

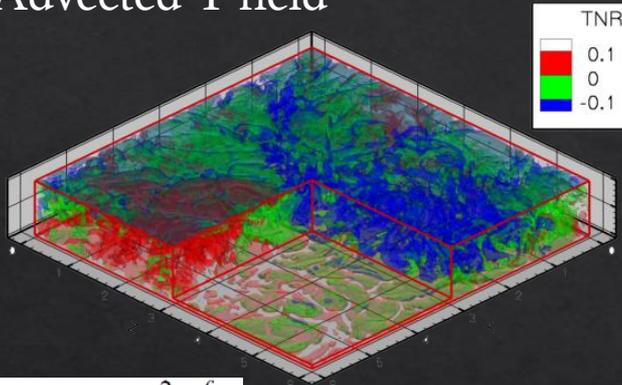
# Newtonian Noise

Jan Harms

Gran Sasso Science Institute (GSSI)  
National Laboratory of Gran Sasso (LNGS)

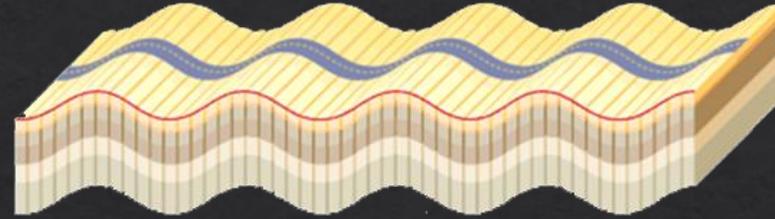
# Main Sources of NN

Advected T field



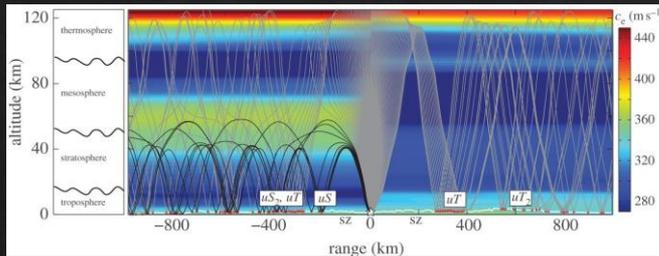
$$\frac{\delta T(f) e^{-\frac{2\pi f r}{v}}}{f^{10/3}}$$

Seismic waves



$$\frac{\xi(f) e^{-\frac{2\pi f h}{c_{\text{hor}}}}}{f^2}$$

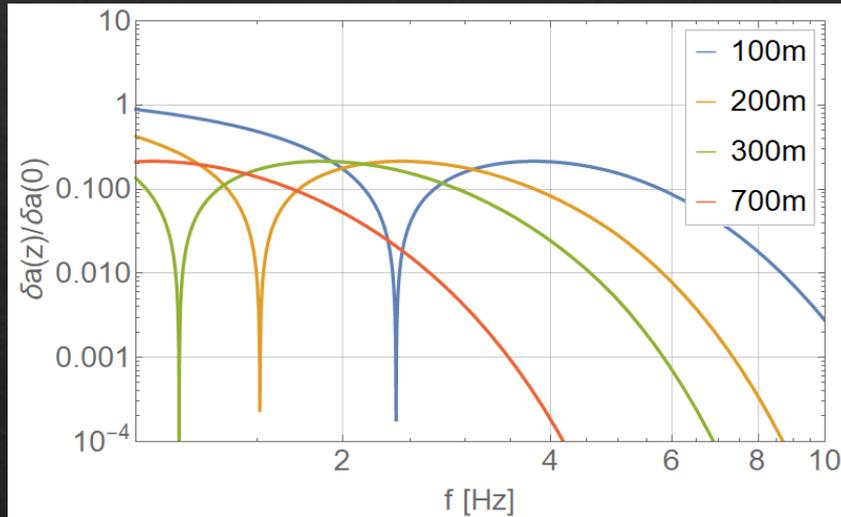
Sound waves



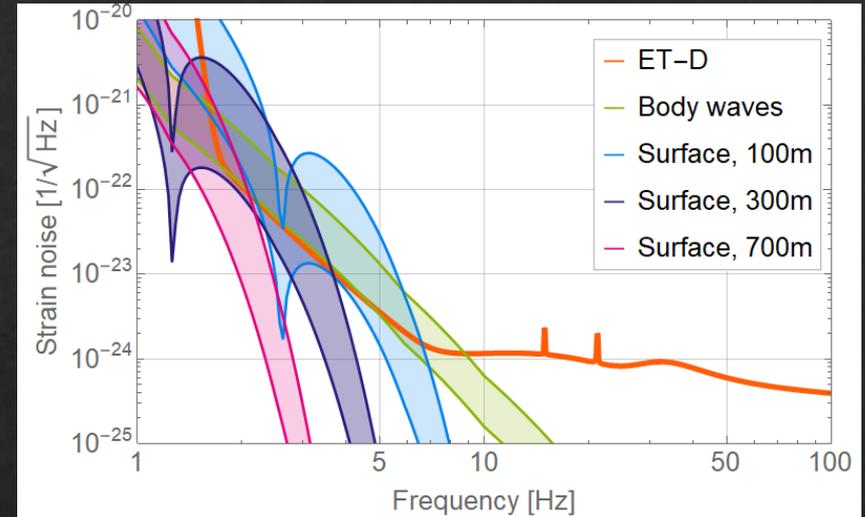
$$\frac{p(f) e^{-\frac{2\pi d f}{c_{\text{hor}}}}}{f^3}$$

- Whenever something follows a **rectilinear** motion, then you get an exponential cut-off in the form:  $\exp(-2*\pi*f*x/c)$
- Examples: sound and seismic waves, advected fields, moving objects, flowing water

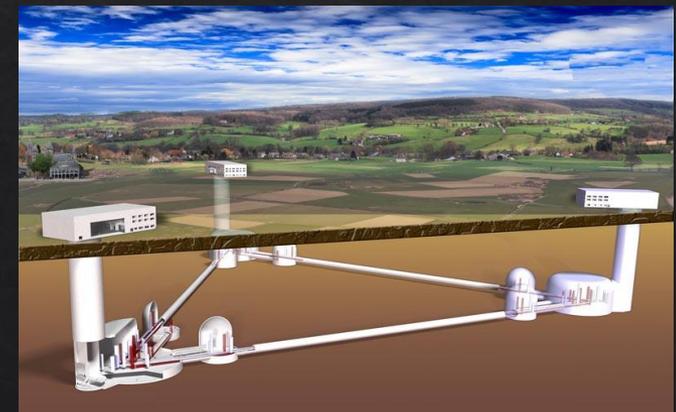
Rayleigh NN reduction



ET NN



- Seismic models:  
Body wave: 3x – 12x LNM, Surface: 50x – 1000x LNM
- Rayleigh dispersion model:  
1.8km/s @ 1Hz @ 400m/s @ 10Hz
- Includes contributions from cavity-wall displacement
- Homogeneous half space (except for Rayleigh dispersion)

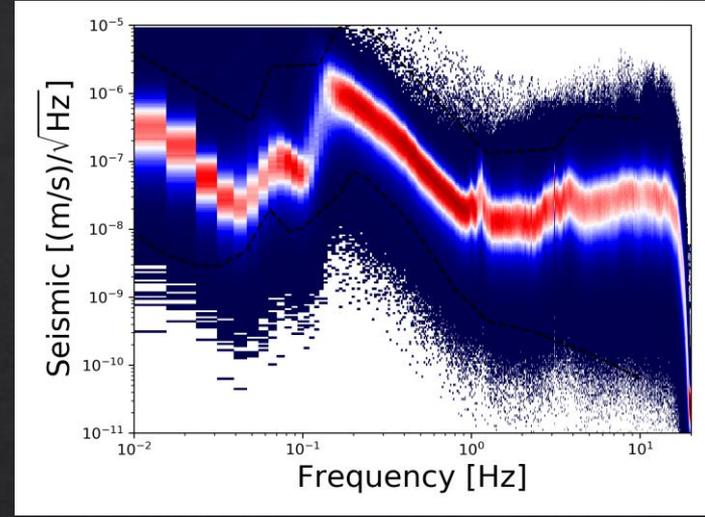
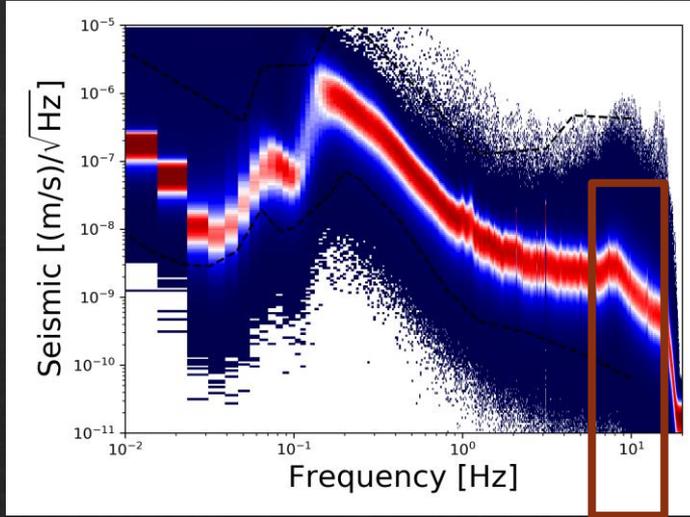


