Introduction to

Einstein Telescope

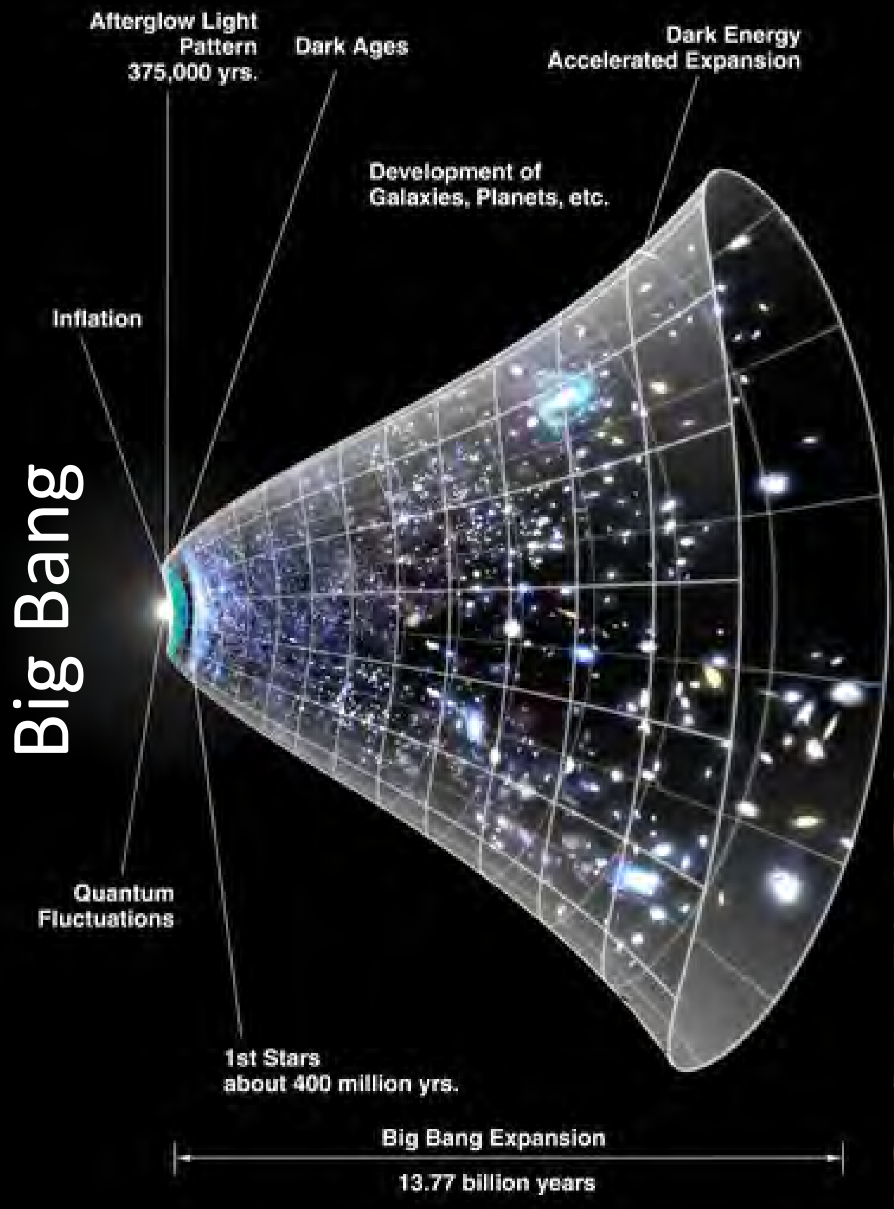
The 3rd Generation GW Observatory in Europe

Dr. Michele Punturo

Istituto Nazionale di Fisica Nucleare (INFN), Perugia, Italy

Spokesperson of the ET Collaboration

The «Gravitational» Universe

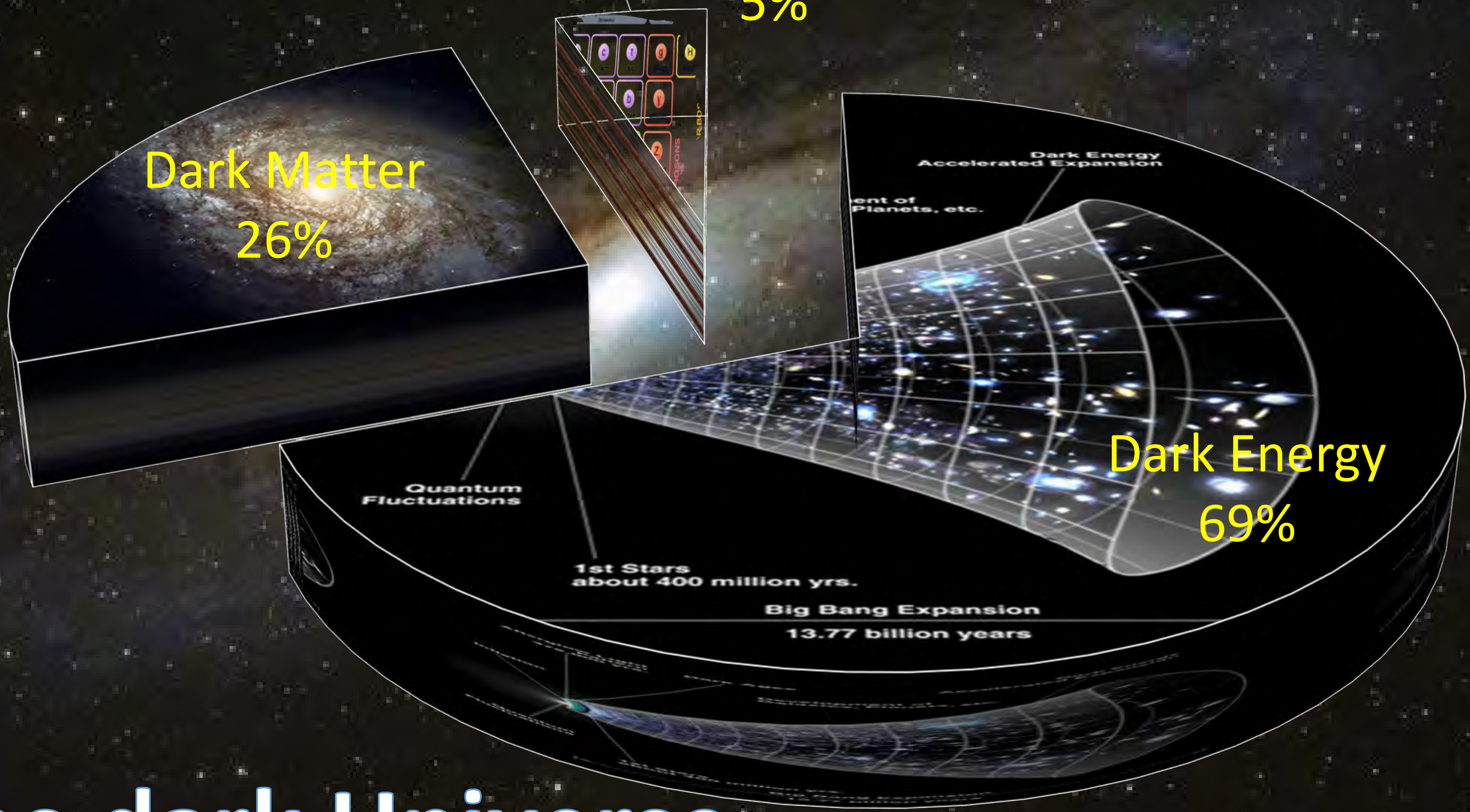


- The current picture of the Universe, painted thanks to the photon, neutrino and gravitational wave messengers, has gravity as its canvas
- Our best understanding of the gravity is described by the Albert Einstein General Relativity

The quantum μ-Universe

- The Standard Model of particle physics is our best description of the microscopic (“femto-scopic”) Universe
- It works incredibly well and it allows to describe the nature of the fundamental interactions and elementary particle

The great contradiction



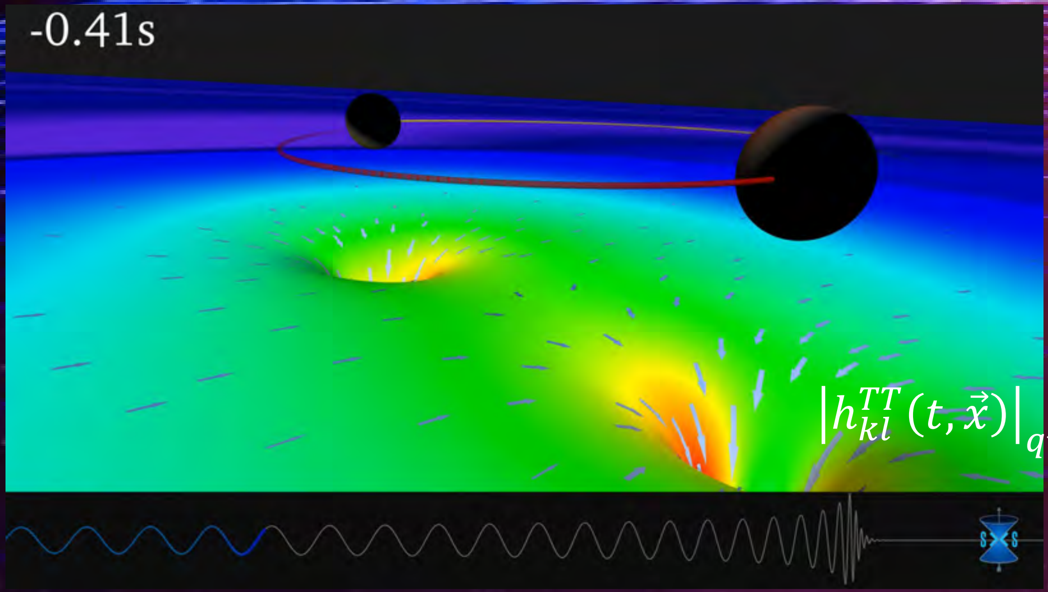
The dark Universe

Gravitational Waves

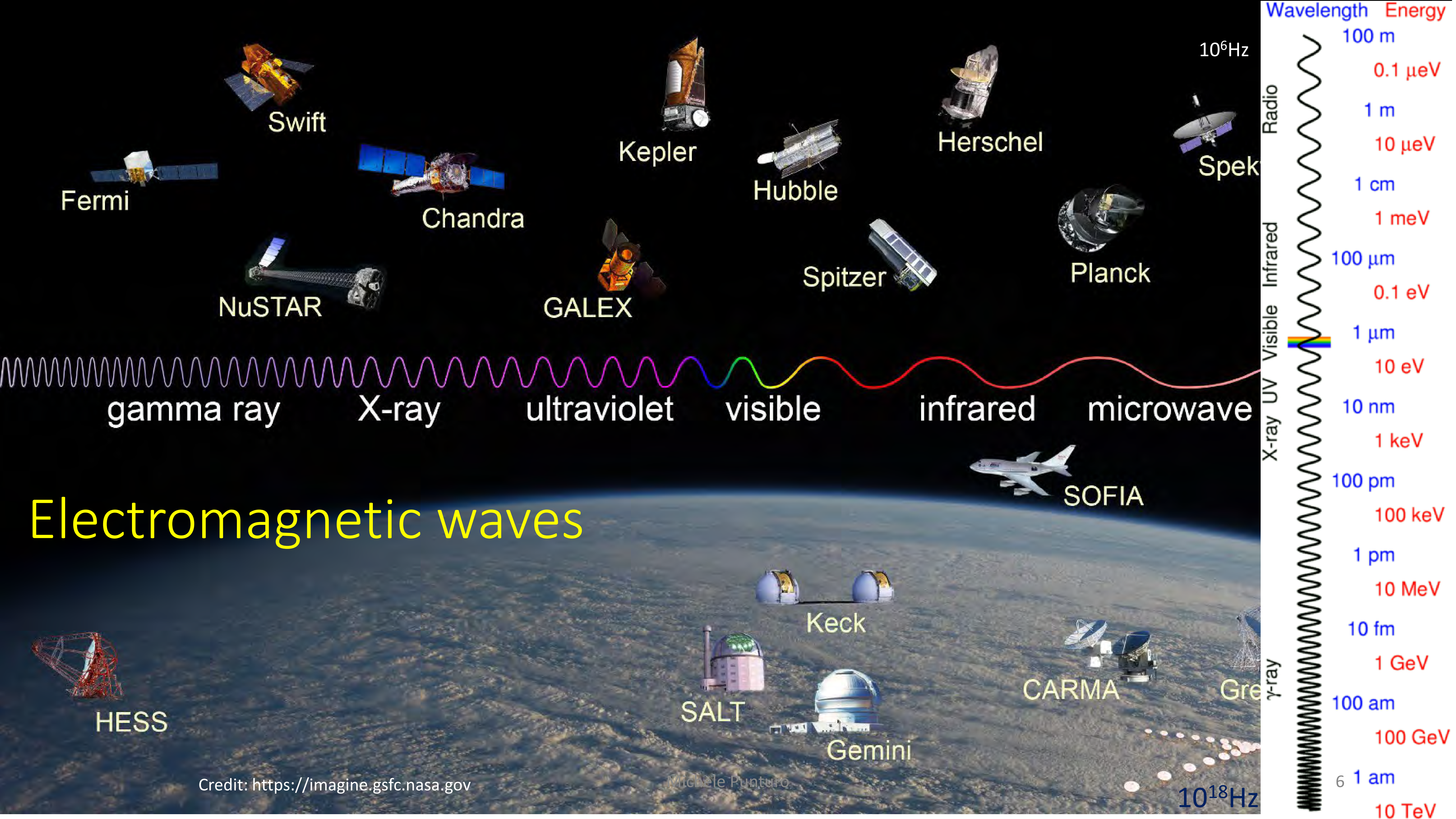
$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

- Prediction of the General Relativity of Albert Einstein
- They are spacetime curvature waves, propagating at the light speed c transporting, as an unstoppable messenger, the most internal information of “cathastrophic” pnenomena, like the coalescence of compact bodies (black holes and/or neutron stars) or the cosmological Big Bang.



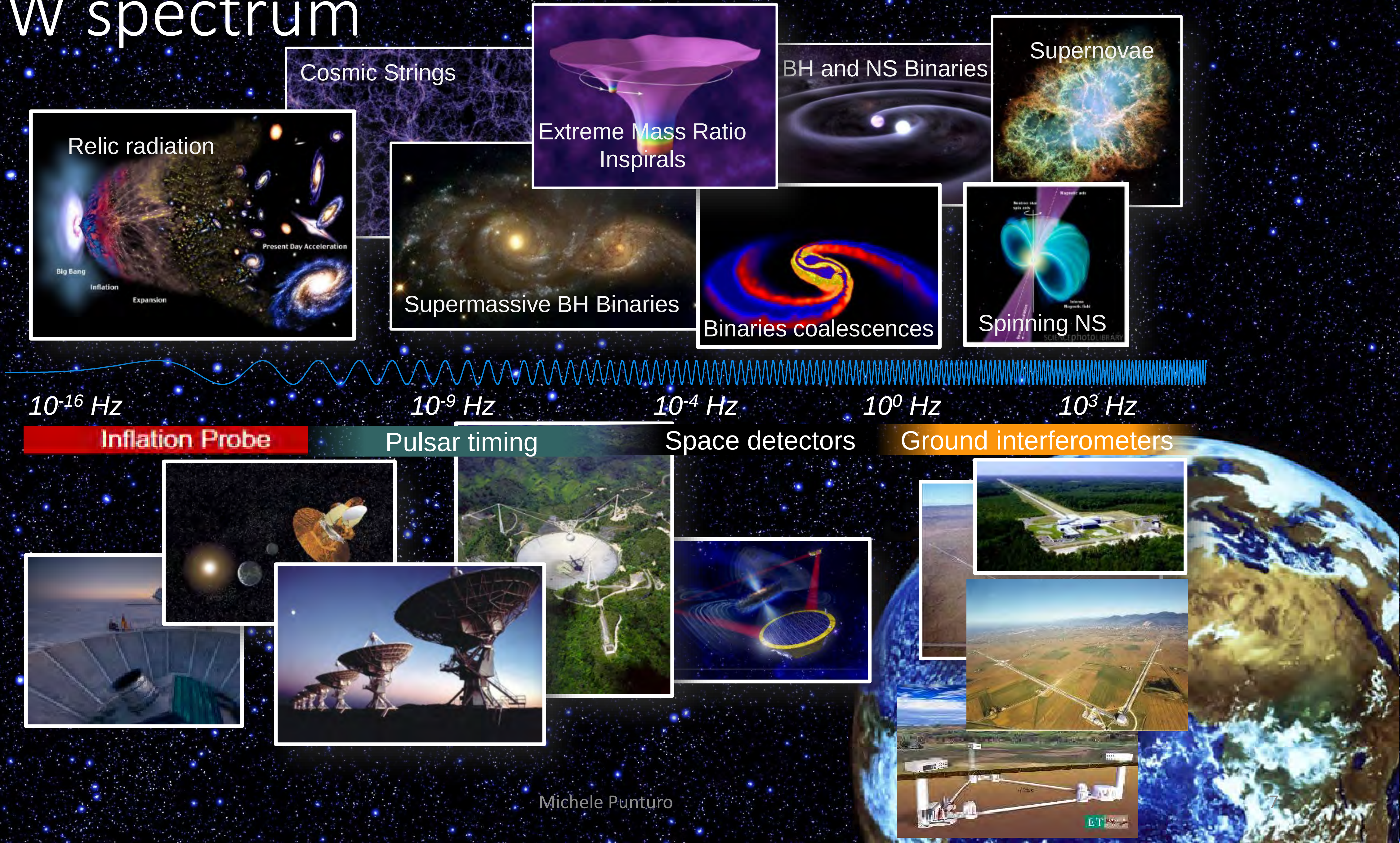
$$\left|h_{kl}^{TT}(t,\vec{x})\right|_{quad} = \frac{1}{r}\frac{2G}{c^4}\frac{1}{3}\ddot{Q}_{kl}^{TT}\left(t - \frac{r}{c}\right)$$



Electromagnetic waves

Credit: https://imagine.gsfc.nasa.gov

The GW spectrum



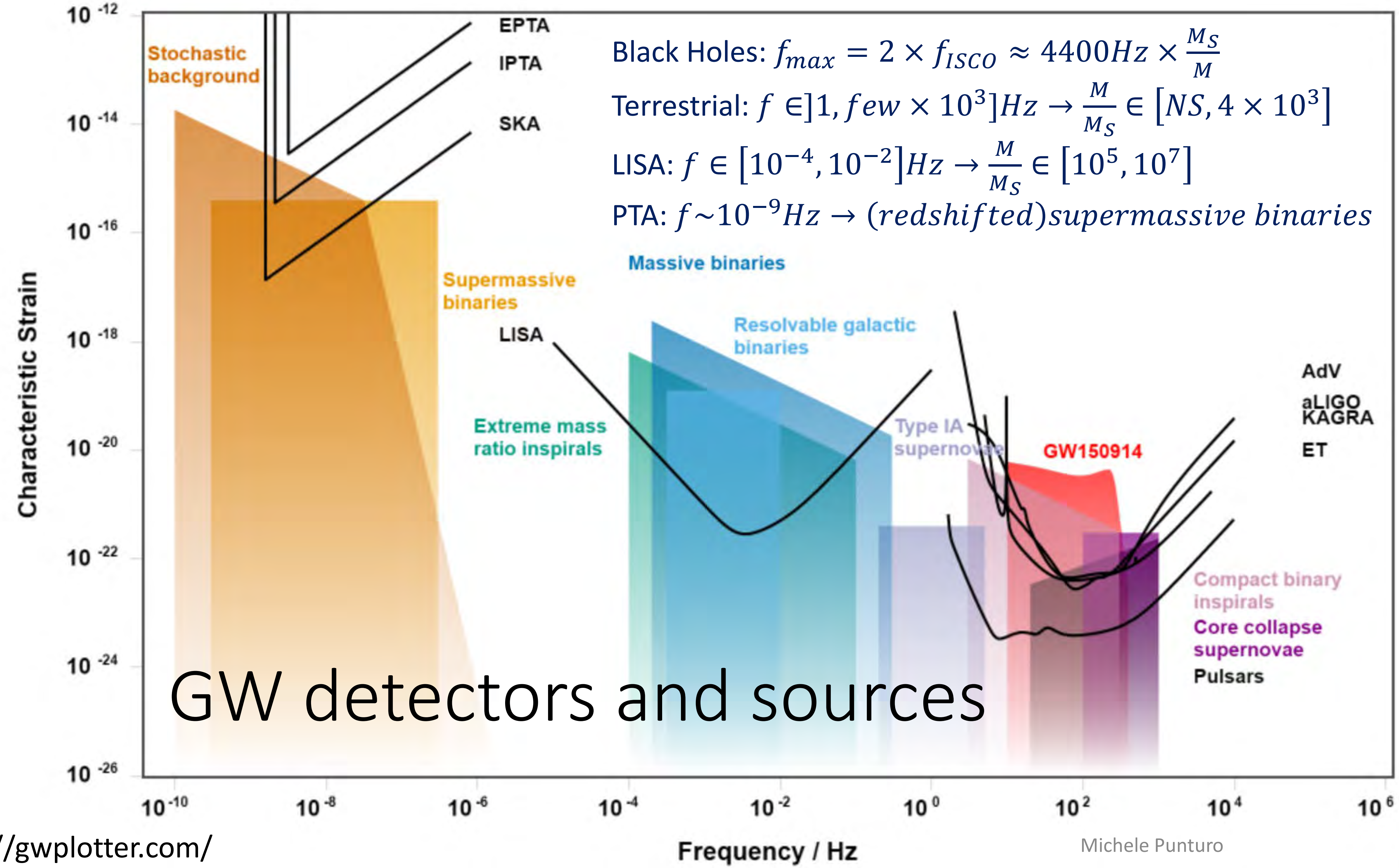
GW detectors and sources

Black Holes: $f_{max} = 2 \times f_{ISCO} \approx 4400Hz \times \frac{M_S}{M}$

Terrestrial: $f \in]1, few \times 10^3]Hz \rightarrow \frac{M}{M_S} \in [NS, 4 \times 10^3]$

