Virgo GW - BelGrav
DEDICATED TO DETECTING GRAVITATIONAL WAVES

University of Antwerp

Correlated seismic noise impact on ET

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IRI Workshop
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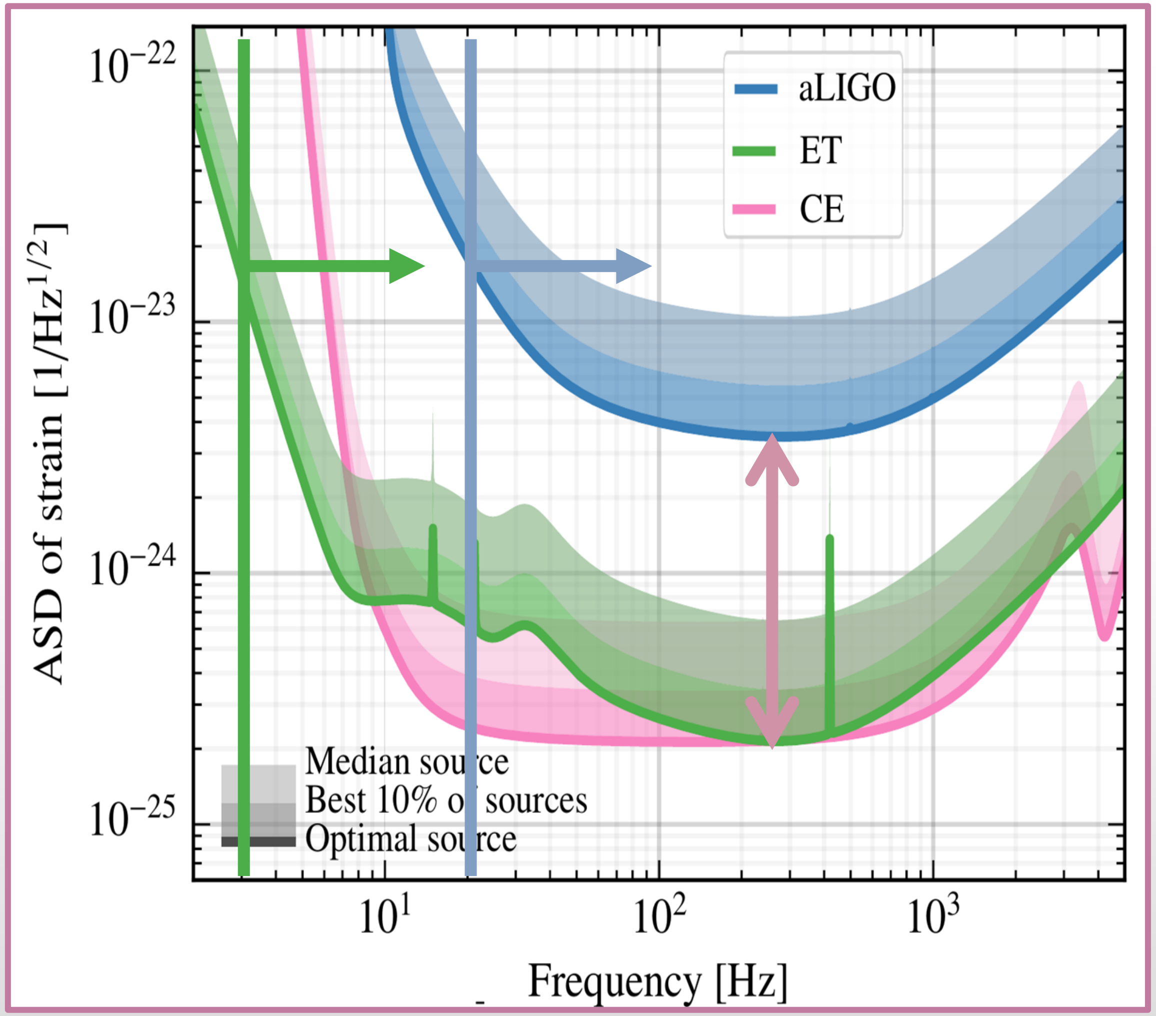
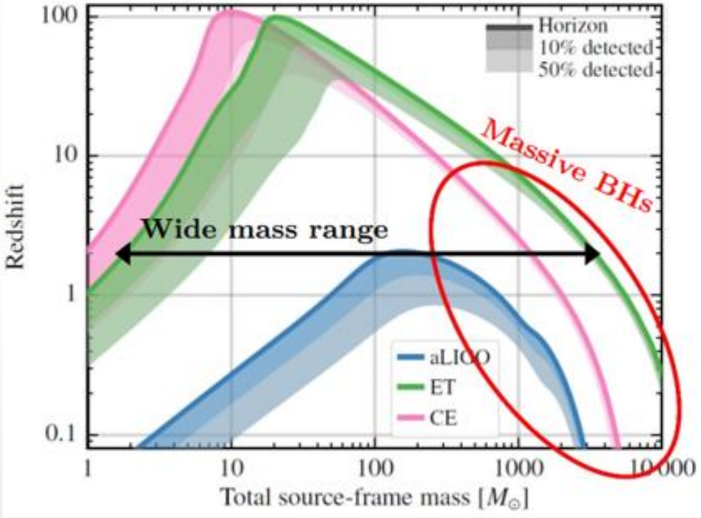
Research Foundation Flanders
Opening new horizons

2nd gen vs 3rd gen GW interferometers:



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

- 2^{nd} Generation (aLIGO, AdV, KAGRA) sensitive down to 20 Hz
- 3^{rd} Generation (ET, CE) will be 10x more sensitive in the bucket
- ET will extend sensitivity down to 2Hz, allowing
  - Detection of more massive binary black holes



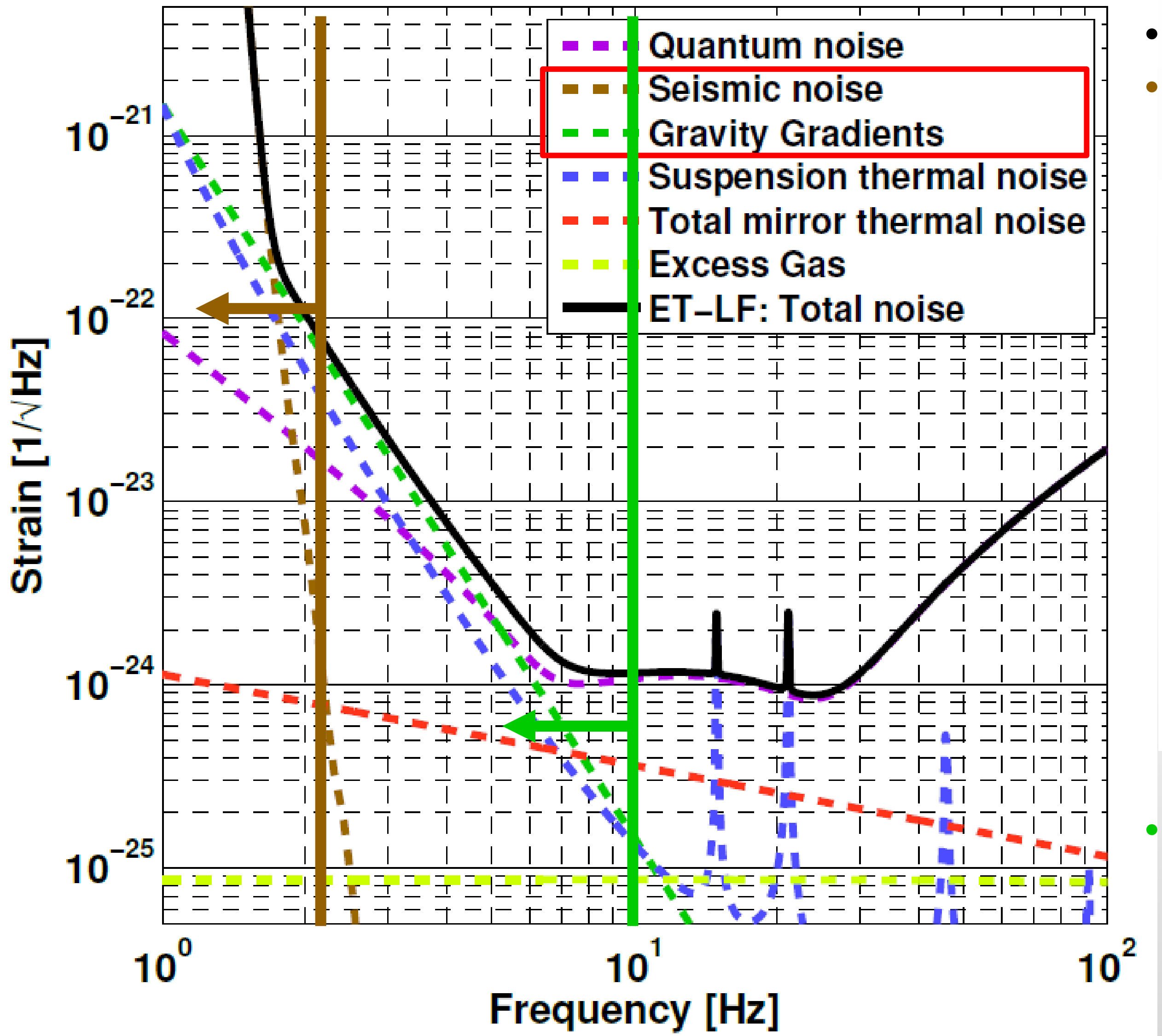
  - Extending the detection time prior to merger from <1sec to 30 minutes!

Source: M. Branchesi *et al* JCAP07(2023)068

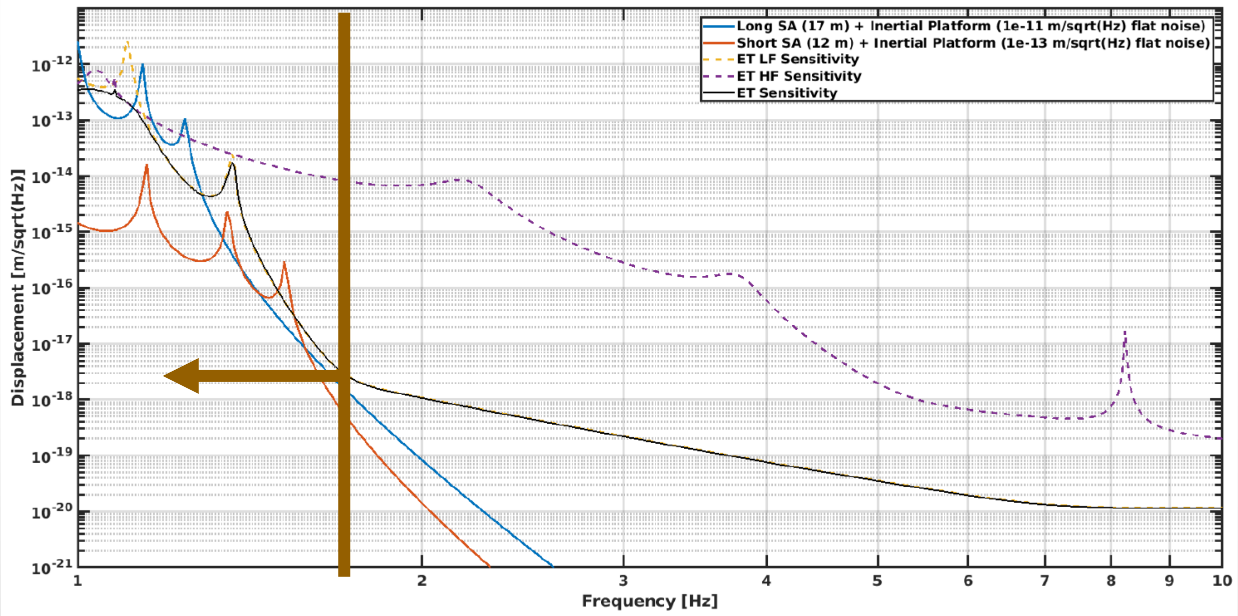
Full (HFLF cryo) sensitivity detectors

Configuration	$\Delta\Omega_{90\%}$	All orientation BNSs			BNSs with $\Theta_v < 15°$		
	[deg^2]	30 min	10 min	1 min	30 min	10 min	1 min
Δ10km	10	0	1	5	0	0	0
	100	10	39	113	2	8	20
	1000	85	293	819	10	34	132
	All detected	905	4343	23597	81	393	2312

Seismic noise contribution for ET:



- Curves shown for underground construction
- Seismic 'wall', after active and passive attenuation at 2Hz using Virgo-like superattenuators of 12-17 meter high!



