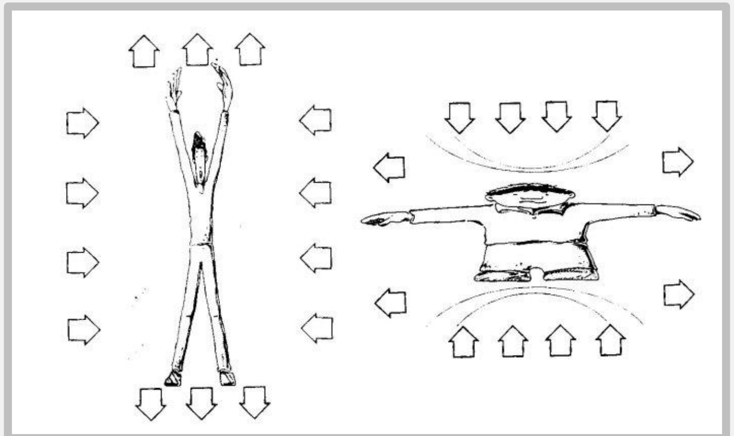
GRAN SASSO SCIENCE INSTITUTE

New technologies for sensitivity improvement of current and future gravitational-wave detectors

17th October 2019

Francesca Badaracco

- What a gravitational wave is
- Why is it important to Astrophysics
- How does a gravitational wave detector work?



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$$\frac{\Delta L}{L} = 10^{-21}$$

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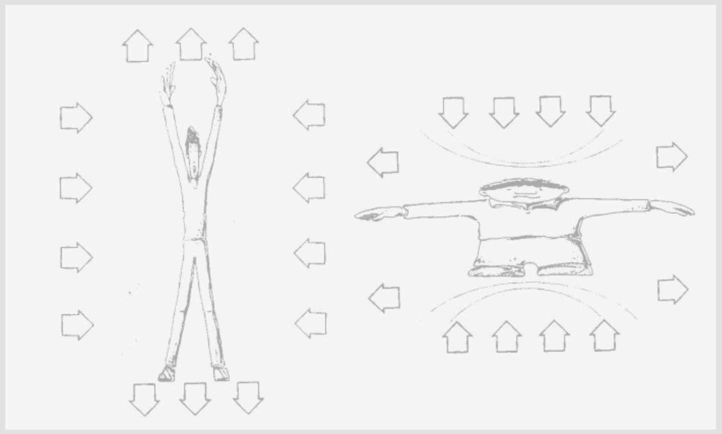

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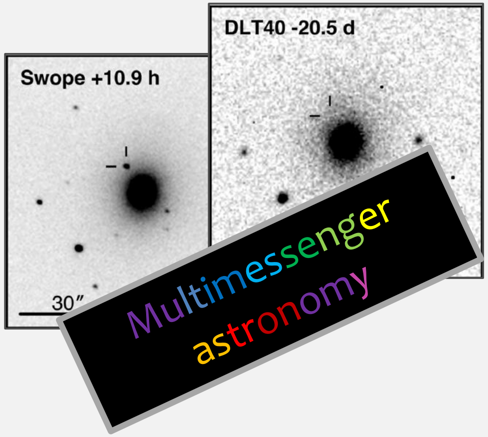

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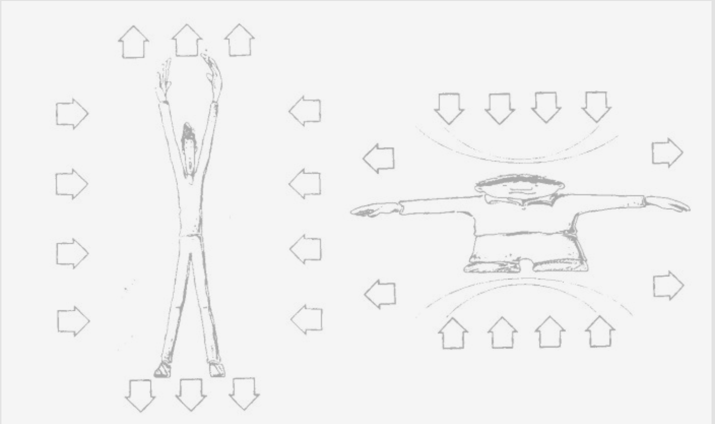

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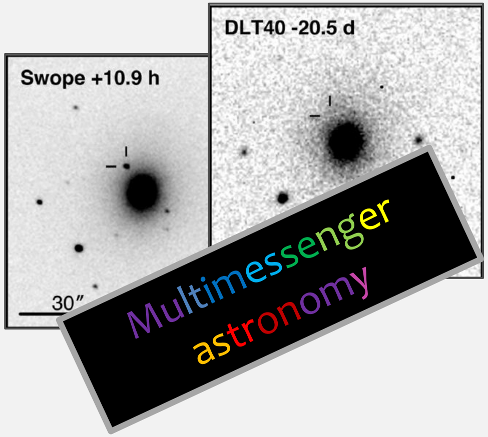

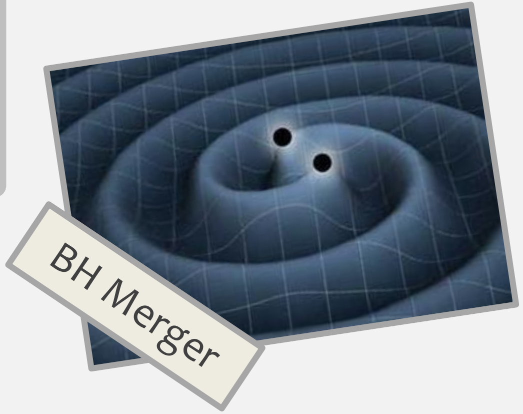

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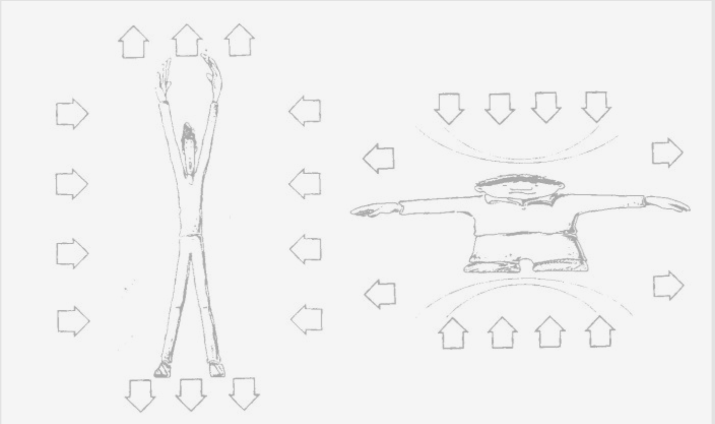

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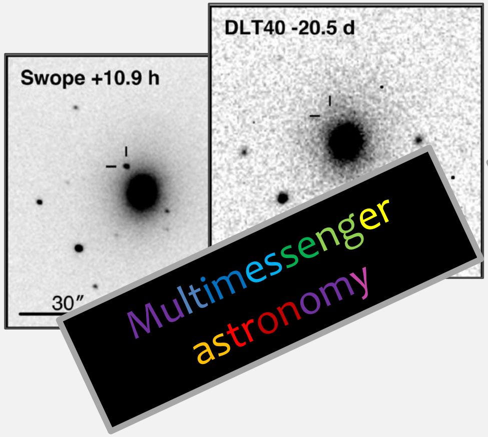

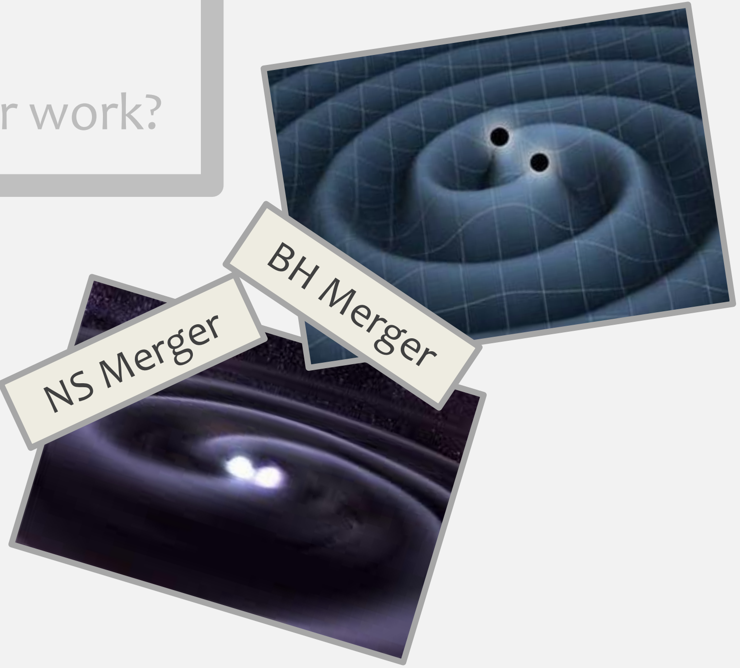

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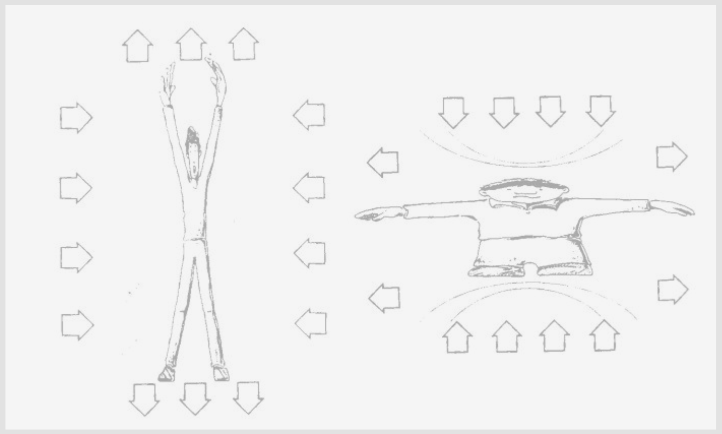

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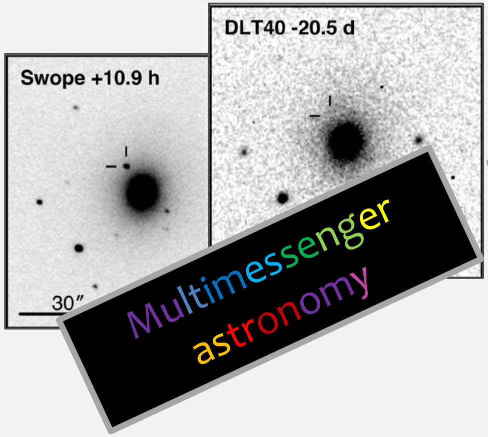

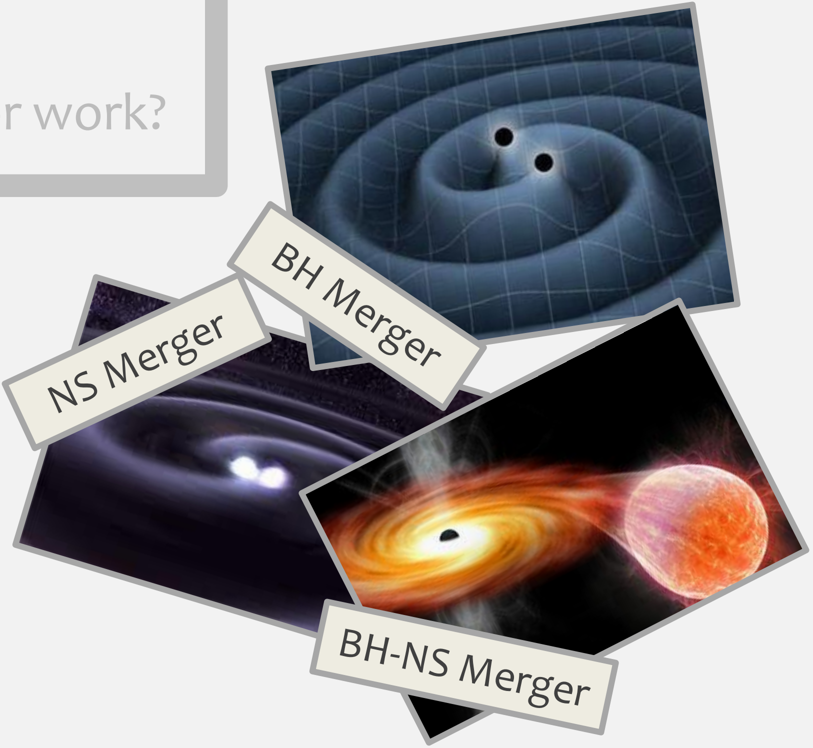

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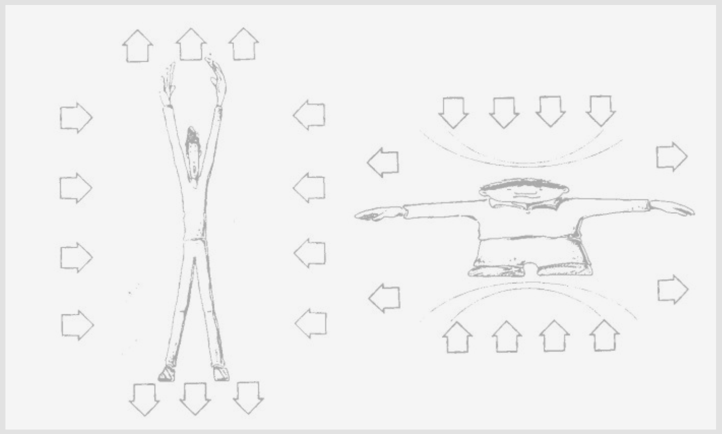