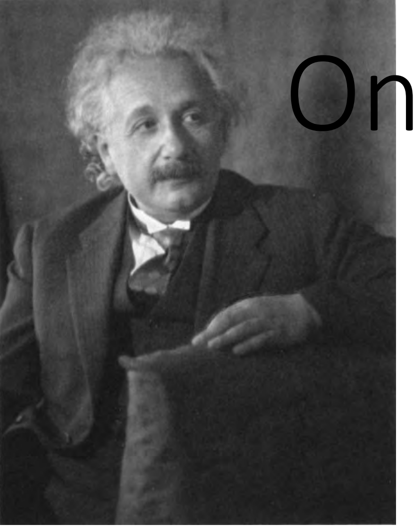
LISA: $f \in [10^{-4}, 10^{-2}]Hz \rightarrow \frac{M}{M_S} \in [10^5, 10^7]$

PTA: $f \sim 10^{-9}Hz \rightarrow (redshifted) supermassive\ binaries$



http://gwplotter.com/

One century of research, study and R&D

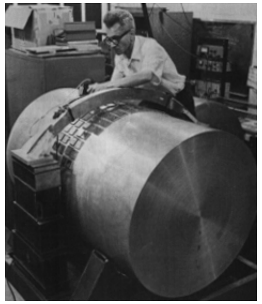


1915 GR

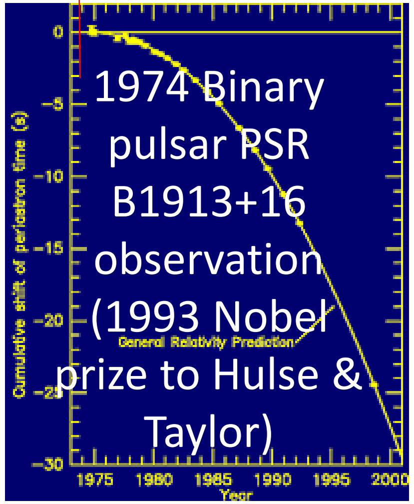
1916-1918 GW

1937 rigth GW equation

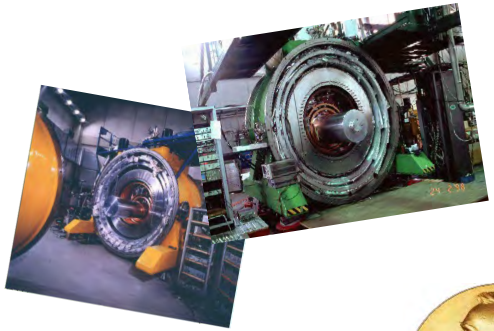
1957 GW transports energy



1966 beginning of the «experimental» era thanks to the J.Weber resonant bar



1974 Binary pulsar PSR B1913+16 observation (1993 Nobel prize to Hulse & Taylor)



’80-’90: Cryogenic Resonant Bars

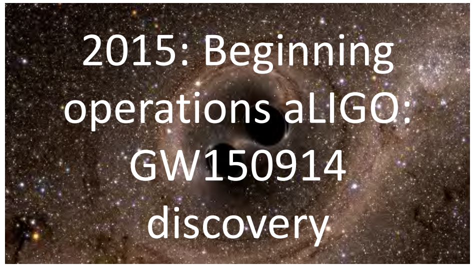
1986: B.Schutz (standard sirens), PPN templates …

1993

1994: Virgo project approval

1999+ Templates: EOB, Numerical relativity

1999+ Beginning operations LIGO and (+4y) Virgo

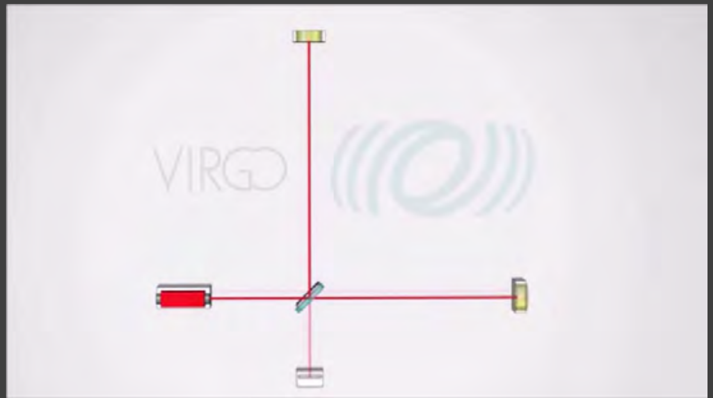


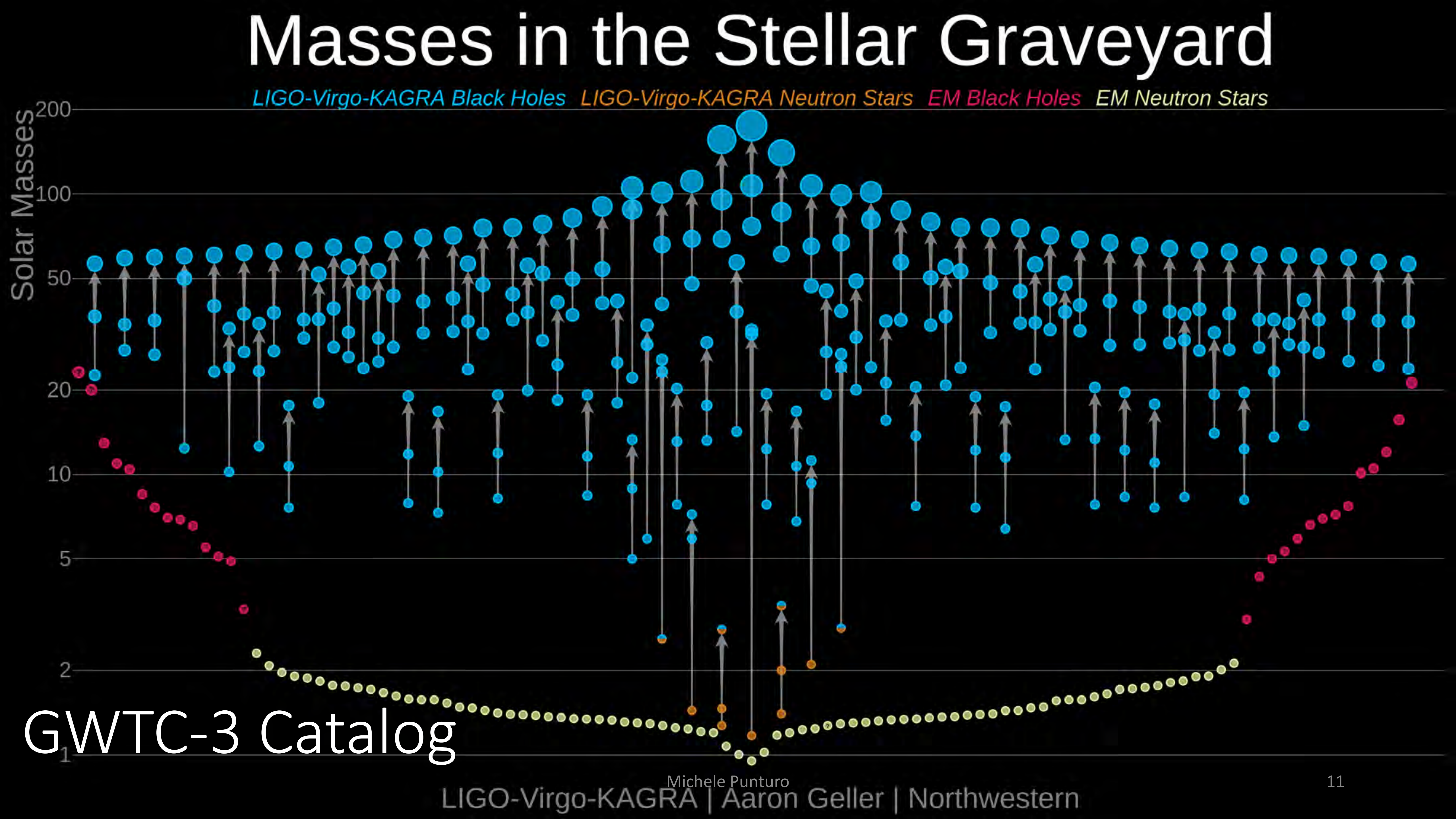
2015: Beginning operations aLIGO: GW150914 discovery

2017 Beginning operations Advanced Virgo: first BNS GW signal discovery: GW170817

t

Current interferometric GW detectors





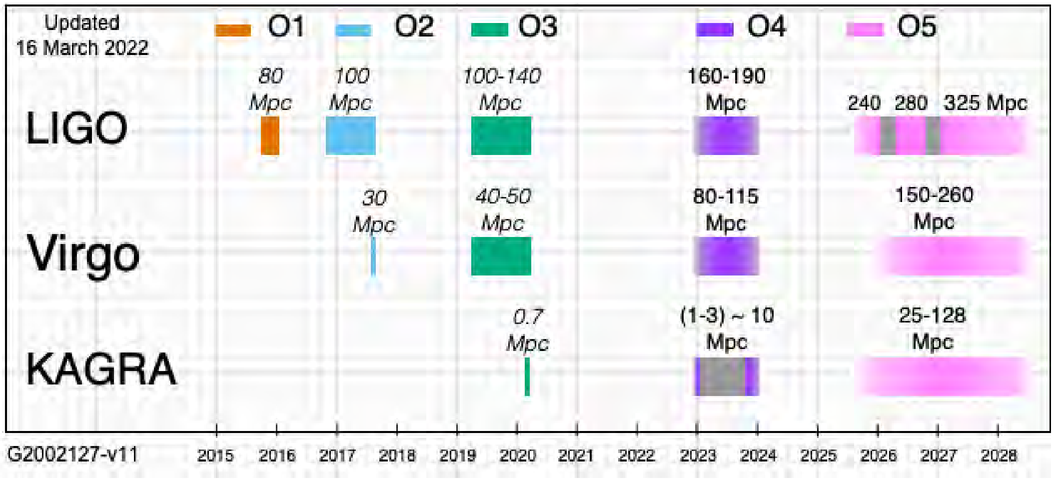
GWTC-3 Catalog

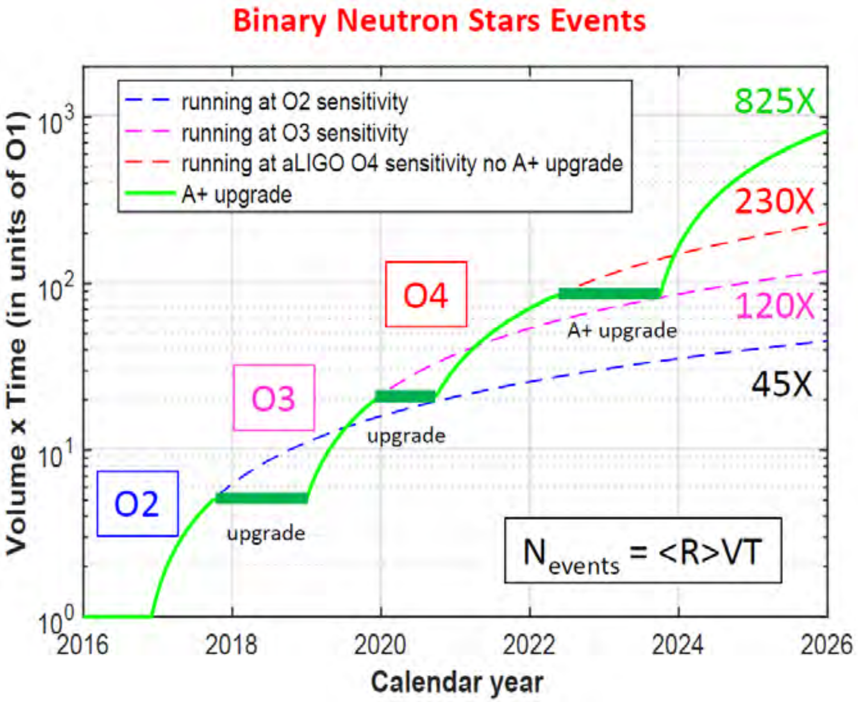
Monumental successes of the Advanced detectors

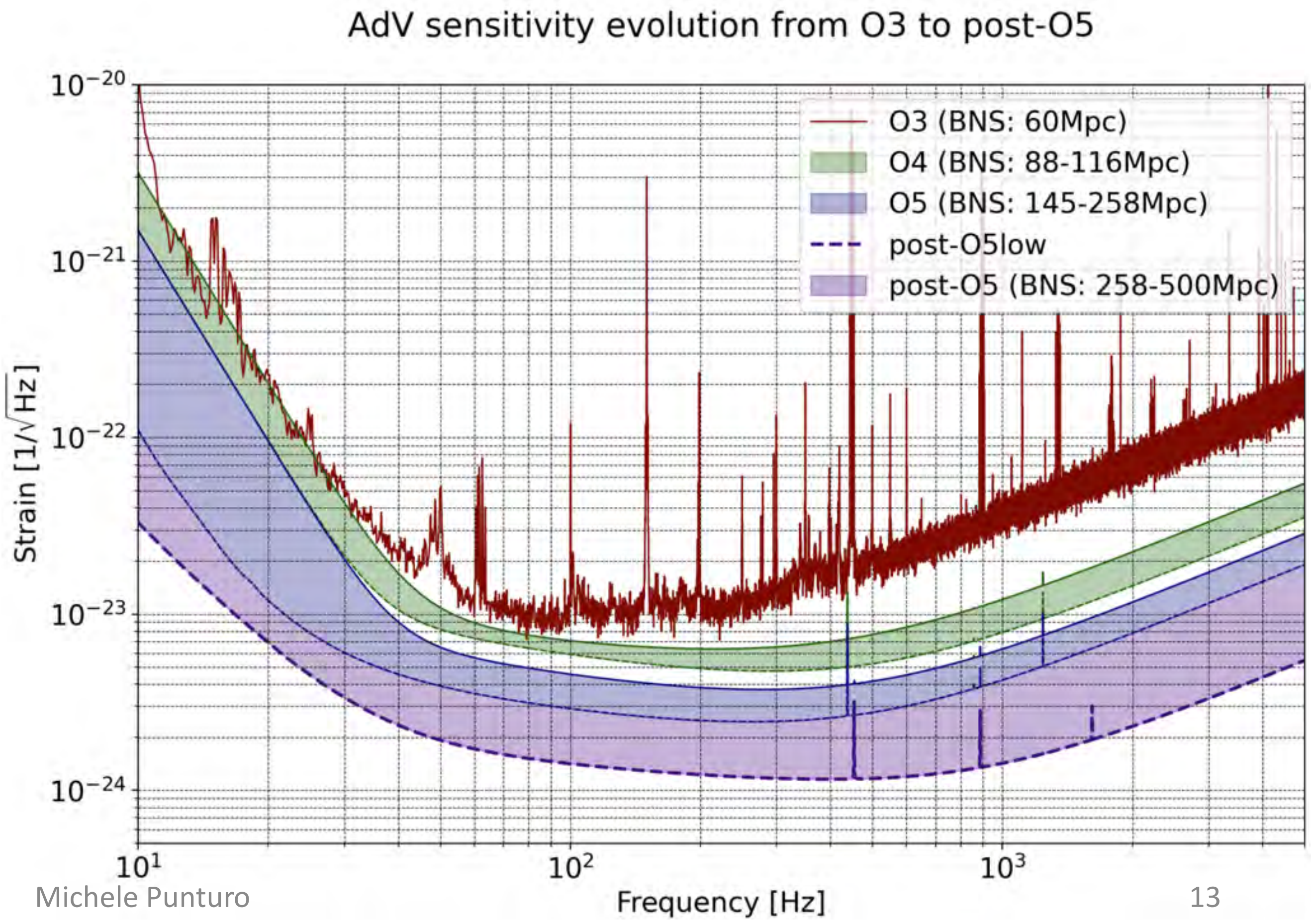
- First detection of GWs from a BBH system (GW150914)
  - Physics of BHs
- First detection of GWs from a BNS system (GW170817)
  - Birth of the multimessenger astronomy with GWs
  - Costraining EOS of NS
- Localisation capabilities of a GW source
- Measurement of the GW propagation speed
- Test of GR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

Near future

- **O4 run started on May 24th (LIGO)**;
- Virgo will join in autumn ’23;
- Current detectors have a well-defined plan of upgrades and science runs in the next years.



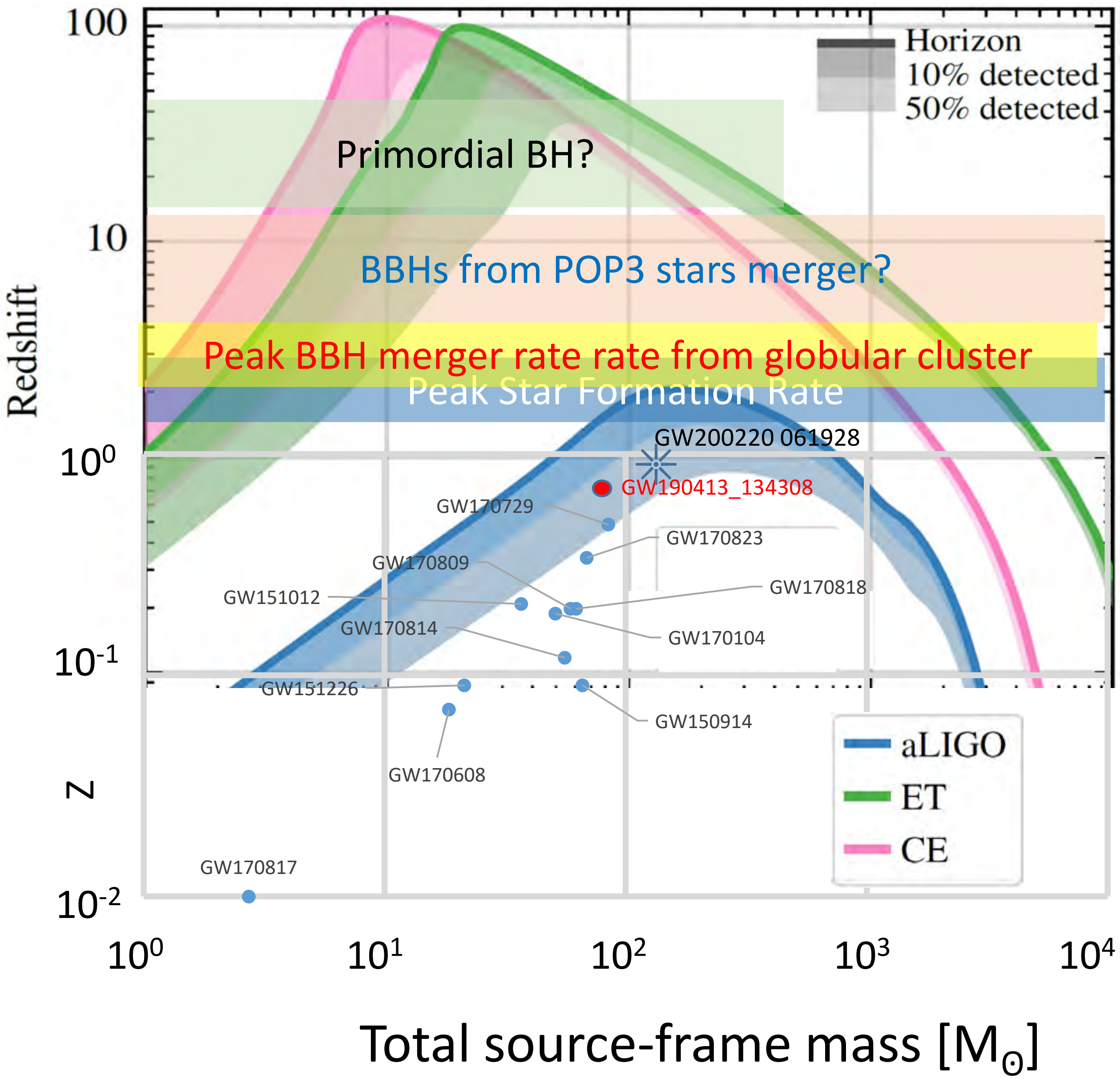




OK, all done?

