

Einstein Telescope

Luca Naticchioni

on behalf of ET Roma1 R.U.



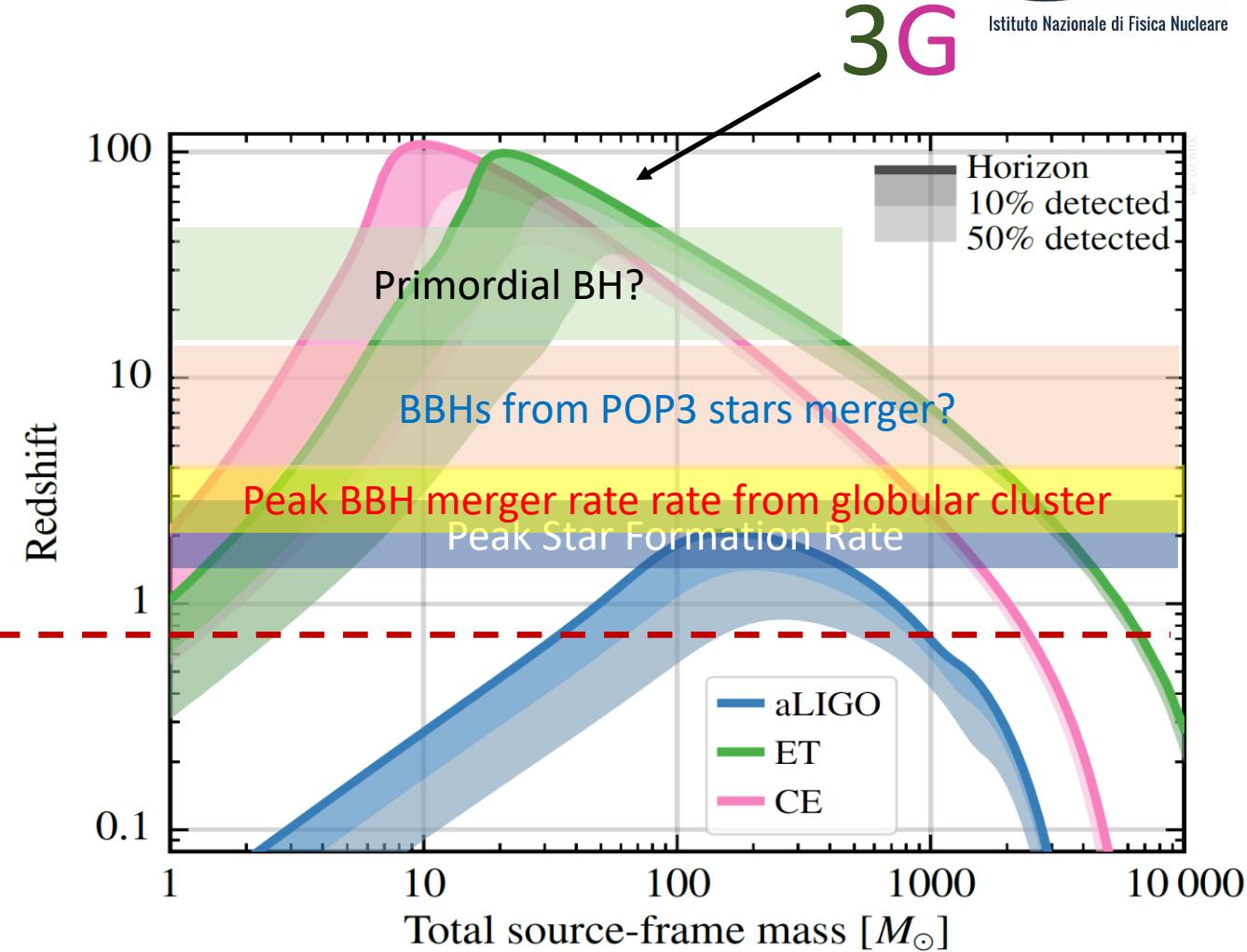
Istituto Nazionale di Fisica Nucleare

Outline

- ❑ Einstein Telescope: science case
- ❑ The ET design
- ❑ ET Status
- ❑ INFN Roma & Sapienza - Dip. di Fisica commitment

Where we are with Advanced GW Detectors

- 2nd generation Gravitational Wave (GW) detectors will explore local Universe, initiating the precision GW astronomy, but to have *cosmological* investigations a factor of 10 improvement in terms detection distance is needed
- Farther event in GWTC-2 are at $z \approx 0.71$
- 3G ground-based detectors will be required to access the high redshift Universe



BH: Black Hole, **NS:** Neutron Star, **BNS:** Binary Neutron Star, **BBH:** Binary Black Hole, **POP3:** Population 3 stars, **3G:** Third Generation, **HF:** High Frequency, **LF:** Low Frequency

Where we aim with 3G GW Detectors

Detection Range of GW detectors



3G GW observatory potential

- To observe Merging Black Holes **throughout the whole universe** and reconstruct **BH demography**
- To explore **new physics in gravity** and fundamental properties of **compact objects**
- To study the **properties of the hottest matter** in the universe
- To investigate the connection between **high energy processes** in radiation/particle and gravitation
- To investigate **primeval universe** and connections with particle physics
- To investigate the **Dark Universe** (95%)

ET: the science case

ASTROPHYSICS

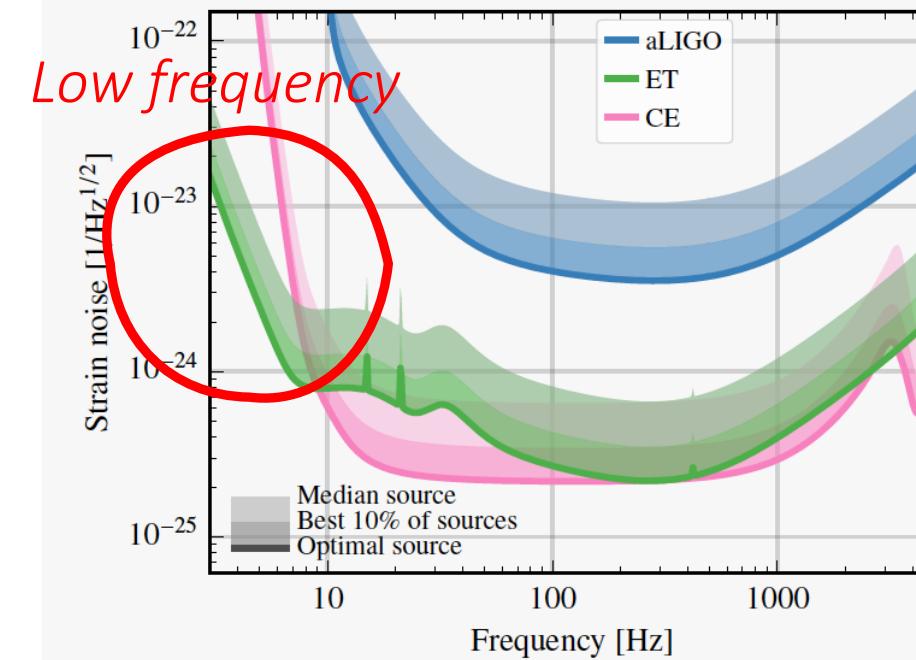
- **Black hole properties**
 - origin (stellar vs. primordial)
 - evolution, demography
- **Neutron star properties**
 - interior structure (QCD at ultra-high densities, exotic states of matter)
 - demography
- **Multi-band and -messenger astronomy**
 - joint GW/EM observations (GRB, kilonova,...)
 - 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

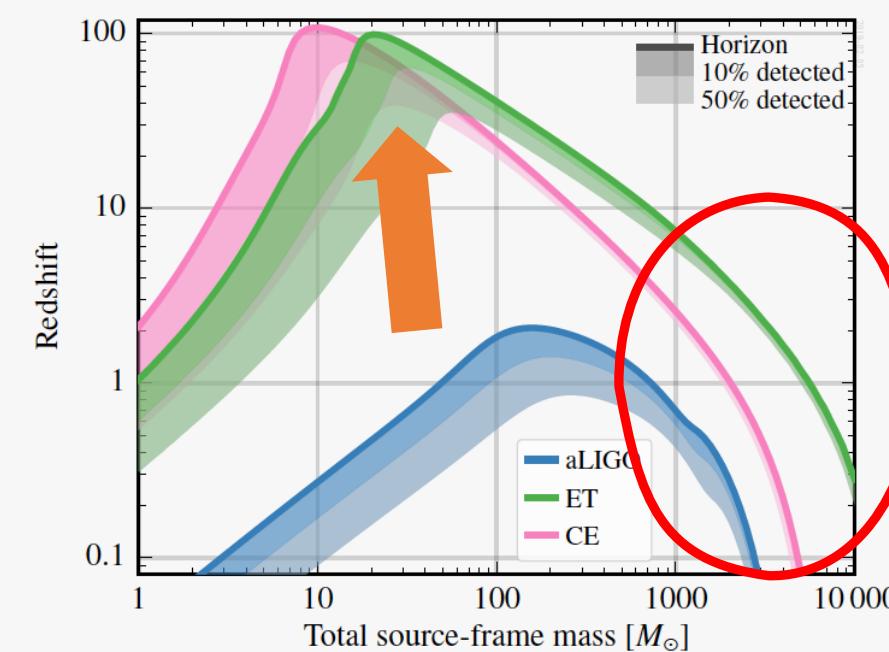
- **The nature of compact objects**
 - near-horizon physics
 - tests of no-hair theorem
 - exotic compact objects
- **Tests of General Relativity**
 - post-Newtonian expansion
 - strong field regime
- **Dark matter**
 - primordial BHs
 - axion clouds, dark matter accreting on compact objects
- **Dark 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: the science case

