Status of the Seismic Noise Study at the Homestake Mine (DUSEL)

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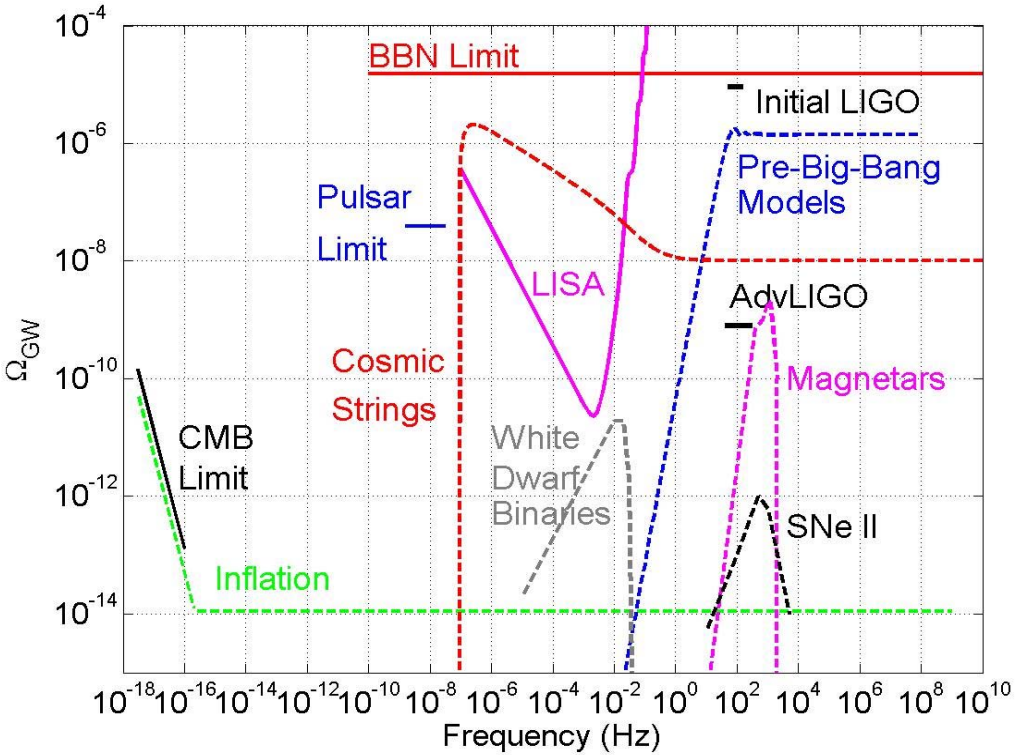
09/22/08

LIGO-G080491-00-Z

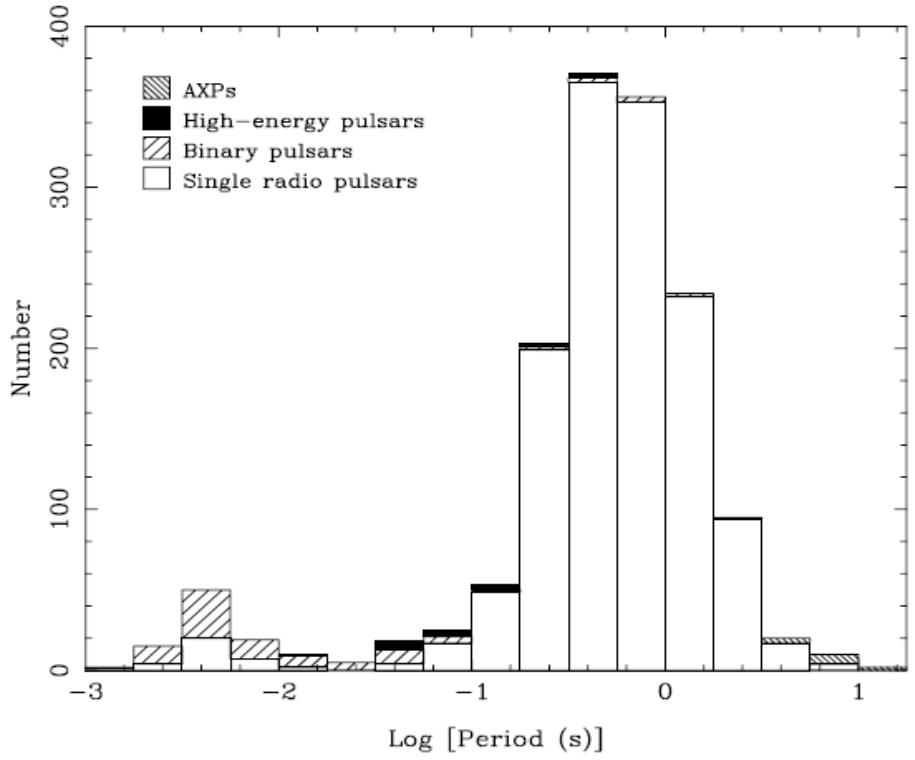
Why Underground?

