Seismic and Newtonian noise in underground GW detectors

ET-Site Studies and Characterization, November 2021

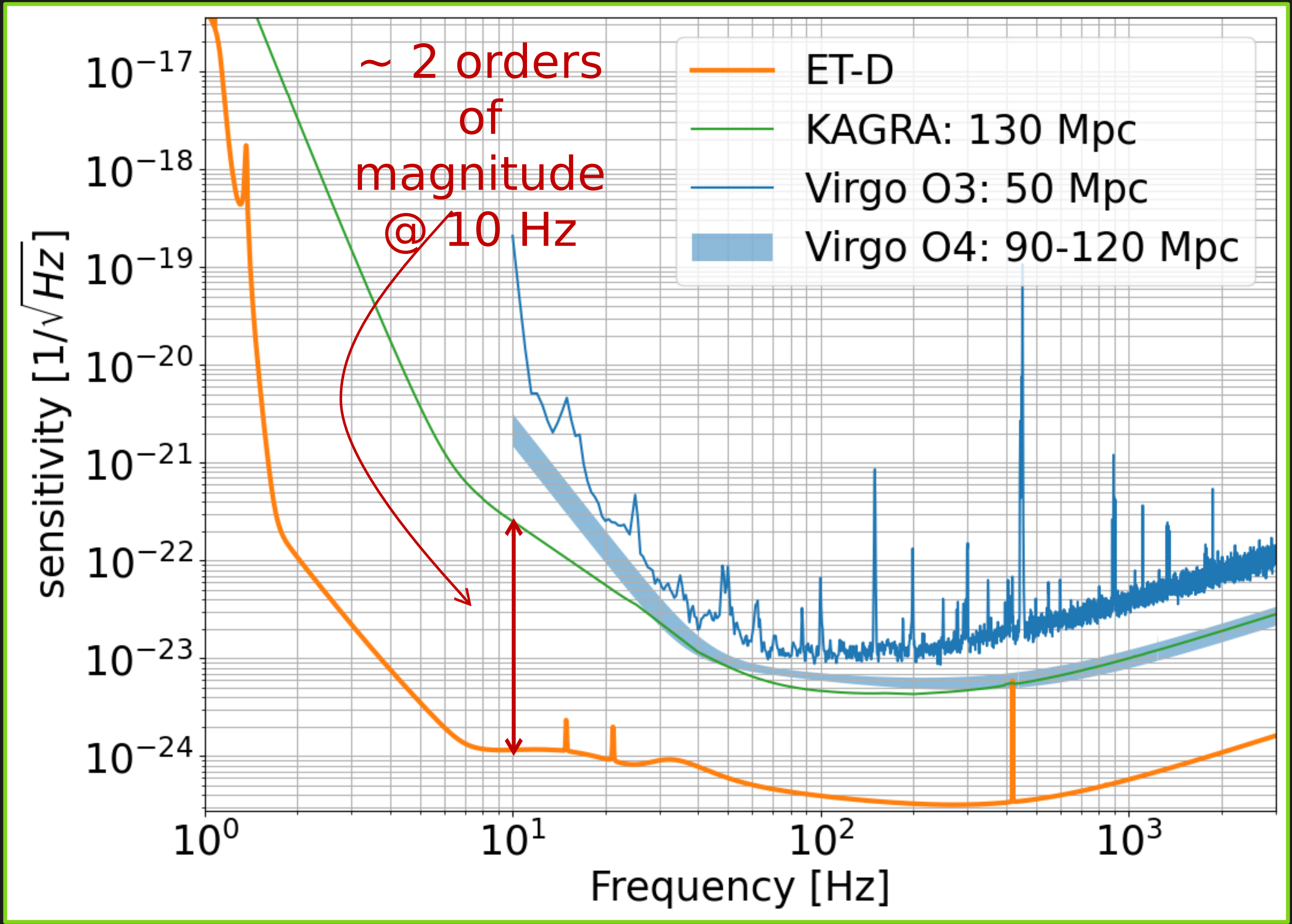
Authors: **Francesca Badaracco**
Jan Harms, Camilla De Rossi, Irene Fiori, Kouseki Miyo, Taiki Tanaka, Takaaki Yokozawa, Federico Paoletti, Tatsuki Washimi

UCLouvain

Main goals:

- Artificially induced seismic noise propagation
- Newtonian noise estimation

Improving the **low frequency** band is very expensive: do we really **need** it?



New possible discoveries

BNS: Hours – Days
Parameter estimation
EM early warning
Sky localization with only ET

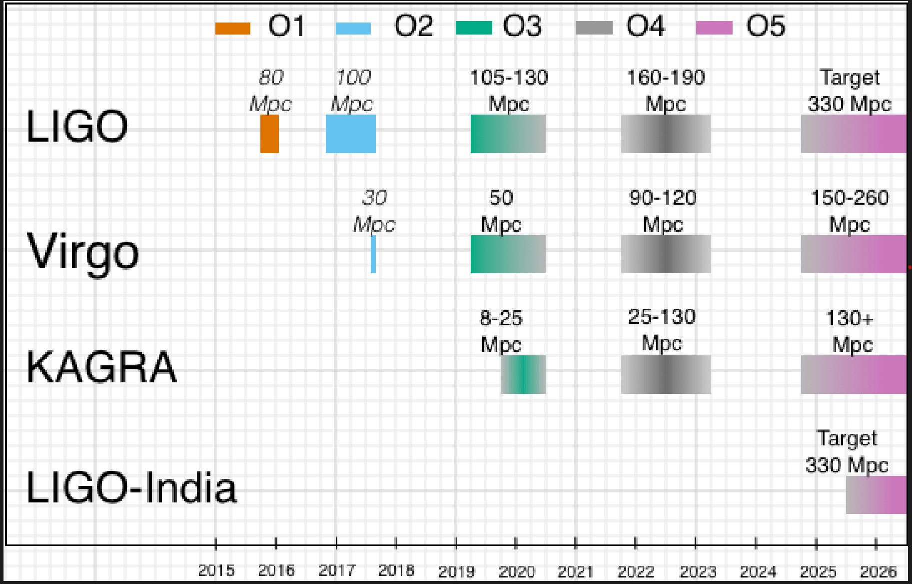
Massive BBHs:
Higher redshift PBHs?

