Einstein Telescope
a 3G gravitational wave observatory

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on behalf of ET coll.

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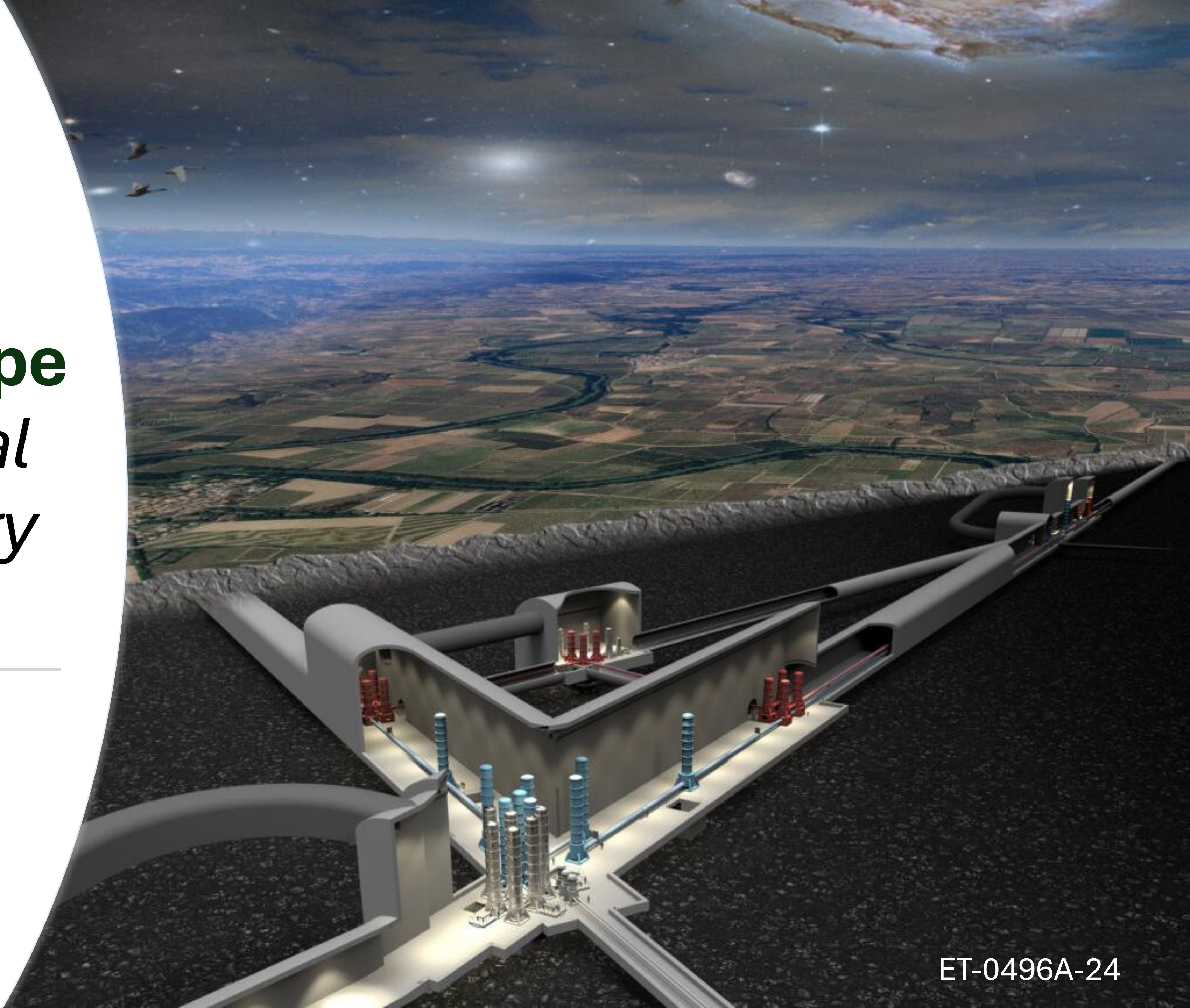
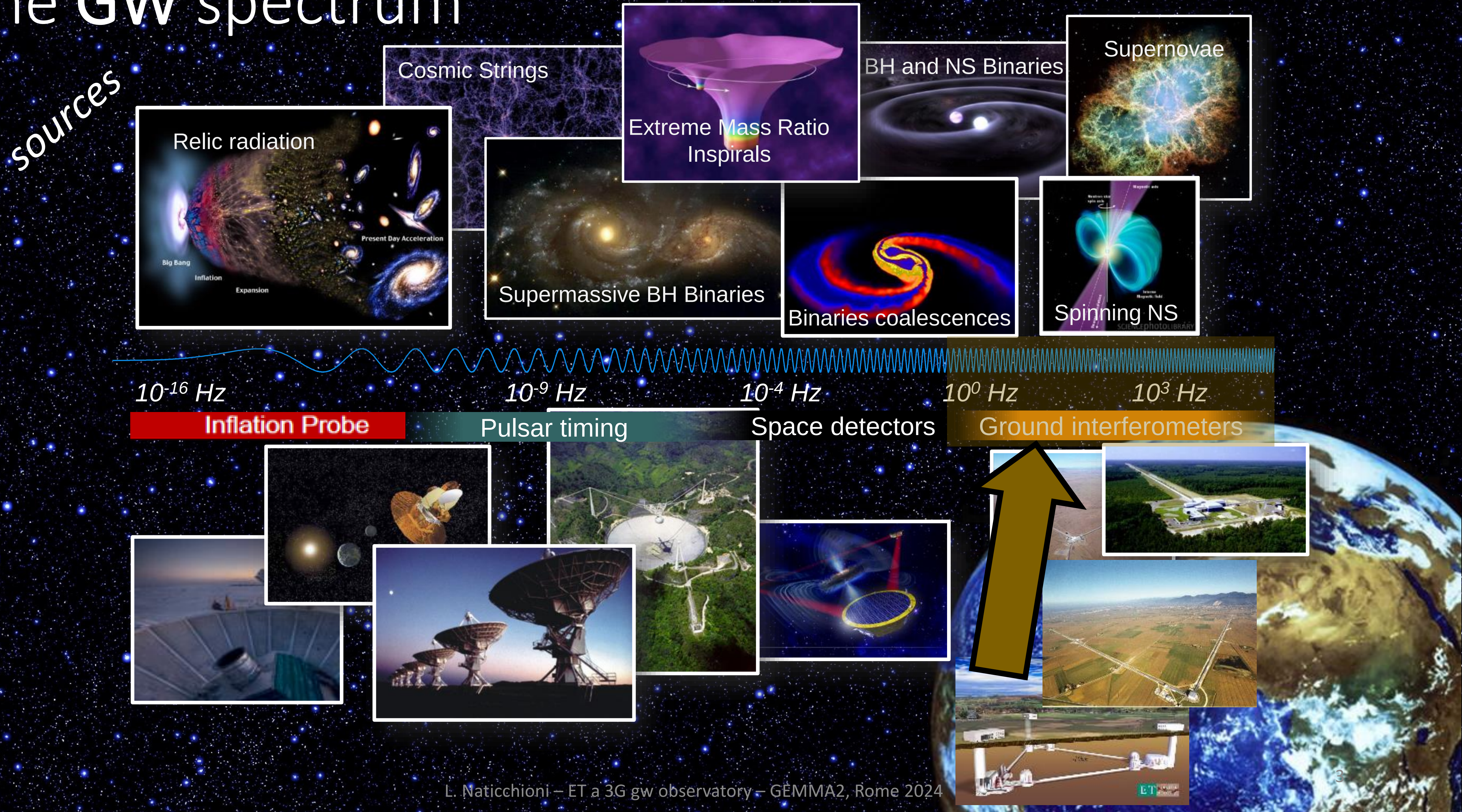
Istituto Nazionale di Fisica Nucleare



Summary

- ❑ **From 2G to 3G gravitational wave detectors**
- ❑ The ET collaboration
- ❑ A 3G GW observatory
- ❑ The ET site(s)
- ❑ Conclusions

The GW spectrum



2G current gravitational wave world network (LVK)

2G current gravitational wave world network (LVK)

2G/2G+ expected timeline

Observation Runs

O4 b
2024-2025

O5
2027~2030

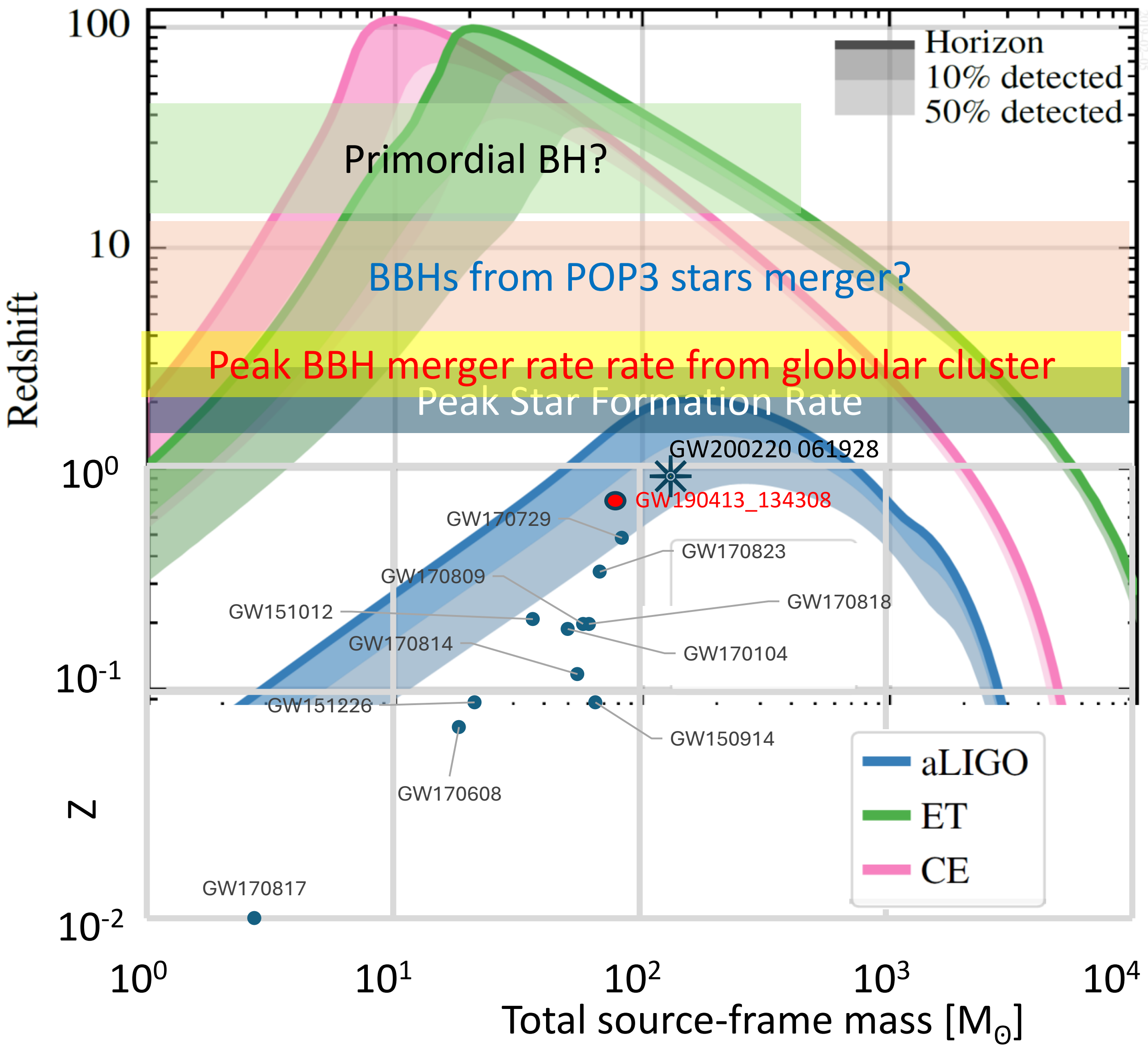
O6
~2032~2034

O7
>2035

3G
~2036

Where we are, where we aim

- 2nd generation GW detectors are exploring the *local Universe*, initiating the precision GW astronomy, but to have *cosmological* investigations **a factor of 10 improvement in terms detection distance is needed**.
- Great results achieved even though with a sensitivity below the nominal one.
- Post-O5 Advanced detector will be able to expand the observation horizon, but still local universe!
- **3G ground-based detectors (ET, CE) will be required to access the high-redshift Universe!**



Where we are, where we aim

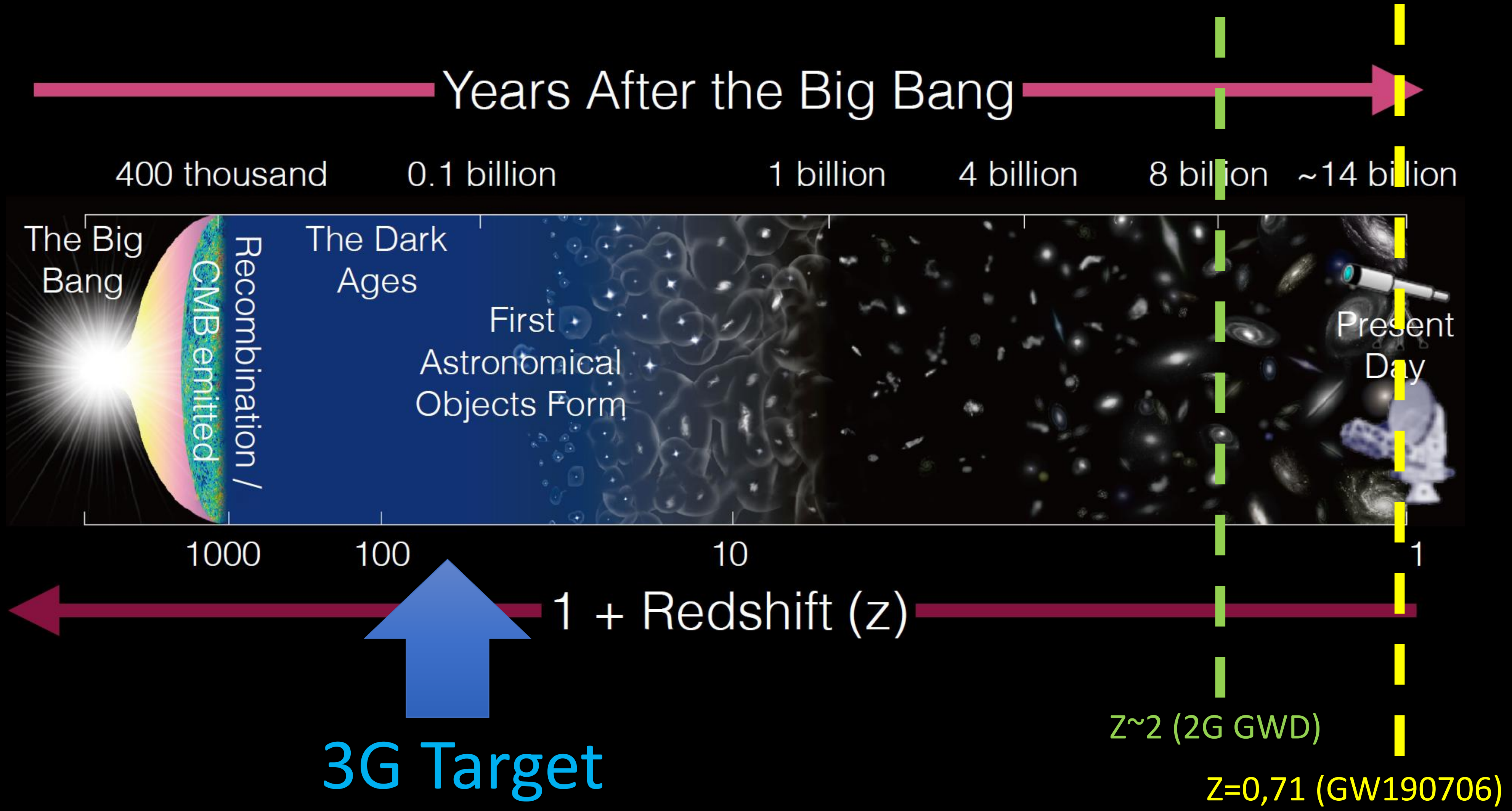
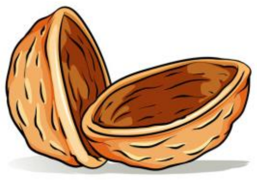


