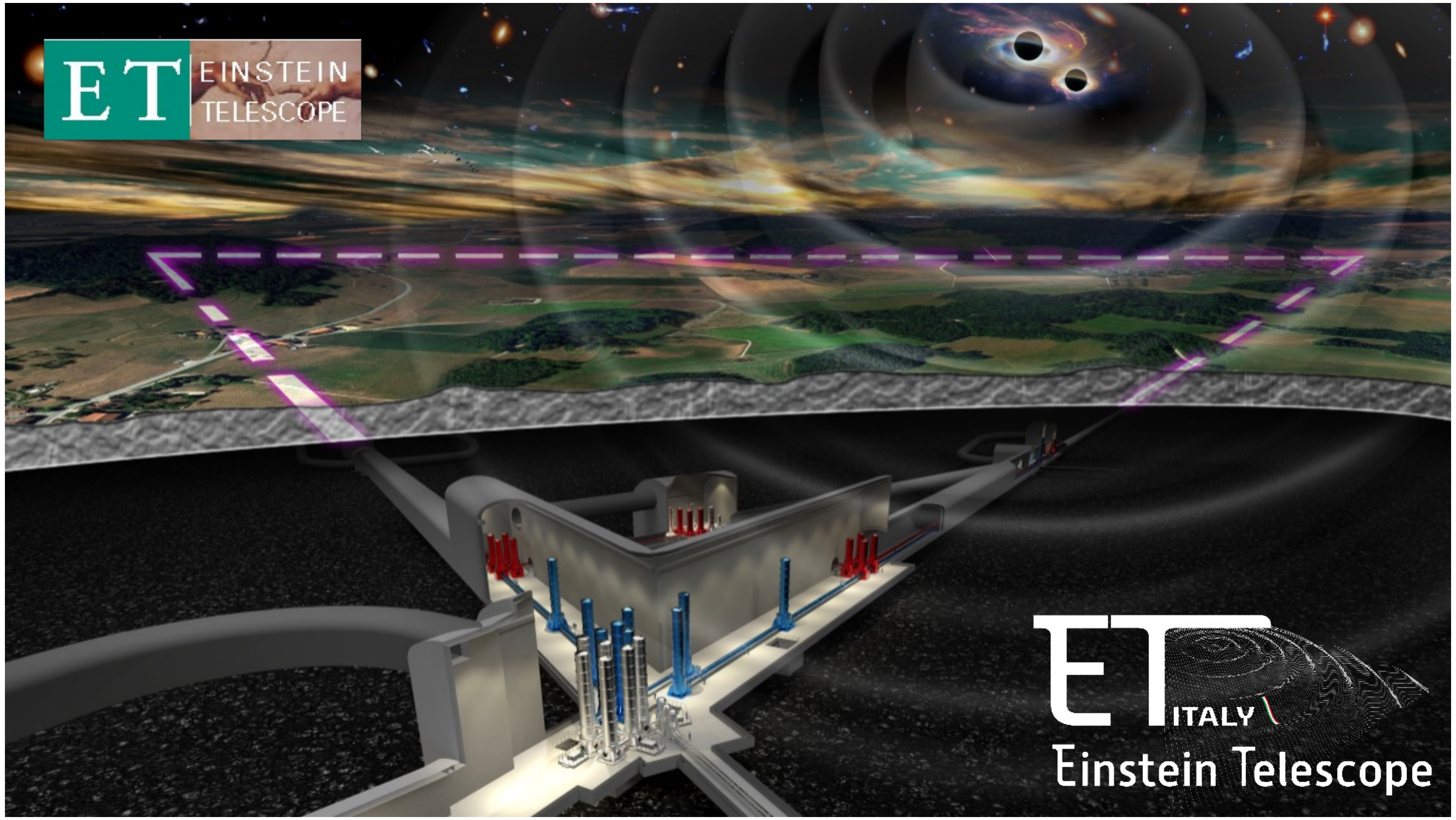
Einstein Telescope:
l'infrastruttura europea per un osservatorio di onde gravitazionali di futura generazione



Michele Punturo

INFN

ConfGARR23

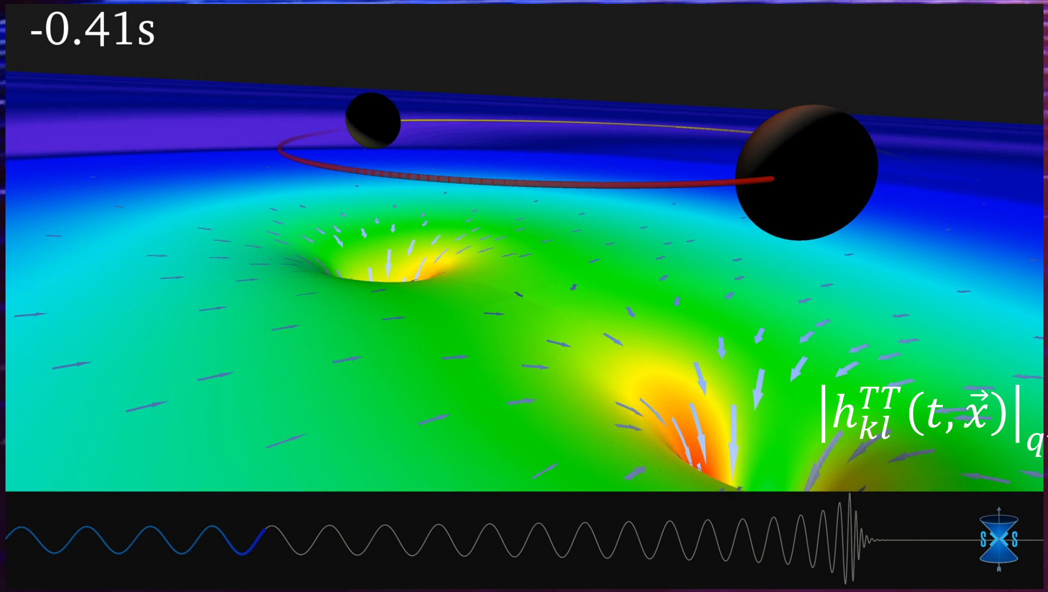
SAPERI INTERCONNESSI

Onde Gravitazionali

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

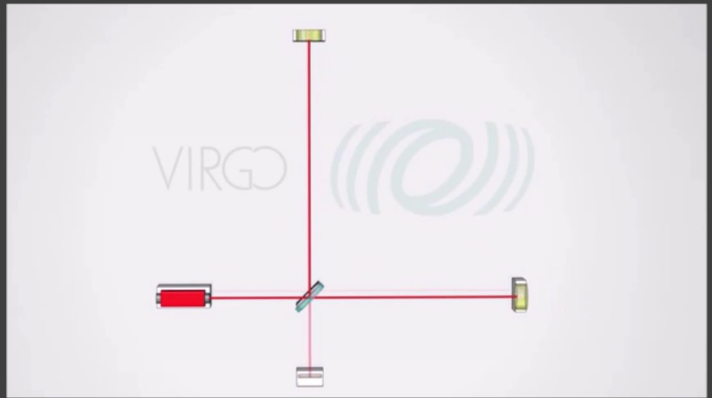
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left(-\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2 \right) \bar{h}_{\mu\nu} = 0$$

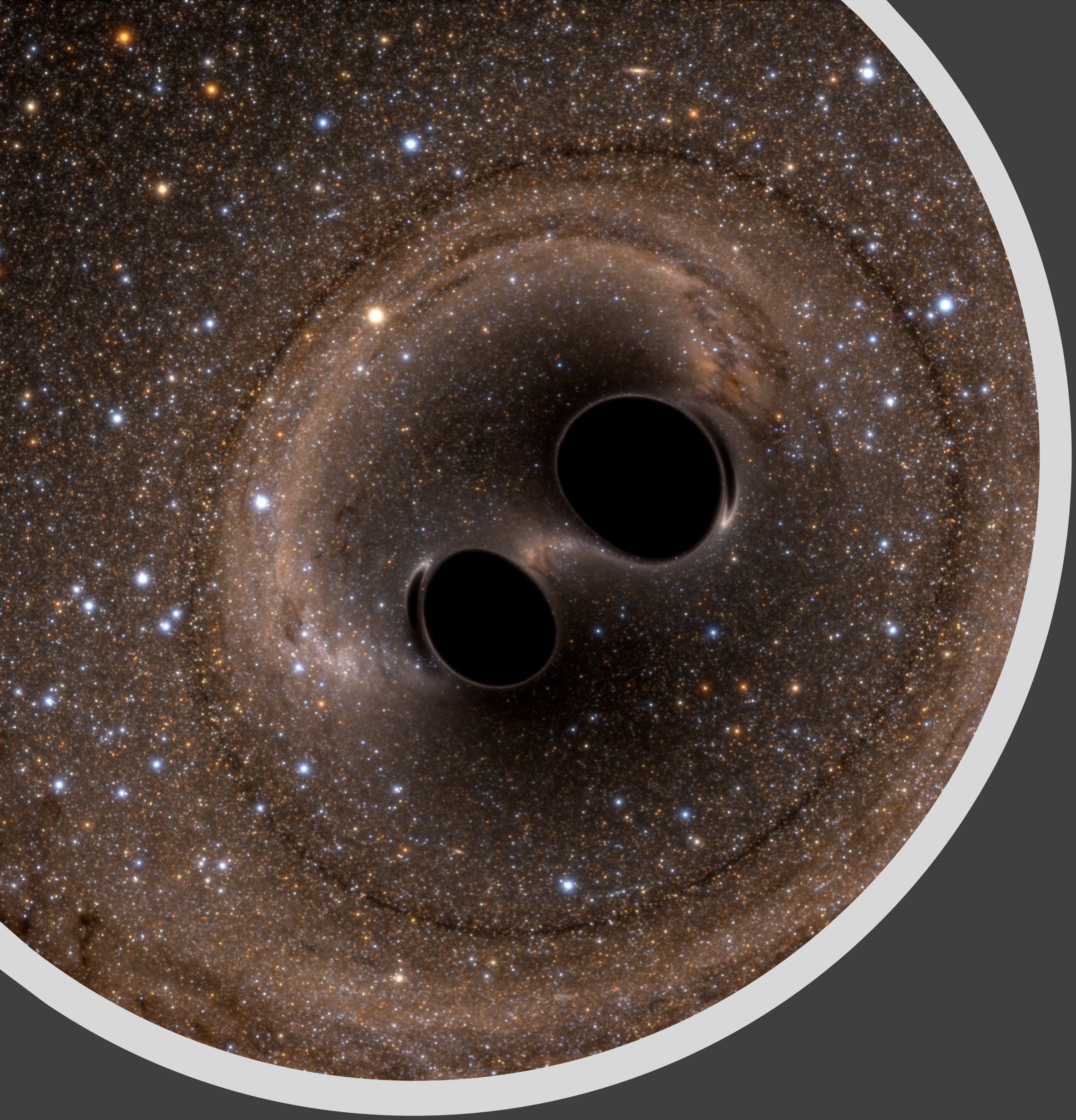
- Previsione della teoria della Relatività Generale di Einstein
- Sono onde di curvatura dello spazio-tempo che si propagano alla velocità della luce nell'Universo trasportando, come un messaggero inarrestabile, le informazioni più intime di fenomeni catastrofici come la collisione di Buchi Neri o di stelle di neutroni o del Big Bang stesso



$$\left| h_{kl}^{TT}(t, \vec{x}) \right|_{quad} = \frac{1}{r} \frac{2G}{c^4} \frac{1}{3} \ddot{Q}_{kl}^{TT} \left(t - \frac{r}{c} \right)$$