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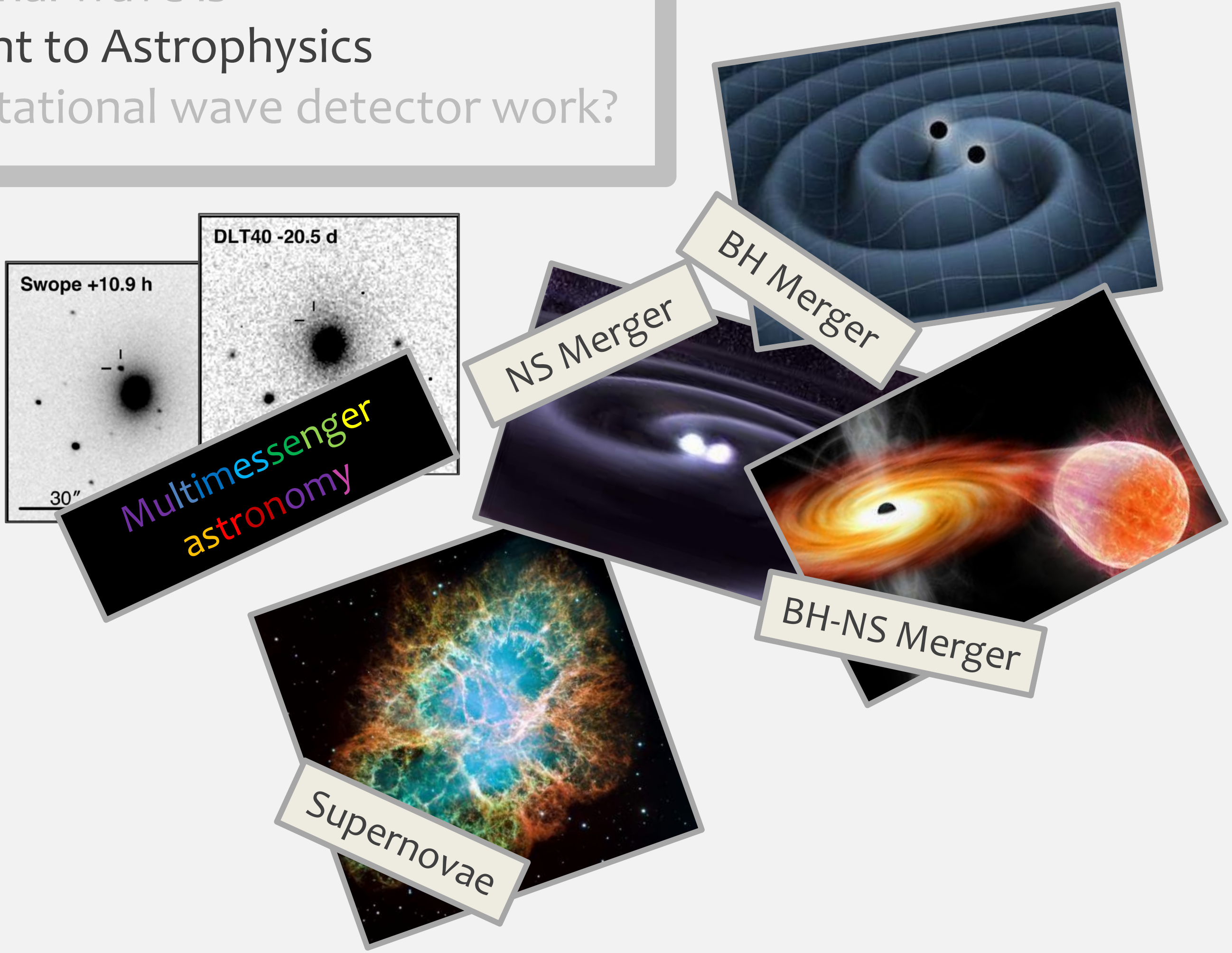

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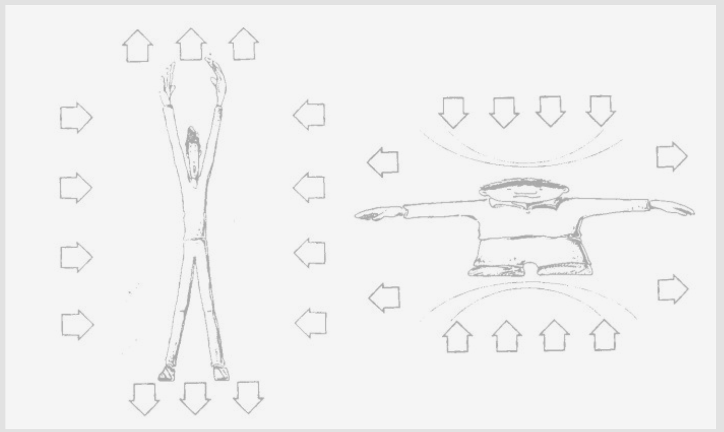

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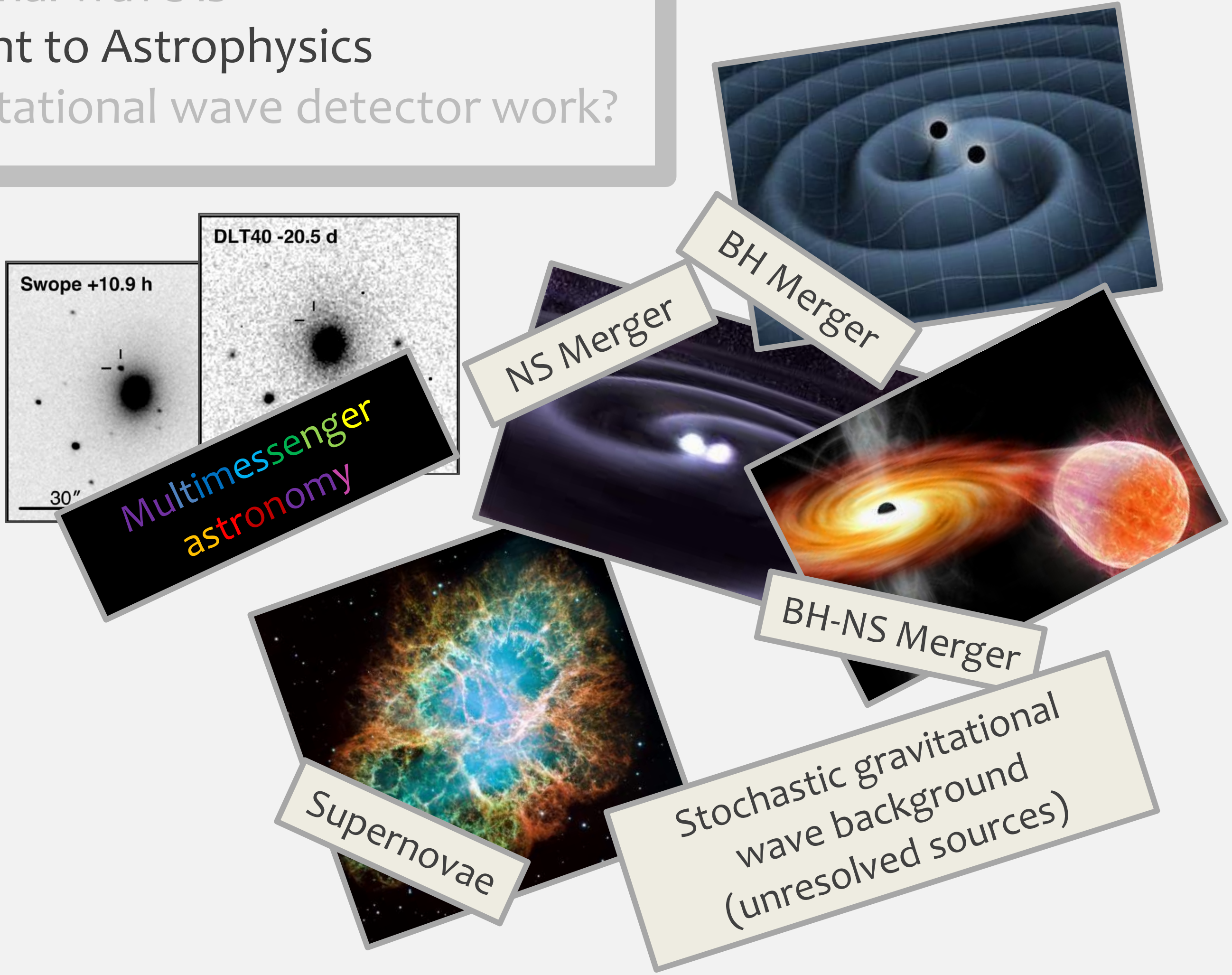

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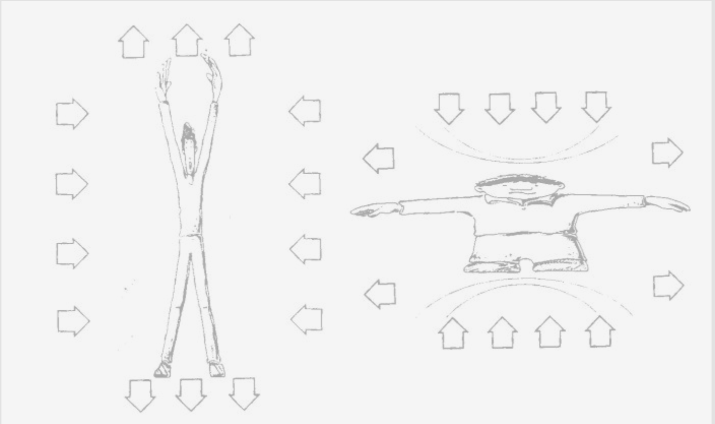

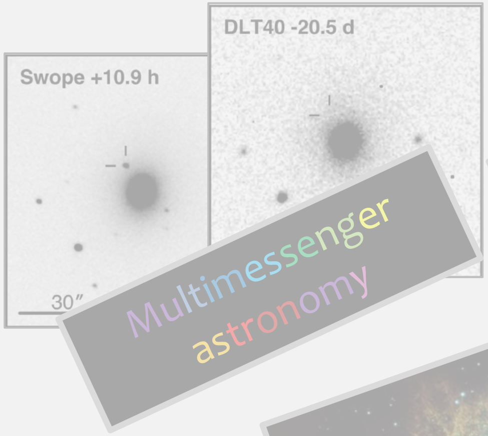

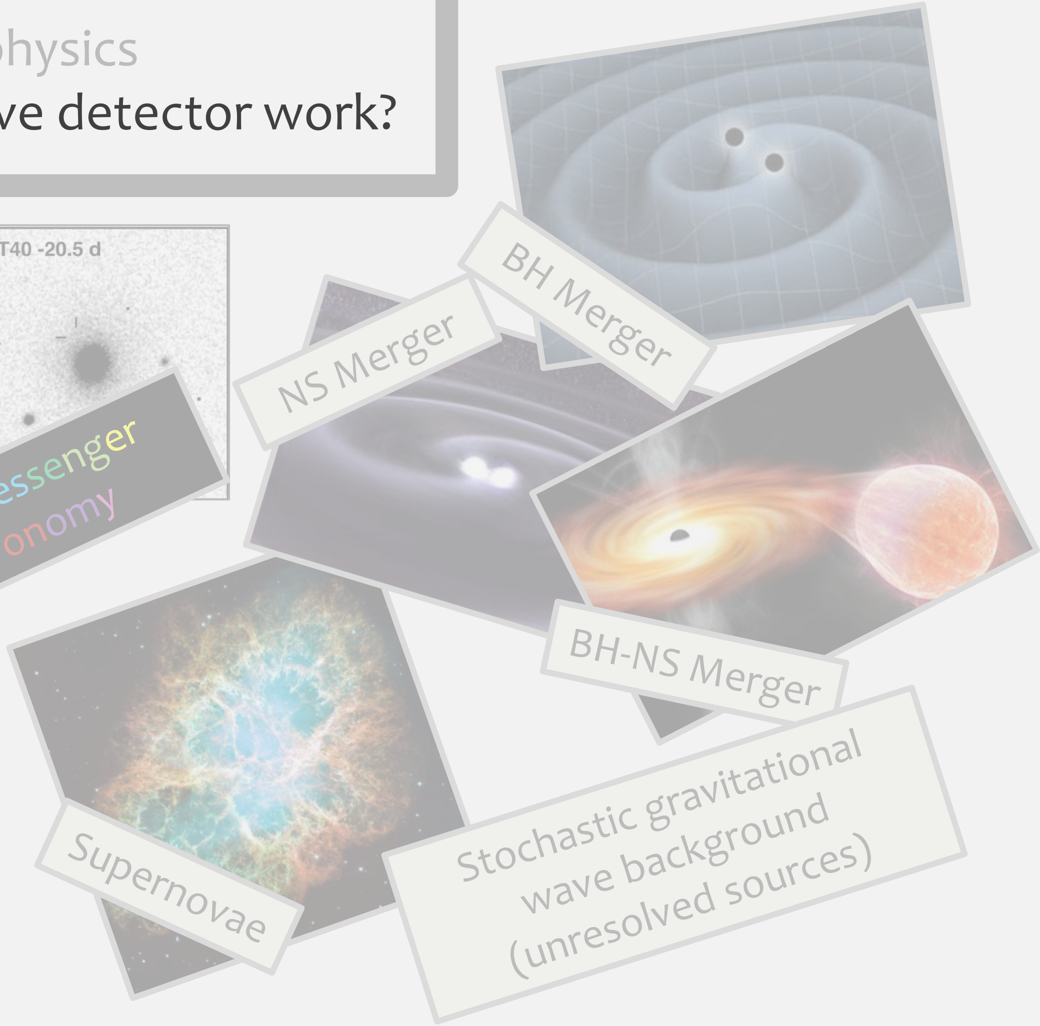

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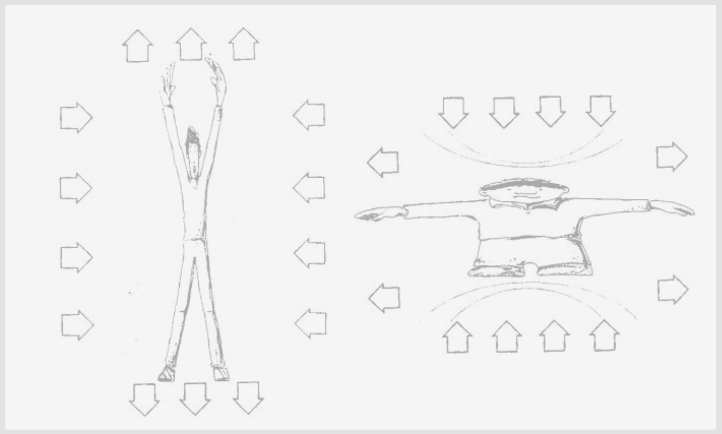