# Examples Limburg Region

Heimansgroeve

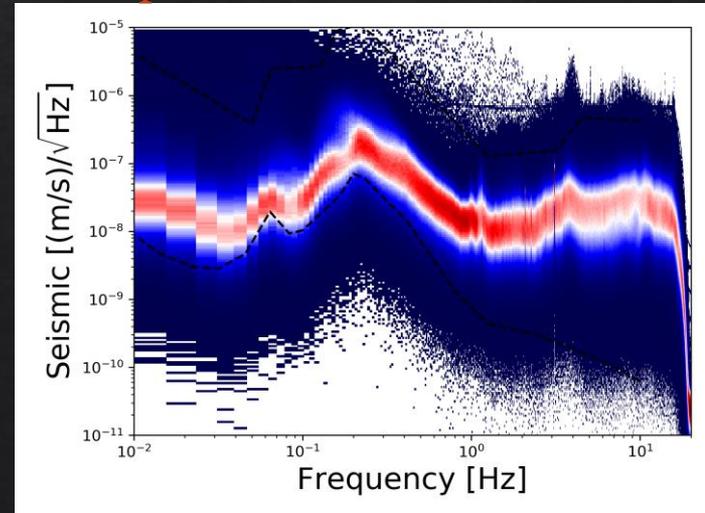
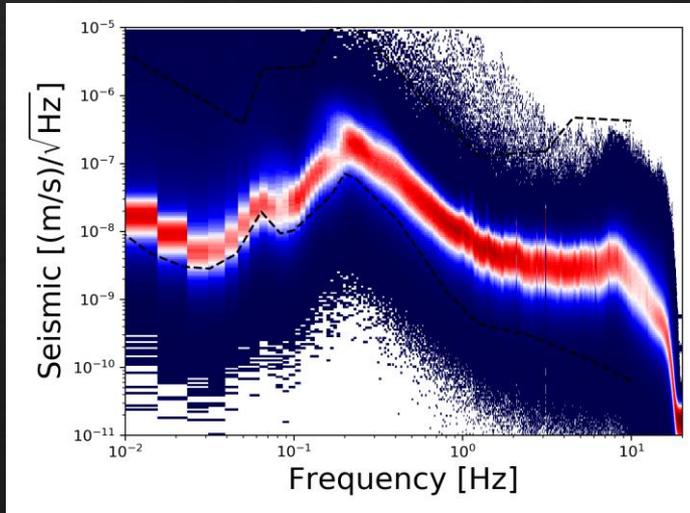
Mamelis

Winter



Flat when correcting for response

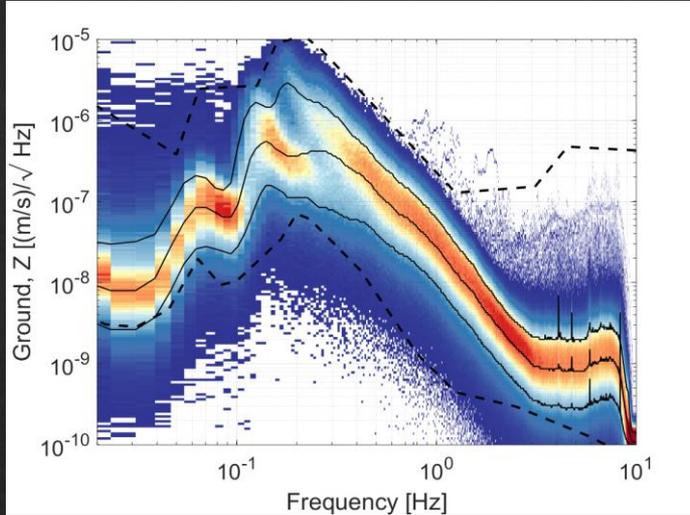
Summer



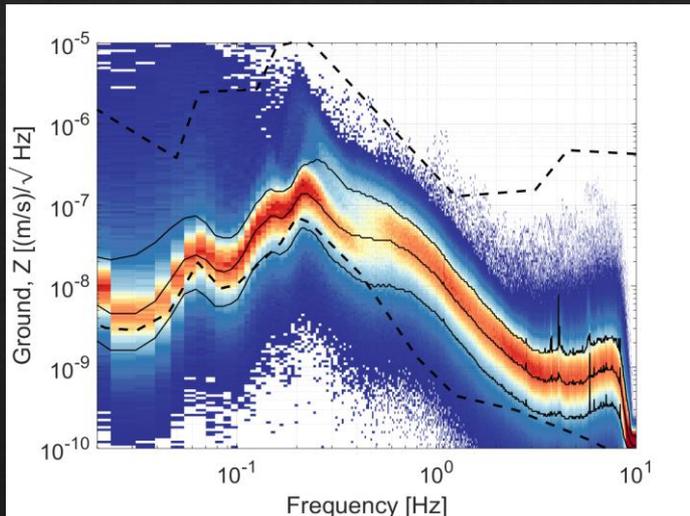
# Example Sardinia

## Villasalto

Winter

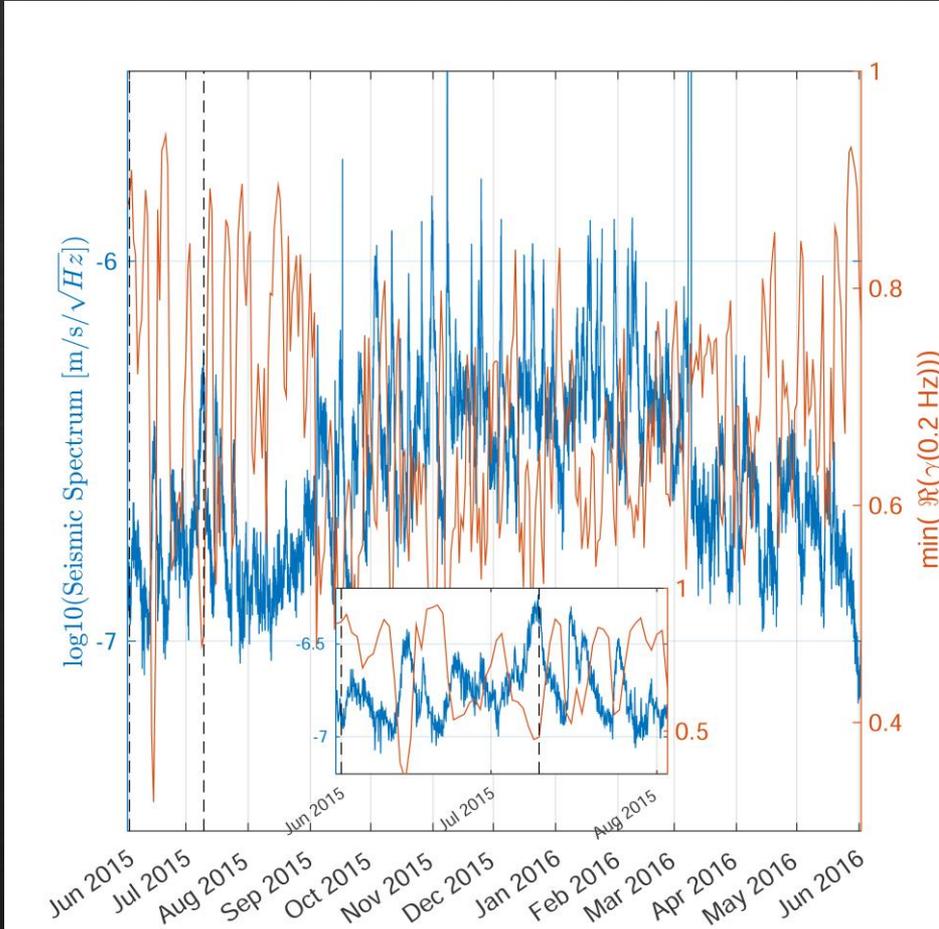


Summer

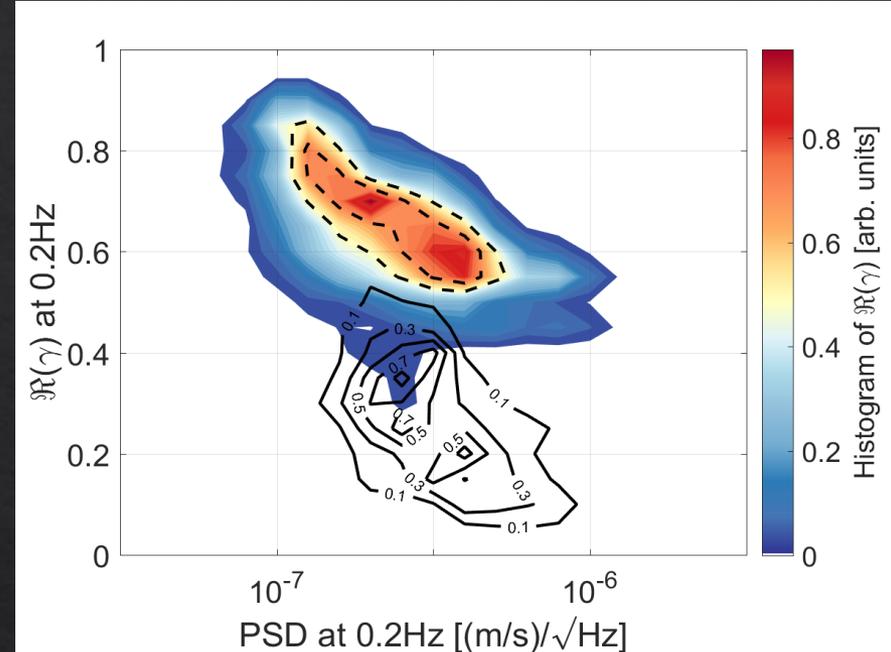


Oceanic microseismic are relatively high nearby (and probably at) the two ET candidate sites.

Sardinia is extremely quiet above a few Hz even at the surface.



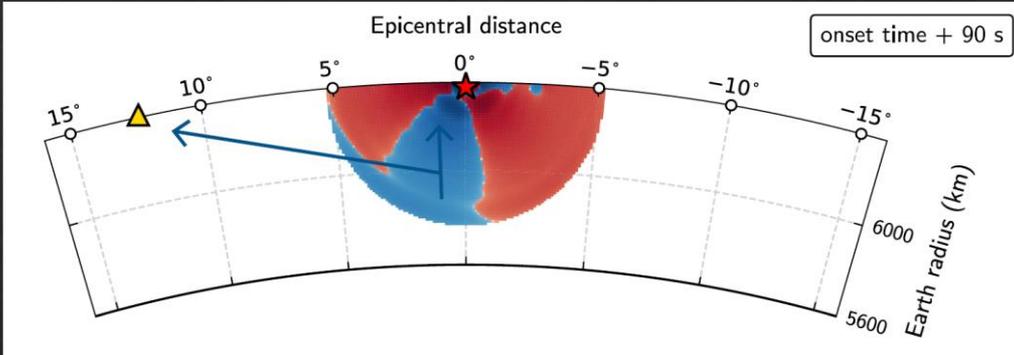
Coughlin et al, 2018



Suggested explanation:

- 1) When oceanic microseisms are strong, then the sources are relatively close and Rayleigh waves dominate
- 2) If microseisms are near the low-noise model, then many distant sources contribute and body waves dominate

# Fundamental Limit of NN Cancellation



Juhel et al, 2018

The prompt effect of the changing gravity field is to put the entire local system (ground, sensor, test mass) into free fall. Only at a later time, elastic back-reaction causes a significant signal.

