

Newtonian Noise: State of the art and future perspectives

Francesca Badaracco



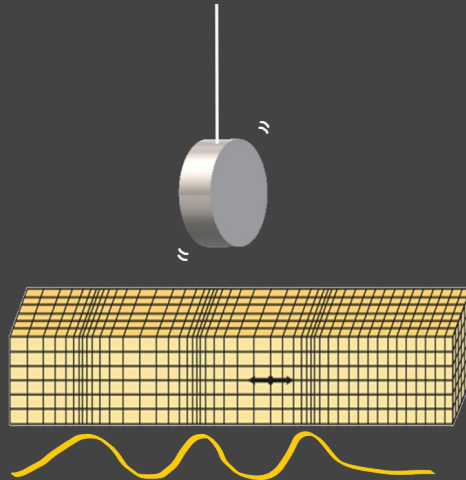
The Genesis:

Weiss (1972): "Electromagnetically coupled broadband gravitational antenna". In: Final Quarterly Report, MIT RLE (1972)

Saulson (1984): "Terrestrial gravitational noise on a gravitational wave antenna", Phys. Rev. D 30 (4 1984)

{ # Beccaria (1998): "Relevance of Newtonian seismic noise for the VIRGO interferometer sensitivity". In: Class. and Quant. Gravity 15.11 (1998)

{ # Hughes and Kip S. Thorne (1998): "Seismic gravity-gradient noise in interferometric gravitational-wave detectors". In: Phys. Rev. D 58.12



Analytical fundamentals development:

Virtual displacement (time do not change)

$$\delta \mathbf{a}(\mathbf{r}_0, t) = G \int \frac{\delta \rho(\mathbf{r}, t)}{|\mathbf{r} - \mathbf{r}_0|^3} (\mathbf{r} - \mathbf{r}_0) dV$$

+ continuity equation: $\delta \rho(\mathbf{r}, t) = \nabla \cdot (\rho(\mathbf{r}) \xi(\mathbf{r}, t))$

$$\delta \mathbf{a}(\mathbf{r}_0, t) = -G\rho_0 \int \frac{\nabla \cdot \xi(\mathbf{r}, t)}{|\mathbf{r} - \mathbf{r}_0|^3} (\mathbf{r} - \mathbf{r}_0) dV \quad \delta \mathbf{a}(\mathbf{r}_0, t) = G\rho_0 \int \frac{\mathbf{n}(\mathbf{r}) \cdot \xi(\mathbf{r}, t)}{|\mathbf{r} - \mathbf{r}_0|^3} (\mathbf{r} - \mathbf{r}_0) dS$$

Only compressional wave contributes (the divergence of the displacement is zero for Shear waves)

Contribution from compressional and shear waves

Publications about Sos Enattos:

Class. Quantum Grav. 31 105016 (2014)

Microseismic studies of an underground site for a new interferometric gravitational wave detector

L Naticchioni^{1,2}, M Perciballi², F Ricci^{1,2}, E Coccia^{3,4}, V Malvezzi³, F Acernese^{5,6}, F Barone^{5,6}, G Giordano⁵, R Romano^{5,6}, M Punturo⁷, R De Rosa^{6,8}, P Calia⁹ and G Loddo⁹

Seismological Research Letters (2021) 92 (1): 352–364.

A Seismological Study of the Sos Enattos Area—the Sardinia Candidate Site for the Einstein Telescope

Matteo Di Giovanni^{1,2,3}, Carlo Giunchi¹, Gilberto Saccorotti¹, Andrea Berbellini⁴, Lapo Boschi^{4,5,6}, Marco Olivieri⁴, Rosario De Rosa^{7,8}, Luca Naticchioni^{9,10}, Giacomo Oggiano^{11,12}, Massimo Carpinelli^{11,12}, Domenico D'Urso^{11,12}, Stefano Cuccuru^{11,12}, Valeria Sipala^{11,12}, Enrico Calloni^{7,8}, Luciano Di Fiore⁷, Aniello Grado¹³, Carlo Migoni¹⁴, Alessandro Cardini¹⁴, Federico Paoletti¹⁵, Irene Fiori¹⁶, Jan Harms^{2,3}, Ettore Majorana^{9,10}, Piero Rapagnani^{9,10}, Fulvio Ricci^{9,10}, and Michele Punturo¹⁷

Geophysical Journal International, ggad178 (2023)

Temporal variations of the ambient seismic field at the Sardinia candidate site of the Einstein Telescope

M Di Giovanni, S Koley ✉, J X Ensing, T Andric, J Harms, D D'Urso, L Naticchioni, R De Rosa, C Giunchi, A Allocca, M Cadoni, E Calloni, A Cardini, M Carpinelli, A Contu, L Errico, V Mangano, M Olivieri, M Punturo, P Rapagnani, F Ricci, D Rozza, G Saccorotti, L Trozzo, D Dell'aquila, L Pesenti, V Sipala, I Tosta e Melo

The European Physical Journal Plus volume 136, Article number: 511 (2021)

Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency

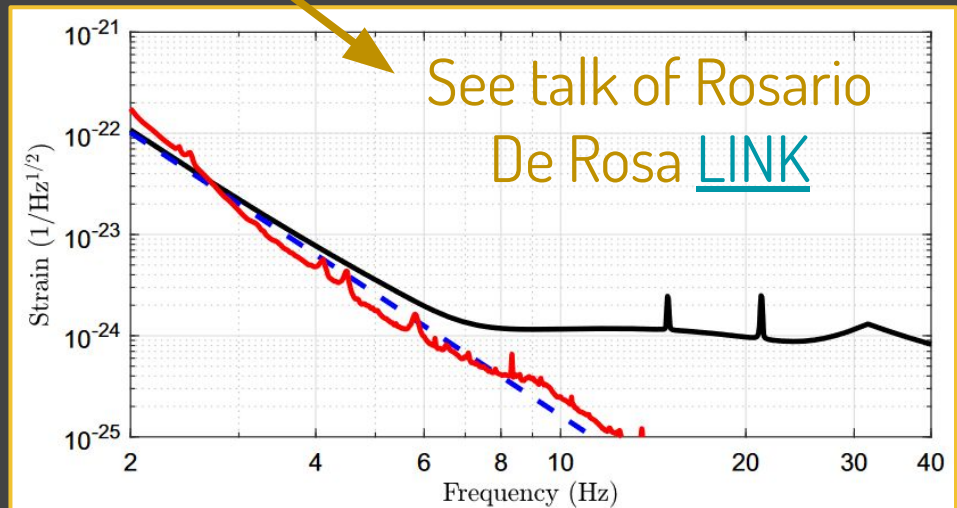
A. Allocca^{1,2}, A. Berbellini³, L. Boschi^{3,4,5}, E. Calloni^{1,2,a}, G. L. Cardello^{6,7}, A. Cardini⁸, M. Carpinelli^{6,7,9}, A. Contu^{8,10}, L. D'Onofrio^{1,2}, D. D'Urso^{6,7}, D. Dell'Aquila^{6,7}, R. De Rosa^{1,2}, L. Di Fiore², M. Di Giovanni^{11,12,13}, S. Di Pace^{14,15}, L. Errico^{1,2}, I. Fiori⁹, C. Giunchi¹¹, A. Grado¹⁶, J. Harms¹², E. Majorana^{14,15}, V. Mangano^{14,15}, M. Marsella^{14,15}, C. Migoni⁸, L. Naticchioni^{14,15}, M. Olivieri³, G. Oggiano^{6,7}, F. Paoletti¹⁷, M. Punturo¹⁸, P. Puppo¹⁵, P. Rapagnani^{14,15}, F. Ricci^{14,15}, D. Rozza^{6,7}, G. Saccorotti¹¹, V. Sequino^{1,2}, V. Sipala^{6,7}, I. Tosta E Melo^{6,7}, L. Trozzo²

