Institut national de physique nucléaire
et de physique des particules

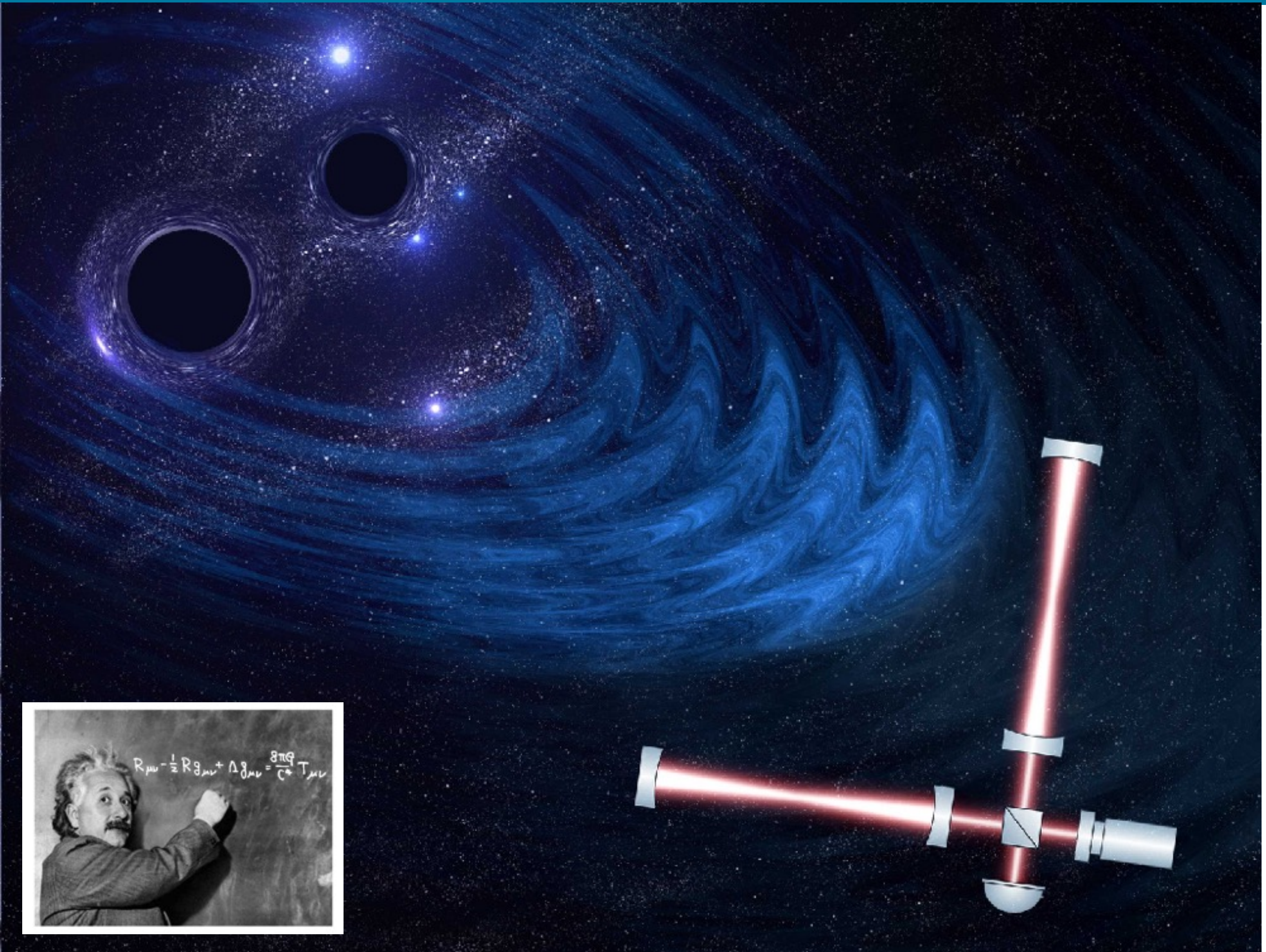
The Einstein Telescope Project @ CNRS

DMLab Annual Workshop

Karlsruhe, November 17th, 2023

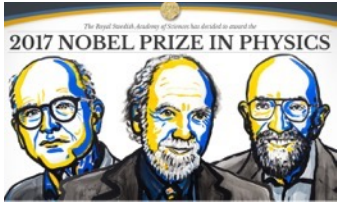
Patrice Verdier (IP2I Lyon – IN2P3) - patrice.verdier@in2p3.fr

Introduction

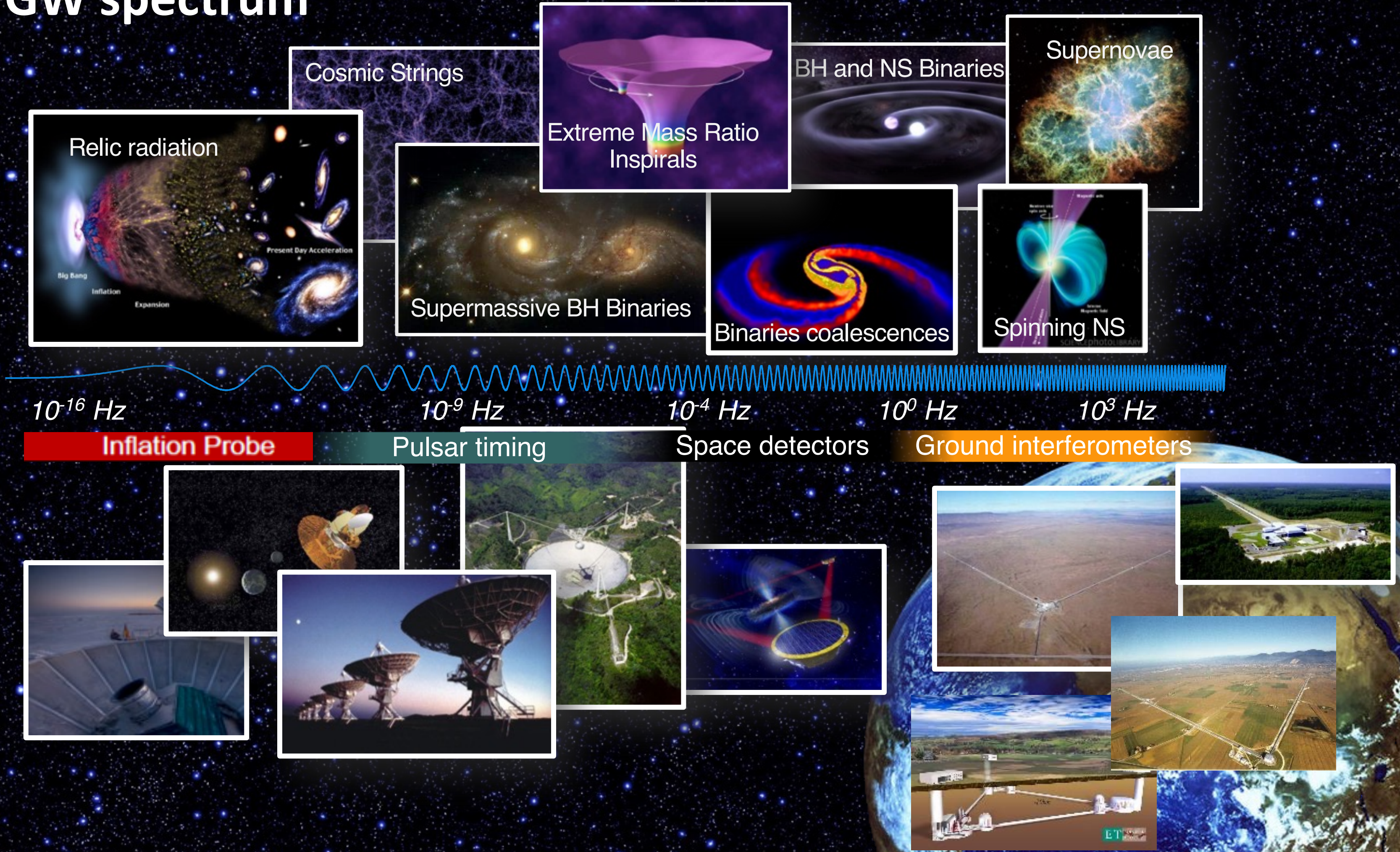


100 years after their prediction as part of Einstein's theory of general relativity, the discovery of gravitational waves opens a new way to explore and study the Universe!

Nobel Prize in Physics 2017



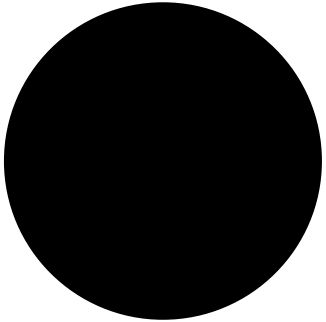
GW spectrum



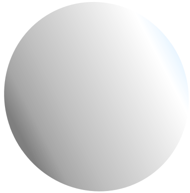
Cosmic Strings
Extreme Mass Ratio Inspirals
BH and NS Binaries
Supernovae
Relic radiation
Present Day Acceleration
Big Bang
Inflation
Expansion
Supermassive BH Binaries
Binaries coalescences
Spinning NS
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
Inflation Probe
Pulsar timing
Space detectors
Ground interferometers

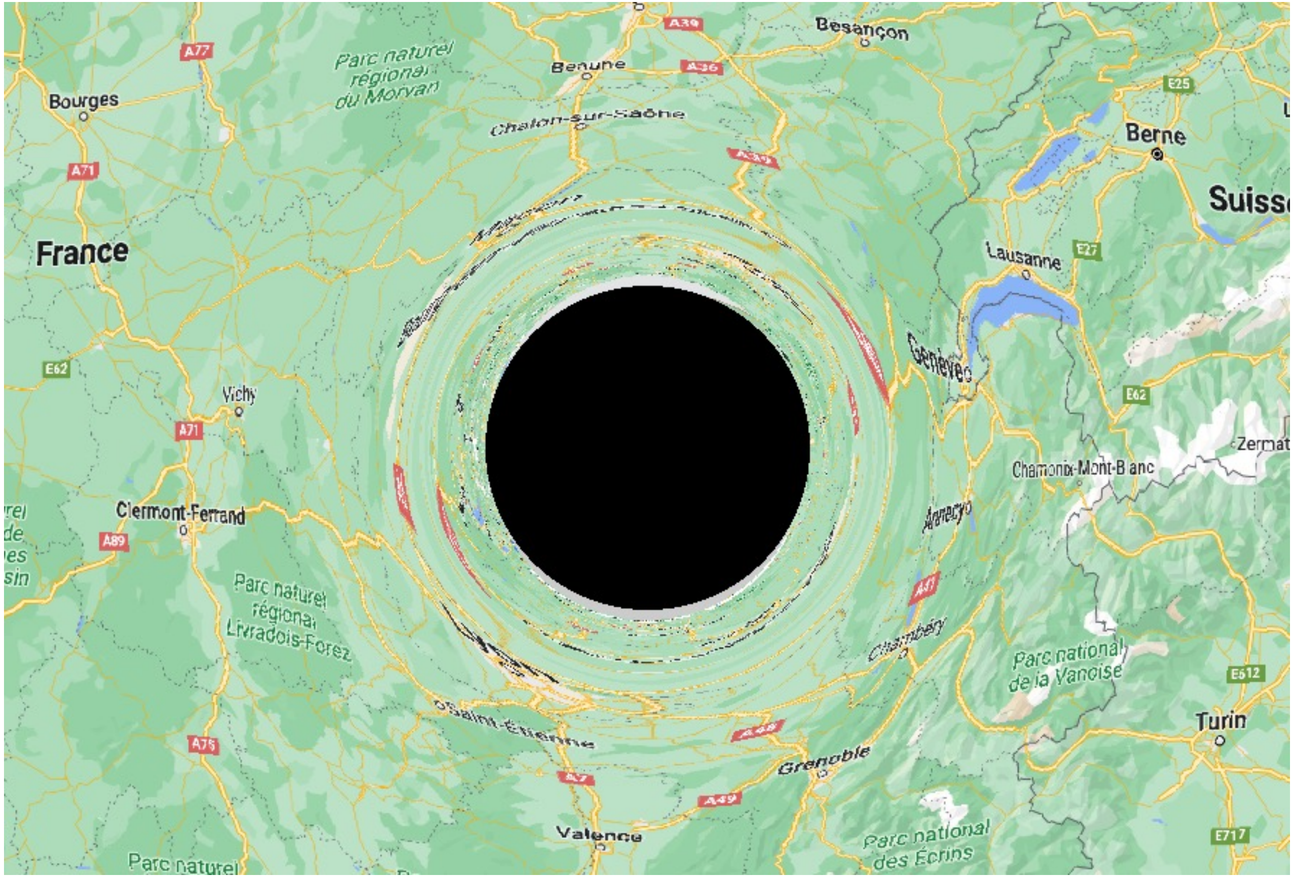
Intodution

Black hole of 15 $M_\odot$



Neutron star 1.4 $M_\odot$





@ David Ball, University of Arizona: http://bhpire.arizona.edu/research/tools/black-hole-photo-filter/

