Deep Underground Environmental Studies for 3rd Generation Gravitational-Wave Detectors

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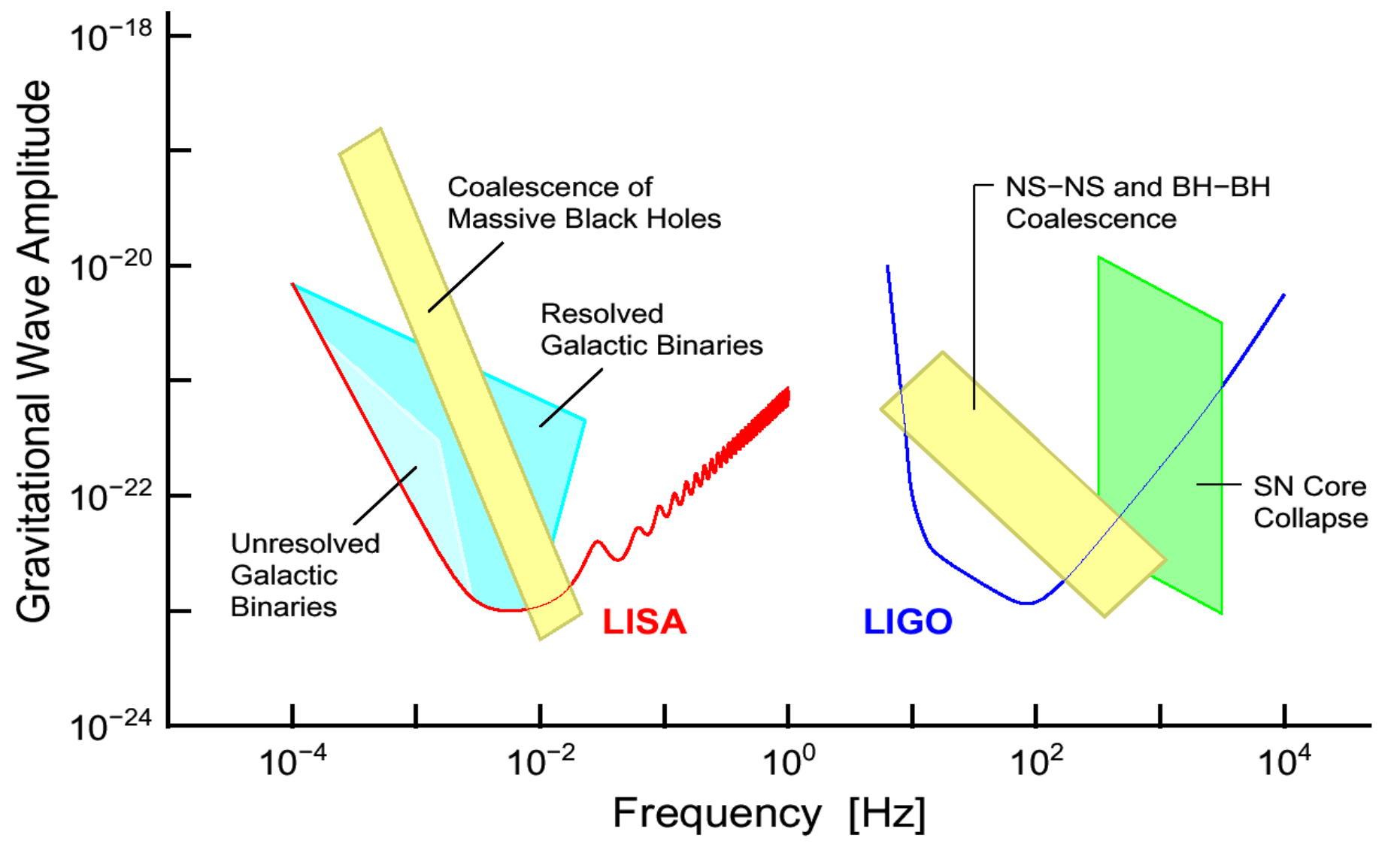
Scientific Motivation: Probing the 0.1-10 Hz band



The 0.1-10 Hz band is not accessible to the current ground based gravitational-wave detectors (LIGO, Virgo).

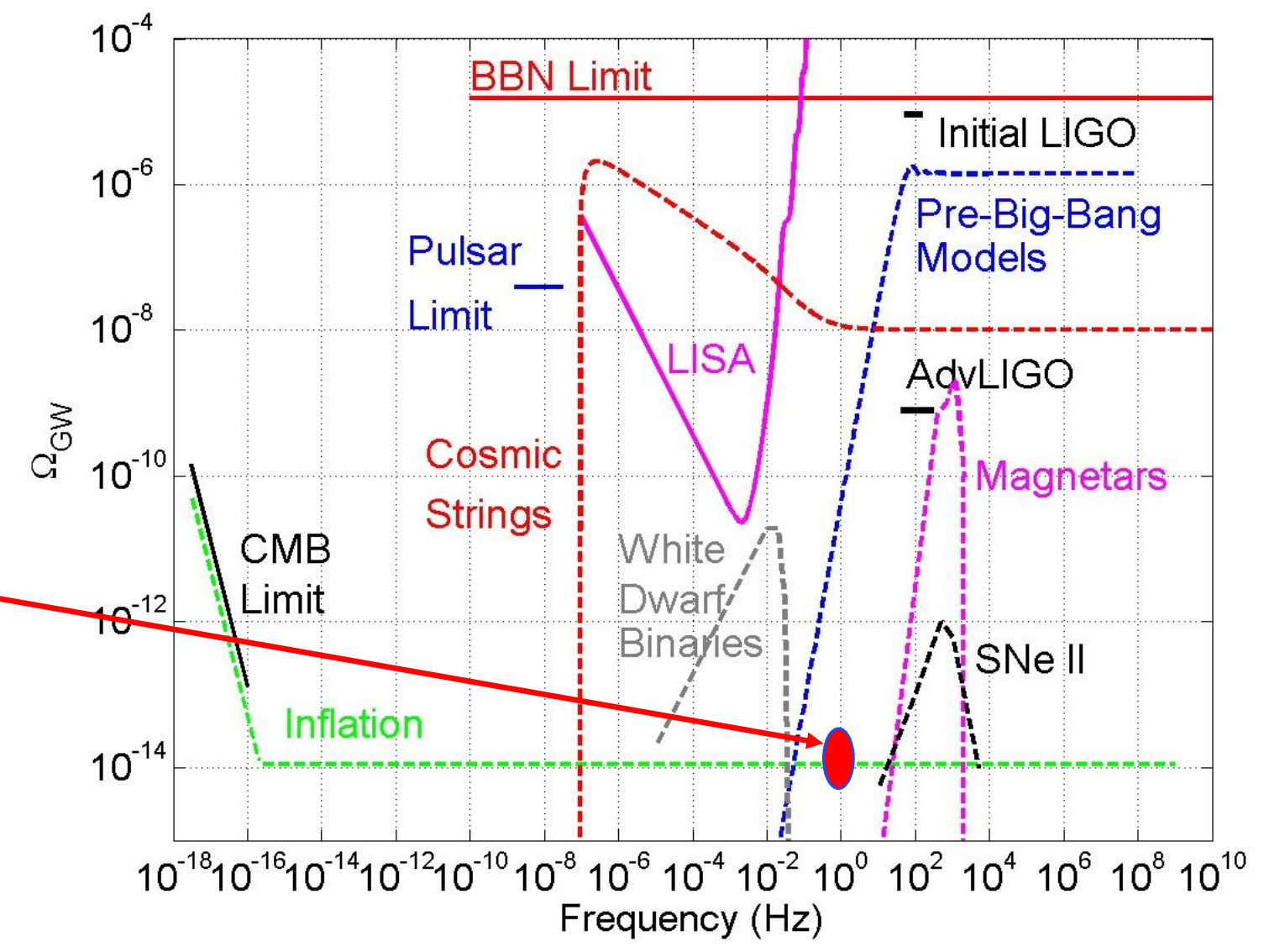
A variety of gravitational-wave sources are expected in this band.

