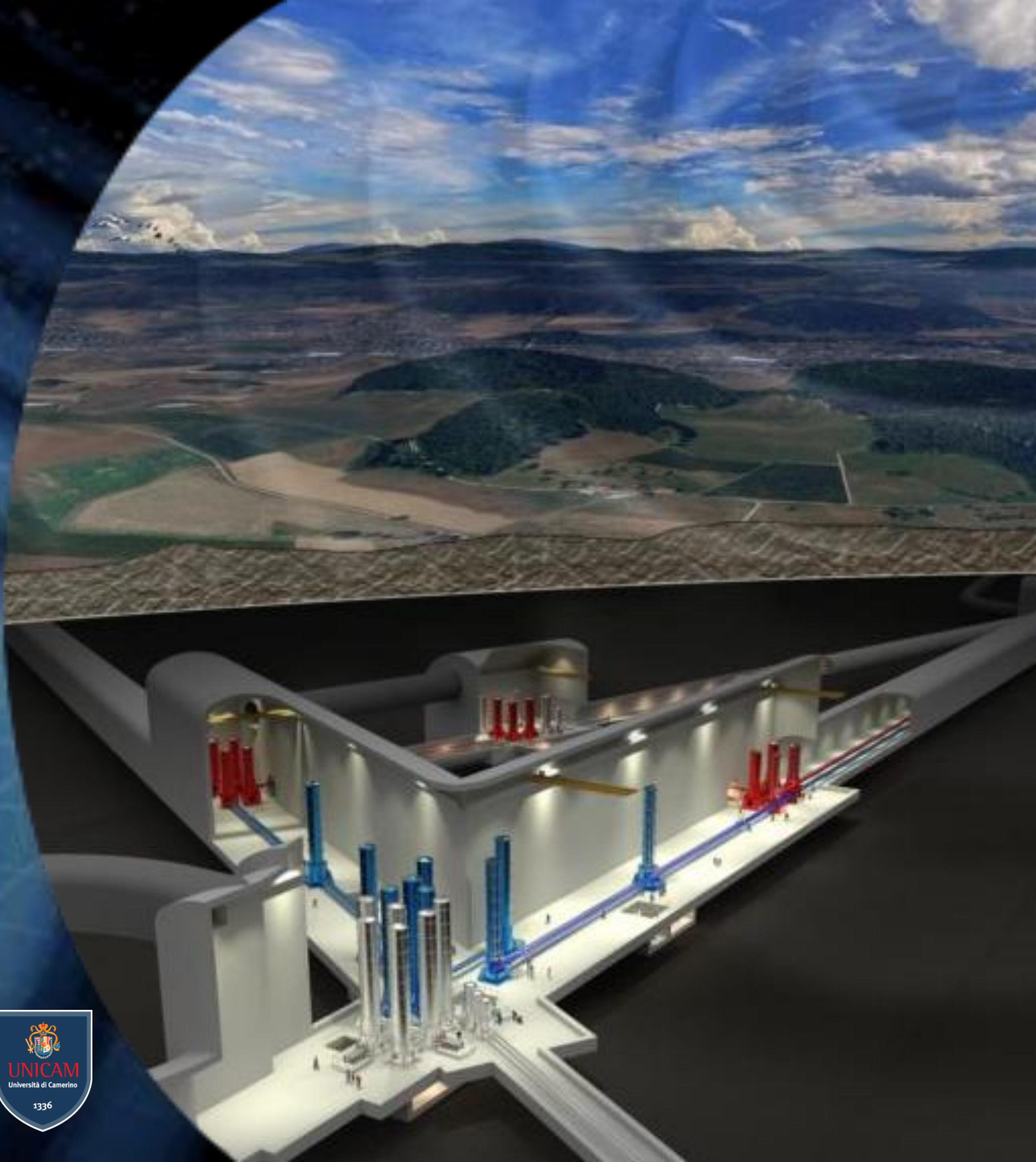
# The Einstein Telescope


## Flavio Travasso

on behalf of ET Collaboration


LWGA Workshop
San Benedetto del Tronto
15-20 Septemper 2025



INFN Istituto Nazionale di Fisica Nucleare

EINSTEIN TELESCOPE

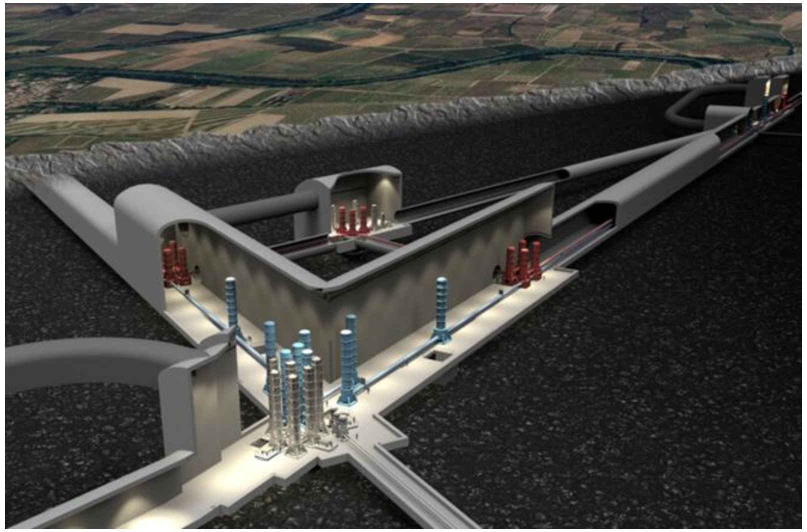
ET ITALY Einstein Telescope

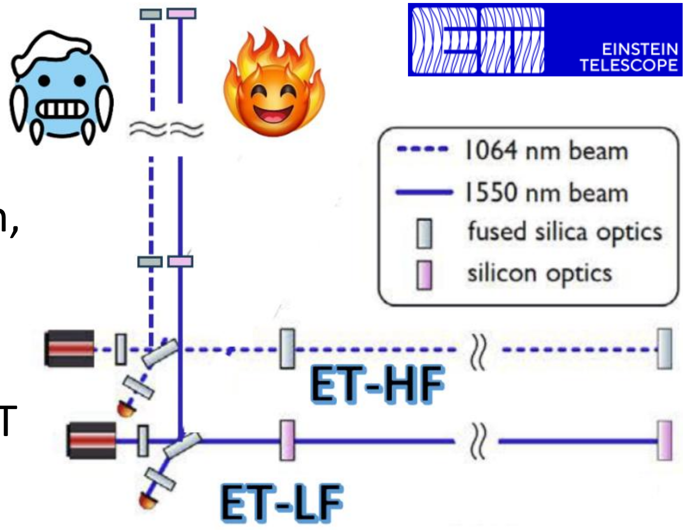
UNICAM Università di Camerino 1336

# The **GW** spectrum


*Slide credit: L.Naticchioni - ET-0149A-25*

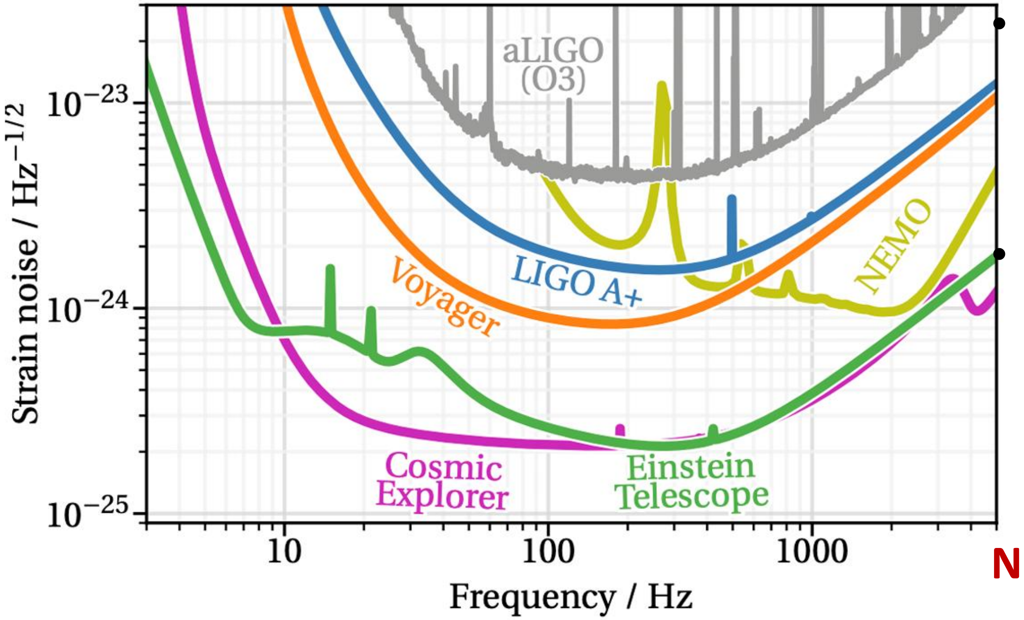
# The low frequency challenge - Design






Increasing sensitivity at high frequencies means pushing technologies that are largely already known, while increasing it at low frequencies means developing a series of new technologies.

For this reason the most challenging key points of ET are defined to be compliant with the low frequency sensitivity => **design** and **technologies**




**DESIGN**

- **Longer arms** (10km-15 km)
  - to improve the wide band sensitivity
- **Underground** (200m-300m)
  - to minimize the impact of the seismic and Newtonian noises
  - to minimize the environmental disturbances (wind, human and industrial activities)
- **Xylophone design** (2 interferometers for each ET detector):
  - one interferometer designed for the low frequencies (**ET-LF**): cryogenic (TN), low power laser (RPN), and so on
  - one interferometer design for the high frequencies (**ET-HF**): room temperature (silica), high power laser (SN), and so on

**NB: Renouncing to the low frequency characteristics is missing the soul of ET**

# Why underground

ET will be one of the largest underground infrastructures in the world

- About 4-5 Millions of cubic meters of rock to be excavated
- More than 30km of tunnels deeper than -200m
- Large experimental halls
  - Tens of cranes to be designed and realized
- Tens of clean rooms for optical manipulation to be realized
- Technical services:
  - Power plants
  - Cryogenic plants
  - Ventilation systems and HVAC
  - Elevators

## Pro

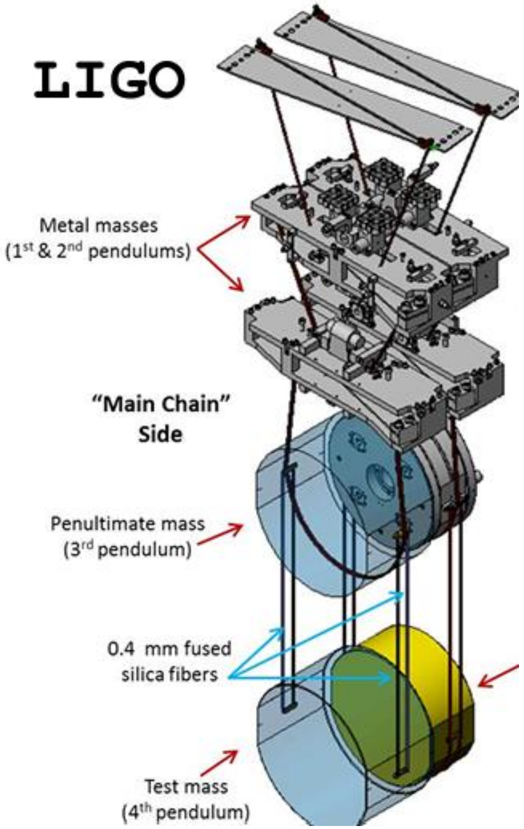
- Access to the low frequency:
  - 2-10Hz for ET
  - Reduction of the seismic and Newtonian Noise
  - Suppression of the atmospheric Newtonian Noise and of the wind impact
  - Reduction of the anthropogenic noise
    - Magnetic
    - Acoustic
    - Vibration
- Easier compatibility with the urbanization of the hosting region
  - Europe is generally a strongly urbanized continent
- Landscape impact

