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

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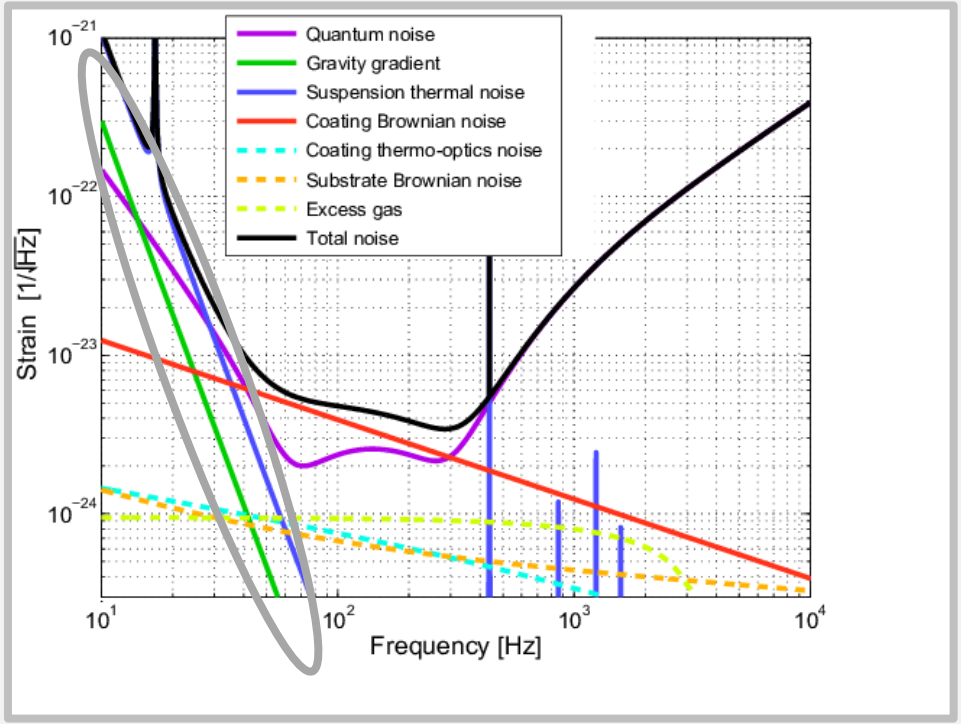
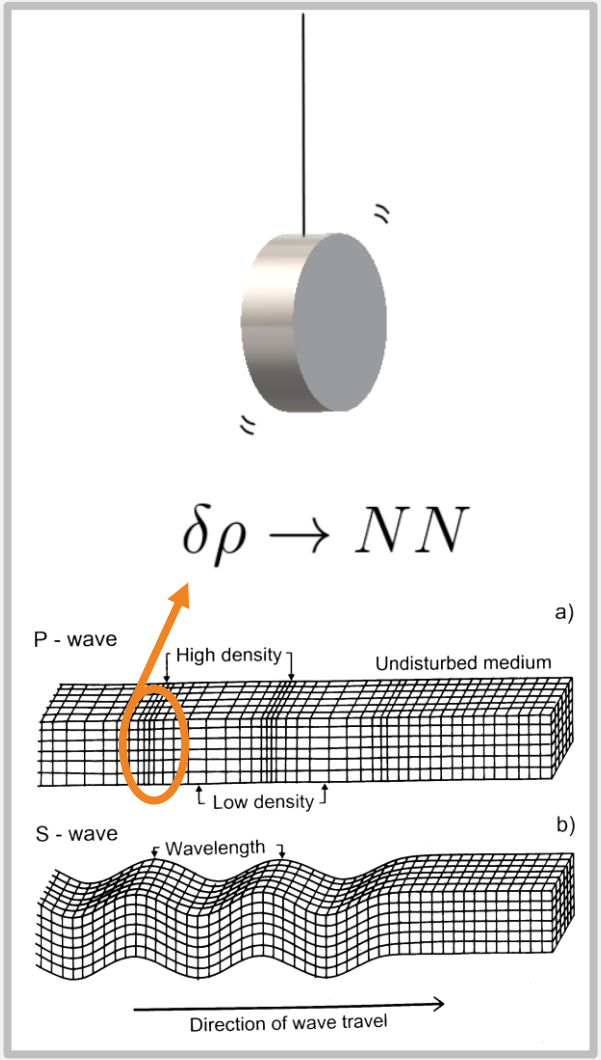
What is Newtonian Noise (NN):

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

Example of NN in Virgo:

