Modelling gravity fluctuations underground above 10mHz

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Why do we care?

Gravity fluctuations above 10mHz have never been observed:

- Sensitivity of gravimeters is (ultimately) limited by seismic noise
- GW detectors are not yet sensitive enough

Terrestrial gravity fluctuations above 10mHz will become relevant since:

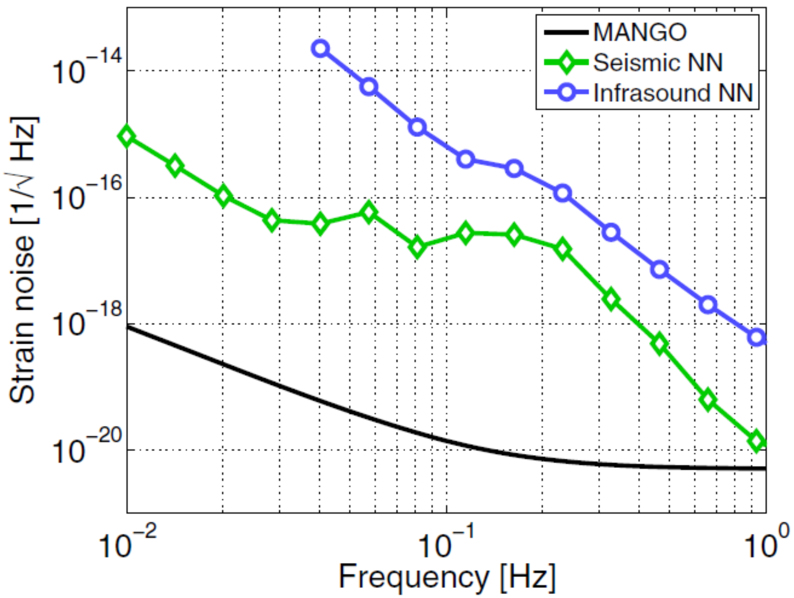
- Future generations of gravity gradiometers will observe terrestrial gravity fluctuations up to a few Hz
- Sensitivity of GW detectors will be limited by terrestrial gravity noise

Underground laboratories promise significant reduction of gravity background noise.

Terrestrial Gravity Noise in GW Detectors

Ground-based GW detection below 1Hz would require extreme reduction of gravity-noise foreground.

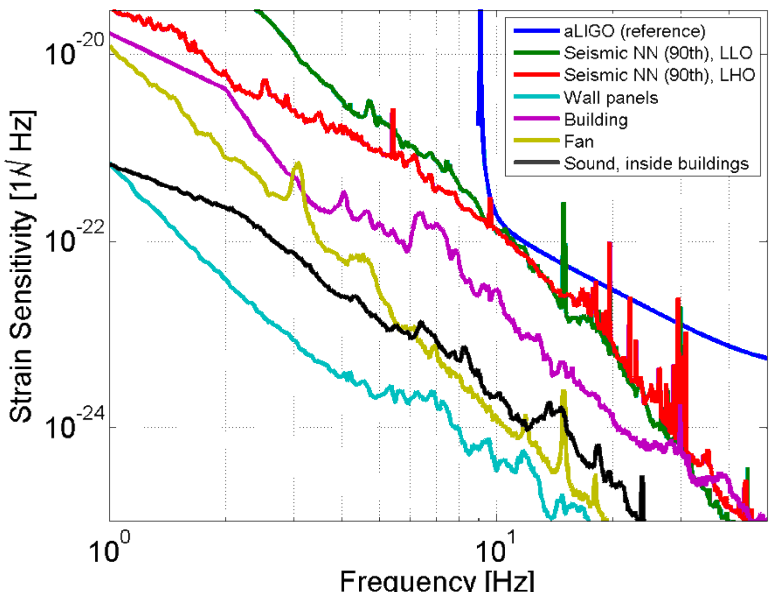
Advanced detectors will already be limited by gravity noise at seismically loud times.