Current 2G Interferometers

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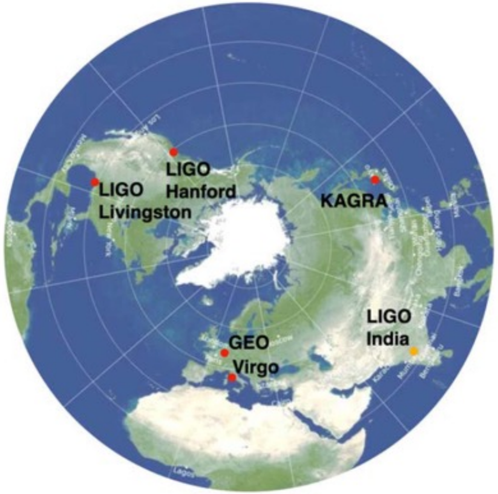
LIGO
Livingston



KAGRA

LIGO
Hanford

Virgo

Einstein Telescope

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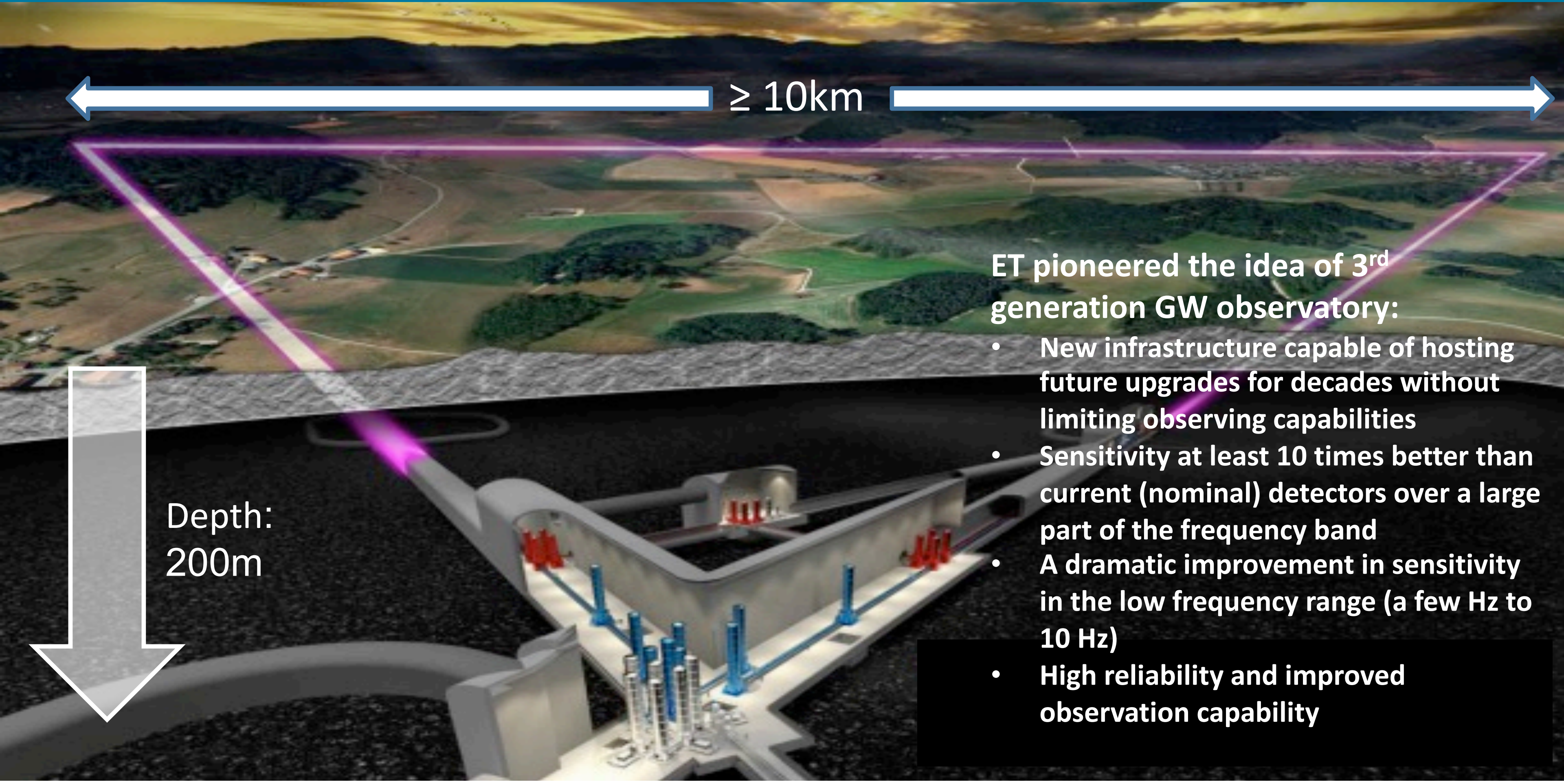

ET pioneered the idea of 3rd generation GW observatory:

- New infrastructure capable of hosting future upgrades for decades without limiting observing capabilities
- Sensitivity at least 10 times better than current (nominal) detectors over a large part of the frequency band
- A dramatic improvement in sensitivity in the low frequency range (a few Hz to 10 Hz)
- High reliability and improved observation capability

GW detection with 3rd gen. interferometers

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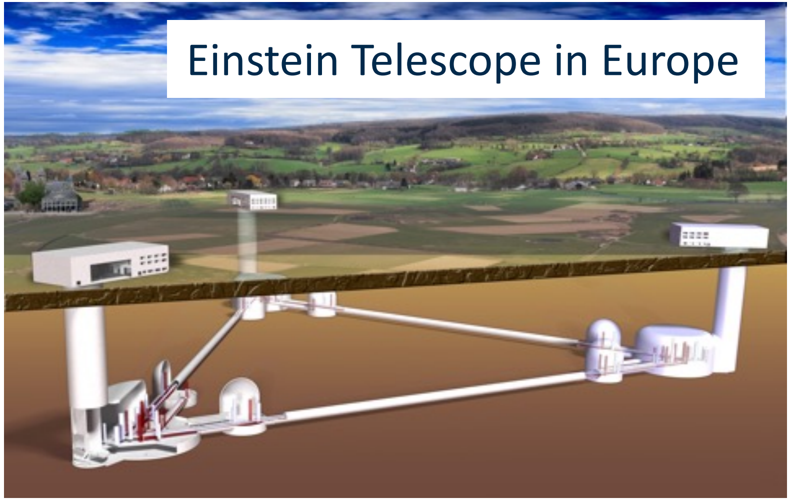
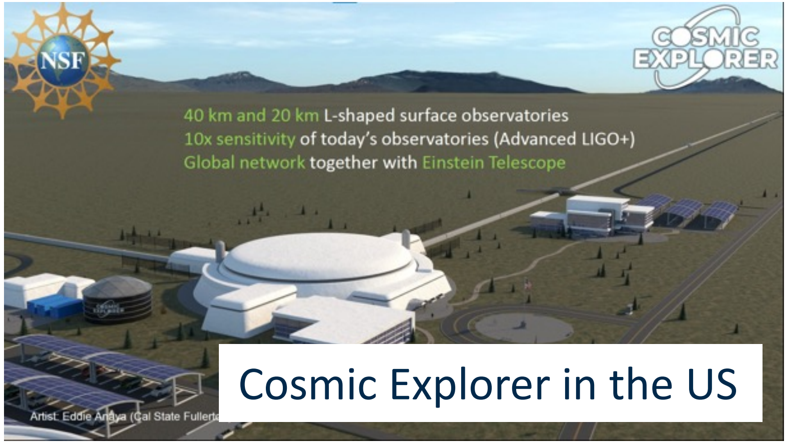
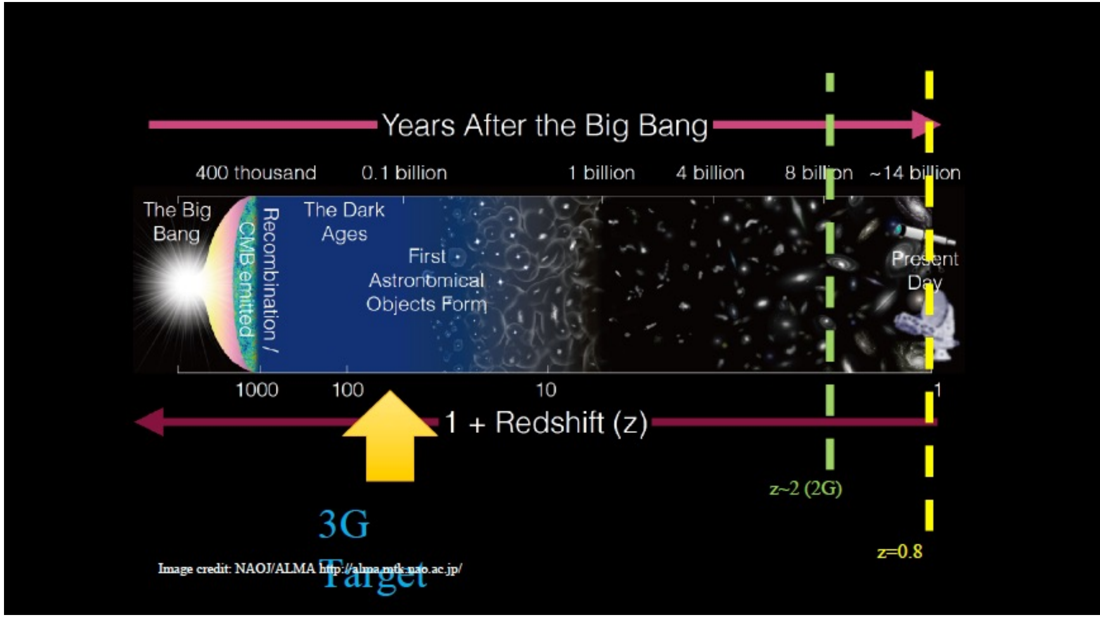
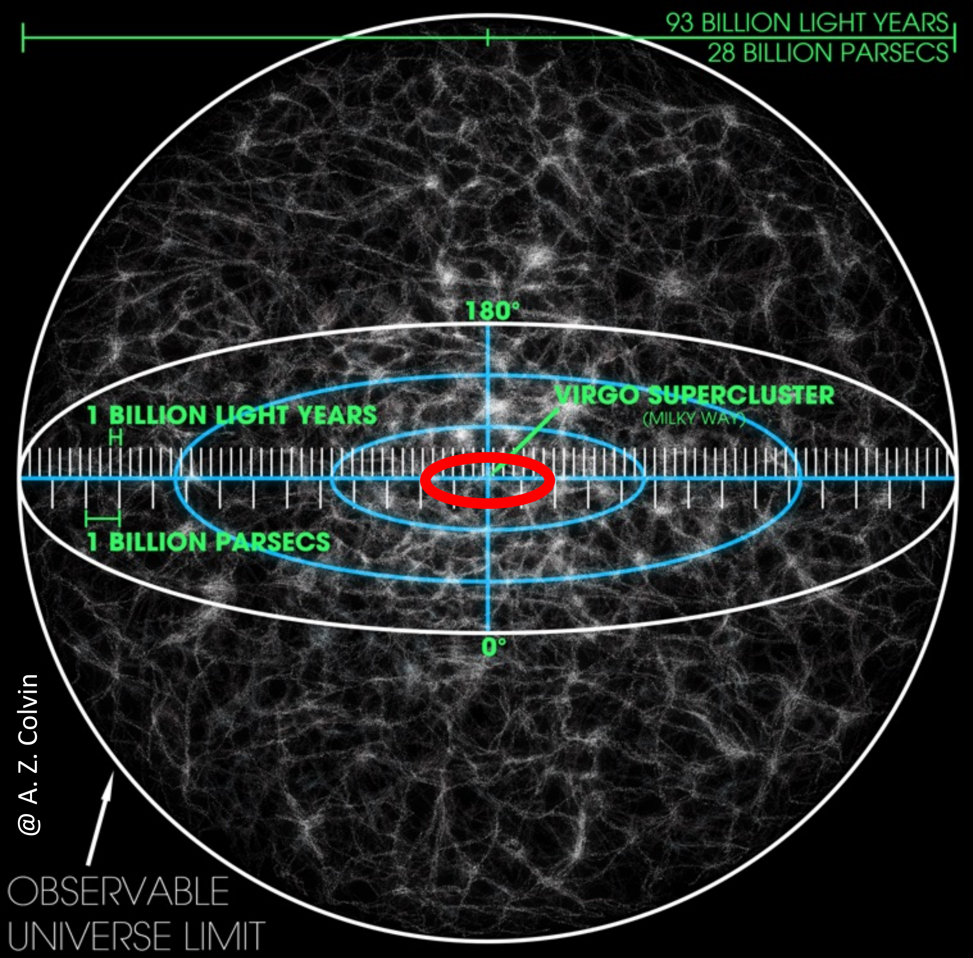


