NN modeling and cancellation methods

Francesca Badaracco

Università di Genova

Site Preparation Board workshop 3 2023, Amsterdam

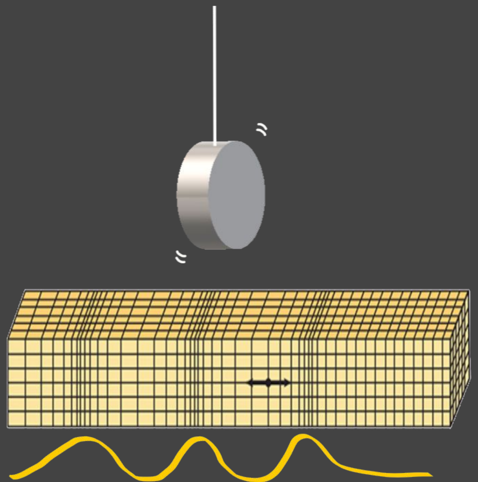
The Genesis:

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:

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

Virtual displacement (time do not change)

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

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

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

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

Contribution from compressional and shear waves

Living Reviews in Relativity **volume 22**, Article number: 6 (2019)

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 Perciballi[2], F Ricci[1,2], E Coccia[3,4], V Malvezzi[3], F Acernese[5,6], F Barone[5,6], G Giordano[5], R Romano[5,6], M Punturo[7], R De Rosa[6,8], P Calia[9] and G Loddo[9]

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. Berbellini[3], L. Boschi[3,4,5], E. Calloni[1,2,a], G. L. Cardello[6,7], A. Cardini[8], 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 Fiore[2], M. Di Giovanni[11,12,13], S. Di Pace[14,15], L. Errico[1,2], I. Fiori[9], C. Giunchi[11], A. Grado[16], J. Harms[12], E. Majorana[14,15], V. Mangano[14,15], M Marsella[14,15], C. Migoni[8], L. Naticchioni[14,15], M. Olivieri[3], G. Oggiano[6,7], F. Paoletti[17], M. Punturo[18], P. Puppo[15], P. Rapagnani[14,15], . Ricci[14,15], D. Rozza[6,7], G. Saccorotti[11], V. Sequino[1,2], V. Sipala[6,7], . Tosta E Melo[6,7], L. Trozzo[2]

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

Characterization of the Sos Enattos site for the Einstein Telescope

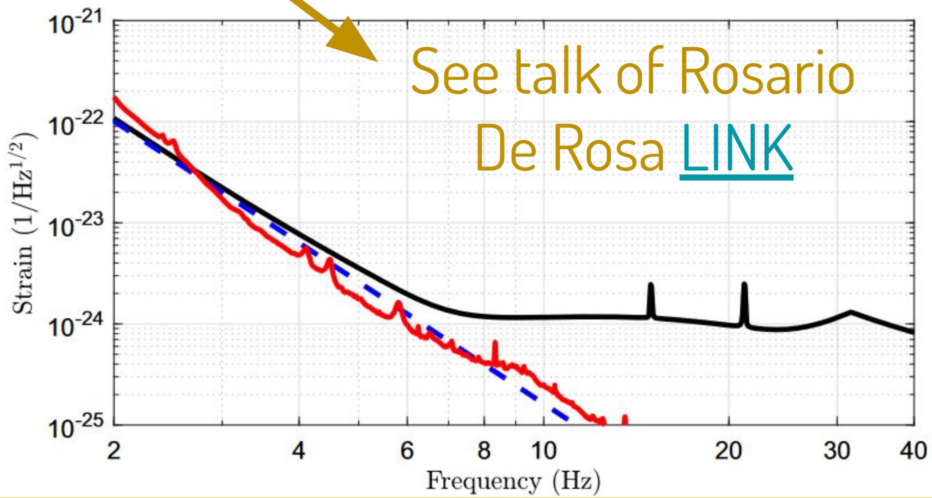
L Naticchioni[1], V Boschi[3], E Calloni[2], M Capello[8], A Cardini[5], M Carpinelli[6,7], S Cuccuru[7], M D'Ambrosio[8], R de Rosa[2], M Di Giovanni[8], D d'Urso[6,7], I Fiori[11], S Gaviano[8], C Giunchi[8], E Majorana[1], C Migoni[5,10], G Oggiano[7], M Olivieri[9], F Paoletti[3], M Paratore[8], M Perciballi[1], D Piccinini[8], M Punturo[4], P Puppo[1], P Rapagnani[1], F Ricci[1], G Saccorotti[8], V Sipala[7], M C Tringali[12]

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 Giunchi[1], Gilberto Saccorotti[1], Andrea Berbellini[4], Lapo Boschi[4,5,6], Marco Olivieri[4], 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 Fiore[7], Aniello Grado[13], Carlo Migoni[14], Alessandro Cardini[14], Federico Paoletti[15], Irene Fiori[16], Jan Harms[2,3], Ettore Majorana[9,10], Piero Rapagnani[9,10], Fulvio Ricci[9,10], and Michele Punturo[17]

Projection of NN contribution at Sos Enattos



See talk of Rosario De Rosa LINK

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

Publications about Terziet:

Class. Quantum Grav. 39 025008 (2022)

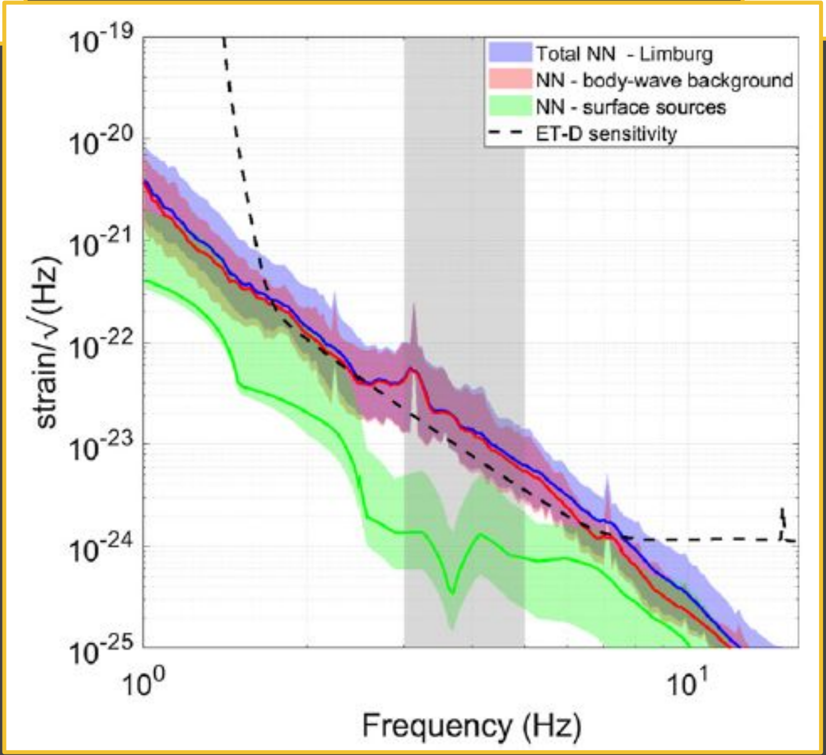
Surface and underground seismic characterization at Terziet in Limburg—the Euregio Meuse–Rhine candidate site for Einstein Telescope

Soumen Koley[1,2,*], Maria Bader[2], Jo van den Brand[2,3], Xander Campman[4], Henk Jan Bulten[2,5], Frank Linde[2,6] and Bjorn Vink[7]

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 Campman[4], Henk Jan Bulten[1,5], Frank Linde[1,6] and Bjorn Vink[7]



See talk of Soumen Koley at the ET Symposium [LINK]

What's missing yet?

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

Sos Enattos:
Digital geological model in preparation.

