

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

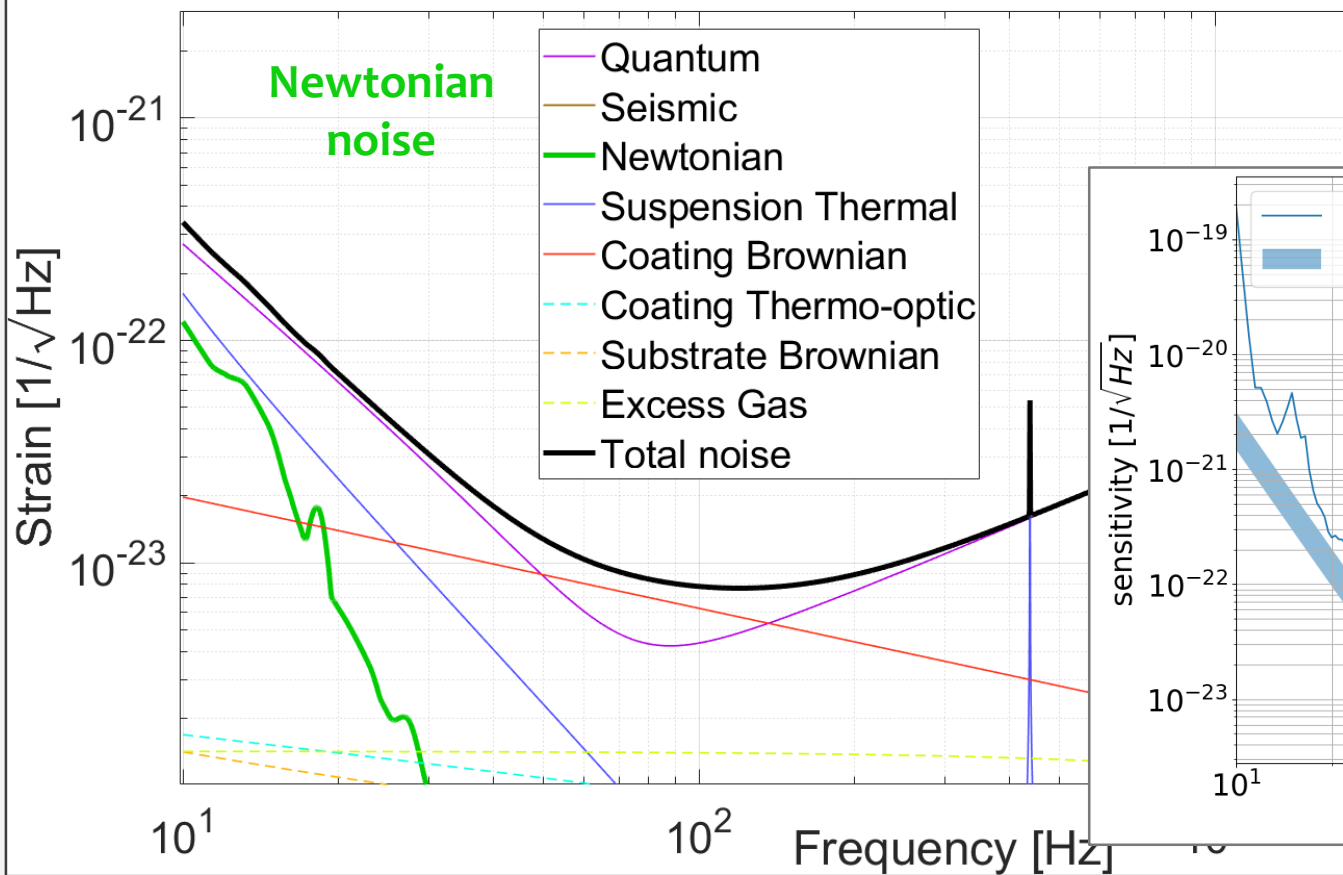
22 March 2021

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(PhD work made in GSSI

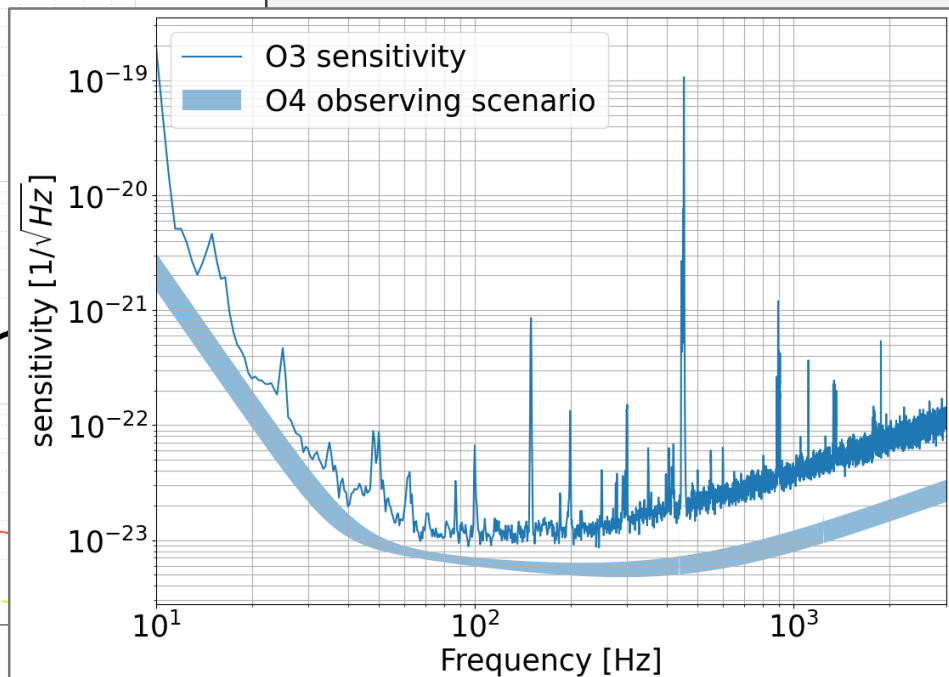


Plenty of different kinds of noises

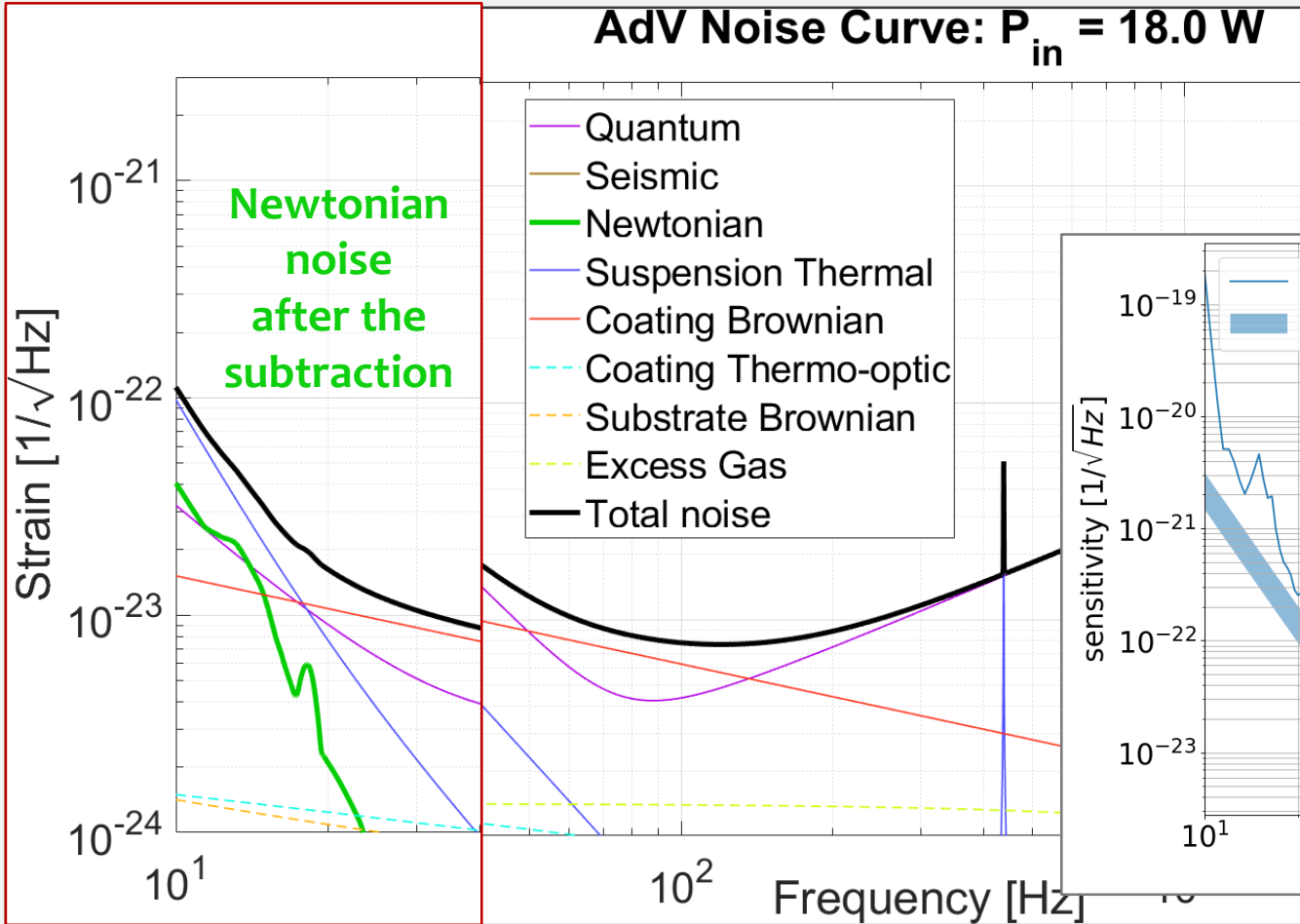
AdV Noise Curve: $P_{\text{in}} = 18.0 \text{ W}$



