Longer-term future ground-based detectors (3G)

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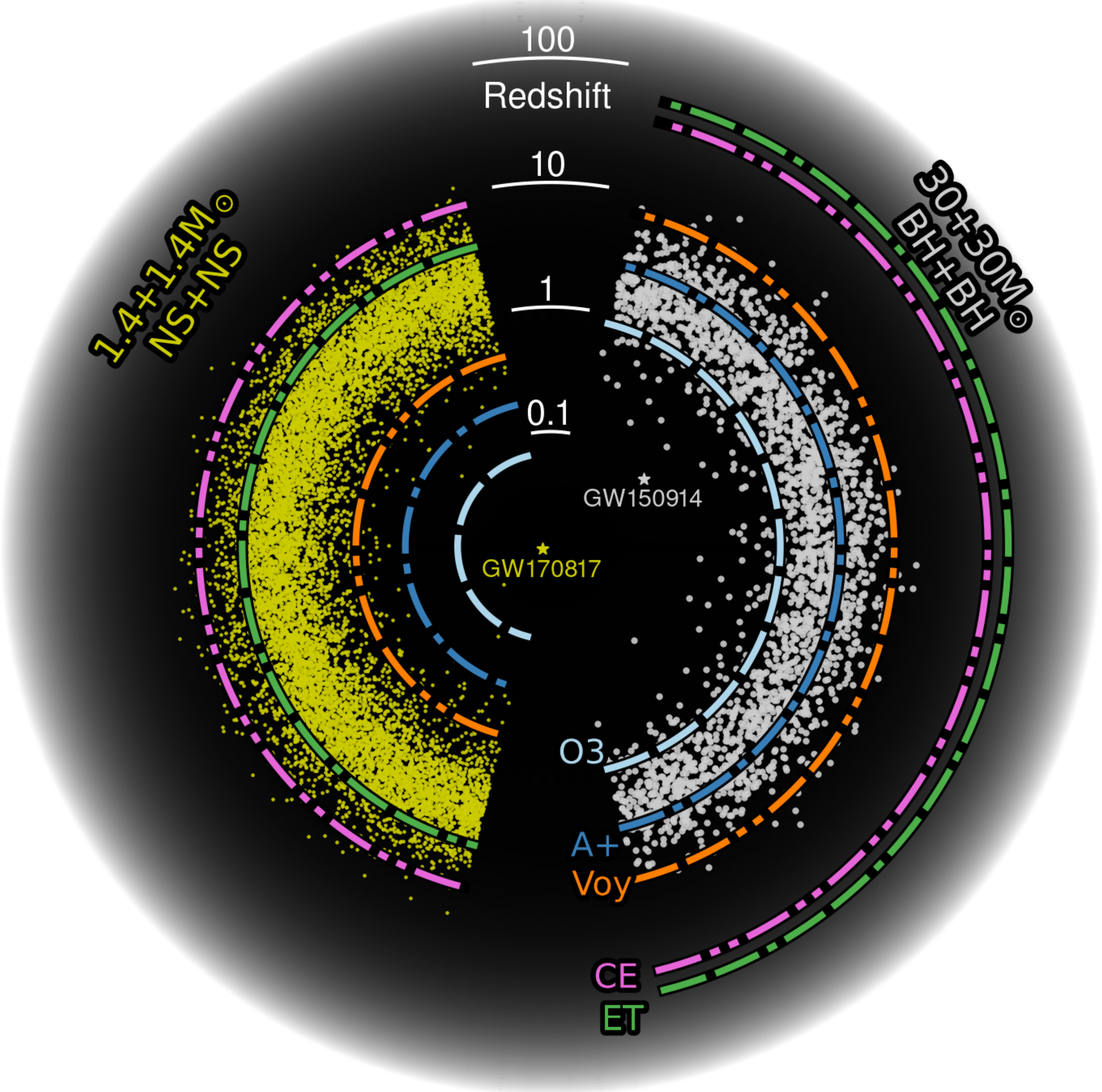
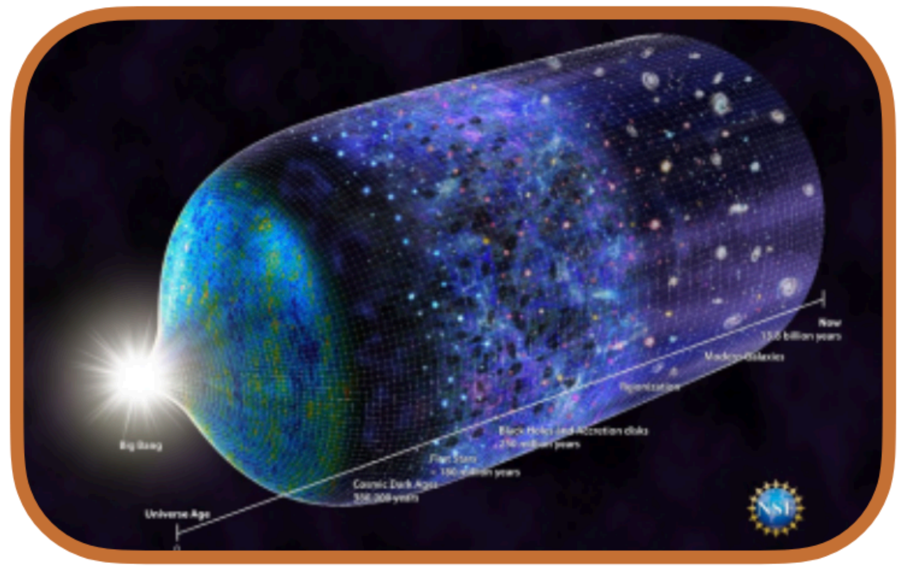
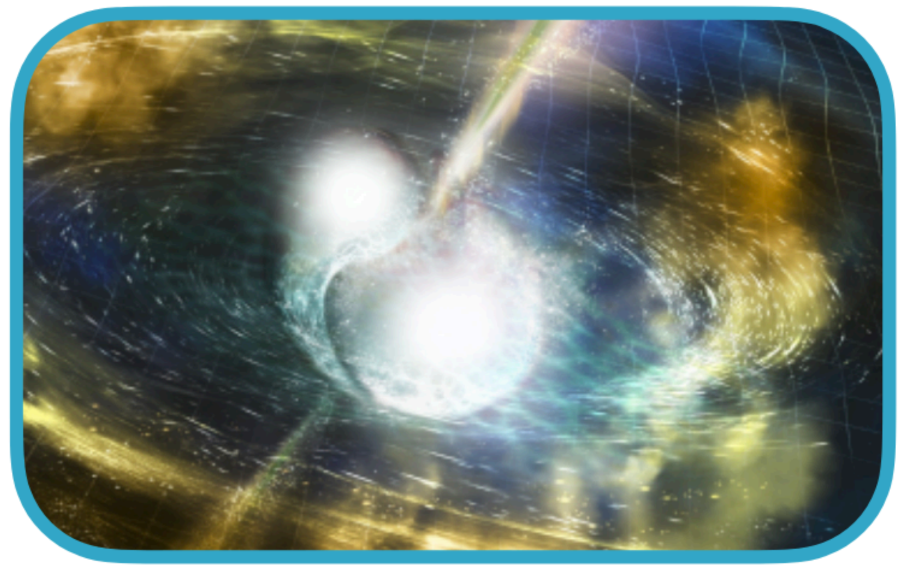
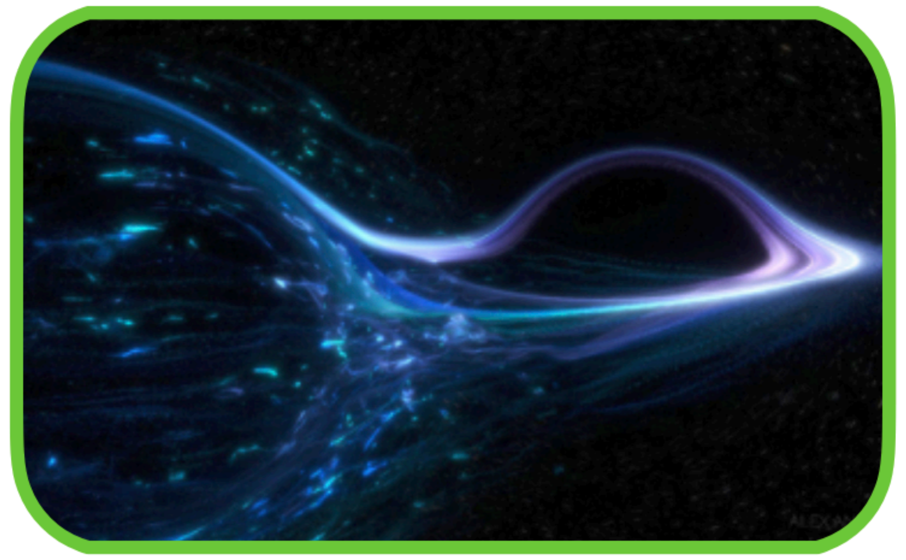
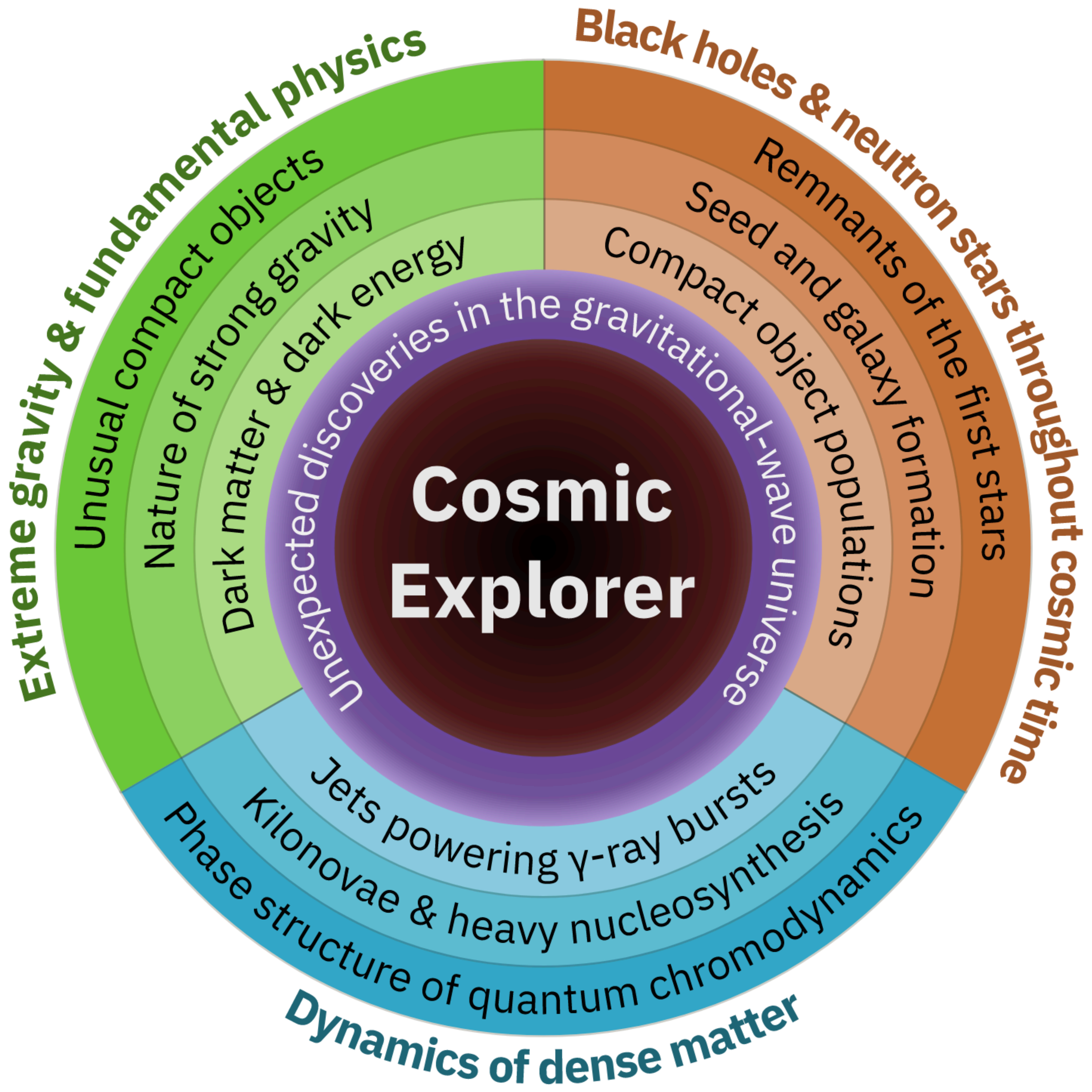
Next Generation Detectors











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

- *Get stellar remnants throughout cosmic time*
- *Look deep into the universe with unprecedented precision*

Outline

- *Next generation gravitational wave detectors will be located at new locations in new infrastructure facilities.*

- *These are also referenced to as third generation (or 3G) detectors.*

- *They will operate in a global network*

1. *Cosmic Explorer - US based project, with two surface observatories*

2. *Einstein Telescope - EU based project, co-located interferometers in one underground facility*