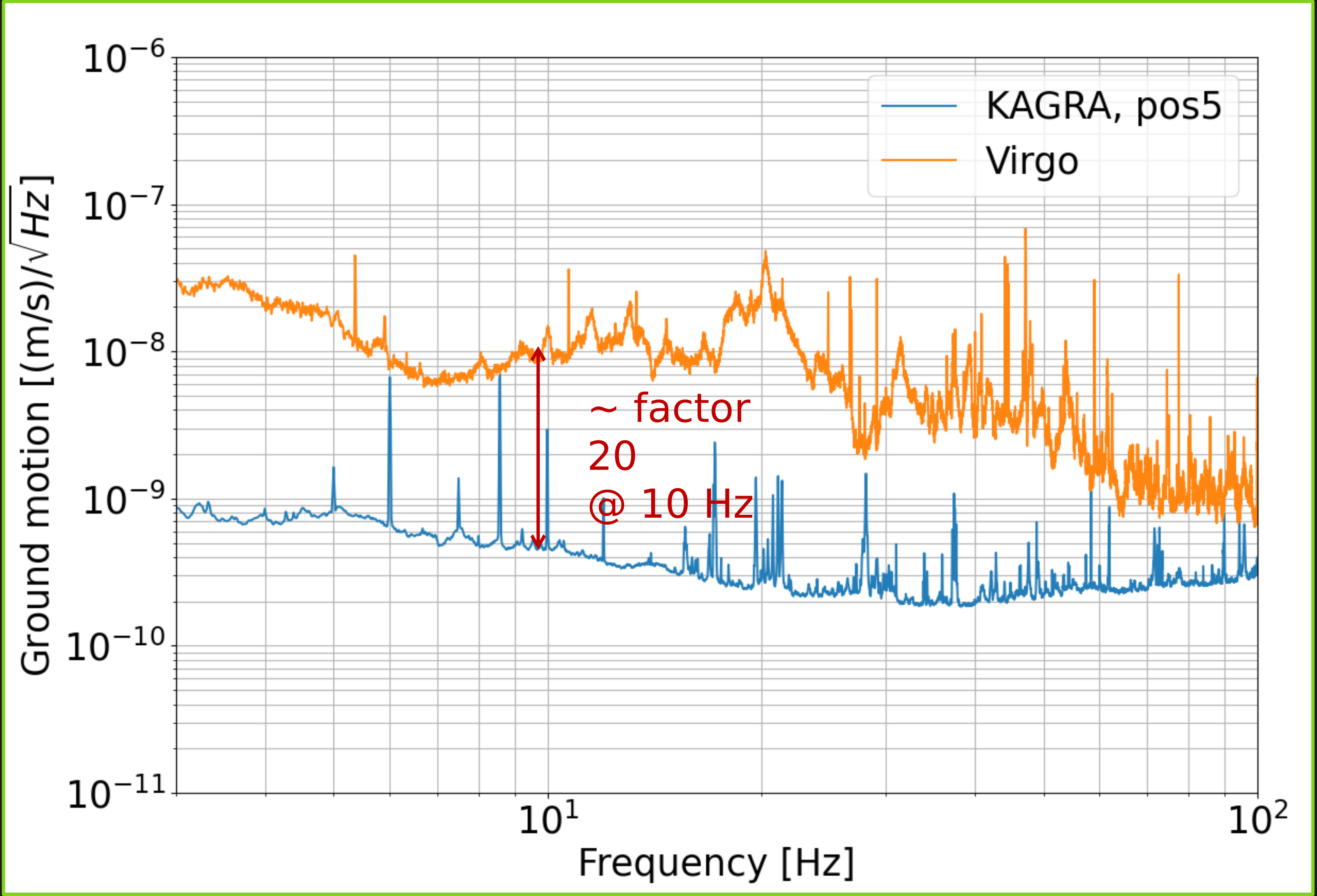
Search of stochastic background

More stable interferometer!

KAGRA is part of a worldwide network of gravitational-wave detectors

But it has something special…





KAGRA, pos5
Virgo
~ factor
20
@ 10 Hz
Ground motion [(m/s)/√Hz]
Frequency [Hz]

It is built underground

...KAGRA plays an important role in the R&D studies for the technologies that ET will need

And we want to study it

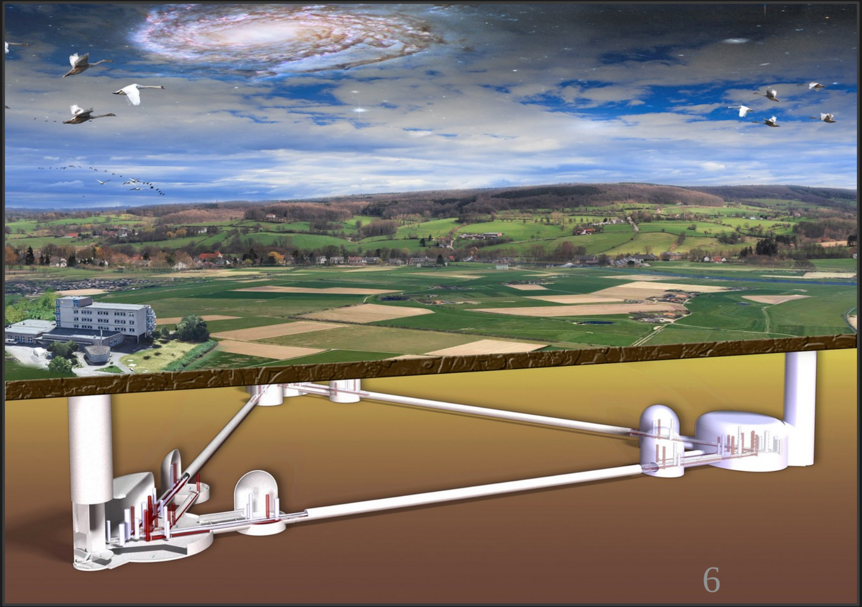
Especially from the Newtonian noise point of view

Questions:

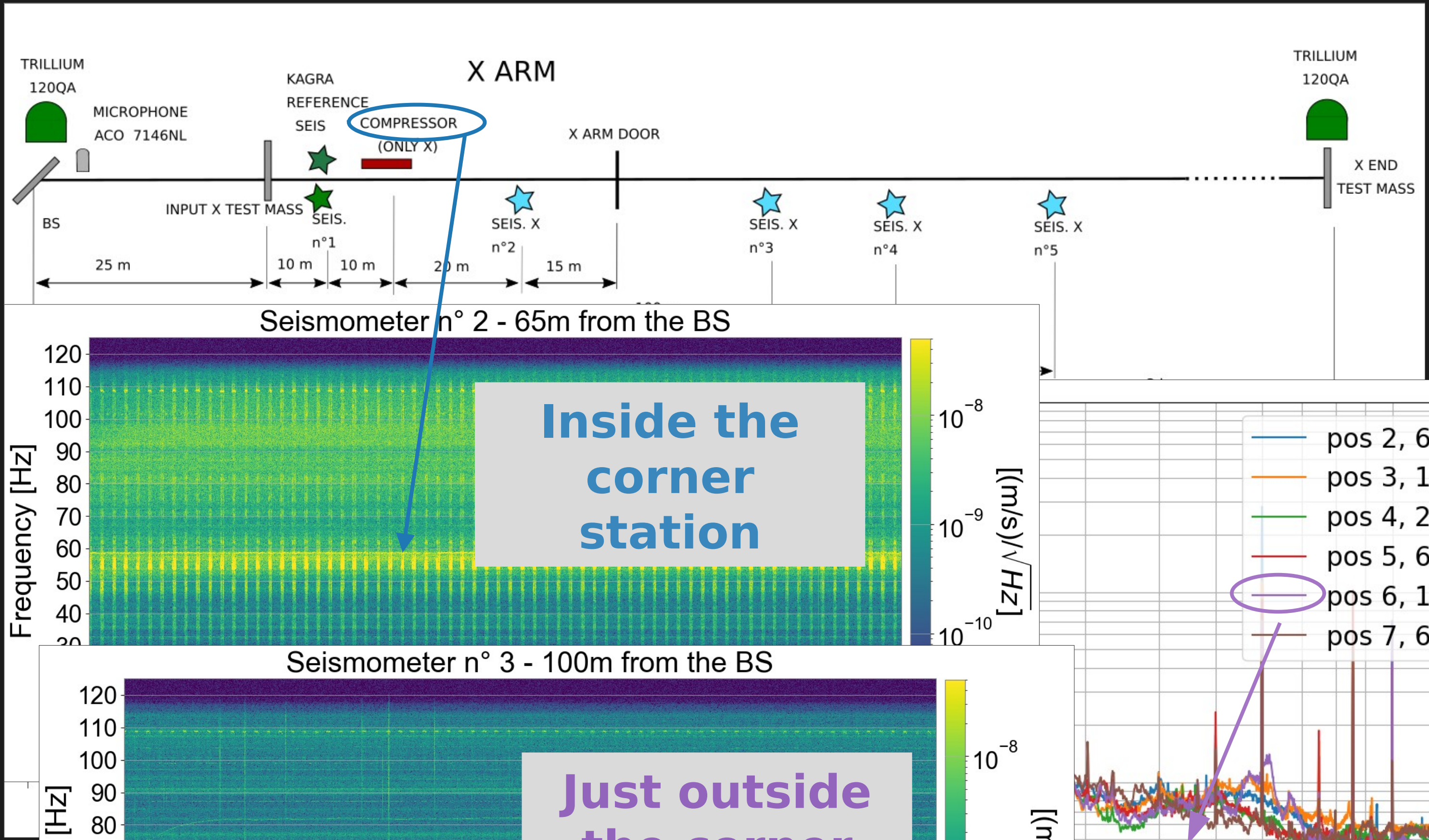
1) How much noise does the underground infrastructure cause?