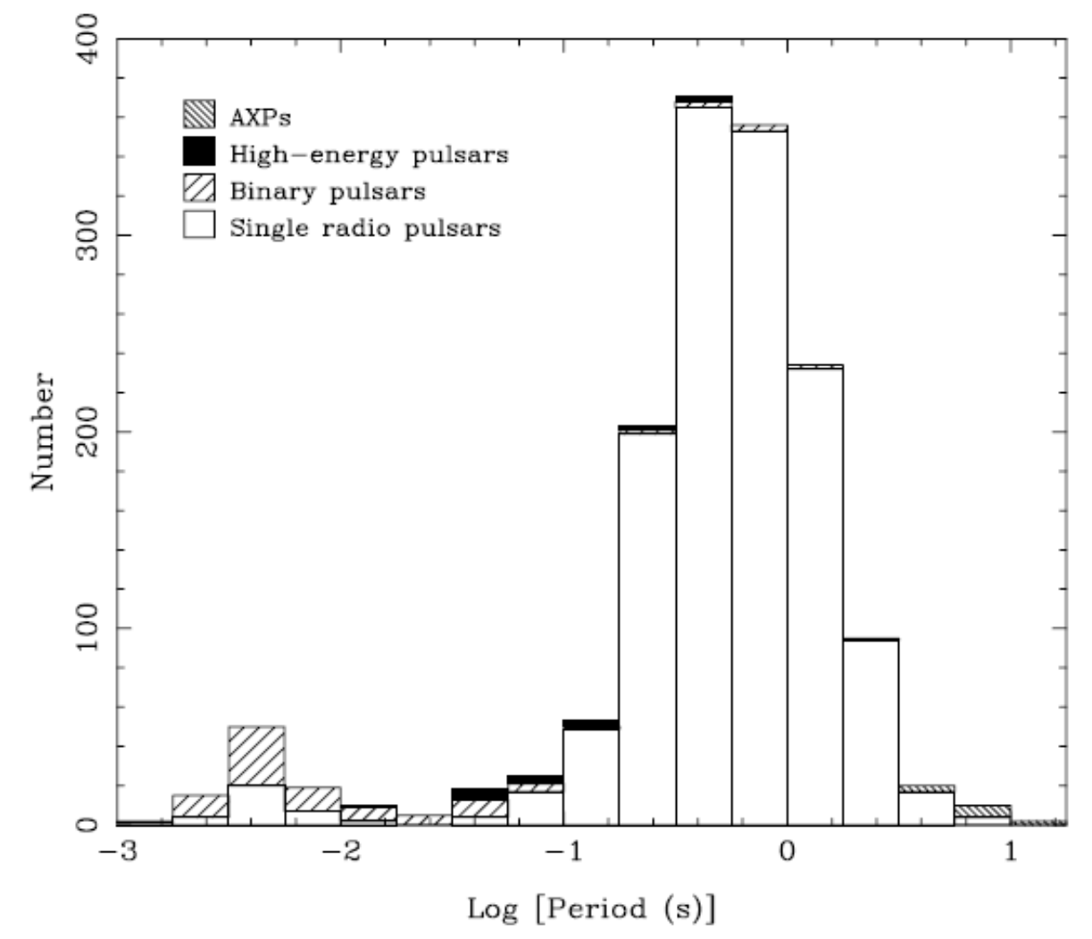
Stochastic Background

- Sensitivity to stochastic background spectrum Ω_{GW} improves quickly at low frequencies:

$$S(f) = \frac{3H_0^2}{10\pi^2}\frac{\Omega_{GW}(f)}{f^3}$$

- Potentially reach 10^{-14} scale:
  - Access some of the most interesting cosmological models.
  - Inflationary (reheating, preheating), cosmic strings, alternative cosmologies
- Appears relatively free of astrophysical stochastic foregrounds.
  - But probably not free of other sources – e.g. binary inspirals.





ATNF Pulsar Catalogue,
The Astronomical Journal 129, 1993 (2005)

Pulsars

- Majority of pulsars have period around 1 sec (~1 Hz):
  - 90% of known pulsars have frequencies in the 0.1-10 Hz band.
- Within 1 kpc, there are 46 known pulsars in the 1-10 Hz band, and 8 in the 10-100 Hz band.
- While strain amplitudes of low-frequency pulsars are likely smaller than those of high-frequency pulsars, the low-frequency pulsars are more numerous and more likely to be found nearby.

Compact Binary Coalescences

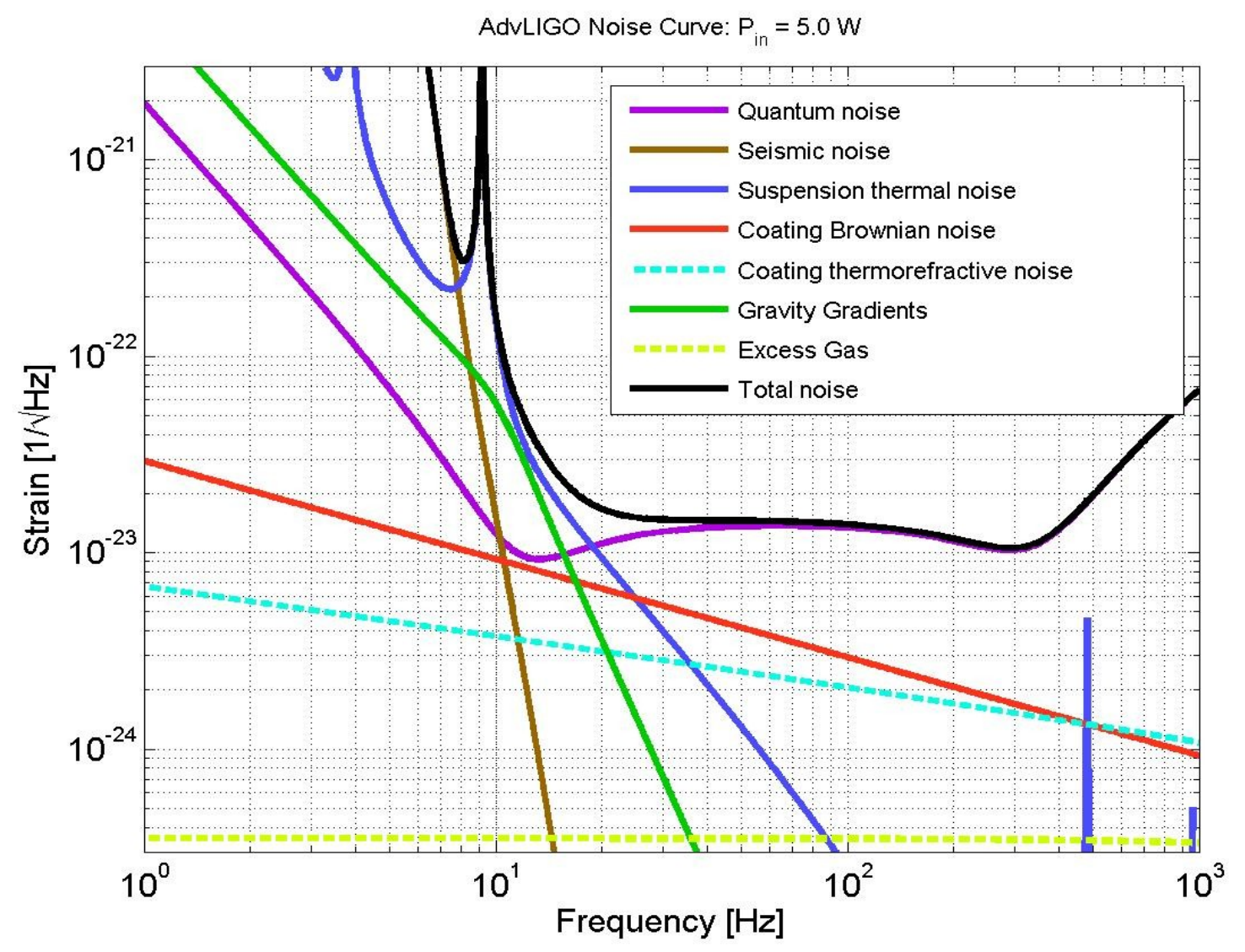
- Binaries with total mass 10^2-10^4 solar masses would inspiral and merge in the 0.1-10 Hz band.
- Study the origin of intermediate-mass black holes:
  - Distinguish between merger (with inspiral component) and accretion (without inspiral component) birth mechanisms.