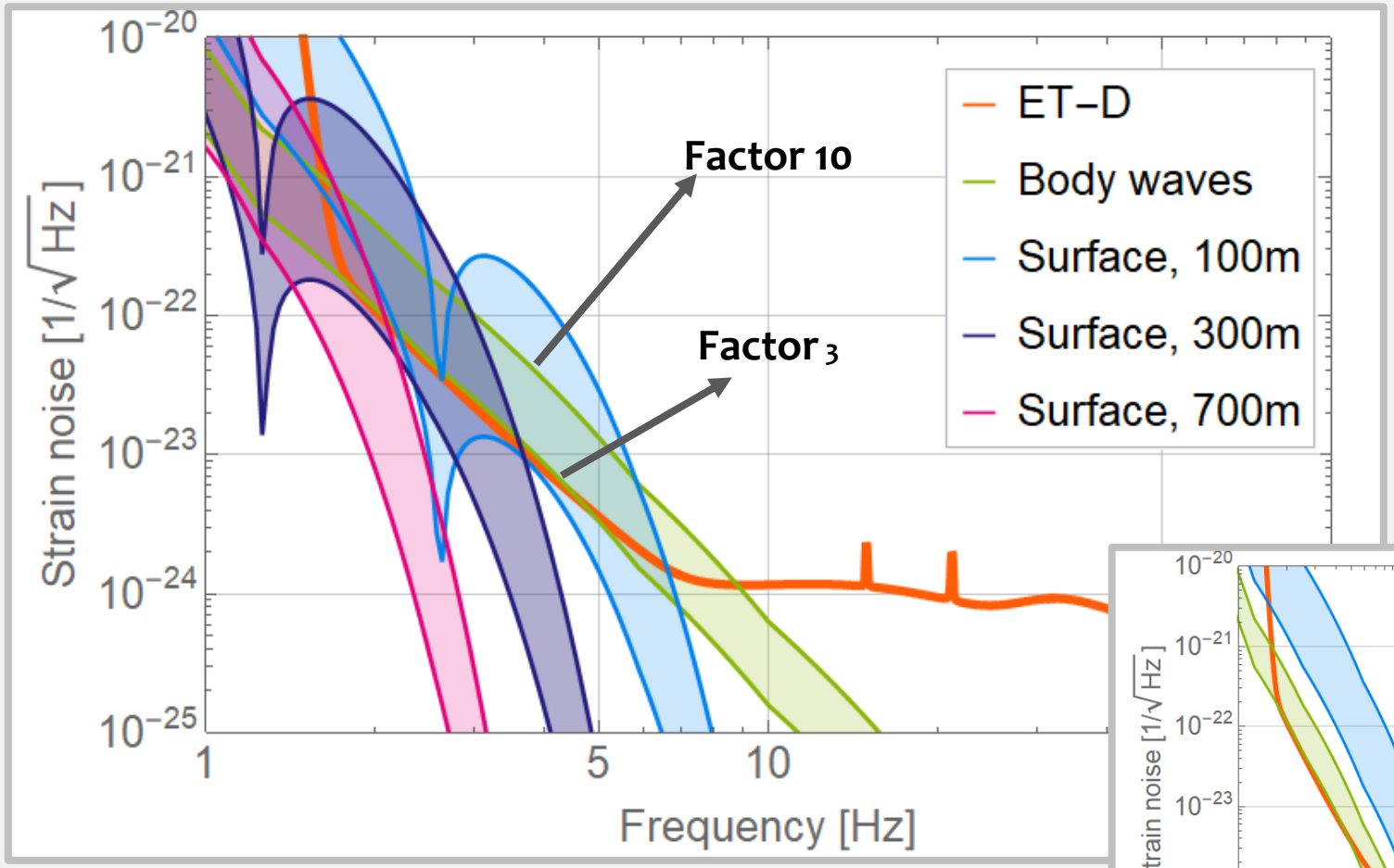




Basic idea: seismometers →
Coherent Newtonian Noise (NN) estimate →
NN subtraction

What has been already done:
Advanced Virgo/LIGO →
Rayleigh waves

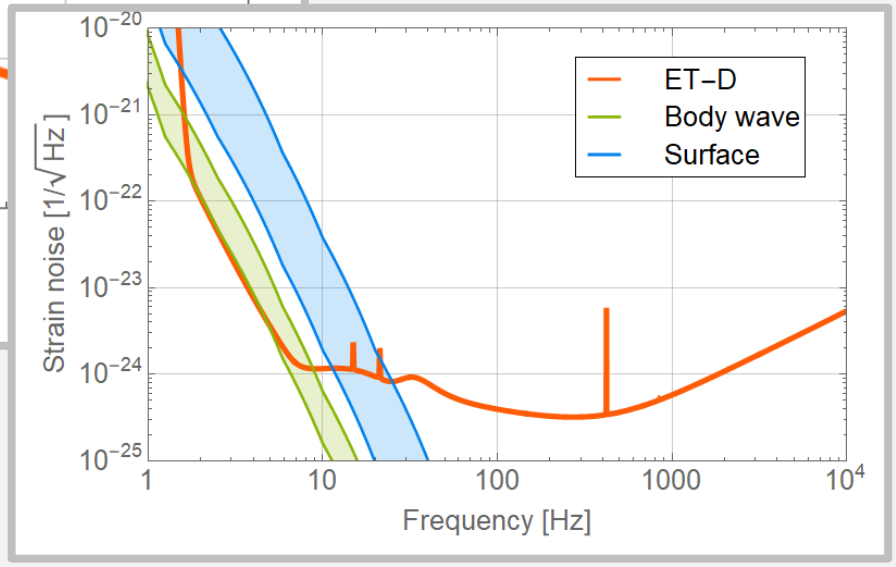
What we did:
Einstein Telescope (ET) → Body waves



