Surrogate Wiener filtering for the prediction and optimized cancellation of Newtonian noise at Virgo

22 March 2021

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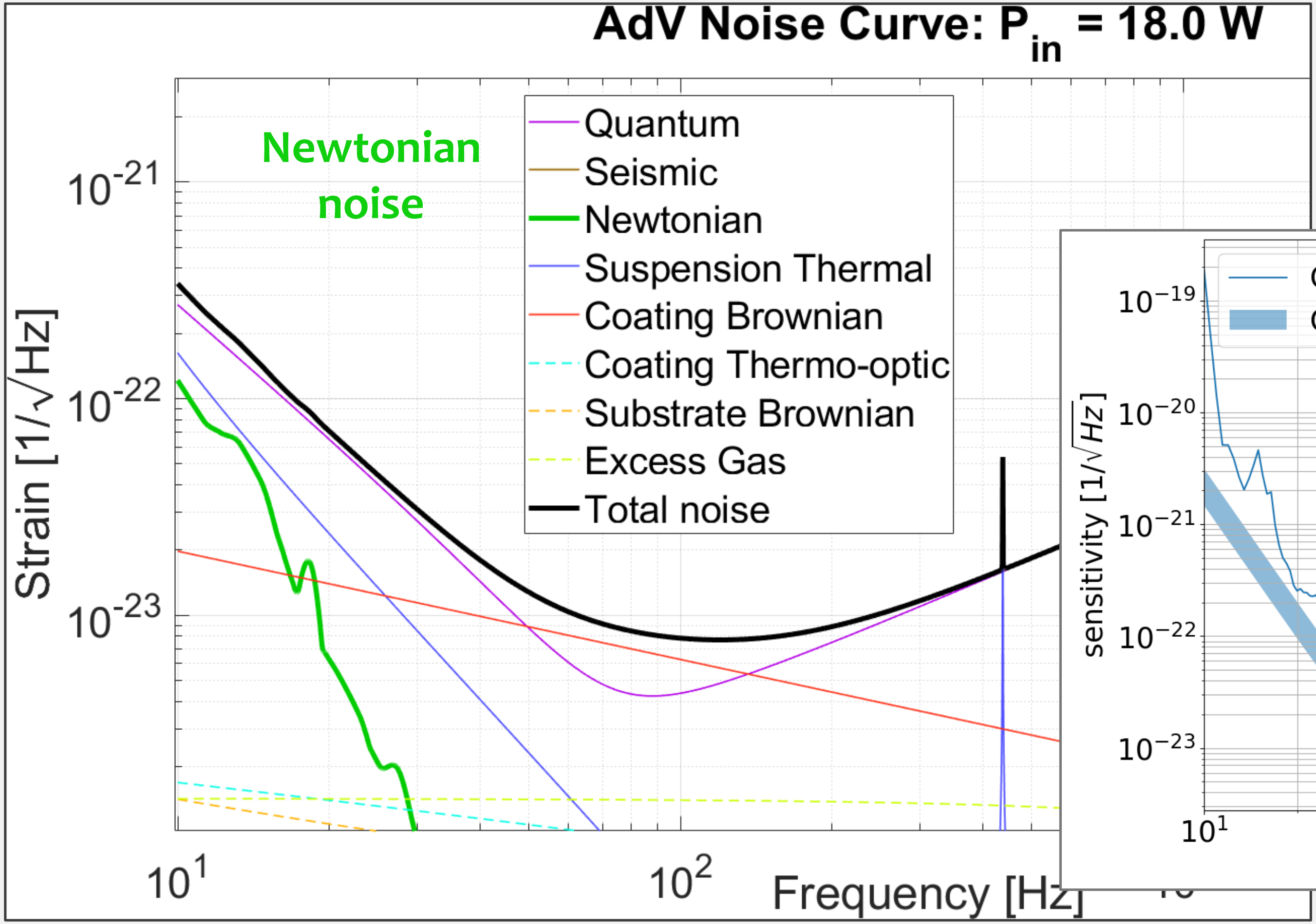
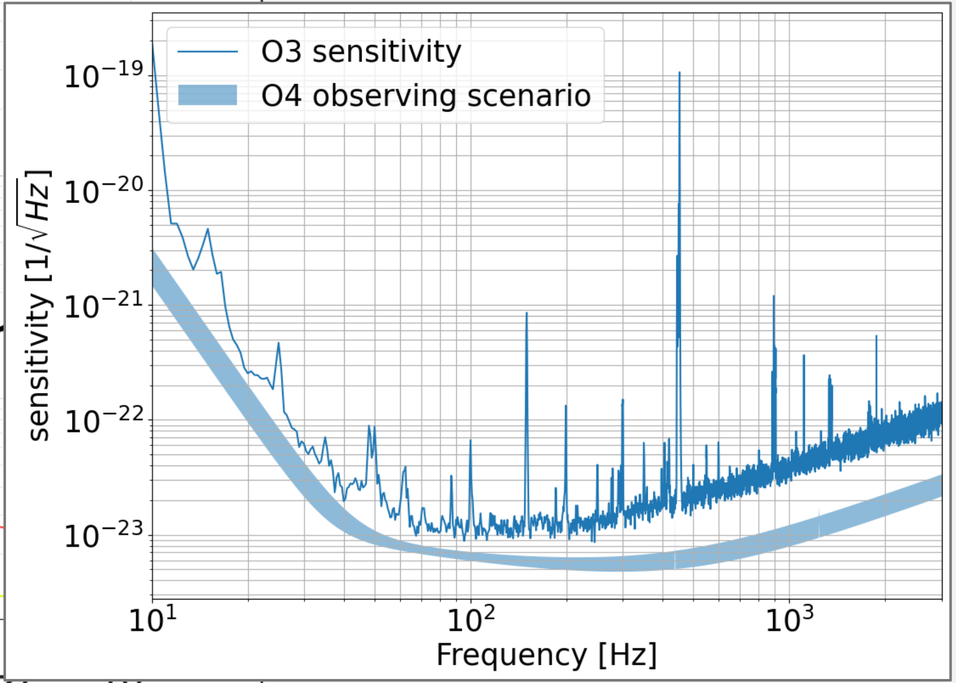
(PhD work made in GSSI)

