Einstein Telescope: scienza e tecnologia del futuro osservatorio Europeo di onde gravitazionali

Francesca Badaracco

Image credit: Marco Kraan, Nikhef

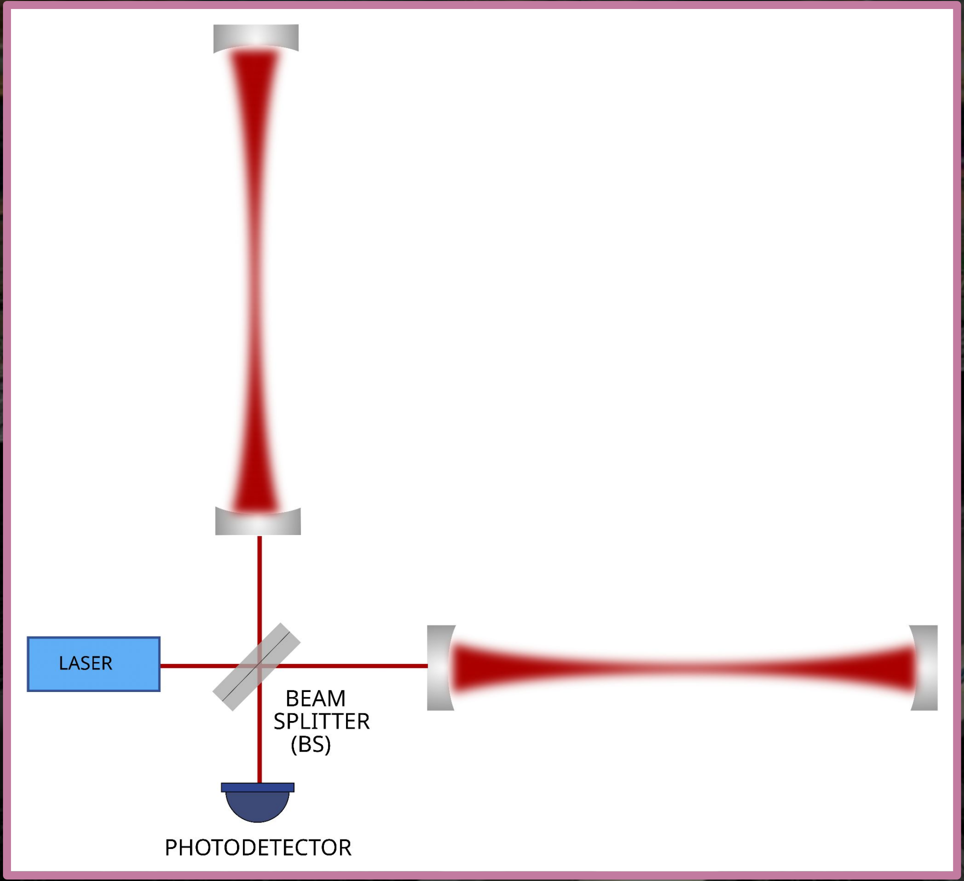
Effetto delle onde gravitazionali sullo spazio-tempo:

https://favpng.com

Le onde gravitazionali **cambiano la distanza tra gli oggetti**, ma localmente gli oggetti restano fermi, quello che cambia è la metrica dello spazio-tempo

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

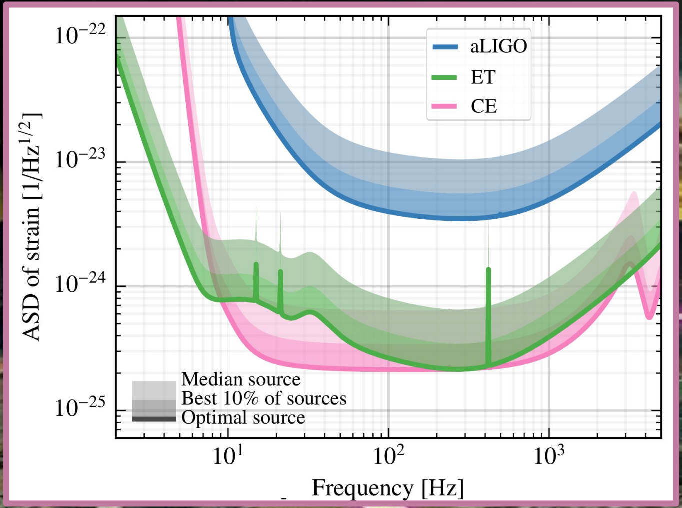
Principio di rivelazione delle onde gravitazionali:



Misurare il **cambiamento di lunghezza**

→

Misurare il **cambiamento di fase**

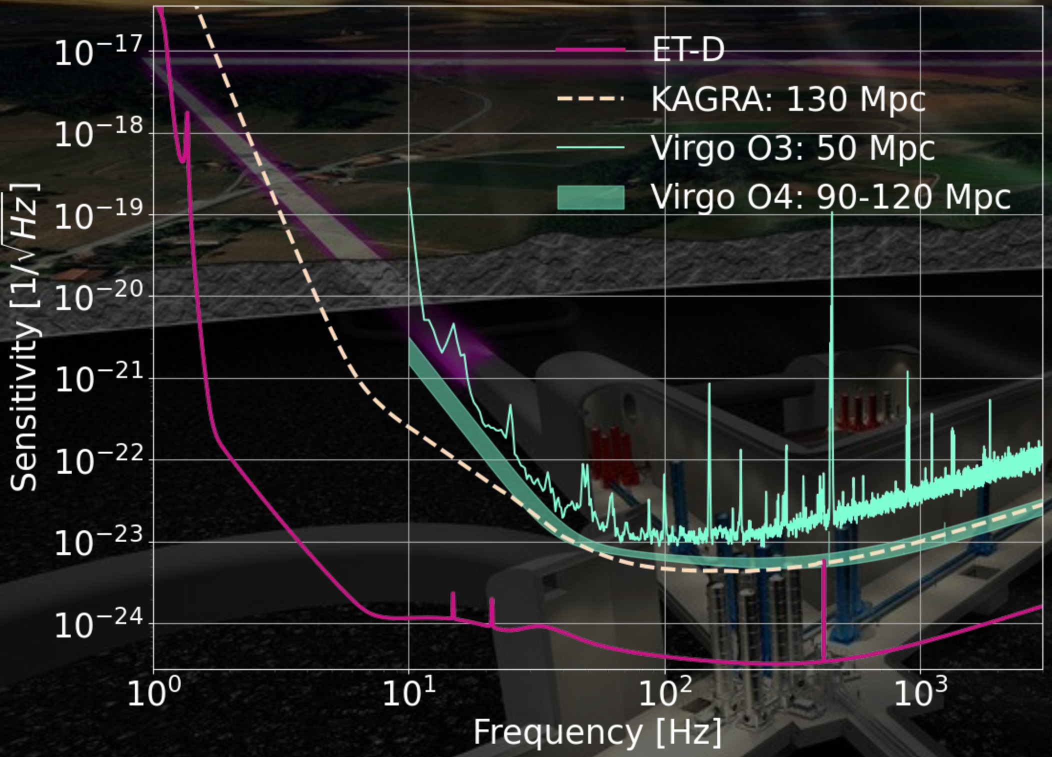


Credits: GWIC 3G Committee, the GWIC 3G Science Case Team, and the International 3G Science Team Consortium, "3G Science Book," 2020

Sotterraneo:

- Interferometro più stabile
- Maggiore sensibilità a bassa frequenza

Migliorare la sensibilità a bassa frequenza richiede sforzi tecnologici ed economici: ne vale davvero la pena?

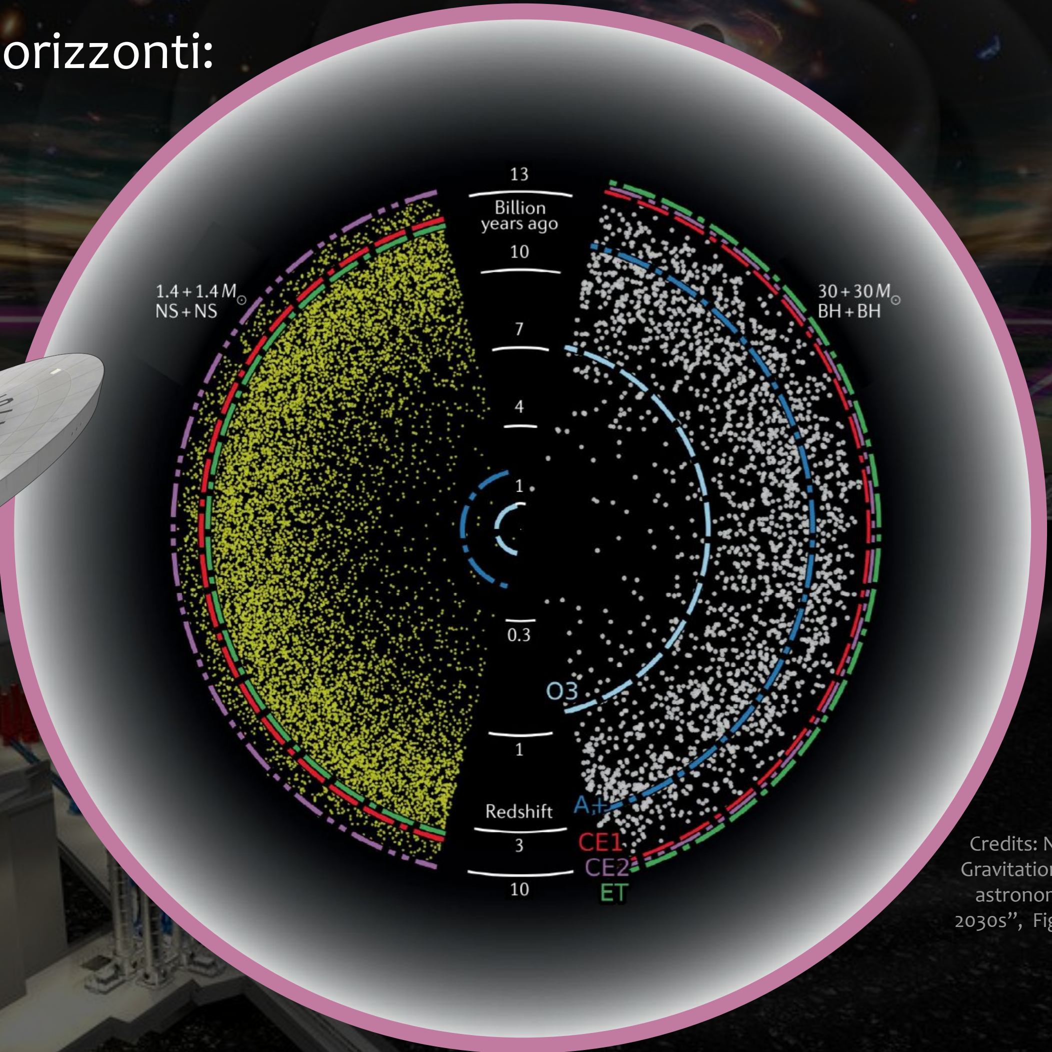


- Nuove possibili scoperte
- BNS: Ore-Giorni
  - Stima dei parametri
  - EM early warning
  - Localizzazione con solo ET
- BBH massivi:
  - BH di massa intermedia (10^2-10^5 masse solari)
  - Alti redshift→PBHs???
- Ricerca di un fondo gravitazionale di origine cosmologica

ET per espandere i nostri orizzonti:

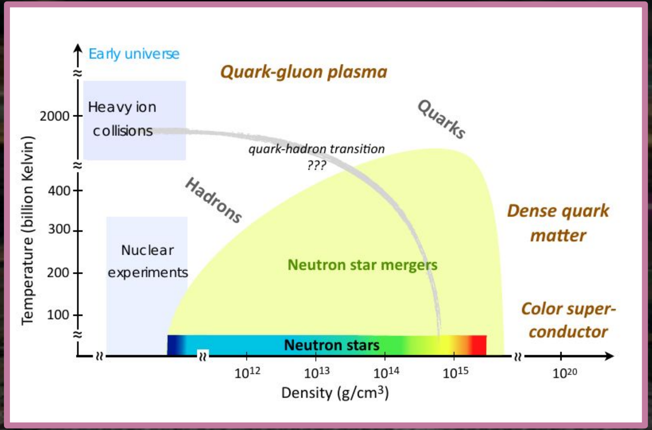
"To boldly go where no man has gone before."

