Seismic Metamaterials and their applications to reducing Newtonian Noise

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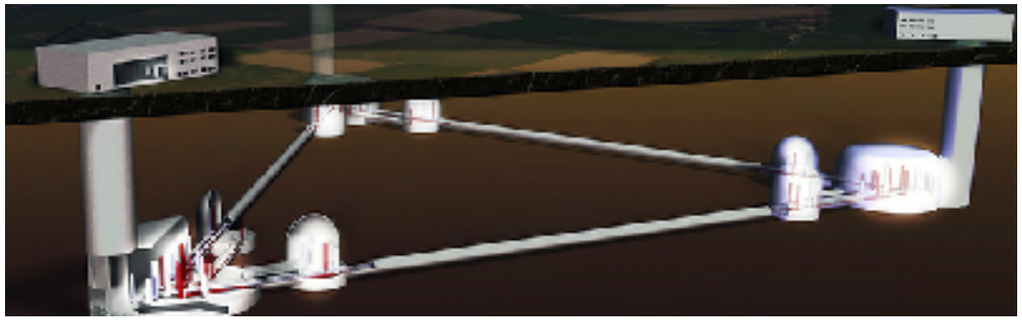
Our goal (GW community) reduce the impact of the environment on the detectors

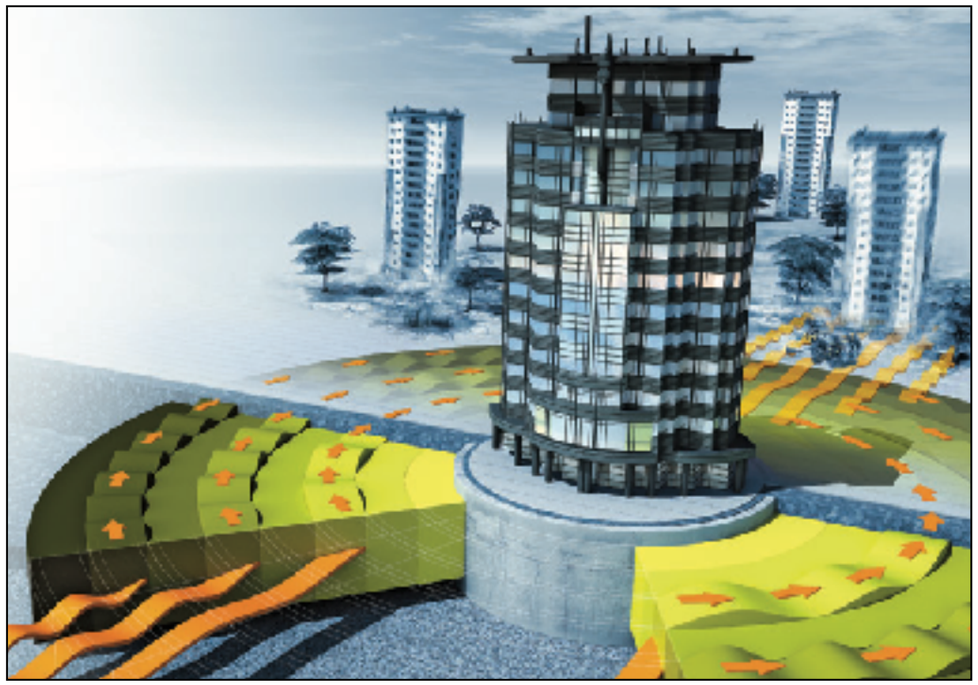
A goal (seismic engineering community) reduce impact of earthquakes on buildings

Our goal (GW community) reduce the impact of the environment on the detectors



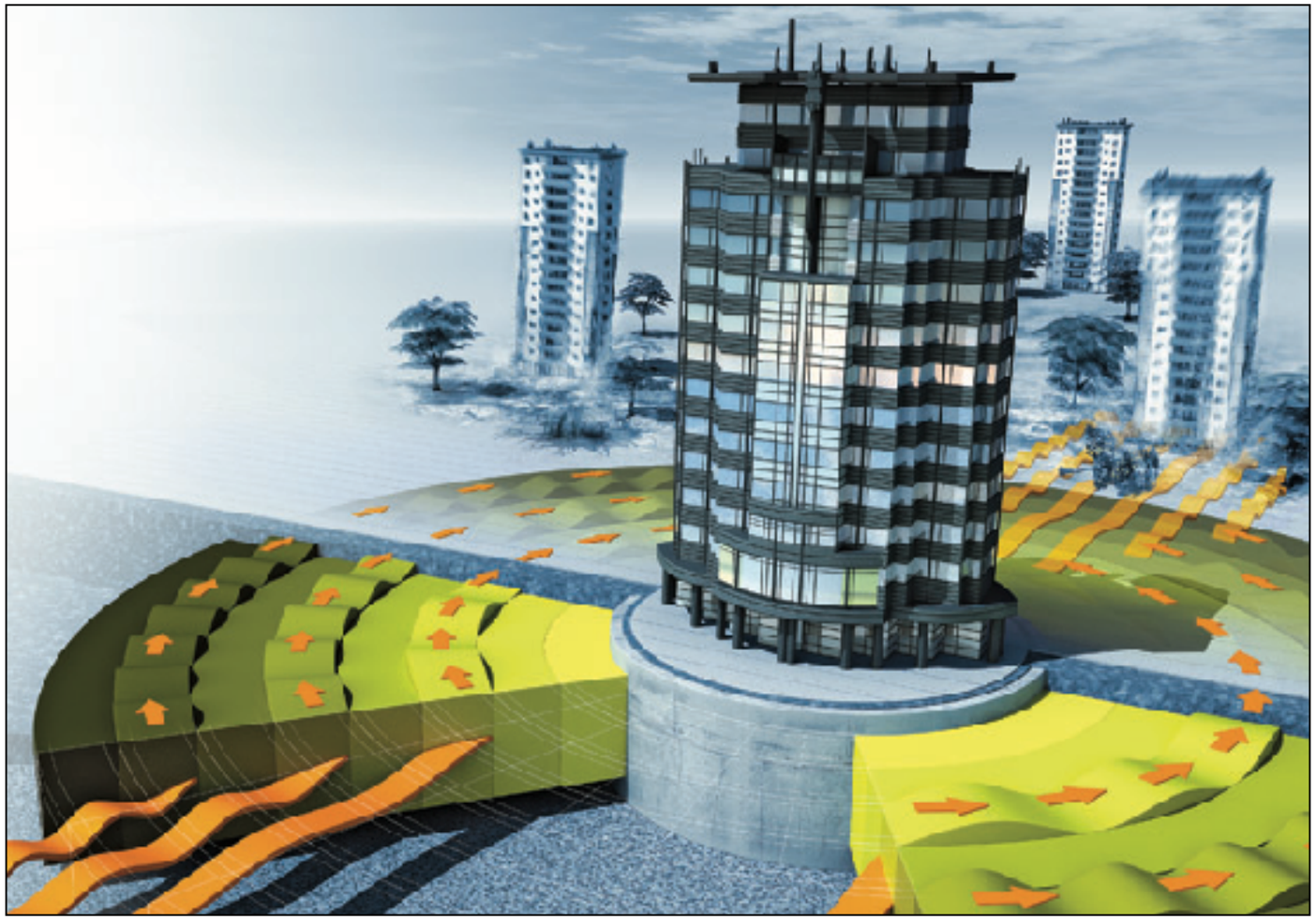
Our past, present and future of ground-based detectors

A goal (seismic engineering community) reduce impact of earthquakes on buildings



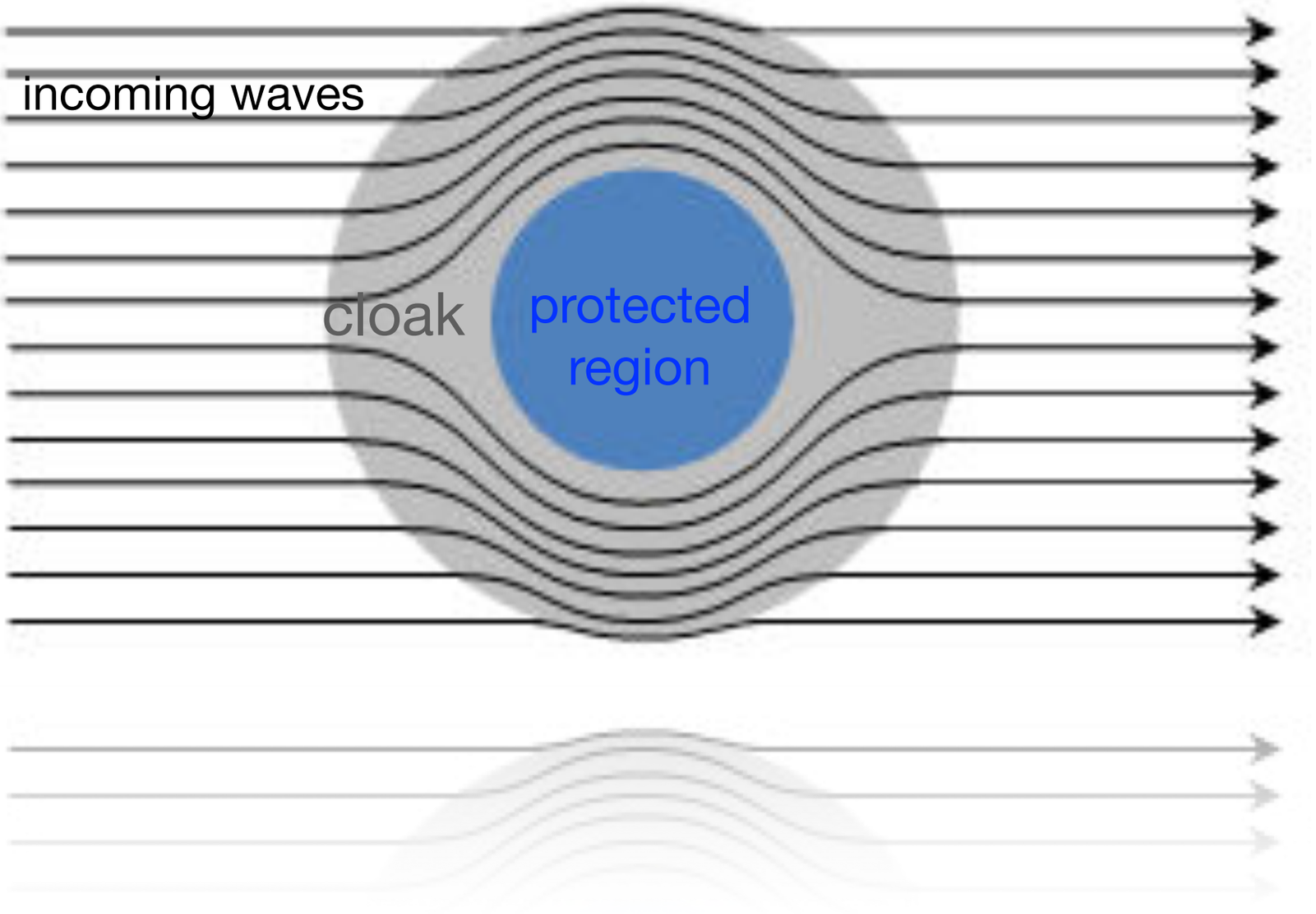
Seismic cloaking as a future direction of seismic engineering

Seismic cloaking :
Maneuvering seismic waves around precious infrastructure

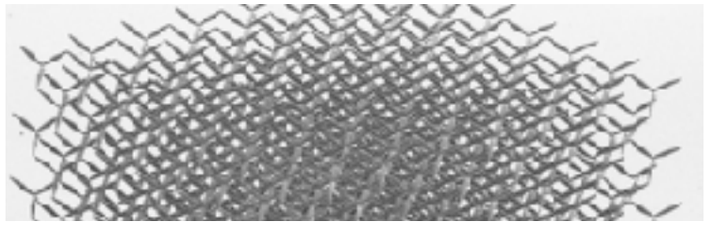


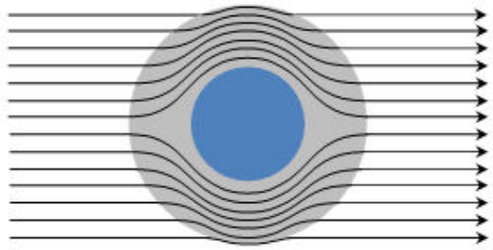
To protect hospitals, nuclear reactors, etc.
from seismic surface waves during earthquake events