Terziet:

Class. Quantum Grav. 39 025009 (2022)

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

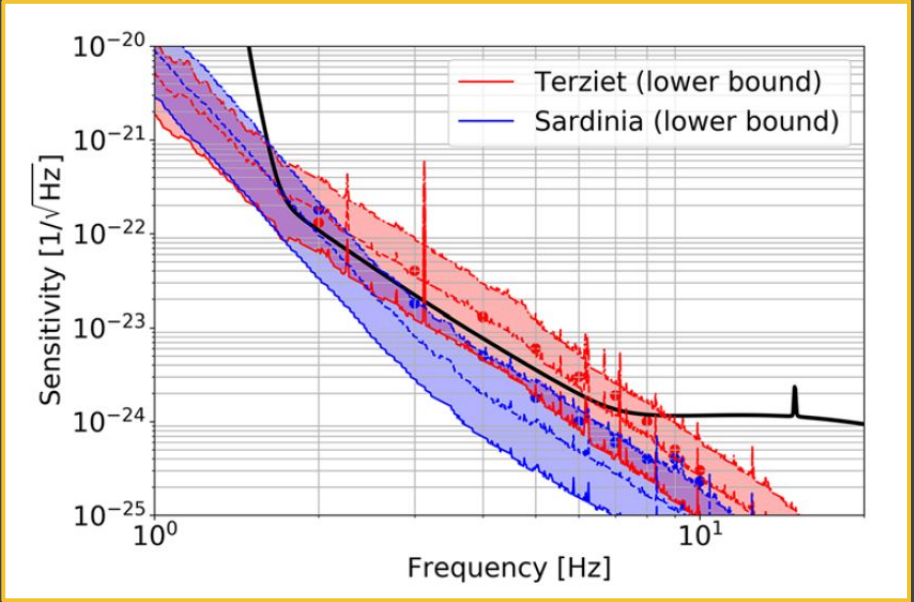
Maria Bader[1,5], Soumen Koley[1,2,*], Jo van den Brand[1,3,5], Xander Campman[4], Henk Jan Bulten[1,5], Frank Linde[1,6] and Bjorn Vink[7]

Horizontally layered model

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 Naticchioni[3], Enrico Calloni[4,5], Rosario De Rosa[4,5], Fulvio Ricci[3,6], Domenico D'Urso[7,8]



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

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 at the ET Symposium LINK

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)

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 Bertolini[3], T Bulik[4], I Fiori[5], B Idzkowski[4], A Kutynia[4], K Nikliborc[4], F Paoletti[6], A Paoli[5], L Rei[7] and M Suchinski[4]

Quantum Grav. 37 195016 (2020)

Cornell University

Astrophysics > Instrumentation and Methods for Astrophysics

arXiv:2310.05709 (astro-ph)

[Submitted on 9 Oct 2023]

Joint Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves in the Einstein Telescope

Francesca Badaracco, Jan Harms, Luca Rei

FOR THE FUTURE:

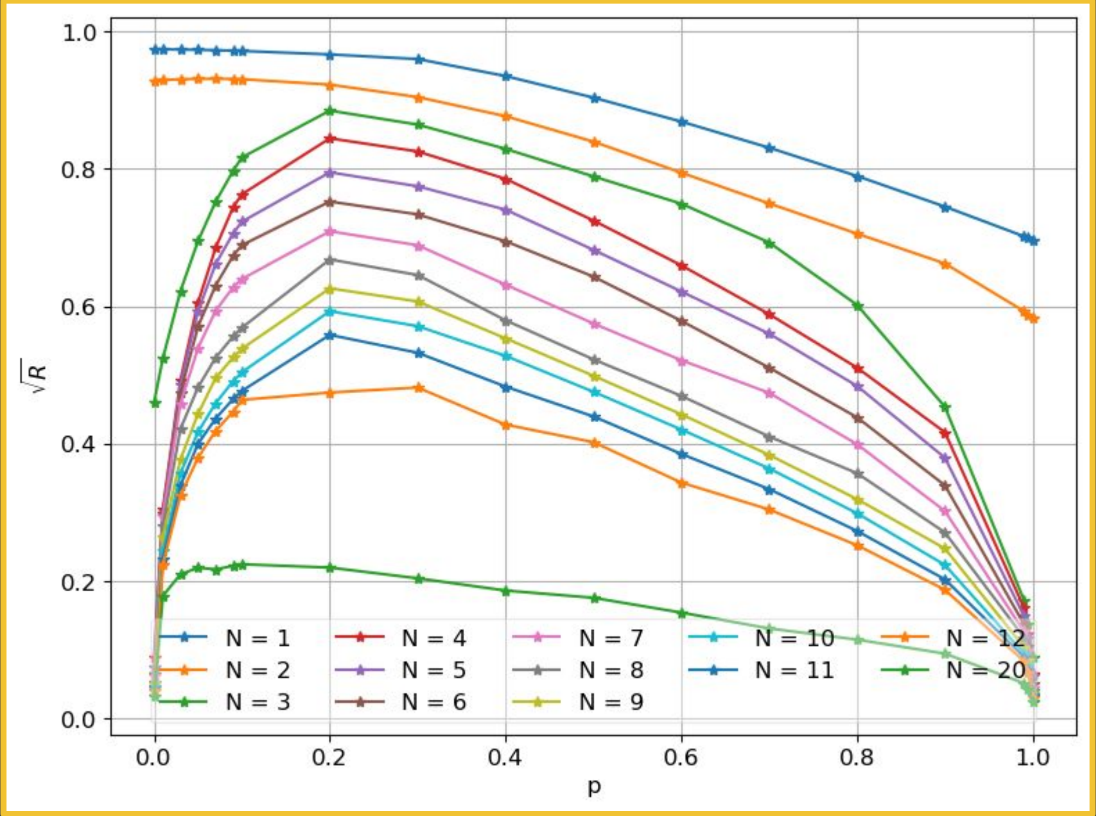
1. Collecting Data
2. Gaussian Process Regression in 3D (GPR) + some tricks
3. Optimization on the inferred seismic field

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!

(see: ArXiv)

Mixing value:

$$p = \frac{\text{Energy(P-waves)}}{\text{Energy(tot)}}$$

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

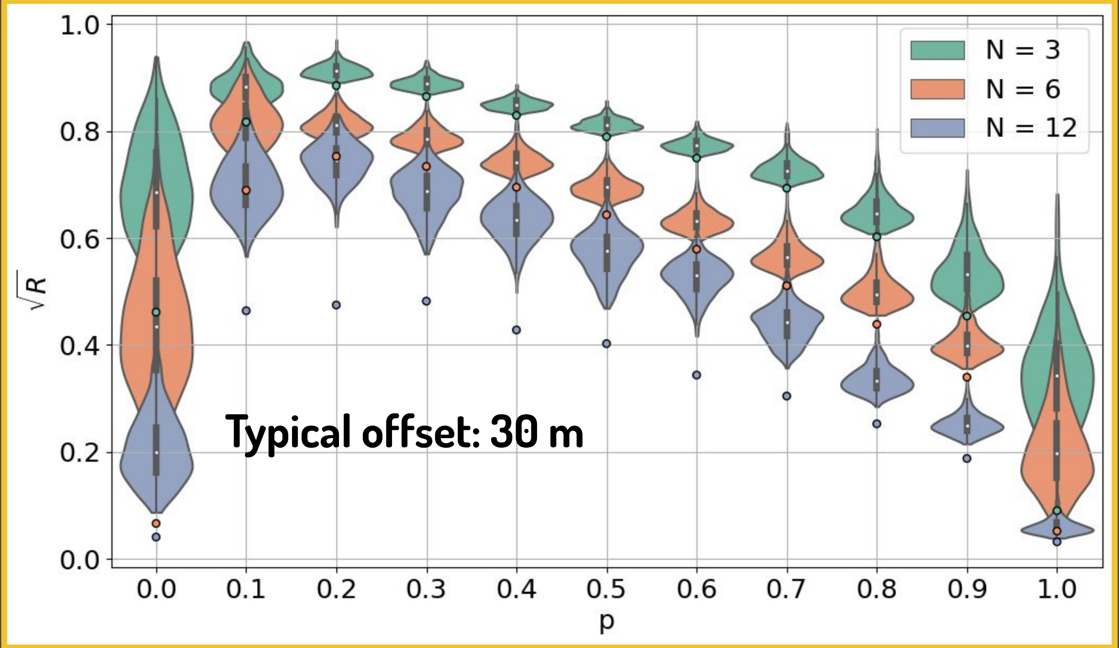
NB: the Residual is in the range (0,1) and it informs about the performances of the NN cancellation:

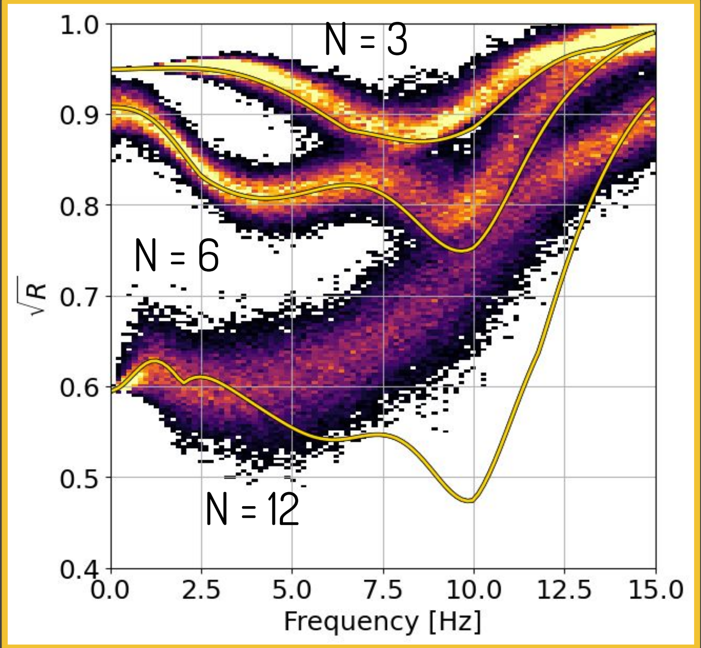
R = 0 → Perfect cancellation

R = 1 → NO cancellation

What about NN cancellation?

