Third-generation detectors, plans & challenge

Andreas Freise

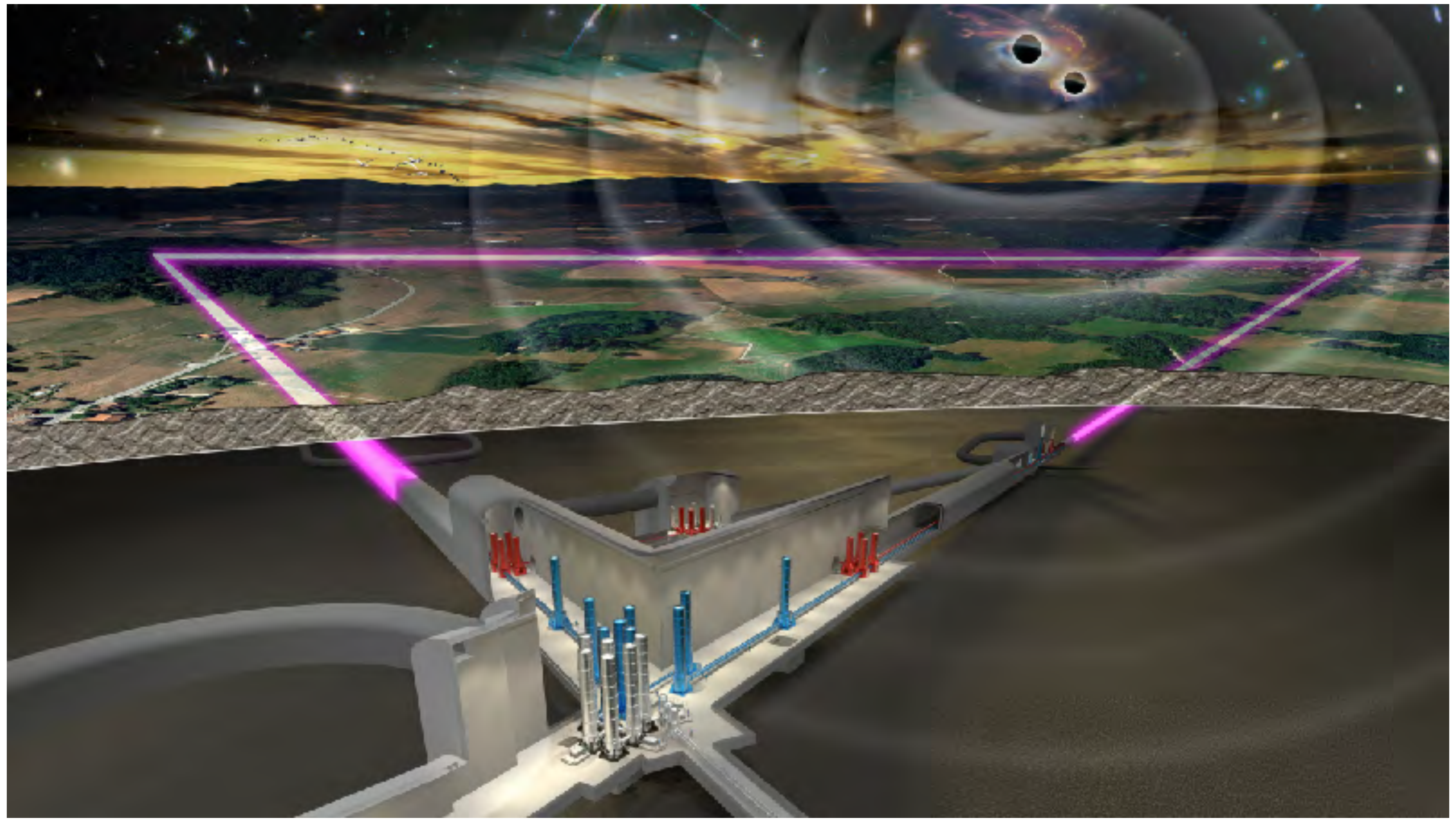
17.06.2021

ISAPP summer school 2021

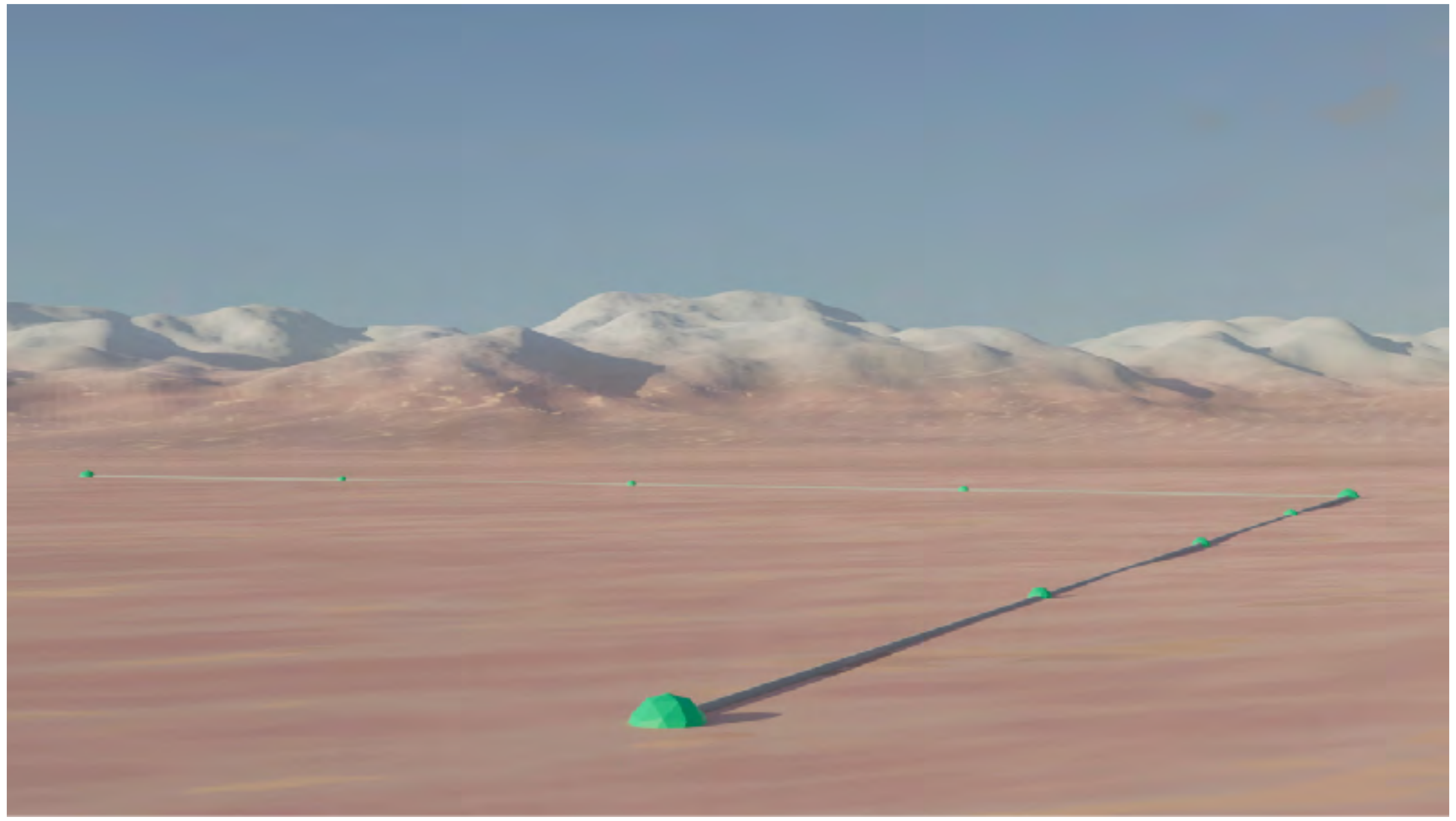
Visions and plans for your future

Third-generation GW observatories

- We expect to have a heterogeneous network of upgraded second-generation detectors, such as Advanced Virgo plus, and aLIGO+.
- 3G, or 'third-generation' typically refers to additional future ground-based observatories in new infrastructures with significant better sensitivity than current observatories.
- Note that these `generations' are not defined very precisely and not always used to mean the same.
- Most of the following material is related two planned projects:



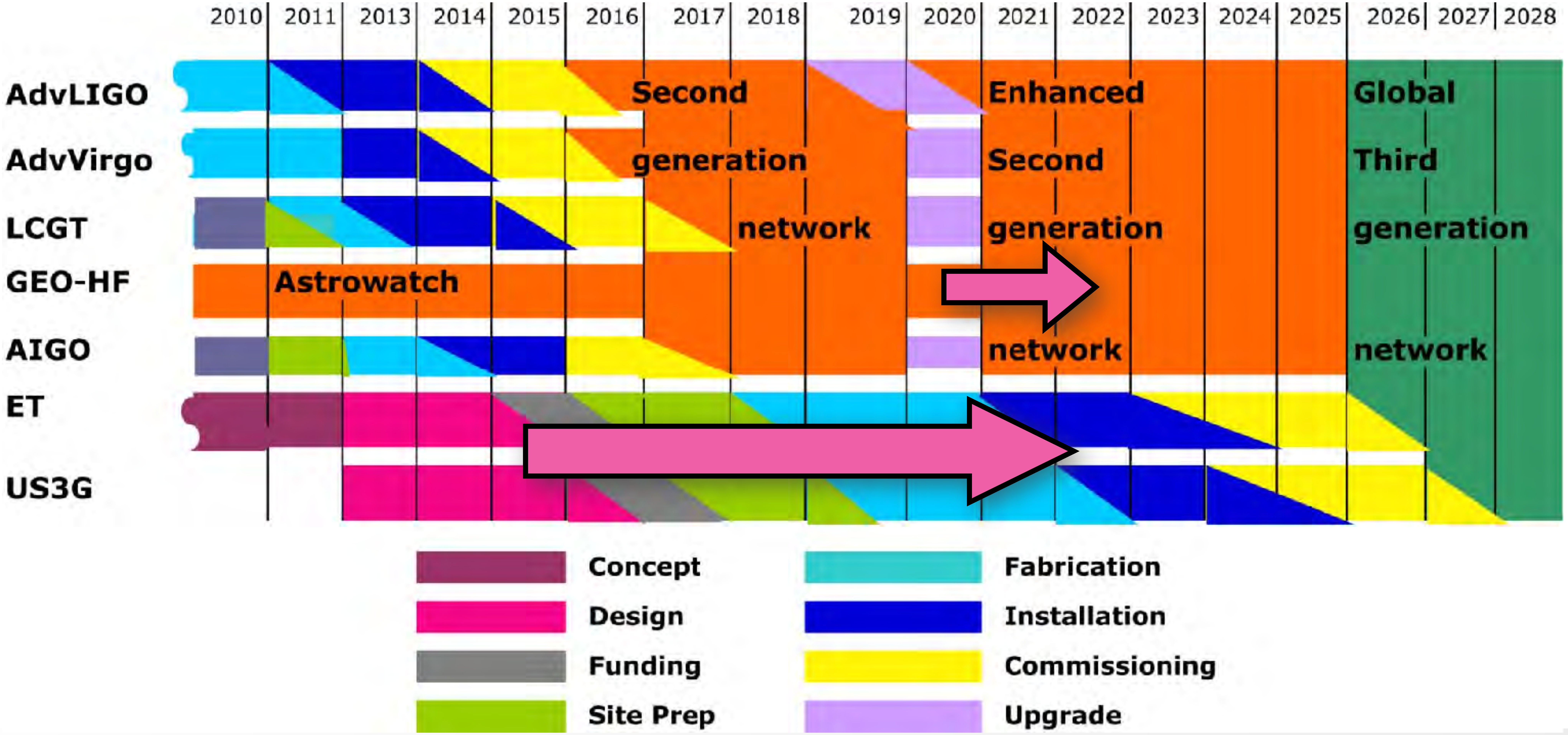
Einstein Telescope (ET)
underground, 10 km, in Europe



Cosmic Explorer (CE)
on surface, 40 km, in the US

International collaboration

- The Gravitational Wave International Committee (GWIC) roadmap, **June 2010**



https://gwic.ligo.org/assets/docs/general/roadmap.pdf

GWIC 3G

- GWIC = Gravitational Wave International Committee

- Members are based on GW projects, include for example LIGO, Virgo, KAGRA, LISA, EPTA and also Matthew Evans for Cosmic Explorer (since 2019) and Michele Punturo for ET (since 2009).

- GWIC 3G = sub-committee `to undertake a study of Third generation detectors and how to get there, chaired by Michele Punturo and Dave Reitze'

- Sub-sub-committees: **Science Case**, **R&D Coordination Networking** among the ground-based GW community and other communities, **Agency interfacing** and advocacy and **Governance**.

- Sub-sub-sub-committees: ….

Dawn meetings

- Series of meetings started in 2015, looking at the future of the field of ground-based GW detection, first LIGO/US specific, now with a more global focus

- Report from Dawn IV, 30-31 August 2018:
  https://dcc.ligo.org/LIGO-P1900028/public
  `In order to maximize the scientific output of the global network of detectors, we propose as a future goal a network of three 3G detectors; potentially an Einstein Telescope in Europe, a Cosmic Explorer in the US, and a third 3G detector in a location that maximizes the sky localization ability of the network.'

- Most recent meeting: Dawn V on Global Strategies for Gravitational Wave Astronomy: 26-27 May 2019 in Cascina, Italy

- Since then ET and CE have seen progress as individual projects. Global coordination and communication somewhat delayed due to Covid.

Case for third-generation detectors

New observatories instead of further upgrades?

- Ground-based GW observatories are currently being upgraded. Project pans exist up to the O5 observing run, planned for **2025-2027**.
- Discussions have started to plan further upgrades of existing detectors in the **post-O5 period**.
- However, eventually the benefits of such upgrades will be **limited by the facilities** (length of the arms, space in the building, environmental noise of the site, paging material)
- New observatories hope to use much **greater arm lengths**, which is not possible in the current locations.
- New locations allow potentially joint observation by a network of 3G and 2G detectors.

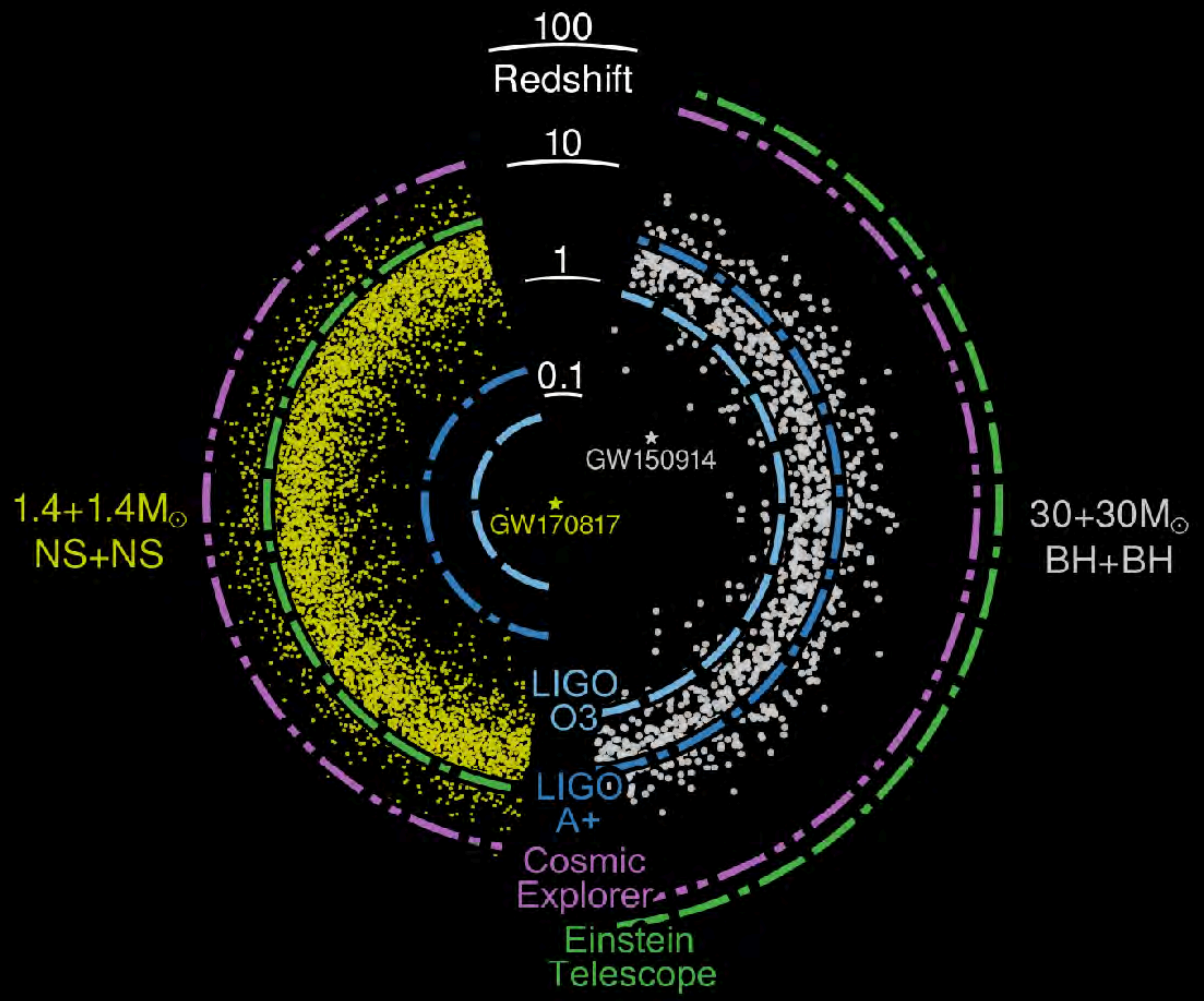


Image by Evan Hall and Salvatore Vitale, see also https://arxiv.org/abs/1907.04833

Star formation rates across the universe

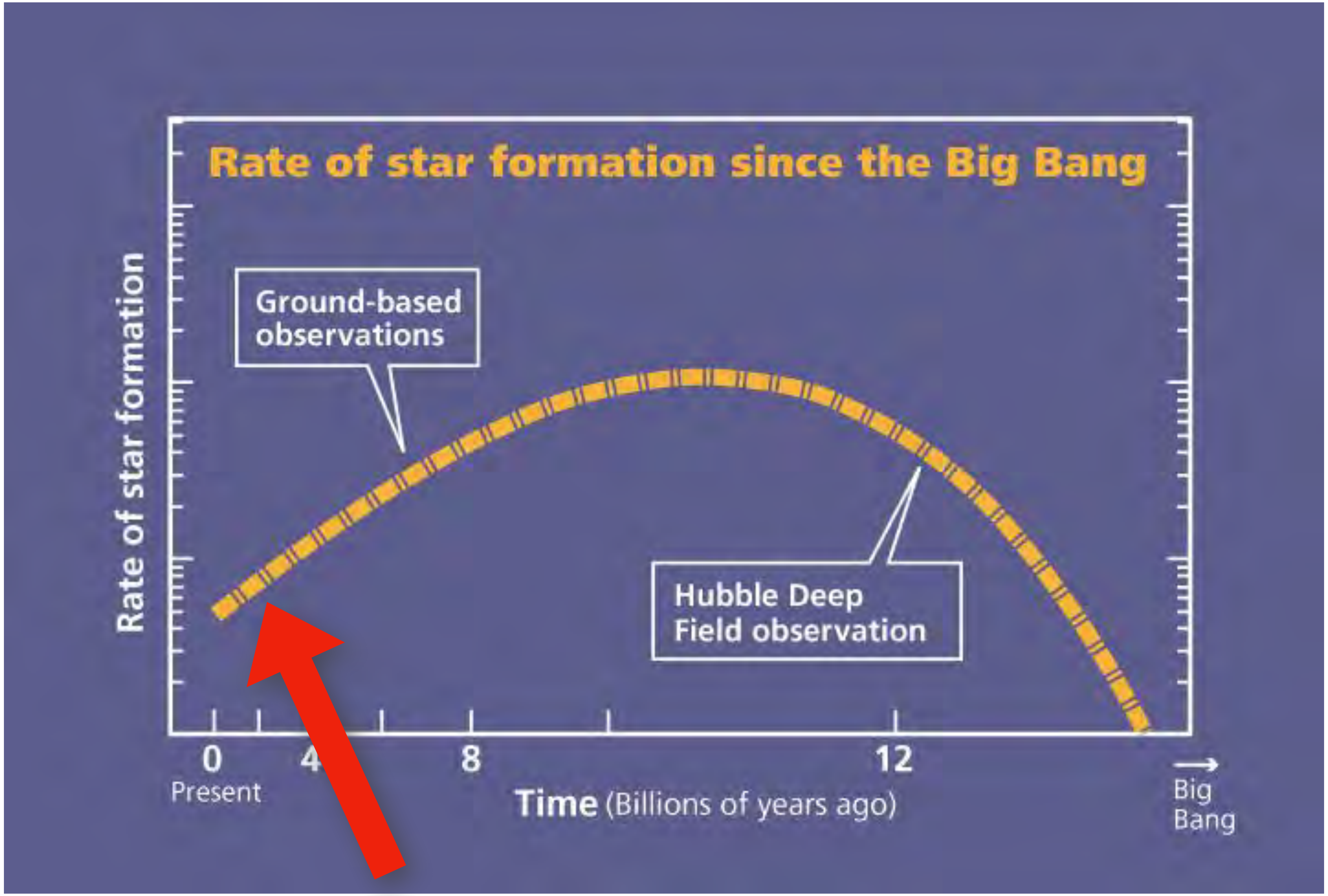
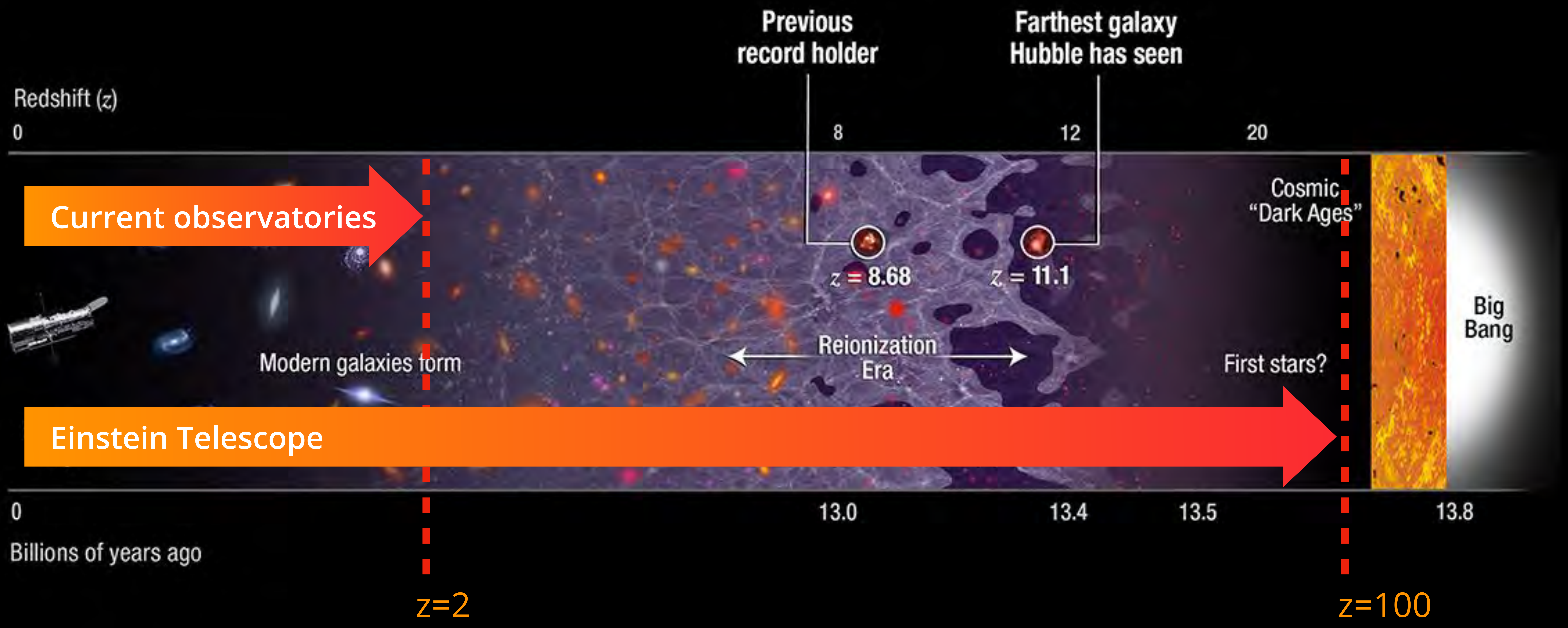


Image: NASA and the Space Telescope Science Institute (STScI)
https://hubblesite.org/image/710/news/85-survey

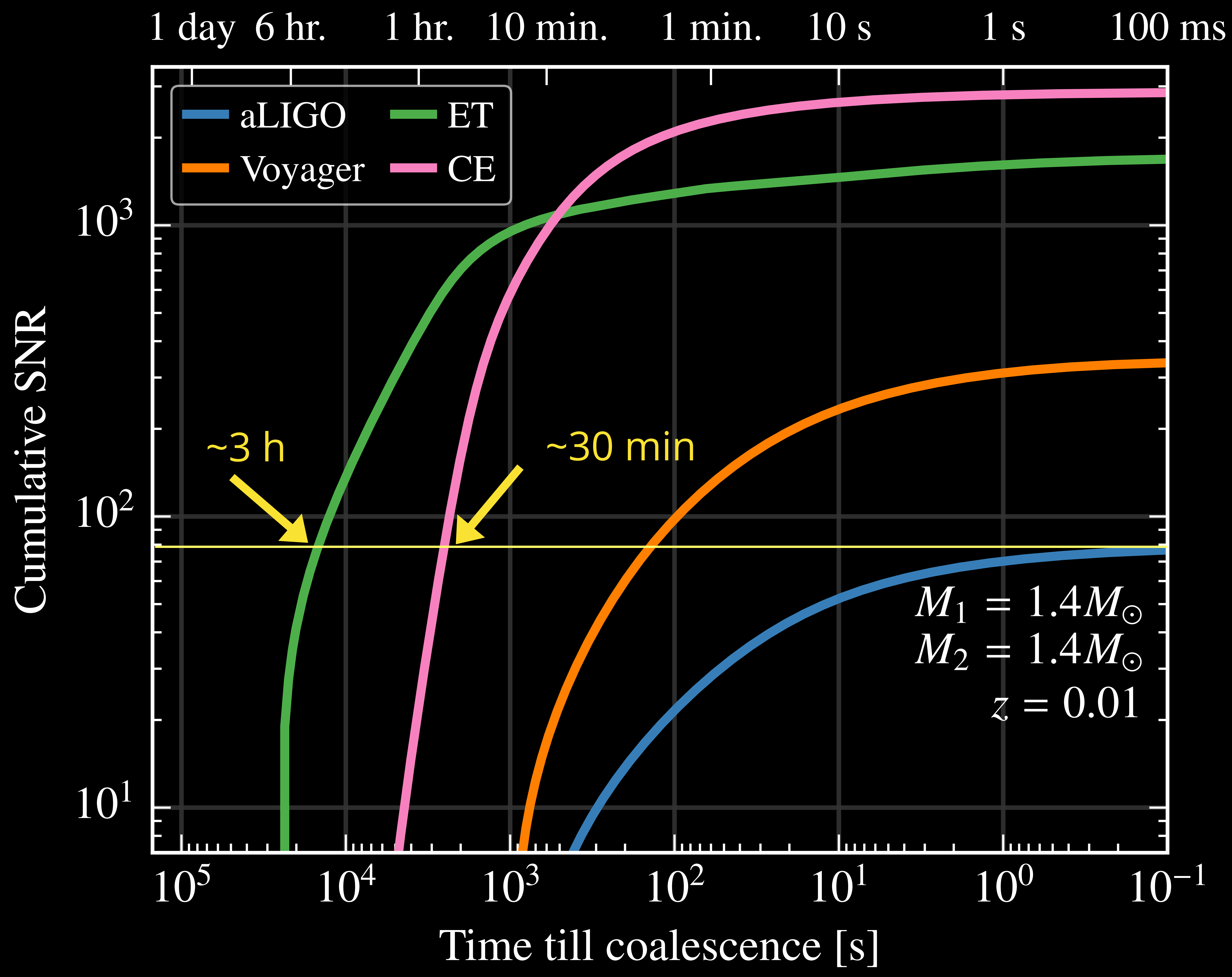
The case for future GW observatories



Early star formation, primordial black holes, seeds of supermassive black holes, standard-sirens to measure Hubble constant to much earlier ages ...

[Credits: NASA, ESA, P. Oesch and B. Robertson (University of California, Santa Cruz), and A. Feild (STScI)]

Set the alarms for astronomers



Credit: Evan Hall

Structure of Neutron Stars

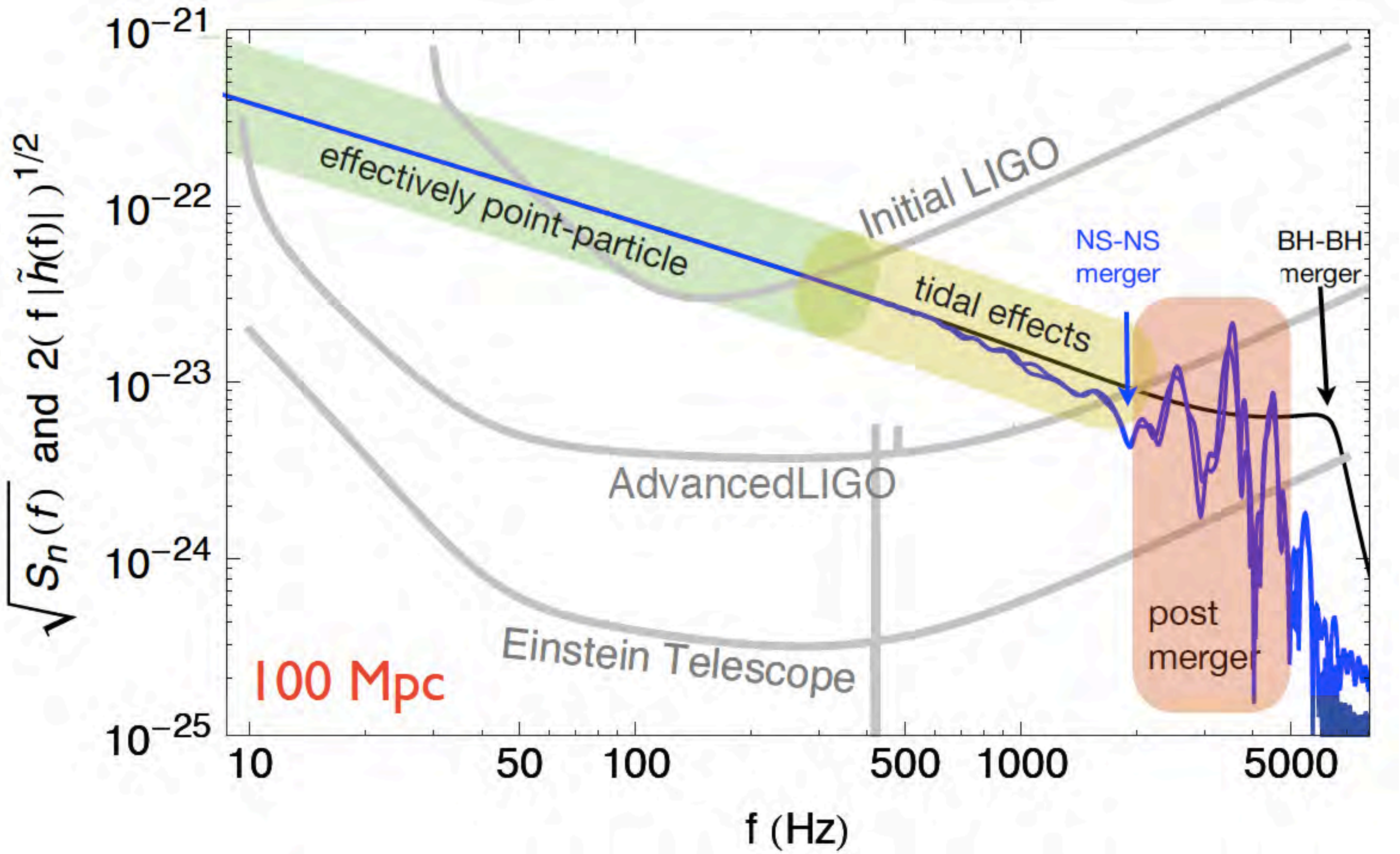
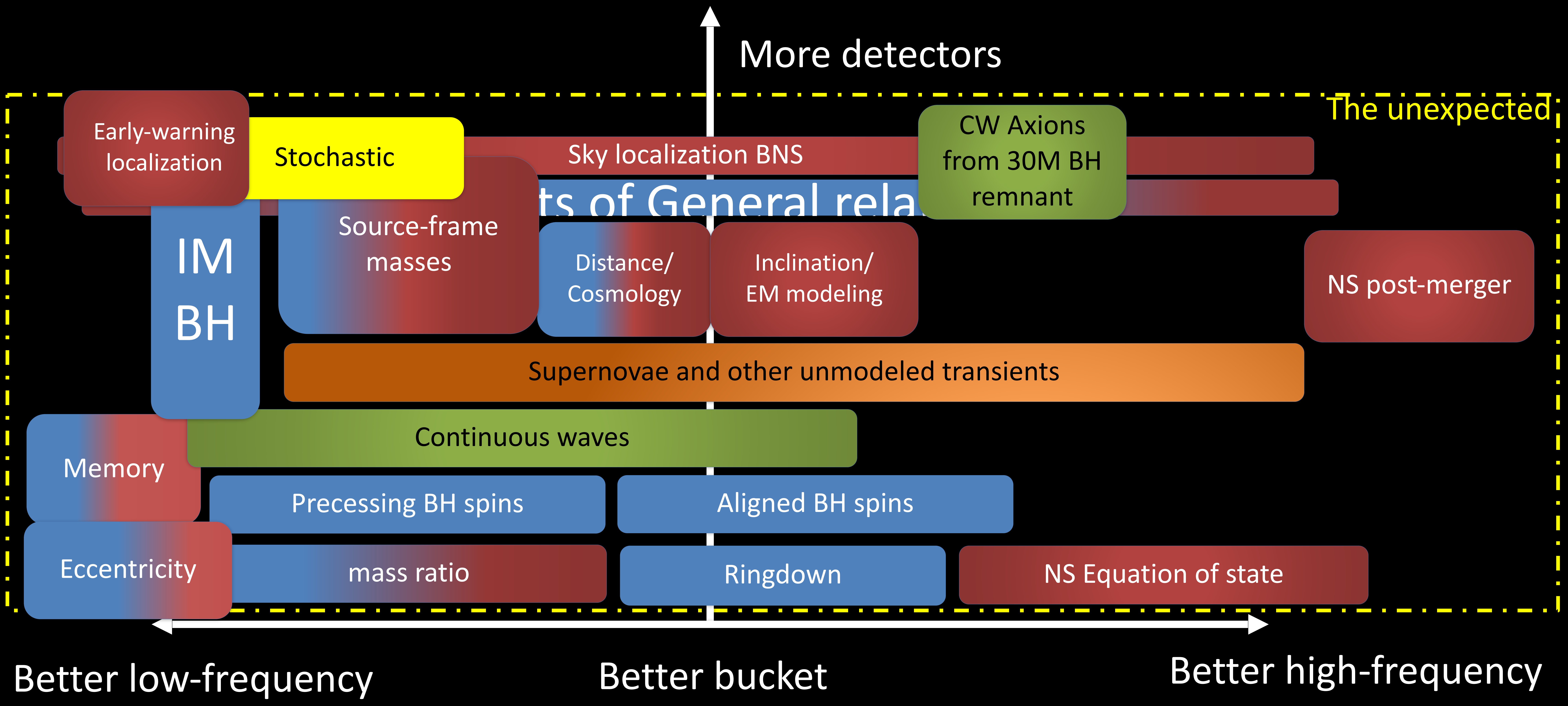


Figure by Jocelyn Read, see also arXiv:1306.4065

Nikhef VU VRIJE UNIVERSITEIT AMSTERDAM

New detectors!
How many? Where?

