Non stationary seismic noise and the search for IMBH

Scientists involved in Site Characterization

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Non stationary noise and the search for IMBH

Motivation of the analysis

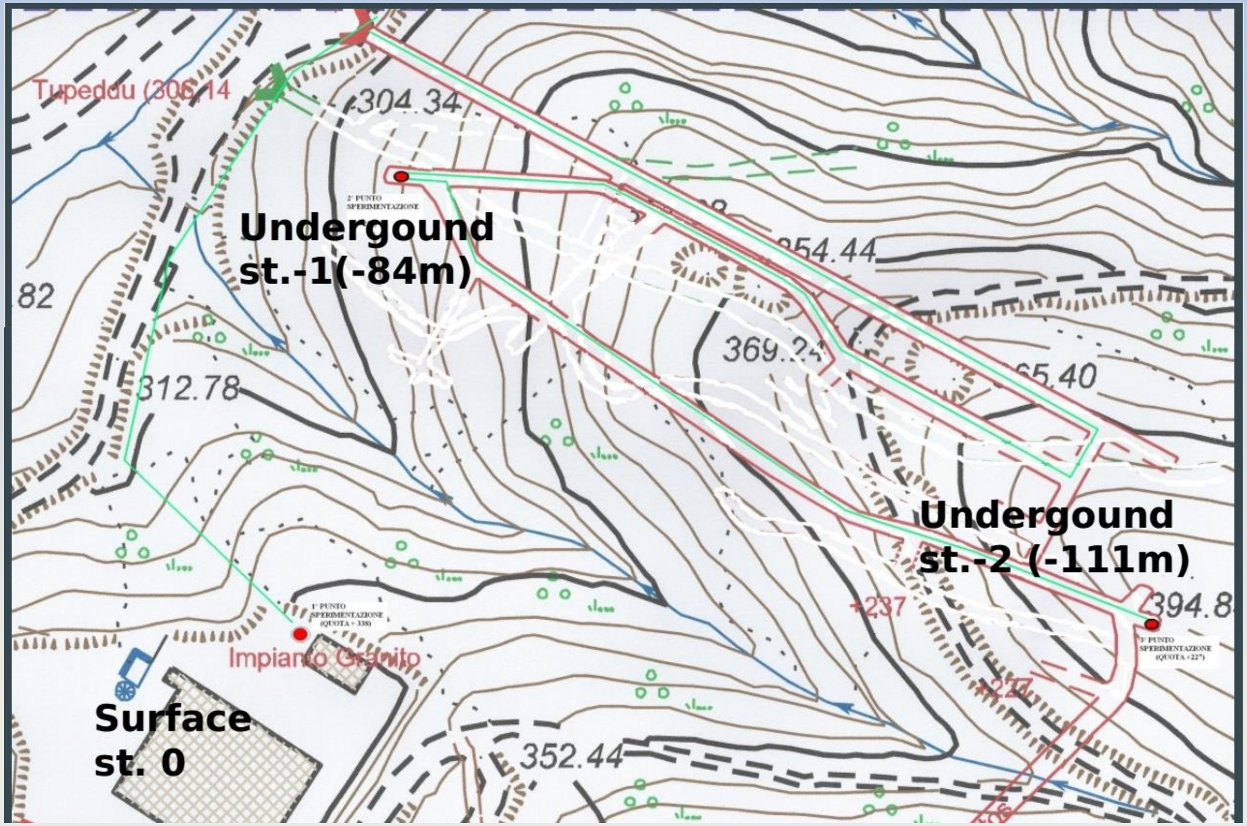
- Extending the bandwidth towards 2 Hz opens the observation to the Intermediate Mass Black Hole coalescing binaries (IMBH)

- Their signal lasts in the detector about 1 minute and the frequency of the signal of the inspiral phase lies within the 10 Hz band

- Considering the Newtonian Noise (NN): what is the probability, for a signal lasting 1 minute, to have the noise in the bandwidth higher than designed?

New installation of seismometer in -84 m station

In July 2020 the seismometer installed in the cavern at -84 m in the Sos-Enattos mine has been repositioned and tuned to high sensitivity

