Terrestrial Gravity Fluctuations

Jan Harms
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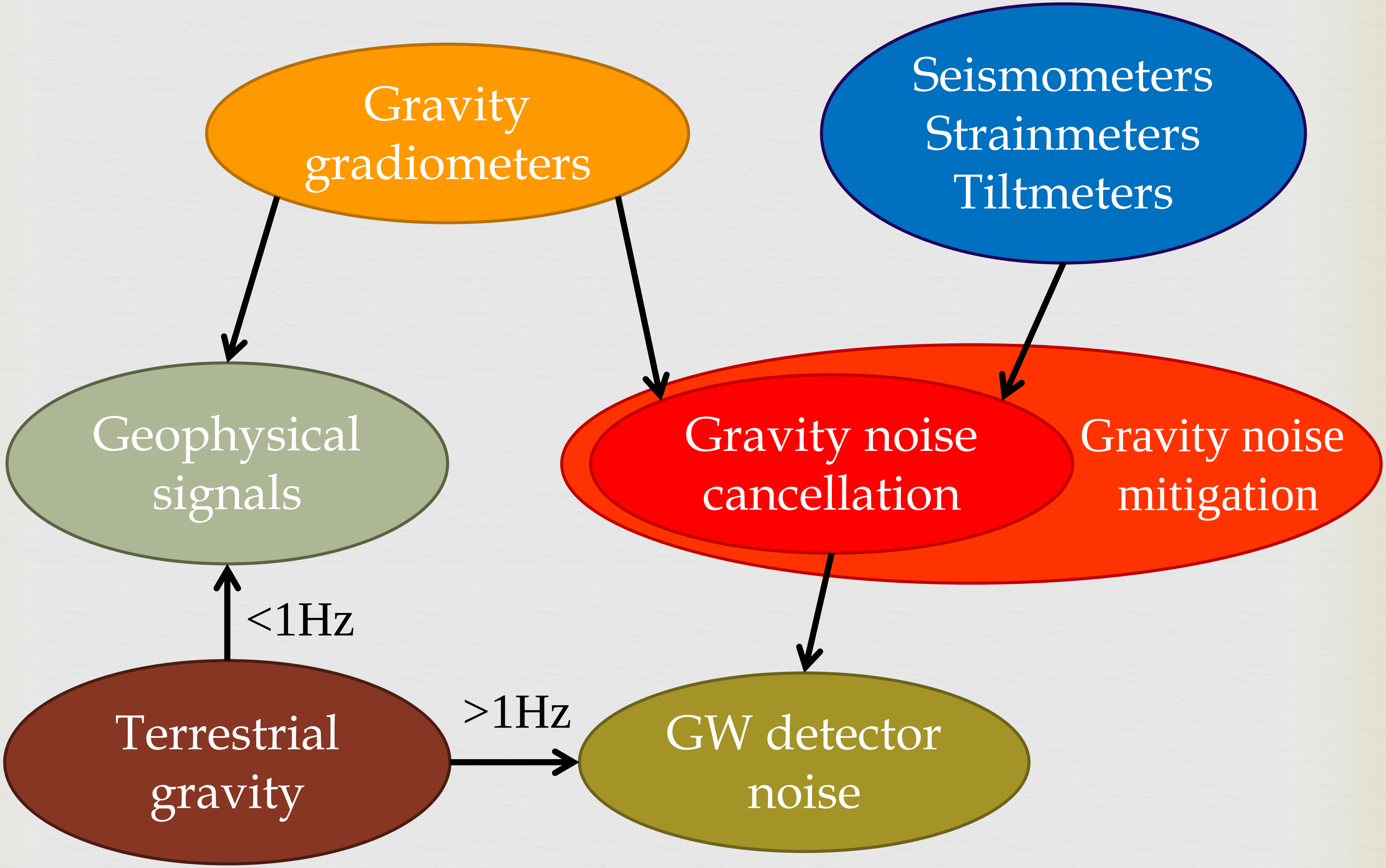


Gravity gradiometers

Seismometers
Strainmeters
Tiltmeters

Geophysical signals

Gravity noise cancellation

Gravity noise mitigation

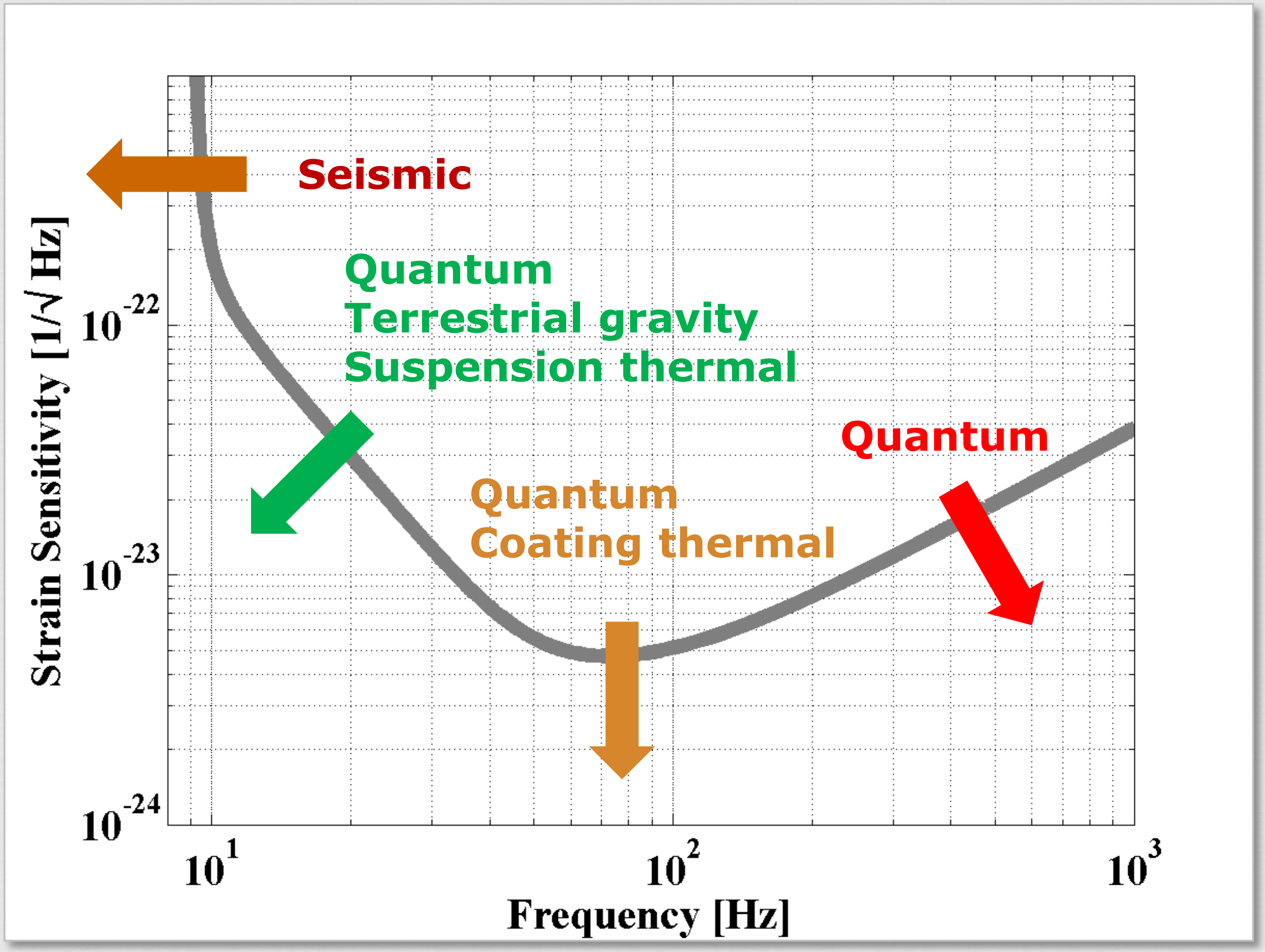
<1Hz

Terrestrial gravity

>1Hz

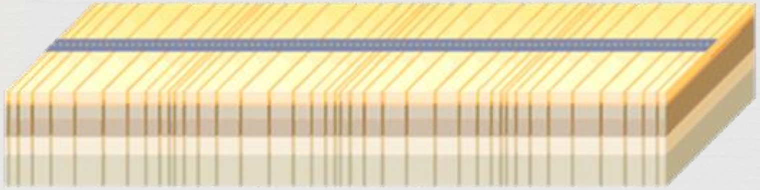
GW detector noise

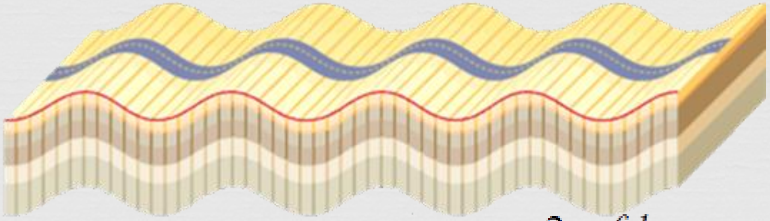
Main Noise Sources



Seismic NN

Density fluctuation inside medium Surface/interface displacement

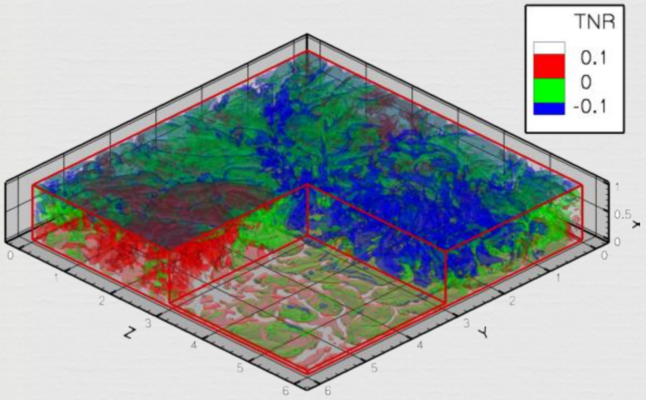


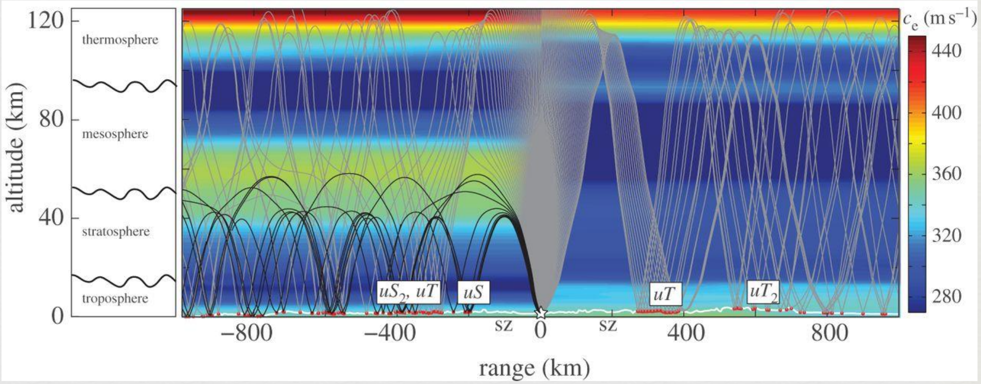


$$\frac{\xi(f)\, e^{-\frac{2\pi f h}{c_{\rm hor}}}}{f^2}$$

- Surface waves: Rayleigh, Love
  Body waves: compressional, shear
- Shear waves relevant when displacing surfaces/interfaces
- NN is non-stationary
- In the foreseeable future relevant only below 30Hz