Problem 1: where do we put the sensors?



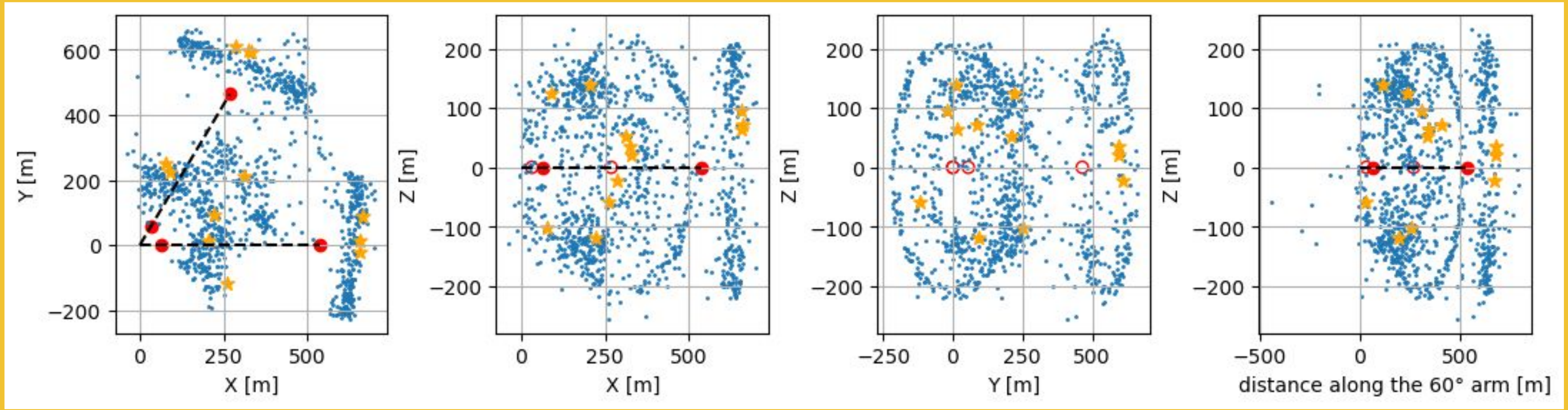


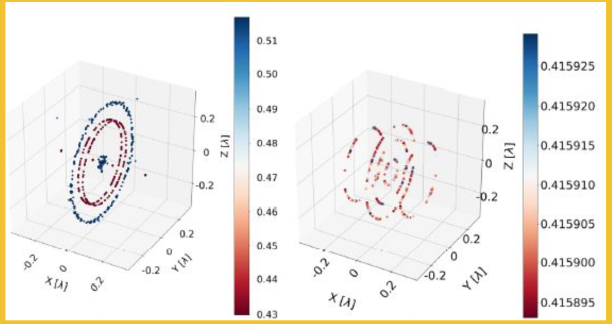
Randomly shifting the sensors from theirs position (left and coloured part on the right) and how the Residual changes with frequency (right). See: [ArXiv]

What about NN cancellation?

Problem 1: where do we put the sensors?

From ArXiv





What's next? → search for the best locations constraining the space to the available surfaces of ET tunnels and caverns

From F Badaracco and J Harms 2019 *Class. Quantum Grav.* 36 145006

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

HELMUT SCHMIDT UNIVERSITÄT
Universität der Bundeswehr Hamburg

Katharina-Sophie Isleif
&
Reinhardt Rading
(see their talk at the 2nd ET Annual meeting)

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?

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

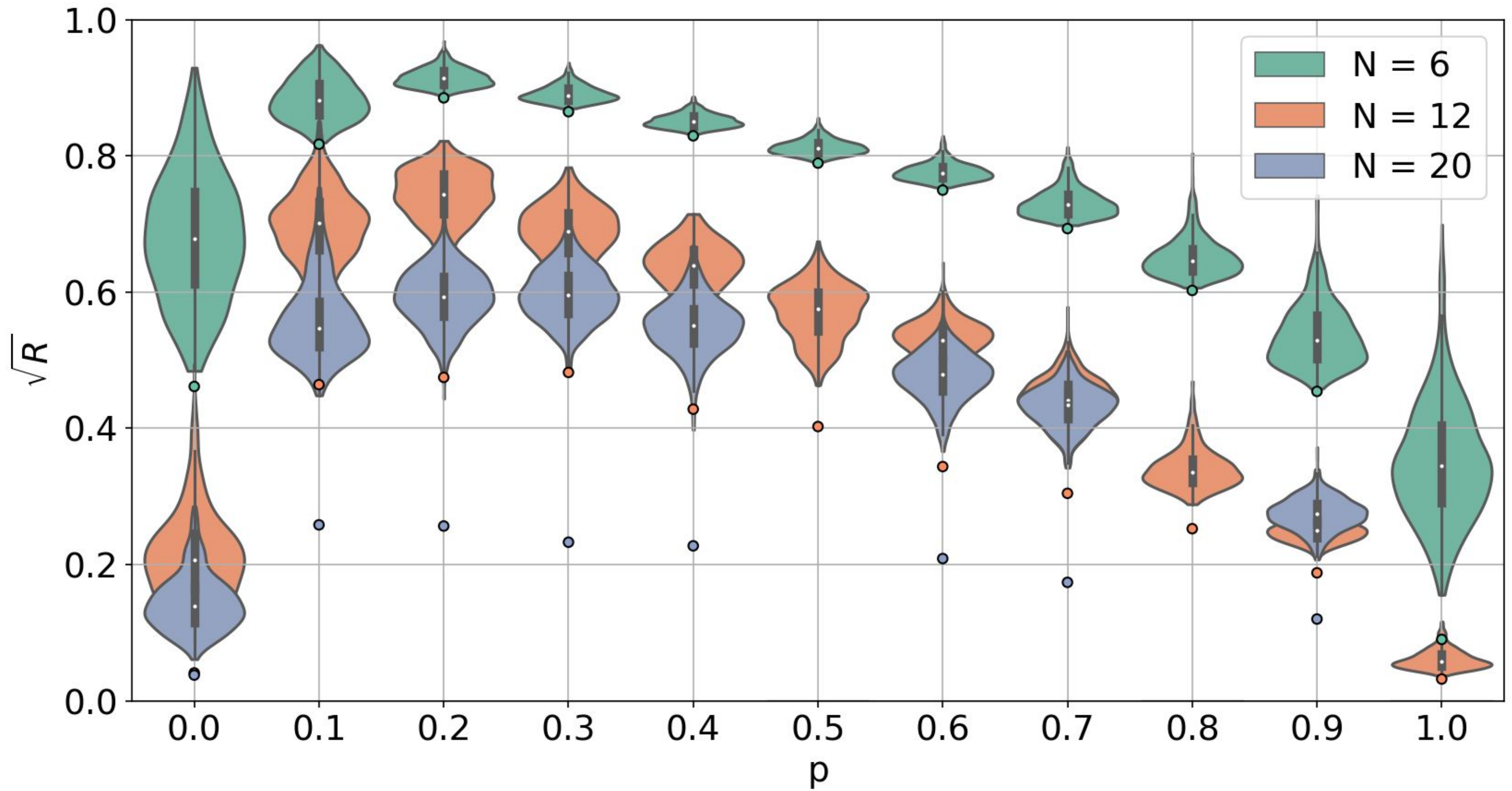
The complete (I hope) list of all NN papers is on the wiki page of the ET ANM : LINK