Image credit: NAOJ/ALMA
http://alma.mtk.nao.ac.jp/

ET EINSTEIN TELESCOPE

GW Science with ET ... in a nutshell



ASTROPHYSICS

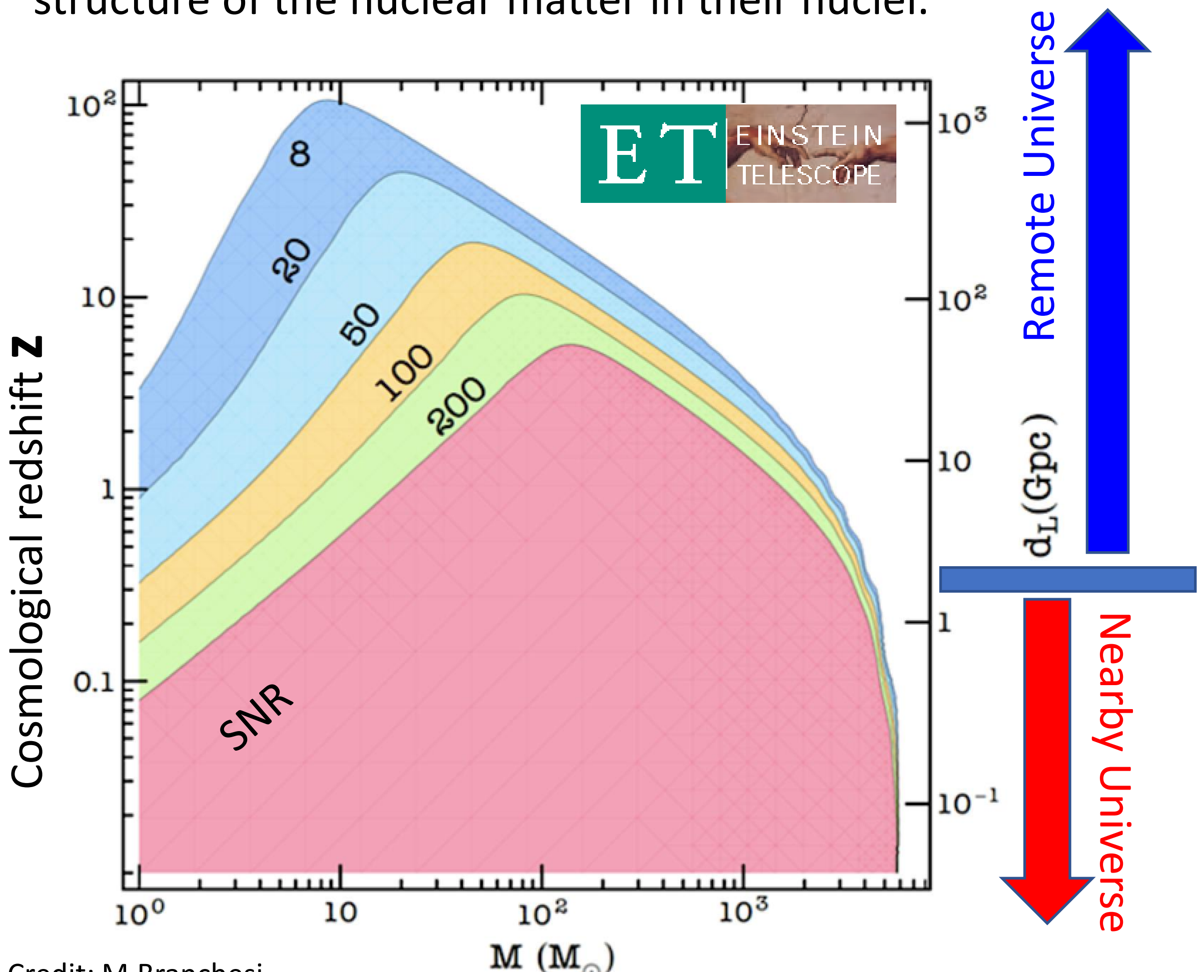
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)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

GW Science with ET

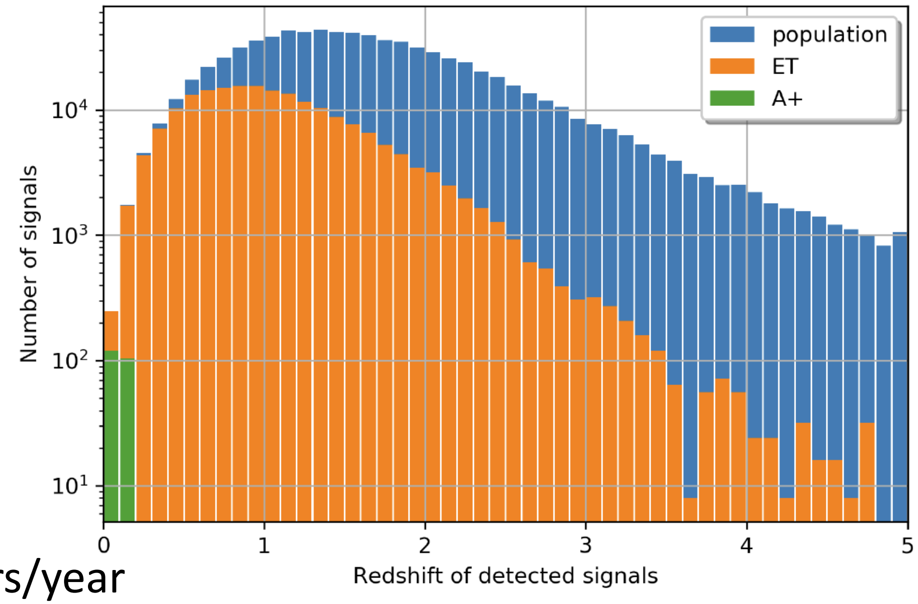
- ET will explore **almost the entire Universe** listening the gravitational waves emitted by **black holes**, back to the **dark ages** after the Big Bang.
- ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of **Neutron Stars** per year, revealing the most intimate structure of the nuclear matter in their nuclei.



Credit: M.Branchesi

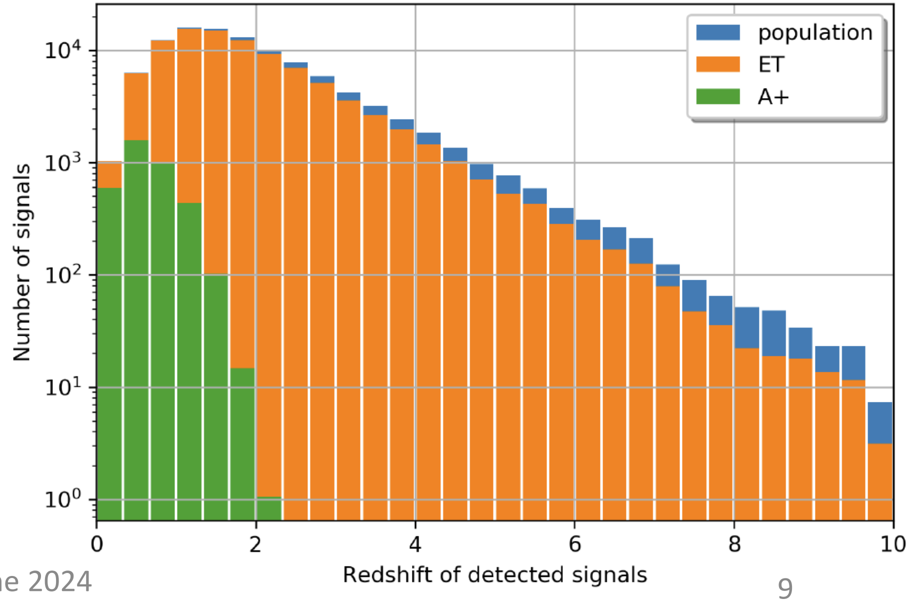
Compact Object Binary Populations

BNS mergers



O(10^5) mergers/year

BBH mergers



GW Science with ET

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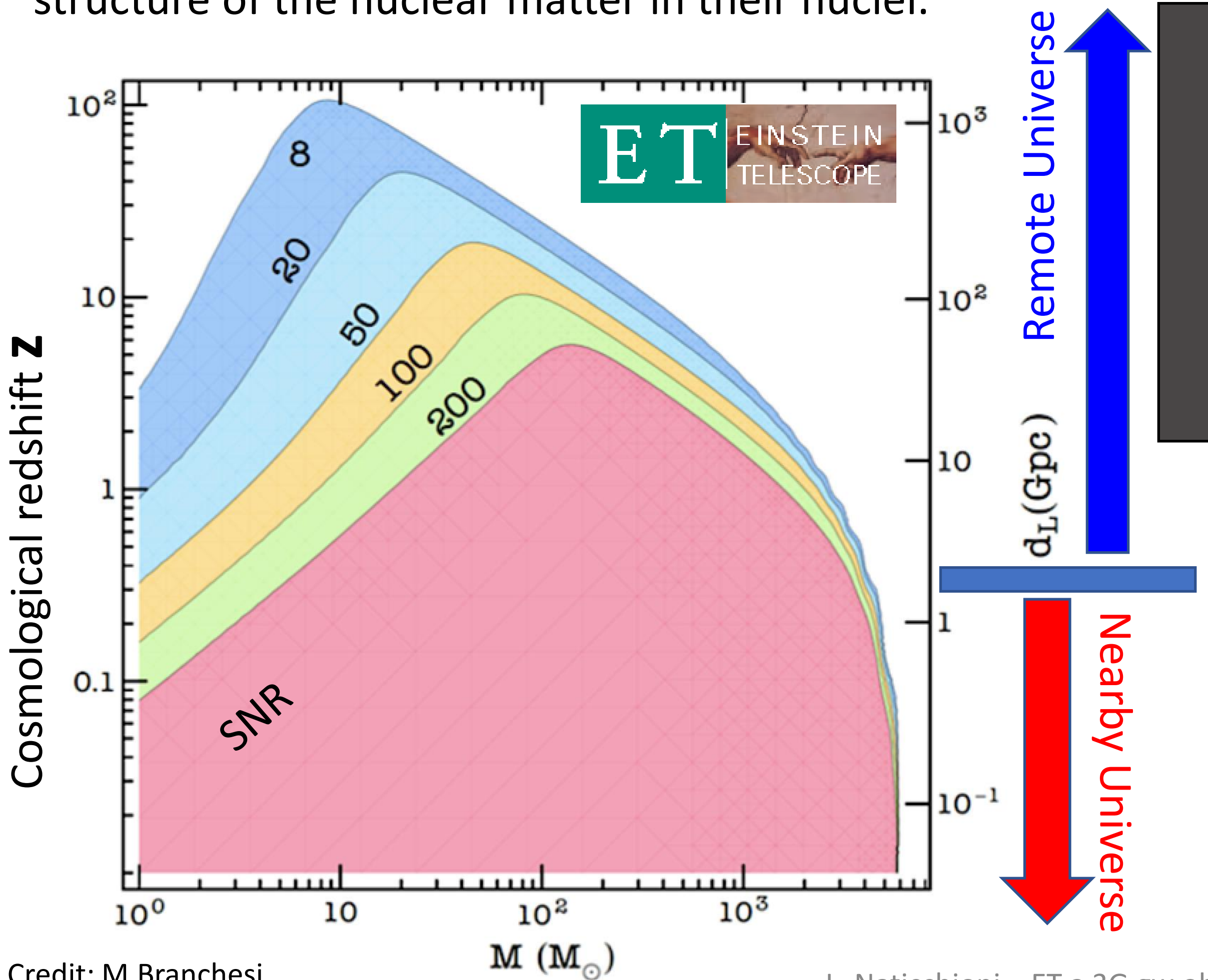
Compact Object Binary Populations



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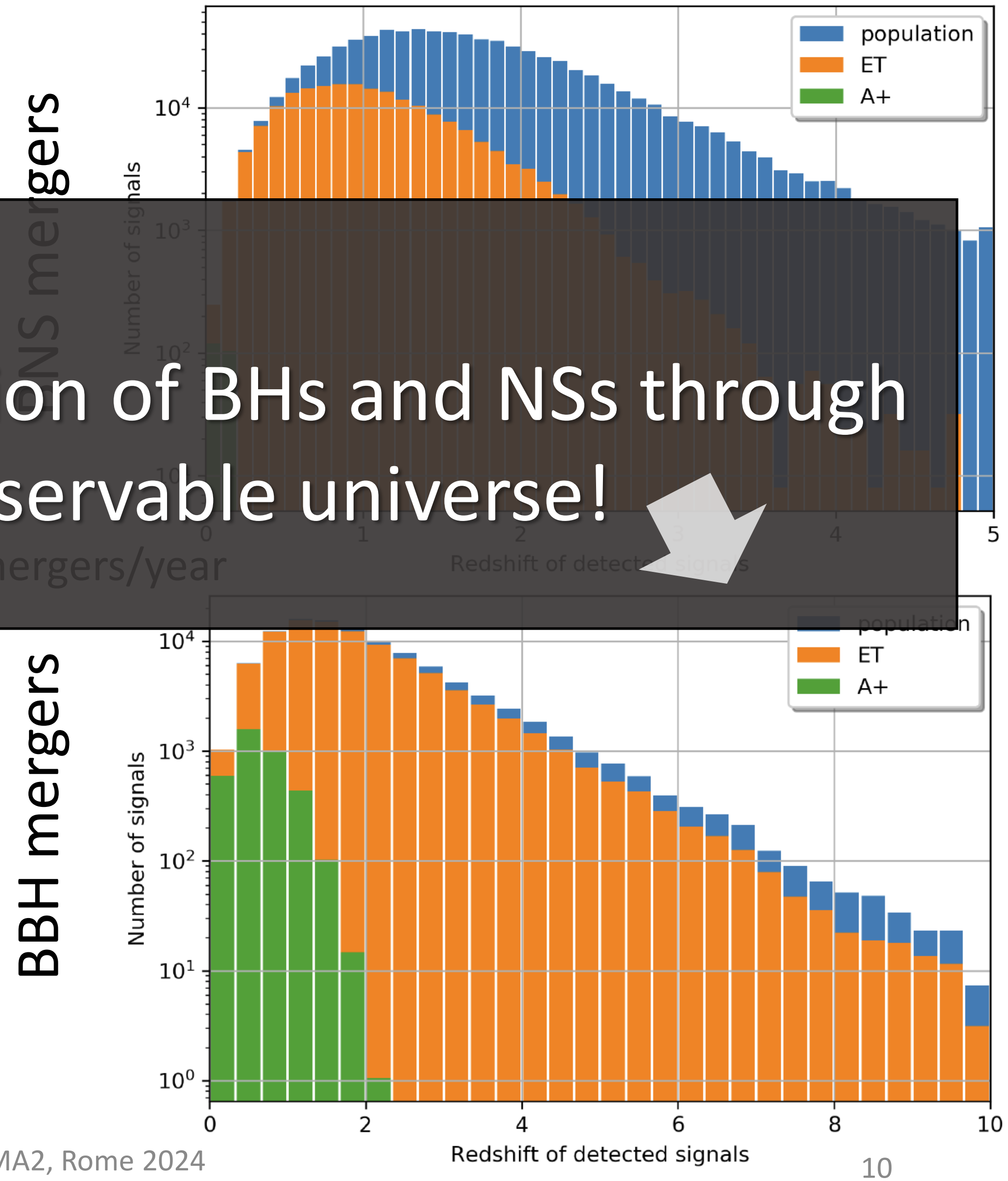


Evolution of BHs and NSs through the observable universe!