Atmospheric NN





$$\frac{\delta \mathrm{T}(f)\, e^{-\frac{2\pi f r}{v}}}{f^{10/3}}$$

$$\frac{p(f)\, e^{-\frac{2\pi d f}{c_{\mathrm{hor}}}}}{f^{3}}$$

- Quasi-static temperature perturbations advected by wind
- Sound propagation inside atmosphere and laboratory buildings
- Turbulence makes accurate modelling very challenging

How Can NN Influence a Detector Design?

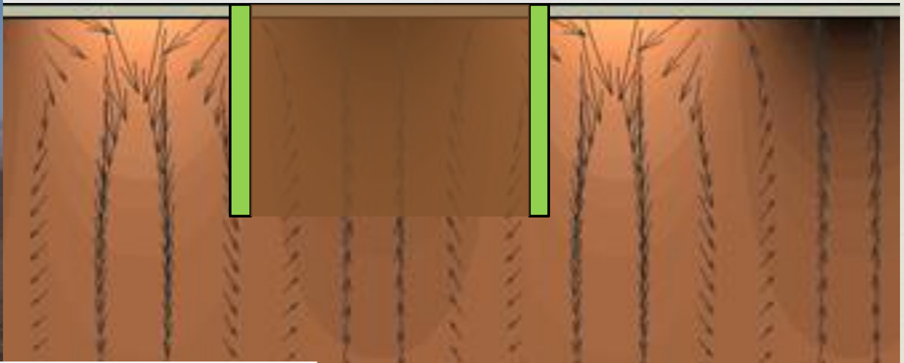
Any influence means that we can do something about NN!

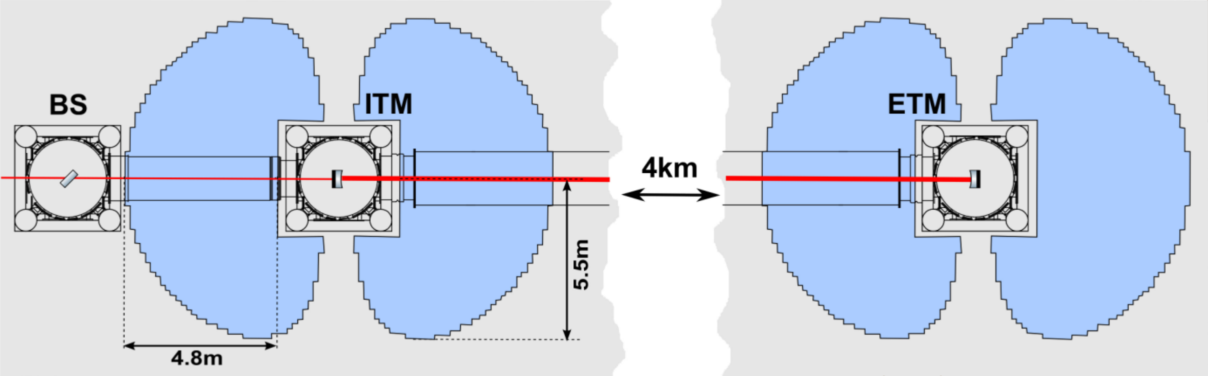
- **Site selection I**: choose a site with low NN (low seismic noise, low atmospheric noise)
- Specifically, one may consider going **underground**
- Suppress noise from **infrastructure** (fans, running water,…)
- **Recess** around test masses and seismic/atmospheric **shields**
- Implement **NN cancellation** using sensor arrays
- **Site selection II**: choose flat site to facilitate noise cancellation

Surface Sites

Domes against atmospheric perturbations

Moat against Rayleigh NN

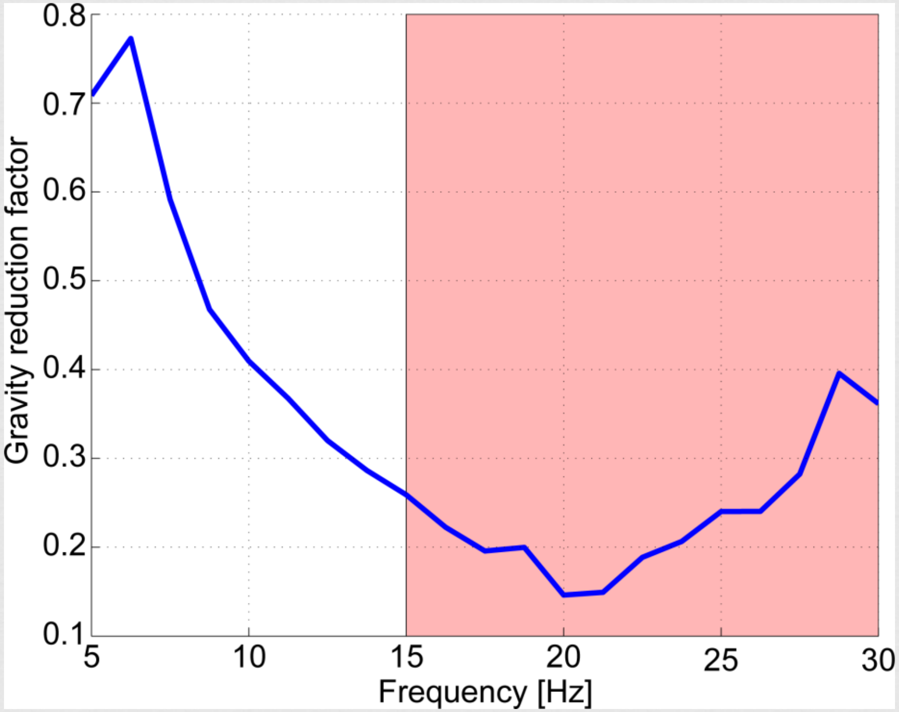




Recess against Rayleigh NN

NN Suppression by Recess

Harms and Hild, 2014

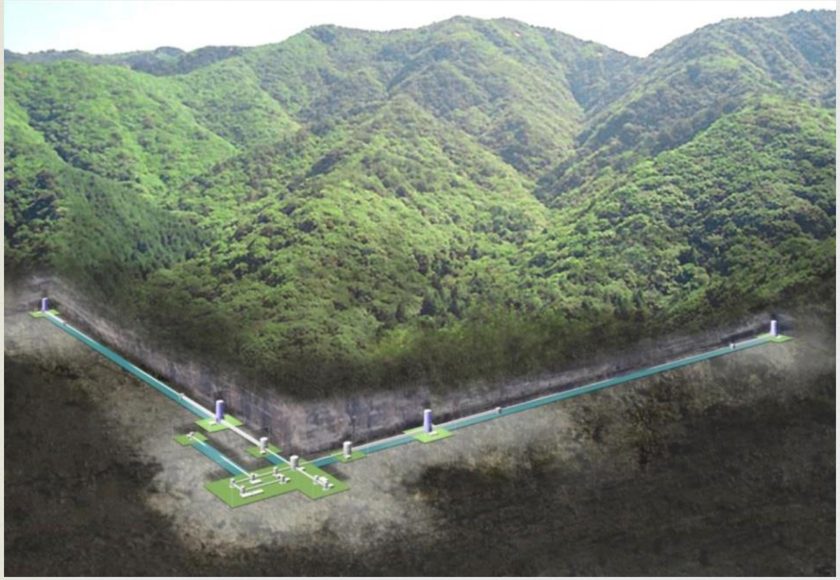


More careful simulation required for red frequency band:

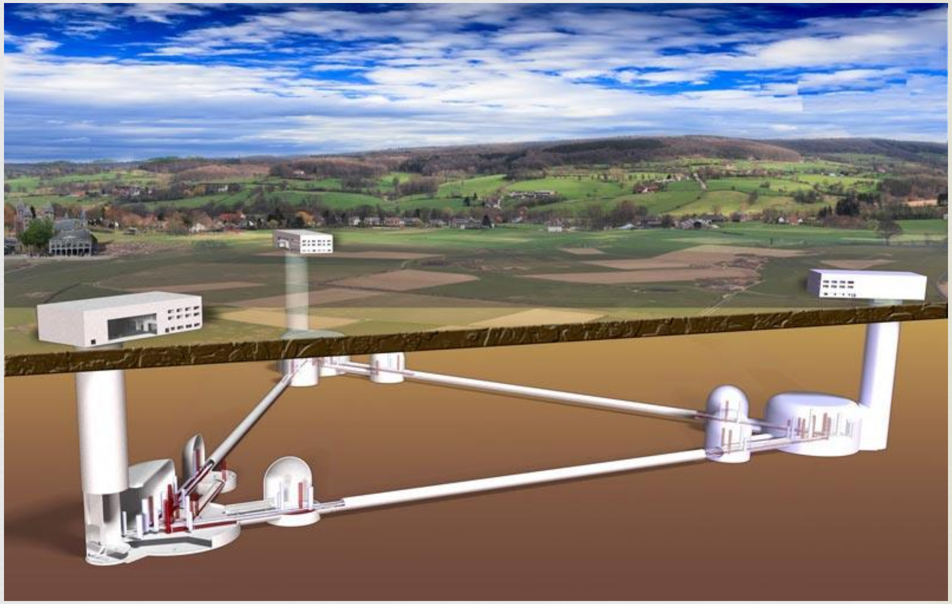
- Scattering of seismic waves from recess
- Seismic-noise suppression in central pillar from recess

