Einstein Telescope

Matteo Barsuglia

On behalf of ET Collaboration

Many slides from Michele Punturo
(ET spokesperson)

(

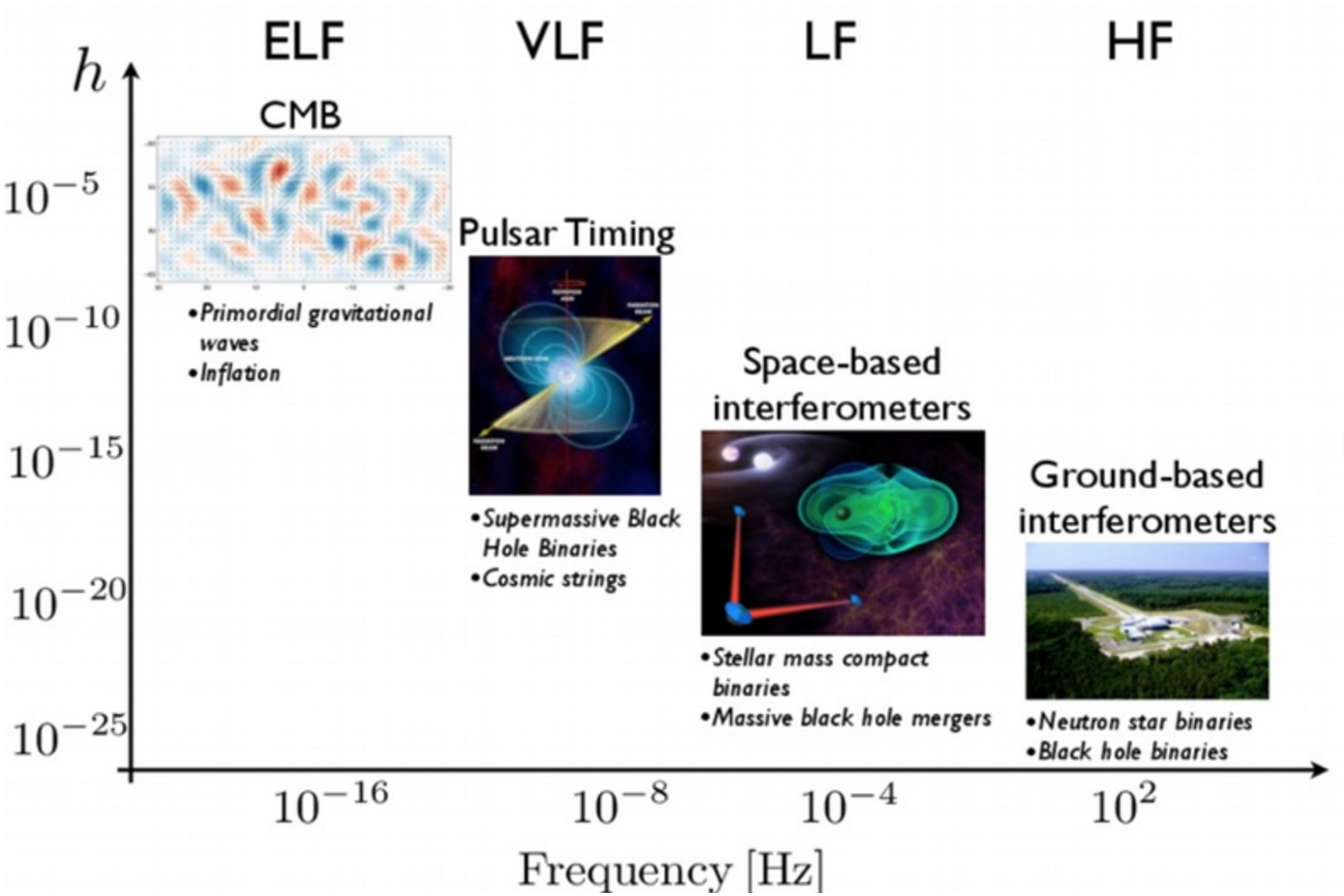
Gravitational-waves (GW) in GR

- Consequence of general relativity
- Oscillatory small perturbation of the metric
- Speed of light
- 2 transverse polarizations
- Produced by acceleration of the mass quadrupole moment

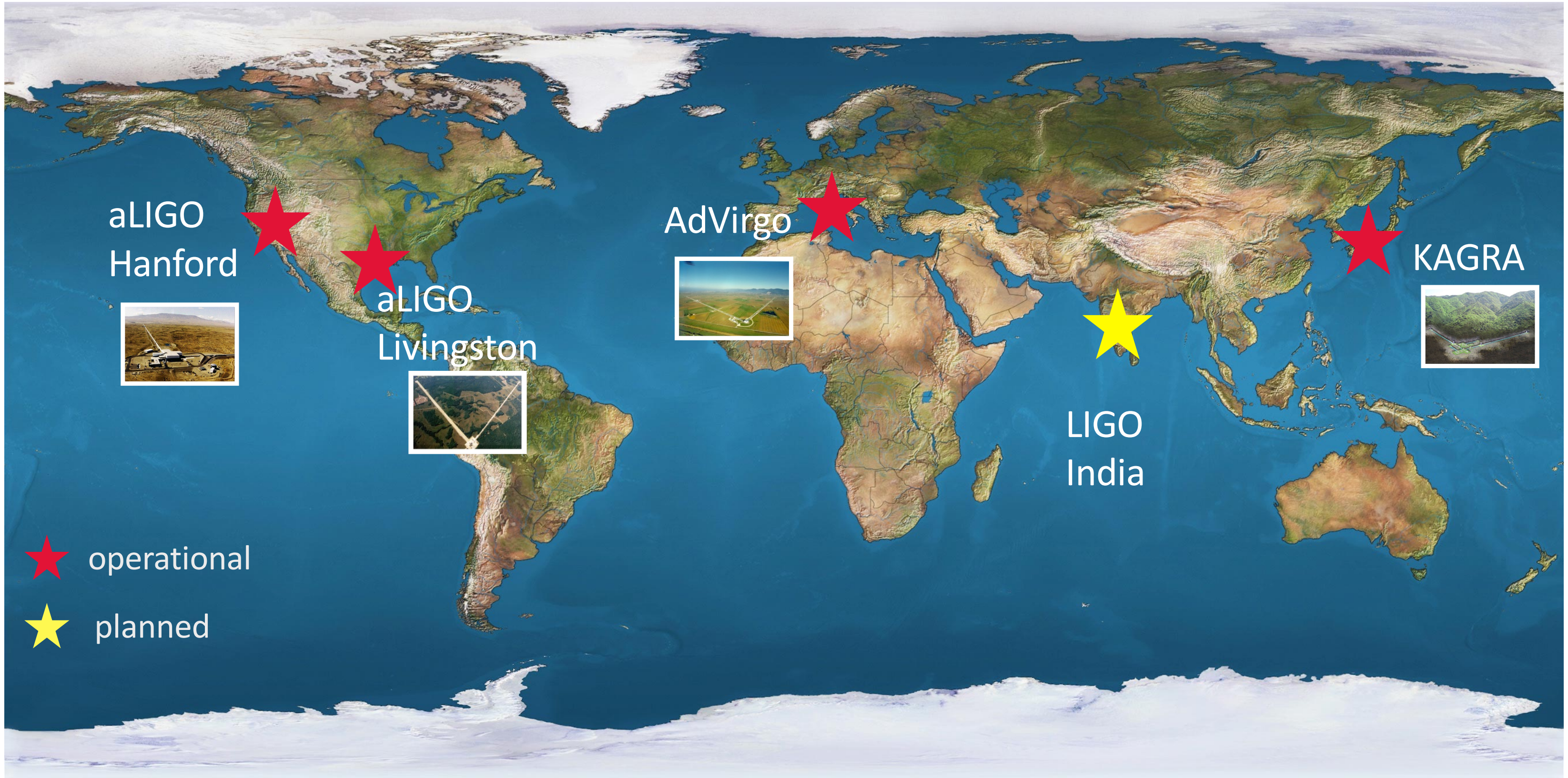
$$h_{ij}(t) = \frac{2}{r}\frac{G}{c^4}\ddot{Q}_{ij}(t - r/c) \qquad \mathcal{L} = \epsilon\frac{c^5}{G}\left(\frac{R_S}{R}\right)^2\left(\frac{v}{c}\right)^6$$