Cloaking = Yes, invisibility cloaks



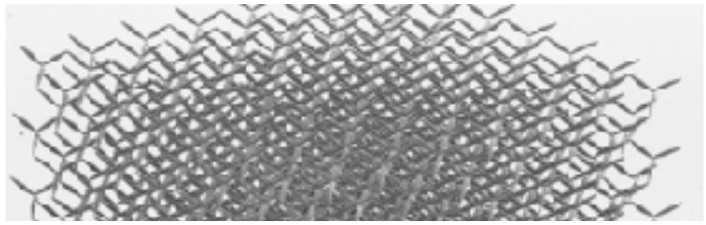
Incoming wave + Metamaterials = Cloaking



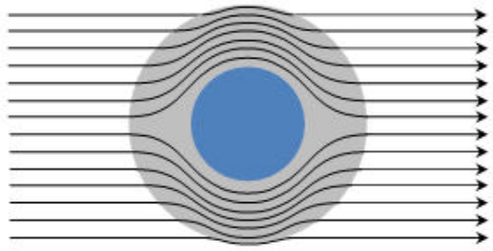


Incoming wave + Metamaterials = Cloaking

Electromagnetic
Acoustic
Seismic
Fluids



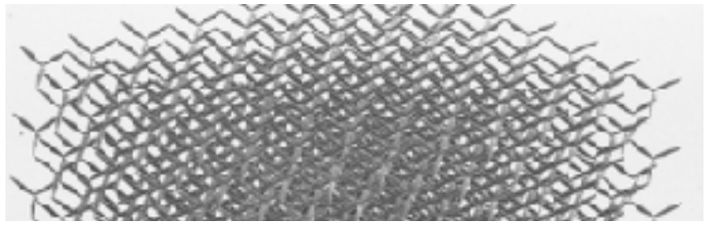
People-designed materials



Fabulous overview : “Metamaterials Beyond Optics” Kadic 2013

Incoming wave + **Metamaterials** = Cloaking

Electromagnetic
Acoustic
Seismic
Fluids



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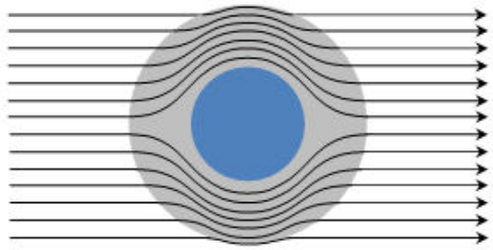


Cloaking has been experimentally demonstrated in a number of these applications (photonics, telecommunications, acoustic, underwater)

Fabulous overview : “Metamaterials Beyond Optics” Kadic 2013

Naturally occurring materials

Unit building block

Building up to the bulk properties of a material

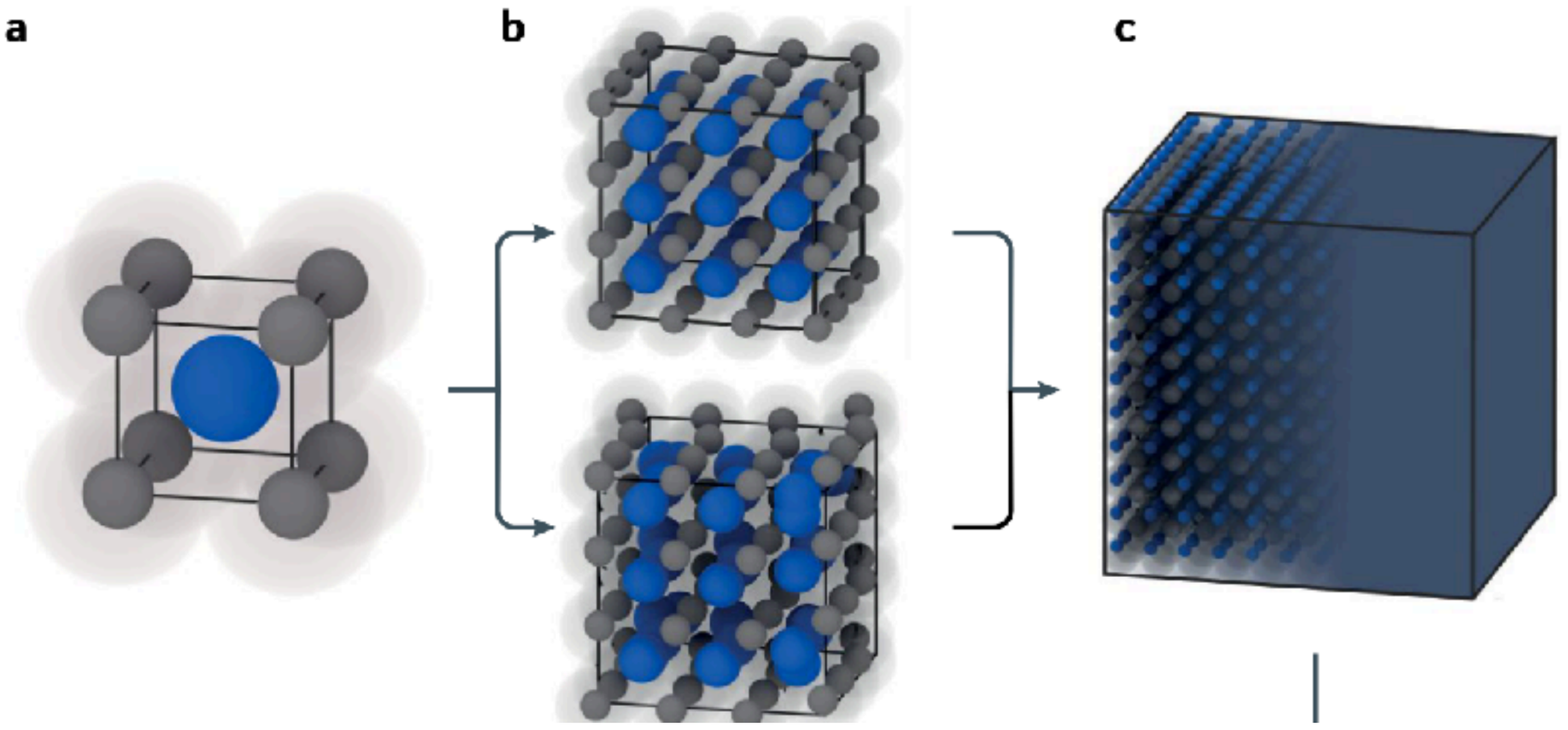
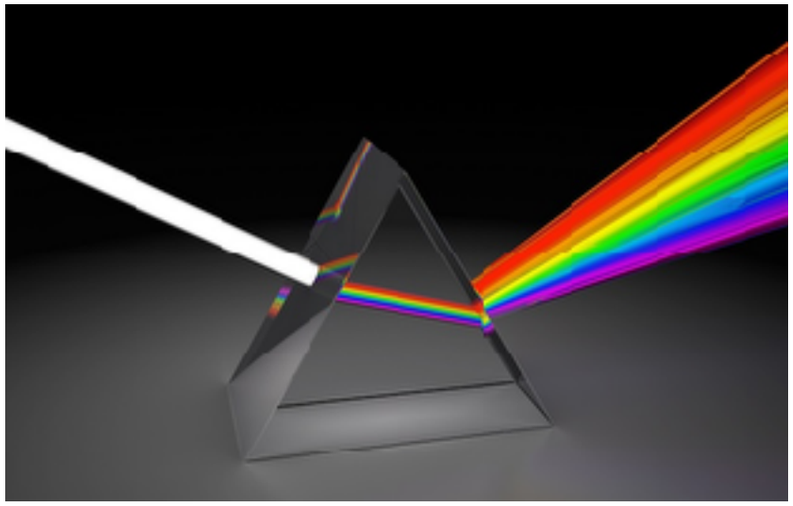
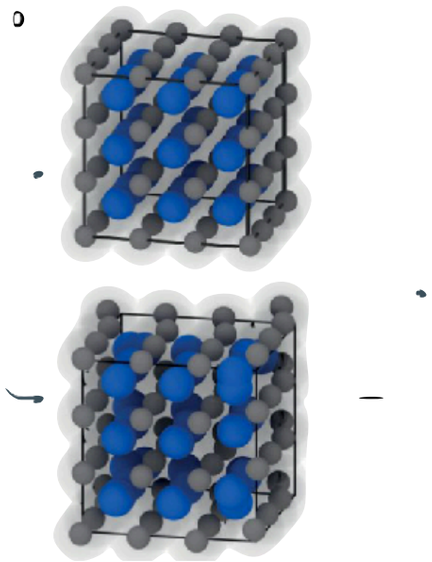


Image credit : “3D metamaterials” Kadic 2019 (also great review!)