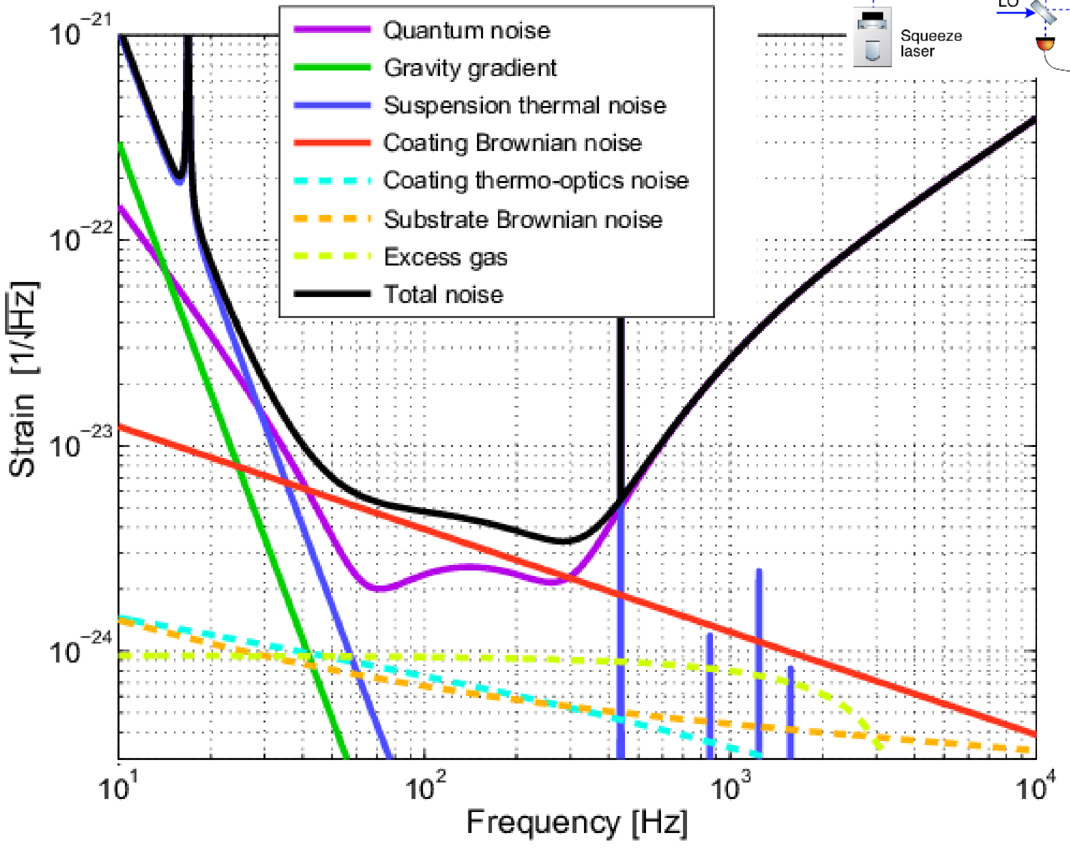
## Cons

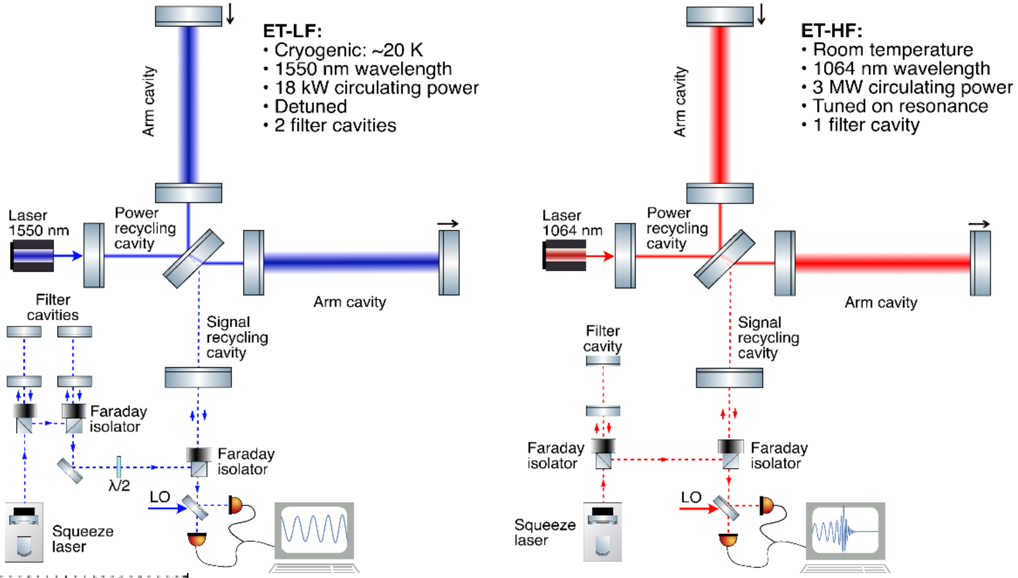
- Costs
- Challenging civil engineering (>30km of tunnels, large caverns…)
- Time needed to build it
- Limited possibility to upgrade the civil infrastructure in a medium-long term timeline
- More difficult operating environment in all the observatory phases (construction, integration, commissioning, maintenance and upgrade)

# Why cryogenic?

At low frequencies the main noises are: Newtonian noise (underground and array of sensors), quantum noise (low power laser, FD squeezing), TM suspension thermal noise (cryogenic temp.)



# The low frequency challenge - Technologies

Challenging engineering

New technology in cryo-cooling

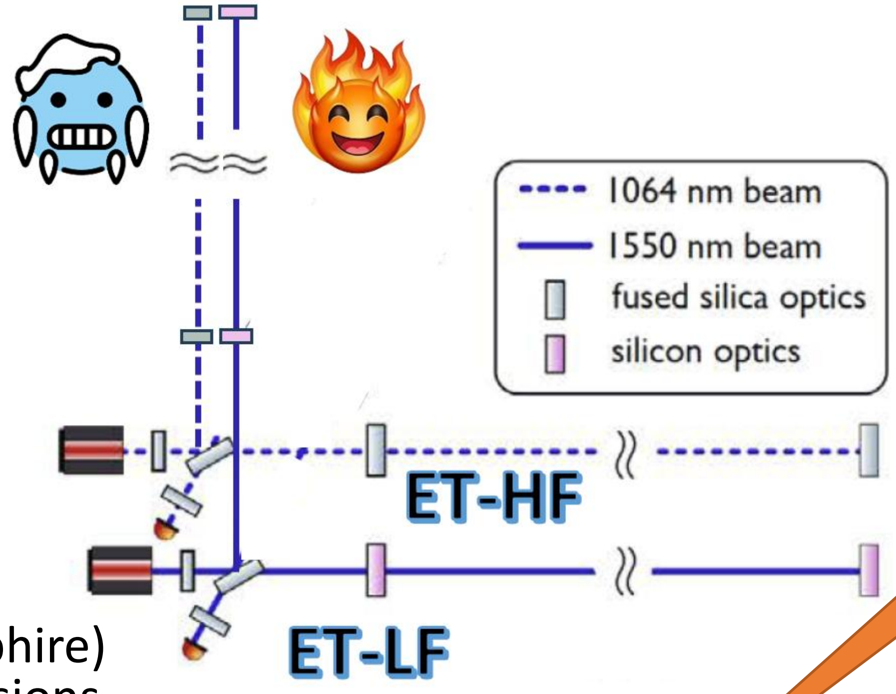
New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

- The multi-interferometer approach asks for two parallel technology developments:
  - **ET-LF**:
    - Underground
    - Cryogenics
    - Crystalline (Silicon, Sapphire) test masses and suspensions
    - 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

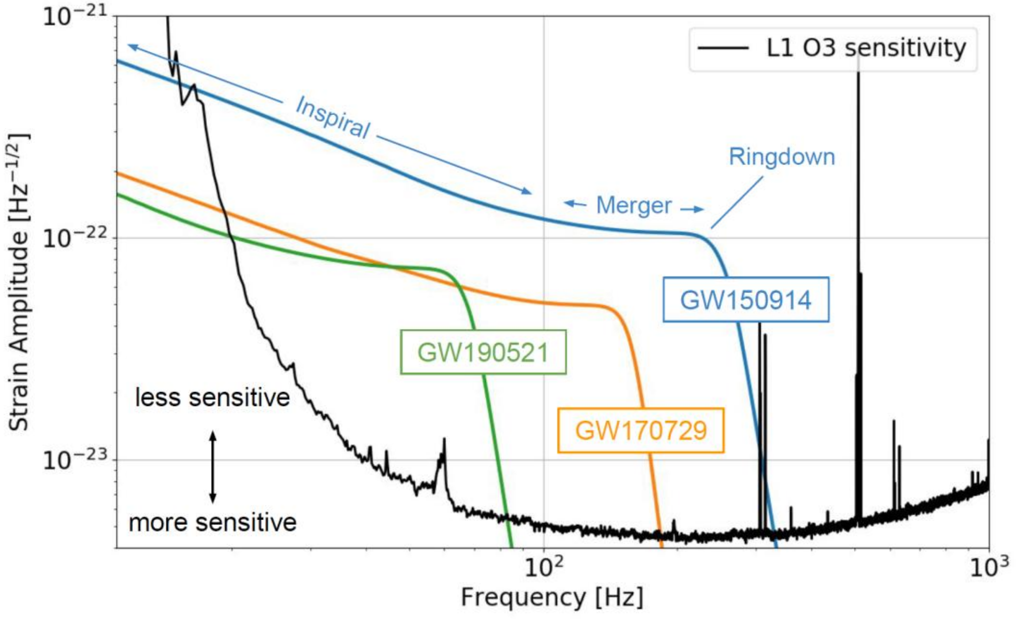
Highly innovative adaptive optics

High quality opto-electronics and new controls

*Slide credit: M.Punturo – 10 Anni GW- Padova*

# Why low frequency focus? Science cases

Higher masses correspond to lower frequency GW emission

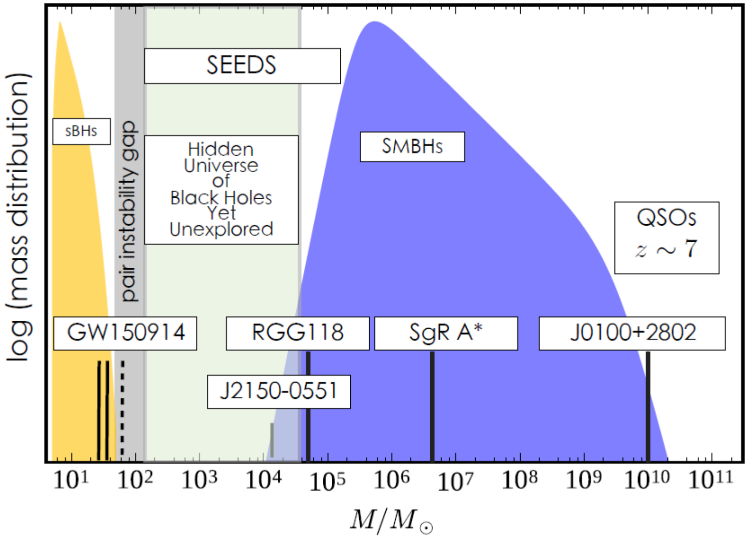



- Early warning in multi-messenger astronomy with GW emitted by BNS

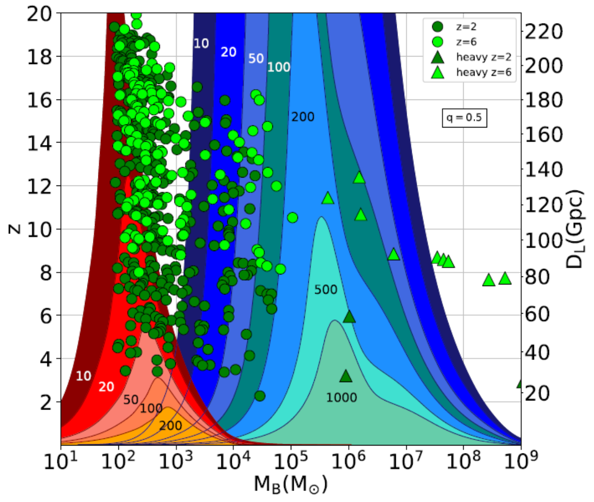
**NB: Again, renouncing to the low frequency characteristics is missing the soul of ET…and some of the most interesting cosmological events**