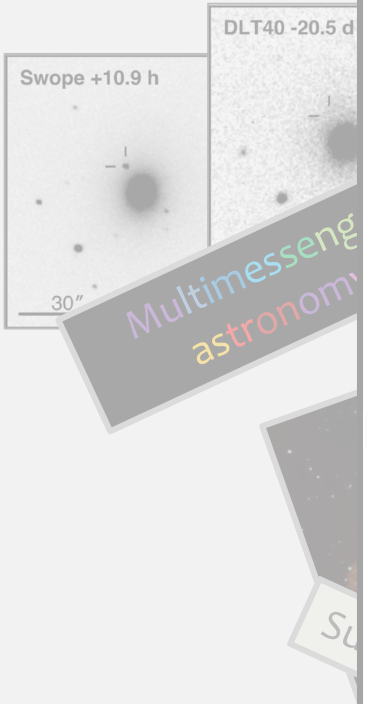

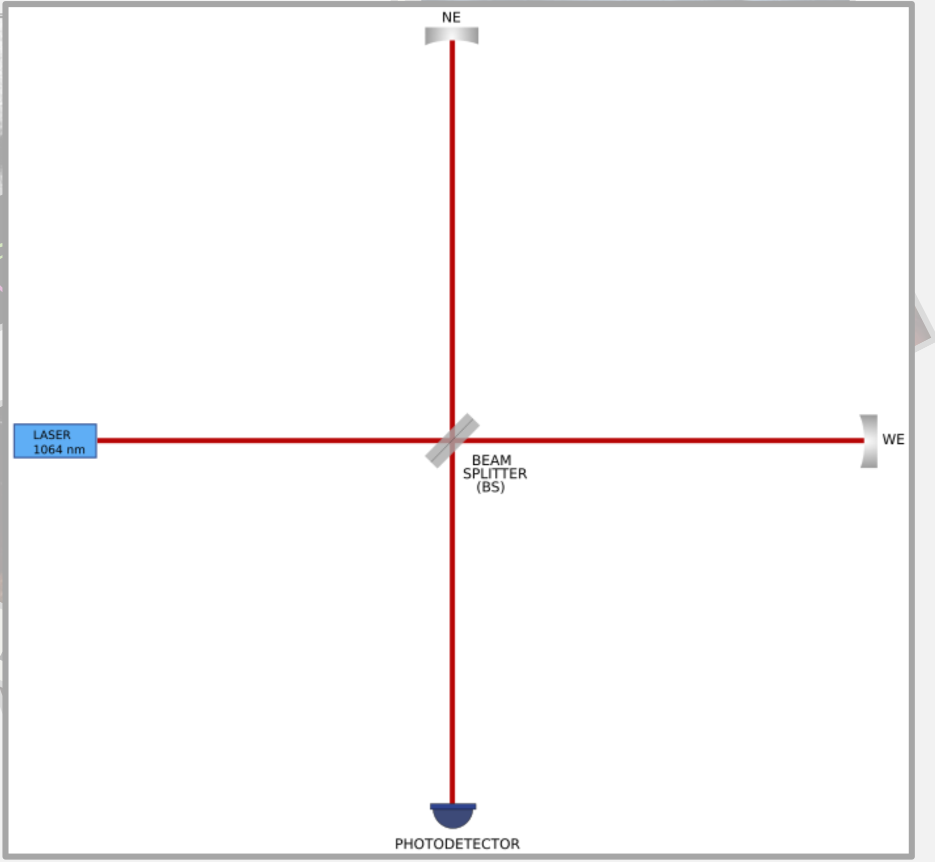

Measure the change in length → Measure change in phase

$$\Delta L \propto hL$$

$$\Delta\phi \propto hL$$

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Introduction of Fabry-Perot cavities (we indeed need interferometers 100 Km long)

$$L \sim \frac{\lambda_{gw}}{2} = \frac{c}{2f_{gw}}$$

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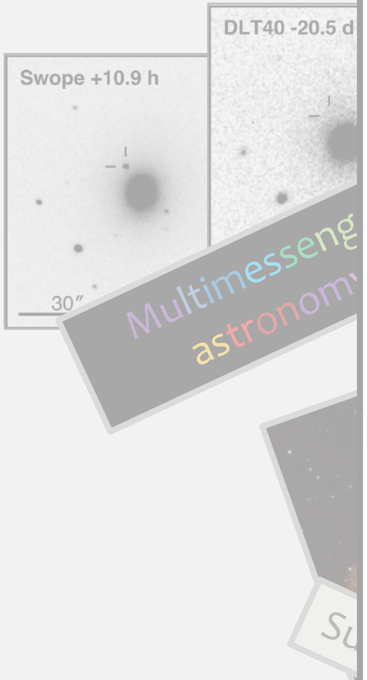

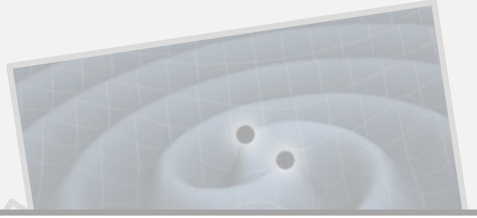

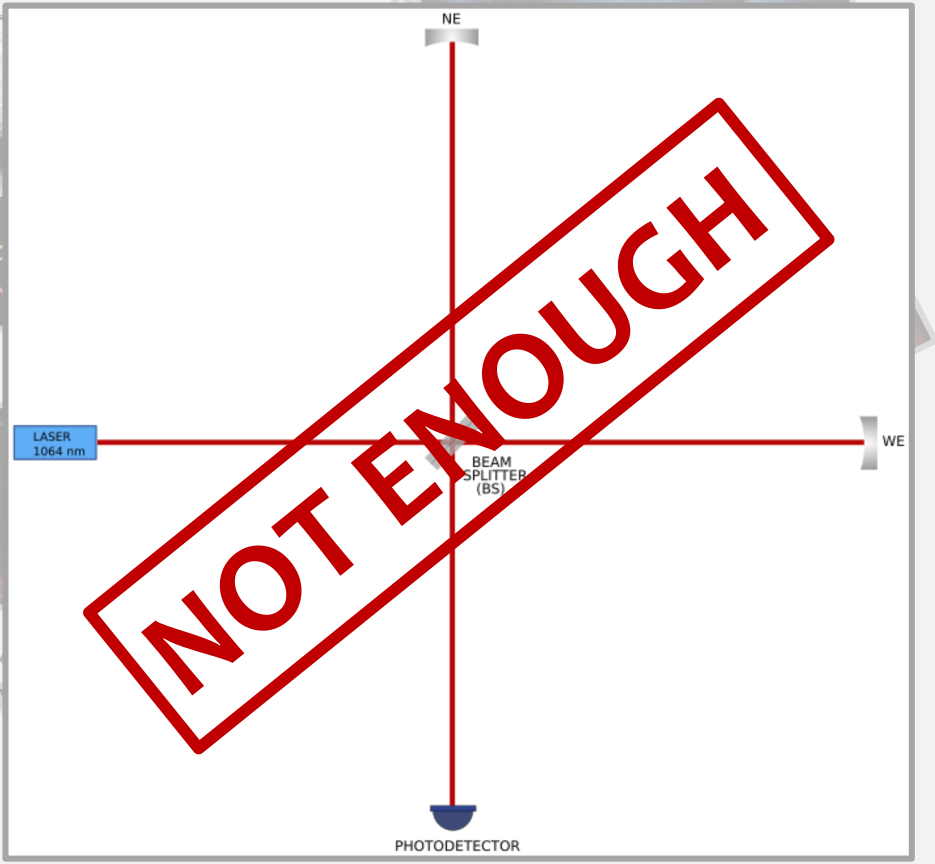

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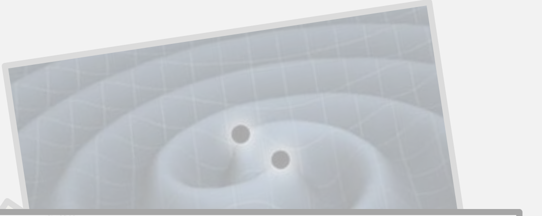

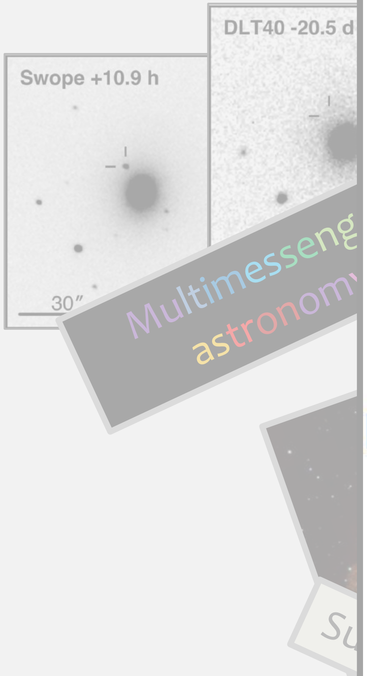

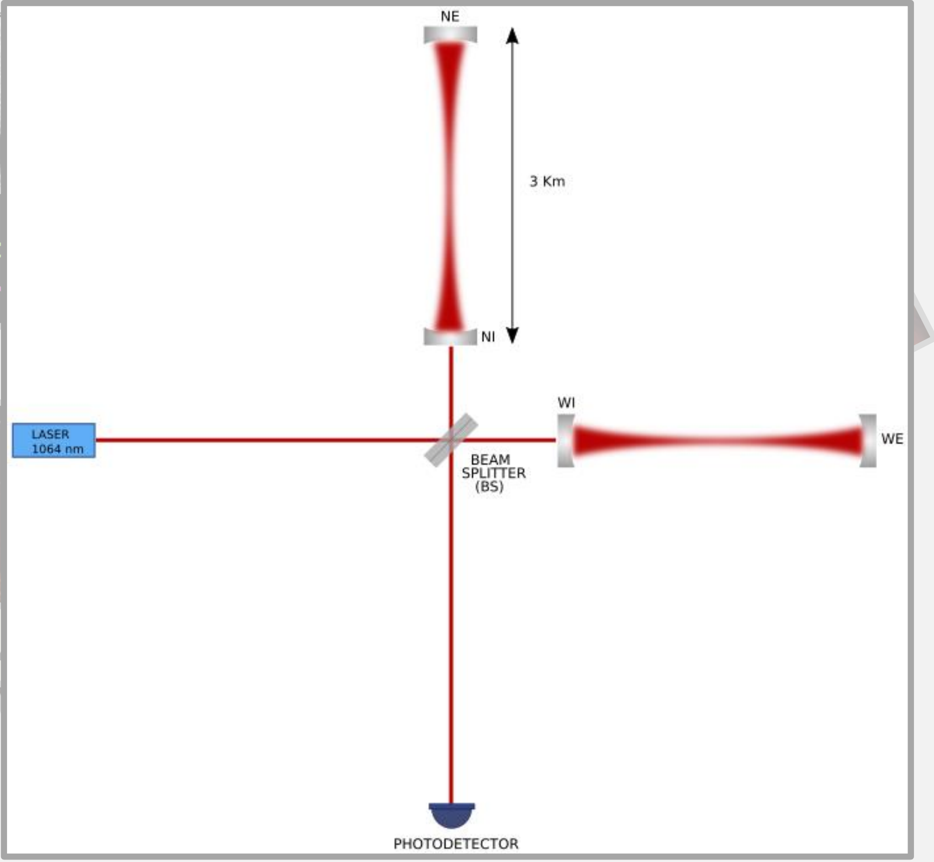

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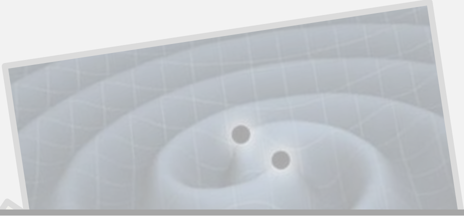

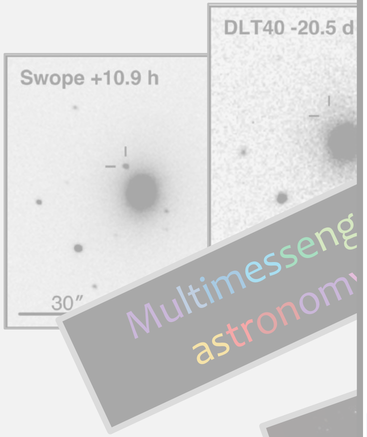

Many different parts to reach the required sensitivity!!!

