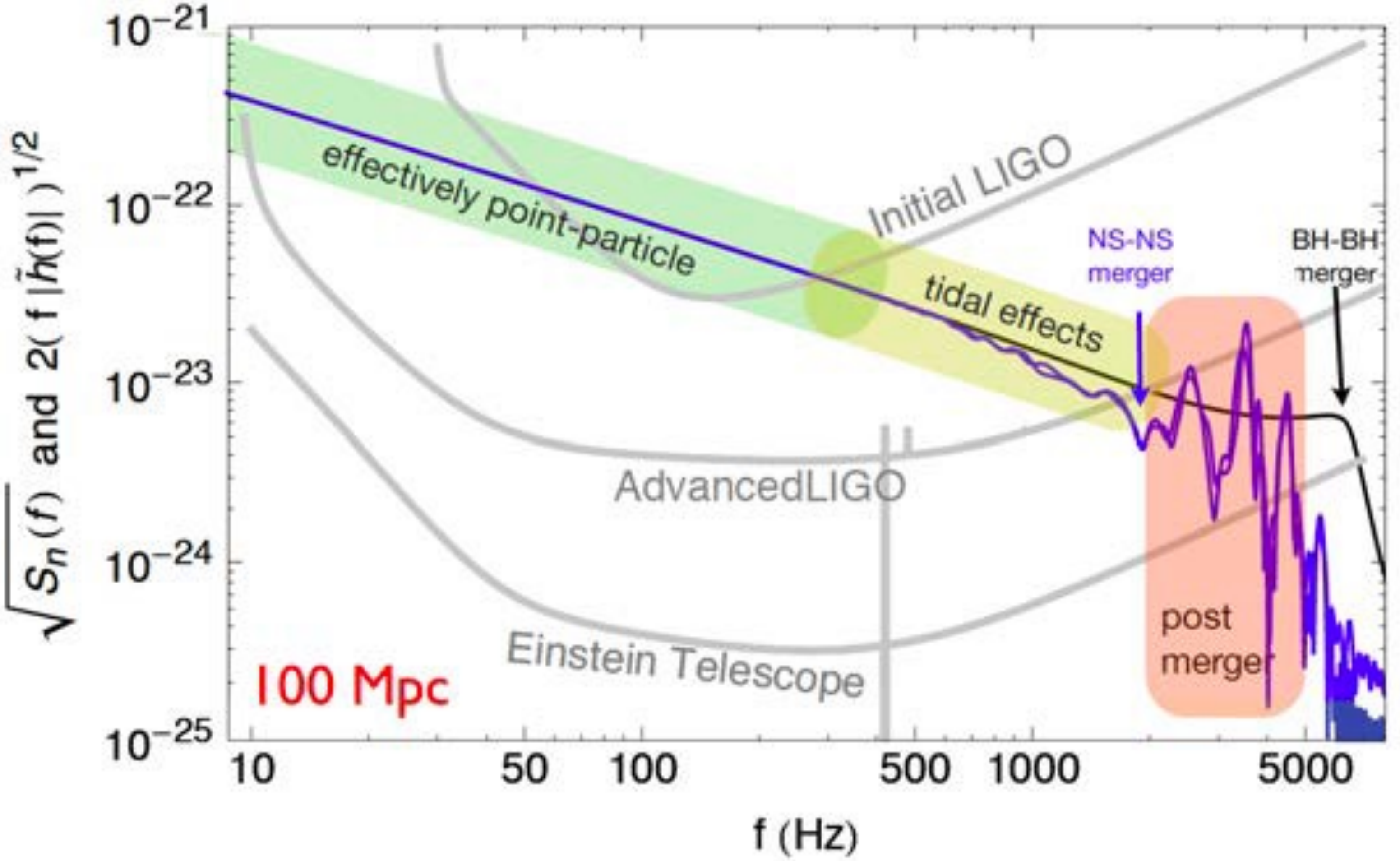


Physics of strong interactions in an extreme regime of high temperatures and densities. The sensitivity of ET in the high-frequency regime will allow us to access the GW signal of the merger phase (inaccessible to 2G detectors) and carries detailed information on the internal structure of neutron stars and on their equation of state.