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

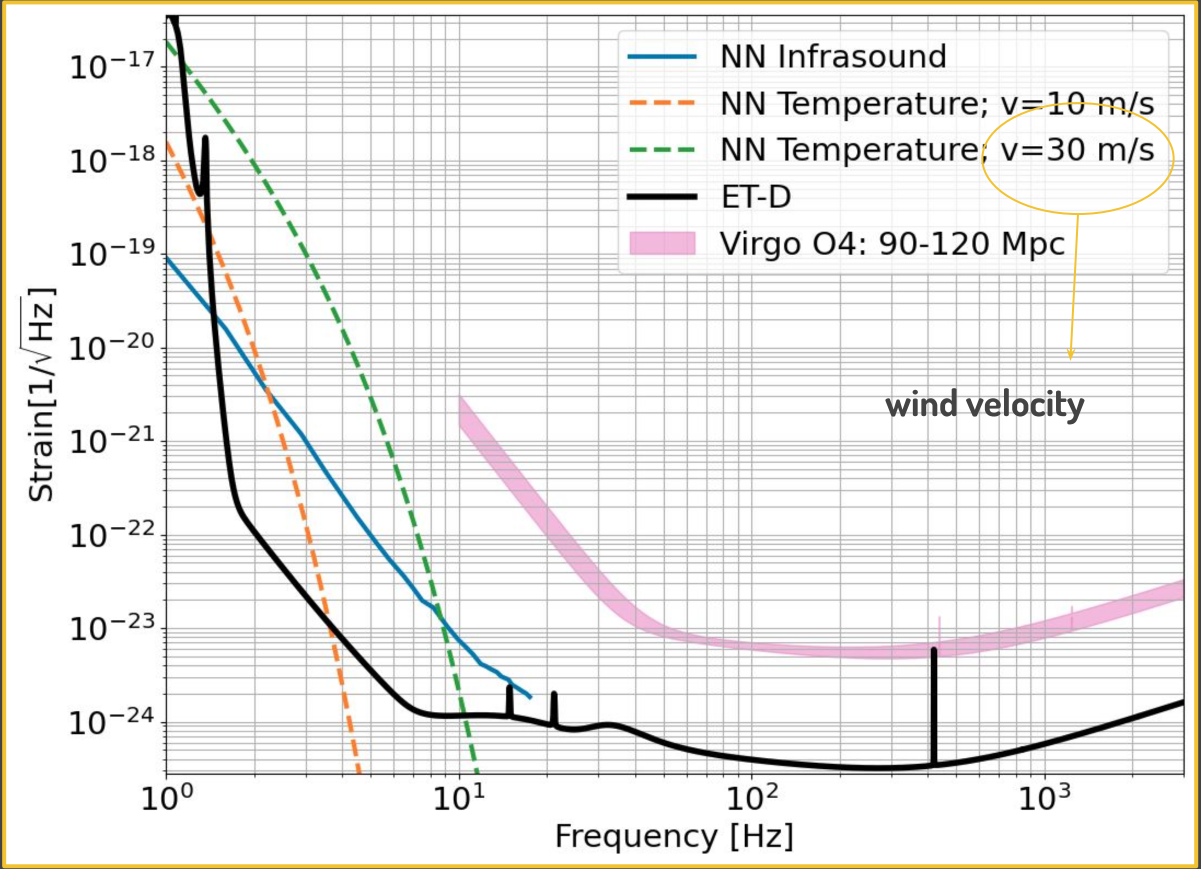
(francesca.badaracco@ge.infn.it)

Thank you for the attention

Backup slides


N = 6
N = 12
N = 20
1.0
0.8
0.6
0.4
0.2
0.0
$\sqrt{R}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
p

Atmospheric NN at the surface (ANN)



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

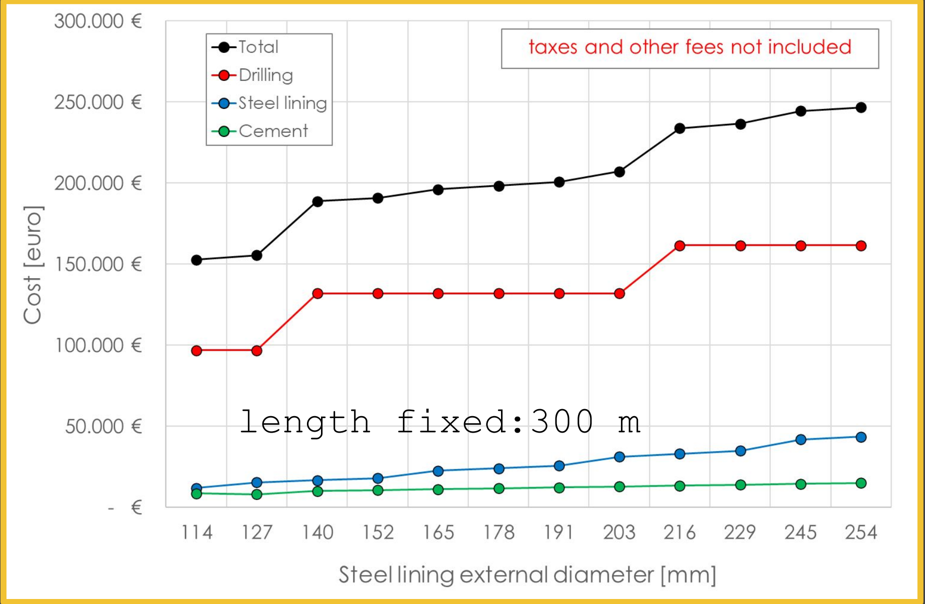
Building ET on the surface would lead to **huge efforts** to reduce ANN

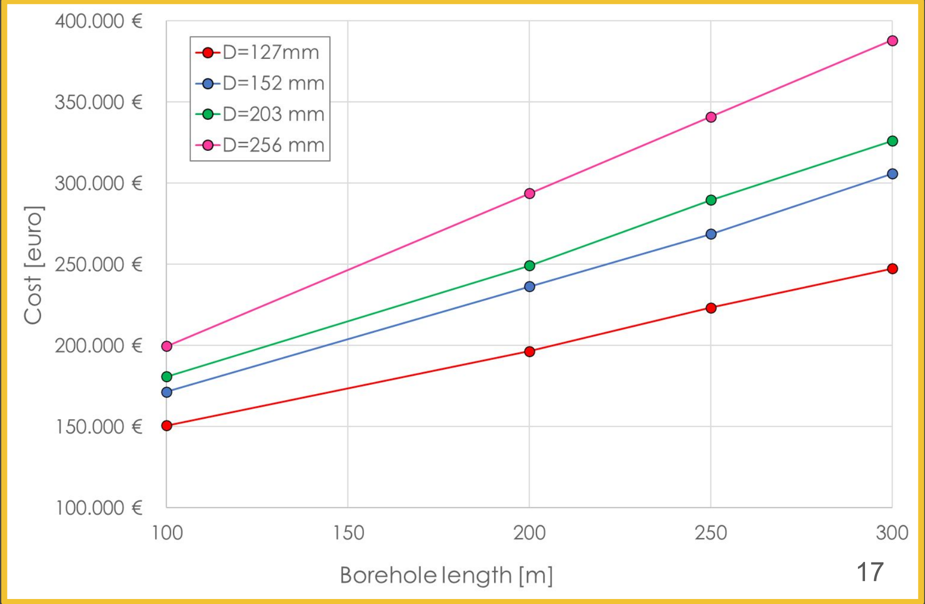
Advected temperature fields estimated for wind velocities of 10 m/s and 30 m/s.

Galaxies **2022**, *10*(1), 20

NN cancellation array: costs

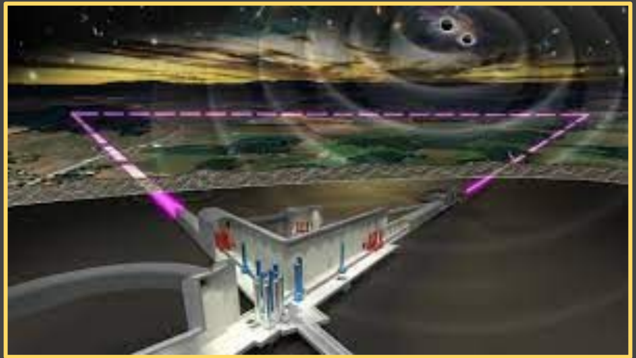
- High-Quality Broadband borehole seismometer ~ 50k€
- Seismometer chains → reducing excavation costs
- Low vertical tilt required (few degrees)
- R&D on sensors for non-vertical boreholes is required



