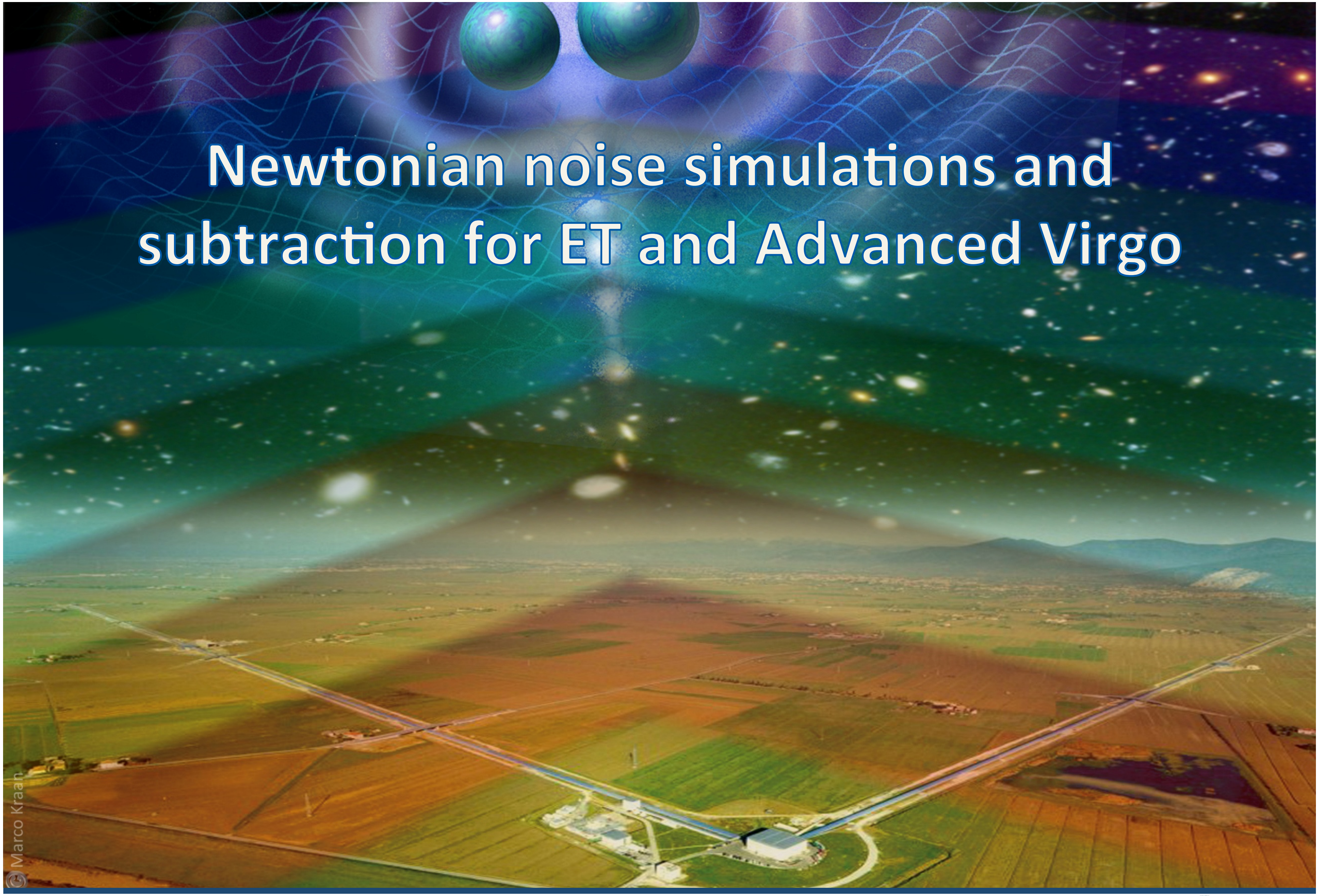
Newtonian noise simulations and subtraction for ET and Advanced Virgo