PHYSICAL REVIEW D **88**, 122003 (2013)

Low-frequency terrestrial gravitational-wave detectors

Jan Harms,[1] Bram J. J. Slagmolen,[2] Rana X. Adhikari,[3] M. Coleman Miller,[4,5] Matthew Evans,[6] Yanbei Chen,[7] Holger Müller,[8] and Masaki Ando[9,10]



PHYSICAL REVIEW D **86**, 102001 (2012)

Subtraction of Newtonian noise using optimized sensor arrays

Jennifer C. Driggers, Jan Harms, and Rana X. Adhikari

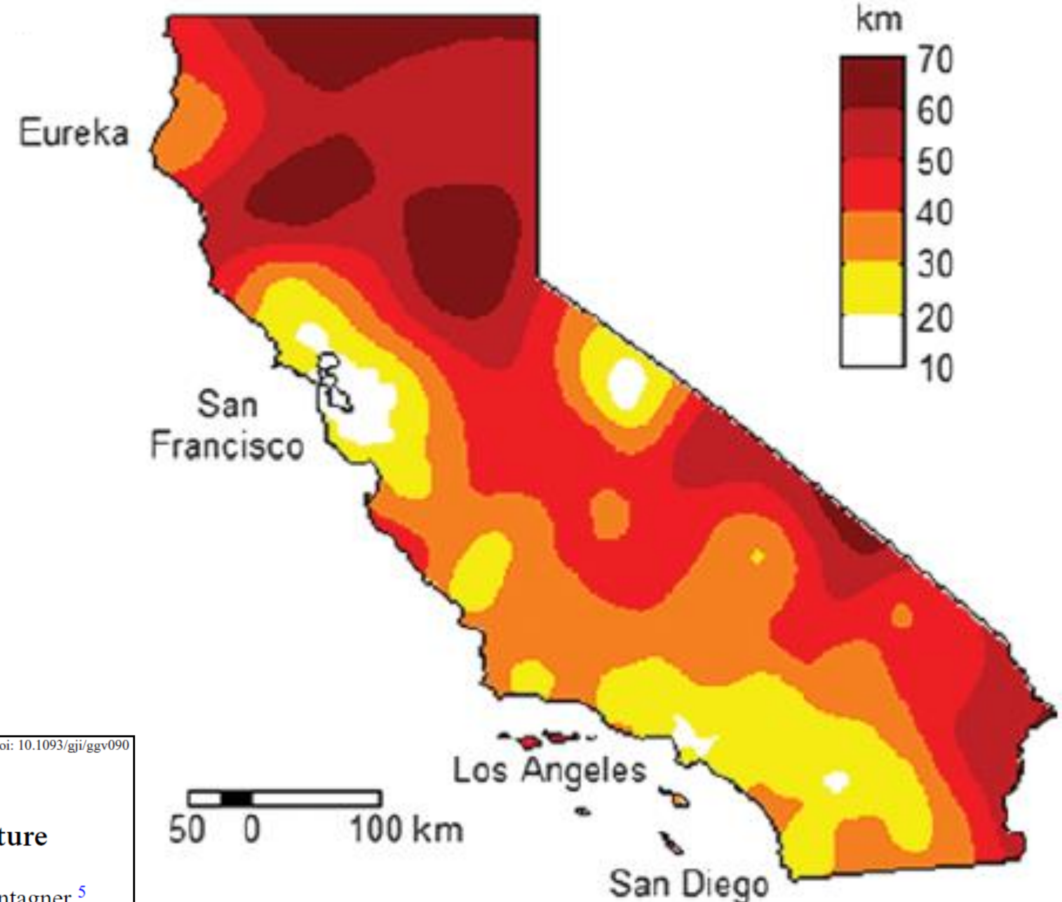
INFN Istituto Nazionale di Fisica Nucleare

VIRGO

Light-Speed Seismology: Earthquake Early Warning

- **Blind zone** = region close to the earthquake epicenter where damaging waves arrive before the warning is declared by a network-based EEWS
- Goal: develop new generation of **gravity gradiometers** to reduce size of blind zones

Blind zone size in California (Kuyuk and Allen, 2013)



Geophys. J. Int. (2015) **201**, 1416–1425 doi: 10.1093/gji/ggv090
GJI Gravity, geodesy and tides

Transient gravity perturbations induced by earthquake rupture

J. Harms,[1,2,*] J.-P. Ampuero,[3] M. Barsuglia,[4] E. Chassande-Mottin,[4] J.-P. Montagner,[5] S. N. Somala[3] and B. F. Whiting[4,6]