- aLIGO and AdV achieved awesome results with a sensitivity poorer than the nominal one
- 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



3G ground-based detectors will be required to access the high redshift Universe

Detection distance of GWD

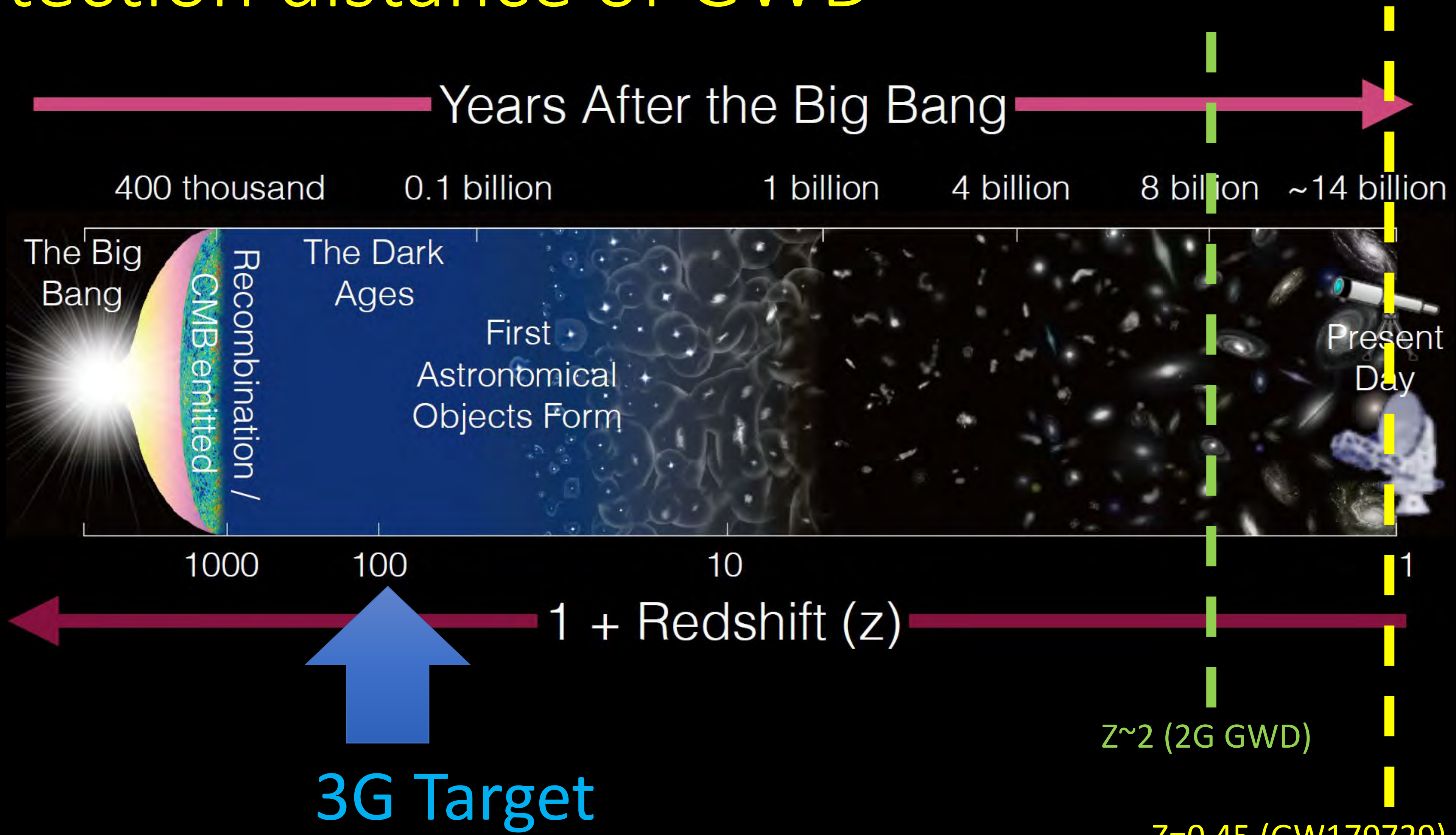
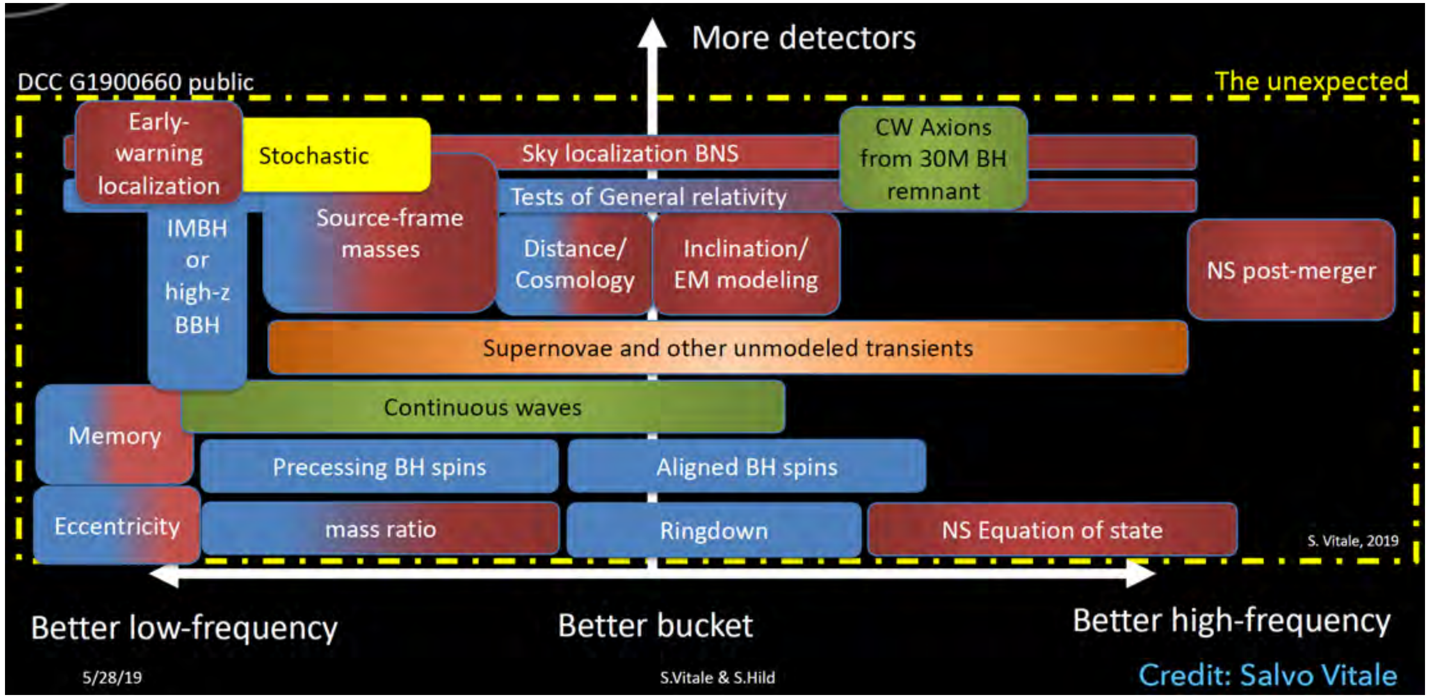


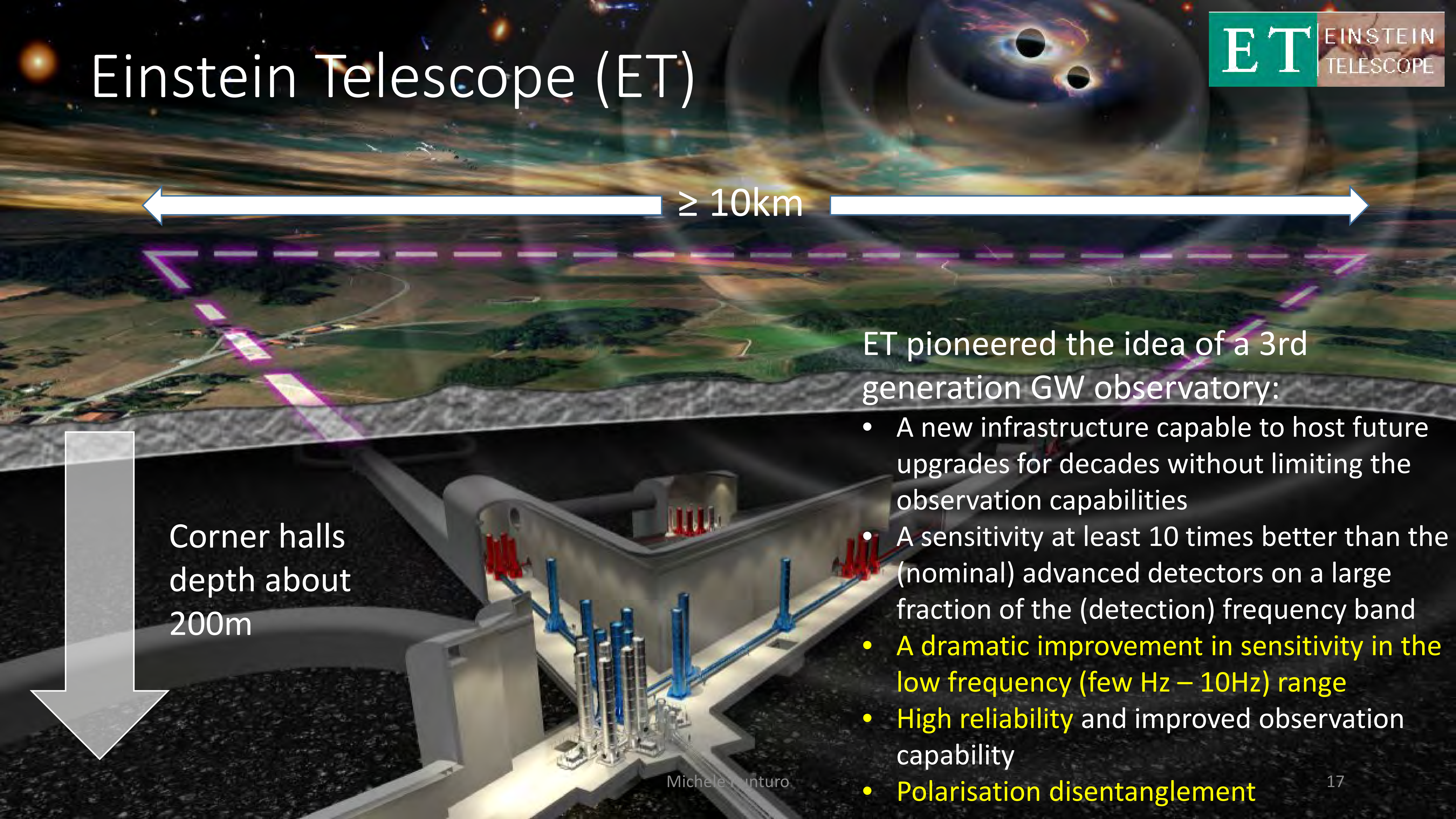
Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

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



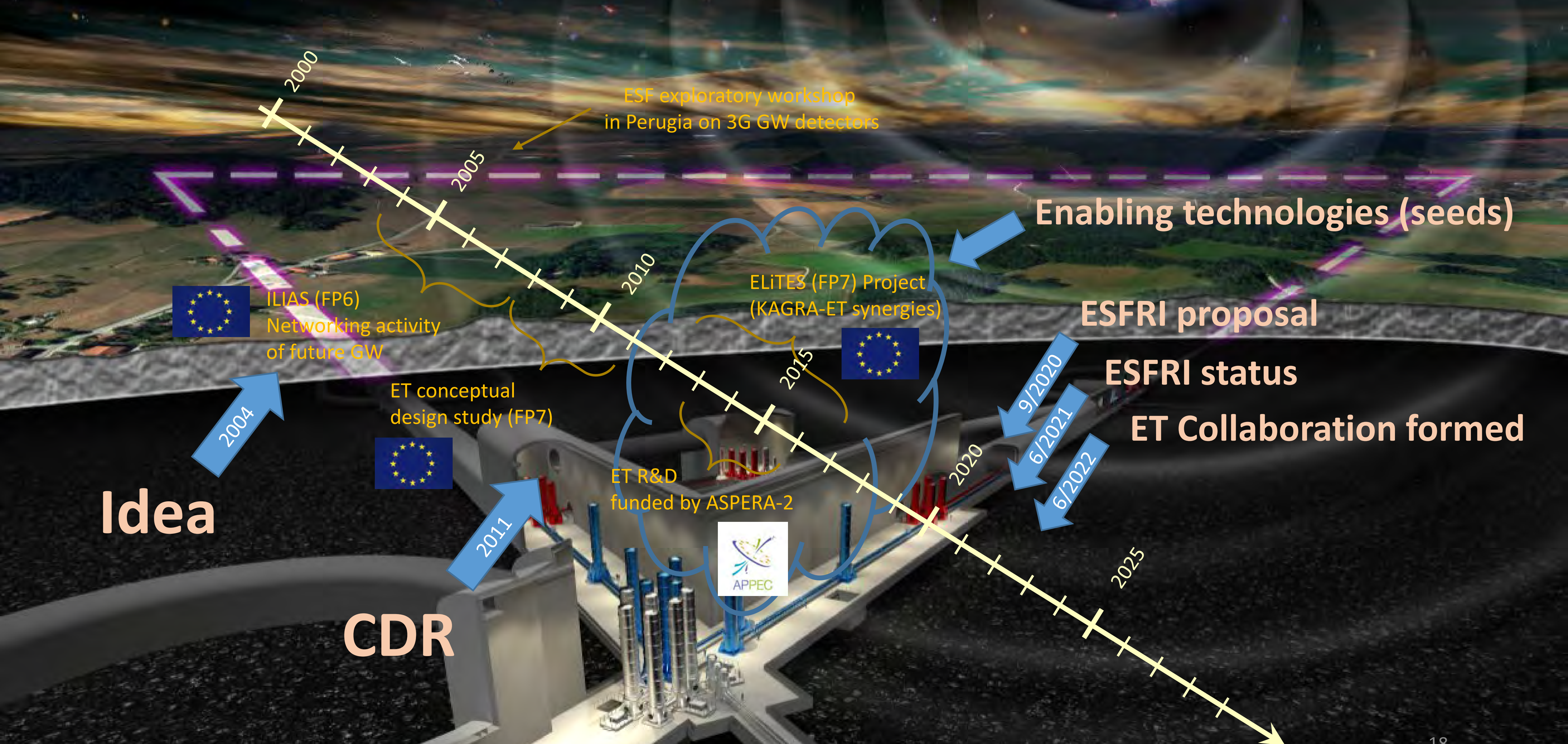
Einstein Telescope (ET)



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

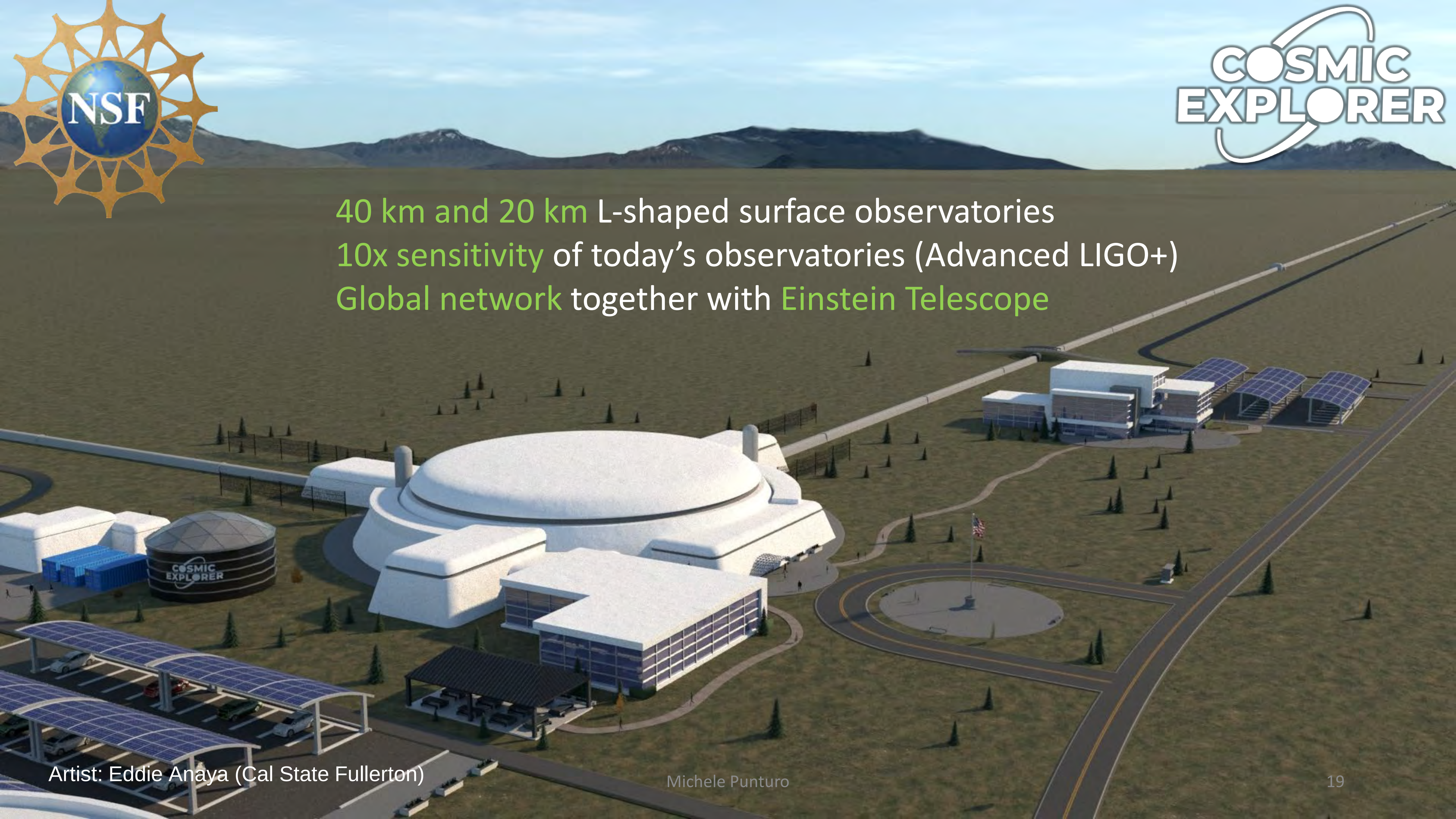
ET: a long path



40 km and 20 km L-shaped surface observatories

10x sensitivity of today's observatories (Advanced LIGO+)

