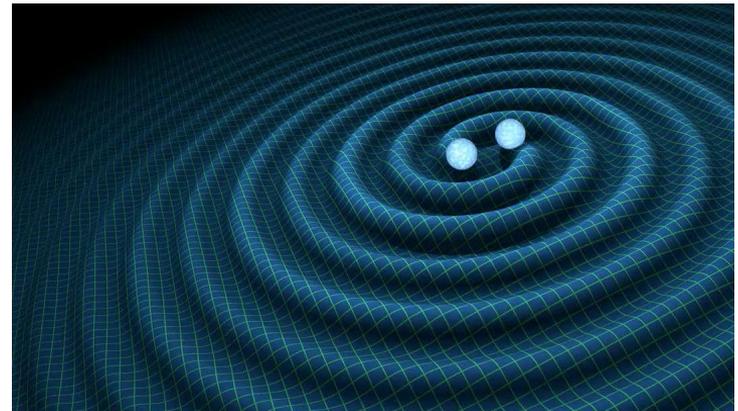


The Einstein Telescope Project

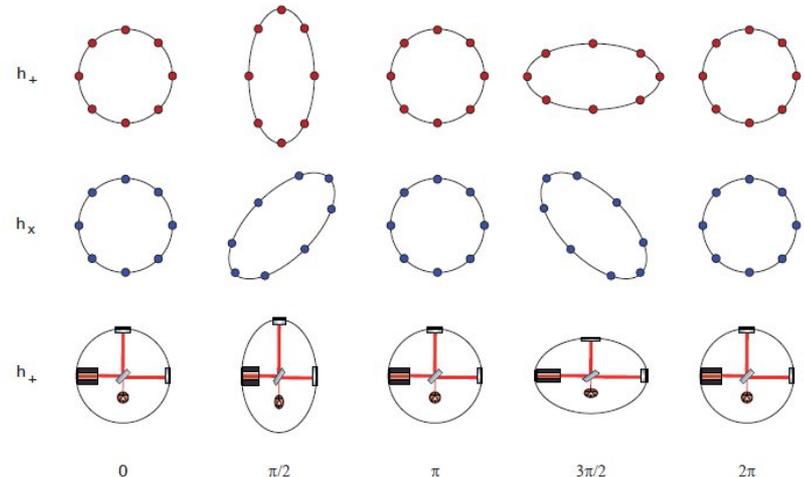
*Saclay – March 17th, 2026
Patrice Verdier (IP2I Lyon – IN2P3) - patrice.verdier@in2p3.fr*

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Gravitational waves are ripples in spacetime caused by the acceleration of massive objects, such as merging black holes or neutron stars.

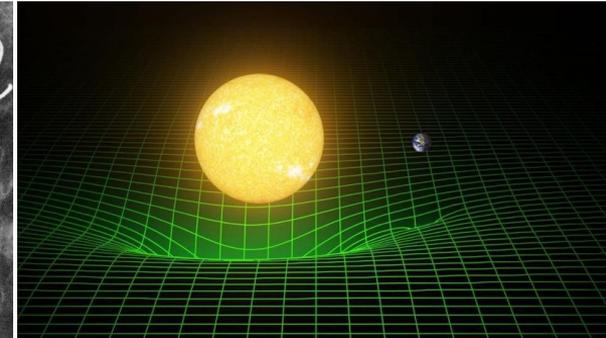
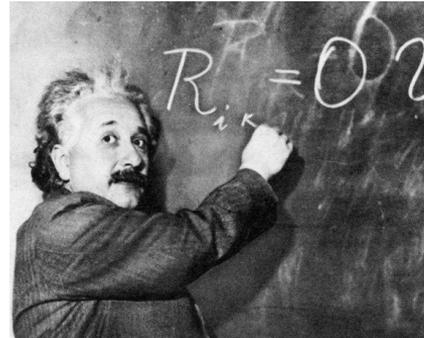


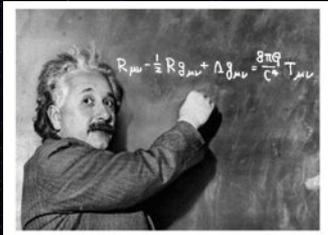
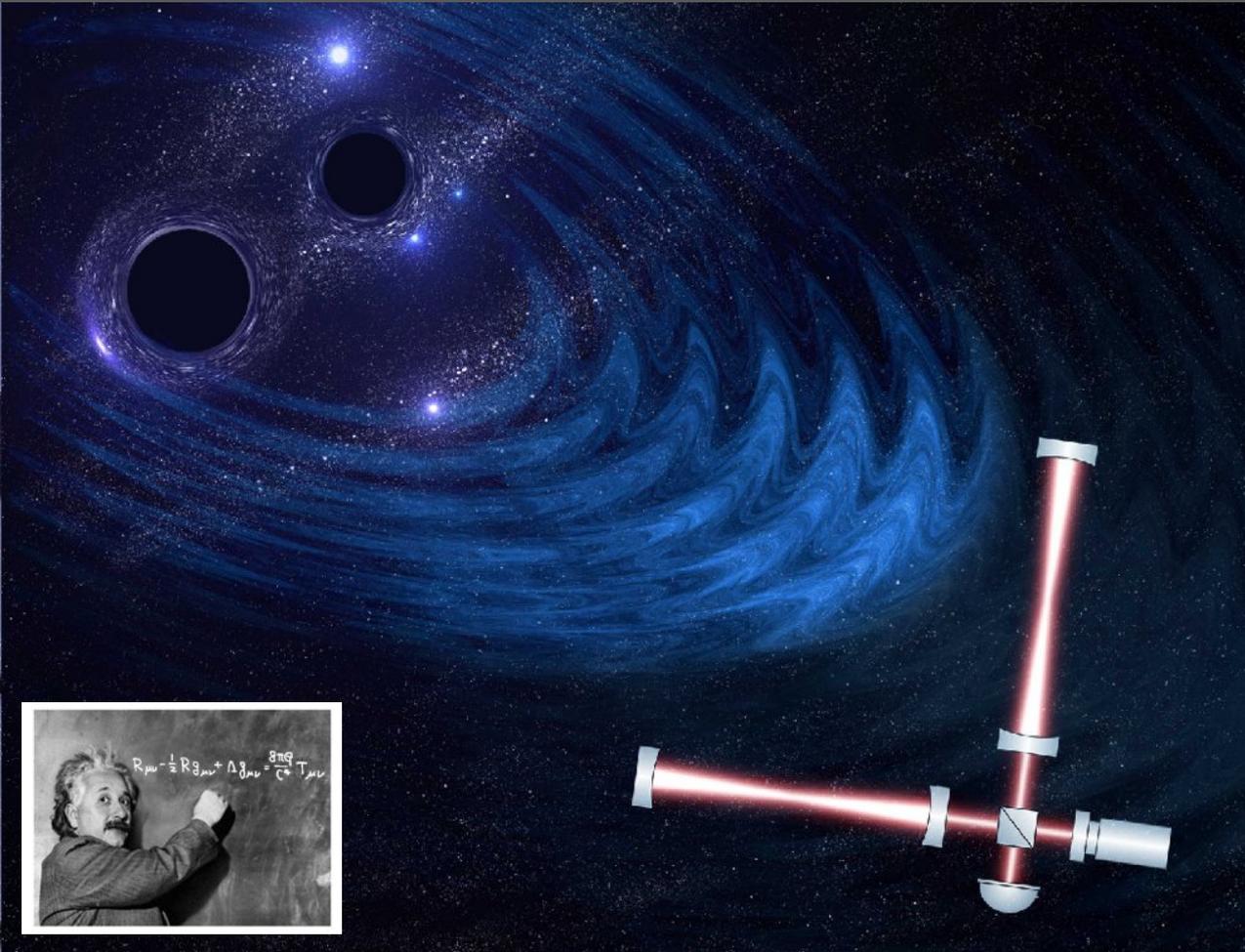
Gravitational waves propagate outward from their source at the speed of light. They carry energy away from the source, causing a gradual decay in the amplitude of the waves as they travel through spacetime.



A long path leading to GW discovery

- 1915 Einstein : Mass/Energy deform space-time
- 1916-1918 Einstein: “Space-time quakes” can be produced by violent phenomena
- 1937 Einstein and Rosen “On Gravitational waves”
- 1957 Pirani/Feynman (Chappel Hill conference) GW can transmit energy and thus be detected
- 1960-1970’s J. Weber first bar detectors
- 1967-1968 R. Weiss, K. Thorne, Drever first interferometers
- 1974 R. Hulse and J.Taylor binary pulsars emit GW (Nobel 1993)
- 1984-1994 US: LIGO proposal period : G. Barish LIGO director (1994)
- 1987-1994 EU: Virgo proposal period : A.Giazotto, A. Brillet
- 2015 First detection of GW by LIGO and Collaboration LIGO-Virgo
- 2017 First multi-messenger event BNS detection by LIGO-Virgo

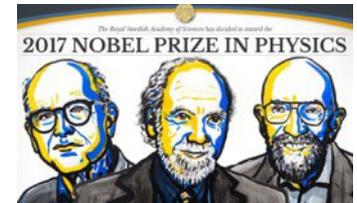




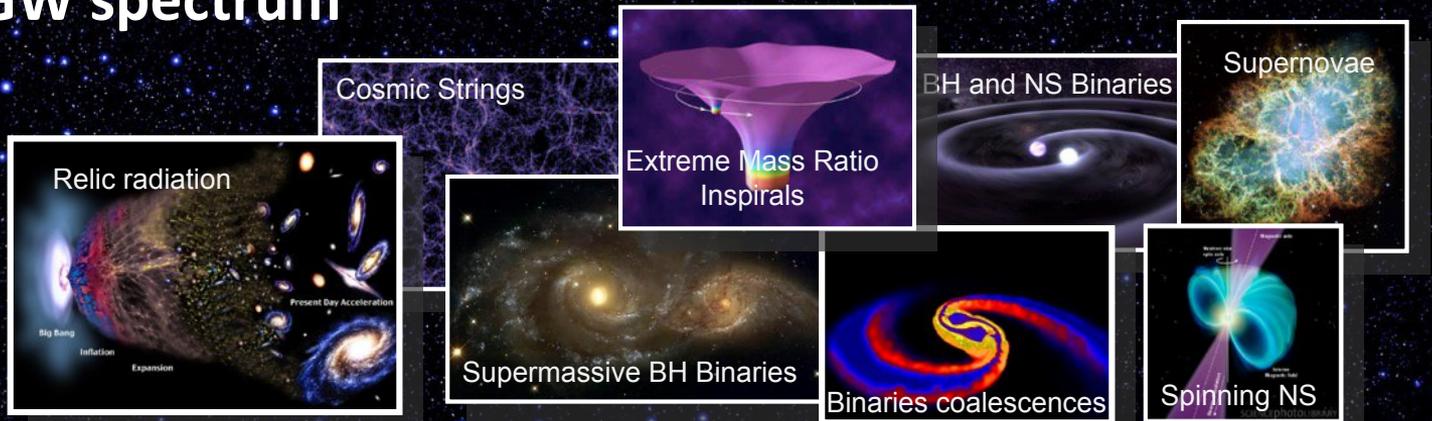
100 years after their prediction as part of Einstein's theory of general relativity, the discovery of gravitational waves opens a new way to explore and study the Universe!



Nobel Prize in Physics 2017



GW spectrum



10^{-16} Hz

Inflation Probe

10^{-9} Hz

Pulsar timing

10^{-4} Hz

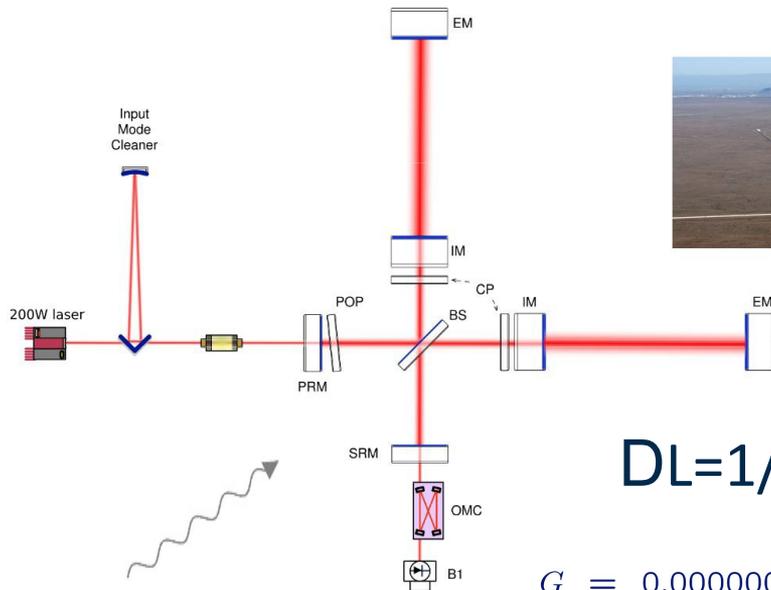
Space detectors

10^0 Hz

Ground interferometers

10^3 Hz





Amplitude h = $\frac{2G}{c^4 r} \ddot{i}$ Mass distribution

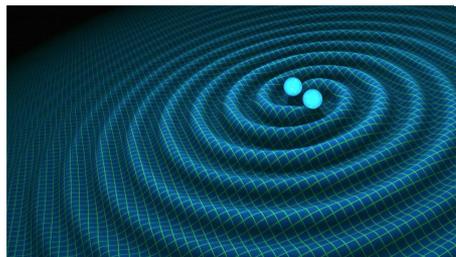
distance

$$DL = 1/2 h \times L$$

$$G = 0,0000000000667 \text{ m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}$$

$$c = 300000000 \text{ m} \cdot \text{s}^{-1}$$

Typical amplitude for a black hole merger: $h = 10^{-21}$
 => Distance measurement (3km) with a precision of 10^{-18} m