UCLouvain

Plenty of different kinds of noises



… which limit our sensitivity



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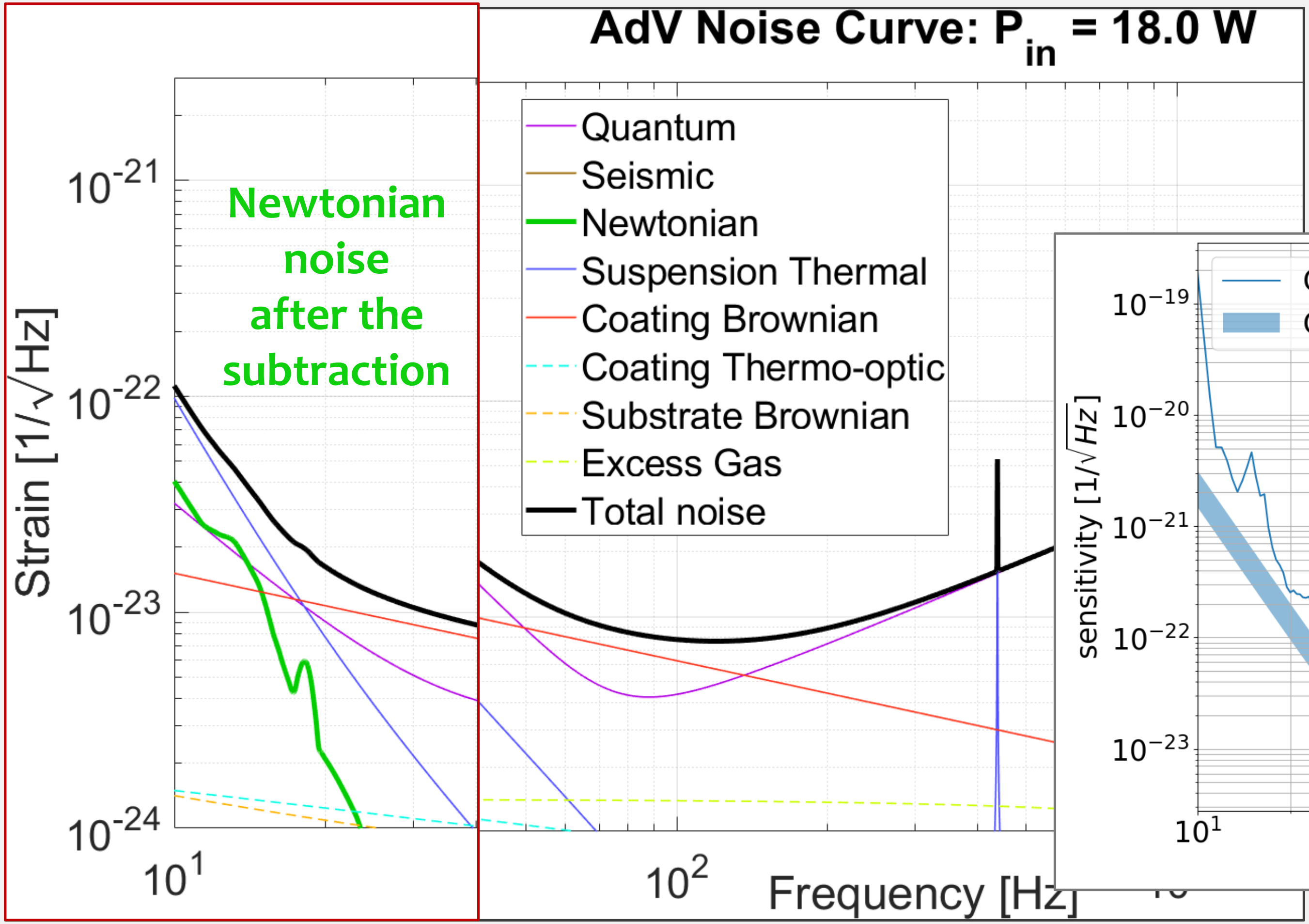
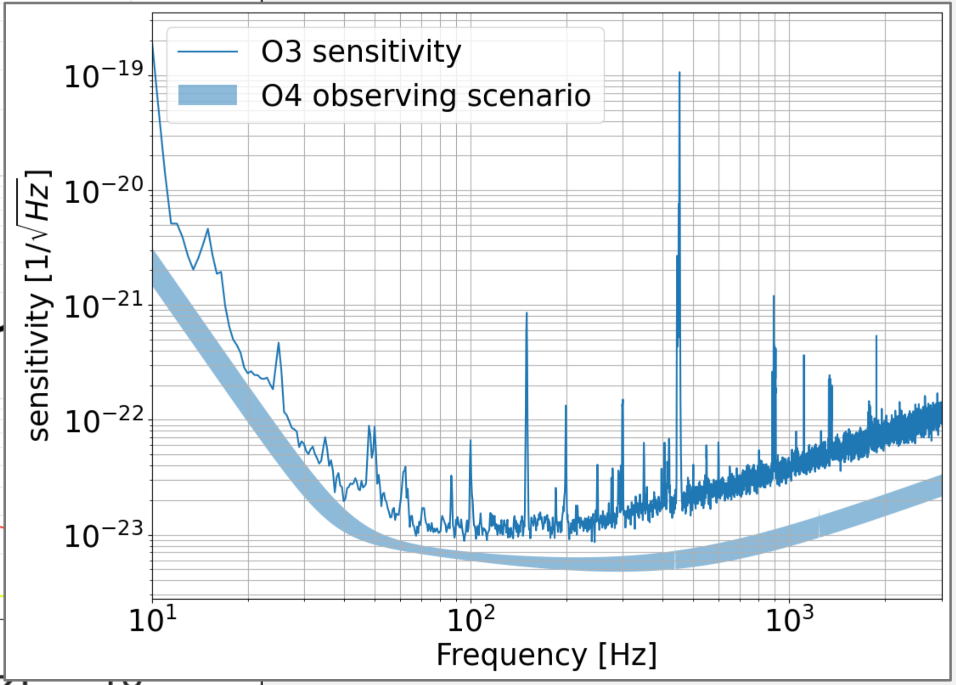


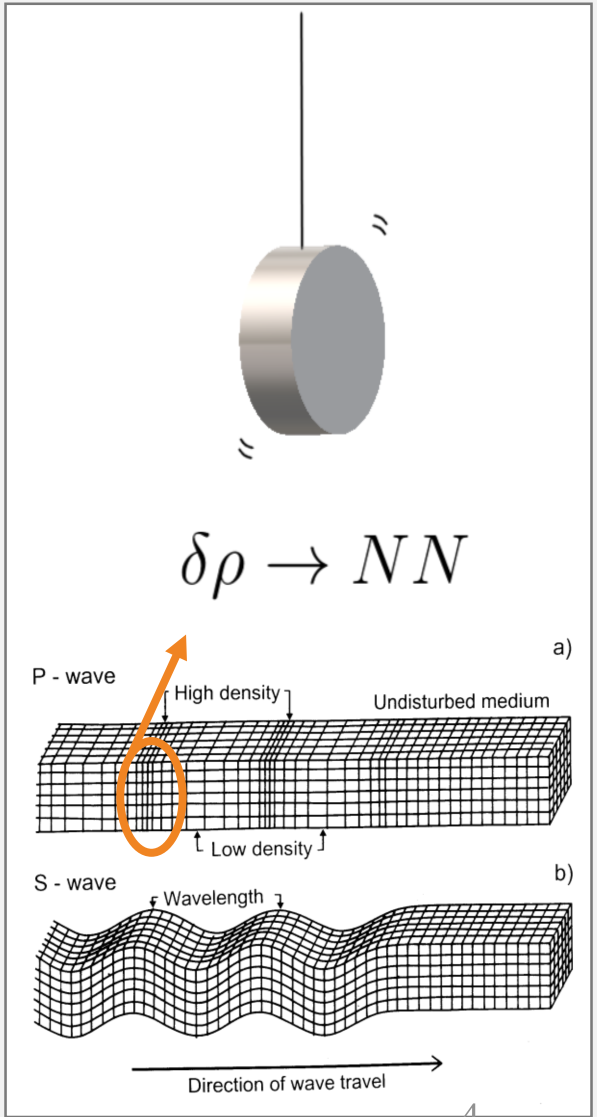
… which limit our sensitivity



What is Newtonian Noise (NN):

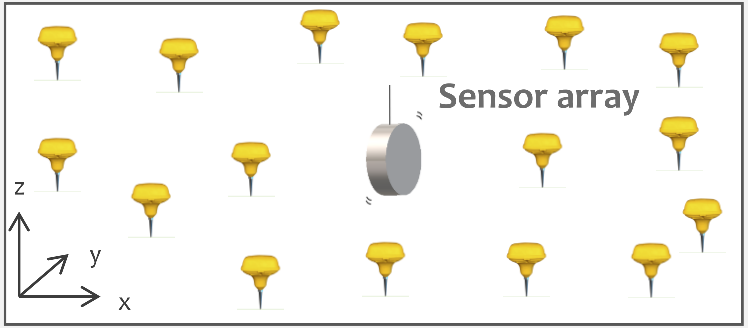
Perturbation of the gravity field due to a variation in the density (δρ) of the surrounding media.

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



Array optimization

- NN: it cannot be physically shielded
- We can perform an active noise cancellation
- Linear filter: Wiener filter (optimal filter)



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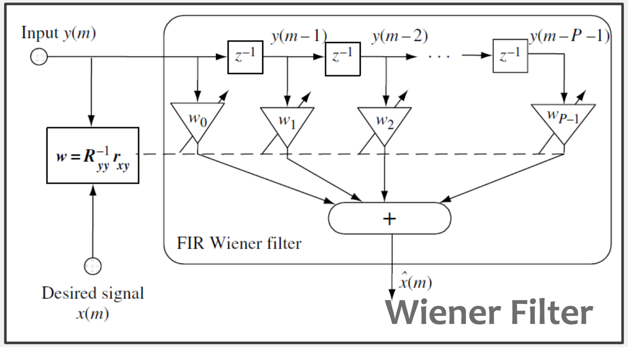

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Newtonian Noise (NN) cancellation