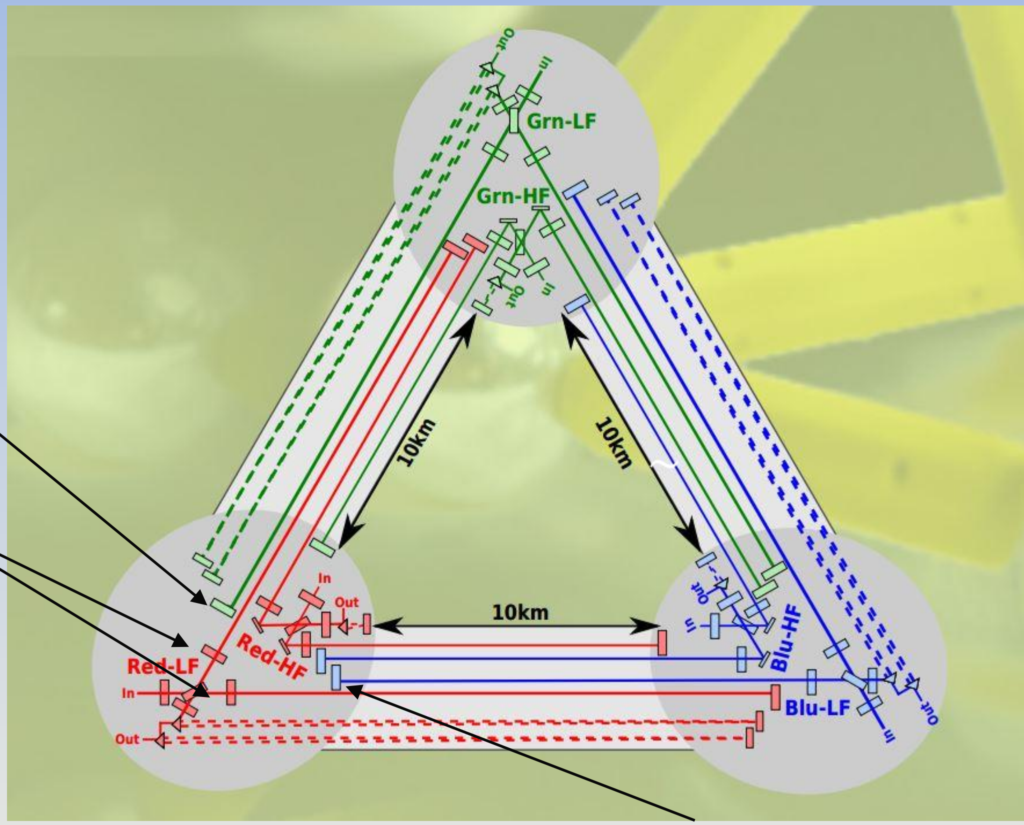


The present analysis begins with August data

ET and NN coupling

ETM

ITMs



ETM

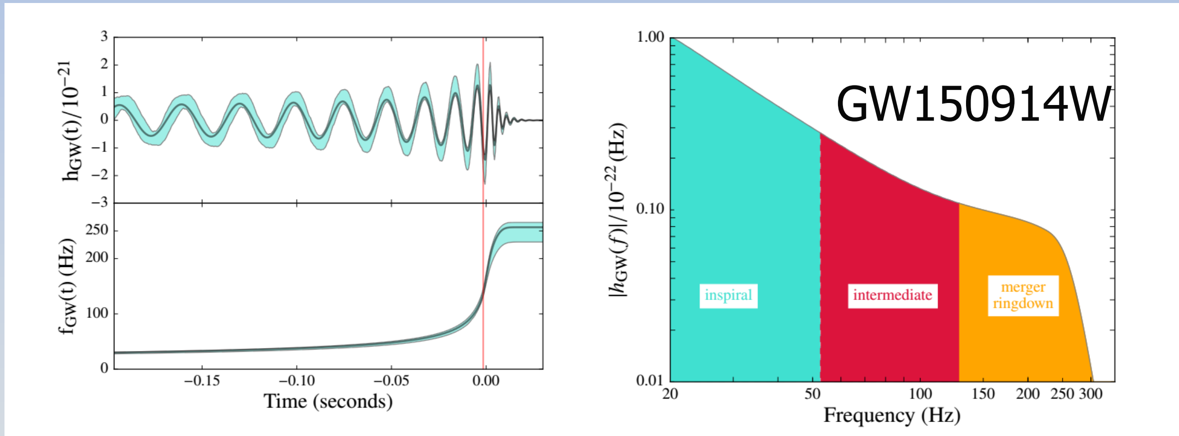
Ground motion $\tilde{x}$ and Newtonian Noise $\tilde{h}_{NN}$

$$\tilde{h}_{NN} = \frac{2\sqrt{(2)}\,\frac{4\pi}{3}G\rho_0}{L(2\pi f)^2}\tilde{x} \qquad (1)$$

1) The ET detector will have test masses of the various interferometer within a 1km range of distances → Newtonian Noise will be probably correlated in the interferometers
2) A deep Newtonian Noise correlation study yet to be carried out → the present analysis is equivalent to a single Detector without accounting for the 60° angle and body waves polarization p = 1/3 (see J. Harms - Class.Quant.Grav. 36 (2019) 14, 145006)

Time window definition

- Some arbitrarity → we focus on sources that have inspiral phase within 2-10 Hz. The main motivation is that under this condition the signal is clearly distinguished by the noise for its frequency-amplitude behaviour.



$$f_{ISCO} = 2.2\,kHz\left(\frac{M_\odot}{m}\right)$$

$$f_f \approx 4 \cdot f_{ISCO}$$

The final frequency f_f of the inspiral + intermediate phase is about 2 times the signal frequency of the gravitational wave signal corresponding to last stable orbit.

Total mass in the range of hundreds to thousands solar masses

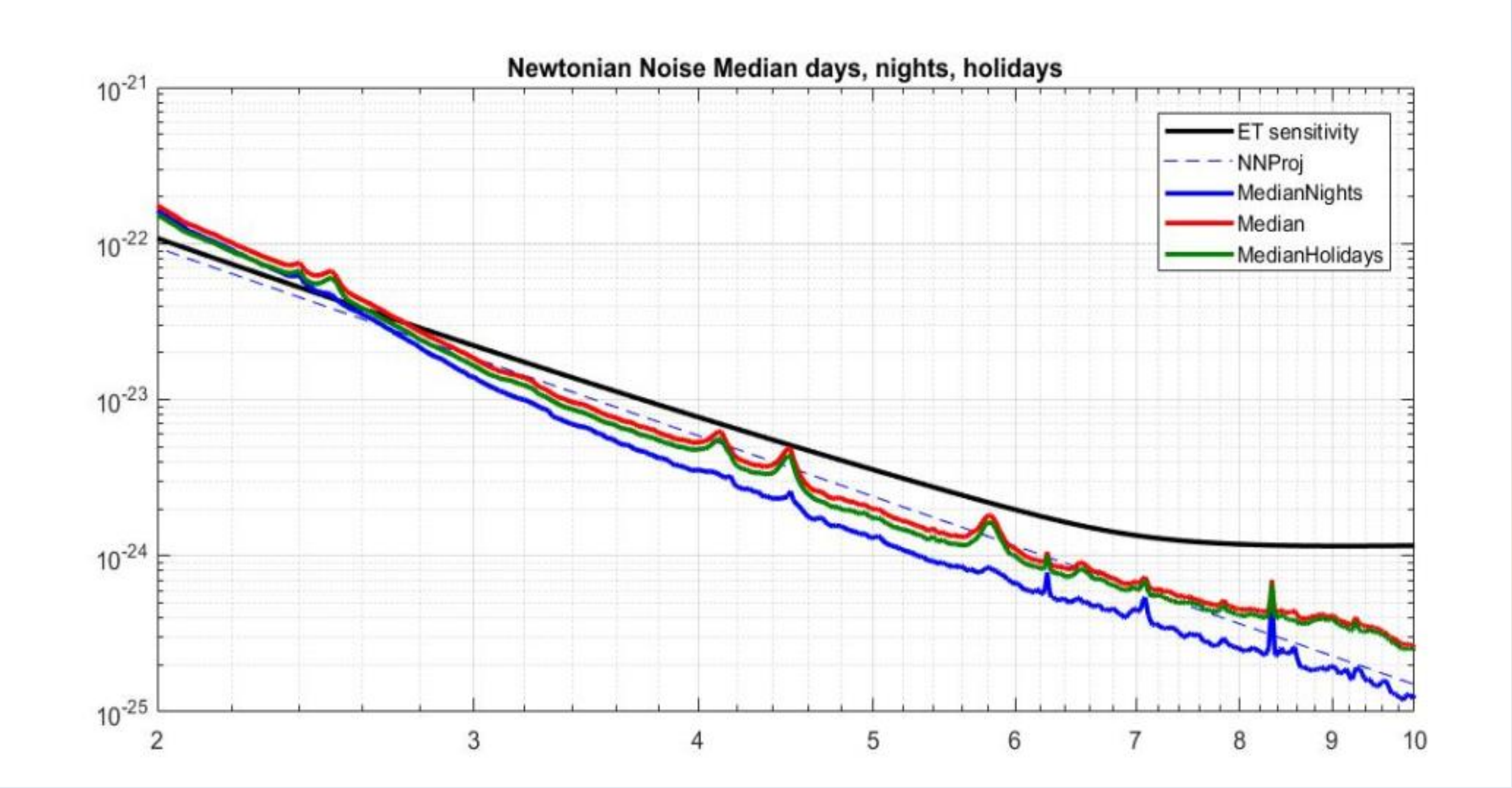
The time before coalescence is

$$\tau \approx 2.2s\left(\frac{1.21M_\odot}{M_c}\right)^{5/3}\left(\frac{100Hz}{f}\right)^{8/3}$$

The time before coalescence once reached the 2 Hz frequency spans from few tens of seconds to a couple of minutes depending on total mass, mass asimmetry etc etc -> **time window chosen: 1 minute**