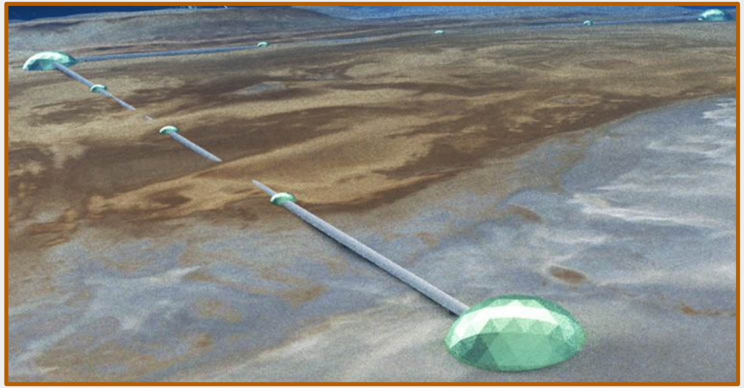


Underground or Surface: differences

Credits: http://www.et-gw.eu/

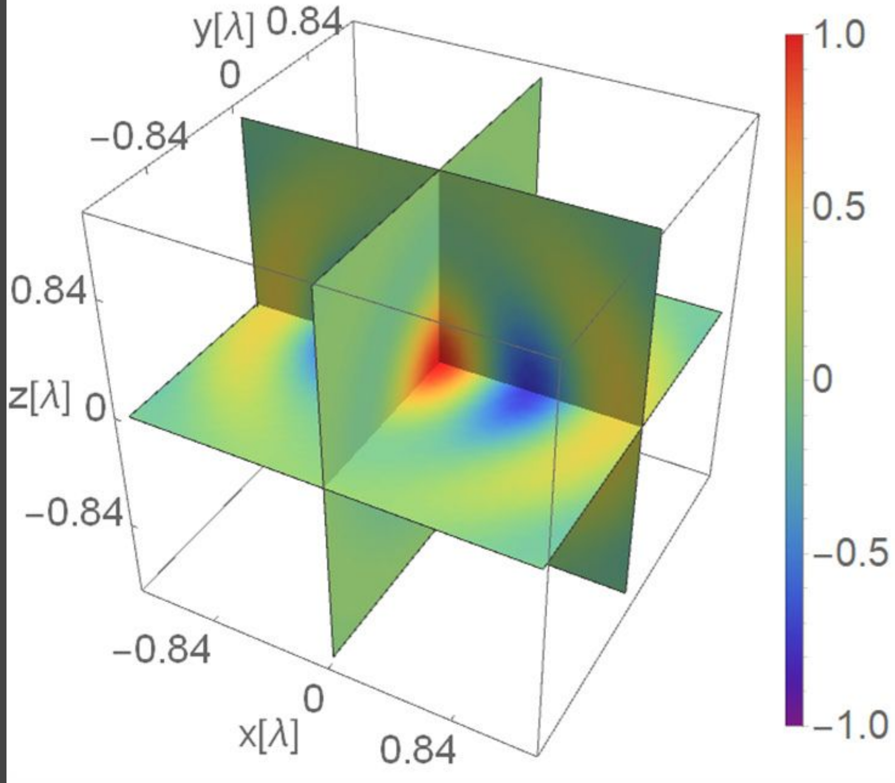


- Suppressed **Rayleigh** waves contribution
- **Body waves** dominate: Compression (P) & Shear (S) waves
- **P and S** → spoiled correlations → bad cancellation
- **Sensor deployment** expensive and difficult
- **Atmospheric** NN partially suppressed (see Phys. Rev. D 106, 064040 - 2022)

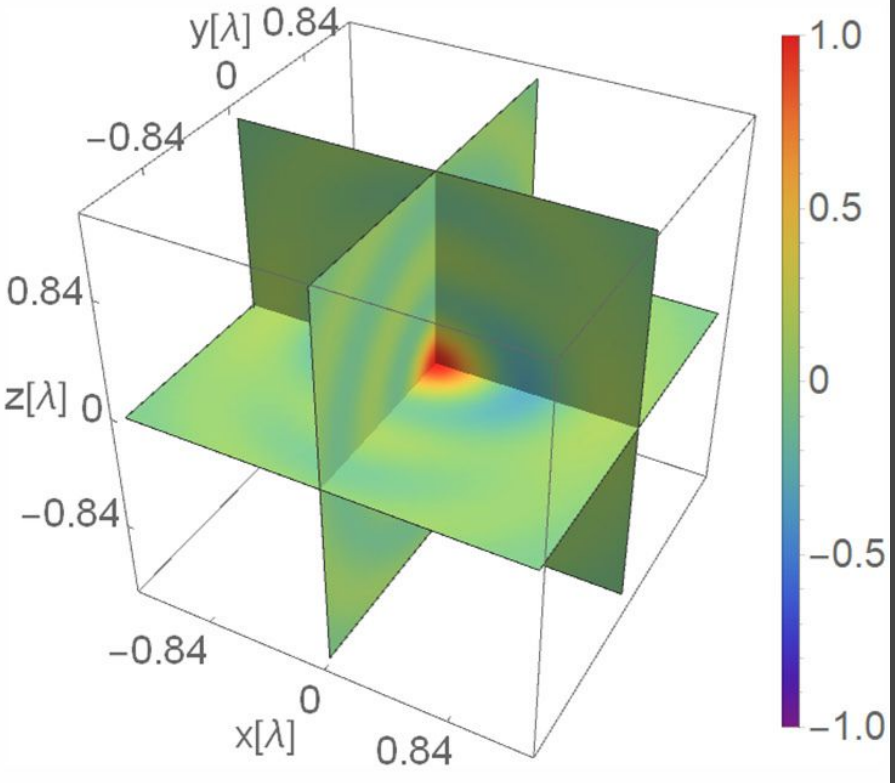


Credits: https://gwic.ligo.org/3Gsubcomm/

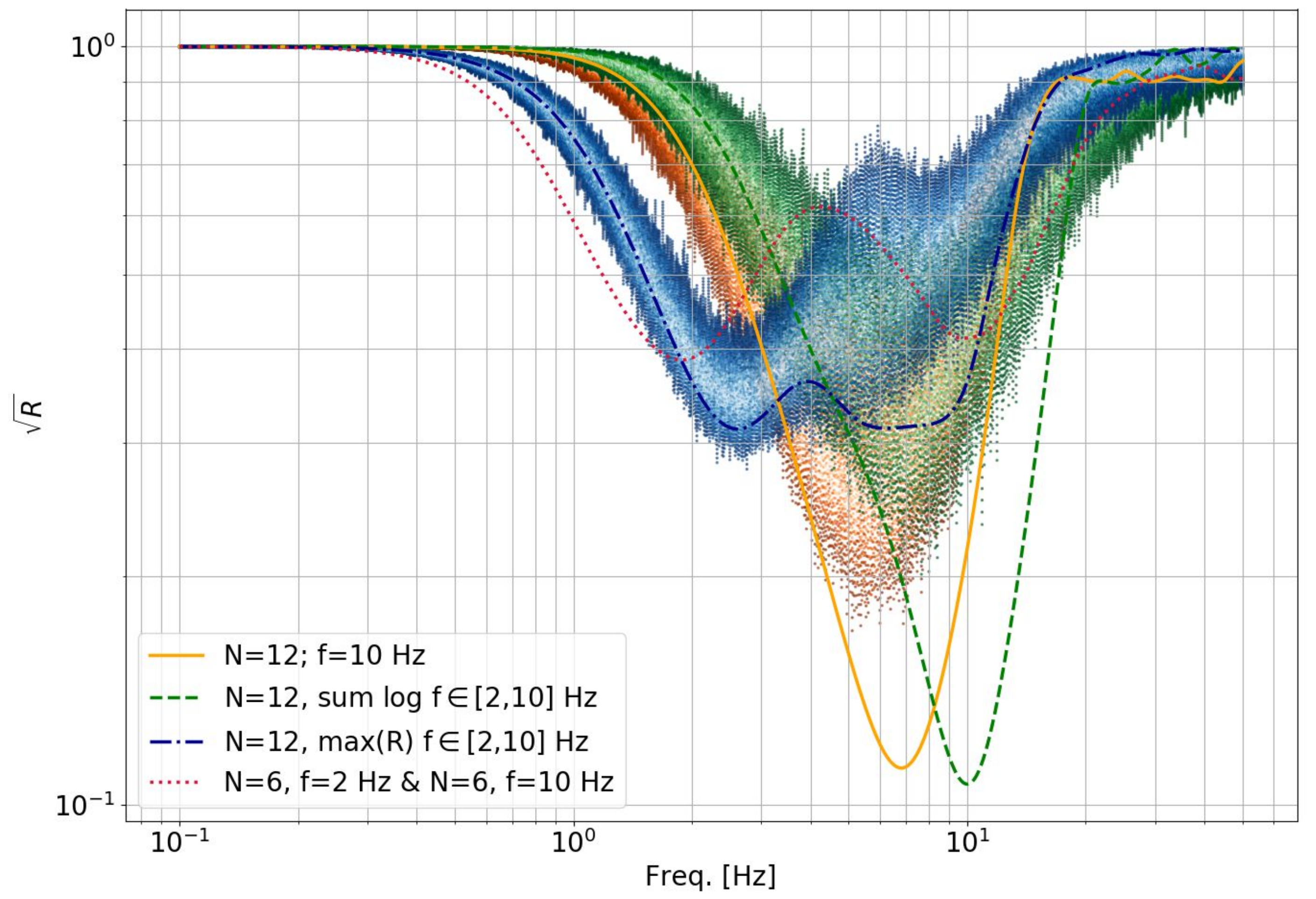
- Surface **Rayleigh** waves dominate
- **Seismic sensor deployment** relatively easy
- Presence of **Atmospheric** NN