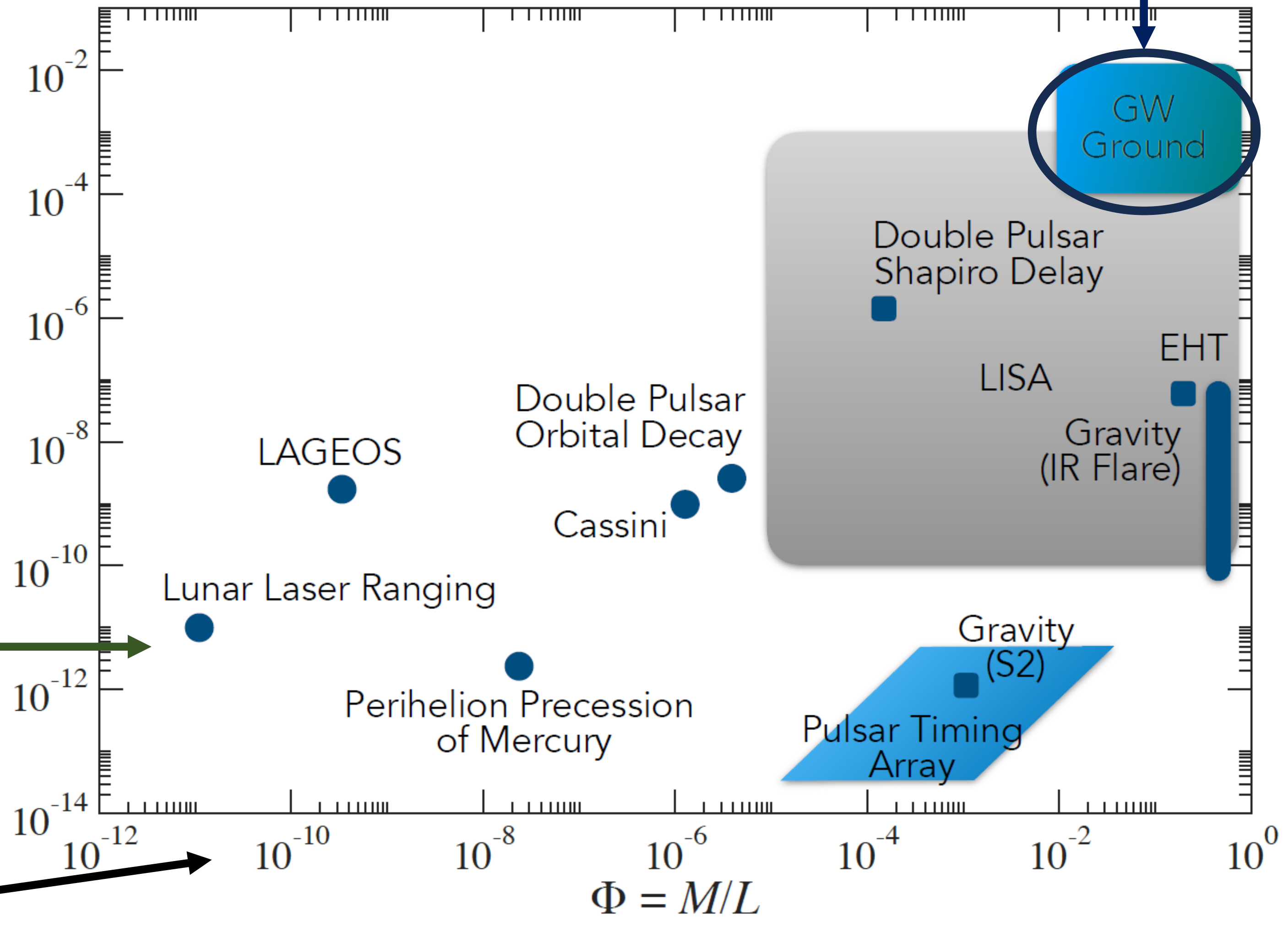
GW Science with ET

GWs from coalescing Binary Black Hole (BBH) allows to test GR in **strong-field** regime

Inverse of the characteristic curvature length scale

Solar System orbital measurements probing the weak-field regime

characteristic gravitational potential

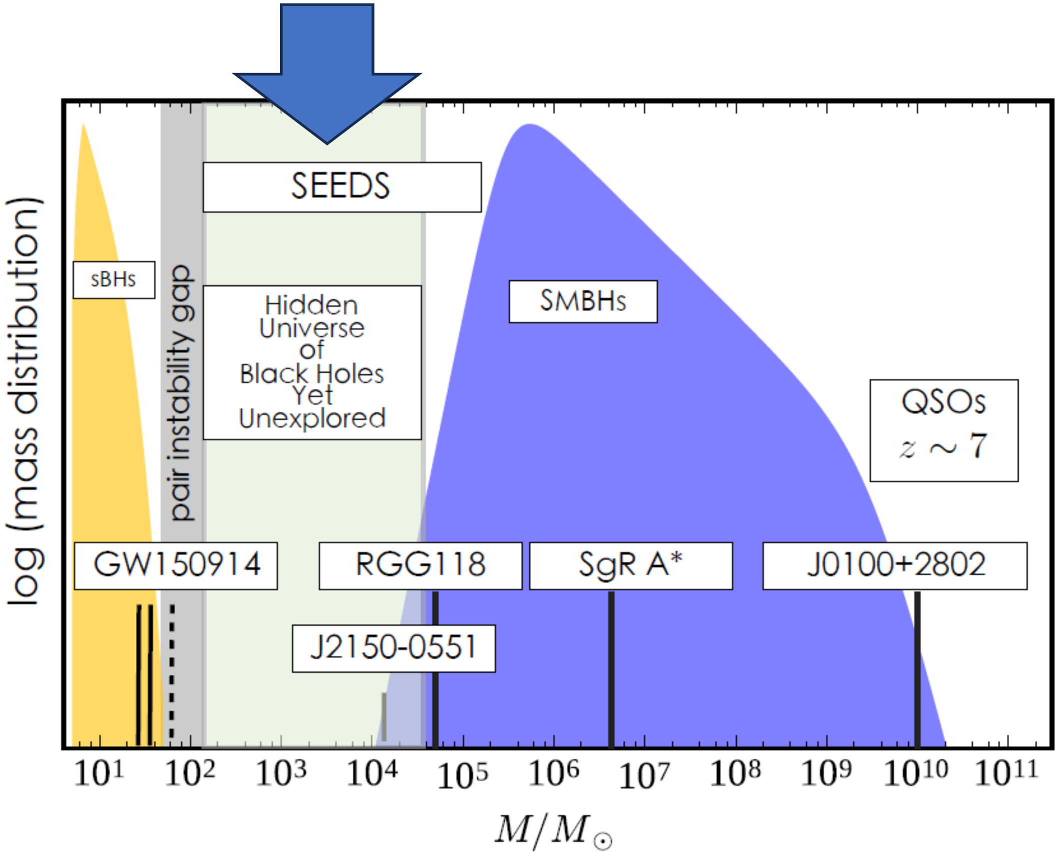


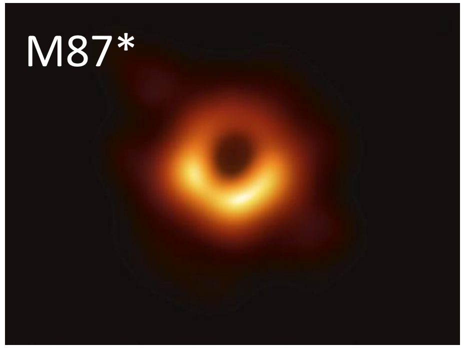
Yunes N. et al. Phys. Rev. D 94, 084002 (2016) Edited by ET science case team

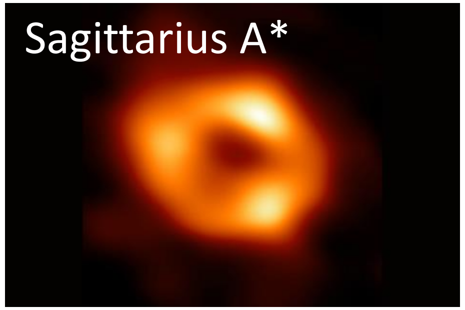
GW Science with ET

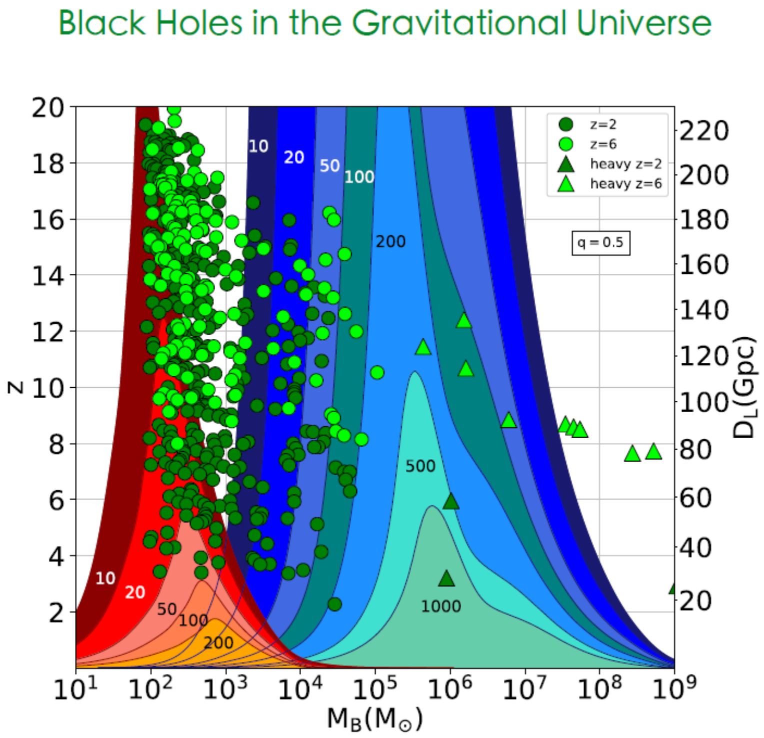
Seeds and Supermassive Black Holes

- **Supermassive Black Holes** (SMBHs) are present at the center of many galaxies:
  - What is their **history** and **evolution**? How have they formed? What are the **seeds**?

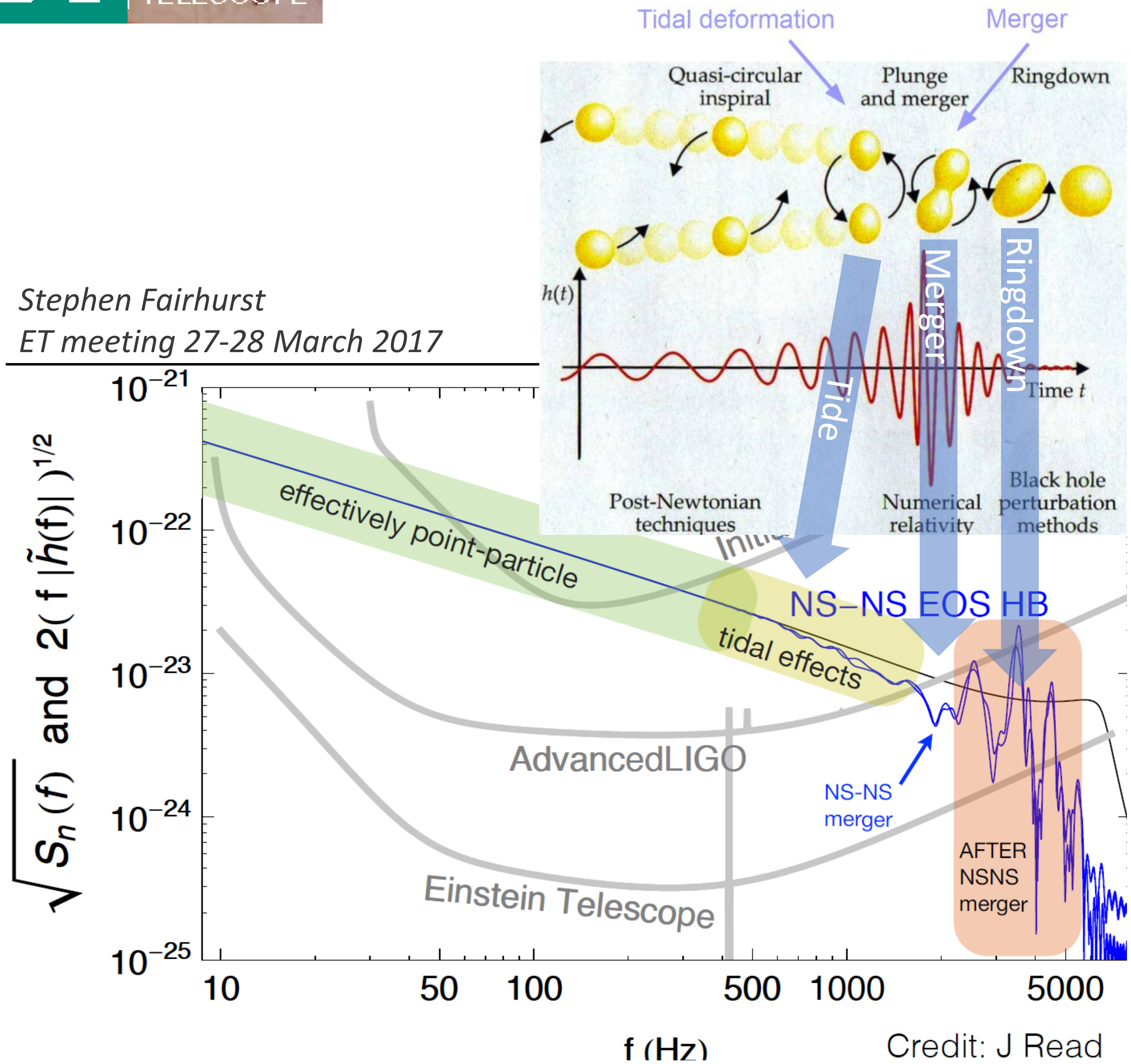




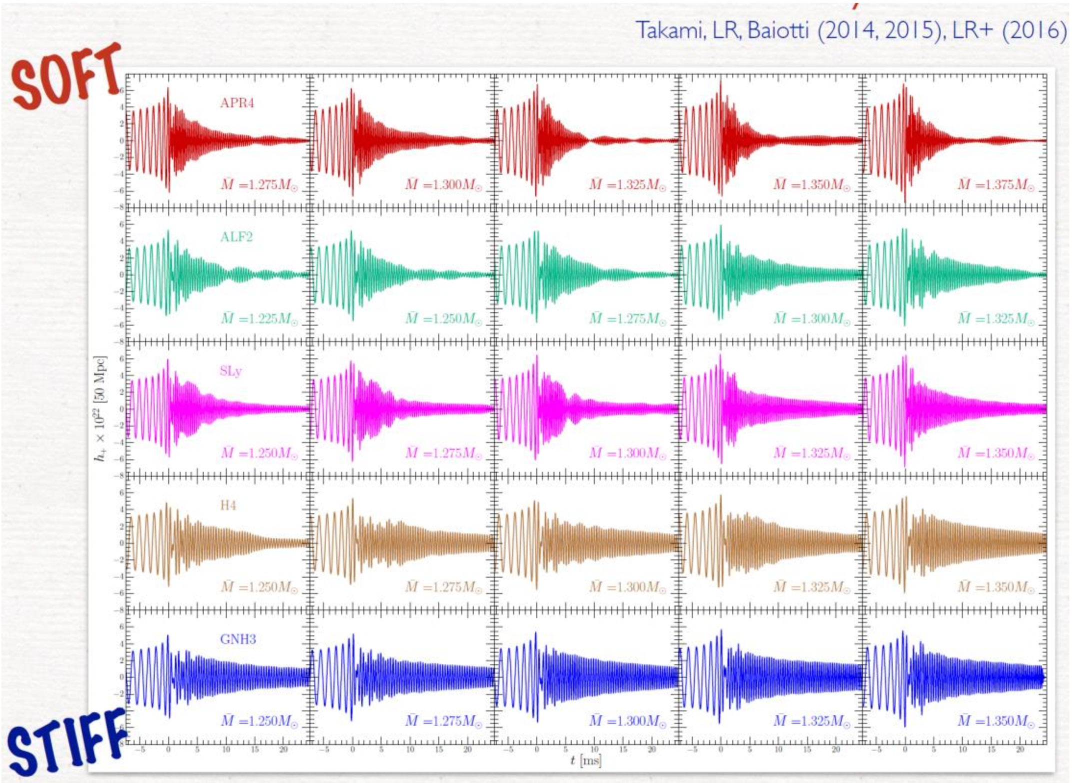




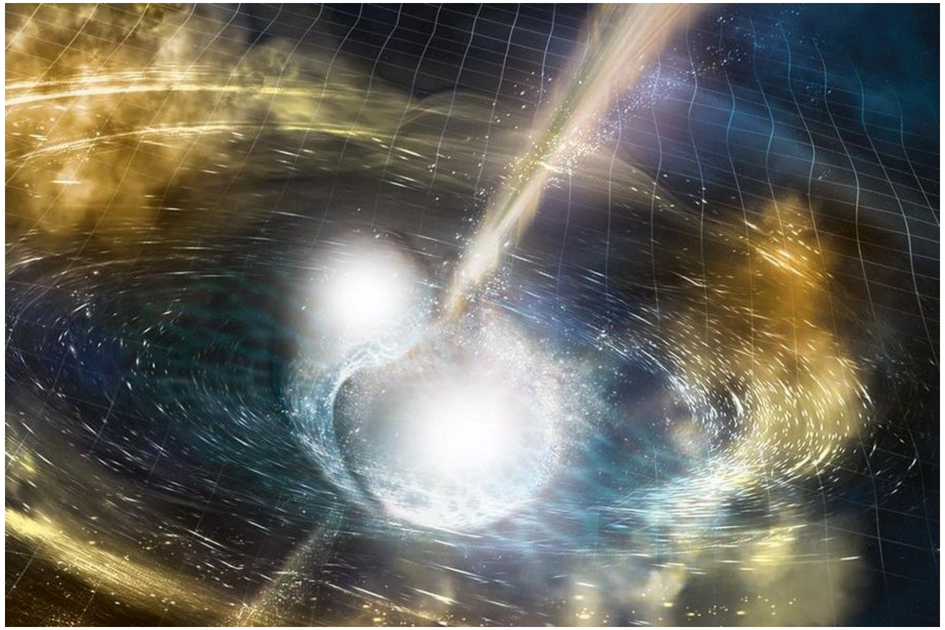
GW Science with ET



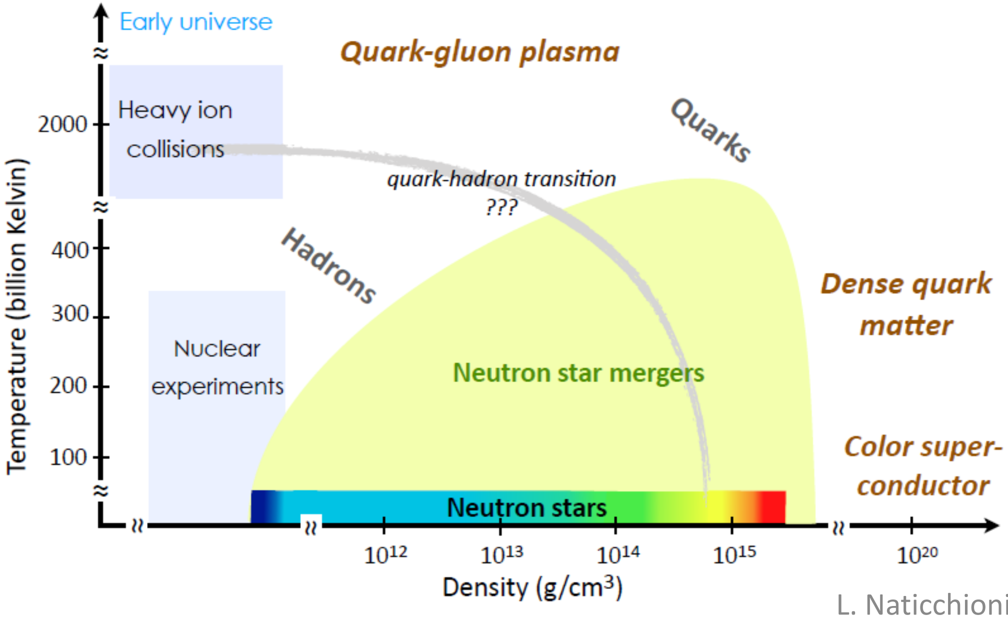
Structure of a Neutron Star: equation of state