Measure the change in length → Measure change in phase

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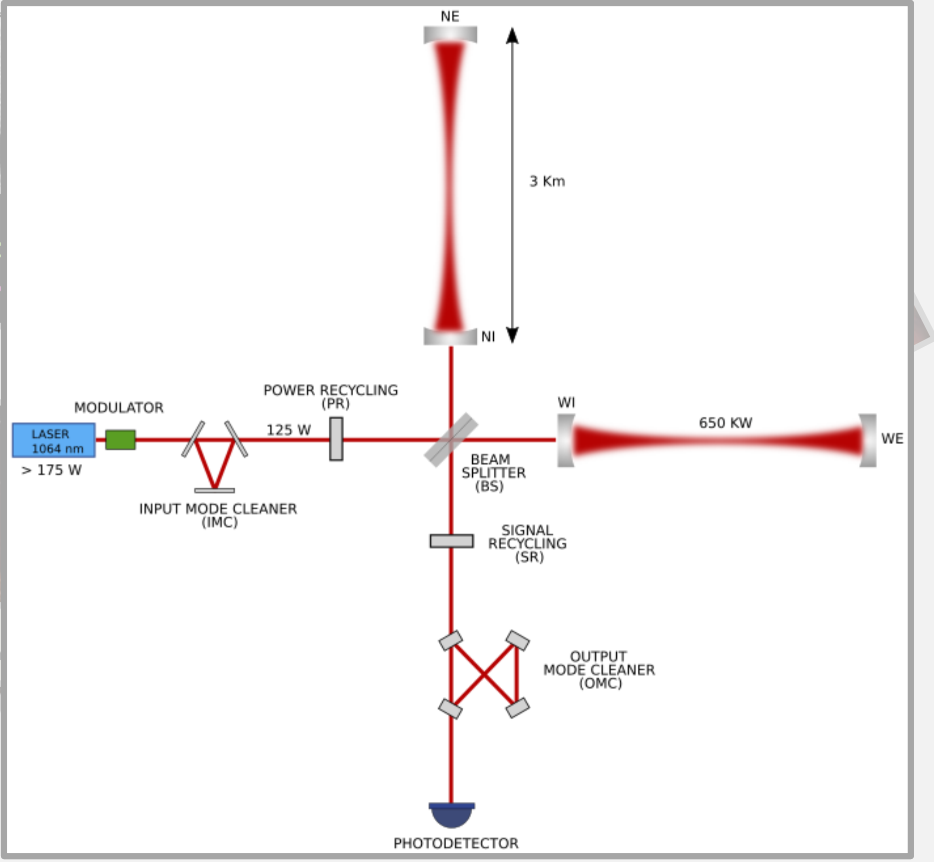

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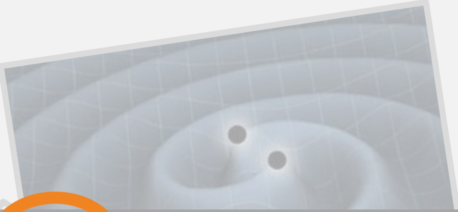

To be kept in mind: when I will mention the ‘TEST MASSES’ I will refer to the end mirrors of the interferometer!!! Which are in free fall along the arms direction.

$$\Delta L \propto hL$$
$$\Delta\phi \propto hL$$
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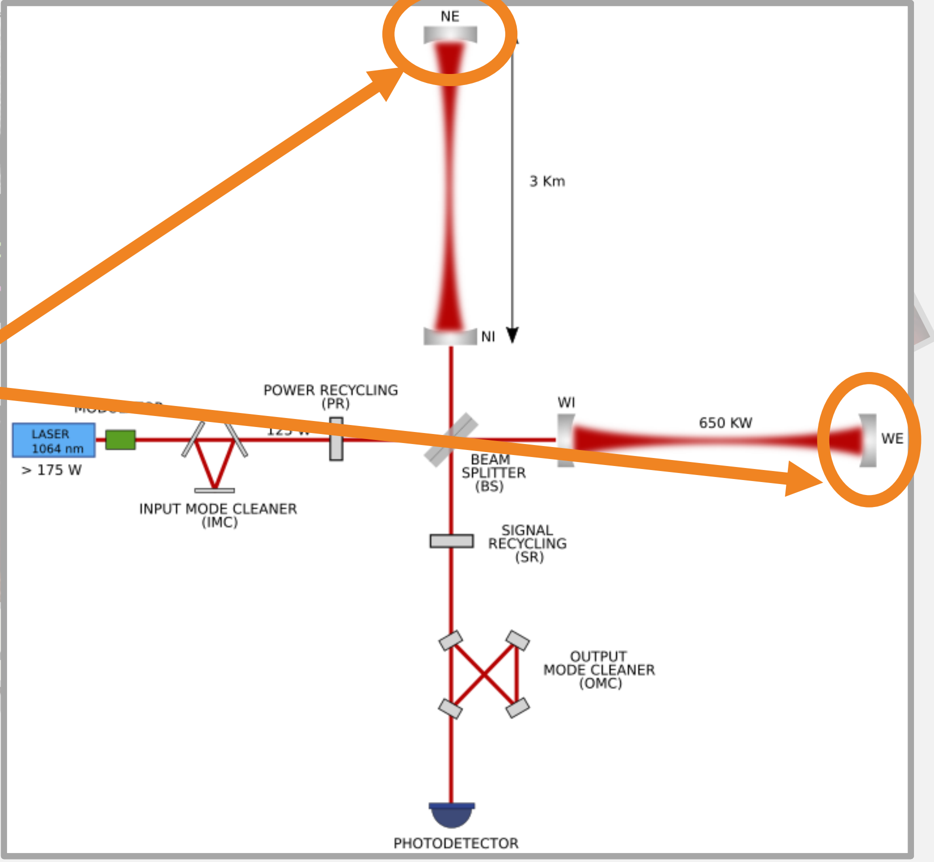
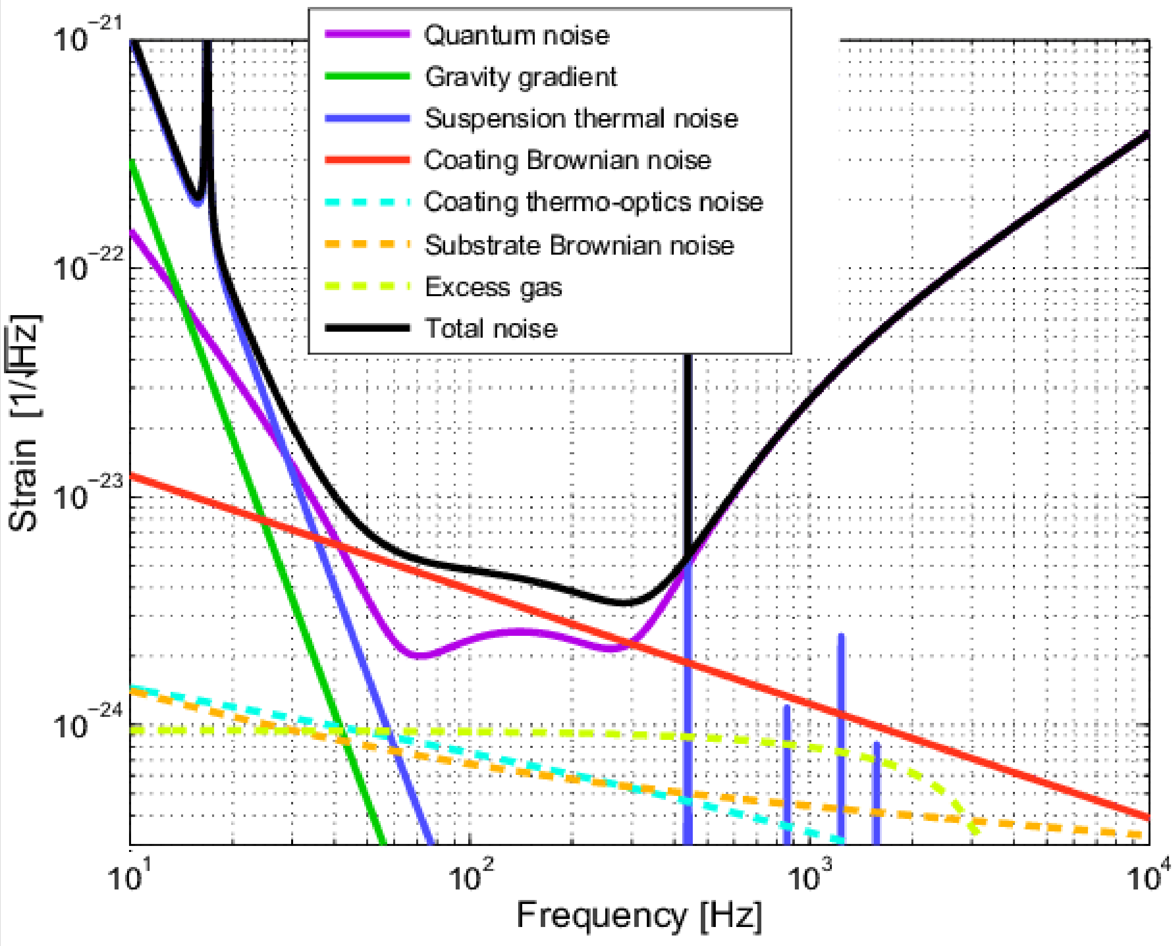


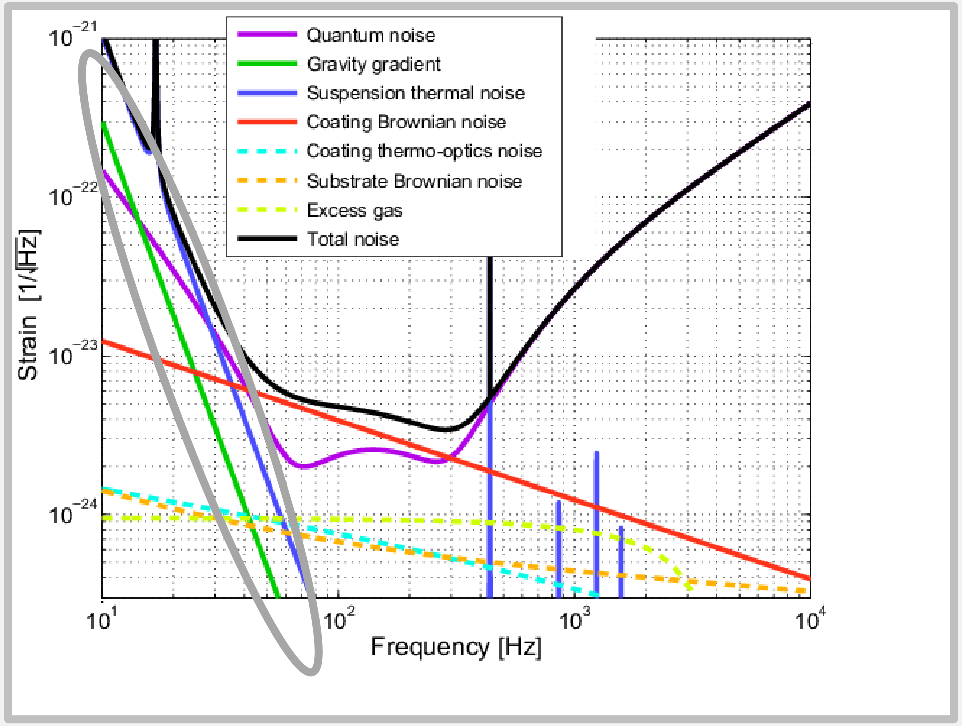
Plenty of different kinds of noises

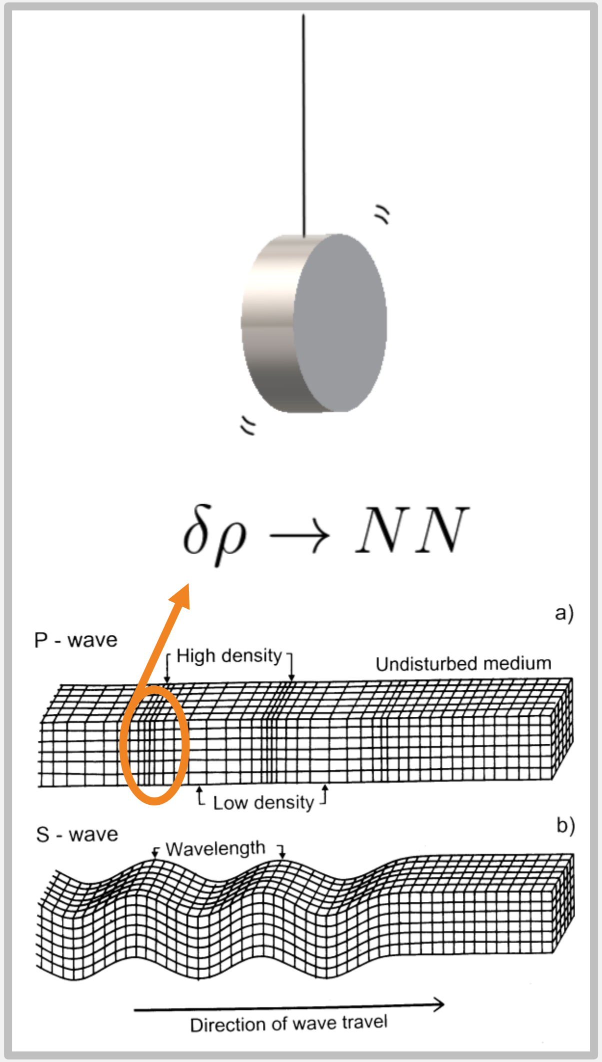


What is Newtonian Noise (NN):

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

Example of NN in Virgo:





What can we do about Newtonian Noise?

↓

Estimation of the noise

↓

Subtraction

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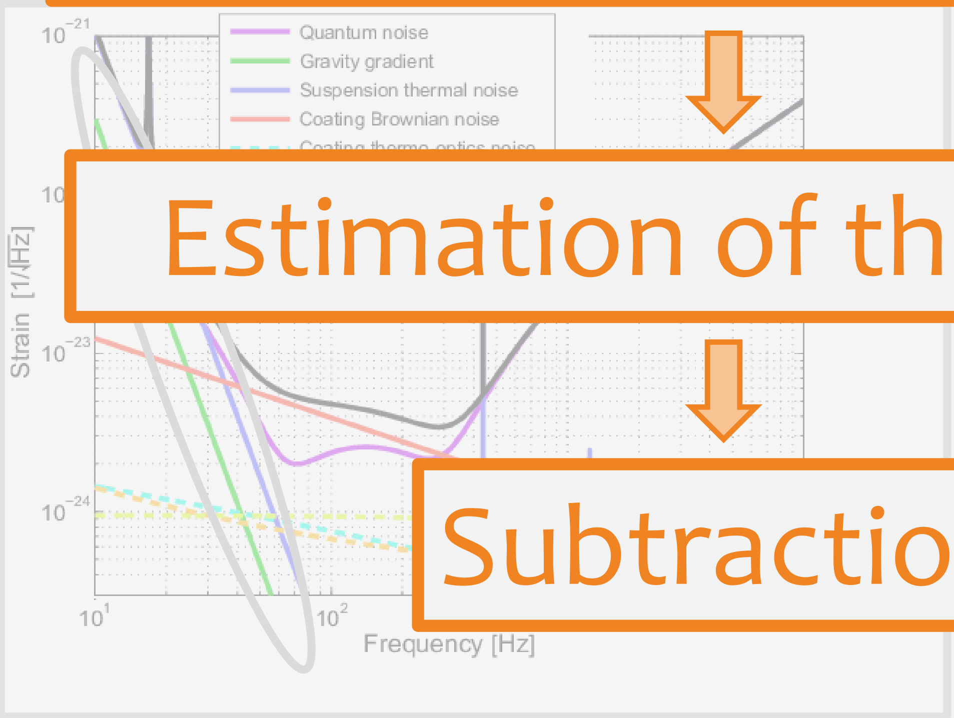