J. Phys.: Conf. Ser. 1468 012242 (2020)

Characterization of the Sos Enattos site for the Einstein Telescope

L Naticchioni¹, V Boschi³, E Calloni², M Capello⁸, A Cardini⁵, M Carpinelli^{6,7}, S Cuccuru⁷, M D'Ambrosio⁸, R de Rosa², M Di Giovanni⁸, D d'Urso^{6,7}, I Fiori¹¹, S Gaviano⁸, C Giunchi⁸, E Majorana¹, C Migoni^{5,10}, G Oggiano⁷, M Olivieri⁹, F Paoletti³, M Paratore⁸, M Perciballi¹, D Piccinini⁸, M Punturo⁴, P Puppo¹, P Rapagnani¹, F Ricci¹, G Saccorotti⁸, V Sipala⁷, M C Tringali¹²

Projection of NN contribution at Sos Enattos



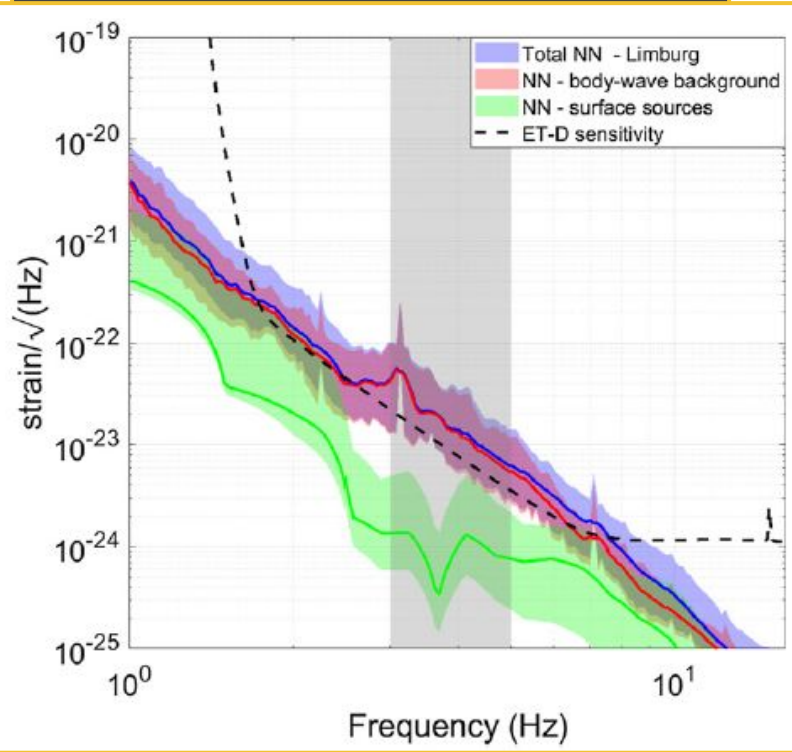
Publications about Terziet:

Surface and underground seismic characterization at Terziet in Limburg—the Euregio Meuse–Rhine candidate site for Einstein Telescope

Soumen Koley^{1,2,*}, Maria Bader², Jo van den Brand^{2,3}, Xander Campman⁴, Henk Jan Bulten^{2,5}, Frank Linde^{2,6} and Bjorn Vink⁷

Newtonian-noise characterization at Terziet in Limburg—the Euregio Meuse–Rhine candidate site for Einstein Telescope

Maria Bader^{1,5}, Soumen Koley^{1,2,*}, Jo van den Brand^{1,3,5}, Xander Campman⁴, Henk Jan Bulten^{1,5}, Frank Linde^{1,6} and Bjorn Vink⁷



See talk of
Soumen Koley
[LINK](#)

What's missing yet?

Sos Enattos:

Digital geological model in preparation.

Simulations of the seismic field taking into account the geology of the site.

Terziet:

Class. Quantum Grav. 39 025009 (2022)

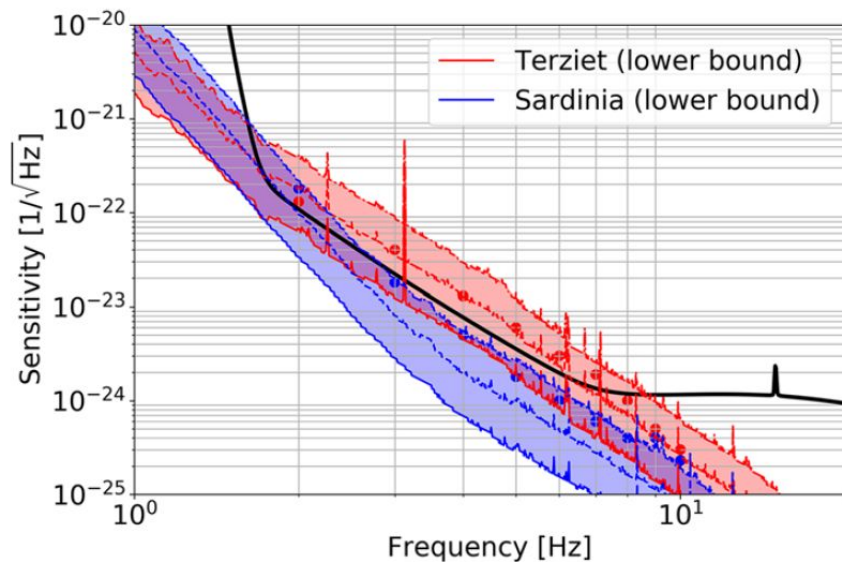
Newtonian-noise characterization at Terziet in Limburg—the Euregio Meuse–Rhine candidate site for Einstein Telescope

Maria Bader^{1,5}, Soumen Koley^{1,2,*},
Jo van den Brand^{1,3,5}, Xander Campman⁴,
Henk Jan Bulten^{1,5}, Frank Linde^{1,6} and Bjorn Vink⁷

The European Physical Journal Plus volume 137, Article number: 687 (2022)

A lower limit for Newtonian-noise models of the Einstein Telescope

Jan Harms^{1,2,a}, Luca Naticchioni³, Enrico Calloni^{4,5}, Rosario De Rosa^{4,5}, Fulvio Ricci^{3,6}, Domenico D'Urso^{7,8}



Horizontally layered model

Lower bounds on seismic NN for the two sites based on the 10th, 50th, and 90th percentiles of the seismic histograms.

What about NN cancellation?

Problem 1: where do we put the sensors?

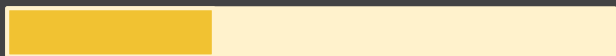
Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves

F Badaracco^{1,2} and J Harms^{1,2}

Class. Quantum Grav. 36 145006 (2019)



Work in progress...



Simulations of Gravitoelastic Correlations for the Sardinian Candidate Site of the Einstein Telescope

Tomislav Andric^{1,2} and Jan Harms^{1,2}

JGR Solid Earth Vol. 125, Issue 10 (2020)

Machine learning for gravitational-wave detection: surrogate Wiener filtering for the prediction and optimized cancellation of Newtonian noise at Virgo

F Badaracco^{1,2,8}, J Harms^{1,2}, A Bertolini³, T Bulik⁴, I Fiori⁵, B Idzkowski⁴, A Kutynia⁴, K Nikliborc⁴, F Paoletti⁶, A Paoli⁵, L Rei⁷ and M Suchinski⁴

Quantum Grav. 37 195016 (2020)

1. Collecting Data
2. Gaussian Process Regression in 3D (GPR) + some tricks
3. Optimization on the inferred seismic field