Underground Sites

KAGRA



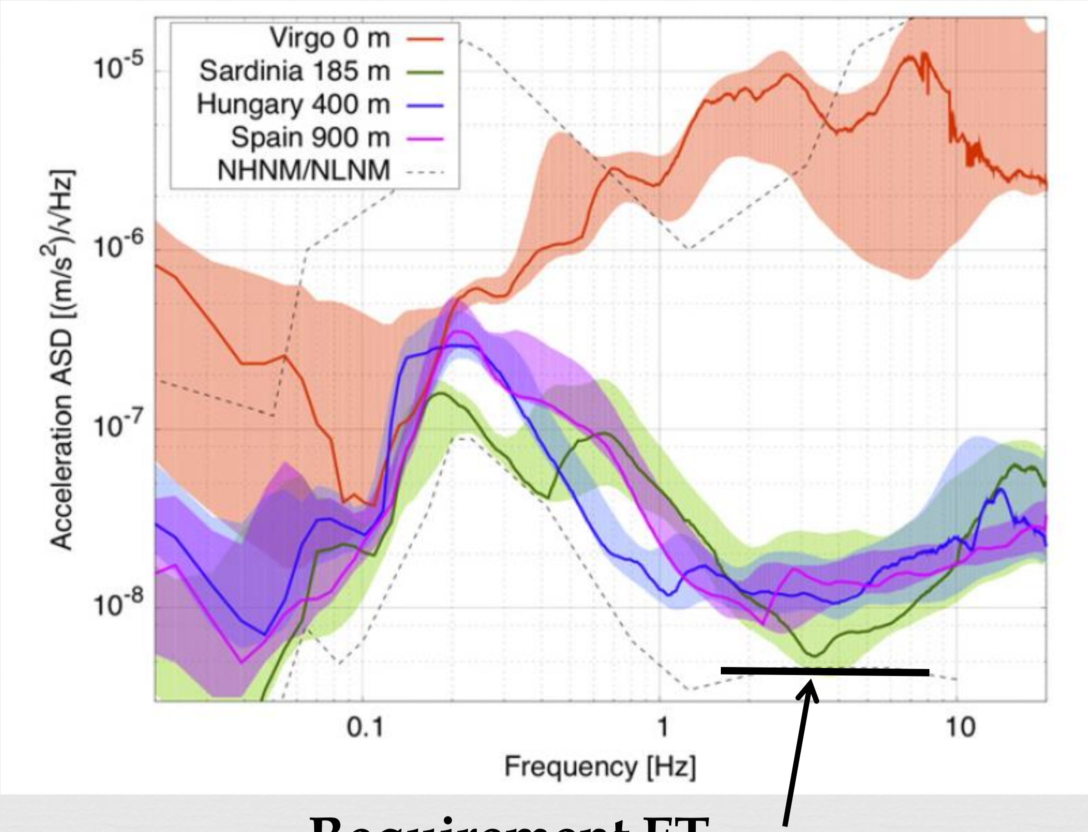
Future: Einstein Telescope



- Reduction of seismic noise and associated gravity noise
- Distance to atmosphere means suppression of gravity noise

Underground Seismic Spectra

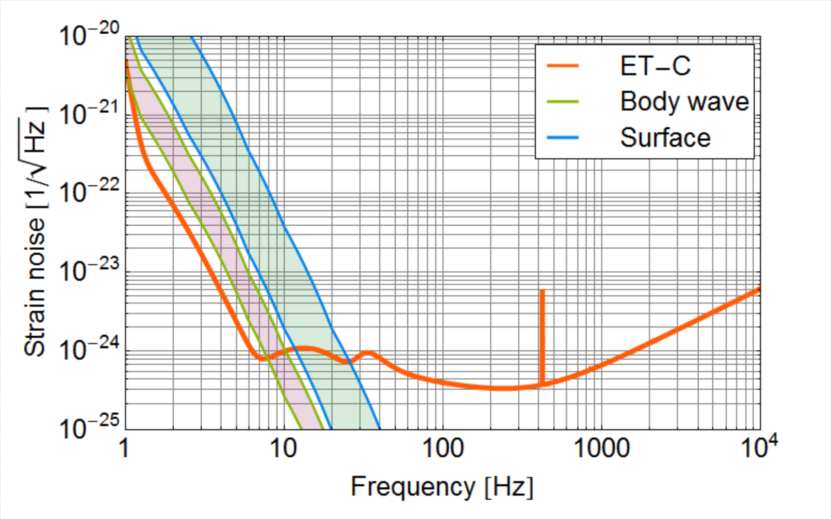
Beker et al, 2012



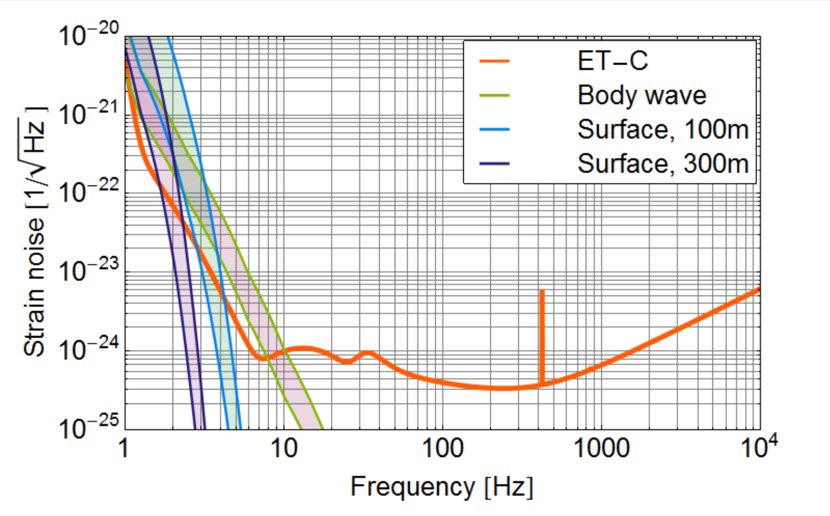
Requirement ET
(conservative: underground displacement dominated by compressional waves)

Seismic NN

Seismic NN in a surface detector



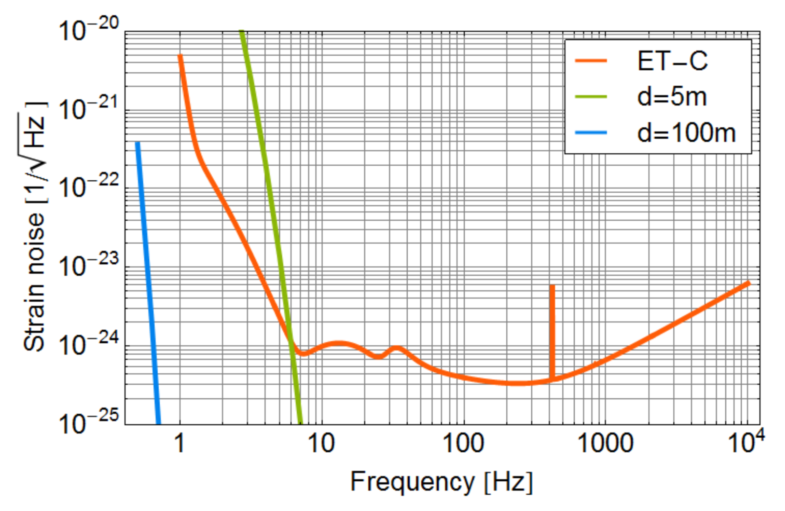
Seismic NN in an underground detector



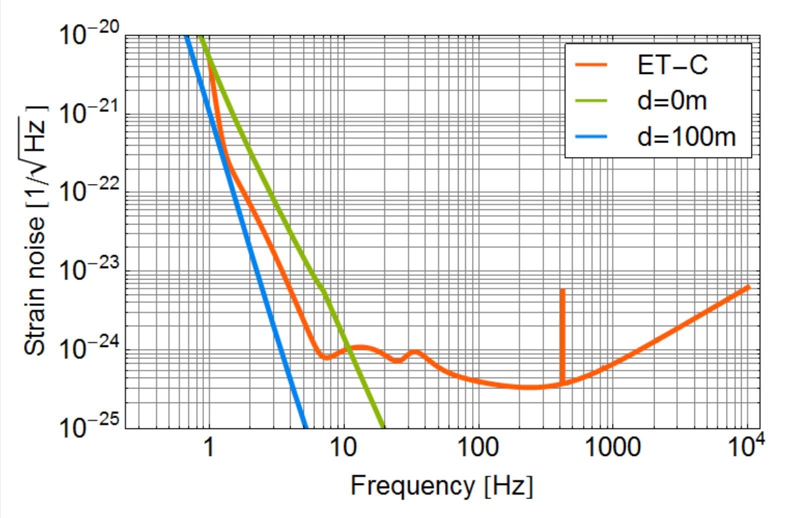
- Seismic models: Body wave: 3x – 12x LNM, Surface: 50x – 1000x LNM
- Rayleigh dispersion model: 1.5km/s @ 1Hz → 300m/s @ 10Hz
- Includes contributions from cavity-wall displacement
- Homogeneous half space (except for Rayleigh dispersion)

Atmospheric NN

Temperature NN
Uniform air flow, v=20m/s



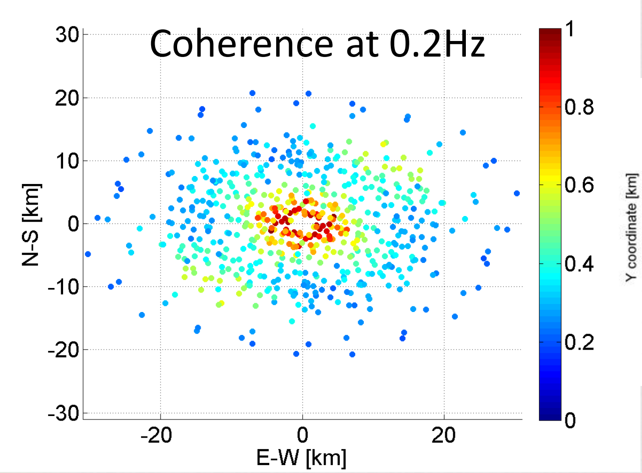
Infrasound NN

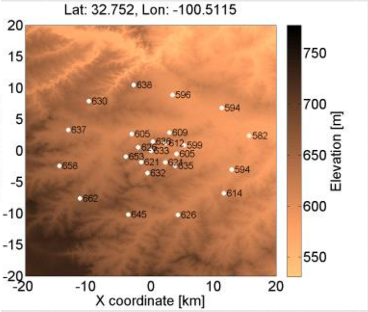


- Atmospheric NN limits sensitivity of ET-type detectors if built at the surface
- Going underground very efficiently suppresses atmospheric NN
- Atmospheric NN will be extremely challenging to cancel