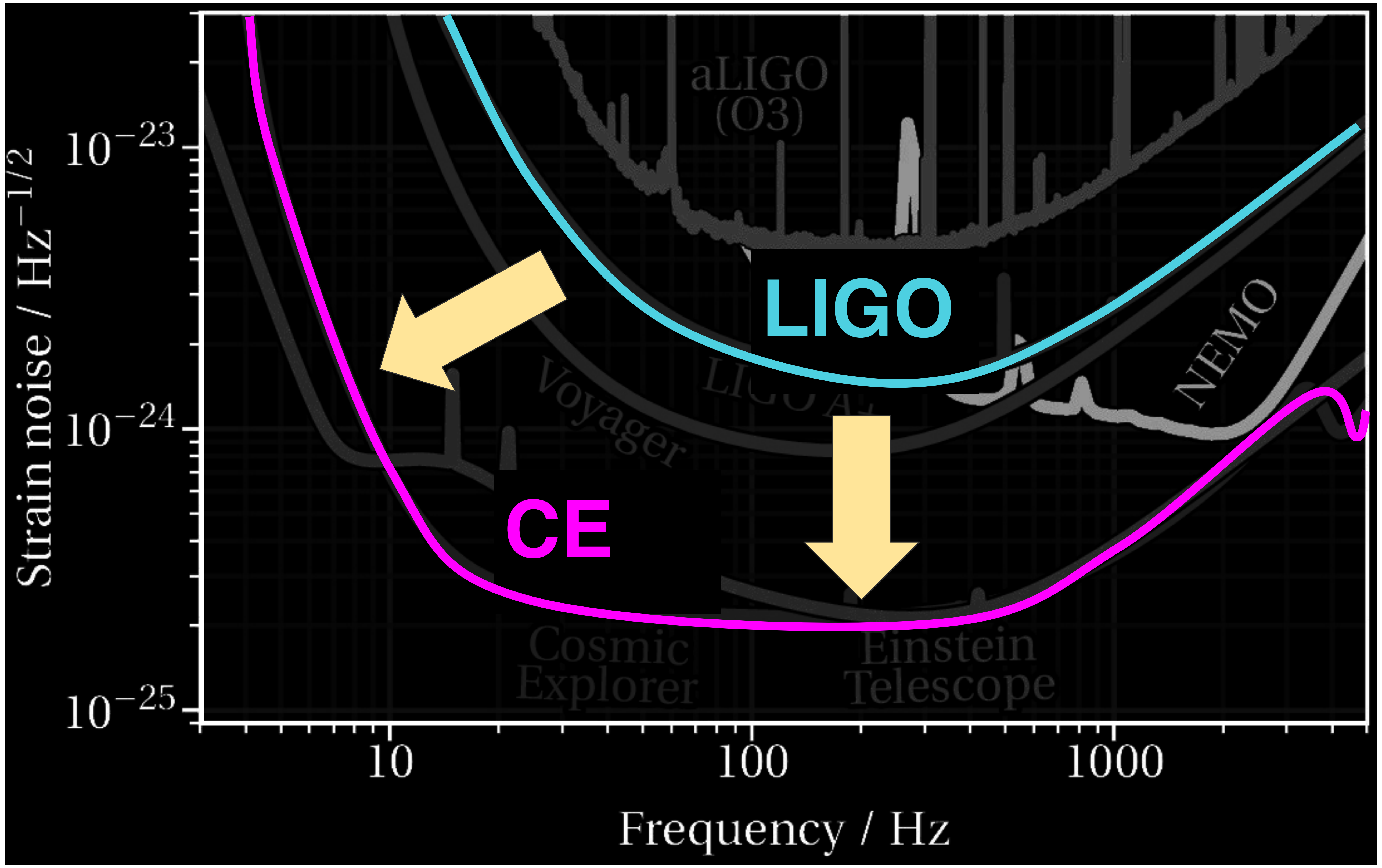
3. *Neutron Star Extreme Matter Observatory (NEMO) - Australia based project?*

Cosmic Explorer

With help from:
Matthew Evans
Joshua smith

Cosmic Explorer

- *Next-generation US-led GW observatory project*
  - *20 km and 40 km L-shaped surface observatories*
  - *10x sensitivity of Advanced LIGO+*
- *Under development, may begin operating in the 2030s*
  - *Initially scaled up A+ technology & enhancements*
  - *Flexible facilities allow building on R&D breakthroughs*
- *Megaproject enabling astro-* breakthroughs*
  - *with ET, 2G detectors, LISA, EM, Particle, …*



http://cosmicexplorer.org

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

Slide: Joshua Smith

CE Design Motivation

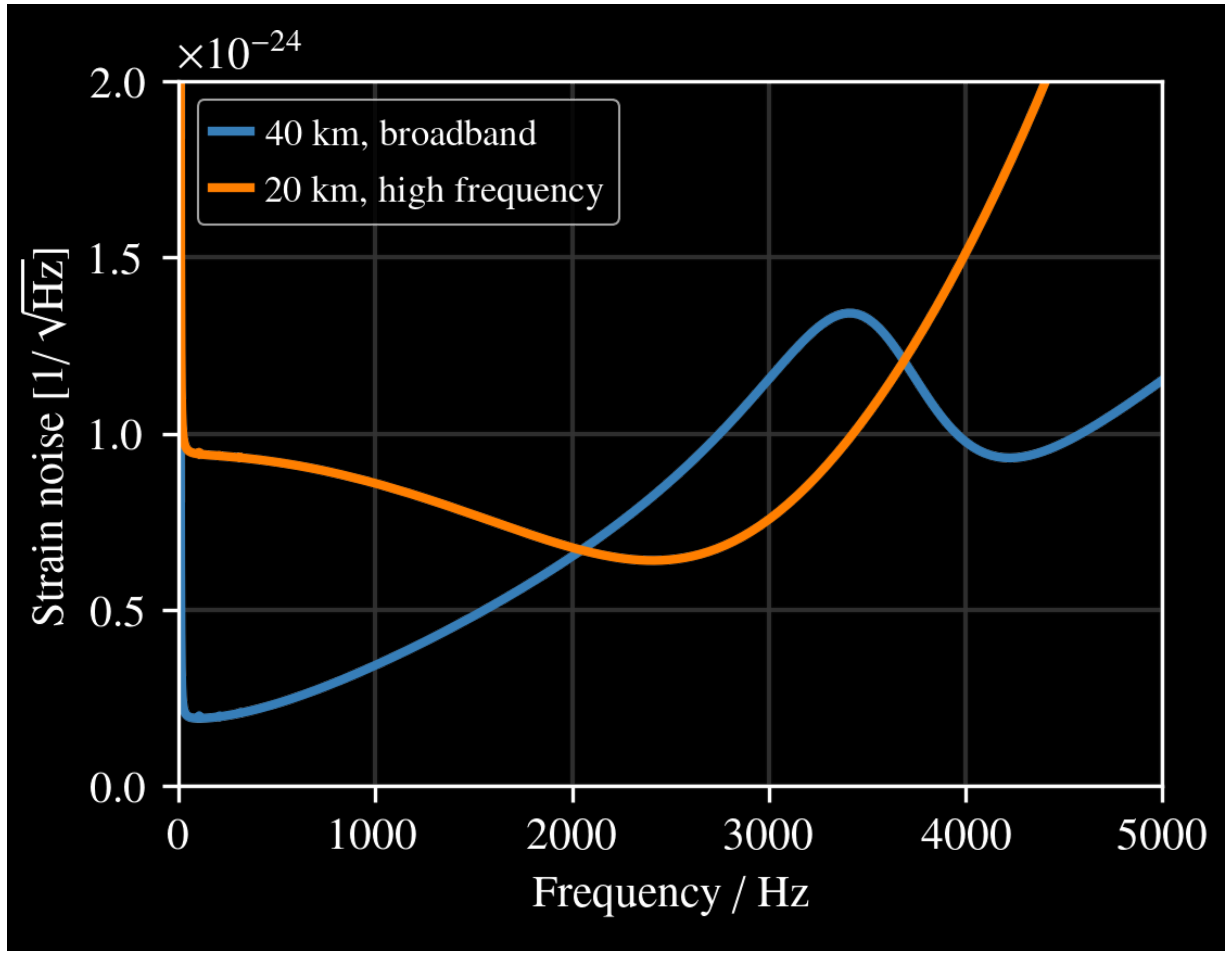
Optimize science output while minimizing risk and complexity

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
- L-shape to reduce vacuum system cost (already 40% of cost); Long arms advantageous where surface feasible (North America, Australia)