Modelled Sources

Gravity models developed so far are summarized in:

"Terrestrial Gravity Fluctuations"
arxiv.org/abs/1507.05850

Effects:

- Reflection of seismic waves from surface (flat or rough)
- Scattering of seismic waves from cavities
- Reflection of infrasound waves from surface (flat or rough)

Sources:

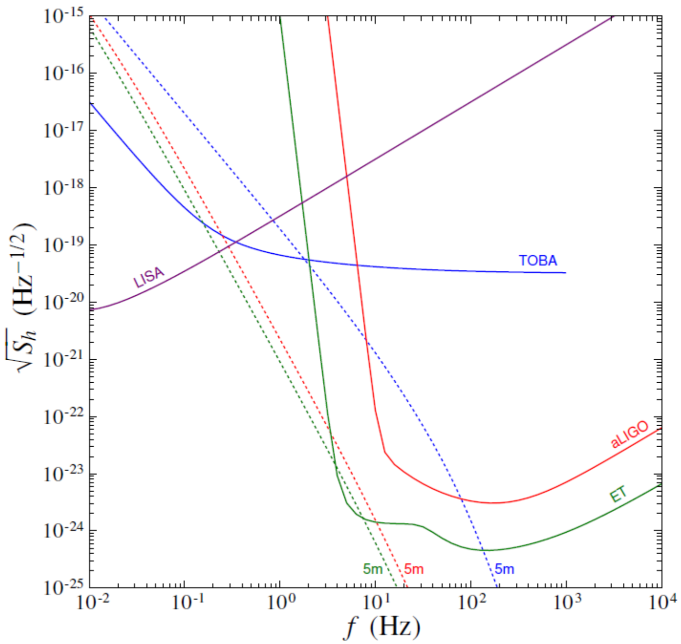
- Seismic fields (surface, body)
- Seismic point sources (force, double couple)
- Lighthill process (turbulent sound generation)
- Advected field of temperature perturbations
- Infrasound field
- Oscillations, translations, rotations of arbitrary bodies
- Shock waves

Gravity Noise Reduction Underground

Gravity noise from sound waves

$$\delta\phi(\vec{r}_0,t) = 4\pi\frac{G\rho_0}{\gamma\, p_0}e^{\mathrm{i}(\omega t-\vec{k}_\varrho\cdot\vec{\varrho}_0)}e^{-k_\varrho|z_0|}\frac{\delta p(\omega)}{k^2}$$

Exponential suppression



Creighton, GWADW 2015

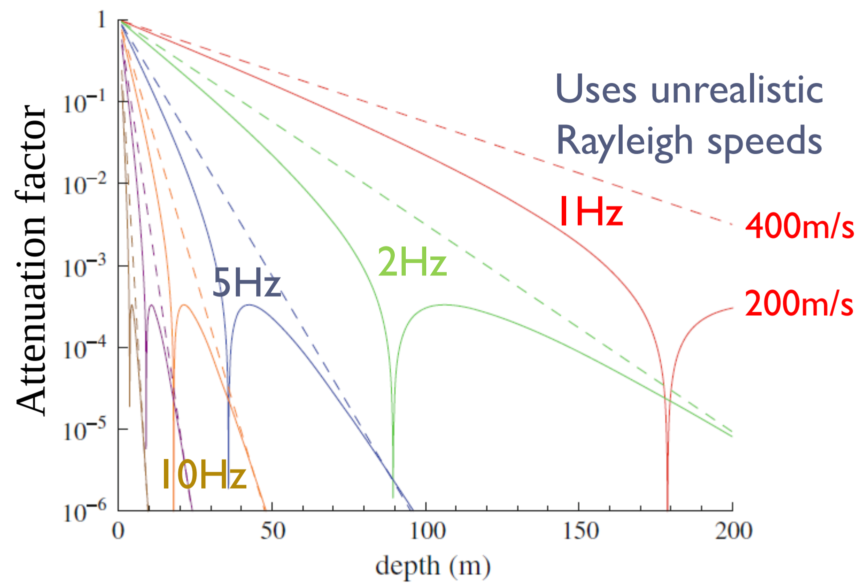
Two examples

Gravity noise from Rayleigh waves

$$\delta\phi_{\mathrm{surf}}(\vec{r}_0,t)+\delta\phi_{\mathrm{bulk}}(\vec{r}_0,t) =$$
$$2\pi G\rho_0 A e^{\mathrm{i}(\vec{k}_\varrho\cdot\vec{\varrho}_0-\omega t)}\left(\left(-2e^{-hq_z^{\mathrm{P}}}\right)+(1+\zeta(k_\varrho))e^{-hk_\varrho}\right)$$