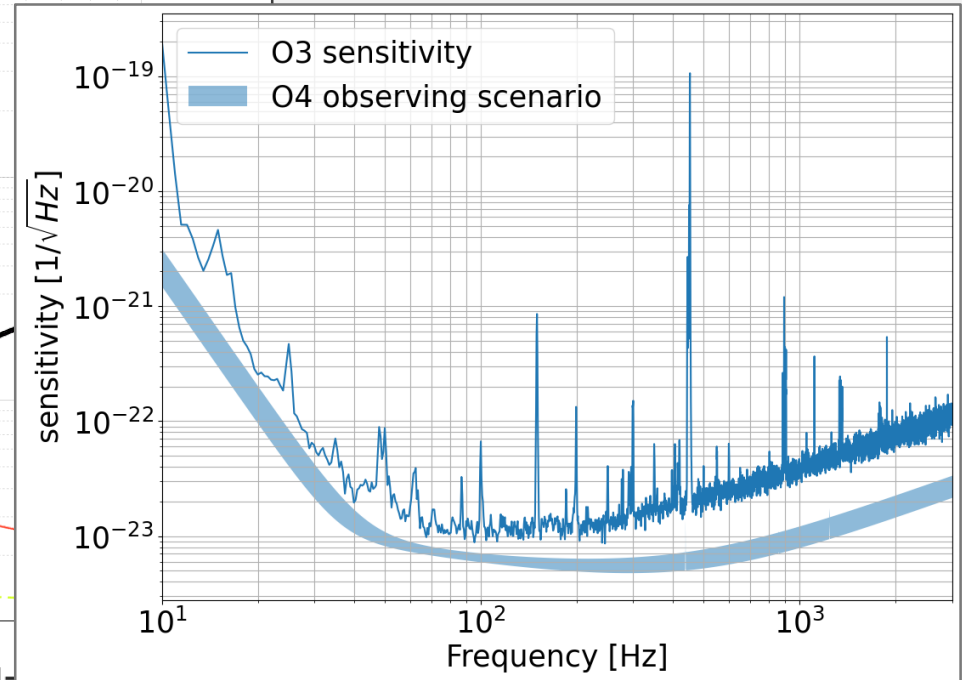
... which limit our sensitivity



Plenty of different kinds of noises



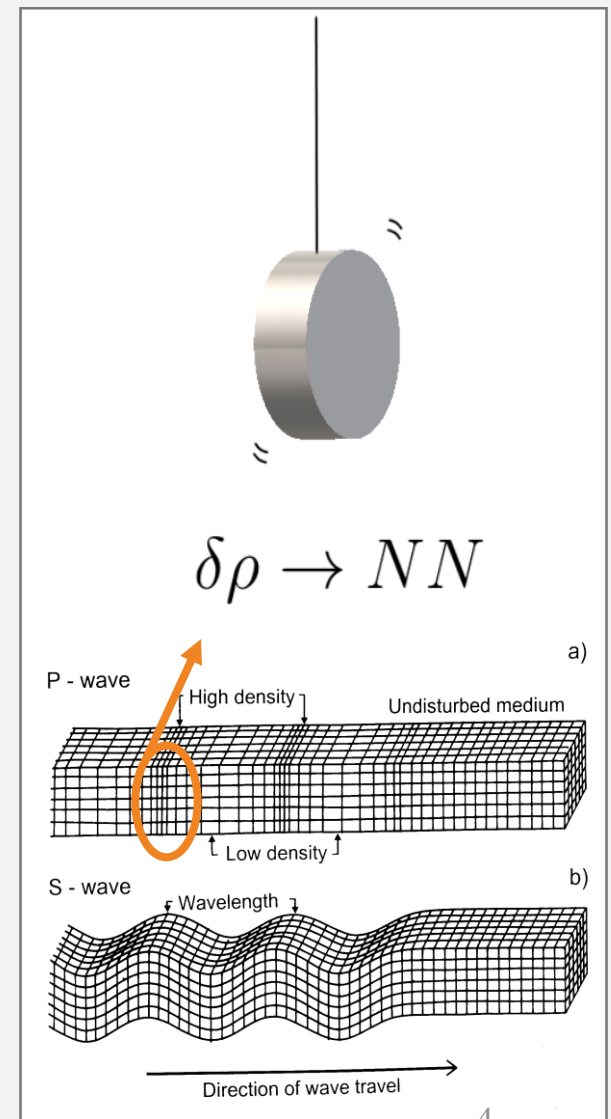
... which limit our sensitivity



What is Newtonian Noise (NN):

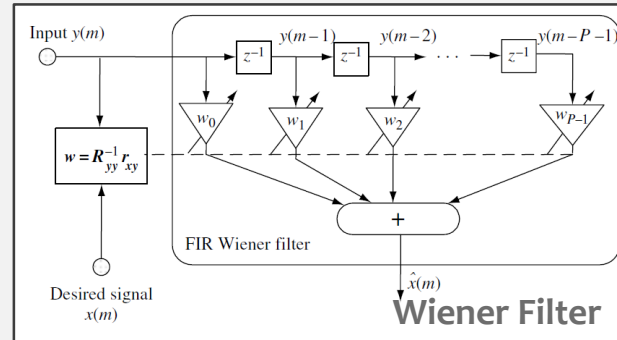
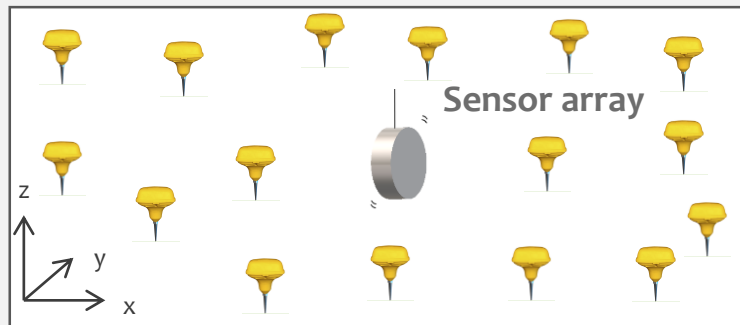
Perturbation of the gravity field due to a variation in the density ($\delta\rho$) of the surrounding media.

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



Array optimization

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



**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):

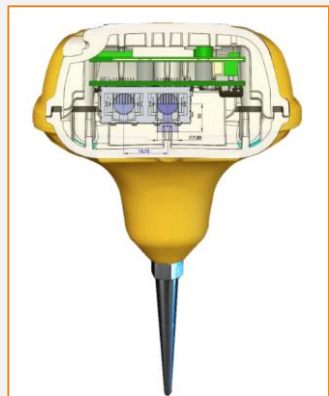
TO REMEMBER!!!

❖ Array optimization for Virgo

- Recess
 - Reflection
 - External sources
-
- The image shows a detailed architectural section of the Basilica of Santa Maria della Salute. The main part of the drawing is a cross-section of the dome, showing its internal structure, including the dome ribs and the central lantern. The dome is labeled with various dimensions and materials, such as 'DOPPIO GIAMM. IN CEMENTO A FACCIA-VERDE' and 'BLOCCHE IN CEMENTO A FACCIA-VERDE'. The section is labeled 'SEZIONE B-B' at the bottom. A red circle highlights a specific area of the section, which appears to be the base of the dome where it meets the exterior wall. This area is labeled with dimensions and materials, including 'DOPPIO GIAMM. IN CEMENTO A FACCIA-VERDE' and 'BLOCCHE IN CEMENTO A FACCIA-VERDE'. The drawing also shows the exterior facade of the basilica, with its arched windows and the central entrance. The overall style is a technical architectural drawing with precise lines and labels.

