
Deep Underground Gravity Lab at DUSEL

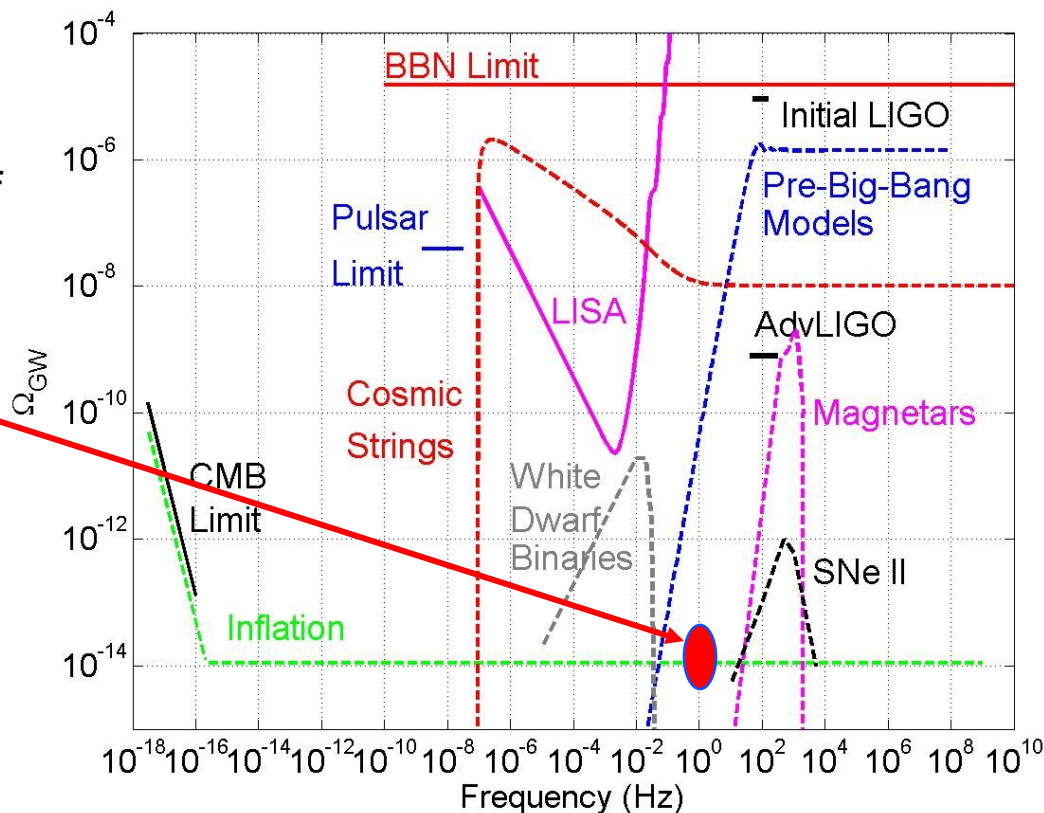
Vuk Mandic, University of Minnesota
DUSEL Workshop, Lead, SD
10/01/09

DUSEL as a Low Gravitational Background Facility

- Much of the motivation for DUSEL comes from the low cosmic-ray background levels.
- DUSEL is also attractive as a low gravitational background facility.
 - » Reduced seismic noise
 - » Gravitational field is more stable (fewer disturbances)
 - » Stable environment (temperature, pressure, ...)
- Useful for fields requiring stable vibrational and gravitational environment:
 - » Gravitational waves
 - » Equivalence principle tests
 - » Natural connections with geology/geophysics/seismology

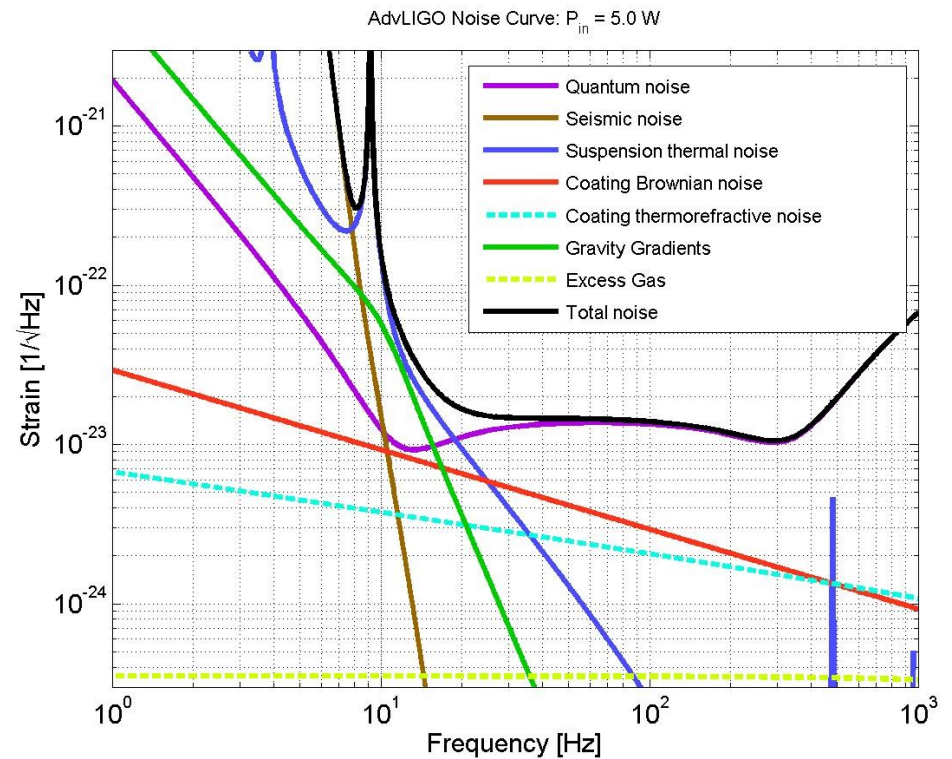
Gravitational Waves: 0.1-10 Hz

- Bridging the gap between LIGO/Virgo and LISA.
- Stochastic background:
 - » Sensitivity improves as $1/f^3$.
 - » 0.1-10 Hz band appears free of astrophysical foregrounds.
 - » Potential to reach cosmological signals.
- Periodic sources:
 - » 90% of known pulsars are in this frequency band.
- Intermediate-mass binary system coalescences.
 - » Origin of IMBH.
- Fundamental physics.



Surface Detectors

- Second generation surface detectors:
 - » Advanced LIGO, Advanced Virgo, 2014 and beyond.
 - » Sensitive above 10 Hz.
- Several noise sources are important below 10 Hz.
- Gravity Gradient Noise (GGN):
 - » Fluctuations in the gravitational field due to the motion of local masses.
 - » Rises steeply below 10 Hz.
 - » Require $\sim 1000x$ suppression at 1 Hz.

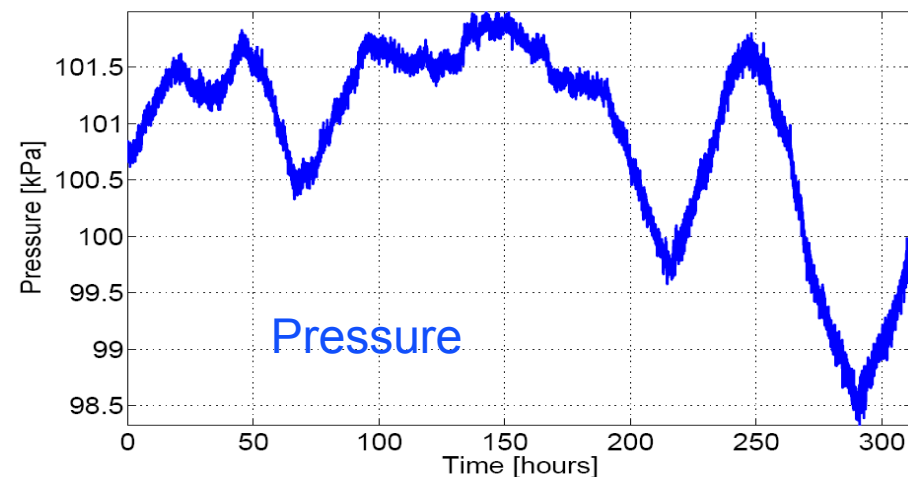
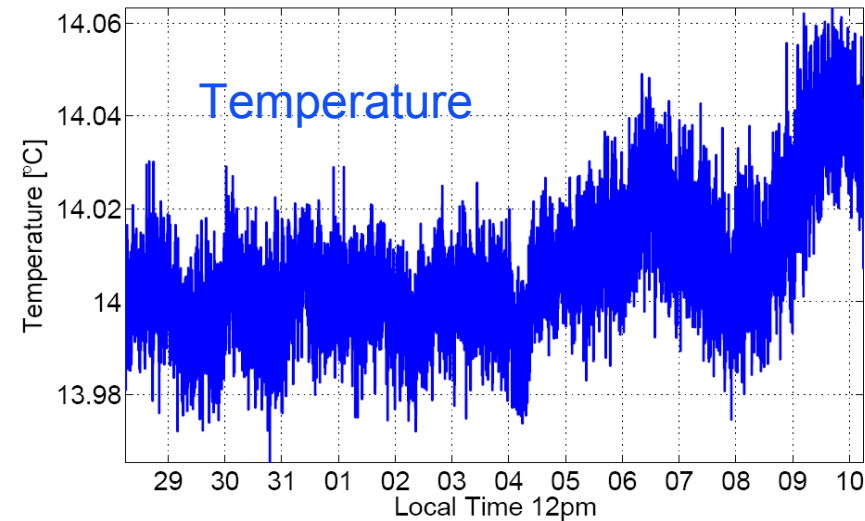


Is Surface an Option?

- Active suppression of gravity gradient noise?
 - » Build an array of environment-monitoring instruments, feed signals to the mirrors.
- Seismic:
 - » Speed of surface waves is ~ 500 m/s, at 1Hz the wavelength \ll arm-length. Correlation length is small, need a dense array.
 - » Speed of bulk waves is ~ 5 km/s, so must also monitor larger distances (and depth!).
 - » Likely need a very large seismometer array.
- Atmospheric:
 - » Harder to monitor and model.
- Local disturbances: human factor, seismic noise caused by rain, etc.
 - » Very hard to monitor.
 - » Coupling complicated – mechanical, ground-tilts, gravitational etc.

Why Underground?

- Atmospheric fluctuations are suppressed.
- Local disturbances much more controlled:
 - » Limited access, no passers-by...
 - » Controlled use of machinery.
 - » Ventilation well understood and controllable.
- Much more stable environment.
 - » Temperature, pressure, humidity etc stable to ~1% or better.
- Surface waves reduced exponentially.
 - » At 1 Hz expect ~10x suppression.
 - Model and measurements.
 - » Depends on depth and rock structure.