Evanescent wave

Surface displacement



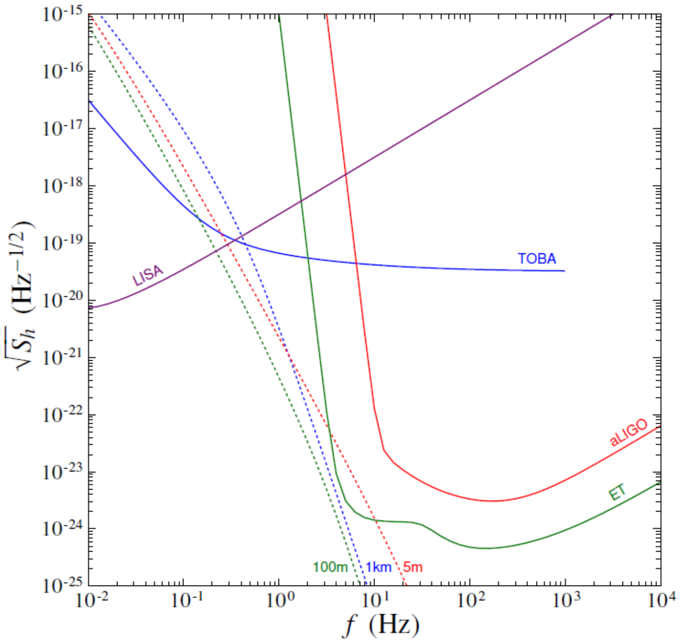
Beker et al, 2011

Gravity Noise Reduction Underground

Gravity noise from sound waves

$$\delta\phi(\vec{r}_0,t) = 4\pi\frac{G\rho_0}{\gamma p_0}e^{i(\omega t-\vec{k}_\varrho\cdot\vec{\varrho}_0)}e^{-k_\varrho|z_0|}\frac{\delta p(\omega)}{k^2}$$

Exponential suppression



Creighton, GWADW 2015

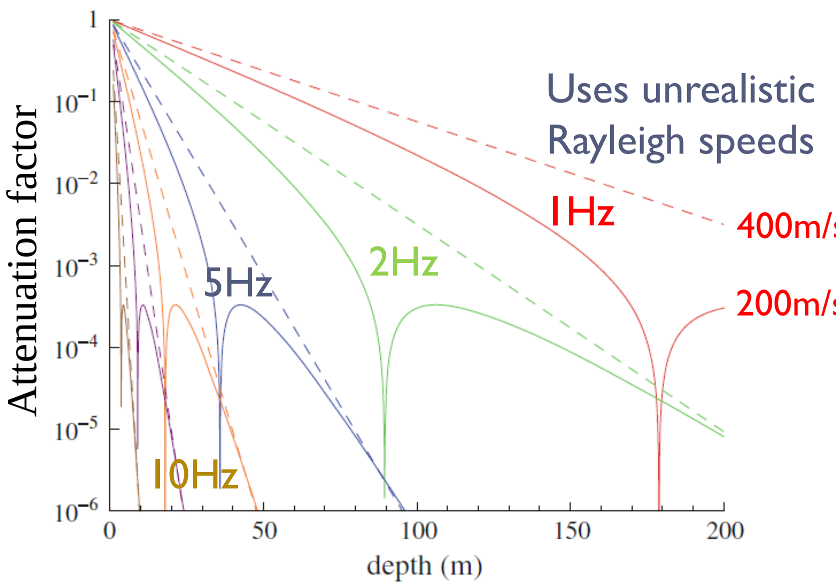
Two examples

Gravity noise from Rayleigh waves

$$\delta\phi_{\rm surf}(\vec{r}_0,t)+\delta\phi_{\rm bulk}(\vec{r}_0,t) =$$
$$2\pi G\rho_0 A e^{i(\vec{k}_\varrho\cdot\vec{\varrho}_0-\omega t)}\left(\left(-2e^{-hq_z^{\rm P}}+(1+\zeta(k_\varrho))e^{-hk_\varrho}\right)\right)$$

