New Trends Towards Seismic Metamaterials

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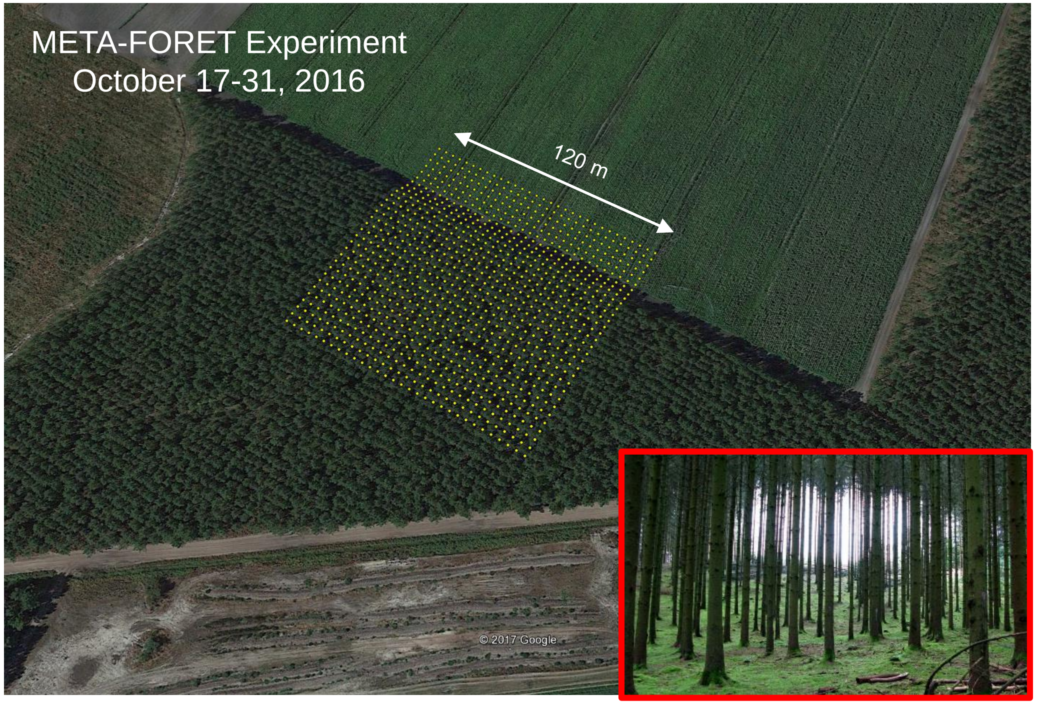
ISTerre
Institut des Sciences de la Terre

- PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR
ANR

META-FORET


META-FORET Experiment
October 17-31, 2016

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In collaboration with M. Rupin, M. Lott, P. Gueguen, S. Ayaz, ***ISTerre****, G. Lerosey, F. Lemoult,* ***Institut Langevin, Paris****, D.J. Colquitt, R. Craster,* ***Imperial College, London,*** *A. Colombi,* ***ETH Zurich,*** *S. Guénneau,* ***Institut Fresnel, Marseille,*** *E.G. Williams,* ***Naval Research Lab, Washington DC,*** *W. A. Kuperman****, Scripps Inst. Oceanography, San Diego***

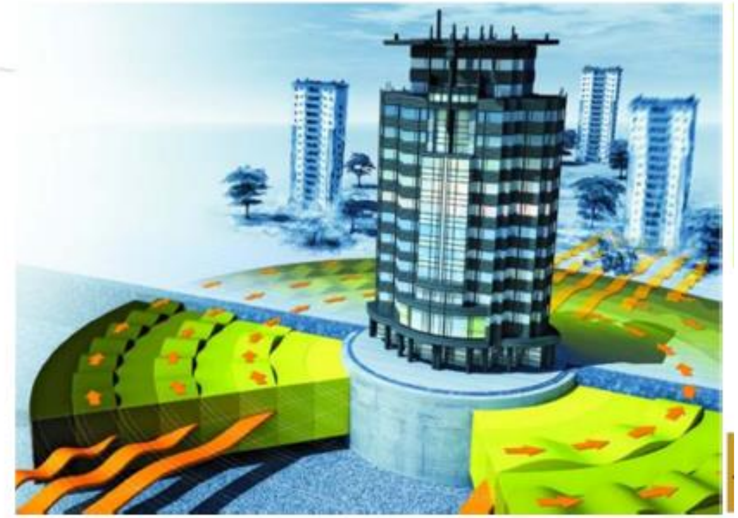
Earthquake Damages : High Social & Human impact

Two possibilities:

- **Predicting major seismic events** : dense seismic arrays and continuous ambient noise

- **Preventing damages from seismic events :** Control of seismic waves with seismic metamaterial (1 Hz - 5 Hz)

Taiwan (1999)

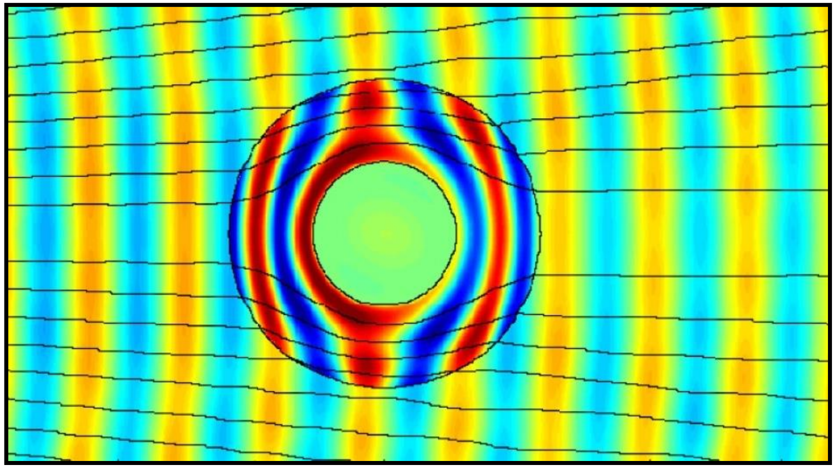


Infographie Popular Science Magazine (2009)

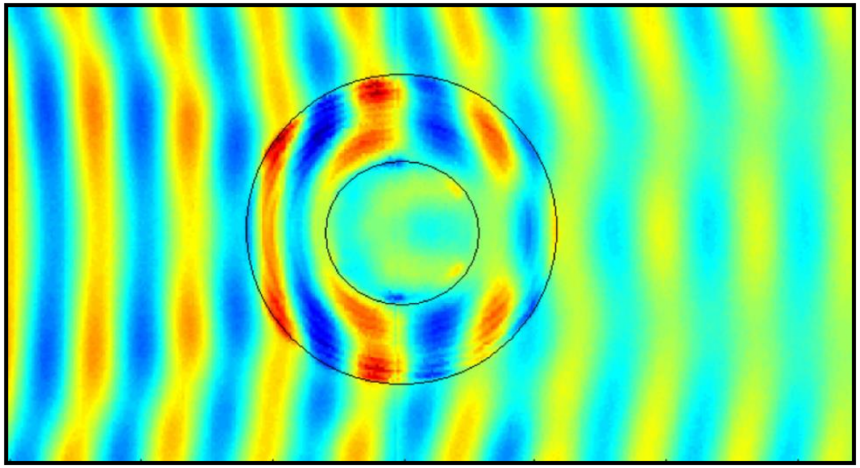
S. Guenneau, Institut Fresnel, Marseille

Concept : Manipulating the Wavefield (1)

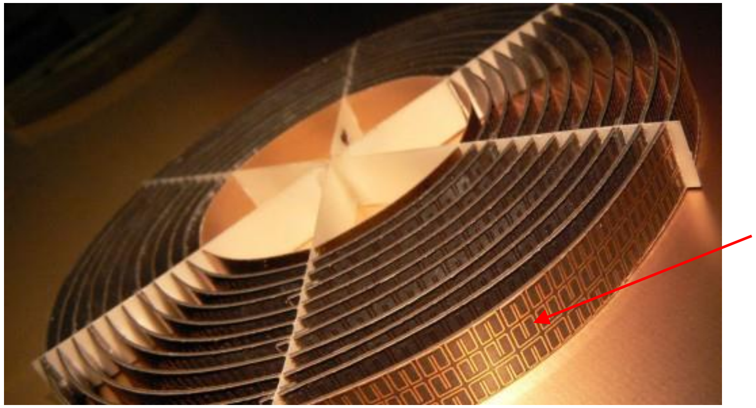
Electromagnetic waves



Simulation



Experiment



Unitary cell

Schurig et al., Science (2006)

WIKIPEDIA

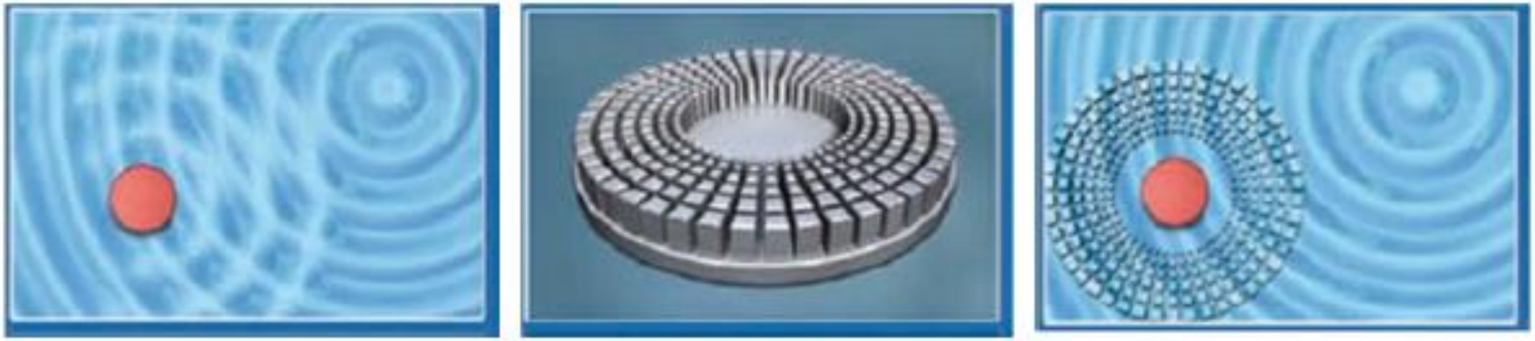
They are **assemblies of multiple individual elements** fashioned from conventional materials such as metals or plastics, but **the materials are usually constructed into repeating patterns**, often with microscopic structures.

Concept : Manipulating the Wavefield (2)

Acoustic waves

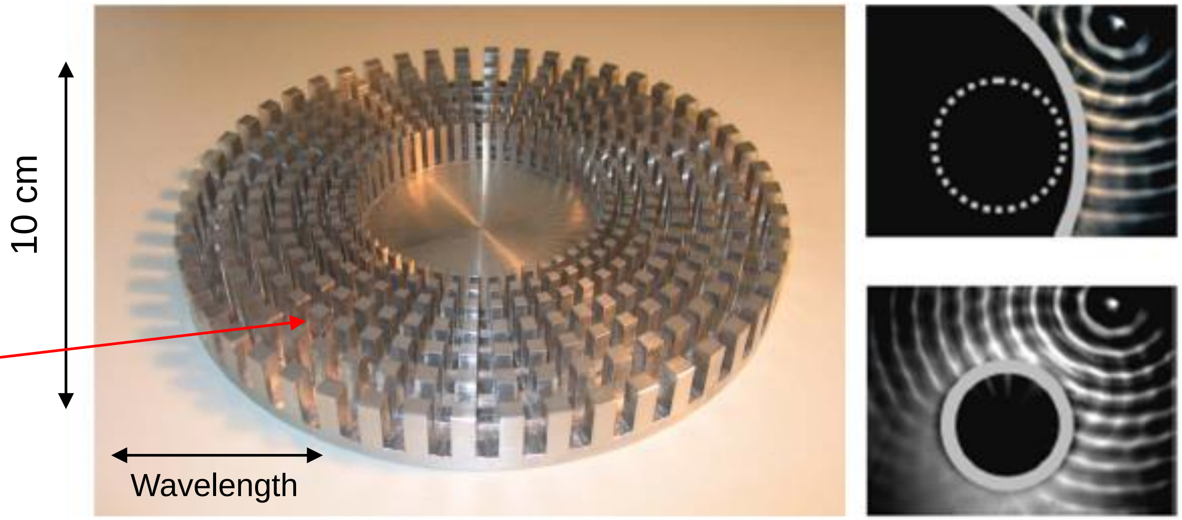
Frahat et al, Institut Fresnel, Marseille

Numerical simulation



Infographie La Recherche (Février 2012)

Laboratory experiment



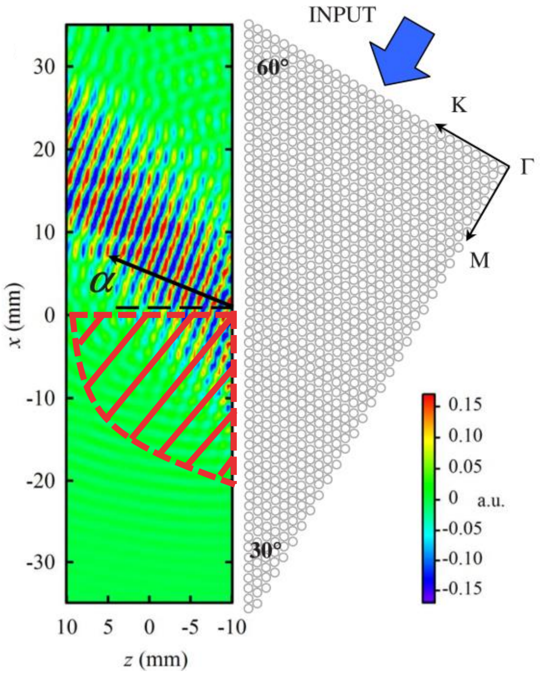
Unitary cell

Physical Review Letters 101, 134501 (2008)

How to Manipulate the Wavefield ?

1- Bragg scattering and Phononic crystals

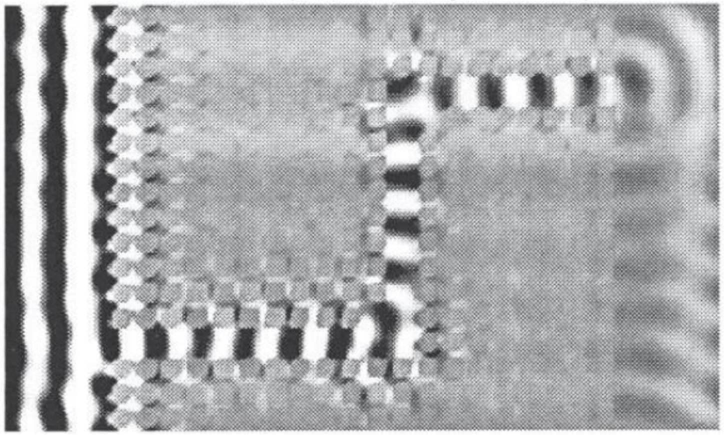
Negative Index of Refraction



Snell-Descartes

Sukhovich et al., Physical Review B (2008)

Guiding / Multiplexing

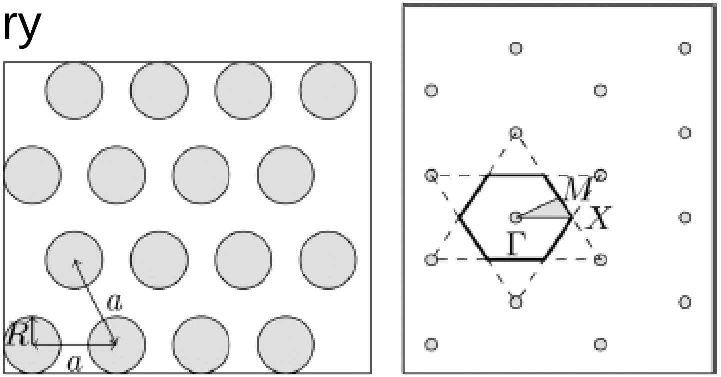


Khelif et al., Applied Physics Letters (2004)

How to Manipulate the Wavefield ?

1- Phononic crystal and Multiple scattering theory

FIG. 4. (Color online) Picture of the tested structure.



a) b)

FIG. 1. Diagram of a triangular lattice for an ideal sonic crystal. (a) Direct space, where rods have a radius *r* and a lattice constant *a*. (b) Reciprocal space with the irreducible Brillouin zone.

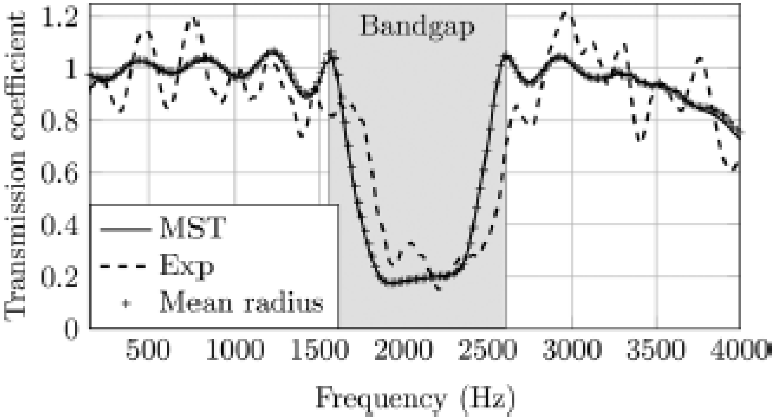


FIG. 6. Comparison between the transmission coefficient calculated by MST with all the radii accounted for (—), by MST with the mean radius (···), and mesured experimentally (– – –) for a triangular lattice sonic crystal of 9 × 5 rods of 4 cm of diameter.

Lagarrigue et al., JASA (2012)

How to Manipulate the Wavefield ?

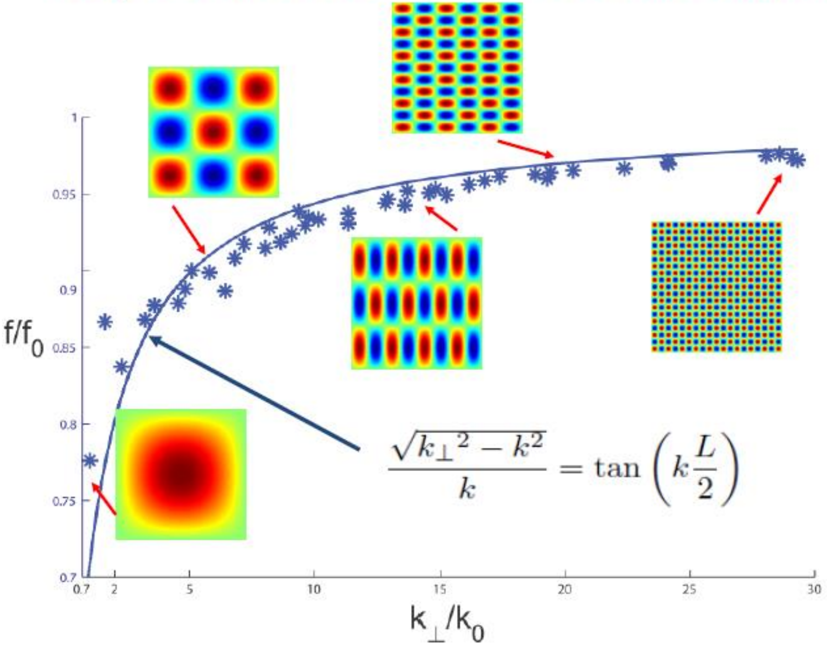
2- Multi-resonators at the sub-wavelength scale

Fabrice Lemoult, Geoffroy Lerosey, Julien de Rosny, Mathias Fink
« Resonant Metalenses for Breaking the Diffraction Barrier »
Phys Rev Lett 104, 203901 (May 2010)

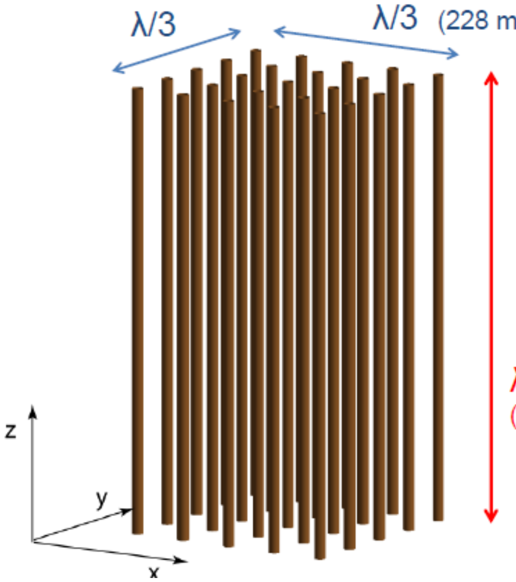
Periodic arrangement
of identical wires

The closely spaced subwavelength resonators approach: « resonant metalens »

Dispersion relation theoretical derivation



$$\frac{\sqrt{{k_\perp}^2 - k^2}}{k} = \tan\left(k\frac{L}{2}\right)$$



In the transverse plane: 20*20 deeply subwavelength (λ/80) spaced resonators!

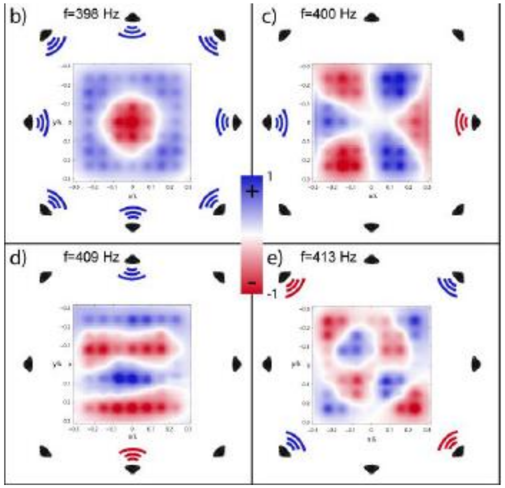
(Resonance in the z dimension)

λ/2
(400 mm, f_0=375 MHz)

How to Manipulate the Wavefield ?

2- Multi-resonators at the sub-wavelength scale

Lemoult et al, PRL, 2010



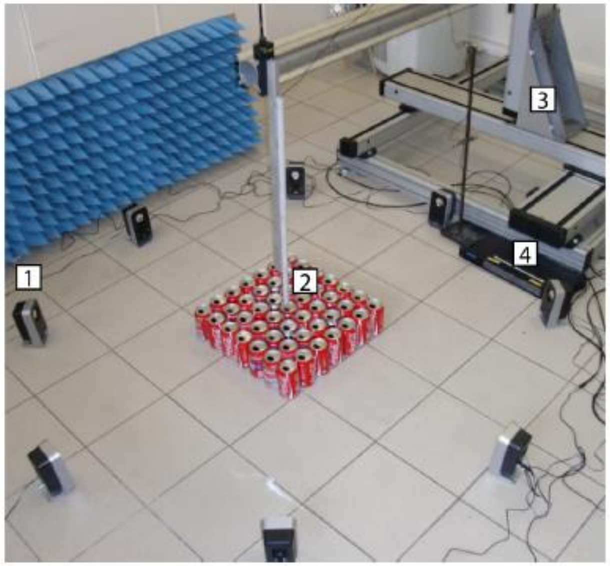
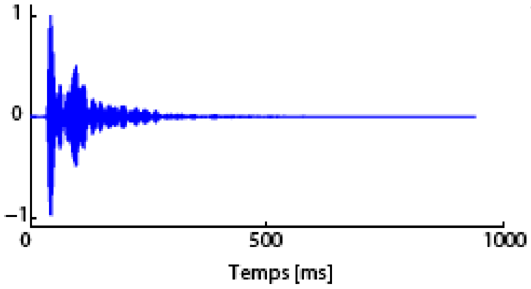
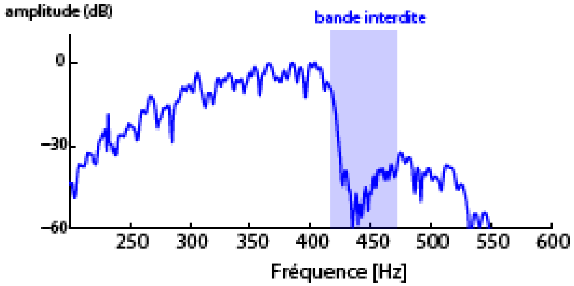
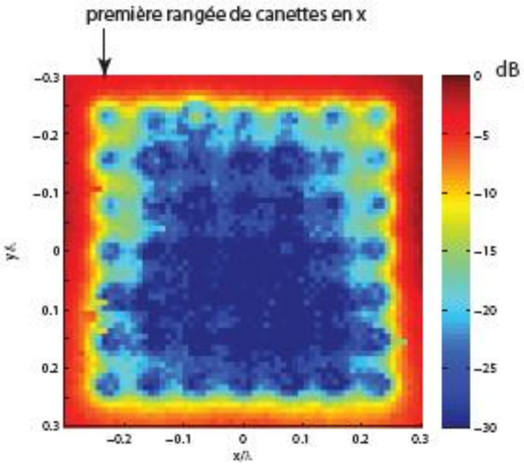


FIGURE IV.6 – Le réseau de 7 × 7 canettes et le dispositif expérimental : (1) 8 haut-parleurs commerciaux pré-amplifiés, (2) microphone monté sur (3) un banc de mesure motorisé, (4) carte son MOTU.

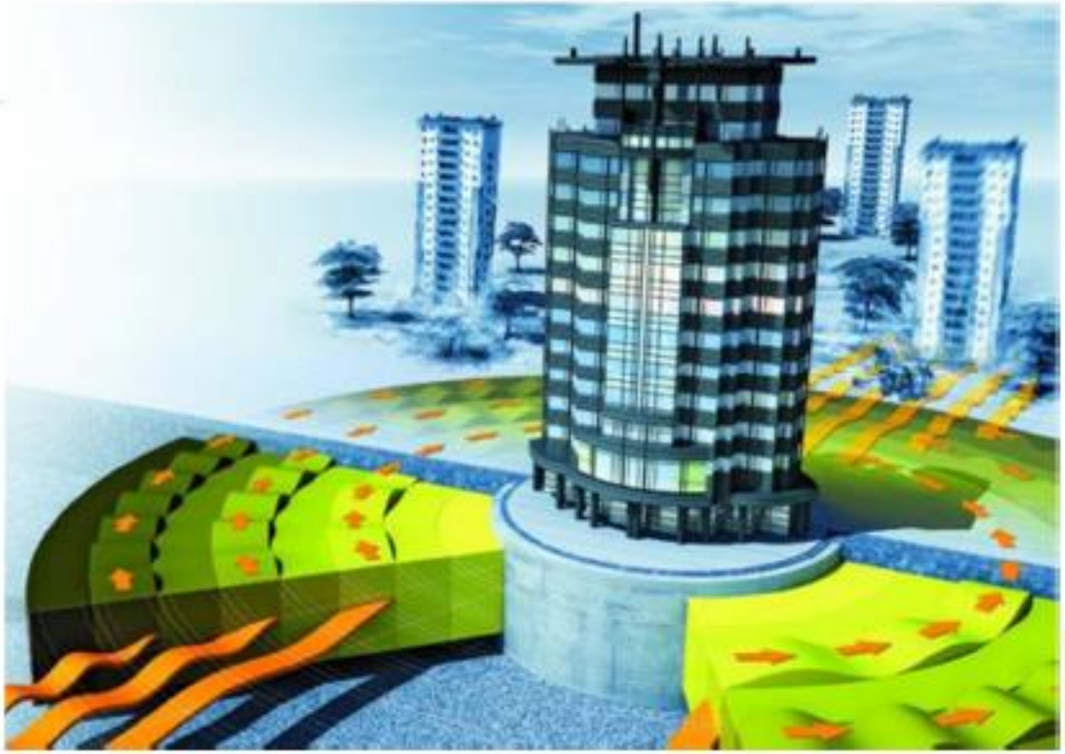




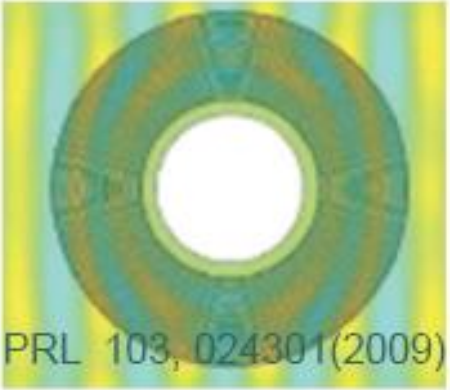


At Larger Scale : Cancellation of Seismic Waves?

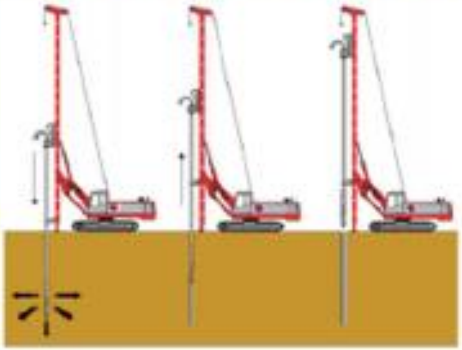
S. Guenneau, Institut Fresnel, Marseille



Infographie Popular Science Magazine (2009)



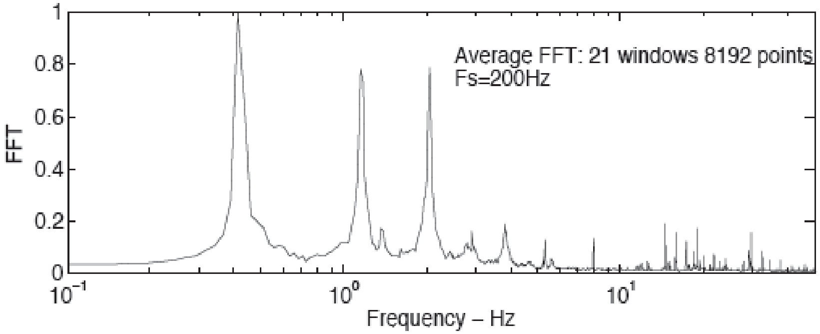
PRL 103, 024301(2009)



Infographie Ménard

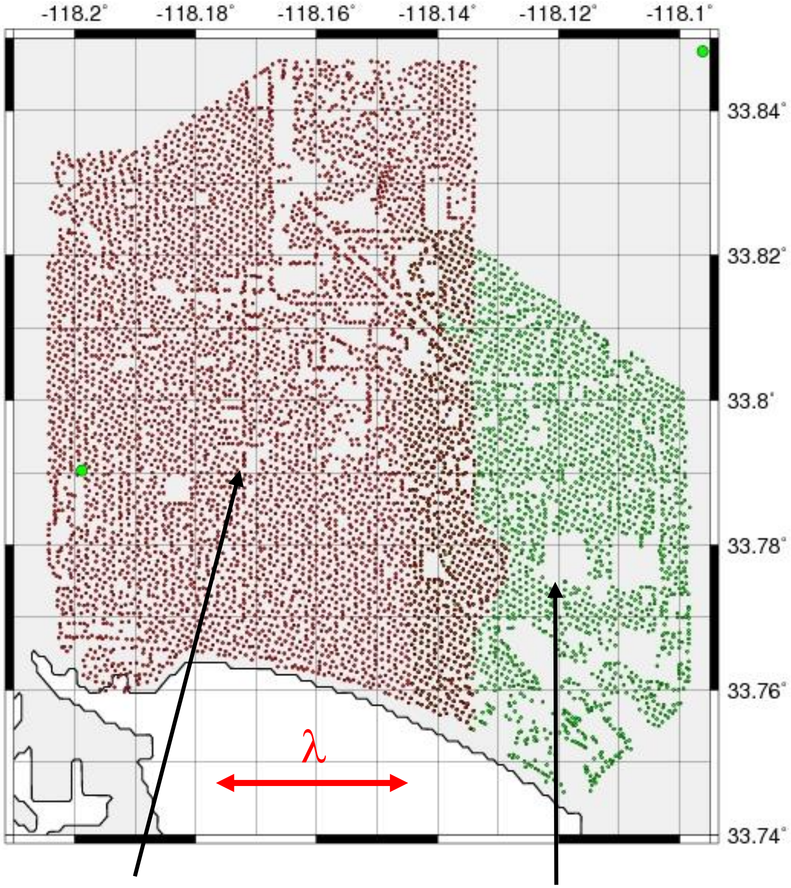
A City : Macroscopic Arrangement of Resonating Elements ?

Tall building : subwavelength resonator
for ~1 Hz seismic wave



Cluster of buildings : locally-resonant metamaterial?

A City : Macroscopic Arrangement of Resonating Elements ?

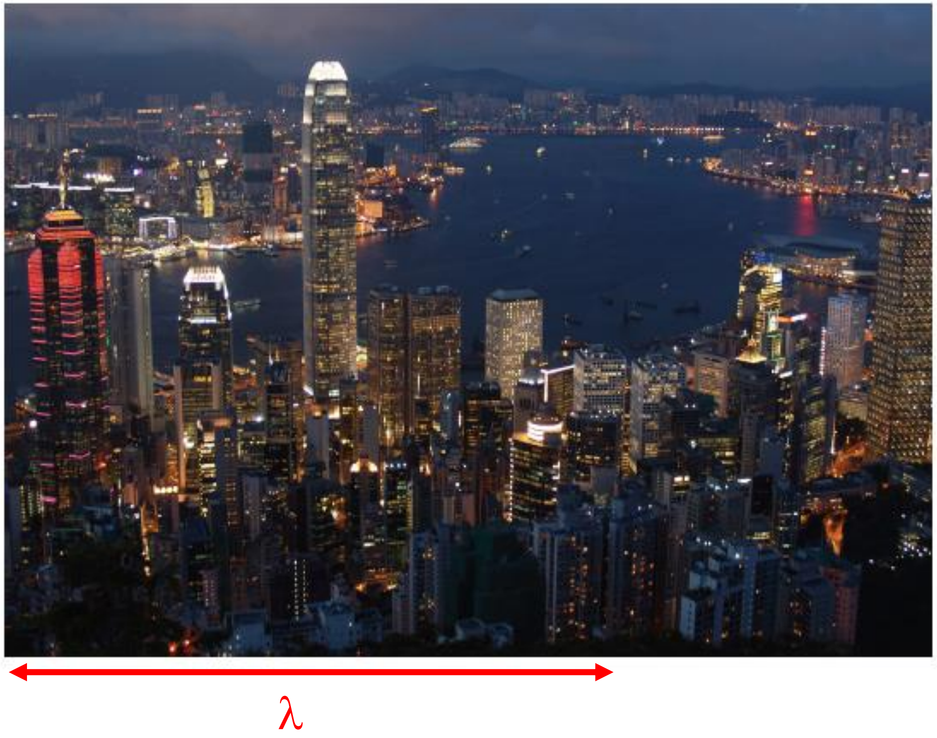


5300 sensors

2500 sensors

Density ~ 75 sensors per
square-km

Cluster of buildings : locally-resonant metamaterial?