Captain James T. Kirk



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

Stelle di Neutroni, fase di post-merger:



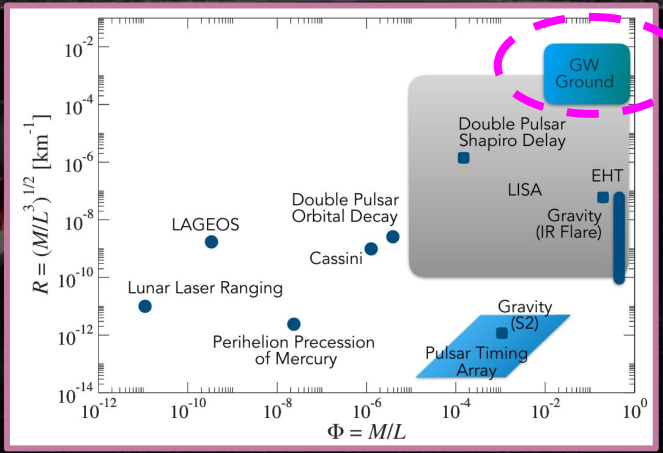
Credits: ET-0007B-20 ET Design Report Update 2020

Energia oscura

H_0

Fondo stocastico gravitazionale di origine cosmologica

Test di gravità in condizioni estreme



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

Materia oscura

- **Buchi neri primordiali?**
- **Bosoni ultraleggeri di materia oscura?**

Non solo sfide tecnologiche legate alla strumentazione, ma anche computazionali, legate all'analisi dati!

- Interferometri 2° Generazione: 1PB/anno (LHC ~ 110 PB/anno nel 2018)
- Binarie coalescenti rivelate tramite l'uso di un filtro adattato basato su modelli di segnali
  - **Modelli di segnali più lunghi** (più memoria)
  - **Segnali sovrapposti**
- Dopo la rivelazione: parametri estratti con **inferenza Bayesiana**
  - Algoritmi meno parallelizzabili
  - La potenza di calcolo scala linearmente con il tasso di rivelazioni
- Distribuzione dei triggers di candidati **tempestivi and affidabili per astronomia multi-messaggera**

Nascita della collaborazione:

Durante il XII simposio dell'Einstein Telescope a Budapest il 7-8 Giugno 2022
~1400 membri 206 istituti e 80 unità di ricerca

- Limburgo (Belgio/Paesi Bassi/Germania) ufficialmente candidato
- Sassonia (Germania)
- Sardegna (Italia) ufficialmente candidato

European Strategy Forum on Research Infrastructures - ESFRI

ET è stato incluso nella roadmap ESFRI 2021 → questo rafforza ET a livello europeo

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

Riassumendo:

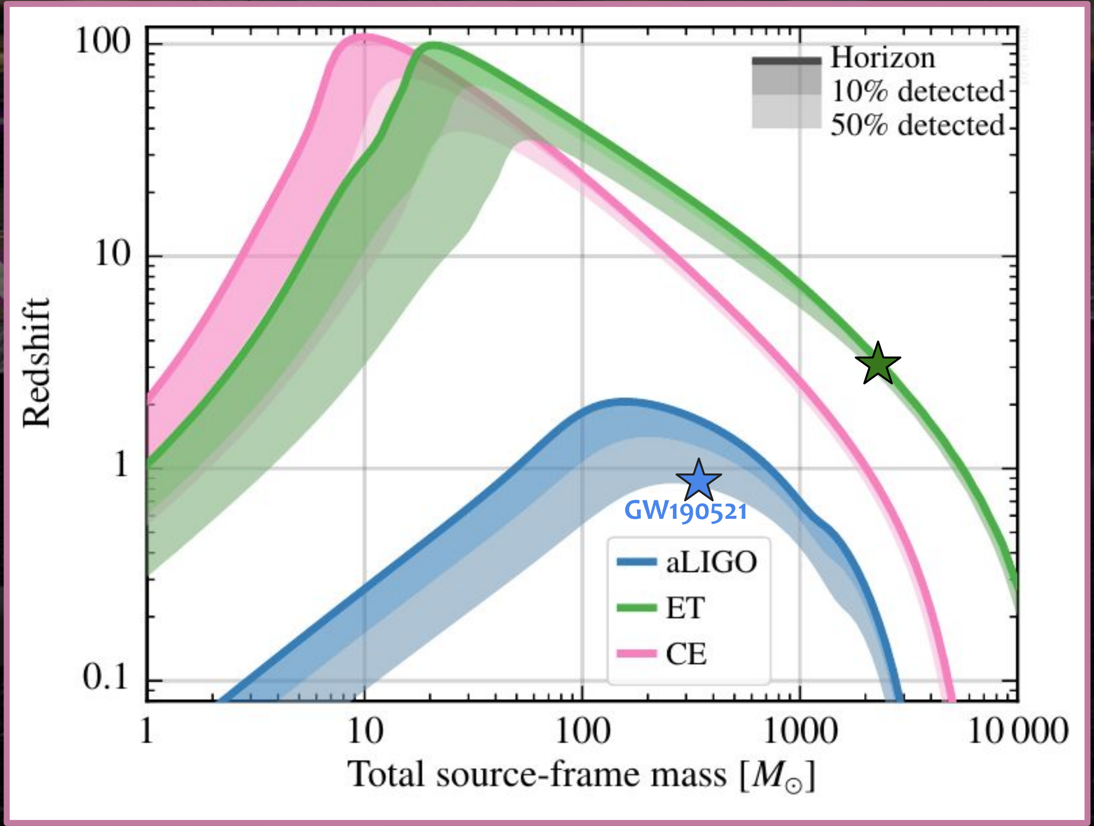
- **ET è una collaborazione appena nata (2022)**
- **Due siti candidati : Limburgo/Sardegna**
- **Sfide tecnologiche**: infrastrutturali, componenti ottici, sospensioni, soppressione del rumore…
- **Ampio e ricco caso scientifico** (astrofisica dei BH, NS, test di relatività generale, materia oscura, energia oscura, cosmologia, QCD, astrofisica multimessaggera)
- **Sfide computazionali**