Step 2. crucial: GPR in 3D with much less data!!! →

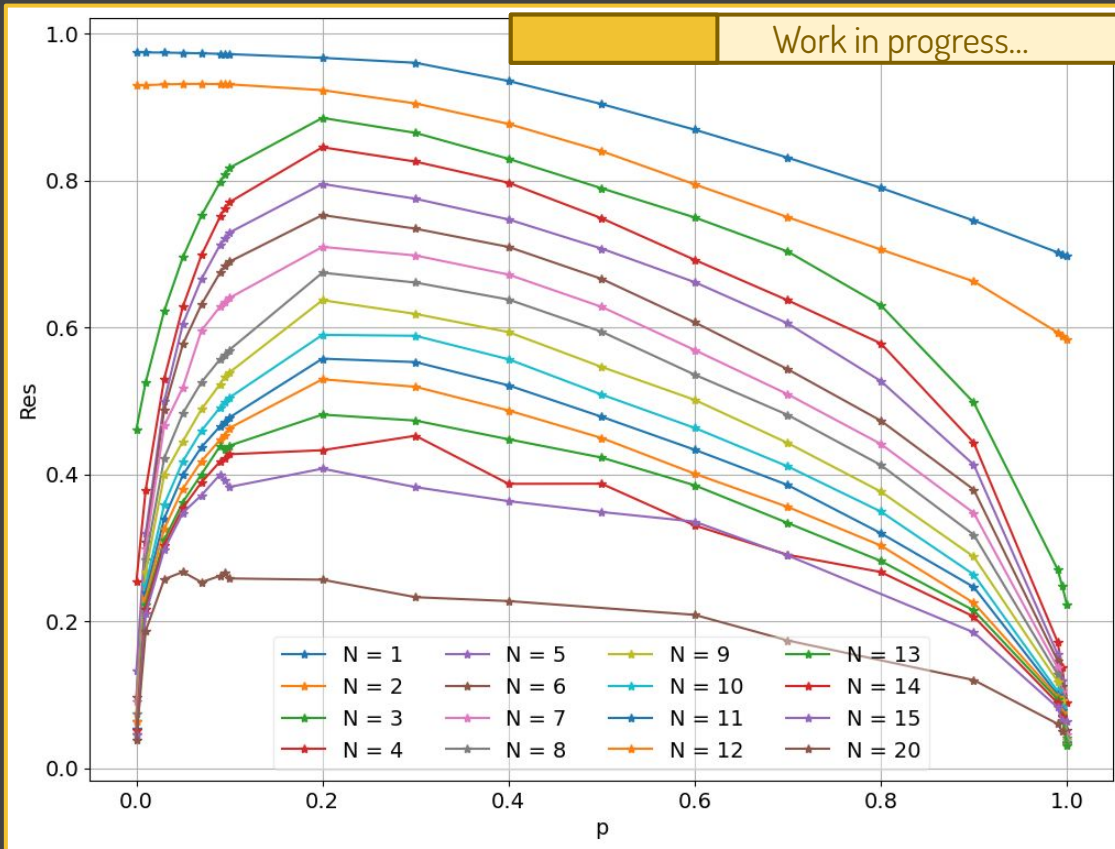
Fully Bayesian approach to GPR

Uniform prior → **Prior inferred from simulations and data**

Expensive both computationally and financially!!!

What about NN cancellation?

Problem 1: where do we put the sensors?



BE CAREFUL!

Mixing value:

Energy(P-waves)

$p = \text{-----}$

Energy(tot)

Depending on the P and S-wave content of the selected site the NN cancellation might be worse or better!!!

NB: the Residual is in the range (0,1) and it informs about the performances of the NN cancellation:

R = 0 → Perfect cancellation

R = 1 → NO cancellation

What about NN cancellation?

Problem 2: which kind of sensors?

- **Accelerometers**
- **Strainmeters** (DAS: Distributed Acoustic Sensing)
- Tiltmeter



See J. Harms talk of the 2nd Site Preparation Board Workshop in Maastricht, 2023: [link](#)



Katharina-Sophie Isleif
&
Reinhardt Rading

Strainmeter location optimization:

1. Strainmeters in boreholes?
2. Many readout points → compensate the lower correlation with NN ?
3. Mixed array (Accelerometers + Strainmeters?)

Problem 3: Something better than Wiener Filter?

Atmospheric NN

NEW ATMOSPHERIC NN ESTIMATES!!!

Atmospheric Newtonian noise modeling
for third-generation gravitational wave detectors

D. Brundu^{1,*}, M. Cadoni^{1,2,†}, M. Oi^{1,2,‡}, P. Olla^{1,3,§} and A. P. Sanna^{1,2,||}

Phys. Rev. D 106, 064040 (2022)

See talk of Mauro Oi [LINK](#)

Conclusions:

A lot of work has been done, but a lot of work still needs to be done for ET!

The complete (I hope) list of all NN papers is on the wiki page of the ET ANM : [LINK](#)

Please contact me if you want to add some papers that are missing!!!

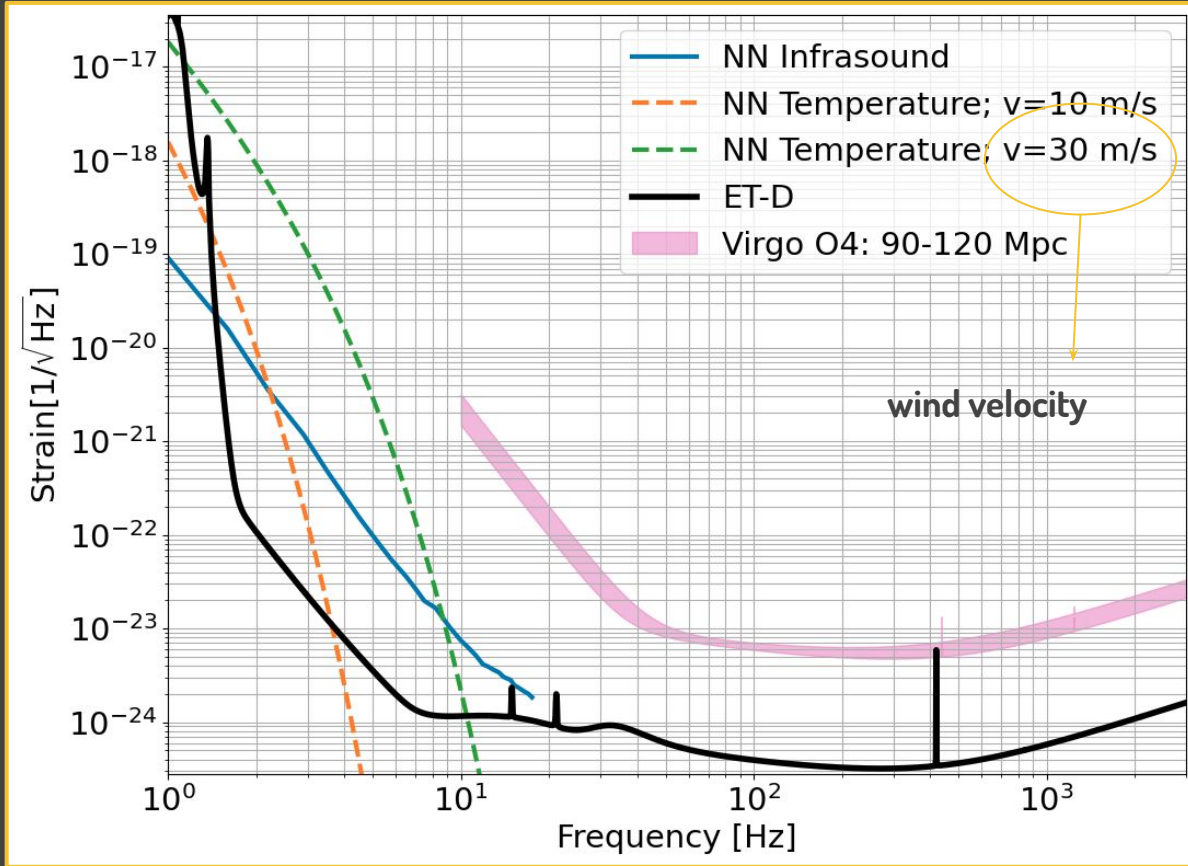
(francesca.badaracco@ge.infn.it)



Thank you for the attention

Backup slides

Atmospheric NN at the surface (ANN)