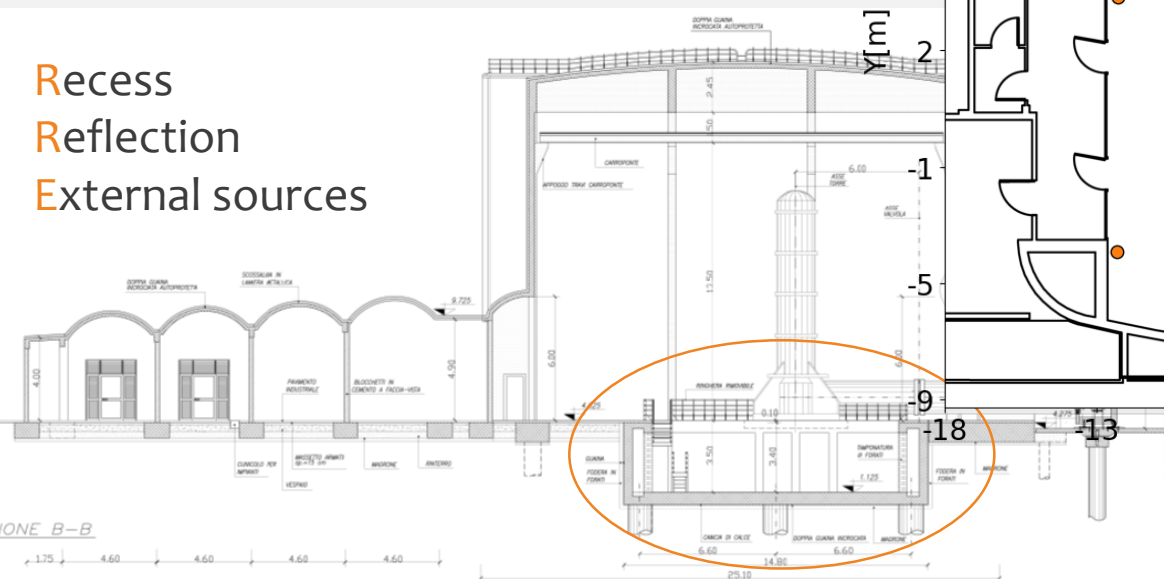
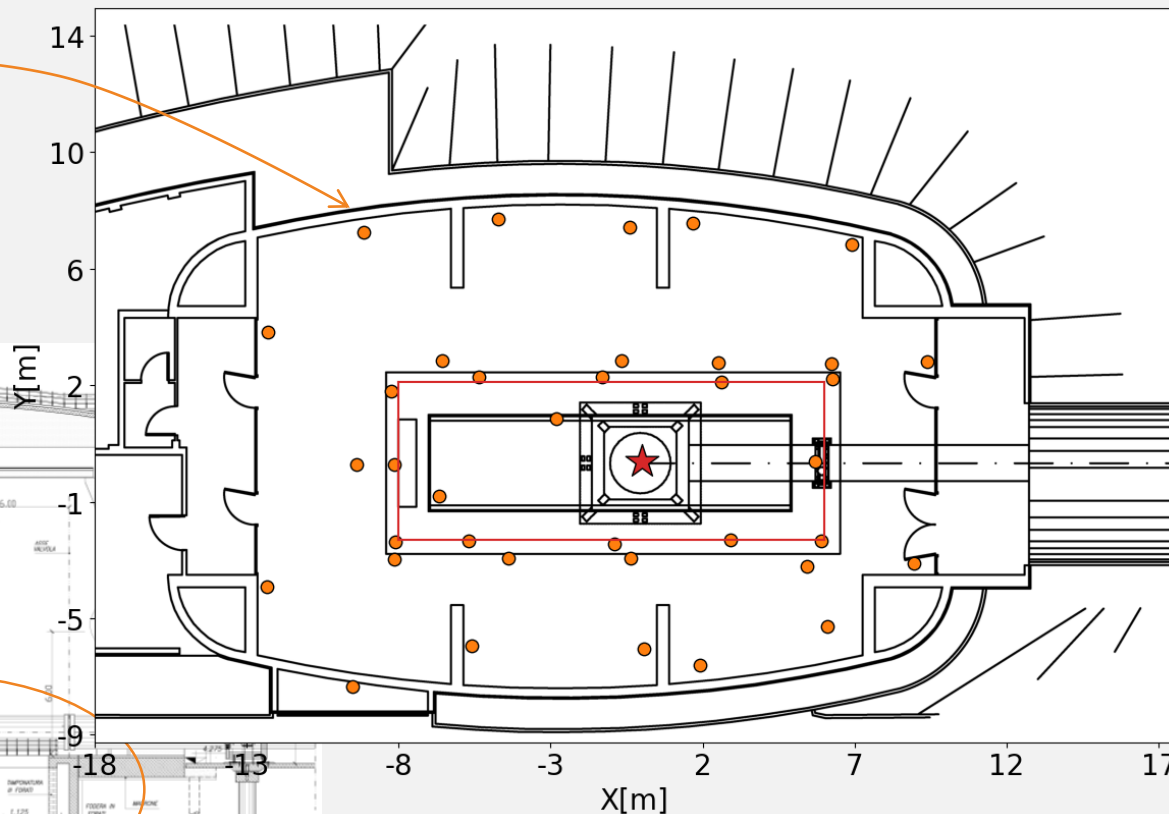
Virgo... another story!

❖ Array optimization
for Virgo



Where we started:

- Recess
- Reflection
- External sources



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

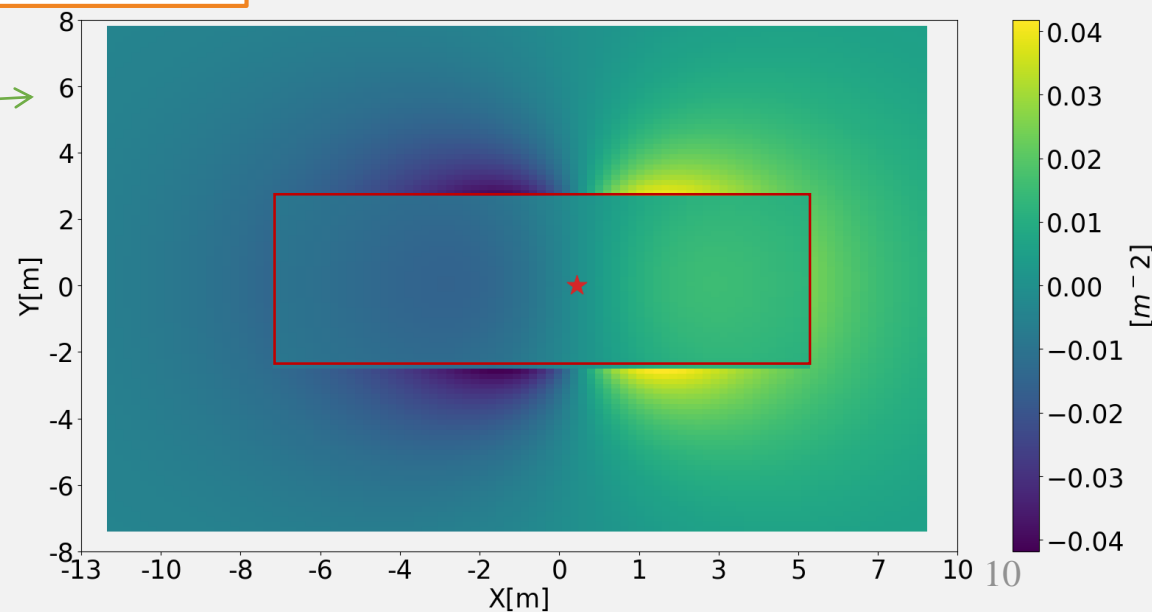
Remember: the residual function
gives a **measure** of the **performance**
of the **Wiener filter** (the lower, the
better!!!)