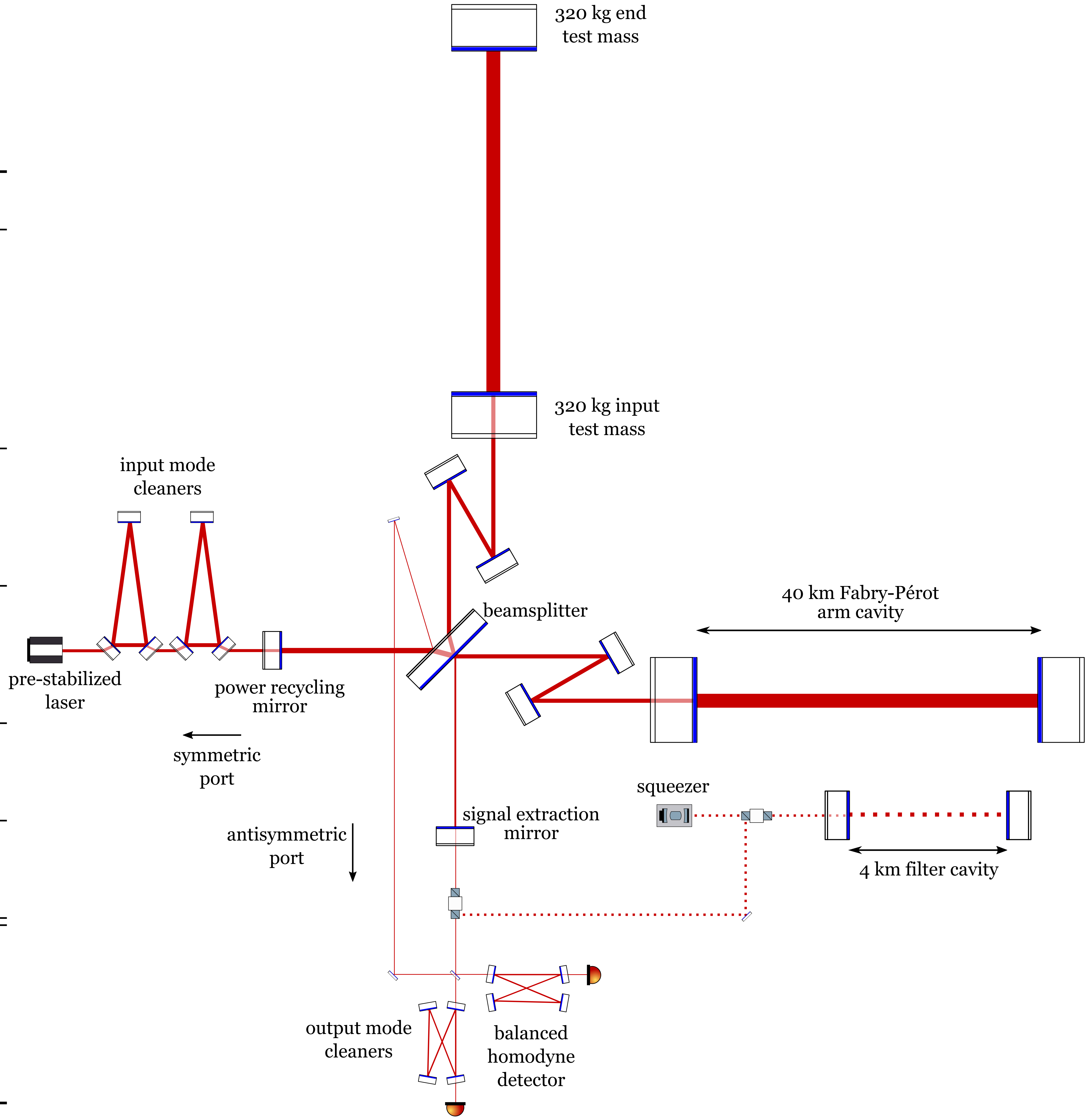
Number of detectors

- Two widely separated CEs advantageous for source localization, polarization



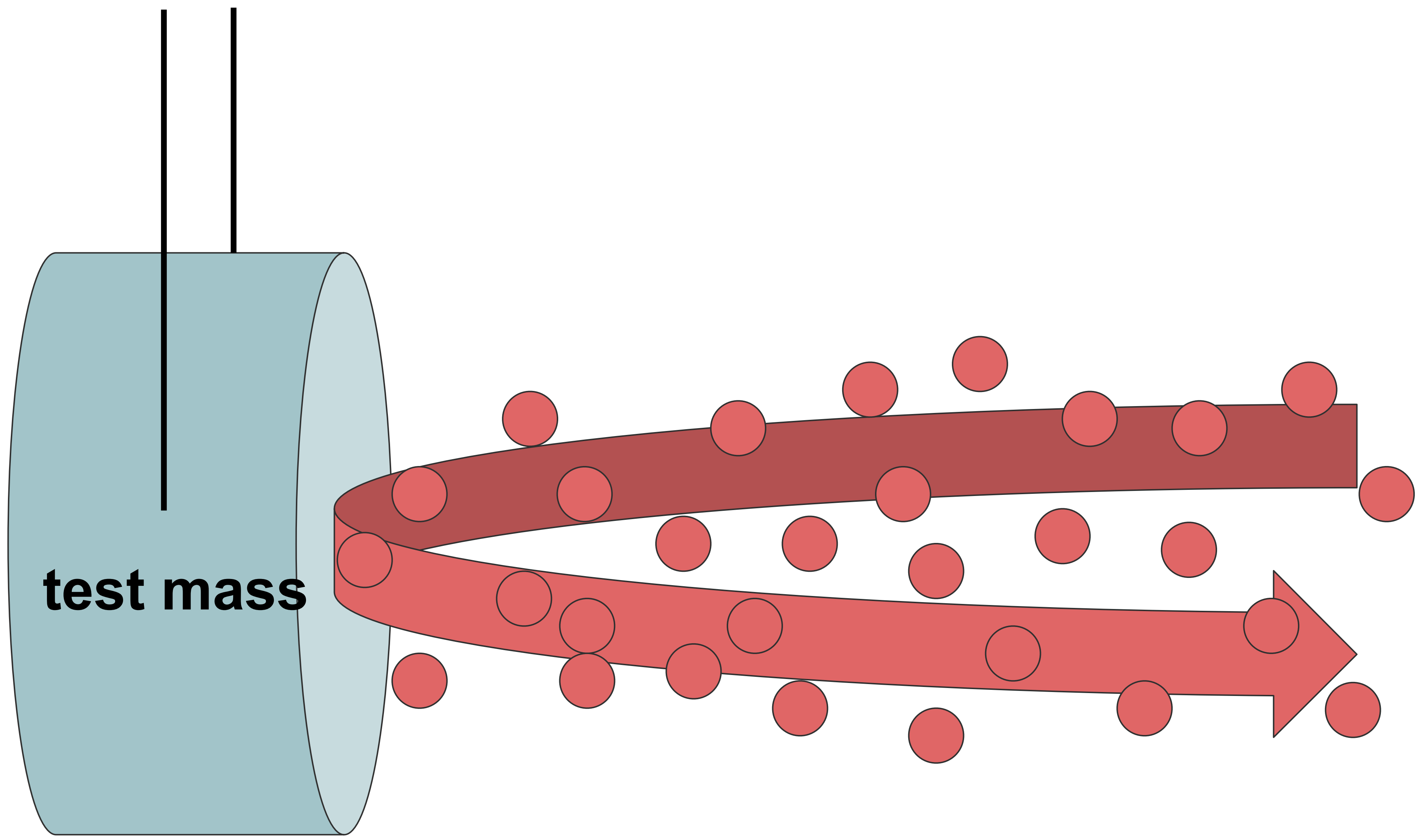
CE Optical Configuration

	Quantity	Units	LIGO A+	CE
	Arm length	km	4	40
	Laser wavelength	µm	1	1
	Arm power	MW	0.8	1.5
	Squeezed light	dB	6	10
	Susp. point at 1 Hz	$\mathrm{pm}/\sqrt{\mathrm{Hz}}$	10	0.1
Test masses	Material		Silica	Silica
	Mass	kg	40	320
	Temperature	K	293	293
Suspensions	Total length	m	1.6	4
	Total mass	kg	120	1500
	Fiber stress	GPa	0.8	1.6
Newtonian noise	Rayleigh wave suppr.	dB	0	20
	Body wave suppr.	dB	0	10
Optical loss	Arm cavity (round trip)	ppm	75	40
	SEC (round trip)	ppm	5000	500
	BNS horizon redshift		0.19	8.3
	BBH horizon redshift		2.7	41
	BNS SNR, $z = 0.01$		75	1260
	BNS warning, $z = 0.01$	min	4	103



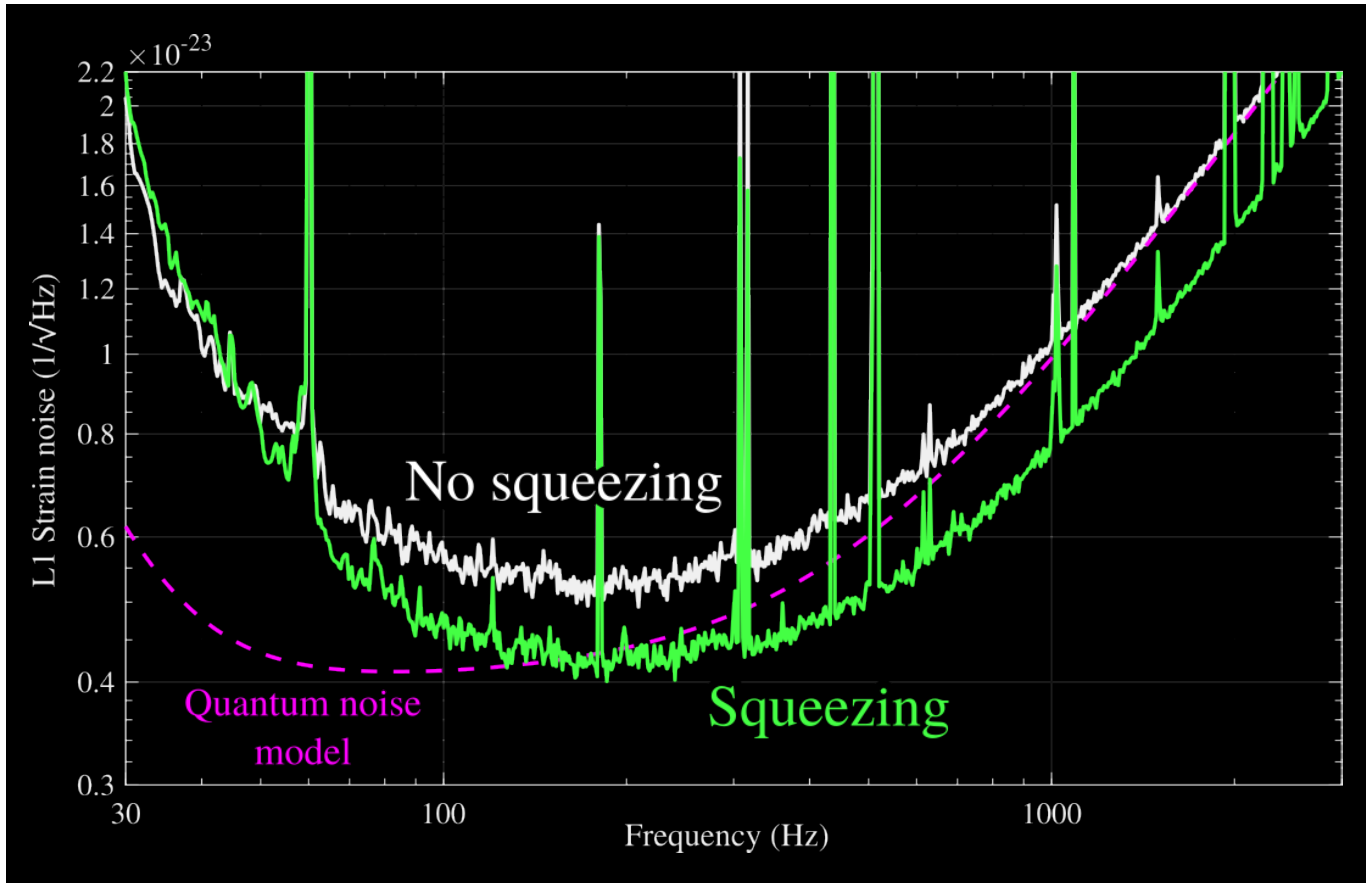
Evans et al., Cosmic Explorer Horizon Study, https://dcc.cosmicexplorer.org/CE-P2100003/public (2021)

CE Quantum noise



Shot noise (photon counting)
⇒ ***need high power: 1.5 MW***

Quantum backaction (photon momentum)
⇒ ***need heavy test masses: 320 kg***



Noise reduction with nonclassical states of light
⇒ ***frequency-dependent squeezed light***

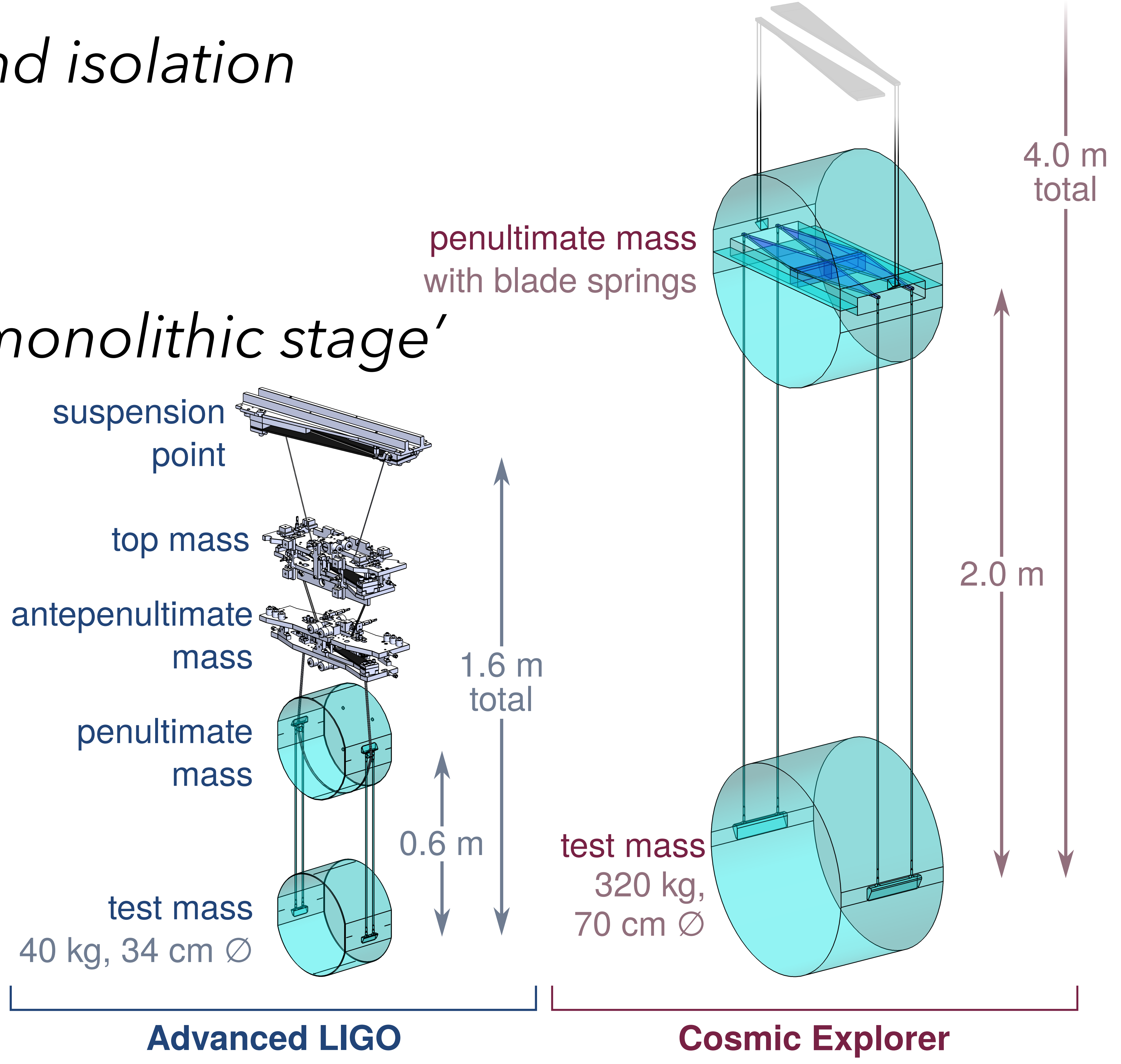
Virgo/LIGO will achieve 2× reduction
Cosmic Explorer targets 3× reduction