y[λ] 0.84
0
−0.84
0.84
z[λ] 0
−0.84
−0.84
0
x[λ]
0.84
1.0
0.5
0
−0.5
−1.0

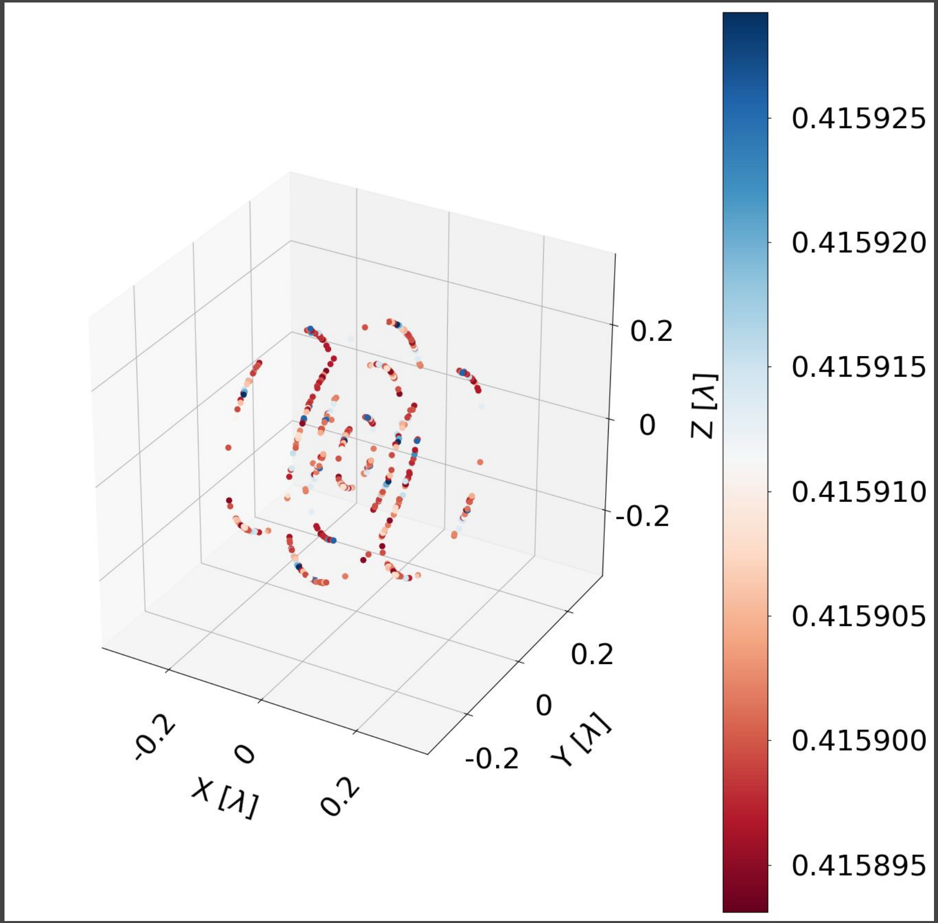
(a)


y[λ] 0.84
0
−0.84
0.84
z[λ] 0
−0.84
−0.84
0
x[λ]
0.84
1.0
0.5
0
−0.5
−1.0

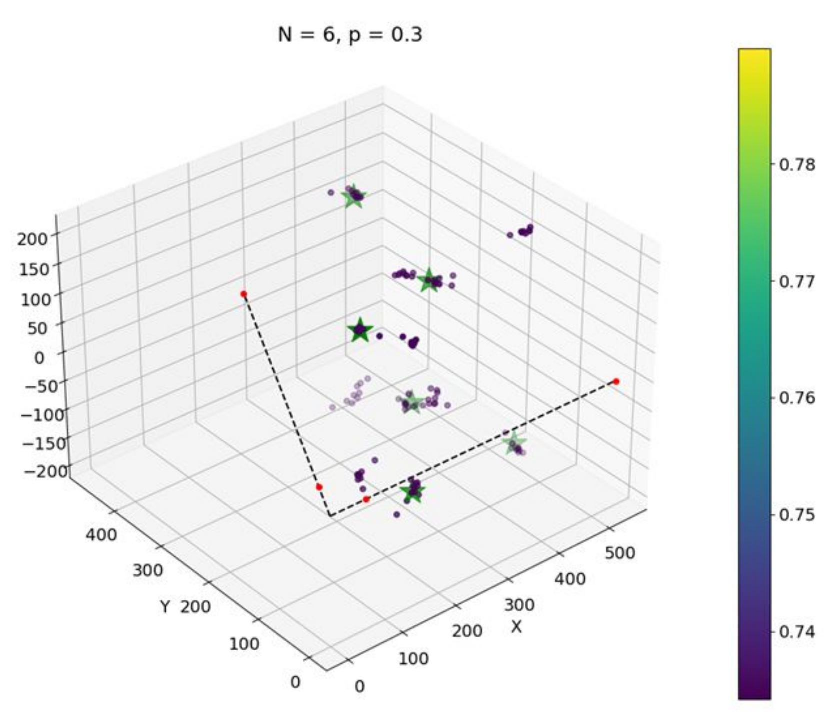
(b)



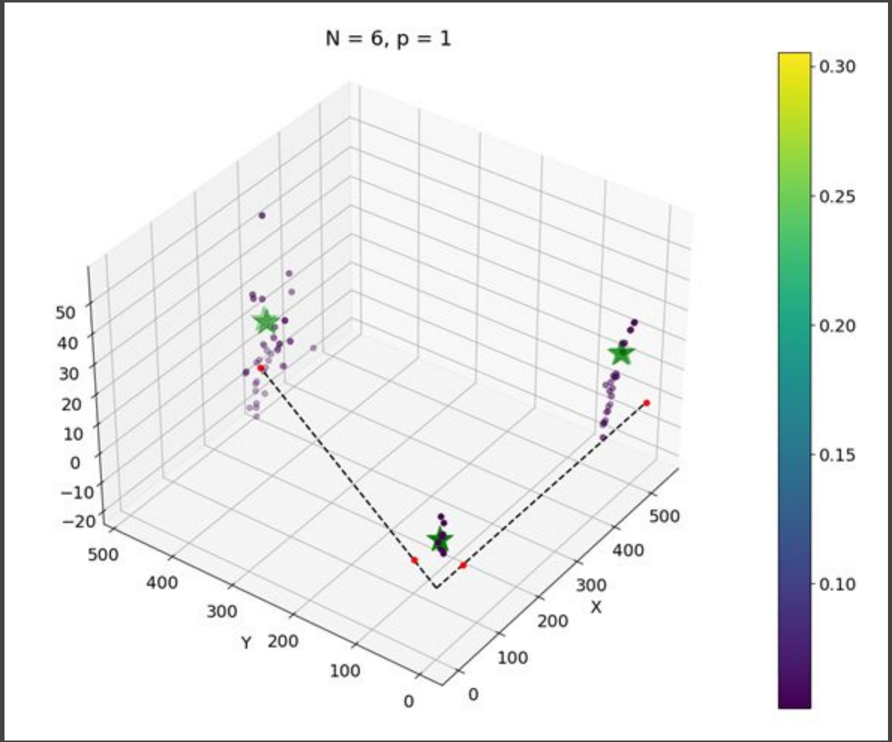
10^0
10^{-1}
$\sqrt{R}$
10^{-1}
10^0
10^1
Freq. [Hz]
N=12; f=10 Hz
N=12, sum log f ∈ [2,10] Hz
N=12, max(R) f ∈ [2,10] Hz
N=6, f=2 Hz & N=6, f=10 Hz



0.415925
0.415920
0.415915
0.415910
0.415905
0.415900
0.415895
0.2
0
-0.2
Z [λ]
0.2
0
-0.2
Y [λ]
-0.2
0
0.2
X [λ]



N = 6, p = 0.3
200
150
100
50
0
−50
−100
−150
−200
400
300
Y 200
100
0
0
100
200
300
400
500
X
0.78
0.77
0.76
0.75
0.74



N = 6, p = 1
50
40
30
20
10
0
−10
−20
500
400
300
Y 200
100
0
0
100
200
300
400
500
X
0.30
0.25
0.20
0.15
0.10

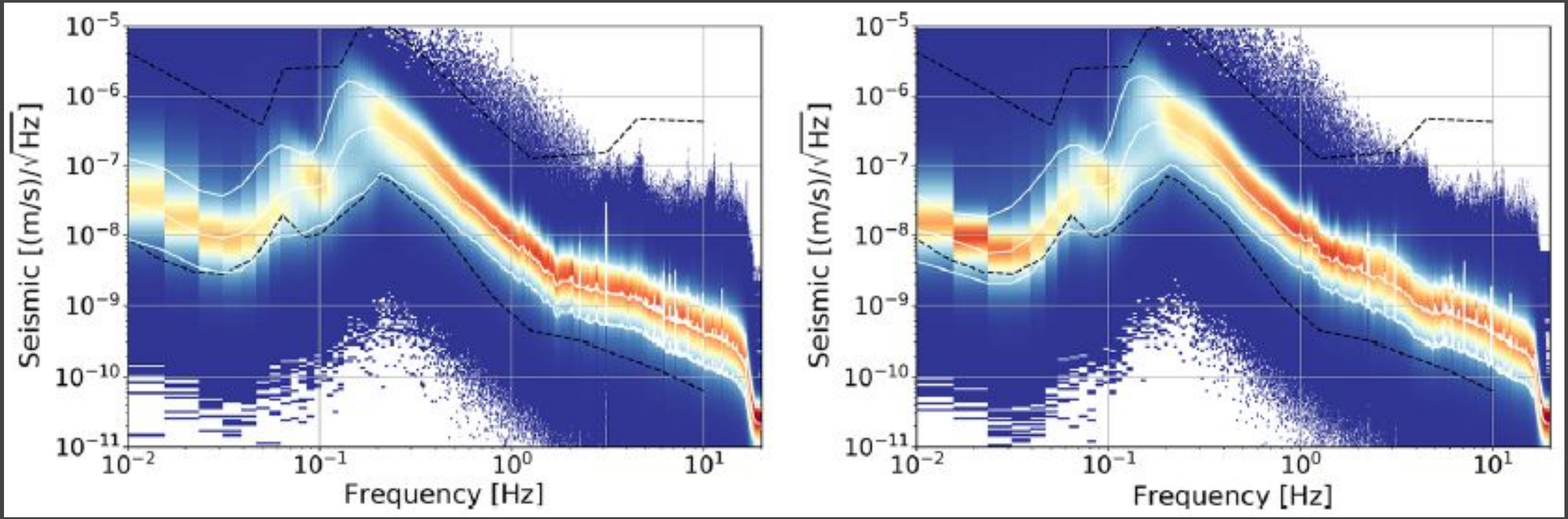


Fig 1 of The European Physical Journal Plus volume 137, Article number: 687 (2022):