Rivelatori attuali di onde gravitazionali

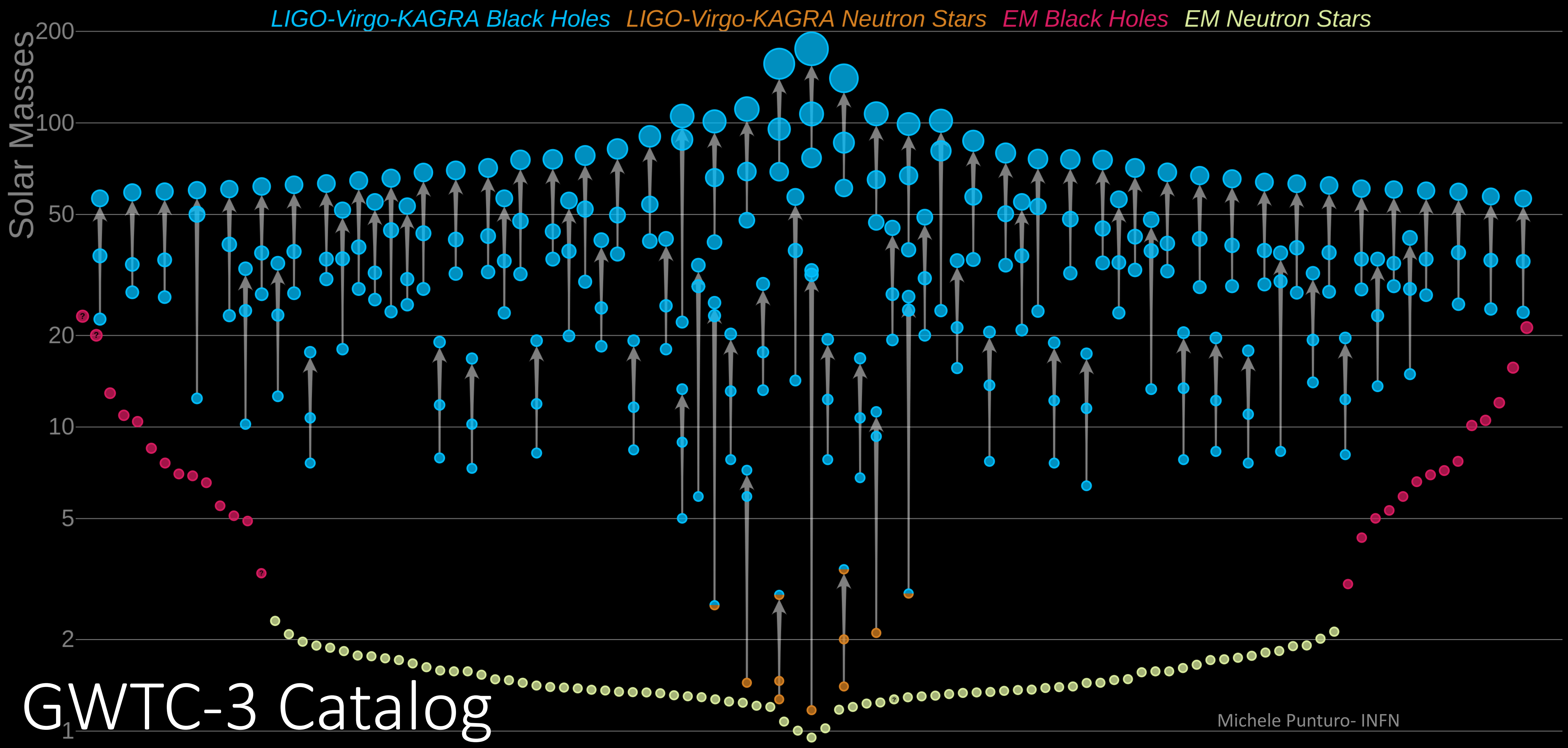




Monumental successes of the Advanced detectors

- First detection of GWs from a BBH system (GW150914)
  - Physics of BHs
- First detection of GWs from a BNS system (GW170817)
  - Birth of the multimessenger astronomy with GWs
  - Costraining EOS of NS
- Localisation capabilities of a GW source
- Measurement of the GW propagation speed
- Test of GR
- Alternative measurement of H_0
- GW polarisations
- Intermediate mass black hole (GW190521)

Masses in the Stellar Graveyard



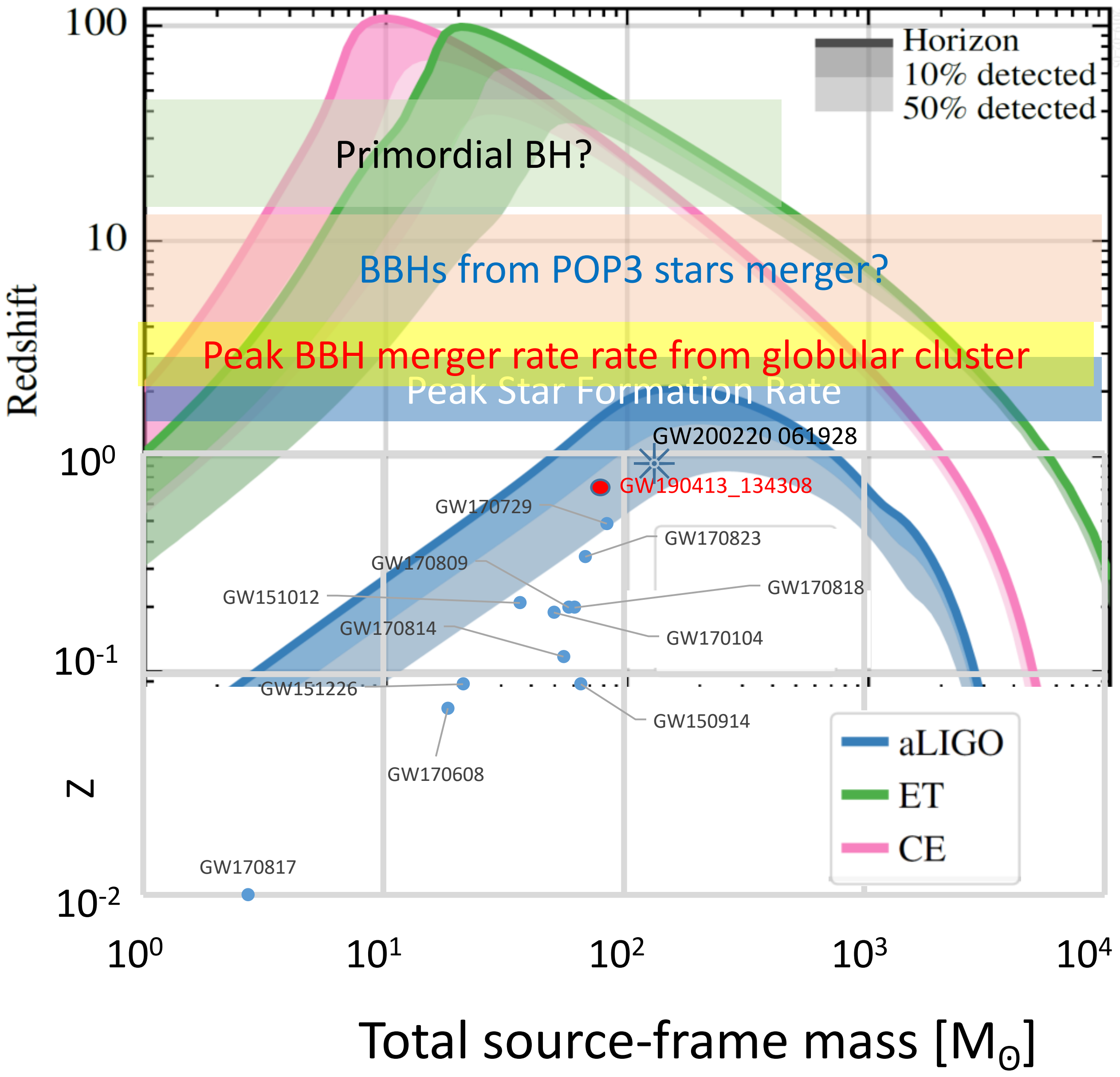
GWTC-3 Catalog

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

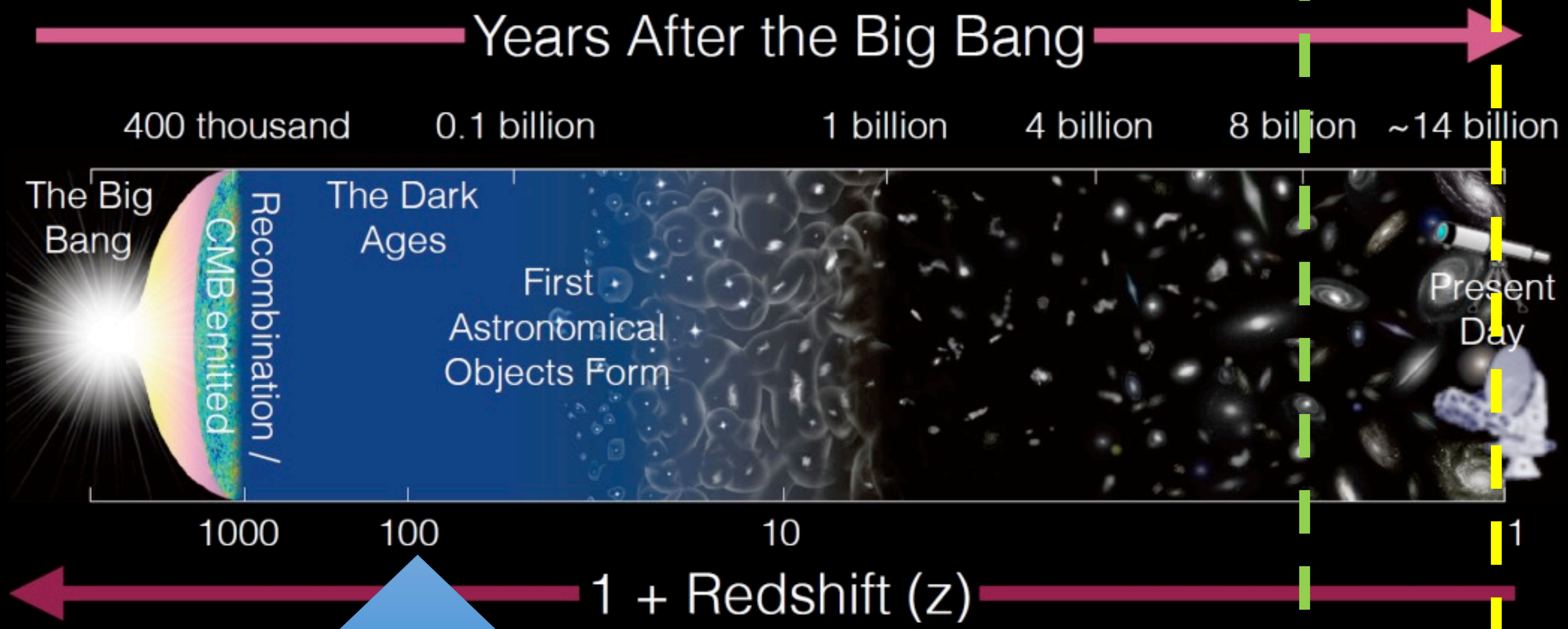
OK, all done?

- aLIGO and AdV achieved awesome results with a sensitivity below the nominal one
- O4 run, including the Advanced LIGO, Advanced Virgo and KAGRA detectors is starting now
- Current detectors have a well defined plan of upgrades and science runs
- When they will reach or over-perform their nominal (updated) sensitivity can we exploit all the potential of GW observations?