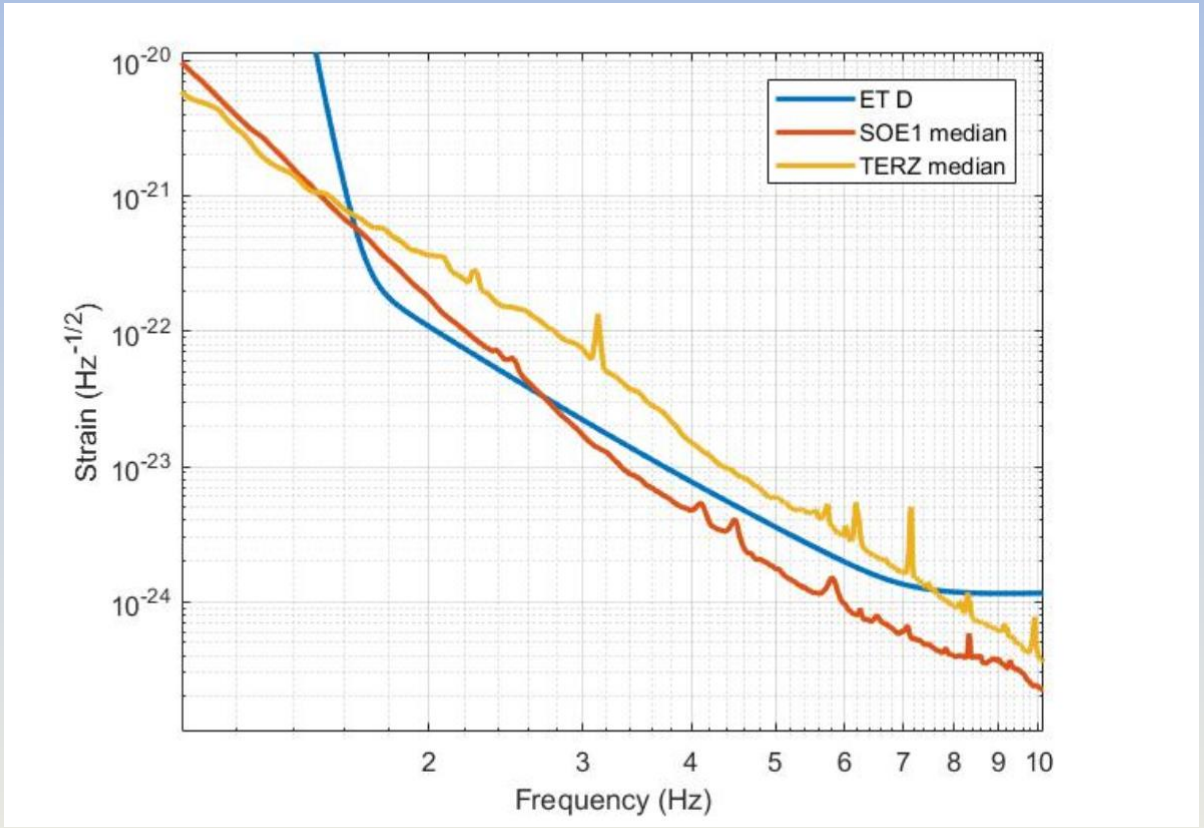
Preliminary analisys: median during whole period, during holidays, and only during nights

- Seismometer SOE1 -- installed at – 84 m
- Dates: from August 1st to August 26° -- Nights: from 9pm to 3 am --
- Holidays: from August 8th to August 23th



Median: Comparison with Terziet

- Whole days from August 1st to August 26th



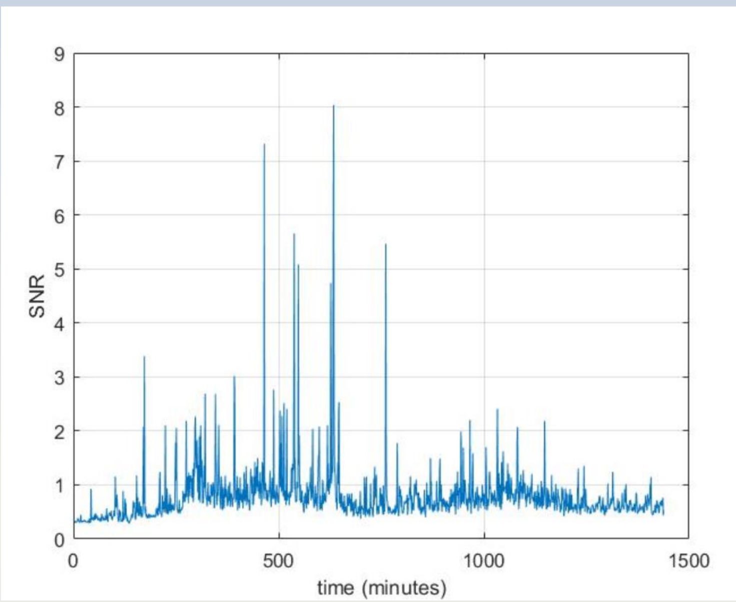
SOE1 (red) and TERZ -- HHZ (yellow)

In Sos-Enattos very encouraging results but seismic noise is tipically non stationary: motivated by previous consideration we focus on 1-minute window to evaluate transients

Noise distribution

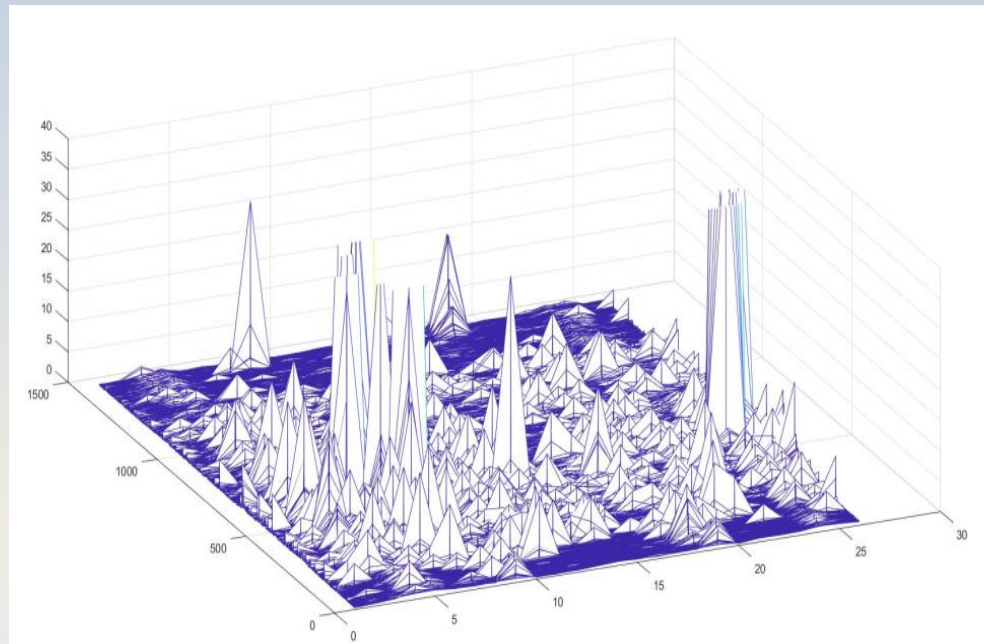
$$\text{NTR} = \sqrt{\frac{1}{\Delta f}\int df \frac{\tilde{N} * \tilde{N}}{Sn}}$$

- NTR expresses the Ratio of Newtonian Noise and Target sensitivity in the bandwidth 2-10 Hz
- Sn is the power spectral density of ET target sensitivity and N*N is the power spectral density of the newtonian Noise – If NN is equal to target sensitivity the value NTR = 1
- In the 2-10 Hz bandwidth NN is expected to limit (2-7 Hz) or to contribute (7-10 Hz) to ET sensitivity → unity can be taken as the critical value to asses if NN, in the minute considered, is degrading the target sensitivity