Surface Limitations: Gravity Gradient Noise

Second generation gravitational wave detectors (Advanced LIGO and Advanced Virgo) will probe frequencies down to ~10 Hz.

Below 10 Hz several noise sources become important:

- Radiation pressure noise.
- Thermal noise (suspension, internal mirror, coatings).
- Seismic noise
- Gravity gradient noise (or Newtonian noise) – fluctuations in the local gravitational field.



Gravity Gradient Noise

Fluctuations in the local gravitational field push/pull interferometer mirrors and add to the overall displacement noise of the interferometer. This noise source is referred to as the gravity gradient (or Newtonian) noise.

On the surface, the Newtonian noise is caused by three types of effects:
1) Seismic motion of the ground
2) Atmospheric fluctuations
3) Local disturbances (human factor, traffic,...)

Theoretical calculations have shown that the seismic noise and atmospheric fluctuations contribute roughly equally to the gravity gradient noise: at 1 Hz, the strain equivalent amplitude is about $10^{-20}/\sqrt{\text{Hz}}$: hence suppression at the level of 1-in-1000 is needed to achieve the Advanced LIGO sensitivity scale ($\sim10^{-23}/\sqrt{\text{Hz}}$),

Is surface detector an option?

It is possible to suppress the gravity gradient noise on the surface by monitoring the sources of this noise (seismic and atmospheric fluctuations) with a large array of instruments (seismometers, barometers, wind-meters etc), and feeding their signals to the mirror actuators to cancel the effect of fluctuating gravitational field. This cancellation must be done at the level of (at least) 1-in-1000.

The seismic noise contribution is dominated by the surface seismic waves (heavy soil replacing light air). The sound speed on the surface is about 500 m/s, implying wavelength of 500m at 1 Hz. The dispersive soil and the local disturbances significantly reduce the correlation lengths: of order 10m at 1 Hz. These conditions would imply a very dense array covering a large area.

While the surface waves are dominant, the amplitude of bulk waves is likely only about 10 times smaller. Hence, for the 1-in-1000 suppression one must monitor the bulk waves as well. These waves are typically characterized by much larger wavelengths (kilometer scale at 1 Hz).

Monitoring atmospheric fluctuations is also a challenge: it is currently not clear how large volume should be monitored, how densely the instruments should be placed, which types of instruments could be used etc.

Hence, while a surface detector option should not be discarded, it appears to be complex. Further studies are needed.

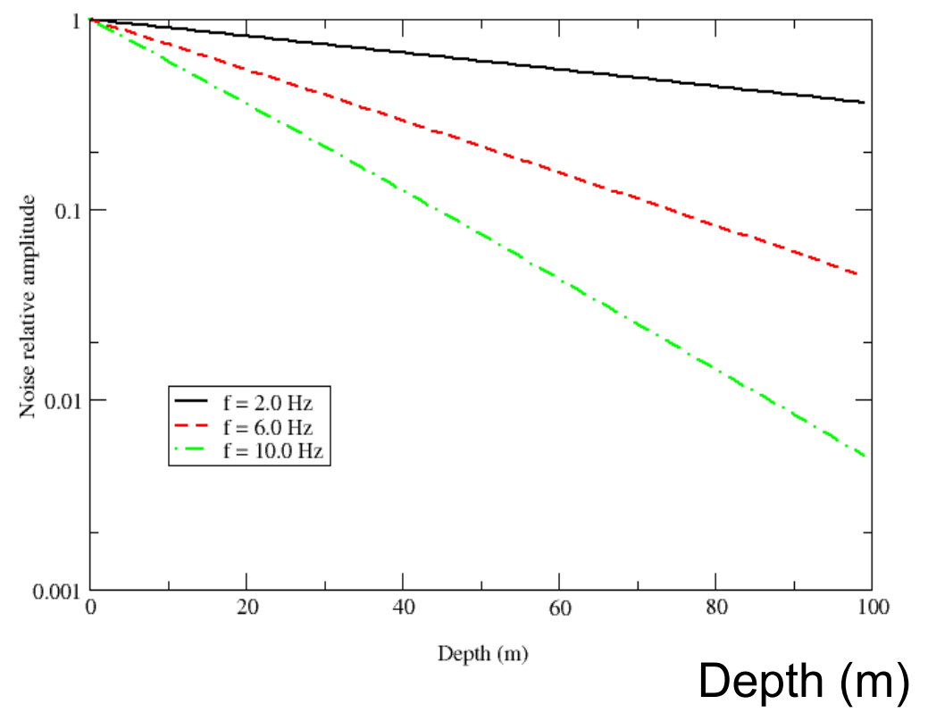
Underground Option: What do we gain?

Underground gravitational-wave detector would benefit from several advantages:

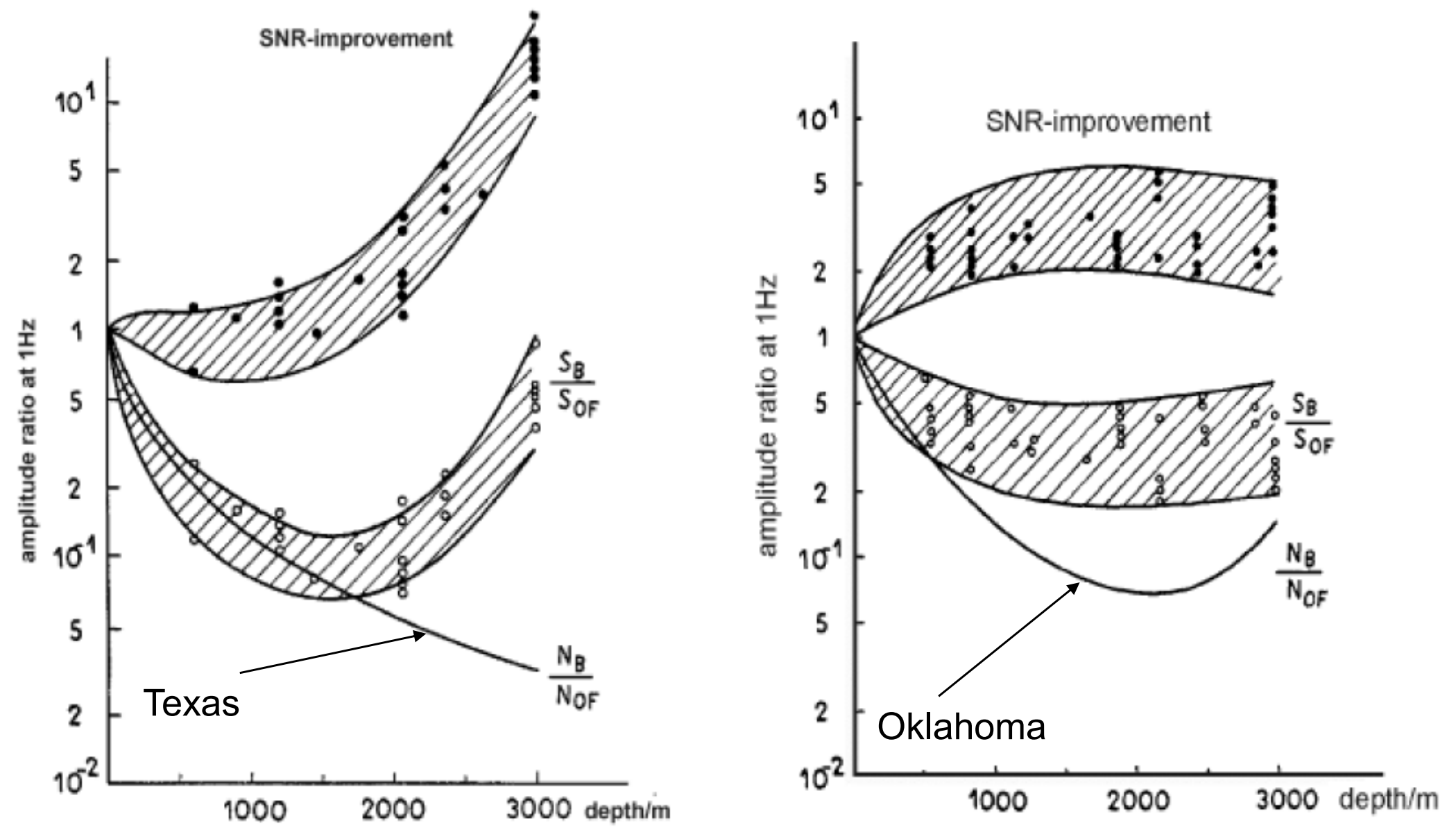
1) Atmospheric fluctuations will be suppressed.
2) Local disturbances will be minimized: underground access is limited and controllable.
3) Local environment is very stable (and controllable) throughout the year: temperature, pressure...
4) Seismic noise amplitude is exponentially reduced: Both theoretical calculations and measurements indicate a factor of 10 suppression at 1 Hz at 1km depth.

These suggest that gravity gradient noise suppression at the level of 1-in-100 may be sufficient at 1km depth.

Theoretical seismic suppression due to depth (G. Cella)



Borehole measurements of underground seismic noise

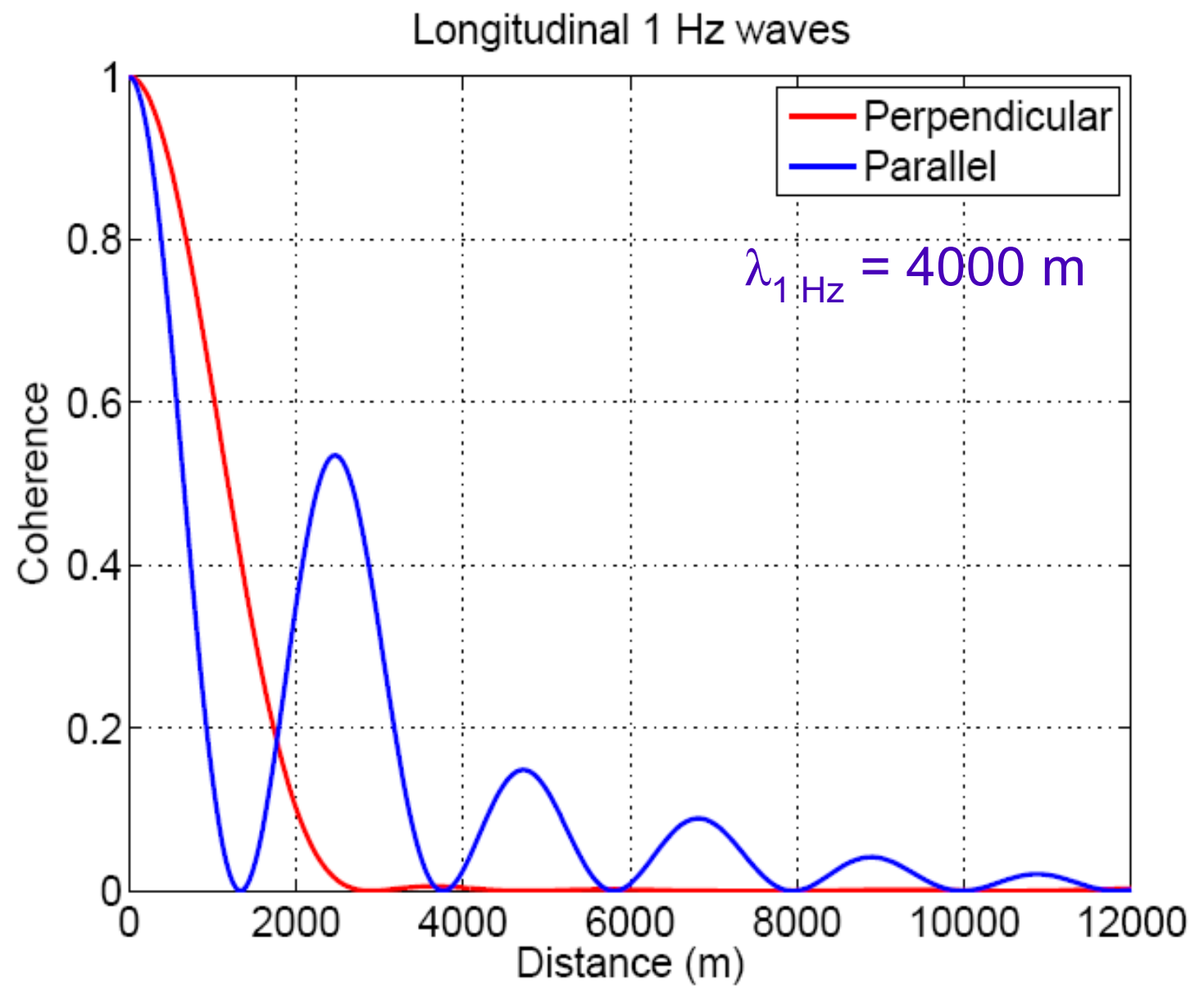


Correlation length for underground (bulk) seismic waves is expected to be very large:
1) speed of sound is ~5 km/s
2) rock is much more compact and less fractured than on the surface.

Hence, at 1 Hz the correlation length may be as large as 5 km, but the rock content and structure (faults, density fluctuations etc) may impact this.

This has two important consequences:
1) The array of instruments needed for monitoring of seismic noise could be much less dense than on the surface.
2) At lowest frequencies, the gravity gradient fluctuations may be correlated on the scale of interferometer arm length, effectively suppressing the gravity gradient noise in the interferometer.

Theoretical calculation of the coherence length for seismic waves for an isotropic medium.