- 2nd generation GW detectors will explore the local Universe, even in their post-O5 configuration, initiating precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed



Detection distance of GWD



Z~2 (2G GWD)

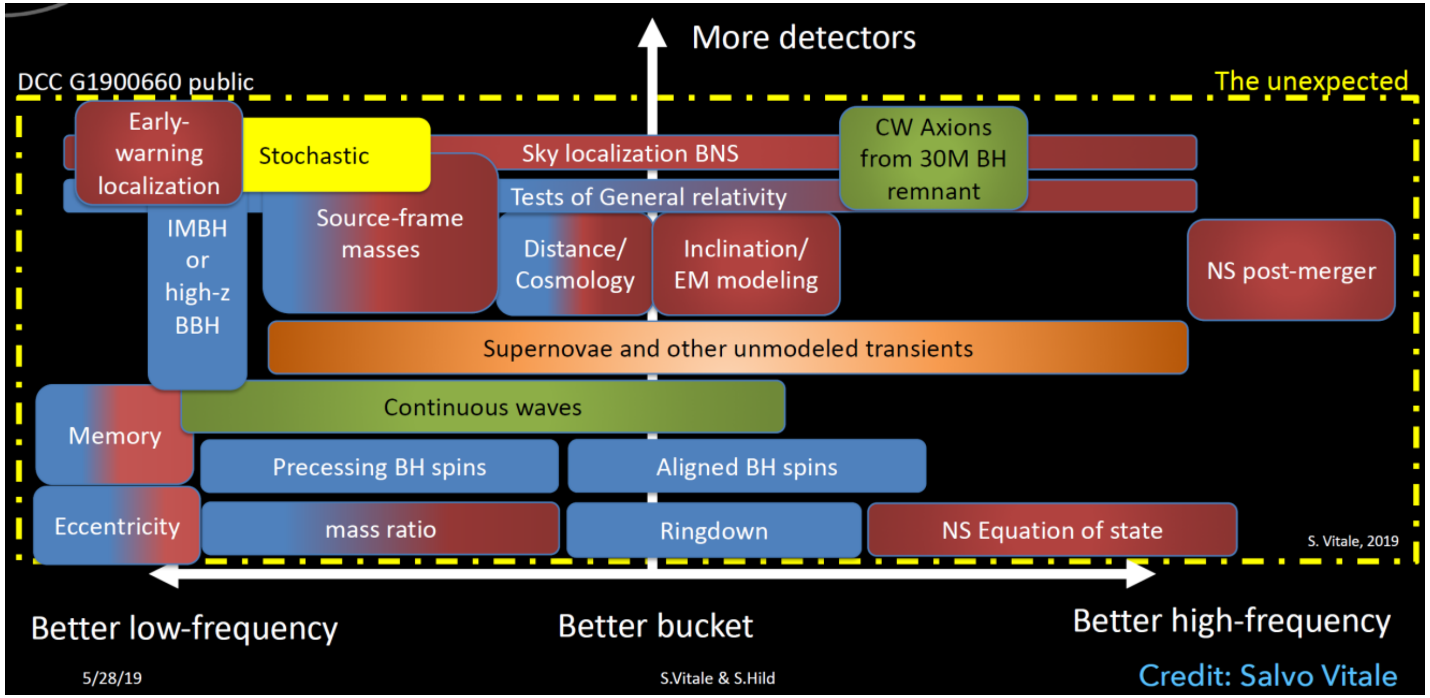
3G Target

Z=0,45 (GW170729)

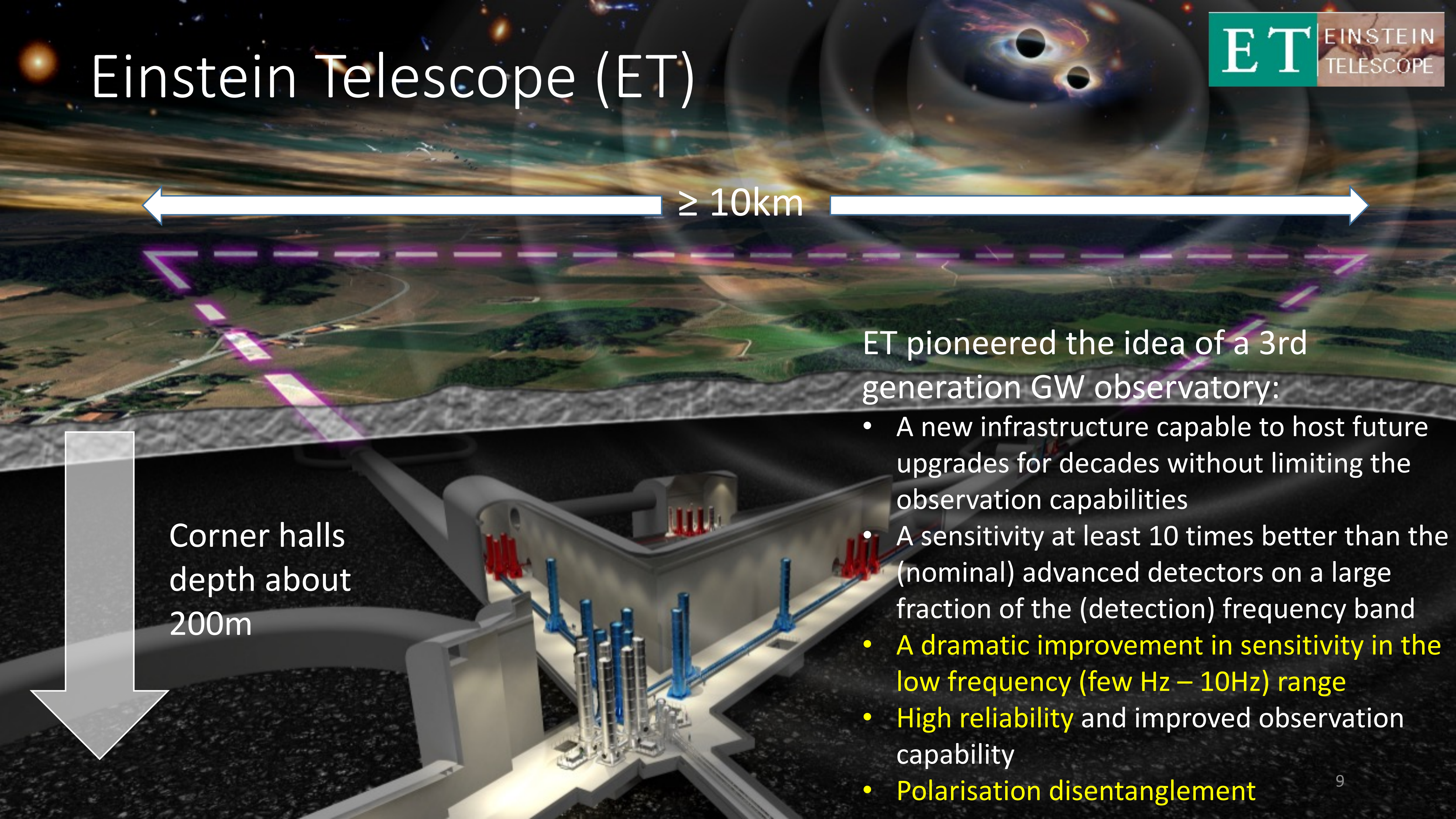
Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

Where to look for new physics?

- Terrestrial interferometric detectors have access roughly to the [few, few×10^3] Hz frequency interval of the GW signal
- GW sources produce signals in different GW ranges
- Discovery machines must have the widest possible frequency range
- Precision measurement machines should have the best sensitivity
- 3G GW observatories must have both



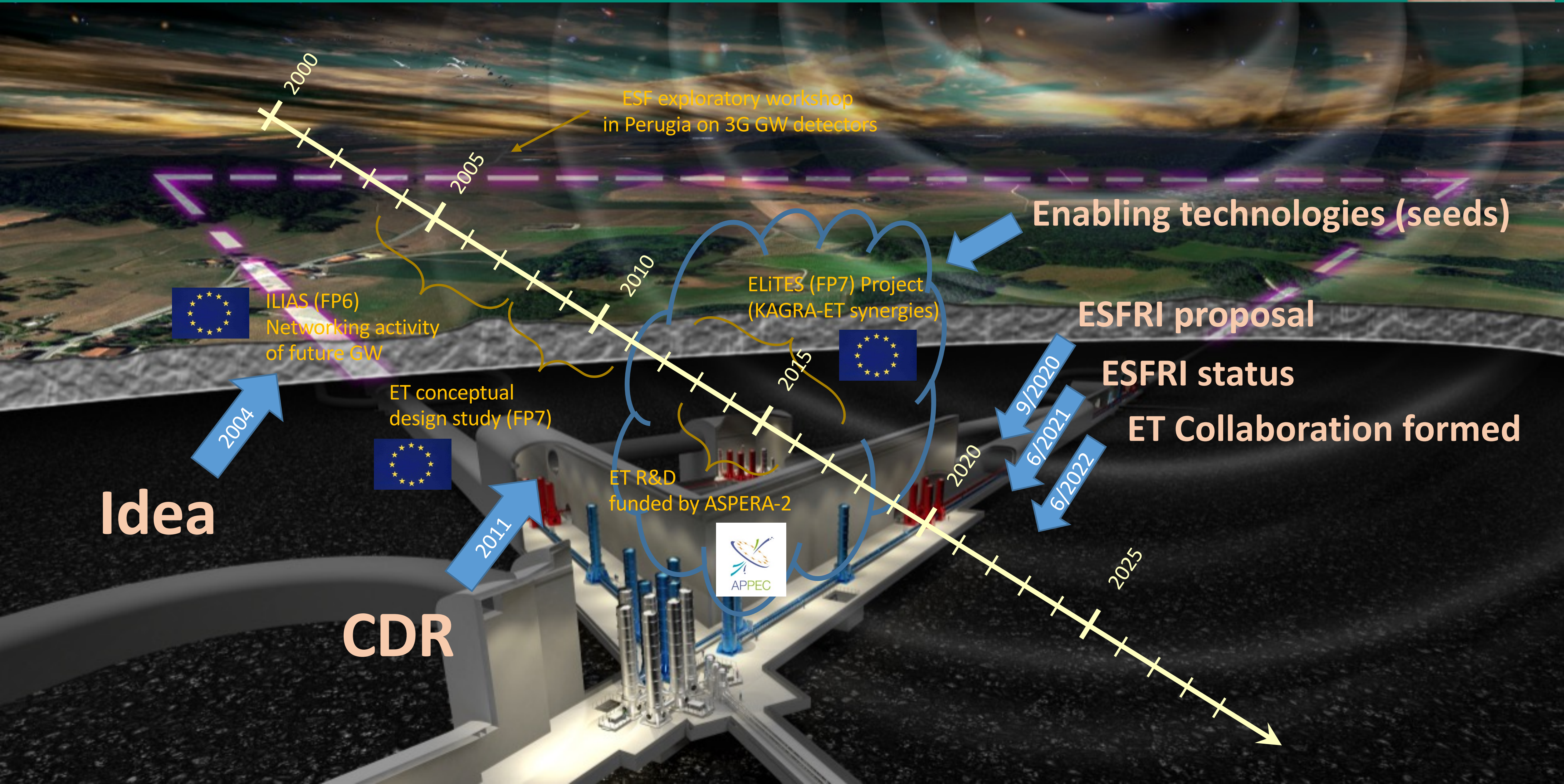
Einstein Telescope (ET)

