Future Instrument for Gravitational Wave Astronomy

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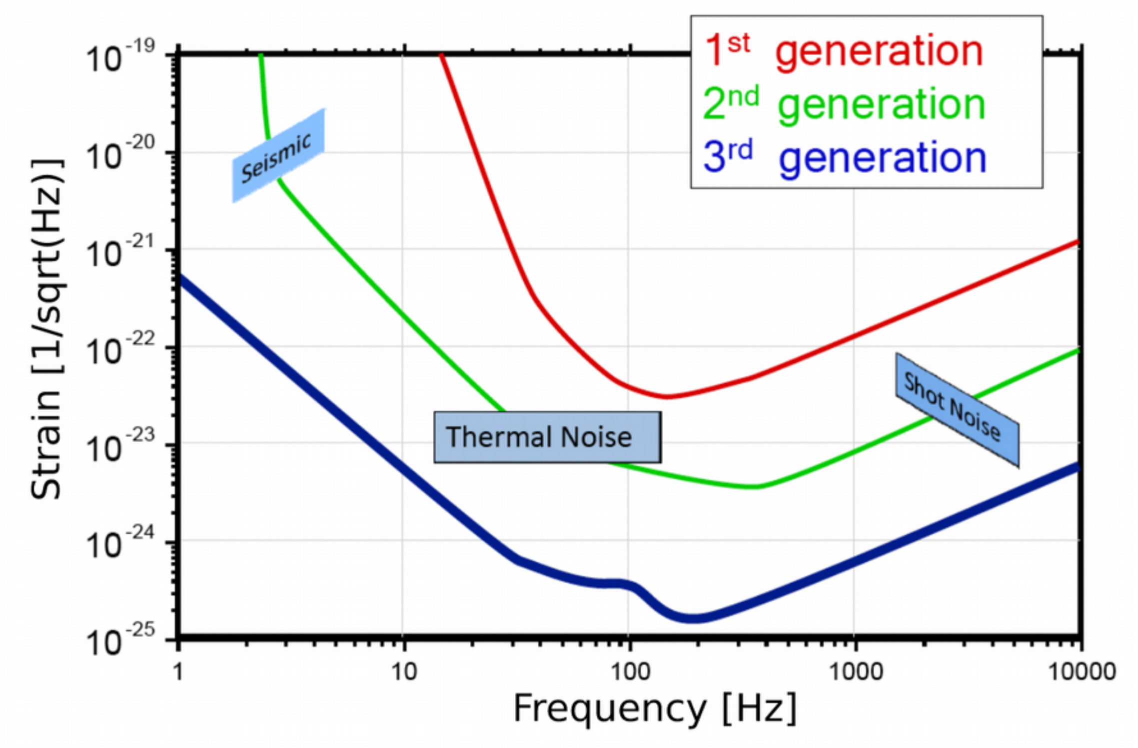
Introduction

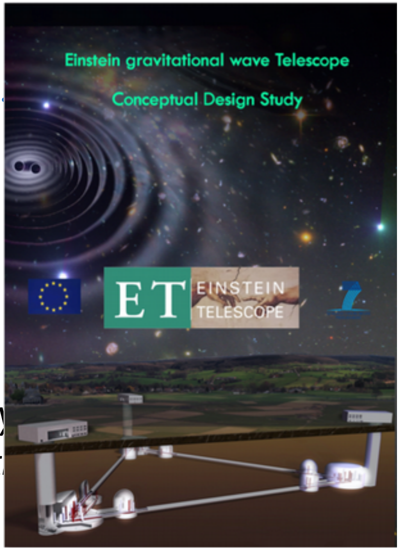
- Gravitational waves astronomy has just started...
- ... we already need to think about the future of the field.
- If we want to catch more gravitational waves we need to improve the detectors sensitivity :
  - Actual capacity will reach their potential limit ⇒ 3G detectors.
  - From 2G to 3G detectors.



From Pushing towards the ET sensitivity using ‘conventional’ Technology - Stefan Hild et al. - arXiv:0810.0604v2

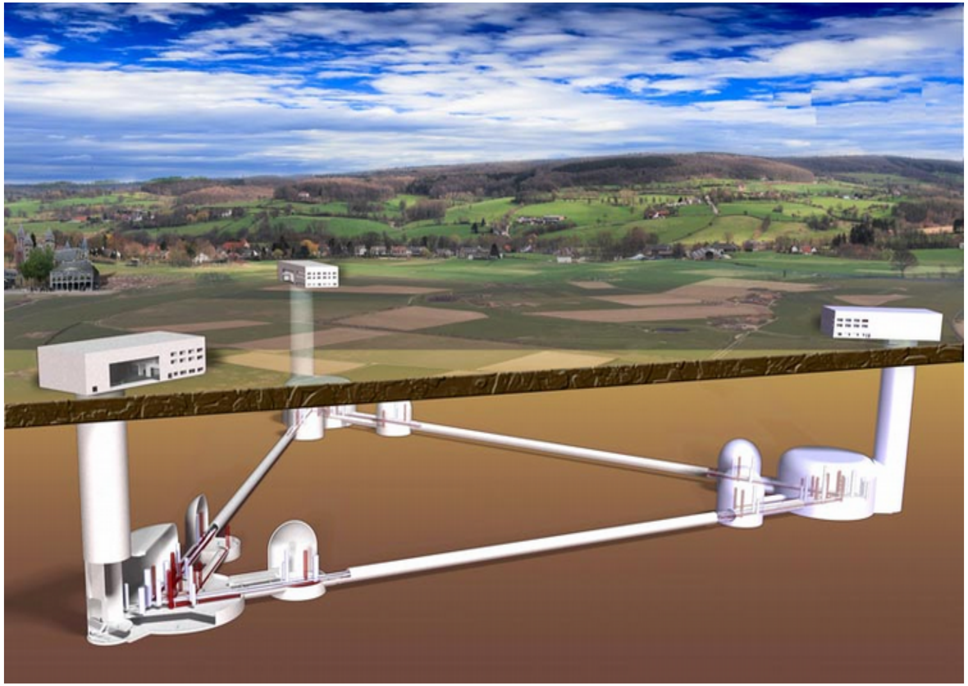
A bit of history

- Einstein Telescope Design study funded by the EC in FP7 (2008-2011).
  - Einstein Telescope Conceptual Design Study issued in 2011 : http://www.et-gw.eu/index.
    - Involved France, Germany, Italy, Netherlands, UK.
- ET community now includes Hungary, Poland, Spain.
- 9th ET symposium happened in April 2018 @ EGO :
  - *The focus of the meeting is the creation of the ET collaboration, the definition of the strategy of the ET proposal to the 2020 update of the ESFRI roadmap. We will discuss the future of t and astrophysics.*
  - *https://events.ego-gw.it/indico/conferenceDisplay.py?ovw=True&confId=64*
- Project includes in various roadmap (GWIC, APPEC, OECD, …).
- Letter of Intent issued in April 2018.
  - http://www.et-gw.eu/index.php/letter-of-intent

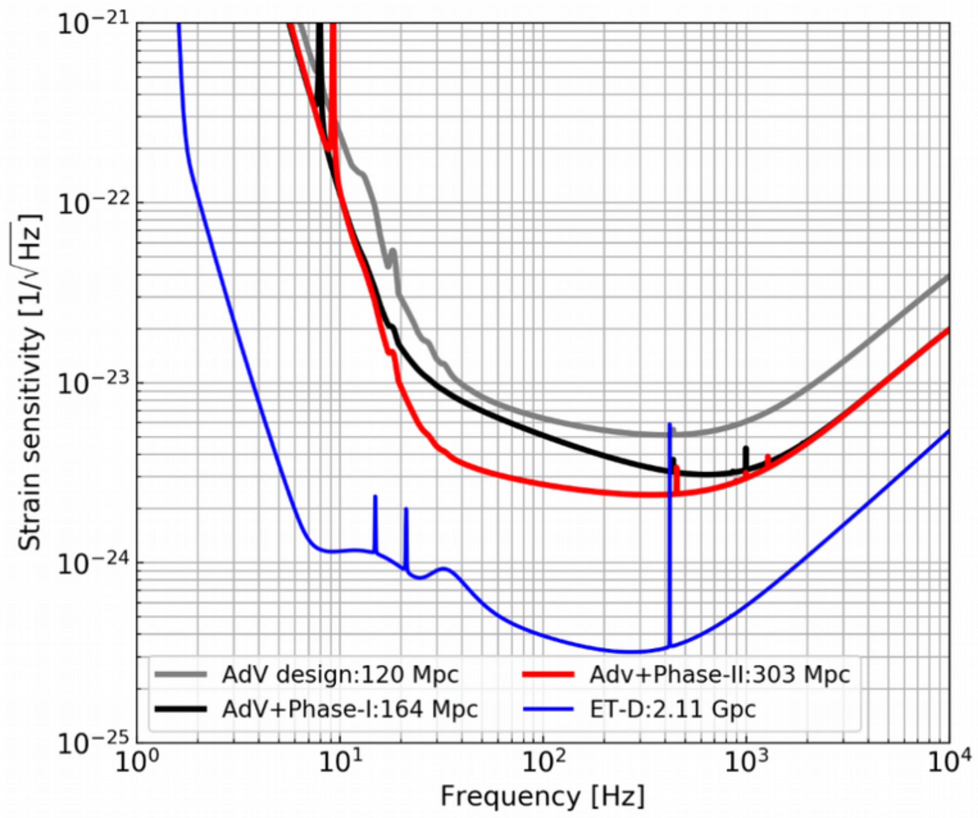


Einstein Telescope main ideas

- 10x better sensitivity then 2G detectors.
- Stand-alone observatory :
  - Wide frequency, with special attention to low frequency (few HZ).
    - Stellar mass Black Holes
  - Capable to work alone (characteristics to be evaluated again) :
    - Localization capability (poor)
    - Gravitational wave polarization
    - High duty cycle: redundancy
  - 50-years lifetime of the infrastructure.
    - Capable to host the upgrades of the hosted detectors



From 2G to 3G detectors :



- **AdV+ :**
  - Short term evolution of Advanced Virgo.
  - Pushing the actual site to maximum sensitivity.
  - 2 phases proposal (BNS range 164 Mpc & 303 Mpc).

- **Einstein Telescope :**
  - New site.
  - Factor 10 improvement in sensitivity wrt AdV (BNS range 2110 Mpc).
  - ET conceptual design issued in May 2011.
  - ET will be a much broader collaboration than Virgo.

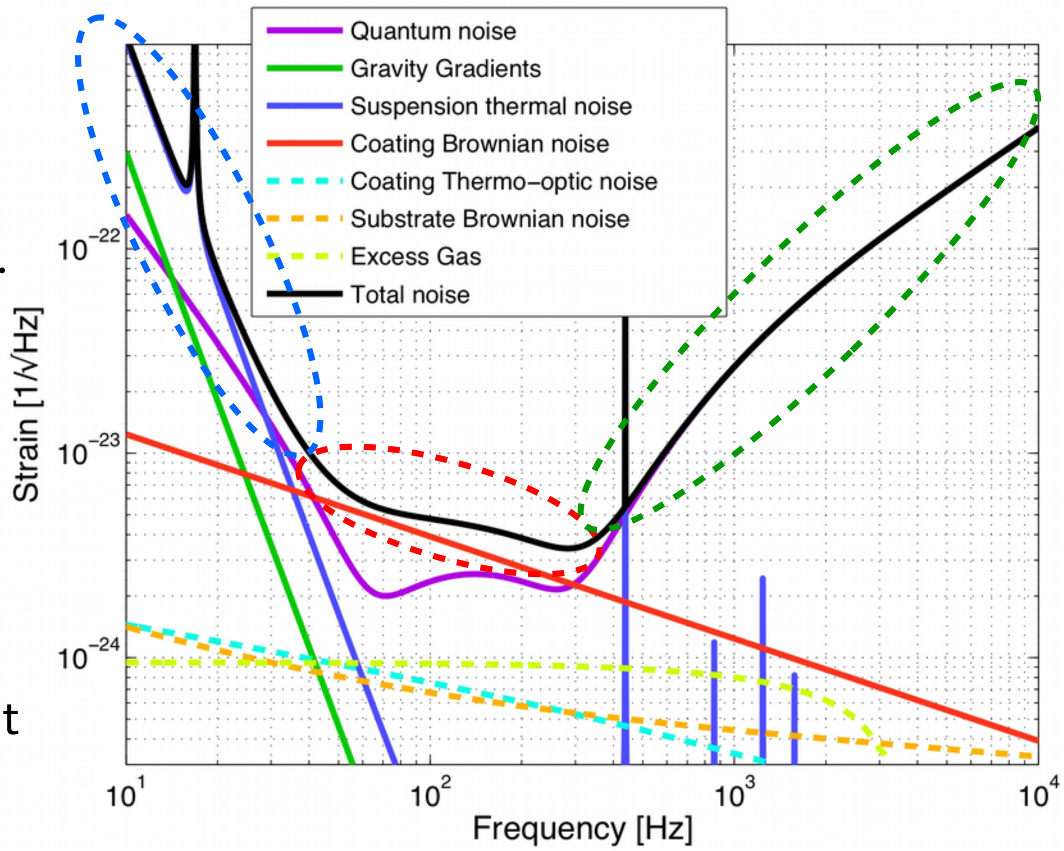
What is limiting the 2G detectors ?