Array optimization

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

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

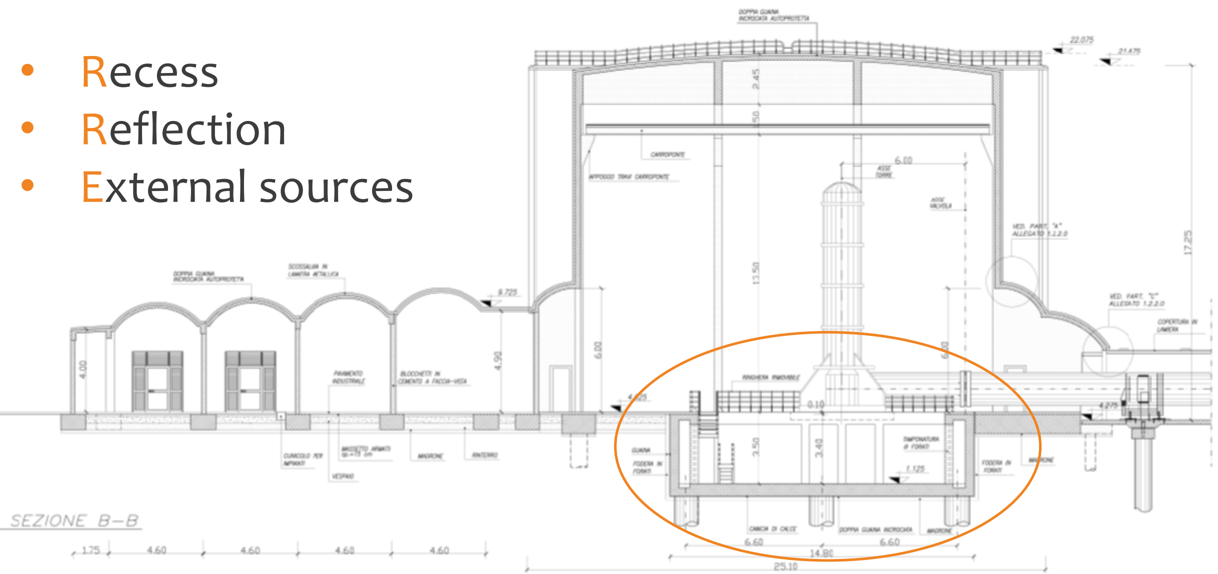
$$R(\omega) = 1 - \frac{\vec{C}_{SN}^{\dagger}(\omega)(\mathbf{C}_{SS}(\omega))^{-1}\vec{C}_{SN}(\omega)}{C_{NN}(\omega)}$$

Wiener filter performances (frequency domain):

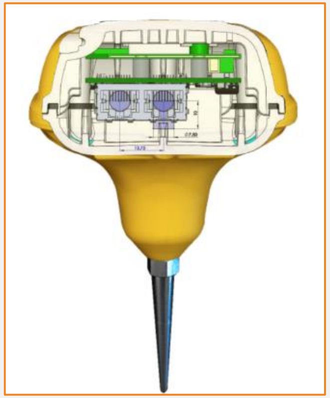
TO REMEMBER!!!

Virgo… another story!

- Recess
- Reflection
- External sources



Virgo… another story!



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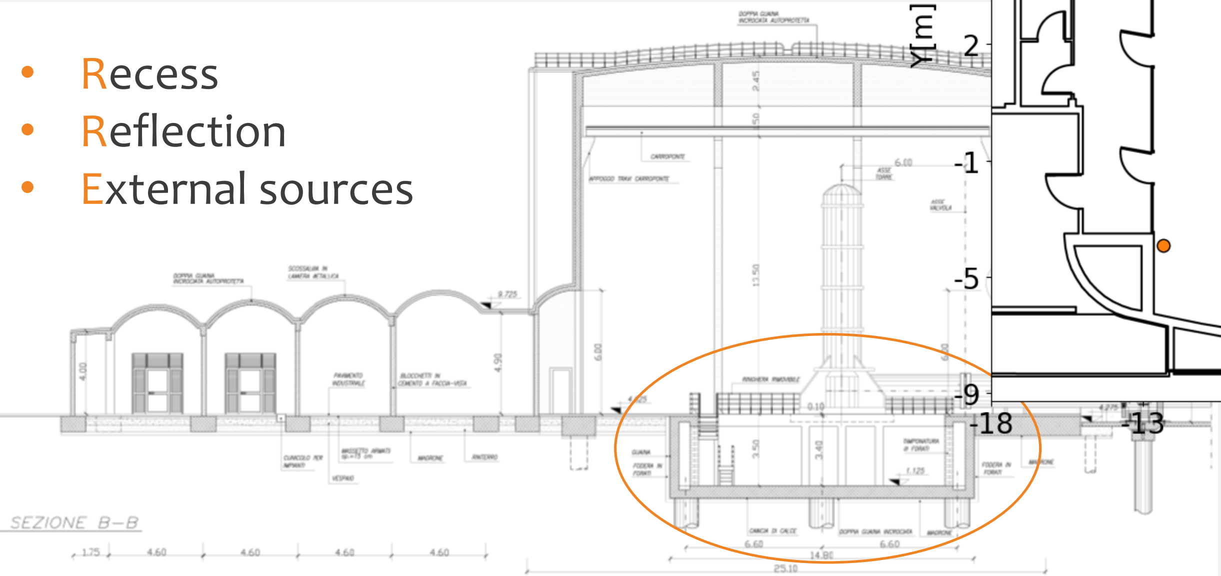
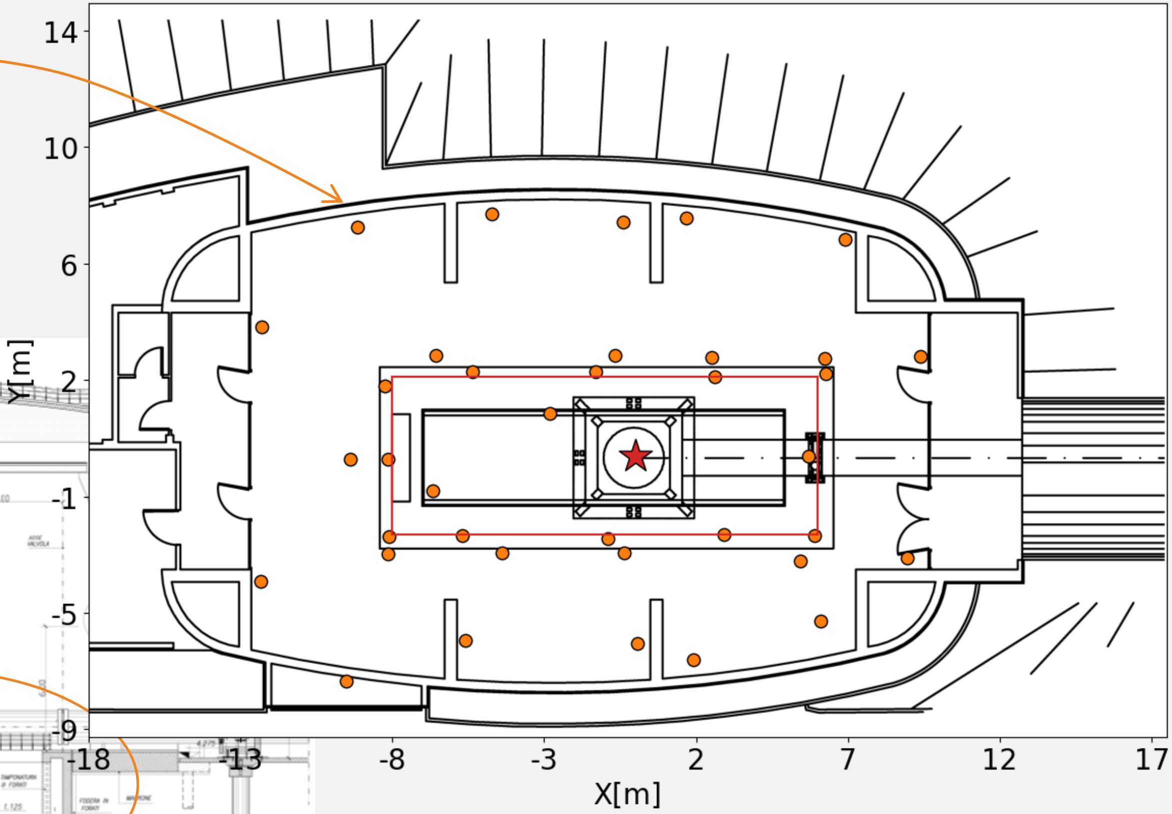


Where we started:



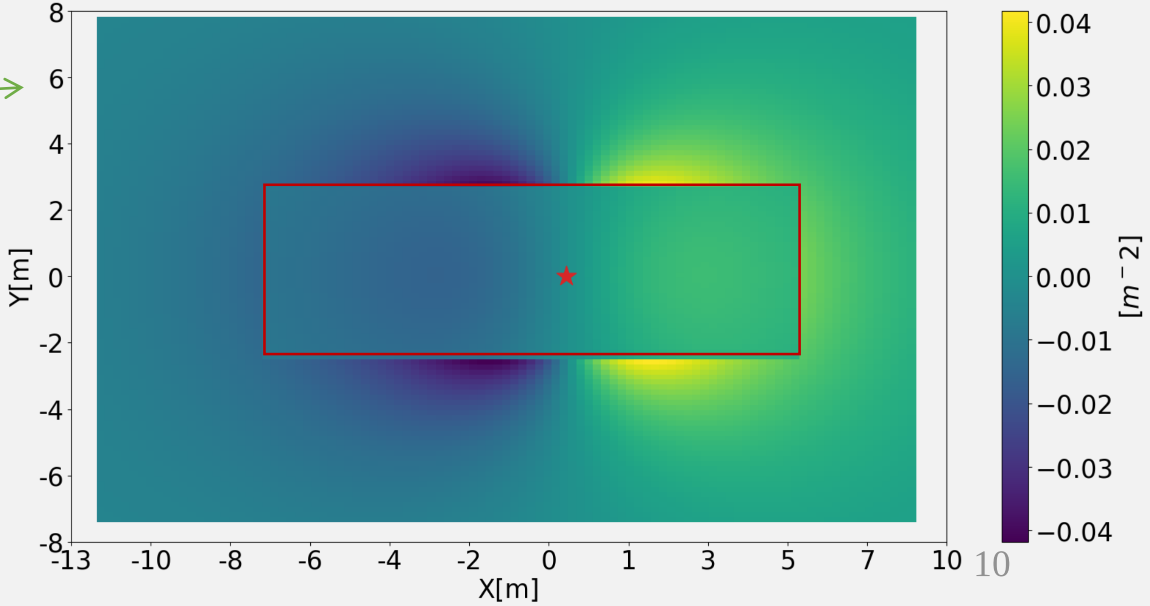
$$R(\omega) = 1 - \frac{\vec{C}^{\dagger}_{\mathrm{SN}}(\omega) \cdot (\mathbf{C}_{\mathrm{SS}}(\omega))^{-1} \cdot \vec{C}_{\mathrm{SN}}(\omega)}{C_{\mathrm{NN}}(\omega)}$$

Remember: the residual function gives a measure of the performance of the Wiener filter (the lower, the better!!!)

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

$$\begin{aligned} C_{\mathrm{SN}}(\vec{r}, \vec{r}_0) &= \mathscr{C} \int C_{\mathrm{SS}}(\vec{r}, \vec{r}_1) \frac{x_0 - x_1}{(h(x_1, y_1)^2 + |\vec{r}_1 - \vec{r}_0|^2)^{3/2}} \mathrm{d}x_1 \mathrm{d}y_1 \\ &= \mathscr{C} \int C_{\mathrm{SS}}(\vec{r}, \vec{r}_1) \mathcal{K}(\vec{r}_1, \vec{r}_0) \mathrm{d}x_1 \mathrm{d}y_1 \end{aligned}$$

CPSDs between the test mass and the seismometers of the array!

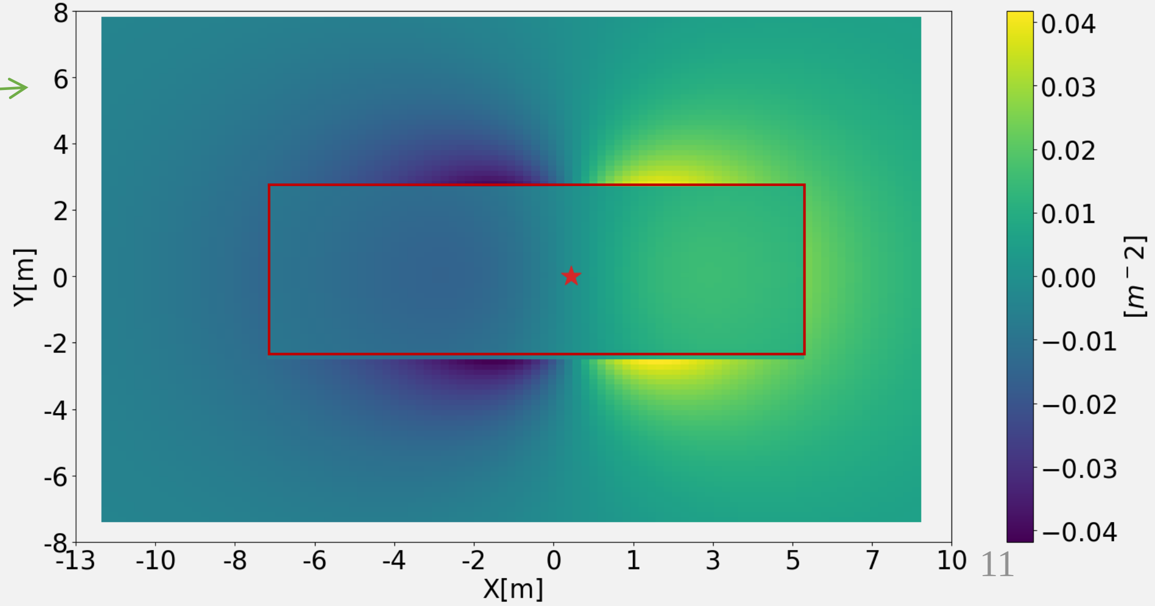


$$R(\omega) = 1 - \frac{\vec{C}_{\mathrm{SN}}^{\dagger}(\omega) \cdot (\mathbf{C}_{\mathrm{SS}}(\omega))^{-1} \cdot \vec{C}_{\mathrm{SN}}(\omega)}{C_{\mathrm{NN}}(\omega)}$$

Correlation between the test mass and the seismometers of the array!

$$C_{\mathrm{SN}}(\vec{r}, \vec{r}_0) = \mathscr{C} \int C_{\mathrm{SS}}(\vec{r}, \vec{r}_1) \frac{x_0 - x_1}{(h(x_1, y_1)^2 + |\vec{r}_1 - \vec{r}_0|^2)^{3/2}} \mathrm{d}x_1 \mathrm{d}y_1$$
$$= \mathscr{C} \int C_{\mathrm{SS}}(\vec{r}, \vec{r}_1) \mathcal{K}(\vec{r}_1, \vec{r}_0) \mathrm{d}x_1 \mathrm{d}y_1$$

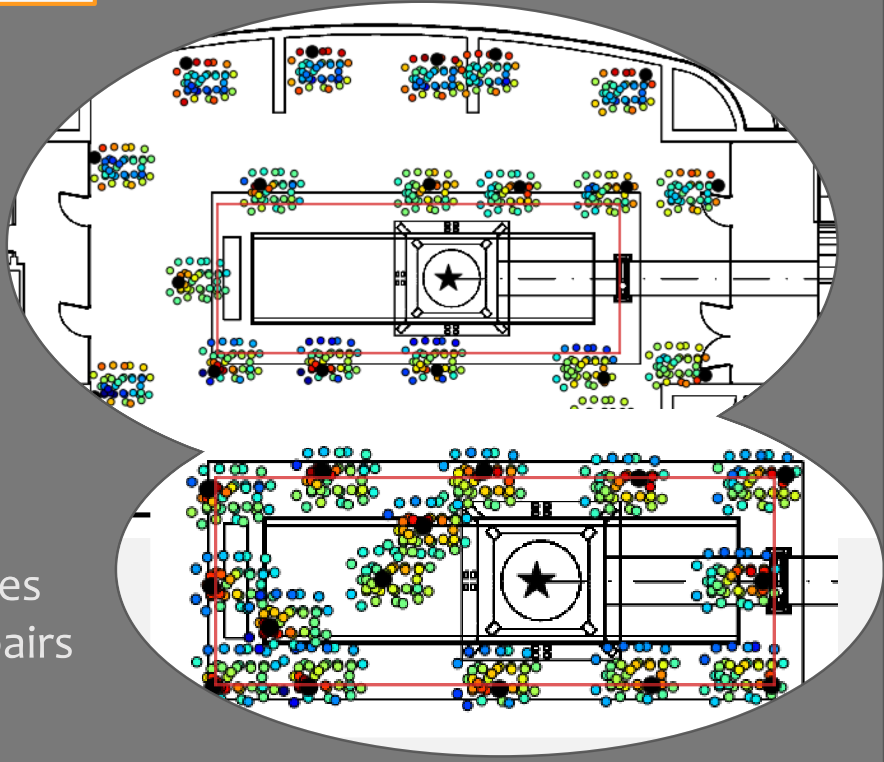
At the end of the line, we only need this value!!!



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

4D: Css(x1,y1, x2,y2)

We can get Css by interpolating data!!!