- Newtonian Noise (Gravity Gradients) important up to 10Hz
  This already assumes a factor 3 suppression

Source: [ET design report update 2020]

Types of Seismic noise:

Are dominant at >200m depth

Are damped exponentially with depth

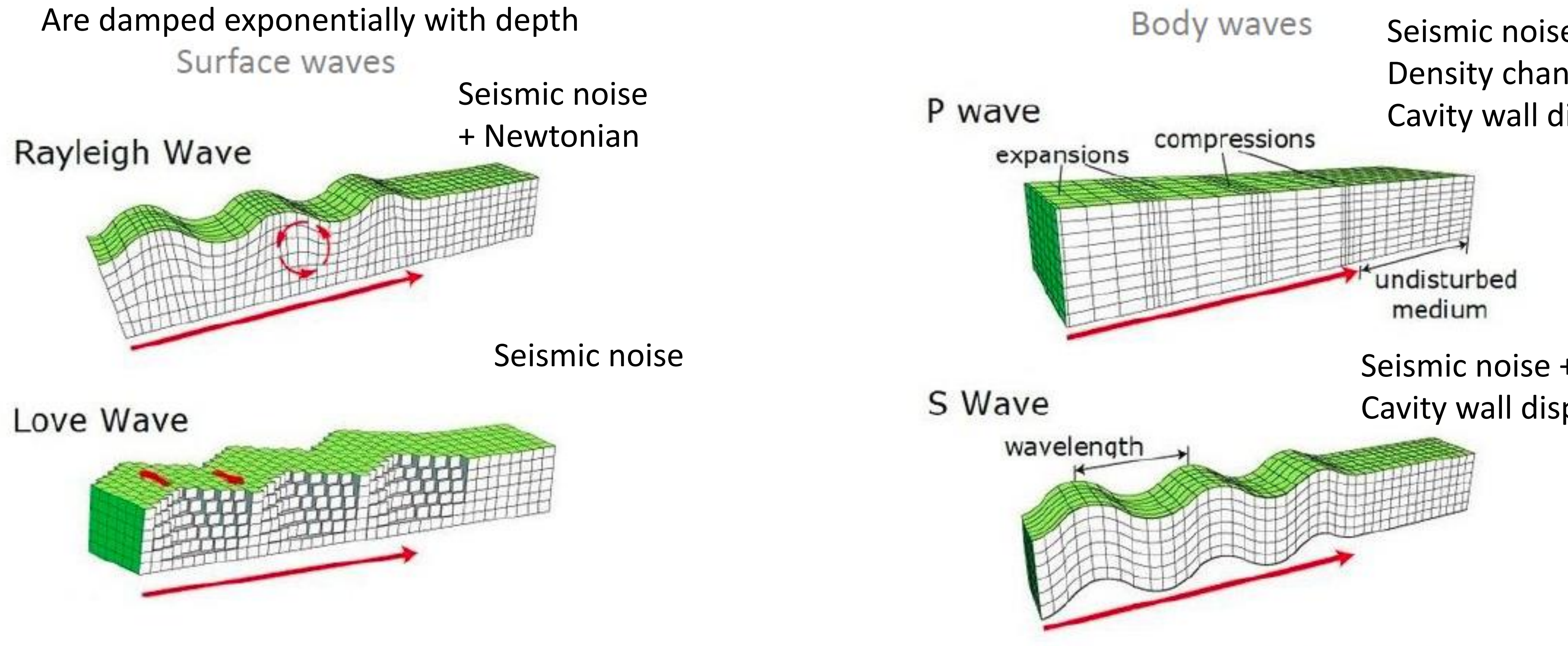


Fig. 10: Illustration of the different types of seismic waves.

Credit: Science Learning Hub – Pokapū Akoranga Pūtaiao, University of Waikato - https://www.sciencelearn.org.nz

Seismic noise + Newtonian (Rayleigh Wave)

Seismic noise (Love Wave)

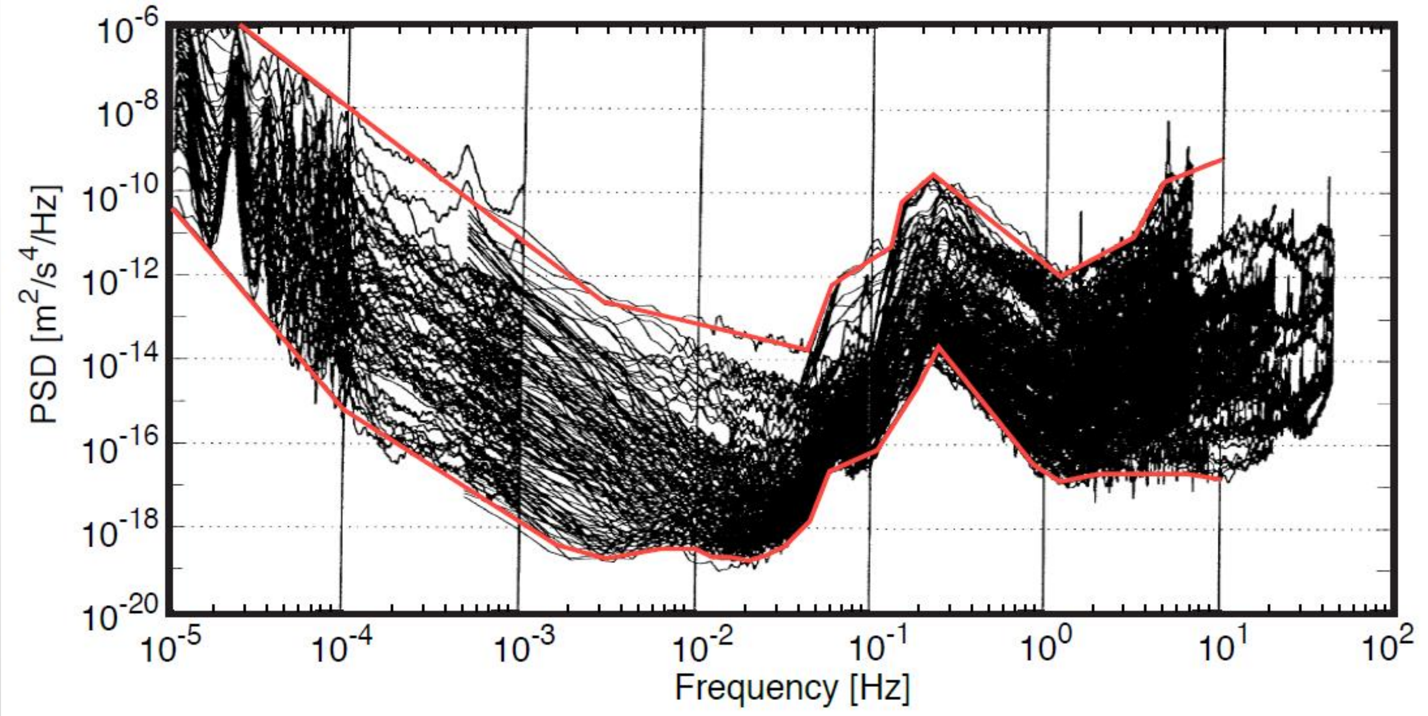
Seismic noise + Newtonian
Density changes
Cavity wall displacement
(P wave)

Seismic noise + Newtonian
Cavity wall displacement
(S Wave)

Seismic Background across the planet:

From: J. Peterson, “Observations and modeling of seismic background noise.” Open-file report 93-322, 1993.

- Long-term seismic measurements from 75 stations across the globe at surface and up to 350m depth
- Determined a global upper and lower level of seismic noise



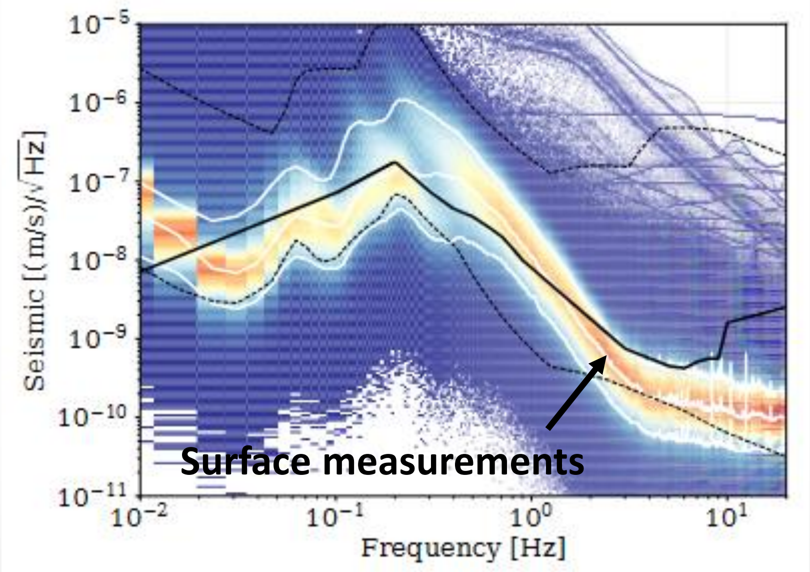
3 main Frequency ranges of interest:

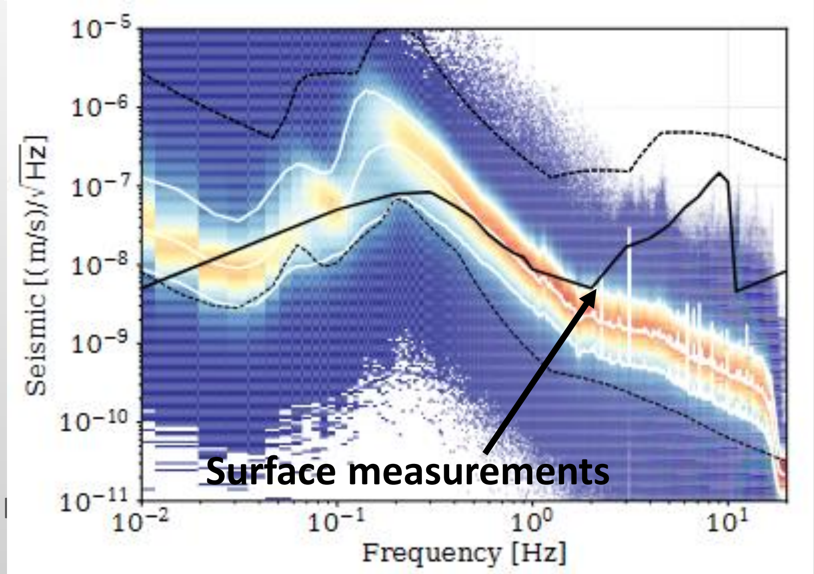
1. f<0.01 HZ: Tidal effects
2. f=0.05 and f=0.2Hz: Miscroseisms due to oceans
3. f>1Hz: Environmental & anthropomorphic noise
   - Reaches a plateau at f> 10Hz
   - Is very time & location dependent
   - Can be suppressed by going underground