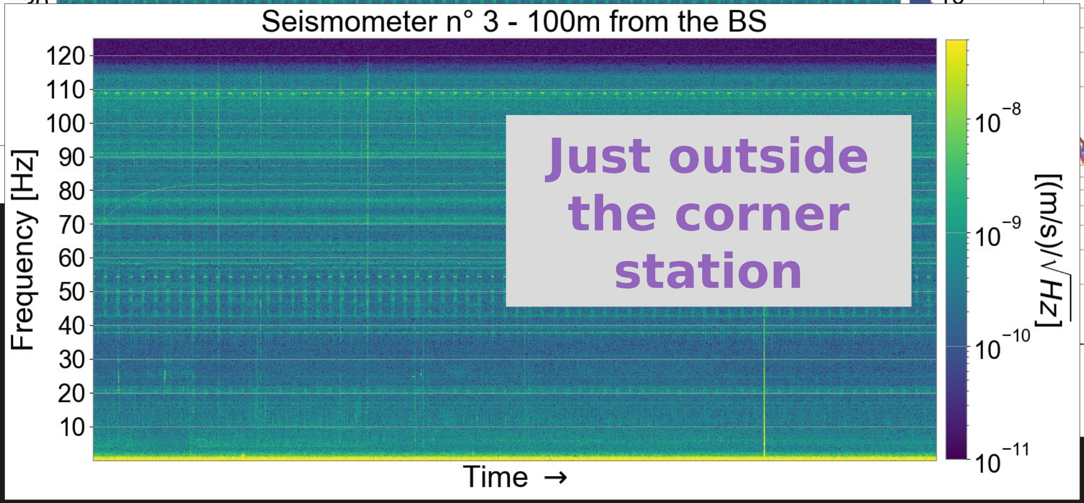
2) How high the Newtonian noise budget is?

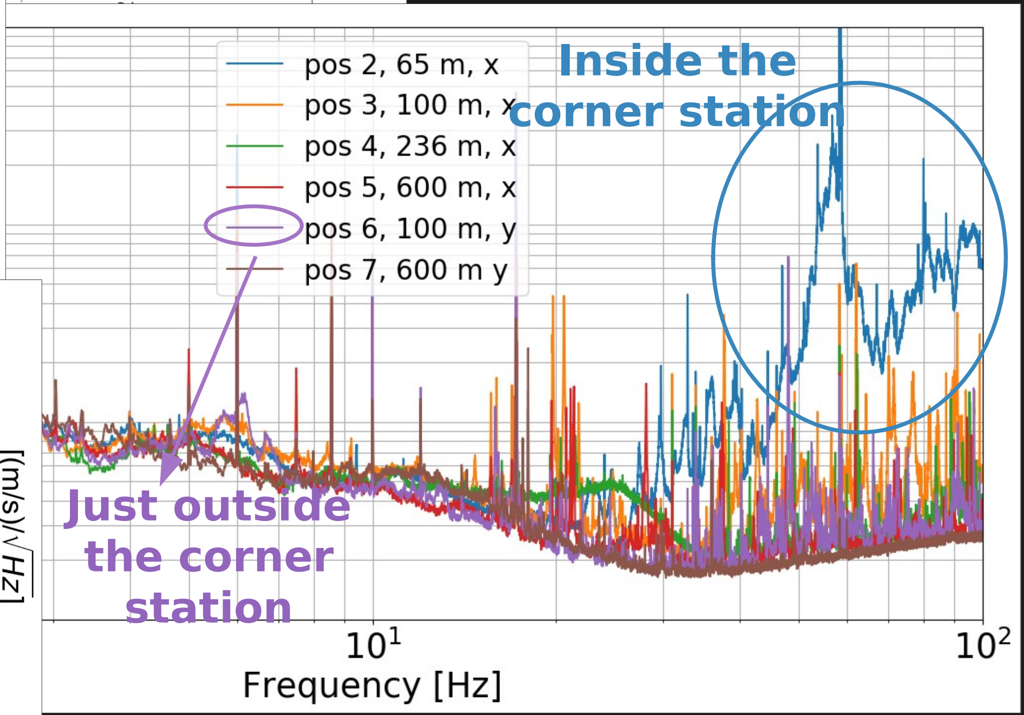
Answers:



Seismic noise induced by all the infrastructures:



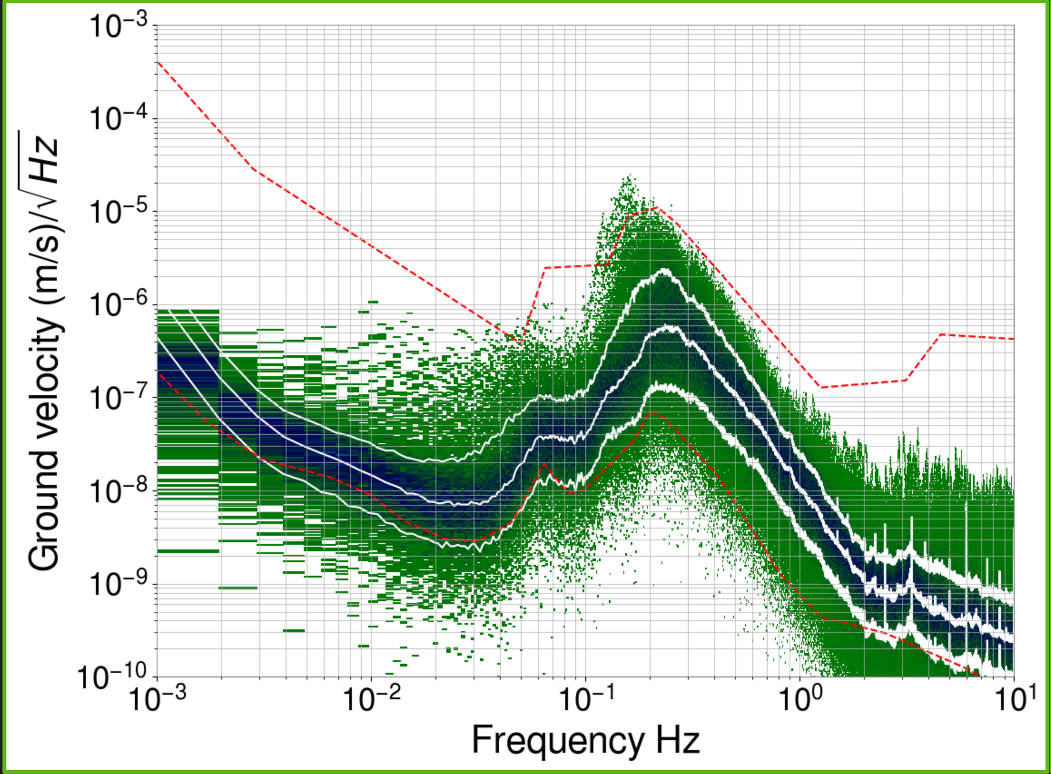


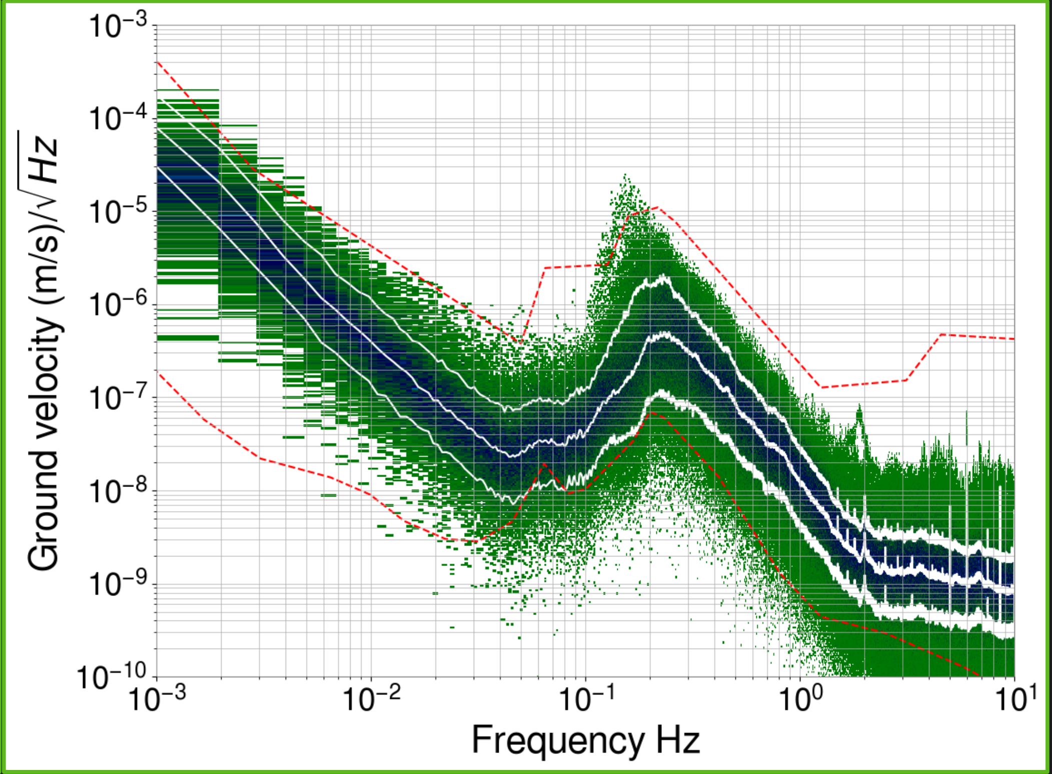


To be inspected: presence of excess horizontal displacement below 50 mHz.