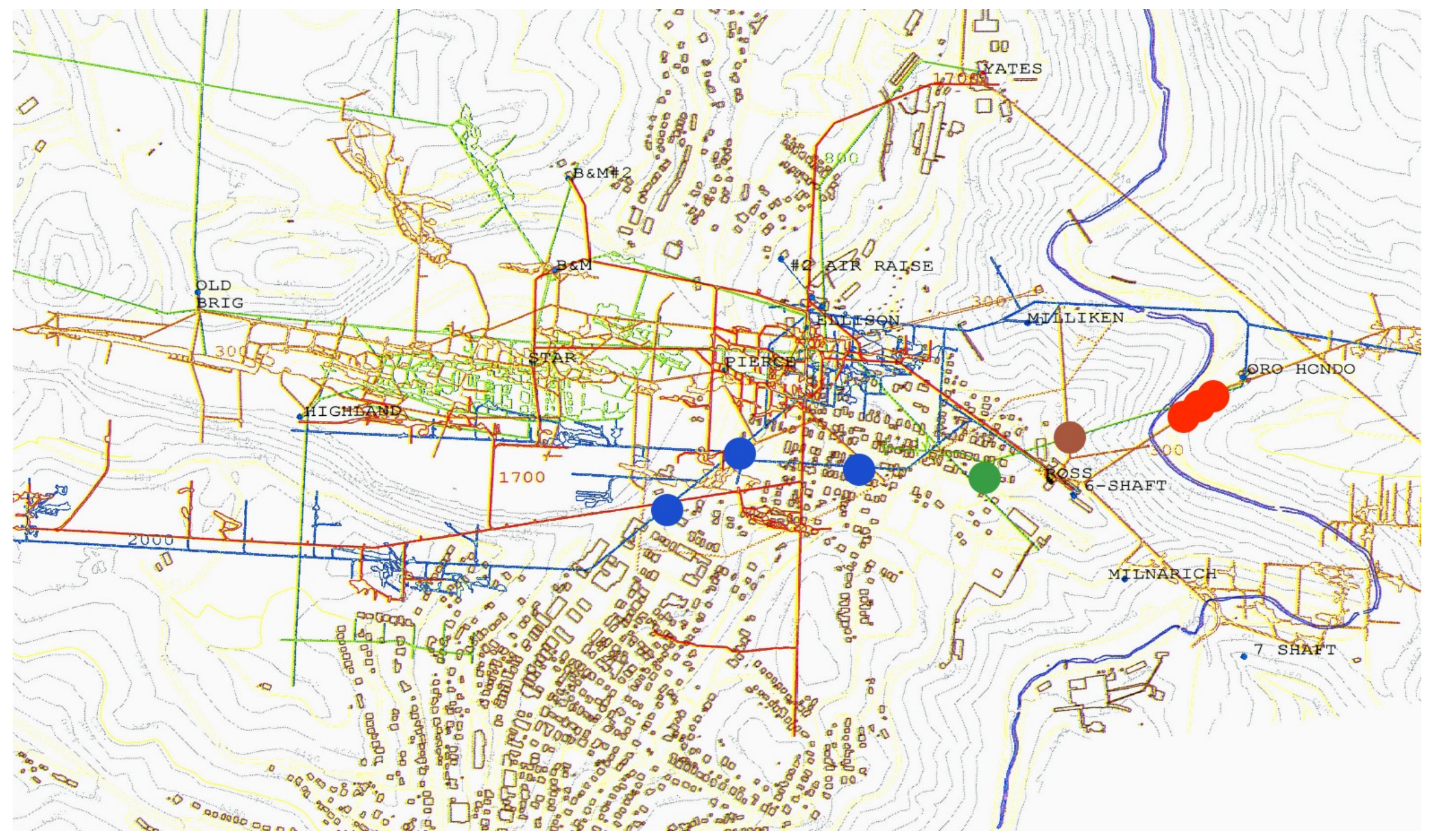
Characterizing Seismic Noise at the Homestake Mine

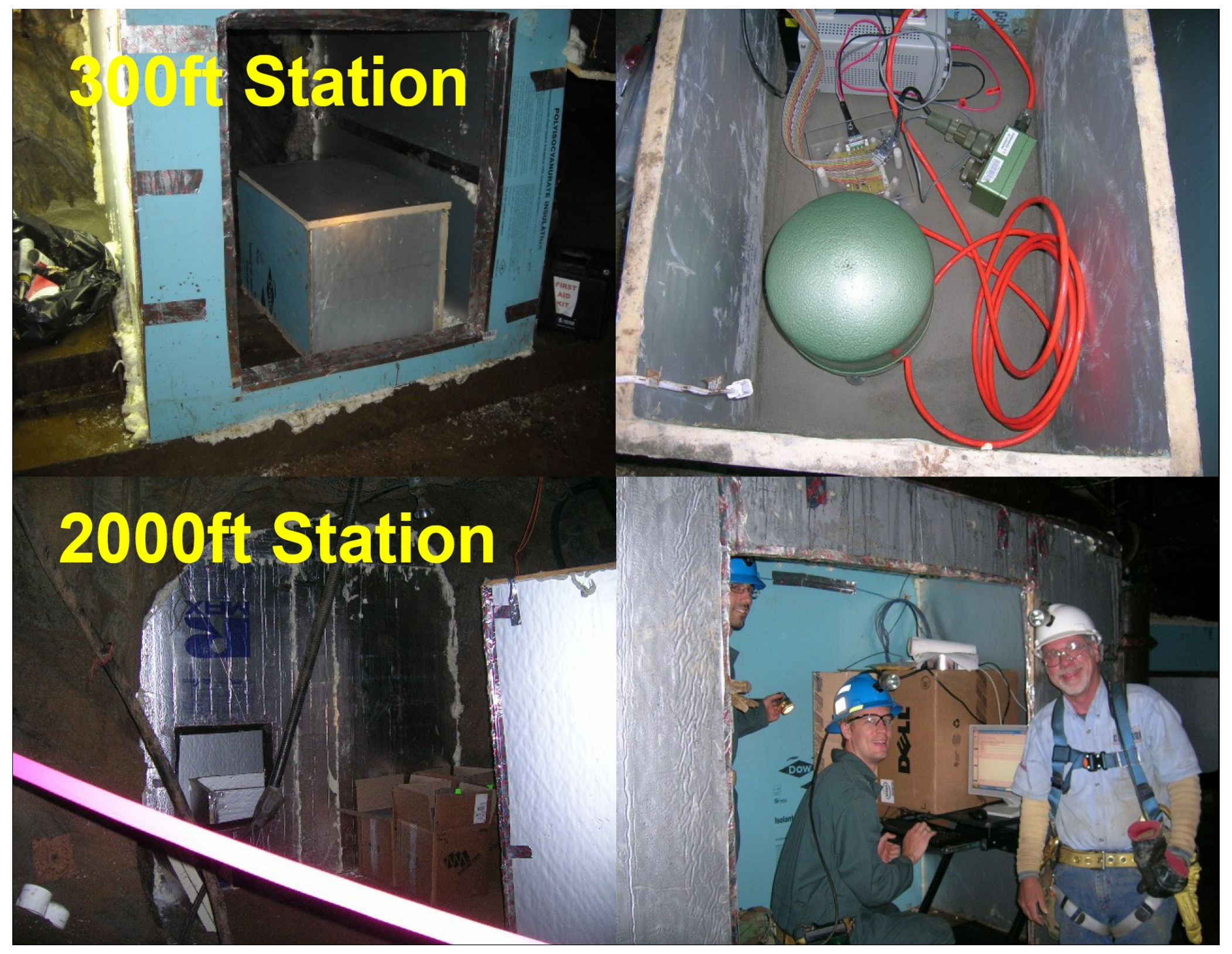
While underground environment offers several advantages for gravitational wave detectors, these advantages must be quantified. We are developing an array of synchronized seismic stations in the Homestake mine, probing the available depth and the vast horizontal extent of the mine. This array will measure the amplitude and correlation length of the seismic noise as a function of depth and frequency. Combined with a finite element model of the underground rock, these measurements will provide an estimate of the gravity gradient noise for a future potential underground GW detector.

Stations are currently operational: at 300 ft, 800 ft, 2000 ft and 4100 ft depths. Plans are in place to add more stations soon, including one on the surface.

