Agence Nationale de la Recherche

Local gravity gradient noise (Newtonian Noise)

Donatella Fiorucci[a], Jan Harms[b], Matteo Barsuglia[a]

[a]Astroparticule et Cosmologie (APC)
[b] Gran Sasso Science Institute (GSSI)

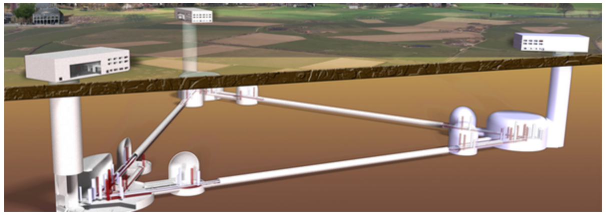
EGRAAL Meeting 10/01/2018

Newtonian Noise frequency range in different detectors

aLIGO, AdVirgo, KAGRA

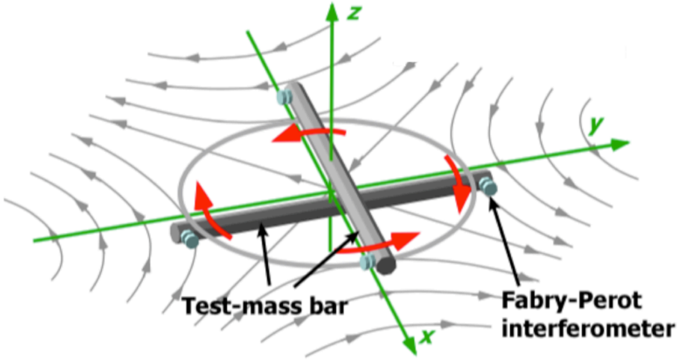
Frequency range
≈ 10Hz – 20Hz

Einstein Telescope (ET)
Cosmic Explorer (CE)



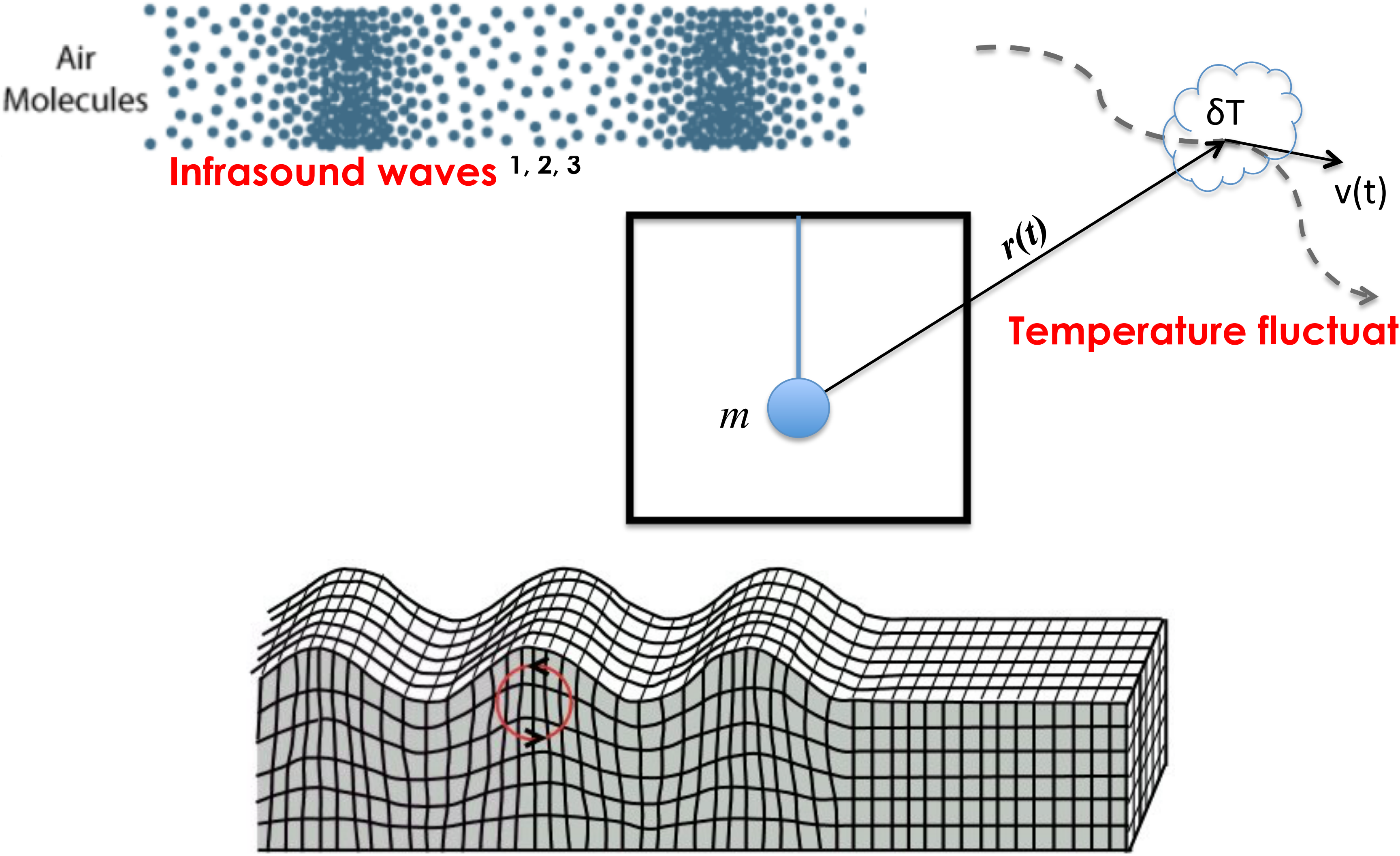
Frequency range
≈ 1Hz – 20Hz

Torsion bar antennas (TOBA, TORPEDO) and other low frequency detectors (atom interferometers, surconducting gradiometers)



