Next Generation Ground-Based Gravitational Wave Detectors

Bram Slagmolen

on behalf of **Cosmic Explorer Project**

XIX International Conference on Topics in Astroparticle and Underground Physics

CE-G2500061

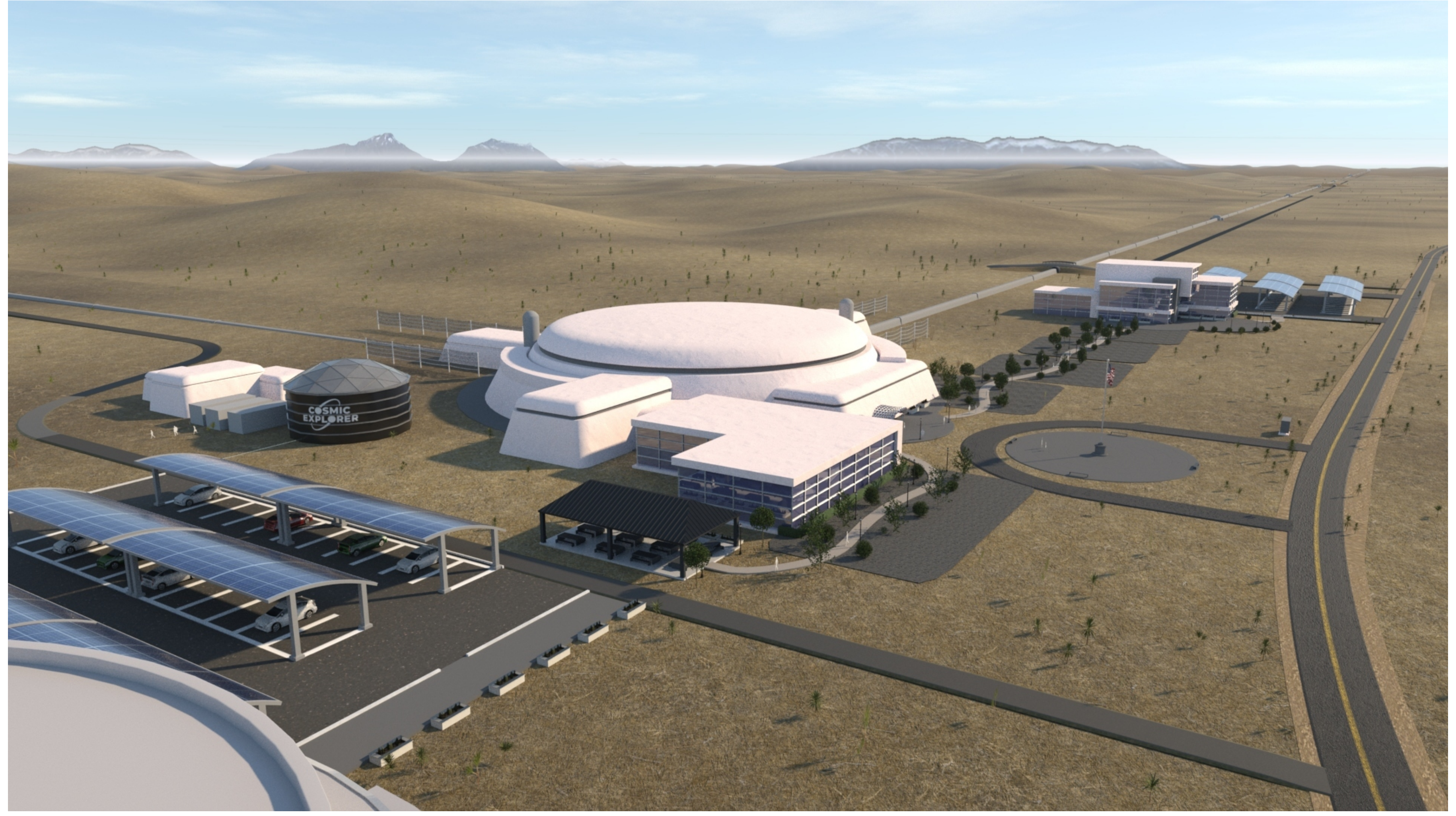
Australian National University

Outline

- *Next generation gravitational wave detectors*
- *Astrophysics and multi-messenger astronomy*
- *Cosmic Explorer*
- *Einstein Telescope*
- *Summary*

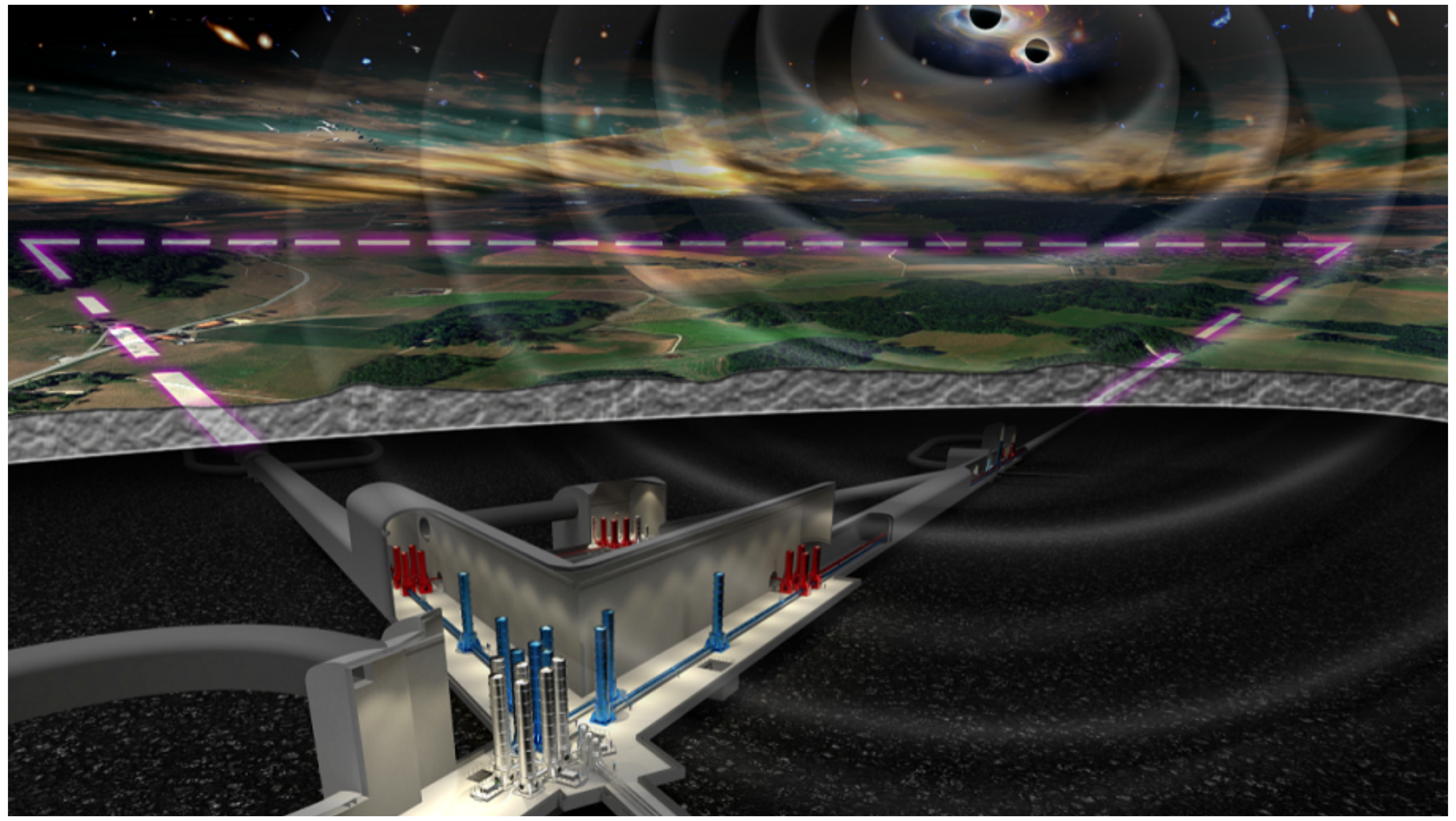
Next Generation Ground based Gravitational Wave Detector

- 10x better performance across the whole frequency band (with respect to aLIGO A+)



Cosmic Explorer (CE)

- 20 km and 40 km L-shaped surface observatories
- scaled up LIGO technology & enhancements
- GW frequencies 10Hz–2kHz



Einstein Telescope (ET)

- 10 km underground triangle*
- 6 interferometers in "xylophone" configuration:
  - Cryogenic low frequency
  - High power high frequency
- GW frequencies 7Hz–2kHz

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Next Gen Gravitational Wave Observations

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Increased event rate

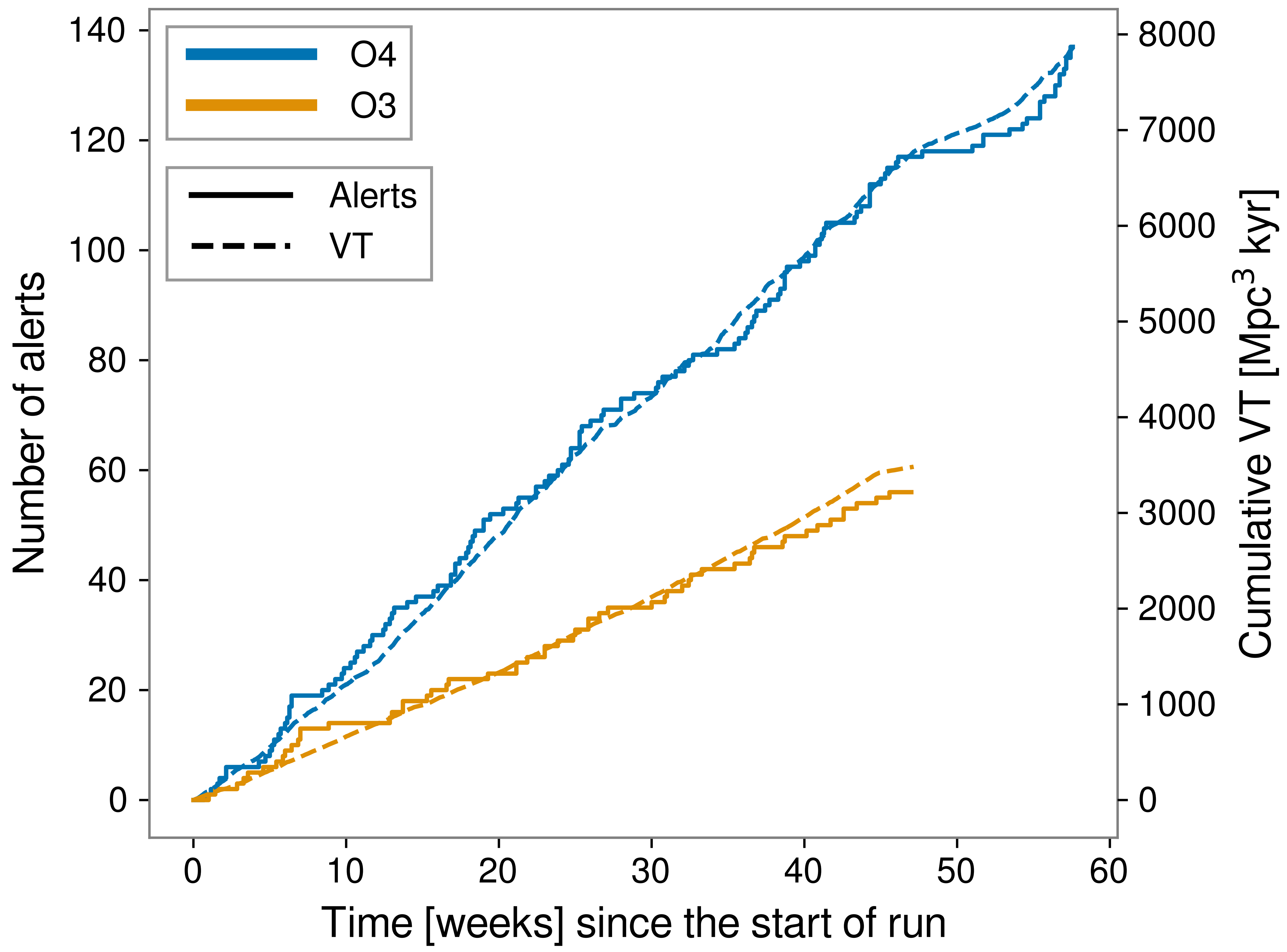
- 10^5 BHBH sources per year
- 10^6 NSNS merger per year

Plan for new facilities

- Implement lessons learned
- Utilizing new techniques and technologies

Next generation observatories

- 10x better performance across the whole frequency band
- Cosmic Explorer (CE)
- Einstein Telescope (ET)



Cosmology and Precision Science

Able to see astrophysical gravitational wave events out to almost the edge of the observable Universe.

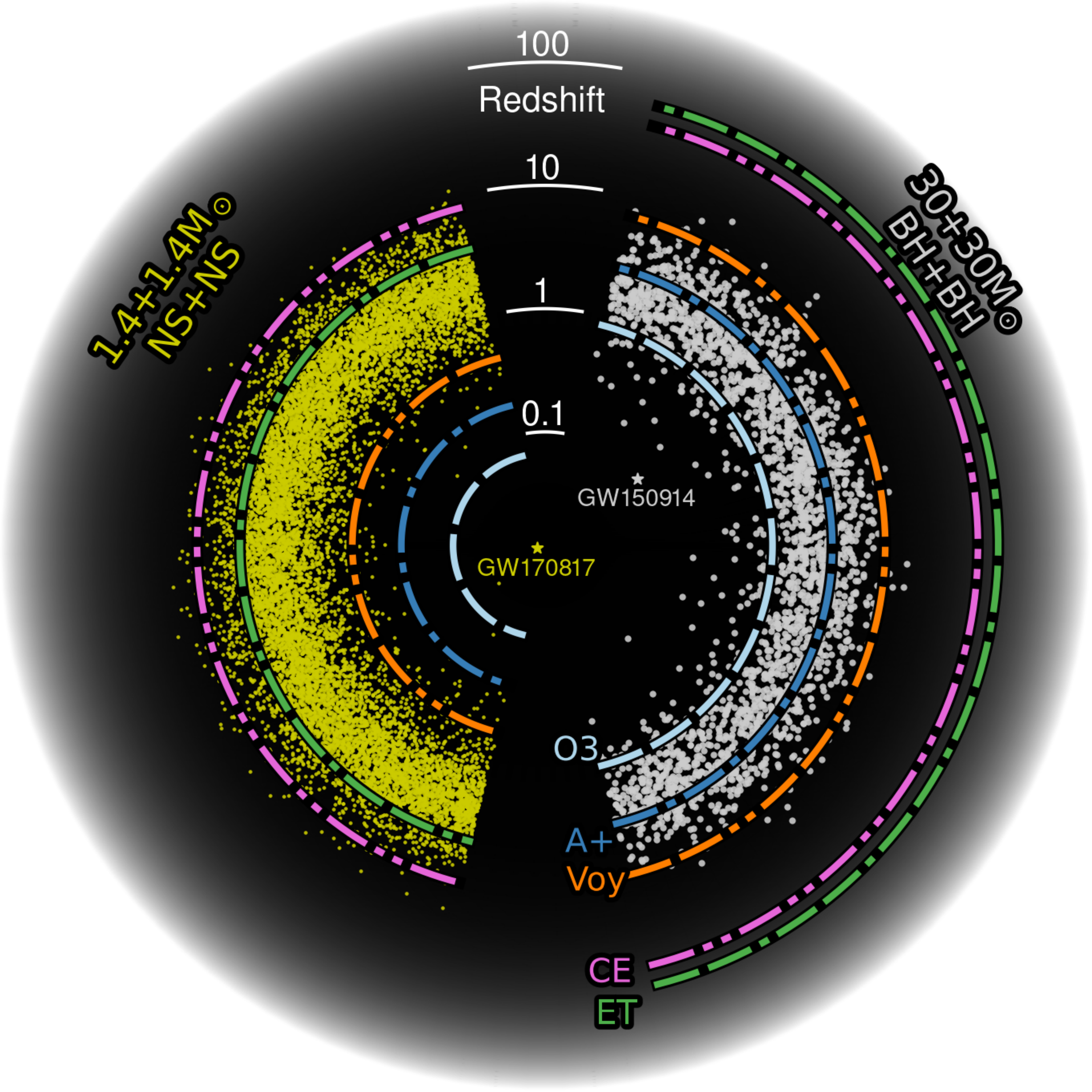
- Aim to see almost all BNS mergers
- To register most of 30+30M_s black-hole mergers