❖ Array optimization
for Virgo

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

$$\begin{aligned} C_{\text{SN}}(\vec{r}, \vec{r}_0) &= \mathcal{C} \int C_{\text{SS}}(\vec{r}, \vec{r}_1) \frac{x_0 - x_1}{(h(x_1, y_1)^2 + |\vec{r}_1 - \vec{r}_0|^2)^{3/2}} dx_1 dy_1 \\ &= \mathcal{C} \int C_{\text{SS}}(\vec{r}, \vec{r}_1) \mathcal{K}(\vec{r}_1, \vec{r}_0) dx_1 dy_1 \end{aligned}$$

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



❖ Array optimization
for Virgo

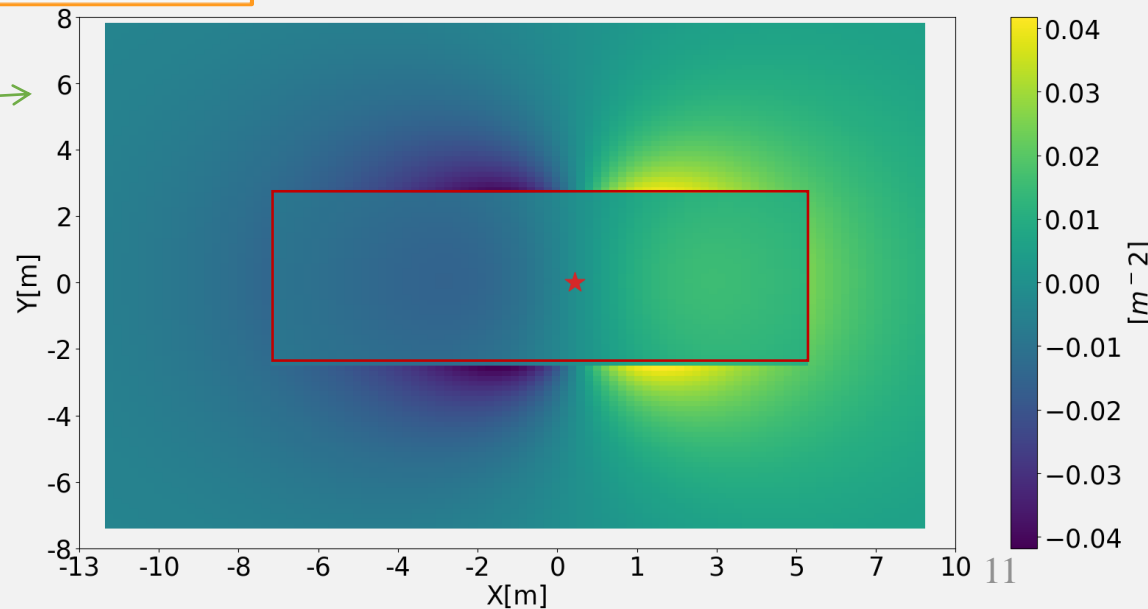
$$R(\omega) = 1 - \frac{\vec{C}_{\text{SN}}^\dagger(\omega) \cdot (\mathbf{C}_{\text{SS}}(\omega))^{-1} \cdot \vec{C}_{\text{SN}}(\omega)}{C_{\text{NN}}(\omega)}$$

$$C_{\text{SN}}(\vec{r}, \vec{r}_0) = \mathcal{C} \int C_{\text{SS}}(\vec{r}, \vec{r}_1) \frac{x_0 - x_1}{(h(x_1, y_1)^2 + |\vec{r}_1 - \vec{r}_0|^2)^{3/2}} dx_1 dy_1$$

$$= \mathcal{C} \int C_{\text{SS}}(\vec{r}, \vec{r}_1) \mathcal{K}(\vec{r}_1, \vec{r}_0) dx_1 dy_1$$

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

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

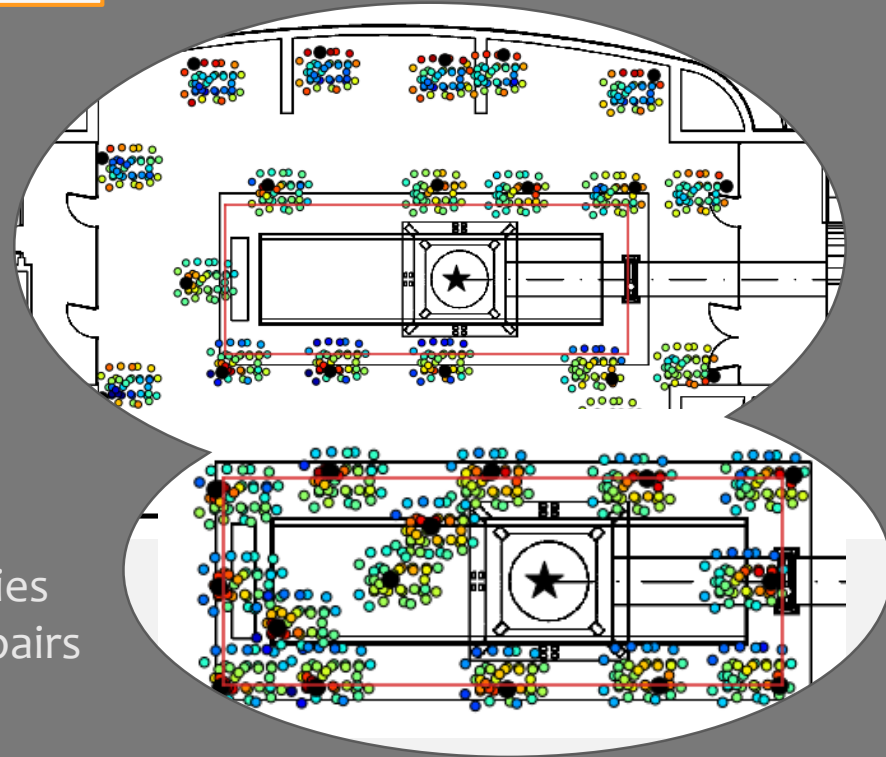


$$R(\omega) = 1 - \frac{\vec{C}_{\text{SN}}^\dagger(\omega) \cdot (\mathbf{C}_{\text{SS}}(\omega))^{-1} \cdot \vec{C}_{\text{SN}}(\omega)}{C_{\text{NN}}(\omega)}$$

4D: $C_{\text{SS}}(x_1, y_1, x_2, y_2)$

We can get C_{SS} by **interpolating**
data!!!

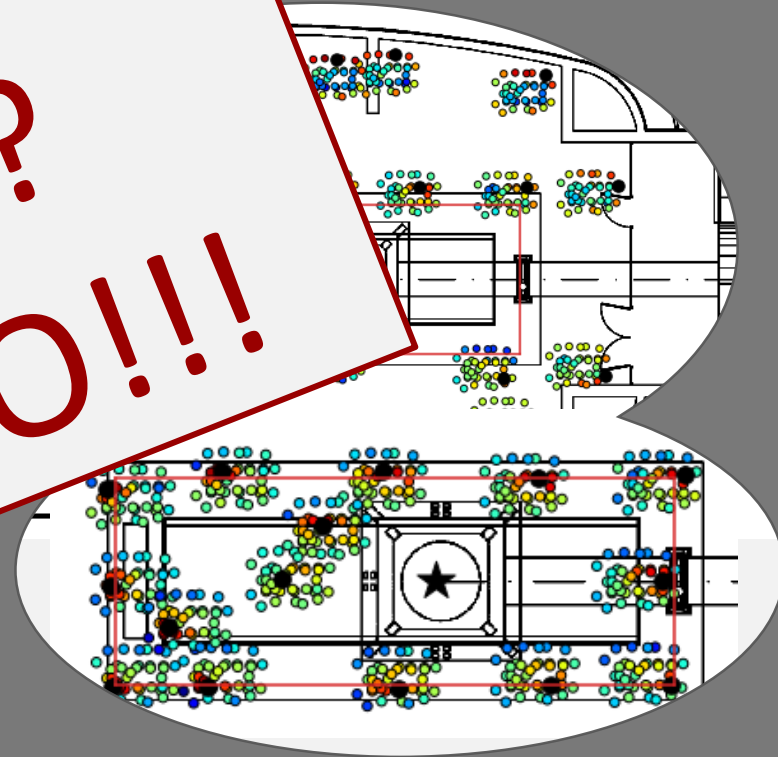
Normalized cross-spectral densities
(coherence) between all possible pairs
of seismometers at 15 Hz



