The Virgo GW Detector

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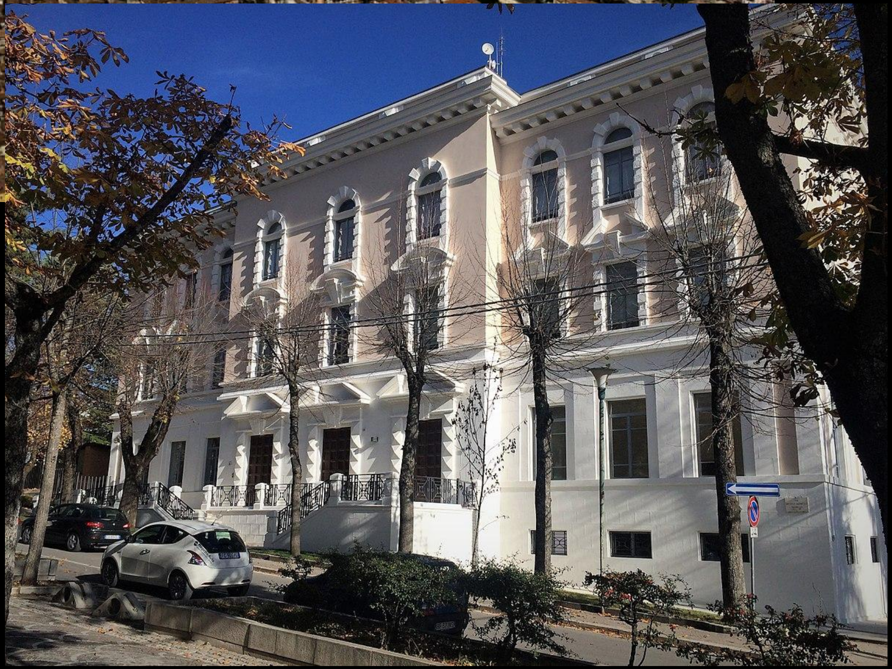


About 20 people in GW group working on GW theory, data analysis, multi-messenger science, instrument science.

Program for today:

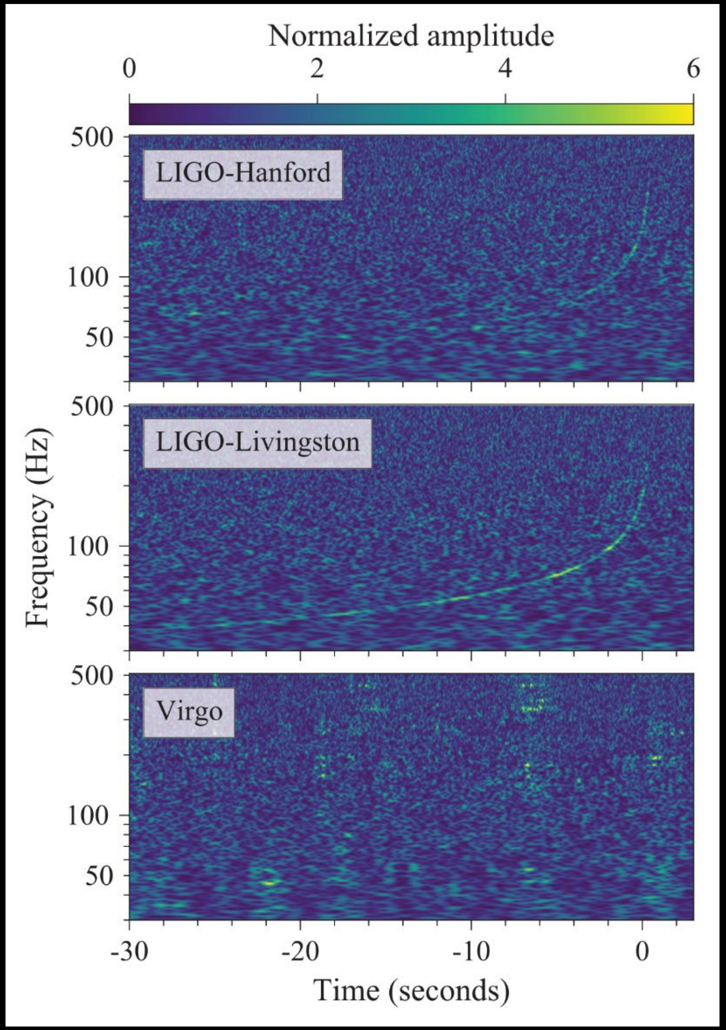
- Seismic environment of Virgo
- Gravitational coupling between seismic field and test masses
- Mitigation of Newtonian noise


Pisa
Cascina
Parco Regionale Migliarino, San Rossore
Gombo
La Pieve
Porta a Mare (Zona Industriale)
Navacchio
Ospedaletto
San Piero a Grado
Marina di Pisa
Tirrenia
Vicarello

Construction started in 1996.

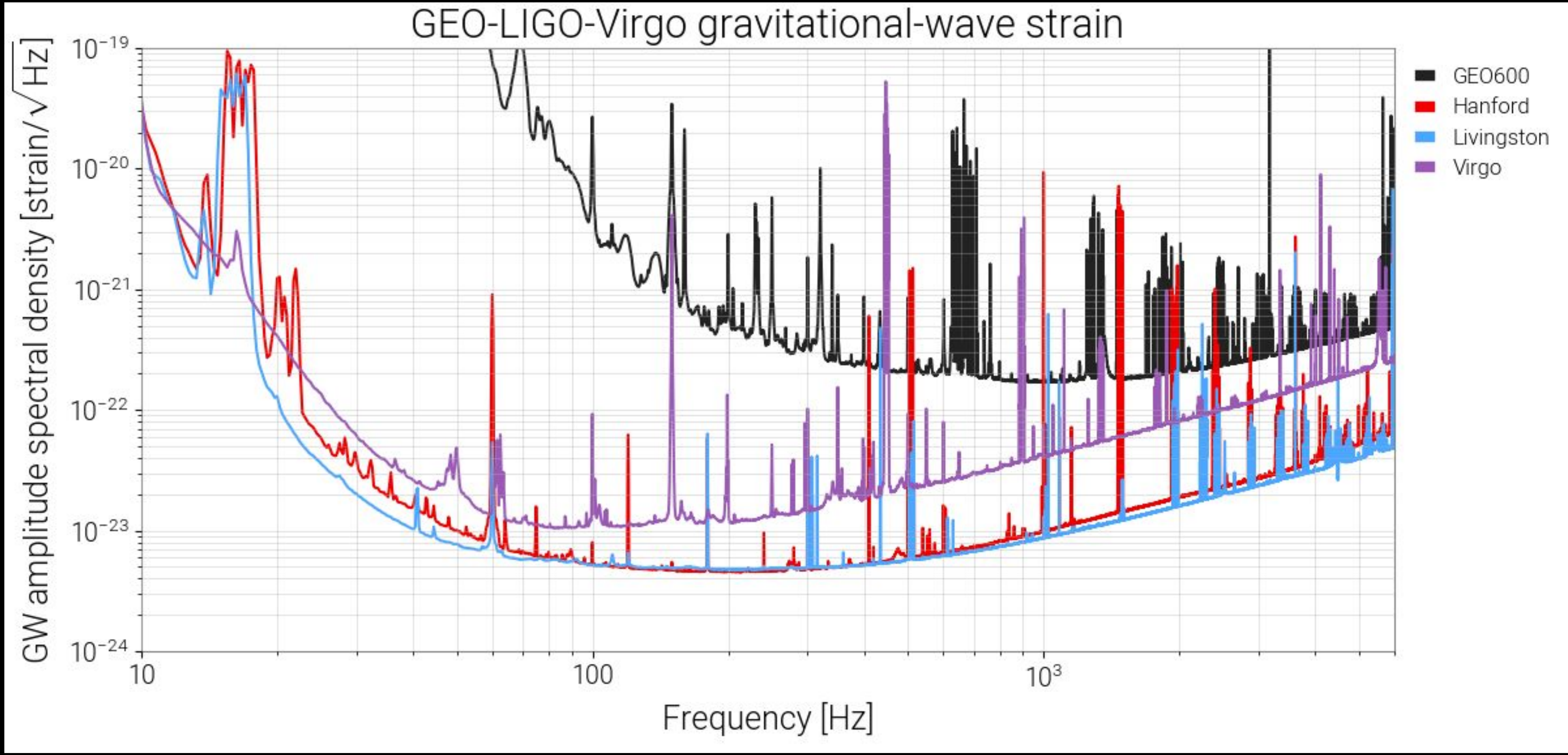
First GW observations in 2017.

GW170817

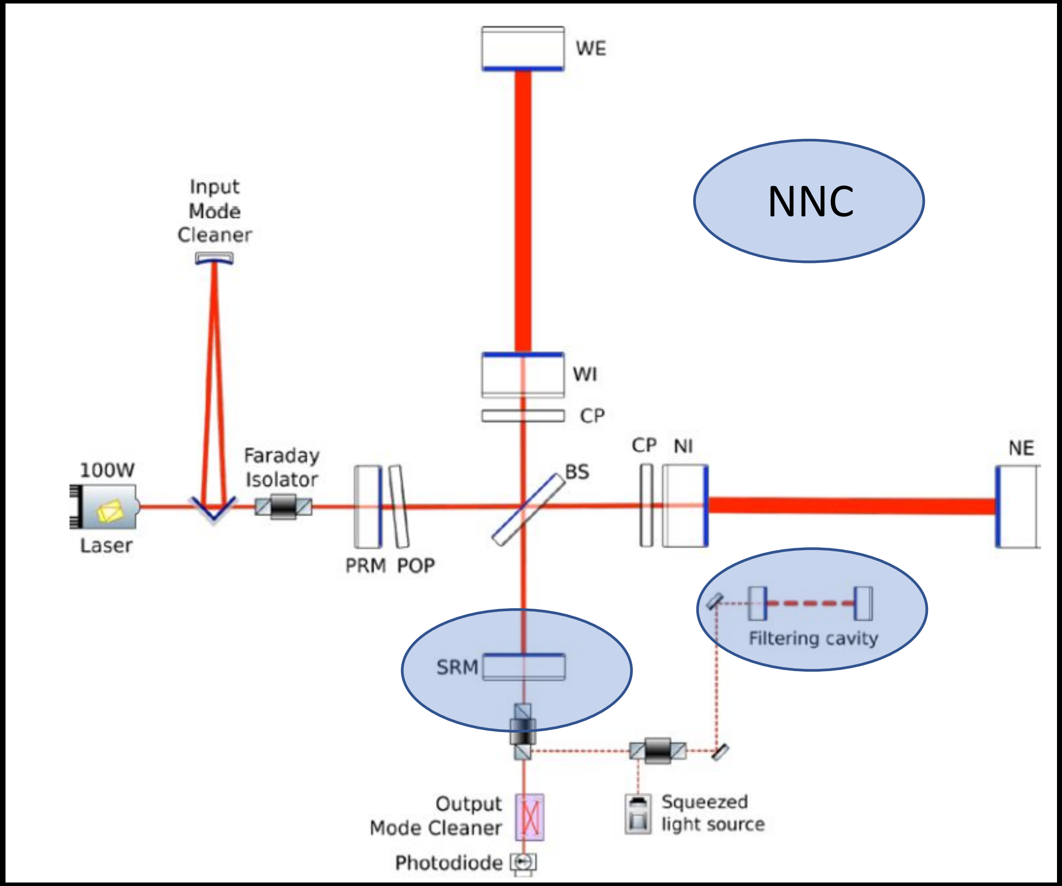


Alain Brillet Adalberto

End of O3


GEO-LIGO-Virgo gravitational-wave strain
GW amplitude spectral density [strain/√Hz]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
10^3
Frequency [Hz]
GEO600
Hanford
Livingston
Virgo