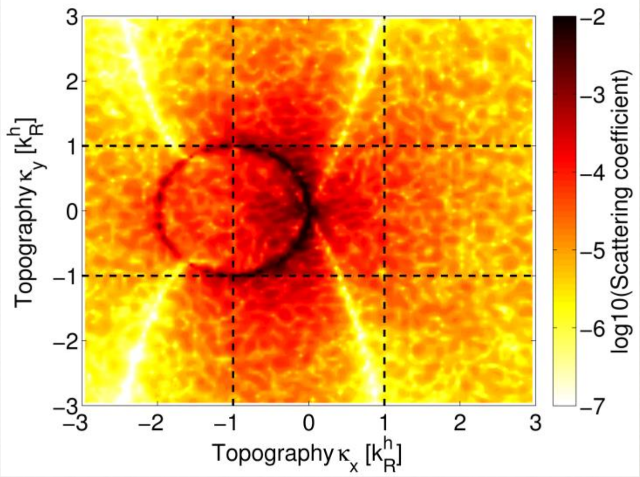
Topographic Scattering

Sweetwater array (TX)





Montana, ΔL=1400m

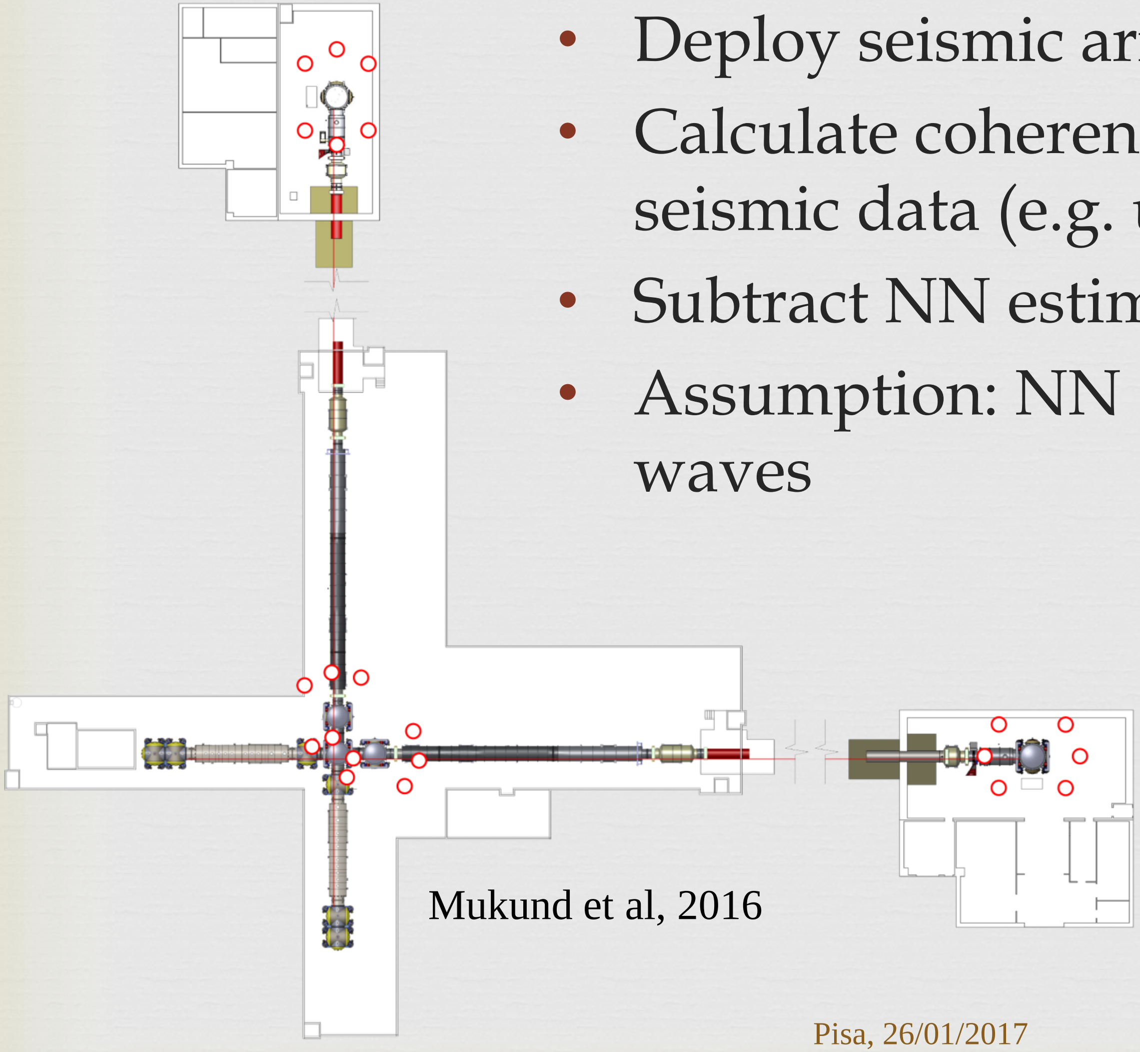


Coughlin and Harms, 2012

- So far, calculations of topographic scattering only carried out in Born approximation
- Measurements with Sweetwater array confirm that seismic correlations are complicated in regions with rough topography

NN Cancellation

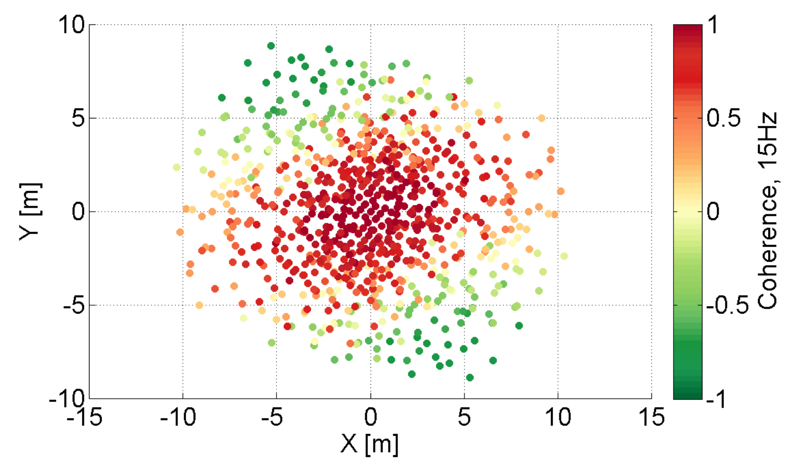
- Deploy seismic arrays around test masses
- Calculate coherent estimate of NN from seismic data (e.g. using Wiener filters)
- Subtract NN estimate from GW data
- Assumption: NN dominated by Rayleigh waves



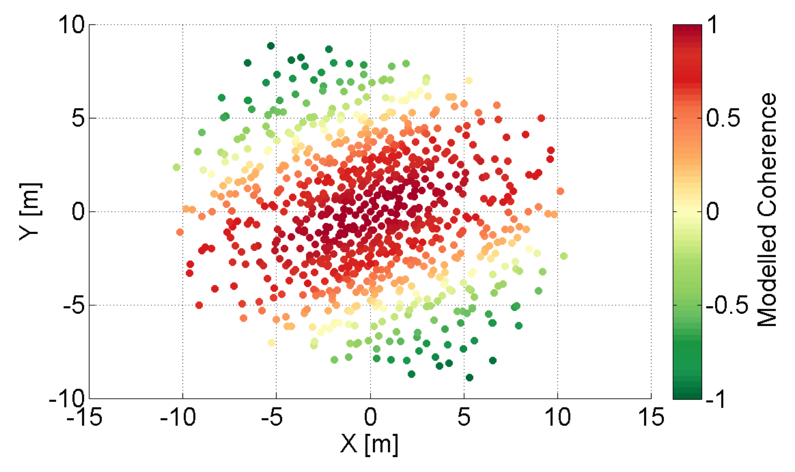
Mukund et al, 2016

LIGO Hanford Measurements (2012)