Each station operates a high-sensitivity broadband seismometer (such as Streckeisen STS-2 or Trillium T240) along with a number of environment monitoring instruments (thermometers, barometers, magnetometers etc).

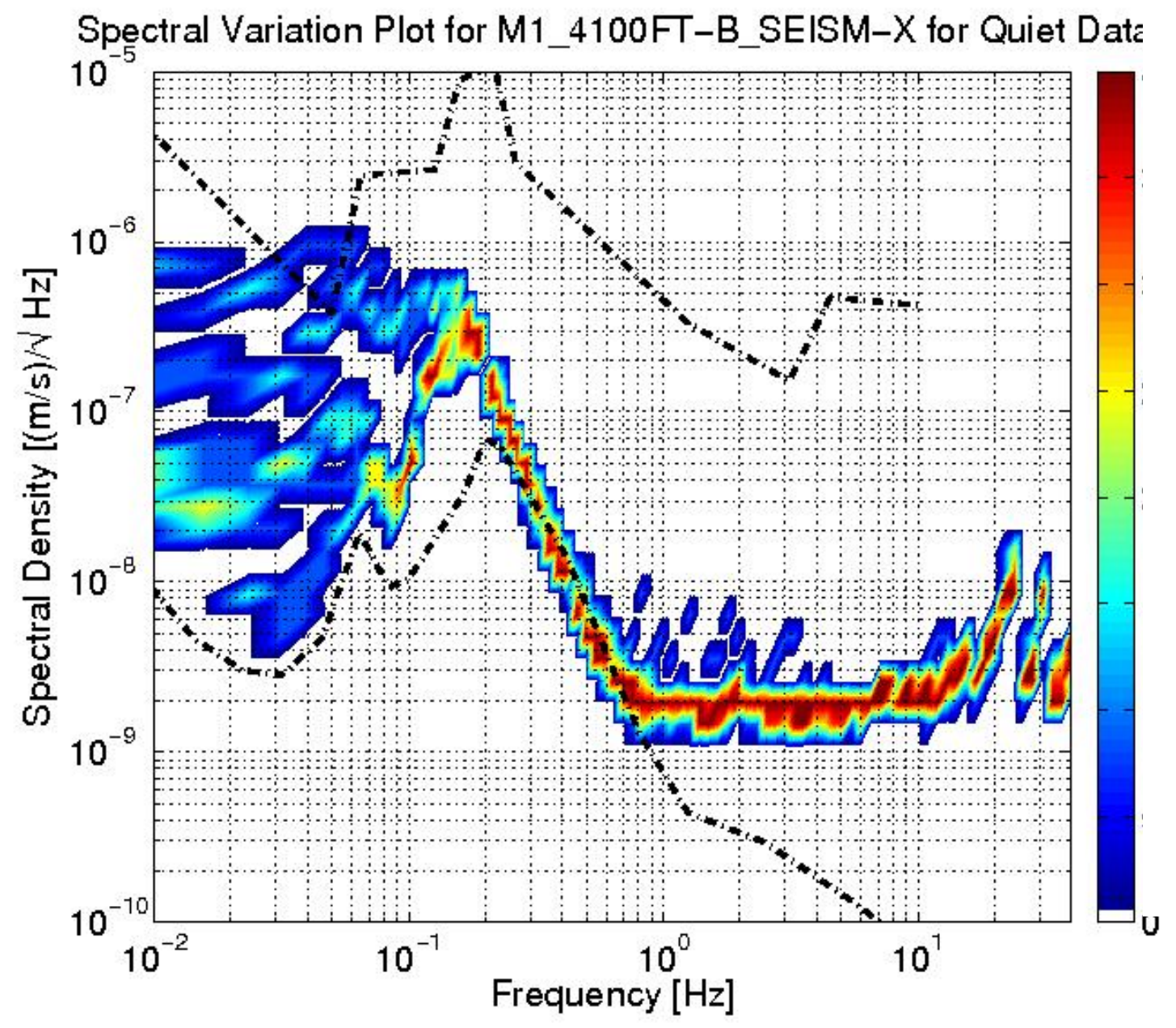
Layout of the Seismic Stations at Homestake



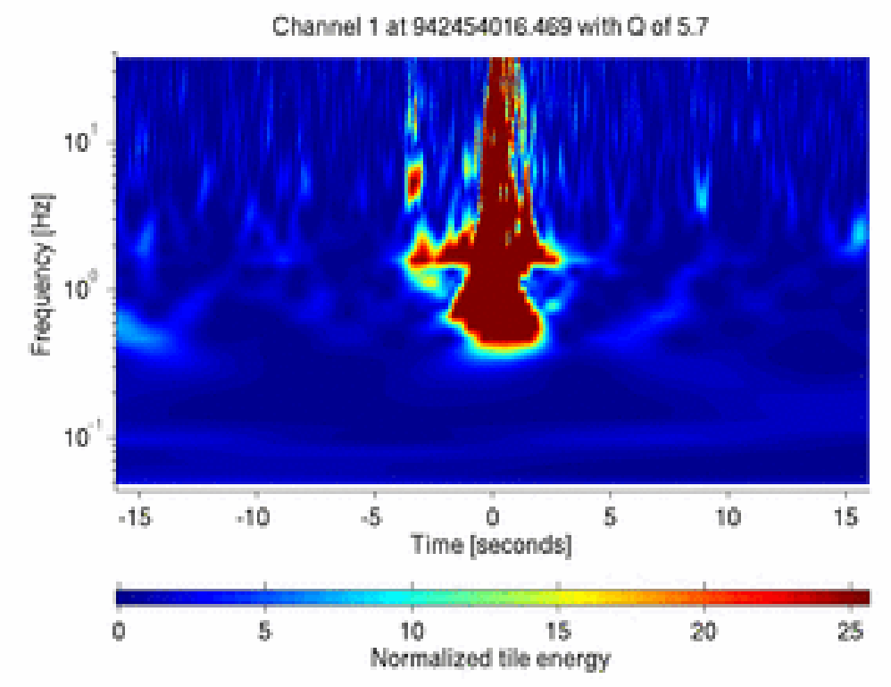


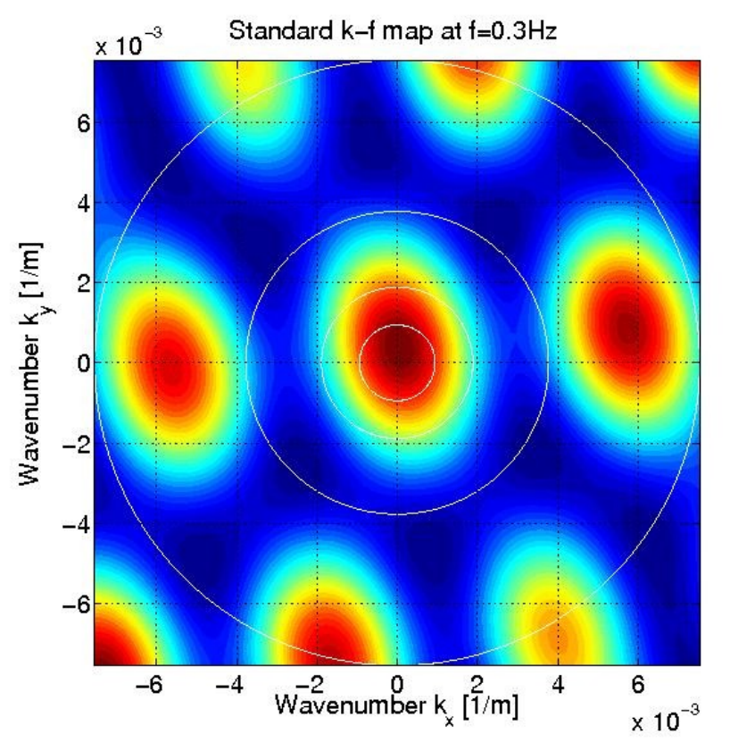
Instruments are installed in nested boxes to minimize acoustic, thermal, air current, and other disturbances.