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

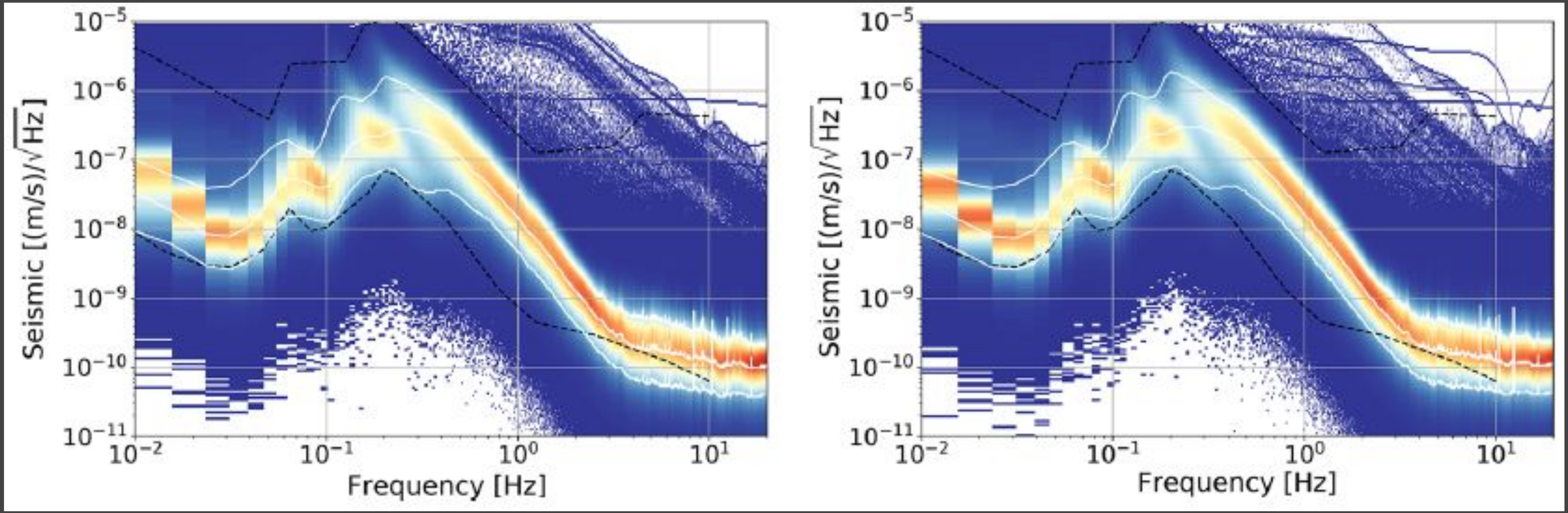
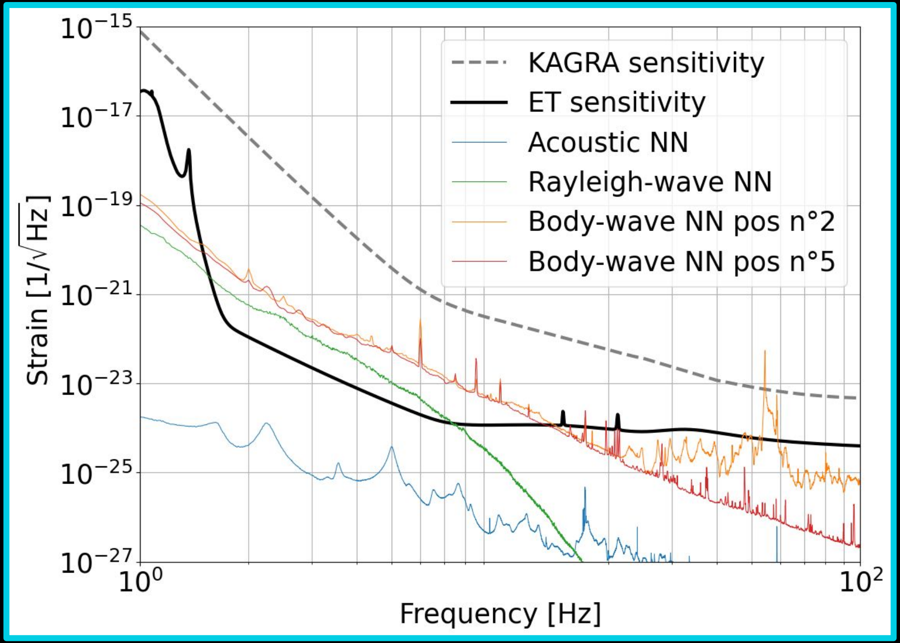


Fig 2 of The European Physical Journal Plus volume 137, Article number: 687 (2022)

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.

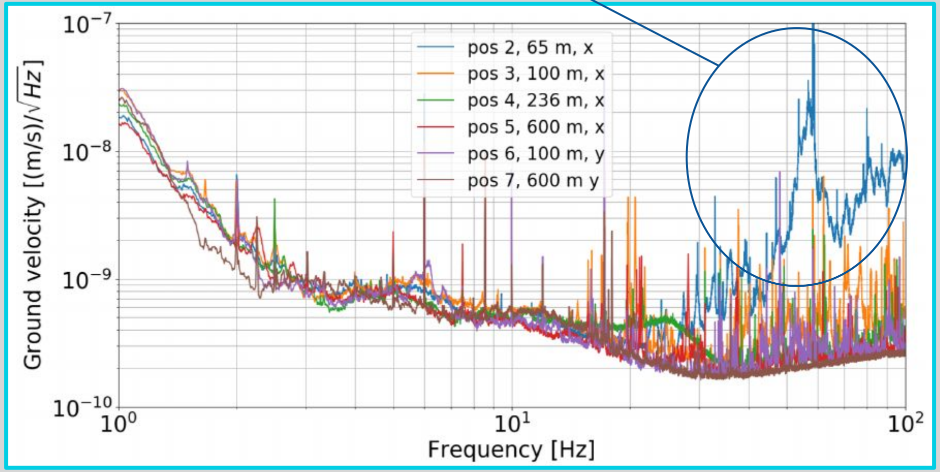
Infrastructural noise:

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):

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

- $\hat{x}(m)$: Expected signal
- w_k: Wiener filter coefficients
- $y(m-k)$: Sensor signal

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

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

- $R(\omega)$: Residual
- $\vec{C}_{SN}^{\dagger}(\omega)$: CPSD between the N sensors and the target (NN)
- $\mathbf{C}_{SS}(\omega)$: CPSD between the N sensors
- $C_{NN}(\omega)$: PSD of the target signal (NN)

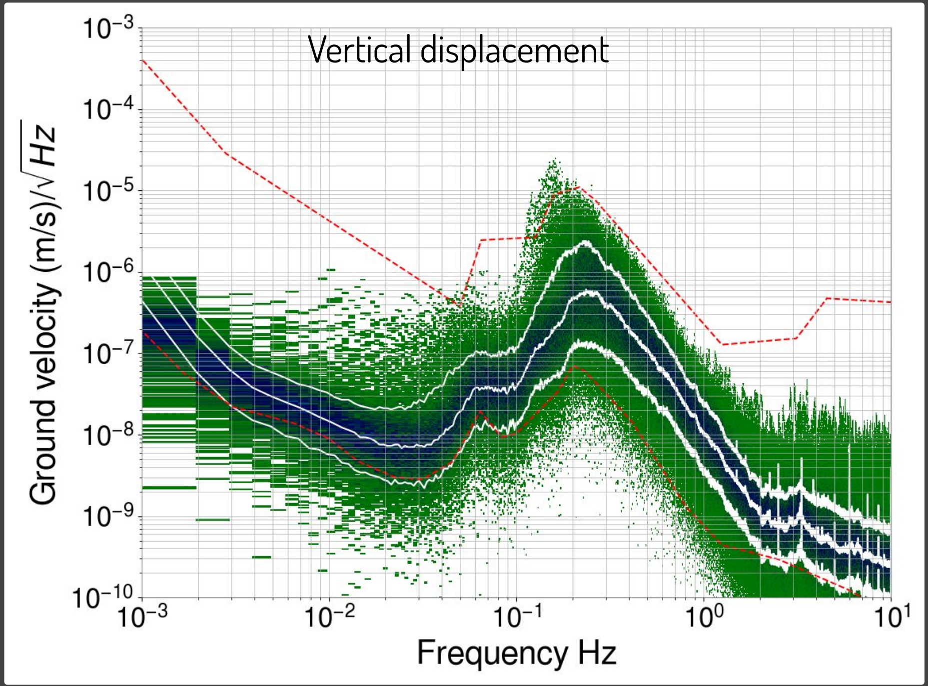
Cross Power Spectral Density = **CPSD**
Power Spectral Density = **PSD**