Frequency range
≈ 10 mHz-1Hz

Newtonian Noise (NN)



Infrasound waves [1, 2, 3]

Temperature fluctuations [2, 3]

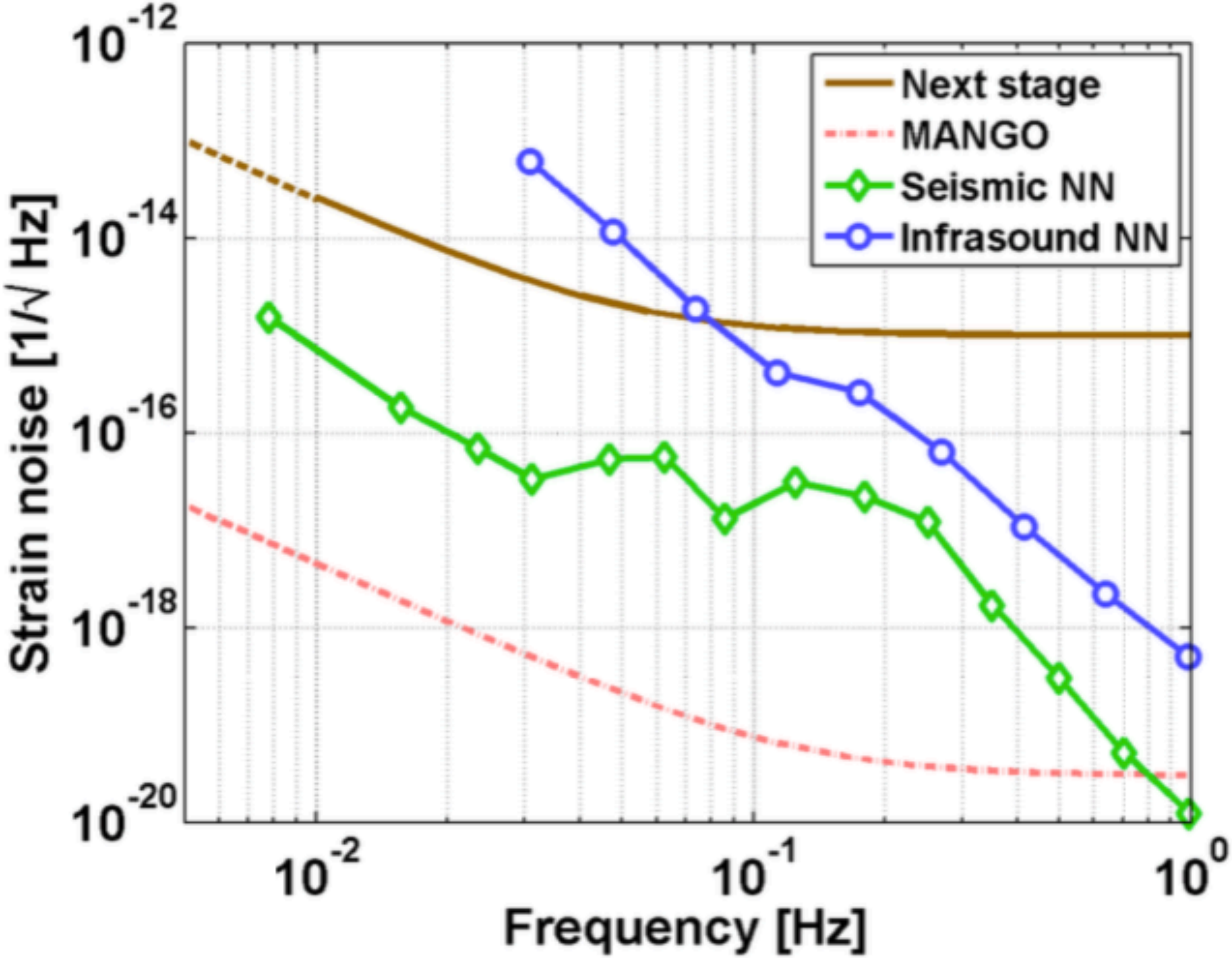
Seismic waves [1, 2]

---

[1] Saulson Phys. Rev. D **30**, 732, [2] J. Harms Terrestrial Gravity Fluctuations,

[3] Creigthon CQG. **25** (2008) 125011, C.Cafaro, S. A. Ali arXiv:0906.4844 [gr-qc]

Infrasound vs seismic NN



*

Seismic NN does not limit the target sensitivity of the next-generation gradiometers

*Harms et al. Phys. Rev. D 88 (2013)

Atmospheric NN

- **Infrasound NN**

  - Model

  - Measurement of pressure fluctuations at the Advanced Virgo (AdV) site

  - AdV infrasound NN

  - ET infrasound NN

  - Torsion bar antenna infrasound NN

- **NN due to temperature fluctuations**

  - Model

  - Laser interferometers (ET case)

  - Torsion bar antenna

Infrasound NN modeling

Equation 1 Relation between pressure and density perturbations

$$\gamma \frac{\delta\rho(\vec{r},t)}{\rho_0} = \frac{\delta p(\vec{r},t)}{p_0}$$

Equation 2 Gravity potential perturbation *

$$\delta\phi(\vec{r}_0,t) = -\frac{G\rho_0}{\gamma p_0}\mathrm{e}^{\mathrm{i}(\vec{k}_\varrho\cdot\vec{\varrho}_0-\omega t)}\delta p(\omega)\cdot\int_H \mathrm{d}V\,\frac{(\mathrm{e}^{\mathrm{i}k_z z}-\mathrm{e}^{-\mathrm{i}k_z z})\mathrm{e}^{-\mathrm{i}\vec{k}_\varrho\cdot\vec{\varrho}}}{(\varrho^2+(z-z_0)^2)^{1/2}}$$

$$= 4\pi\frac{G\rho_0}{\gamma p_0}\mathrm{e}^{\mathrm{i}(\vec{k}_\varrho\cdot\vec{\rho}_0-\omega t)}\cdot(\mathrm{e}^{-k_\varrho|z_0|}(2\Theta(z_0)-1)-2\cos(k_z z_0)\Theta(z_0))\frac{\delta p(\omega)}{k^2}$$

Measurement of pressure fluctuations at infrasound frequencies

Eq. 2 is used to derive the infrasound NN both for laser interferometers and for TOBA.