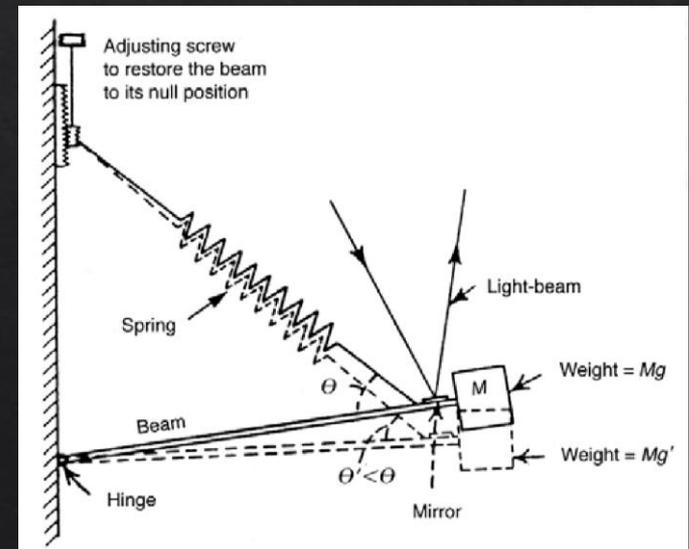
Freeman Dyson was the first to apply the equivalence principle to elastodynamics, concluding that the signal of an inertial sensor is described by the equation

$$\rho \partial_t^2 \vec{u}(\vec{r}, t) = \nabla \cdot (\mathbf{C}(\vec{r}) : \boldsymbol{\eta}(\vec{r}, t)) + 2(\nabla \mu(\vec{r})) \cdot \mathbf{h}(\vec{r}, t)$$

Seismic sources produce (slowly) propagating seismic waves, and prompt gravity change everywhere.

Gravity change induces ground motion

$$\rho \partial_t^2 \vec{\xi}(\vec{r}, t) = \nabla \cdot \boldsymbol{\sigma}(\vec{r}, t) - \rho \nabla \phi(\vec{r}, t)$$

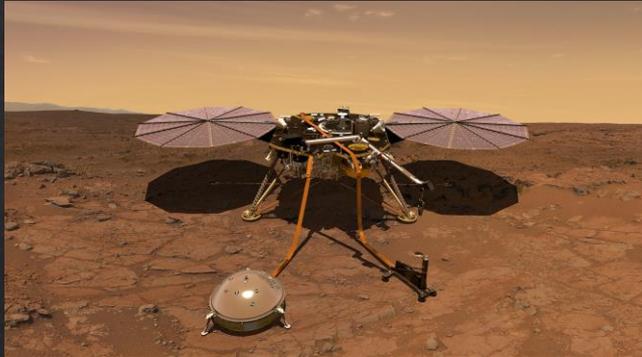


Inertial sensor

# InSight Lander



Broadband seismometer



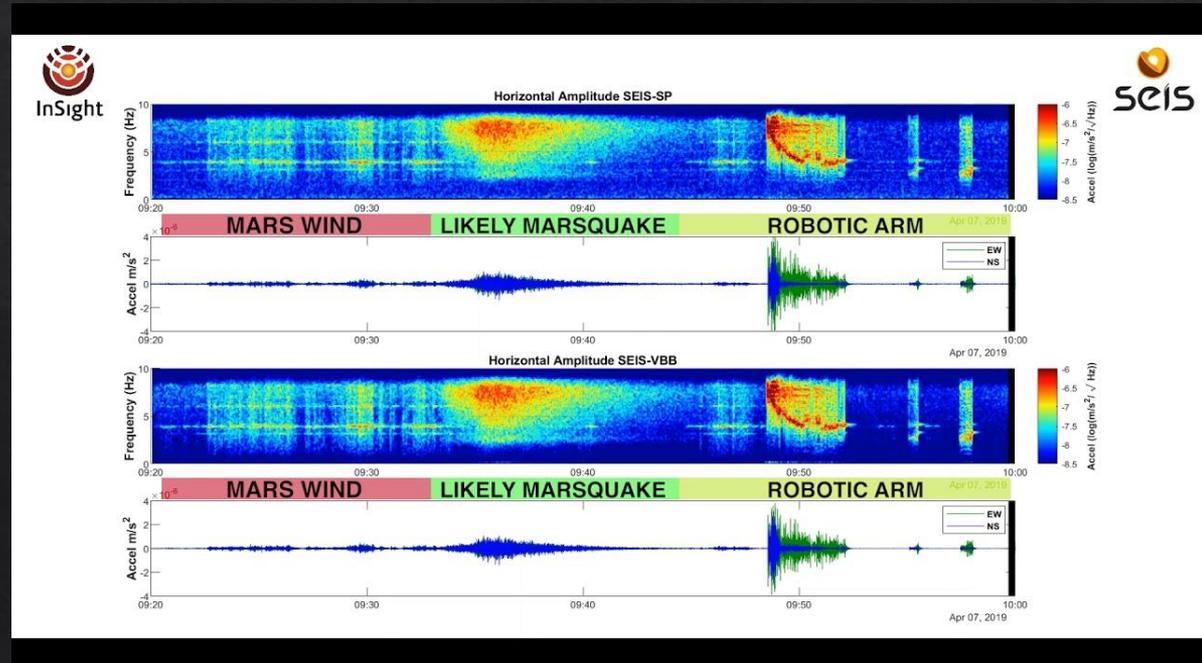
Weber's failed GW detector



Lunar surface gravimeter

Unknown how they filtered data, but it seems that:

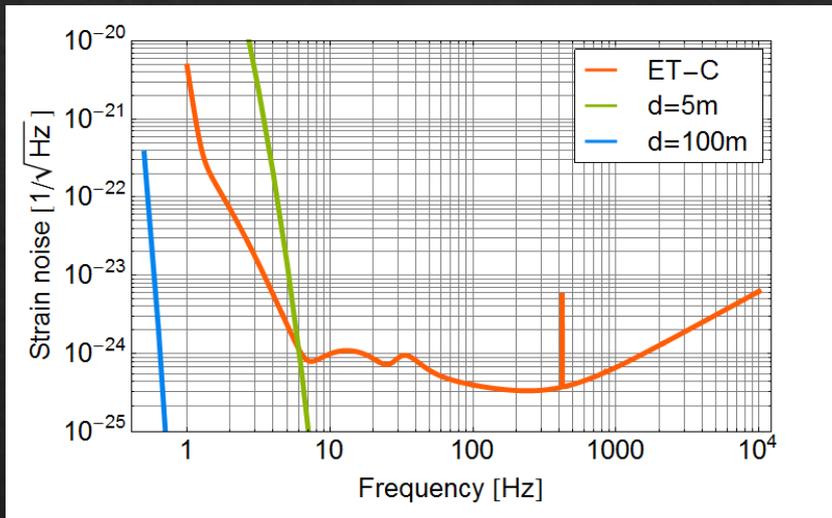
- 1) High-f Rayleigh waves are faster than the low-f waves
- 2) Without wind noise, it is extremely quiet (unexpectedly quiet for me)
- 3) Unexpectedly good conditions to observe GWs



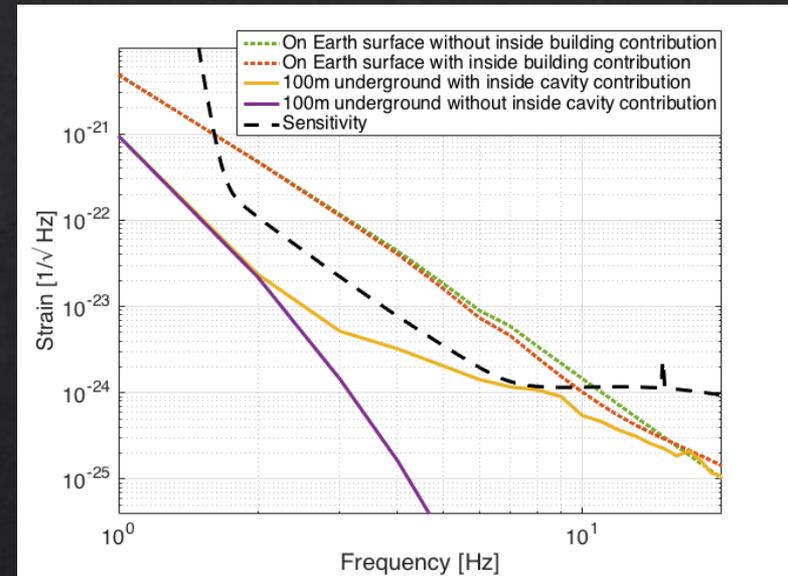
# ET Atmospheric NN

## Temperature NN

Uniform air flow,  $v=20\text{m/s}$  (very fast)



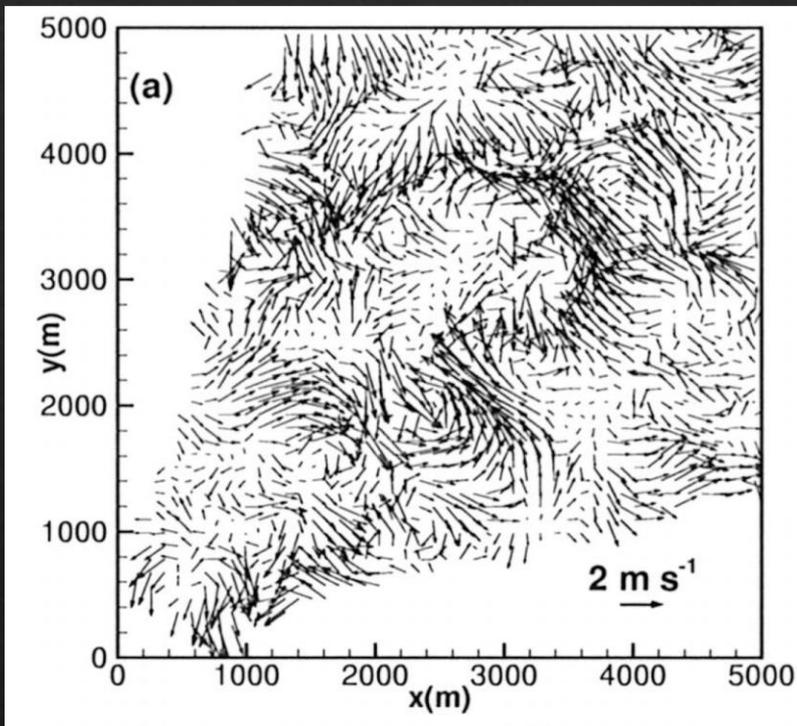
## Infrasound NN



- Atmospheric NN limits sensitivity of ET-type detectors if built at the surface
- Going underground very efficiently suppresses atmospheric NN
- Atmospheric NN will be extremely challenging to cancel

Current LIDAR systems are able to monitor, among others, wind speeds, and temperature or humidity fields.