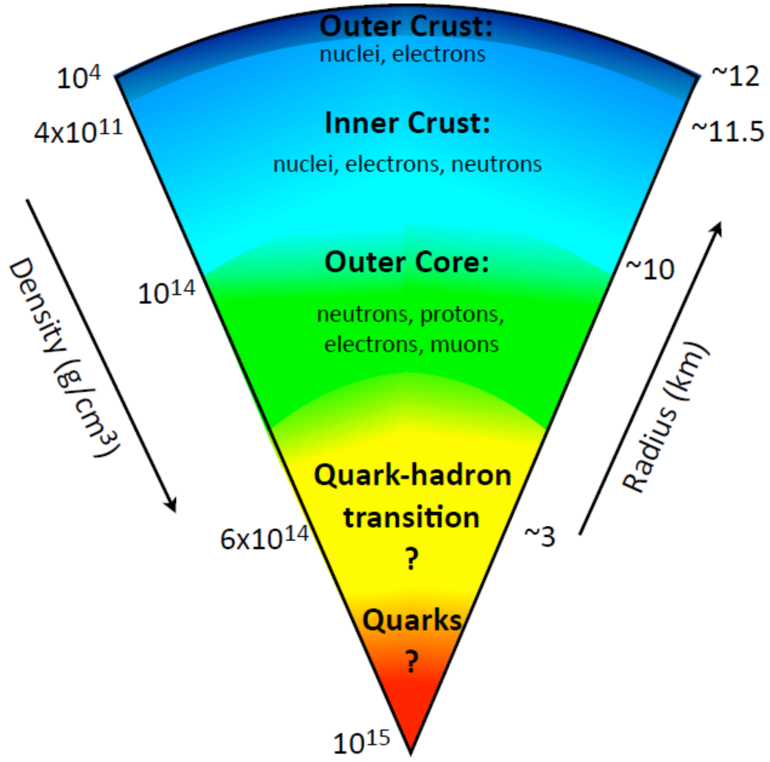
GW Science with ET



- Neutron stars are an **extreme laboratory for nuclear physics**
  - The external crust is a Coulomb Crystal of progressively more neutron-reach nuclei.
  - The core is a Fermi liquid of uniform neutron-rich matter ("Exotic phases"? Quark-Gluon plasma?)



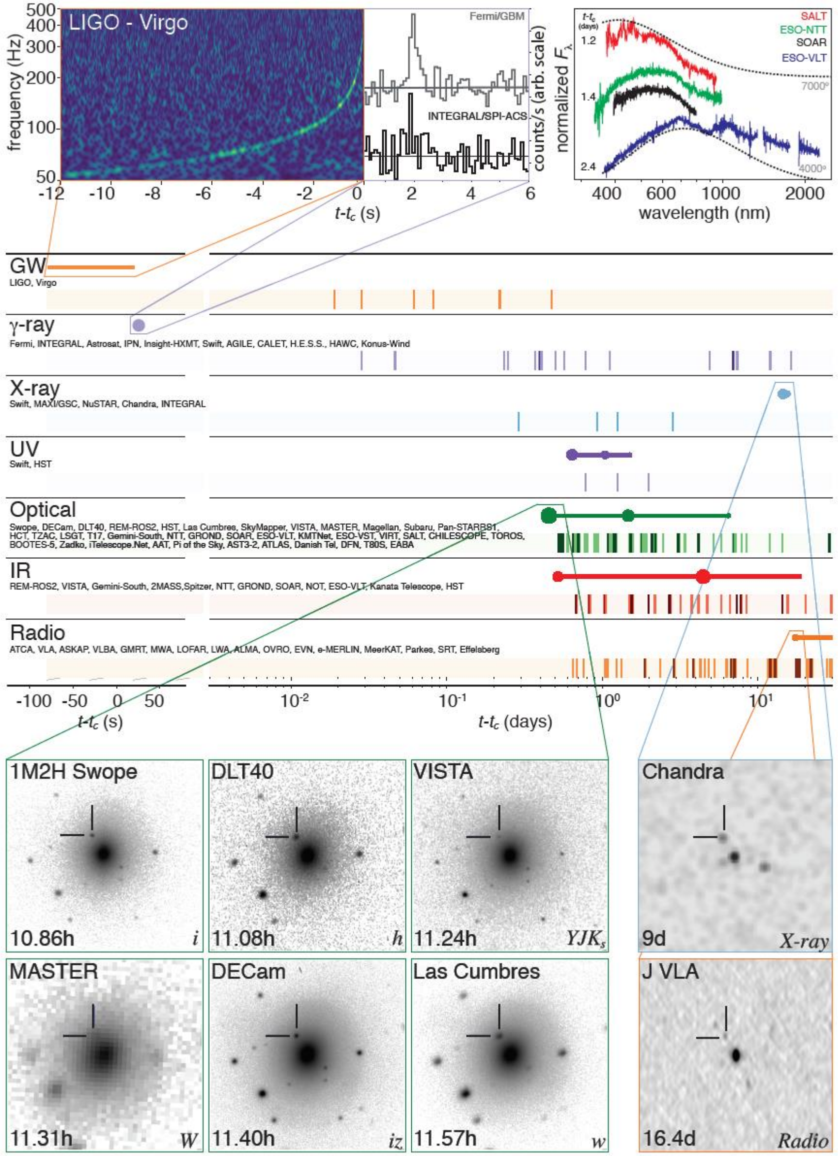
- Tidal deformation from the dephasing in the GW signal → constrain the EOS of the NS.
- EM information → more stringent constrain.
- EOS describes the status of the matter in the over-critical pressure condition.



GW Science with ET

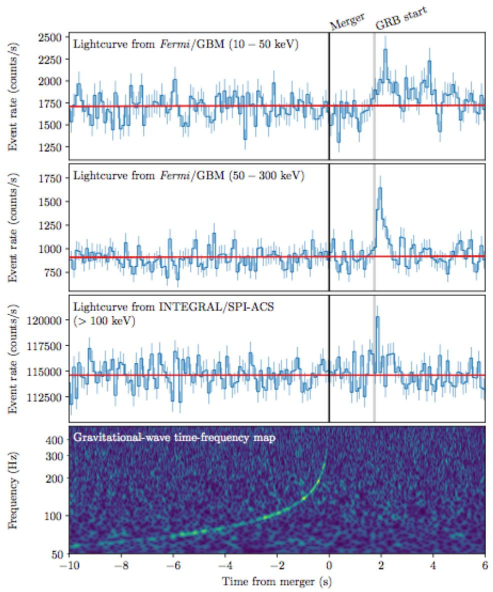
The power of MMA

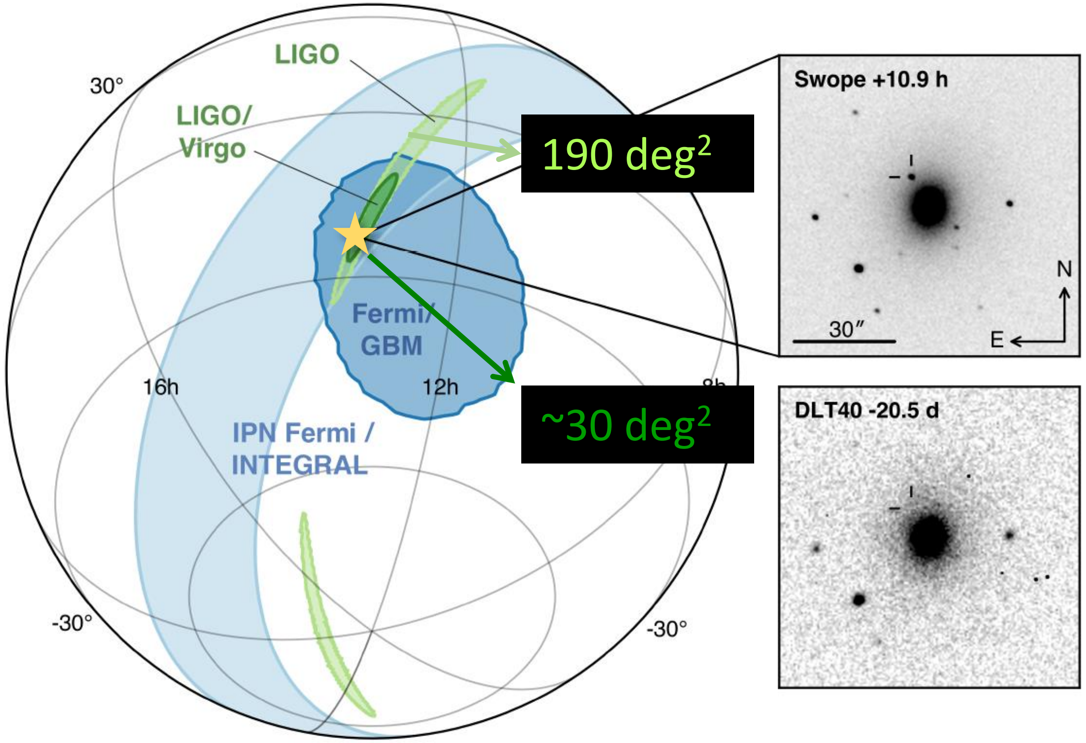
GW170817 BNS: the birth of **MultiMessenger Astronomy**

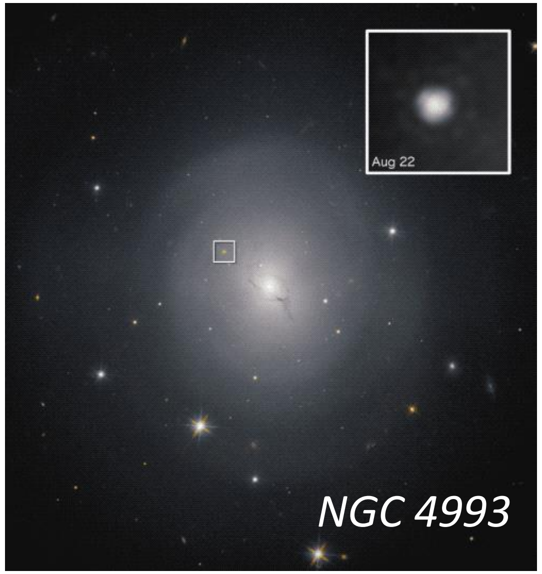


- BP Abbott et al. (LVC), 2017, *Phys. Rev. Lett.* **119**
- BP Abbott et al. (LVC), 2017, *ApJL.* **848** (2)

- **LIGO+Virgo (GW)**
- **Fermi+Integral (GRB)**
- **70 observatories follow-up (EM)**







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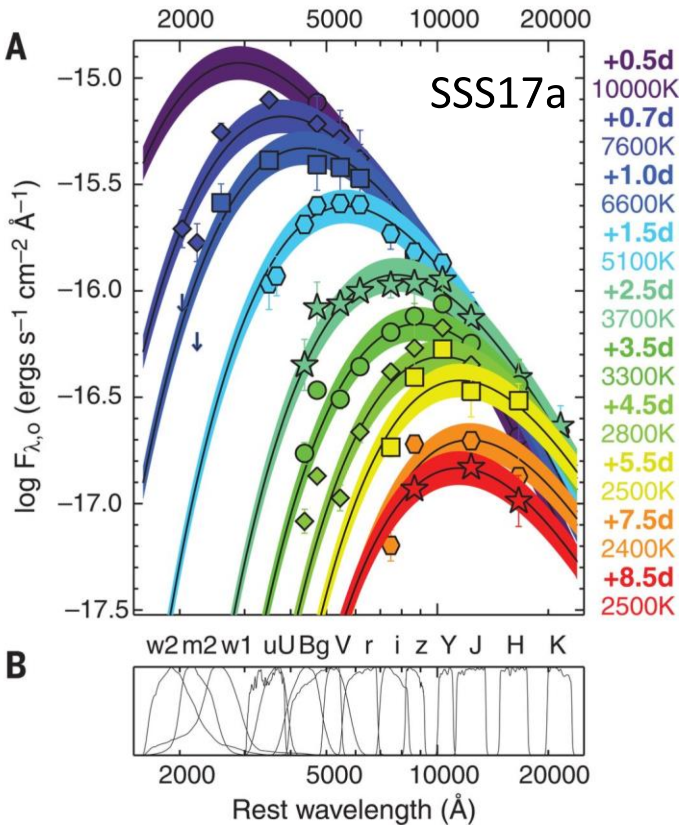
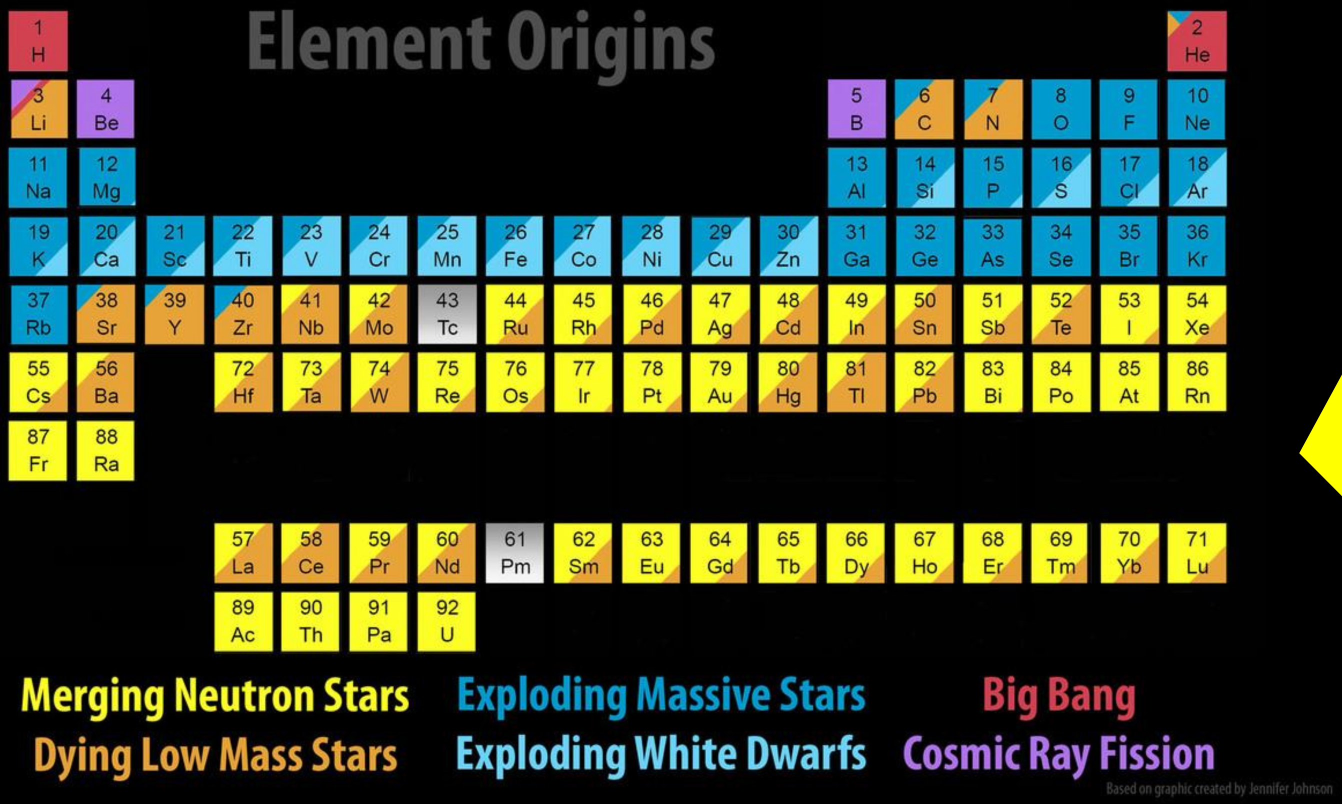


Drout M.R. et al., *Science* Vol. 358, Issue 6370

- The e.m. counterpart light curve evolution of GW170817 is compatible with rapid neutron capture process (r-process) nucleosynthesis
  - It explains the observed lanthanide abundances
  - GW170817 produced and ejected $\sim 0.05 M_{\odot}$ of heavy elements