* Harms, Living Rev. Relativ. (2015)

Infrasound NN modeling

Laser interferometer

$$-\frac{\partial}{\partial x_0}\delta\phi(\vec{r}_0,t) = a_x(\vec{r}_0,t) \qquad \ddot{h}(t) = a_x(t)/L$$

$$FT[\ddot{h}(t)] = -\omega^2 h(\omega) \qquad \pi S_h(\omega)\delta(\omega-\omega') = \langle h(\omega)h^*(\omega')\rangle$$

Test mass building modeling for **laser interferometers on Earth**

$$\delta\phi(\vec{r}_0,t) = \delta\phi_{\text{ext}}(\vec{r}_0,t) + \delta\phi_{\text{int}}(\vec{r}_0,t)$$

Test mass cavity modeling for **underground laser interferometers**

$$\delta\phi(\vec{r}_0,t) = \delta\phi_{z>0}(\vec{r}_0,t) + \delta\phi_{\text{cavity}}(\vec{r}_0,t)$$

The exterior and interior pressure fluctuations are assumed to be incoherent.

Infrasound NN modeling

TOBA

$$\ddot{\mathbf{h}}(\vec{r},t) = -\nabla \otimes \nabla \delta\phi(\vec{r},t) \qquad h_\times(\vec{r},t) = \vec{e}_1 \cdot \mathbf{h}(\vec{r},t) \cdot \vec{e}_2^\top$$

TOBA **on Earth, $z_0 = 0$**

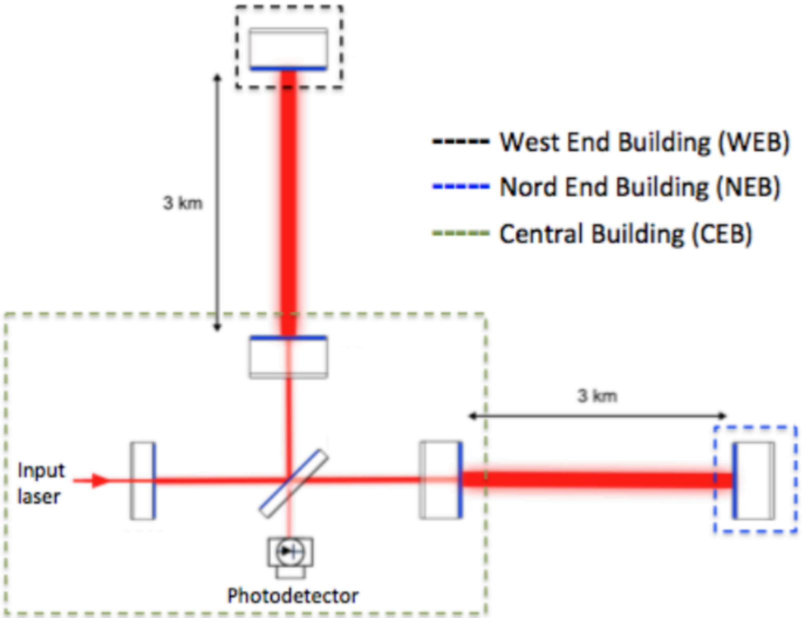
$$S_{h^s_\times}(\vec{r}_0,\omega) = \left(4\pi \frac{G\rho_0}{\gamma p_0 \omega^2}\right)^2 \cdot \langle (\sin^2(\theta)\sin(\phi)\cos(\phi))^2 \rangle S_{\delta p}(\omega)$$

TOBA **underground, $z_0 < 0$**

$$S_{h^u_\times}(\vec{r}_0,\omega) = \left(4\pi \frac{G\rho_0}{\gamma p_0 \omega^2}\right)^2 \cdot \langle \mathrm{e}^{2k\sin\theta z_0} (\sin^2(\theta)\sin(\phi)\cos(\phi))^2 \rangle S_{\delta p}(\omega)$$