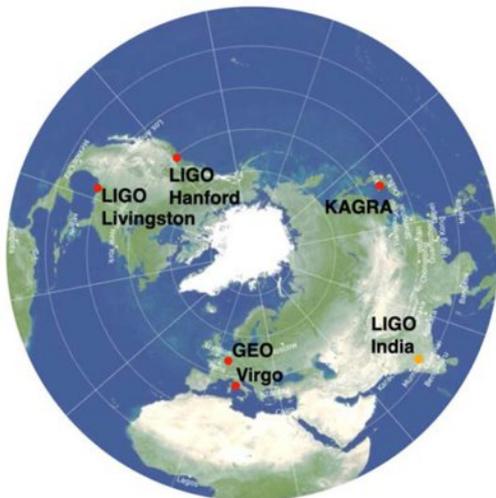




LIGO
Livingston



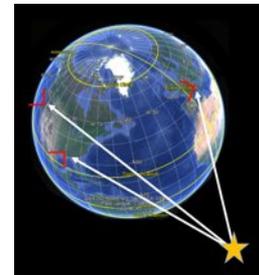
LIGO
Hanford

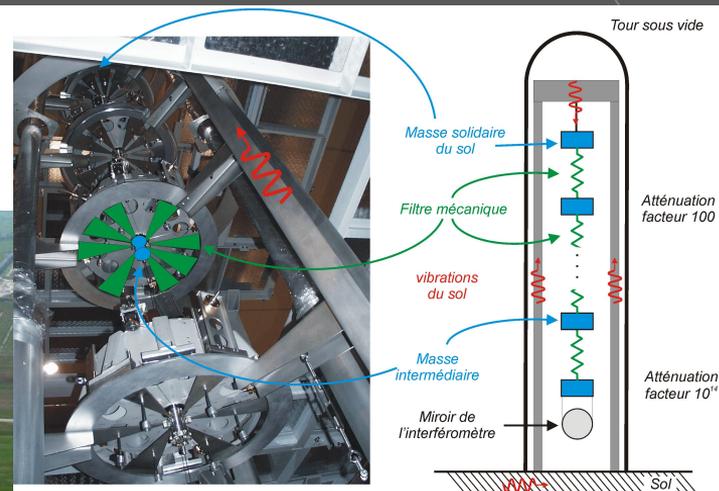
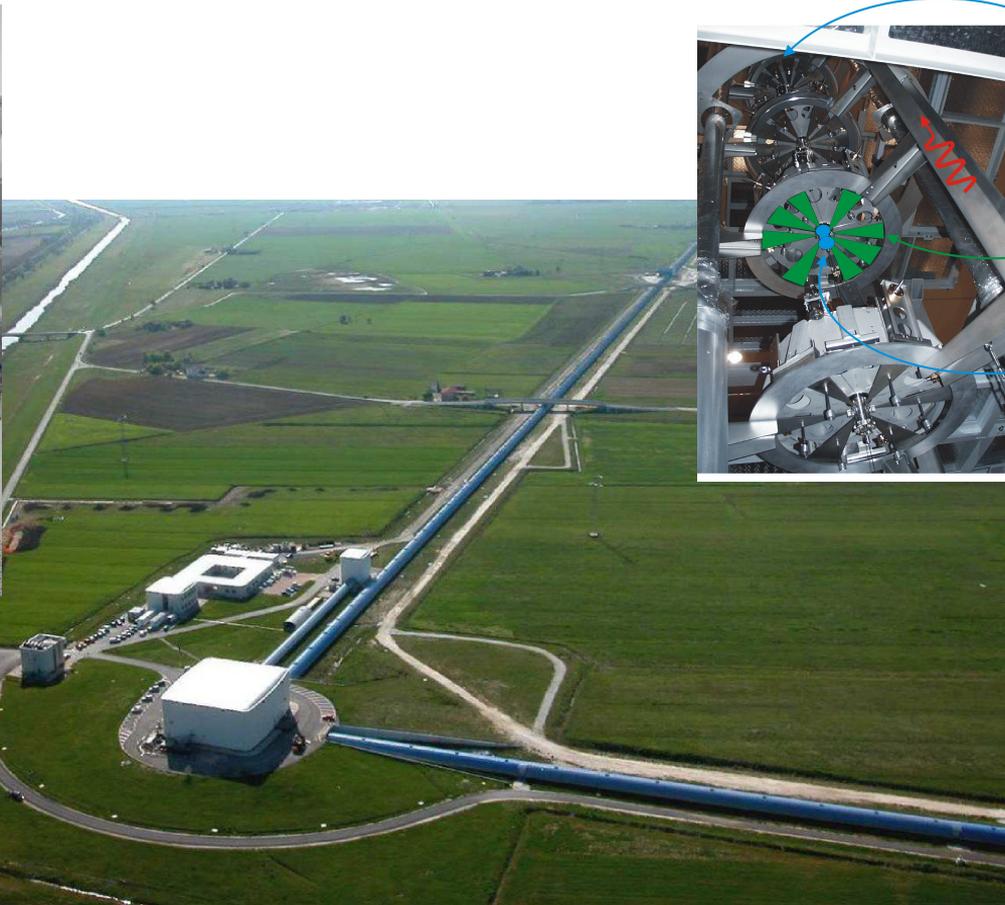
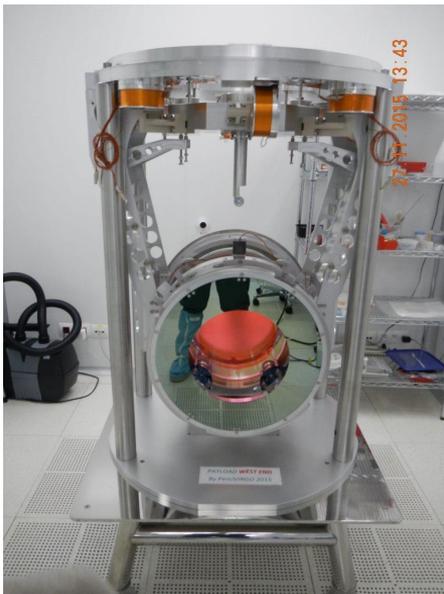


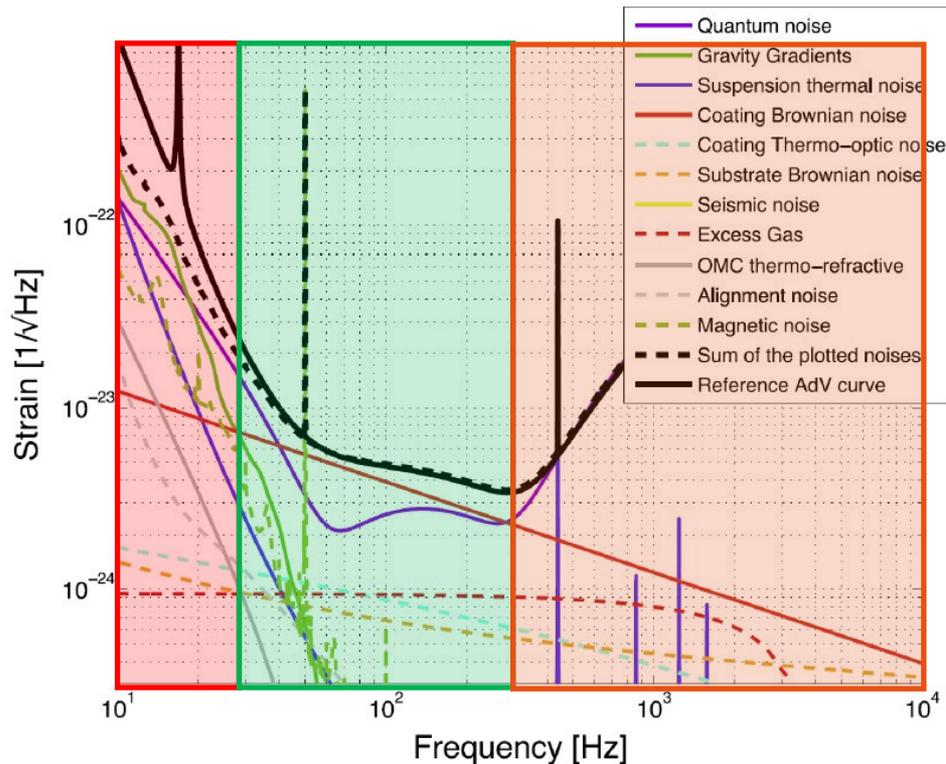
Virgo



KAGRA







LOW-FREQUENCY ($f < 30$ Hz)

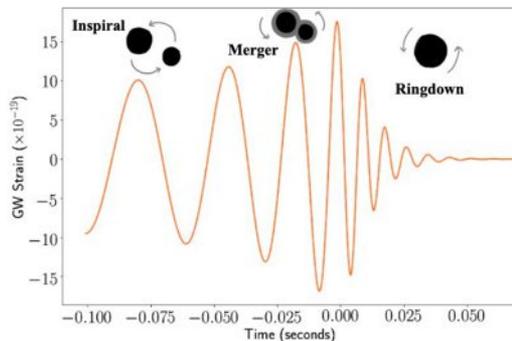
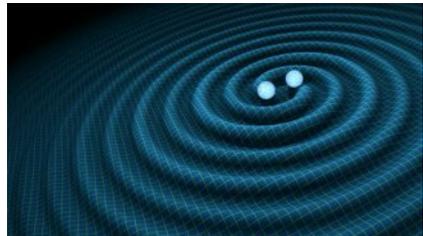
- Seismometer arrays and tiltmeters in order to cancel Newtonian noise
- Improvement of the suspension system in order to further reduce the seismic noise
- Use of fused silica fibers to reduce suspension thermal noise

MID-FREQUENCY ($30 \text{ Hz} < f < 300 \text{ Hz}$)

- Super-polished mirrors to reduce scattered light;
- New mirror coatings (silica and titania doped tantala) to reduce coating thermal noise;

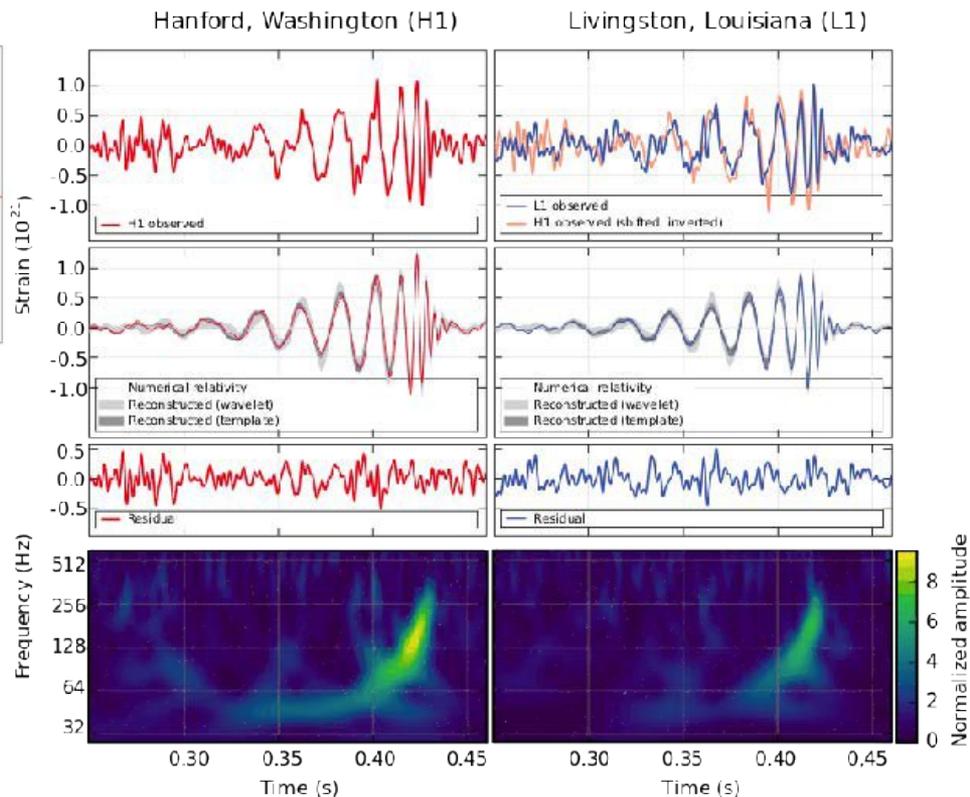
HIGH-FREQUENCY ($f > 300 \text{ Hz}$)

- Higher power laser and squeezed vacuum injection to reduce quantum noise

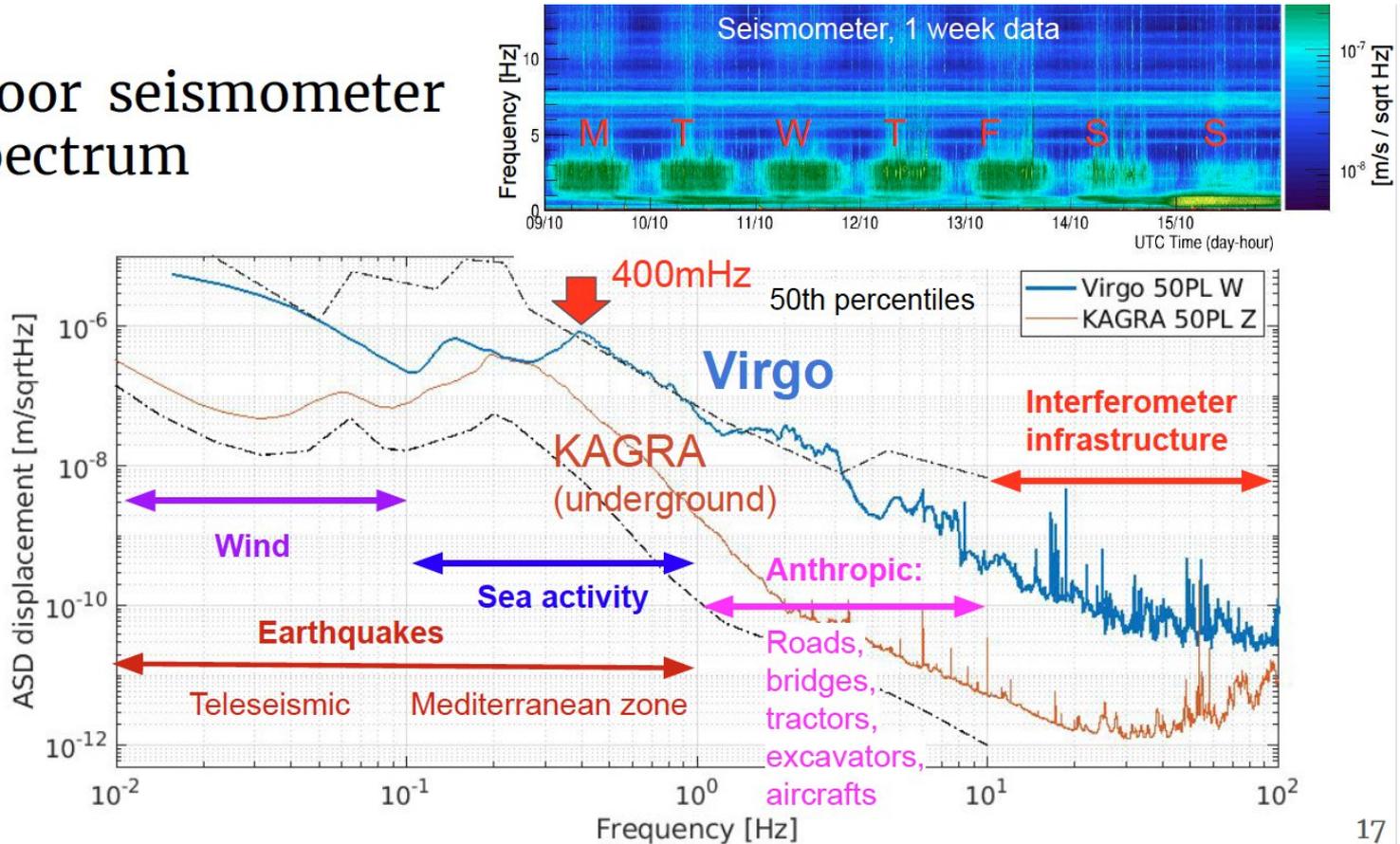


GW150914

Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$

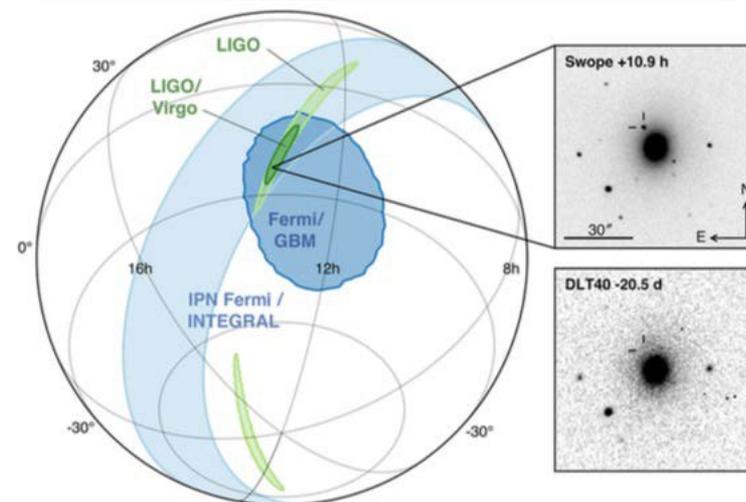
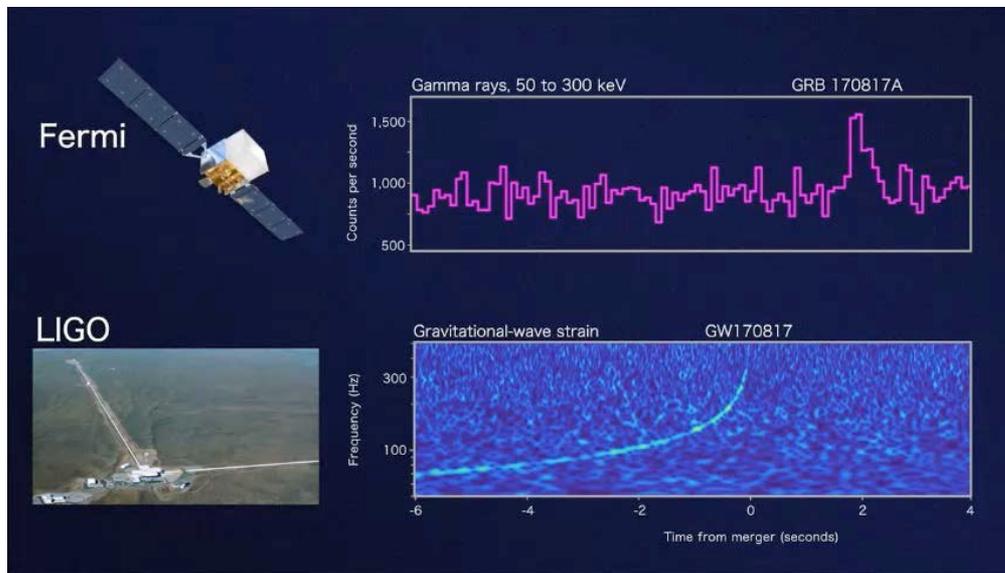