Summary

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- **The ET collaboration**
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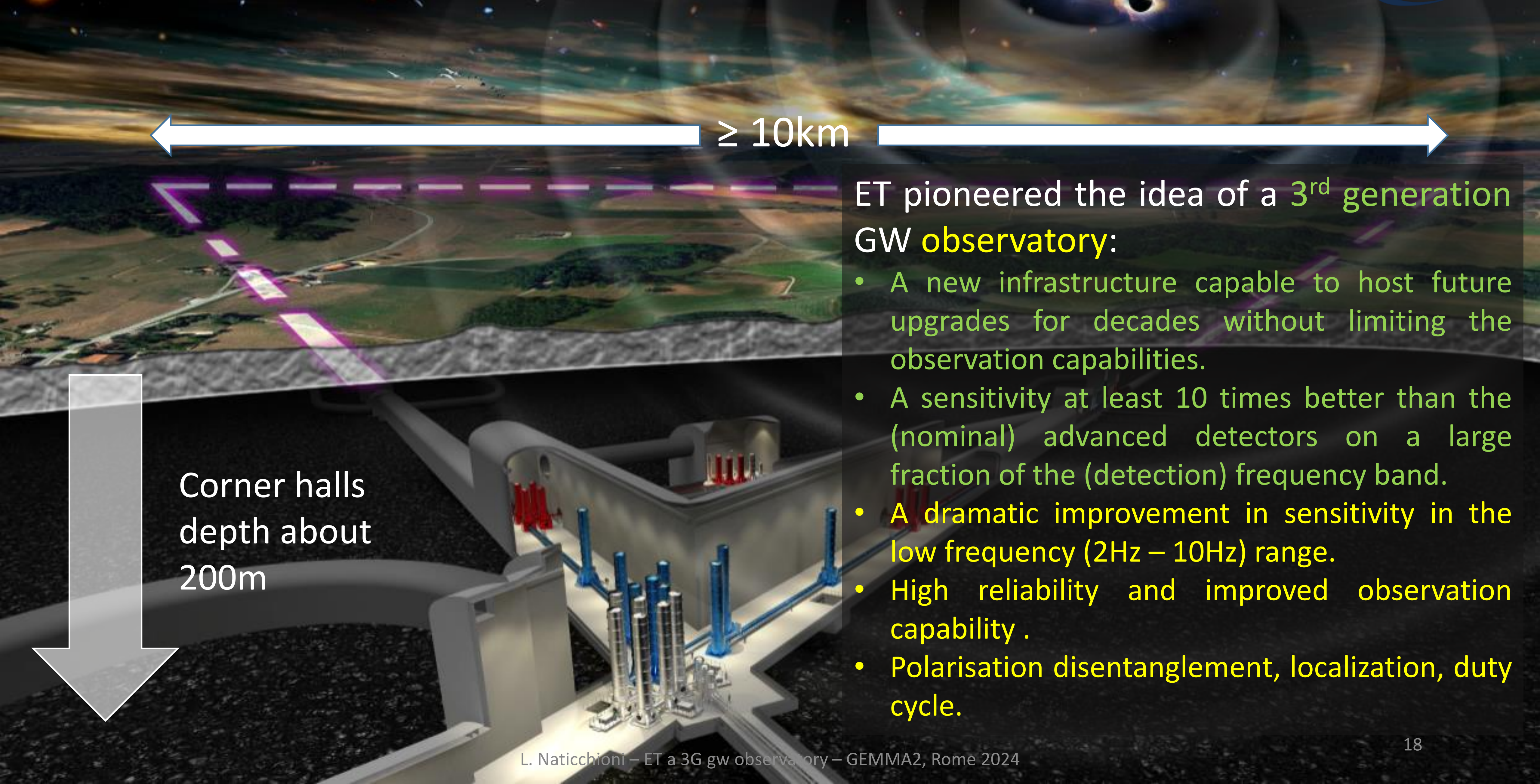
ET: a 3G GW Observatory

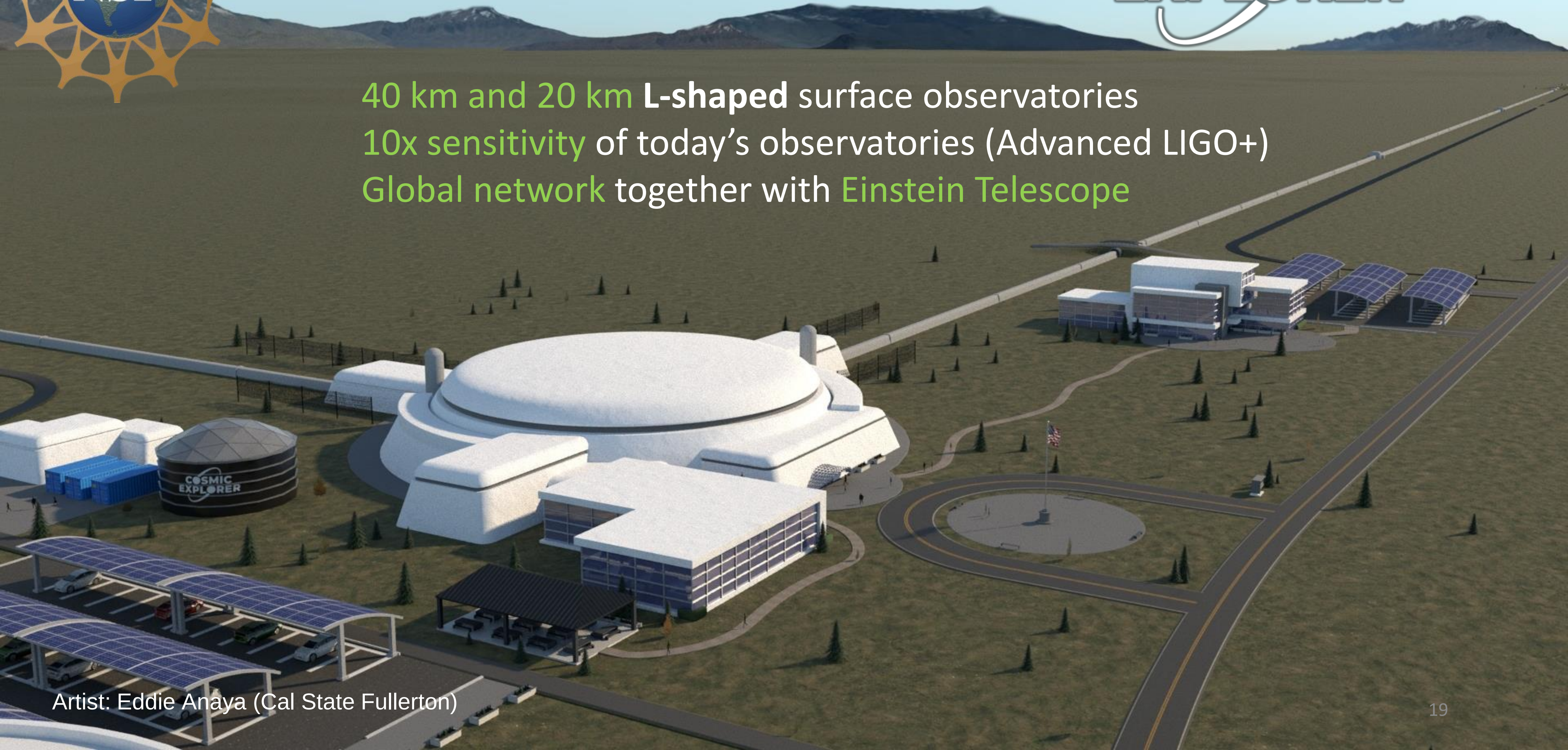


ET pioneered the idea of a 3rd generation GW observatory:

- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities.
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band.
- A dramatic improvement in sensitivity in the low frequency (2Hz – 10Hz) range.
- High reliability and improved observation capability .
- Polarisation disentanglement, localization, duty cycle.

ET will be not alone…

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



Artist: Eddie Anaya (Cal State Fullerton)

Design of ET

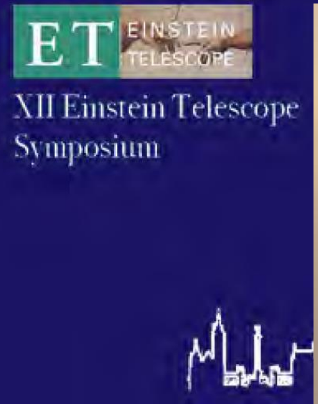
2004-3G idea
2005-ET idea
2007-ET CDR proposal
2011-ET CDR
2012-2018 Tech development (in background)
2020-ESFRI ET proposal

ESFRI proposal (2020)

2021-ET in the ESFRI 2021 roadmap!

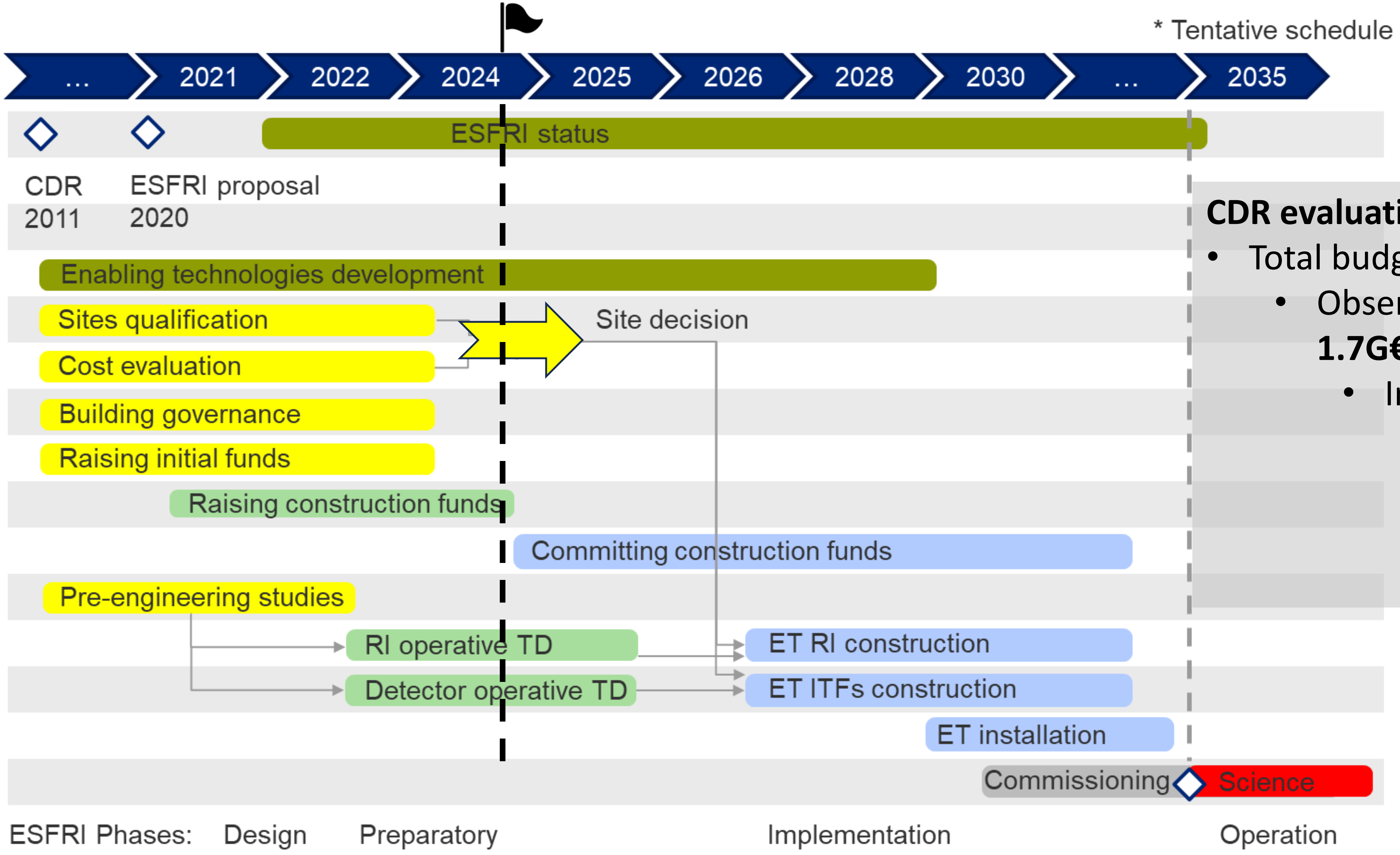
ET Collaboration formed June 2022

https://indico.ego-gw.it/event/411/



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

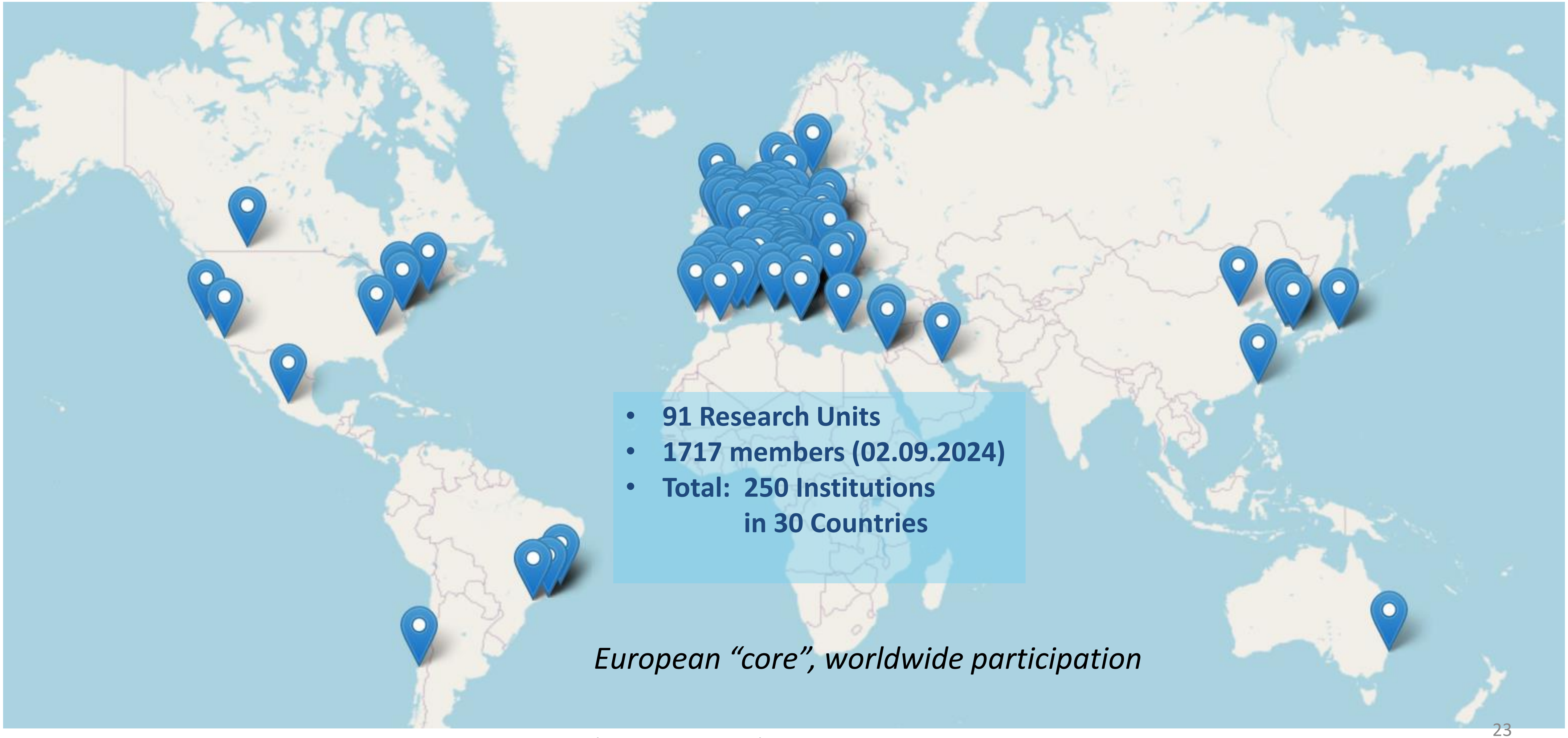
ET timeline as presented to ESFRI



CDR evaluations:

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

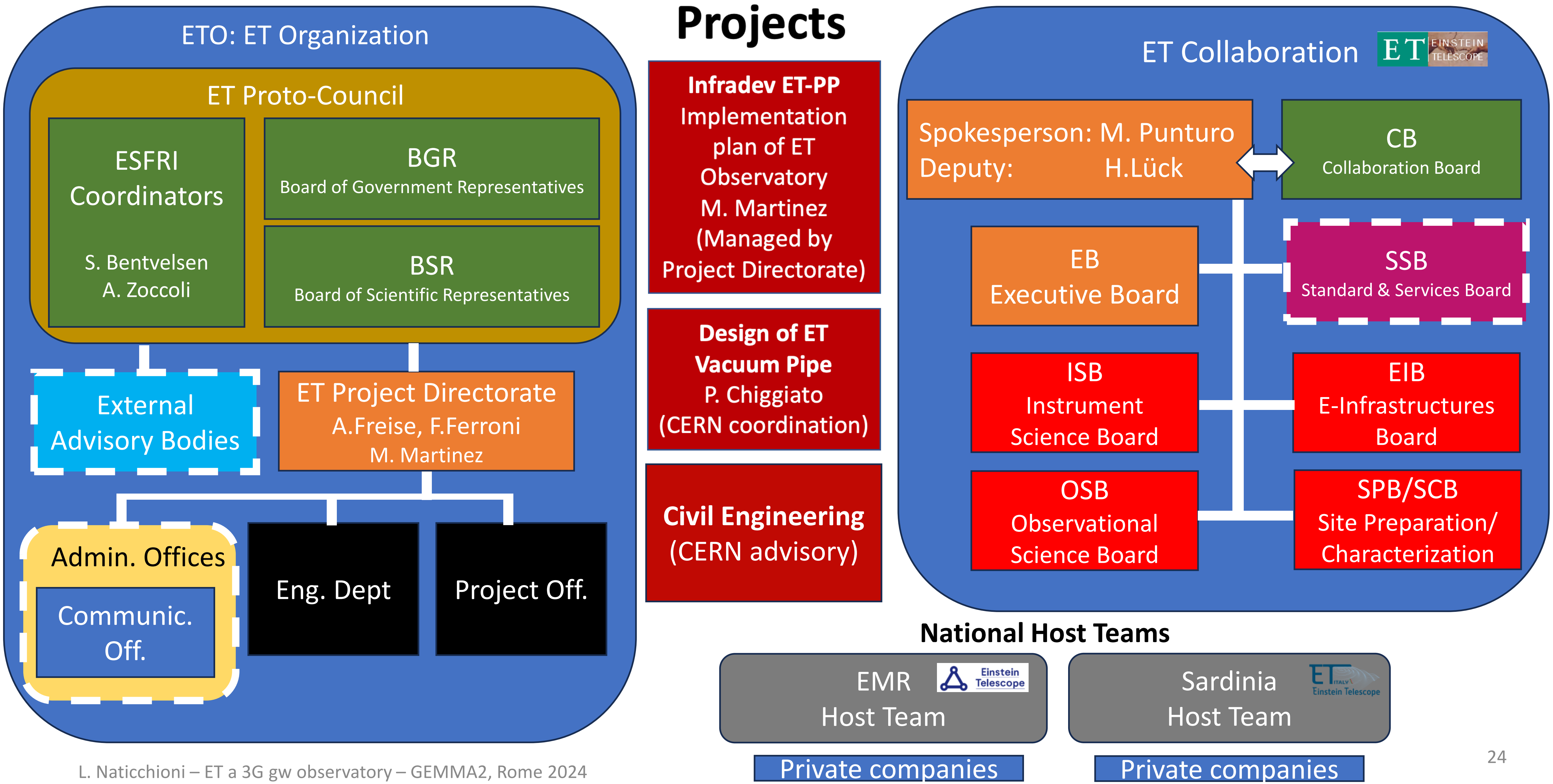
ET Collaboration

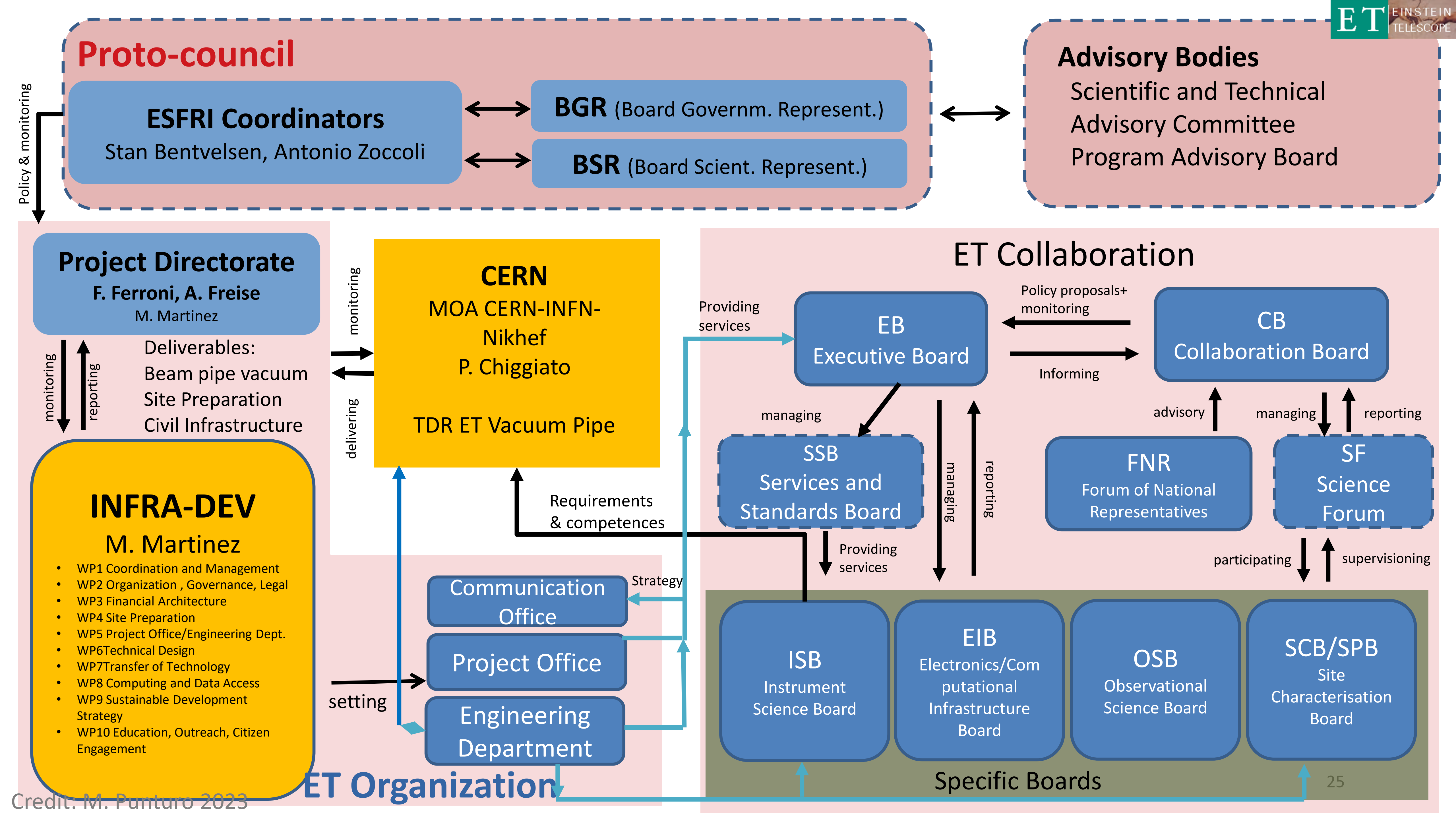


- **91 Research Units**
- **1717 members (02.09.2024)**
- **Total: 250 Institutions in 30 Countries**

European "core", worldwide participation

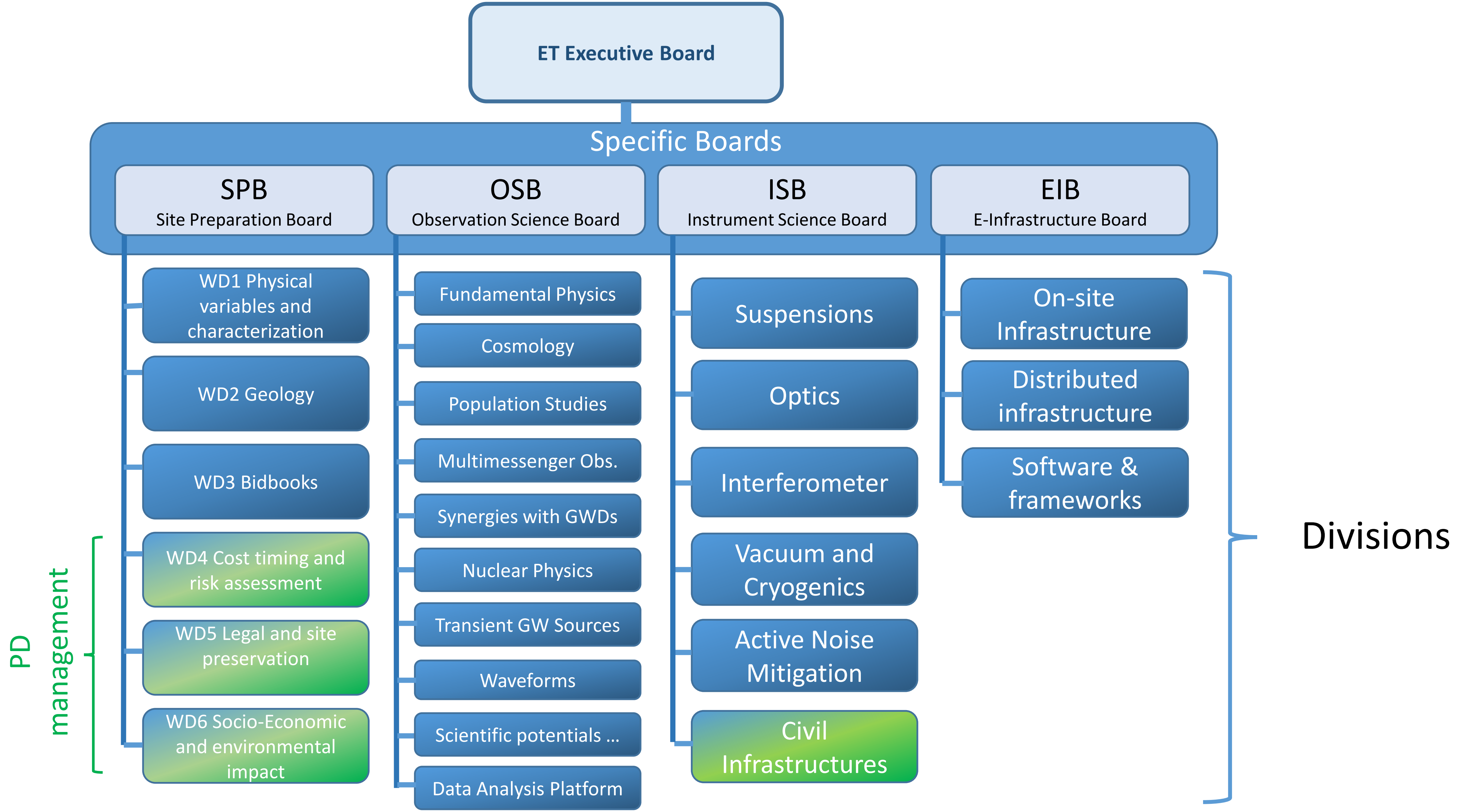
ET Framework





Proto-council
ESFRI Coordinators
Stan Bentvelsen, Antonio Zoccoli
BGR (Board Governm. Represent.)
BSR (Board Scient. Represent.)
Advisory Bodies
Scientific and Technical
Advisory Committee
Program Advisory Board
Policy & monitoring
Project Directorate
F. Ferroni, A. Freise
M. Martinez
monitoring
reporting
Deliverables:
Beam pipe vacuum
Site Preparation
Civil Infrastructure
monitoring
delivering
CERN
MOA CERN-INFN-Nikhef
P. Chiggiato
TDR ET Vacuum Pipe
Requirements & competences
INFRA-DEV
M. Martinez
WP1 Coordination and Management
WP2 Organization , Governance, Legal
WP3 Financial Architecture
WP4 Site Preparation
WP5 Project Office/Engineering Dept.
WP6Technical Design
WP7Transfer of Technology
WP8 Computing and Data Access
WP9 Sustainable Development Strategy
WP10 Education, Outreach, Citizen Engagement
Communication Office
Strategy
Project Office
setting
Engineering Department
ET Organization
ET Collaboration
Providing services
EB
Executive Board
Policy proposals+ monitoring
Informing
CB
Collaboration Board
managing
SSB
Services and Standards Board
managing
reporting
advisory
managing
reporting
FNR
Forum of National Representatives
SF
Science Forum
Providing services
participating
supervisioning
ISB
Instrument Science Board
EIB
Electronics/Computational Infrastructure Board
OSB
Observational Science Board
SCB/SPB
Site Characterisation Board
Specific Boards
Credit: M. Punturo 2023

ET Specific Boards



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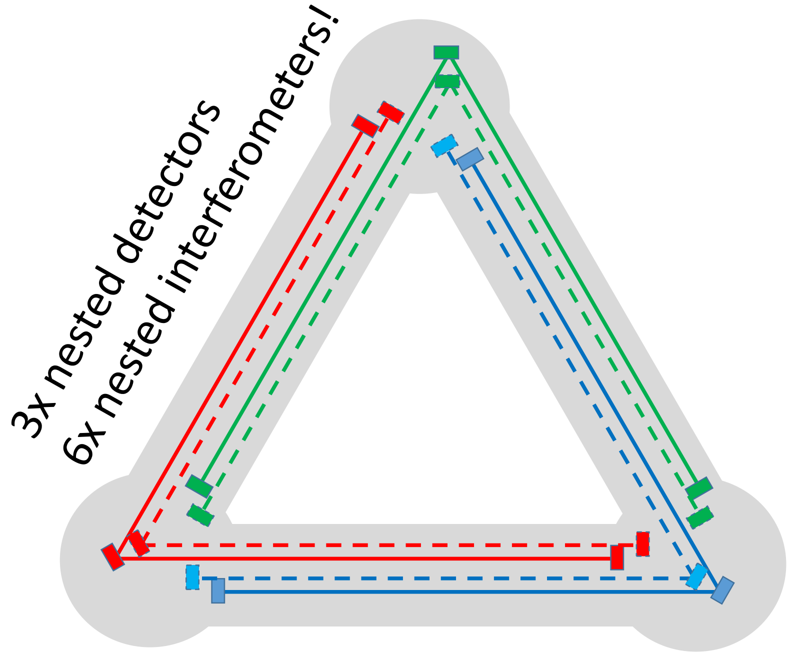
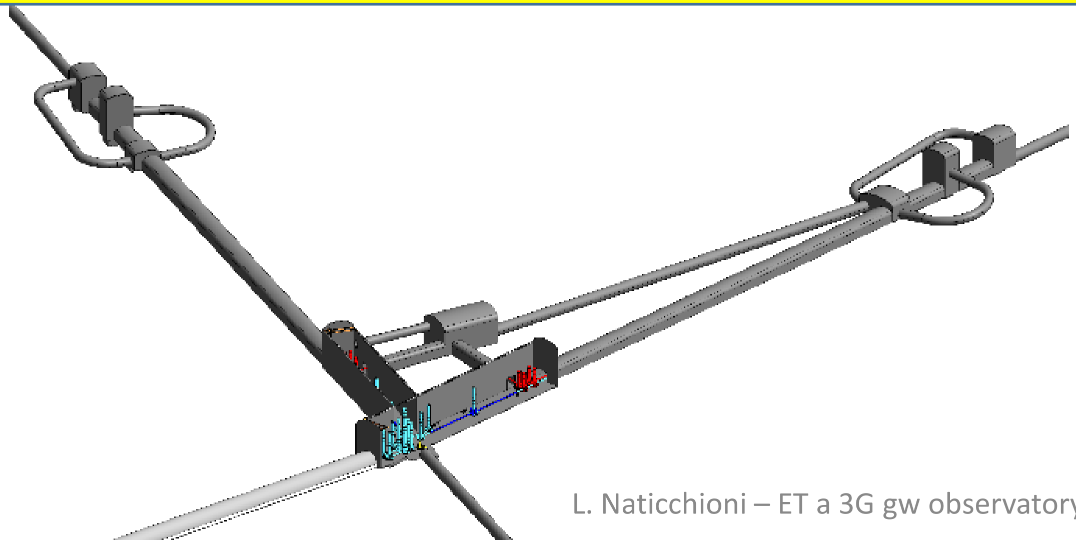
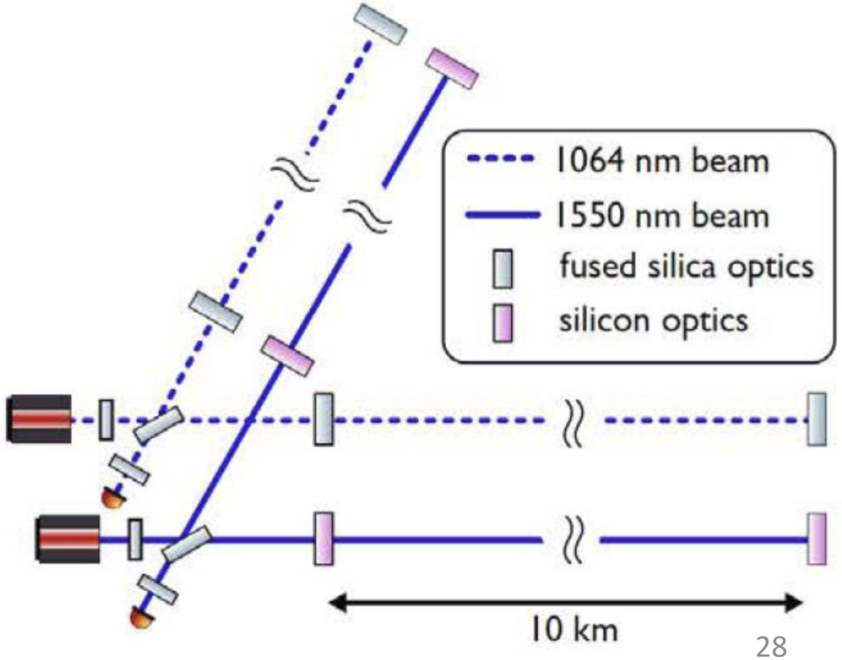
ET: Key elements