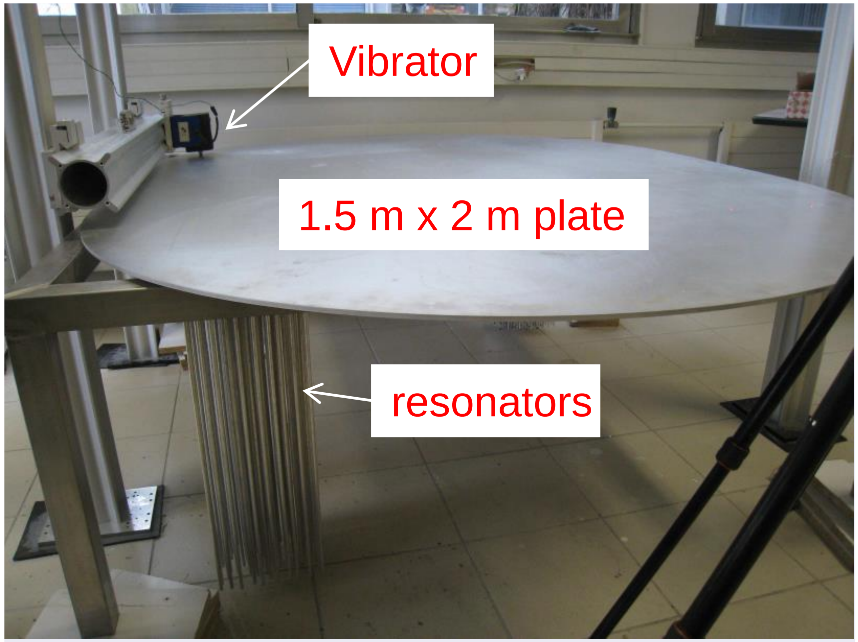


Experimental / Theoretical / Numerical Approach at ISTerre

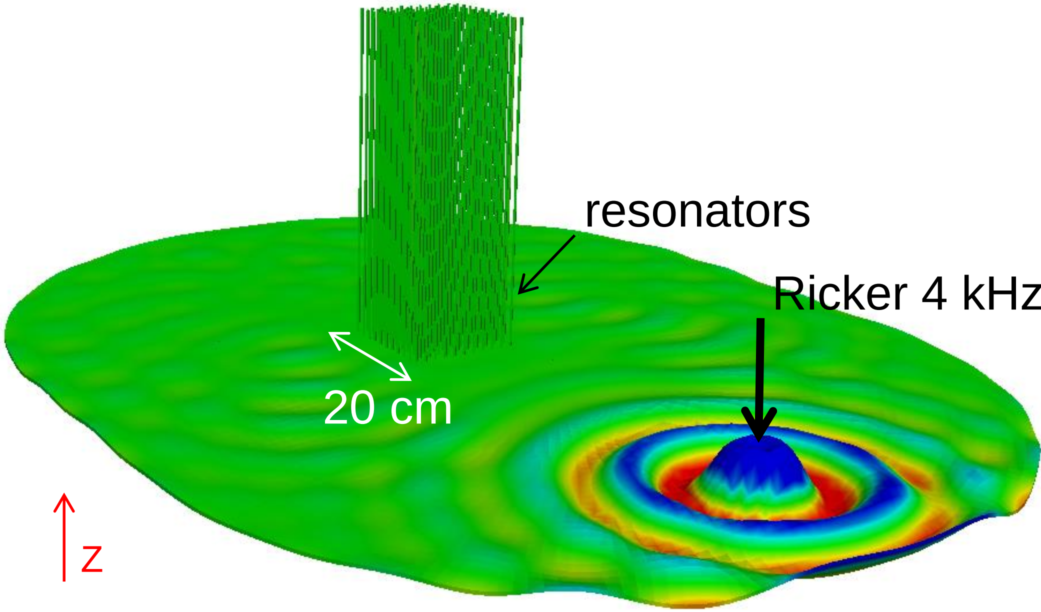
Coupling Surface wave (Geophysics)

and

Multi-Resonators (Acoustics)

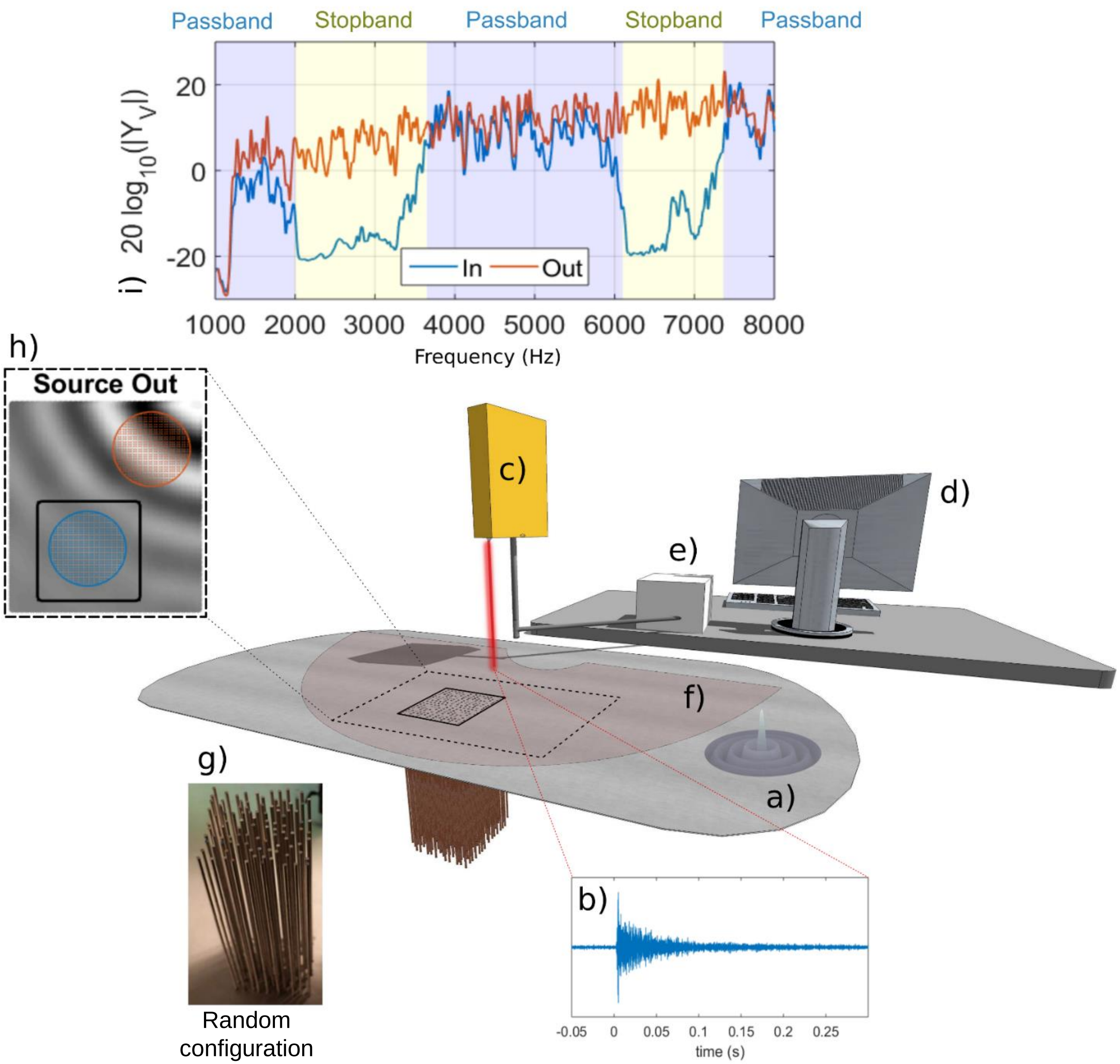


Laboratory set-up



Simulation setup

Experimental Configuration

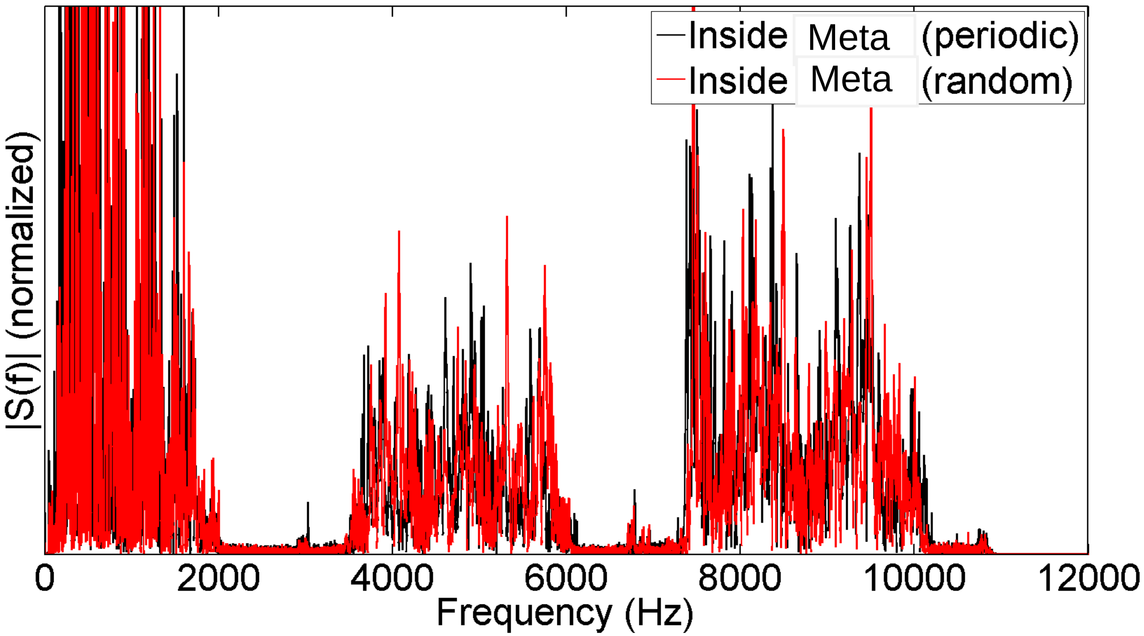


Random configuration

Periodic / Random Distribution of Beams

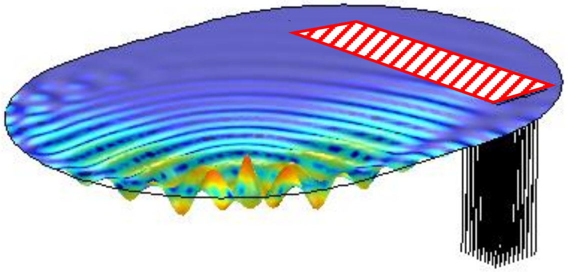
Periodic configuration

Random configuration



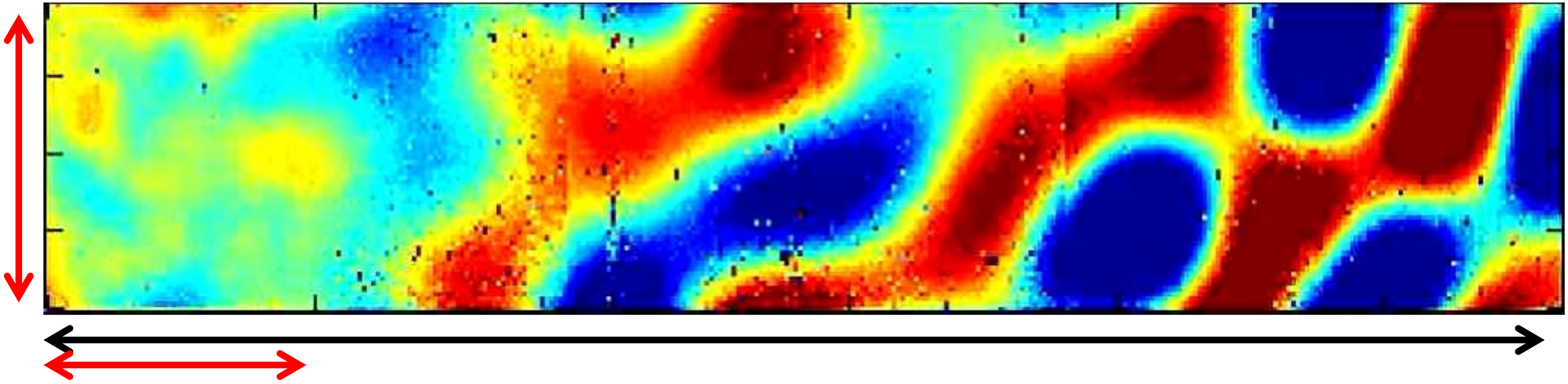
Cowan et al. Phys. Rev. B, 2011

Temporal Evolution of the Wavefield



Vertical Displacement filtered in [2100Hz - 2800Hz]

0,18 m



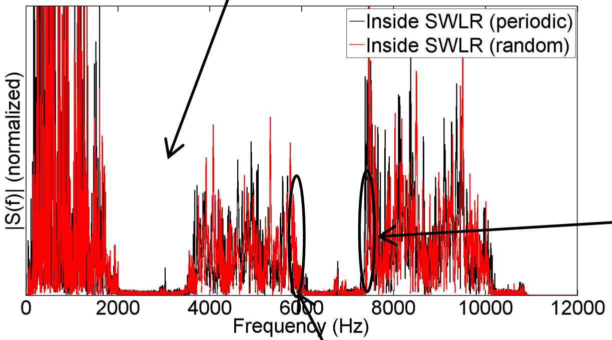
1,1m

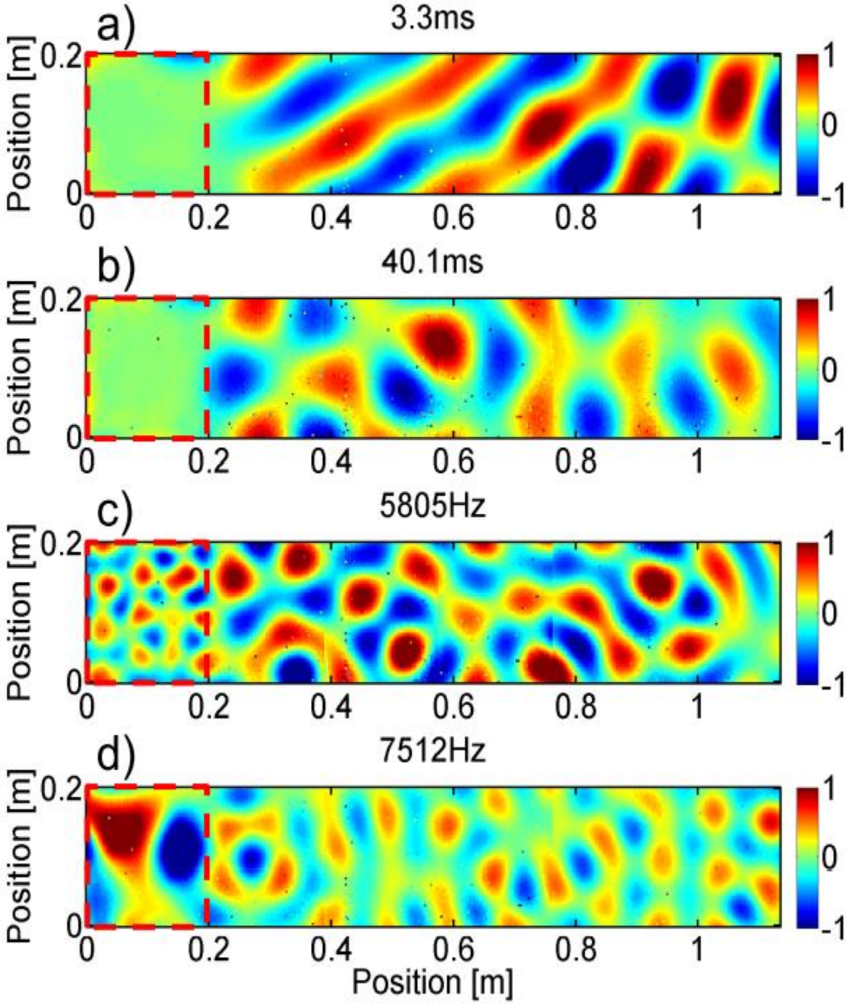
0,18 m
Metamaterial

Data available at https://isterre.fr/annuaire/pages-web-du-personnel/philippe-roux/article/laboratory-data-available

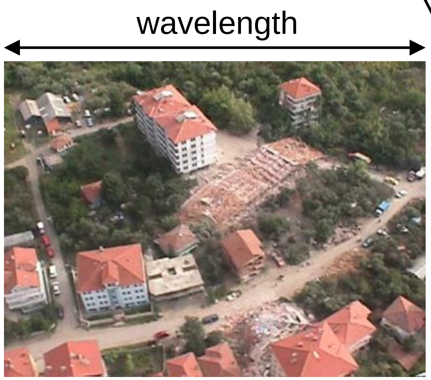
Outside the Bandgaps :
Sub- or Supra-Wavelength Modes

Inside bandgap



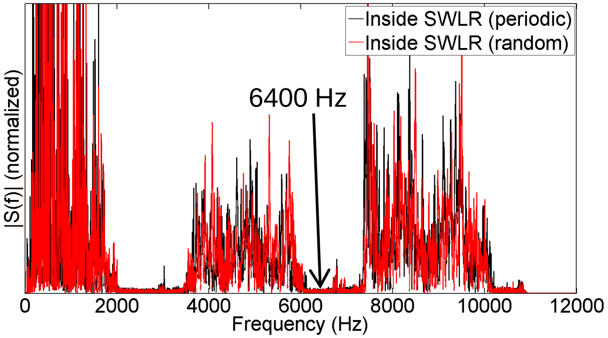


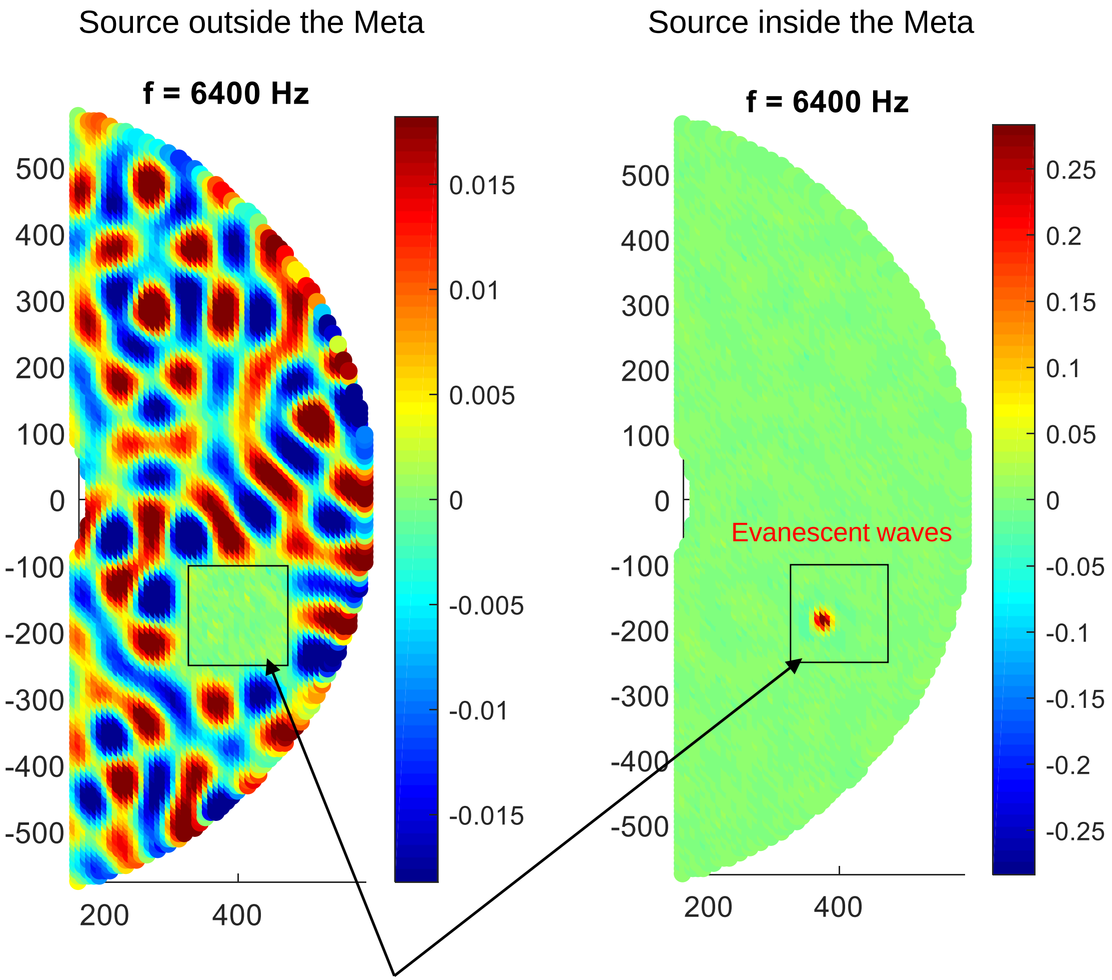
Outside bandgap



Rupin et al., PRL 2014; APL, 2015

Inside the Bandgap :
Source outside or inside the Metamaterial





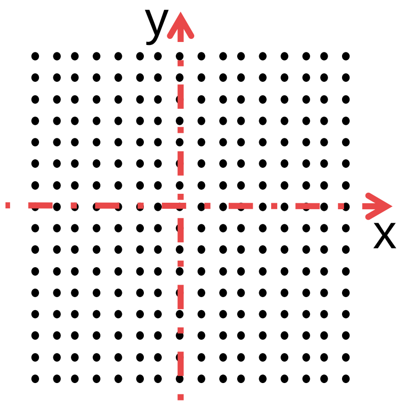
Source outside the Meta

Source inside the Meta

Random Metamaterial

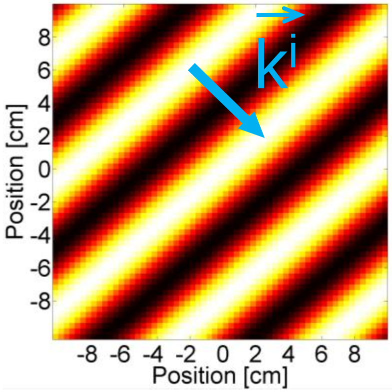
Metamaterial description through Dispersion relation

- 2-D Frequency-Wavenumber projection



2D antenna
(NxN receivers)

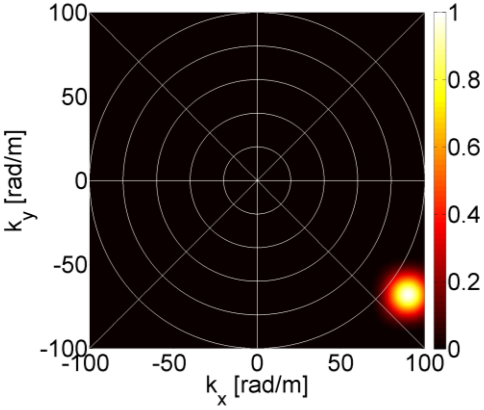
Plane
Wave



x-y field
representation

f-k

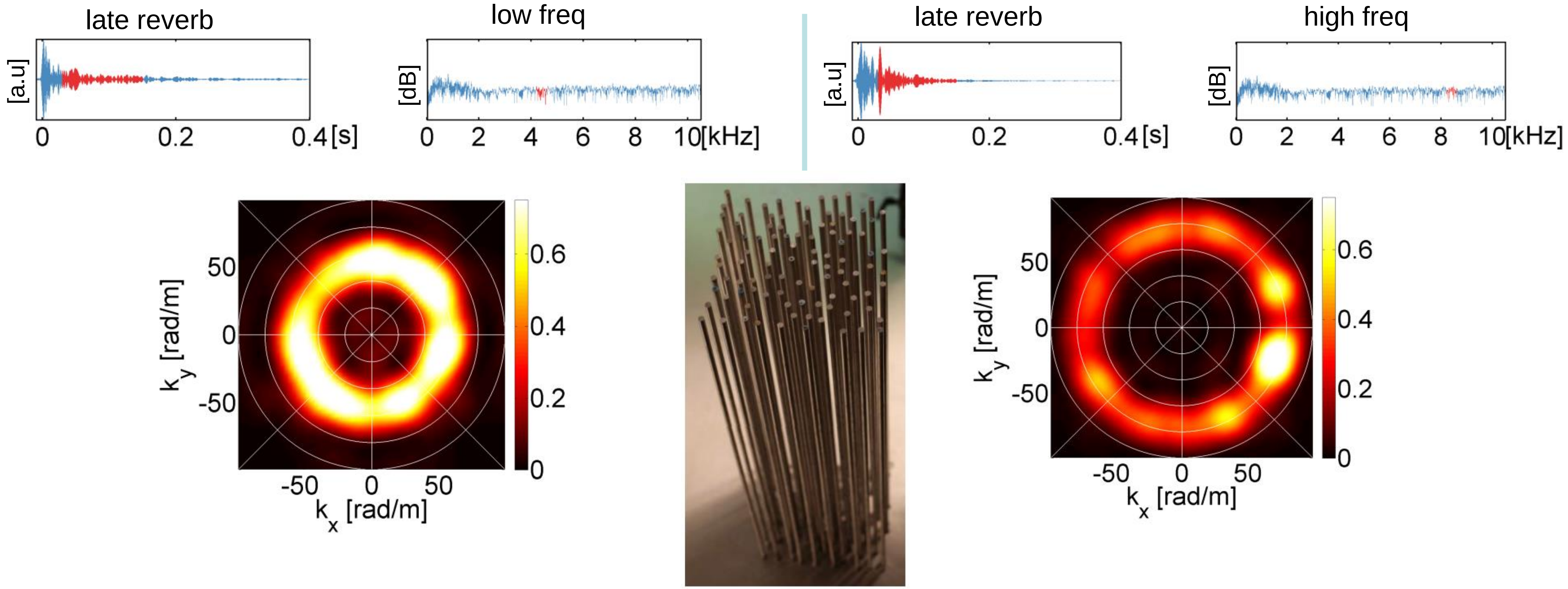
f-k^{-1}



k_x-k_y field
representation

Metamaterial description through Dispersion relation

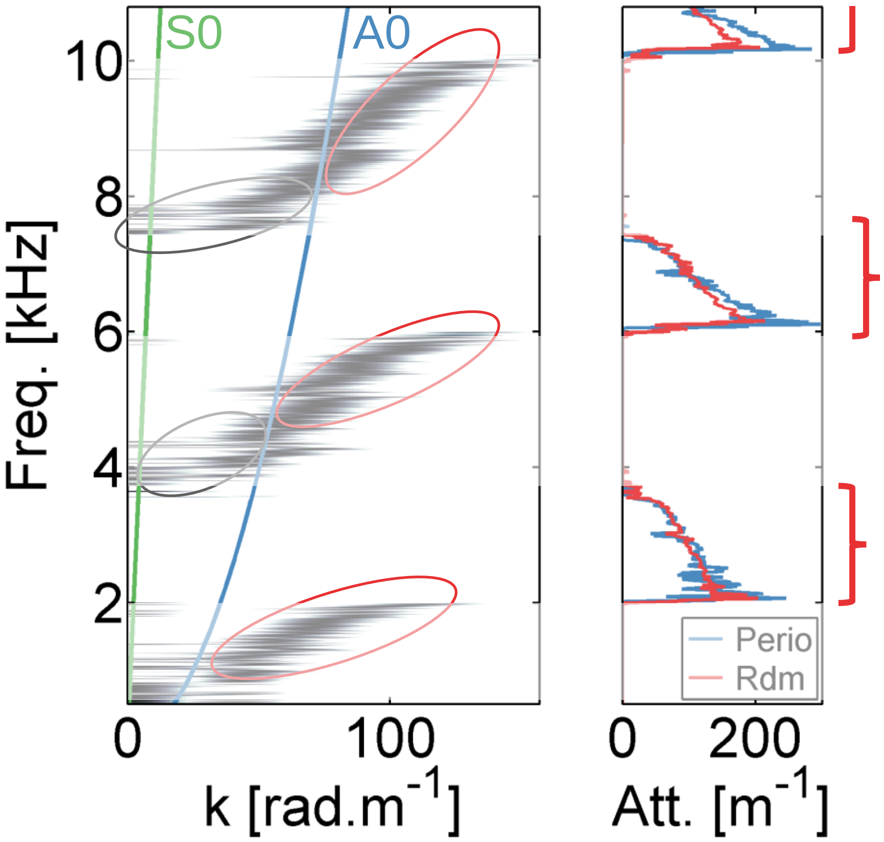
Examples of experimental F-K



Isotropic Wavenumber Distribution = Diffuse Field

Metamaterial description through Dispersion relation

- Dispersion relation inside the Metamaterial



Band-gap

Sub-λ modes

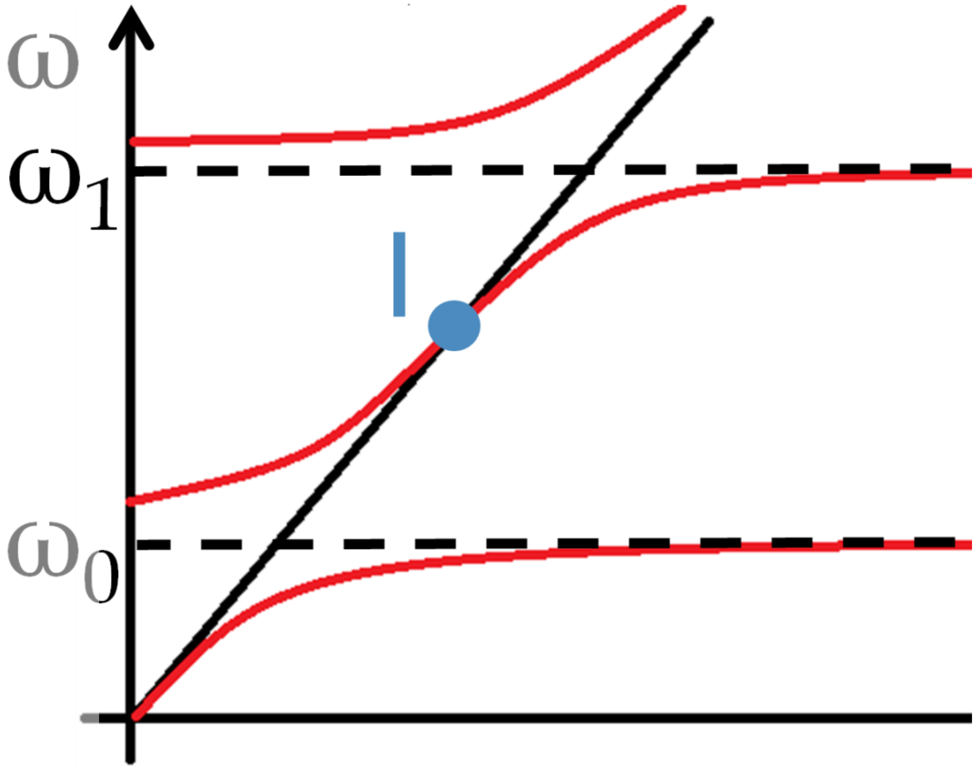
Supra- λ modes

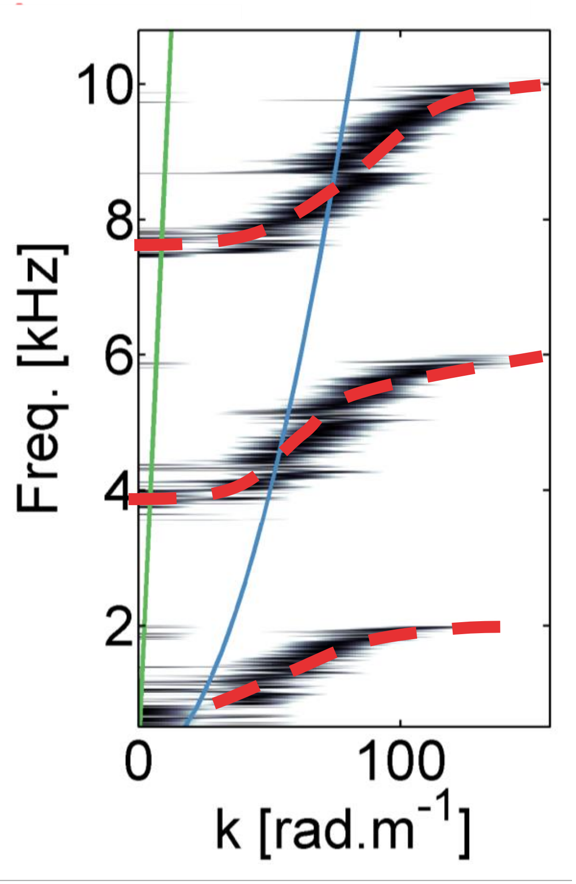
Band-gap

Band-gap

Metamaterial description through Dispersion relation

Role of the resonances : the hybridation phenomenon

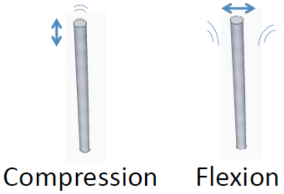




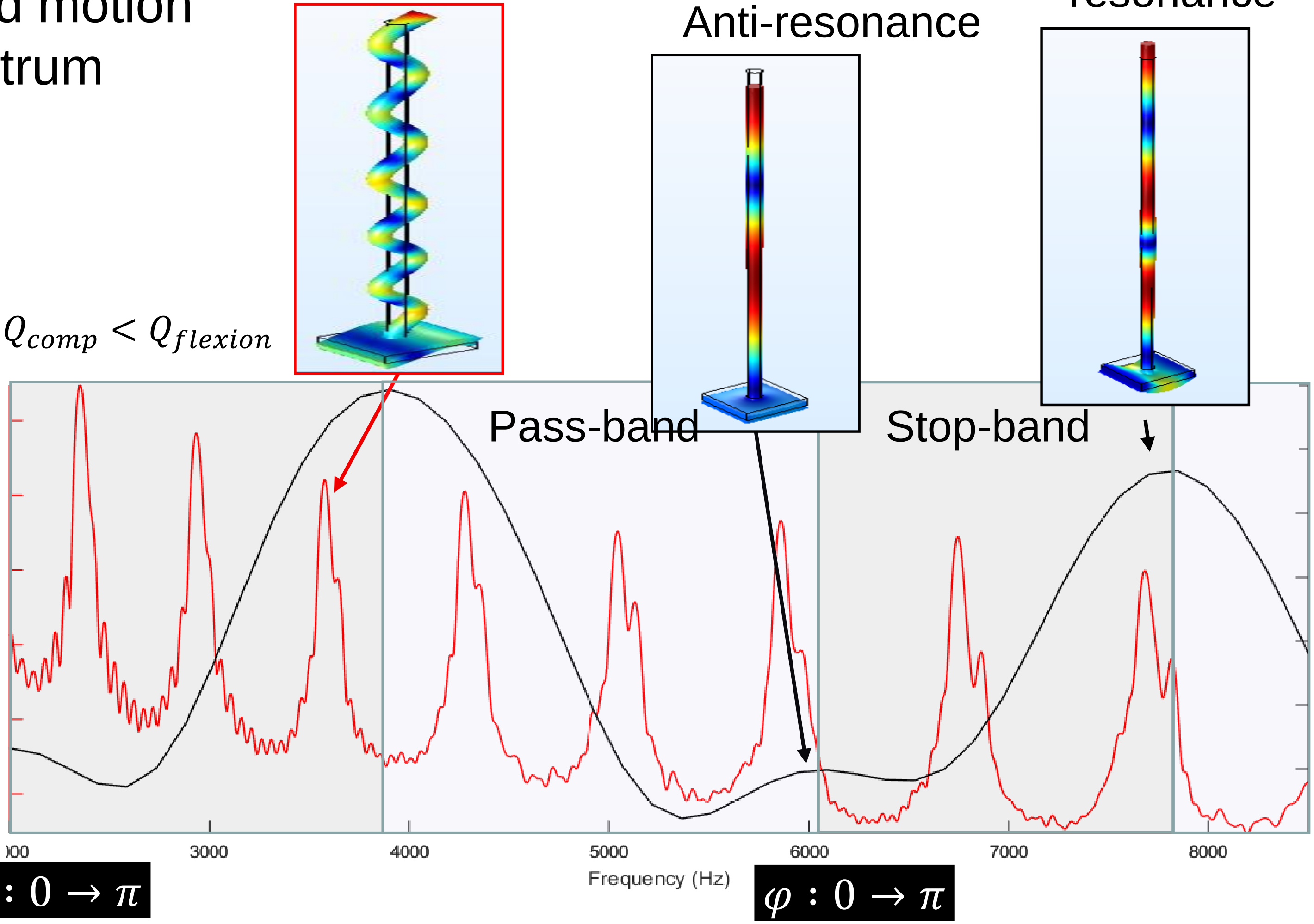
Rupin et al., PRL, 2014

Multi-resonance problem

Single-rod motion spectrum



$Q_{comp} < Q_{flexion}$



$\varphi : 0 \rightarrow \pi$

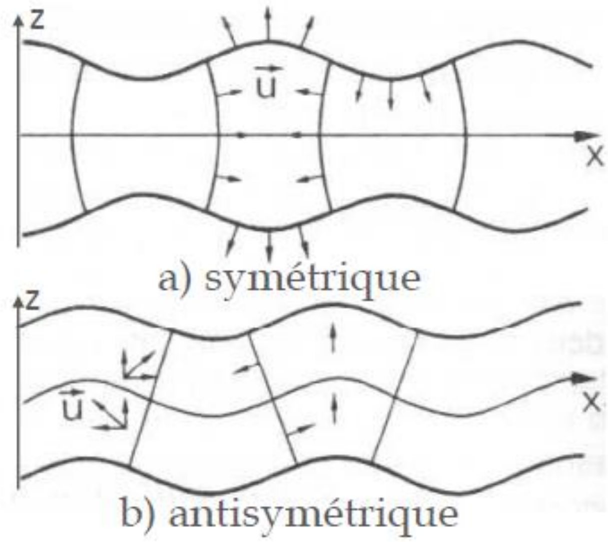
$\varphi : 0 \rightarrow \pi$

Mutli-wave + Multi-resonance problem

In the plate…

S0 wave

A0 wave

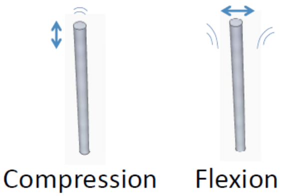


Displacement is mostly horizontal

Displacement is mostly vertical

Two types of waves

In one resonator…

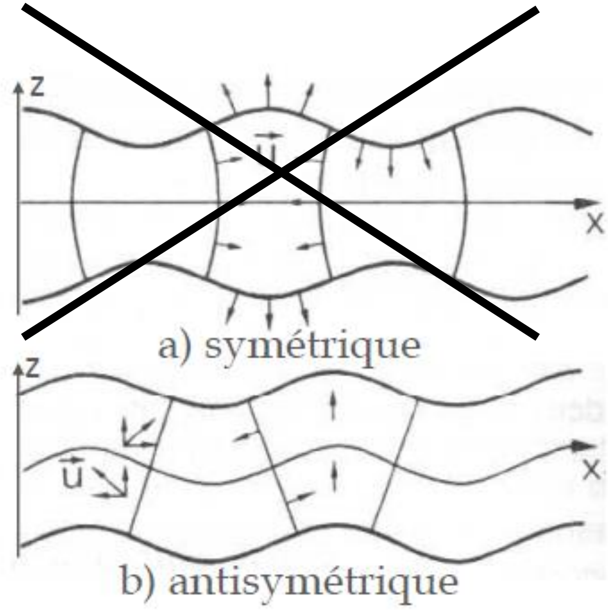


Two types of resonances

Royer & Dieulesaint, 1996

First (scalar) approximation :
A0 wave + Compression resonance

In the plate…



~~S0 wave~~

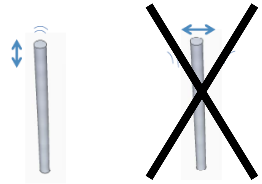
~~Displacement is mostly horizontal~~

A0 wave

Displacement is mostly vertical

Two types of waves

In one resonator…



Two types of resonances

➡ Vertical displacement (A0 mode) interacting with compressional resonance

Theoretical (scalar) approach through Bloch Theorem

$$EI\frac{\partial^4 u(x)}{\partial x^4} - \rho A\omega^2 u(x) = \boxed{f_b}\delta(x-x_0) - \xcancel{\boxed{m_b}\delta'(x-x_0)}.$$

$$W^{(n)} = CU^{(n}$$

$$C = \begin{bmatrix} 1-i\Theta & -i\Theta & -i\Theta & -i\Theta \\ \Theta & \Theta+1 & \Theta & \Theta \\ i\Theta & i\Theta & i\Theta+1 & i\Theta \\ -\Theta & -\Theta & -\Theta & 1-\Theta \end{bmatrix}$$