Increased precision in waveform detection

- SNR ~300 for NS-NS events
- SNR ~3000 for BH-BH event
- Testing GR, ringdown measurements

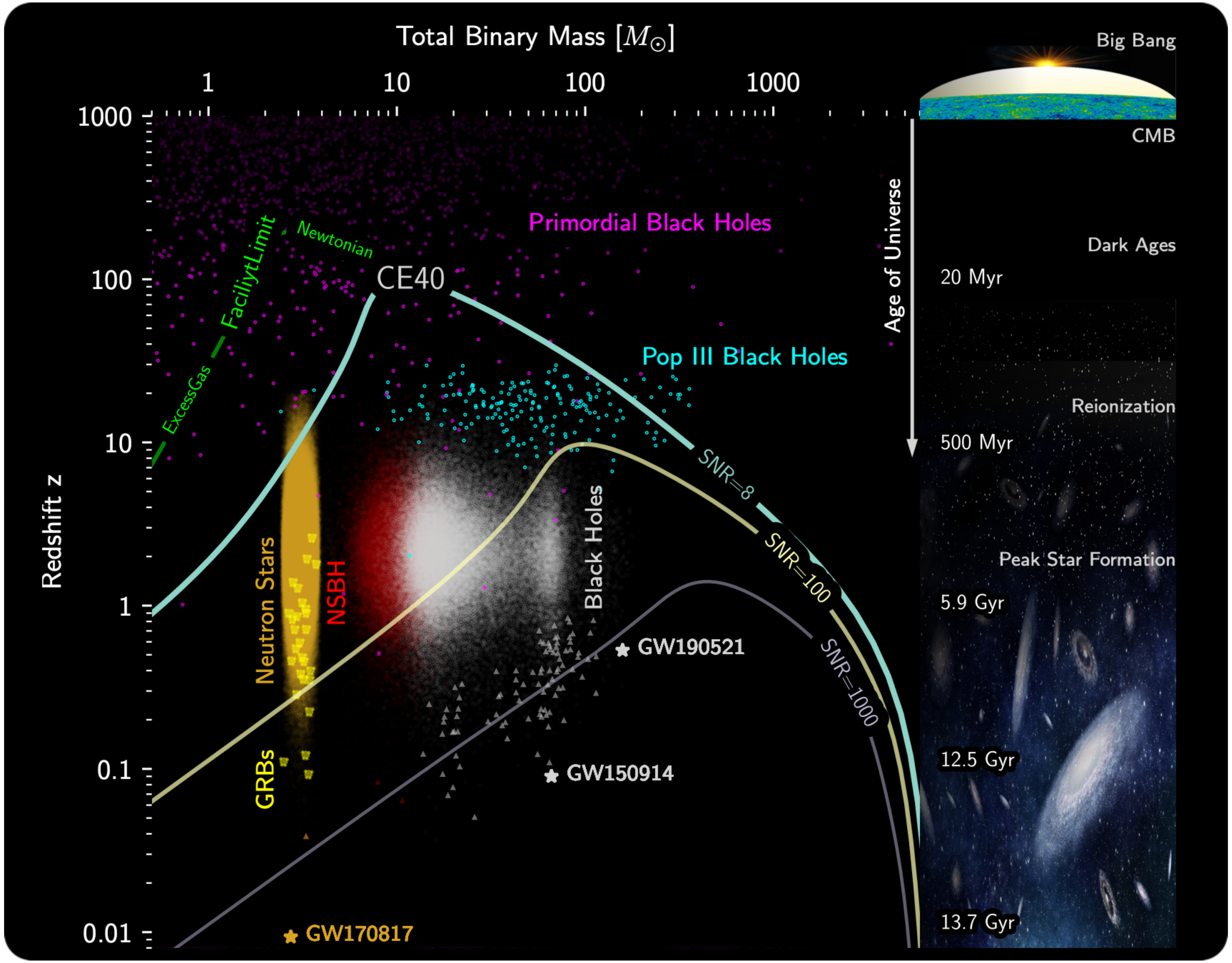
Multi-Messenger Astronomy

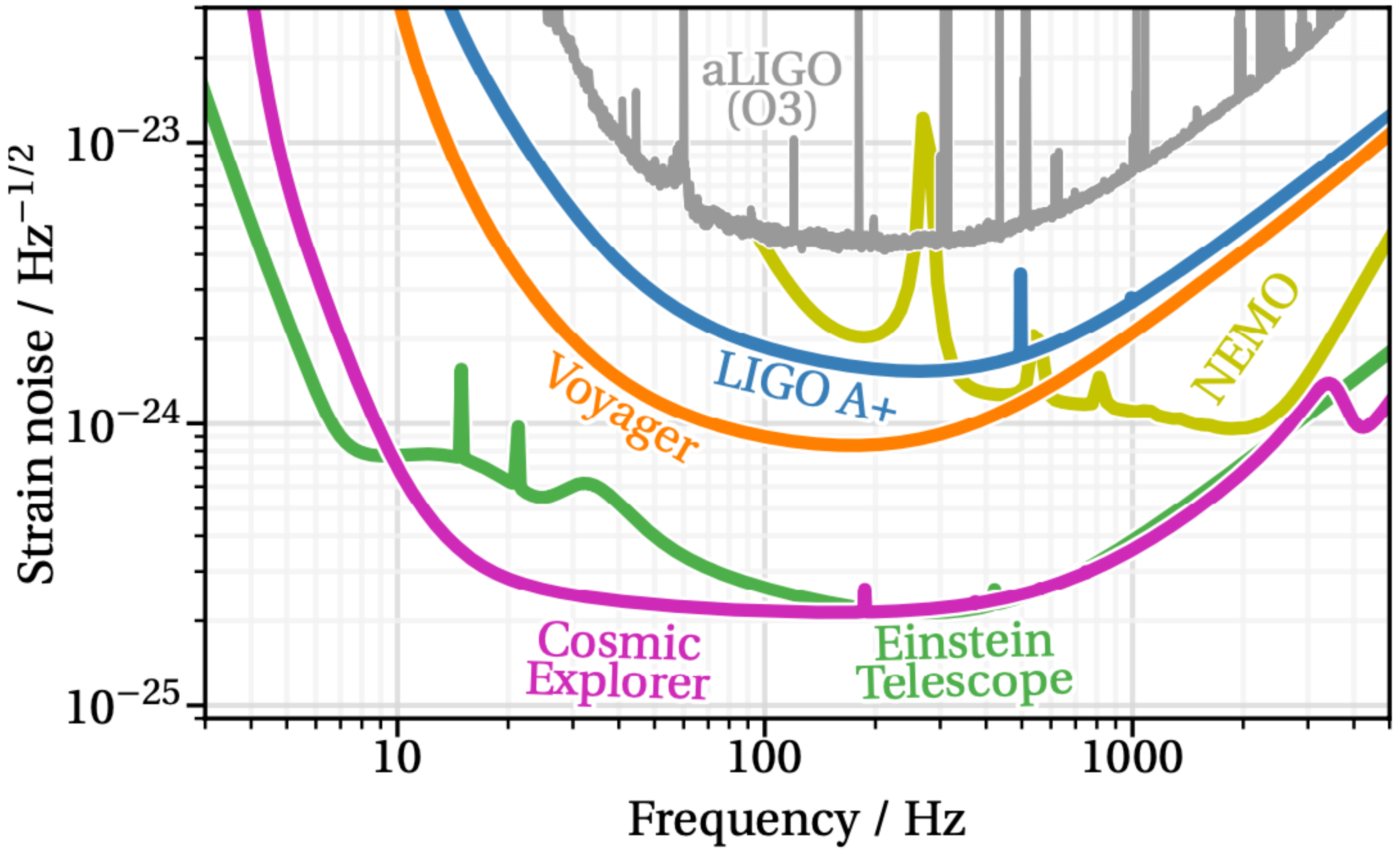
- More neutron star mergers …

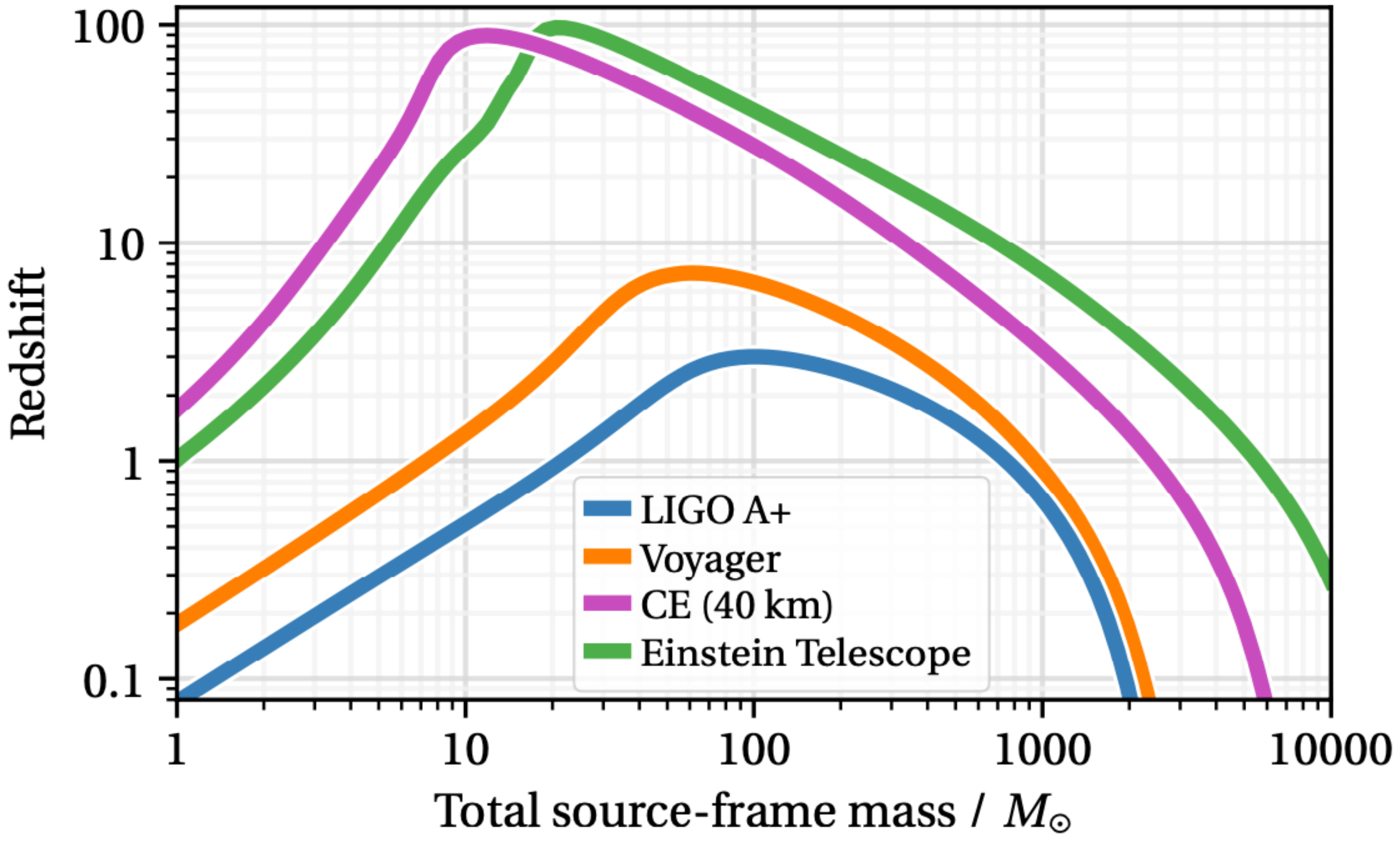


Evans et al., arXiv:2109.09882 (2021)

Science with Next Generation Observatories







Evans et al., arXiv:2109.09882 (2021), arXiv:2306.13745 (2023)

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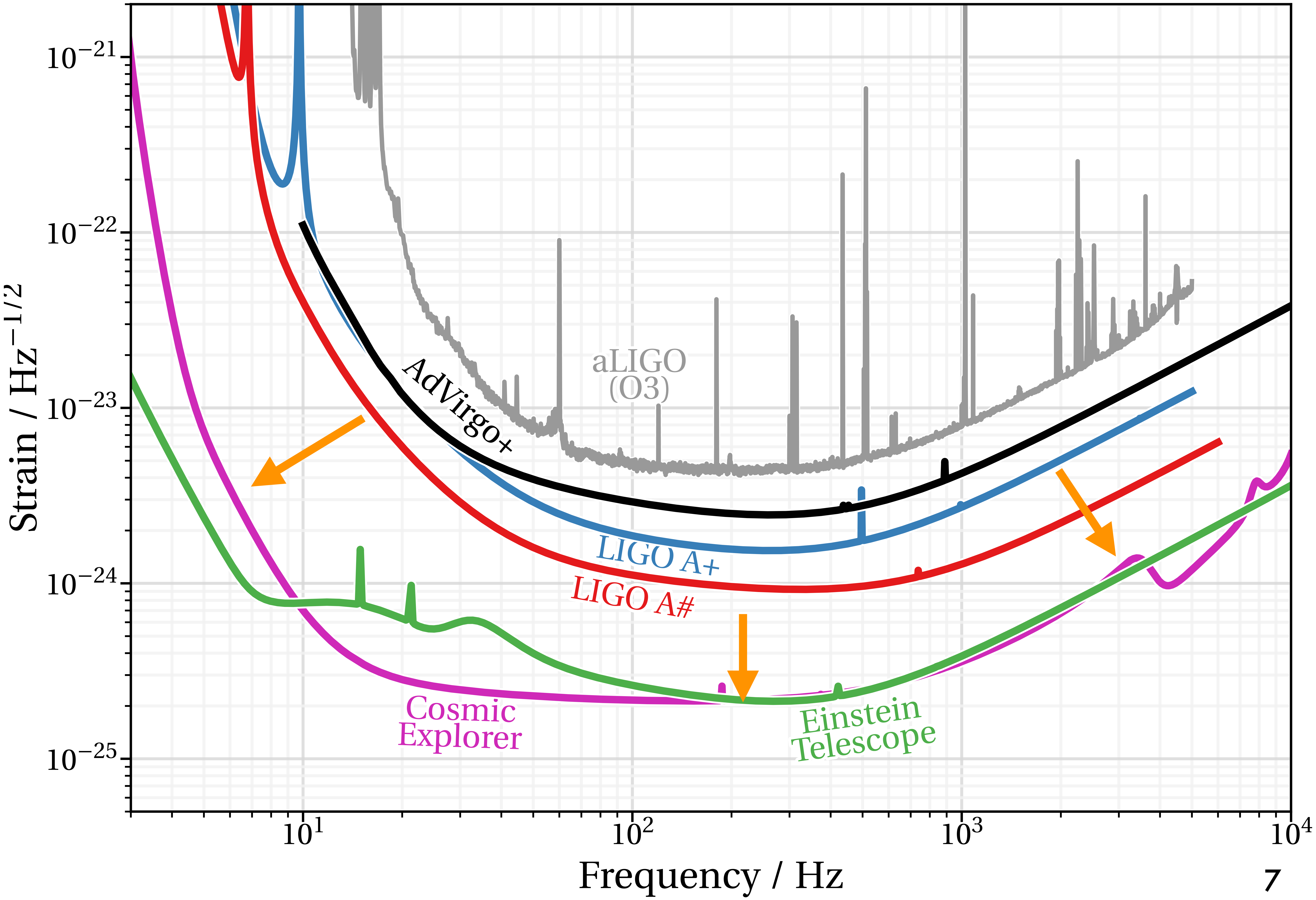
New Facilities