## Volumetric Doppler scans with LIDAR



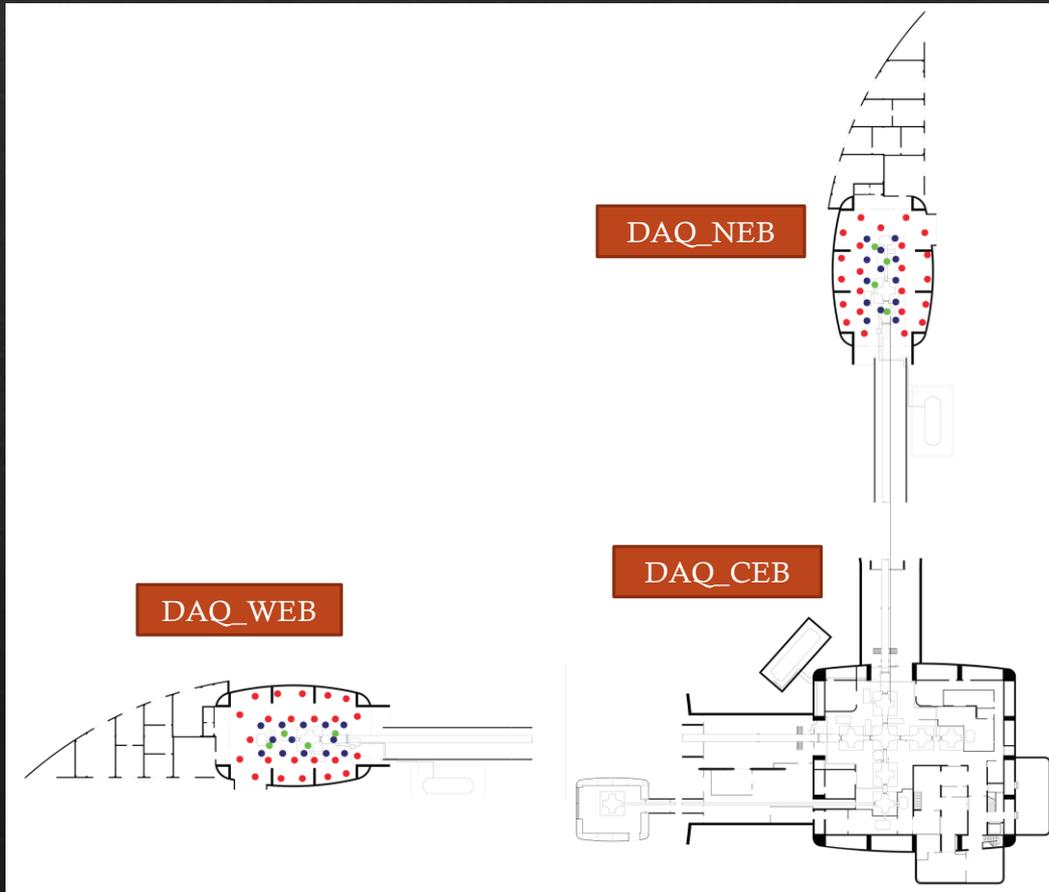
Chai et al, 2004

In principle, technology is ready to cancel atmospheric NN from advection.

LIDAR is not sensitive enough yet (by some orders of magnitude) to sense pressure fluctuations.



# Sketch of a NNC System



Seismic arrays deployed around test masses at all three stations.

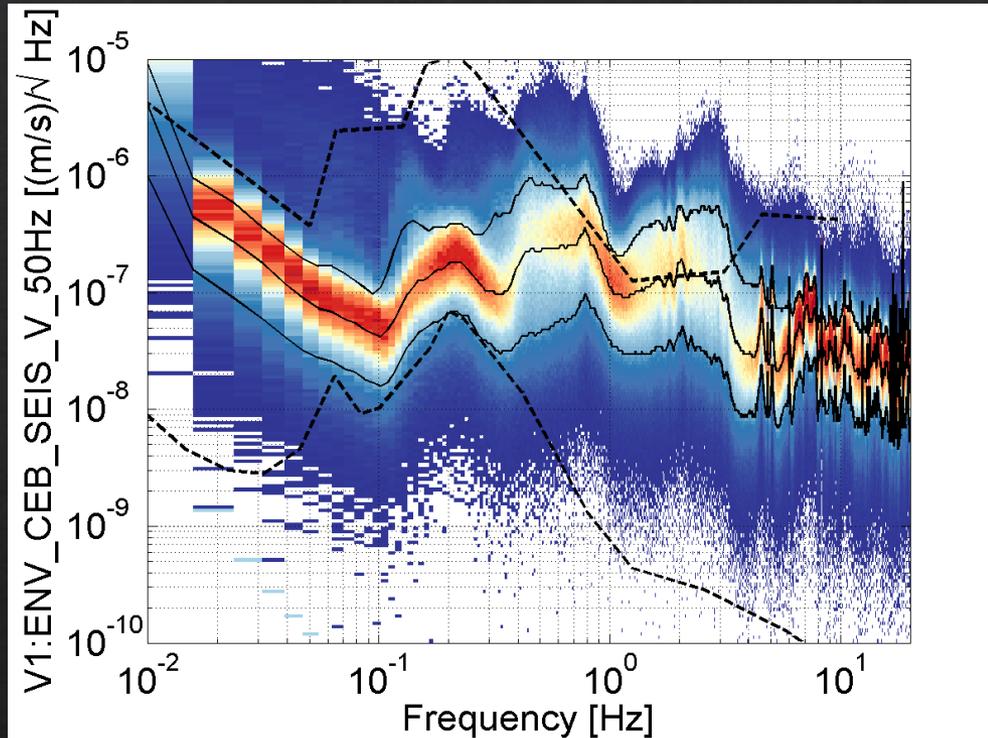
All channels passed through an optimal linear filter with a single-channel output.

Output subtracted offline from GW data.

# Virgo Seismic Noise



## Histogram from April, 2017



Excess NN to be avoided



Chillers



Credit: I Fiori

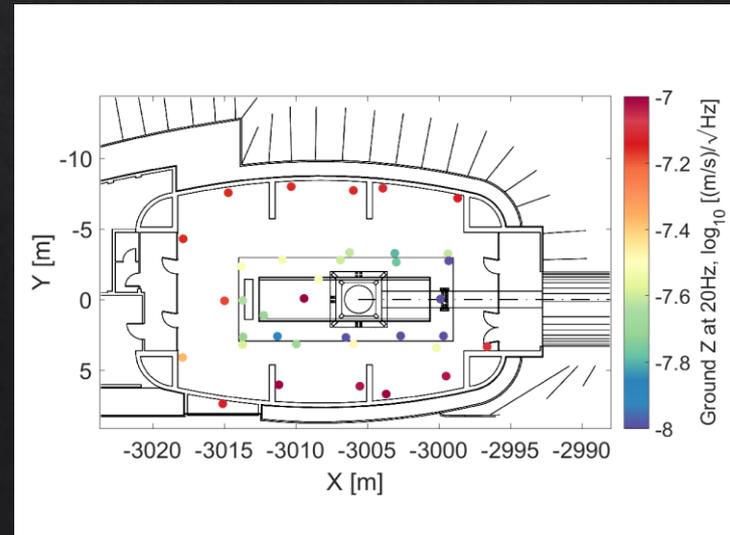
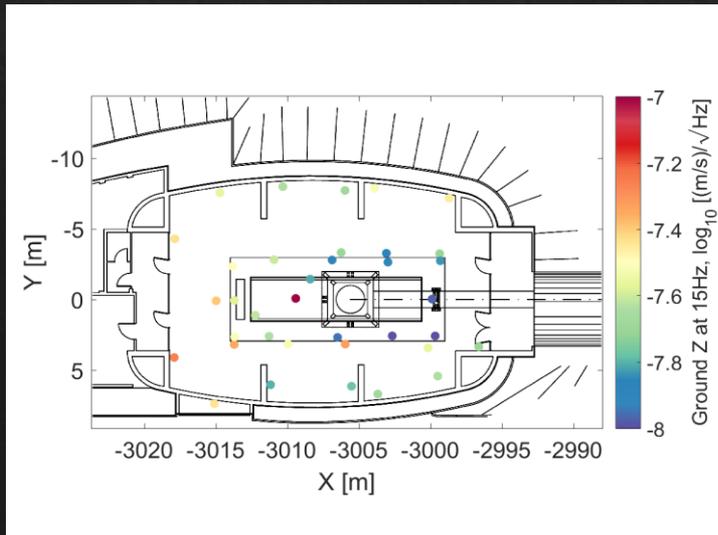
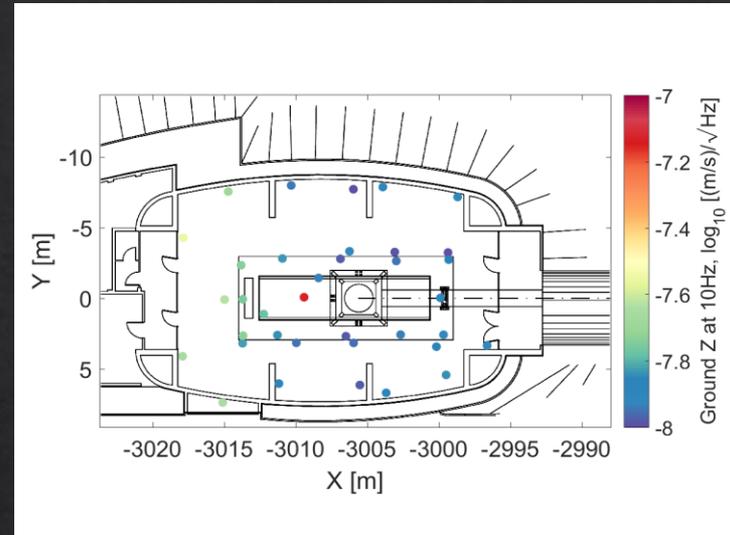
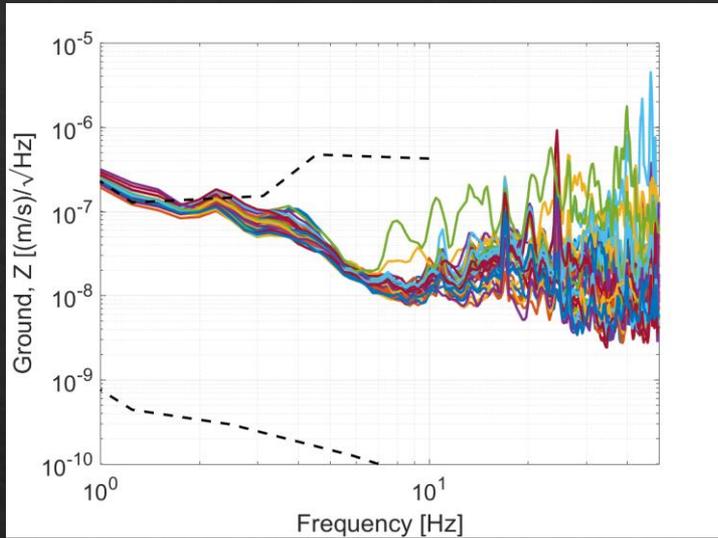