Normalized cross-spectral densities (coherence) between all possible pairs of seismometers at 15 Hz

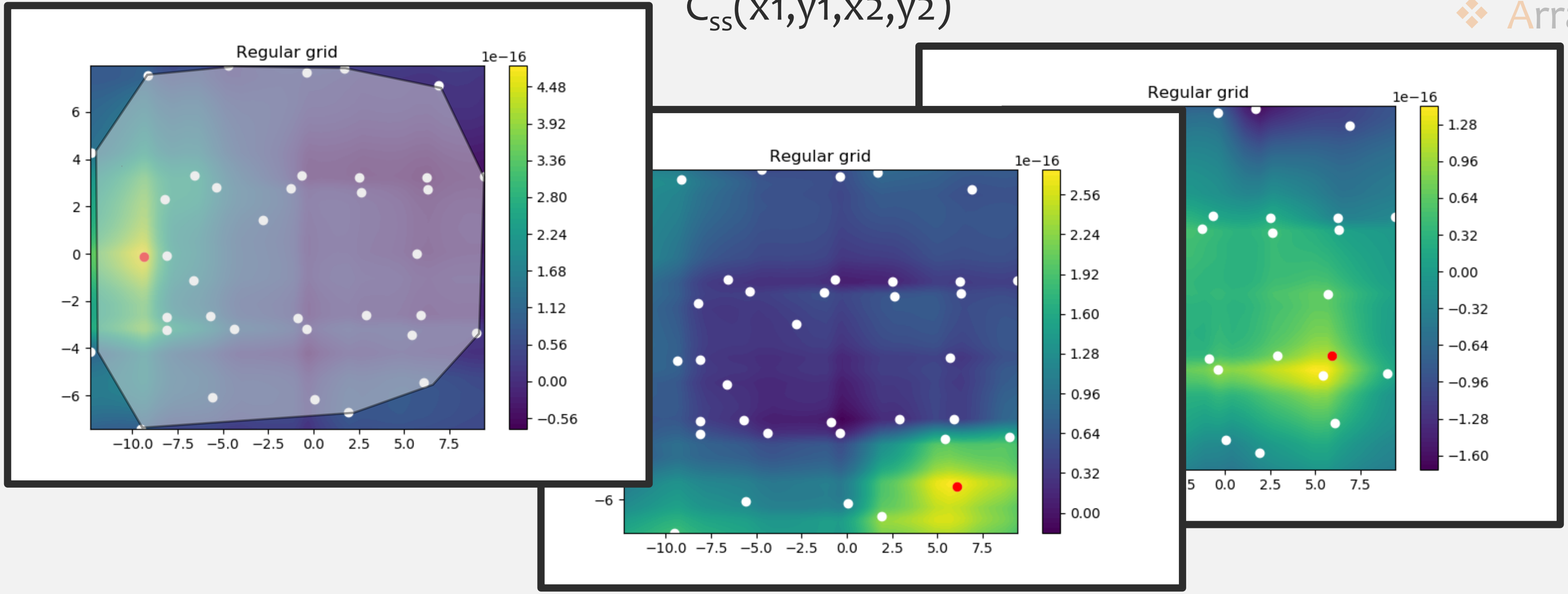
$$R(\omega) = 1 - \frac{\vec{C}^{\dagger}_{\mathrm{SN}}(\omega) \cdot (\mathbf{C}_{\mathrm{SS}}(\omega))^{-1} \cdot \vec{C} \ldots}{C_{\mathrm{N}} \ldots}$$

We can get C…

4D gaussian process?!? NO, NO, NO!!!

convex envelope

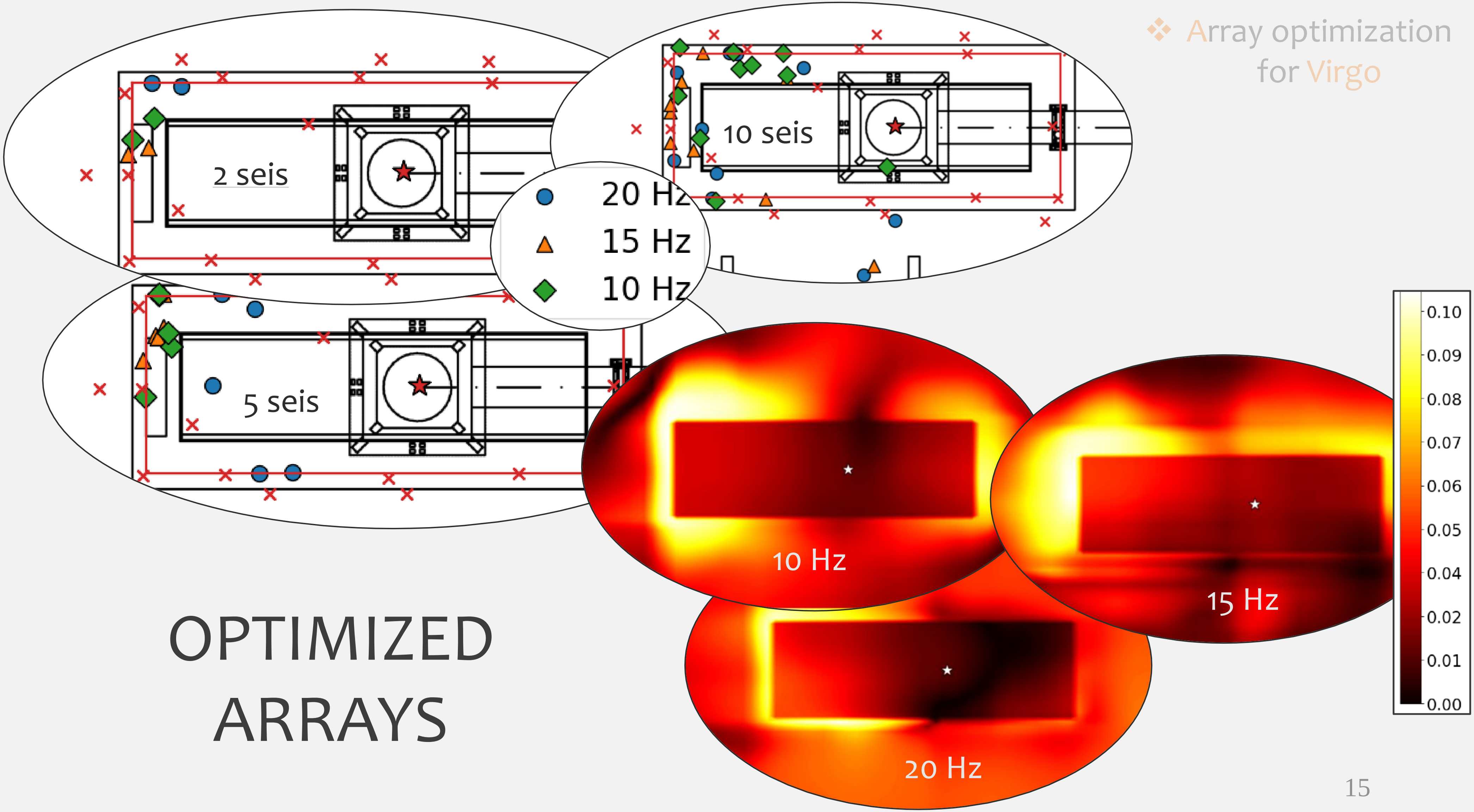
$C_{ss}(x1,y1,x2,y2)$



1) FFT of 37 seismometers' data (seismic displacement) → 2D gaussian process at a frequency f0:

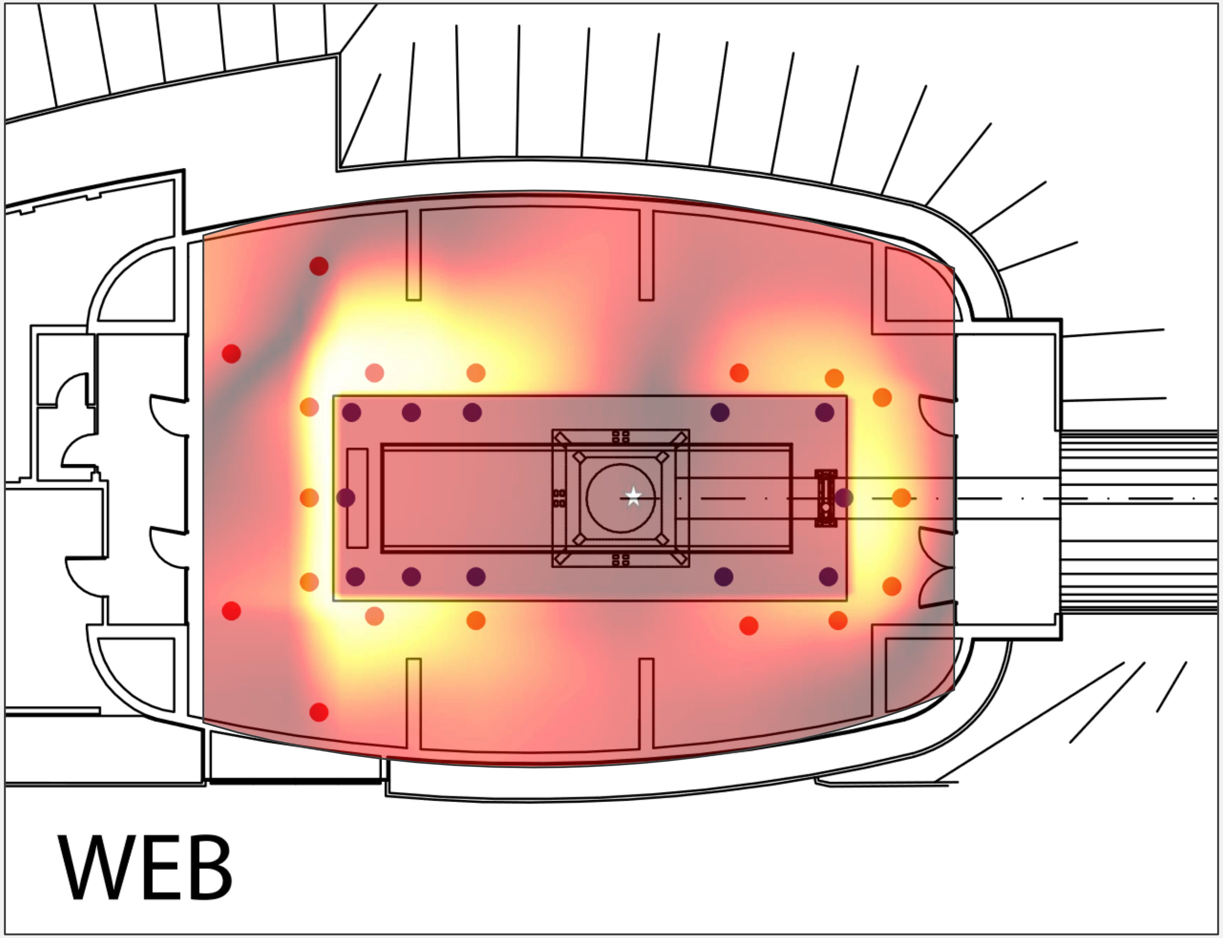
Convolution theorem → surrogate model of Css: $Css\,(x1,y1,x2,y2) = \frac{1}{T} < (FFT^{*}_{(x1,y1)}(\omega)\ FFT_{(x2,y2)}(\omega)) >$

