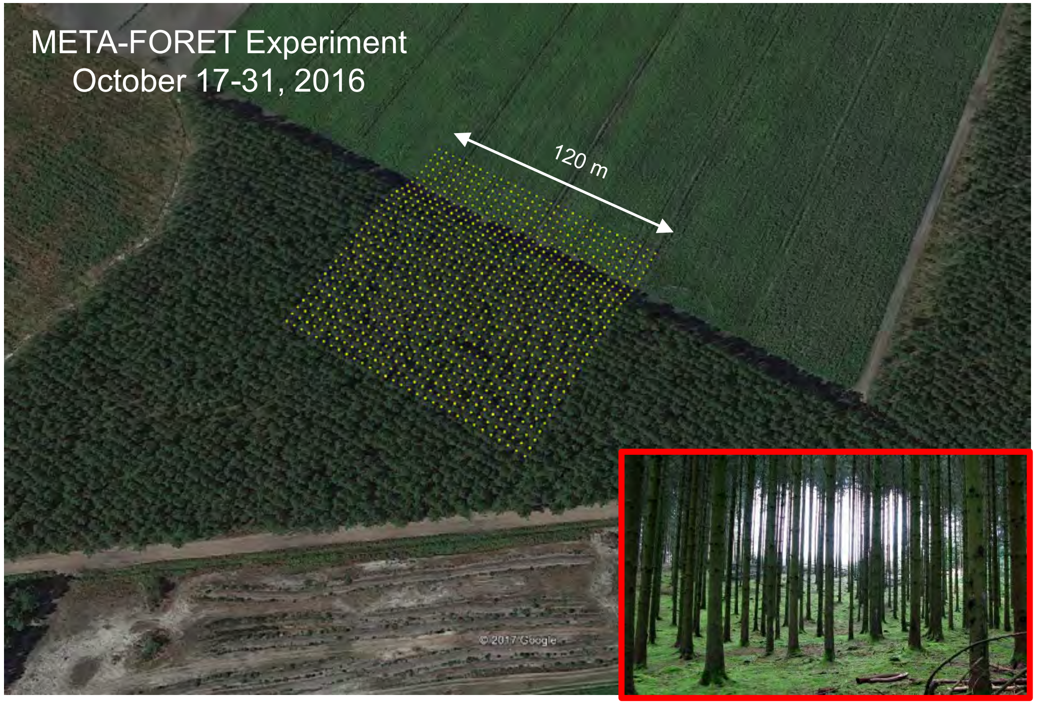
# New Trends Towards Seismic Metamaterials

**Philippe Roux**

ISTerre, Université Grenoble-Alpes, CNRS

*Journée d'Acoustique de l'IEMN*



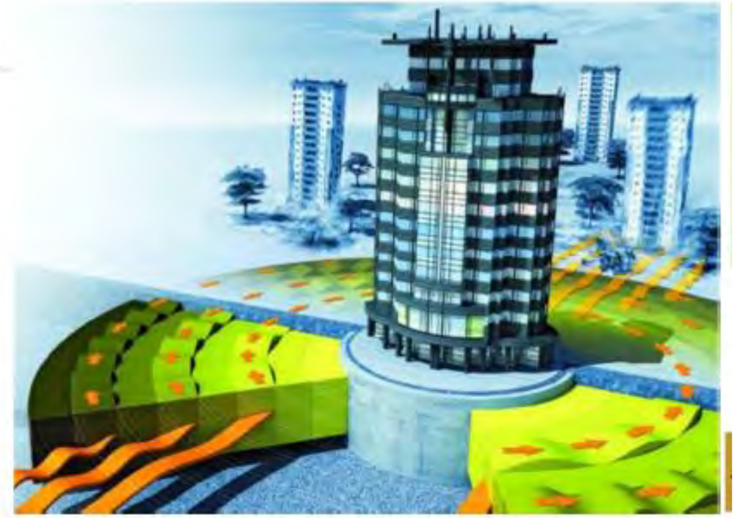
*In collaboration with M. Rupin, G. Lerosey, F. Lemoult,* ***Institut Langevin, Paris*** *& D.J. Colquitt, A. Colombi, R. Craster,* ***Imperial College, London*** *& S. Guénneau,* ***Institut Fresnel, Marseille*** *& E.G. Williams,* ***Naval Research Lab, Washington DC &*** *W. A. Kuperman****, Scripps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

# Earthquake Damages : High Social & Human impact

Taiwan (1999)

**Two possibilities:**

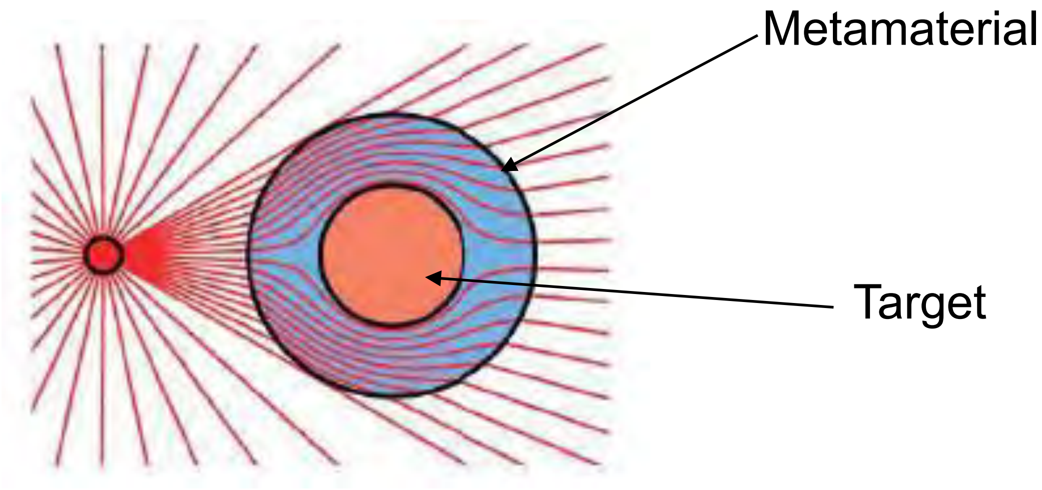
- **Predicting major seismic events** : dense seismic arrays and continuous ambient noise
- **Preventing damages from seismic events :** Control of seismic waves with seismic metamaterial (1 Hz - 5 Hz)



Infographie Popular Science Magazine (2009)

S. Guenneau, Institut Fresnel, Marseille

# Concept : Manipulating the Wavefield (1)



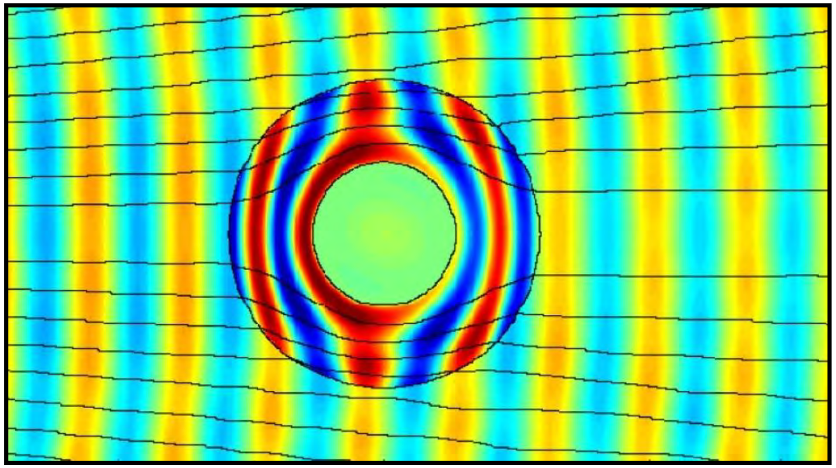
WIKIPEDIA

**Metamaterials** are artificial materials engineered to have properties that have not yet been found in nature.

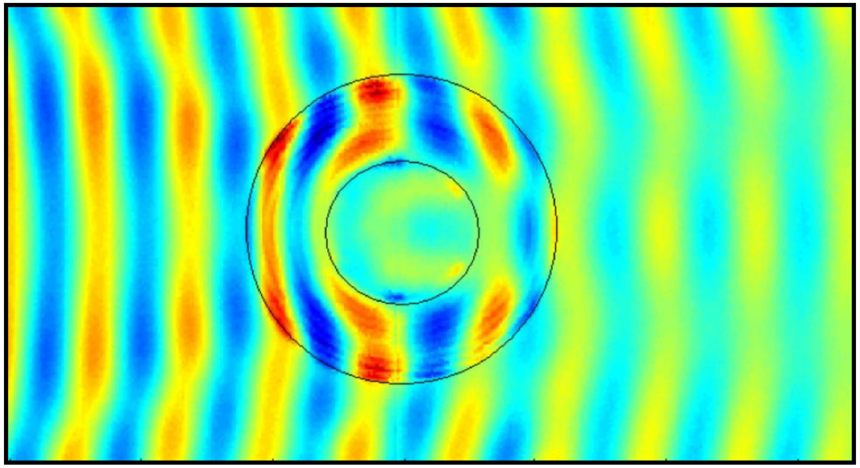
**! Hot Topic ! : >** 70 « Science Magazine » papers since 2001

# Concept : Manipulating the Wavefield (2)

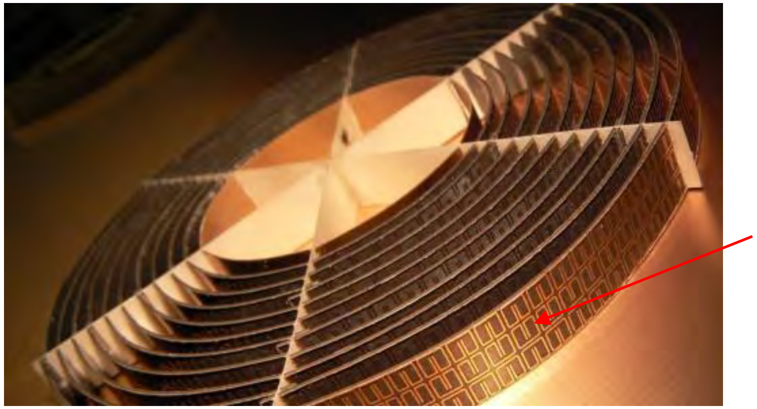
## Electromagnetic waves



Simulation



Experiment



*Schurig et al., Science (2006)*

WIKIPEDIA

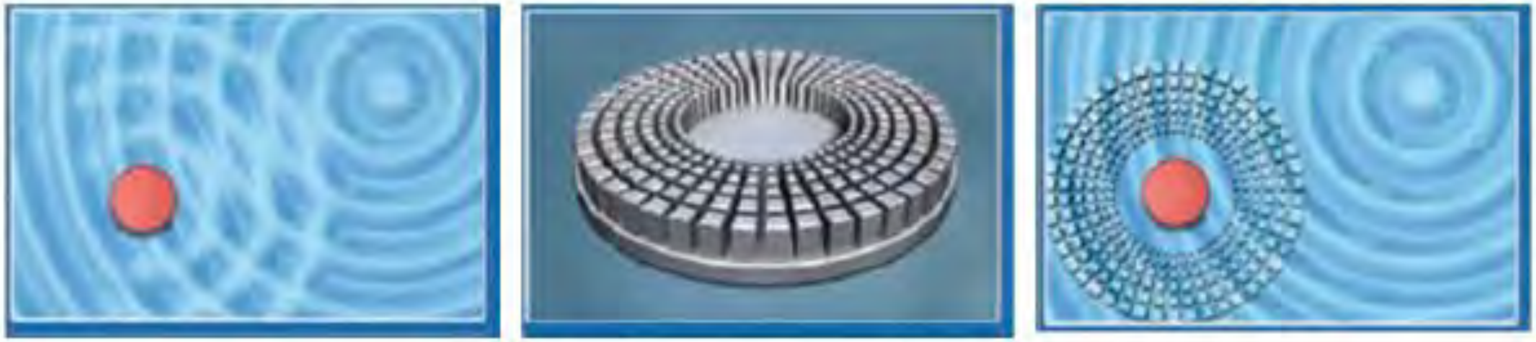
They are assemblies of multiple individual elements fashioned from conventional materials such as metals or plastics, but **the materials are usually constructed into repeating patterns**, often with **microscopic structures**.

# Metamaterial: Spatial Distribution of Scatterers

**Acoustic waves**

*Frahat et al, Institut Fresnel, Marseille*

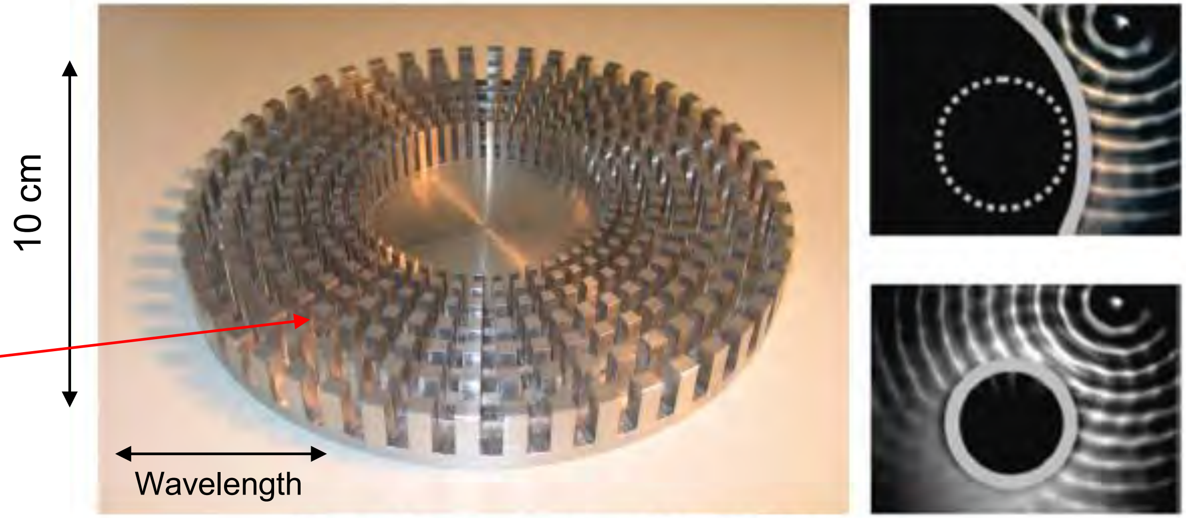
Numerical simulation



Infographie La Recherche (Février 2012)

Laboratory experiment

Unitary cell



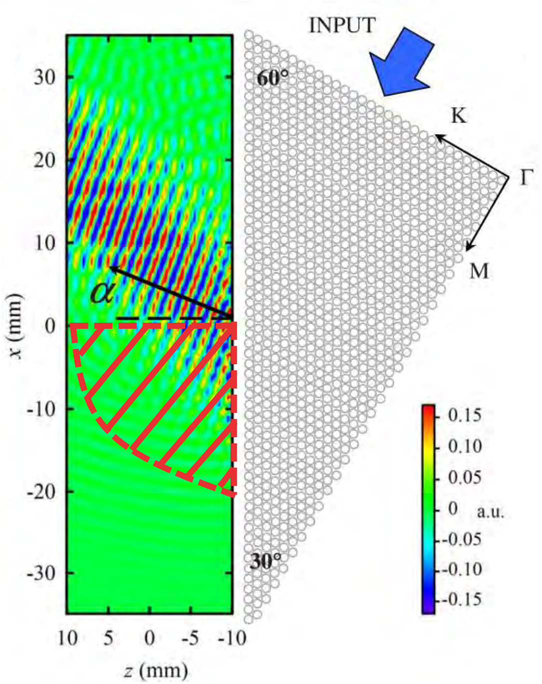
Physical Review Letters 101, 134501 (2008)

# How to Manipulate the Wavefield ?

1- Bragg scattering and Phononic crystals

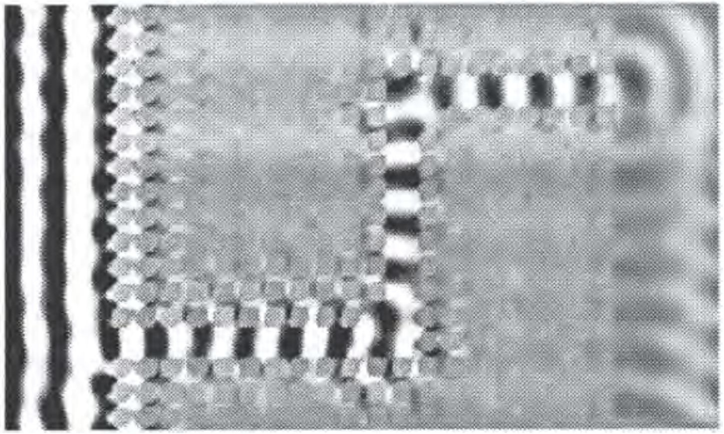
Negative Index of Refraction

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.

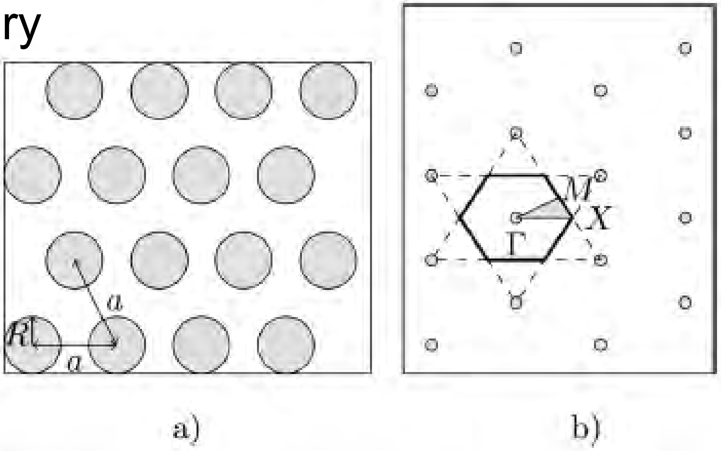


FIG. 1. Diagram of a triangular lattice for an ideal sonic crystal. (a) Direct space, where rods have a radius $r$ and a lattice constant $a$. (b) Reciprocal space with the irreducible Brillouin zone.

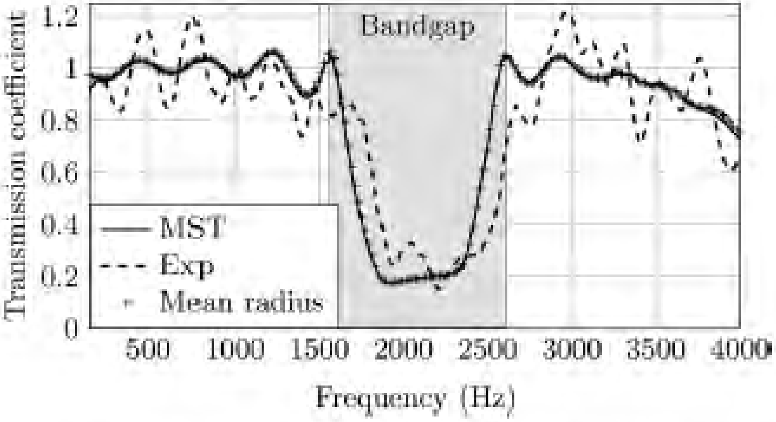


FIG. 6. Comparison between the transmission coefficient calculated by MST with all the radii accounted for (—), by MST with the mean radius (· · ·), and mesured experimentally (– – –) for a triangular lattice sonic crystal of 9 × 5 rods of 4 cm of diameter.

*Lagarrigue et al., JASA (2012)*

# How to Manipulate the Wavefield ?

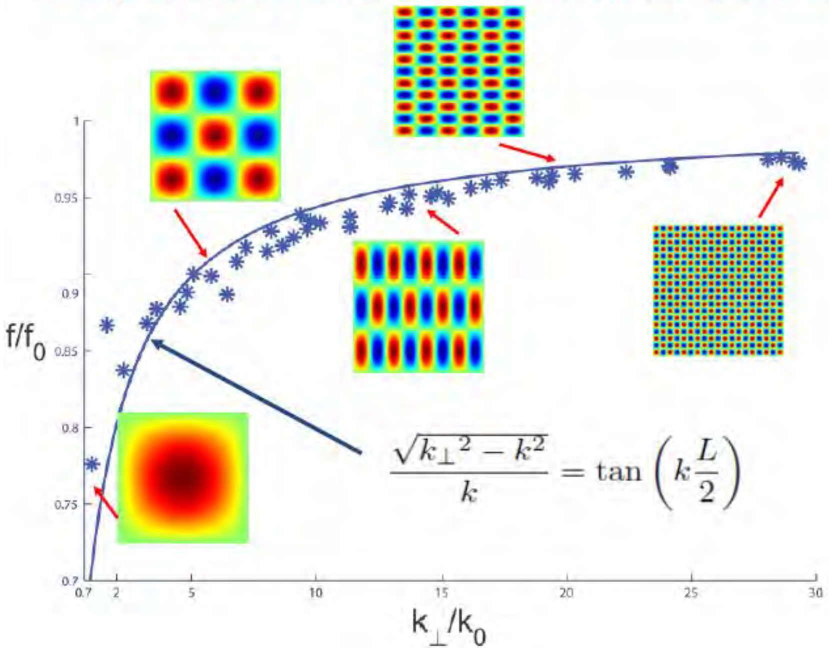
## 2- Multi-resonators at the sub-wavelength scale

Periodic arrangement of identical wires

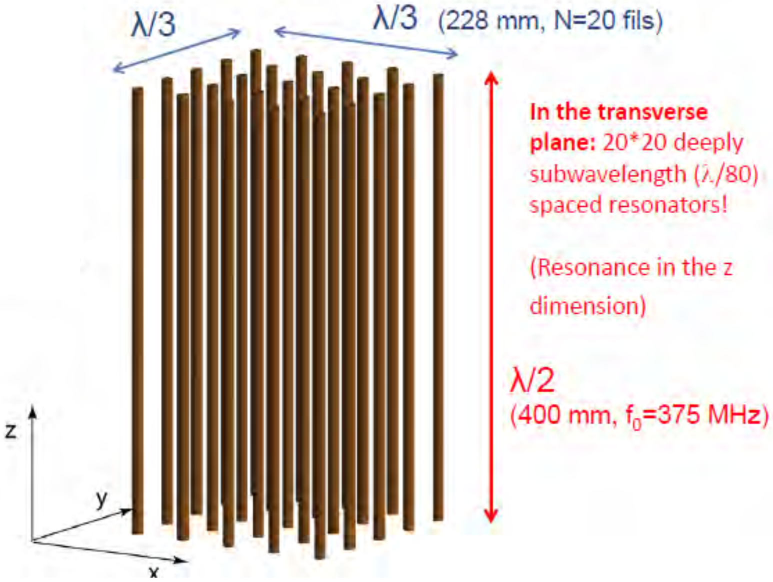
*Fabrice Lemoult, Geoffroy Lerosey, Julien de Rosny, Mathias Fink*
« Resonant Metalenses for Breaking the Diffraction Barrier »
Phys Rev Lett 104, 203901 (May 2010)

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!

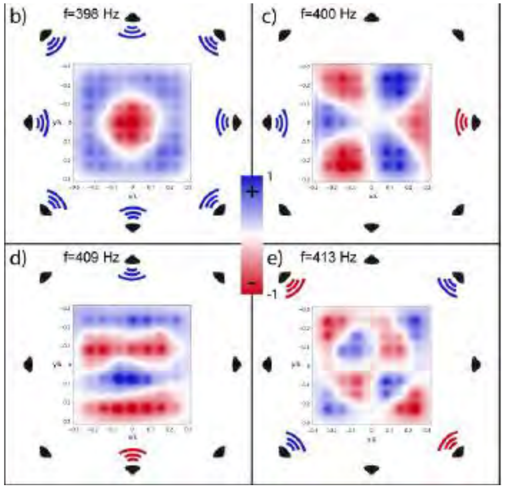
(Resonance in the z dimension)

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*



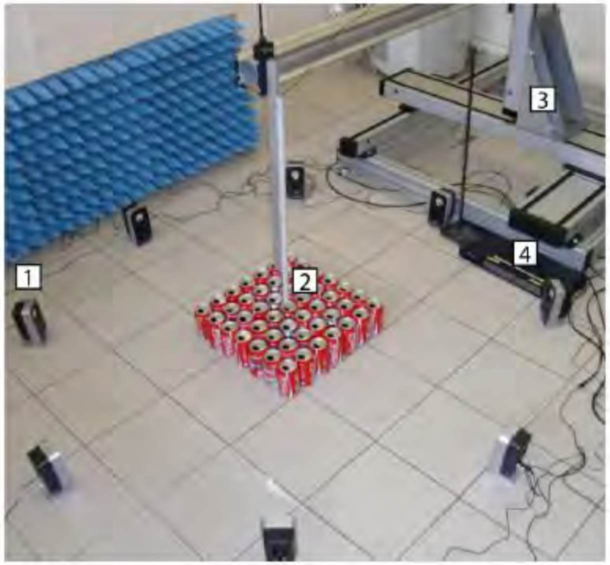
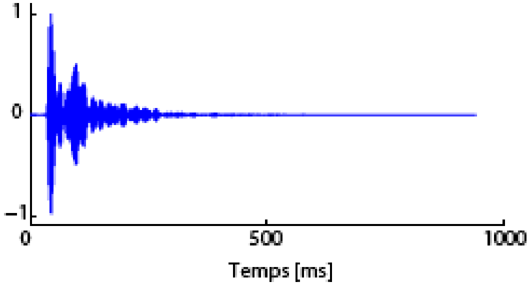
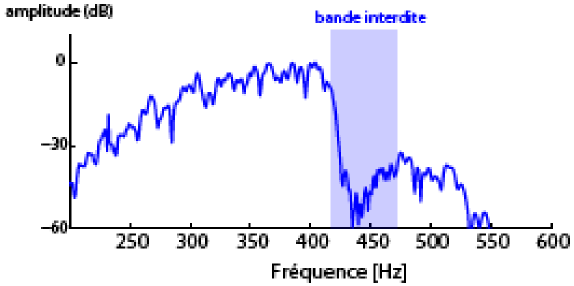
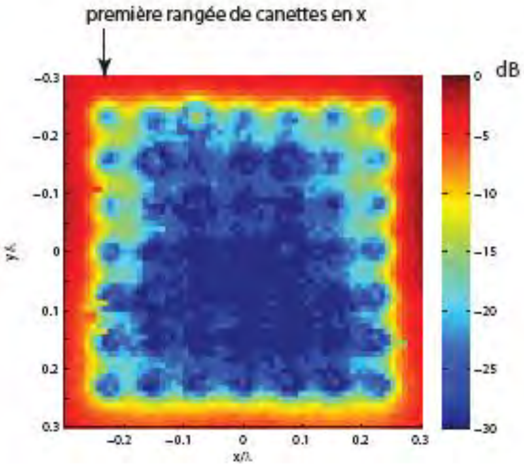


FIGURE IV.6 – Le réseau de 7 × 7 canettes et le dispositif expérimental : (1) 8 haut-parleurs commerciaux pré-amplifiés, (2) microphone monté sur (3) un banc de mesure motorisé, (4) carte son MOTU.