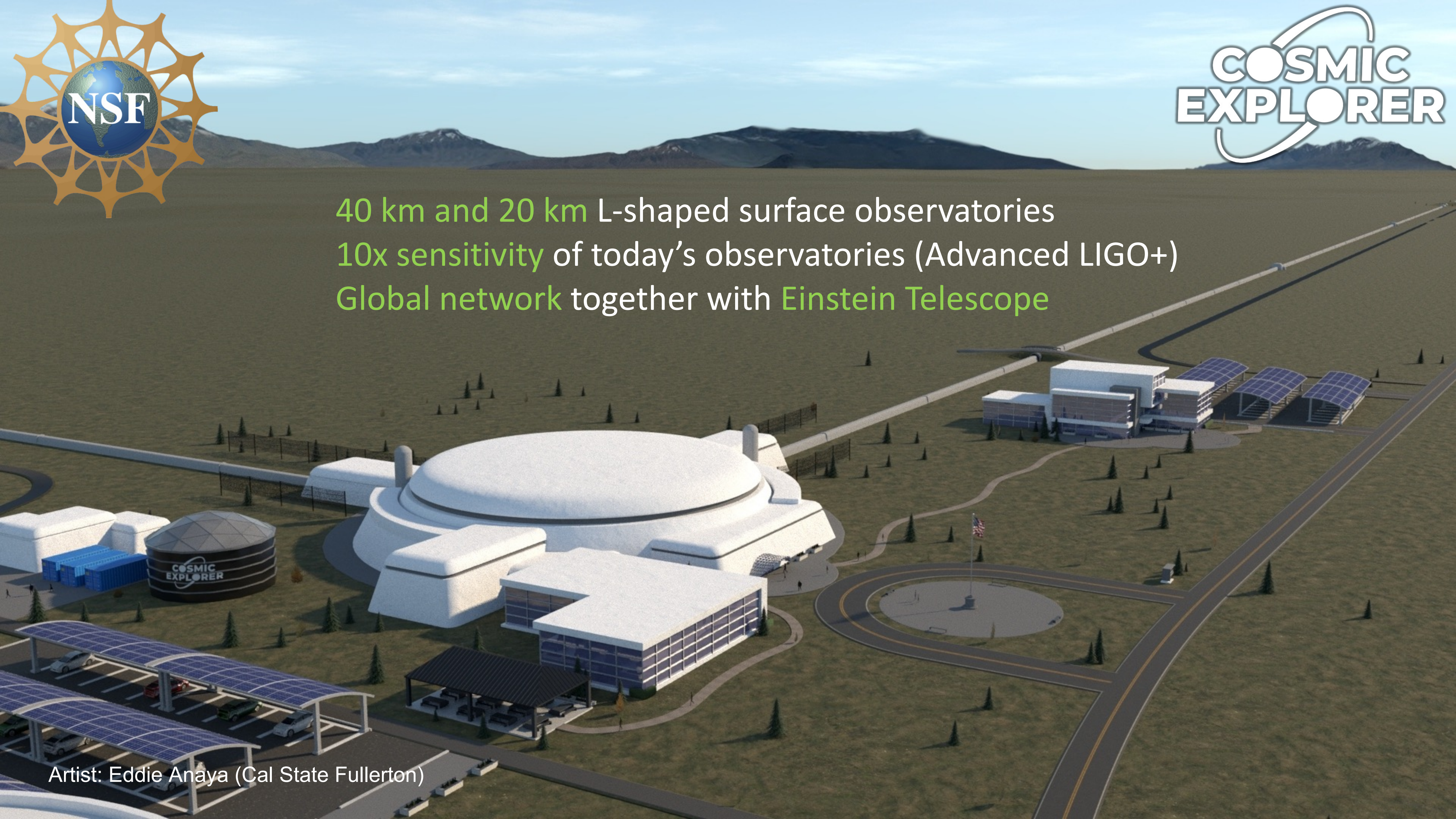


ET pioneered the idea of a 3rd generation GW observatory:

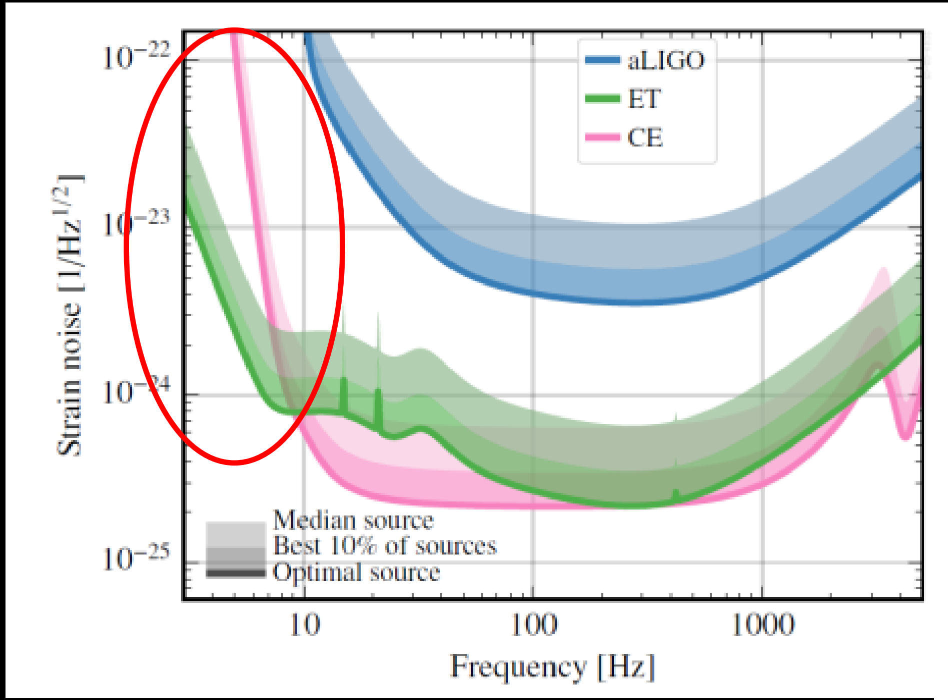
- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency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

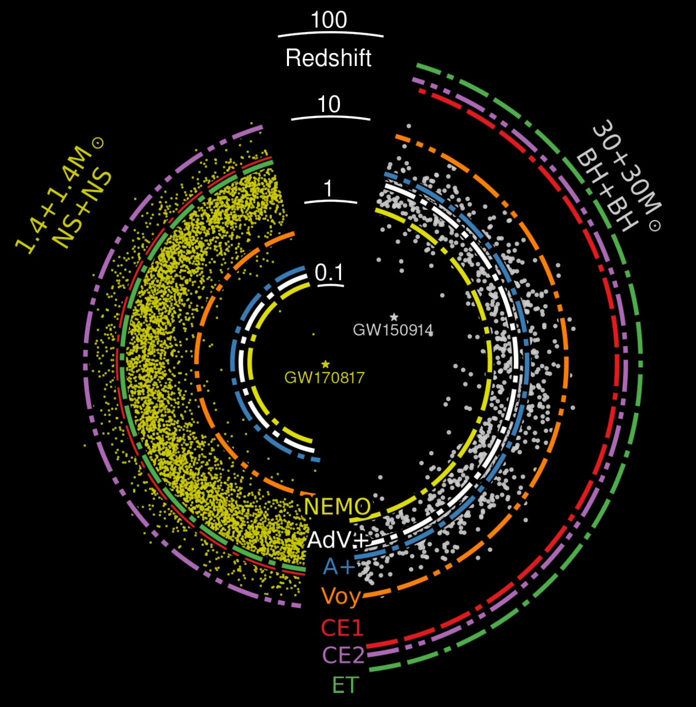
ET: a long path



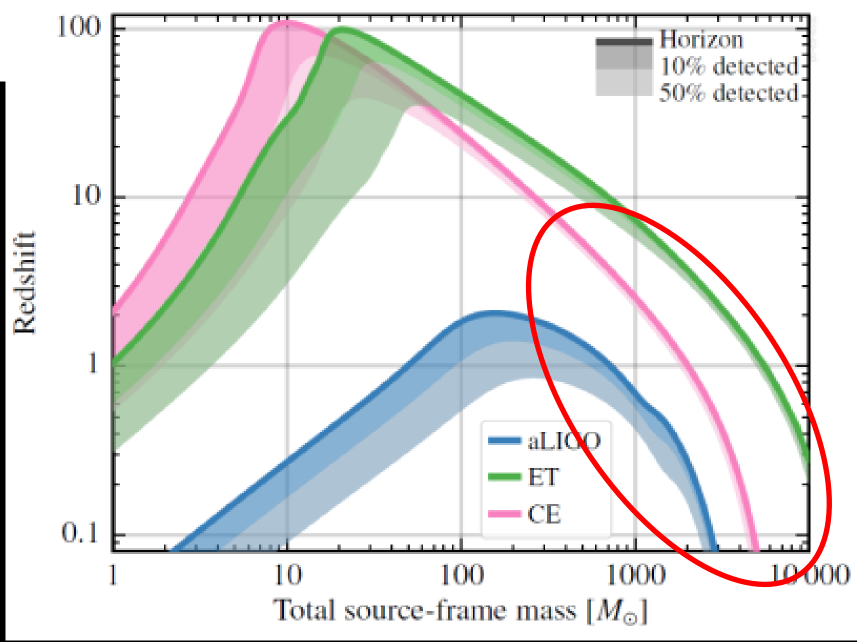

NSF
COSMIC EXPLORER
40 km and 20 km L-shaped surface observatories
10x sensitivity of today's observatories (Advanced LIGO+)
Global network together with Einstein Telescope
COSMIC EXPLORER
Artist: Eddie Anaya (Cal State Fullerton)

Observation performance of ET & CE





- BBH up to z~50-100
- 10^5 BBH/year
  - Masses $M_T \gtrsim 10^3\ M_\odot$
- BNS to z~2
  - 10^5 BNS/year
  - Possibly O(10-100)/year with e.m. counterpart
- High SNR



ET Science in a nutshell

EINSTEIN TELESCOPE

ASTROPHYSICS

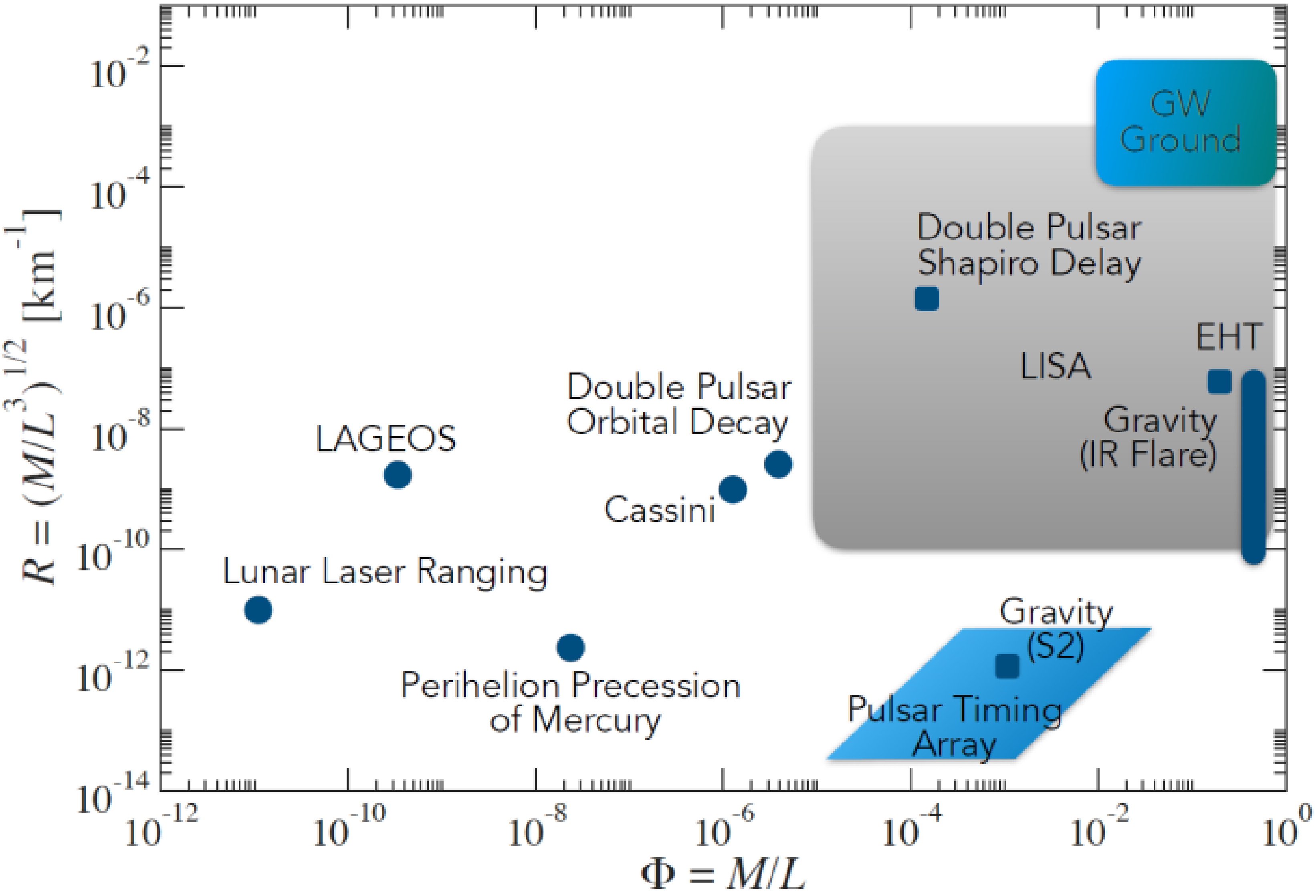
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)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