GWADW 2012, Waikoloa Beach, Hawaii

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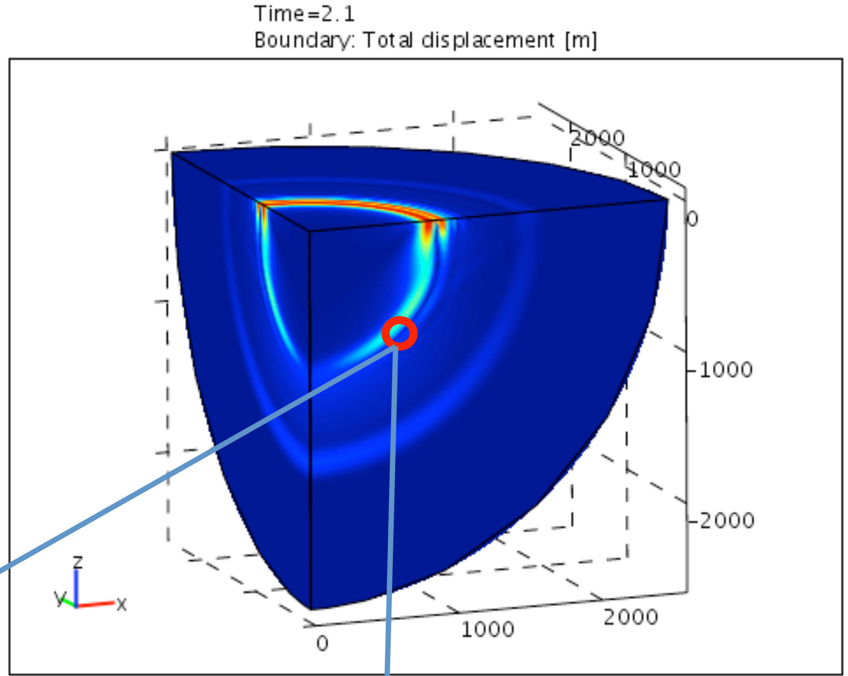
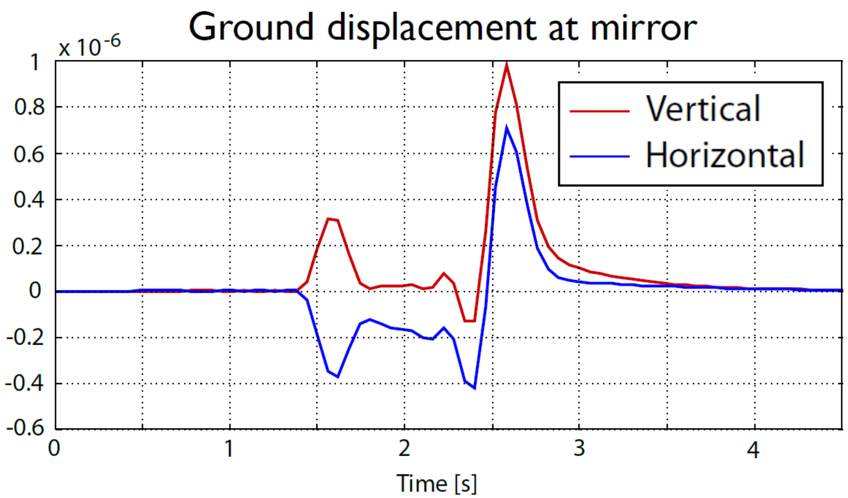
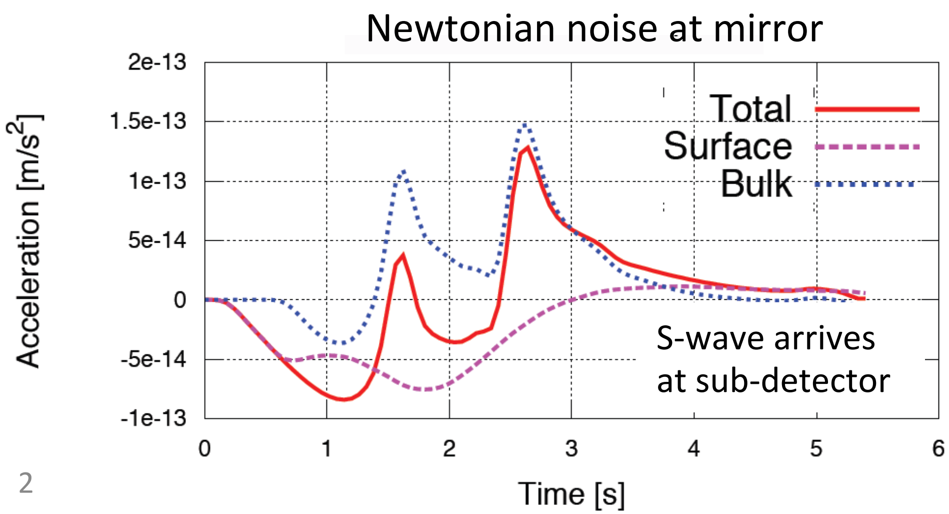
Simulations made in the context of ET

- Cultural noise / Impulse excitations
  - NN “felt” at test mass before seismic wave field arrives