$h \sim 10^{-21}$

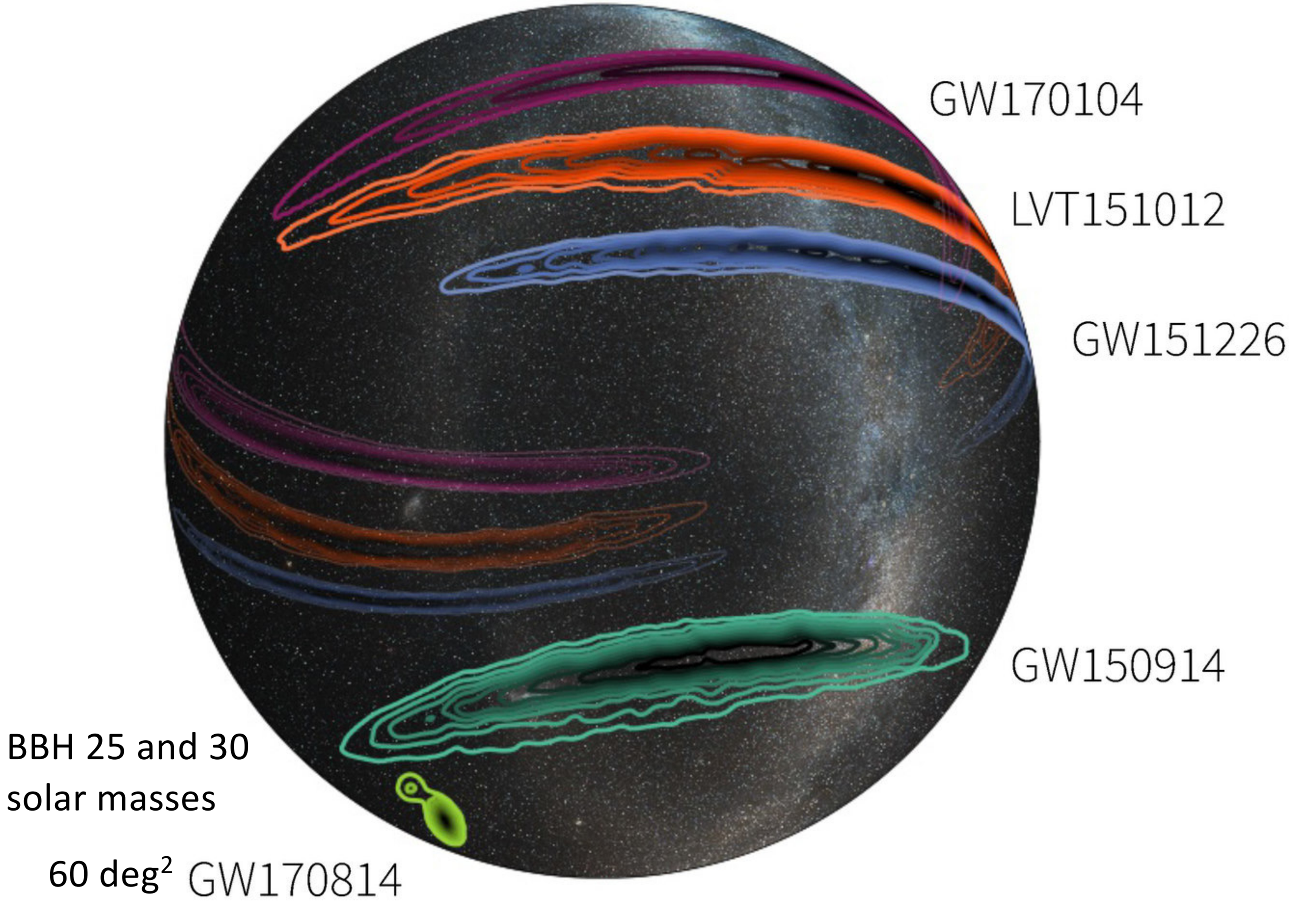
Detectors/projects and science goals



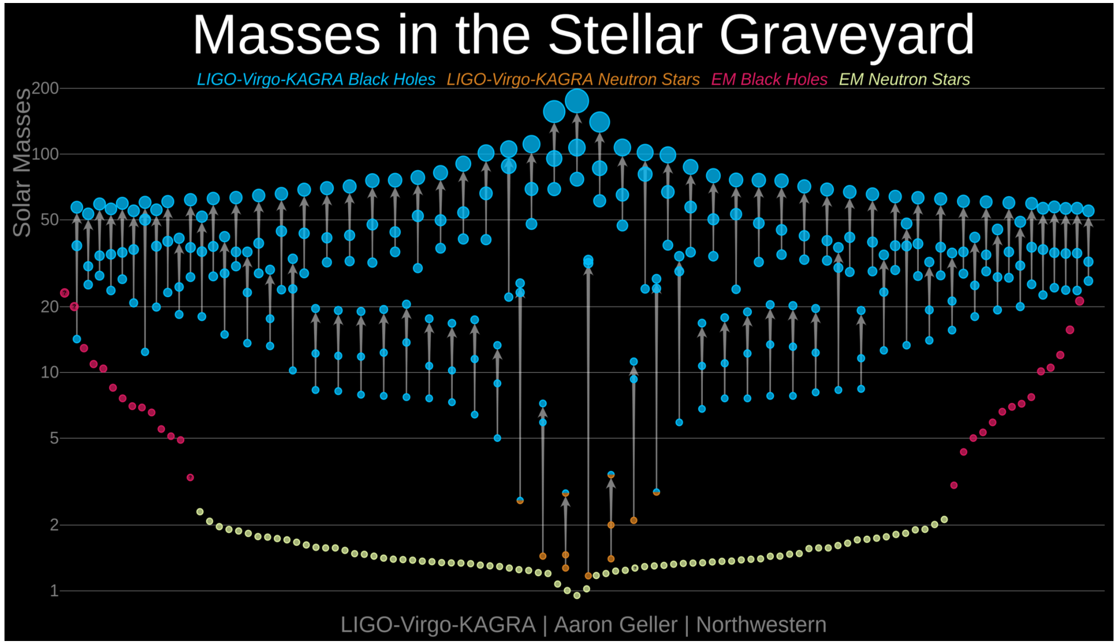
Gravitational-wave observatory network



Triple detection – 14 August 2017

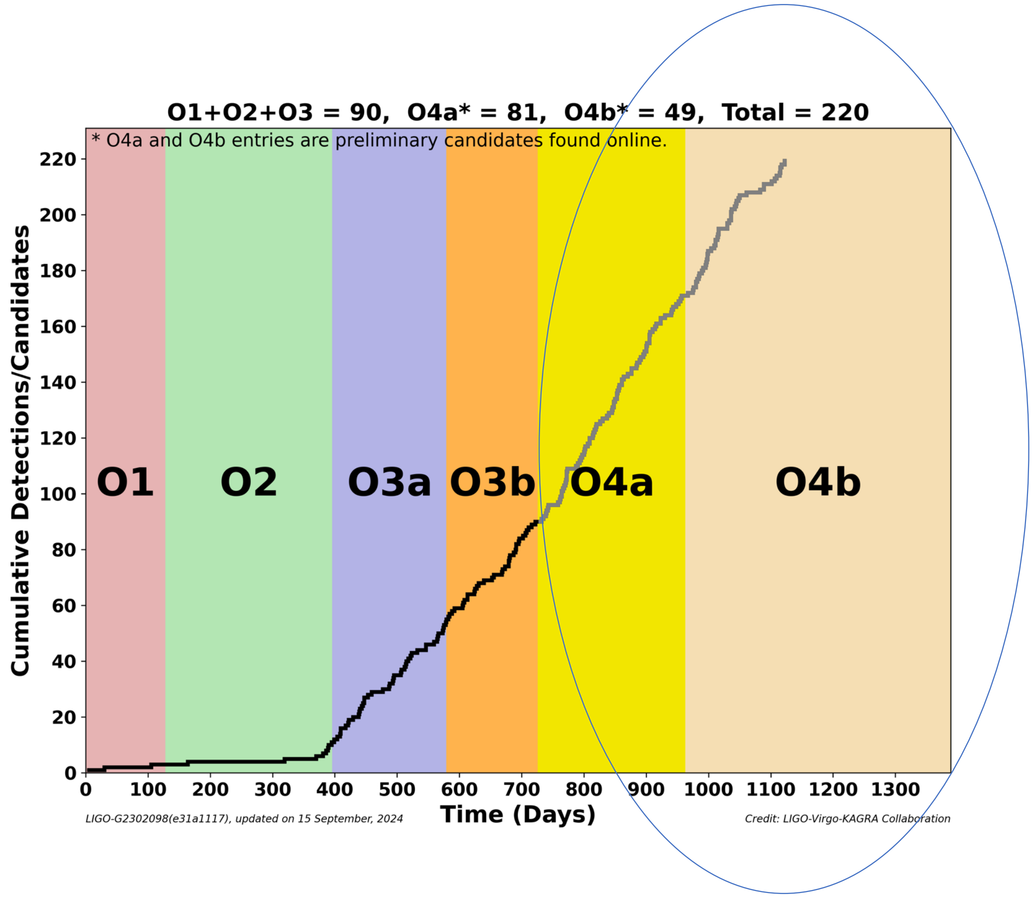


Detections so far by LIGO-Virgo-KAGRA



GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run; LIGO-Virgo-KAGRA collaborations, https://arxiv.org/abs/2111.03606

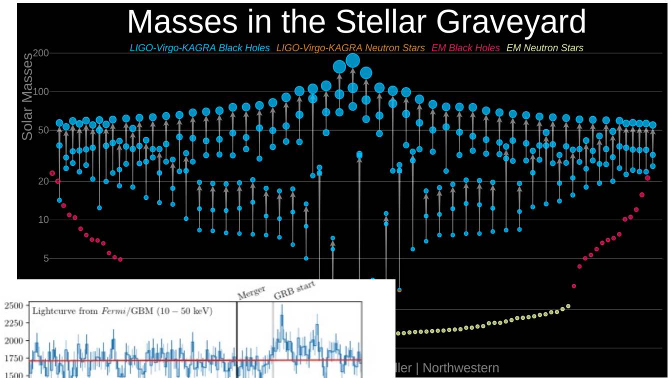
Detections and online candidates so far by LIGO-Virgo-KAGRA



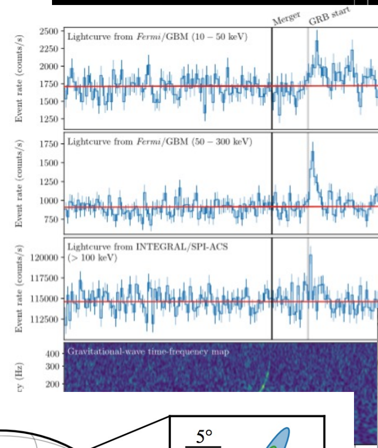
Online candidates

Why GW with (ground-based) detectors science?

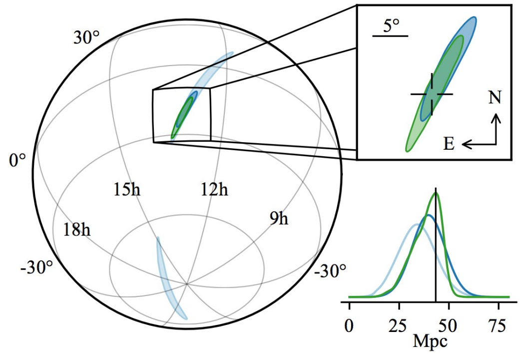
New objects, new populations

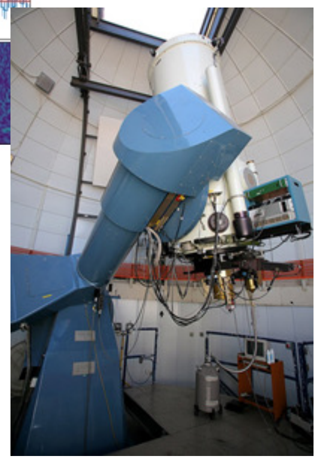


Same objects observed in a new way



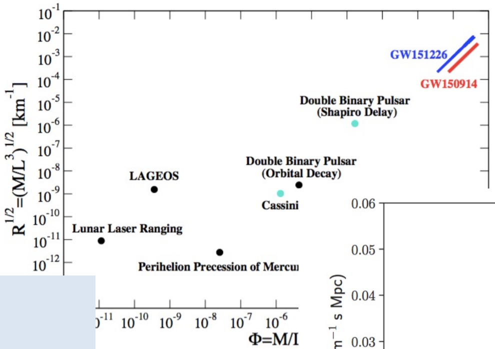
Alerts for electromagnetic observatories



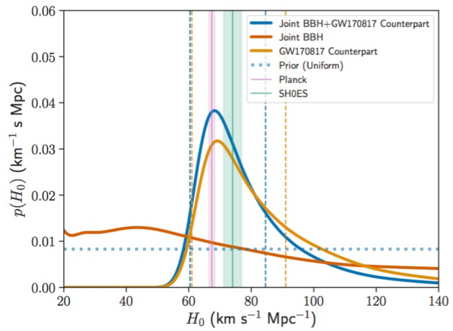


Why GW with (ground-based) detectors science?