Incoming wave

+



Material

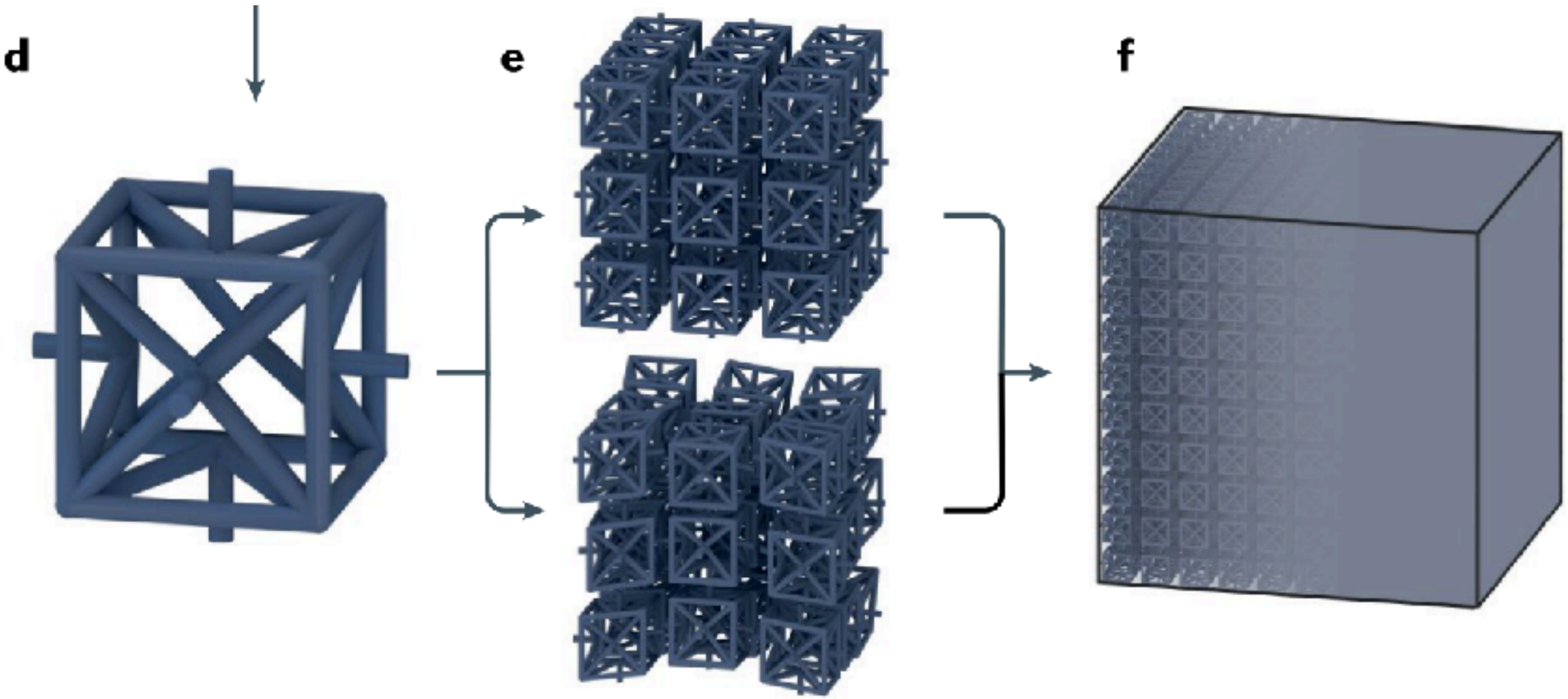
=

Outgoing phenomenon

New people-designed material = Metamaterials

Unit building block

Building up to the bulk properties of a material



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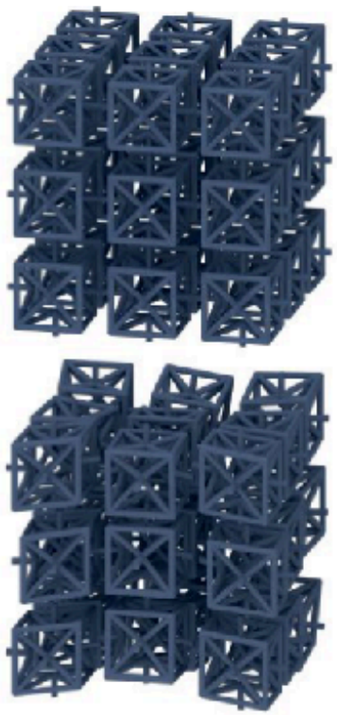
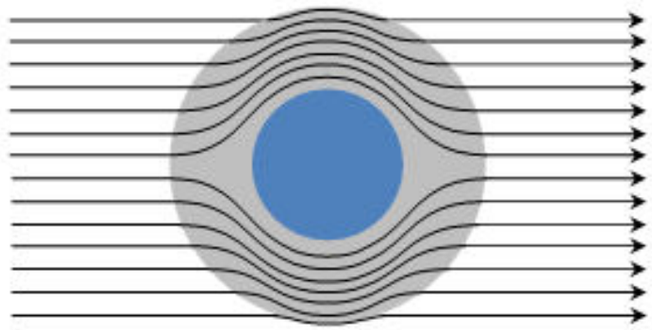


Cloaking



Incoming wave

+

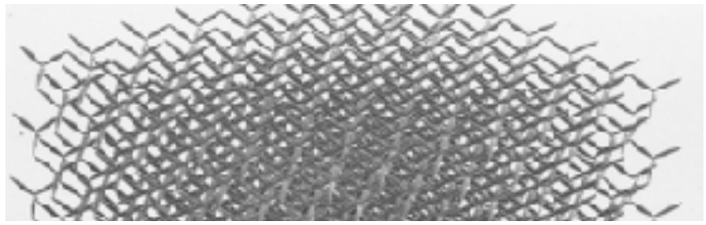
Meta-Material

=

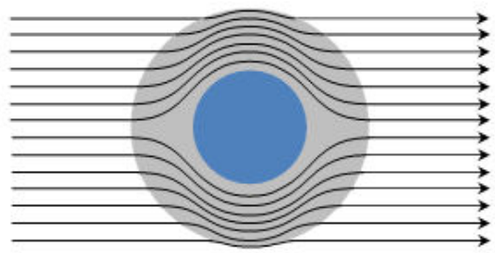
Outgoing phenomenon

Incoming wave + Metamaterials = Cloaking

Seismic waves



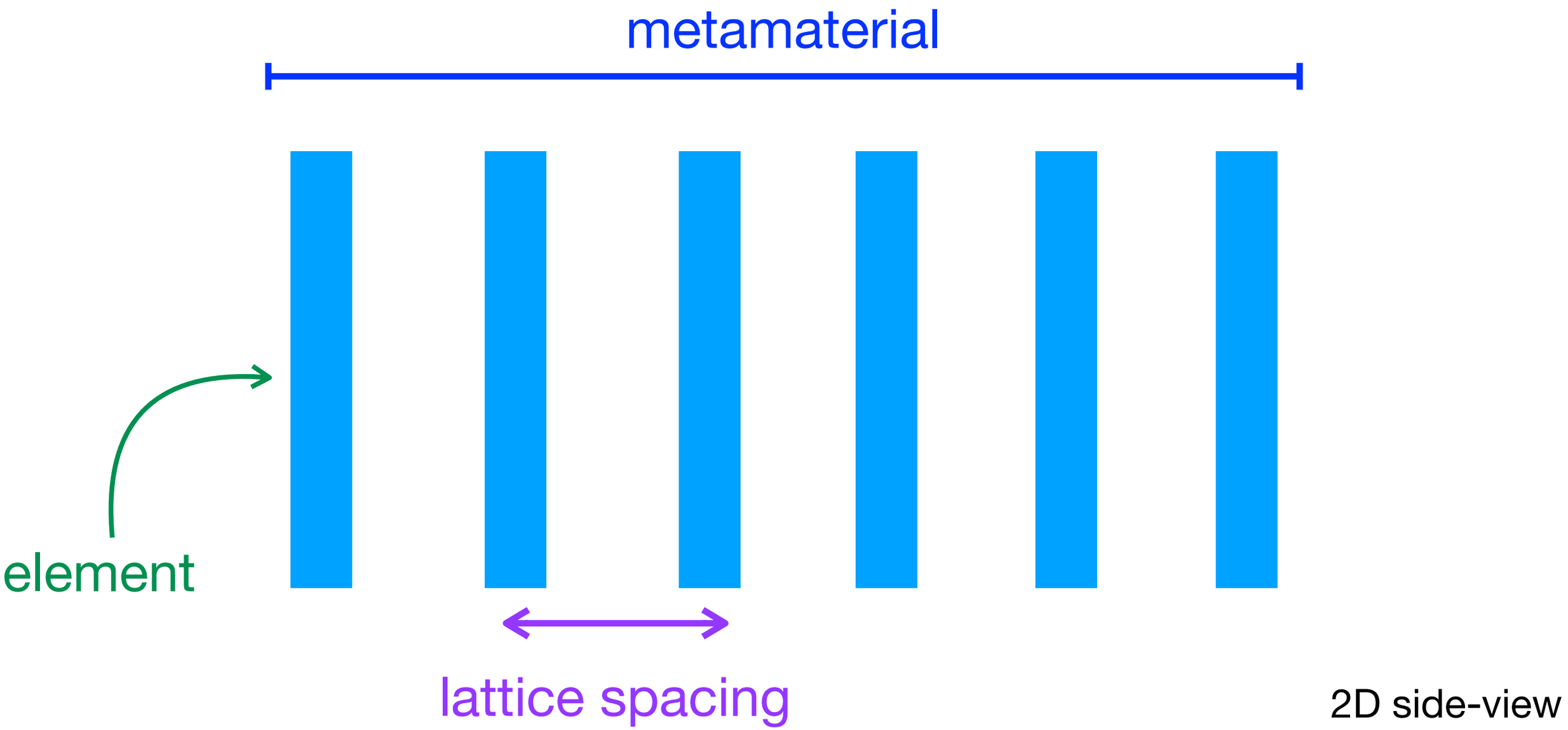
Seismic meta-materials



Seismic cloaking

What is a seismic metamaterial?

It is lattice-like structure designed
to mitigate low-frequency seismic waves



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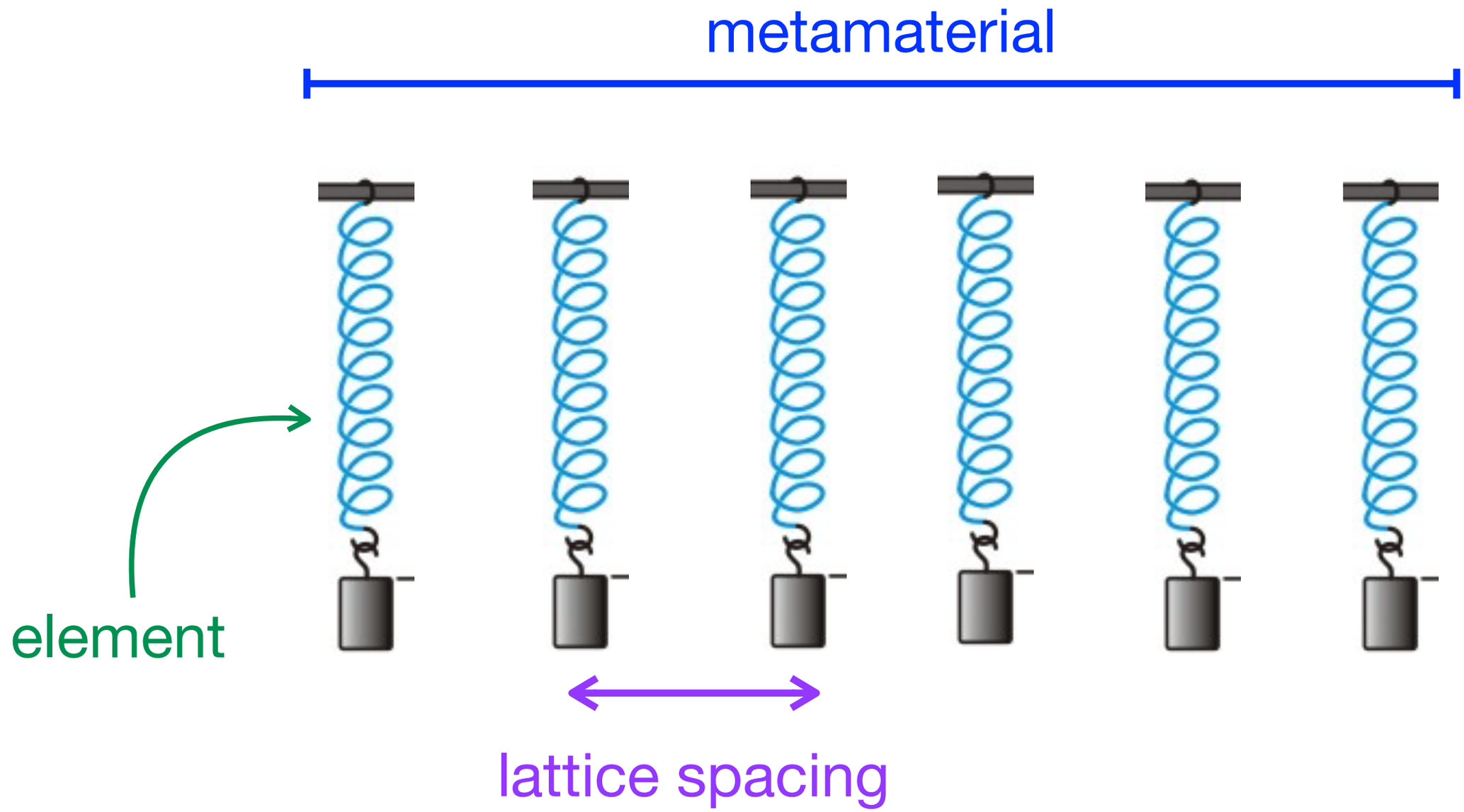
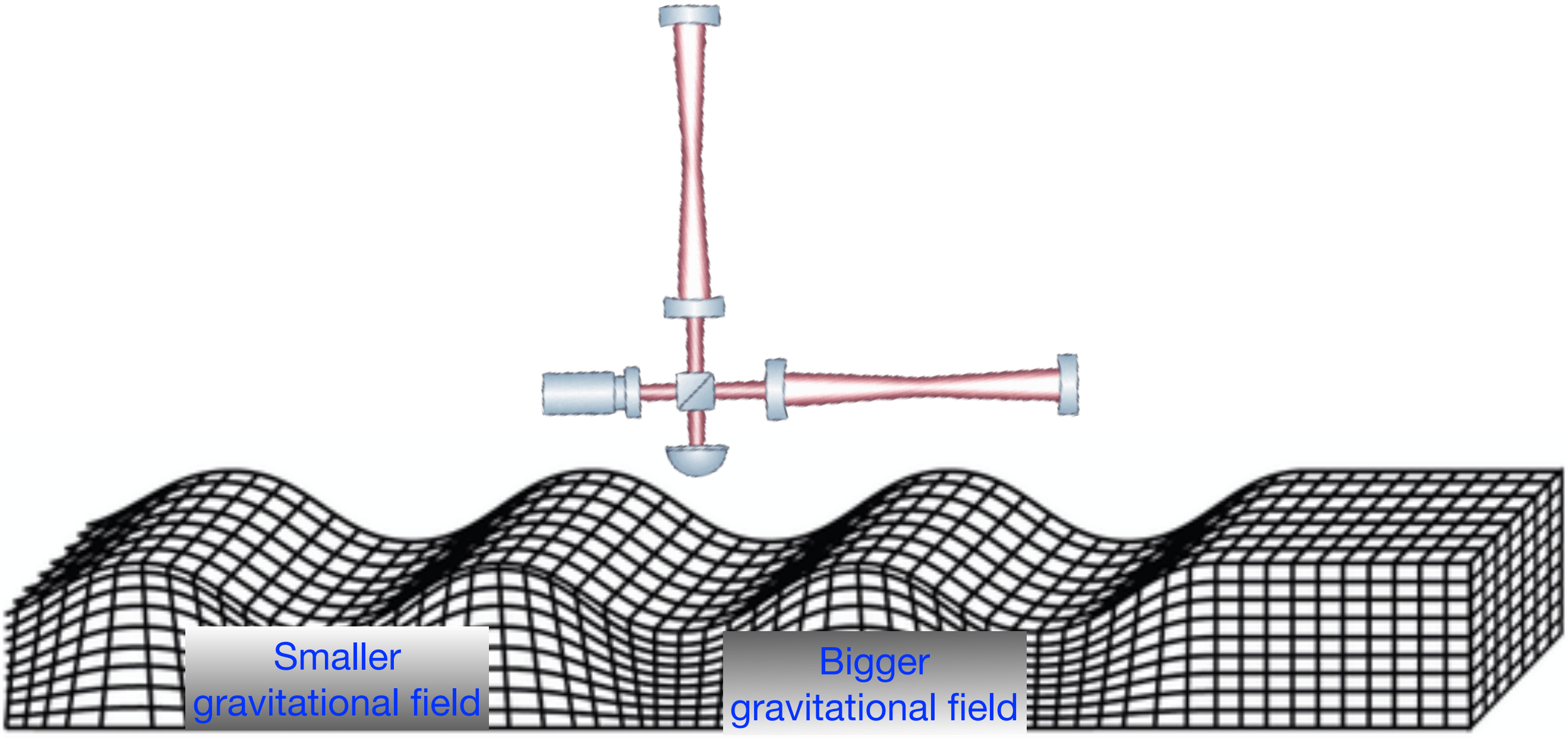