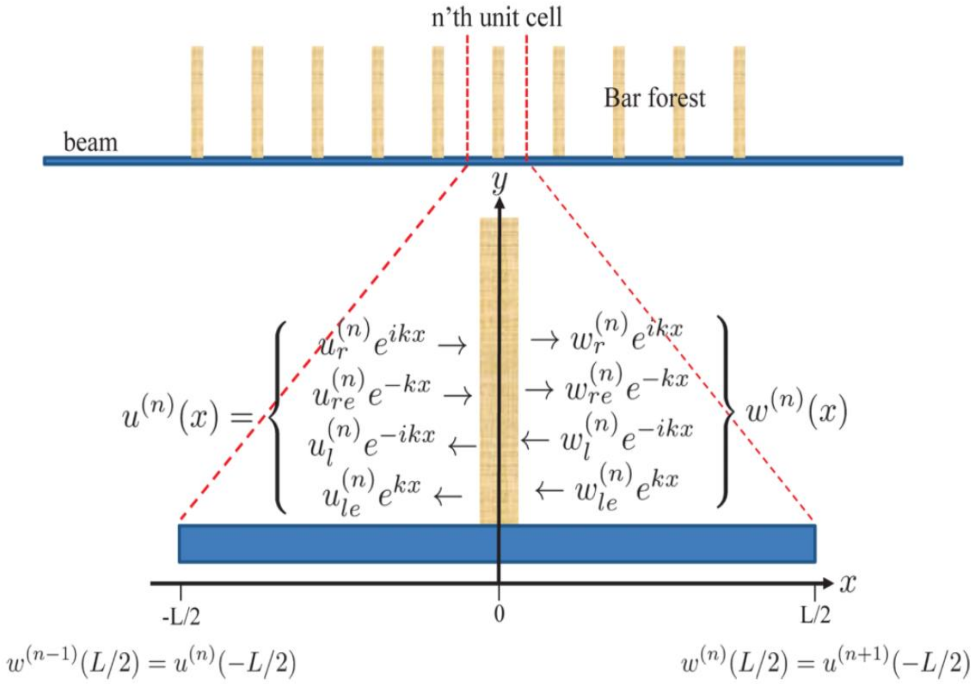
Account for boundary conditions at the bar-plate interface

$$\Theta = \frac{1}{4}\frac{\rho_b A_b c_b}{\rho A c_p}\tan(k_b L_b)$$

$$D \equiv \begin{bmatrix} e^{-ikL/2} & 0 & 0 & 0 \\ 0 & e^{kL/2} & 0 & 0 \\ 0 & 0 & e^{ikL/2} & 0 \\ 0 & 0 & 0 & e^{-kL/2} \end{bmatrix}$$

Account for propagation accross the unit cell

1-D model

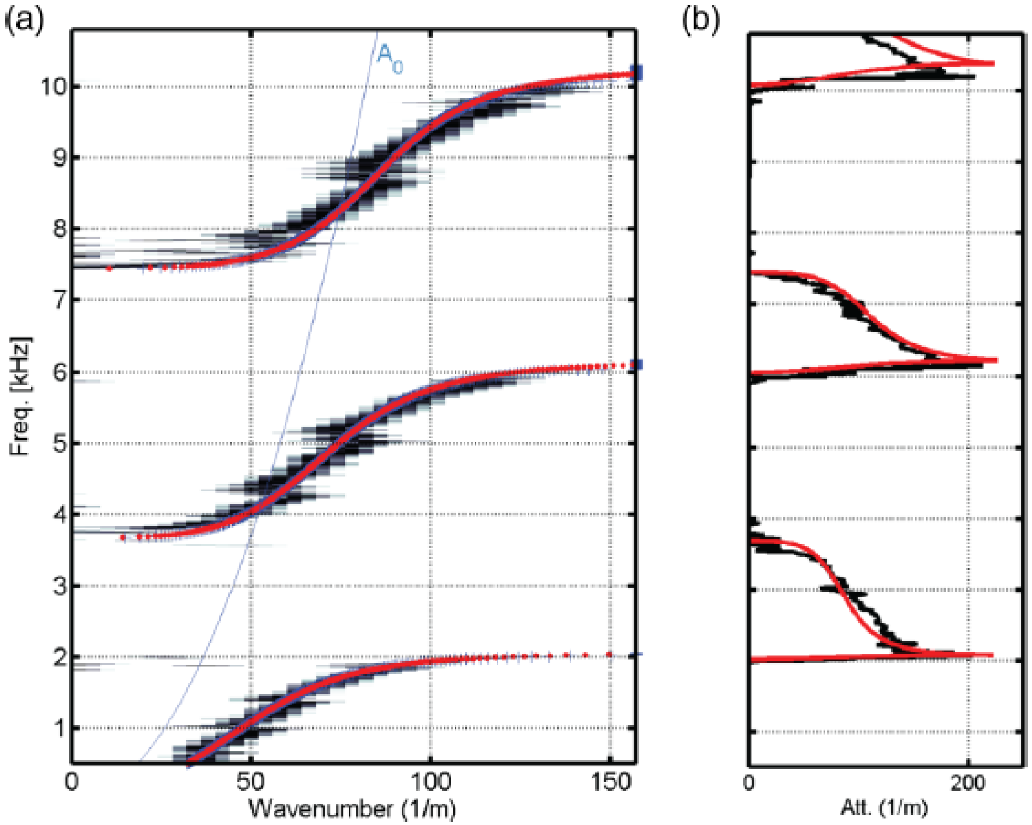


Dispersion curves are obtained from the solution of an eigenvalue problem

$$W_+^{(n)} = \underbrace{DCD}\,W_+^{(n-1)}$$

Transfer matrix between two cells

Theoretical (scalar) approach through Bloch Theorem



$$c_{\mathrm{eff}}/c_p = \left[\frac{M_b}{M}\frac{\tan(k_b L_b)}{k_b L_b}+1\right]^{-1/4}$$

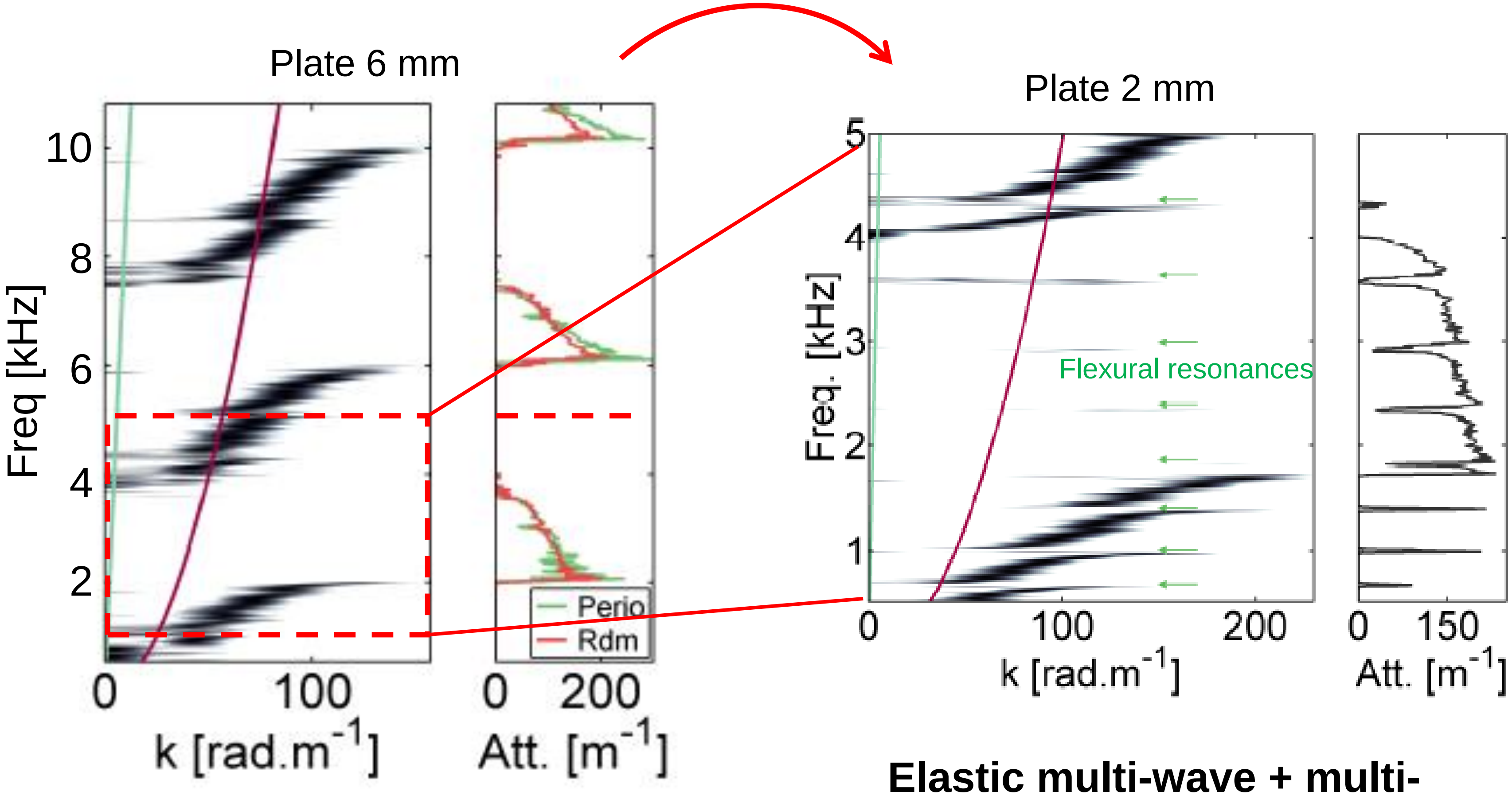
$$\alpha(\omega) = \frac{k}{\sqrt{2}}\left|\frac{M_b}{M}\frac{\tan(k_b L_b)}{k_b L_b}+1\right|^{1/4}$$

M_b *= rod mass*
L_b *= rod length*
M= local plate mass

Williams et al., Phys. Rev. B, 2015

When is the scalar approach no longer valid?

Plate stiffness varies as h^3

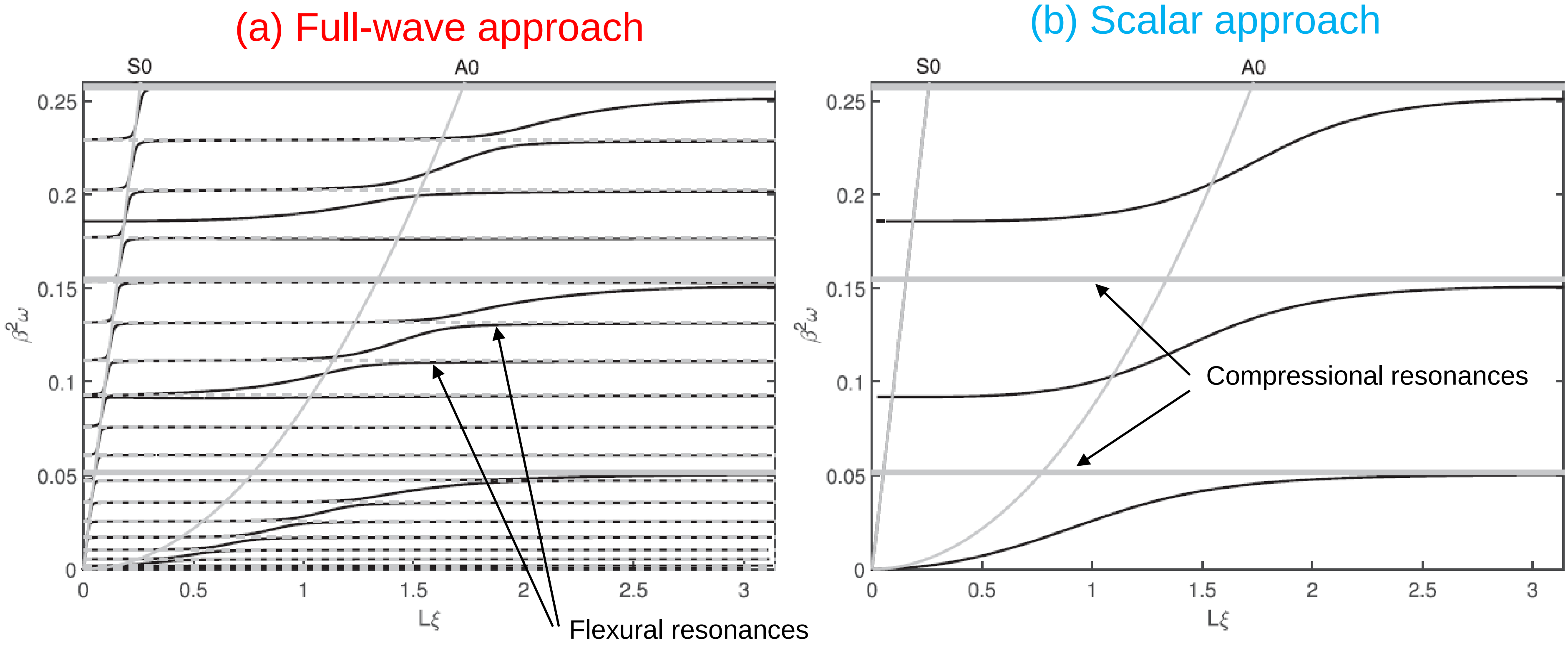


Scalar wave + resonator interaction

Elastic multi-wave + multi-resonances interaction

Rupin et al., Scientific Reports, 2016

Elastic vs Acoustic approach



(a) Full-wave approach

(b) Scalar approach

Flexural resonances

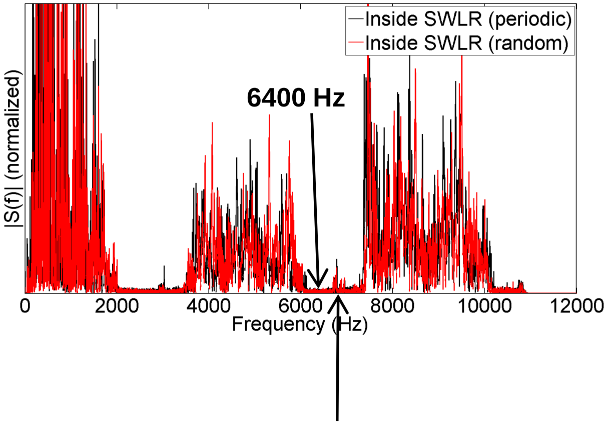
Compressional resonances

Fig. 2. The dispersion curves for the plate system. Panel (a) shows the case when the flexural interactions of the resonators are accounted for; panel (b) shows the curves when we neglect these flexural interactions and consider the compressional resonator modes only. The solid black lines show the solutions of the dispersion equation. The dashed grey lines indicate the flexural resonances of the resonators, whilst the thick solid grey lines denote the compressional resonances of the resonators.

Colquitt et al., JMPS, 2017

What happens inside the bandgap at a flexural resonance?

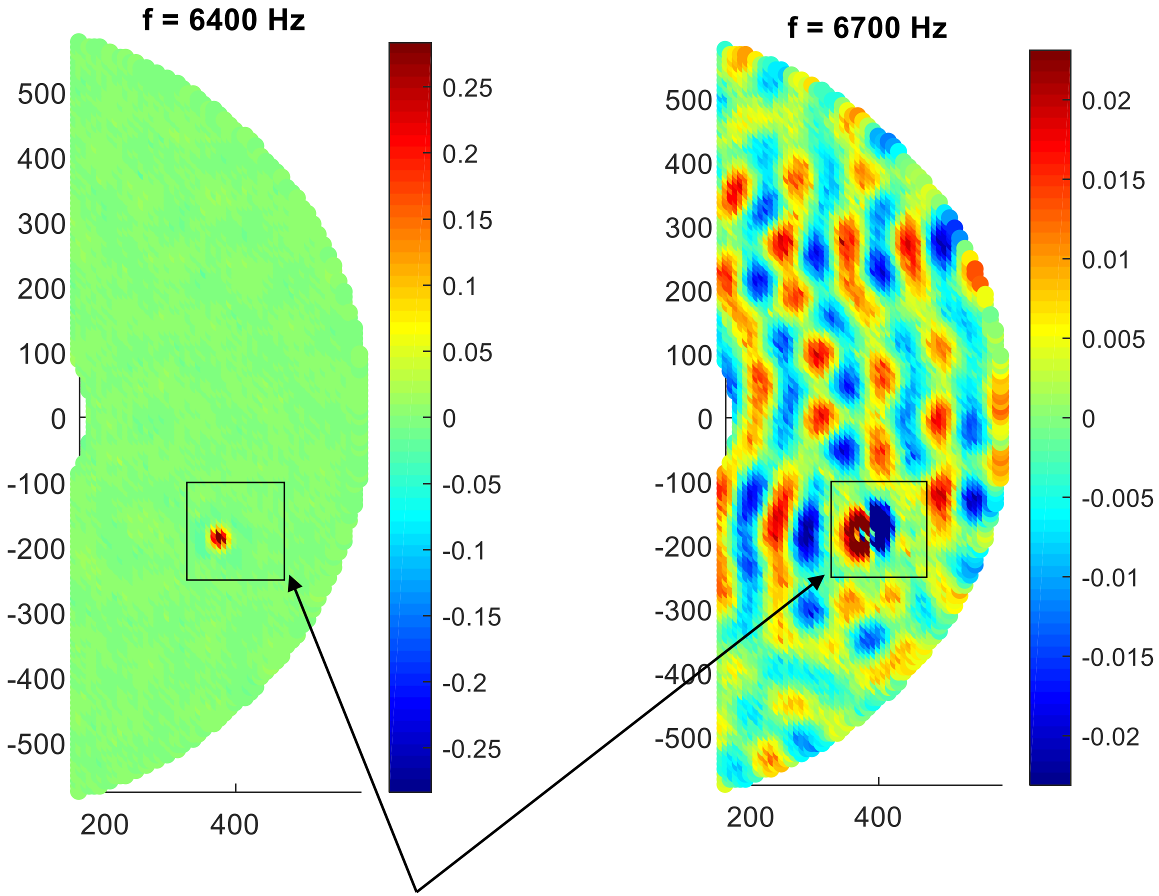
Plate 6 mm



6400 Hz

6700 Hz

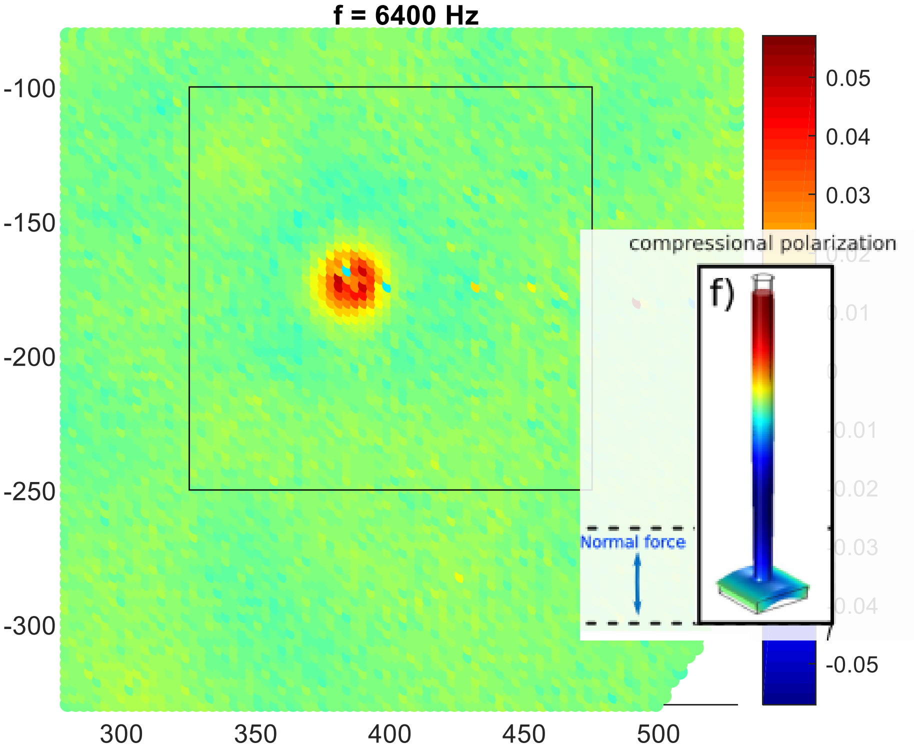
Source inside the Meta



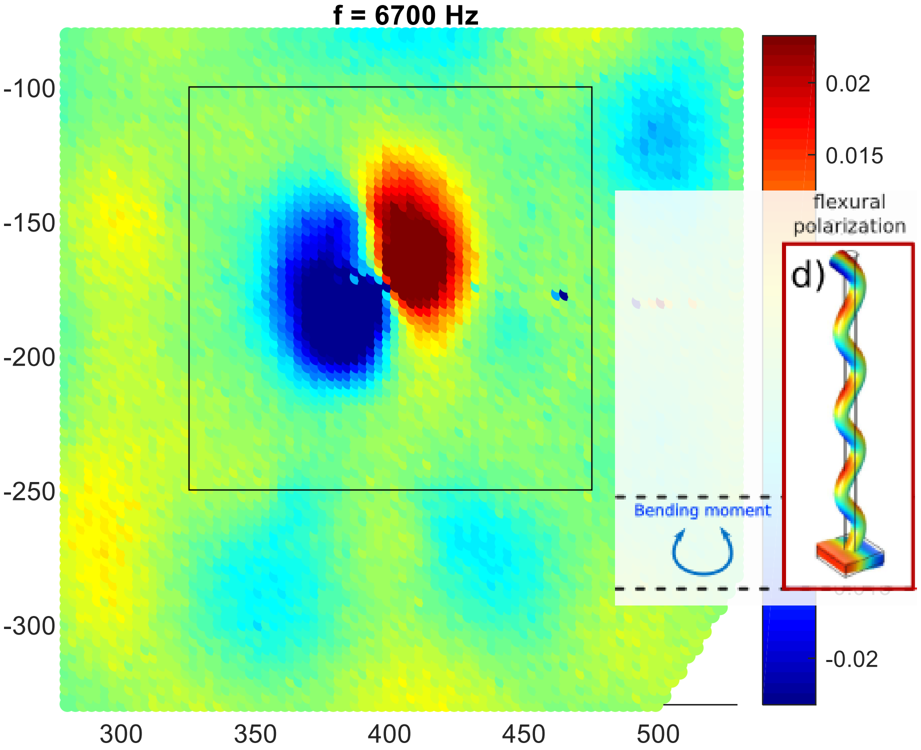
Random Metamaterial

What happens inside the bandgap at a flexural resonance?

Source inside the Meta



Monopole source away from flexural resonances

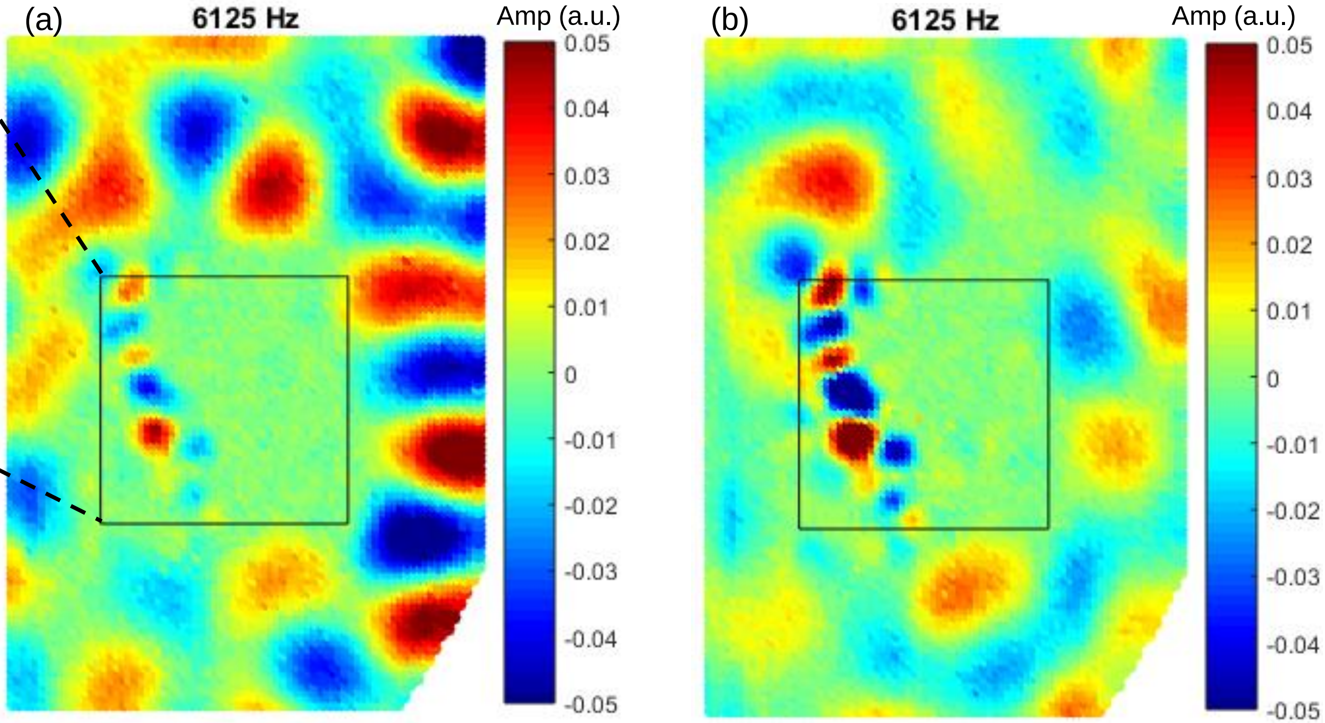


Dipole source at a flexural resonance

What happens when the flexural resonance occurs at the start of the bandgap?

Random Metamaterial

wavelength



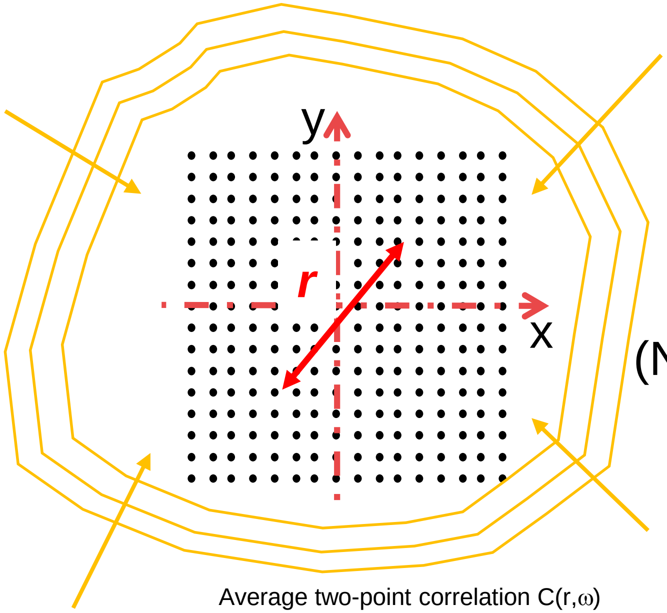
Source outside of the metamaterial

Source inside the metamaterial

Lott et al., Phys Rev Mat, 2020

Anderson localization inside the Metamaterial?

Field-Field correlation inside the Metamaterial

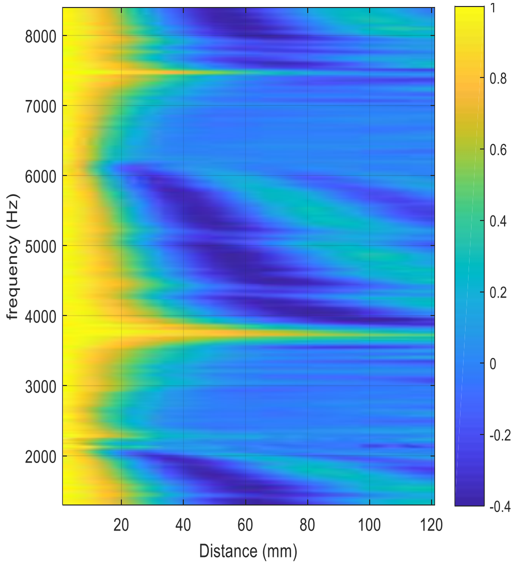


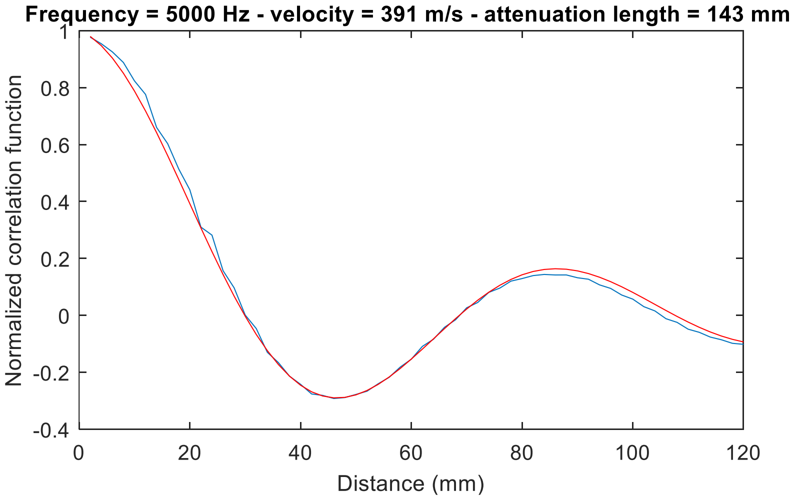
2D antenna
(NxN receivers)

$$C(r,\omega) \sim H_0(kr)\exp\left(-\frac{r}{l}\right)$$

Ensemble average performed on receiver pairs and coda reverberation

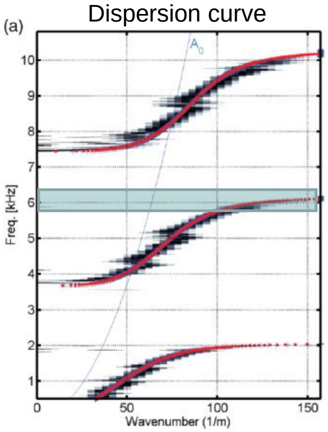
Average two-point correlation C(r,ω)
Inside the Metamaterial

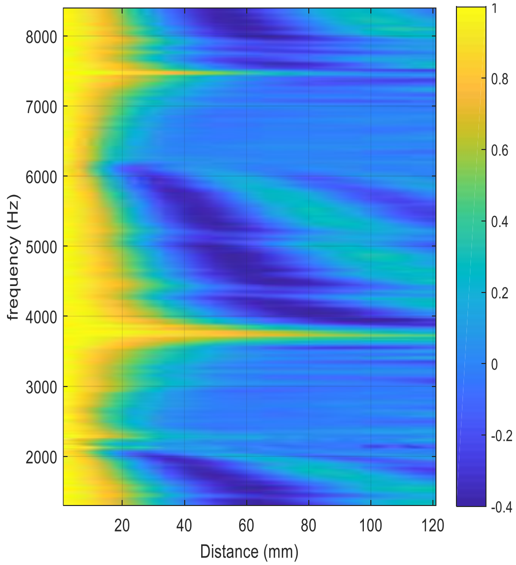


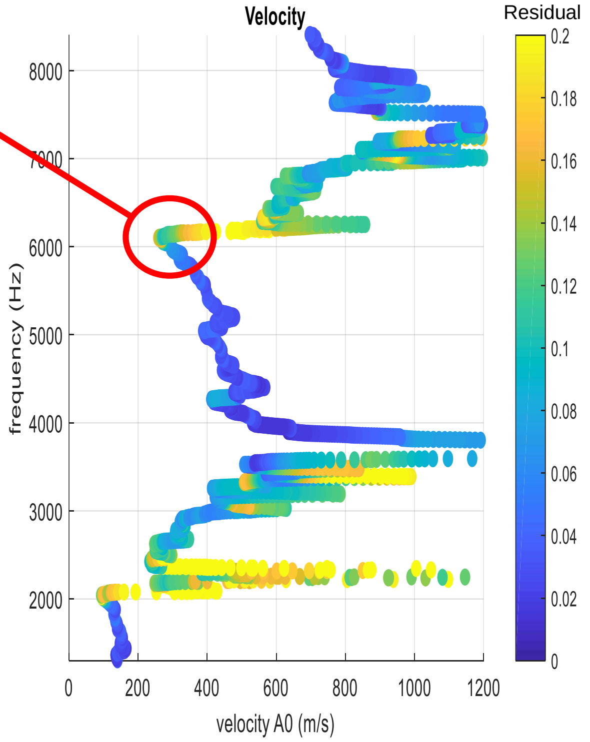


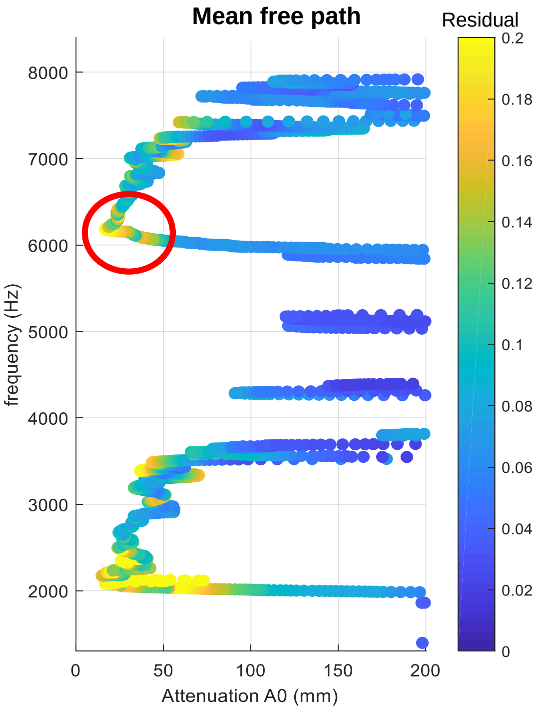
Field-Field correlation inside the Metamaterial

$$C(r,\omega)\sim H_0(kr)\exp\left(-\frac{r}{l}\right)$$


Dispersion curve


Averaged two-point correlation C(r,ω)
Inside the Metamaterial


Velocity


Mean free path

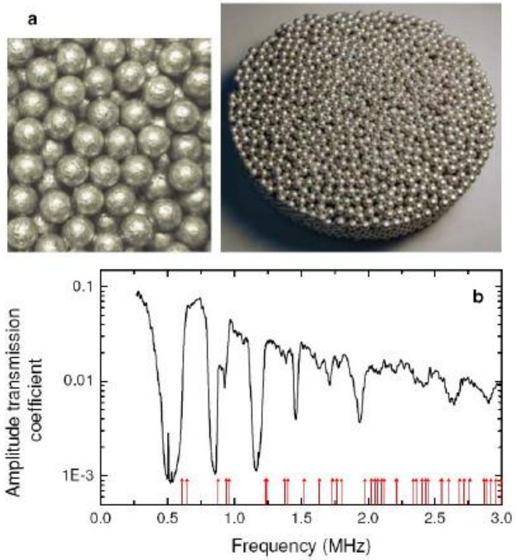
⇨ λ ~ l (mean free path) ~ 2a (distance between rods) = 4 cm

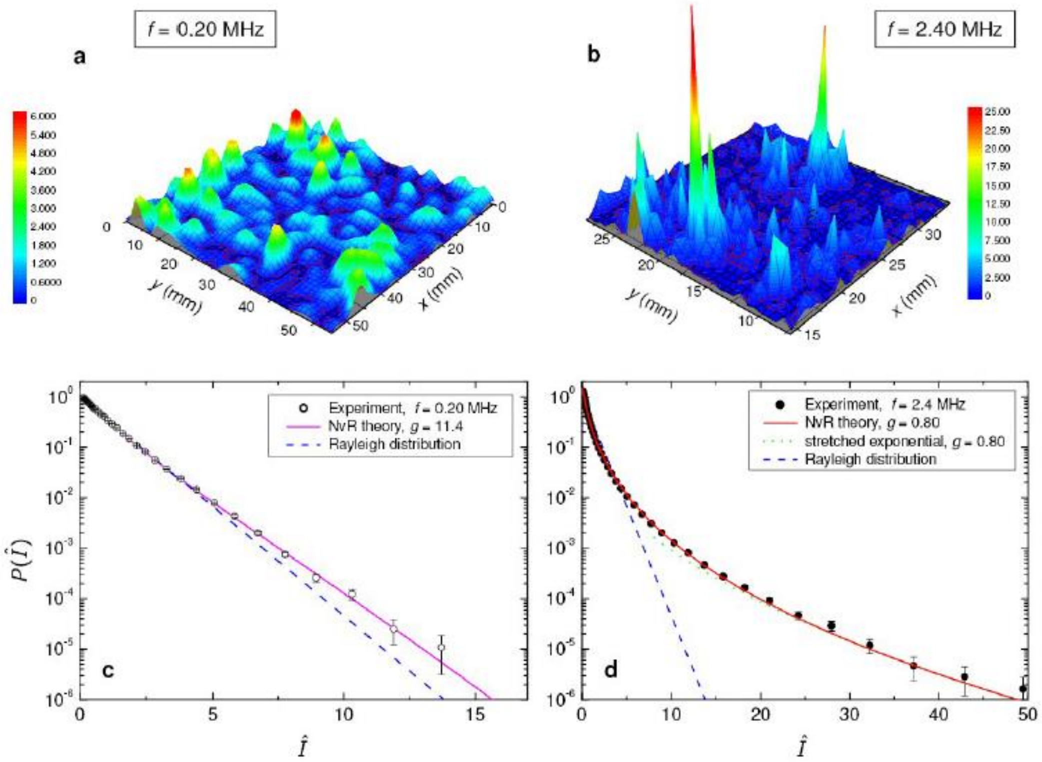
Localization of Ultrasound in a Three-Dimensional Elastic Network[*]