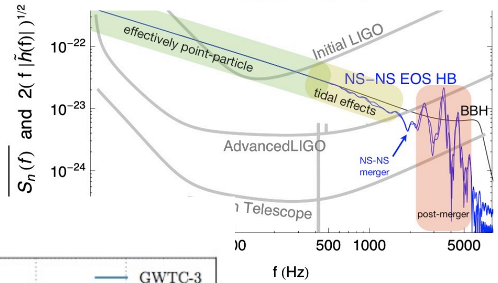
New tests of gravity



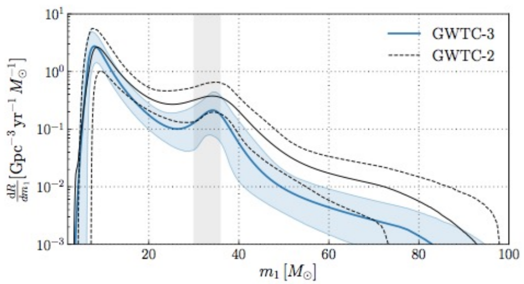
New cosmological measurements



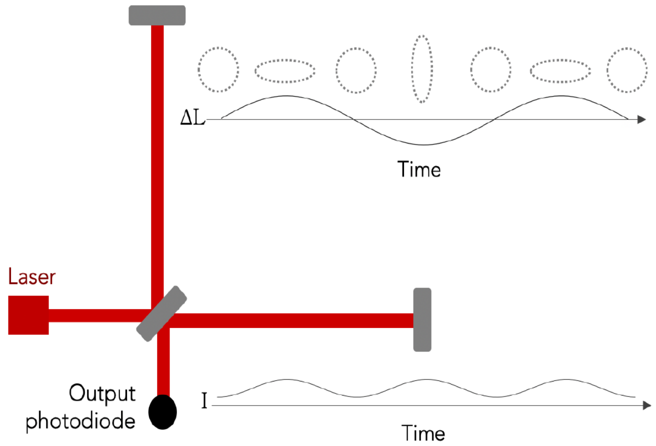
Study of extreme states of matter



Populations of compact objects



Interferometric detectors



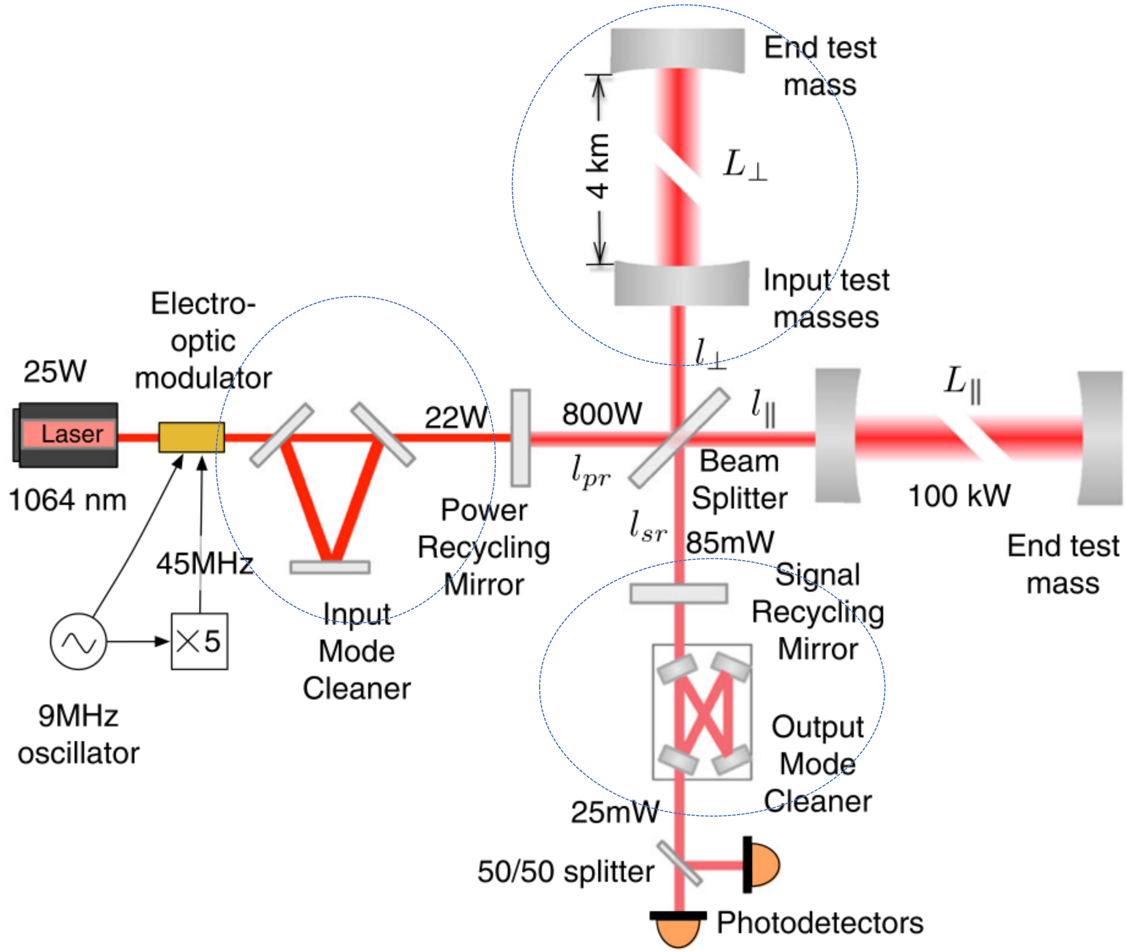
• Concept/ideas: Gertsenshtein and V. I. Pustovoit (1962), Pirani (1962)

• Unpublished work by Weber and Forward (Weber's student), foreground for Forward experiment in Malibù

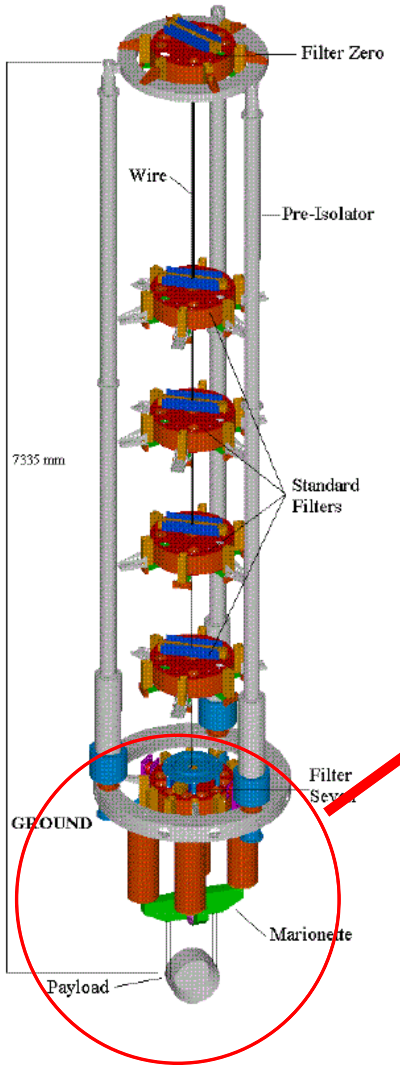
• First prototype: E. Moss, L. R. Miller, and R. L. Forward (1971)
~ 10^{-14} m$\text{Hz}^{-1/2}$

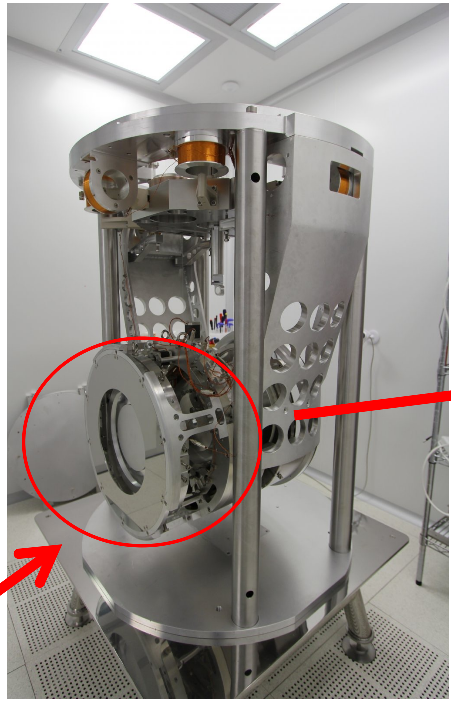
• R. Weiss (1972) – realistic study of the noises

Fabry-Perot cavities

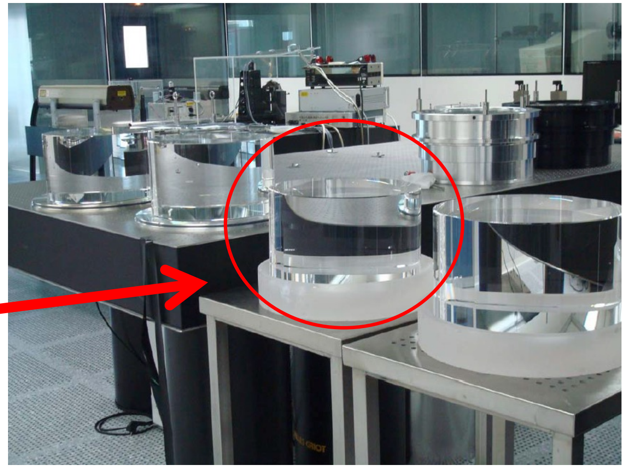


Bulding blocks: mirrors

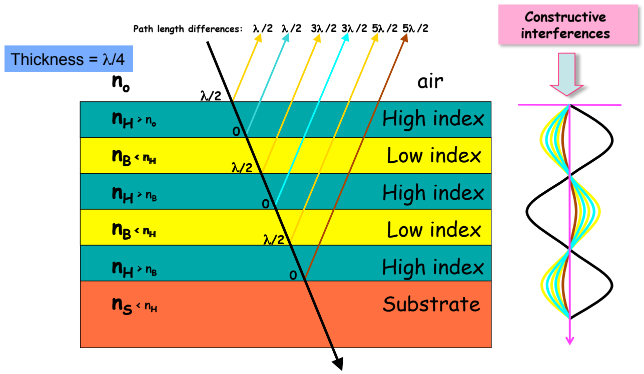


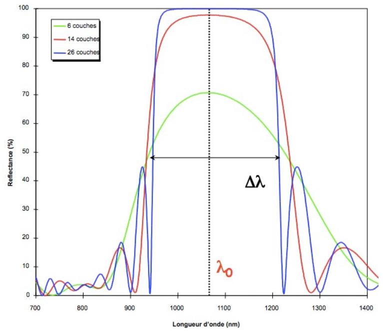


Credit Virgo



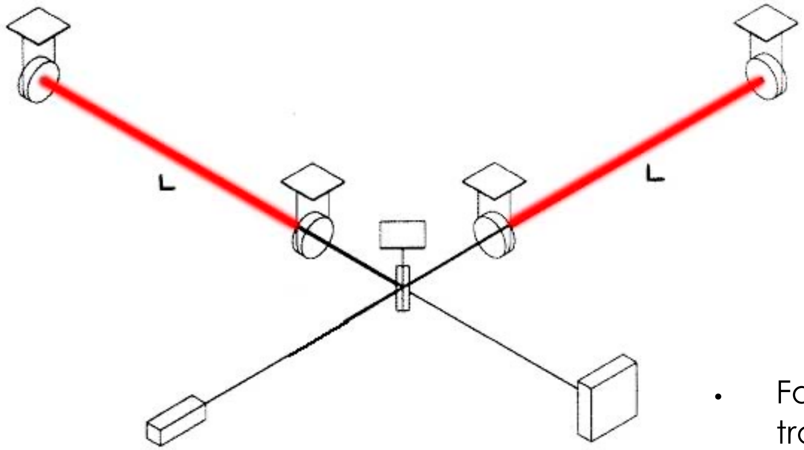
Bulding blocks Mirror = substrate + coating

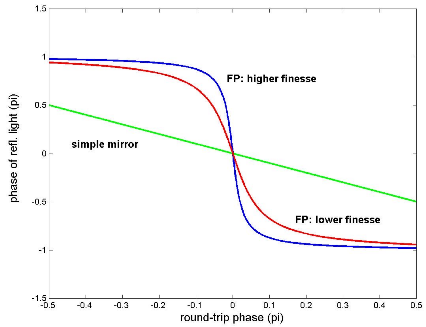




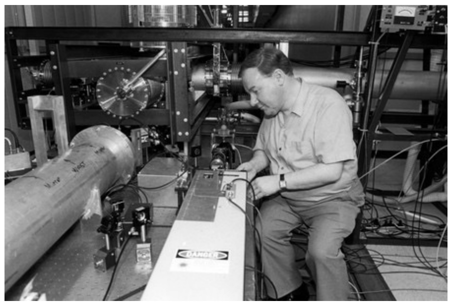
Credit: LMA, www.lma.in2p3.fr

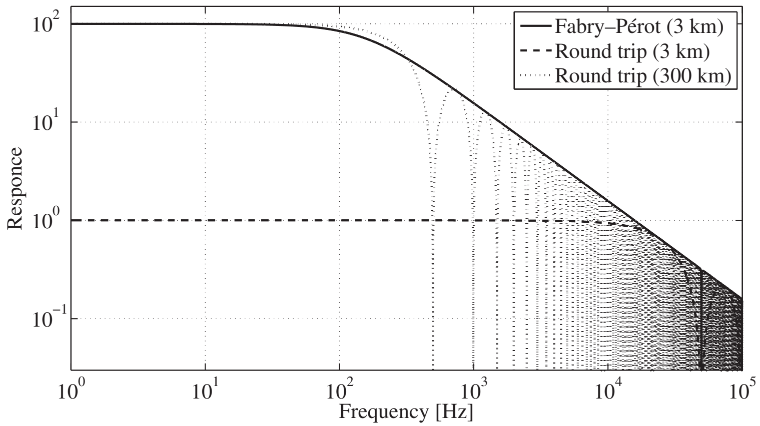
Bulding blocks: Fabry-Perot cavities





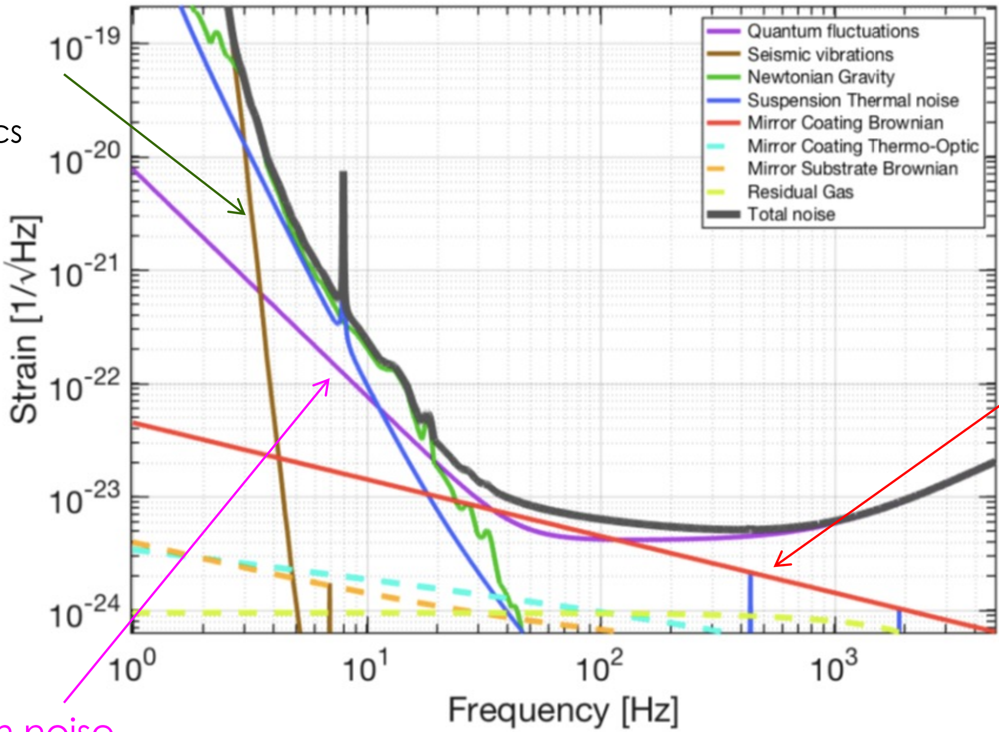
- Fabry-Perot cavities: amplify the length-to-phase transduction
- Drawback: works only at resonance