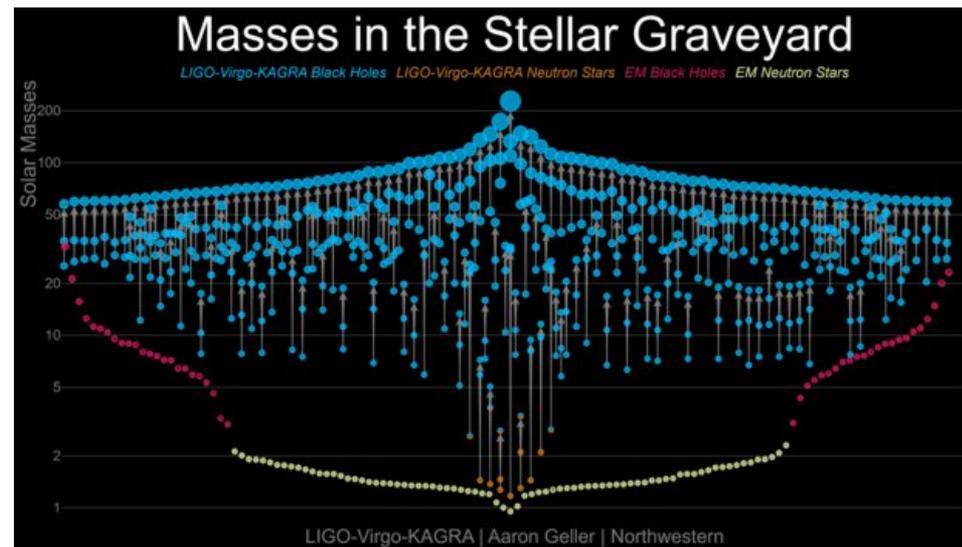
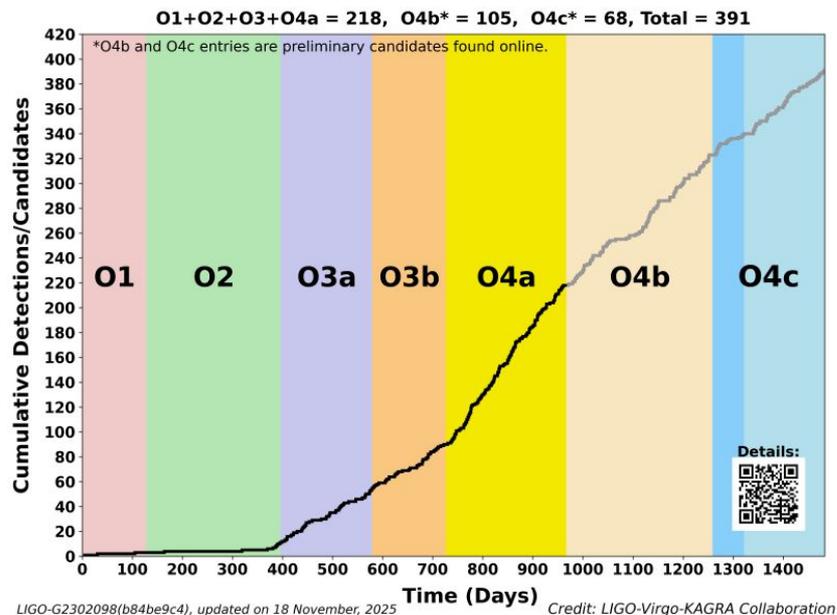
Floor seismometer spectrum



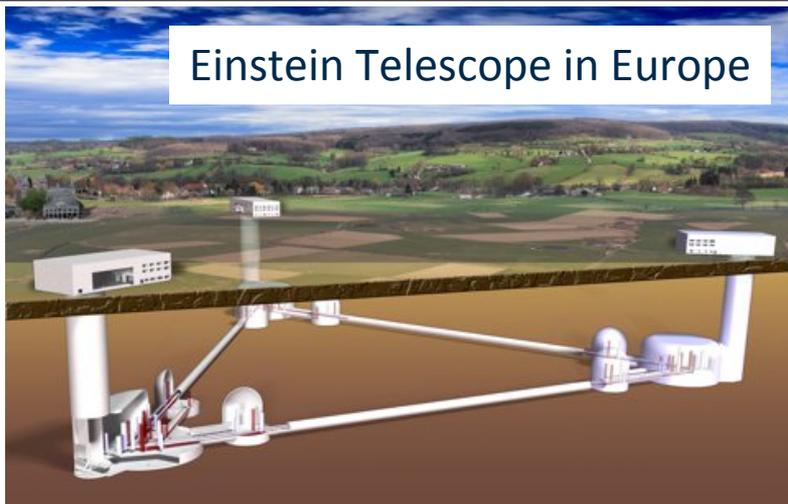
start of multi messenger astronomy with GW

Gamma rays reached Earth 1.7 seconds after GW

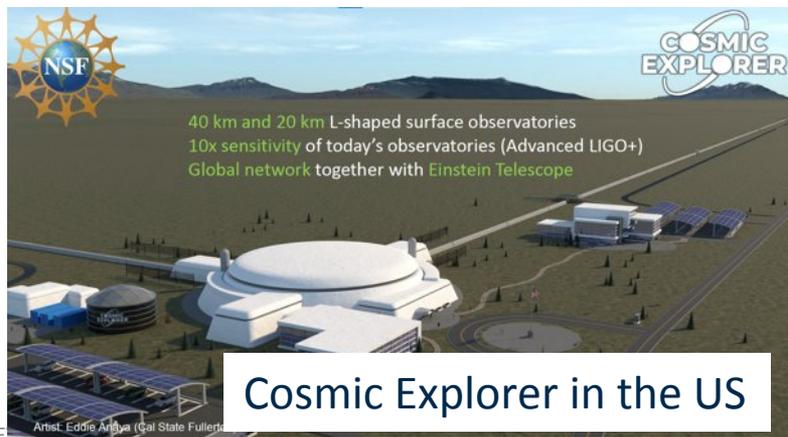




2-3 GW signals per week detected by Ligo-Virgo



Einstein Telescope in Europe

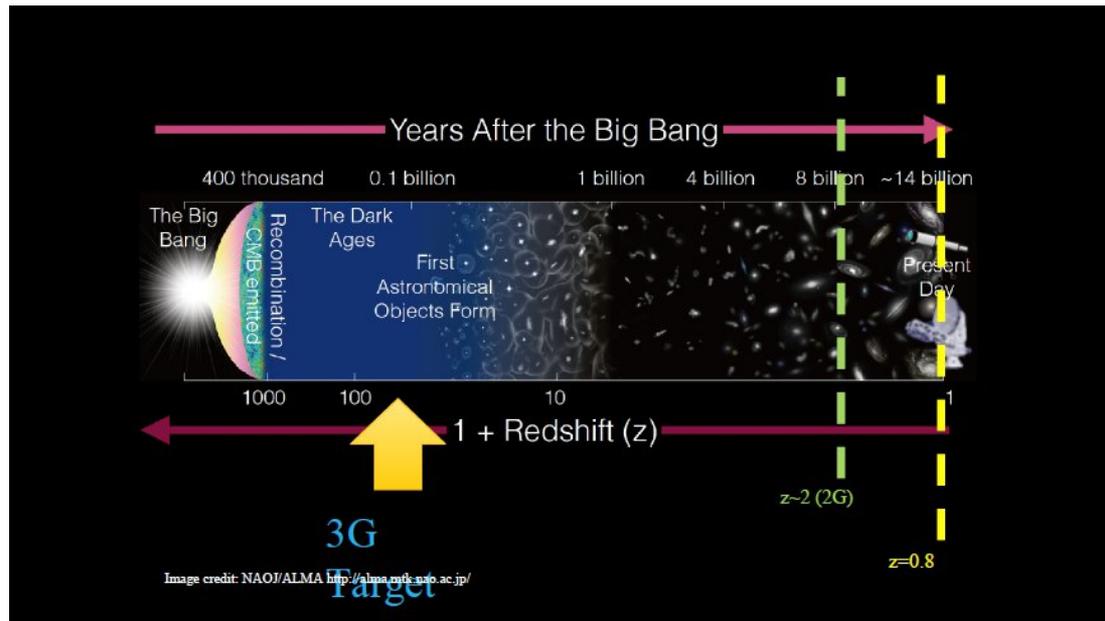


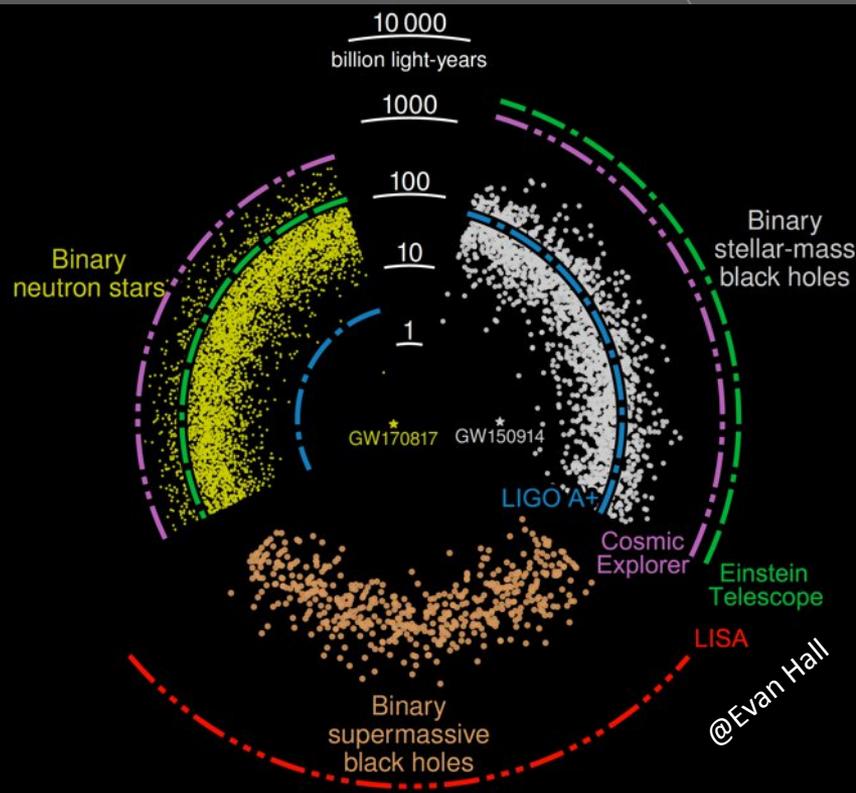
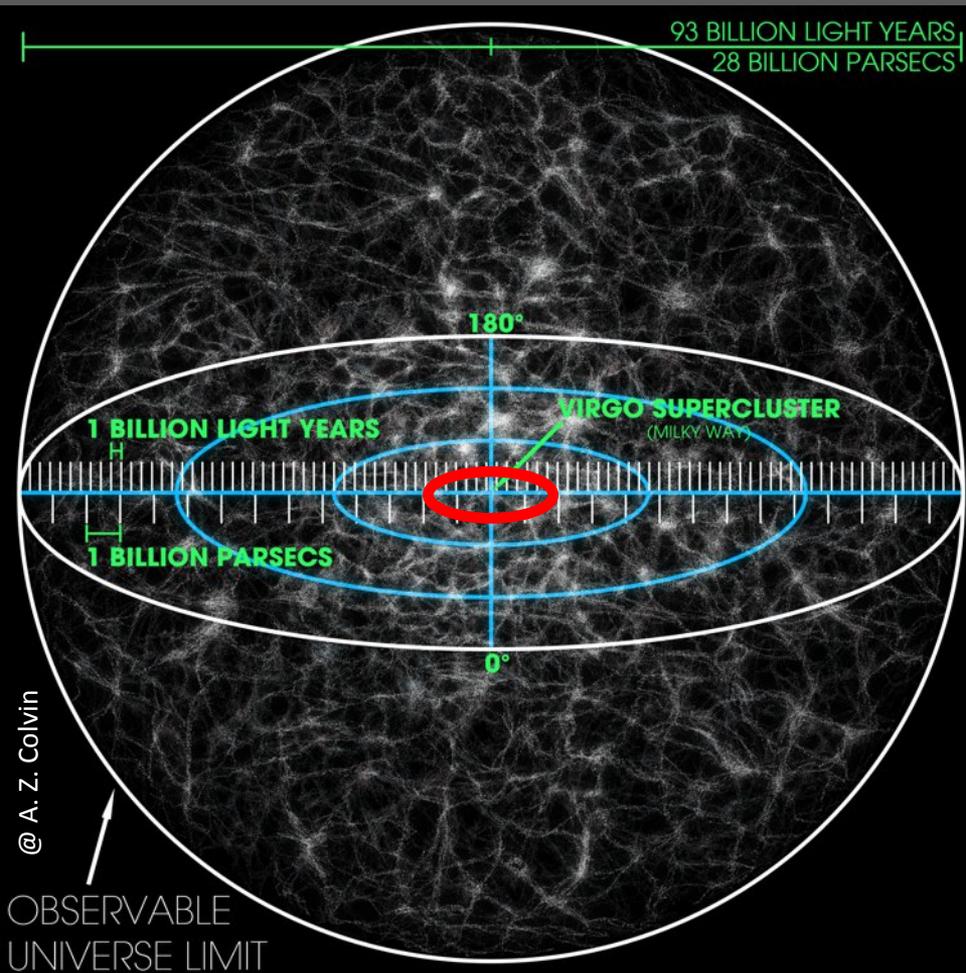
NSF

COSMIC EXPLORER

40 km and 20 km L-shaped surface observatories
 10x sensitivity of today's observatories (Advanced LIGO+)
 Global network together with Einstein Telescope

Cosmic Explorer in the US





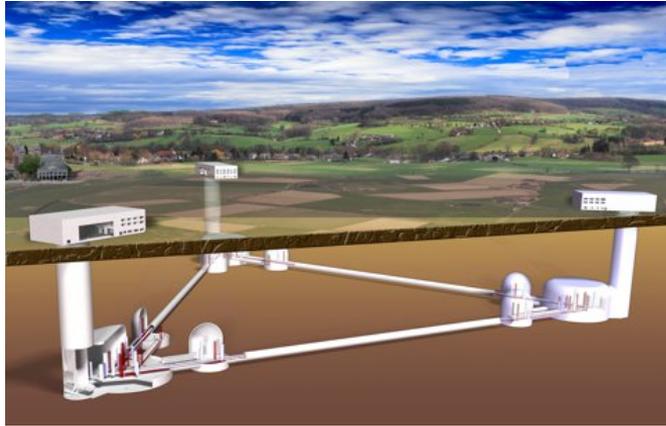
Einstein Telescope aims to study most of the observable Universe