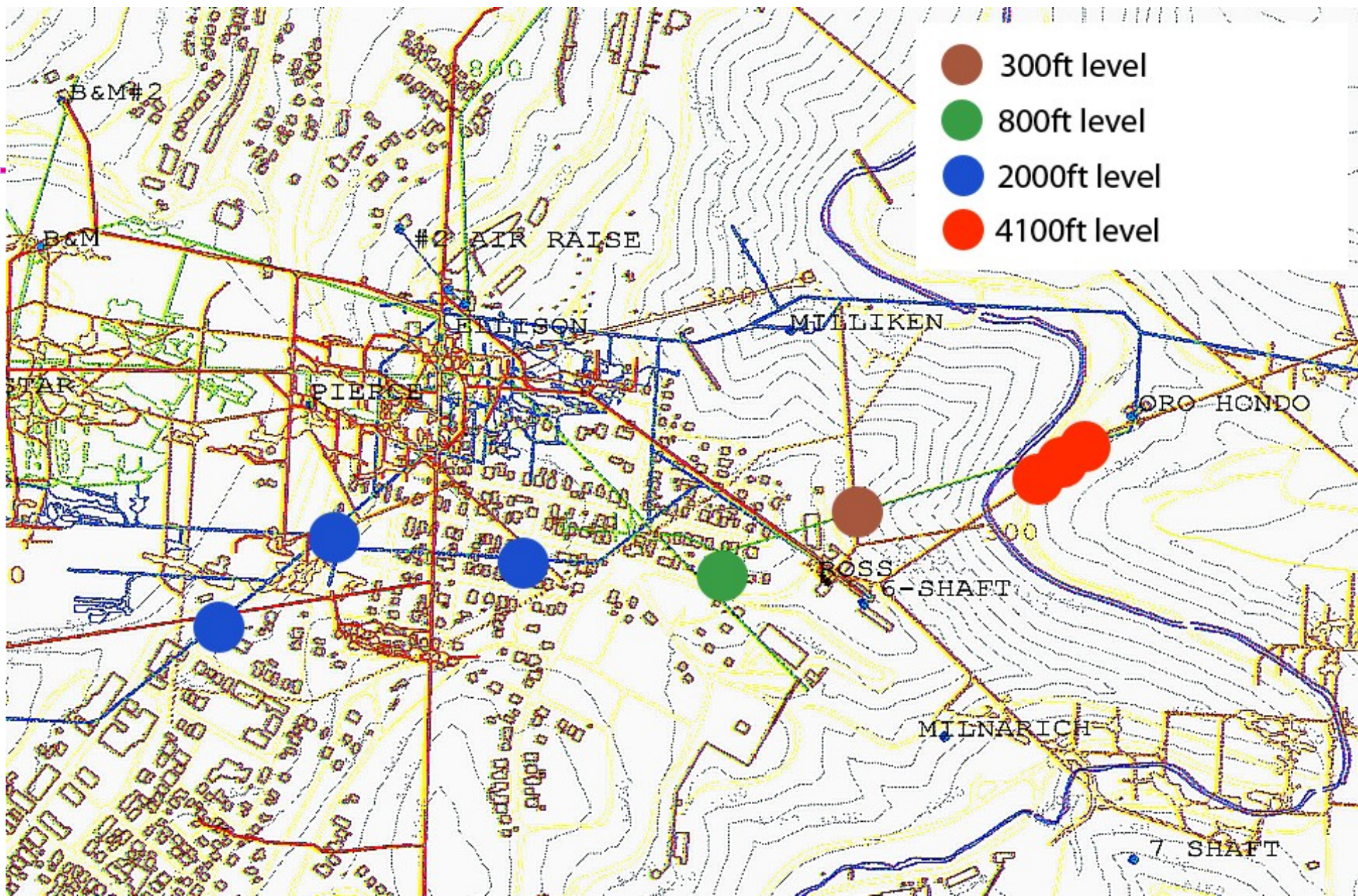


Why Underground?

- Correlation lengths are significantly longer (several km at 1 Hz):
 - » Larger speed and more uniform medium than on the surface.
- Two consequences:
 - » Gravity gradients correlated between mirrors, depending on frequency (at 0.1 Hz, expect ~ 50 km wavelength...)
 - » Track the seismic noise with a relatively few instruments spanning the entire detector.
 - Active suppression may be more plausible.
 - And the requirement is a bit more relaxed: need $\sim 100x$.
- Simulations show that $2-3\lambda$ volume should be monitored to estimate the GGN at the 1% level of accuracy.

Homestake Seismometer Array

- Probe available depth/distances.
 - » Characterize the seismic noise in 10 mHz – 30 Hz band.
 - » Amplitude, correlation depth, speed of sound as a function of depth/frequency.
- Goal: understand the structure of the seismic noise underground.
 - » Pressure vs shear, surface vs bulk, fault lines, scattering...
 - » Estimate how large seismic array would be needed for active suppression of gravity gradient noise.
- Started in February 2008.
 - » Over the summers in 2008 and 2009 built 8 stations, all of which are fully operational.
- Each station operates:
 - » High sensitivity broadband seismometer, well linked to the rock.
 - » Environmental monitors (thermometers, barometers etc).
 - » Nested huts used to suppress ambient noise.
- Support from SUSEL has been absolutely crucial!



300ft Station

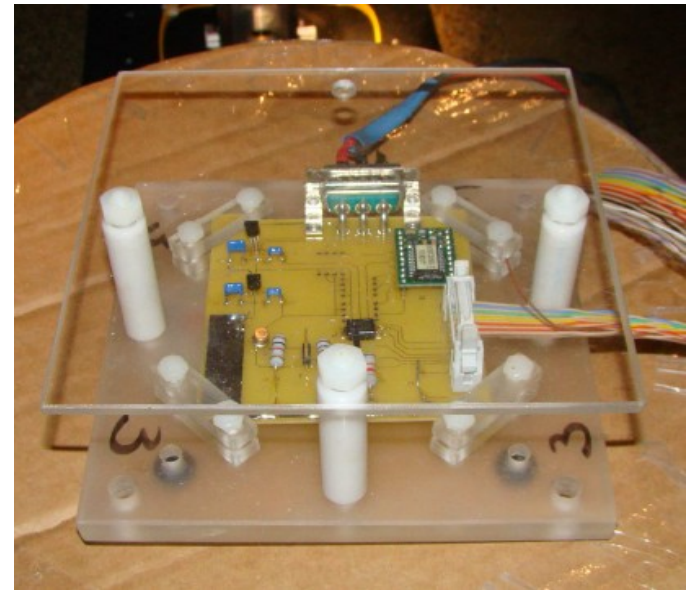


2000ft Station



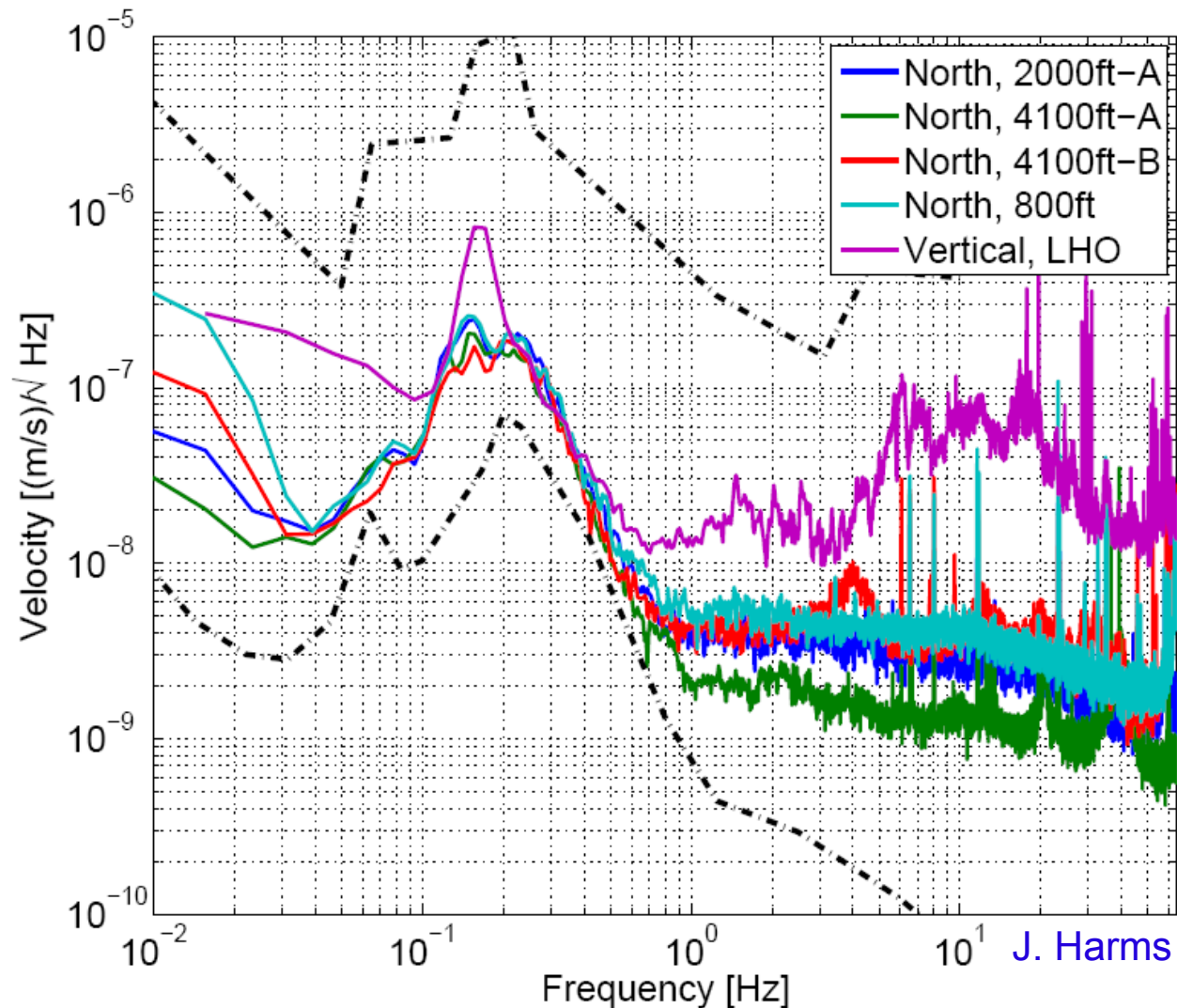
Data Acquisition

- All data digitized locally (PC with a digitization card).
- Data copied to the surface PC periodically, via fiber link.
- All PC's are synchronized to ~ 0.2 ms (NTP protocol).
 - » Plan to implement the Advanced LIGO timing distribution system, with precision of 10 ns or better.
- Remote access to surface PC, copy the data to the outside world.



First Results

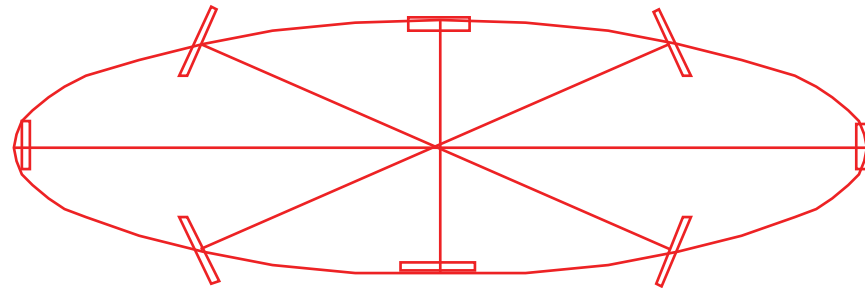
- Observe 10x lower seismic noise at 1 Hz at 4100 ft depth, as compared to the surface.
- Particularly bad microseism is shown.
 - » 2x quieter spectra have been obtained.
- Starting to look at correlations between stations.
- 4100-ft station: Comparable (and sometimes even better) than the Peterson 1993 Low-Noise model.