- Third generation GW detectors will likely go after the 1Hz region.
- Possibilities discussed at GWADW at Elba (May 2008).
  - » Strong scientific motivation (stochastic background, pulsars, inspirals).

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

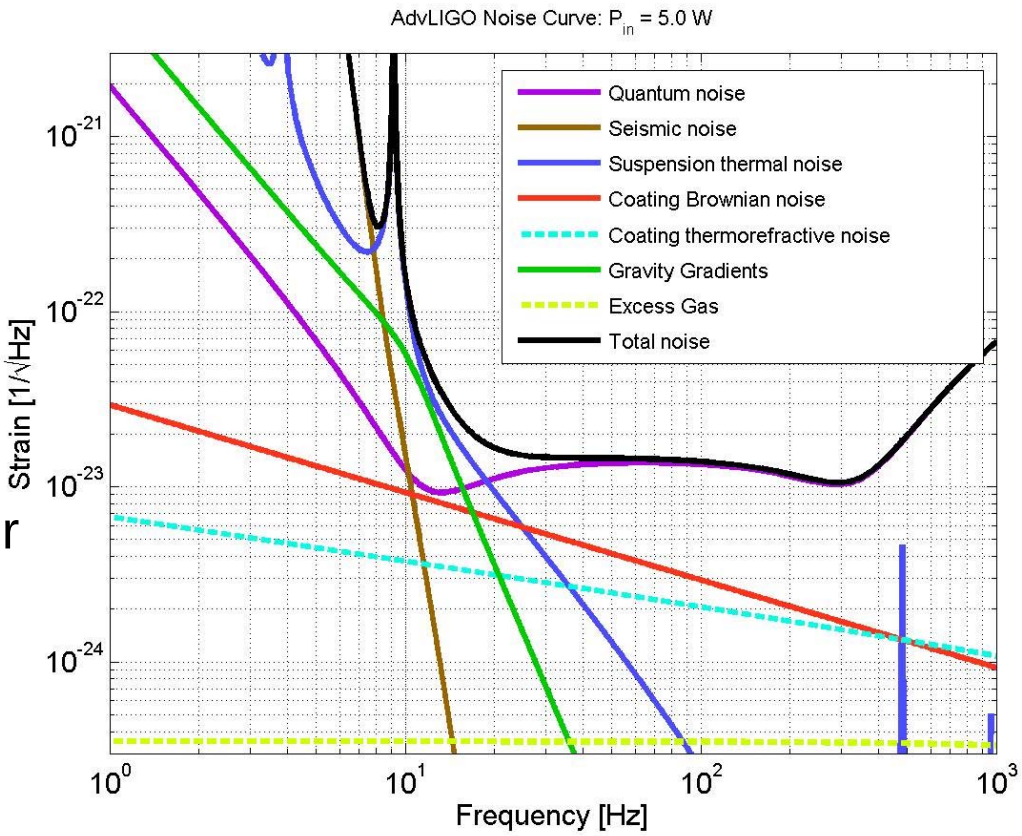


ATNF Pulsar Catalogue,
The Astronomical Journal 129, 1993 (2005)



Why Underground?