One of the primary science targets of ET is to access the 1-10Hz frequency range

- Intermediate mass black holes ($10^2$ - $10^5$ solar masses)
  - Fill the gap between the stellar mass black holes (à la LIGO/Virgo) and the supermassive black holes (à la LISA)
  - Seeds for SMBH?: What is their history? How have they formed? What are the seeds?
- Cosmology
  - high red-shift → low frequency
  - Primordial BH and the Dark Matter quest
  - Population III stars



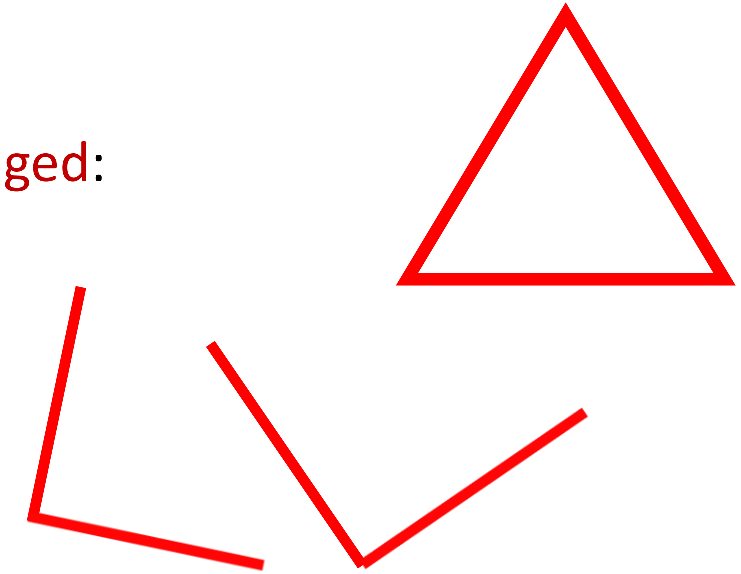

Black Holes in the Gravitational Universe




*Slide credit: M.Punturo – 10 Anni GW- Padova*

# ET geometry debate: Δ or (two) L

In the last three years, the collaboration started the evaluation of the best configuration for ET, considering the alternative of two L configuration (as LIGO, Cosmic Explorer) to maximize the science return and reduce risks.



Since 2011 (CDS, triangle configuration) the situation drastically changed:

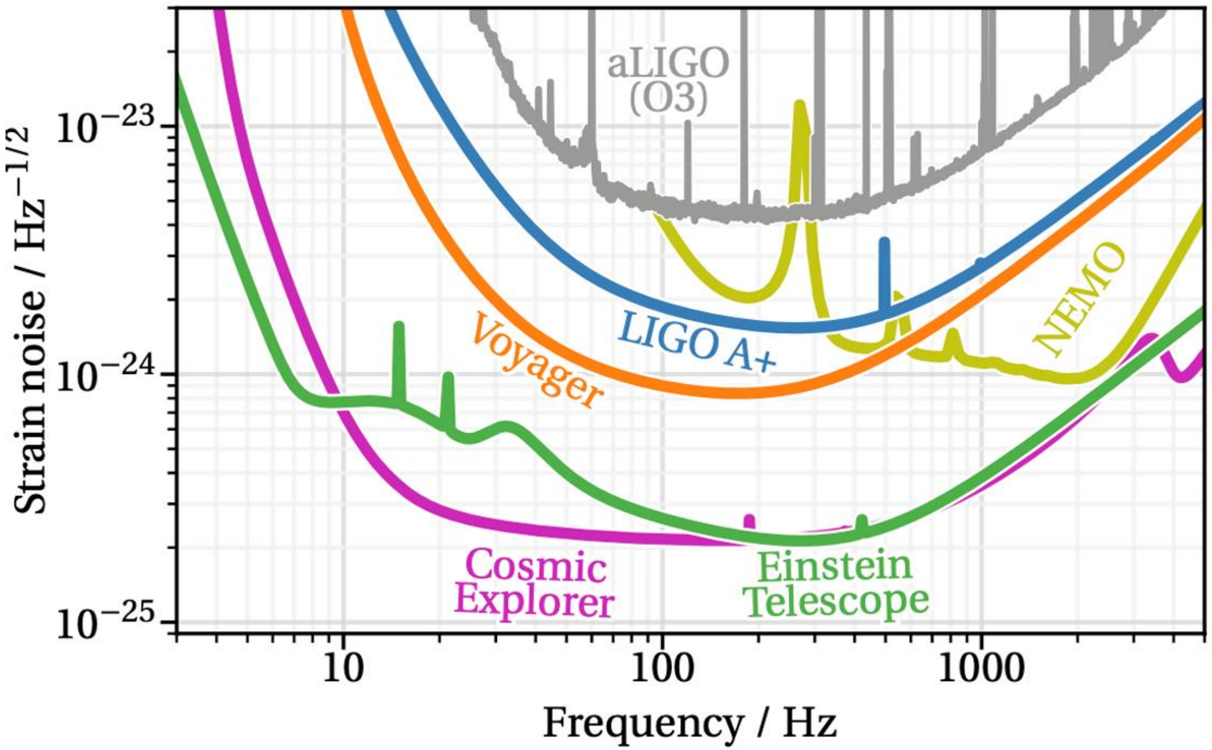
- ❑ International scenario (+ Cosmic Explorer in US);
- ❑ GTWC-4 catalog → BH population → new evolution models;
- ❑ Science case developed;
- ❑ Know-how with advanced (L) detectors;
- ❑ Two candidate sites strongly supported and a new third site.

The collaboration analysed both configurations: optimizing science return, differential risk assessment**.**
First results on the science return published in *M. Branchesi et al JCAP07(2023)068*:

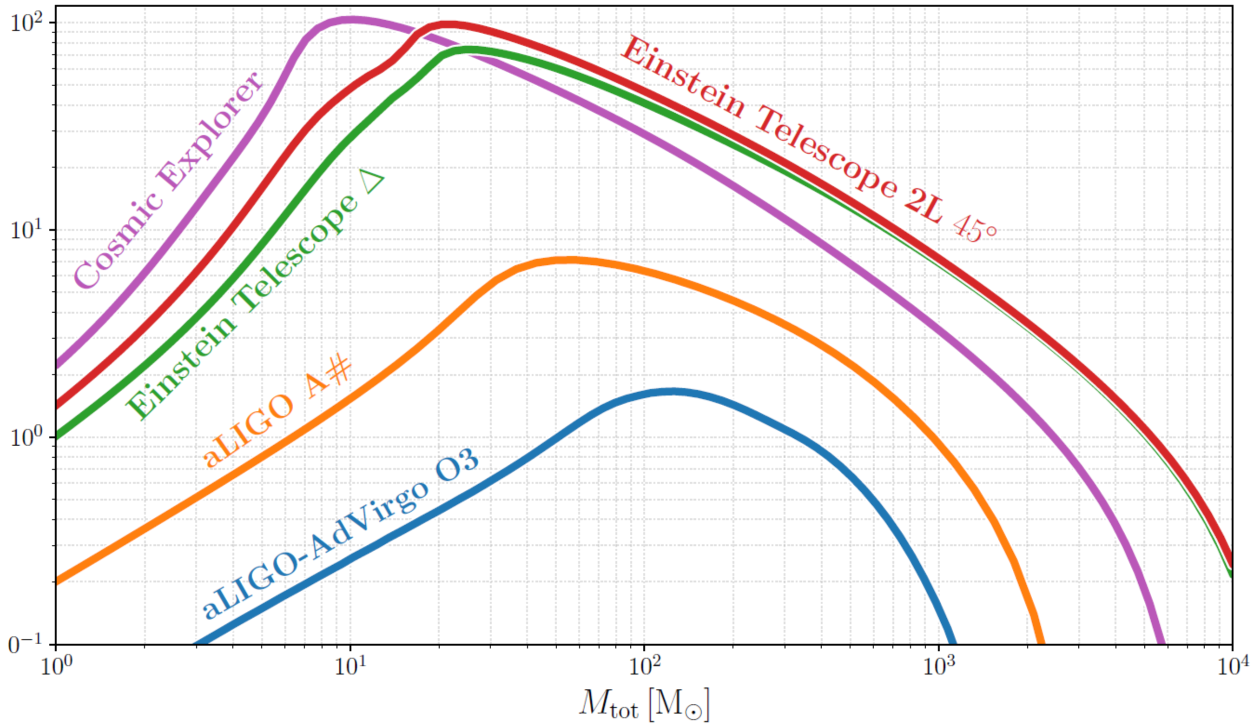
The 2L 15 km geometry shows an improved science return in the majority of the science targets.
A preliminary differential risk analysis, provided by a scientific committee, highlighted a lower risk for the integration, commissioning and upgrade phases in 2L geometry

# GW Science with ET

Whatever the chosen configuration, **ET will make a great leap forward** compared to 2G detectors!




ET configurations and CE vs 2G
Observation horizons for equal-mass spin-less binaries.