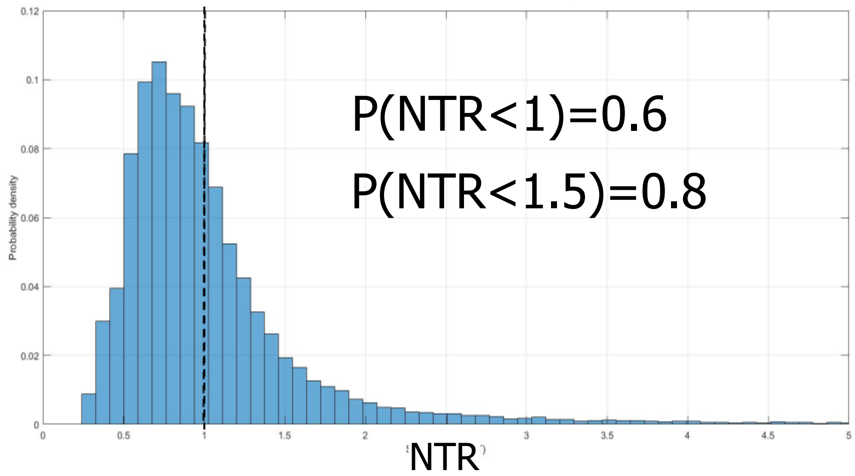
NTR during a day (UTC)

Clear effects of anthropic origin

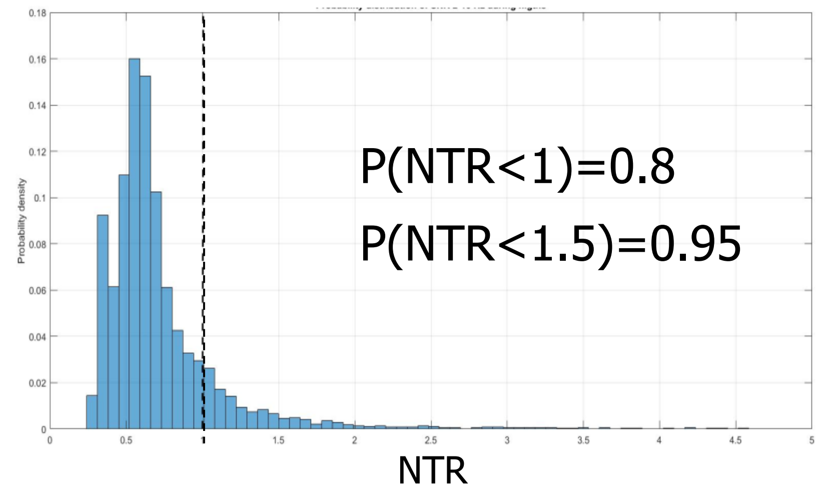


NTR during the days of August (UTC)