2) Css Sampling → 4D Linear Interpolation on a Regular grid (faster) → **Css** & **Csn** (integrated with Simpson method)



OPTIMIZED ARRAYS

@Virgo:



- Left side → stronger noise
- Platform edges very important
- No sensors in the basement → results indicated stronger contributions in surface sensors.

Work in progress for the Newtonian noise cancellation system:

70%

- Optimization of the array: ✓
- Array deployment: ✓
- Pipeline of subtraction: SOON

Thank you!

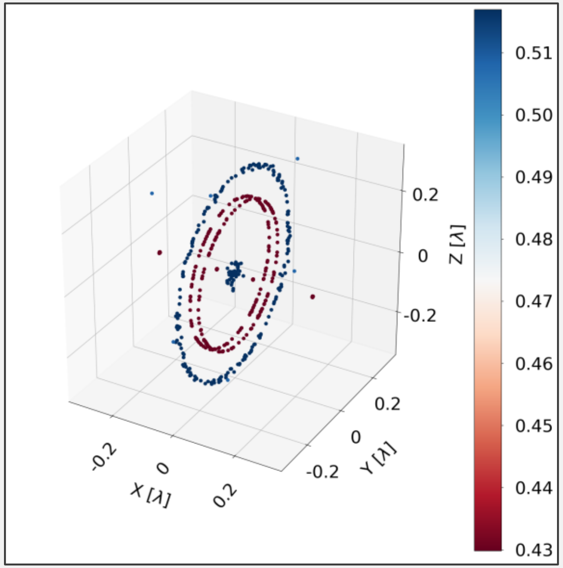
Backup slides

State of the art:

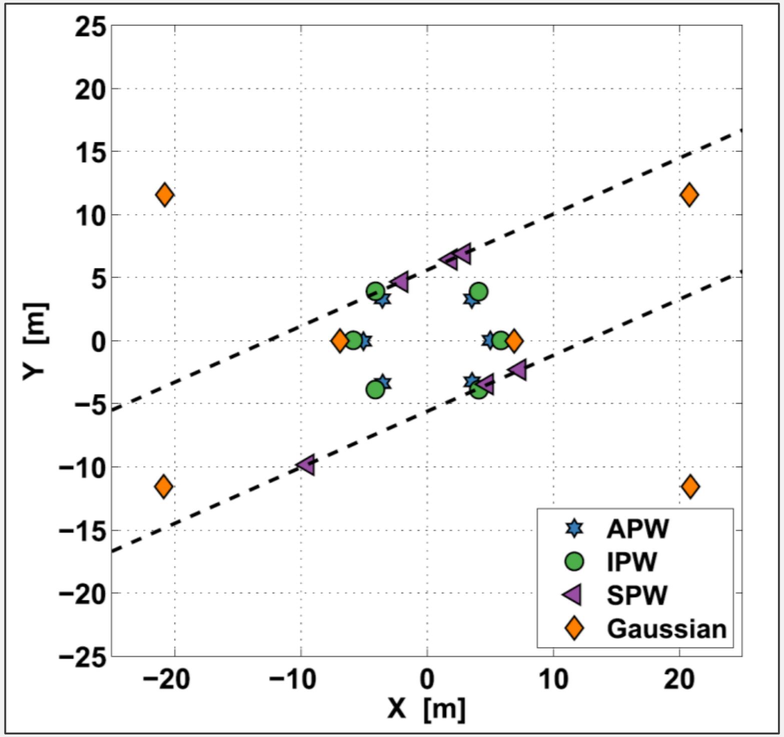
Array optimization

Array optimization fulfilled only for a surface detector (2D) with simple seismic field models → not enough for Virgo.

Optimization for underground detectors (3D).

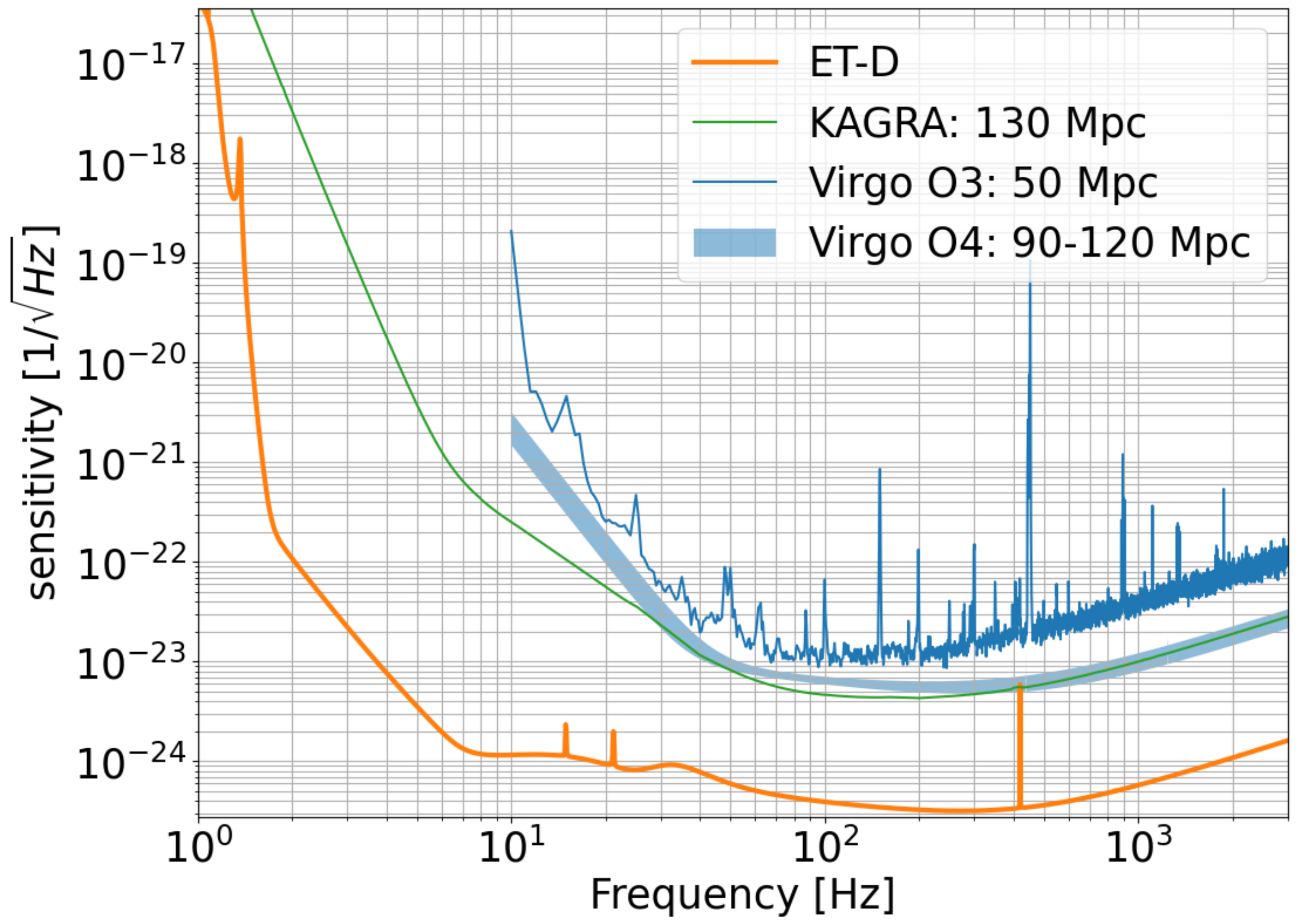


F Badaracco and J Harms. \Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves". In: Classical and Quantum Gravity 36.14 (2019), p. 145006. [Link]



M Coughlin et al. Towards a first design of a Newtonian-noise cancellation system for Advanced LIGO". In: Classical and Quantum Gravity 33.24 (2016), p. 244001. [Link].