Underground

Suppression up to a factor 10

Surface



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

CPSDs between seismometers and test mass

Cross Power Spectral Densities (CPSDs) between seismometers

Power Spectral Density of test mass

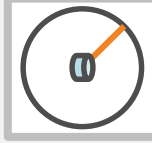
Gravitational coupling model: mirror <-> field

$$\delta\vec{a}(\omega) = \frac{4}{3}\pi G\rho_0\left(2\vec{\xi}^{\mathrm{P}}(\omega) - 1\vec{\xi}^{\mathrm{S}}(\omega)\right)$$

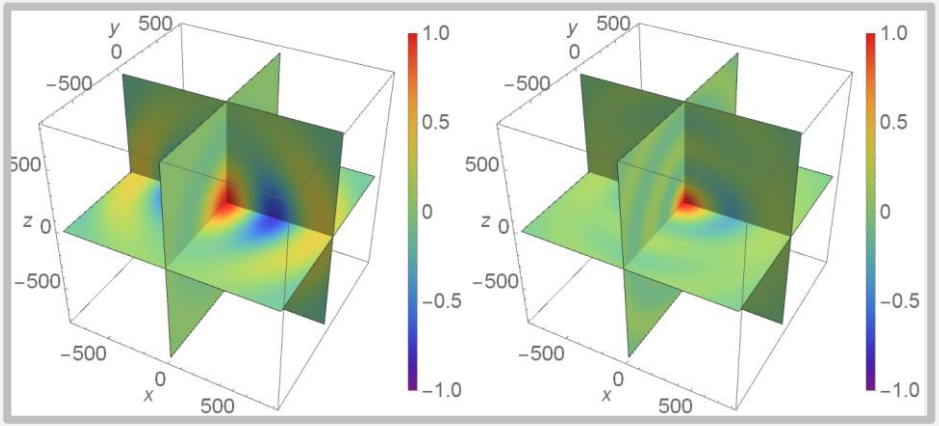
Isotropic & Homogeneous seismic field hypothesis

Body waves
P (compressional) & S (shear)

+



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

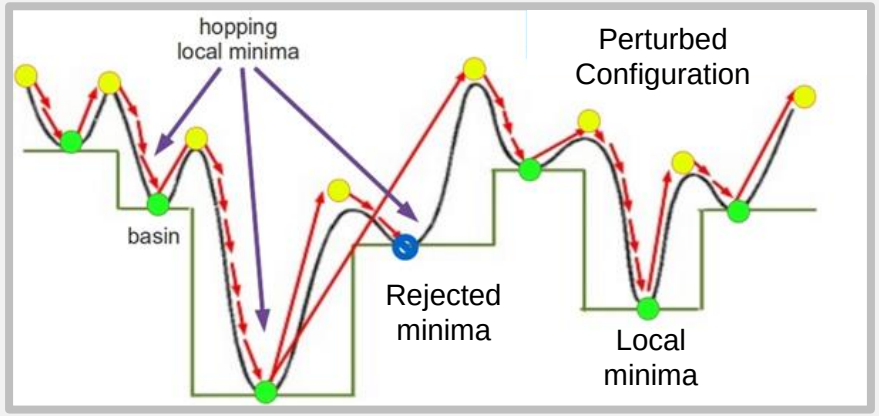


only P-waves

P & S mixture

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

p = 1/3

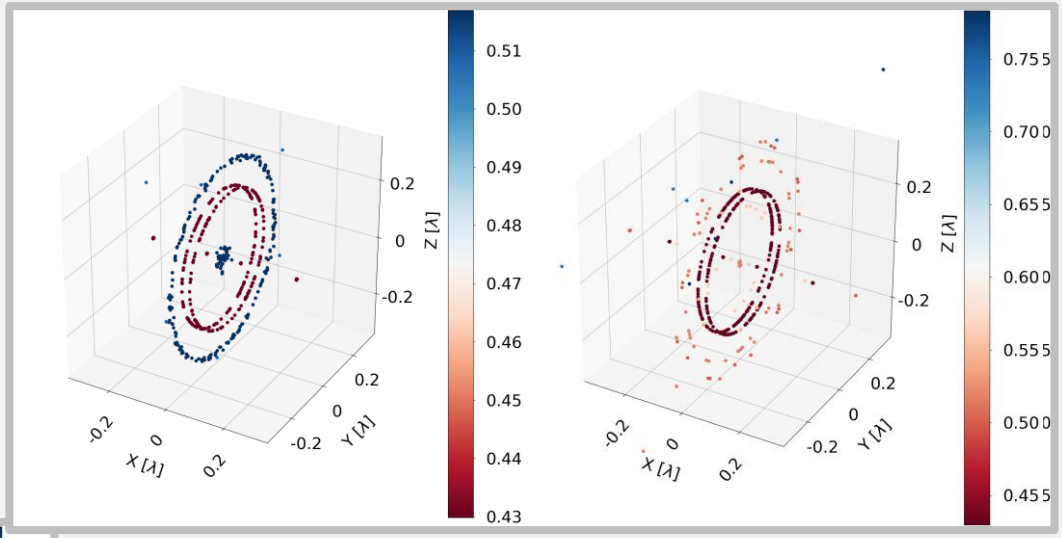
N fixed (6)