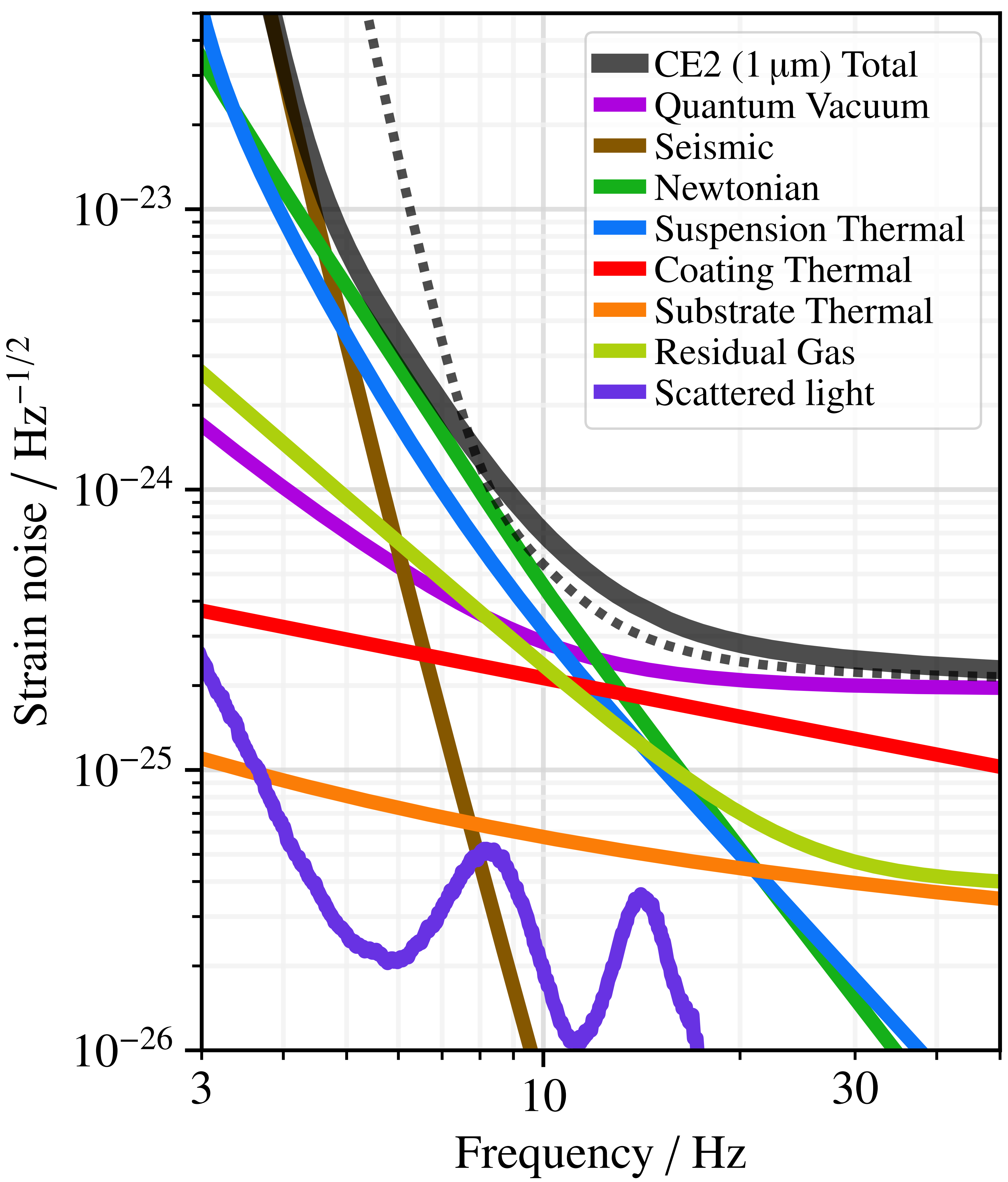
M. Tse et al.
Phys. Rev. Lett. 123, 231107

Slide: Evan Hall, MIT

CE Vibration Isolation

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



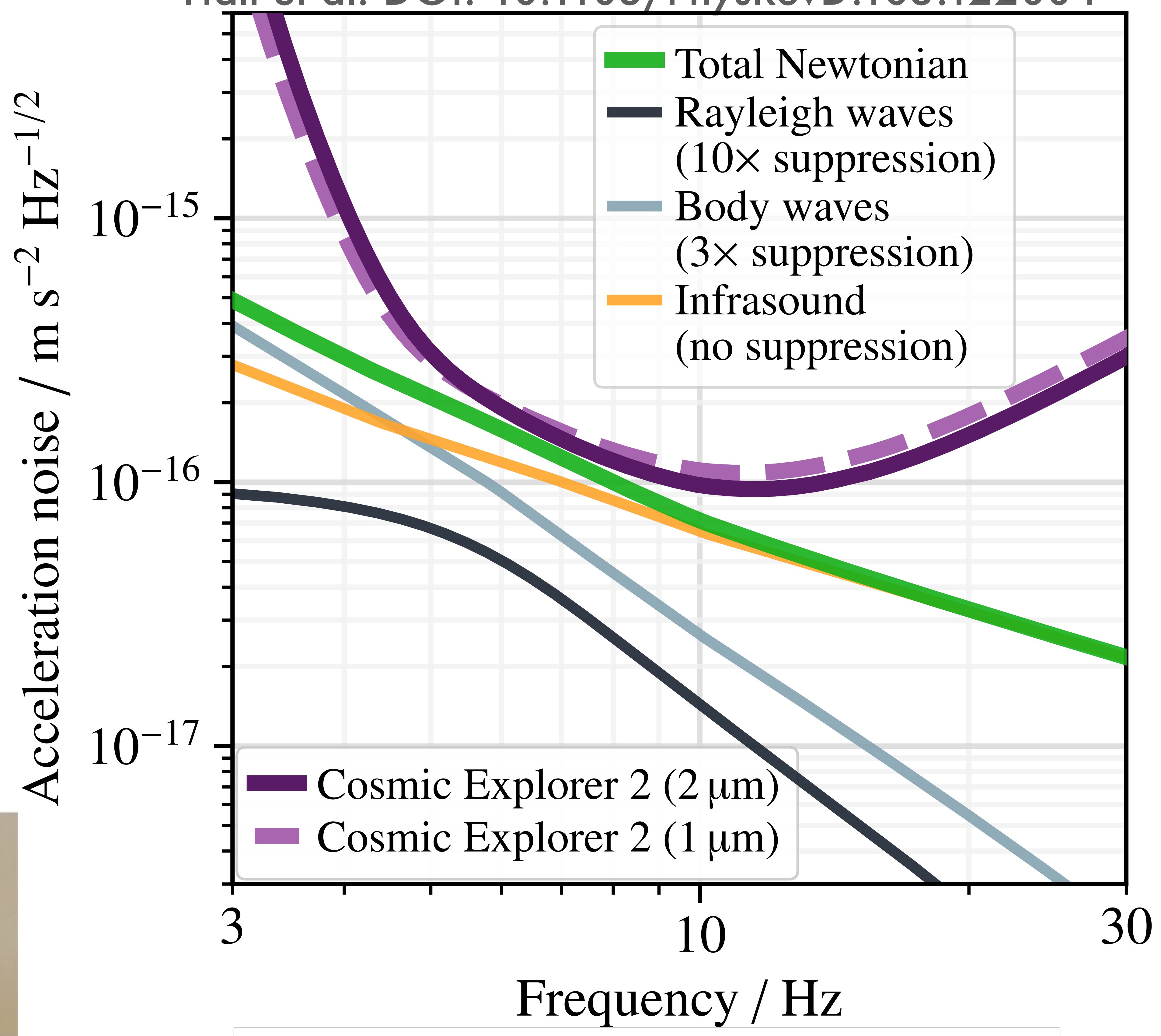


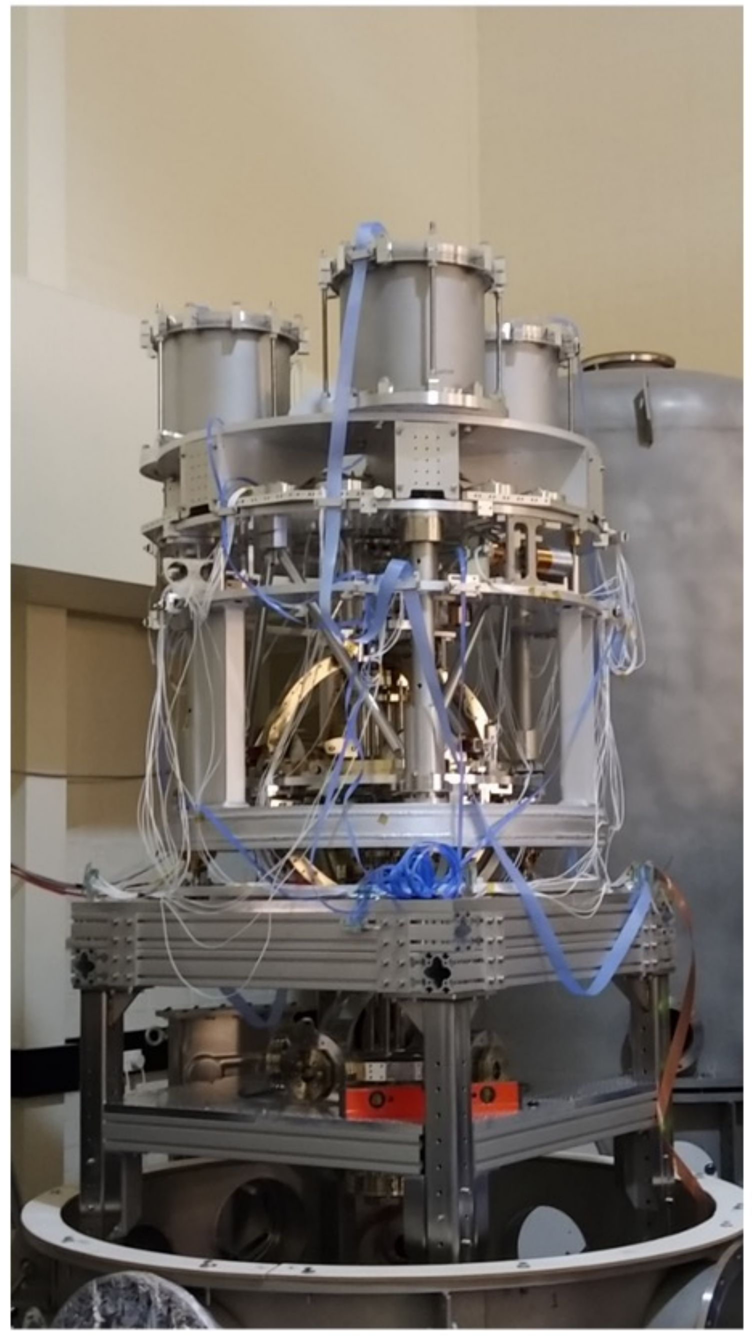
Hall et al. DOI: 10.1103/PhysRevD.103.122004

CE Newtonian noise

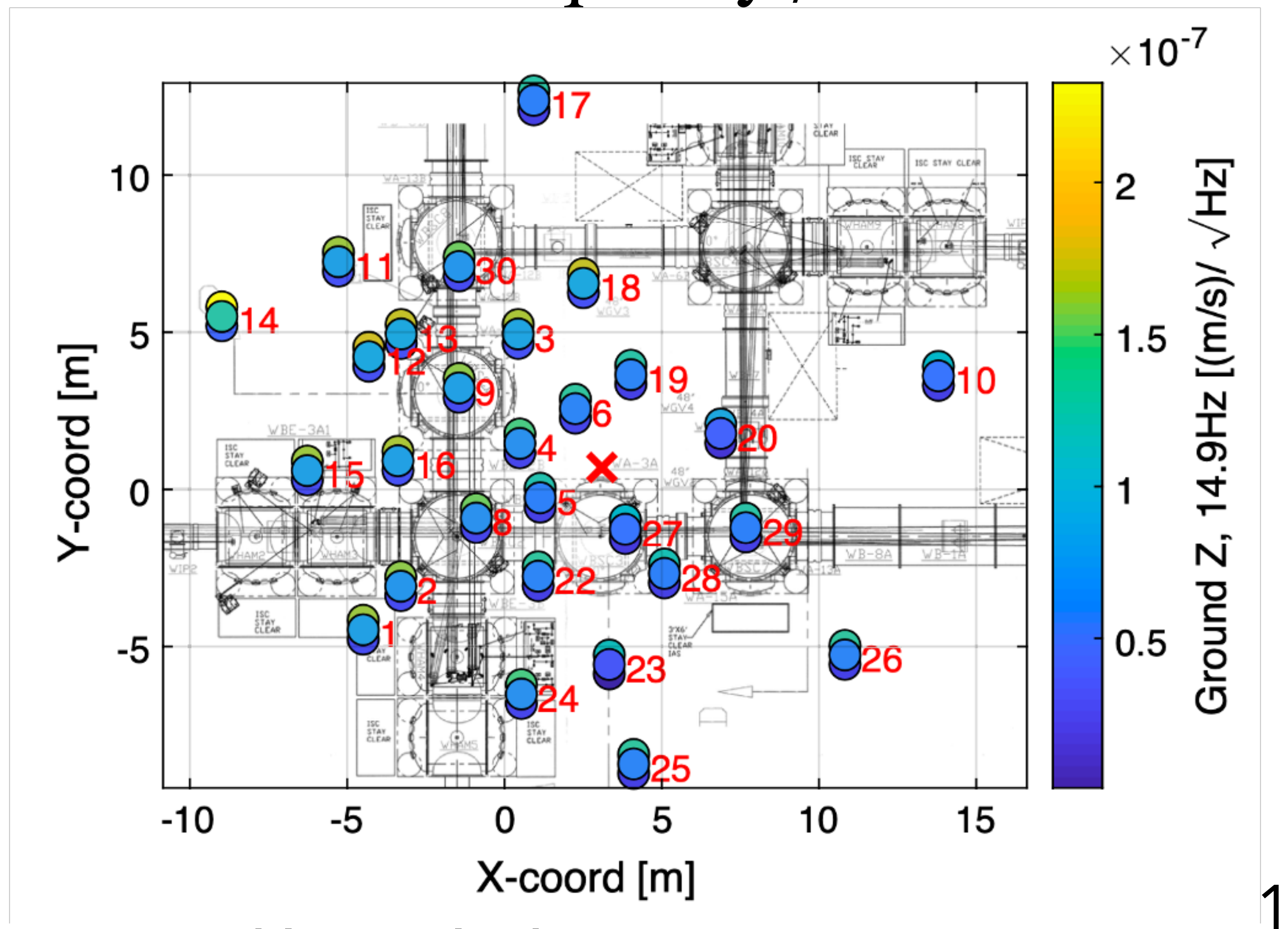
- *Newtonian noise is classical Newtonian force acting on the Test Masses.*
- *Driven by local density changes*
    - *From seismic activity*
    - *From atmospheric disturbance*
- *Required mitigation of upto 10x suppression*
    - *Research underway to develop techniques*
    - *Develop dual torsion to directly measure Newtonian noise*
    - *Infrastructure features*