≥ 10km

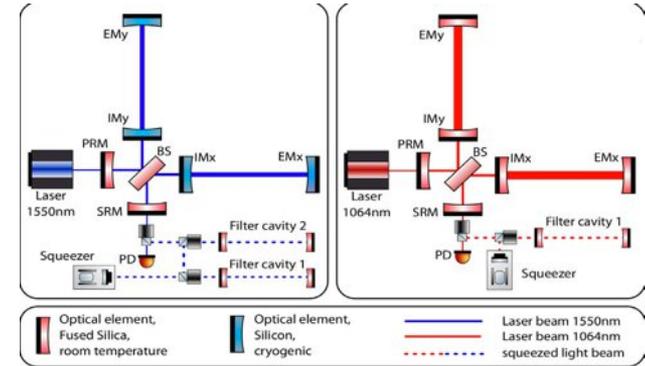
Depth:
200m

ET pioneered the idea of 3rd generation GW observatory:

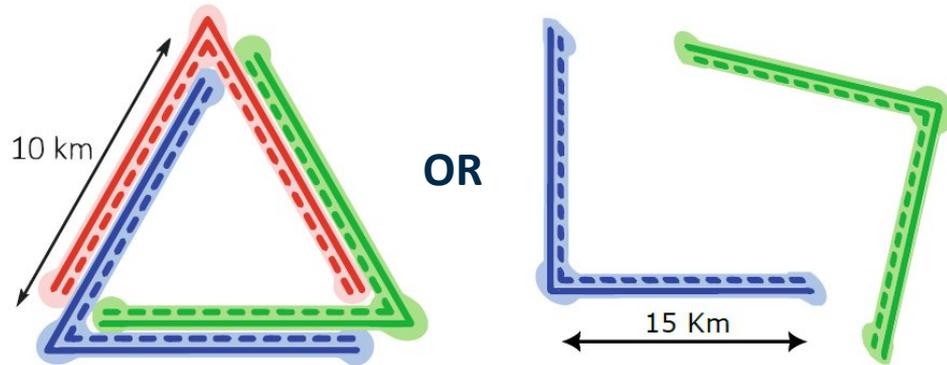
- New infrastructure capable of hosting future upgrades for decades without limiting observing capabilities
- Sensitivity at least 10 times better than current (nominal) detectors over a large part of the frequency band
- A dramatic improvement in sensitivity in the low frequency range (a few Hz to 10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



Xylophone: 2 sensitive interferometers at different frequencies



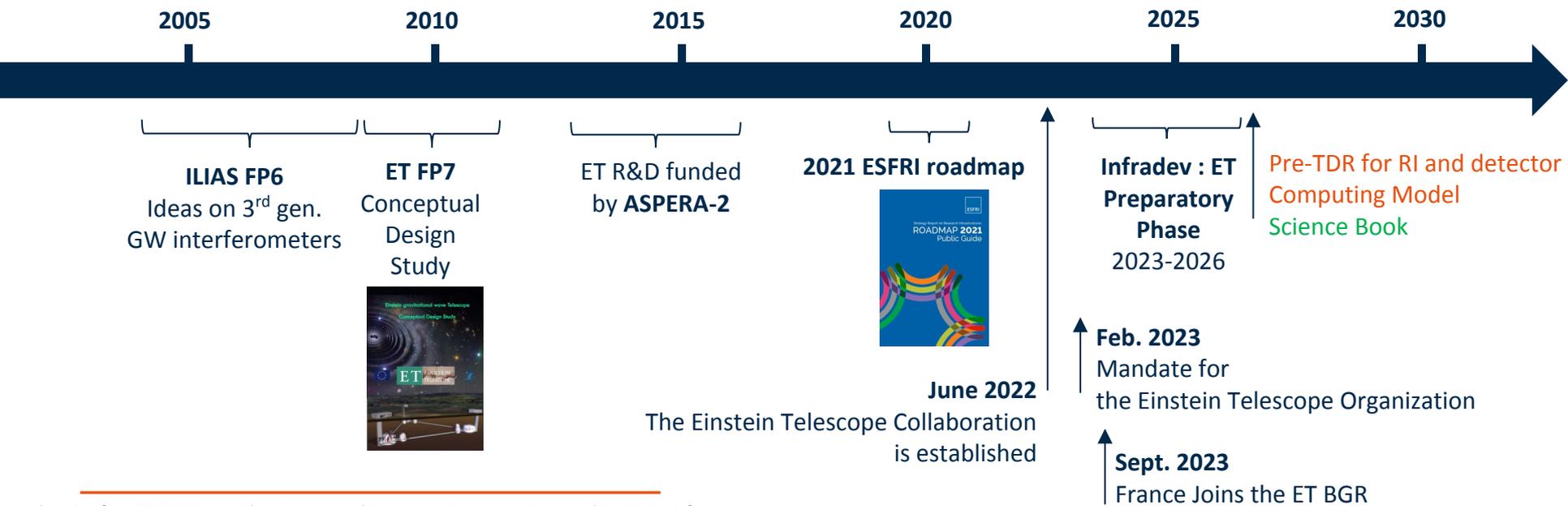
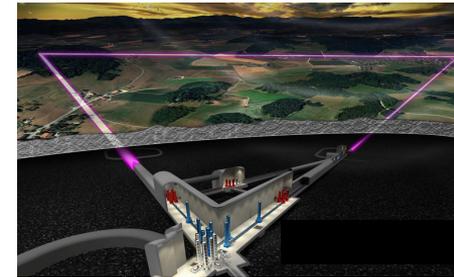
Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1x300 m	2x1.0 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)	$5 \cdot 10^{-10}$ m/f ²	$5 \cdot 10^{-10}$ m/f ²
Gravity gradient subtraction	none	factor of a few



OR

ET pioneered the idea of 3rd generation GW observatory:

- A new infrastructure for >50 years
- Sensitivity at least 10 times better than 2nd generation
- Huge improvement in sensitivity at low frequency (a few Hz to 10 Hz)
- **Essential French contribution since the initial studies**



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” ?

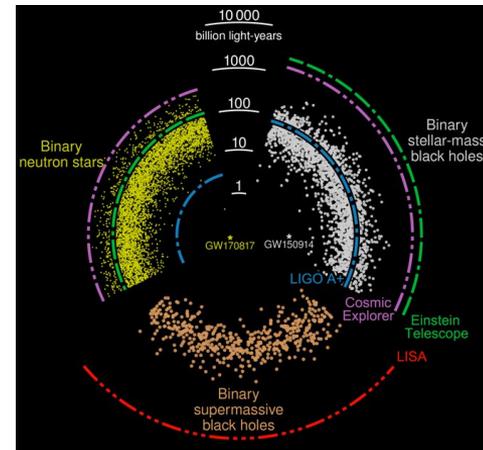
The discovery of GWs has opened a new avenue for the observation and study of the Universe: booming scientific field !

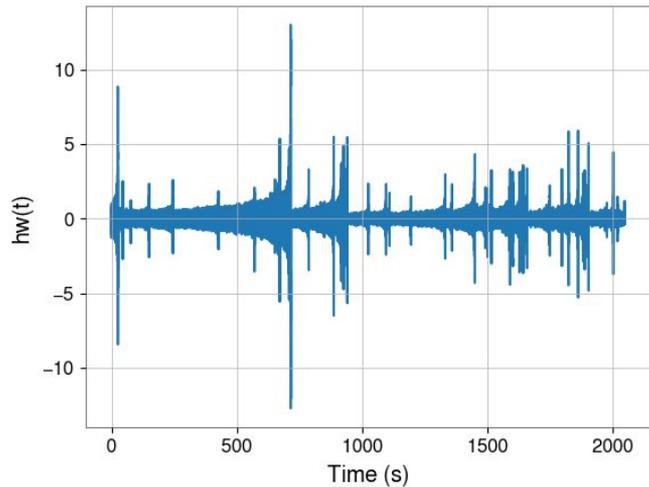
March 2025: ET blue book publication

<https://arxiv.org/abs/2503.12263>

Accepted by JCAP

880 pages document

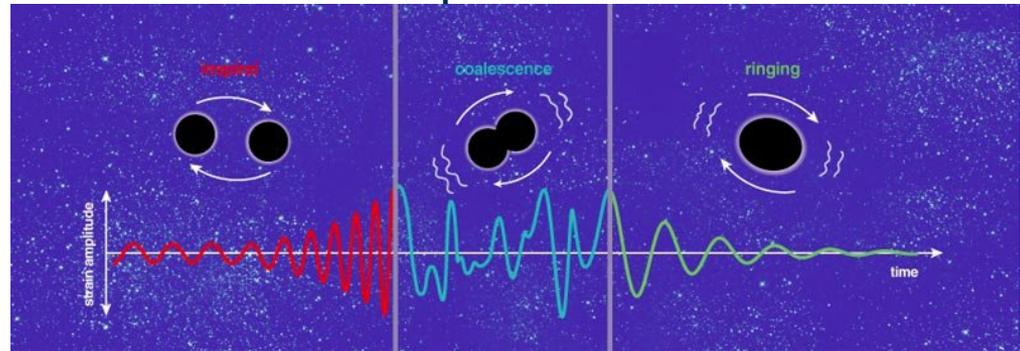




Regimbau, Suresh arXiv:2506.12237

- $O(10^5)$ BBH detections per year
- $O(10^4)$ BNS detections per year among which ~ 100 with EM counterparts
- Early universe : up to $z=100$
- High SNR events
- Very long signals (up to minutes or hours): early warning alerts
- Overlapping events

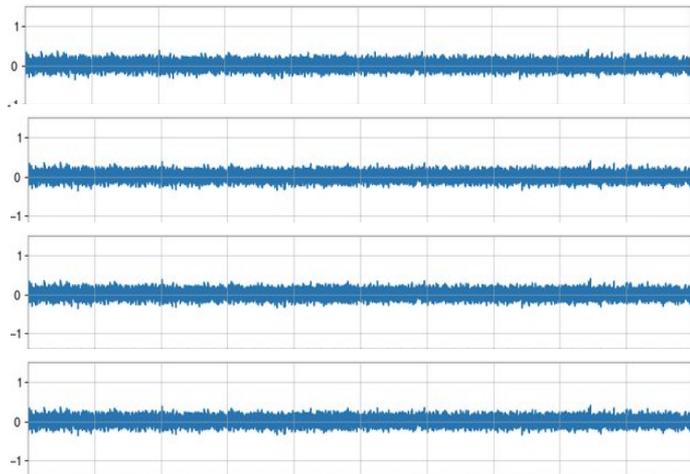
The precision era !



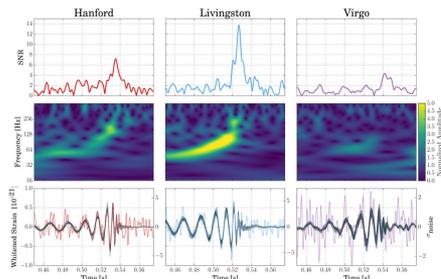
ET with Cosmic Explorer (3G in the US) in a network for multi-messengers astrophysics

Advanced GW detectors+

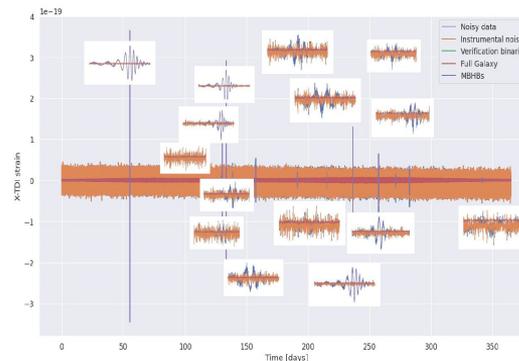
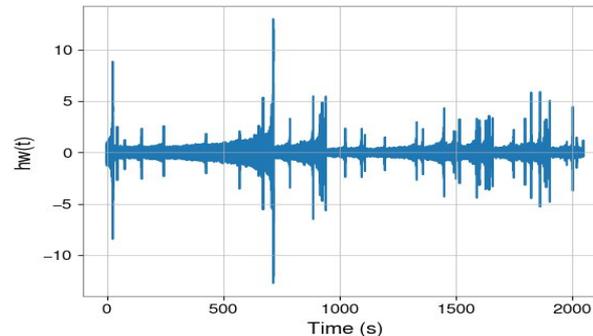
2G : LVK are dominated by backgrounds



And 2-3 times per week



ET and LISA will be dominated by signals

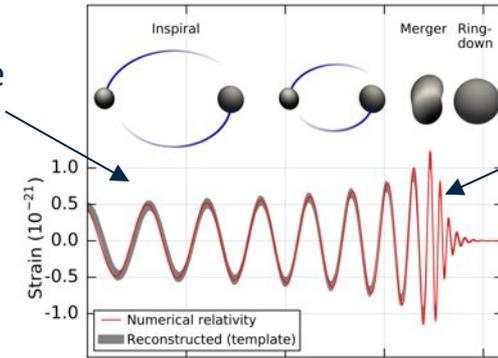


Simulated LISA Data: Sangria

Dataset size won't change so much
Complexity and computing power to reduce the data
and reconstruct events will increase a lot

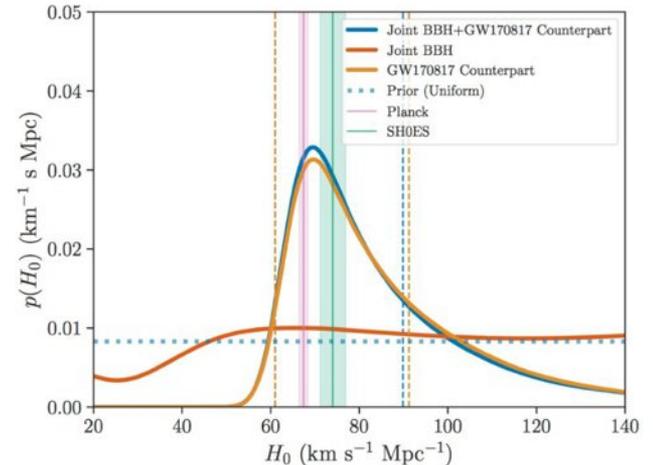
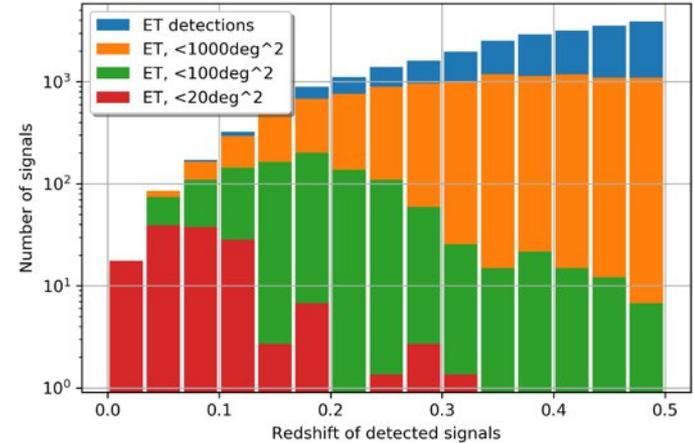
- **BNS detection with EM counterparts and localization precision $< 20 \text{ deg}^2$** : o(10-100) per year
- Overlap with many BBH signals
- Potentially, very long signals
- ET will be able to provide alerts few hours before the merger

Identify early the inspiral ...