Low/High frequency - Network size trade off

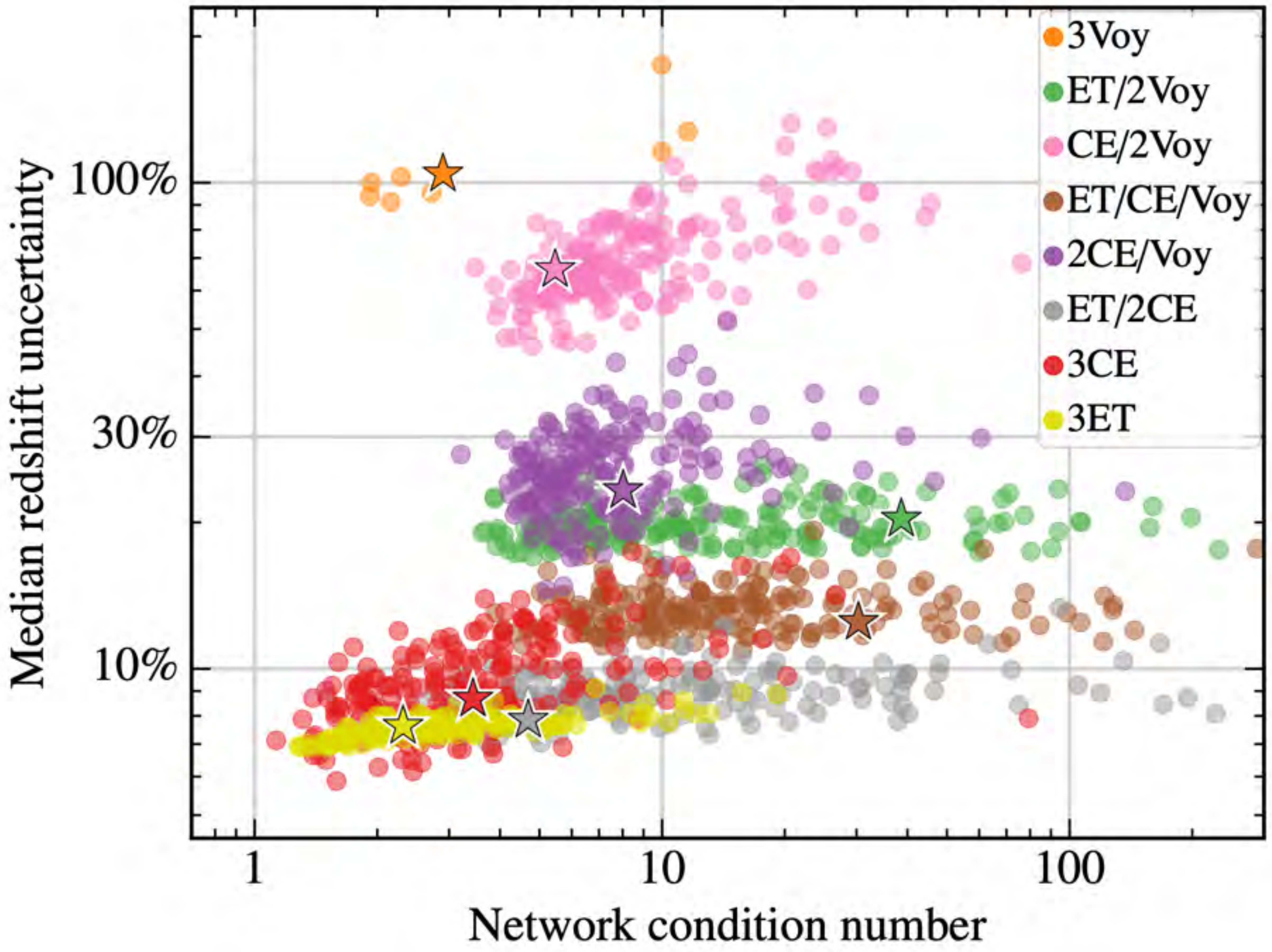


[Salvatore Vitale, https://dcc.ligo.org/G1900660]

Shape and size of networks

Code	Location	Lat.	Long.	θ_{XE}
H	Hanford, USA	46.5	−119.4	126
L	Livingston, USA	30.6	−90.8	−162
V	Pisa, Italy	43.6	10.5	71
I*	India	14.2	76.4	45
K	Kamioka, Japan	36.4	137.3	28
E*	Europe	47.4	8.5	11
A*	Western Australia	−31.5	118.0	−58
U*	Utah, USA	40.8	−113.8	−30

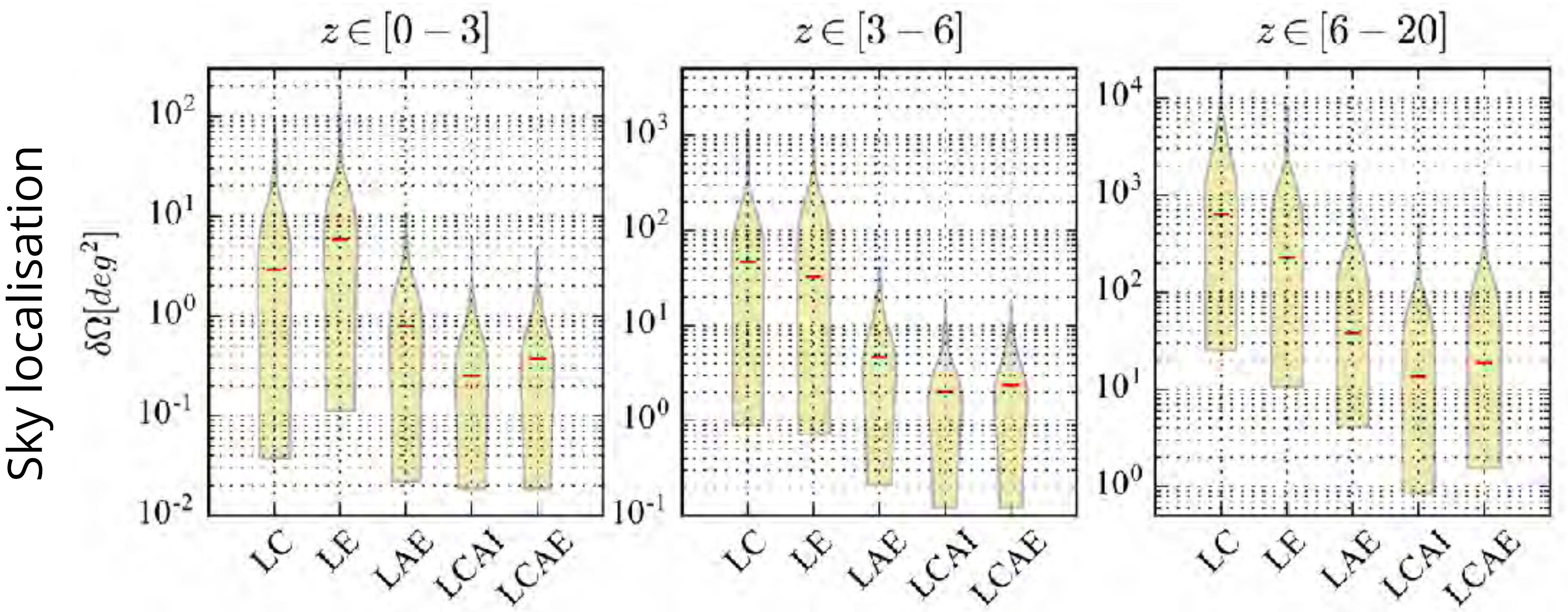
Network	H	L	V	I	K	E	A	U
HLV	aL	aL	AdV	—	—	—	—	—
3Voy	Voy	—	Voy	Voy	—	—	—	—
ET/2Voy	—	Voy	—	—	Voy	ET	—	—
CE/2Voy	—	—	Voy	—	Voy	—	—	CE
ET/CE/Voy	—	—	—	Voy	—	ET	—	CE
2CE/Voy	—	—	—	—	Voy	—	CE	CE
ET/2CE	—	—	—	—	—	ET	CE	CE
3CE	—	—	—	—	—	CE	CE	CE
3ET	—	—	—	—	—	ET	ET	ET



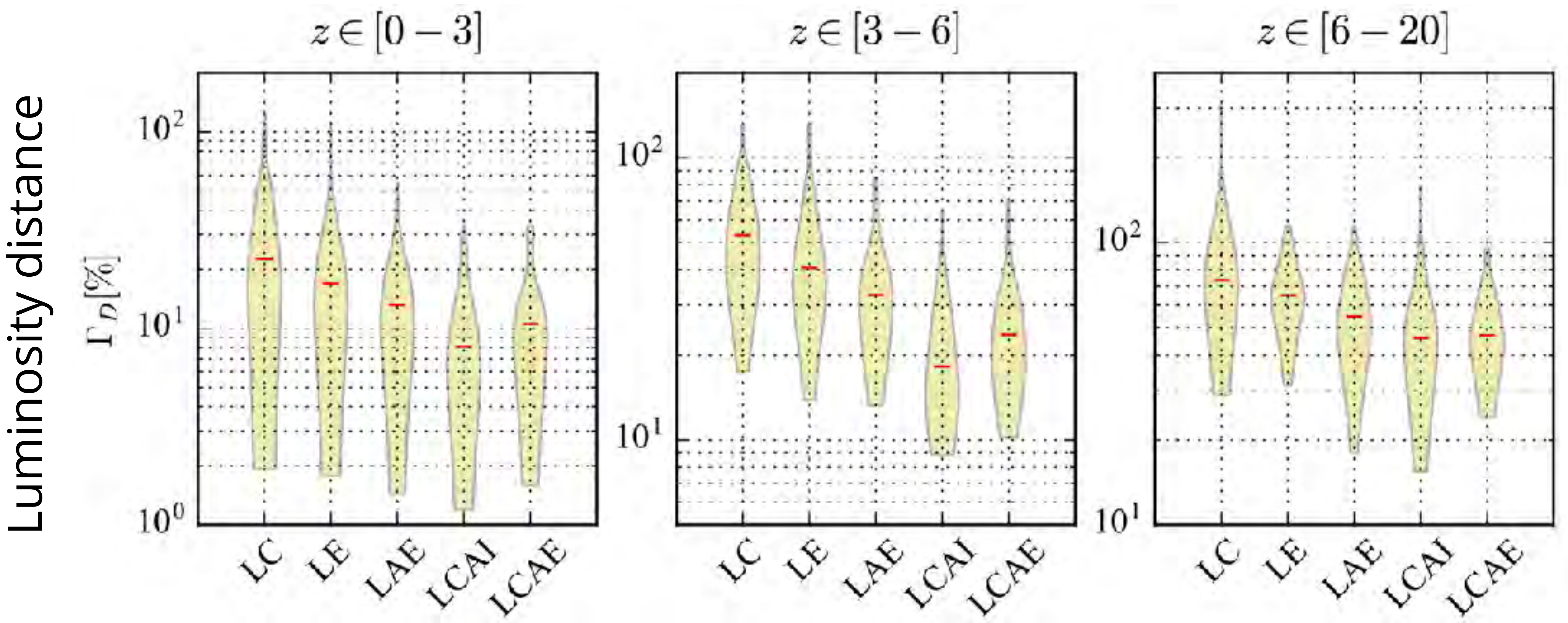
Redshift uncertainty (z=2, M1=M2=30M_{sun})

`we conclude that when designing a three-facility next-generation network, one must think carefully about which detectors should comprise the network. However, one has a great deal of freedom to choose the locations and orientations of the facilities.'

Network effects on parameter estimation errors



	Longitude	Latitude	Orientation	Type	
L	-1.58	0.533	2.83	CE	US
C	1.82	0.67	1.57	CE	China
I	1.34	0.34	0.57	CE	India
E	0.182	0.76	0.34	ET	Europe
A	2.02	-0.55	0	CE	Australia



https://doi.org/10.1103/PhysRevD.95.064052

Cosmic Explorer

Cosmic Explorer (CE) is a US-based concept for a third-generation ground-based GW observatory.

Current status: three-year horizon study, funded by the NSF, 2018–2021, by Caltech, Cal State Fullerton, Penn State, Syracuse and MIT (results will be published soon) .

www.cosmicexplorer.org

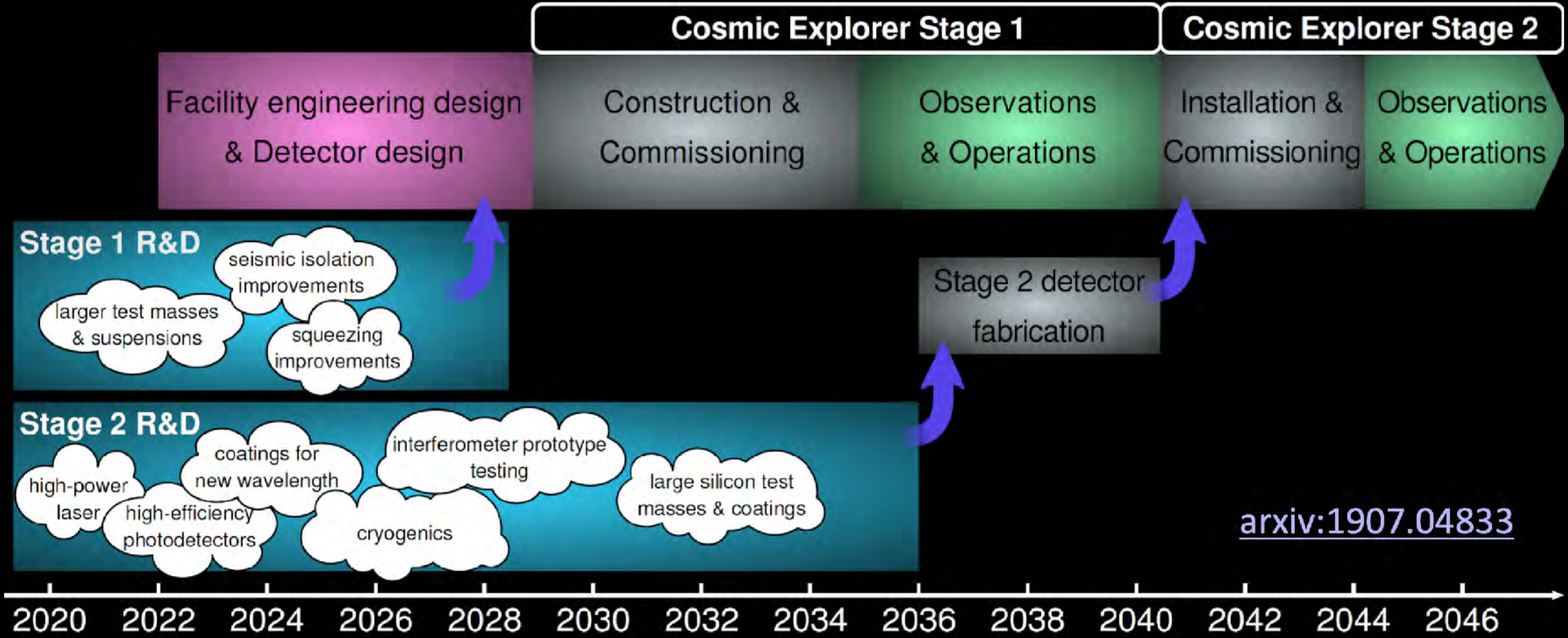
[Matt Evans]

CE baseline

- The Cosmic Explorer concept consists of **two widely-separated L-shaped observatories** in the United States, they are facilities on the **surface**, one with **40 km long** arms and another with **20 km** arms. Their instrumentation is based on the well-known dual-recycled **Fabry–Perot Michelson interferometer** configuration**.**

- **First observations planned for 2035**. The expected minimum **lifetime of the infrastructure is 50 years**, the interferometers installed in the Cosmic Explorer observatories will evolve as the technologies and science evolve.

Timeline for Cosmic Explorer (very funding dependent!)



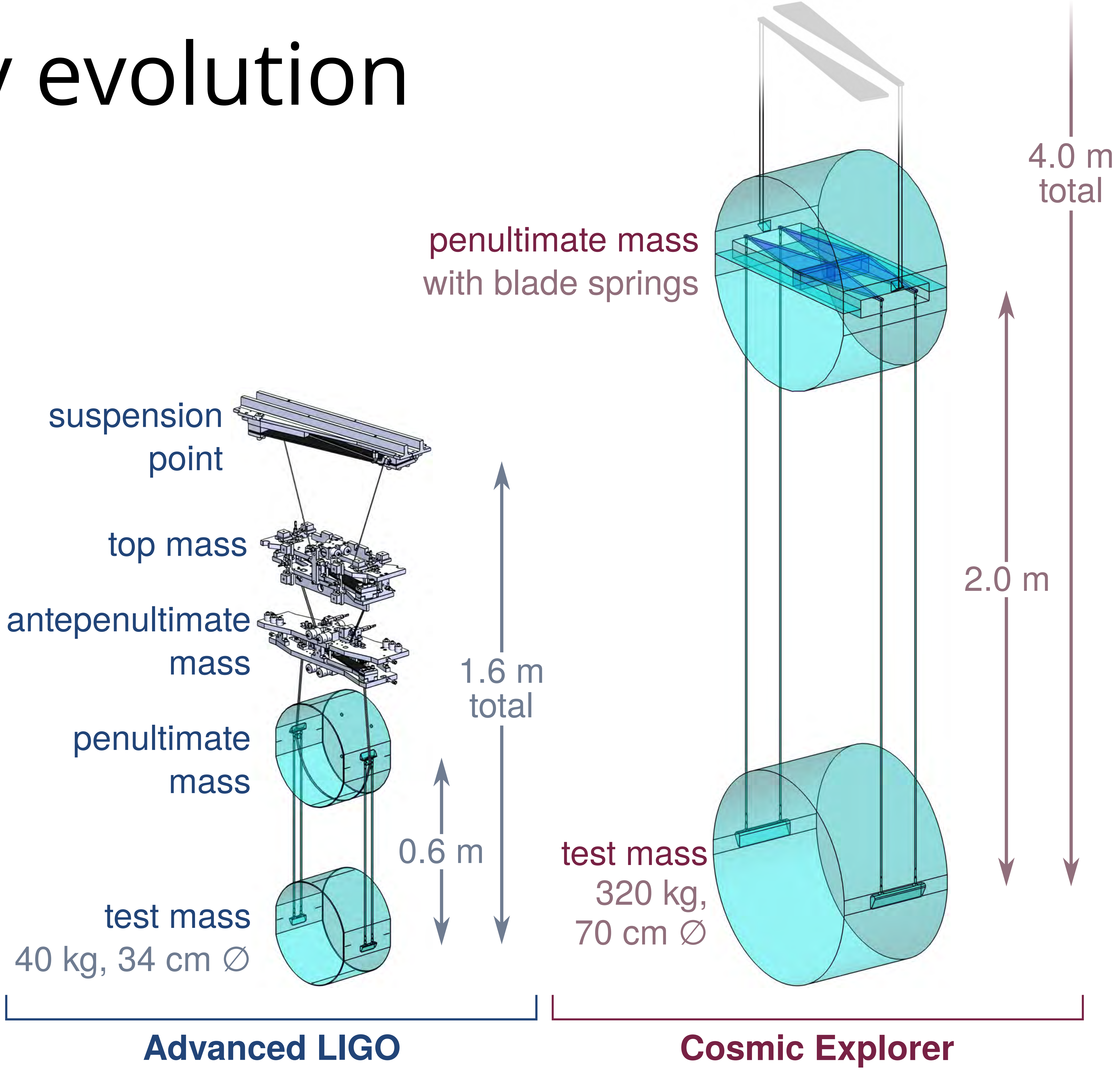
arxiv:1907.04833

[Matt Evans]

Potential technology evolution

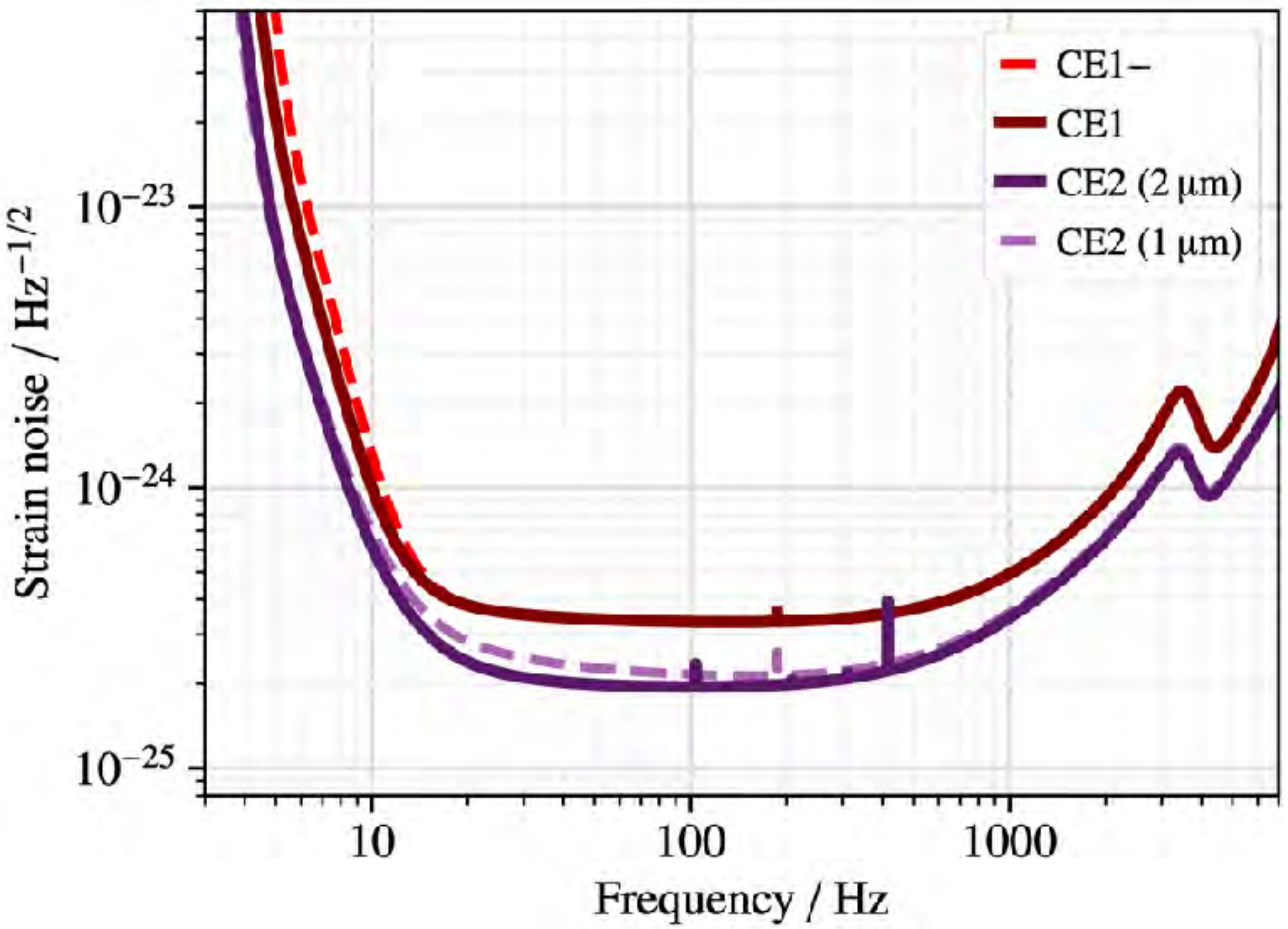
Example: Mirror suspension

- aLIGO+: 1μm, 0.8MW, 6dB squeezing
- CE: 1μm, 1.5MW, 10dB squeezing (or 2μm, 3MW, 10dB squeezing)



https://arxiv.org/abs/2012.03608

Design evolution and design options

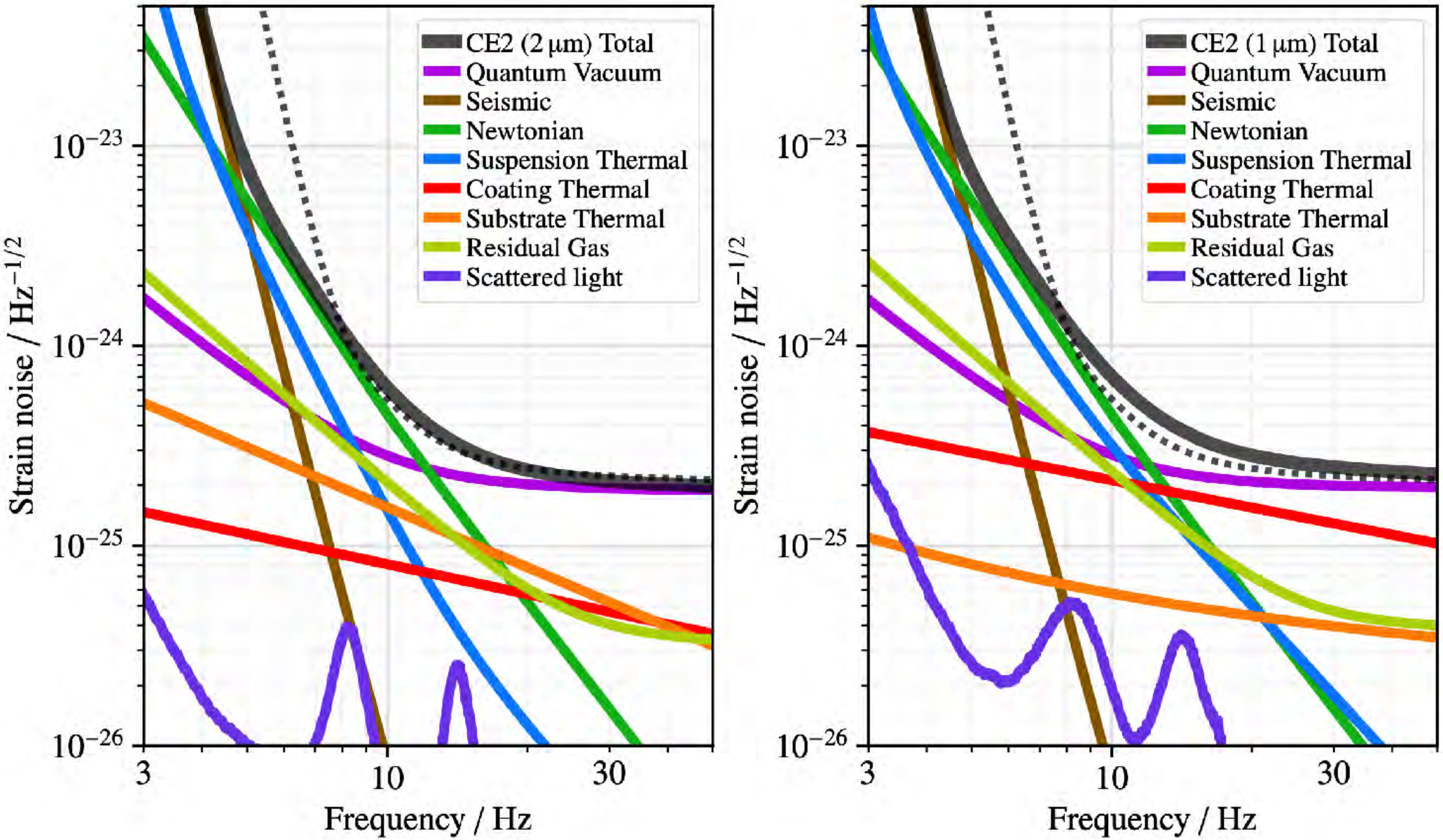


Quantity	Units	CE1–	CE1	CE2 (1 μm)	CE2 (2 μm)
Arm power	MW	1.5	1.5	1.5	3
Wavelength	μm	1	1	1	2
Squeezing	dB	6	6	10	10
Material		Silica	Silica	Silica	Silicon
Temperature	K	293	293	293	123
Final stage blade		No	Yes	Yes	Yes
Rayleigh wave suppr.		None	2×	10×	10×
Body wave suppr.		None	None	3×	3×
Susp. point at 1 Hz	pm $Hz^{-1/2}$	10	1	0.1	0.1
Coatings		A+	A+	A+	Voyager
ITM spot size	cm	12	12	12	16
ETM spot size	cm	12	12	12	16

- Design study to explore different technology options towards the sensitivity target
- CE1: achieve significantly higher sensitivities than the second generation detectors mostly using the existing technology developed for LIGO A+
- CE2: further significant improvement possible with two different technology options

https://arxiv.org/abs/2012.03608

Similar sensitivity with different technology options (CE2)



https://arxiv.org/abs/2012.03608

Required technology development for the CE2 options

1μm

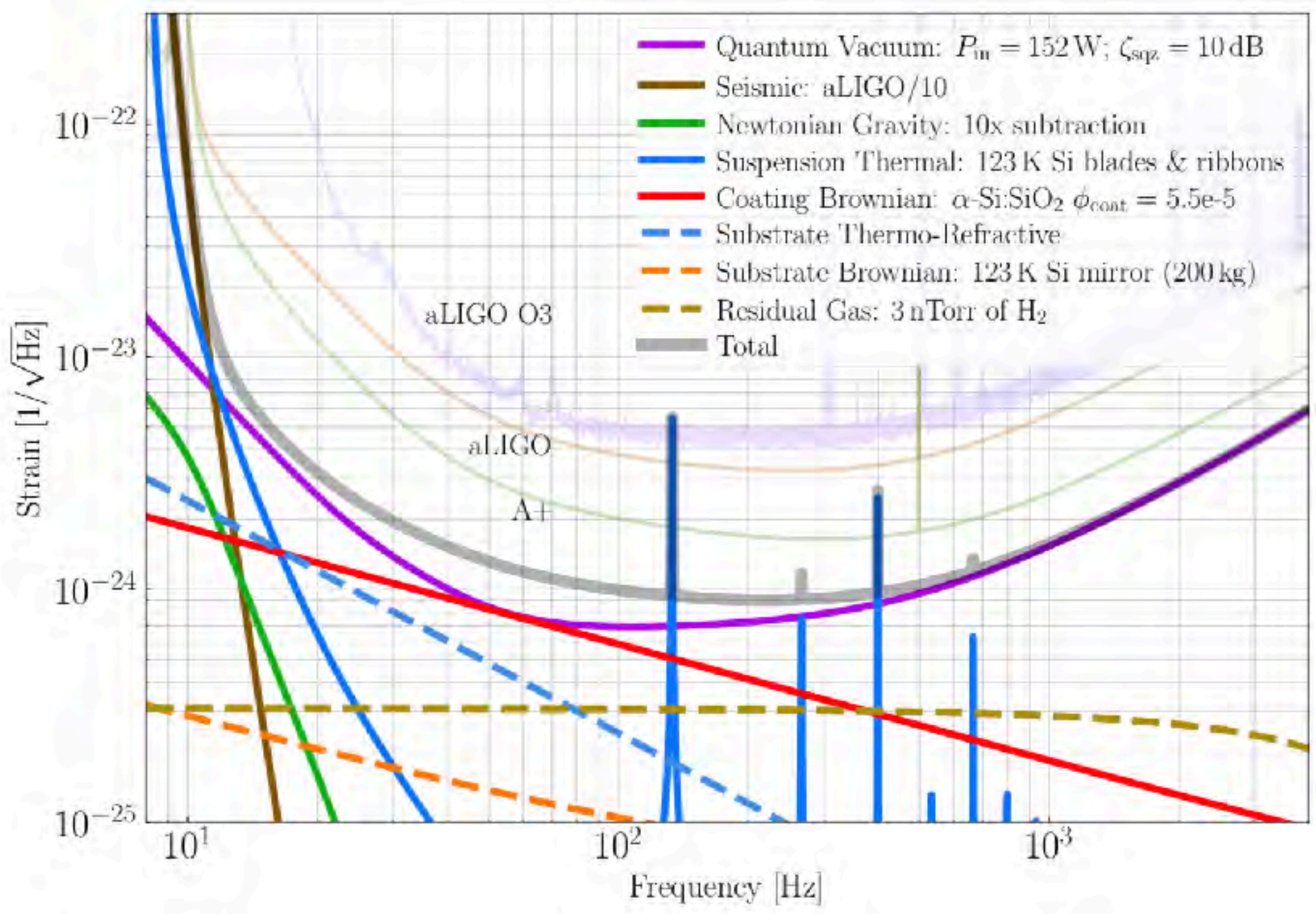
- Silica test mass, 70 cm ⌀; low impurity
- Silica blade springs with 800 MPa of tensile stress
- A+ coatings over 70 cm ⌀
- FD squeezing down to 5 Hz: 6 dB for CE1; 10 dB for CE2
- 1.5 MW arm power
- Mitigation of point absorbers

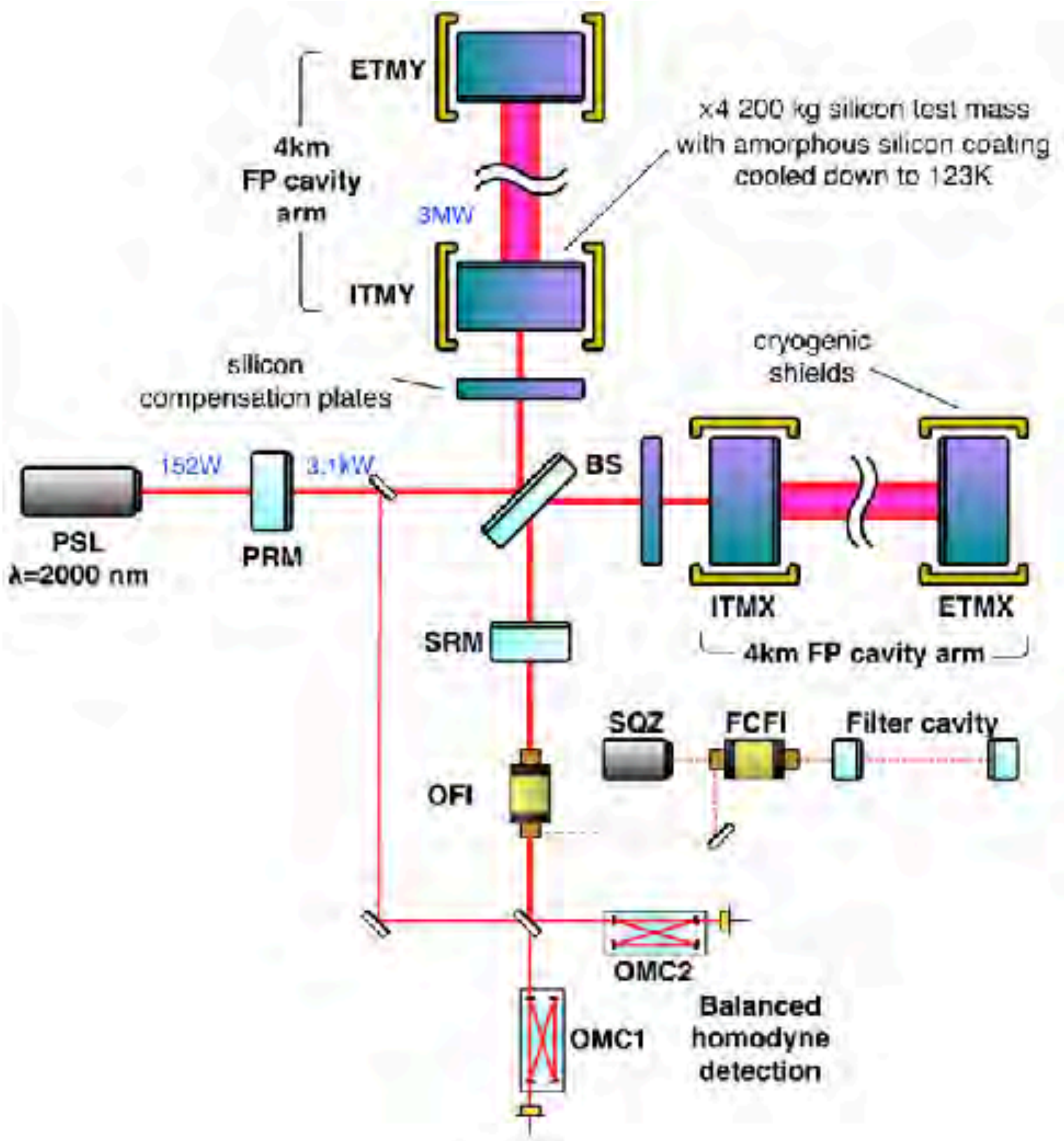
2μm

- Silicon test mass, 80 cm ⌀; low impurity
- Silicon ribbons and blade springs with 400 MPa of tensile stress
- Voyager coatings over 80 cm ⌀
- 10 dB FD squeezing down to 5 Hz
- High quantum efficiency photodiodes
- 3.0 MW arm power
- 123 K cryogenics

Kevin Kuns, see also https://arxiv.org/abs/2012.03608

Voyager: exploiting the LIGO facility





`A Cryogenic Silicon Interferometer for Gravitational-wave Detection'

https://arxiv.org/abs/2001.11173

UNIVERSITY OF BIRMINGHAM

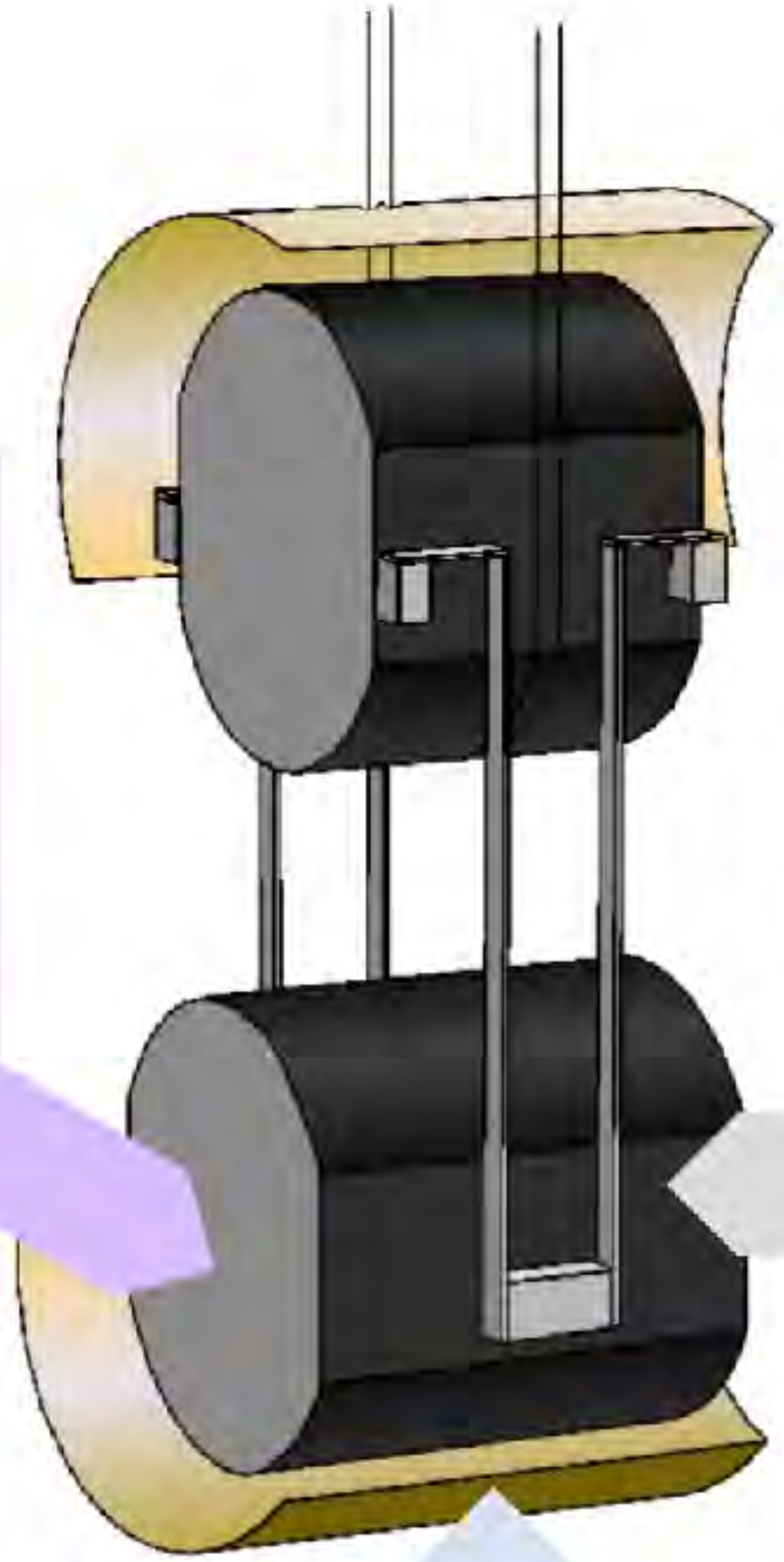
Nikhef

VU VRIJE UNIVERSITEIT AMSTERDAM

Voyager

[Adhikari et al, CQG 37 165003 (2020)](#)

Potential high-tech upgrade of LIGO observatories, research and development for 3G observatories



① Amorphous silicon coating
- Reduces coating noise. Prospect of a **4–7x** reduction from aLIGO level
- Favors **2 µm** wavelength

② Crystalline silicon substrate
- Improves quantum noise. **200 kg** mass, **3 MW** power
- High thermal conductivity, ultra-low expansion at **123 K**

③ Radiative cooling
- Remains efficient at **123 K**
- Suspension design not constrained* by cryogenics