- Second generation detectors:
  - » Several noise sources dominate below 10 Hz.
  - » Difficult to probe below 10 Hz.
- Third generation detectors:
  - » Will have to address the radiation pressure and thermal noise. Research programs already under way.
  - » Gravity gradient and seismic noise: possible solution is an underground detector.

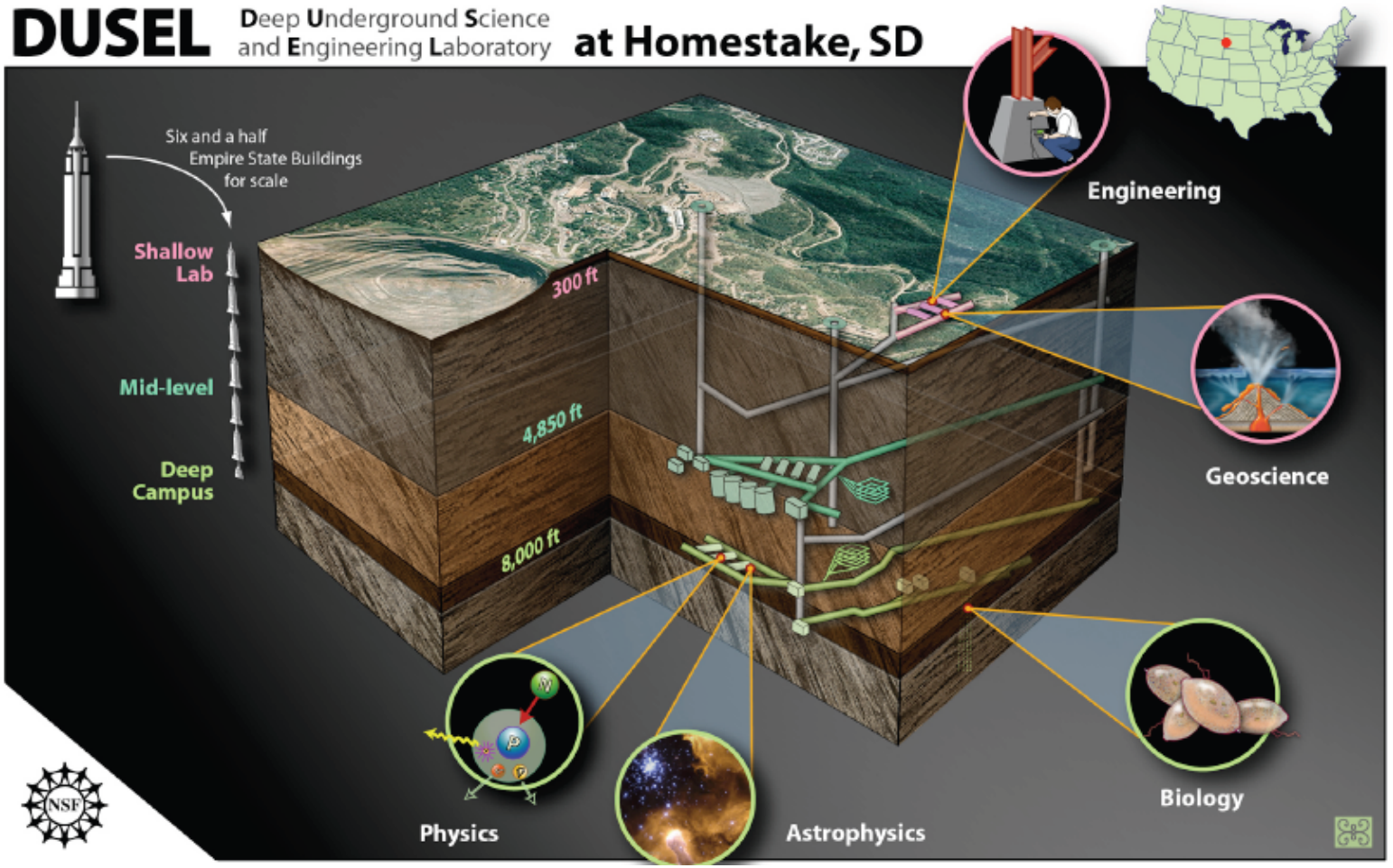


What Do We Know About Underground?