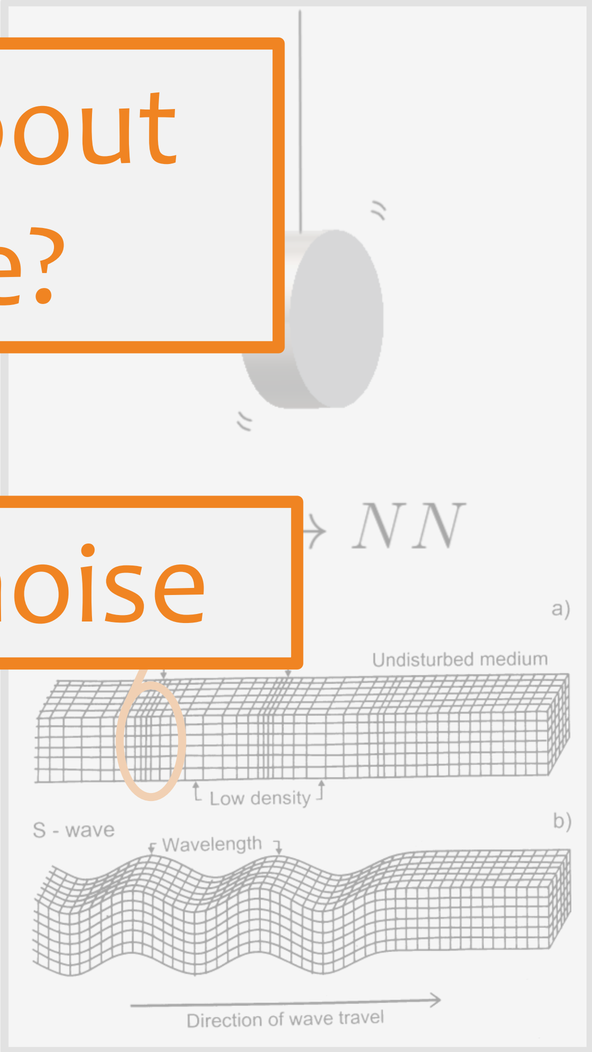

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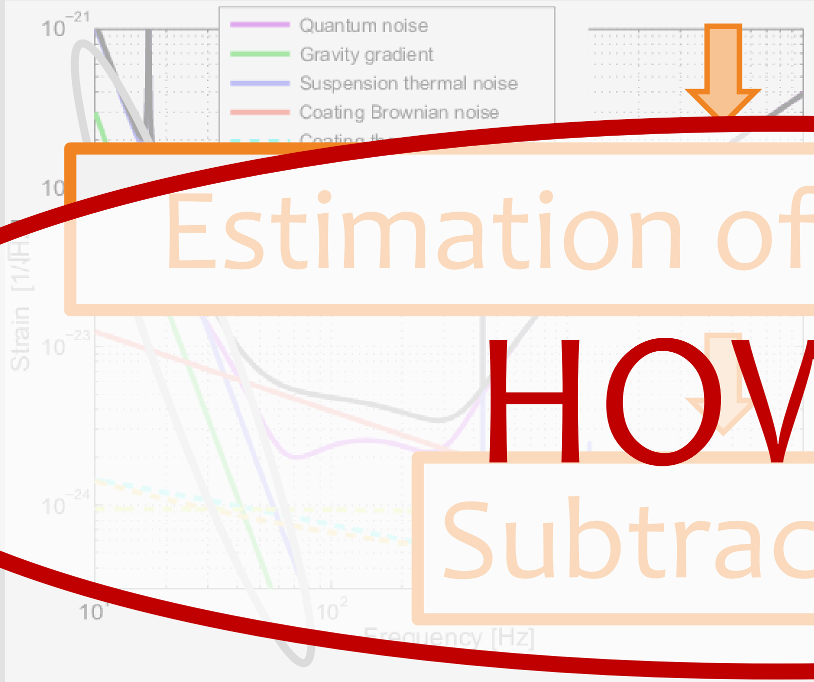
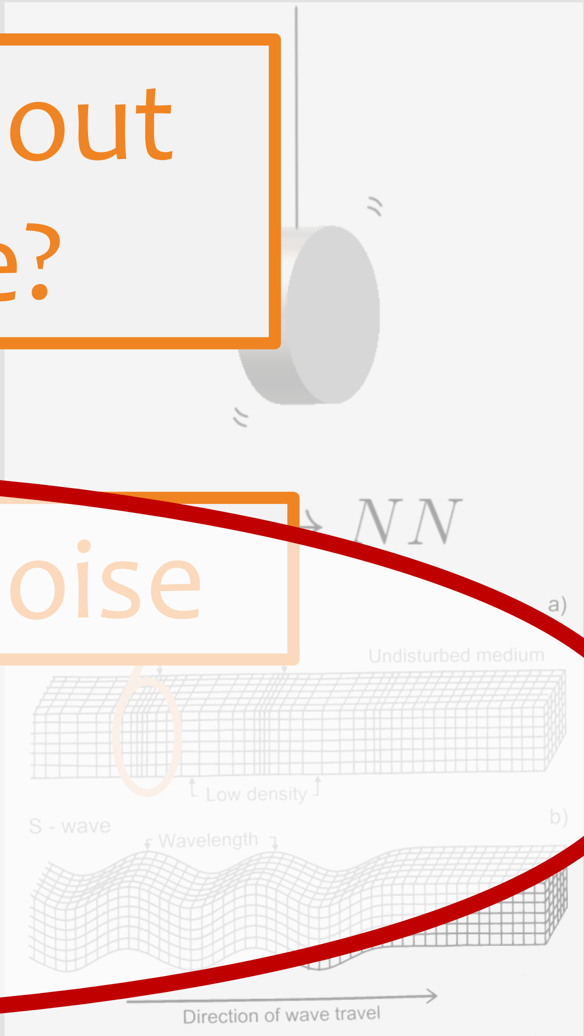




Estimation of the noise

HOW?!?

Subtraction

Wiener filter is the way

Assumptions:

- Stationary signal
- Linear relationship: $\mathrm{x} \propto y$

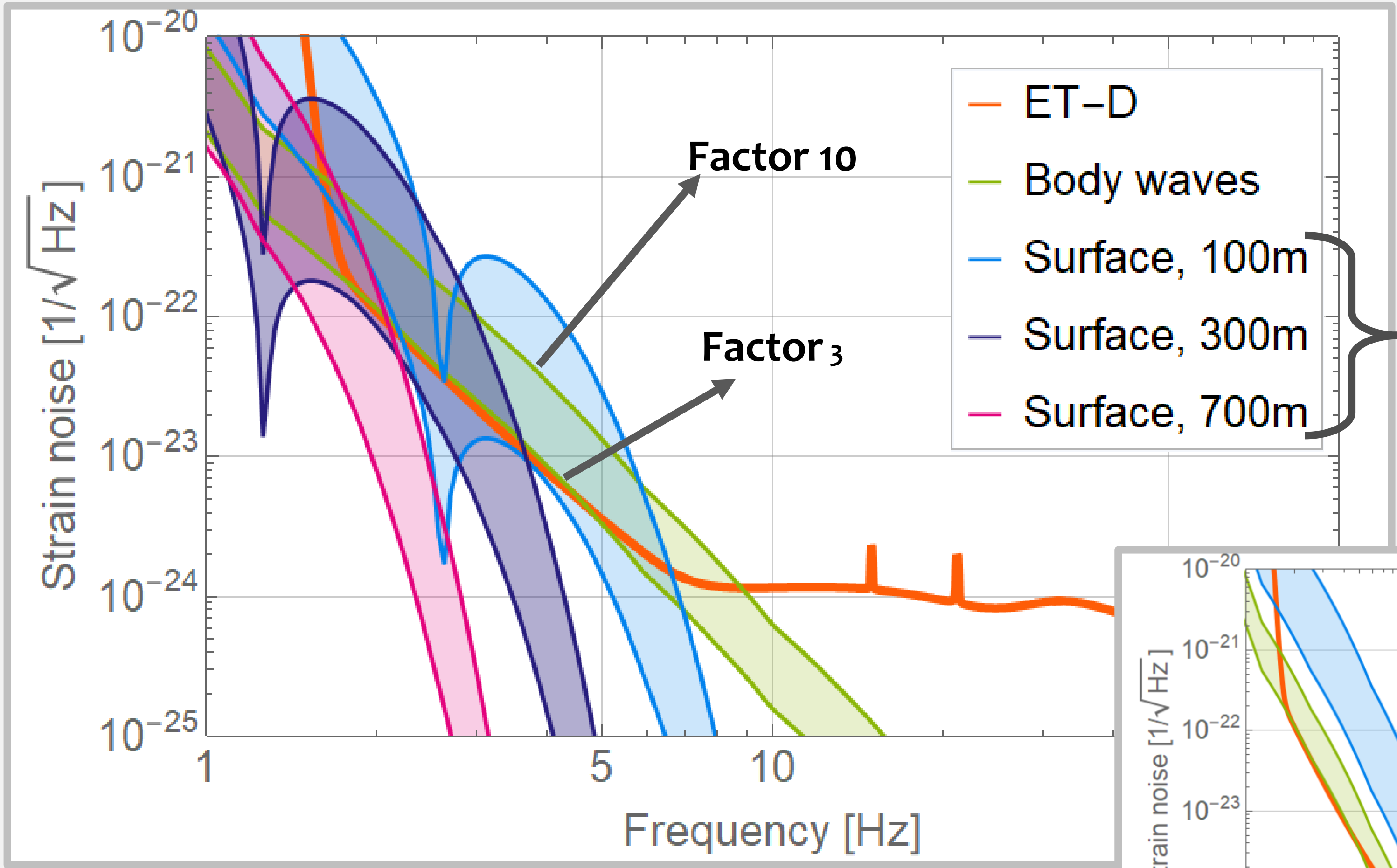
$$\hat{x}(m) = \sum_{k=0}^{P-1} w_k y(m-k)$$

Estimated value of the **Newtonian Noise**

Wiener filter **coefficients**

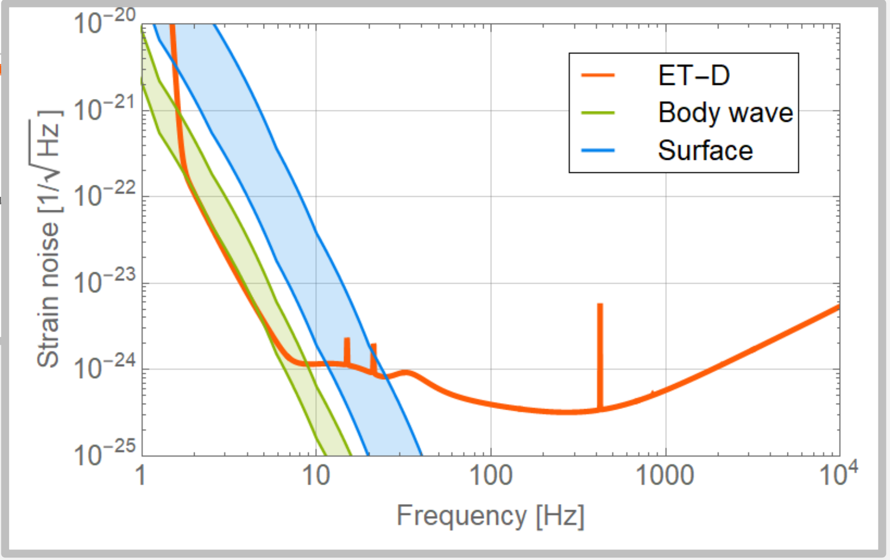
Measured signal (**seismic displacement**)

Subtraction ⇨ $DATA - \hat{x}$



How much deep?

Surface



Underground

Suppression up to a factor 10

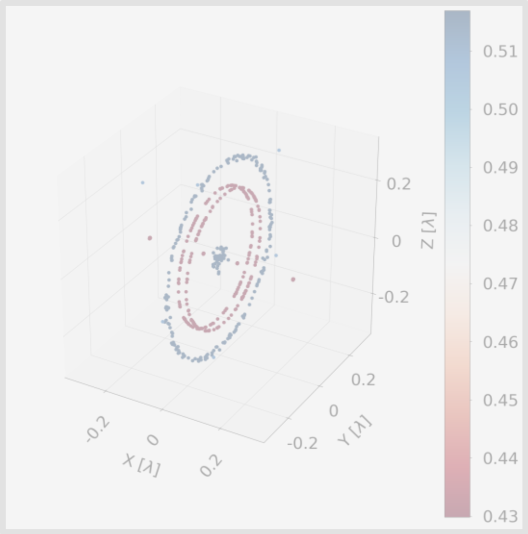
OPTIMIZATION of:

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

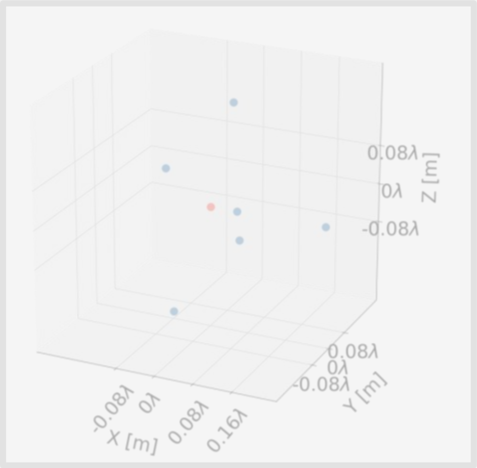
Cross Power Spectral Densities (CPSDs) between seismometers

Power Spectral Density of test mass

CPSDs between seismometers and test mass



Single example



Isotropic & Homogeneous seismic field hypothesis

+

& $k^{P,S}a << 1$

+

Gravitational coupling model: mirror <-> field

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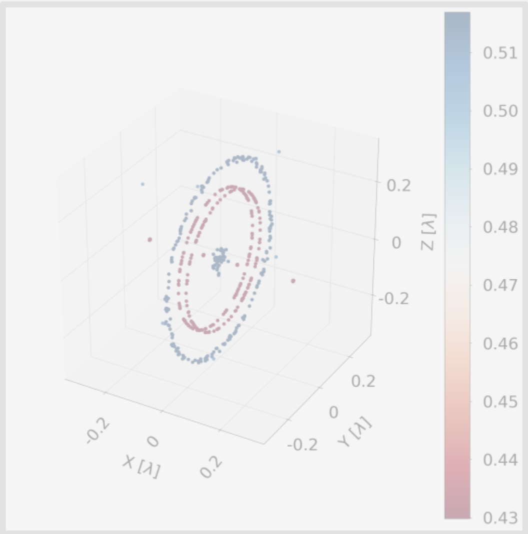