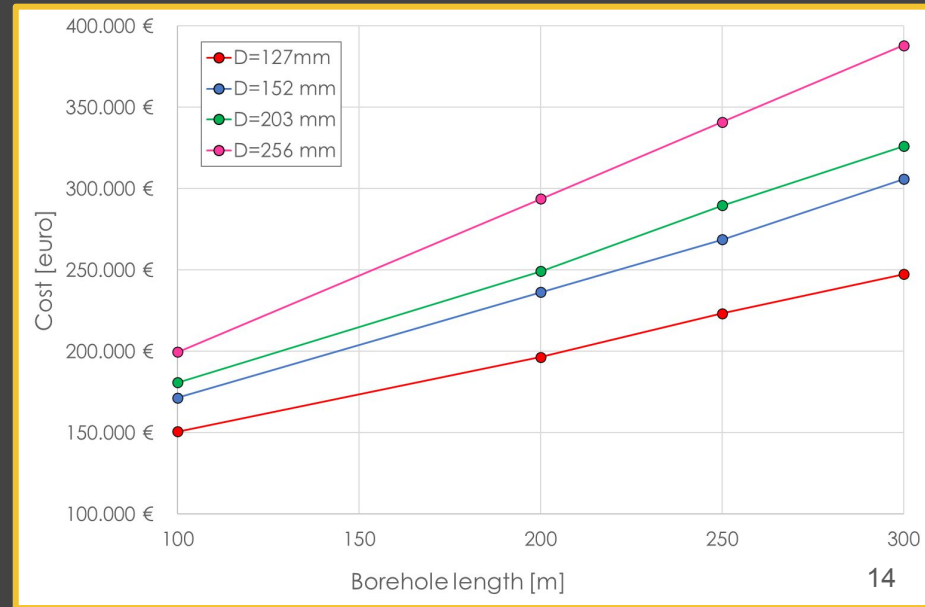
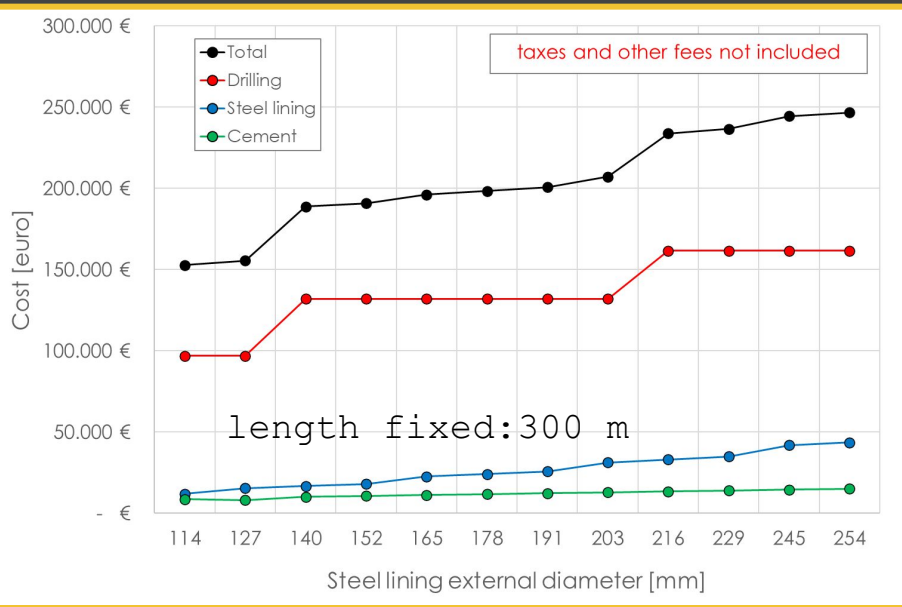
External **infrasound** and **advected temperature** fields at the Earth's surface

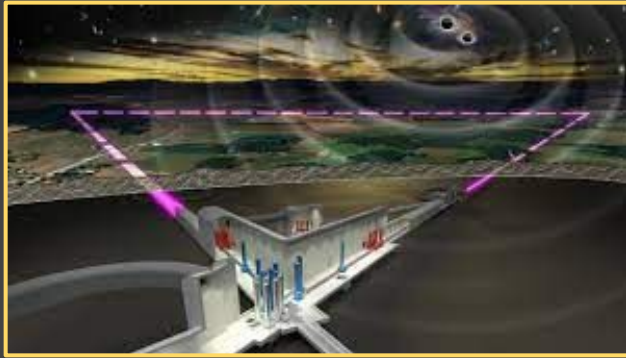
Building ET on the surface would lead to **huge efforts** to reduce ANN

Advected temperature fields estimated for wind velocities of 10 m/s and 30 m/s.

NN cancellation array: costs

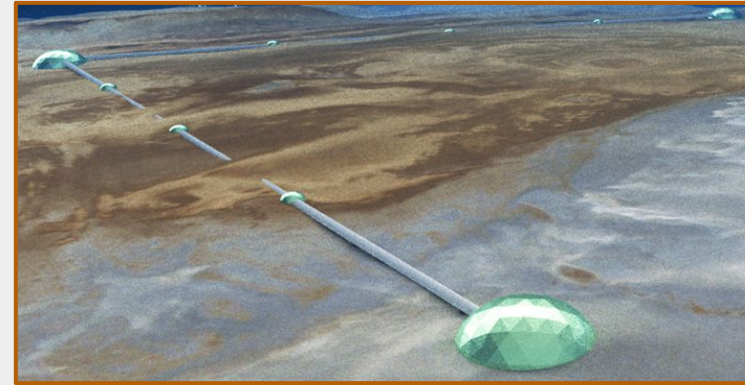
- High-Quality Broadband borehole seismometer ~ 50k€
- Seismometer chains → reducing excavation costs
- Low vertical tilt required (few degrees)
- R&D on sensors for non-vertical boreholes is required





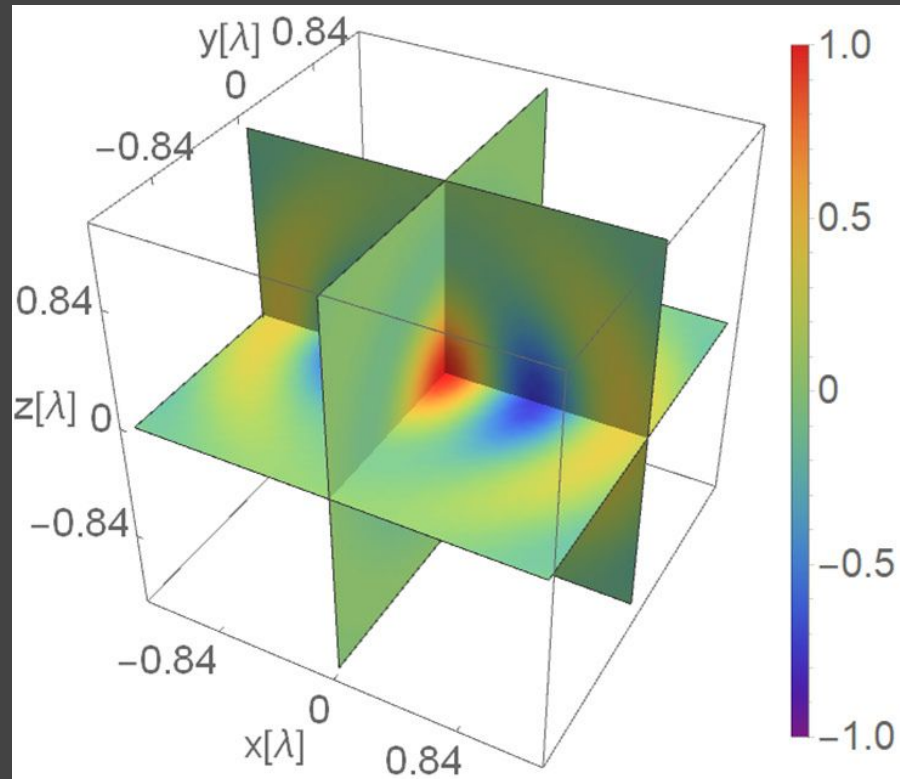
Underground or Surface: differences

- Suppressed **Rayleigh** waves contribution
- **Body waves** dominate: Compression (P) & Shear (S) waves
- **P and S** → spoiled correlations → bad cancellation
- **Sensor deployment** expensive and difficult
- **Atmospheric NN** partially suppressed (see Phys. Rev. D 106, 064040 - 2022)