- Not much!
- Gravity gradient on the surface dominated by the vertical motion (heavy dirt displacing light air).
  - » Win quickly with depth, but how deep should we go?
- How does seismic noise change as a function of depth?
  - » Depends on the speed of sound, rock content, frequency of interest…
- Expect to gain by building large cavities.
  - » How much can we gain? How large can the cavities be? Does the rock content matter?
- Speed of sound underground is 3-5 km/s. For 0.1 Hz, the wavelength is 30-50 km! What does this imply for km-scale interferometers?
- Many questions!
  - » Need to perform measurements underground to assess how much can be gained.

What is DUSEL?

- DUSEL is an underground laboratory space providing infrastructure for science and engineering research (J. Kotcher, NSF).
  - » The primary motivation has been for fundamental physics research, exploiting the shielding from cosmic rays.



DUSEL Planning and Timeline

- Solicitation 3 (S3): technical facility design for an MREFC candidate (awarded to Homestake, U.C. Berkeley, Sep. 2007)
- Solicitation 4 (S4): Develop project plans for the Initial Suite of Experiments (ISE) for DUSEL.
  - » Expected in the summer 2008, but is delayed.
  - » Anticipate $15M total from Physics/MPS, over 3 (or more) years.
- Solicitation 5 (S5): Preliminary design proposals for the ISE.
  - » Expected in February 2009, proposals due summer 2009.
- S3+S4+S5 are intended to enable development of a comprehensive project plan for DUSEL: facility + experiments.
- Assembly of MREFC and submission for funding in ~December 2009.
  - » Construction probably FY 2012, or later.
- Expect $500M for the initial phase of MREFC (facility and experiments).
  - » 7-8 year construction period.
- Planning assumes facility costs would be borne by NSF.
  - » Partnerships with DOE & others will be sought.

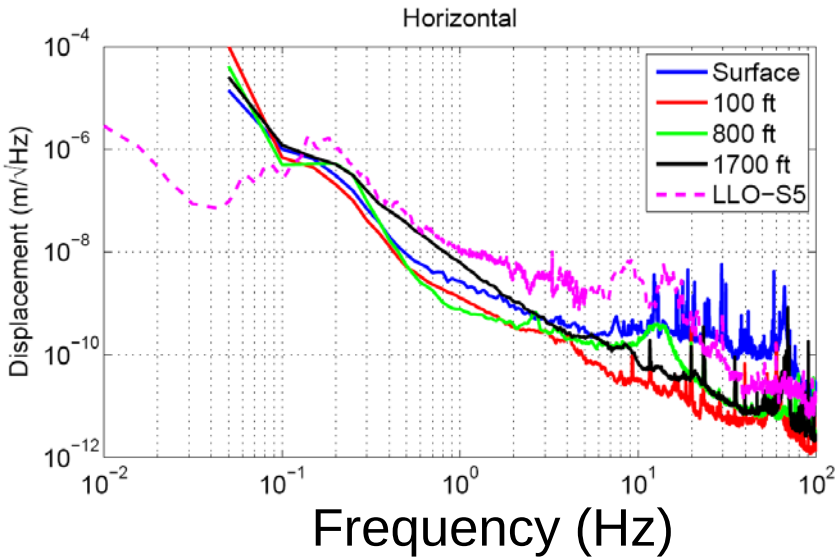
DUSEL as a Low Gravitational Background Facility

- Much of the drive for DUSEL comes from the low cosmic ray background levels.
- But, DUSEL is also attractive as a low gravitational background facility.
  - » Gravitational waves
  - » Equivalence principle tests
  - » Natural connections with geology/geophysics/seismology.
- Brain-storming sessions held in April 23-26, 2008 at Lead, SD.
  - » Included a number of discussions with geophysicists, engineers, Lab administration, NSF representatives.
  - » Emerged with an outline of activities to be pursued in the coming 3-4 years.

