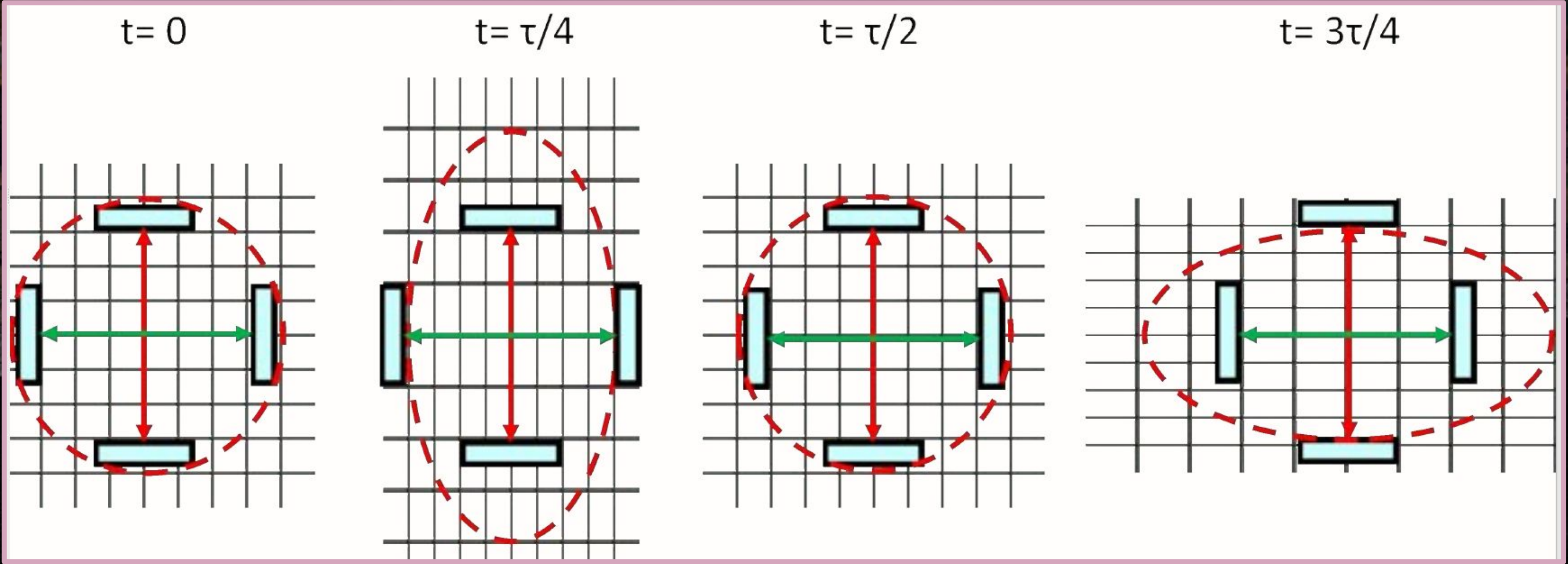
The Einstein Telescope and its technological challenges

Francesca Badaracco

UCLouvain

Image credit: Marco Kraan, Nikhef

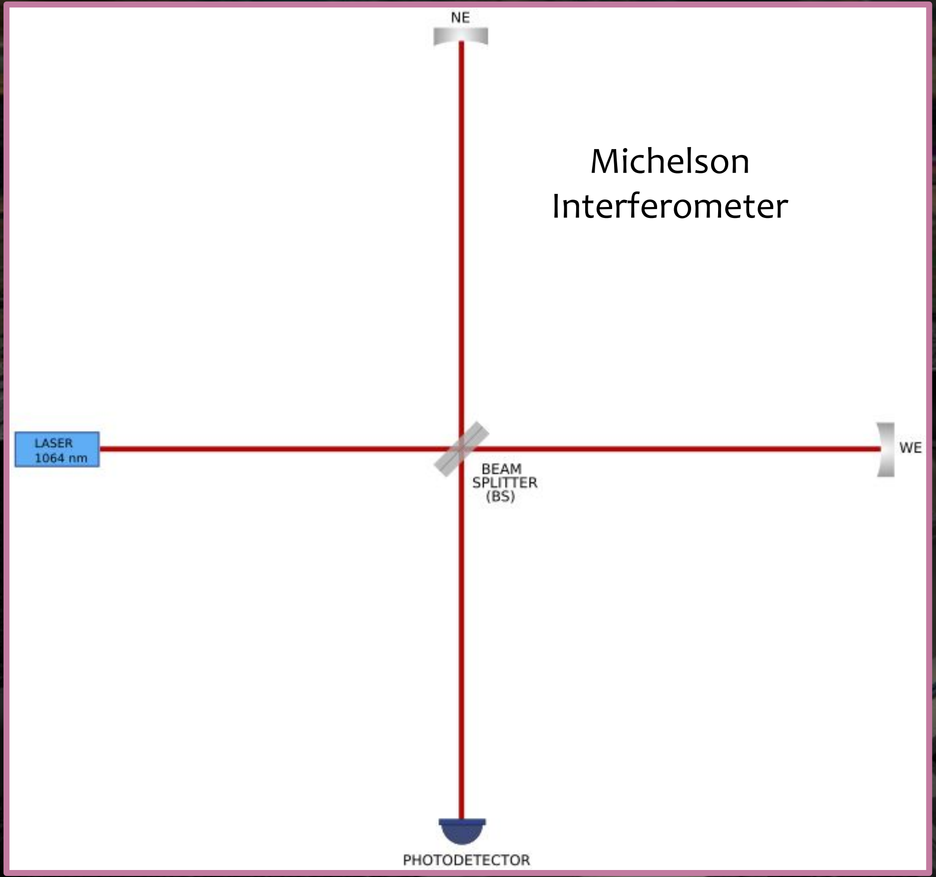
Gravitational wave detection working principle:



GW **change distances between objects**, while the objects themselves locally remain at rest, by changing the metric of space-time

Credits: ET-0007B-20 ET Design Report Update 2020

Gravitational wave detection working principle:

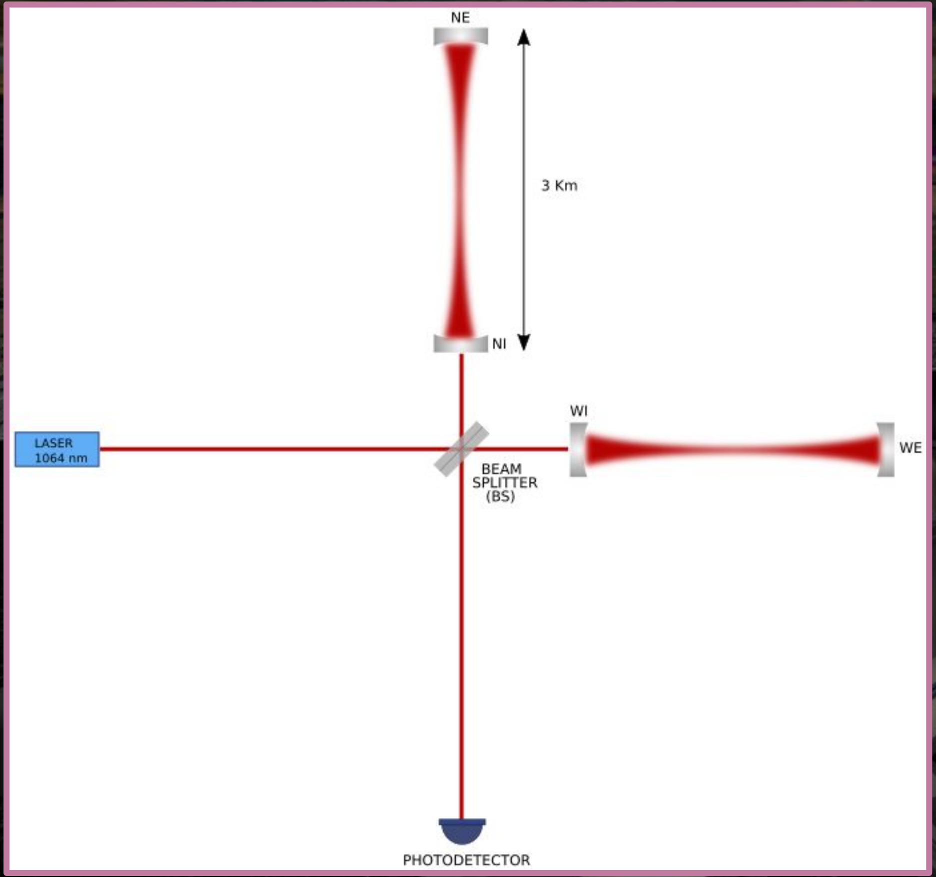


Measure the **change in length**

→

Measure **change in phase**

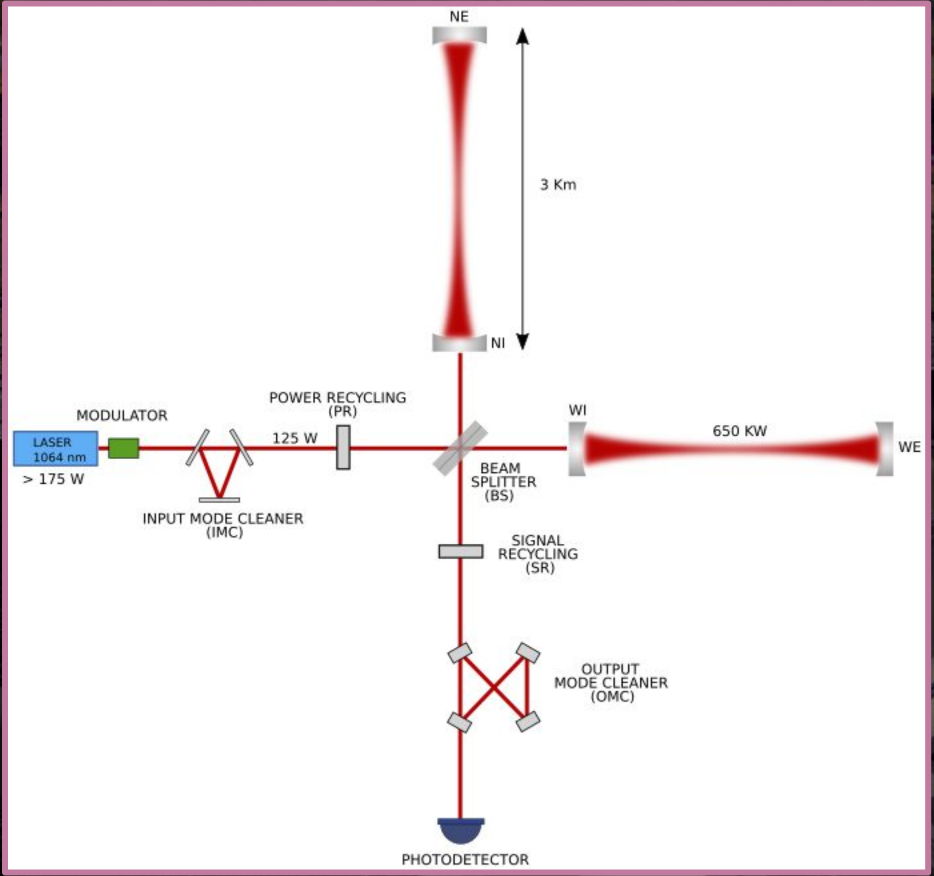
Gravitational wave detection working principle:



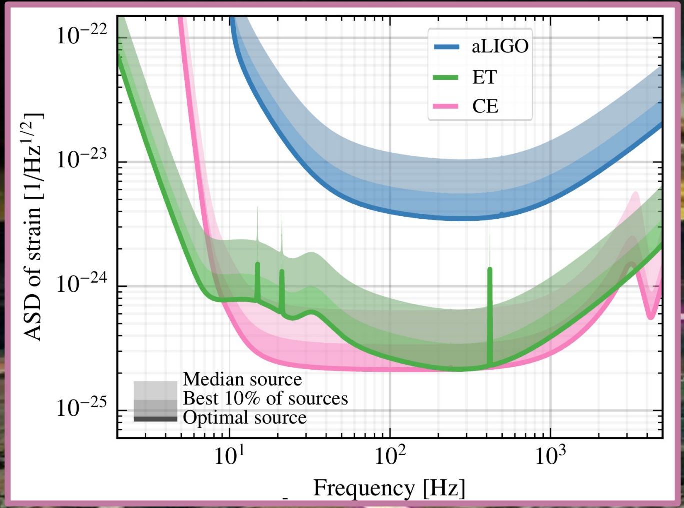
Actually… it is much more complicated:

We need a stratagem to have longer arms and more power → **optical cavities + Pound-Drever Hall technique** .