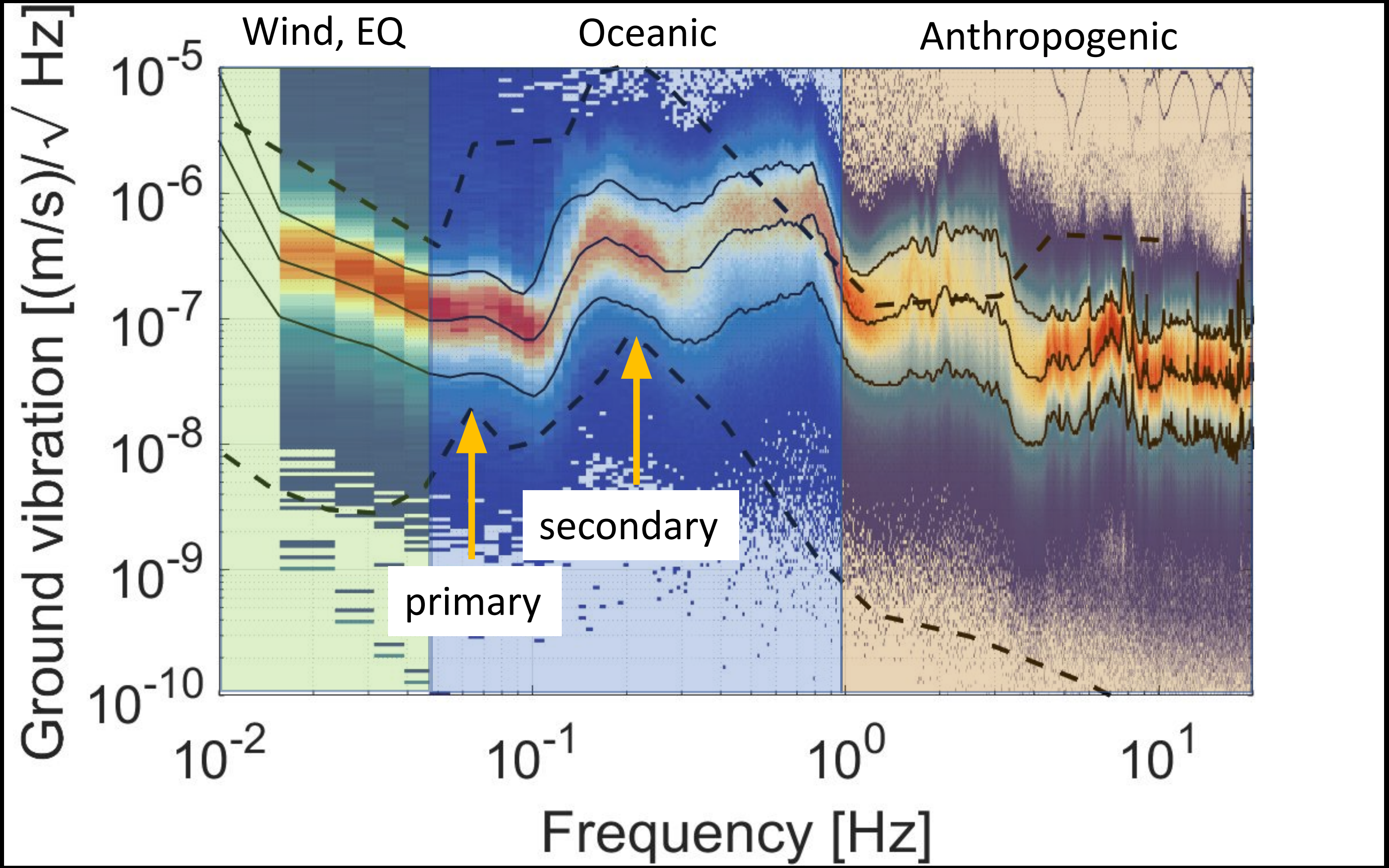
Virgo will have a new look in O4: AdV+ Phase I



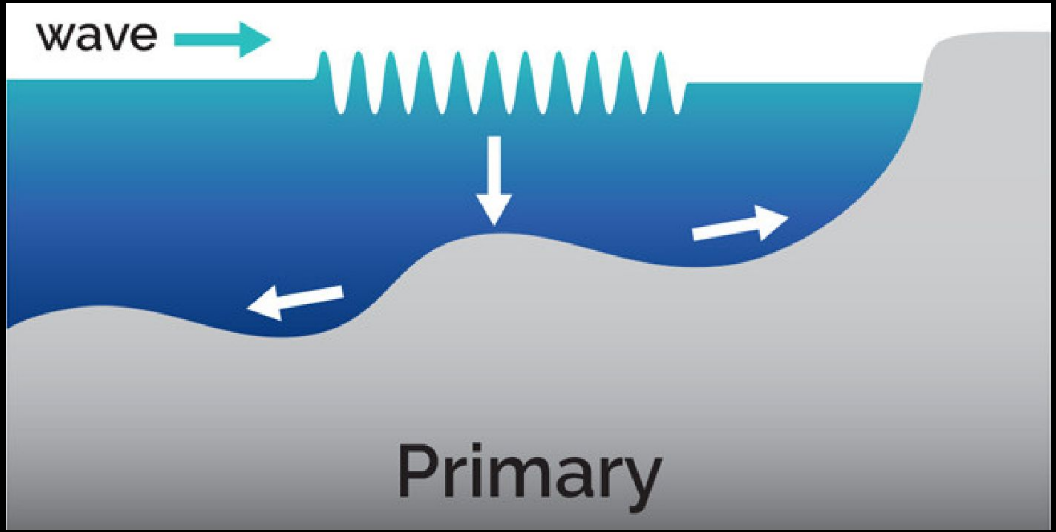
Configuration changes

- Interferometer has a signal-extraction mirror
- Interferometer has a squeezed-light filter cavity
- Detector augmented by a Newtonian-noise cancellation system

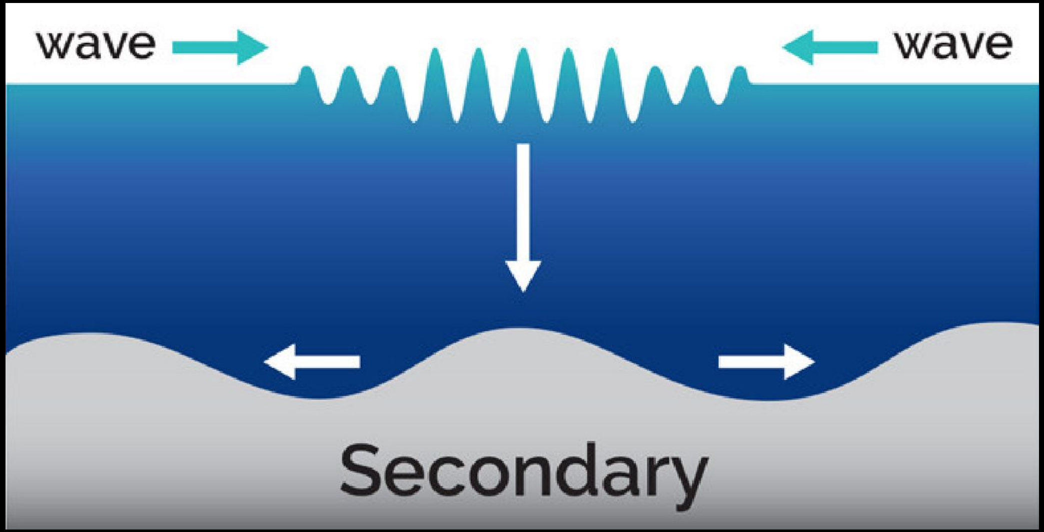
Virgo seismic noise



In shallow waters, the evanescent pressure field under waves couples to sea floor.



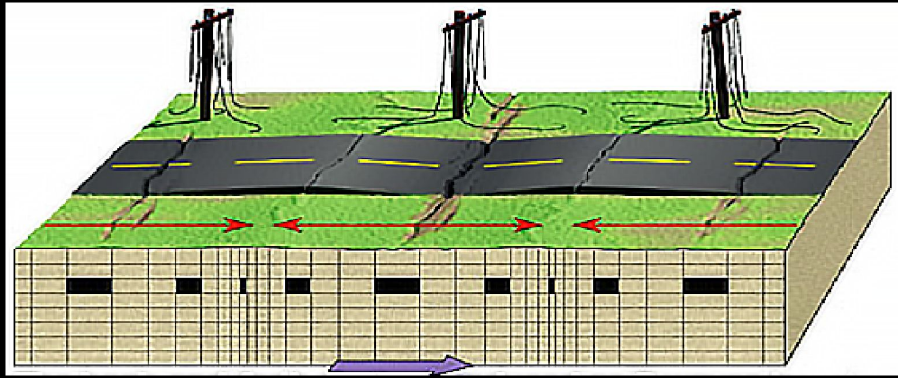
In deeper waters, standing ocean waves can emit pressure waves, which interact with sea floor.



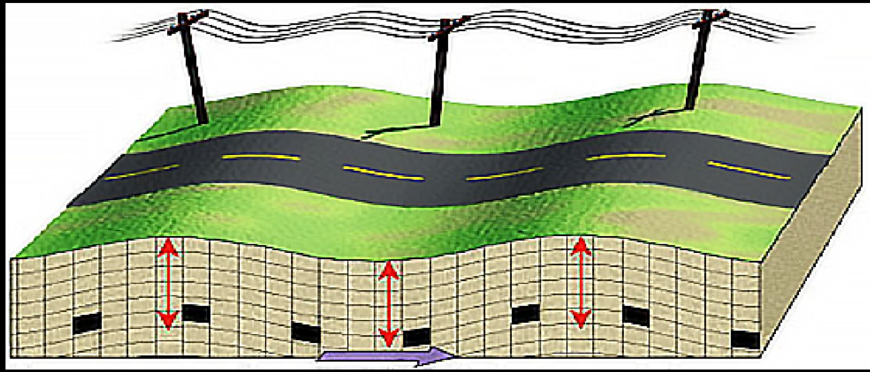
Seismic waves

Body waves

Compressional waves (P)

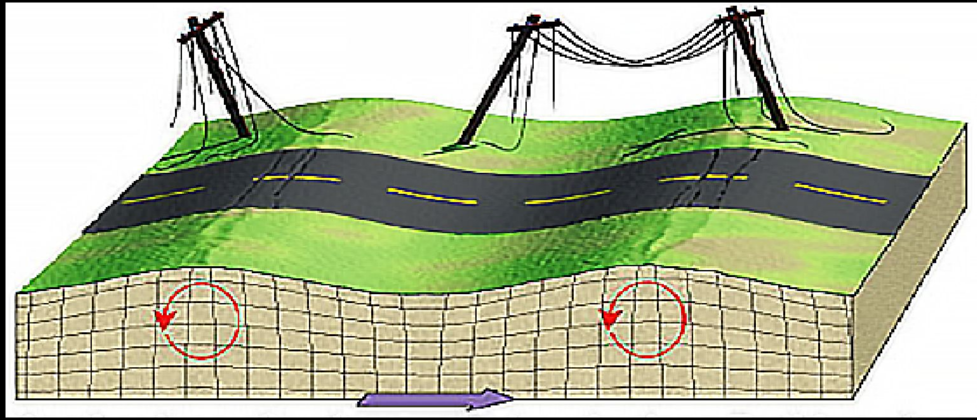


Shear waves (S)