Long-known fact: some pressure fluctuations (or thermal induced effects) Can produce seismic tilt that can couple with horizontal seismic channels.

Problem: tilt might cause troubles to the active seismic isolations of interferometric GW detectors.





$$\delta\rho_{\text{temp}}(\mathbf{r},t) = -\frac{\rho_0}{T_0}\delta T(\mathbf{r},t)$$

$$\delta\rho_{\text{press}}(\mathbf{r},t) = \frac{\rho_0}{\gamma p_0}\delta p(\mathbf{r},t)$$

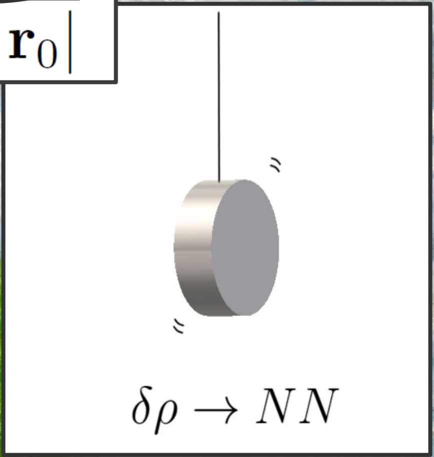
Adiabatic index

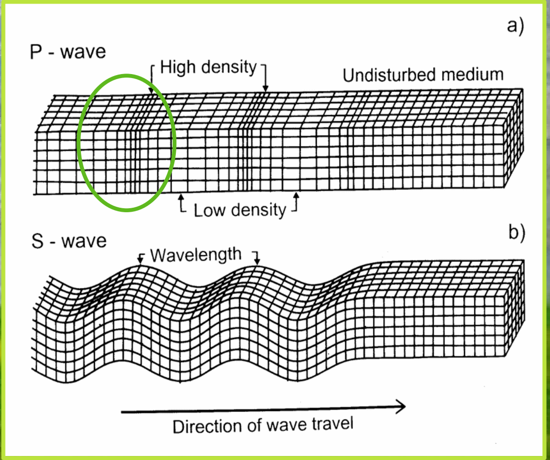
ATMOSPHERIC NN

$$\delta\phi(\mathbf{r}_0,t) = -G\int dV \frac{\delta\rho(\mathbf{r},t)}{|\mathbf{r}-\mathbf{r}_0|}$$

Newtonian Noise (NN):

Perturbation of the gravity field due to a variation in the density (δρ) of the surrounding media.





$$\delta\rho_{\text{seis}}(\mathbf{r},t) = -\nabla\cdot(\rho(\mathbf{r})\boldsymbol{\xi}(\mathbf{r},t))$$

SEISMIC NN

Newtonian noise **budget**, 3 contributions:

1) Body waves

$$\delta\vec{a}(\vec{0},t) = 4\pi G\rho_0\left(2\vec{\xi}^{\mathrm{P}}(\vec{0},t)\frac{j_1(k^{\mathrm{P}}a)}{(k^{\mathrm{P}}a)} - \vec{\xi}^{\mathrm{S}}(\vec{0},t)\frac{j_1(k^{\mathrm{S}}a)}{(k^{\mathrm{S}}a)}\right)$$

$$S\left(\delta a_x^P;\omega\right) = \left(\frac{8}{3}\pi G\rho_0\right)^2 S\left(\xi^P;\omega\right)$$

x-axis + only P-wave content + negligible cavern radius a → 0

2) Rayleigh waves propagating underground from the surface

$$S^R\left(\delta a_x;\omega\right) = \left(2\pi G\rho_0\gamma(\nu)e^{-h\omega/v}\right)^2\frac{1}{2}S\left(\xi^R;\omega\right)$$

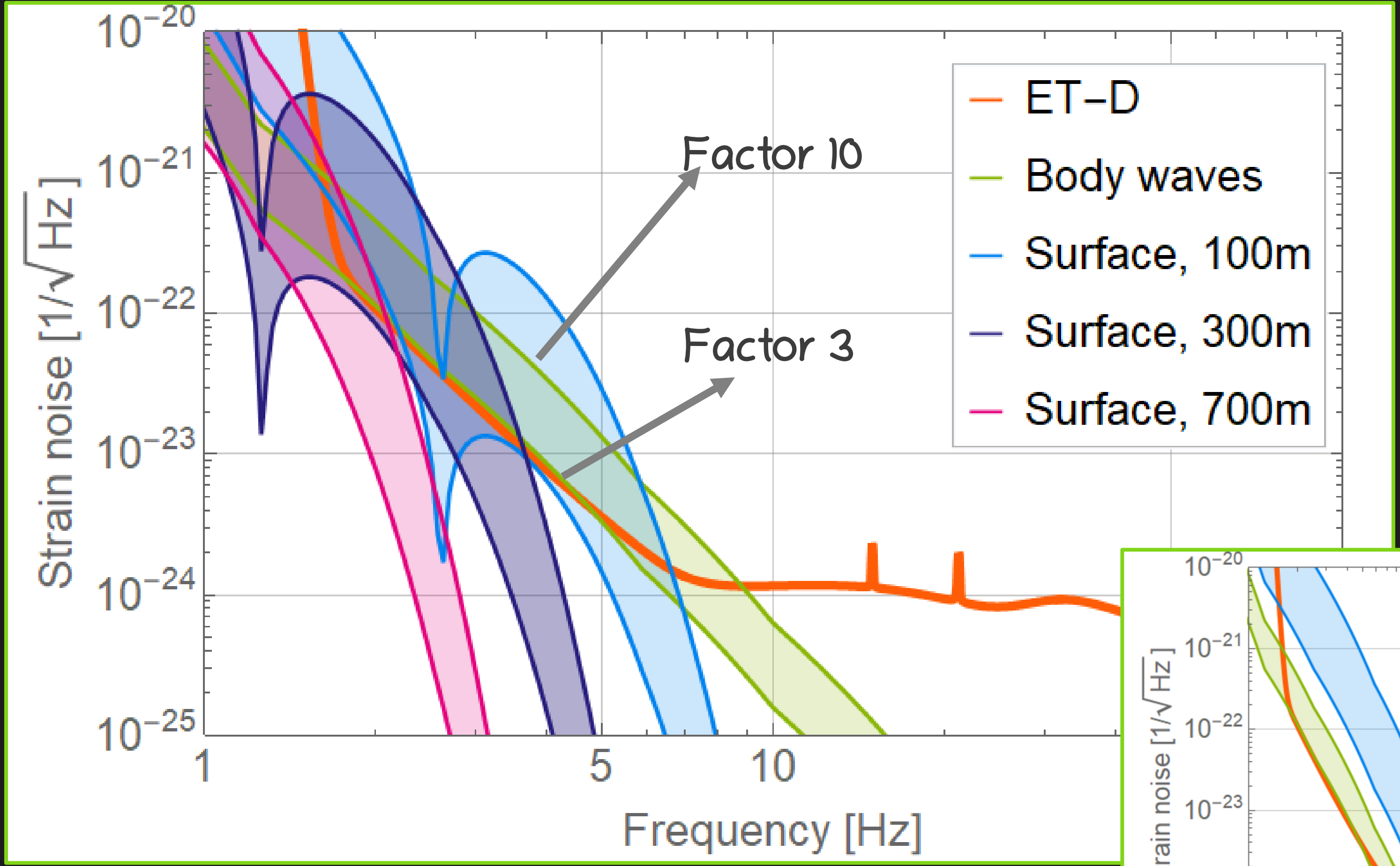
γ = determined by the elastic properties of the medium

The microseism below 1 Hz consists mainly of fundamental mode of the Rayleigh waves, thus we can retrieve Rayleigh wave velocity from an underground array.