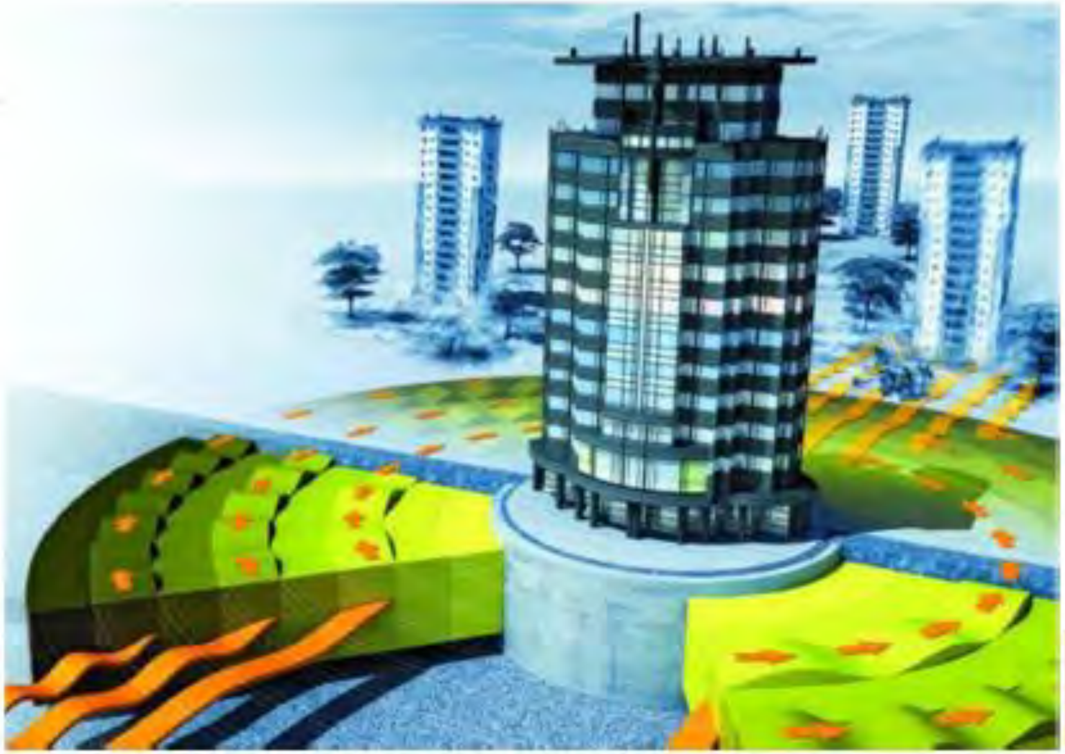






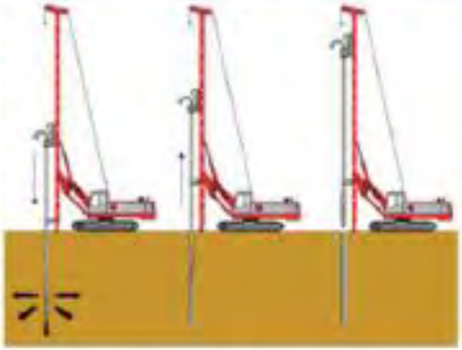
# At Larger Scale : Cancellation of Seismic Waves?

S. Guenneau, Institut Fresnel, Marseille



Infographie Popular Science Magazine (2009)

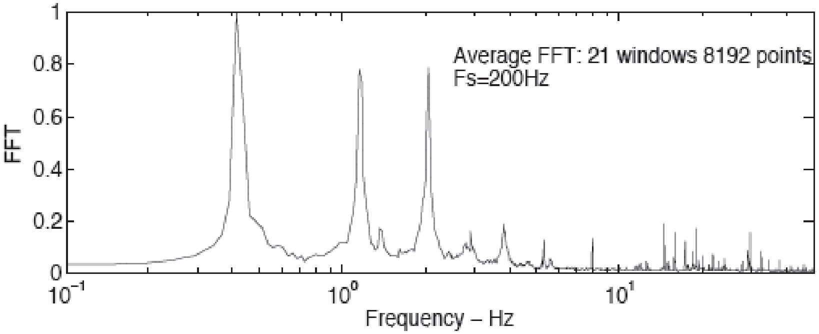
PRL 103, 024301(2009)



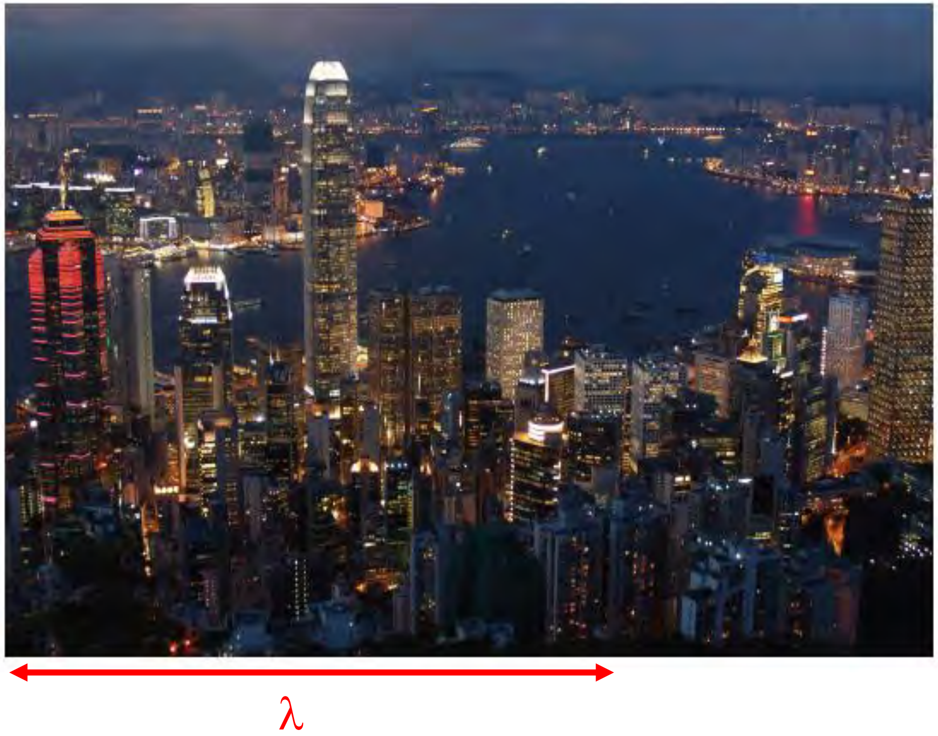
Infographie Ménard

# A City : Macroscopic Arrangement of Resonating Elements ?

Tall building : subwavelength resonator
for ~1 Hz seismic wave



Cluster of buildings : locally-resonant metamaterial?

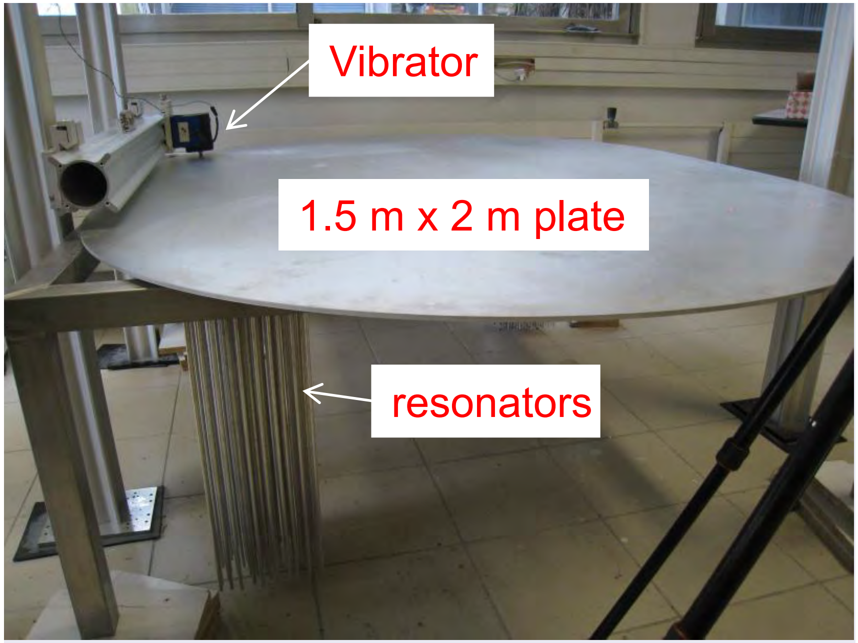


# Experimental / Theoretical / Numerical Approach at ISTerre

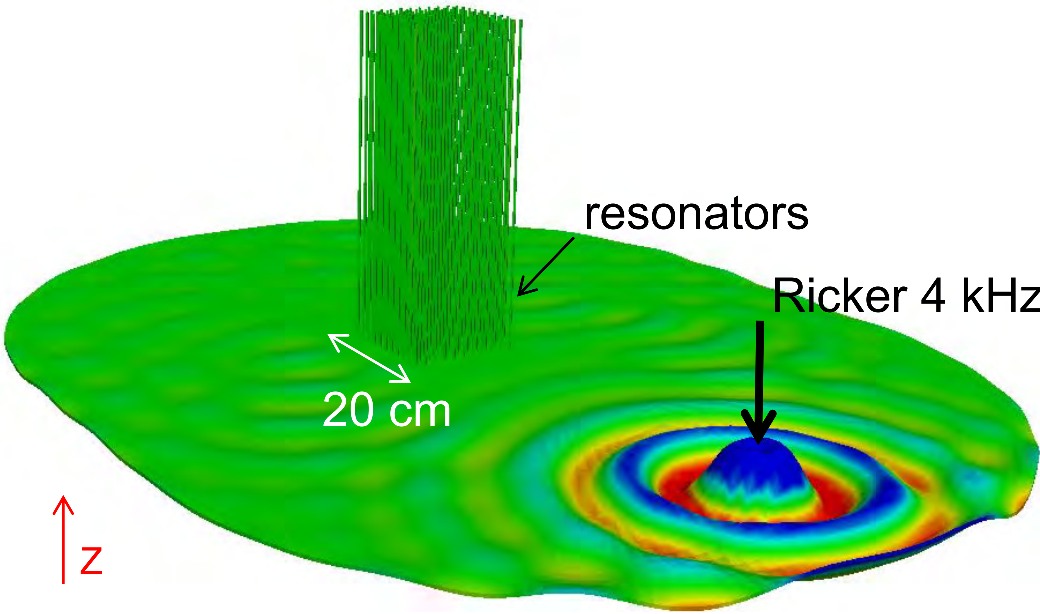
Coupling Surface wave (Geophysics)

and

Multi-Resonators (Acoustics)

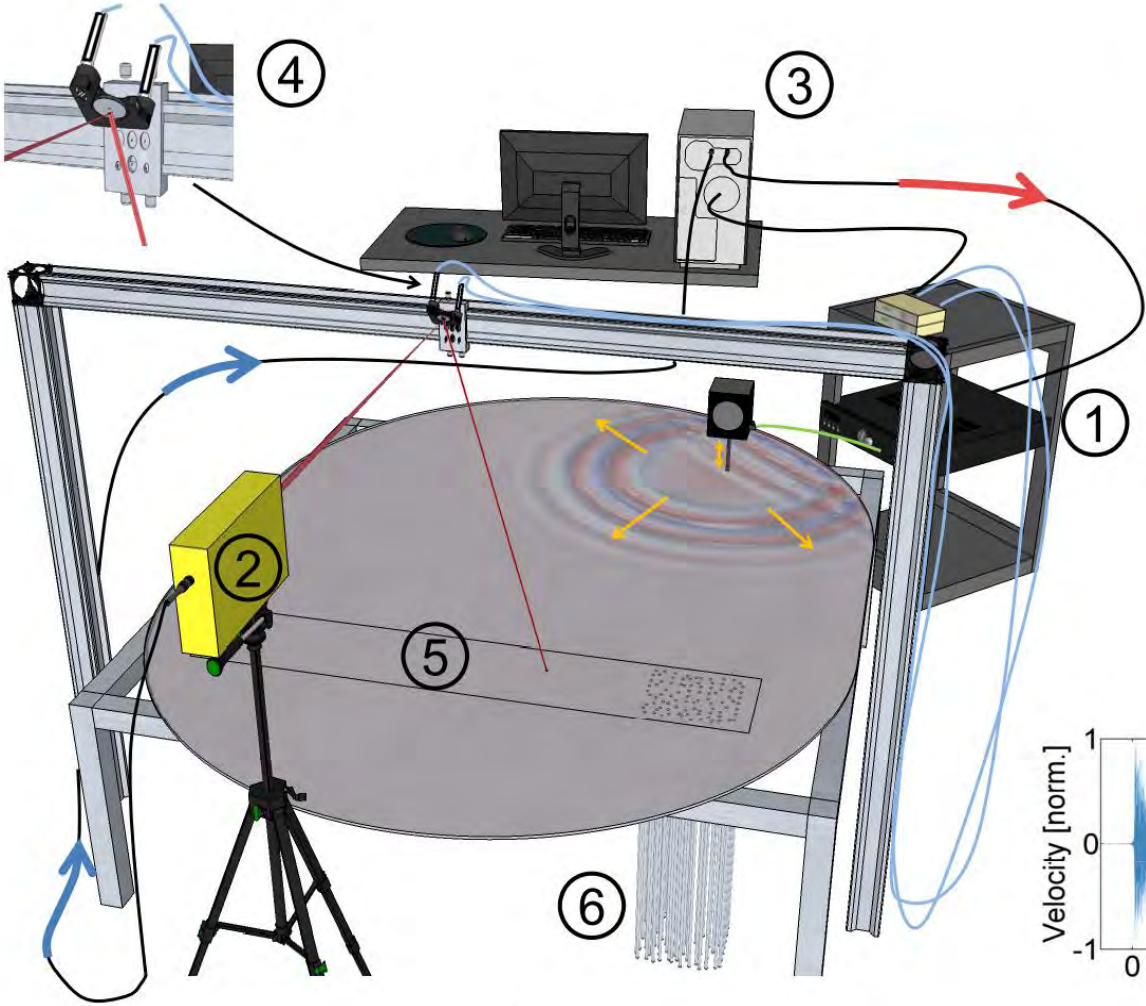


Laboratory set-up



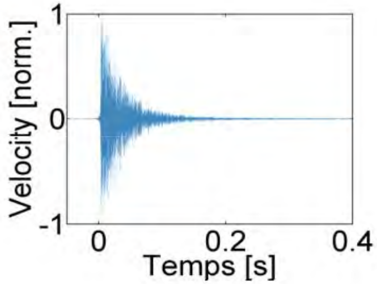
Simulation setup

# Experimental Configuration (1)



a)

b)

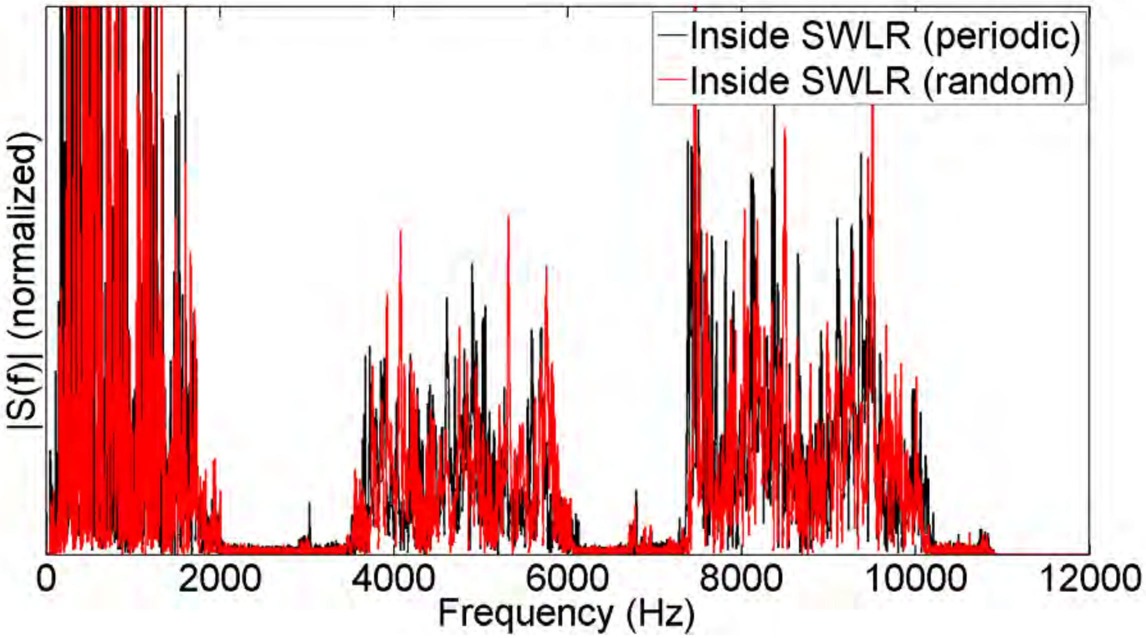


c)

# Periodic / Random Distribution of Beams

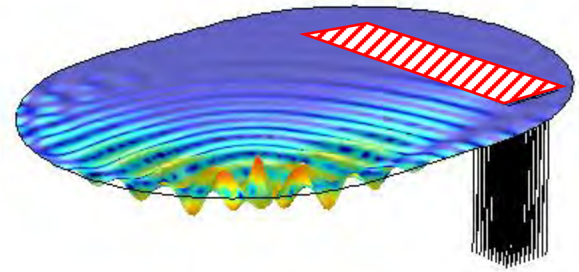
Periodic configuration

Random configuration

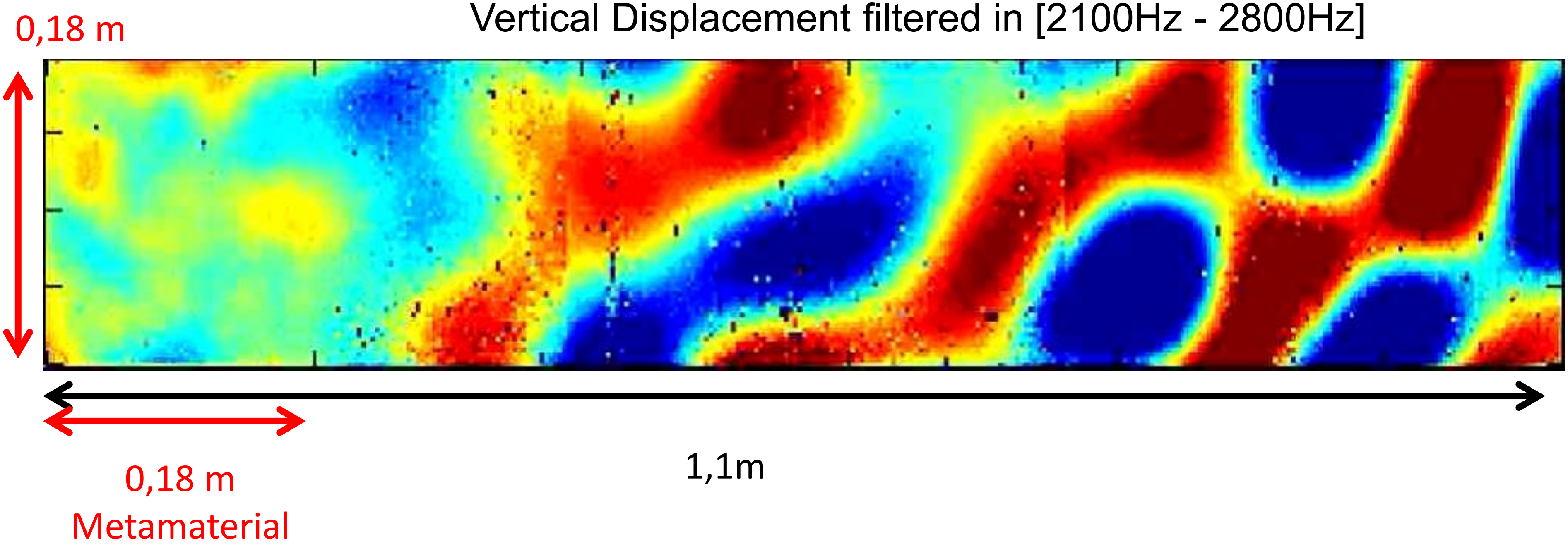


*Cowan et al. Phys. Rev. B, 2011*

# Temporal Evolution of the Wavefield



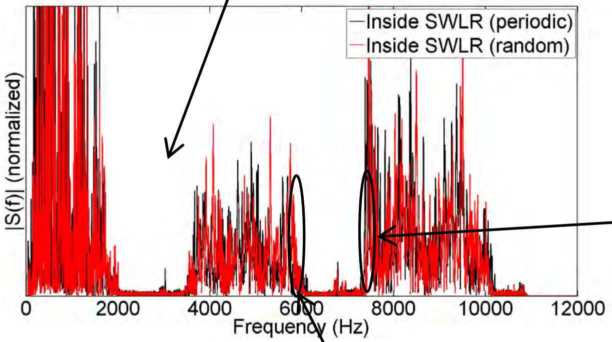
Vertical Displacement filtered in [2100Hz - 2800Hz]

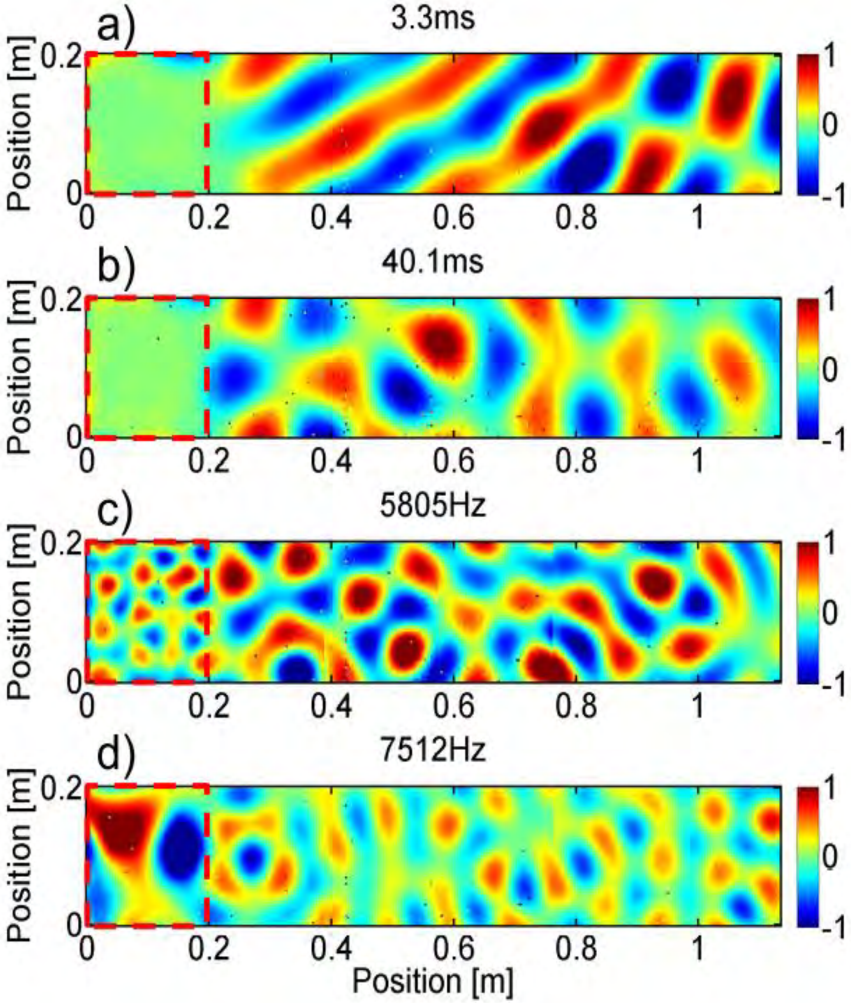


*Data available at https://isterre.fr/annuaire/pages-web-du-personnel/philippe-roux/article/laboratory-data-available*

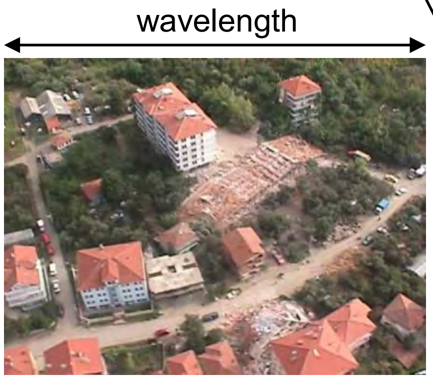
# Outside the Bandgaps :
# Sub- or Supra-Wavelength Modes