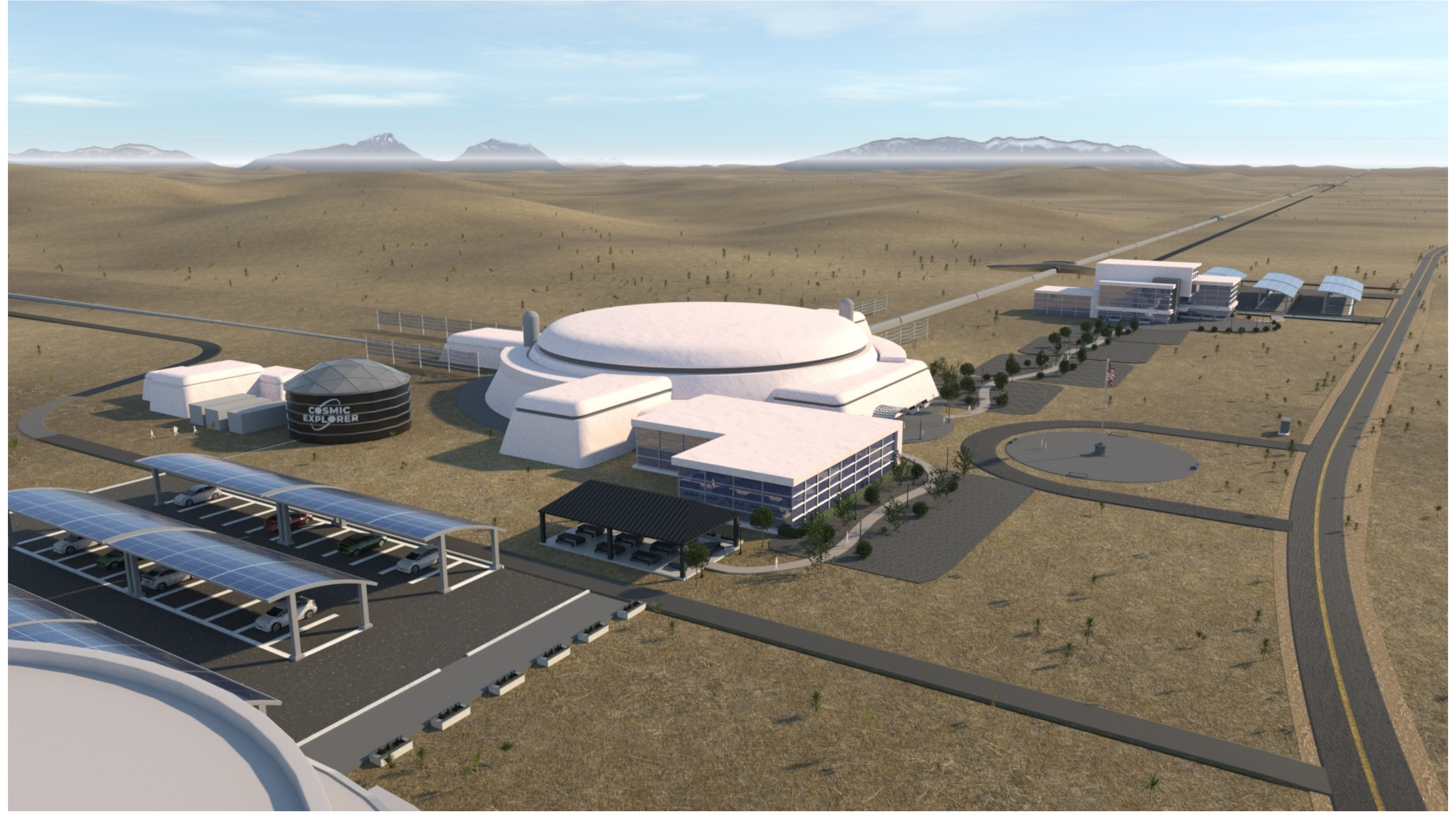
COSMIC EXPLORER

Next generation observatories

- New facilities
- New locations
- Incorporating lessons learned from current observatories



Next Generation Ground based Gravitational Wave Detector



Cosmic Explorer (CE)

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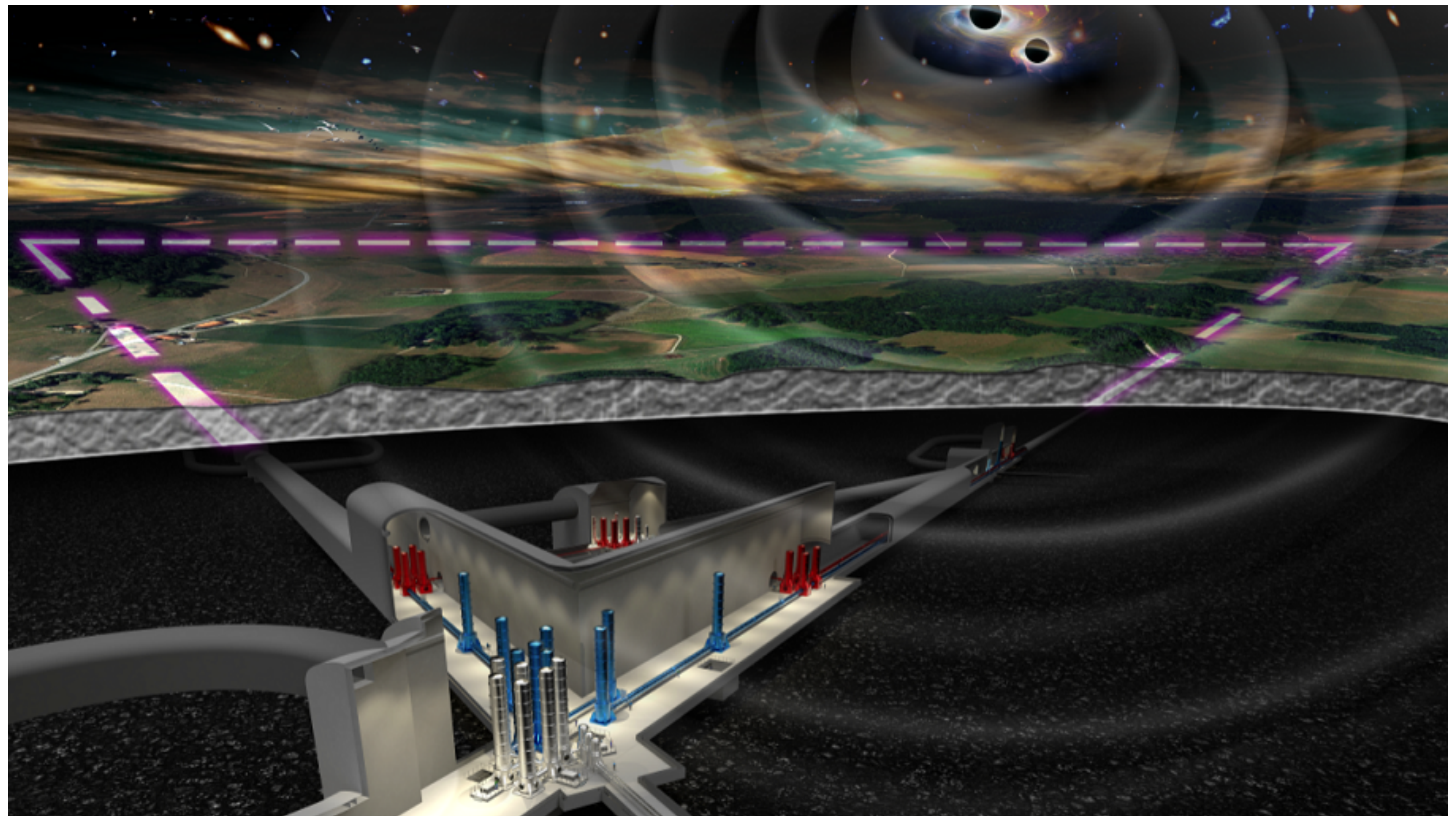

Einstein Telescope (ET)

- 10 km underground triangle*
- 6 interferometers in "xylophone" configuration:
  - Cryogenic low frequency
  - High power high frequency

* under reevaluation

Cosmic Explorer

cosmicexplorer.org

Cosmic Explorer

- Next-generation US-led gravitational-wave observatory project
  - 40-km and 20-km L-shaped surface observatories
  - Estimated operating in 2030s
  - Synergies with other facilities (Einstein Telescope, 2G detectors, space-based detector LISA, EM telescopes, particle detectors, etc.) for enabling astronomy and astrophysics breakthroughs
- Envisioned as an NSF-funded Project
  - Horizon Study (2021) – arXiv:2109.09882 (key science questions, design overview, community, organisation and planning, etc.)

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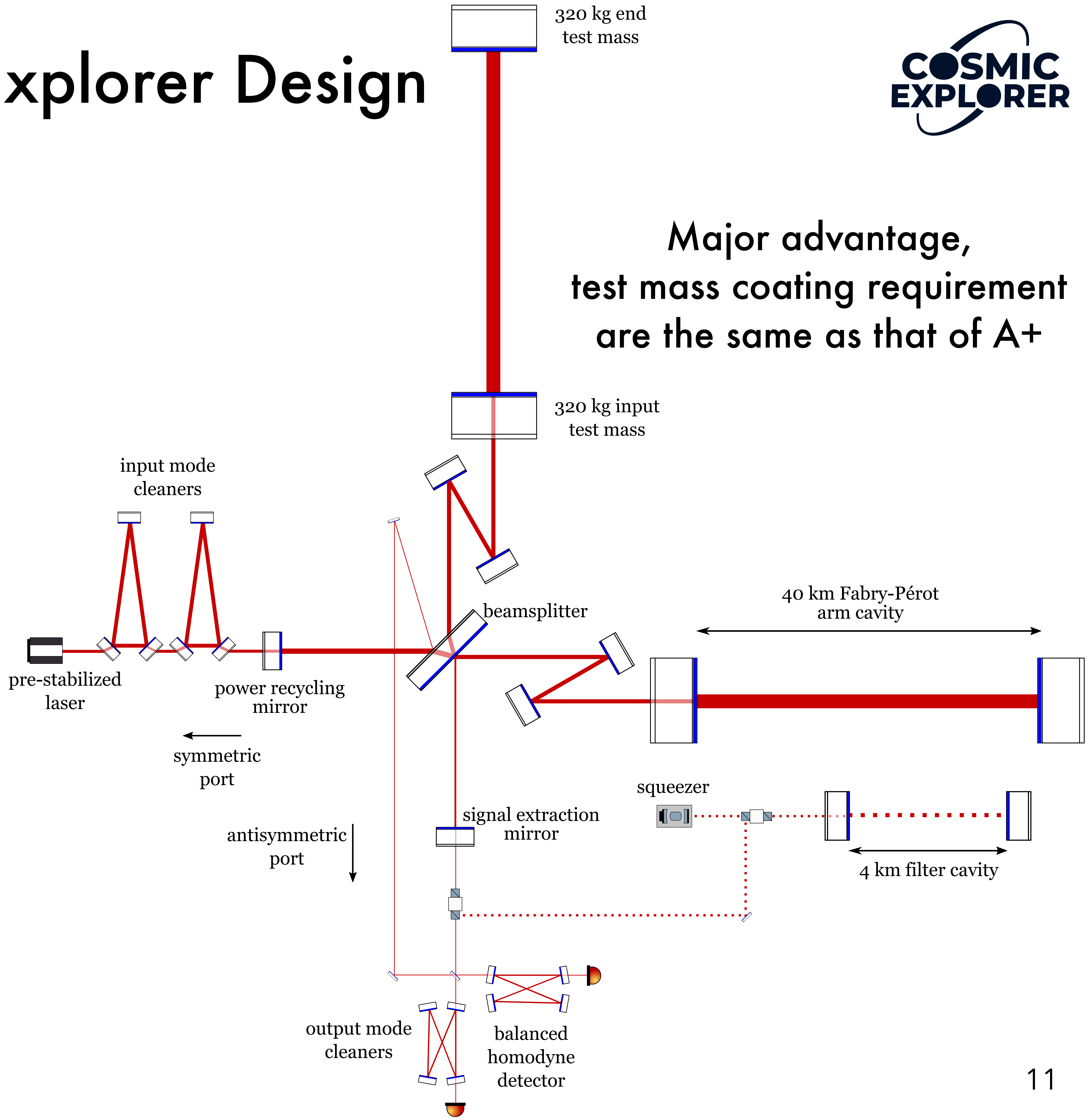
Cosmic Explorer Design

Quantity	LIGO A+	LIGO A#	CE
Arm length	4 km	4 km	40 km / 20 km
Wavelength	1 um	1 um	1 um
Mirror mass	40 kg	100 kg	320 kg
Mirror Material	Fused Silica	Fused Silica	Fused Silica
Arm Power	0.8 MW	1.5 MW	1.5 MW
Squeezing	6 dB	10 dB	10 dB
Newtonian Noise Suppression	-	3x	10x

Evans et al., Cosmic Explorer Horizon Study, *https://dcc.cosmicexplorer.org/CE-P2100003/public* (2021)



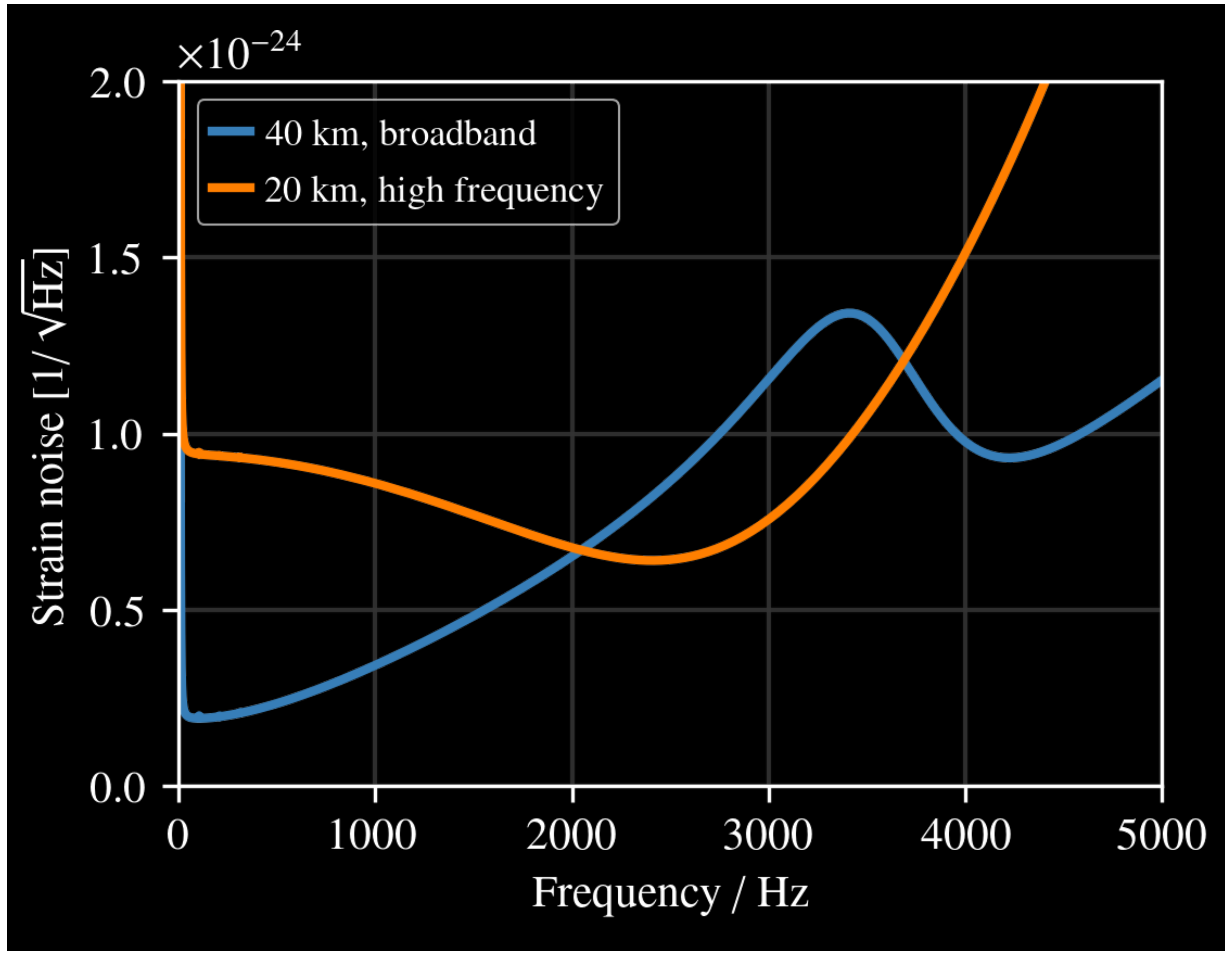
Major advantage, test mass coating requirement are the same as that of A+