Grazie

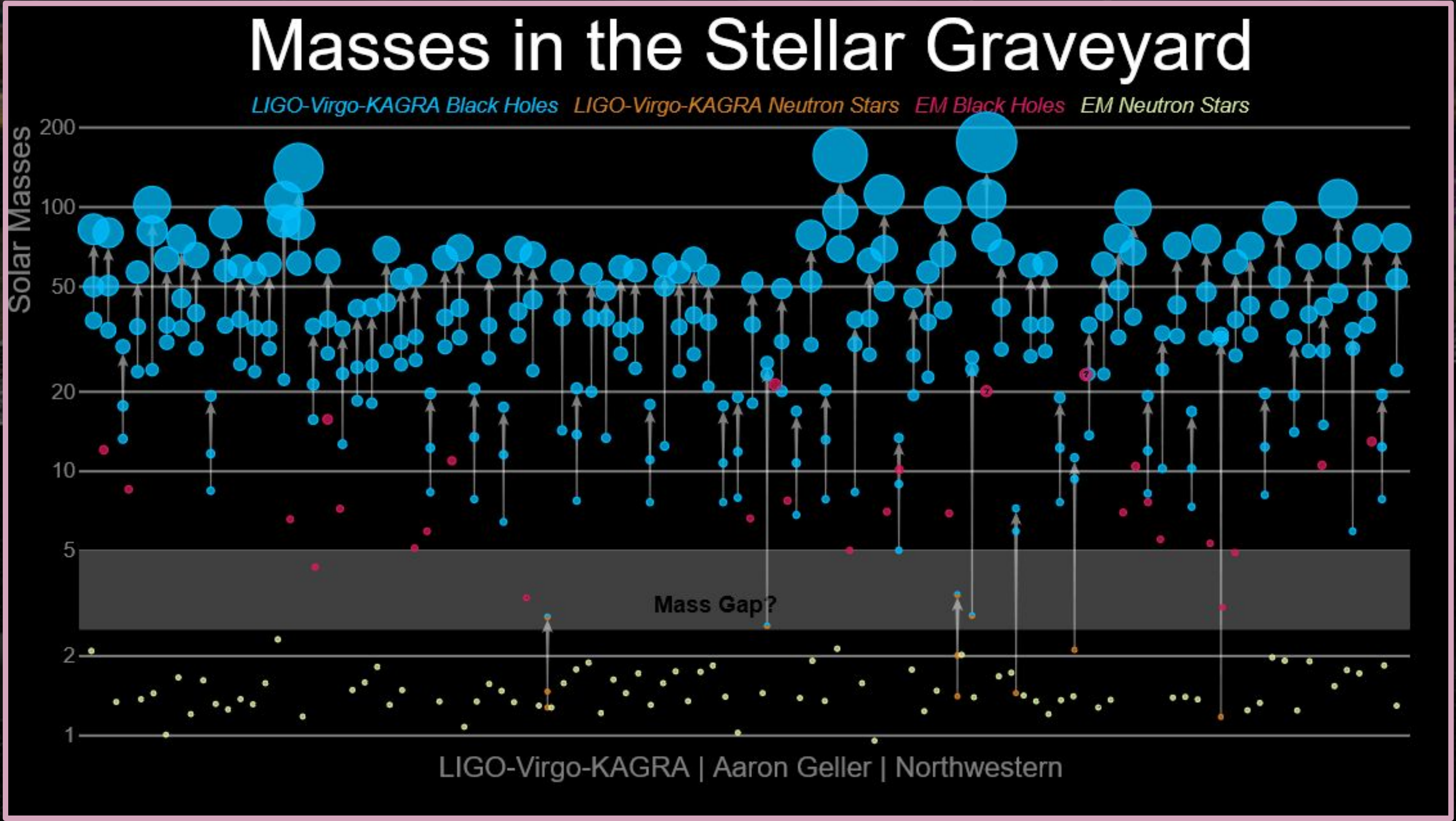
Backup

A comparison between present and future detectors

Astrophysical reach for equal-mass, non-spinning binaries



What has been reached with LIGO-Virgo-KAGRA

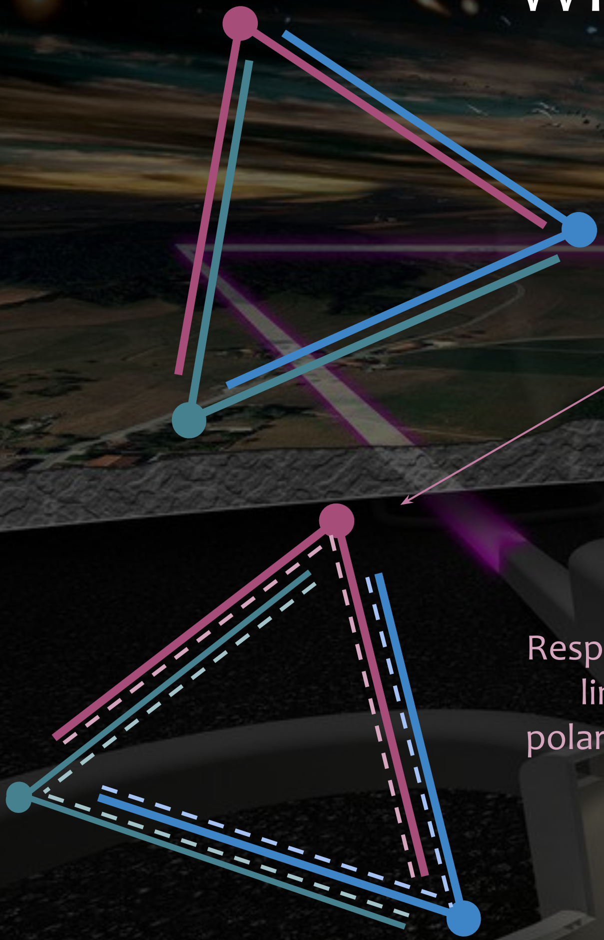


Why a △ ?

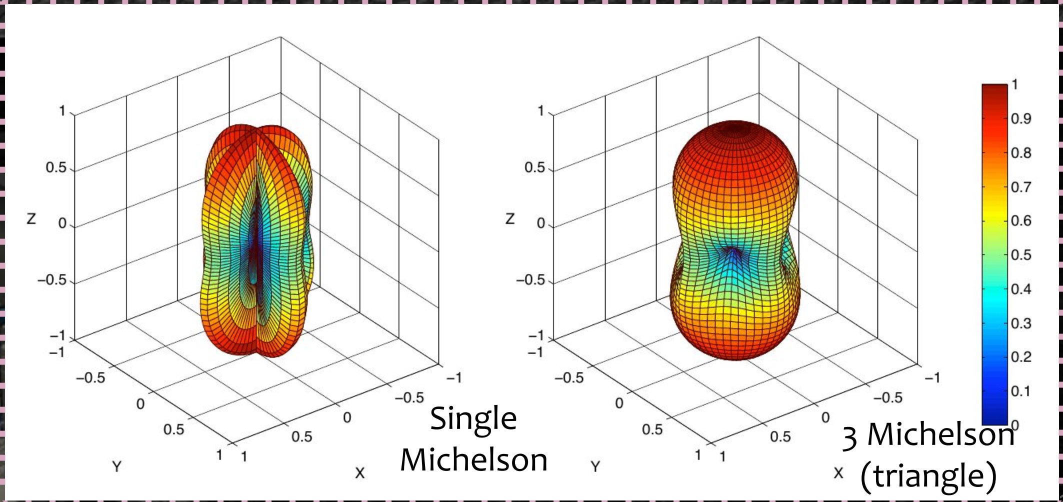
- Equilateral triangle (xylophone):
  - 3 **nested** detectors
  - Each one split in two interferometers:
    - Low-frequency (cold)
    - High-frequency (hot)
- Why this shape?
  - Equally sensitive for both GW **polarisations**
  - **Redundancy**
    - **Null stream**
    - **Observation continuity**

Universiteit Antwerpen

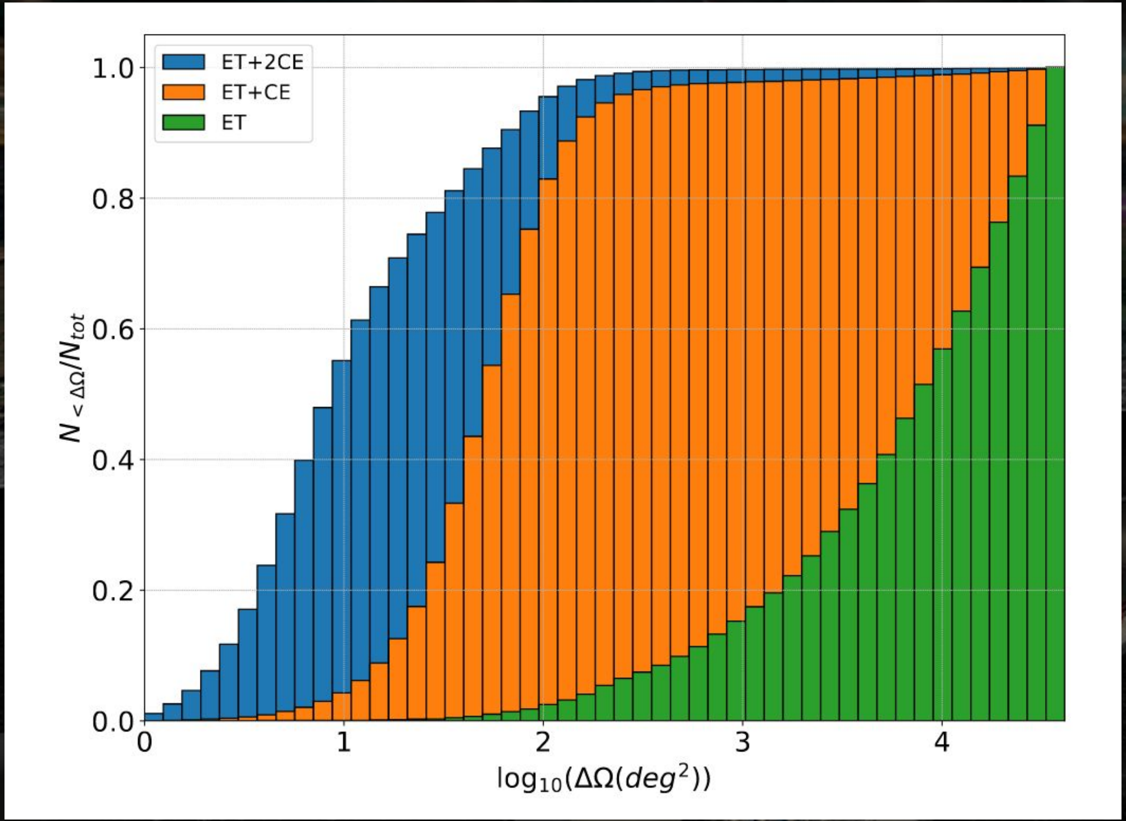
Janssens et al
arXiv:2205.00416



Response to linear polarization:



From the ET conceptual design study



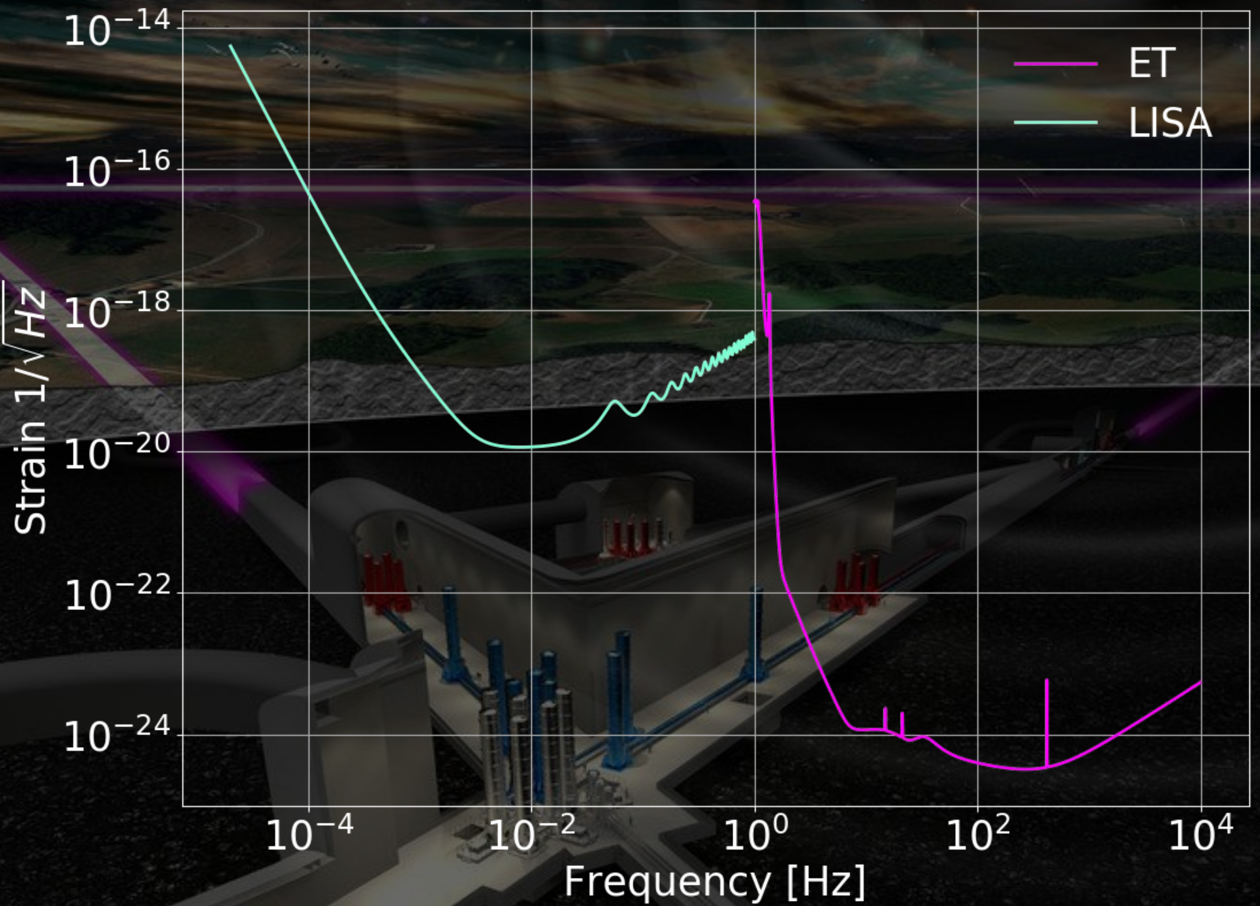
Cumulative distribution of the **sky-localisation uncertainty** for three detector configurations: ET (green), ET+CE (orange) and ET+2CE (blue).