Strain sensitivity

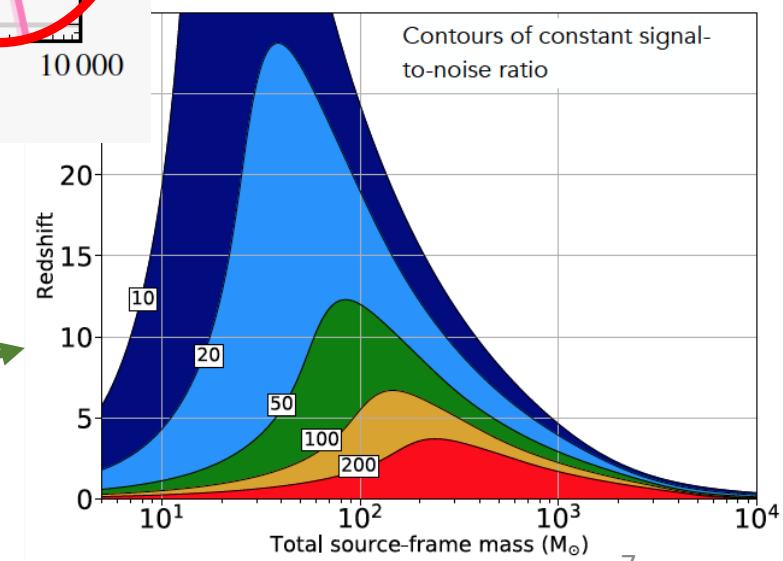


Coalescence of compact binary objects



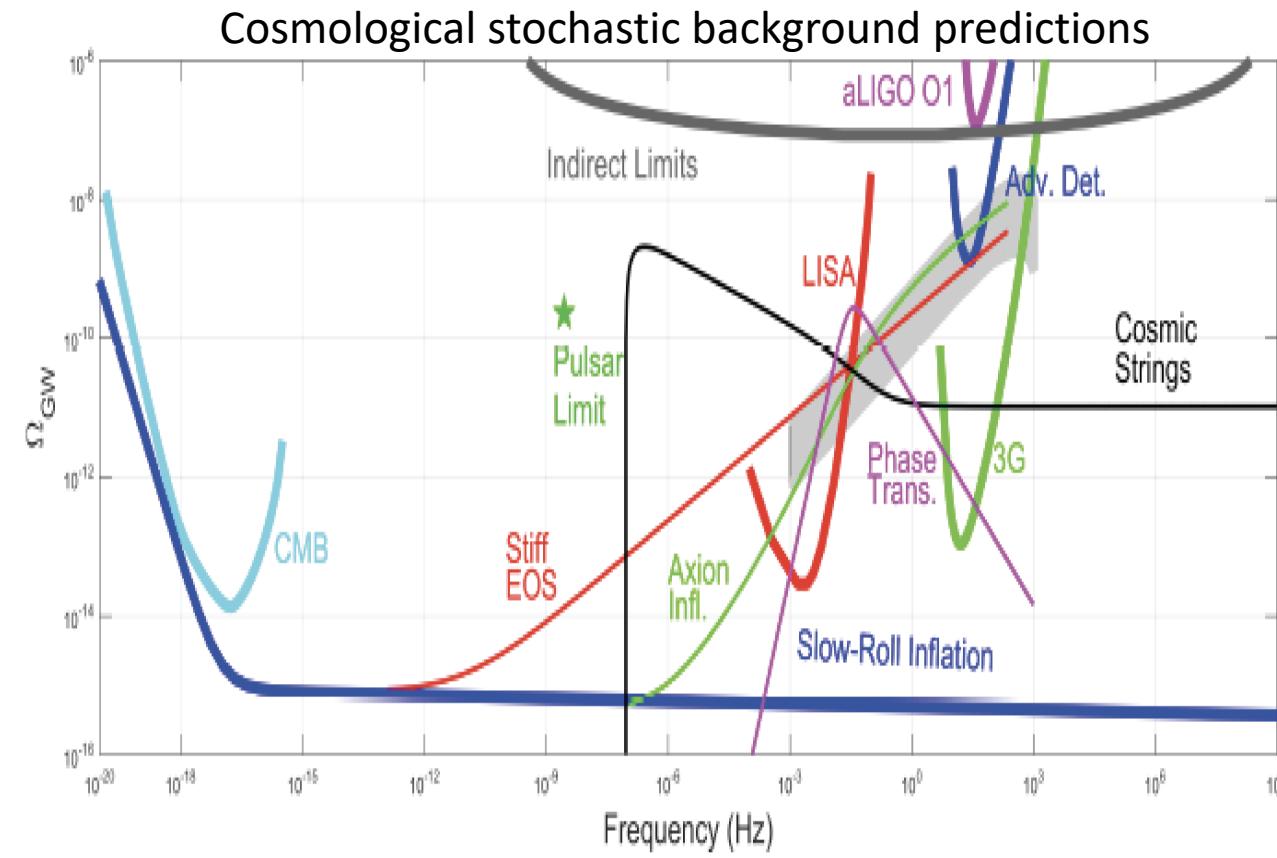
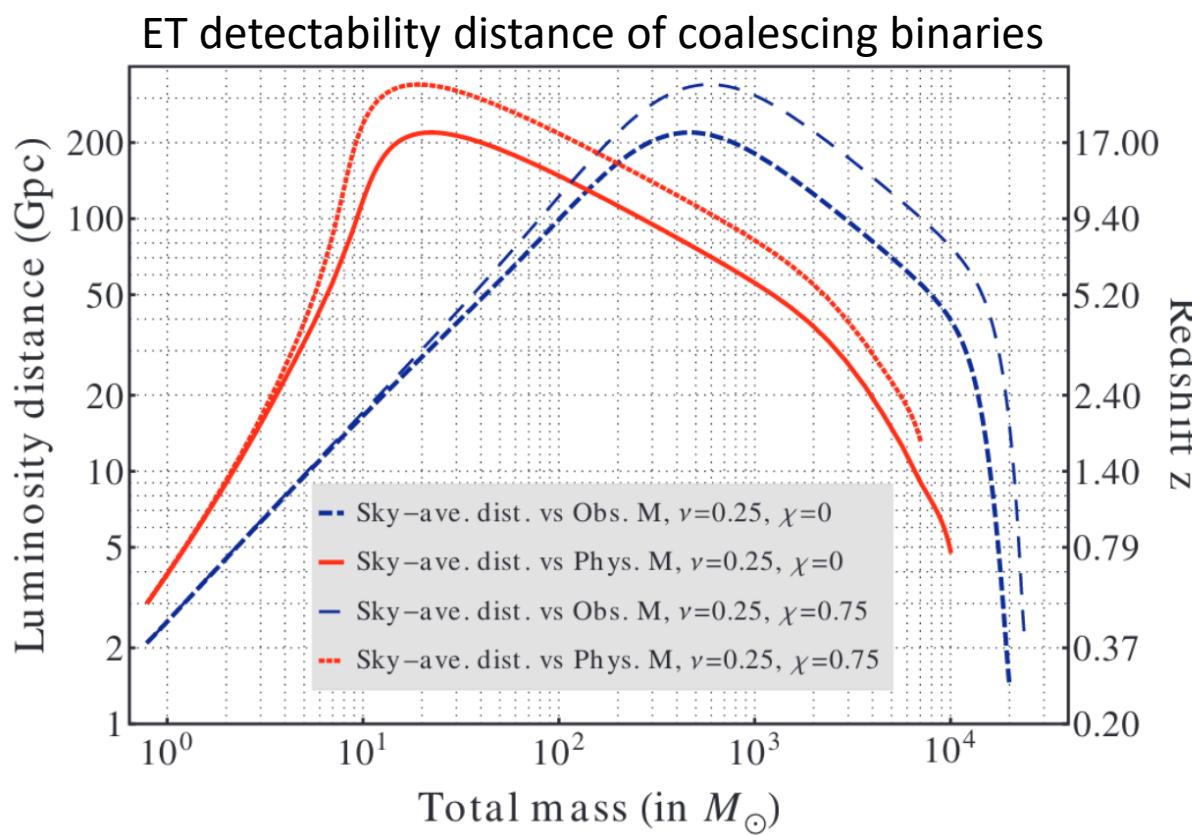
Our target: 10^5 to 10^6 events/year

A network of 3 detectors (ET+CENorth+CESouth)



ET: the science case

- **Big challenges** in terms of **Data Analysis** (DA) and **computing**: longer signals, subtle physics effects, huge number of events, ‘noise’ foreground,...
- **But the reward will be impressive**



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The Einstein Telescope

10km

...and Cosmic Explorer (CE) in USA

The Einstein Telescope project

- ET is a **3G** new GW **observatory** in Europe

➤ **3G:**

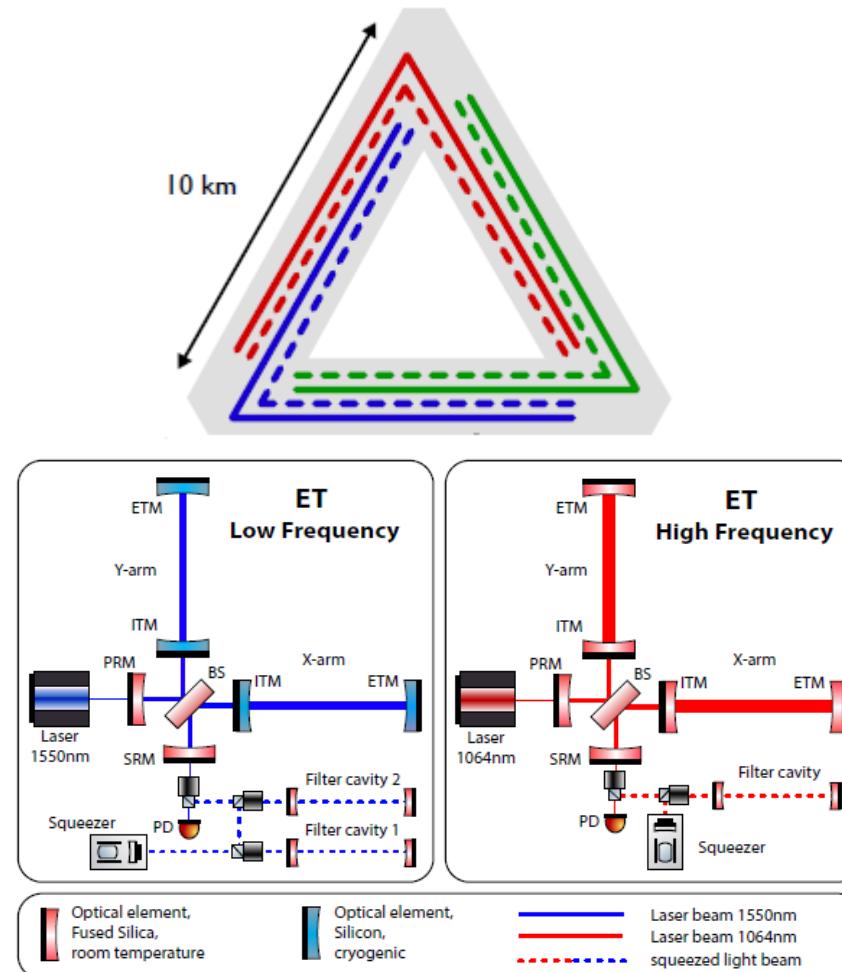
- Sensitivity a factor 10 better than 2G (advanced) detectors
- 50-years lifetime infrastructure (→compliant with the upgrades of the hosted detectors)