2D side-view

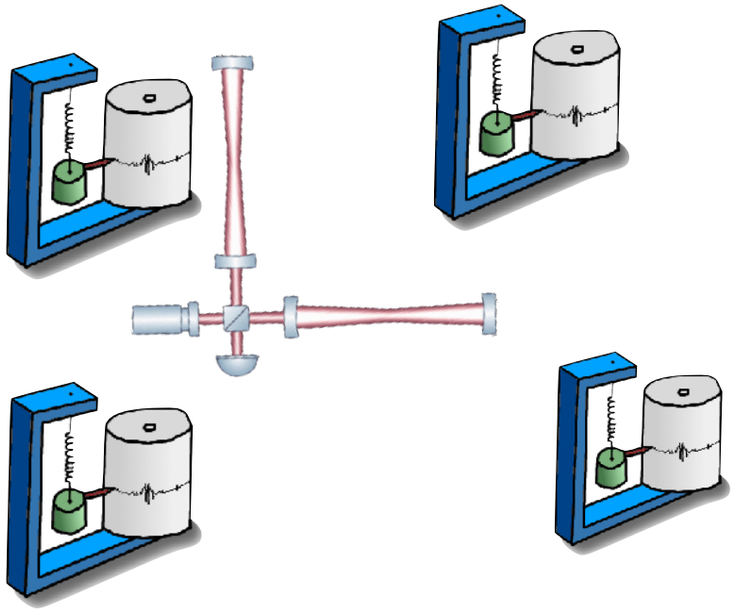
Connecting Seismic Metamaterials to Newtonian Noise

Newtonian Noise (Gravitational Gradient noise)
comes from Rayleigh waves (surface seismic waves)



“Terrestrial Gravity Fluctuations
Jan Harms, Living Relativity Reviews 18, 2015 (great review!)

Current works towards mitigating Newtonian Noise



Larger Network of sensors

"Subtraction of Newtonian Noise using optimized sensor arrays"
Driggers 2012

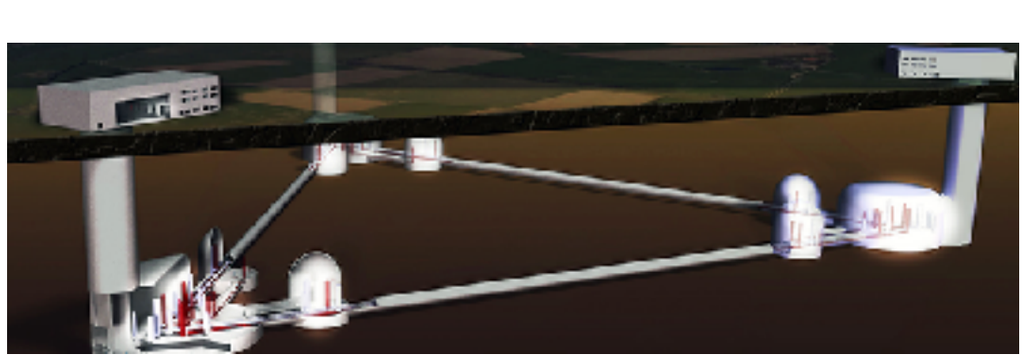
"Towards a first design of a Newtonian-noise cancellation system for Advanced LIGO"
Coughlin 2016

Underground facilities

Kagra + ET + CE

Sensor Network + Underground facilities

Other talks in this session!
(Francesca Bonatella, Donatella Fiorucci, Jan Harms)

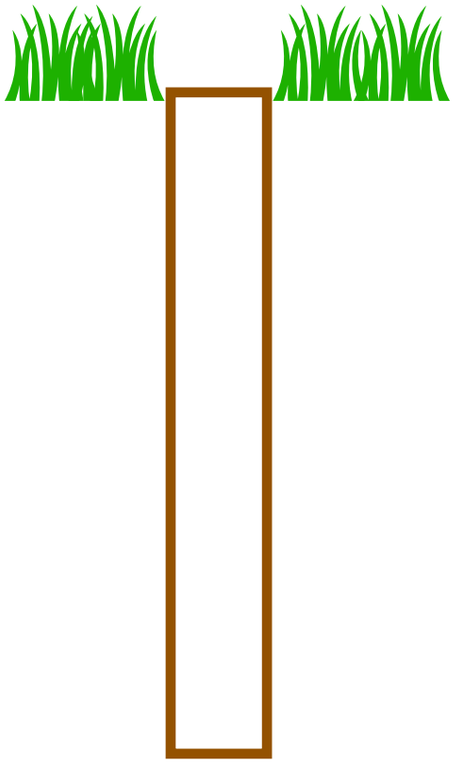


Shaping the local topology

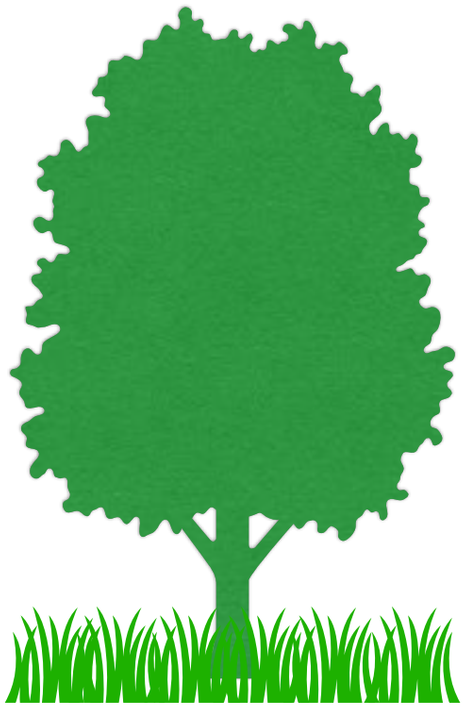
"Passive Newtonian noise suppression for gravitational-wave observatories based on shaping of the local topography"
Harms and Hild, arXiv:1406.2253

& Seismic metamaterials?

Advances in the field of Seismic metamaterials



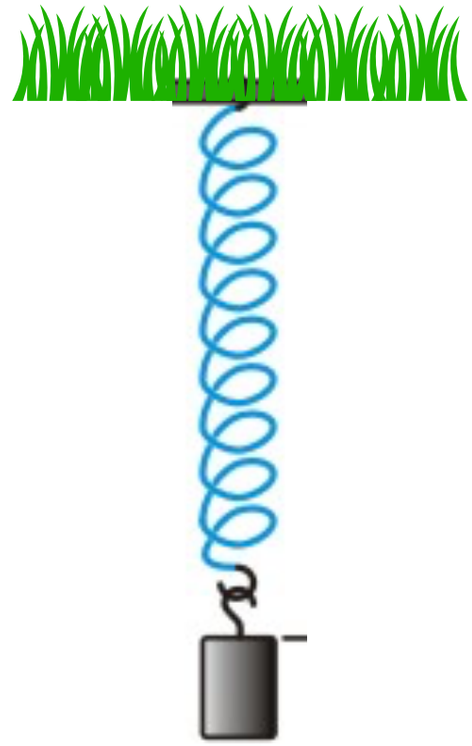
50 Hz notch-filter using holes in the ground



Bandgaps at 40 &110 Hz

Low pass filter 50 Hz

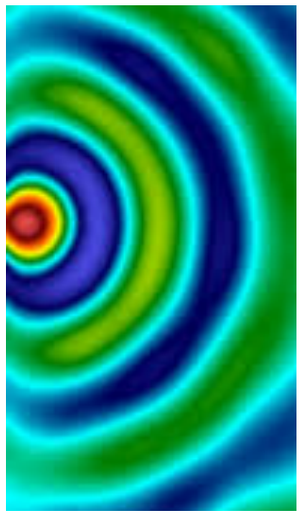
using trees

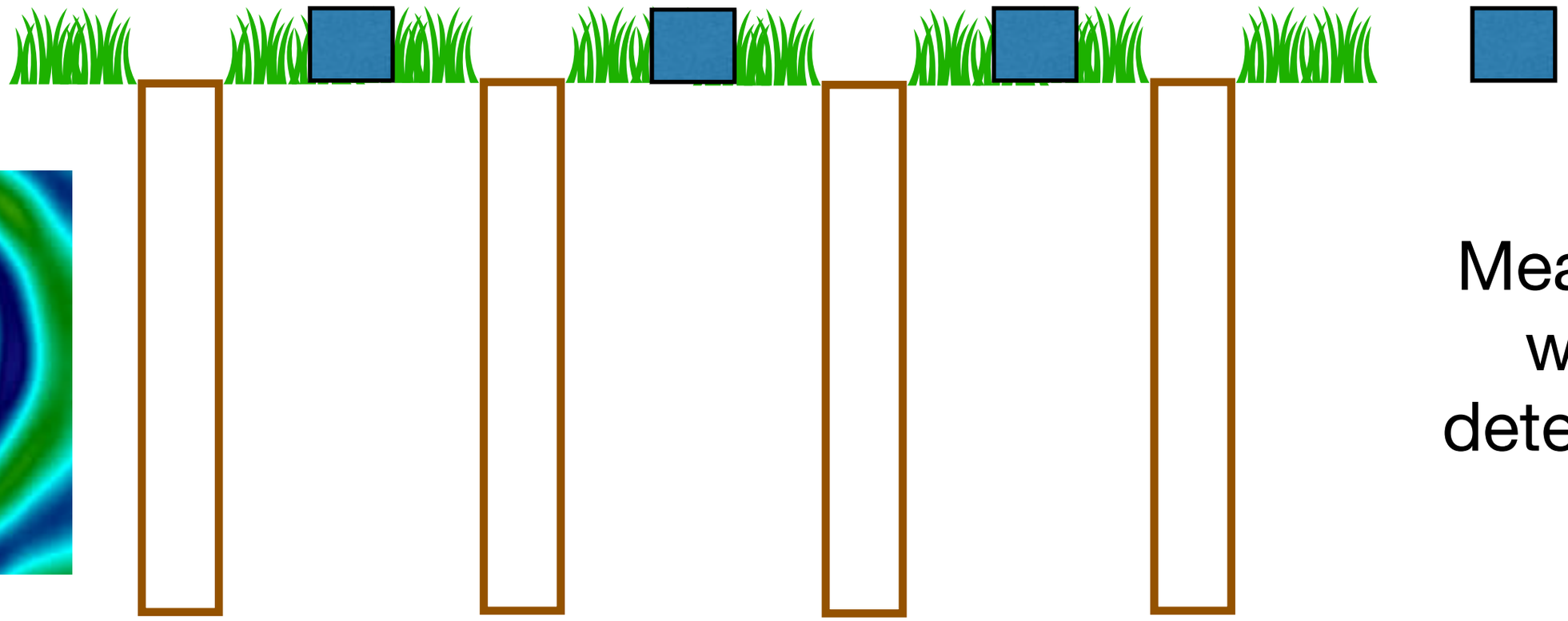


Buried resonators < 50Hz

"Experiments on Seismic Metamaterials: Molding Surface Waves"
Brule, et al, PRL 2014