- Low frequency ⇒ suspension thermal noise (+ gravity gradient & radiation pressure).
  ==> new suspensions, cryogenic detectors.

- Medium frequency ⇒ Coating thermal noise.
  ==> new coating ? Materials ?

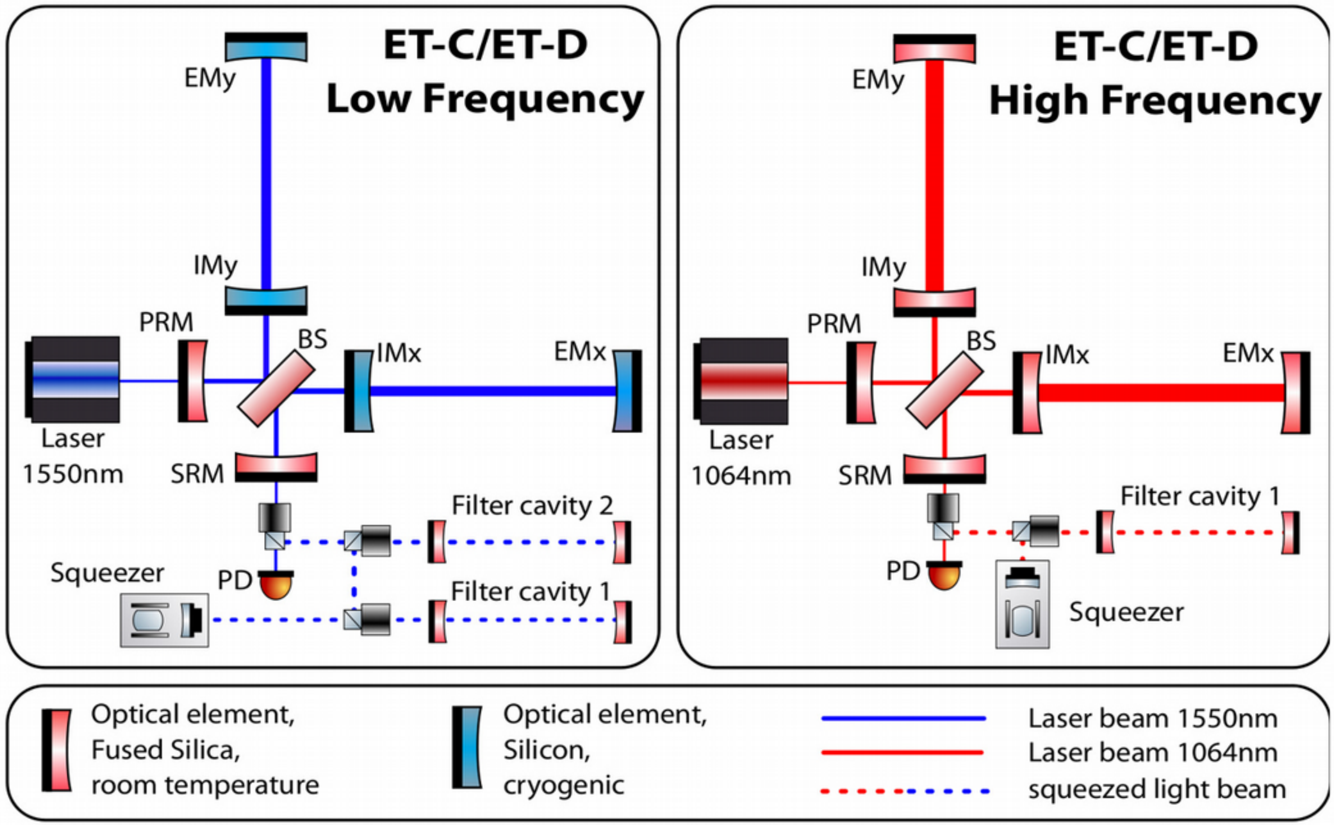
- High frequency ⇒ quantum noise (shot noise).
  ==> higher power, squeezed light.

- 3G detectors aimed at factor 10 improvement at all frequencies.



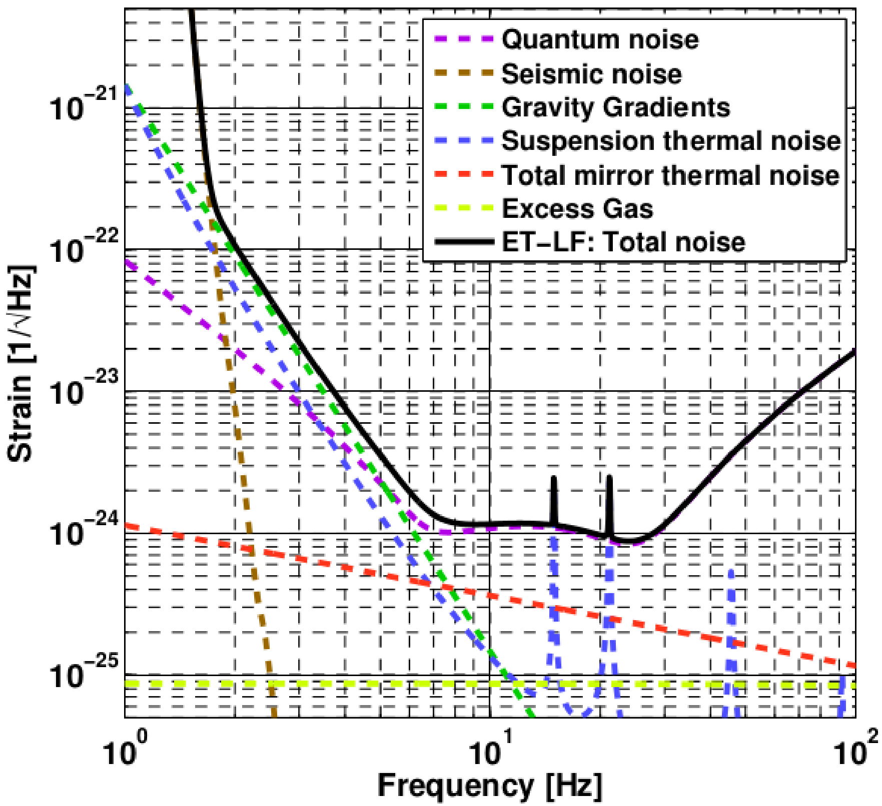
An underground xylophone detector !

- Improving low and high frequencies sensitivity in a single detector is very challenging :
  - HF requires higher power.
  - LF requires cold mirrors.
- Building 2 specialized detectors to cover low and high frequencies.



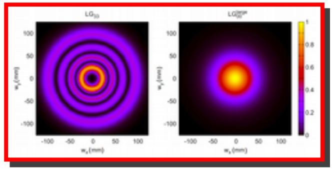
ET – Low Frequency

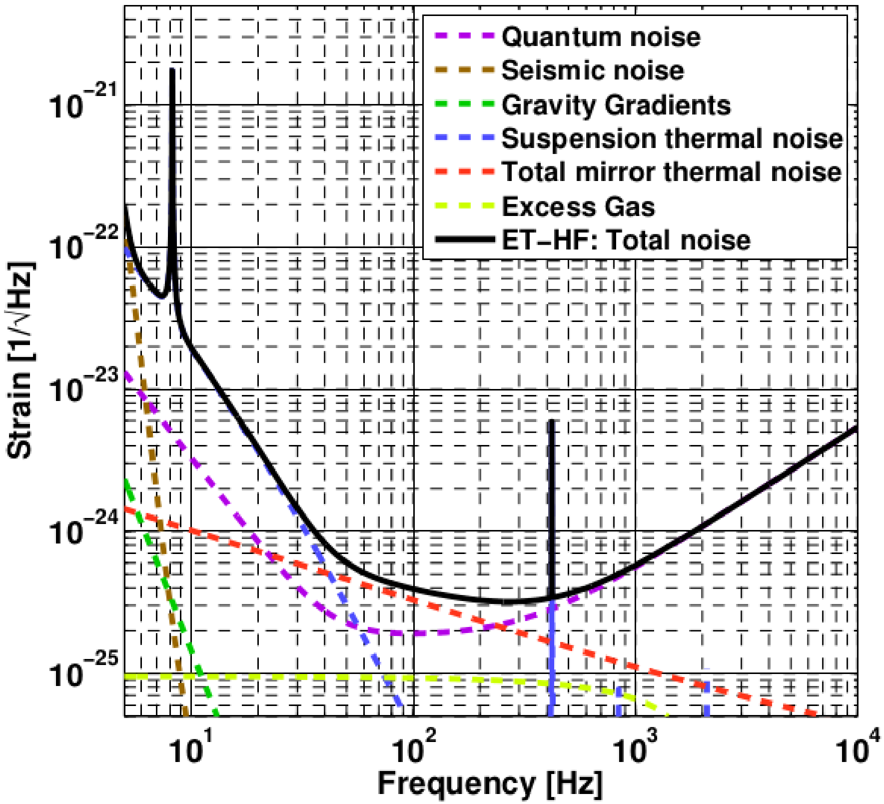
- **Quantum noise:**
  - 18kW (arm power), detuned Signal-Recyling, 10 dB frequency dependent squeezing, 211kg mirrors, 1550 nm.
- **Seismic:**
  - 17 m Superattenuator.
- **Gravity gradient:**
  - Underground.
- **Mirror thermal :**
  - 10K, Silicon, 9 cm beam radius, TEM00.
- **Suspension Thermal:**
  - Penultimate mass@2K, 3mm diameter silicon fibres, 2m long.