➤ **Observatory:**

- *broadband*, focused to *low frequency* (few Hz)
- Capability to work *alone* (depending on international scenario)
 - *Localisation* capability (limited if alone)
 - *Polarisation* discrimination (→triangle configuration)
 - High *duty cycle* (→redundancy)

The Einstein Telescope project

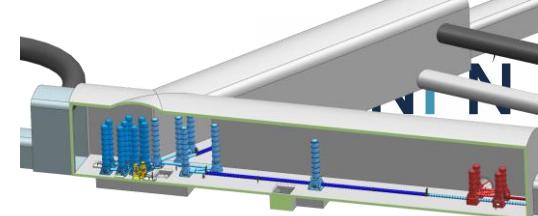
- ET is a **3G new GW observatory** in Europe



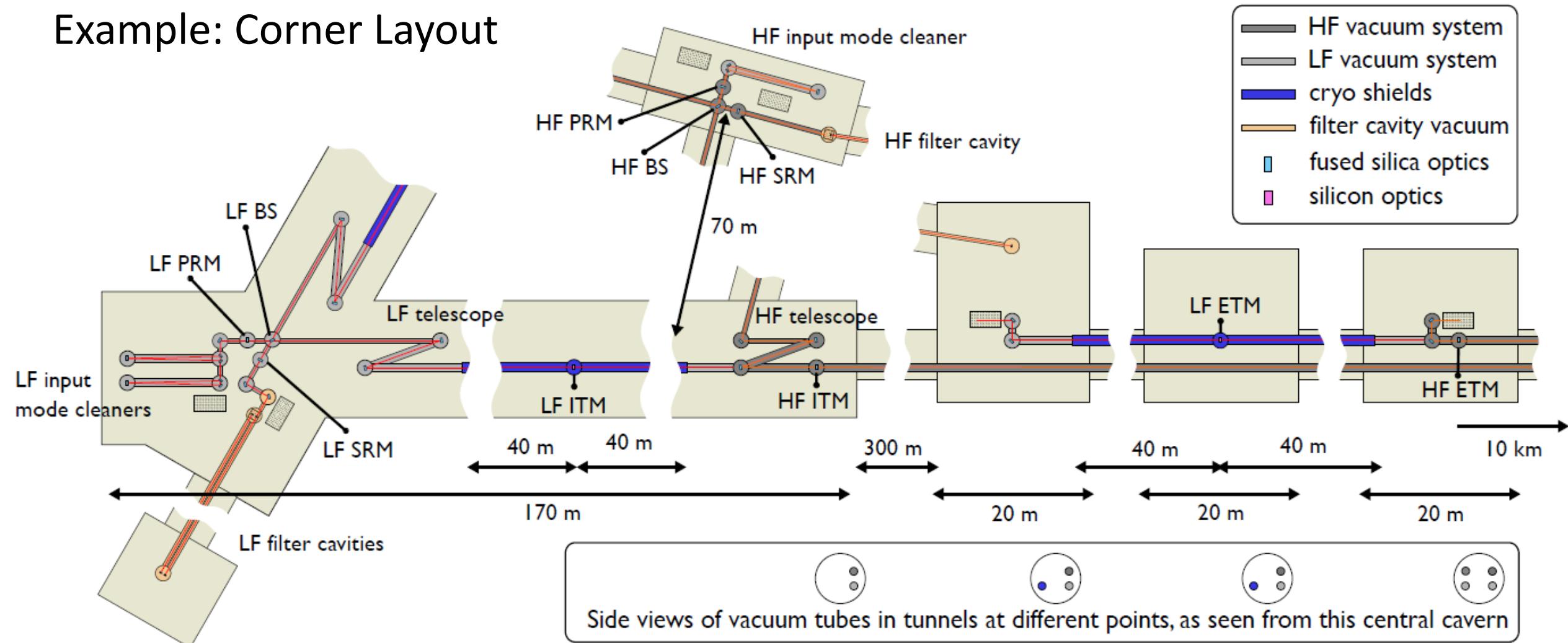
- Triangle configuration: 3 detectors
- Xylophone configuration: 6 interferometers (3HF + 3LF)
- Interferometer orientations for both polarisations
- Co-aligned interferometers (\rightarrow null streams)
- Redundancy for duty cycle
- Single infrastructure for cost efficiency
- **Underground and cryogenic (LF)**

ET Design

...quite complicated wrt current generation GWDS

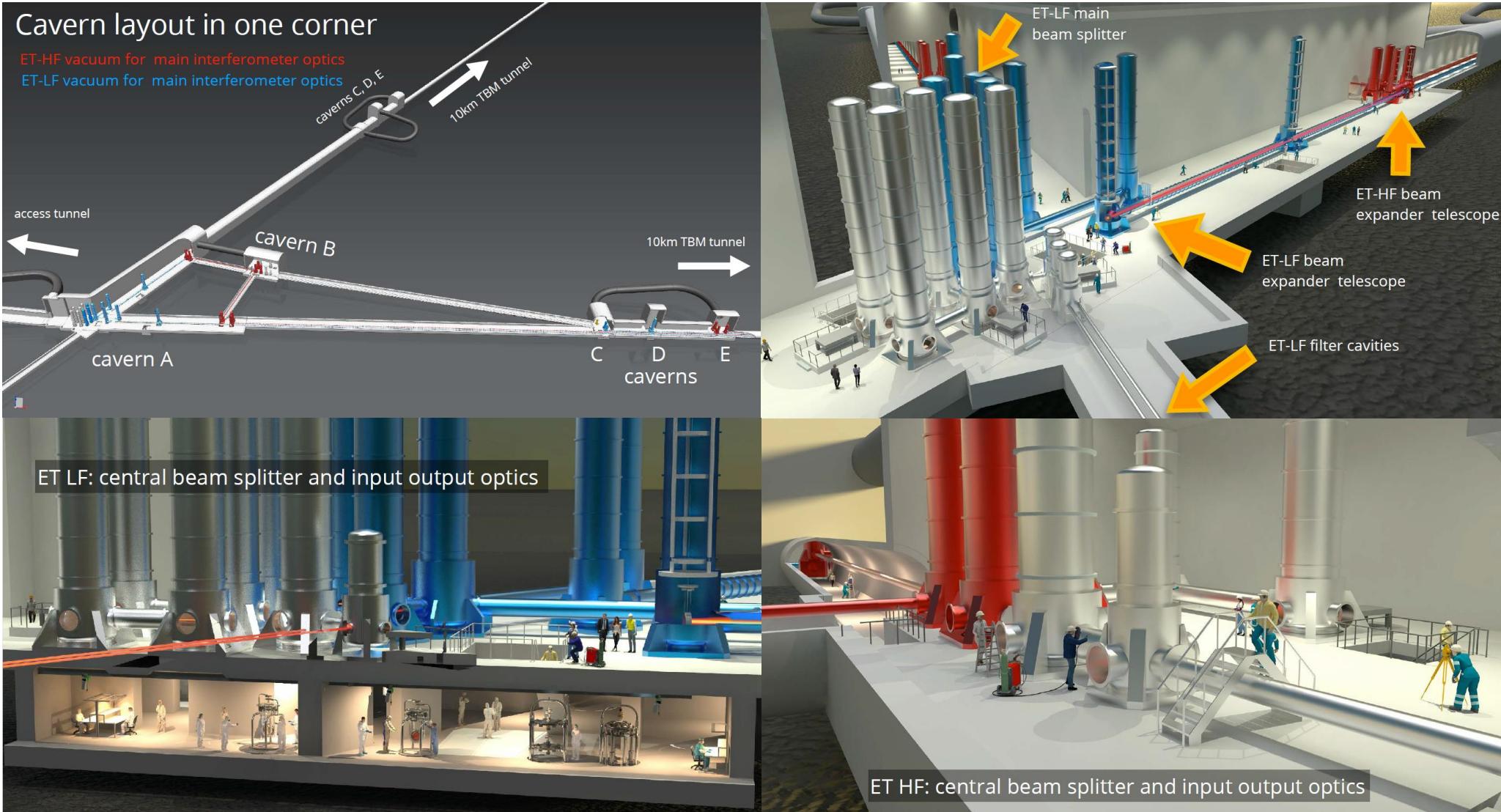


Example: Corner Layout



ET Design

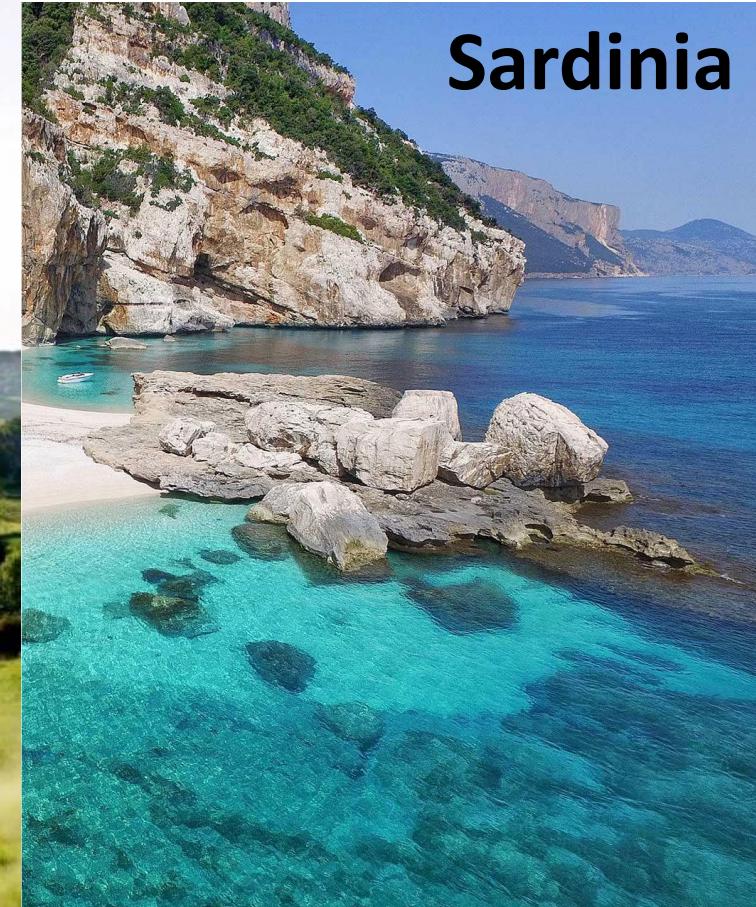
...quite complicated wrt current generation GWDS



Where?