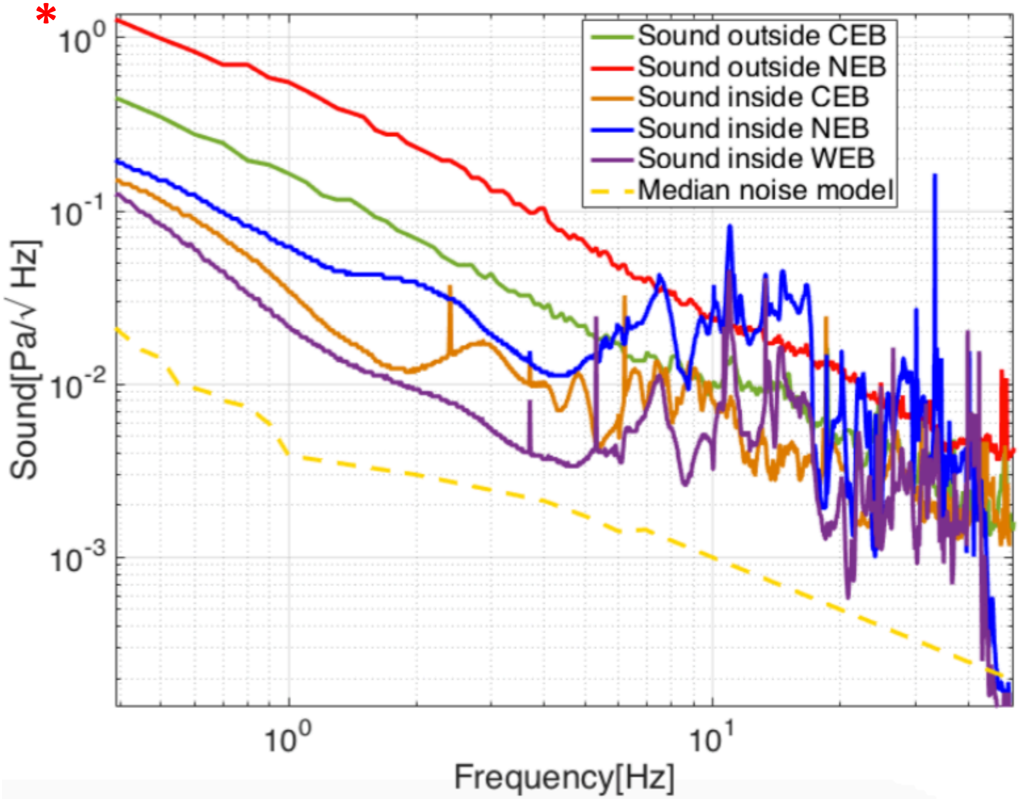
Building effect neglected: the cavity or building hosting the detector is much smaller than the length of infrasound waves.

Measurements of pressure spectra at the AdV site



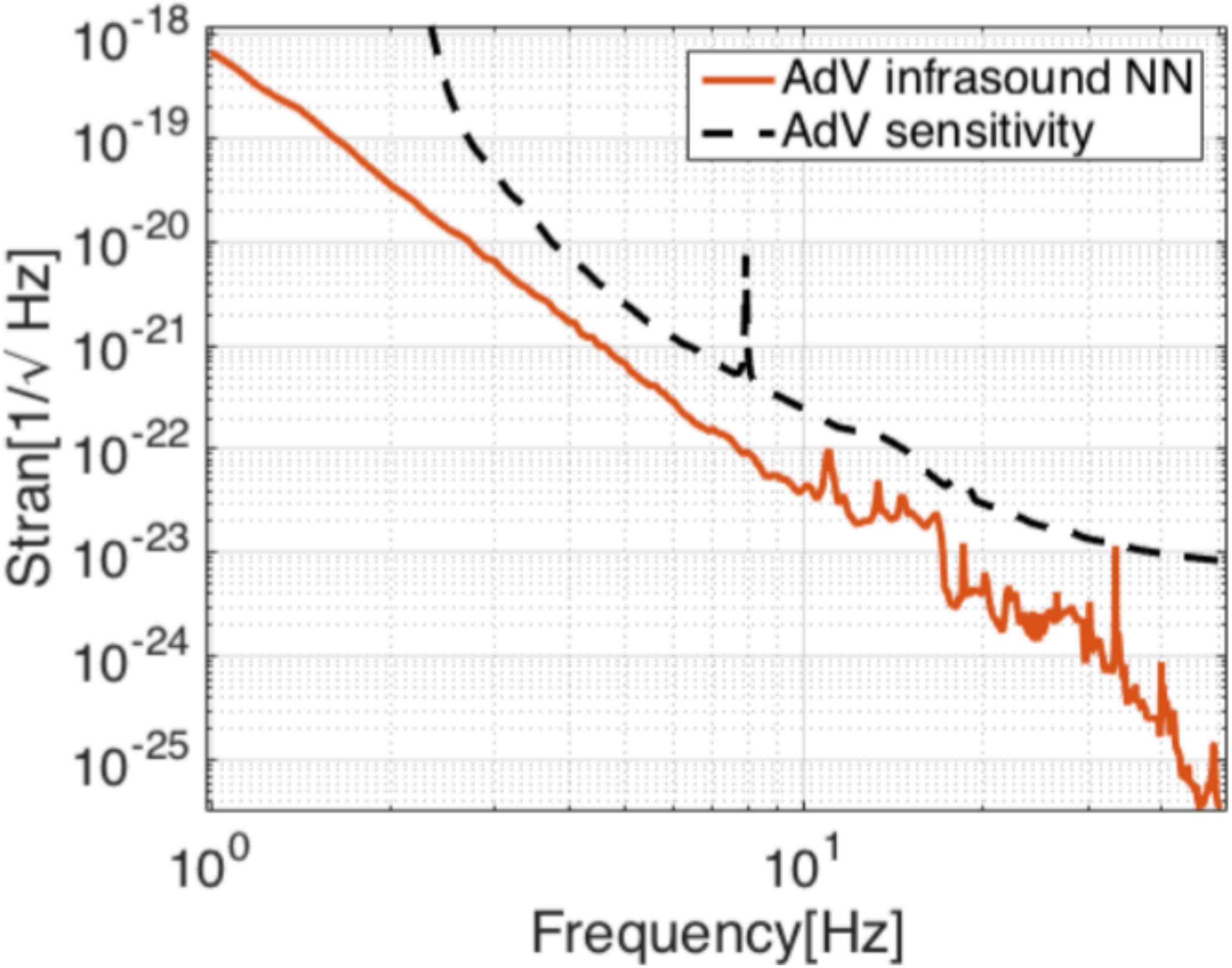
Simplified scheme of AdV.