Observation



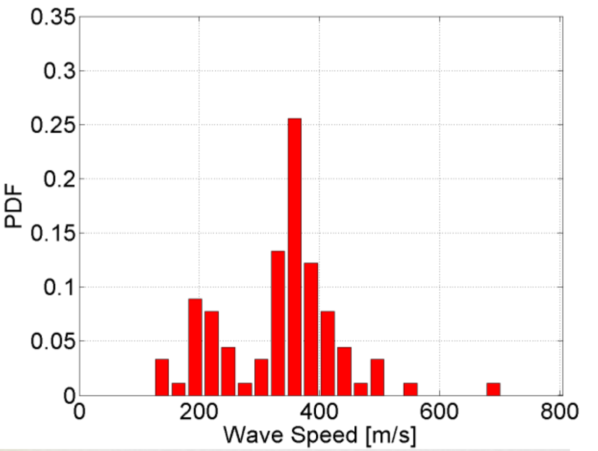
Plane-wave model

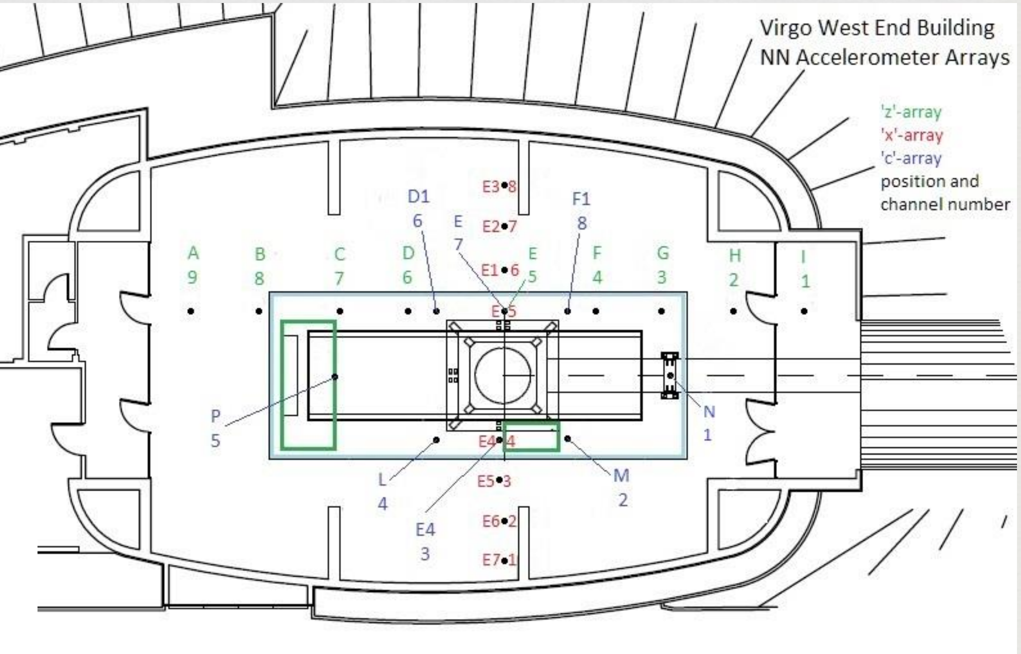


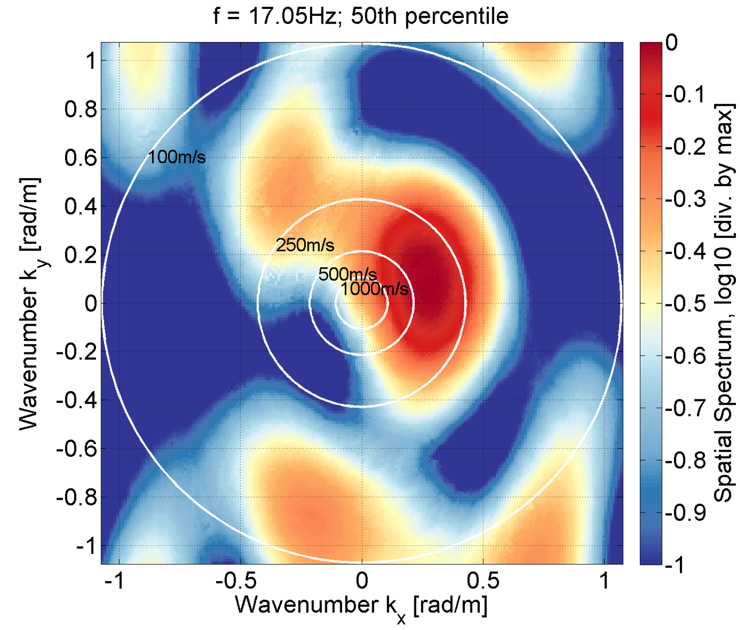
- Anisotropic, plane-wave model gives qualitatively good match with observation
- Mismatch is not minor. It demonstrates inhomogeneity of the seismic field, due to local seismic sources

Seismic Arrays at Virgo Site

Blackburn et al, 2016



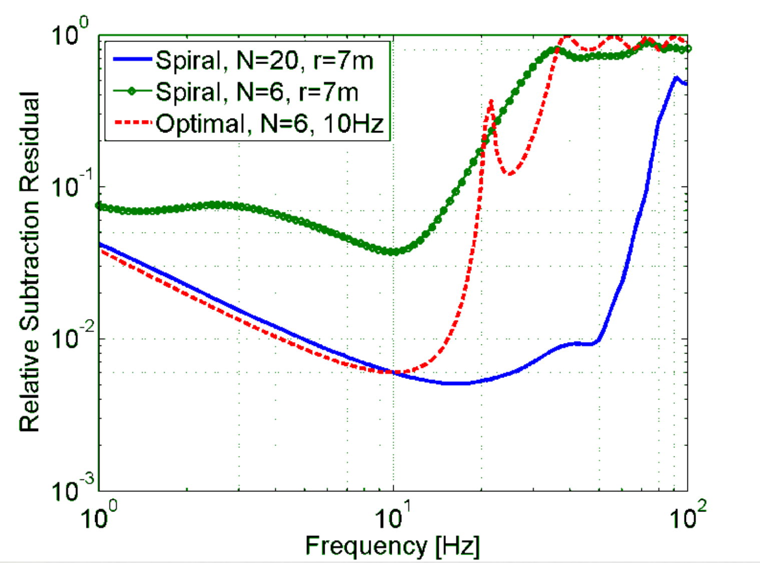




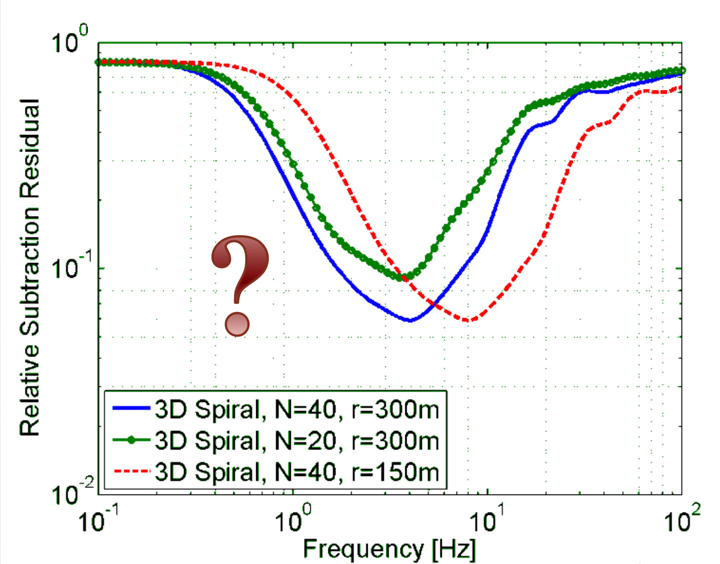
- Identification and characterization of several local seismic sources
- Measurement of seismic speed
- Measurement of correlation lengths
- Impact of platform structure on seismic field

Importance of Array Optimization

Rayleigh waves, c_R=250m/s



Body waves (1/3 P, 2/3 S), c_P=5km/s

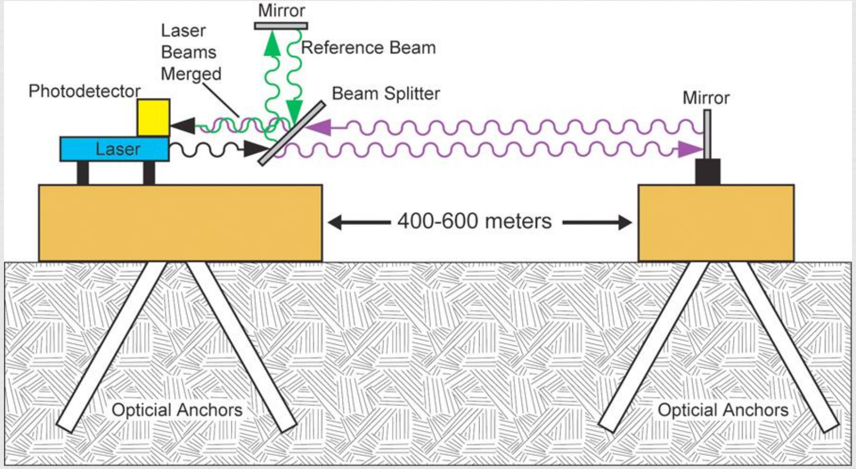


Harms, 2015

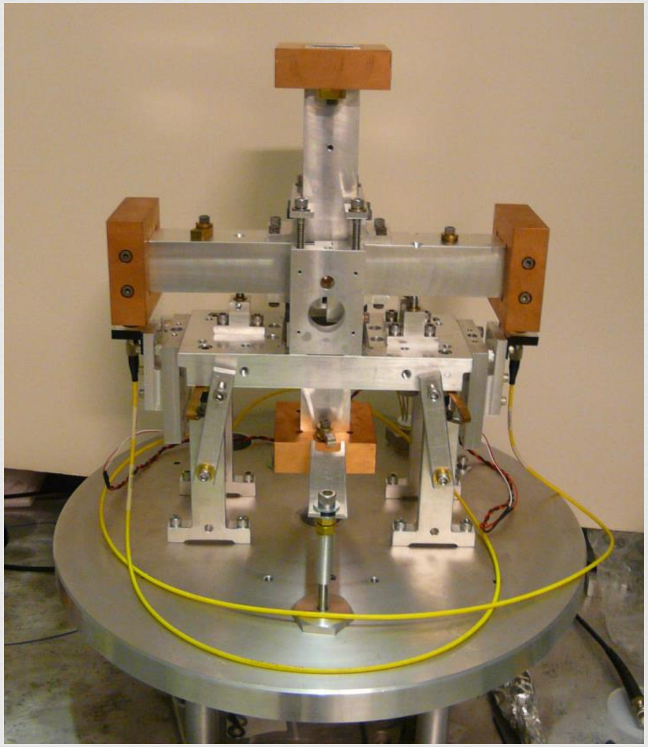
- Optimization can make a big difference in performance
- Shear waves are a huge challenge for underground NN cancellation
- We haven't tried optimization of underground arrays yet
- We need to consider alternative sensors (tiltmeters, strainmeters, dilatometers)

Alternative Seismic Sensors

Strainmeter



Tiltmeter



Venkateswara, 2016

- **Tiltmeter**: best imitation of Rayleigh NN in large-scale GW detectors
- **Strainmeter**: best imitation of body-wave NN in gravity gradiometers