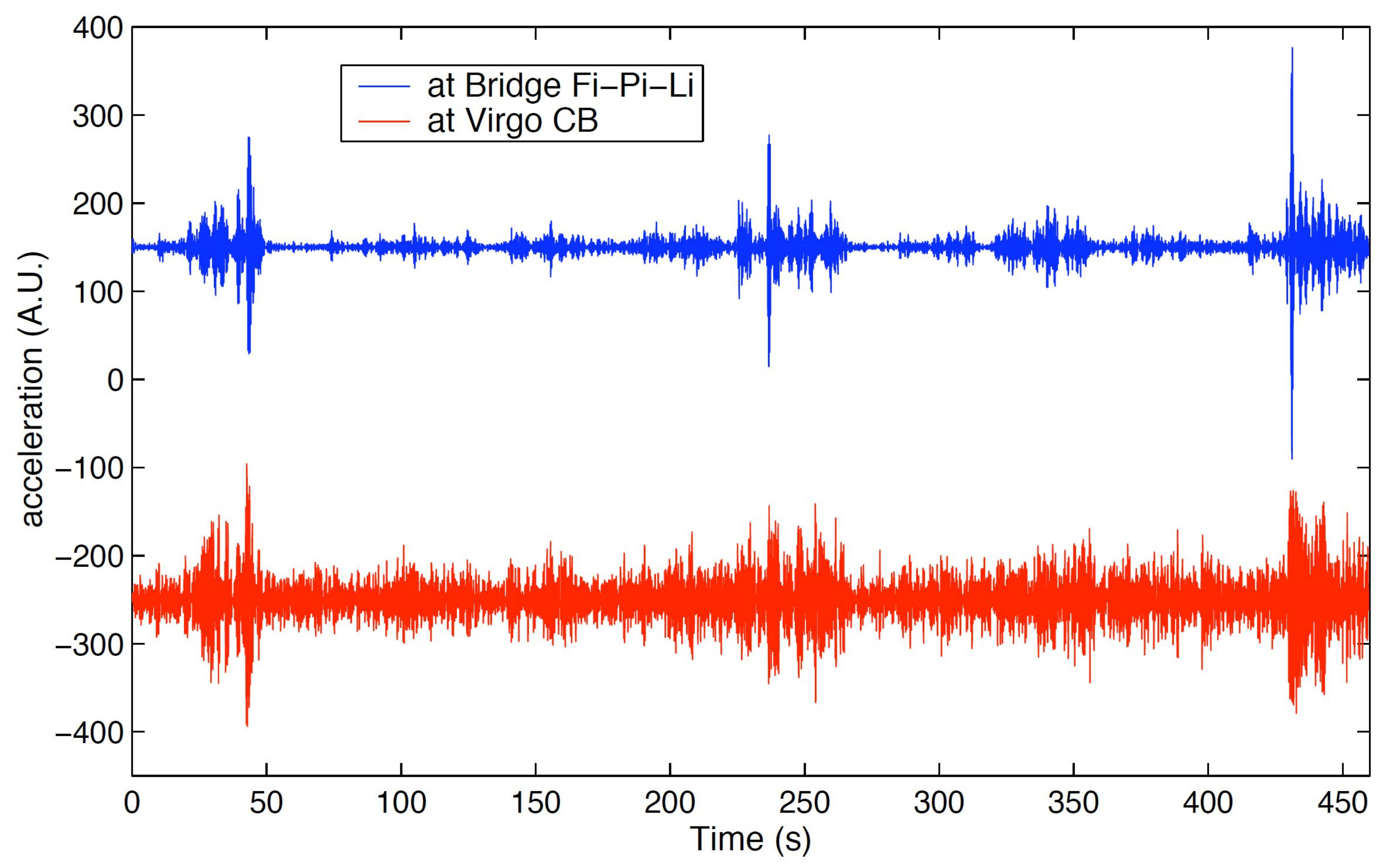
Surface waves

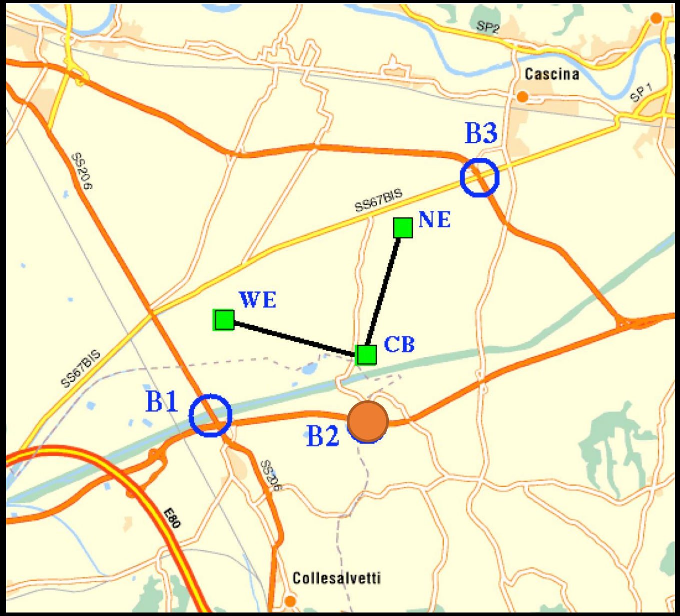
Rayleigh waves



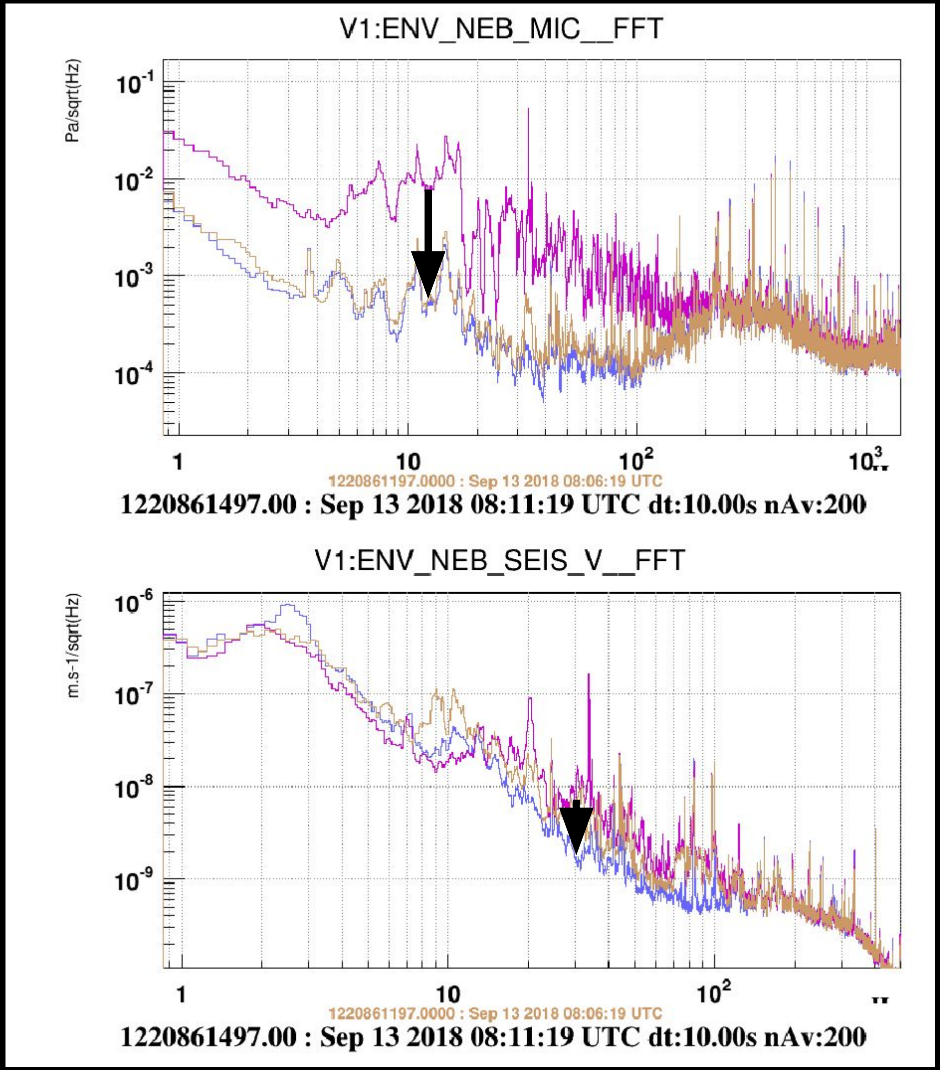
Rayleigh waves typically dominate seismic displacement at the surface.

Trucks passing highway bridge

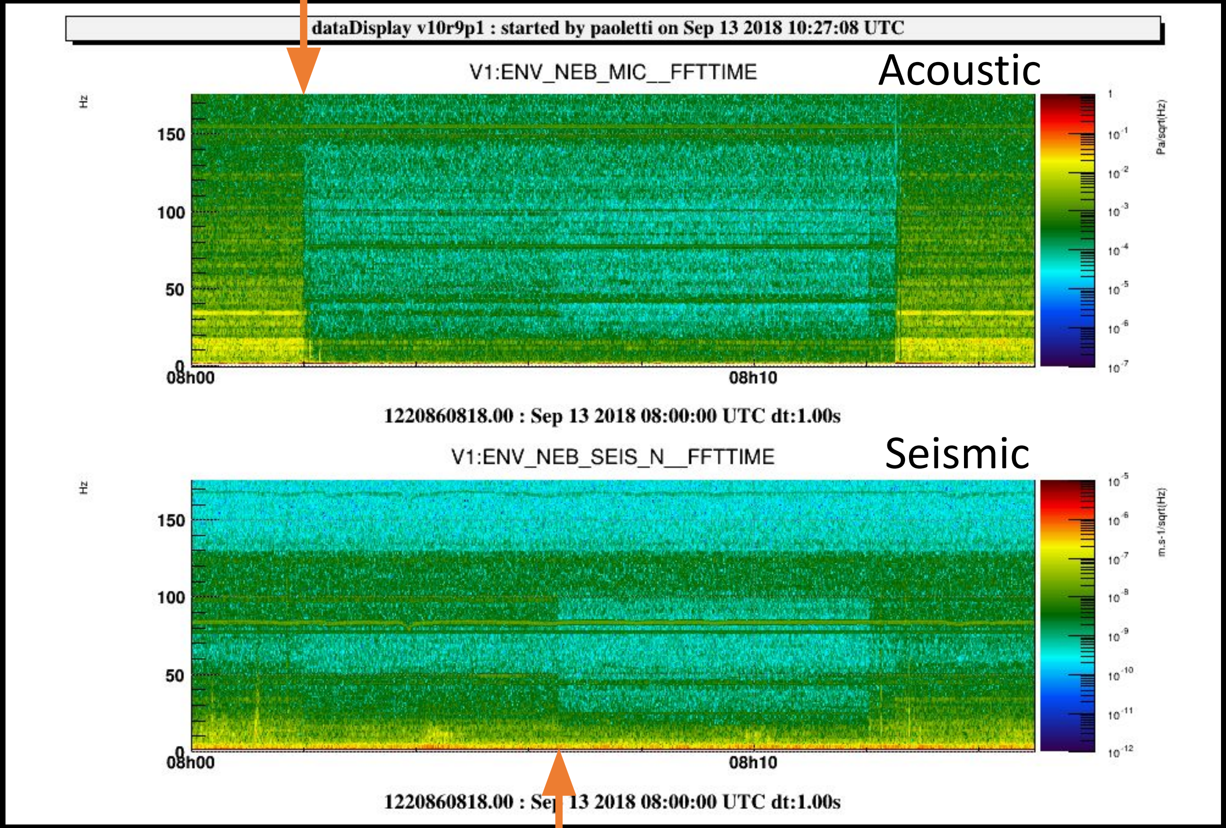




Ventilation switch-off test

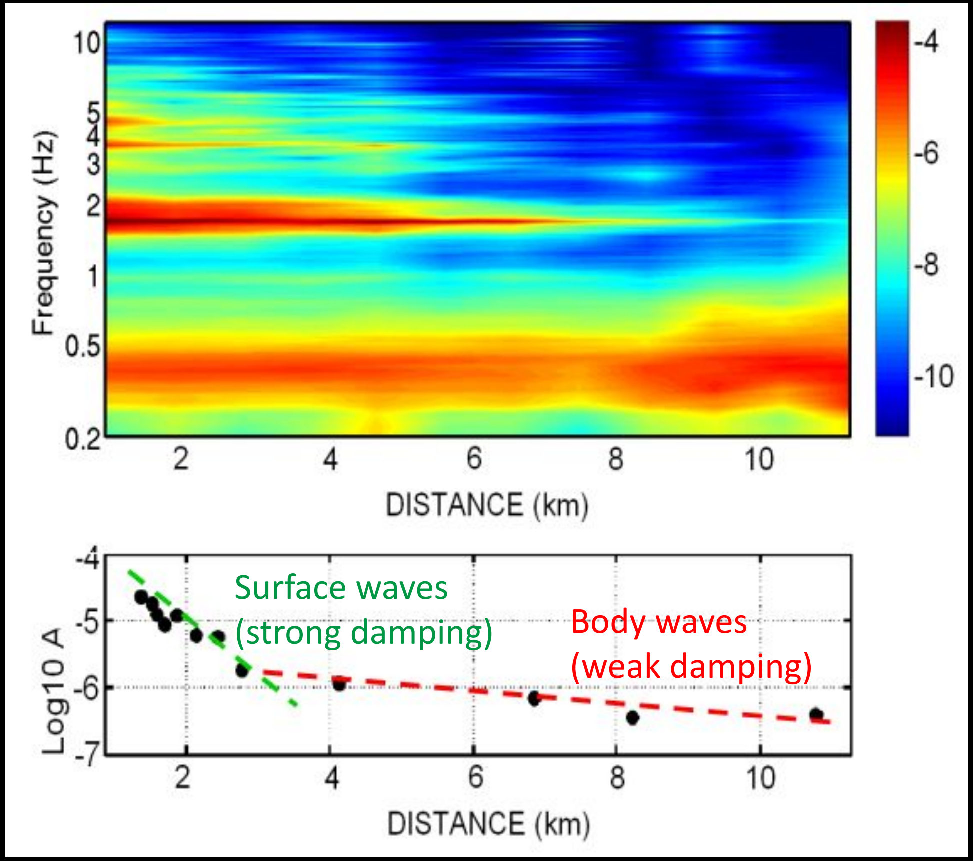


Airflow off



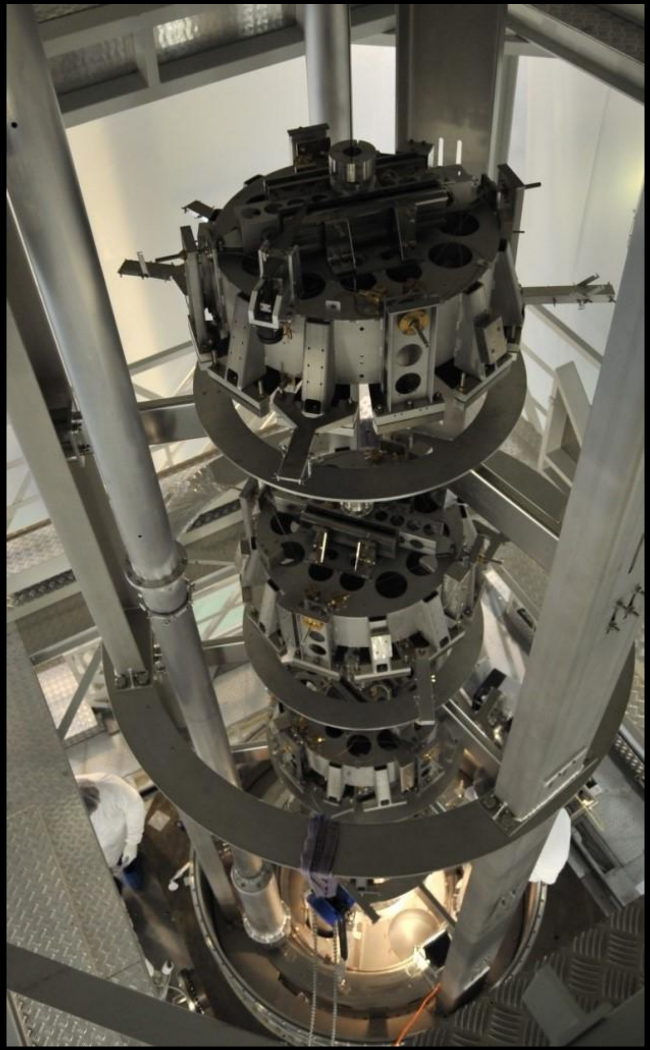
HVAC off

Wind turbines at 6km to Virgo buildings



Wind turbines are a strong source of acoustic and seismic noise detectable over several kilometers.