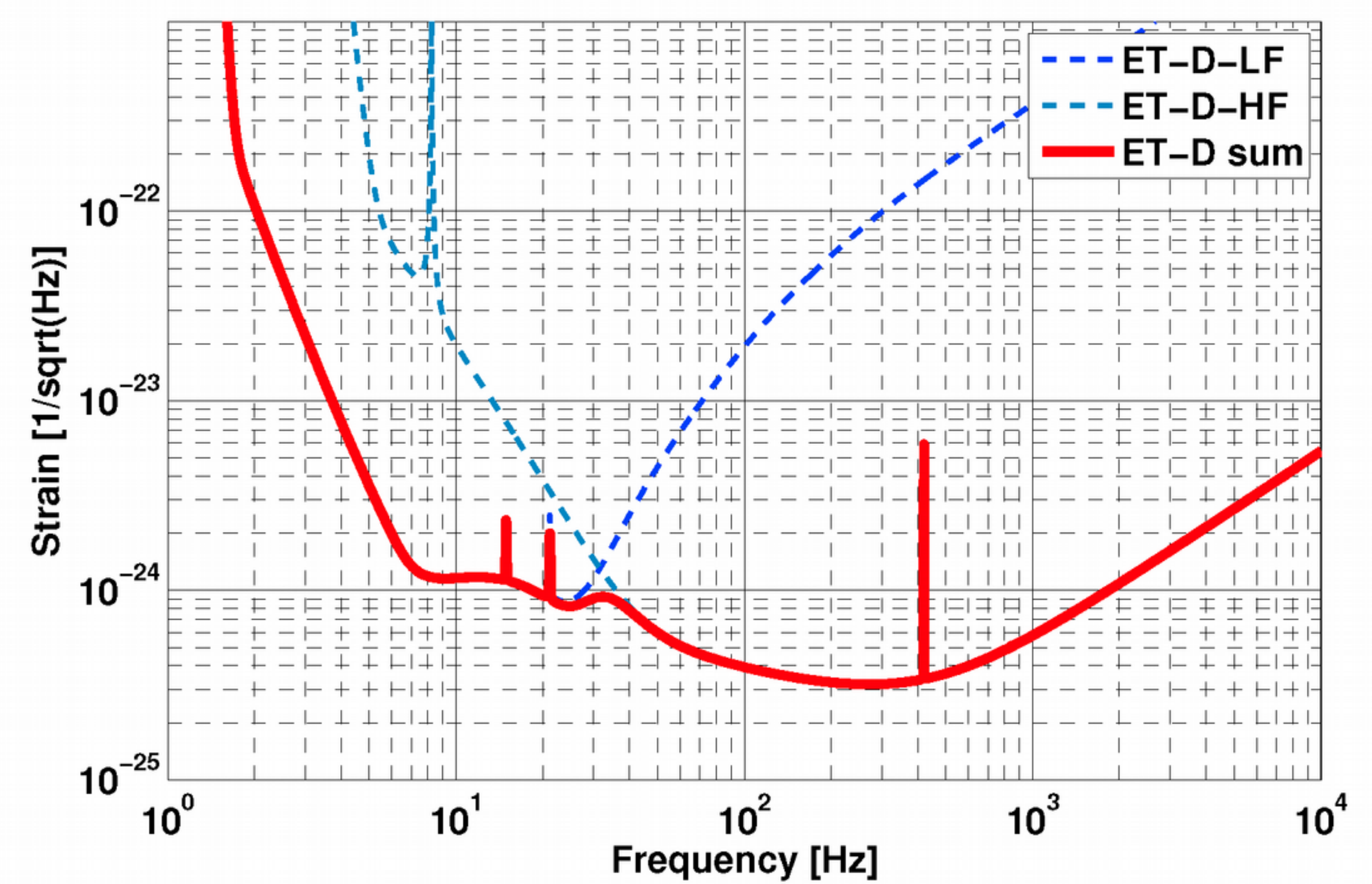
ET – High Frequency

- Quantum noise:
  - 3MW (arm power), 200kg fused silica mirrors, 63cm Ø. tuned Signal-Recyling, 10dB Squeezing,
- Suspension Thermal and Seismic:
  - Superattenuator (standard Virgo)
- Gravity gradient:
  - No subtraction needed
- Thermal noise:
  - 290K, 12cm beam radius, fused Silica, LG33.





Xylophone detector sensitivity



Xylophone detector summary :

- Common characteristics :
  - Large test masses
  - New coatings
  - Frequency dependent squeezing
  - Long arms (10 km vs 3 km).

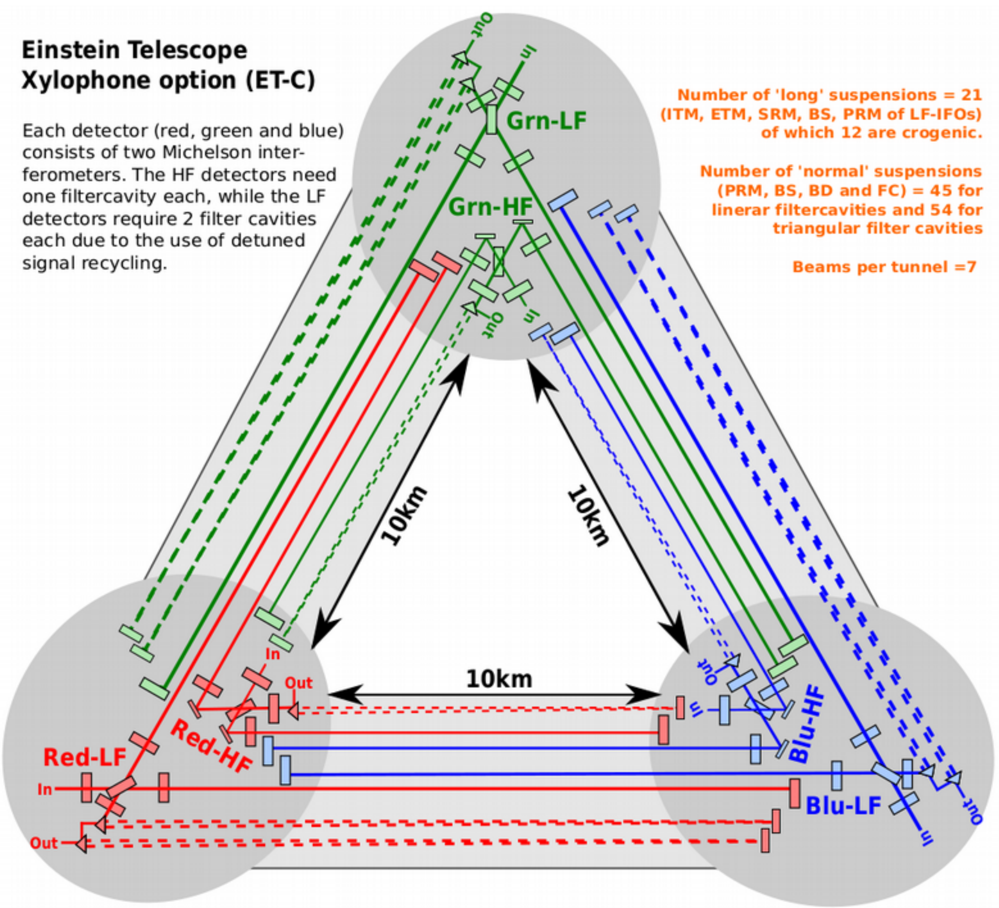
- ET – LF :
  - Underground
  - New seismic suspensions
  - Cryogenics
  - Silicon (sapphire) test masses
  - New laser wavelenght

- ET – HF
  - High power laser
  - Thermal compensations
  - Laguerre-Gauss mode

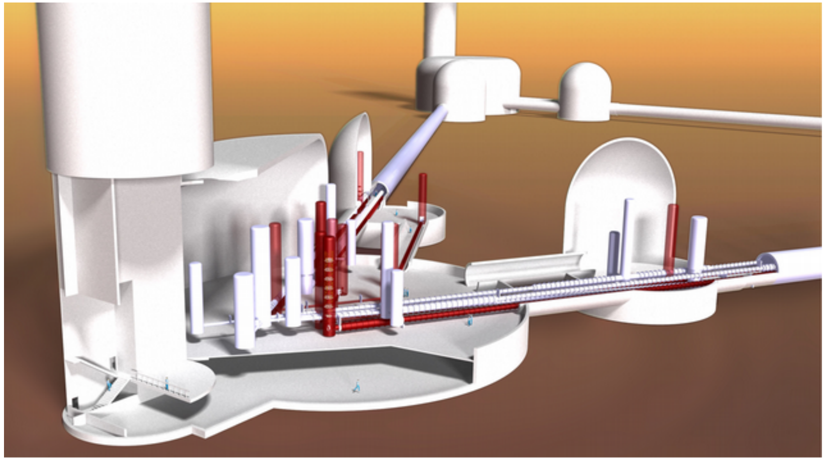
- Pushing down the fundamentals limits of the ITF sensitivity means pushing down the technological noises :
  - Electronics noise.
  - Better controls of stray lights (new absorbing materials?).
  - Optical losses.
  - Phase noise, magnetic noise…
  - Parametric instabilities.
  - Unknown technical noises ?
  - Improved calibration.
  - …

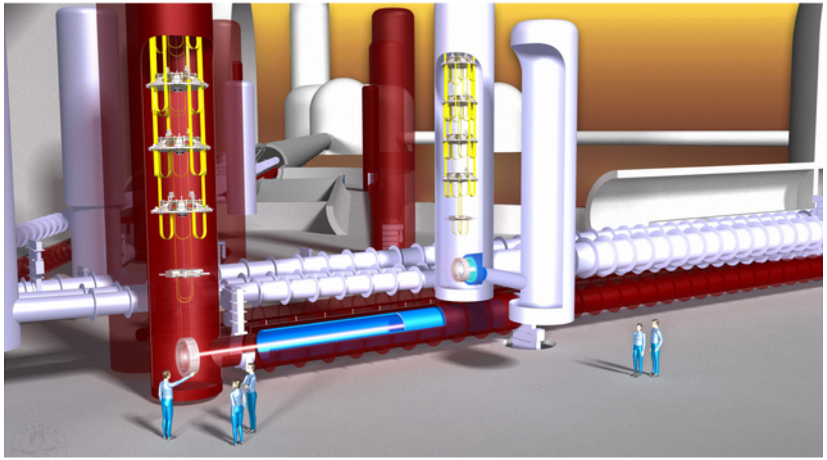
ET conceptual design : layout

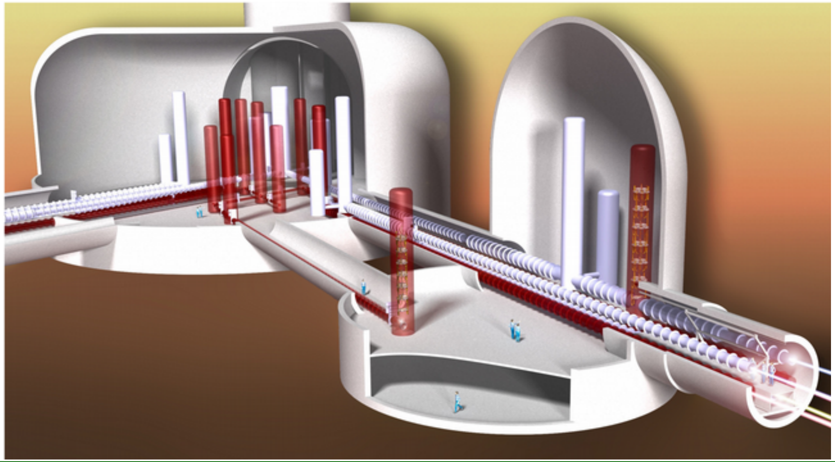
- Start with a single (xylophone) detector.
- 2 detector to resolve GW polarization.
- 3 detector for redundancy.

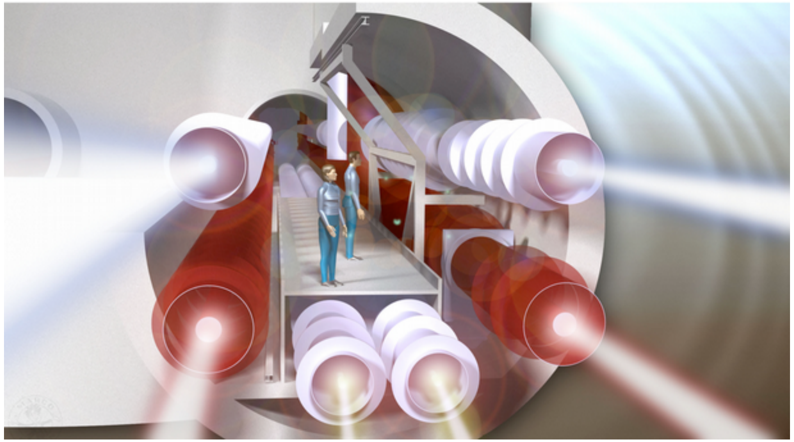


What would look like an underground interferometer ?