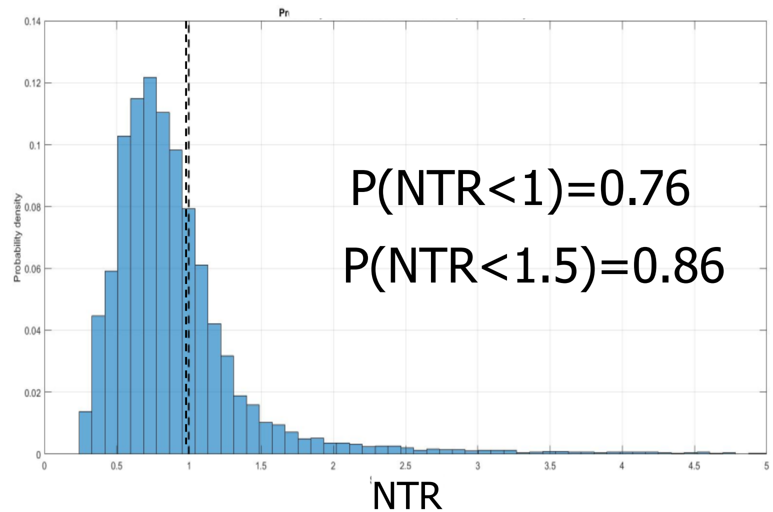
Distributions: Results



NTR probability distribution over the whole period

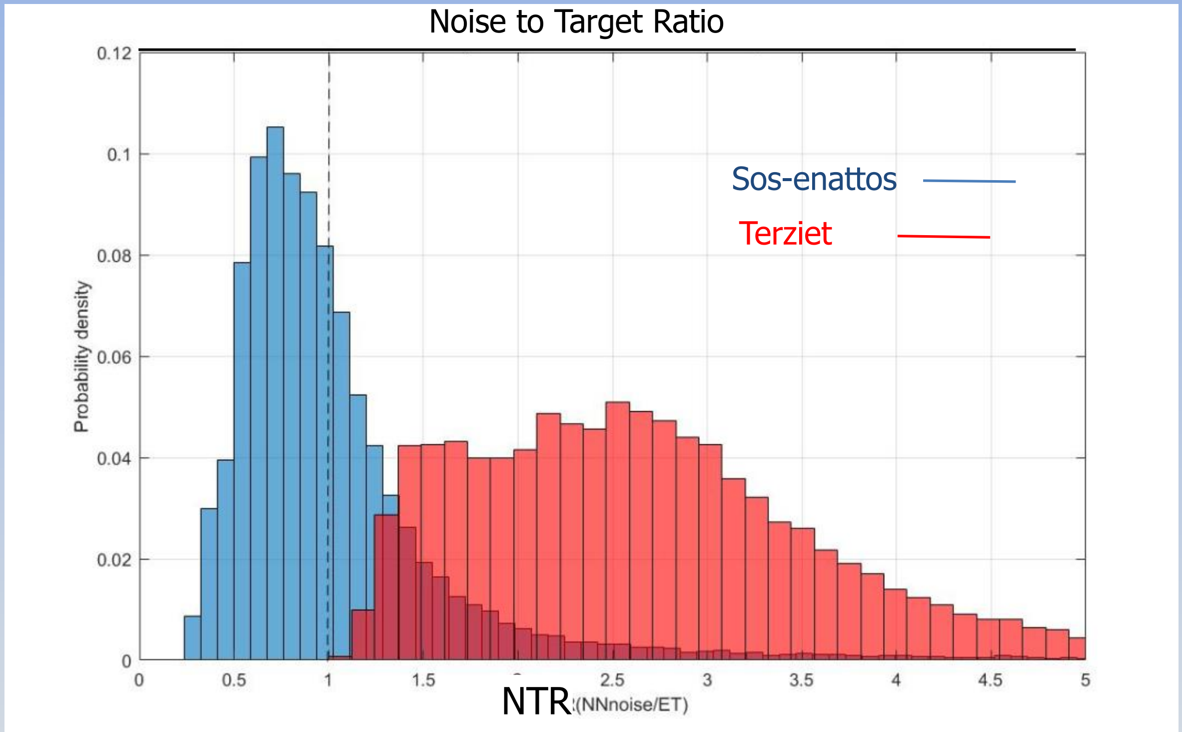


NTR probability distribution during the nights



NTR probability distribution during the holidays weeks

Comparison with Terziet

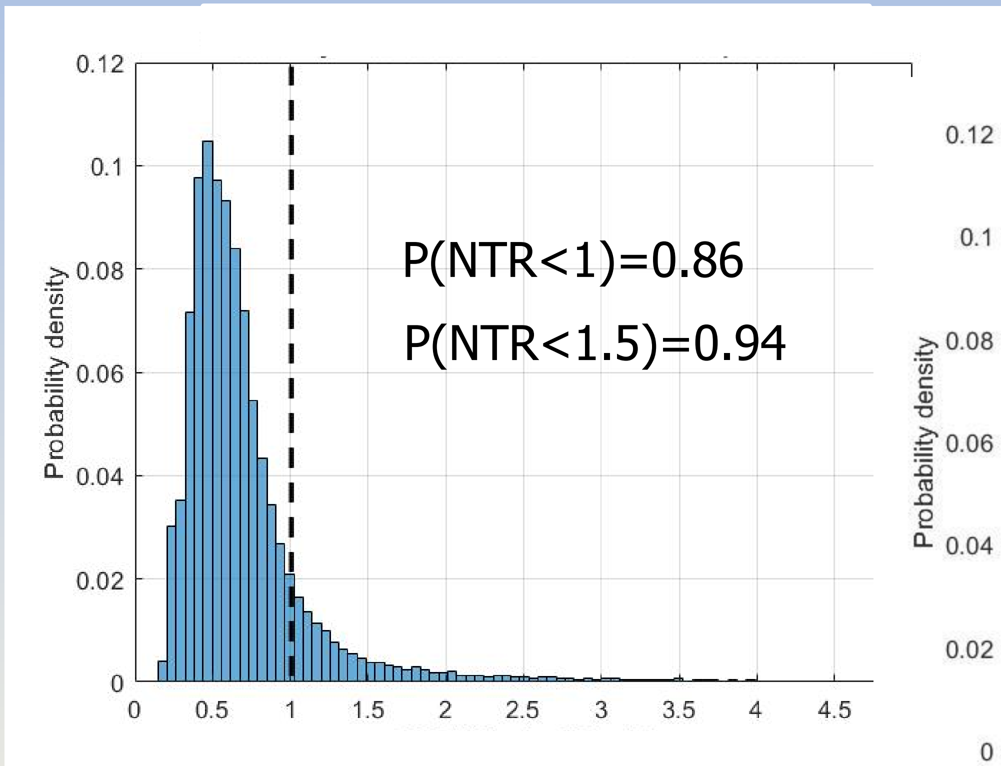


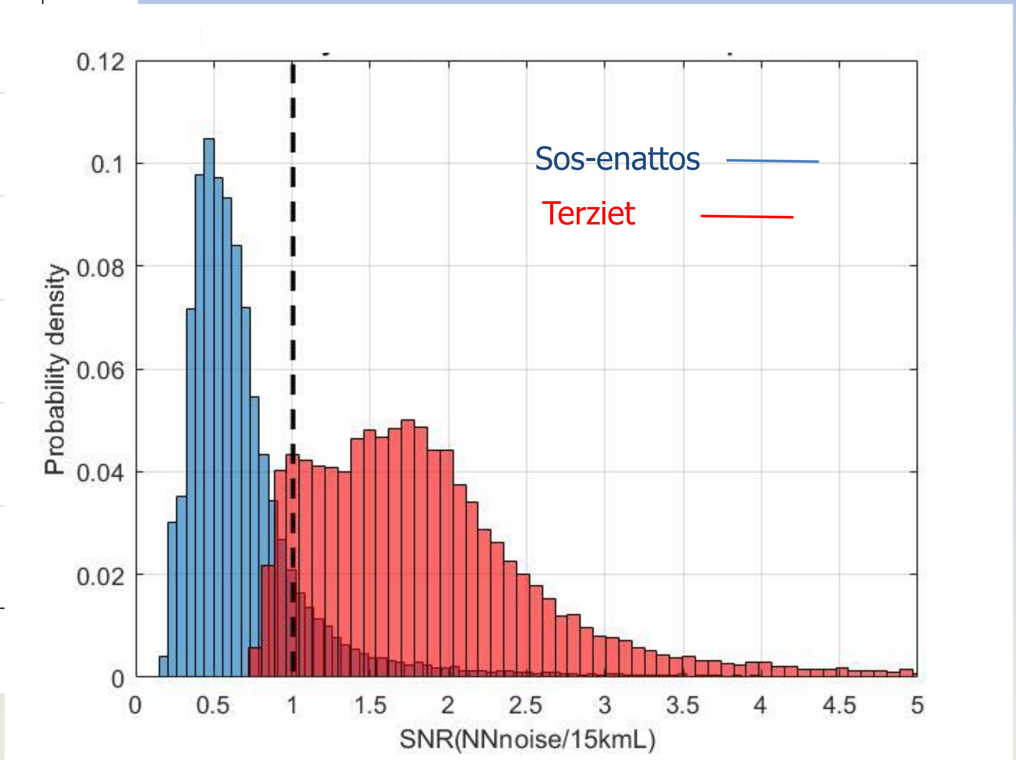
The probability to be lower than 1 is negligible
The reduction by a factor 3 with NNC would bring P(NTR < 1) =0.64
The reduction by a factor 5 with NNC would bring P(NTR < 1) =0.92

Contrary to sos-enattos the seismometer is already at -250m
Surface waves not taken into account (negligible for sos-enattos)

L shaped

- 15 km L shaped (same tunnel lenght)





- ➢ **Sos-Enattos: almost compatible with NN**
- ➢ **Terziet: relaxed constraints on Newtonian Noise Cancellation**

CONCLUSIONS

- Sos-Enattos → No degradation of sensitivity for IMBH search, for the majority of time, even without Newtonian Noise Cancellation (particularly for 15 km L shaped)
- Sos-Enattos → Newtonian Noise Cancellation will improve the ET sensitivity with respect to target

Remarks:

1. Further studies needed to identify NN coherence among nearby masses of different interferometers for the triangular shape
2. The Sos-Enattos mine is still accessed and daily maintained for safety by miners & the seismometer is not at -250 m (this brings to overestimate the NN)
3. Studies and mitigations of local noise sources like pumps, visitors, animals are needed.

An August day..

Next steps

- Estimation of NN coherences in the triangular multi-interferometer shape
- Weigh the probability with expected IMBH populations
- Identify «very local noise sources» to better estimate natural noise and design ET no-self-noise generating infrastructures