Gravitational wave detection working principle:



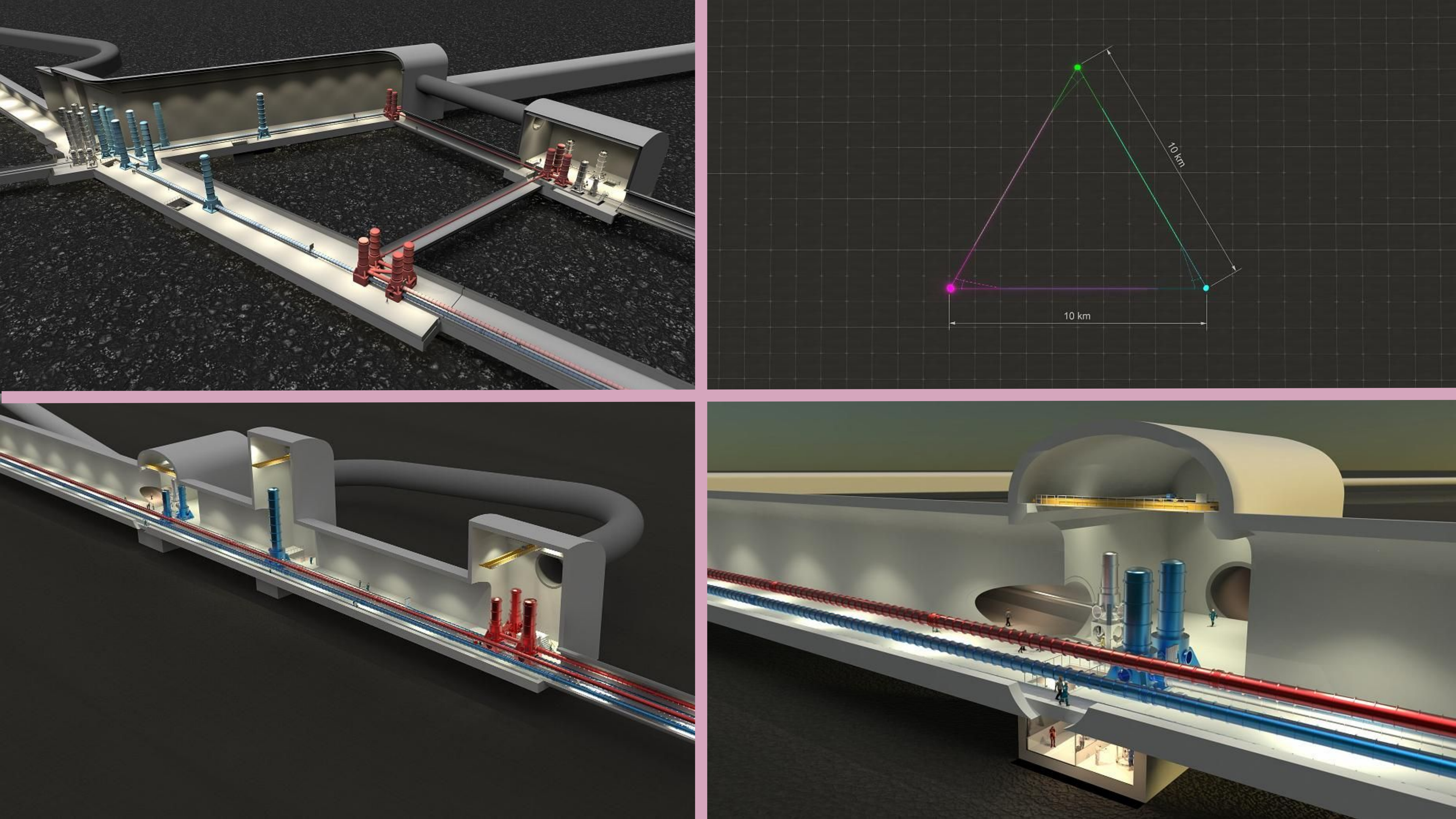
Much, much more…



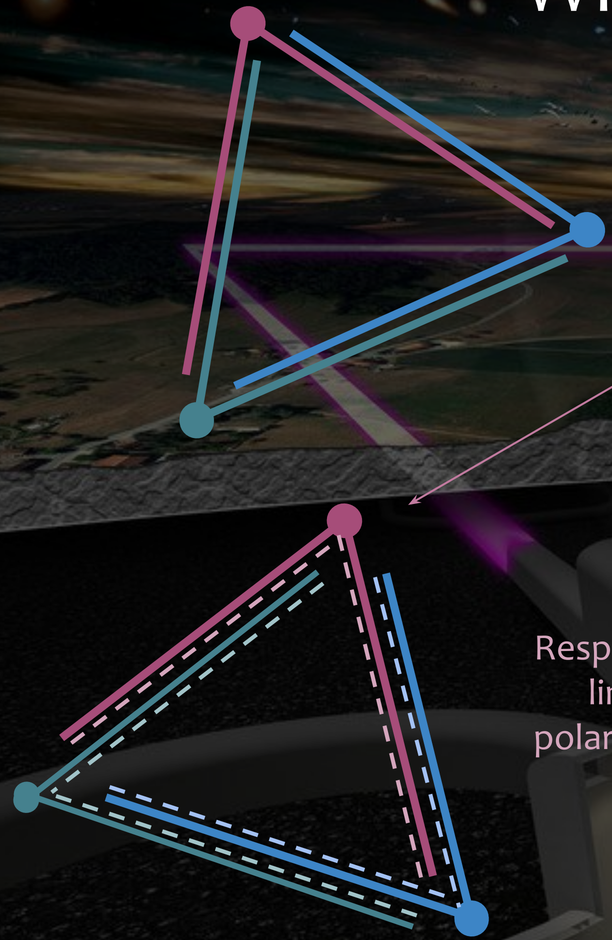
Credits: GWIC 3G Committee, the GWIC 3G Science Case Team, and the International 3G Science Team Consortium, "3G Science Book," 2020

Underground:

- More stable interferometer!
- Better low frequency sensitivity


10 km
10 km

Why a △ ?

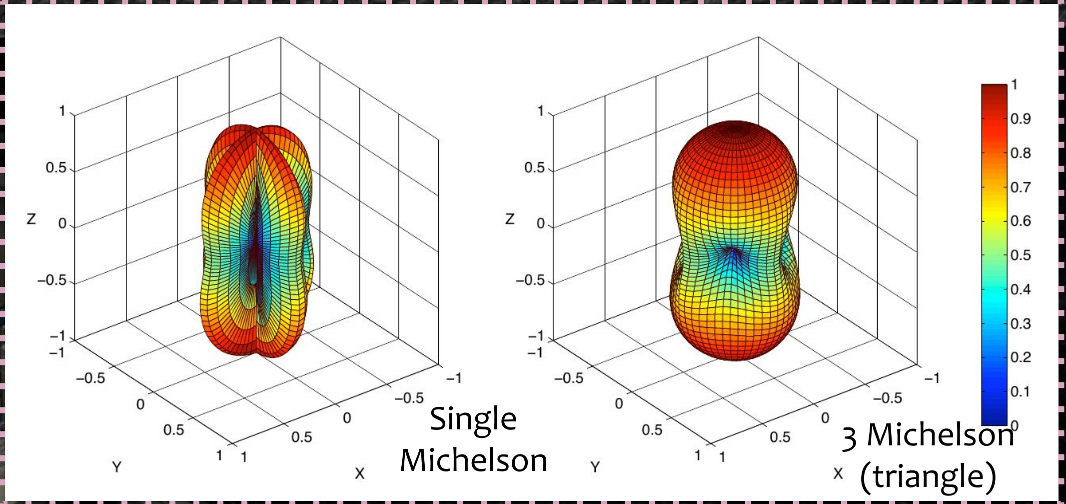


- Equilateral triangle (xylophone):
  - 3 **nested** detectors
  - Each one split in two interferometers:
    - Low-frequency (cold)
    - High-frequency (hot)
- Why this shape?
  - Equally sensitive for both GW **polarisations**
  - **Redundancy**
    - **Null stream**
    - **Observation continuity**

Universiteit Antwerpen

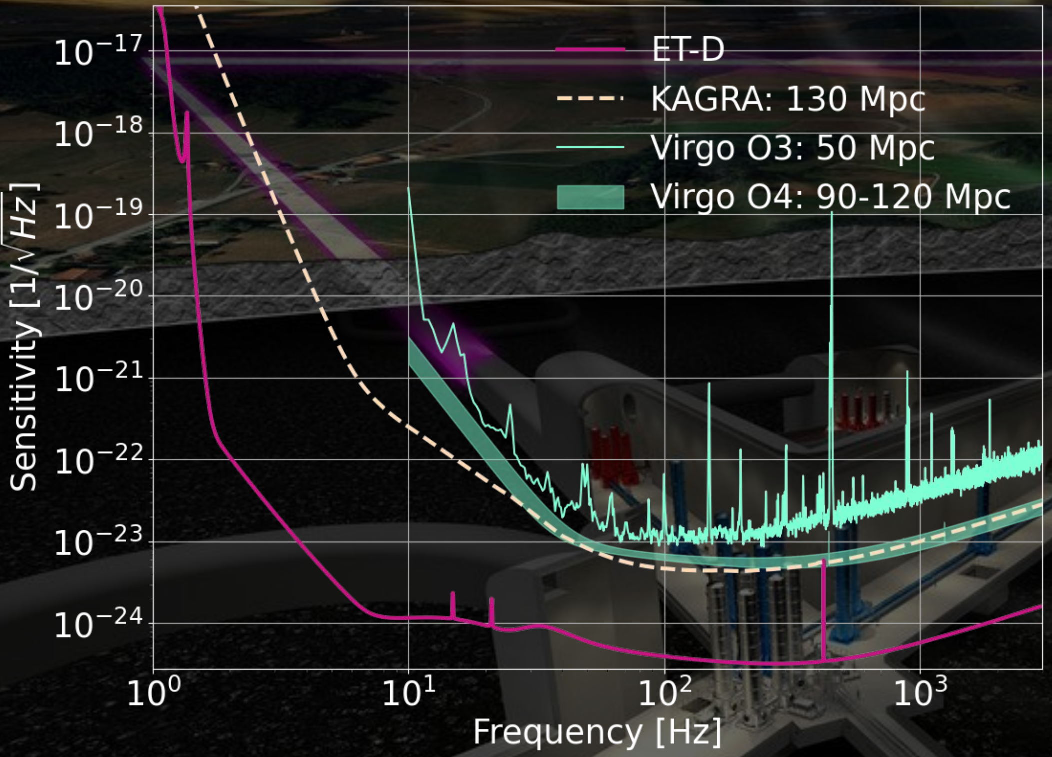
Janssens et al
arXiv:2205.00416

Response to linear polarization:



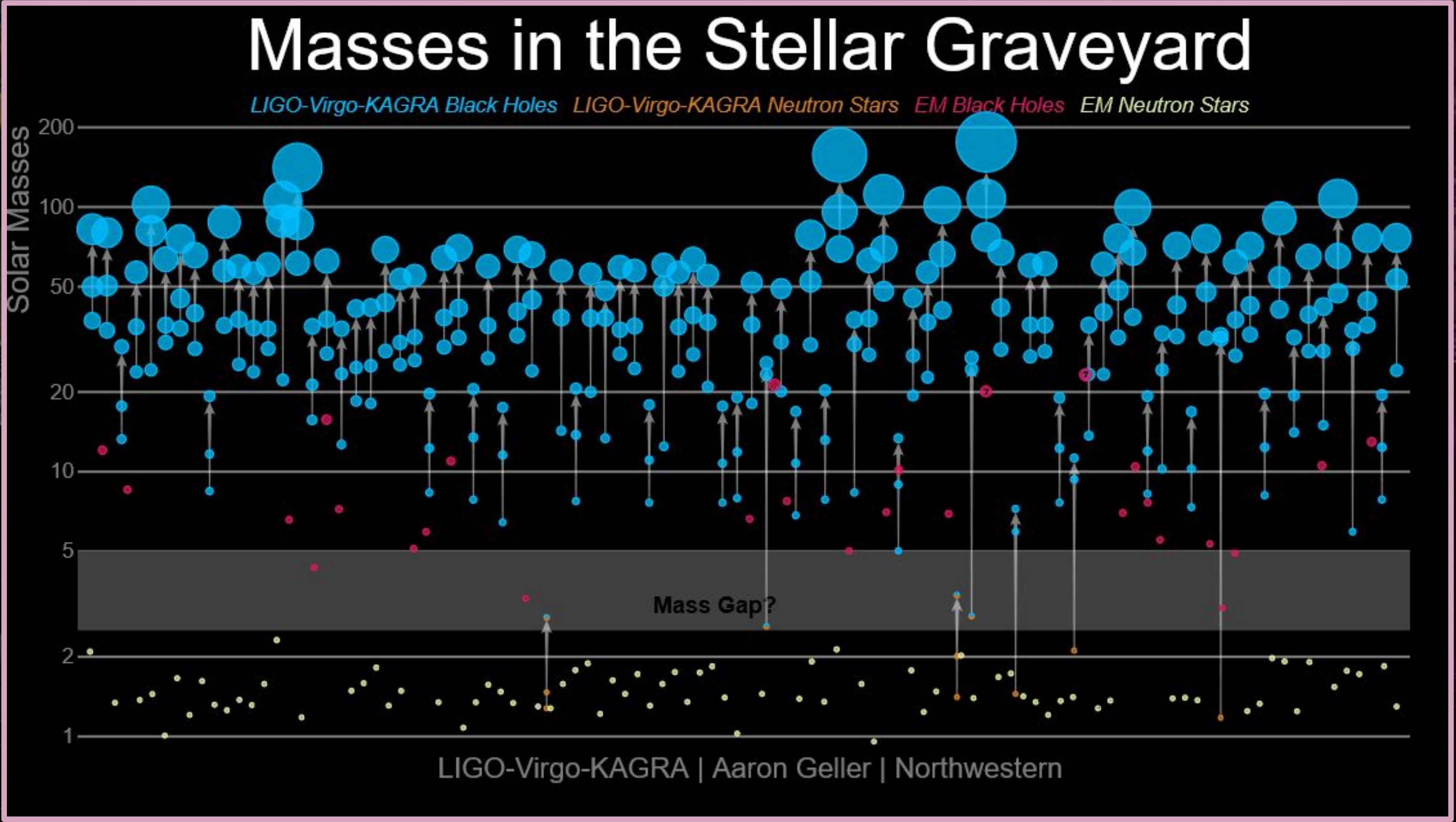
From the ET conceptual design study

Improving the low frequency band is very expensive: do we really need it?