R&D Directions: Seismometer Array

- Probe available depth/distances.
  - » Go after 10 mHz – 30 Hz band.
  - » Measure seismic noise as a function of depth.
  - » Measure correlations as a function of distance.
  - » Measure the sound velocity and its potential anisotropy.
- Also of interest for geology/seismology:
  - » Transparent Earth (Glaser, Roggenthen) focuses on >1 Hz.
  - » Deformations due to excavations/dewatering etc.
  - » Possibly Earth eigenmodes.
- Preliminary measurements done in Feb. 2008.
  - » Known to have problems.
  - » Initiated a campaign in the summer 2008.

Preliminary Measurements



R&D Directions: Seismometer Array

- Developing a collaboration to investigate the gravitational field noise underground.
  - » Minnesota, Caltech, U of Florida, Carleton, Louisiana State.
- First trip in February 2008.
  - » Preliminary measurements, established contacts.
- Initiated a more detailed campaign in the summer 2008.
  - » Building an array of seismic stations:
    - – Completed three: 300ft, 800ft, 2000ft.
  - » Monitor environmental conditions (magnetometers, thermometers...)
  - » Combine with theoretical models to estimate gravity gradient noise.
  - » Goal: inform the design of a multi-km gravitational-wave interferometer.
  - » Jan Harms (postdoc, Minnesota) and Angelo Sajeva (summer student, Caltech) spending 2-3 months at Homestake.
    - – Riccardo DeSalvo (Caltech) and Vuk Mandic (Minnesota) on rotation-schedule.
    - – Also help from Nelson Christensen (Carleton), Vinzenz Wand (Florida)
  - » Seismometer Loans: STS-2 (LIGO), Guralp (Carleton), T240 (Nanometrics)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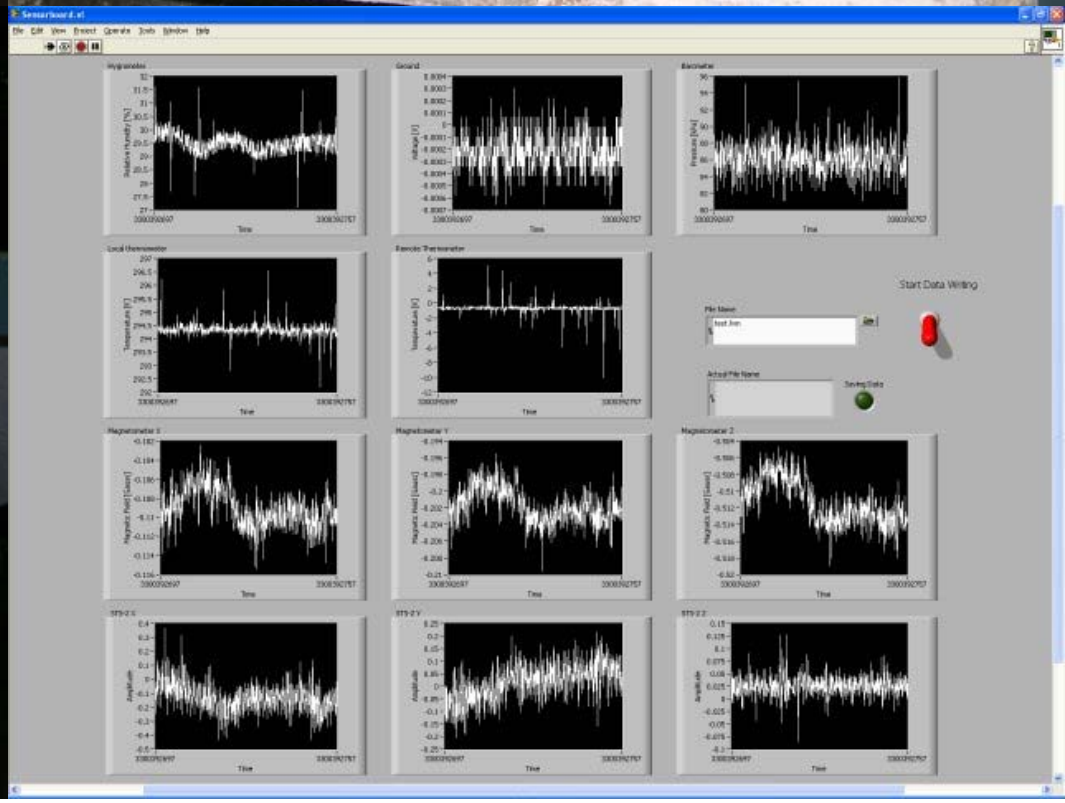
DANGER