Advanced Virgo sensitivity curve

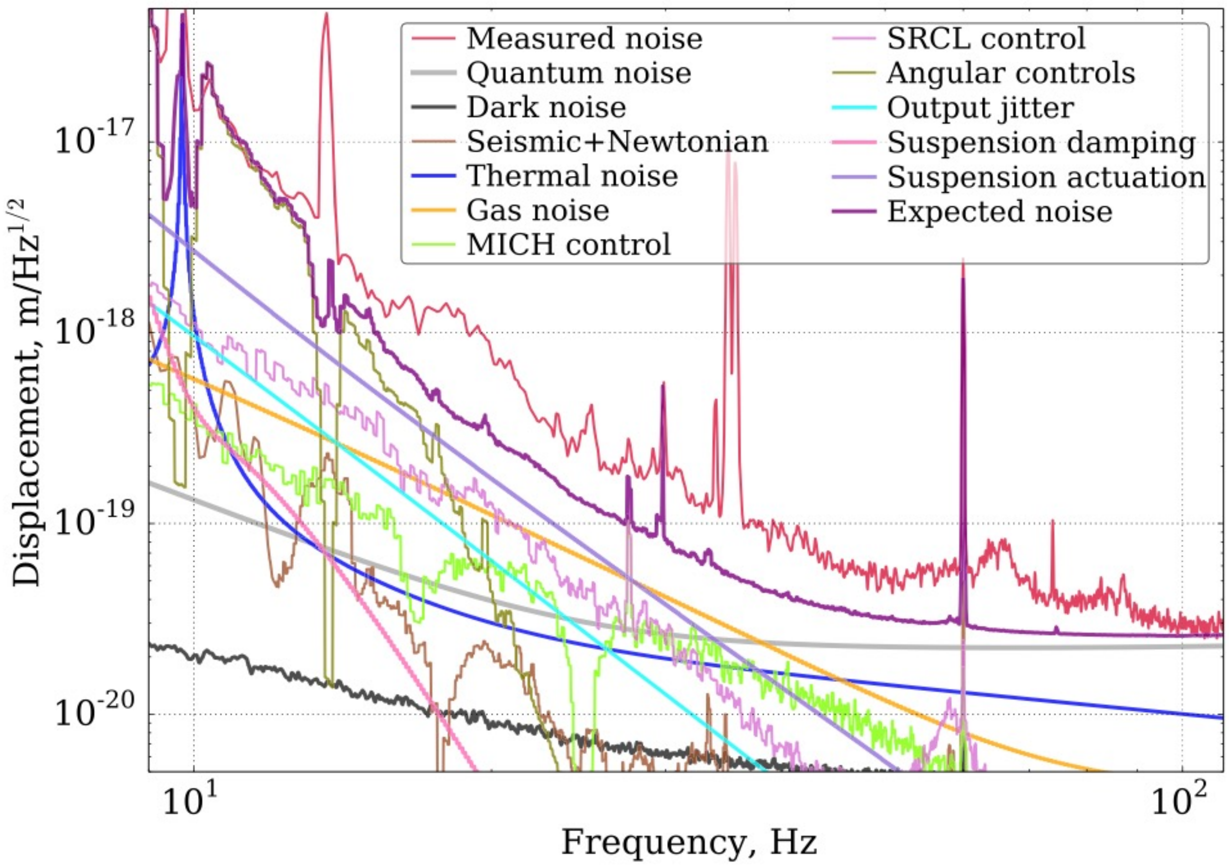
Seismic and gravity gradient noise
Geophysics



Thermal noise
Thermodynamics

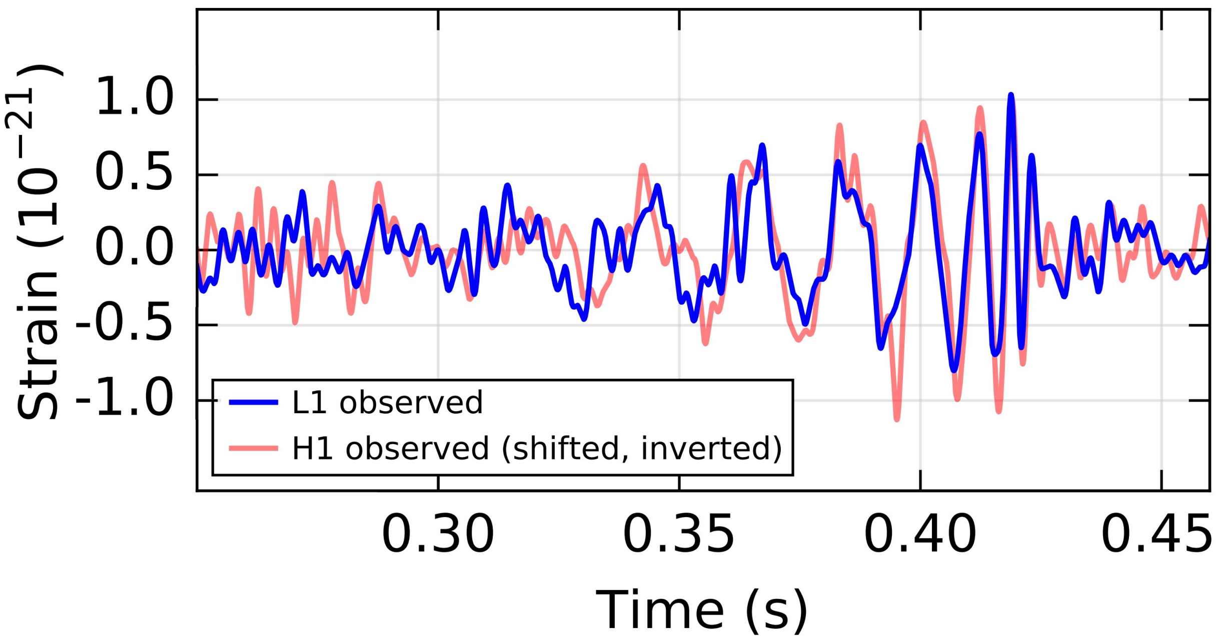
Quantum noise
Quantum mechanics

The real sensitivity curve

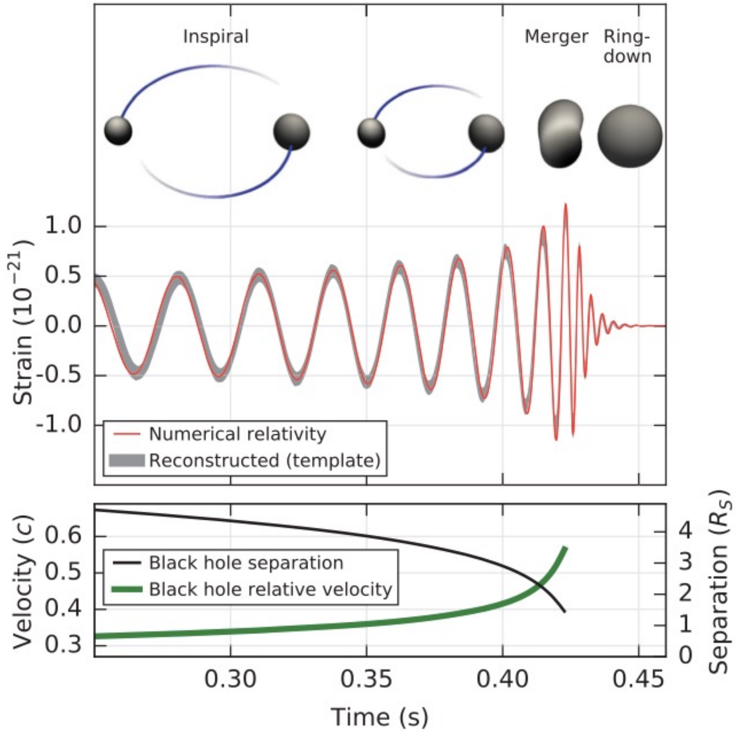


Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy
D. V. Martynov *et al.* Phys. Rev. D **93**, 112004 – (2016)

GW150914


1.0
0.5
0.0
-0.5
-1.0
Strain (10^{-21})
0.30
0.35
0.40
0.45
Time (s)
L1 observed
H1 observed (shifted, inverted)

GW150914



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Energy in GW $3.0^{+0.5}_{-0.5} M_\odot c^2$

Luminosity $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s

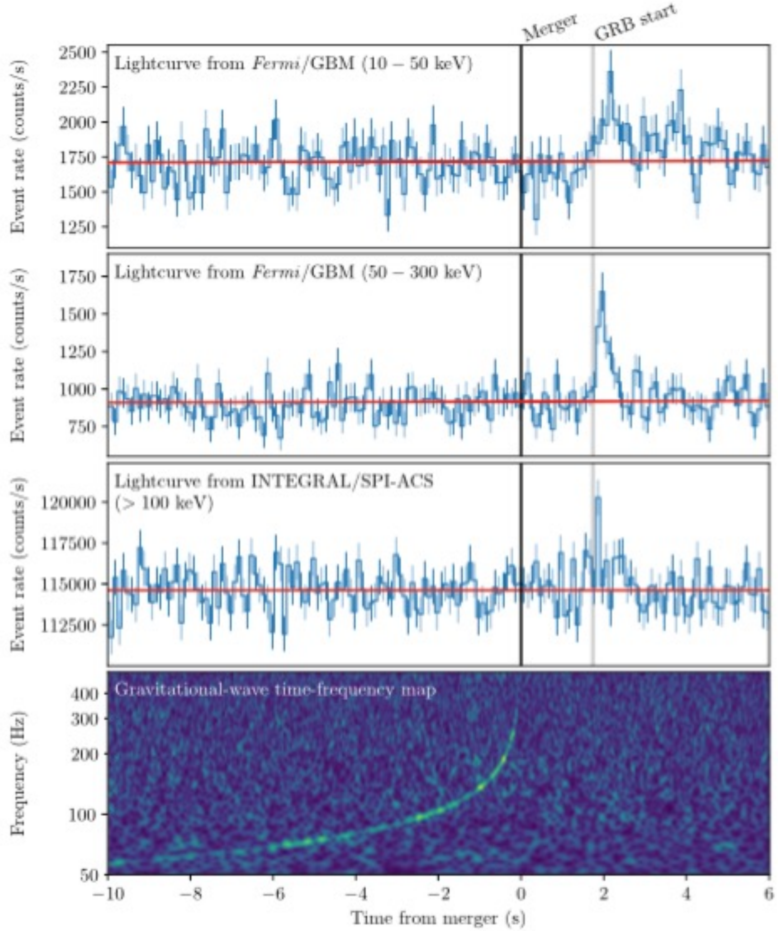
Summary of the results

- First detection of gravitational-waves
- First test of gravitational-wave polarisation
- Gravitational waves travel at the speed-of-light
- Tests of the emission at higher harmonics of GW
- Tests of GR in strong field regime

- First observations of a NS-NS merger
- First observations of BH-BH mergers
- A new population of BH with high masses
- First measurements on NS tidal deformability
- Link between GRB and neutron star mergers
- Kilonova powered by binary NS merger

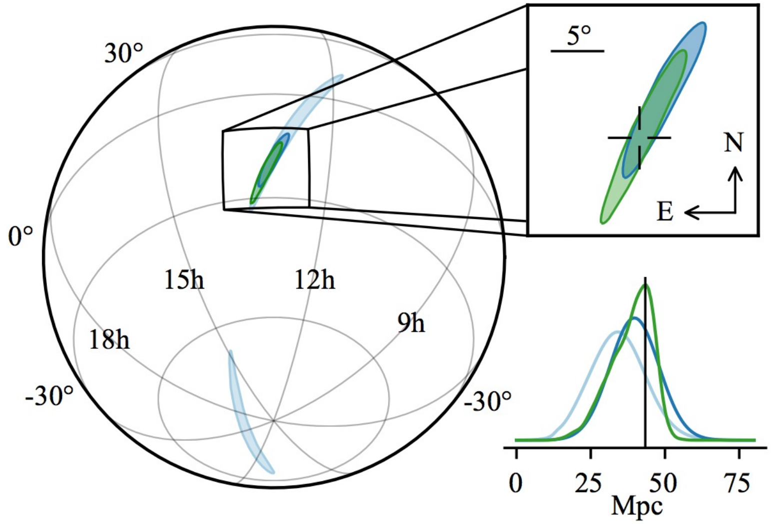
- Alternative measurement of Hubble constant
- Speed of gravity → consequences on gravity alternative theories