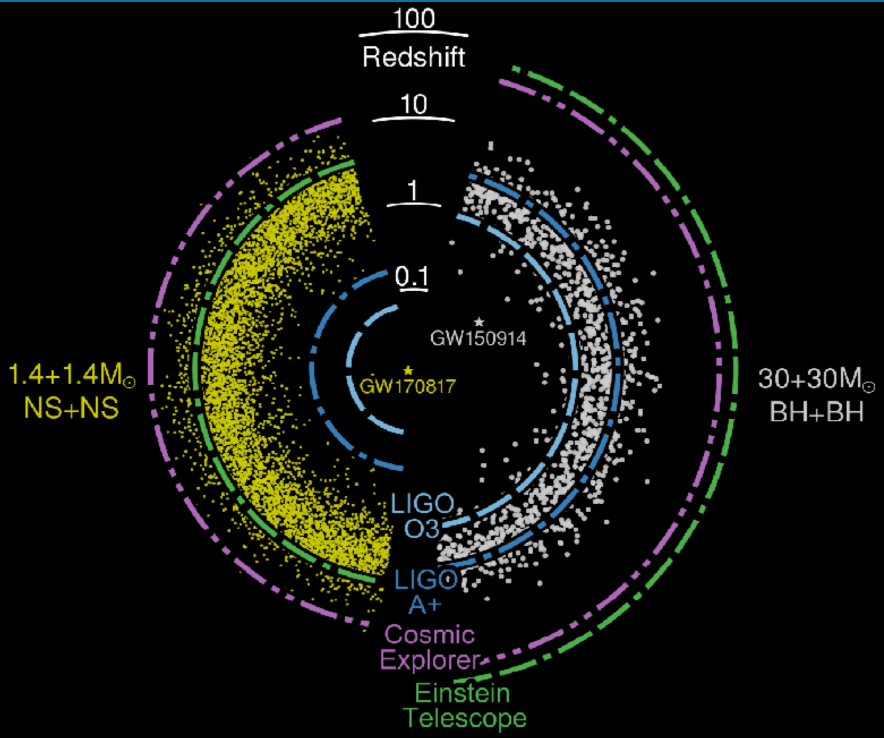




Introduction



@ A. Z. Colvin



Einstein Telescope aims to study most of the observable Universe

GW science programme

ASTROPHYSICS

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

Neutron star properties
interior structure, equation of state & properties
of dense 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 (Radio, X, g and GW, FRB, …)
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, phase transition in dense matter

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

Dark matter
primordial BHs
axions, dark matter accreting on compact objects

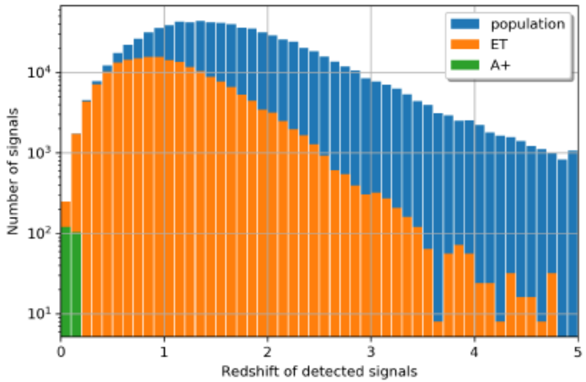
Dark energy and modifications of gravity on cosmological scales
dark energy equation of state,
modified GW propagation

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

The “unexpected” ?

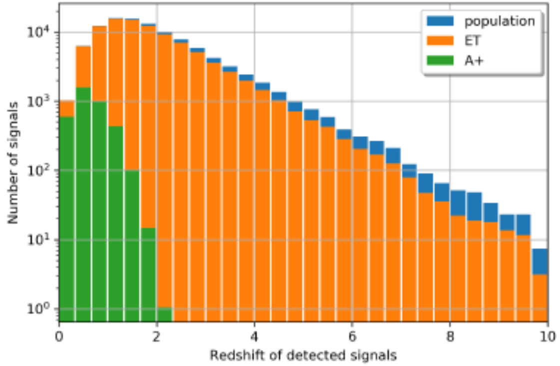
ET sensitivity

BINARY NEUTRON-STAR MERGERS



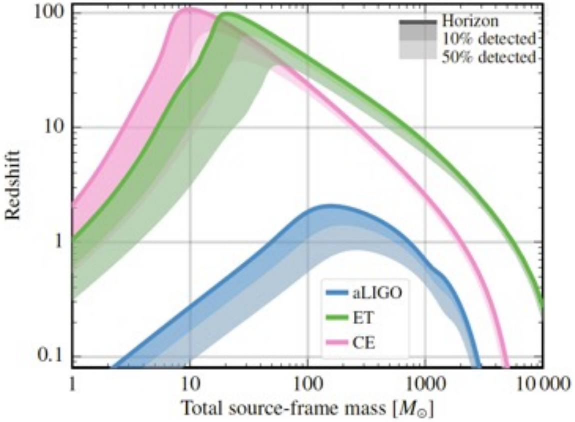
~1 detection every 30s

BINARY BLACK-HOLE MERGERS



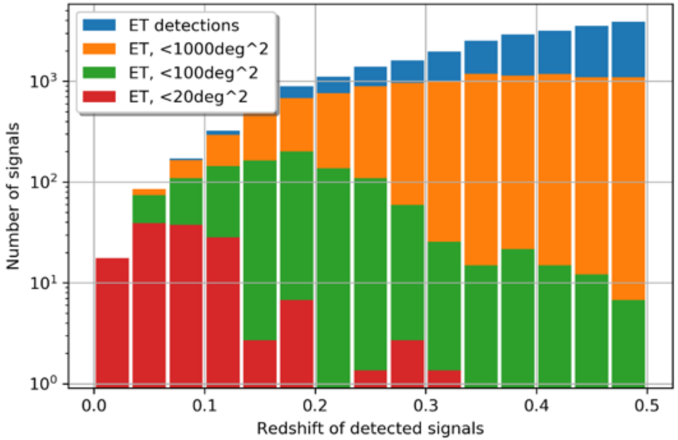
- 10^5-10^6 BBH detections per year
- 10^4-10^5 BNS detections per year among which ~10-100 with EM counterparts
- High SNR events
- Overlapping events

- ET 1st Mock Data challenge in progress
- 40 papers since 2022 summer on ET science

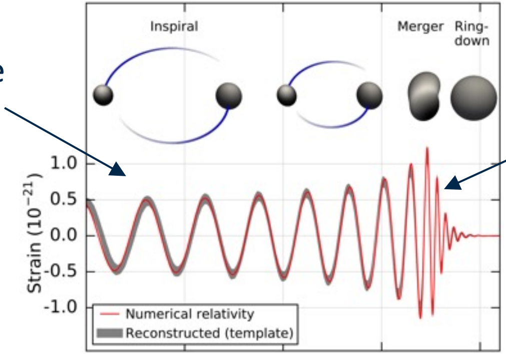


ET sensitivity

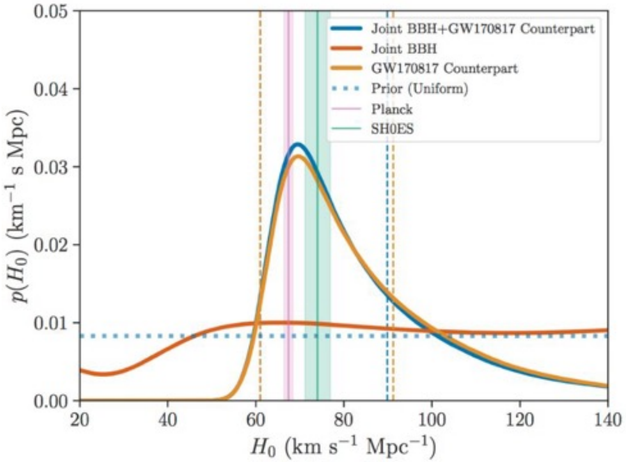
- **BNS detection with EM counterparts and localization precision < 20 deg²** : o(10-100) per year
- Overlap with many BBH signals
- Potentially, very long signals
- ET will be able to provide alerts few hours before the merger



Identify early the inspiral …

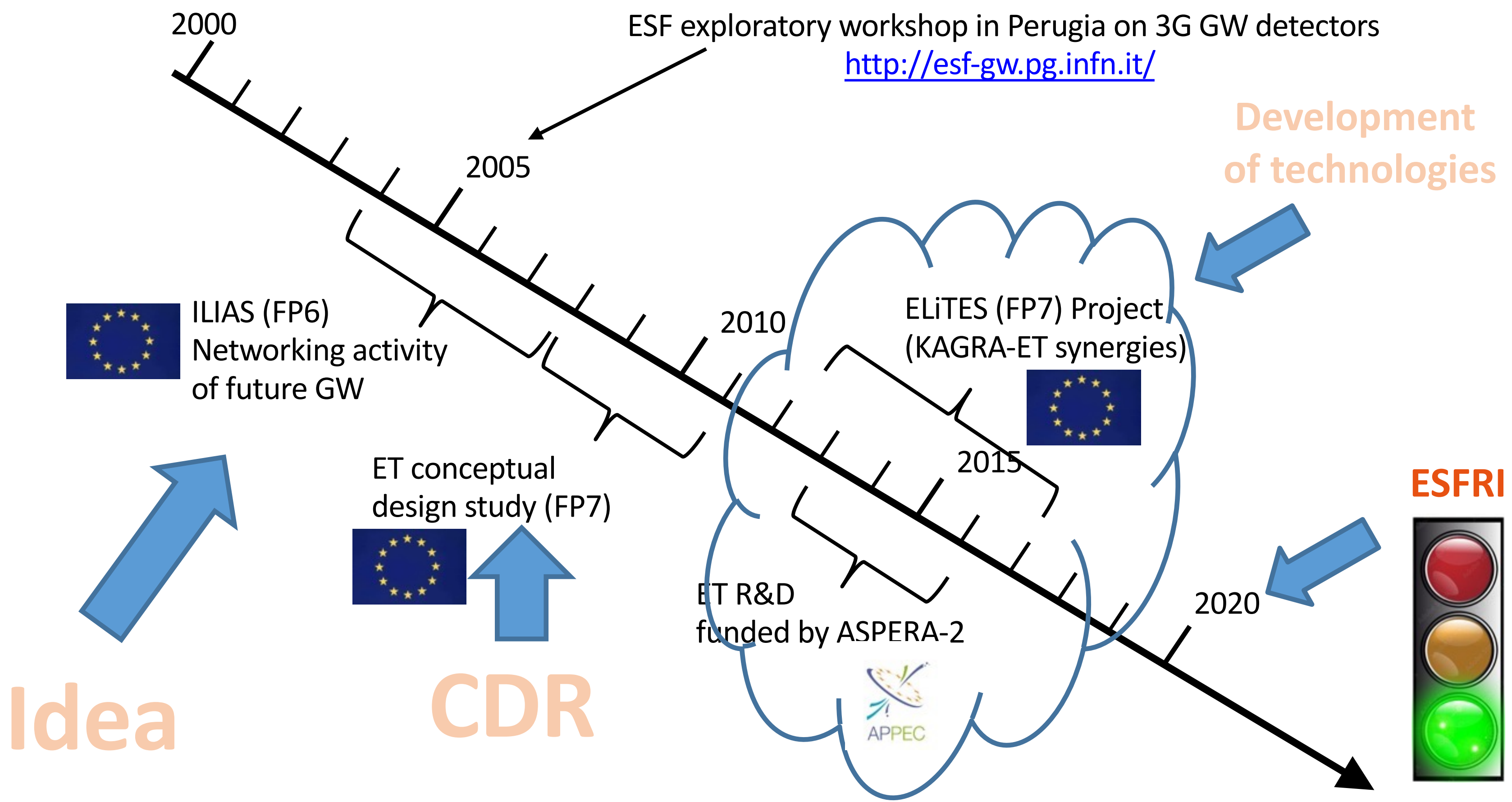


… and provide alert before the merger phase



- And with ~500 BNS-EM detection, we can reach Planck resolution on H_0 measurement