Optical Strainmeter

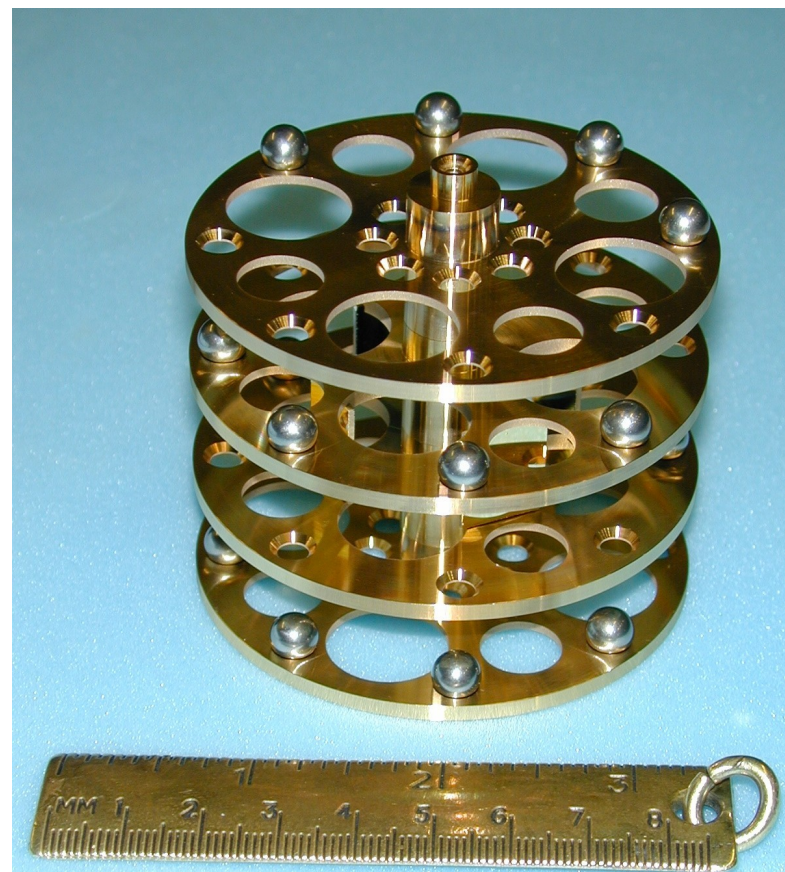
- Plan to install an optical strainmeter.
- Mount mirrors on the cavity walls.
 - » Measure differential mode (vs common mode measured by seismometers).
- Relatively insensitive to tilts.
- Use interferometer configurations to probe x-y, x-z, y-z anisotropies.
- Help distinguish between different seismic modes.
- Requires a vacuum chamber.
- Study caverns of different sizes.
 - » Wall-off part of the drift?
 - » Connect neighboring caverns.

Expect sensitivity at the level of $<10^{-10}$ m.



Gravity Gradiometer

- Fluctuating gravitational gradients cause force and torque noise on gravitational-wave interferometer end masses or on torsion balances.
- Also indicate changes in the ambient mass distribution i.e. gravitational field.
- Gradients can be measured with asymmetric torsion pendulum balances.
- Example: University of Washington gradiometer pendulum
 - » Projected sensitivity @ 100 mHz : 10^{-3} E/ $\sqrt{\text{Hz}}$ (corresponding to 10^{-13} m/ $\sqrt{\text{Hz}}$)
 - » 1-2 order of magnitude better may be possible by cross-correlating a pair of gradiometers or by improving suspension fibers.



Tests of the Equivalence Principle

- Equivalence principle: gravitational free fall is independent of the material
 - » uniform gravitational field = accelerated reference frame
- General Relativity is based on the equivalence principle
 - » Most theories connecting gravity with particle physics predict a violation of the equivalence principle
 - » A violation of the equivalence principle may have something to do with the dark matter or dark energy puzzles
- Torsion balance testing for differential material-dependent accelerations towards the Sun or towards the center of the Milky Way (which tests for galactic dark matter).
- What are the advantages operating at DUSEL?
 - » Low seismic disturbances
 - » Expect extremely stable gravitational gradients (so may be sensitive to small signals such as galactic gradients)
 - » Highly reduced cosmic ray flux: Reduced electrostatic fluctuations may allow for non-conducting high-Q fused silica torsion fibers
 - » Stable thermal environment

Other Possibilities

- Possible links with geology/geophysics/seismology at DUSEL:
 - » Relations between fluid-flow, temperature and stress.
 - » Microseisms and stress realignments due to de-watering.
 - » Transparent Earth:
 - Also array of seismometers, but mostly above 1 Hz.
- Possibly of interest to a broader geology and seismology communities:
 - » EarthScope, IRIS...
- Torsion balances of use in rotational seismology.
 - » Measuring rotational normal modes of the Earth...
- Laboratory for testing new instrumentation:
 - » Accelerometers, tilt-meters, dilatometers etc.
 - » Already ongoing...
- Atom-interferometry:
 - » Interesting applications, starting to explore cross-couplings.

Future Prospects

- Proposed Deep Underground Gravity Laboratory (DUGL) project.
 - » 3-year proposal, not part of the S4/S5 process.
 - » Includes expanding the seismic array, building the optical strainmeter and torsion balance experiments.
 - » Do the studies now, before the major construction begins.
- Not funded yet.
 - » Future hinges on the success of this proposal.

DUGL Collaboration

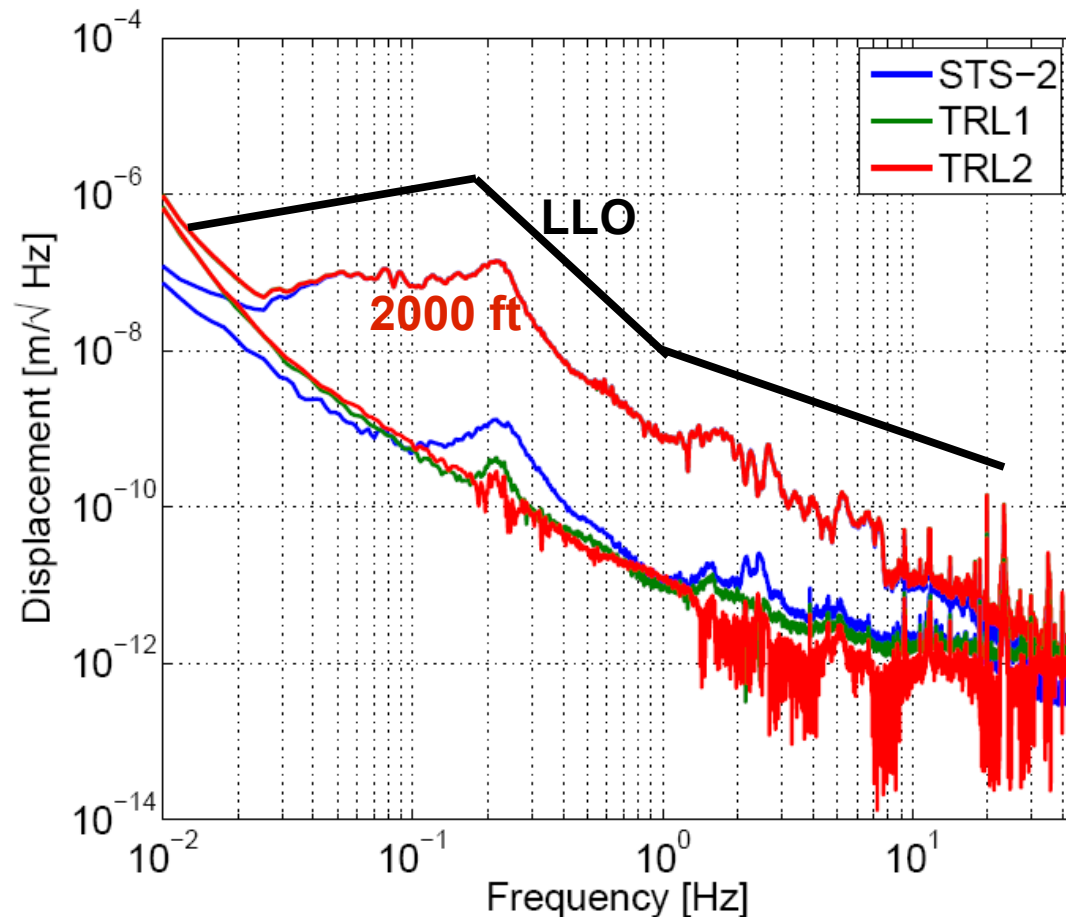
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Conclusions

- DUSEL offers unique research opportunities, as a low gravitational and vibrational noise site.
 - » New dimension with good potential to further enrich the scientific scope of DUSEL.
 - » Gravitational-wave physics, equivalence principle tests, atom interferometry...
- Already invested significant effort, and first interesting results are being produced.
 - » Expect the first paper using Homestake seismic-array data in the coming few months.
 - » Many thanks for the support from the SUSEL team!
- DUGL proposal has been submitted.
 - » Hope for significant advances over the next 3 years.

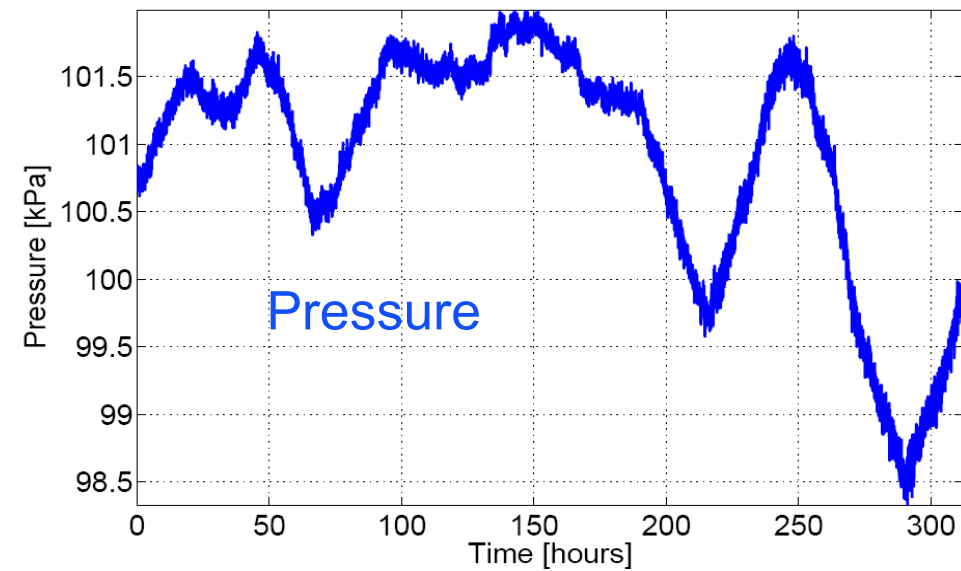
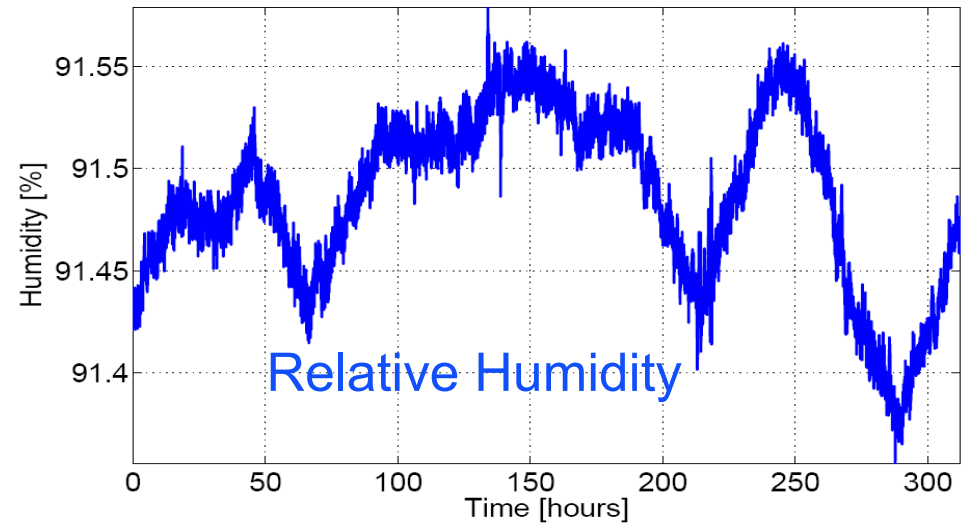
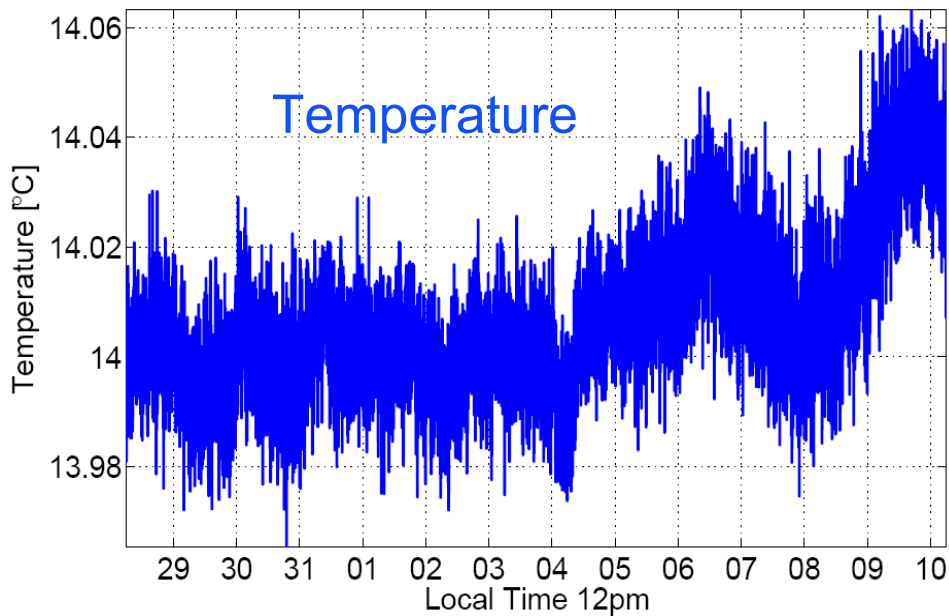
First Results