Virgo superattenuator

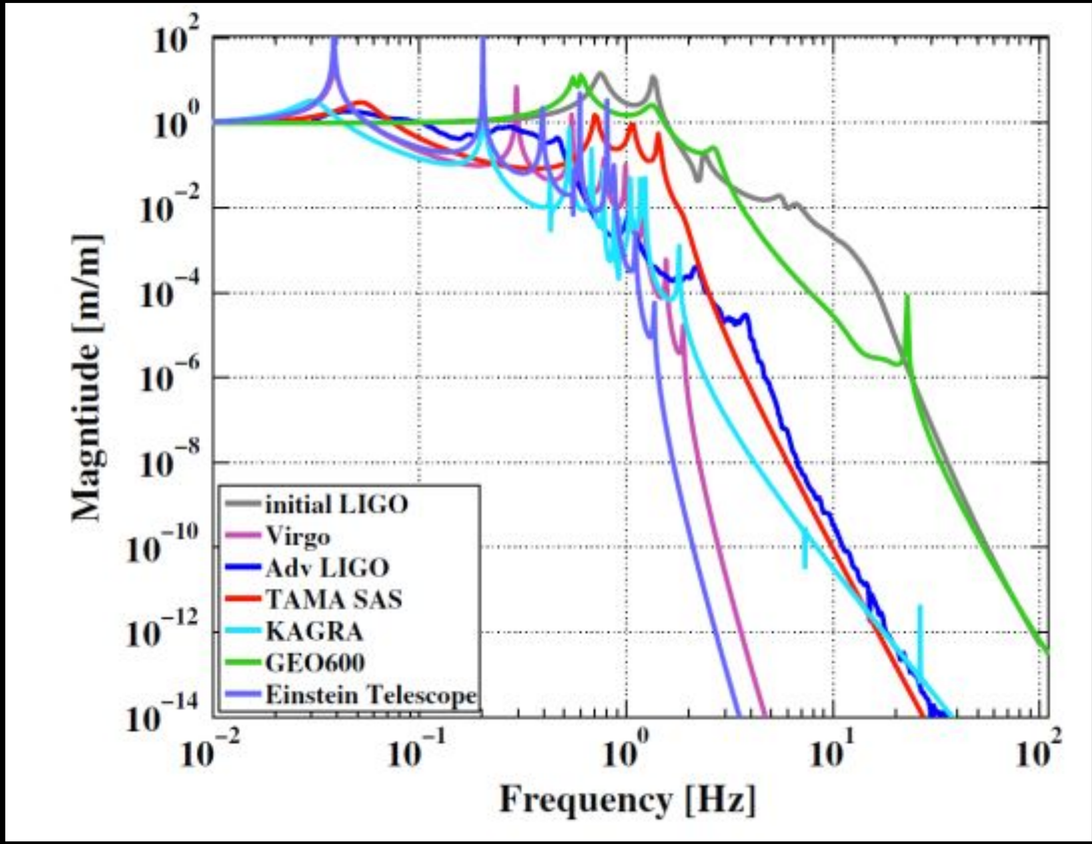


An iconic component of the Virgo detector is the superattenuator inside the 10m tall towers.

It is a design choice initially made to enable low-frequency GW observations.

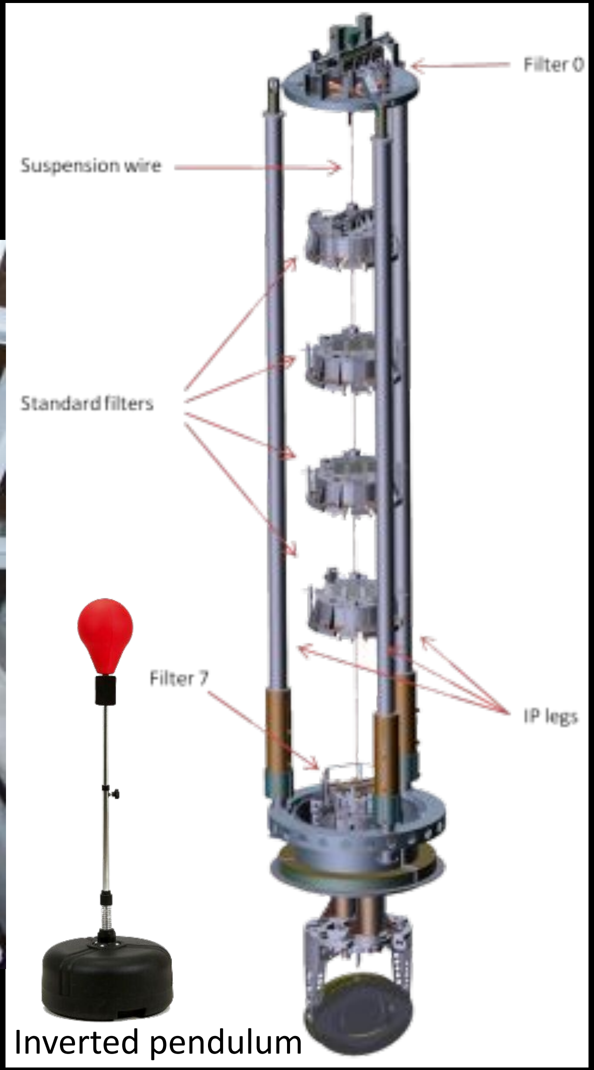
Virgo seismic isolation

Seismic isolation



Mechanical filters

Superattenuator



Gravitational fluctuations

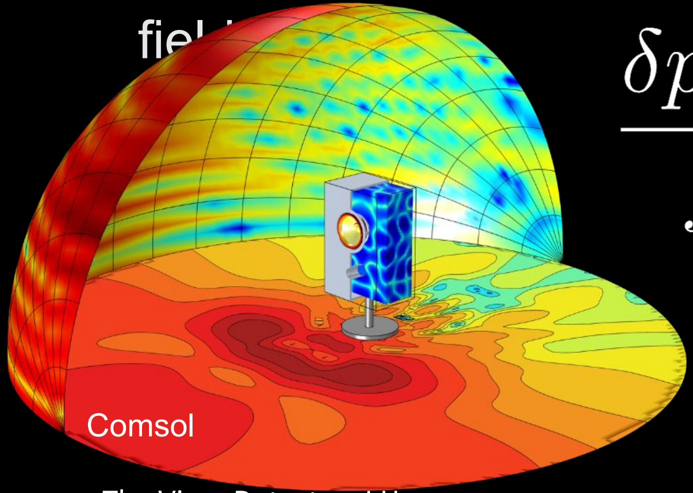
Seismic

$$\frac{\xi(f)}{f^2}\mathrm{e}^{-2\pi f h/c_{\mathrm{seis}}}$$

Advected temperature fields

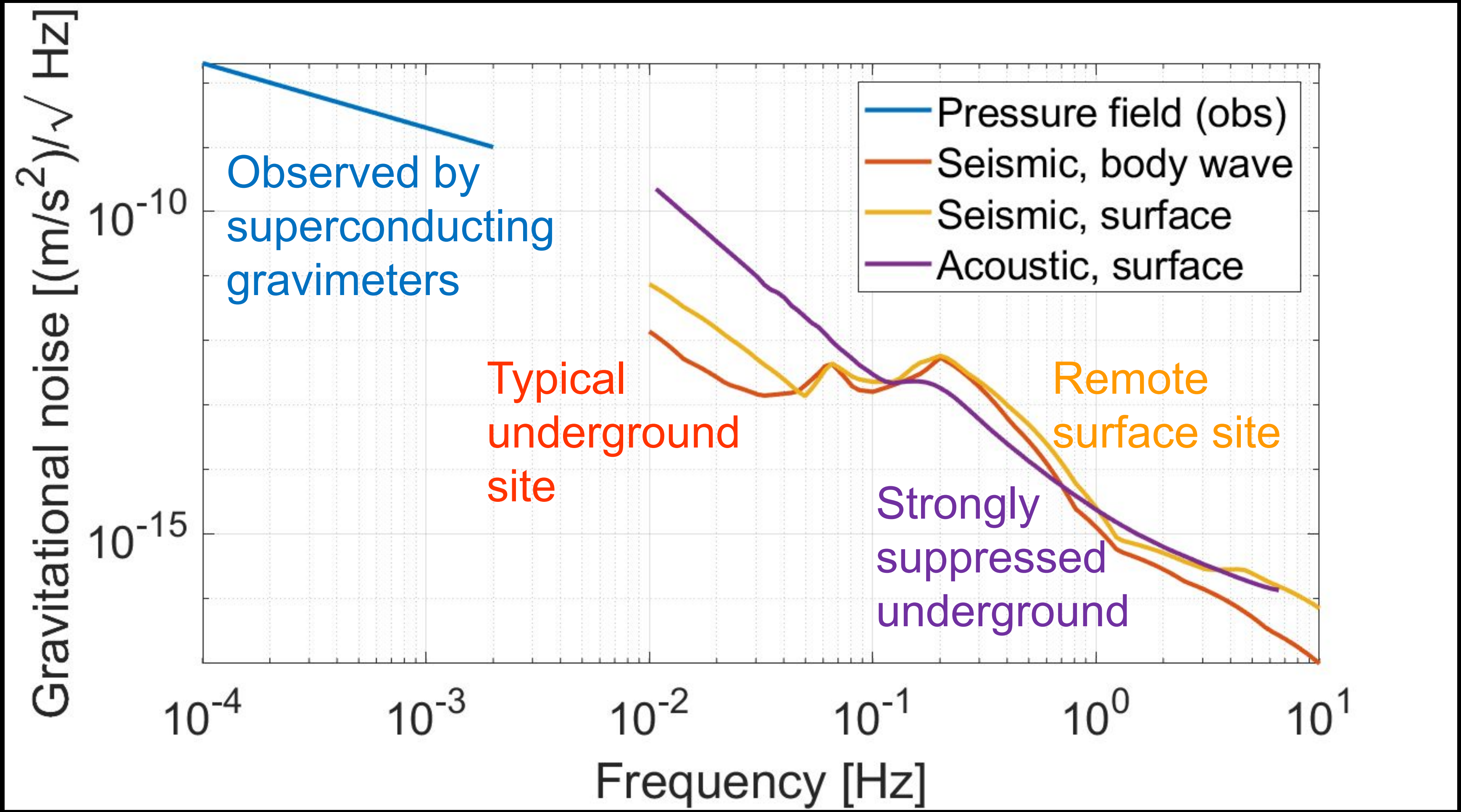
$$\frac{\delta T(f)}{f^{10/3}}\mathrm{e}^{-2\pi f r/v}$$

Infrasound fiel



$$\frac{\delta p(f)}{f^3}\mathrm{e}^{-2\pi f d/c_{\mathrm{snd}}}$$

Gravity spectra



Linearized density perturbation

$$\delta\rho(\vec{r},t) = -\nabla\cdot\left(\rho(\vec{r})\vec{\xi}(\vec{r},t)\right)$$

Neglect time variations of density here

Homogeneous medium

$$\delta\phi_{\text{bulk}}(\mathbf{r}_0,t) = G\rho_0\int_{\mathscr{V}} \mathrm{d}V\,\frac{\nabla\cdot\xi(\mathbf{r},t)}{|\mathbf{r}-\mathbf{r}_0|} \quad + \quad \delta\phi_{\text{surf}}(\mathbf{r}_0,t) = -G\rho_0\int \mathrm{d}S\,\frac{\mathbf{n}(\mathbf{r})\cdot\xi(\mathbf{r},t)}{|\mathbf{r}-\mathbf{r}_0|}$$

Bulk term: (de)compression

Surface term: normal surface displacement

Simplest analytical models

Body-wave NN

$$C_{\rm NN} = \left(\frac{4}{3}\pi G\rho_0\right)^2 \left[4\langle(\vec{e}_{\rm tm}\cdot\vec{\xi}^{\rm P}(\vec{r}_0,\omega))^2\rangle + \langle(\vec{e}_{\rm tm}\cdot\vec{\xi}^{\rm S}(\vec{r}_0,\omega))^2\rangle\right]$$
$$= \left(\frac{4}{3}\pi G\rho_0\right)^2 S(\xi;\omega)(3p+1)$$

Surface and Rayleigh-wave NN

$$C_{\rm NN} = \frac{1}{2}\left(2\pi\gamma G\rho_0 \exp(-2\pi h/\lambda)\right)^2 S(\xi;\omega)$$

How to obtain these equations:

- Calculate the gravitational perturbation caused by a single plane wave
- Average over propagation directions