SPARES

Sos Enattos site Newtonian Noise projections

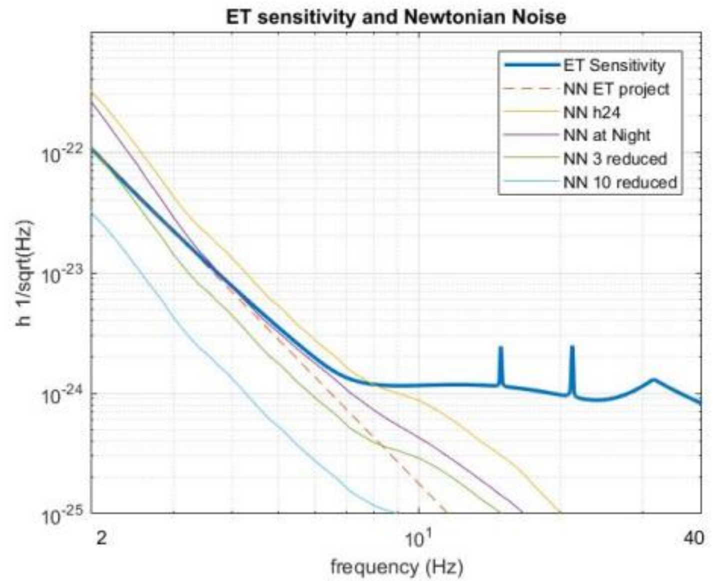


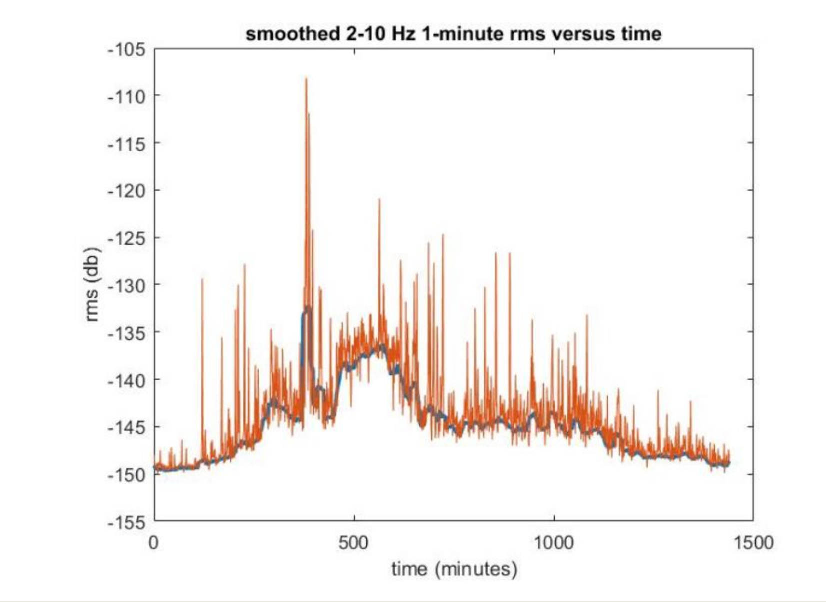
Figure 2. ET target sensitivity and NN contribution

The results are extremely encouraging, the curve are the median of the noise. Due to the non-stationarity we need also an estimation of the probability that in a given minute the NN degrades the sensitivity: we take the SNR of the NN with respect to ET sensitivity, normalied to bandwidth so that when NN is equal to target sensitivity NNR = 1

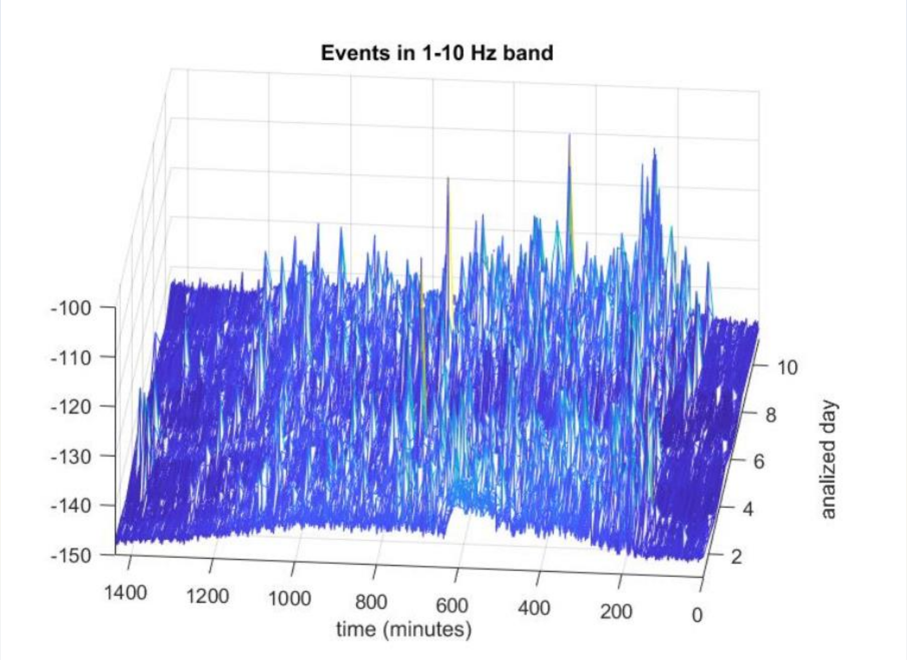
$$NNR = \sqrt{\frac{1}{\Delta f} \int df \frac{\tilde{N} * \tilde{N}}{Sn}}$$

Non stationariety of seism RMS in 2-10 Hz band

- Brief description of how measurements are taken
- Variability of RMS in the 2-10 Hz bandwidth

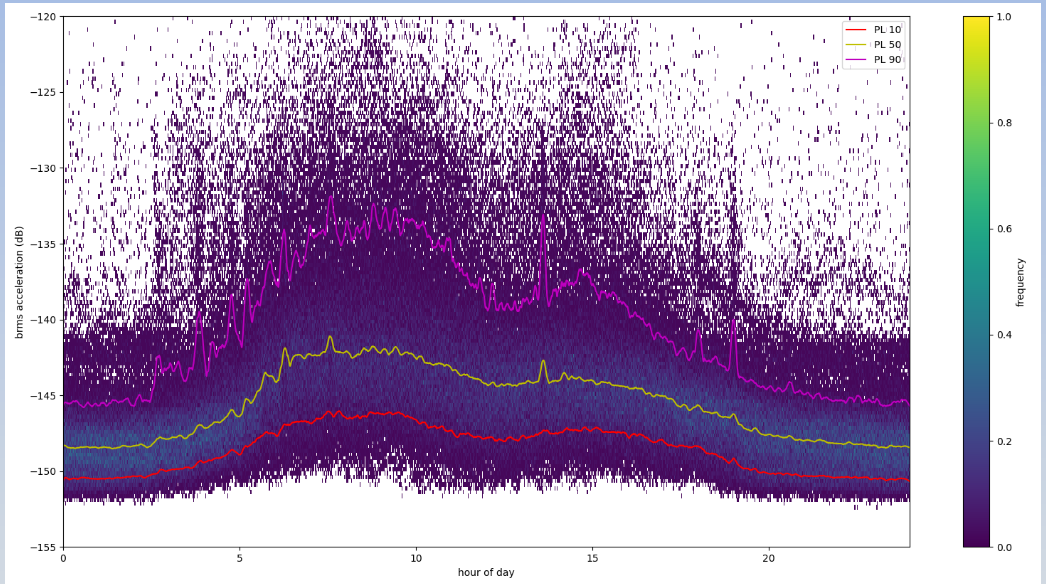


Single day



Several days

Daily distribution (to be added to the paper)