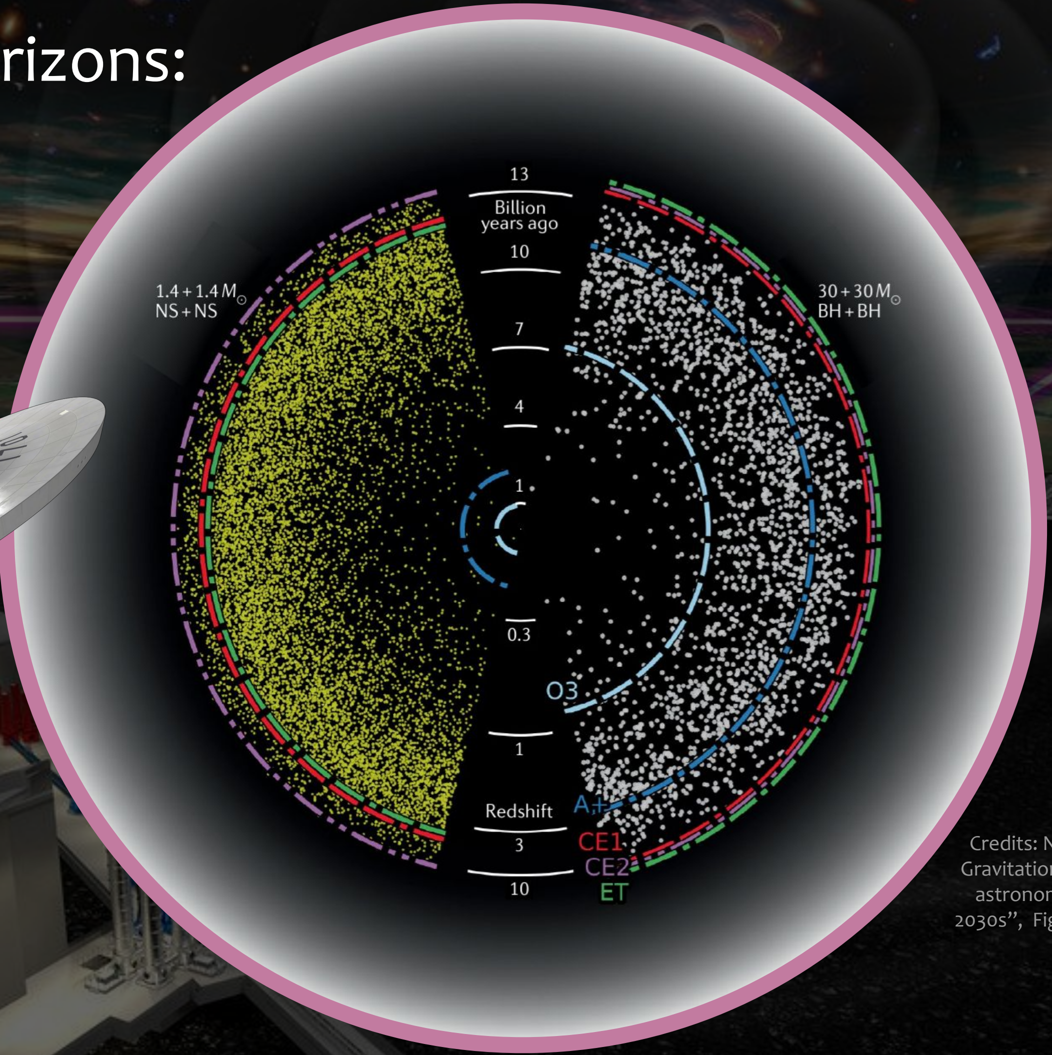


- New possible discoveries
- BNS: Hours – Days
  - Parameter estimation
  - EM early warning
  - Sky localization with only ET
- Massive BBHs:
  - intermediate mass BH (10^2-10^5 solar masses)
  - Higher redshift→PBHs?
- Search of GW cosmological signal

What has been reached with LIGO-Virgo-KAGRA



ET to expand our horizons:



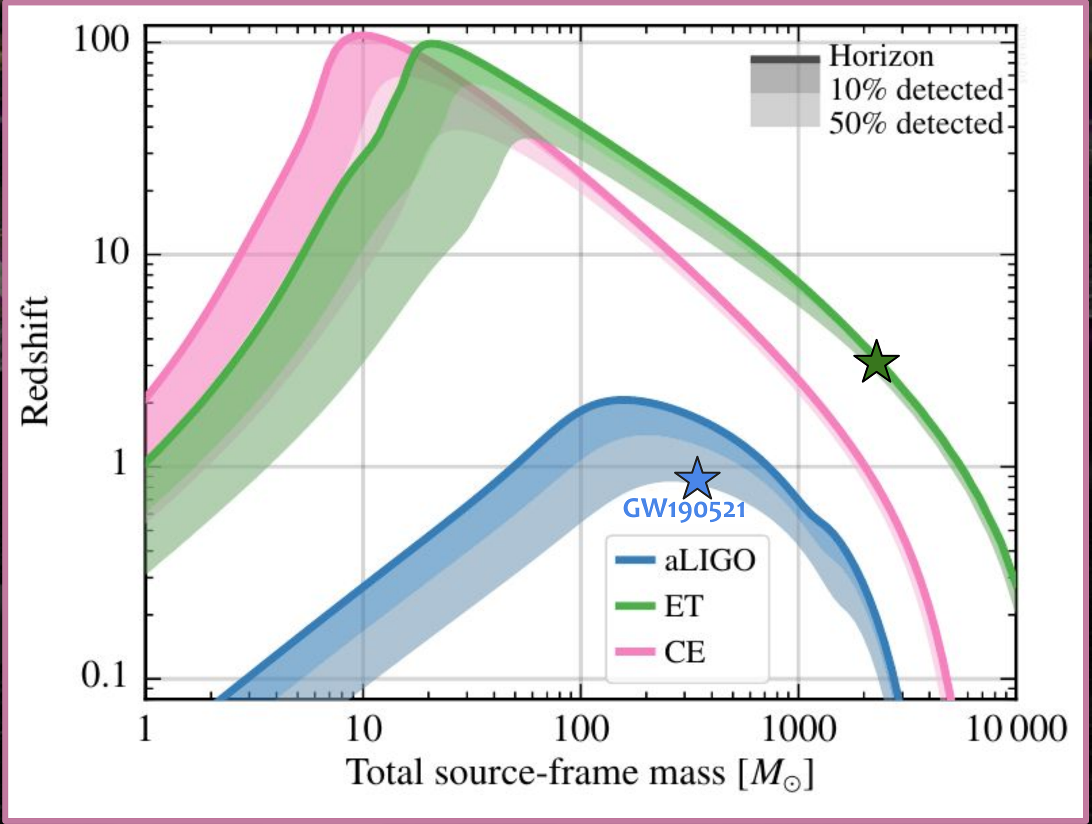
"To boldly go where no man has gone before."

Captain James T. Kirk

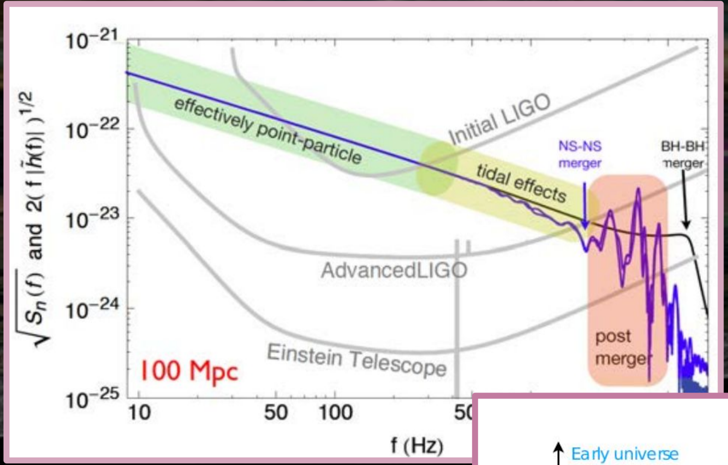
Credits: Nature, "ROADMAP, Gravitational-wave physics and astronomy in the 2020s and 2030s", Figure courtesy of **Evan Hall**

A comparison between present and future detectors

Astrophysical reach for equal-mass, non-spinning binaries



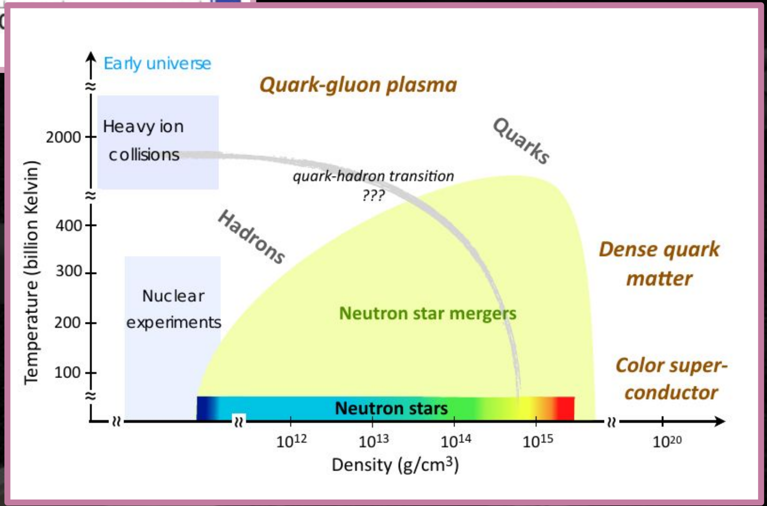
Neutron Star post-merger phase:



From M. Maggiore, Gravitational Waves. Vol. 2. Astrophysics and Cosmology. Oxford University

Gravitational wave signal from a NS-NS merger at a distance 100 Mpc, as it sweeps across the detector-accessible frequency range.

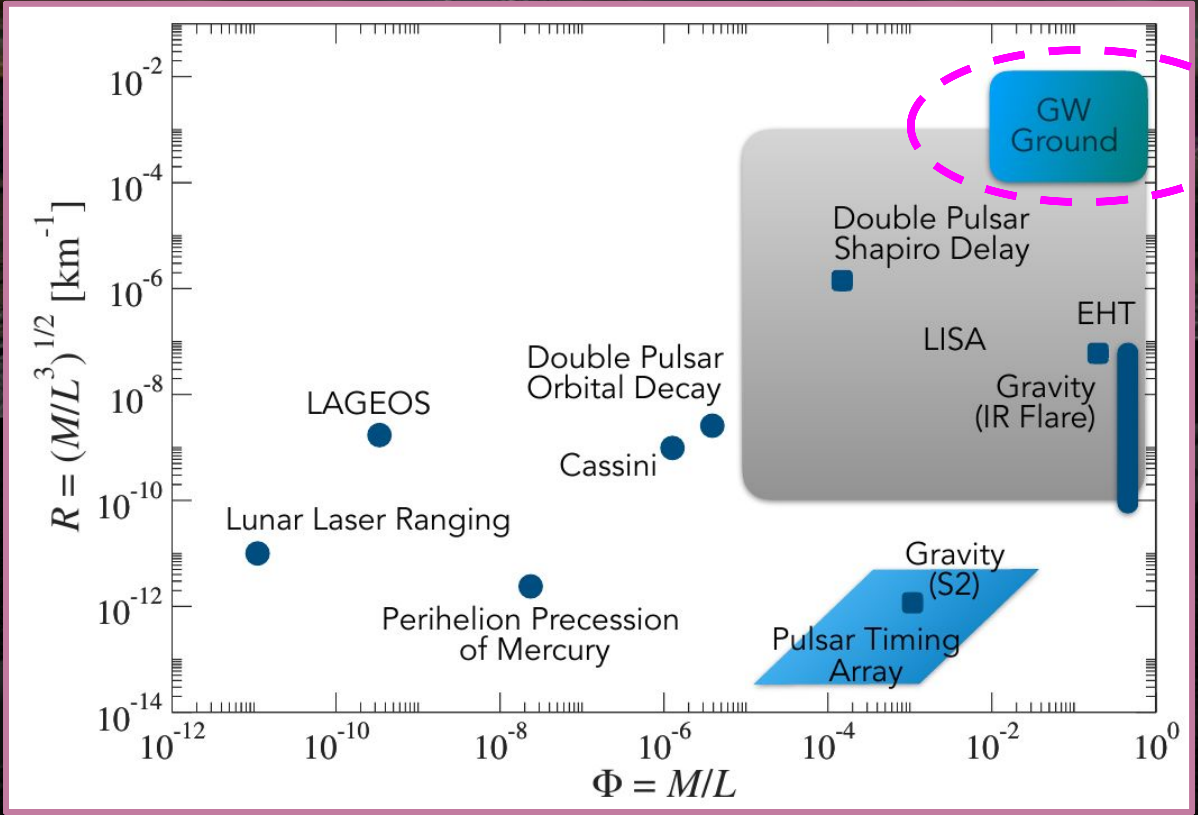
- Properties of **cold, dense matter in NSs**
- New physics during a **binary NS merger (higher temperatures** and **more extreme densities)**
- **Formation of heavy elements** from synergies with **electromagnetic observations.**



Credits: ET-0007B-20 ET Design Report Update 2020

Matter encountered in neutron stars and binary mergers explores a **large part of the QCD phase diagram** in regimes that are **inaccessible** to terrestrial collider experiments.

Probing gravity in its most extreme conditions



Reach in spacetime curvature versus potential energy.

M and L: characteristic mass and length involved in the observed system.

Credits: GWIC 3G Committee, the GWIC 3G Science Case Team, and the International 3G Science Team Consortium, "3G Science Book," 2020

Dark matter

Primordial black holes?

Miller et al
arXiv:2012.12983
Clesse et al
arXiv:2110.07487v1

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UCLouvain

Ultralight dark matter bosons?