H. Hu,[1] A. Strybulevych,[1] J. H. Page,[1] S.E. Skipetrov,[2] and B.A. van Tiggelen[2]

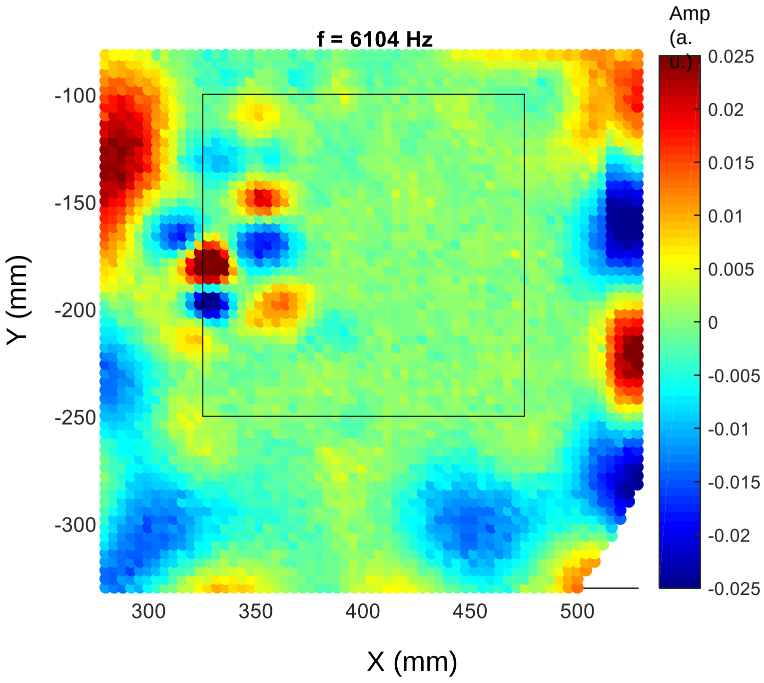
[1] *Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, R3T 2N2 Canada*
[2] *Université Joseph Fourier, Laboratoire de Physique et Modélisation des Milieux Condensés,*
CNRS, 25 Rue des Martyrs, BP 166, 38042 Grenoble, France

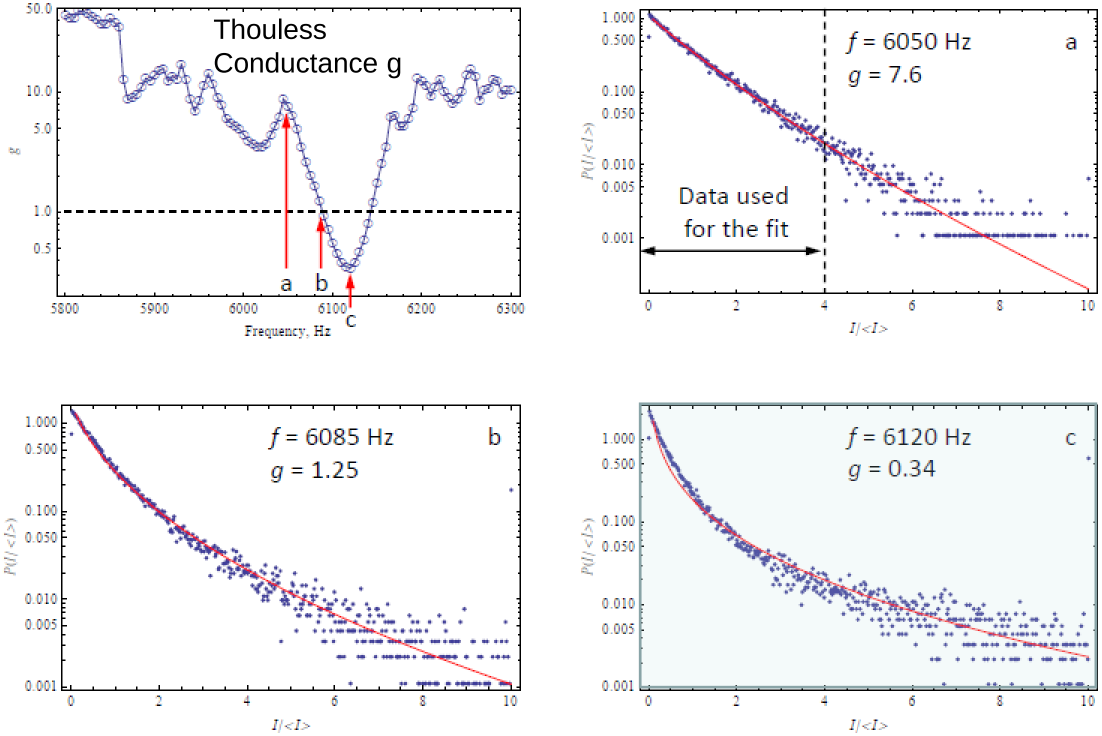
(Dated: June 18, 2009)





Signature of Anderson localization inside the Metamaterial



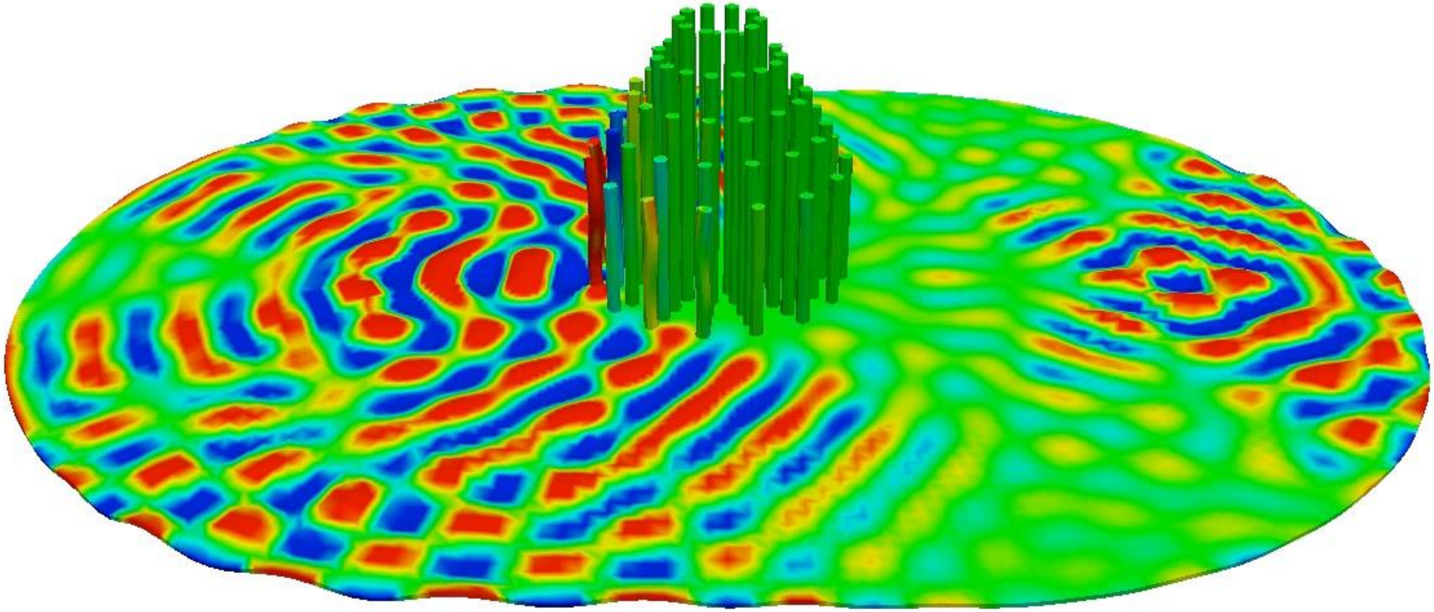


Lott et al., Phys Rev Mat, 2020

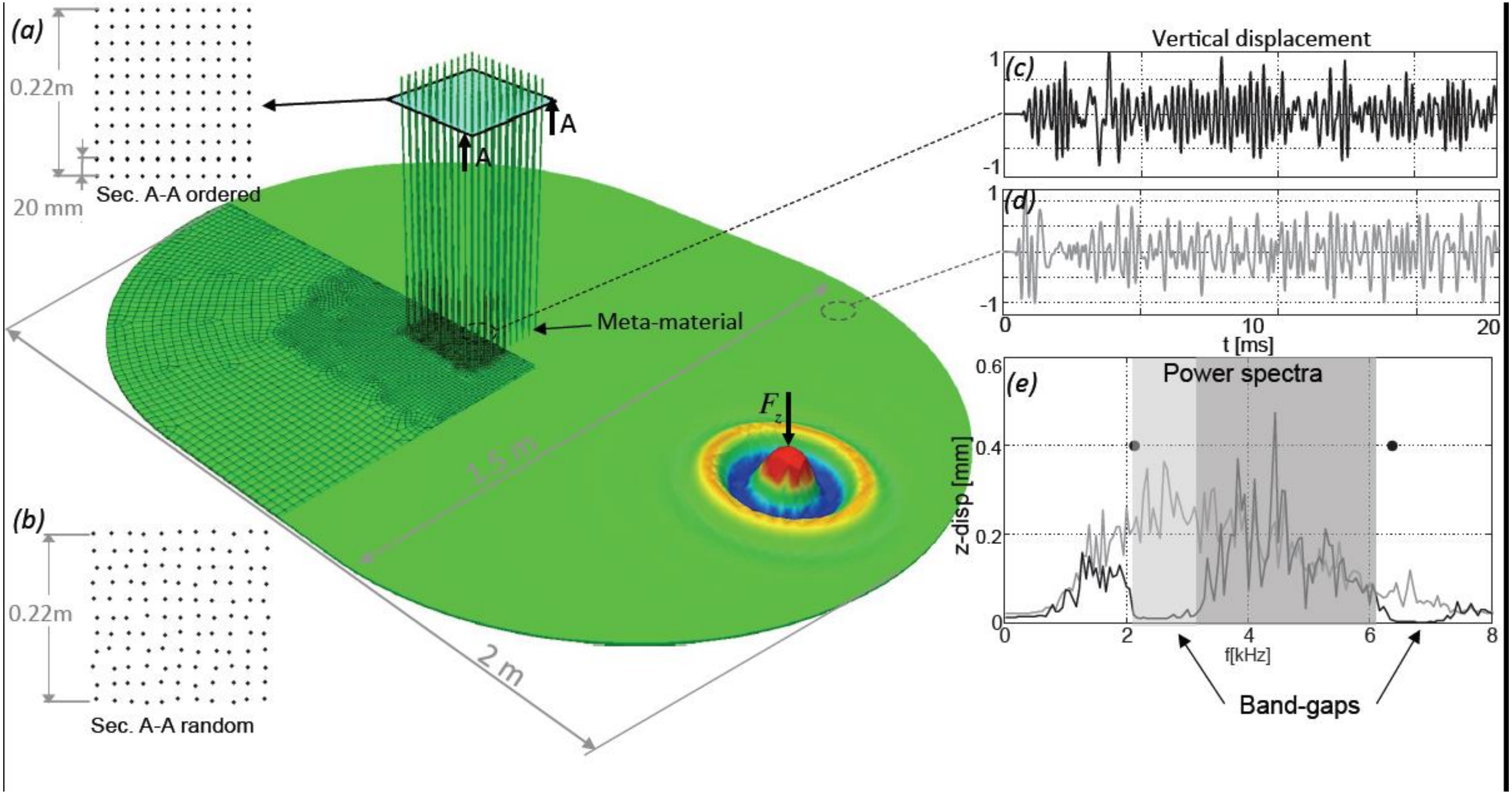
Seismo-Acoustic Cloaking using a numerical approach

Some Degrees of Freedom:

- Length of the Beams
- Spatial Distribution of the Beams

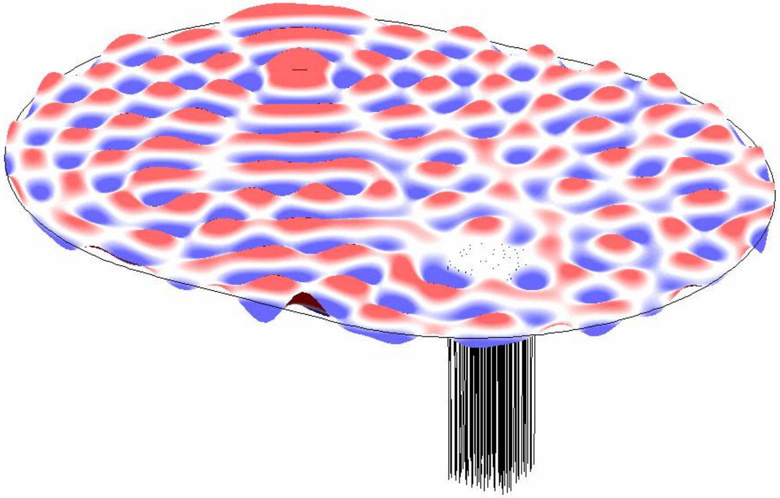


Numerical approach : Spectral Element Method with 3-D Adaptive Meshing

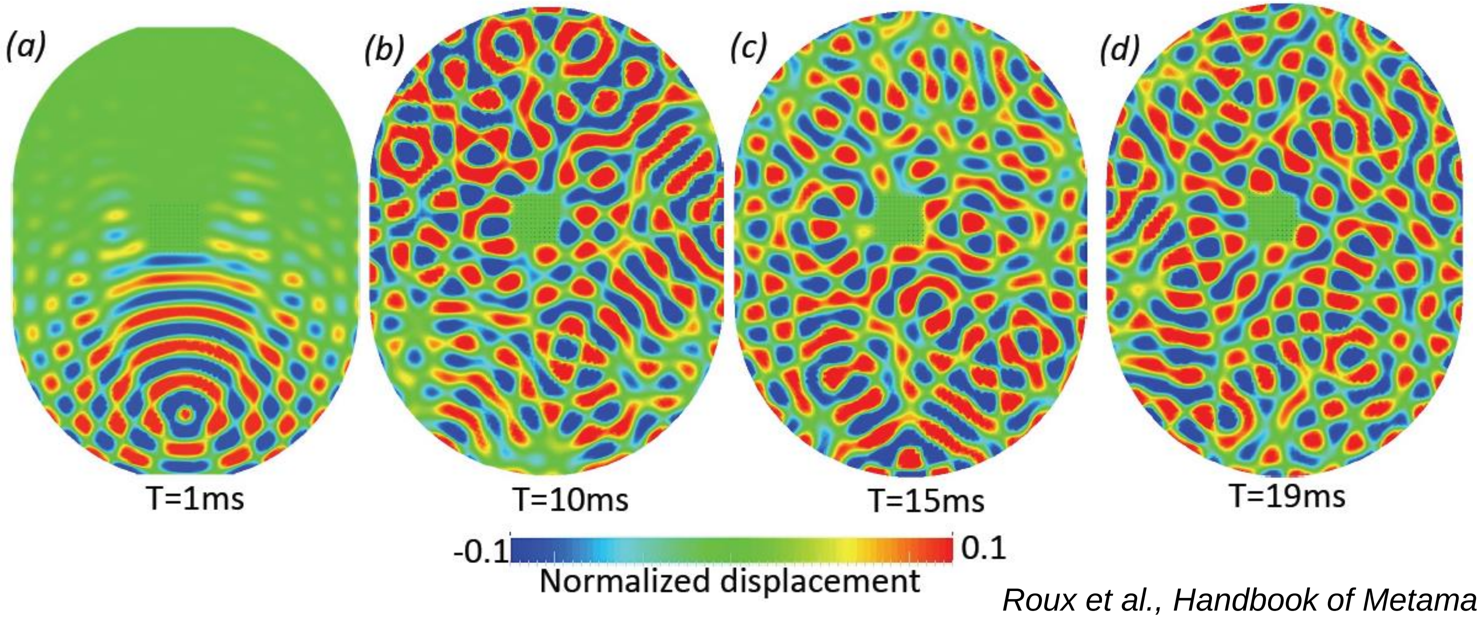


Colombi et al., JASA-EL, 2014

Numerical Results (Filtered in the Bangap)

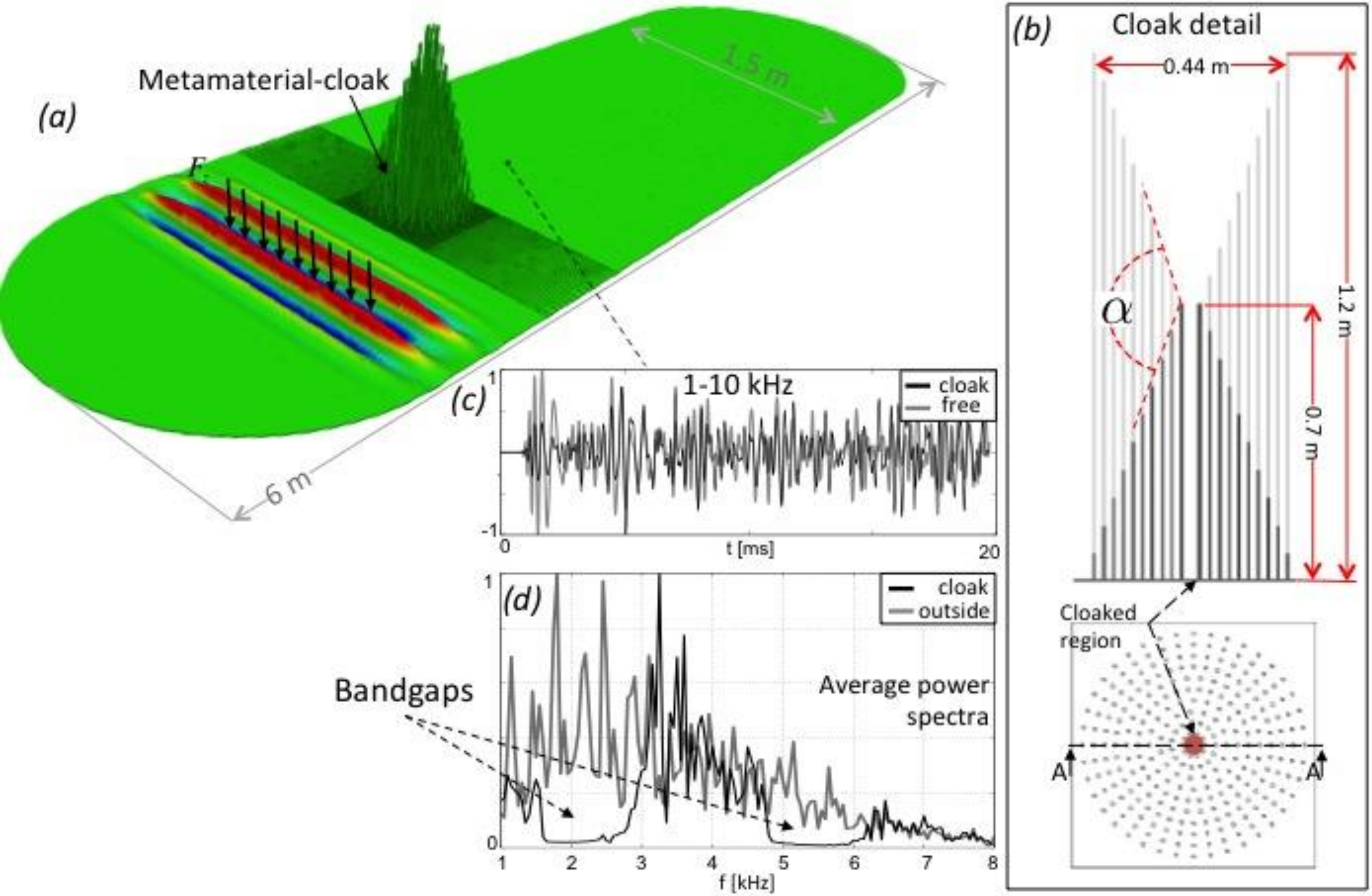


A few snapshots of the wavefield…

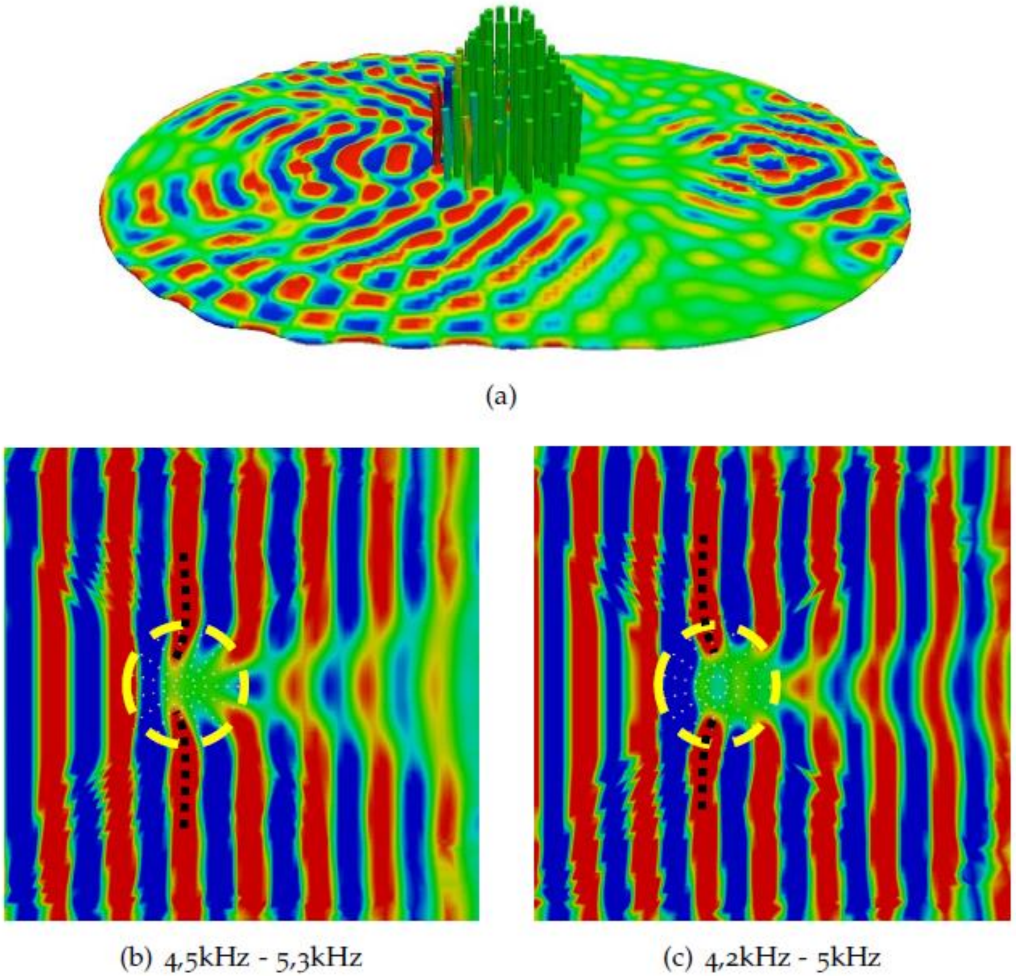


Roux et al., Handbook of Metamaterial, 2017

Toward Acoustic Cloaking (Numerical Results)



Effective Speed inside the Meta-Material



(a)

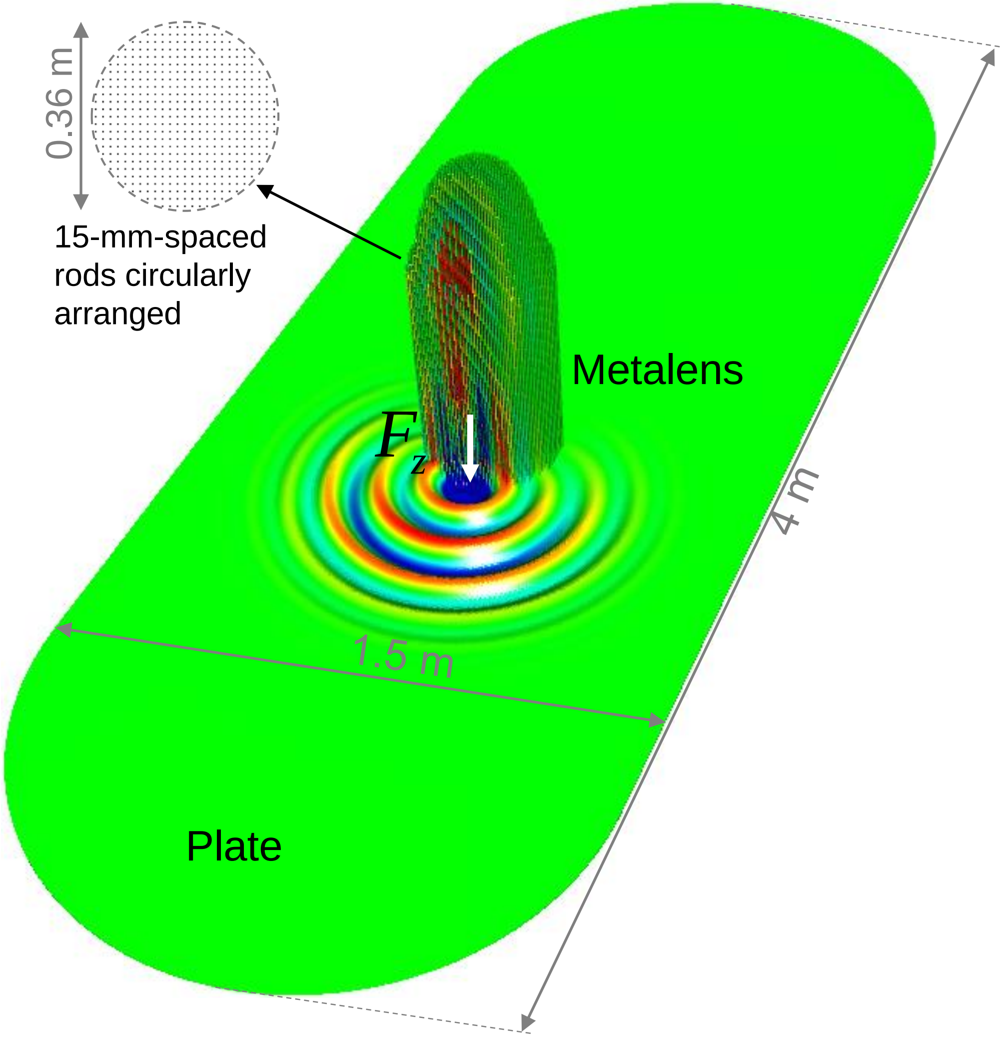
(b) 4,5kHz - 5,3kHz

(c) 4,2kHz - 5kHz

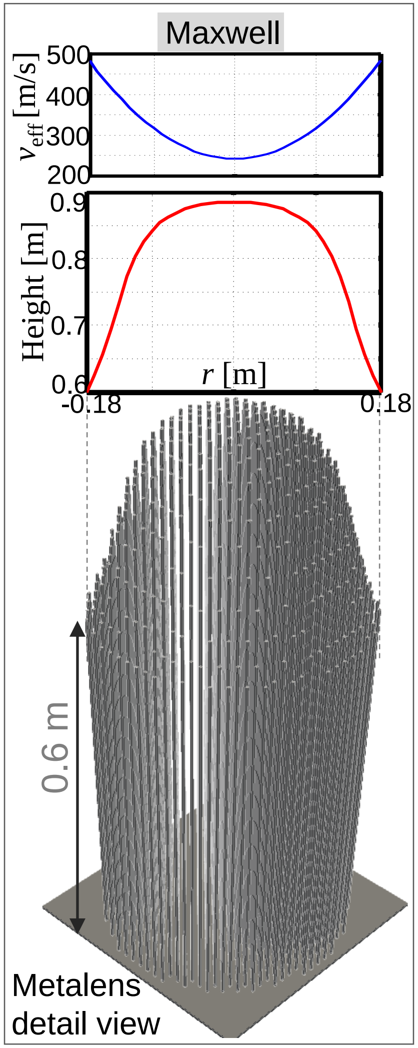
FIGURE 3.36 – *Illustration des travaux en cours de développement pour la mise au point d'une cape d'invisibilité pour les ondes de Lamb A0. a) Exemple de configuration étudiée : un ensemble de tiges de différentes longueurs disposées en étoile. b-c) Allure du champ d'ondes (vitesses verticales) au dessus du métamatériau (repéré en tirets jaunes) pour deux gammes de fréquences. On observe alors un fléchissement du front d'onde incident : (b) vers l'arrière et (c) vers l'avant.*

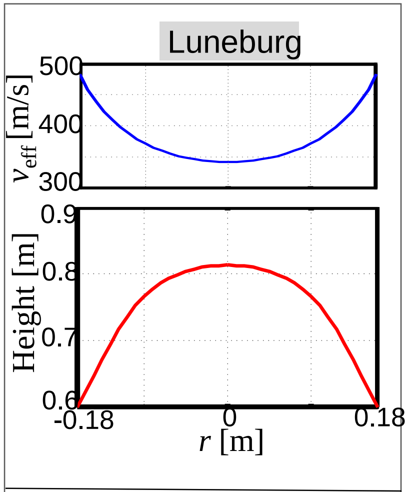
Gradient Index Lenses with Plate Waves

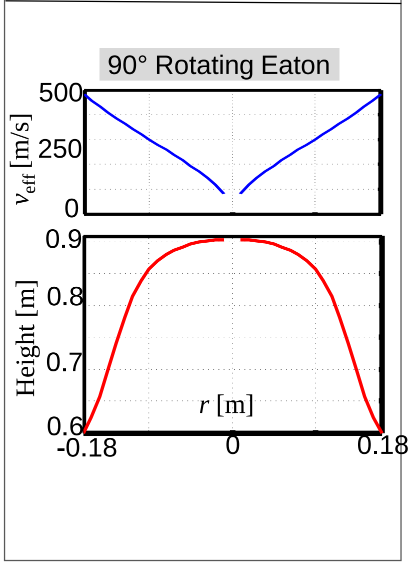
Numerical model



Lens type:

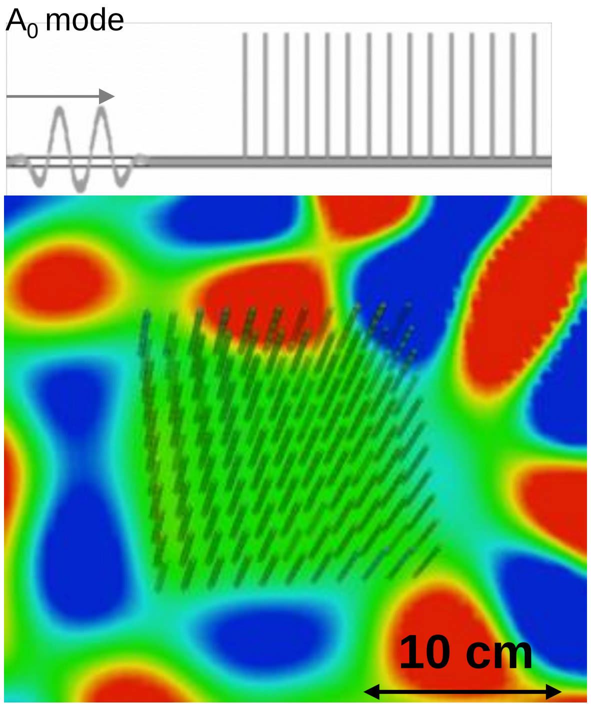




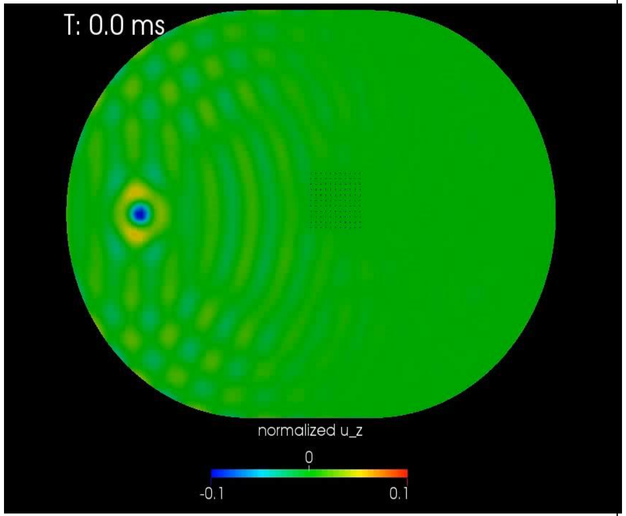


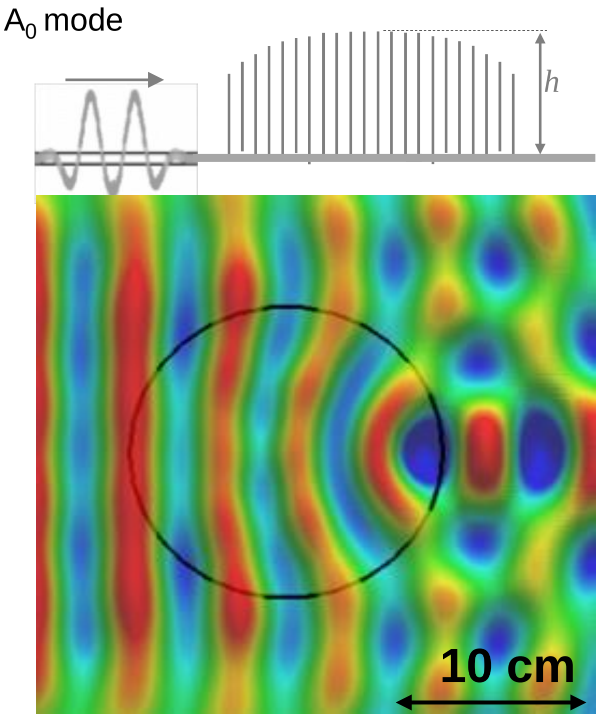
Colombi, JASA-EL, 2016

Plate Wave Manipulation with Gradient Index Lenses

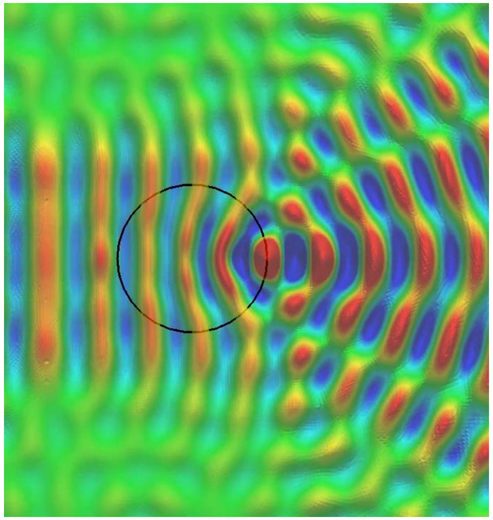


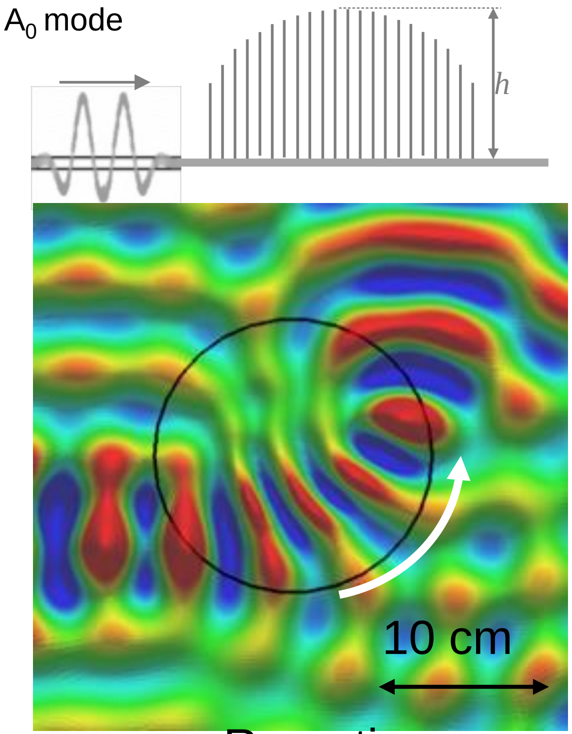
Bandgap



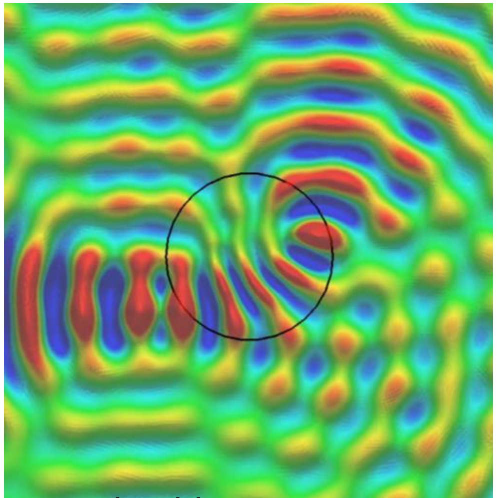


Focusing





Rerouting



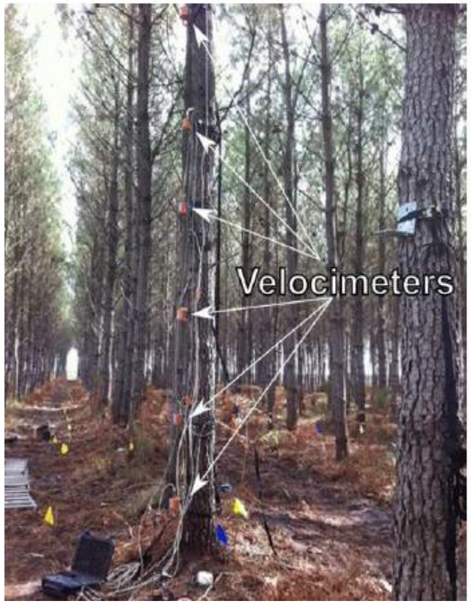
Colombi, JASA-EL, 2016

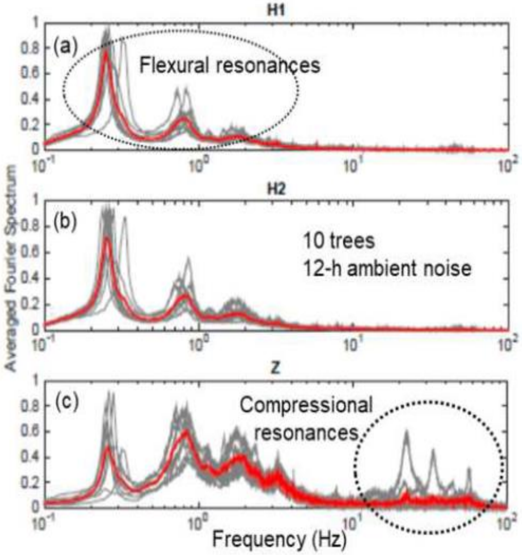
Application at the geophysics scale : can we consider a forest as a natural Metamaterial?