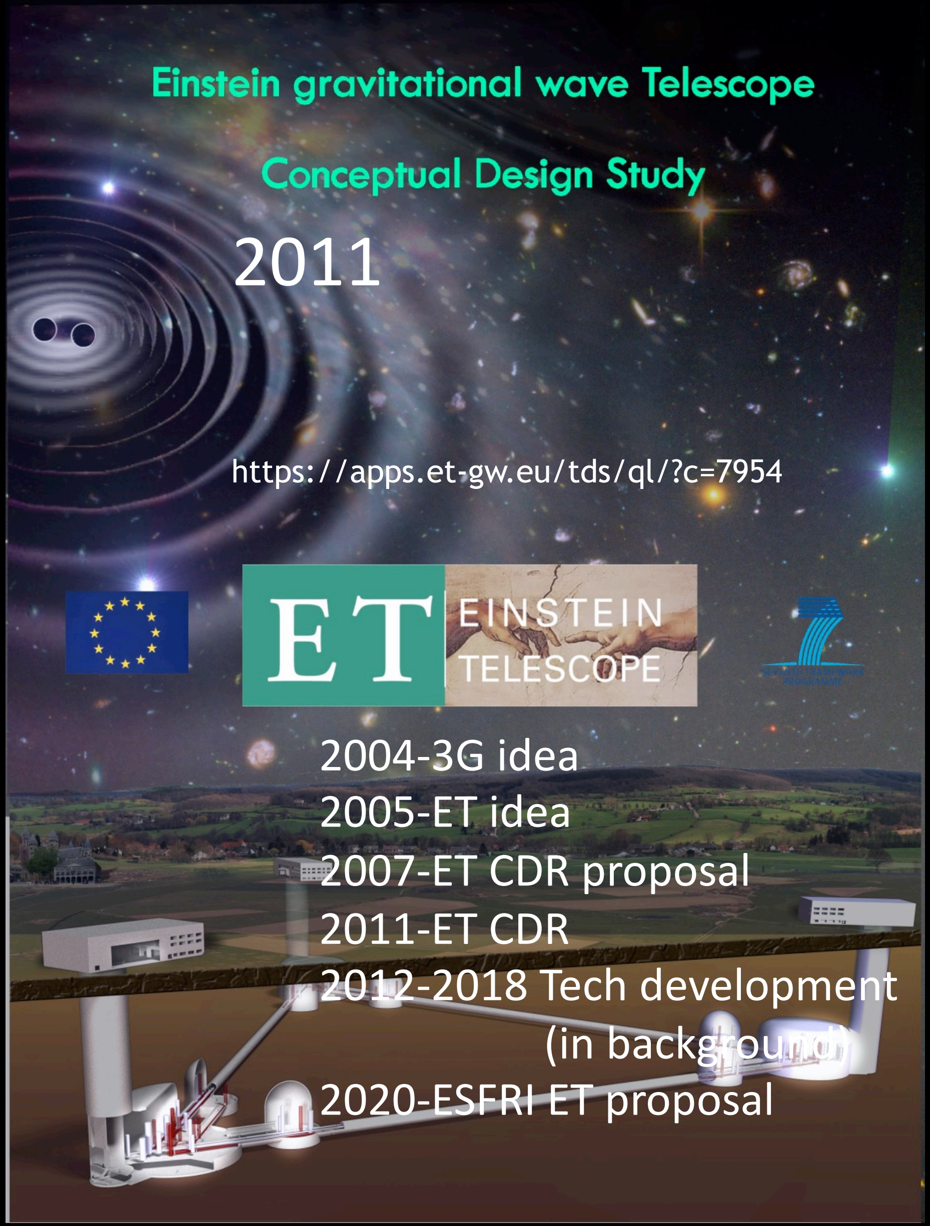
GWs are probing GR in strong field conditions

- BBH coalescences allow to test GR in strong field conditions



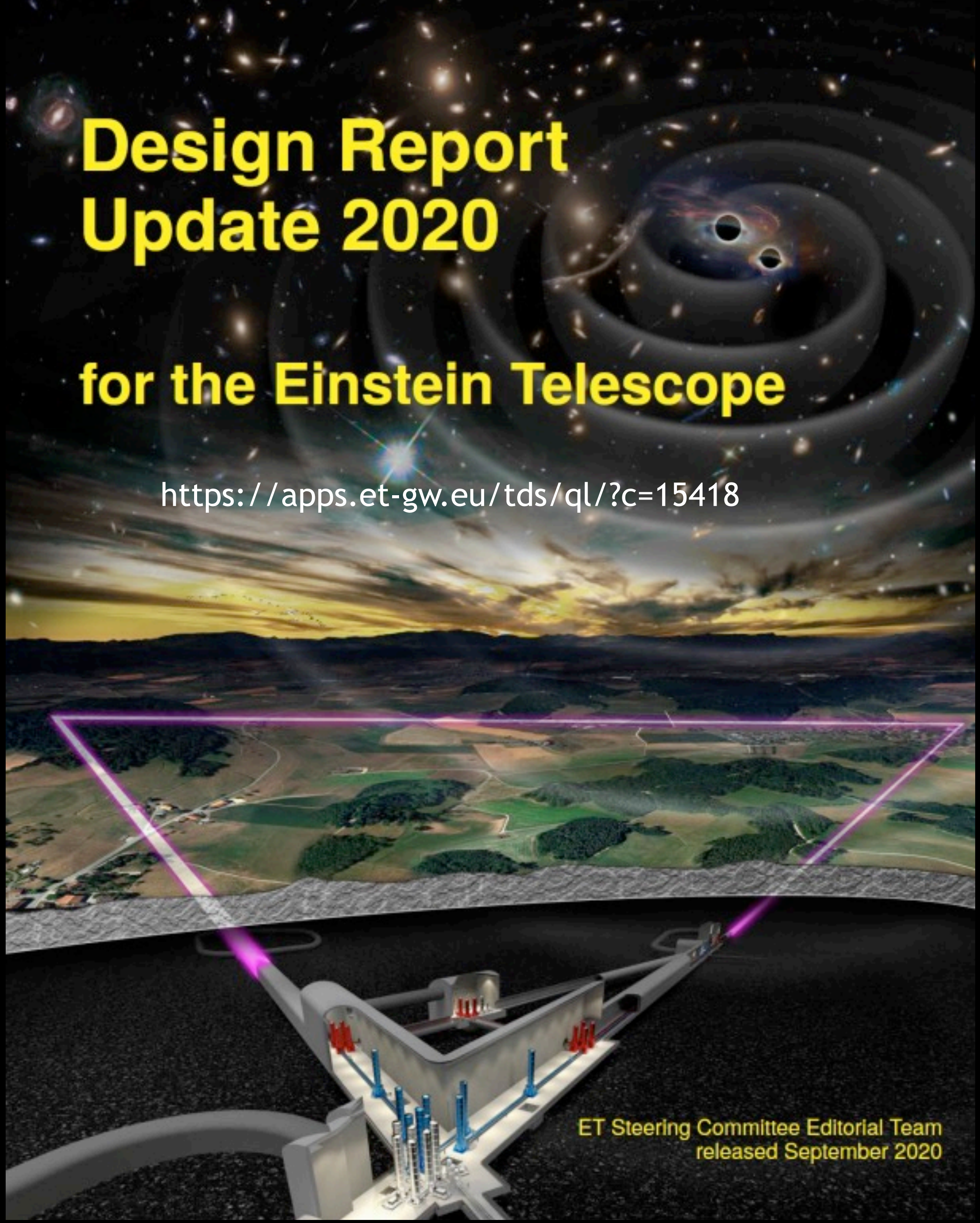
Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)
Edited by ET science case team

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 →



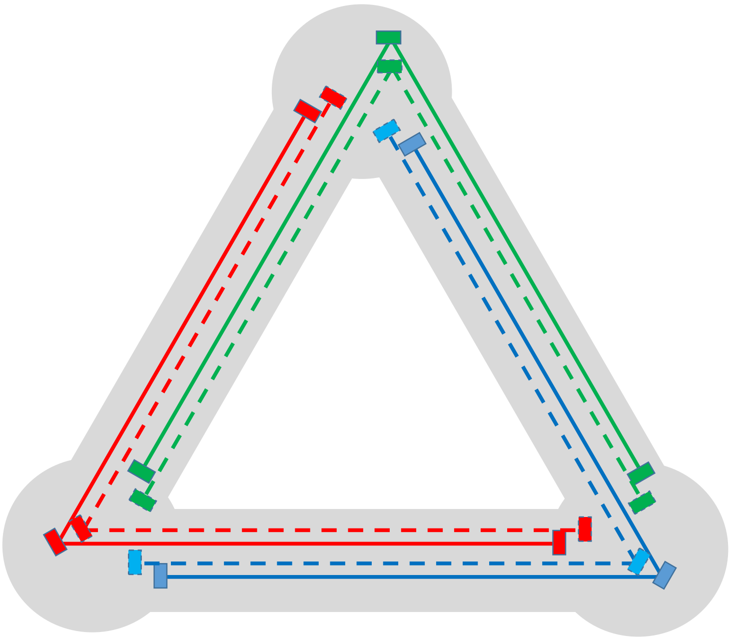
ET key elements

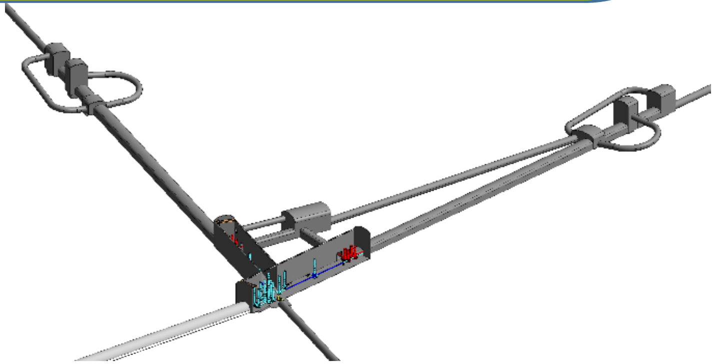
Requirements

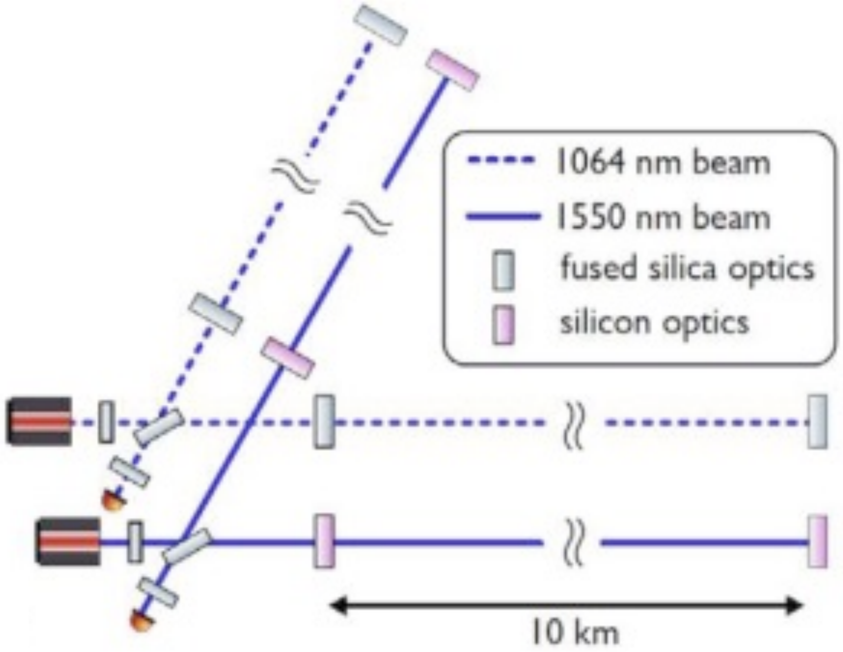
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape
- Multi-detector design
- Longer arms