2014





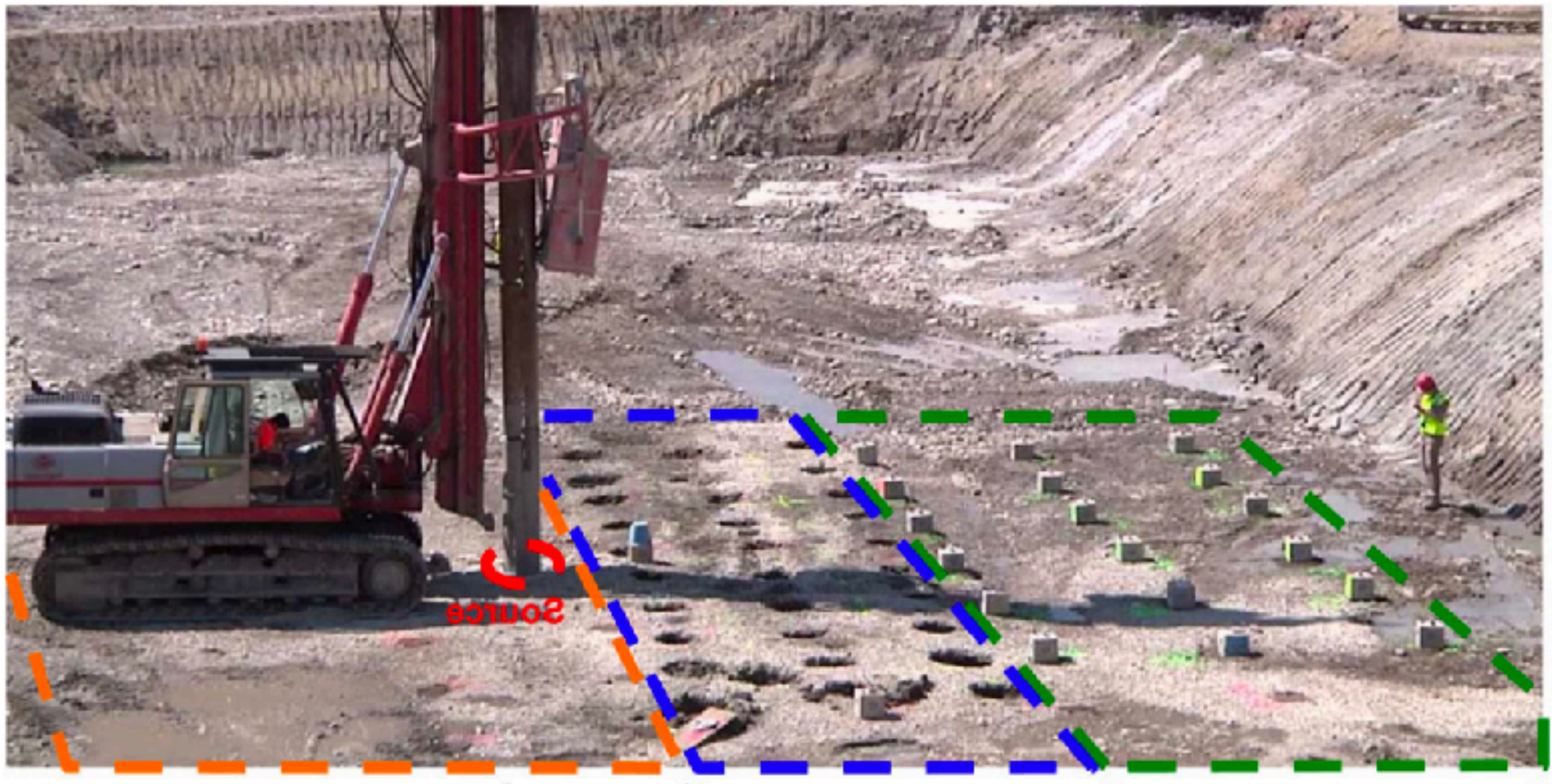
Measure with detectors

Generate 50 Hz waves

Set scale of metamaterials

"Experiments on Seismic Metamaterials: Molding Surface Waves"
Brule, et al, PRL 2014

2014



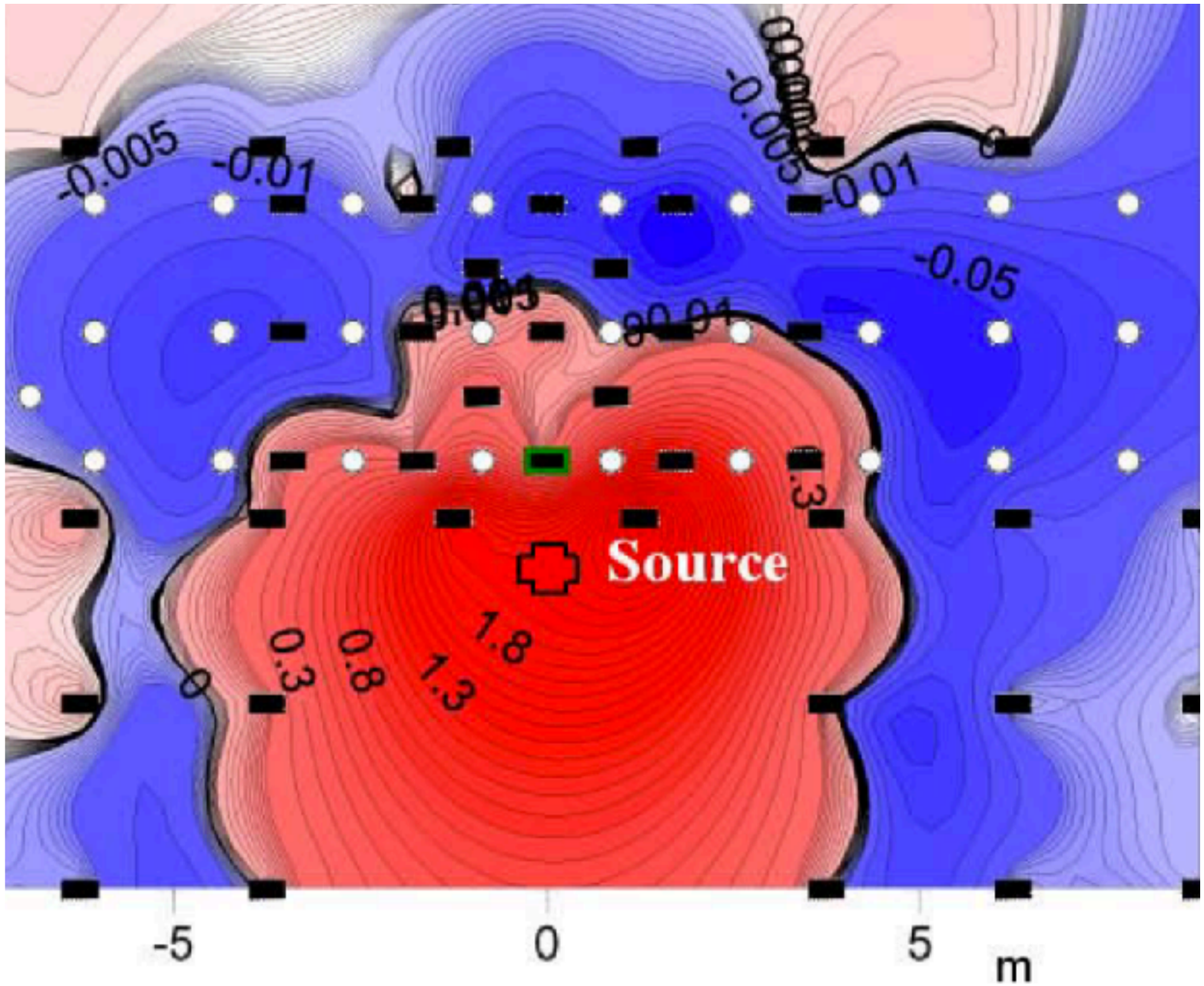
Source :
- Frequency : 50 Hz
- Horizontal displacement : 14 mm

Five meters deep
320 mm holes

Sensitive three components
velocimeters (green grid)

"Experiments on Seismic Metamaterials: Molding Surface Waves"
Brule, et al, PRL 2014

2014



source (cross)

metamaterial (white circles)

detectors (black squares)

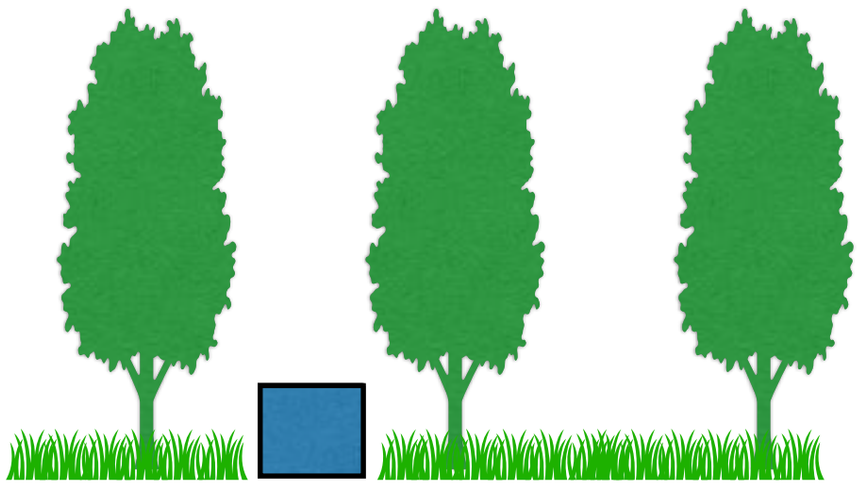
Main Results

- Reflected waves back towards the source
- Achieved a factor of 2 attenuation

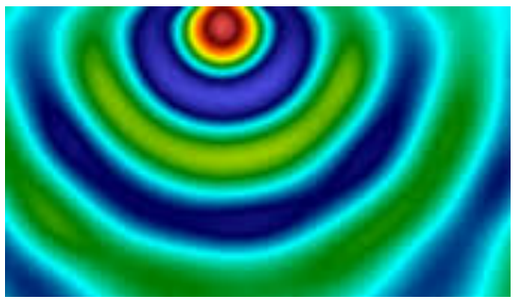
"Forests as a natural seismic metamaterial:
Rayleigh wave bandgaps induced by local resonances"
Colombi, et al Scientific Reports 6, 19238 (2016)