Design motivations

Optimize science output while minimizing risk and complexity

Arm length

- 40 km detector with deep broadband sensitivity, from Hz - kHz (limited by free spectral range of 3.7 kHz)
- 20 km detector trades off sub-kHz sensitivity for better high-frequency (1-3 kHz) performance, neutron star post-mergers
  - This required tuning of operating point
- L-shape to reduce vacuum system cost (already 40% of cost); Long arms advantageous where surface feasible (North America, Australia)



Number of detectors

- Two widely separated CEs advantageous for source localization, polarization

CE - Test Mass Suspension

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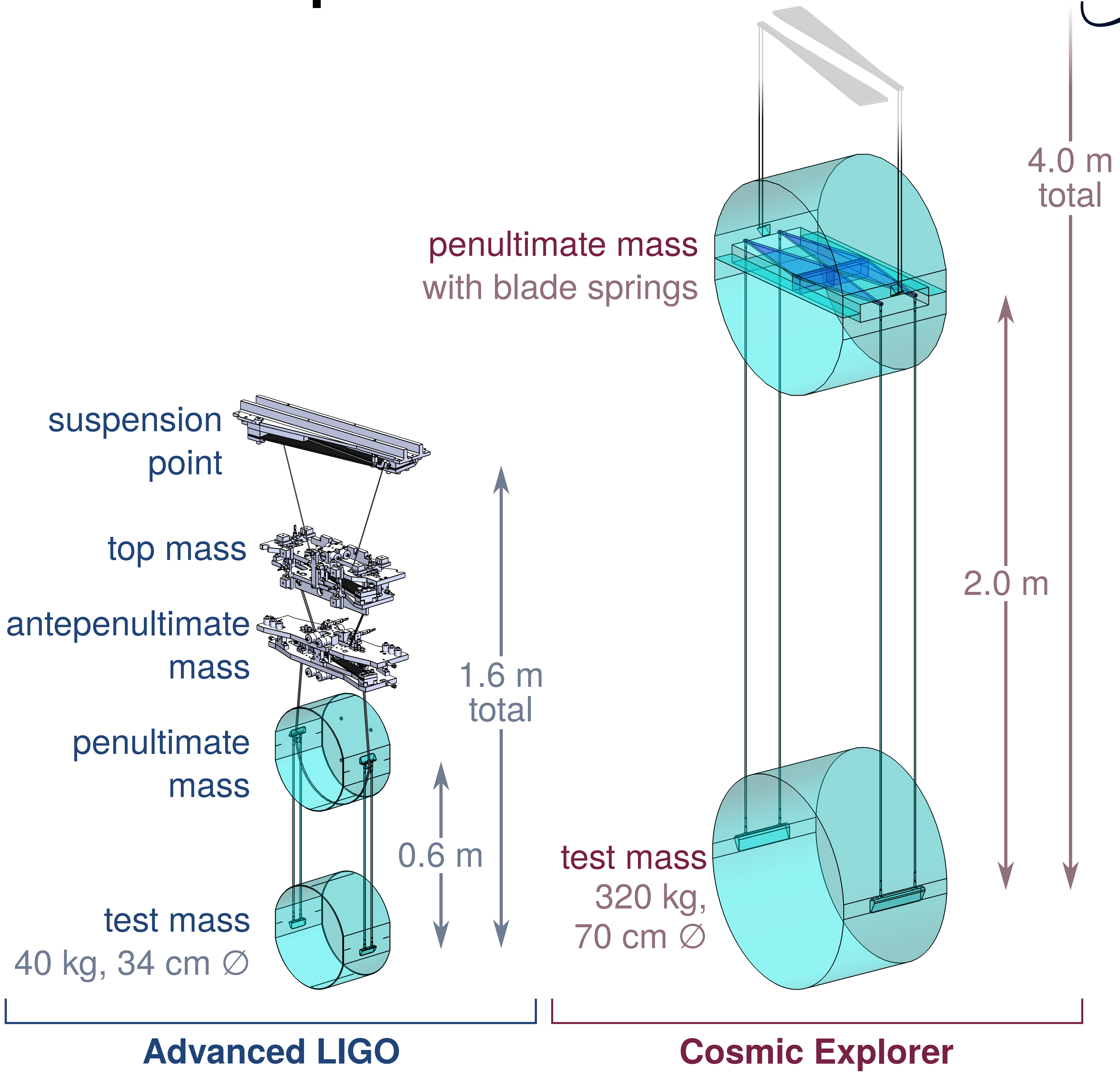
- Quadruple pendulums
- Filter vibrations above 5 Hz
- Test mass 320 kg, 70 cm diameter
- Improved suspension and isolation
  - Additional blades in 'monolithic stage'
  - Longer pendulums
- Lower noise sensors
  - Displacement sensors
  - Accelerometers



Hall et al. DOI: 10.1103/PhysRevD.103.122004

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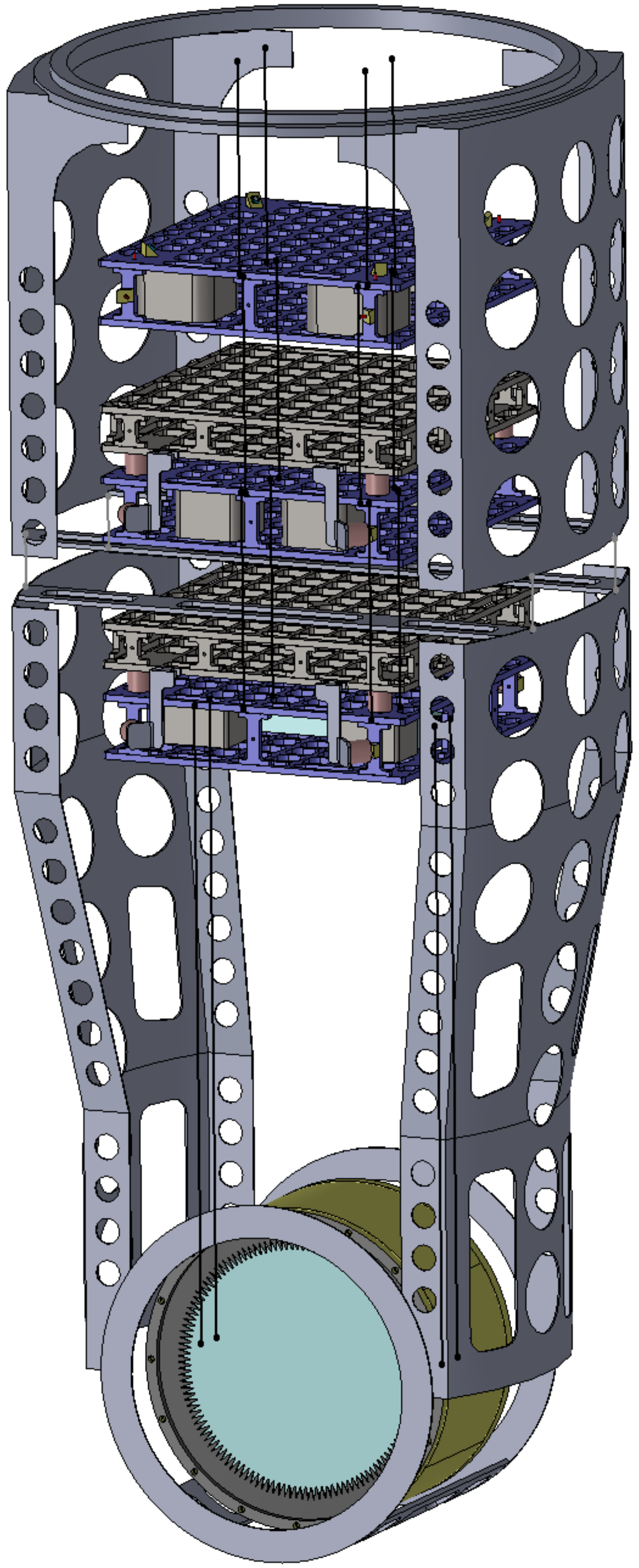
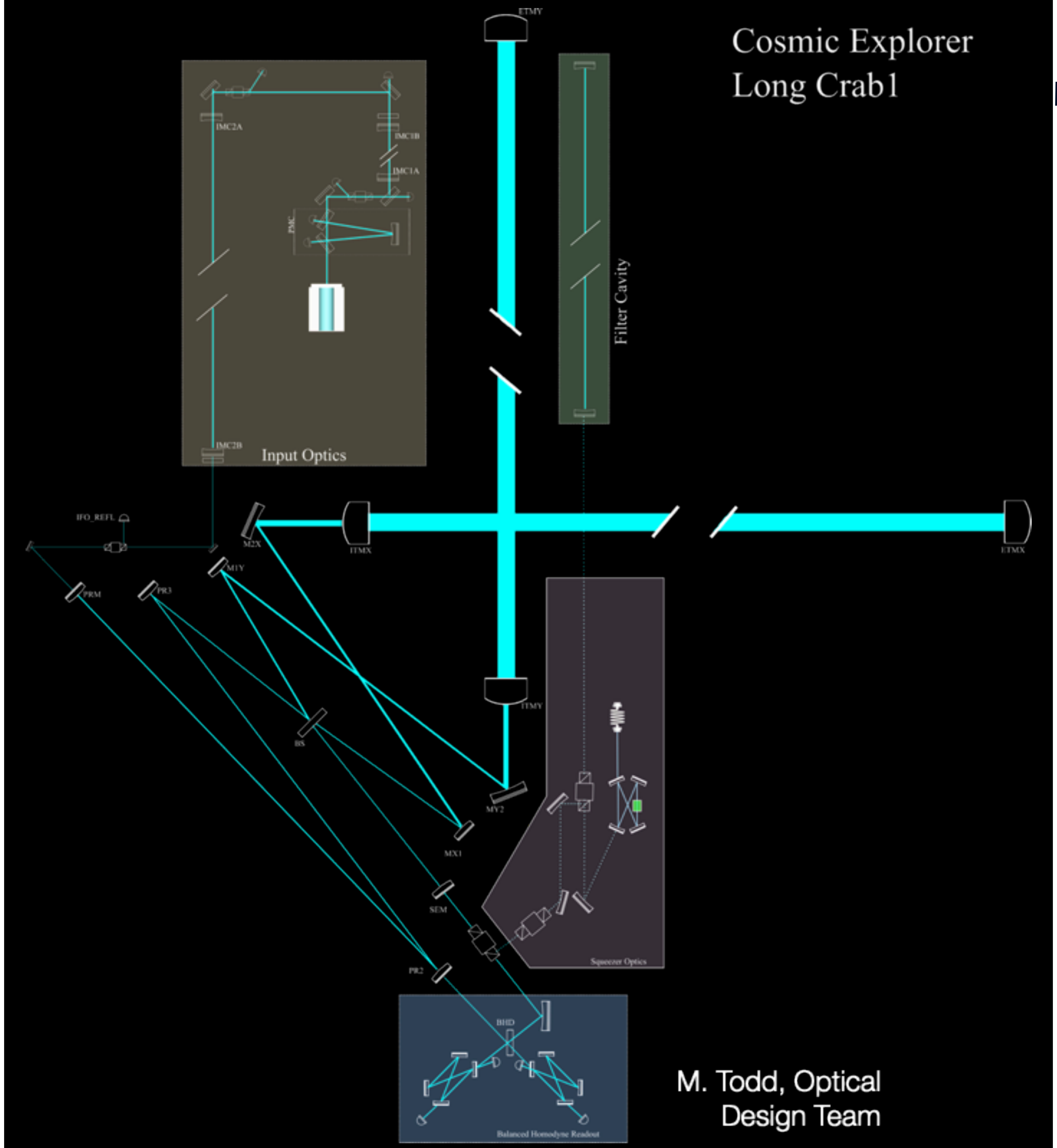