ET Enabling Technologies

- 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

EINSTEIN TELESCOPE

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

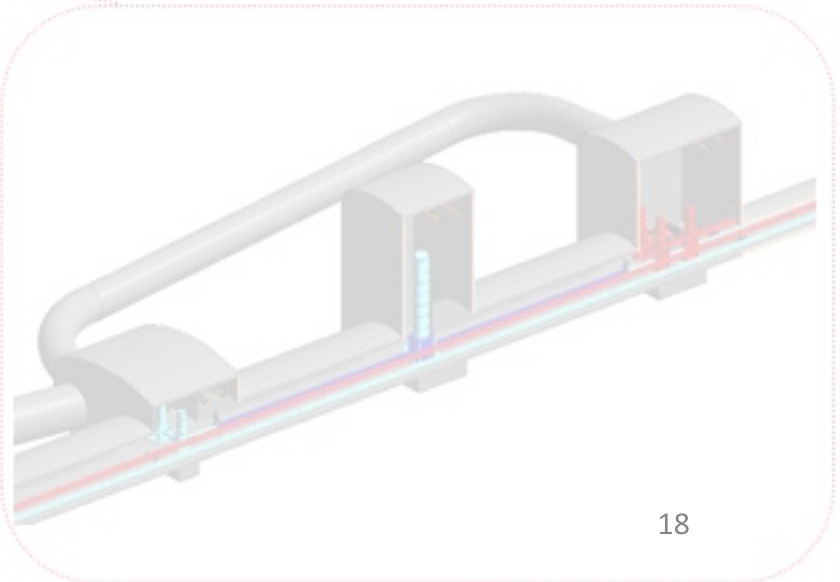
Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

Challenging Engineering: key points

- **~30km of underground tunnels**
  - 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



Cryo-cooling

ET operative temperature ~10K

Key issues

- Acoustic and vibration noises
- Laser absorption and heat extraction
- Cleanliness and contamination
- Cooling time (large masses, commissioning time, …)
- Infrastructures
- Technology (gasses or cryo-coolers)
- Materials
- Safety

Low Frequency special focus

- Underground infrastructure
- 17m tall seismic filtering suspensions
  - Large impact on cavern engineering and costs
- R&D in active-passive filtering systems and seismic sensors

Credits: A.Freise

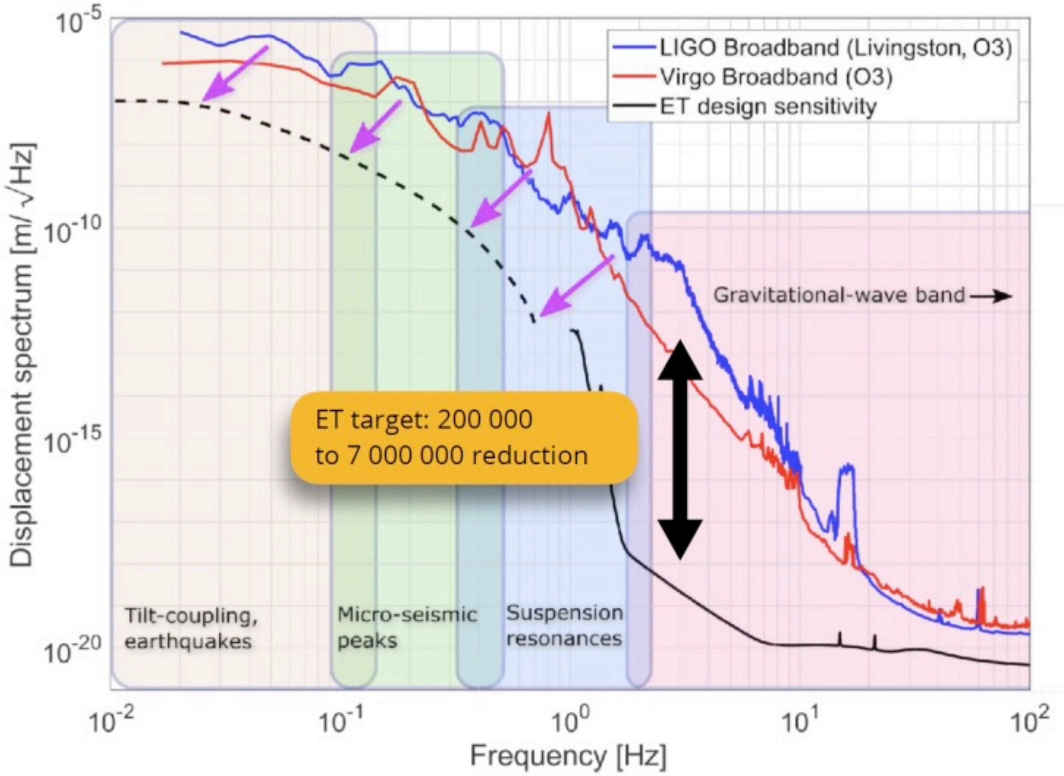
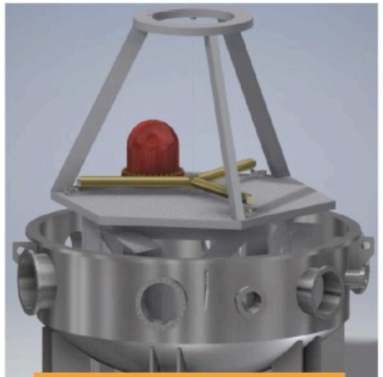
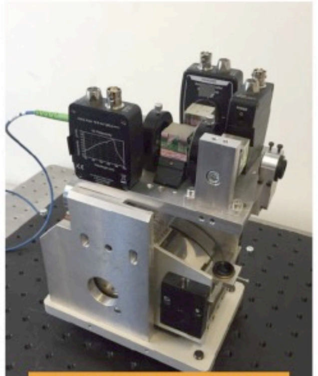


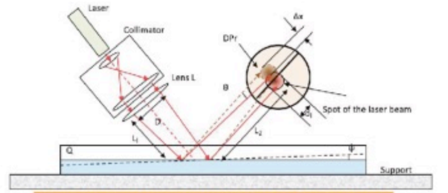
Image: Conor Mow-Lowry



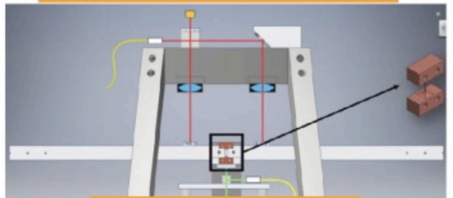
6-D interferometric readout inertial sensor
Credit: Conor Mow-Lowry, VU Amsterdam



Low frequency seismometers
Credit: Christophe Collette, U. Liege



Laser inclinometer, Credit: B. Di Girolamo, CERN

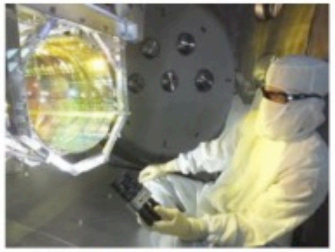


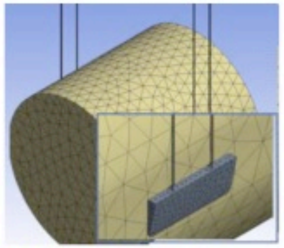
Ultralow frequency tiltmeter
Credit: ARCHIMEDES and VIRGO Coll.

ET EINSTEIN TELESCOPE

Credits: A.Freise

New Optics



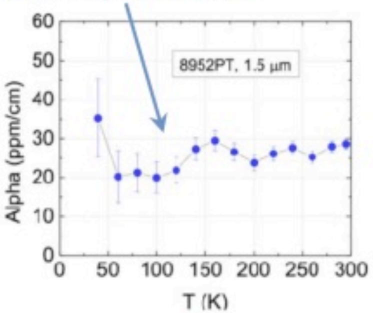


Advanced LIGO – 40 kg / ET 200 kg

Nikon SiO_2

Absorption of "best 45 cm" MCZ Si: 1.5um

Stanford/Glasgow/Berkeley/Caltech 2019



- **Substrates Challenge:**
  - Substrate (ET-HF silica / ET-LF silicon) of 200 kg-scale, diam≥45cm, with required purity and optical homogeneity/abs.
  - Silicon Challenge:
    - Czochralski (CZ) method produced test masses could have the required size, but show absorption excesses due to the (crucible) contaminants
    - Float Zone (FZ) produced samples show the required purity, but of reduced size (20cm wrt ≥45cm required)
    - Magnetic Czochralski (mCZ) could be the possible solution?
- **Coating Challenge:**
  - major challenge over recent years:
    - Amorphous dielectric coating solutions often either satisfy thermal noise requirement (3.2 times better than the current coatings) **or** optical performance requirement (less than 0.5ppm) – not both
    - AlGaAs Crystalline coatings could satisfy ET-LF requirements, but currently limited to 200mm diameter.

New Laser and Opto-Electronic Technology

Virgo and LIGO developed CW low noise lasers at 1064nm

- In ET-HF their evolution toward higher power will be investigated

In ET-LF we will use a different wavelength because of the Silicon test masses:

- λ=1.55μm or 2μm?

New electro-optic components:

- High quantum efficiency photodiodes
- Low absorption e.o.m.
- Low dissipation faraday isolators

Other relevant challenges

- Auxiliary optics, adaptive optics and thermal compensation of optical aberrations
- Precision mechanics, alignment and positioning
- **Vacuum** (*the largest volume under UHV in the World*):
  - More than 120km of vacuum pipes
    - ~1 m diameter, total volume 9.4×10^4 m^3
    - 10^{-10} mbar for H_2, 10^{-11} mbar for N_2 and less than 10^{-14} mbar for Hydrocarbons
  - Joint development with CERN involving ET and CE
- Low noise controls
- Computing
  - Computation intensive, not data intensive
- Governance & Organisation

European Strategy Forum on Research Infrastructures

ESFRI Roadmap

EINSTEIN TELESCOPE

ESFRI partners:

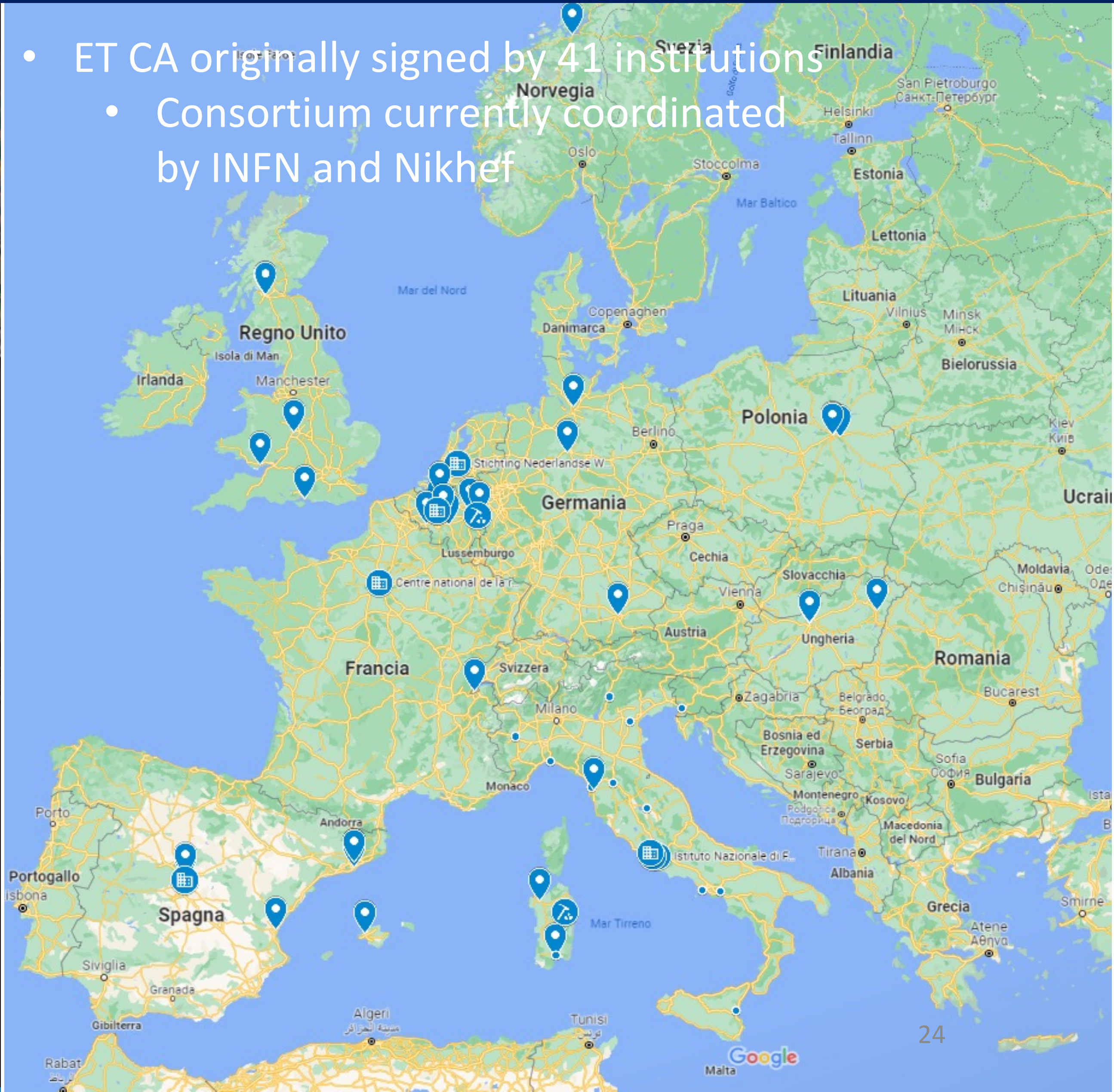
- **Italy** (Lead Country)
- Belgium
- Netherlands
- Poland
- Spain