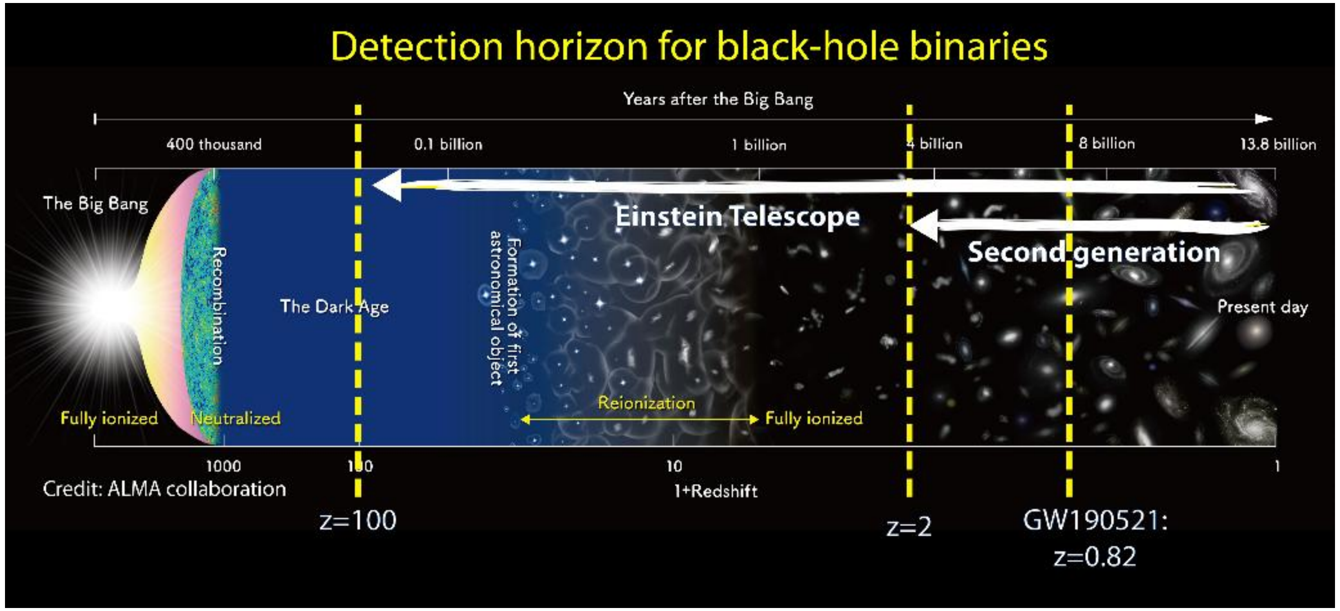


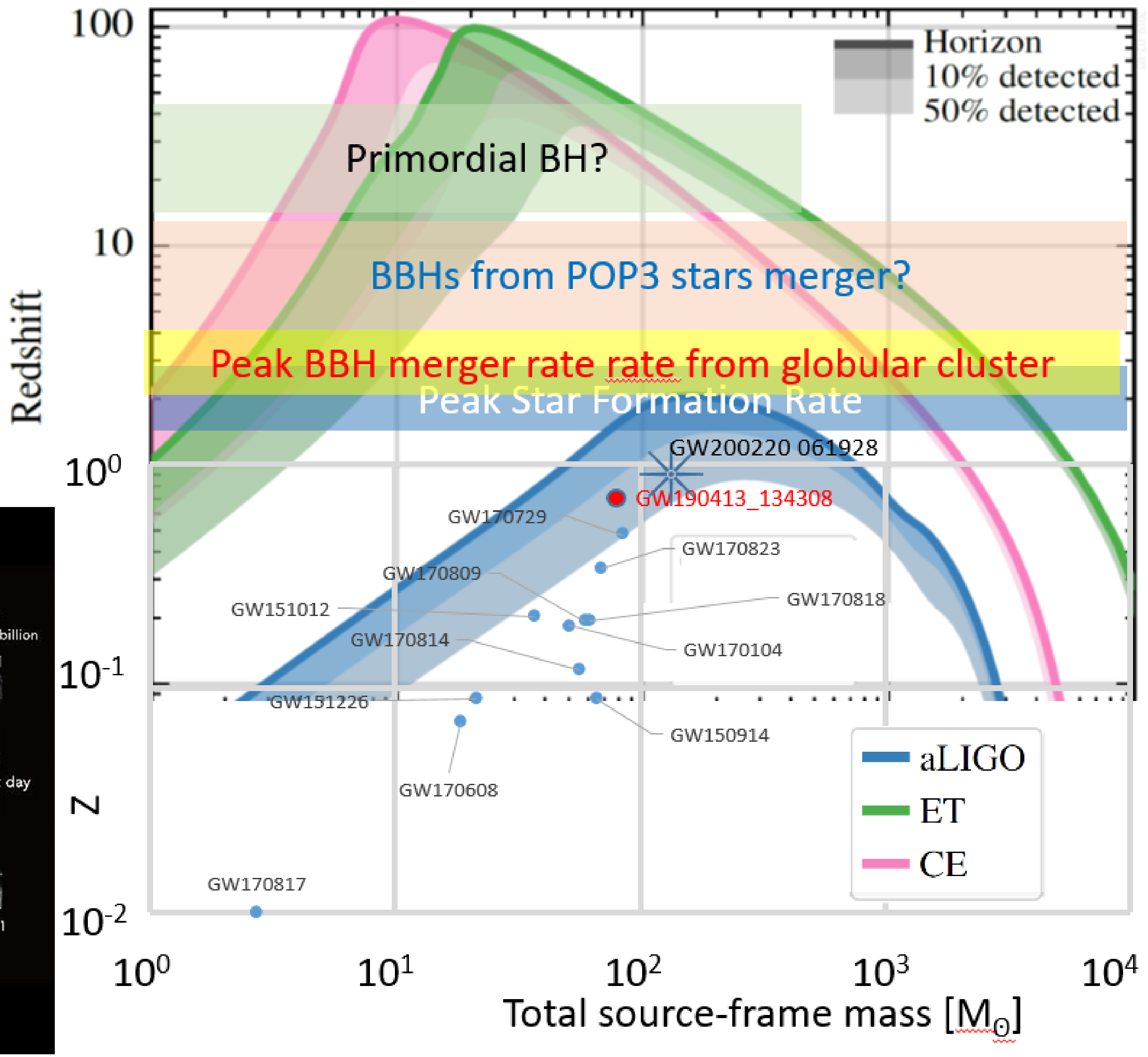

*Credit to: M. Maggiore & F. Iacovelli, arXiv:2407.21442v1*

# GW Science with ET

2nd generation GW detectors are exploring the *local Universe*, initiating the precision GW astronomy, but to have ***cosmological*** observations we need a **factor of 10 improvement in terms of detection distance**.

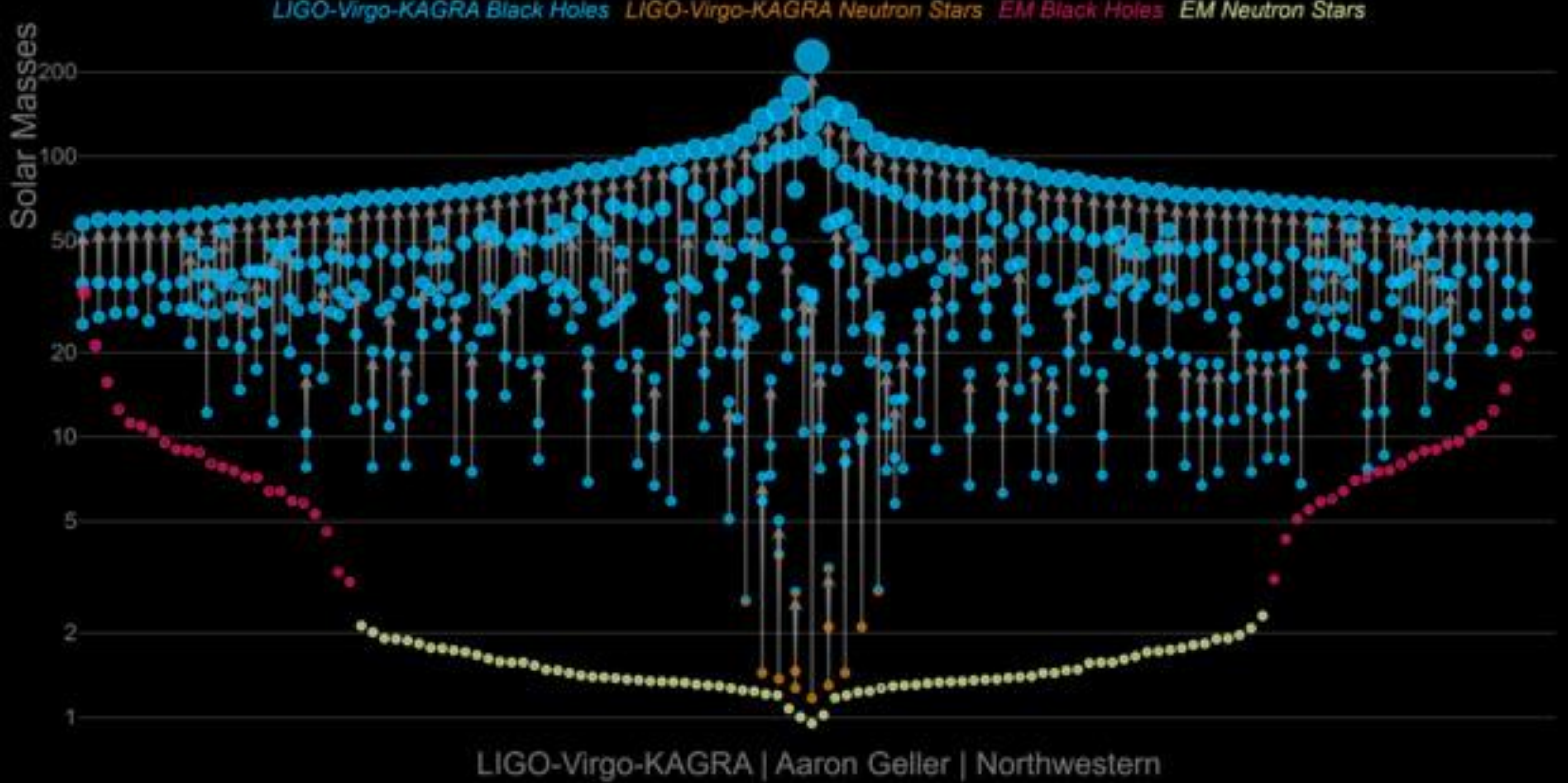
ET will explore **almost the entire Universe** listening the gravitational waves emitted by **black holes**, back to the **dark ages** after the Big Bang.




*Slide credit: L.Naticchioni - ET-0149A-25*

# Masses in the Stellar Graveyard



# GW Science with ET... **in a nutshell**

## ASTROPHYSICS

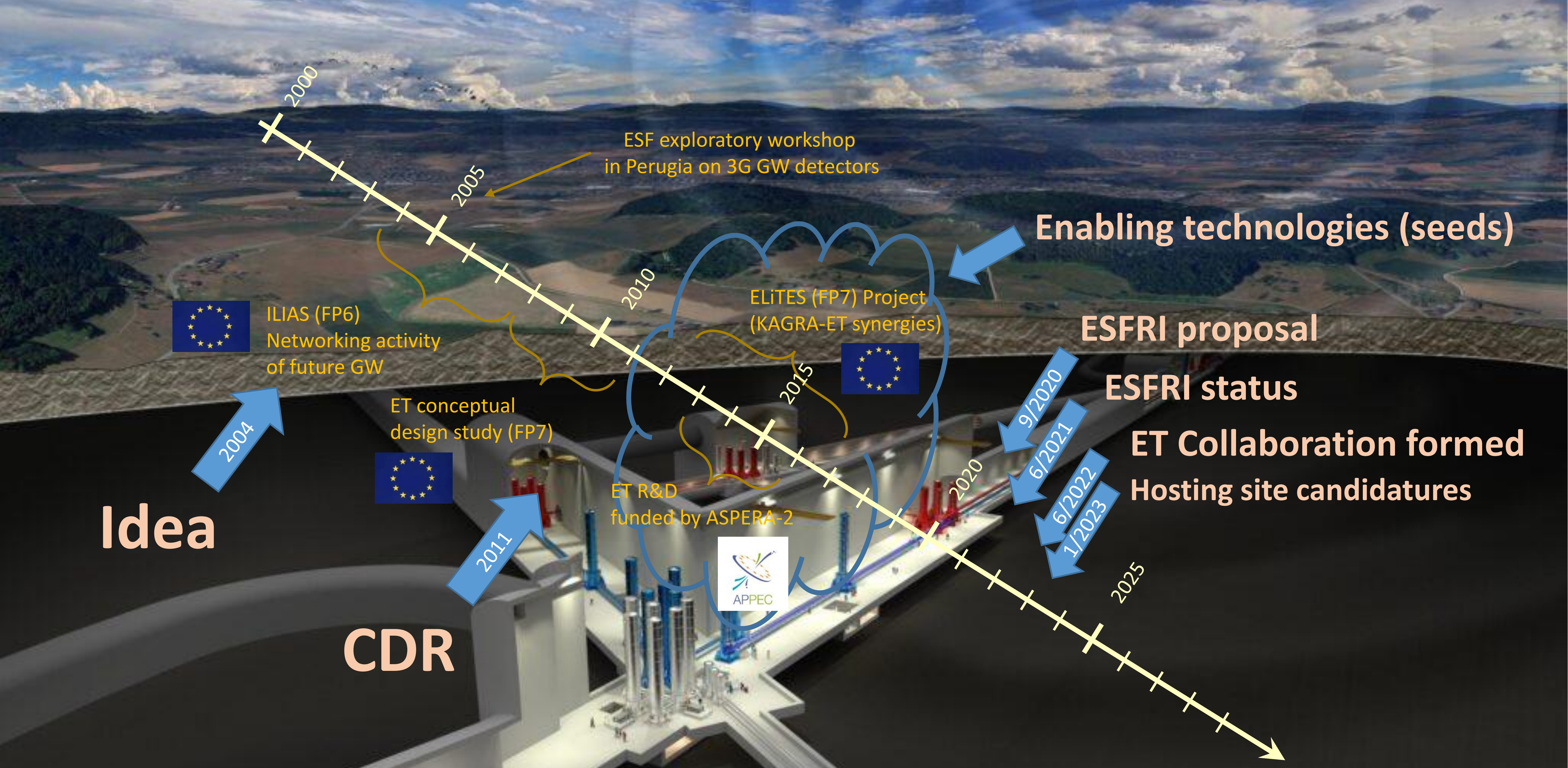
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography, interior structure (GW250114)
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM 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