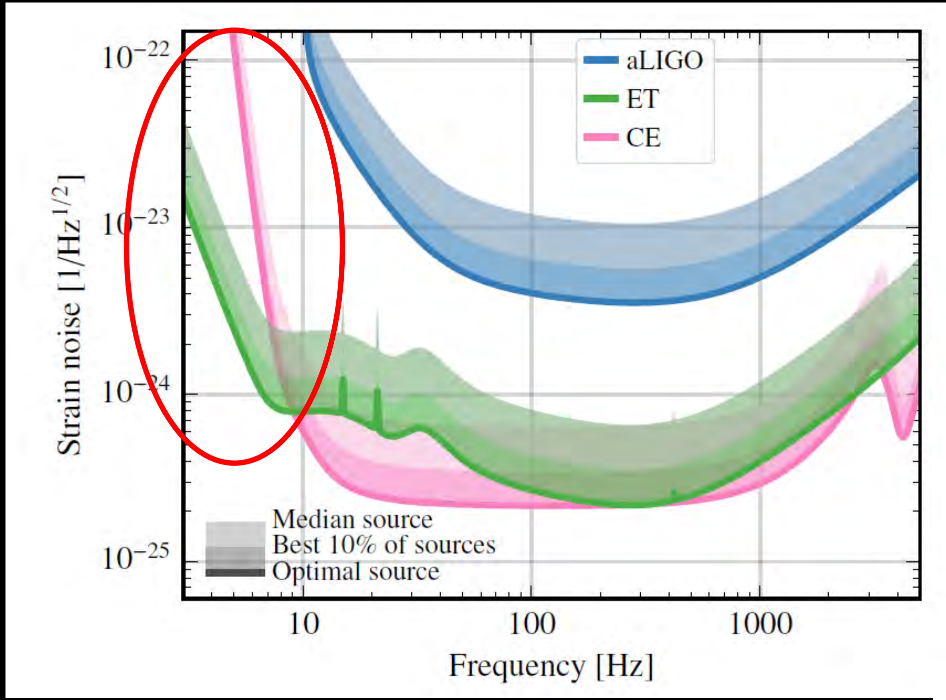
Global network together with Einstein Telescope

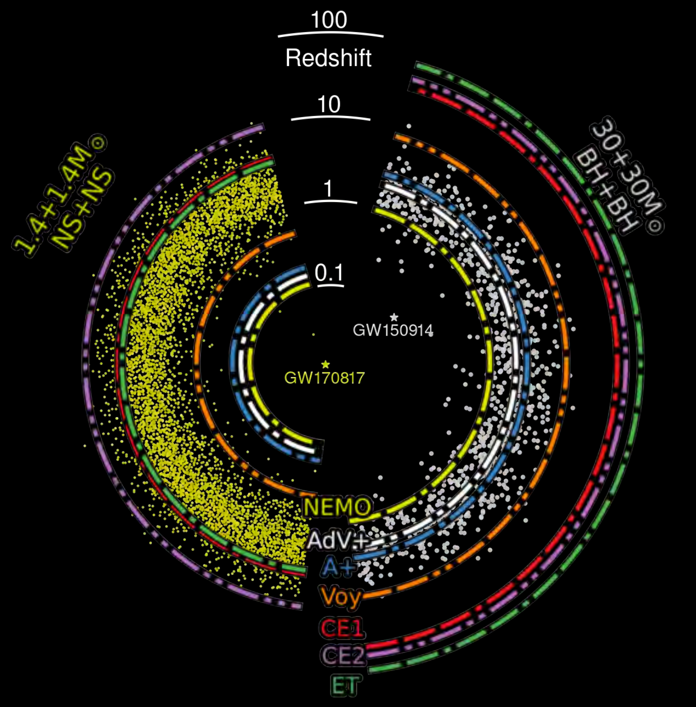


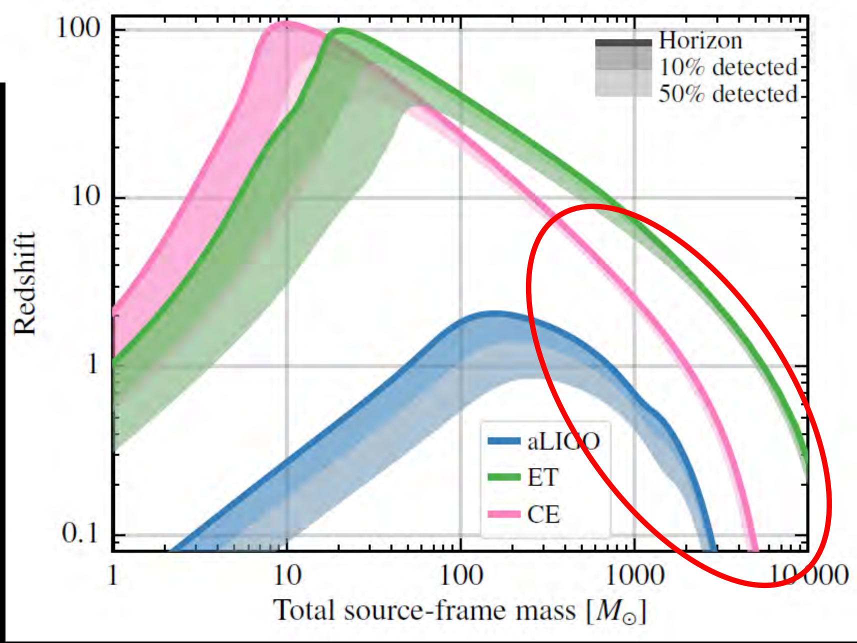
Artist: Eddie Anaya (Cal State Fullerton)

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





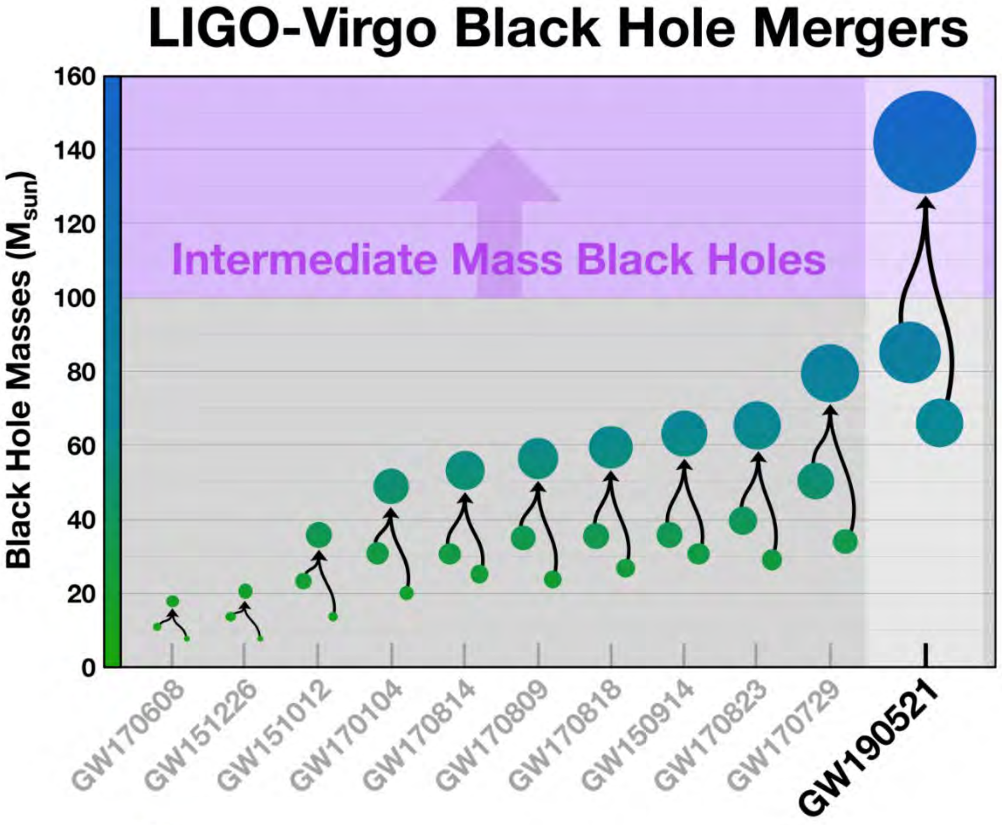


Michele Punturo

Why low frequency focus?

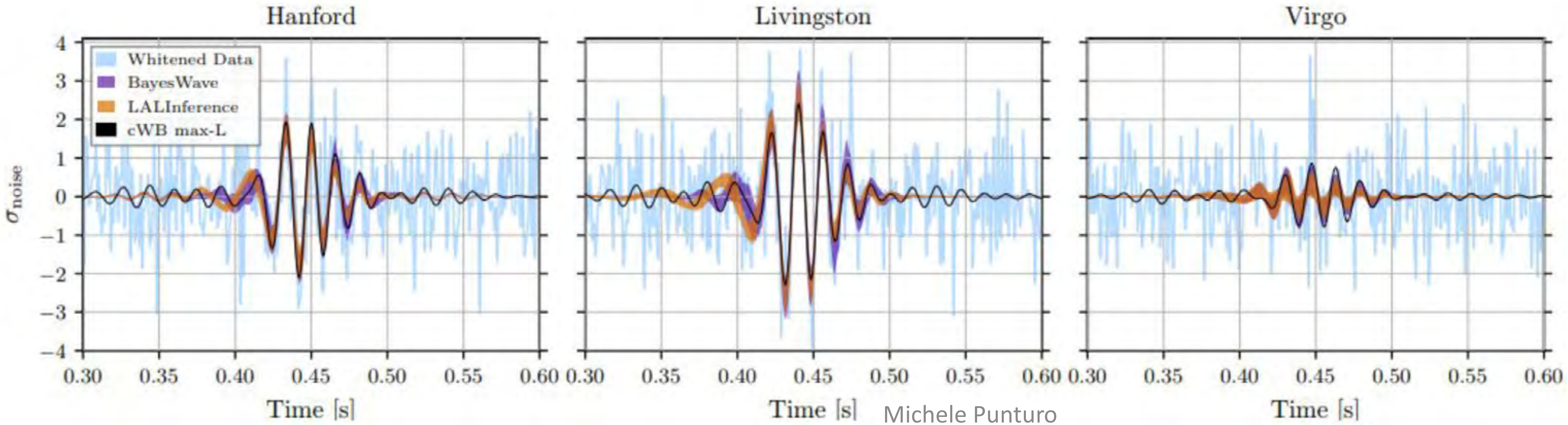
GW190521

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



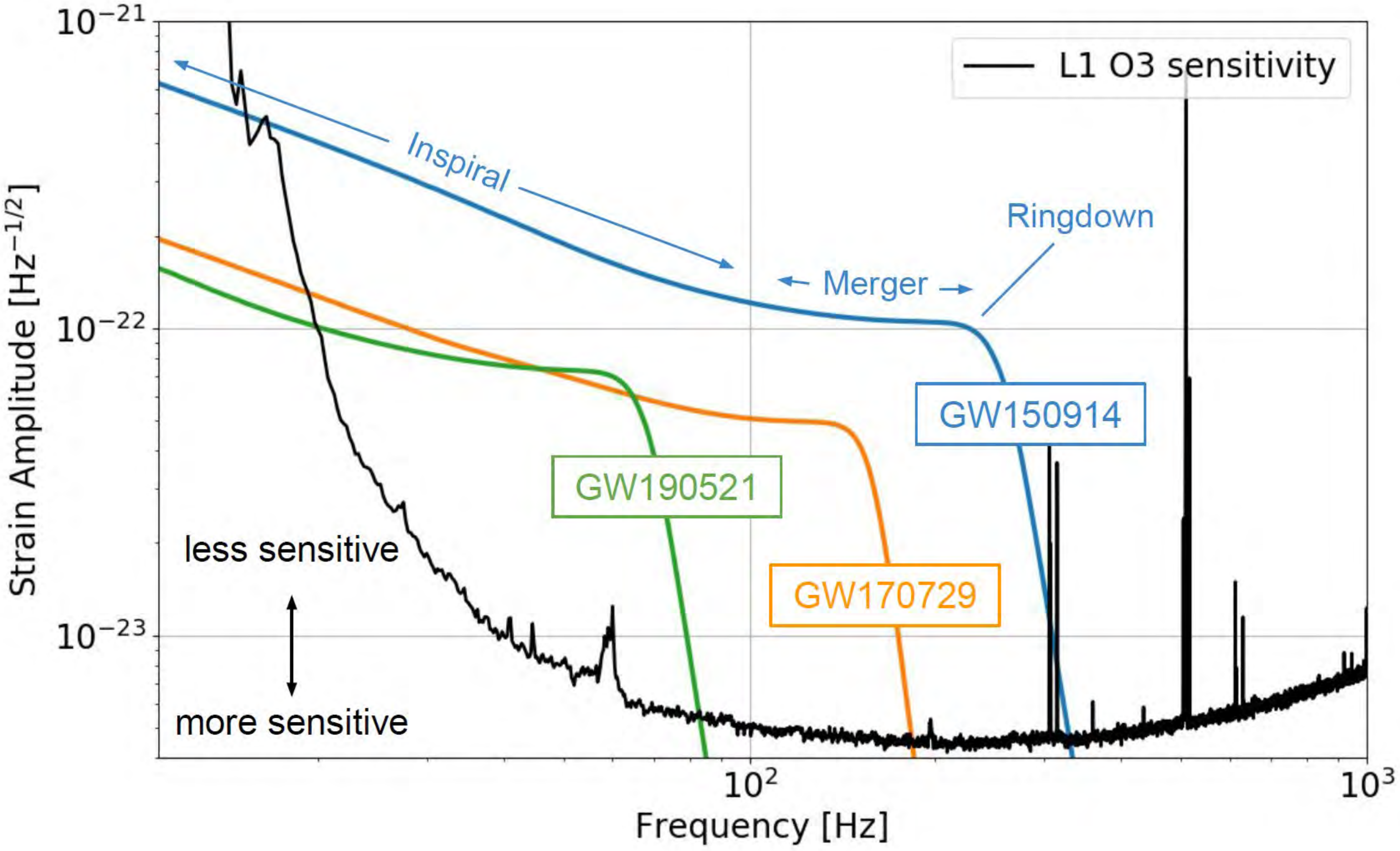
- Very special event:
  - M_1, a black hole that should not exist
  - M_f, the first IMBH ever seen

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



Where is the chirp?

GW190521: LIGO-Virgo sensitivity to the BBH merger



- Higher masses correspond to lower frequency GW emission

ET Science in a nutshell

EINSTEIN TELESCOPE

ASTROPHYSICS

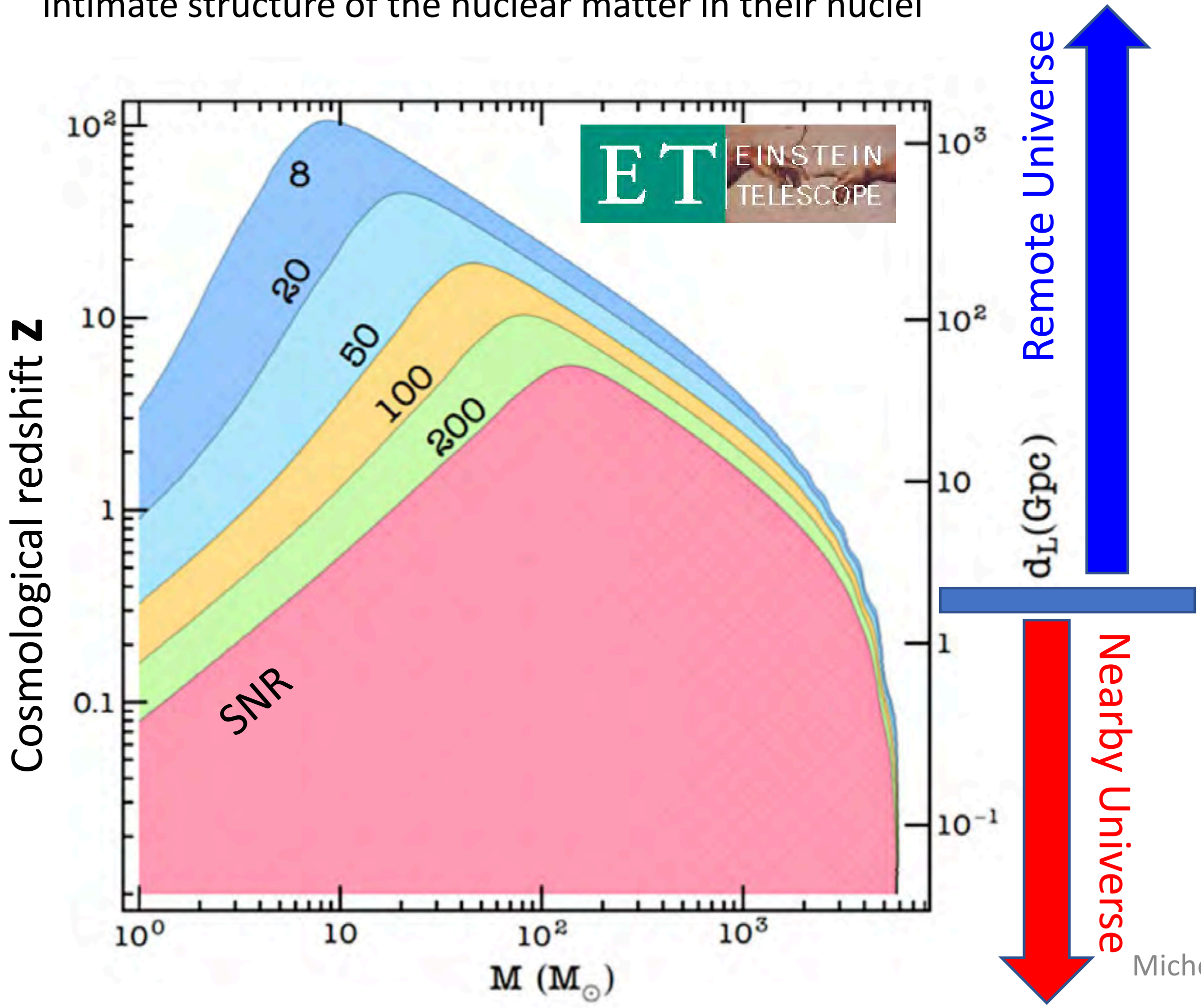
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)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

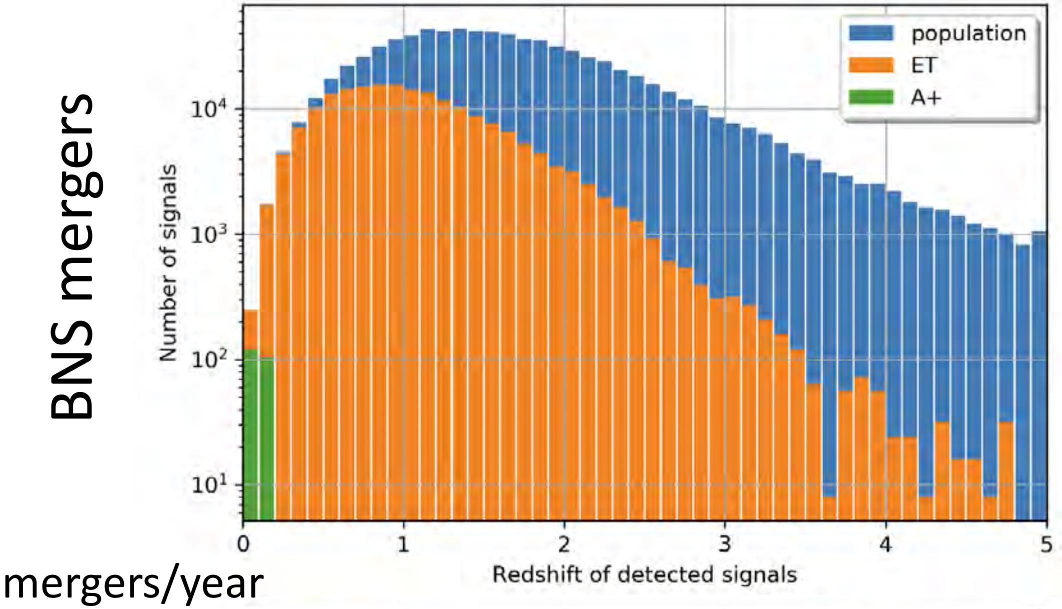
ET Science in a nutshell

- ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, 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