Two official candidate sites:

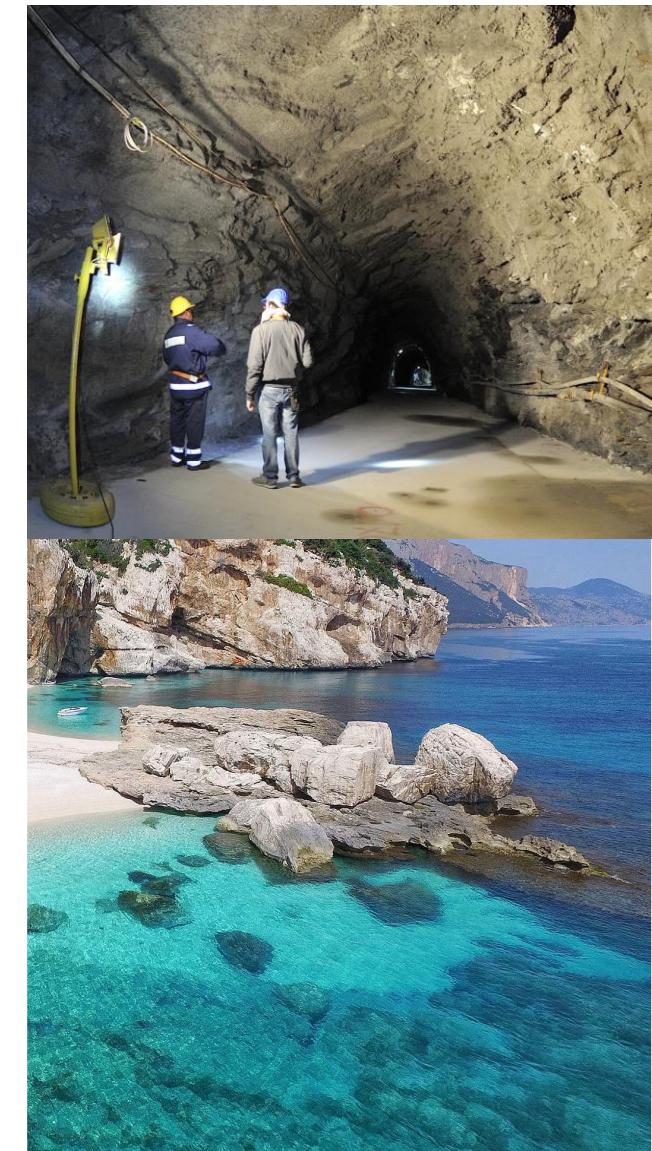
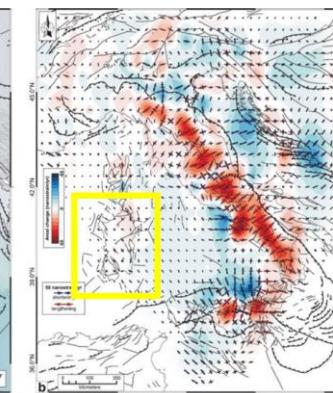
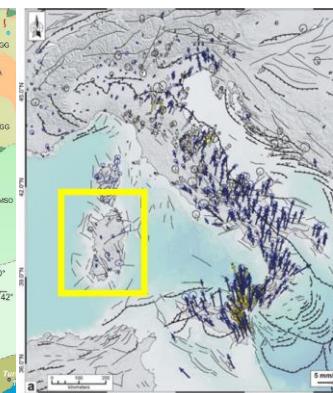
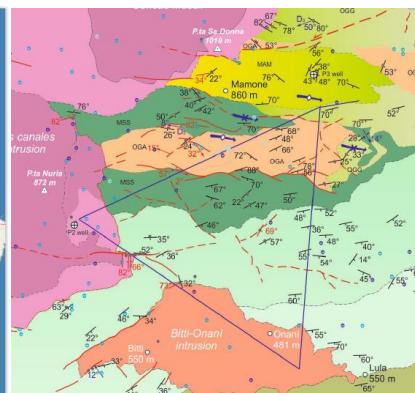
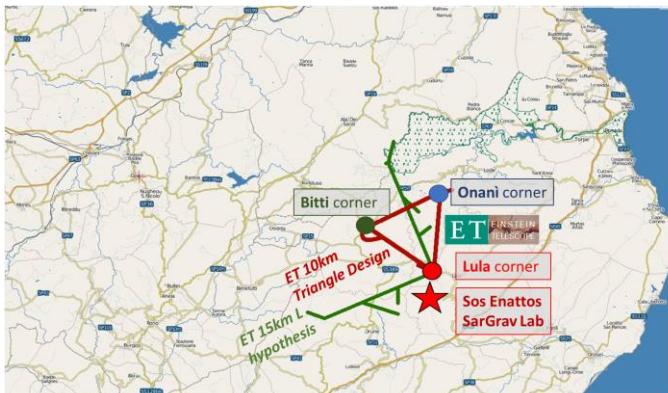
EUregio Meuse-Rhine



... plus a possible third site in Saxony (DZA)

The Sardinia site

- Long standing characterization of the mine in one of the corners continuing (*started by Roma1 12 years ago!*);
- Environmental (Seismic, magnetic, acoustic...) noise and geological characterization of the former mine of Sos Enattos (where the SarGrav laboratory hosts also the Archimedes experiment);
- Characterization of the other two corners with two boreholes (265m and 280m deep) excavated and instrumented;
- **ROMA1 has a leading role in the site characterization!**



The Sardinia site

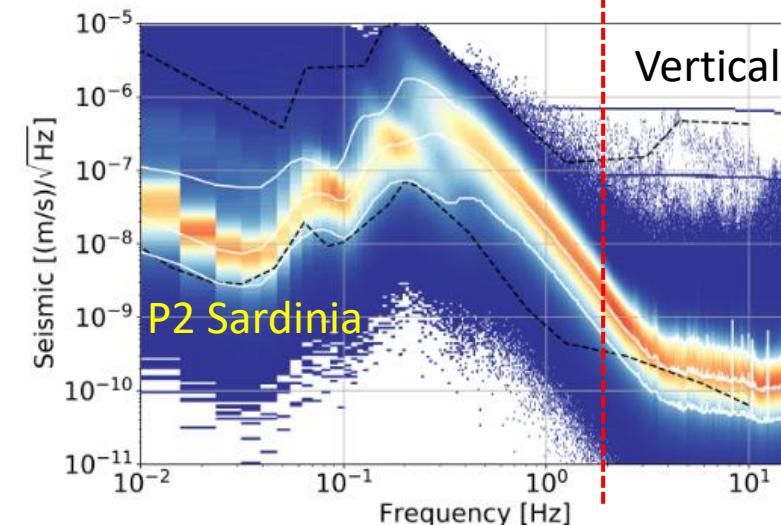
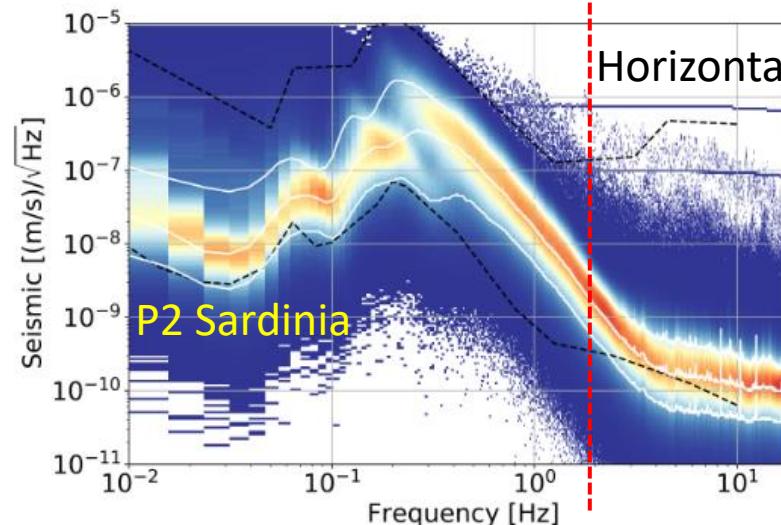
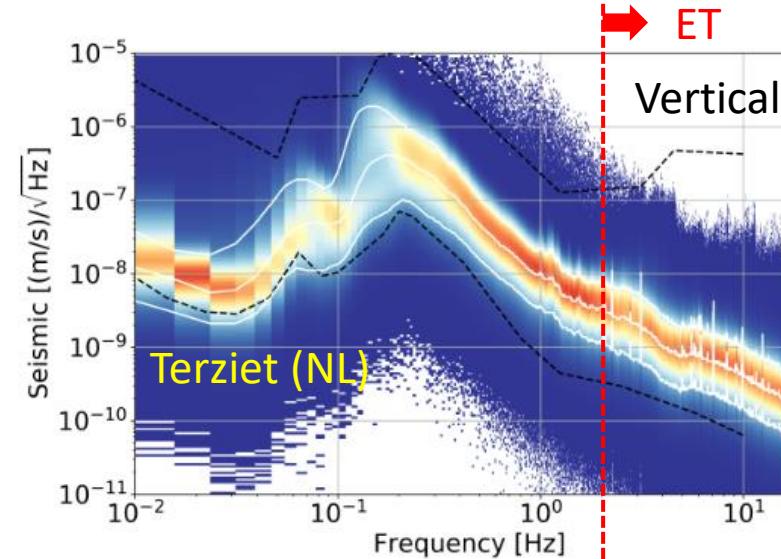
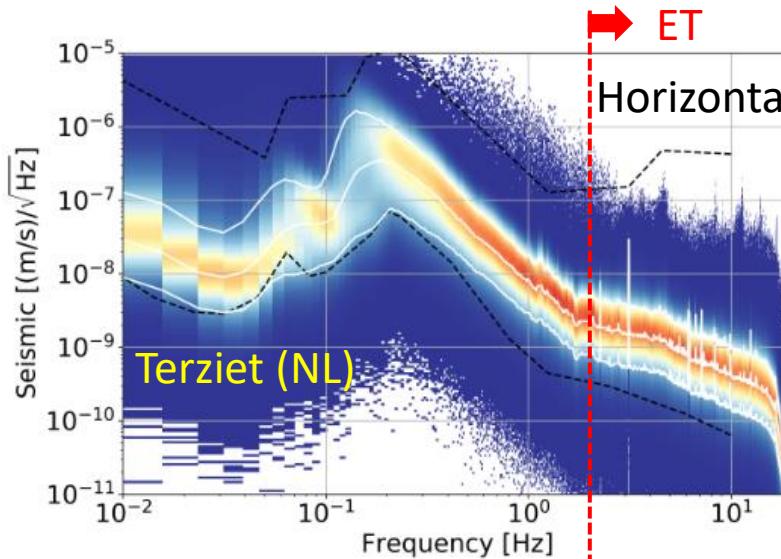
INFN ROMA is the leaseholder of the two corner sites and was committed to excavate and setup the borehole stations P2 and P3.