Surface vs underground:

Seismic velocity spectra measured at

- Left: Sos-Enattos (Sardinia) P2 borehole at 264m depth
- Right: Terziet (NL) borehole at 250 m depth

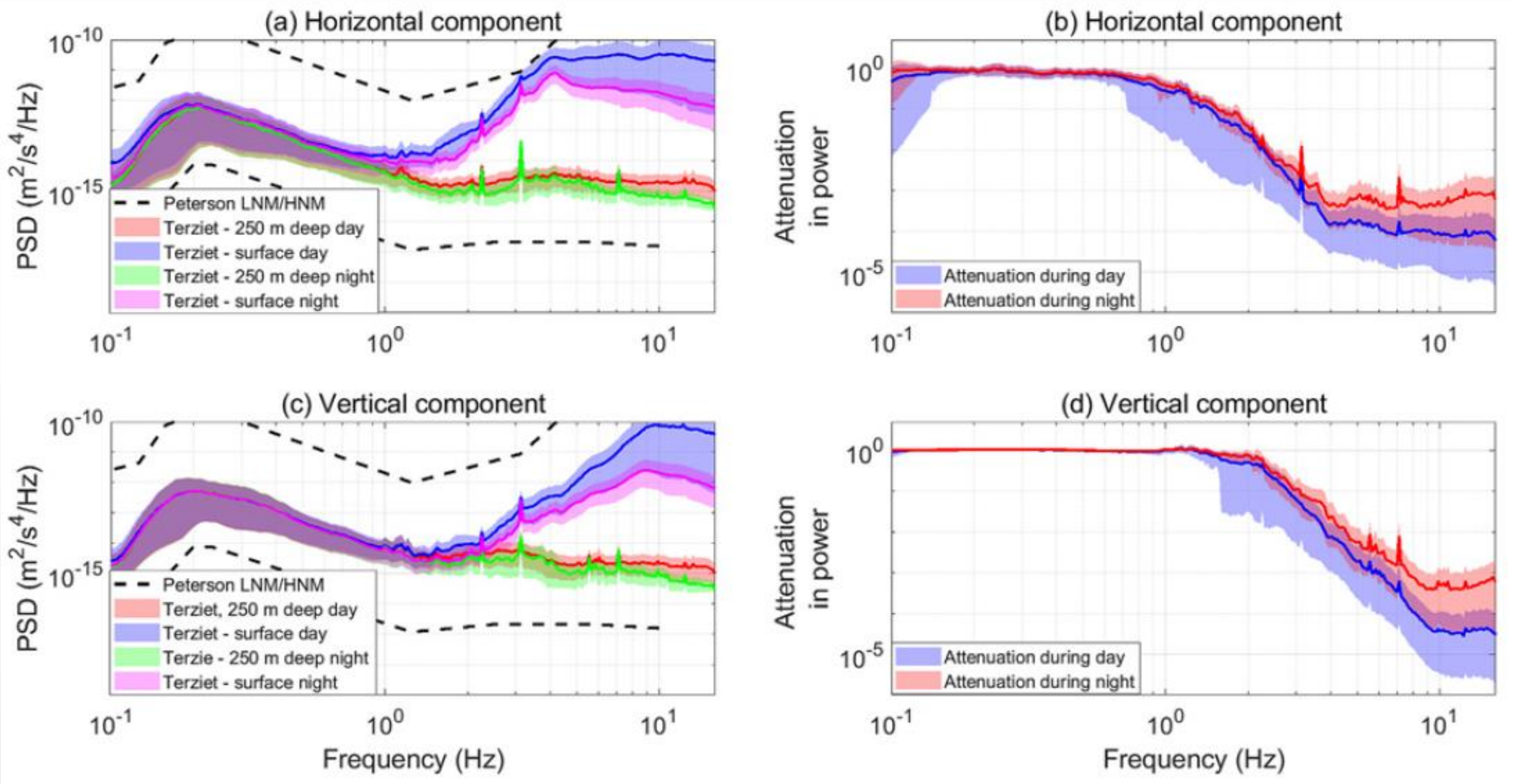




Power Spectral Density at Terziet Borehole:

- Day night difference at the surface indicates anthropomorphic component
- Power density can be suppressed by 4 orders of magnitude

Source: S. Koley *et al* 2022 *Class. Quantum Grav.* **39** 025008



From: Conceptual design and noise budget of Einstein Telescope (paper in preparation)

Gravity gradient, aka. Newtonian Noise:

From: R. Weiss, ''Quarterly Progress Report of the Research Laboratory
of Electronics of the Massachusetts Institute of Technology'' ~1972!, Vol. 105, p. 54.

h. Gravitational-Gradient Noise

The antenna is sensitive to gravitational field gradients, that is, differential gravitational forces exerted on the masses defining the ends of the interferometer arms. No data are available concerning high-frequency gravitational gradients that occur naturally on or near the surface of the earth. Two effects can bring about gravitational-gradient noise: first, time-dependent density variations in both the atmosphere and the ground, and second, motions of existing inhomogeneities in the mass distribution around the antenna.

- Seismic displacement noise can be suppressed by passive/active attenuation systems
- Newtonian noise exerts a physical force on the test masses and can not be attenuated
- Newtonian Noise is caused by
  - Coupling of seismic waves to environment
    - Rayleigh waves & Body waves
  - Changes in atmospheric condition
- Rayleigh waves >4Hz have wavelengths of ~125m and attenuate exponentially with depth
- Key Point: Dominant contribution to NN in underground due to Body waves

Source:
F. Amann *et al* 2020 Rev. Sci. Instrum. 91, 094504
S. Koley *et al* 2022 *Class. Quantum Grav.* **39** 025008
M. Bader et al 2022 Class. Quantum Grav. 39 025009

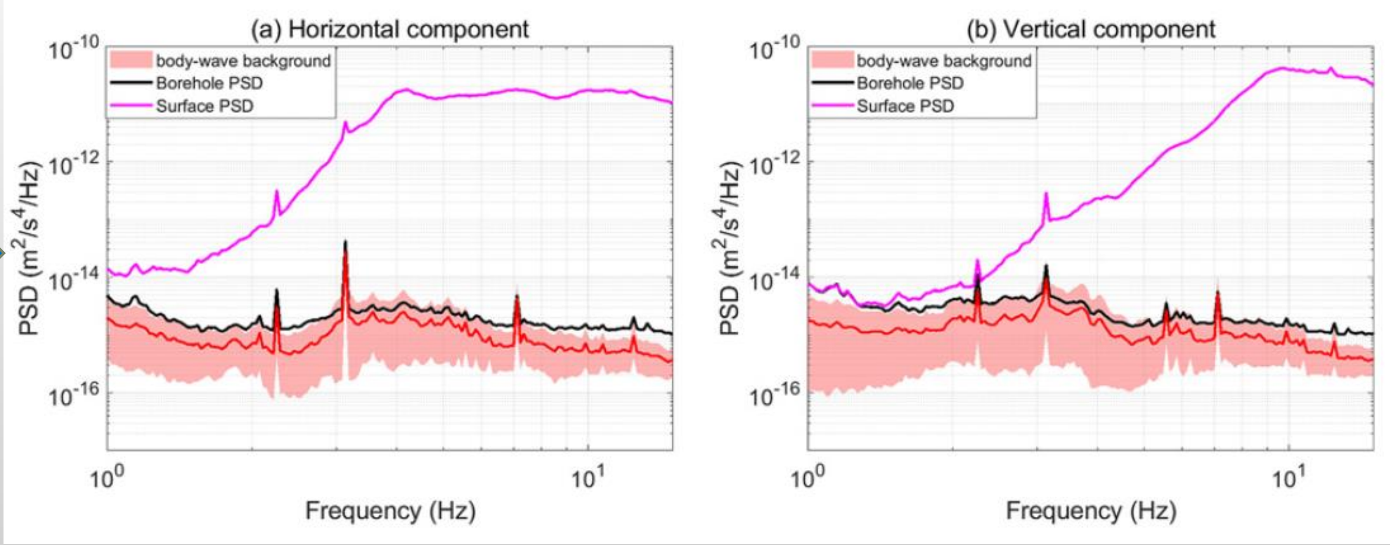
$$S_{h,\mathrm{Rayleigh}}(f) = \left(\sqrt{2}\pi G\gamma\rho_{0,\mathrm{Surface}}\right)^2 \frac{1}{L^2(2\pi f)^4} \mathcal{R}(h,f) S_{\xi_z}(f)$$

Exponential decrease with depth, h

Measured
Vertical displacement PSD

No decrease with depth, h

$$S_{\text{Body-wave}}(f) = \left(\frac{4\pi}{3} G\rho_{0,\mathrm{Bulk}}\right)^2 (3p+1)\frac{1}{L^2(2\pi f)^4} S_{\xi_x}(f)$$

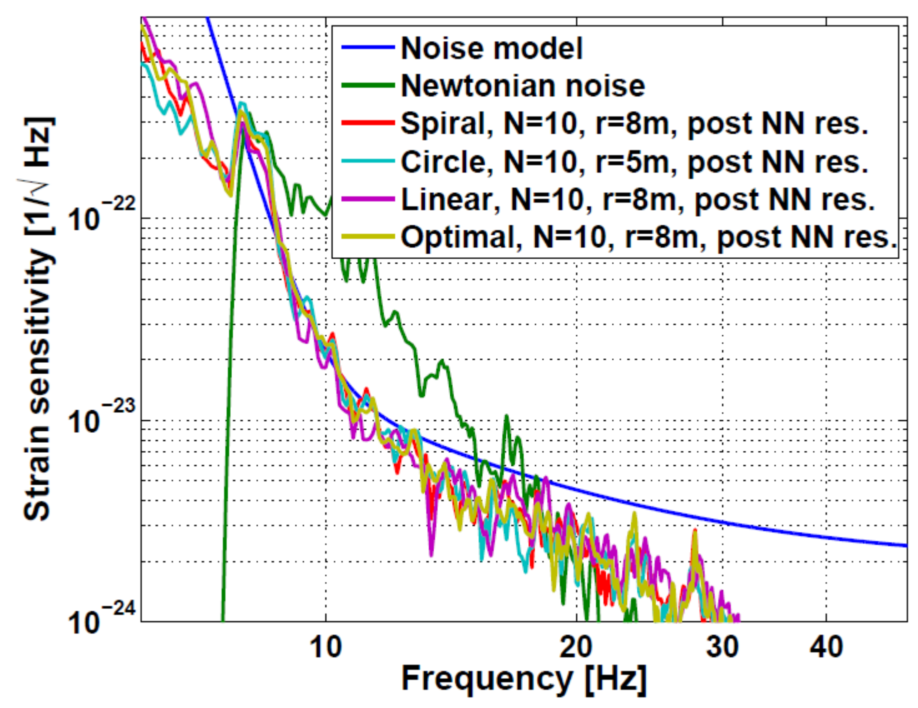


Suppression of Newtonian Noise

Sources:

J. C. Driggers, Phys. Rev. D 86, 102001 (2012)
M. Coughlin et al Phys. Rev. Lett. 121, 221104 (2018)
M Coughlin et al 2014 Class. Quantum Grav. 31 215003
M Coughlin *et al* 2016 *Class. Quantum Grav.* **33** 244001

- Predict Newtonian Noise from measured seismic waves
- This is model dependent: reduction factors of 3-100!
- Apply residual correction via offline measurements →