*



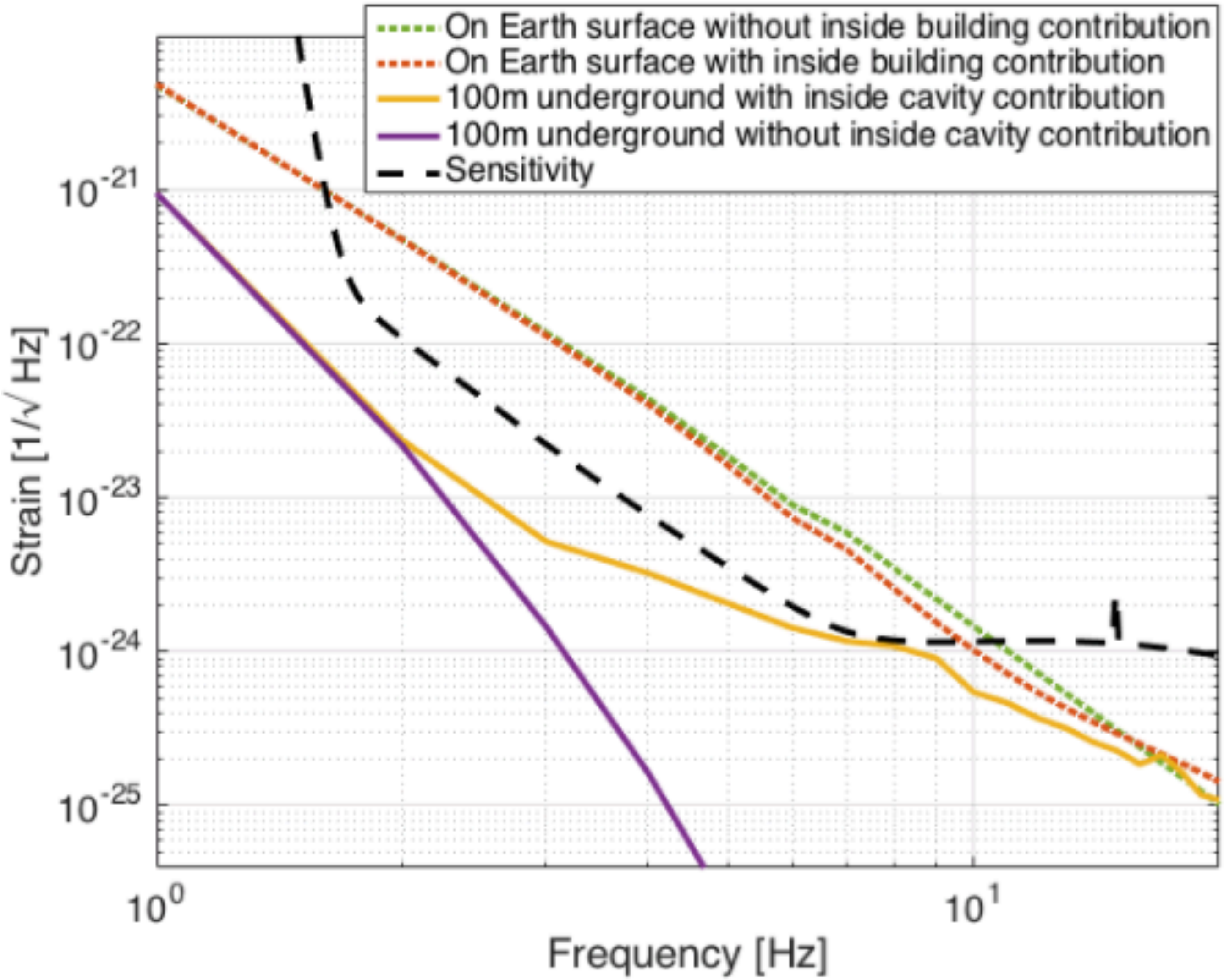
Solid lines: sound spectra measured at the AdV site. Dashed yellow line: pressure fluctuation median noise model presented in *Geophys. Res. Lett.32, L09803.*