Inside bandgap



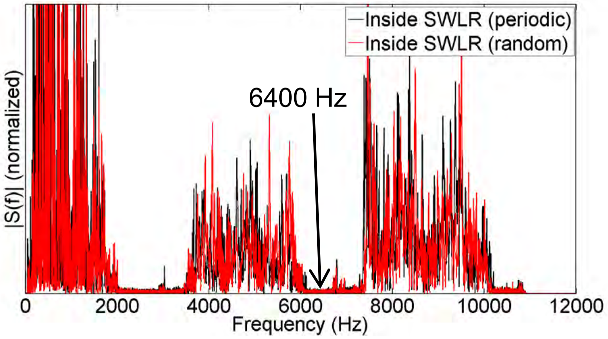


Outside bandgap



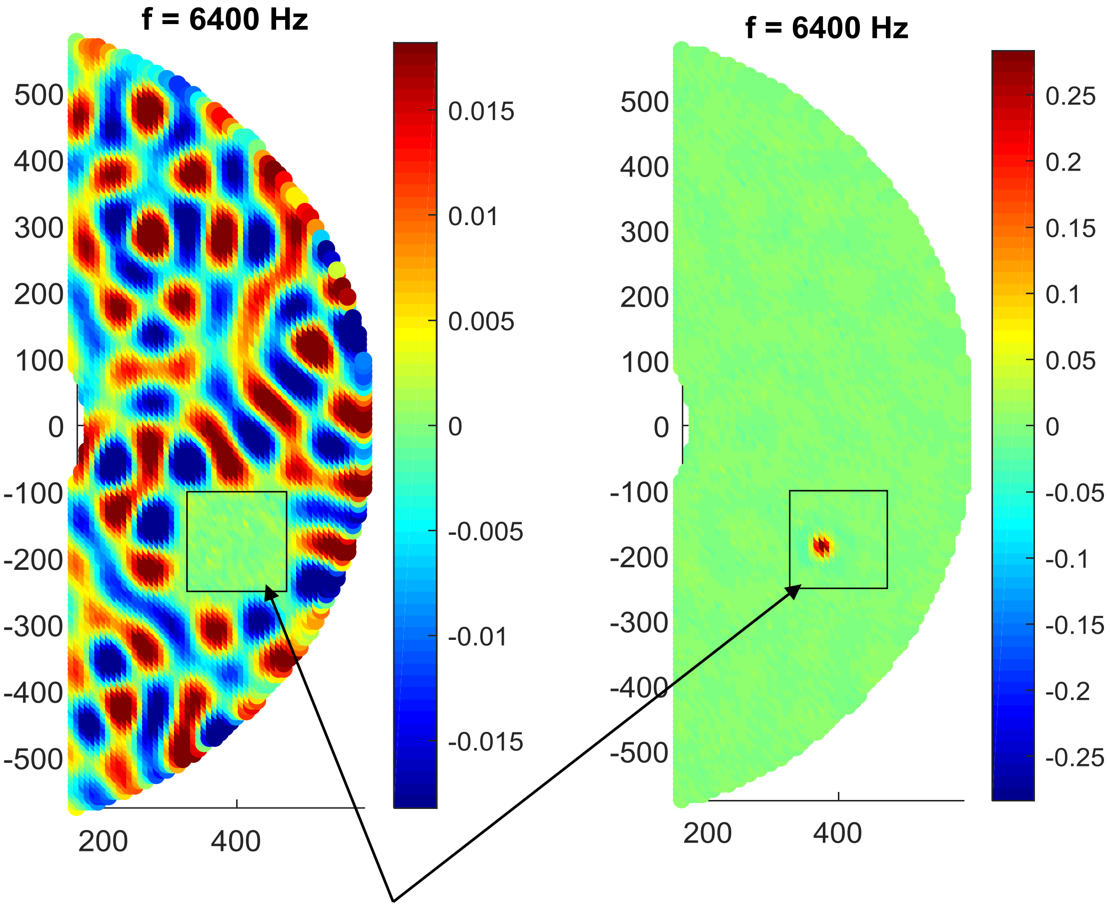
*Rupin et al., PRL 2014; APL, 2015*

# Inside the Bandgap :
# Source outside or inside the Metamaterial



Source outside the Meta

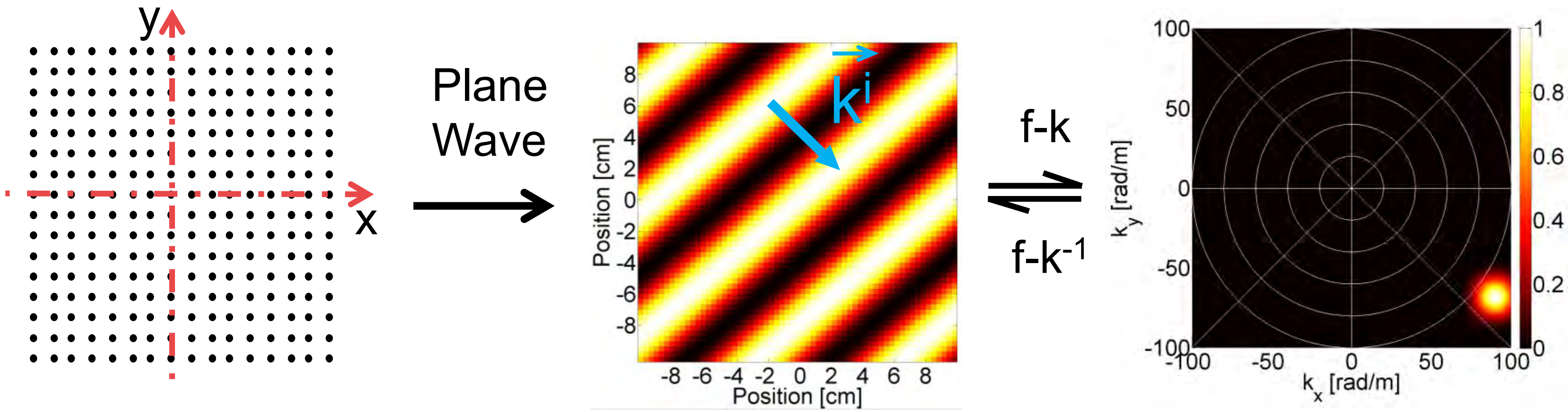
Source inside the Meta



Random Metamaterial

# Metamaterial description through Dispersion relation

- 2-D Frequency-Wavenumber projection



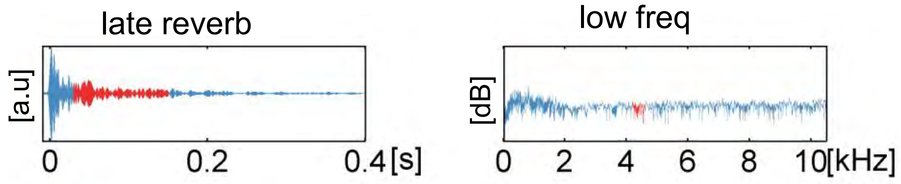
2D antenna
(NxN receivers)

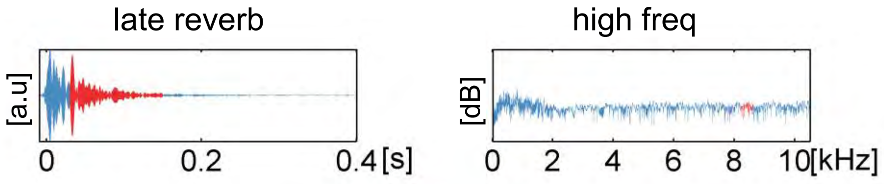
x-y field
representation

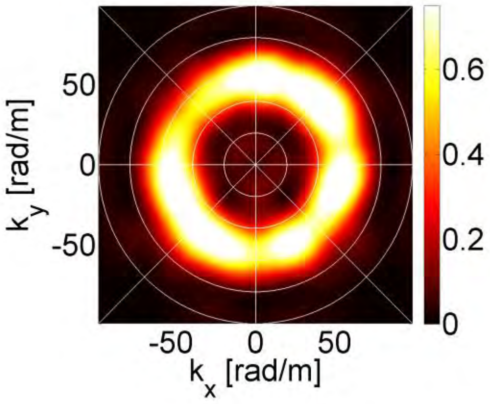
$k_x$-$k_y$ field
representation

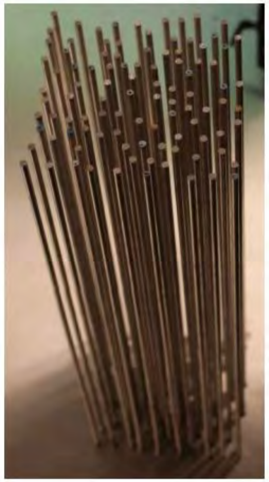
# Metamaterial description through Dispersion relation

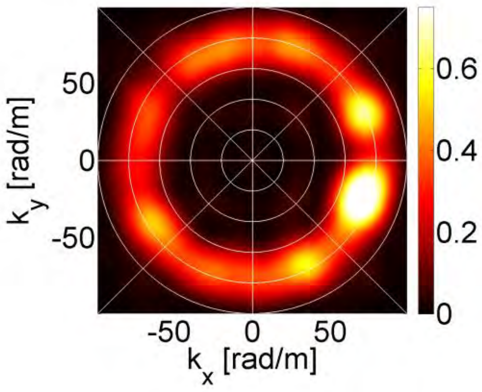
## Examples of experimental F-K







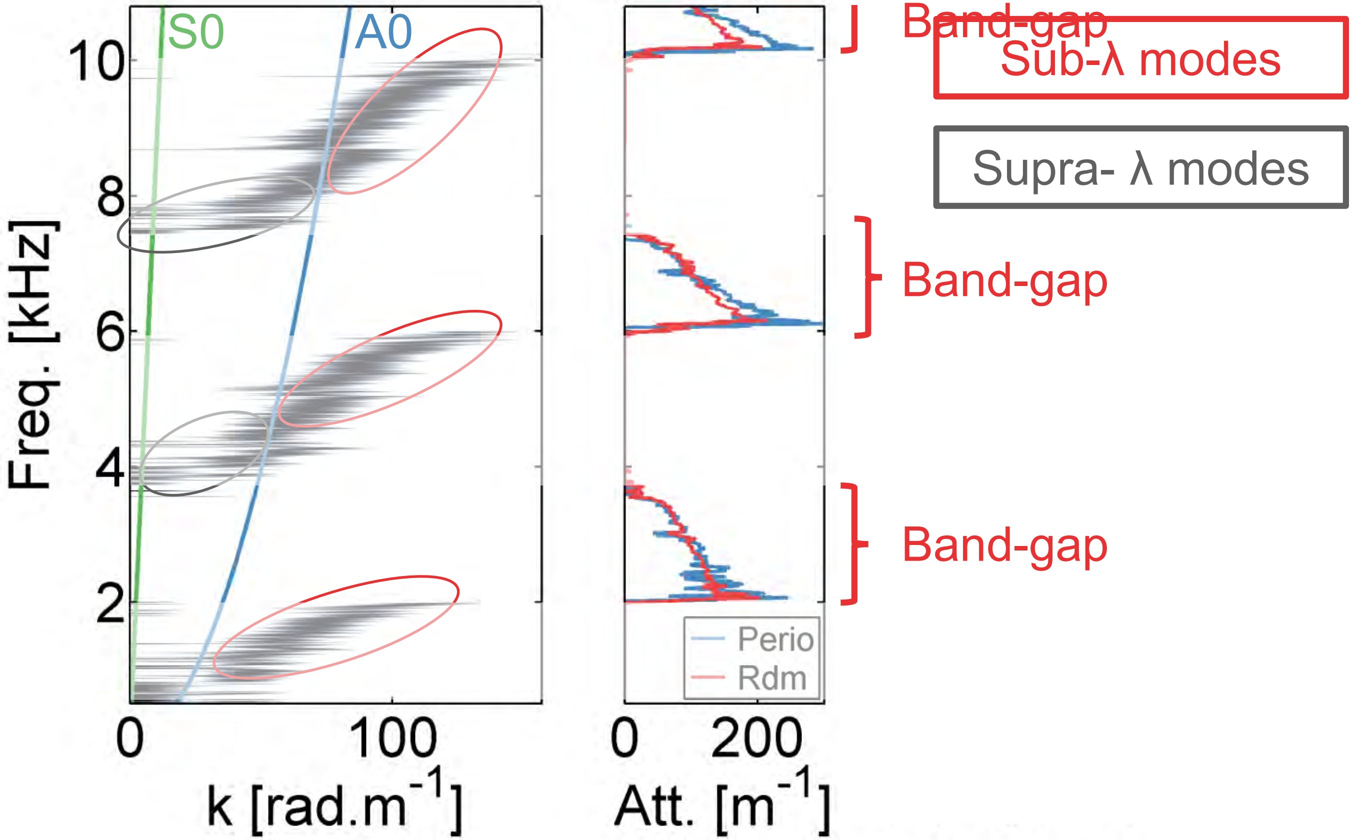




Isotropic Wavenumber Distribution = Diffuse Field

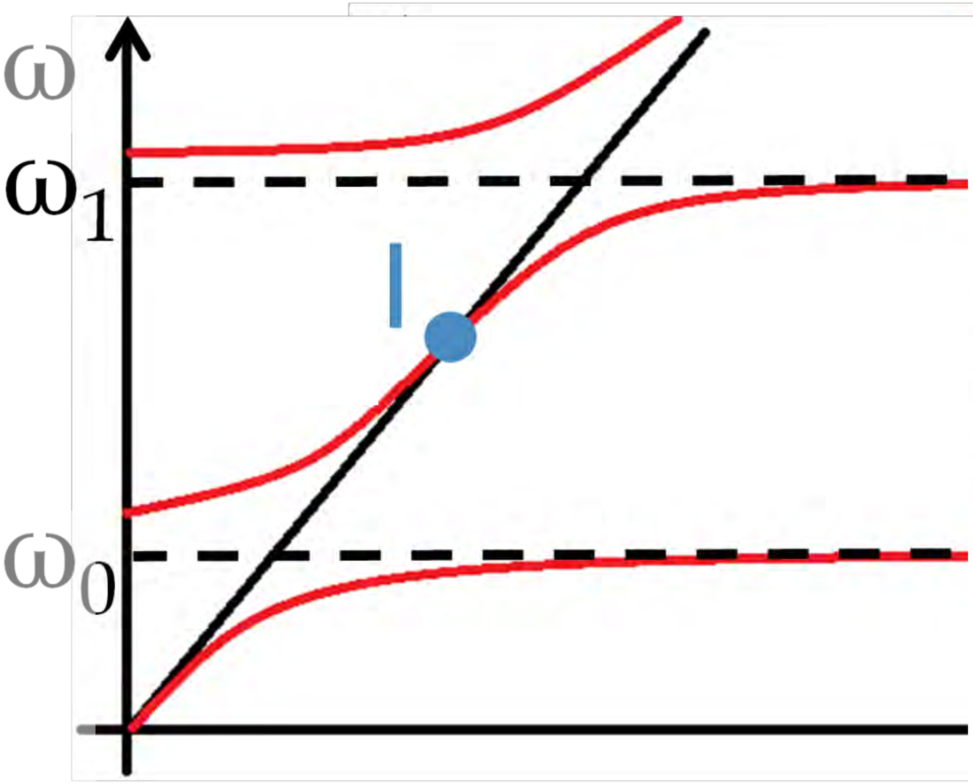
# Metamaterial description through Dispersion relation

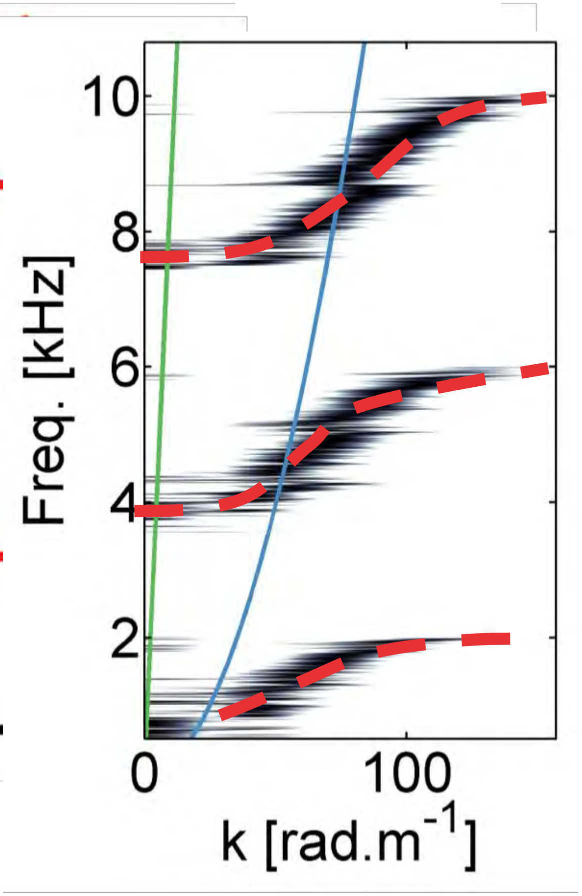
- Dispersion relation inside the Metamaterial



# Metamaterial description through Dispersion relation

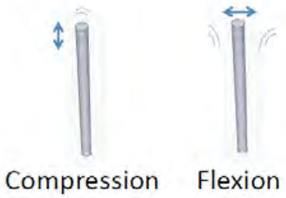
Role of the resonances : the hybridation phenomenon

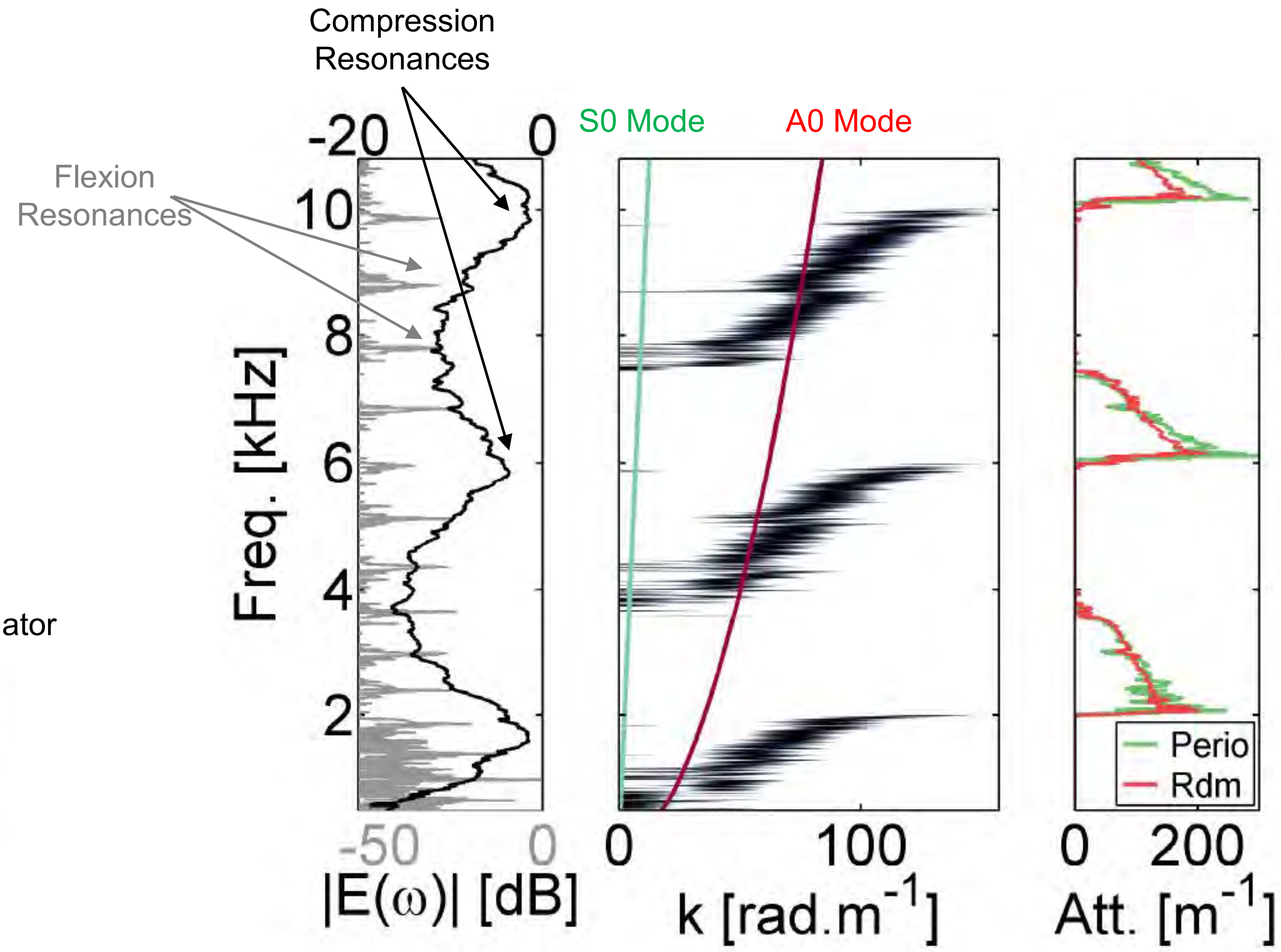




# Metamaterial description through Dispersion relation

One Single Resonator





Compression Resonances

Flexion Resonances

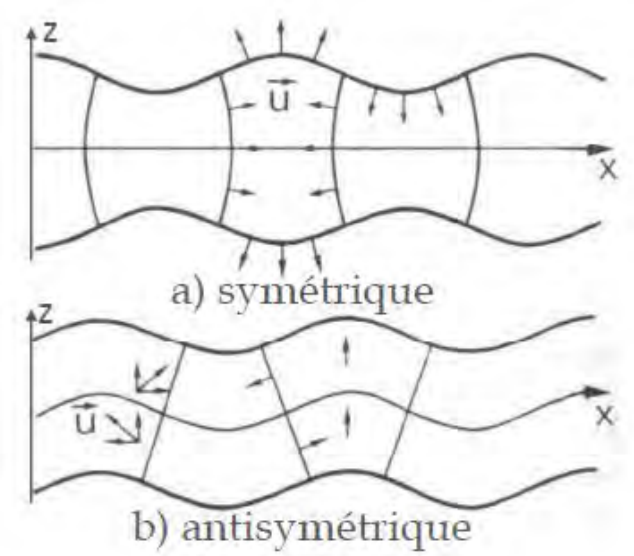
*Rupin et al., PRL, 2014*

# Mutli-wave + Multi-resonance problem

In the plate…

S0 wave

A0 wave

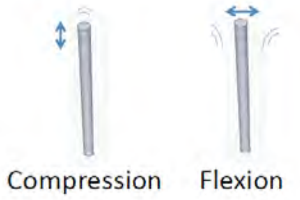


Displacement is mostly horizontal

Displacement is mostly vertical

Two types of waves

In one resonator…

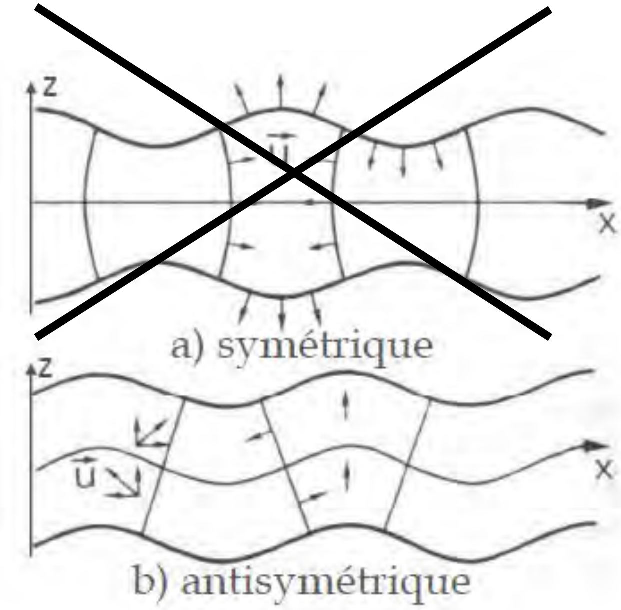


Two types of resonances

*Royer & Dieulesaint, 1996*

# First (scalar) approximation :
# A0 wave + Compression resonance

In the plate…



~~S0 wave~~

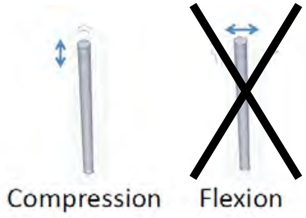
~~Displacement is mostly horizontal~~

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

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

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

Account for boundary conditions at the bar-plate interface

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

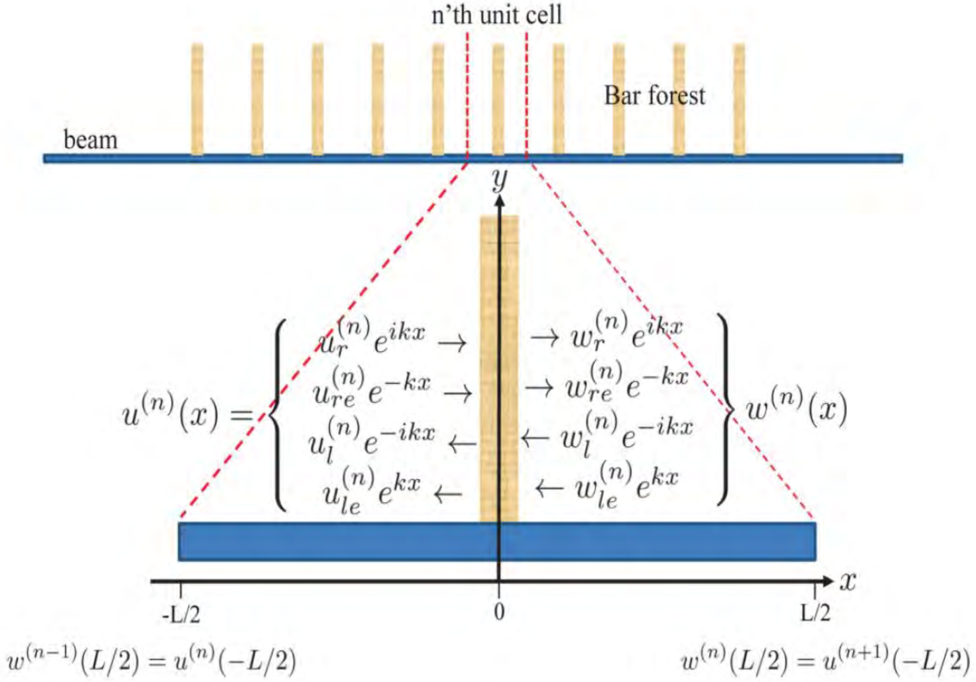
$$D \equiv \begin{bmatrix} e^{-ikL/2} & 0 & 0 & 0 \\ 0 & e^{kL/2} & 0 & 0 \\ 0 & 0 & e^{ikL/2} & 0 \\ 0 & 0 & 0 & e^{-kL/2} \end{bmatrix}$$