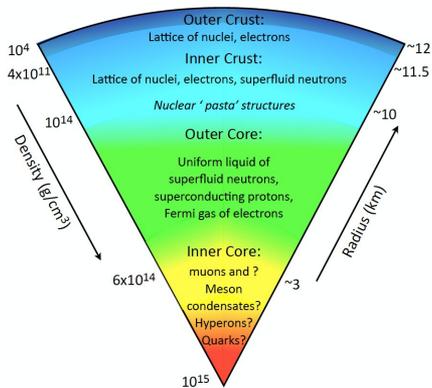


... and provide alert before the merger phase

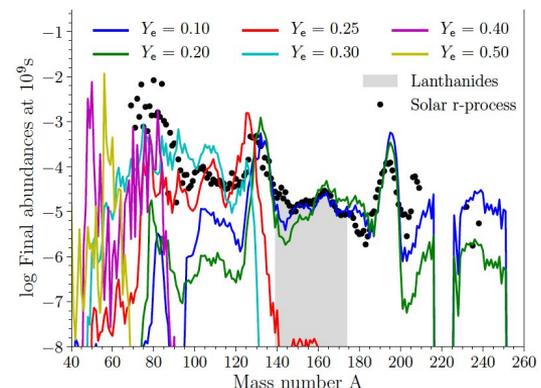
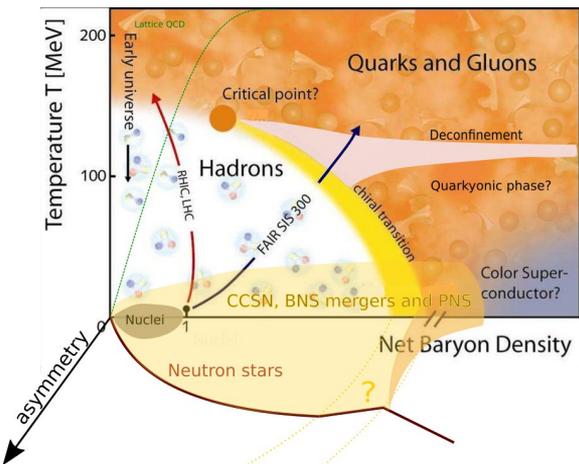
- And with ~ 500 BNS-EM detection, we can reach Planck resolution on H_0 measurement



@Micaela Oertel



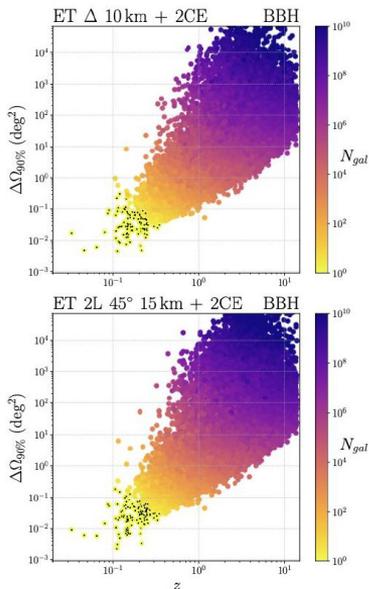
- Inspiral : NS EoS can be determined very precisely with 3rd generation detectors
- But : no information a priori about composition in absence of a phase transition
- During inspiral, a strong PT with a low density onset probably detectable, high density onset masked
- Post-merger : characteristic imprint of PT in dominant oscillation frequency



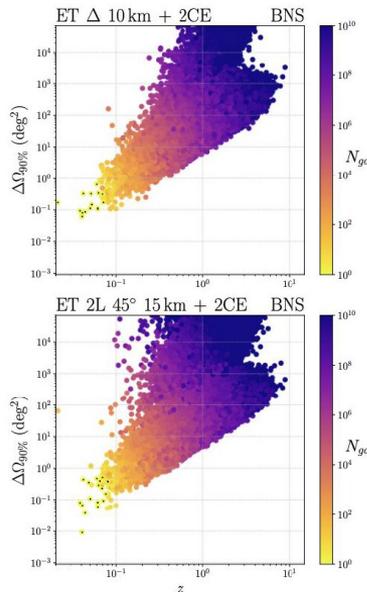
@Nicola Tamanini

From OSB Div 5 Blue Book chapter

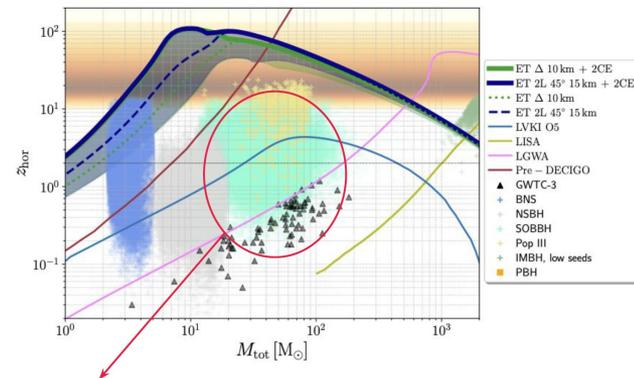
BBHs



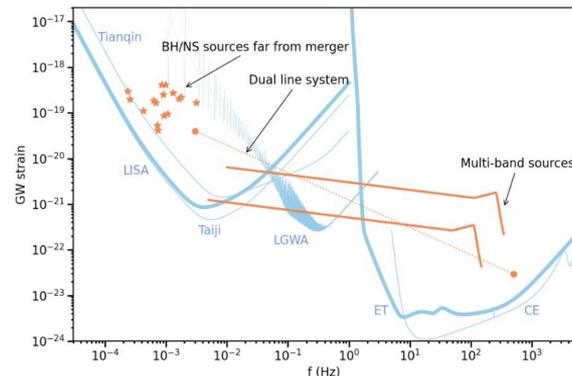
BNSs



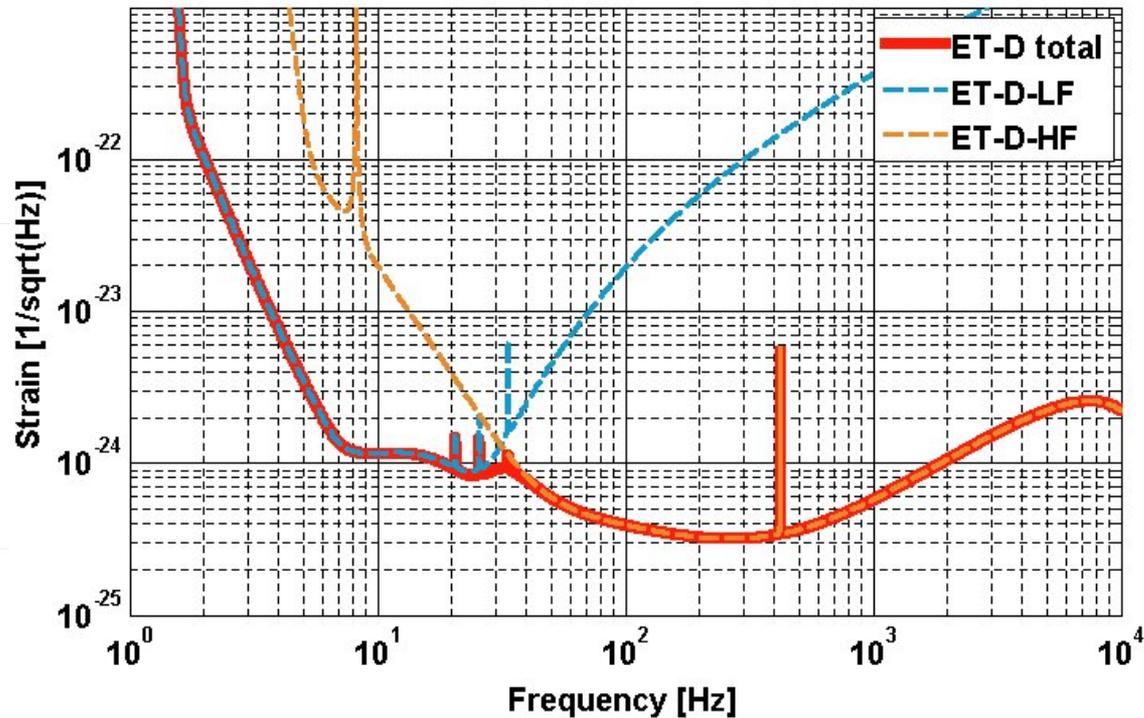
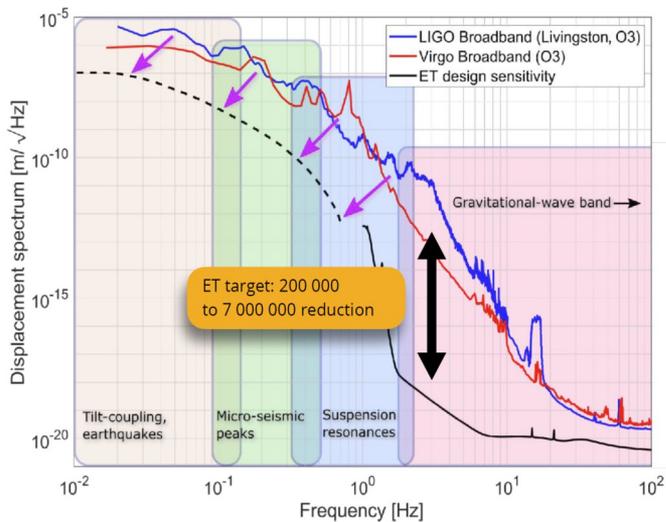
Synergy with CE essential for sky-localisation (cosmology, ...)



Stellar-mass BBHs synergies with LGWA, DECIGO, LISA, ...



Stellar-mass BBHs synergies with LGWA, DECIGO, LISA, ...



HF

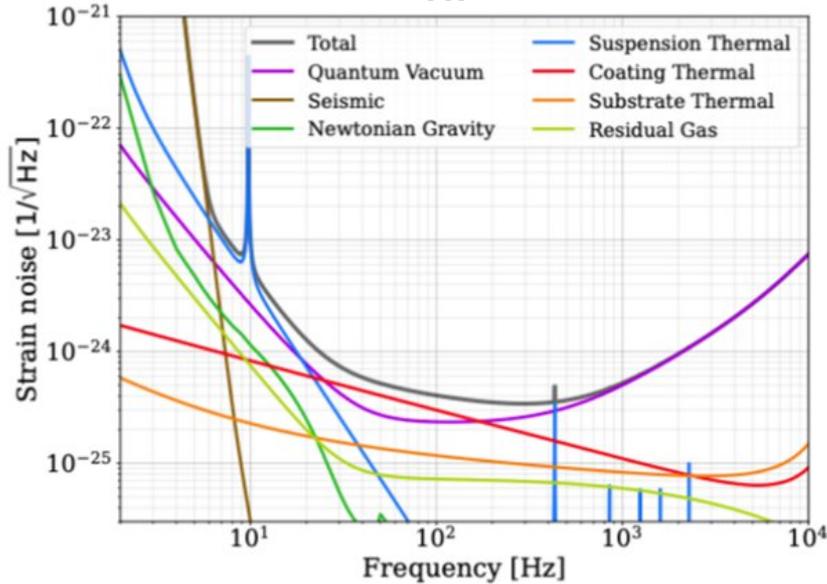


Figure 1: Strain noise budget of the HF detector. Noise traces shown in this figure correspond to a single interferometer with an intersection angle of 90 degrees (“L” shape).

LF

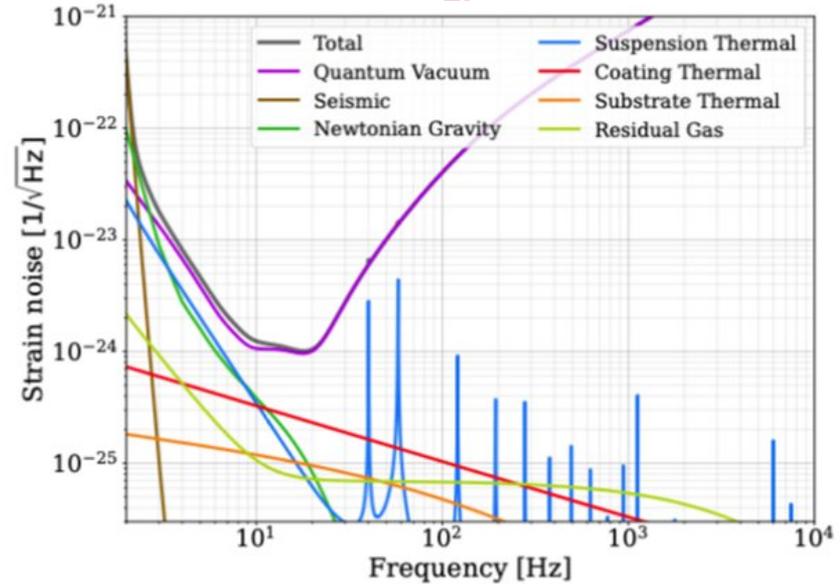
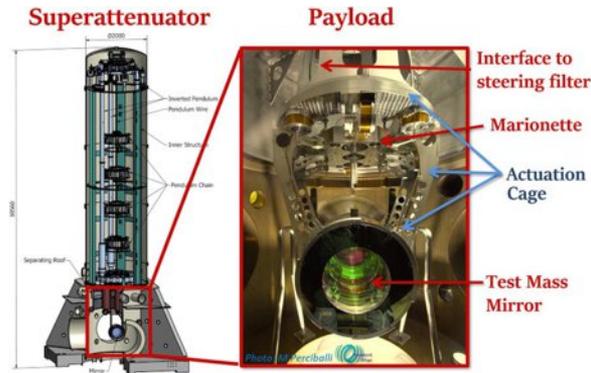


Figure 2: Strain noise budget of the LF detector. Noise traces shown in this figure correspond to a single interferometer with an intersection angle of 90 degrees (“L” shape).