AdV infrasound NN



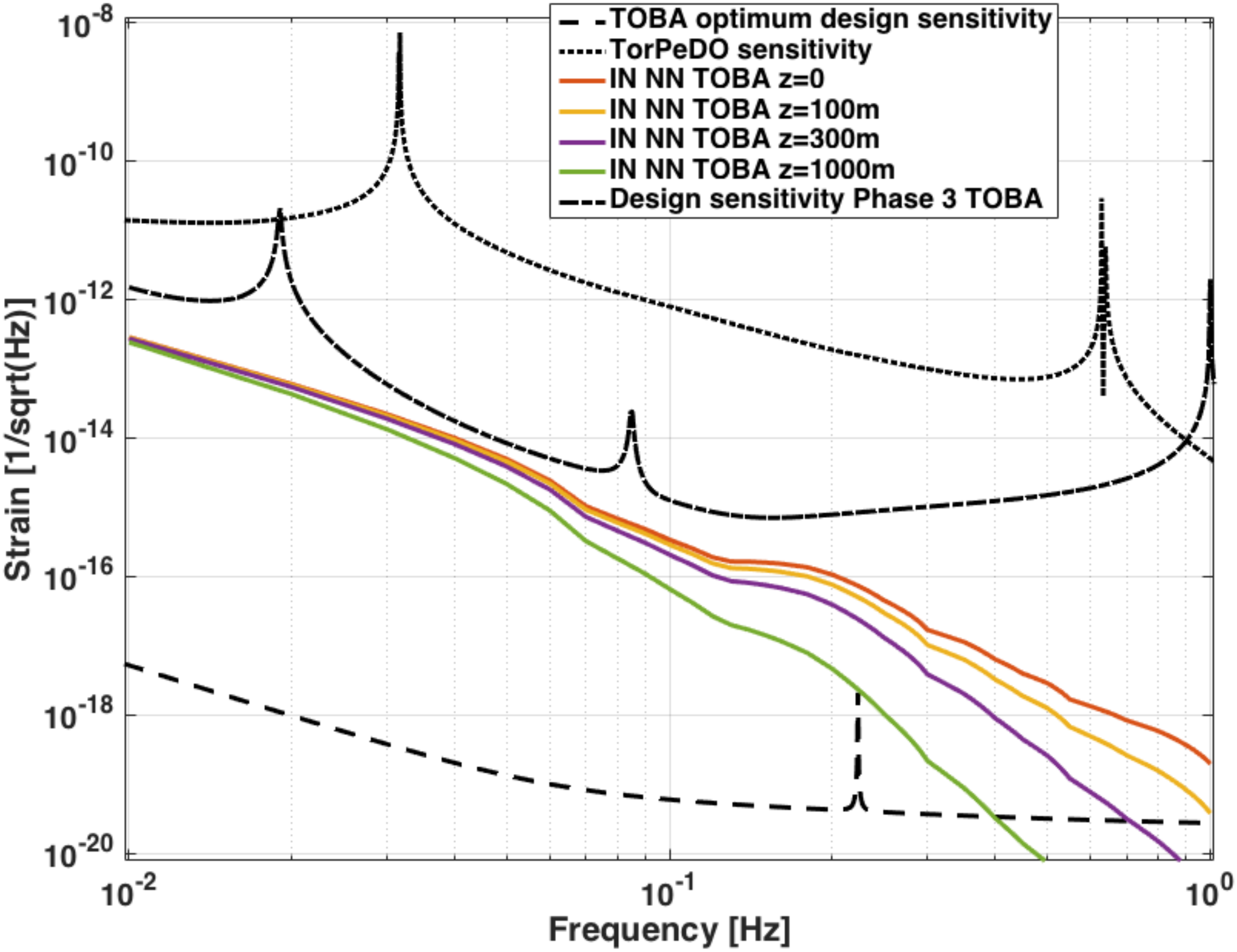
Estimate of the AdV infrasound NN, by using sound spectra recorded at the AdV site.

Infrasound NN for an ET-like detector



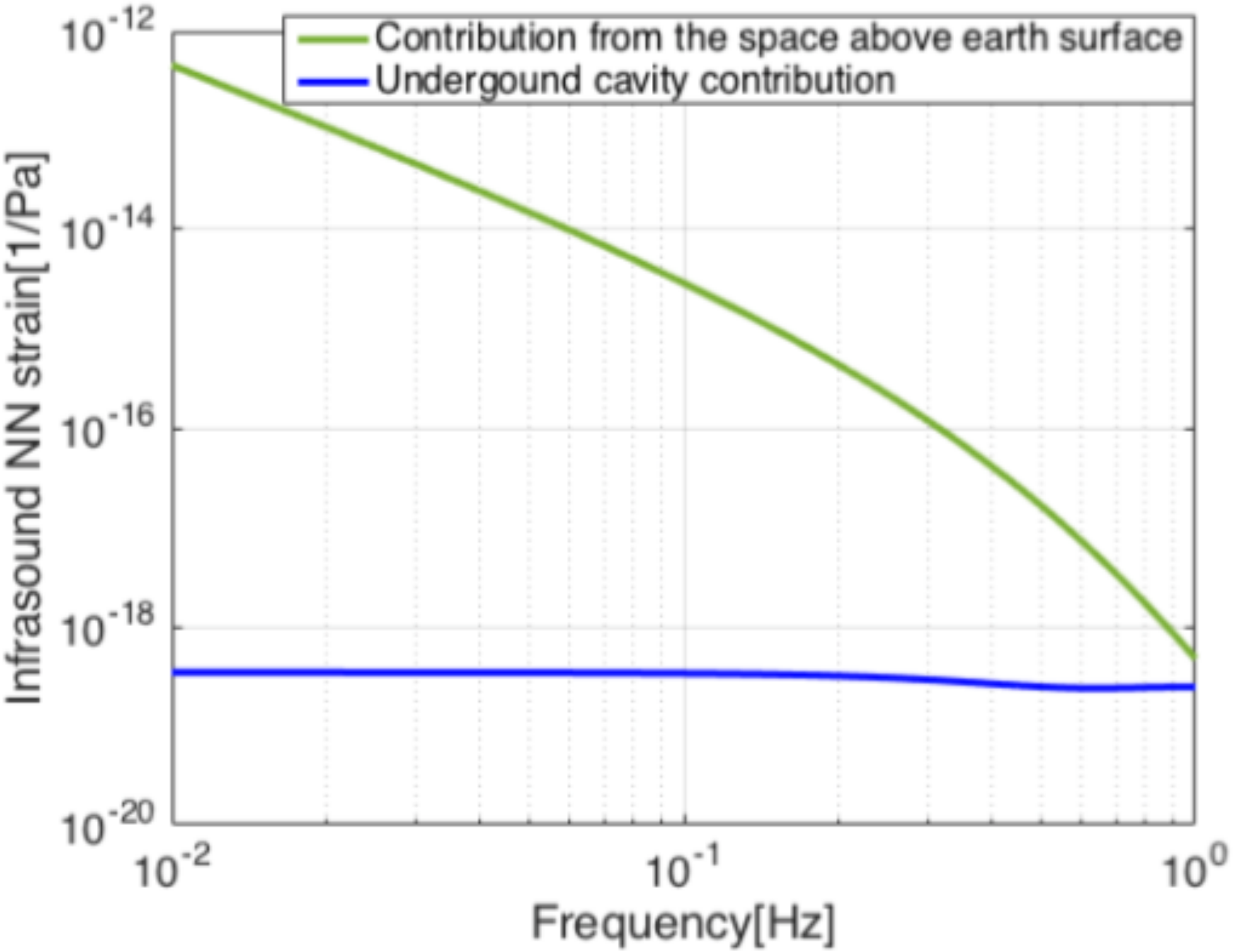
Infrasound NN for an ET like laser interferometer using the pressure fluctuation median noise model presented in Geophys. Res. Lett.32, L09803.