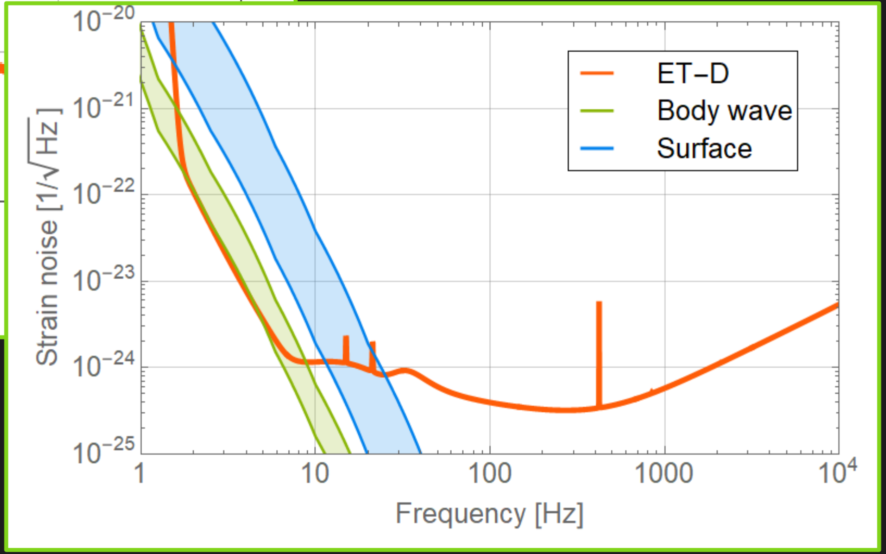
3) Acoustic noise

$$S^h_{\mathrm{cav}}(f) = \left(\frac{2c_s G\rho_0\delta p_{\mathrm{cav}}(f)}{p_0\gamma f}\right)^2\frac{1}{3}(1-\mathrm{sinc}(2\pi fR/c_s))^2\frac{4}{L^2(2\pi f)^4}$$

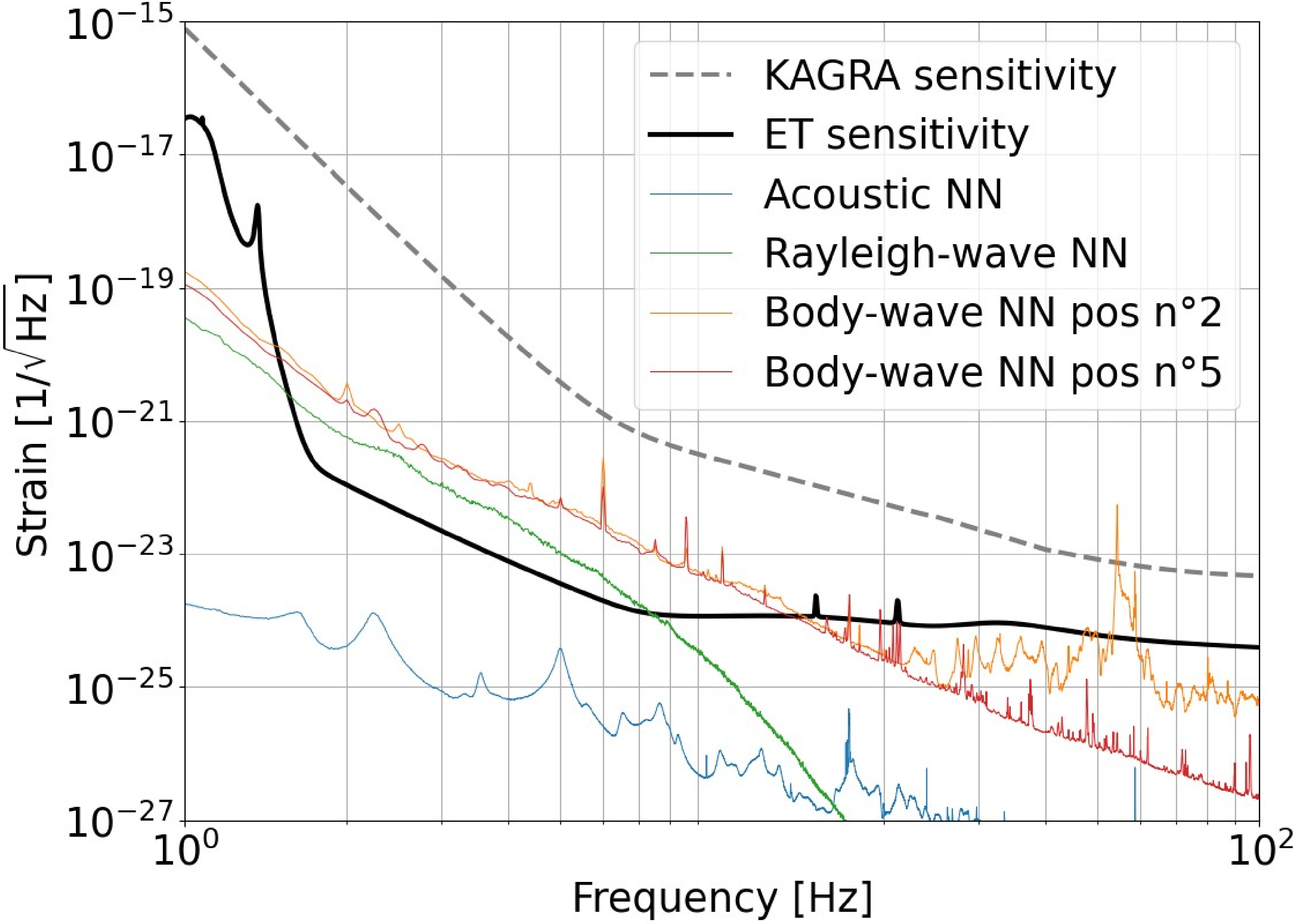
γ = adiabatic coefficient



Factor 10
Factor 3
ET-D
Body waves
Surface, 100m
Surface, 300m
Surface, 700m
Strain noise [1/√Hz]
Frequency [Hz]



ET-D
Body wave
Surface
Strain noise [1/√Hz]
Frequency [Hz]