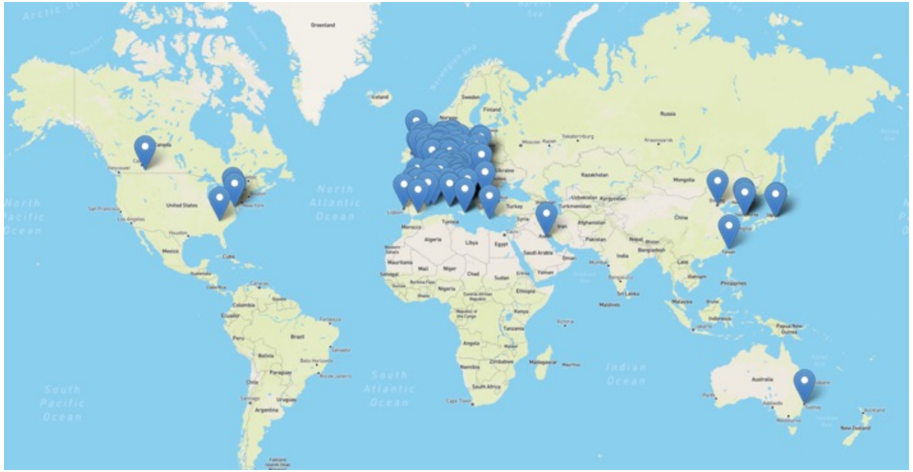
The genesis of the Einstein Telescope



The genesis of the Einstein Telescope

ESFRI

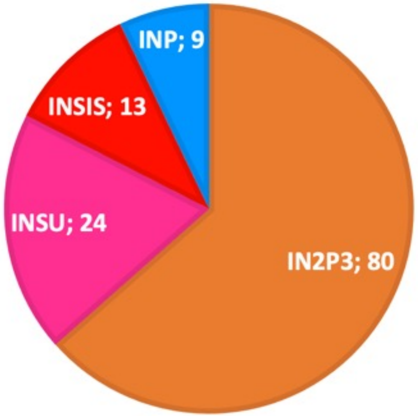
ET Collaboration



1500 collaborators from 217 institutes in 24 countries worldwide

Birth of the ET Collaboration
in June 2022 in Budapest

ET France



126 French collaborators Officially joined the ET Collaboration

Mailing list ET-France:
ET-FRANCE-L@IN2P3.FR

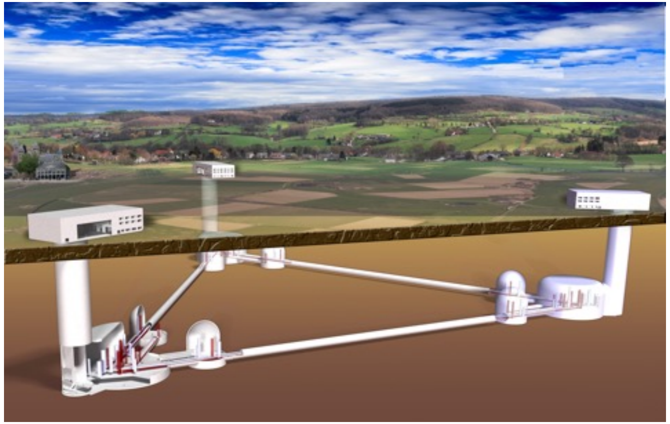
ET-France web site: https://et-france.in2p3.fr

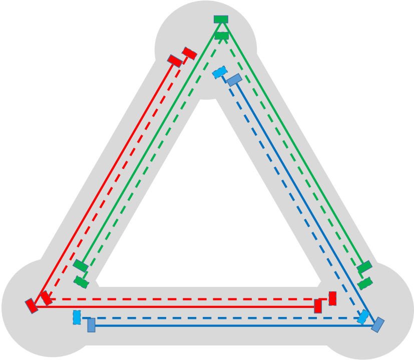
Einstein Telescope France

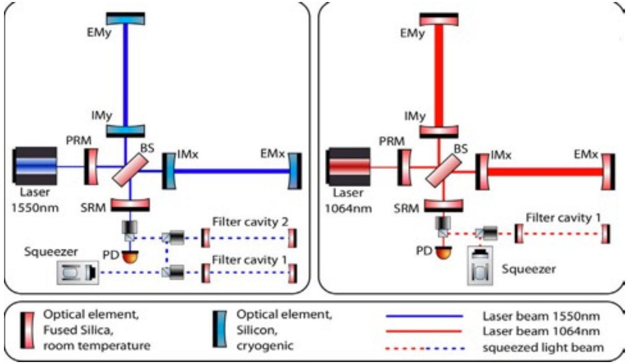
Research Unit (RU)	Laboratories
Artemis	ARTEMIS
Astroparticule et Cosmologie (APC)	APC
	IAS
	SUBATECH
IF-ILM	IF
	ILM
	MSME
IJCLab	IJCLab
	LKB Paris
IP2I - LMA	IP2I Lyon - IN2P3
	LMA - IN2P3
IPHC-L2IT	IPHC
	L2IT
LAPP	LAPP
Paris - Caen	Observatoire de Paris (GEPI, LUTH, SYRTE)
	GANIL / LPC Caen
	IAP

+ CC-IN2P3

Underground infrastructure



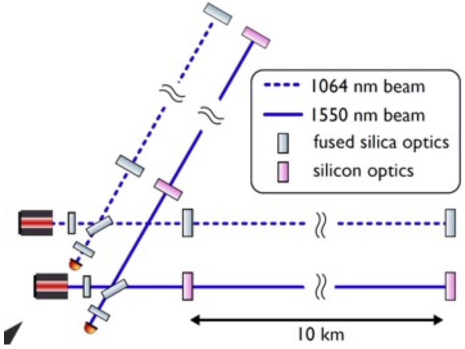




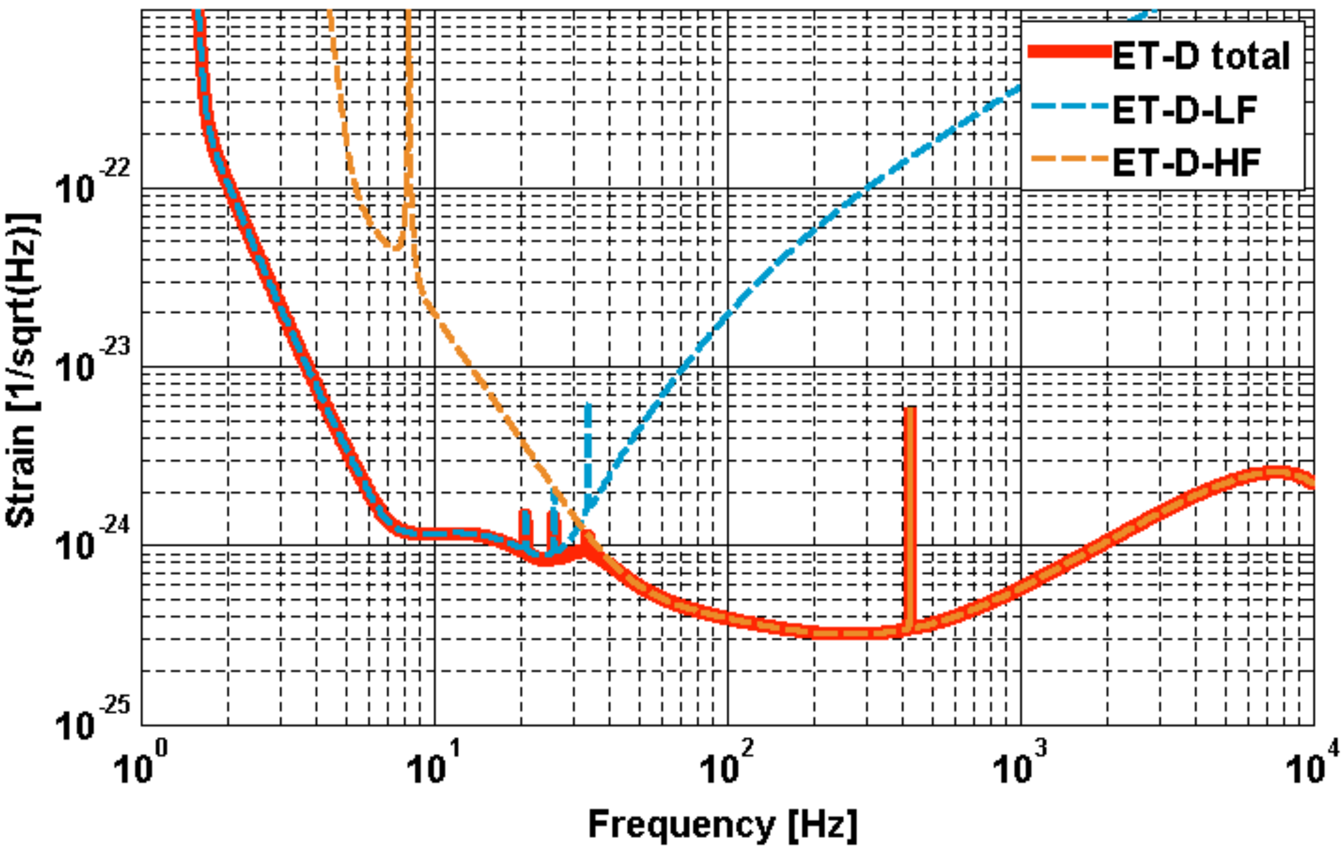
Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

Xylophone: 2 sensitive interferometers at different frequencies

Triangle configuration to have 3 detectors in the same infrastructure



ET Sensitivity



Site candidates

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There are currently two sites in Europe that are candidates to host ET:

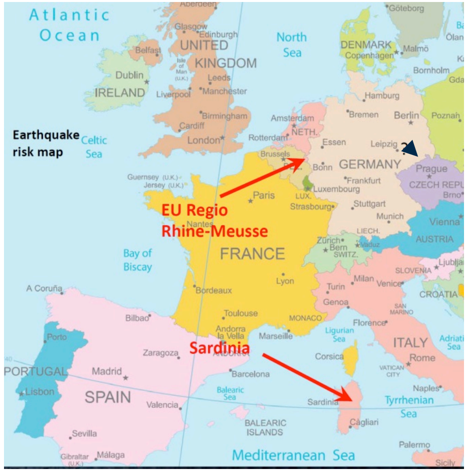
- The Sardinia site, near the Sos Enattos mine
- The EU Regio Rhine-Meuse site, close to the NL-B-D border

[A third option in Saxony in the future ?]