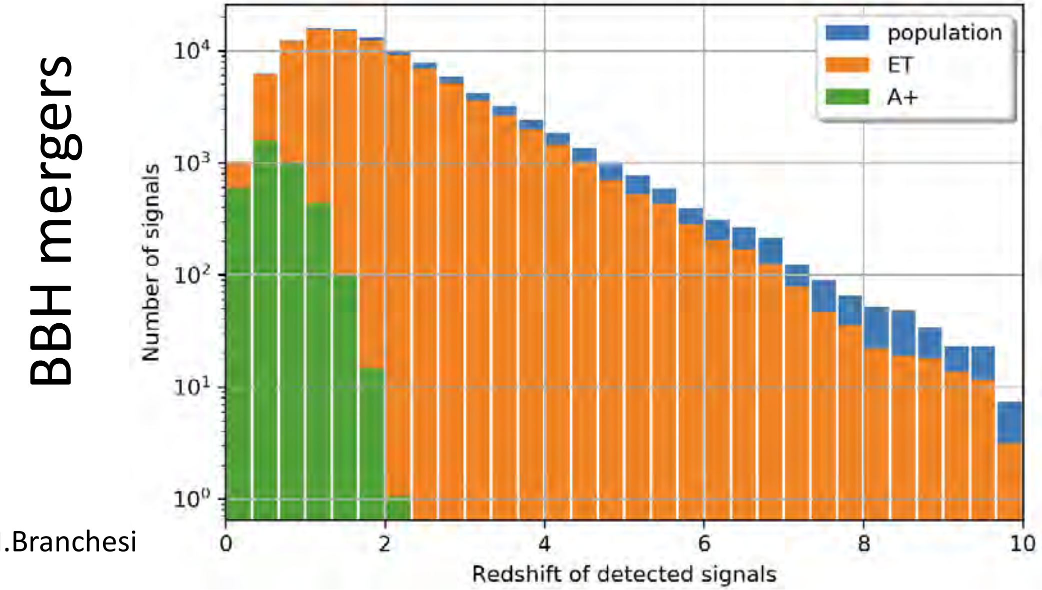


Michele Punturo

Compact Object Binary Populations



O(10^5) mergers/year

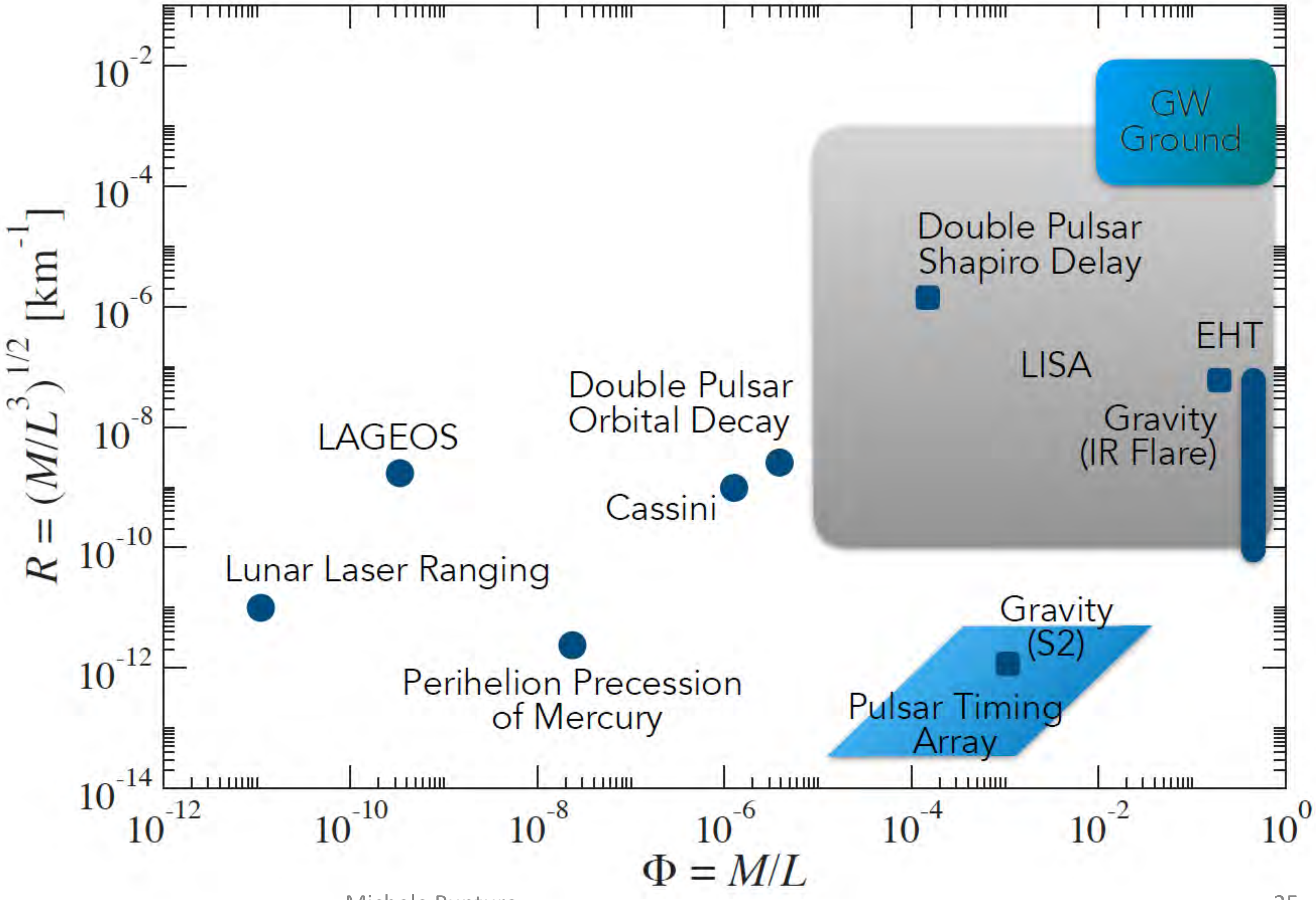


Credit: M.Branchesi

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



EINSTEIN TELESCOPE

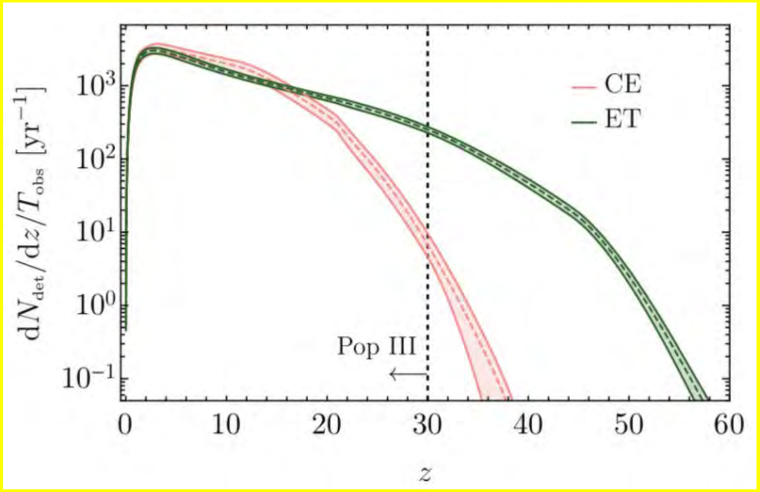
GW Science with ET

Extreme Gravity conditions

- In GR, no-hair theorem predicts that BHs are described only by their mass and spin (and charge)
  - However, when a BH is perturbed, it reacts (in GR) in a very specific manner, relaxing to its stationary configuration by oscillating in a superpositions of quasi-normal (QN) modes, which are damped by the emission of GWs.
  - A BH, a pure space-time configuration, reacts like an elastic body → Testing the "elasticity" of the space-time fabric
  - Exotic compact bodies could have a different QN emission and have echoes.

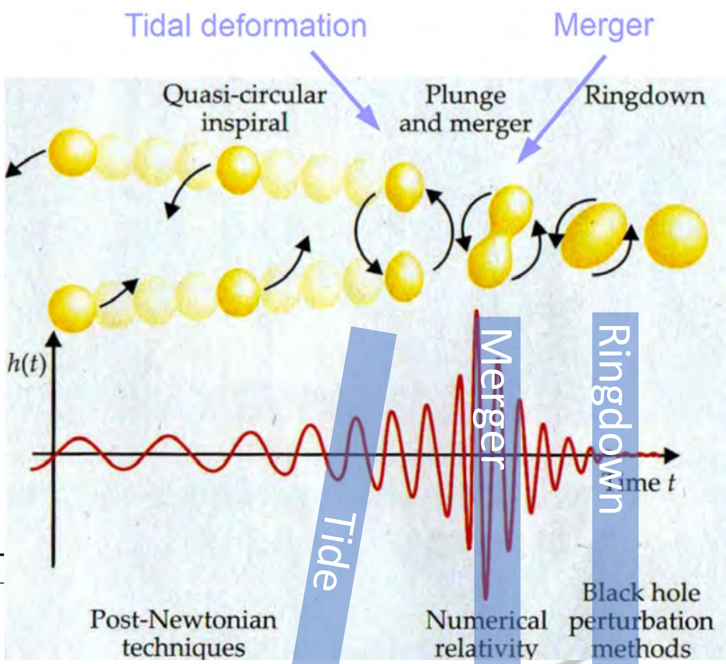
Primordial Black Holes

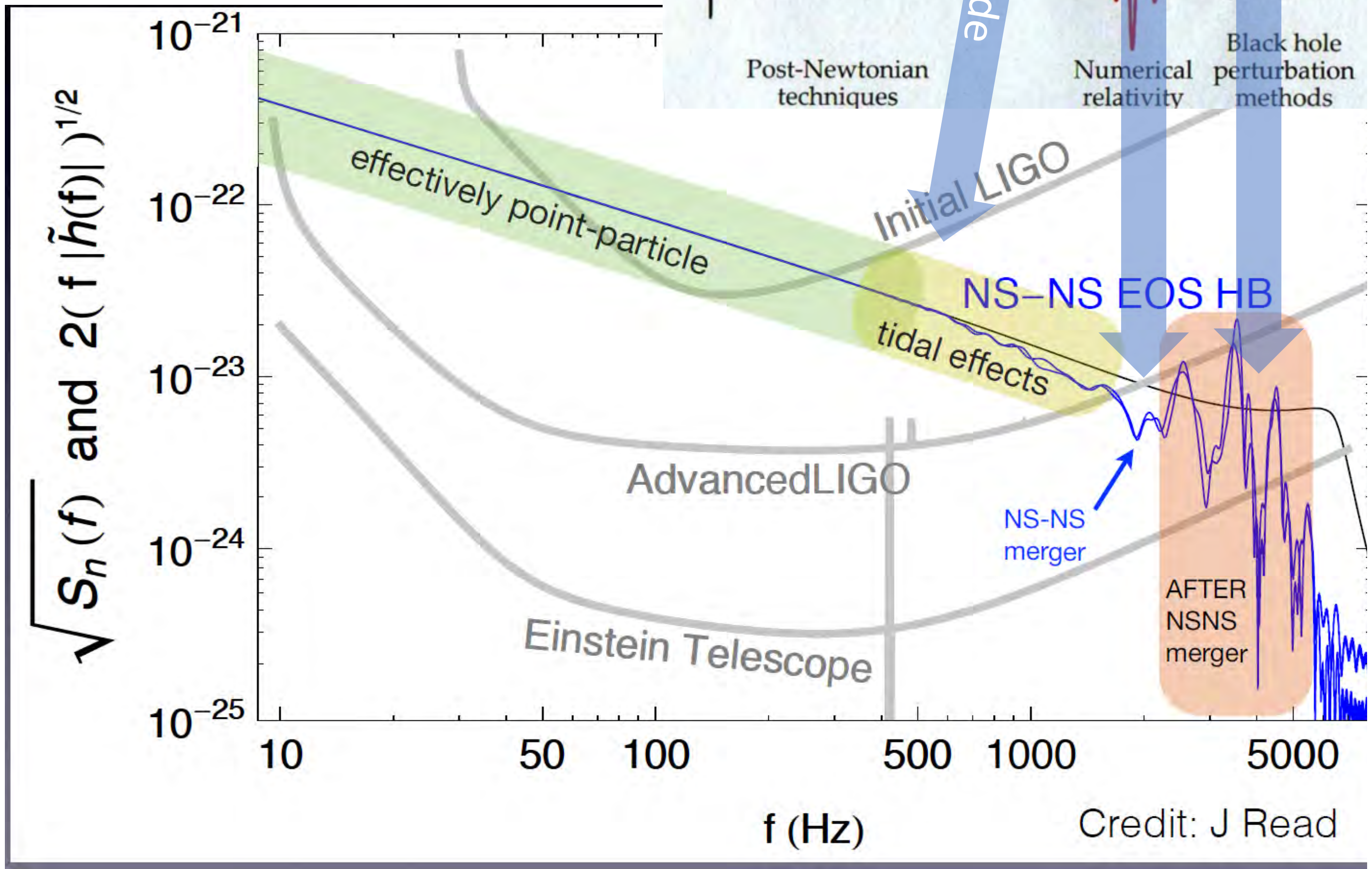
- ET (and CE) will detect BH well beyond the SFR peak z~2
  - comparing the redshift dependence of the BH-BH merger rate with the cosmic star formation rate to disentangle the contribution of BHs of stellar origin from that of possible BHs of primordial origin: any BBH merger at z>30 will be of primordial origin.

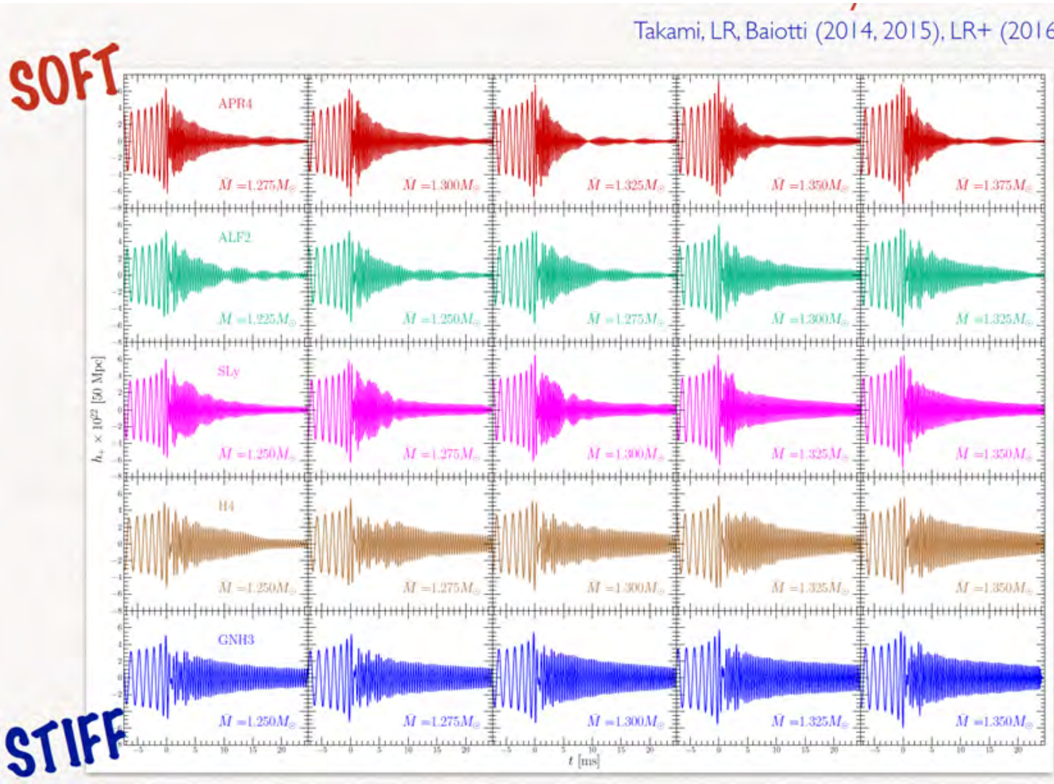


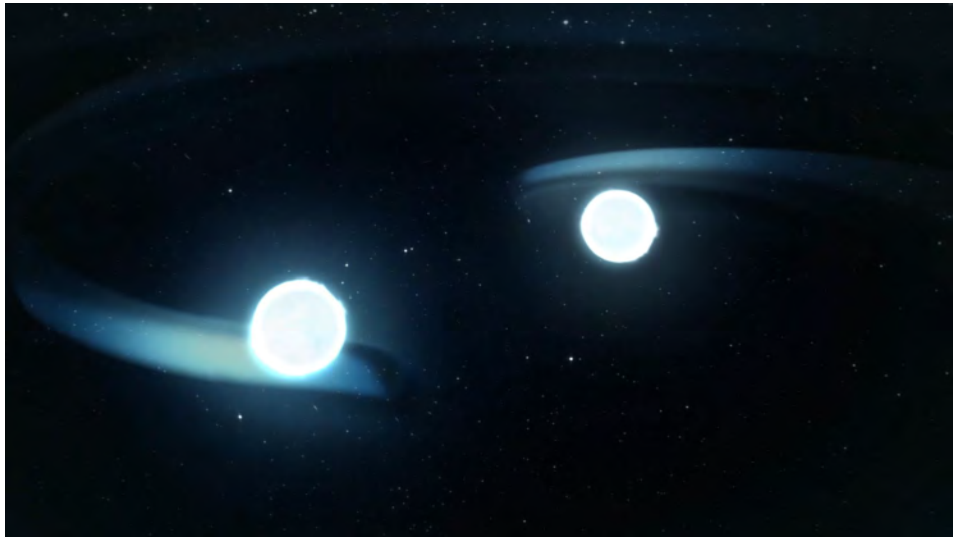
Structure of a Neutron Star

Stephen Fairhurst
ET meeting 27-28 March 2017

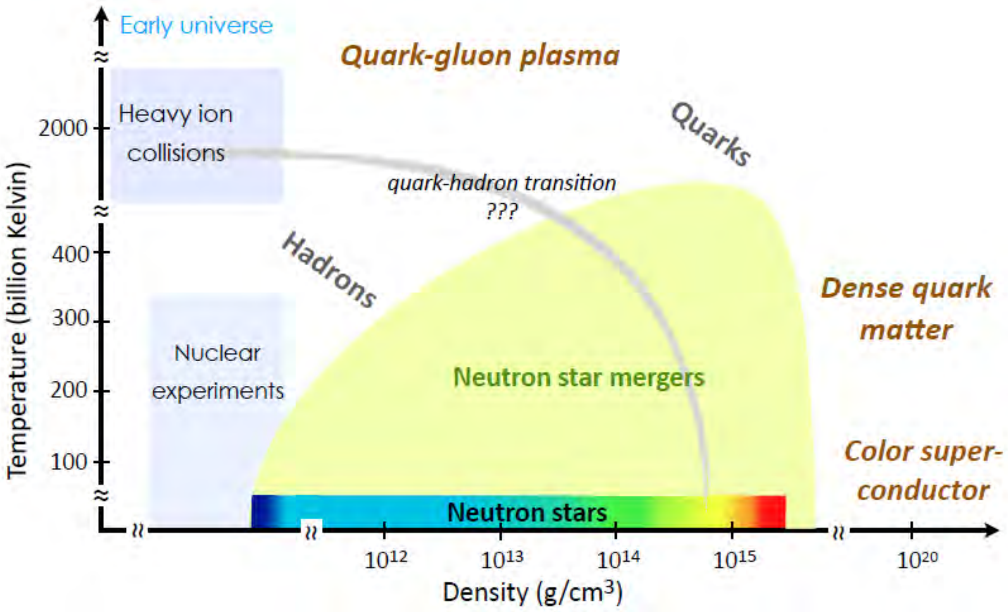




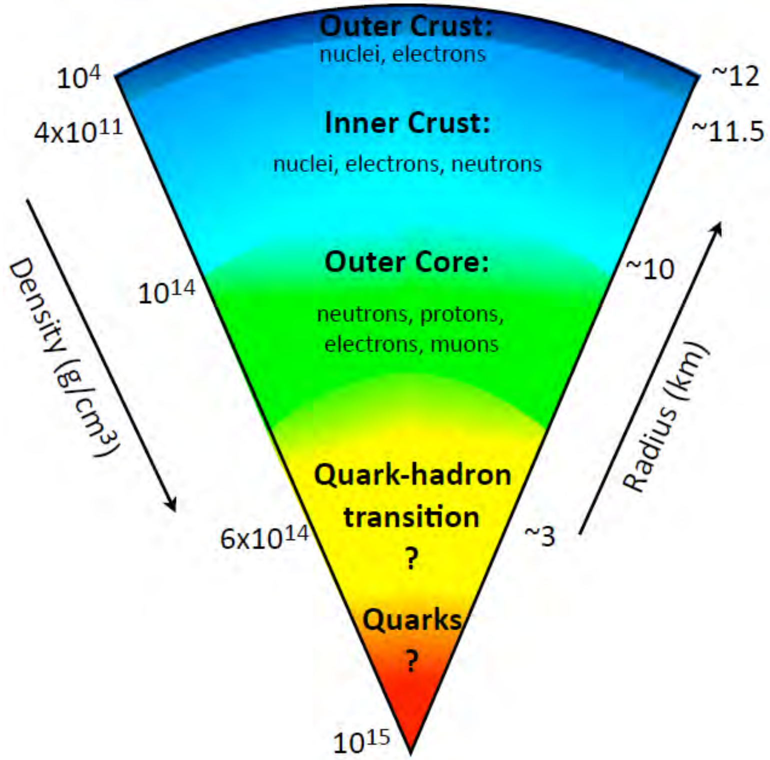




- Neutron stars are an **extreme laboratory for nuclear physics**
  - The external crust is a Coulomb Crystal of progressively more neutron-reach nuclei.
  - The core is a Fermi liquid of uniform neutron-rich matter (“Exotic phases”? Quark-Gluon plasma?)