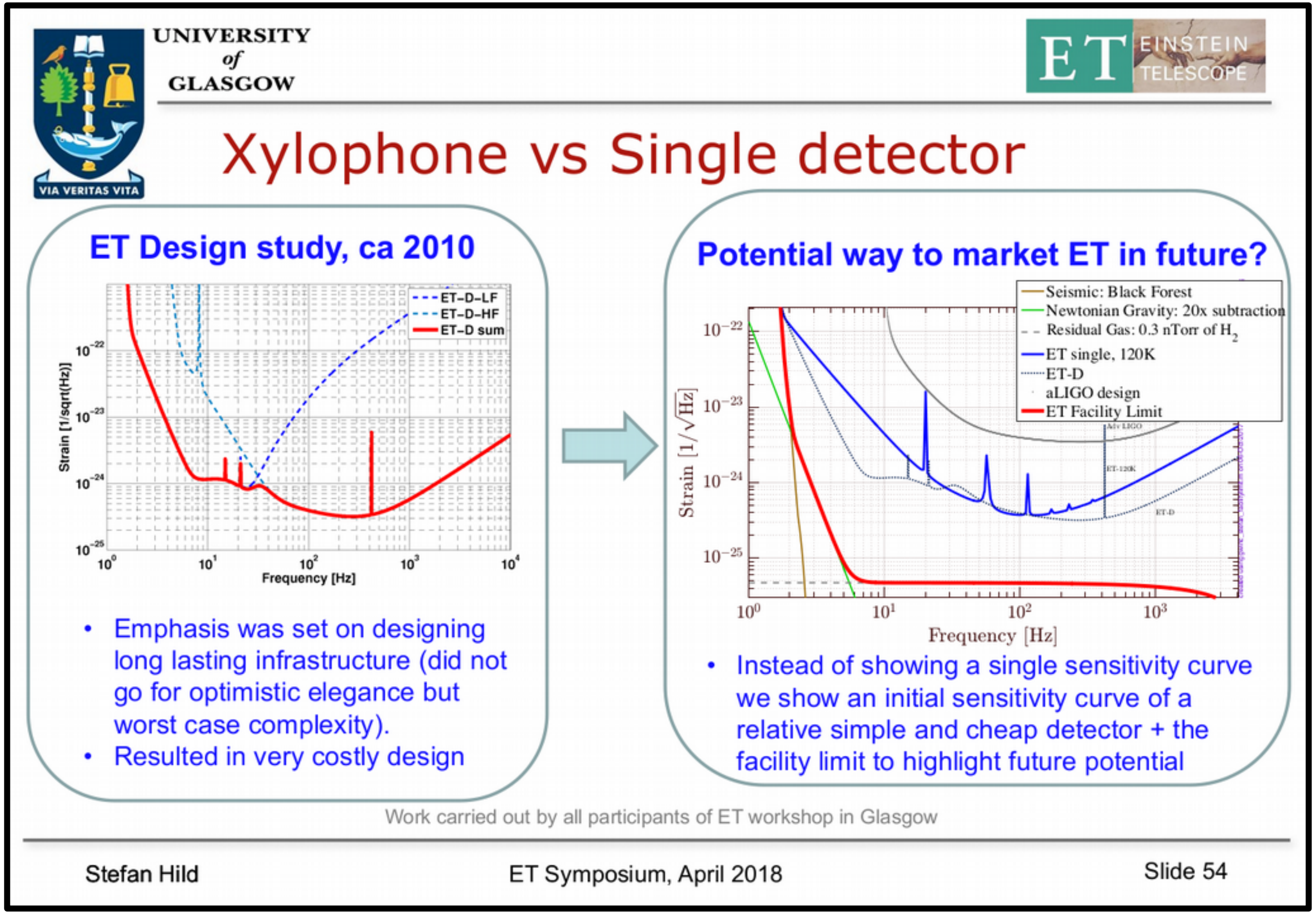


Design needs to be re-evaluated

- Situation changed compared to 2011.
  - New findings from R&D.
  - New context (ET not alone, Cosmic explorer (USA)).
- Re-evaluation of L-shape vs triangular shape :
  - 3G network instead of stand-alone observatory.
  - 1 detector vs 3 detectors ⇒ save money.
  - L-shape reduces complexity.
  - 15 km arms vs 10 km.
- Xylophone vs single detector ?
- Re-evaluation of the design has just started.

Xylophone vs single detector ?

From: ET technologies – S. Hild – ET symposium, April 2018



Xylophone vs single detector ?

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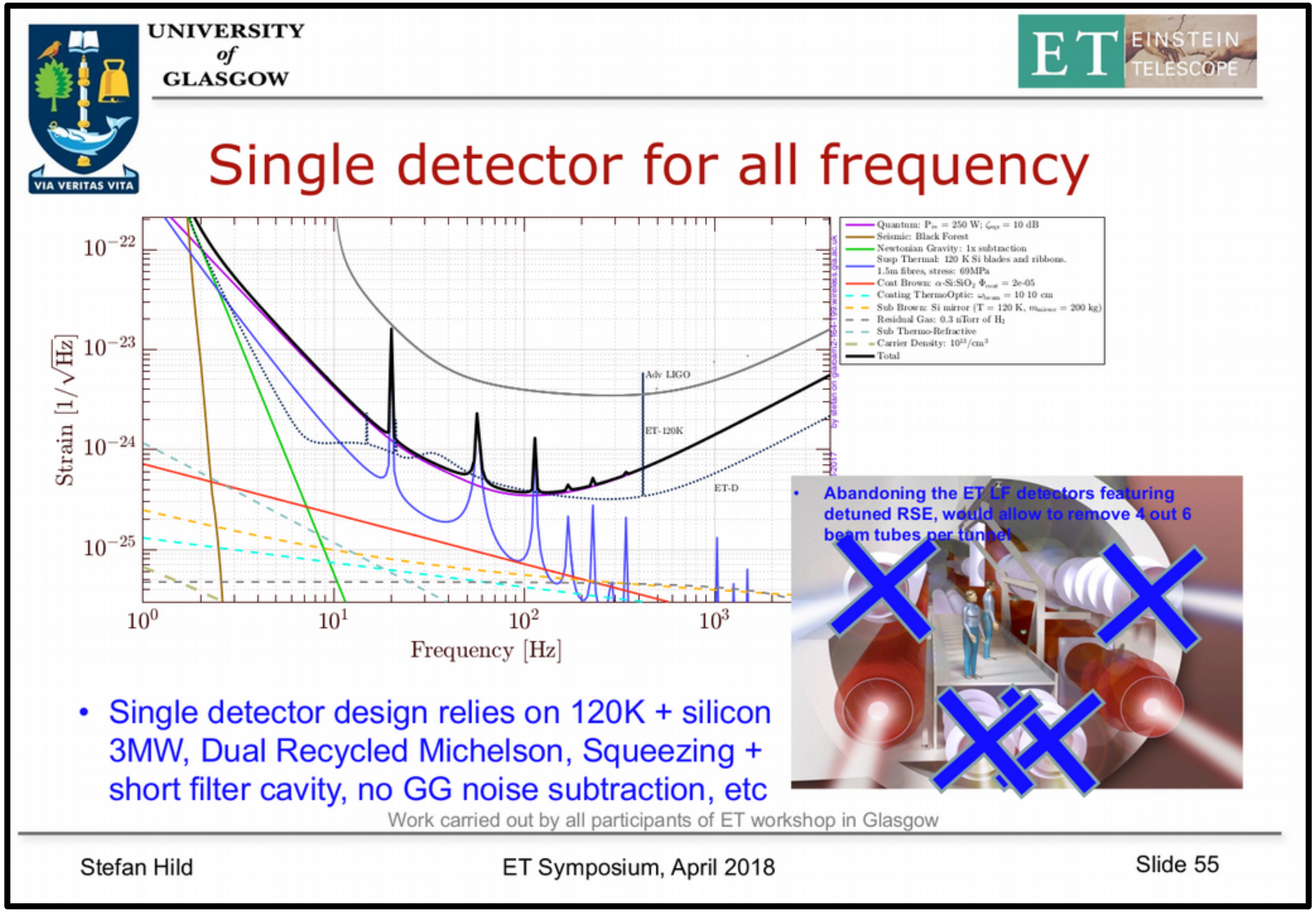
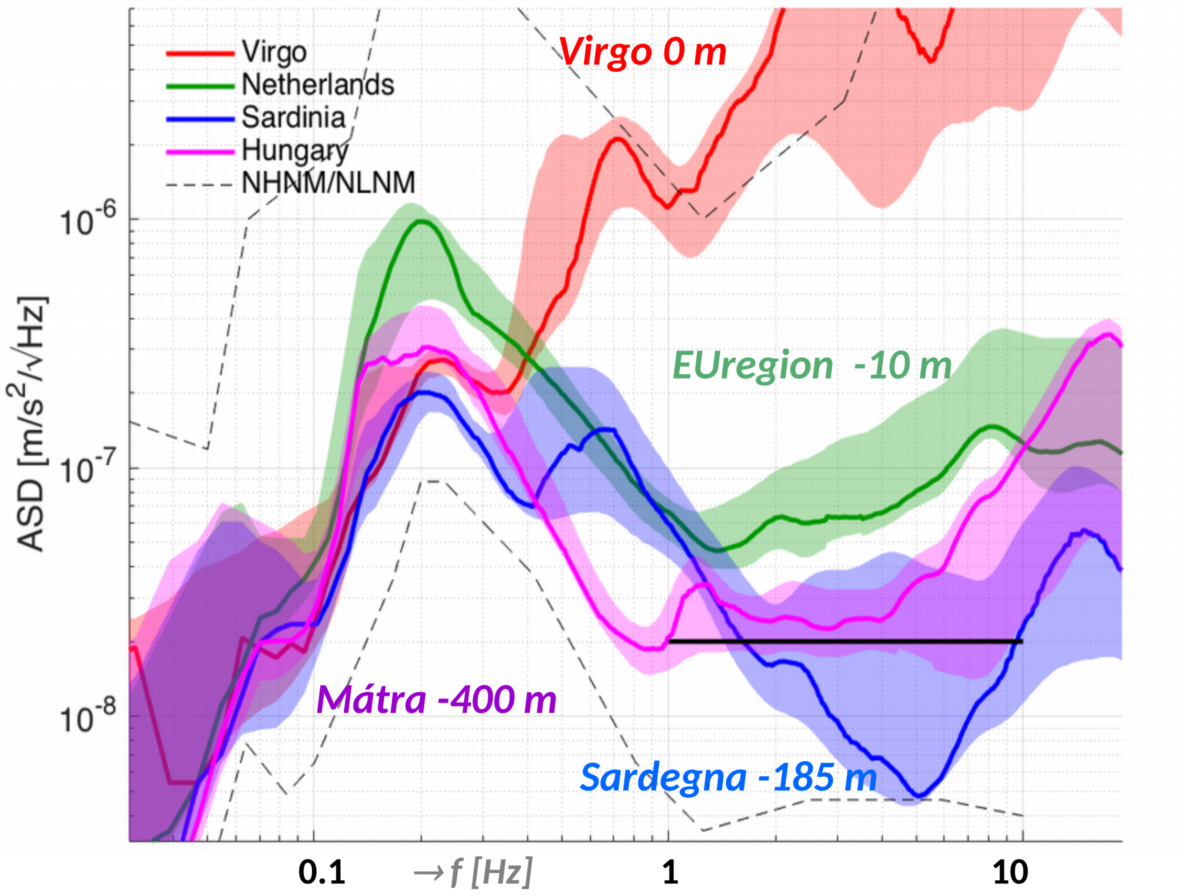


Where ?

- 3 sites candidates :
  - Limburg region.
  - Mátra, Hungary.
  - Sardinia, Italy.

- Seismic measurements :



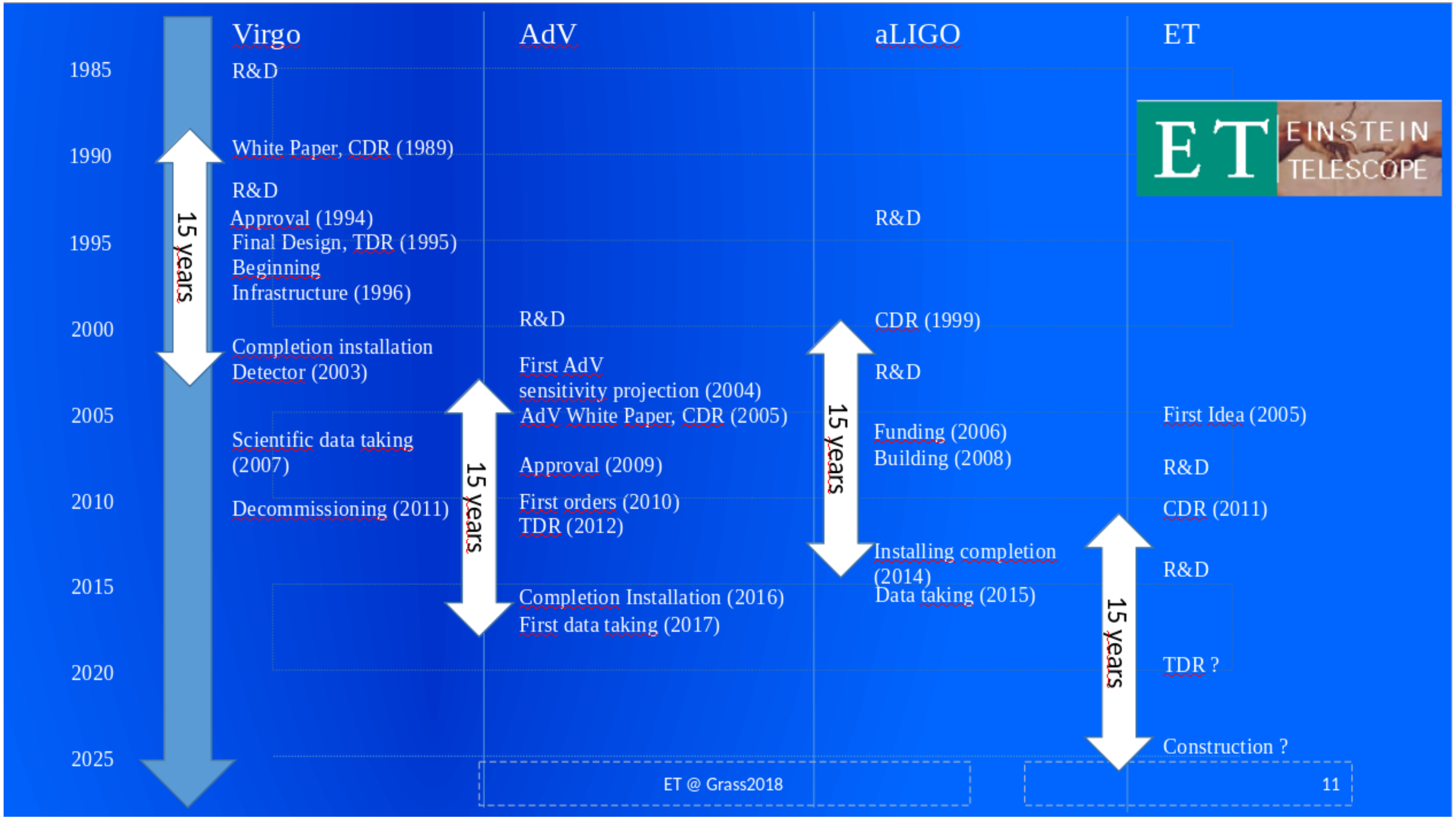
From: G-B-N site – F. Linde – ET symposium, April 2018

Why ?