(Ronchini et al, arXiv:2204.01746v1)

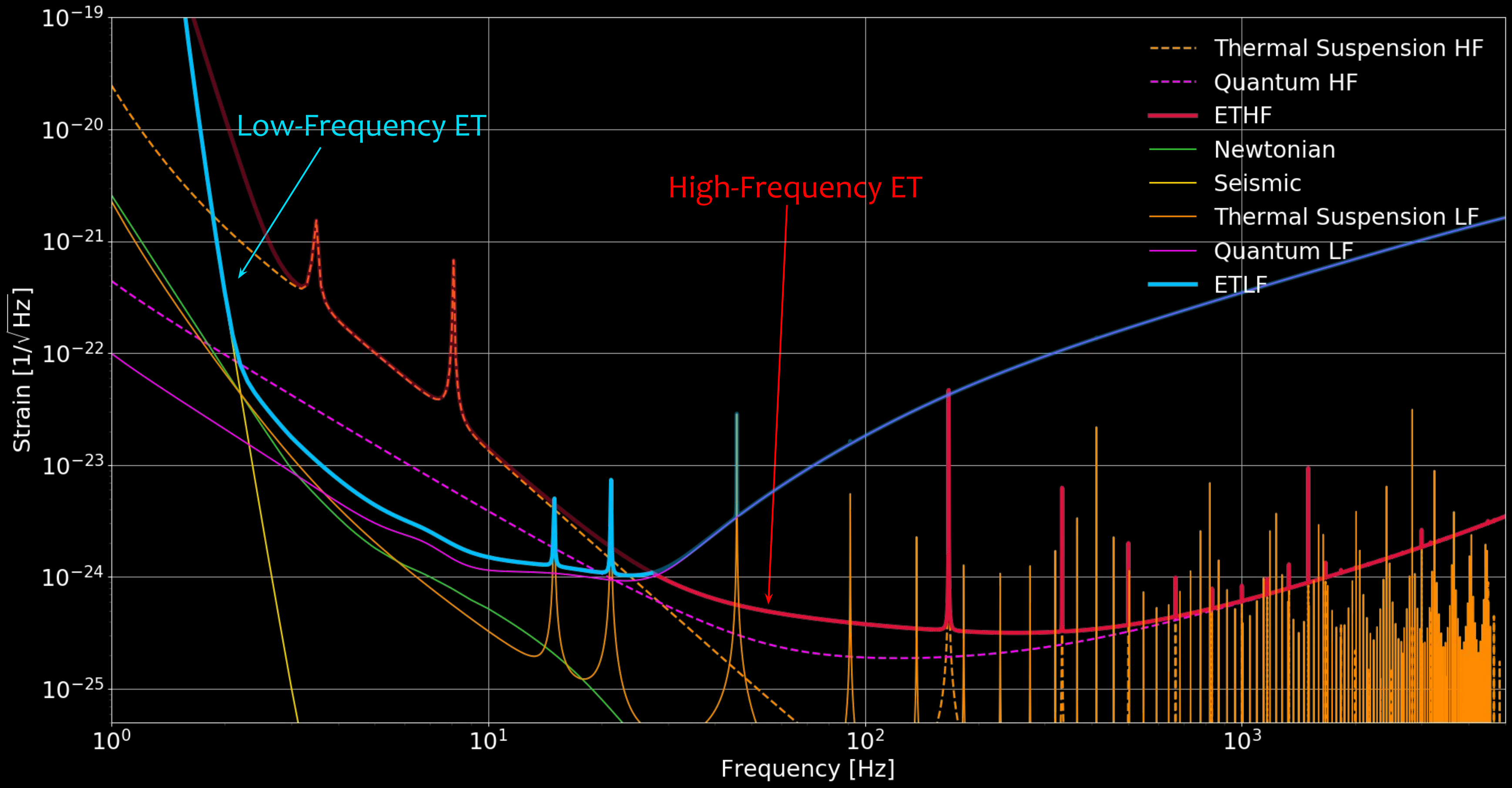
Table A1: Summary of the most important parameters for both ETpathfinder interferometers at two different temperatures. Both interferometers have a similar baseline of 9.2 m and their seismic isolation system is similar with last stage suspension fibres length of 0.4 m.

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}

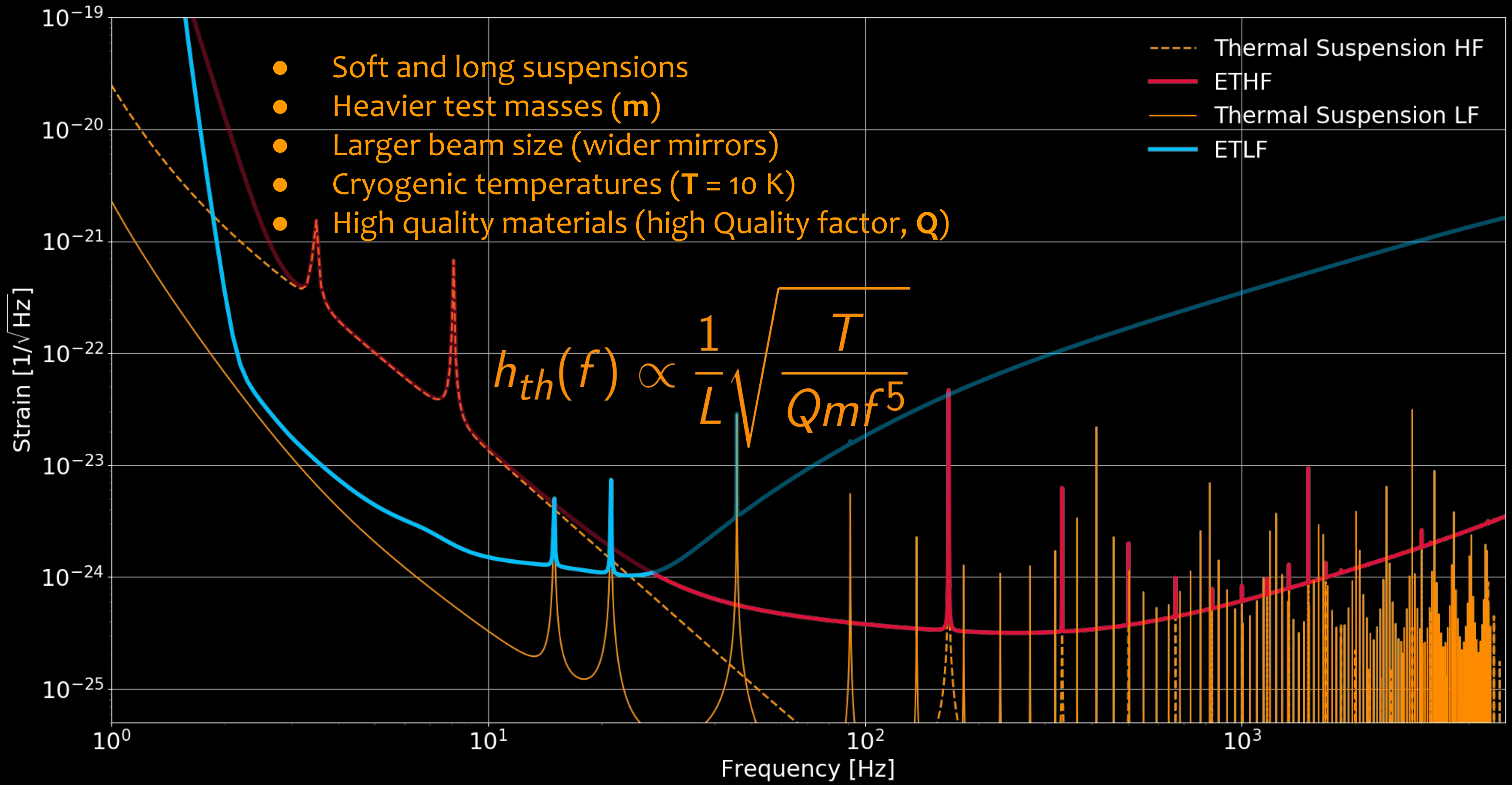
Multiband detection:



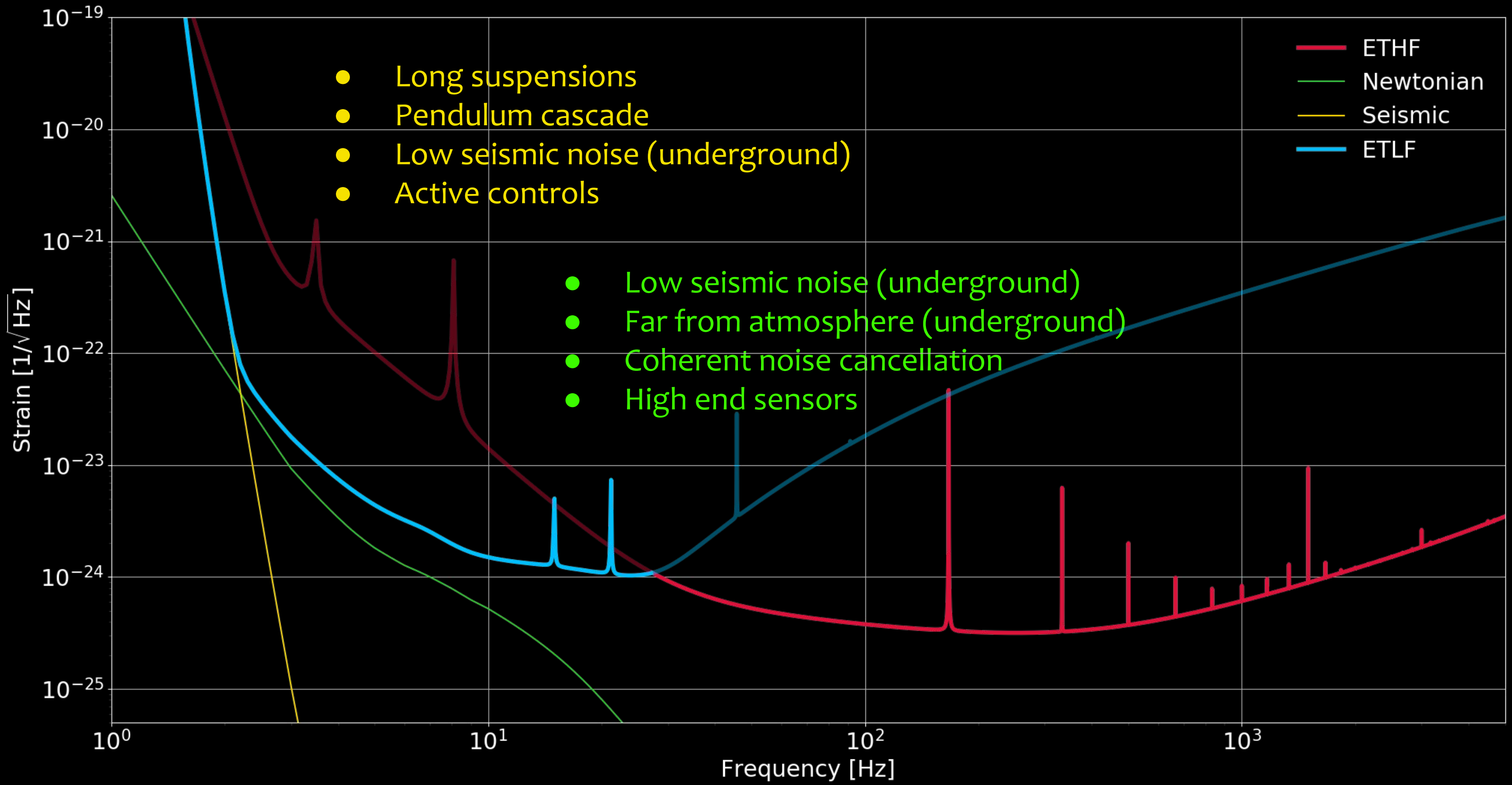
ET sensitivity curve:



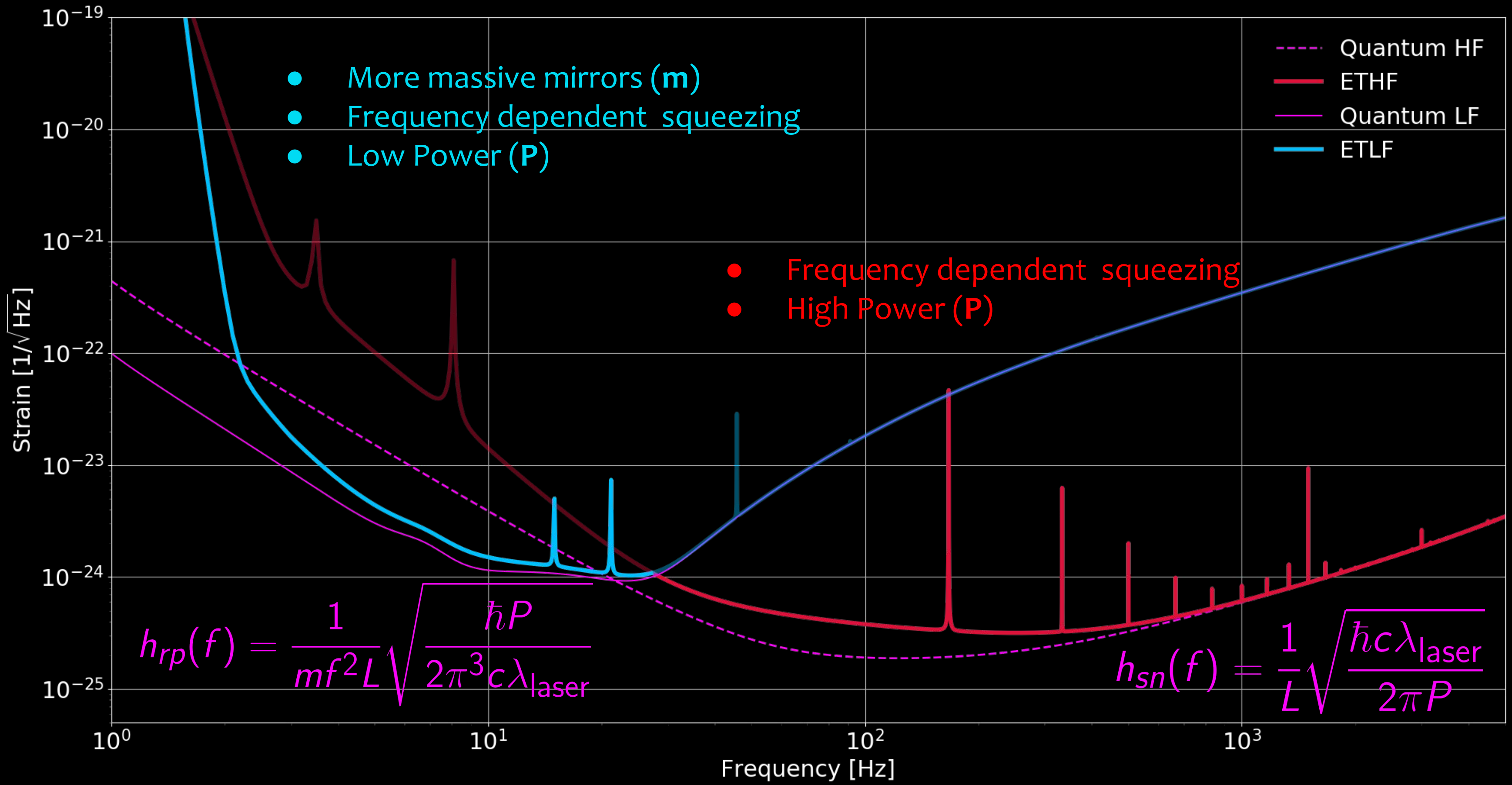
ET sensitivity curve: thermal noise



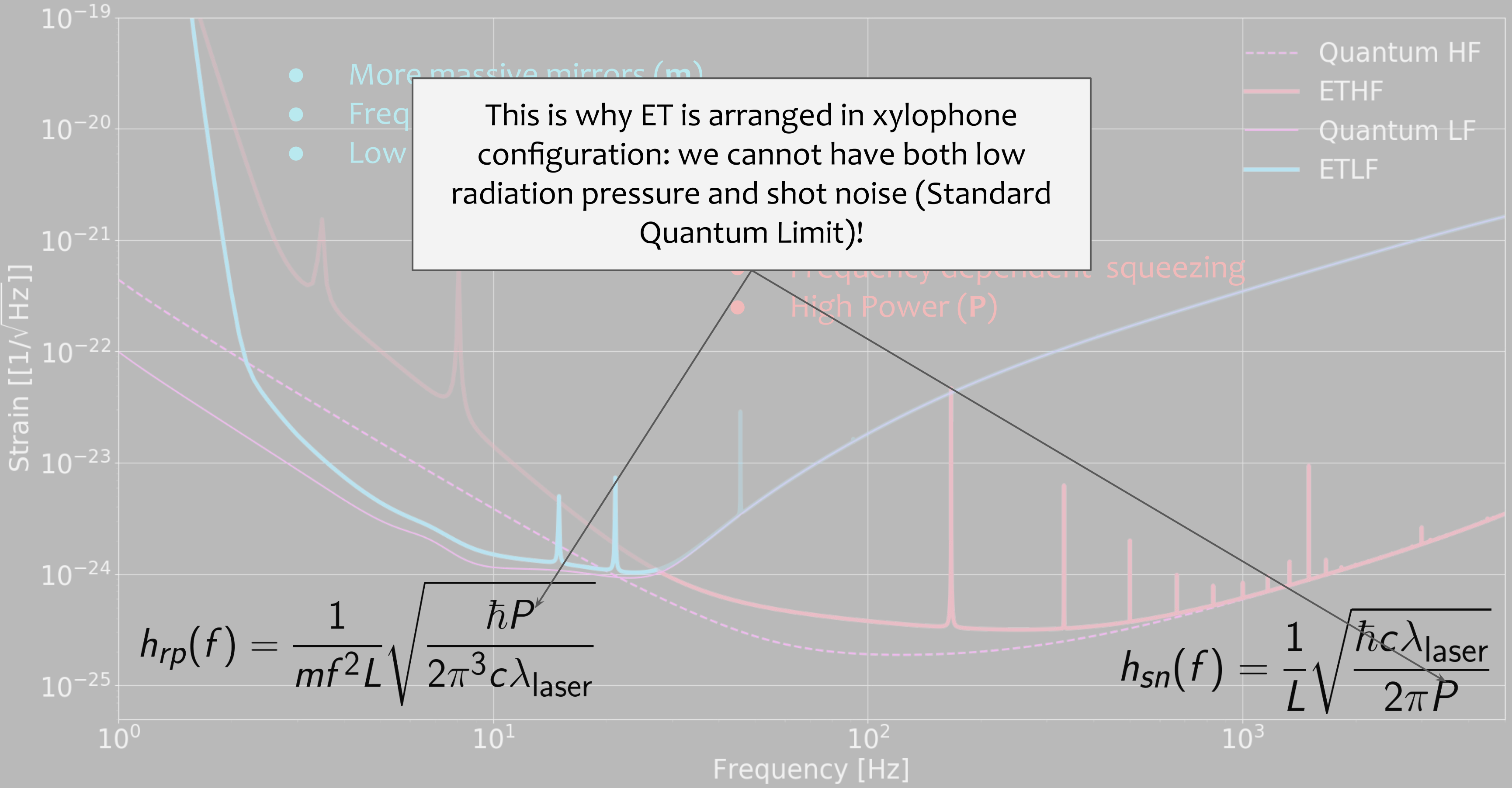
ET sensitivity curve: seismic and Newtonian noise



ET sensitivity curve: quantum noise



ET sensitivity curve:

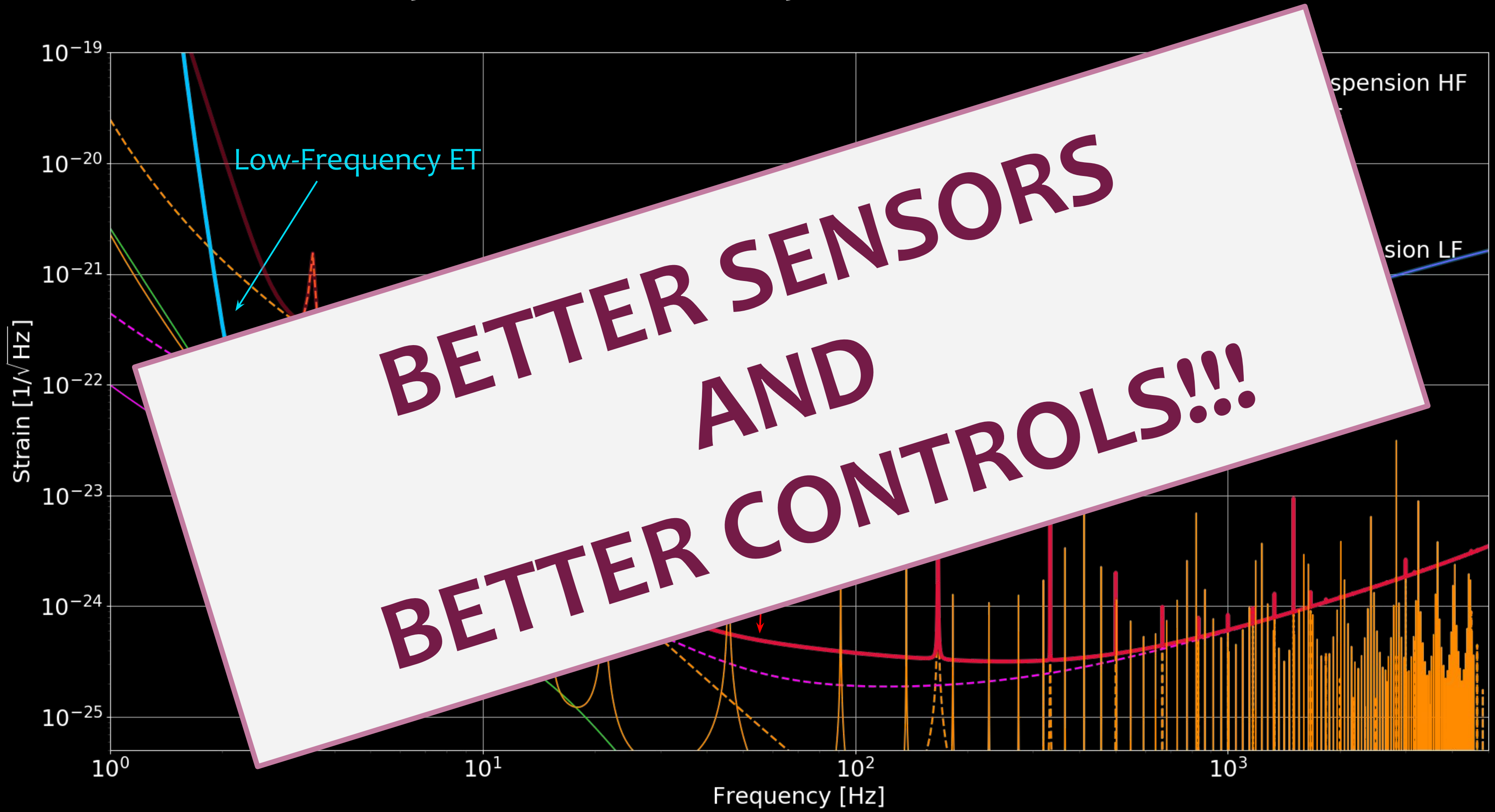


This is why ET is arranged in xylophone configuration: we cannot have both low radiation pressure and shot noise (Standard Quantum Limit)!