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!

$$R = 1 - \frac{\hat{C}_{NN}}{C_{NN}}$$

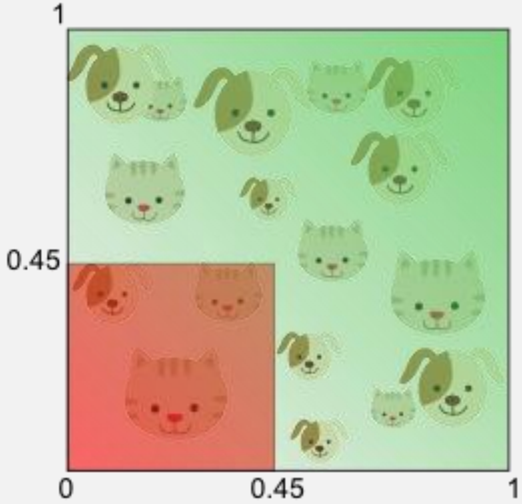
$$RC_{NN} = C_{NN} - \hat{C}_{NN}$$

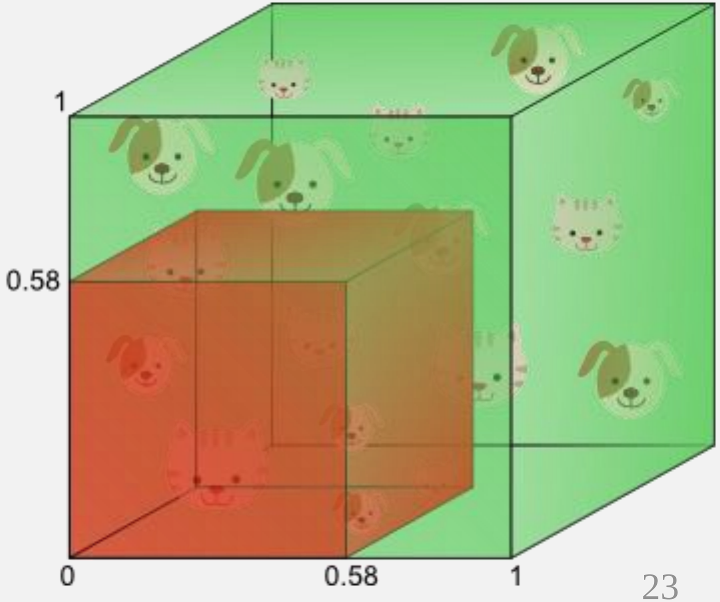
Curse of dimensionality

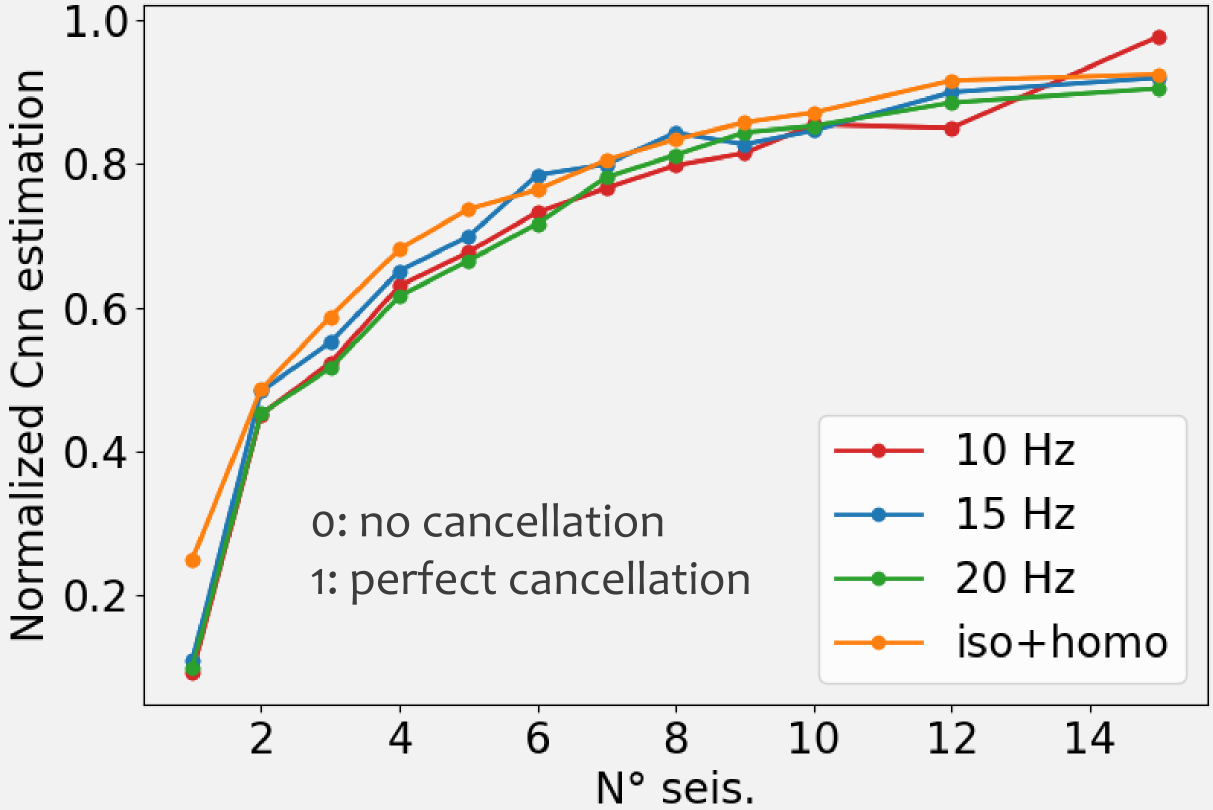
$\rho_{2D} = 0.30$

$\rho_{4D} = 0.05$

$\rho_{4D\_Regular\_grid} = 29$





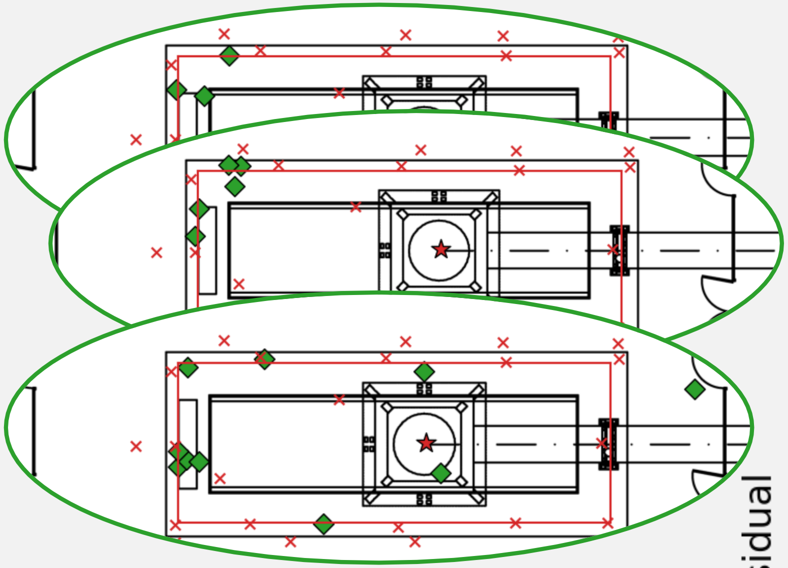


Reduction factor from **10 to 50**

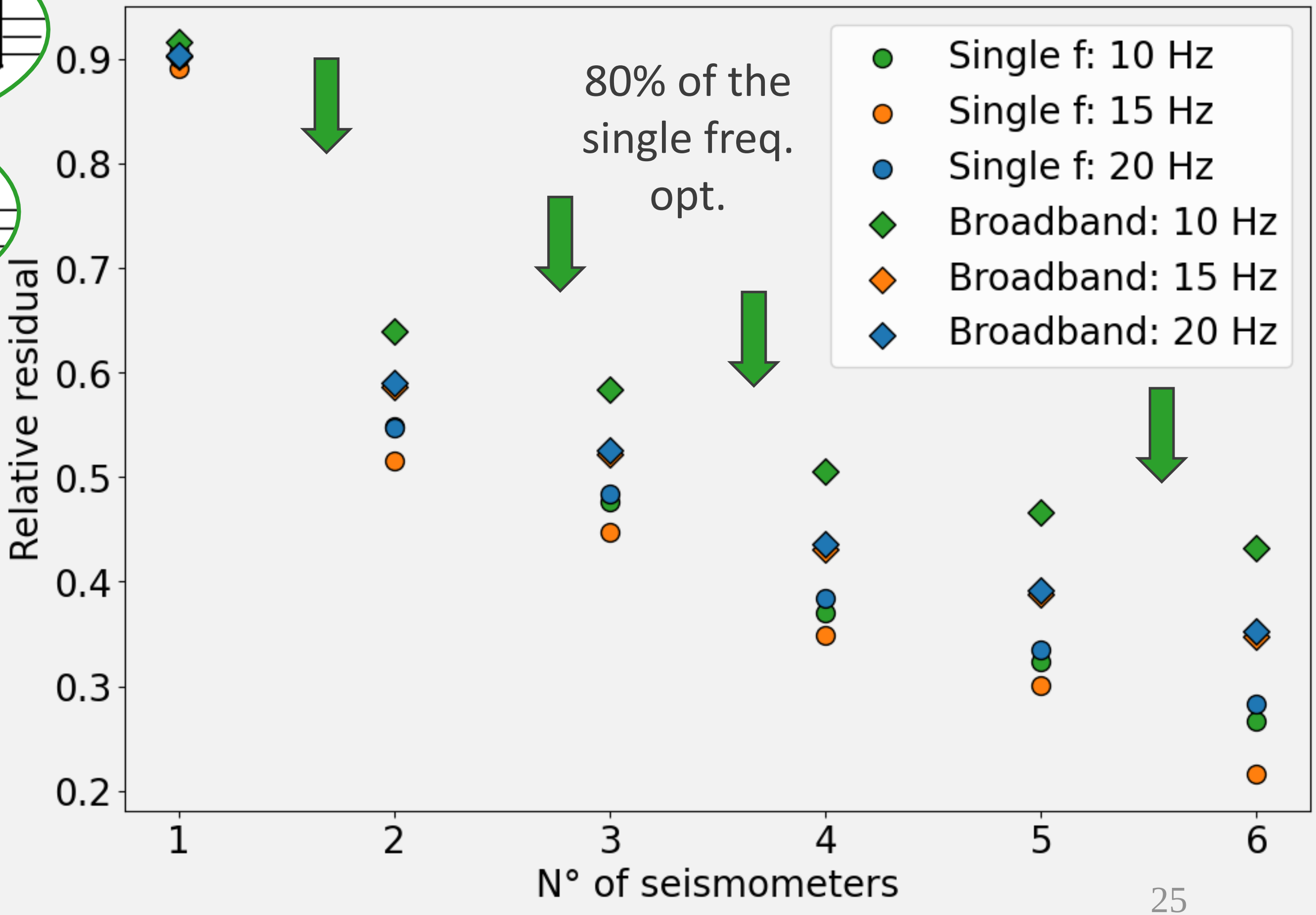
15 sensors →

	$\sqrt{\vec{C}^{\dagger}_{\mathrm{SN}}(\omega)\cdot(\mathbf{C}_{\mathrm{SS}}(\omega))^{-1}\cdot\vec{C}_{\mathrm{SN}}(\omega)}$	Relative residual	Relative residual; 15 Hz optimized
10 Hz	$3.95\cdot10^{-23}\ 1/\sqrt{\mathrm{Hz}}$	0.02	0.39
15 Hz	$9.60\cdot10^{-24}\ 1/\sqrt{\mathrm{Hz}}$	0.08	0.08
20 Hz	$4.01\cdot10^{-24}\ 1/\sqrt{\mathrm{Hz}}$	0.09	0.47