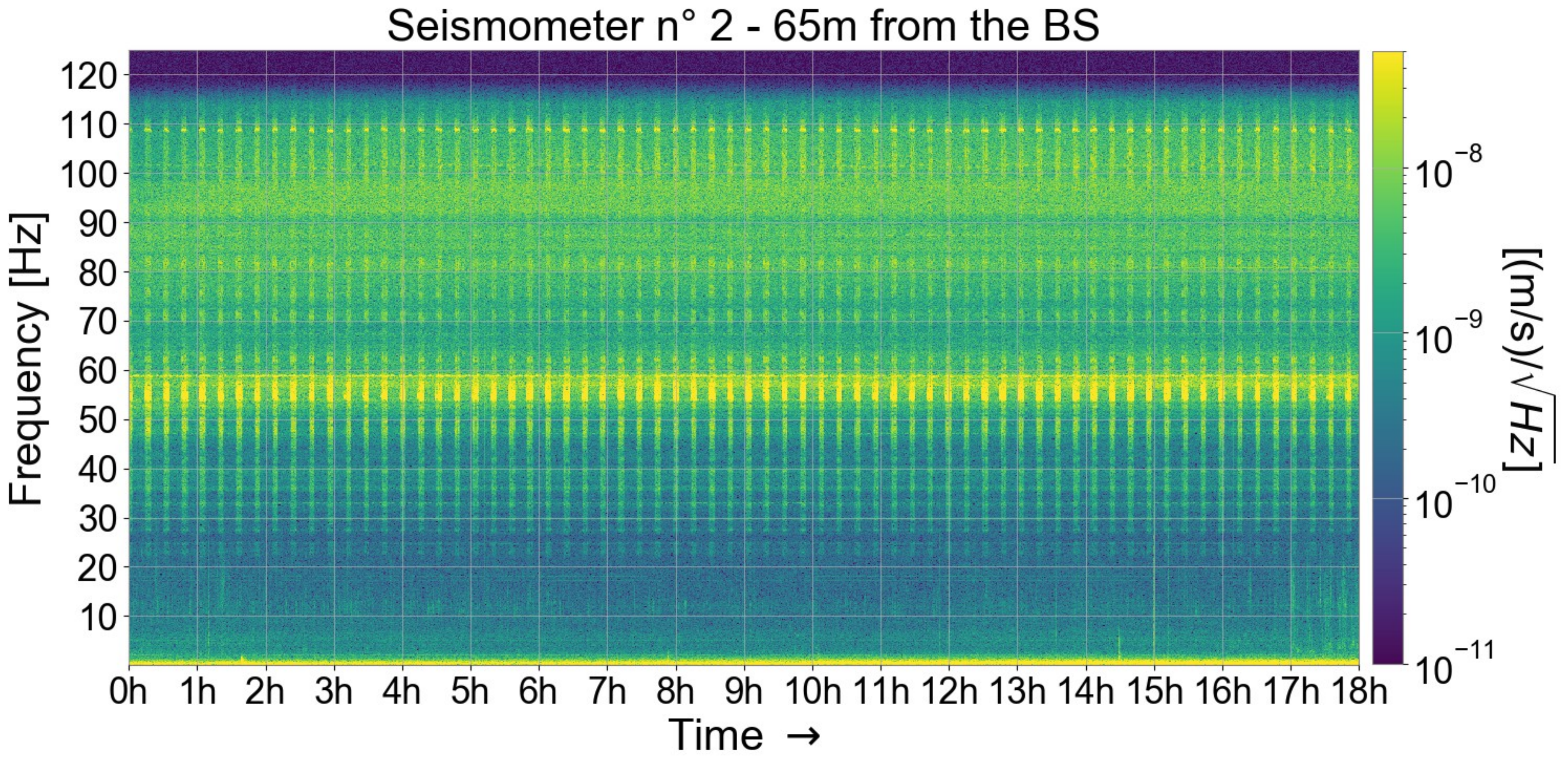


KAGRA sensitivity
ET sensitivity
Acoustic NN
Rayleigh-wave NN
Body-wave NN pos n°2
Body-wave NN pos n°5
Strain [1/√Hz]
Frequency [Hz]
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-25}
10^{-27}
10^{0}
10^{2}