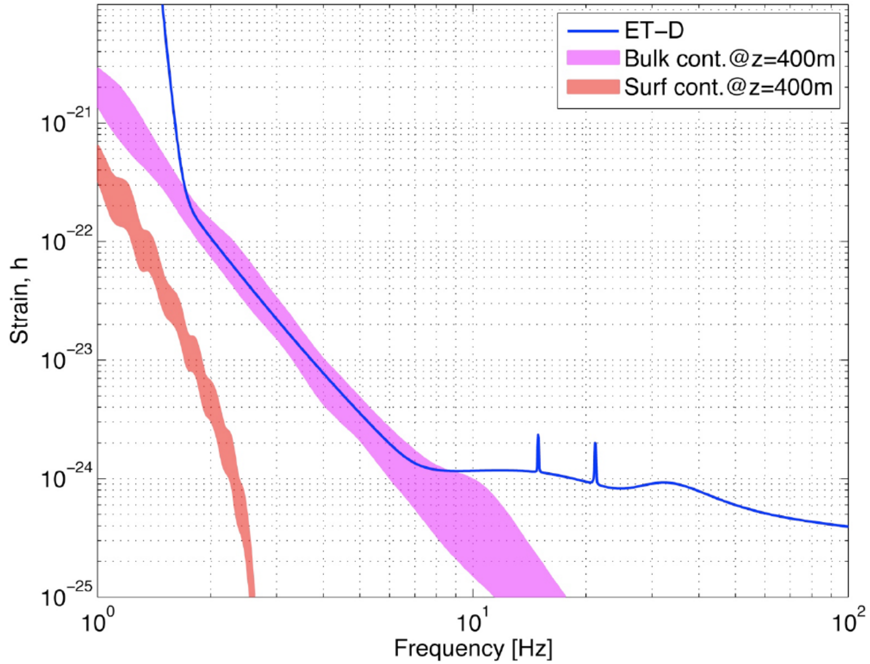




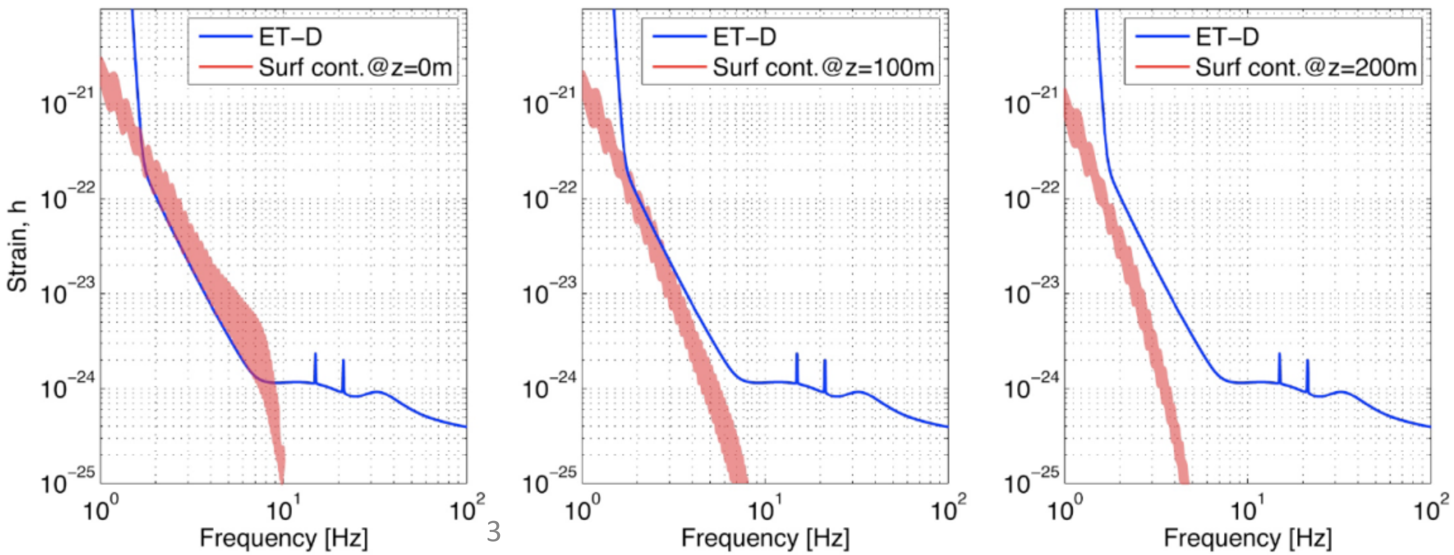


Simulations made in the context of ET

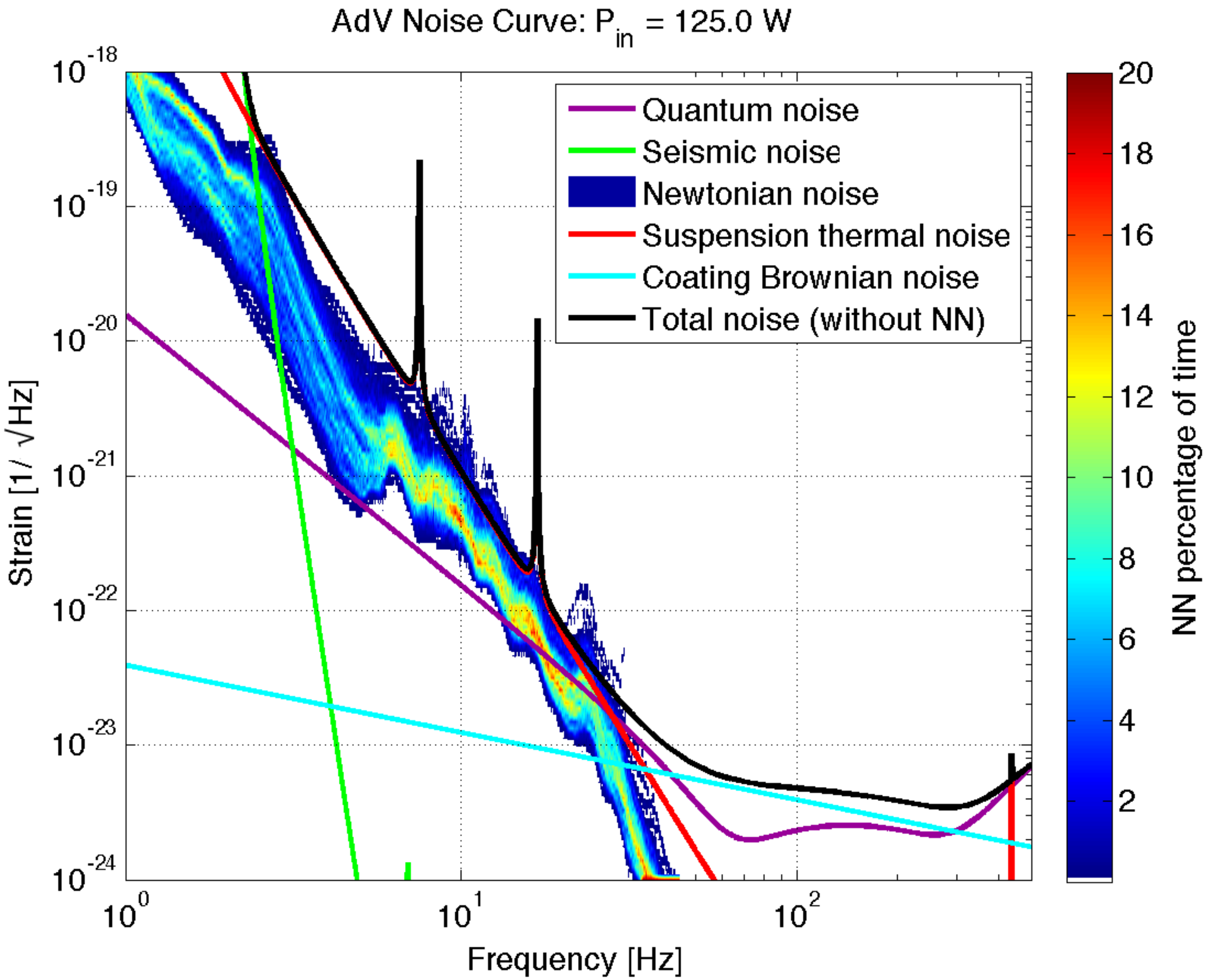
- Cultural noise / Impulse excitations
  - NN "felt" at test mass before seismic wave field arrives
- Ambient seismic motion
  - Surface wave models developed by Cella
  - Thorne and Hughes model for bulk contribution
  - Estimates made using real seismic data