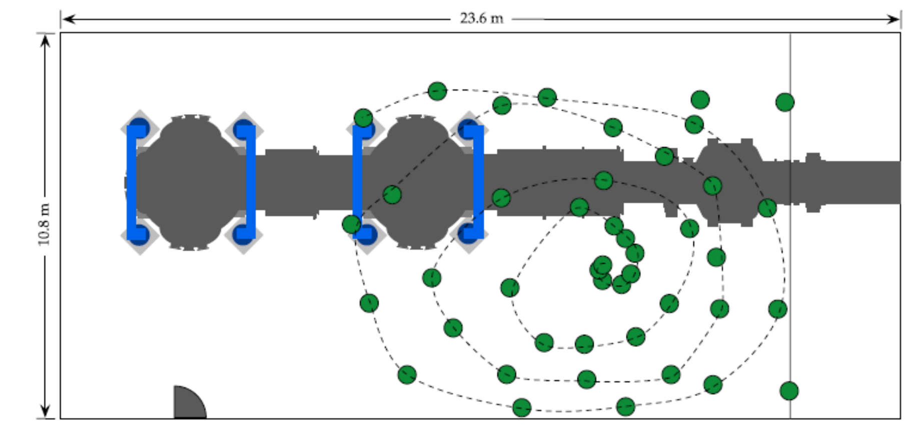
- Via network of seismometers surrounding a test mass
- Correlate the output of seismometers with the measured movement of the test mass
- Apply a feed forward Multiple-Input-Single-Output Wiener filter

Seismometer-test mass   Seismometer-Seismometer

$$R = 1 - \frac{\vec{C}_{\mathrm{SN}}^{\,\mathrm{T}} \cdot (C_{\mathrm{SS}})^{-1} \cdot \vec{C}_{\mathrm{SN}}}{C_{\mathrm{NN}}}$$

Testmass-testmass

Typical seismometer array at LIGO end station



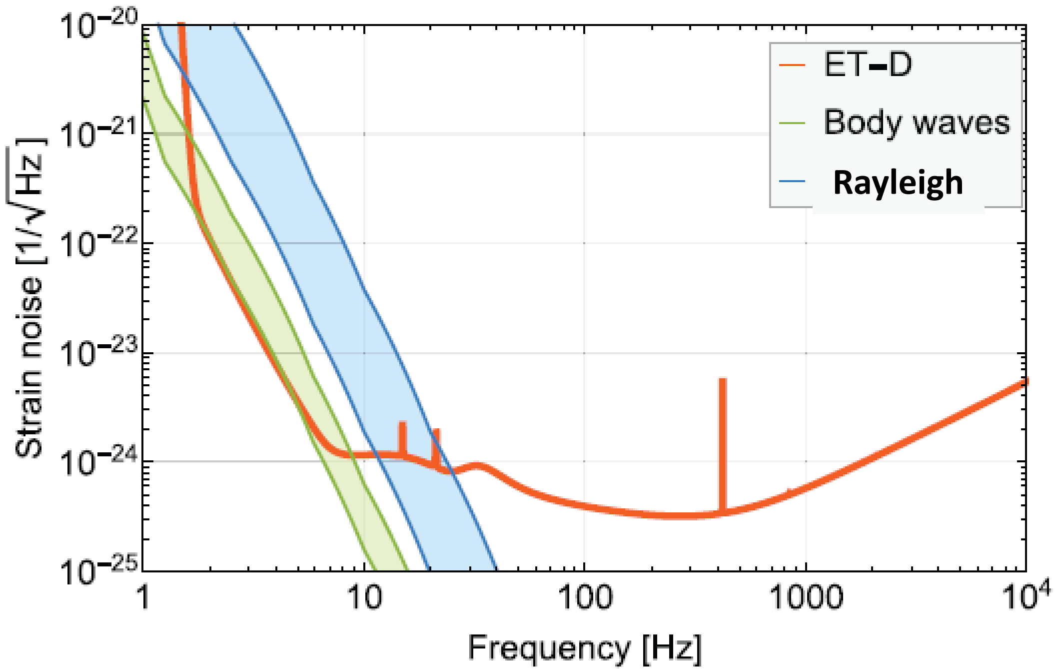
Suppression of Newtonian noise underground

Source: F Badaracco and J Harms 2019 Class. Quantum Grav. 36 145006

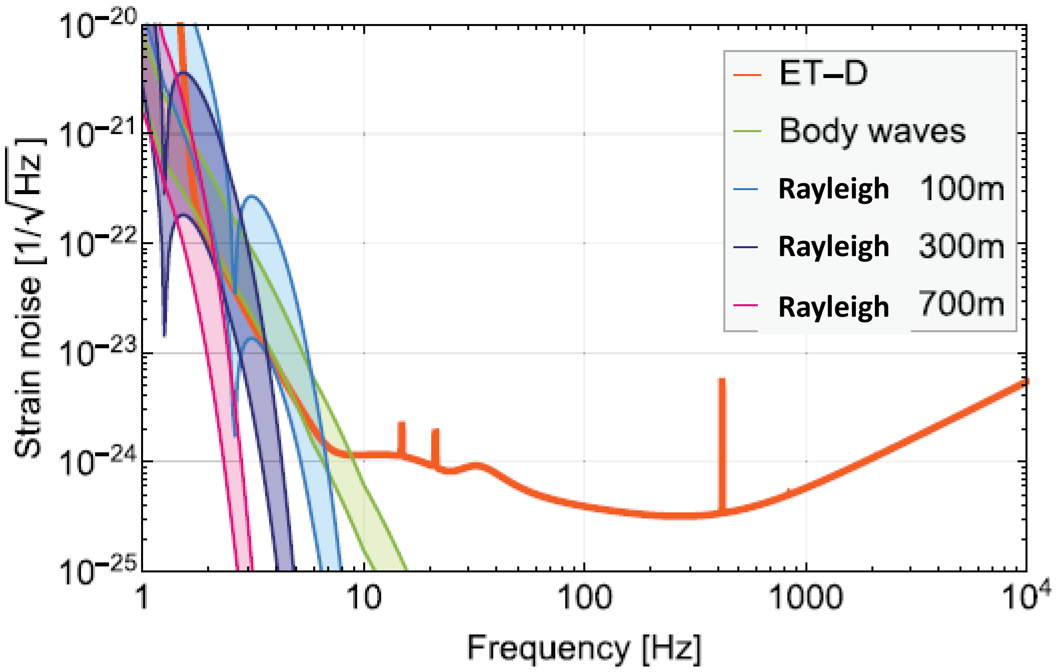
Key messages:

- Main reason to build ET underground is the suppression of Rayleigh waves that induce Newtonian Noise
- Even then, Newtonian Noise dominates the sensitivity at low Frequencies and needs to be suppressed
- Conservative suppression factor 3 assumed in all ET sensitivity curves, independent of frequency

ET at the surface



ET below the surface



How correlated is seismic + newtonian noise over large distances?

The Einstein Telescope's **triangular design** leads to several, **short distance** (~500m) **coupling locations** for **noise** sources, e.g. seismic noise, to couple **coherently** to multiple interferometers.

Credit: ET collaboration - https://www.einsteintelescope.nl

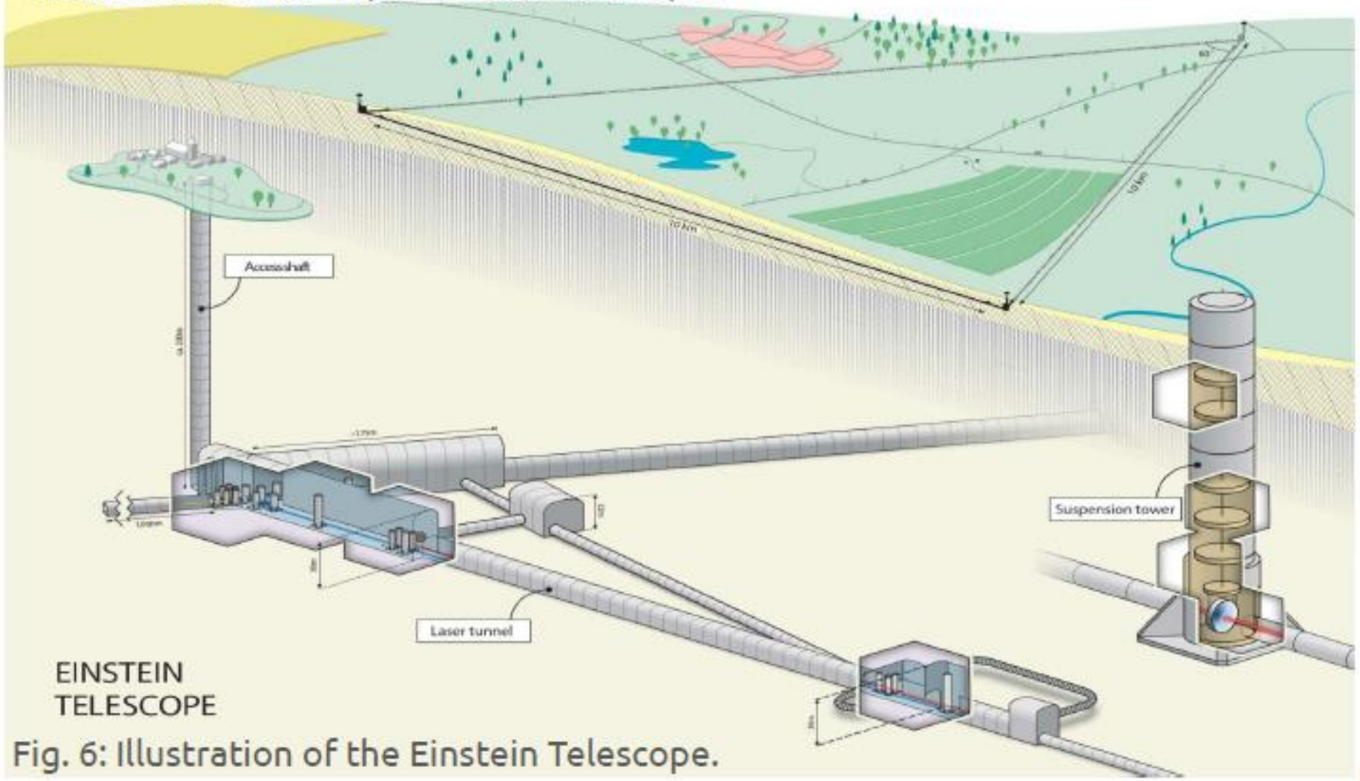
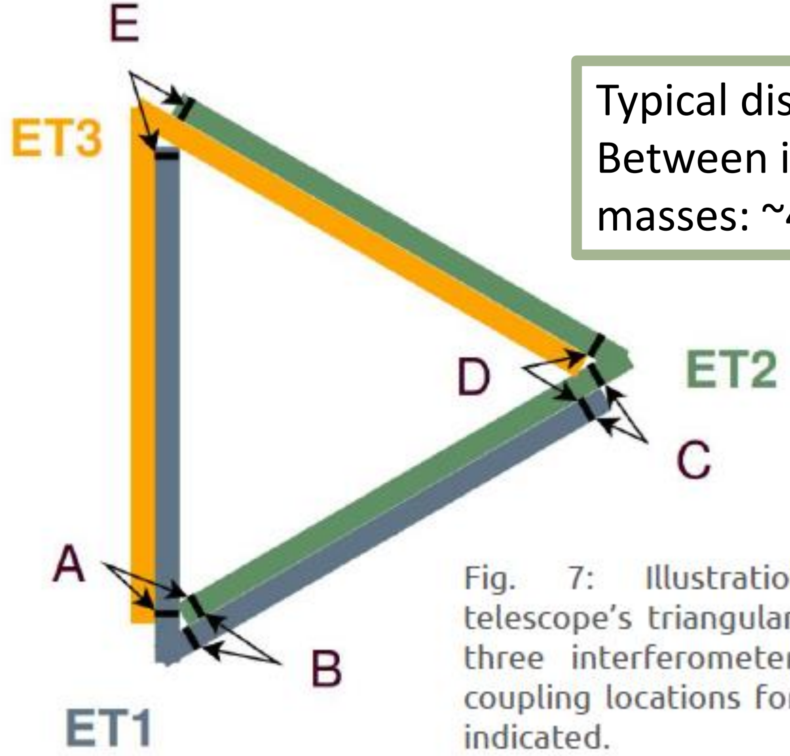


Fig. 6: Illustration of the Einstein Telescope.