Cosmic Explorer Long Crab1

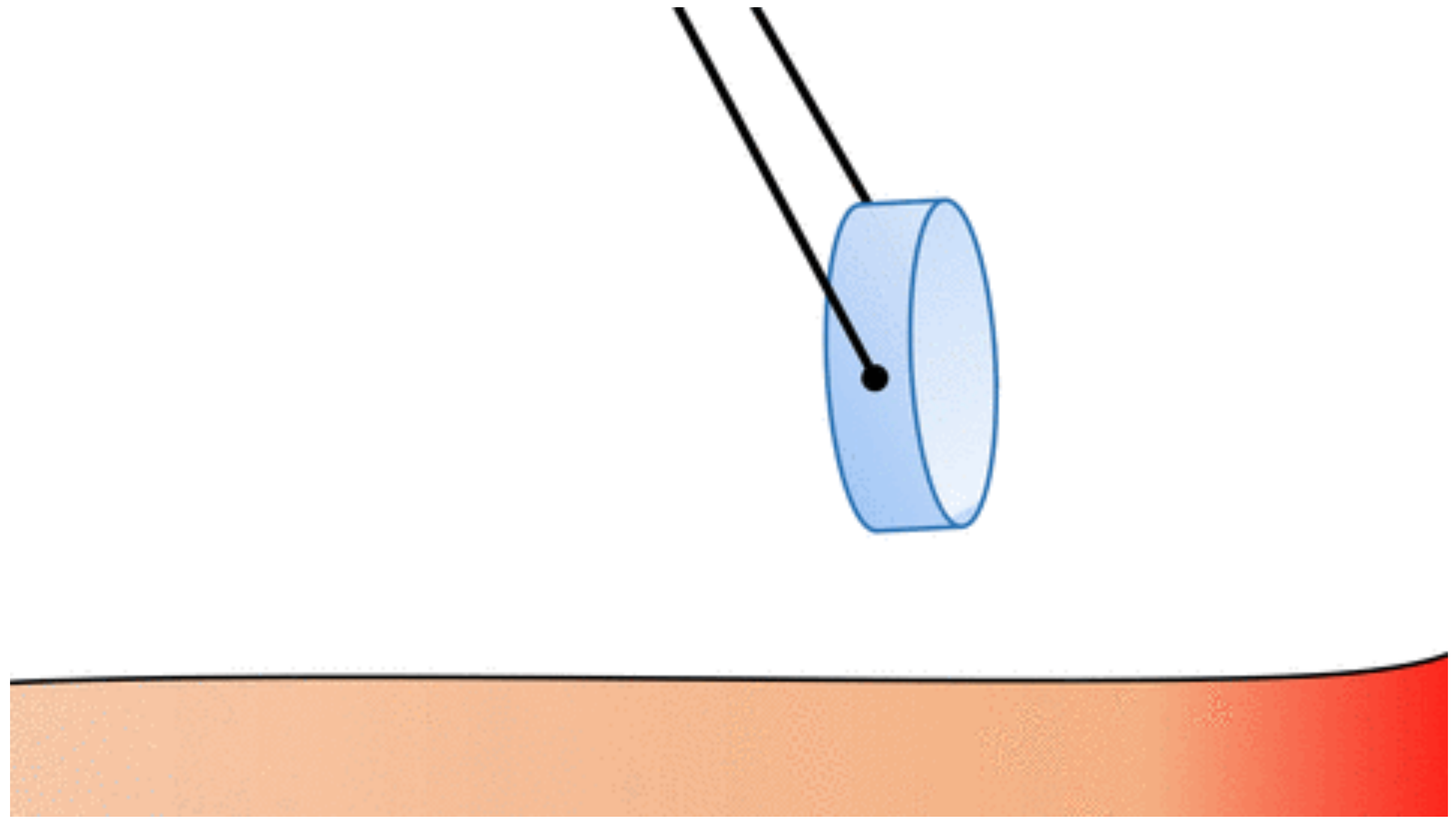


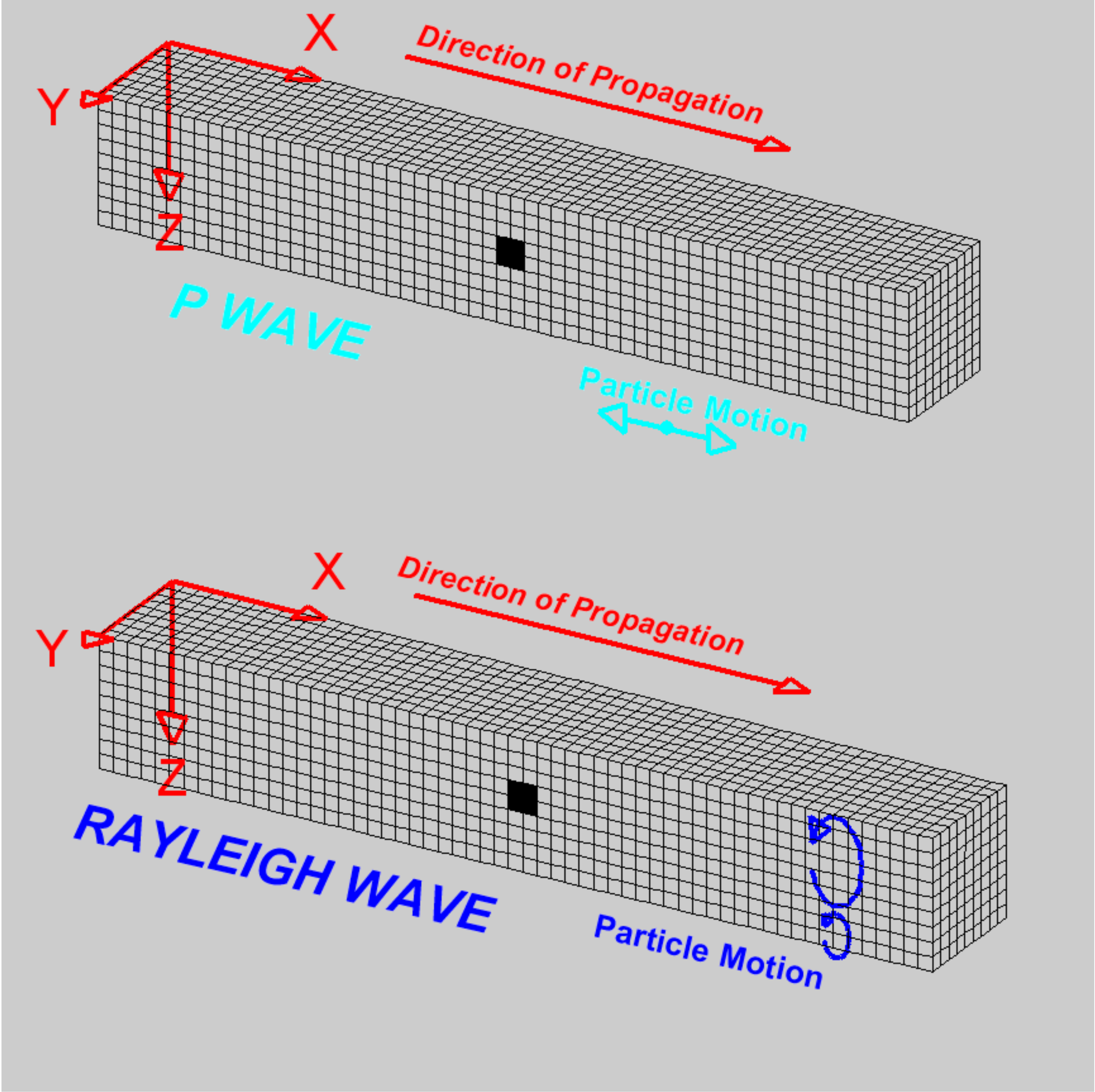
M. Todd, Optical Design Team

Newtonian Noise

Newtonian noise is classical Newtonian force acting on the Test Masses.

- Driven by local density changes
  - From seismic activity
  - From atmospheric disturbance





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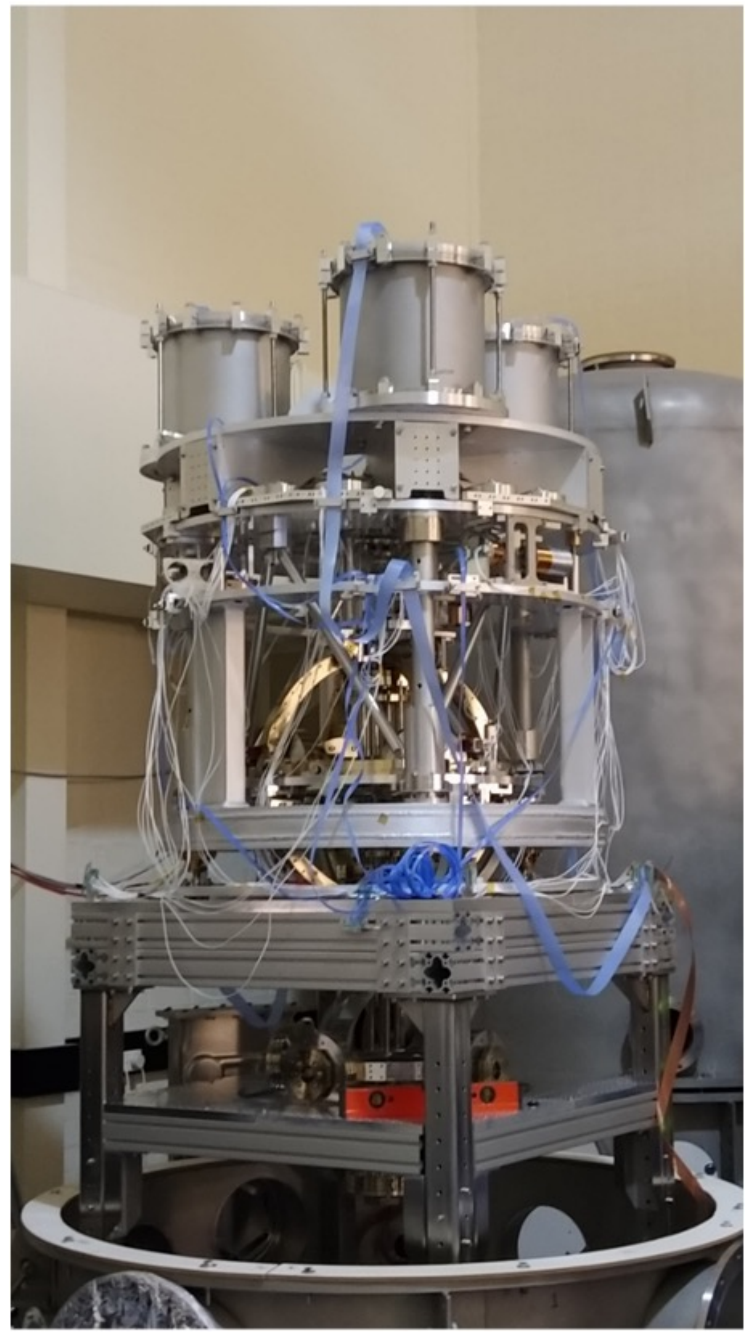
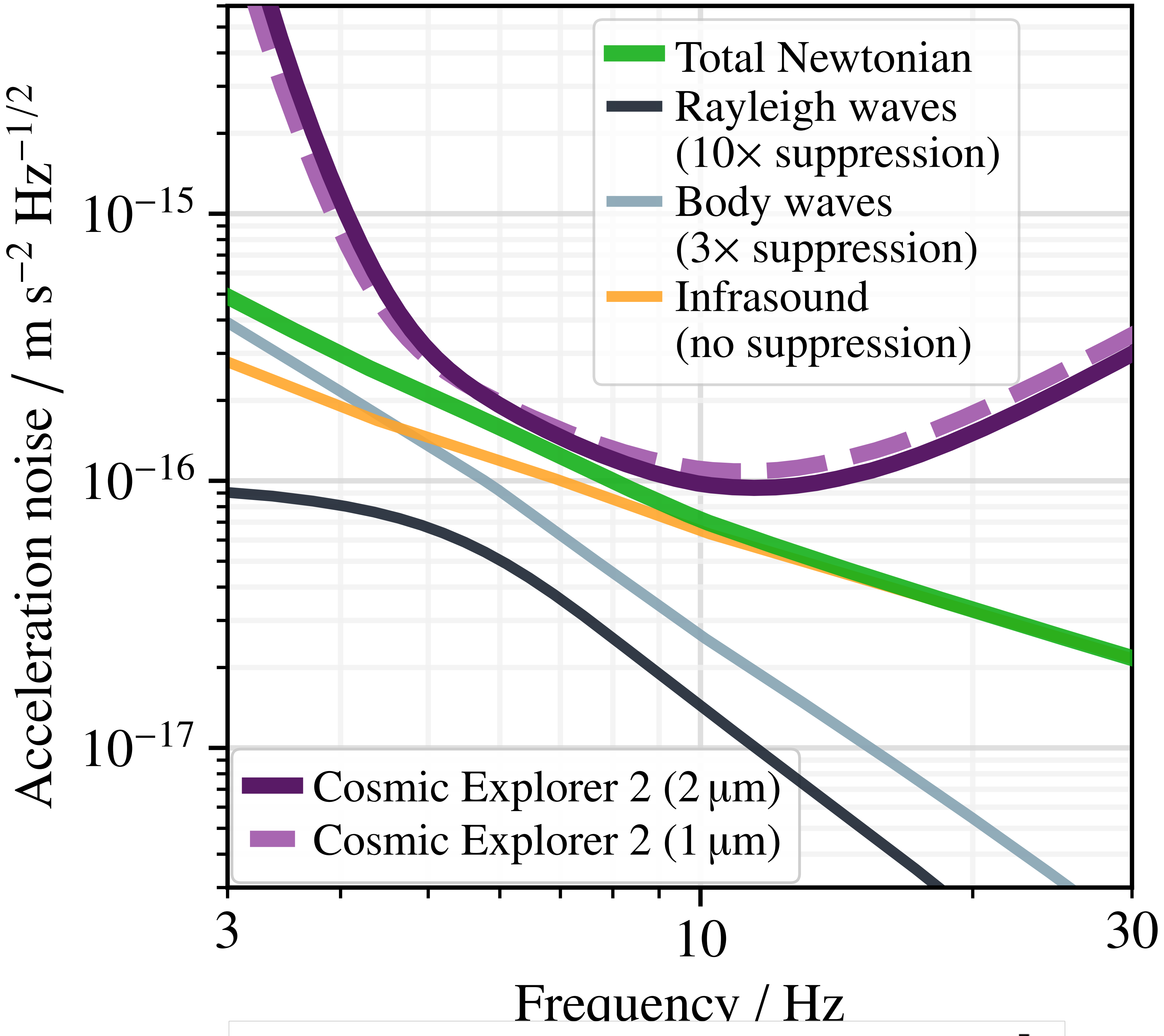
CE - Newtonian Noise

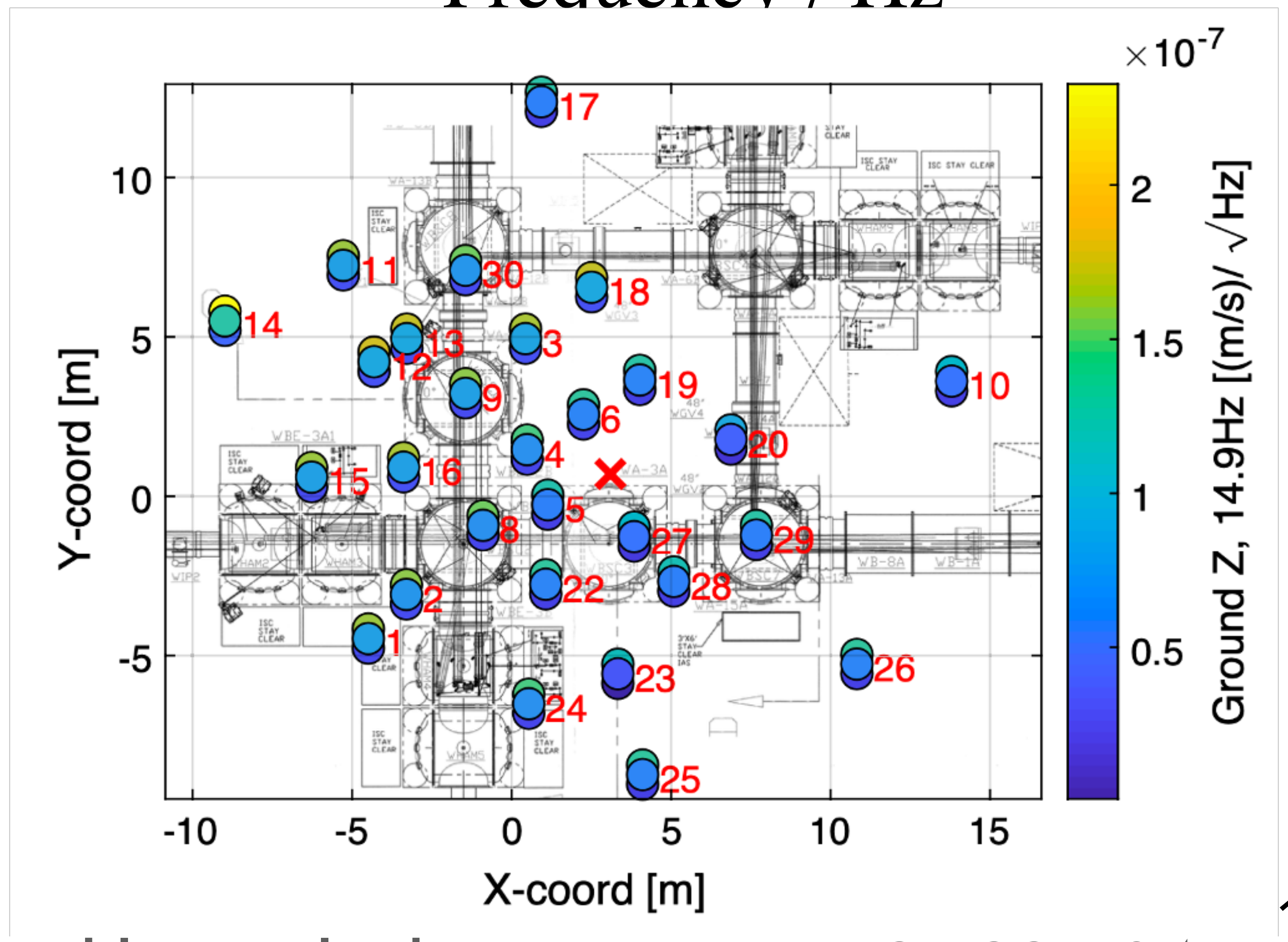
- Required mitigation of upto 10x suppression
  - Predominantly surface wave
  - Research underway to develop techniques
- Infrastructure features
  - Low density around/underneath test mass
  - Meta-material/refraction near stations.