2016

Construction worker
generating seismic noise



Detector within the trees



Detector outside of the trees

"Forests as a natural seismic metamaterial:
Rayleigh wave bandgaps induced by local resonances"
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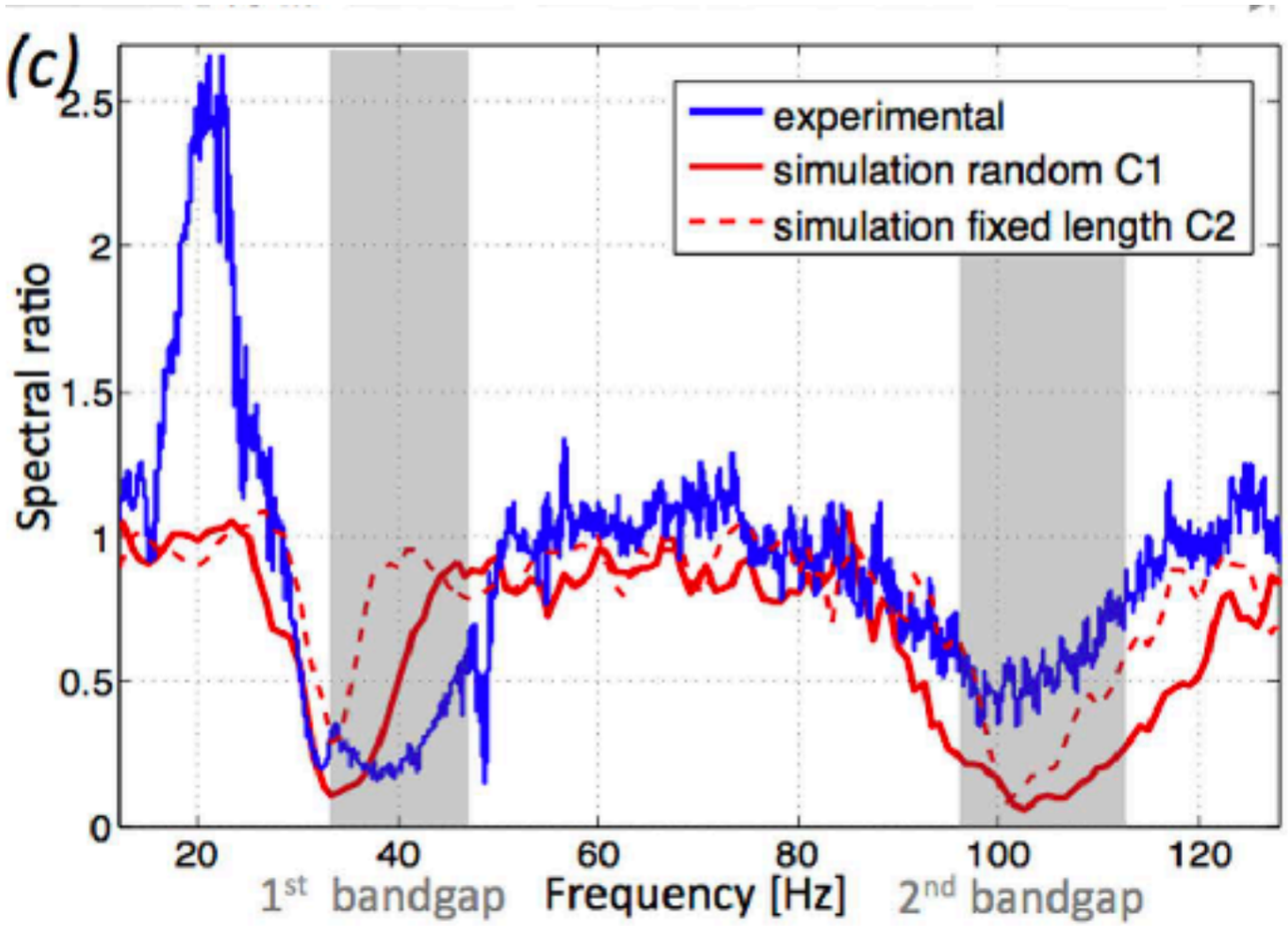
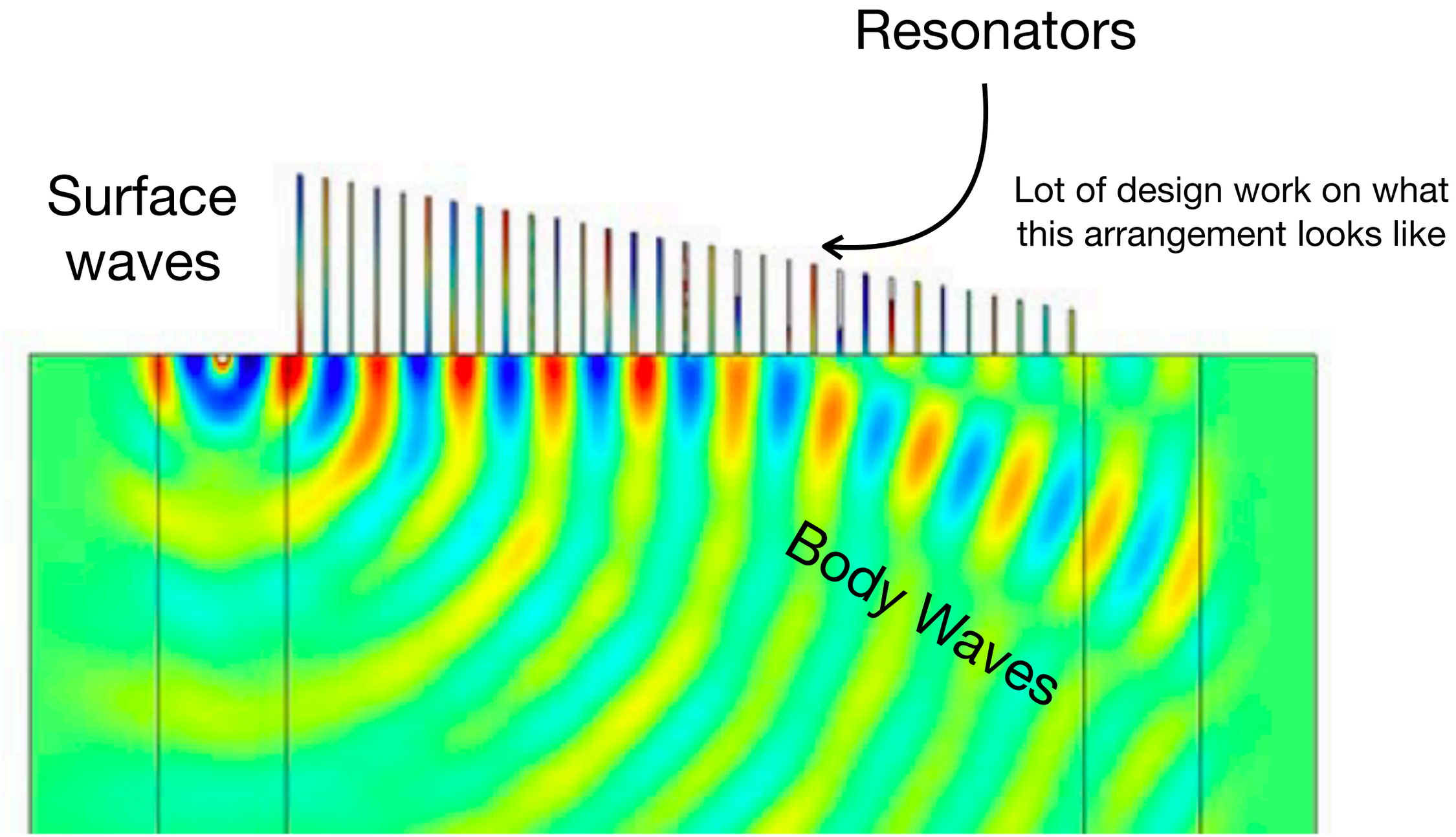
2016



Main Results

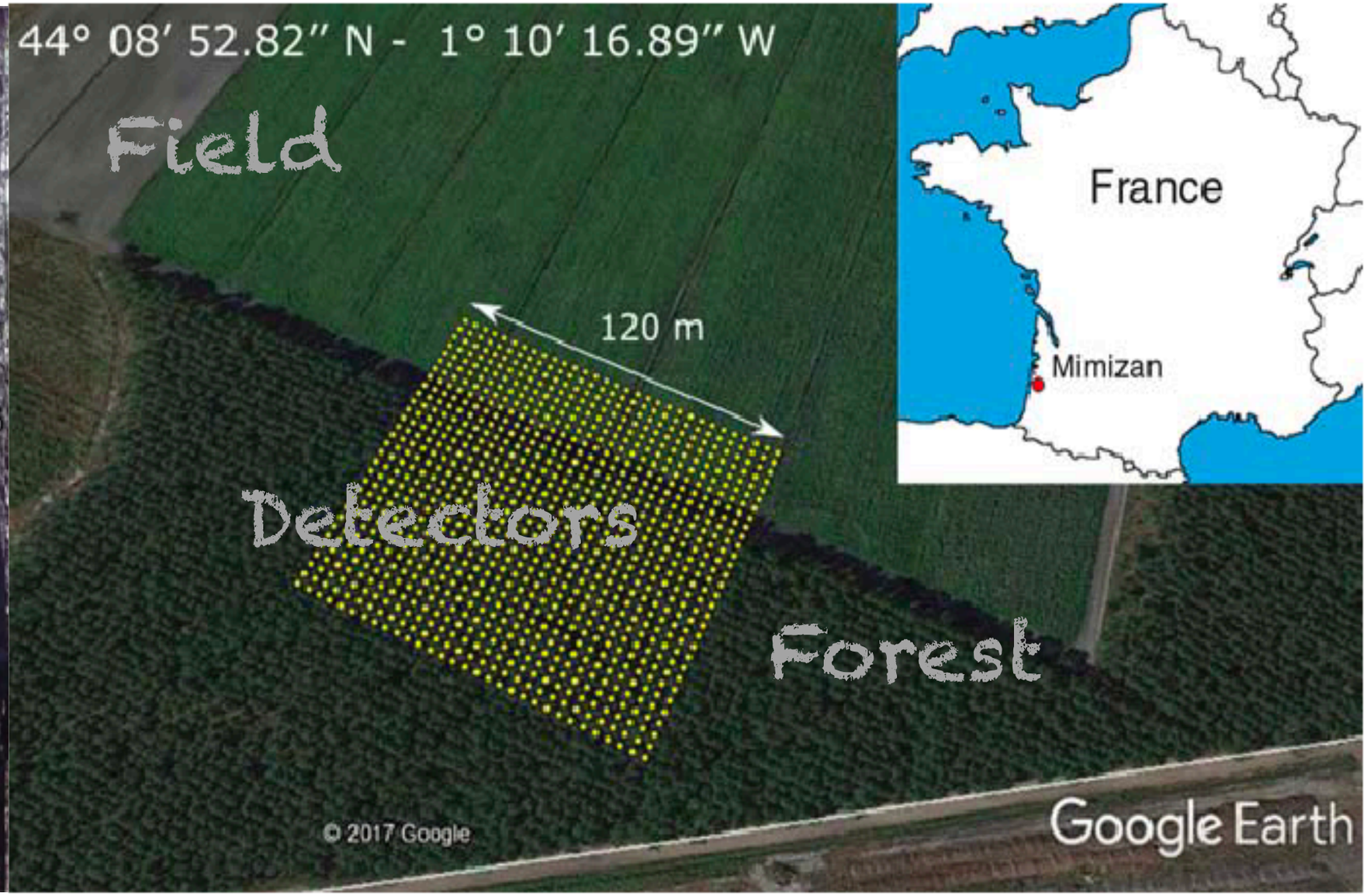
- Bandgaps at ~40 & 110 Hz
- Consistent with properties of the tree forest parameters
- Achieved a factor of 6 attenuation

Trees are a class of surface acoustic resonators



"Toward seismic metamaterials: The METAFORET project"
Roux et al Seismological Research Letters 2018