Evanescent wave

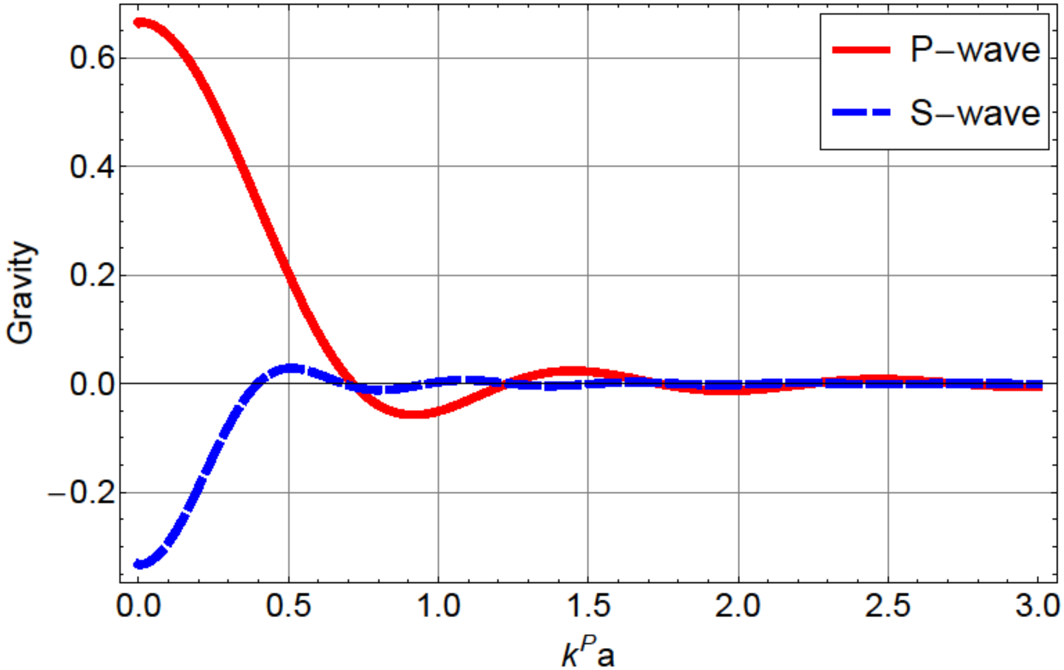
Surface displacement



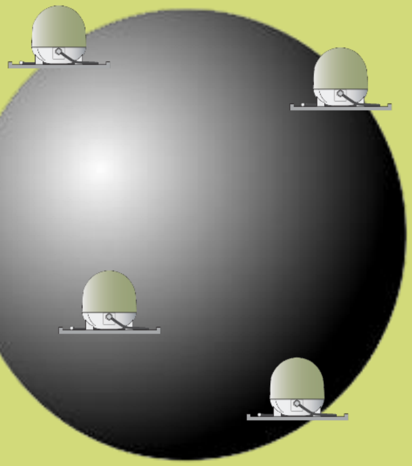
Beker et al, 2011

Underground Effects: Seismic

Cavities have to be extremely large to have a suppressing effect on gravity perturbations from seismic fields.