Miller et al
Phys. Rev. D 103, 103002
Phys. Rev. D 105, 103035

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Fundamental physics

Caldwell et al
arXiv:2203.07972v1

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H_0

Janssens et al
arXiv:2206.06809

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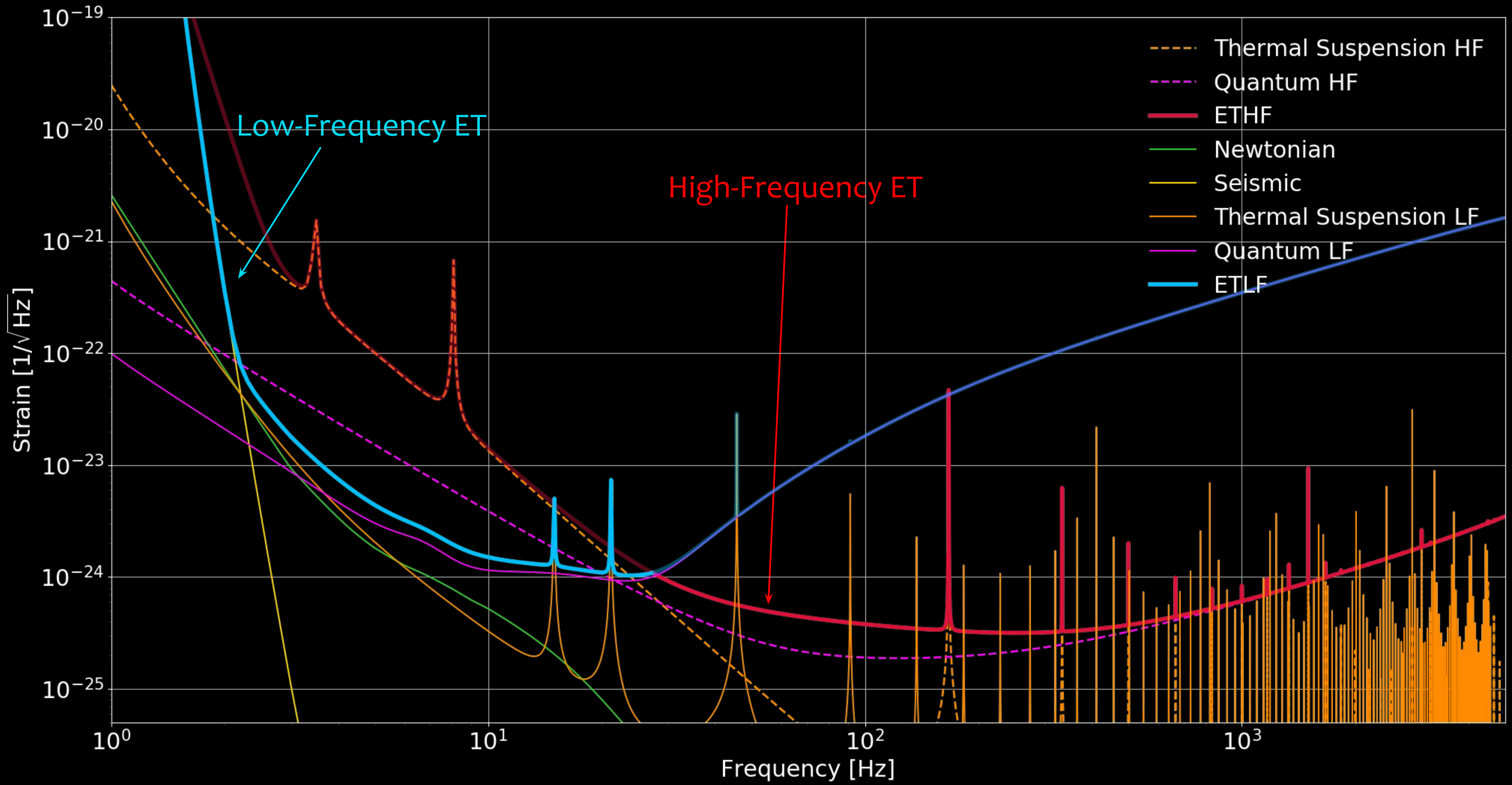
Cosmological Stochastic GW background

VUB VRIJE UNIVERSITEIT BRUSSEL

Not only instrumental related challenges: also computational and data analysis!

- 2G interferometer: 1PB/year (LHC ~ 110 PB/year in 2018)
- Compact binary coalescences: detected by template-based matched-filtering
  - **Longer templates** (more memory)
  - **Overlapping signals**
- After detection: parameters extracted with **Bayesian inference**
  - much less parallelisable algorithms
  - computing power scales linearly with the detection rate
- Day-long signals: the detector moves with respect to the source
- **Timely and reliable** distribution of candidate triggers
- **Rapid parameter estimation**, before the objects merge (multi-messenger astronomy)

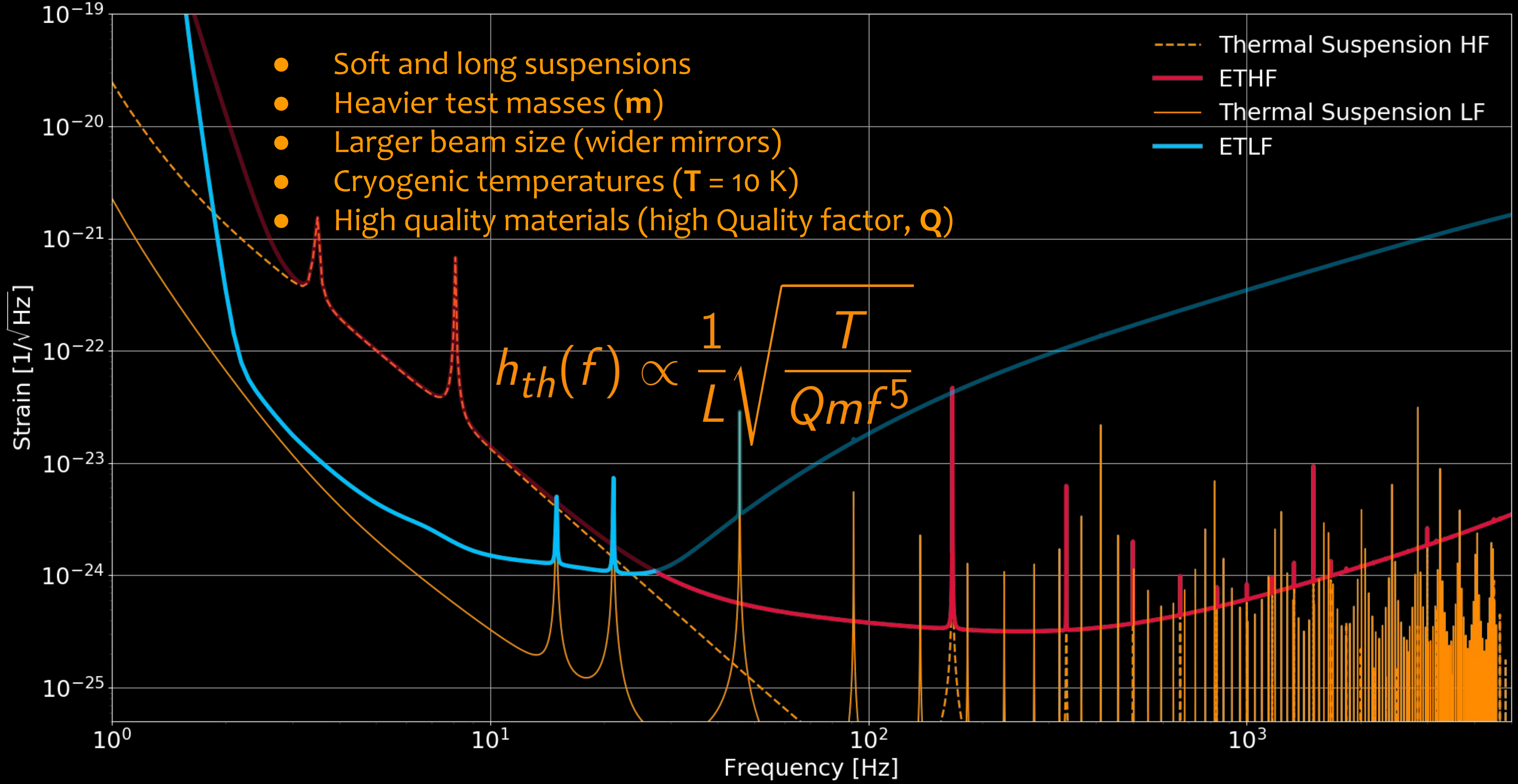
ET sensitivity curve:



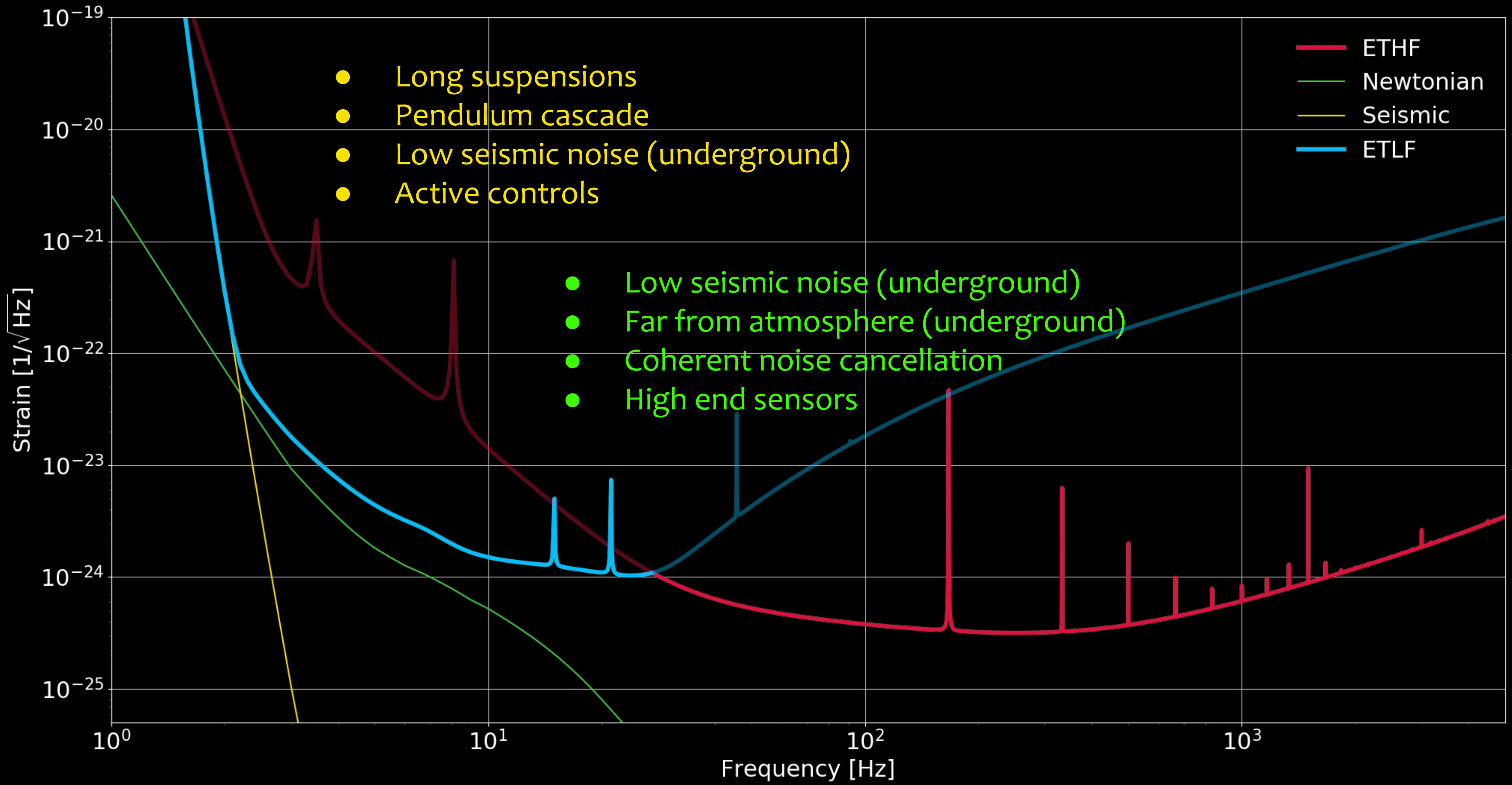
ET sensitivity curve: thermal noise

- Soft and long suspensions
- Heavier test masses (**m**)
- Larger beam size (wider mirrors)
- Cryogenic temperatures (**T** = 10 K)
- High quality materials (high Quality factor, **Q**)

$$h_{th}(f) \propto \frac{1}{L}\sqrt{\frac{T}{Qmf^5}}$$



ET sensitivity curve: seismic and Newtonian noise



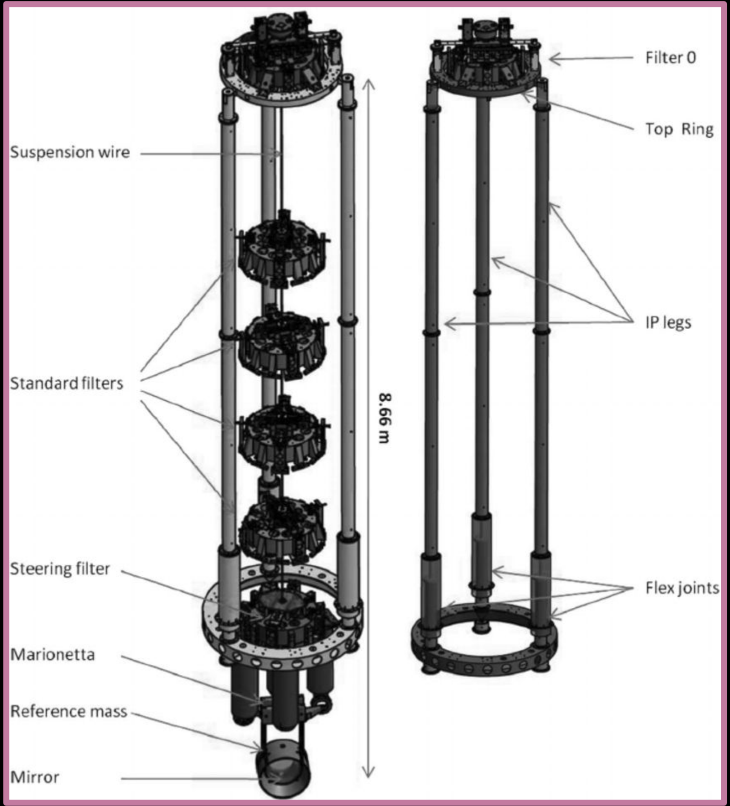
ET sensitivity curve: **seismic** and Newtonian noise