Typical distance
Between input-end test
masses: ~400m

Fig. 7: Illustration of Einstein telescope's triangular configuration of three interferometers, with possible coupling locations for correlated noise indicated.

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

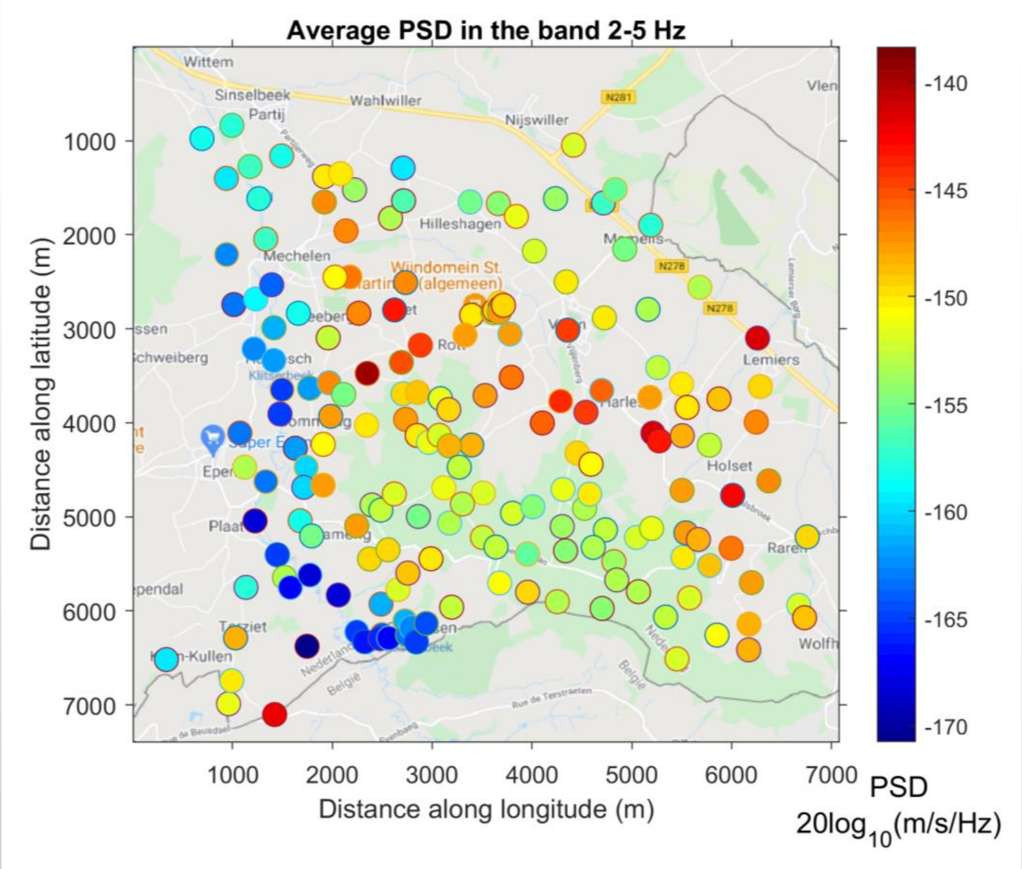
The Terziet and Homestake seismometer networks

S. Koley *et al* 2022 *Class. Quantum Grav.* **39** 025008

Website of network:

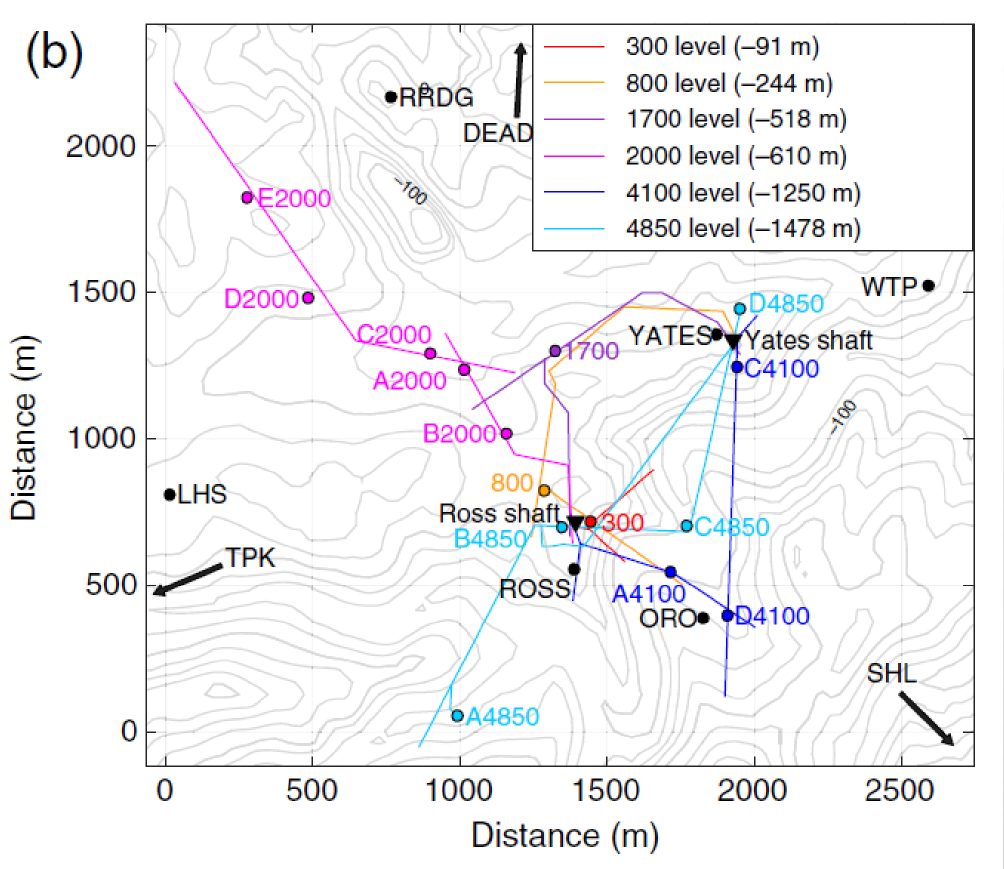
https://www.fdsn.org/networks/detail/3T_2020/

Hundreds of geophones in EMR region, including two boreholes with surface and subsurface seismometers



V. Mandic et al 2018 Seismological Research Letters 89 (6): 2420–2429

Sanford lab at Homestake mine South Dakota
24 broadband seismometers of which 15 underground
With depths varying between 91m and 1478 m



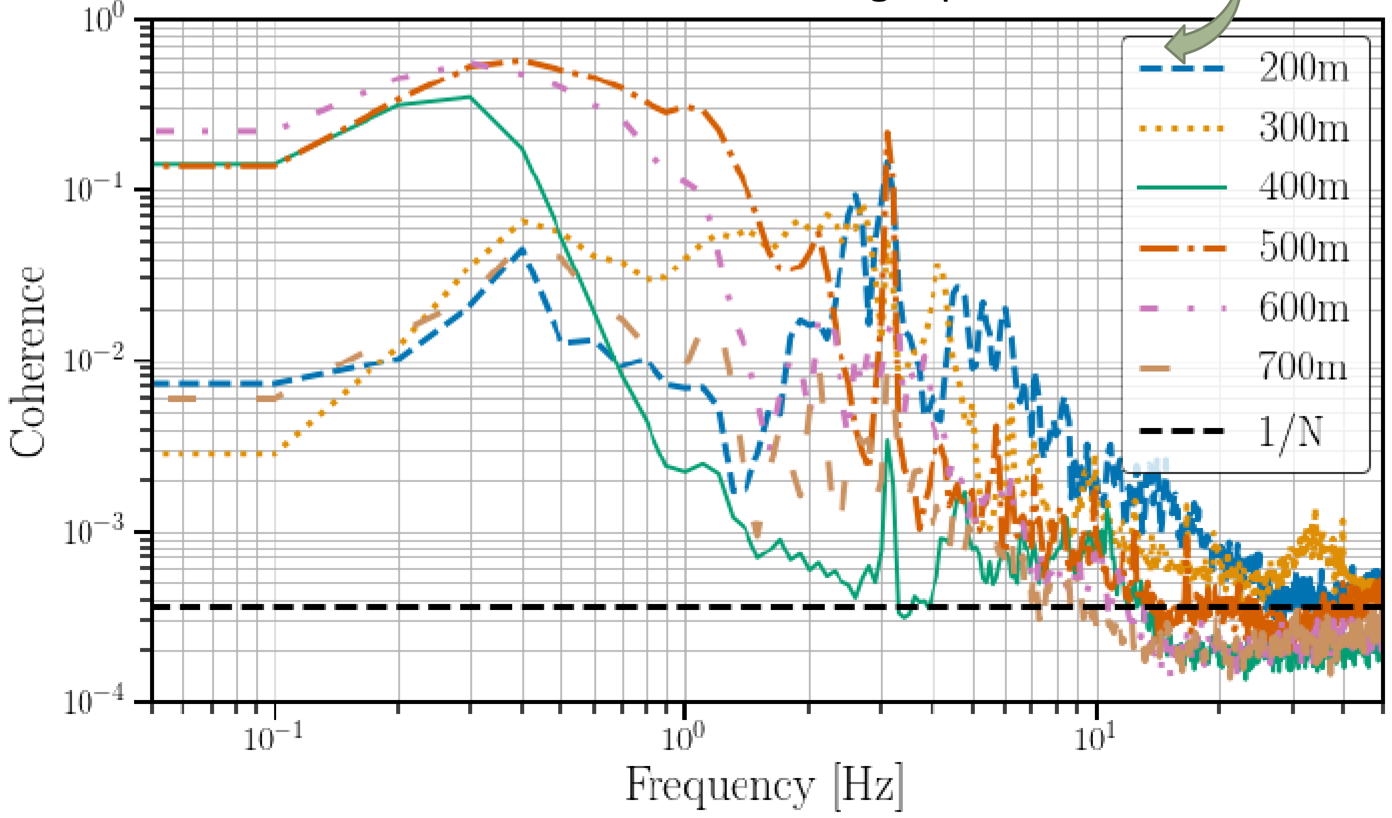
Coherence and PSD vs distance at surface:

Source: K. Janssens et al 2022 Phys. Rev. D 106, 042008

Coherence: is there correlated seismic noise beyond random? ⟹ YES! Up to 700m or longer!