L. Naticchioni - Einstein Telescope - Retreat INFN Roma1 2022

The Sardinia site

Seismic noise: in the few Hz band among the quietest sites in the world!



EMR Terziet (NL) borehole



Sardinia P2 borehole



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Building ET

On June 30th 2021, ET was adopted into the ESFRI roadmap!

ET CA signed by 41 institutions, lead by INFN and NIKHEF

01 LUGLIO 2021

ET ED EUPRAXIA CON L'ITALIA CAPOFILA ENTRANO NELLA ROADMAP DI ESFRI



Istituto Nazionale di Fisica Nucleare



ET Einstein Telescope ed EuPRAXIA: due grandi infrastrutture di ricerca competitive a livello mondiale, rispettivamente nella ricerca sulle onde gravitazionali e nello sviluppo di futuri acceleratori di particelle al plasma. Sono questi i due progetti internazionali di cui l'INFN Istituto Nazionale di Fisica Nucleare è capofila, e che l'Italia attraverso il MUR Ministero dell'Università e della Ricerca ha candidato lo scorso settembre per la Roadmap 2021 di ESFRI European Strategy Forum on Research Infrastructure, il forum strategico europeo che individua le grandi infrastrutture di ricerca su cui investire a livello europeo. Dopo un lungo e accurato processo di valutazione dei progetti candidati, il 30



giugno, l'Assemblea di ESFRI ha approvato entrambi, ET ed EuPRAXIA, che entrano così nel novero delle grandi infrastrutture di ricerca su cui l'Europa punterà nel prossimo futuro.

"L'inclusione di ET ed EuPRAXIA nella Roadmap di ESFRI è un importante risultato che ne rafforza il valore strategico a livello europeo", commenta **Antonio Zoccoli, presidente dell'INFN**. "Le grandi infrastrutture di ricerca sono una risorsa per la scienza e la conoscenza, ma anche per lo sviluppo industriale, l'innovazione tecnologica, la crescita economica, culturale e sociale. Forti della leadership scientifica del nostro Paese a livello internazionale, metteremo il massimo impegno per il loro sviluppo, e per valorizzare la candidatura del sito italiano a ospitare ET, e siamo certi che con il sostegno del MUR, della Regione Sardegna, delle Istituzioni nazionali e locali, abbiamo ottime possibilità di raggiungere l'obiettivo, a beneficio del territorio e del Paese".

L'Italia, con la Sardegna, è uno dei due siti candidati a ospitare ET, e vi partecipa con l'INFN, l'INAF Istituto Nazionale di Astrofisica e l'INGV Istituto Italiano di Geofisica e Vulcanologia, e le Università di Sassari e Cagliari. La sede principale di EuPRAXIA, pro-

***ESFRI: European Strategy Forum on Research Infrastructures**

Nikhef

Menu

Search

Einstein Telescope approved for ESFRI Roadmap 2021

1 July 2021

On June 30th, the European Strategy Forum on Research Infrastructures (ESFRI) decided to include the Einstein Telescope in the 2021 upgrade of its roadmap. This confirms the relevance of this major international project for a next generation gravitational waves observatory for the future of research infrastructures in Europe and gravitational wave research at a global level.

Building ET

ETIC – Einstein Telescope Infrastructure Consortium

PNRR – next generation EU proposal

- *establish a network of research infrastructures in Italy and enable the technologies for ET.;*
- *coordinated by INFN and co-proposed by INAF, ASI + 11 universities in Italy;*
- *establish 15 laboratories co-hosted by INFN units and participating universities;*
- *deliver the preliminary engineering design of ET.*

ETIC – Einstein Telescope Infrastructure Consortium



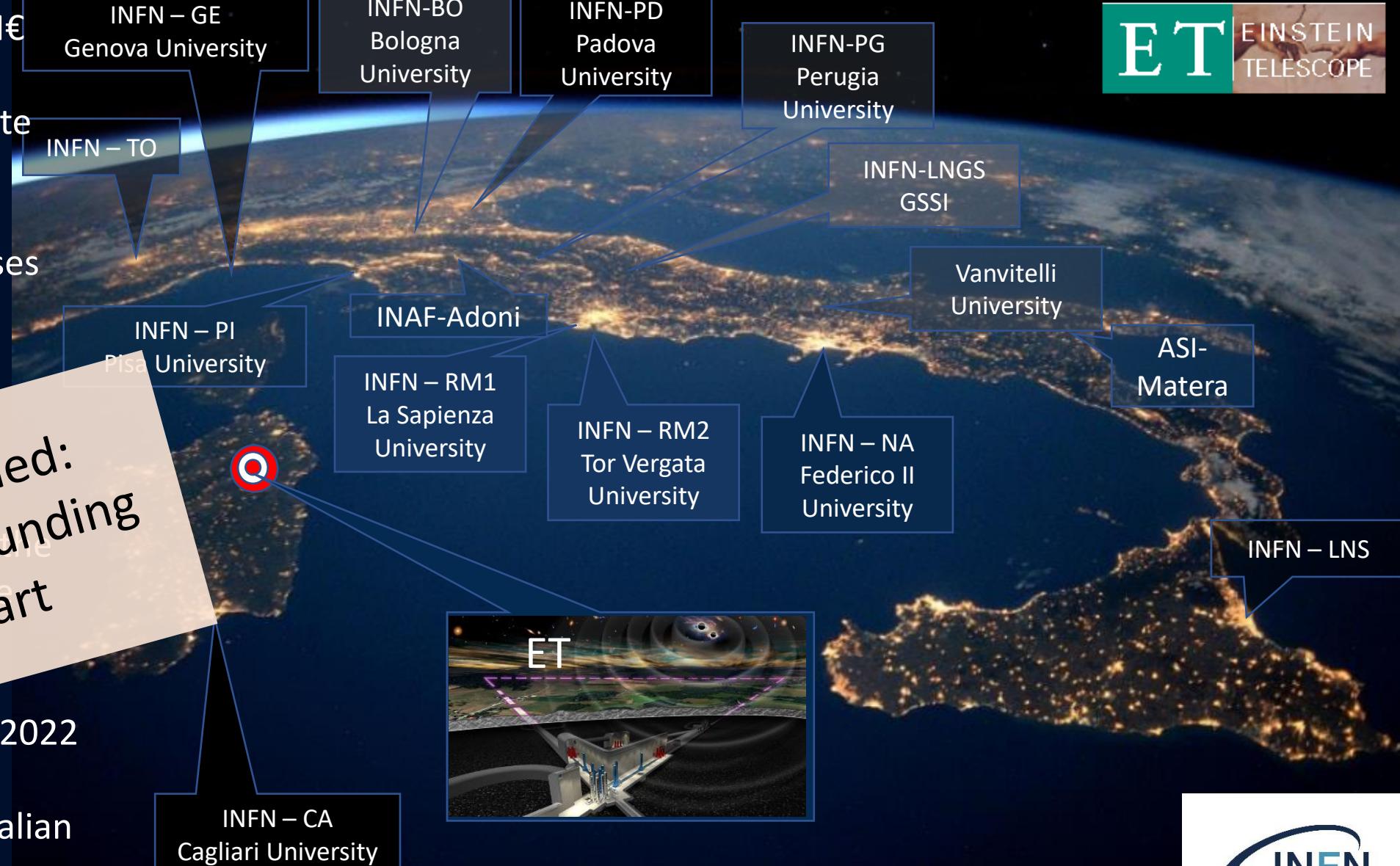
Next Generation EU
Investment proposed 100M€
focused on ET enabling
technology and Sardinian site
candidature support

- 8% Human Resources
- 30% Scientific apparatuses
- 12% Distributed Infrastructures
- 28% ET design
- 12% Training