Requirements	Design Specifications
• Wide frequency range • Massive black holes (LF focus) • Localisation capability • (more) Uniform sky coverage • Polarisation disentanglement • High Reliability (high duty cycle) • High SNR	• Xylophone (multi-interferometer HF+LF) Design • Underground • Cryogenic (LF) • 1 “Triangle” or 2 “L” • Multi-detector design • Longer arms (≥10km)







ET Enabling Technologies

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

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

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

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

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

Evolved laser technology

Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

Credit: M. Punturo 2023

ET – Low Frequency challenge

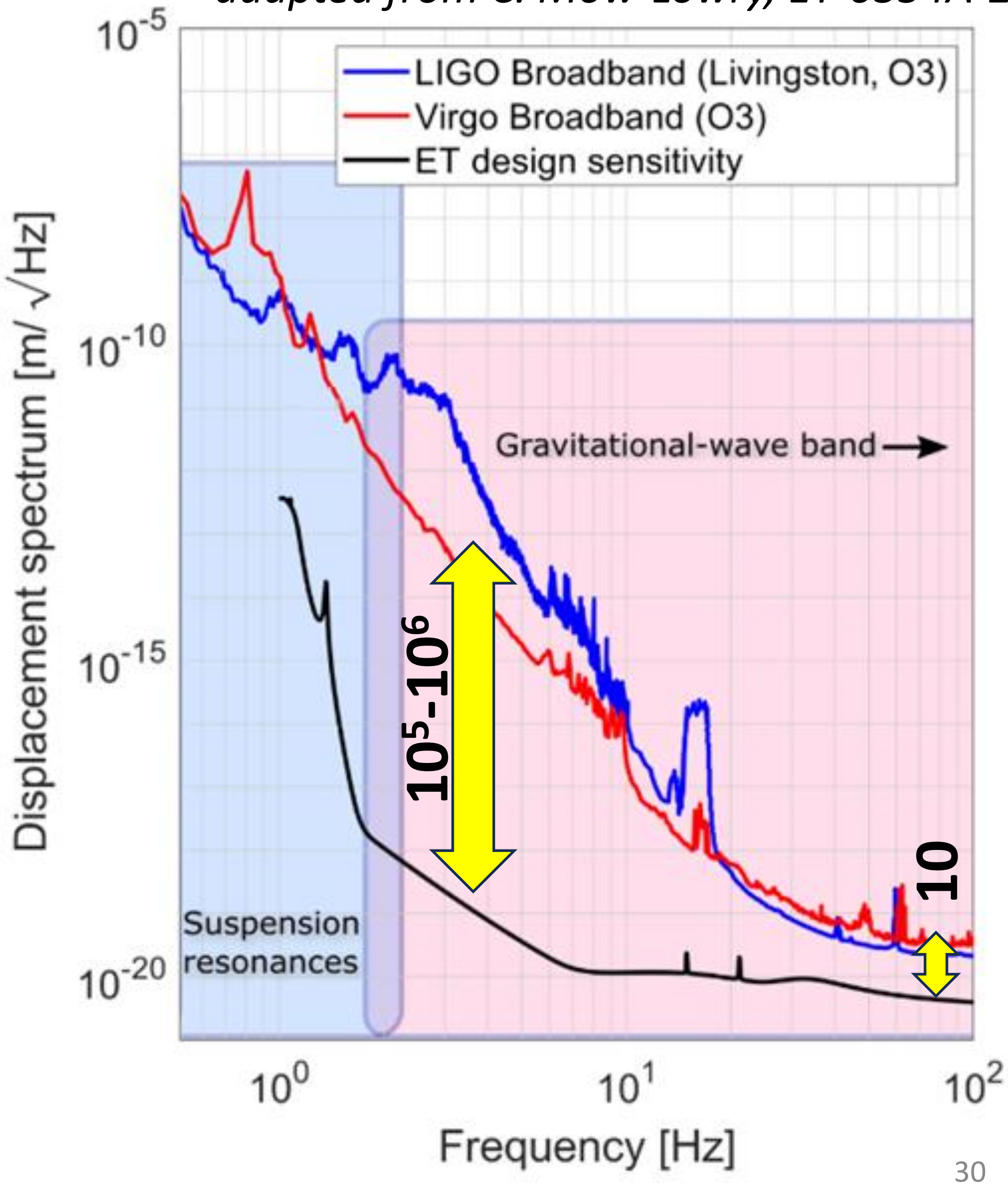
ET target sensitivity will be on average **10x** wrt to current GW detectors...

BUT

2-10 Hz band, that is crucial for ET, requires a dramatic improvement: $10^5 - 10^6$!

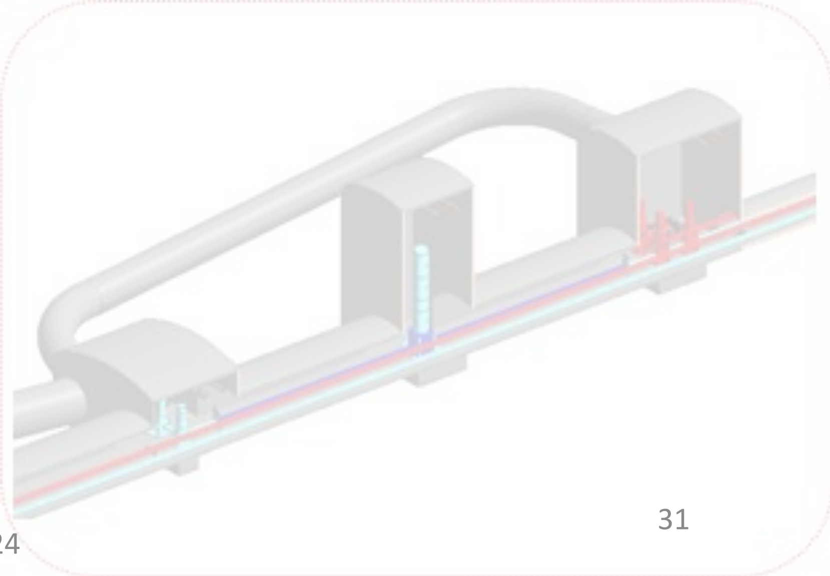
- start from a low-noise site
- apply mitigation strategies
- learn from 2G detectors

adapted from C. Mow-Lowry, ET-0354A-23



Challenging Engineering: key points

- **~30km of underground tunnels** (10km Δ or 15km L configuration)
  - Safety (fire, cryogenic gasses, escape lanes, heat handling during the vacuum pipe backing)
  - Noise (creeping, acoustic noise, seismic noise, Newtonian noise)
  - Minimisation of the volumes, but preservation of future potential)
  - Water handling, hydro-geology and tunnels inclination
  - Cost!
- **Large caverns**
  - In addition to the previous points:
  - Stability
  - Cleanliness
  - Thermal stability
  - Ventilation and acoustic noise



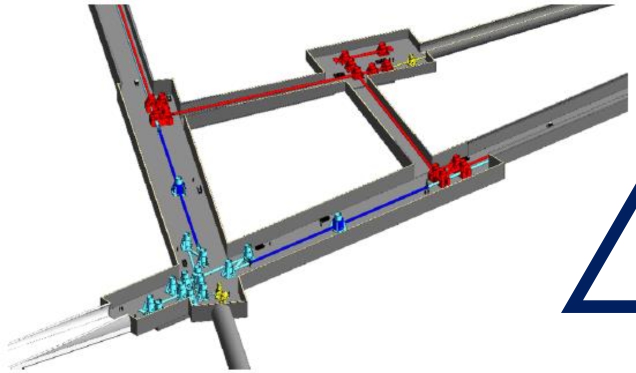
ET design: Δ or 2L

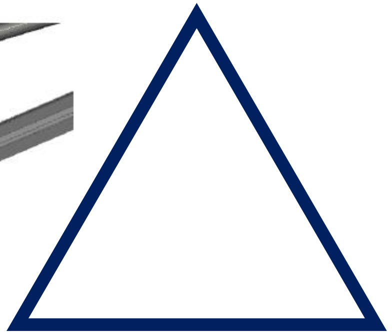
In the last ~3 years, the collaboration started the evaluation of the best configuration for ET, considering the alternative of two L configuration (as LIGO, Cosmic Explorer) to maximize the science return and reduce risks.

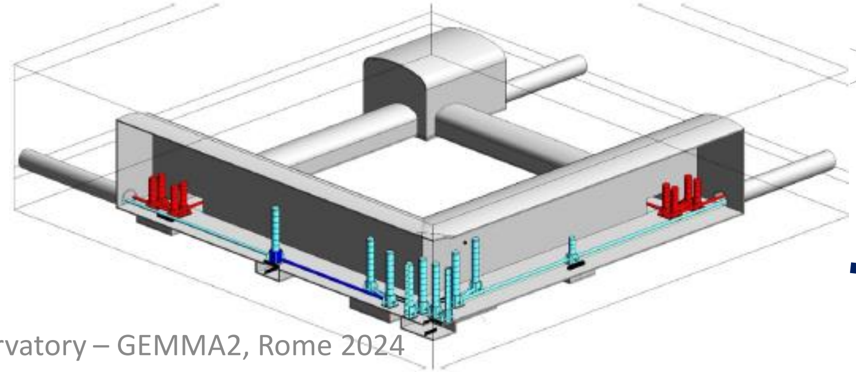
Since 2011 (CDS, triangle configuration) the situation drastically changed:

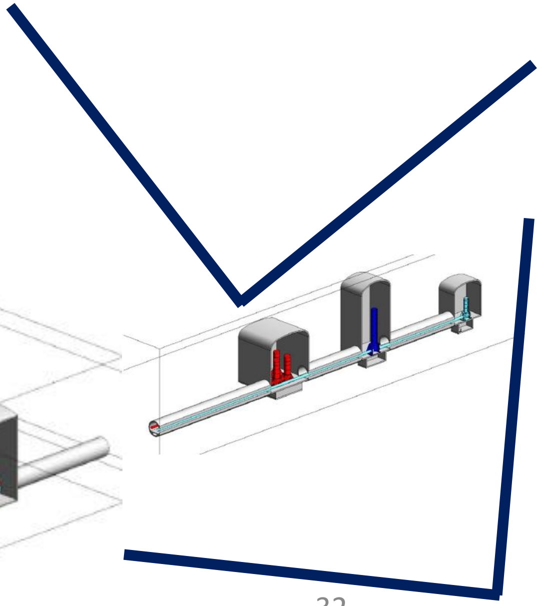
- ❑ First detections, GTWC-3 catalog, O4… → BH population → new SF and evolution models;
- ❑ Science case developed;
- ❑ Know-how with advanced (L) detectors;
- ❑ Risk & costs ∝ layout complexity;
- ❑ International scenario (+ Cosmic Explorer in US);
- ❑ Two candidate sites strongly supported (and a potential third site…).

The collaboration is analyzing both configurations: **science case**, **risk assessment.**









ET design: Δ or 2L : science case

The **science case** for different ET designs has been studied by a dedicated committee (the Cost Benefit Analysis, CoBA).

Impressive work resulted in a detailed report of 197 pages (ET-0084A-23) and a published paper:
M. Branchesi *et al* JCAP07(2023)068, doi:10.1088/1475-7516/2023/07/068

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Science with the Einstein Telescope: a comparison of different designs

ET design: Δ or 2L : risk assessment

The **risk evaluation** for different ET layouts has been studied by a dedicated committee (the ET Risk Assessment Committee, ETRAC), composed of experts in GW interferometer commissioning (Virgo, LIGO, GEO600).

The committee duty is to evaluate and compare the integration, commissioning, science and operation risks of the different ET configurations studied in the CoBA-Science document.
Political and financial risks are NOT considered in the study!

A detailed report (45 pages) is under review of the ET Executive Board and will be released soon

Likelihood \ Severity	Negligible	Minor	Moderate	Significant	Severe
Very Likely	Low Med	Medium	Med Hi	High	High
Likely	Low	Low Med	Medium	Med Hi	High
Possible	Low	Low Med	Medium	Med Hi	Med Hi
Unlikely	Low	Low Med	Low Med	Medium	Med Hi
Very Unlikely	Low	Low	Low Med	Medium	Medium

ET design: Δ or 2L

Based on the COBA and ETRAC studies of all the possible configurations, two of them are currently under consideration in the ET collaboration:

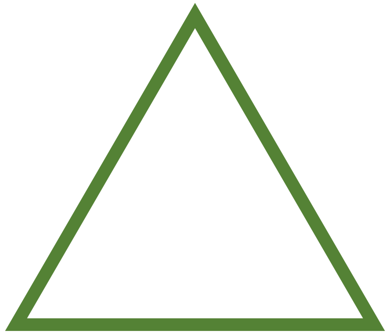
- **Triangle, 10km-long arms** (original baseline of ET) → one site.
- **2L, 15km-long arms** at 45° wrt local north → two sites.

*In general, **2L** option seems better for several aspects, but the discussions and evaluations considering **all the concerned aspects** and **mitigation strategies** will continue at higher level (funding agencies, government representatives, etc) to define the definitive baseline and hosting site(s) in the next few years.*

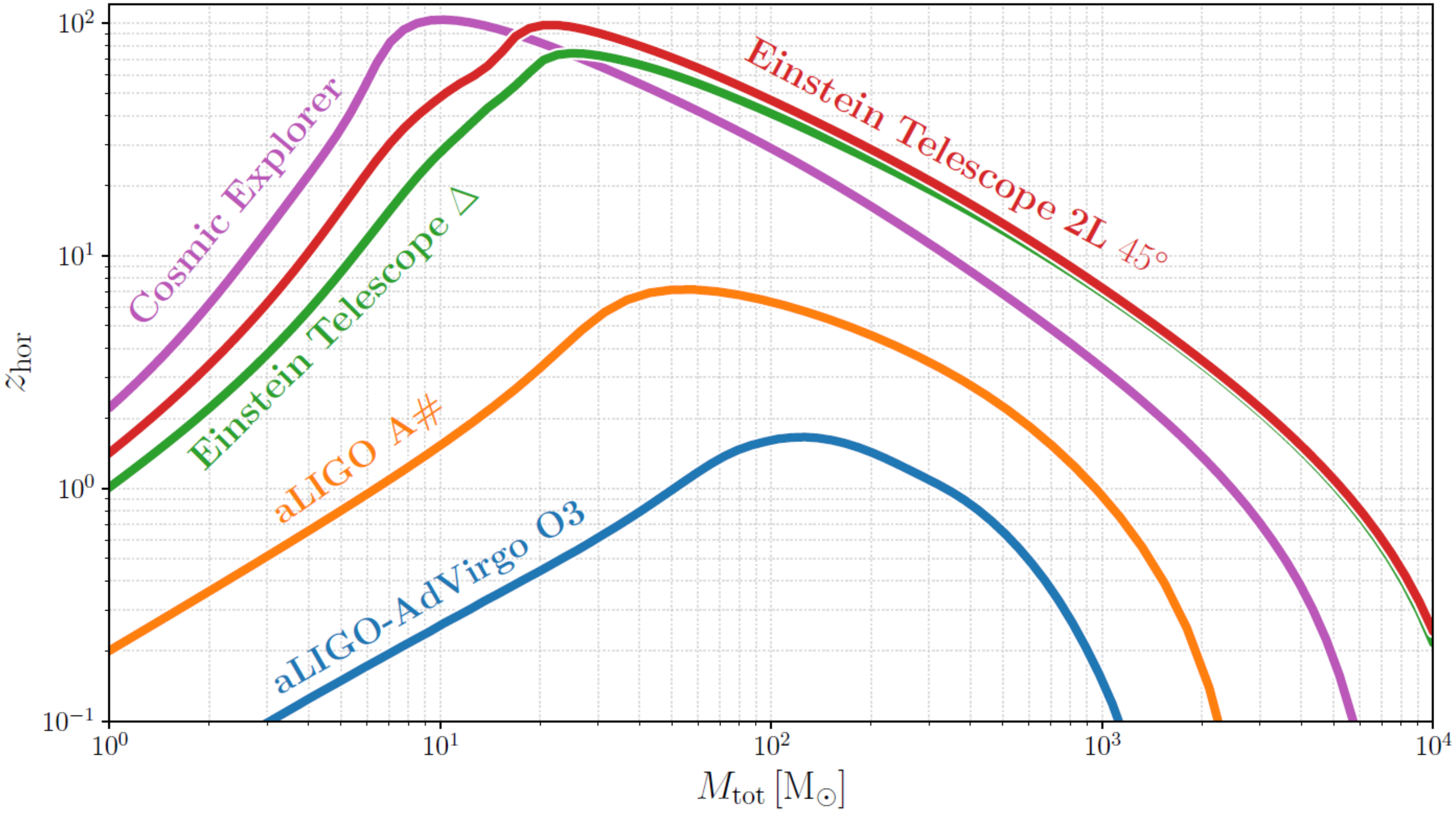
ET design: Δ or 2L

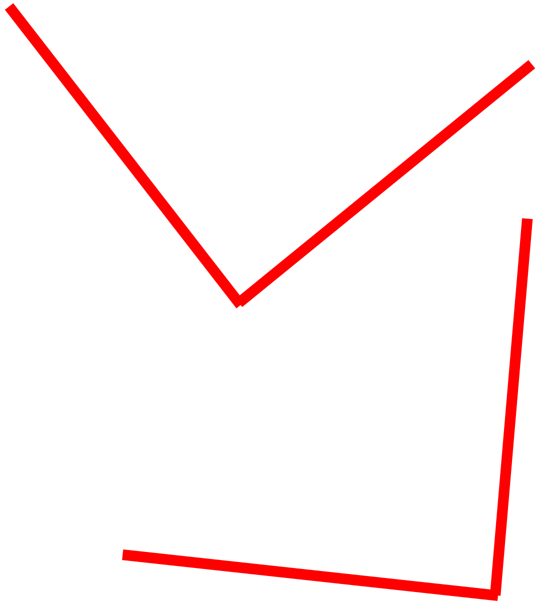
Whatever the chosen configuration, **ET will make a great leap forward** compared to 2G detectors!