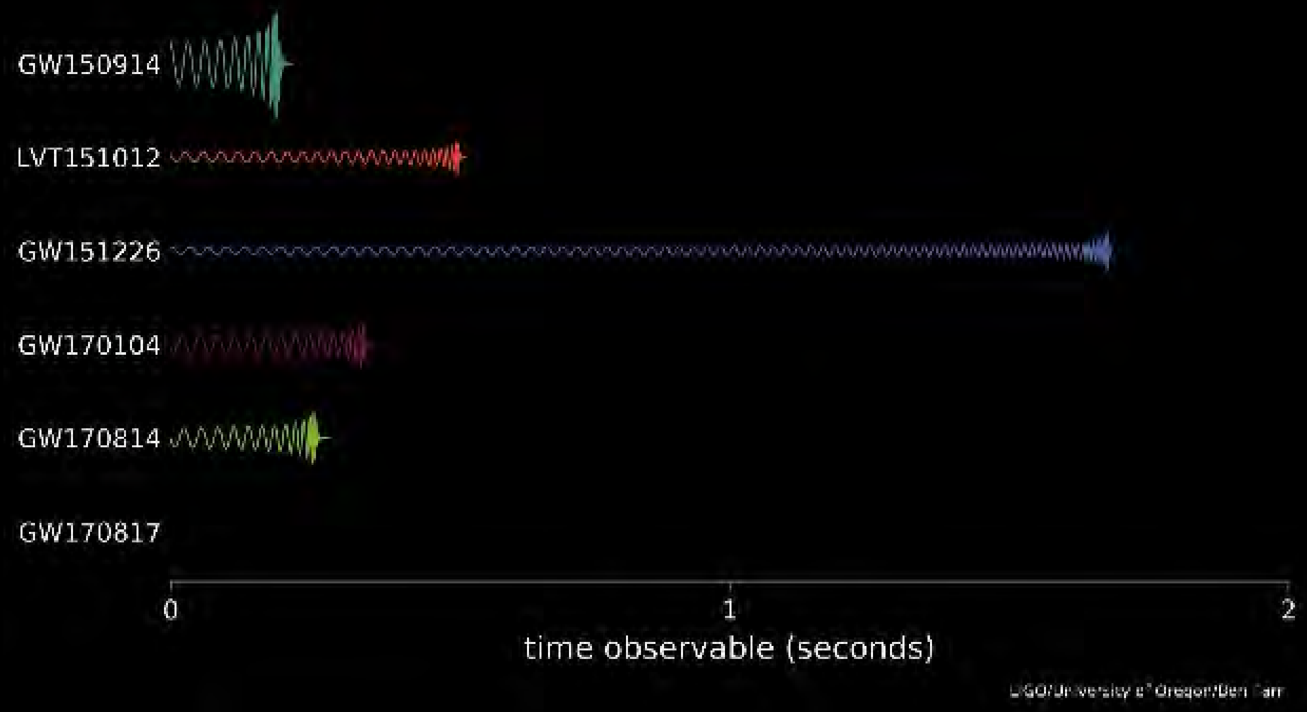


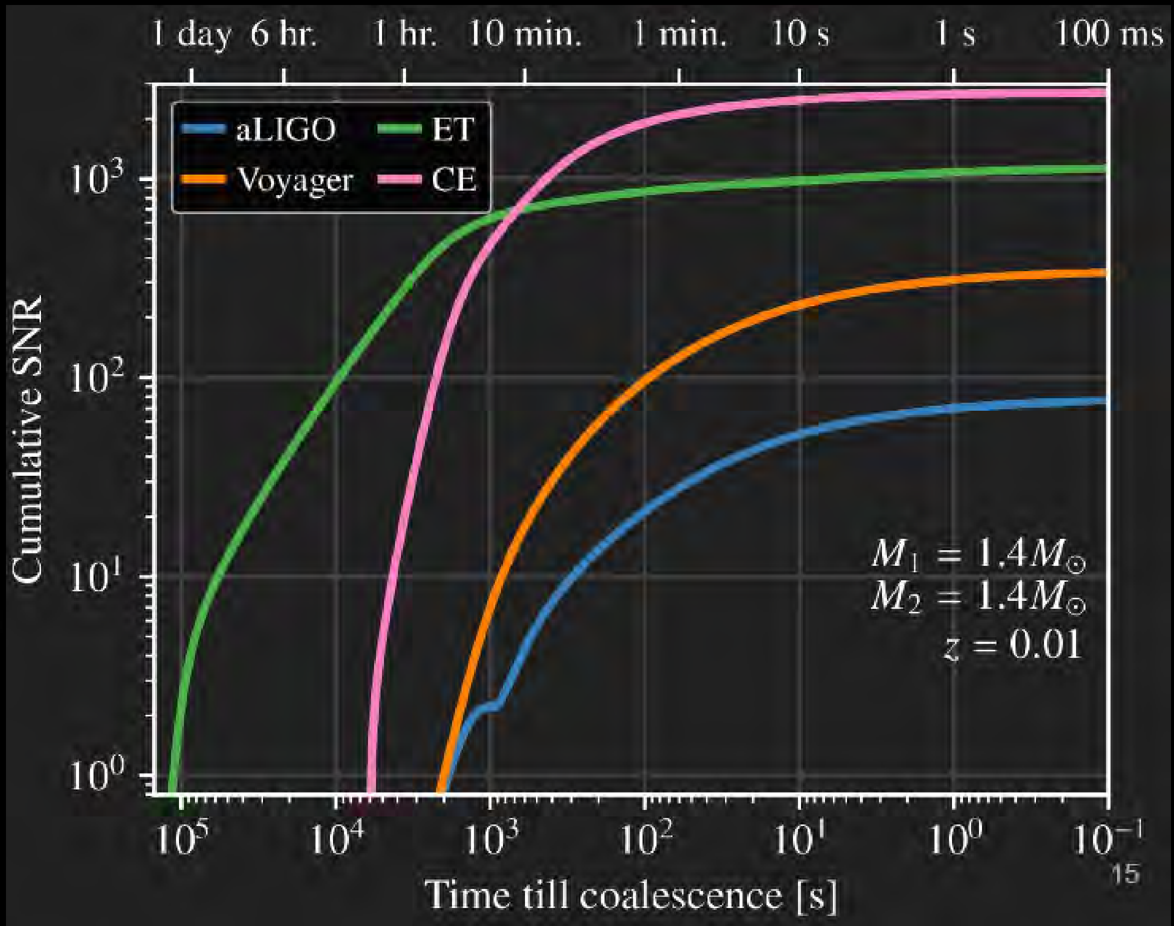
- Tidal deformation from the dephasing in the GW signal → constrain the EOS of the NS.
- EM information → more stringent constrain.
- EOS describes the status of the matter in the over-critical pressure condition.



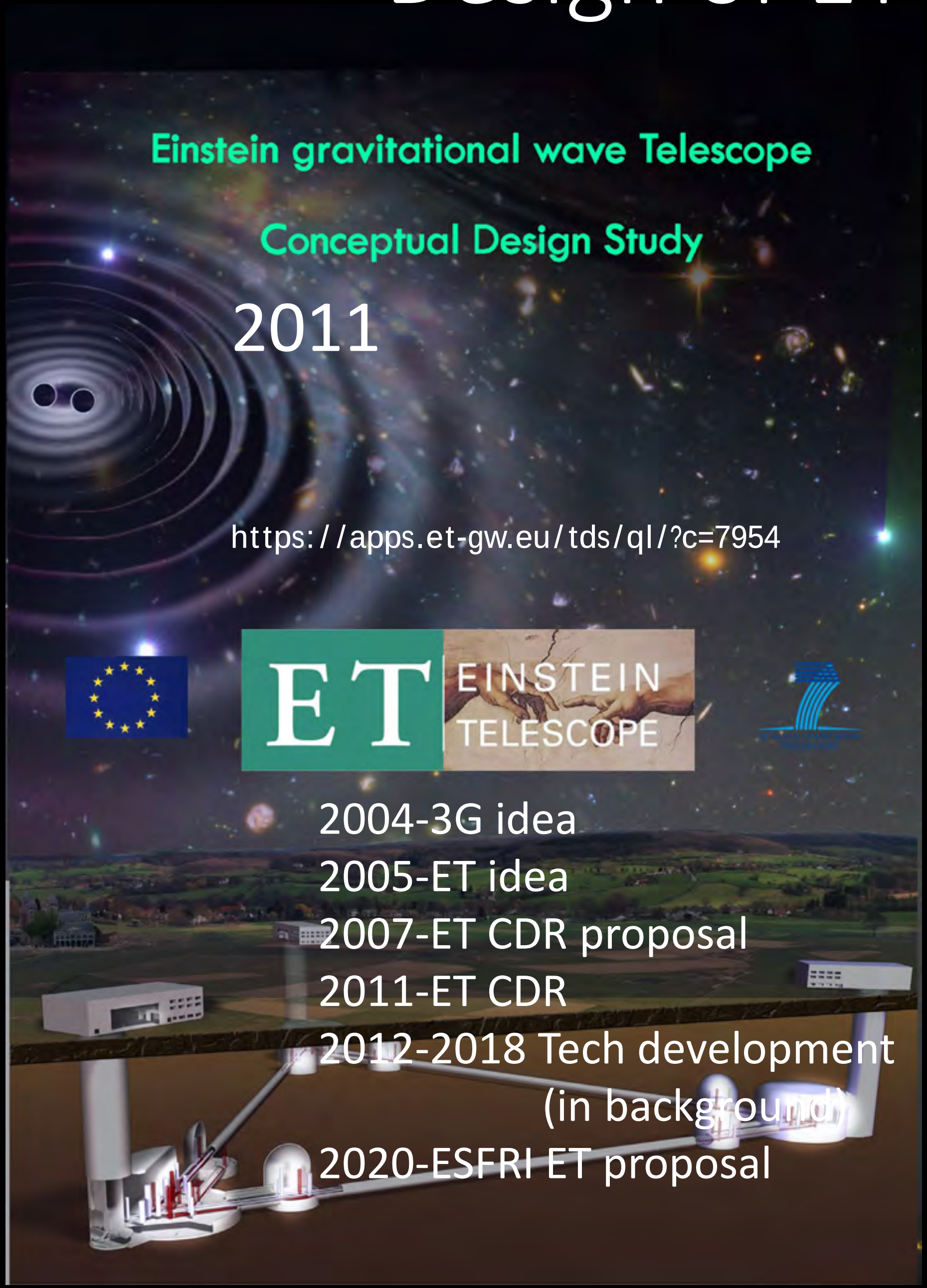
Low frequency: Multi-messenger astronomy

- If we are able to cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons
- Keyword: low frequency sensitivity:





Design of ET

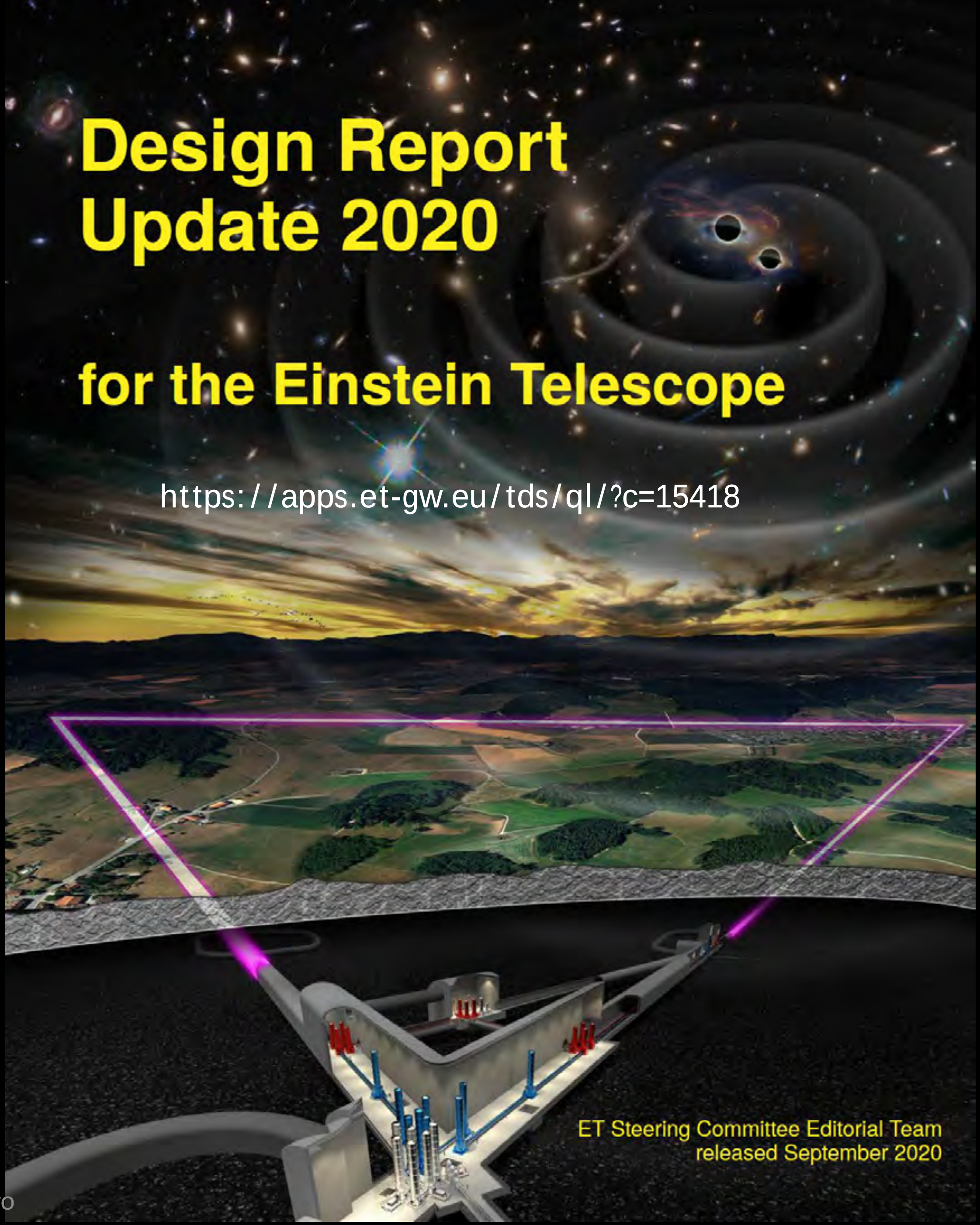


2011

https://apps.et-gw.eu/tds/ql/?c=7954

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

ESFRI



https://apps.et-gw.eu/tds/ql/?c=15418

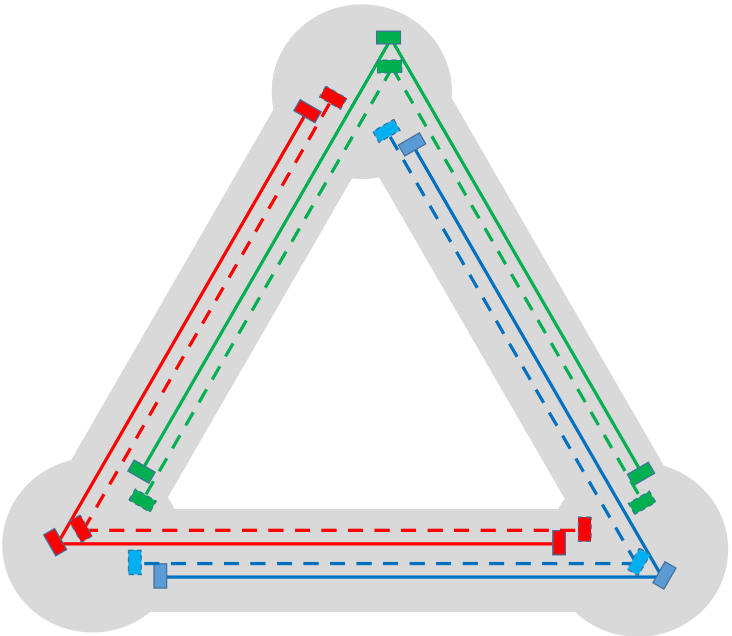
ET key elements

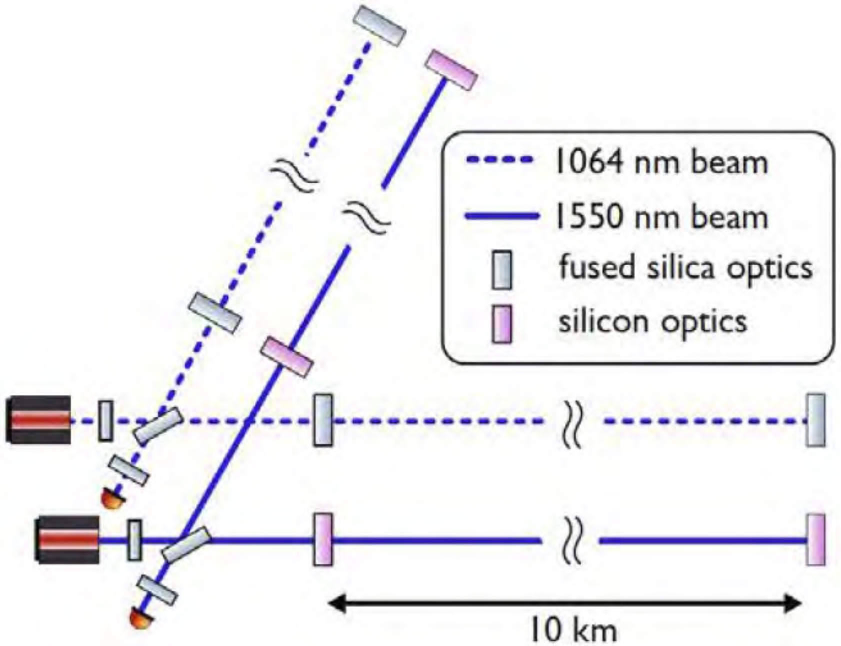
Requirements

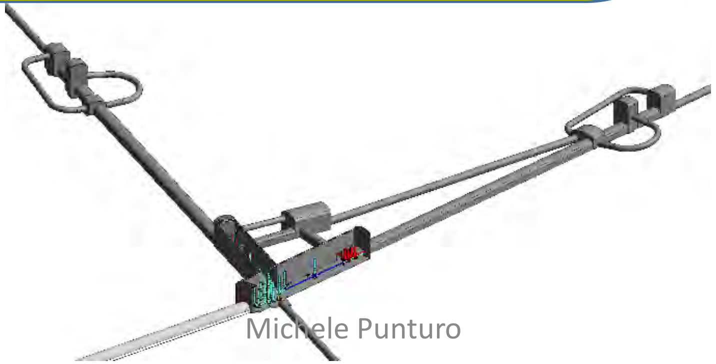
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

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







EINSTEIN TELESCOPE

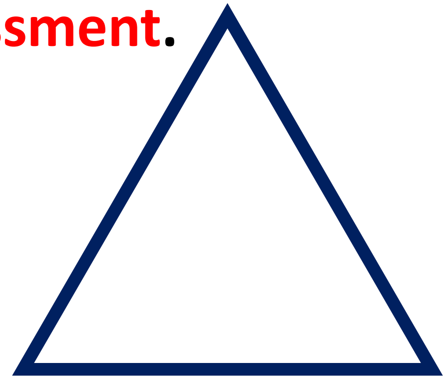
ET design: Δ or (two) L

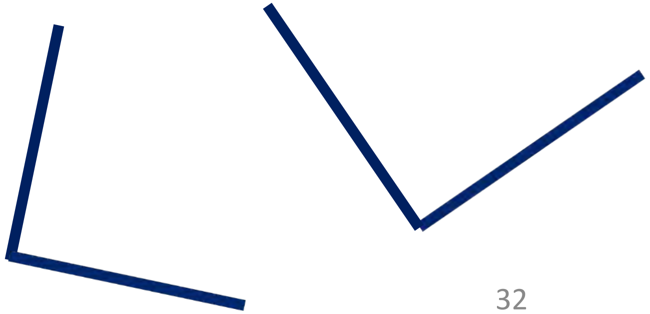
In the last couple of years, the collaboration started the evaluation of the best configuration for ET, considering the alternative of two L configuration (as LIGO, Cosmic Explorer) to maximize the science return and reduce risks.