S. S. Y. Chua, et al. APL, 122(20), 05 2023. 201102.

Hall et al. DOI: 10.1103/PhysRevD.103.122004





M. W. Coughlin et al Phys. Rev. Lett., 121:221104.

Einstein Telescope

https://www.et-gw.eu/index.php/etimages

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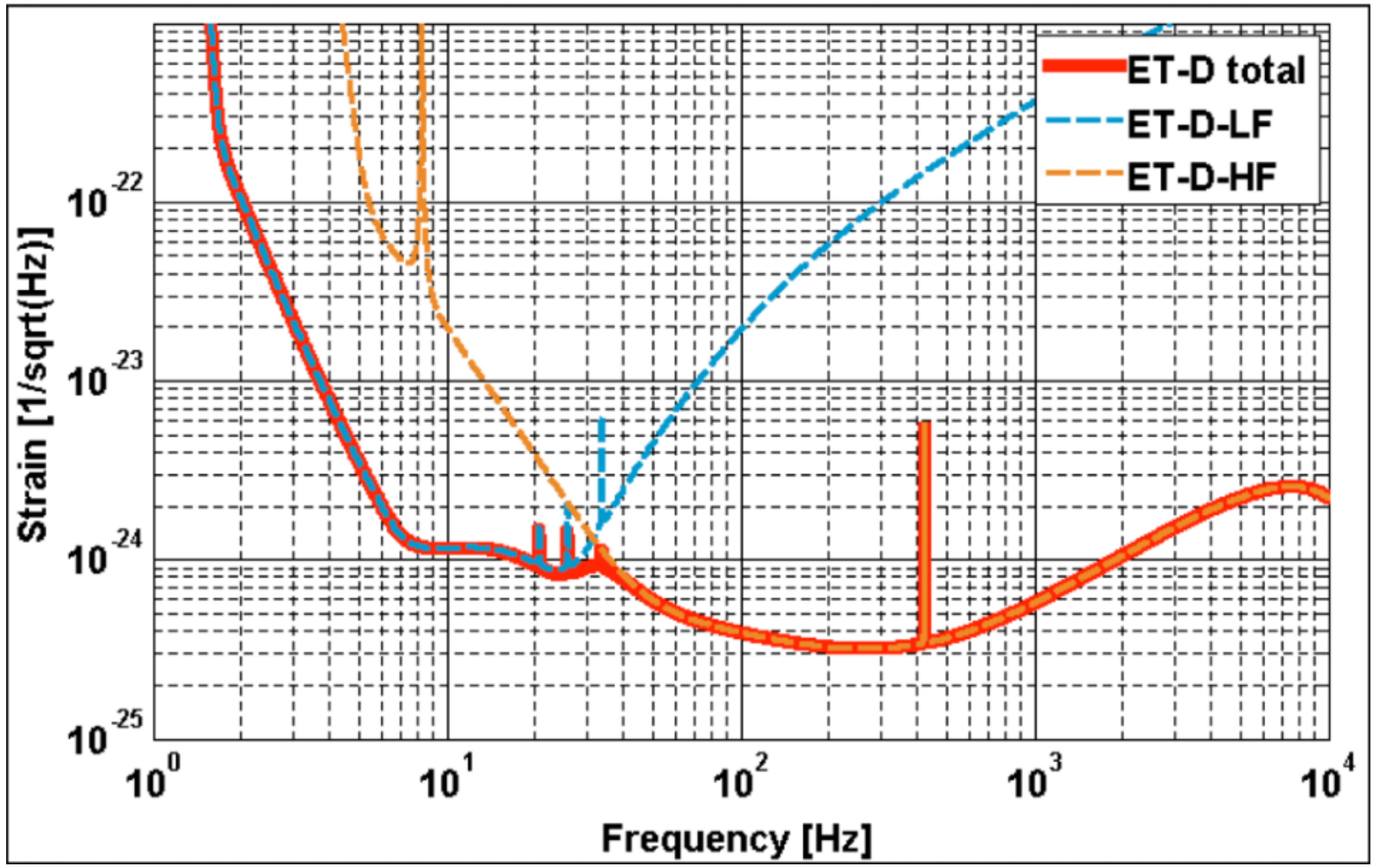
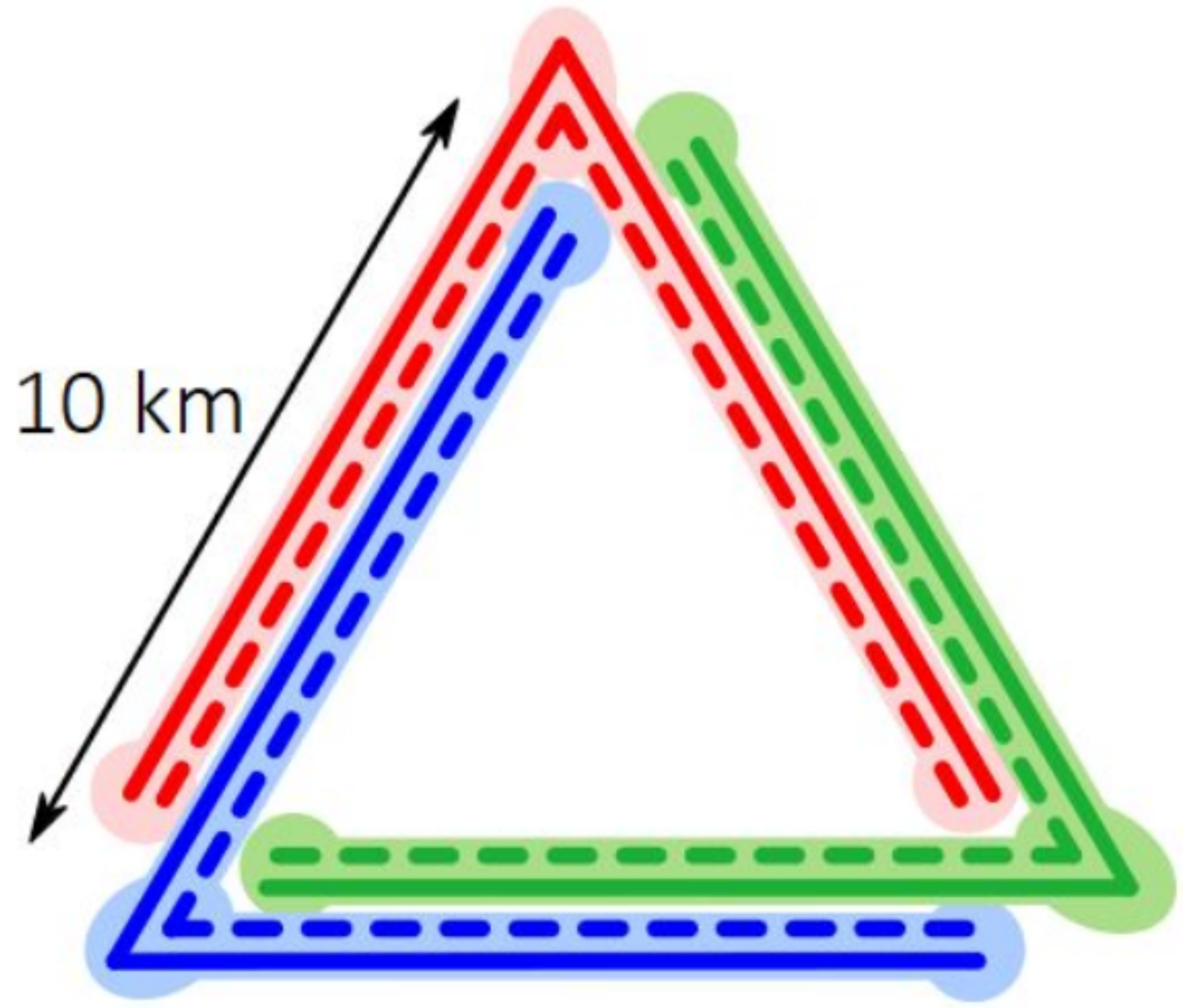
Einstein Telescope

Next-generation European-based gravitational-wave observatory

- Planned to be operation in the 2030s
- 10-km triangle underground observatory*
- Sense both polarisations; sensitive to low frequencies down to a few Hz





- Solid – room temperature high-frequency
- Dashed – cryogenic low-frequency

* Nominal design, under revision

https://www.et-gw.eu/index.php/etimages

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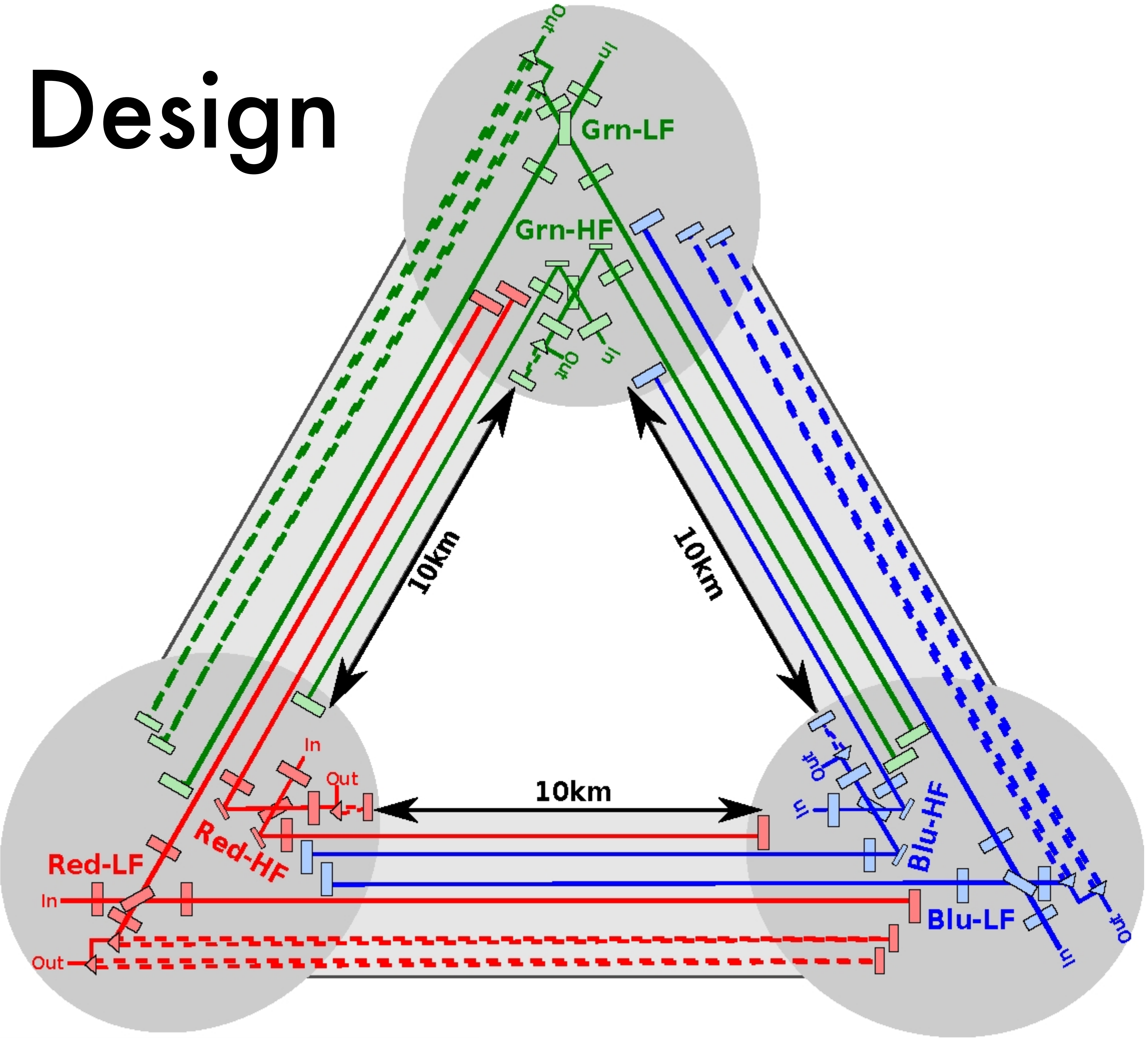
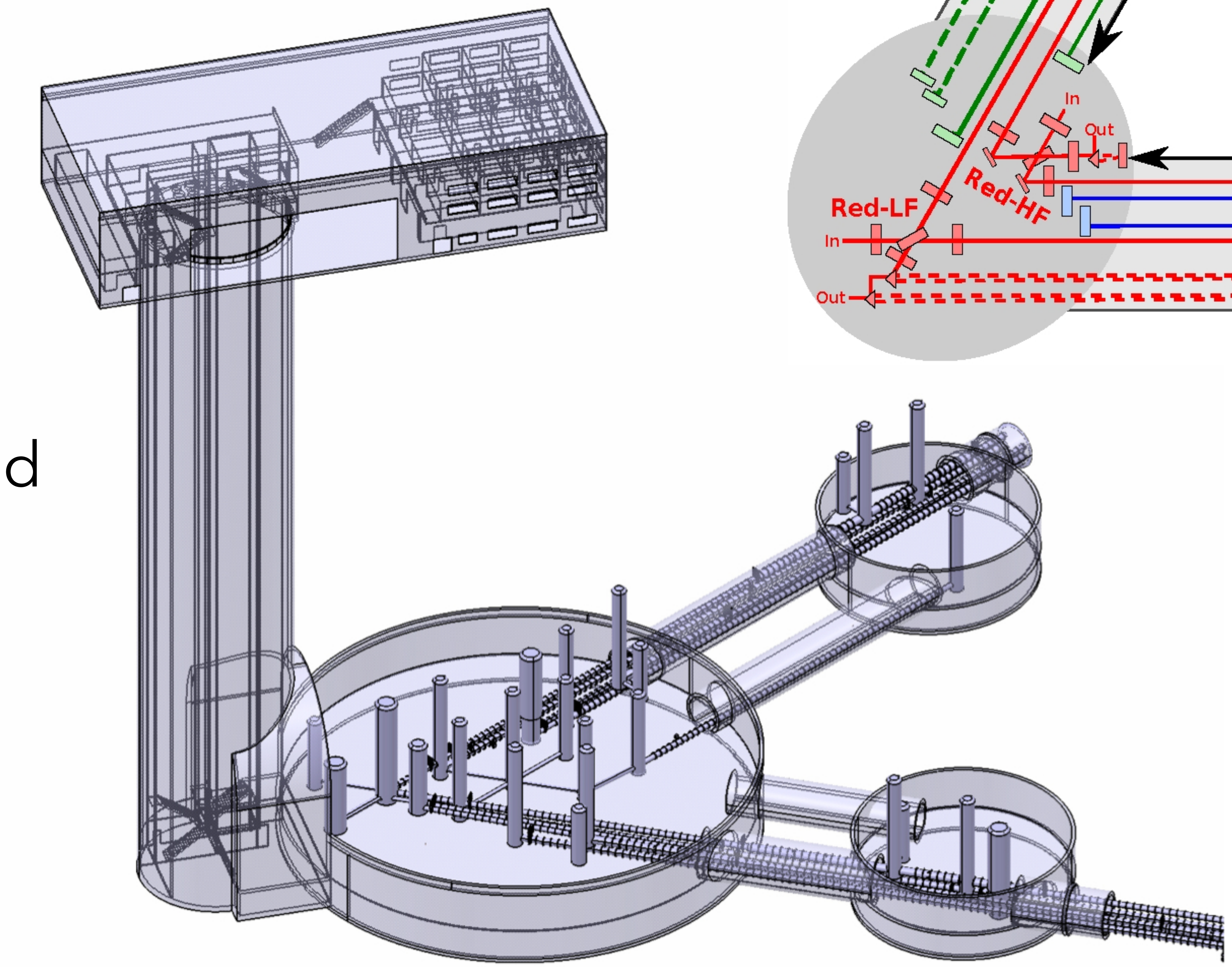
Einstein Telescope Nominal Design



- Equilateral triangle
- Arm length 10km
- 200-300 m underground
  - Mitigate Newtonian Noise
- 3 'detectors'
  - Each detector consist of a low- and high-free interferometer.