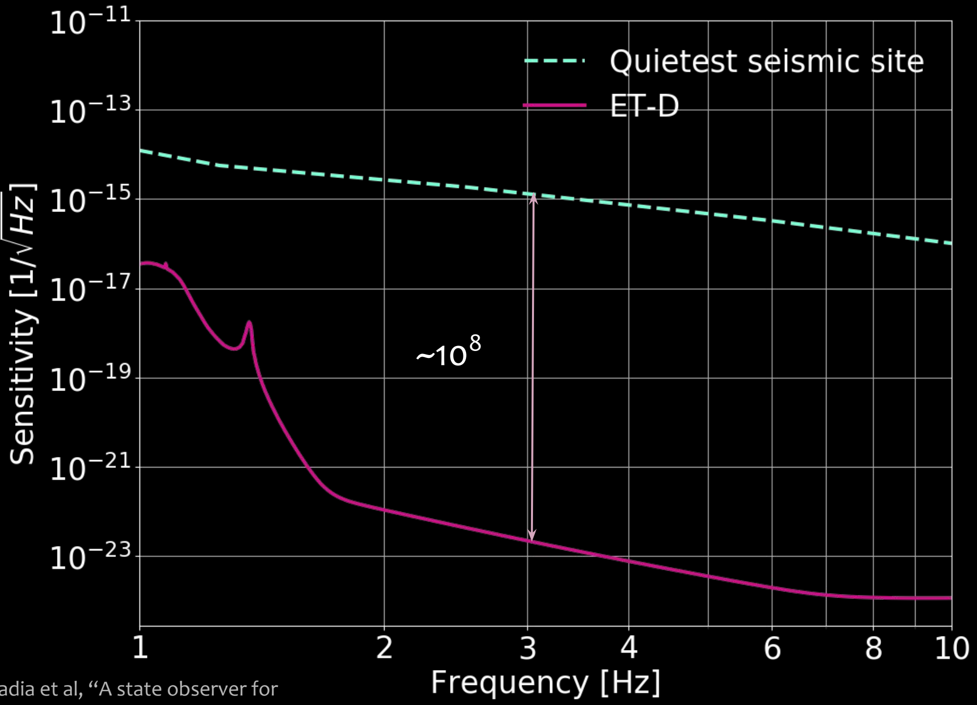
Just a glimpse of the complexity of GW detectors suspensions …

Suspensions concepts for ET

UCLouvain

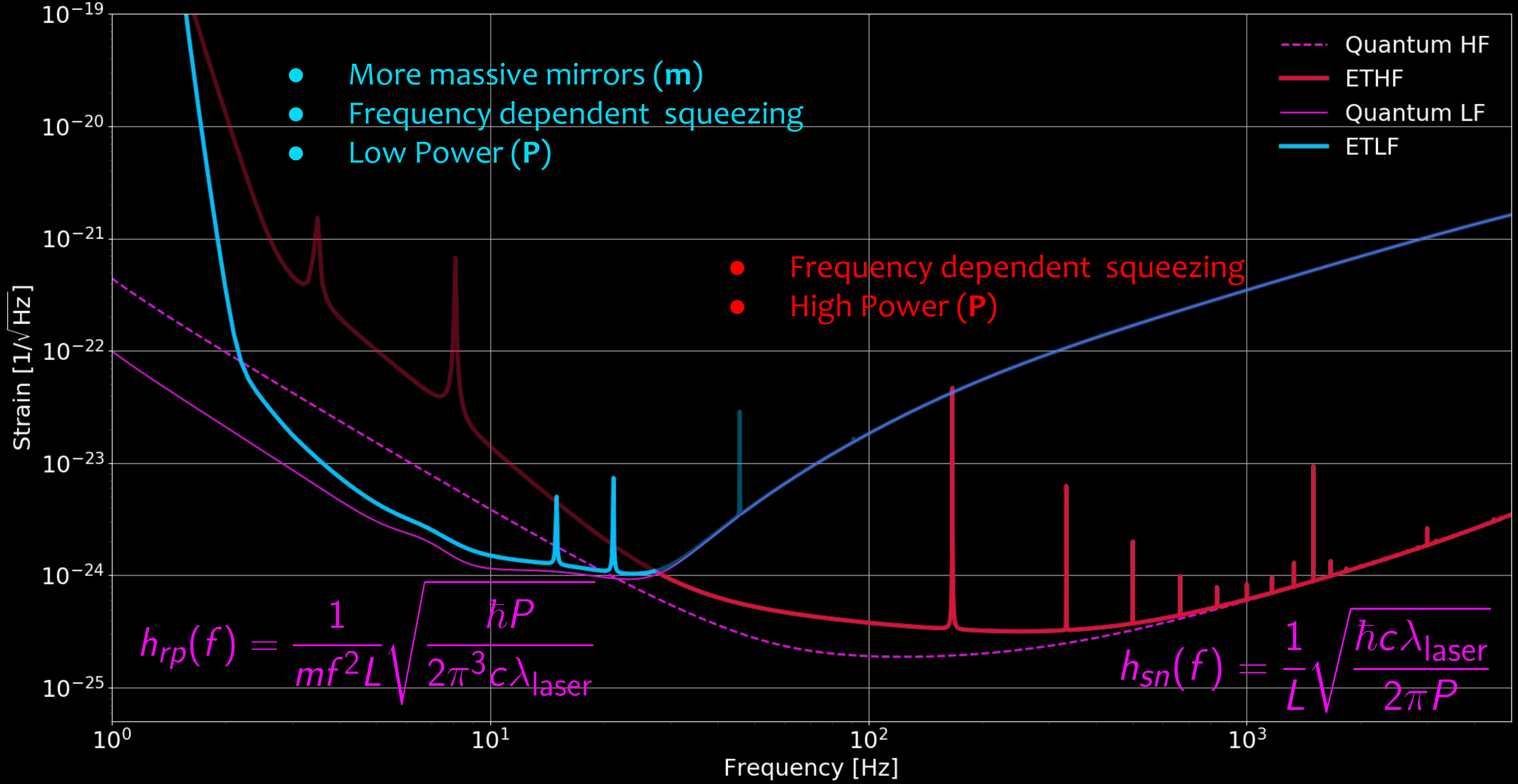
Attenuation $\propto 1/f^{2N}$



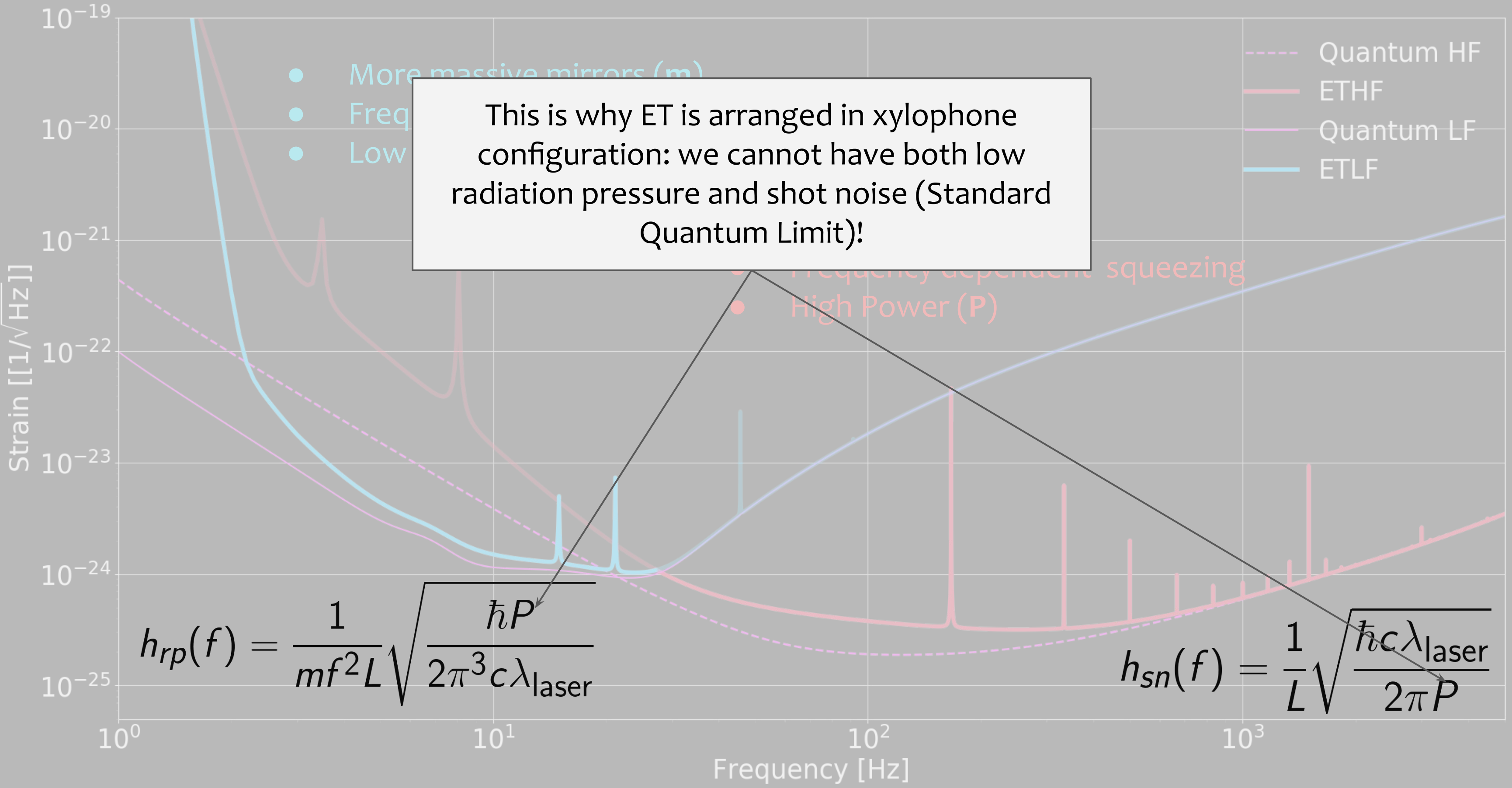


From: Accadia et al, "A state observer for the Virgo inverted pendulum", Review of Scientific Instruments 82, 094502 (2011)

ET sensitivity curve: quantum noise



ET sensitivity curve:

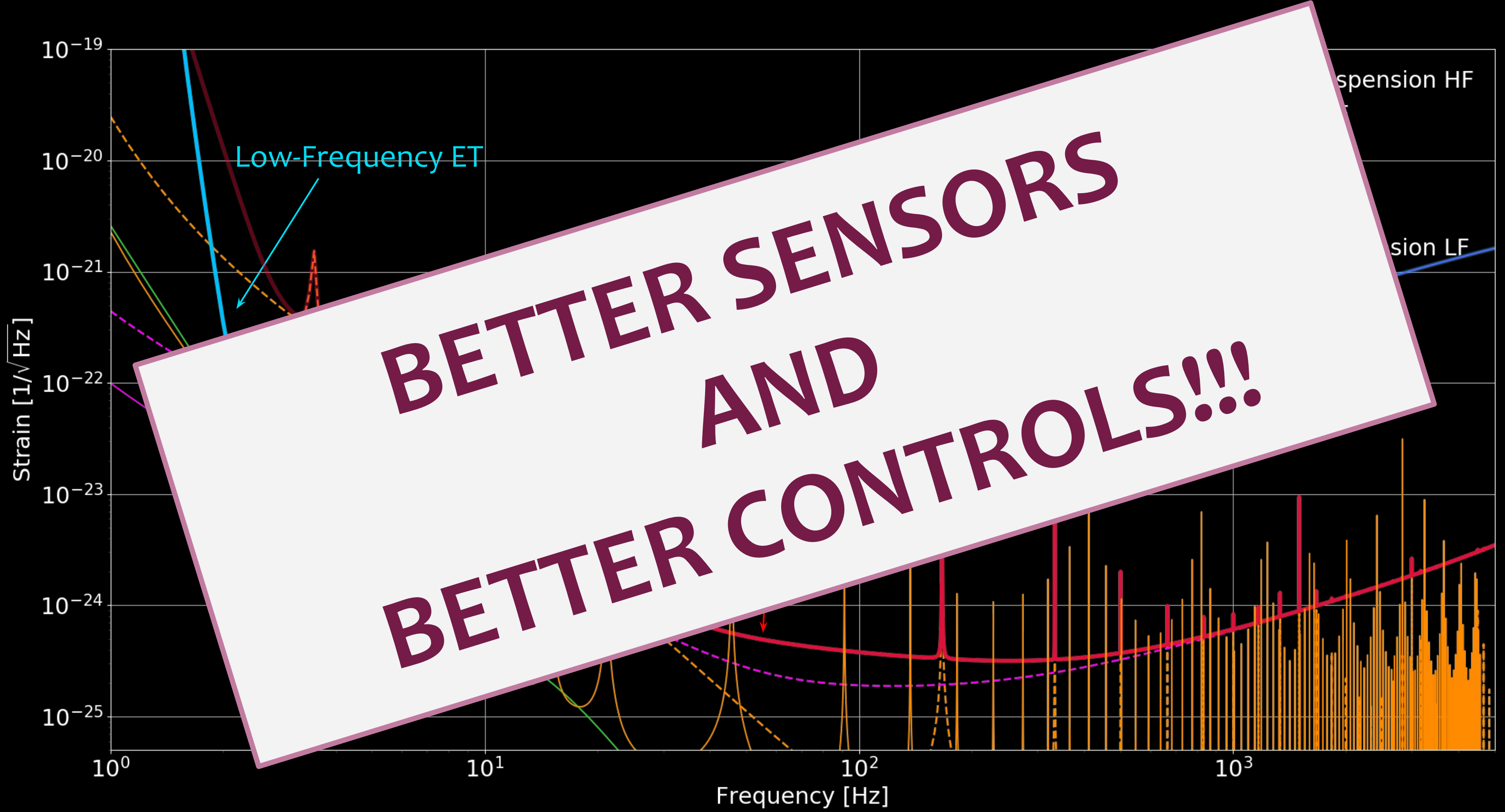


This is why ET is arranged in xylophone configuration: we cannot have both low radiation pressure and shot noise (Standard Quantum Limit)!