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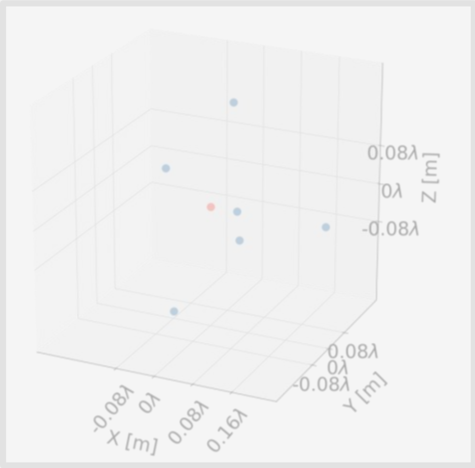

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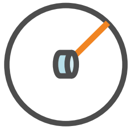 & $k^{P,S} a \ll 1$

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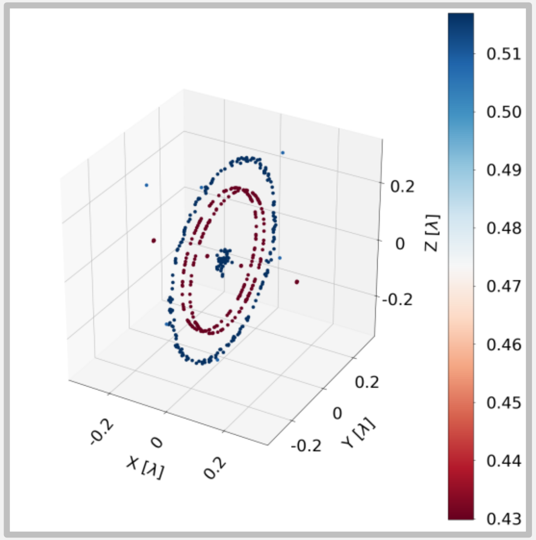

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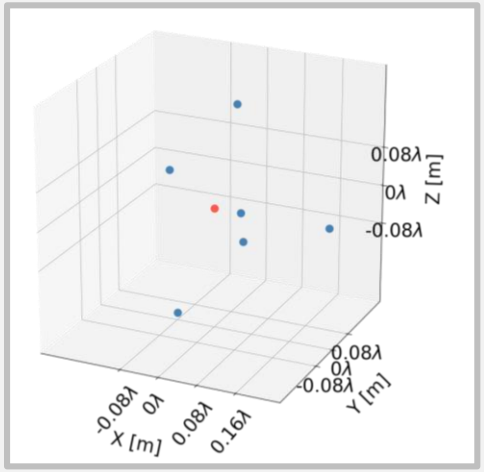

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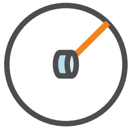

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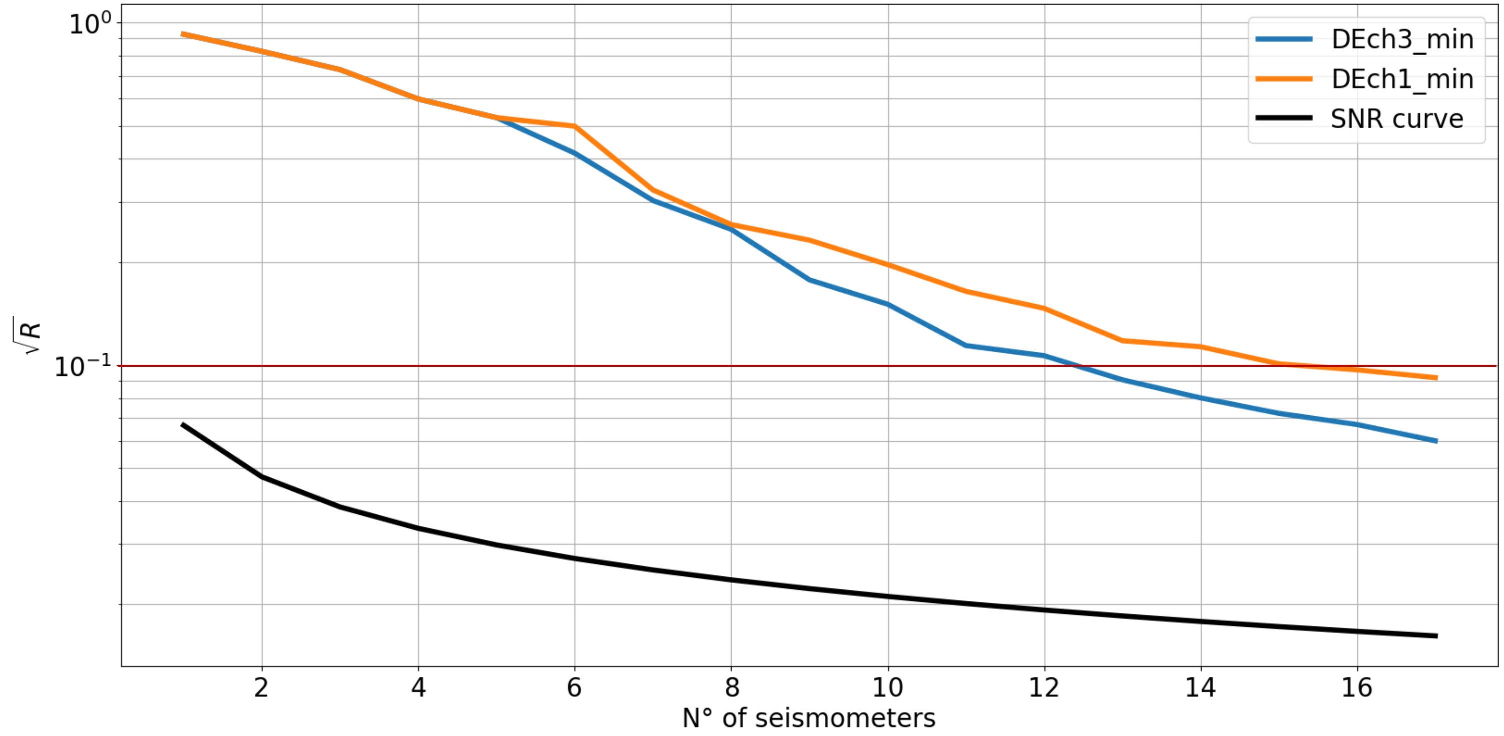
Gravitational coupling model: mirror <-> field

Succesful mission: factor 10 of reduction already with 13 seismometers per test mass



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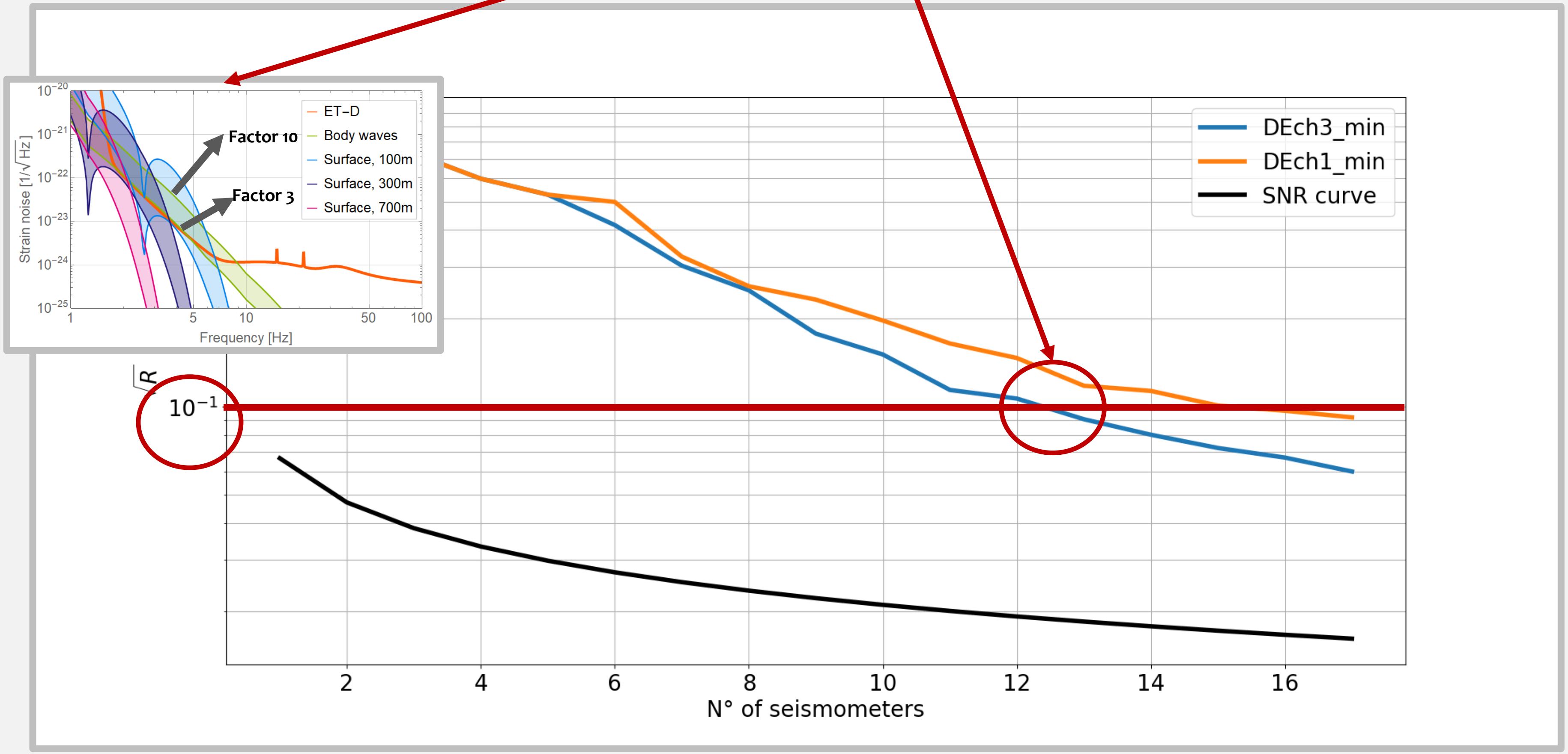
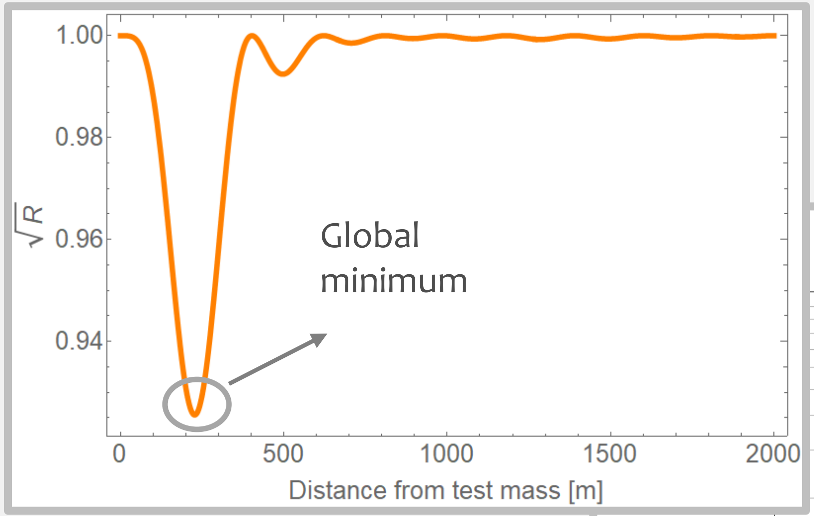
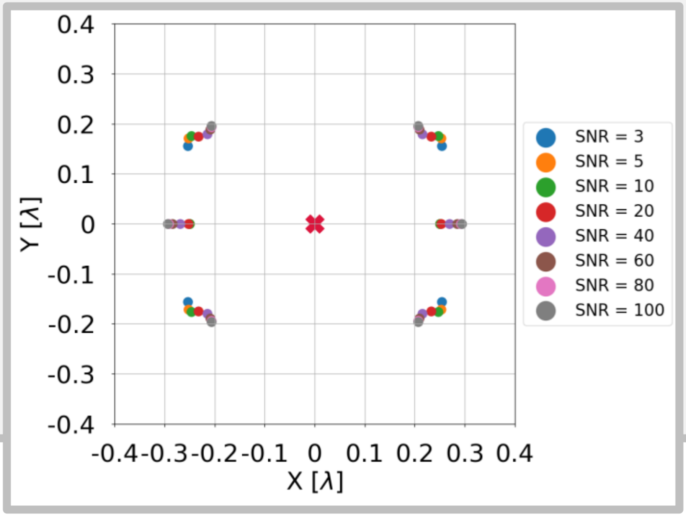
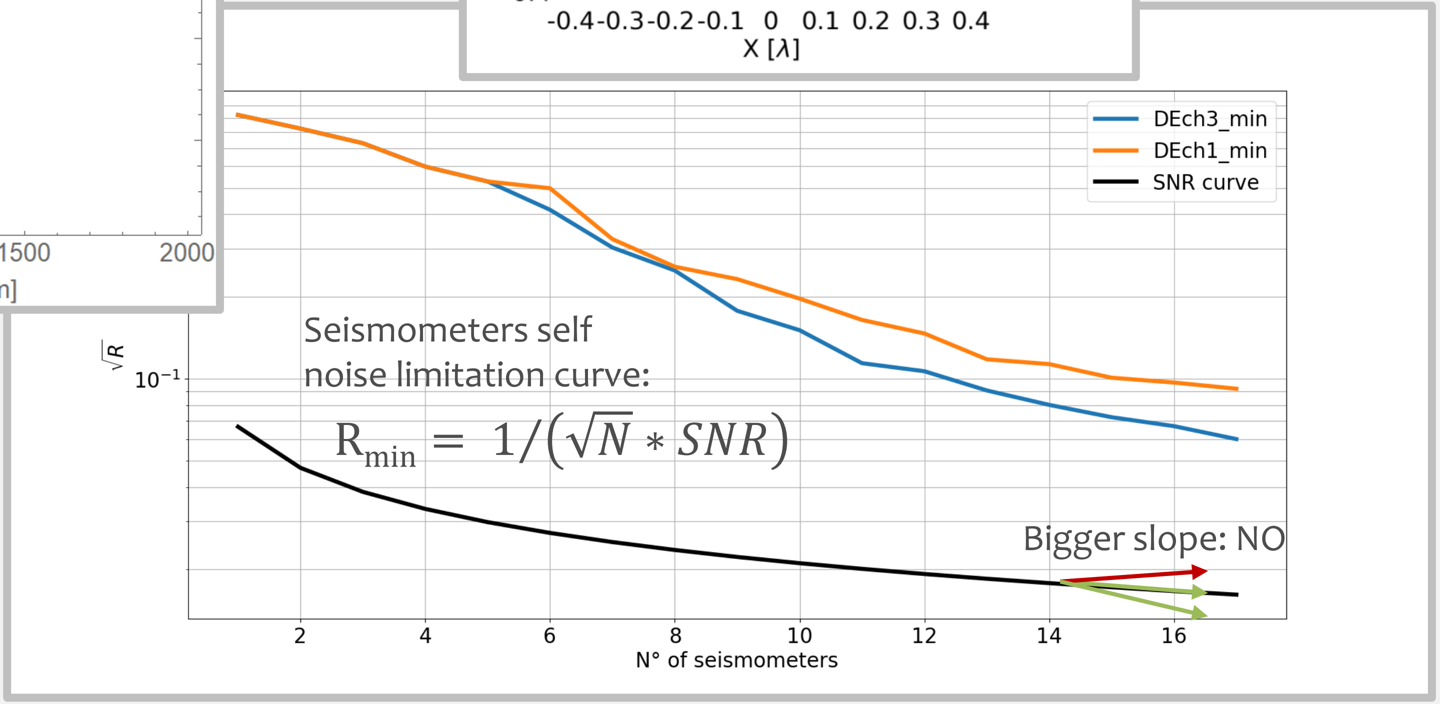