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

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

The collaboration is analyzing both configurations: **optimizing science return**, **differential risk assessment**.





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

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

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

Evolved laser technology

Evolved technology in optics

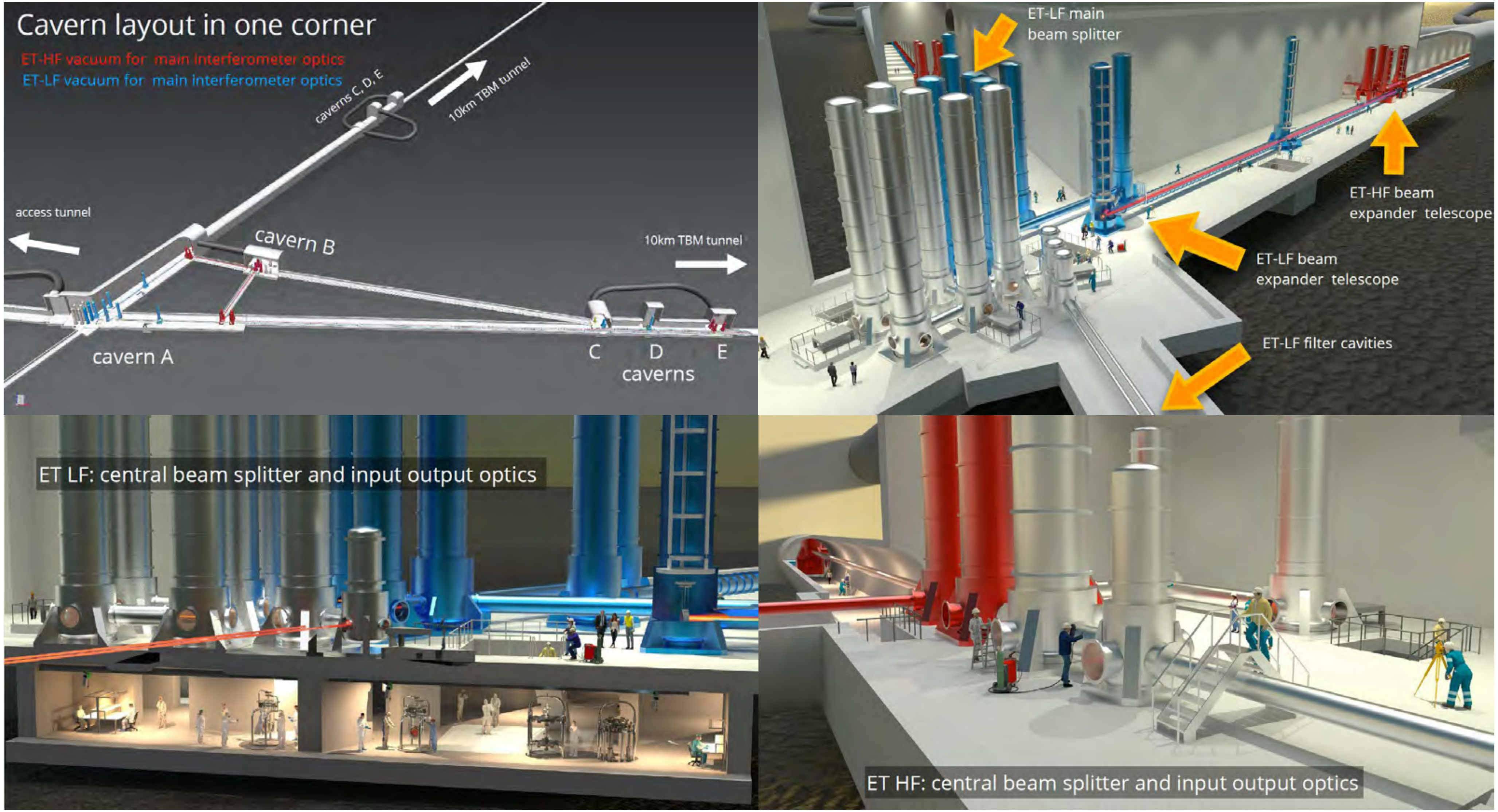
Highly innovative adaptive optics

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

ET: large scale and complex infrastructure



Credit: A.Freise, 2020 XI ET Symposium

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 (cryo-fluids or cryo-coolers)
- Materials
- Safety

Low Frequency special focus

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

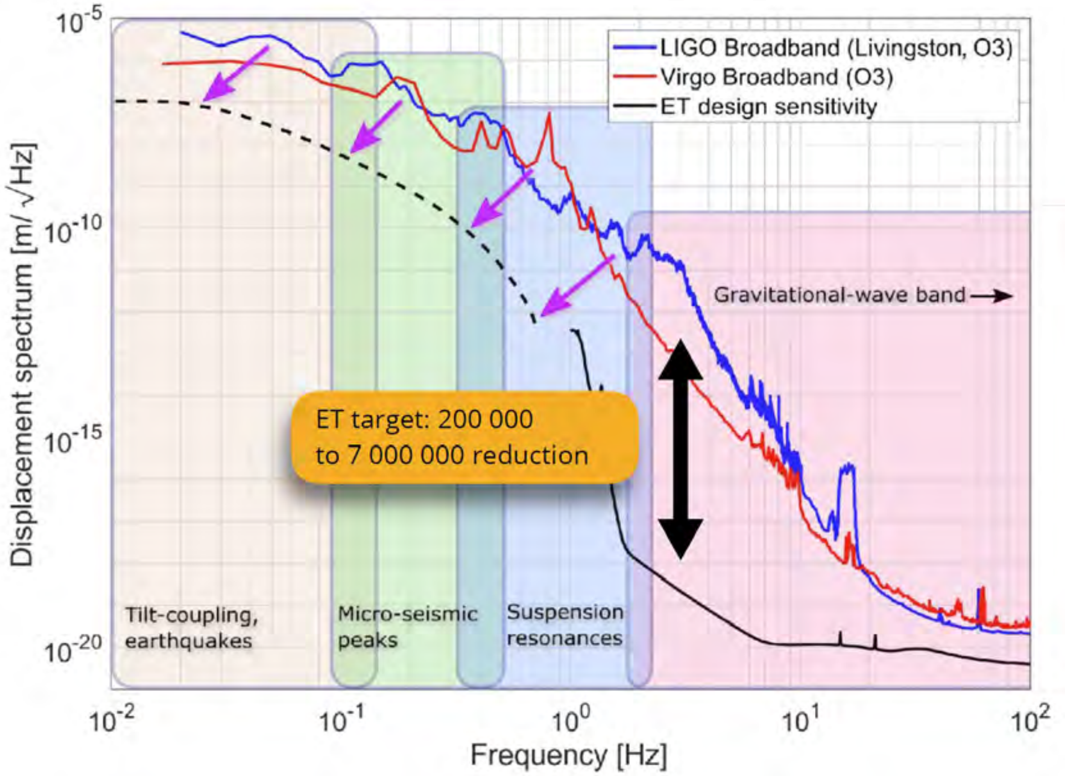
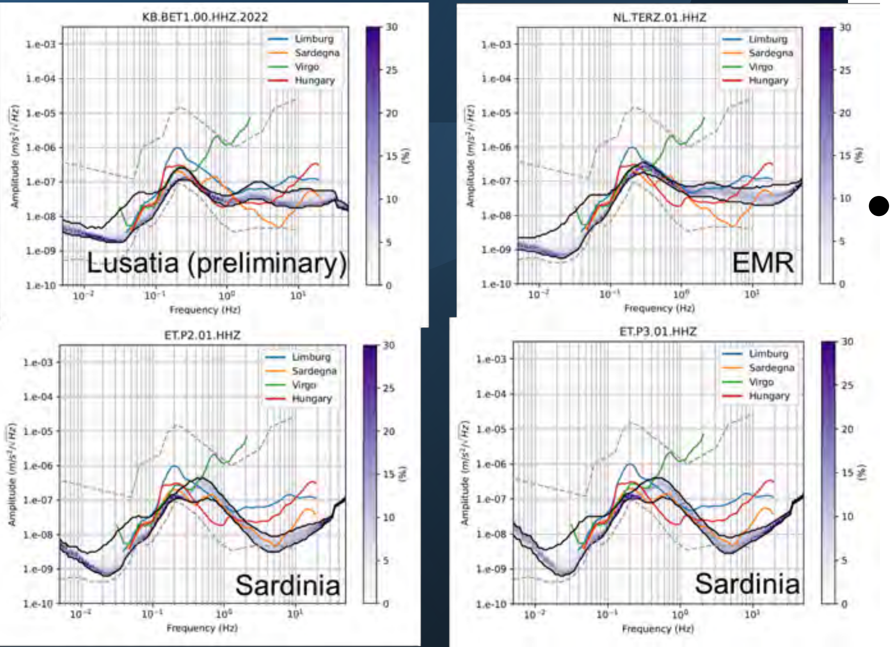


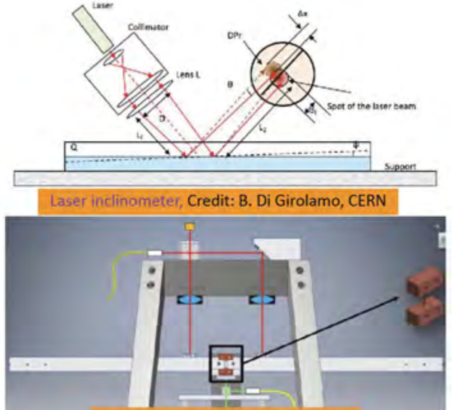
Image: Conor Mow-Lowry



Credits: A.Freise

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

Low frequency seismometers
Credit: Christophe Collette, U. Liege

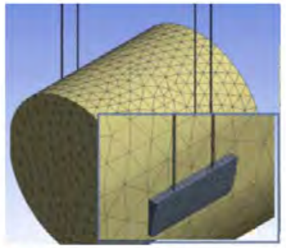


Laser inclinometer, Credit: B. Di Girolamo, CERN

Ultralow frequency tiltmeter
Credit: ARCHIMEDES and VIRGO Coll.

Credits: A.Freise

New Optics

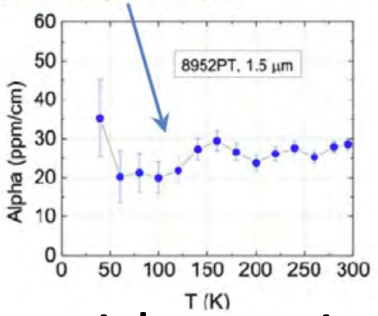



Advanced LIGO – 40 kg / ET 200 kg

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:

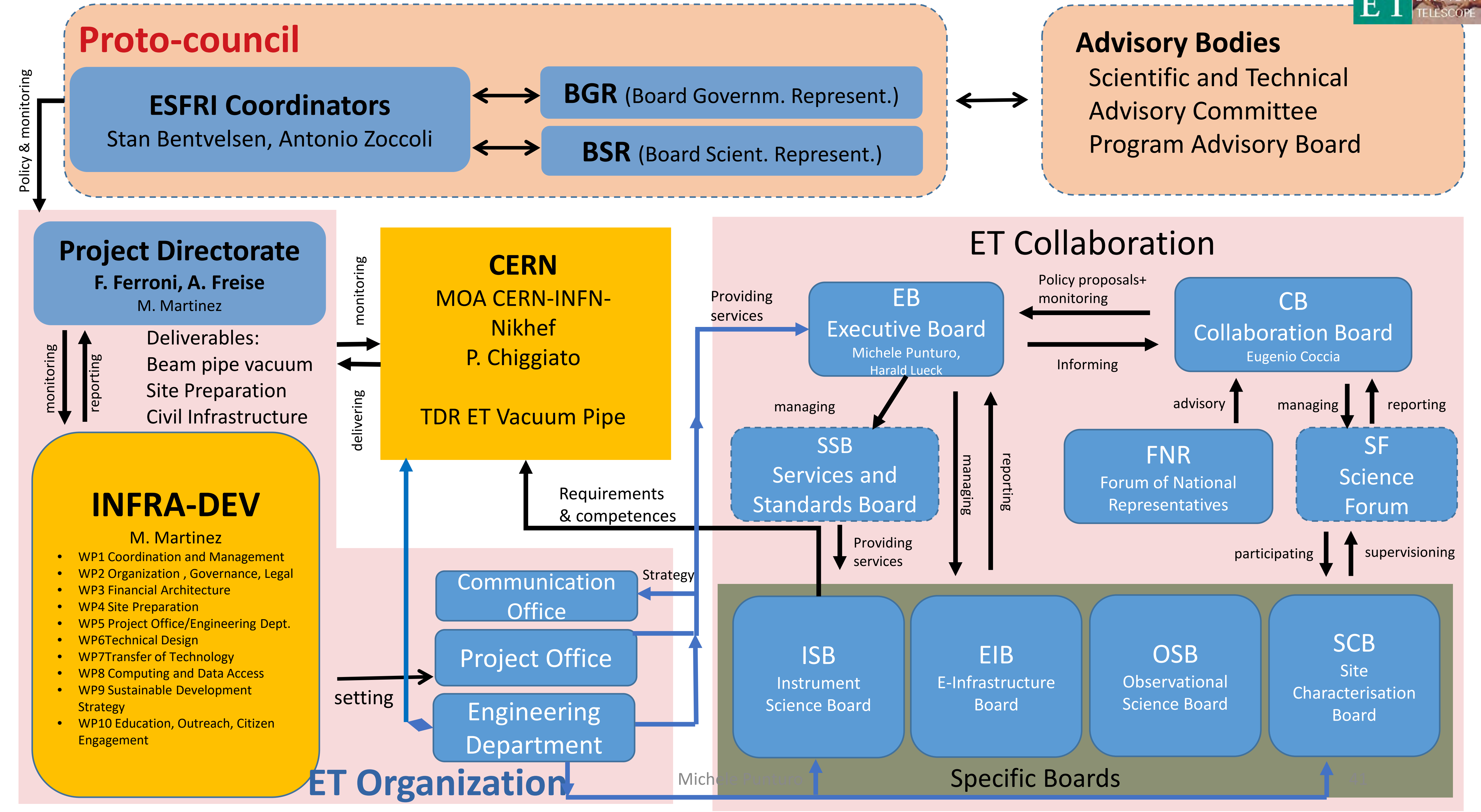
- λ=1.55μm or 2μm?

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



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
Michele Punturo, Harald Lueck
Policy proposals+ monitoring
Informing
CB
Collaboration Board
Eugenio Coccia
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
E-Infrastructure Board
OSB
Observational Science Board
SCB
Site Characterisation Board
Specific Boards

ET Collaboration formed

EINSTEIN TELESCOPE

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

XII Einstein Telescope Symposium

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.

One year ago

The Einstein Telescope Collaboration

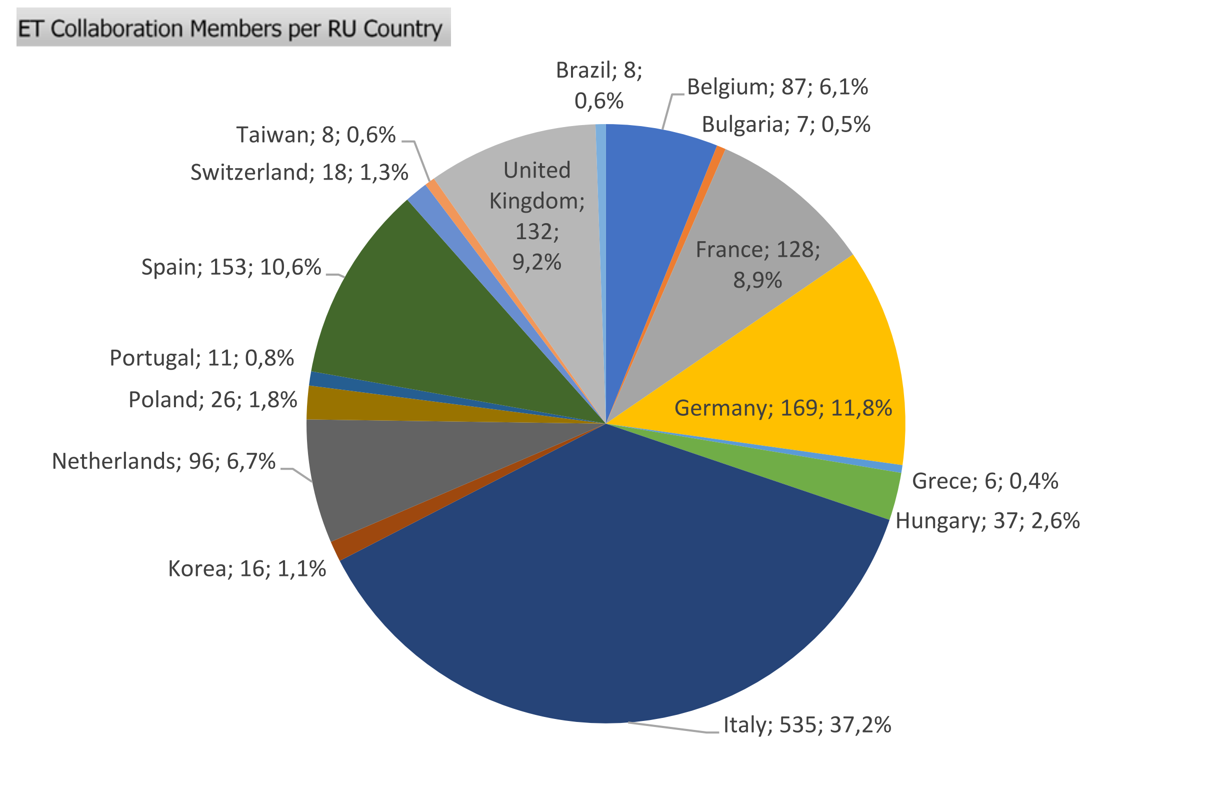
EINSTEIN TELESCOPE

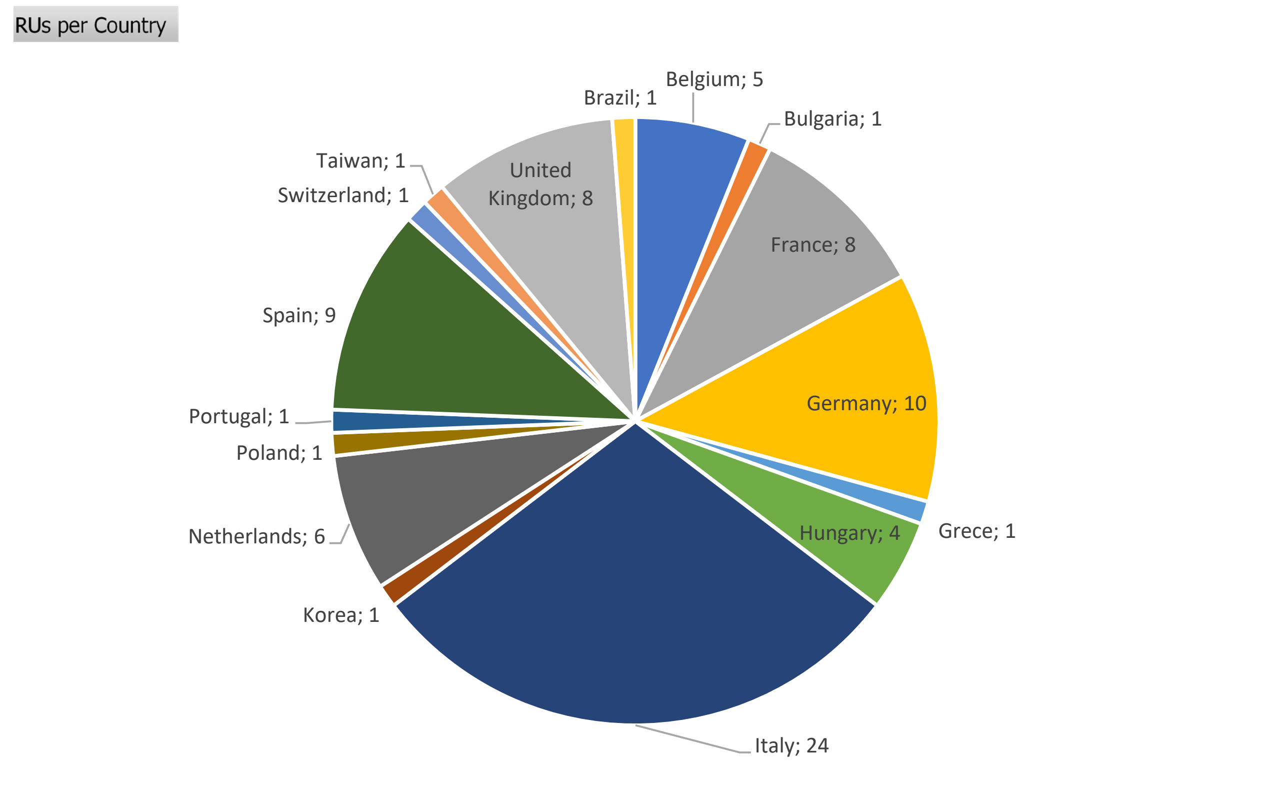
ET Member's affiliation map

- **ET member database (https://apps.et-gw.eu/etmd/)**

- **82 Research Units (+2 request pending)**
- **1437 members (09.06.2023 09:25)**
- **Total: 211 Institutions in 23 Countries**