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

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

ET sensitivity curve: not only fundamental noises…



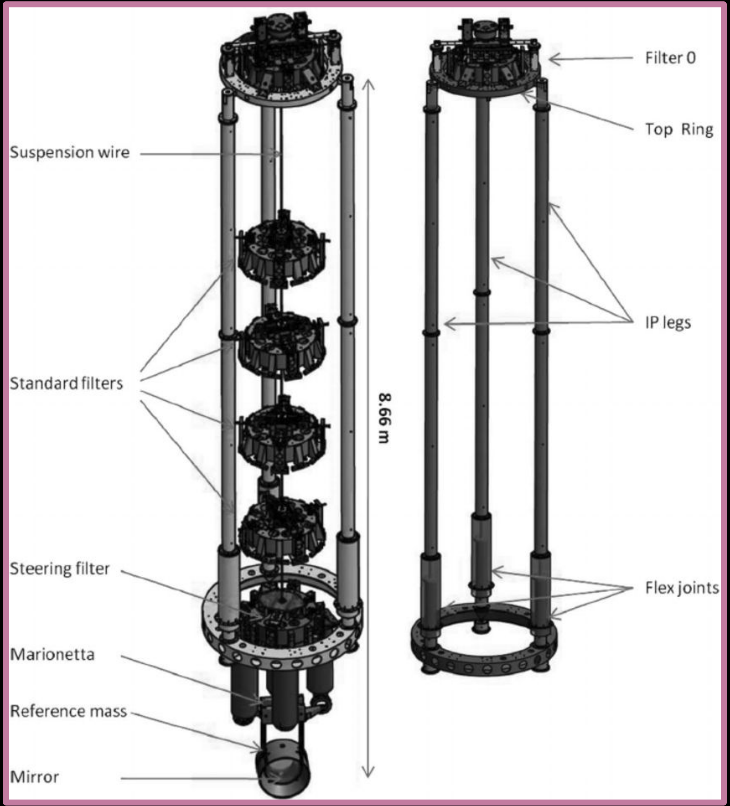
ET sensitivity curve: **seismic** and Newtonian noise

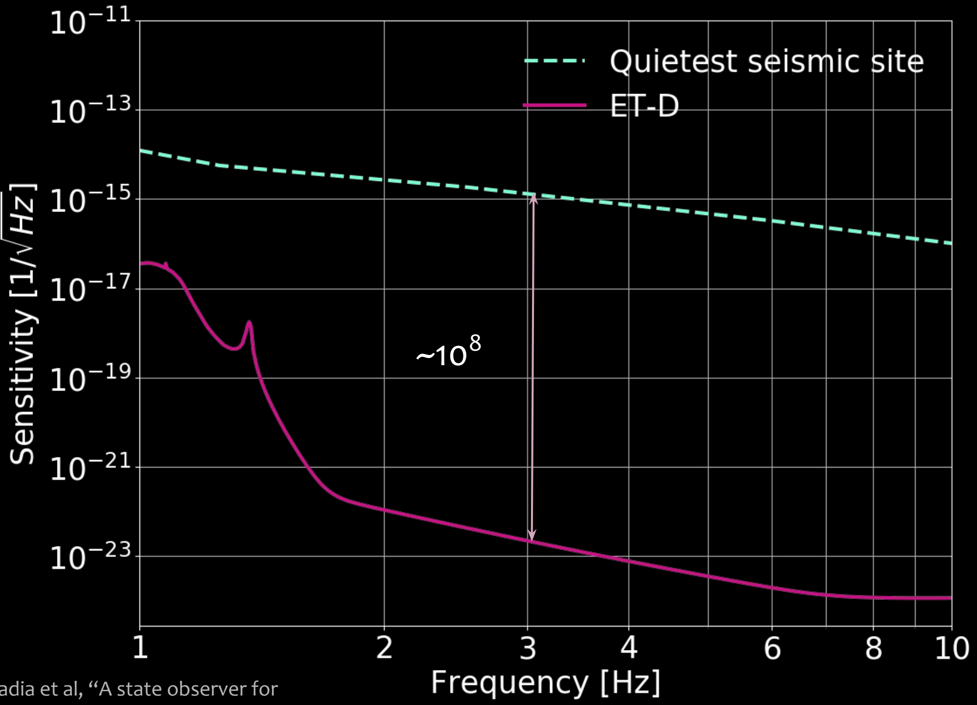
Just a glimpse of the complexity of GW detectors suspensions …

Suspensions concepts for ET

UCLouvain

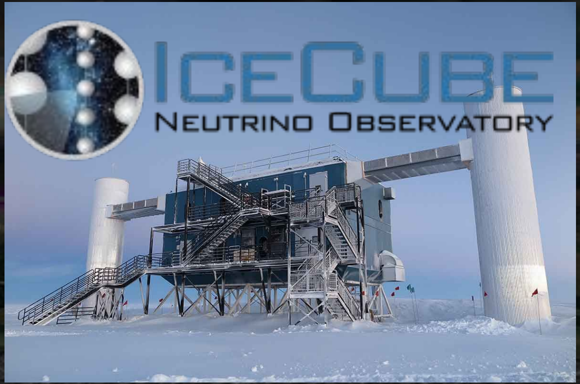
Attenuation $\propto 1/f^{2N}$

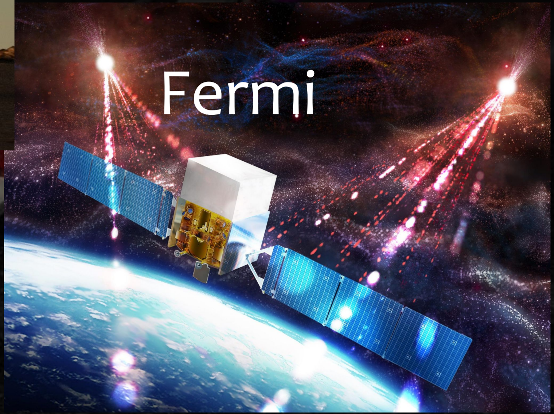


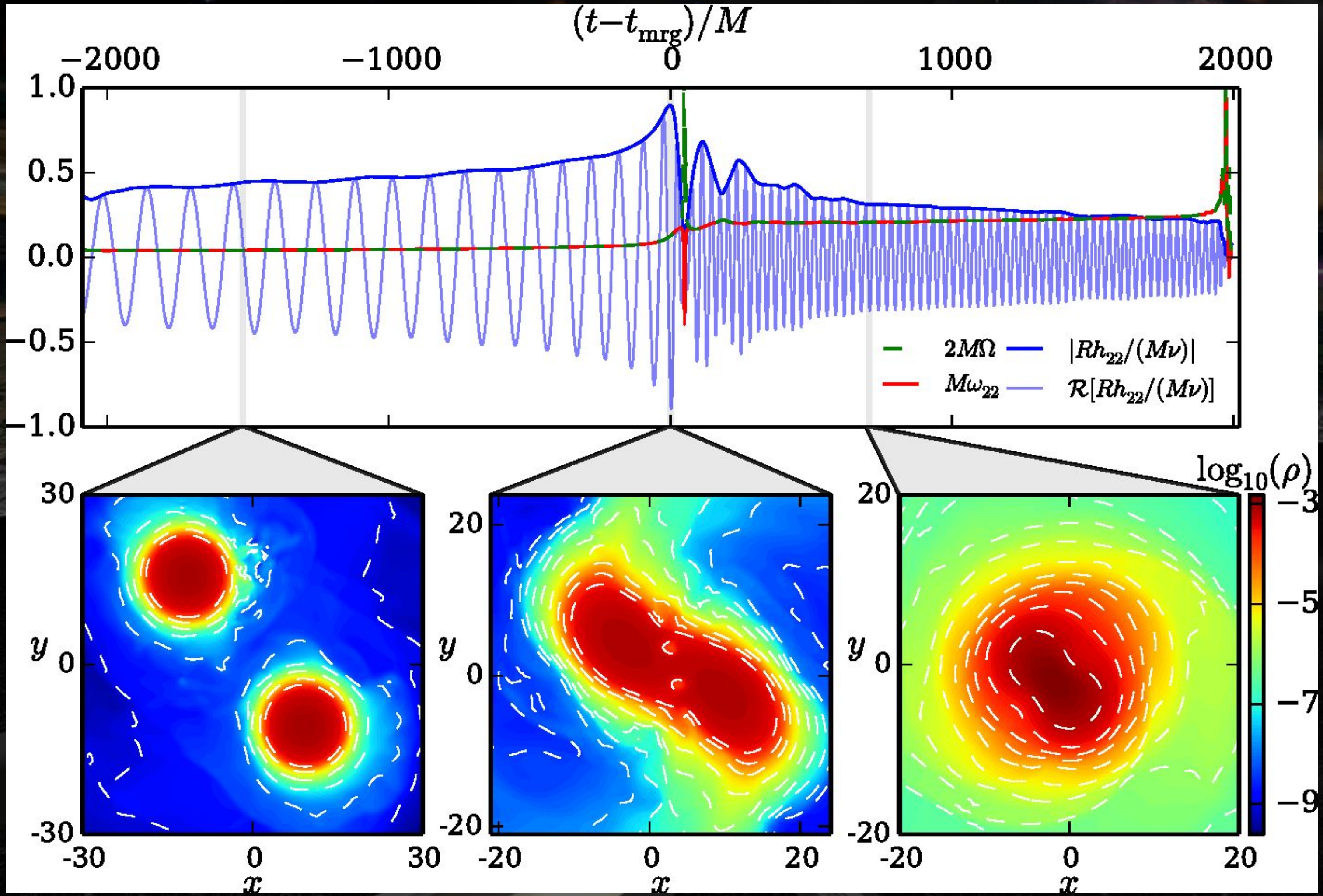


From: Accadia et al, "A state observer for the Virgo inverted pendulum", Review of Scientific Instruments 82, 094502 (2011)