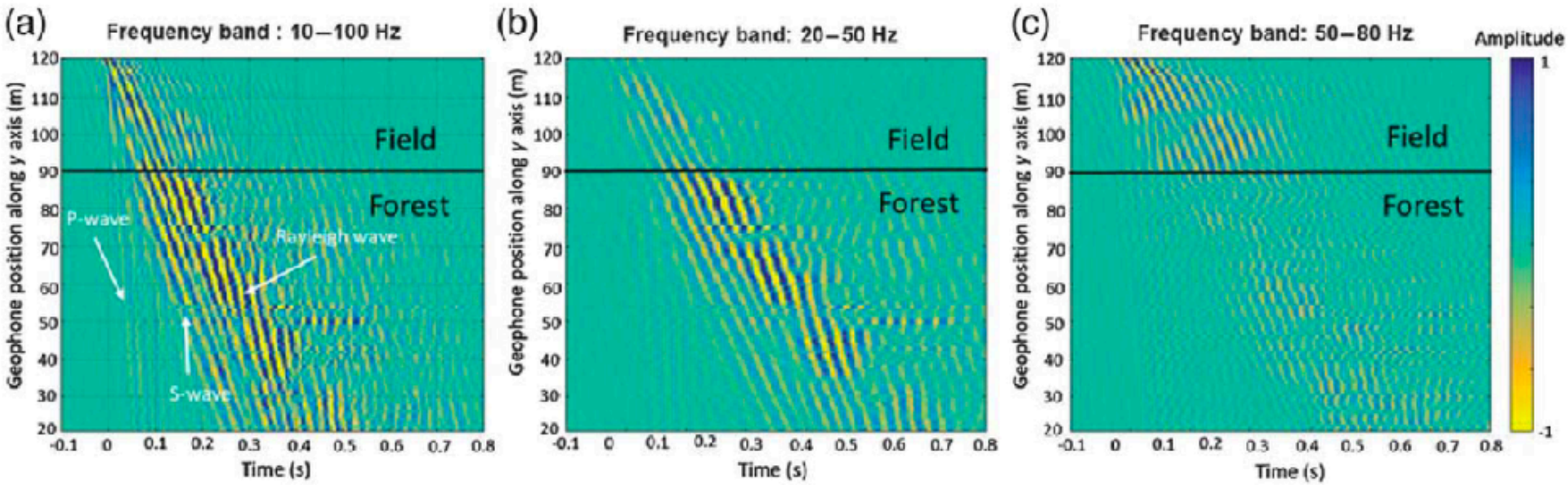
Jan 2018



"Toward seismic metamaterials: The METAFORET project"
Roux et al Seismological Research Letters 2018

Jan 2018

10-100Hz (all the waves) 20 - 50 Hz 50-80 Hz

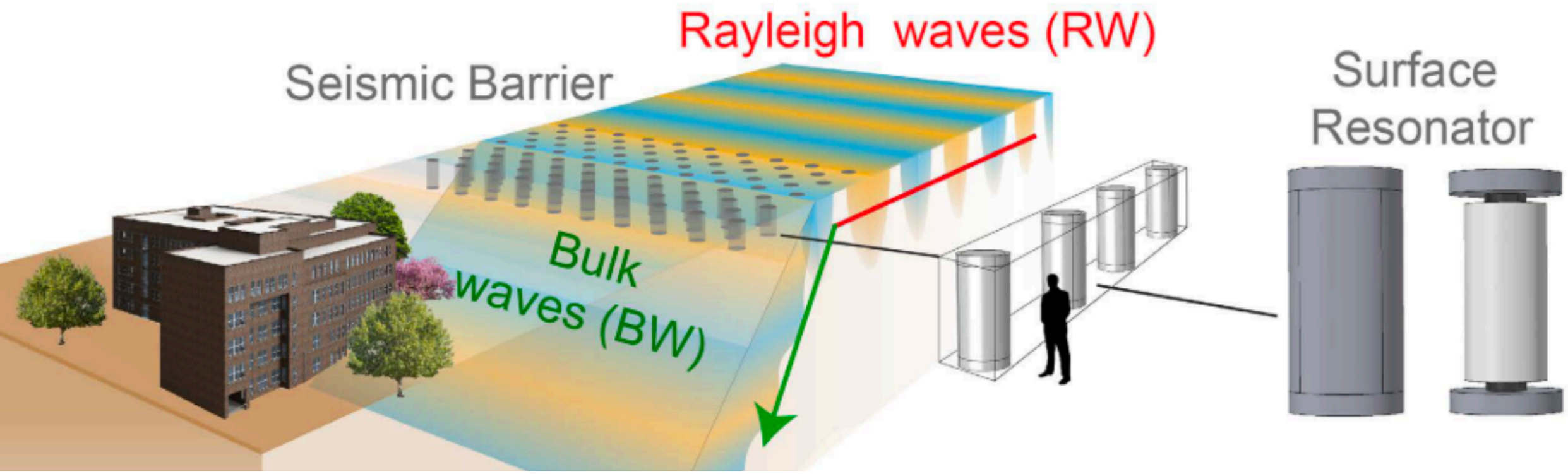


Map of sensing area

Main Results

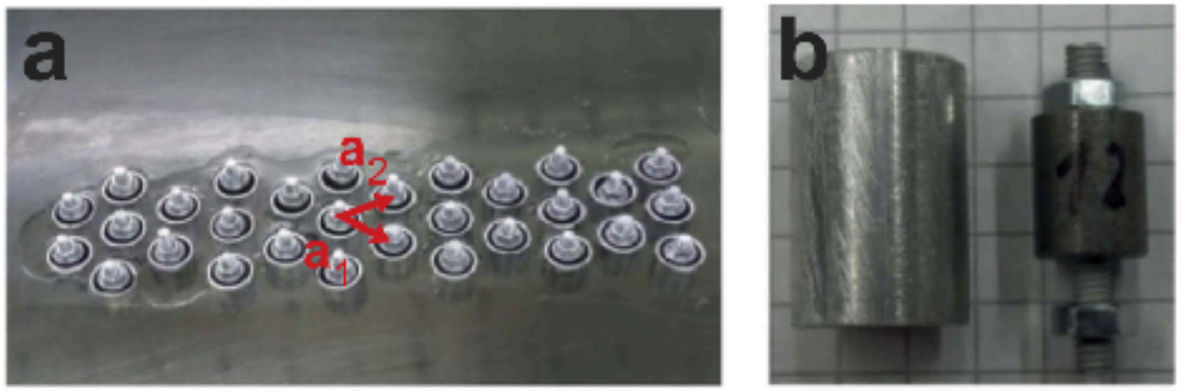
- Forest is filtering waves > 50Hz
- Directly connected with compressional modes of the trees
- Achieved a factor of 6 attenuation

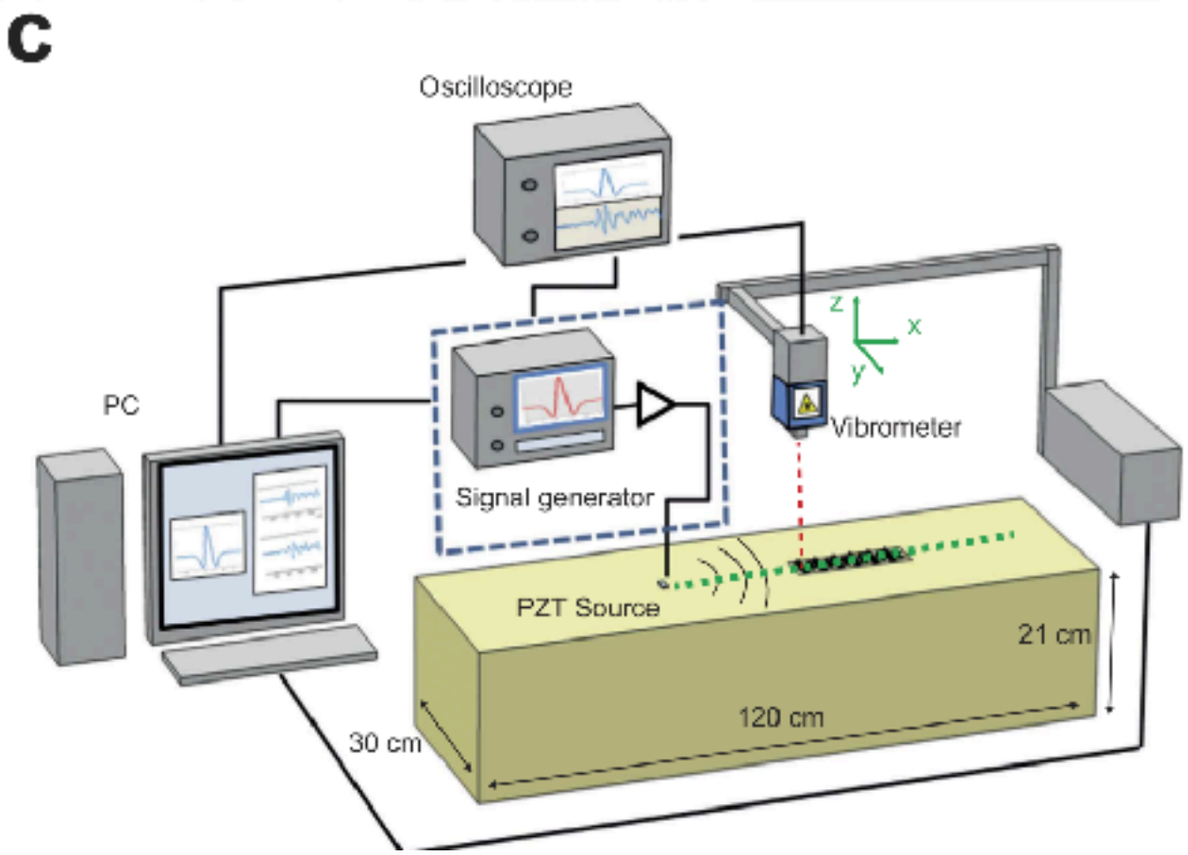
"Engineered metabarrier as shield from seismic surface waves" Dec 2018
Palermo et al Nature 6, 39356



Theoretical modeling of underground resonators below 10 Hz

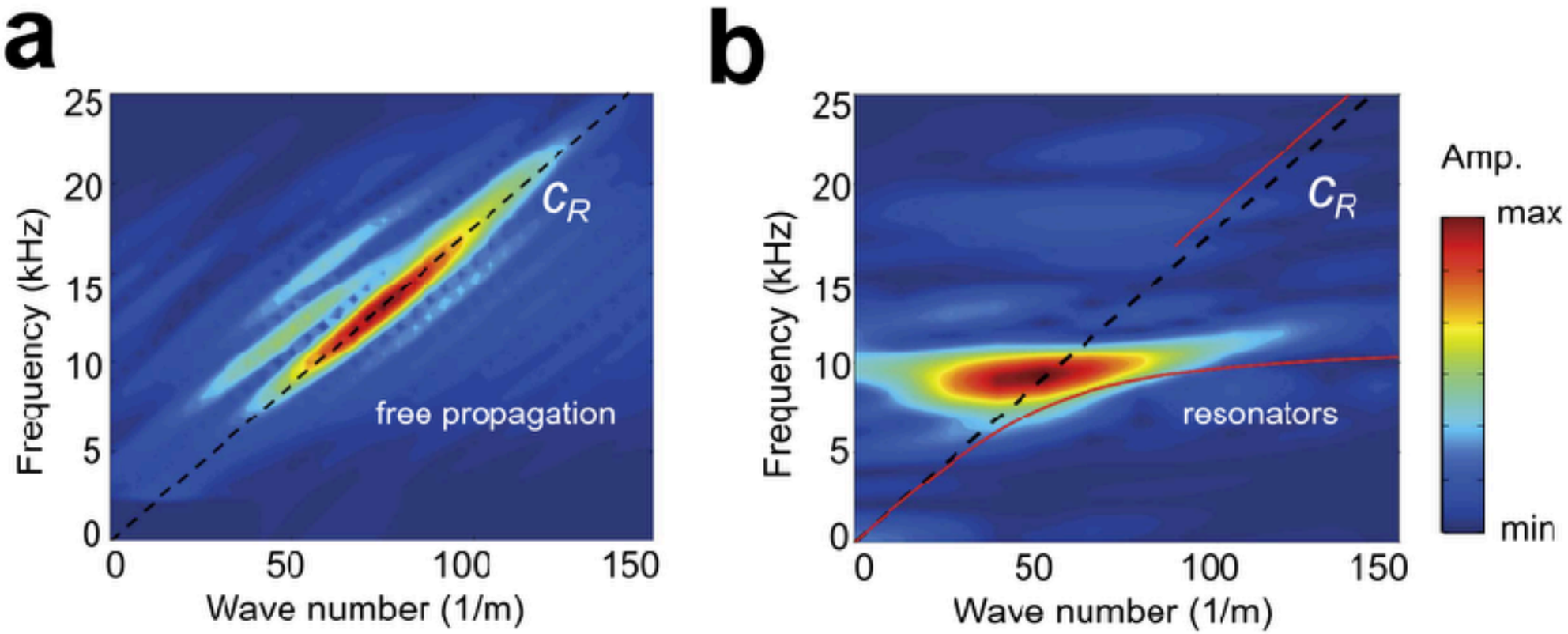
"Engineered metabarrier as shield from seismic surface waves"
Palermo et al Nature 6, 39356