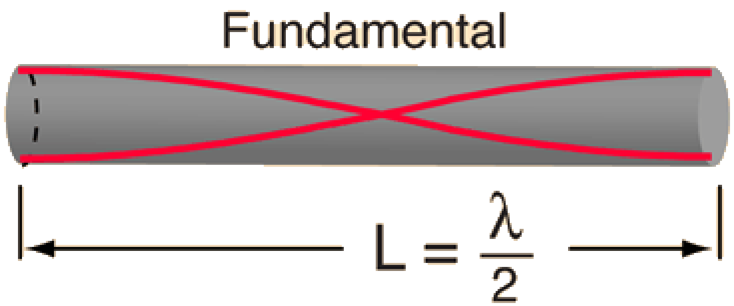


Cavity wall

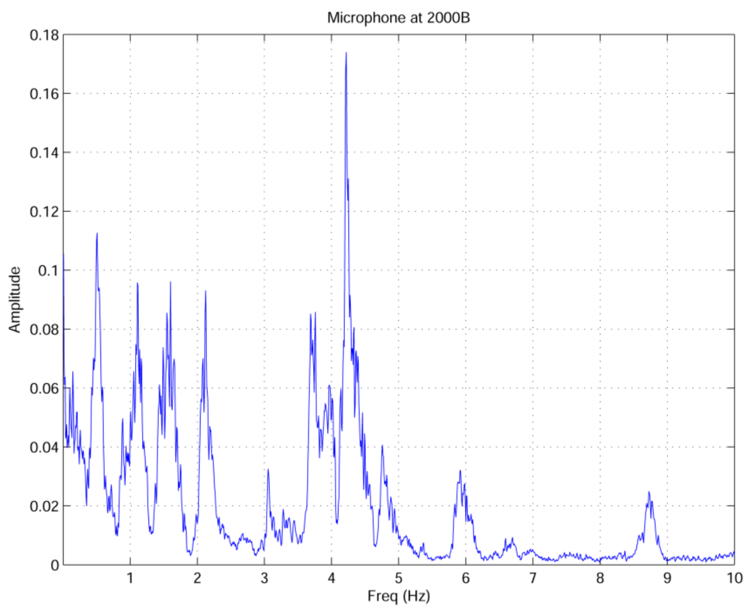


If cavity is small, cavity-wall displacement is approximately equal to seismic wave amplitudes (not true for a flat surface).

Underground Effects: Sound

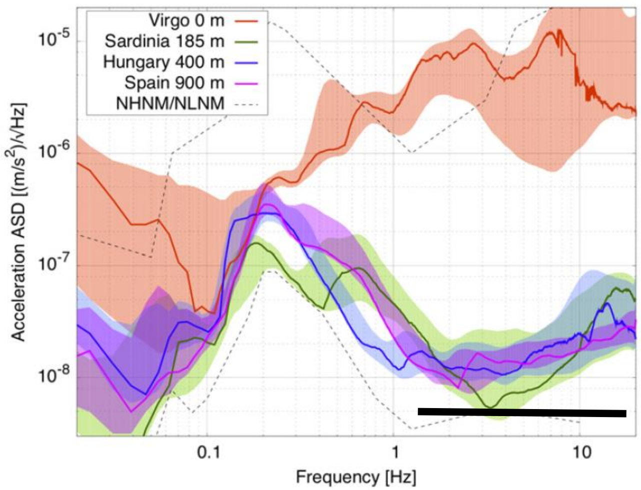


$$f_1 = \frac{v_{sound}}{2L}$$



Infrasound measurements at the Sanford Underground Research Facility (South Dakota) have clearly shown several resonances in the Newtonian-noise band.

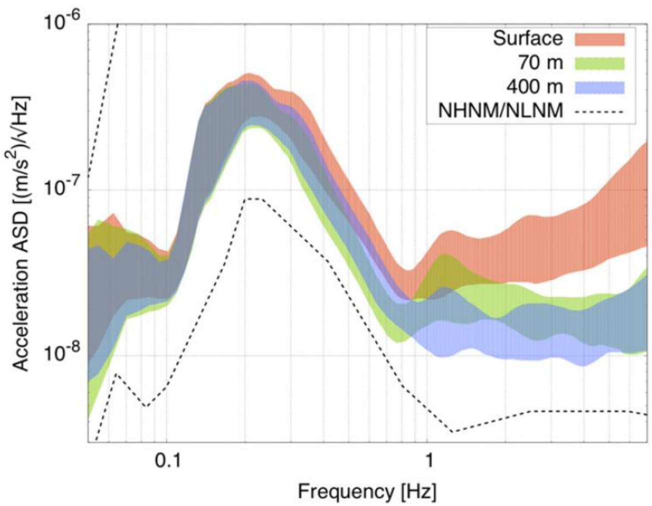
Einstein Telescope



Underground seismic noise orders of magnitude weaker. Note: Virgo seismic noise >1Hz is mostly infrastructural.