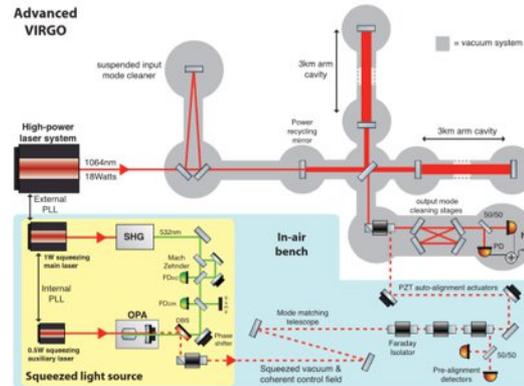
- Extrapolation of current or planned technologies for Virgo and LIGO
 - Squeezing (quantum states of light)
 - High power lasers
 - Bigger mirrors
 - New thin films for mirrors
 - Thermal compensation techniques
 - Seismic suspension systems



- Technologies not tested in Virgo and LIGO (prototypes and/or R&D in progress)

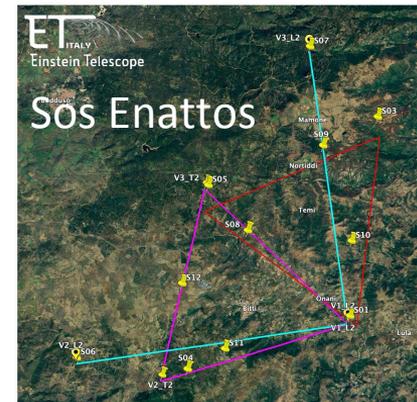
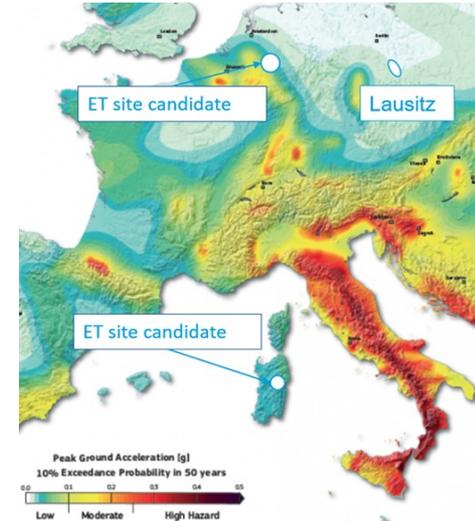
- Cryogenics (=> KAGRA)
- New cryogenic materials
- New laser wavelengths

⇒ Implementation of R&D programs

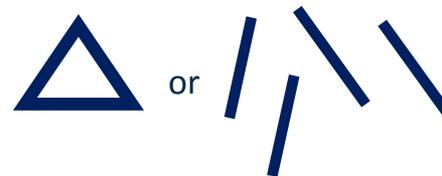


EGO/Virgo Laser Lab

- **Three candidate sites** candidates to host ET: **EMR, Sardinia, and Lusastia**
 - Italy and the Netherlands have pledged to cover nearly half of the cost if their proposed sites are selected
 - Important budget in Italy (50M€), The Netherlands (42M€), and Germany (~90M€) to support **site characterizations** (boreholes, seismometer, environmental studies), **civil engineering studies** (tunnels and caverns), **Instrumental &D and physics studies**
 - **All 3 are underground** :
 - **Seismic noise attenuates with depth**
 - **Newtonian noise is less significant and NN cancelation system can be developed to reach sensitivity below 10 Hz**
- **Geometry:**
 - Studies of physics potential has led to two geometry possibilities which are jointly evaluated: "2L 15 km" is generally better (45° orientation) and less risky than the triangle
 - Site Selection Criteria Committee will provide recommendations to BGR in 2026



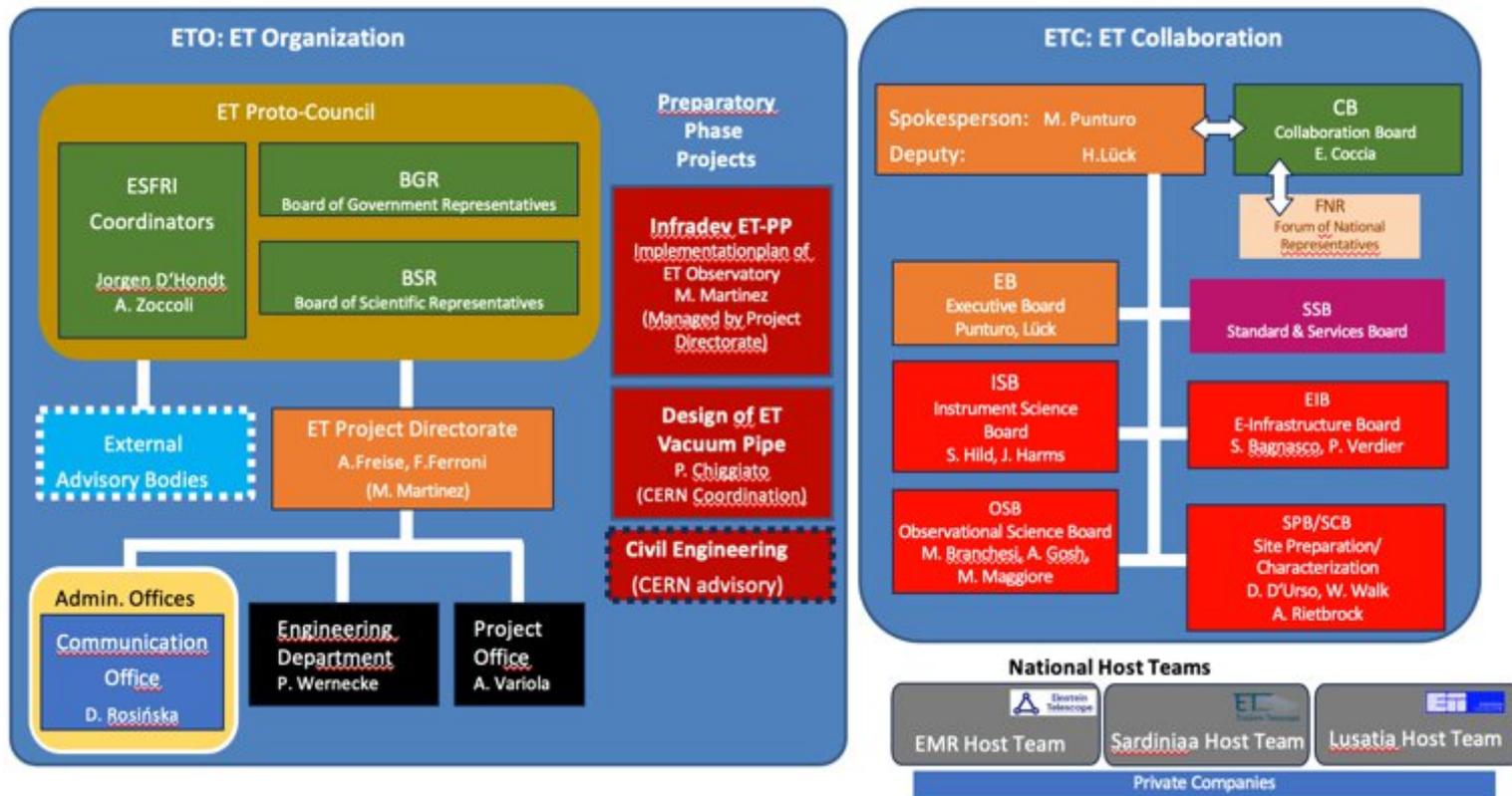
Decisions on site and geometry are expect in 2026-2027



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

Einstein Telescope Preparatory Phase (ET-PP) 2023-2026

The Einstein Telescope Collaboration: 1900 scientists from 271 institutions



Since the summer of 2022, the ET structures are being put in place
French scientists took important responsibilities in ETC

CNRS took important responsibilities in the ET-Preparatory Phase project (Infradev 2023-2026)

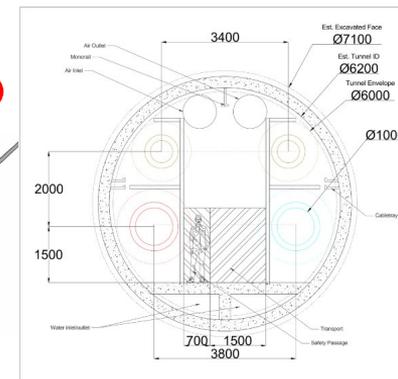
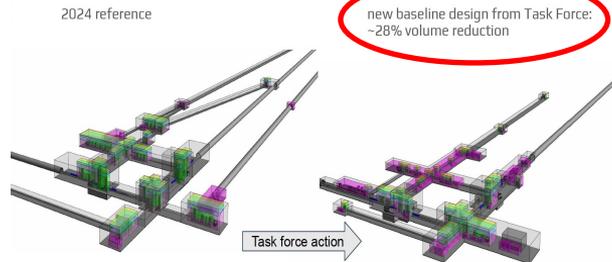
<https://etpp.ifaes.es/>

- Setting up the Project Office: Risk management, PBS database, schedule & configuration management
- Vacuum pipe design with CERN
- ET-LF Tower Design

ETO is working with CERN on:

- Vacuum pipe TDR (delivered in 2025)
- Civil Engineering
- Technical Infrastructure: HVAC, Electricity, Access & Alarms
- Safety
- Integration

Detector layout - 2L



X-arm

0 - 5km



o(200) towers with heights from 13 to 18 m



Vacuum pipe – full pilot sector at CERN

120 km of 1m diameter vacuum pipes

4 CNRS Institutes: IN2P3, INP, INSIS, INSU

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

154 French collaborators officially joined
the ET Collaboration
(~2/3 are also members of Virgo)

Organized in **8 Research Units** :
FTE threshold to get 1 voting voice at
the ET Collaboration Board

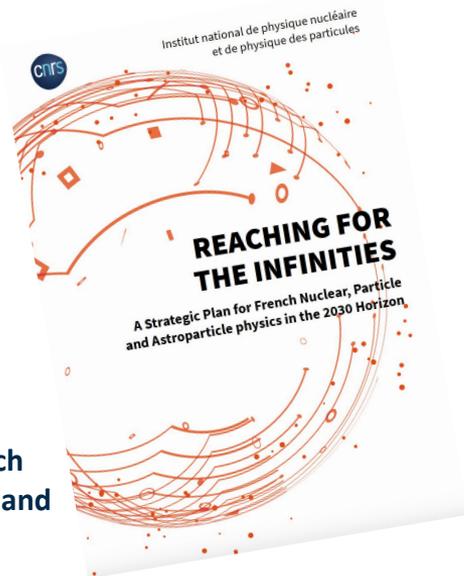


New RIs for Roadmap
2021 announced

The ET project entered the
ESFRI roadmap in 2021

ET is a strong priority in the French
strategic plan for Nuclear, Particle, and
astroparticle physics (2021)

« Participate in the 3G GW interferometer
development guided by the leveraging of
French Virgo expertise and facilities. »



- Almost 40% of survey answers mentioning **gravitational-waves**
- **Einstein Telescope** is the most cited experiment, followed by LISA and Virgo
- *Based on the survey, ET stands out as the most indicated next-generation infrastructure to be included in the roadmap.*
- *It is of interest not only to the GW community but also to a broader range of astroparticle scientists*

European FAs are working together towards an integrated European R&D roadmap for ET



Einstein Telescope is applying to enter this roadmap

- April 2025: eligibility application – **OK**
- July 2025: application to enter as IR
- October 2025: audition by the GT PNHE

Next steps:

End of October 2025 : WG evaluation

February 2026: decision at MESR

April 2026 : validation of the final list by CD TGIR

Final publication: September 2026

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

- Allowing a rich physics program with **high discovery potential**
- Included in a **3G GW detection network** together with neutrino and EM telescope detectors **for multi-messengers studies of the Universe**
- Increased synergies between the astroparticle, astrophysics and geophysics communities
- R&D roadmap in preparation between European Funding Agencies

There are important synergies between Einstein Telescope, existing 2G detectors (LIGO-Virgo-KAGRA) and other future detectors (Cosmic Explorer): CNRS teams and laboratories have acquired essential knowledge and skills in EGO-Virgo and LVK:

- Building on Virgo to prepare ET-HF
- Building especially on ET-Pathfinder (Maastricht) and KAGRA to prepare ET-LF

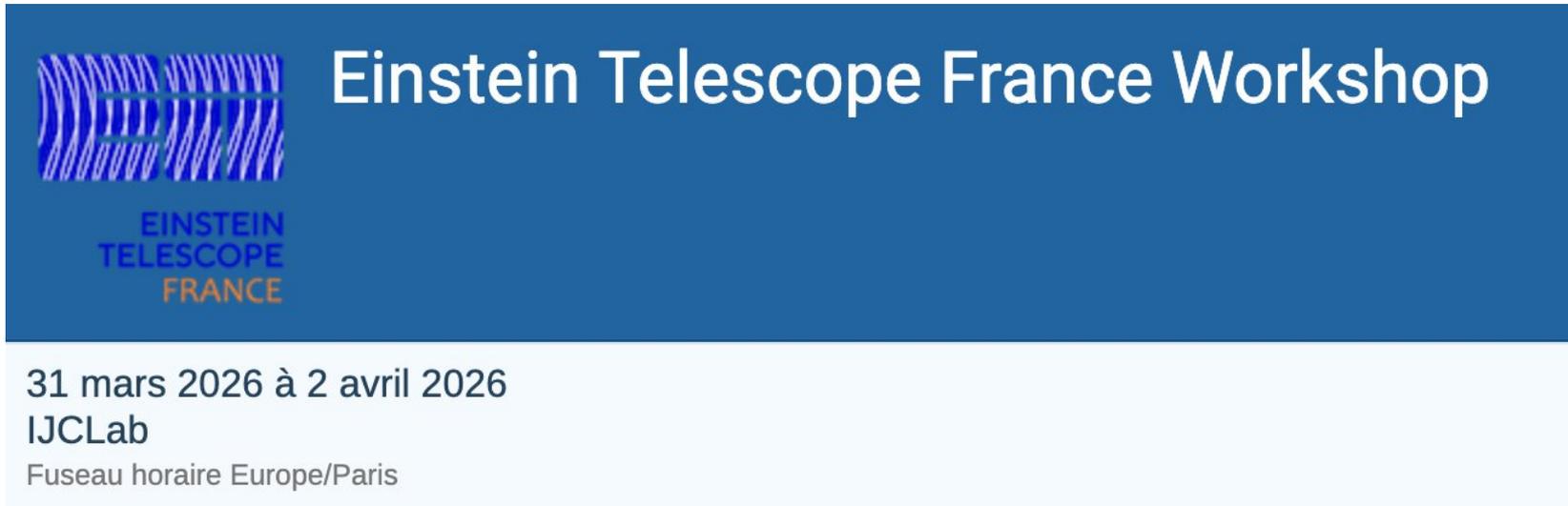
2026 will be end of the ET Preparatory-Phase:

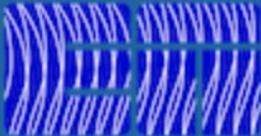
Preparing all documentation (including governance & financial model, socio-economic to allow a wise site-decision and proceed to the next stage of the project