GW170817: Binary neutron star merger



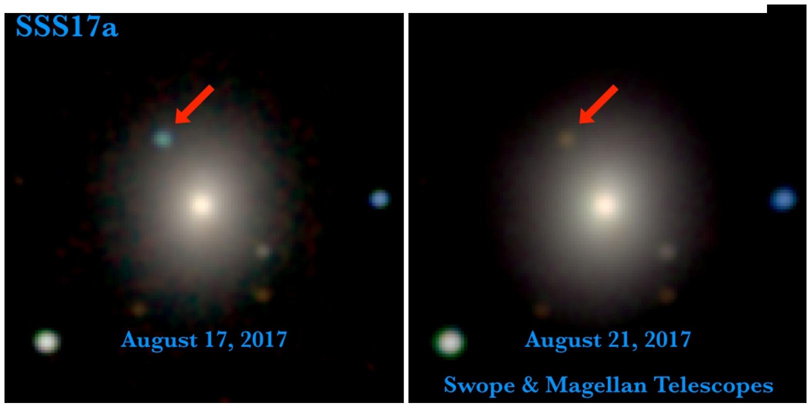
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, B.P.Abbott, Phys. Rev. Lett. 119, 161101 (2017)

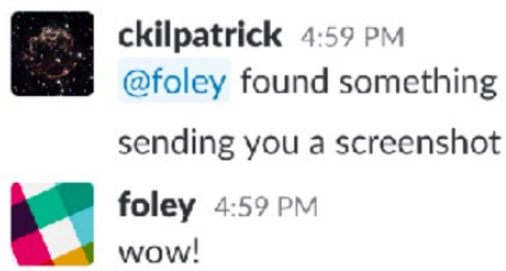
The galaxy identification and the kilonova



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, B.P.Abbott, Phys. Rev. Lett. 119, 161101 (2017)

Properties of the Binary Neutron Star Merger GW170817, B. P. Abbott et al., Phys. Rev. X 9, 011001 (2019)