Requirement ET

(conservative: underground displacement dominated by compressional waves)

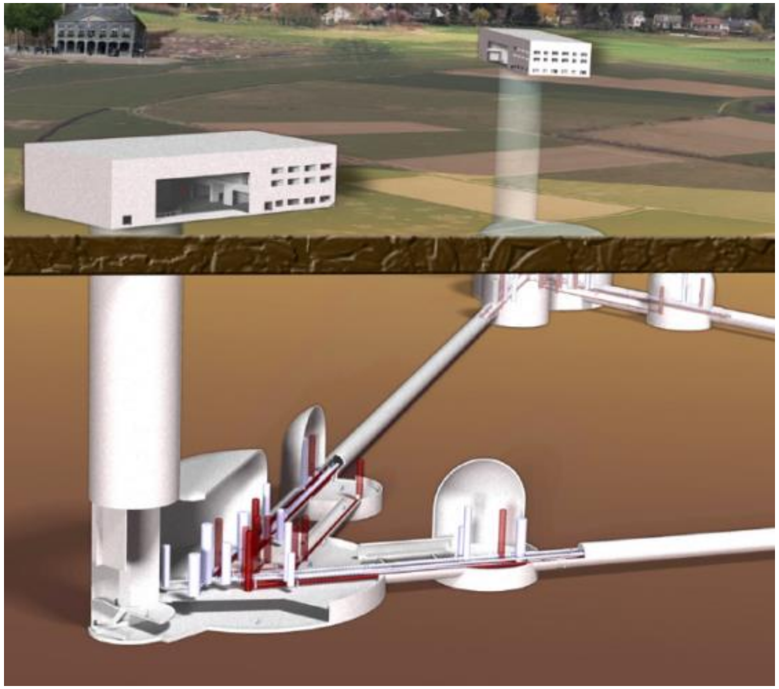


Beker et al, 2015

Observation at the same site: Surface noise >1Hz significantly reduced below about 100m (strongly site dependent).

Einstein Telescope Open Modelling Problems

"Underground laboratories promise significant reduction of gravity background noise."

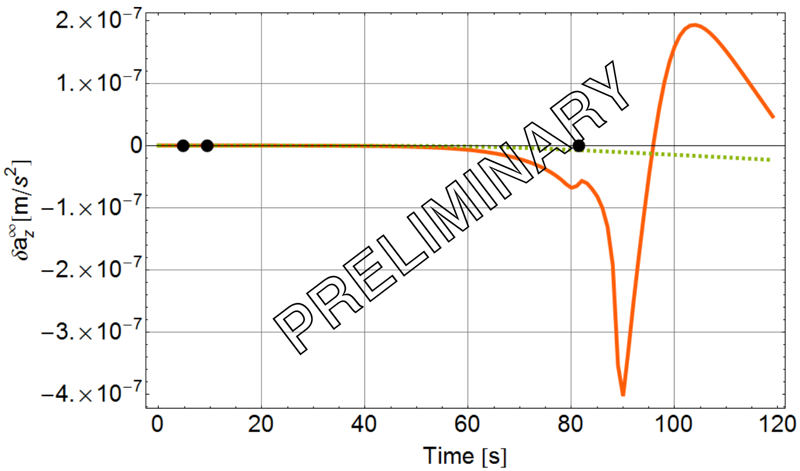


Under investigation:

- Does detector infrastructure elevate underground seismic noise?
- Do air currents from ventilation produce significant gravity noise?
- How far from test masses do we need to keep water accumulation?
- If gravity noise is still significant, is underground compatible with alternative mitigation techniques?

Light-Speed Seismology
Open Modelling Problems

Kamioka – Tohoku EQ



Under investigation:

- What can mimic earthquake signals?
- Can we improve fast magnitude estimation with gravity signals?
- How do we optimally position a network of gravity gradiometers?

- Are perturbations from large-scale atmospheric phenomena (gravity waves, convection) sufficiently suppressed underground?
- Below which frequency does finite thickness of atmosphere matter?