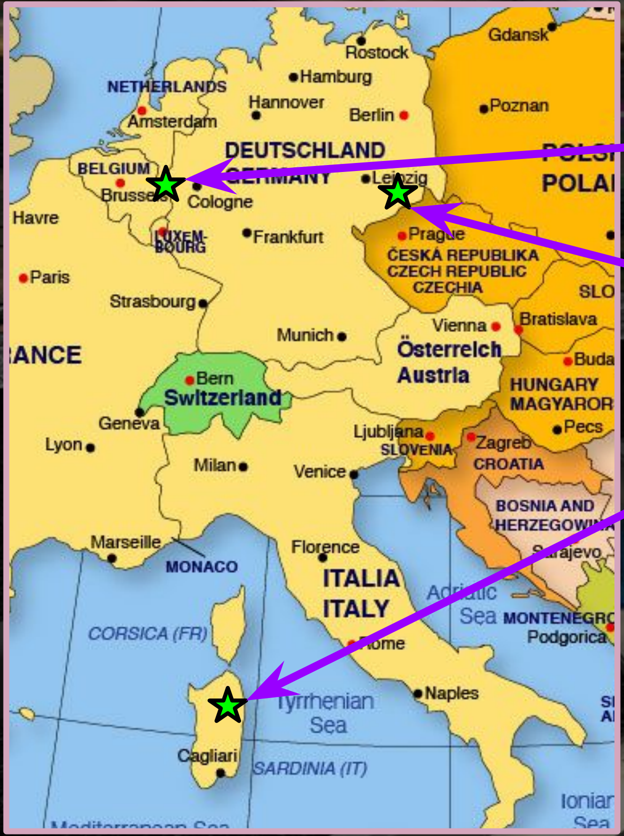
$$h_{rp}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda_{\text{laser}}}}$$

$$h_{sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda_{\text{laser}}}{2\pi P}}$$

ET sensitivity curve: not only fundamental noises…



The birth of the ET Collaboration



- Euregio Meuse-Rhine (Belgium/Netherlands/Germany)
- Saxony (Germany)
- Sardinia (Italy)

During the XII symposium of the Einstein Telescope (ET) in Budapest on the 7th - 8th of June 2022
~1200 members and 40+ institutions

European Strategy Forum on Research Infrastructures - ESFRI

ET was included in the 2021 **upgrade** of its roadmap → it **strengthens** ET at the European level

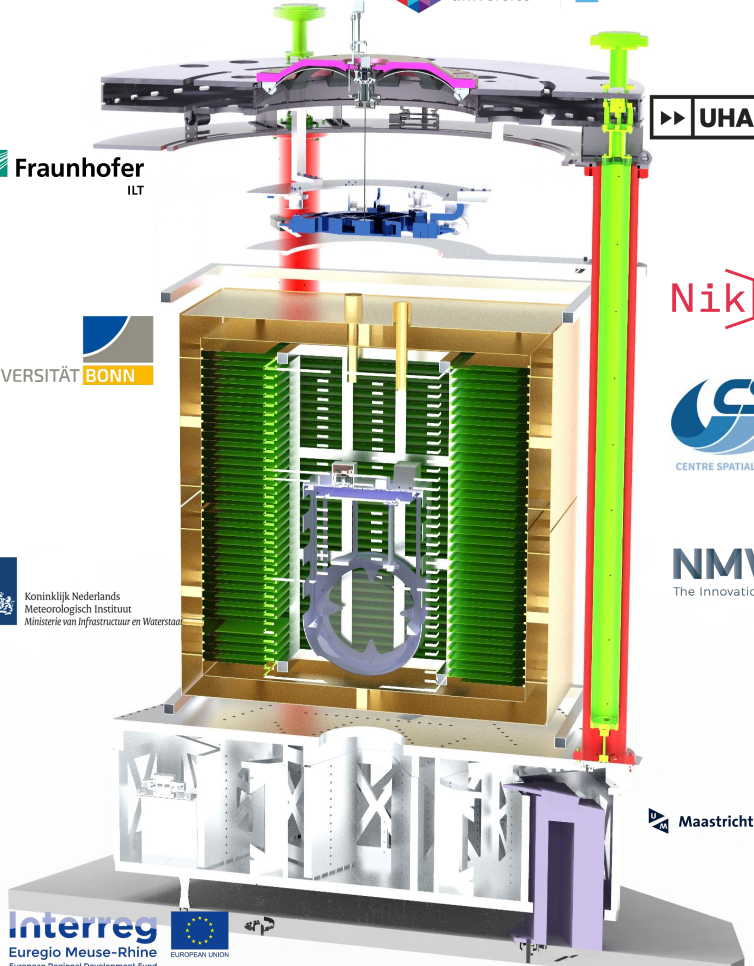
ESFRI PROJECTS

PHYSICAL SCIENCES & ENGINEERING

NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	INVESTMENT COST (M€)	OPERATION COST (M€/Y)
EST	European Solar Telescope	single-sited		2016	2029*	200.0	12.0
ET	Einstein Telescope	single-sited		2021	2035*	1,912.0	37.0
EuPRAXIA	European Plasma Research Accelerator with Excellence in Applications	distributed		2021	2028*	569.0	30.0
KM3NeT 2.0	KM3 Neutrino Telescope 2.0	distributed		2016	2020	196.0	3.0

Belgian effort towards ET:

KU LEUVEN · RWTH AACHEN UNIVERSITY · LIÈGE université · UCLouvain · UHASSELT · Fraunhofer ILT · Nikhef · UNIVERSITÄT BONN · CSL CENTRE SPATIAL DE LIÈGE · NMWP. The Innovation Engineers. · Koninklijk Nederlands Meteorologisch Instituut, Ministerie van Infrastructuur en Waterstaat · Maastricht University · Interreg Euregio Meuse-Rhine, European Regional Development Fund · EUROPEAN UNION

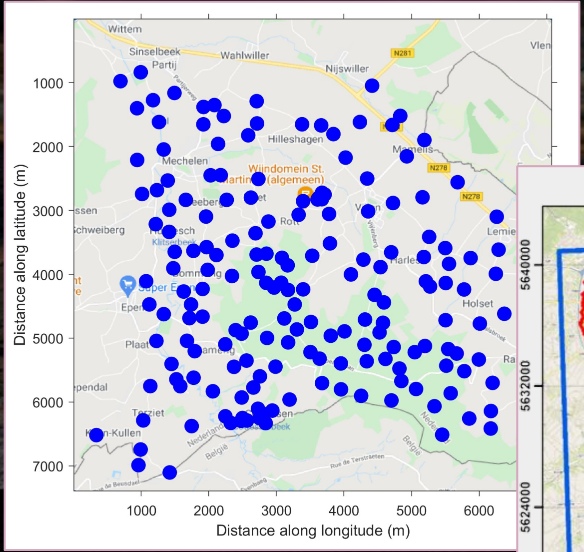


Di Pace et al
Galaxies 2022, 10, 65

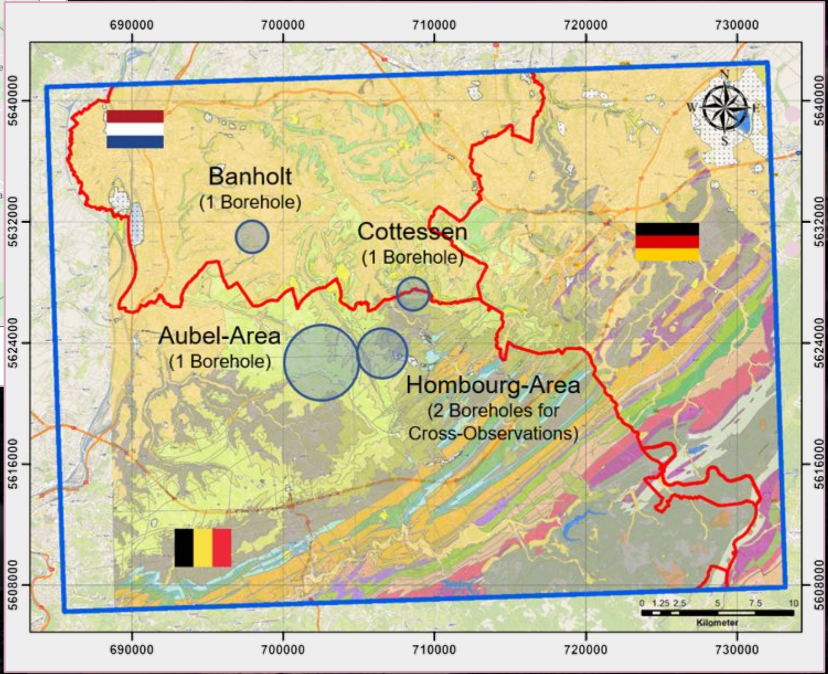
E-TEST:

- funded by the European program Interreg Euregio Meuse-Rhine
- Goals:
  - **develop a prototype of large suspended cryogenic silicon mirror**
    - Cryo (20K)
    - Radiative cooling
    - Suspension

Belgian effort towards ET:



Credits: Koley, meeting in Nuoro link



Credits: E-Test website

E-TEST:

funded by the European program Interreg Euregio Meuse-Rhine

Goals:

- **develop a non-invasive imaging of the geology in the EMR region and development of an observatory of the underground**
  - Geophysics
  - Tunnel layout

Belgian effort towards ET:

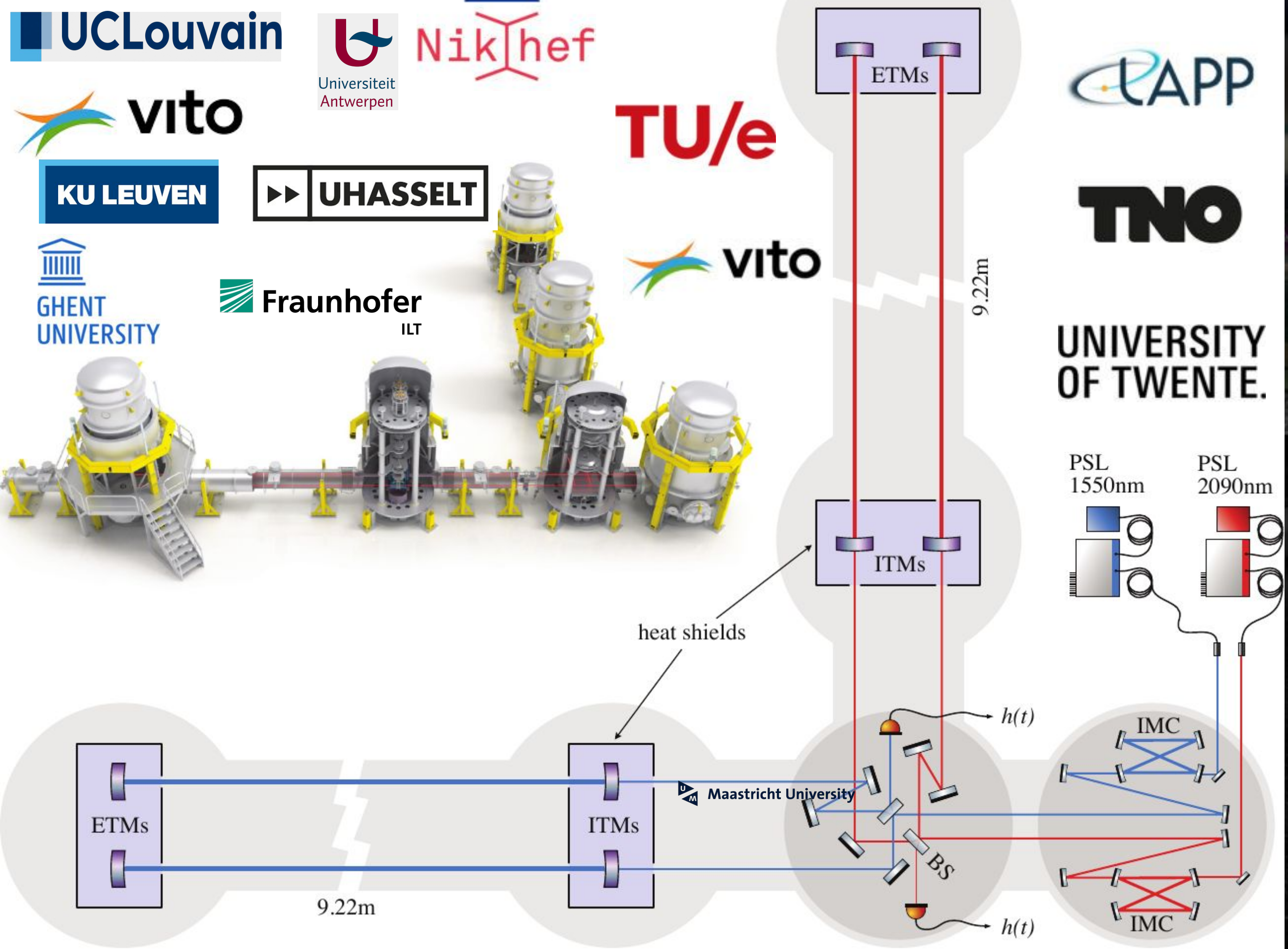


Image from the ET-Pathfinder first publication arXiv:2206.04905v1

ET Pathfinder:

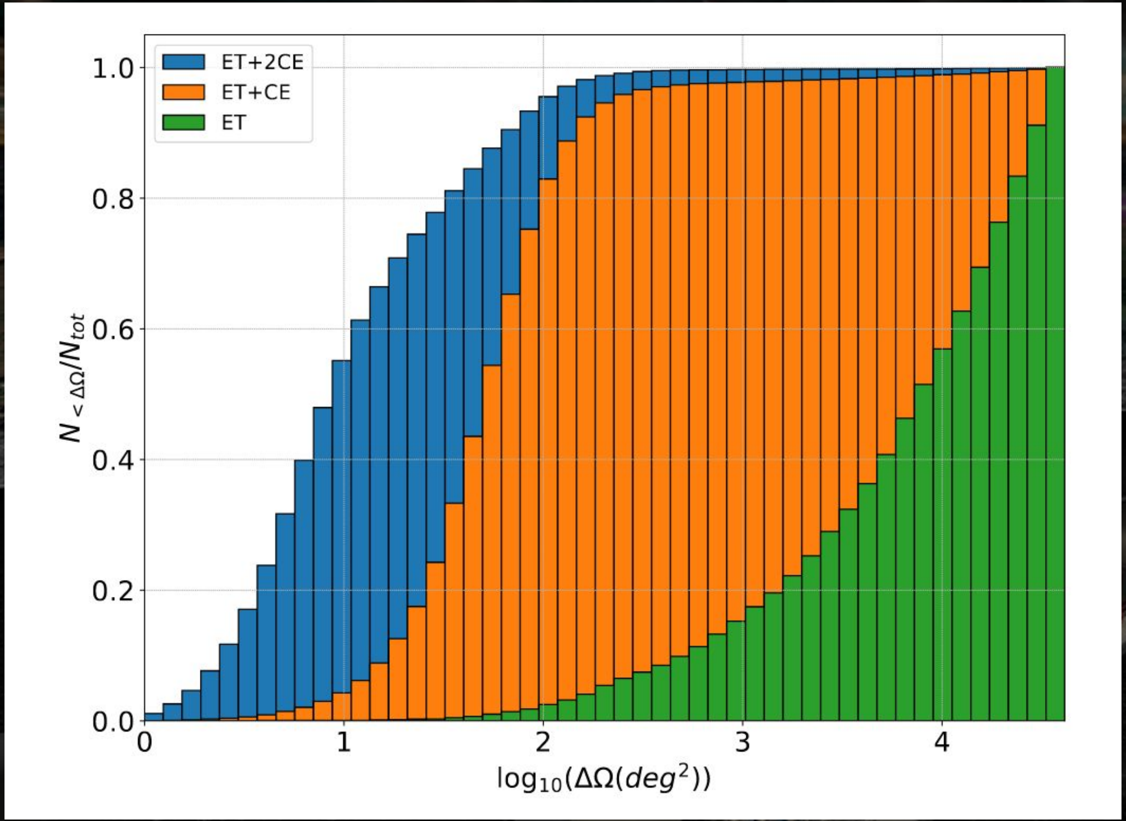
- Unique test environment for ET: fully integrated interferormeter
- Conductive Cryo (120 K and < 20 K)
- Vacuum
- laser 1550 – 2100 nm
- Silicon instead of fused silica
- Directly observe coating thermal noise
- Later stage: single T and laser wavelength (depending on previous results)

Summary:

- **Brand new collaboration (2022)**
- **Two candidate sites: Limburg/Sardinia**
- **Technologic challenges**: infrastructural, optical components, suspensions, noise mitigation…
- **Large and rich science case** (astrophysics of BHs, NSs, GR tests, dark matter, dark energy, cosmology, QCD, multi-messenger astrophysics…)
- **Computational challenges**

Merci for listening…

Backup



Cumulative distribution of the **sky-localisation uncertainty** for three detector configurations: ET (green), ET+CE (orange) and ET+2CE (blue).

(Ronchini et al, arXiv:2204.01746v1)

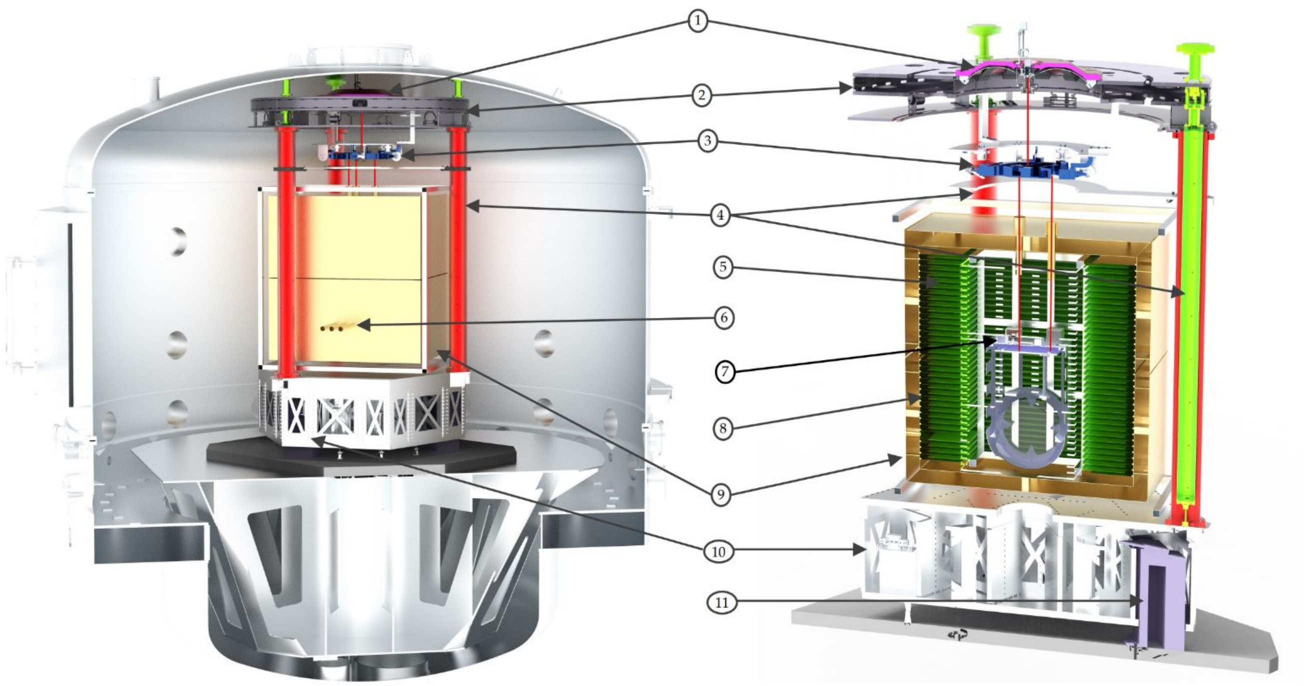


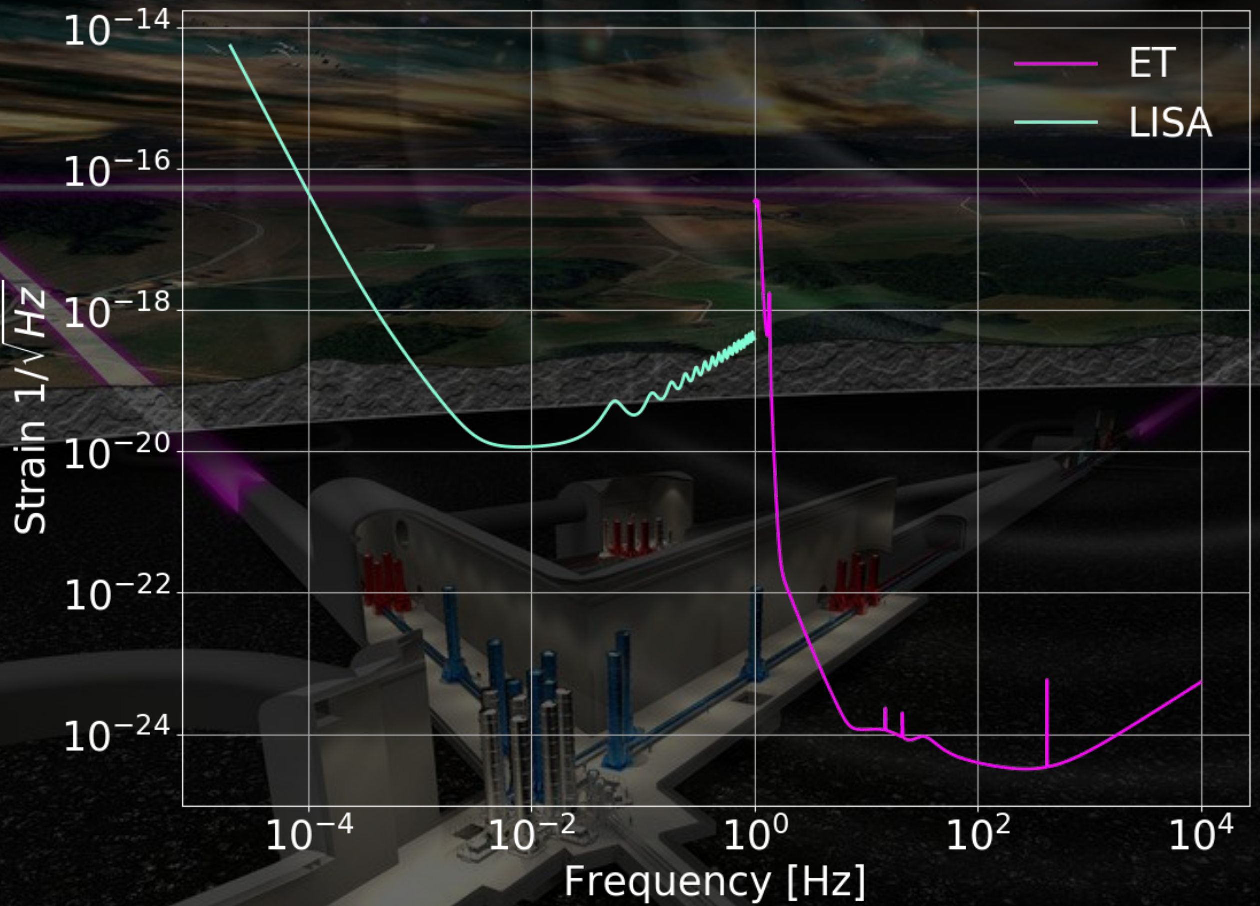
Figure 2.21: Overview of the E-TEST prototype design. A large vacuum tank (left) hosts the cryogenic mirror suspension (right). From top to bottom we can see 1) the top GAS filter, 2) the top stage, 3) the marionette and 4) the inverted pendulum legs within pipes that support a reference ring below the top stage. The cryogenic part features 5) the inner cryostat which has the interlacing fin type heat exchanger. The whole cryostat features (6) three access points for outside experiments to interact with the cryogenic mirror. The inner cryostat is attached to 7) the cold platform. The inner cryostat fins interlace into the fins of the 8) outer cryostat which provides a cold environment and houses the (9) 100 kg silicon mirror. All of this is supported by 10) an active platform, which provides a stable and quiet environment. In turn, the active platform hangs from three large blades with have a (11) support pillar on the ground.

Image from:
TEST_Conceptual-Design-Report_June_2022.pdf

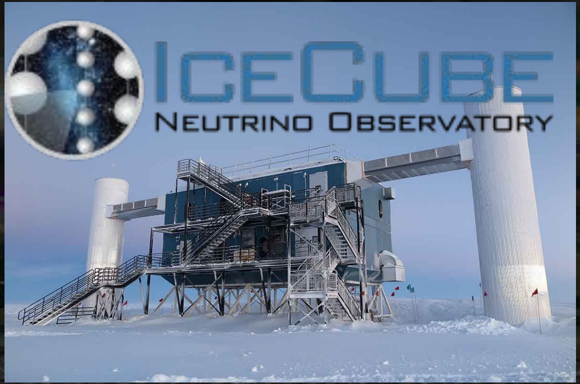
Table A1: Summary of the most important parameters for both ETpathfinder interferometers at two different temperatures. Both interferometers have a similar baseline of 9.2 m and their seismic isolation system is similar with last stage suspension fibres length of 0.4 m.

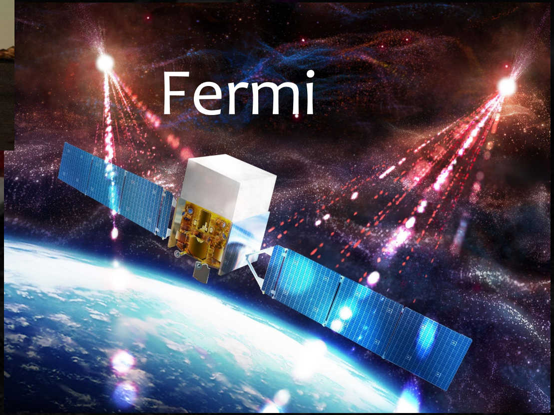
Parameter	ETpathfinder-Light	ETpathfinder-A	ETpathfinder-B
Temperature [K]	123	18	123
Wavelength [nm]	1550	1550	2090
Arm-cavity finesse	2050	2050	2050
Test mass weight [kg]	3.2	3.2	3.2
Beam waist [m]	1.8×10^{-3}	1.8×10^{-3}	2.12×10^{-3}
Beam radius at test mass [m]	2.2×10^{-3}	2.2×10^{-3}	2.56×10^{-3}
Substrate young modulus [Pa]	155.8×10^{9}	162.0×10^{9}	155.8×10^{9}
Substrate thermal conductivity [W/(m·K)]	700	3000	700
Thermal expansion coefficient [1/K]	1×10^{-9}	1×10^{-9}	1×10^{-9}
Substrate specific heat [J/(kg·K)]	333	3.5	333
Thermorefractive coefficient	1×10^{-4}	1.1×10^{-6}	1×10^{-4}
Substrate loss angle	1.25×10^{-9}	1.25×10^{-9}	1.25×10^{-9}
Last stage suspension material	Copper Beryllium	Silicon	Silicon
Last stage suspension fibres diameter [m]	1.5×10^{-4}	7×10^{-4}	7×10^{-4}
Coating ϕ_{high}	5.7×10^{-4}	5.6×10^{-4}	5.7×10^{-4}
Coating ϕ_{low}	4.8×10^{-4}	9.2×10^{-4}	4.8×10^{-4}