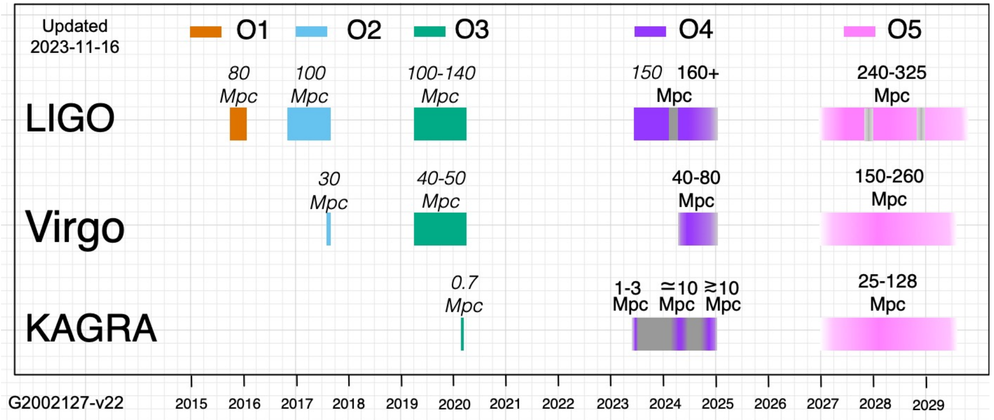




https://ziggy.ucolick.org/sss17a/

Ground based GW detectors: possible roadmap

Current infrastructures



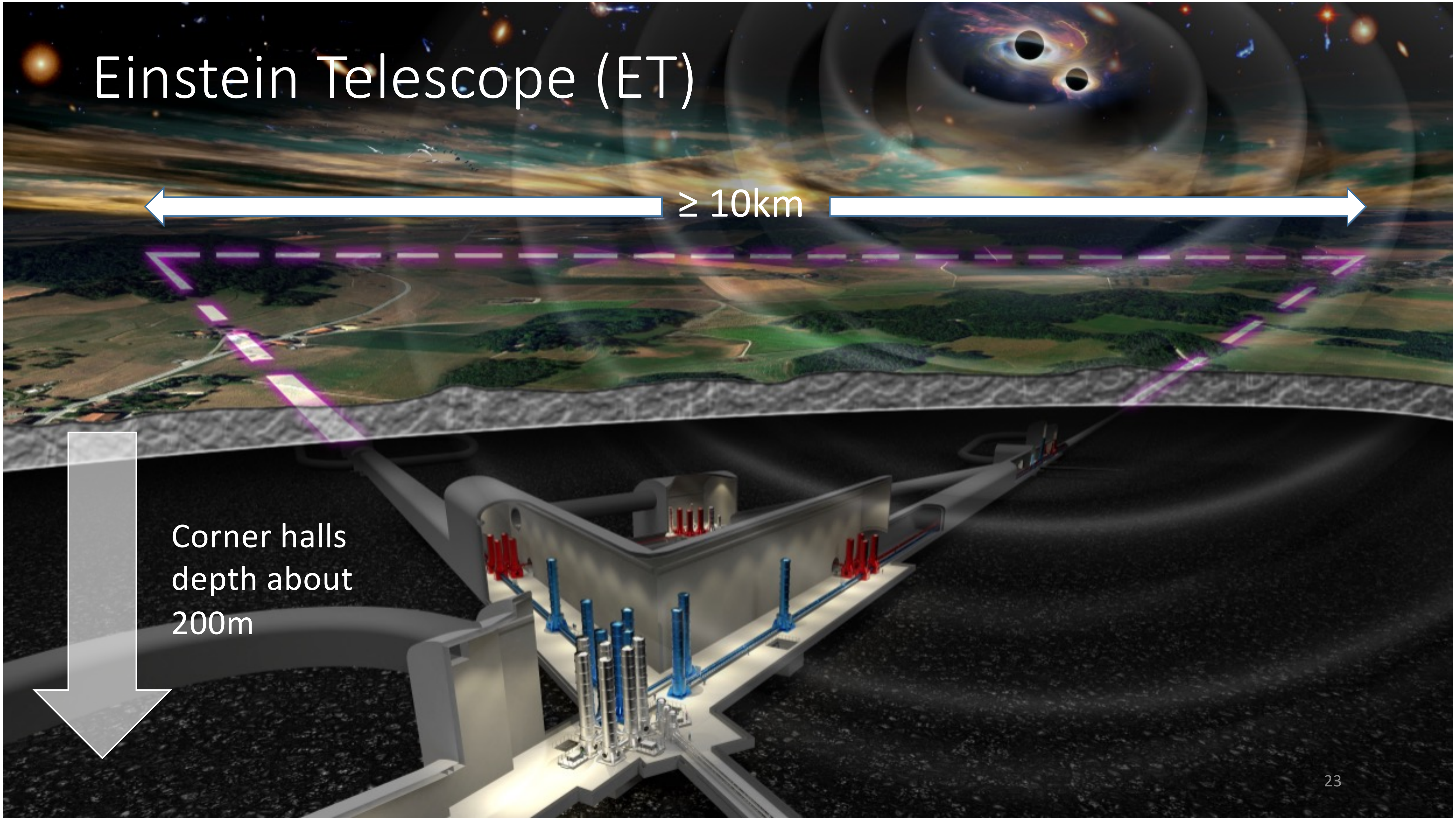
- A#
- Virgo_nEXT

Decade 2030

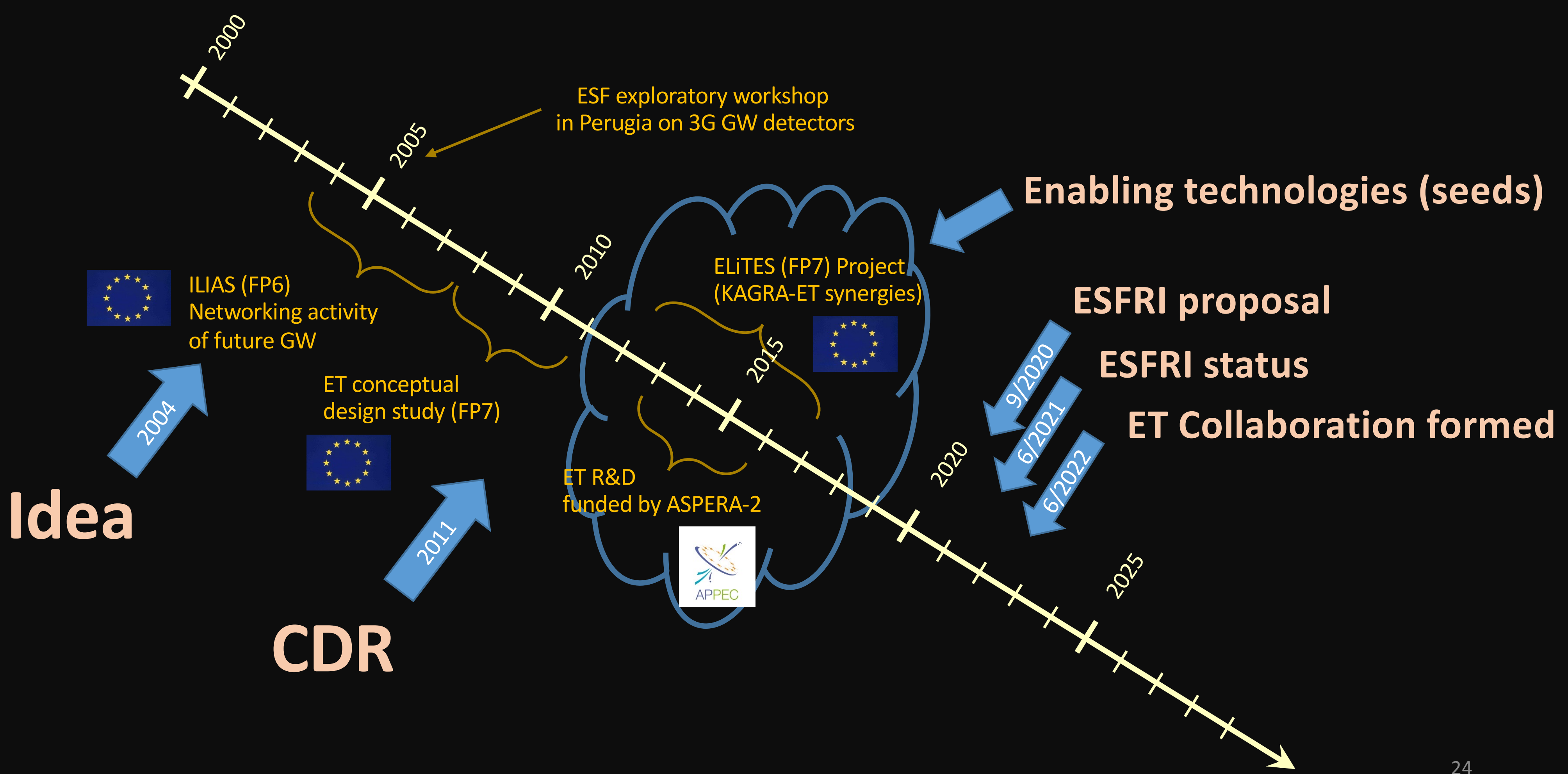
New infrastructures

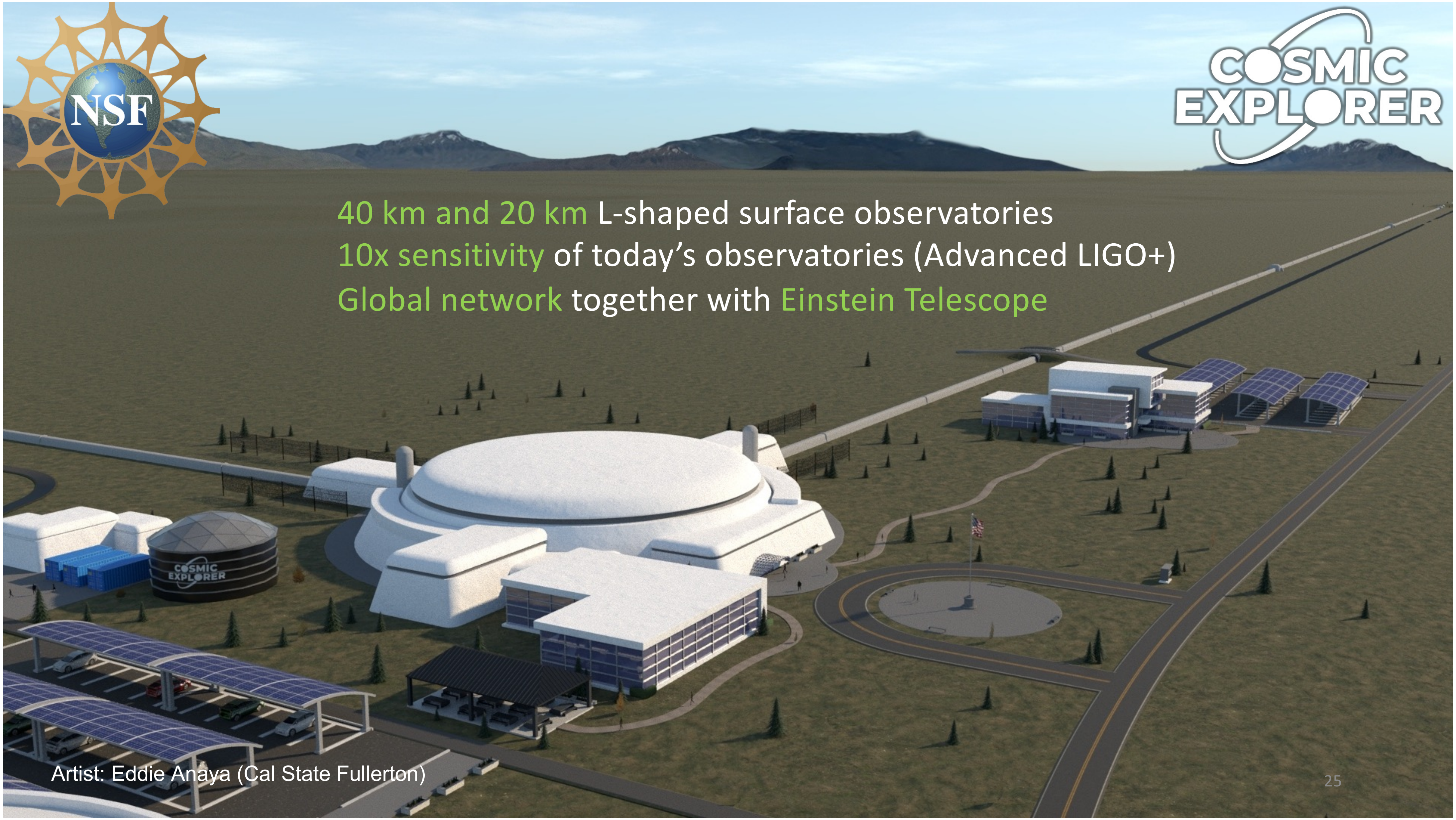
- Cosmic Explorer
- EinsteinTelescope

Einstein Telescope (ET)



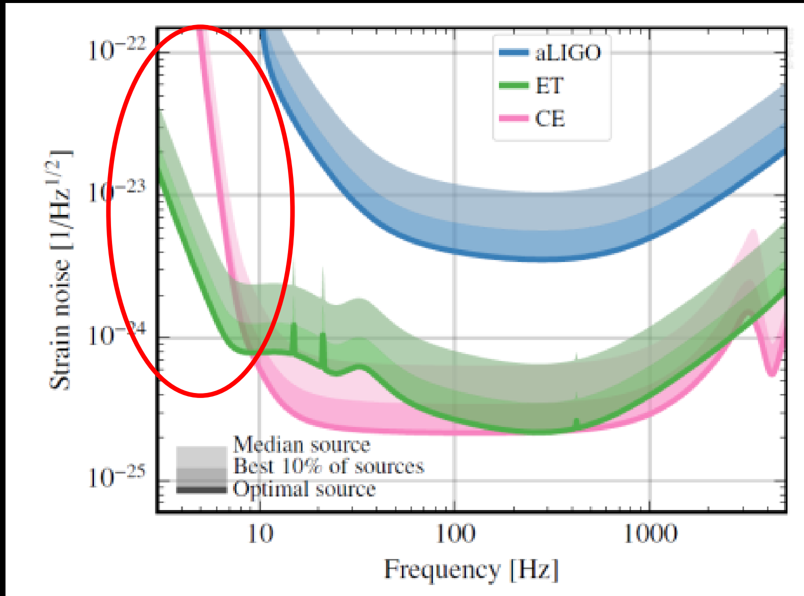
ET: a long path

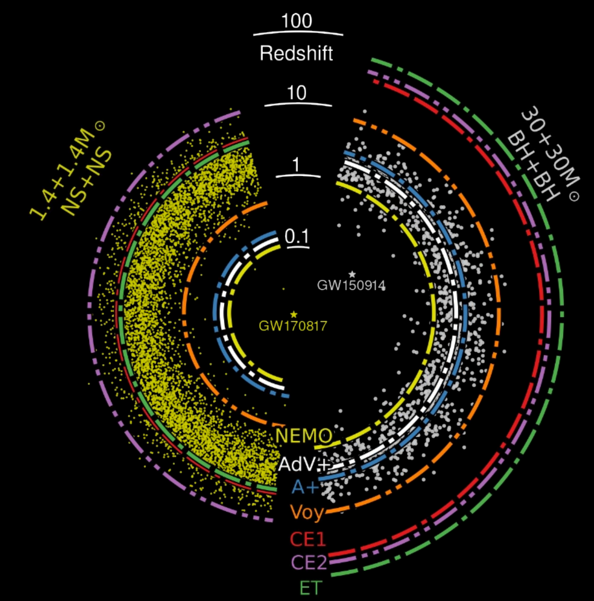


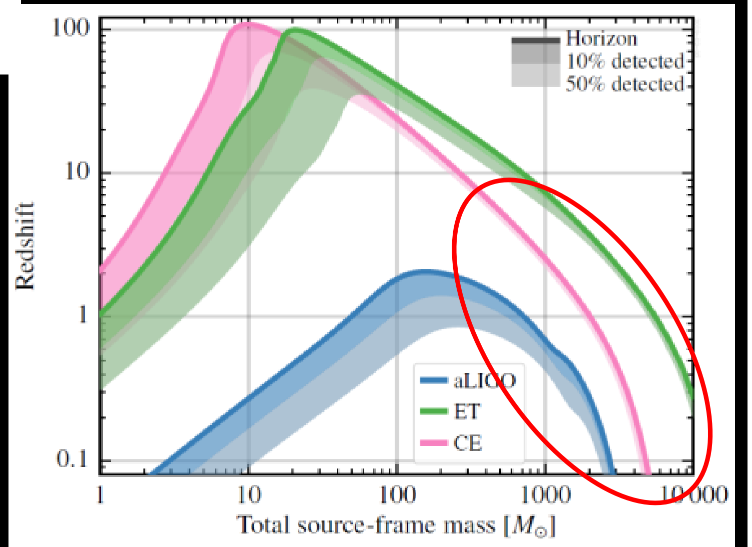

NSF
COSMIC EXPLORER
40 km and 20 km L-shaped surface observatories
10x sensitivity of today’s observatories (Advanced LIGO+)
Global network together with Einstein Telescope
COSMIC EXPLORER
Artist: Eddie Anaya (Cal State Fullerton)

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







EINSTEIN TELESCOPE

ET Observational Science in a nutshell

ASTROPHYSICS

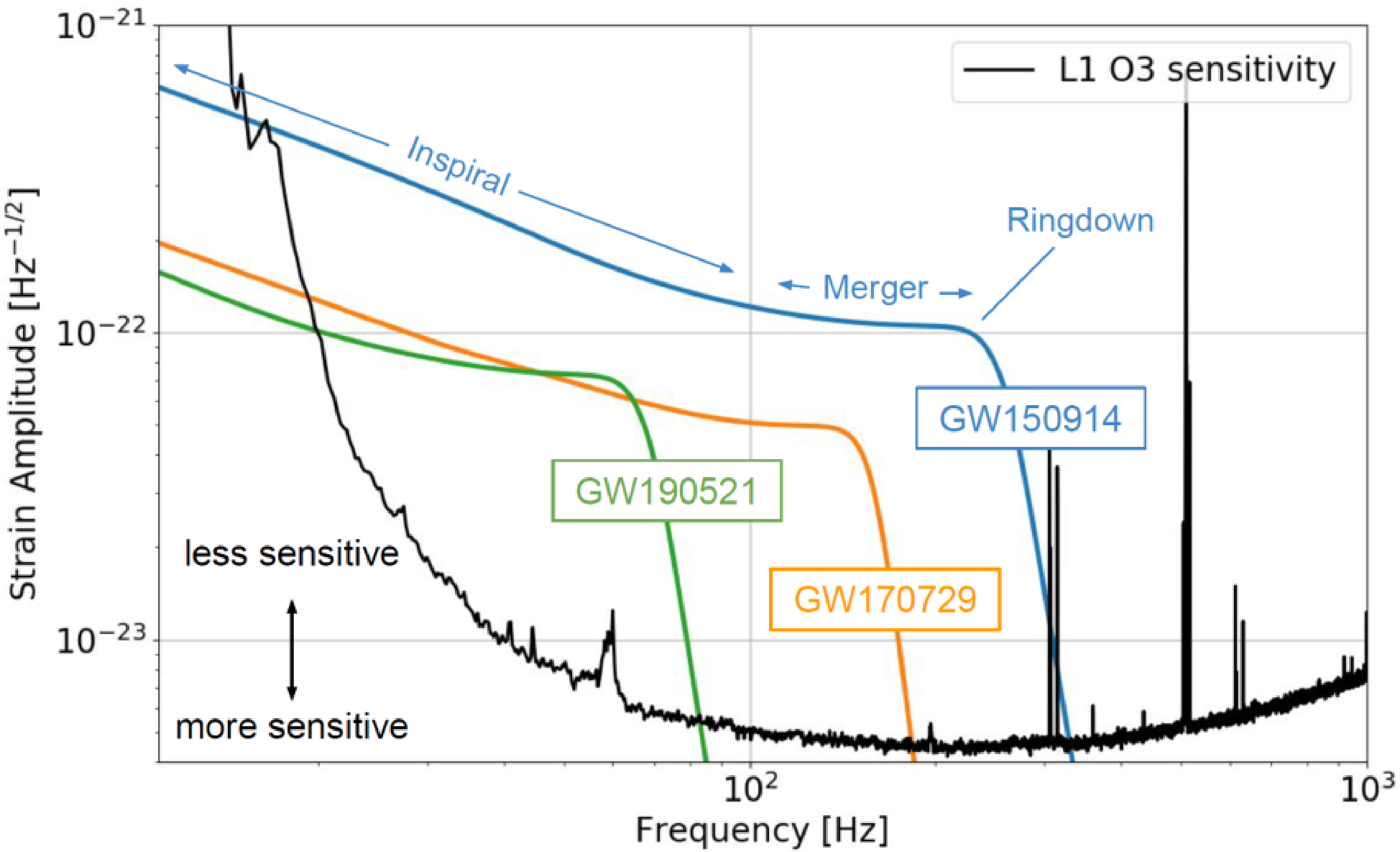
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)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

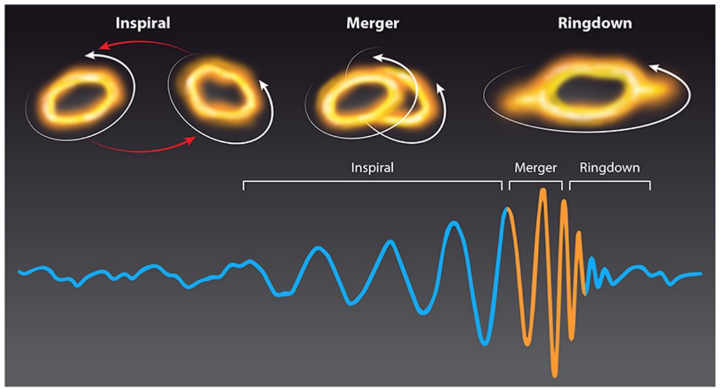
Why low frequency focus?