A few hundreds meters enough to suppress surface contribution
Bulk contribution remains



Newtonian noise could limit Advanced Virgo sensitivity during high seismic activity



[VIR-0073B-12]

Seismic sensor networks could be used for Newtonian noise subtraction

- Seismic sensor (signal + noise) $$X_I = s_I + \sigma_I$$
- ITF output (GW signal + N. noise) $$Y = H + N$$
- Find $\alpha_I(\omega)$ to minimize "subtracted" signal

$$Y_s(\omega) = Y(\omega) + \int d\omega' \sum_I \alpha_I(\omega,\omega') X_I(\omega')$$

$$\frac{\delta \langle Y_s(\omega)^* Y_s(\omega) \rangle}{\delta \alpha_I(\omega,\omega')} = 0$$

Sensor noise appears in diagonal elements of cross-correlation matrix

- Optimal filters

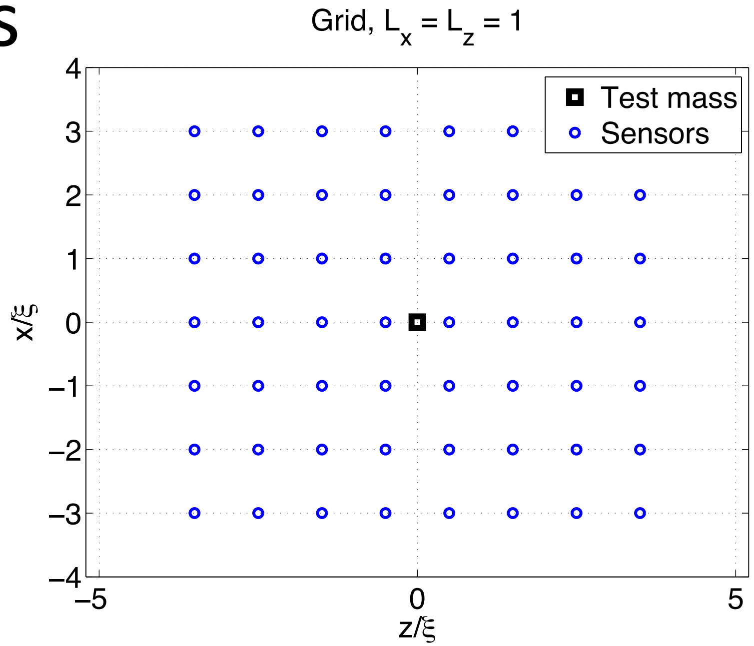
$$\alpha_I(\omega,\omega') = -\sum_K \int d\omega' \langle X_I(\omega)^* X_K(\omega') \rangle^{-1} \langle X_K(\omega')^* Y(\omega) \rangle$$

- Subtraction efficiency
  - 1 = No subtraction
  - 0 = 100% subtraction

$$(1-\epsilon(\omega))^2 = 1 - \frac{C_{SN}^{\dagger}(\omega) C_{SS}(\omega)^{-1} C_{SN}(\omega)}{C_{NN}(\omega)}$$

[G. Cella, *et. al.*, Gen. Rel. Grav. (2010)]

Newtonian noise subtraction simulations

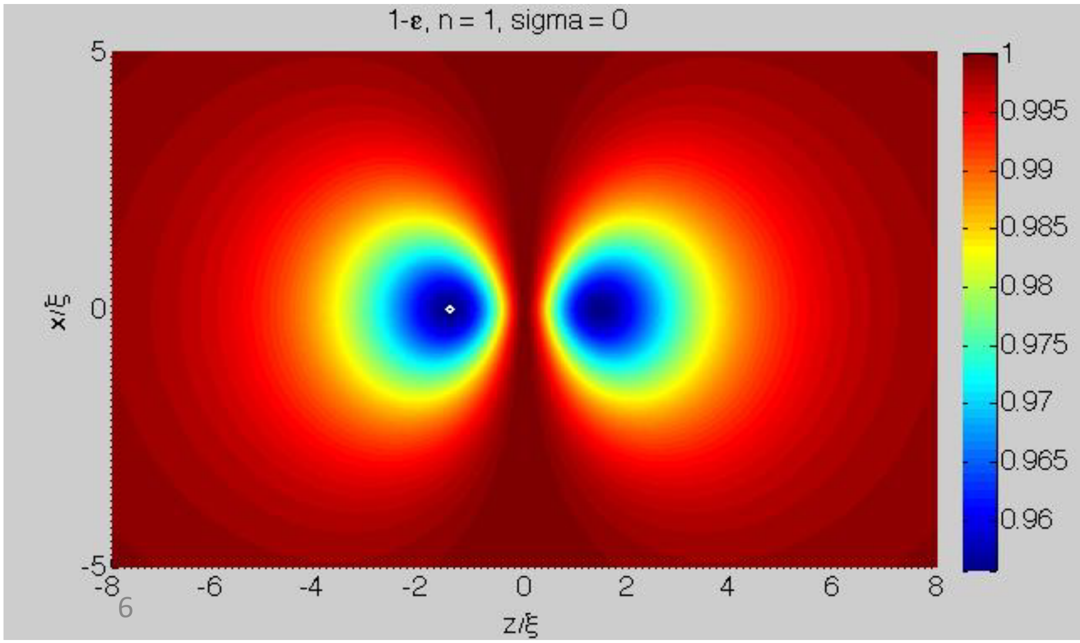


- Simplified model
  - Exponential cross correlation function between sensors

$$\langle \rho(\omega, \mathbf{x})^* \rho(\omega', \mathbf{x}') \rangle = 2\pi \Gamma(\omega)^2 \delta(\omega - \omega') e^{-\frac{|\mathbf{x}-\mathbf{x}'|}{\xi(\omega)}}$$