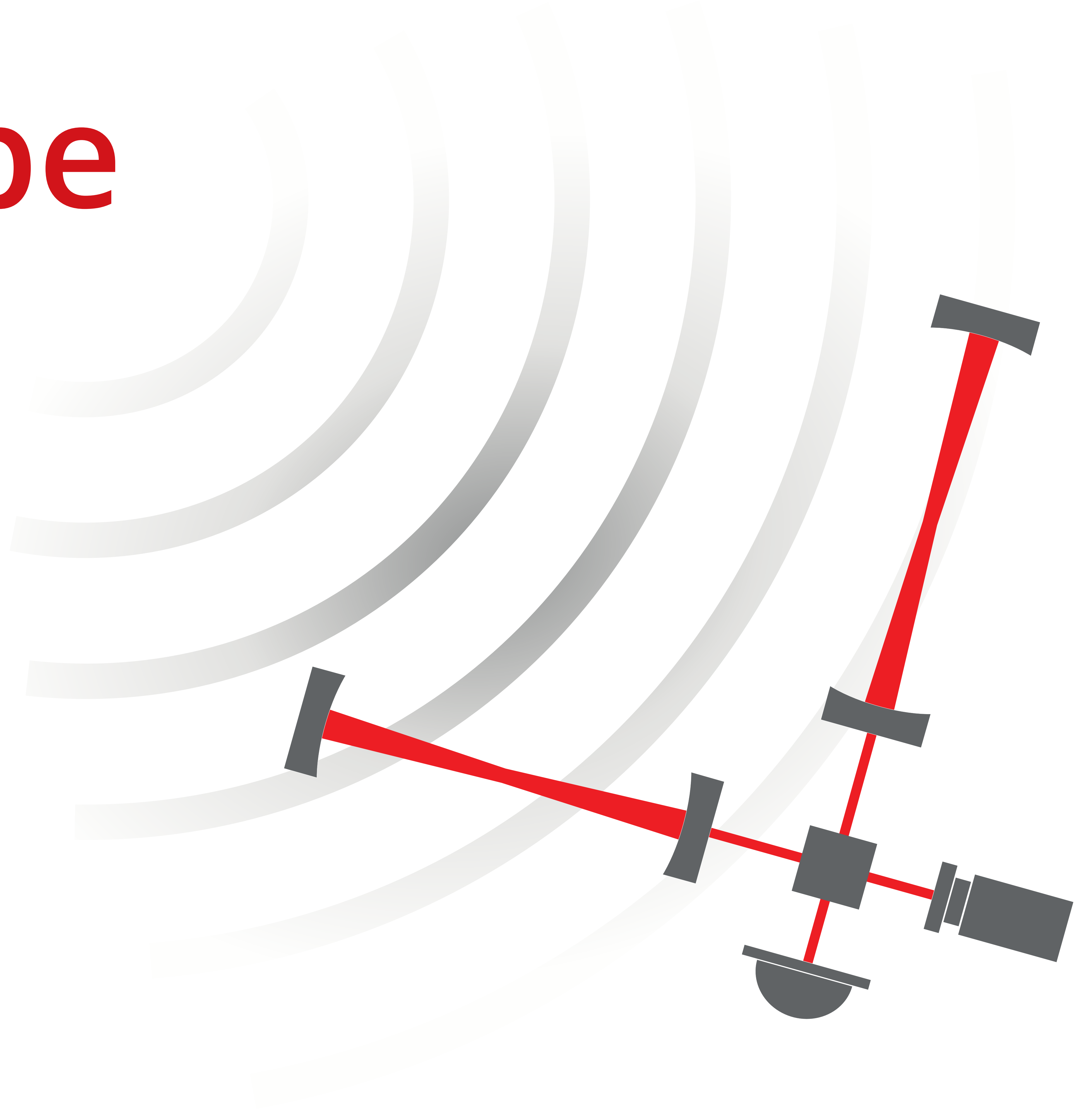
*i.e. the suspension is not required to conductively extract any heat

Mariner

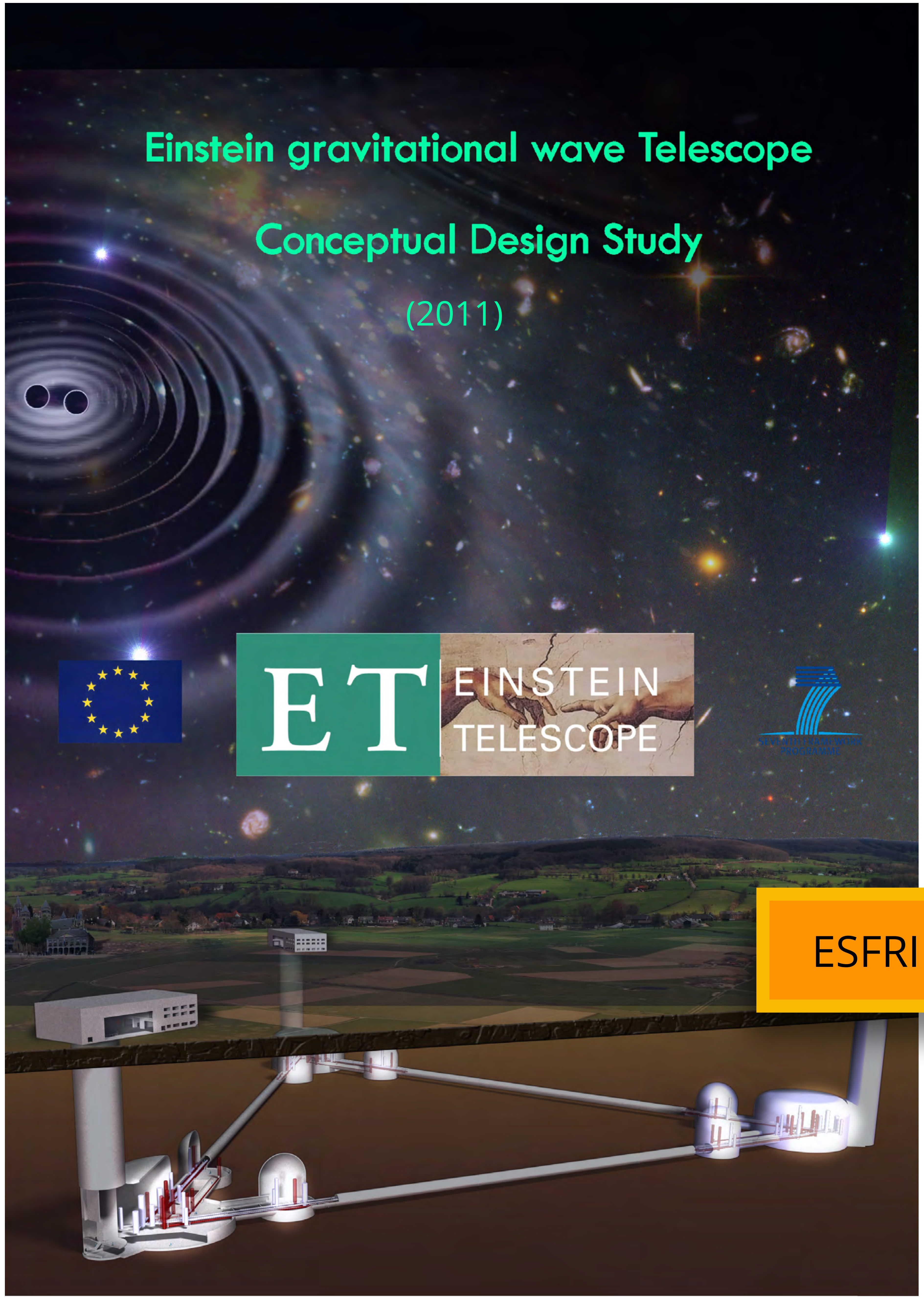
- Voyager-like prototype in the Caltech 40 m Lab
- (Phase 0: balanced homodyne for A+)
- Phase 1: cryo silicon FPMI
- Phase 2: ~Voyager DRFPMI

Will Test	Won't Test
Silicon optics	Quad suspensions
123 K operation	Active seismic isolation
Pre-stabilized laser at 2 μm	High power
Arm length stabilization at 1.4 μm	Big beam spots
Sensing & control (DRFPMI, balanced homodyne)	Thermal compensation
Maybe squeezing?	Filter cavities

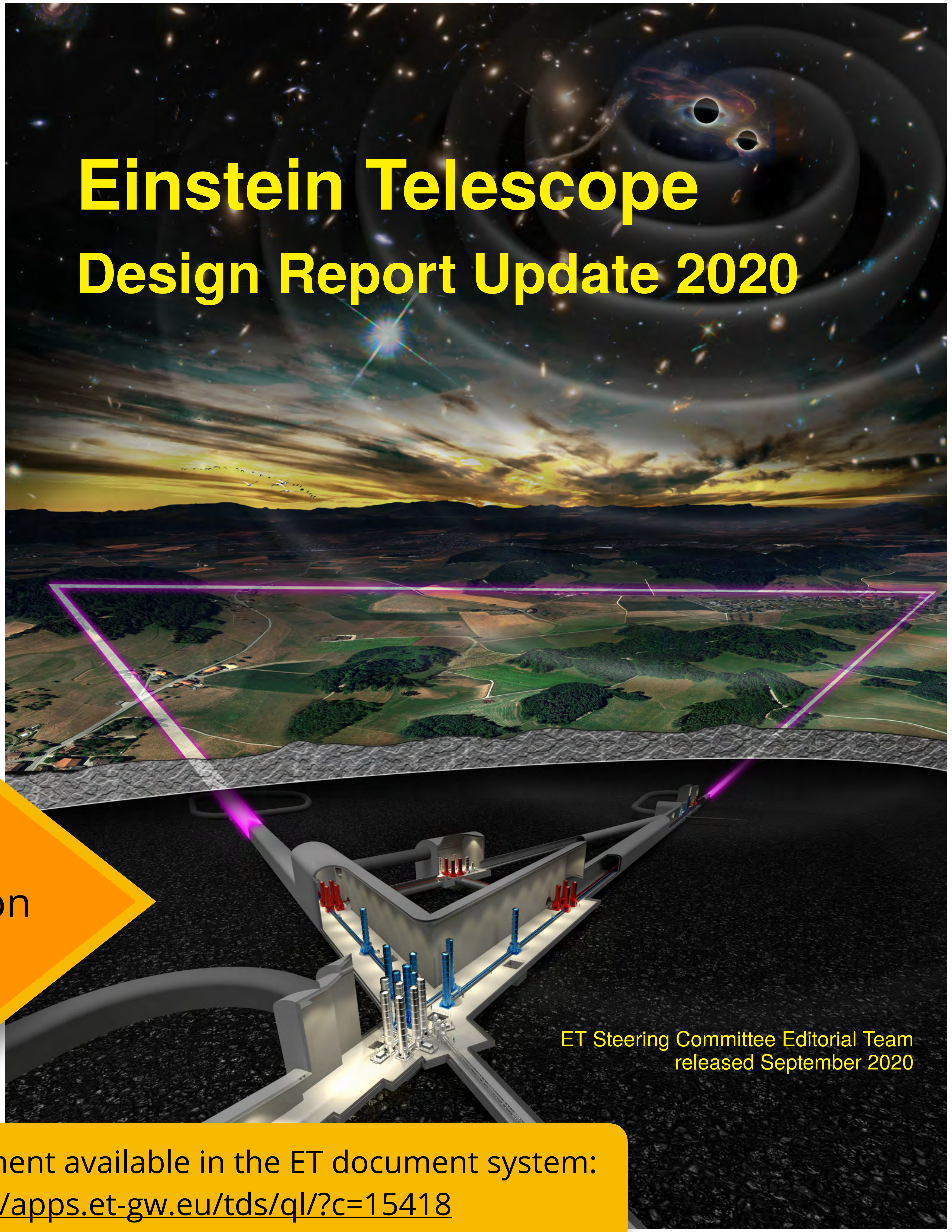
The Einstein Telescope




Einstein Telescope
10 km
Large laboratories and
three 10 km long tunnels,
more than 200m underground
A future European
gravitational waves
observatory



ESFRI Application

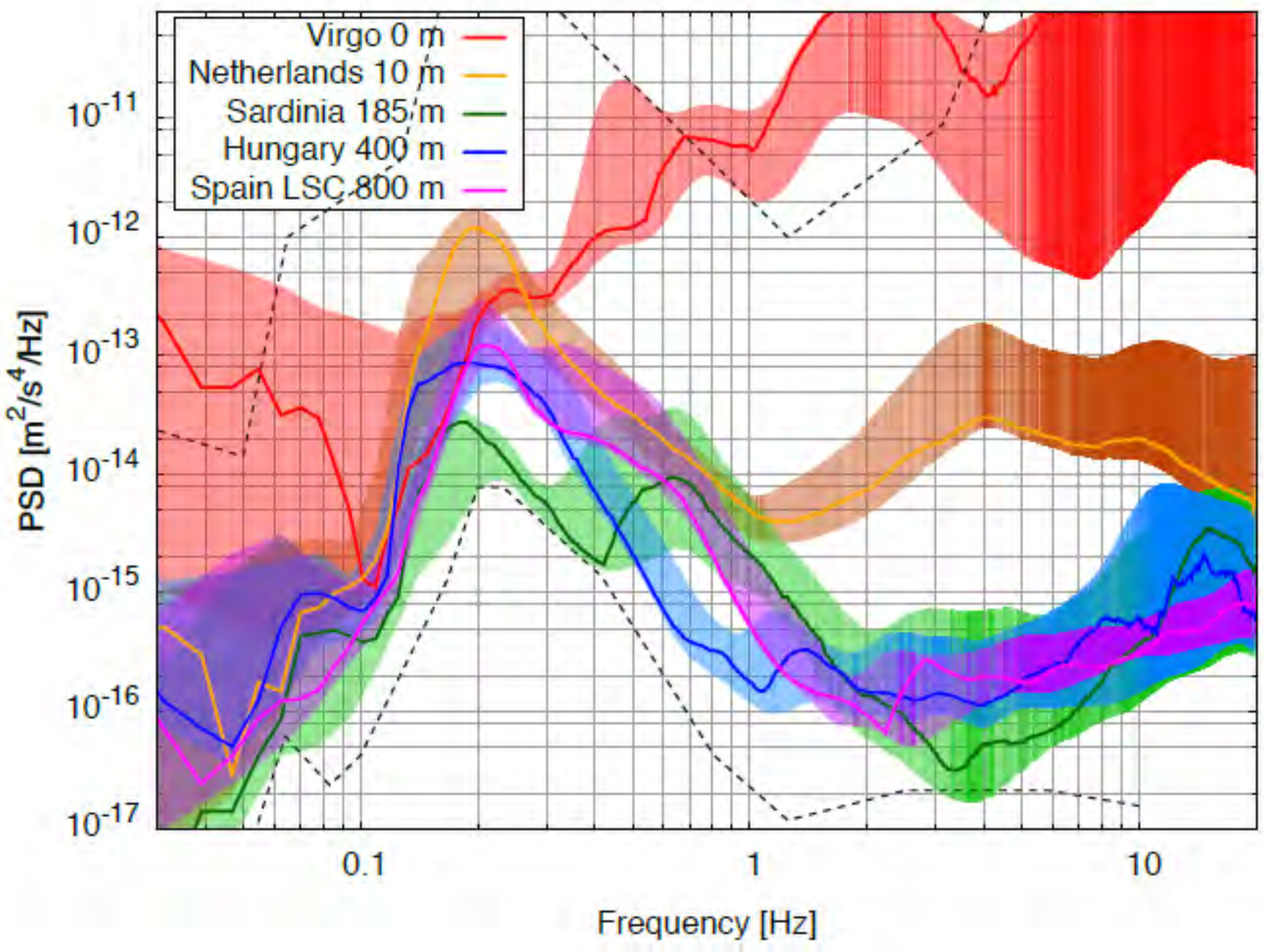


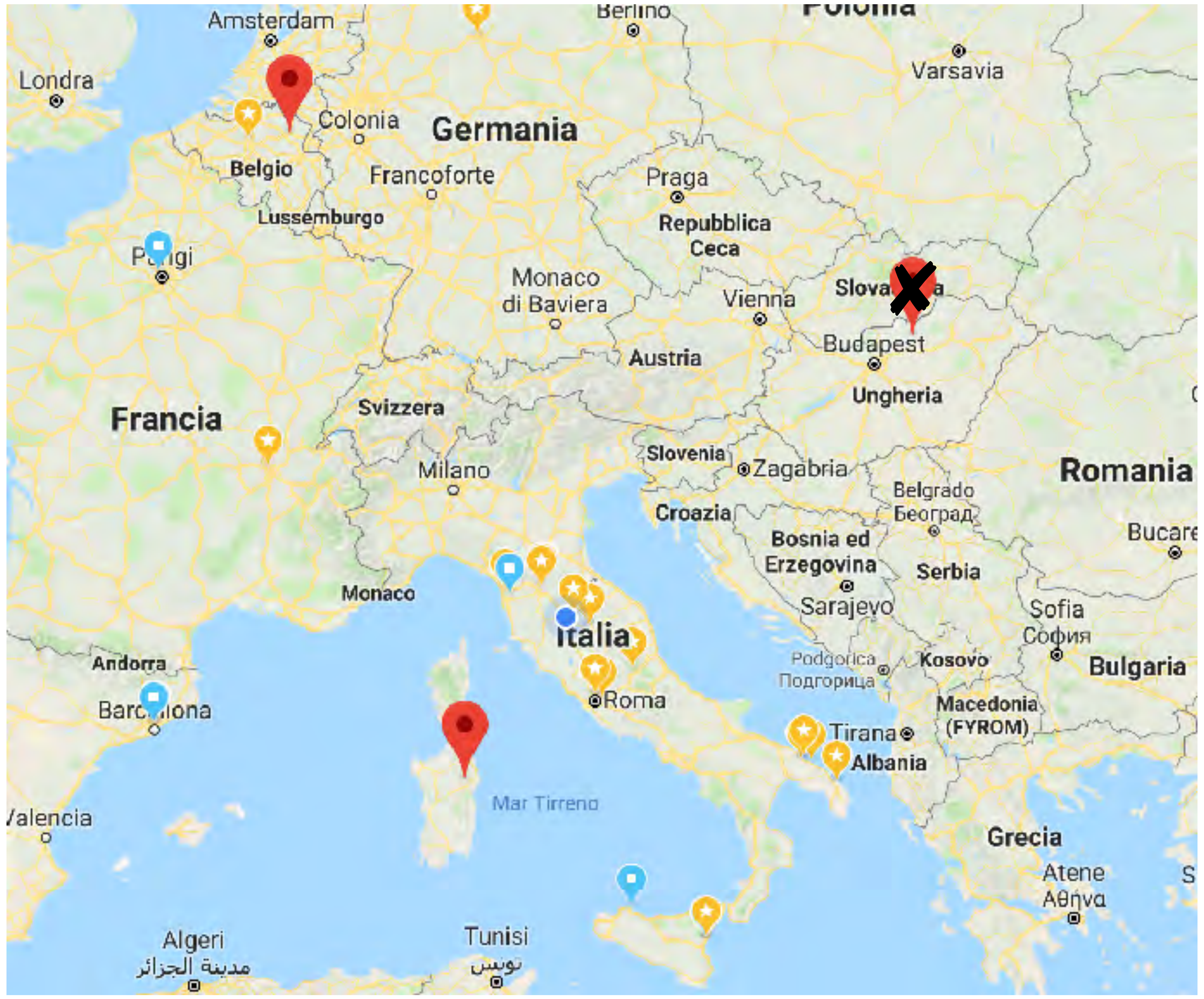
Document available in the ET document system:
https://apps.et-gw.eu/tds/ql/?c=15418

Slide: Michele Punturo

ET Site Candidates

ET has two site candidates with community support and political support: a) **Euregion Meuse-Rhine**, a cross-border region in the Netherlands, Belgium, Germany, and b) **Sardinia** Italy





Einstein Telescope timeline

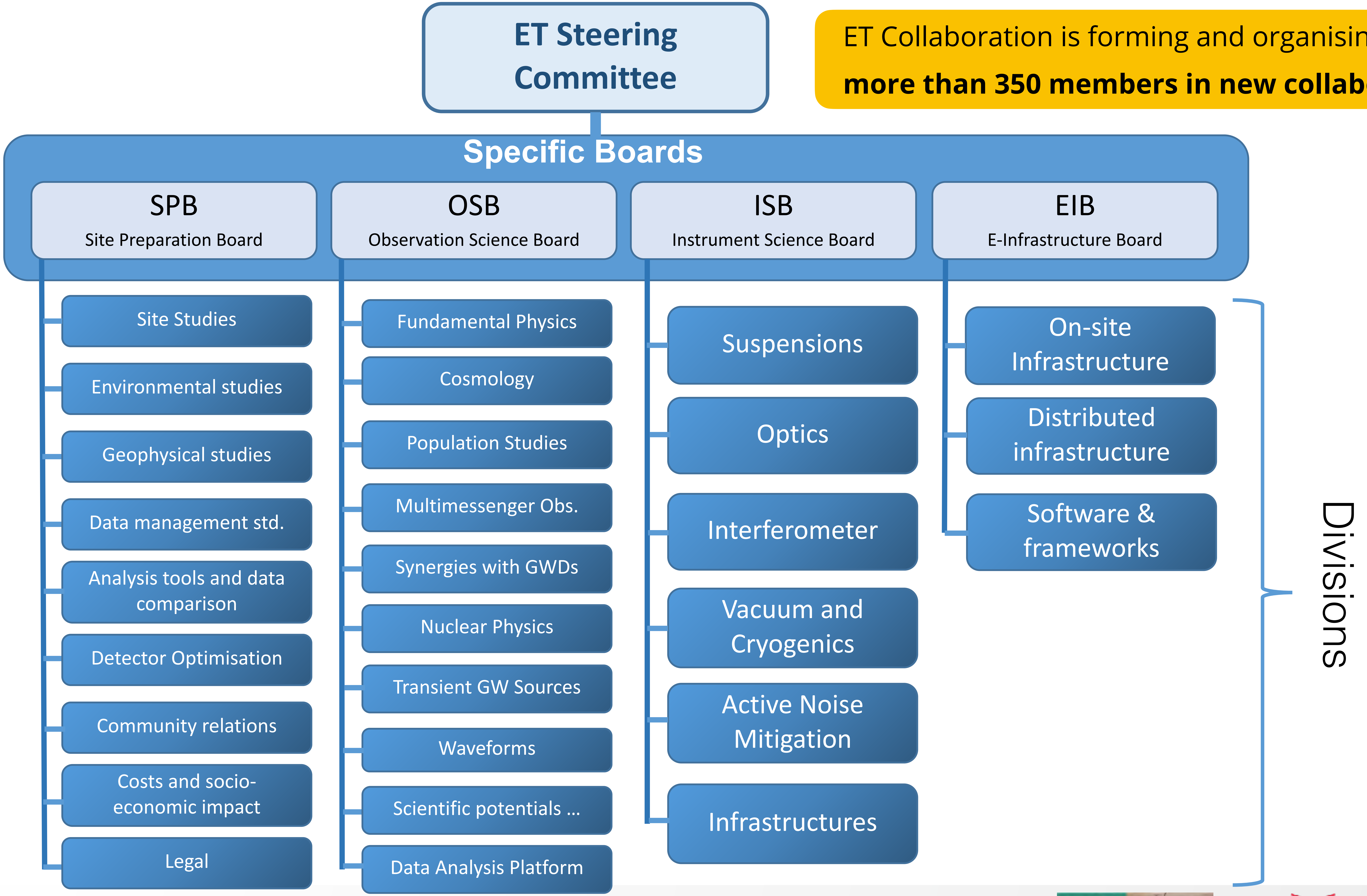
The Einstein Telescope is planned as a large underground facility with a **50+ years lifespan.**

- 2010 ET conceptual design completed
- **2020/2021 Design update, forming the ET collaboration, ESFRI application**
- **2024/2025 Site selection**
- 2026 Full technical design
- 2027 Infrastructure realisation start (excavation, ...)
- 2032+ installation / commissioning / operation

Join us at: https://wiki.et-gw.eu/ISB/WelcomePage

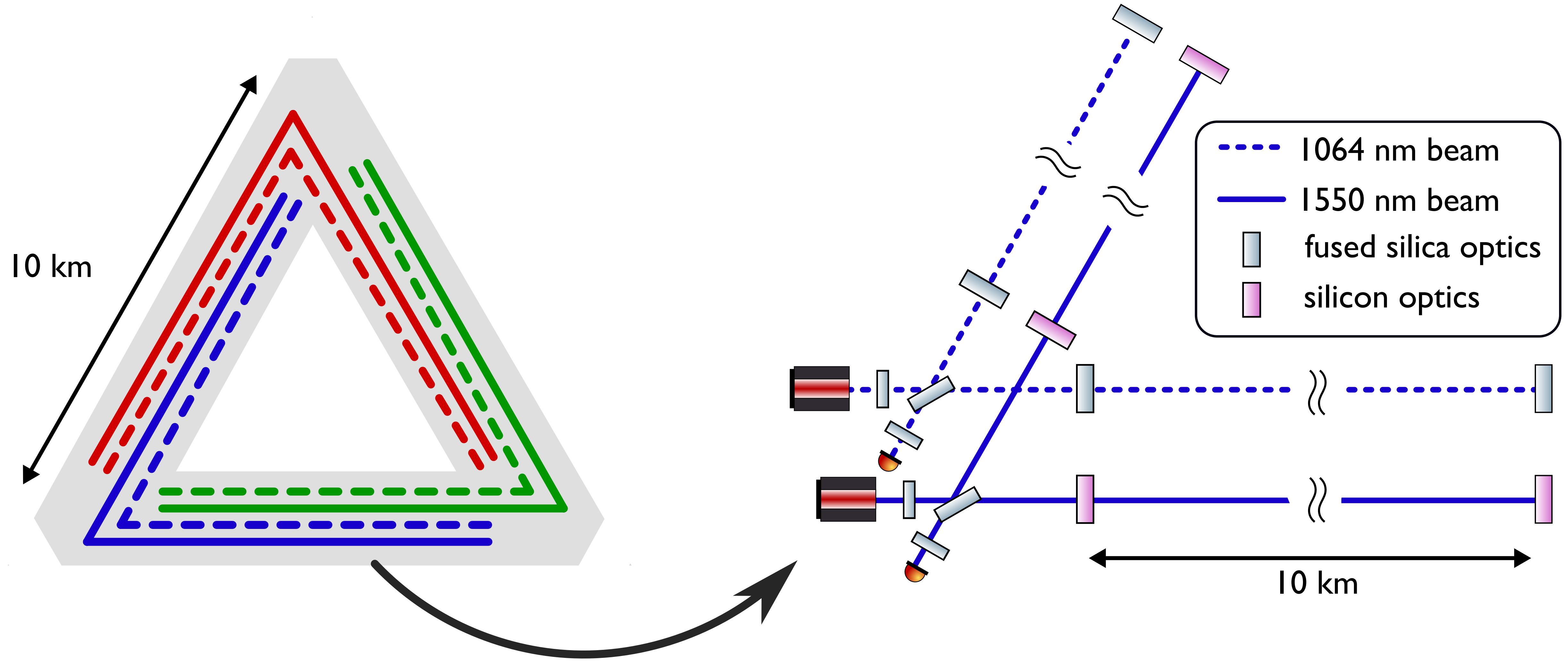
ET Collaboration is forming and organising

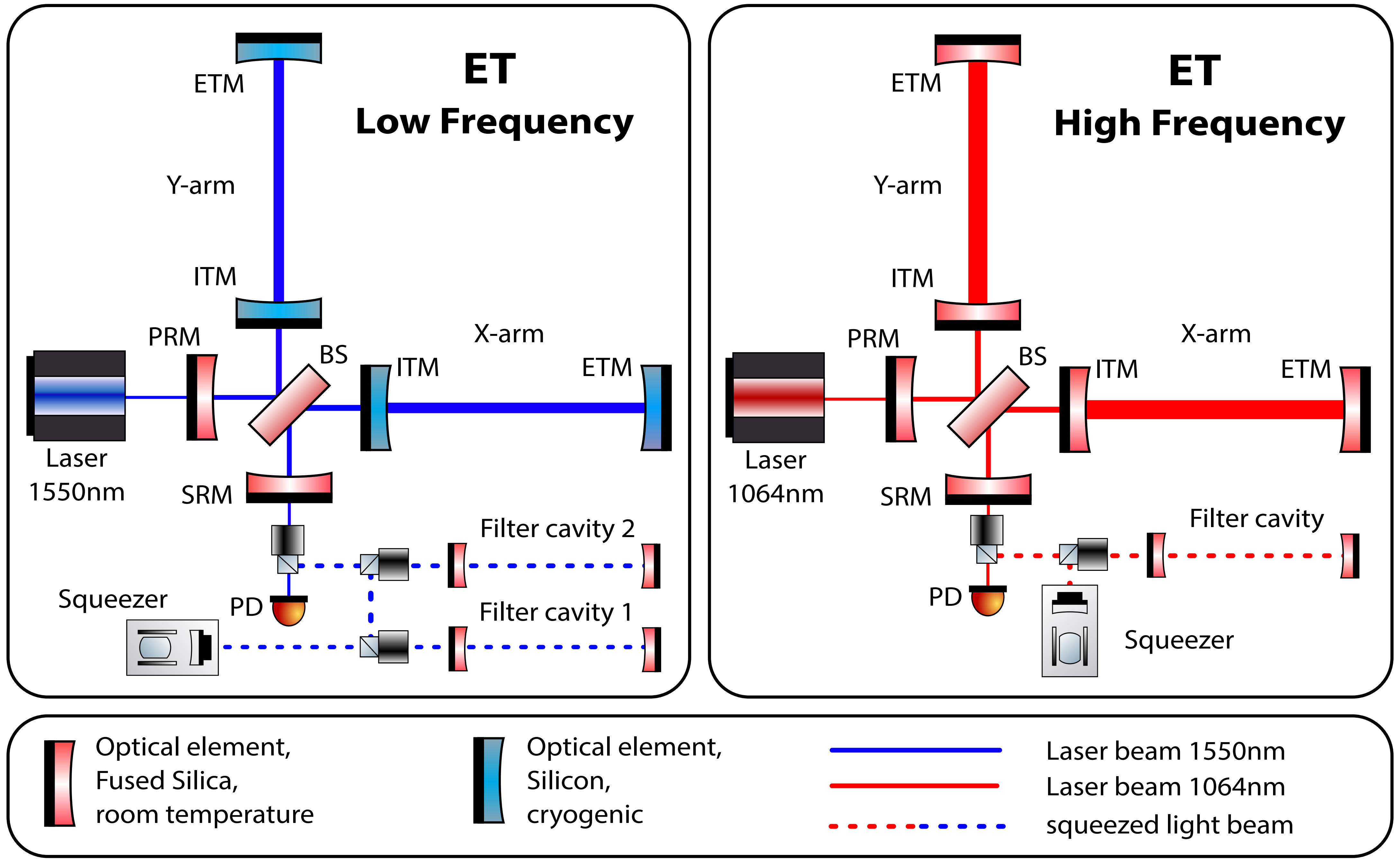
more than 350 members in new collaboration database



Einstein Telescope design

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



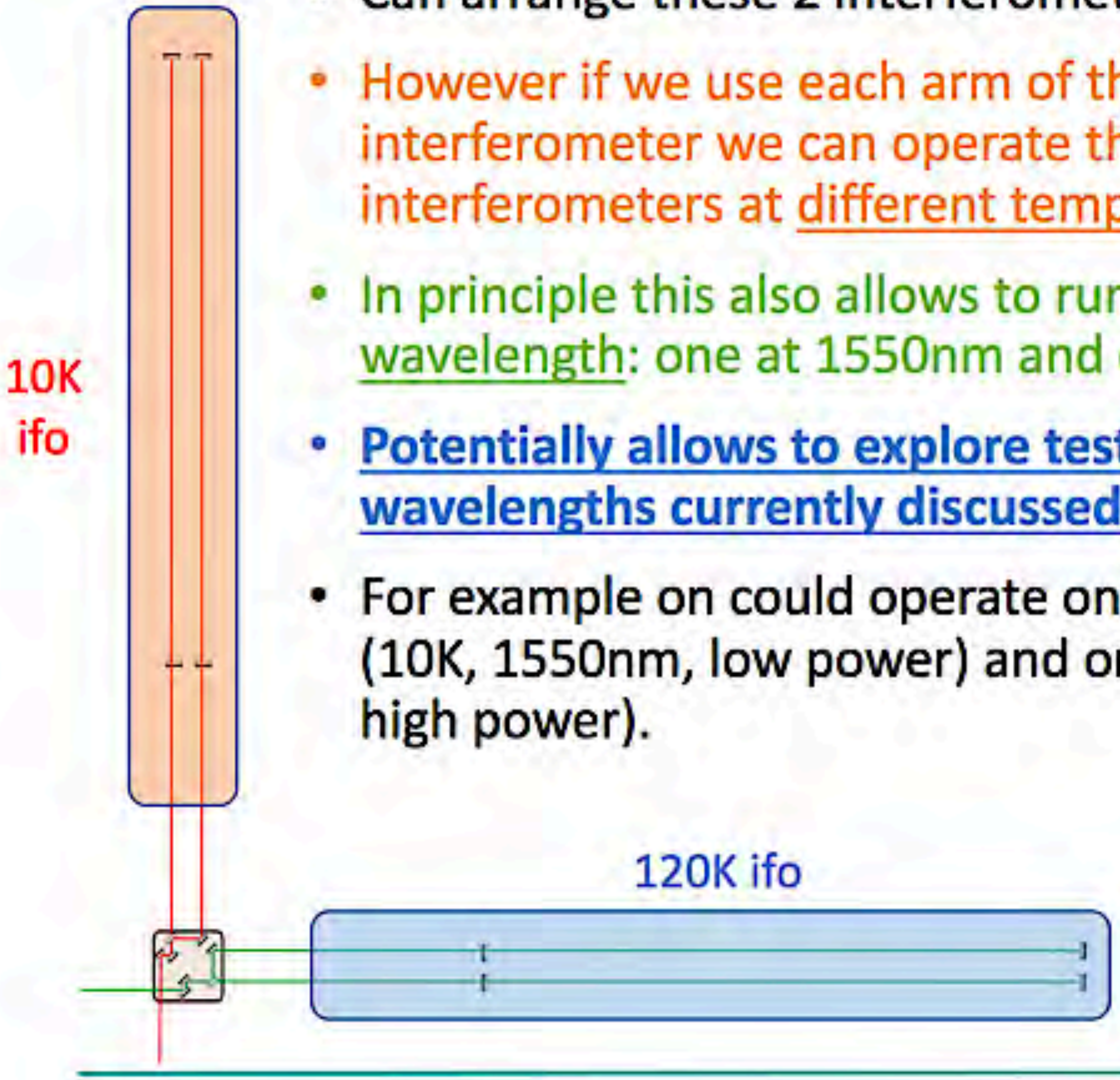


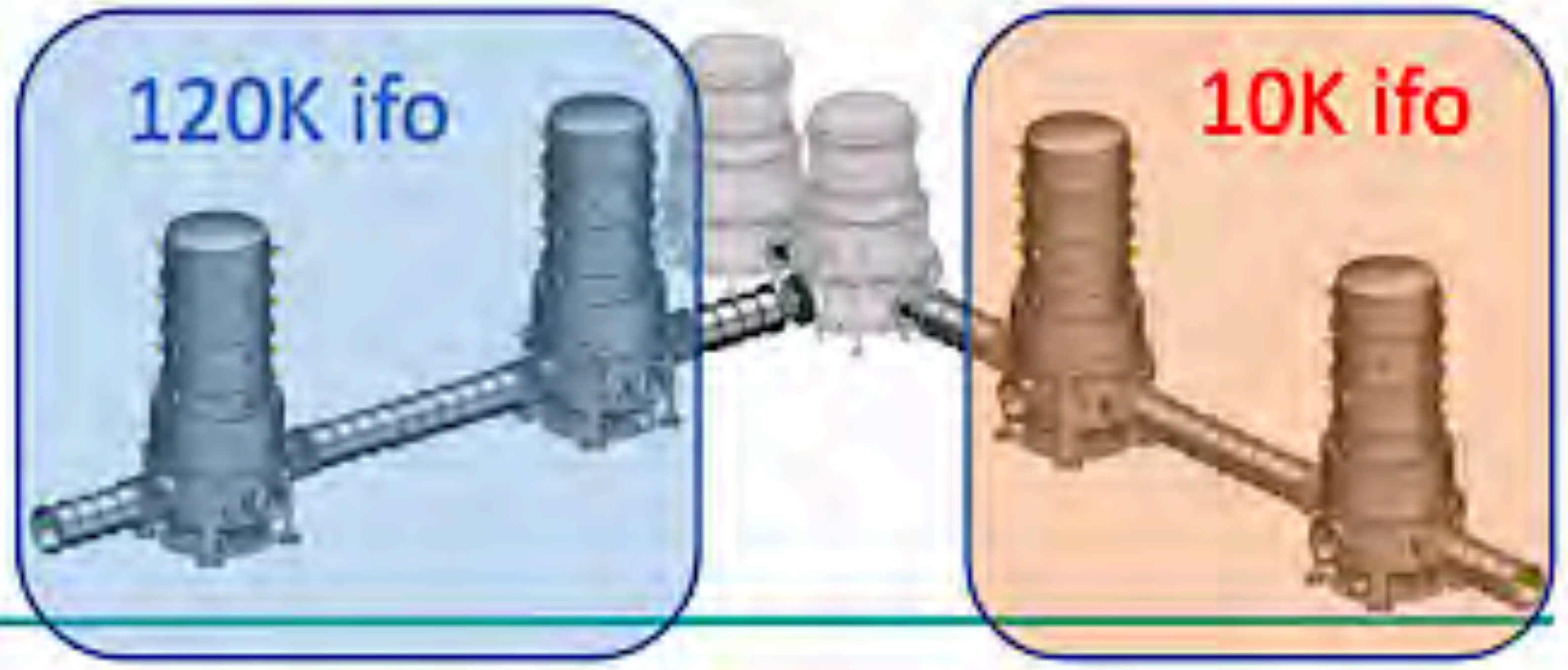
ETpathfinder

- 10m prototype facility, currently under construction in Maastricht
- 14.5M€ investment
- ~20 universities and research institutes from NL/BE/DE/F contribute

Cryogenic Prototyping: ET Pathfinder

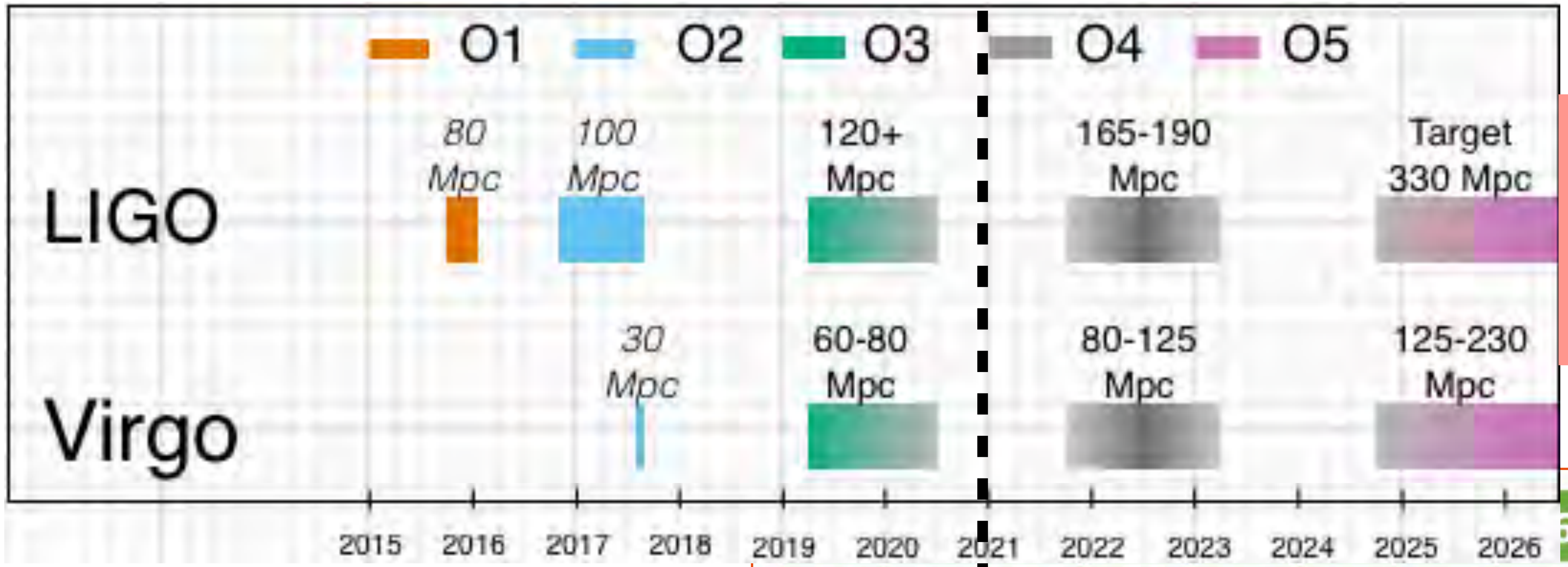
- Can arrange these 2 interferometers as 2 'L'.
- However if we use each arm of the vacuum system for one interferometer we can operate the two arms and hence interferometers at <u>different temperatures</u>: one at 120K and one at 10K.
- In principle this also allows to run the two interefreometers at <u>different wavelength</u>: one at 1550nm and one more towards 2um.
- <u>**Potentially allows to explore test the full matrix of temperatures and wavelengths currently discussed.**</u>
- For example on could operate one interferometer as in ET-D-LF config (10K, 1550nm, low power) and one in Voyager/CE config (120K, 2um, high power).