https://www.et-gw.eu/index.php/etimages

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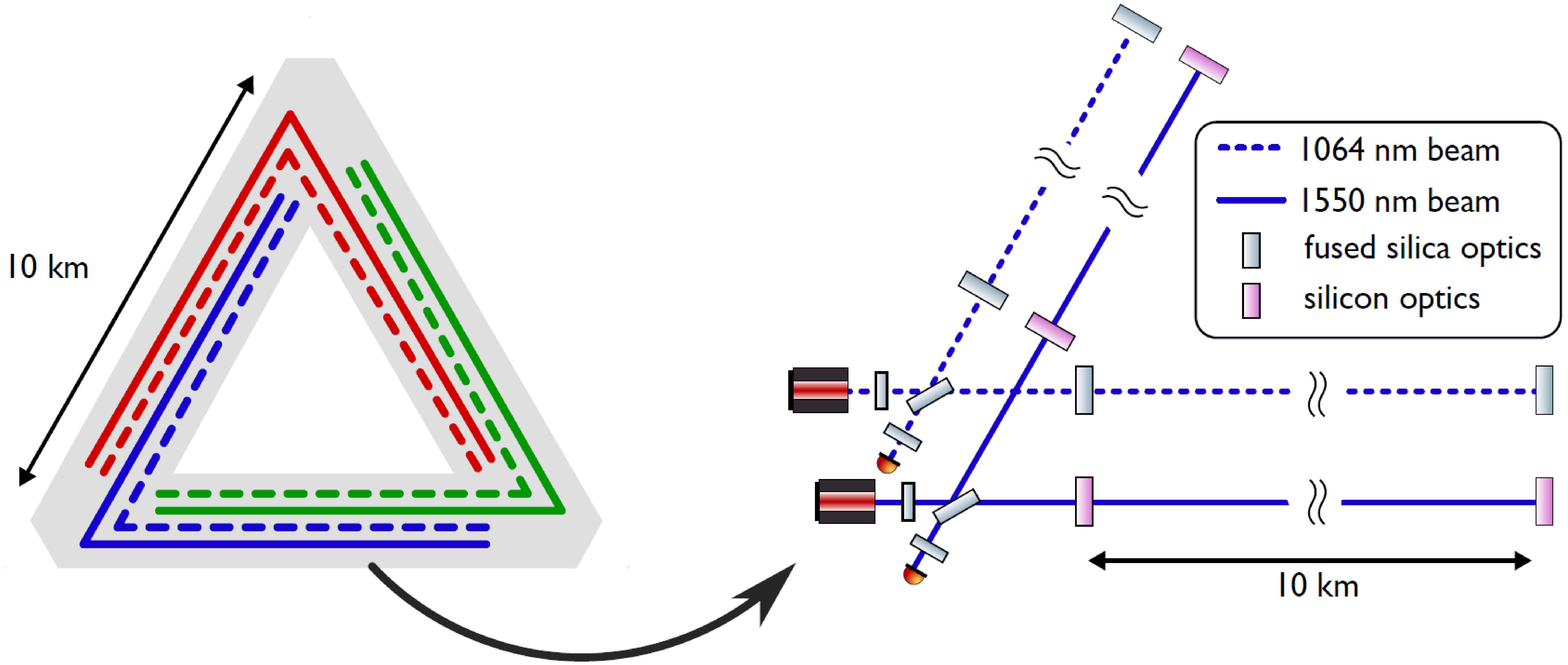
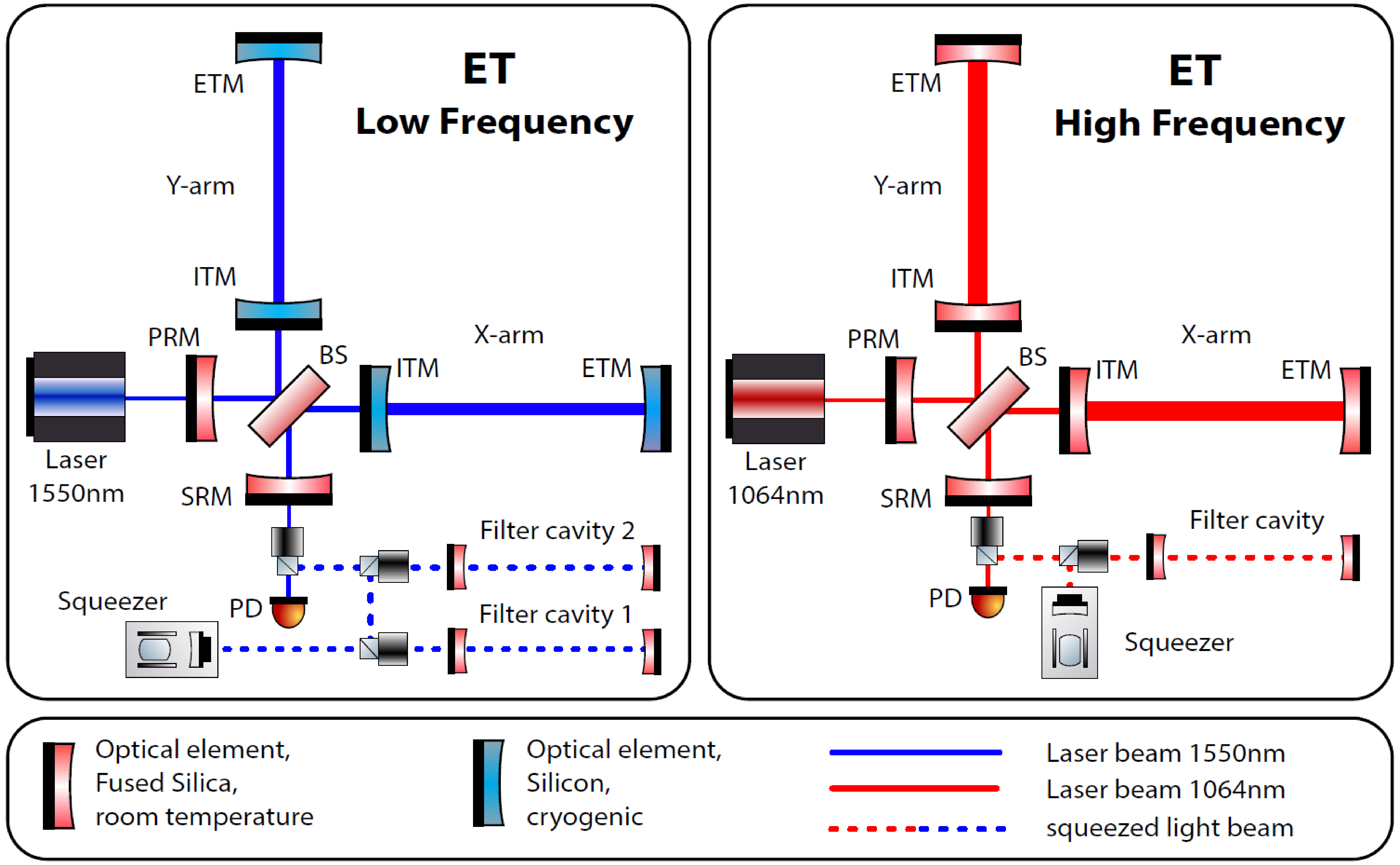
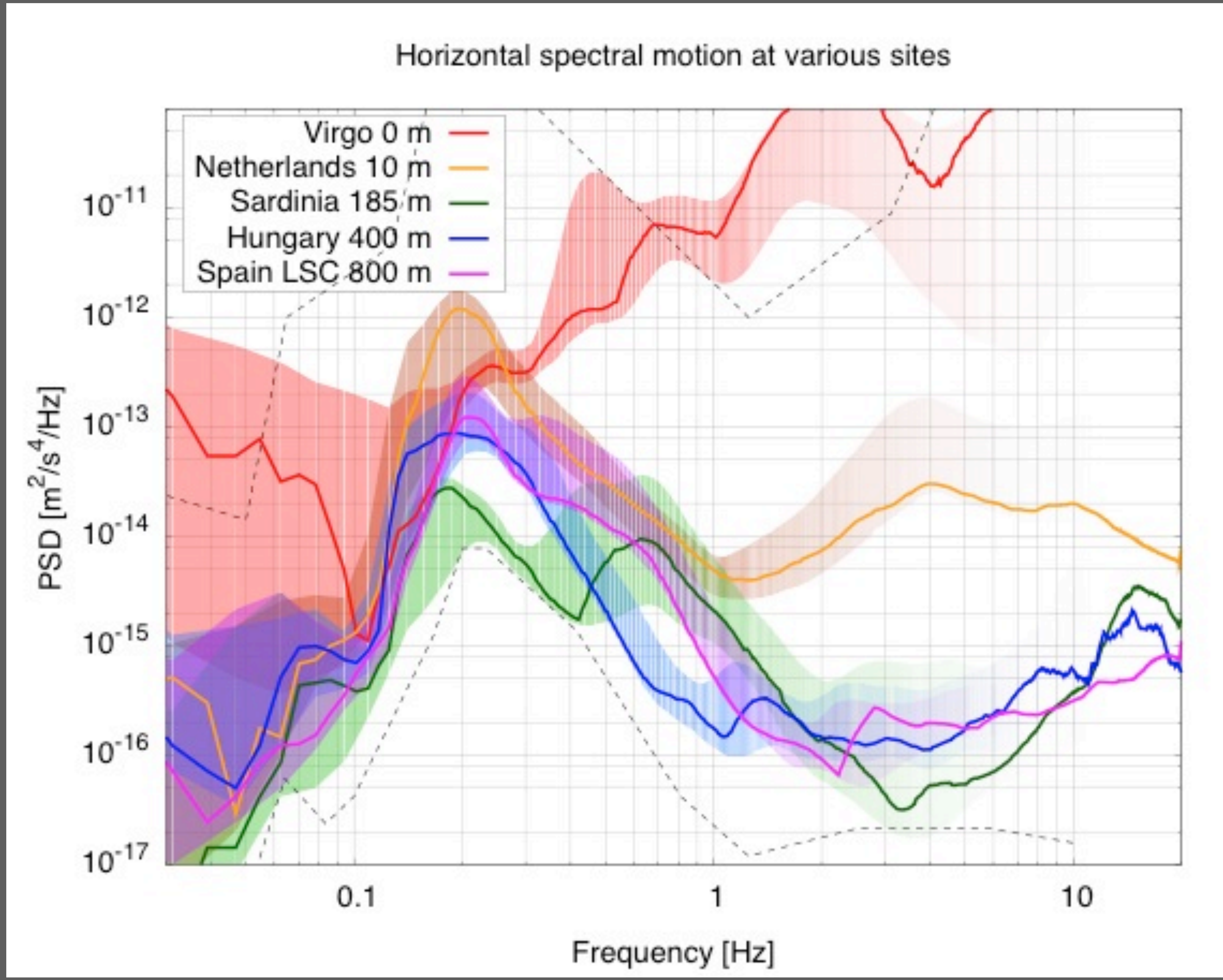
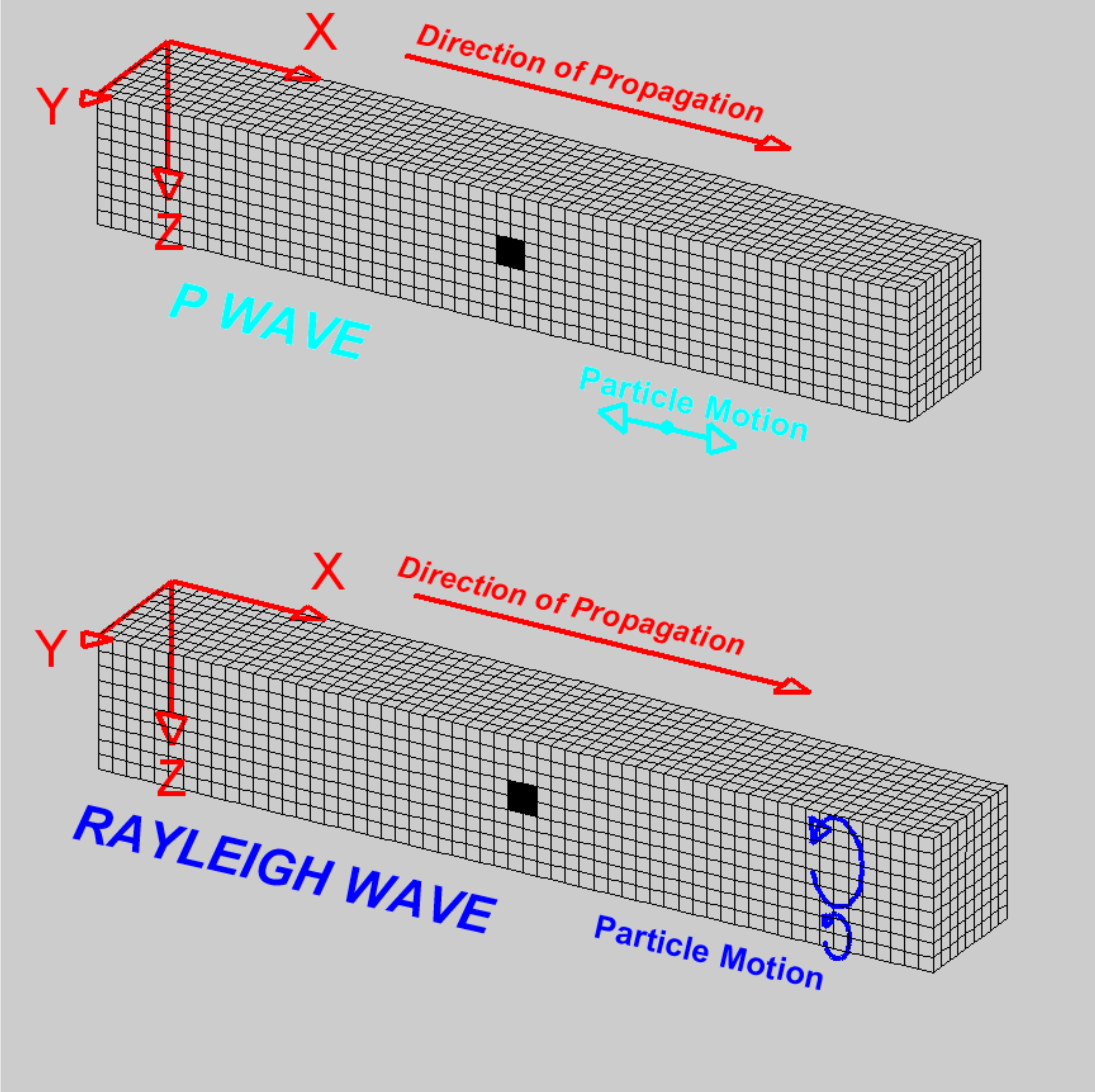
Quantity	ET-HF	ET-LF
Arm length	10 km	10 km
Wavelength	1 um	1.55 um
Mirror mass	200 kg	211 kg
Mirror Material	Fused Silica	Silicon
Arm Power	3 MW	18 kW
Operating Temp	290 K	10-20 K
Squeezing	10 dB	10 dB
Newtonian Noise Suppression	-	3x







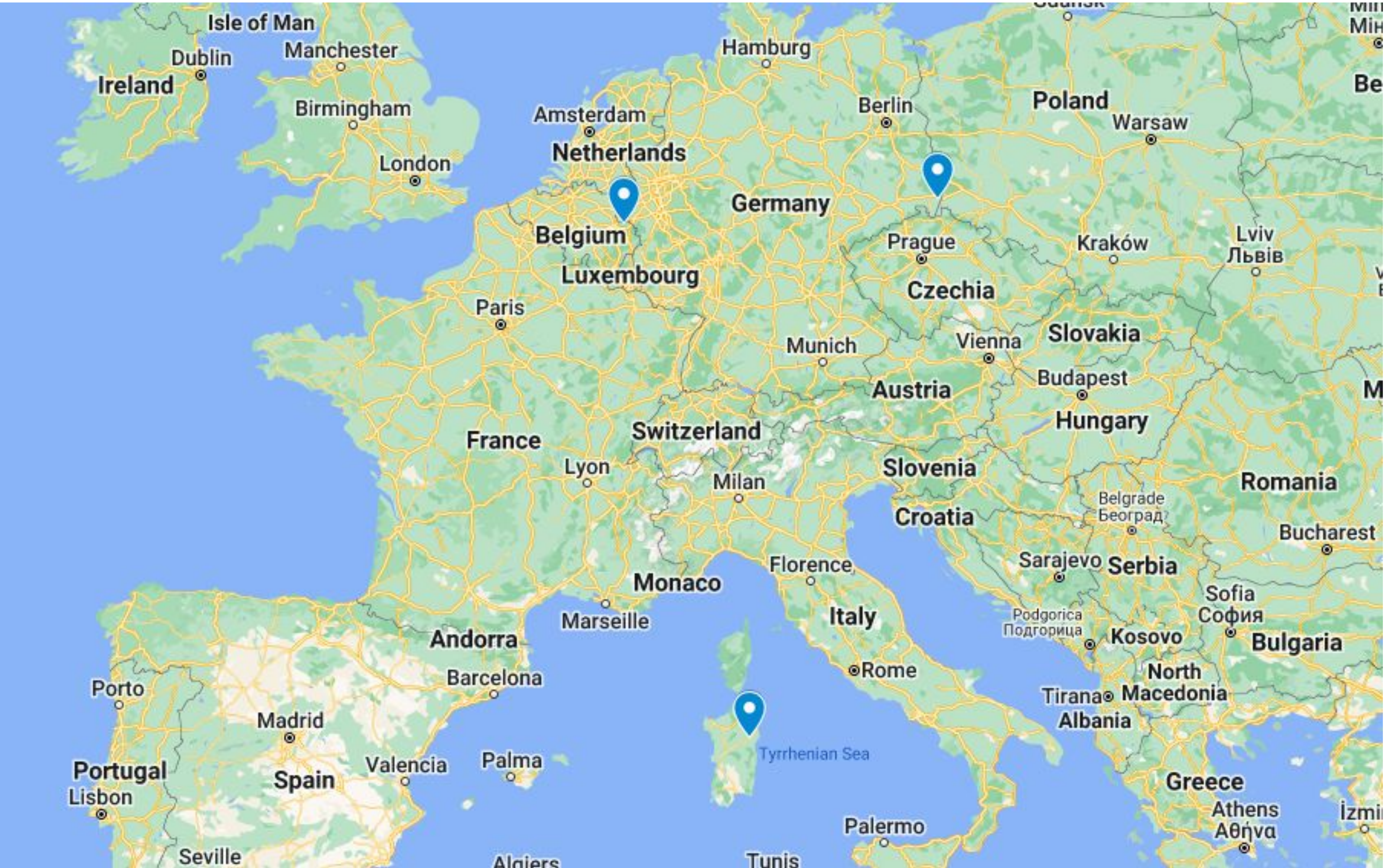
Underground location for reduction of seismic and atmospheric GGN + long baseline



Slide Courtesy Einstein Telescope, Archisman Ghosh

EINSTEIN TELESCOPE

Where?