- Fundamental physics & gravity :
  - Nature of GW as predicted by Einstein's theory ?
  - Physics of gravitational collapse ?
  - Equation of state of matter in neutron star core ?
  - Maximum mass of neutron star ?
  - …
- Astrophysics & Multimessenger Astronomy :
  - How do CB form and evolves ?
  - Physical mechanism behind supernovae & asymmetry of gravitational collapse ?
  - Nature of neutron star crust & interaction with core?
  - Population of GW sources at high redshifts ?
  - …
- Cosmology :
  - How did the black holes form & evolves ?
  - What are the true distances of cosmological sources ?
  - …

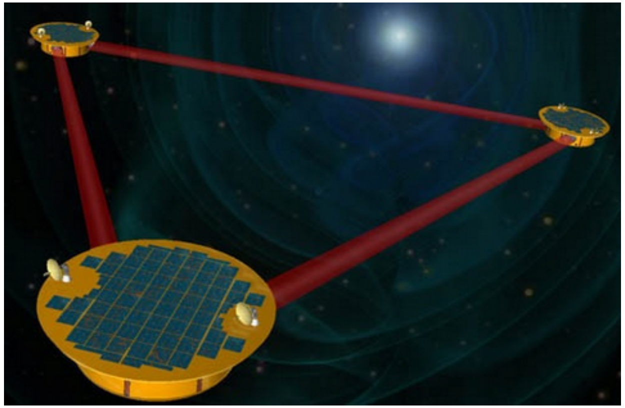
When ?

From: Motivations – M. Punturo – ET symposium, April 2018



What else ?

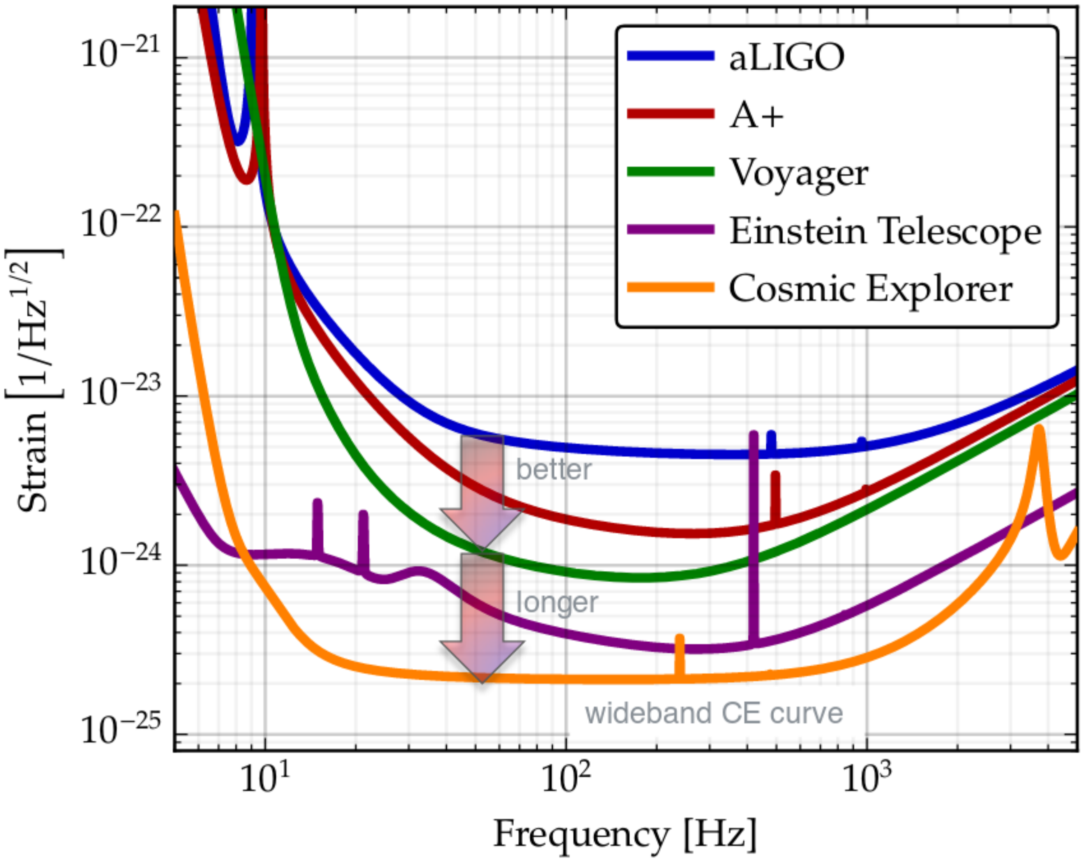
- LISA :
  - Space-based experiment (ESA & NASA).
  - Massive & galactic binaries, extreme mass ratio inspirals.
  - Early 2030s.
  - LISA pathfinder launched with success.



- PTA (Pulsar Timing Array):
  - Stochastic background.
  - 100 m class radio-telescope.
- Cosmic Explorer (USA):
  - Earth-based interferometer, 3rd generation.
  - Mid 2030s.

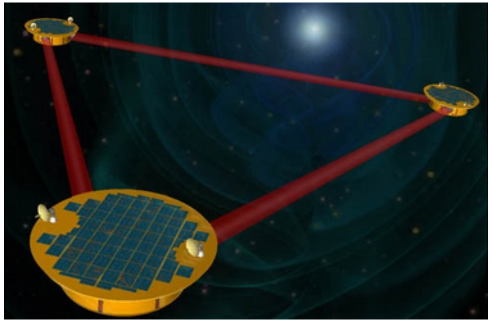
Cosmic Explorer

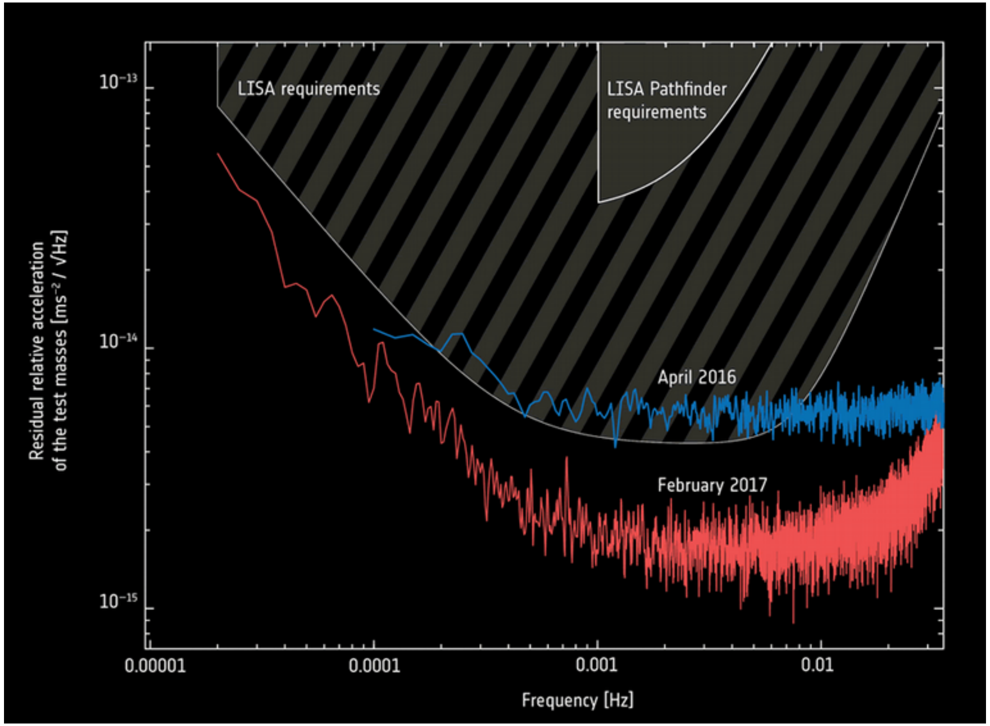
- 40 km long L-shape interferometer.
- Surface facility.
- Not-intended as stand alone observatory, rather 3G network.
- Voyager : using actual facilities (cryogenics & high power, heavier test masses).
- Cosmic Explorer sensitivity curves based on expected R&D improvements.



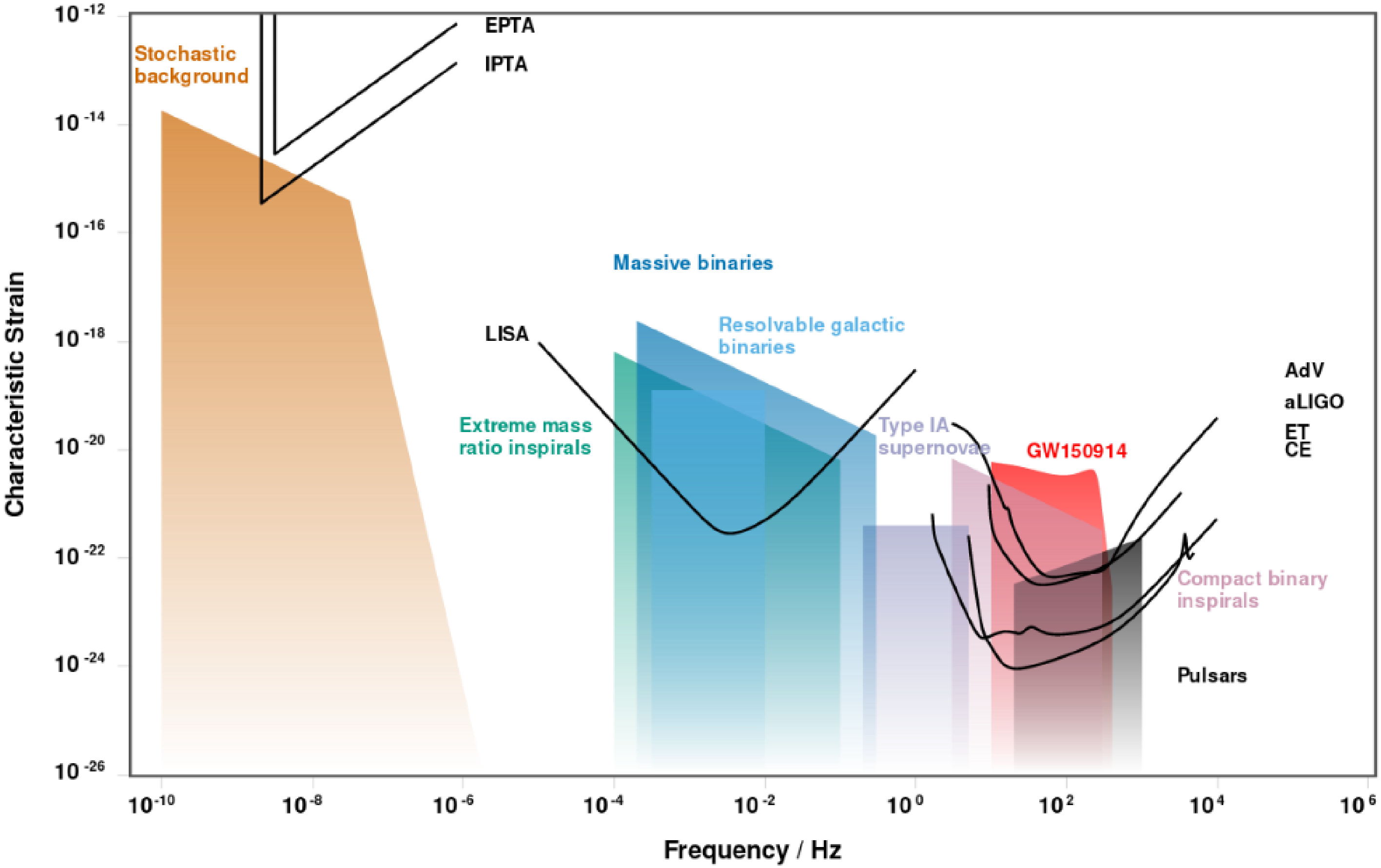
LISA

- Interferometric detector.
  - 3 spacecrafts.
  - 2.5 million km between test masses.
- Detectable sources :
  - Ultra compact binaries.
  - Supermassives black hole mergers.
  - Extreme mass ration inspiral.
- LISA pathfinder launched with success.
- Early 2030s.