Hall et al. DOI: 10.1103/PhysRevD.103.122004





D. J. McManus, et al. CQG, 34(13):135002, 2017



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

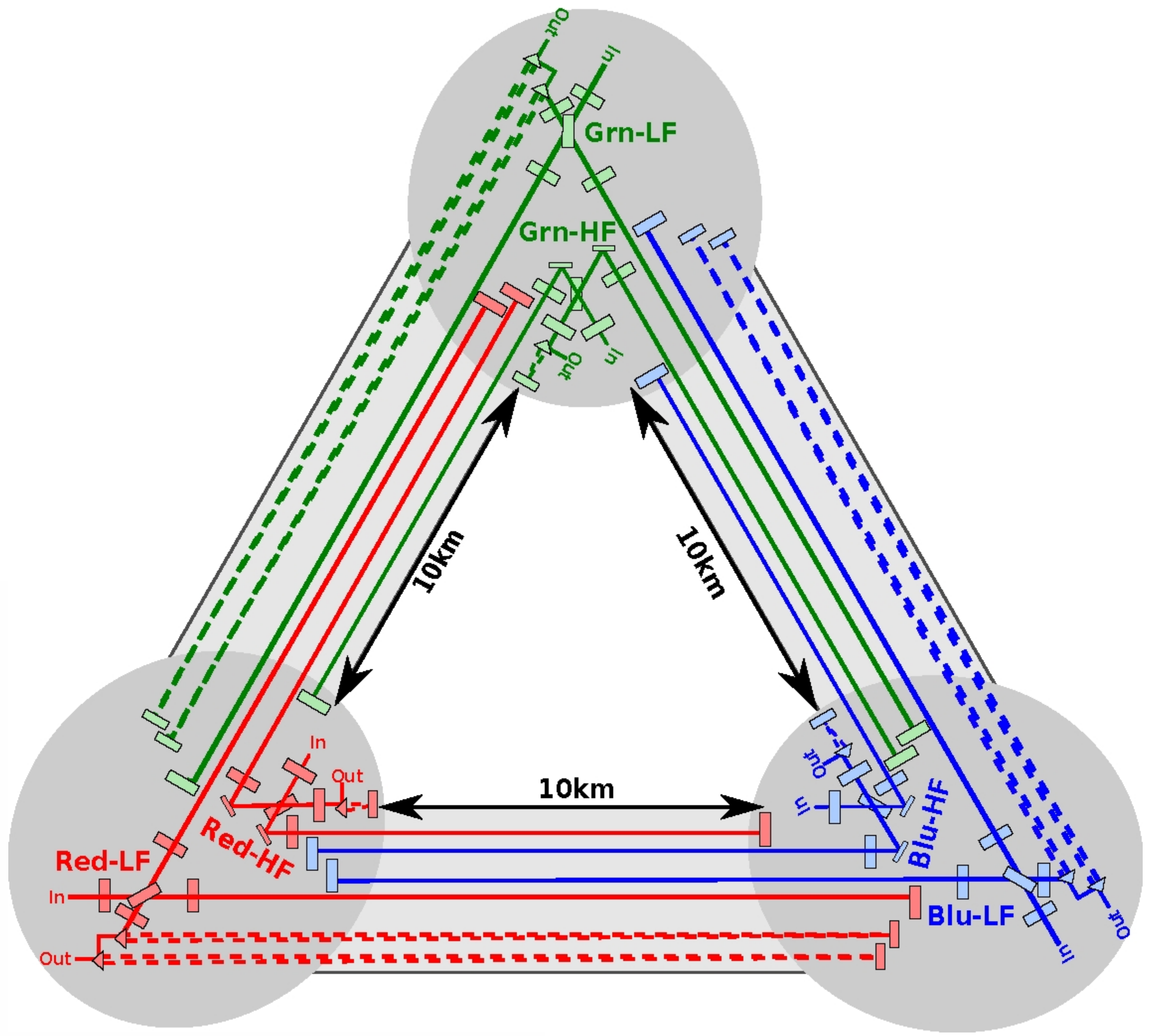
Einstein Telescope

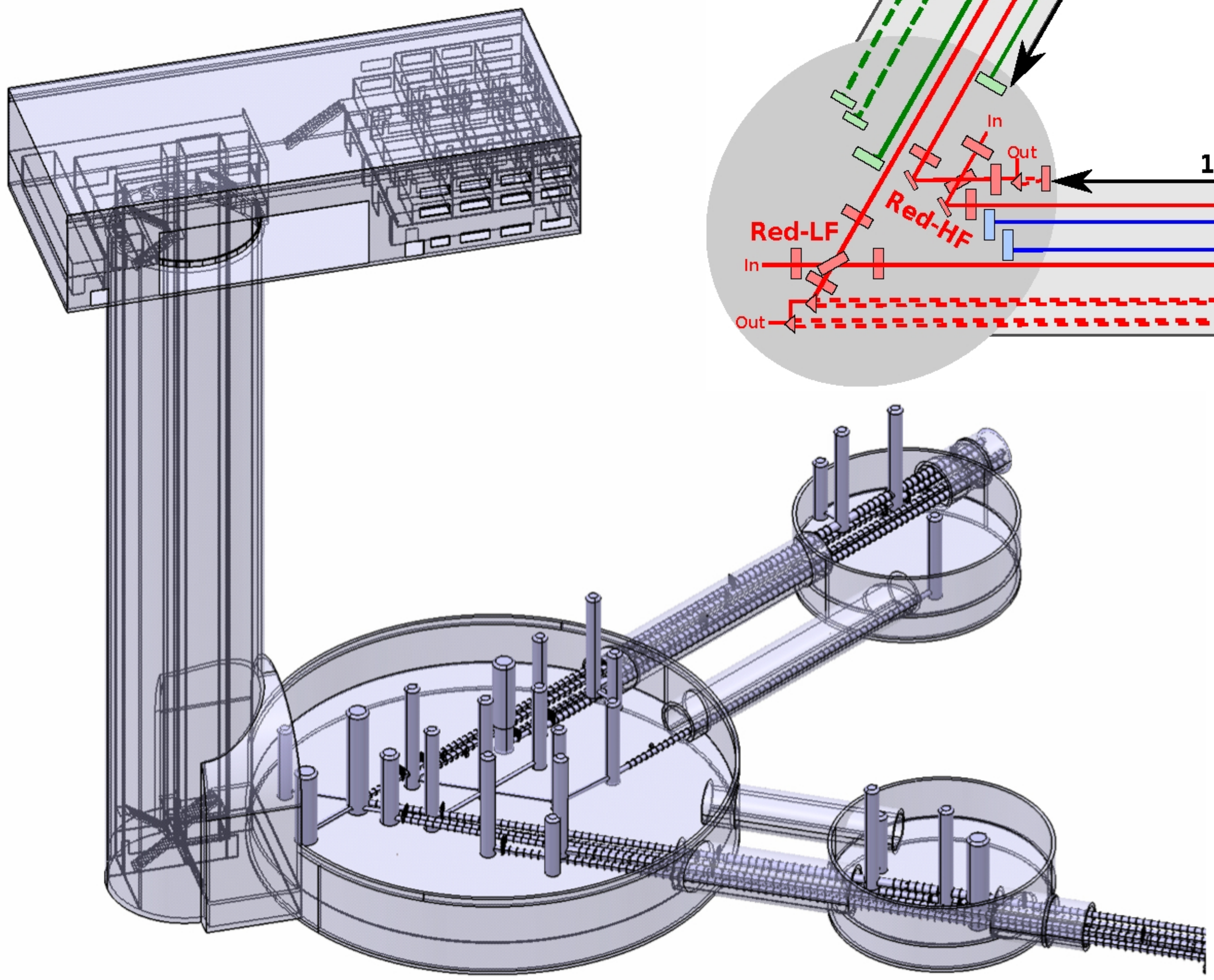
With help from:
Stefan Hild

Einstein Telescope

European based next generation gravitational wave observatory.

- *Equilateral triangle*
- *Arm length 10km*
- *200 -300 m underground*
- *3 'detectors'*
    - *Each detector consist of a low- and high-free interferometer.*
- *Sense both polarisations, sensitive to low frequencies down to a few Hz*