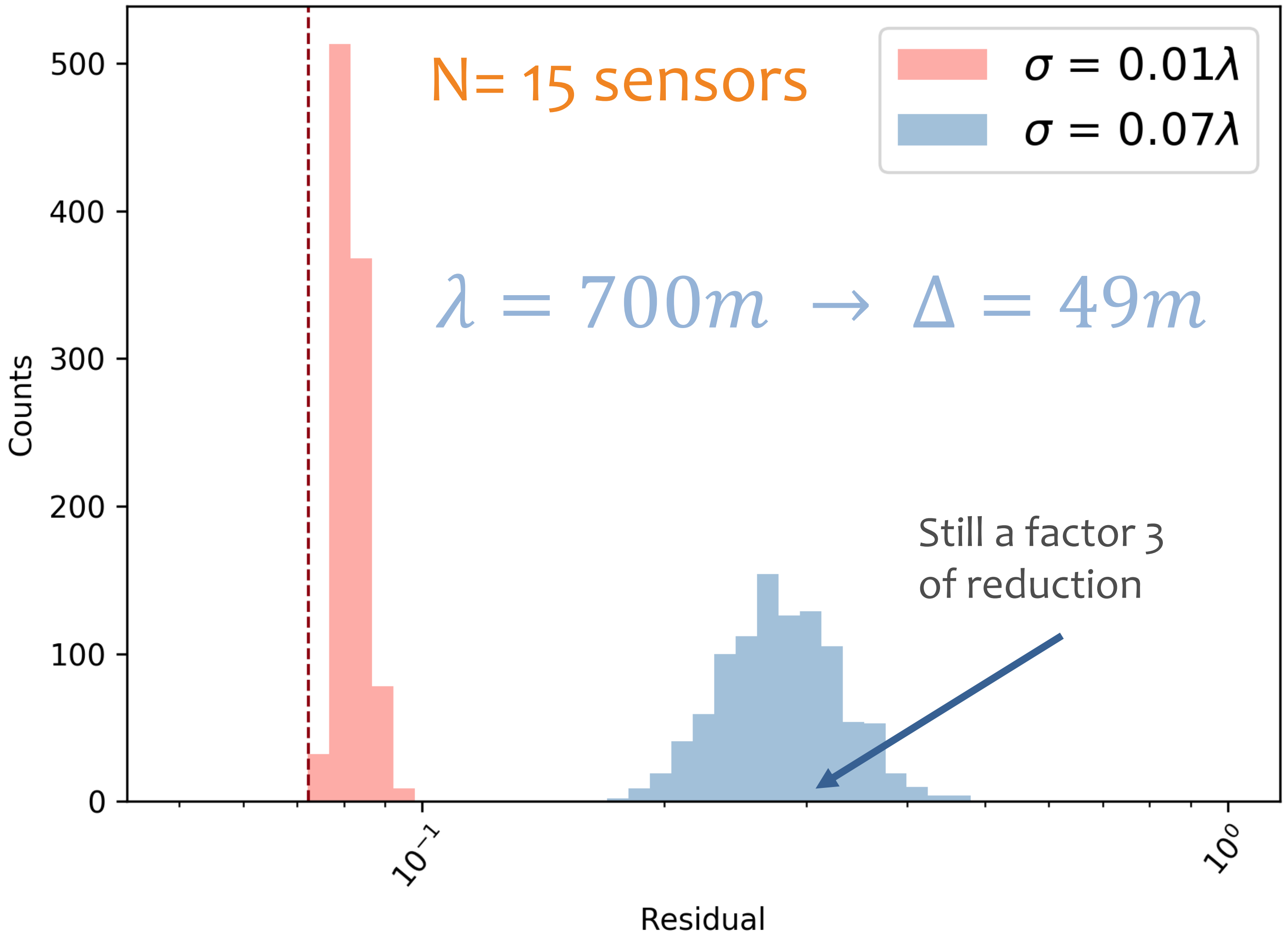
Validation:

Analytical solution for N = 1



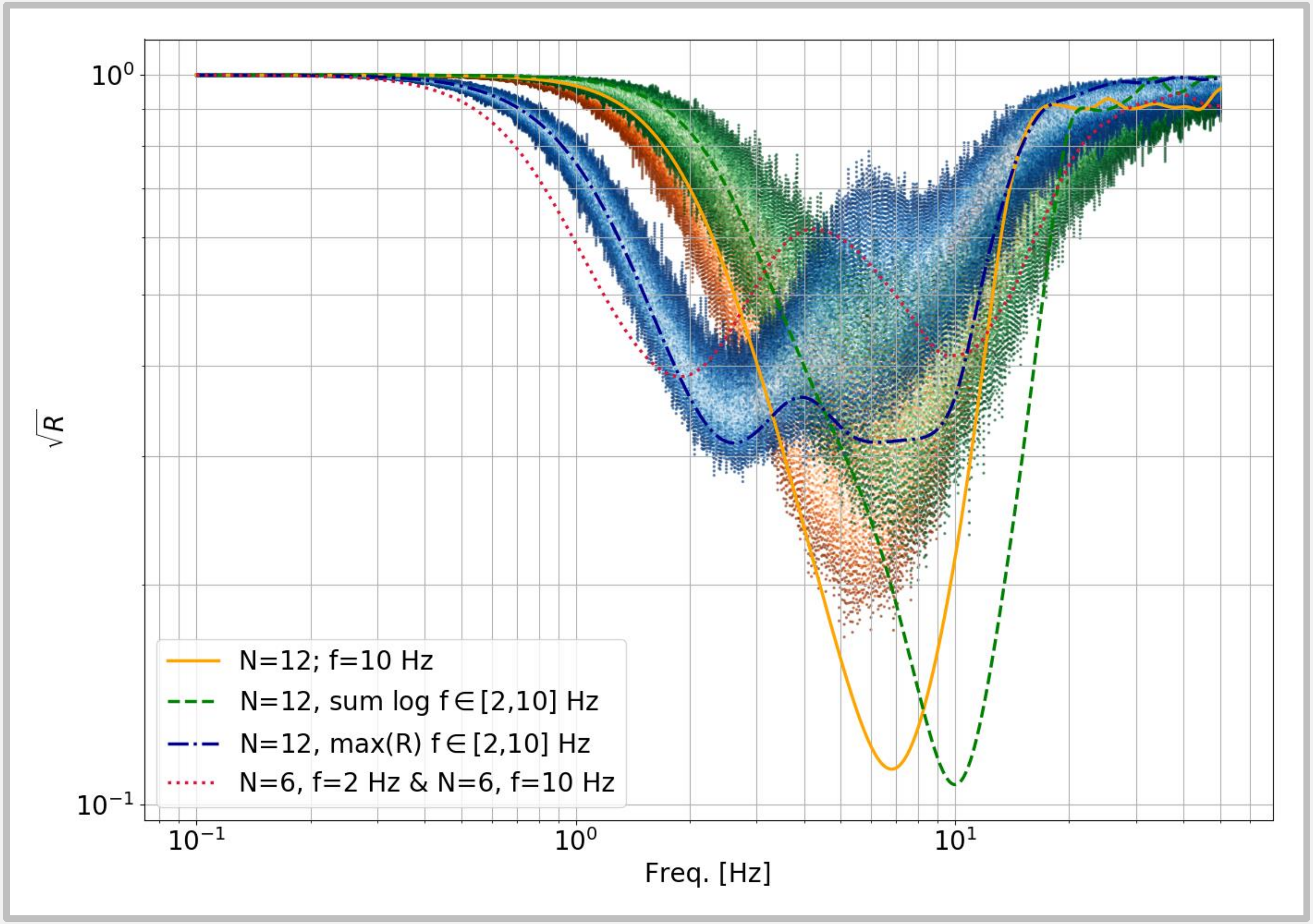






N= 15 sensors
σ = 0.01λ
σ = 0.07λ
λ = 700m → Δ = 49m
Still a factor 3
of reduction
Counts
500
400
300
200
100
0
10^−1
10^0
Residual

Broadband optimization:



Broadband optimization:

IOP Publishing Classical and Quantum Gravity

Class. Quantum Grav. 36 (2019) 145006 (15pp) https://doi.org/10.1088/1361-6382/ab28c1

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

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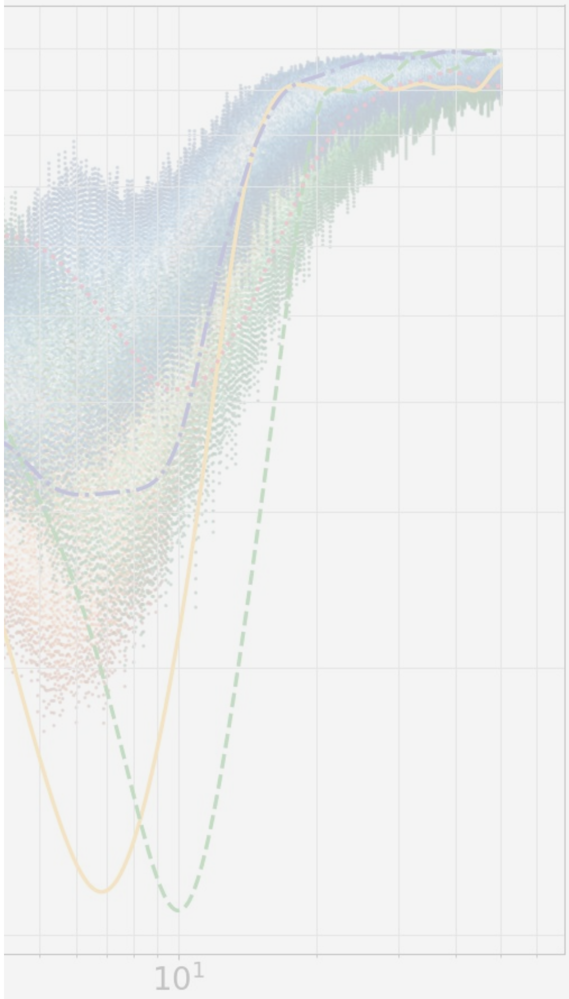
Abstract

Newtonian noise (NN) from seismic fields is predicted to become a sensitivity limiting noise contribution of the gravitational-wave detectors Advanced LIGO and Virgo in the next few years. It also plays a major role in the planning of next-generation detectors, which might be constructed underground as planned for the Einstein telescope (ET) mostly to suppress NN. Coherent noise cancellation using Wiener filters provides a way to mitigate NN. So far, only the cancellation of NN produced by seismic surface waves has been studied in detail due to its relevance for Advanced LIGO and Virgo. However, seismic body waves can still contribute significantly to NN in surface detectors, and they might be the dominant source of gravity fluctuations in underground detectors. In this paper, we present the first detailed analysis of coherent cancellation of NN from body waves. While the required number of seismometers to achieve a certain level of noise suppression is higher than for seismic surface waves, we show that optimal seismometer arrays can greatly reduce body-wave NN. The optimal array configurations and achieved residuals depend strongly on the composition of the seismic field in terms of average compressional-wave and shear-wave content. We propose Newtonian-noise cancellation to achieve the ambitious low-frequency target of the ET.