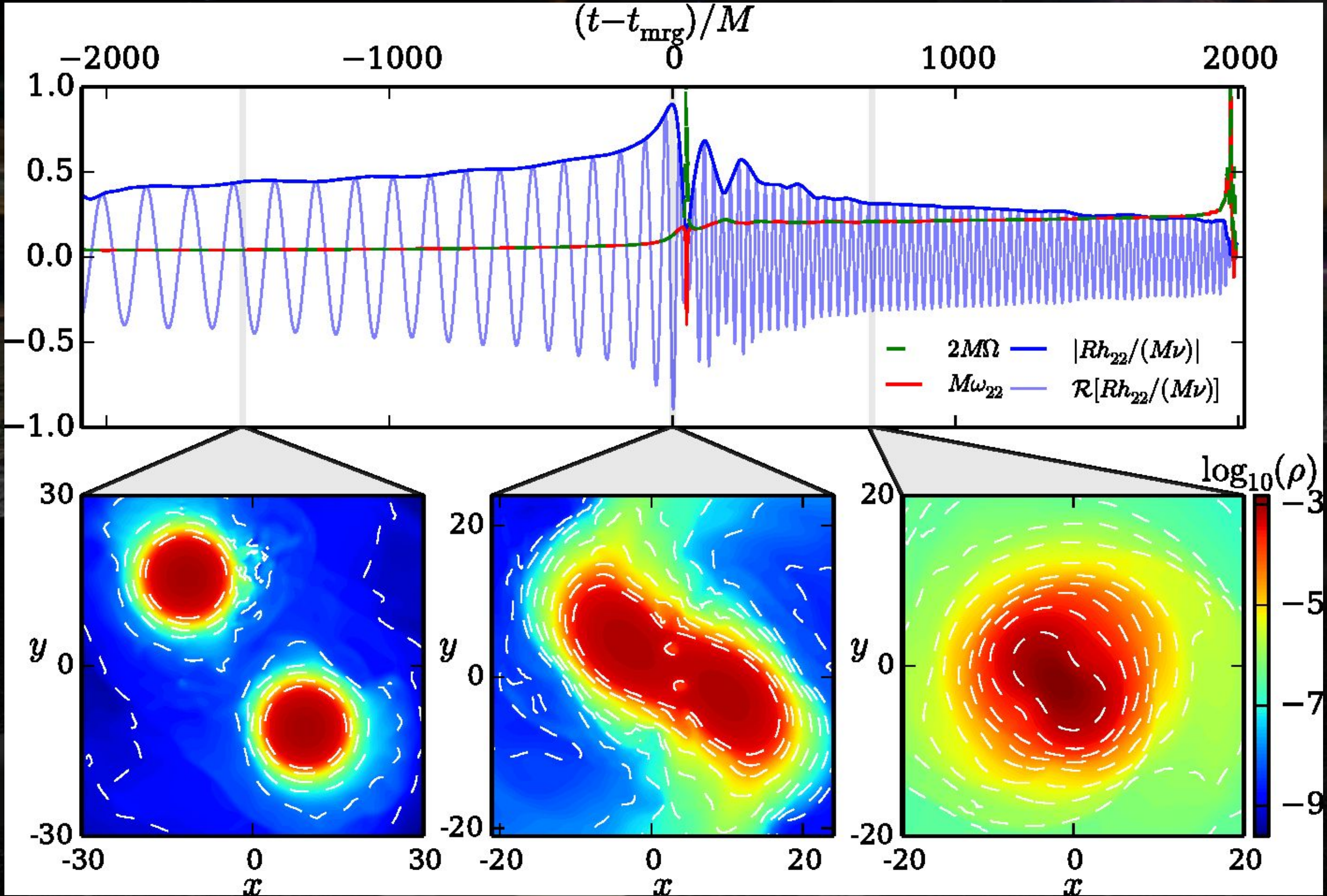
Multiband detection:



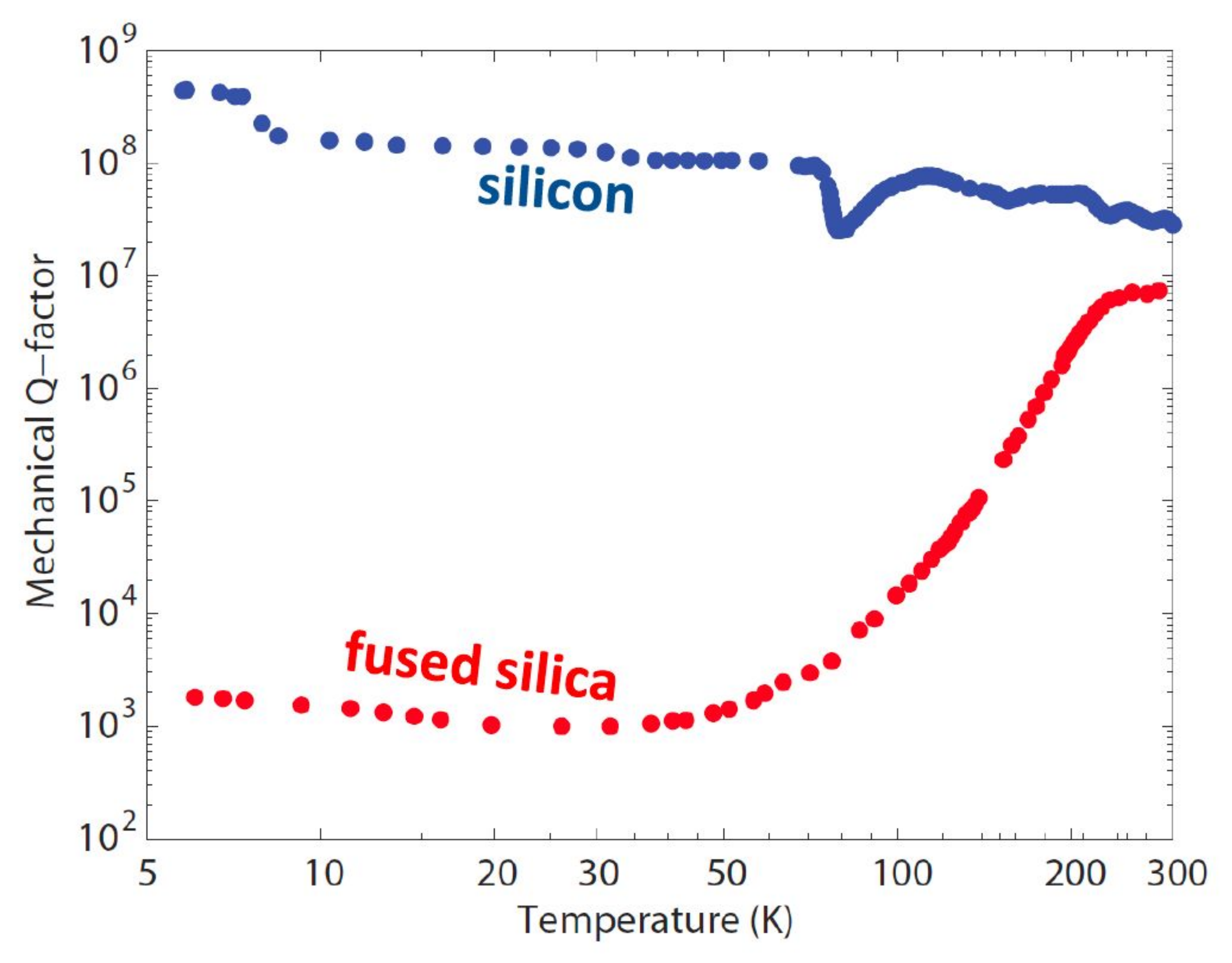
Multimessenger challenges:





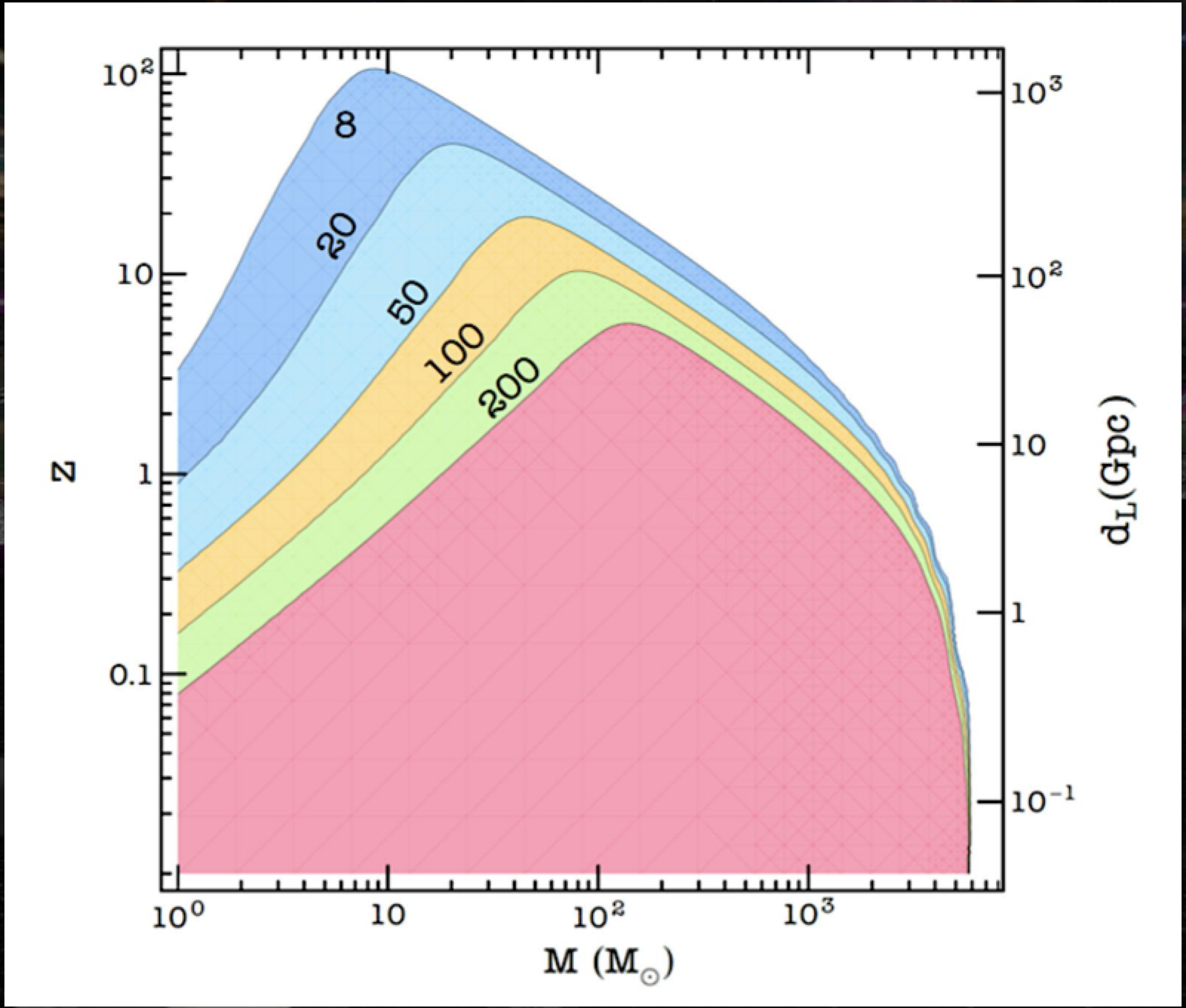


$(t-t_{mrg})/M$
−2000
−1000
0
1000
2000
1.0
0.5
0.0
−0.5
−1.0
$2M\Omega$
$|Rh_{22}/(M\nu)|$
$M\omega_{22}$
$\mathcal{R}[Rh_{22}/(M\nu)]$
$\log_{10}(\rho)$
−3
−5
−7
−9
30
y
0
-30
-30
0
30
x
20
y
0
-20
-20
0
20
x
20
y
0
-20
-20
0
20
x



silicon
fused silica
Mechanical Q−factor
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
5
10
20
30
50
100
200
300
Temperature (K)

SNR



8
20
50
100
200
z
10^2
10
1
0.1
d_L(Gpc)
10^3
10^2
10
1
10^{-1}
10^0
10
10^2
10^3
M ($M_\odot$)

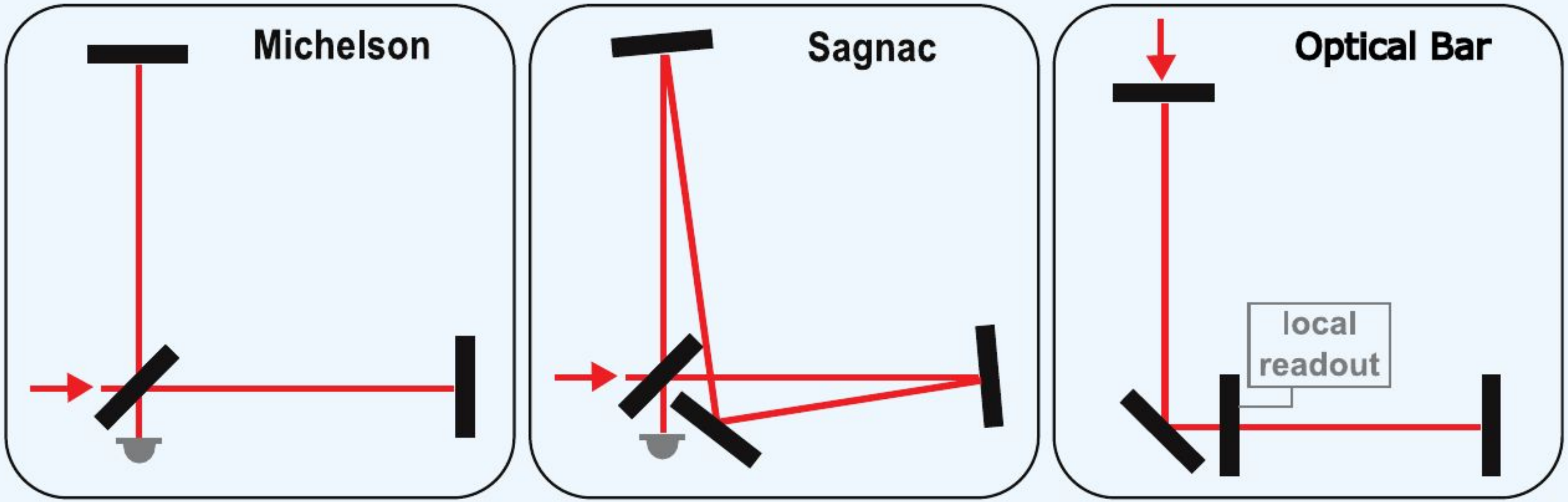


Figure 162: Different (basic) topology options: simple Michelson interferometer topology (left panel); zero-area Sagnac interferometer topology (midd3le panel); optical bar topology (right panel)

- The case for alternative topologies for **quantum noise reduction**.
- Signal-to-noise ratio or sensitivity vary dramatically with the interferometer configuration.
- A Michelson-based detector → using the experience and the optical technologies of the first two detector generations.