300ft Station



800ft Station

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

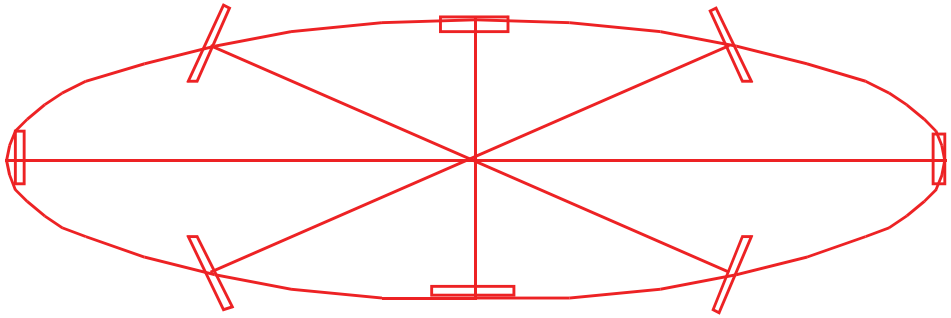
2000ft Station

- 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 Nanometric 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.

R&D Directions: Strainmeters

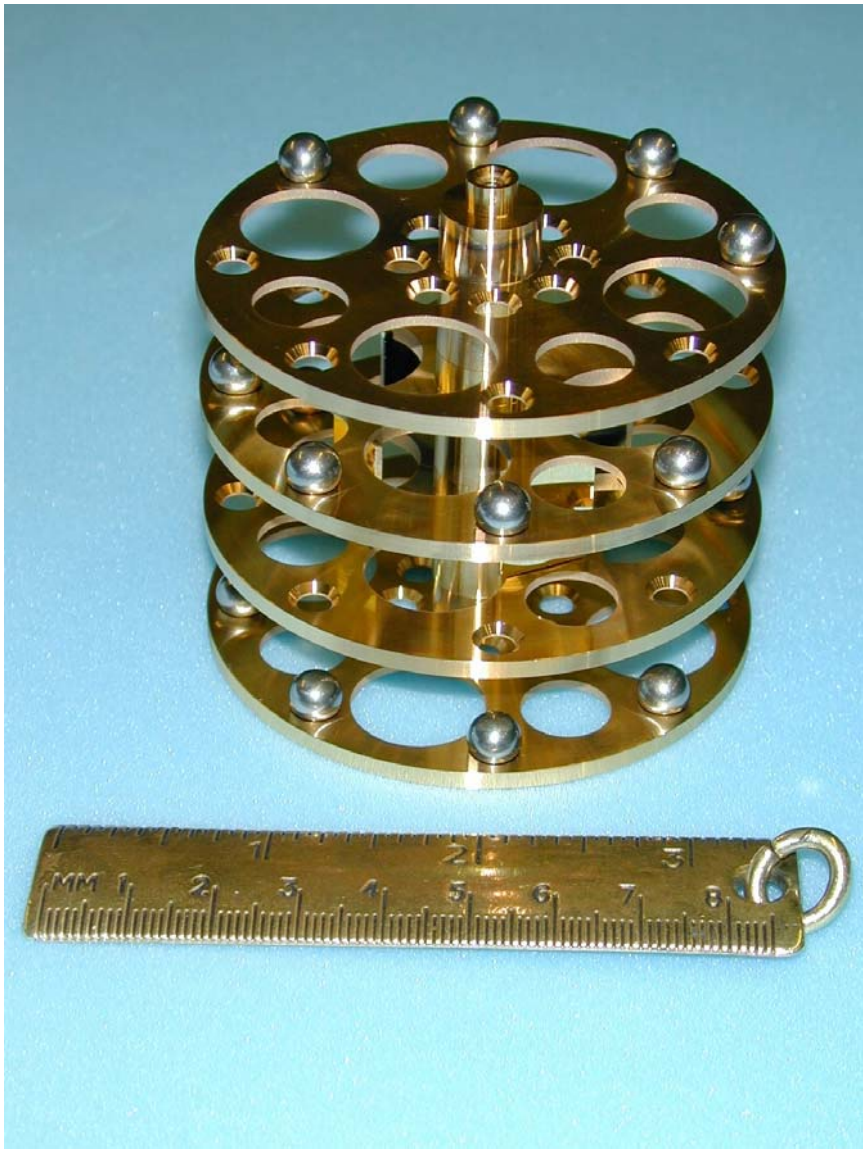
- Motion of the cavern wall surface appears to be dominant source of Newtonian noise.
  - » Based on preliminary calculations.
- Measure the relative motion of wall surfaces
  - » Mount mirrors on the walls.
  - » Cavities or interferometers as optical strainmeters.
  - » Probe different directions.
  - » Study correlations between different points.
  - » Probably require 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.