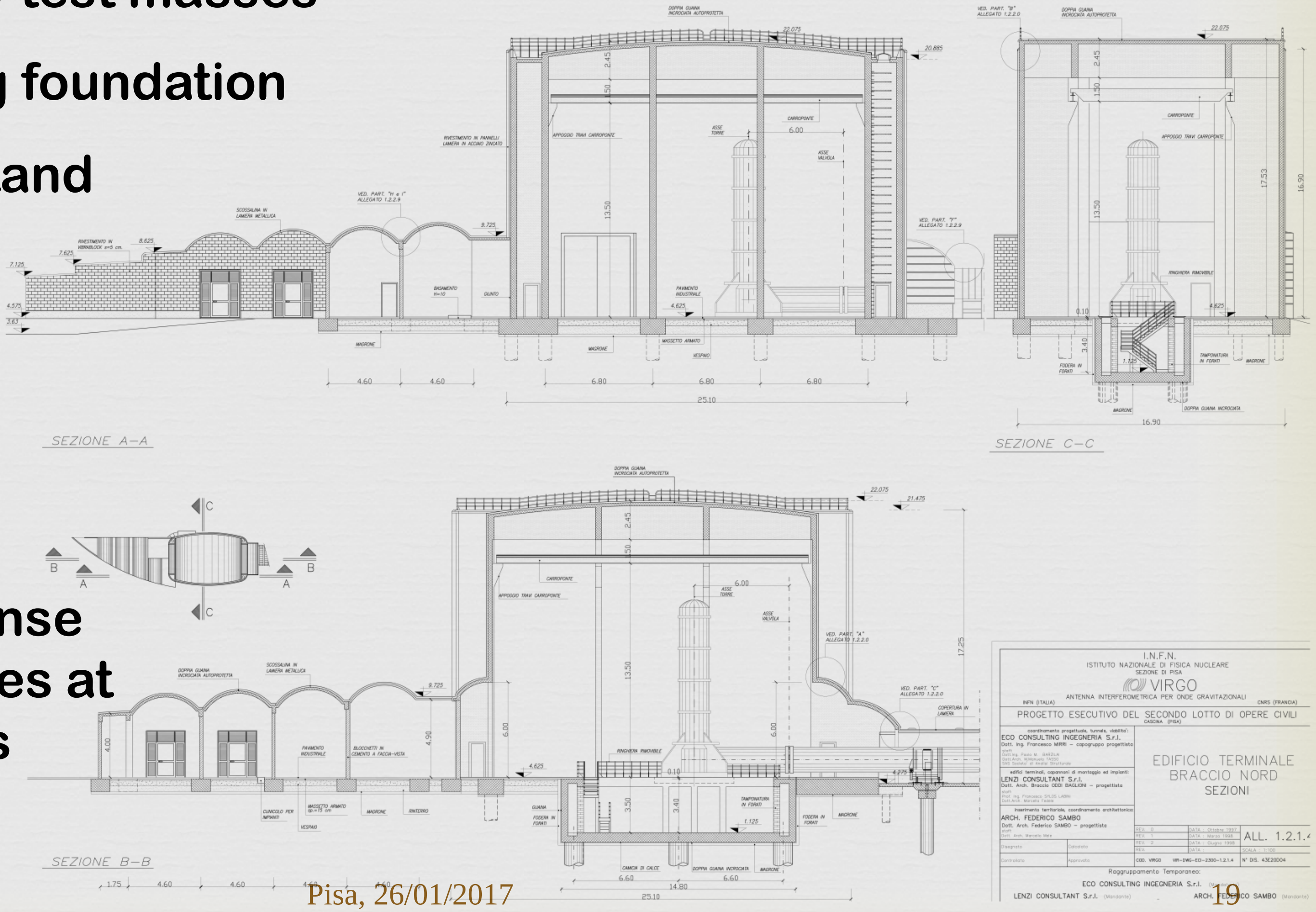
Numerical Simulation

Modelling NN for Virgo is not simple

- **Lab space below test masses**
- **Poles supporting foundation**

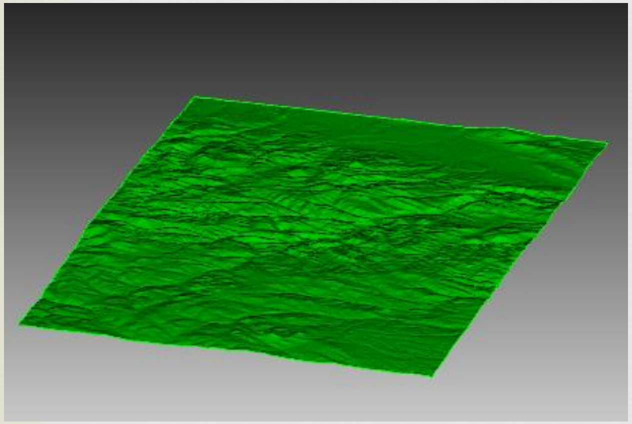
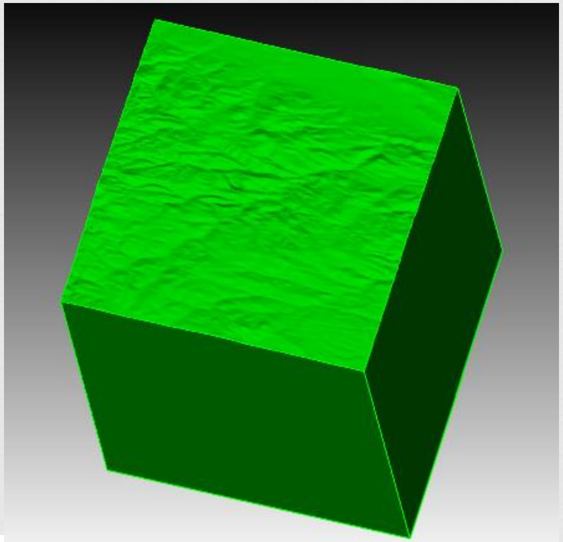
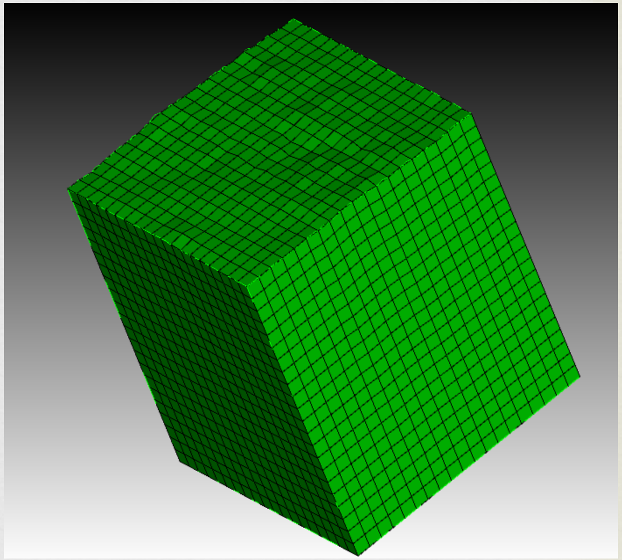
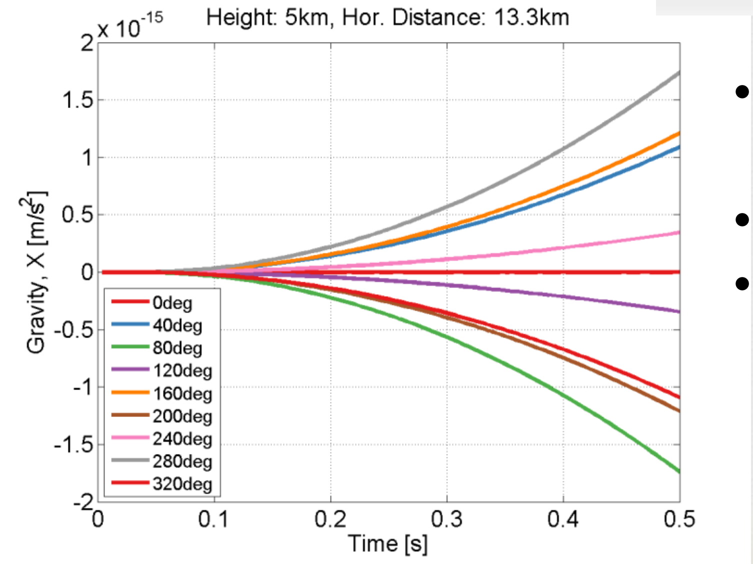
We need to understand

- **Seismic correlation**
- **Seismometer placement**
- **Structural response to seismic sources at various locations**