GW190521: LIGO-Virgo sensitivity to the BBH merger



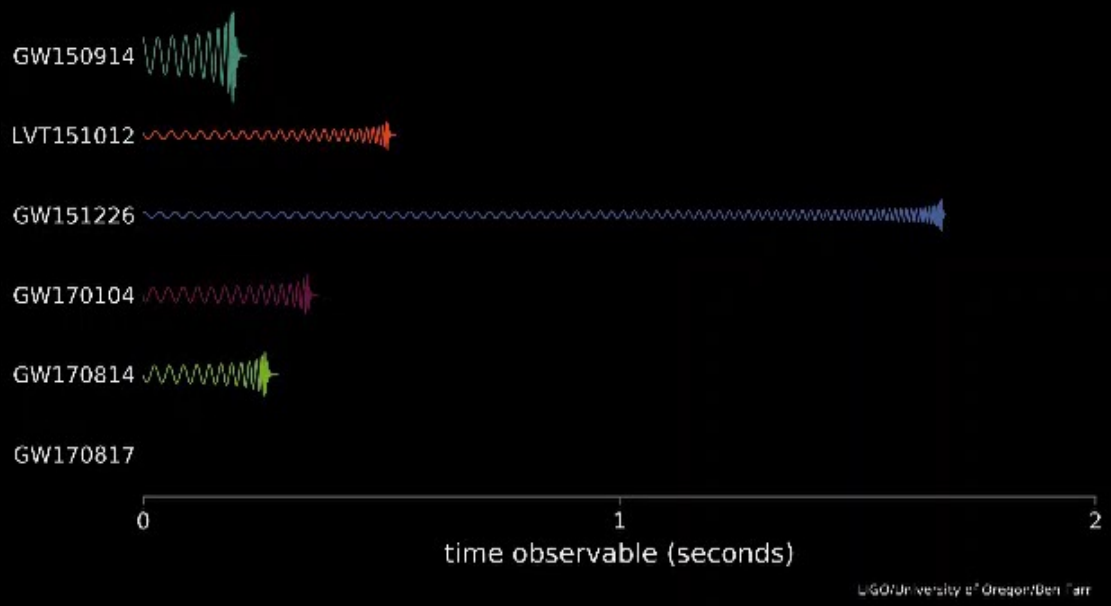
- Higher masses correspond to lower frequency GW emission

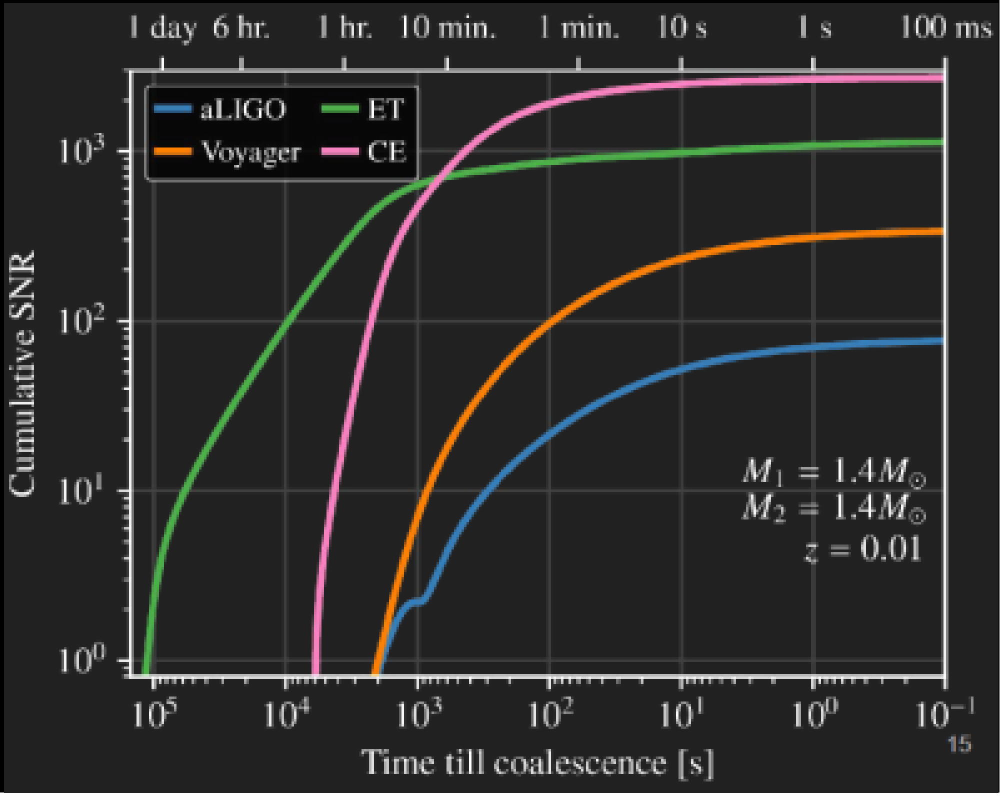
(Top) Kip Thorne; (Bottom) B. P. Abbott *et al.*; adapted by APS/Carin Cain



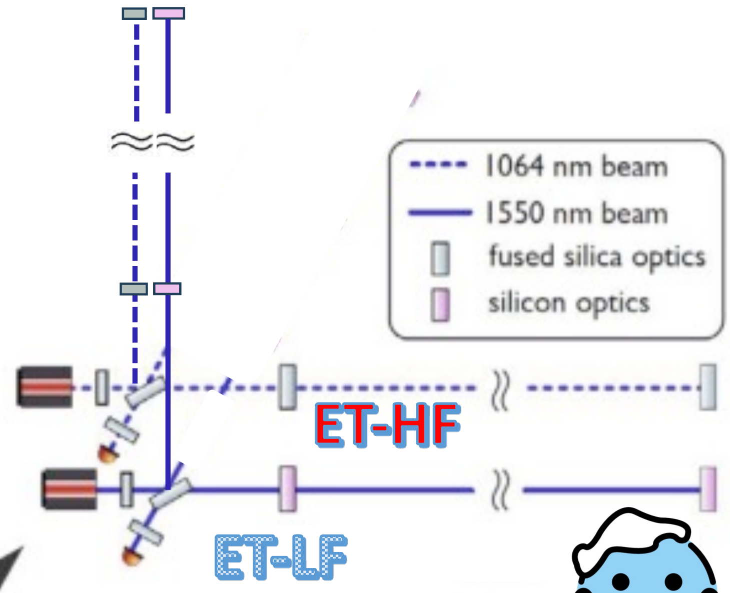
Low frequency: Multi-messenger astronomy

- 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:





ET key elements

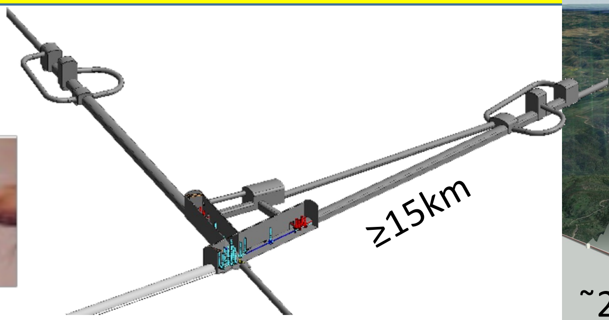


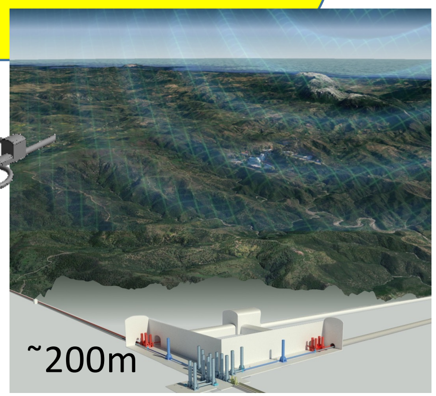
Requirements

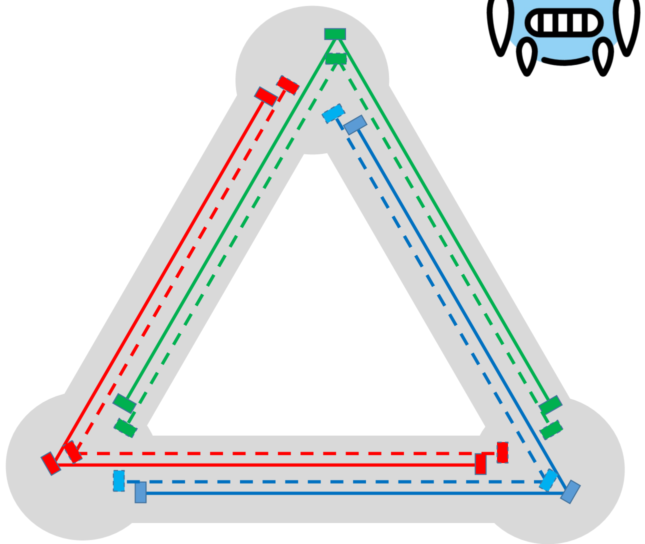
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape (2011)
- Multi-detector design
- Longer arms







Underground location

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

- Cost
- Challenging civil engineering
- 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)

ET geometry debate: Δ or (two) L

In the last two 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:

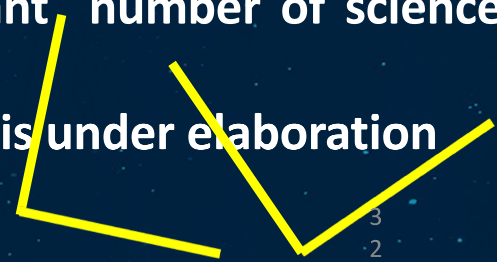
- ❑ First detections, GTWC-3 catalog → BH population → new evolution models;
- ❑ Science case developed;
- ❑ Know-how with advanced (L) detectors;
- ❑ International scenario (+ Cosmic Explorer in US);
- ❑ Two candidate sites strongly supported (and a potential third site…).

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

First results on the science return published in Marica Branchesi et al JCAP07(2023)068:

The 2L 15 km geometry shows an improved science return in a relevant number of science targets

A preliminary differential risk analysis, provided by a specific committee, is under elaboration



ET Enabling Technologies

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

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)	$5 \cdot 10^{-10}$ m/f^2	$5 \cdot 10^{-10}$ m/f^2
Gravity gradient subtraction	none	factor of a few

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INFN
Istituto Nazionale di Fisica Nucleare