The sites are studied through

- Seismic noise measurements at surface, in boreholes and mines (Sardinia)
- Magnetic and ambient noise measurements
- Geophysical and geotechnical characterizations

Significant funds are required to develop and submit a site application



Highlight 2023

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Highlights 2023

"COBA" (Cost-Benefit Analysis) conducted by a sub-group of the OSB:

- Impact of the geometry on the physics potential
- Essential inputs from ISB
- ETRAC risk analysis

The result of these analyses put strong emphasis on the comparison between the configurations: “1Δ 10km” and “2L 15km”

Physics potential with "2L 15 km" is generally better (45° orientation) and less risky: Detailed analysis of the costs to be carried out

arXiv:2303.15923 - *JCAP* 07 (2023) 068

Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi,[1,2] Michele Maggiore,[3,4] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11] Ssohrab Borhanian,[12] Daniel David Brown,[13] Man Leong Chan,[14] Giulia Cusin,[15,3,4] Stefan L. Danilishin,[16,17] Jerome Degallaix,[18] Valerio De Luca,[19] Arnab Dhani,[20] Tim Dietrich,[21,22] Ulyana Dupletsa,[1,2] Stefano Foffa,[3,4] Gabriele Franciolini,[8] Andreas Freise,[23,16] Gianluca Gemme,[24] Boris Goncharov,[1,2] Archisman Ghosh,[7] Francesca Gulminelli,[25] Ish Gupta,[20] Pawan Kumar Gupta,[16,26] Jan Harms,[1,2] Nandini Hazra,[1,2,27] Stefan Hild,[16,17] Tanja Hinderer,[28] Ik Siong Heng,[29] Francesco Iacovelli,[3,4] Justin Janquart,[16,26] Kamiel Janssens,[10,11] Alexander C. Jenkins,[30] Chinmay Kalaghatgi,[16,26,31] Xhesika Koroveshi,[32,33] Tjonnie G. F. Li,[34,35] Yufeng Li,[36] Eleonora Loffredo,[1,2] Elisa Maggio,[22] Michele Mancarella,[3,4,37,38] Michela Mapelli,[39,40,41] Katarina Martinovic,[6] Andrea Maselli,[1,2] Patrick Meyers,[42] Andrew L. Miller,[43,16,26] Chiranjib Mondal,[25] Niccolò Muttoni,[3,4] Harsh Narola,[16,26] Micaela Oertel,[44] Gor Oganesyan,[1,2] Costantino Pacilio,[8,37,38] Cristiano Palomba,[45] Paolo Pani,[8] Antonio Pasqualetti,[46] Albino Perego,[47,48] Carole Périgois,[39,40,41] Mauro Pieroni,[49,50] Ornella Juliana Piccinni,[51] Anna Puecher,[16,26] Paola Puppo,[45] Angelo Ricciardone,[52,39,40] Antonio Riotto,[3,4] Samuele Ronchini,[1,2] Mairi Sakellariadou,[6] Anuradha Samajdar,[21] Filippo Santoliquido,[39,40,41] B.S. Sathyaprakash,[20,53,54] Jessica Steinlechner,[16,17] Sebastian Steinlechner,[16,17] Andrei Utina,[16,17] Chris Van Den Broeck,[16,26] and Teng Zhang[9,17]

arXiv:2303.15923v1 [gr-qc] 28 Mar 2023

Timeline remains unchanged: Preliminary/Preparatory Phase 2022-2026

- Writing the Science Book
- Preparation of the TDR and computing model for 2025-2026: ET-PP deliverables
- And site selection in 2025-2026

Timeline : 2G and 3G

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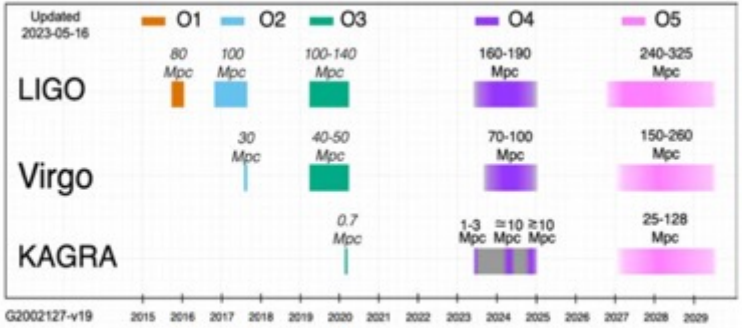
Current infrastructures



First detection

GW170817

90 sources

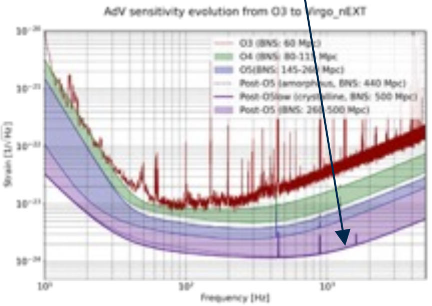
Advanced Virgo+
Advanced LIGO+

LIGO upgrade A#

Virgo_nEXT

KAGRA upgrade

2030's

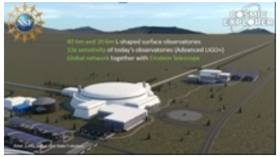


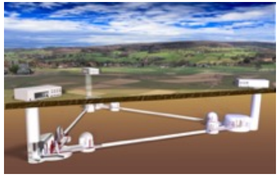
New infrastructures

Cosmic Explorer

Einstein Telescope

- First light before end of 2030' decade
- Full sensitivity a few years later (TBC)





Schedule

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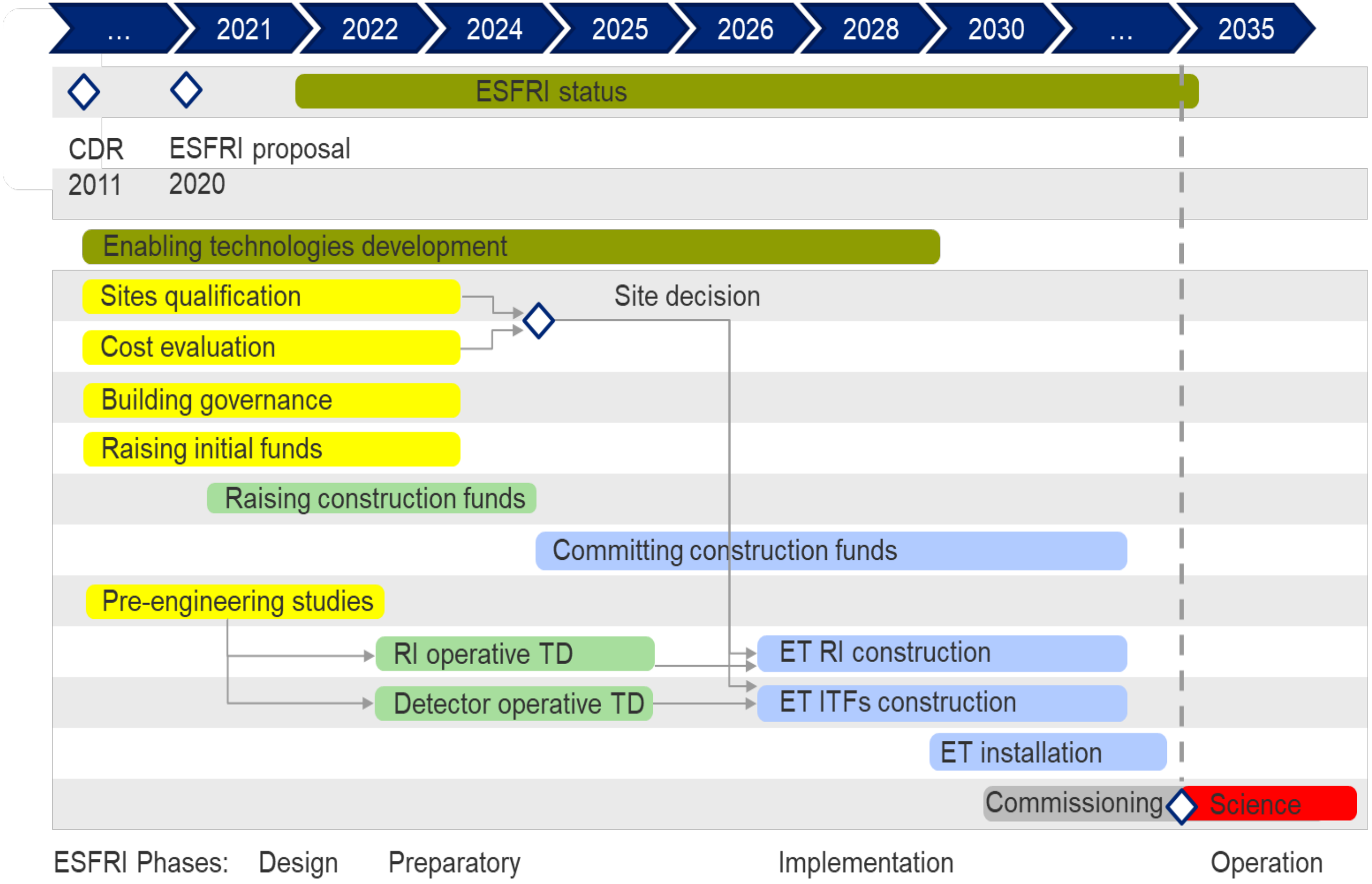
* Tentative schedule



R&Ds – ongoing and in preparation

Several studies and research axes underway at the CNRS for the needs of ET or for the improvements of the current detectors – Advanced Virgo+ and Virgo_nEXT – which will be used for ET (non-exhaustive list):

Vacuum Tubes

- Approx. 120-130 km of ~1m diameter vacuum tubes
- 120,000 m^3 of vacuum (2000 m3 LHC at CERN for comparison) - ~100 vacuum revolutions
- Expected pressure < 10^{-10} mbar
- Many associated components: pumps, sensors, valves, etc
- Creation of a vacuum tube prototype – LAPP/IJCLab

Squeezing/Quantum Technology

- Quantum noise reduction through high-frequency squeezing -> Virgo/LIGO 3dB for 03, improvement in progress for 04
- 10dB expected for and Developments, Demonstrations, Improvements of Frequency-Dependent Vacuum Squeezing Sources – APC/IJCLab

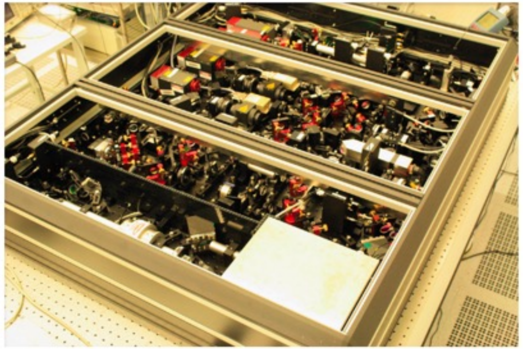
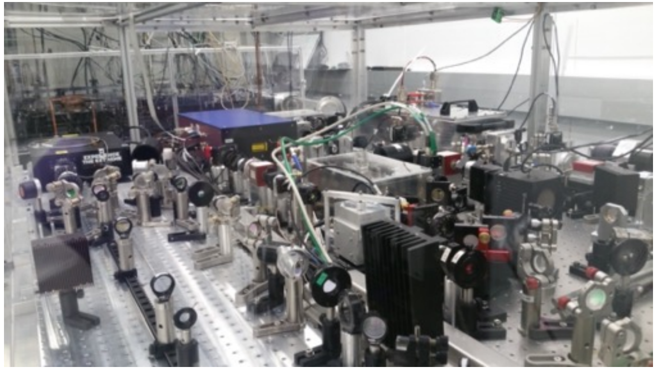


Photo: AEI/GEO600

Mirrors: Coatings and Substrates

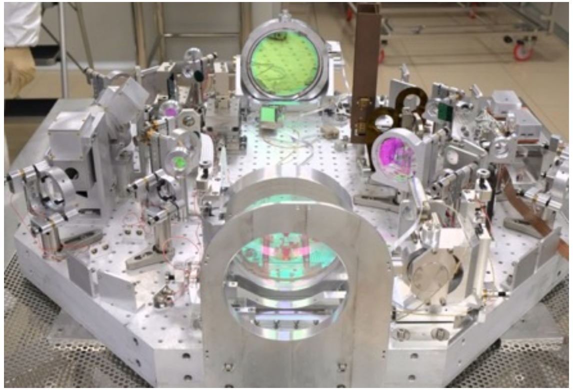
- Large mirrors with extreme optical properties
- Thin-film coatings with low optical and mechanical losses
- Lack of diffusion and absorption points
- New Technology: Crystalline Coatings
- Improvement of amorphous coatings – LMA/ILM
- Studies and development of new crystalline coatings – LAPP/LMA
- Sapphire substrate studies – ILM/IP2I