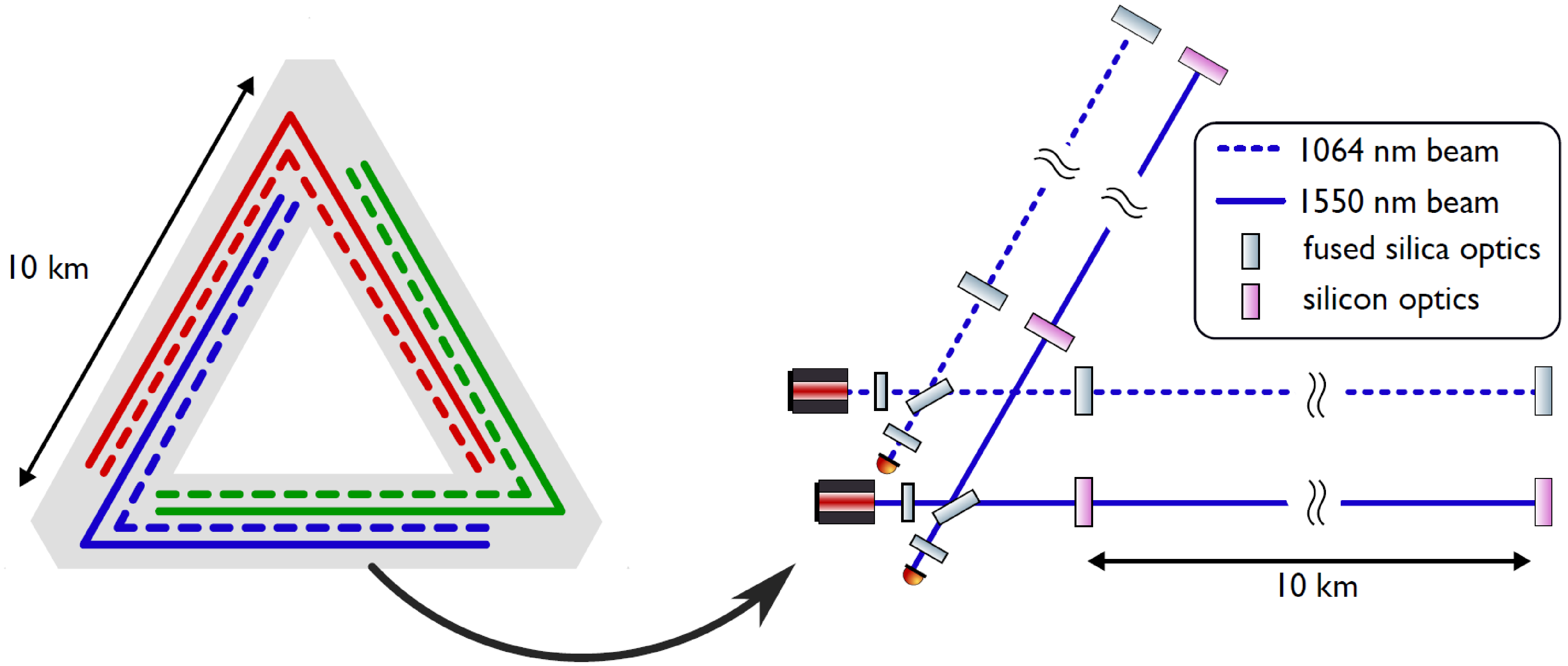


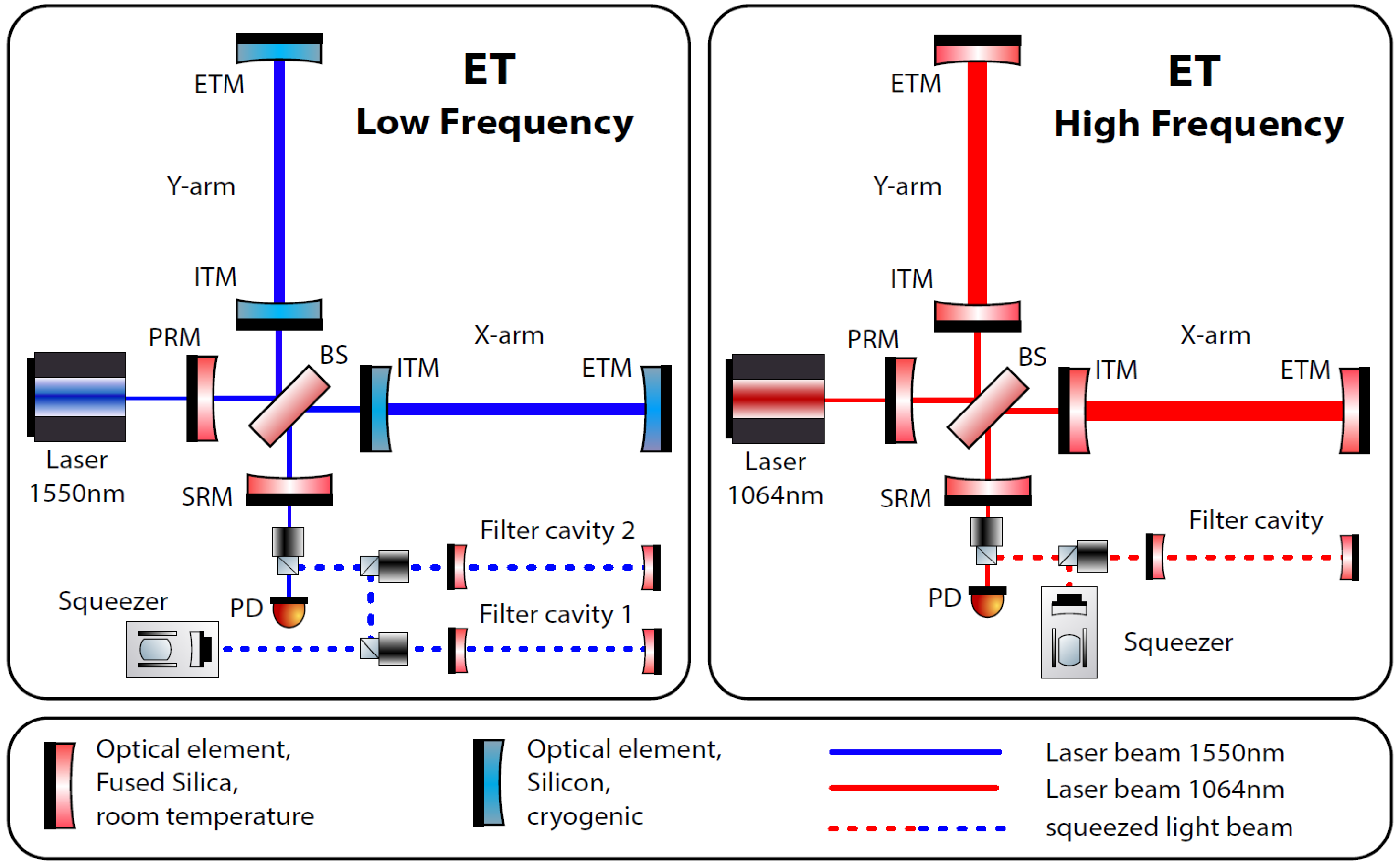


https://www.et-gw.eu/index.php/etimages

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)	$5 \cdot 10^{-10}\ \mathrm{m}/f^2$	$5 \cdot 10^{-10}\ \mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few