f = 10 Hz

SNR = 15

v_P = 6000 m/s

v_S = 4000 m/s



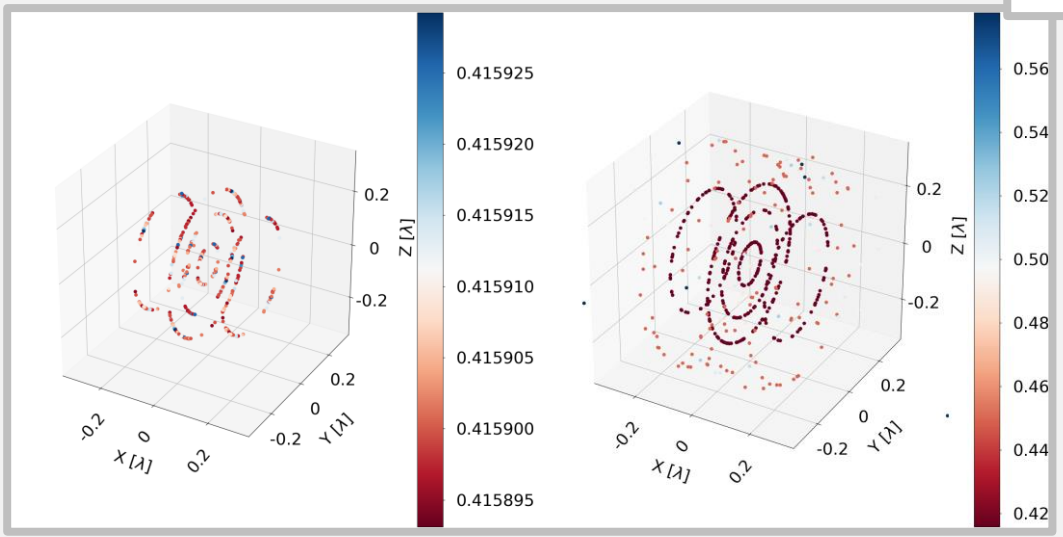
DE

1 channel axis seismometer

X

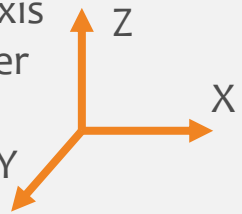
BH

Test mass moving along X axis:

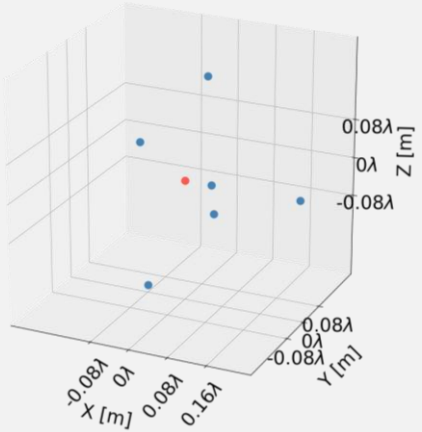


DE BH

3 channel axis seismometer

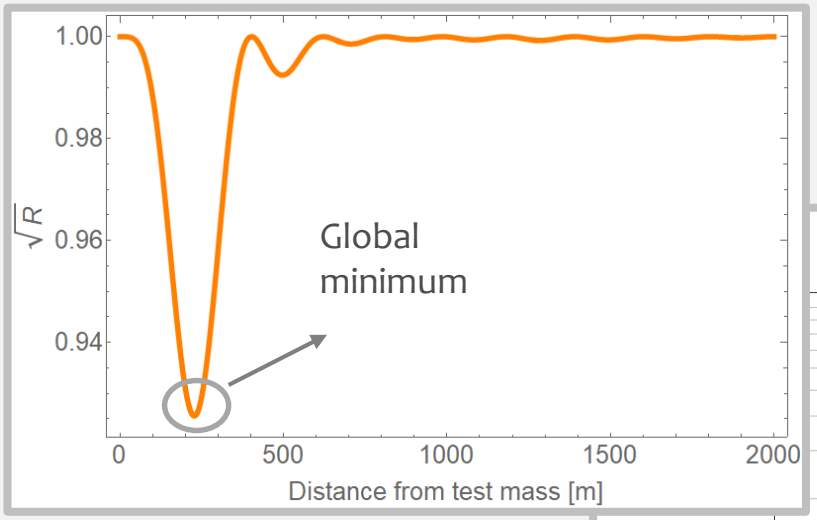


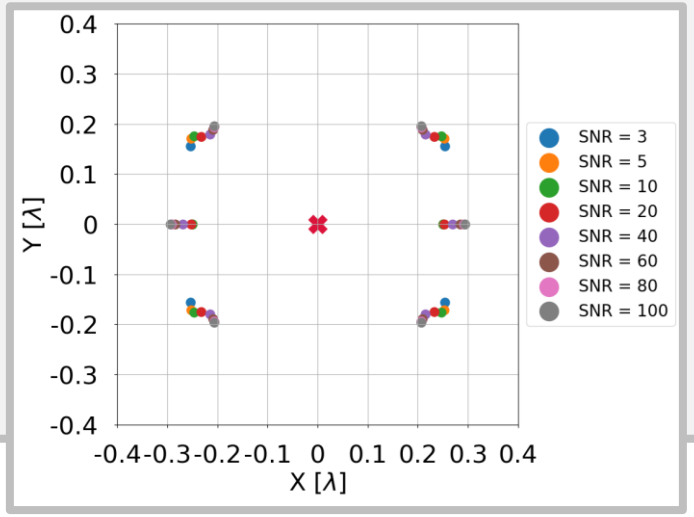
Single example

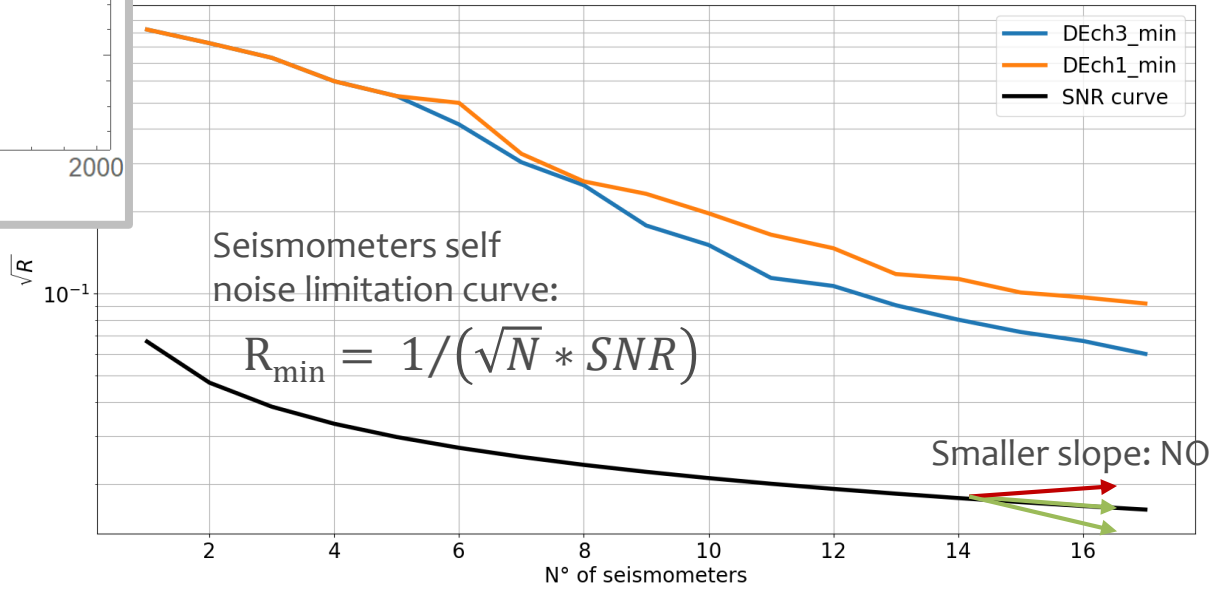


Validation:

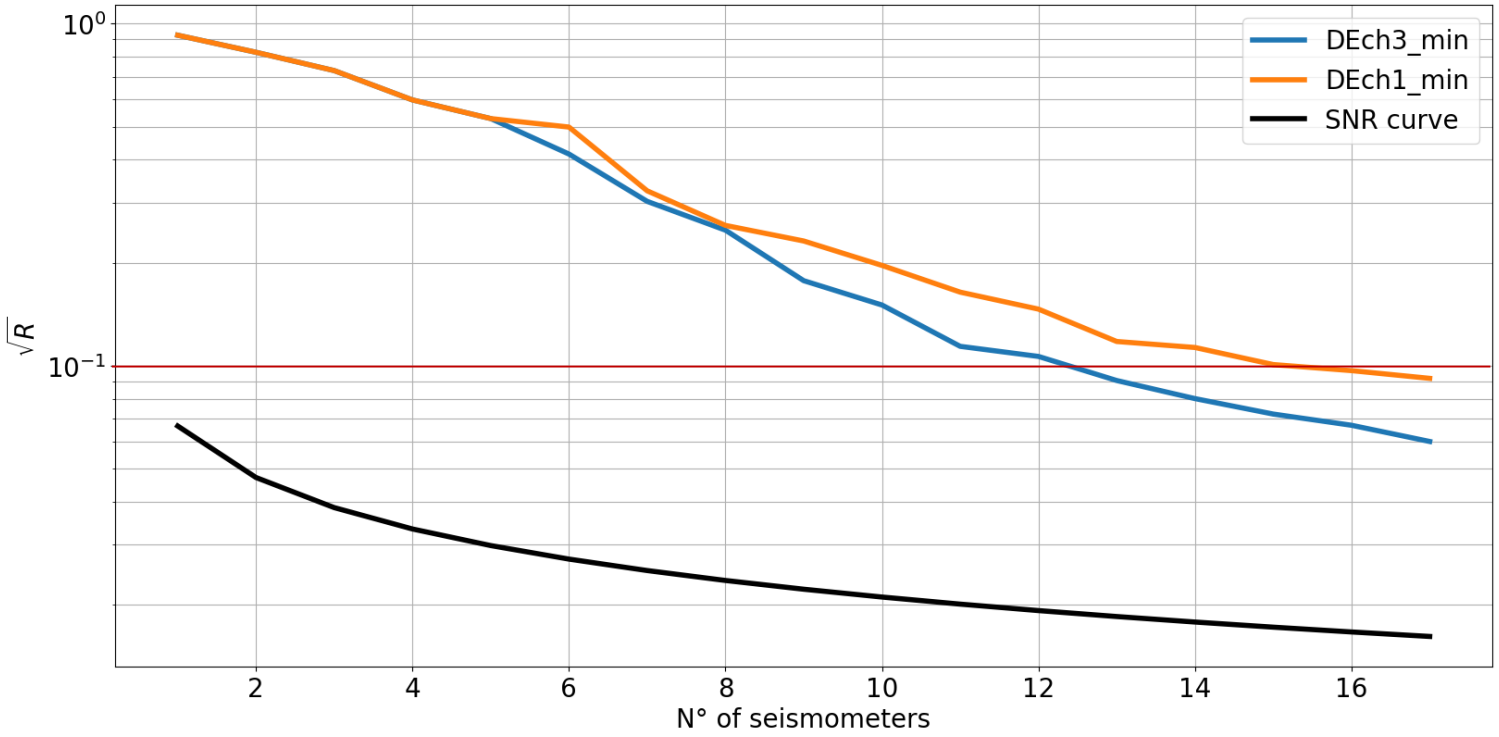
Analytical solution for N = 1

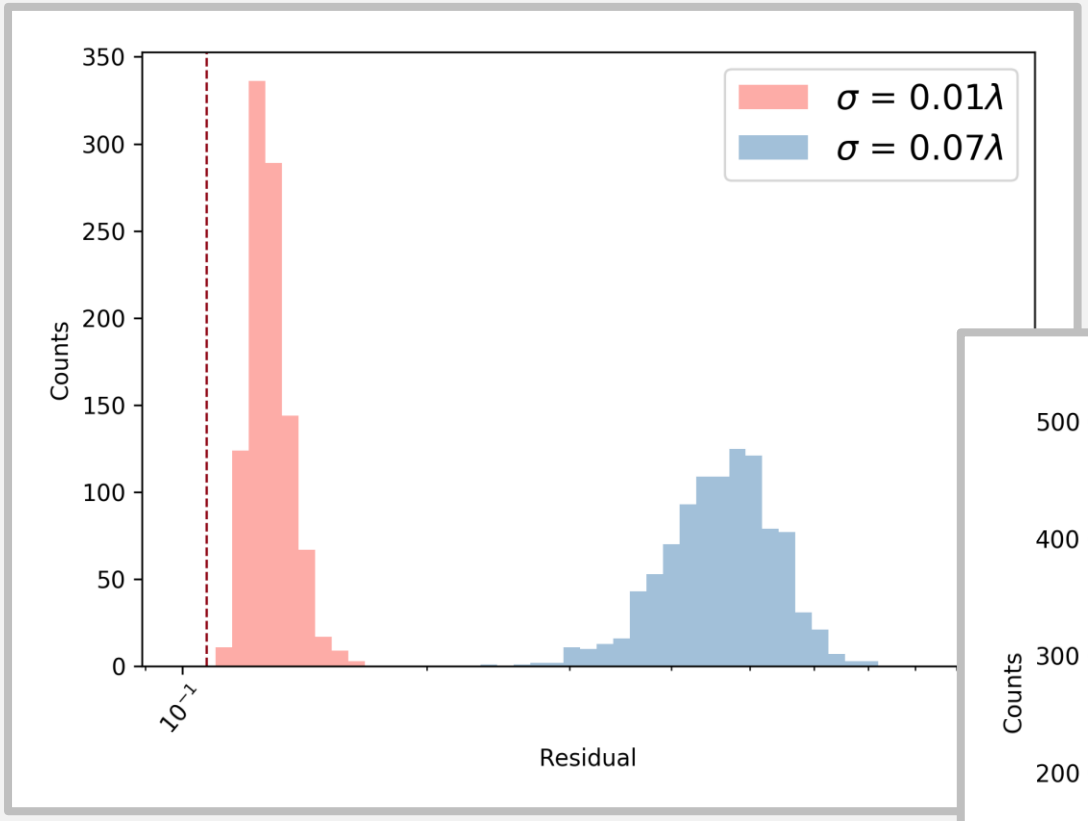