Ranking published:
Negotiation for funding
about to start

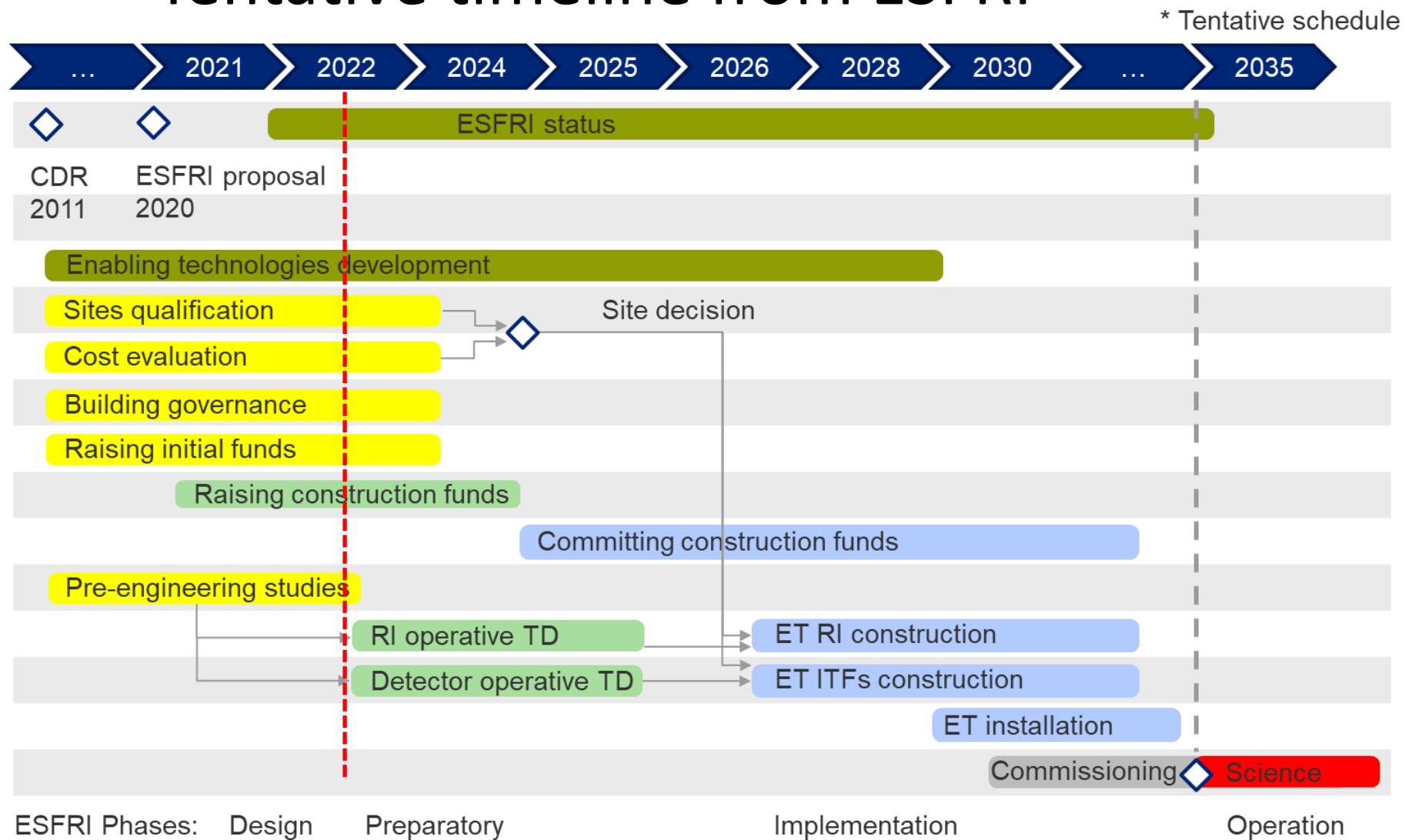
Feedback expected in June 2022

Discussion ongoing on an Italian
share toward ET realization



Building ET

Tentative timeline from ESFRI

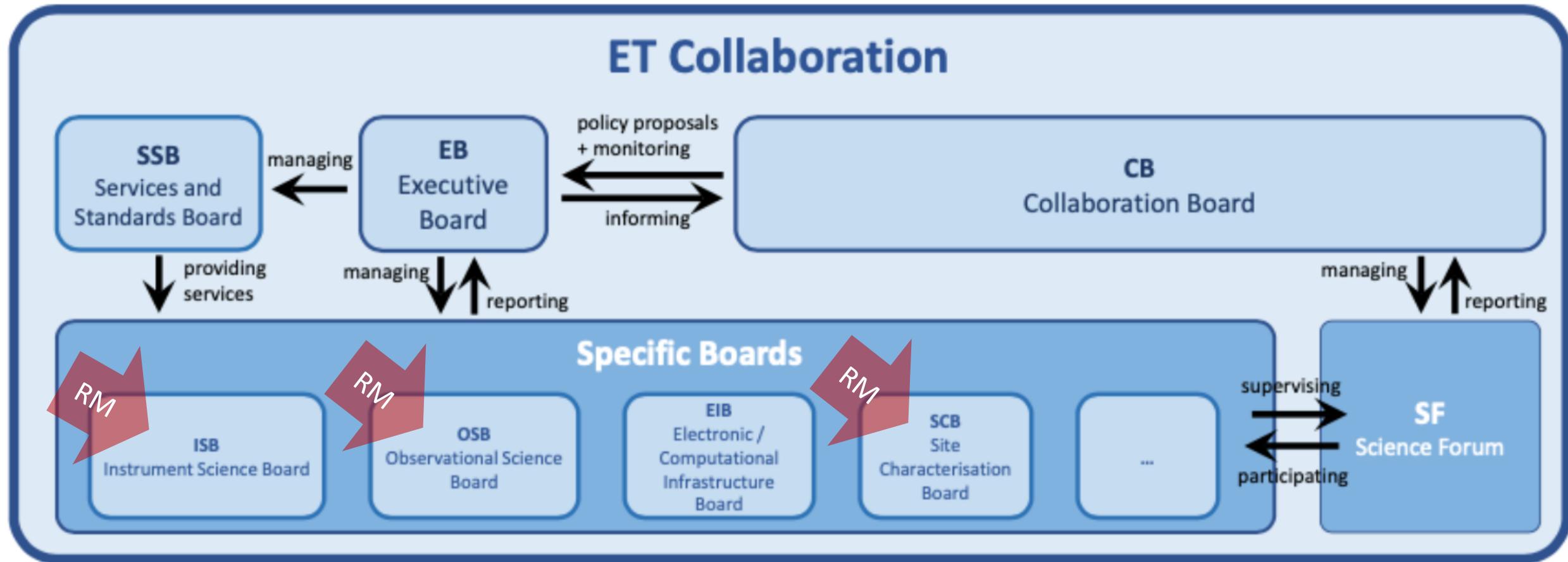


The ET collaboration

At XII Einstein Telescope Symposium (7-8th June 2022) the ET collaboration has been officially established!



The ET collaboration



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

The ET collaboration

- The ET steering committee has established an initial set of rules and definitions (**Bylaws**);
- The collaboration is made up of local **Research Units (RU)**;
- Initial RUs submitted before the XII ET Symposium, first **Collaboration Board** meeting of the RUs coordinators;
- **INFN Roma1 & Dipartimento di Fisica entered in the ET Collaboration with one of the largest RUs: ROMA1**

about 1300 members in 65 RUs

Roma1 RU in the ET coll.

Surname	Name	Position	FTE
Astone	Pia	Staff researcher	0,2 (V)
Cruciani	Angelo	Staff researcher	0,2
Dall'Osso	Simone	Staff researcher	0,1 (V)
Di Pace	Sibilla	RTDA	0,4 (V)
Drago	Marco	RTDB	0,1 (V)
Franciolini	Gabriele	Post-doc	0,2
Graziani	Luca	Staff researcher	0,1
Leaci	Paola	Staff researcher	0,2 (V)
Loutrel	Nicholas	Post-doc	0,1
Majorana	Ettore	Staff researcher	0,3 (V)
Mangano	Valentina	Post-doc	0,2 (V)
Marsella	Maria	Staff researcher	0,5
Musco	Ilia	Staff researcher	0,1
Naticchioni	Luca	Staff researcher	0,3 (V)
Pacilio	Costantino	Post-doc	0,2
Palomba	Cristiano	Staff researcher	0,2 (V)
Pani	Paolo	Staff researcher	0,3
Pannarale	Francesco	Staff researcher	0,1 (V)

Surname	Name	Position	FTE
Pierini	Lorenzo	Post-doc	0,1 (V)
Placidi	Ernesto	Staff researcher	0,2 (V)
Pnigouras	Pantelis	Post-doc	0,1
Puppo	Paola	Staff researcher	0,2 (V)
Rapagnani	Piero	Staff researcher	0,4 (V)
Ricci	Fulvio	Staff researcher	0,4* (V)
Schneider	Raffaella	Staff researcher	0,1
Serra	Marco	Staff researcher	0,1 (V)
Trinca	Alessandro	PhD	0,1
Vaglio	Massimo	PhD	0,1
Valiante	Rosa	Staff researcher	0,1
14 Engineers from DICEA, DIMA, DISG			3,3
2 Physicists from KAGRA (KEK,NAOJ, Japan)			0,2
<i>Experimental</i>		<i>Teongrav</i>	
<i>Data Analysis</i>		<i>Multimessenger Astronomy</i>	
<i>Engineer (DICEA, DIMA, DISG)</i>			(V): in Virgo collaboration

Roma1 RU in the ET coll.

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Rapagnani	Piero	Staff researcher	0,4 (V)
Ricci	Fulvio	Staff researcher	0,4* (V)
Schneider	Raffaella	Staff researcher	0,1
Serra	Marco	Staff researcher	0,1 (V)
Trindade			0,1
Vaglianti			0,1
Valiante			0,1
Experimental			2,8
Data Analysis			1,1
Teongrav			1,1
Multimessenger Astronomy			0,4
Engineer			3,8
45 members			TOTAL FTE 9,2

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- ❑ Einstein Telescope: science case
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- Site qualification activities and seismic & Newtonian noise characterization;
- Development of the cryogenic system for the LF Payload;
- Payload design and test for ET (LF and HF);
- R&D on inertial sensors for cryogenic applications;
- *Coordination roles of ISB divisions and WPs (vacuum&cryogenics, payloads, active noise mitigation/Newtonian noise...) and in SPB/SCB.*
- Data Analysis (DA): search for spinning neutron stars, early inspiral of NS binaries, dark matter, primordial BHs;
- *Active role in OSB.*
- Teongrav: Gravity theory and gravitational-wave phenomenology,
- *Coordination role of fundamental physics WP in OSB.*



Explorer GW
Antenna, 3000 I
He-II @ 2K (1984)