Account for propagation accross the unit cell

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

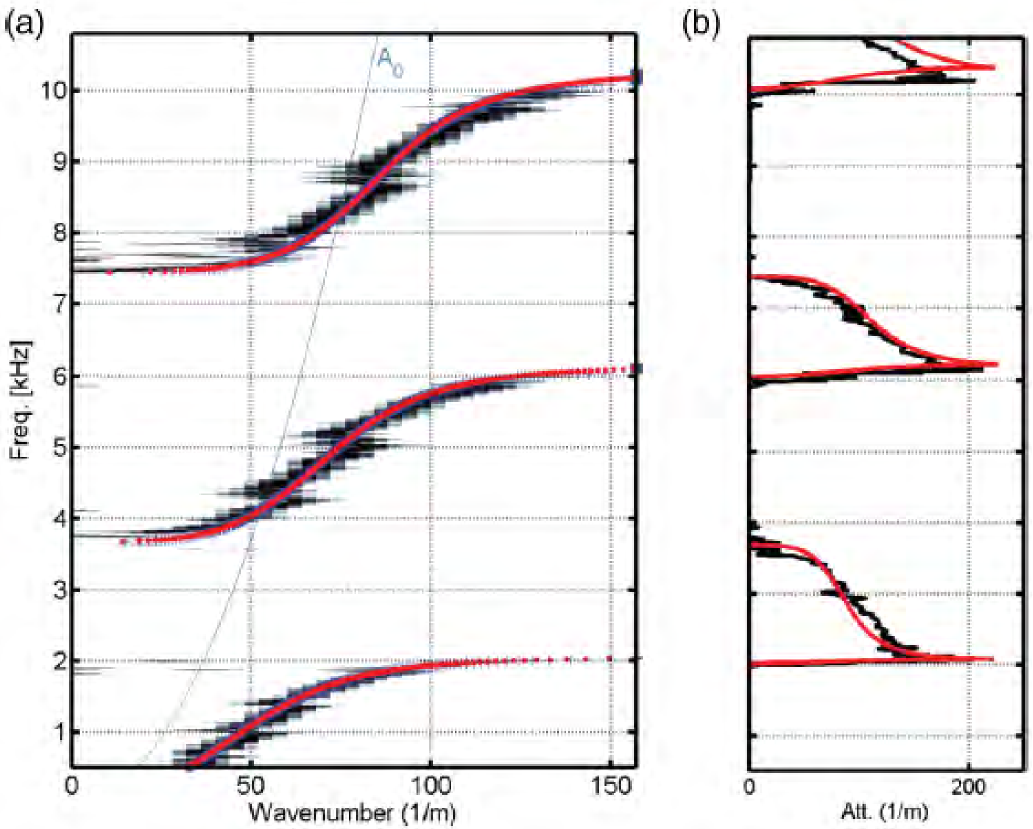
Transfer matrix between two cells

1-D model



Dispersion curves are obtained from the solution of an eigenvalue problem

# Theoretical (scalar) approach through Bloch Theorem



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

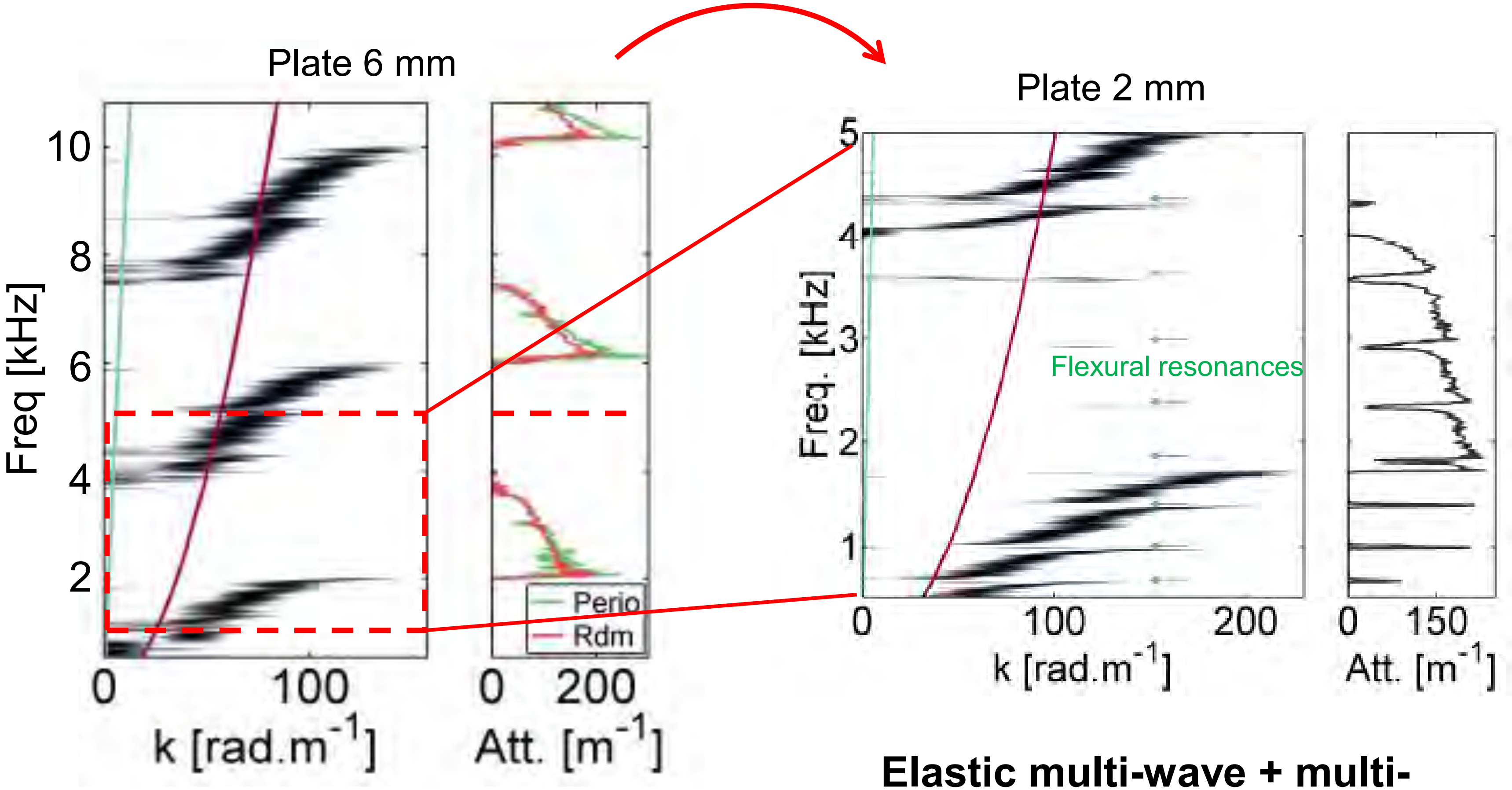
$$\alpha(\omega) = \frac{k}{\sqrt{2}}\left|\frac{M_b}{M}\frac{\tan(k_b L_b)}{k_b L_b} + 1\right|^{1/4}$$

*$M_b$ = 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?

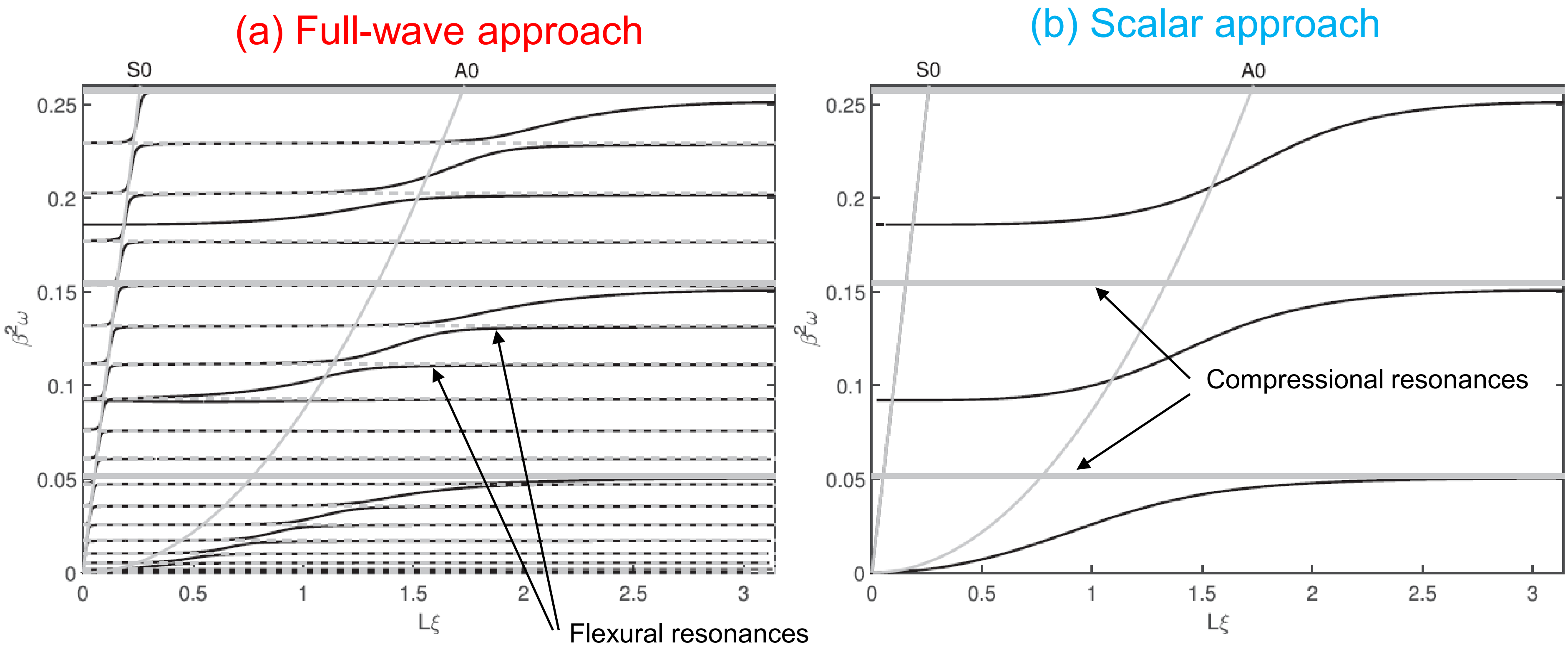
Plate stiffness varies as $h^3$



**Scalar wave + resonator interaction**

**Elastic multi-wave + multi-resonances interaction**

*Rupin et al., Scientific Reports, 2016*



(a) Full-wave approach

(b) Scalar approach

Flexural resonances

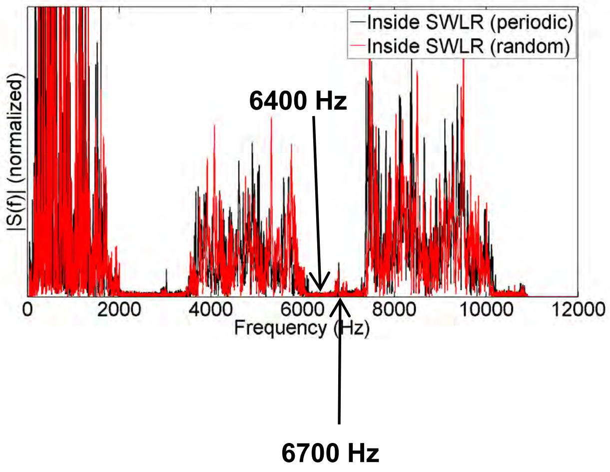
Compressional resonances

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.

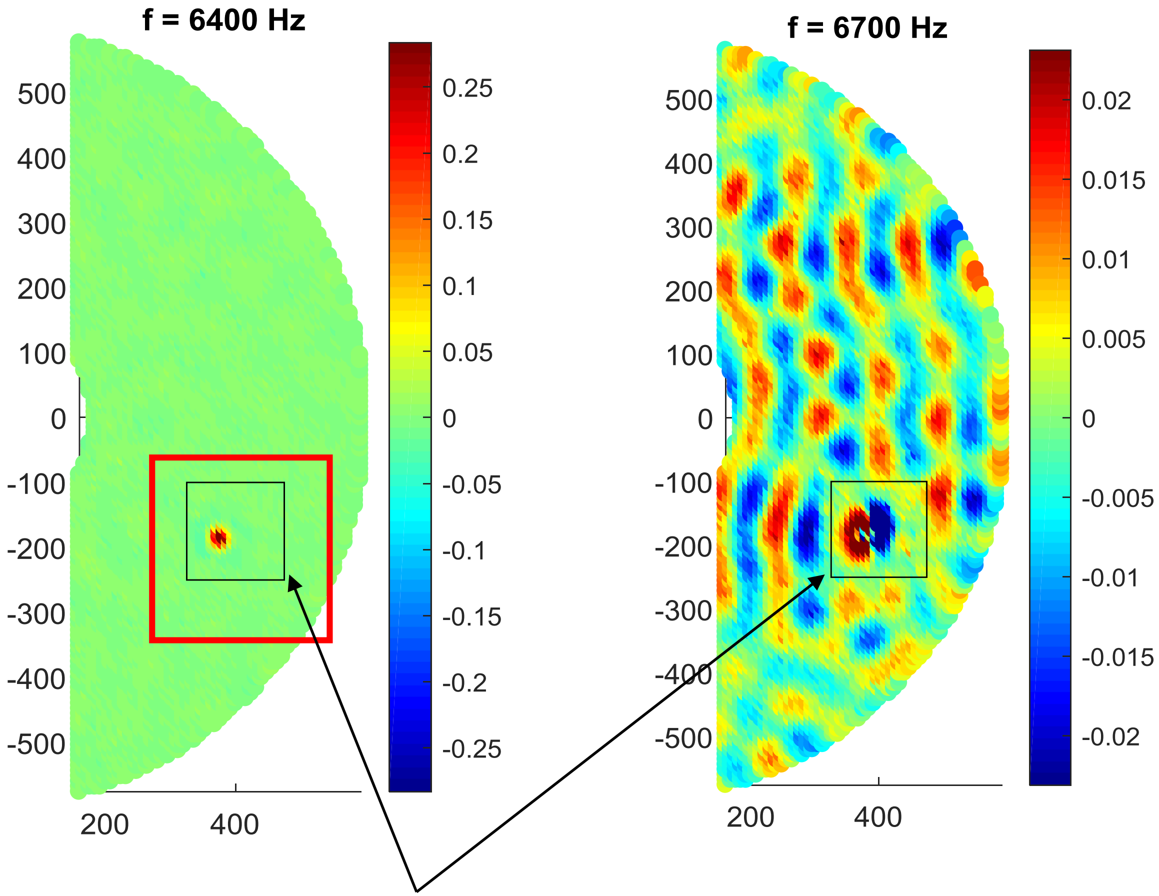
*Colquitt et al., JMPS, 2017*

# What happens inside the bandgap at a flexural resonance?

Plate 6 mm



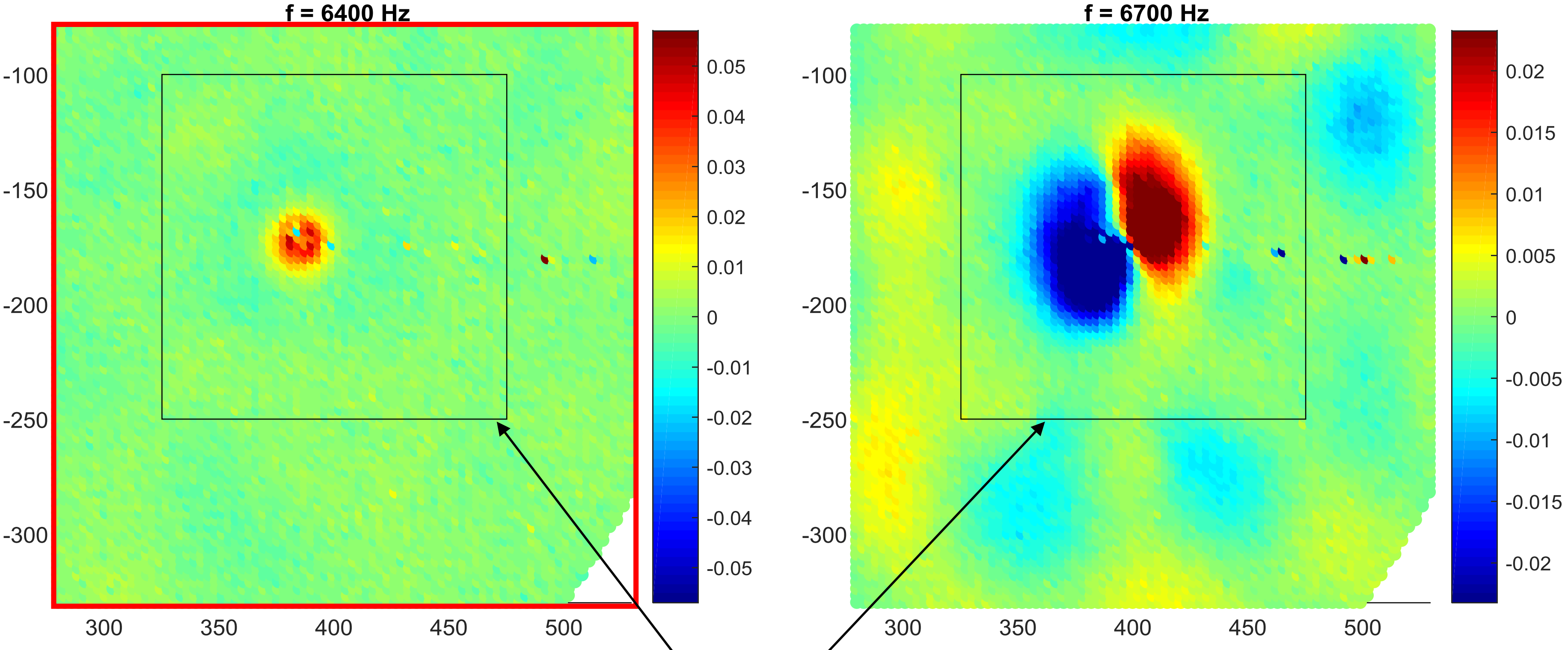
Source inside the Meta



Random Metamaterial

# What happens inside the bandgap at a flexural resonance?

Source inside the Meta



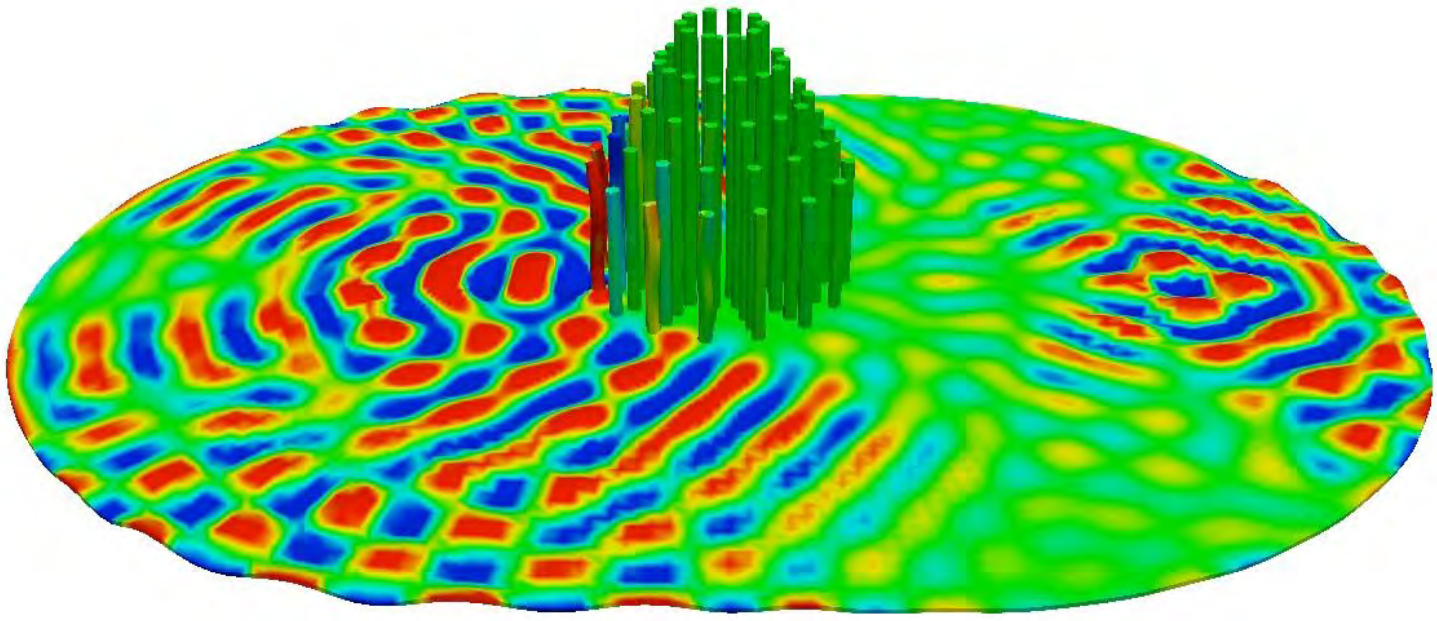
Monopole source away from flexural resonances

Dipole source at a flexural resonance

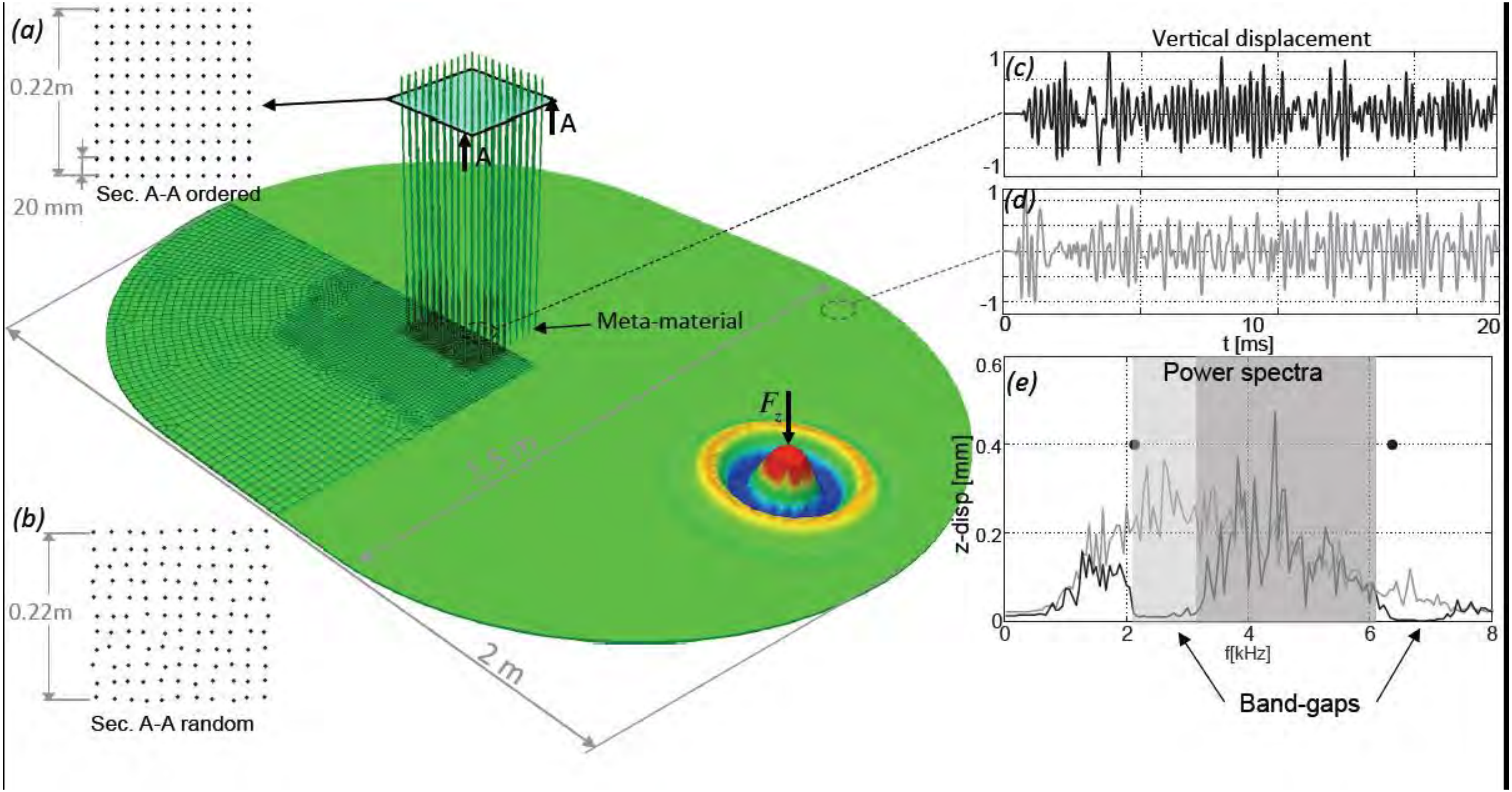
Random Metamaterial

# Seismo-Acoustic Cloaking using a numerical approach

Some Degrees of Freedom:
- Length of the Beams
- Spatial Distribution of the Beams