Seismic noise in “quiet” times. Large events found using KleineWelle pipeline and coincident triggers.



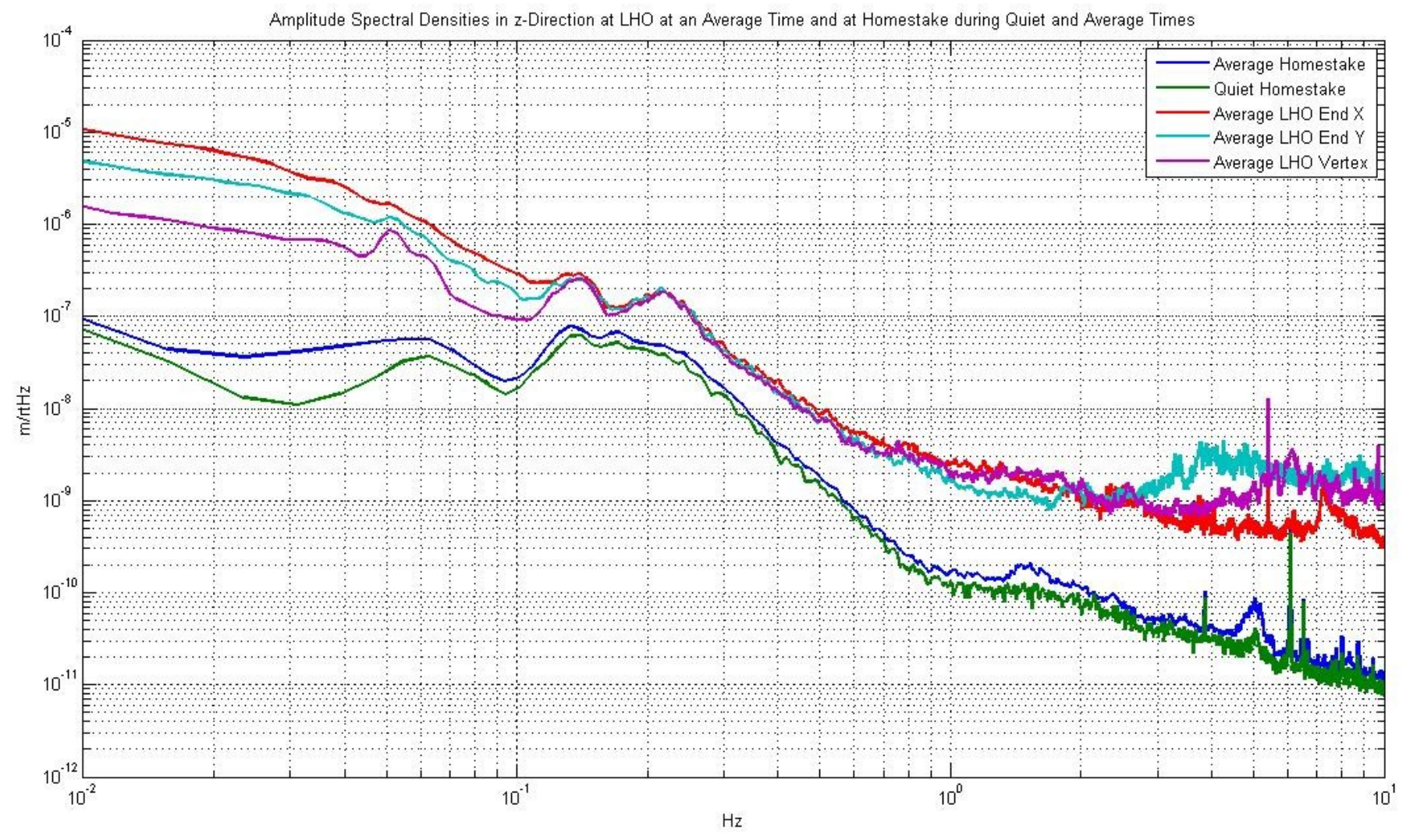
Earthquakes and blasting are easily observed. Speed of waves determined from timing, k-f maps and coherence. Below : Omega scan and k-f map for a recent blast event. Data below gives v~6km/s



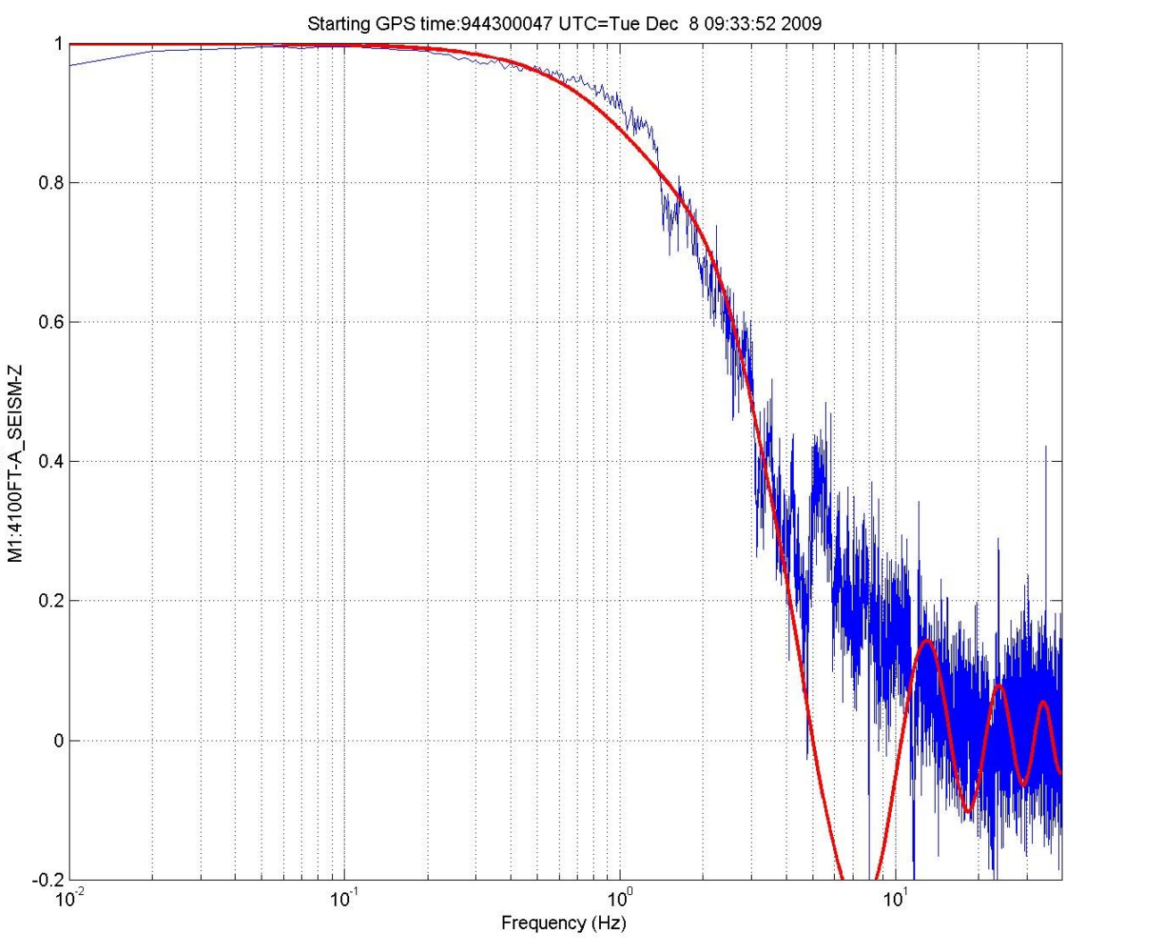


Observations:

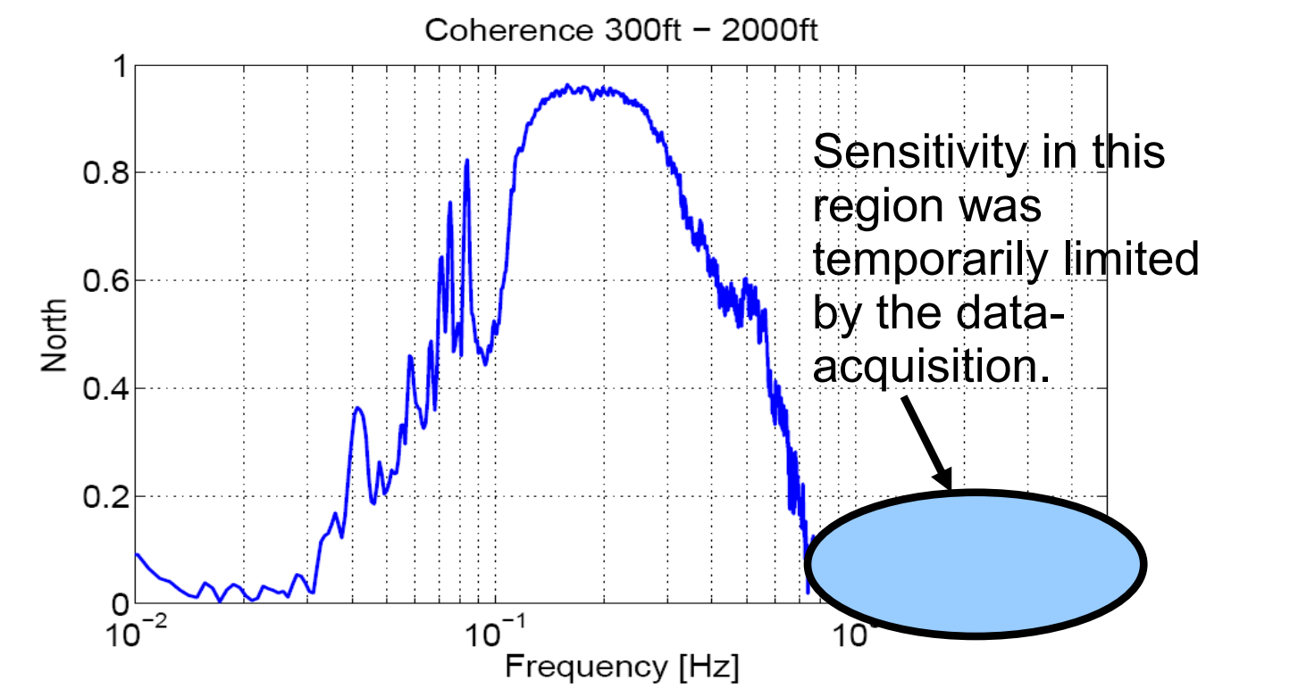
Observe 10 times smaller seismic noise at 4100 ft depth at 1Hz as compared to typical LIGO site noise.



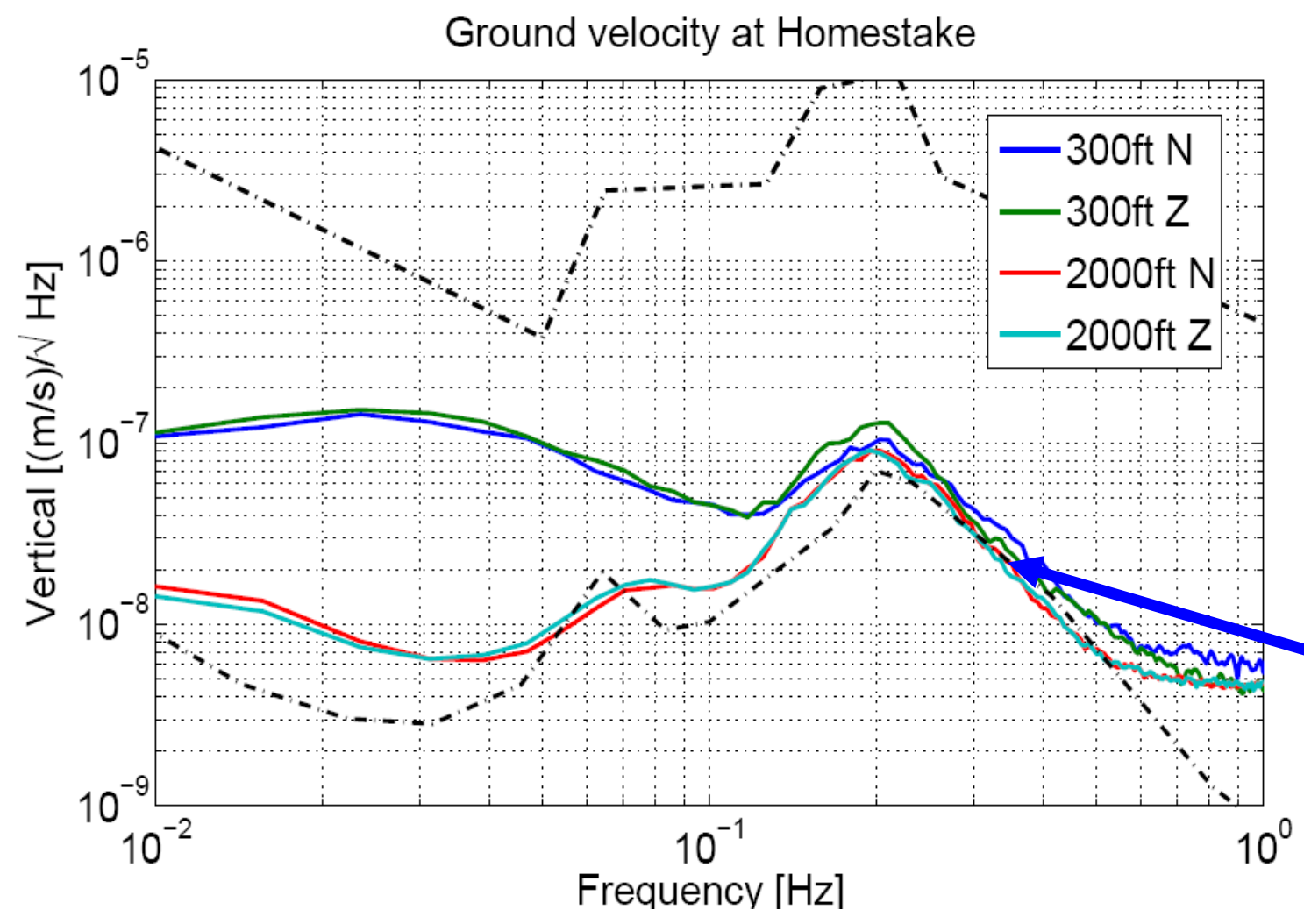
Right: a plot of the coherence between 2000 ft and 4100ft seismometers then fit an isotropic S and P wave model to it.



Observe large correlations between the 300 ft and 2000 ft stations in horizontal directions.



Sensitivity in this region was temporarily limited by the data-acquisition.



The Homestake low-noise model, obtained by minimizing over time at each frequency bin, is remarkably quiet. At some frequencies it surpasses the Peterson 1993 model obtained by a similar minimization over a large network of seismic stations.