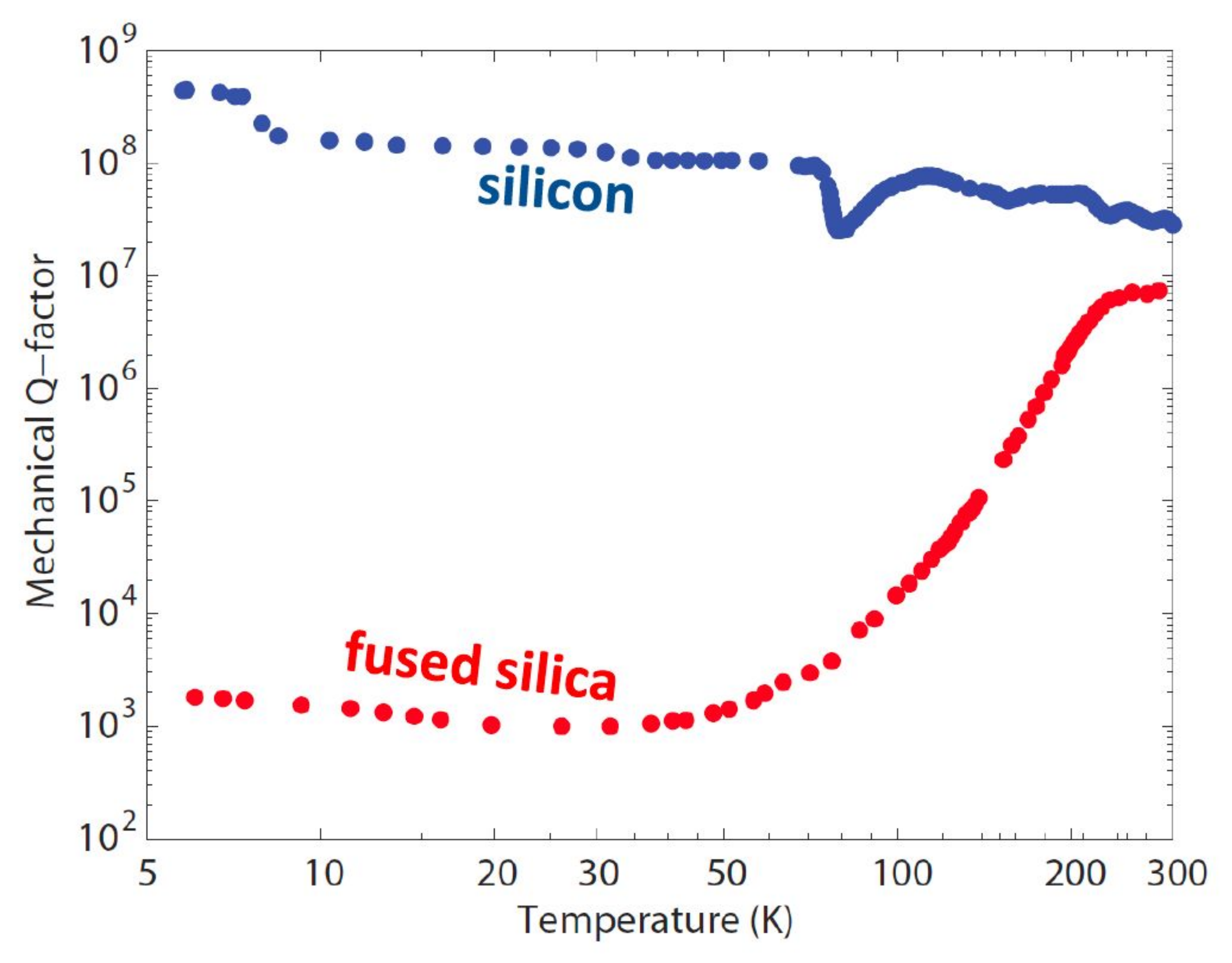
Multimessenger challenges:



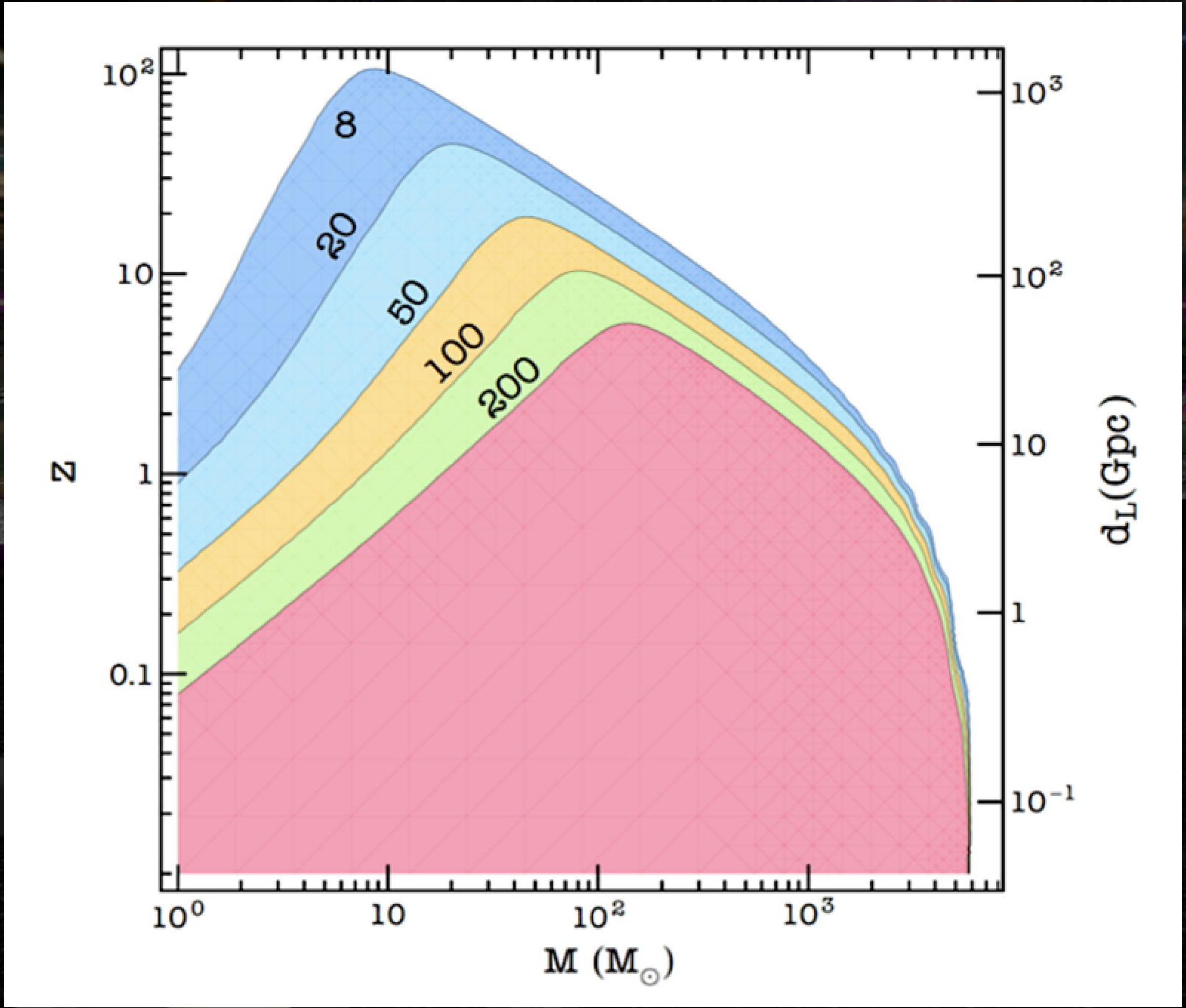




$(t-t_{\rm mrg})/M$
−2000
−1000
0
1000
2000
1.0
0.5
0.0
−0.5
−1.0
$2M\Omega$
$|Rh_{22}/(M\nu)|$
$M\omega_{22}$
$\mathcal{R}[Rh_{22}/(M\nu)]$
$\log_{10}(\rho)$
−3
−5
−7
−9
30
y 0
-30
-30
0
30
x
20
y 0
-20
-20
0
20
x
20
y 0
-20
-20
0
20
x


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

SNR



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

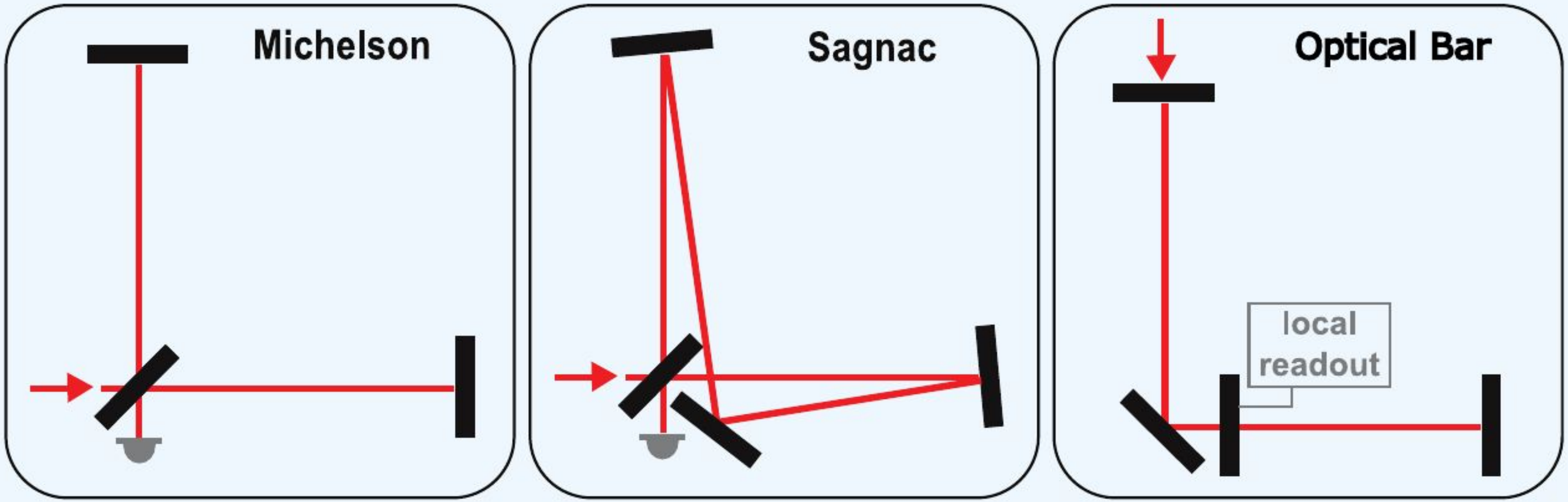


Figure 162: Different (basic) topology options: simple Michelson interferometer topology (left panel); zero-area Sagnac interferometer topology (midd3le panel); optical bar topology (right panel)

- 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.