Note: not all baselines are at same central location and measured at same time

Median coherence of Terziet surface geophones vs distance

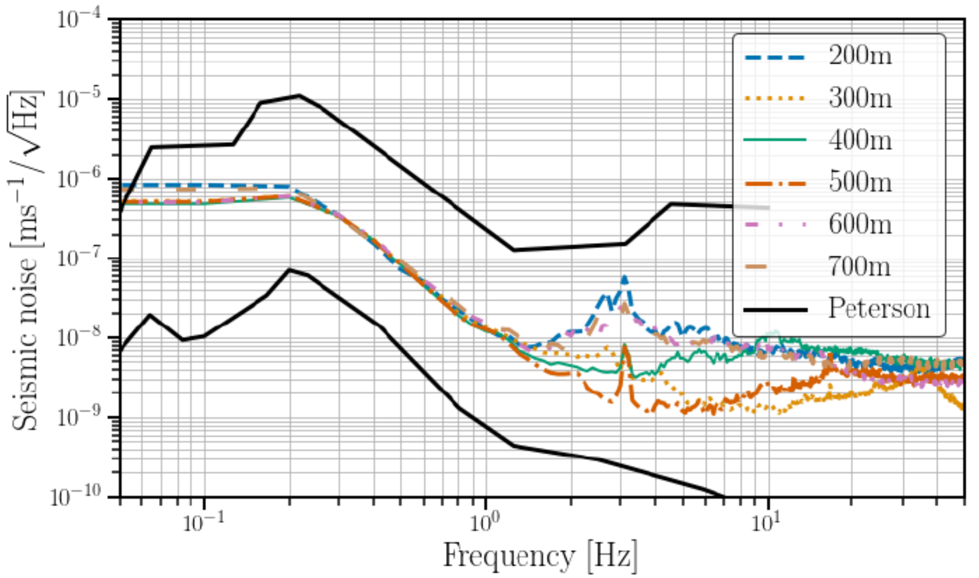


Findings:

- Significant coherence measured up to f<10Hz
- Up to large distances: <700m
- No clear decrease with increasing separation
- Not compatible with assumption of isotropic, homogeneous seismic field
- Points to large antropogenic noise

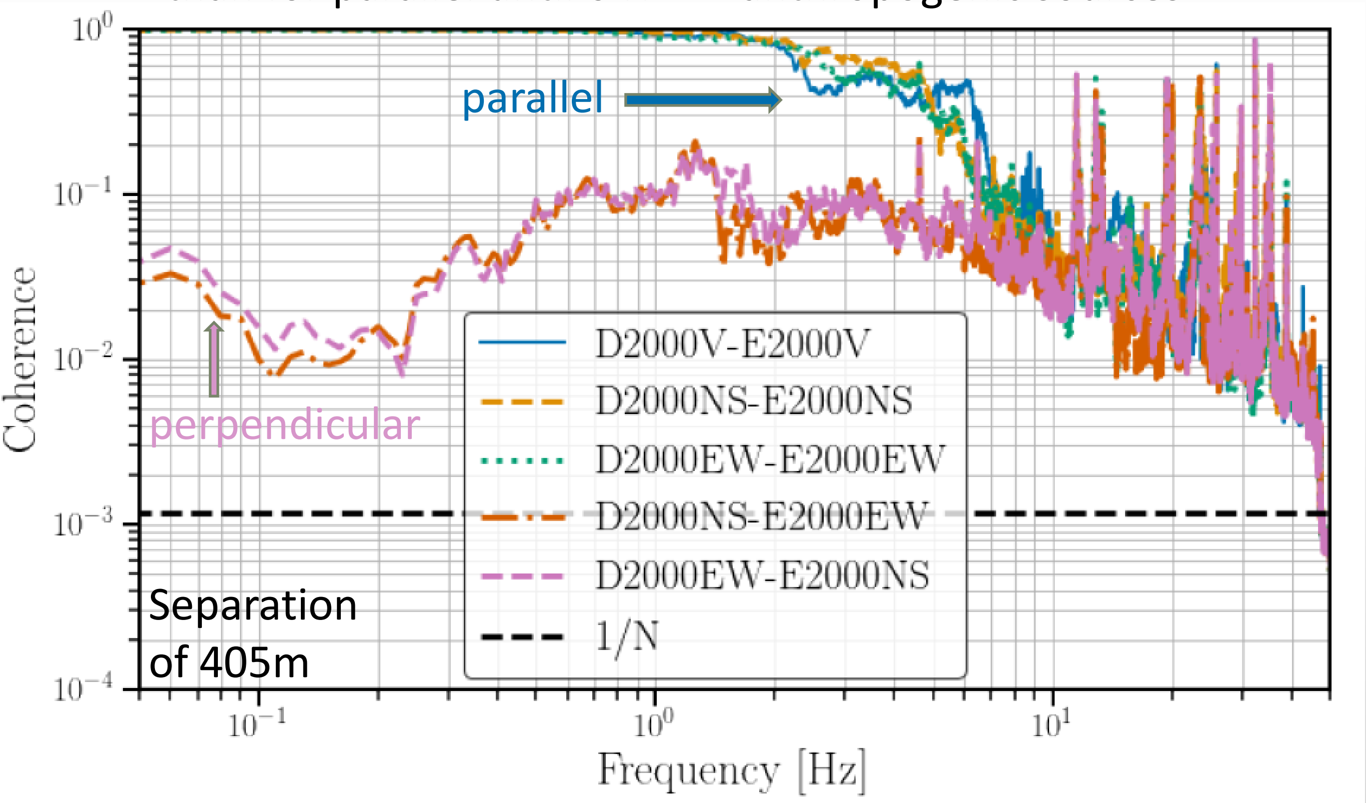
T. Yokoi and S. Margaryan, Geophysical Prospecting 56, 435 (2008).

Cross Spectral density: How big is the impact on Cross correlated techniques

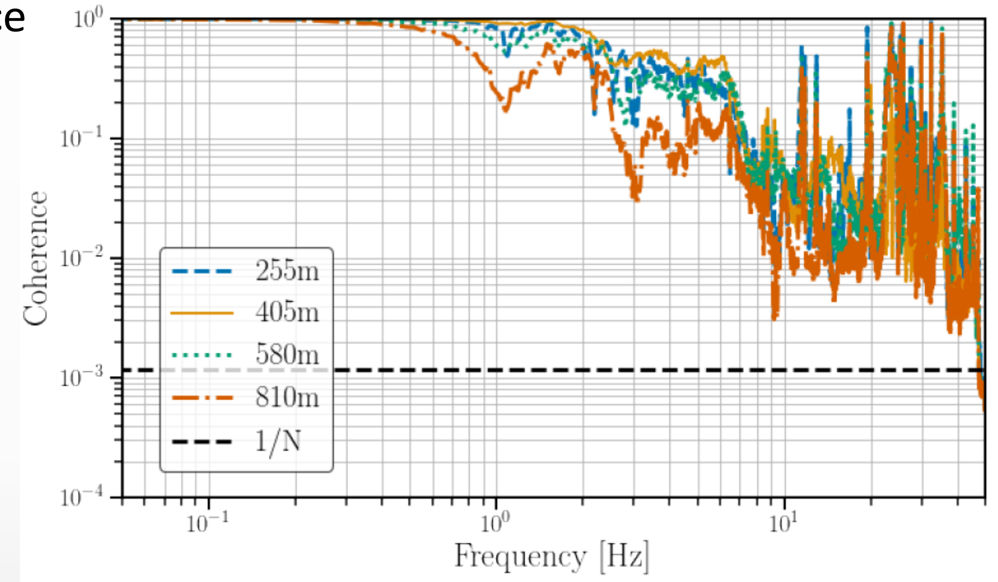


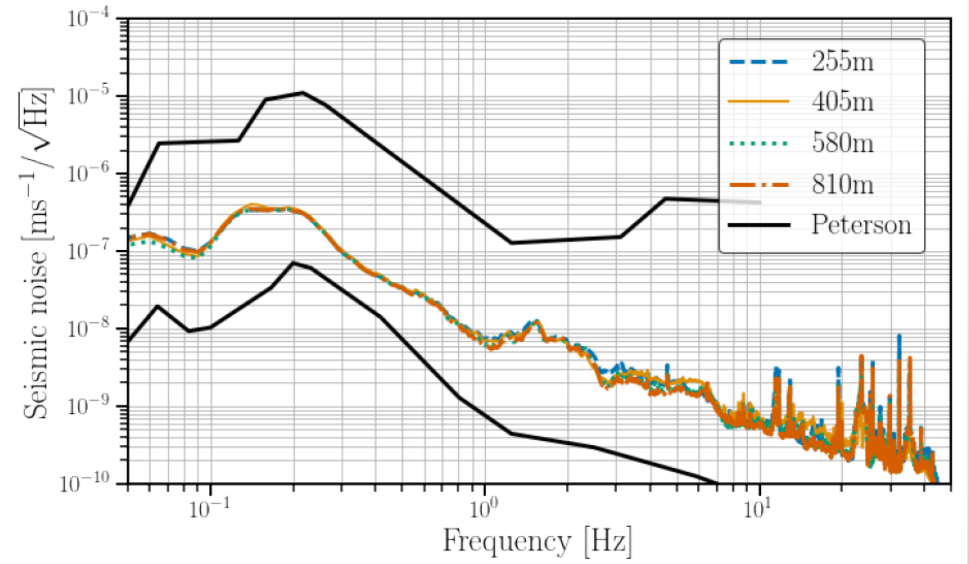
Homestake mine @600m depth

- Choice of depth motivated by several seismometers with separations between 125m and 1200m
- Seismometers can measure in 3 directions!
- More than 50% of time there is significant coherence up to f<40Hz
- Coherence in perpendicular directions significantly lower than for parallel until 6 Hz → anthropogenic sources



- Coherence seems to diminish with depth, except for 405m
- CSD does not vary with depth and at least 10x lower than at surface





Projection of CSD into the ET Noise curve

$$S_{h,\mathrm{Rayleigh}}(f) = \left(\sqrt{2}\pi G\gamma\rho_{0,\mathrm{Surface}}\right)^2 \frac{1}{L^2(2\pi f)^4} \mathcal{R}(h,f) S_{\xi_z}(f)$$