ET Collaboration Demography





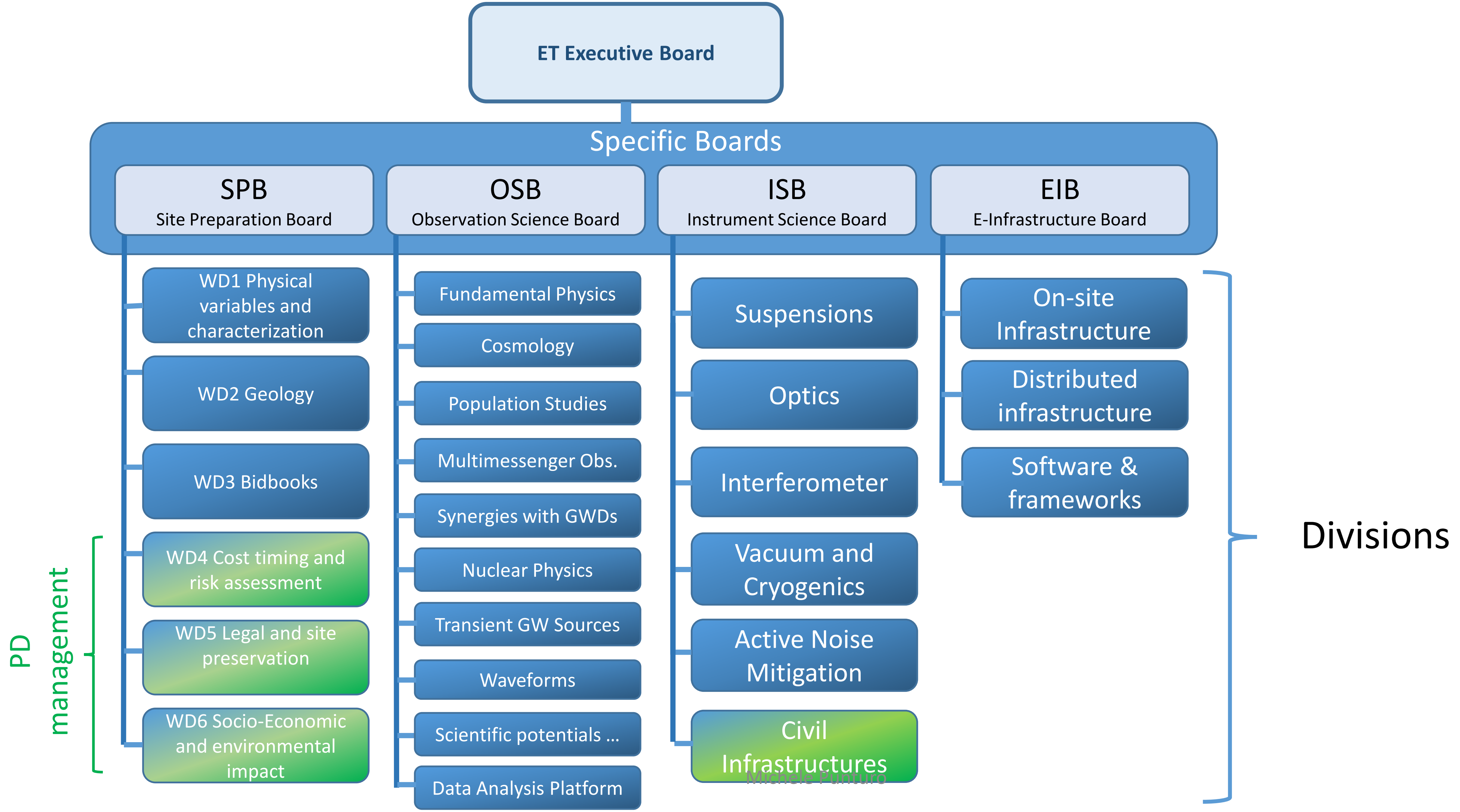
- The data in the ETMD suffer a certain level of inaccuracy:
  - Some RU leaders have not inserted their RU members
  - A few ET members are not updating their information

Data from the ET Member Database (ETMDB), tool based in EGO, governing the Authorization and Authentication to the ET collaboration resources: https://apps.et-gw.eu/etmd

We adopted a "particular" flavor of FTE: FRTE (full research time equivalent)

- The declared FRTE need to be matched to an effective activity
  - This will be a major effort in the next years and we should find a realistic method in the Bylaws
- Currently we have about 295 FrTE →24% on average per member - quite low

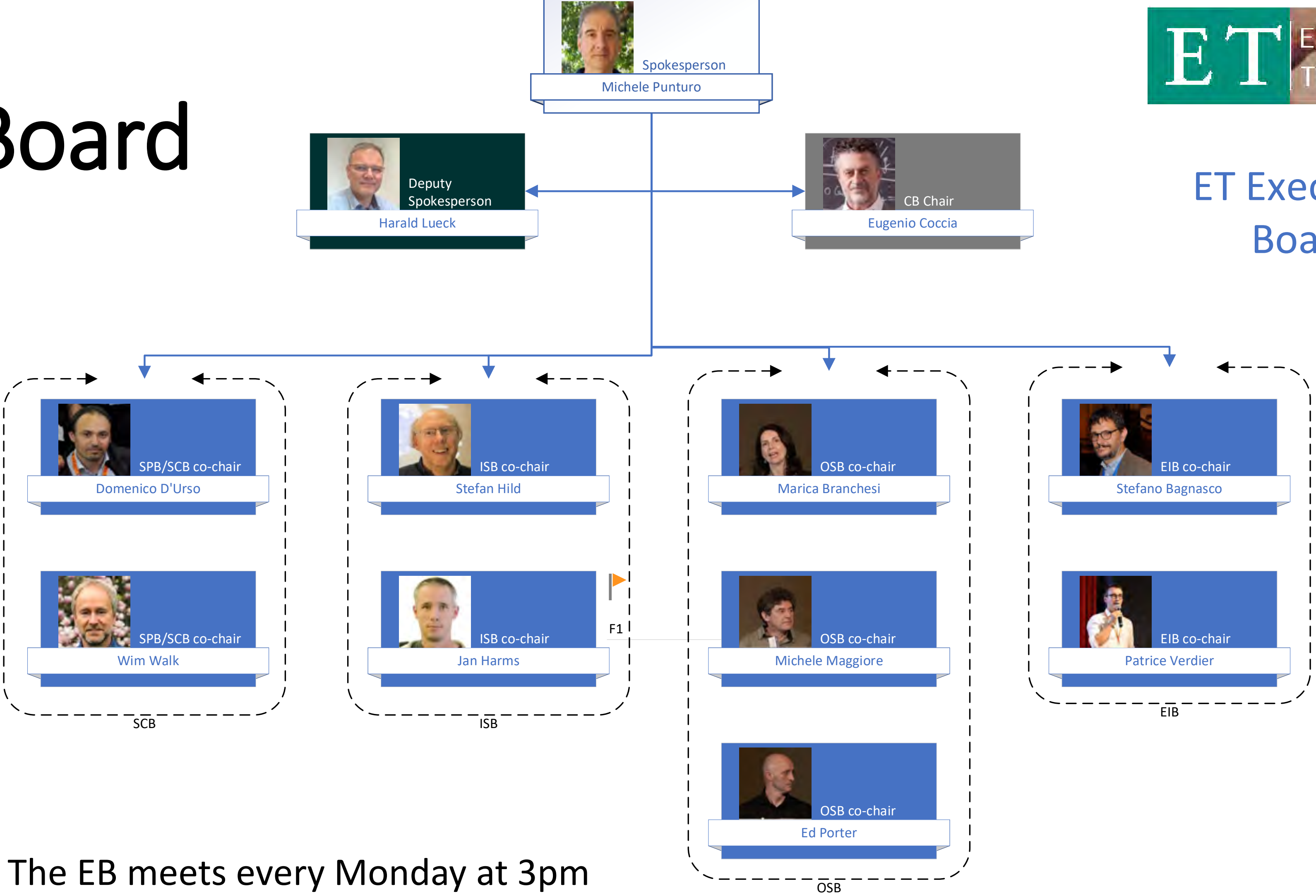
ET Specific Boards

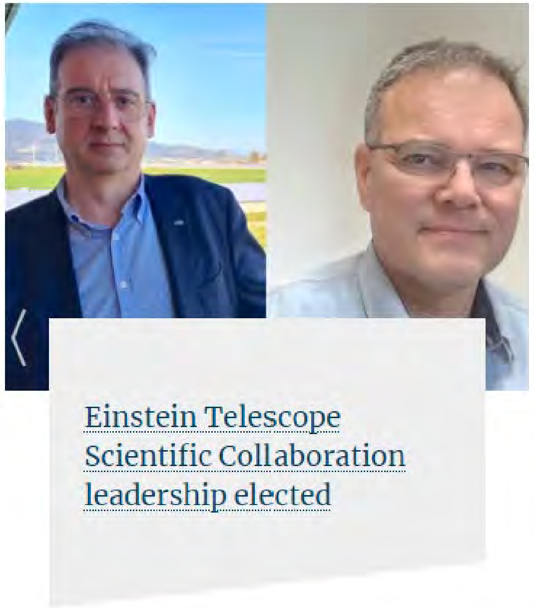


The Executive Board

ET Executive Board

- On the 23rd of March, 2023 the ET Collaboration elected the Spokesperson/Deputy Spokesperson team

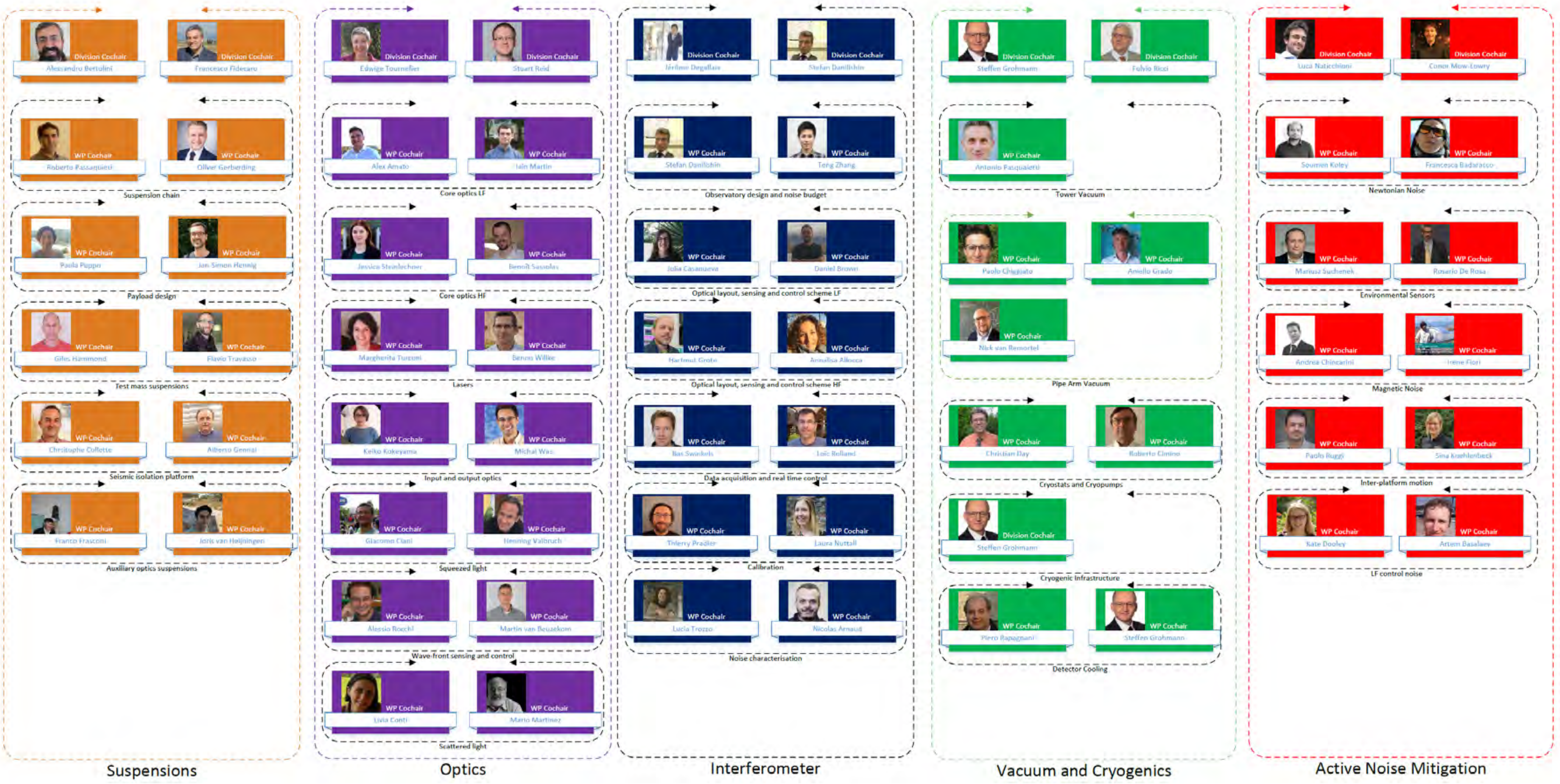




- The EB meets every Monday at 3pm
- You can follow its activities through the meeting minutes on the ET Collaboration Technical Documentation System (TDS): https://apps.et-gw.eu/tds/ *
- More info here: https://wiki.et-gw.eu/EB/WebHome *
- ET Collaboration web site (since 2008): https://www.et-gw.eu/ *
- Indico (all international ET coll. meetings): https://indico.ego-gw.it/category/23/ *

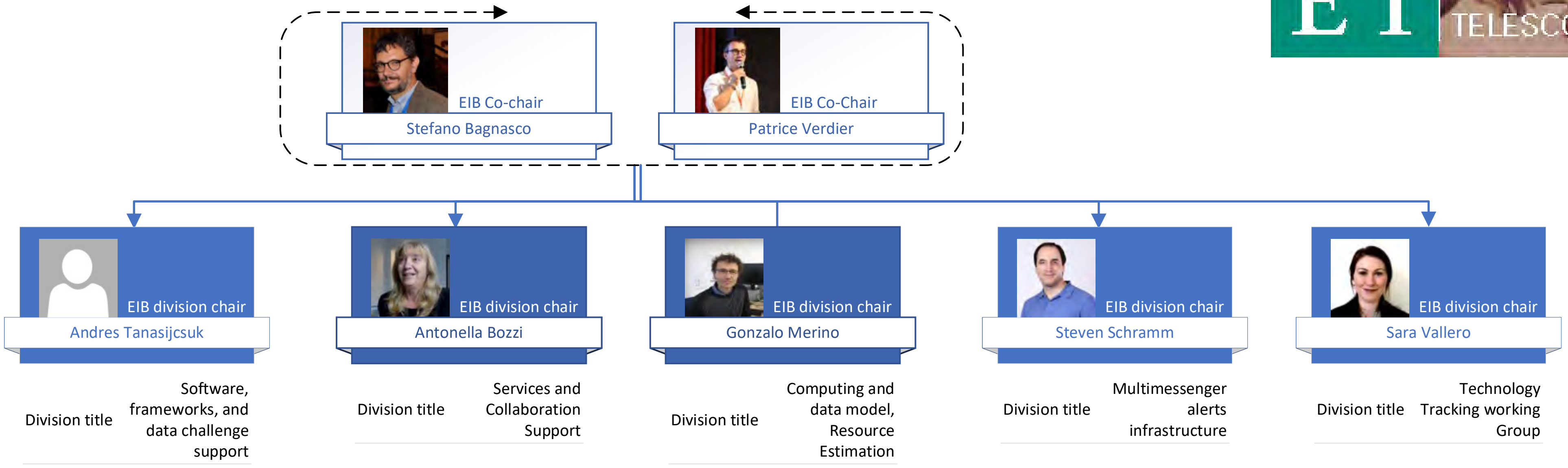
(*) Services provided by EGO, based on the ETMDB service (Active Directory)

ET Instrument Science Board (ISB) Organigram

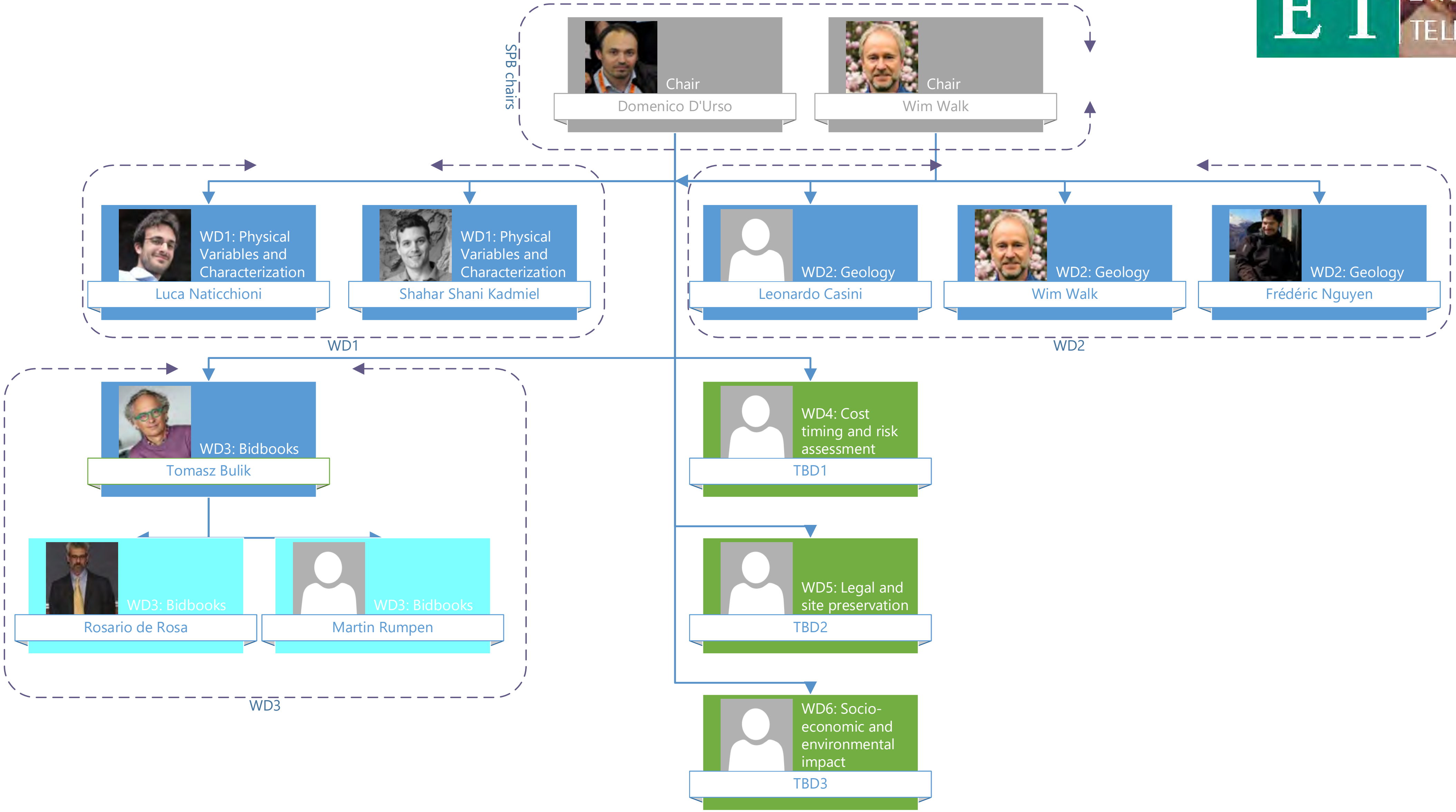


The Observational Science Board OSB

The E-Infrastructure Board



The Site Preparation Board



ET candidate sites

- Two sites officially candidate to host ET:
  - EMR EUregio, border region between Nederland, Belgium and Germany
  - Sardinia (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

How to propose a new RU in the ET collaboration