$$\xi(\omega) : \text{Correlation length}$$

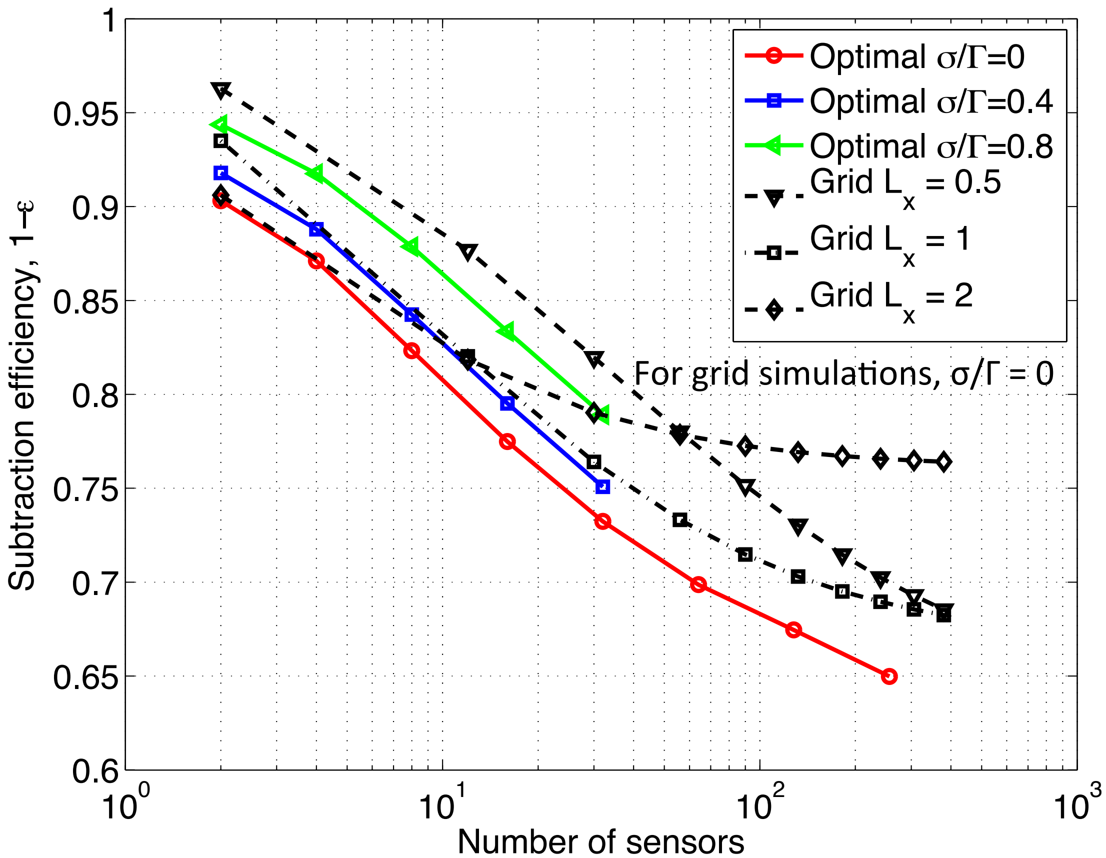
- Regular grid
  - Centered around test mass
  - For NN in z direction only
- "Optimal" positioning of sensors
  - Keeping previous sensors fixed, calculate subtraction efficiency as function of position of next sensor
  - Optimized for particular correlation length (frequency)



NIKHEF

Newtonian noise subtraction simulation results

- Based on this model several hundred sensors needed to achieve a 50 % reduction
- Sensitivity of seismic sensors SNR > 5
- Sensor network optimized for frequency and geology
- Optimization easier for homogeneous media
  - Longer correlation lengths
- What is a realistic model of seismic activity?



Develop a seismic model based on measureable quantities

- Most relevant quantities for Newtonian noise subtraction:
  - (Power) spectral densities
    - NN scales linearly with amplitude
  - Correlation
    - As a function of distance between sensors / frequency
    - Between vertical and horizontal motion
    - Subtraction techniques rely on (cross)correlation amongst sensors and between sensors and NN

$$\alpha_I(\omega,\omega') = -\sum_K \int d\omega' \langle X_I(\omega)^* X_K(\omega')\rangle^{-1} \langle X_K(\omega')^* Y(\omega)\rangle$$

- Complex correlation: $K_k = \frac{\langle u_k z_k^* \rangle}{\sqrt{\langle u_k u_k^* \rangle \langle z_k z_k^* \rangle}}$
- Coherence: $|K_k|$
- Correlation: $\Re[K_k]$

Examples of seismic correlation measurements

- CERN
- DESY
- High coherence from micro-seismics
- Above a few Hz coherence is lost within ~100 m
- Literature provides models for typically behavior
  - Exponential
  - Bessel function

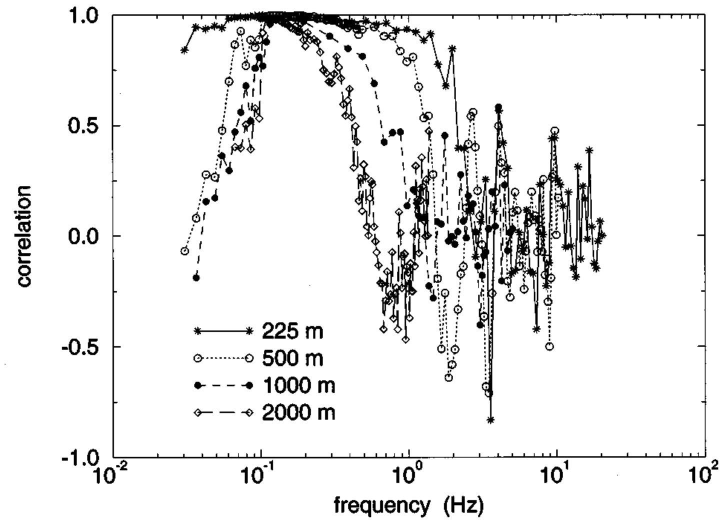


FIG. 3. Correlation spectra of ground motion measured at CERN in the LEP tunnel [7]. The distances between sensors were 225, 500, 1000, and 2000 m. A. Sery and O. Napoly, Phys. Rev E 54 (1996)