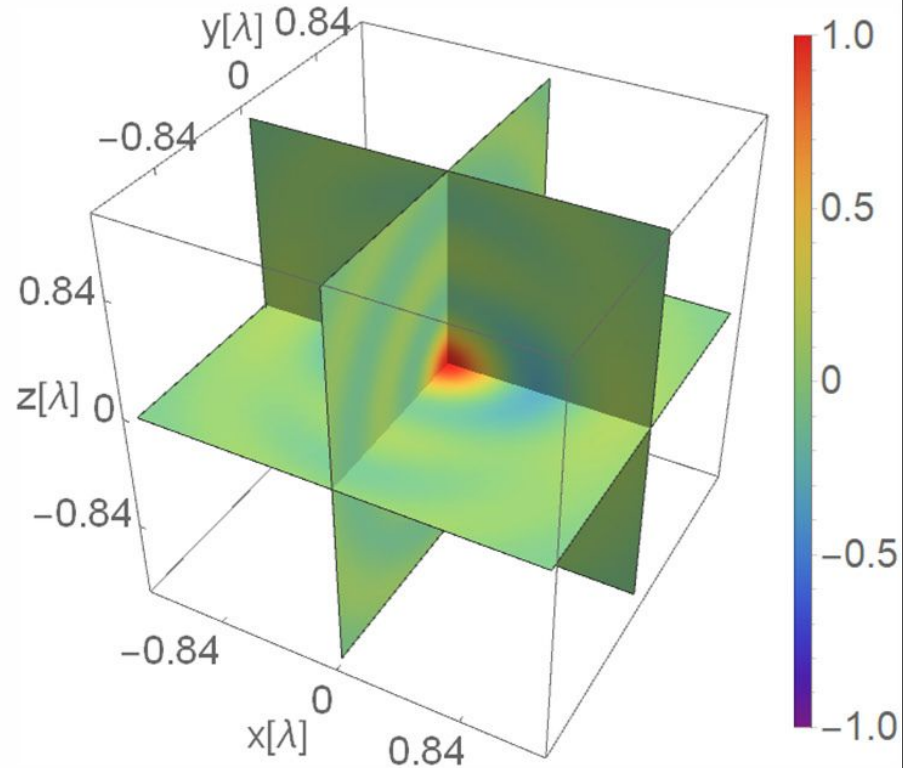


Credits: <https://gwic.ligo.org/3Gsubcomm/>

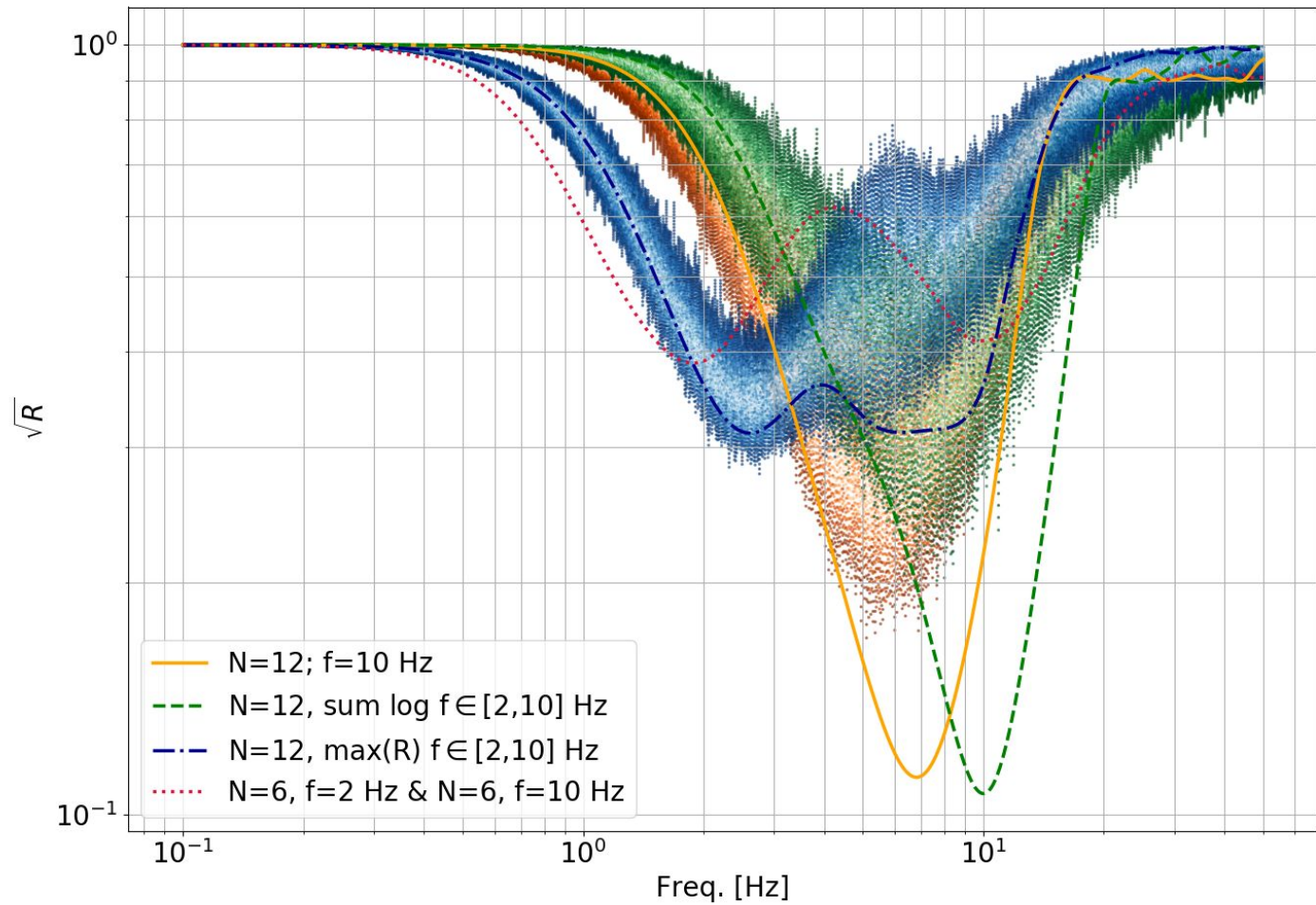
- Surface **Rayleigh** waves dominate
- **Seismic sensor deployment** relatively easy
- Presence of **Atmospheric NN**

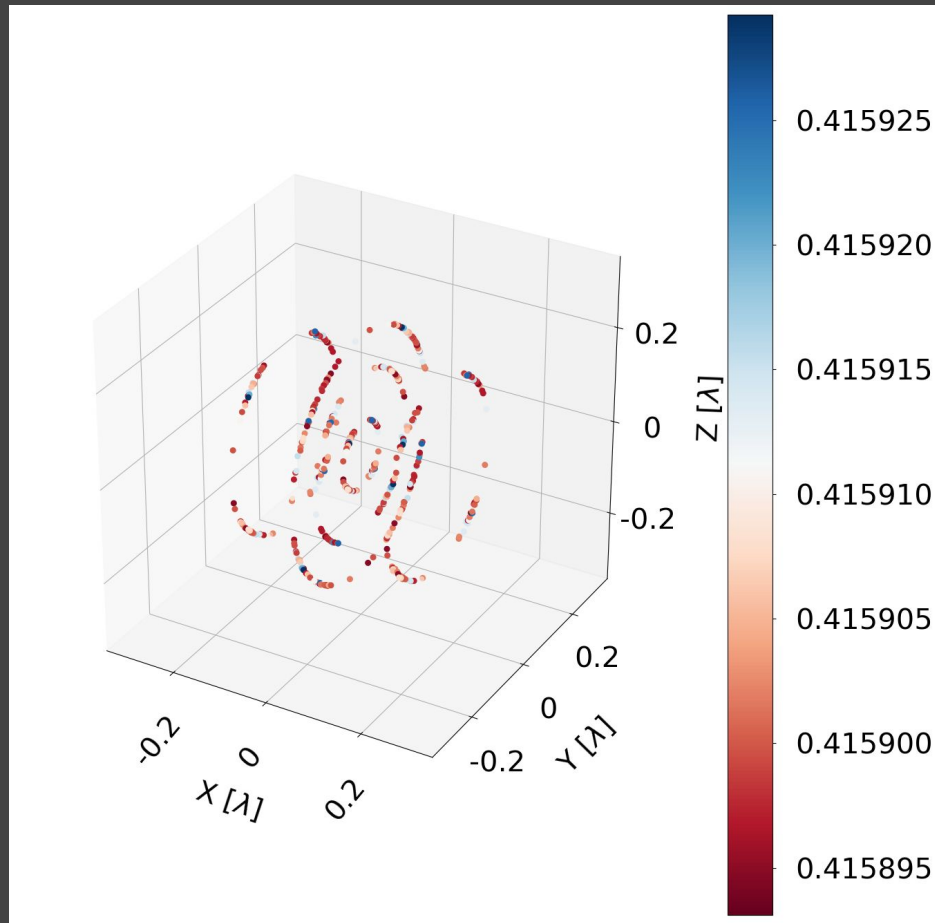


(a)