Tabletop experiments in kHz range to verify models

"Engineered metabarrier as shield from seismic surface waves"
Palermo et al Nature 6, 39356



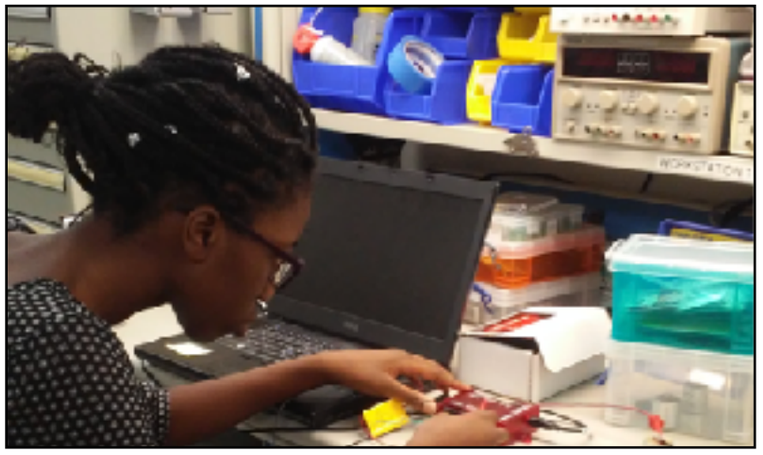
Main Results

- Theoretical prediction of bandgaps at ~4 & 7 Hz
- Attenuation by up to 60%
- Low pass filtering in 10kHz range from buried resonators

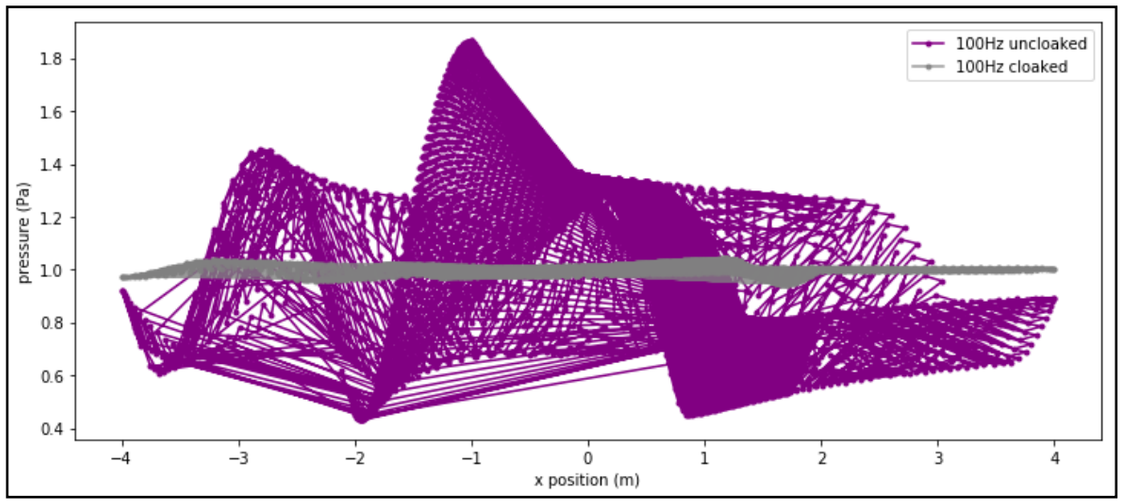
Pathway towards understanding seismic metamaterials

Kaila Nathaniel
(UG heading to UBonn+RIT)

Ayooluwa Odemuwiya
(Caltech UG)



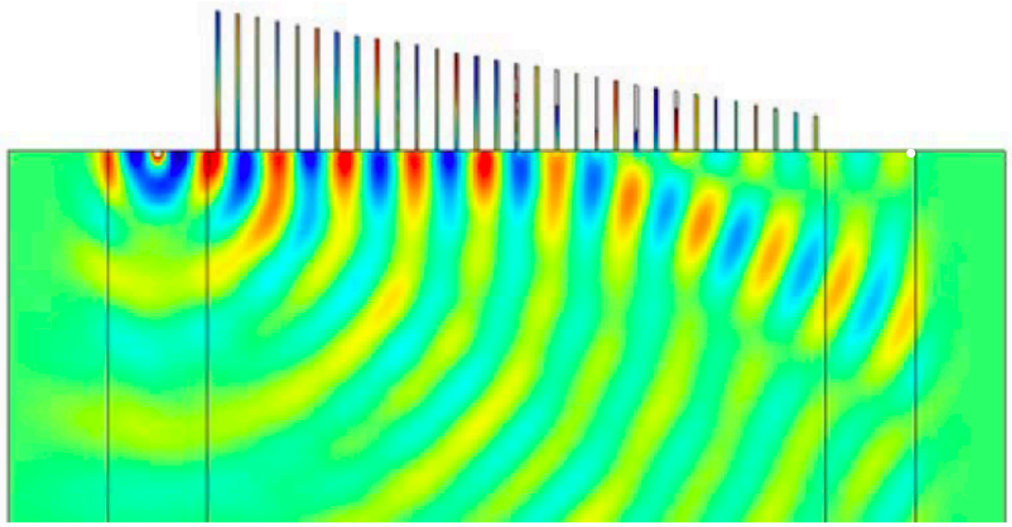
COMSOL models of acoustic cloaks



Preliminary Fieldwork

summer
2017

Building a collaboration with metamaterials, earthquake engineers+ soil engineering experts



Prof. Chiara Daraio (Caltech)

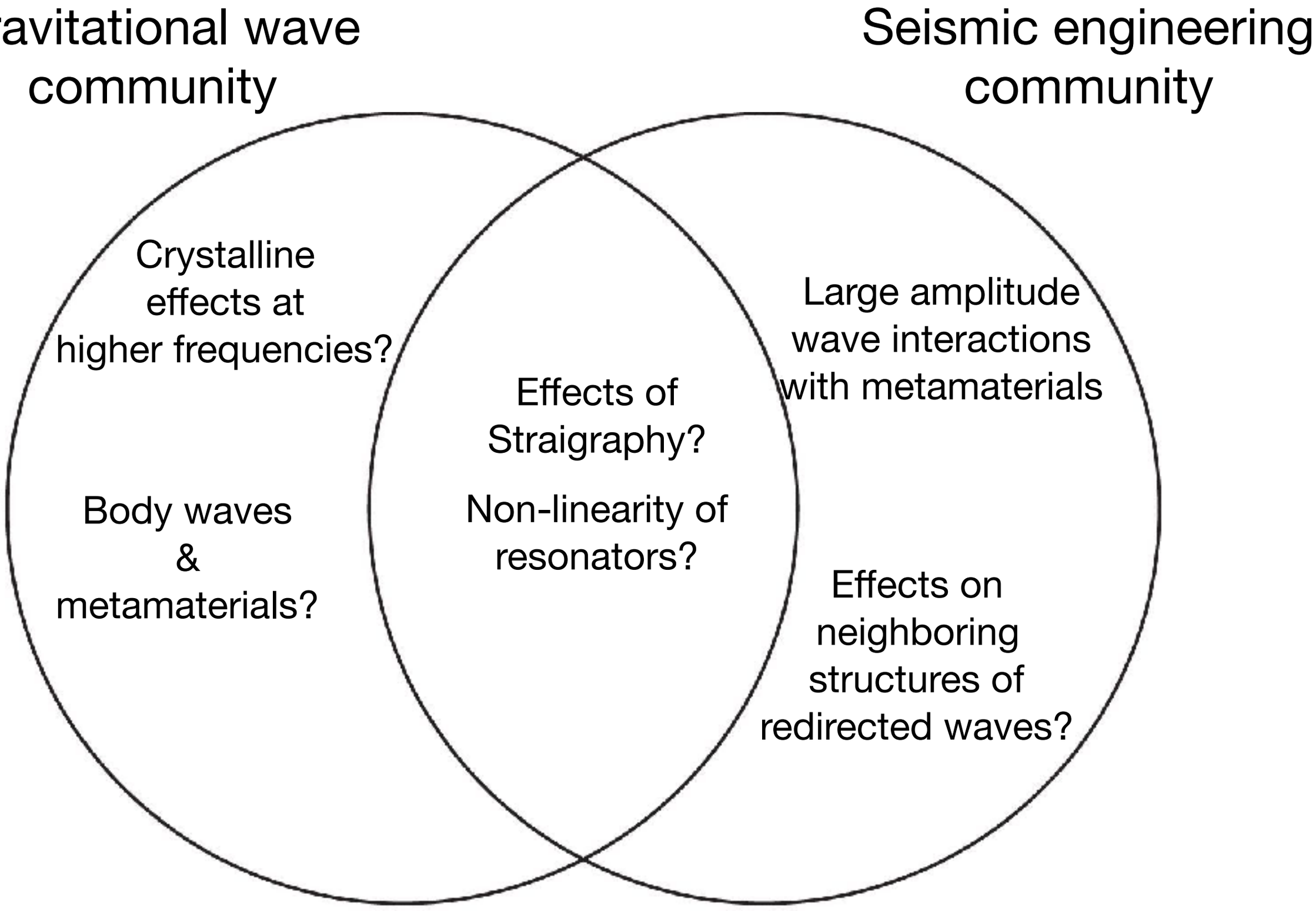
Dr. Antonio Palermo (Bologna)

Prof. Andrea Calabrese (CSU Long Beach)

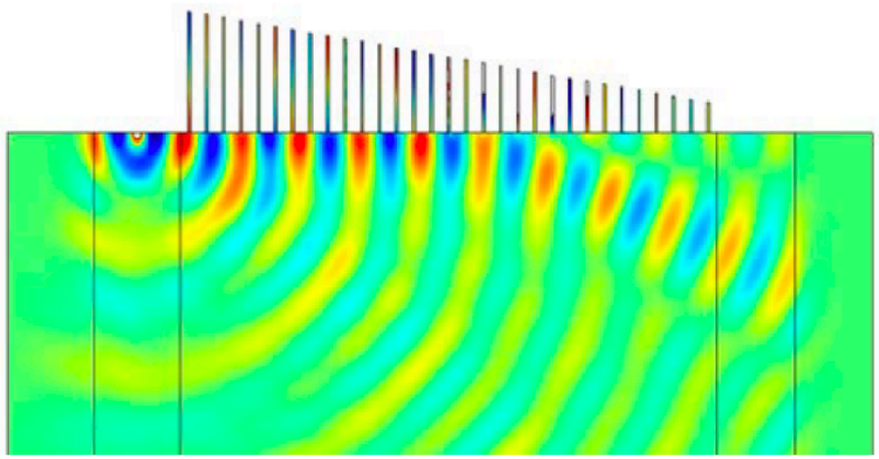
Dr. Paolo Celli (Caltech)

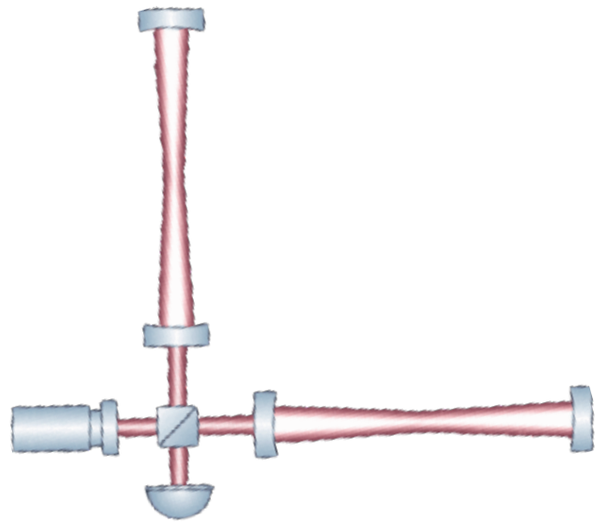
Prof. Dominiki Asimaki (Caltech)

Open questions in seismic metamaterials



Future of seismic metamaterials has a lot of potential for future GW detector designs





So happy. Together...