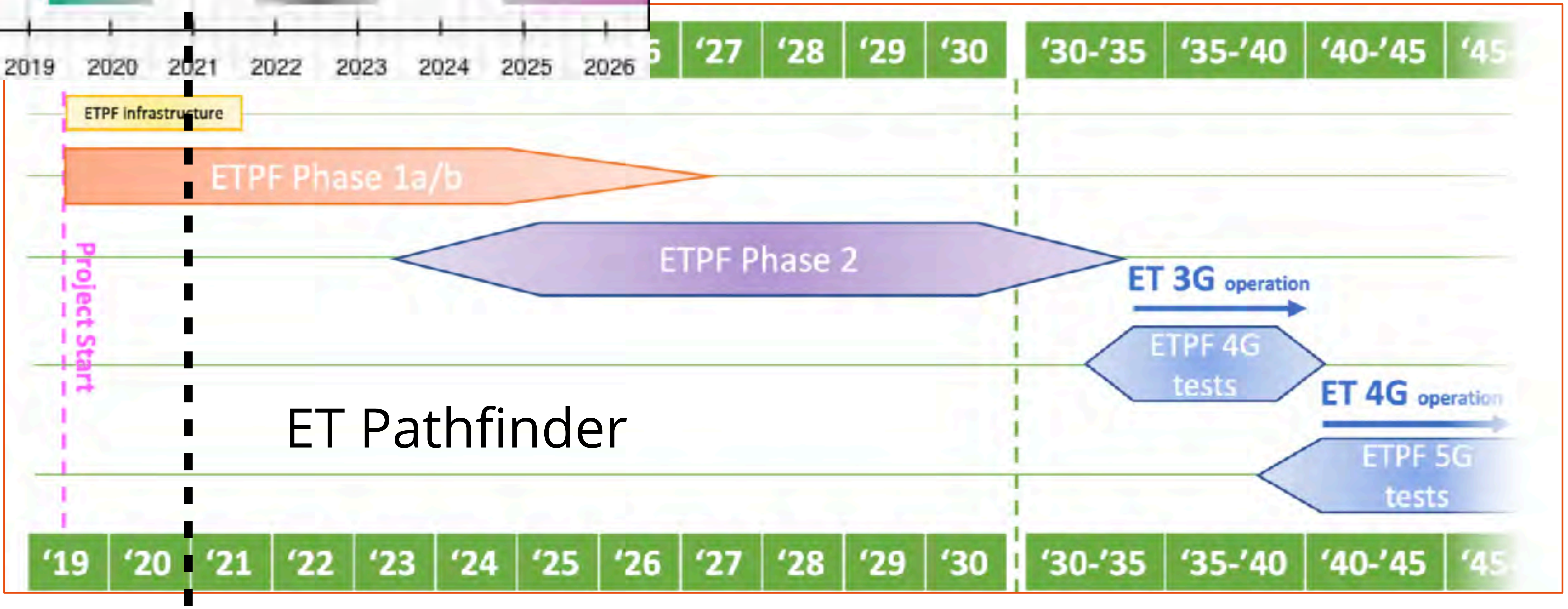


[Stefan Hild 2019]

Timelines towards and around ET



Further upgrades and observations until ET operates (2035), joint network with ET?

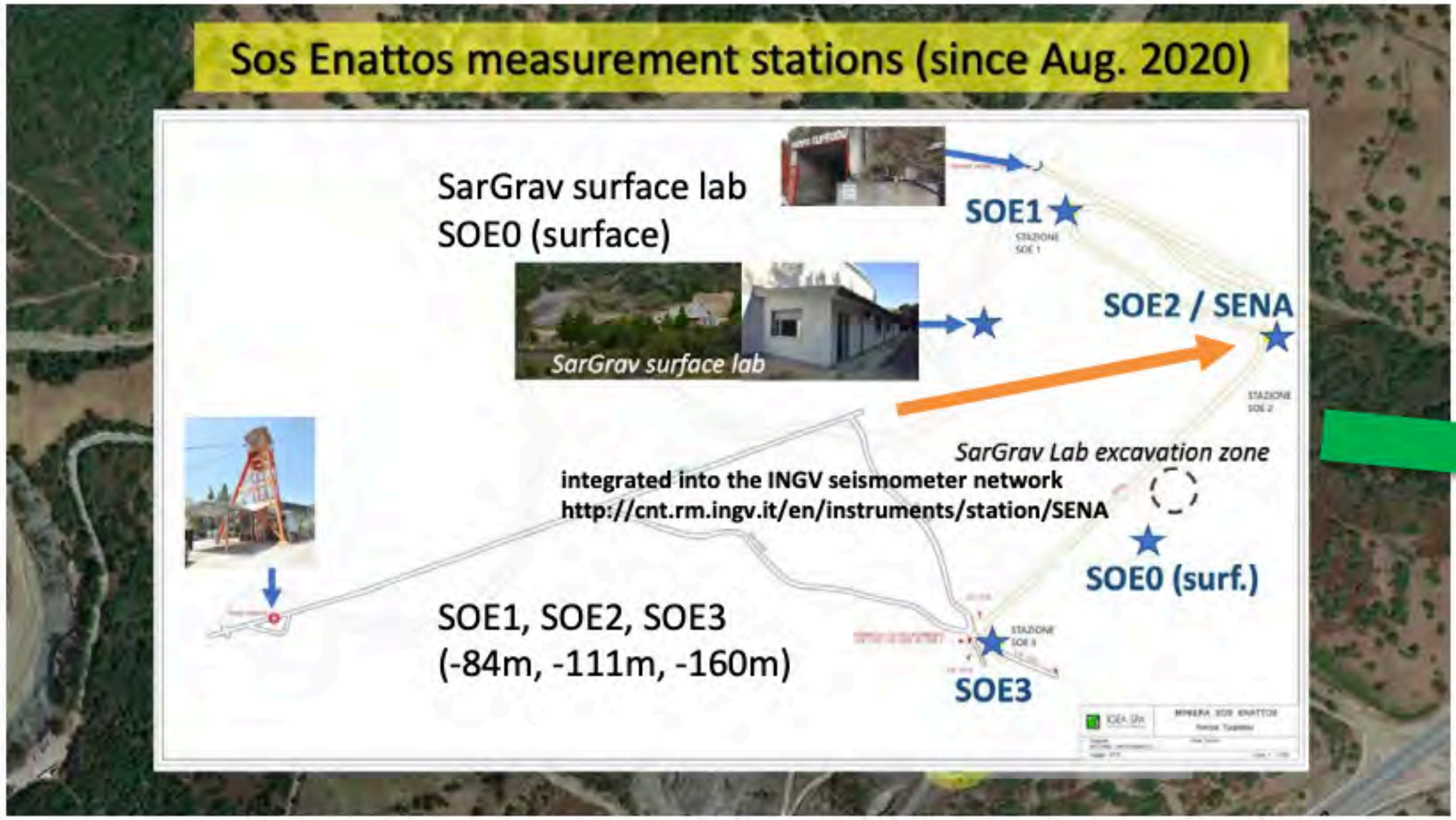


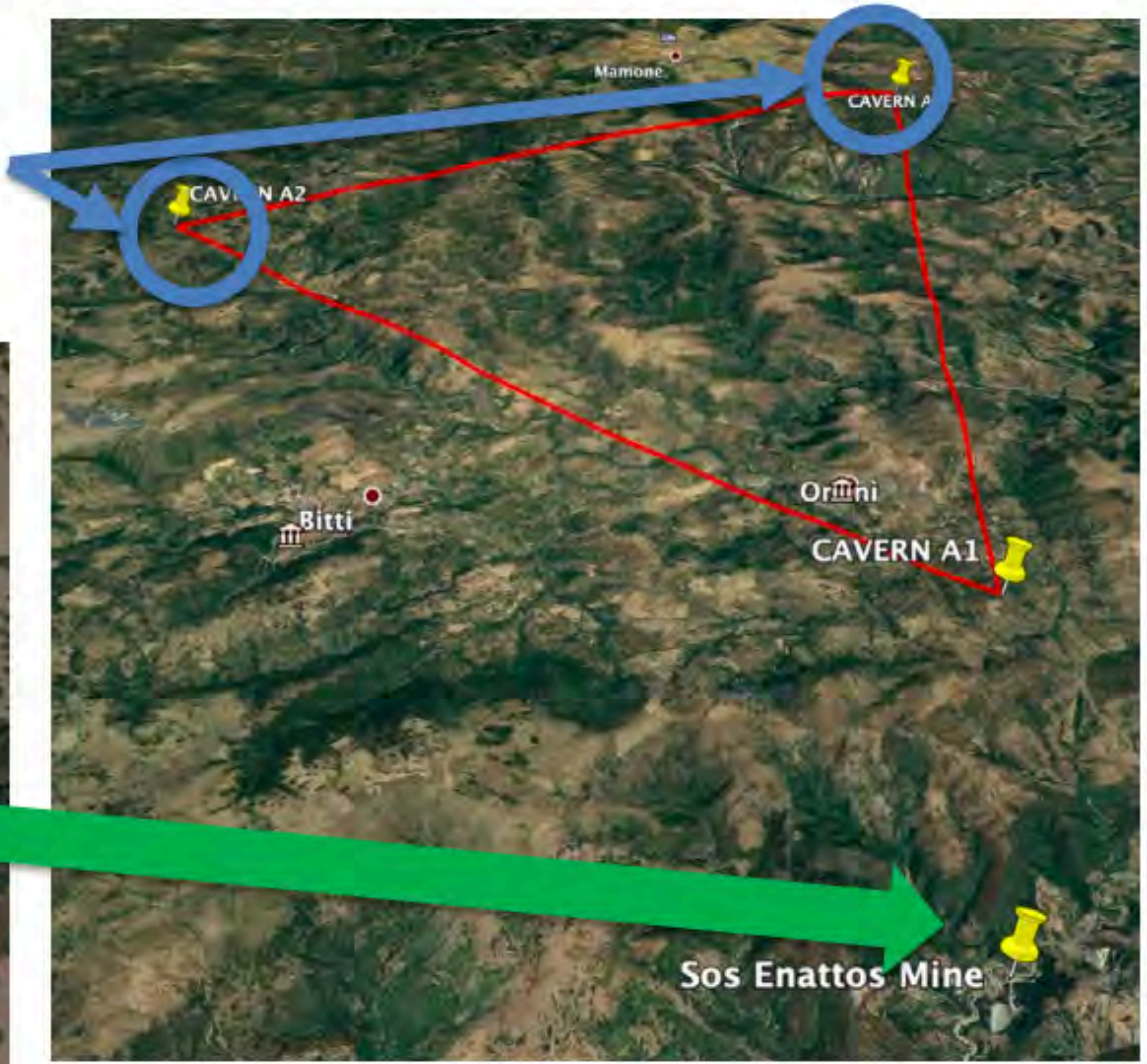
today

Slide: Domenico D'Urso

Measurement in Sardinia

Characterization of the Bitti and Onanì corners:
Surface and underground seismic and environmental measurements will start soon





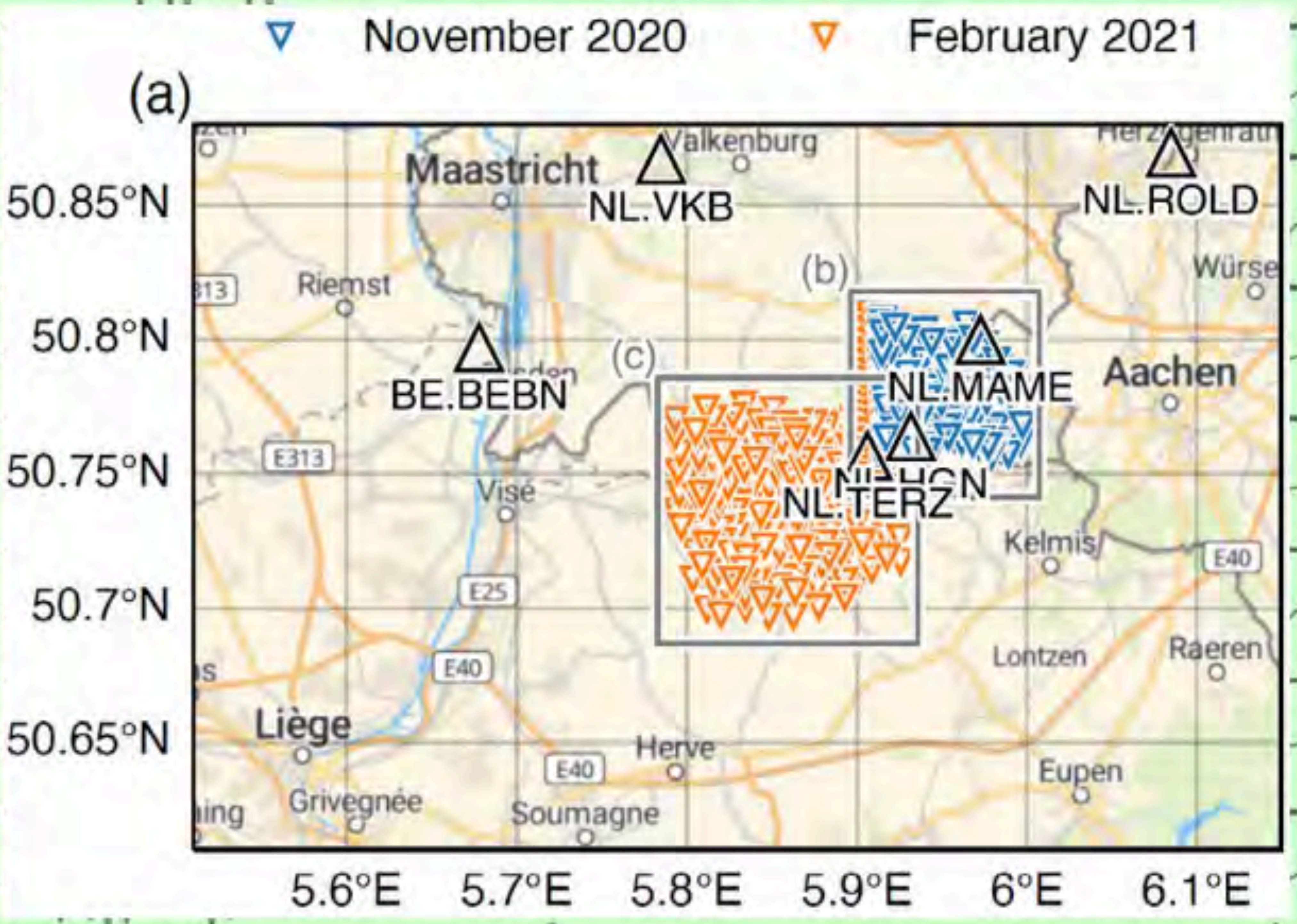
4 broadband seismometers, 3 short-period seismometers, 2 magnetometers, 1 tiltmeter distributed over underground and surface stations

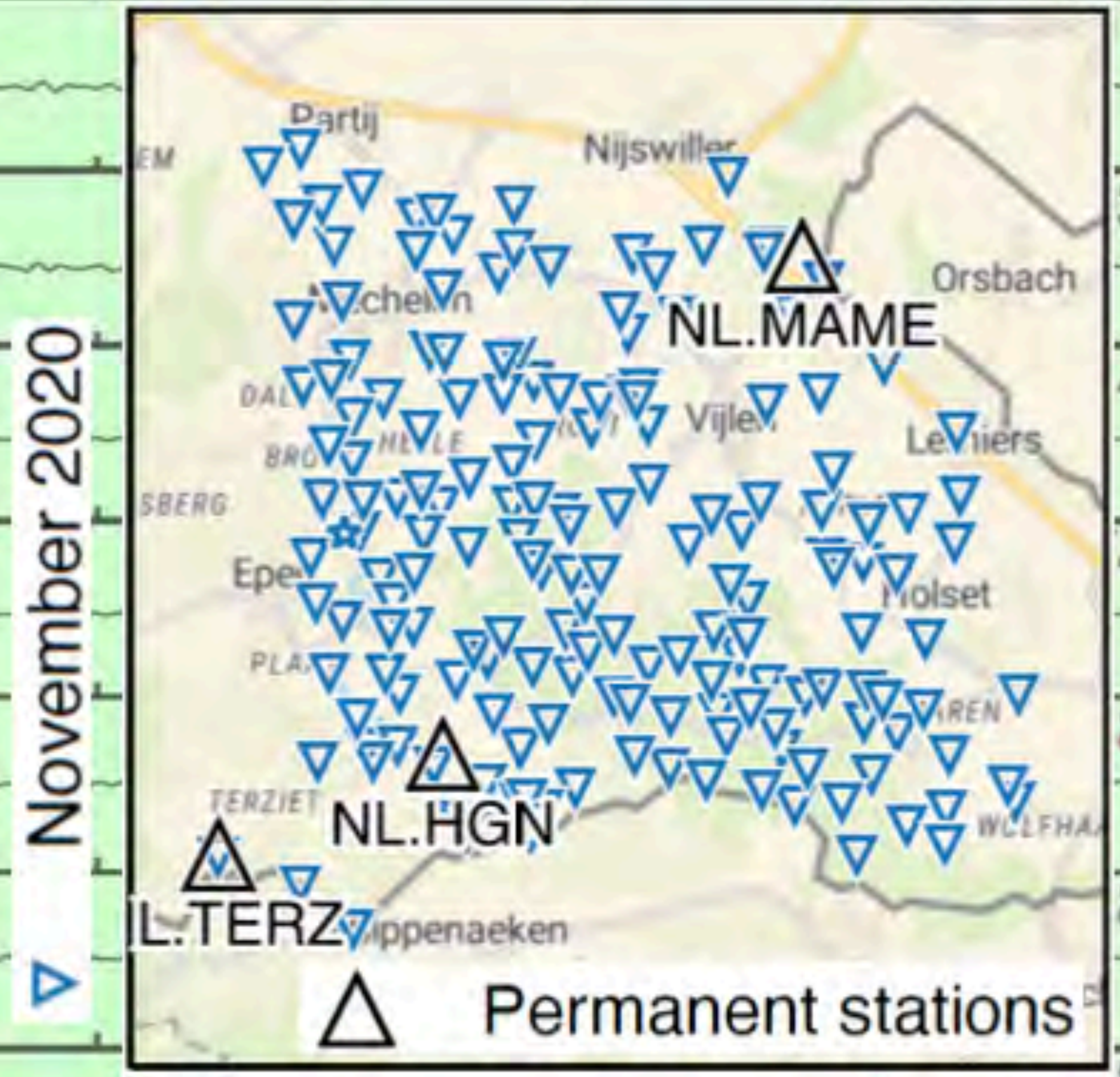
26
Credits to L. Naticchioni

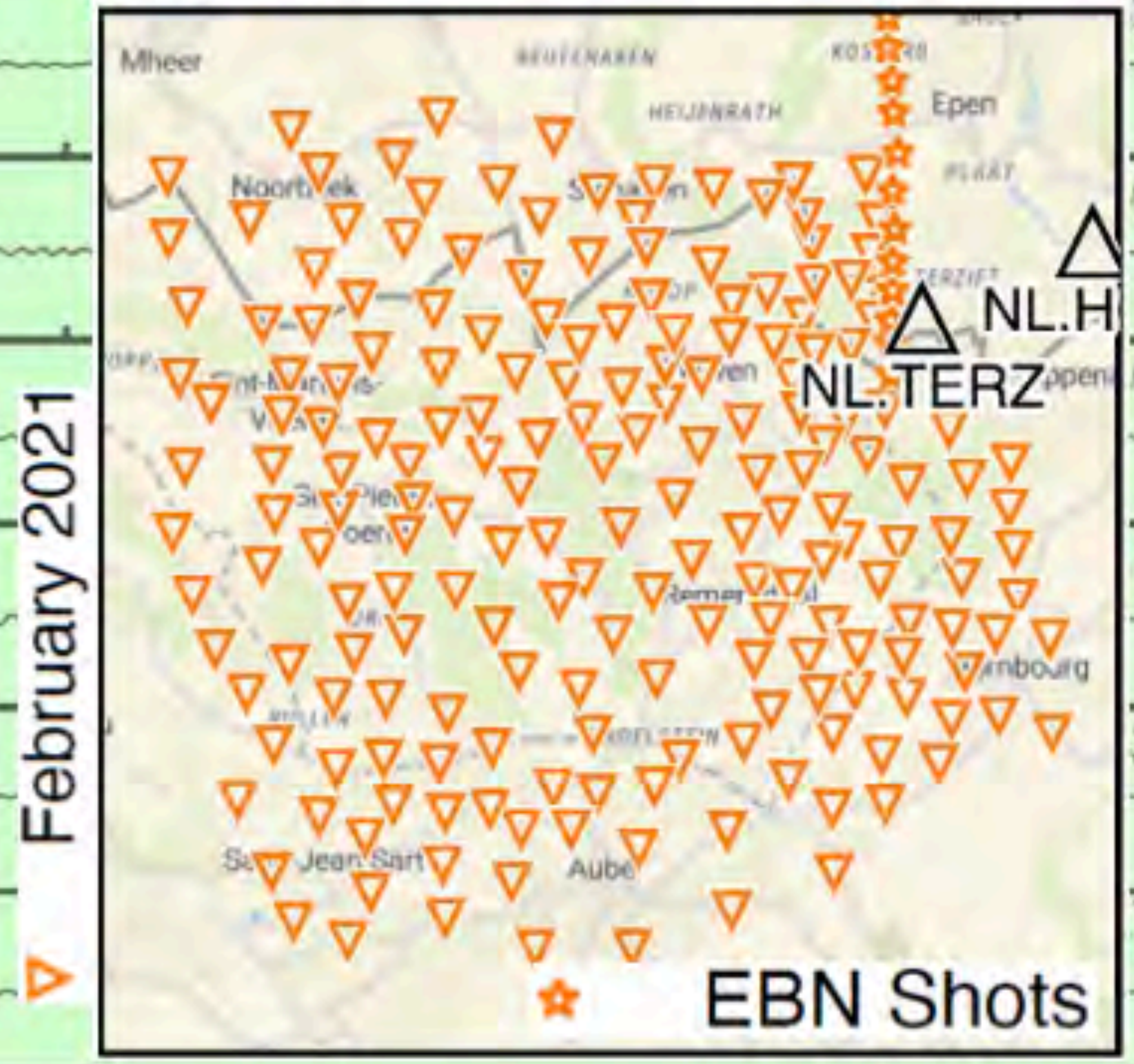
ET EINSTEIN TELESCOPE

Measurements in the Euregio Meuse-Rhine

Data:
https://www.fdsn.org/networks/detail/3T_2020/



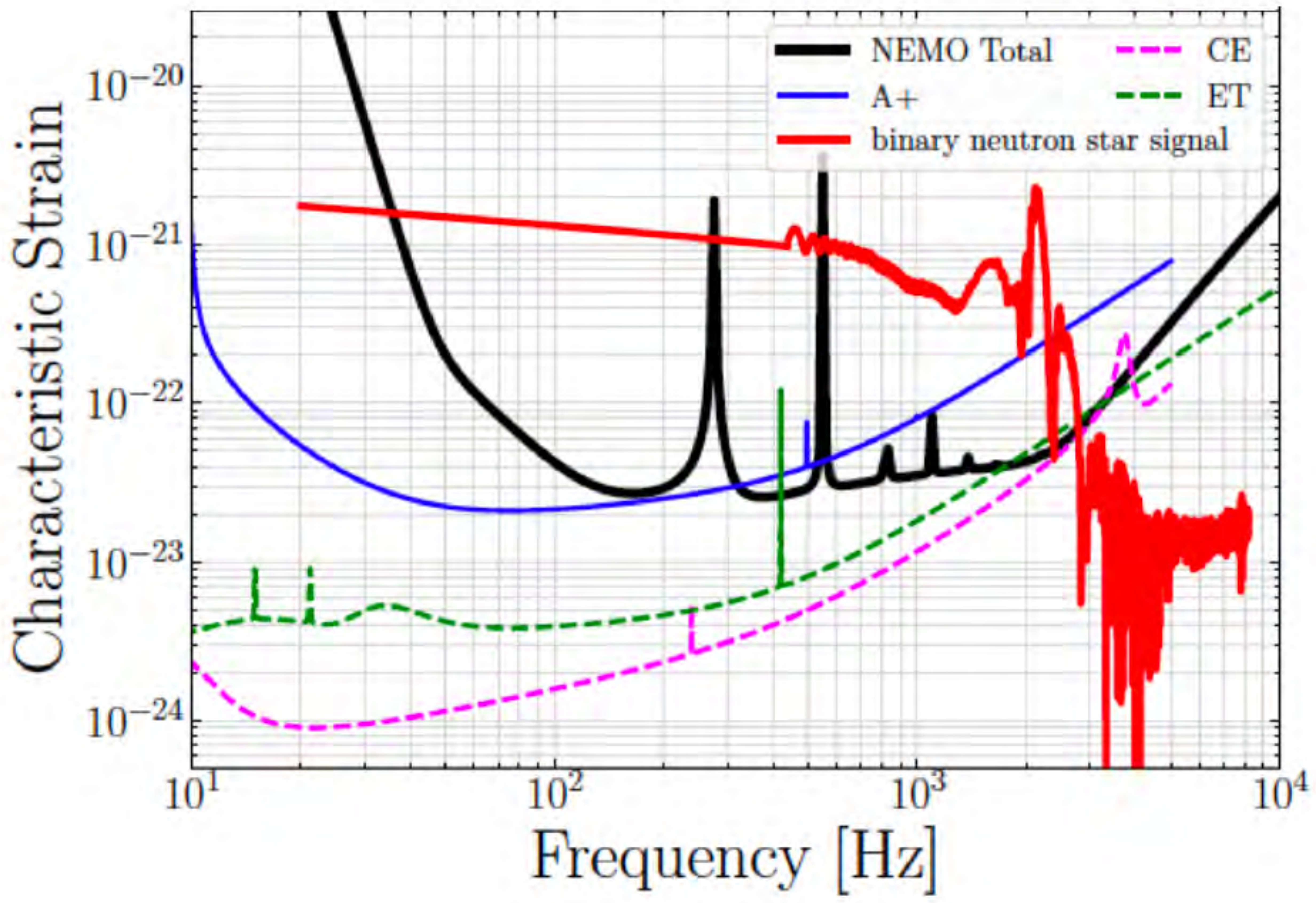


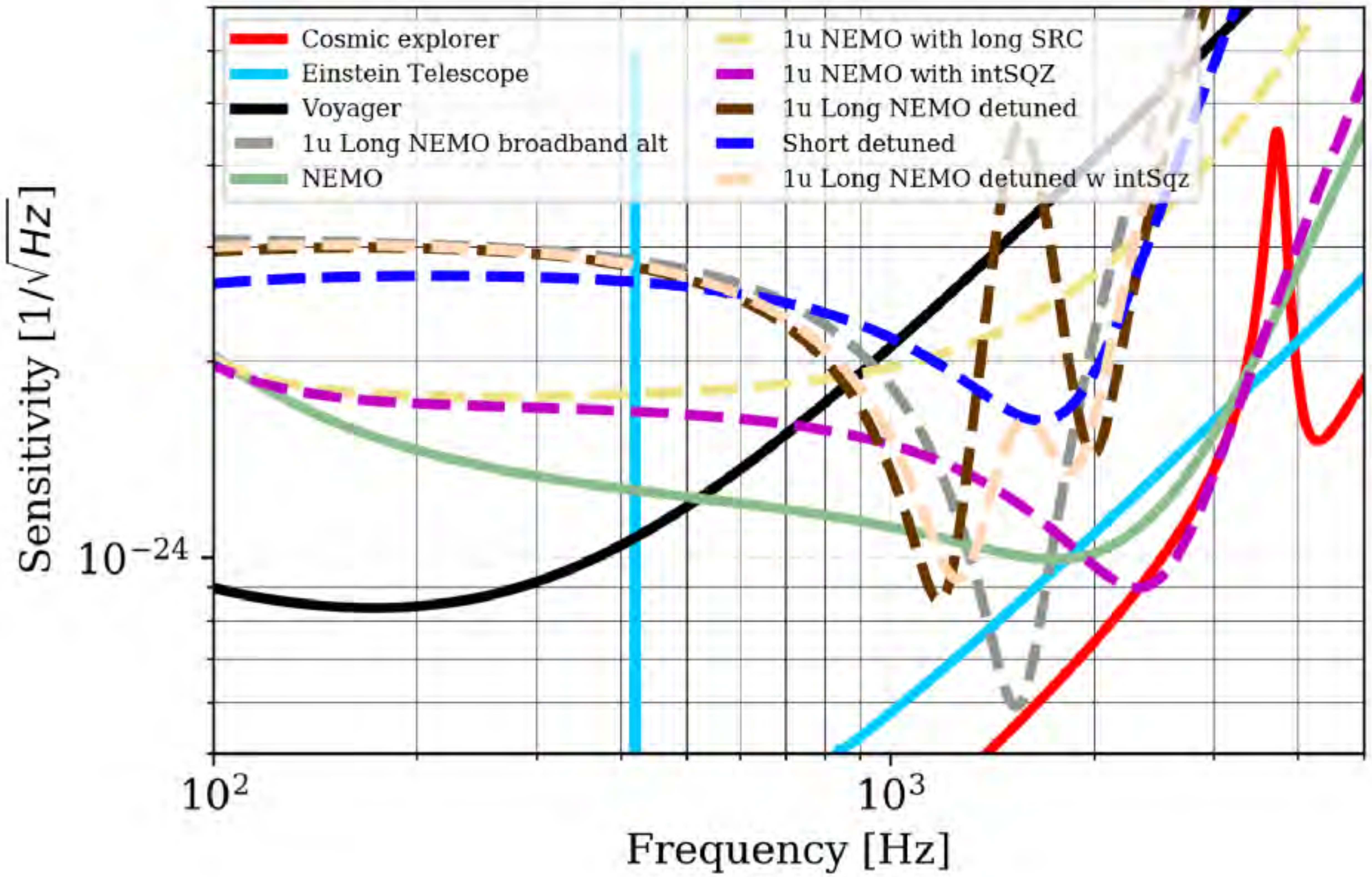


Terziet: Live data:
http://www.orfeus-eu.org/data/odc/realtime/?network=NL&station=TERZ
First three: on ground
Lower three: down hole sensor

NEMO

Australian concept for a high-frequency observatory



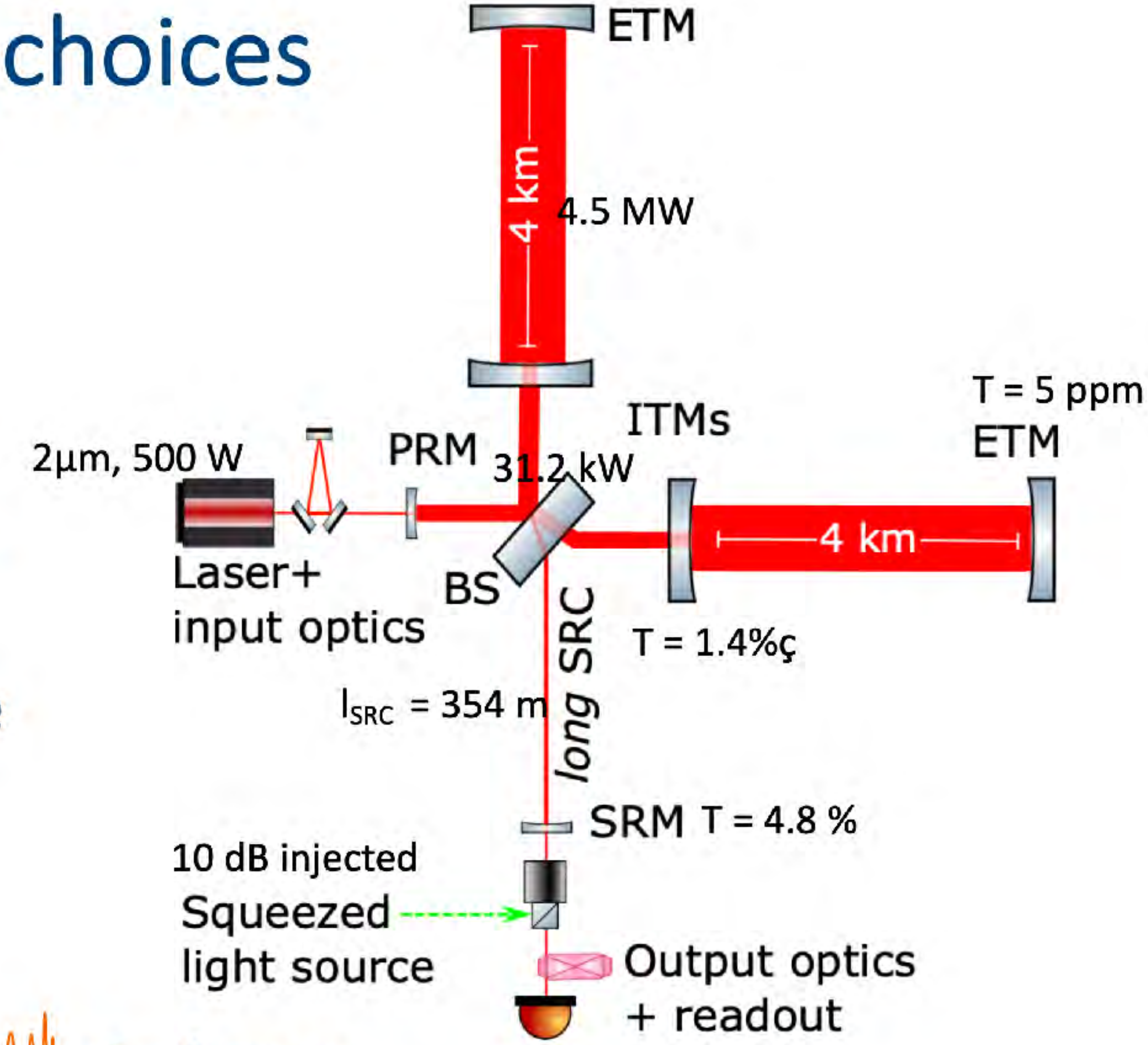


Vaishali Adya, see also NEMO paper : doi:10.1017/pasa.2020.39

NEMO current design choices

- Test mass weight = 74.1 kg
- Test mass coating : AlGaAs/GaAs*
- ITM = 150 K, ETM = 123 K
- ROC_{ITM} = 1800 m; ROC_{ETM} = 2500 m
- Suspension material : steel*
- Test mass cooling method : radiative