The ET-PP (preparatory phase) funded by EU commission with 3.45M€: t0=01/09/2022

It includes also agencies and institutions belonging to:

- **Austria**
- **France**
- **Germany**
- **Hungary**
- **Switzerland**
- **UK**

- ET CA originally signed by 41 institutions
  - Consortium currently coordinated by INFN and Nikhef



The Einstein Telescope Collaboration

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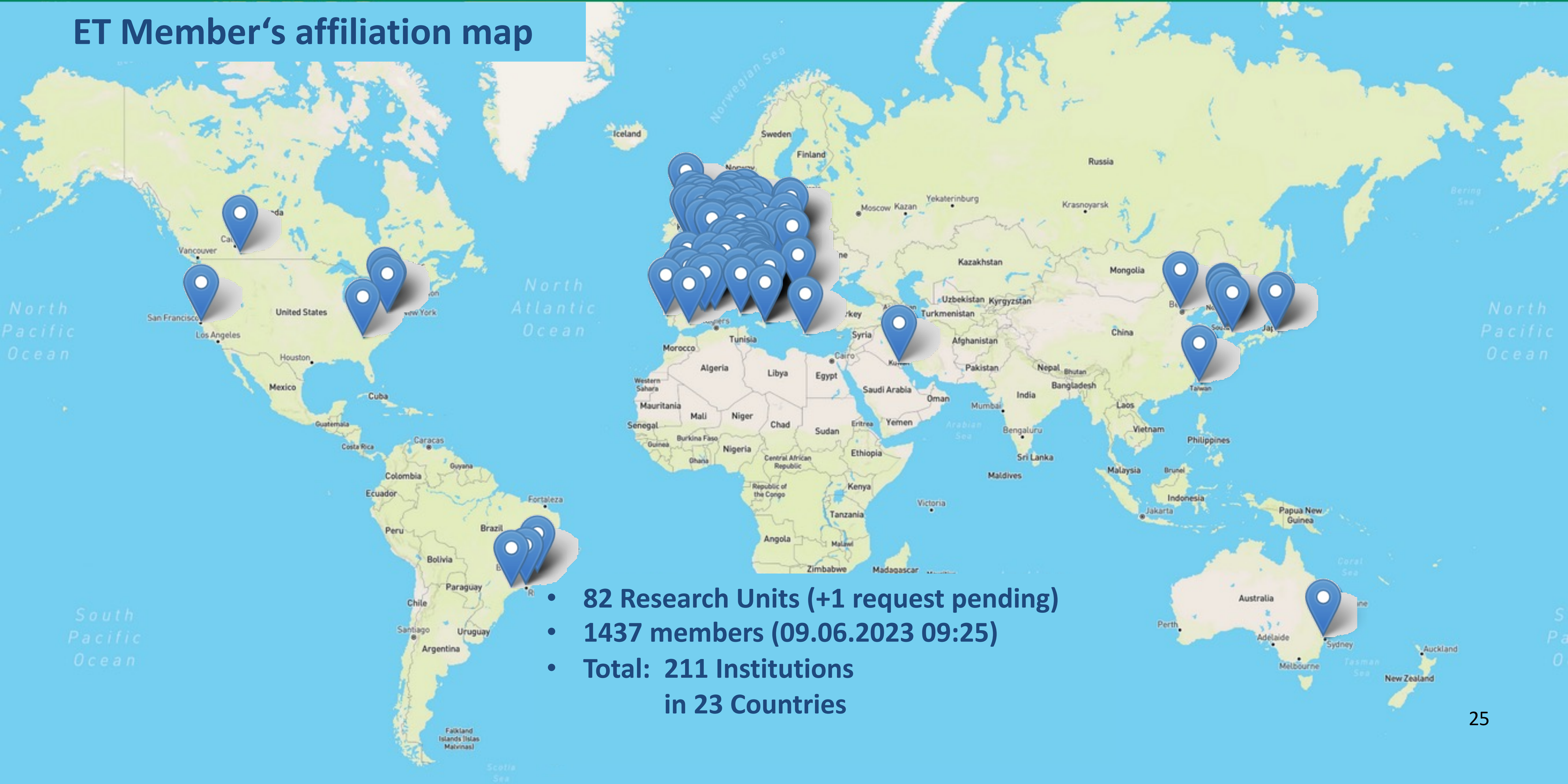
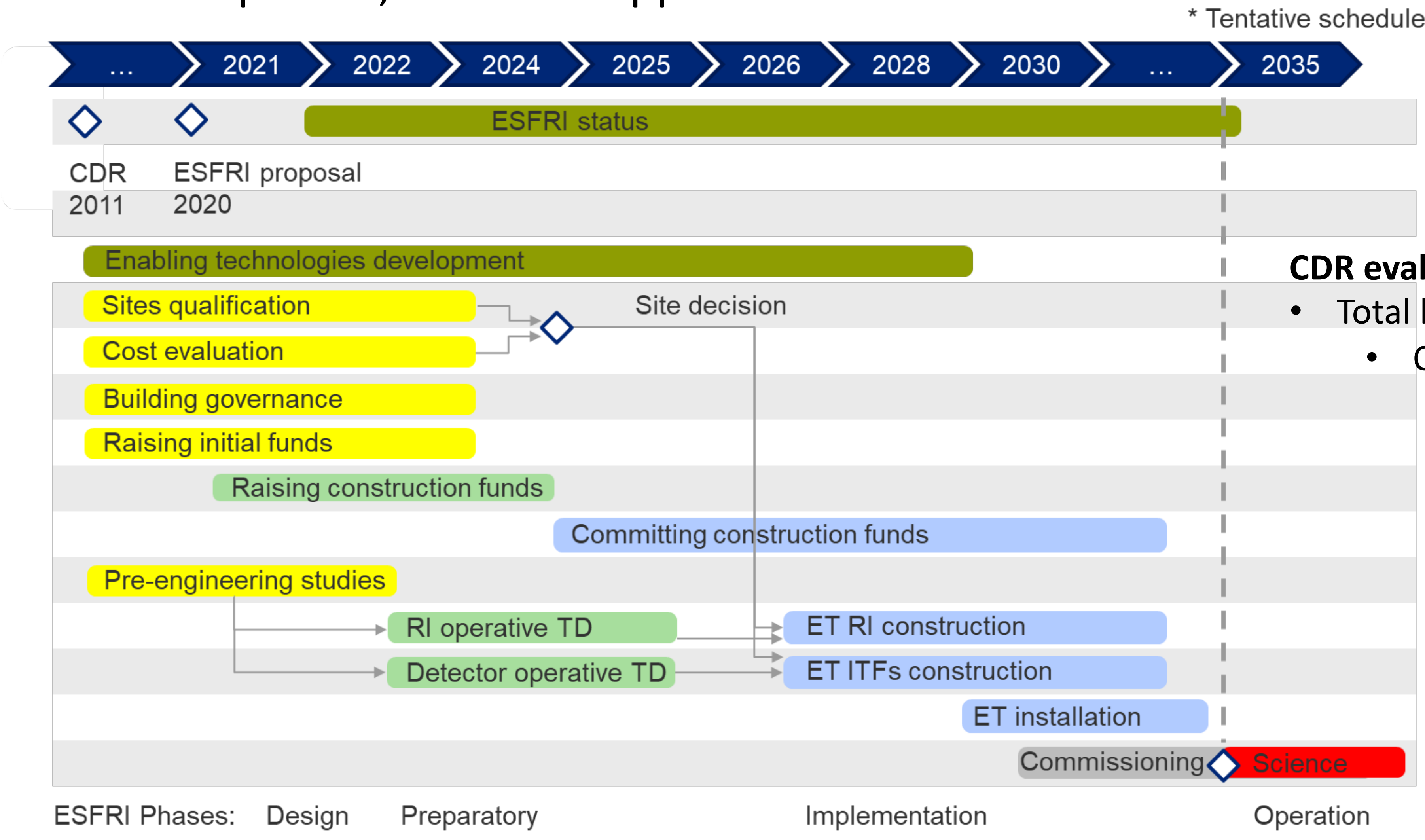
ET Member‘s affiliation map



- 82 Research Units (+1 request pending)
- 1437 members (09.06.2023 09:25)
- Total: 211 Institutions
  in 23 Countries

ET timeline

- ET timeline presented to ESFRI
  - As expected, the ESFRI approval boosted the activities at all the levels:
    - Scientists
    - Agencies
    - Governments



CDR evaluations:

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

Siti candidati

- Due siti si sono candidati ad ospitare ET
  - Mosa-Reno Euregio, al confine fra Olanda, Belgio e Germania
  - Sardegna, in Barbagia, vicino a Lula
- Una terza candidatura in Sassonia è in elaborazione
- La valutazione della candidatura è un complesso processo multi-fattoriale:
  - Qualità geofisiche e ambientali
  - Fattori finanziari e organizzativi
  - <u>Servizi offerti</u>

Einstein Telescope in Euregio Meuse-Rhine (EMR)

Connected institutions in:
Belgium,
Germany &
the Netherlands

approved

Nationaal Groeifonds (the Netherlands)

Emphasis on potential socio-economic Impact

Submitted by OCW Ministry
(EZK Ministry support)

Supported by ~70 Dutch Industries/institutions

In October 2021 the Netherlands submitted large funding proposal within context of the '*Nationaal Groeifonds*'. Decision in April 2022.