Ventilation

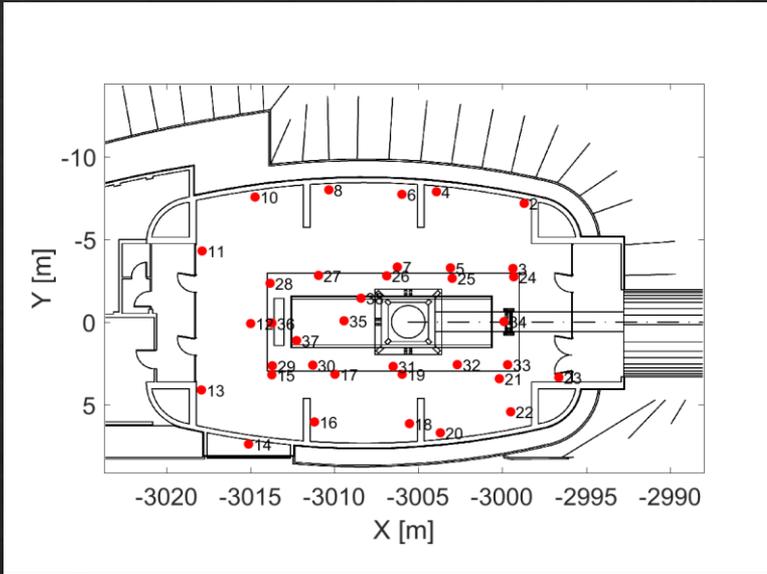


Vacuum pumps

# Seismic Noise at Virgo

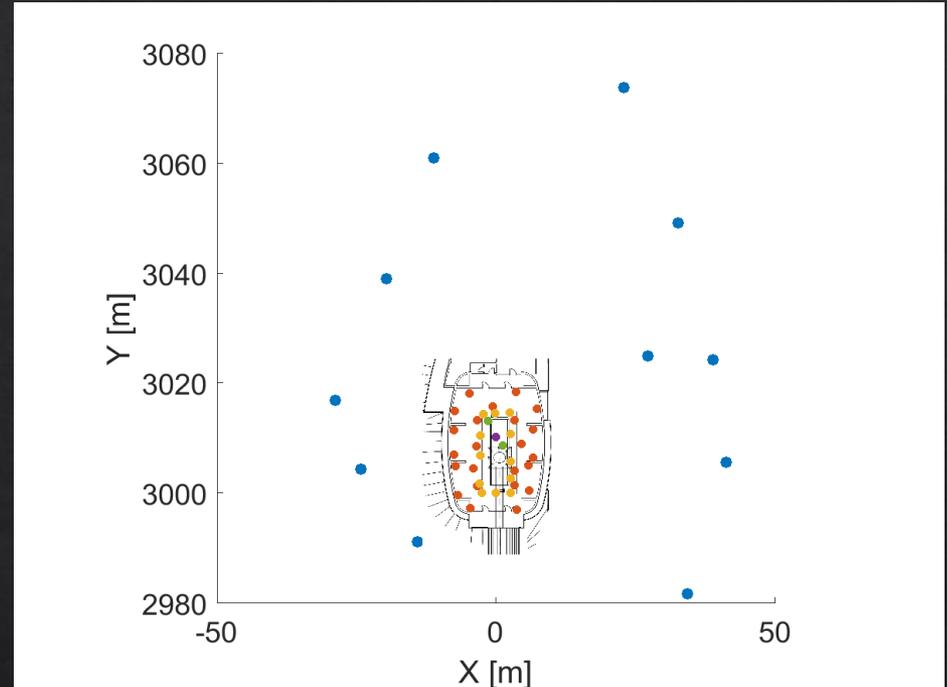


WEB (2018)



5 days of good-quality data.

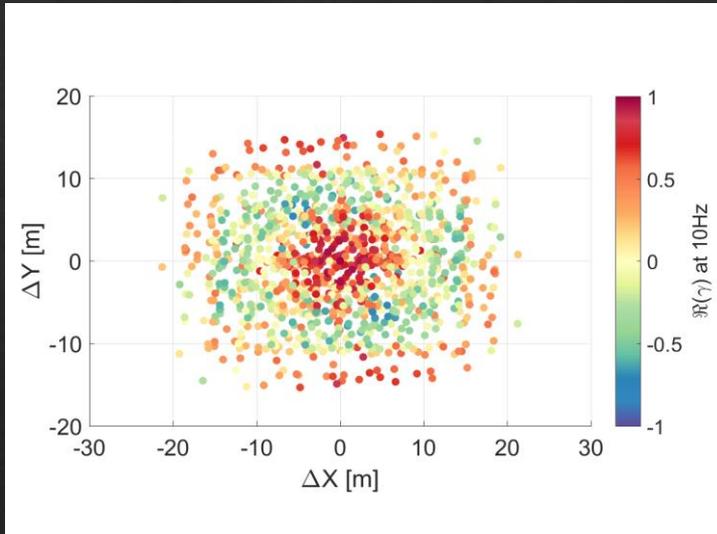
NEB (2019)



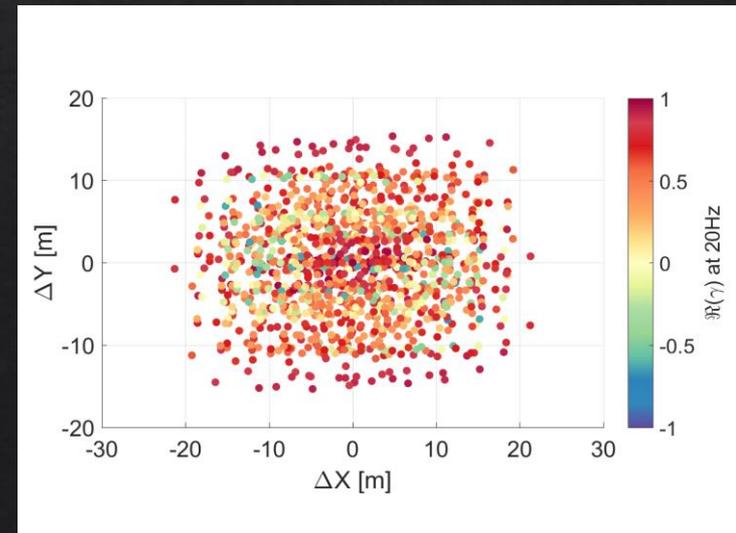
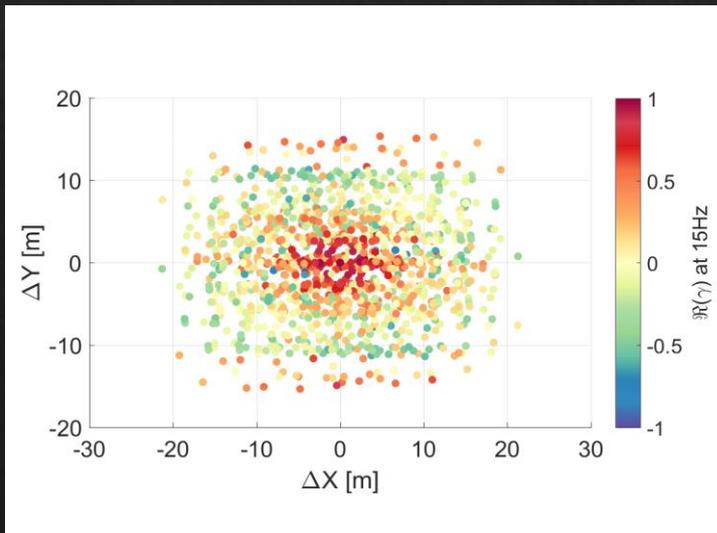
Hopefully a few weeks of good-quality data also with locked interferometer.

Outdoor sensors can be included this time due to improved position measurement.