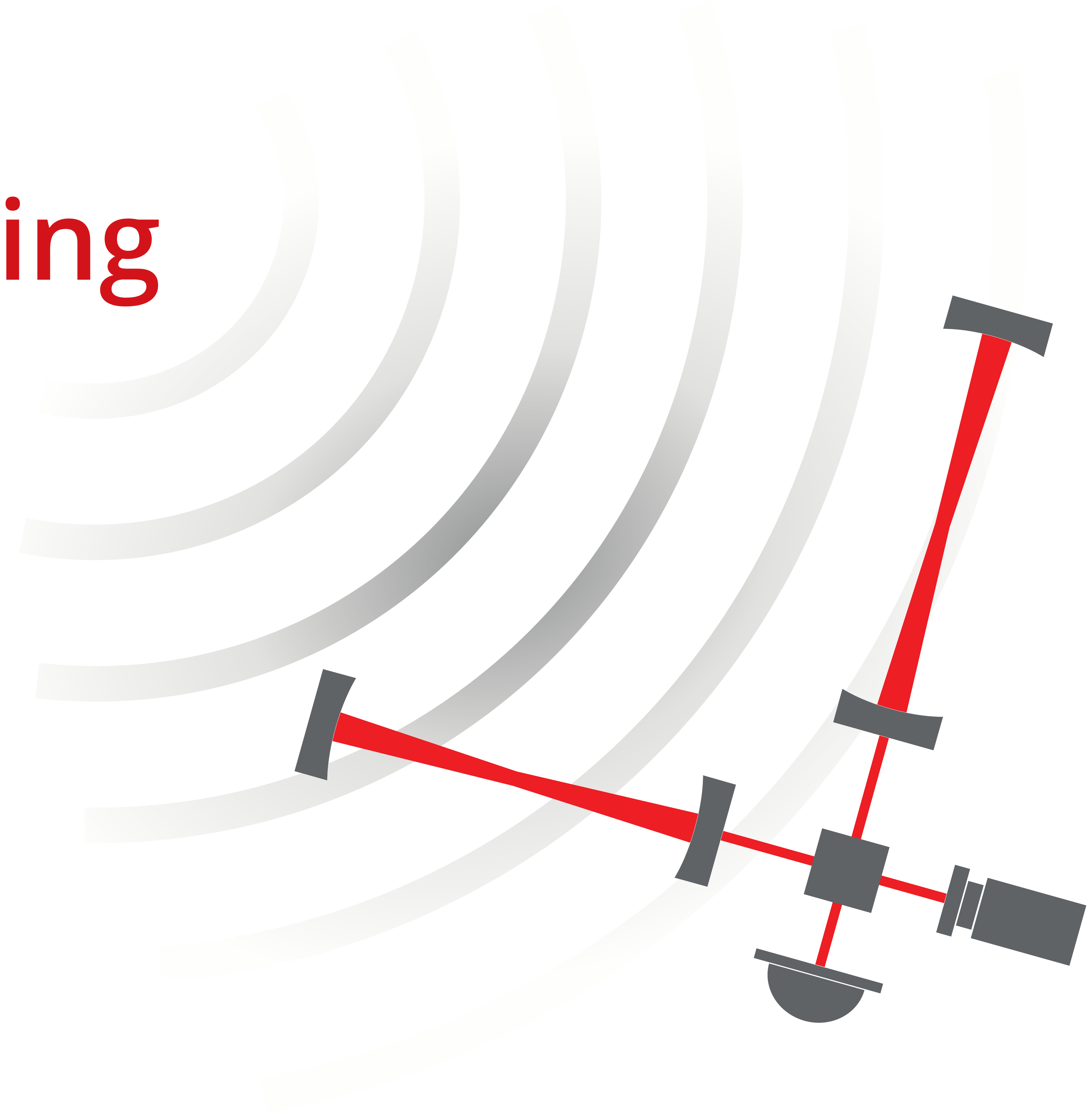
- Laser wavelength 2µm
- mirror material: silicon
- arm power 4.5 MW



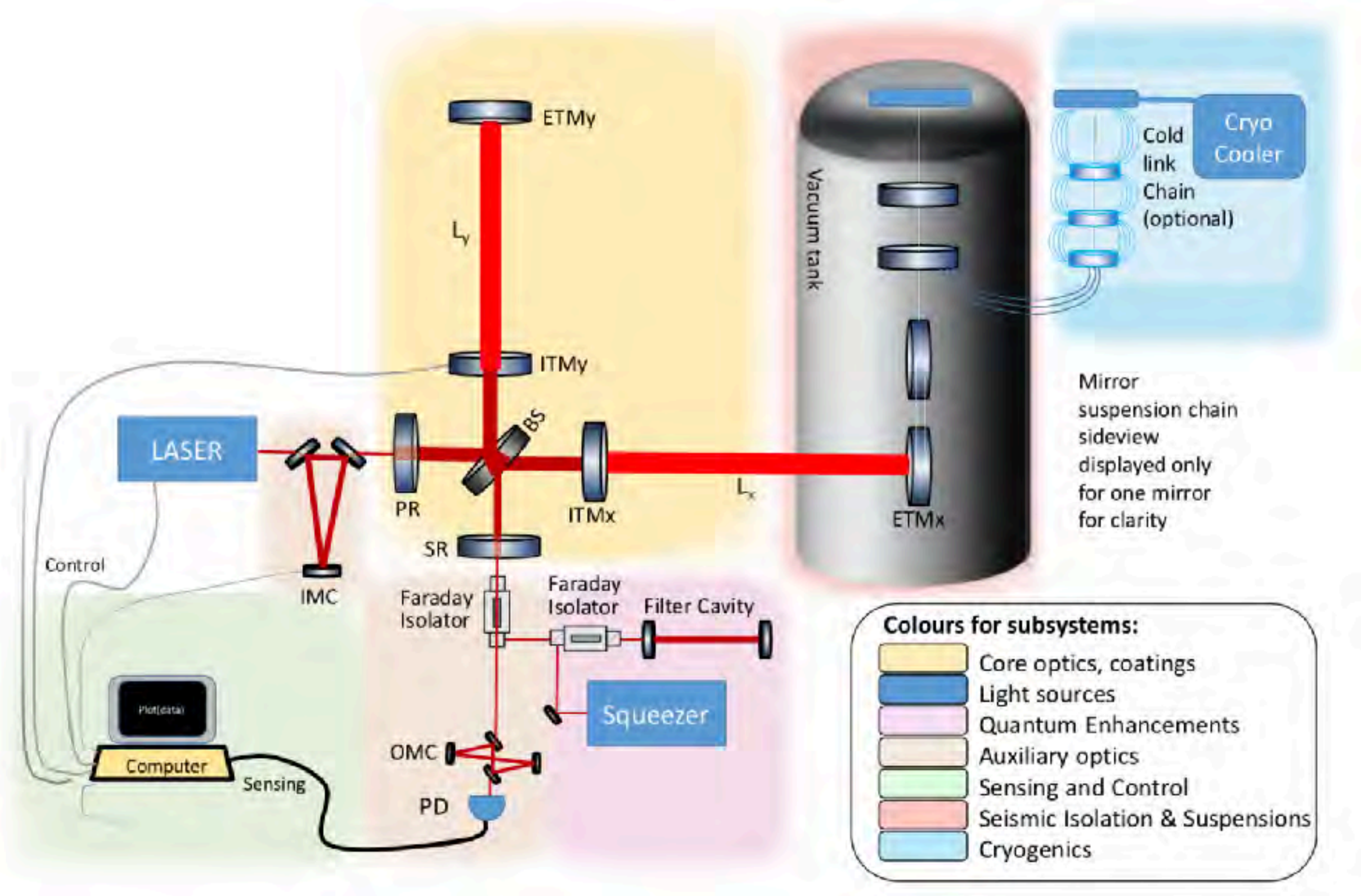
OzGrav

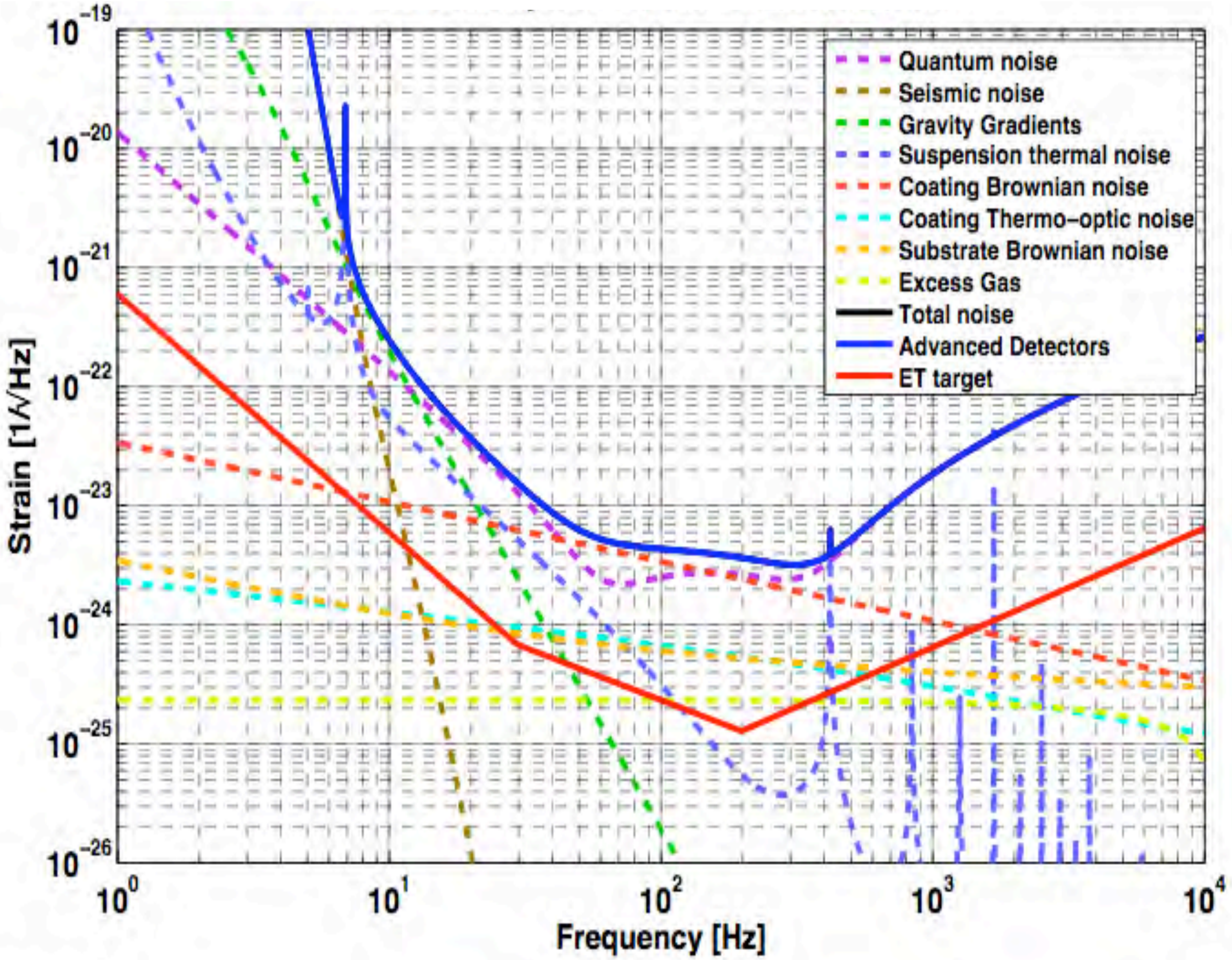
Challenges

some examples for interesting new ideas or challenges



Improving technology





- Reducing the self noise by improving each subsystem of the detector.
- State-of-the-art research on laser, materials, cryogenics, …

https://gwic.ligo.org/3Gsubcomm/documents/GWIC_3G_R_D_Subcommittee_report_July_2019.pdf

Examples for 3G challenges

- the identification of a facility site with low seismic and acoustic noise, and other suitable environmental properties
- development of mitigation techniques for Newtonian noise
- development of low-noise, efficient cryogenic mirror suspension
- the production of large, high-quality test mass substrates, both silica and silicon or sapphire
- the polishing and coating of large test mass substrates to very low spatial roughness at larger spatial scales
- the development of suitable mirror coatings
- the development of multi-stage suspensions supporting test masses of several 100 kg
- the development lower cost vacuum technology for ultra-high vacuum in vacuum chambers and the beam tubes
- …

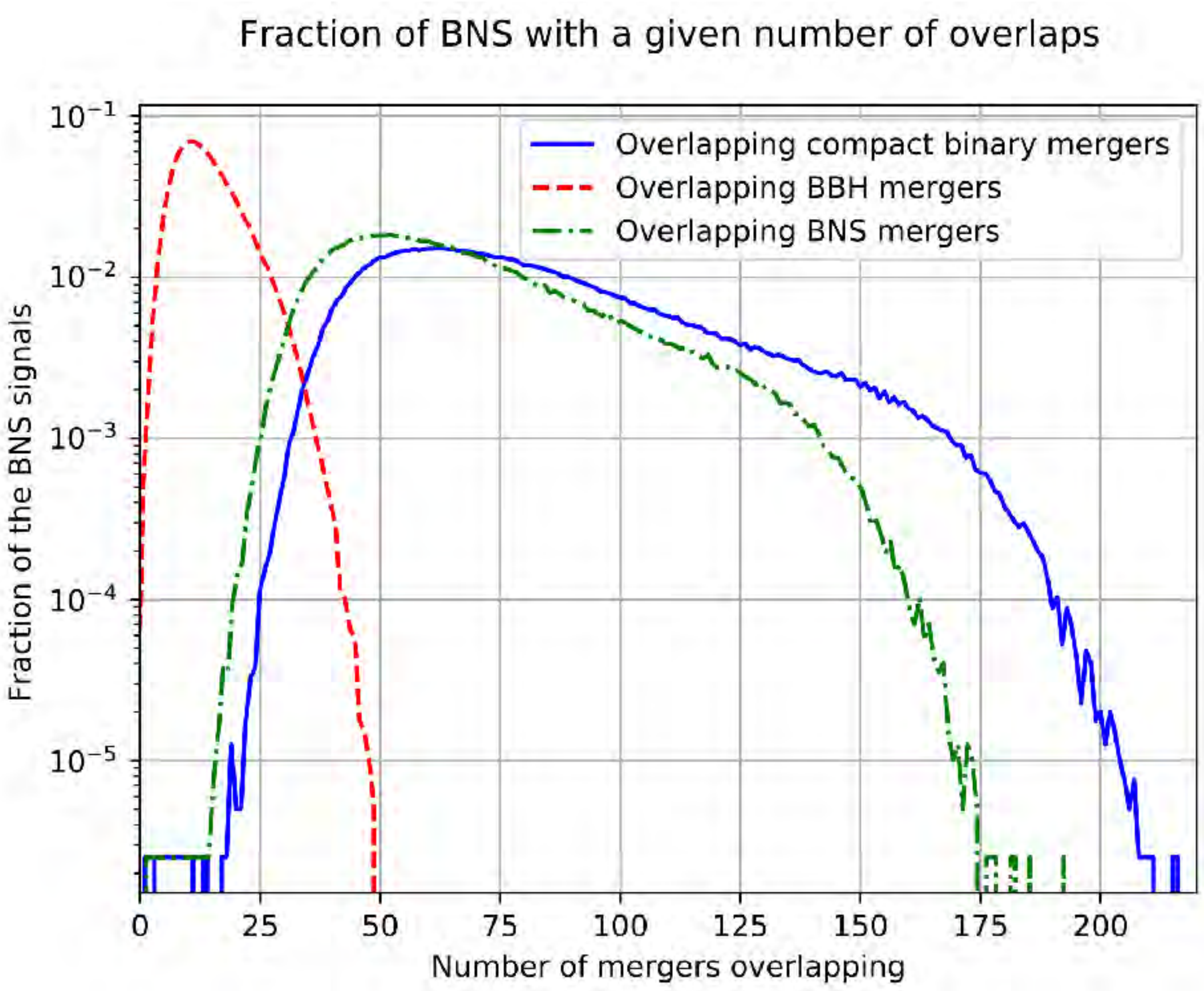
[adapted excerpts from ET and CE design studies]

Selected stories: What happens …

- with much better sensitivity
- when we chose cryogenic silicon
- when we need a 40km long site
- with very long interferometer arms
- when we push for low-frequency signals
- with a triangle detector shape
- when we design a large underground infrastructure

With better sensitivity...

Overlapping signal

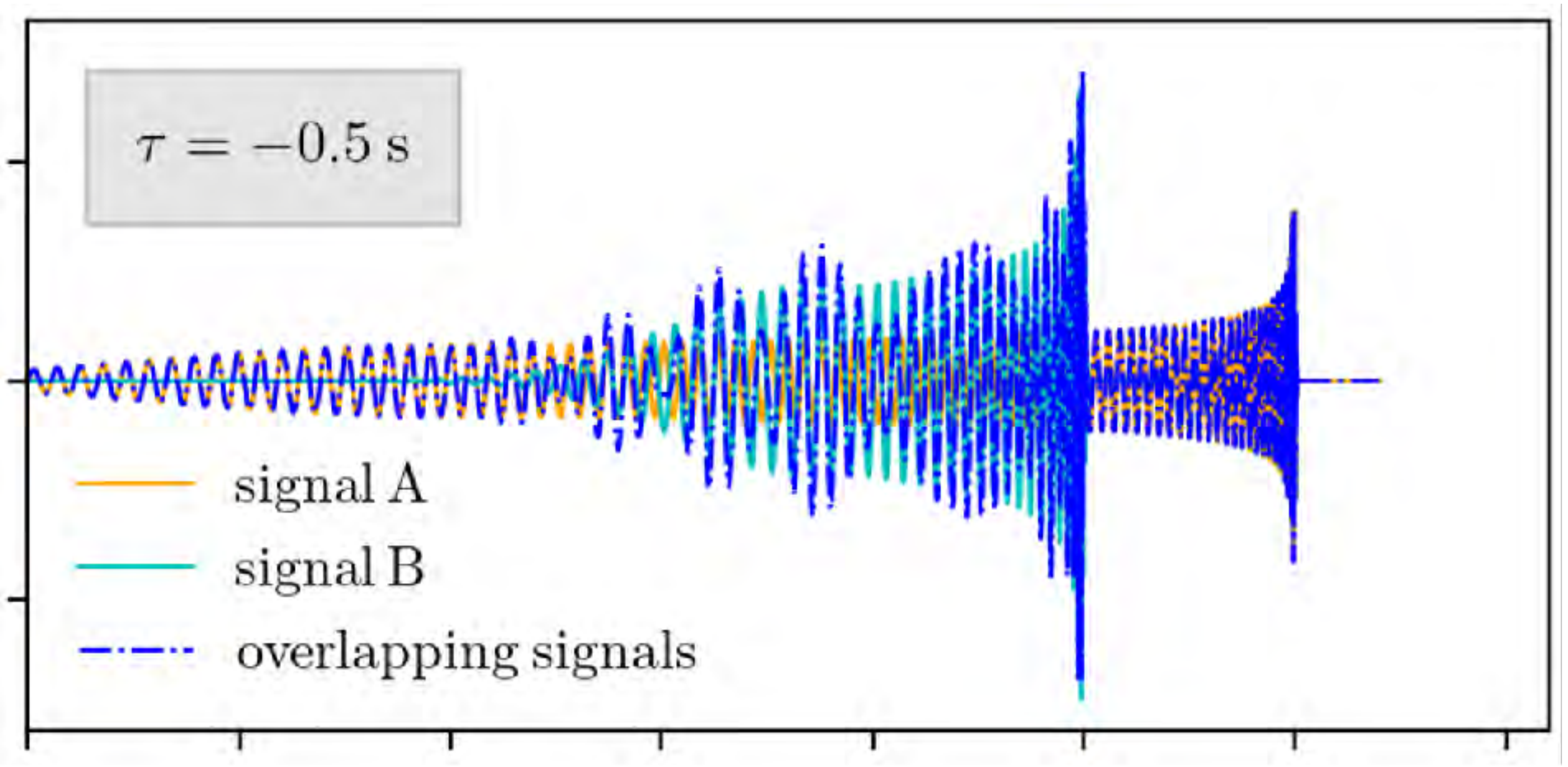


	# of detections	SNR_{net}	# with $SNR_{net} > 250$	# with $SNR_{net} > 100$	# with $SNR_{net} > 50$
BBH					
Low rate	53756	$81.1^{+94.2}_{-57.3}$	3069 (5%)	20605 (35%)	40063 (68%)
Median rate	85725	$81.3^{+93.9}_{-57.5}$	4972 (5%)	33148 (39%)	63958 (75%)
High rate	137225	$81.5^{+94.2}_{-57.4}$	7860 (6%)	53419 (39%)	102766 (75%)
BNS					
Low rate	98898	$19.2^{+22.1}_{-4.9}$	17 (0.017%)	298 (0.30%)	2712 (2.7%)
Median rate	396793	$19.1^{+22.0}_{-4.8}$	73 (0.018%)	1257 (0.32%)	10659 (2.7%)
High rate	1004525	$19.1^{+22.1}_{-4.8}$	196 (0.020%)	3255 (0.32%)	27135 (2.7%)

The number of events detected by a network of two CEs and one ET in one year of simulated data

https://arxiv.org/abs/2102.07544
https://arxiv.org/abs/2102.07692

Overlapping signal



- 3G detectors will roughly have the same data rate as current detectors, but the very large amount of signals pose challenge for parameter estimation pipelines

- When two signals are overlapping with less than 2 seconds separation (merger time) there can be significant biases in the parameter estimation for shorter/weaker signal.

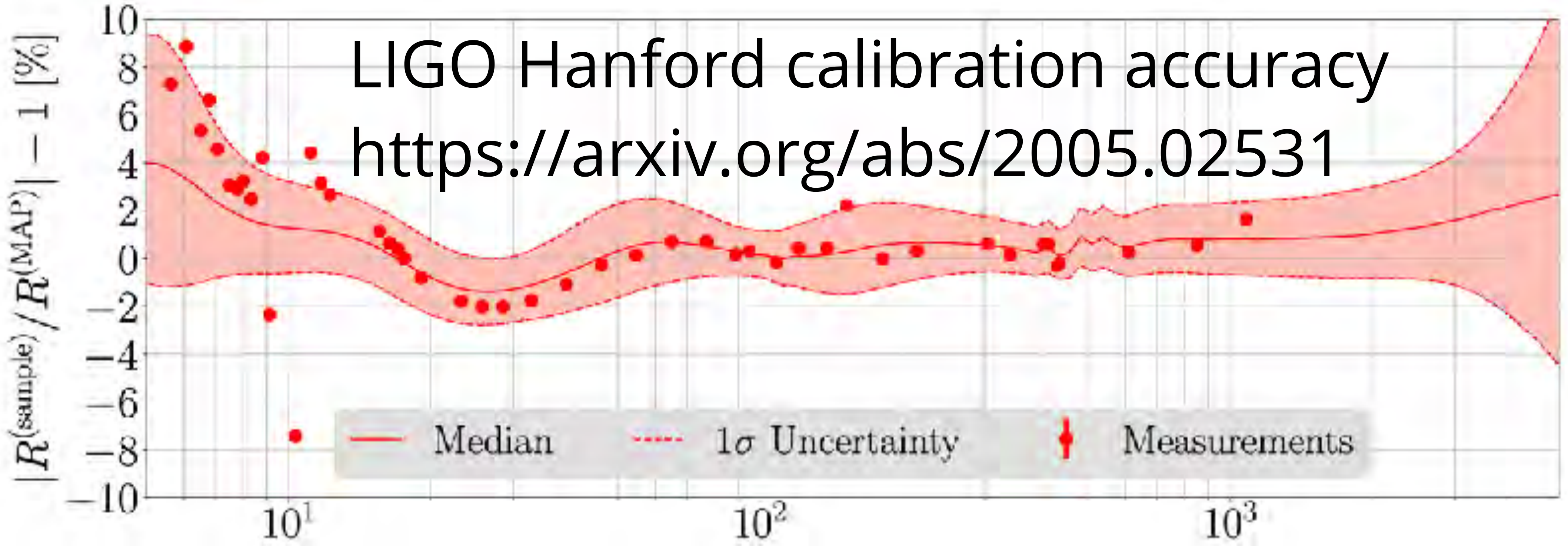
https://arxiv.org/abs/2102.07544
https://arxiv.org/abs/2102.07692

Calibration must improve as much as SNR

- 3G detectors such as ET will require sub-one-percent calibration accuracy in order to fully benefit from their increased sensitivity

- Self-calibration, i.e. calibrating the detector using the detected signal and null-streams can help to achieve that.

- ET provides such a null-stream stand-alone, which is sky-position and polarisation independent (this is not the case for a distributed network).



LIGO Hanford calibration accuracy
https://arxiv.org/abs/2005.02531

Self-calibration of Networks of Gravitational Wave Detectors

Bernard F. Schutz
School of Physics and Astronomy, Cardiff University, Cardiff, UK, CF24 3AA and Max Planck Institute for Gravitational Physics (Albert Einstein Institute), 14476 Potsdam/Golm, Germany

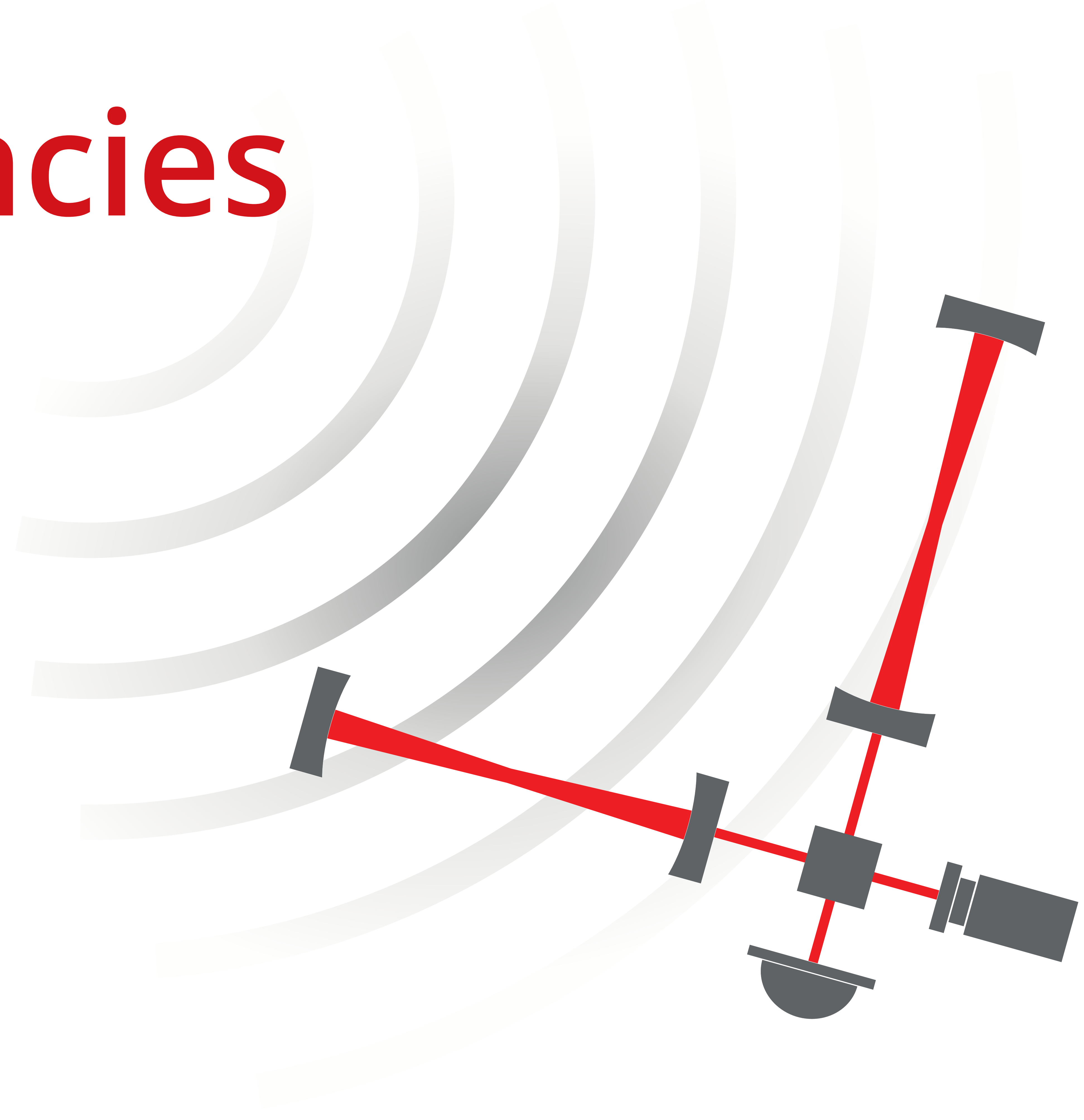
B. S. Sathyaprakash

September 2020, https://arxiv.org/abs/2009.10212

B. Sky-independent null stream

The design of the proposed 3G detector ET envisages three V-shaped interferometers, one each at the three vertices of an equilateral triangle. The sum of the responses of the three interferometers, as we shall see below, is a null stream no matter where the source is in the sky. In fact, this is true more generally for any configuration that has a closed topology. Consequently, self-calibration with ET is significantly simpler.

Going for low-frequencies



New special focus: noise at low freqencies

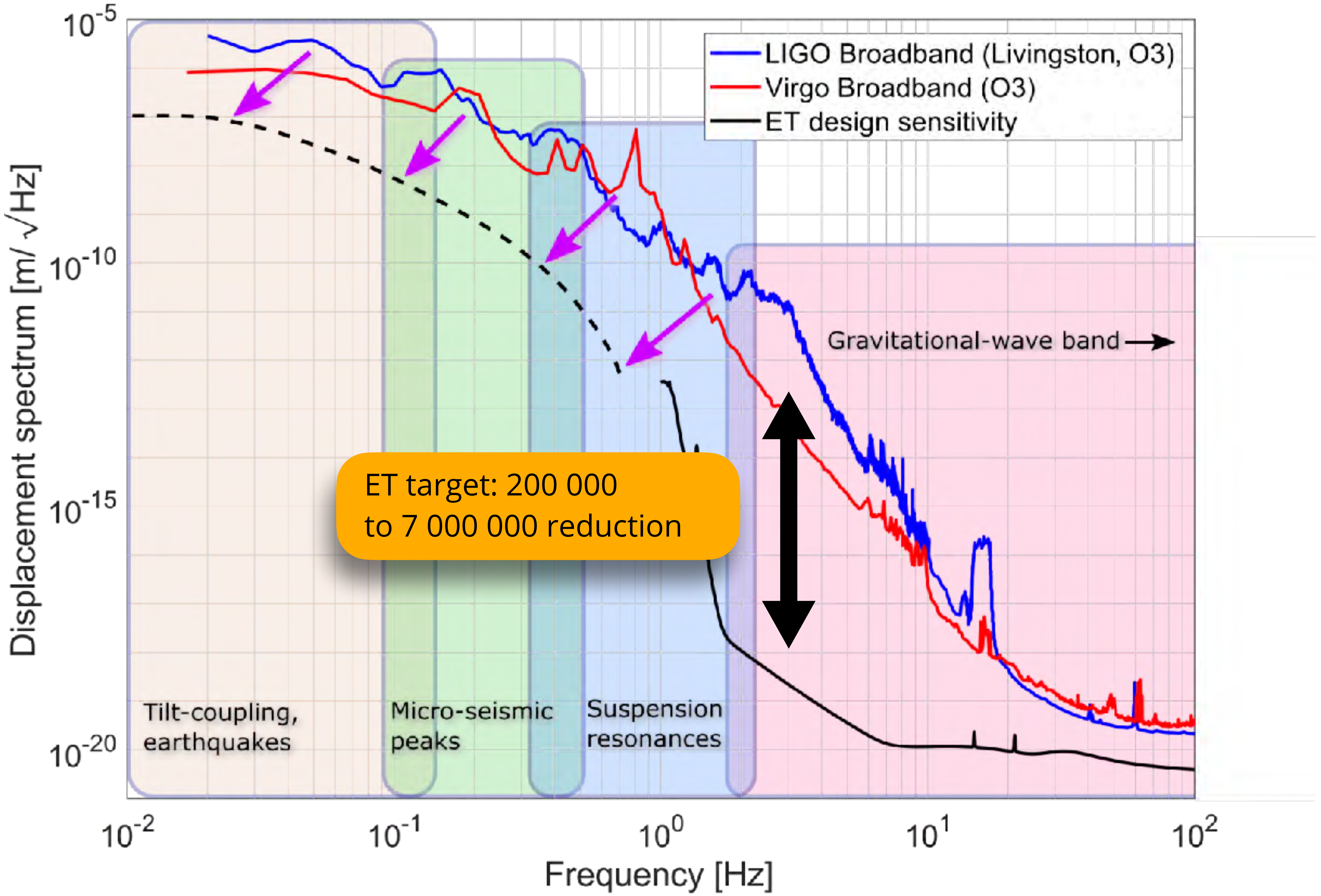
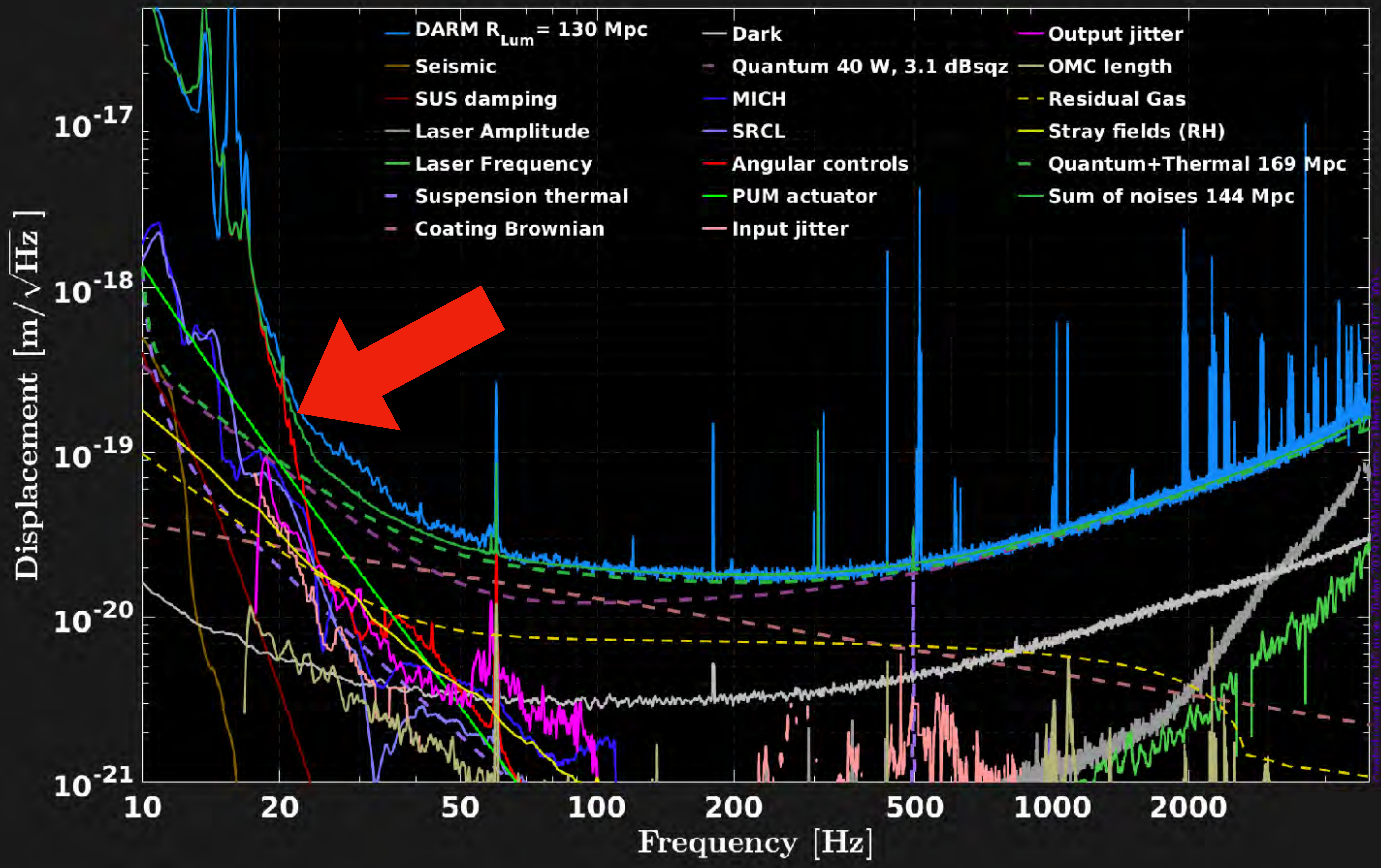