*Slide credit: L.Naticchioni - ET-0149A-25*

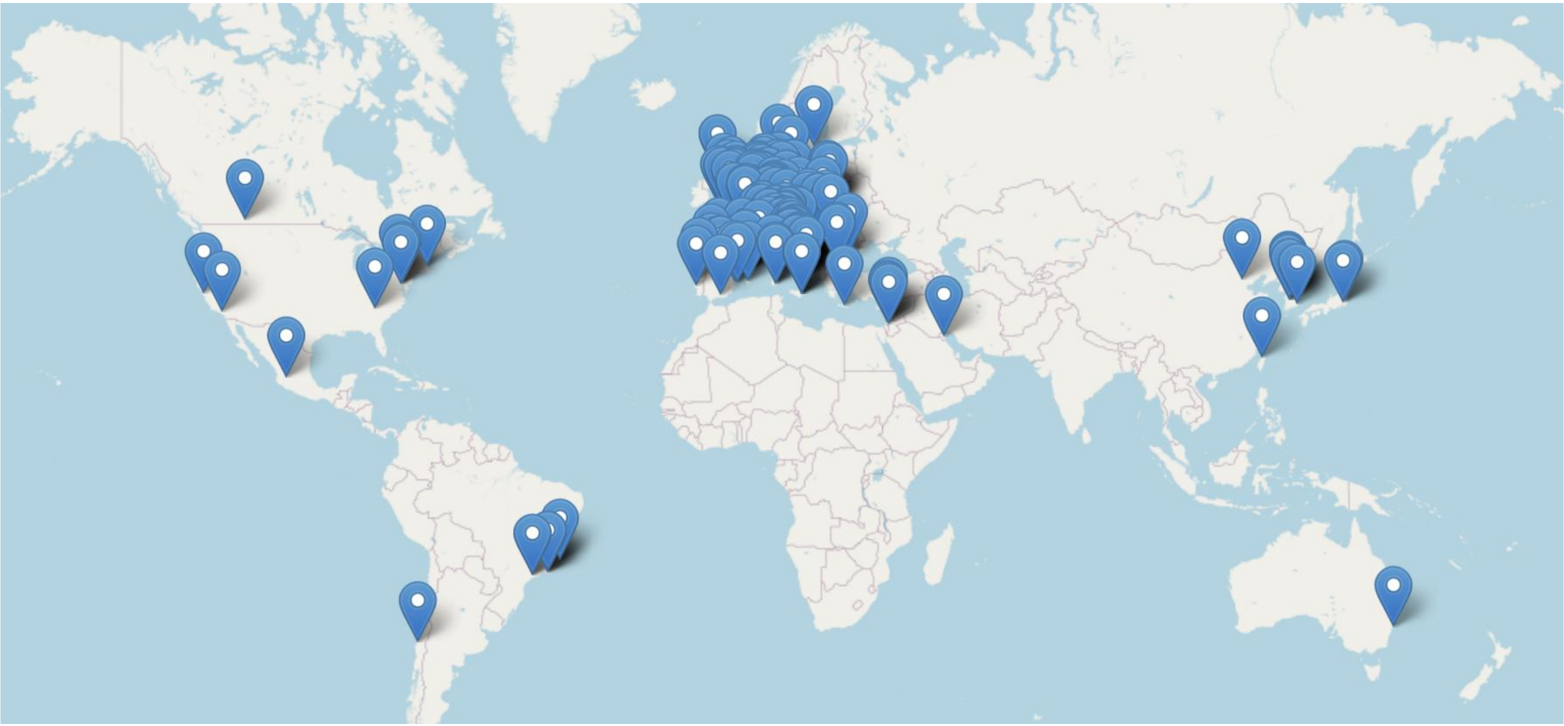
# ET: a long path

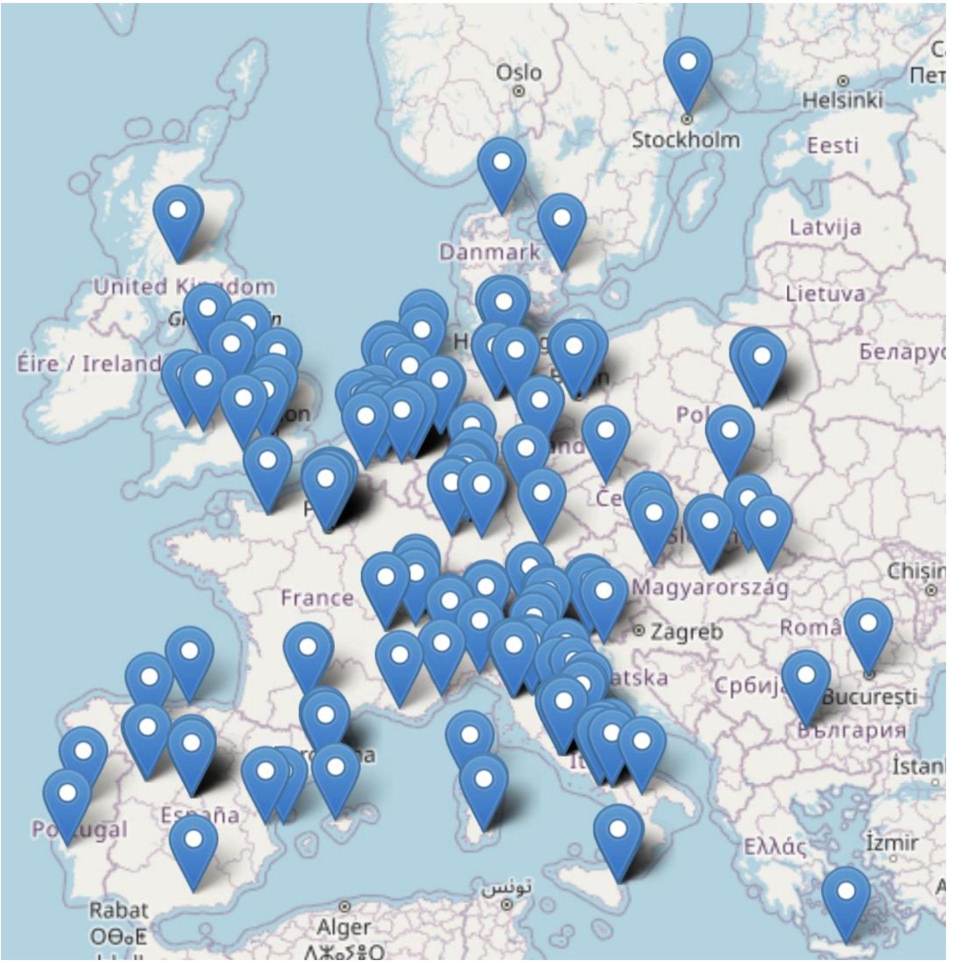



*Slide credit: M.Punturo – 10 Anni GW- Padova*

# ET Collaboration

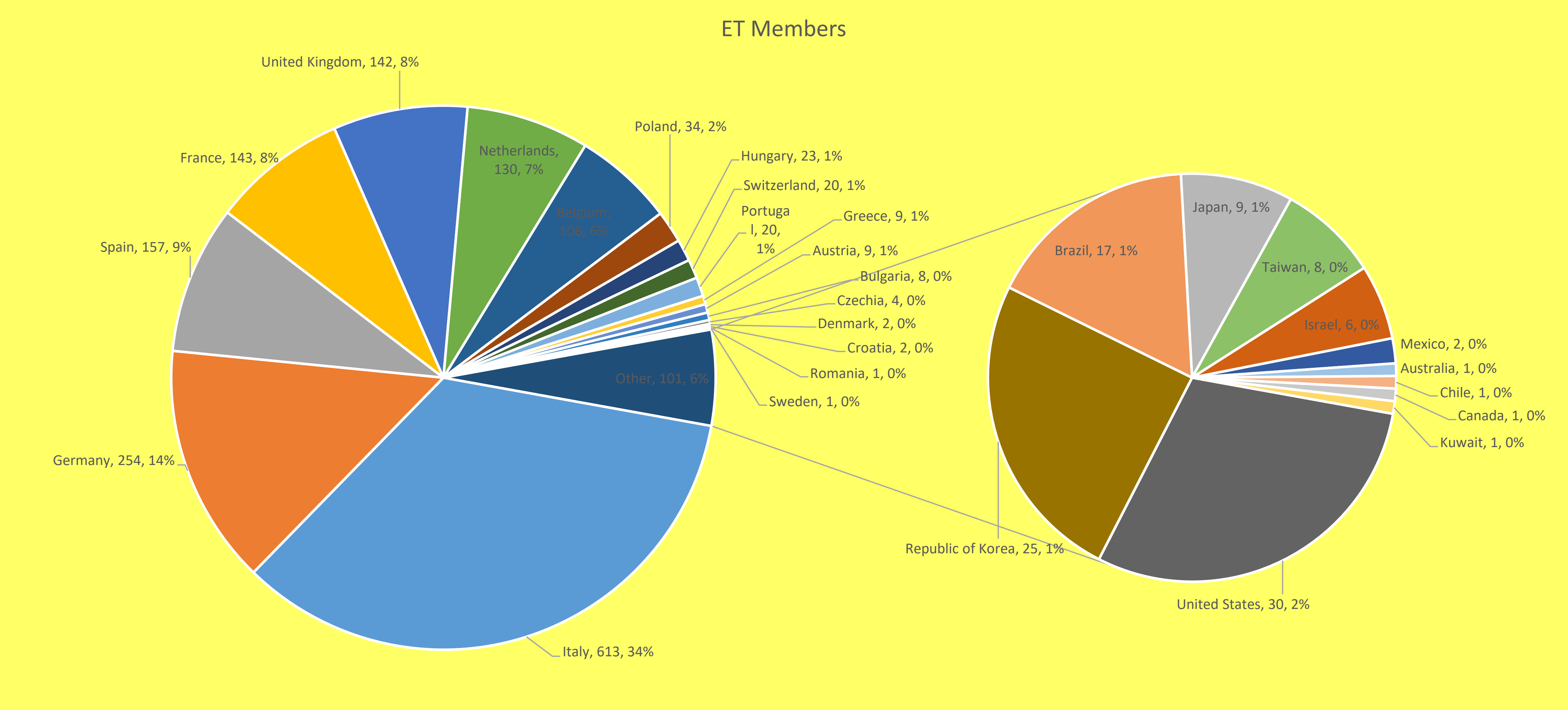
- **93 Research Units**
- **1864 members (14/09/2025)**
- **Total: 270 Institutions in 31 Countries**