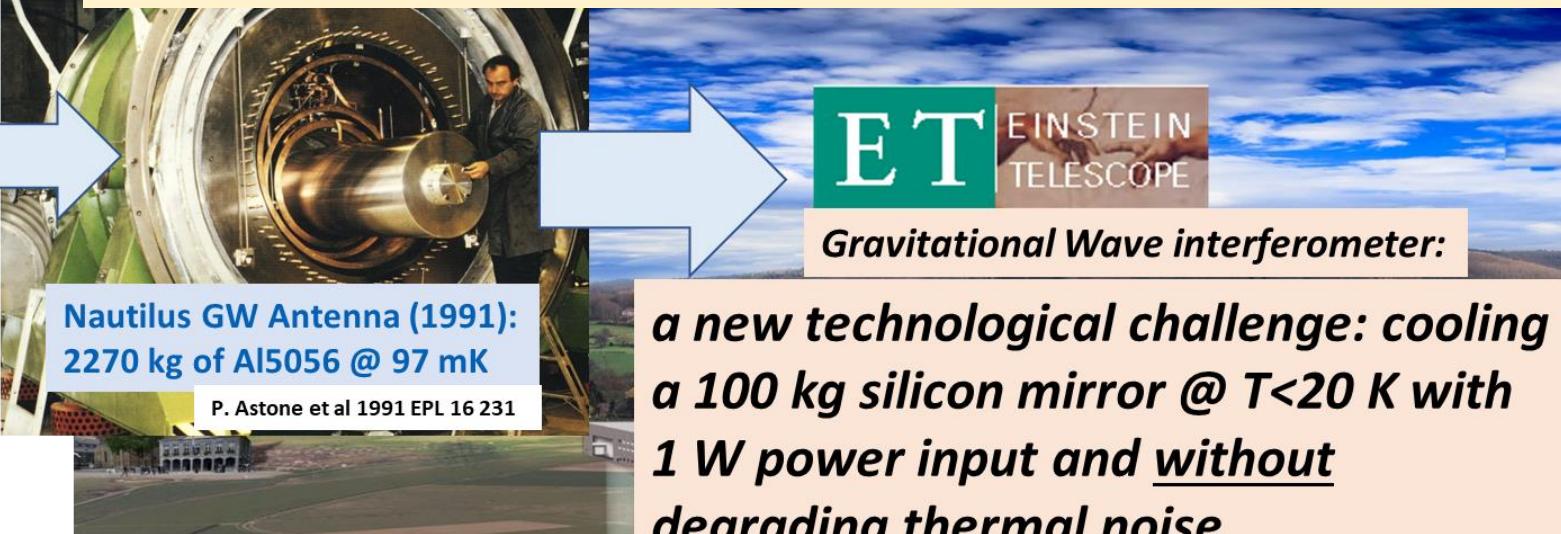
Cryogenics 32 7 668 (1992)



Needed: a special design
of cryostat and mirror
suspension to bring
cooling power to the
mirror without
increasing the
dissipations

Credit to P. Rapagnani, 2022

Rome «La Sapienza» University and INFN Rome Group has a 50 years-long tradition in cryogenics in Gravitational Wave detection.



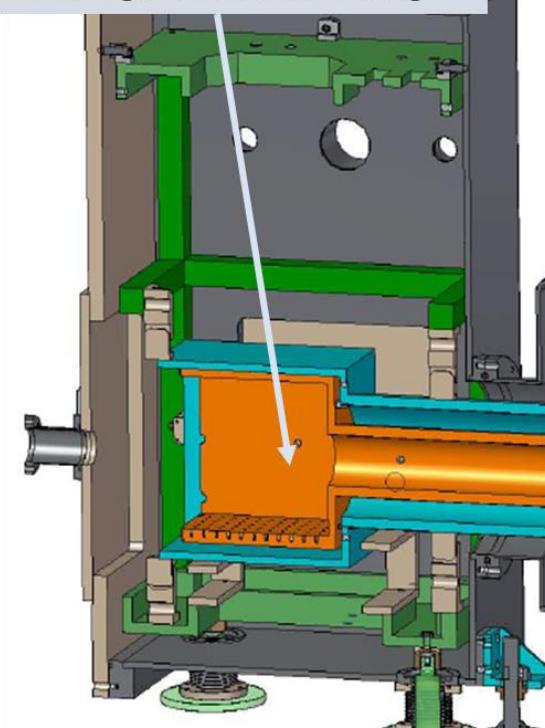
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Pulse Tube Cooling Station prototype for Rome1 Test Facility

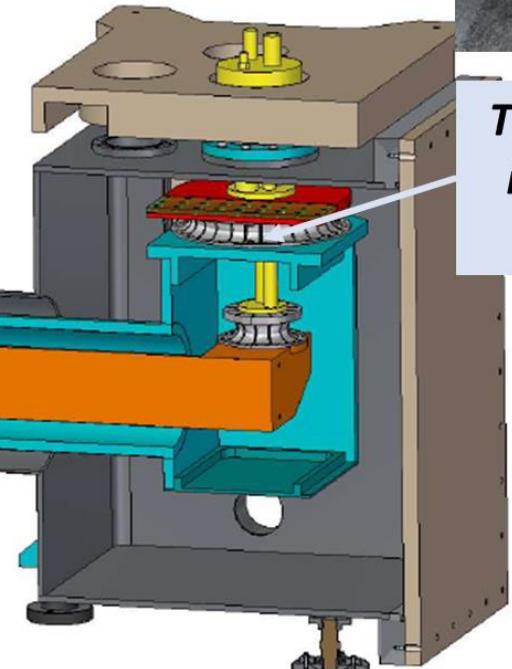
Cryogenic test Chamber:

- Dissipation Measurements,
- Residual vibrations,
- Sensing and actuators testing



*Cryogenic cooling lines
suspensions
(GW Interferometers
technology)*

*Soft thermal links
(KAGRA like)*



2 Pulse Tubes
Cryomech PT400
(1.8 W @ 4.2 K) in
counterphase



*Thermal links
in Al5N and
Al6N*

**More details in A.
Cruciani's talk**

*Construction ongoing: assembly in
summer 2022*

Design by Antonio Marra,
Franco Bronzini

ET-LF Cryo Payload:**A closer look to the thermal path**

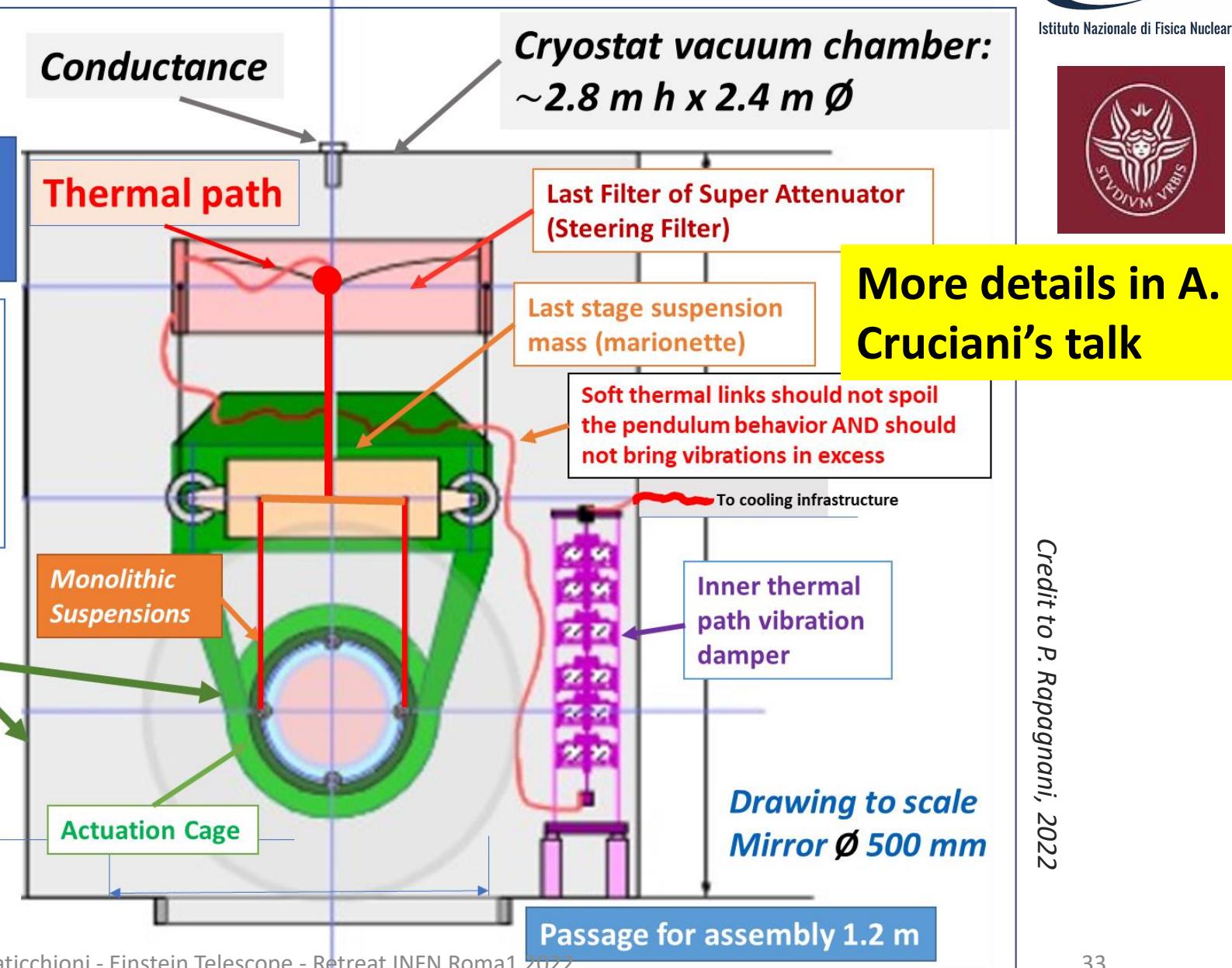
Whatever the cooling technique, the payload must be cooled by conduction through the suspensions AND by radiation.