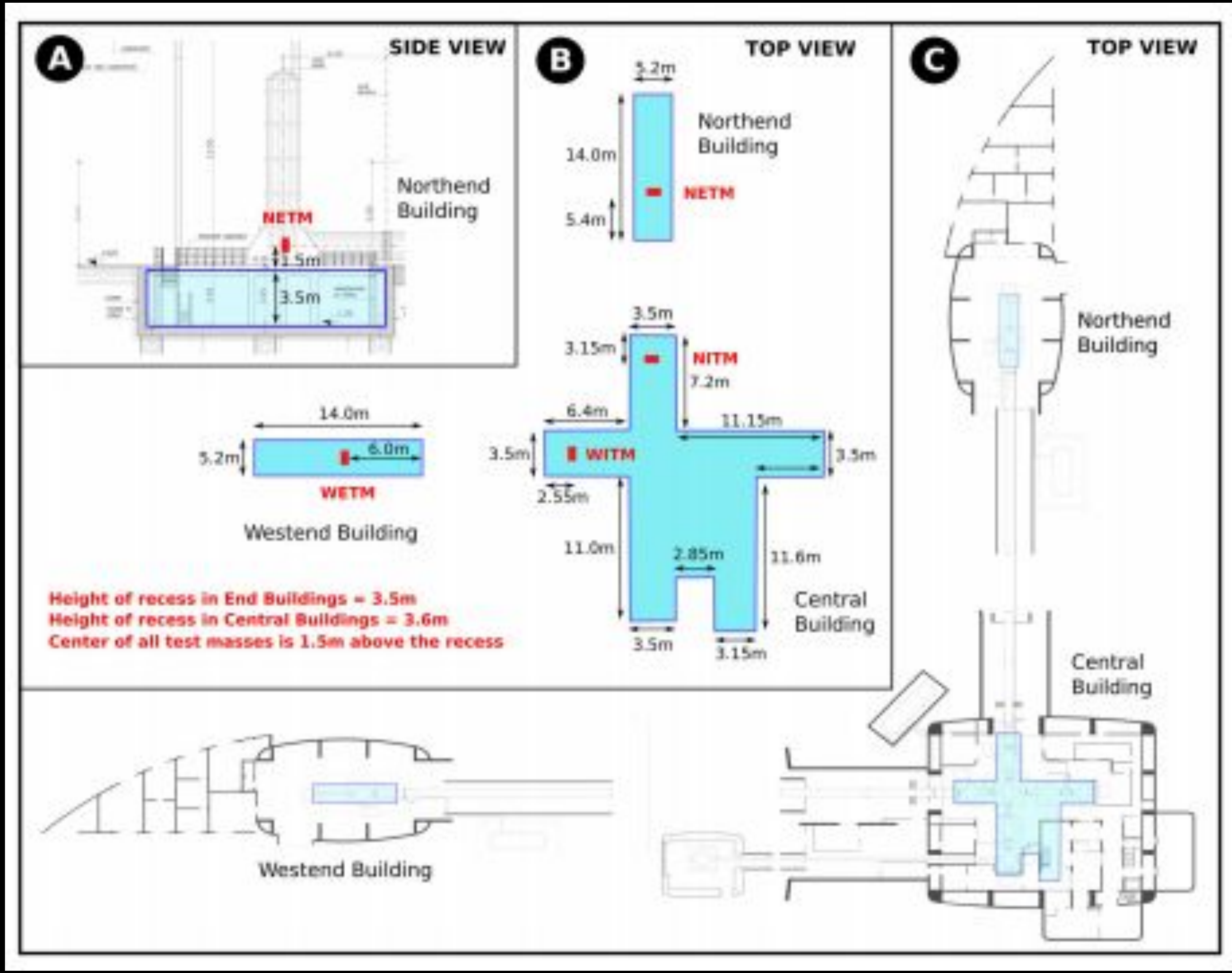
Simplest numerical models

Dipole equation (oscillating mass elements)

$$\begin{aligned}\delta\mathbf{a}(\mathbf{r}_0,t) &= -G\int \mathrm{d}V\,\rho(\mathbf{r})(\xi(\mathbf{r},t)\cdot\nabla_0)\cdot\frac{\mathbf{r}-\mathbf{r}_0}{|\mathbf{r}-\mathbf{r}_0|^3}\\ &= G\int \mathrm{d}V\,\rho(\mathbf{r})\frac{1}{|\mathbf{r}-\mathbf{r}_0|^3}\left(\xi(\mathbf{r},t)-3(\mathbf{e}_{rr_0}\cdot\xi(\mathbf{r},t))\mathbf{e}_{rr_0}\right)\end{aligned}$$

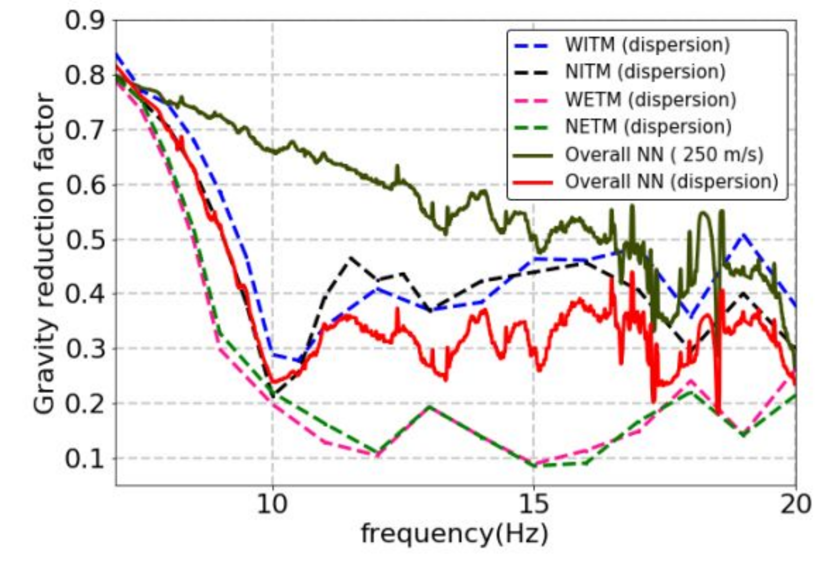
Method

- Propagate waves of known analytical form through a finite-element model
- Numerically integrate the associated gravity perturbation using the dipole equation



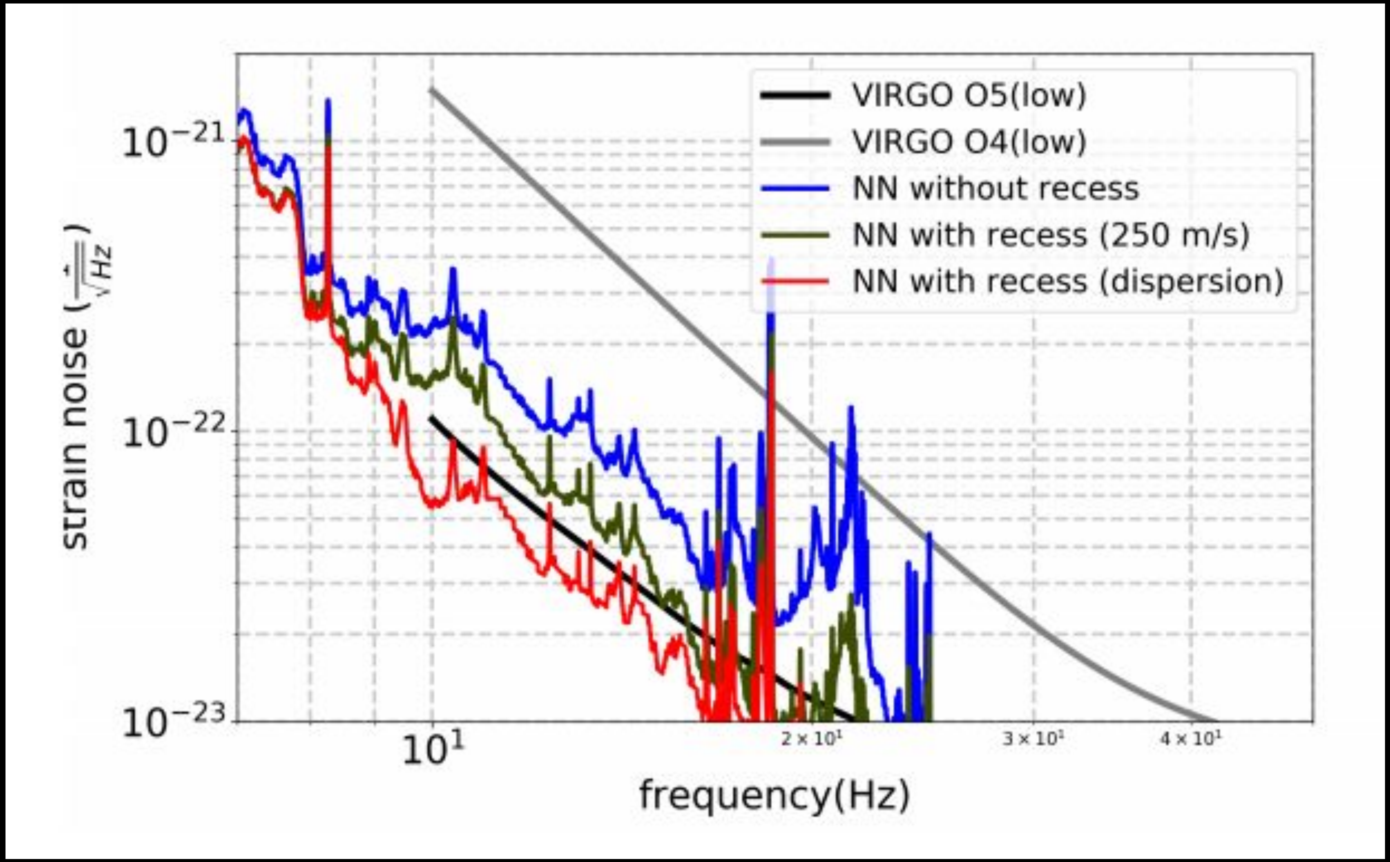
This type of simple numerical analysis was used for the current Virgo NN estimate (matches Bayesian estimate).

It takes into account the presence of clean rooms under the towers.



Lucky! Twice!

- Clean rooms under the towers increase distance between test masses and ground
- In the 10-20Hz band, the dominant seismic waves are extremely slow (<100m/s)



Singha et al (2021)

Numerical models based on seismic correlations

Example: surface NN, homogeneous model

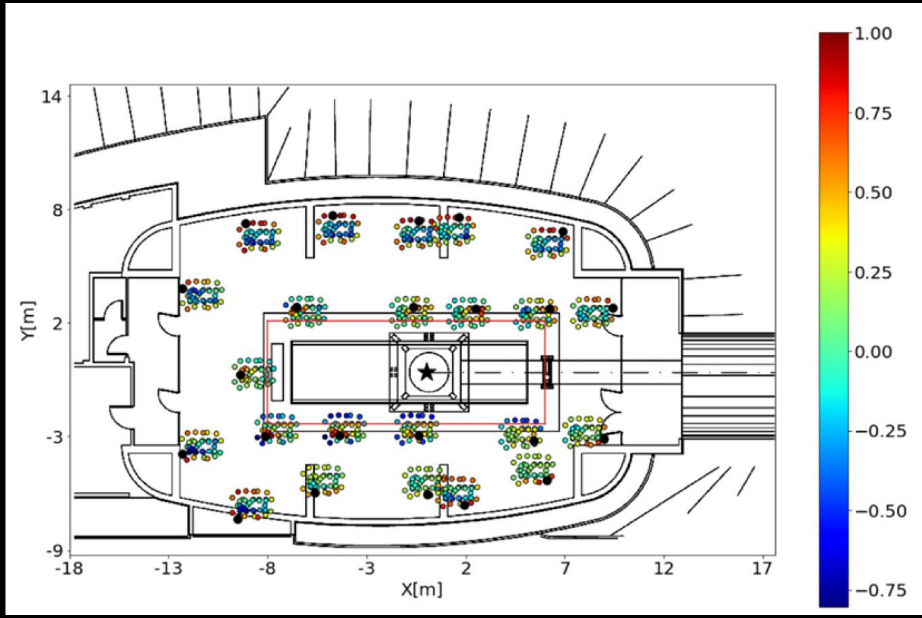
$$S(\delta a_x;\omega) = (2\pi G\rho_0\gamma(\nu))^2 \frac{1}{2\pi}\int \mathrm{d}^2\varrho \left[\frac{x^2}{\varrho^2}\frac{2h}{\left((2h)^2+\varrho^2\right)^{3/2}} + \frac{y^2-x^2}{\varrho^4}\left(1-\frac{2h}{\left((2h)^2+\varrho^2\right)^{1/2}}\right)\right] C(\xi_z;\varrho,\omega)$$