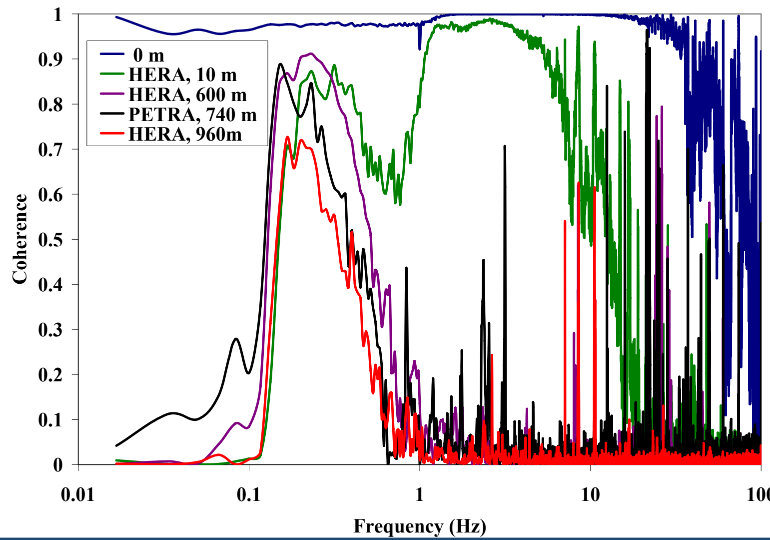


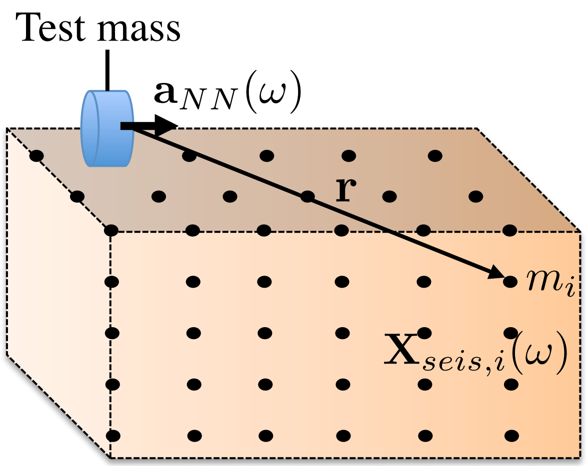
FIG. 6: (Color) Coherence spectra measured at different distances at DESY: 0 m, 10 m, 600 m, 740 m (diameter of PETRA ring) and 960 m in the HERA tunnel.

W. Bialowons et. al, EURO-TeV Report (2007)

Frequency domain numerical correlation propagation algorithm

- Simulated seismic noise
  - Noise distributed with depth dependent $\beta_{P,S,R}$:
  - Given ratio between pressure, shear and Rayleigh waves
- A random phase and isotropic direction of propagation is selected for each frequency bin
- Correlation and relative phase of the noise between all grid points is calculated:
  - Coherence follows given function
  - Direction and wave-dependent correlation factor
  - Relative phase and relative direction of the correlated noise is calculated from the wave direction and the grid point positions.
- Correlation relationships between transverse / longitudinal directions and horizontal / vertical components

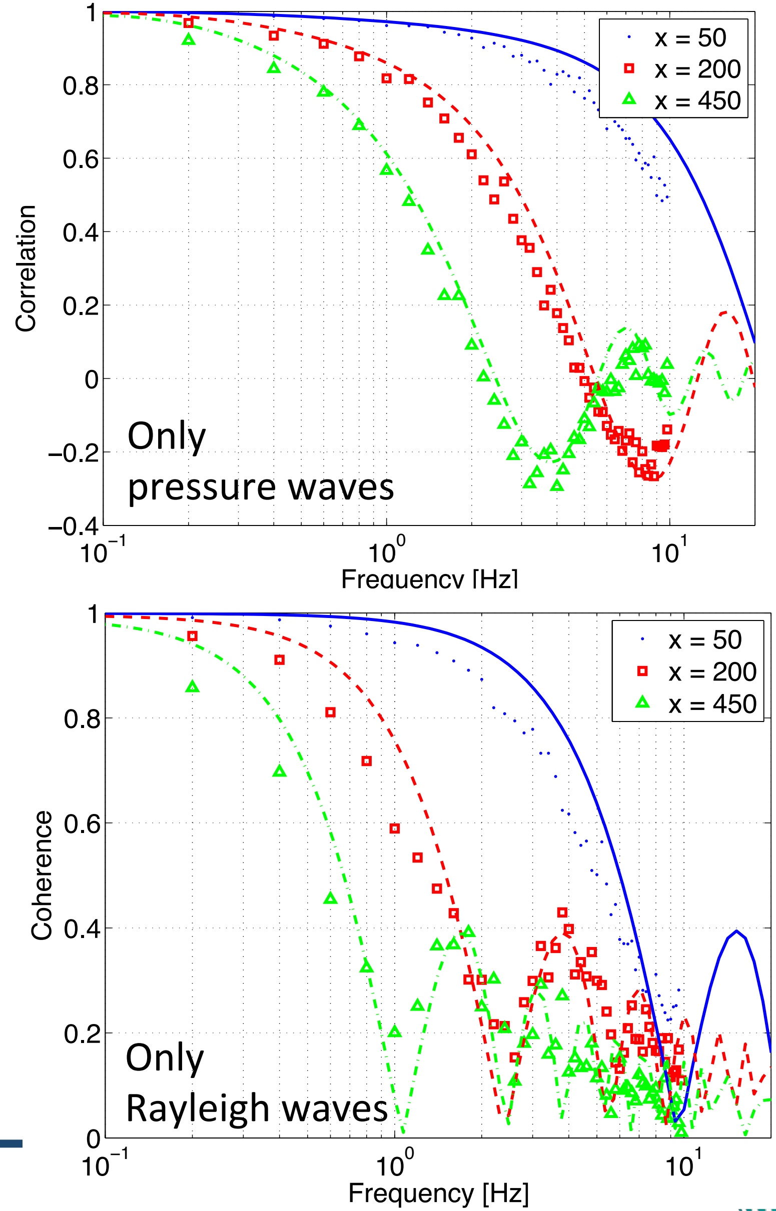
$$|X_{seis}(\omega)| \propto \frac{A_{P,S,R}}{f} e^{-z\beta_{P,S,R}/\lambda}$$