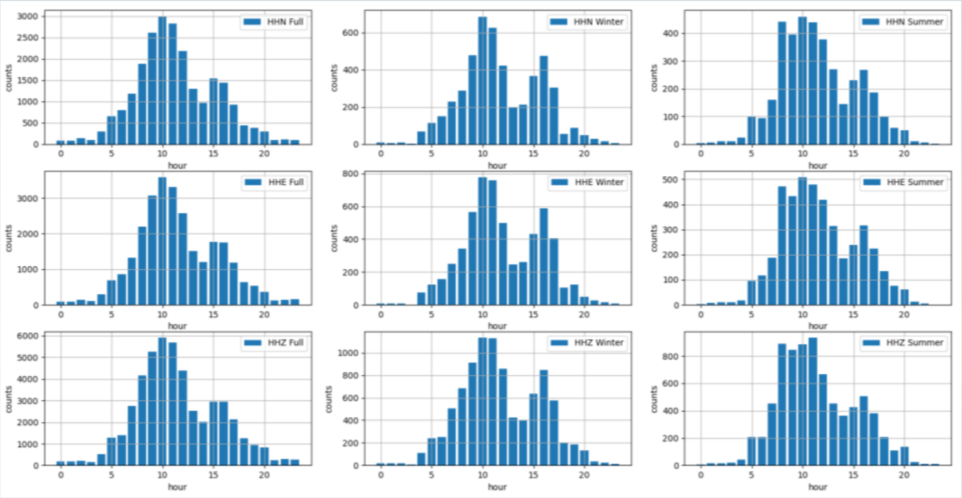
RMS of acceleration during the day in 1 year data taking

Local Time

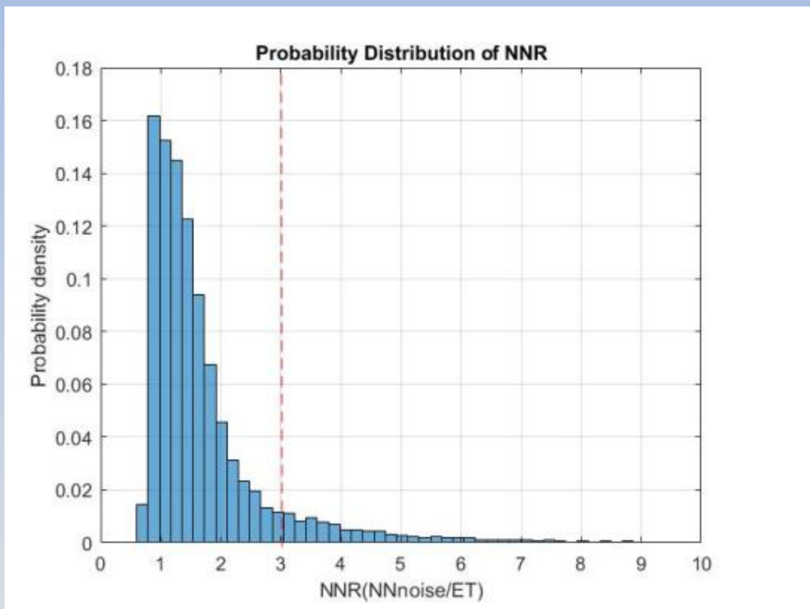
Daily distribution of rms > 10*NLNM

Clear effect of antropic activities

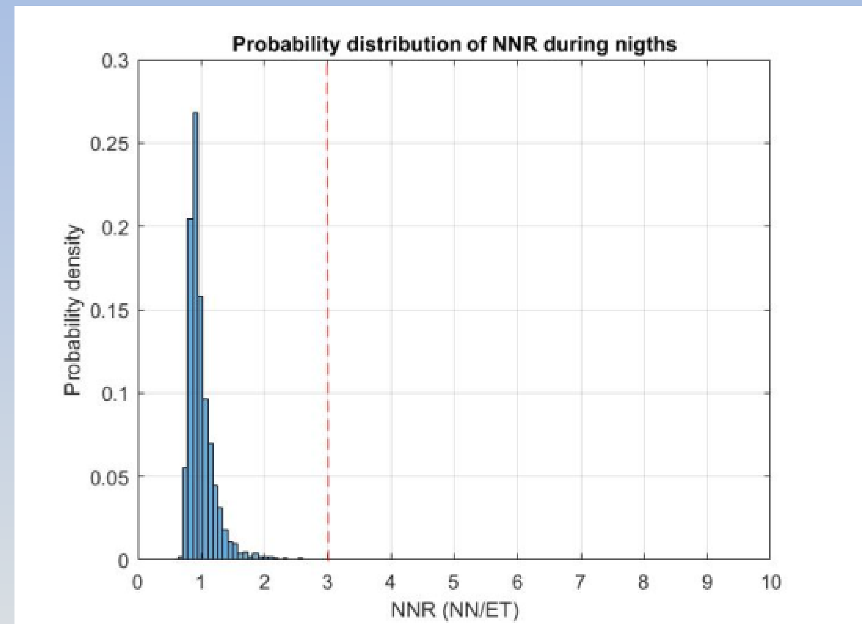
Local hours were used



Distribution of NNR Probabilities



Probability distribution - the dashed Line is the new value of the unity if The NN is reduced by a factor 3



Nights Probability distribution - the dashed line is the new value of the unity if The NN is reduced by a factor 3

Some remarks: for Sos-Enattos these are upper limits, because the seismometer is not yet in the final position (-250m) , the mine is still accessed, other neighborhood activites are present – Outside the 91% probability means that the interferometer correctly working but the sensitivity is not optimal.

Conclusion of the paper

From this preliminary analysis it results that the ET detector, if hosted by the Sos-Enattos site will be for the great majority of time in the position of detecting the new sources like IMBH with no degradation of sensitivity even considering a very conservative reduction of the Newtonian noise. These results, whenever showing an optimal site for hosting the detector, can be considered as preliminary for three main reasons. The first is that the mine is still maintained, various activities are performed in the immediate neighborhood, and the seismometers are not yet placed at their ultimate depth of 250 m. In these sense the presented results can be considered as upper limits in the noise, as it can be particularly appreciated by looking at the behavior during nights. Part of the next activity will be the better isolation of the seismometers and, if needed, an evaluation of the seismicity of the site with boreholes at 250 m depth.

The second motivation is related to the evaluation of the seismic field and the resulting Newtonian Noise. We presently considered the noise as generated by compressional waves, that could overestimate the noise if the seismic field is mainly composed by shear waves. Due to the fact that compressional waves dont produce tilt on the ground, while shear waves do, a coherent analysis of seismometers and a tiltmeter signals could solve the problem. Finally, a deep study of source localization is foreseen. This is important because not only the present day analysis could overestimate the noise with respect to the ET cavities, placed at higher depth, but also to help in the design of the future ET infrastructures, avoiding the generation of noise.