Seismic correlations

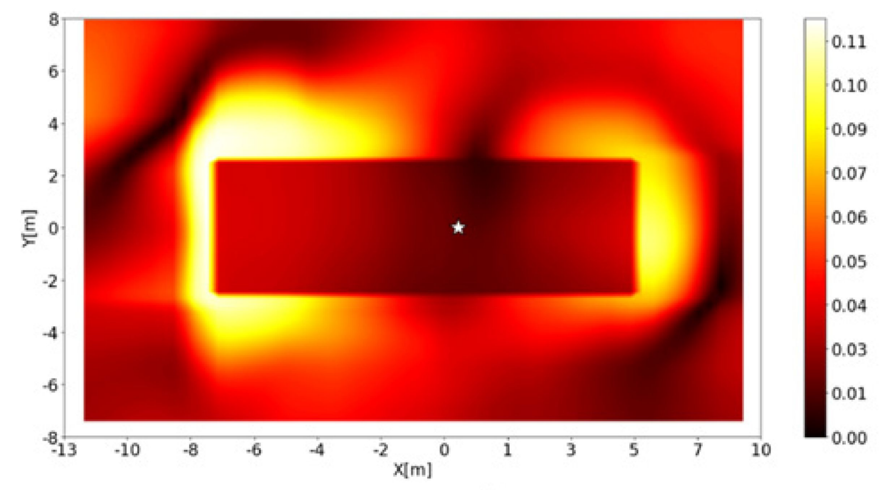
Method

- Use observed seismic correlations
- Integrate numerically using an appropriate kernel

Seismic correlations at Virgo

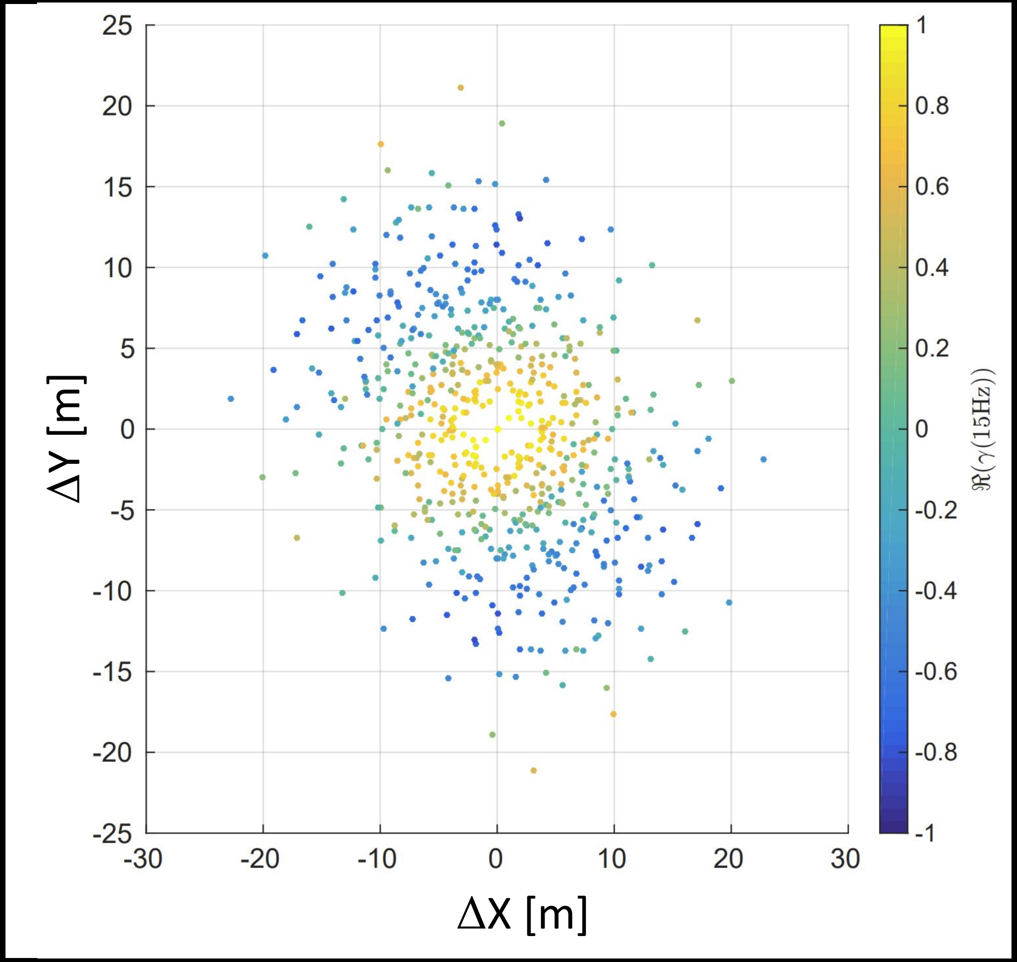


Modeled gravitational coupling



Badaracco et al (2020)

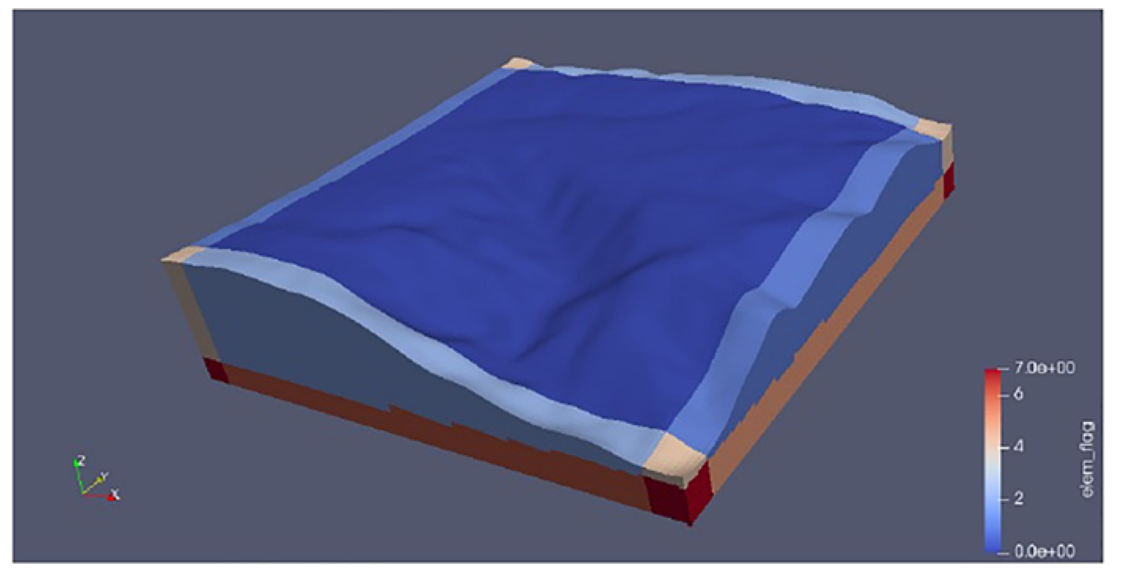
Seismic correlations at LIGO



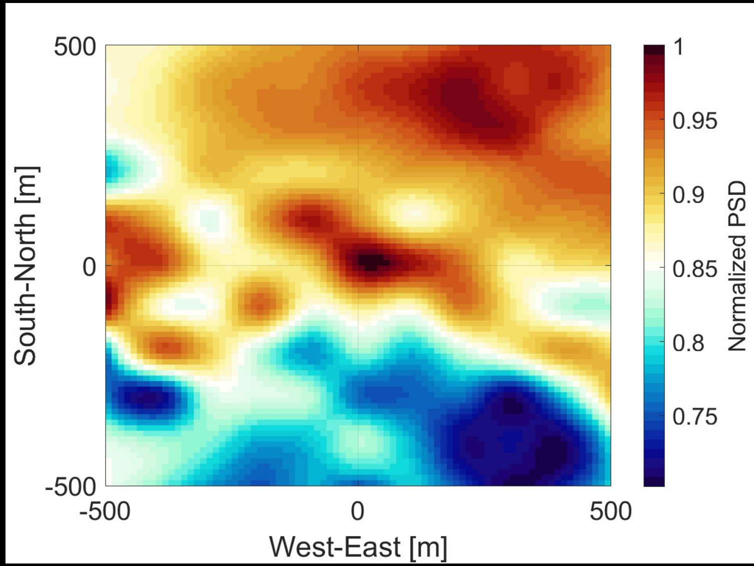
Coughlin et al (2018)

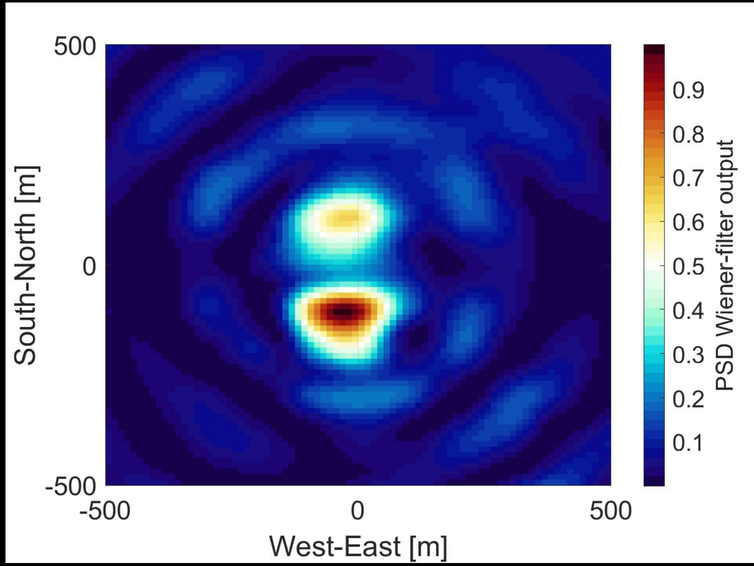
Dynamical finite-element simulations

Any scenario can in principle be modelled



Example: site in Sardinia

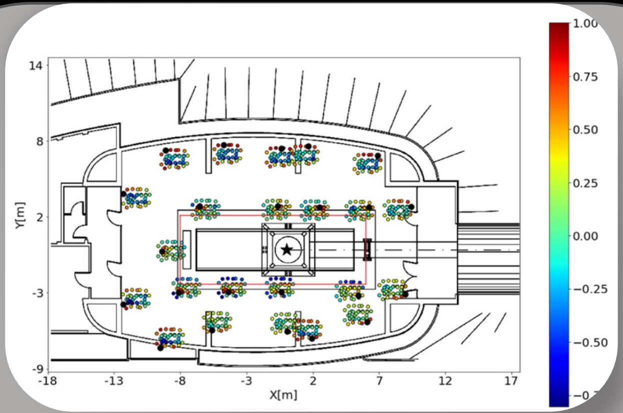


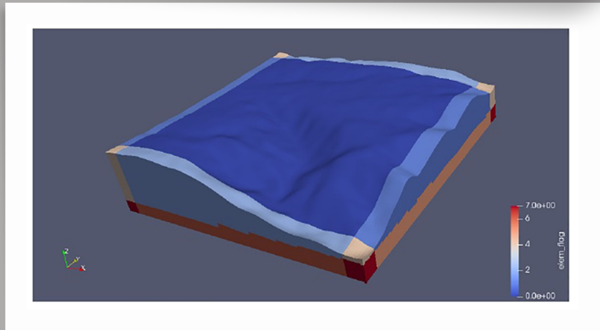


Andric/Harms (2020)

Bayesian NN estimation

Combine models and measurements

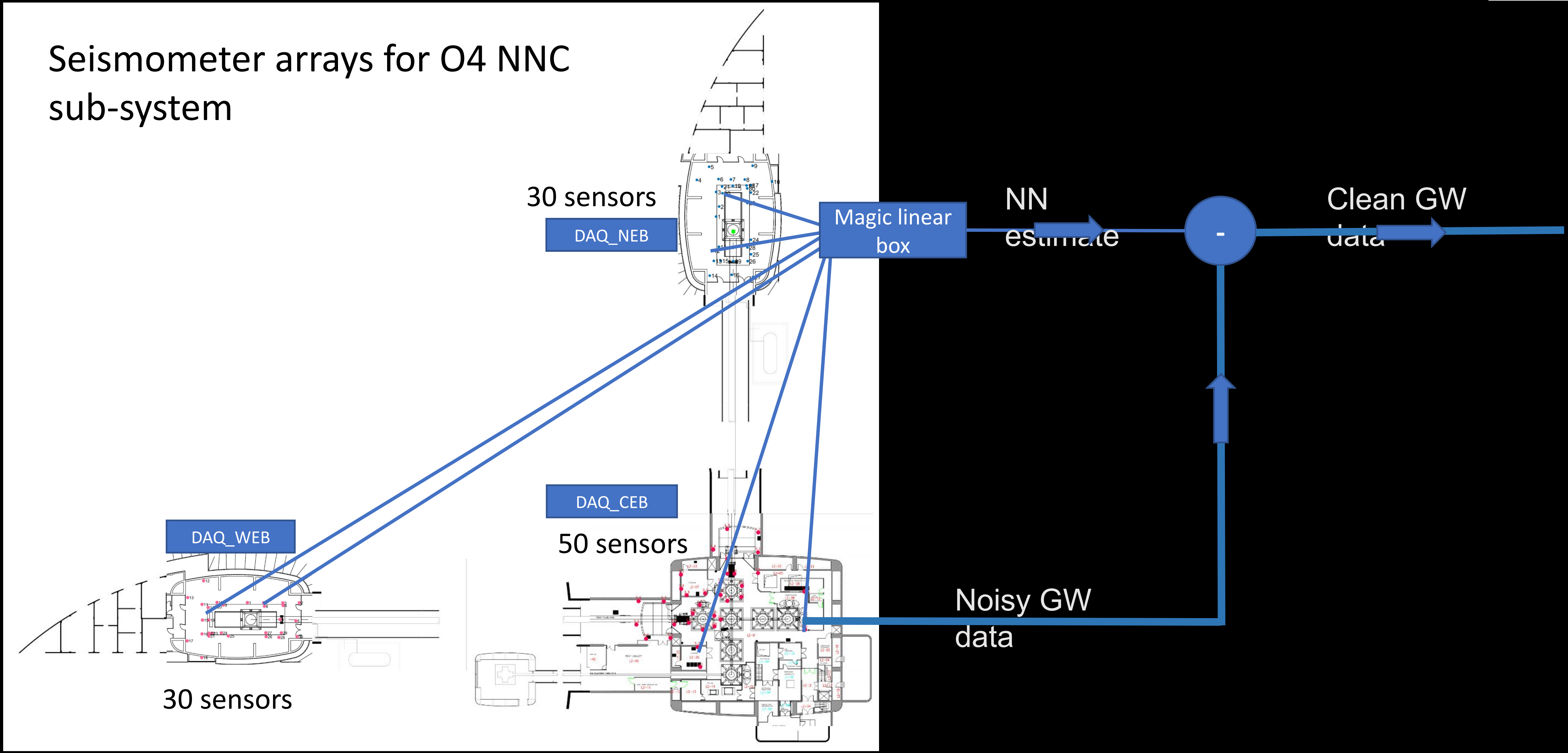




Method

1. Measure seismic correlations
2. Model seismic correlations, e.g., with SPECFEM3D
3. Set up surrogate model of seismic correlations (e.g., using GPR)
4. Numerically integrate surrogate model with appropriate kernel to obtain Newtonian noise