- In the summer 2008, operated STS-2 and two T240's next to each other at 2000ft level.
- Nanometrics provided the T240's and the data acquisition for them.
- Simultaneous data:
 - » Instrument self-noise.
- Good measurement of the seismic noise level at 2000 ft.
 - » ~10x quieter than LLO at 1 Hz.
- Residual microseismic peaks in the self-noise spectra probably indicate imperfections in the set-up.
 - » Made improvements since.

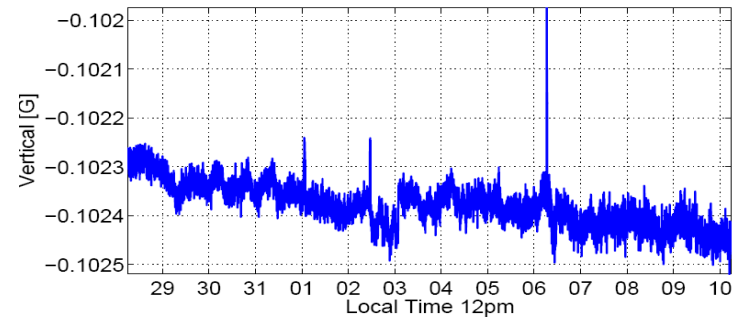
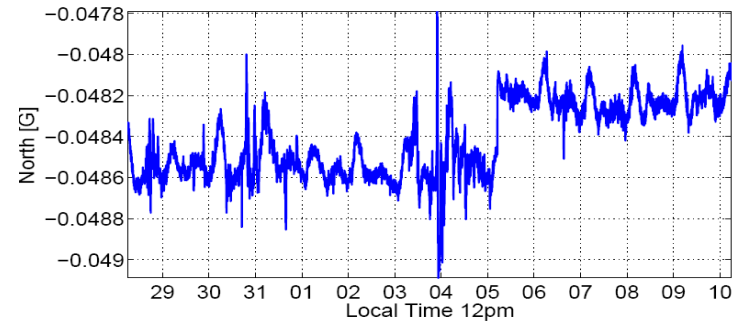
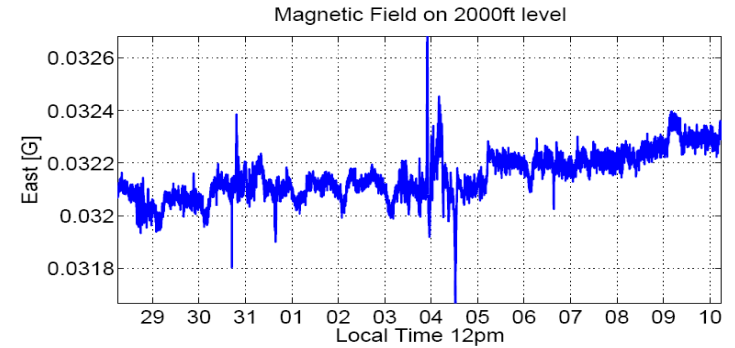
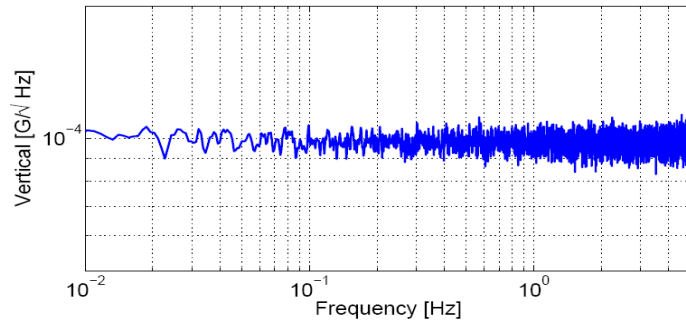
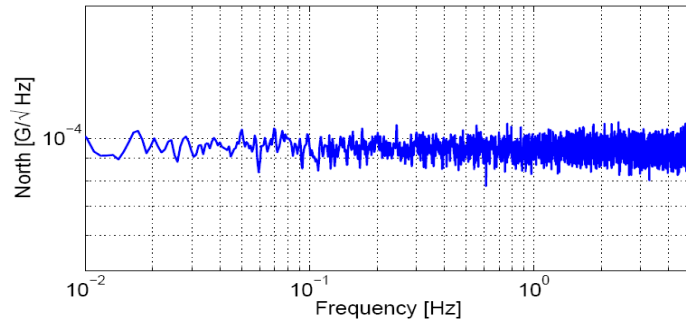
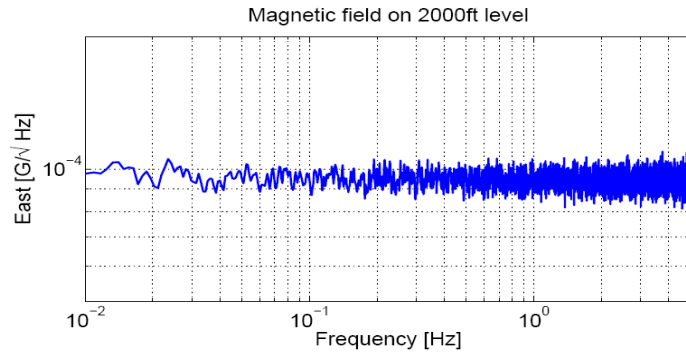


Environment Stability

- Analyzed about 12 days of 2000ft data in Jan/Feb 2009 (Jan Harms).
- Environment very stable!

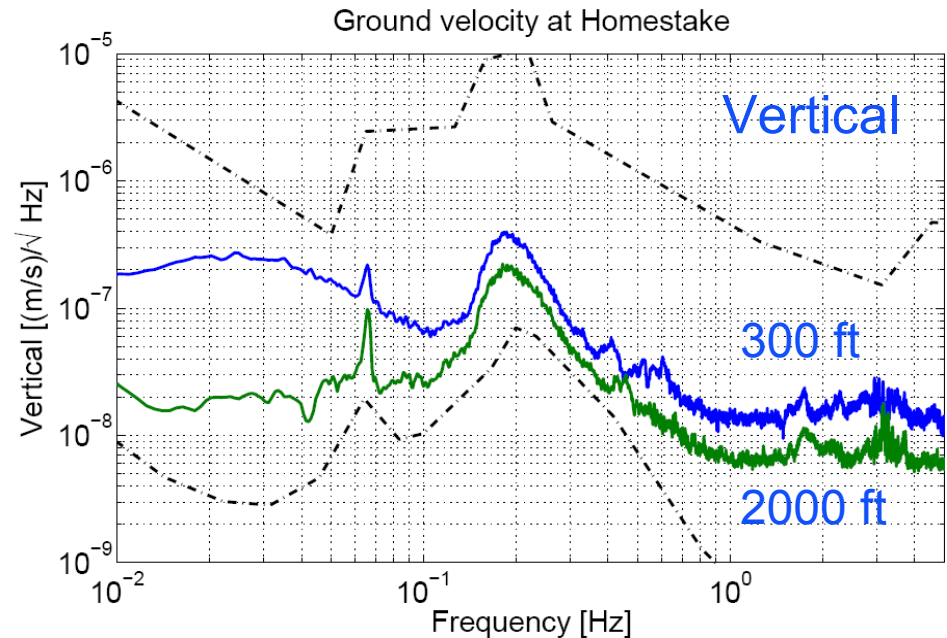
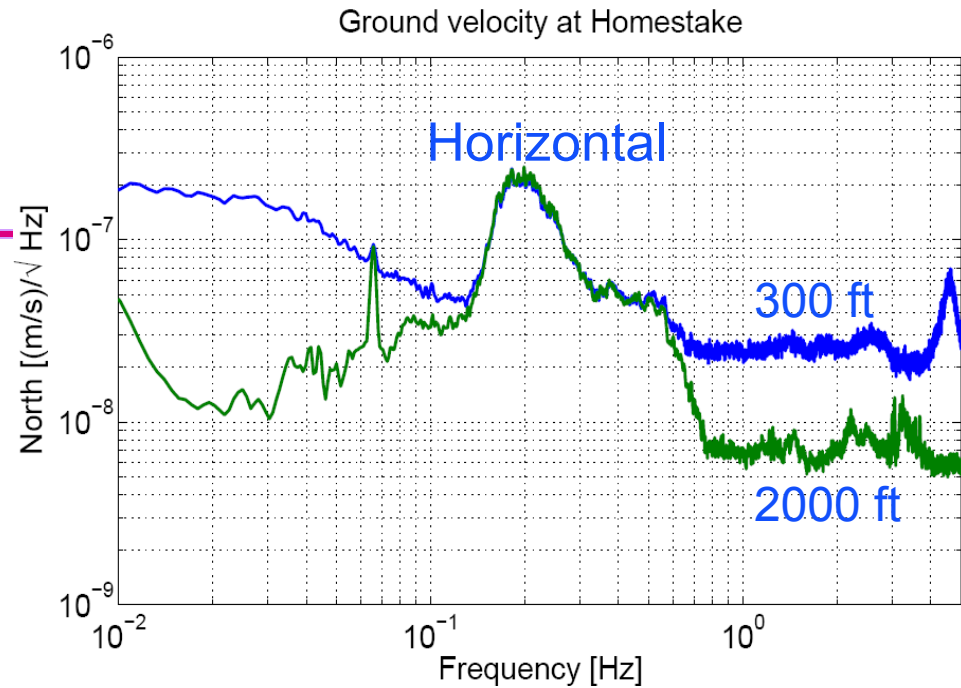