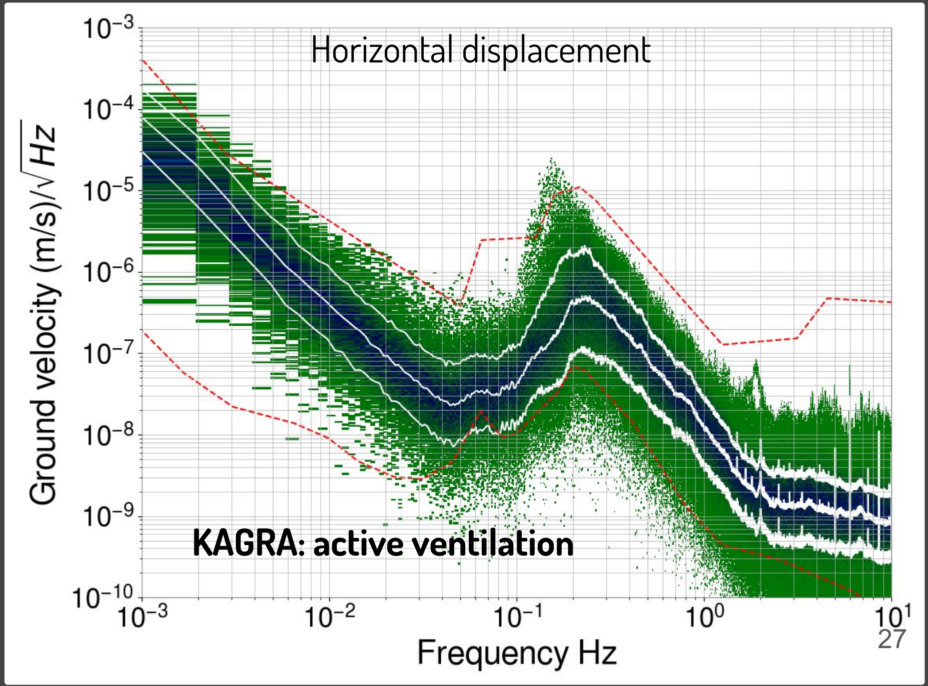
What causes underground excess tilt?

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





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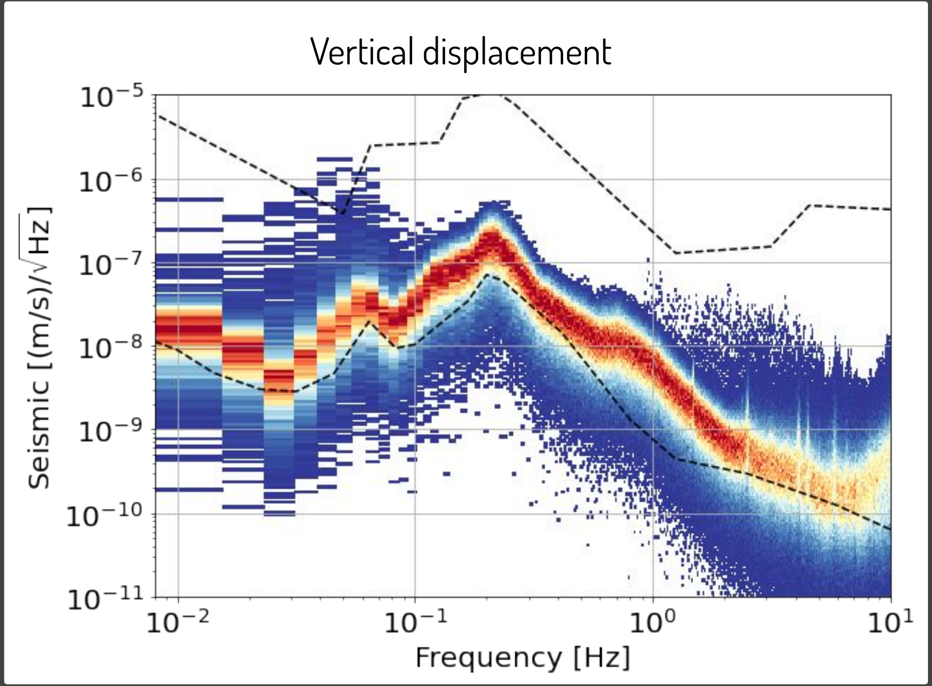

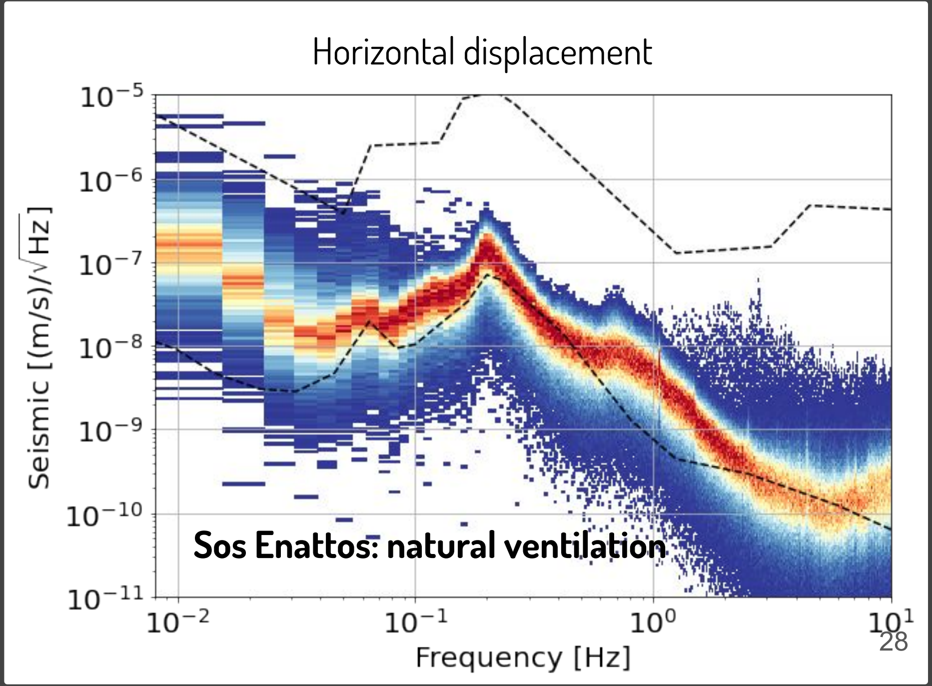

NN simulation papers:

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 Mandic[1]

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 Coughlin[1] and J Harms[2]

Class. Quantum Grav. 37 105007 (2020)

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

Ayatri Singha[1], Stefan Hild[1] 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 Harms[1] and Stefan Hild[2]

Phys. Rev. D 103, 122004 (2021)

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

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Class. Quantum Grav. 38 2450072021)

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

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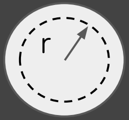
Shell theorem and NN shear-wave equation: contrast or agreement?

Inside a spherical shell the gravity field is ZERO everywhere

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

Long wavelength approximation: constant Shear-wave displacement → rigid displacement of the spherical cavern

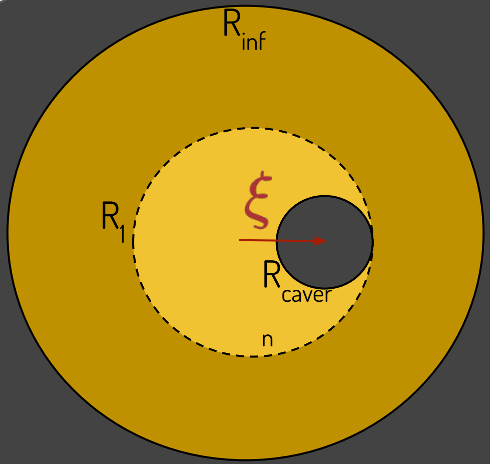
Gravitational field inside a sphere:



$$\delta \mathbf{a}(\mathbf{r}, t) = \frac{4}{3}\pi G \rho_0 \mathbf{r}$$

Gravitational field inside a spherical hole moved by ξ inside a sphere:

$$\delta \mathbf{a}(\xi, t) = \frac{4}{3}\pi G \rho_0 \xi$$



Surface integration over a shell with infinite outer radius (internal radius = cavern radius)

$$\delta \mathbf{a}(\mathbf{r}_0, t) = \frac{4}{3}\pi G \rho_0 \xi(t)$$