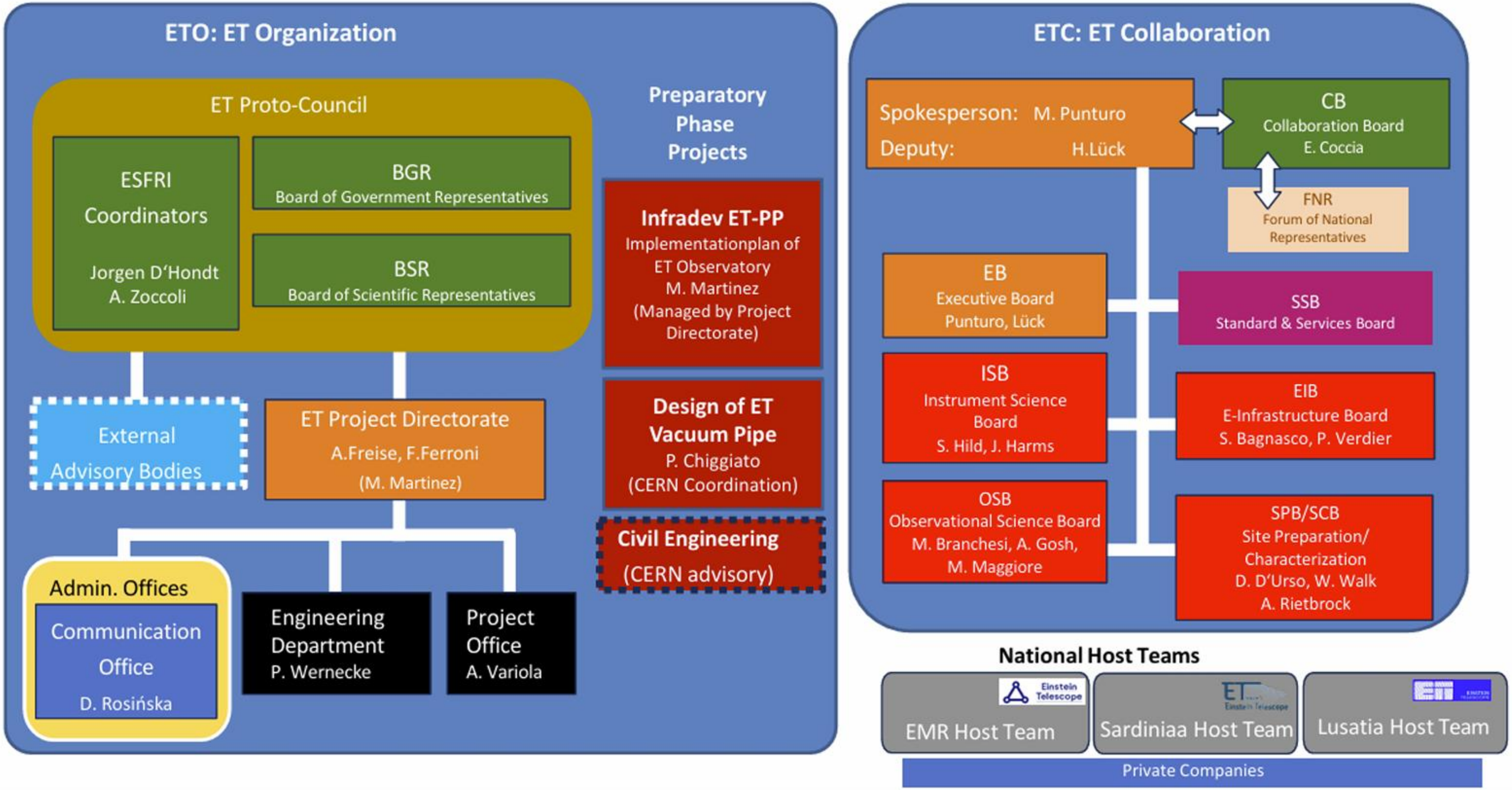



**ET Member‘s affiliation map**

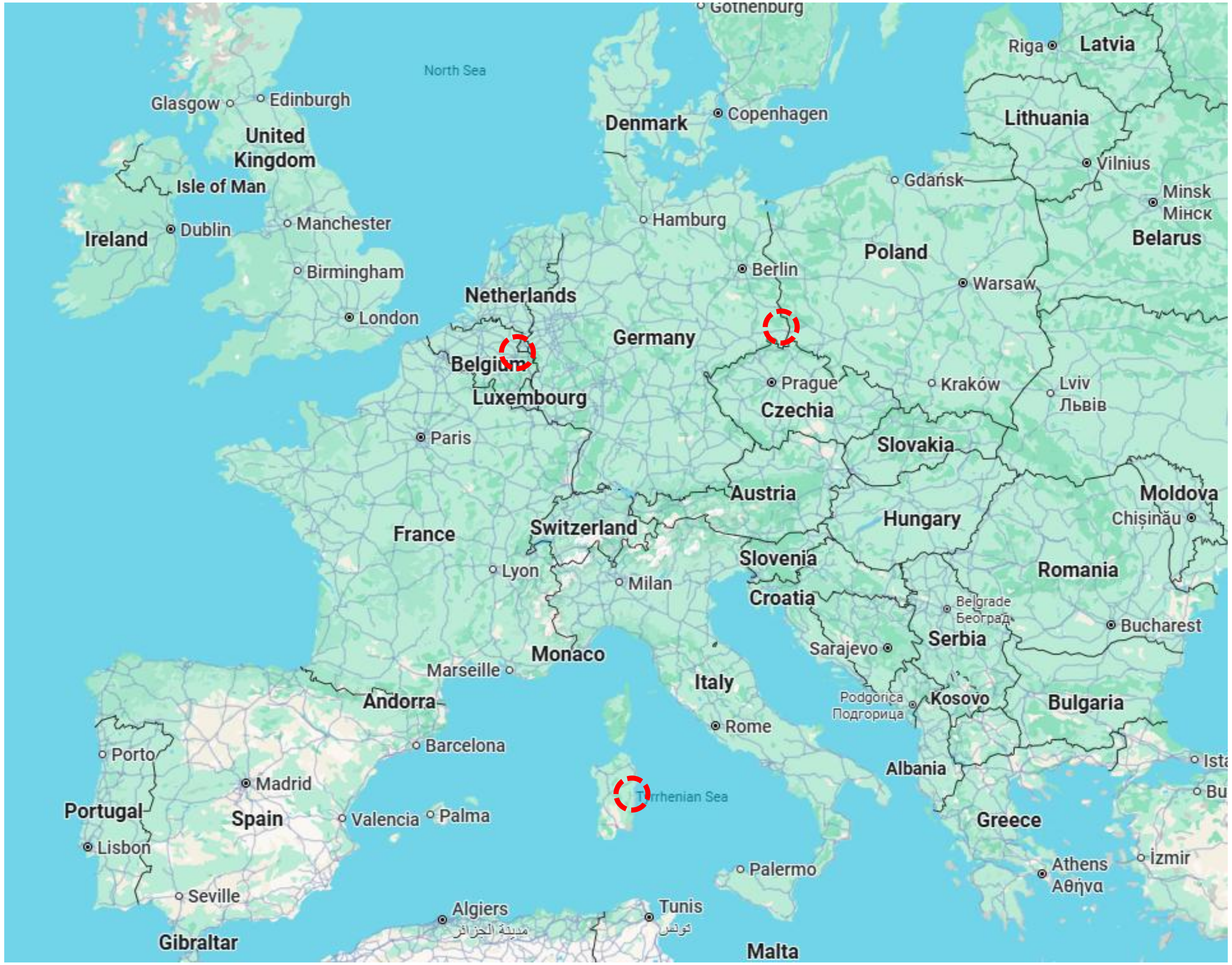
# ET Collaboration



# ET Organization



# Candidate sites




The three candidate sites for the Einstein Telescope (ET) are:

- Sos Enattos in Sardinia, Italy;
- the Meuse-Rhine Euroregion (border of Belgium, the Netherlands, and Germany);
- Lusatia in Saxony, Germany.

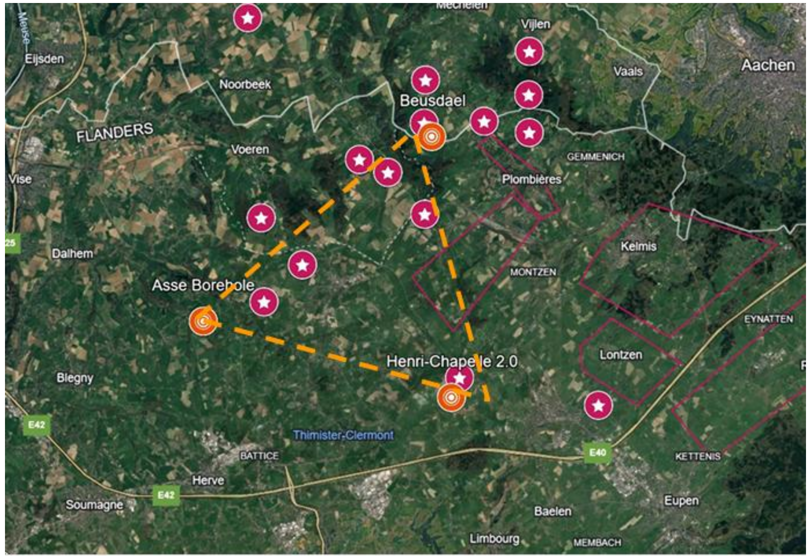
Sardinia is known for its low seismic noise, while the other two sites also offer geological conditions suitable for a gravitational-wave observatory.

# Site Updates

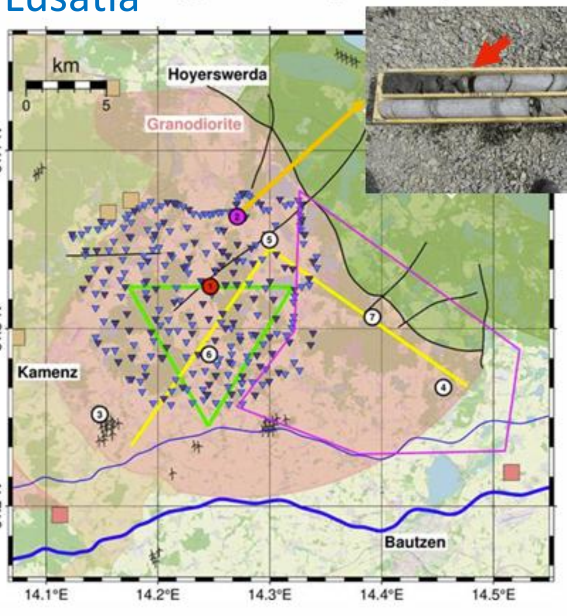
The final site will be chosen after in-depth feasibility and characterization studies, with a decision expected around 2026 with construction to begin around 2028 and operations starting in 2035. All the SBCs are strongly working to improve the site characterization: new drilled boreholes, instrumentation of borehole, noise impact evaluation, etc.