NN cancellation at Virgo



Linear noise cancellation

Wiener filter

$$\mathbf{C}_{xx} \cdot \mathbf{w}(:) = \mathbf{C}_{xy}$$

Seismometer correlation matrix

Correlations between seismometers and GW data

Finite-impulse response (FIR) filter

$$\hat{y}_n = \sum_{k=0}^{N} \mathbf{w}_k \cdot \mathbf{x}_{n-k} \equiv \mathbf{w} \circ \mathbf{x}_n$$

Noise subtraction

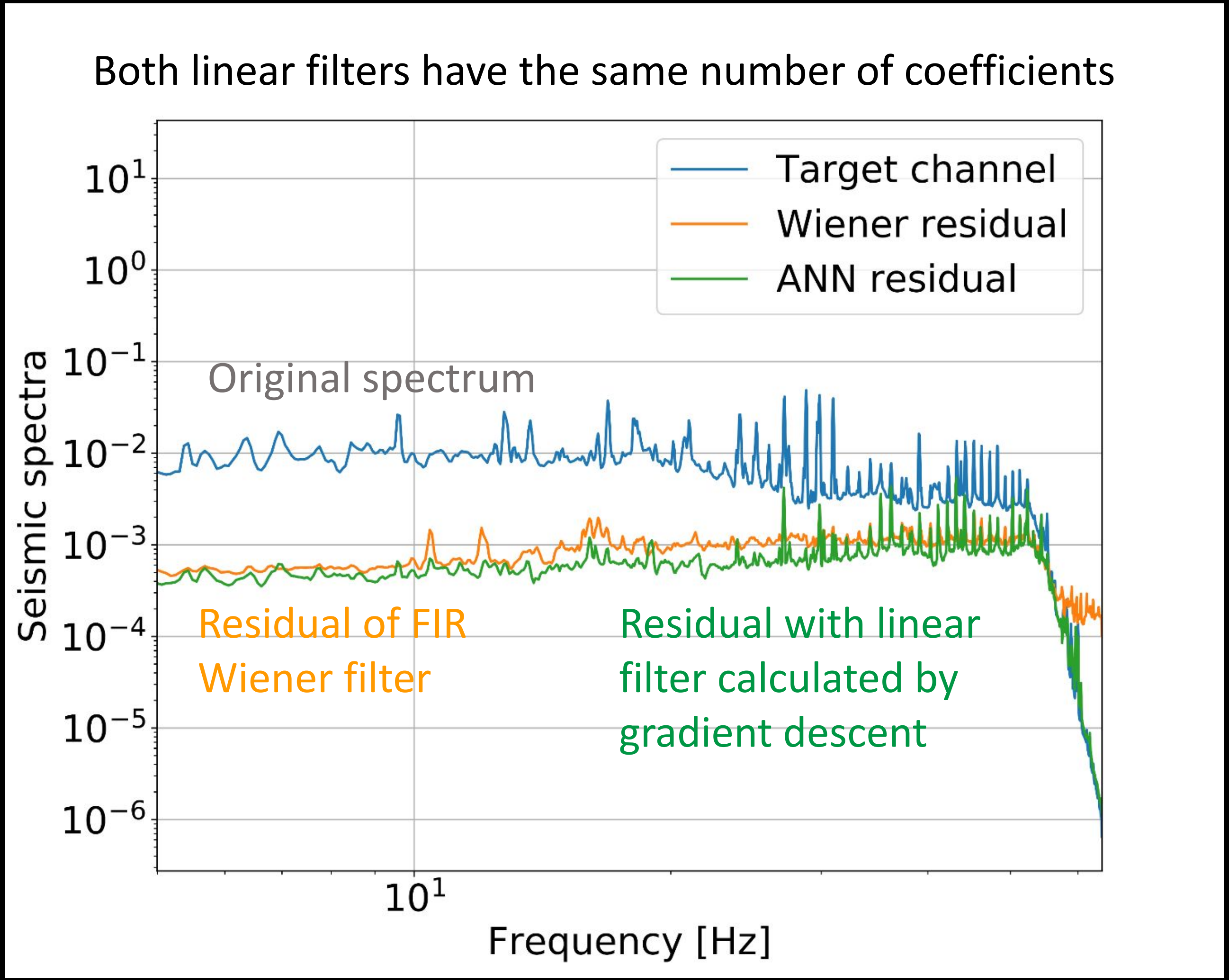
$$r_n = y_n - \mathbf{w} \circ \mathbf{x}_n$$

- Requires estimate of a huge number (up to millions) of correlation coefficients (large statistical error)
- Filter is stationary

Alternative approaches:

- FIR with gradient descent
- Kalman filter
- Supervised ML

Filter designs

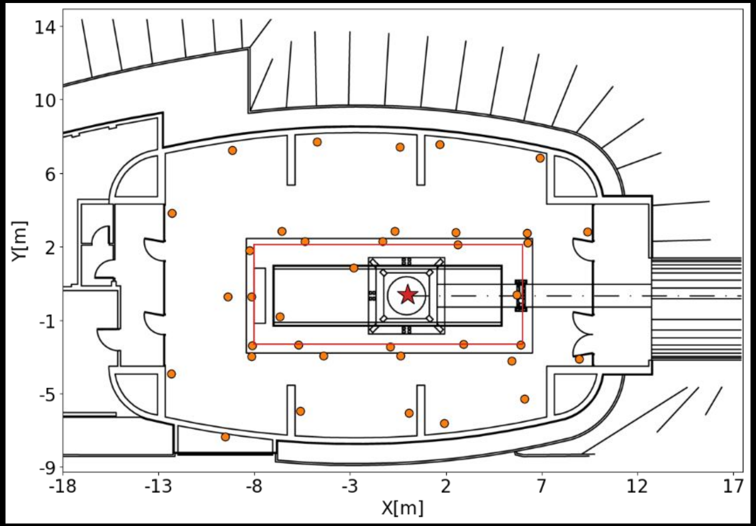


Wiener filter is the **optimal filter** for reduction of noise variance.

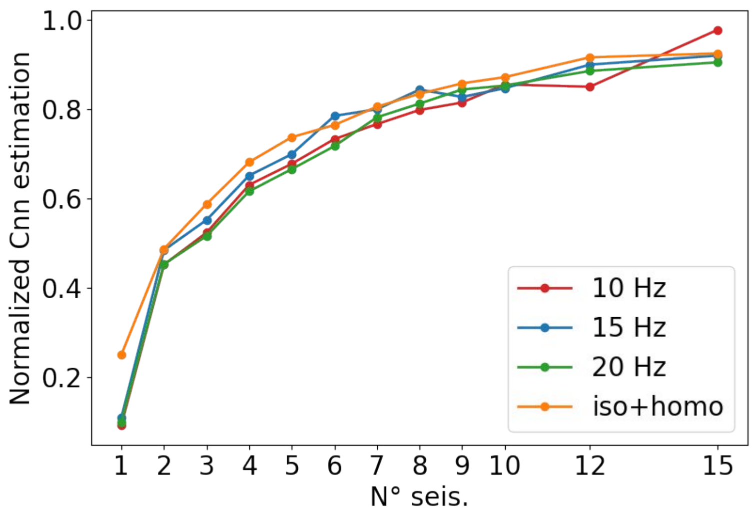
Reality: It depends on details. Statistical errors can limit how accurately we can calculate the Wiener filter.