Broadband optimization

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Optimiza[illegible]on of seismometer ar[illegible]ys for the ca[illegible]ellation of Newtonian [illegible]oise from seis[illegible]c body waves

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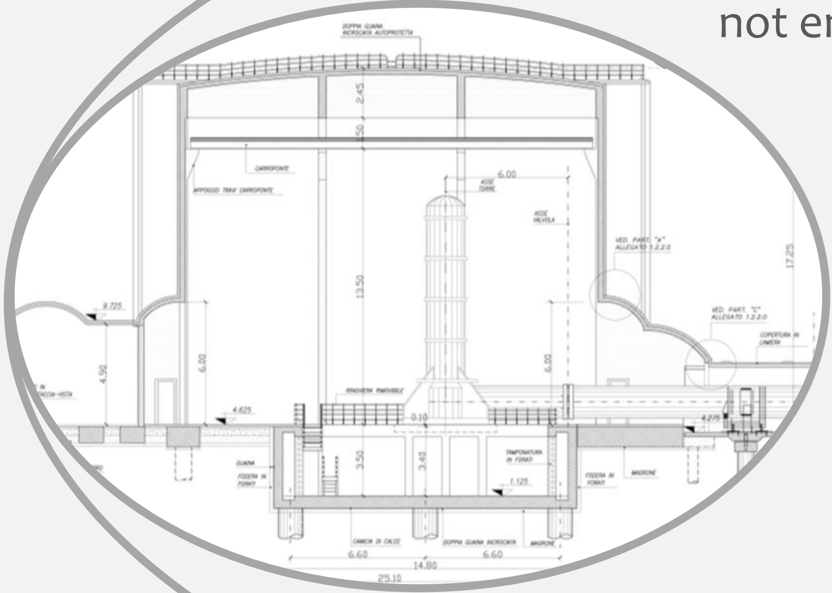
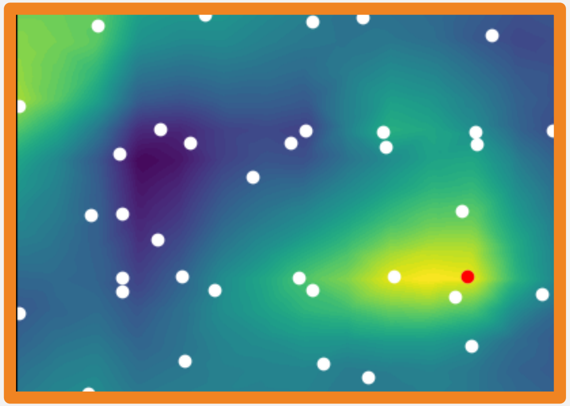
Virgo: Newtonian Noise from body AND surface seismic waves



Virgo end buildings are complex. A fitted model is not enough.

We can base our optimization on ***seismic data***



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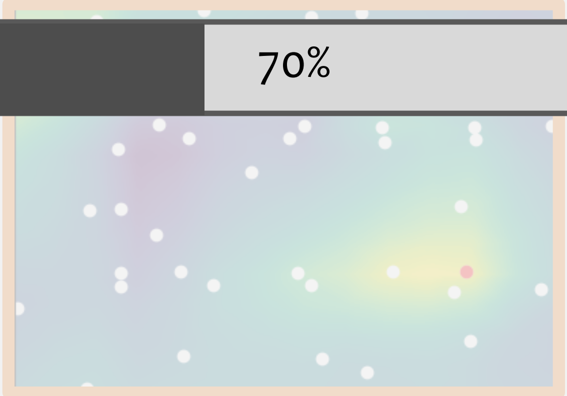
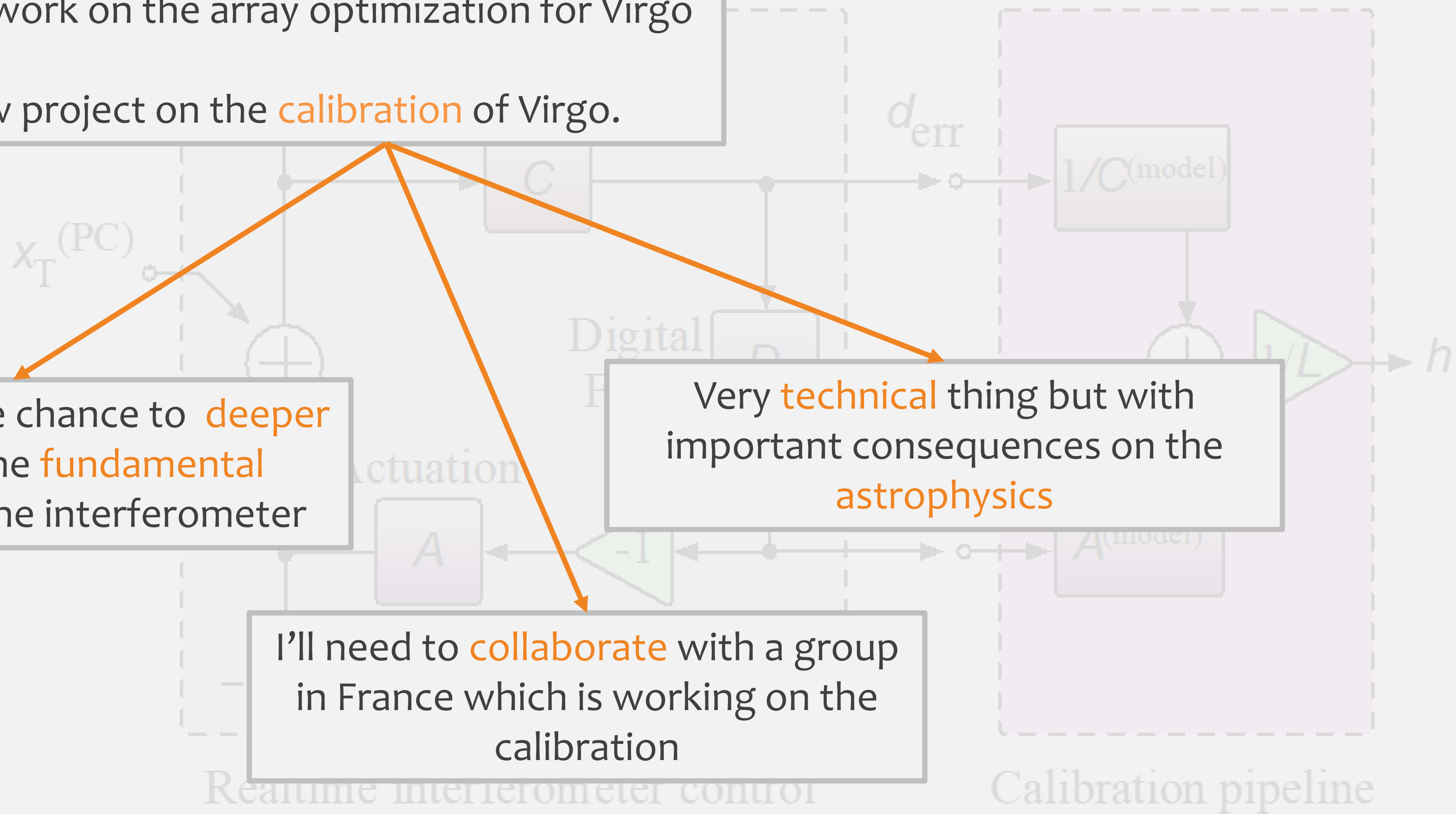


Work in progress…

70%

Future perspectives:

- Finishing the work on the array optimization for Virgo
- Starting a new project on the calibration of Virgo.



It will give me the chance to deeper understand the fundamental functioning of the interferometer

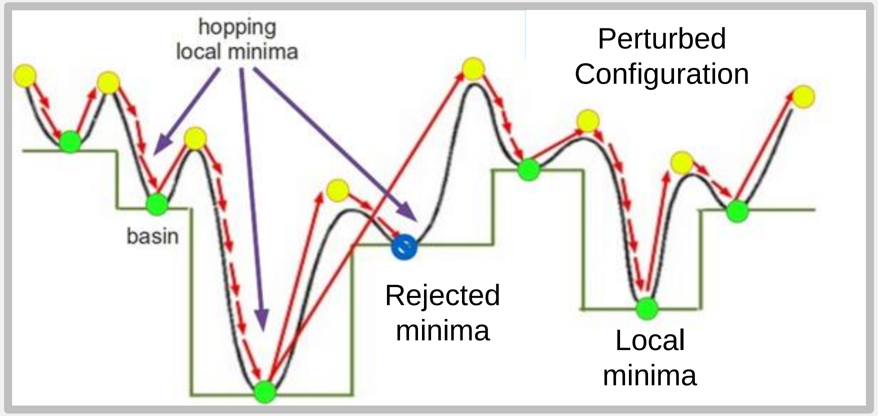
Very technical thing but with important consequences on the astrophysics

I'll need to collaborate with a group in France which is working on the calibration

Thank you for your attention

Optimization algorithms:

Basin Hopping:



1) Perturbation
2) Local minimization
3) Acceptance/Rejection

Metropolis

Differential Evolution:

Mutation

Crossover

Selection

Stopping Criterion
(convergence of
population)

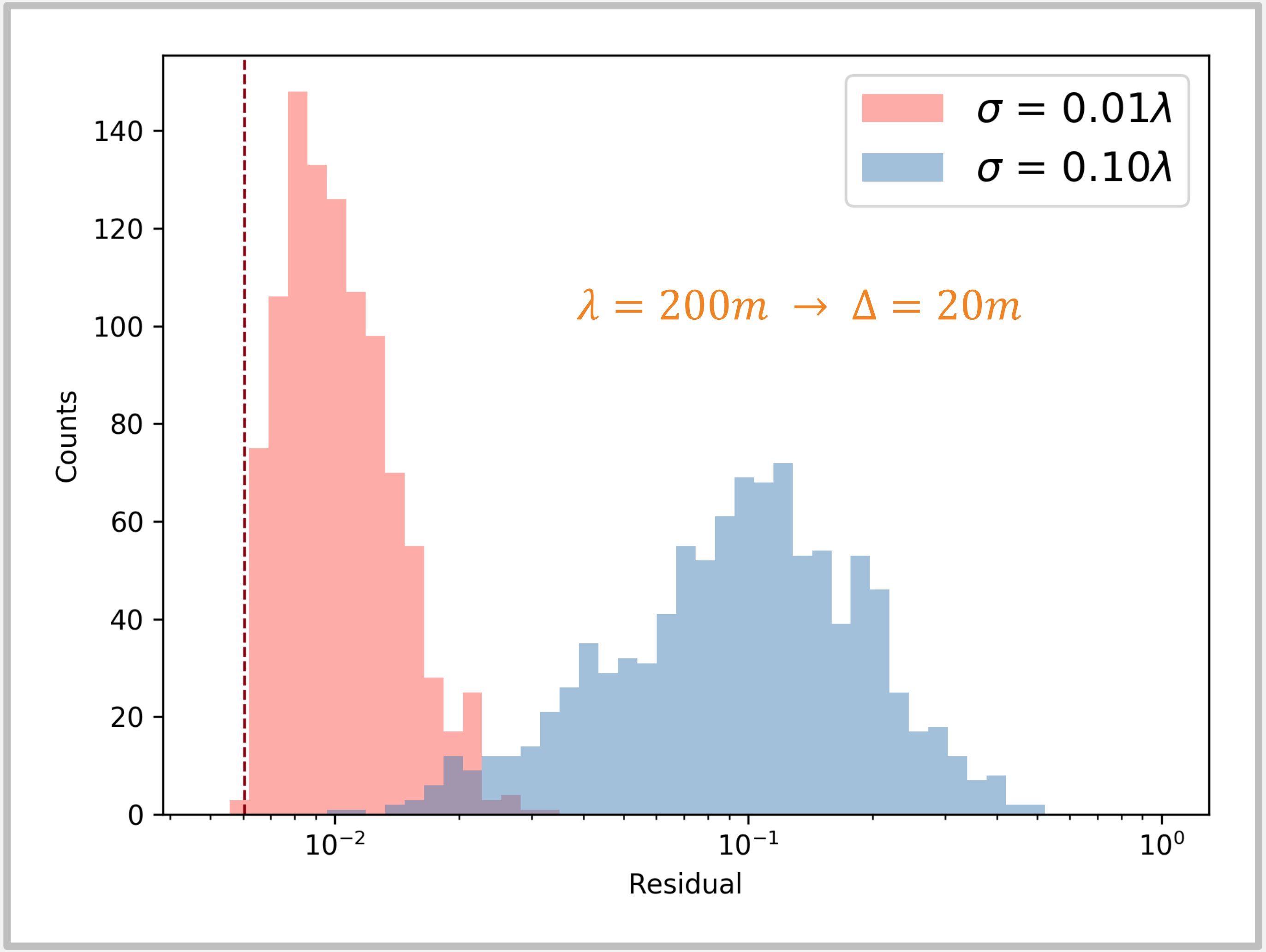
no

yes

Global minimum

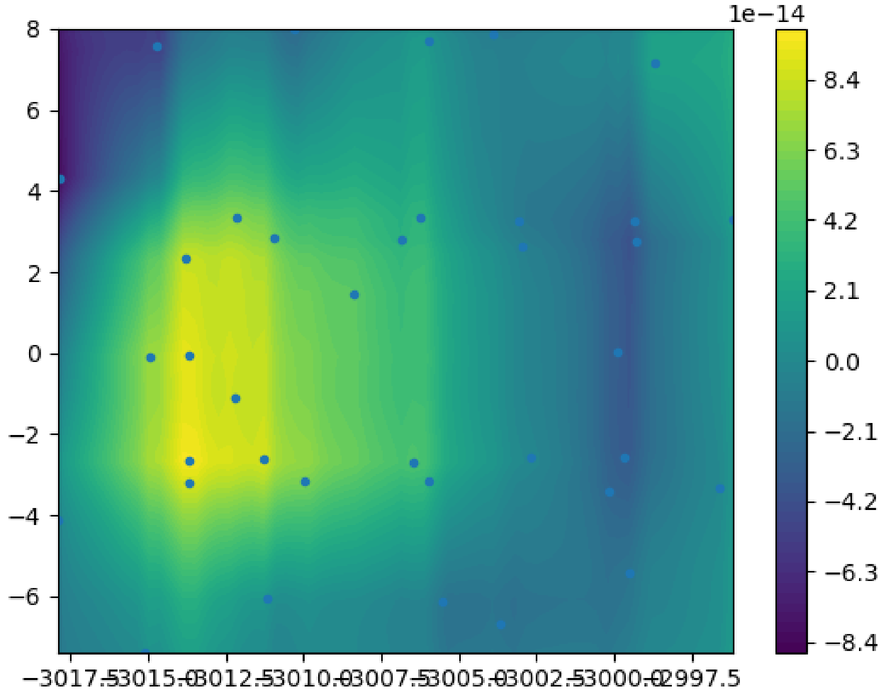
Rayleigh, N = 6

Already limited by the self noise



This entails a worse NN reduction for a degraded array configuration

What about 4d interpolation?



CPSD of the 30° sensor

Convolution theorem:

$CPSD\ (s1, s2) = \langle (Fx_1(\omega)^* Fx_2(\omega)) \rangle$

For each seismometer take N samples in the data → FFT

For each sample period calculate the interpolation of the FFT(ω) in the 2D space

Calculate CPSD (s1, s2) = CPSD (x1,y1,x2,y2) (just one element of the matrix)