# Seismic Correlations at Virgo

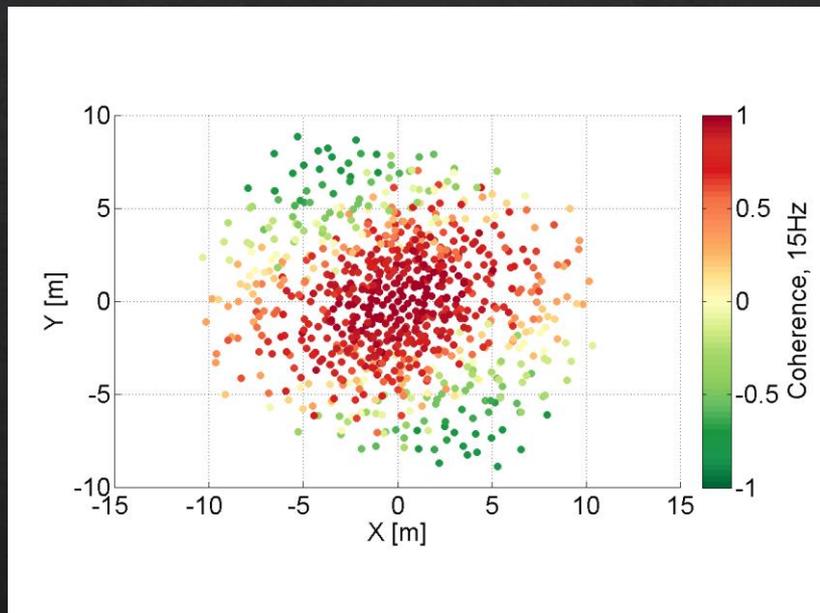


- Correlation map at 10Hz is close to expectation from simple models
- 15Hz correlations do not fit simple models, and it looks as if seismic speeds are higher than at 10Hz
- 20Hz correlations are a mess

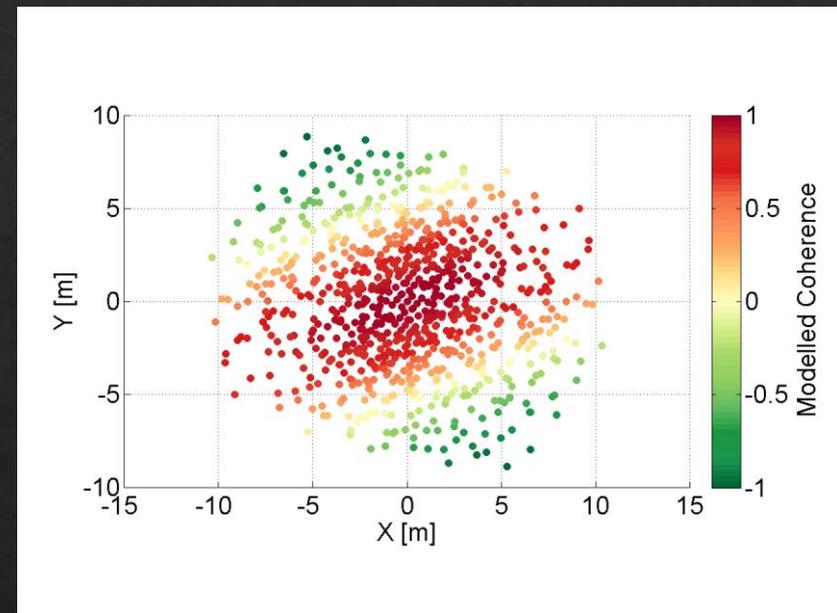




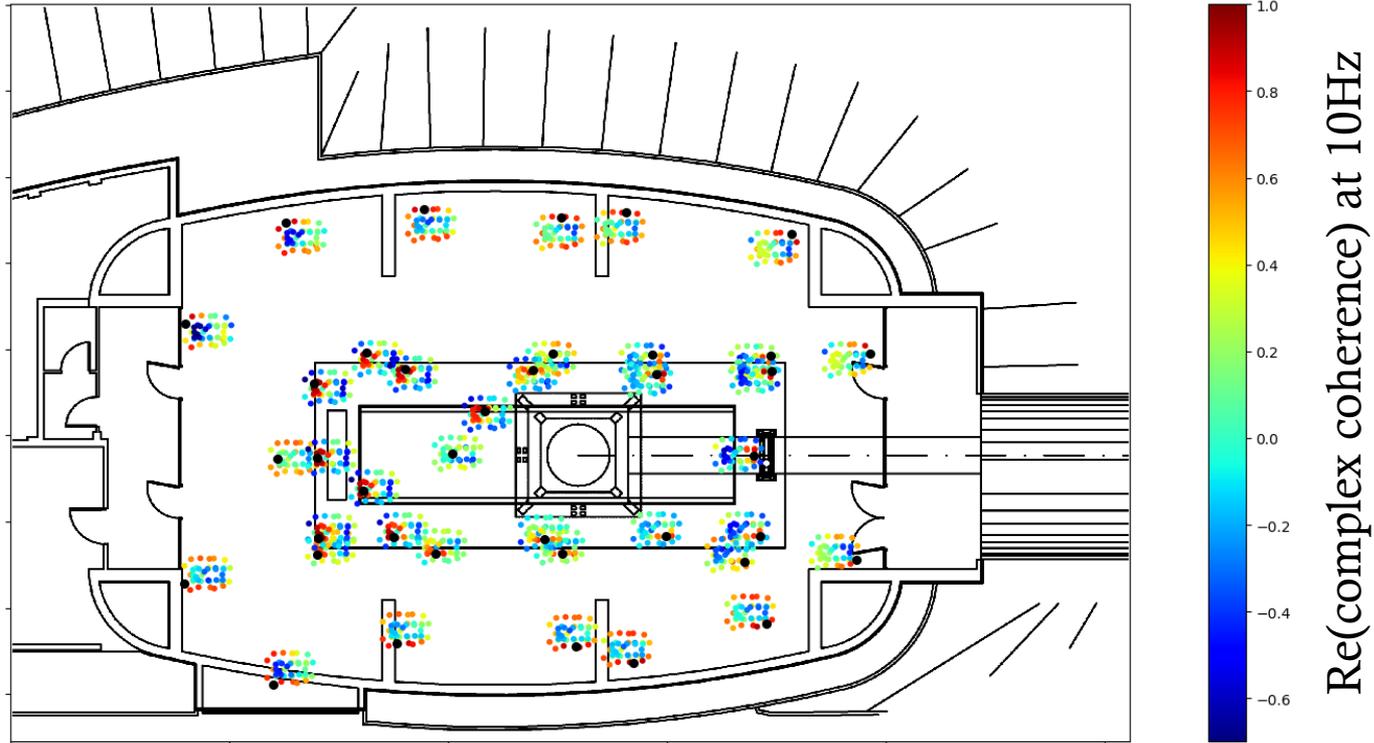
Observed



Modeled



- ◆ Observed correlations are close to a perfect match with an anisotropic plane Rayleigh-wave model of the seismic field
- ◆ This is likely a consequence of a very simple infrastructure (no poles, no sub-surface lab space, uniform concrete slab).



Array optimization will be done by GSSI group using standard surrogate-modeling techniques, based on observed seismometer correlations.

Fourier transform of two-point spatial correlation gives spectral density:  
(defined for homogeneous, stationary fields)

$$S(\vec{k}, \omega) = \int d^2r \mathcal{C}(\vec{r}, \omega) e^{-i\vec{r} \cdot \vec{k}}$$

Estimate of spectral density using correlation between seismometer pairs:

$$p(\vec{k}, \omega) = \sum_{i,j=1}^N \mathcal{C}(\vec{r}_i, \vec{r}_j, \omega) e^{-i\vec{k} \cdot (\vec{r}_j - \vec{r}_i)}$$

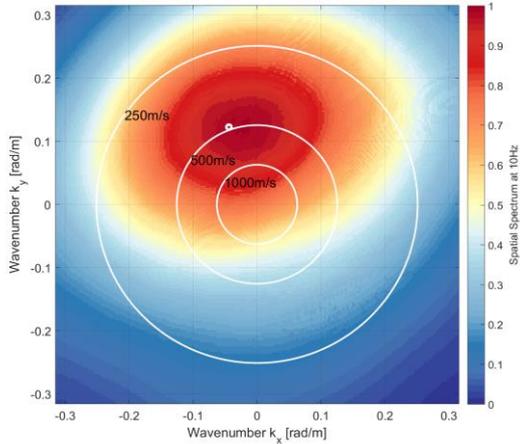
Neglects areal weights, but this is OK since the optimal weights

- depend on the spectrum that you expect
- depend on the array configuration

Many alternative methods of estimating the spectrum exist.

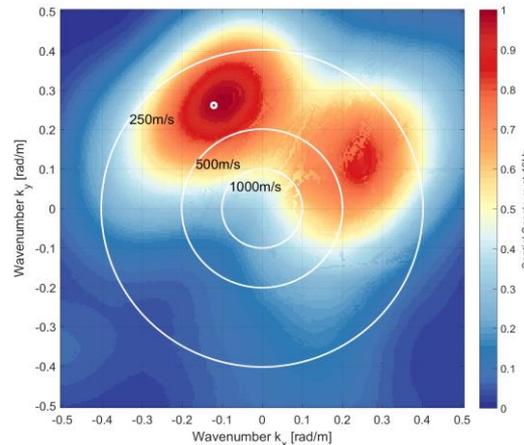
# Spatial Spectral Density

10Hz

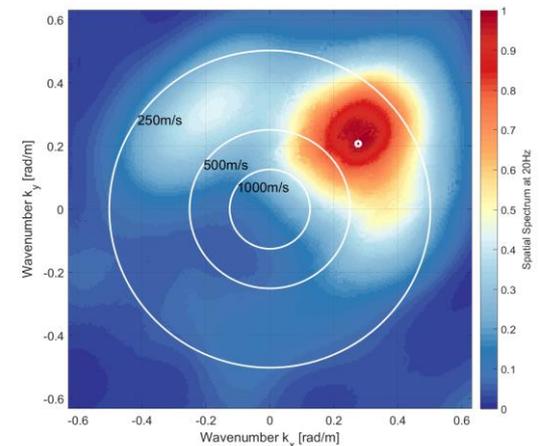


At most frequencies, one Rayleigh wave dominates.