Future Instrument sensitivity in a nutshell



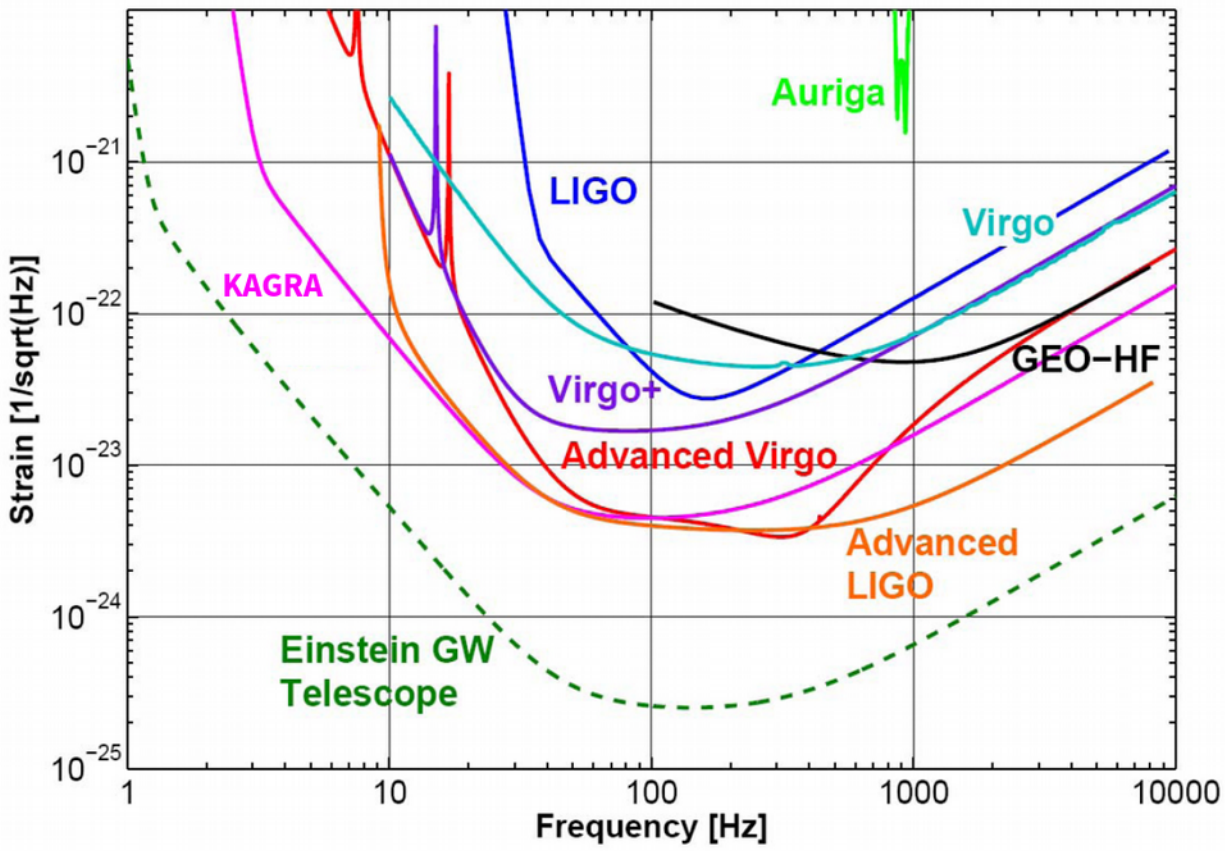
From: gwplotter.com

Conclusion

- Actual 2G detectors will go through important updgrade.
- Earth-based 3G detectors are being studied :
  - First study at the corner of the 2010'.
  - Conceptual design study needs to be updated :
    - Xylophone vs single detector interferometer ?
    - Stand-alone observatory vs 3G network ?
  - Einstein Telescope is moving from a community to a collaboration.
    - Site selection.
    - Writing of a TDR.
- There will be a lot to do in gravitational astronomy in the future !

Thanks !

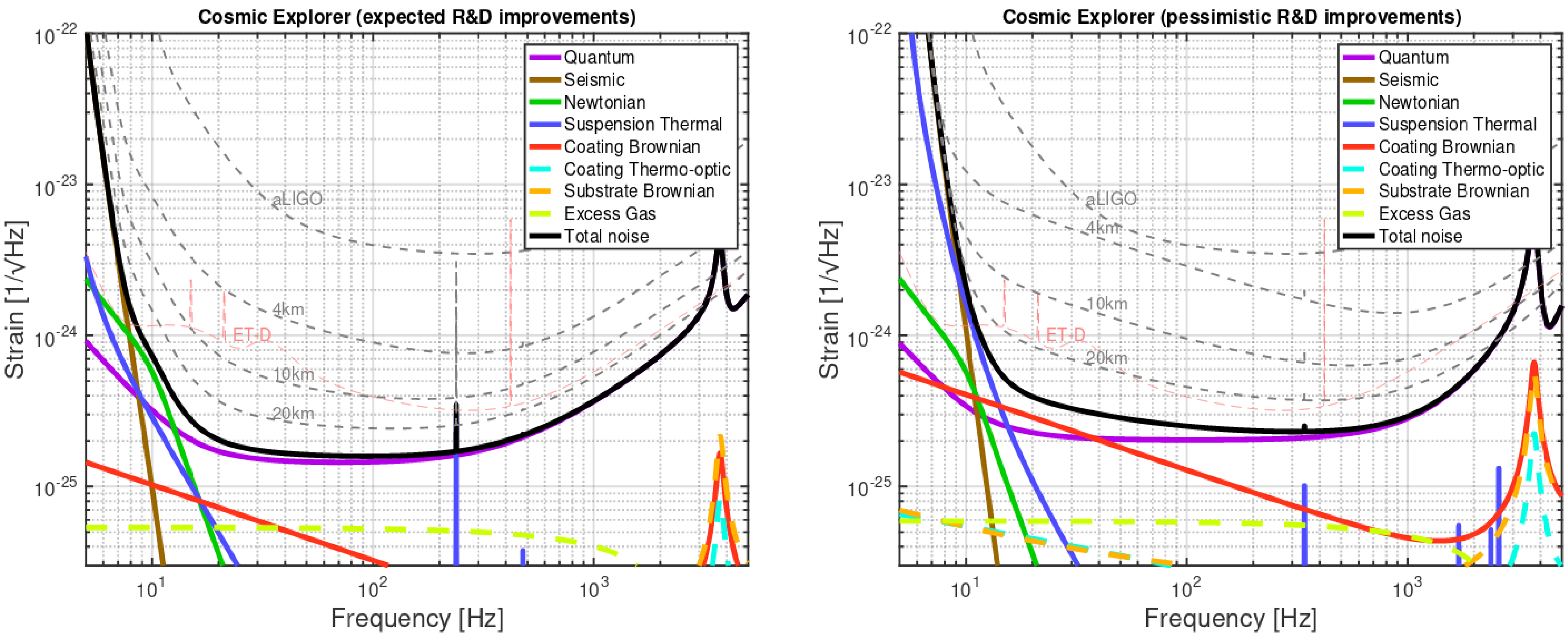
- Bibliography :
  - Slides from 9th ET symposium : https://events.ego-gw.it/indico/conferenceDisplay.py?ovw=True&confId=64
  - Einstein gravitational waves Telescope Conceptual Design Study.



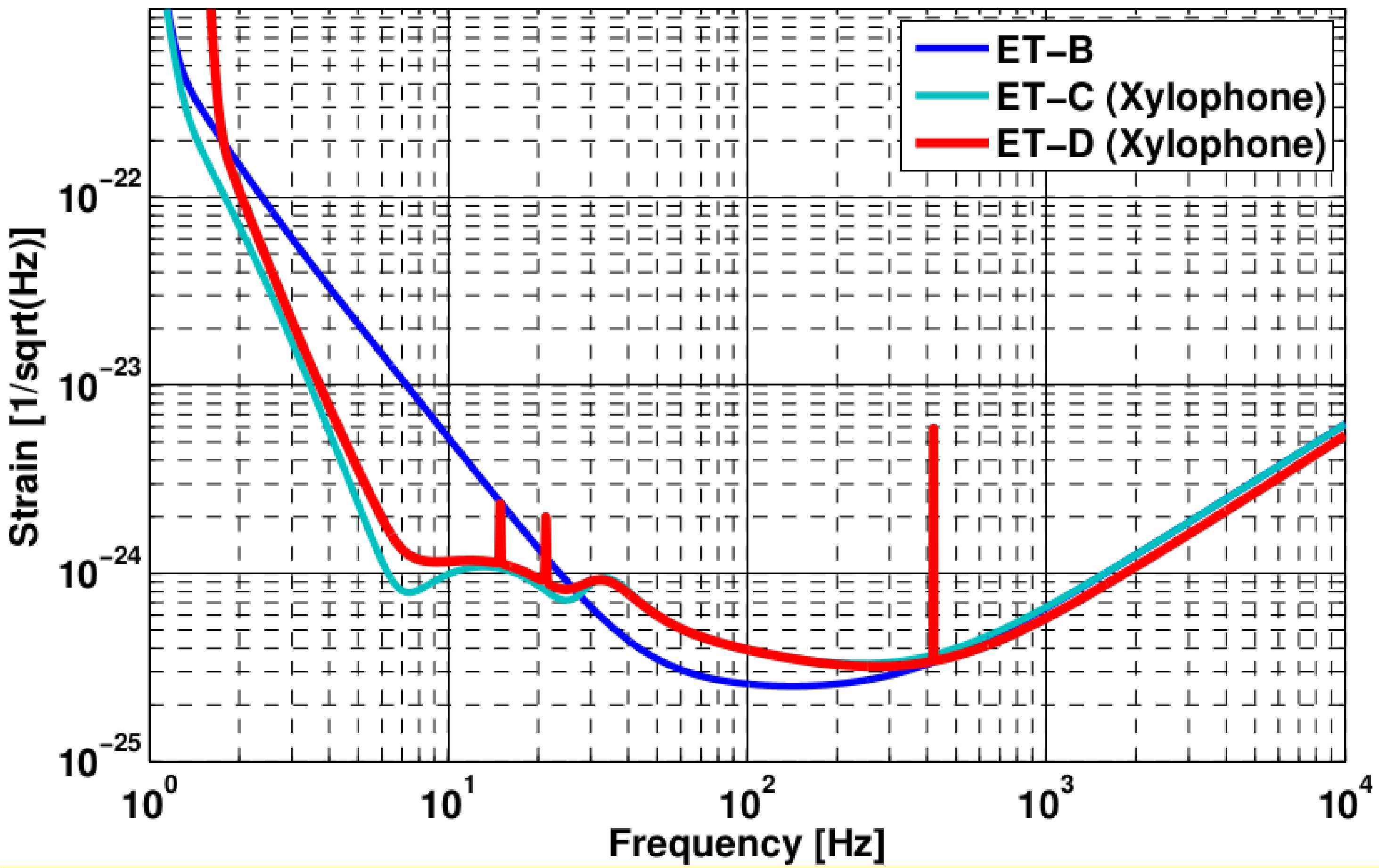
Auriga
LIGO
Virgo
KAGRA
GEO−HF
Virgo+
Advanced Virgo
Advanced LIGO
Einstein GW Telescope
Strain [1/sqrt(Hz)]
Frequency [Hz]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
1
10
100
1000
10000