see ET Design Report (https://apps.et-gw.eu/tds/?call_file=ET-0007B-20_ETDesignReportUpdate2020.pdf)

GW and BNS

- The outcome of BNS merger may lead to many scenarios.
    - a short-lived hypermassive NS that is temporarily stabilized by rotational effects yet ultimately collapses to a BH
    - a BH that forms immediately upon merger
    - a temporary supra-massive NS that settled to a NS remnant
- The emitted GWs are distinct for the different scenarios and contain copious information on the complex microphysics



Accurate measurements of both the GWs from the inspiral, that determine the progenitor properties (e.g. masses, spins, cold NS matter, orbital eccentricity), and the GW signatures of the new physics encountered at the merger and its aftermath

see ET Design Report (https://apps.et-gw.eu/tds/?call_file=ET-0007B-20_ETDesignReportUpdate2020.pdf)

Conclusions

- ET is a huge enterprise: scientific, engineering, technological, financial, management and human challenge
- ET Collaboration founded on June 2022
- Site characterization activities on going. Site Selection expected in 2024
- The Science Case of ET is broad, and addresses crucial problems in astrophysics, in cosmology, in particle and fundamental physics
  - probe the GRB population, their progenitors, and the jet properties and composition
  - probe of cosmic-ray acceleration in GRBs and of the physics of relativistic jets associated with NS-NS and NS-BH mergers
  - *discovering, or ruling out, several dark-matter candidates like primordial BH or ultralight bosons*
  - *existence of* primordial BH
  - *physics of neutron stars (particle and nuclear physics)*
  - *…*

ET EINSTEIN TELESCOPE

The Einstein Telescope

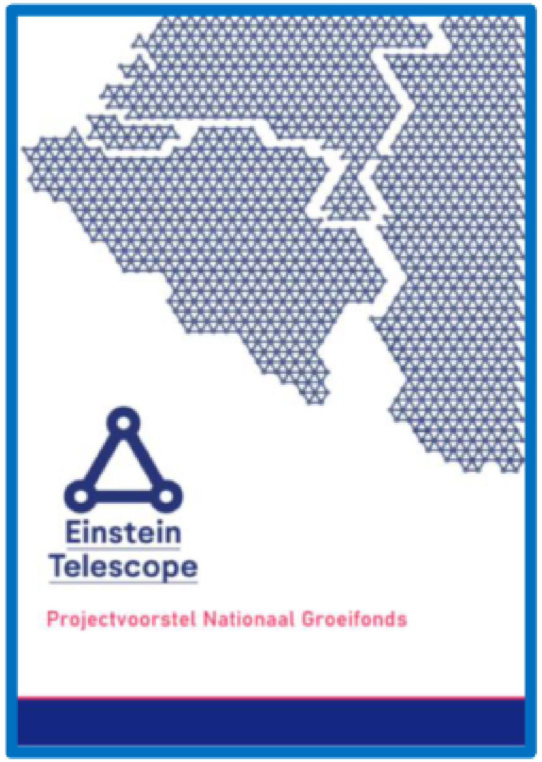
D. D’Urso – University of Sassari
and INFN-LNS

On behalf and with the contribution of
the ET Collaboration

Einstein Telescope in Euregio Meuse-Rhine (EMR)

Connected institutions in:
Belgium,
Germany &
the Netherlands

Nationaal Groeifonds (the Netherlands)



Emphasis on potential socio-economic Impact

Submitted by OCW Ministry
(EZK Ministry support)

Supported by ~70 Dutch Industries/institutions

In October 2021 the Netherlands submitted large funding proposal within context of the '*Nationaal Groeifonds*'. Decision on April 2022.