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



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





Summary

- ❑ From 2G to 3G gravitational wave detectors
- ❑ The ET collaboration
- ❑ A 3G GW observatory
- ❑ **The ET site(s)**
- ❑ Conclusions

ET - Candidate Sites

- Two sites officially candidate to host ET:
  - **EMR** EUregio, border region between Nederland, Belgium and Germany
  - **Sardinia** (Sos Enattos - Lula area, Barbagia)
- A third potential site is located in Saxony (Lusatia), *still not official*
- Overall site evaluation is a complex task depending on:
  - Geophysical and environmental quality
  - Financial and organization aspects
  - Services, infrastructures
- Ongoing measurements to evaluate the seismic (→NN), magnetic, acoustic (→NN) noise

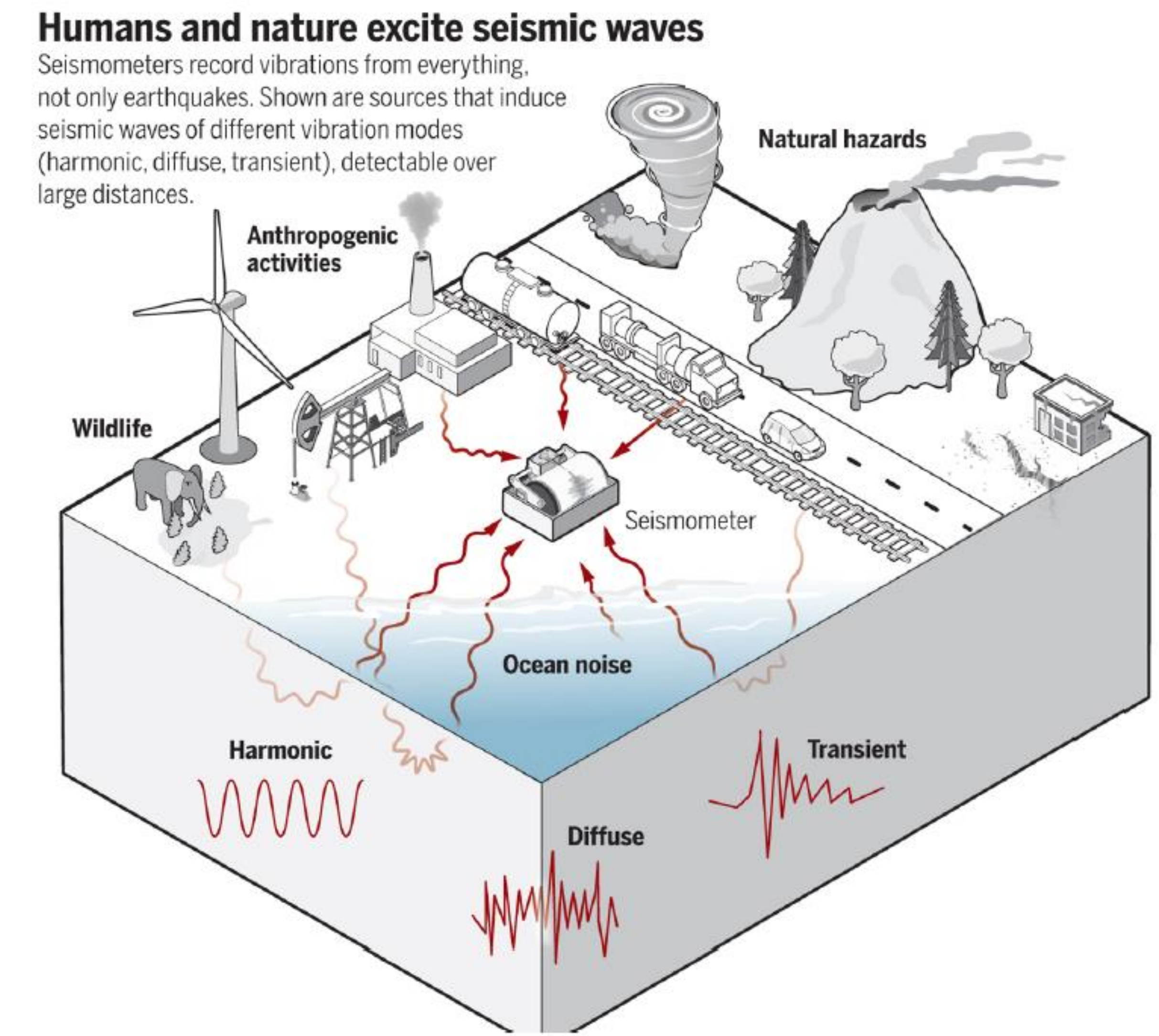
Understanding the noise contributions

- ET will be much more **susceptible to environmental noise** with respect to 2G detectors (LIGO, Virgo).

- For ET the characterization of environmental (in particular, seismic) noise sources at **low frequency** (<20Hz) is paramount.

- Understanding the **sources of seismic noise** provides crucial information to design and adapt the detector **noise mitigation** and its **control systems**.

- Since ET will be an **underground** observatory, we are interested in measuring noise underground (in former mines, boreholes, ~250m is a representative depth).



ET - Candidate Sites

- Strong support from local/national governments for hosting ET at both sites!
  - ~ 900M€ by Netherlands for the EMR site option.
  - ~ 950M€ by Italy (+300M€ by Sardinia local gov.) for the Sardinia site option.

More than 900 million euros for Einstein Telescope

42 million for the preparations and 870 million for when the installation is actually built in Limburg

14-04-2022 · News

MAASTRICHT. The Dutch government is investing in the Einstein Telescope: almost 1 billion. The money, from the National Growth Fund, is partly for the preparations (42 million) and partly a reservation for when the installation is actually built in the Heuvelland (870 million). That is still uncertain; the decision will be made in 2025 whether the gigantic project will be awarded to South Limburg or Sardinia.

28 DECEMBER 2023

THE ITALIAN GOVERNMENT STRENGTHENS THE EINSTEIN TELESCOPE CANDIDACY

The Italian Government is ready to support the financial commitment required to host the Einstein Telescope (ET), the large research infrastructure dedicated to the study of gravitational waves that Italy has proposed to build in Sardinia, in the area of Sos Enattos, in Lula.

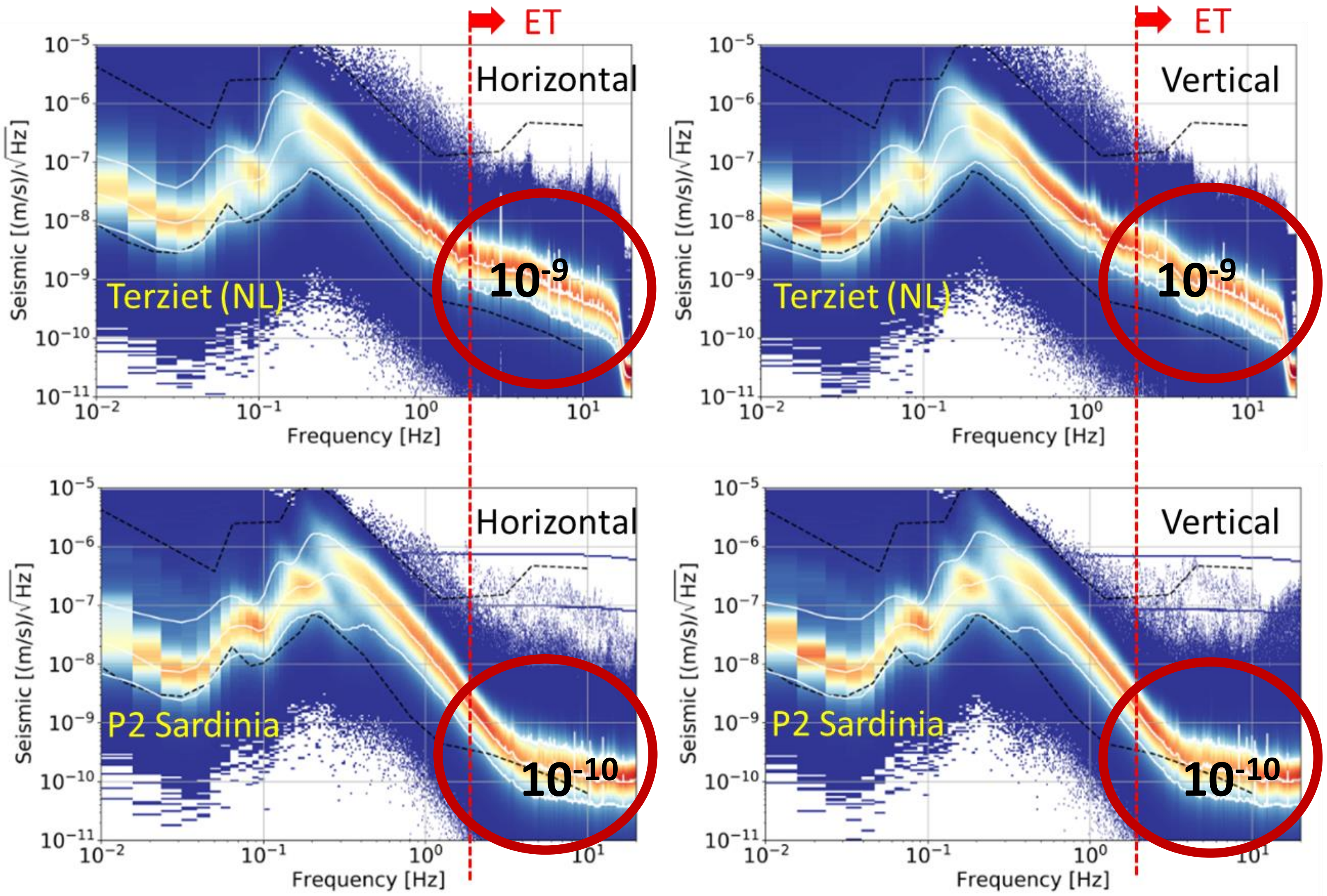
The government has expressed its commitment, both institutional and financial, to strengthen our country's candidacy for ET in a letter addressed to Antonio Zoccoli, the President of the

- Currently, contracts started at the two sites with the aim of providing geotechnical and geophysical evaluation of the ET infrastructure (preparatory for the engineering design of the infrastructure at the sites).
  - ~ 2M€ contract in Netherlands (EMR site).
  - ~ 12M€ contract in Italy (Sardinia site).

ET EINSTEIN TELESCOPE

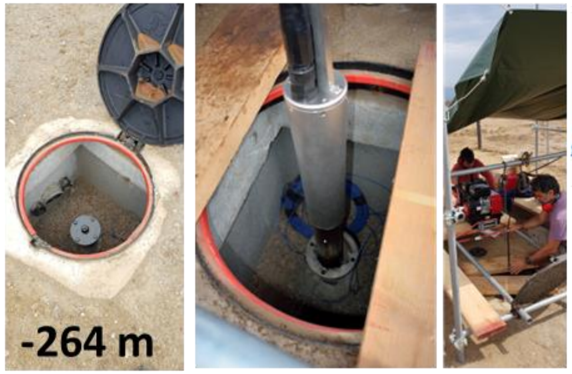
ET - Candidate Sites

Borehole seismic data (1yr)



EMR Terziet (NL) borehole

Sardinia P2 borehole



ET - Candidate Sites

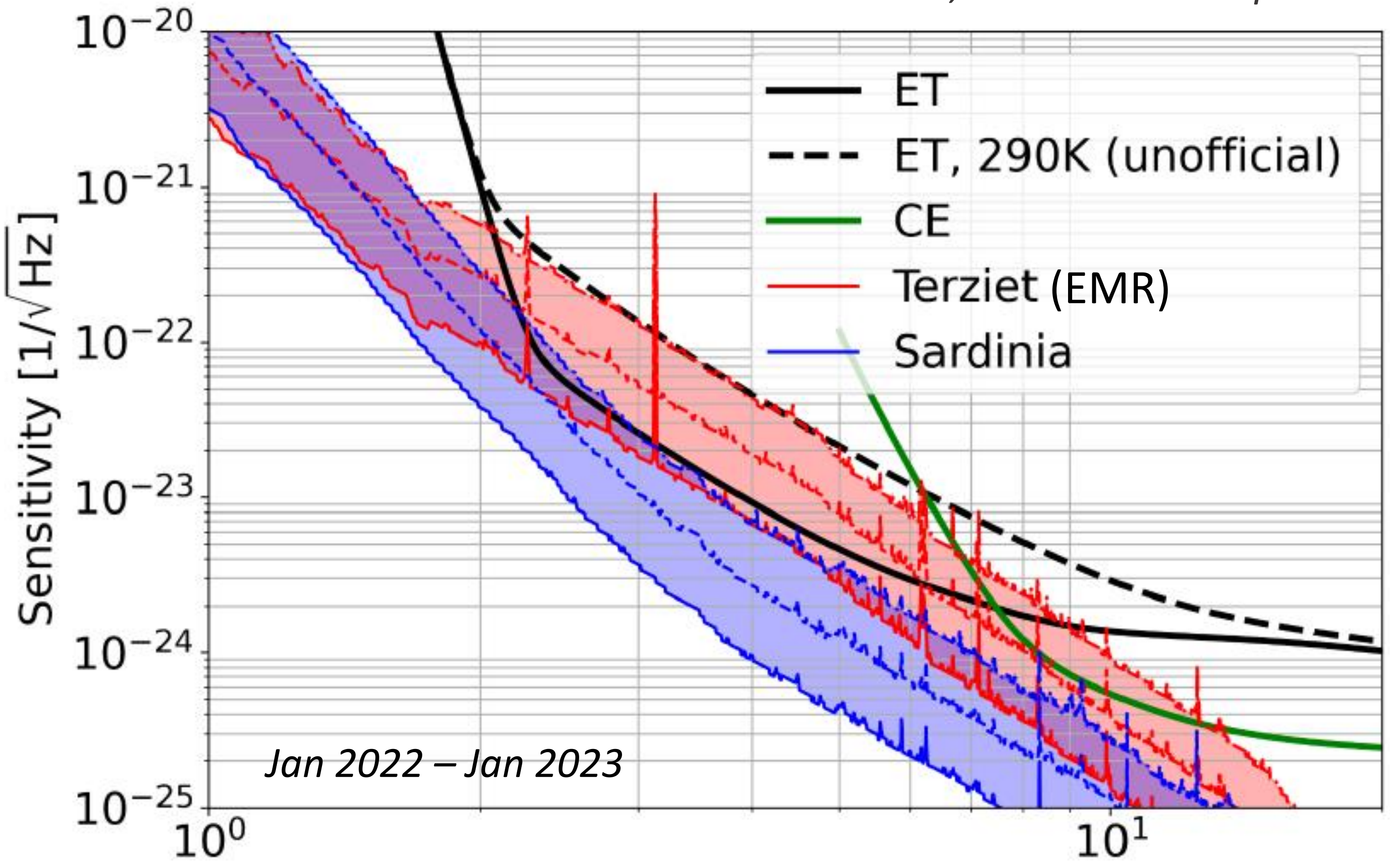
Seismic Newtonian Noise projections for LF sensitivity

J.Harms, ET-SPB workshop 2023

Defining the Newtonian Noise ASD as:

$$\tilde{h}_{NN}(f) = \frac{4\pi}{3} G\rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f)$$

seismic noise displacement ASD



Conclusions

- **ET** will be a **3G GW Observatory**, and it will be able to extend the detection horizon to the whole observable universe: routine (Multimessenger) 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** under study: **10km-long triangle** and **15km-long (double) L**, new science case released by the COBA committee considering different configurations.
- **ET** intl. **Collaboration**: 250 institutions, 30 countries, 1717+ members, still growing!
- **Two sites officially candidate** to host the infrastructure(s): **EMR** (NL, BE, GE) and **Sardinia** (Italy), **large financial support for both** sites by host countries.
- **Extensive site characterization** studies **ongoing** at the 2 (+1) candidate sites.

Thank you for your attention!

Any question?