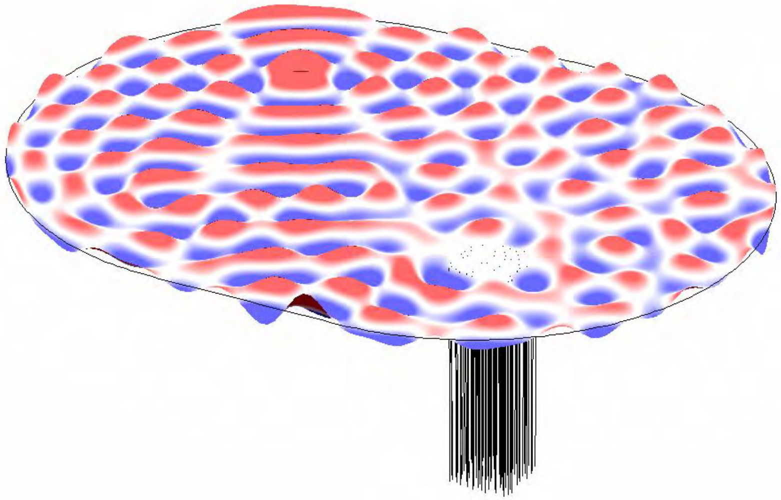


# Numerical approach : Spectral Element Method with 3-D Adaptive Meshing

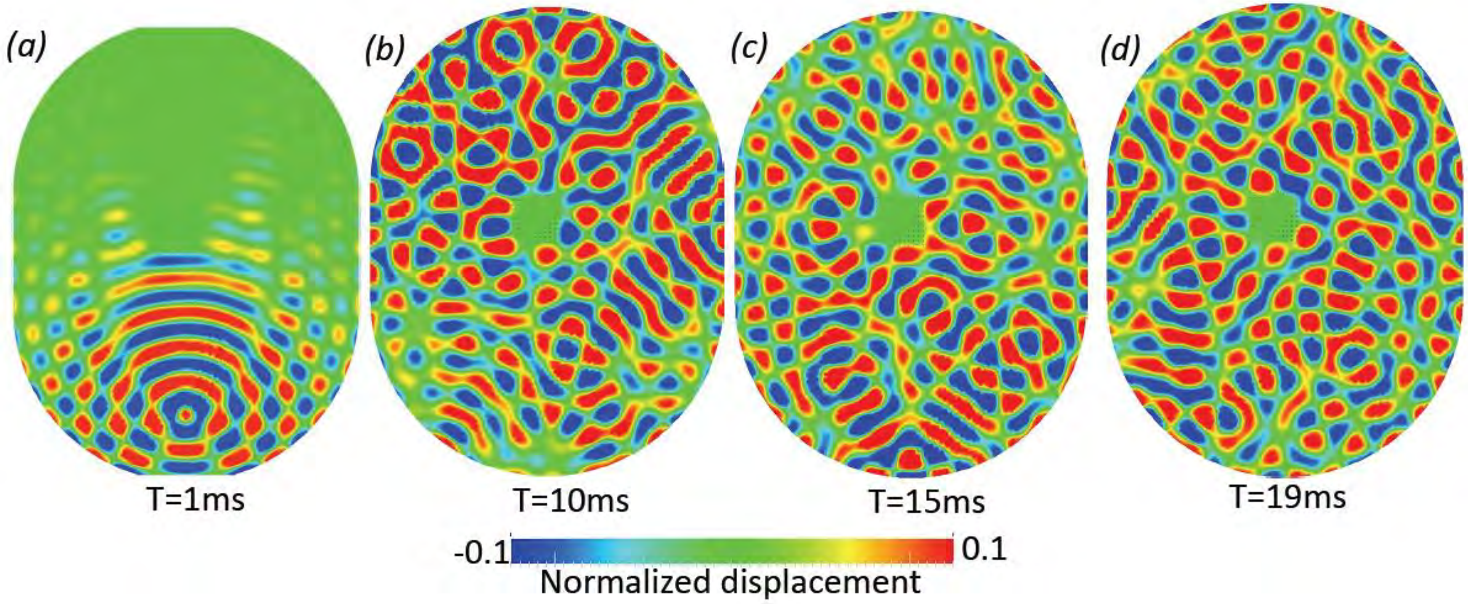


*Colombi et al., JASA-EL, 2014*

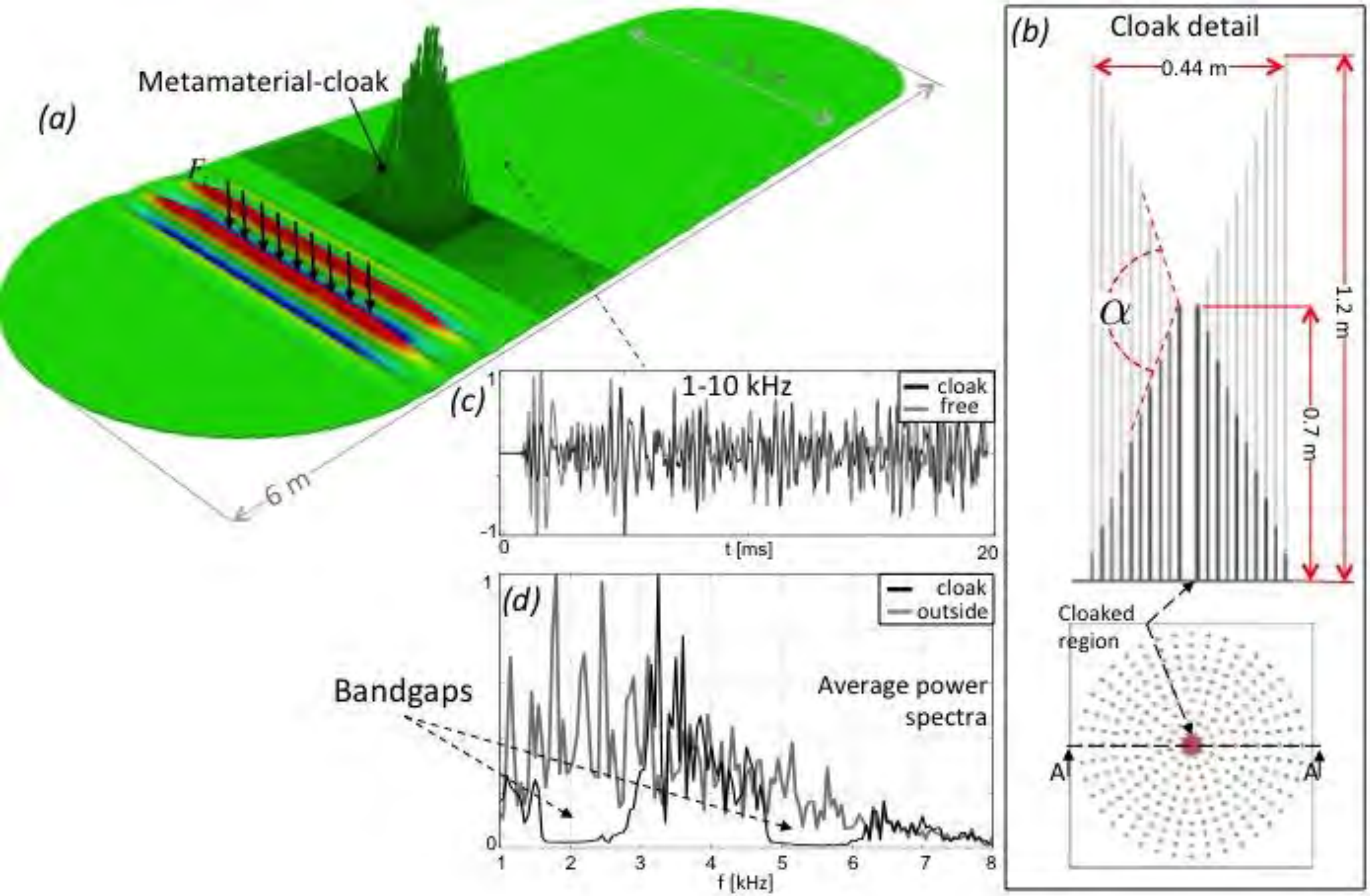
# Numerical Results (Filtered in the Bangap)



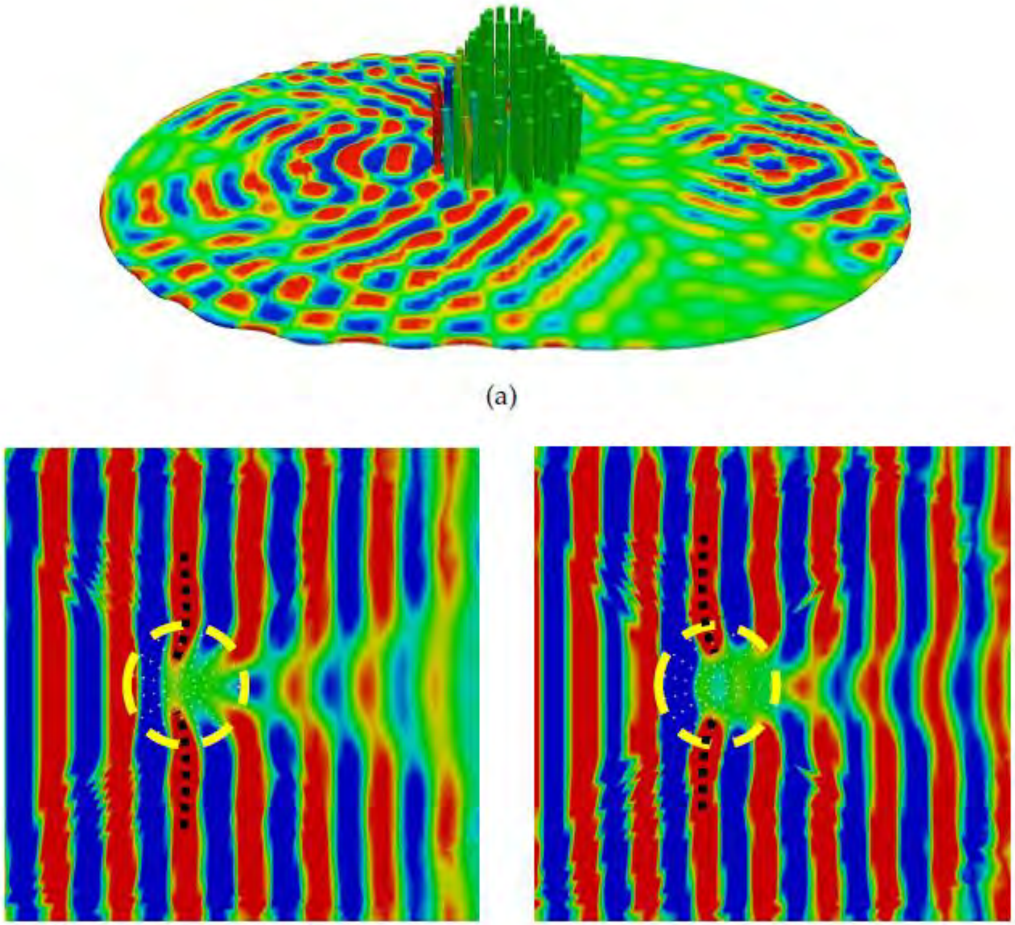
A few snapshots of the wavefield…



# Toward Acoustic Cloaking (Numerical Results)



# Effective Speed inside the Meta-Material



(a)

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

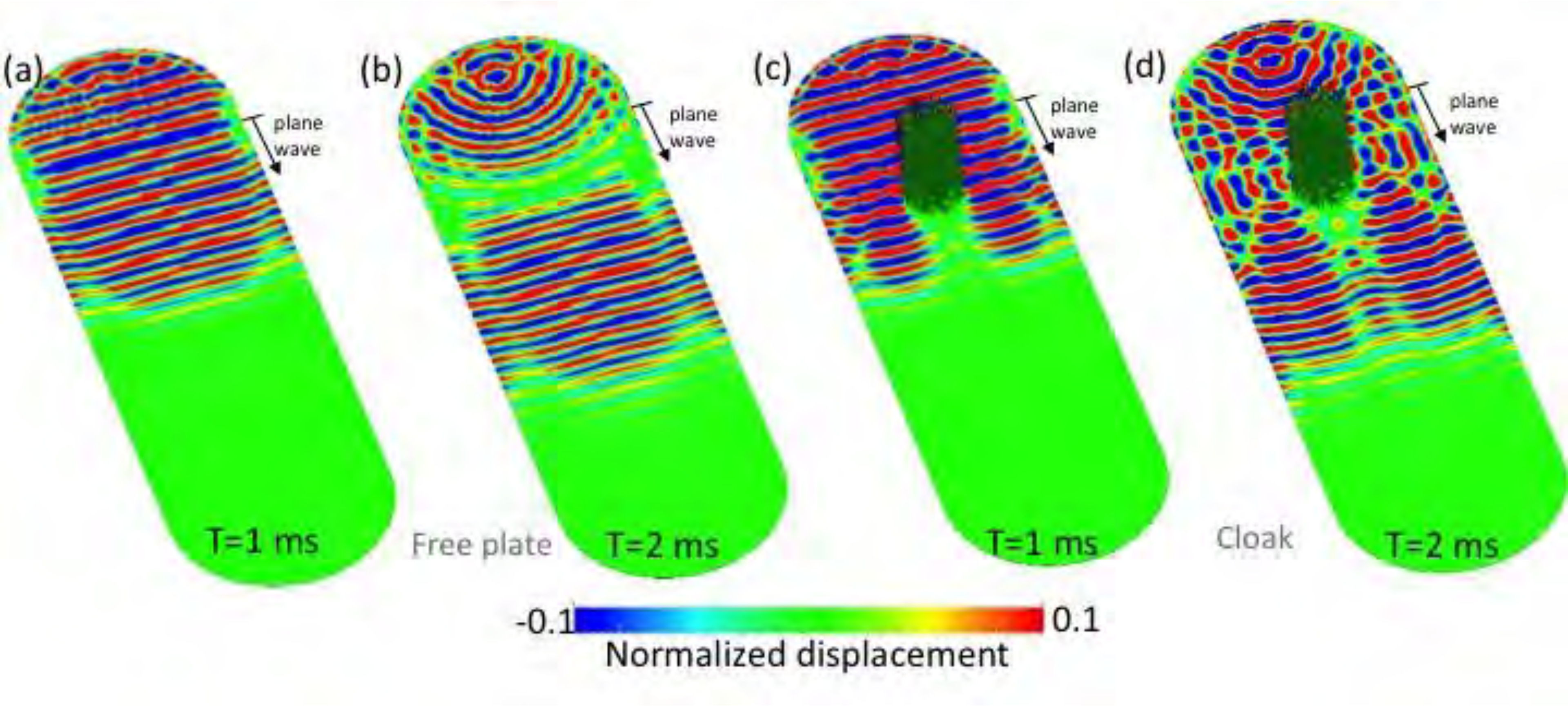
(c) 4,2kHz - 5kHz

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.*

# Toward Acoustic Cloaking (Numerical Results)

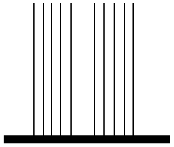
Without Metamaterial

With Metamaterial

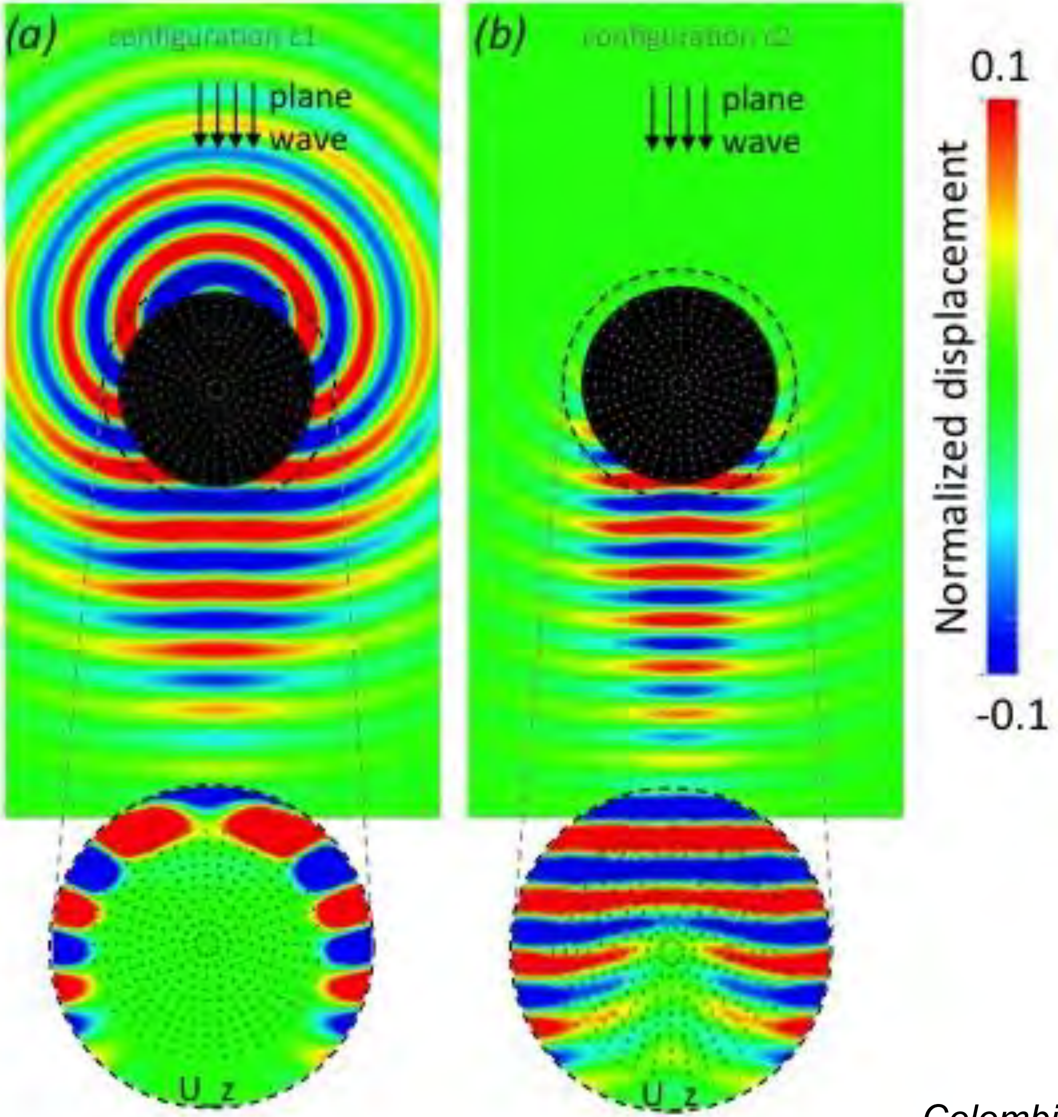


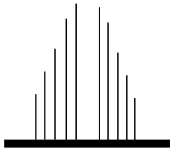
# Intermediate Result : optimal Cloak for Backscattered field

**Scattered Field**



Configuration c1



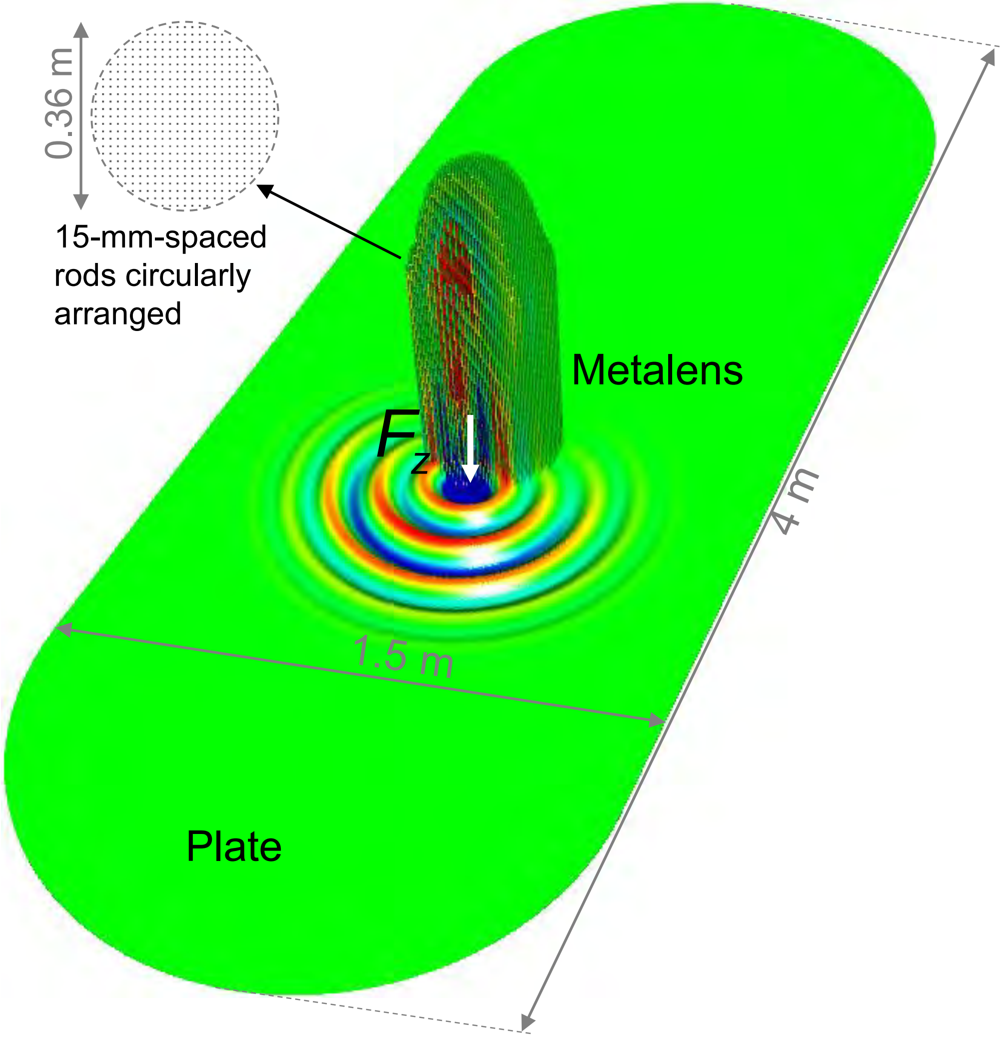


Configuration c2

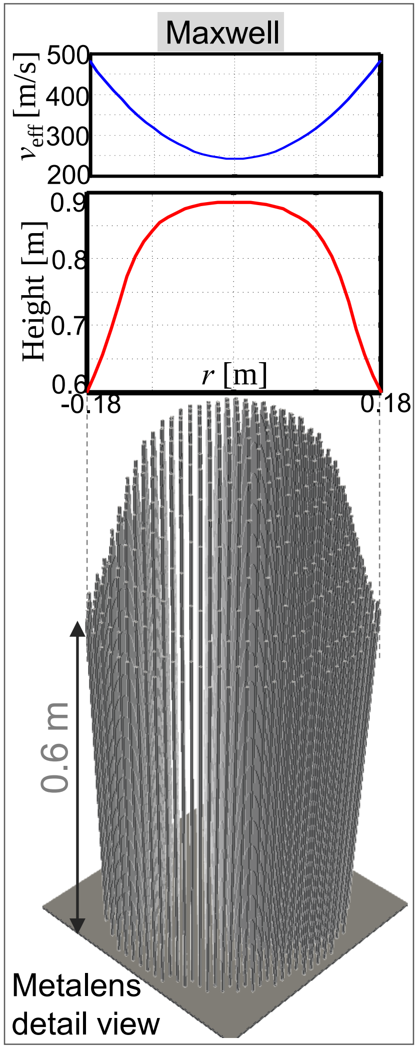
*Colombi et al., JASA, 2015*

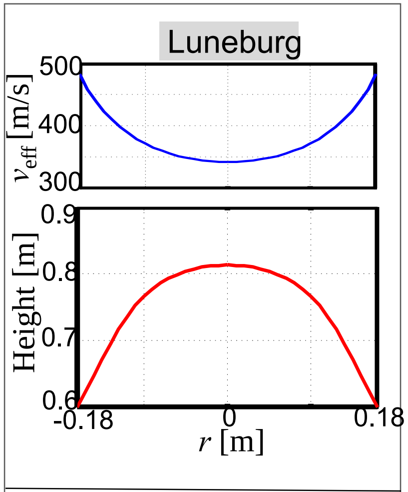
# Gradient Index Lenses with Plate Waves