R&Ds – ongoing and in preparation



High Power Laser
- Two wavelengths: 1064 nm and 1550 nm
- Ultra-stable continuous lasers – amplified up to ~ hundred W
- Bandwidth <1 kHz and stabilization at ~mHz
- Low noise of RIN intensity
- Low phase noise
    - High-power, ultra-stable laser R&D developments – ARTEMIS

Auxiliary optics: telescopes, mode-cleaner
- Telescopes, mode-cleaner (among others) – ultra-stable optics, motorized mounts
- Associated Opto-Mechanics
- Adaptive Optics
- Thermal compensation
    - Optical and mechanical developments, simulations, design, realization – APC/L2IT/LAPP
    - Development of a suspended bench for optical and mechanical tests – LAPP



Electronics – real-time
- Several thousand sensors, actuators, controllers
- Need for electronic developments
    - Real-time electronics – specific developments – LAPP/IP2I
    - White Rabbit Upgrade – IJCLab

R&Ds – ongoing and in preparation

Stray Light

- Limiting Factor of Gravitational Wave Detectors
    - Development of tools for more accurate calculations – measurements and control - Institut Fresnel/APC

Optical Simulations

- Need to understand, control and improve gravitational wave detectors
- Implement reliable and robust simulation tools
- Linear simulations: studying linear effects, opto-mechanical effects, the impact of high power
- Time-domain simulations to study control noise
    - 3D simulation
    - The French community is being set up in this area – APC/L2IT/LMA/LAPP

Other aspects under study:

- Sizing of Cryogenic Ultra Vacuum Towers (IJCLab)
- Calibration (LAPP/IPHC)
- Acoustics (LAUM)

New developments not studied for Virgo (Virgo_nEXT) or LIGO, to be prepared for ET:

- Cryogenics – R&Ds in preparation (IJCLab/APC)
- 1550 nm
- Machine Learning / AI / High Parallel Computing

R&D Facilities in Europe

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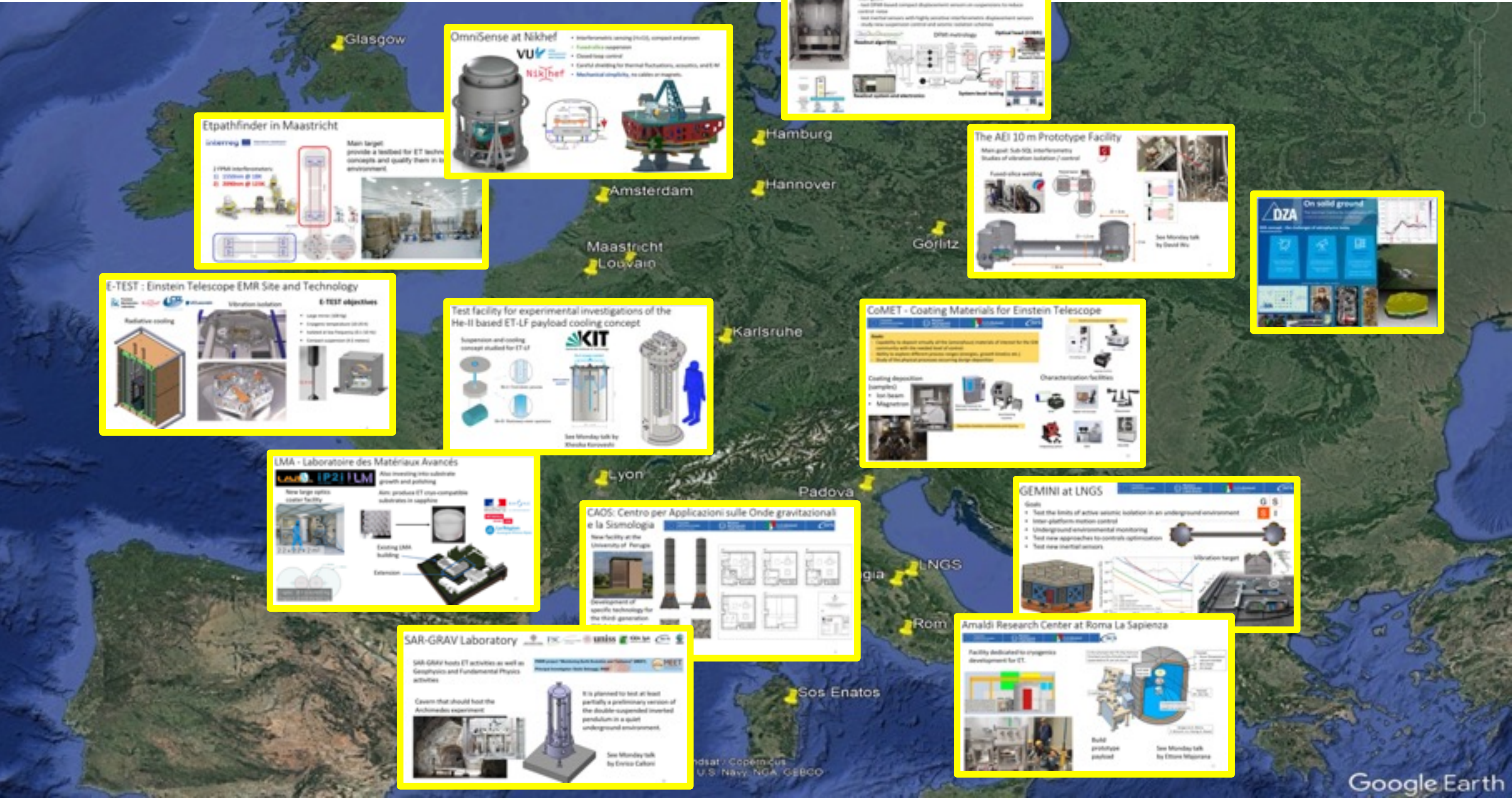
cnrs

From the XIII ET symposium, an incomplete selection of thepresented large facilities

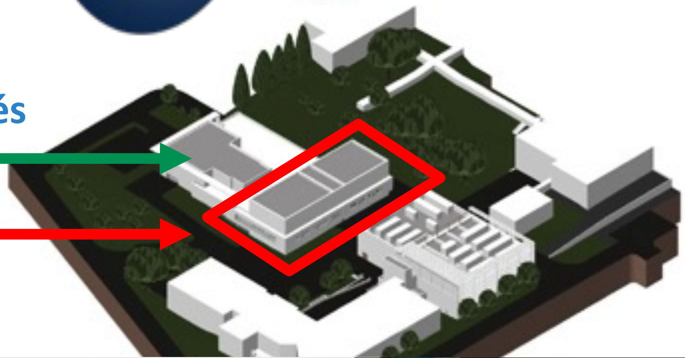


Extension of the LMA in Lyon

Laboratoire des Matériaux Avancés

Current

Extension



Contrat de Plan Etat-Région 2021-2027

An investment for:

- the extension of the LMA building
- the construction of a new coater allowing the deposition of thin films on very large substrates: Ø 1.6 m, 600 kg
- associated optical and metrology tools

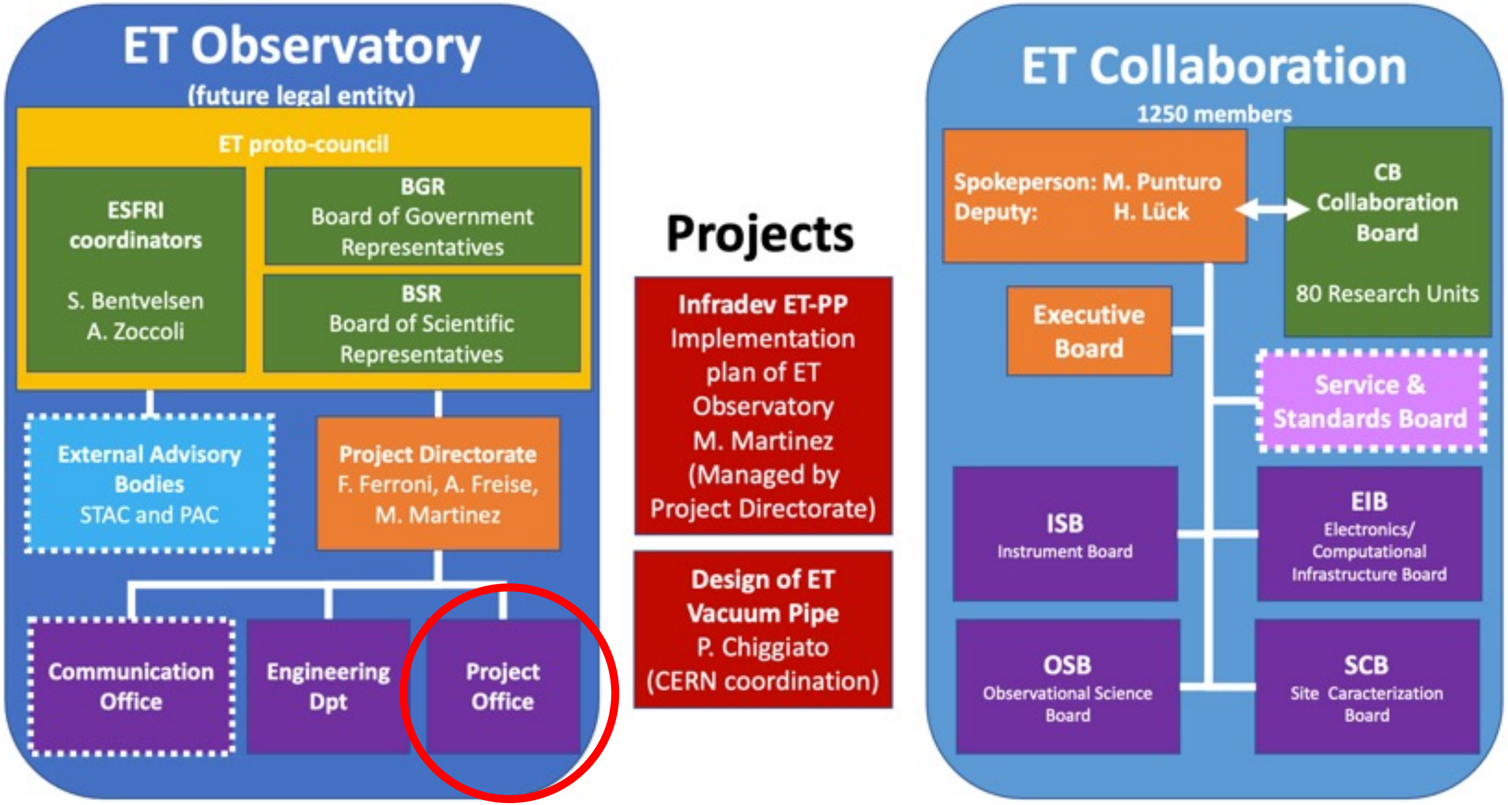
LMA is a research infrastructure unique in the world

Developing technologies for future experiments (e.g. Einstein Telescope)

ET Infrastructure and ET Collaboration

The EU supports the creation of the ET infrastructure (ETO) through the financing of an Infradev project:

Einstein Telescope Preparatory Phase (ET-PP)



Since the summer of 2022, the ET structures are being put in place

E-Infrastructure

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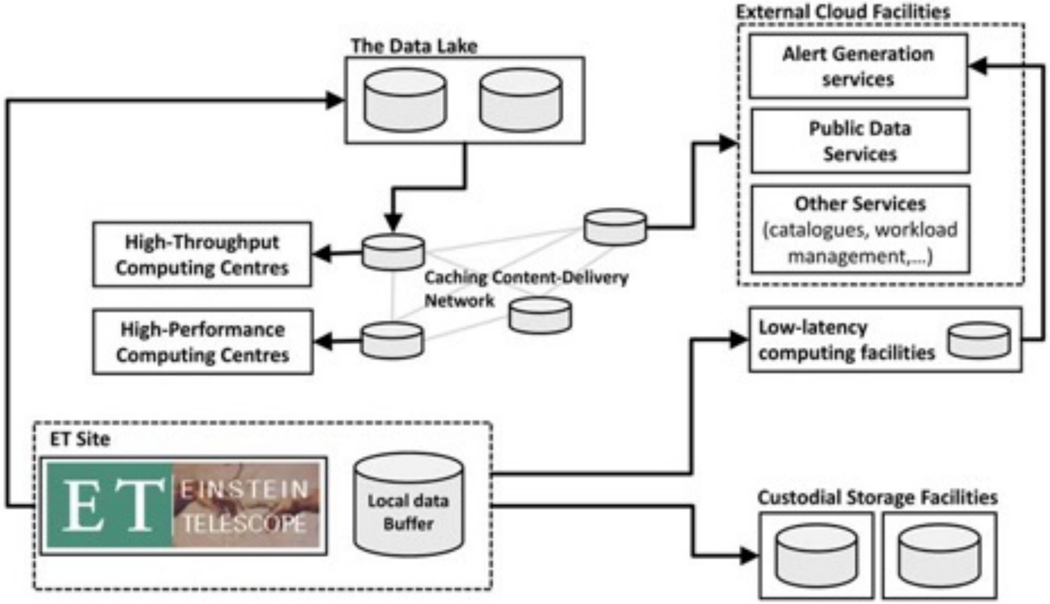
ET will use a **distributed computing infrastructure** in Europe, based largely on existing infrastructures such as CC-IN2P3 in France (ET = ~10% of an LHC exp. at CERN).
Increasing use of **high-performance parallel computing** (HPC) vs HTC computing.
Use of tools and services developed in the framework of the **European Open Science Cloud** and European projects such as ESCAPE for **multi-messenger physics**