Magnetic Field at 2000 ft



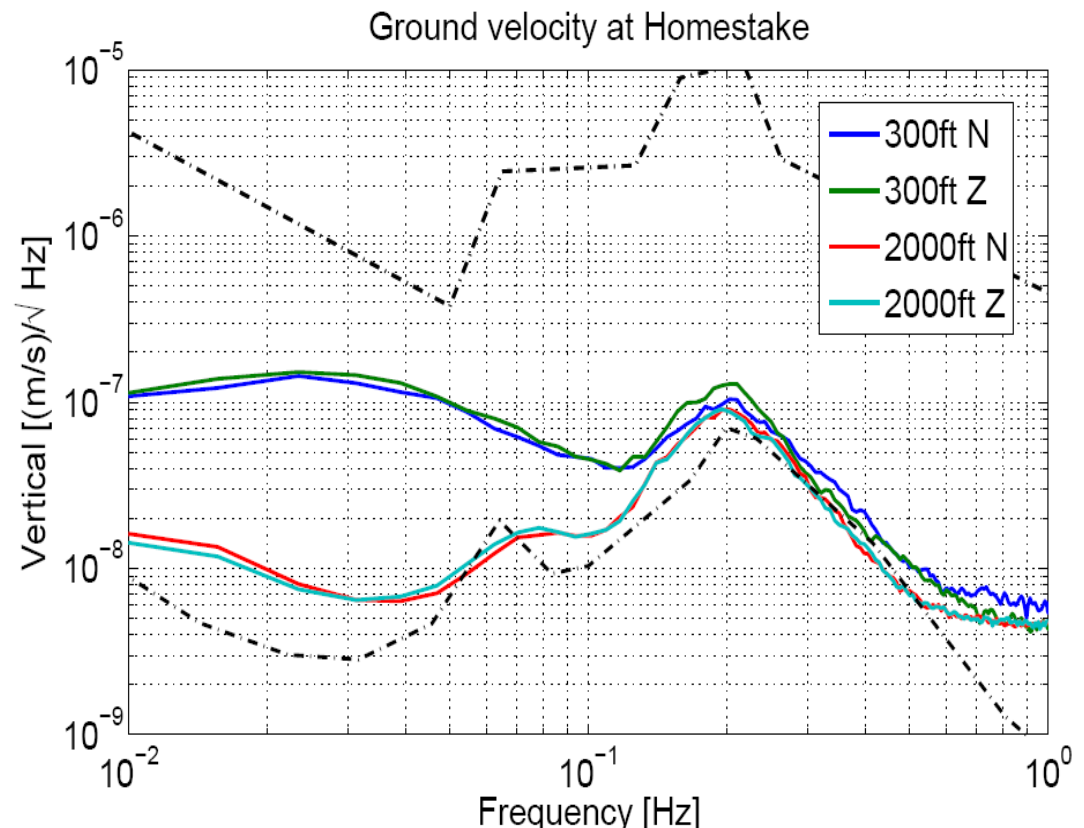
Ground Velocity

- 300 ft: Guralp not reliable below 50 mHz
- 2000 ft: above 0.7 Hz dominated by digitizer noise.
- Note: 300 ft is NOT surface!



Homestake Low Noise Model

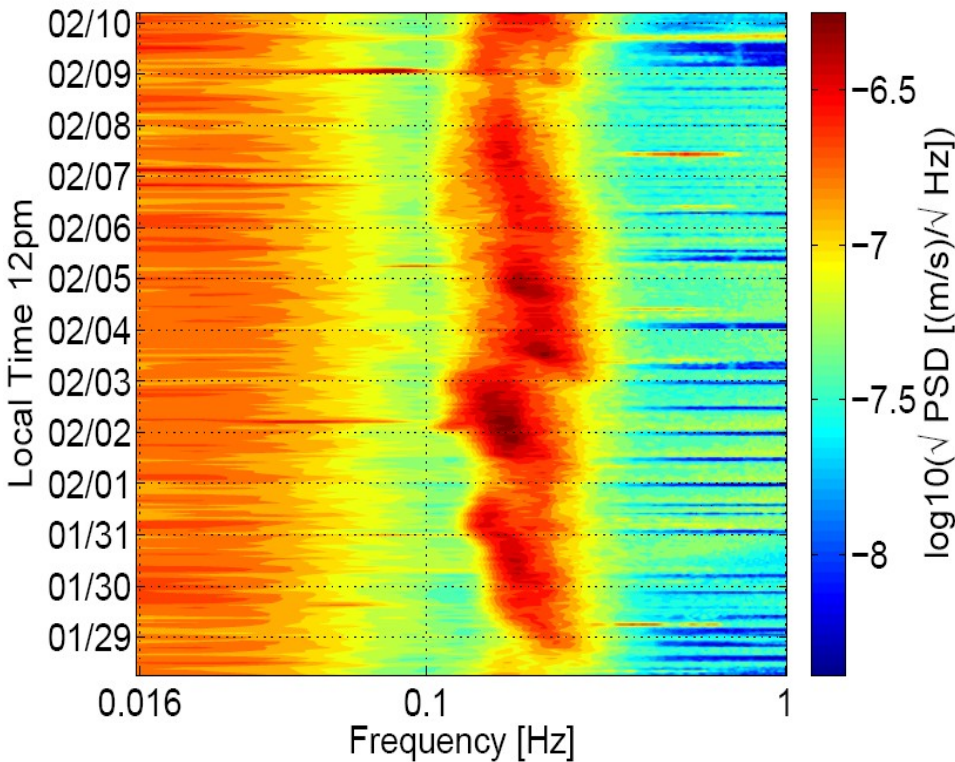
- Minimize over time for each frequency bin.
- Similar (or even quieter) than the USGS New Low Noise Model (Peterson 1993)!
- 300 ft level also has quiet times, although not quite as good as 2000 ft.



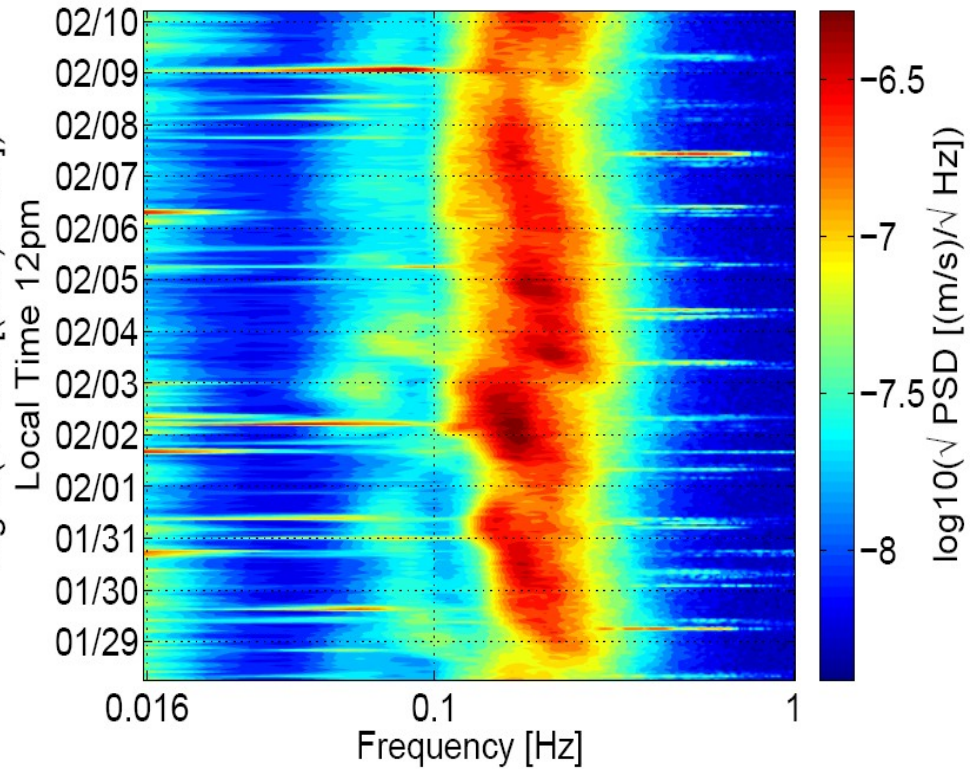
Homestake Horizontal Motion

300ft appears to have significantly more local disturbances.
Possibly due to proximity of the shaft and the hoist?

Horizontal Motion at 300ft



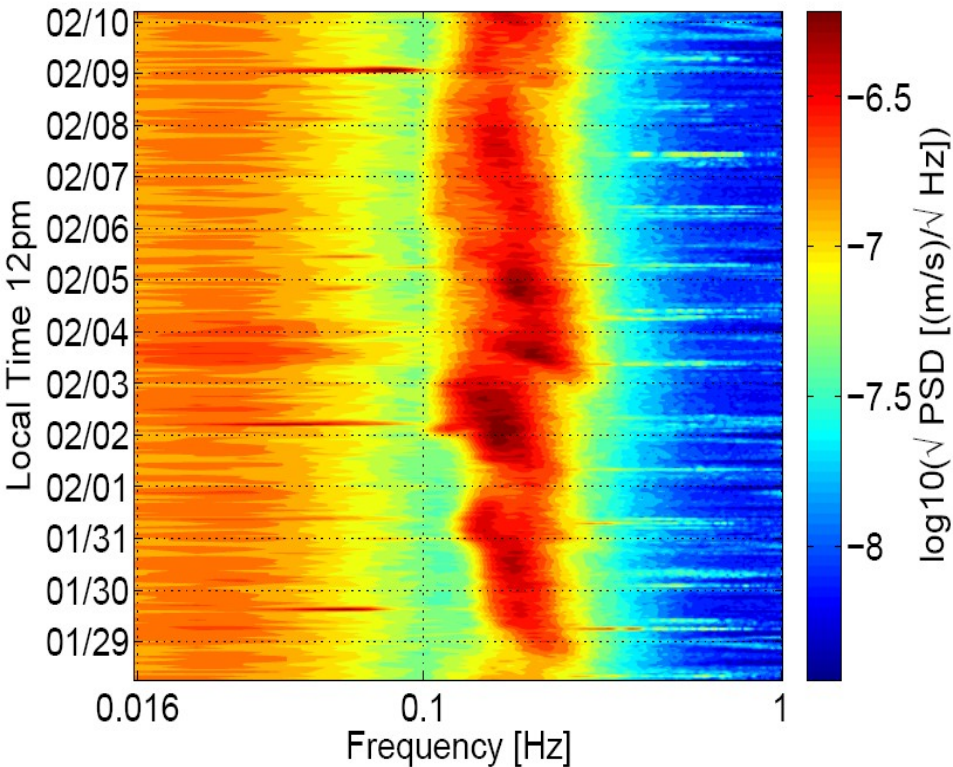
Horizontal Motion at 2000ft



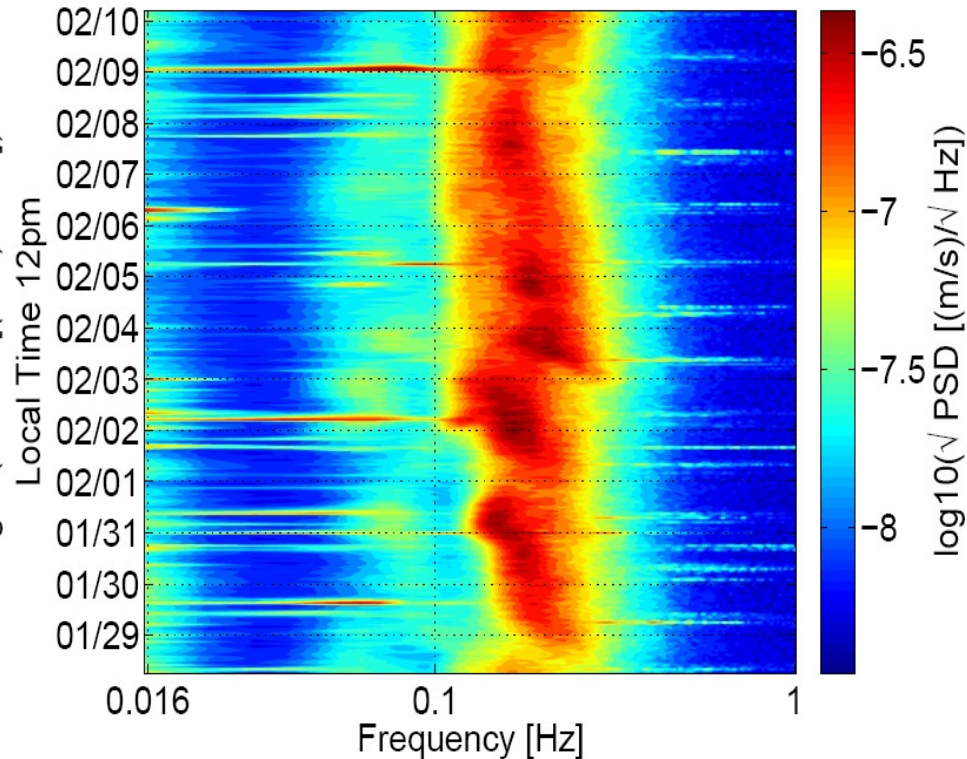
Homestake Vertical Motion

300ft appears to have significantly more local disturbances.
Possibly due to proximity of the shaft and the hoist?