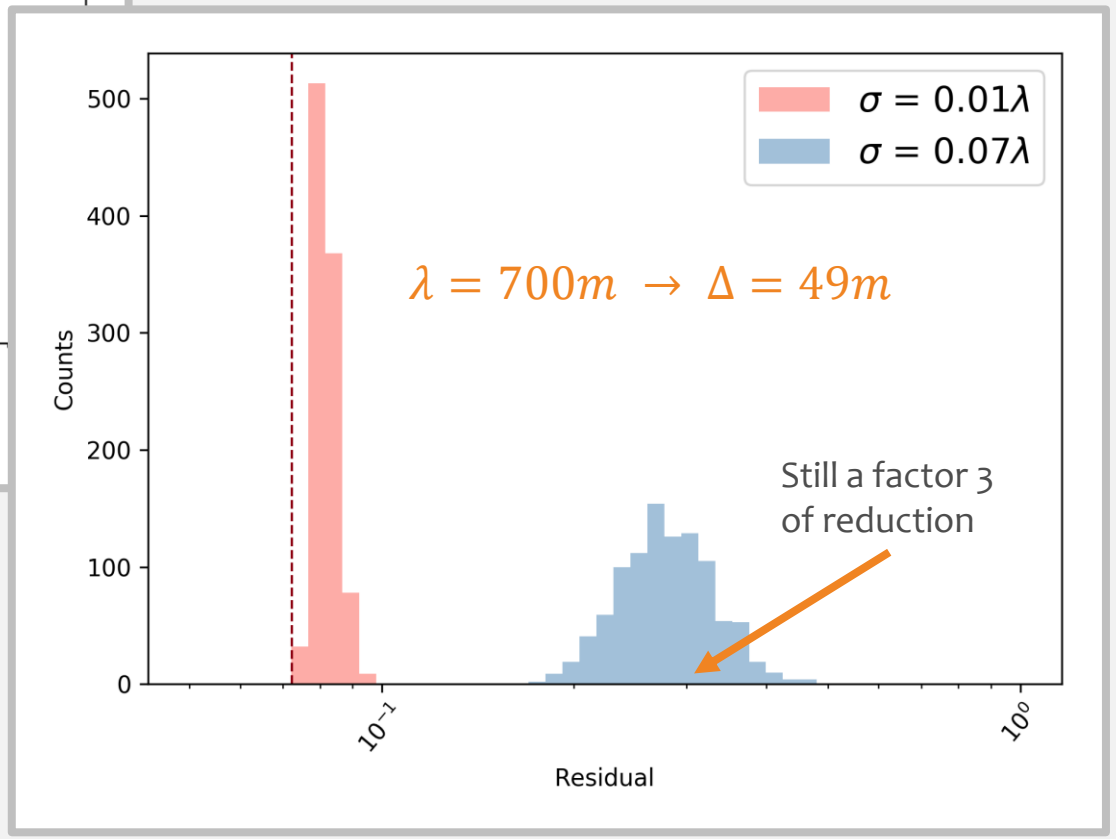
Succesful mission: factor 10 of reduction already with 13 seismometers per test mass