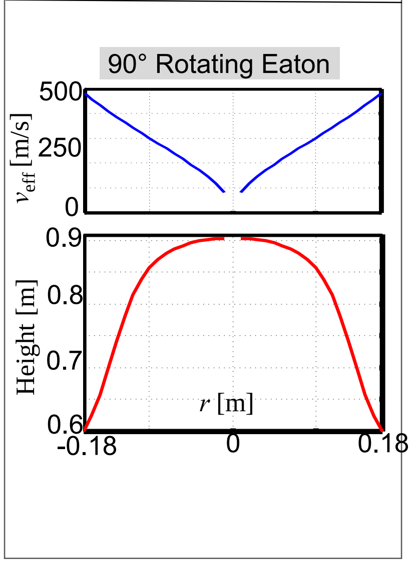
## Numerical model



## Lens type:

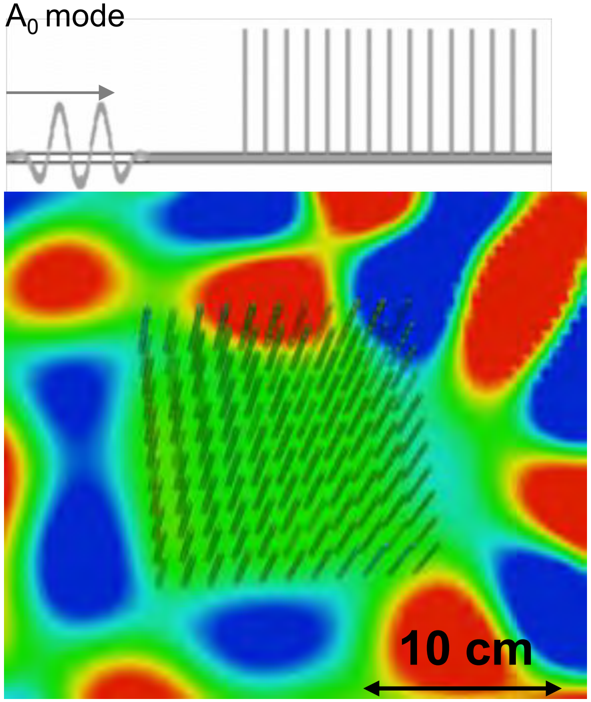




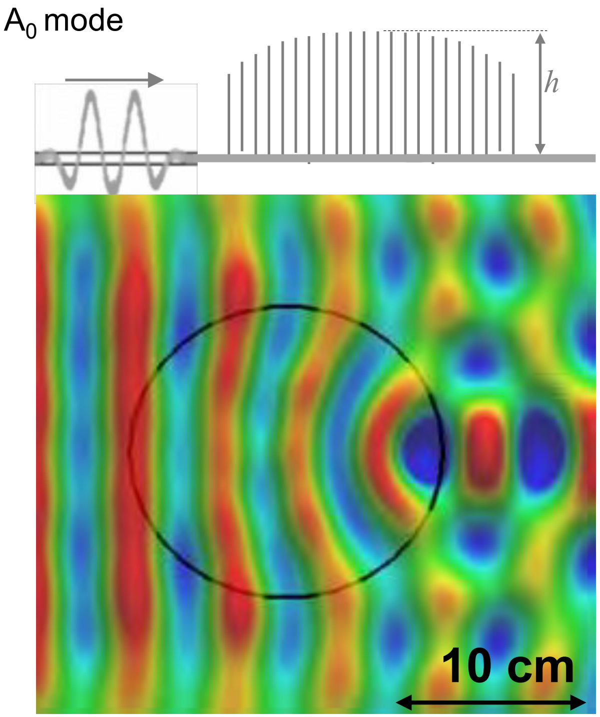


*Colombi, JASA-EL, 2016*

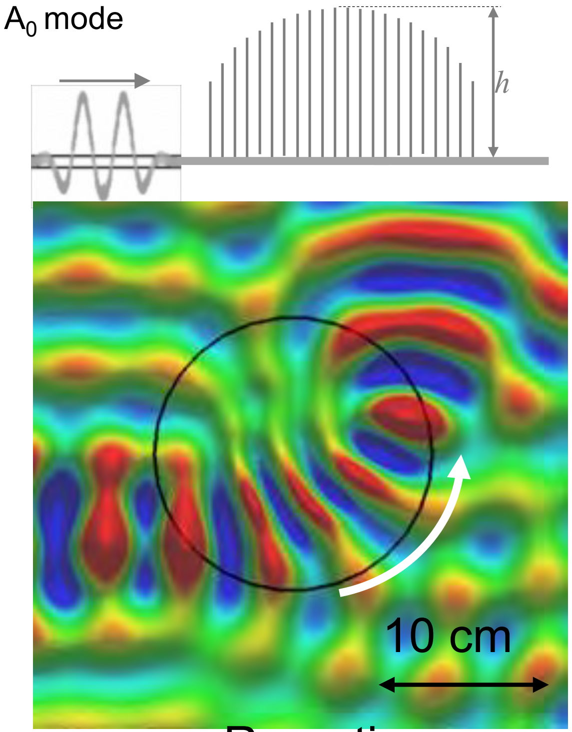
# Plate Wave Manipulation with Gradient Index Lenses



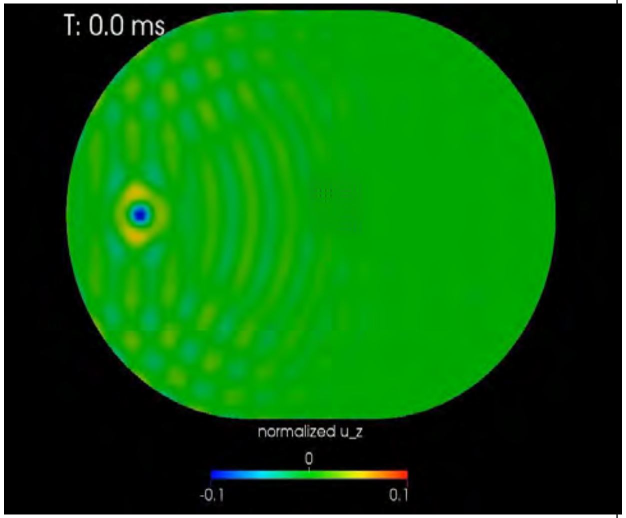
Bandgap

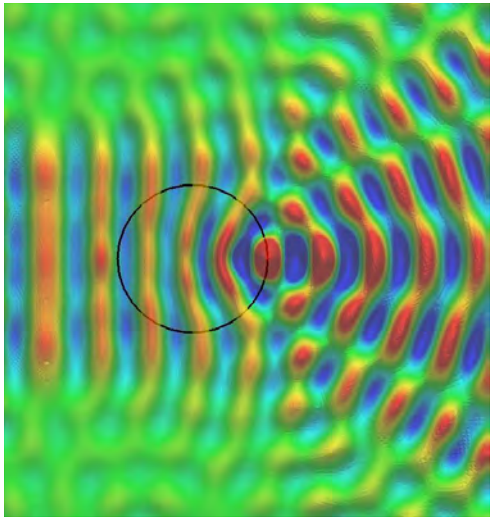


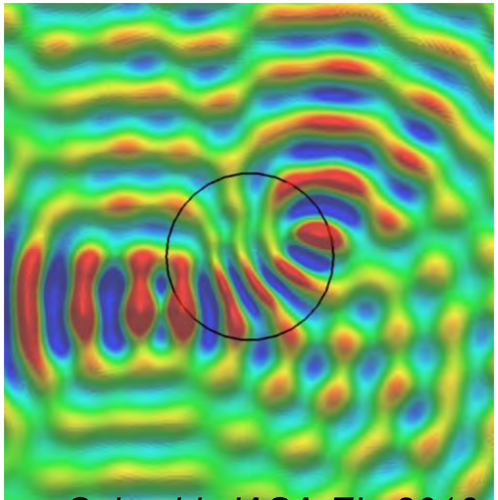
Focusing



Rerouting







*Colombi, JASA-EL, 2016*

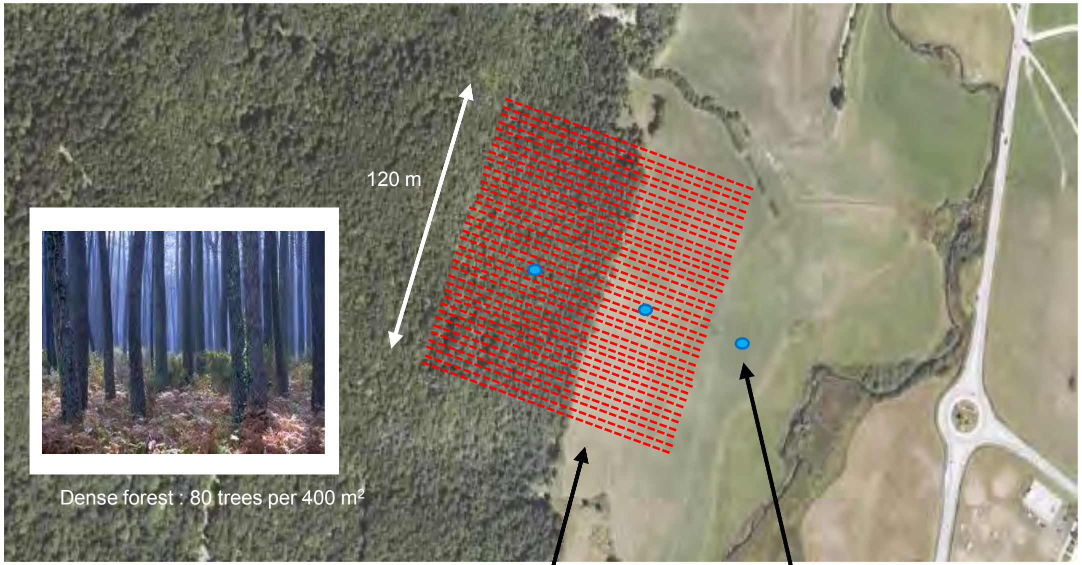
# Application at the geophysics scale : can we consider a forest as a natural Metamaterial?

ANR Project METAFORET
First experiment :
October 17-31st, 2016

META-FORET

https://metaforet.osug.fr

AGENCE
NATIONALE
DE LA
RECHERCHE

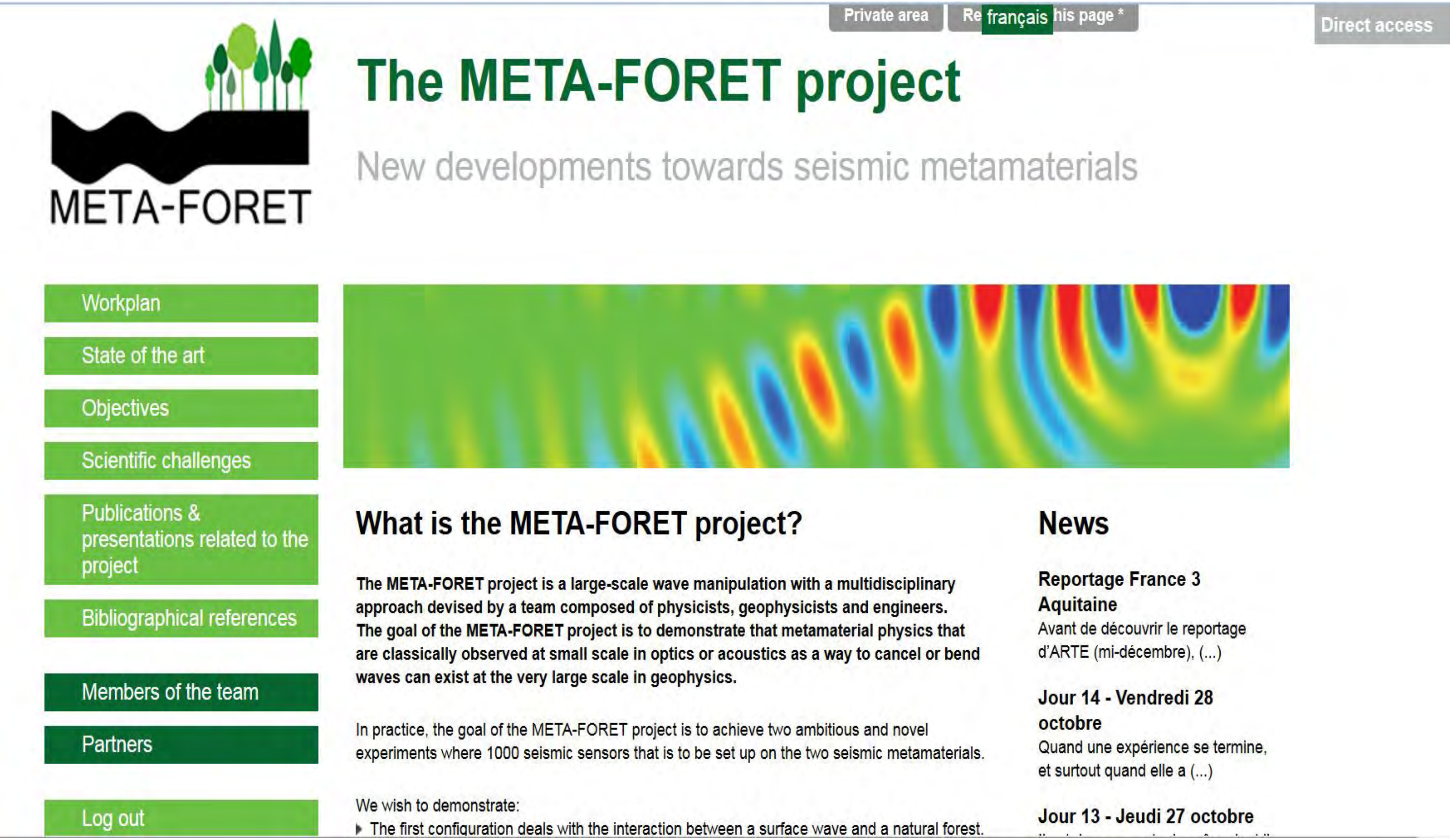


Dense forest : 80 trees per 400 $m^2$

Dense geophone array with
31 x 31 = 961 sensors

Wireless geophone

Vibrating source :
vibrometer



# 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**

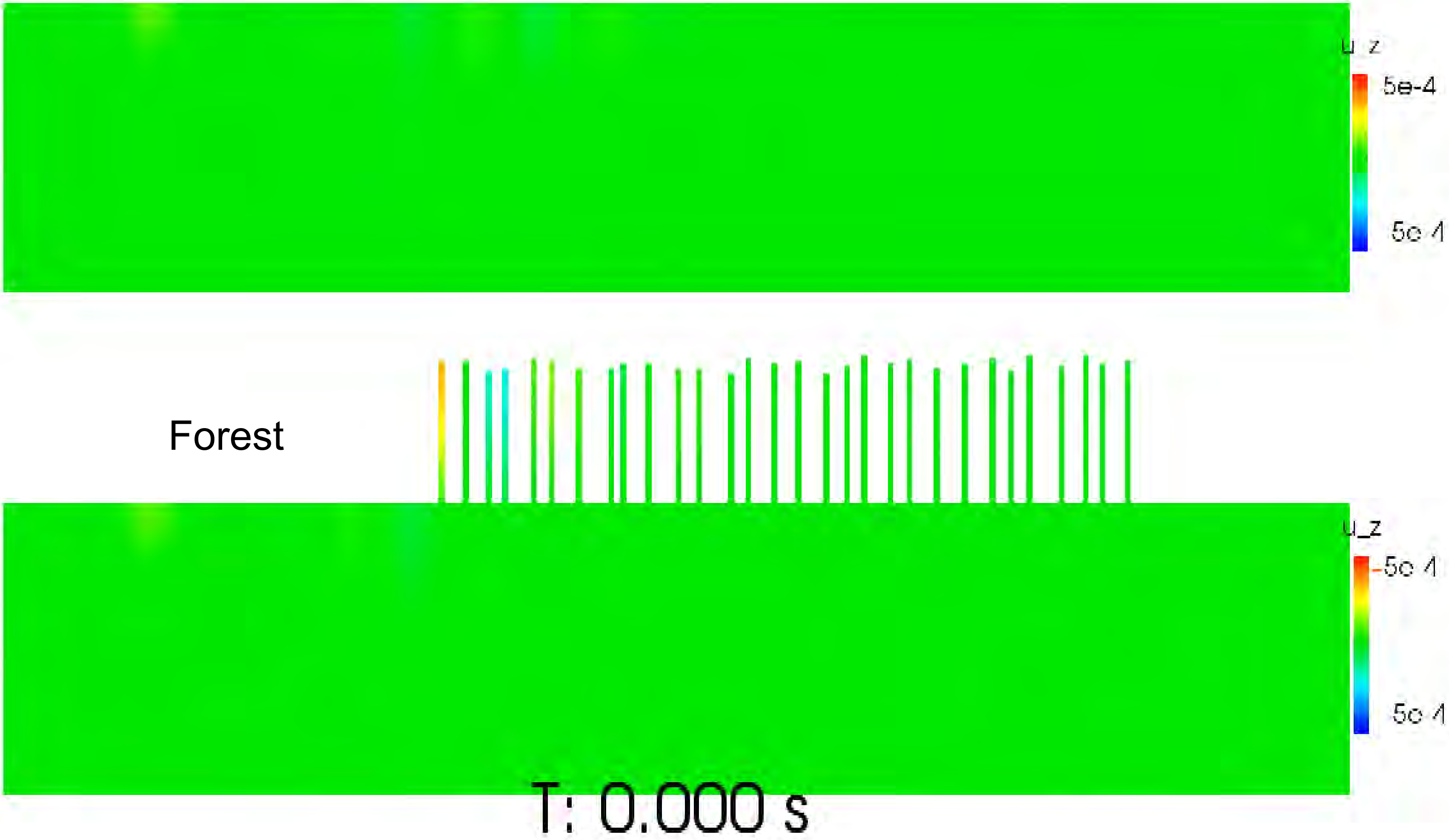
*Data available at htpps://metaforet.osug.fr*

# Rayleigh wave interacting with resonating trees?

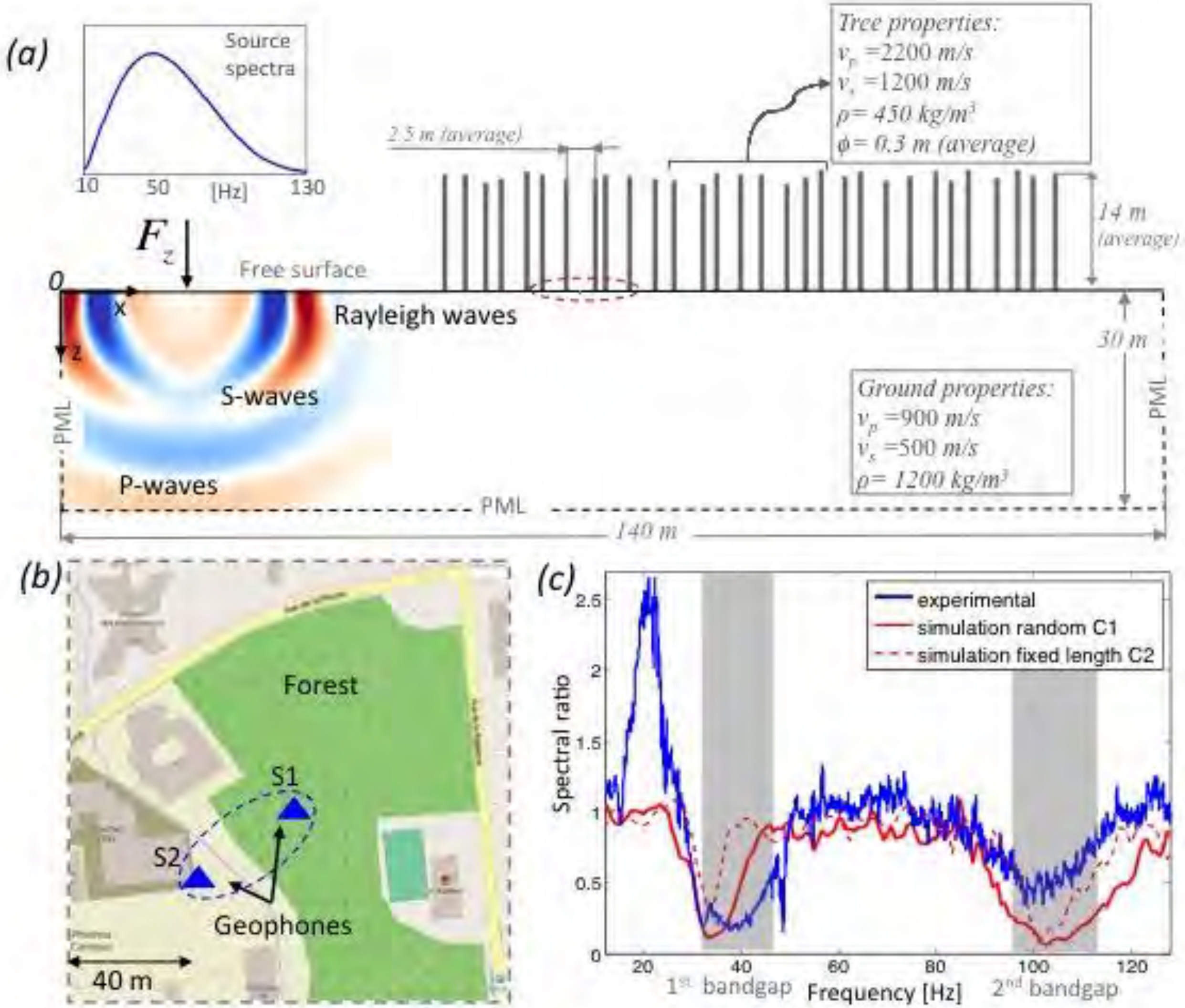
Reference

32 Hz - 42 Hz

Forest



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



*Colombi et al., Scientific Reports, 2016*

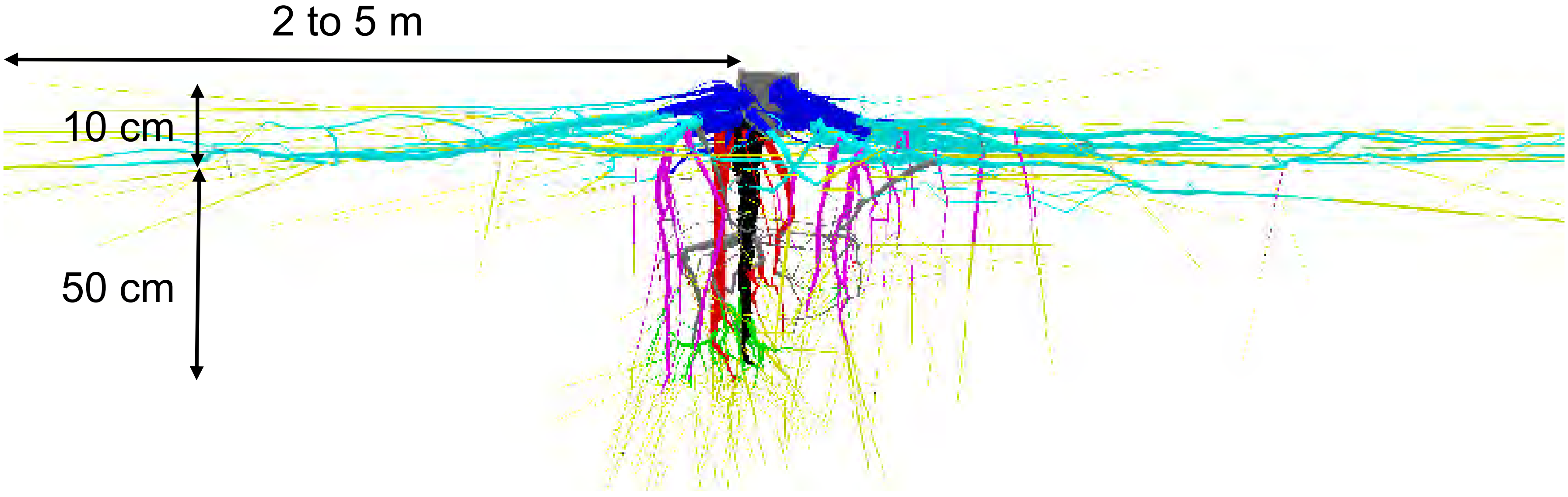
# Preparation of the METAFORET Experiment (2016)