Approved

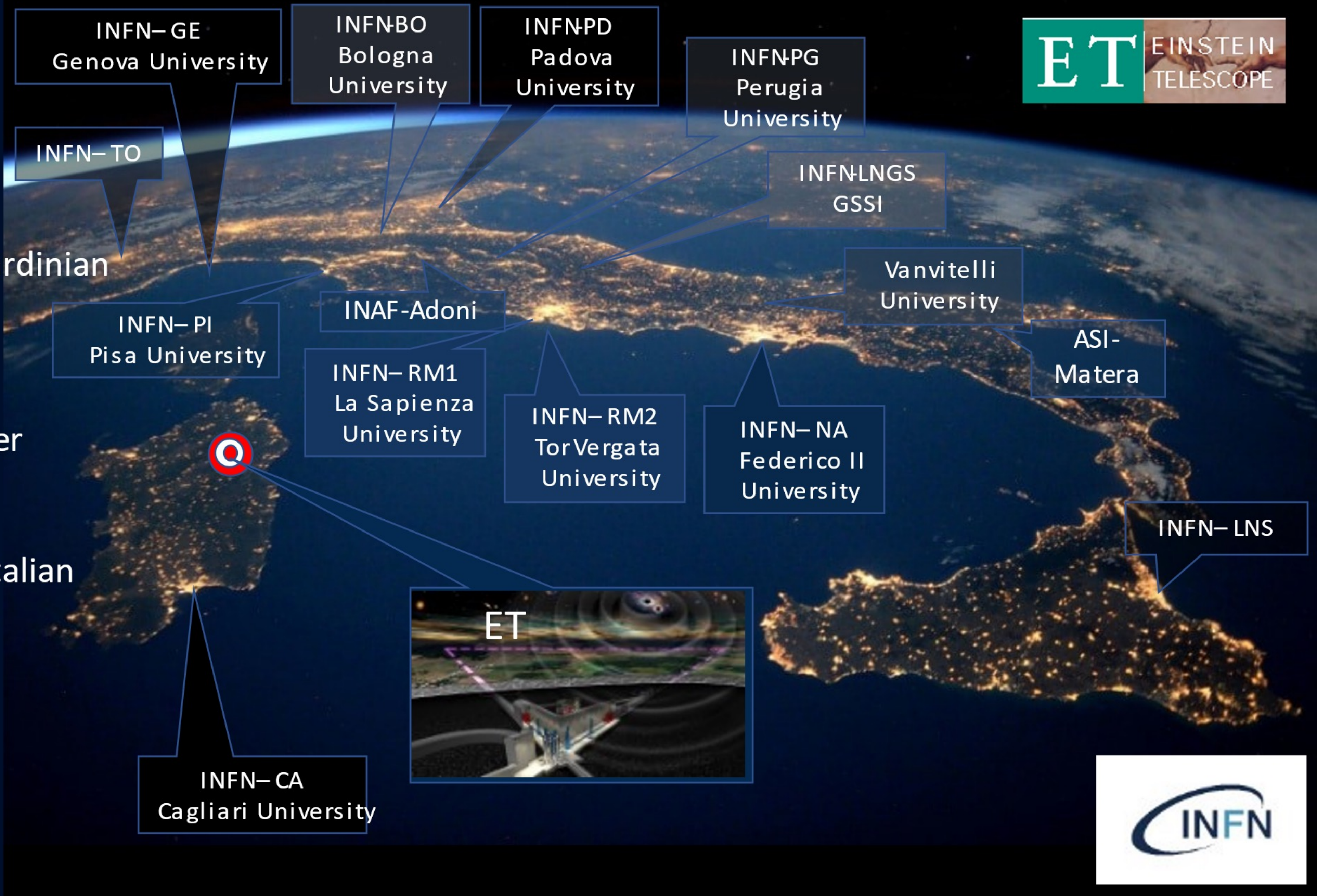
Includes 42 M€ for geology, R&D & organization
as well as possible Dutch share towards ET realization

ETIC – Einstein Telescope Infrastructure Consortium

Next Generation EU Investment focused on ET enabling technology and Sardinian site candidature support

Negotiation 7th of September 2022

Discussion ongoing on an Italian share toward ET realization



α_G is typically defined in terms of the gravitational attraction between two electrons:

$$\alpha_G = \frac{Gm_e^2}{\hbar c} = \left(\frac{m_e}{m_P}\right)^2 \approx 1.7518 \times 10^{-45}$$

where:

- G is the gravitational constant;
- m_e is the electron rest mass;
- c is the speed of light in vacuum;
- $\hbar$ is the reduced Planck constant;
- m_P is the Planck mass.

In Planck units, where $G = c = \hbar = 1$, the expression becomes the square of the electron mass

If α_G is defined using the mass of one electron, m_e, and one proton, m_p, then $\alpha_G = 3.217 \times 10^{-42}$