SPECFEM3D Simulation of Underground NN

Somala and Harms, 2016

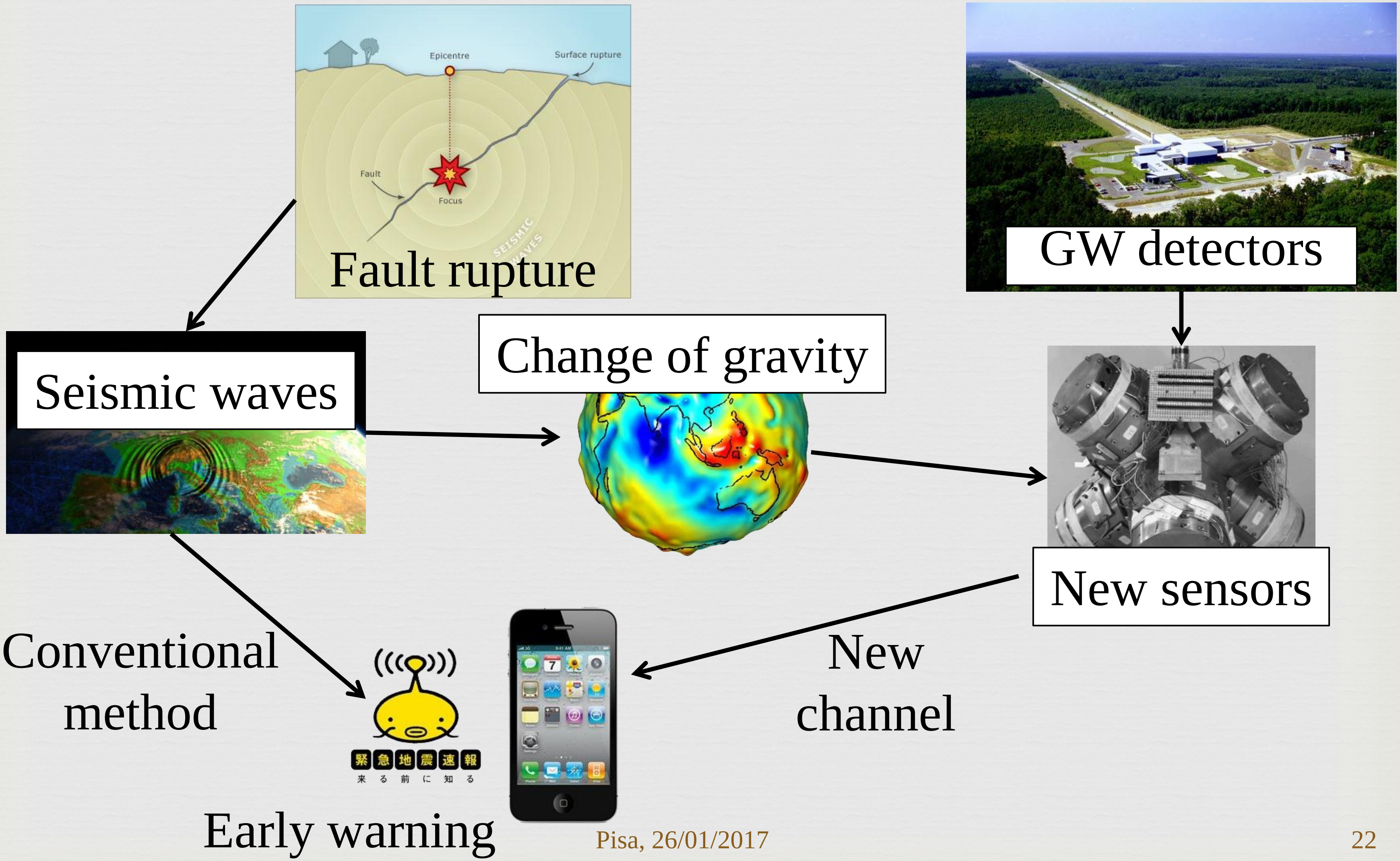





- Use of high-resolution topographic data at former Homestake mine to define finite-element model
- Impact of topography on seismic fields and NN
- Help understanding seismic data from local explosions recorded by an underground seismic array

NN Mitigation and R&D

- **Present**
  - Seismometer development
  - Homestake: composition of seismic field (body-waves, Rayleigh waves), *seismic correlations*
- **Near future**
  - Alternative sensors (seismic strainmeters, tiltmeters, dilatometers)
  - Hydrodynamical simulations for *atmospheric NN*
  - *NN cancellation* for underground sites: we need an idea of the degree of anisotropy and inhomogeneity of body-wave fields
- **Distant future**
  - Atmospheric tomography (LIDAR,…)
  - Use gravity gradiometers for NN cancellation