My personal view

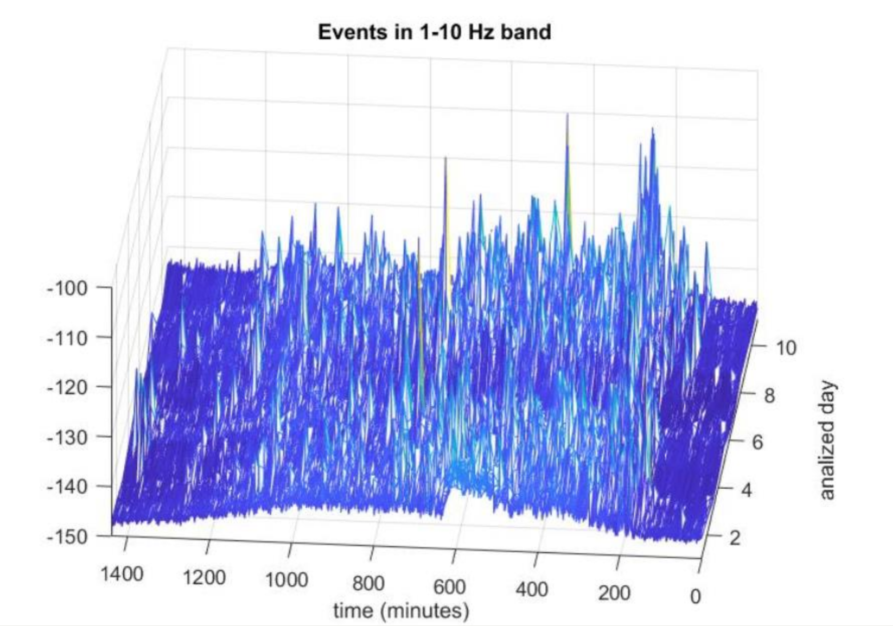
Out of the paper - My personal view of the message/goal to be passed/verified in the very next future (based on the fact that these results are preliminar)

ET in Sos Enattos can reach the target sensitivity even without Newtonian Noise Reduction

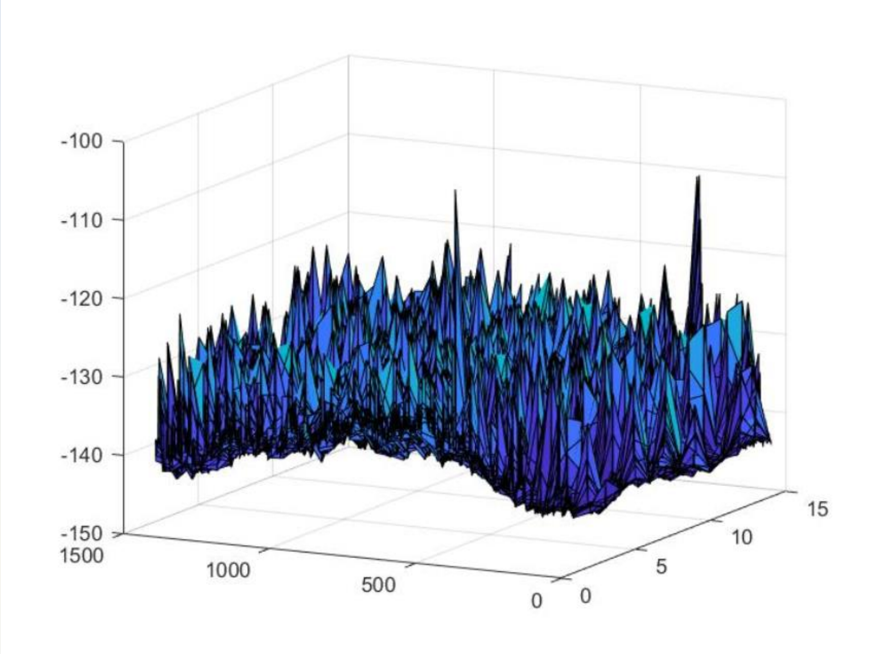
(clearly Newtonian Noise reduction will be pursued, but for Sos Enattos this means to reach an even better sensitivity with respect to initial target)

Glitchness – Comparison Sos-Enattos Terziet

Terziet «never sleeps»



Sos-Enattos



Terziet

NNR Comparison with Terziet

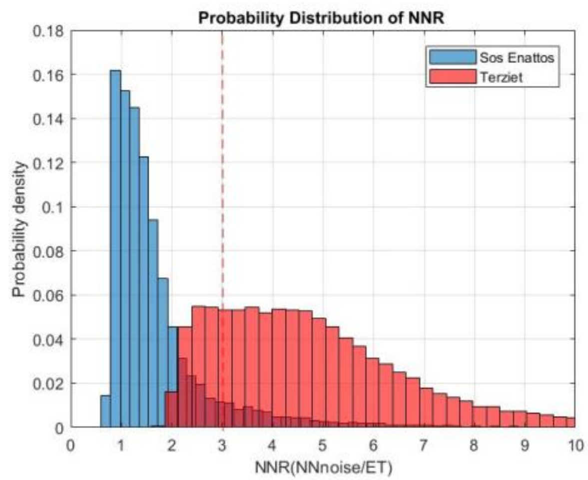


Figure 7. Distribution of NNR for Sos Enattos (blue) and Terziet (red)

The Terziet results, compared with Sos Enattos, are reported in figure 7. In ths case, if a reduction of Newtonian noise is not considered, the probability of being better that 1.5 is negligible, the probability to be worst than 3 is 81% and the probability to be worst than 10 is 6%.
Thus in this case, a conservative reduction of Newtonian Noise of a factor 3 would not be acceptable, because the probability of having the sensitivity degraded by noise would be still of the 80%. A reduction of a factor 10 would bring at the surely acceptable, resulting in a 94% probability of not being degraded during the detection of the IMBH signal. Contrary to Sos Enattos site, in this case the seismometer is placed already at -250 m, in an isolated environment. Thus this results are the best that we can expect to have in Terziet, at least from the pure measurement of the seismic noise.

Seismic perturbations and Newtonian noise

the Newtonian Noise contribution. On the contray, body waves are expected to give a significant contribution. They are described with the help of the seismic displacement vector $\vec{\xi}$, extremely useful because it can be measured directly:

$$\vec{\xi}^{P,S} = \vec{e}^{P,S}\xi_0^{P,S}(\vec{k}^{P,S},\omega)exp(i(\vec{k}^{P,S}\cdot\vec{r}-\omega t)) \quad (3)$$

where the indexes P and S distinguish respectively the compressional (P) and shear (S) waves $\vec{k}$ the wavenumber, $\vec{e}_k$ is the polarization unit vector, and ω is the frequency. Compressional waves are longitudinal: $\vec{e}^P = \frac{\vec{k}^P}{k^P}$ while shear waves are transversal: $\vec{e^S}\cdot k^S = 0$. Following the Newton law the acceleration $\delta\vec{a}$ of a mass placed at the point $\vec{r}_0$ is given by:

$$\delta\vec{a}(r_0,t) = -G\int dV\rho(\vec{(r)})\left(\vec{\xi}(\vec{r},t)\cdot\vec{\nabla}_0\right)\frac{\vec{r}-\vec{r}_0}{|\vec{r}-\vec{r}_0|^3} \quad (4)$$

In the first approximation the underground cavities of the detector can be assumed to be spherical, with radius much shorter that the seismic wavelenghts and the mass in the center [?]. Further, assuming that the density variations in space and time can be neglected and $\rho(\vec{r},t) = \rho_0$ assumed constant, the above integral can be solved to give:

$$\delta\vec{a}(\omega) = \frac{4\pi}{3}G\rho_0\left(2\vec{\xi}^P(\omega)-\vec{\xi}^S(\omega)\right) \quad (5)$$

Estimation of NN

Newtonian Noise reduction -- > Range of reduction factor conservatively estimate at the present : **from 3 to 10**

the desired sensitivity. An estimation of the possible reduction of Newtonian Noise is at the moment quite difficult. Many studies are on going, showing that the performance of the reduction will depend on the number of seismic sensors, the composition of the rocks, the complexity of the seismic fields and positions of seismic noise sources. At the present, as a conservative estimation, the reduction factor can range from a factor 3 to 10 [8].