IFO Cases	aLIGO	A+	Voyager	CE (pess)	CE	ET LF	ET HF
Arm Length [km]	4	4	4	40	40	10	10
Mirror Mass [kg]	40	40	200	320	320	211	200
Mirror Material	Silica	Silica	Silicon	Silica	Silicon	Silicon	Silica
Mirror Temp [K]	295	295	123	295	123	10	290
Sus Fiber	0.6m SiO_2	0.6m SiO_2	0.6m Si	1.2m SiO_2	1.2m Si	2m Si	0.6m SiO_2
Fiber Type	Fiber	Fiber	Ribbon	Fiber	Ribbon	Fiber	Fiber
Input Power [W]	125	125	140	150	220	3	500
Arm Power [kW]	710	750	3000	1400	2000	18	3000
Wavelength [nm]	1064	1064	2000	1064	1550	1550	1064
NN Suppression	1	1	10	10	10	1	1
Beam Size [cm]	5.5 / 6.2	5.5 / 6.2	5.8 / 8.4	12 / 12	14 / 14	9 / 9	12 /12
SQZ Factor [dB]	0	6	8	10	10	10	10
F. C. Length [m]	none	300	300	4000	4000	10000	500

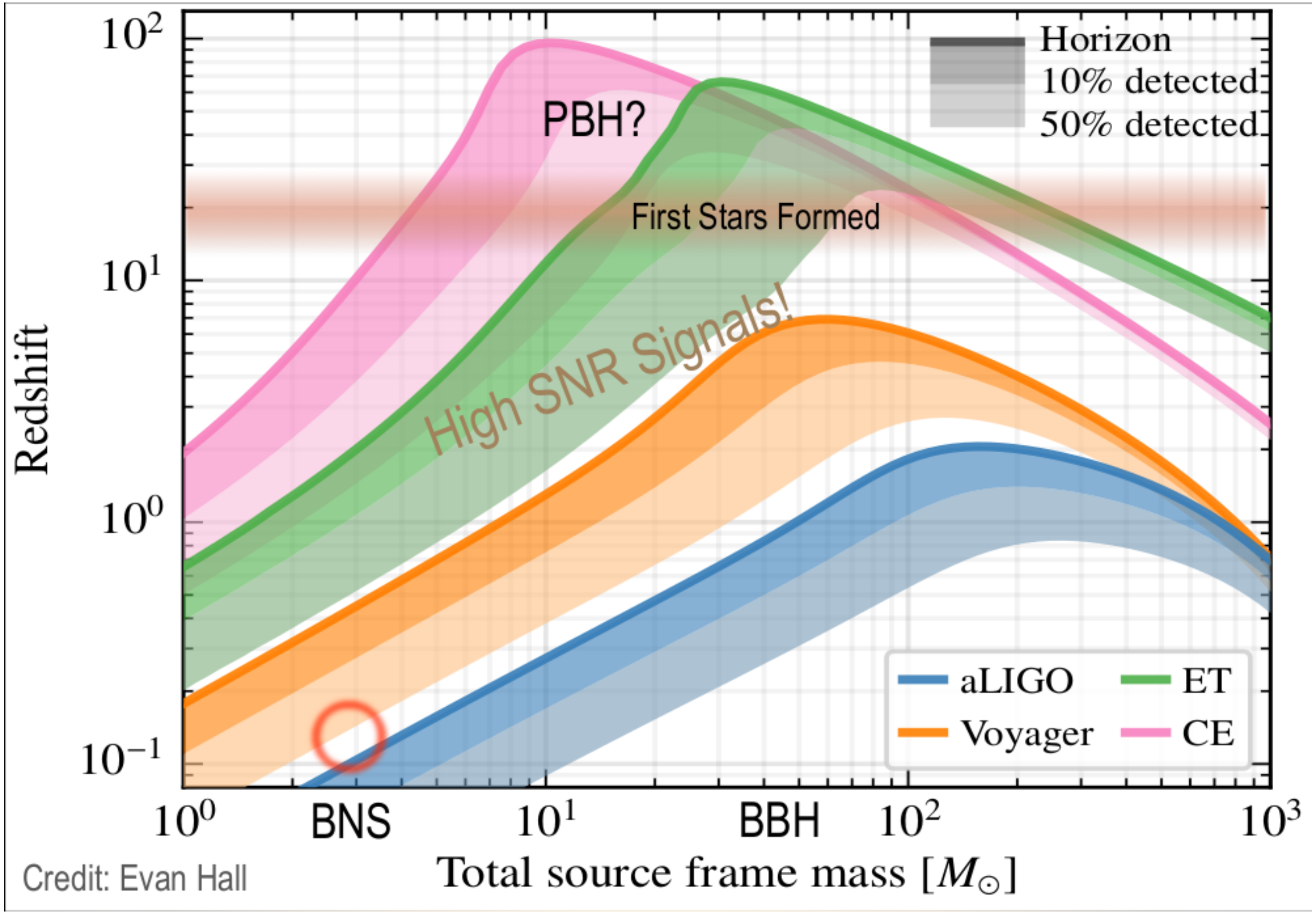
Table 2: Baseline parameters for present and future detector configurations

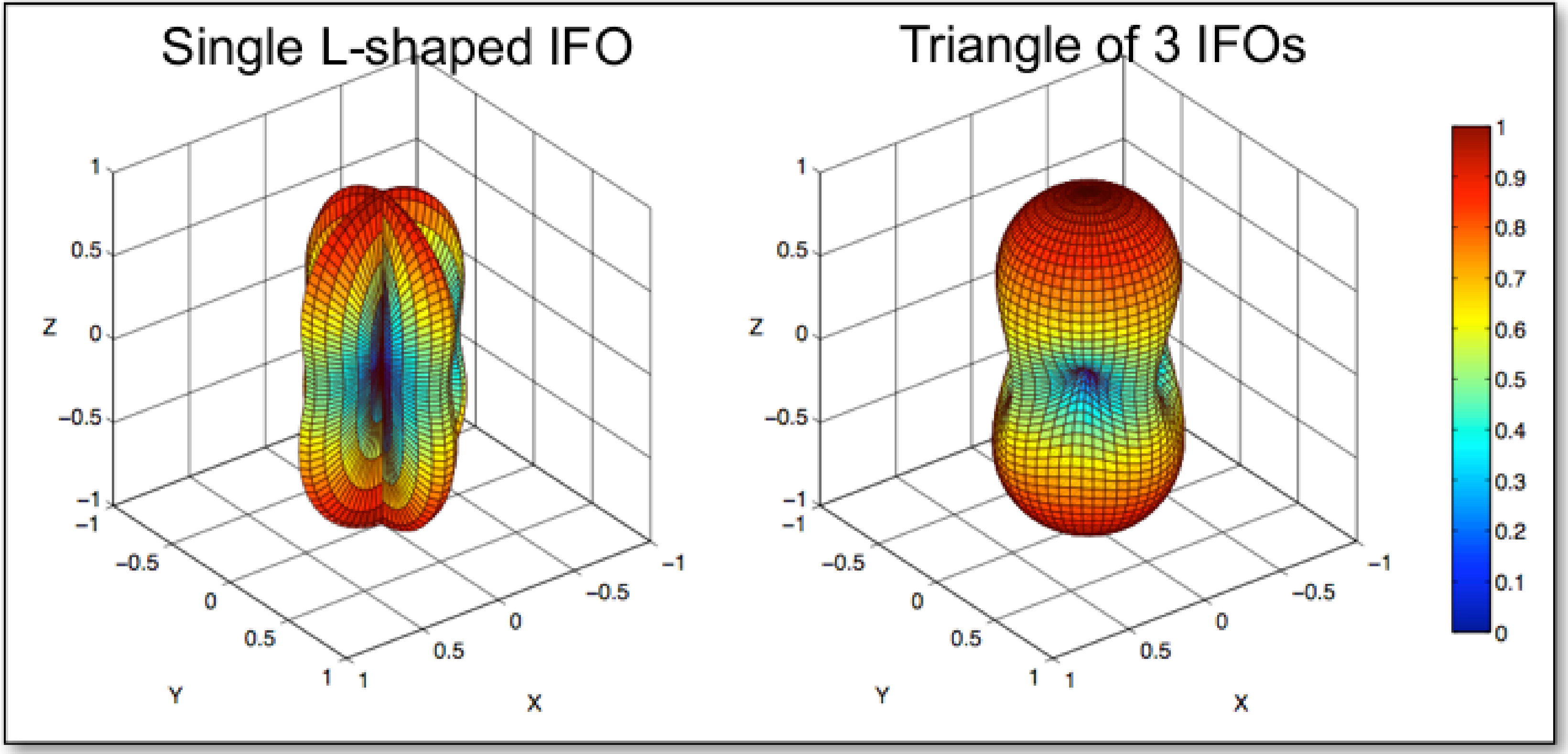


Cosmic Explorer (expected R&D improvements)
Strain [1/√Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}
Quantum
Seismic
Newtonian
Suspension Thermal
Coating Brownian
Coating Thermo-optic
Substrate Brownian
Excess Gas
Total noise
aLIGO
4km
ET-D
10km
20km
Cosmic Explorer (pessimistic R&D improvements)

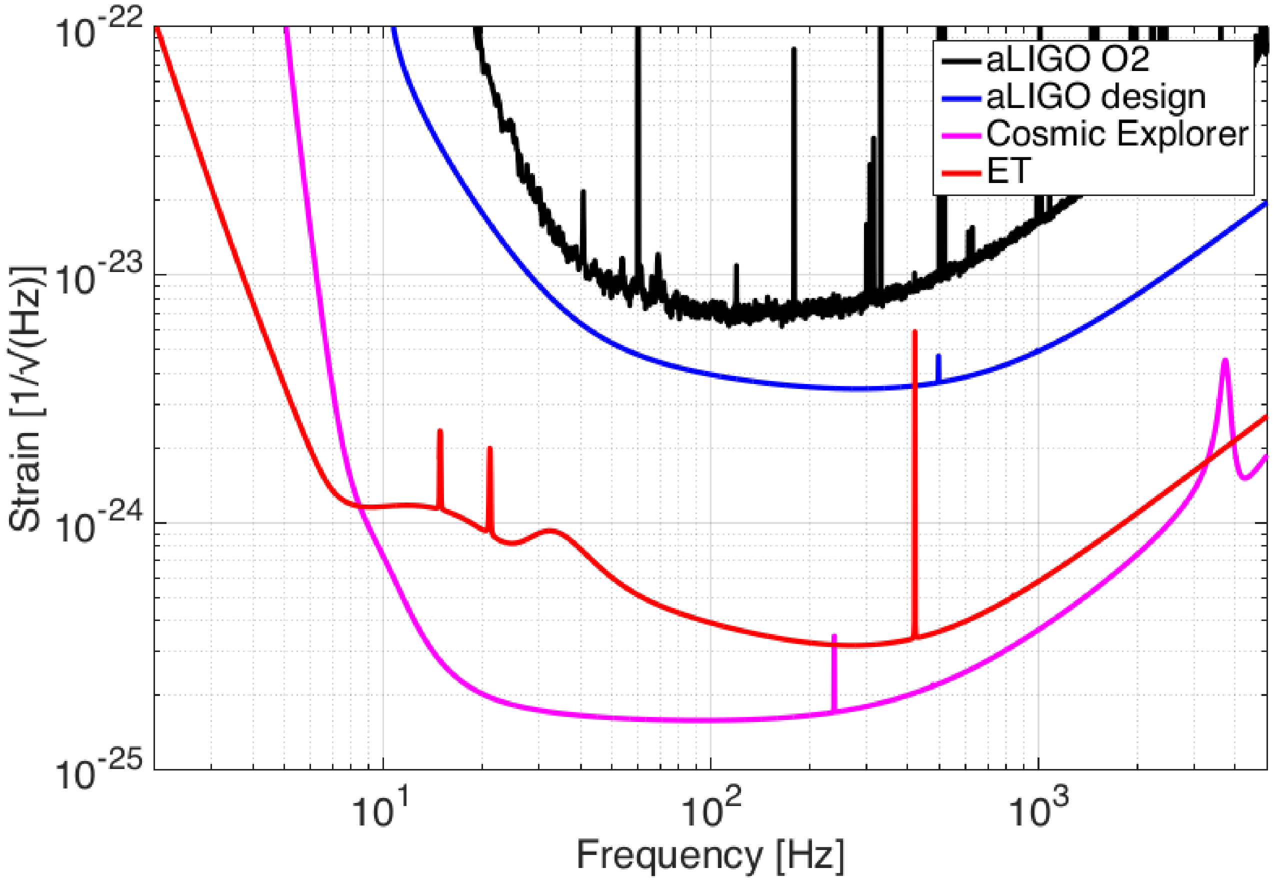


ET–B
ET–C (Xylophone)
ET–D (Xylophone)
Strain [1/sqrt(Hz)]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