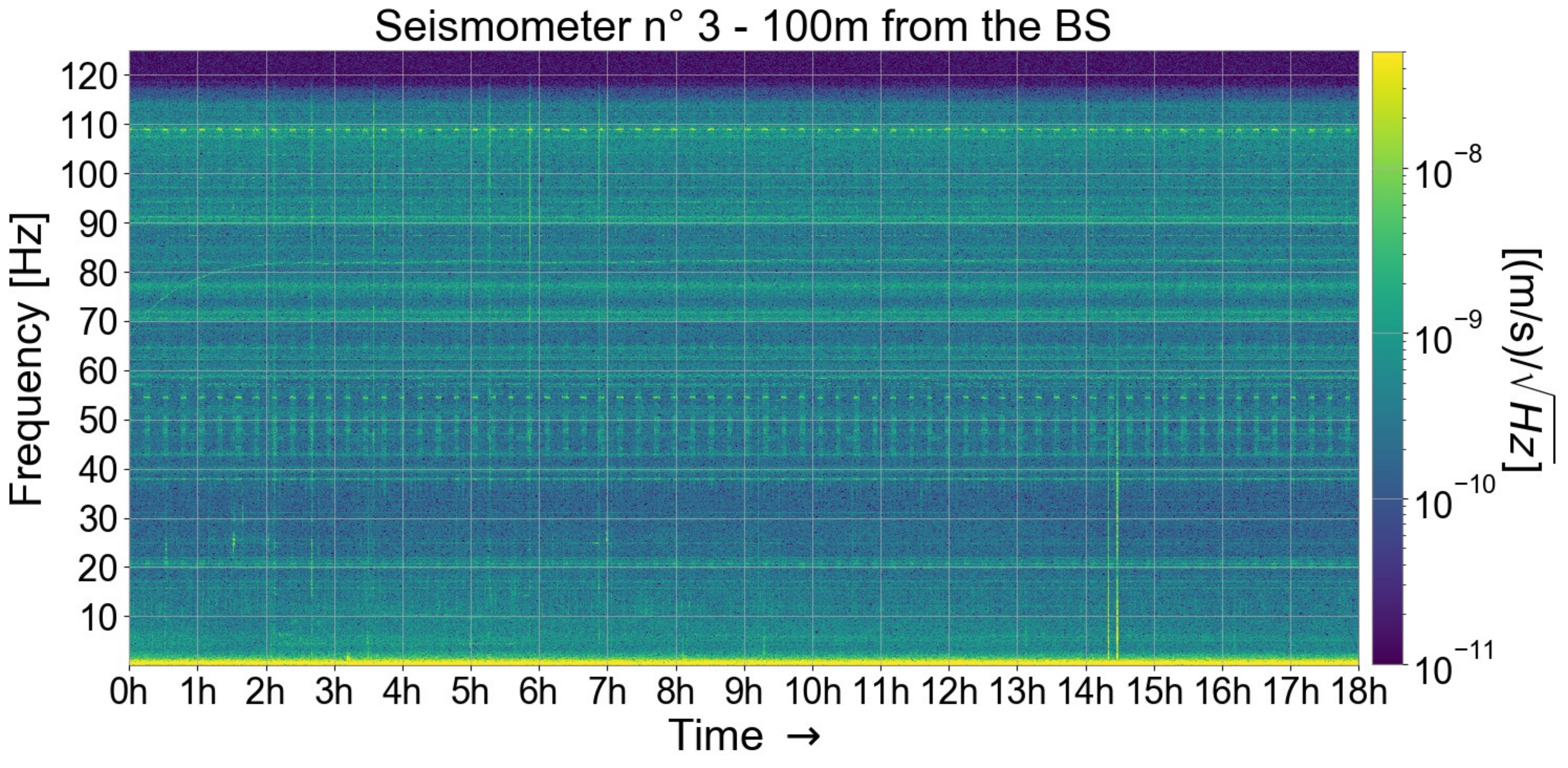
Conclusions

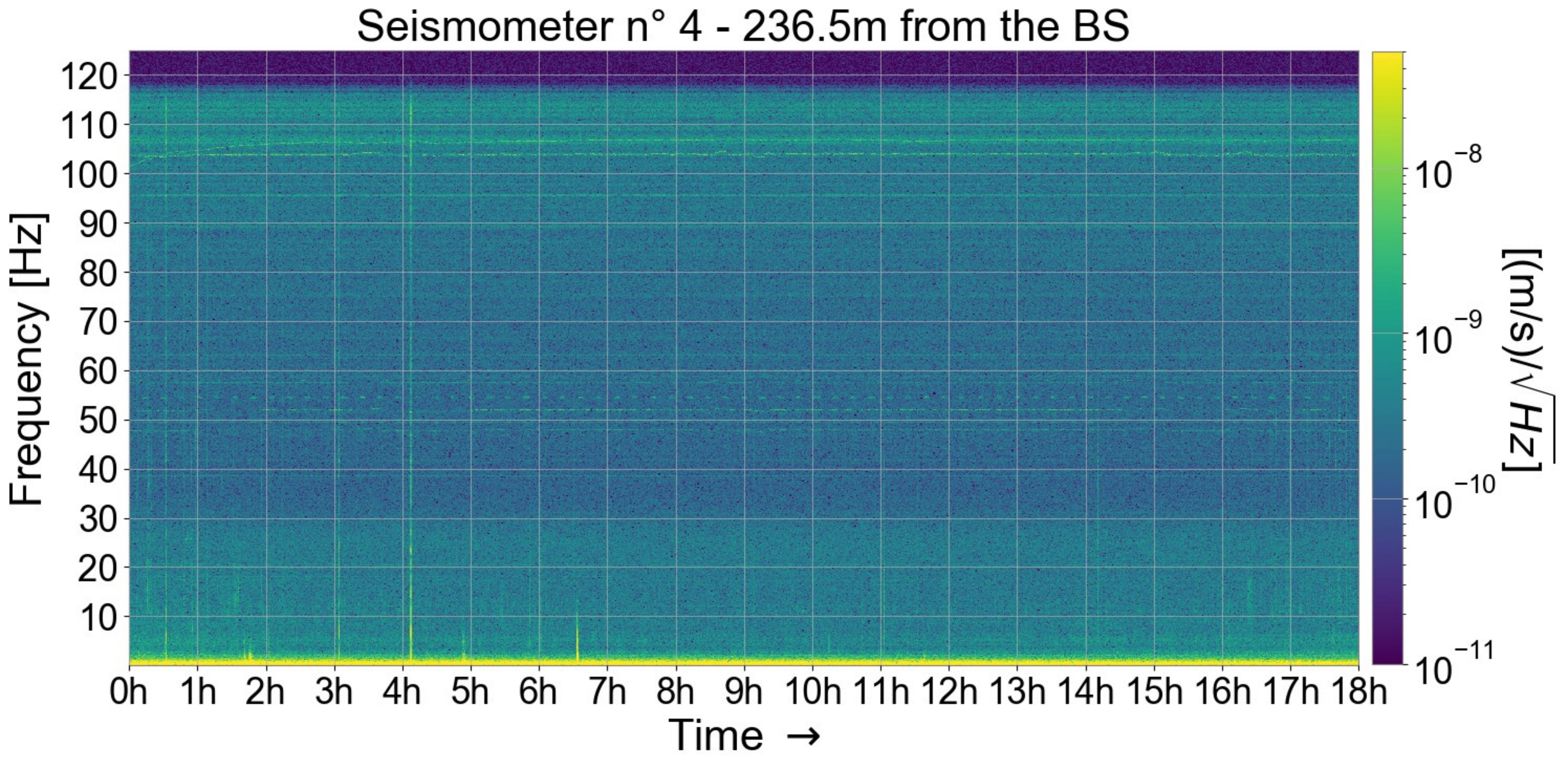
- Below 20 Hz, seismic spectra seem to be unperturbed by infrastructure sources.
- The seismic excess noise above 20 Hz quickly attenuates.
- Are the machines particularly silent or the hard rock helps to mitigate the coupling with the ground?
- The quick attenuation indicates that the excess noise originates from the acoustic noise in the corner station.

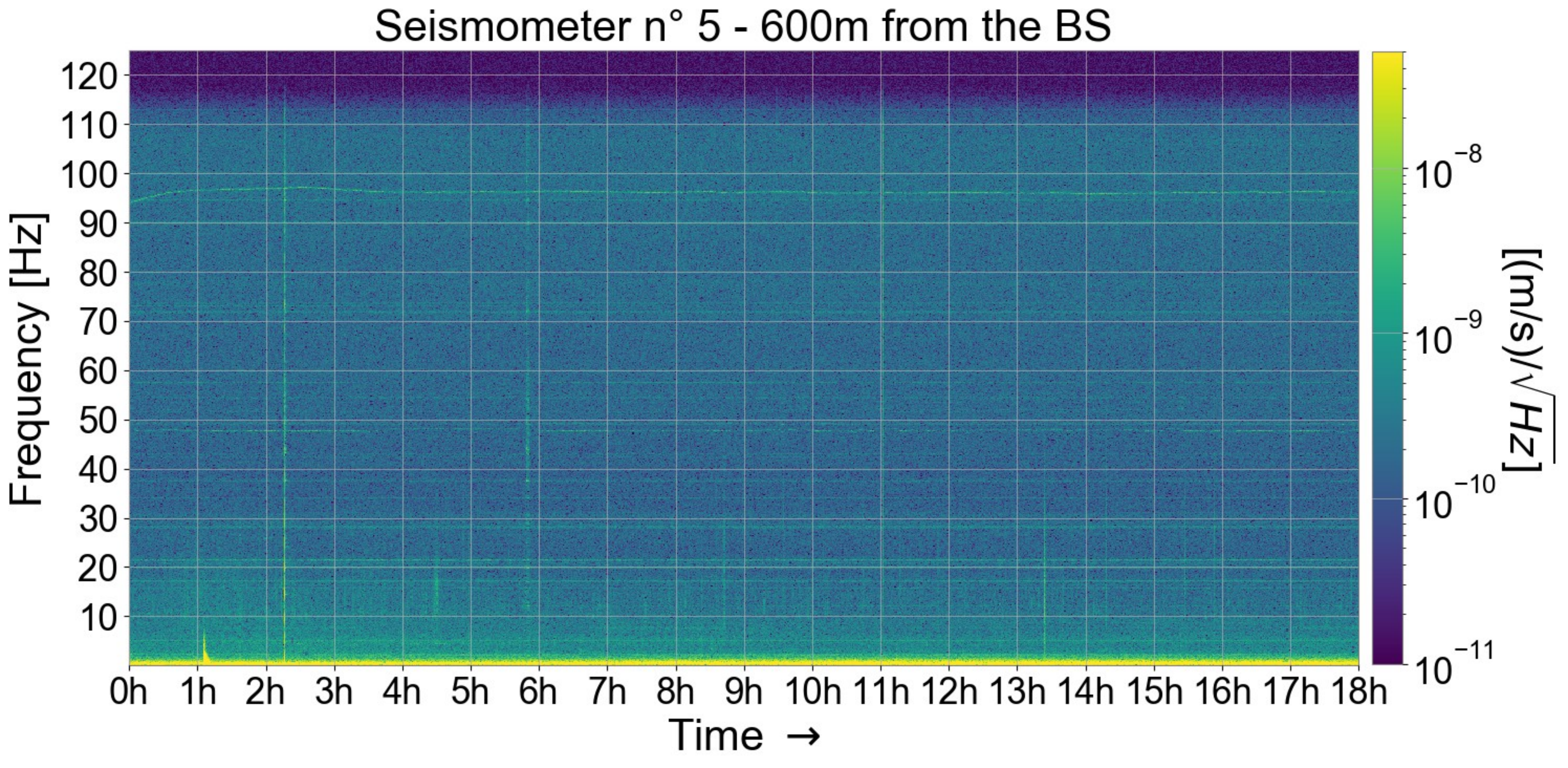
Thank you for your attention!!!