- Deliverables for Site Selection
  - report on site characterization: seismic, magnetic, acoustic noise in surface and in depth, gravimetric measures, NN model, 3D geology, hydrology, noise impact evaluation, etc.
  - quantification of all the aspects impacting the ET performance for each site
  - updated cost and schedule estimates of the excavations
- Bidbook submission Q4 of 2026

EMR

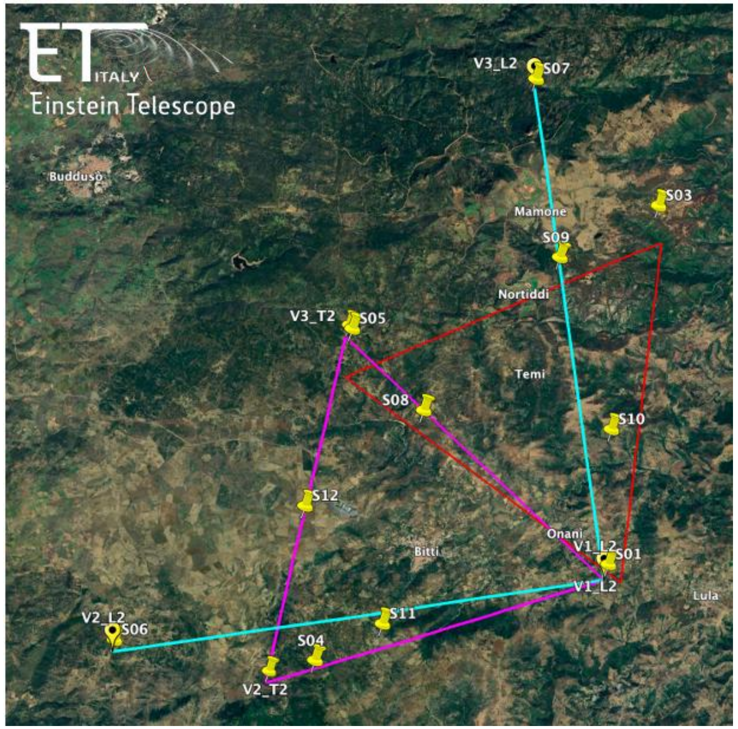



Lusatia




Based on re-evaluation of hundreds of borelogs

Sos Enattos



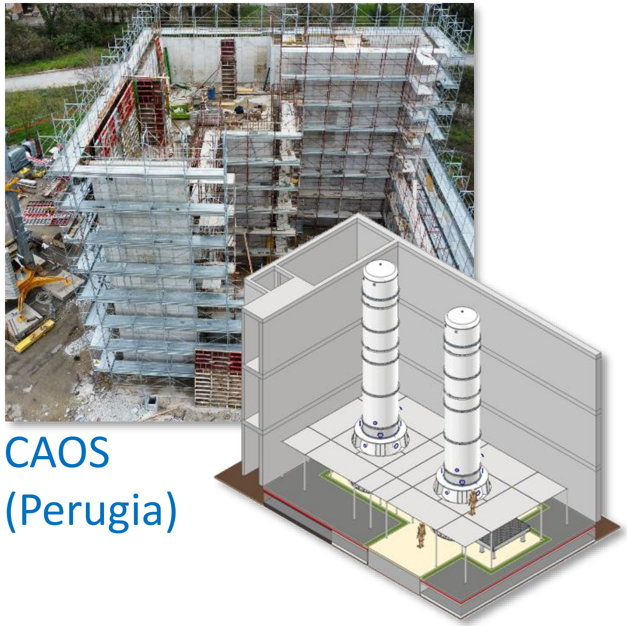
# Infrastructures for ET in Italy - ETIC

### Optics, Electronics and Photonics

- CoMET (INFN-PD e UniPD)
- GALILEO (INFN-GE e UniGE)
- PLANET (INFN-NA e UniNA)
- AiLoV-ET (INFN-RM2 e UniRM2)
- ETICO2 (INFN-CA e UniCA_Fis)
- ADONI (INAF)
- DIFAET (UniBO)
- PisaET-IR@CISUP (UniPI)

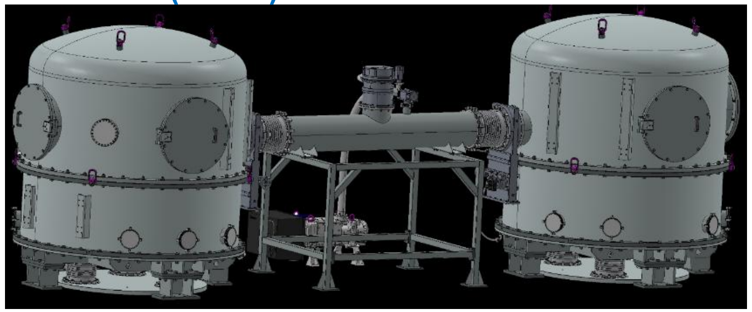
### Vacuum and Cryogenics

- ARC_CRYO (INFN-RM1 e UniRM1_Fis)
- CALATIA (INAF, INFN-NA e UniVanvitelli)



CAOS (Perugia)

GEMINI (GSSI)



ARC (Roma1)

### Suspensions and Interferometric large facilities

- CAOS (INFN-PG e UniPG)
- GEMINI (LNGS e GSSI)
- PLANET (INFN-NA e UniNA)
- SAMANET (INFN-PI)

### Computing & Data Acquisition

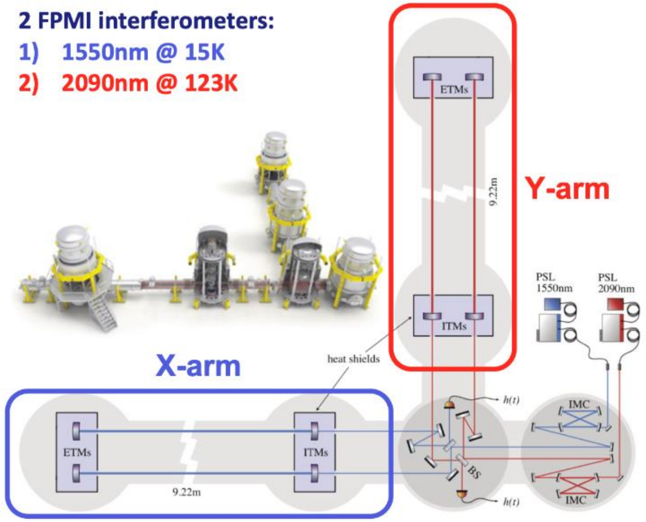
- DIFAET (UNIBO)
- BETIF (INFN-BO)
- CTLAb (INFN-TO)

### Sustainable Design

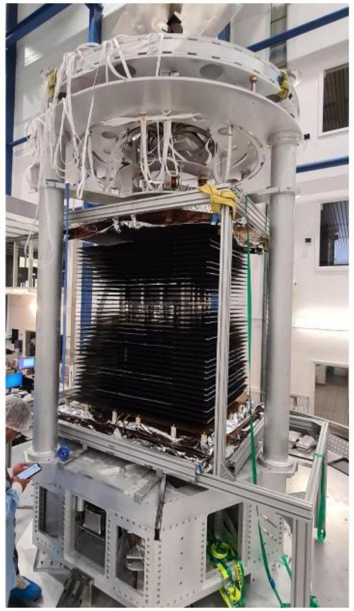
- ET_3G LAB (UniRM1_DICEA, ASI e UniPI)
- AT_LAB (UniCA_ing)

# Infrastructures for ET in Europe

Too much to cover, … a few highlights




ET Pathfinder, Maastricht. Test ET technologies

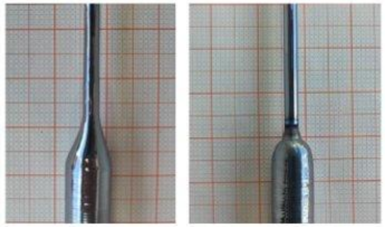


E-TEST, Liege. Isolation / cooling strategies

Glasgow 10m cryogenic interferometer


CERN, agreement on vacuum pipe construction/welding and on engineering and safety.

Lots of fibre development in silica, sapphire and silicon (IKZ, Rome, Glasgow, Perugia, …)



*Slide credit: G.Hammond - ET-0414A-25*

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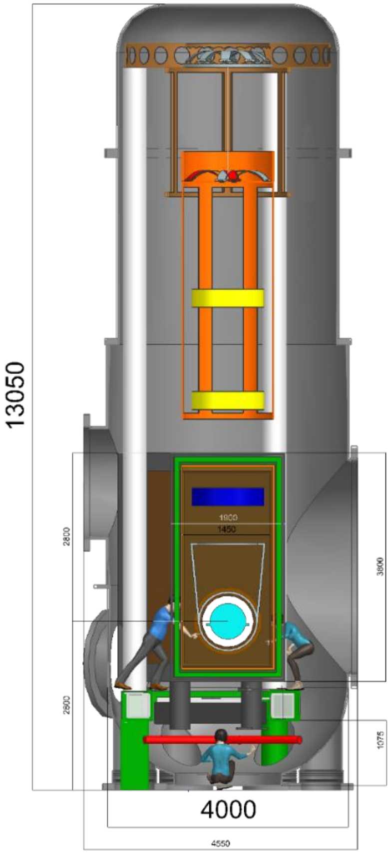
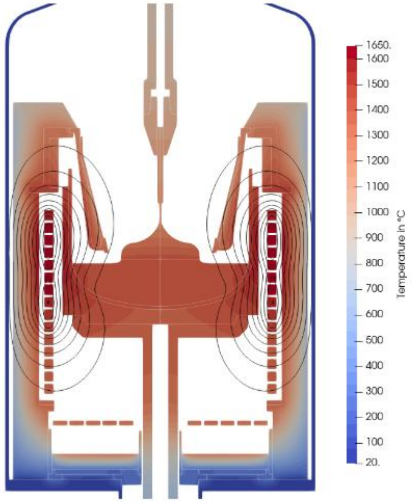
# Infrastructures for ET in Europe

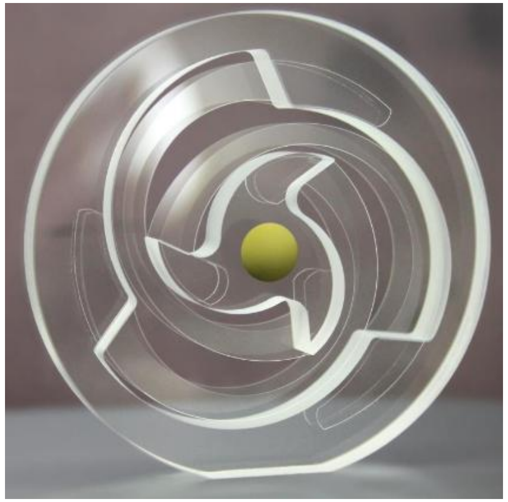


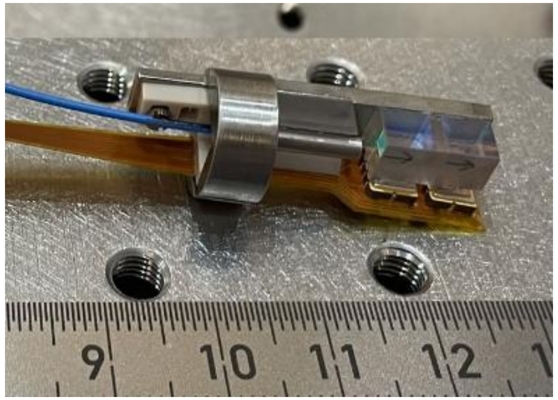

- Coatings/Substrates
- Work ongoing with large sapphire (Lyon) and silicon (growth techniques and composite masses, IKZ, DZA, Glasgow)