Vertical Motion at 300ft

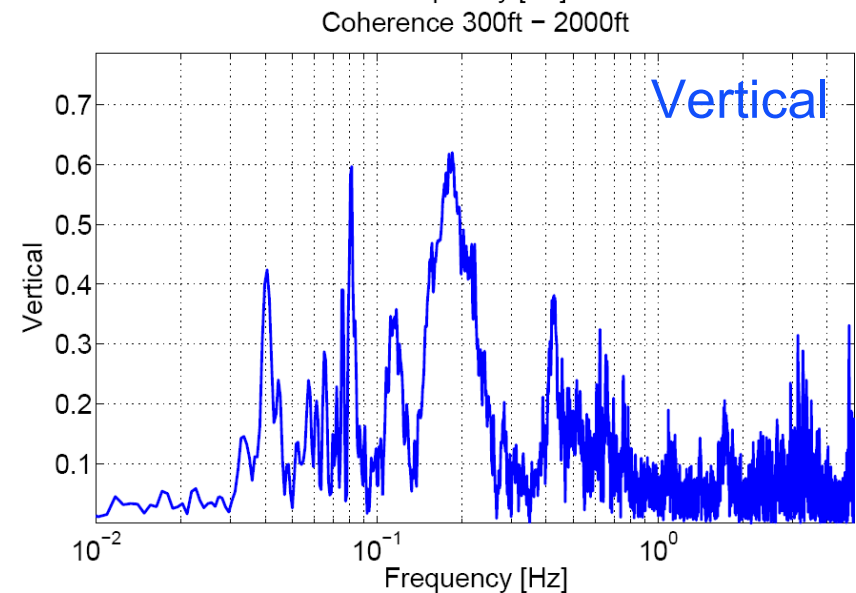
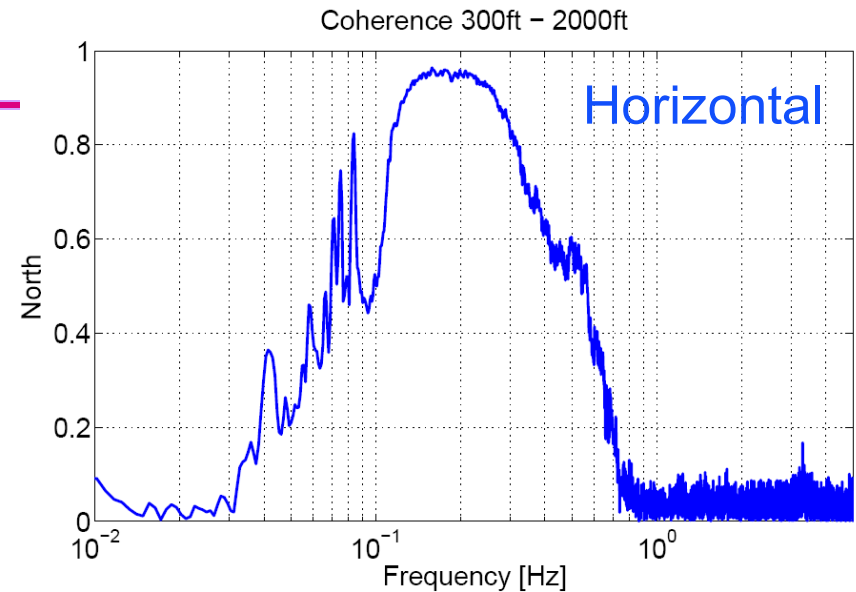


Vertical Motion at 2000ft



Coherence Between Levels

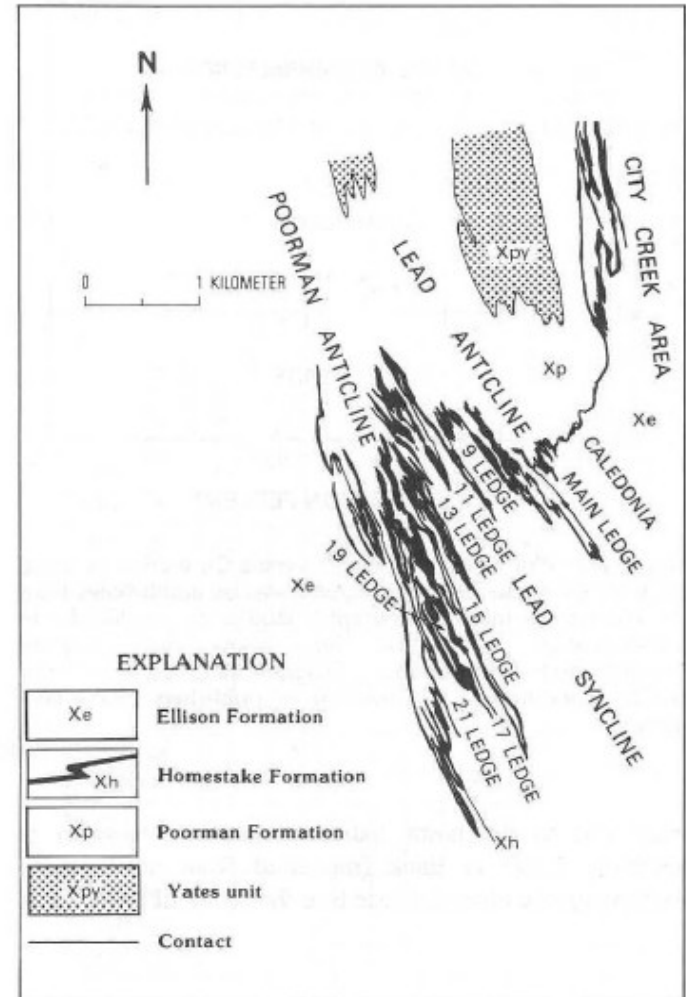
- Microseismic peak appears coherent, especially in horizontal DOF.
- Elsewhere the coherence is strongly reduced:
 - » Reliable range is: 50 mHz – 0.7 Hz.
 - » Effect of local disturbances at 300 ft?
 - » Effect of the rock structure between 300ft and 2000ft?
- Of course, we really care about coherence at a given level.
 - » Hopefully soon...



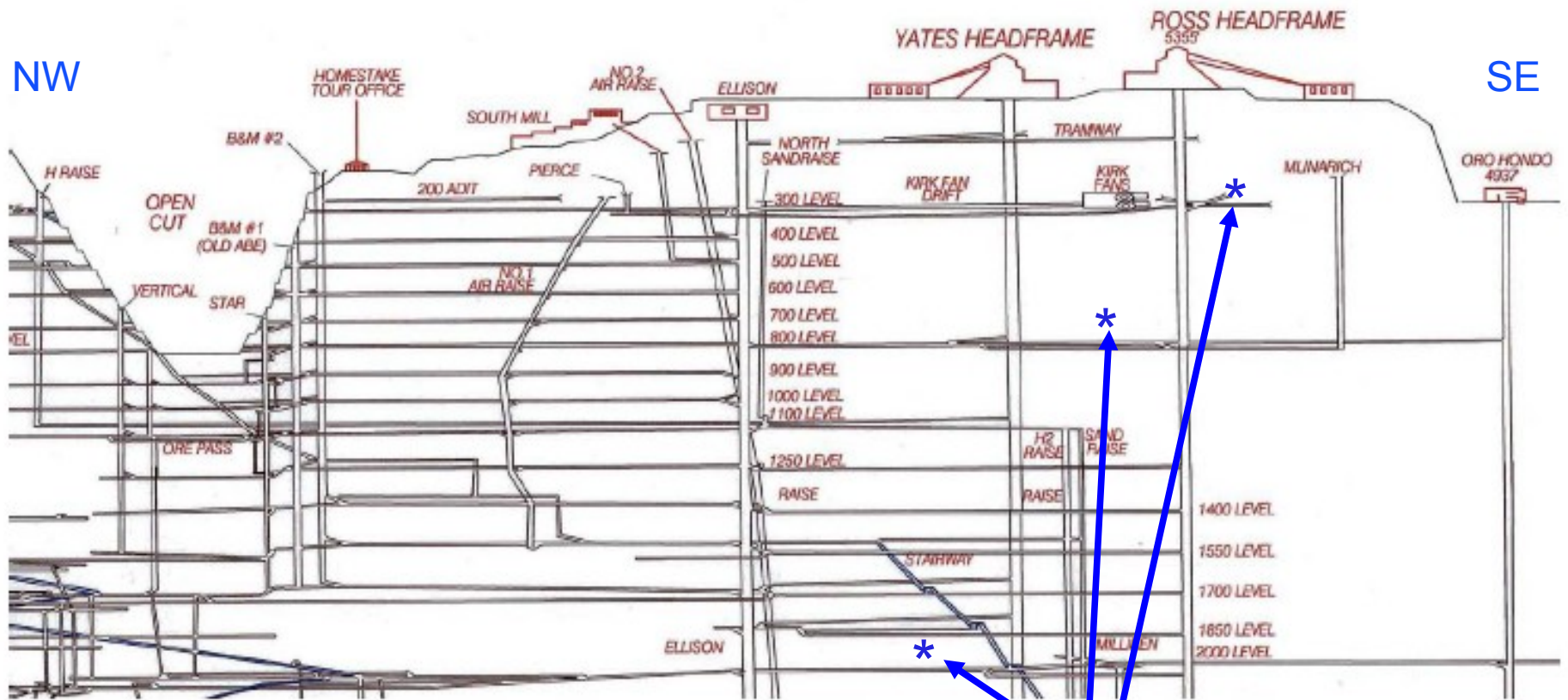
Homestake Mine

- Three formations:
 - » Poorman – oldest.
 - » Homestake – iron formation, contains gold ore.
 - » Ellison - youngest.
- Geological evolution significantly deformed these formations.
 - » Ledge-like structure, thicknesses vary.
- But it is very well understood.