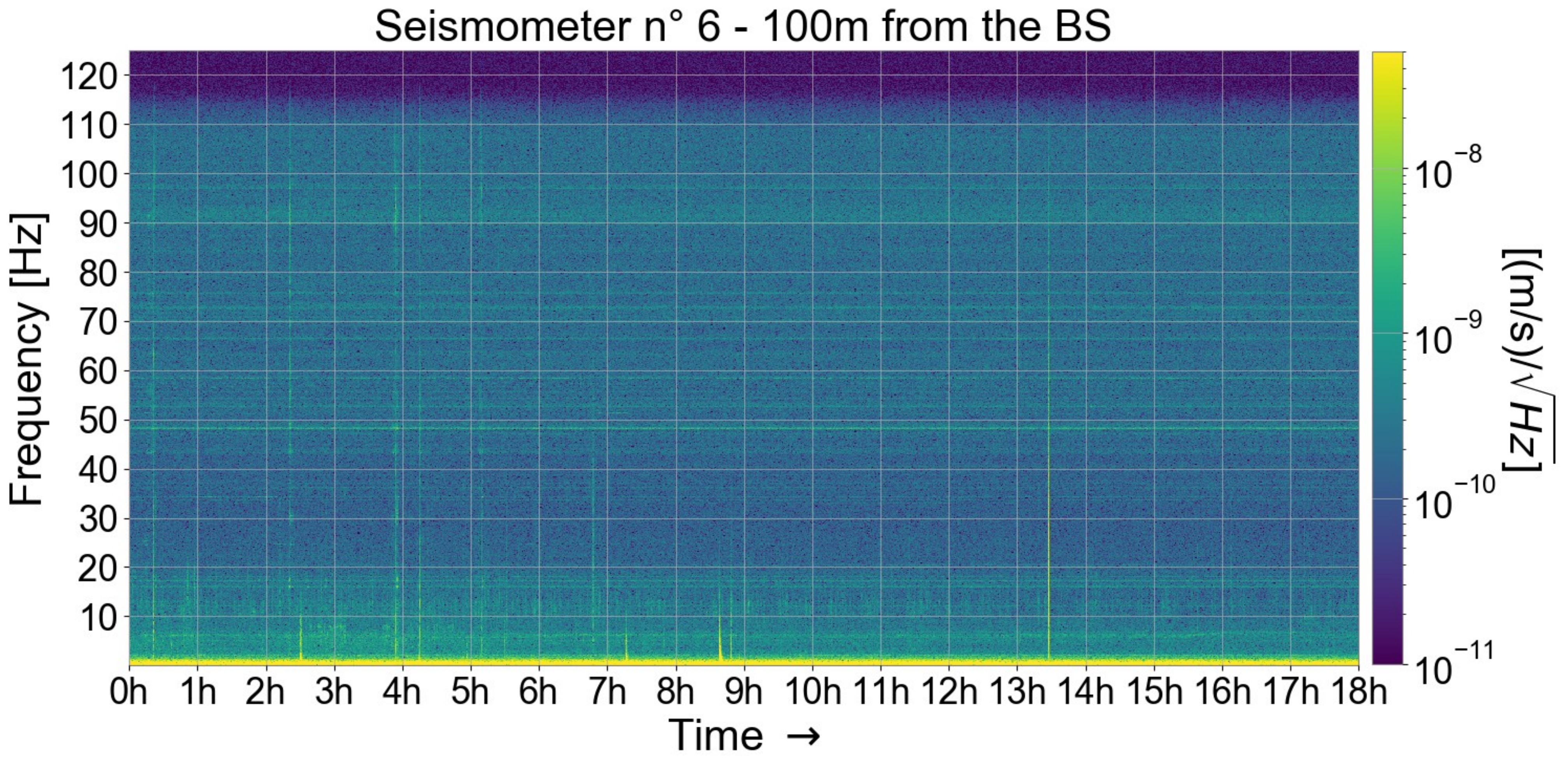


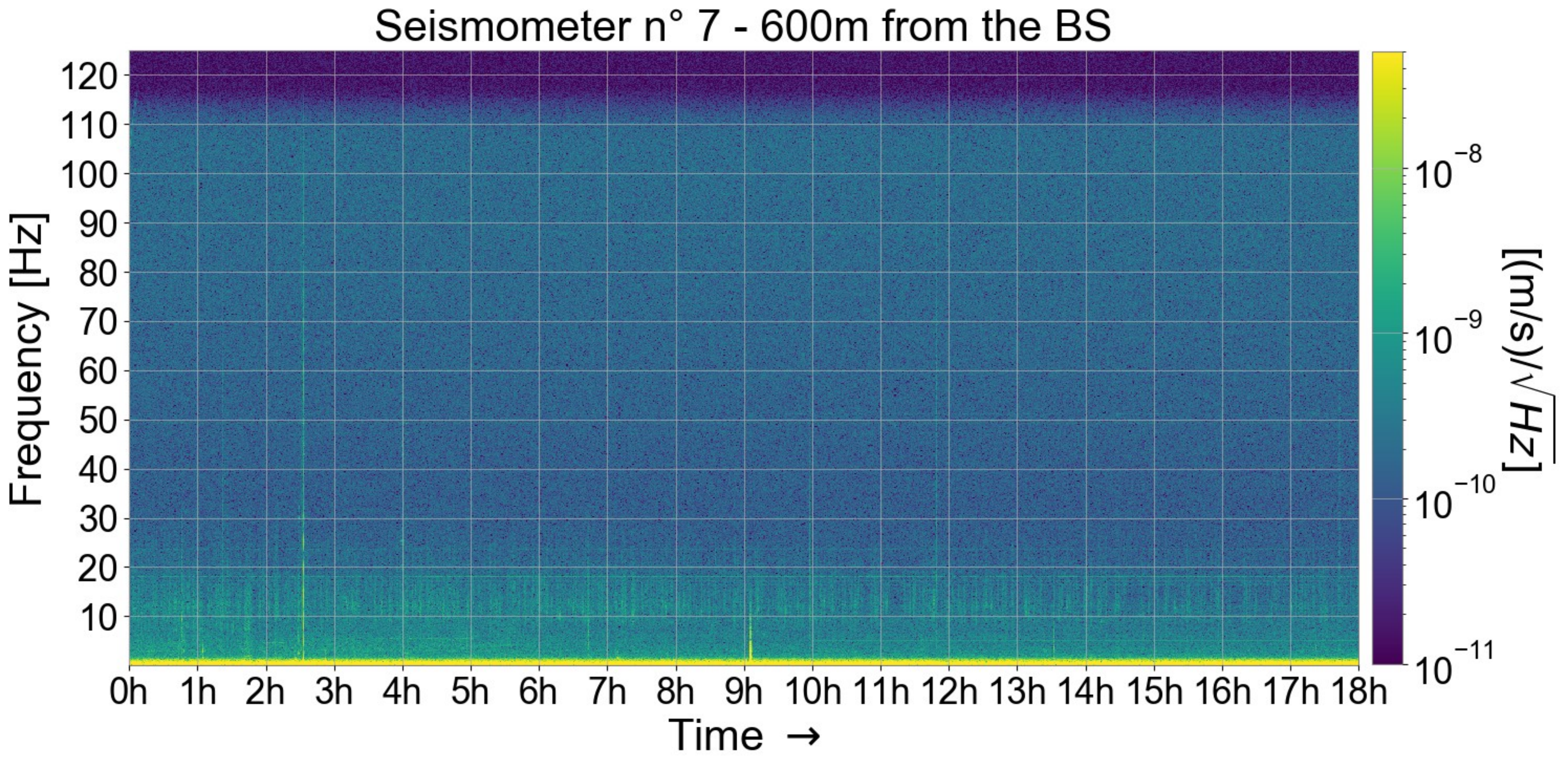
Seismometer n° 2 - 65m from the BS
Frequency [Hz]
120
110
100
90
80
70
60
50
40
30
20
10
0h 1h 2h 3h 4h 5h 6h 7h 8h 9h 10h 11h 12h 13h 14h 15h 16h 17h 18h
Time →
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$[(m/s)/\sqrt{Hz}]$


Seismometer n° 3 - 100m from the BS
Frequency [Hz]
120
110
100
90
80
70
60
50
40
30
20
10
0h 1h 2h 3h 4h 5h 6h 7h 8h 9h 10h 11h 12h 13h 14h 15h 16h 17h 18h
Time →
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$[(m/s)/\sqrt{Hz}]$


Seismometer n° 4 - 236.5m from the BS
Frequency [Hz]
120
110
100
90
80
70
60
50
40
30
20
10
0h 1h 2h 3h 4h 5h 6h 7h 8h 9h 10h 11h 12h 13h 14h 15h 16h 17h 18h
Time →
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$[(m/s)/\sqrt{Hz}]$


Seismometer n° 5 - 600m from the BS
Frequency [Hz]
120
110
100
90
80
70
60
50
40
30
20
10
0h 1h 2h 3h 4h 5h 6h 7h 8h 9h 10h 11h 12h 13h 14h 15h 16h 17h 18h
Time →
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$[(m/s)/\sqrt{Hz}]$


Seismometer n° 6 - 100m from the BS
Frequency [Hz]
120
110
100
90
80
70
60
50
40
30
20
10
0h 1h 2h 3h 4h 5h 6h 7h 8h 9h 10h 11h 12h 13h 14h 15h 16h 17h 18h
Time →
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$[(m/s)/\sqrt{Hz}]$


Seismometer n° 7 - 600m from the BS
Frequency [Hz]
120
110
100
90
80
70
60
50
40
30
20
10
0h 1h 2h 3h 4h 5h 6h 7h 8h 9h 10h 11h 12h 13h 14h 15h 16h 17h 18h
Time →
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$[(m/s)/\sqrt{Hz}]$