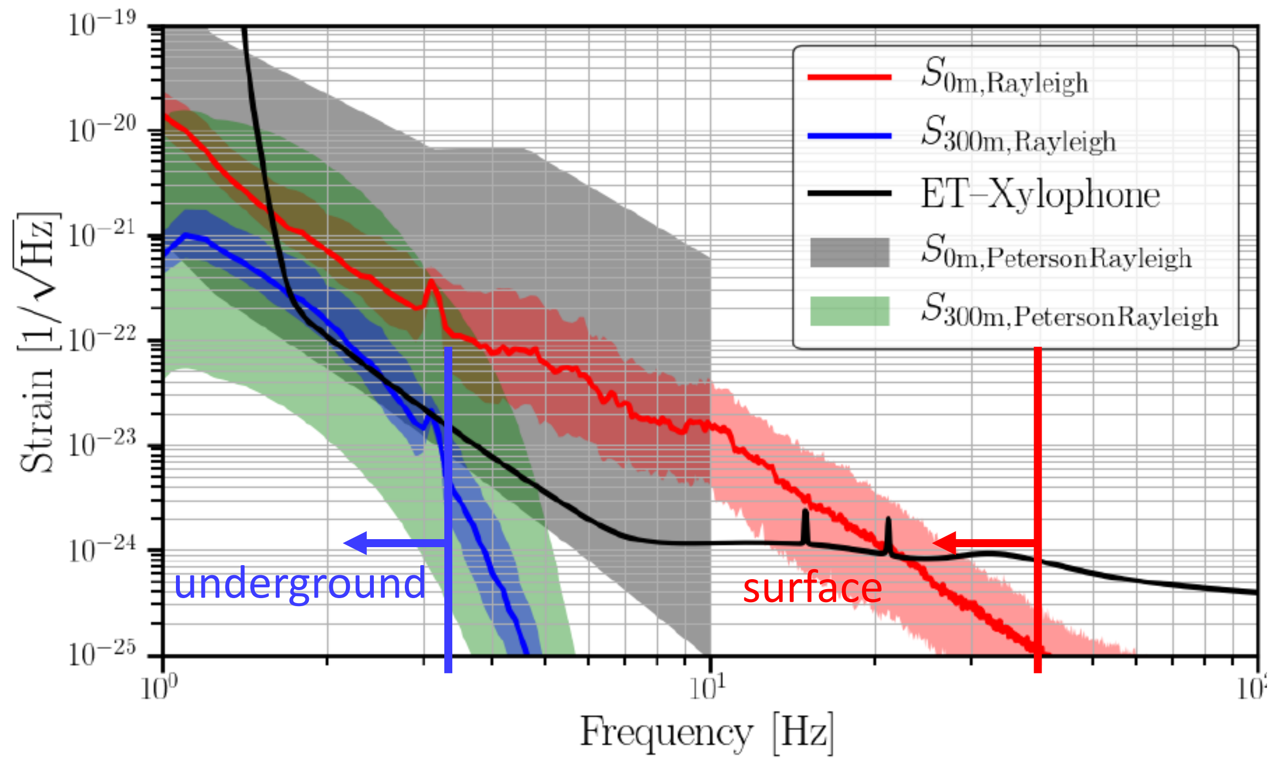
Exponential decrease with depth, h

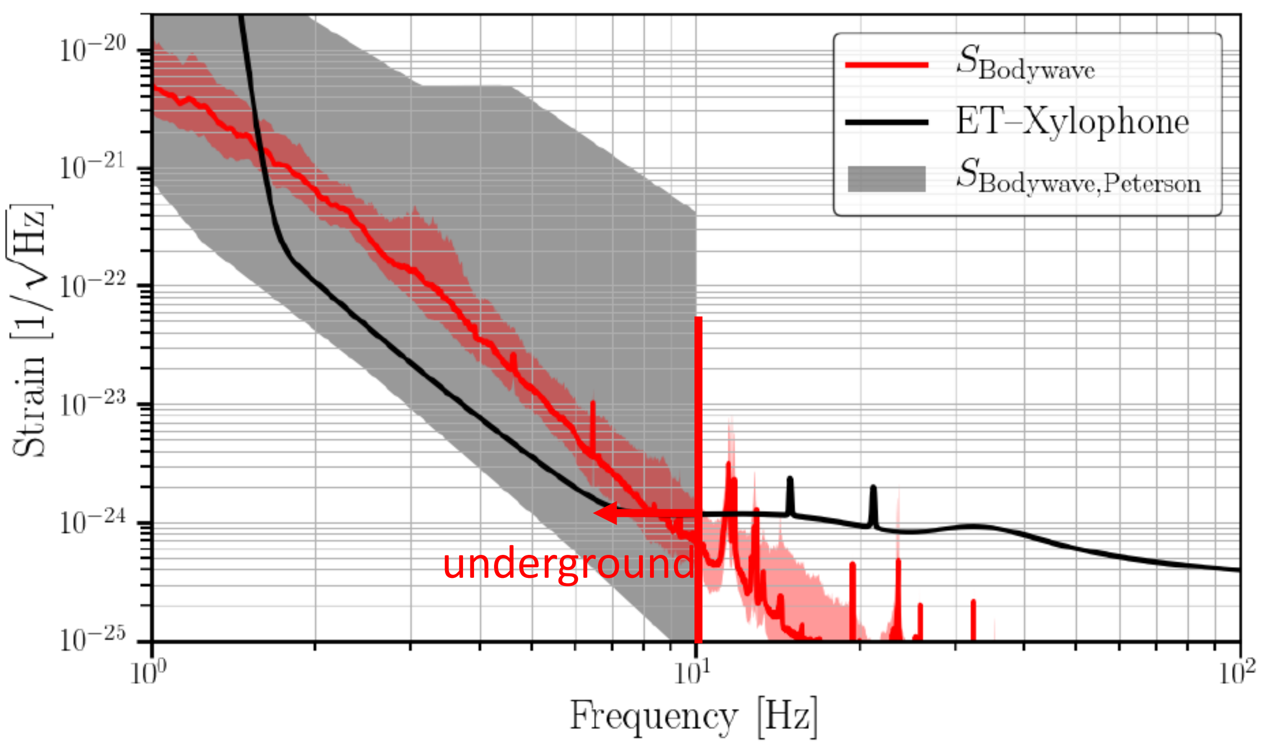
Measured
Vertical displacement PSD (or CSD)

$$S_{\text{Body-wave}}(f) = \left(\frac{4\pi}{3} G\rho_{0,\mathrm{Bulk}}\right)^2 (3p+1) \frac{1}{L^2(2\pi f)^4} S_{\xi_x}(f)$$

- If ET is located at surface: NN curve from Rayleigh up to f<30Hz
- At 300m depth: NN from Rayleigh troublesome up to f<3Hz

- Measured correlated body waves at 60mm depth in quiet environment are detrimental up to f<10Hz
- Direct measurements confirming earlier estimates
- Reduction by factor 10 needed



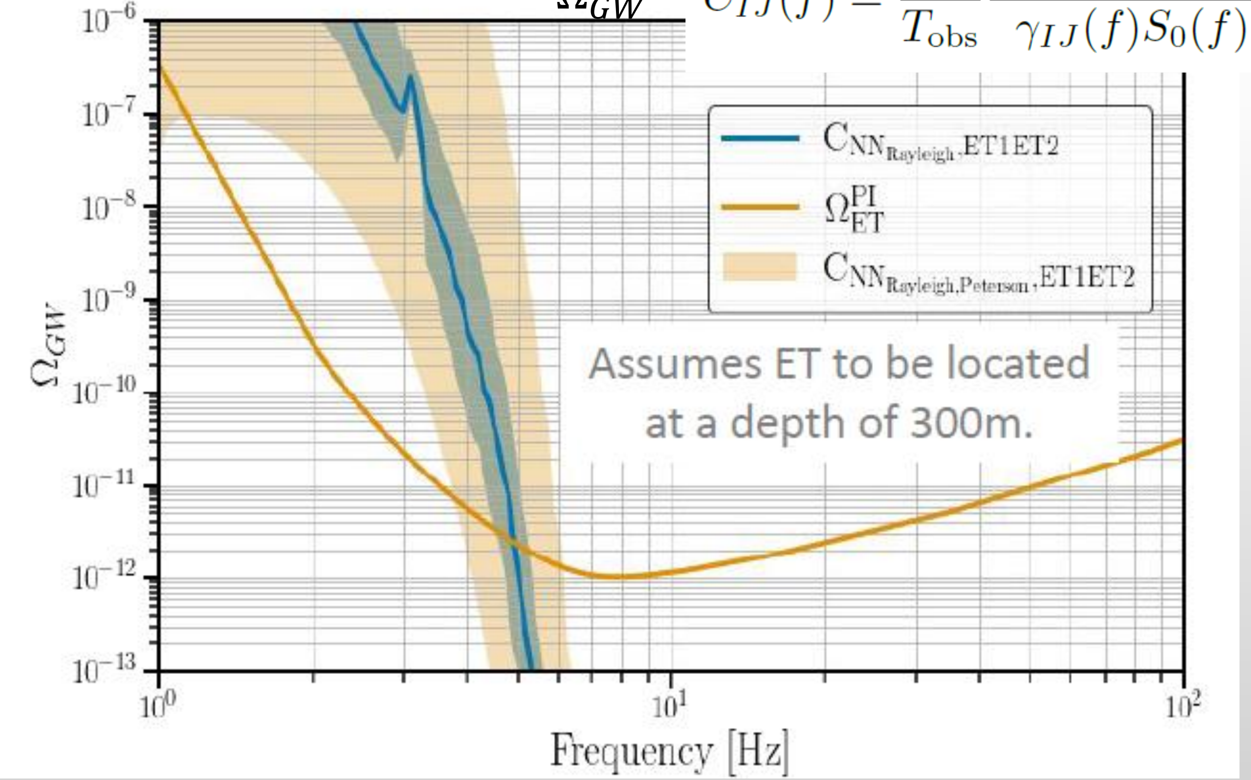


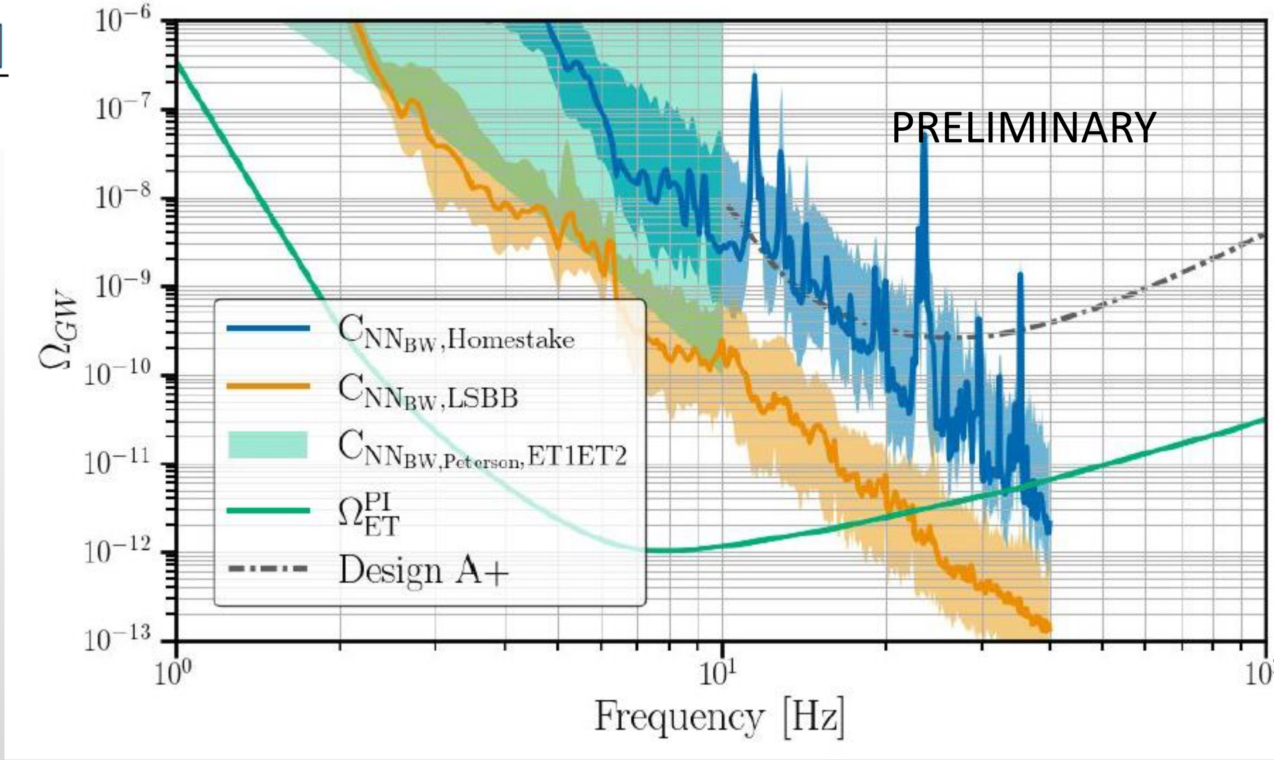
Impact of correlated Newtonian Noise on stochastic GW searches

- Many physics extracted by correlating two interferometers
- Stochastic searches look for signals **below** the noise curve
- This is achieved by cross-correlating multiple interferometer data, assuming uncorrelated noise