16Hz

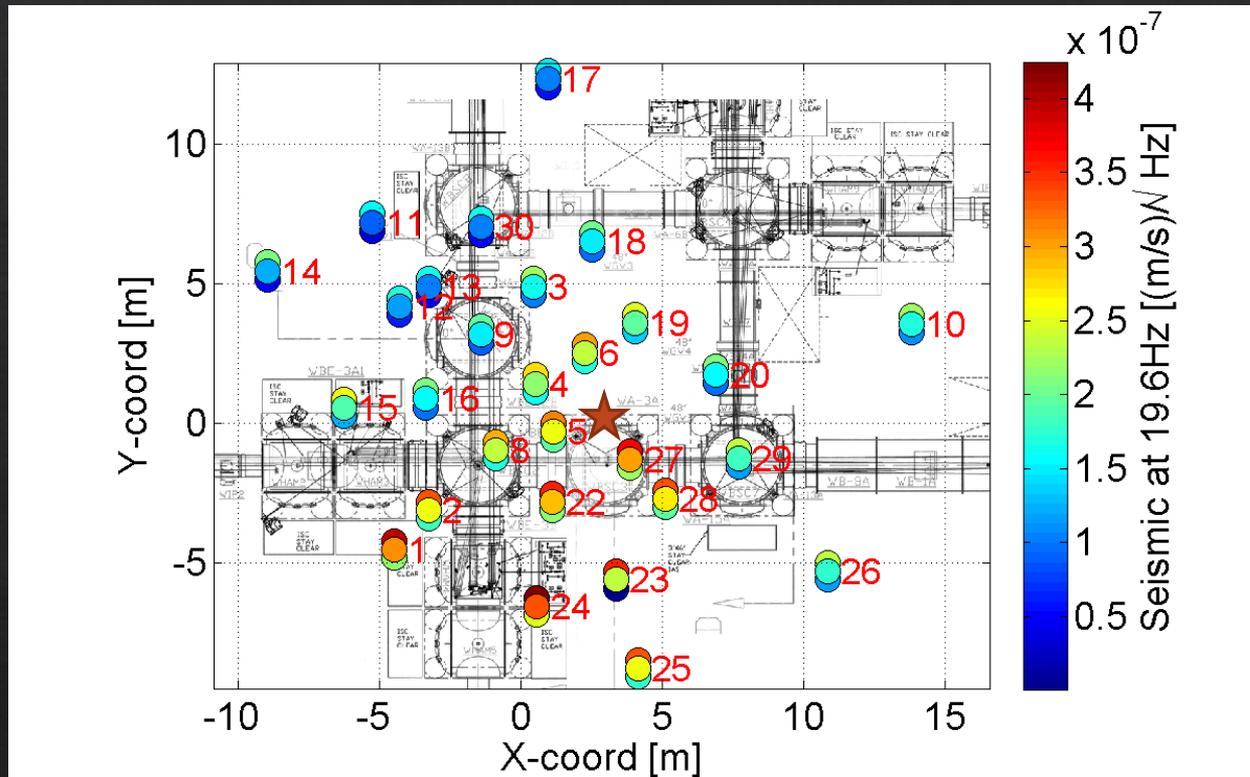


20Hz



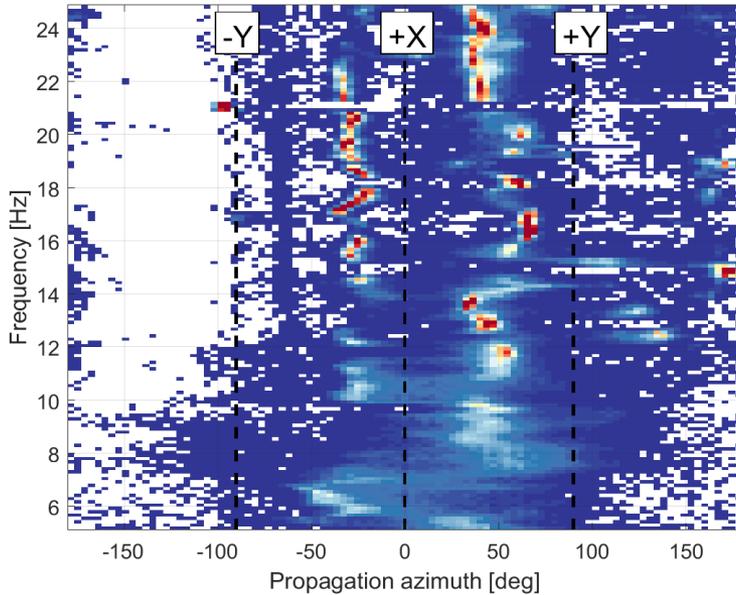
Wave-vector resolution of speed and azimuth measurements improves towards higher frequencies.

# LHO Array

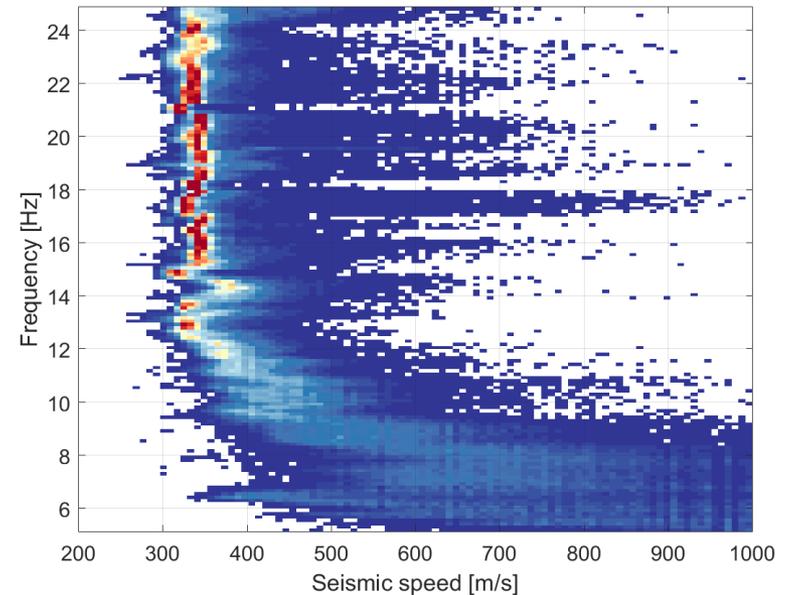


★ Tiltmeter

# Histograms from Maximum Spectral Density



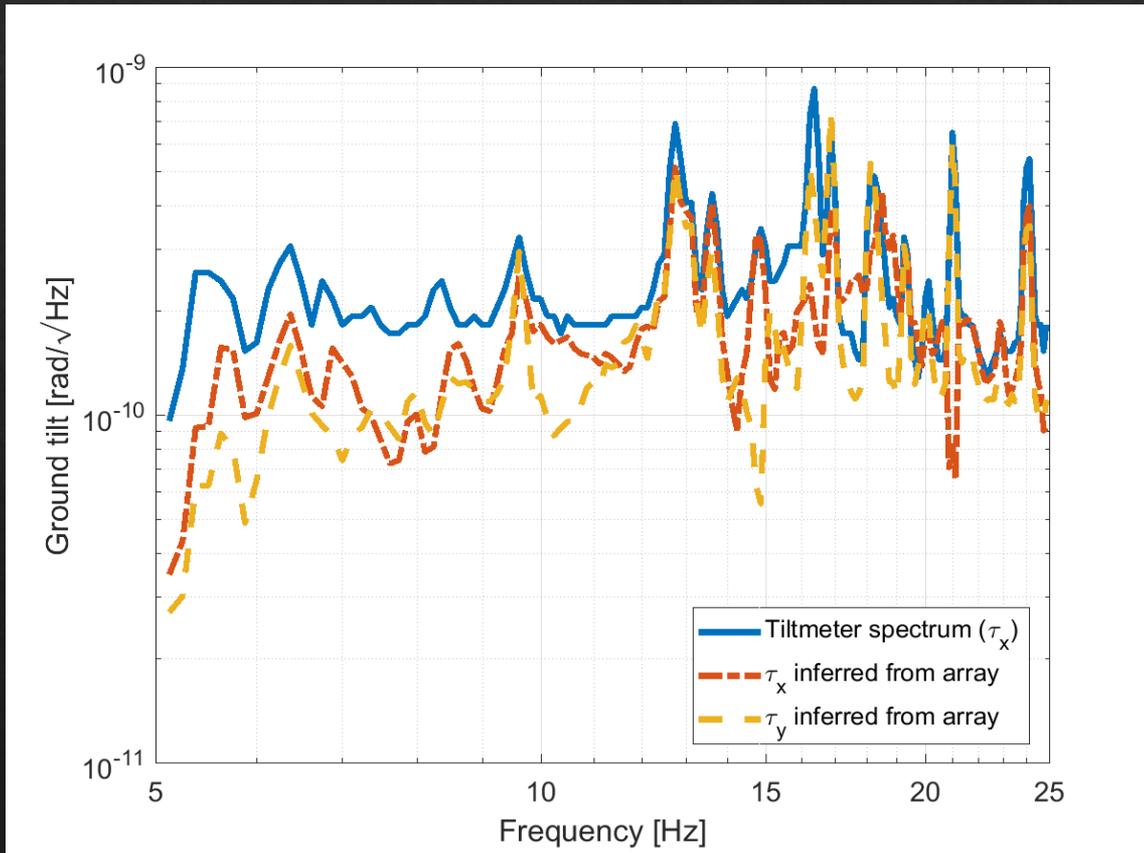
Few seismic sources produce the dominant Rayleigh waves in the NN band.



Initial indication of anomalous dispersion not confirmed, but clear indication of normal dispersion below 13 Hz.

# Tilt Spectrum

$$\langle |\tau_x(\omega)|^2 \rangle = \langle k^2 \cos^2(\phi) |\xi_z(\omega, \vec{k})|^2 \rangle$$



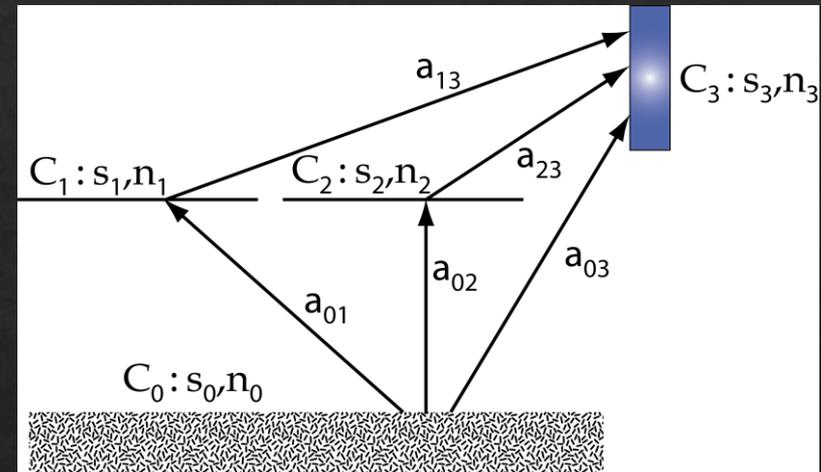
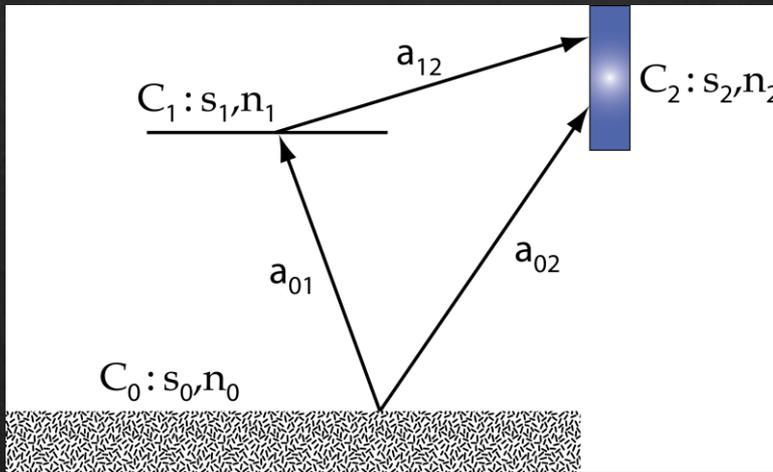
The array-inferred tilt spectrum is consistent with tiltmeter spectrum only if multiplied by 2...