Collaborations with CNPF,

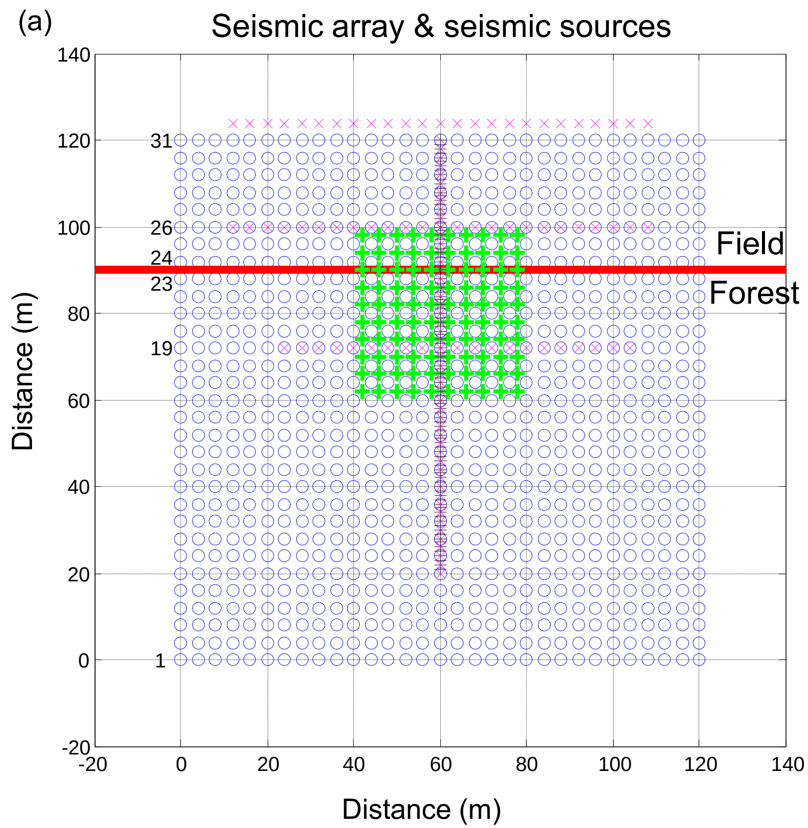
INRA BIOGECO & ISPA

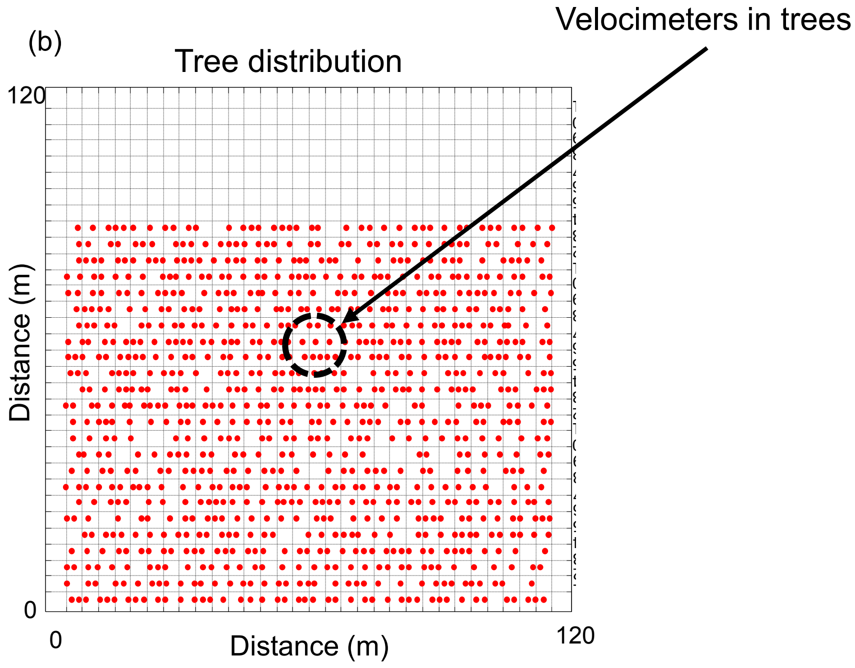
Choice of the forest area

Role of roots, soil properties, …



# The METAFORET project : experimental configuration





**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

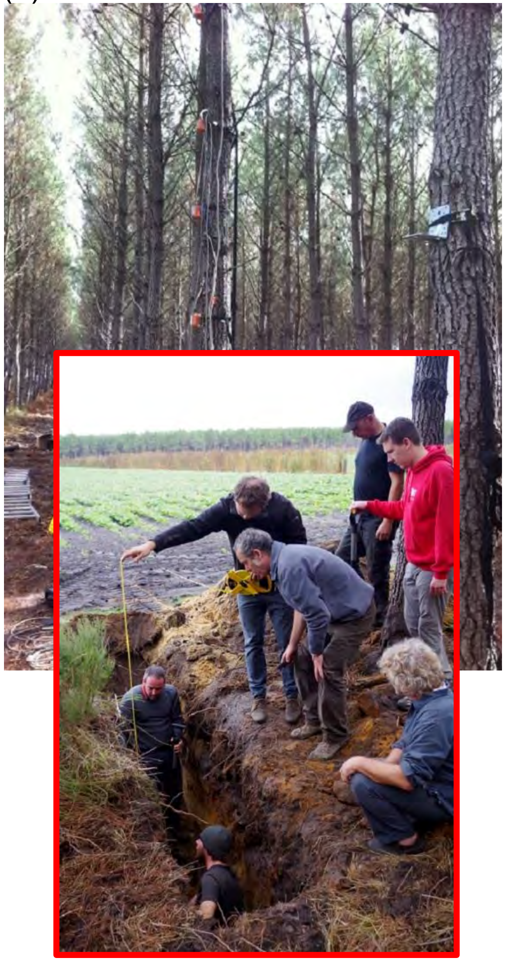
(a) 2D Seismic array with Z-land geophones

(b) Line array with GFZ geophones

(c) Vibrometer source (> 15 Hz)

# The METAFORET experiment

(a) Tree instrumented with 6 velocimeters



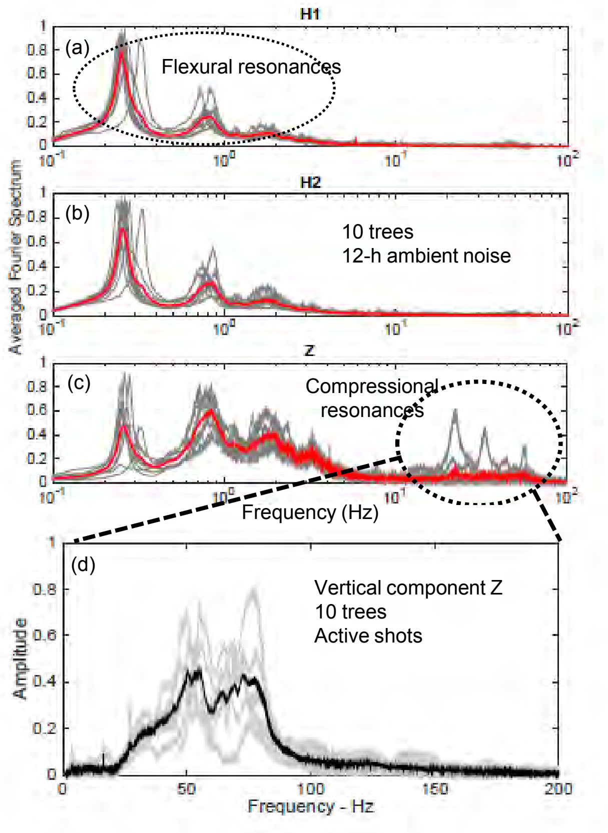
(b) Ground Penetrating Radar survey

# The METAFORET project : seismic data

## Velocimeters in trees

Ambient noise

Active source
(above 15 Hz)



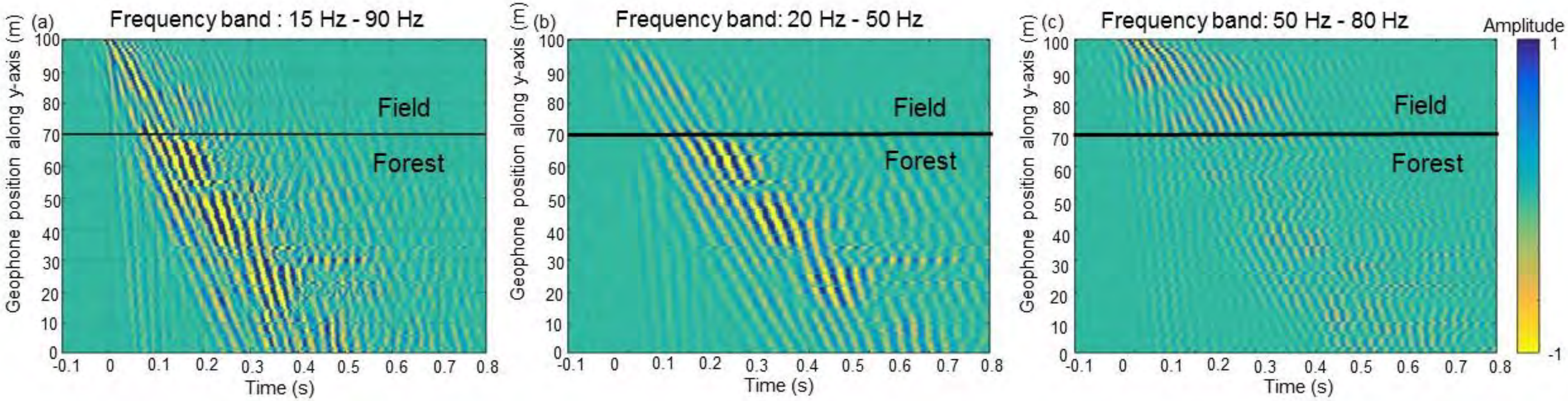
Flexural resonances

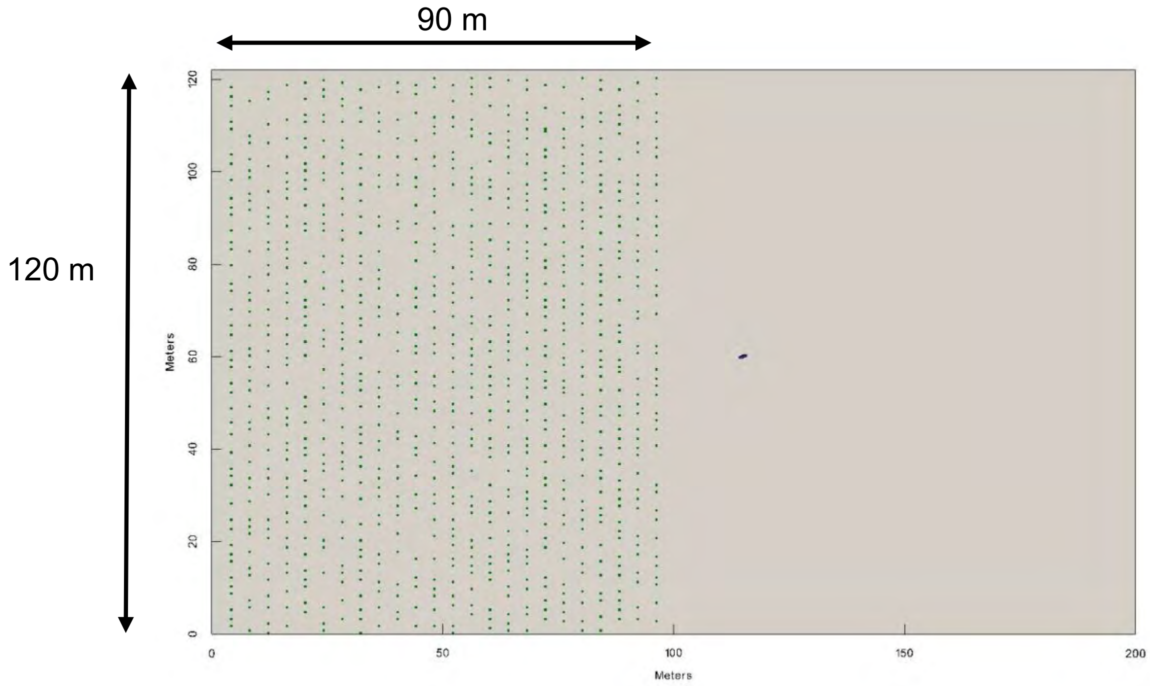
10 trees
12-h ambient noise

Compressional
resonances

Vertical component Z
10 trees
Active shots

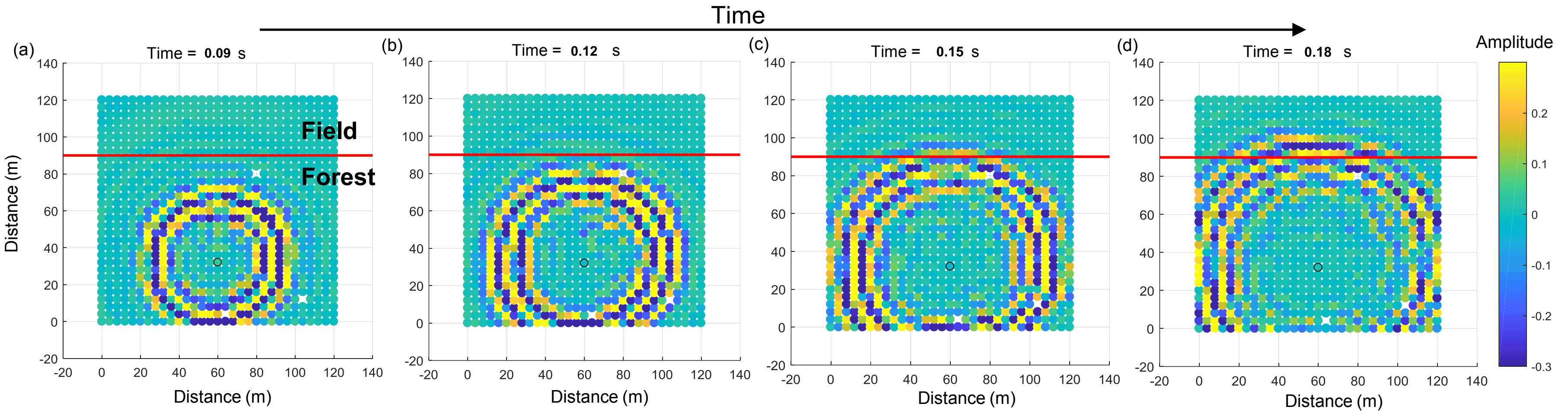
# The METAFORET data : Active Source on 1-D Line Array



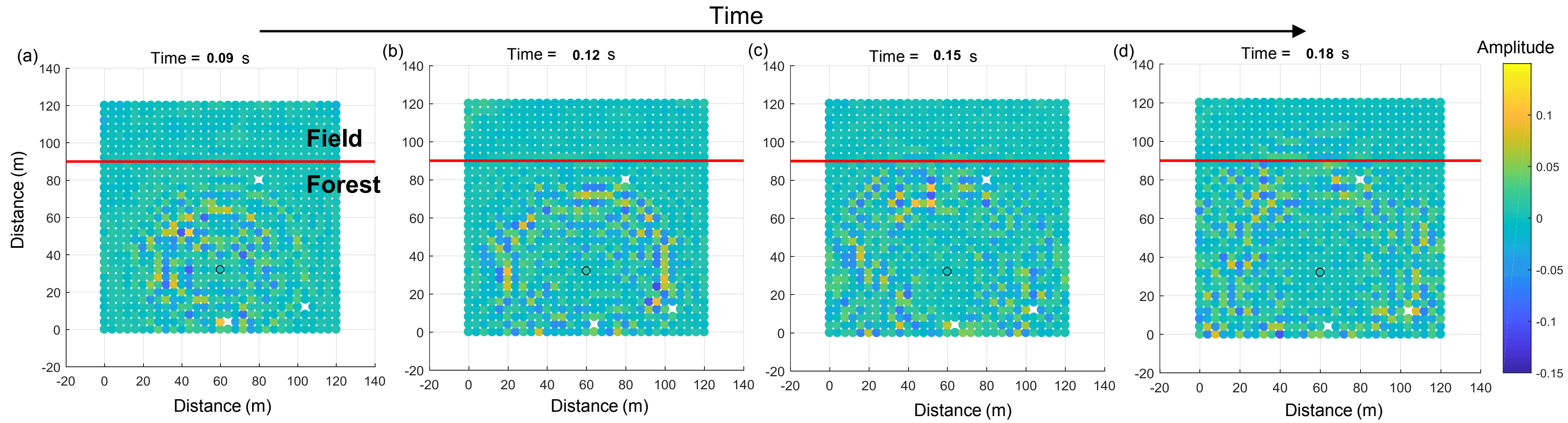


# The METAFORET data : Active Source on 2-D Surface Array

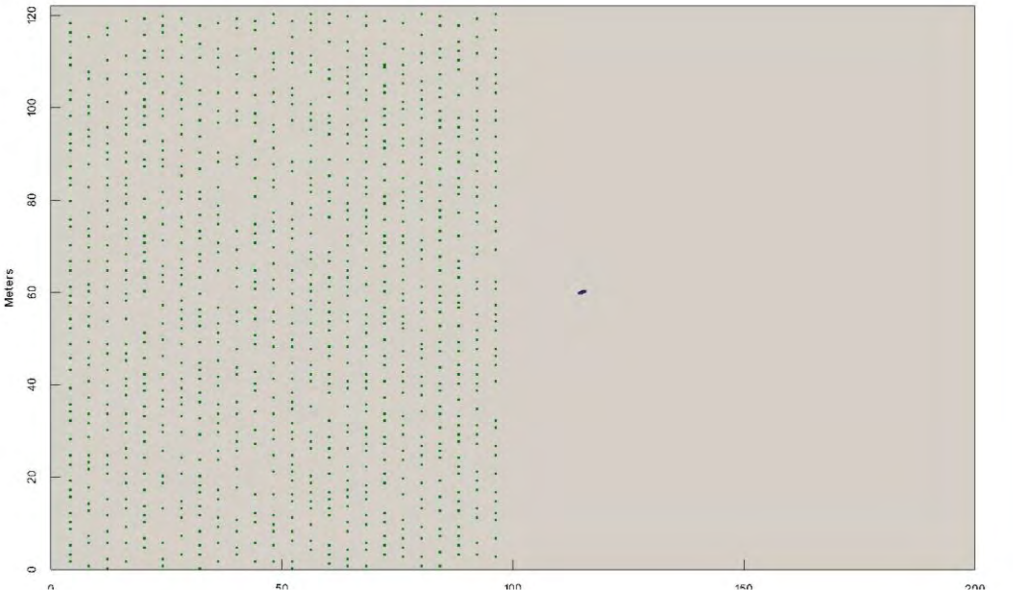
Frequency : 20 Hz - 50 Hz : below the tree compressionnal resonances



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



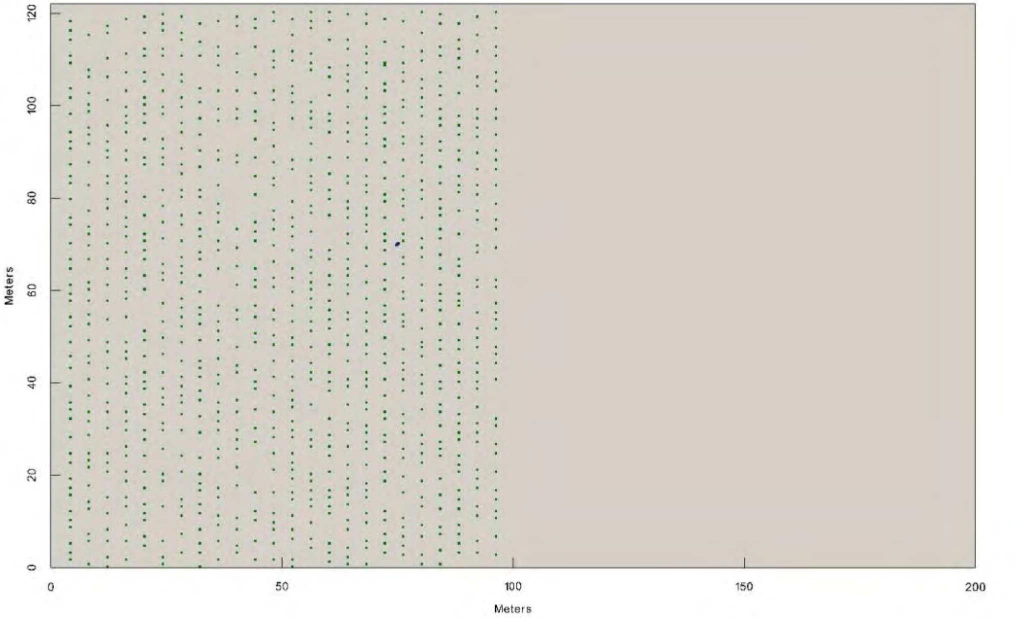
Active source
outside of the forest



90 m

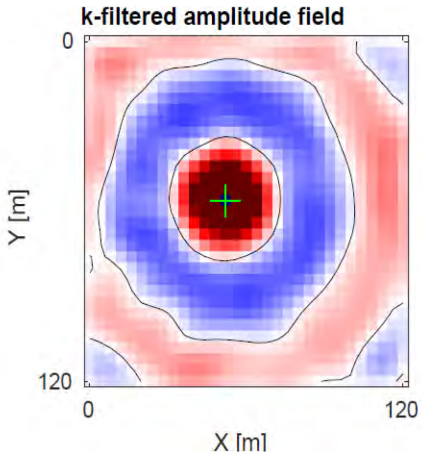
120 m

Active source
inside the forest

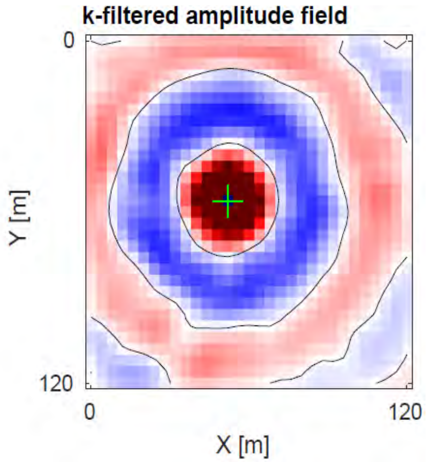


# The METAFORET data : Ambient noise on 2-D Surface Array

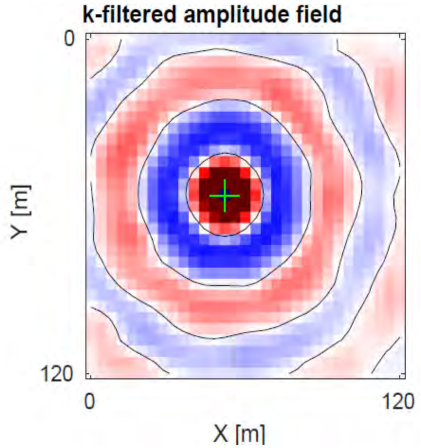
(a) **4 Hz**



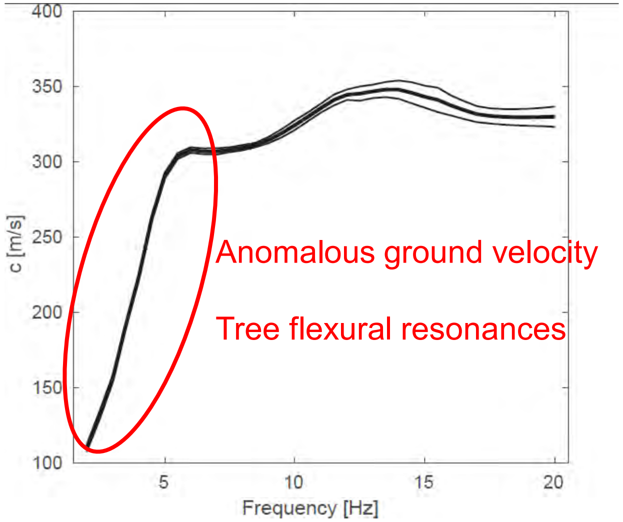
(b) **6 Hz**



(c) **8 Hz**



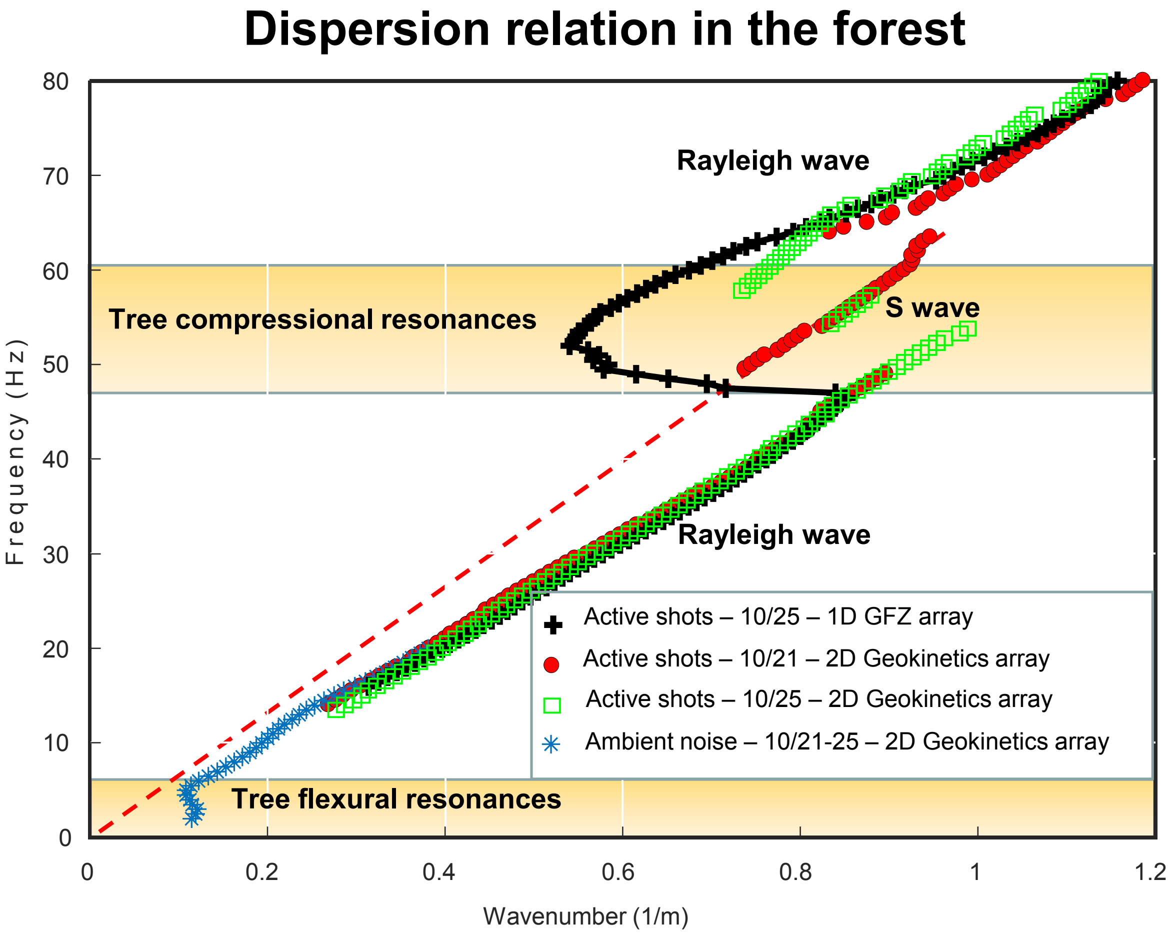
Dispersion curve from ambient noise (<20 Hz)



Anomalous ground velocity

Tree flexural resonances

# The METAFORET Experiment : First Conclusions



# (Nearby) Perspectives for Seismic Metamaterial (2019)

Wind turbine fields (California)

NEW!