Includes 42 M€ for geology, R&D & organization
as well as possible Dutch share towards ET realization

German Center for Astrophysics

Pressemitteilung

Forschung von Weltrang in der Lausitz

Deutsches Zentrum für Astrophysik – Forschung. Technologie. Digitalisierung. (DZA) gewinnt Wettbewerb zur Strukturförderung

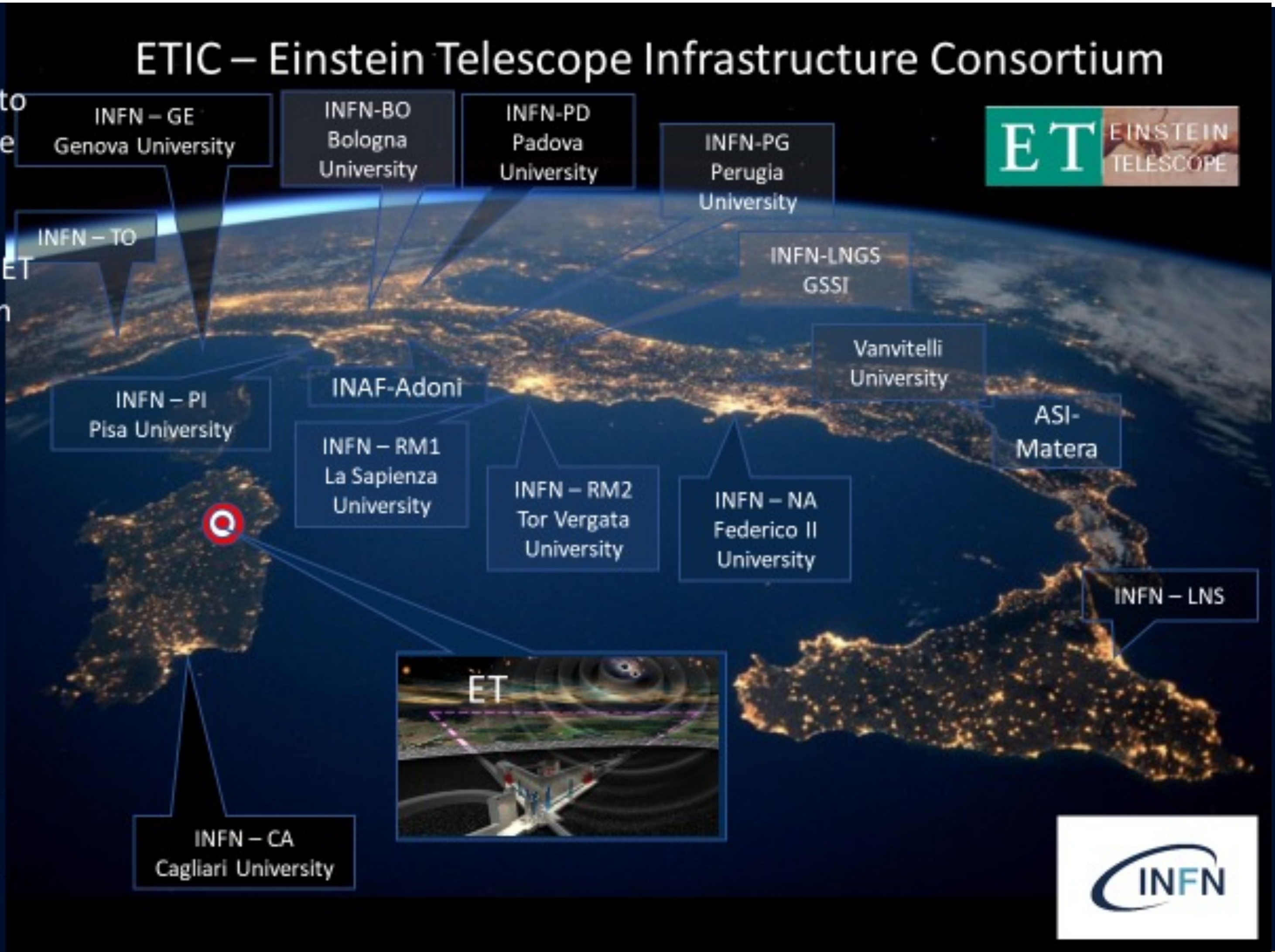
Görlitz, 29.09.2022 Die Entscheidung im Wettbewerb „Wissen.schafft.Perspektiven“ ist getroffen: Mit dem Deutschen Zentrum für Astrophysik - Forschung. Technologie. Digitalisierung. (DZA) entsteht ein nationales Großforschungszentrum mit internationaler Strahlkraft, das ressourcensparende Digitalisierung vorantreibt, neue Technologien entwickelt, für Transfer sorgt und Perspektiven für die Region schafft – fest verwurzelt in der sächsischen Lausitz.

Investimento PNRR focalizzato sulla realizzazione di una rete di infrastrutture di ricercar (laboratory) per lo sviluppo delle tecnologie abilitanti di ET e sulla candidatuta del sito in Sardegna attraverso uno studio di pre-fattibilità

A guida INFN,
Partners:
11 Università, INAF e ASI

Budget 50M€

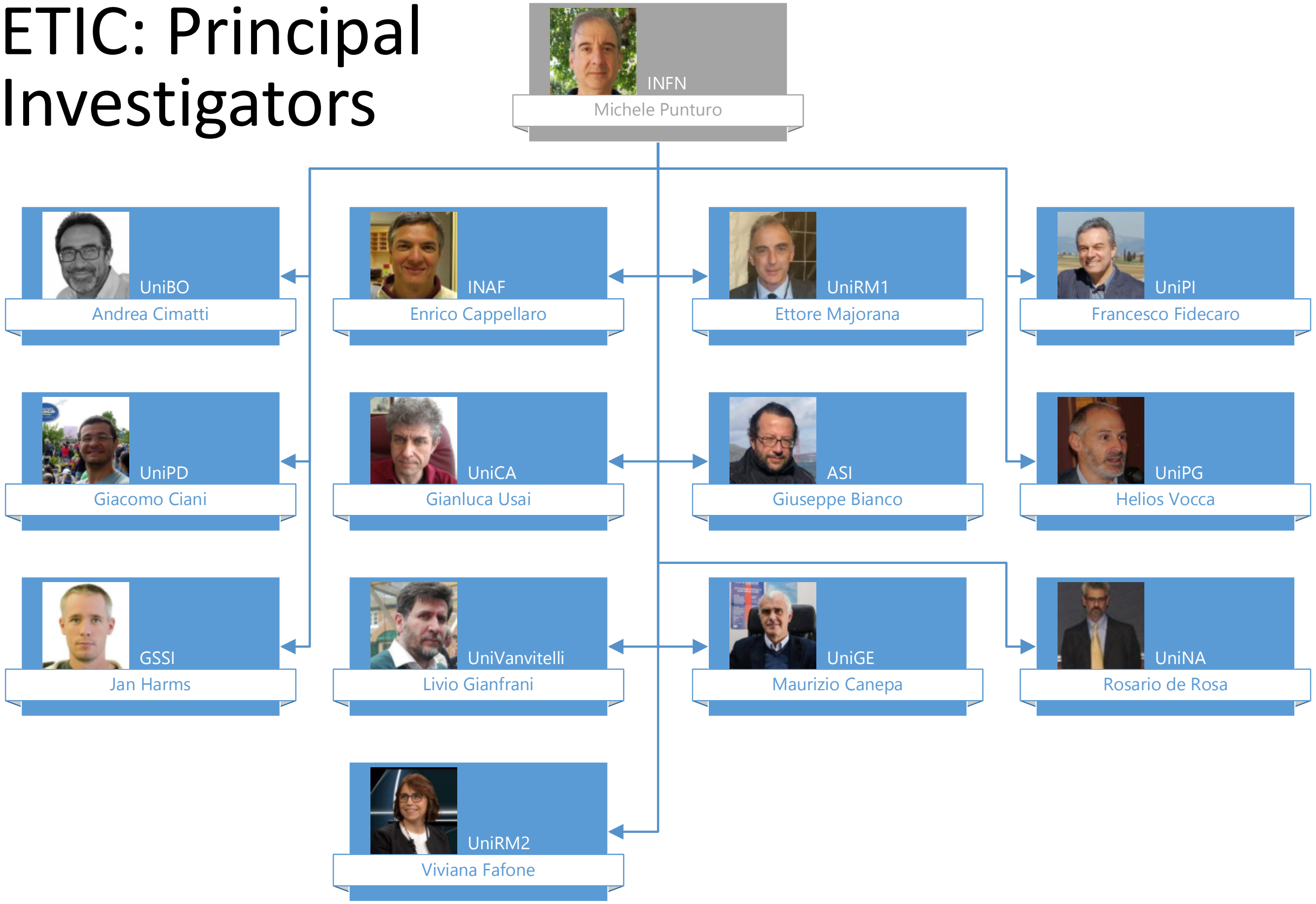
Iniziato il 1 Gennaio 2023
Pieno support del governo e della regione Sardegna alla candidatura del sito italiano



Finanziato dall'Unione europea
NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN

ETIC Project: OBS

ETIC: Principal Investigators

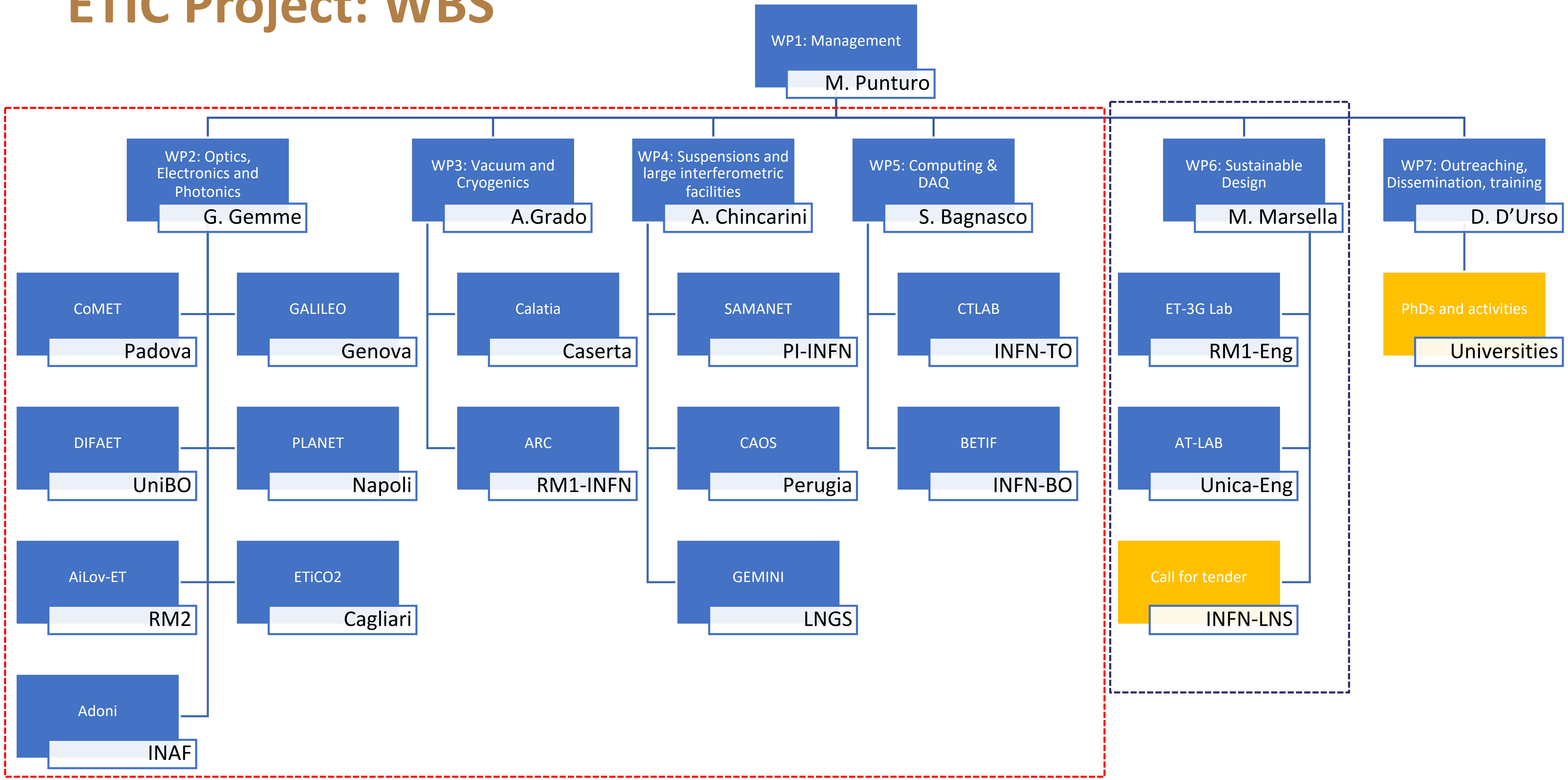


ETIC: OU Board

ETIC Project: WBS

ETIC realizza

1) un network di laboratori e infrastrutture presso le varie UO partecipanti
2) Uno studio di pre-fattibilità di ET in Sardegna



Studio di prefattibilità

- La candidatura italiana per Einstein Telescope passa per lo studio di prefattibilità finanziato all'interno del WP6 di ETIC
  - Una gara da 14M€ + IVA già pubblicata indirizzata a operatori privati con elevati livelli di competenza
  - Studi ingegneristici, geologici e sondaggi
  - Gara gestita dall'INFN (LNS) all'interno di un WP coordinato da DICEA-UniRM1
- La candidatura italiana per Einstein Telescope è supportata dal MUR e dal governo al massimo livello

Candidatura Italiana

Ulteriori Informazioni

ET Italia: https://www.einstein-telescope.it/

ETIC: https://web.infn.it/einsteintelescope/index.php/it/home-it-it

ET International Collaboration: https://www.et-gw.eu/