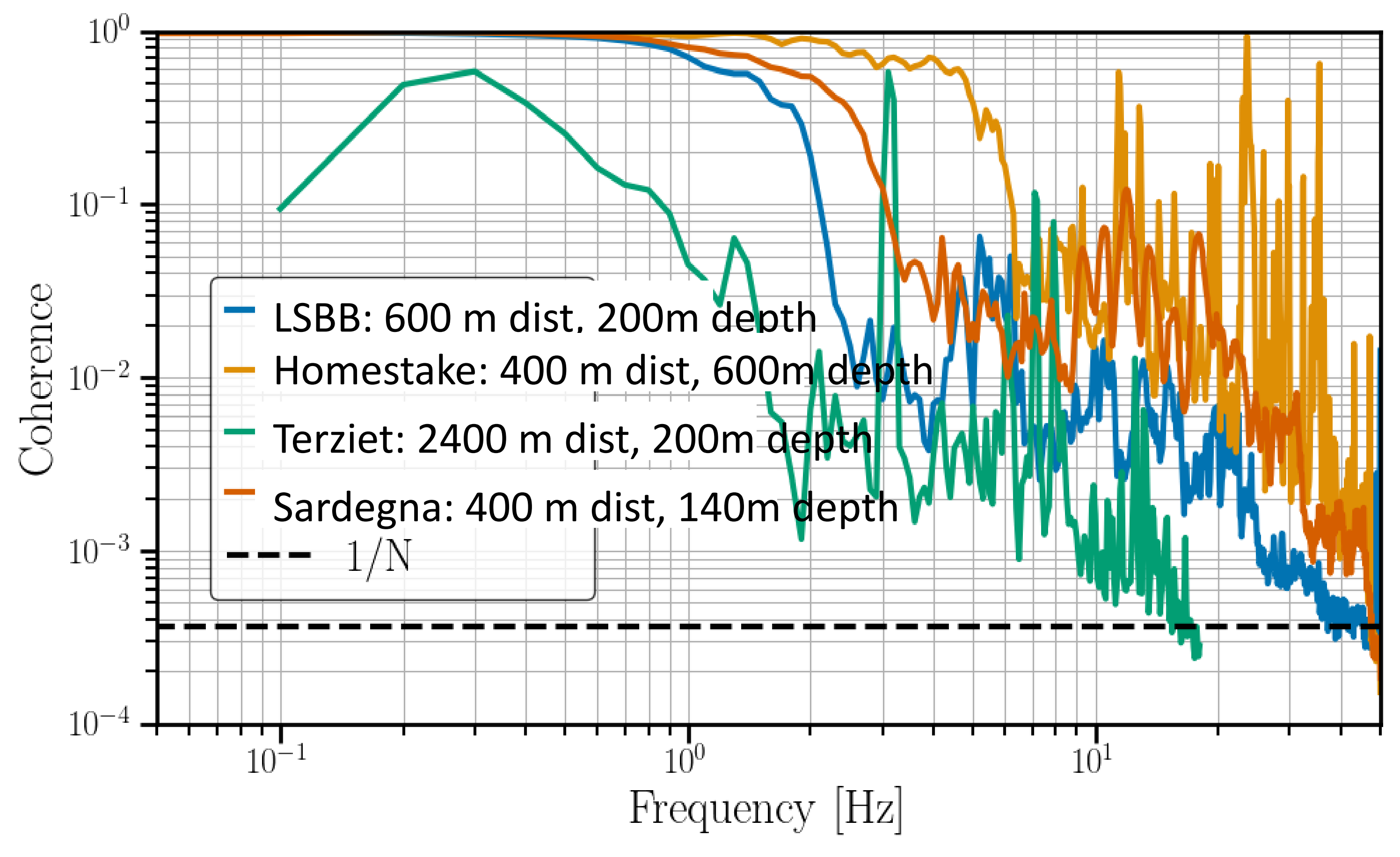
- Impact of correlated Newtonian noise due to body waves is detrimental for stochastic searches up to f<40Hz (containing 95% of sensitivity)
- NN Reduction factors of order 100 needed at each interferometer to suppress this impact
- New measurements at LSBB indicate order of magnitude better (is very quiet site)

$$\Omega_{GW} \sim \hat{C}_{IJ}(f) = \frac{2}{T_{\text{obs}}} \frac{\text{Re}[\tilde{s}_I^*(f)\tilde{s}_J(f)]}{\gamma_{IJ}(f)S_0(f)}$$





Site comparison

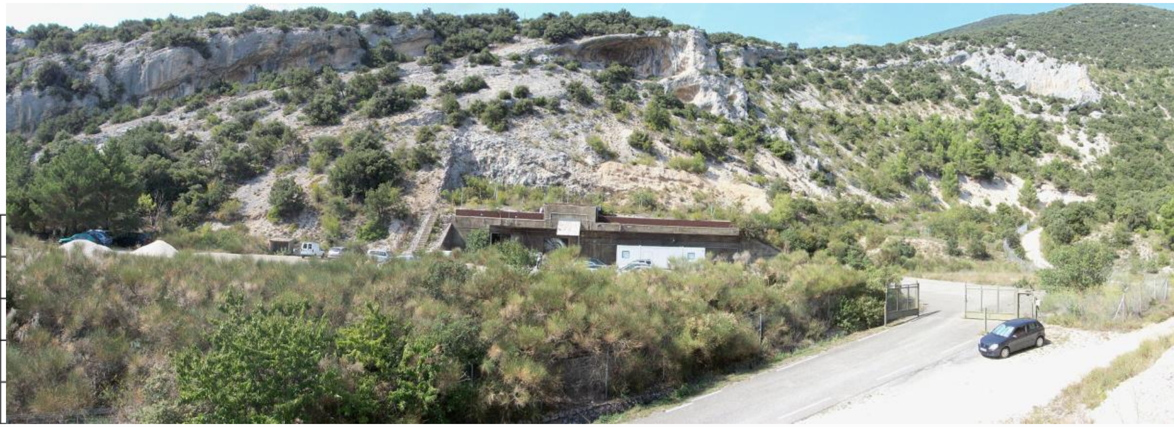


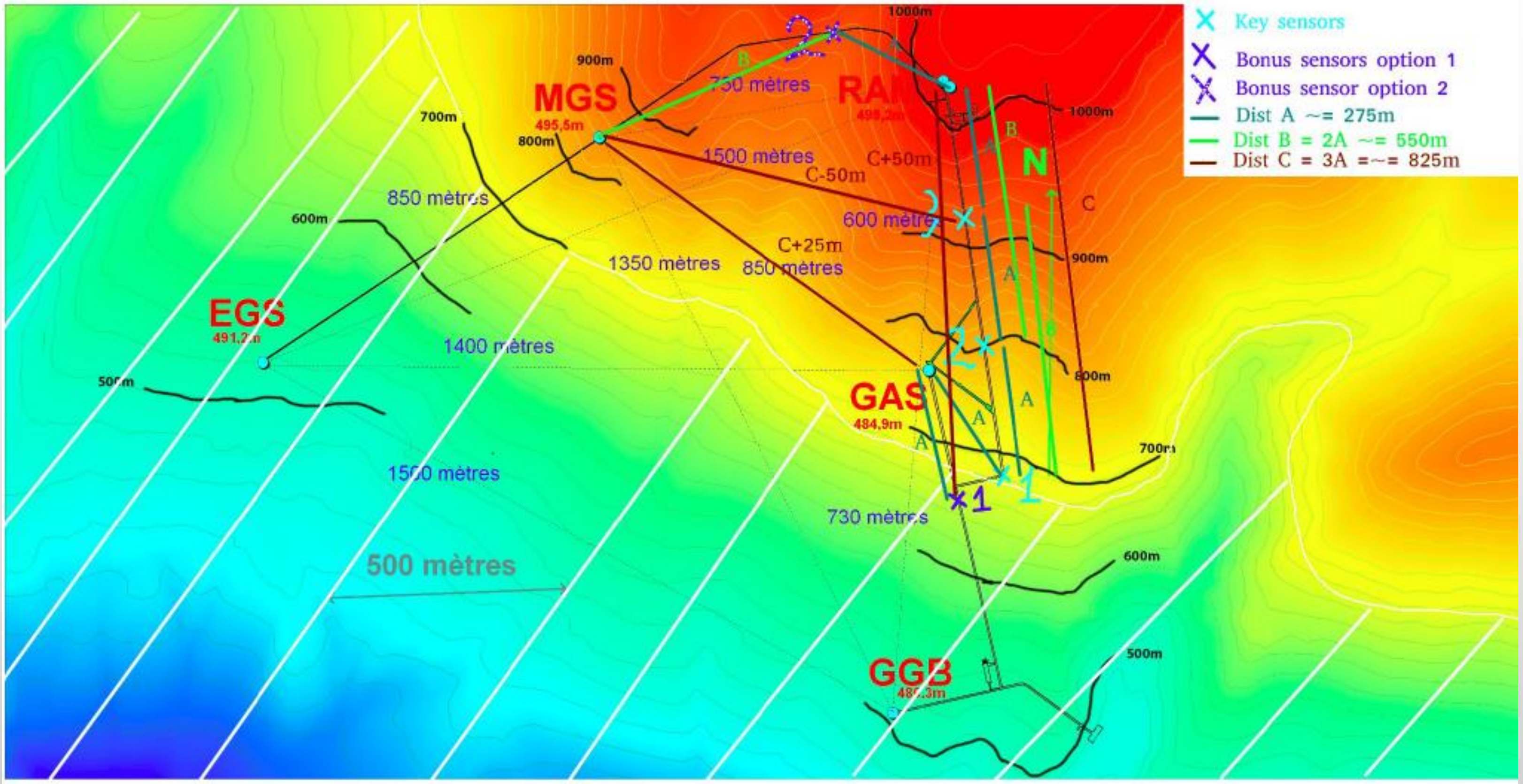
- There seems to be strong site dependence on level of coherence
- Coherence at LSBB (200m deep) lower than Homestake and Sardegna (400-600m deep)
- Note: Distance between underground borehole seismometers at Terziet is 2,4 km and not representative
- Ideally: 2nd borehole in EMR region close to Terziet surface area separated by 400m
- For the moment: Measure at LSBB

The LSBB seismic project

Laboratoire Souterrain à Bas Bruit (Rustrel, Vaucluse FR)

Location	Model 1	Model 2	Name 1	Name 2	Horizontal distance	Vertical distance	Depth 1
Homestake (US)	STS-2	STS-2	D2000	E2000	~ 405 m	~ 0 m	610 m
LSBB (FR)	STS-2	STS-2	GAS	RAM	~ 600 m	~ 14 m	260 m
	STS-2	STS-2	MGS	RAM	~ 750 m	~ 4 m	240 m
	STS-2	STS-2	MGS	GAS	~ 850 m	~ 11 m	240 m





- Former nuclear launch site of France
- Seismically very quiet
- Electromagnetically shielded
- Tunnel complex of 4km
- Anti-blast gallery at 280m depth with existing fixed seismometer array diatance range 600m-850m
- Possible location for interfereometer w. cold atoms
- We propose: Extend existing array with 4 new mobile seismometers (one of which we purchased on IRI budget: 20kEur)
- Start campaign investigating dependence on depth, distance, orientation …

Conclusions & Outlook



- Seismic fields being mapped in various regions
- Subsurface fields are less known in EMR region
- High quality data from subsurface seismometer arrays at Homestake and LSBB are being exploited
- Newtonian Noise induced by subsurface body waves is the biggest limitation for ET sensitivity in Frequency range up to 10Hz!
- Correlated Newtonian Noise is very significant for co-located interferometers in the standard ET triangle geometry
- These correlated NN noise contributions make an improved measurement of the stochastic GW background with a triangular ET nearly impossible!
- New interesting seismic campaign starting at LSBB to elucidate dependence on depth, distance, orientation, …. In collaboration with ARTEMIS Nice and UGent
- Open to other collaborators!