R&D Directions: 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/√Hz (corresponding to 10^{-13} m/√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

Costs and Plans

- Expected costs:
  - » Seismometer array: ~$200k.
  - » Strainmeter: ~$200k
  - » Gravity Gradiometers: ~$200-300k
  - » Operations/Maintenance/Data Analysis: ~$500k
- Not clear if S4/S5/MREFC process is the best way forward.
  - » Relatively small scope projects.
  - » Timing would overlap with major DUSEL construction.
  - » Not anxious to go through WBS etc…
- Considering SUSEL as the appropriate venue/time.
  - » Considering DUSEL R&D proposal (due Dec 2008).
  - » Perform measurements before the DUSEL construction begins.

Conclusion

- DUSEL offers very interesting possibilities for gravitational physics, as an exceptionally quiet Newtonian force environment.
- But, need to understand the levels of seismic noise and gravity gradient noise as a function of depth.
- Planning a collection of measurements to characterize the site.
  - » Interesting connections with geology/geophysics/seismology.
- The results would inform future experiments:
  - » Underground 10km-scale gravitational-wave interferometers.
  - » Torsion-balance tests of the equivalence principle.
  - » Possibly others (e.g. atom interferometers as gravitational-wave detectors).

Theoretical Models (Cella)

Active suppression

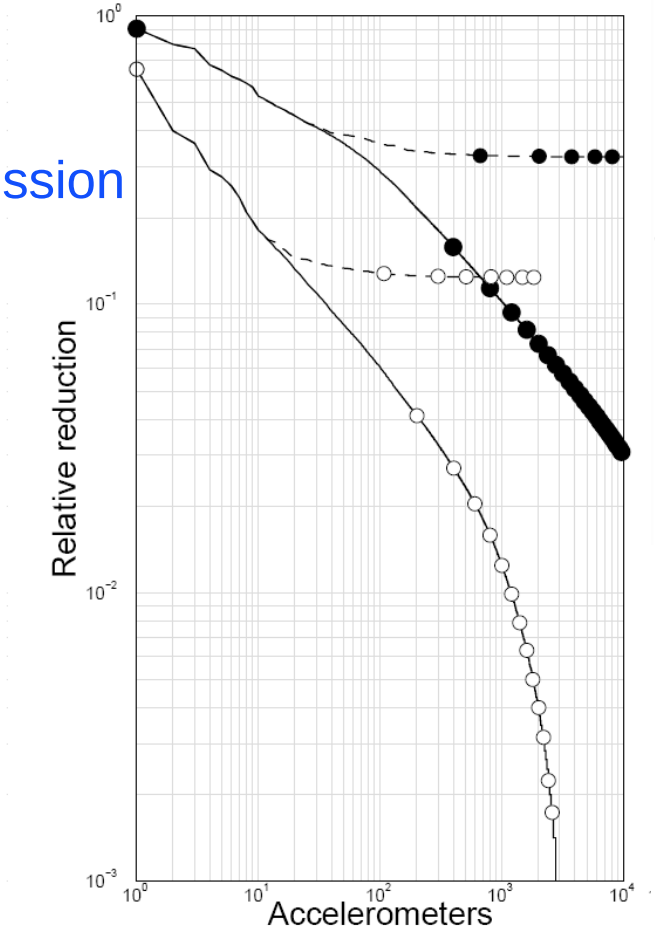
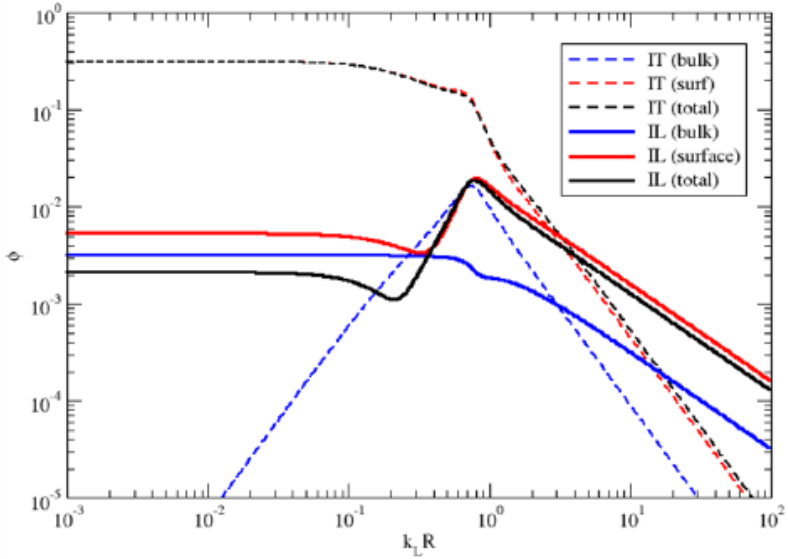
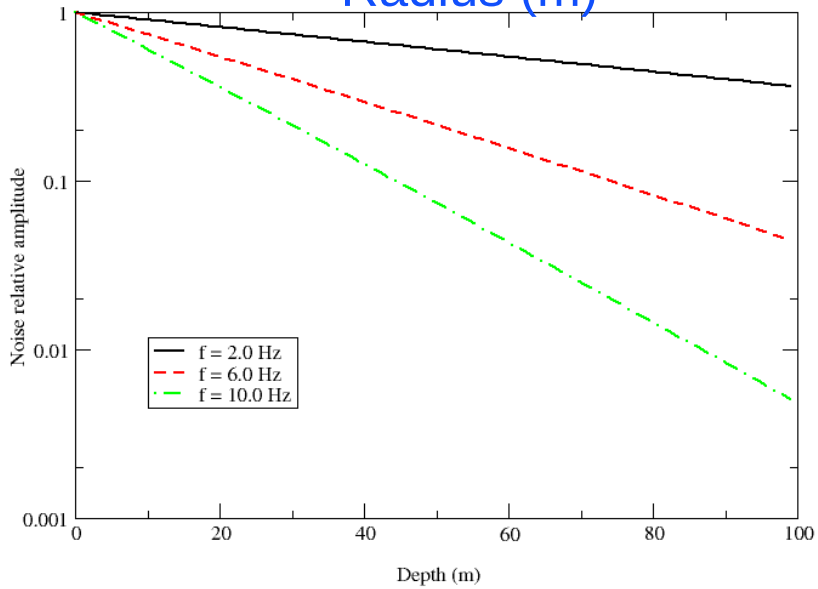


Figure 1: Relative reduction of noise amplitude for Saulson's symbols are for $f_0 = 0.1$ Hz, the filled ones for $f_0 = 1$ Hz. The the accelerometers to



Suppression due to cavity

Radius (m)



Suppression due to depth