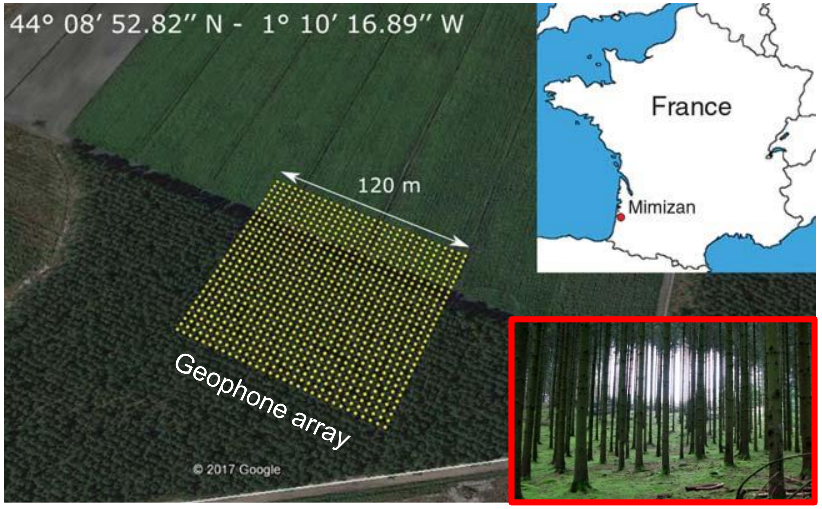
Roux et al.. SRL. 2018

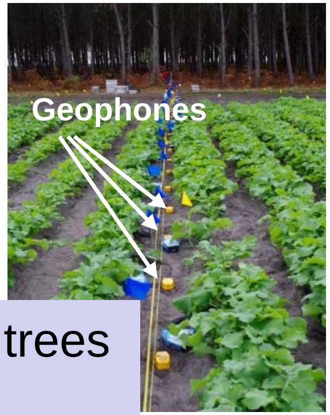
META-FORET

Trees as resonators



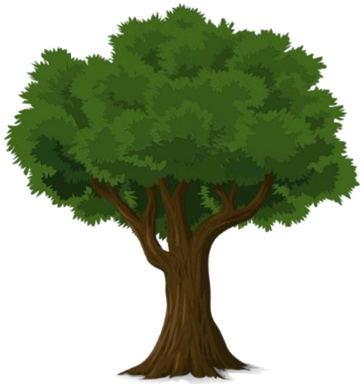


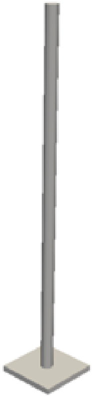




- Compressional and Flexural motion for the trees
- Sources inside and outside the forest

Transposition from Laboratory study to Geohysics





Compression/flexion

Tree

Beam

ground

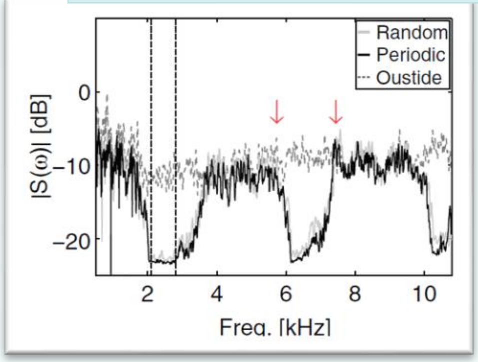
plate

Surface waves
Freq : 10-100 Hz

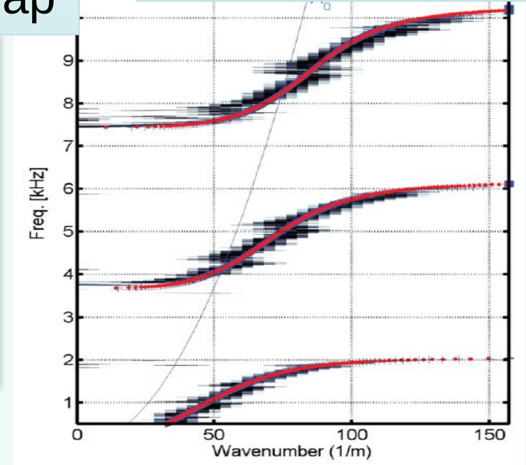
A0 Lamb waves
Freq : 1-10 kHz

Forest of rods on
A0 Lamb wave

Frequency band-gap

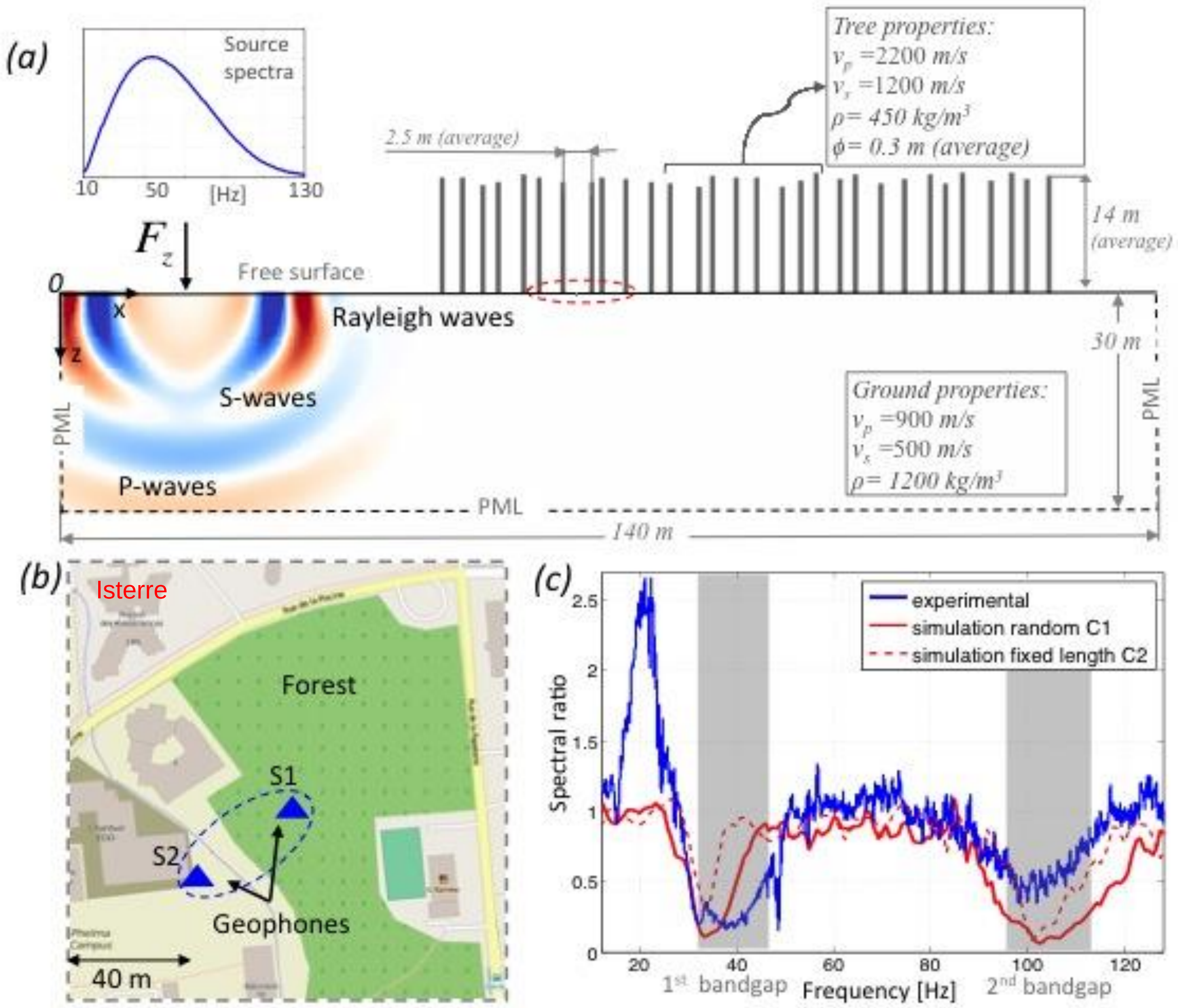


Hybridization-like
dispersion curve



Rupin et al. PRL 2014

First experimental / numerical demonstration at the geophysics scale (2015)

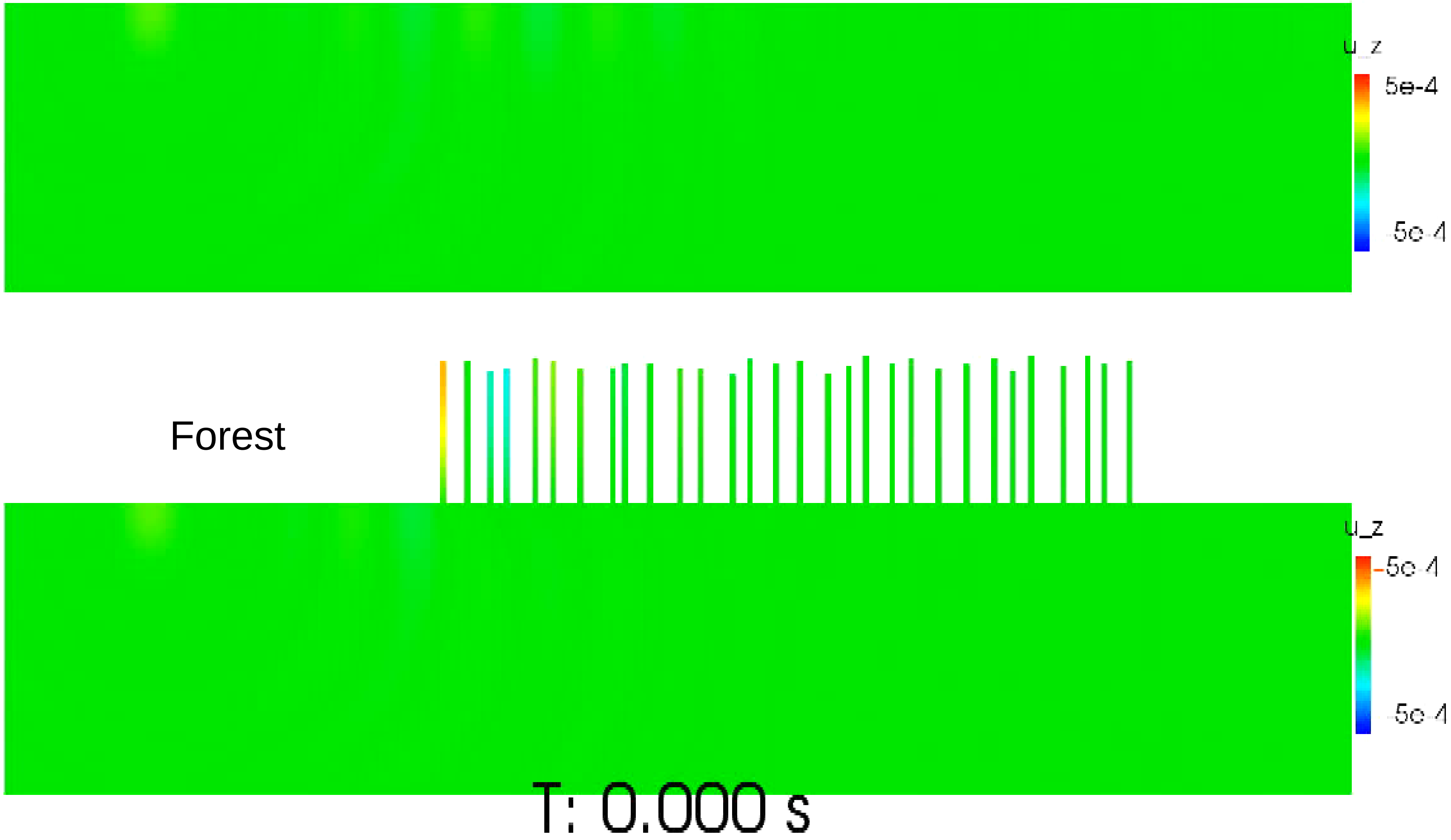


Colombi et al., Scientific Reports, 2016

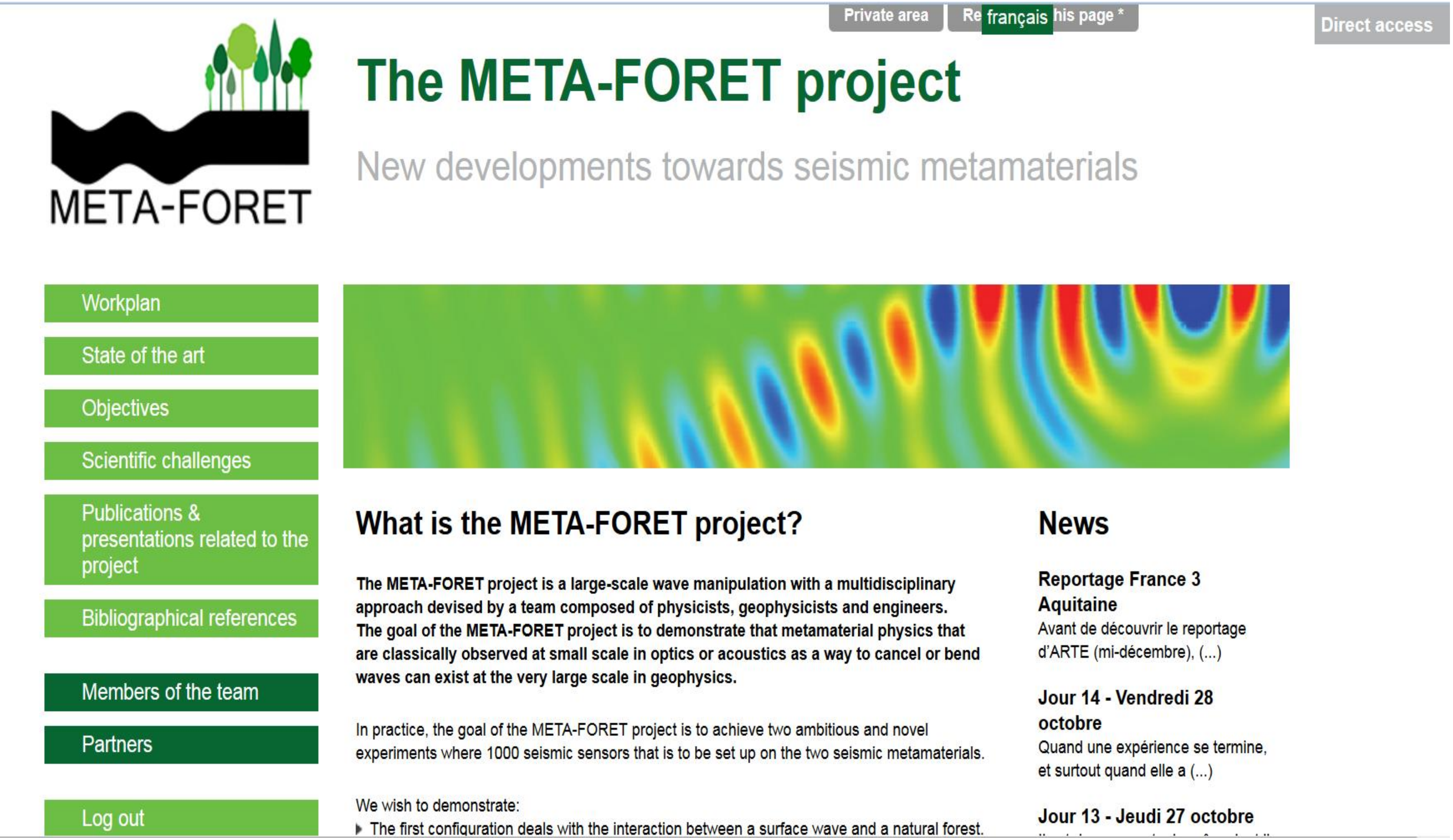
Rayleigh wave interacting with resonating trees?

Reference

32 Hz - 42 Hz



Forest



The META-FORET project

New developments towards seismic metamaterials

What is the META-FORET project?

The META-FORET project is a large-scale wave manipulation with a multidisciplinary approach devised by a team composed of physicists, geophysicists and engineers.
The goal of the META-FORET project is to demonstrate that metamaterial physics that are classically observed at small scale in optics or acoustics as a way to cancel or bend waves can exist at the very large scale in geophysics.

In practice, the goal of the META-FORET project is to achieve two ambitious and novel experiments where 1000 seismic sensors that is to be set up on the two seismic metamaterials.

We wish to demonstrate:

- The first configuration deals with the interaction between a surface wave and a natural forest.

News

Reportage France 3 Aquitaine
Avant de découvrir le reportage d'ARTE (mi-décembre), (...)

Jour 14 - Vendredi 28 octobre
Quand une expérience se termine, et surtout quand elle a (...)

Jour 13 - Jeudi 27 octobre

Data available at htpps://metaforet.osug.fr

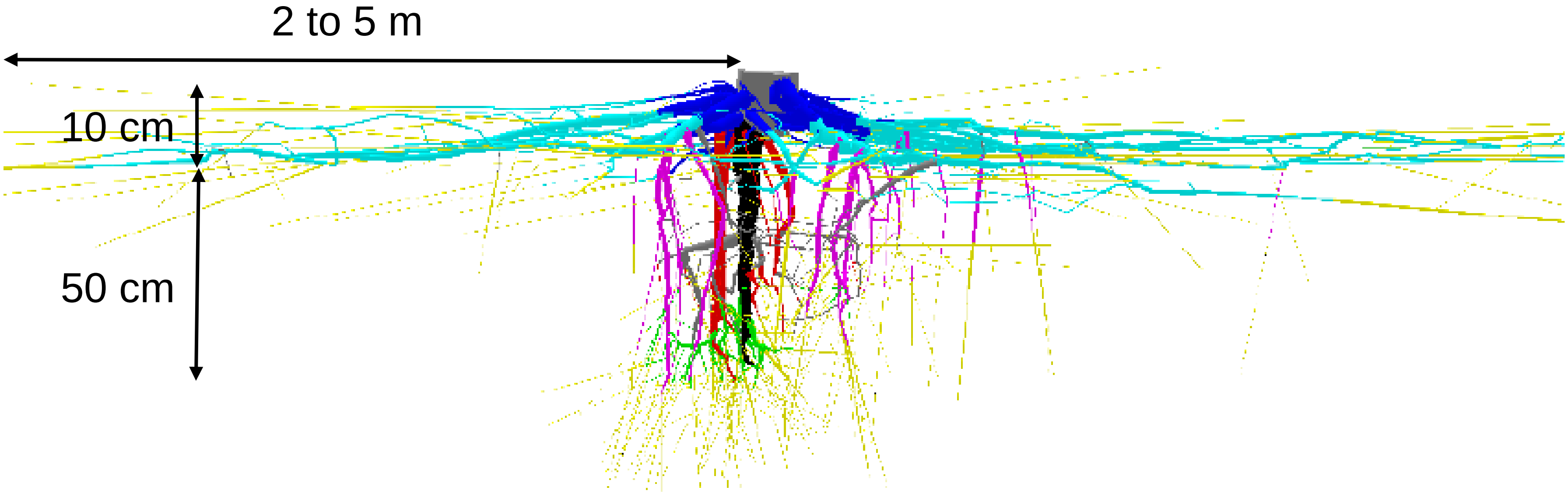
Preparation of the METAFORET Experiment (2016)

Collaborations with CNPF,

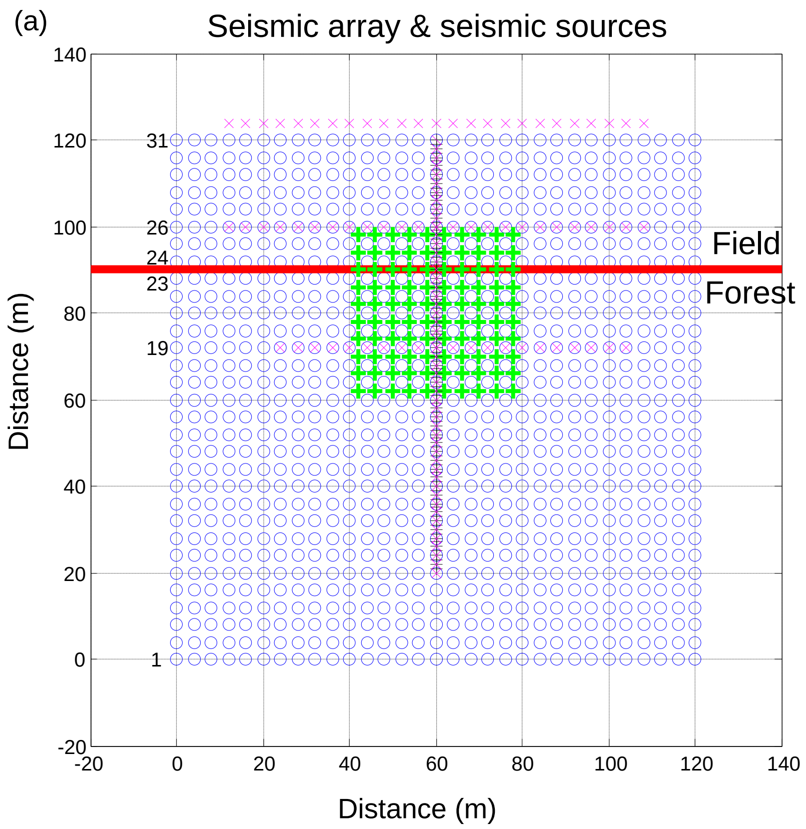
INRA BIOGECO & ISPA

Choice of the forest area

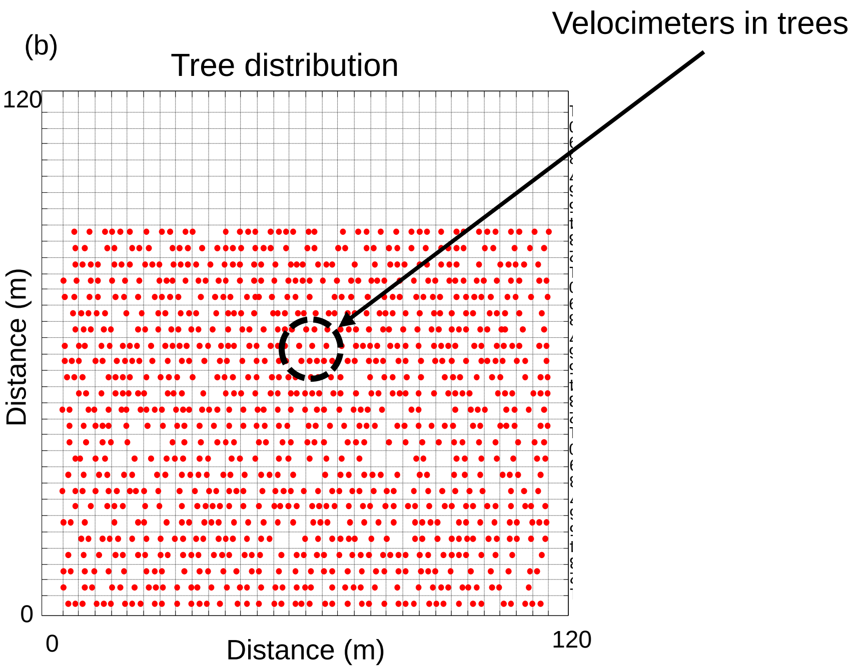
Role of roots, soil properties, …



The METAFORET project : experimental configuration



(a) Seismic array & seismic sources



(b) Tree distribution

Velocimeters in trees

Seismic configuration

- 1000 vertical geophones (Z-land sensors, Geokinetics)
- 100 geophones (3-C, GFZ cubes, Postdam)
- 9 velocimeters (3-C, ISTerre)
- 150 active sources (vibrometer 15-90 Hz, ISTerre)
- Ambient noise (10 days, continuous recording)

Average tree properties

(measured on 50 trees)

- Diameter ~ 20 cm
- Height ~ 10 m
- Weight ~ 250 kg / tree
- Tree density ~ 900 trees / ha

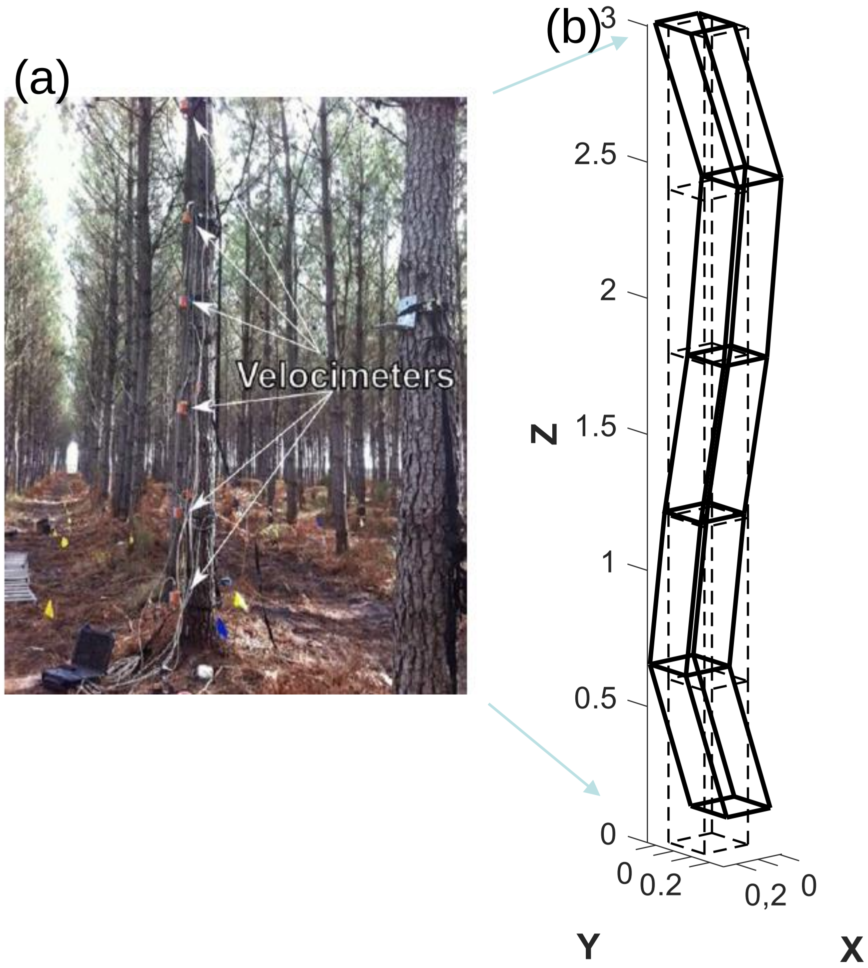
The METAFORET experiment

(a) 2D Seismic array with Z-land geophones

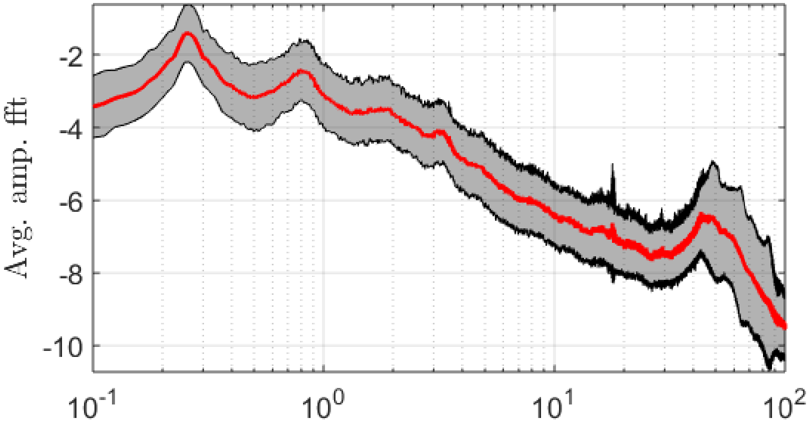
(b) Line array with GFZ geophones

(c) Vibrometer source (> 15 Hz)

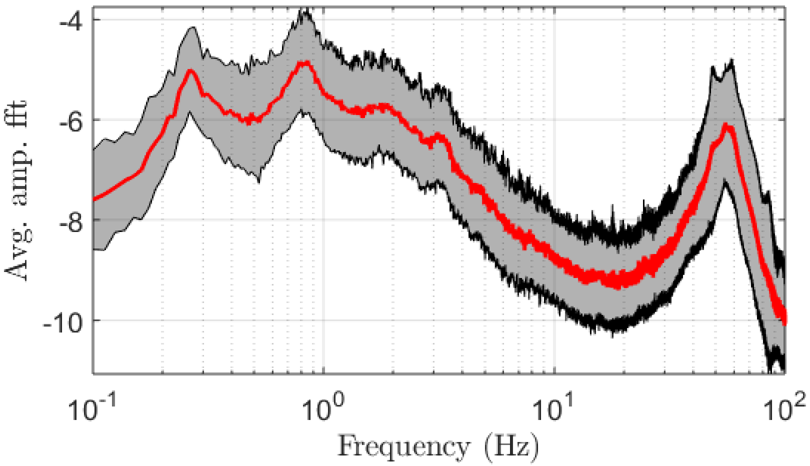
The METAFORET data : The tree spectral response



(c) Horizontal motion

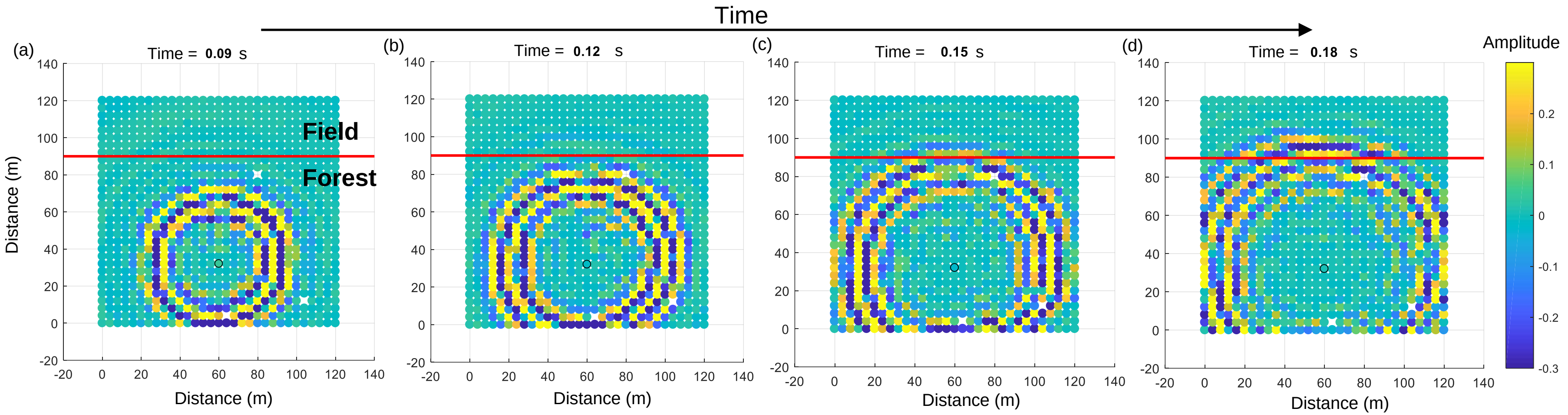


(d) Vertical motion

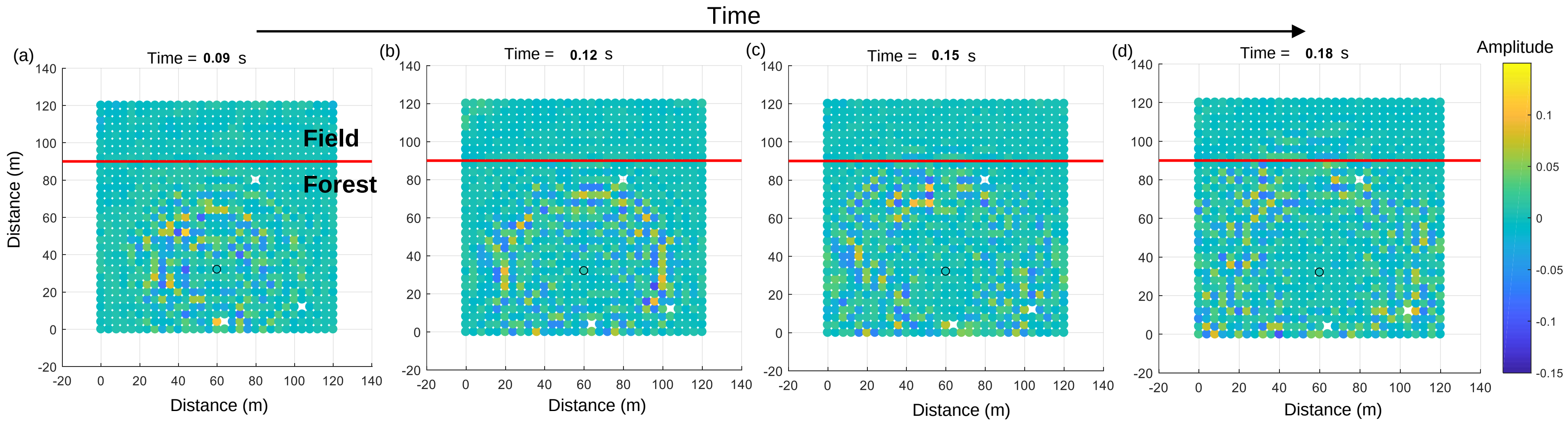


The METAFORET data : Active Source on 2-D Surface Array

Frequency : 20 Hz - 50 Hz : below the tree compressionnal resonances



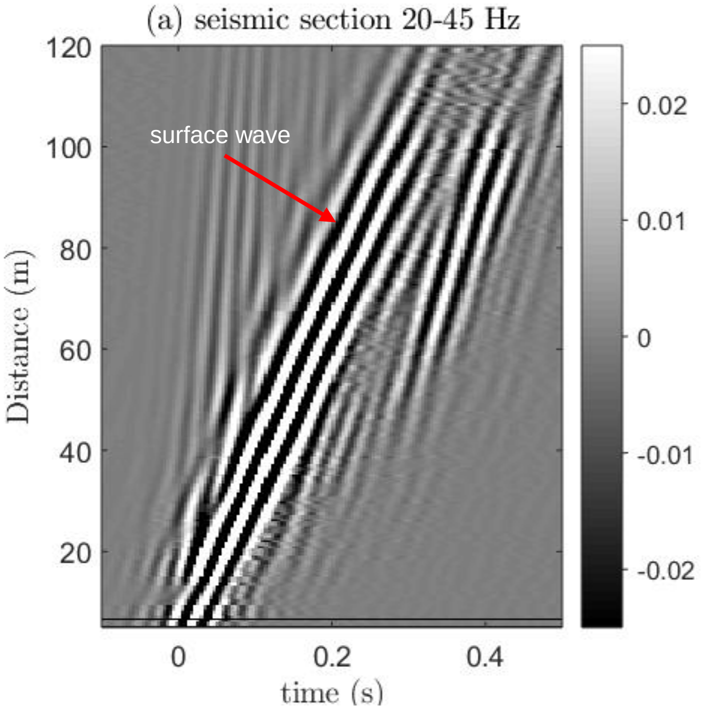
Frequency : 50 Hz - 80 Hz : above the tree compressionnal resonances

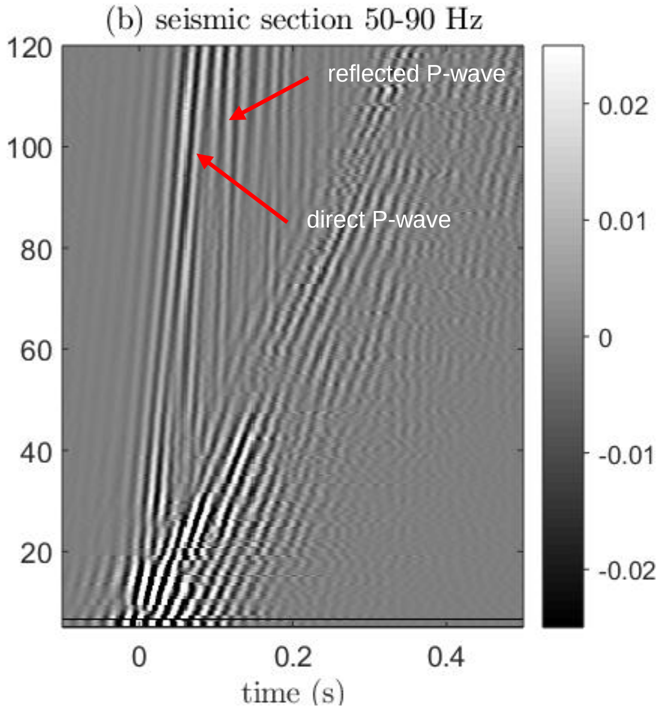


Roux et al., SRL, 2018

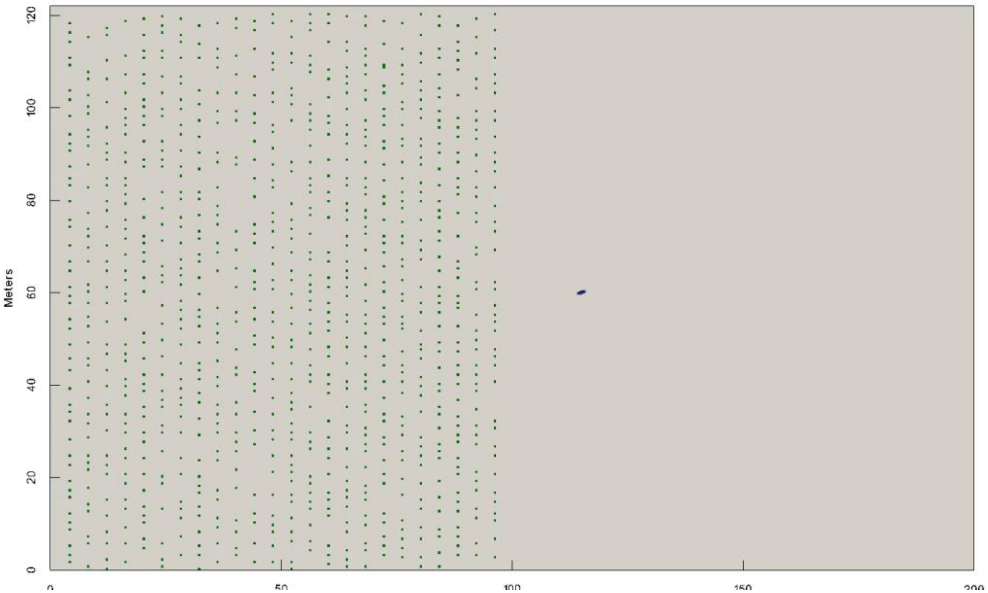
The METAFORET data :