ET France workshop : **March 31 – April 2 at IJCLab**

Goal: setting up the organization of ET-France

<https://indico.in2p3.fr/event/37982>

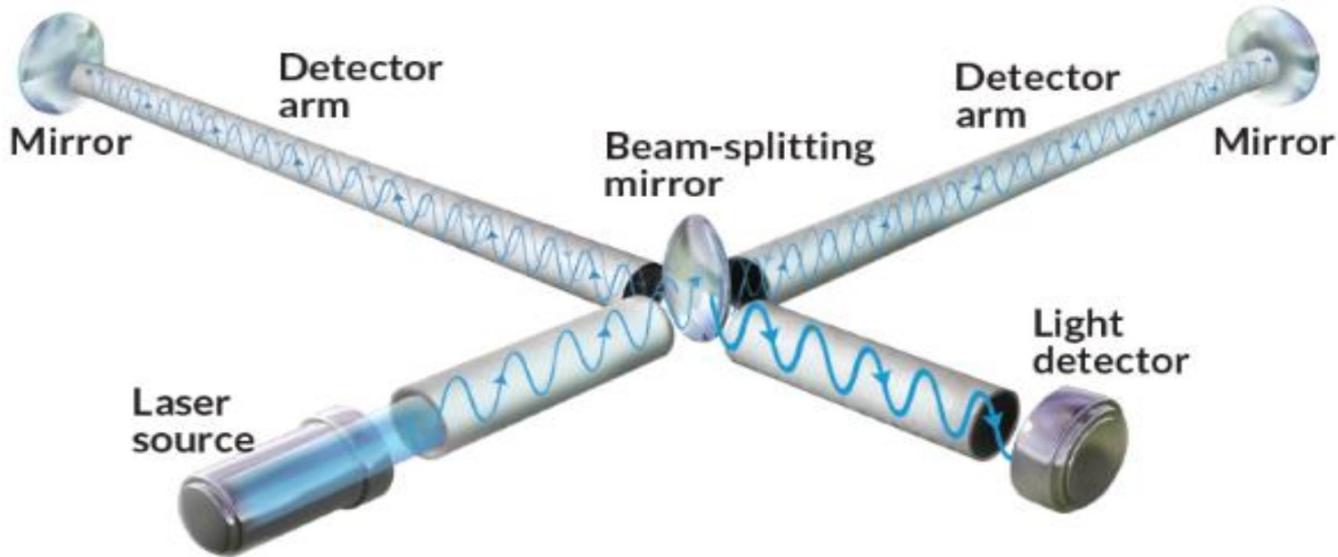


 **Einstein Telescope France Workshop**

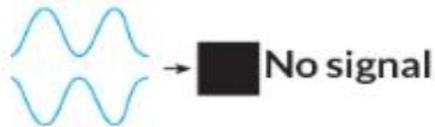
**EINSTEIN
TELESCOPE
FRANCE**

31 mars 2026 à 2 avril 2026
IJCLab
Fuseau horaire Europe/Paris

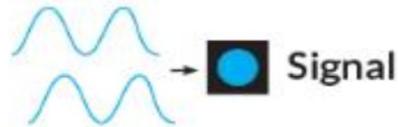
RESERVE



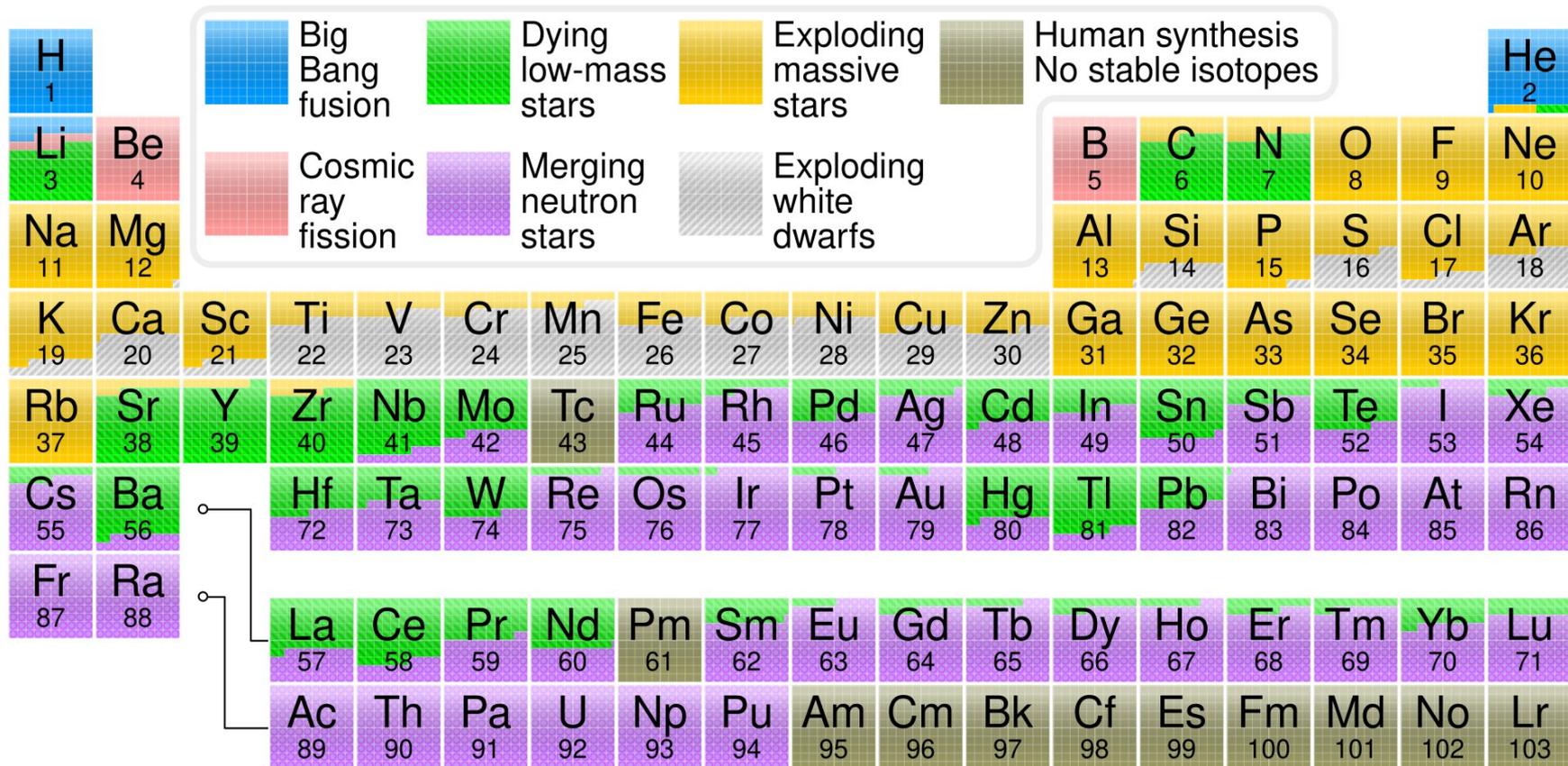
Normal situation



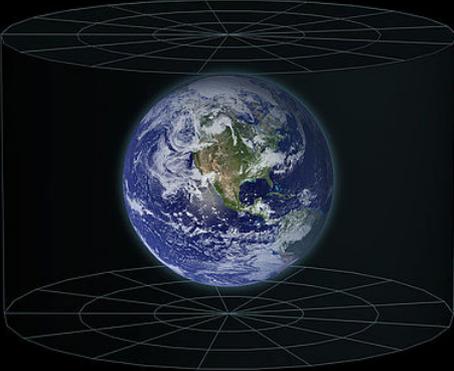
Gravitational wave detection



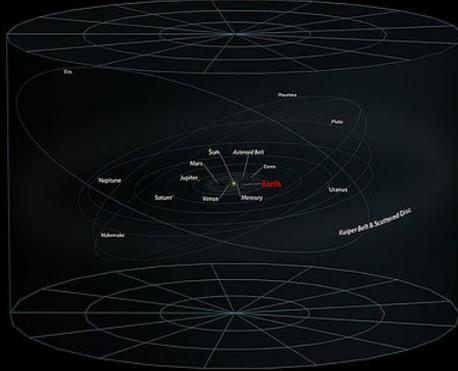
NICOLLE RAGER FULLER



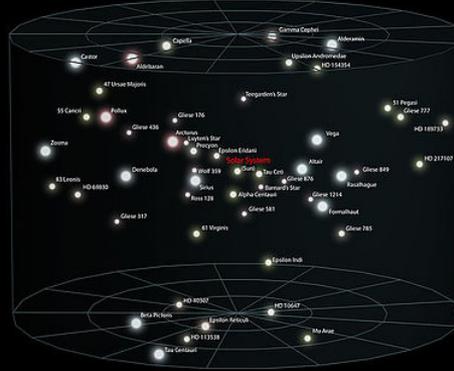
EARTH



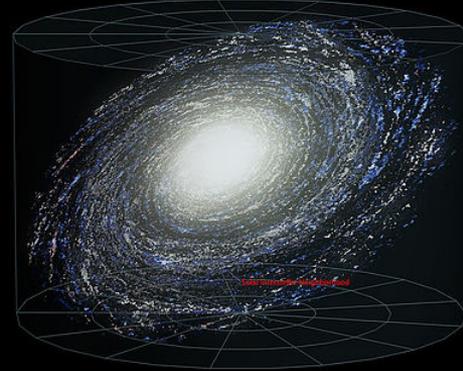
SOLAR SYSTEM



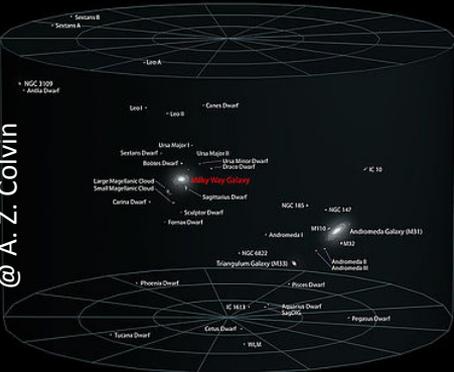
INTERSTELLAR NEIGHBORHOOD



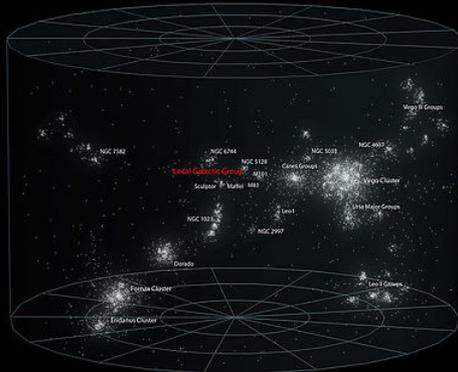
MILKY WAY GALAXY



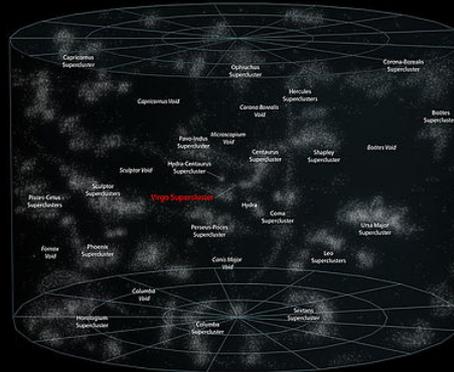
LOCAL GALACTIC GROUP



VIRGO SUPERCLUSTER



LOCAL SUPERCLUSTERS



OBSERVABLE UNIVERSE



@ A. Z. Colvin

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 m³ 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

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

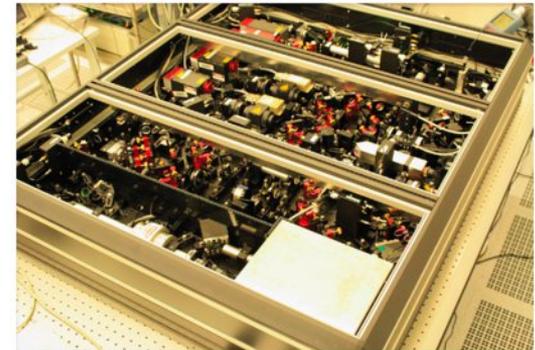


Photo: AEI/GEO600

High Power Laser

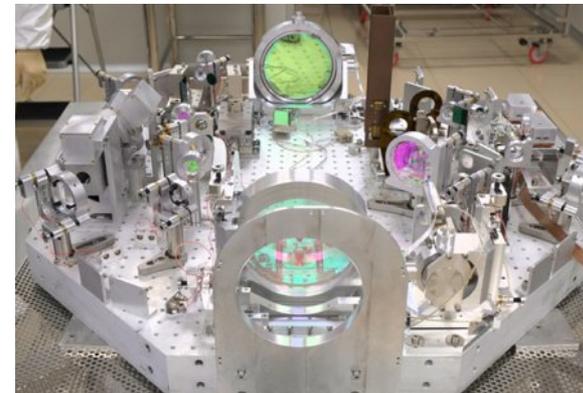
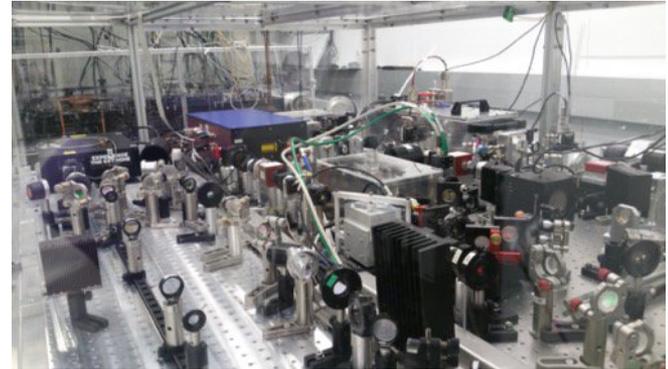
- Two wavelengths: 1064 nm and 1550 nm
- Ultra-stable continuous lasers – amplified up to ~ hundred W
- Bandwidth <1 kHz and stabilization at ~mHz
- Low noise of RIN intensity
- Low phase noise
 - High-power, ultra-stable laser R&D developments – ARTEMIS

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



Stray Light

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

Optical Simulations

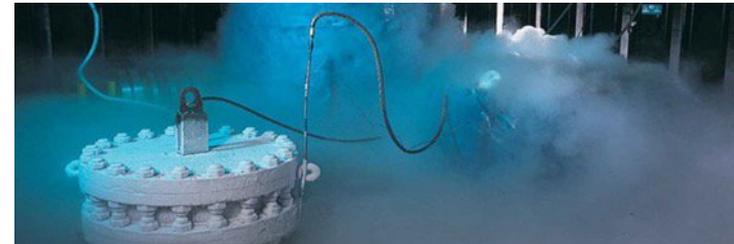
- Need to understand, control and improve gravitational wave detectors
 - Implement reliable and robust simulation tools
 - Linear simulations: studying linear effects, opto-mechanical effects, the impact of high power
 - Time-domain simulations to study control noise
 - 3D simulation
 - The French community 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



Infrastructure

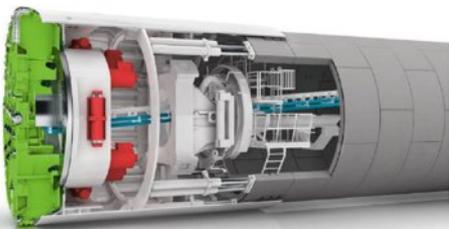
@J. Degallaix



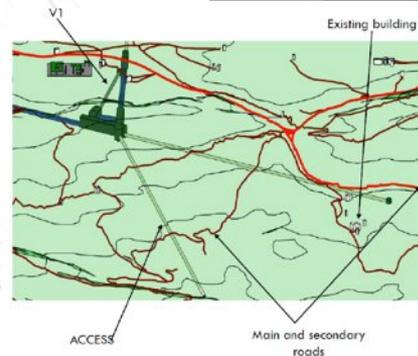
- stratégie pour la construction des tunnels et cavernes
- gestion infrastructure souterraine
- intégration dans l'environnement local



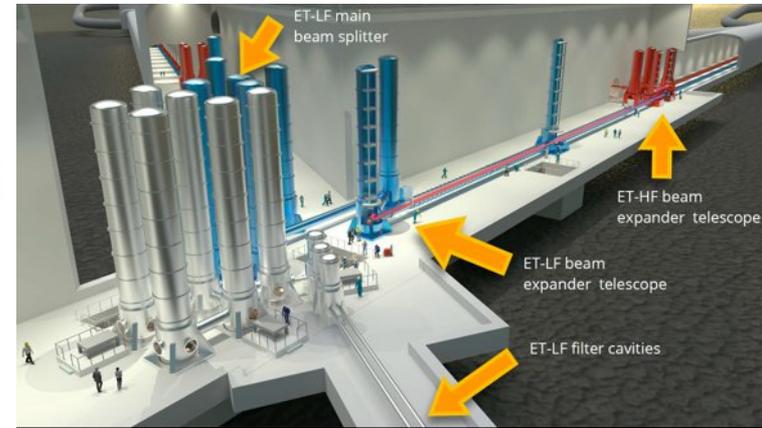
Taille, forme des cavernes ?



Méthode d'excavation ?



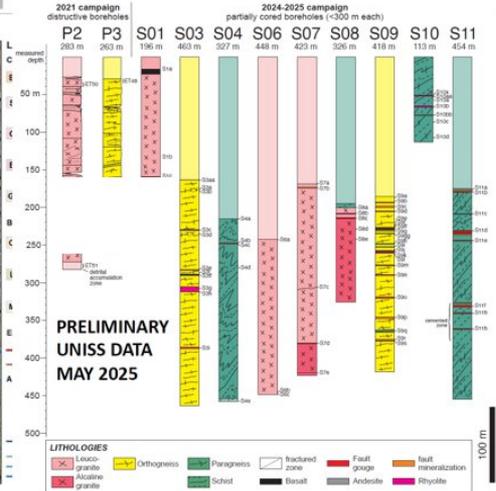
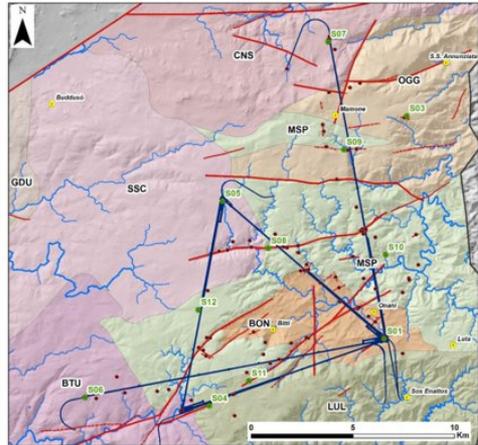
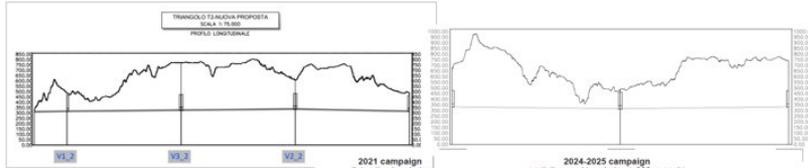
Installations existantes ?