Preliminary results show coincidence with expectation

- 10 x 10 x 10 grid
- Averaged over 400 simulated FFTs
- Correlation can be modeled by exponentially decaying Bessel function
  [G.A. Prieto *et. al.* Journ. Geophy. Res. 114 (2009)]

$$\Re[K_k(\omega, r)] = J_0(kr) \cdot e^{-\alpha(\omega)r}$$

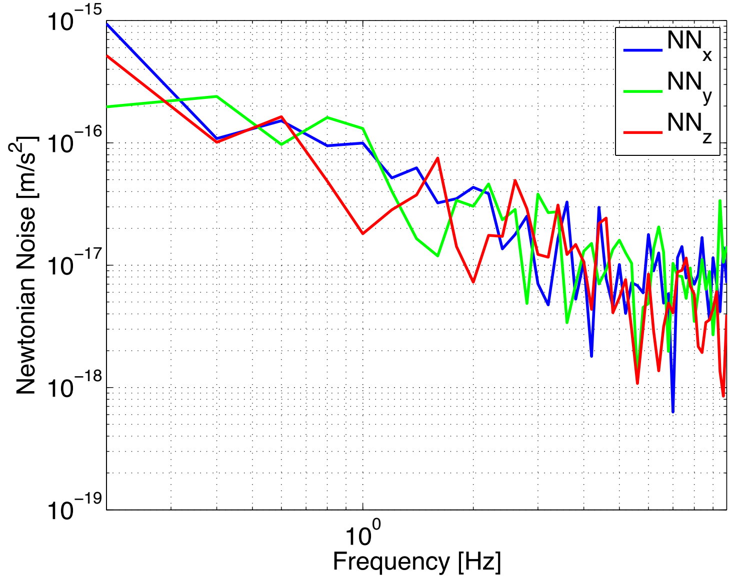


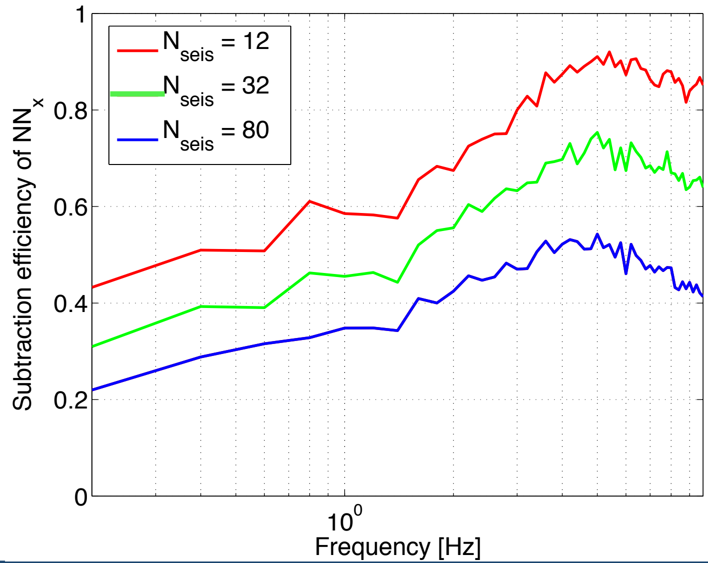
Newtonian noise computation and subtraction using correlation model

- Calculate Newtonian Noise

$$\mathbf{a}_{NN}(\omega) = G\sum_i m_i(\nabla \otimes \frac{\mathbf{r}_i}{|\mathbf{r}_i|^3})\mathbf{X}_{seis,i}(\omega)$$

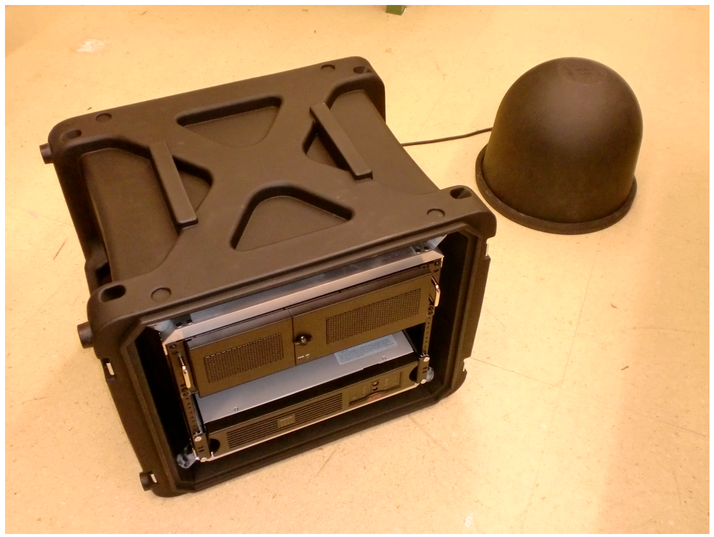
- Place a number of seismometers and evaluate subtraction efficiency
- Preliminary results
  - Basic regular grid of surface seismometers
  - No optimization of network
  - Simple seismic amplitude model
  - Sparse grid