Array Optimization

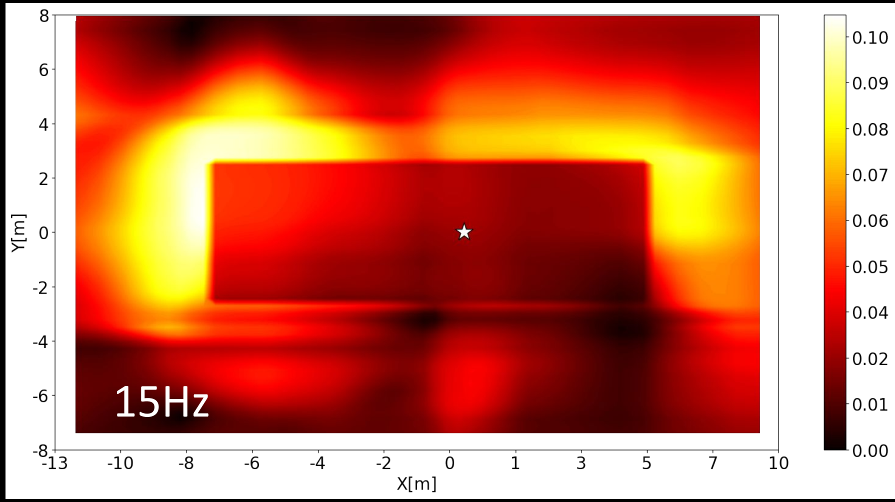
(1) Site characterization



(3) Performance prediction

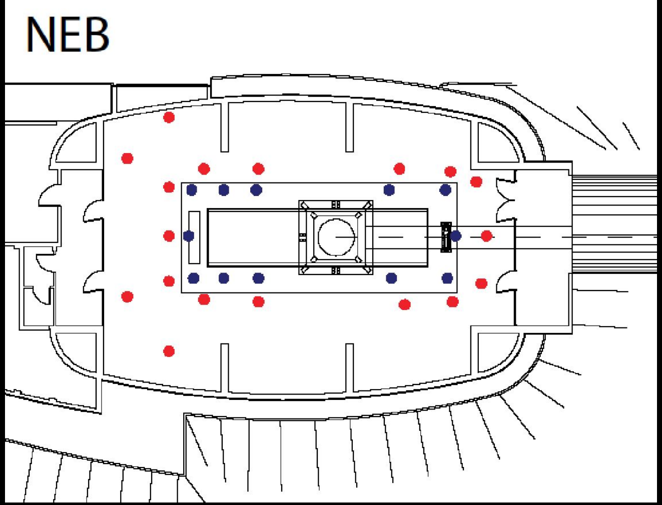


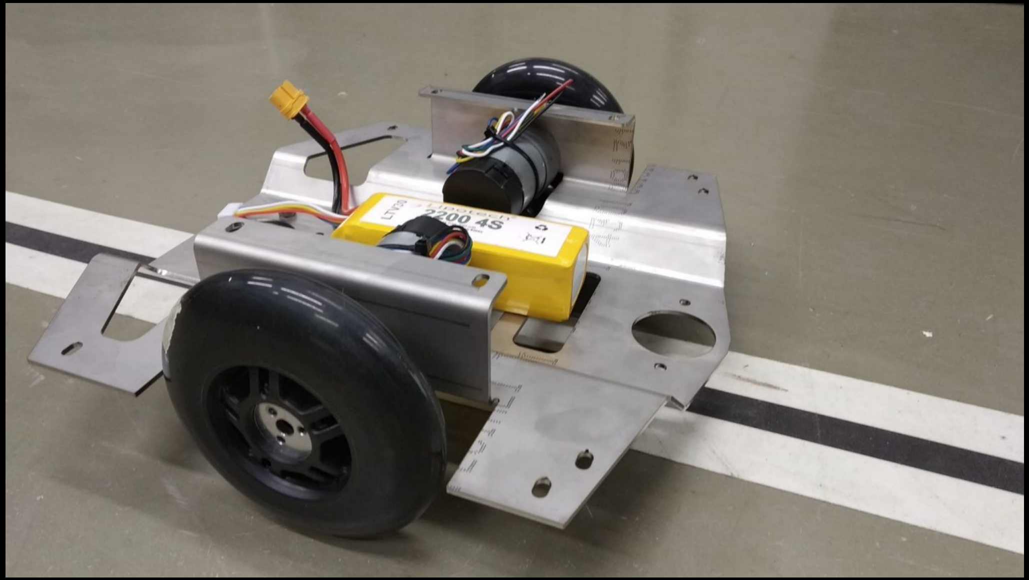
(2) Optimal seismometer placement

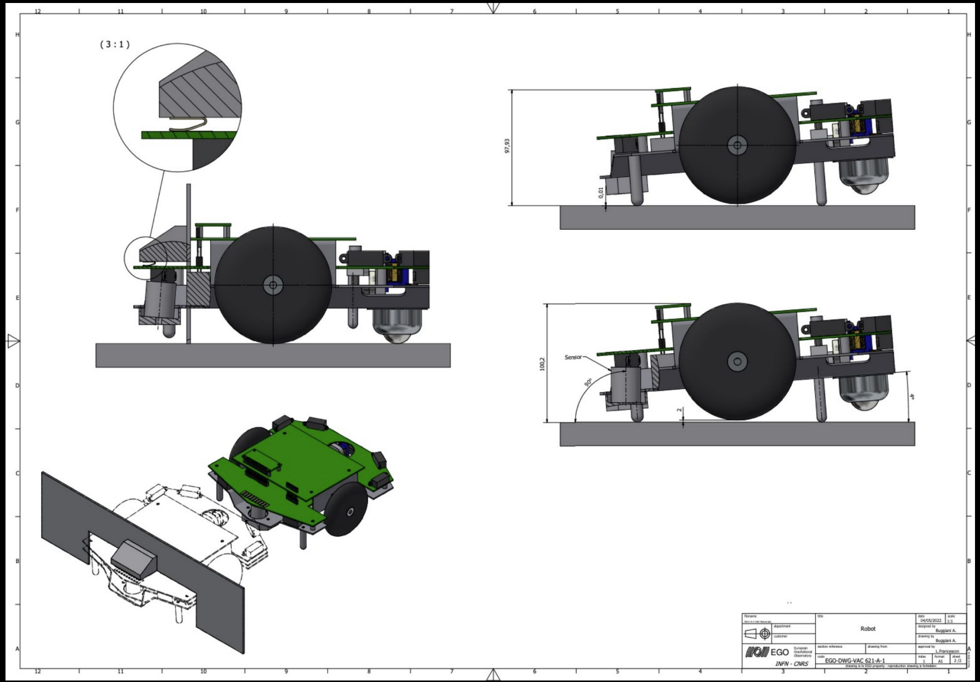


Badaracco et al (2020)

(4) Final array configuration at Virgo



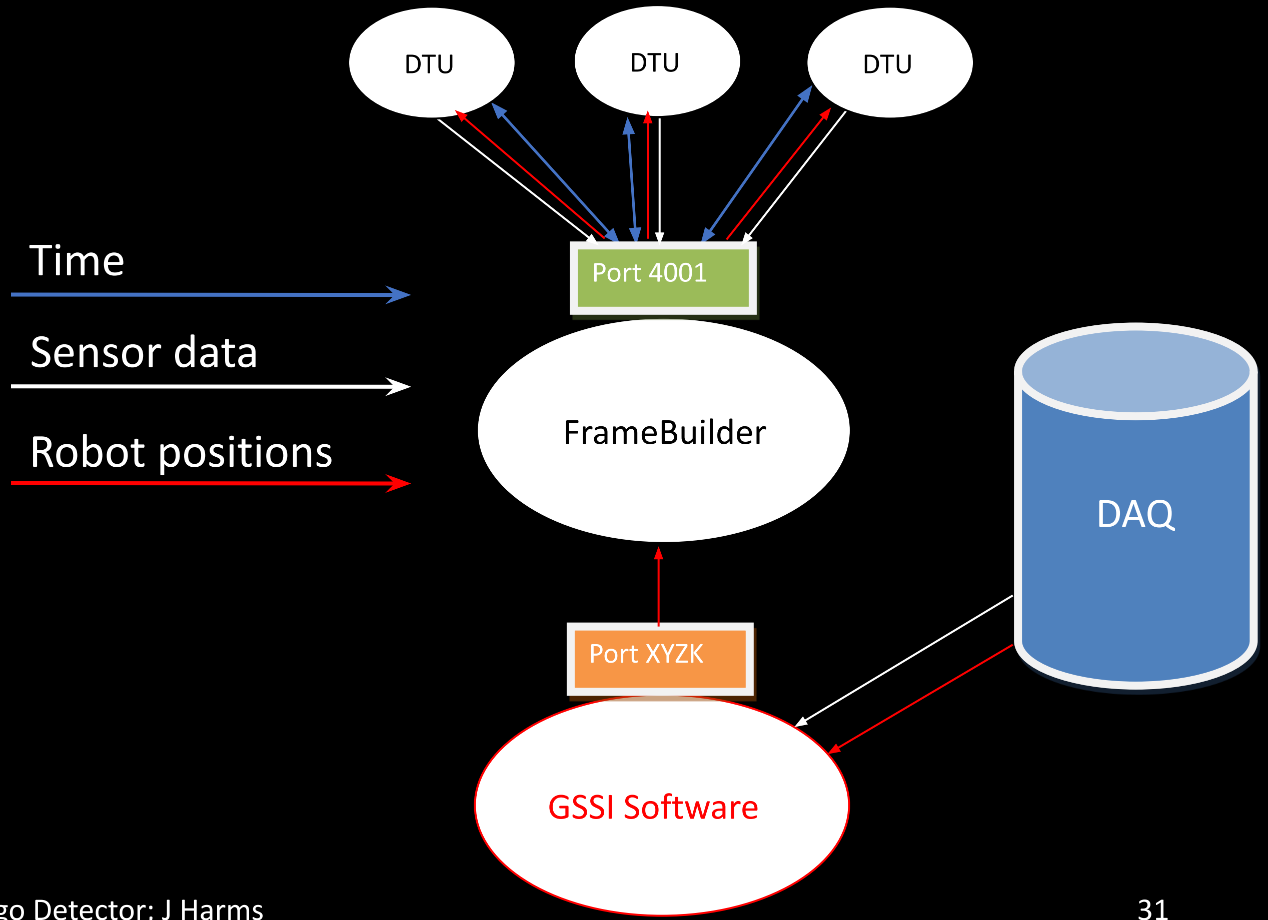




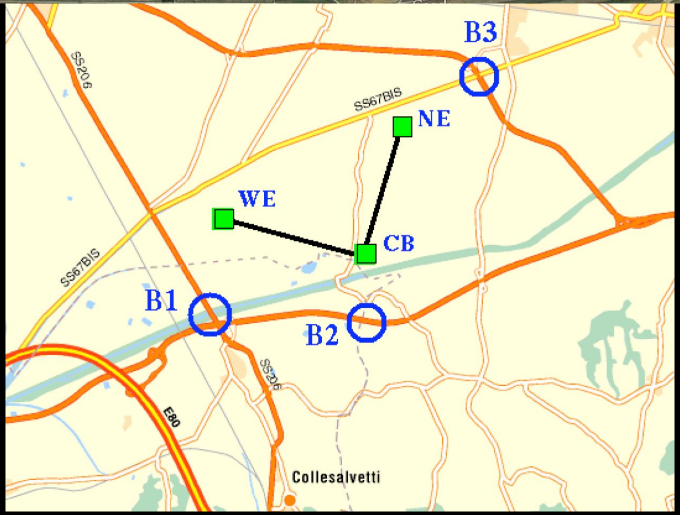
EGO robot team

Robot platforms with seismic sensors

Use the same array-optimization algorithm in real time and converge to optimal array configuration.



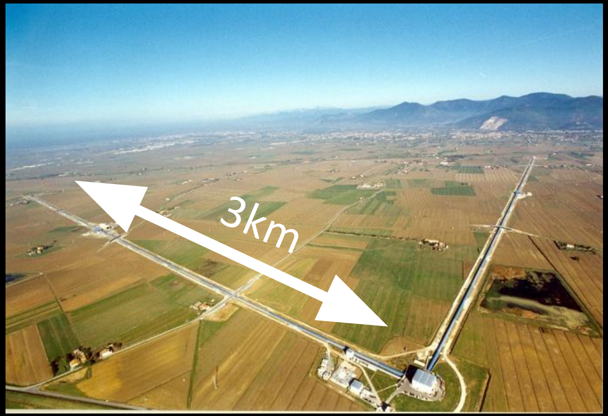
Detector site

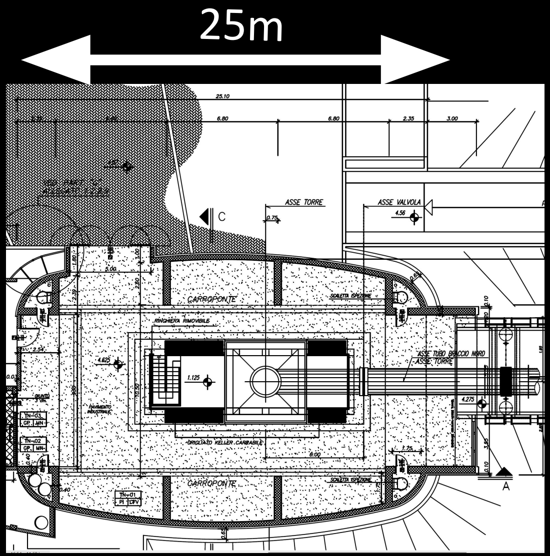


Infrastructure

Noise

Geometry





Optical layout (OptoCad)

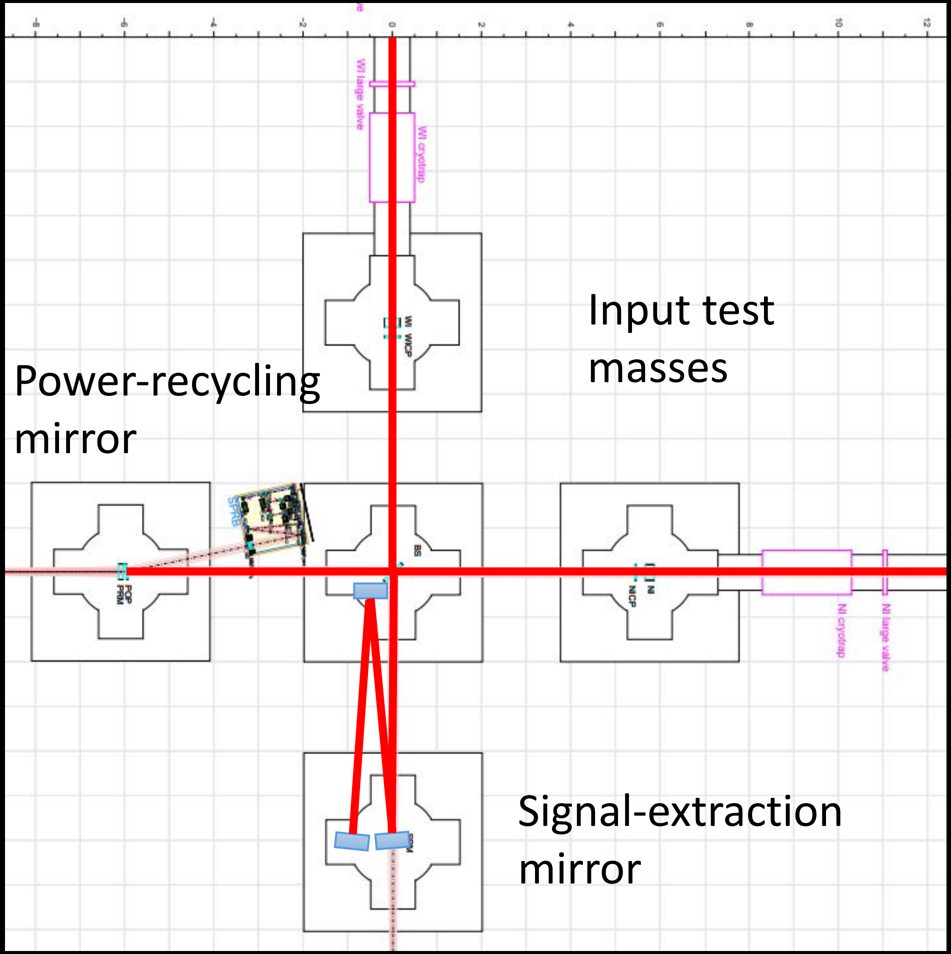
Virgo’s Central Building is small

⇓

Distance between chambers cannot be increased

⇓

Limits the length of recycling cavities, and forces you into «riskier» solutions



Folded cavity (non-degenerate recycling cavity)

⇓

Multiple optics suspended inside BS and SE/PR towers

⇓

Eventually dismissed in favor of marginally-stable recycling cavities

CHRoCC: mirror curvature correction

One cannot operate the interferometer stably if the main optics have the wrong radius of curvature.