Two formal candidate sites:

- North of **Sardinia** (Sos Enattos, Lula area, Barbagia)
- **EMR** EURegio (border between Belgium, the Netherlands, and Germany)

Proposed third potential site:

- Lausitz, **Saxony**, Germany

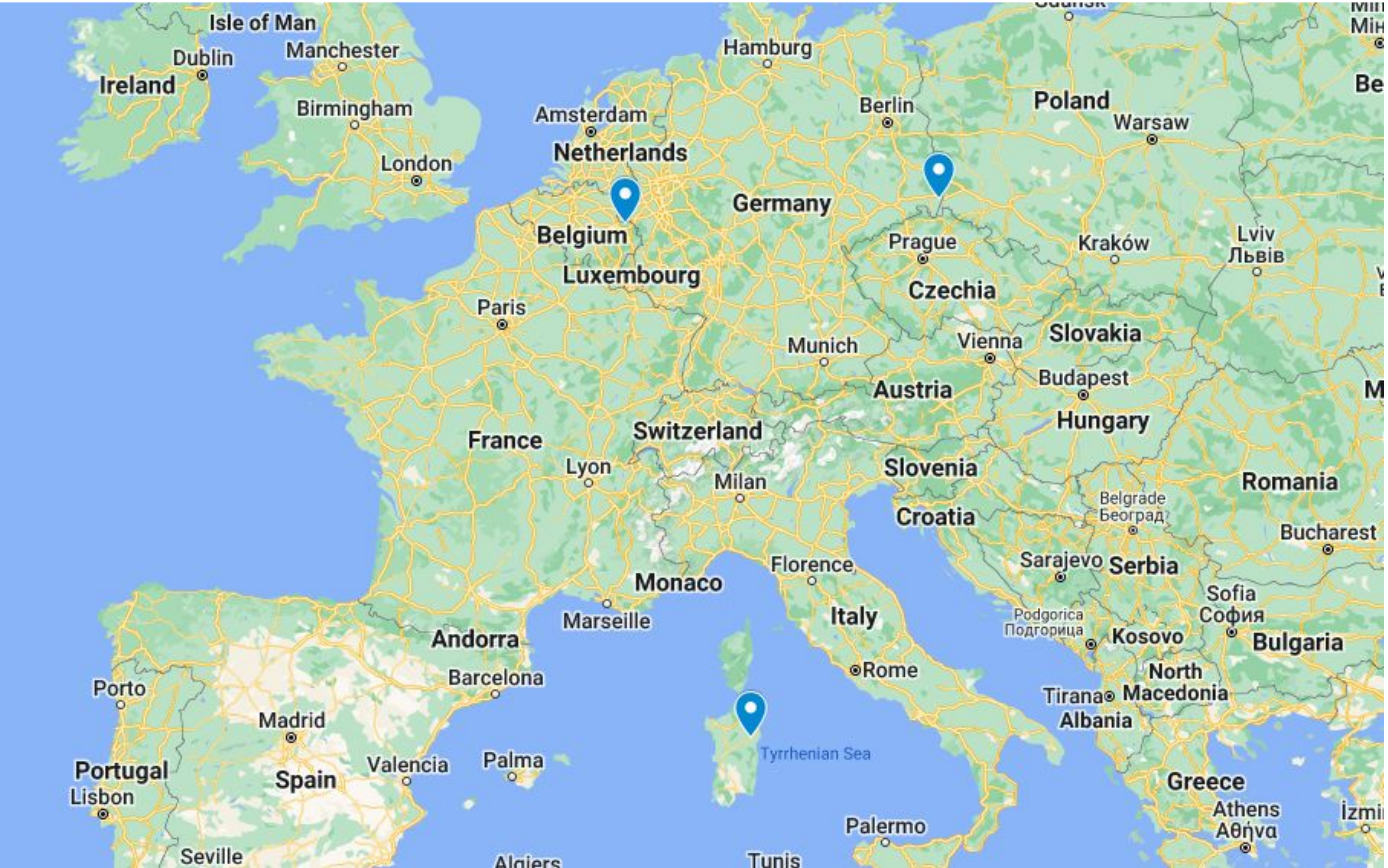
Site evaluation is a complex task dependent on:

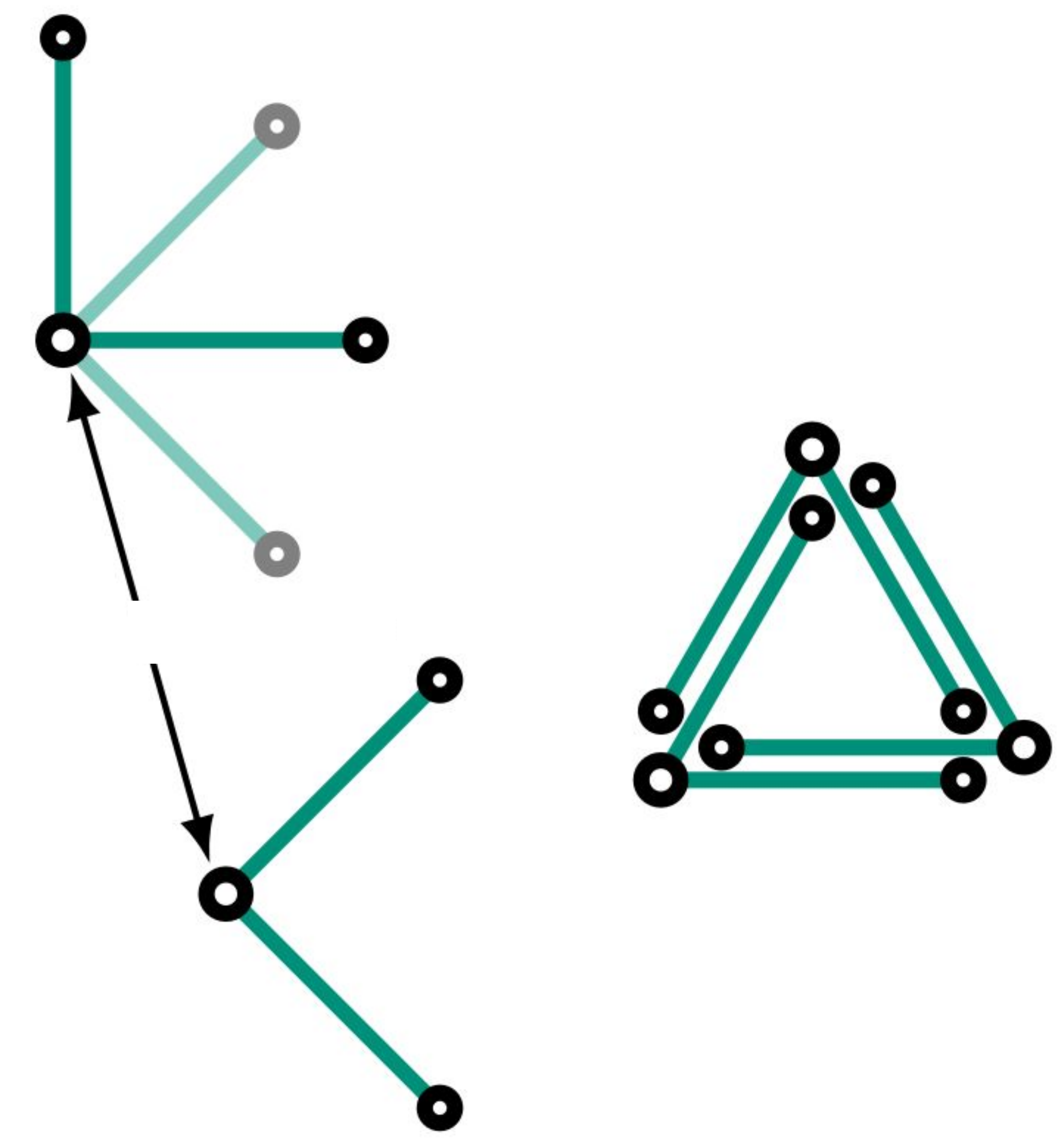
- Geophysics and environment
- Finances and organization
- Services, infrastructures

Slide Courtesy Einstein Telescope, Archisman Ghosh

EINSTEIN TELESCOPE

Geometry





***J**ournal of **C**osmology and **A**stroparticle **P**hysics*
An IOP and SISSA journal

Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi,[1,2,*] Michele Maggiore,[3,4,*] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Enis Belgacem,[3,4] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11]

CPP #: Conference Room F1-R3

COSMIC EXPLORER

Tue 26/08 GW-3-CPP

14:00

Constraints on Lorentz and parity violations with g
Conference Room F1-R3

Wave Effects of Gravitational Waves
Conference Room F1-R3

Gravitational Wave Birefringence in Fuzzy Dark Ma
Conference Room F1-R3

15:00

A treatment to gravitational perturbations and Lor
Conference Room F1-R3

GW-4-CPP

16:00

Implications of Cosmological Gravitational Wave S
Conference Room F1-R3

Probing Dark Matter with Space and Ground-based
Conference Room F1-R3

Bayesian model selection of Primordial Black Hole
Dr Xin-yi Lin

17:00

Wed 27/08 GW-5-CPP

14:00

Gravitational wave emission from merging strange quark star - strange planet. — *永锋 黄*
Conference Room F1-R3 — 14:00 - 14:20

Multiband Gravitational Wave and Multimessenger Astronomy with Galactic compact binaries — *Yan Wang*
Conference Room F1-R3

Long-term multi-messenger signal simulation of a super
Conference Room F1-R3

15:00

Gravitational Waves with Complex Features as Precision
Conference Room F1-R3

Detecting Gravitational Waves from Exoplanets Orbiting
Conference Room F1-R3

GW-6-CPP

16:00

Gravitational waves from preheating in the early Univers
Conference Room F1-R3

Search for an isotropic Gravitational Wave Background w
Alba Romero-Rodríguez

Enhancing Taiji's Estimation on Galactic Binaries and Ins
Minghui Du

17:00

Dawning of a new era in gravitational wave data analysis
赵 天宇

Accelerating Stochastic Gravitational Wave Backgrounds
Bo Liang

Impact of Massive Black Hole Binaries Source Confusion
Qing Diao

18:00

Thu 28/08 GW-7-CPP

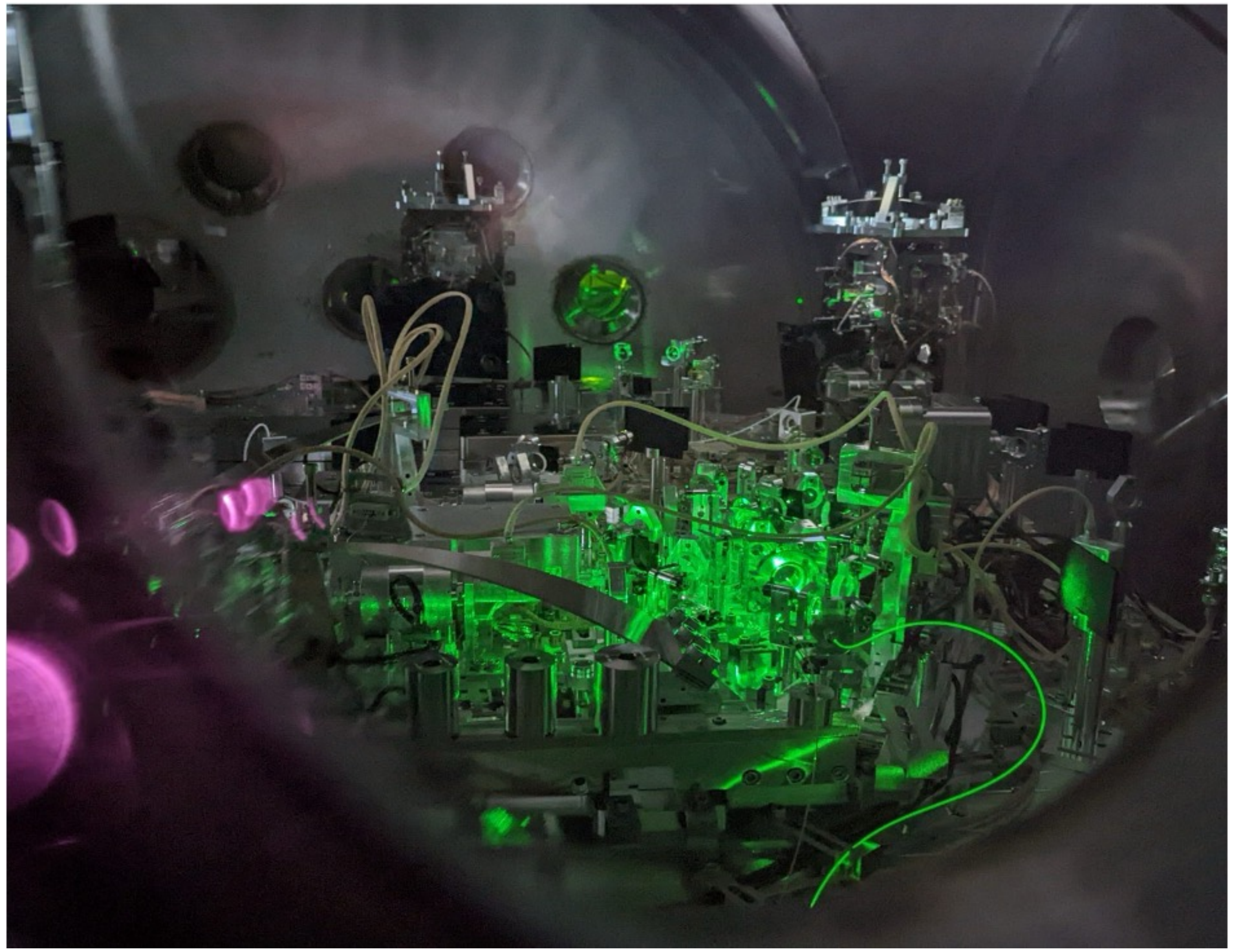
14:00	The staus of KAGRA Large-scale Cryogenic Gravitational Wave Telescop	Prof. Shinji MIYOKI	Conference Room F1-R3	14:00 - 14:20
	Use of phase sensitive amplifier for the back-action evasion scheme	Kentaro Somiya	Conference Room F1-R3	14:20 - 14:40
	Quantum entanglement for gravitational-wave detectors	Mr Yohei Nishino	Conference Room F1-R3	14:40 - 15:00
15:00	Space-based optical lattice clocks as gravitational wave detectors	Bo Wang	Conference Room F1-R3	15:00 - 15:20
	Fundamental Quantum Limits for Detecting Ultra-high Frequency Gravitational Waves	Xinyao Guo	Conference Room F1-R3	15:20 - 15:40

GW-8-CPP

16:00	New dark matter production mechanism and the gravitational wave signals	Fa Peng Huang	Conference Room F1-R3	16:00 - 16:20
	Gravitational wave spectrum from metastable cosmic string network and the delayed scaling scenario	Kohei Kamada	Conference Room F1-R3	16:20 - 16:40
	The Equilibrium Spectrum of Stochastic Gravitational Wave Background and Its Role in Cosmic Evolution	Manjia Liang	Conference Room F1-R3	16:40 - 17:00
17:00	Detecting Gravitational Waves from Cosmic Phase Transitions in Space	Qingyuan Liang	Conference Room F1-R3	17:00 - 17:20
	Compact Four degree-of-freedom Seismometer with Capacitive Readout	Yulin Xia	Conference Room F1-R3	17:20 - 17:40

Summary

- Next generation detector with an increase in sensitivity of 10x
- Astrophysics delight
  - Ability to see most NS-NS merger events
  - High SNR detections
  - Ability to test GR, merger ringdown measurements
  - Cosmology with high volume of events
- Cosmic Explorer, US based, 40 km and 20 km facilities
- Einstein Telescope, EU based, underground facility



Operational quantum manipulated and optimised light source within the LIGO detectors (photo G. Mansell)

Thank you

Questions?