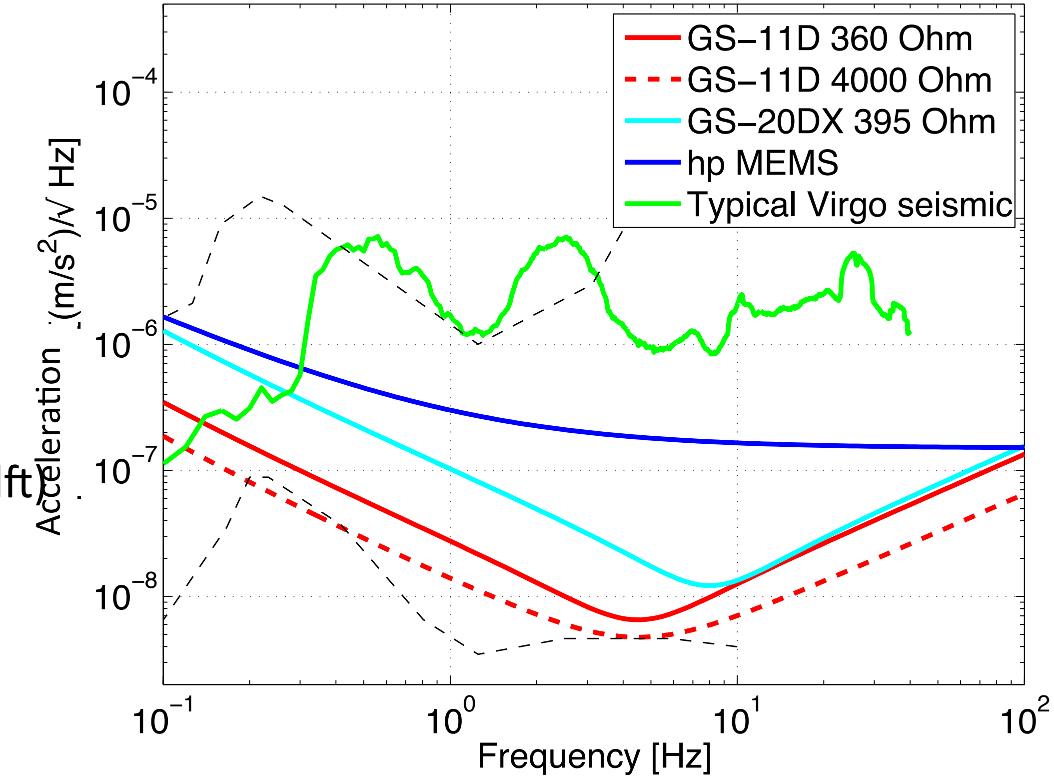
Numerical models will help to determine requirements for seismic sensor networks

- Measurements to be done at Virgo to provide input for model
  - With two portable T240 stations
- Produce an estimate of NN at the site
- Optimal density and distribution of sensors
- Requirements on the sensor sensitivity
- Expected subtraction efficiency



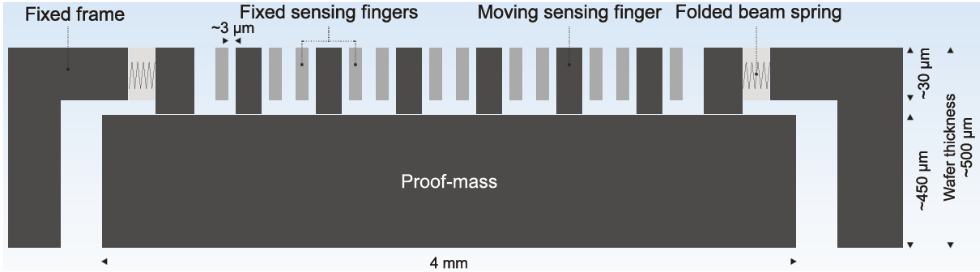
Seismic sensor network

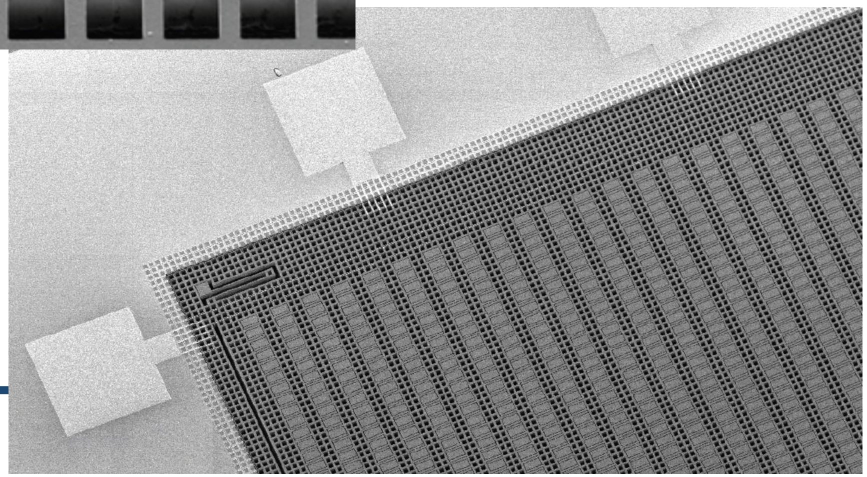
- Performance
  - Geophone has superior sensitivity
- Low cost
- Low power
- Noise sources
  - Pre-amp voltage / current
  - Digitization noise
  - Sensor noise negligible
- In collaboration with other scientific endeavors
  - Seismic interferometry (TU Delft)
  - Lofar seismic array
  - Pierre Auger observatory



R&D into MEMS accelerometers also underway

- In cooperation with MESA+ / Universiteit Twente
- Silicon structure
- Capacitive interfaces
  - Position detection
  - Range 100 um, nm resolution
  - 2096 pF/g; 1 fF/um
- Closed-loop force-feedback control of sensing electrodes
- Potentially cheaper and more robust than geophones





Summary

- AdvVirgo sensitivity is limited by NN during high seismic activity
- A numerical model incorporating measureable seismic quantities is being developed
- Model will be used in combination with measurements to predict NN and required subtraction parameters
- Seismic networks and sensors under development including MEMS technology