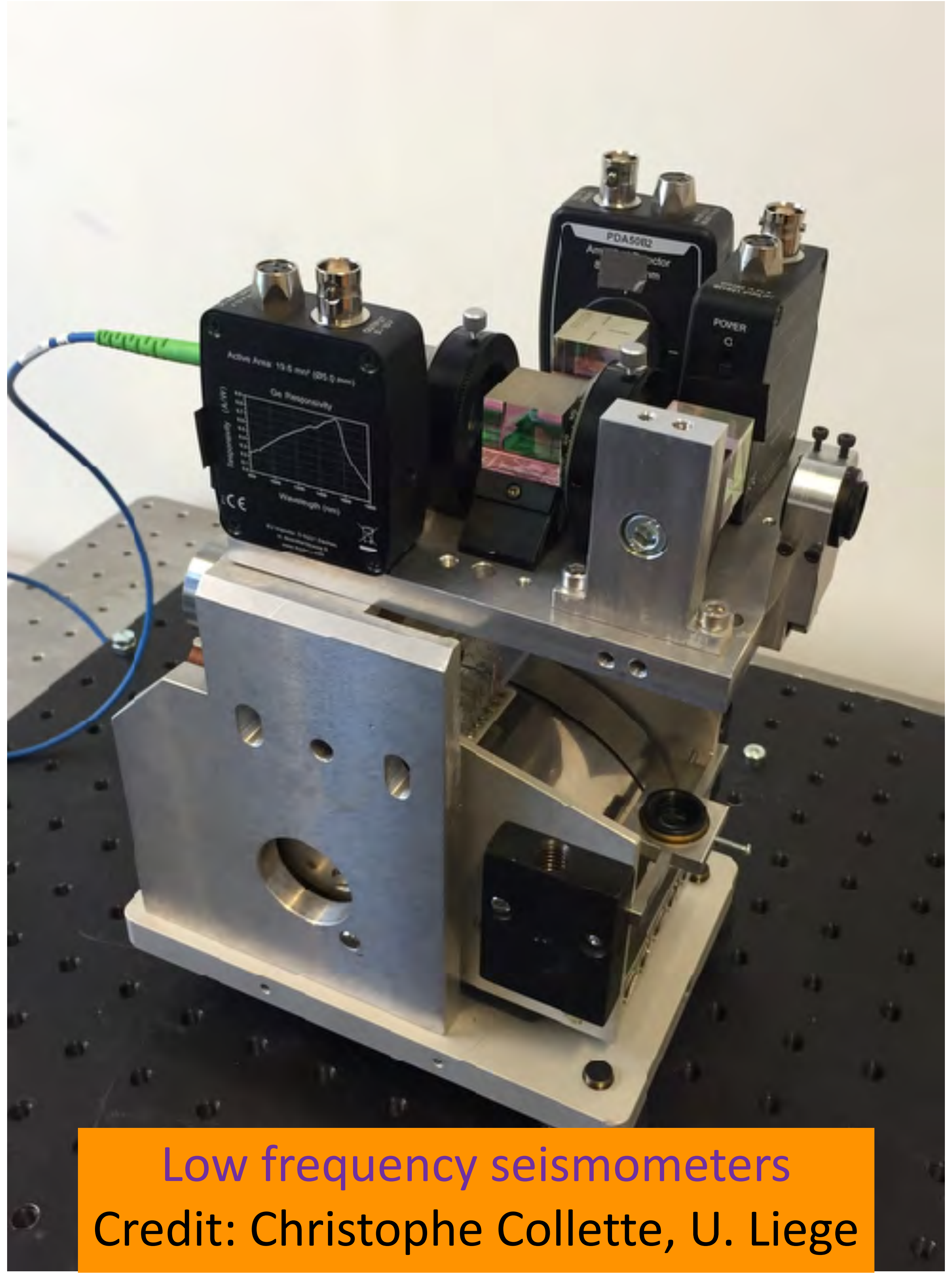
Image: Conor Mow-Lowry

LIGO Livingston Noise budget 27.03.2019

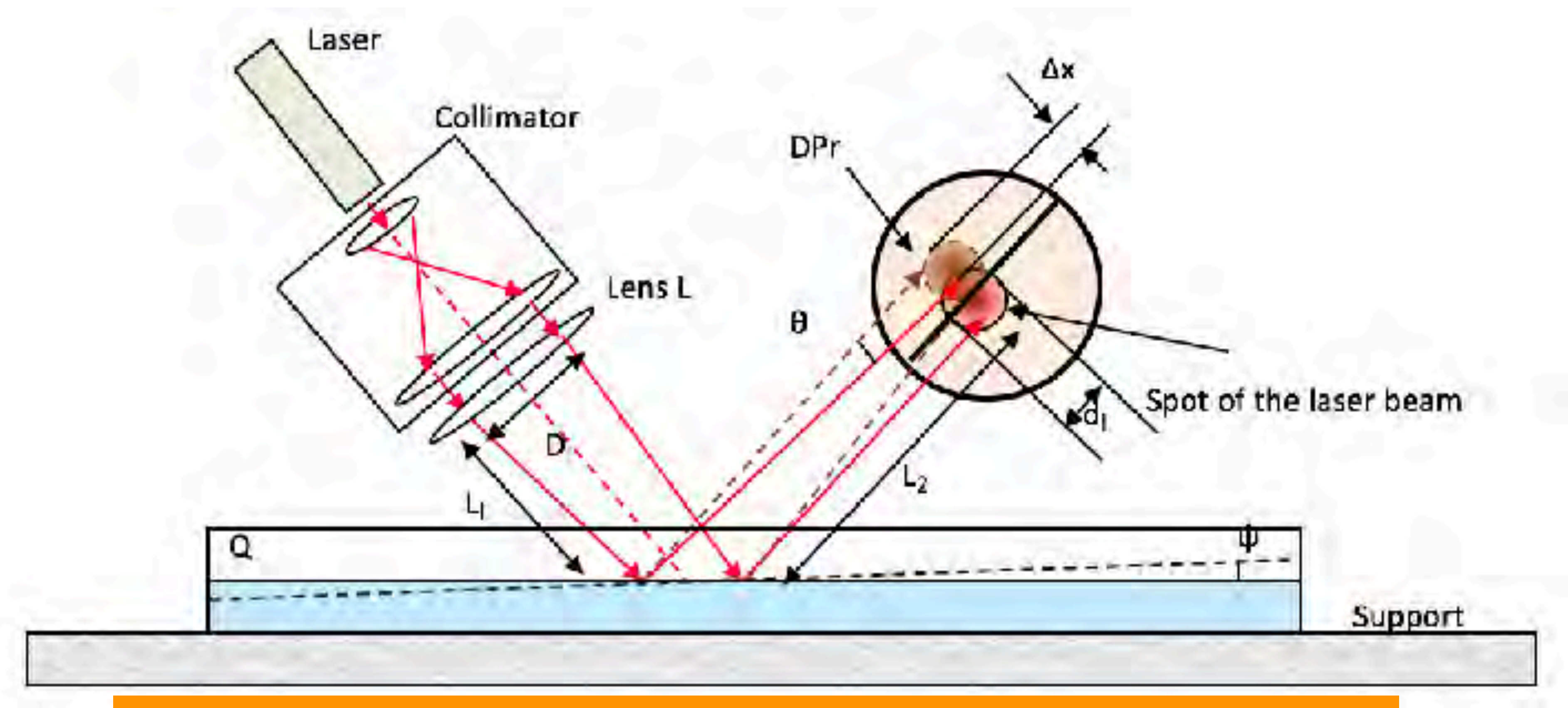


R&D example: advanced seismic sensors

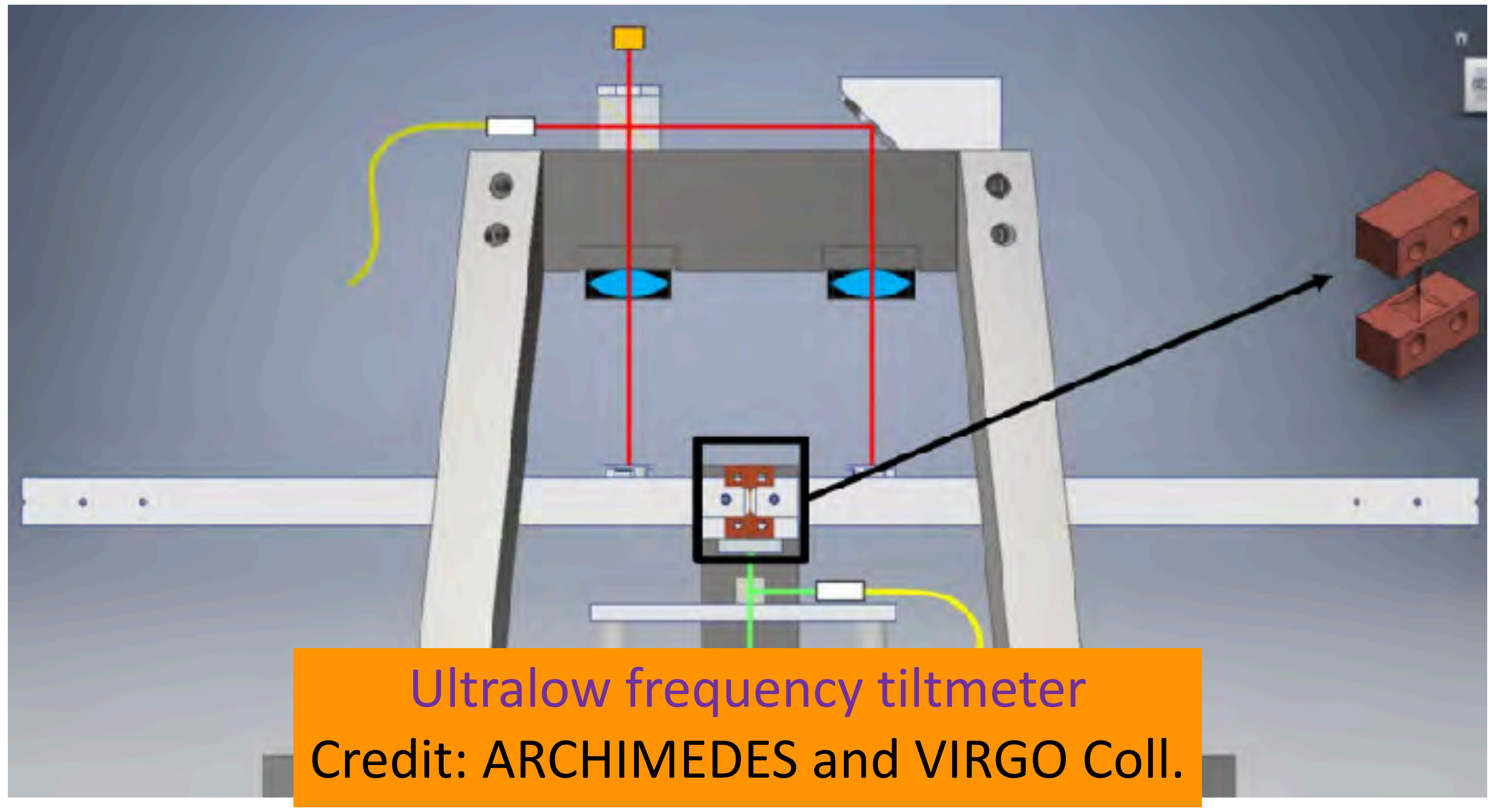
6-D interferometric readout inertial sensor
Credit: Conor Mow-Lowry, VU Amsterdam



Low frequency seismometers
Credit: Christophe Collette, U. Liege



Laser inclinometer, Credit: B. Di Girolamo, CERN

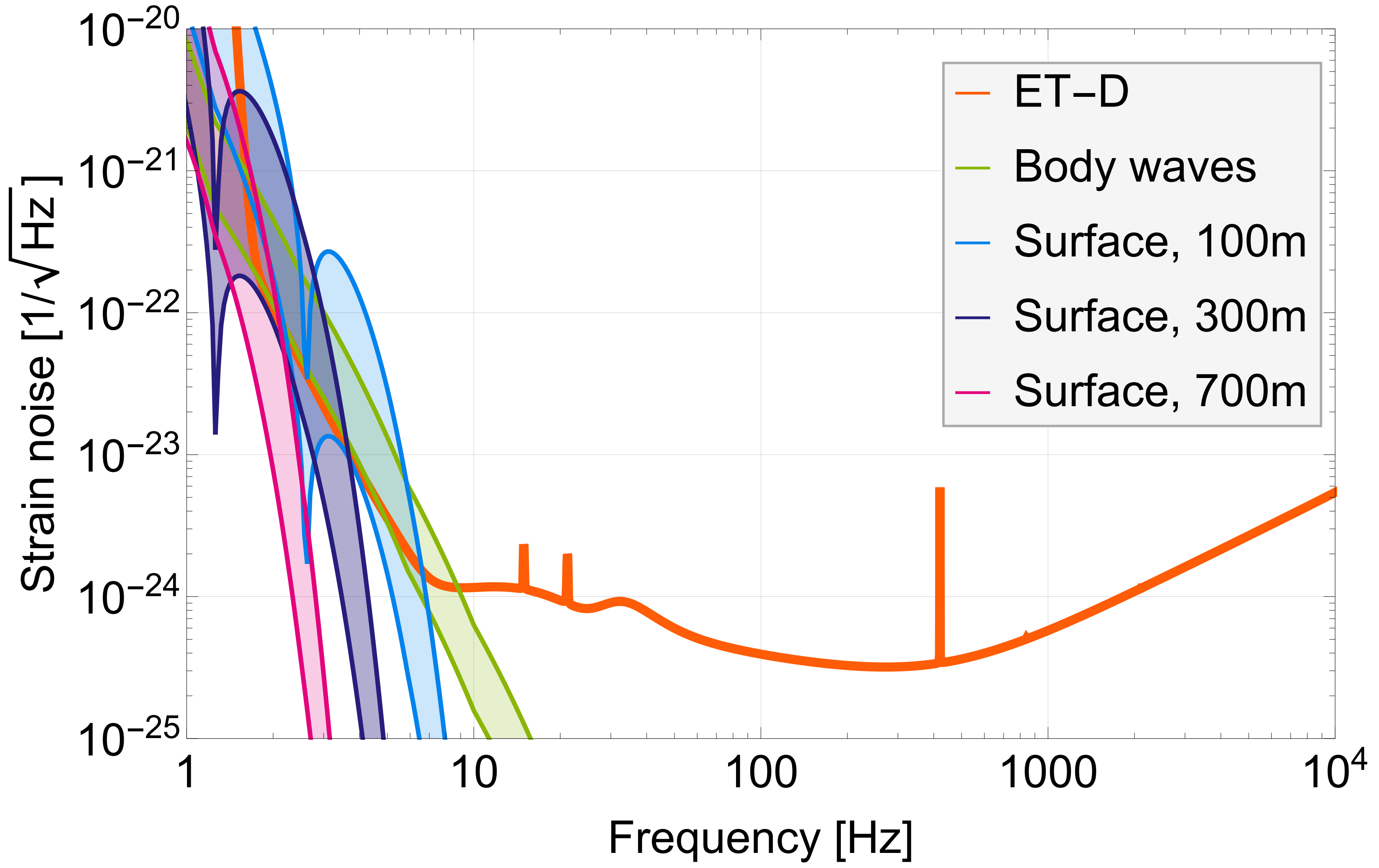


Ultralow frequency tiltmeter
Credit: ARCHIMEDES and VIRGO Coll.

Goal: inertial control at low frequencies for suspension shortening and RMS motion suppression

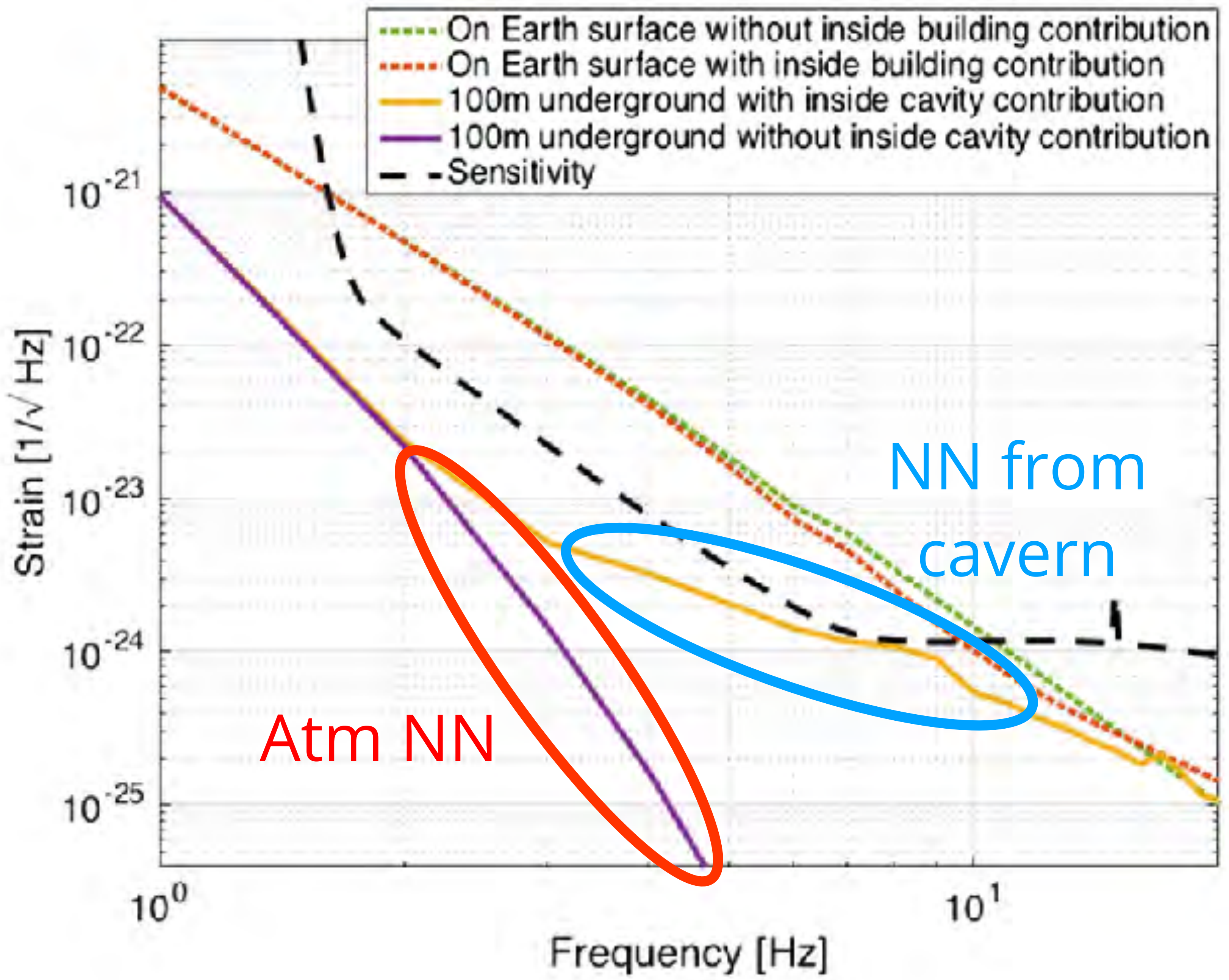
Underground and low noise

Seismic Newtonian noise (NN)



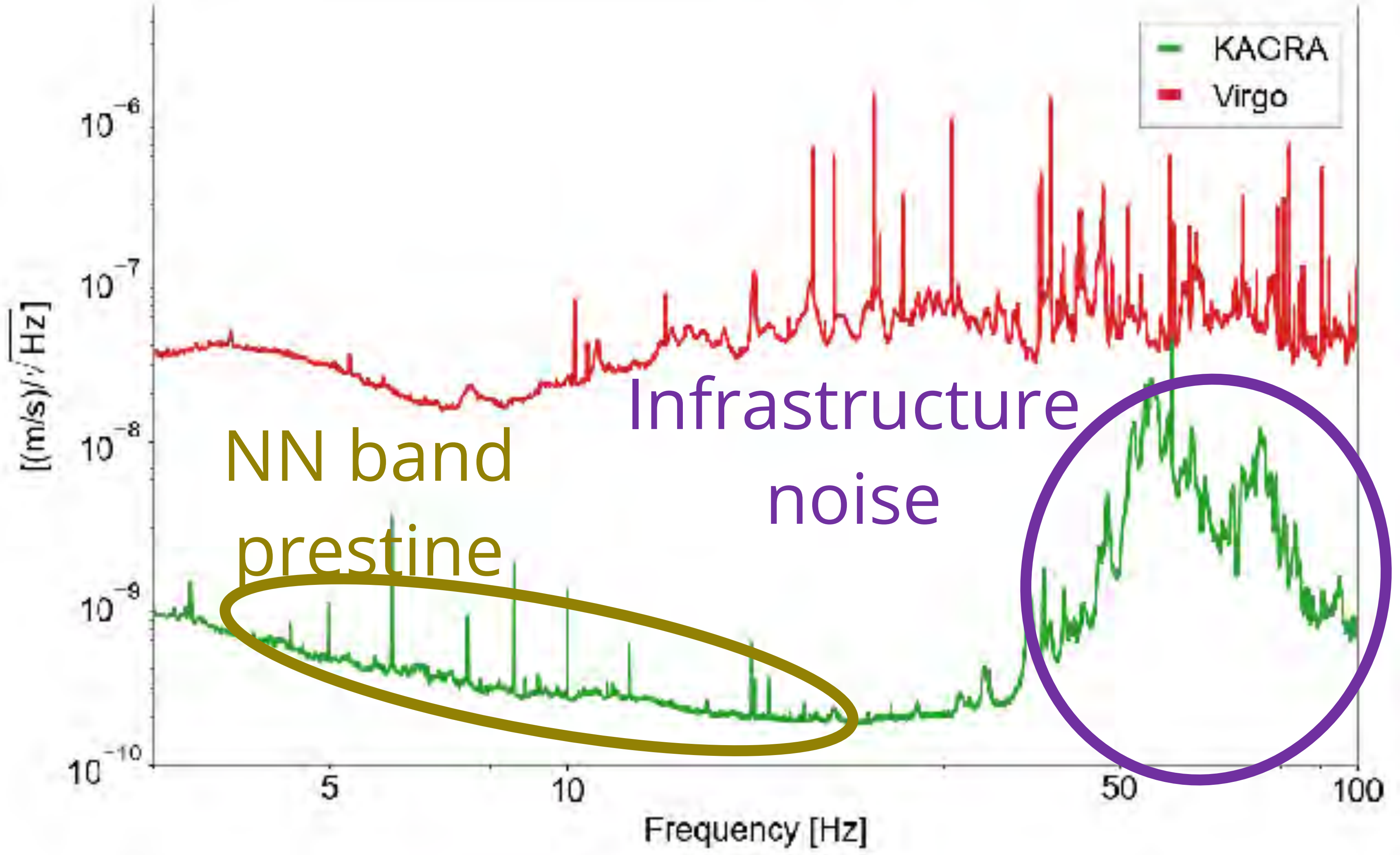
ET is planned >200m underground. Further mitigation of NN from seismic surface and underground fields might be achieved with noise cancellation using arrays of seismometers.

Acoustic NN



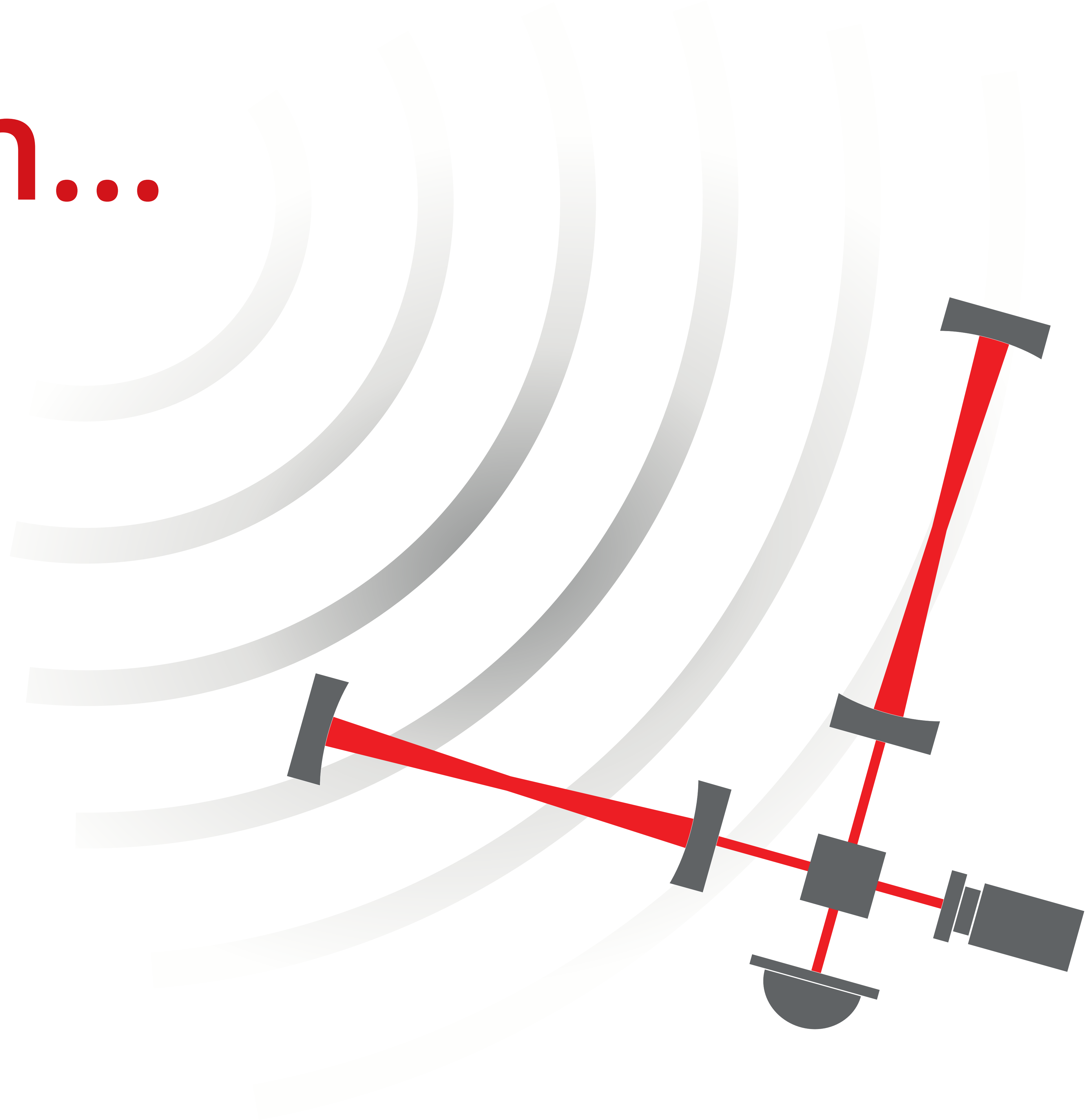
Atmospheric NN cancellation would be extremely challenging due to lack of a good monitoring system. ET can avoid it by going underground!

Low-noise environment



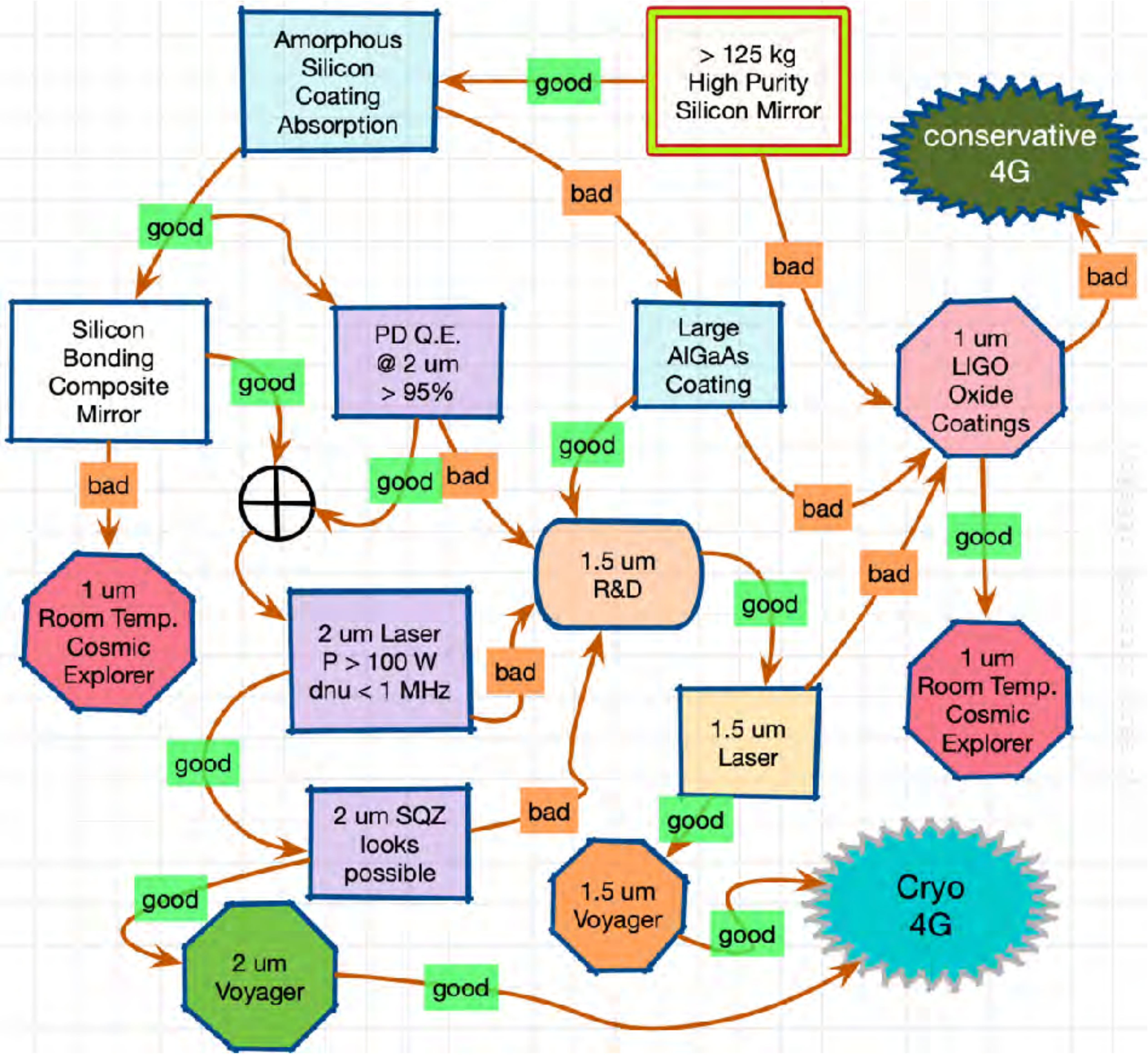
We must create a low-noise infrastructure. If KAGRA can do it (not creating excess noise in the NN band), so can the Einstein Telescope.

With cryogenic silicon…



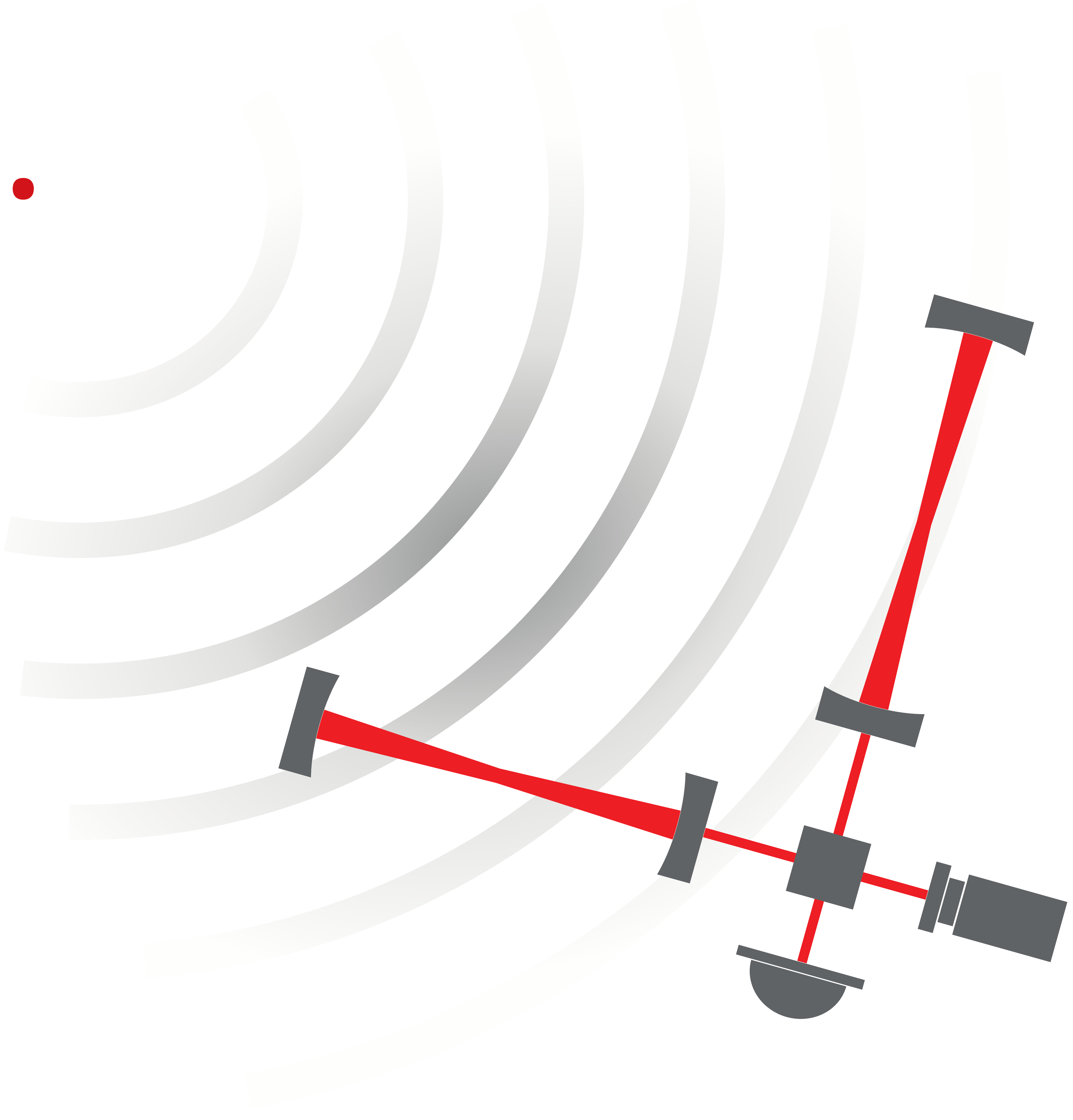
Cryogenics and laser wavelength

- Cryogenic mirrors and mirror suspensions can significantly reduce the thermal noise
- This requires change of material as fused silica does not show this effect. Alternatives crystalline materials such as silicon and sapphire
- Silicon cannot be operated at 1u, different wavelength is requires
- Wavelength change impacts many aspects of the interferometer and depends on many technology developments



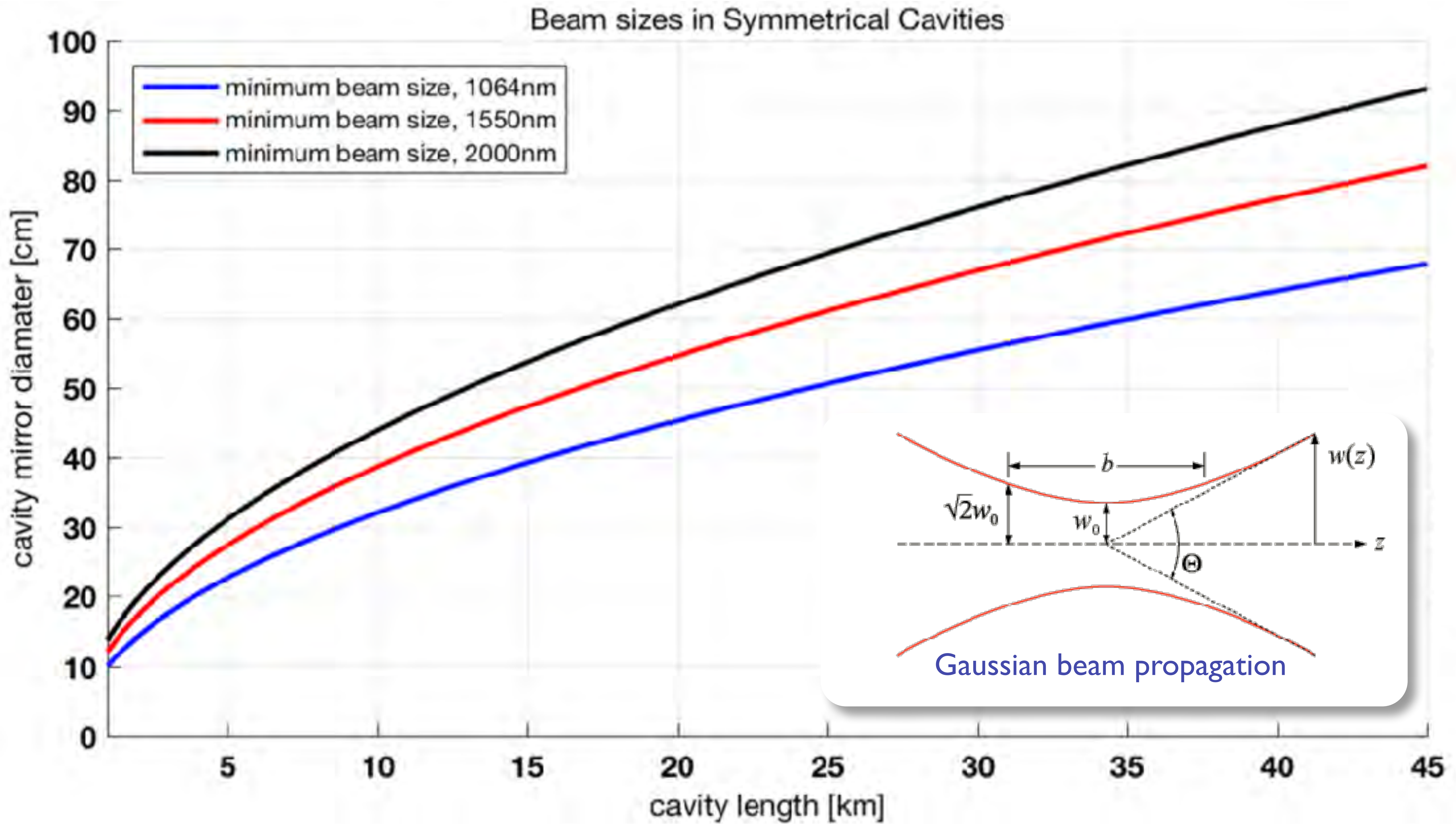
Rana Adhikari GWADW 2018

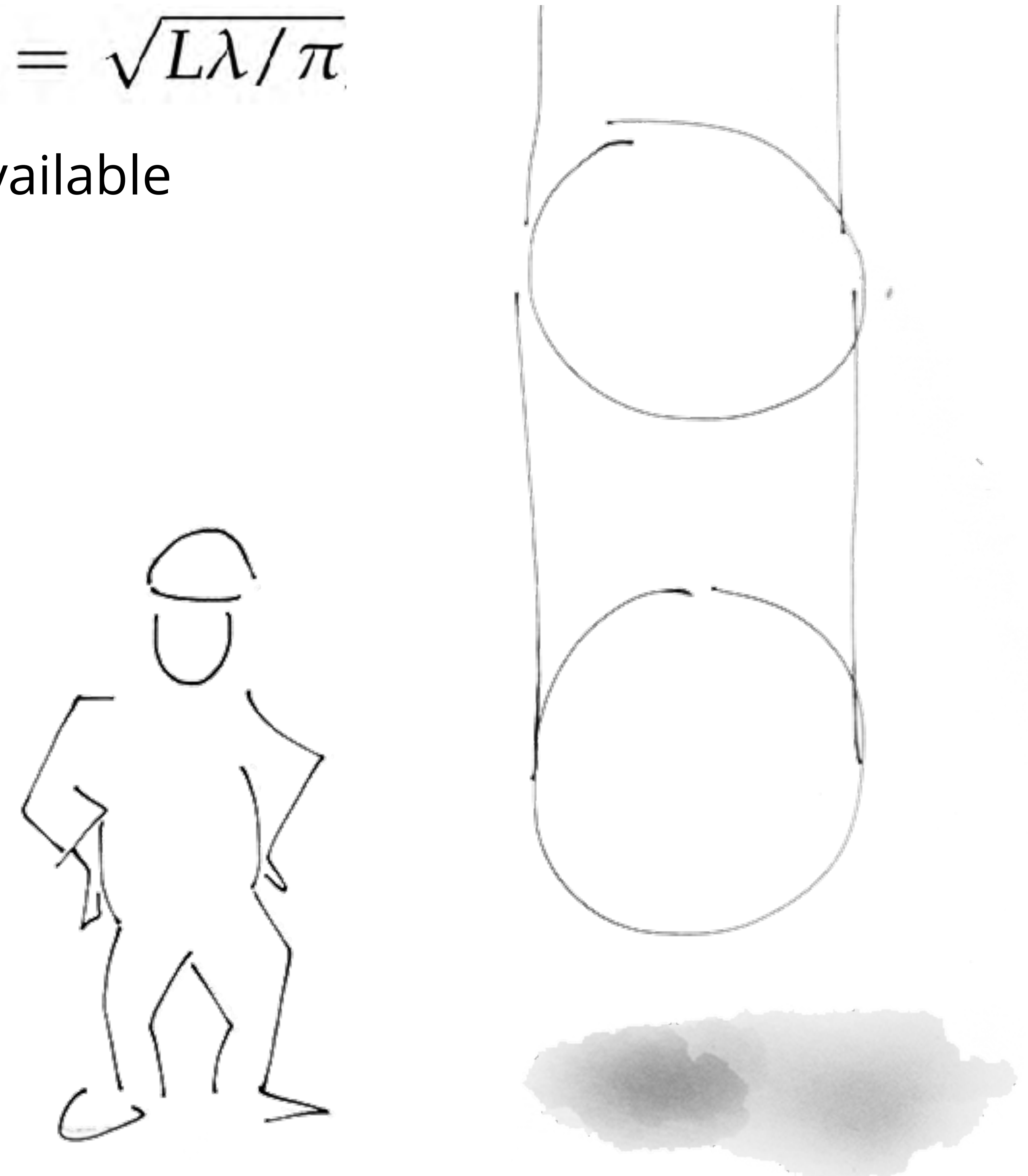
With very long arms...