Broadband



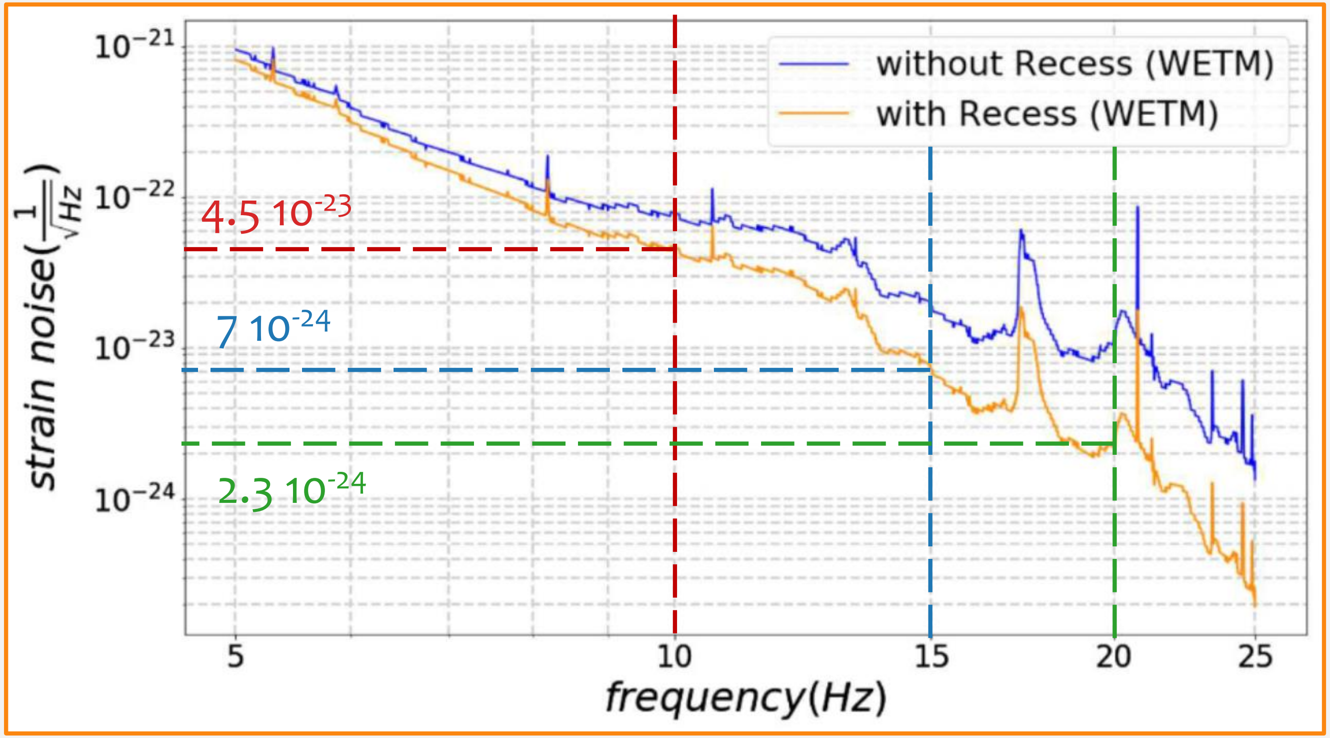
$$\mathcal{L} = \max_{\forall \omega \in \omega_i} R(\omega)$$



Frequency	$\sqrt{C_{\mathrm{NN}}^{\mathrm{iso}}}$	$\sqrt{a}$
10 Hz	$1.33 \cdot 10^{-23}\ 1/\sqrt{\mathrm{Hz}}$	$4.04 \cdot 10^{-23}\ 1/\sqrt{\mathrm{Hz}}$
15 Hz	$7.21 \cdot 10^{-24}\ 1/\sqrt{\mathrm{Hz}}$	$1.04 \cdot 10^{-23}\ 1/\sqrt{\mathrm{Hz}}$
20 Hz	$4.34 \cdot 10^{-24}\ 1/\sqrt{\mathrm{Hz}}$	$4.44 \cdot 10^{-24}\ 1/\sqrt{\mathrm{Hz}}$

Homogeneous and isotropic model

Estimated Newtonian Noise



finite-element simulation

Ayatri Singha, Stefan Hild, and Jan Harms. \Newtonian-noise reassessment for the Virgo gravitational-wave observatory including local recess structures". In: Classical and Quantum Gravity 37.10 (Apr. 2020), p. 105007.
doi: 10.1088/1361-6382/ab81cb. url: https://doi.org/10.1088/1361-6382/ab81cb.