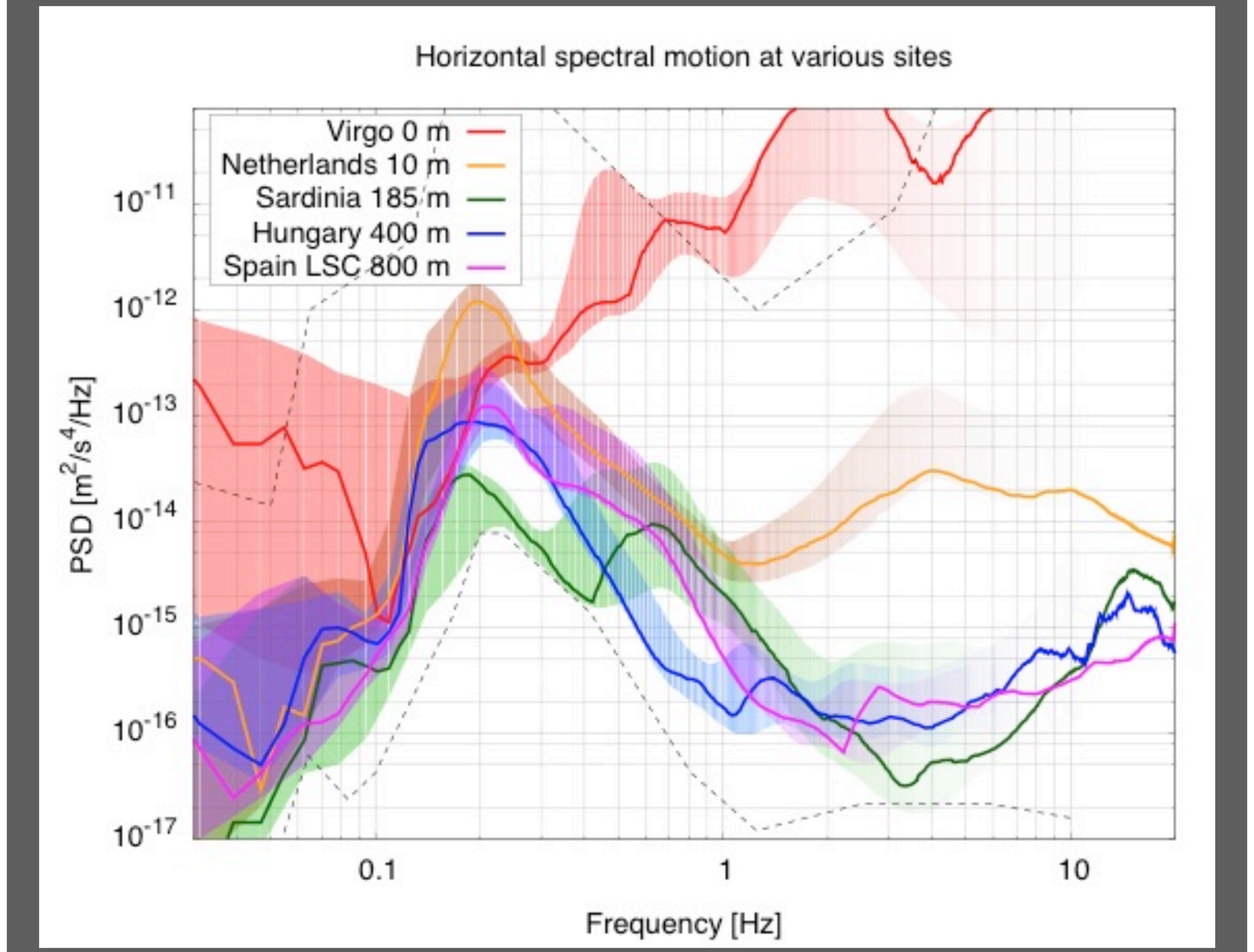


Slide: Stefan Hild

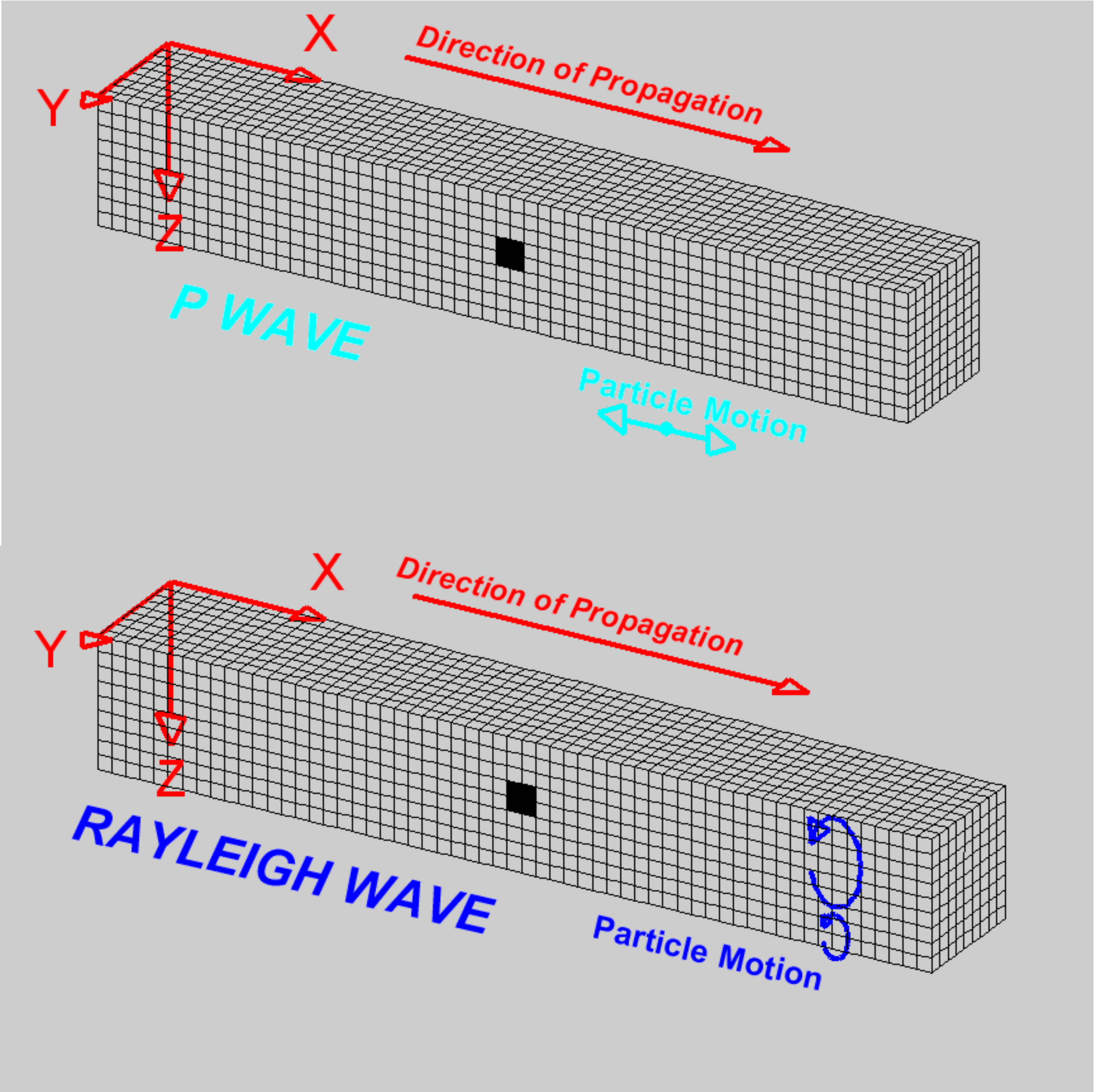
ET Xylophone Sensitivity

Slide: Stefan Hild

ET Seismic noise



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



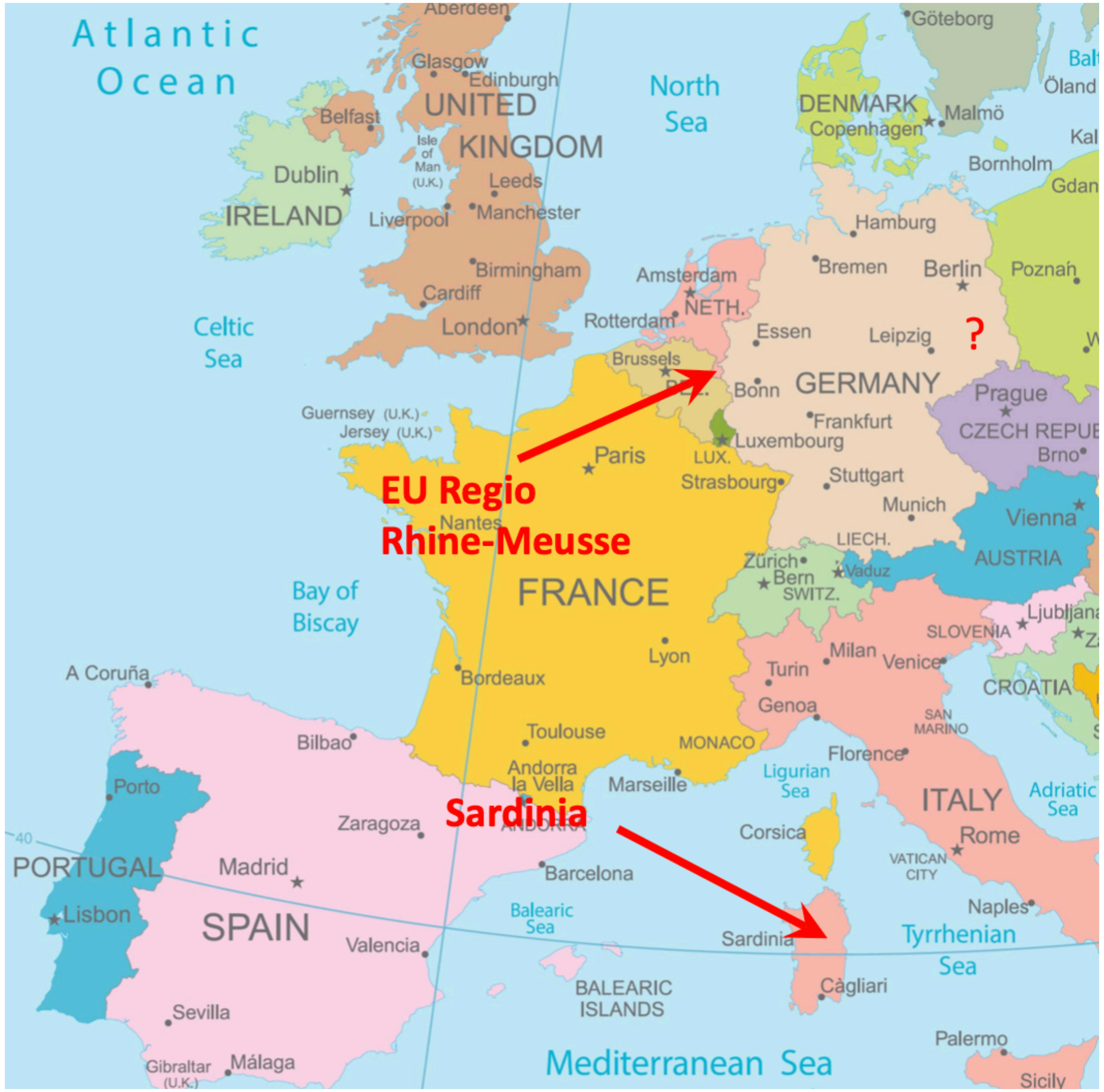
Slide: Stefan Hild

ET Candidate Sites

Currently two site candidates:
- Sardinia
- EU Regio Meuse-Rhine / Limburg

Geological properties and underground seismic being investigated

ETpathfinder, Maastricht University



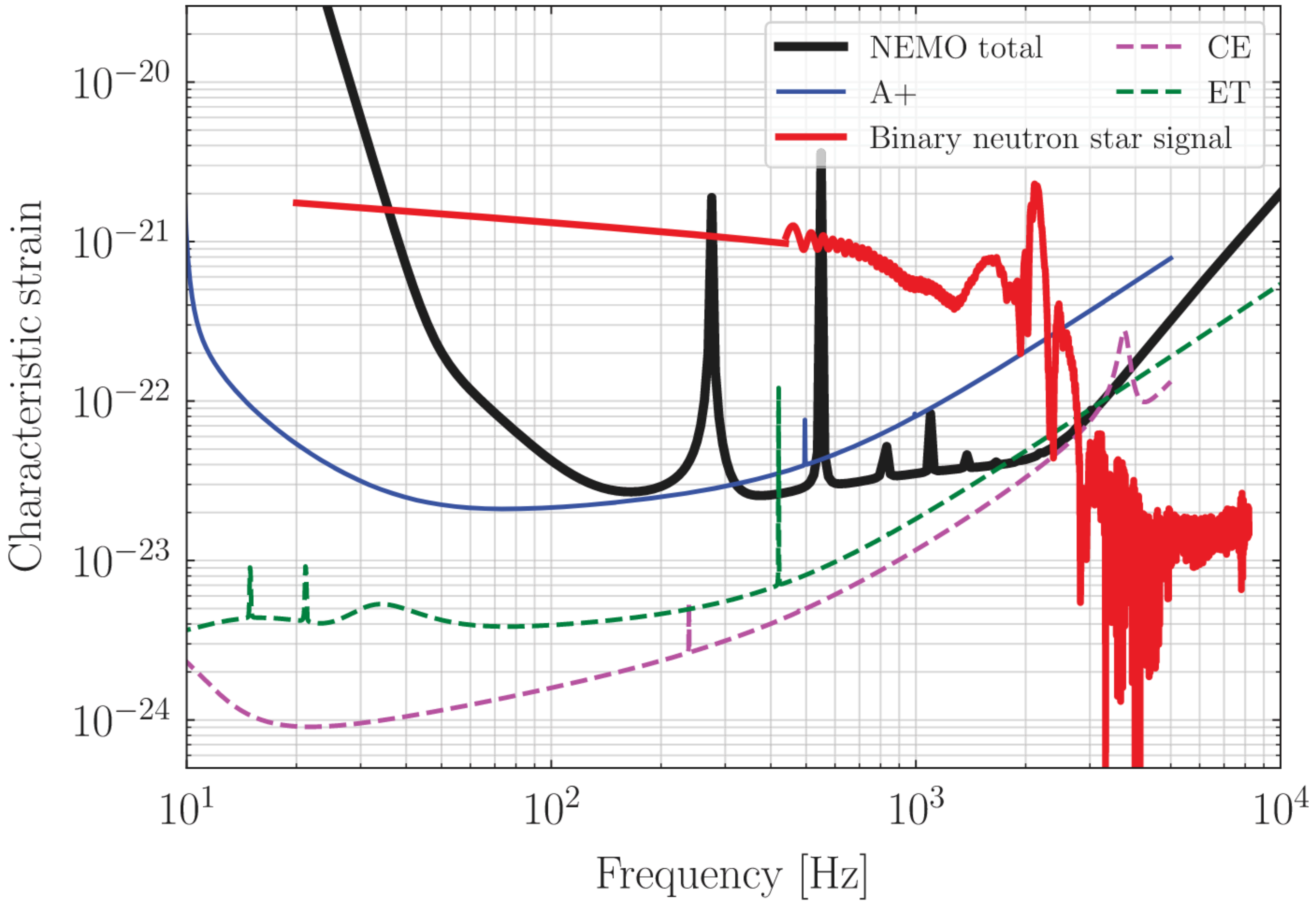
What could we build in Australia

Carl Knox | OzGrav-Swinburne

Gravitational Wave Observatory

When or if Australia host a gravitational wave observatory

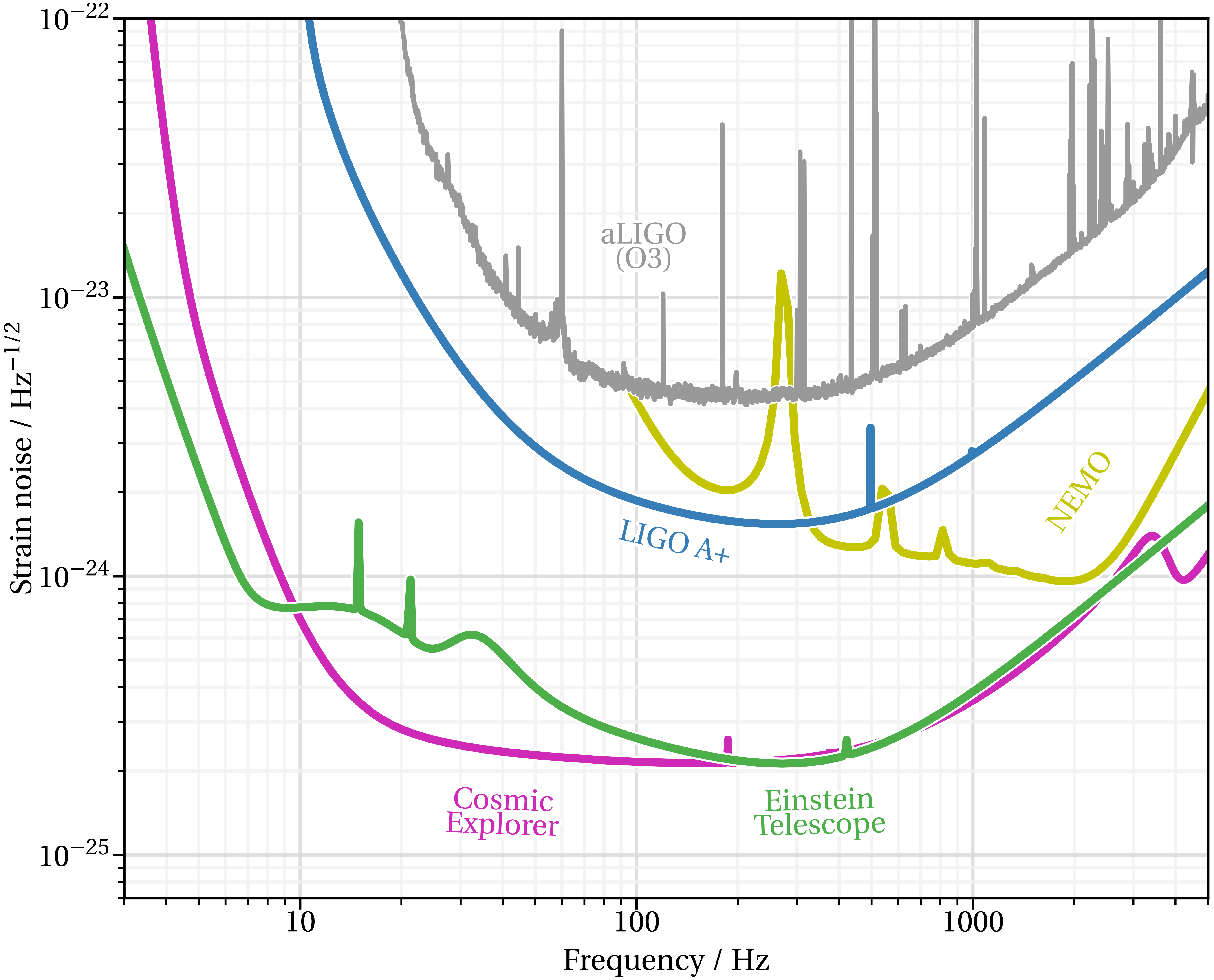
- *Maximising GW Science*
- *What detector config maximised the science outcome*
- *How many global detectors are required*
  - *Duty cycle (global/individual)*
  - *Sky localisation*
  - *Polarisation*



Ackley et al., doi:10.1017/pasa.2020.39 (2020)

Summary

- *Long-term ground based detectors are being actively considered*
- *Huge astrophysical observations*
- *Cosmic Explorer, US based, 40 km and 20 km facilities*
- *Einstein Telescope, EU based, triple detectors in single underground facility*
- *NEMO, potentially AU based, focused on kHz observations*



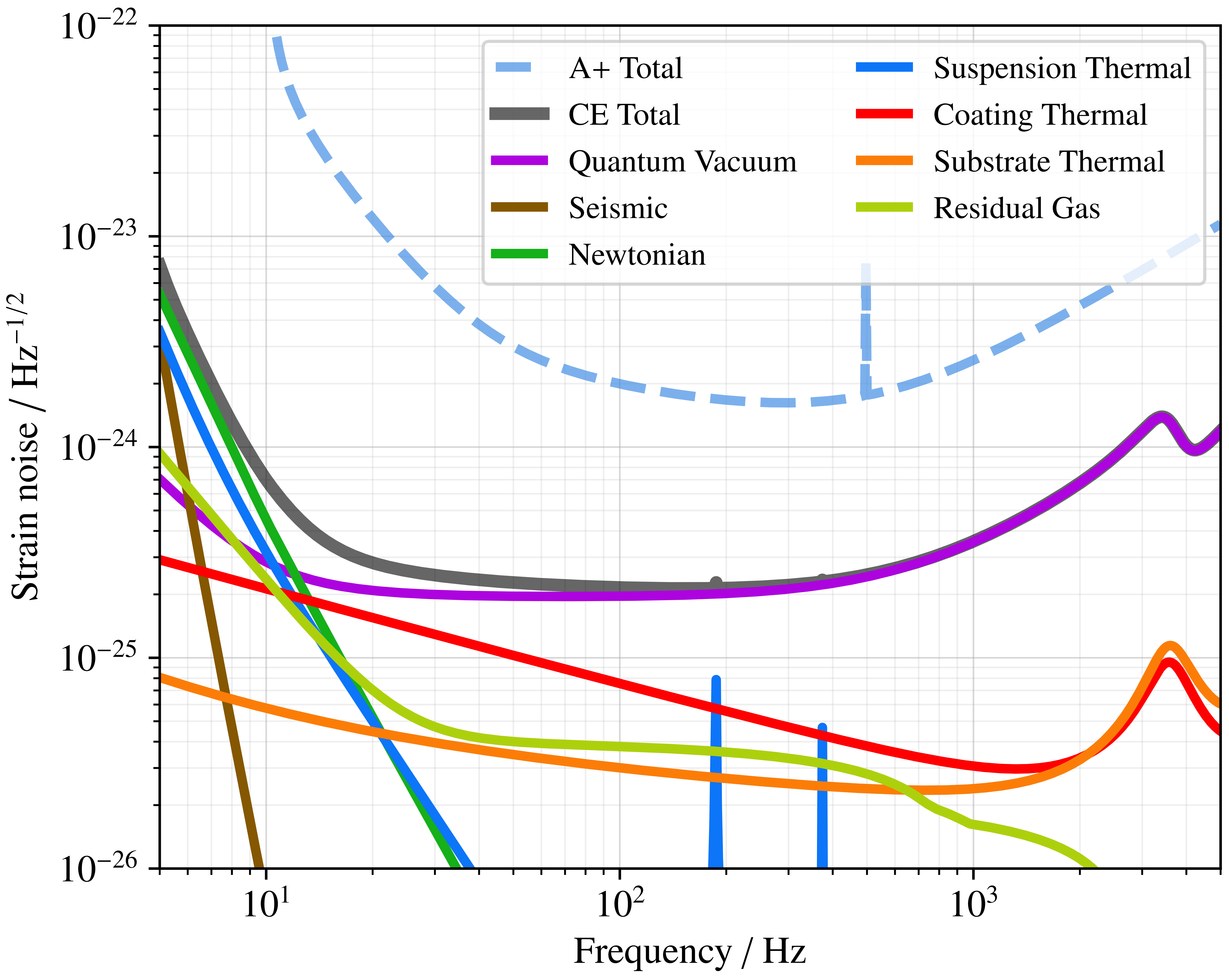
Questions

ET Timeline

- *2010 ET conceptual design completed*
- *2021 Design update, forming the ET collaboration, ESFRI approval*
- *2021 – 2025 stagewise technical report updates (…, preliminary, detailed, …)*
- *2021 – 2024 Detailed site characterisation, refine cost evaluation*
- *2024/2025 Site Selection*
- *2026 Full Technical Design*
- *2027 Infrastructure realisation start (excavation, vacuum system, ….)*
- *2032+ detector installation / commissioning / operation (50+ years)*