2600 ft level

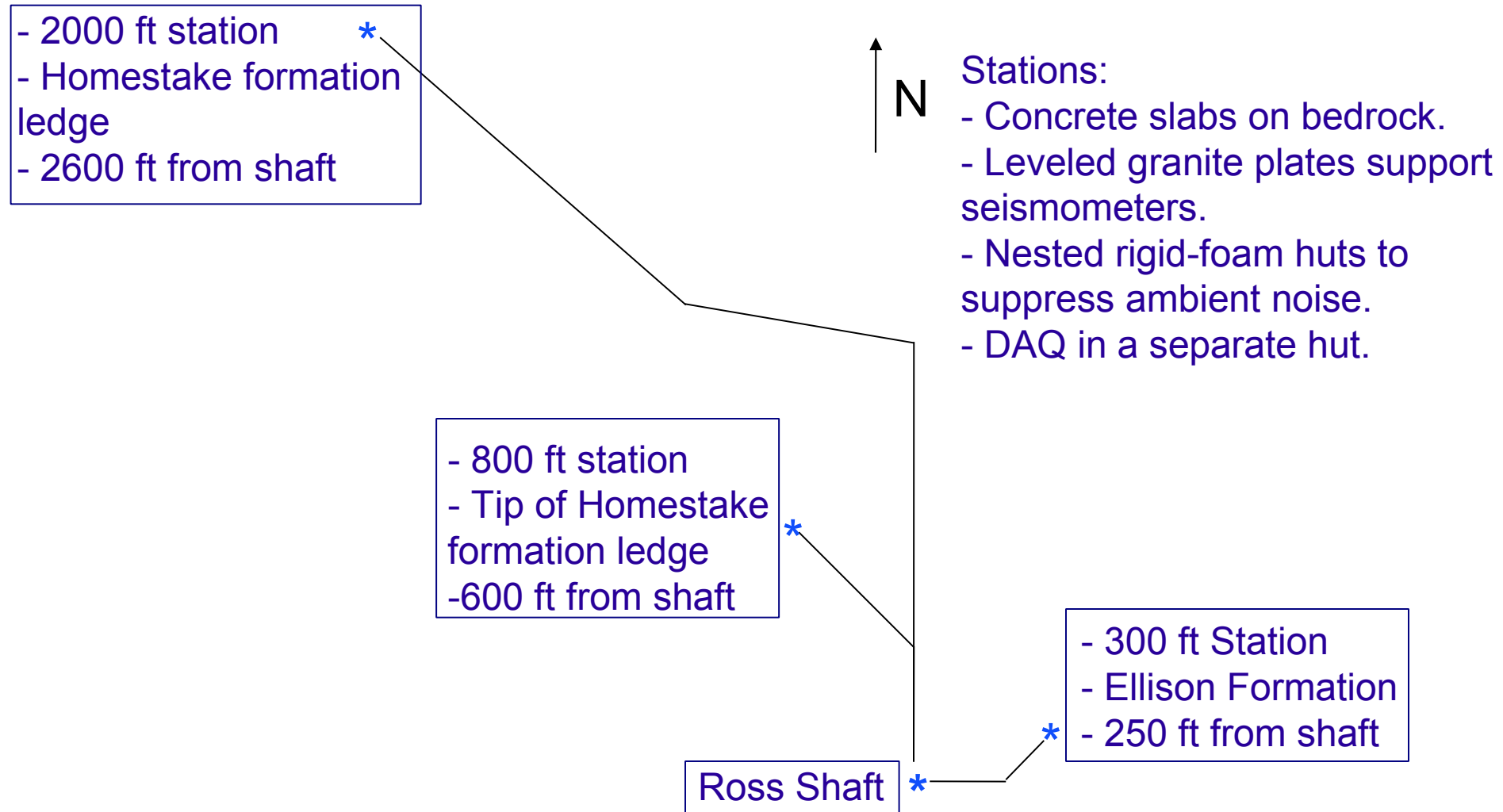


Homestake Mine

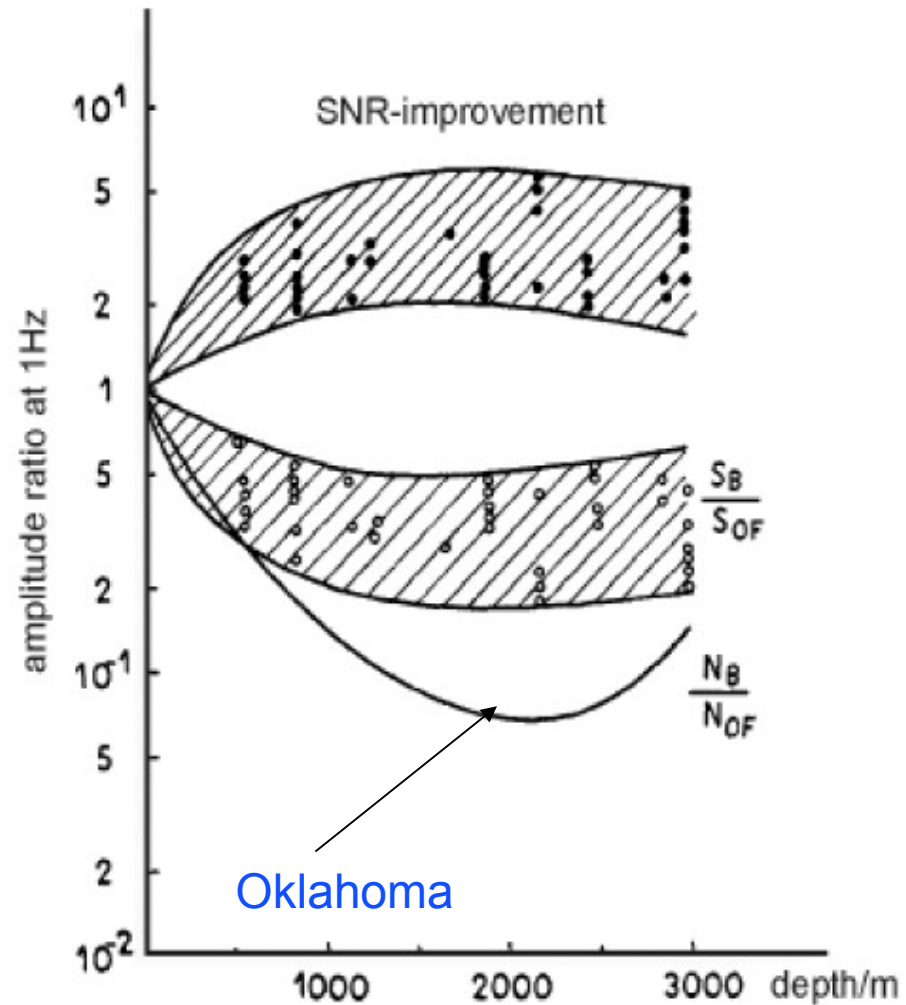
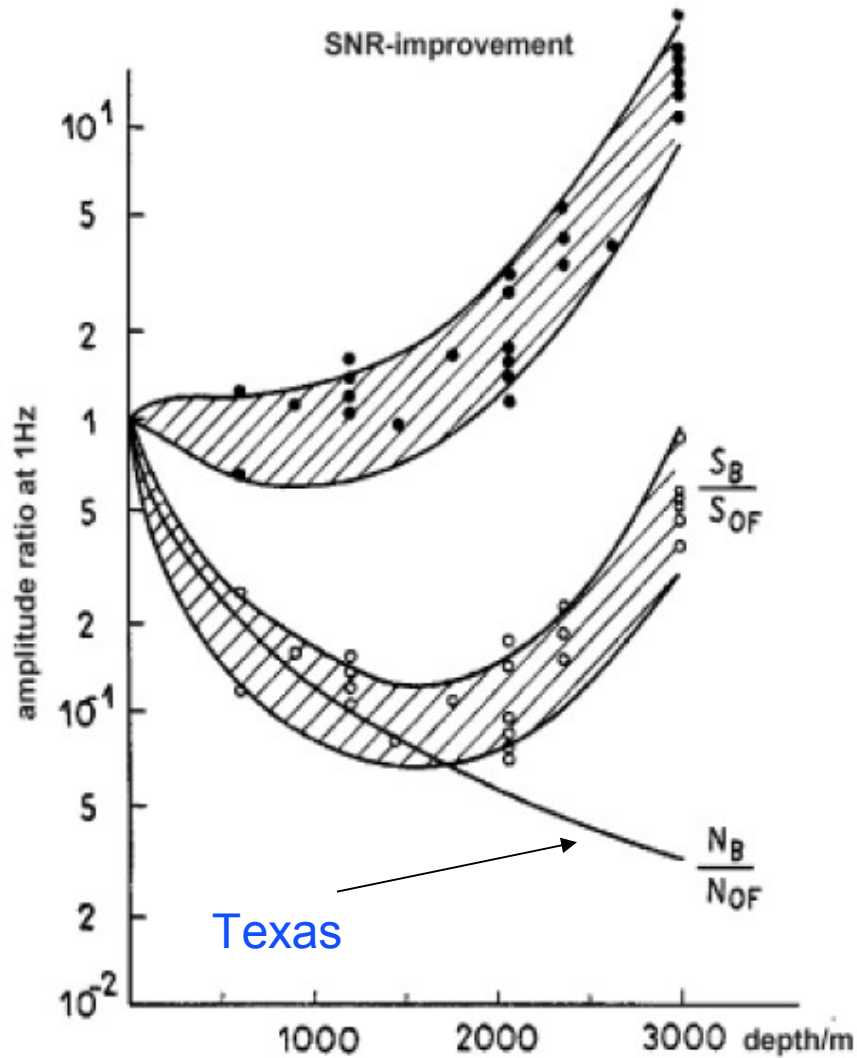


Rough locations of stations

Seismic Stations

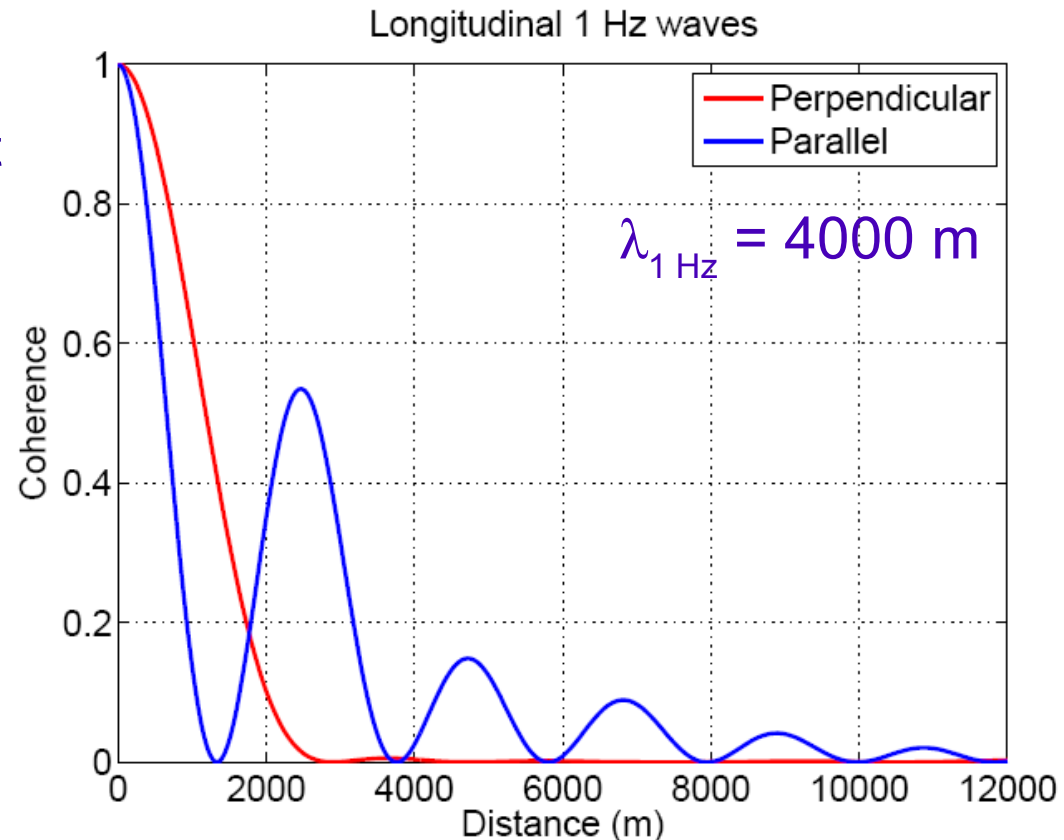


Measured Seismic Noise Suppression



Why Underground?

- Simulation:
 - » In a perfect medium expect coherence over ~ 2 wavelengths.
 - » At 1 Hz, this is about 8-10 km.
- Intuitively:
 - » $\Delta x \sim 1/\Delta k = \lambda / 2\pi$
- Imperfect medium may reduce the correlation length.