TOBA infrasound NN



TOBA infrasound NN for different detector depth using the pressure fluctuation median noise model presented in Geophys. Res. Lett.32, L09803.

TOBA infrasound NN - Cavity/building effect



Contributions to the infrasound NN of a TOBA detector located 300 m beneath the earth surface. Blue line: contribution due to the space inside the underground cavity housing the detector. Green line: contribution of the space above the earth surface.

Atmospheric NN

- **Infrasound NN**

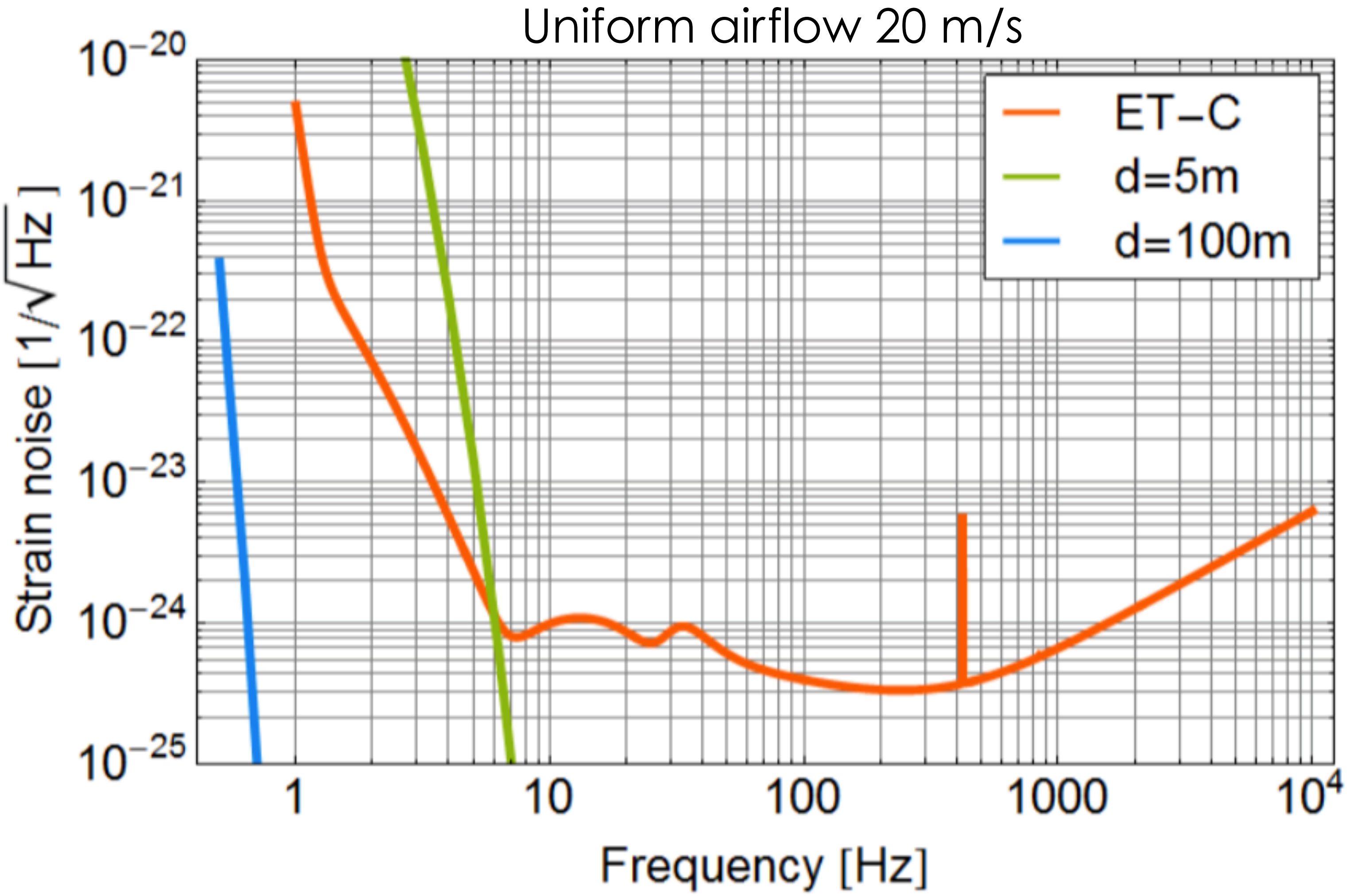
  - Model
  - Measurement of pressure fluctuations at the Advanced Virgo (AdV) site
  - AdV infrasound NN
  - ET infrasound NN
  - Torsion bar antenna infrasound NN

- **NN due to temperature fluctuations**

  - Model
  - Laser interferometer (ET case)
  - Torsion bar antennas

Temperature fluctuation NN-ET

$$\delta\rho(\vec{r},t) = -\frac{\rho_0}{T_0}\delta T(\vec{r},t) \qquad \delta\vec{a}(\vec{r}_0,t)^{*} = -\frac{G\rho_0}{T_0}\int \mathrm{d}V\,\frac{\delta T(\vec{r},t)}{|\vec{r}-\vec{r}_0|^3}(\vec{r}-\vec{r}_0)$$