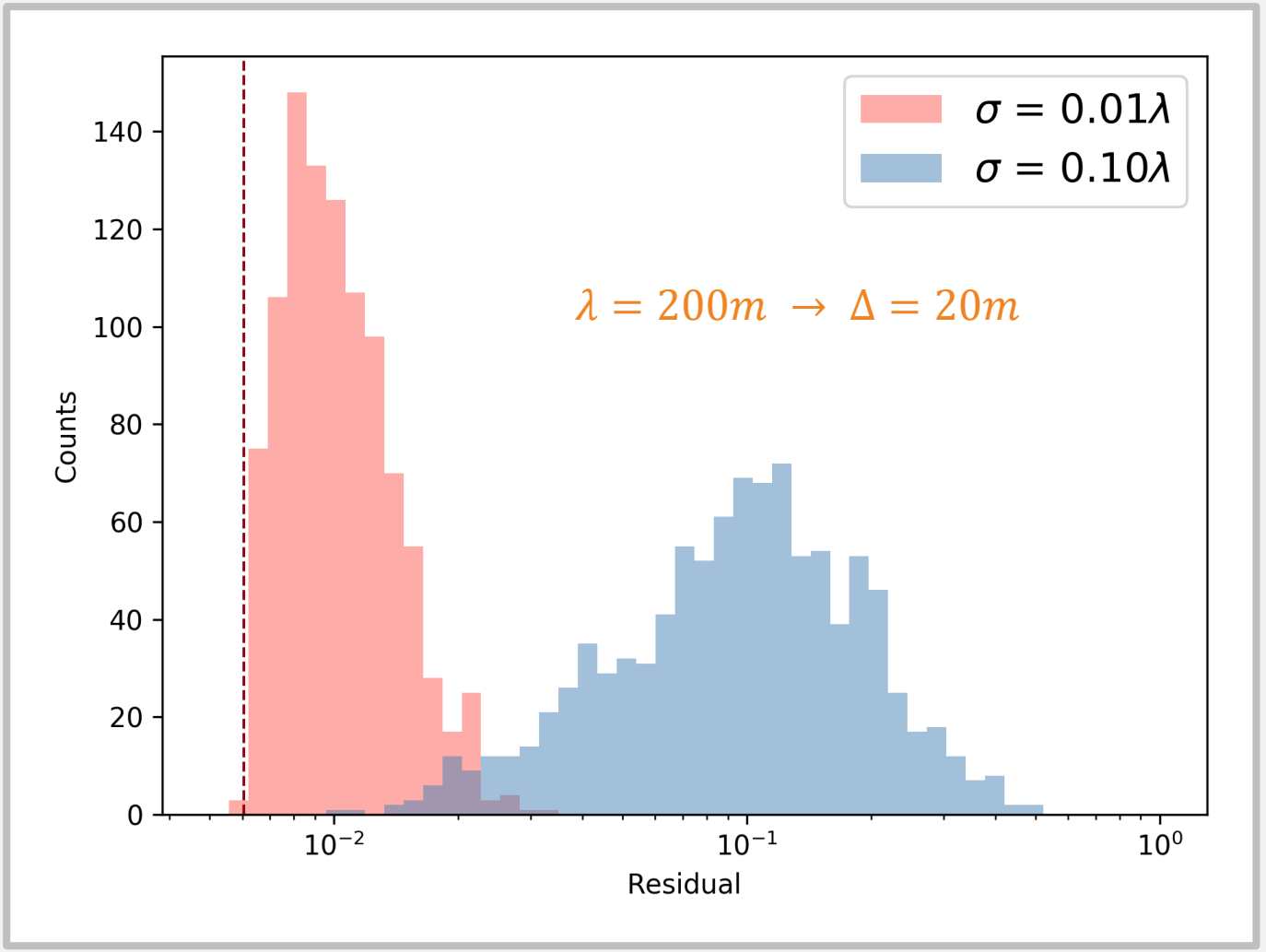
Ch1, N=15

Ch3, N= 15



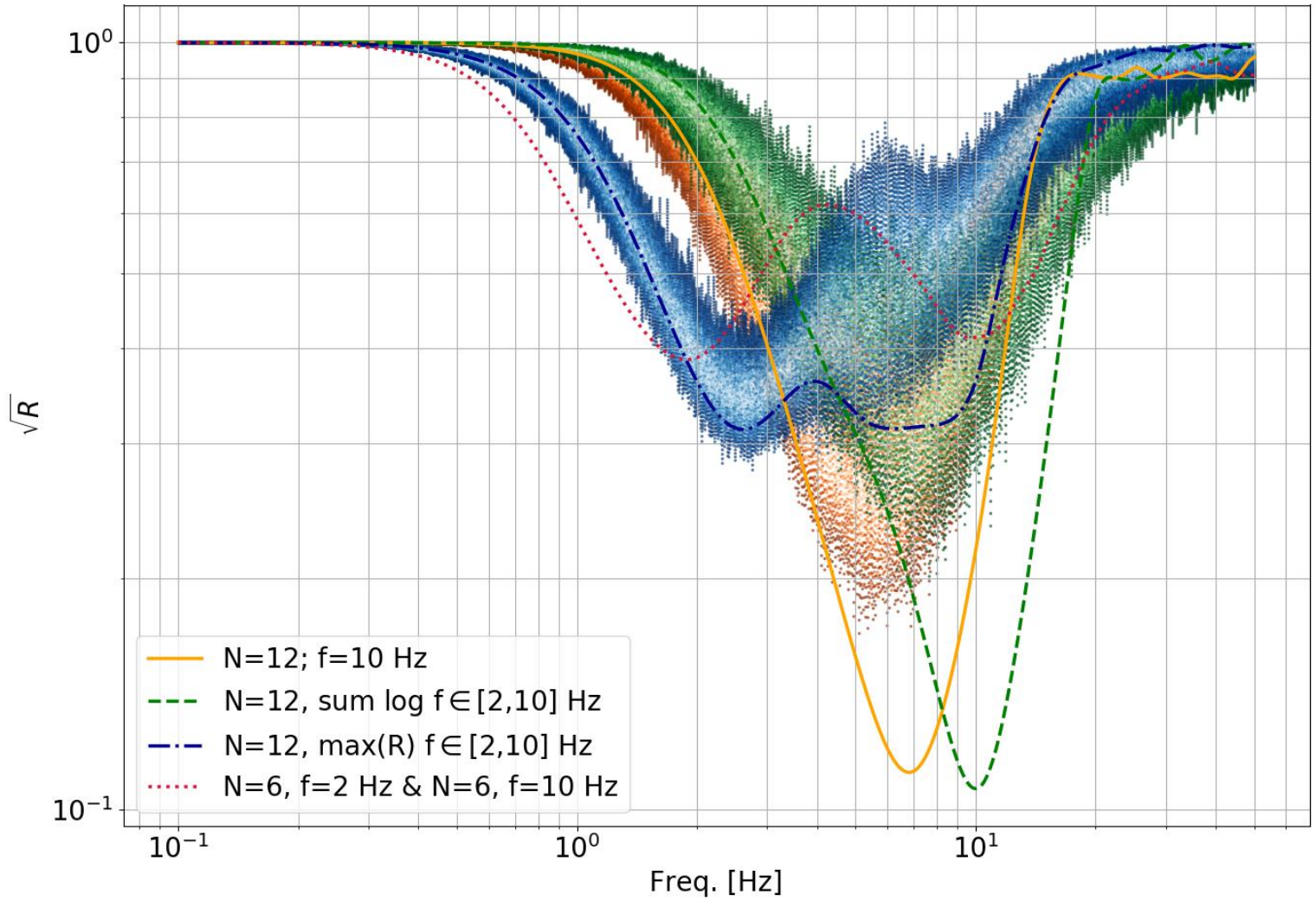
Rayleigh, N = 6

Already limited by the self noise



This entails a worse NN reduction for a degraded array configuration

Broadband optimization:



Conclusions:

- NN cancellation up to a factor 10 should be feasible
- Important result: even a degraded array can still work
- A simplified analysis
- Still, n° of seismometers, related residual and stability of solution should be robust
- Optimization based on real data (site characterization) required for accurate seismometer placement

Thanks for the attention!
Questions?