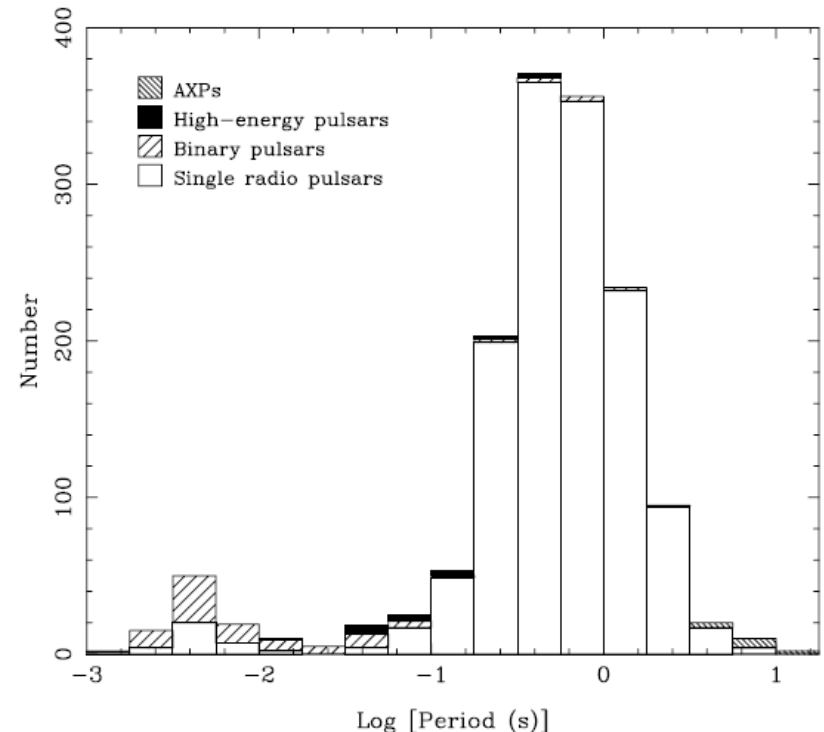
What Do We Know About Underground?

- Not much!
- How does seismic noise amplitude depend on depth and frequency?
 - » How deep should we go?
 - » How much does rock content matter?
 - » How much does rock non-uniformity matter?
- How does correlation length change as a function of depth and frequency?
 - » How deep should we go?
 - » How much does rock content matter?
 - » How much does rock non-uniformity matter?
- How much can we gain by building large cavities?
 - » Less sensitive to tilts?
- What does this mean for the gravity gradient noise?
- How does this constrain the design of an underground GW detector?
- Many questions!
 - » Need detailed underground measurements and finite-element models to answer these questions!

Science Case: Periodic Sources

- Majority of pulsars have period around 1 sec (~ 1 Hz):
 - » More than 90% of the 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.
- Spin-down rates are higher.
- Strain amplitudes are expected to be smaller.
 - But there are more of them.
 - Likelier to be closer.

Pulsar Period Distribution



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

Science Case: Binary Inspirals

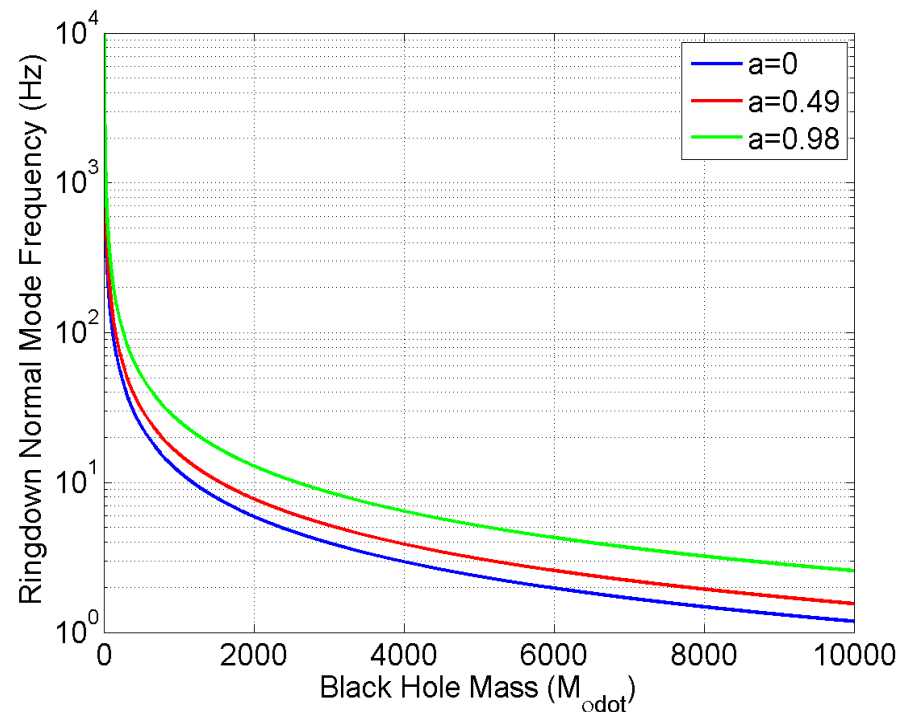
- Among the best motivated sources.
- Highest inspiral frequency (last stable orbit):

$$f_{\text{merge}} = \frac{c^3}{6\sqrt{6}\pi GM} \sim 4.4 \text{ kHz} \times \left(\frac{M_{\odot}}{M_{\text{tot}}} \right)$$

- Dominant mode during the ringdown phase:

$$f \simeq 32 \text{ kHz} \times \left[1 - 0.63 (1 - \hat{a})^{0.3} \right] \left(\frac{M_{\odot}}{M} \right)$$

- Observe more massive binary objects.
- Track the less-massive objects longer.
- Origin of intermediate mass black-holes (IMBH), 10^2 - 10^4 solar masses.
 - » Direct collapse (no inspiral)
 - » Accretion/merger (with inspiral).
 - » Distinguish between two formation mechanisms.



Science Case: Fundamental Physics

- Physics of highest energy scales:
 - » Stochastic background (inflationary models, cosmic strings...)
- Cosmology:
 - » Binary inspirals are standard sirens: from apparent luminosity (strain) and other measured parameters (location, polarization, chirp mass) can deduce the luminosity distance.
 - » Need EM counterpart to measure redshift.
 - » Can probe Dark Energy with $z \sim 1$.
 - » Can study Dark Matter distribution via gravitational lensing.
- Neutron stars:
 - » Still don't know what makes pulsars pulse.
 - » Don't understand the interior properties (equation of state, source of magnetic field etc).
- Graviton mass:
 - » Speed of gravitational waves (with EM counterpart?).
 - » Modification of inspiral waveforms.





800ft Station

- 800ft station completed, but does not have power or network access yet.
- Required significant construction.
 - » Building concrete platforms underground is not trivial!

2000ft Station



- 2000ft station completed.
 - » Has power, fiber cable laid out.
 - » Expect network access this week.
- Currently running two Nanometrics T240 seismometers and STS-2 side-by-side.
 - » Read out by local Nanometrics data acquisition, will transition to ours soon.
- Preliminary results are very encouraging.
 - » Our station is within a factor of 3 from the quietest measured on Earth!
 - » May get even better with time, as the instruments settle and we learn how to set them up.

Theoretical Models (Cella)

Active suppression

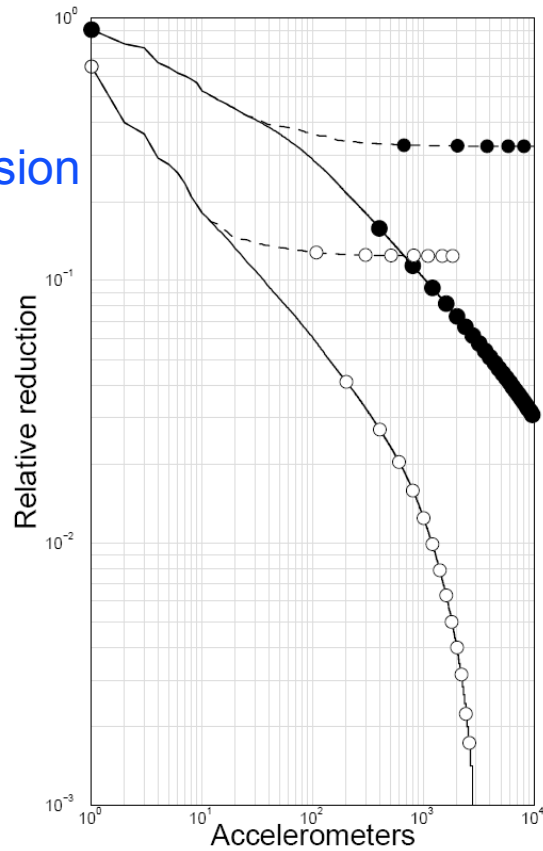
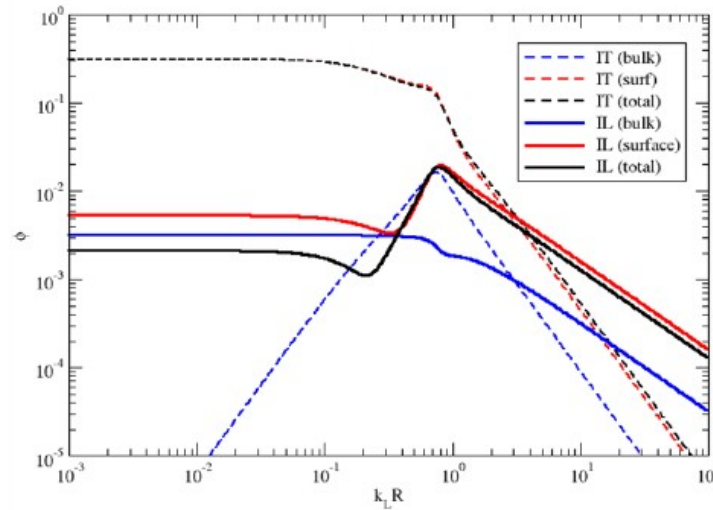
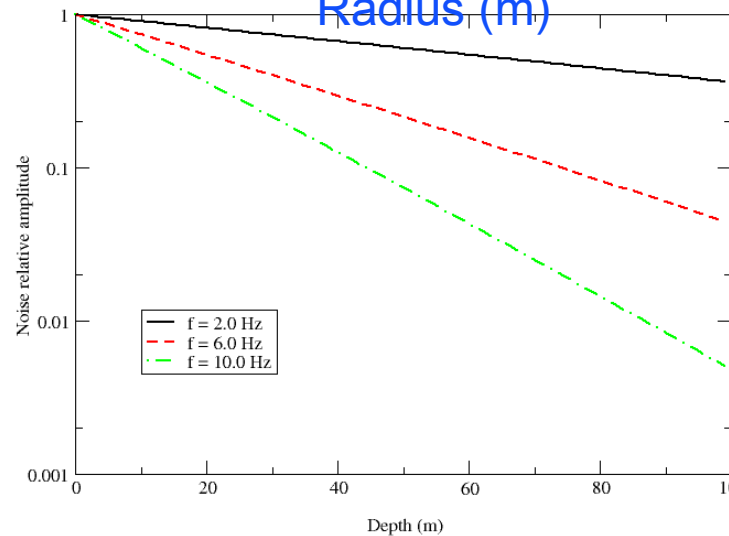


Figure 1: Relative reduction of noise amplitude for Saulson's symbols are for $f_0 = 0.1$ Hz, the filled ones for $f_0 = 1$ Hz. The the accelerometers to



Suppression due to cavity

Radius (m)



Suppression due to depth

Other Experimental Efforts

- Einstein Telescope

- » European 3rd generation gravitational-wave observatory.
- » Conceptual design study already funded: 3M euro for 3 years.
- » Already started: investigating site selection, tunneling costs etc.

- Kamioka mine:

- » A number of activities: strain meters, gravimeters, seismometers...
- » CLIO: underground 100m interferometer, in operation, deploying cryogenic techniques.
- » LCGT: 3km, underground, cryogenic interferometer already proposed.