Active Source for Average Seismic Section





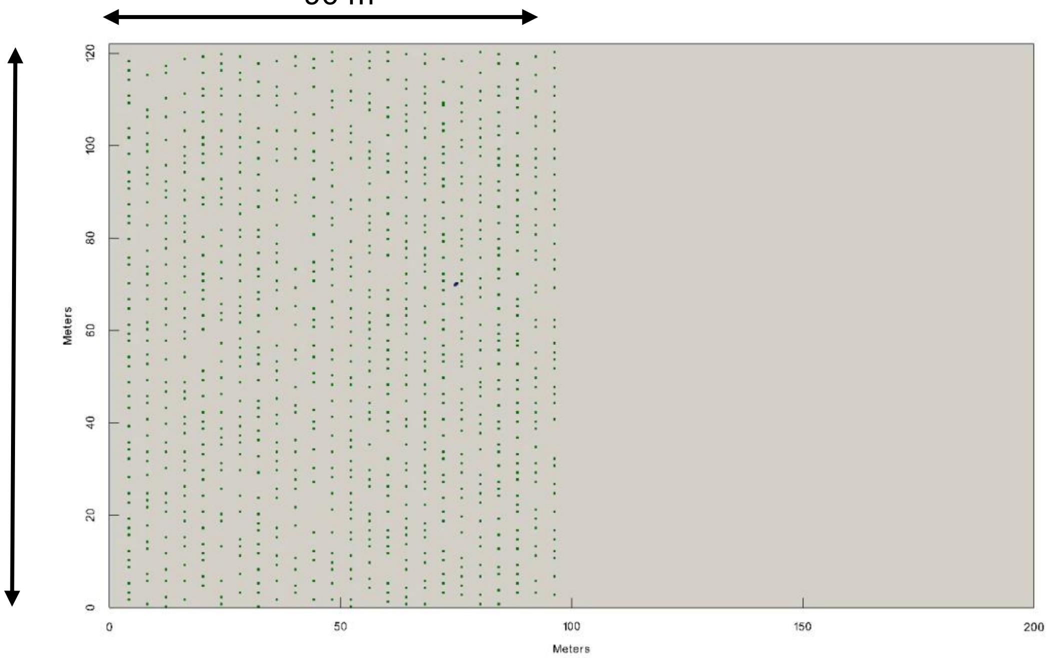
Active source
outside of the forest



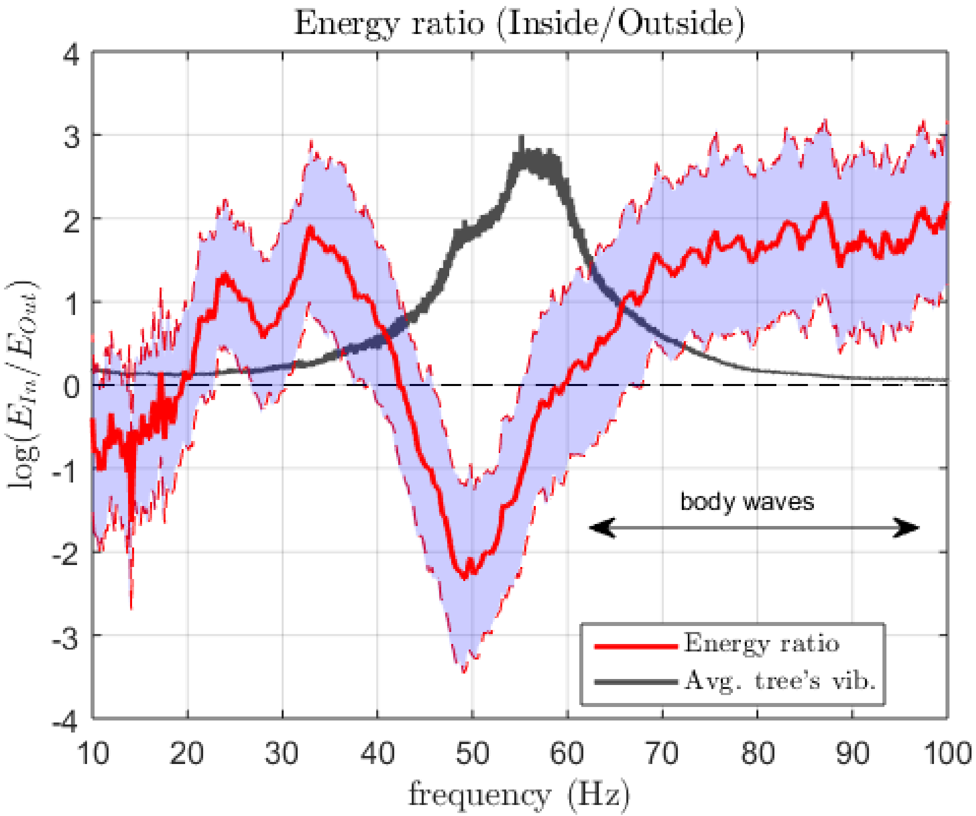
90 m

120 m

Active source
inside the forest



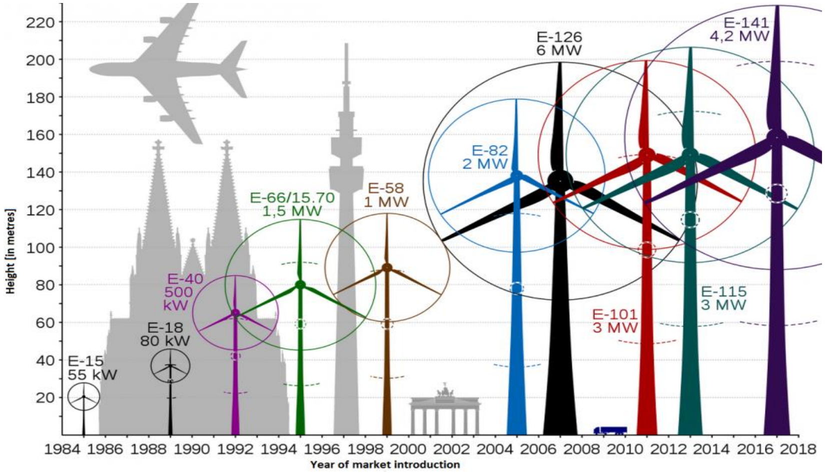
The METAFORET data : Spectral ratio in / out of the forest



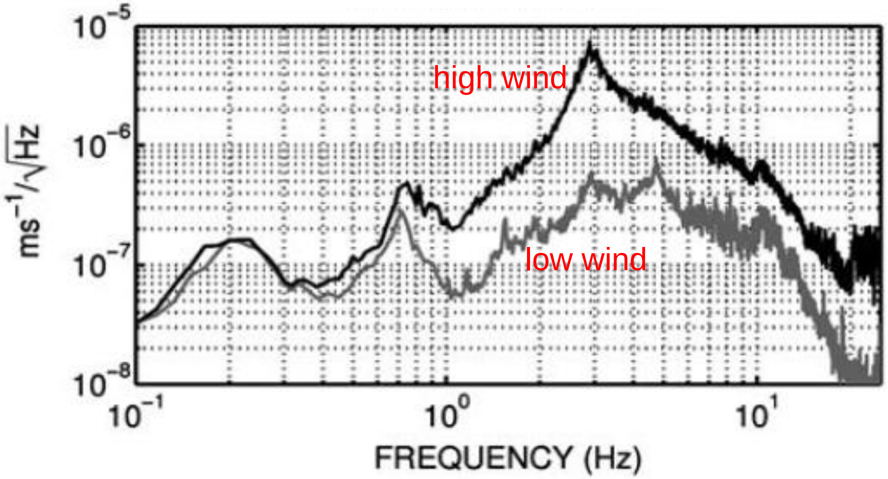
Lott et al., Geophy J Int, 2019

Perspectives for Seismic Metamaterial (Jan. 2021)

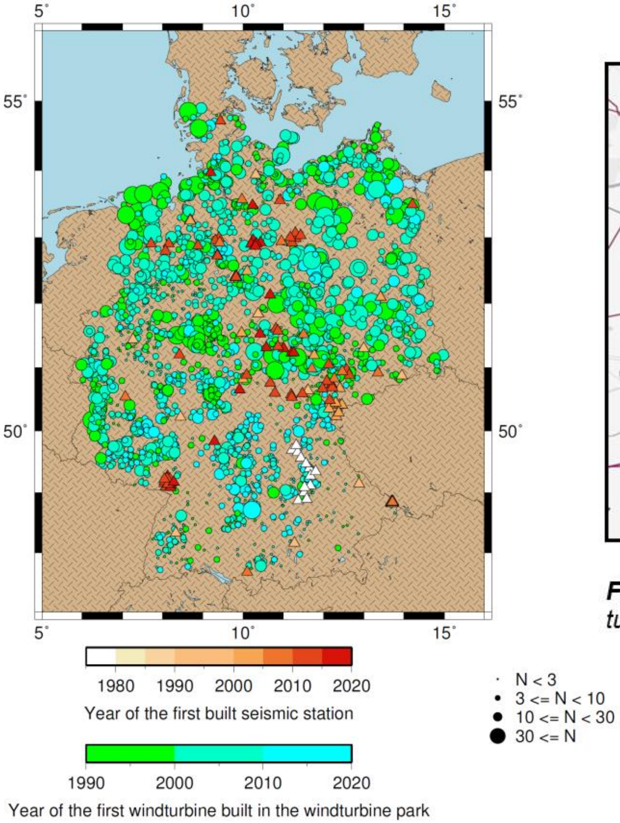
Wind turbine fields



Saccorotti et al., 2011



META-WT project
(planned in Feb. 2023)



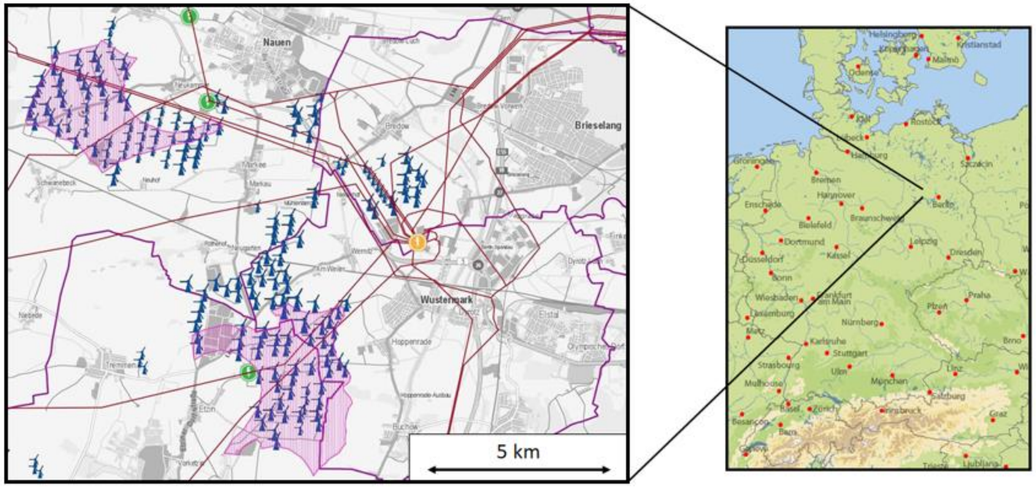
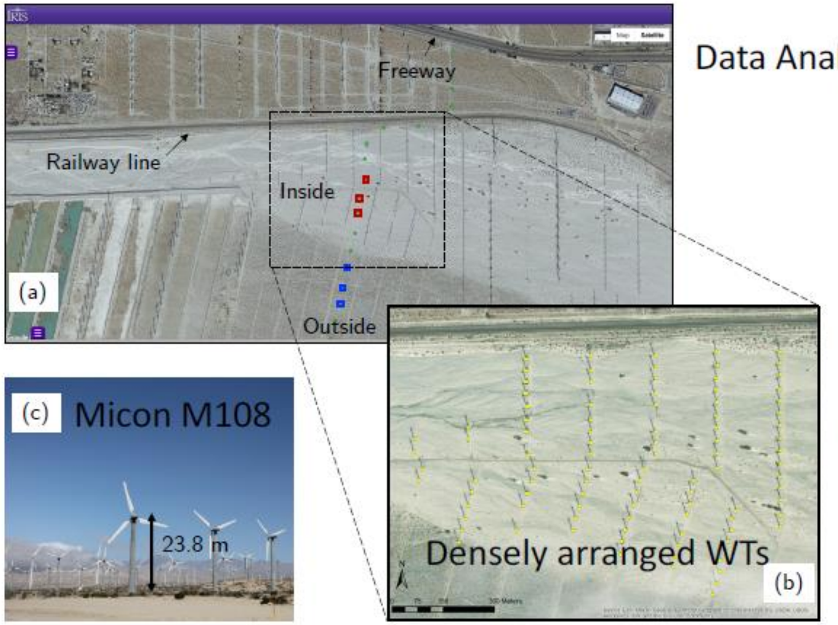
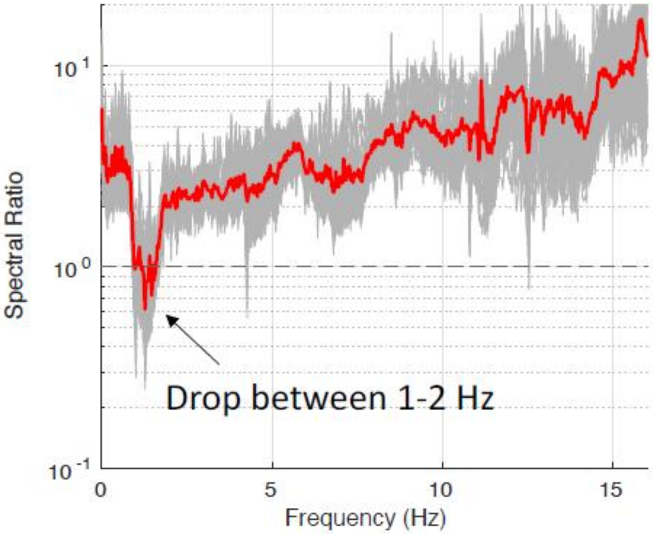


Figure 5: *(a) Map of wind turbines (blue symbols) on the Nauen plateau in Germany. The size of the wind turbine on the map is proportional to its dimension. The two possible installation sites are hatched in purple.*

Why should it work? Preliminary data (work of Shoaib Ayaz)

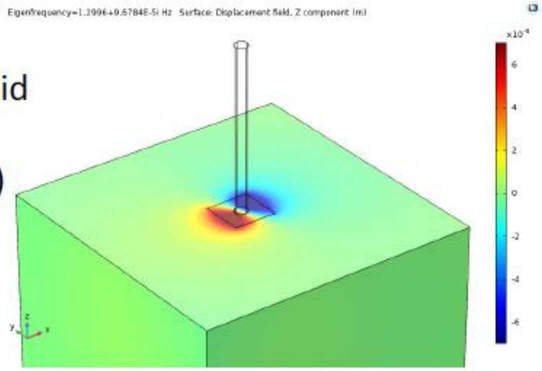


Data Analysis: Mean Spectral Ratio, $\frac{PSD\ stations\ Inside}{PSD\ stations\ Outside}$

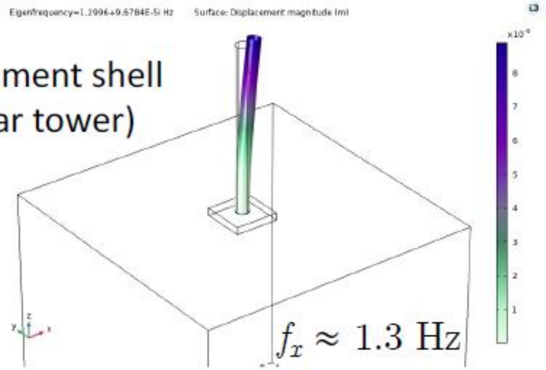


COMSOL modelling: solid-shell coupling, Eigenfrequency Analysis

Displacement solid (soil+footing & assembly block)

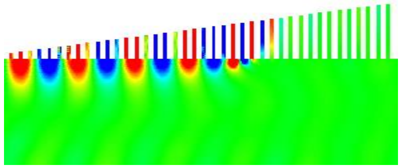


Displacement shell (tubular tower)

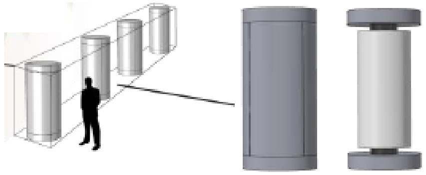


Other Attempts with Seismic Metamaterials

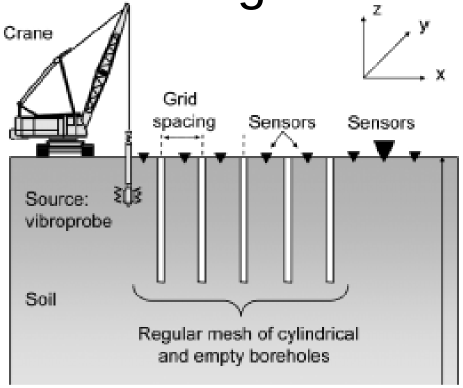
- The Metawedge configuration



- Seismic wave cancellation using buried resonators

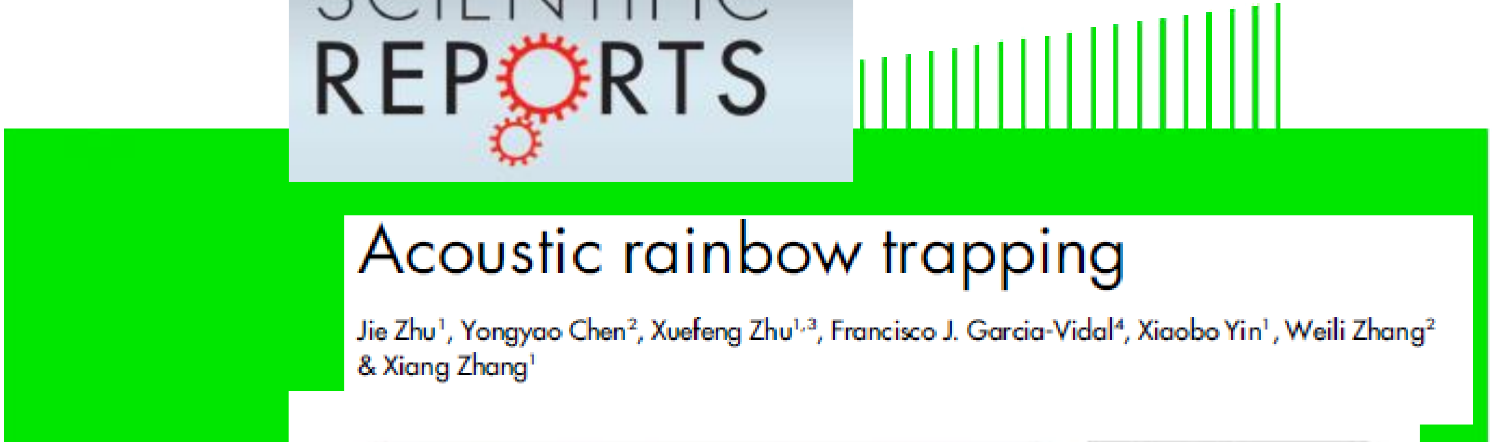


- Seismic wave cancellation using buried beams



Trees with different height : The seismic rainbow

40 Hz

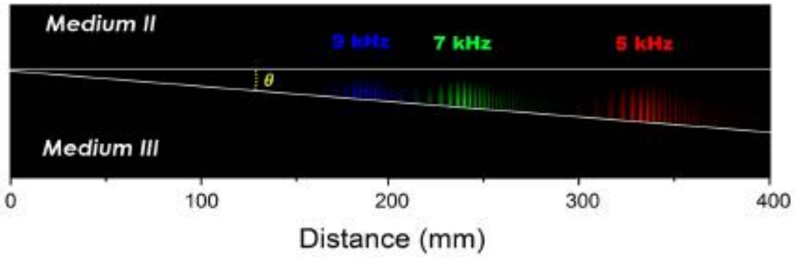


SCIENTIFIC REPORTS

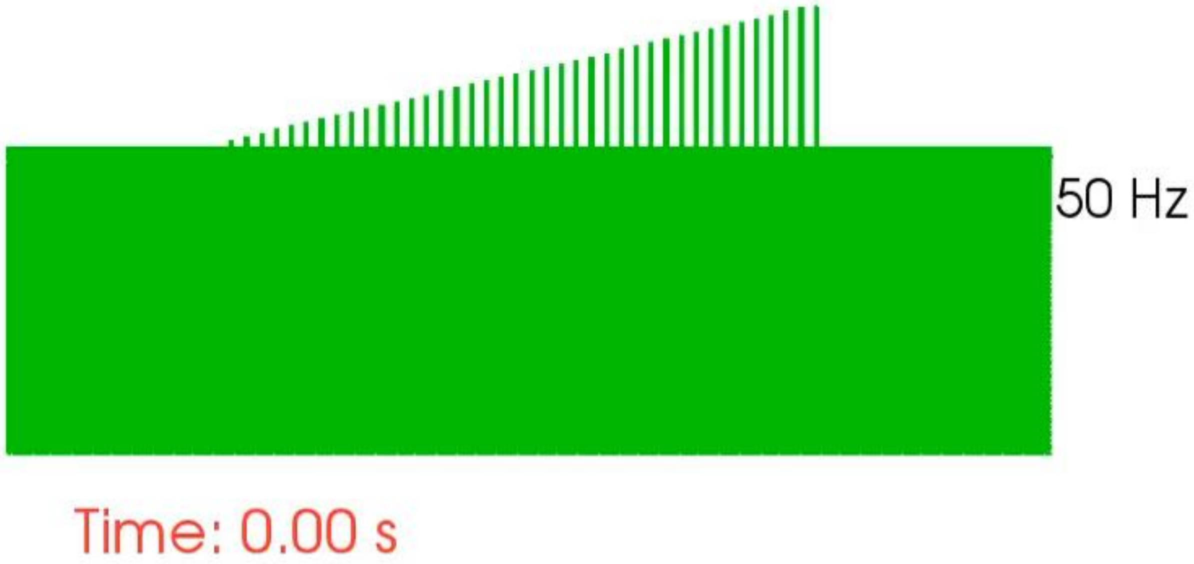
Acoustic rainbow trapping

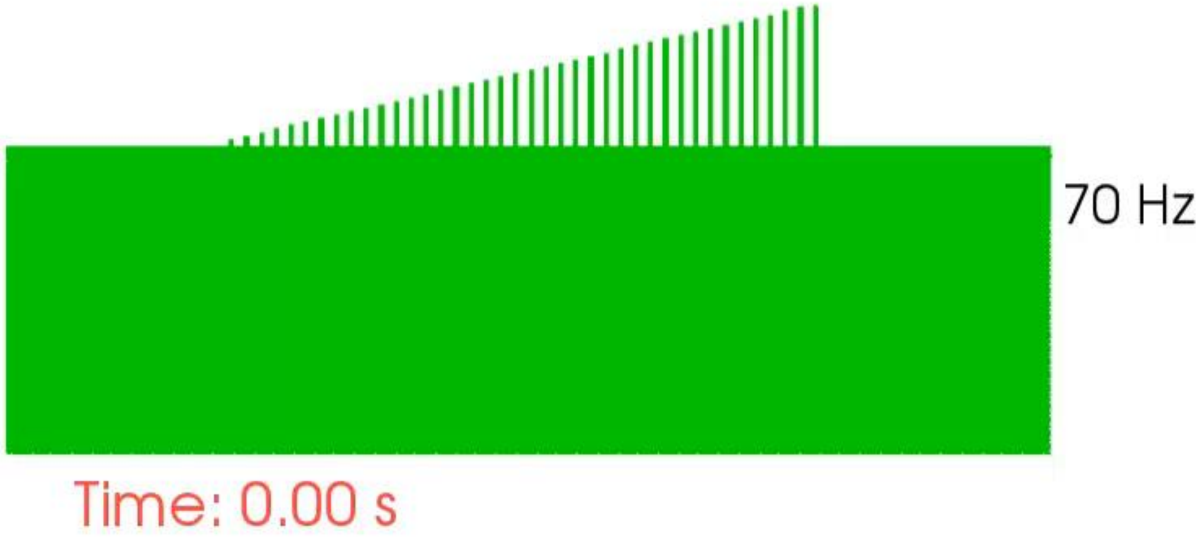
Jie Zhu[1], Yongyao Chen[2], Xuefeng Zhu[1,3], Francisco J. Garcia-Vidal[4], Xiaobo Yin[1], Weili Zhang[2] & Xiang Zhang[1]

70 Hz

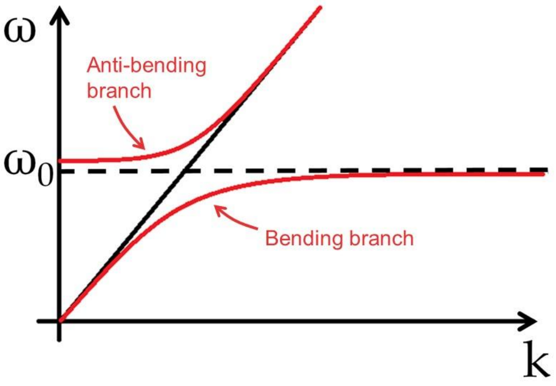


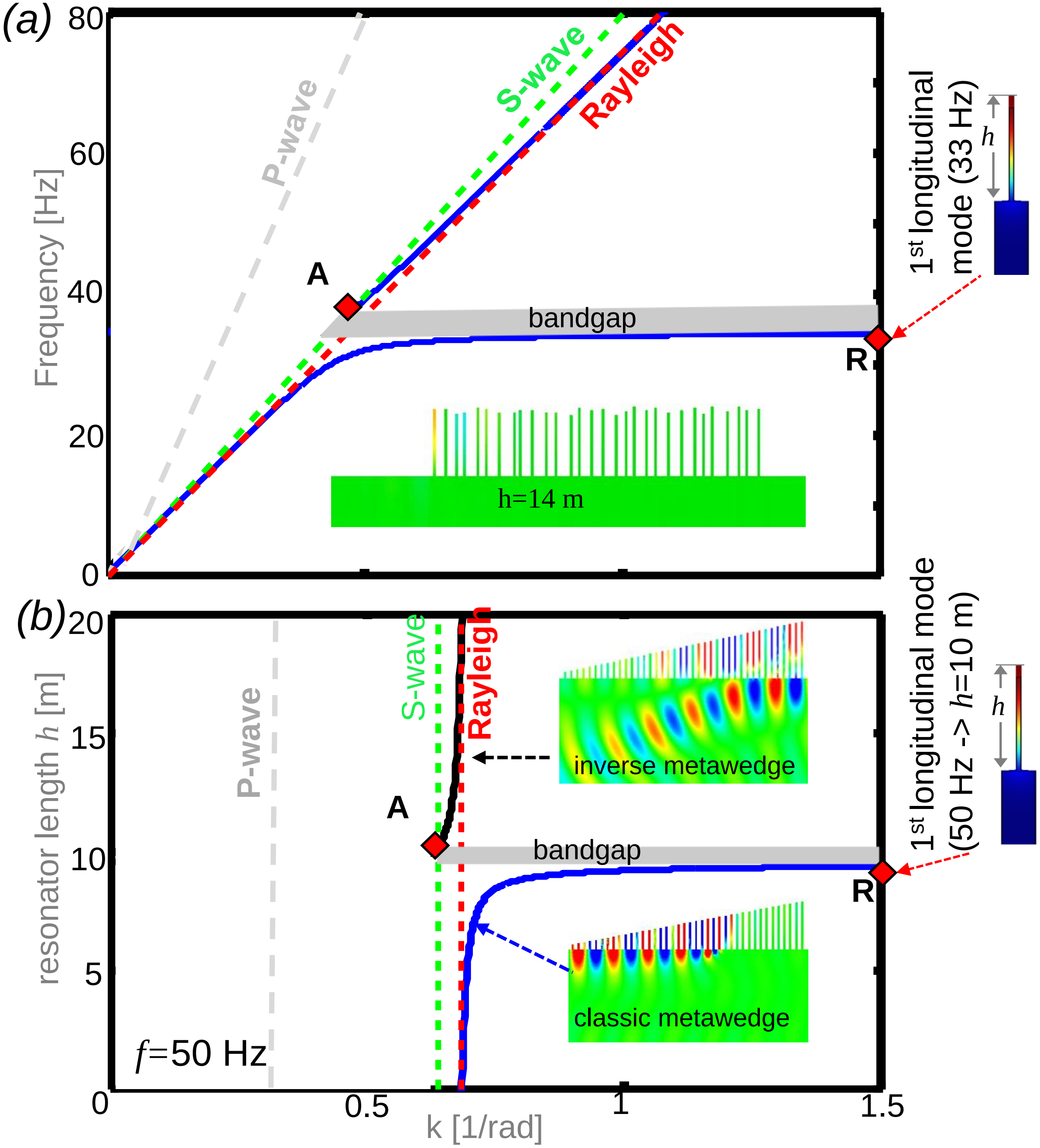
Trees with different height : The inverse wedge effect





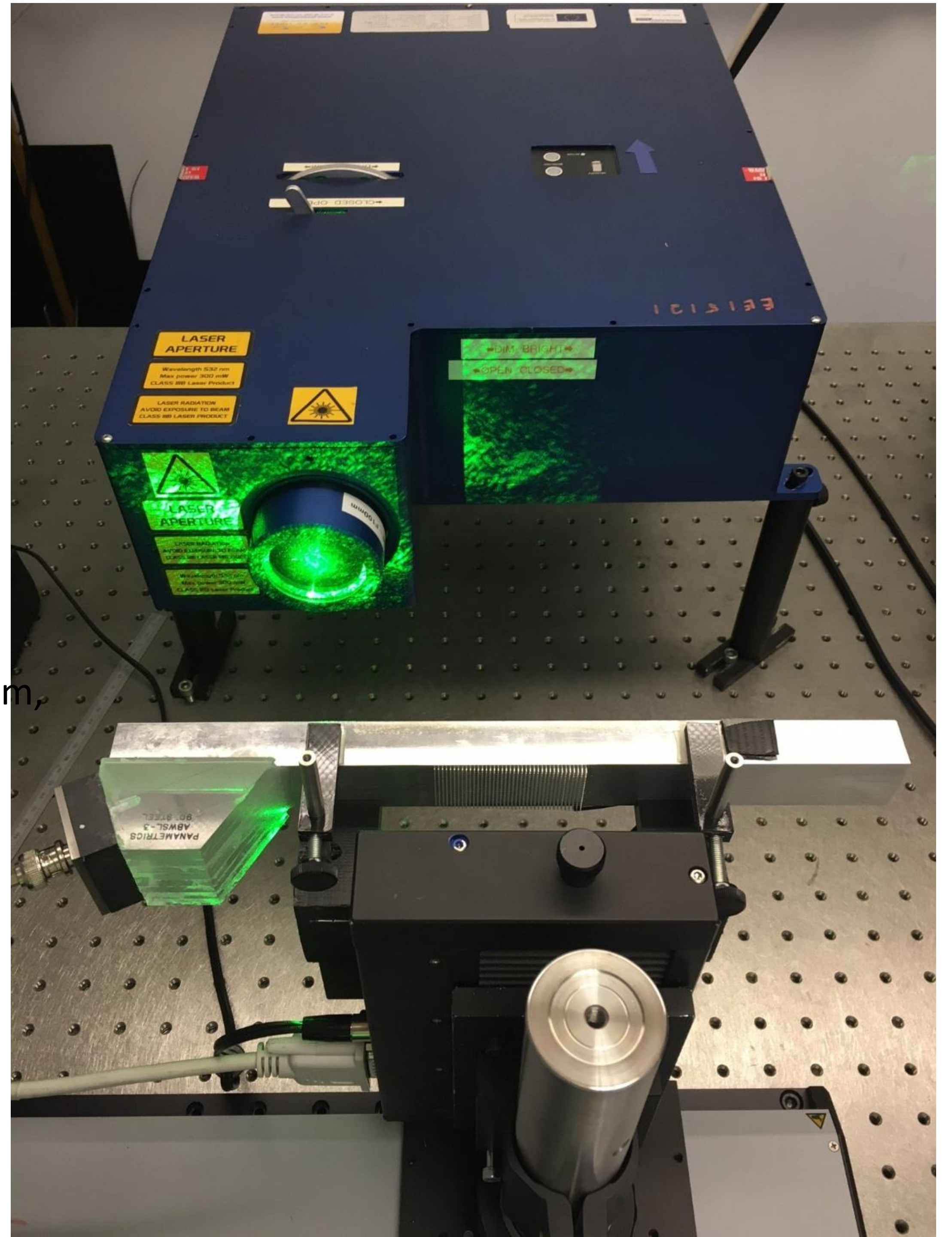
« acoustic » approach





Colombi et al., Scientific Reports, 2016

Experimental Demonstration of the Resonant Meta-Wedge at the Ultrasonic Scale (~500 kHz)

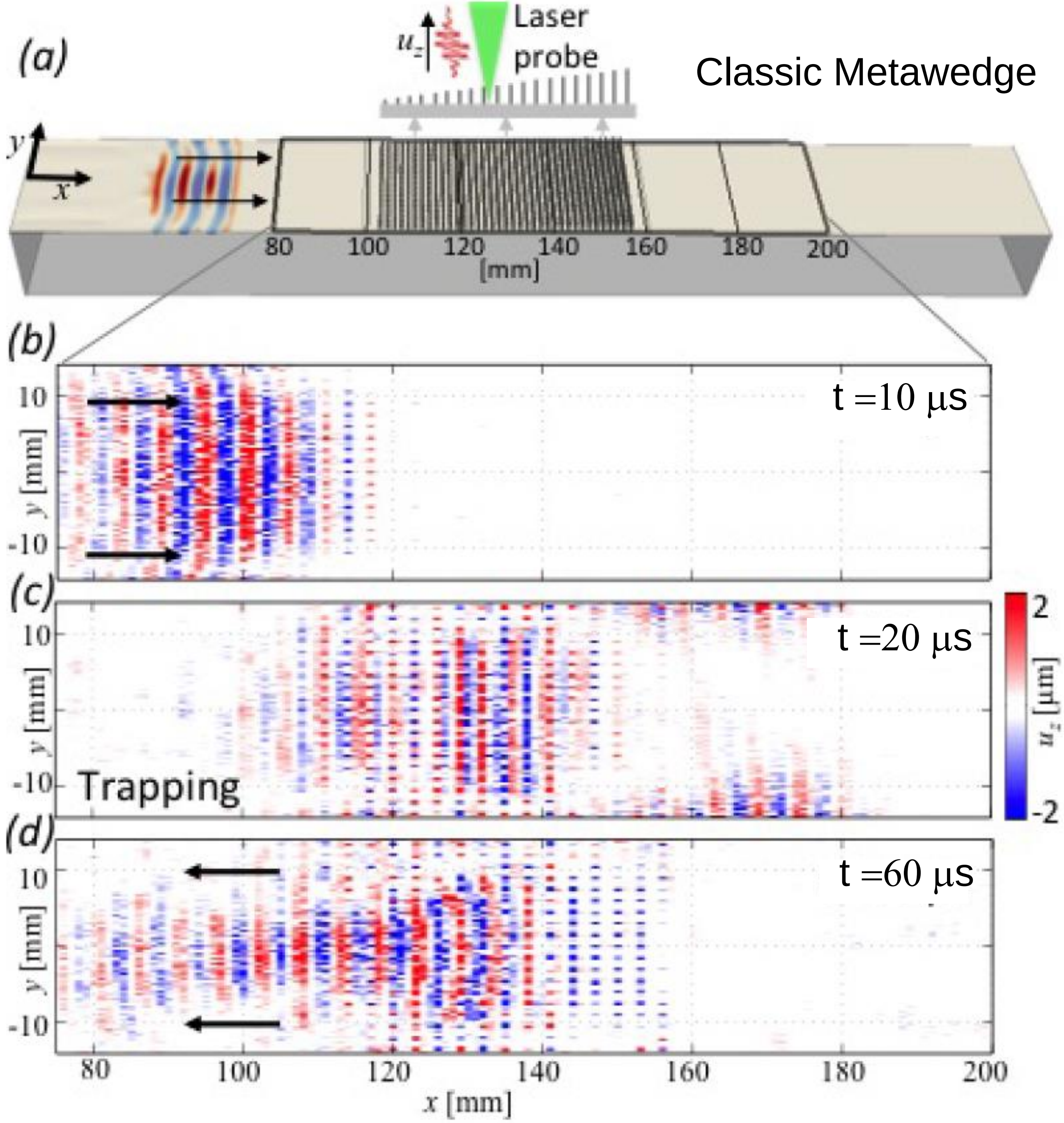


Matt Clark's group

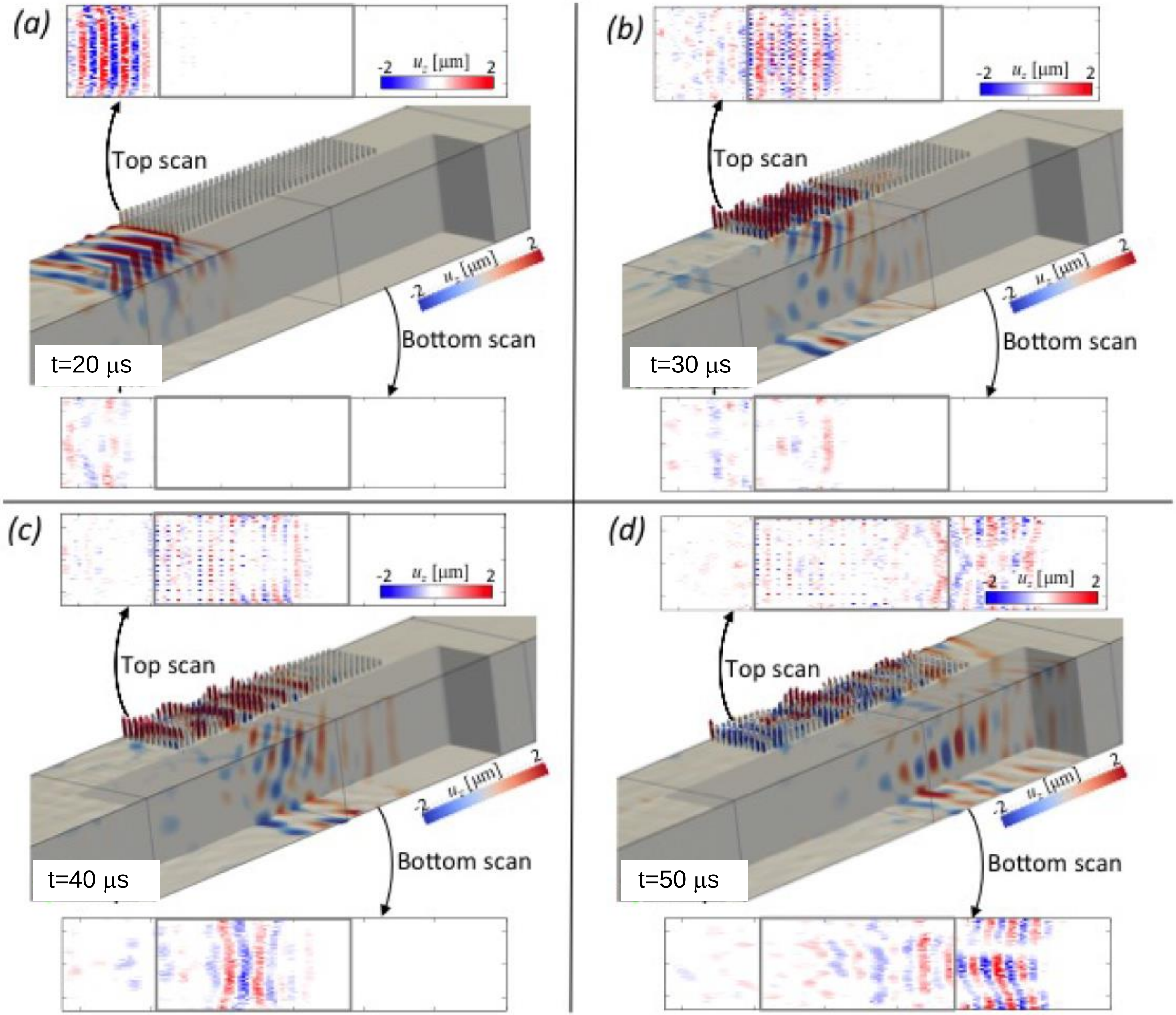
Applied Optics lab, University of Nottingham,
U.K.