Conclusion

Einstein Telescope is a very ambitious project for the late 2030s

In France, preparing 3G experiments for ground-based GW detection has been identified as a priority in the Strategic Plan for French Nuclear, Particle and Astroparticle physics in the 2030 Horizon

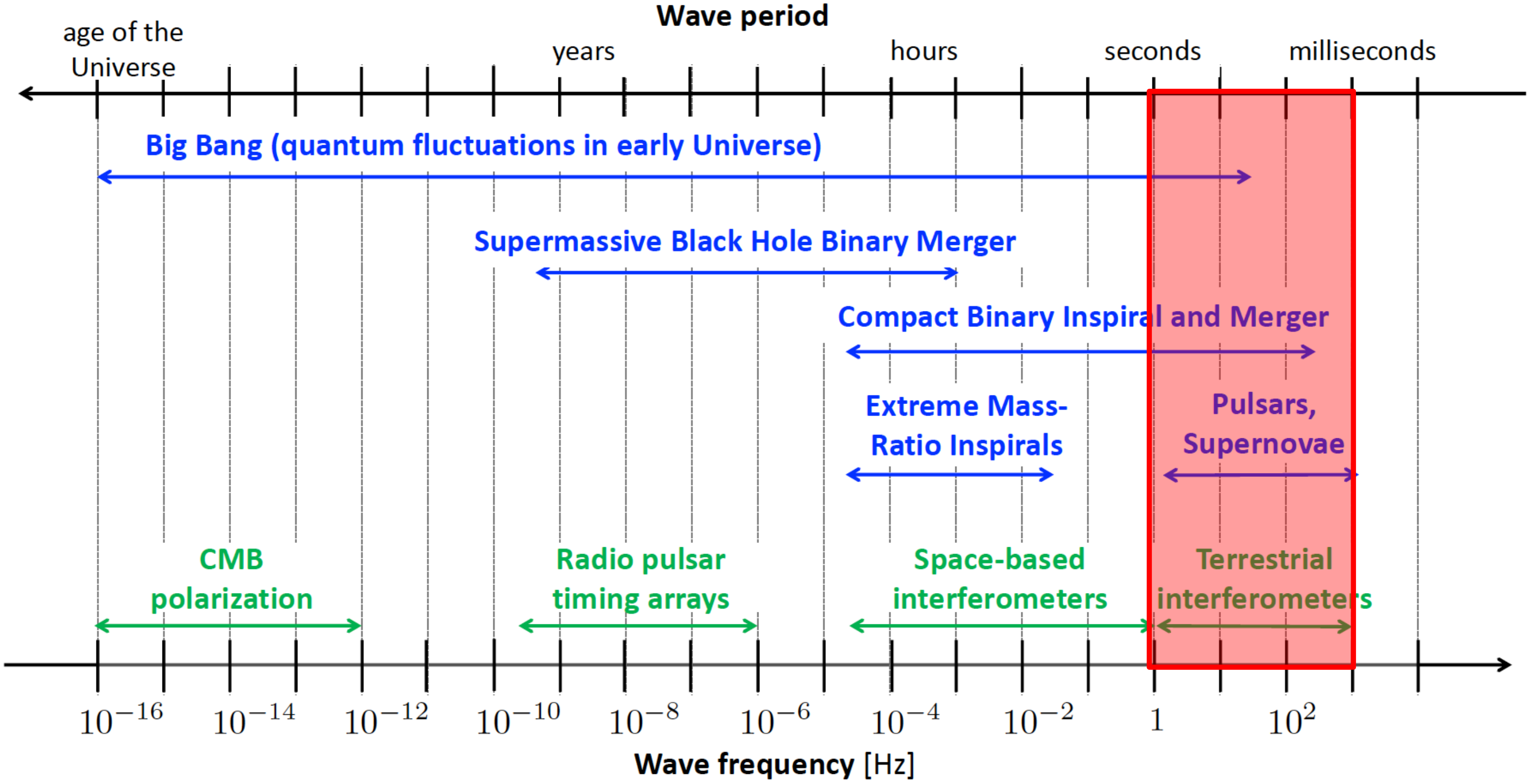
There are important synergies between Einstein Telescope, existing 2G detectors (LIGO-Virgo-KAGRA) and future detectors (Cosmic Explorer)

- Expertise acquired on EGO-Virgo and in LVK is an important asset
- French participation to ET is at this stage well controlled regarding the challenges of 2G detectors for the next ~15 years

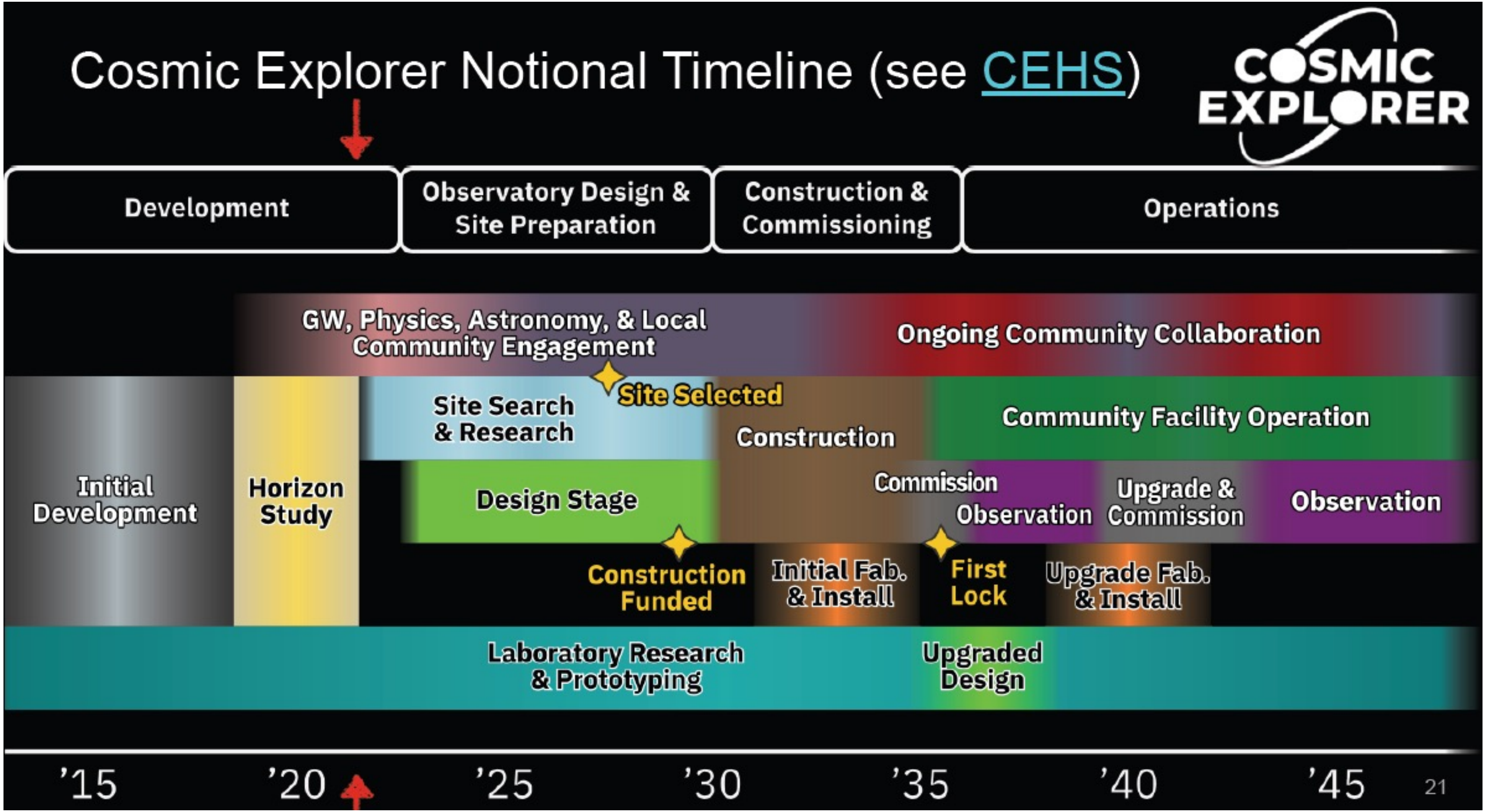
Several subjects of collaboration on GW physics between Helmholtz and IN2P3 labs have been identified : from physics studies (analysis, multimessenger, …) to technological developments (cryogeny, mirrors, computing …). It is now the right time to develop new collaborations on these subjects

RESERVE

Physical phenomenon, Search techniques



CE Timeline


Cosmic Explorer Notional Timeline (see CEHS)
COSMIC EXPLORER
Development
Observatory Design & Site Preparation
Construction & Commissioning
Operations
GW, Physics, Astronomy, & Local Community Engagement
Ongoing Community Collaboration
Initial Development
Horizon Study
Site Search & Research
Site Selected
Construction
Community Facility Operation
Design Stage
Commission
Observation
Upgrade & Commission
Observation
Construction Funded
Initial Fab. & Install
First Lock
Upgrade Fab. & Install
Laboratory Research & Prototyping
Upgraded Design
'15
'20
'25
'30
'35
'40
'45
21

ET technologies

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cnrs

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

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

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

Technologies and challenges for ET

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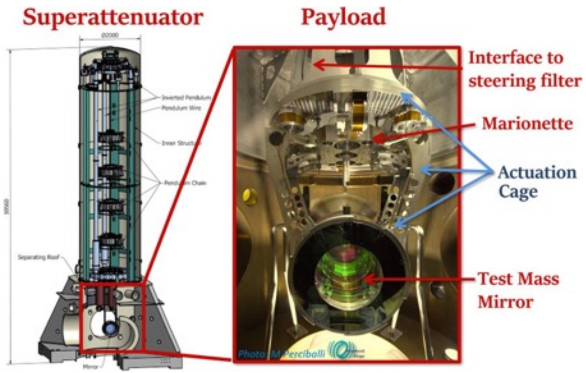
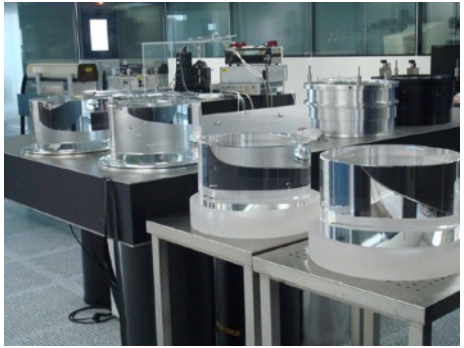
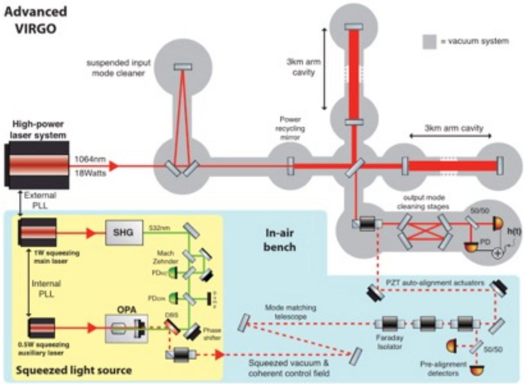
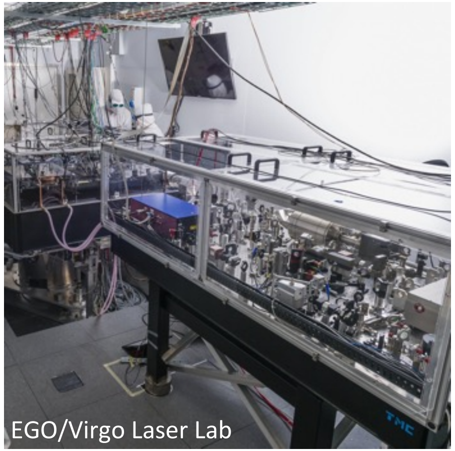
- Extrapolation of current or planned technologies for Virgo and LIGO
  – Squeezing (quantum states of light)
  – High power lasers
  – Bigger mirrors
  – New thin films for mirrors
  – Thermal compensation techniques
  – Seismic suspension systems
- Technologies not tested in Virgo and LIGO (prototypes and/or R&D in progress)
  – Cryogenics (=> KAGRA)
  – New cryogenic materials
  – New laser wavelengths