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

We can get

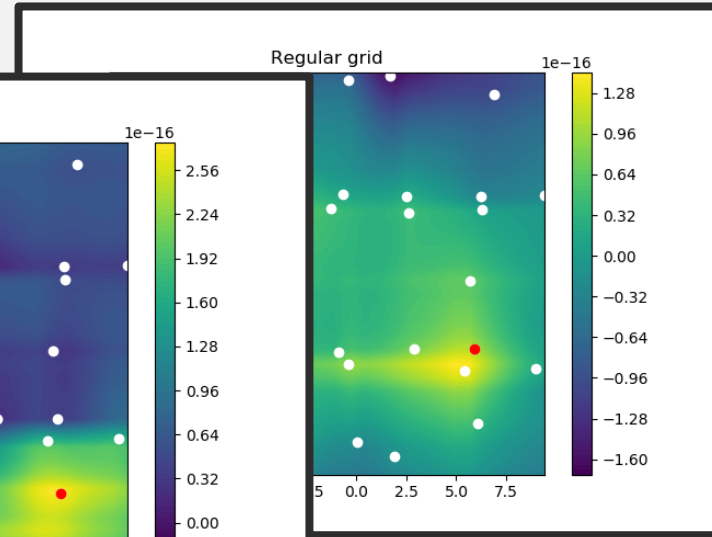
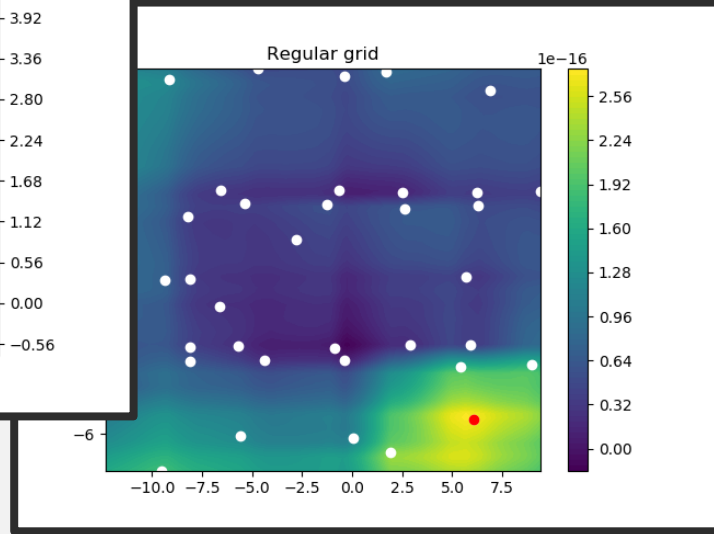
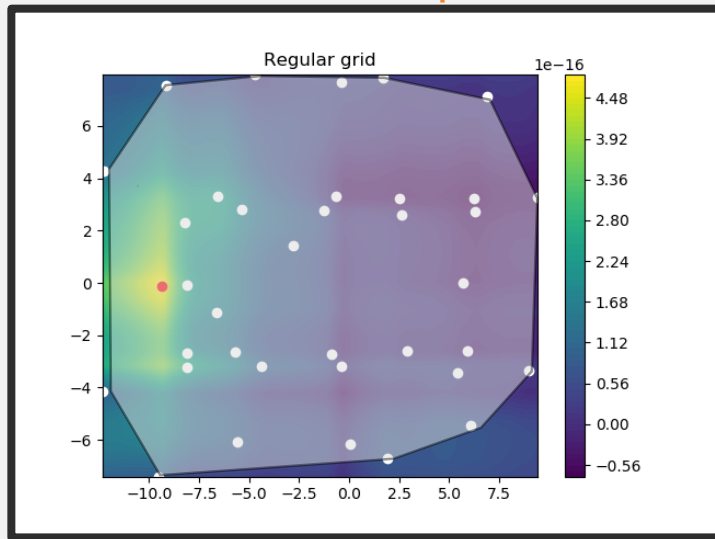
4D gaussian
process?!?
NO, NO, NO!!!



convex envelope

$$C_{ss}(x_1, y_1, x_2, y_2)$$

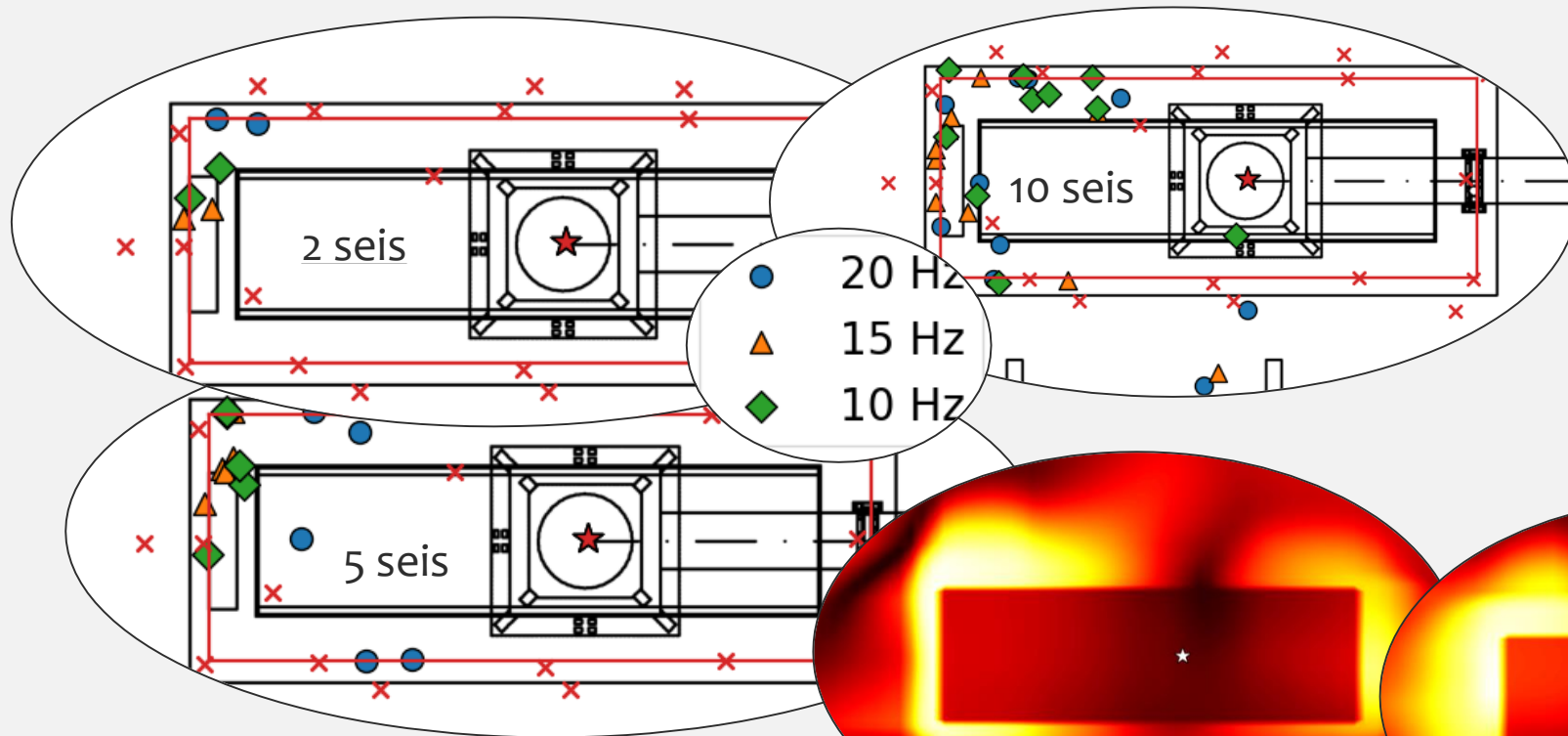
❖ Array optimization
for Virgo



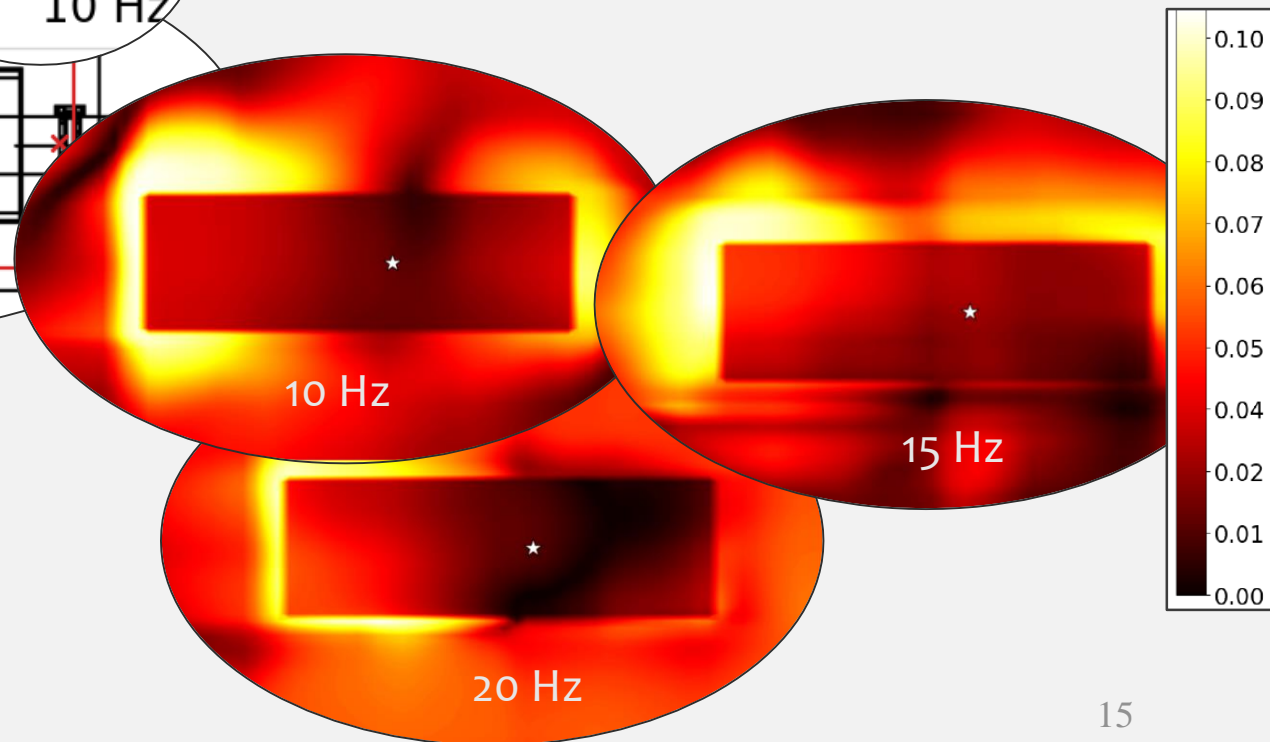
1) FFT of 37 seismometers' data (seismic displacement) \rightarrow 2D gaussian process at a frequency fo:

Convolution theorem \rightarrow surrogate model of C_{ss} : $C_{ss}(x_1, y_1, x_2, y_2) = \frac{1}{T} \langle \text{FFT}_{(x_1, y_1)}^*(\omega) \text{FFT}_{(x_2, y_2)}(\omega) \rangle$

2) C_{ss} Sampling \rightarrow 4D Linear Interpolation on a Regular grid (faster) \rightarrow C_{ss} & C_{sn} (integrated with Simpson method)

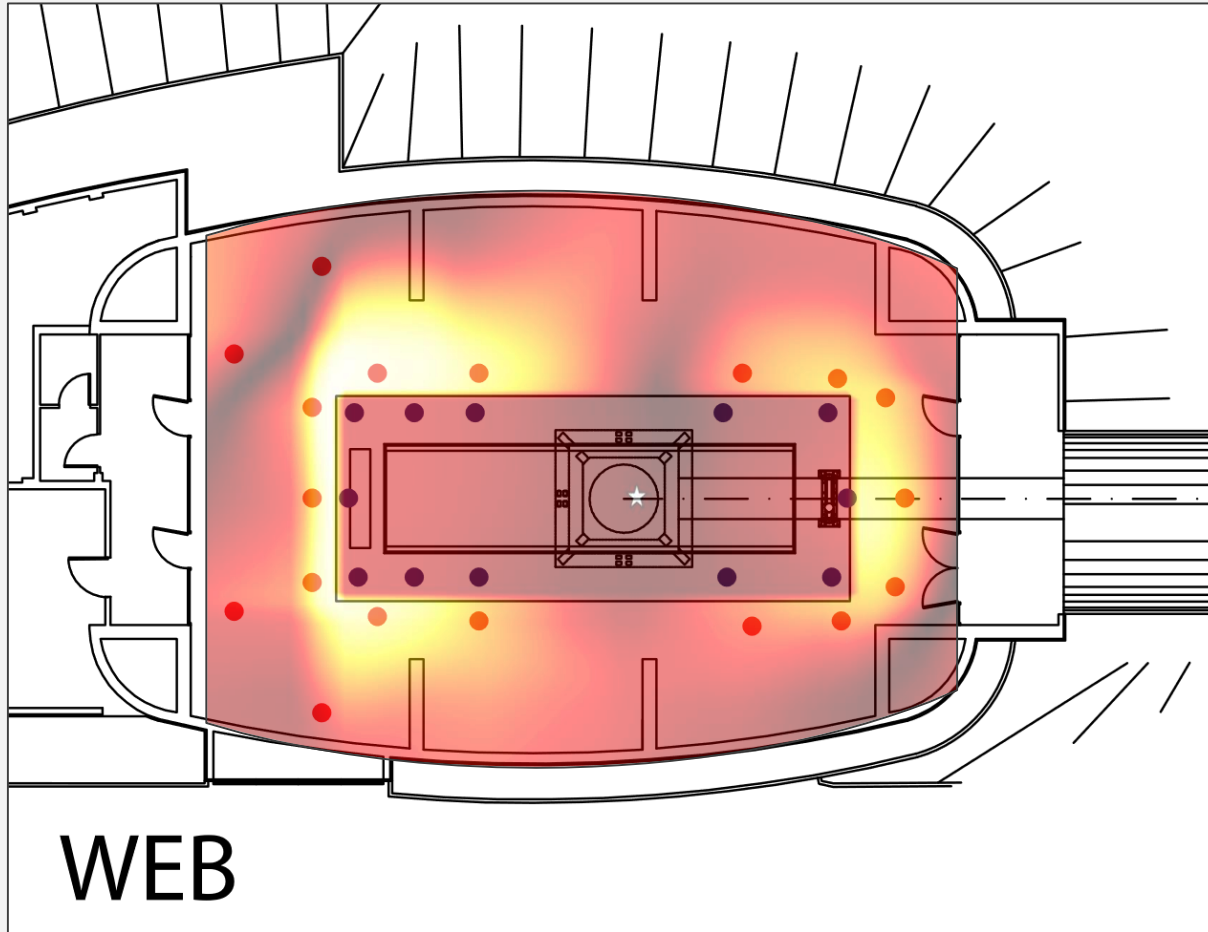


OPTIMIZED
ARRAYS



@Virgo:

❖ Array optimization for 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:

❖ Array optimization
for Virgo



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

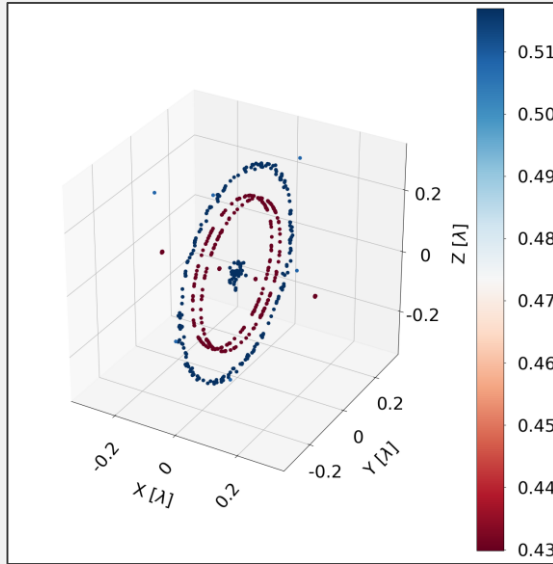
Thank you!

Backup slides

State of the art:

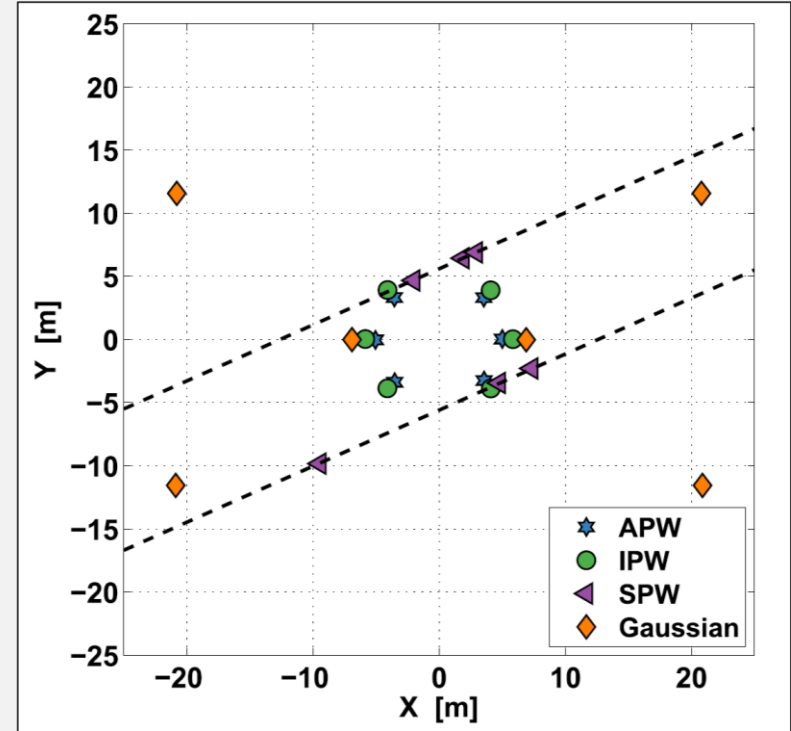
Array optimization fulfilled only for a surface detector (2D) with simple seismic field models → not enough for Virgo.