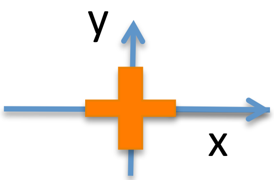
◆ **credit: Jan Harms**

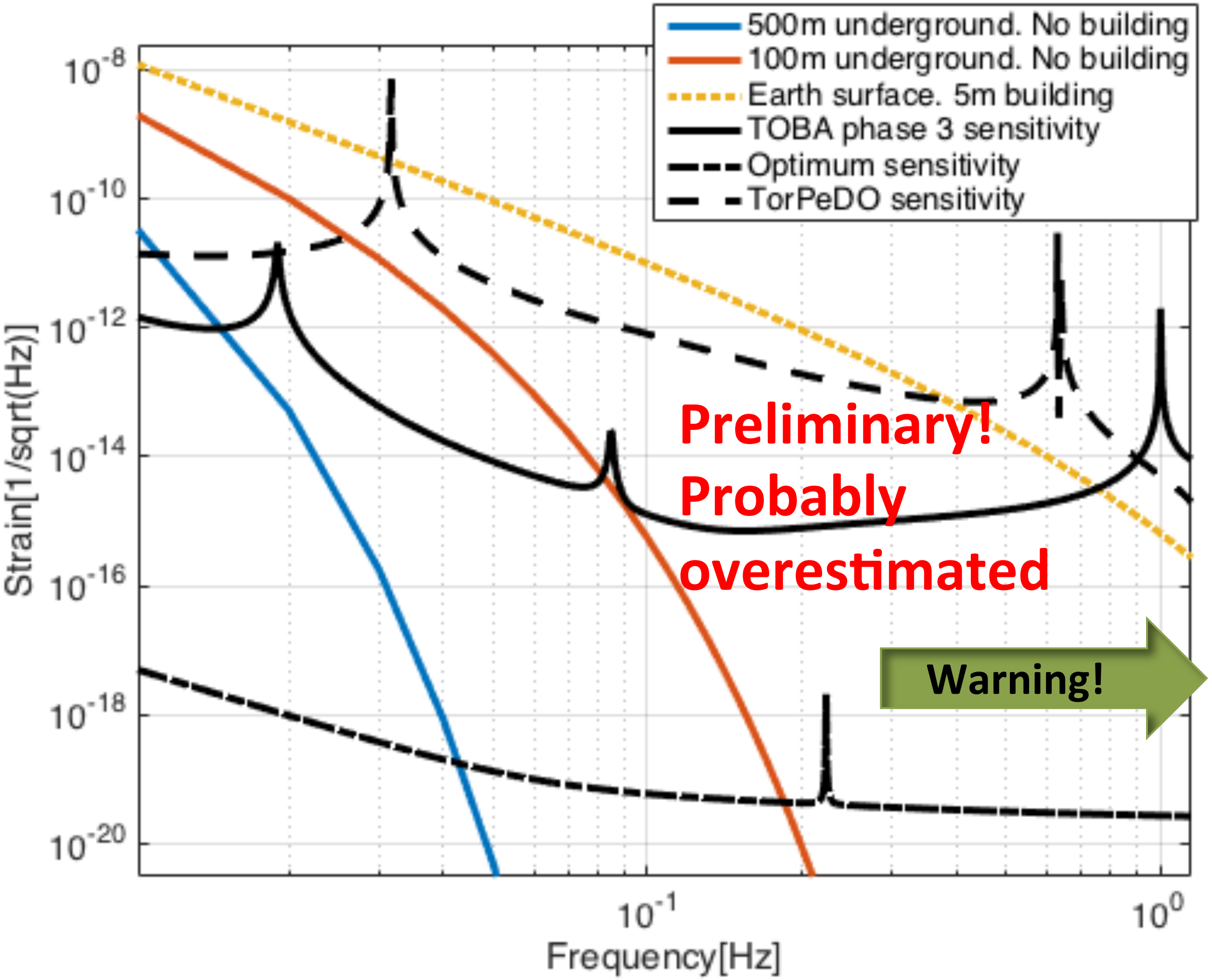
* Harms, Living Rev. Relativ. (2015)

Temperature fluctuation NN-TOBA

Wind speed, v=10m/s, along the x axis

TOBA orientation





Preliminary!
Probably overestimated

Warning!

Turbulent mixing theory breaks down at f ≲ few tens of mHz [1]

Gravimeter data show that this noise is overestimated by few orders of magnitude at 10mHz [2]

Validity of the model for 10 mHz < f < hundreds of mHz must be checked

Model should be ok (but simplified) for f ≥ 1 Hz.

---

[1] Kukharets, V.P. and Nalbandyan, H.G. *Izv., Atmos. Ocean. Phys.*, 42, (2006)

[2] Hinderer, Crossley, Warburton, Gravimetric Methods, 2007 Elsevier B.V.

Conclusion and Perspectives

Infrasound NN

- Pressure fluctuations variate significantly with location, time and season. It is important to characterize the detector sites in terms of pressure fluctuations.
- Characterization of the AdV site in terms of pressure fluctuations and infrasound NN level.
- For an ET-like detector the Infrasound NN is strongly suppressed, when going underground. However the attenuation can be significantly spoiled by the internal contribution of the test mass cavity.
- TOBA infrasound NN is below the next stage sensitivity and a few orders of magnitude above the sensitivity required for gravitational-wave detection. This allows the exploitation for geophysical applications.

TOBA NN from Temperature fluctuations

- Check and improve the model.
- Strongly attenuated when going underground.