Long arms make wide beams

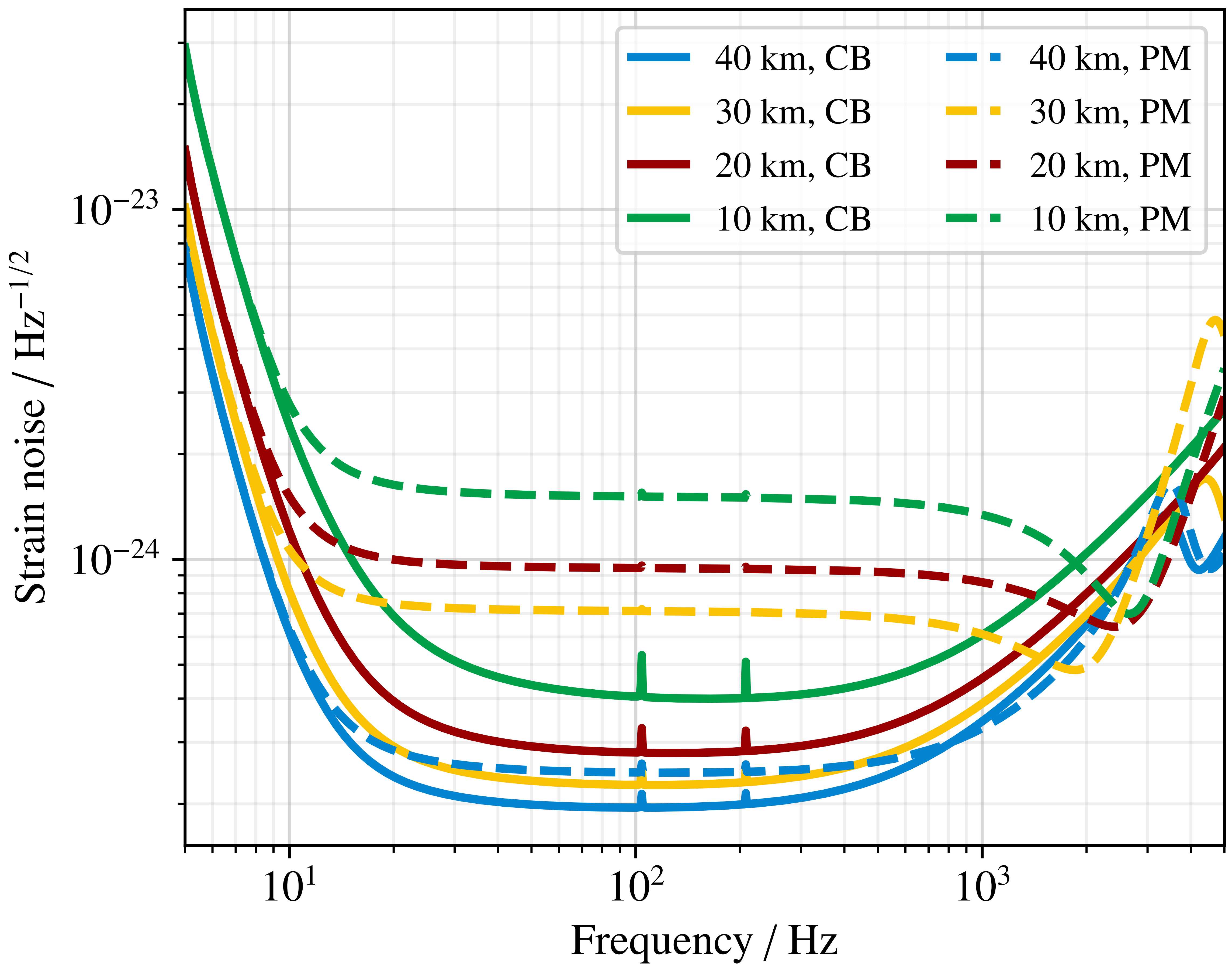
- Laser beams cannot be fully collimated. They are diverging due to diffraction
- For a given interferometer arm, there is a minimal beam width $w_{\min} = \sqrt{L\lambda/\pi}$
- Coating thermal noise scales as 1/w, but large enough mirrors not yet available





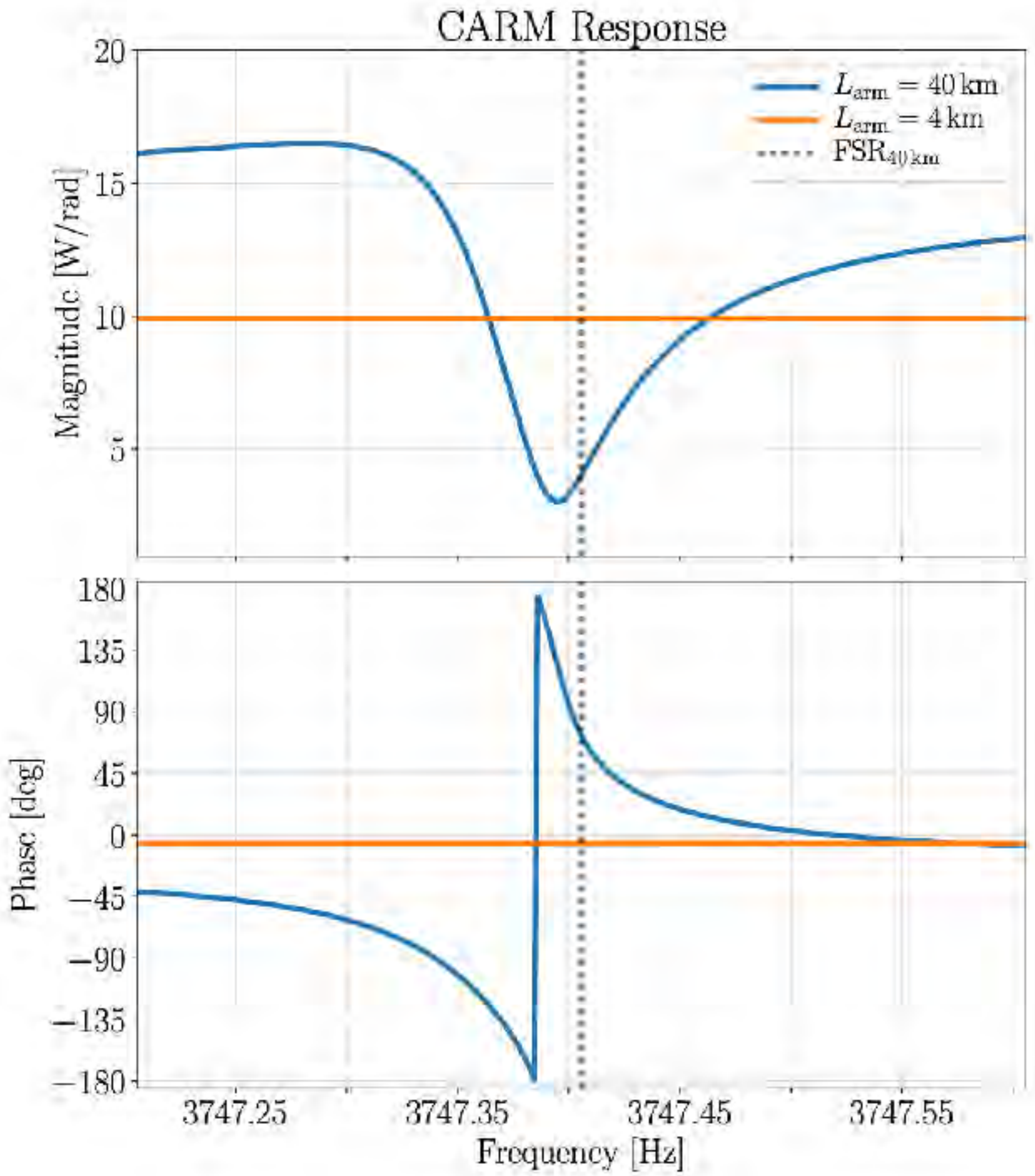
Long arms (CE: 40km and 20km)

- The free-spectral range (FSR) of about 3.7 kHz for a 40km interferometer coincides with a decrease in sensitivity at frequencies of most interest for post merger science.
- Signal recycling allows changing the detector response at low-cost (change one mirror), e.g. changing from broadband to narrowband operation.
- 20km is the right length for 2-3kHz signals in a narrowband configuration optimised for **post-merger** observations.
- 40km is better when operating for boradband **compact binary** detection.



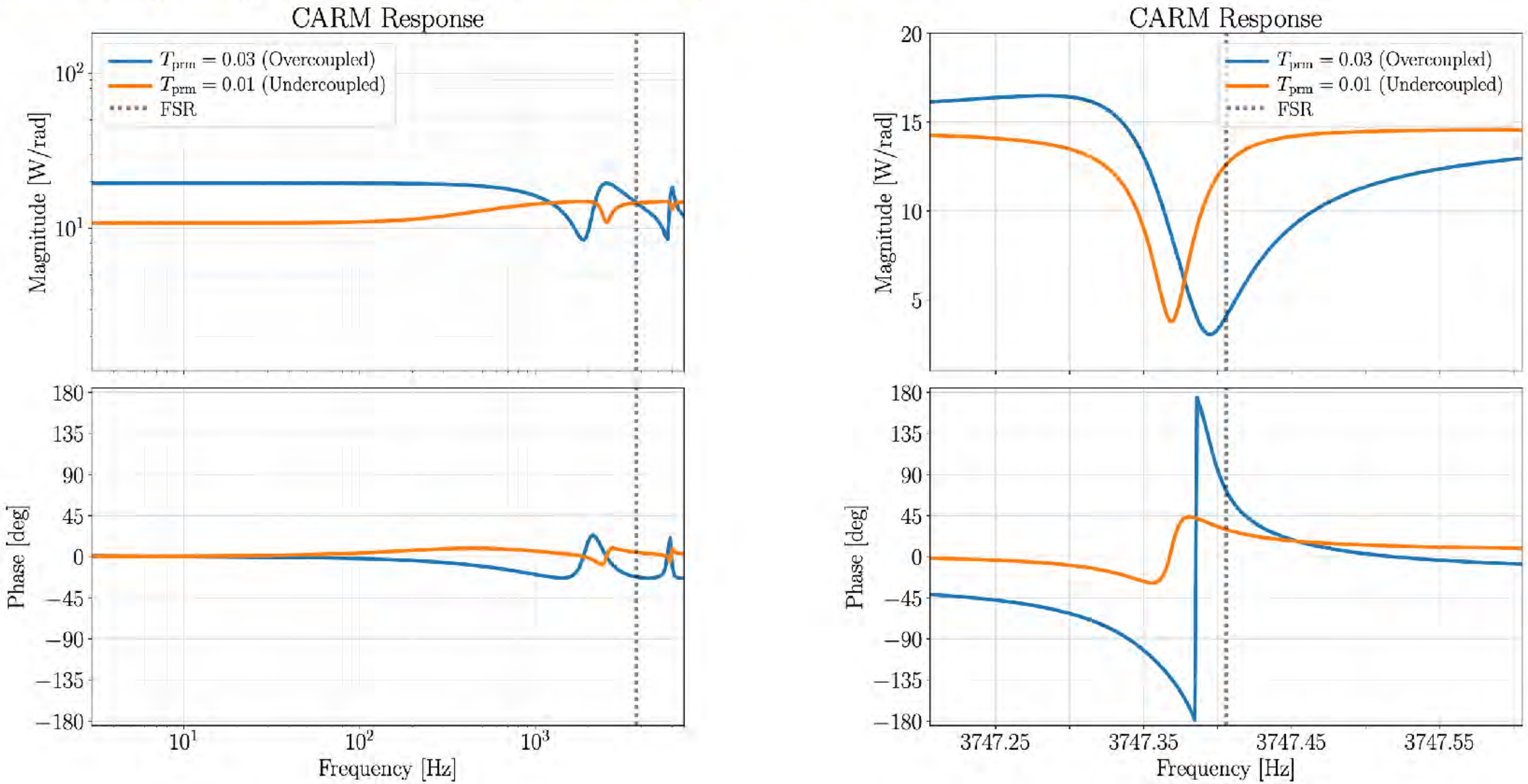
Frequency Stabilization

- In LIGO, the laser frequency is stabilized in three steps. In the last step the frequency is stabilized to the common arm length of the interferometer with a loop with a bandwidth of about 20 kHz.
- FSR of LIGO is 37.5 kHz but for CE is 3.75 kHz.
- Right half-plane zeros at the FSR makes this difficult to control.



Kevin Kuns
https://agenda.infn.it/event/15928/contributions/89737/attachments/63320/76221/main.pdf

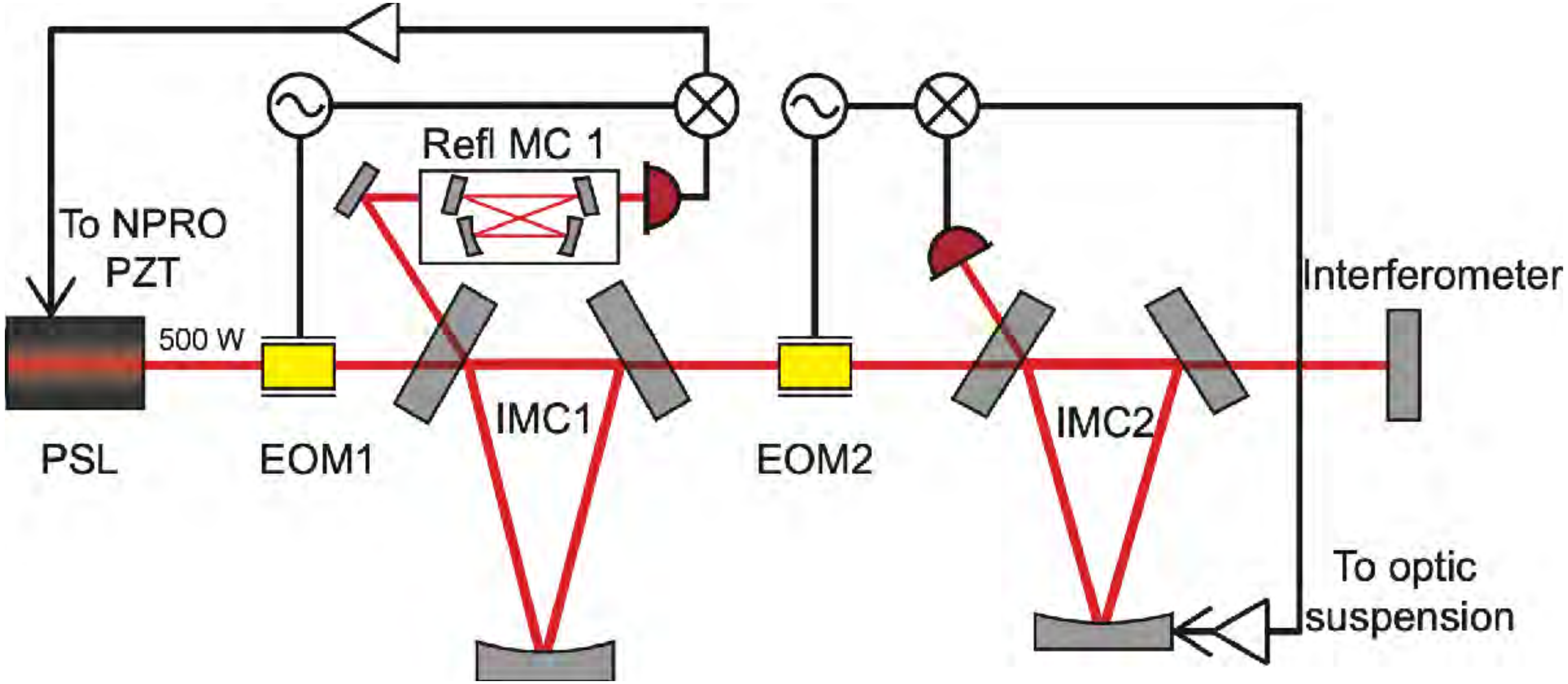
Undercoupling leads to left half plane zeros



Kevin Kuns
https://agenda.infn.it/event/15928/contributions/89737/attachments/63320/76221/main.pdf

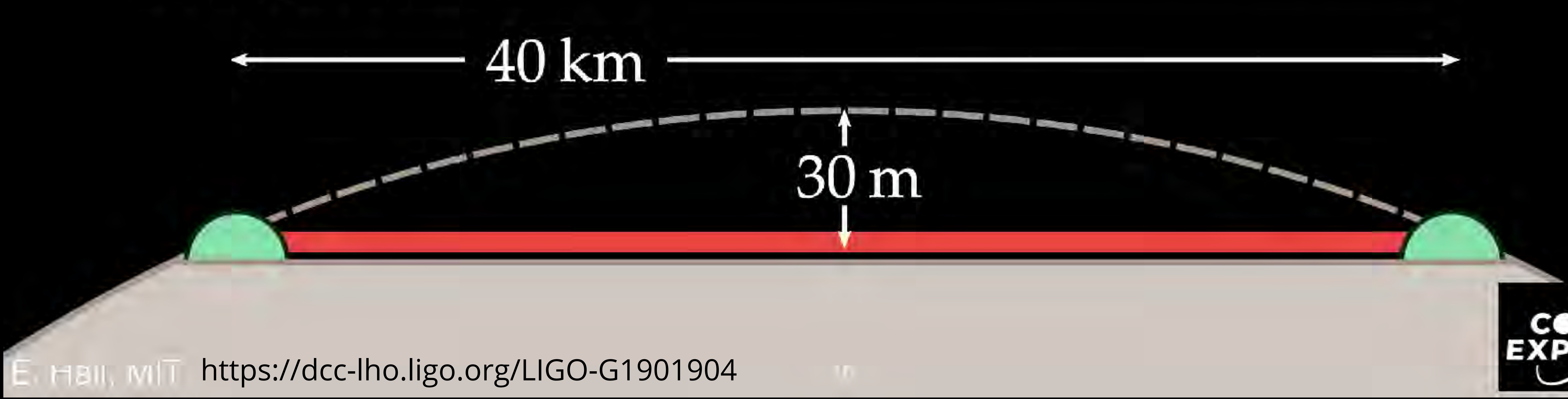
Frequency stabilisation scheme using 2OMC for passive filtering

Cavity	Length	Bandwidth	Note
Reference cavity	20 cm	500 kHz	Optional
Input mode cleaner 1	100 m	100 kHz	High BW feedback to laser frequency
Input mode cleaner 2	90-330 m	30 Hz	Low BW feedback to IMC2 suspension
Common-arm length	10-40 km	200 Hz	Low BW feedback to arm suspensions



Site search, CE example

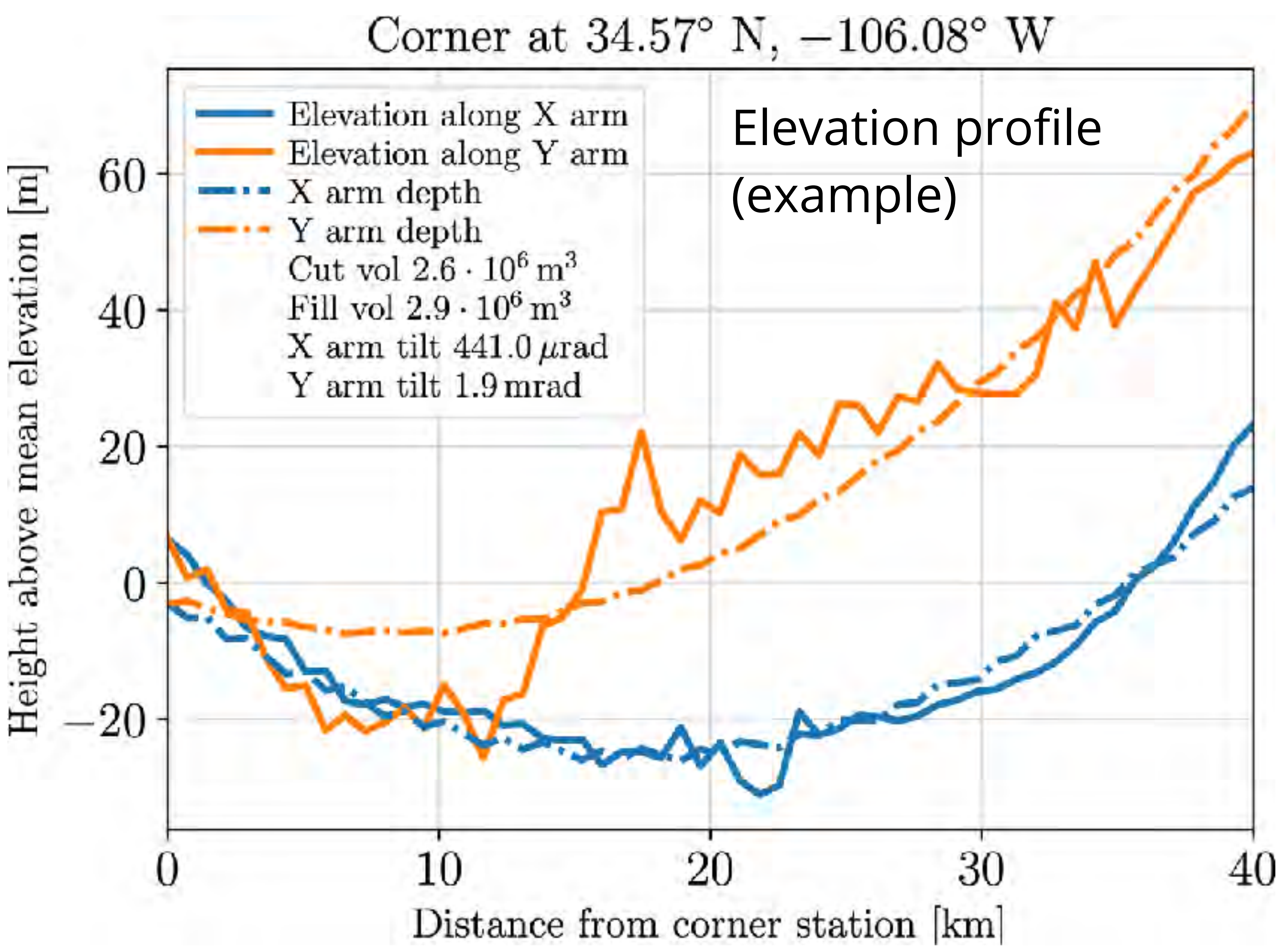
- 20km and 40 km flat surface site
- low seismic noise
- frequency of earthquakes and likelihood of natural disasters
- need to study potential cultural, environmental, socio-economic, political, and other impacts of hosting a large observatory.



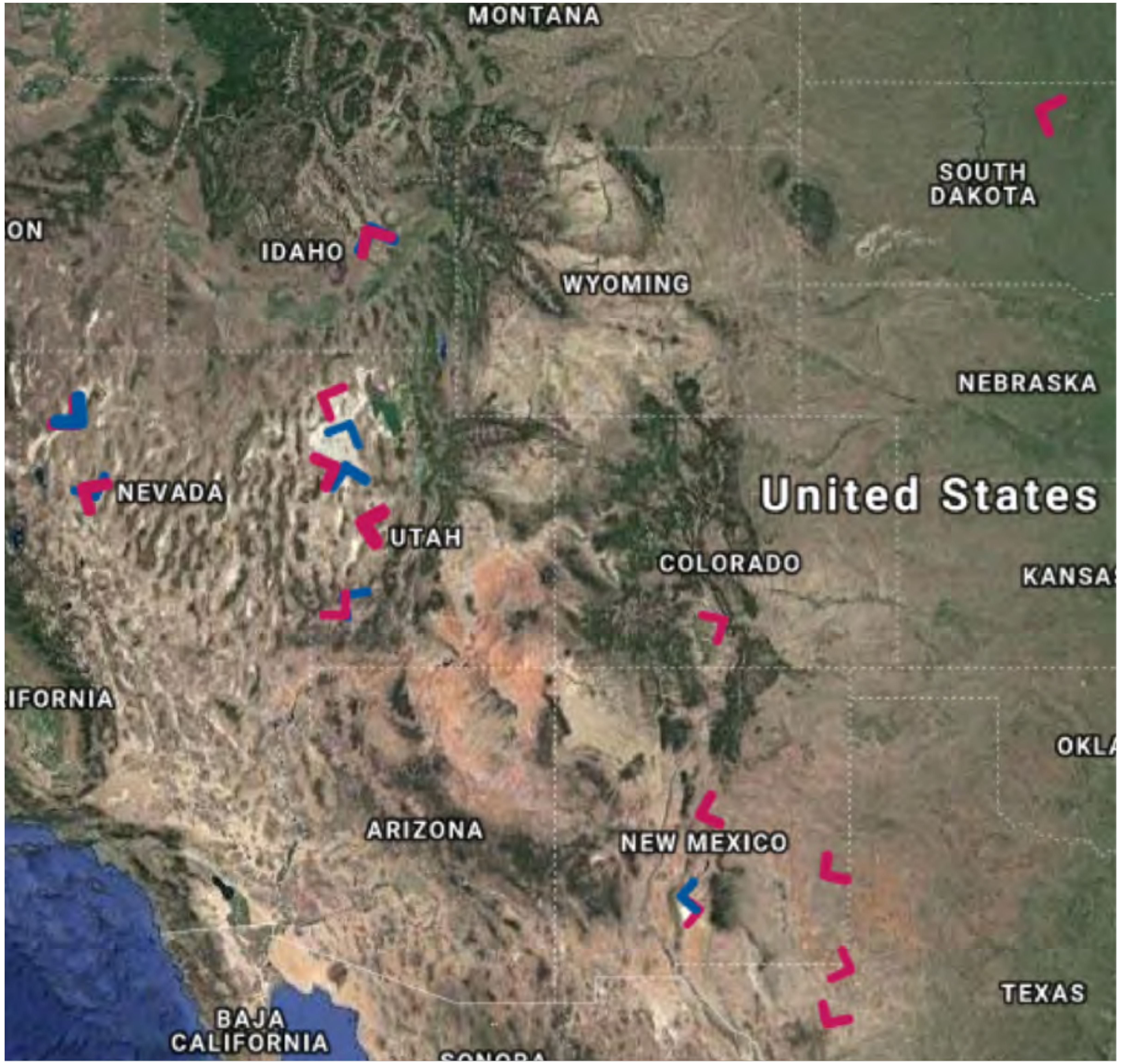
https://dcc-lho.ligo.org/LIGO-G1901904

COSMIC EXPLORER

Site search example, optimise for earth removal



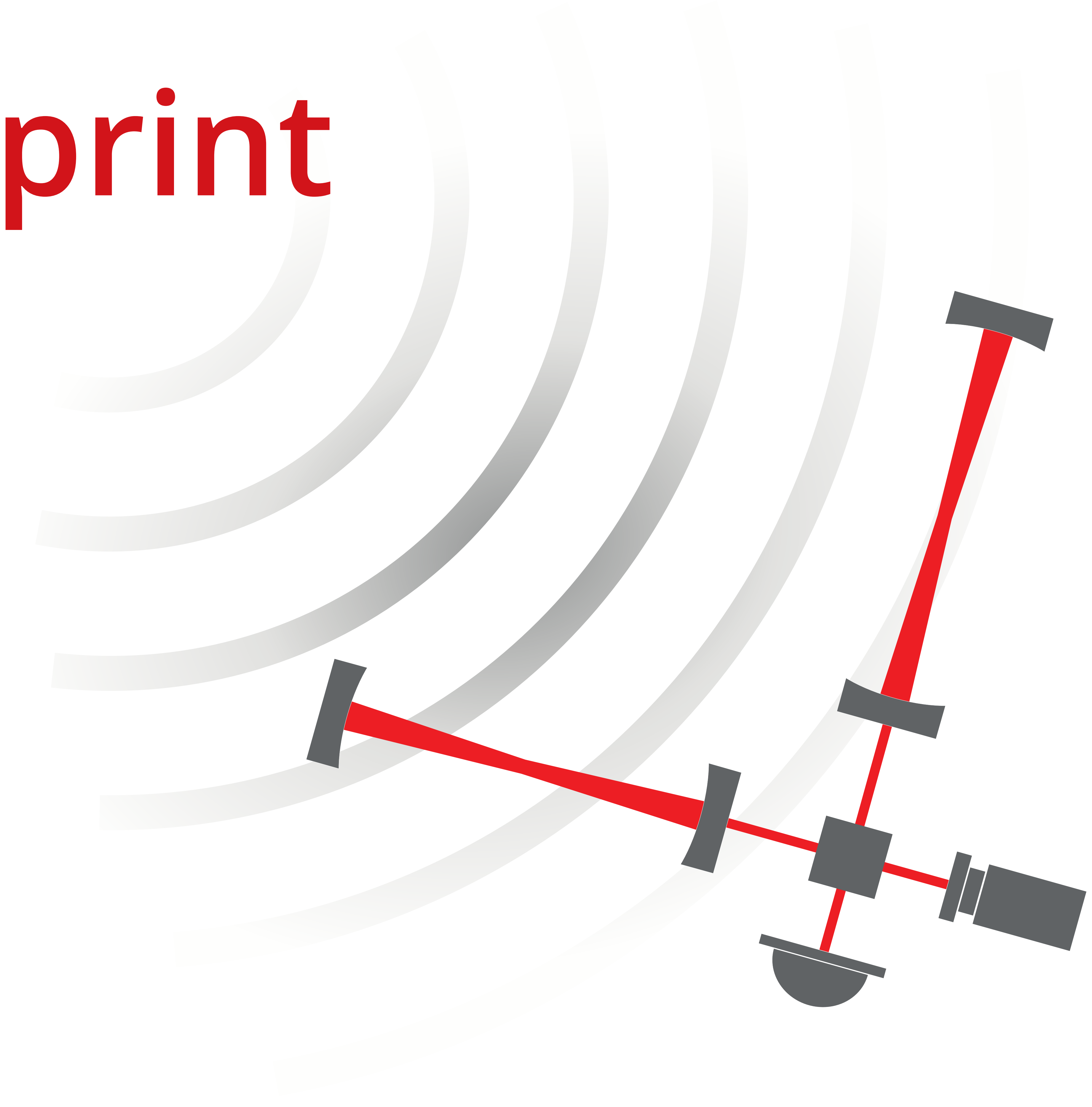
Elevation profile (example)



Well-chosen sites require moving of less than 5 x 10^6 m^3 of dirt, compared to ~10^7 m^3 for a flat site.

Kevin Kuns https://dcc-lho.ligo.org/LIGO-G1901564

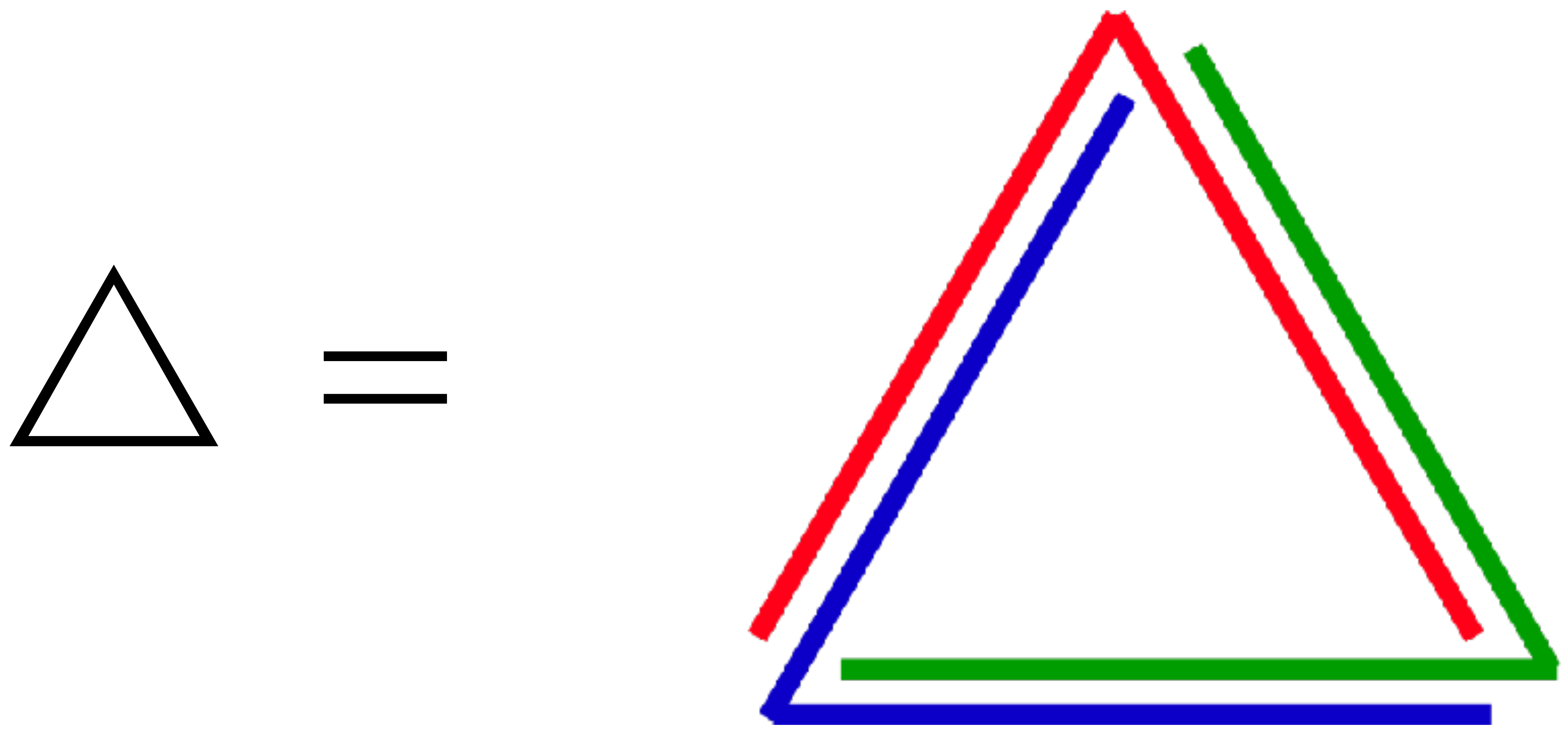
Rethinking your footprint



The origins of the ET triangle

Triangle first proposed:1985, MPQ-101. W.Winkler, K.Maischberger, A.Rüdiger, R.Schilling, L.Schnupp, D.Shoemaker: Plans for a Large Gravitational Wave Antenna in Germany

3 detectors



Might be confusing: current ET design has two interferometers per detectors (xylophone). But those could be replaced by **one** interferometer each. This is **not relevant** for the discussion of the triangle as a detector shape.