Optimization for underground detectors (3D).



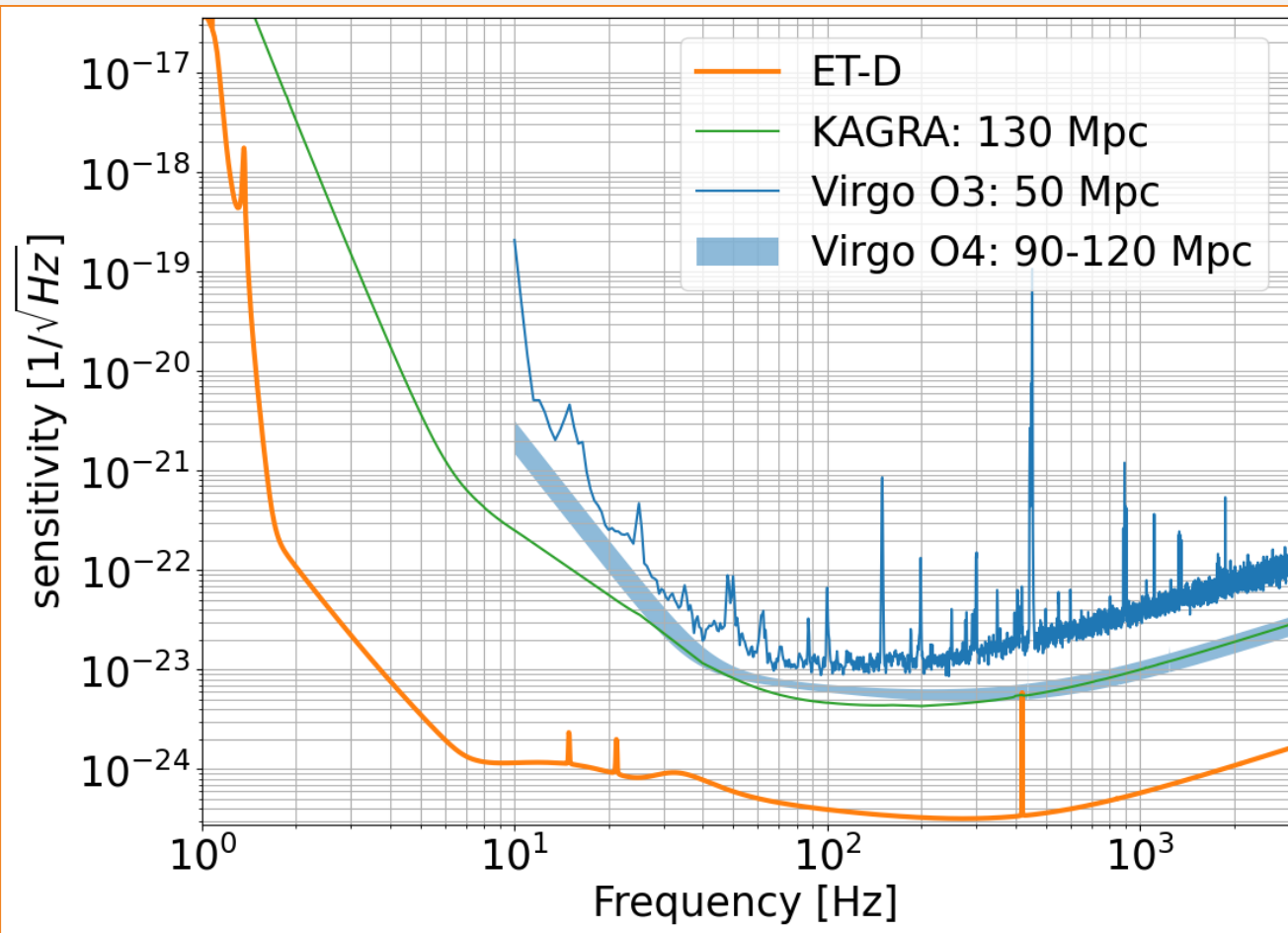
F Badaracco and J Harms. "Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves". In: Classical and Quantum Gravity 36.14 (2019), p. 145006. [Link](#)