⇒ Implementation of R&D programs








EGO/Virgo Laser Lab

Vacuum pipe system

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Vacuum systems planned for 3G detectors are likely to be the largest UHV systems built

- The beam tube is its most important component (~1/2 of the cost of the system)
- 120 km of UHV tubes of 1 m diameter, total volume ~10^5 m3
- Vacuum requirements: factor > 5 stricter than Virgo:
- 10^{-10} mbar for H2, 10^{-11} mbar for N2, < 10^{-14} mbar for hydrocarbons
- Lifespan: 50 years - Preliminary estimated cost ~560 M€

Joint development with CERN involving Einstein Telescope and Cosmic Explorer (US Project)

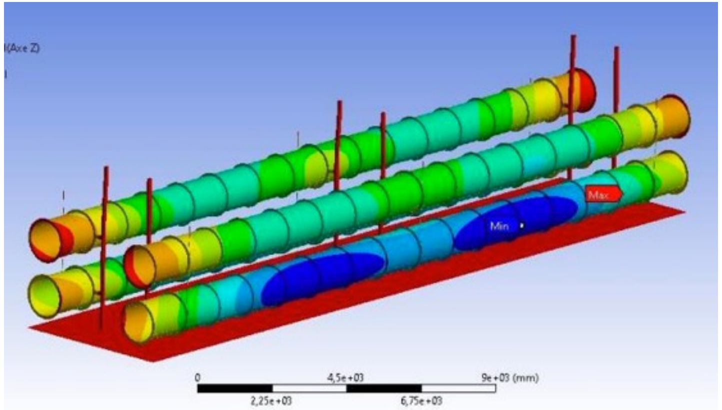
WP1: Design and engineering of the vacuum chamber [CNRS coordination]

Four designs are being considered:

- Baseline: Virgo-like solution adapted to ET tunnel
- Corrugated wall: 1.3-mm thick wall with regular corrugations
- Double wall chamber with thermal insulator between the two walls
- Pipeline

For the first two, we have a detailed:

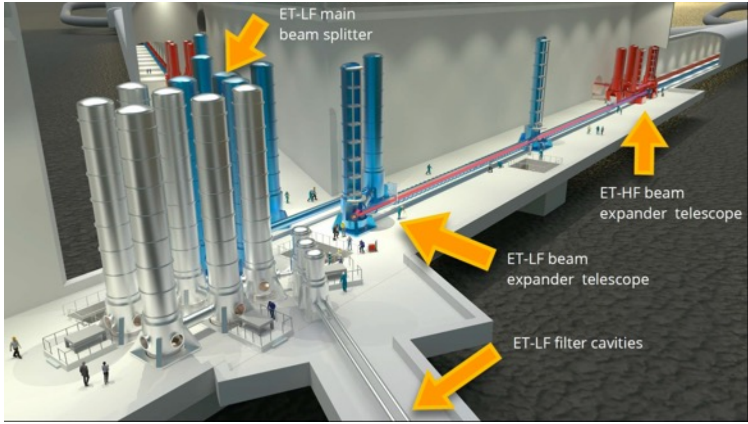
- thermal-structural analysis;
- vibration modal analysis;
- design of different support systems (rigid and suspended);
- positioning in the tunnel.



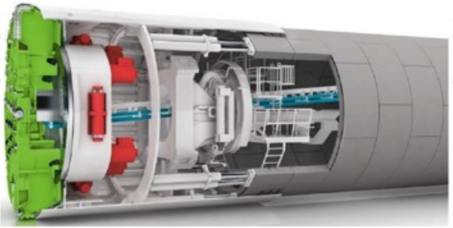
Infrastructure

@J. Degallaix

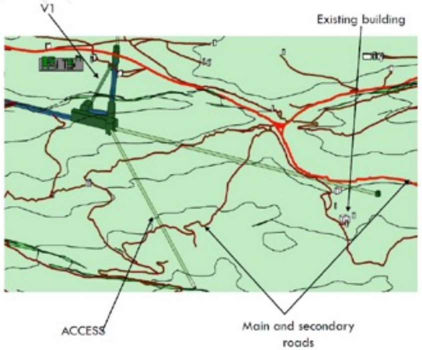
- stratégie pour la construction des tunnels et cavernes
- gestion infrastructure souterraine
- intégration dans l'environnement local



Taille, forme des cavernes ?



Méthode d'excavation ?



Installations existantes ?

+ Studies for the characterization of candidate sites in progress: drilling, ambient noise (seismic, wind turbine, magnetic ...)

ET-PP

HORIZON-INFRA-2021-DEV-02 : « Developing and consolidating the European research infrastructures landscape, maintaining global leadership » - and therefore, accompanying EU to the assembly of newly registered IR ESFRI

Einstein Tescope Preparatory Phase (ET-PP): 4 years project (2022-2026)

Coordination: Mario Martinez (Espagne, IFAE)

Countries of participating institutes & laboratories:

Germany, Austira, Belgium, Spain, France, Hungary, Italy, Netherlands, Poland, UK, Switzerland

EU Budget: 3,45 M€ **Total Budget :** 13,9 M€ i.e. in-kind of 10,45 M€ (salairies of permanent staff involved)

ET-PP will provide a detailed implementation plan for the ET infrastructure:

- the expansion of the ET consortium
- the legal framework, governance regimes and financial regulations to build and operate
- detailed technical design and costing of the ET observatory
- preparing the site selection
- costs of the site's infrastructure, socio-economic and environmental impacts
- technology transfer, procurement and industry involvement programs in engineering design and construction
- the required link with the scientific communities concerned regarding the detailed definition of the scientific programme
- User services and data access mode

ET-PP

WP1 Coordination and Management
WP2 Organization, Governance and Legal Aspects
WP3 Financial Architecture
WP4 Site Selection
WP5 Project Office
WP6 Technical Design
WP7 Transfer of Technology
WP8 Computing and Data Access
WP9 Sustainable Development Strategy
WP10 Education, Outreach and Citizen Engagement

IN2P3 Co-coordination

WP1: Spanish responsibility in close connection with INFN and Nikhef

WP2-3-4: essentially INFN & Nikhef

WP6 & WP8: Responsibilities for collaboration scientific AND that is being set up => essentially in-kind

Essential IN2P3 contributions to ET-PP in order to prepare ETO

Site candidates in Europe

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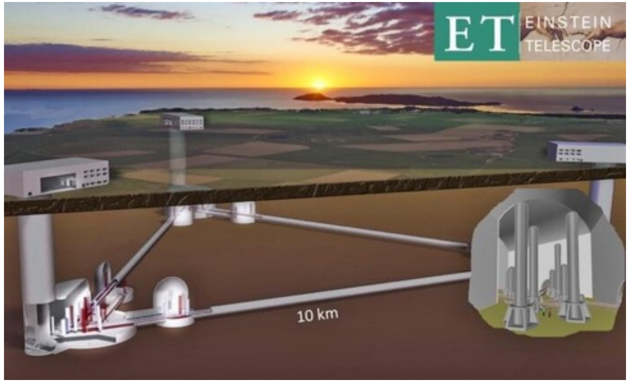
Sardinia – Italy



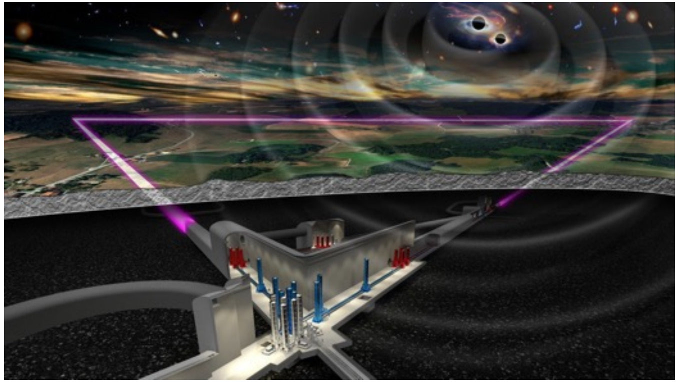
€50 million for R&D and preparatory work

ETIC in Italy

Einstein Telescope Infrastructure Consortium

"Multi-100 M€" financing to support ET's site in Sardinia

Euregio Meuse-Rhin Netherland



€42 million for R&D and preparatory work

ET-Pathfinder in Maastricht

"Multi-100 M€" financing if the ET site is in Euregio Meuse-Rhine

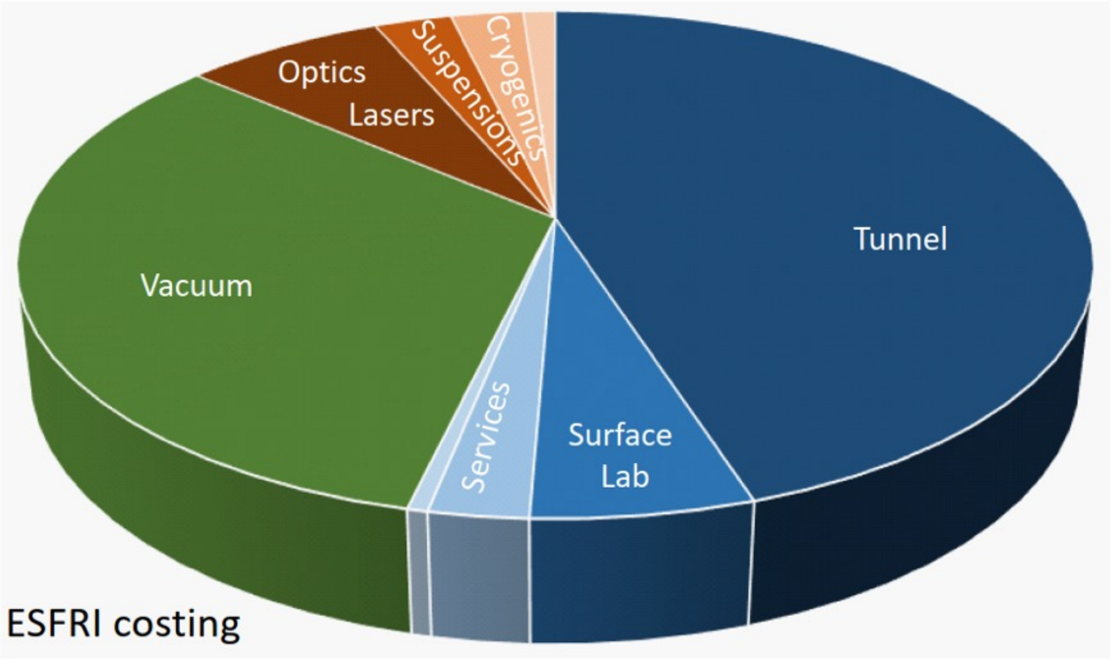
Saxe – Germany

New DZA laboratory (2022)

170 M€/year over 10 years

3 pillars: astrophysics, data science, technology

Construction costs



2021

Tunnel	781 M€
Surface Lab	98 M€
Underground Services	44 M€
Direction	9 M€
	932 M€
Vacuum Systems	566 M€
	566 M€
Optics & Lasers	125 M€
Suspensions	48 M€
Cryogenics	45 M€
Installation	20 M€
	238 M€