The match is less good at low frequencies due to inaccurate speed measurements.

Above 13Hz, larger mismatch between tilt spectra at some frequencies not always easy to explain.

# Cause and Correlation

Links are directional, as is approximately the case in seismic isolation systems (e.g., radiation-pressure noise does not produce significant seismic waves)



$$a_{02} = \frac{\mathcal{T}_{02}(1 - \text{SNR}_1^{-2}) - \mathcal{T}_{01}\mathcal{T}_{12}}{(1 - \text{SNR}_0^{-2})(1 - \text{SNR}_1^{-2}) - |\gamma_{01}|^2}$$

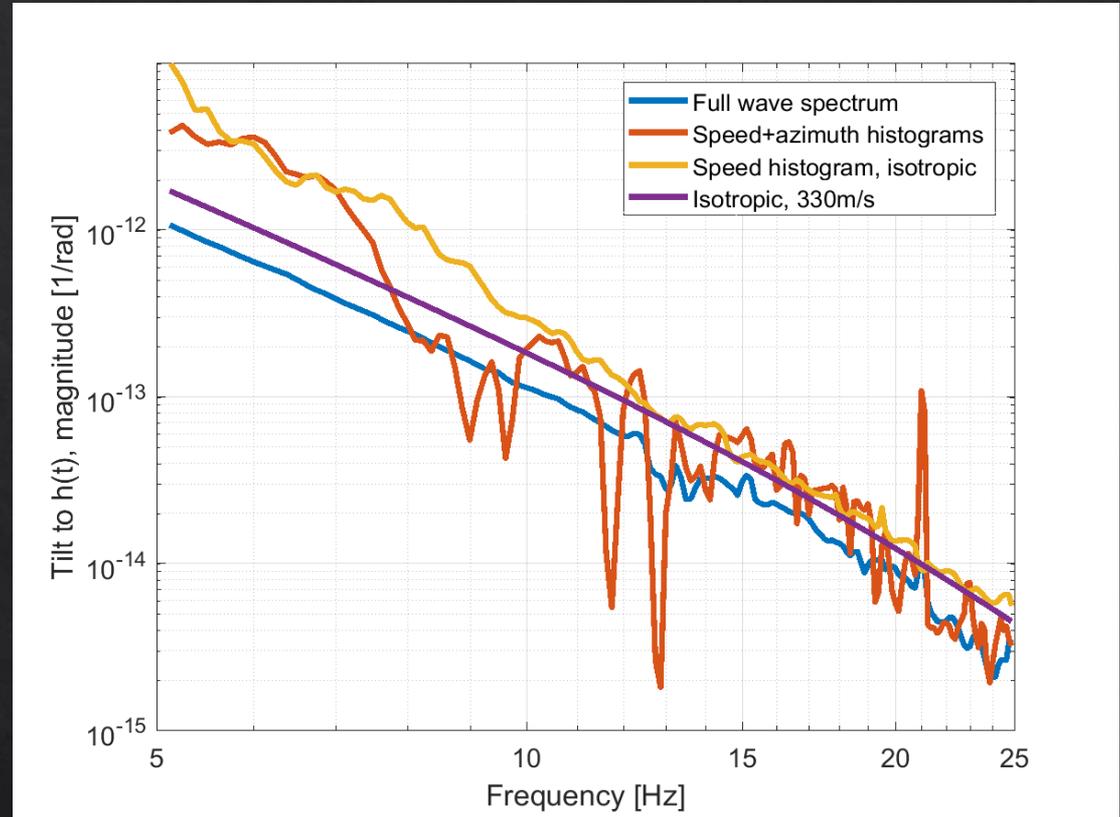
$$a_{03} = \frac{\mathcal{N}_0^2 \mathcal{N}_1 \mathcal{N}_2 - |\gamma_{01}|^2 |\gamma_{02}|^2}{\mathcal{N}_0 (\mathcal{N}_0 \mathcal{N}_1 - |\gamma_{01}|^2) (\mathcal{N}_0 \mathcal{N}_2 - |\gamma_{02}|^2)} \mathcal{T}_{03} - \frac{\mathcal{T}_{01} \mathcal{T}_{13}}{\mathcal{N}_0 \mathcal{N}_1 - |\gamma_{01}|^2} - \frac{\mathcal{T}_{02} \mathcal{T}_{23}}{\mathcal{N}_0 \mathcal{N}_2 - |\gamma_{02}|^2}$$

Transfer function

Complex coherence

# Tilt to $h(t)$ Models

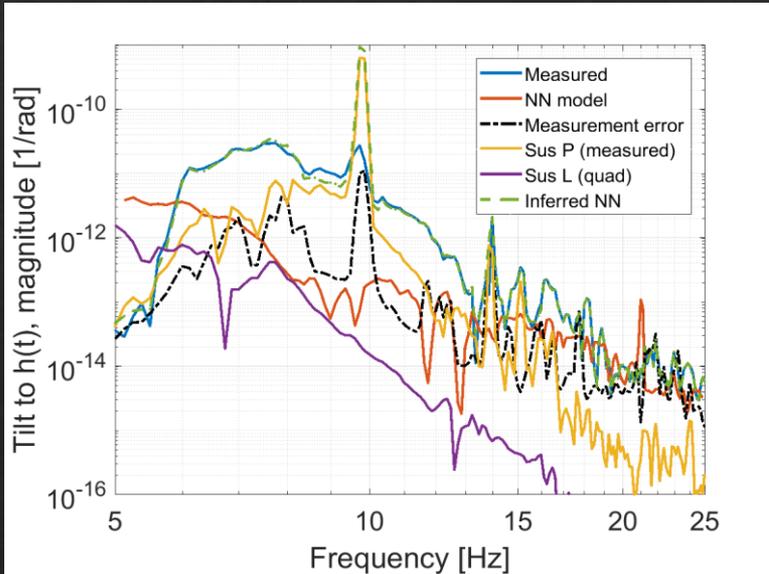
There are significant differences between averages that only use the maximum mode, and the entire wave-vector spectrum.



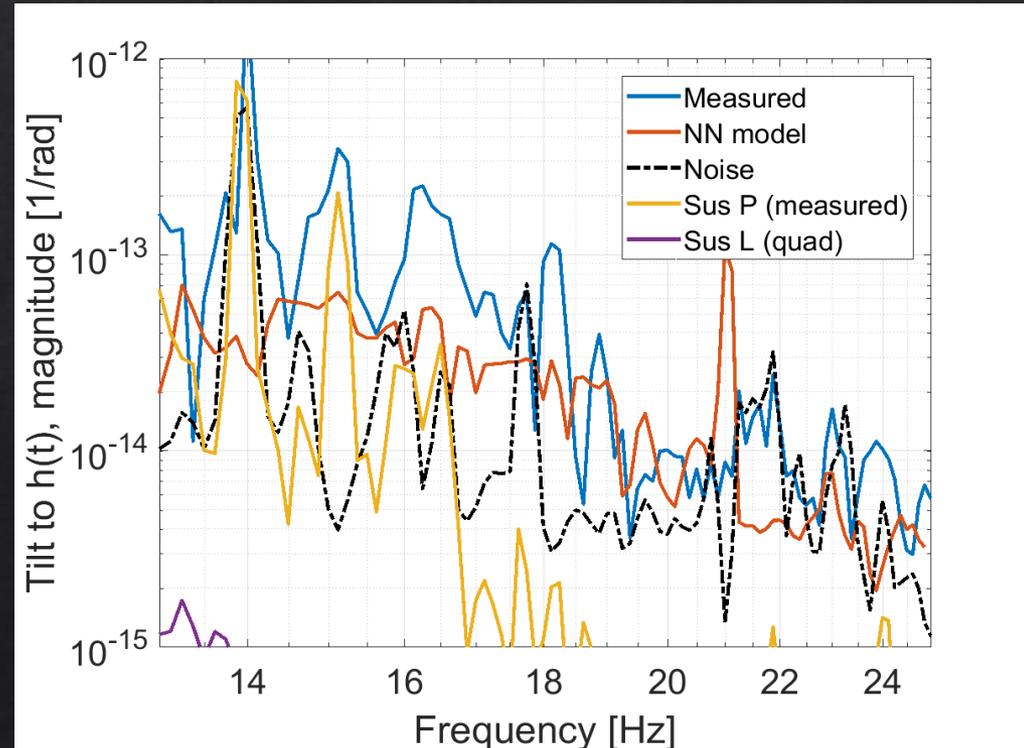
$$\frac{\langle \tau_x(\omega) h^*(\omega) \rangle}{\langle |\tau_x(\omega)|^2 \rangle} = \frac{2\pi G \rho_0 \gamma}{L \omega^2}$$

$$\frac{\langle |\xi_z(\vec{k})|^2 k e^{-hk} (\cos^2(\phi) e^{i\vec{k} \cdot \delta \vec{r}_X} - \sin(\phi) \cos(\phi) e^{i\vec{k} \cdot \delta \vec{r}_Y}) \rangle}{\langle |\xi_z(\vec{k})|^2 k^2 \cos^2(\phi) \rangle}$$

# Coupling Measurement



Gravitational coupling model does not match observation very well, and at some frequencies, the mismatch is large enough to require a reinvestigation of NN models for LIGO.



Anything going through the suspension table cannot explain the transfer function from ground tilt to  $h(t)$ .