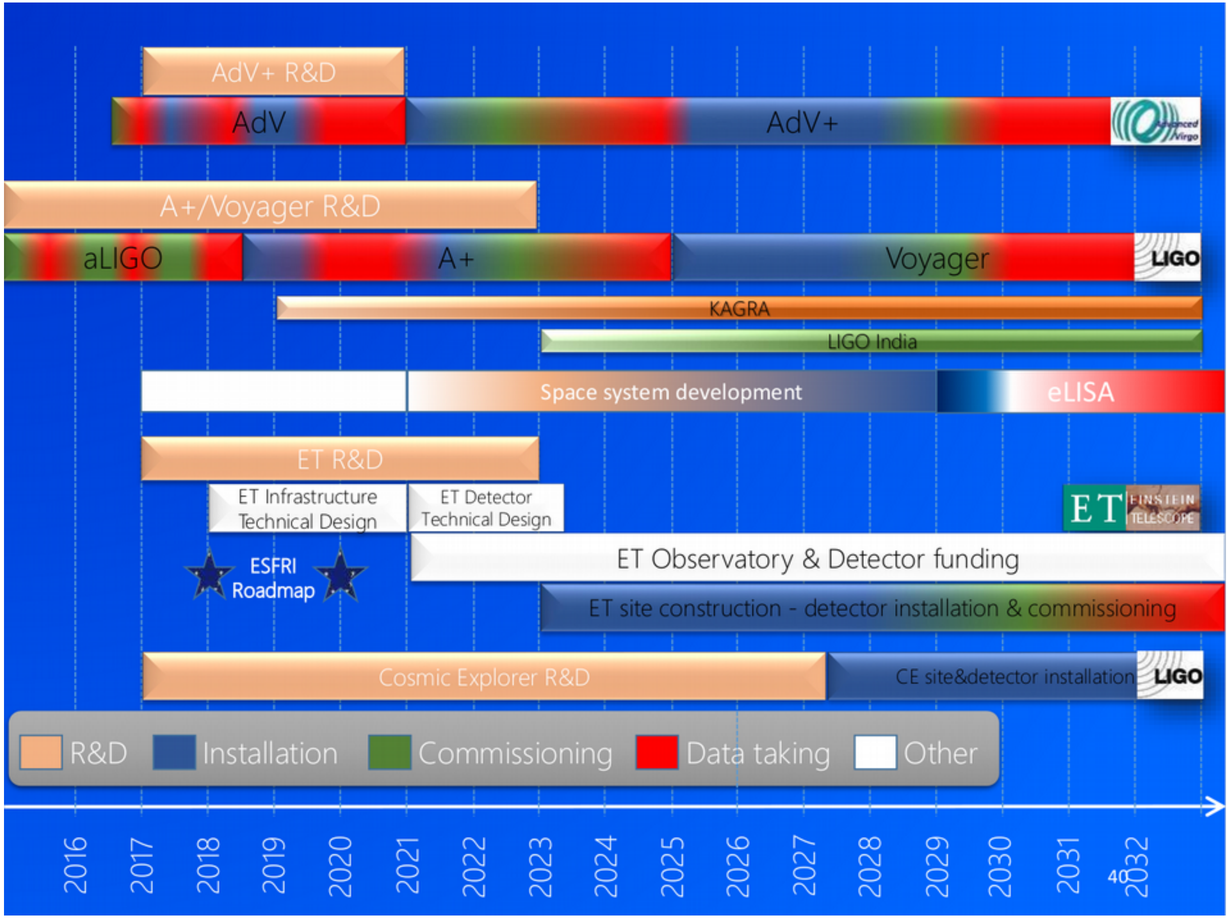

Horizon
10% detected
50% detected
PBH?
First Stars Formed
High SNR Signals!
aLIGO
ET
Voyager
CE
Redshift
10^2
10^1
10^0
10^{-1}
10^0
BNS
10^1
BBH
10^2
10^3
Total source frame mass [$M_\odot$]
Credit: Evan Hall



Freise, A.; Chelkowski, S.; Hild, S.; Pozzo, W. D.; Perreca, A. & Vecchio, A. *CQG*, **2009**, *26*, 085012 (14pp)



aLIGO O2
aLIGO design
Cosmic Explorer
ET
Strain [1/√(Hz)]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}


AdV+ R&D
AdV
AdV+
A+/Voyager R&D
aLIGO
A+
Voyager
LIGO
KAGRA
LIGO India
Space system development
eLISA
ET R&D
ET Infrastructure Technical Design
ET Detector Technical Design
ET EINSTEIN TELESCOPE
ESFRI Roadmap
ET Observatory & Detector funding
ET site construction - detector installation & commissioning
Cosmic Explorer R&D
CE site&detector installation
LIGO
R&D
Installation
Commissioning
Data taking
Other
2016
2017
2018
2019
2020
2021
2022
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2025
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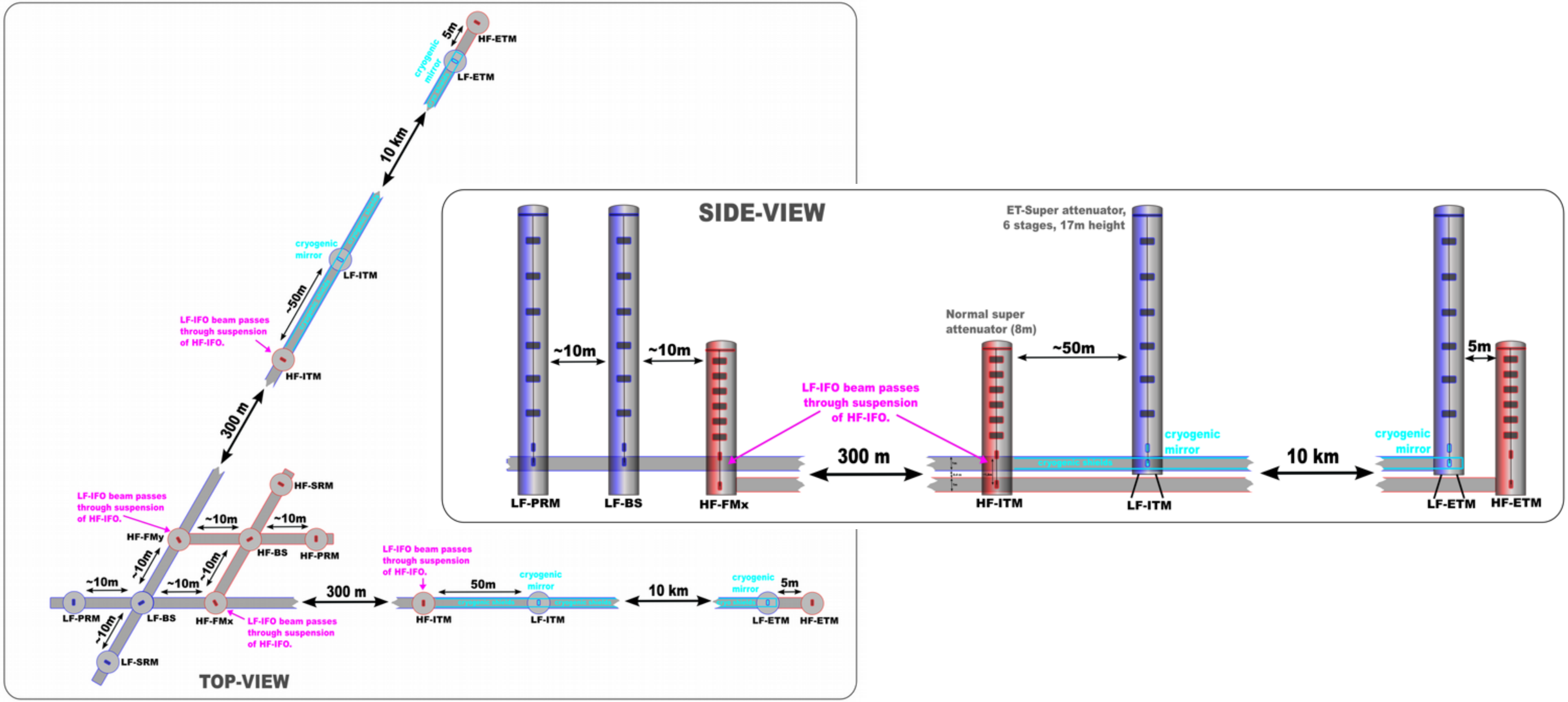
2030
2031
2032
40


SIDE-VIEW
ET-Super attenuator,
6 stages, 17m height
Normal super
attenuator (8m)
~10m
~10m
~50m
5m
LF-IFO beam passes
through suspension
of HF-IFO.
300 m
10 km
cryogenic
mirror
cryogenic
mirror
LF-PRM
LF-BS
HF-FMx
HF-ITM
LF-ITM
LF-ETM
HF-ETM
TOP-VIEW
HF-ETM
5m
cryogenic
mirror
LF-ETM
10 km
cryogenic
mirror
LF-ITM
~50m
LF-IFO beam passes
through suspension
of HF-IFO.
HF-ITM
300 m
HF-SRM
LF-IFO beam passes
through suspension
of HF-IFO.
~10m
~10m
HF-FMy
HF-BS
HF-PRM
~10m
~10m
~10m
~10m
LF-PRM
LF-BS
HF-FMx
LF-IFO beam passes
through suspension
of HF-IFO.
~10m
LF-SRM
300 m
LF-IFO beam passes
through suspension
of HF-IFO.
50m
cryogenic
mirror
10 km
cryogenic
mirror
5m
HF-ITM
LF-ITM
LF-ETM
HF-ETM

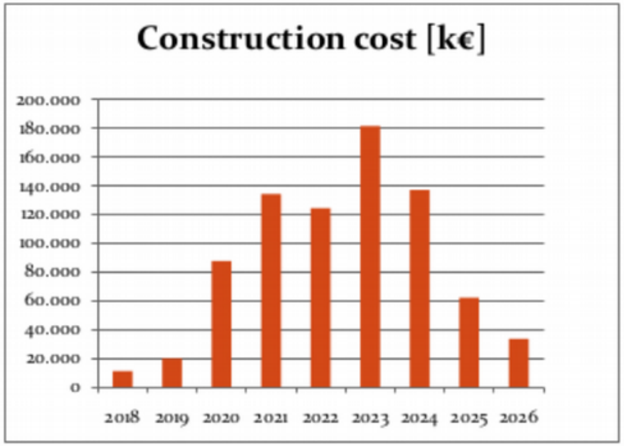
Costs

Figure 212: ET observatory cost summary and expenditure time distribution

ET Observatory Costs Evaluation

Configuration: Xylophone configuration, 30 km arm total length, 100 m underground

Total Construction (M€)	827
contingency	30%
Total with contingency	1075



IDsystem	System	Configuration	Option	Subtotal (k€)	2018	2019	2020	2021	2022	2023	2024	2025	2026	Subtot (M€)
1	Site	Xylophone - Triangular	=Baseline OR =Commo	591.746	5251	12011	79283	1E+05	1E+05	136102	84289	11691	4501	555
2	Vacuum	Xylophone - Single detector	=Baseline	169.864	5730	7800	6800	10210	10960	30566	38079	38079	21639	170
3	Cryogenics	Xylophone - Single detector	ALL	13.200	0	0	0	720	3880	2640	2640	3320	0	13
4	Suspensions	Xylophone - Single detector	<>	14.274	0	0	0	0	2211	2847,6	3973	2975	2267	14
5	Optics	Xylophone - Single detector	=Baseline	37.590	0	0	1400	4630	3644	9145,5	7949	5908	4915	38
			Construction Totals	826.674	10981	19811	87483	1E+05	1E+05	181302	1E+05	61973	33322	790,174