- **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

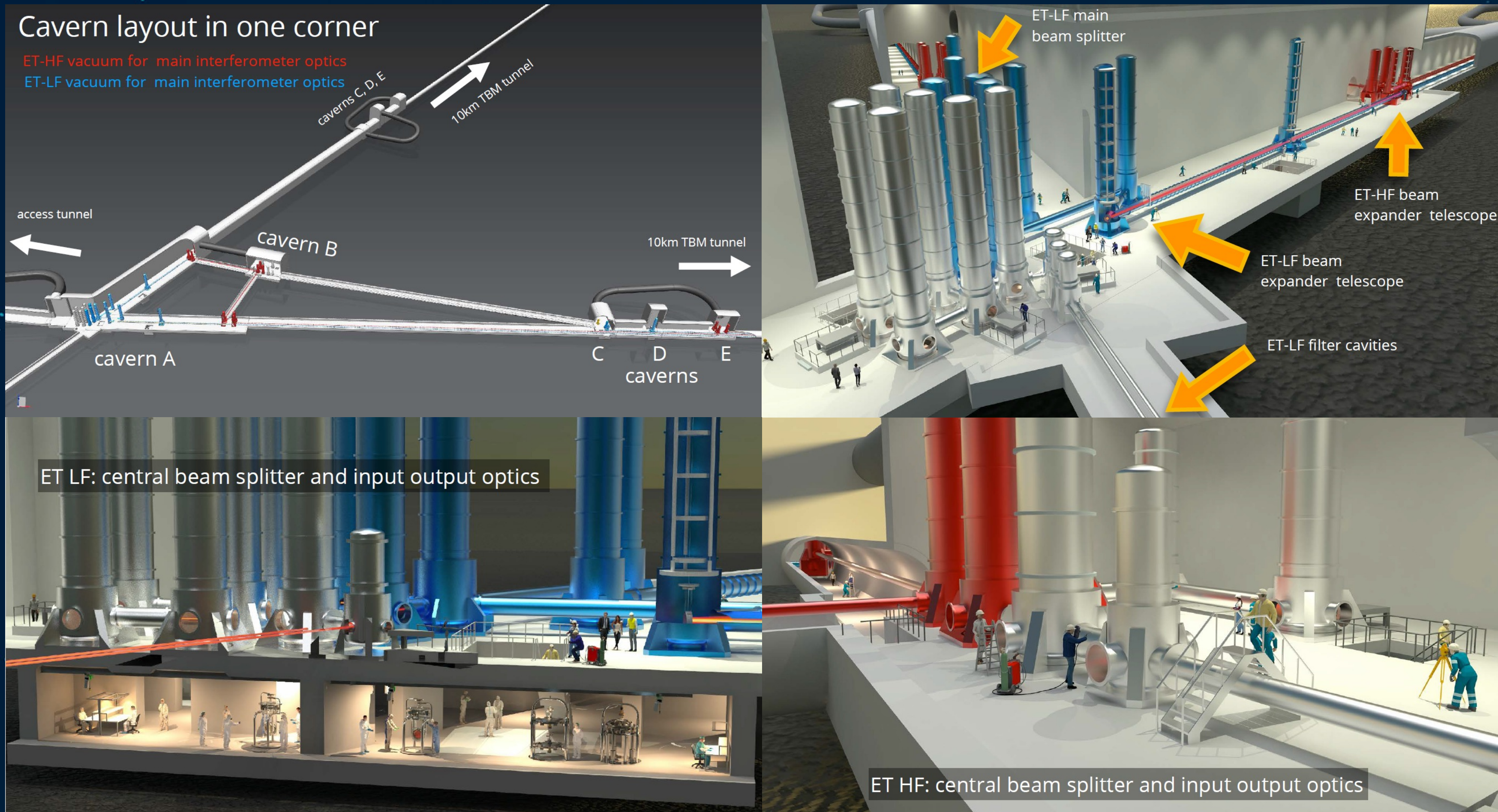
Evolved laser technology

Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

ET: large scale and complex infrastructure



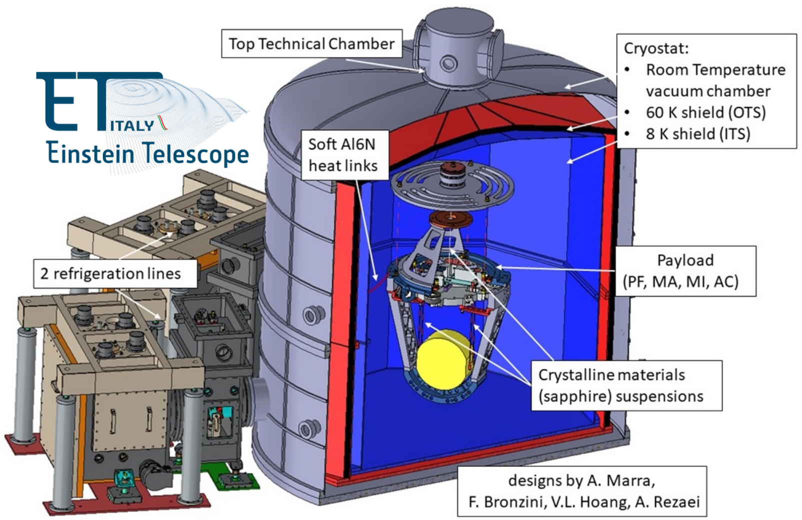
Credit: A.Freise, 2020 XI ET Symposium

Challenges in Cryo-cooling

ET operative temperature ~10K

Key issues

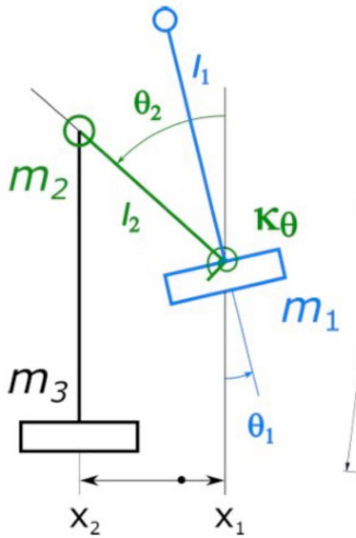
- Acoustic and vibration noises
- Laser absorption and heat extraction
- Cleanliness and contamination
- Cooling time (large masses, commissioning time, …)
- Infrastructures
- Technology (cryo-fluids or cryo-coolers)
- Materials
- Safety

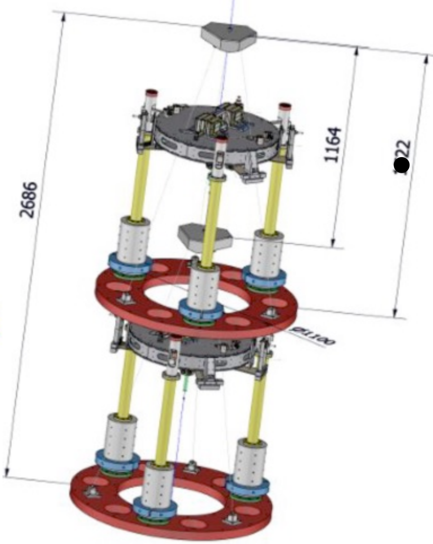


Amaldi Research Center in Rome

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





Credits: A.Freise

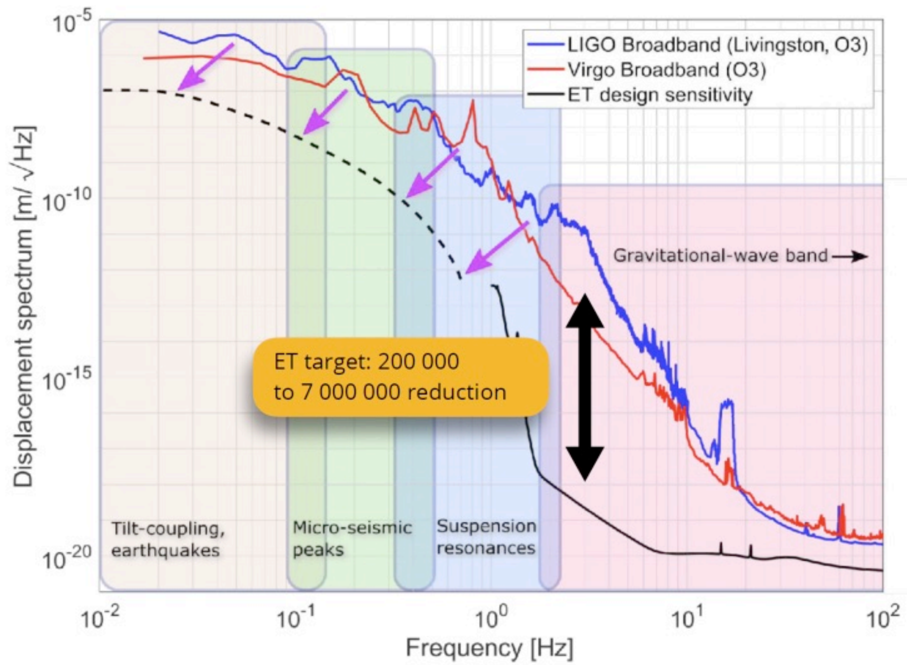
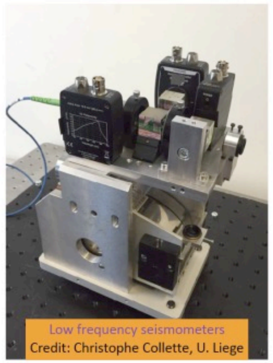
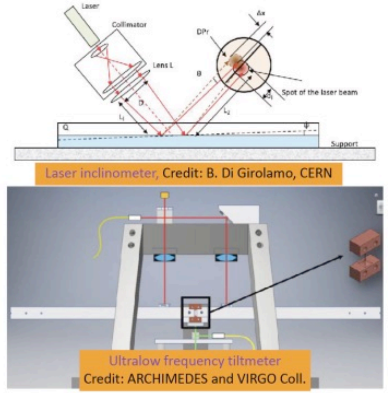


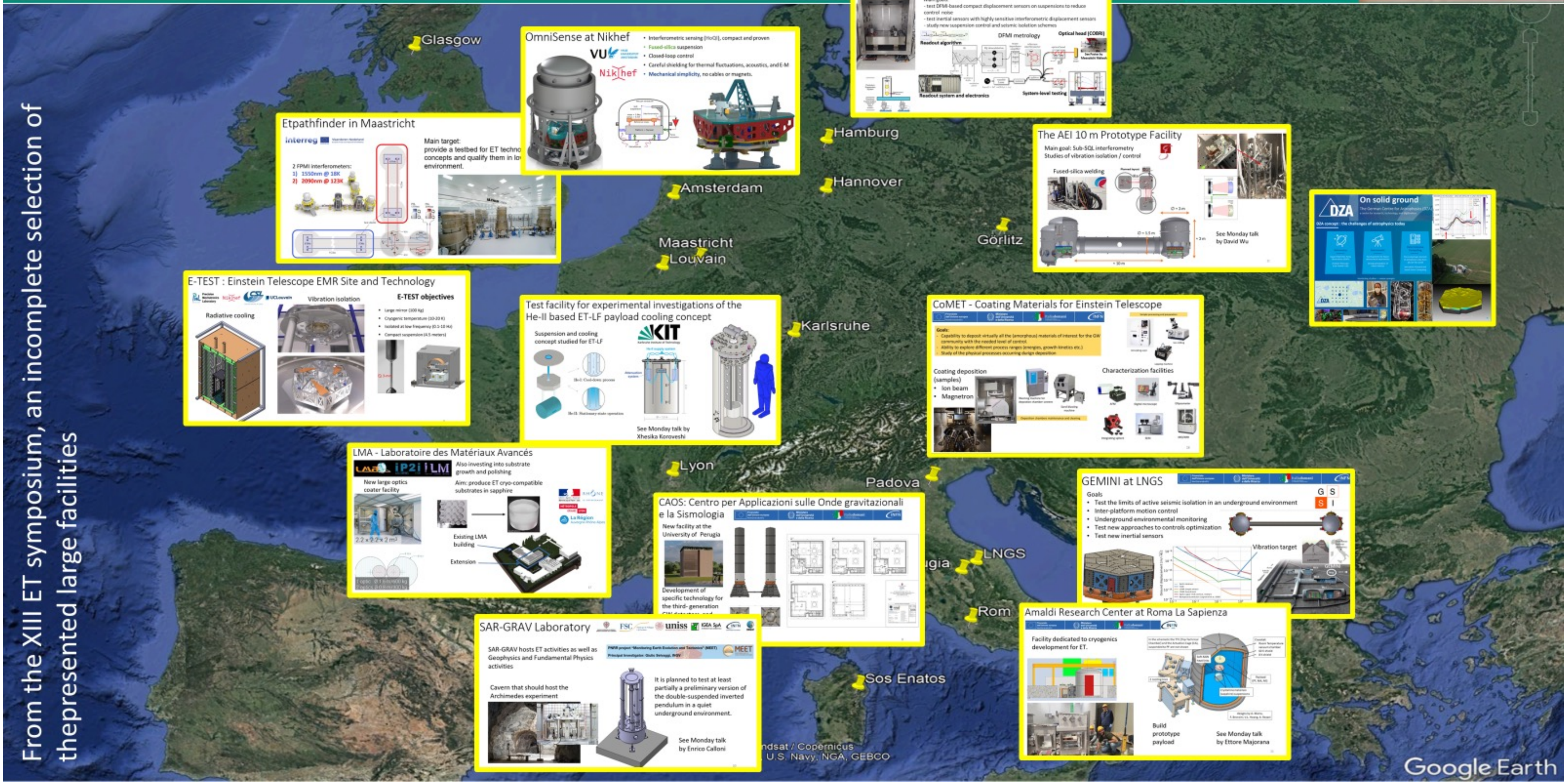
Image: Conor Mow-Lowry





Major R&D Facilities in ET (incomplete)

ET EINSTEIN TELESCOPE



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

Summary

- Gravitational astronomy started (> 200 detections and candidates)
- Huge science case for 3rd generation observatories
- ET timeline is under review, but grosso modo:
  - ET science case (Blue Book) will be updated in 2024, early 2025
  - We expect to define geometry, site(s) and roughly evaluate the cost of the civil infrastructures within the 2026
  - In the same time window, the future ET legal entity should be defined
  - We started to work on the ET Technical Design Report and a preliminary, iterative document should be initiated in the next months and drafted in one year
- Funding
  - Large funding O($\leq 10^9$€) promised by the Italian and the Dutch Governments
  - O ($\leq 10^8$€) investment aggregated in the two sites for the candidature and the development of the enabling technologies

The Einstein Telescope Collaboration

- **91 Research Units**
- **1722 members (21/09/2024)**
- **Total: 252 Institutions**
  in 30 Countries

- **ET member database**

ET Member‘s affiliation map