Earthquake Early Warning



Fault rupture

GW detectors

Seismic waves

Change of gravity

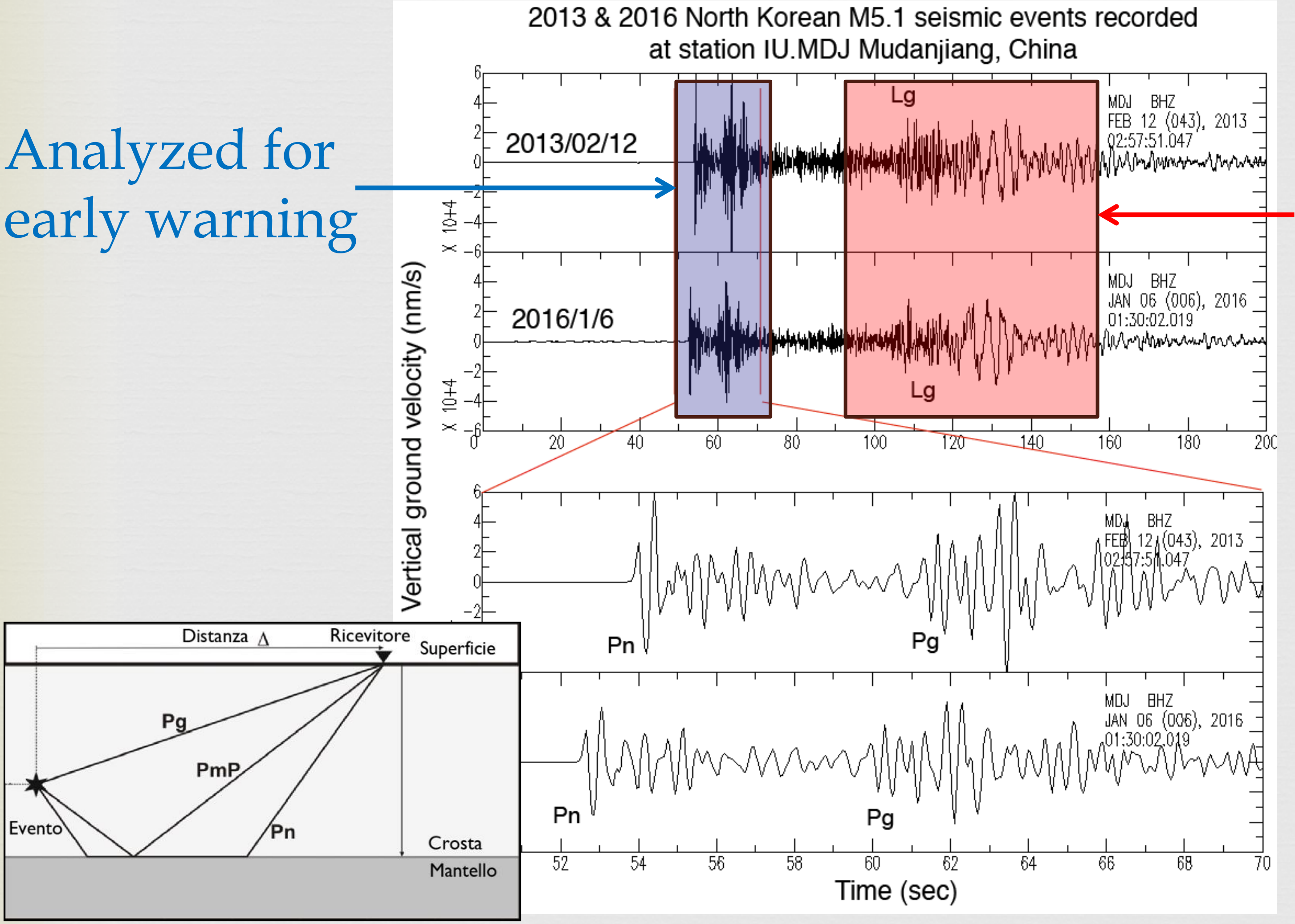
New sensors

Conventional method

New channel

Early warning

Seismic Phases

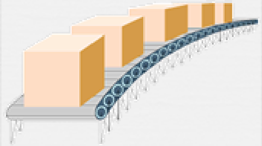


Analyzed for early warning

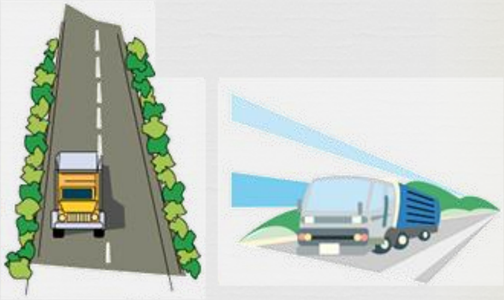
Part that causes damage

Seconds Count


Control trains

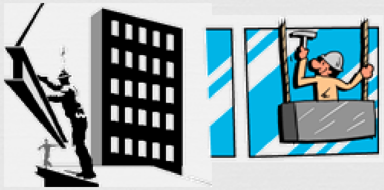


Control factory lines



Prevent traffic accidents

Control lifts



People executing dangerous work

Permit individual protection

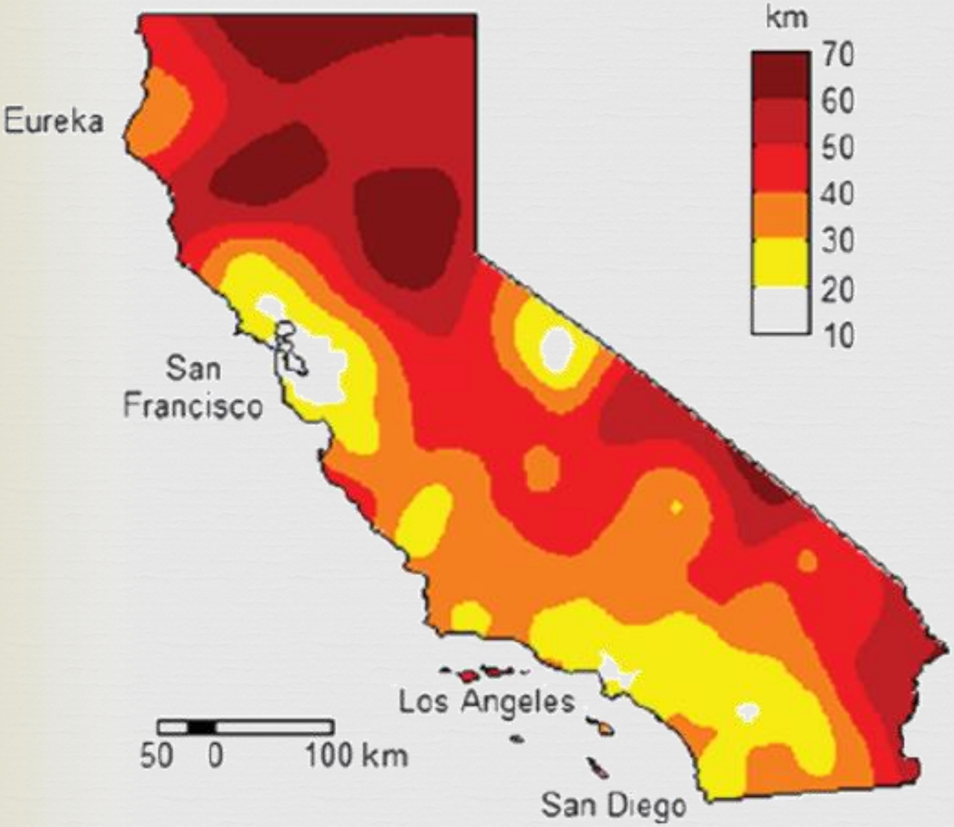
Suspend work in progress

Alert schools and meetings

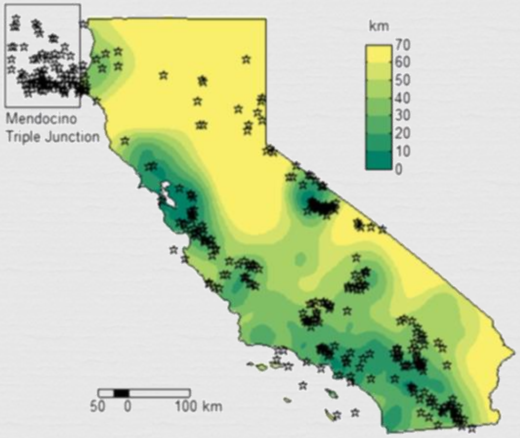
The Blind Zone

Example: California

Blind zone



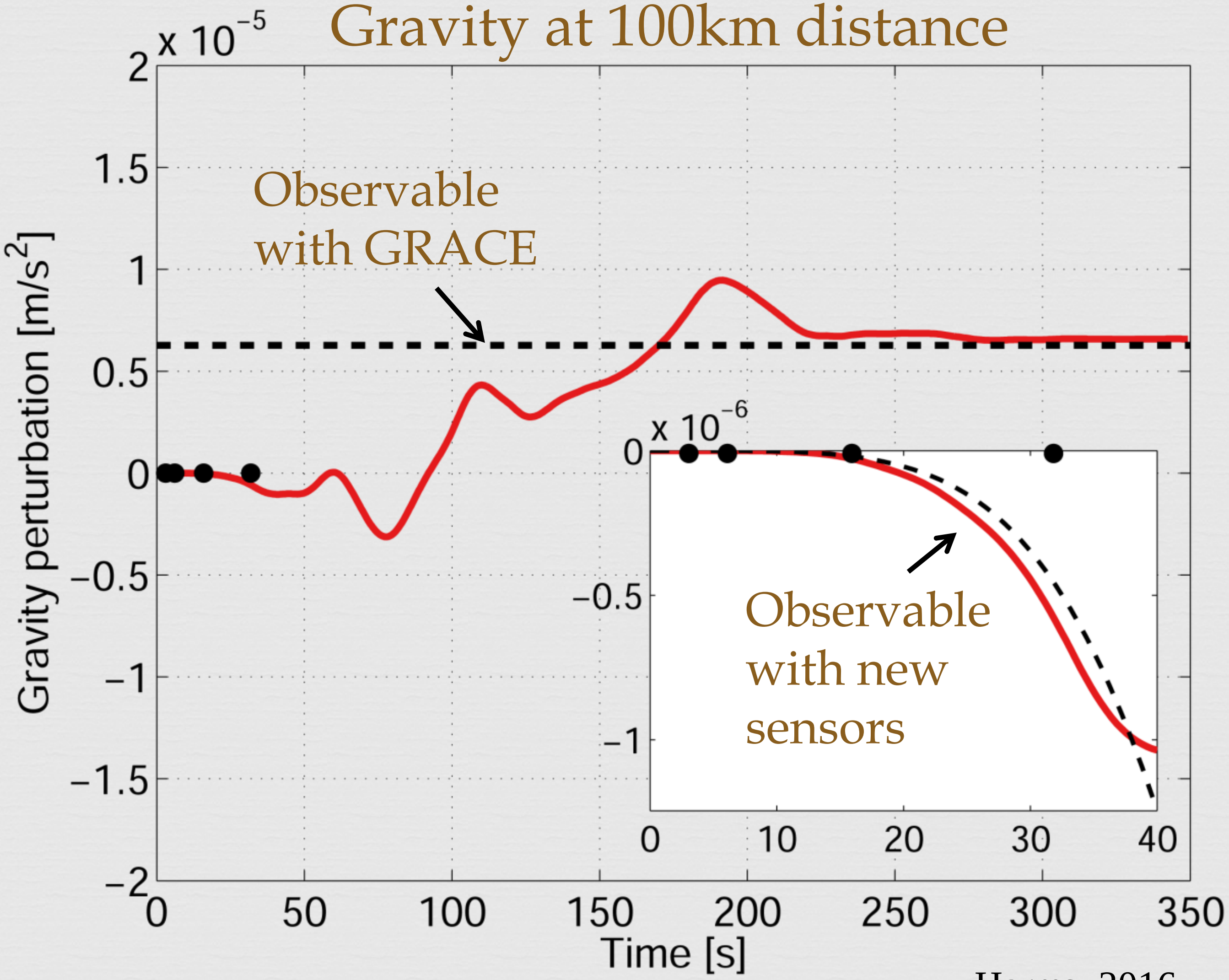
Sensor distribution



Kuyuk and Allen, 2013

High sensor density
→ small blind zone

Change of Gravity



Observable with GRACE

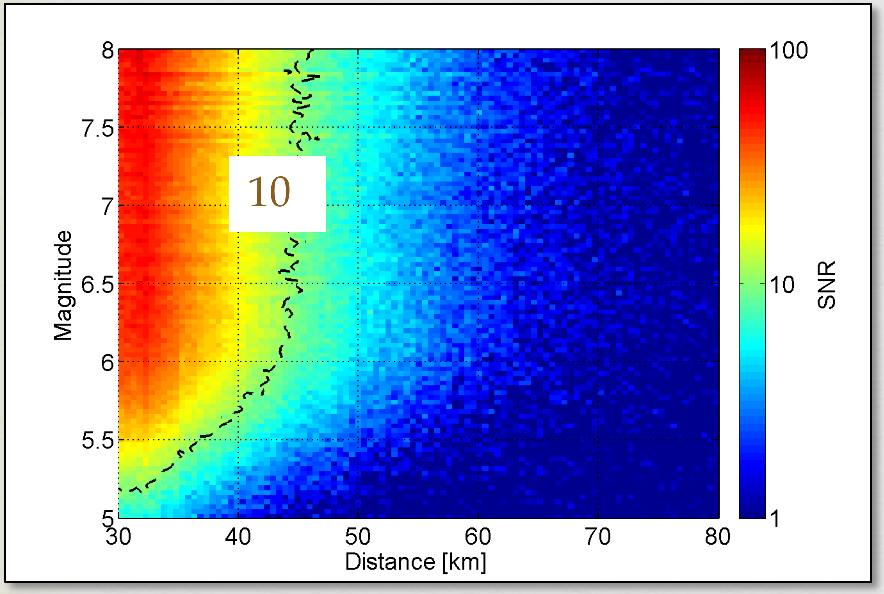
Observable with new sensors

Harms, 2016

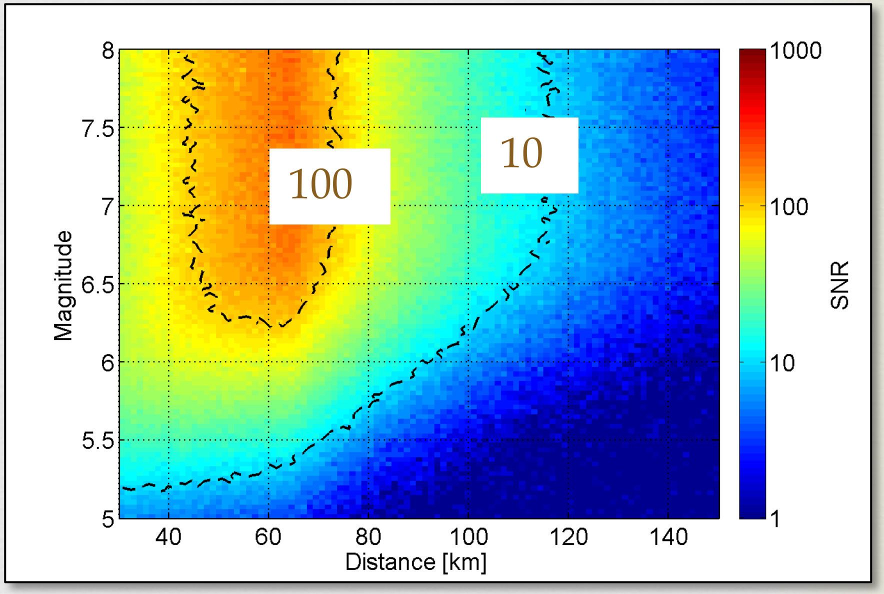
Potential SNRs

Integrate gravity signal up to 5s/10s or until P-wave arrival.

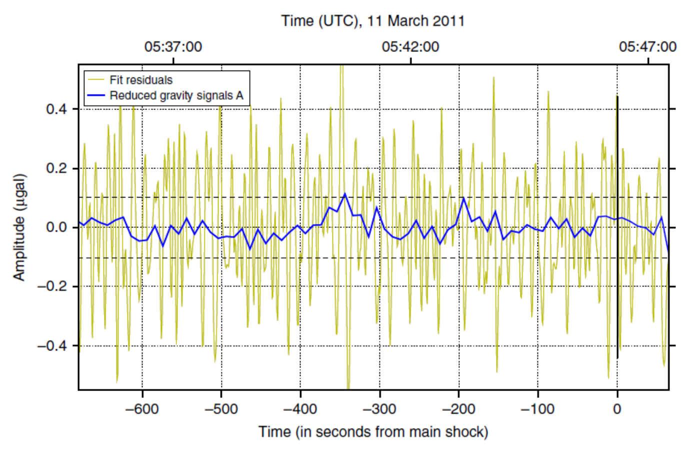
5s after fault rupture

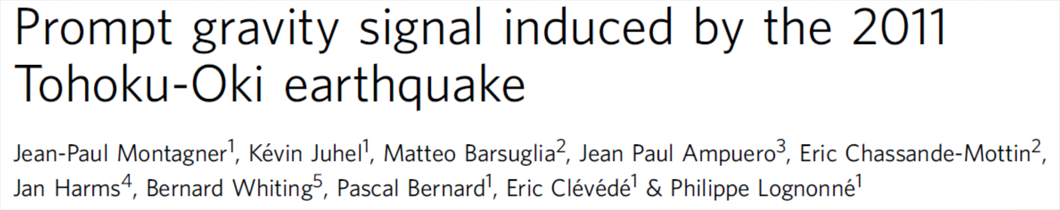


10s after fault rupture



First Observation





Prompt gravity signal induced by the 2011 Tohoku-Oki earthquake

Jean-Paul Montagner[1], Kévin Juhel[1], Matteo Barsuglia[2], Jean Paul Ampuero[3], Eric Chassande-Mottin[2], Jan Harms[4], Bernard Whiting[5], Pascal Bernard[1], Eric Clévédé[1] & Philippe Lognonné[1]