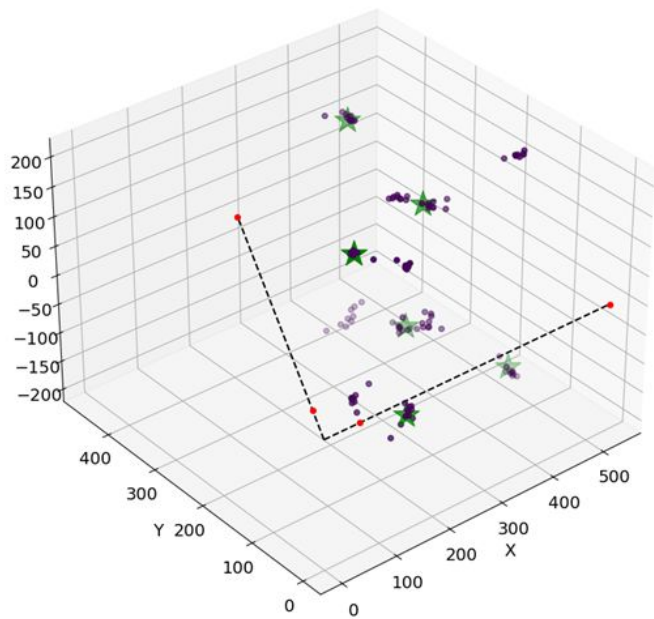


(b)

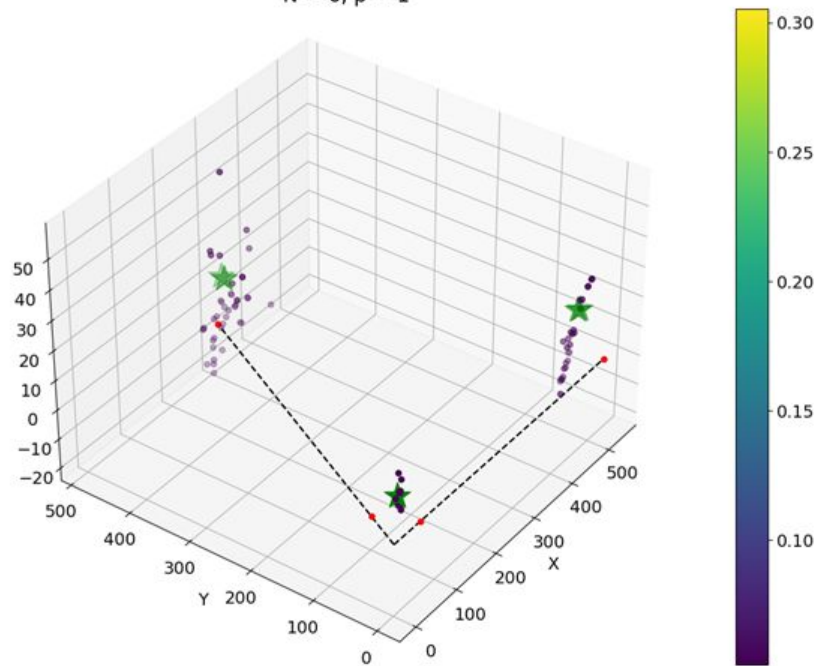




$N = 6, p = 0.3$



$N = 6, p = 1$



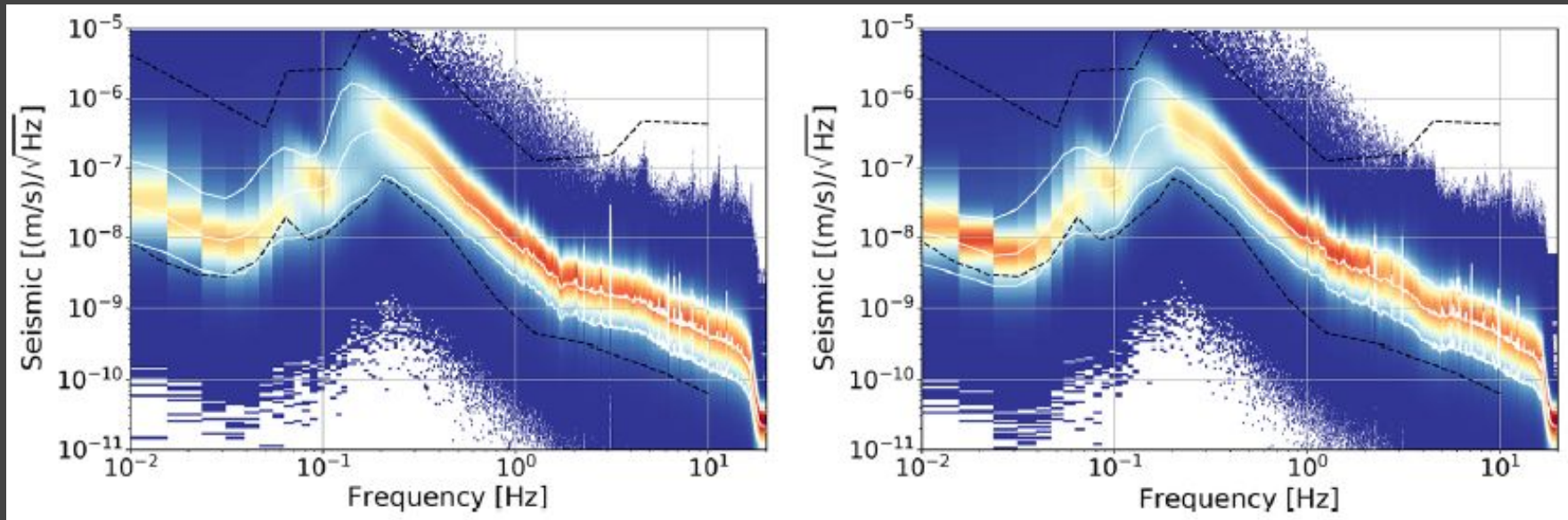


Fig 1 of The European Physical Journal Plus volume 137, Article number: 687 (2022):

Histogram of horizontal (left) and vertical (right) ground motion measured in the Terziet borehole, EMR site, at 250m depth (data from September 30, 2019 to September 14, 2020). The dashed curves represent the New Low-noise Model (NLNM) and high-noise model [40]. White curves are the 10th, 50th and 90th percentiles of the distribution