Colombi et al., Scientific Reports, 2017

Classic Metawedge

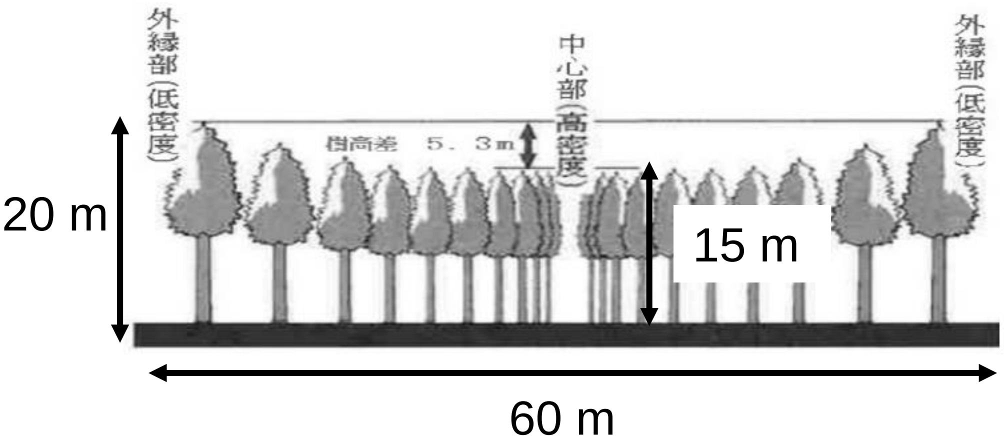


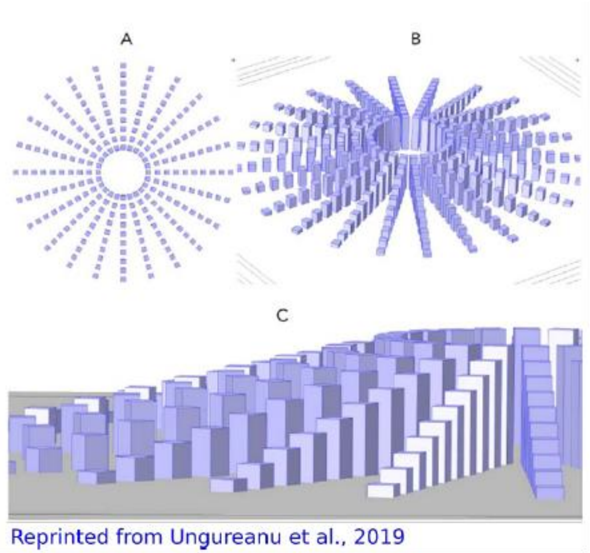
Inverse Meta-wedge



ANR MIYASAKI: The silent eyes of the forest (not yet funded)

Miyasaki forest, Japan

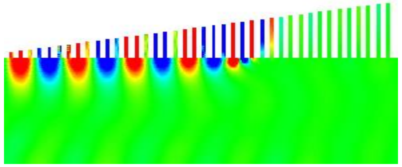




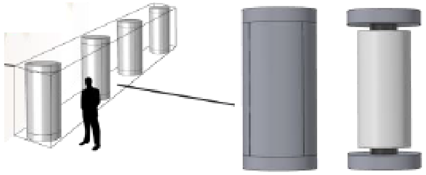
Reprinted from Ungureanu et al., 2019

Other Attempts with Seismic Metamaterials:

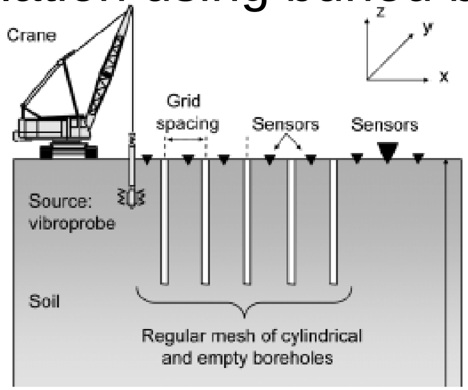
- The Metawedge configuration



- Seismic wave cancellation using buried resonators

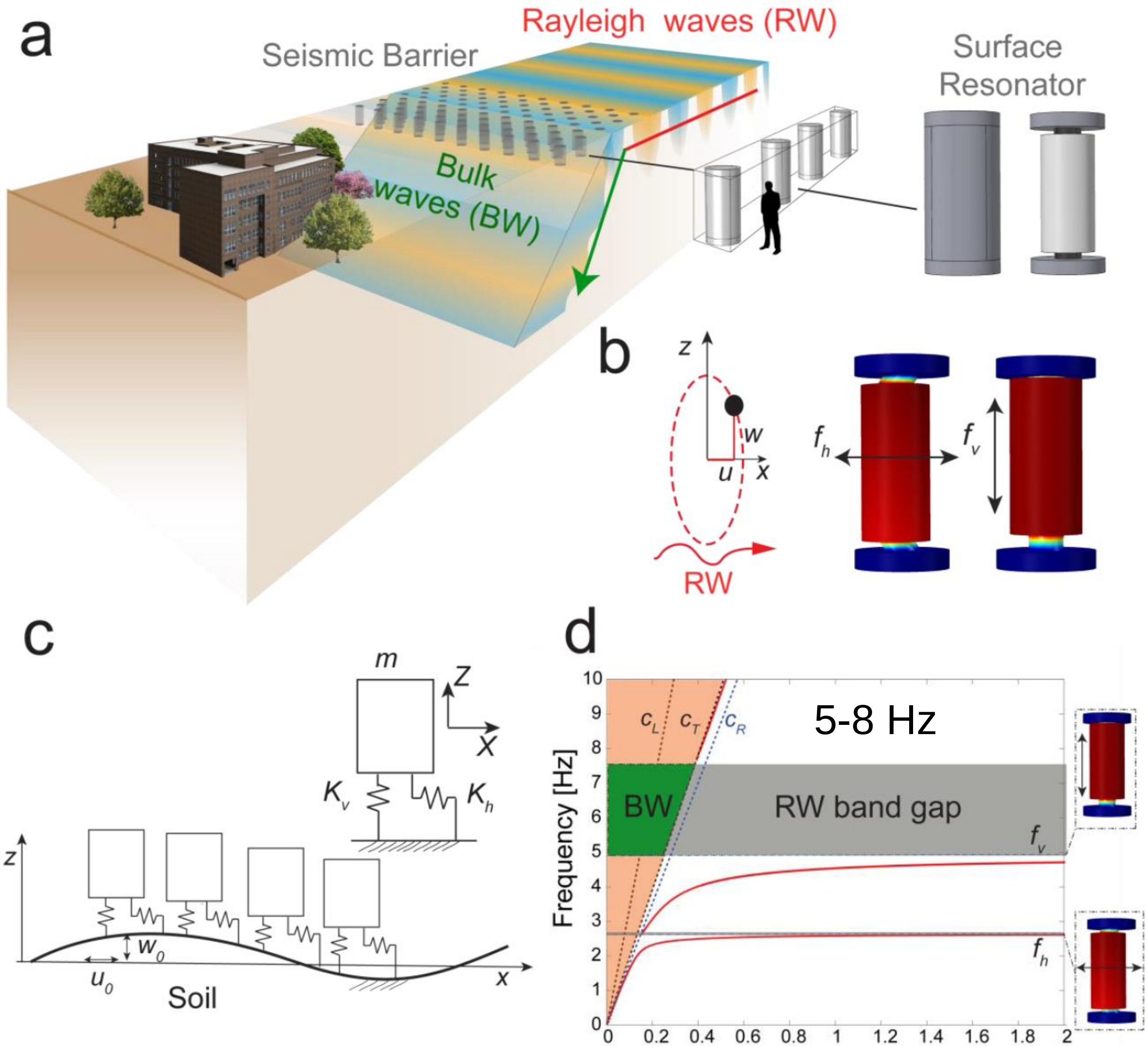


- Seismic wave cancellation using buried beams

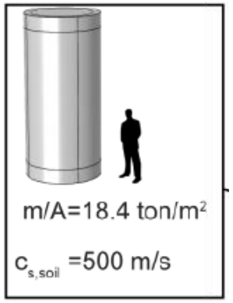


Engineered Metabarrier as Shield from Seismic Surface Waves (1)

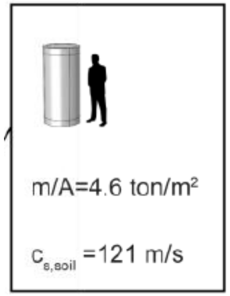
Palermo et al., Scientific Reports, 2017



5-8 Hz


m/A=18.4 ton/m²

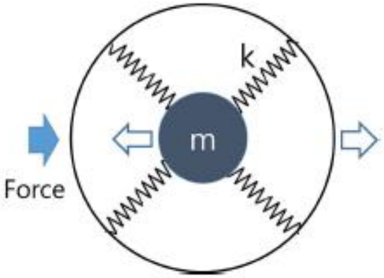
$c_{s,soil}$ =500 m/s

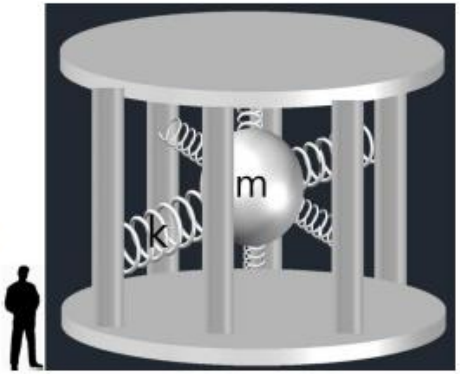

m/A=4.6 ton/m²

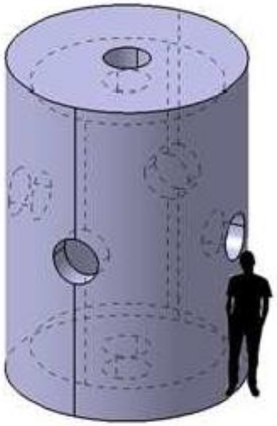
$c_{s,soil}$ =121 m/s

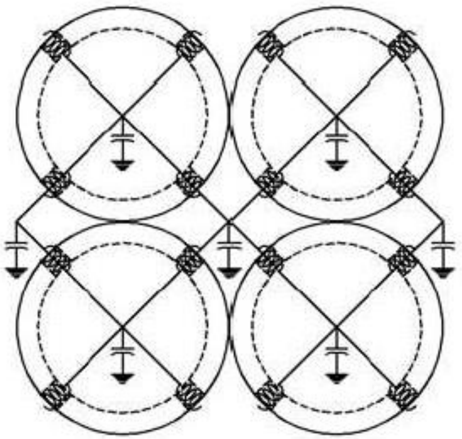
Engineered Metabarrier as Shield from Seismic Surface Waves (2)

m ~ 1000 kg









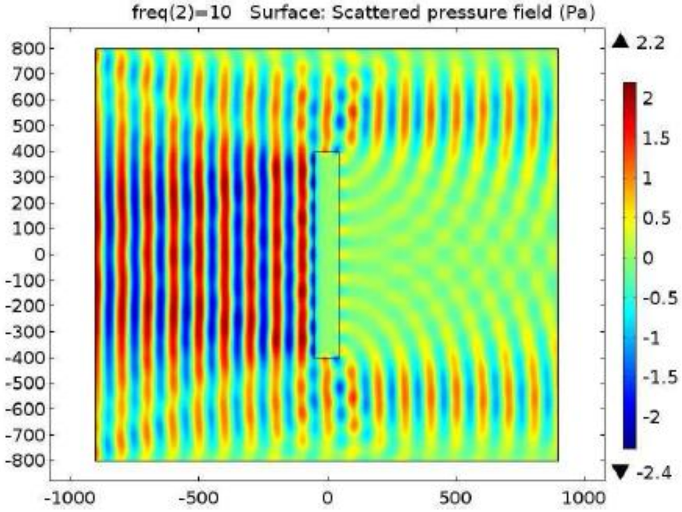
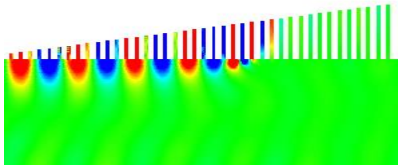


FIG. 3: Pressure distribution by a negative belt. Acoustic wave comes from the left side. Freq.= $10Hz$. The units are m.

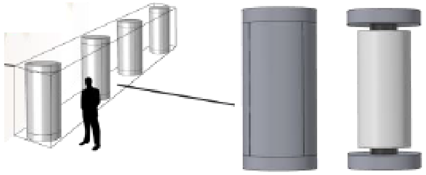
S-H Kim and M. Das, 2017

Other Attempts with Seismic Metamaterials:

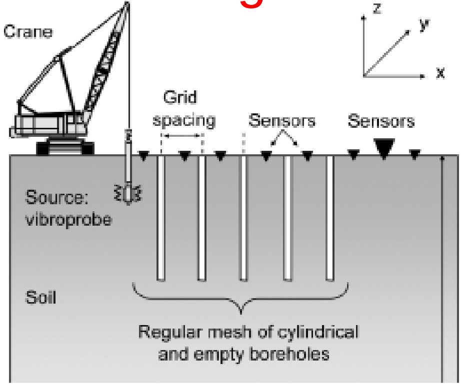
- The Metawedge configuration



- Seismic wave cancellation using buried resonators

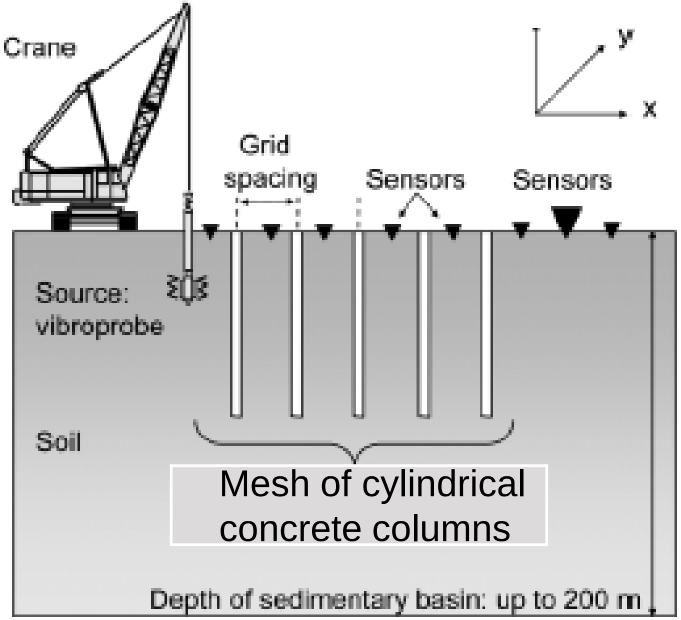


- Seismic wave cancellation using buried beams



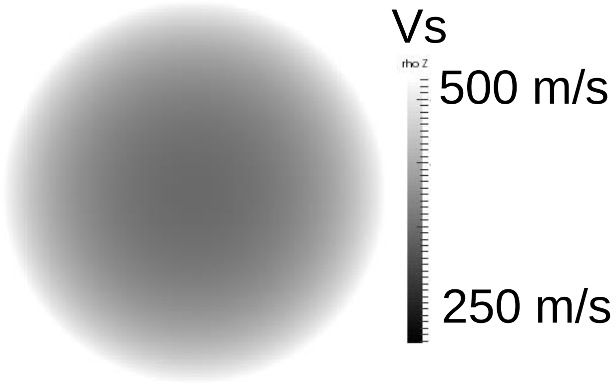
Soil Reinforcement using Buried Vertical Concrete Beams

Brule et al, PRL, 2014

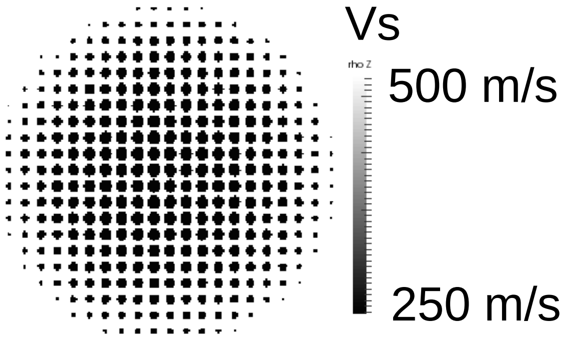


→ Local change of refraction index

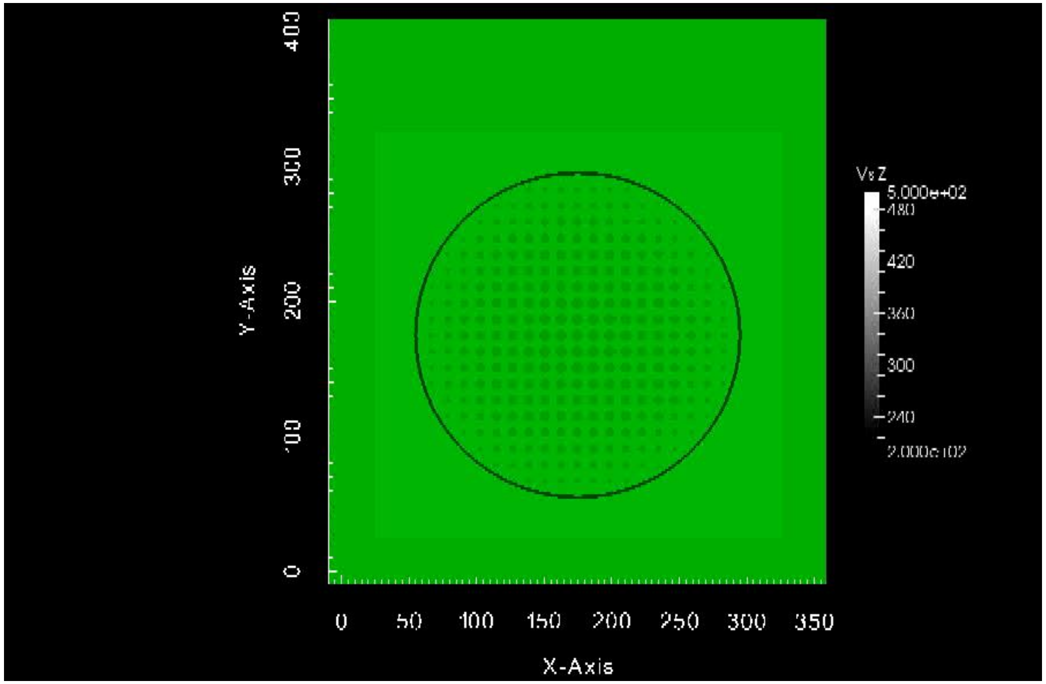
Luneberg Lens applied to Geophysics



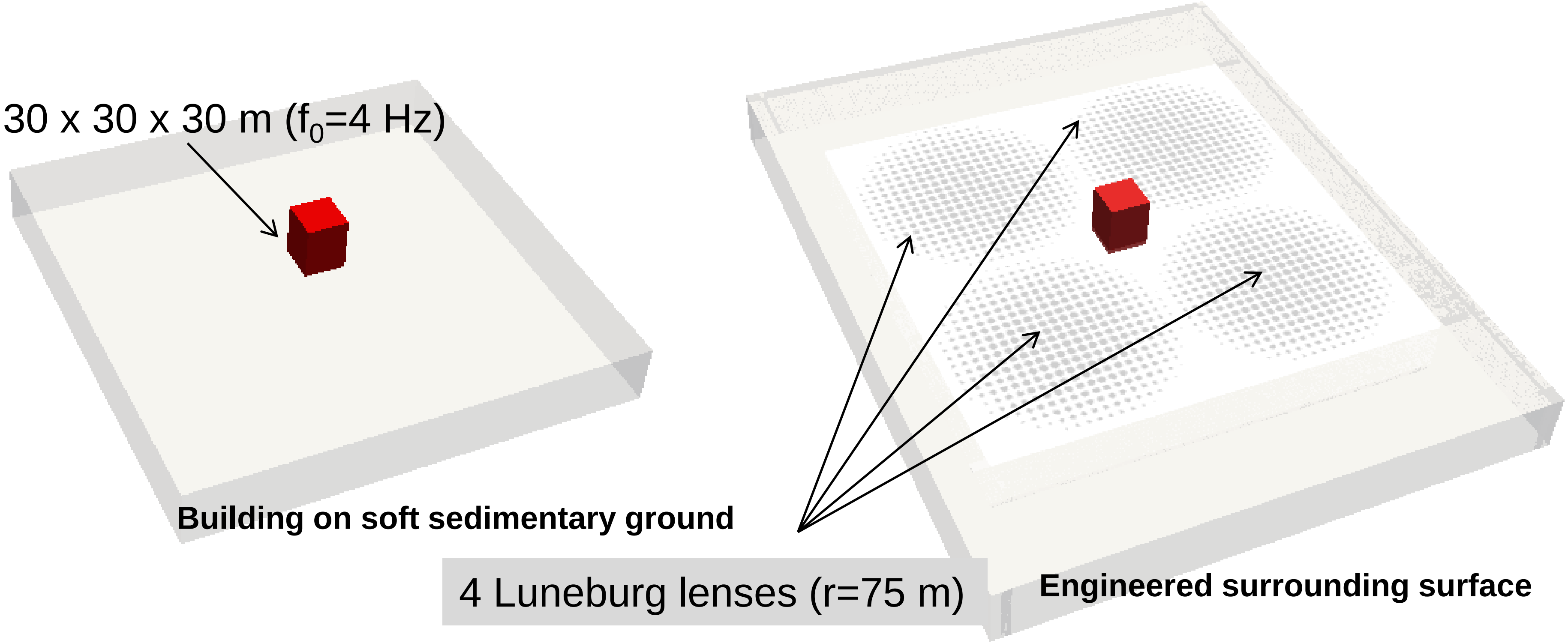
Continuous version



Discrete version



Application to Seismic Protection (1 – 5 Hz)



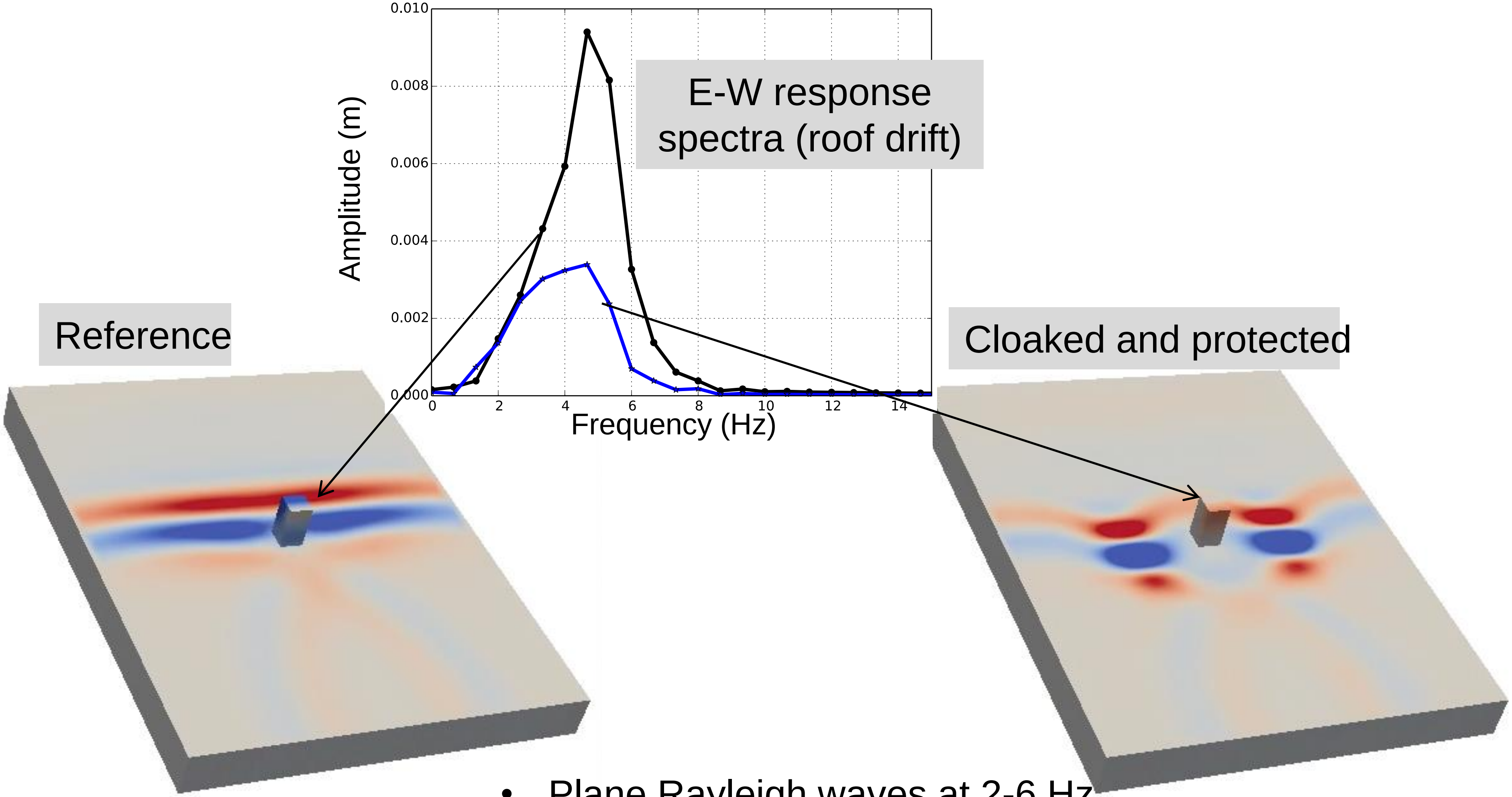
30 x 30 x 30 m (f_0=4 Hz)

Building on soft sedimentary ground

4 Luneburg lenses (r=75 m)

Engineered surrounding surface

Application to Seismic protection (1 – 5 Hz)



E-W response spectra (roof drift)

Reference

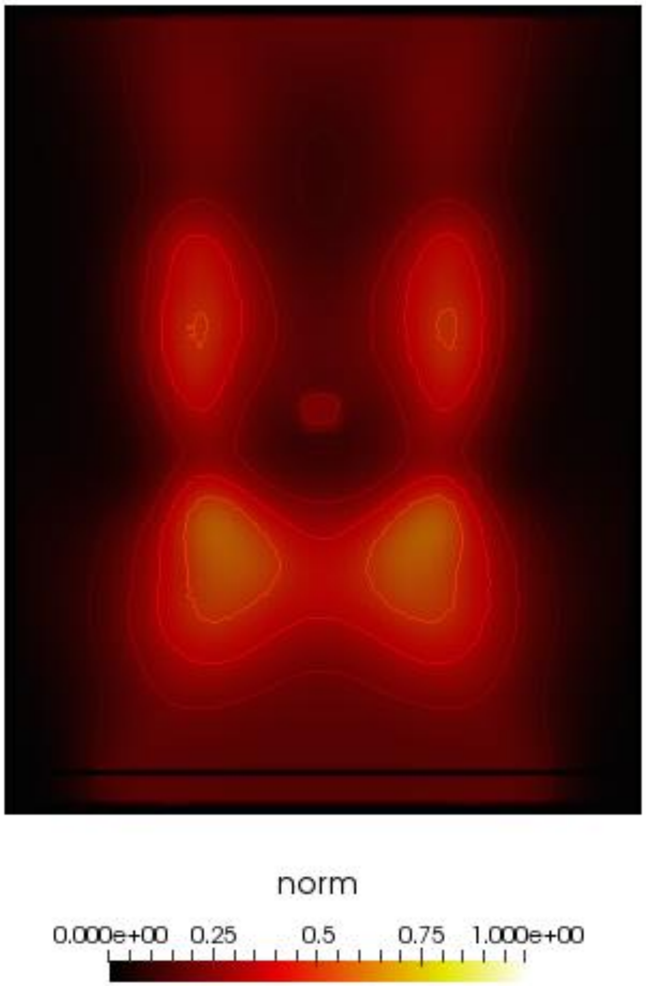
Cloaked and protected

- Plane Rayleigh waves at 2-6 Hz
- Soft sedimentary soil

Colombi et al., Scientific Reports, 2016

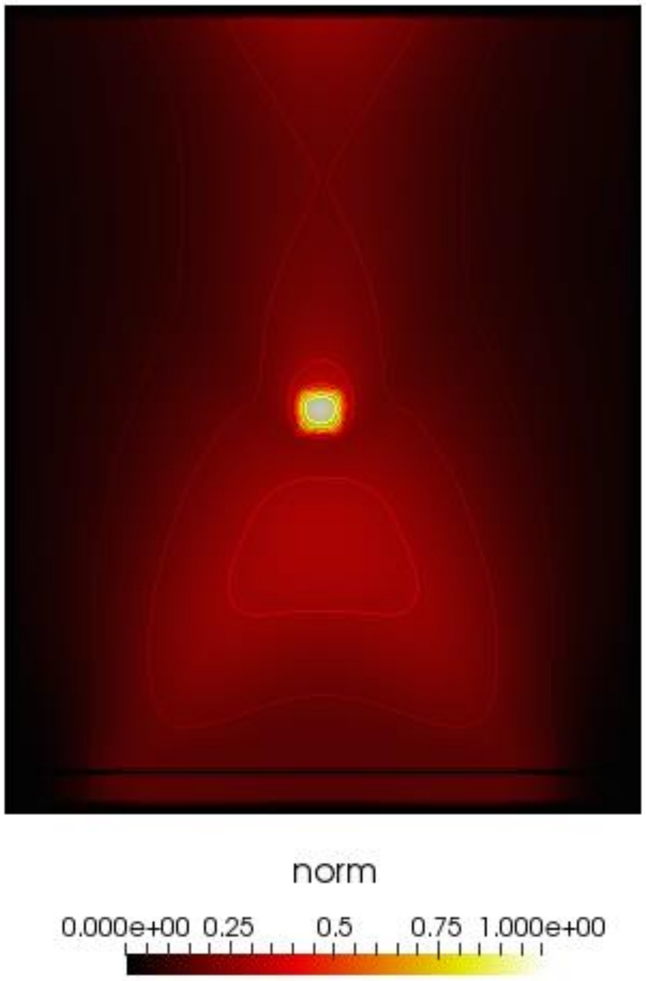
Application to Seismic protection (1 – 5 Hz)

Cloaked and protected



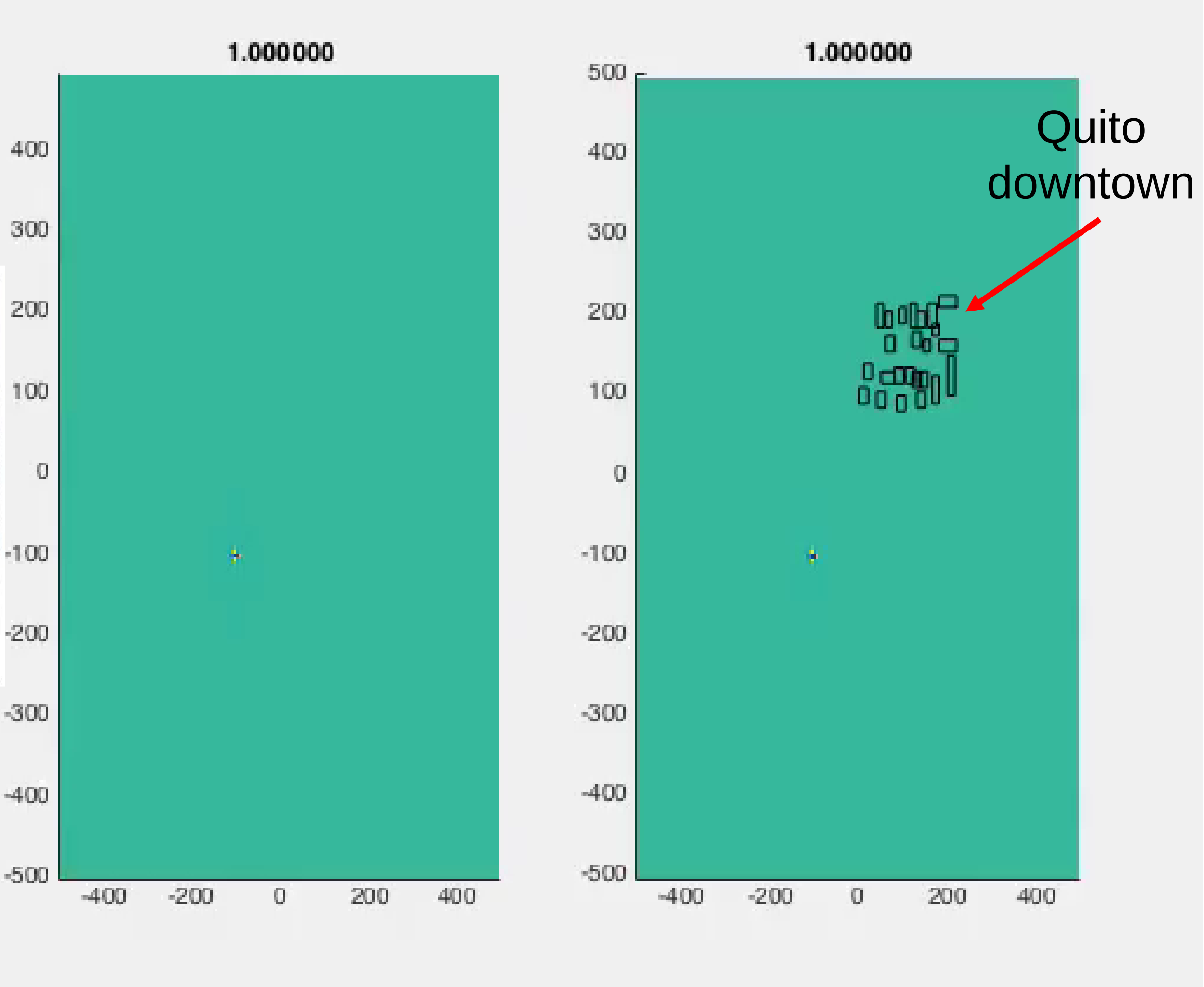
Energy distribution

Reference



Work for the Future

A City : Macroscopic Arrangement of Resonating Elements ?