In order not to spoil thermal noise, suspension wires should be good conductors AND with very low dissipations: e.g. Marionette cable could be chosen to act both as a suspension element and a cooling power carrier. In this case, Q of the pendulum should be $\sim 10^6$

The inner shield and the actuation cage should be at a temperature low enough to have an efficient radiative cooling

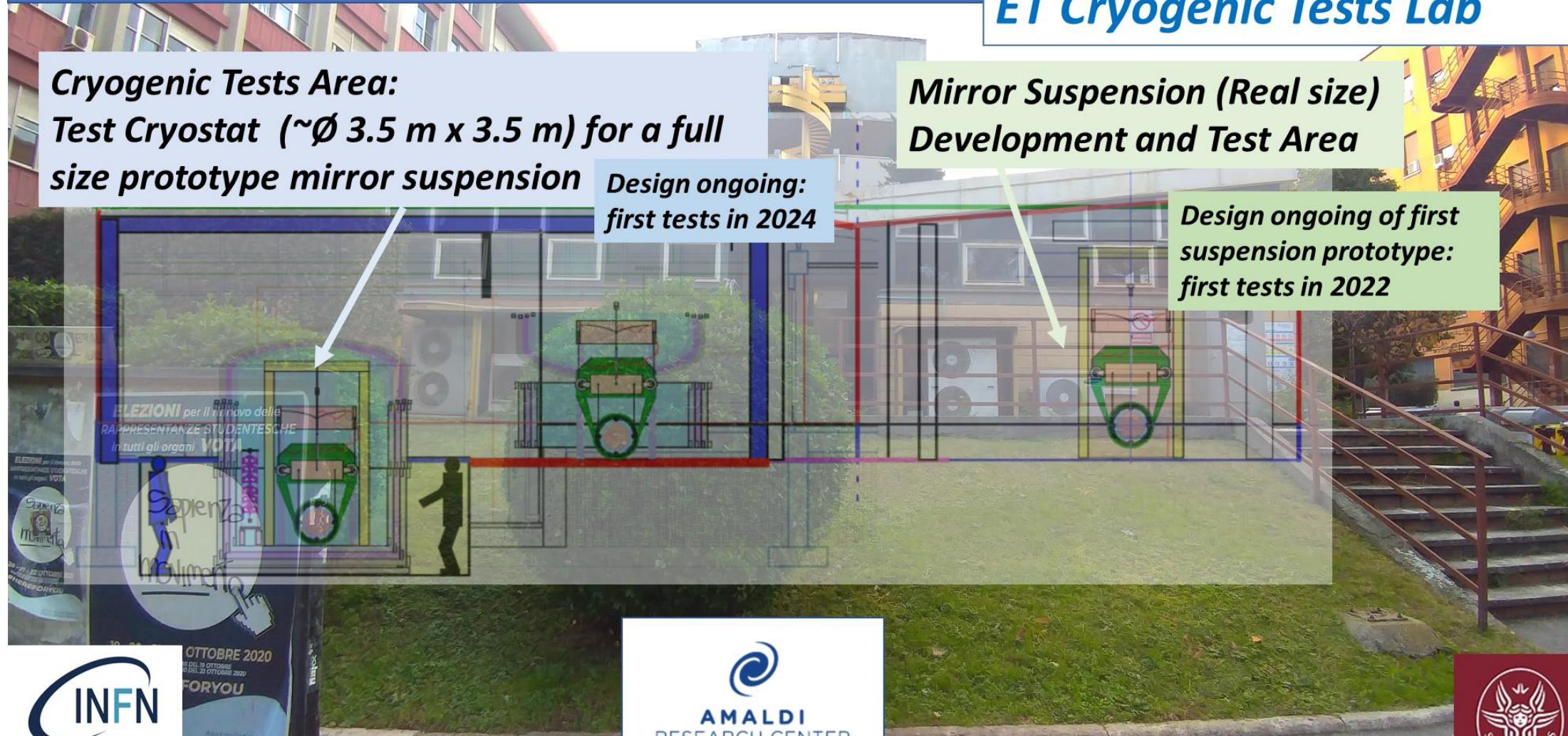
Tradeoff between:

- Thermal noise
- Control Strategies
- Cooling Efficiency



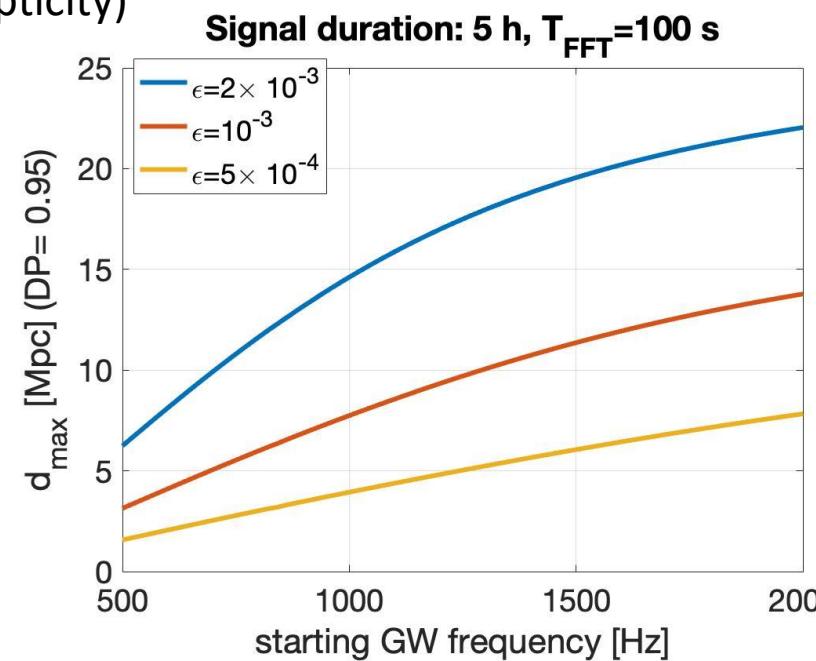
In Rome, we are preparing a lab for low temperature tests on a real size prototype of an ET cryogenic mirror suspension:

Amaldi Research Center ET Cryogenic Tests Lab

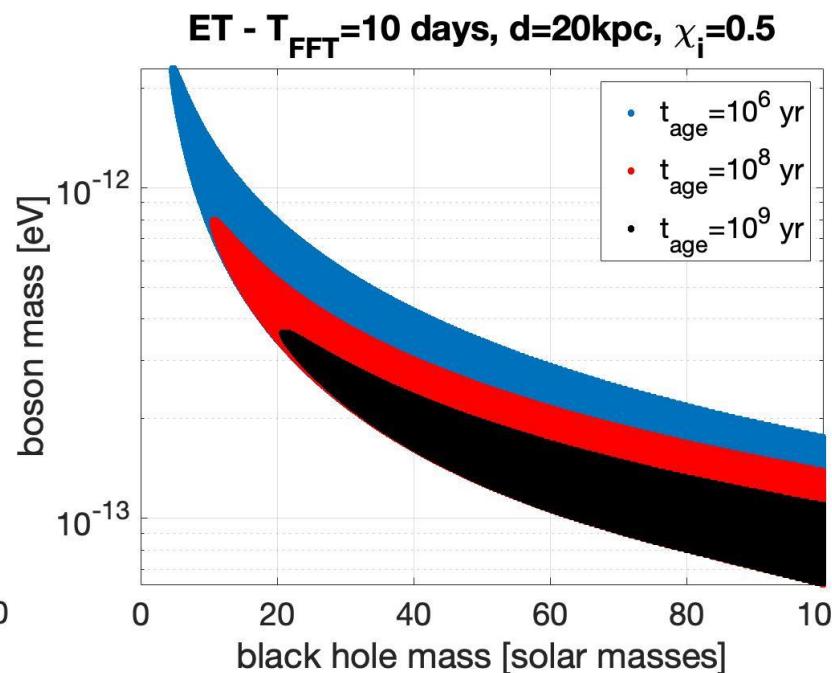


The group is involved in a rich program of developments from DA/computing in view of 3G detectors era (spinning neutron stars, early inspiral of NS binaries, dark matter, primordial BHs,...)

Example 1: distance reach for GW signals emitted by young **magnetars** (for different values of the star ellipticity)



Example 2: accessible boson/BH masses from GW waves emitted by **ultra-light boson clouds** around Kerr BHs (for different cloud ages)



DA challenges:

- * Huge parameter space for template-based searches
- * ML approaches in development
- * Superposition of signals in frequency

Active role in the ET Observational Science Board (OSB)

Computing challenges for DA:

- * Widespread use of GPU clusters
- * Interest in FPGA exploitation
- * Initial thinking on Quantum Computing

Rome1 TEONGRAV & ET

Gravity theory and gravitational-wave phenomenology [web.uniroma1.it/gmunu]Strongly involved in **ET Observational Science Board (OSB)**:

- Div1: Fundamental Physics (Coordinator: P. Pani, with R. Porto and C. Van den Broeck)
 - Tests of gravity & GW modelling [Bhagwat+ PRD 2022; Maselli+ Nature Astronomy 2022]
 - Near-horizon physics [Maggio+ PRD 2020; Cardoso-Pani Liv. Rev. Rel. 2019]
 - Ultralight dark-matter searches with GWs [De Luca+ JCAP 2021; Brito+ PRL 2020]
- Div3: Populations
 - Detectability of primordial black holes & population studies [Franciolini+ 2021 PRD, De Luca+ PRL 2021, JCAP 2021; Ng+ 2204.11864; Musco+ (work in progress)]
 - Subsolar EMRIs as new ET sources [Barsanti+ PRL 2022]
- Div6: Nuclear matter
 - ET unique ability to constrain the nuclear equation of state [Pacilio+ PRL 2022]

Thank you for listening!

10 km

Backup slides

Some of the questions addressed by GW with ET & LISA

- Fundamental questions in Gravity:
 - New/further tests of GR
 - Exploration of possible alternative theories of Gravity
 - How to disprove that Nature black holes are black holes in GR (e.g. non tensorial radiation, quasi normal modes inconsistency, absence of horizon, echoes, tidal deformability, spin-induced multipoles)
- Fundamental questions in particle physics
 - Axions and ultralight particle through the evaluation of the consequences of new interactions, their impact on two bodies mechanics, in population and characteristics of BHs, NSs
- Probing the EOS of neutron stars
 - HEPP Nuclear physics, quark-gluon plasma
- Exotic objects and phenomena (cosmic strings, exotic compact objects: boson stars, strange stars/gravastars, ...)
- Cosmology and Cosmography with GWs
 - HEPP Cosmology
- Accurate Modelling of GW waveforms
- GW models in alternative theory of gravitation
 - HEPP Cosmology
- The population of compact objects discovered by GWs is the same measured by EM? Selection effects on BHs and NSs?
- What is the explosion mechanism in Supernovae?
 - HEPP Nuclear physics
- What is the history of SuperMassive black holes?
- GW Stochastic Background? Probing the big bang?
 - HEPP Cosmology, inflation
- Multimessenger Astronomy in 3G?
 - HEPP Astroparticle, GRB, Neutrino Physics



ET Design – some numbers

Parameter	ET-D-HF	ET-D-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 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm / T
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	$1 \times 10 \text{ km}$	$2 \times 10 \text{ km}$
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m t
Seismic (for $f > 1 \text{ Hz}$)	$5 \cdot 10^{-10} \text{ m}/f^2$	$5 \cdot 10^{-10} \text{ m}/f^2$
Gravity gradient subtraction	none	<i>A few factors</i>