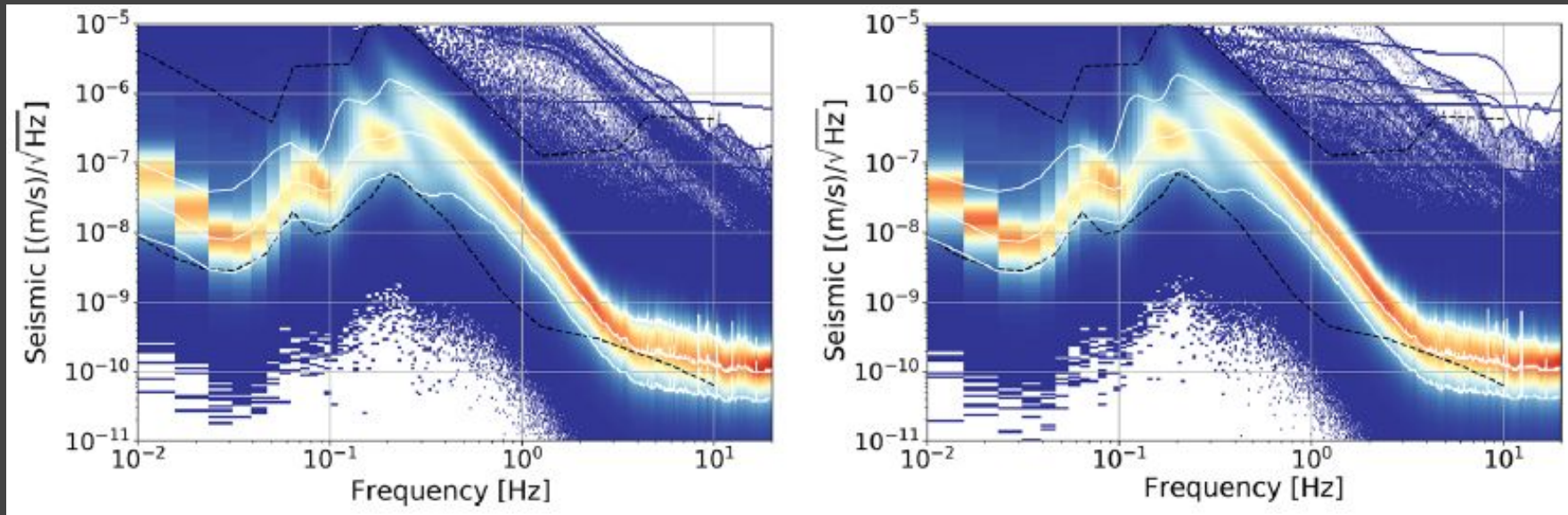
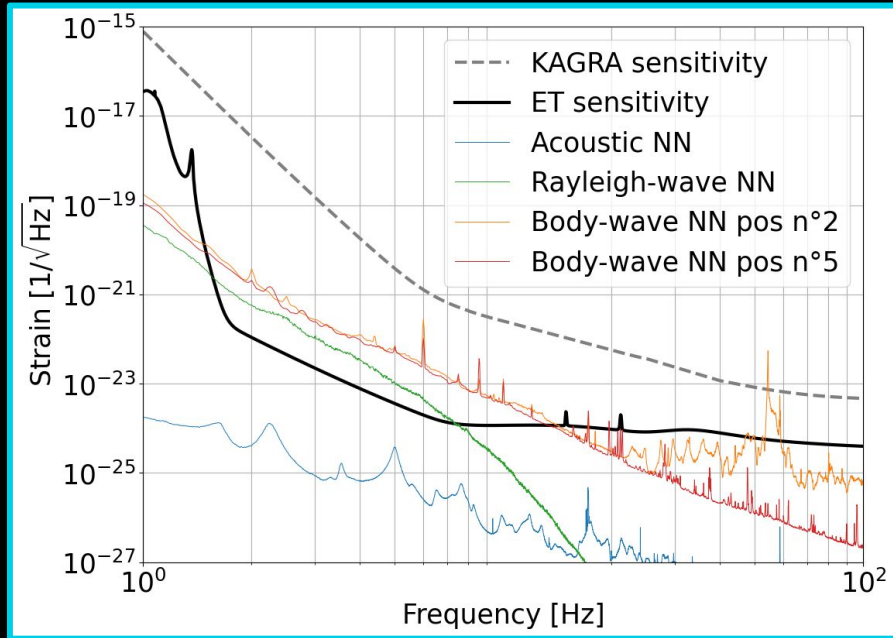


Fig 2 of The European Physical Journal Plus volume 137, Article number: 687 (2022)

Histogram of horizontal (left) and vertical (right) ground motion measured in the P2 borehole, Sardinia site, at 264m depth (data from October 1, 2021 to April 30, 2022). The dashed curves represent the New Low-noise Model (NLNM) and high-noise model [40]. White curves are the 10th, 50th and 90th percentiles of the distribution.

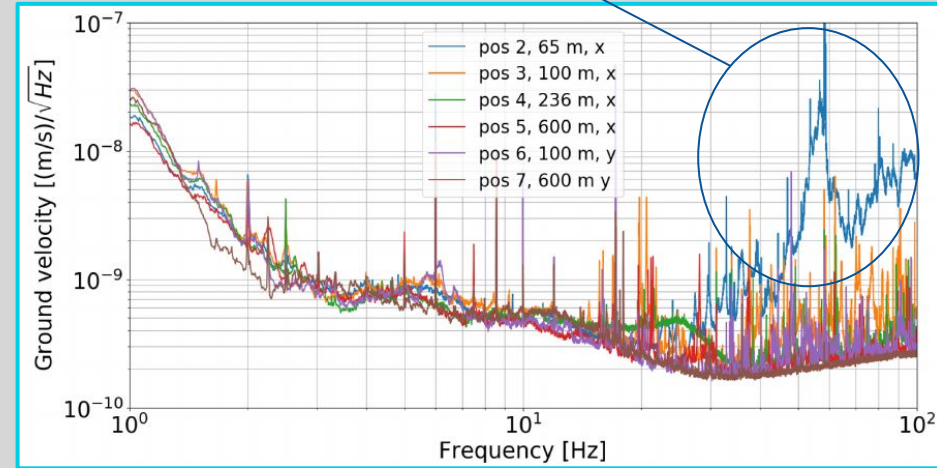
Infrastructural noise:

Self-induced acoustic noise



Self-induced seismic noise

known source: it can
be switched off
during observation
runs



WIENER FILTER

Wiener filter to perform a
NN cancellation (**time**
domain):

$$\hat{x}(m) = \sum_{k=0}^P w_k y(m - k)$$

Expected
signal

Wiener filter
coefficients

Sensor
signal

Wiener filter performances
(**frequency** domain):

$$R(\omega) = 1 - \frac{\vec{C}_{SN}^\dagger(\omega)(\mathbf{C}_{SS}(\omega))^{-1}\vec{C}_{SN}(\omega)}{C_{NN}(\omega)}$$

Residual

CPSD between the
N sensors and the
target (NN)

CPSD between the
N sensors

PSD of the target
signal (NN)

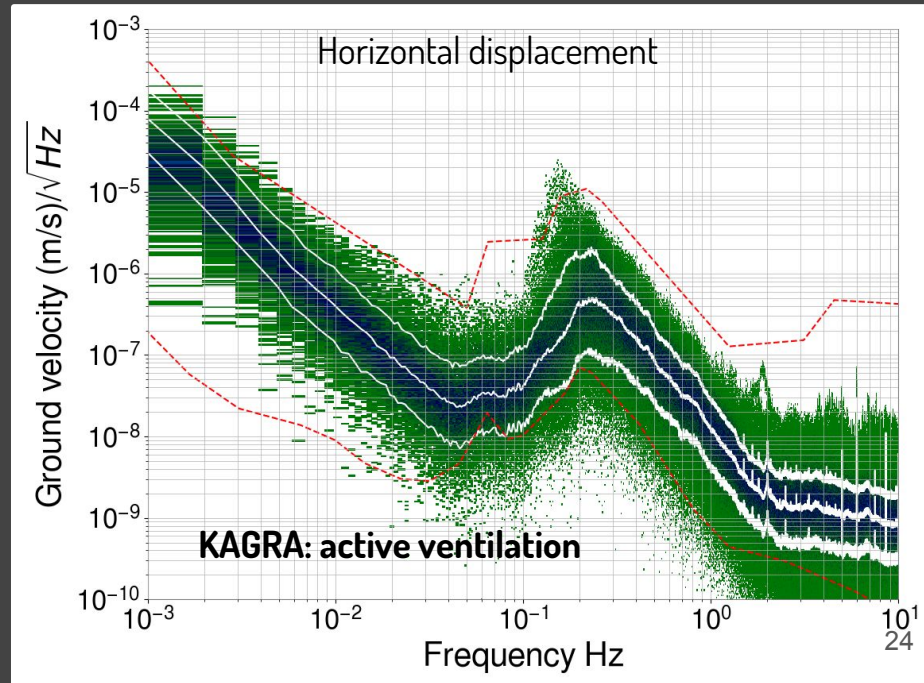
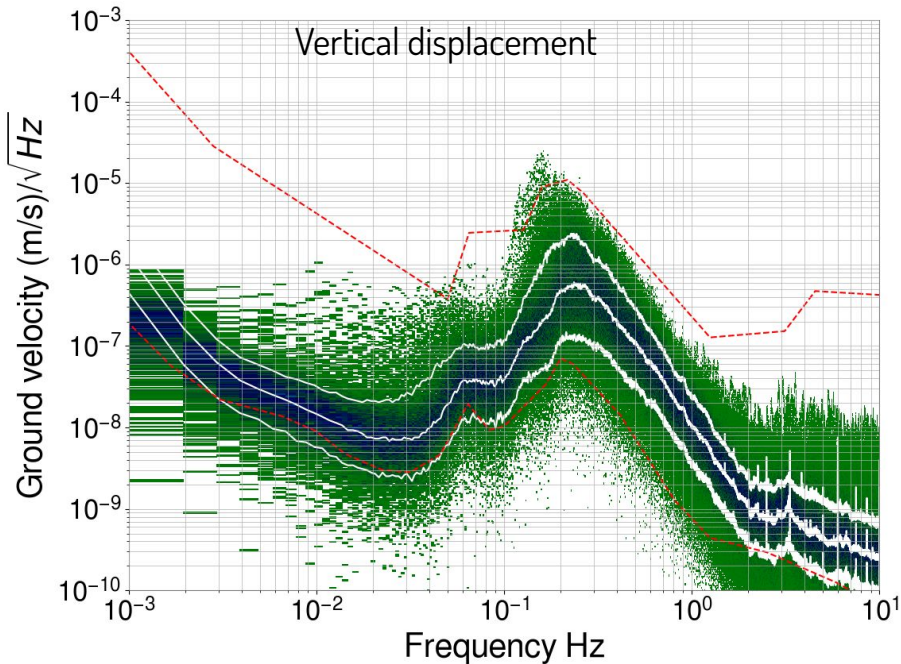
Cross Power Spectral Density = **CPSD**
Power Spectral Density = **PSD**