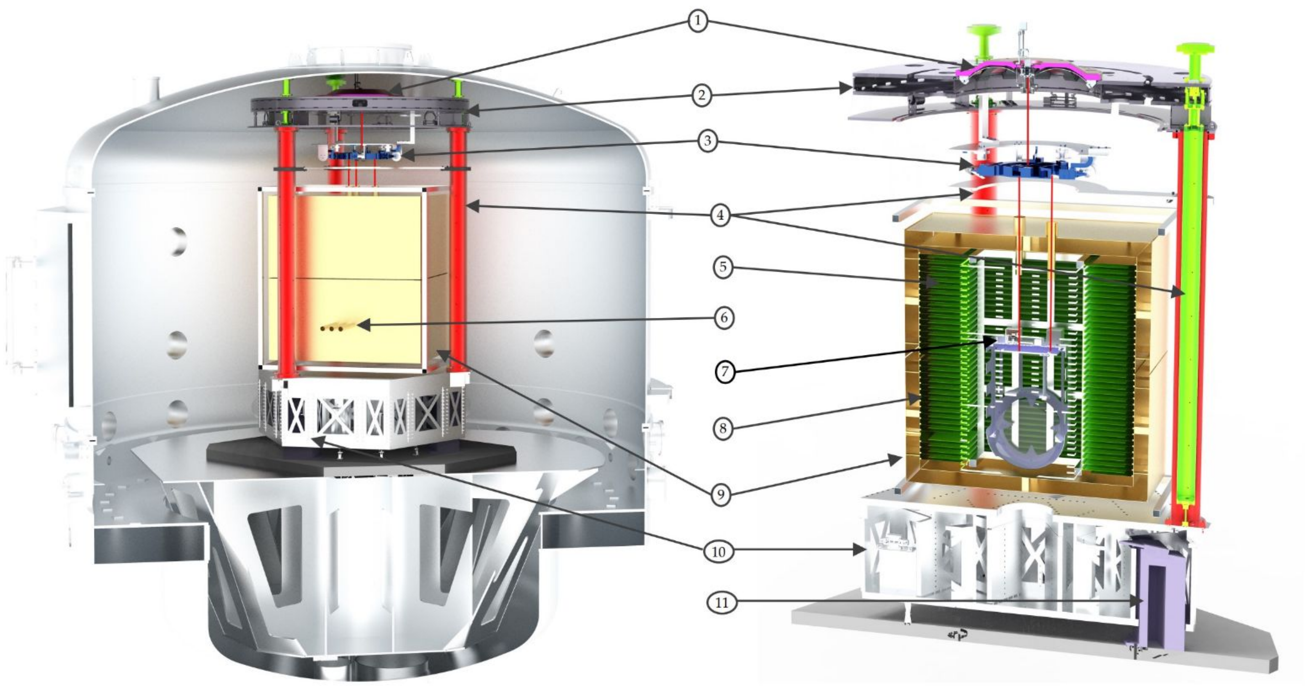
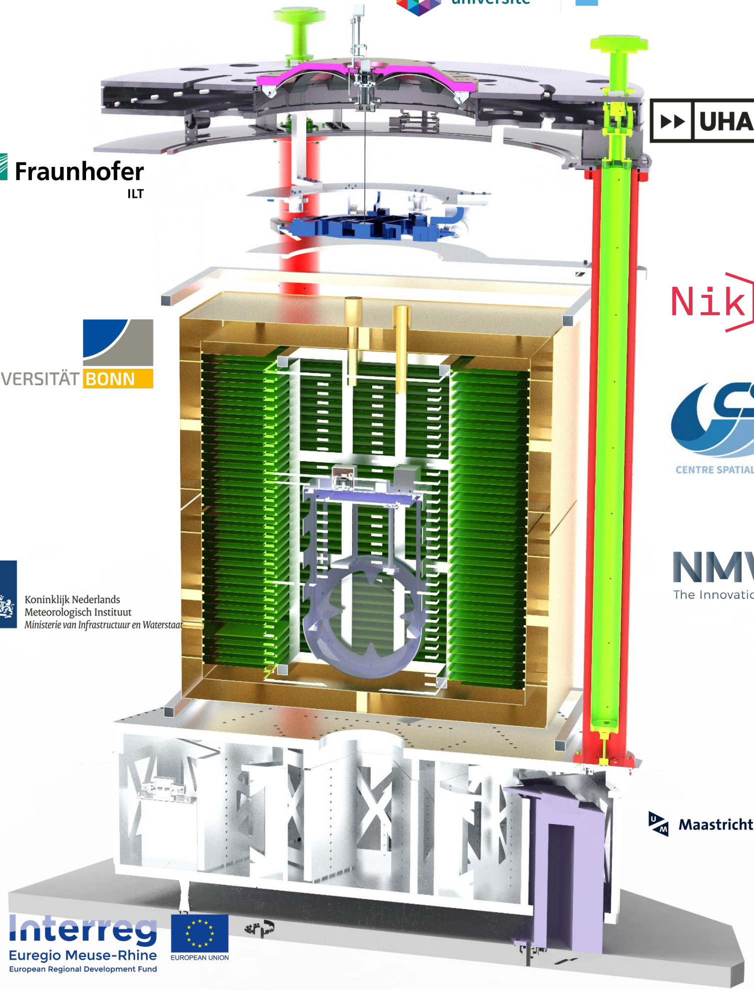


Figure 2.21: Overview of the E-TEST prototype design. A large vacuum tank (left) hosts the cryogenic mirror suspension (right). From top to bottom we can see 1) the top GAS filter, 2) the top stage, 3) the marionette and 4) the inverted pendulum legs within pipes that support a reference ring below the 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]

Belgian effort towards ET:

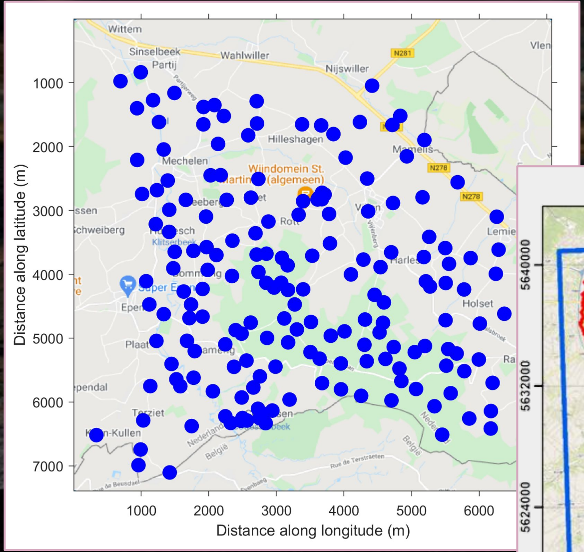


Di Pace et al
Galaxies 2022, 10, 65

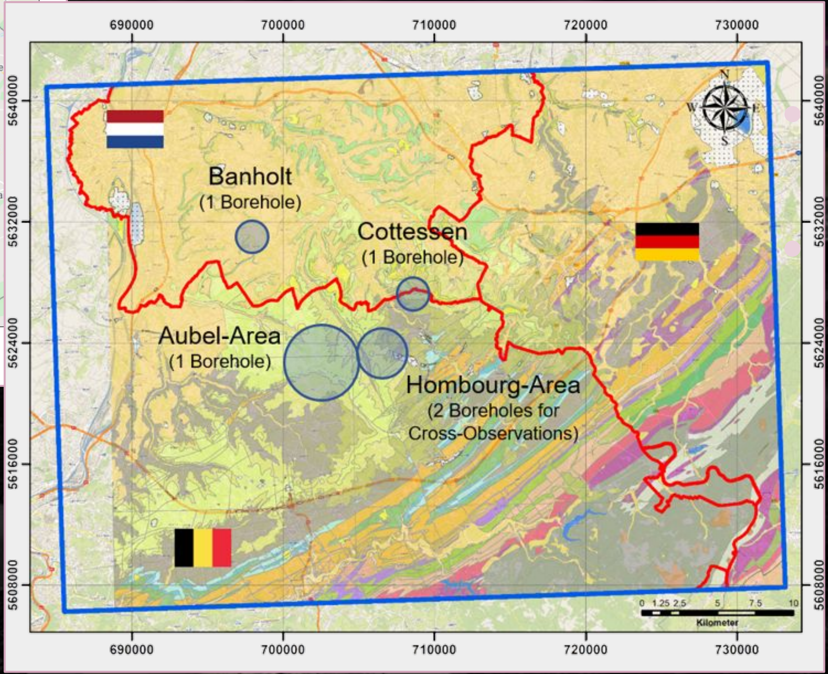
E-TEST:

- 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:

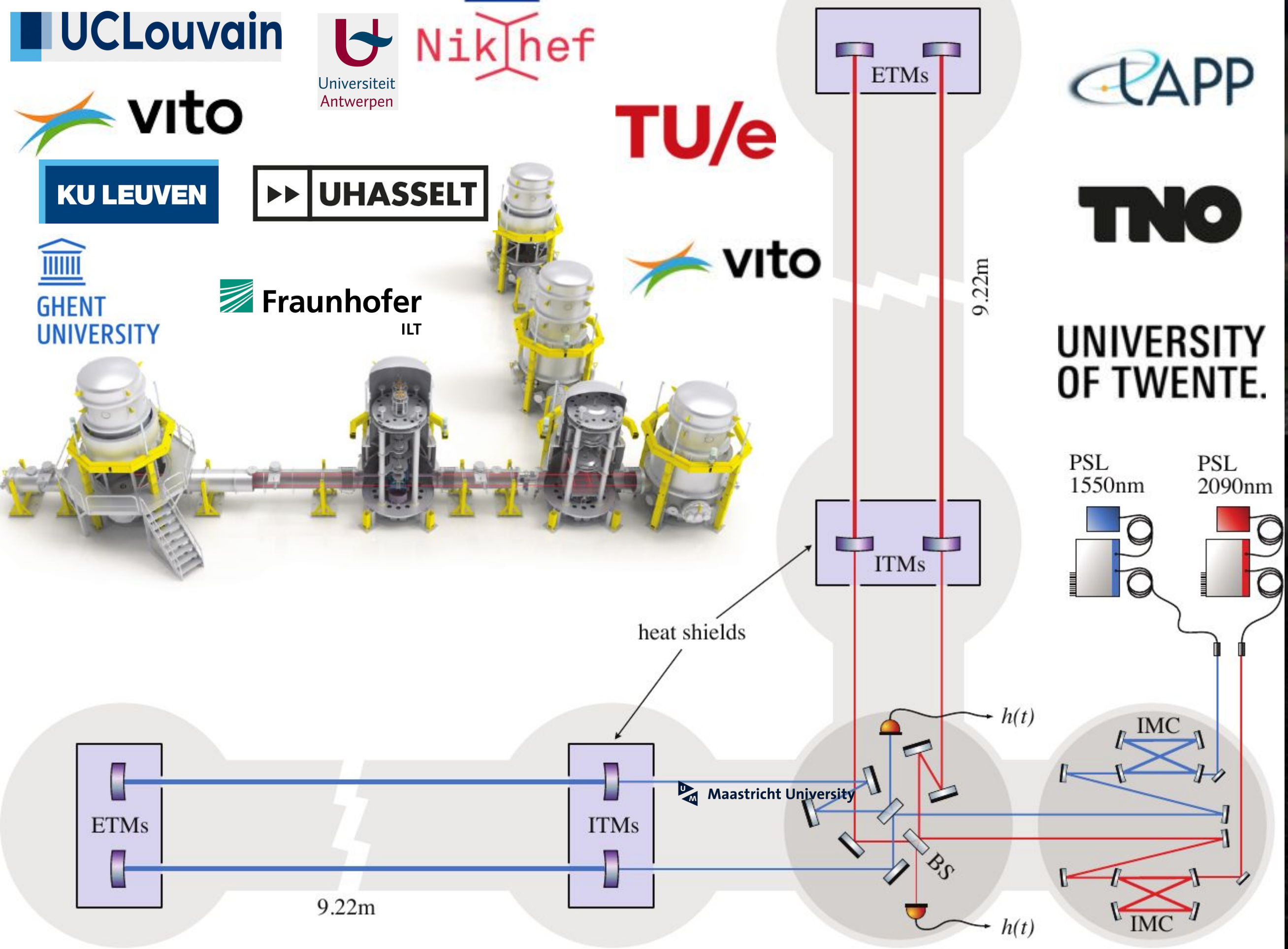


Image from the ET-Pathfinder first publication arXiv:2206.04905v1

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)