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

Geological study completed for Δ and L: granodiorites on all vertices, no water issues anywhere

Caverns at 200÷400 m underground

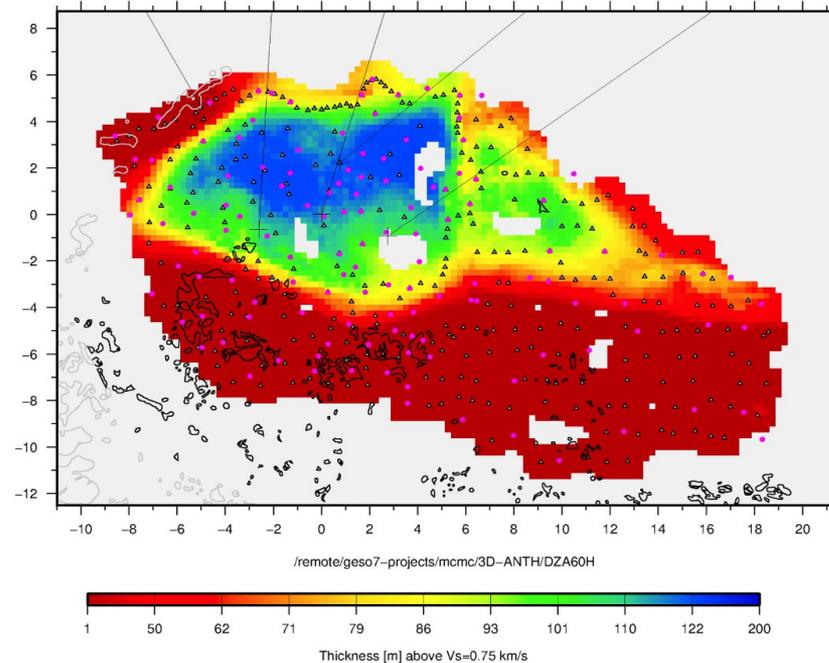


Developing a Digital Twin: Shallow Seismic Velocity Structure

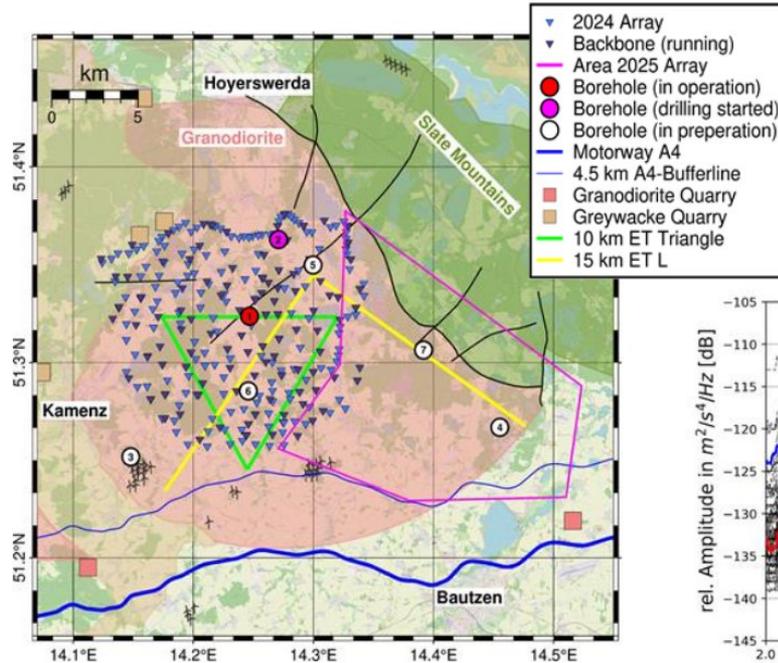
Iso velocity of 0.750 km/s used as proxy for thickness of sedimentary cover:

- Clear 3D basin like structure is observed
- Excellent agreement with borehole data

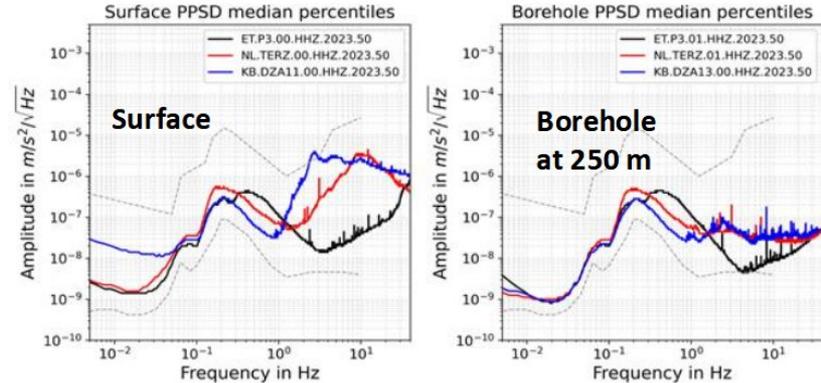
→ Ambient Newtonian Noise modelling now under way using real 3D geometry of the subsurface



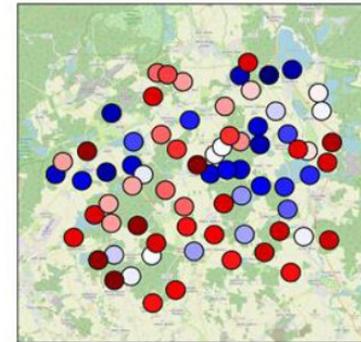
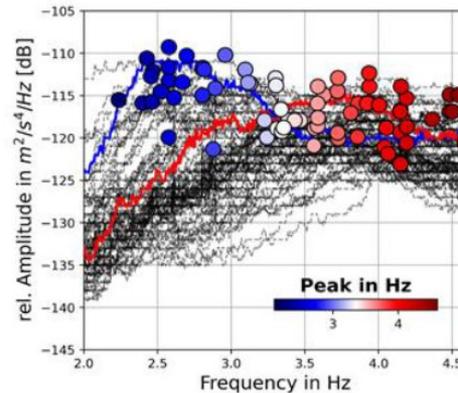
Ambient noise analysis



Ambient noise network in Lusatia



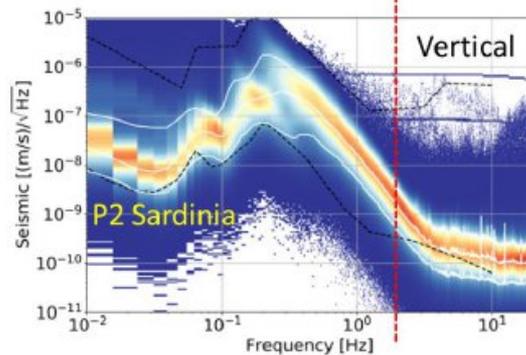
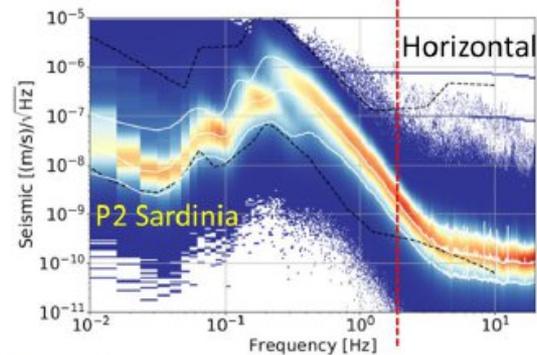
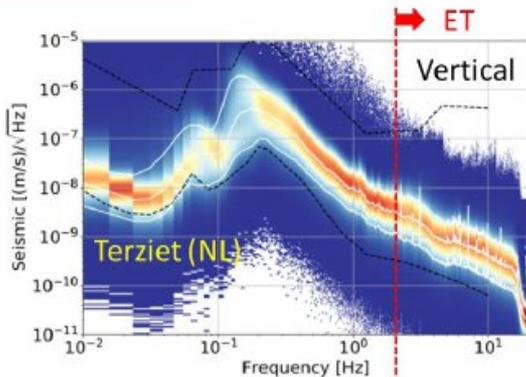
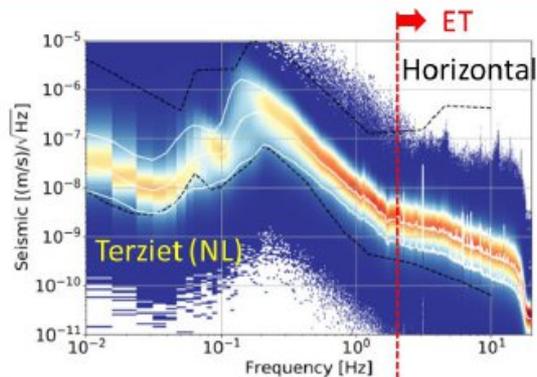
Comparison median PPSD: Surface v.s. Borehole



Spatial pattern of noise peak in Lusatia. Borehole is located in blue area

Borehole measurements comparison

+ a large set of other environmental noise sources measures (wind, magnetic, ...)



EMR Terziet (NL) borehole



Sardinia P2 borehole



Credit L. Naticchioni

Detector layout - Triangle

2024 reference

New baseline design from Task Force:
-25% volume reduction

Task force action

2024 reference

Huge effort :

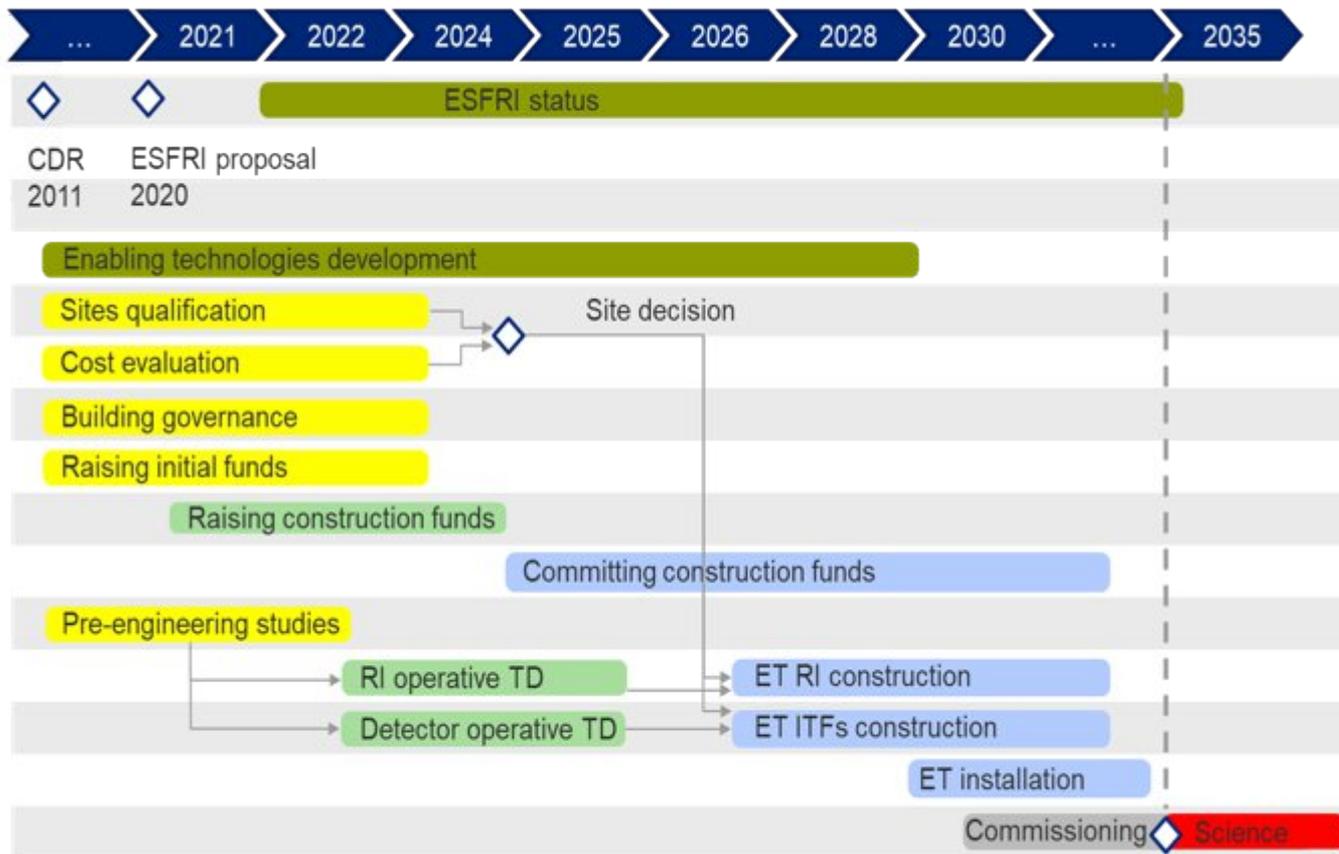
- to optimize the optical layout design
 - To design the associated infrastructure
- => **cost optimization & reduction**

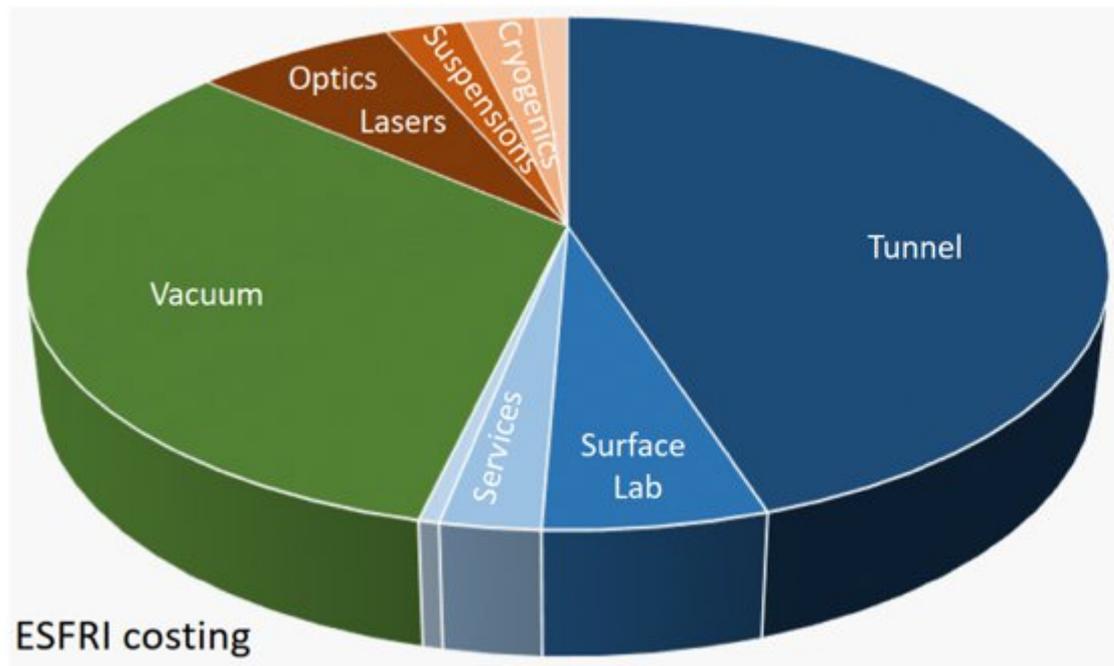
Detector layout - 2L

New baseline design from Task Force:
-28% volume reduction

Task force action

* Tentative schedule





ESFRI costing
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€