Colombi et al., BSSA, 2017

RAJOUTER DISTANCE SUR L’AXE VERTICAL

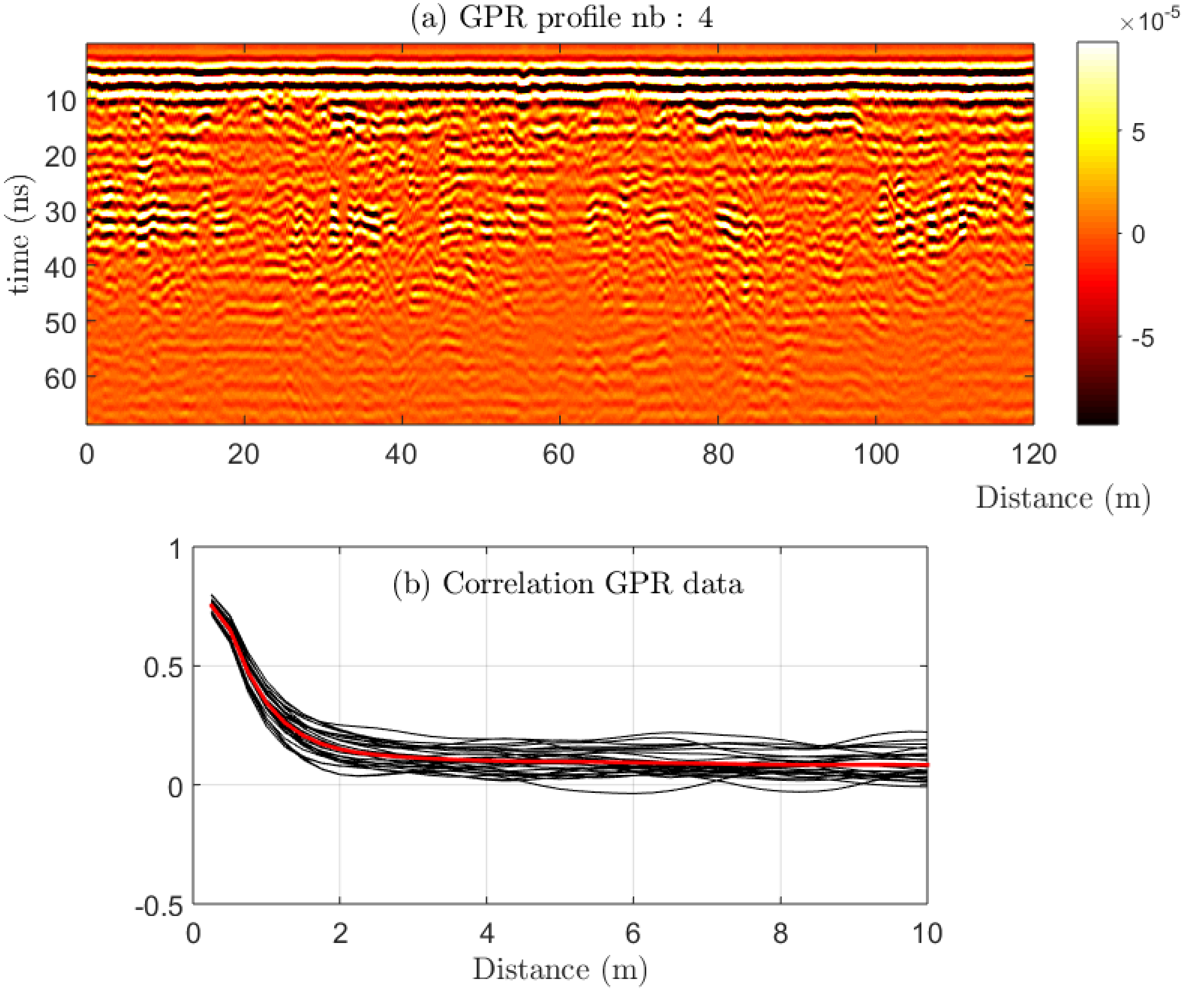


Fig. 2

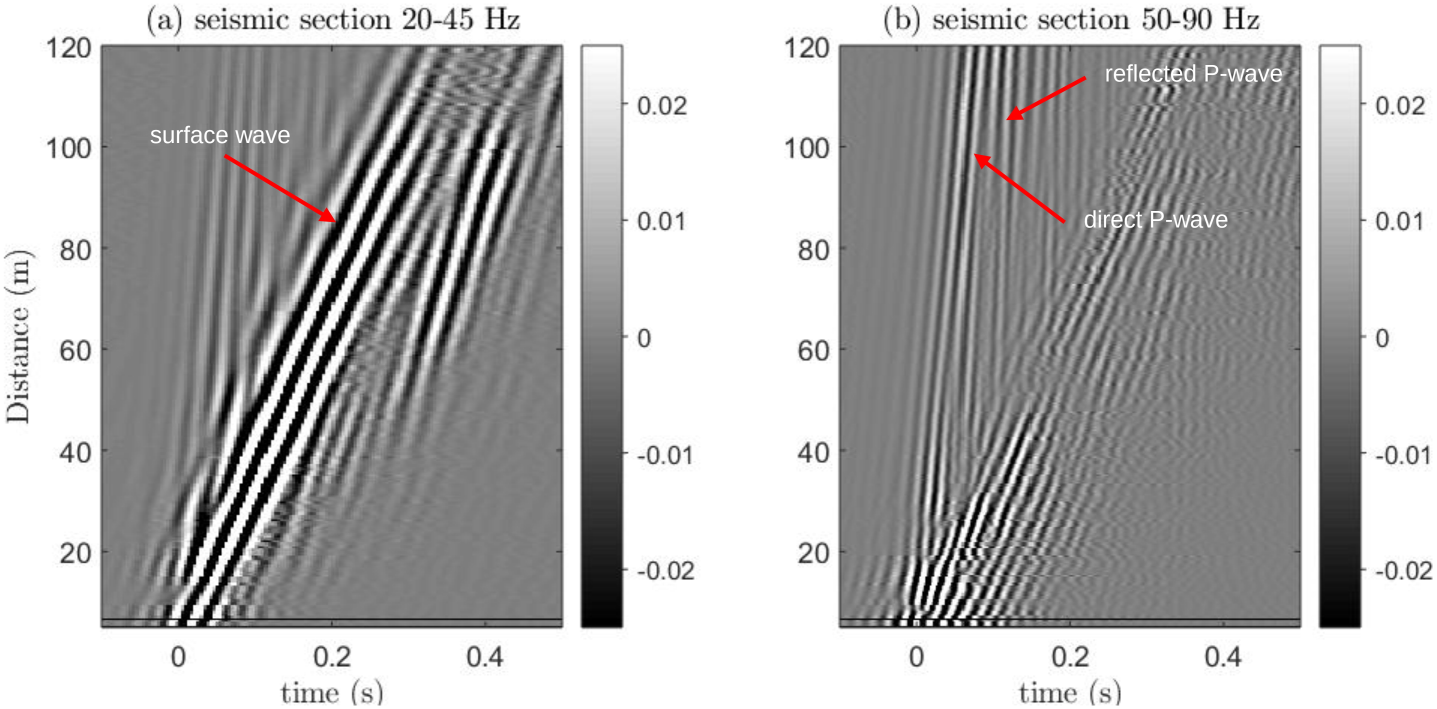

(a) seismic section 20-45 Hz
(b) seismic section 50-90 Hz
Distance (m)
time (s)
surface wave
reflected P-wave
direct P-wave
120
100
80
60
40
20
0
0.2
0.4
0.02
0.01
0
-0.01
-0.02

Fig. 3

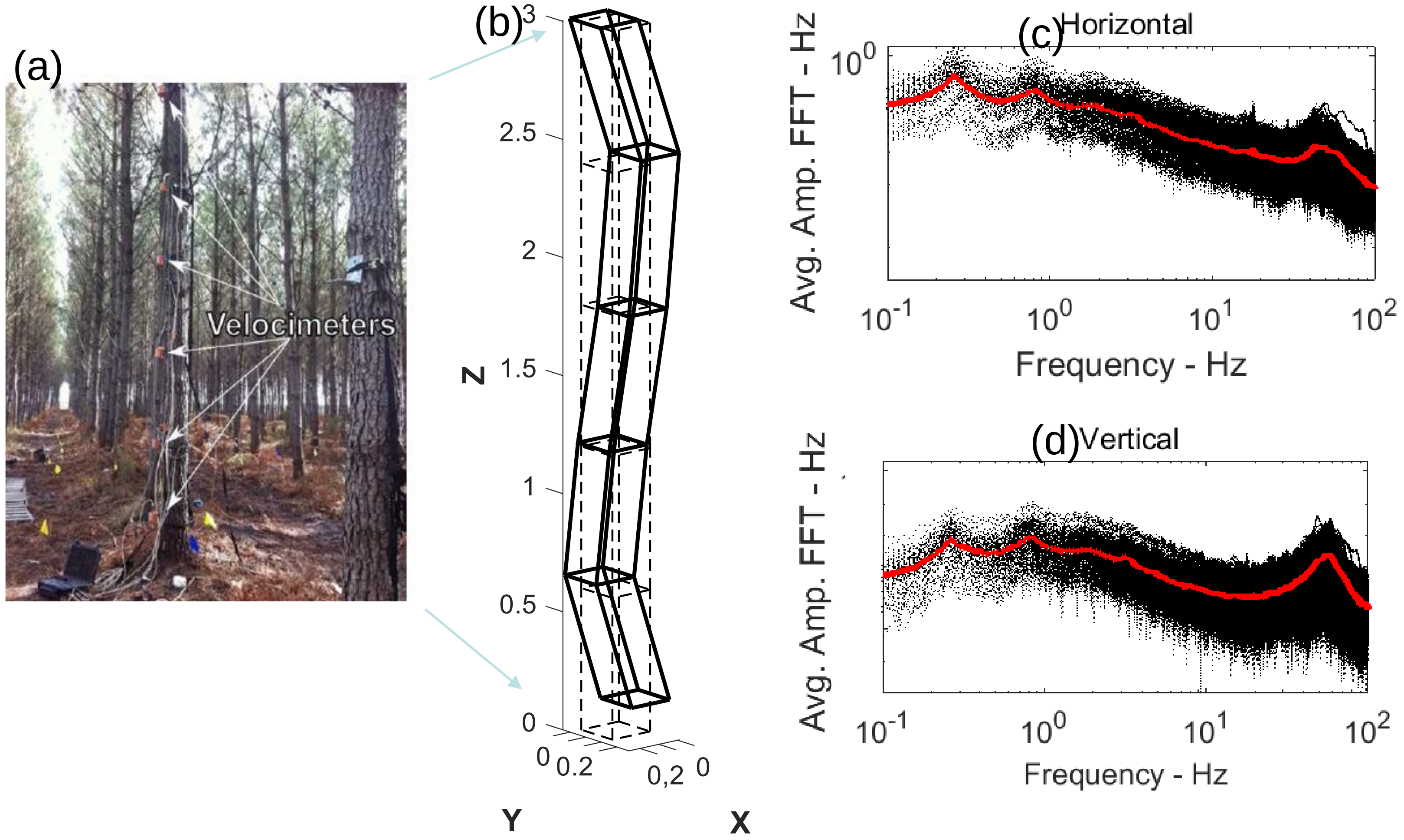
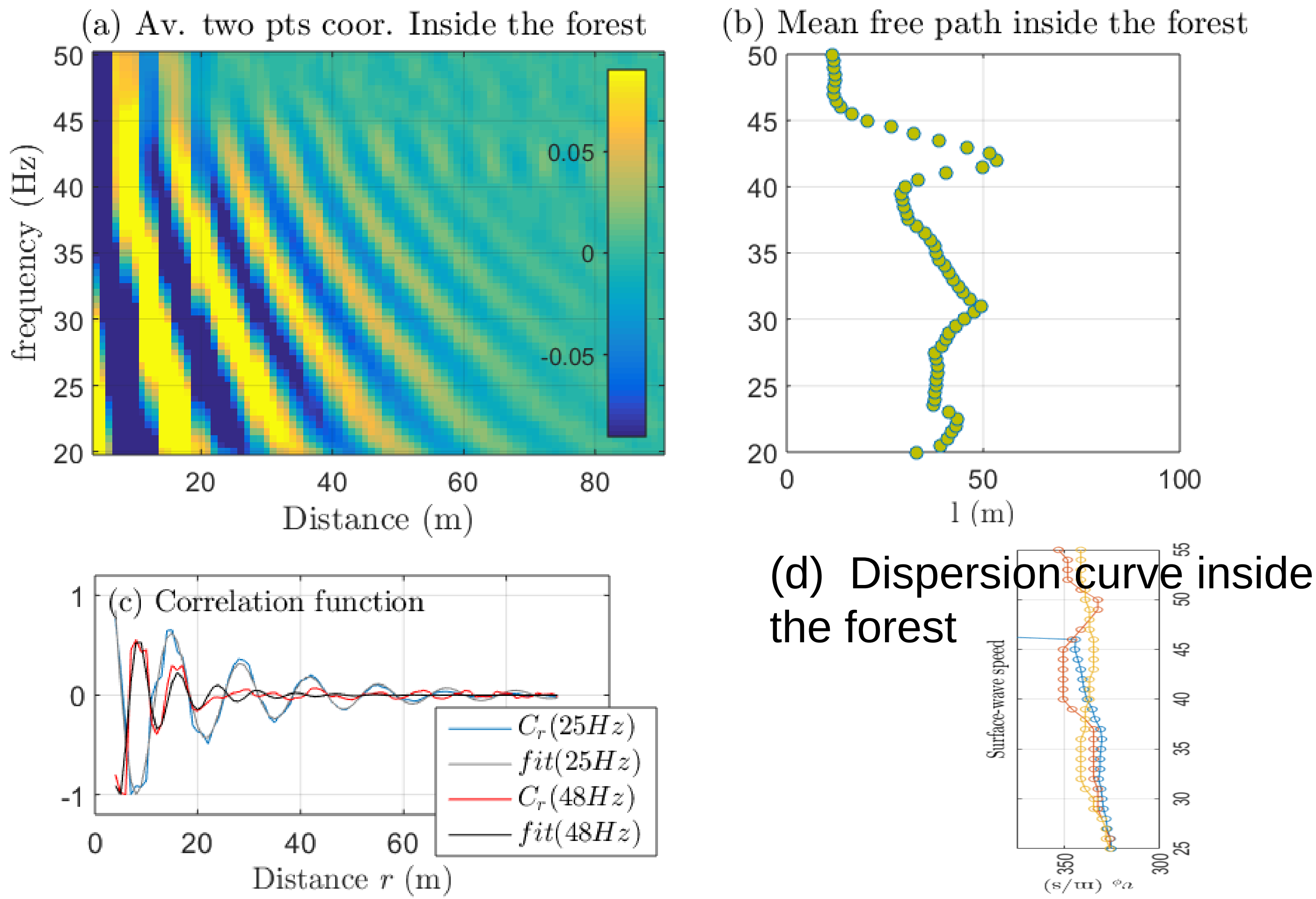

(a)
Velocimeters
(b)
3
2.5
2
Z
1.5
1
0.5
0
0
0.2
0,2
0
Y
X
(c) Horizontal
Avg. Amp. FFT - Hz
10^0
10^{-1}
10^0
10^1
10^2
Frequency - Hz
(d) Vertical
Avg. Amp. FFT - Hz
10^{-1}
10^0
10^1
10^2
Frequency - Hz

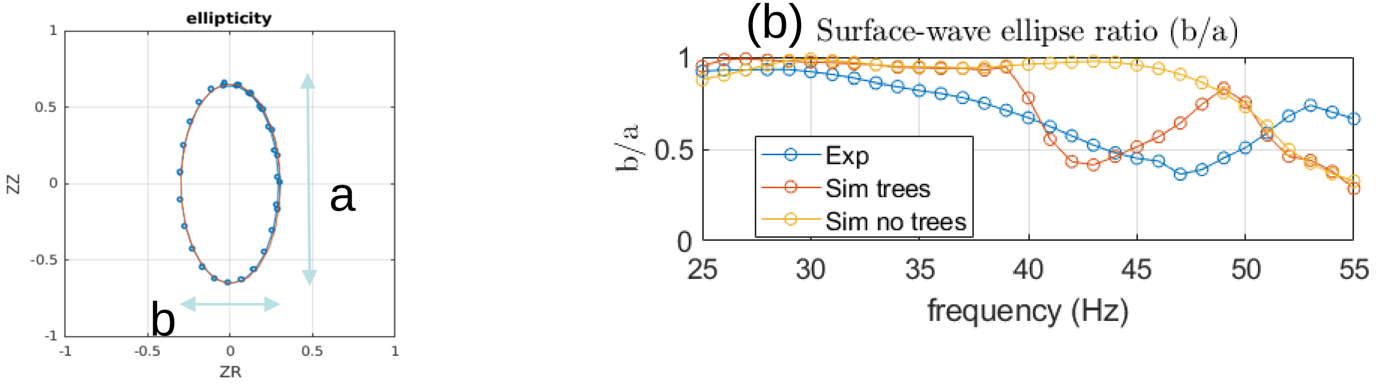
Fig. 5



(d) Dispersion curve inside the forest

Fig. 7

Fig. 8


(a) Particle motion @ 45 Hz

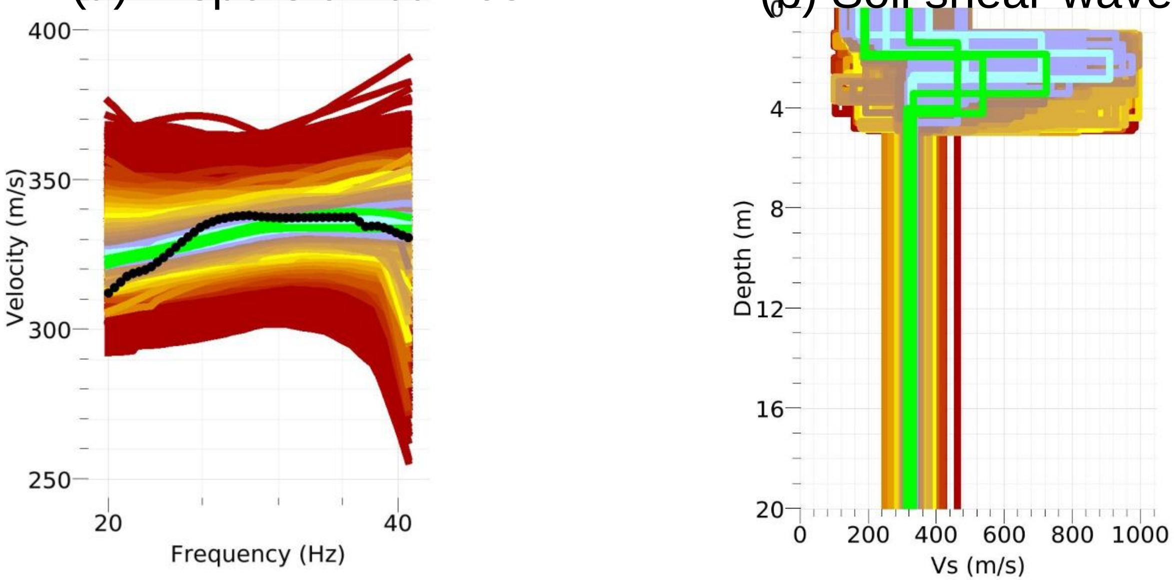
(b) Surface-wave ellipse ratio (b/a)

Fig. 8

Fig. 9

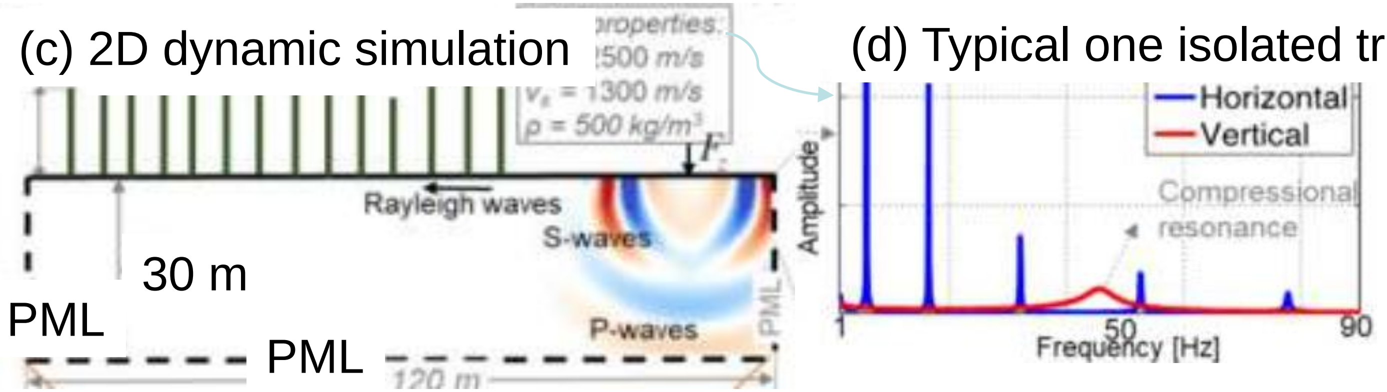
(a) Dispersion curves

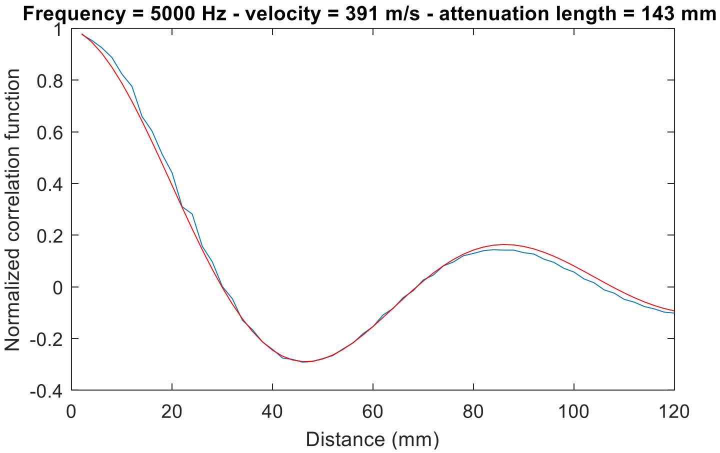
(b) Soil shear-wave speed



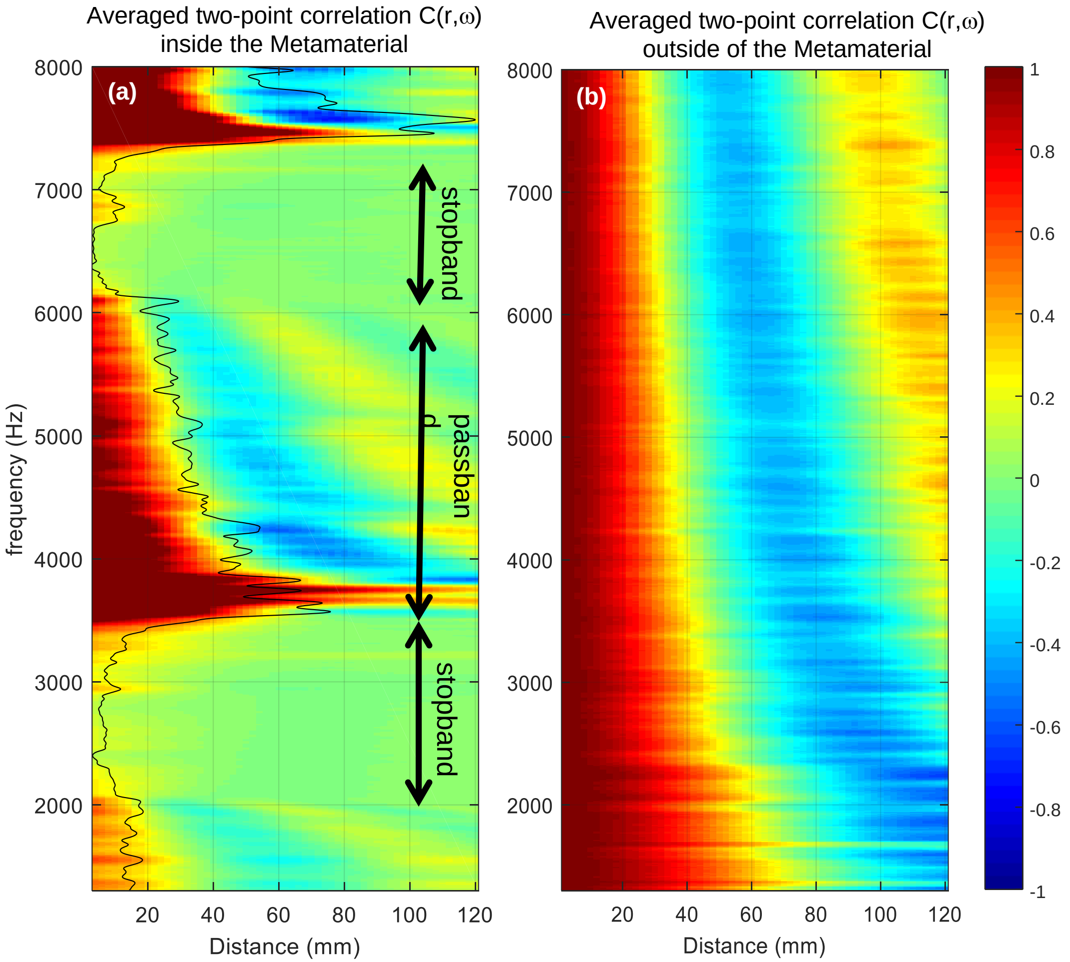
(c) 2D dynamic simulation

(d) Typical one isolated tree response



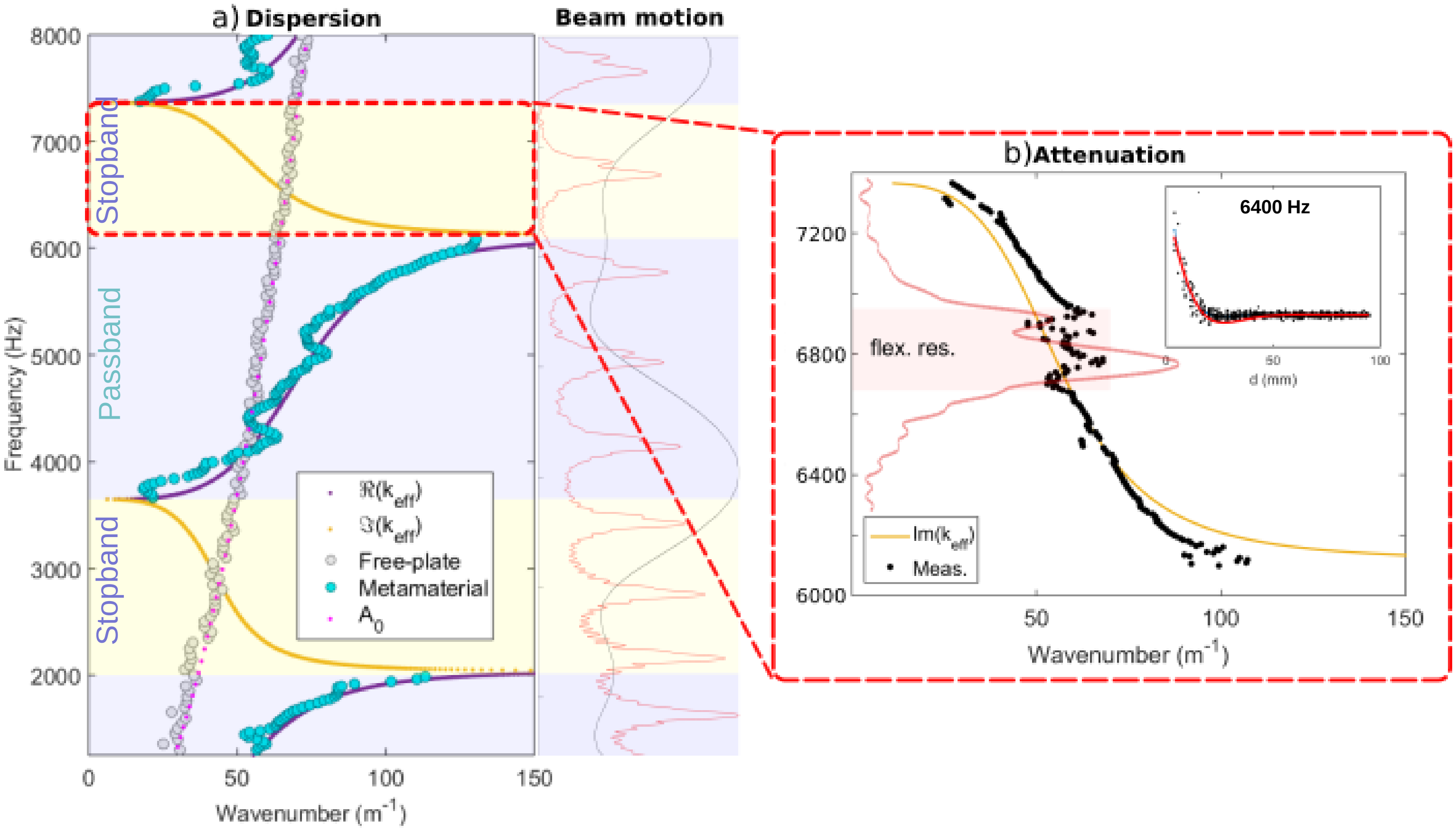


Frequency = 5000 Hz - velocity = 391 m/s - attenuation length = 143 mm



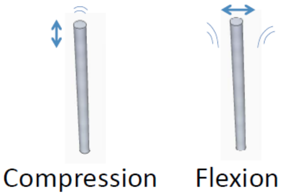
Averaged two-point correlation C(r,ω)
inside the Metamaterial

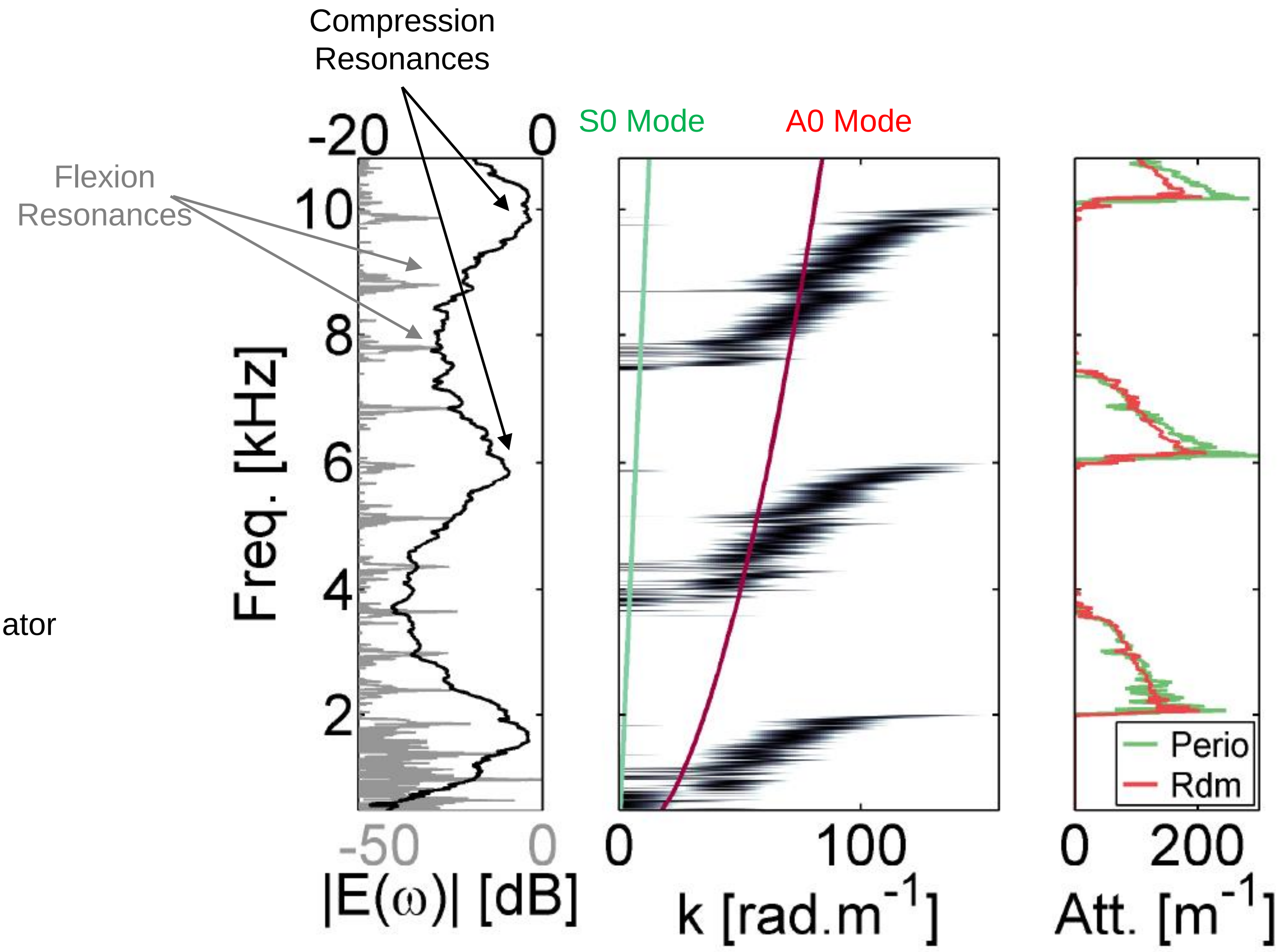
Averaged two-point correlation C(r,ω)
outside of the Metamaterial


a) Dispersion
Beam motion
8000
7000
6000
5000
4000
3000
2000
Frequency (Hz)
Stopband
Passband
Stopband
ℜ(k_eff)
ℑ(k_eff)
Free-plate
Metamaterial
A_0
0
50
100
150
Wavenumber (m^-1)
b) Attenuation
7200
6800
6400
6000
flex. res.
6400 Hz
0
50
100
d (mm)
Im(k_eff)
Meas.
50
100
150
Wavenumber (m^-1)

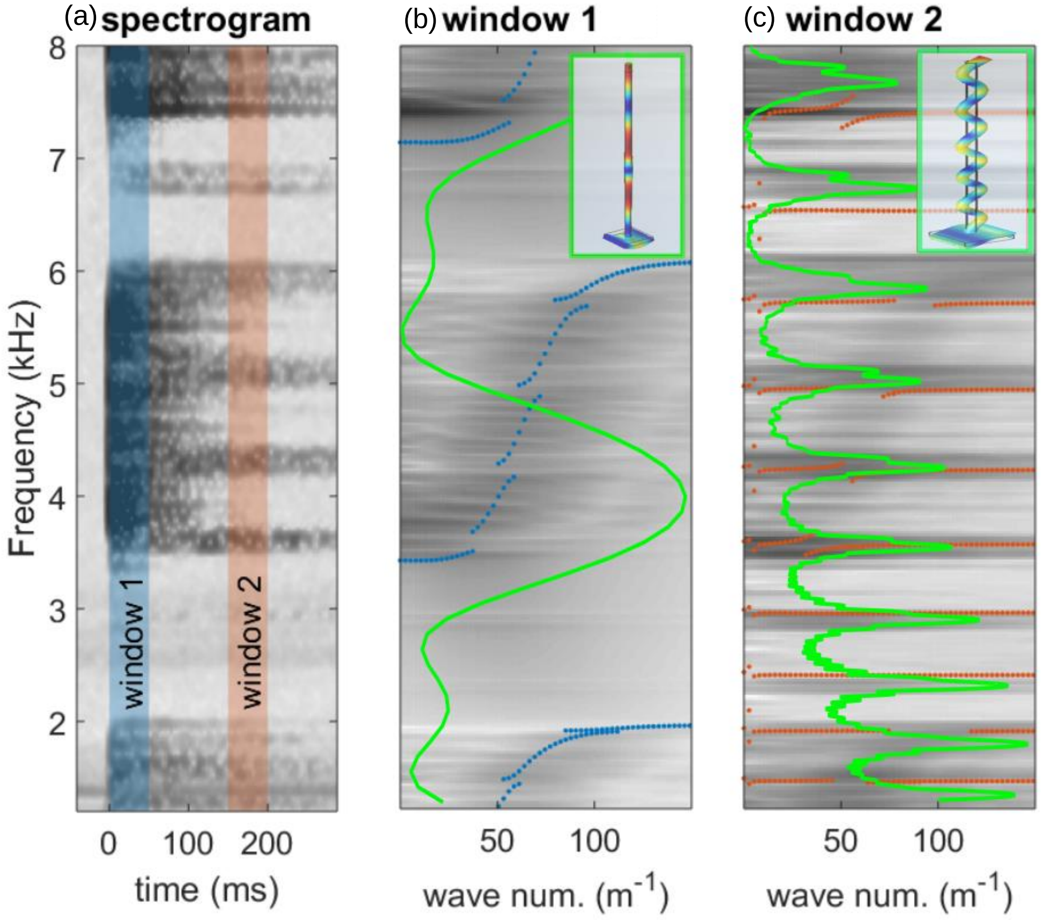
Metamaterial description through Dispersion relation

One Single Resonator





Rupin et al., PRL, 2014


(a) spectrogram
(b) window 1
(c) window 2
Frequency (kHz)
8
7
6
5
4
3
2
window 1
window 2
0
100
200
time (ms)
50
100
wave num. (m^{-1})
50
100
wave num. (m^{-1})