Array optimization



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!**

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

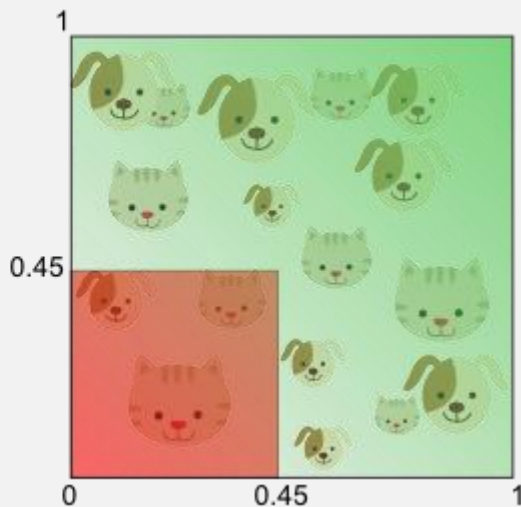
$$RC_{NN} = C_{NN} - \hat{C}_{NN}$$

Curse of dimensionality

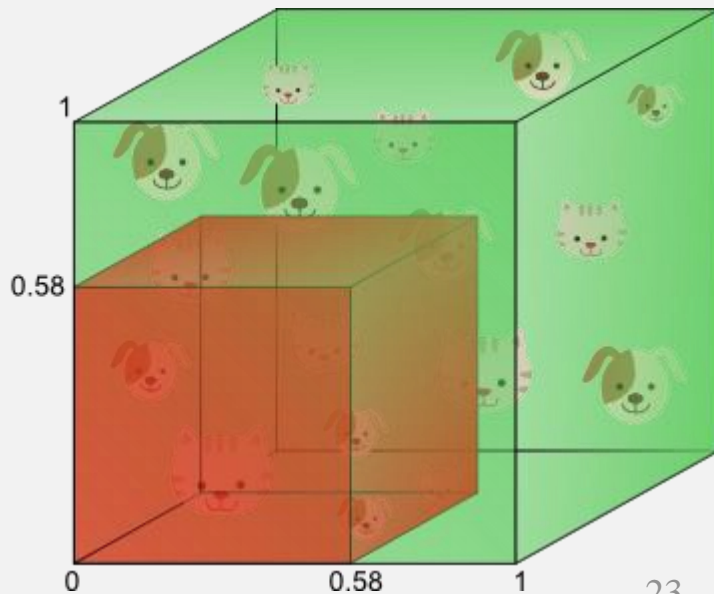
$$\rho_{2D} = 0.30$$

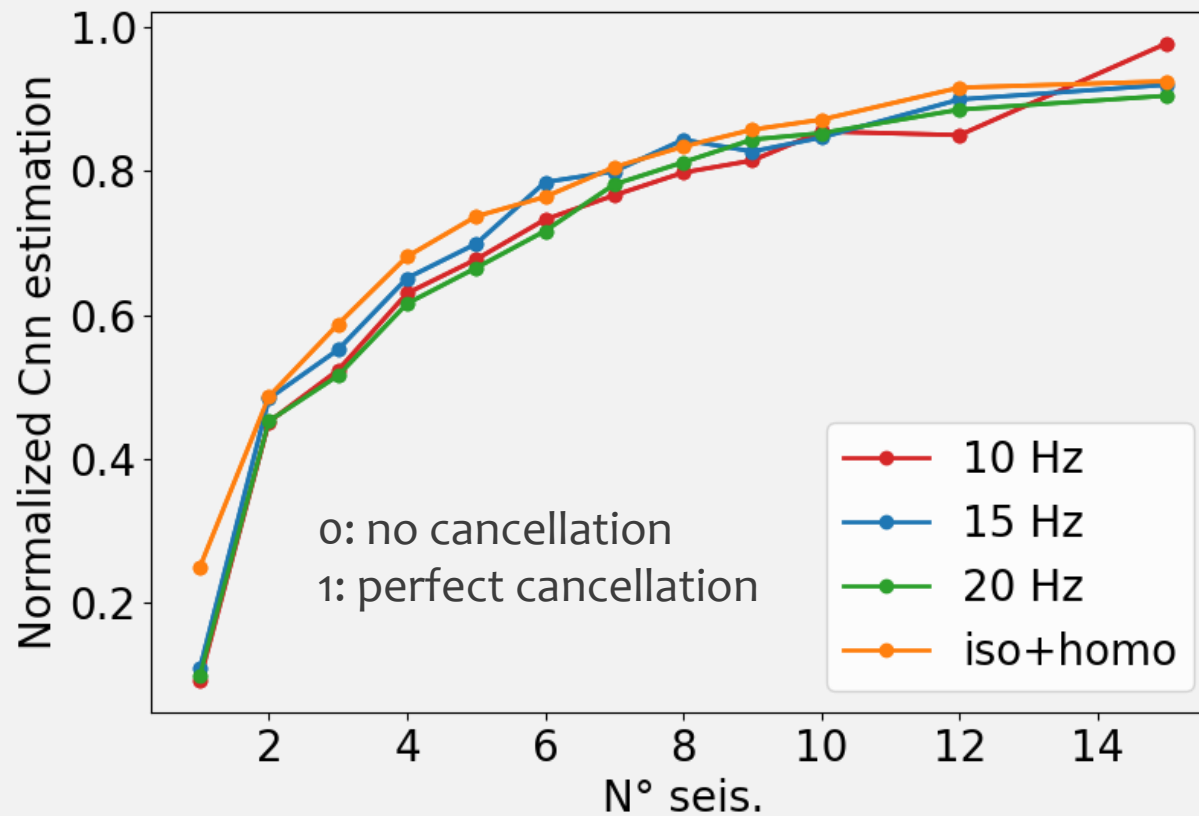


$$\rho_{4D} = 0.05$$



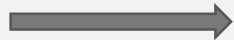
$$\rho_{4D_Regular_grid} = 29$$





Reduction
factor from
10 to 50

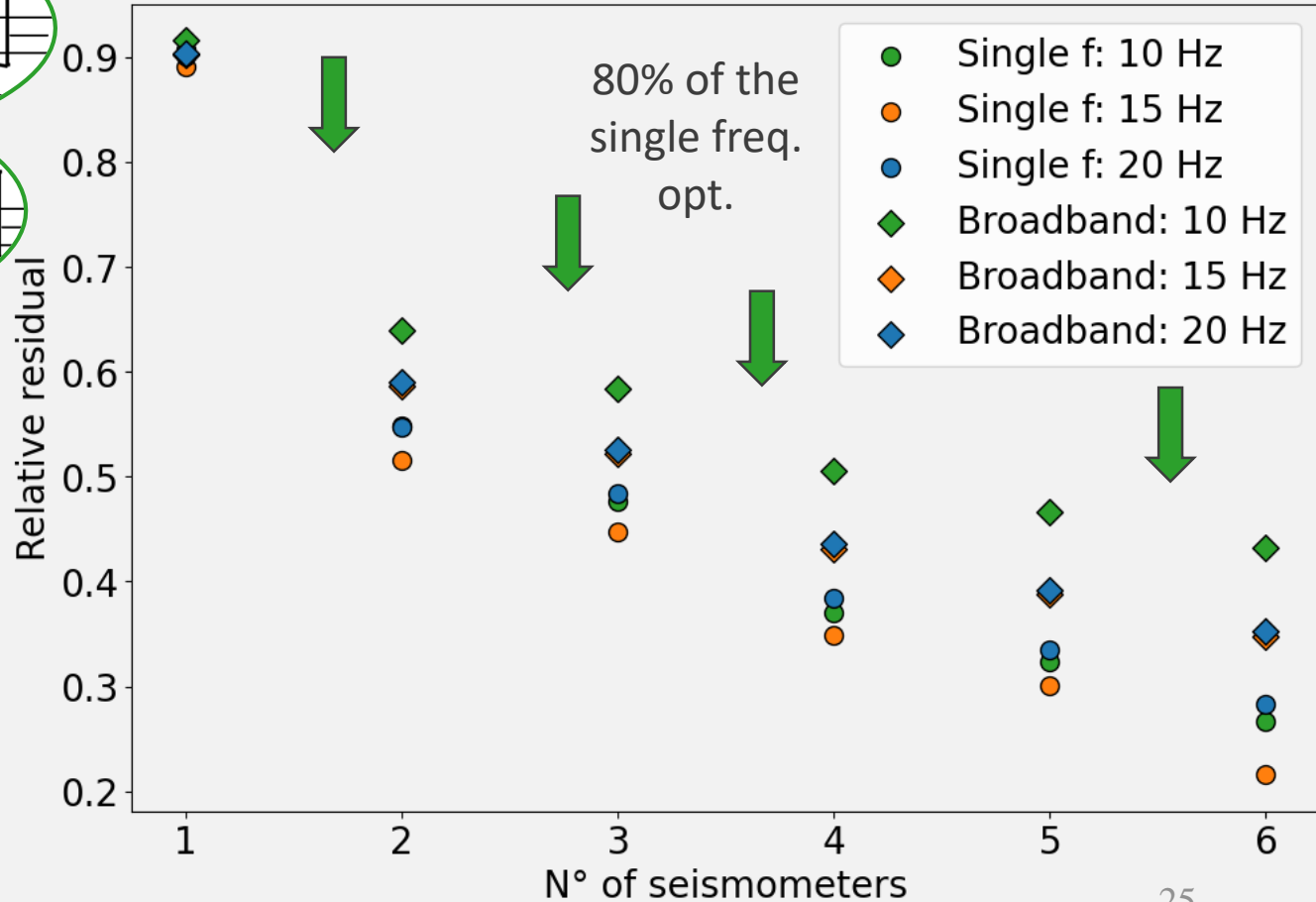
15 sensors



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

Broadband

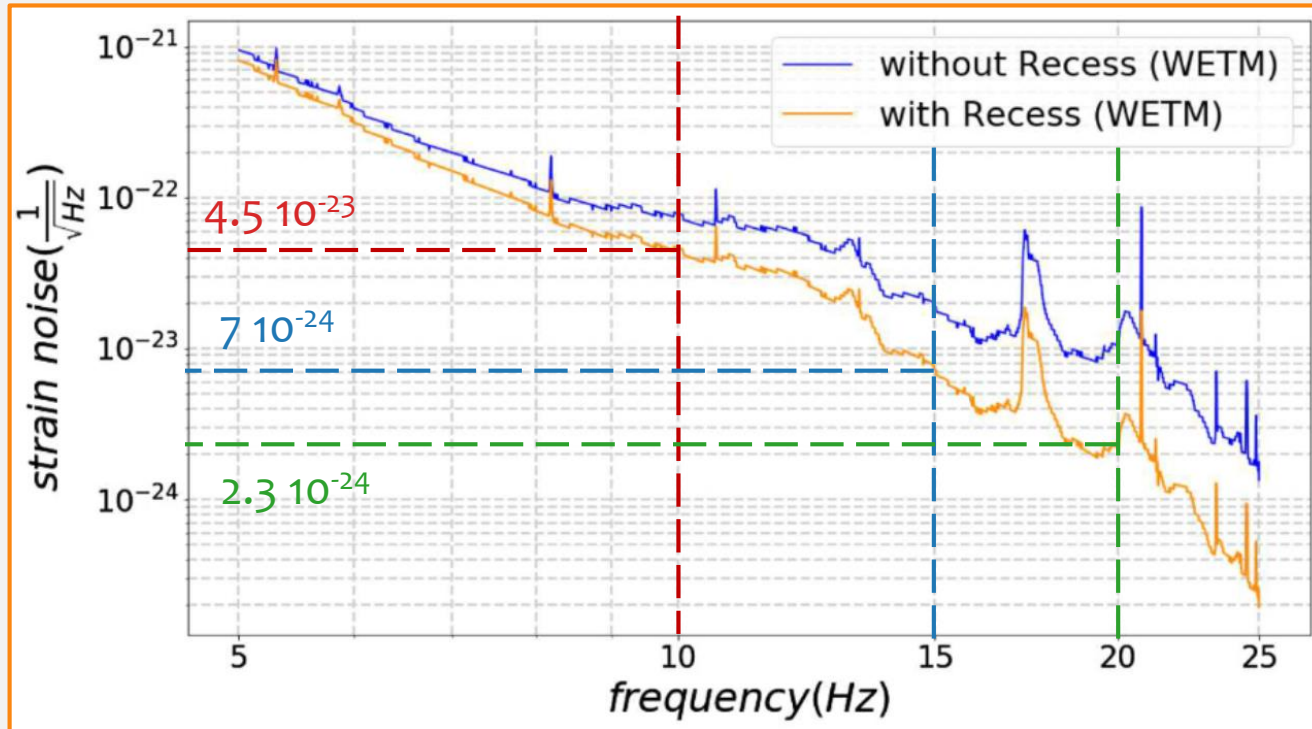
$$\mathcal{L} = \max_{\forall \omega \in \omega_i} R(\omega)$$



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

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>.