Slide: Stefan Hild/Michele Punturo

Cosmic Explorer



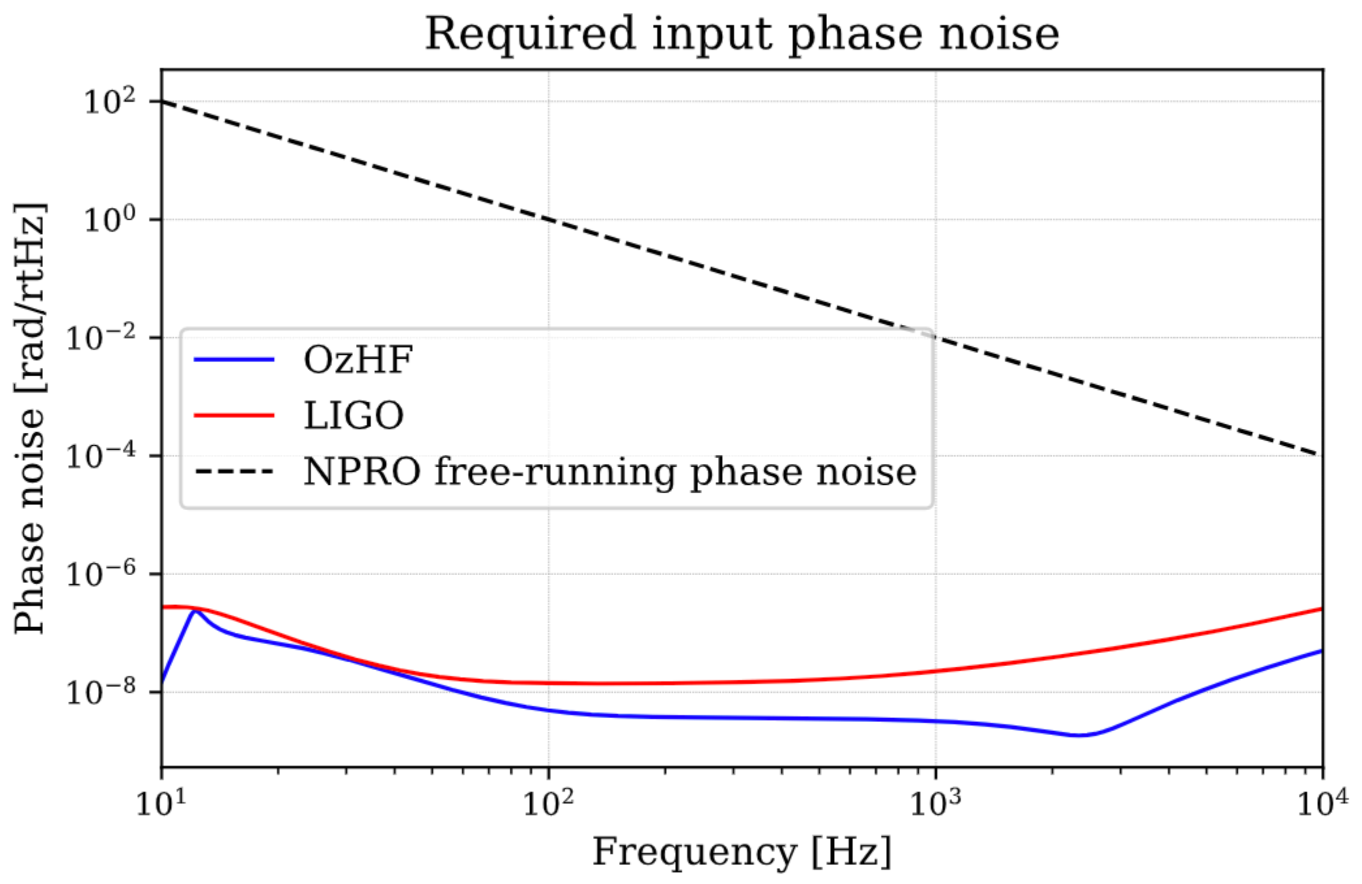
Main Configuration Highlights

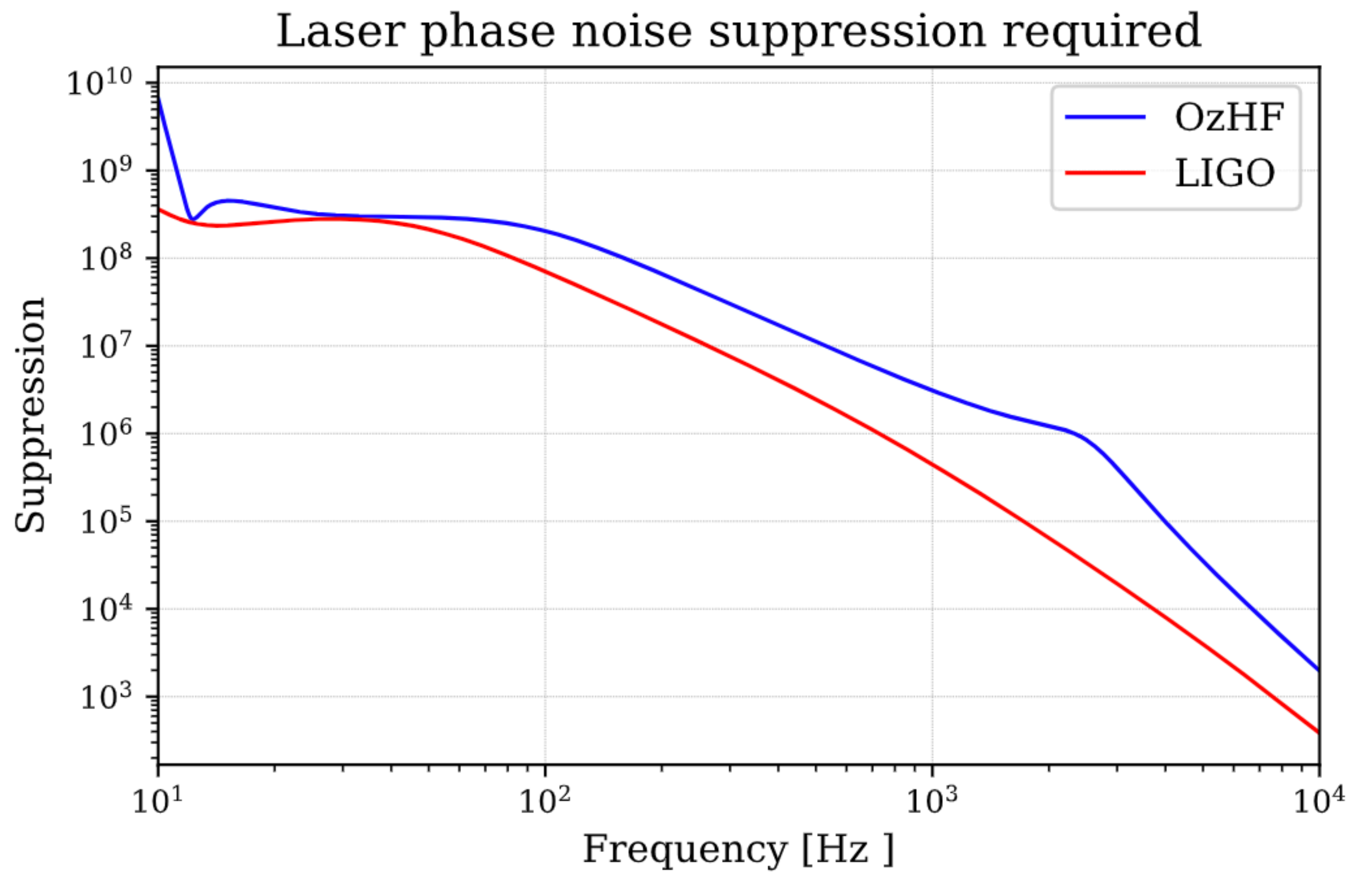
- *Improved suspension and isolation*
  - *longer pendulums,*
  - *Improved lower noise sensors*

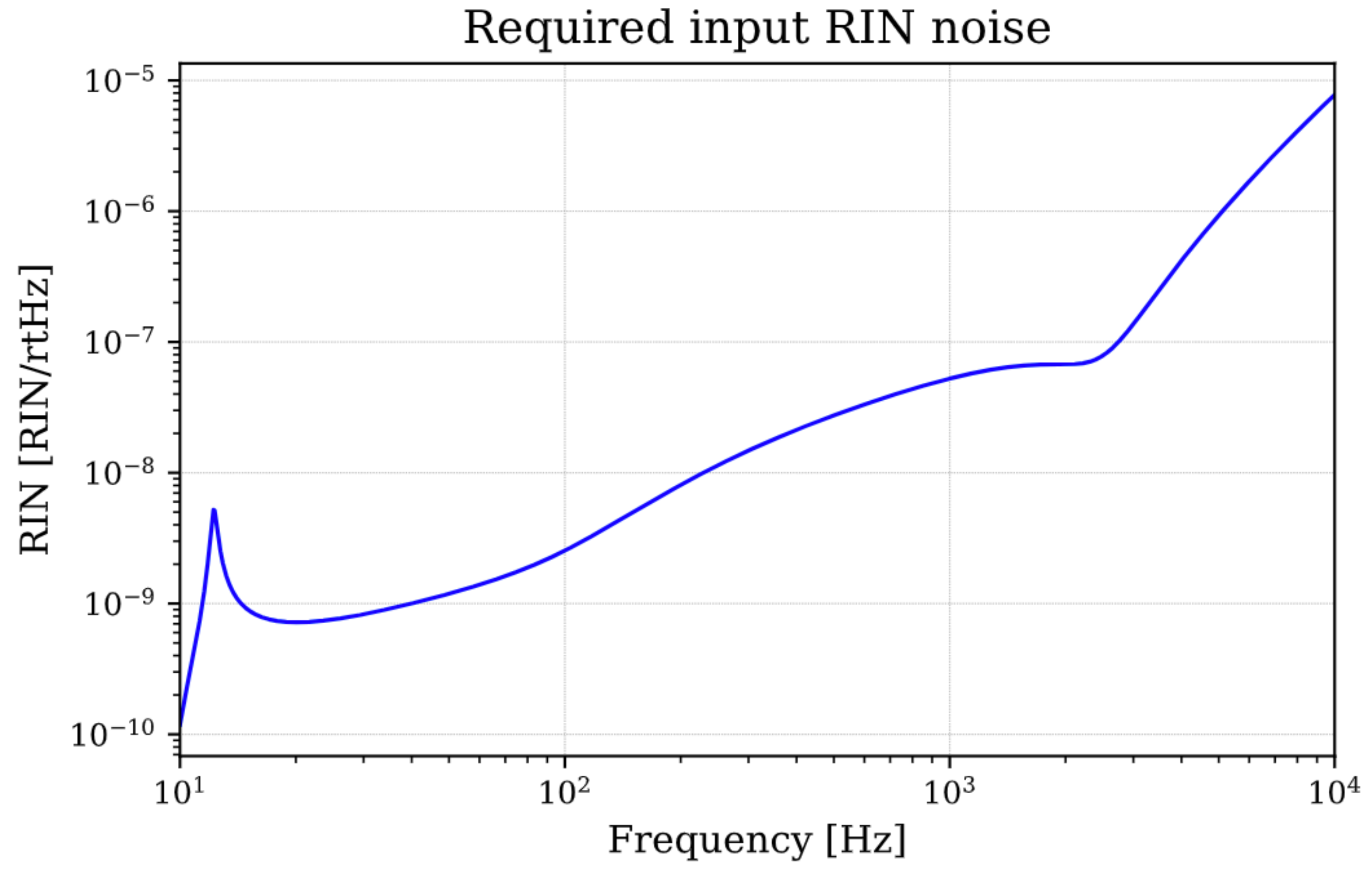
Evans et al., Cosmic Explorer Horizon Study, https://dcc.cosmicexplorer.org/CE-P2100003/public (2021)

RIN and frequency noise

- RIN/Phase noise requirement at PRC input in GW band
  - 1% power imbalance in arm
  - Safety factor of 10 below
  - ~10pm DC offset
  - Plane wave model
- Requirement around 2kHz:
  - Require RIN of 10^{-7}
  - Require Phase noise of ~3 x 10^{-9}
  - Or would need 10^6 suppression of NPRO noise
- Concern: Higher frequency/RIN noise coupling seen in LIGO than simple model would predict at higher frequencies.
  - Could potentially be attributable to thermal effects which would be significantly less of an issue with cryo IFO







Requirements here are to beat QN limited sensitivity at GW frequencies, haven't considered requirements in control band yet.