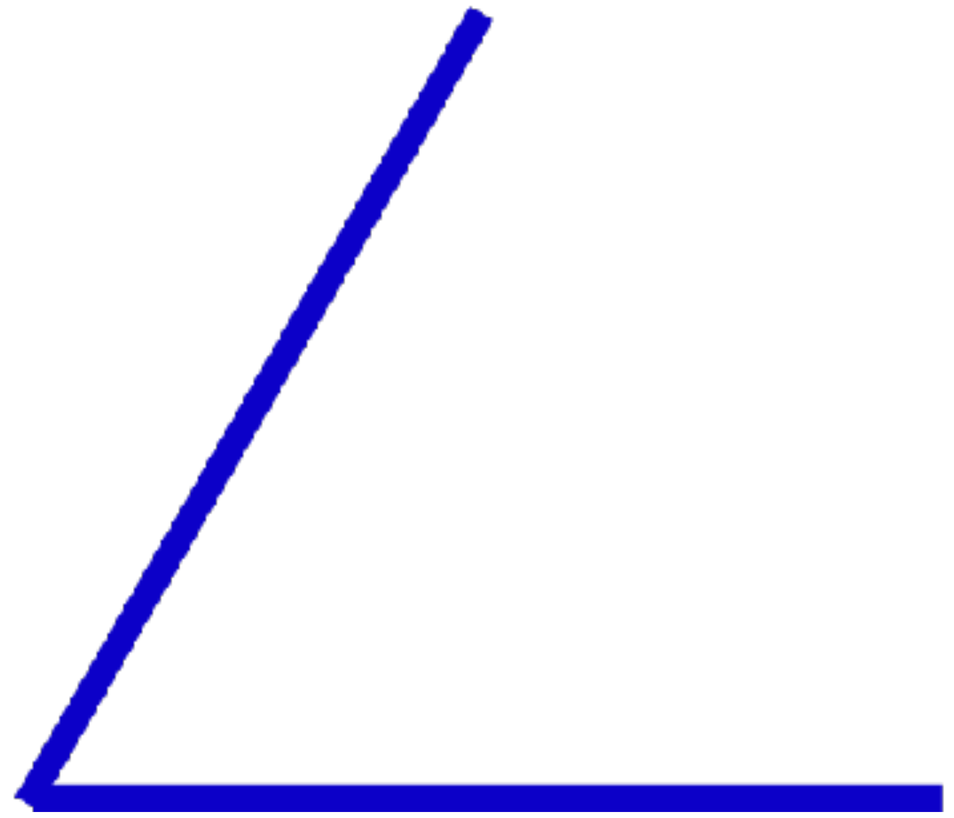
https://arxiv.org/abs/0804.1036

Simple equations

$$h(t) = F_+(t)h_+(t) + F_\times(t)h_\times(t)$$

[P Jaranowski et al, Phys Rev D 58 1998]

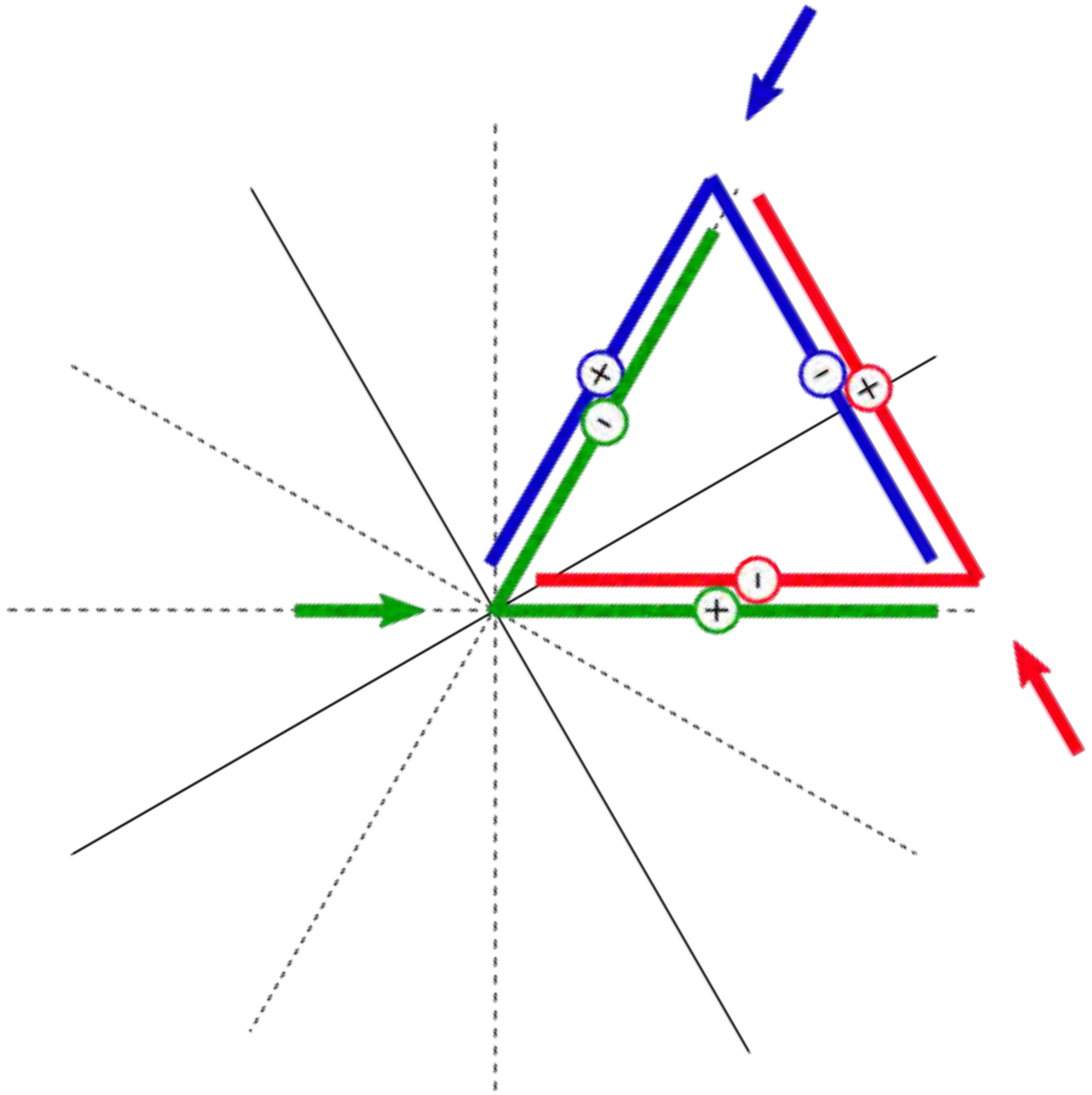
Opening angle:



$$h(t) = \sin(\zeta) \times (\dots)$$

$$\sin(60°) \;=\; \sqrt{3/4} = 0.87$$

Simple equations



$$h(\gamma) = \sin\zeta\,[(C_1 \sin 2\gamma + C_2 \cos 2\gamma)\,h_+ + (C_3 \sin 2\gamma + C_4 \cos 2\gamma)\,h_\times]$$

Oriented at different angles the instrument measure combinations of the different polarisations. Combine signals for reconstructing signals from other orientations:

$$-h_{0^\circ} = h_{240^\circ} + h_{120^\circ}$$

$$h_{45^\circ} = \frac{1}{\sqrt{3}}\left(h_{240^\circ} - h_{120^\circ}\right)$$

https://arxiv.org/abs/0804.1036

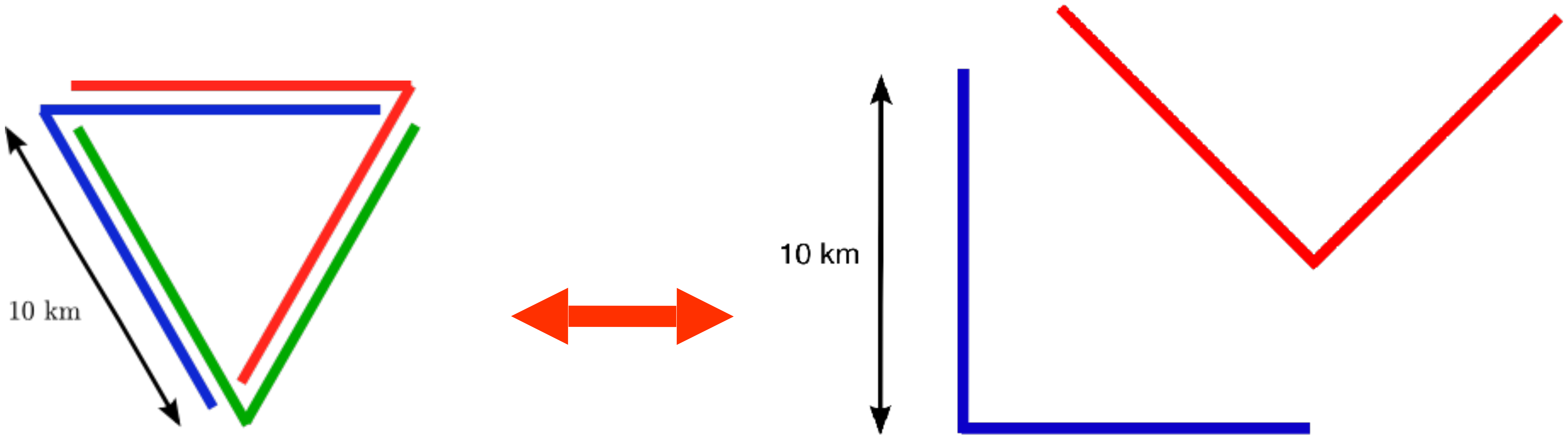
Simple equations

Sensitivity:

+ $$h_\Delta(0^\circ) = h(0^\circ) - h(120^\circ) - h(240^\circ) = 2h(0^\circ)$$

$$\mathrm{SNR}_{\Delta,10\,\mathrm{km}} = \frac{2}{\sqrt{3}}\sqrt{\frac{3}{4}}\mathrm{SNR}_{L,10\,\mathrm{km}} = \mathrm{SNR}_{L,10\,\mathrm{km}}$$

X $$\mathrm{SNR}_{\Delta,10\,\mathrm{km}} = \sqrt{\frac{3}{2}}\sqrt{\frac{3}{4}}\mathrm{SNR}_{L,10\,\mathrm{km}} \approx 1.06\ \mathrm{SNR}_{L,10\,\mathrm{km}}$$

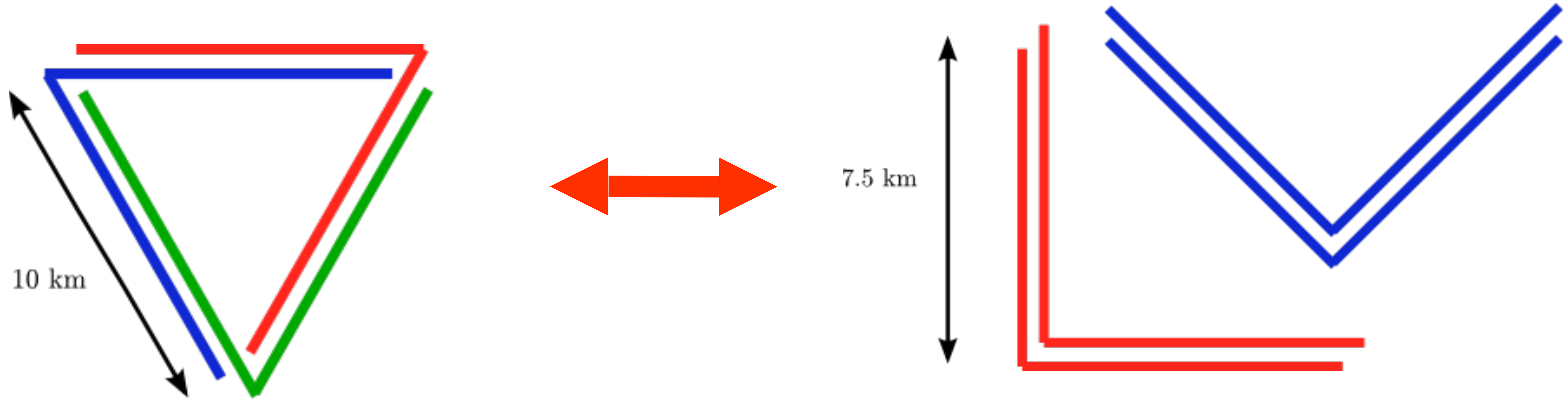


https://arxiv.org/abs/0804.1036

Simple equations

Co-aligned, and both polarisation:

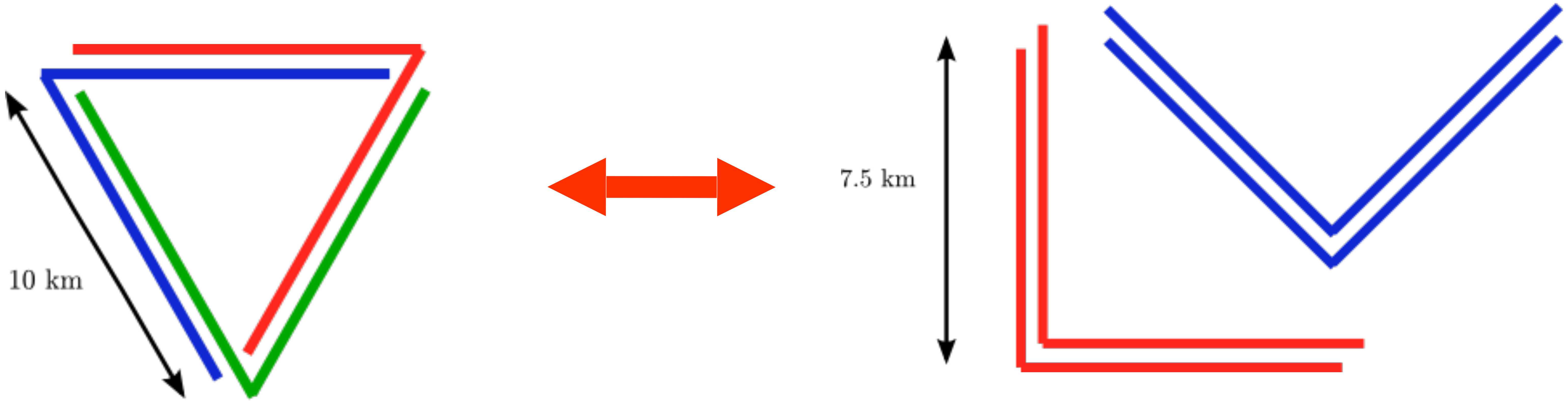
$$\mathrm{SNR}_{2L,7.5\,\mathrm{km}} = \frac{2}{\sqrt{2}}\frac{7.5}{10}\mathrm{SNR}_{L,10\,\mathrm{km}} \approx 1.06\ \mathrm{SNR}_{L,10\,\mathrm{km}}$$



https://arxiv.org/abs/0804.1036

Simple equations

- Same sensitivity, same features
- 30 km `tunnel’ length, 60 km beam tube length
- **Triangle expected to be cheaper because of lower number of vertices**
- Provides smaller peak sensitivity than single L with same integrated arm length

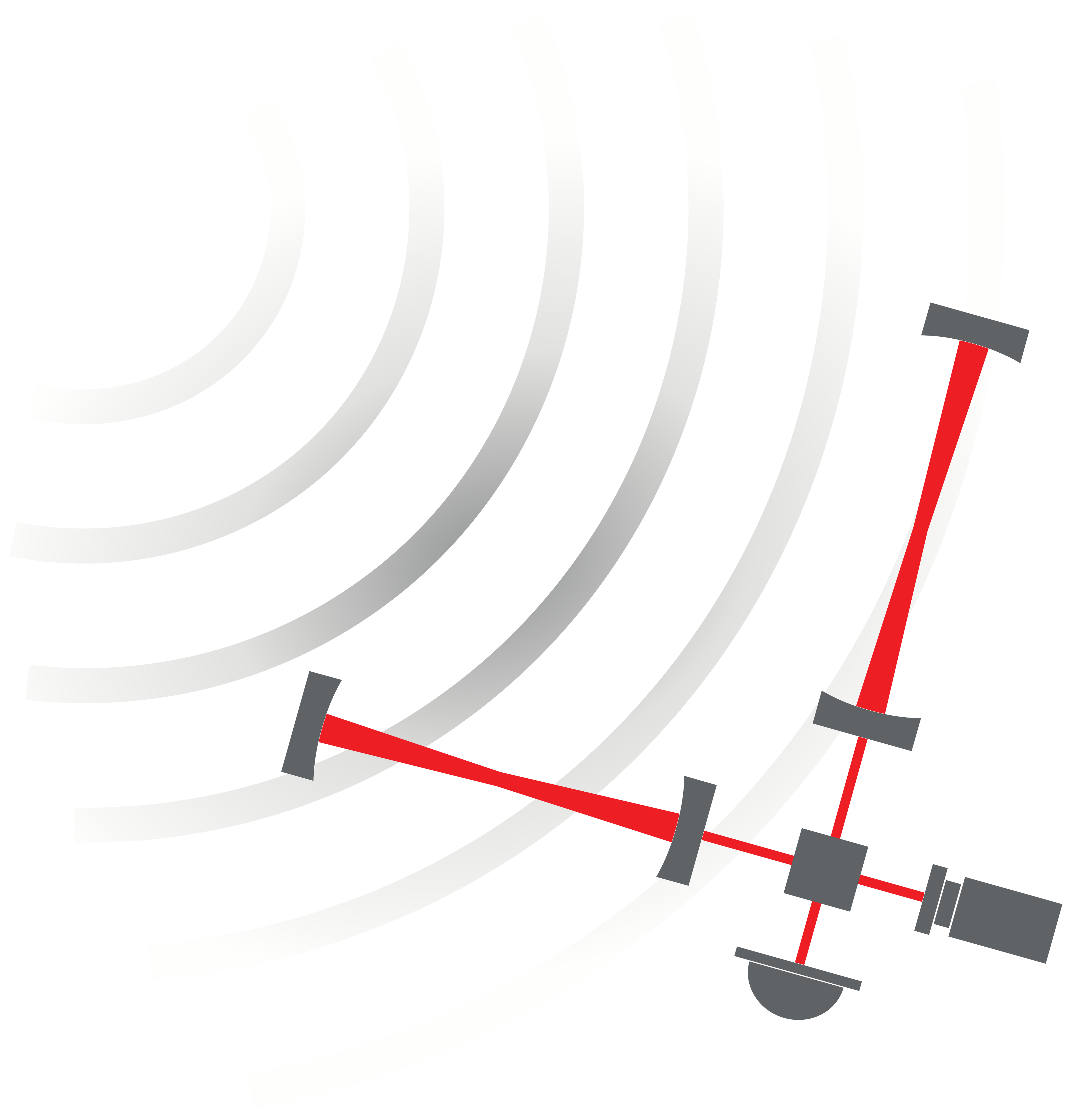


https://arxiv.org/abs/0804.1036

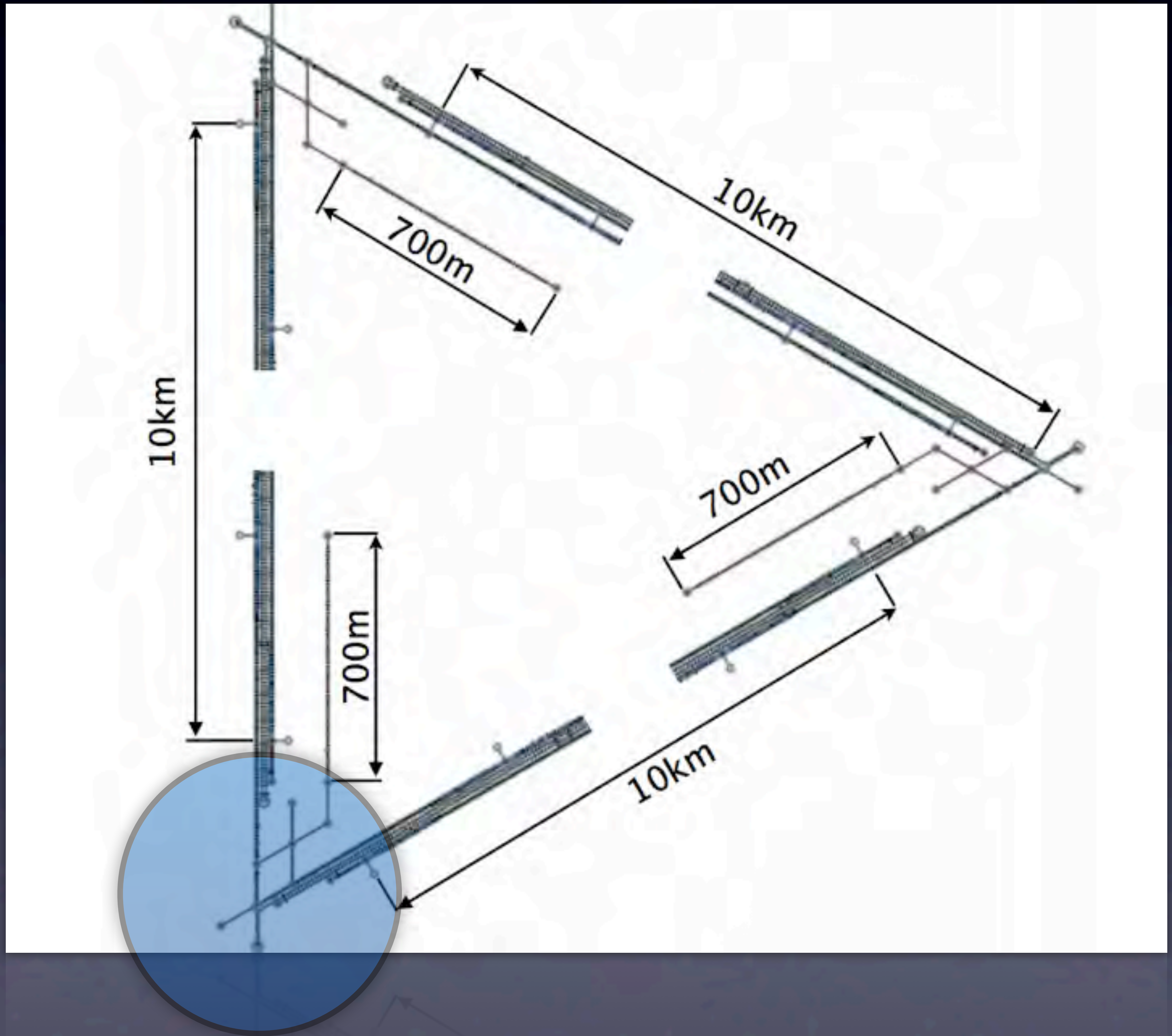
Triangle motivation summary

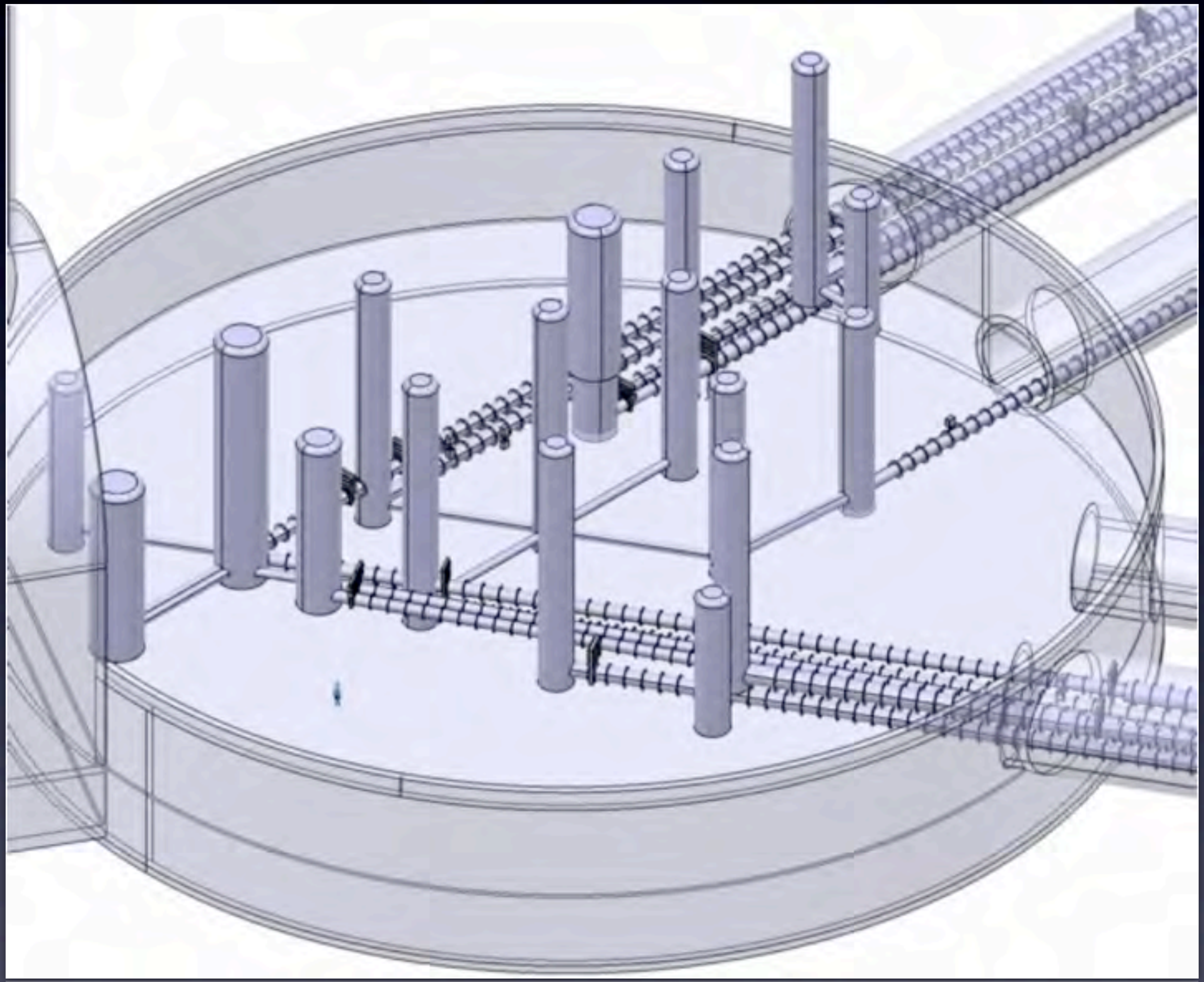
- Designed to optimise an observatory in a single-site
- Observatory optimised for both polarisation
- Co-aligned interferometers (null-streams)
- Single infrastructure (cost efficient and prominent)
- Redundant detectors: allows installation or upgrade of one detector while two are taking data

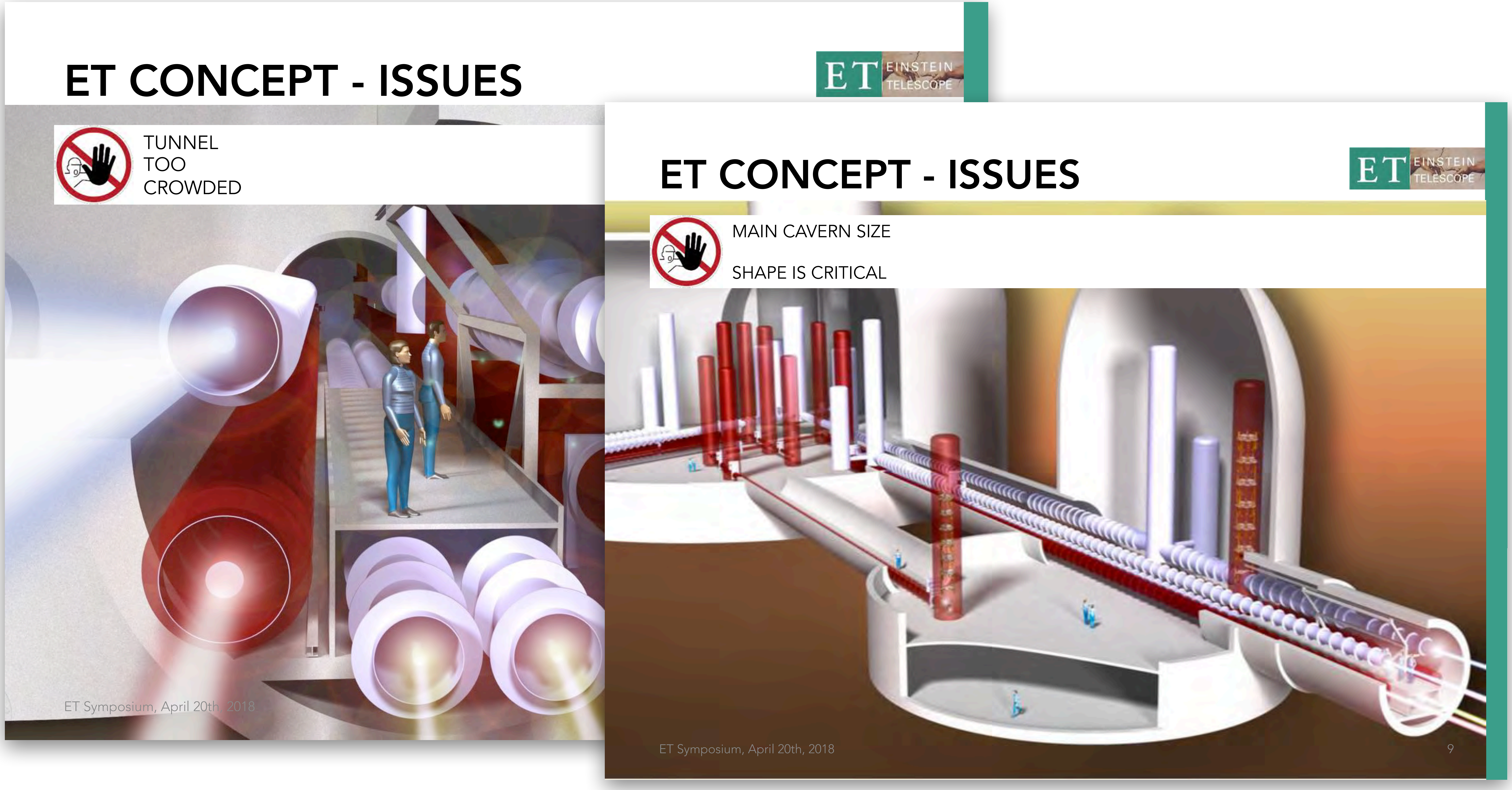
Designing large underground infrastructures



Large Infrastructure







- 'Some consideration on the ET infrastructure, the case for a Sardinian site' G. Losurdo 20.04.2018
- Similar plots in https://apps.et-gw.eu/tds/ql/?c=13309

Implenia civil engineering study

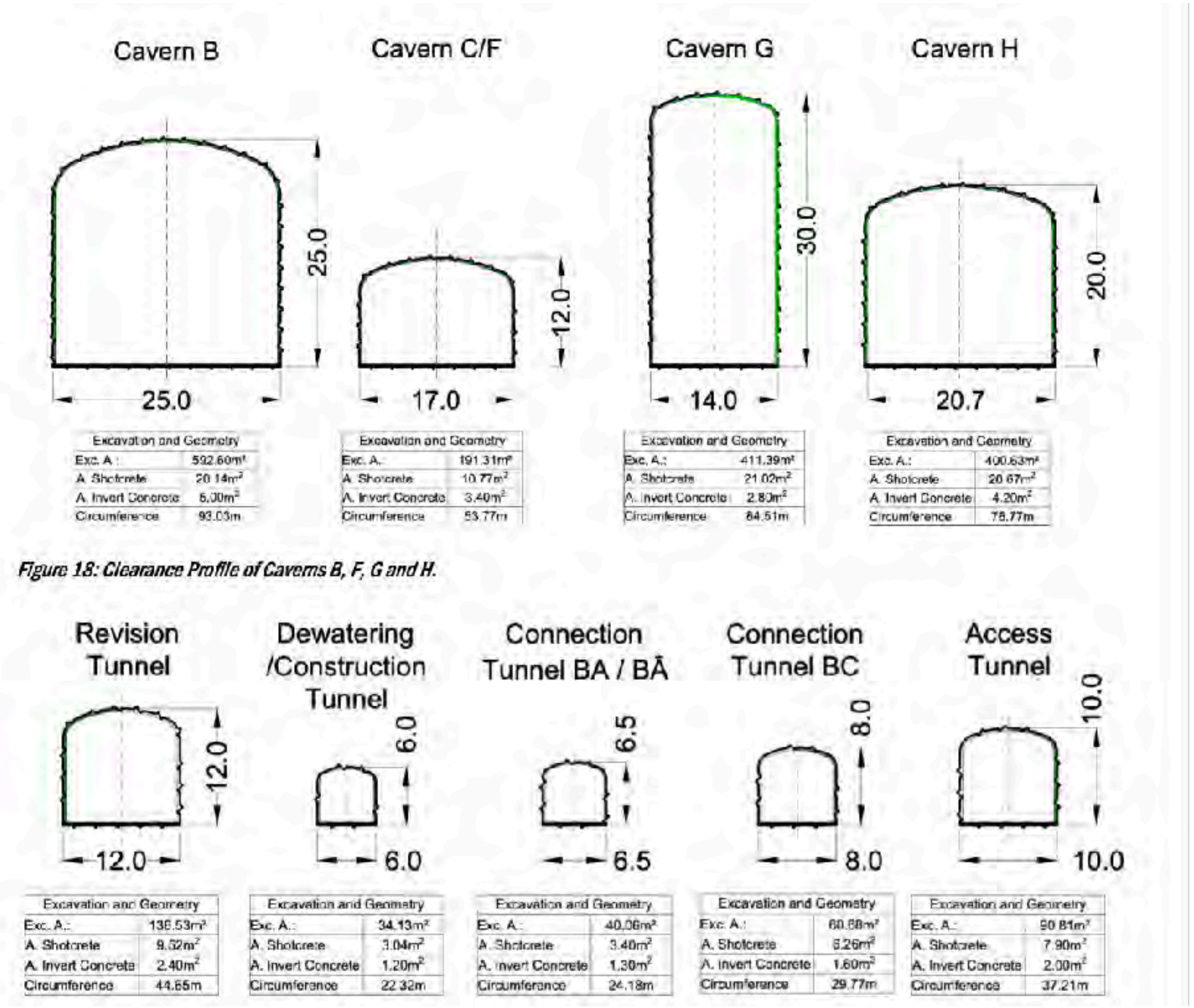
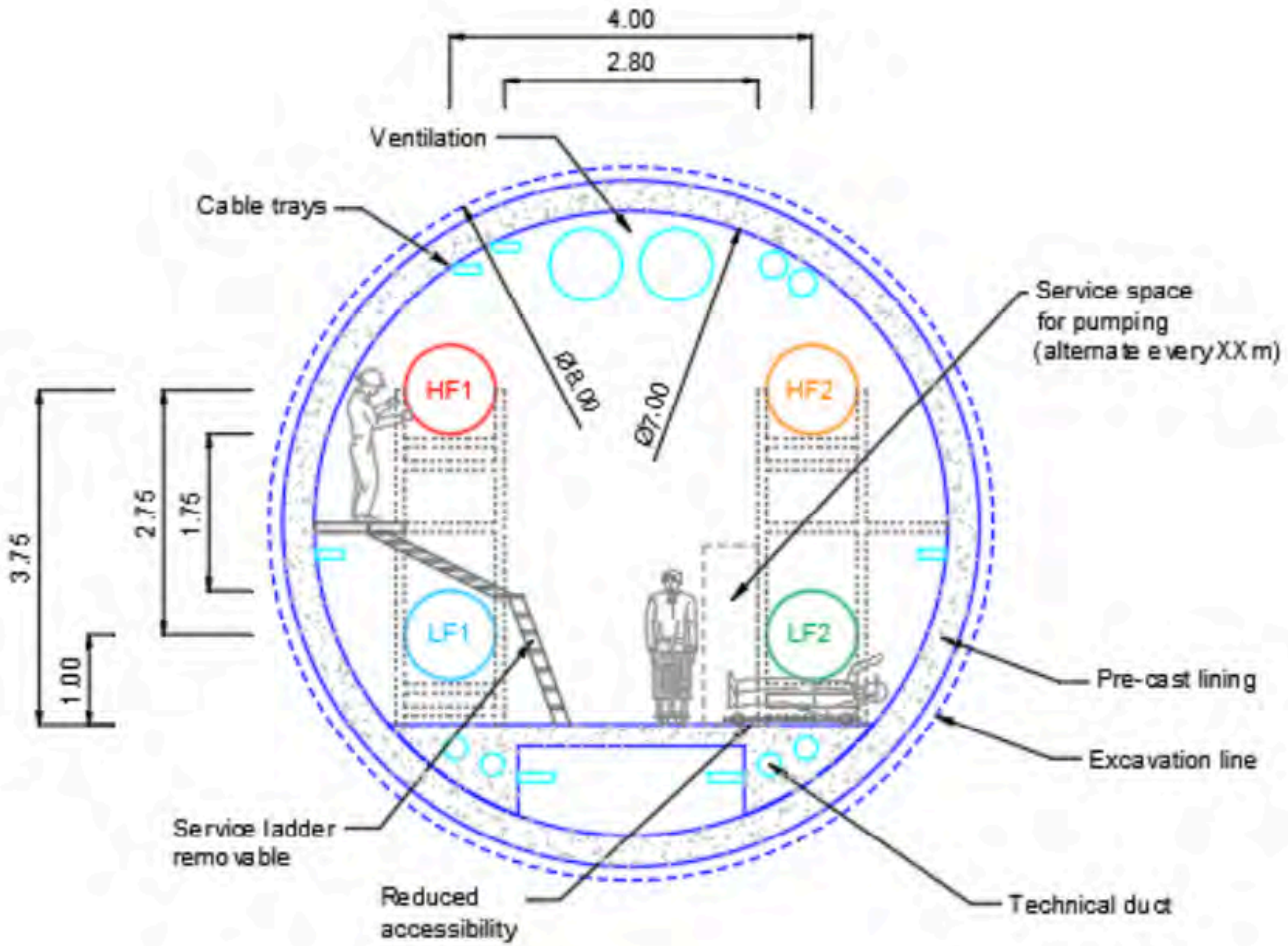


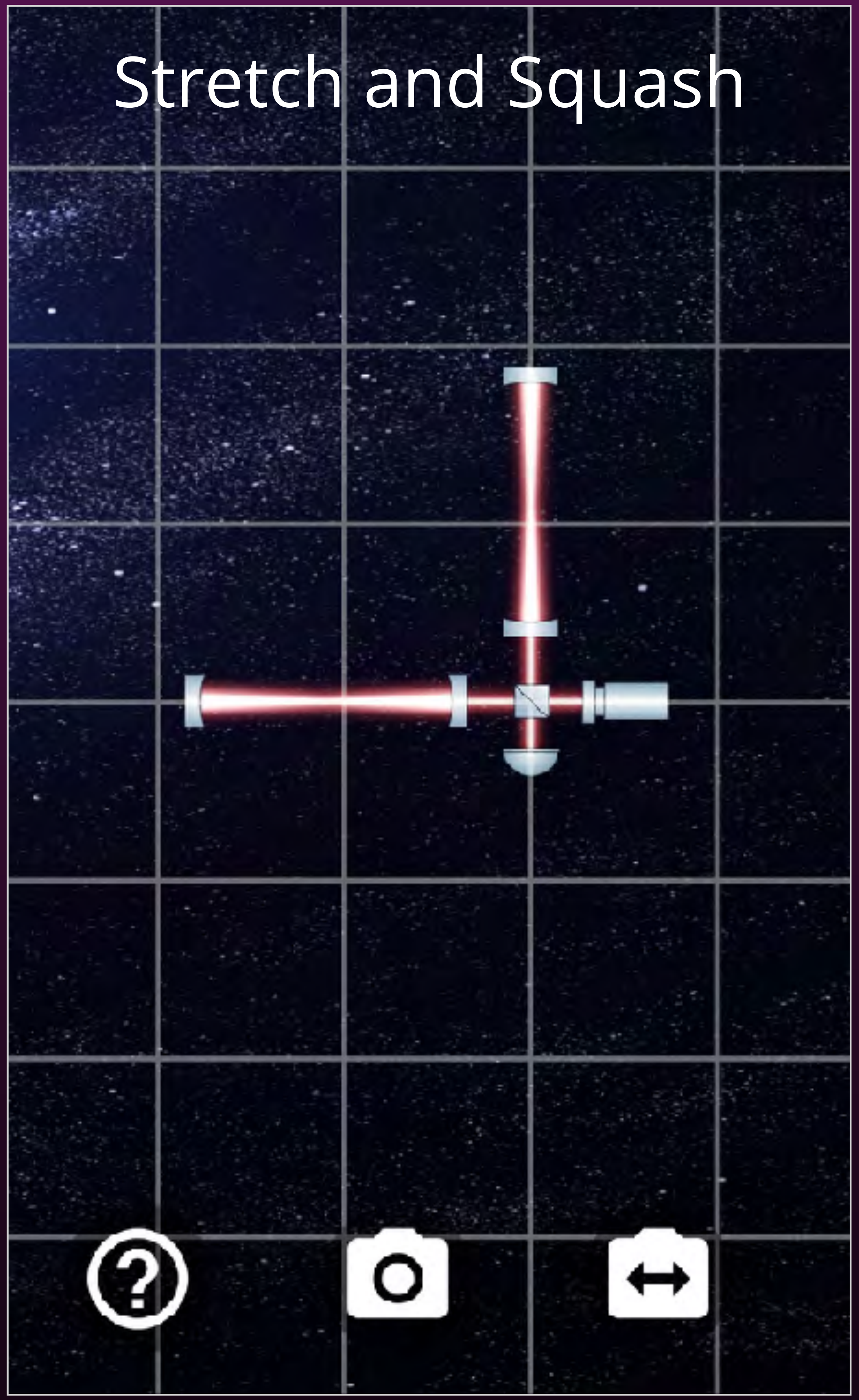
Figure 18: Clearance Profile of Caverns B, F, G and H.

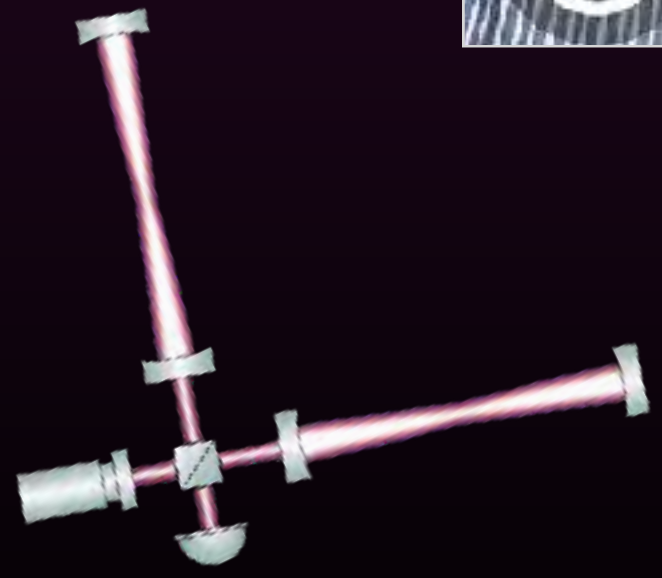
Tunnel layout with technical details



Cavern layout in one corner

ET-HF vacuum for main interferometer optics
ET-LF vacuum for main interferometer optics





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