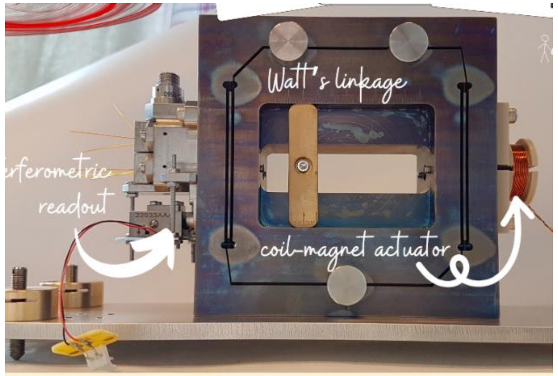




KRISTMAG®

Glass resonators: Hannover






Watts linkage: VU Amsterdam

- ANM:
- Looking at single cavern solutions for isolation (Vrije Universiteit Amsterdam)

- Sensors (SUS/ANM):
- Lots of development on warm / cold sensors

*Slide credit: G.Hammond - ET-0414A-25*

# Conclusions

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- **ET** is a great scientific **adventure** but also a technological, engineering, political and financial **challenge**
- **ET** will be a **3G GW Observatory**: multi-messenger astronomy, cosmology, fundamental physics in extreme conditions.
- **ET** will be the **larger** and **more complex underground research infrastructure**!
- **ET** will require and push great **technological improvements** in many fields
- **ET** is in the European **ESFRI roadmap**.
- **Two baselines** considered: **10km-long triangle** and **15km-long (double) L**
- Product Breakdown Structure (**PBS**) produced in the last 2 years towards **TRD**
- New science case (**Blue Book**) released in March 2025.
- **ET** intl. **Collaboration**: 263 institutions, 31 countries, 1808+ members, still growing!
- **Three promising sites officially candidate** to host the infrastructure(s): **EMR** (NL, BE, GE), **Sardinia** (Italy) and **Lusatia** (GE), extensive site characterization ongoing.
- Geometry, site(s), overall costs and ET legal entity are expected to be defined by 2026.

# Thank you!

*Slide credit: Marco Kraan/Nikhef*

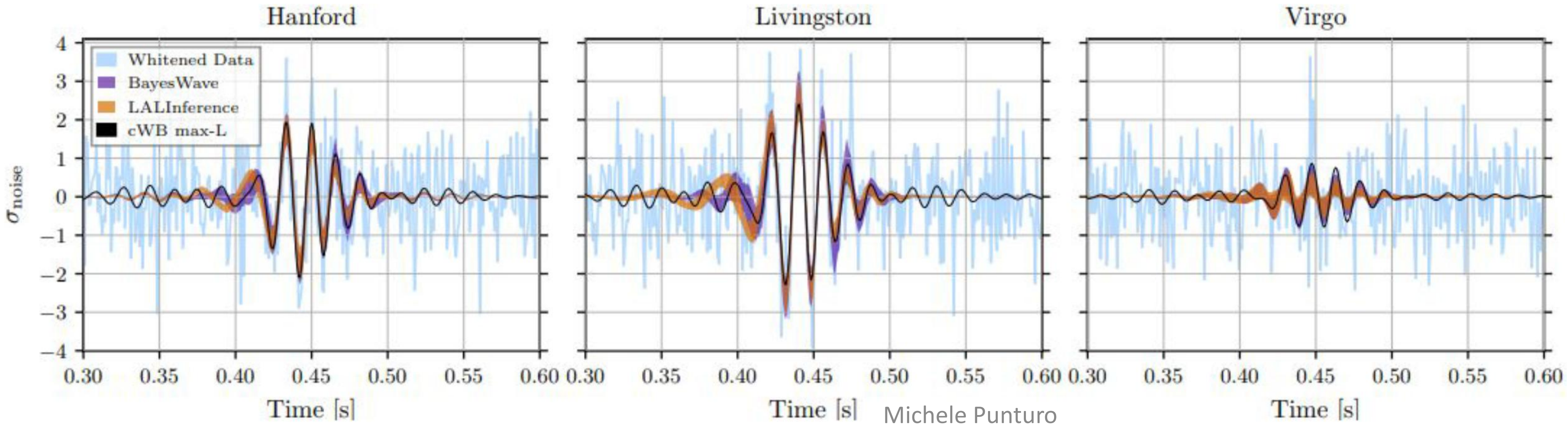
Urgency of the low frequency?

# GW190521

$M_1 = 85^{+21}_{-14} M_\Theta$, $M_2 = 66^{+17}_{-18} M_\Theta$
at $z \sim 0.82$ (5.3Gpc)
Remnant $M_f = 142^{+28}_{-16} M_\Theta$

# GW231123

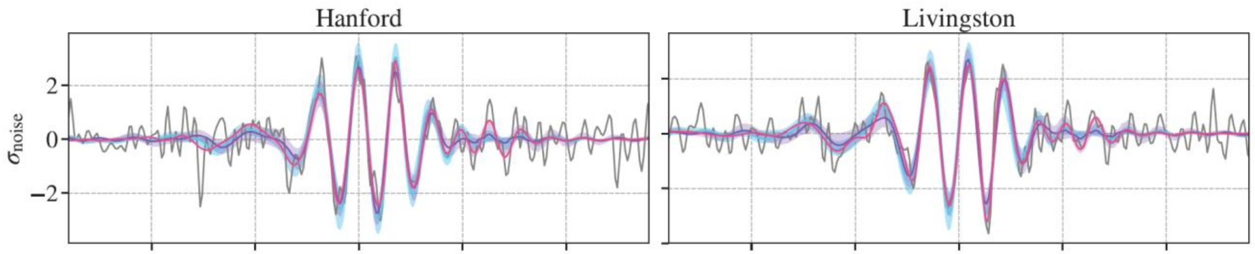
$M_1 = 137^{+22}_{-17} M_\Theta$, $M_2 = 103^{+20}_{-52} M_\Theta$
at $z \sim 0.39$ (07-4.1Gpc)
Remnant $M_f = 225^{+26}_{-43} M_\Theta$



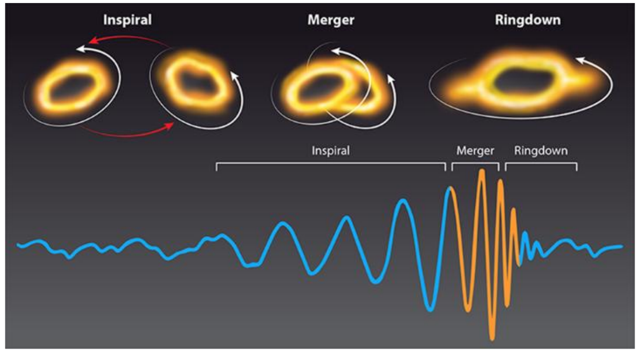

Michele Punturo

GW190521

Phys. Rev. Lett. 125, 101102 (2020)
Astrophys. J. Lett. 900, L13 (2020)

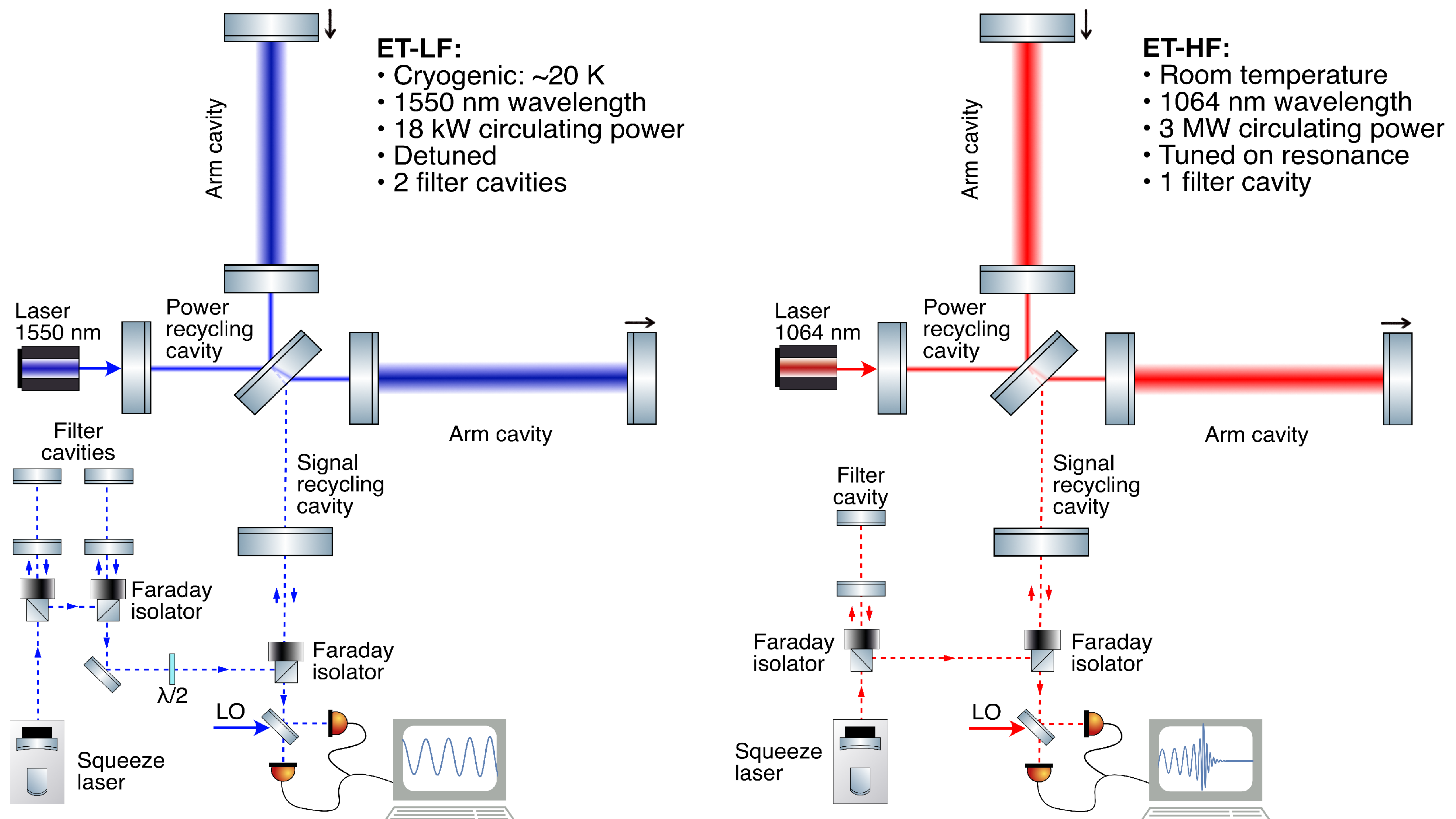



GW231123 arXiv:2507.08219 [astro-ph.HE]




Where is the chirp?

*Slide credit: M.Punturo – 10 Anni GW- Padova*


ET-LF:
• Cryogenic: ~20 K
• 1550 nm wavelength
• 18 kW circulating power
• Detuned
• 2 filter cavities
Arm cavity
Laser 1550 nm
Power recycling cavity
Arm cavity
Filter cavities
Signal recycling cavity
Faraday isolator
Faraday isolator
λ/2
LO
Squeeze laser
ET-HF:
• Room temperature
• 1064 nm wavelength
• 3 MW circulating power
• Tuned on resonance
• 1 filter cavity
Arm cavity
Laser 1064 nm
Power recycling cavity
Arm cavity
Filter cavity
Signal recycling cavity
Faraday isolator
Faraday isolator
LO
Squeeze laser