What causes underground excess tilt?

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

Long-known fact: pressure fluctuations (or thermally induced effects) → seismic tilt

Problem: coupling with horizontal displacement → active seismic controls issues



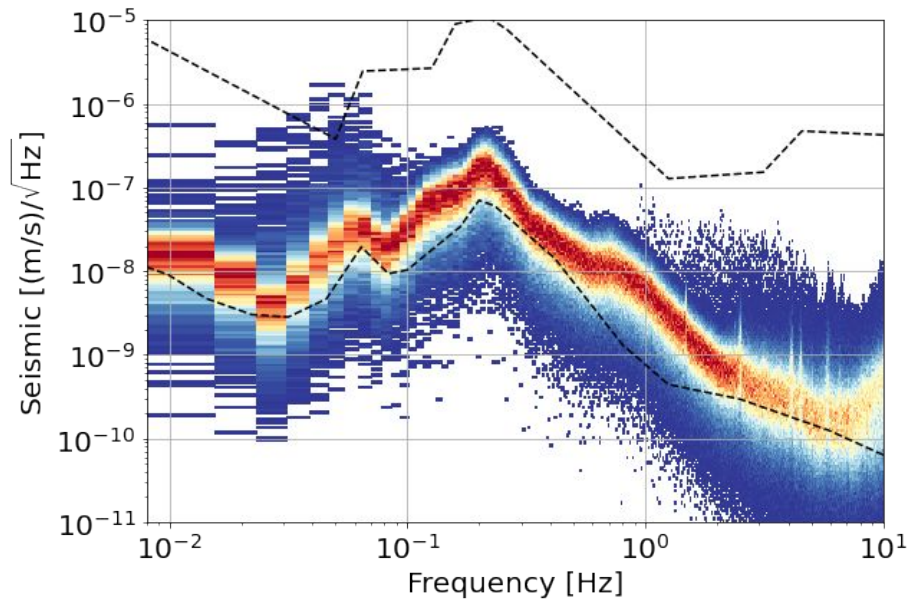
What causes underground excess tilt?

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

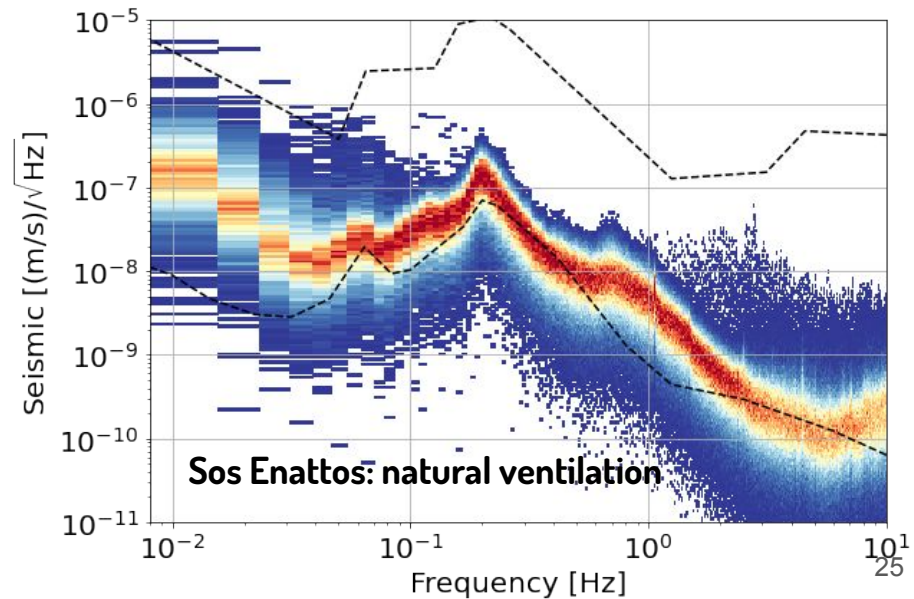
Long-known fact: pressure fluctuations (or thermally induced effects) → seismic tilt

Problem: coupling with horizontal displacement → active seismic controls issues

Vertical displacement



Horizontal displacement



NN simulation papers:

Phys. Rev. D 80, 122001 (2009)

Simulation of underground gravity gradients from stochastic seismic fields

Jan Harms,¹ Riccardo DeSalvo,² Steven Dorsher,¹ and Vuk Mandic¹

Code for simulating **stochastic**, **isotropic** and **plane wave** seismic field (assuming rock homogeneity, stationarity and neglect Love waves and higher order modes of Rayleigh waves)

Class. Quantum Grav. 29 (2012)

Seismic topographic scattering in the context of GW detector site selection

M Coughlin¹ and J Harms²

Class. Quantum Grav. 37 105007 (2020)

Newtonian-noise reassessment for the Virgo gravitational-wave observatory including local recess structures

Ayatri Singha¹, Stefan Hild¹ and Jan Harms^{2,3}

Class. Quantum Grav. 31 185011 (2014)

Passive Newtonian noise suppression for gravitational-wave observatories based on shaping of the local topography

Jan Harms¹ and Stefan Hild²

Phys. Rev. D 103, 122004 (2021)

Gravitational-wave physics with Cosmic Explorer: Limits to low-frequency sensitivity

Evan D. Hall¹, Kevin Kuns¹, Joshua R. Smith², Yuntao Bai³, Christopher Wipf⁴, Sebastien Biscans^{4,1}, Rana X Adhikari⁴, Koji Arai⁴, Stefan Ballmer⁵, Lisa Barsotti¹, Yanbei Chen³, Matthew Evans¹, Peter Fritschel¹, Jan Harms^{6,7}, Brittany Kamai^{8,9}, Jameson Graef Rollins⁴, David Shoemaker¹, Bram J. J. Slagmolen¹⁰, Rainer Weiss¹ and Hiro Yamamoto⁴

Class. Quantum Grav. 38 245007 (2021)

Characterization of the seismic field at Virgo and improved estimates of Newtonian-noise suppression by recesses

Ayatri Singha^{1,2}, Stefan Hild^{1,2}, Jan Harms^{3,4}, Maria C Tringali⁵, Irene Fiori⁵, Federico Paoletti⁶, Tomasz Bulik^{7,8}, Bartosz Idzkowski⁷, Alessandro Bertolini⁹, Enrico Calloni^{10,11}, Rosario De Rosa^{10,11}, Luciano Errico¹¹ and Alberto Gennai¹²