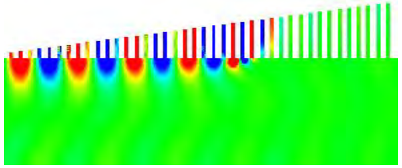
*http://www.vortexbladeless.com/home.php*

H = 170 m
Power ~ 1 MW

New generation of « seismic – environmentally » friendly metamaterial : Vortex Bladeless use laminar flows

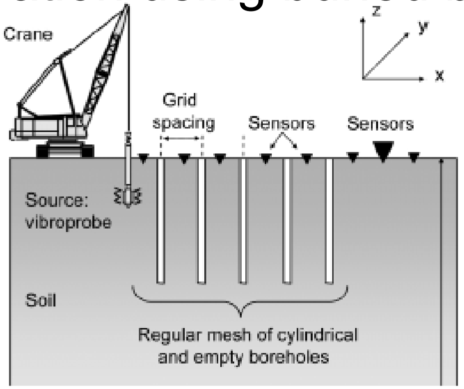
# Other Attempts with Seismic Metamaterials

- The Metawedge configuration

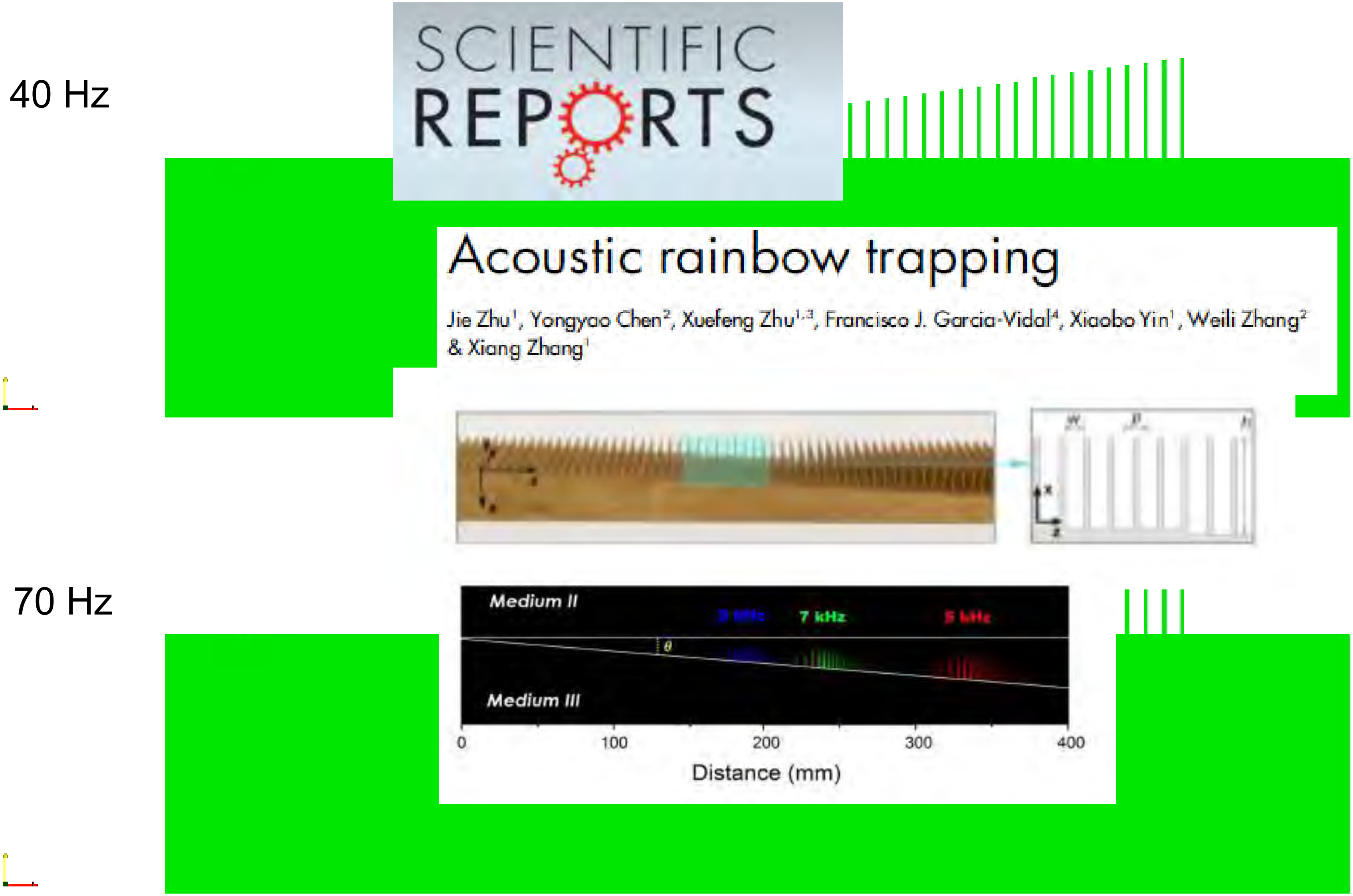


- Seismic wave cancellation using buried resonators

- Seismic wave cancellation using buried beams



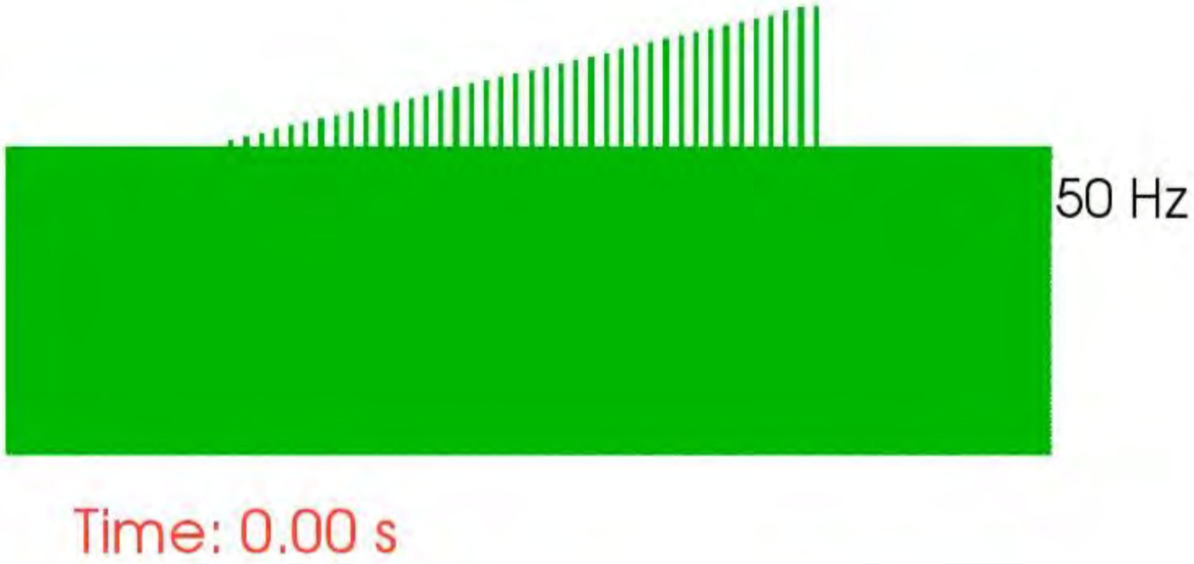
# Trees with different height : The seismic rainbow

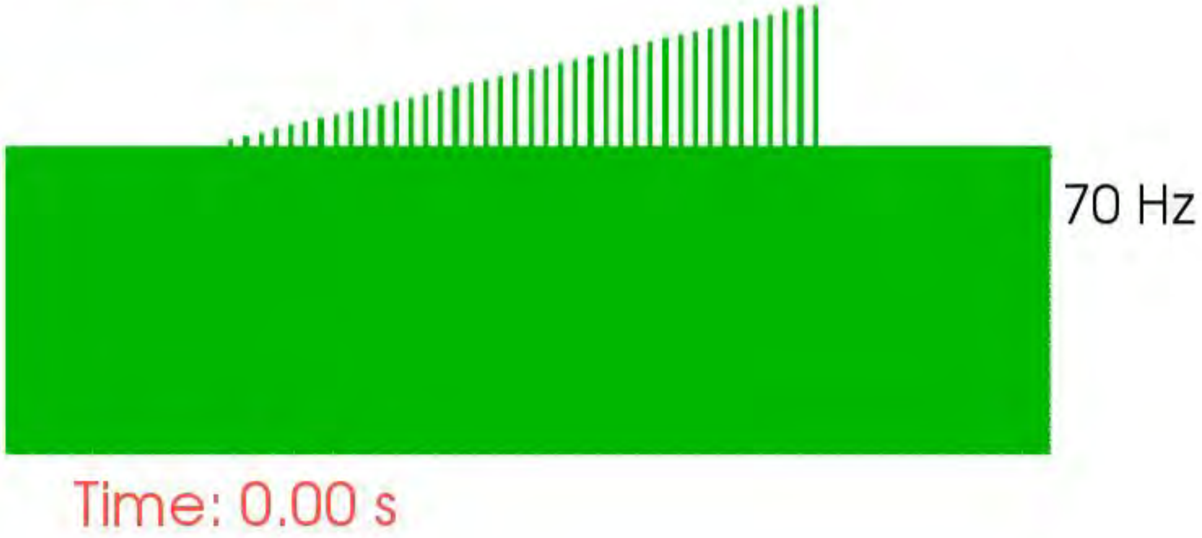


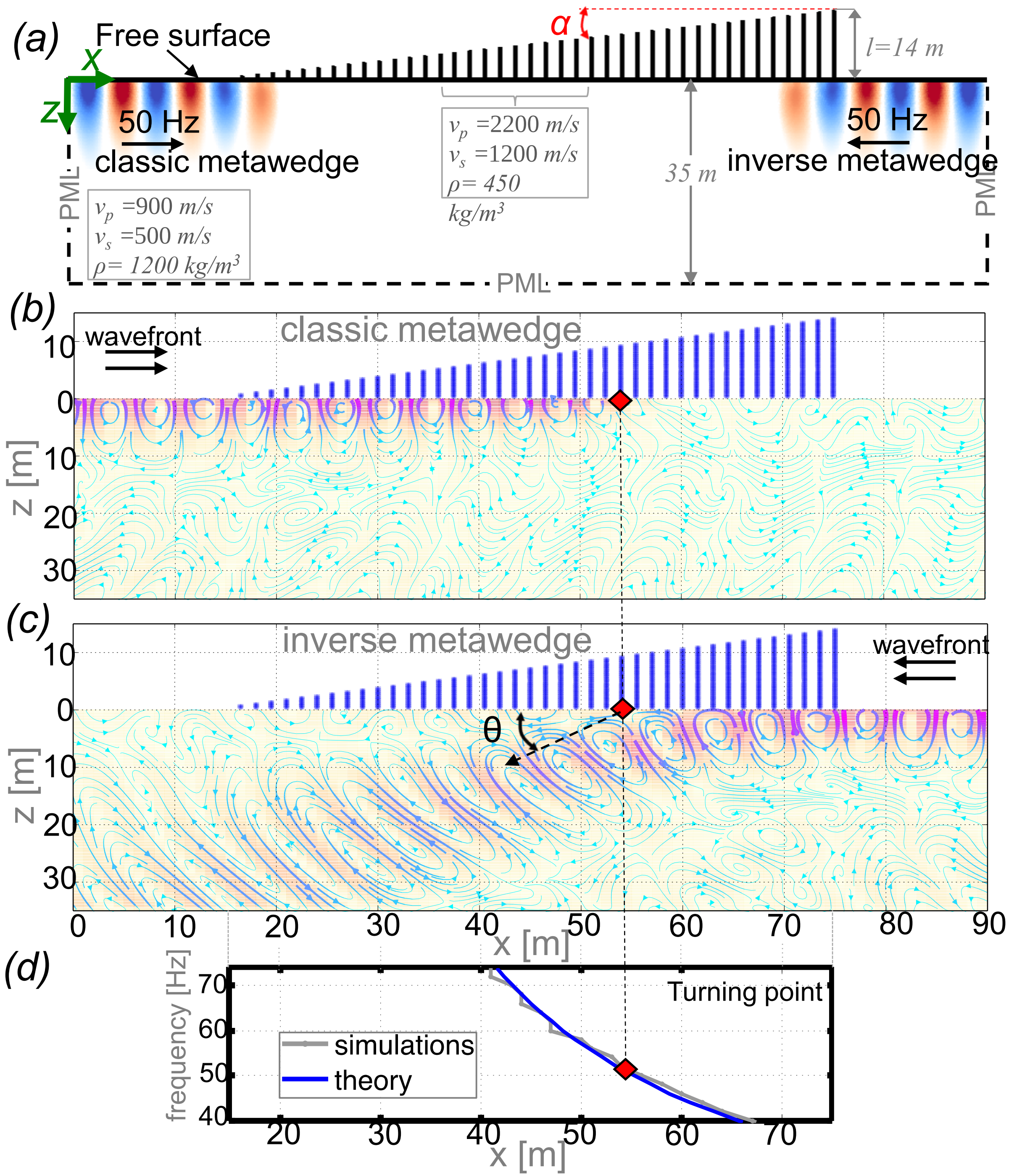
Acoustic rainbow trapping

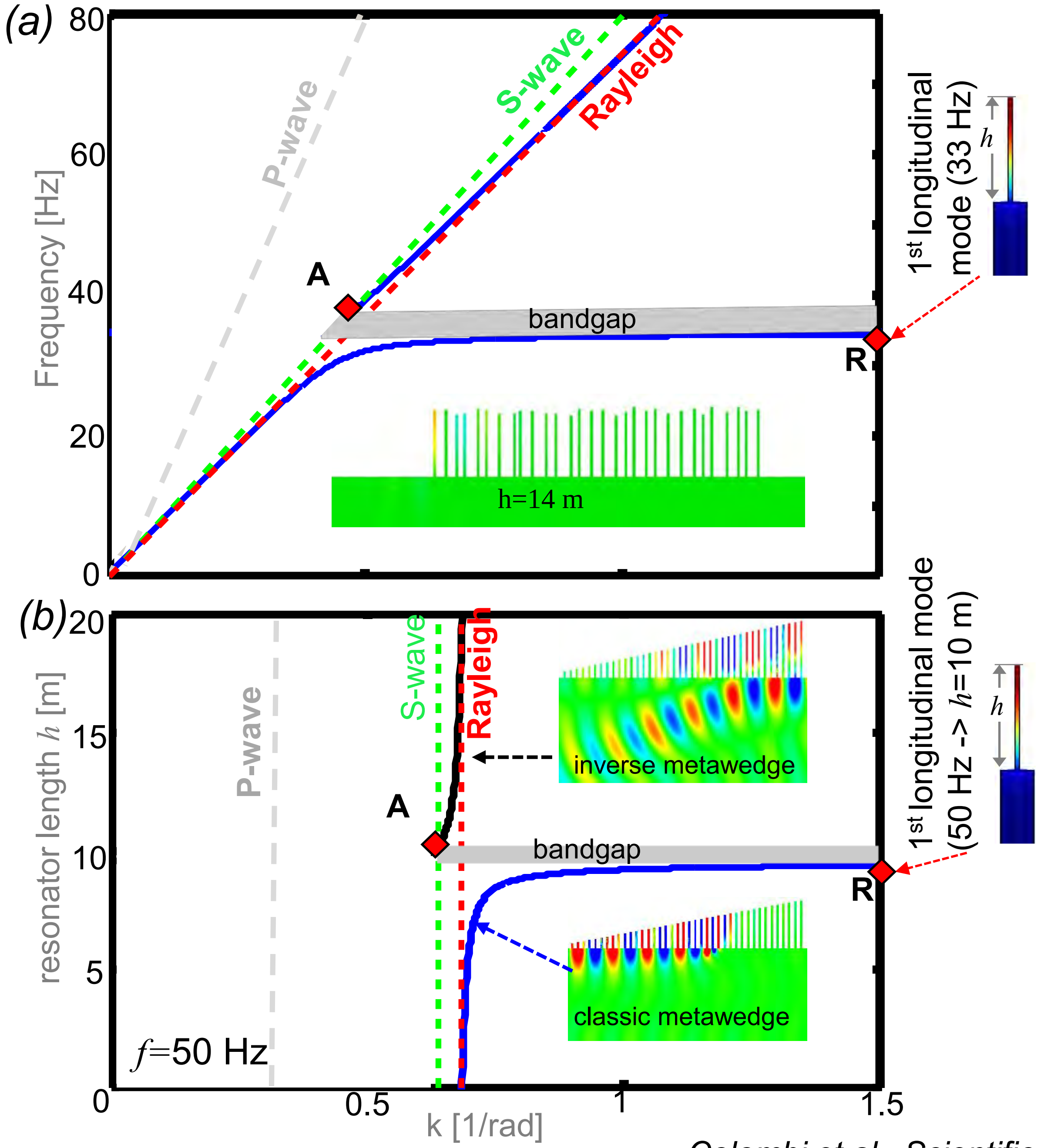
Jie Zhu[1], Yongyao Chen[2], Xuefeng Zhu[1,3], Francisco J. Garcia-Vidal[4], Xiaobo Yin[1], Weili Zhang[2] & Xiang Zhang[1]

# Trees with different height : The inverse wedge effect






(a)
Free surface
x
z
α
l=14 m
50 Hz
classic metawedge
$v_p$ =2200 m/s
$v_s$ =1200 m/s
ρ= 450 kg/m³
35 m
50 Hz
inverse metawedge
PML
$v_p$ =900 m/s
$v_s$ =500 m/s
ρ= 1200 kg/m³
PML
PML
(b)
wavefront
classic metawedge
10
0
10
20
30
z [m]
(c)
inverse metawedge
wavefront
θ
10
0
10
20
30
z [m]
0
10
20
30
40
50
60
70
80
90
x [m]
(d)
frequency [Hz]
70
60
50
40
Turning point
simulations
theory
20
30
40
50
60
70
x [m]



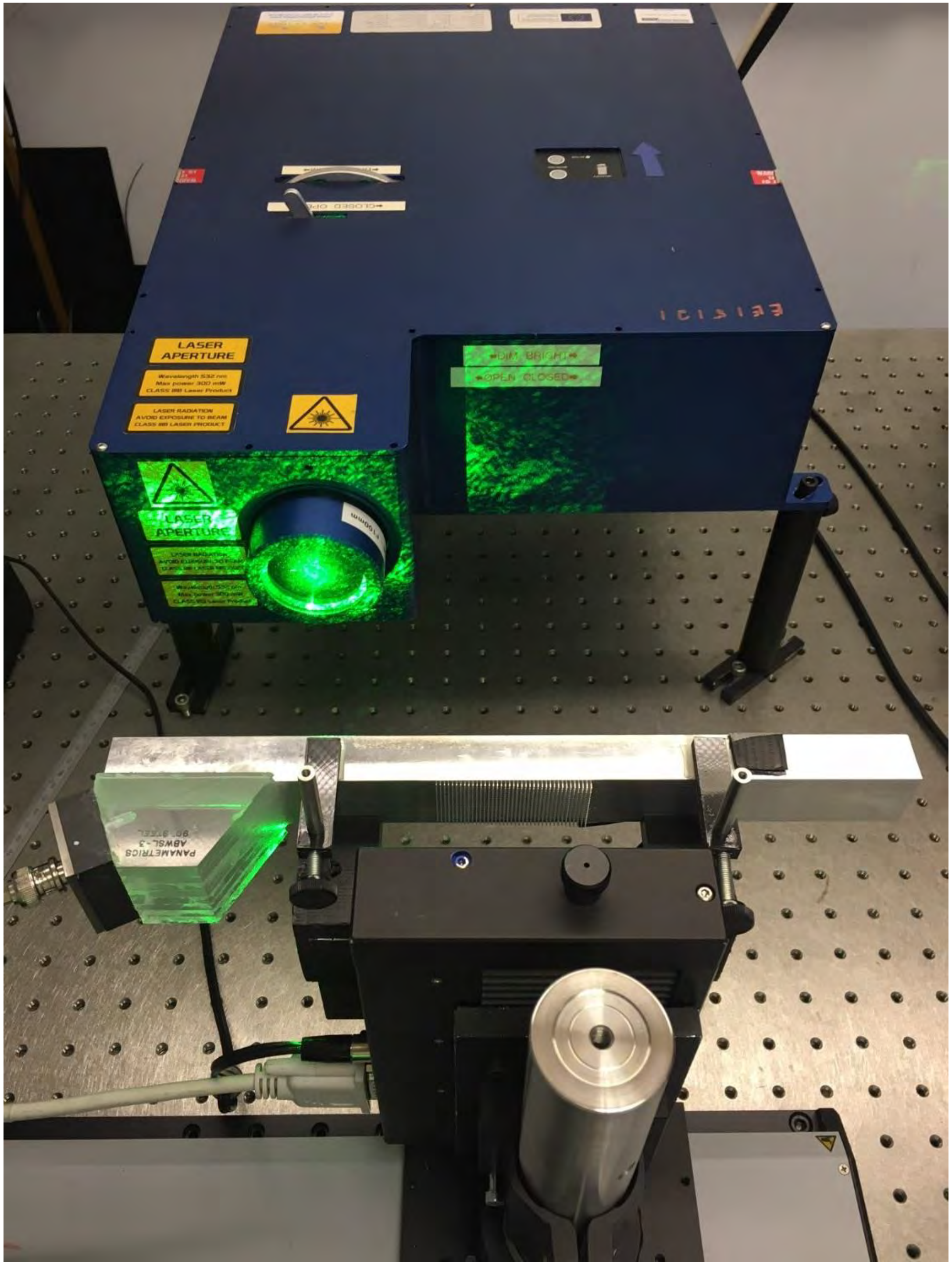
*Colombi et al., Scientific Reports, 2016*

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

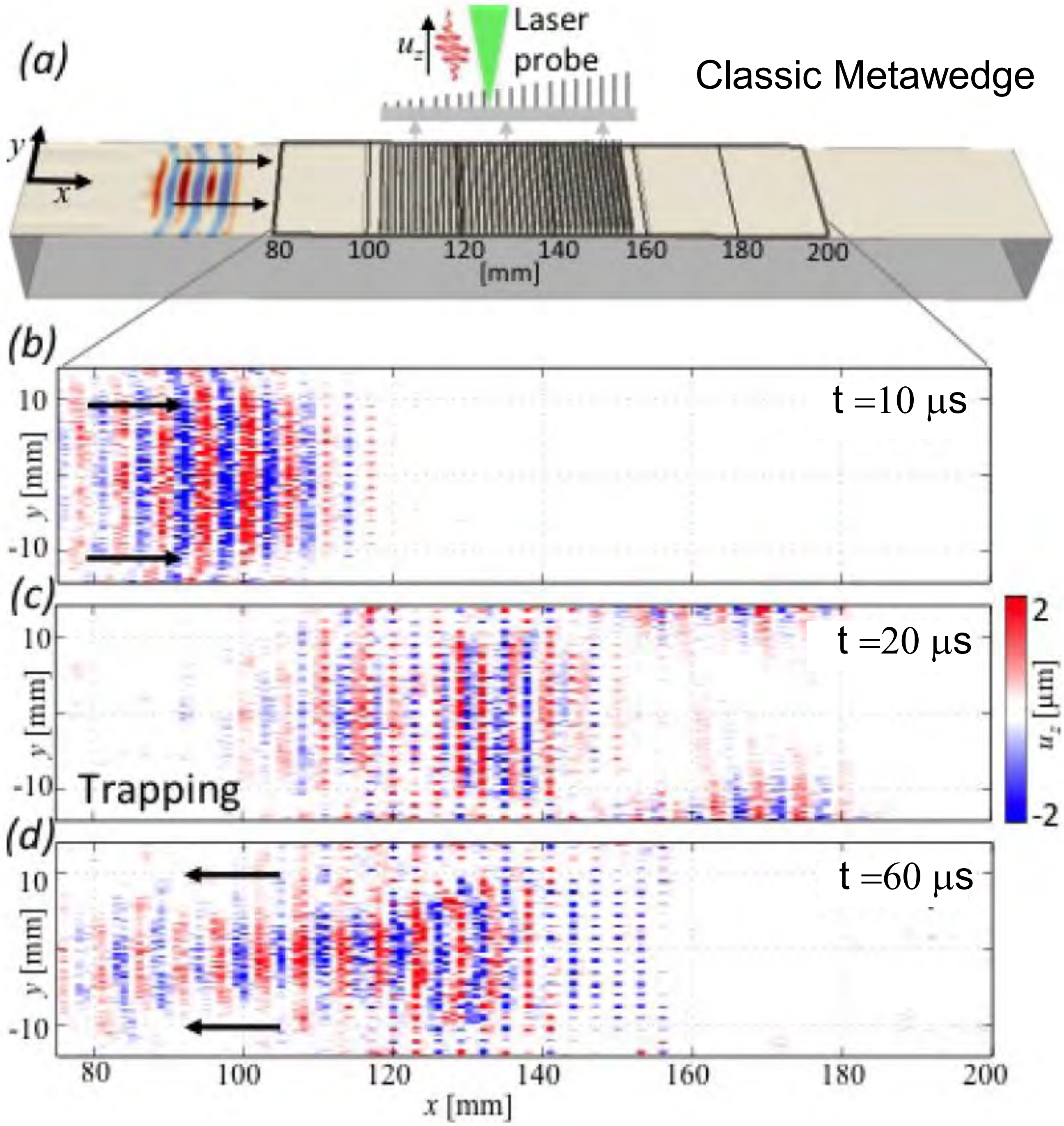
**Matt Clark's group**

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

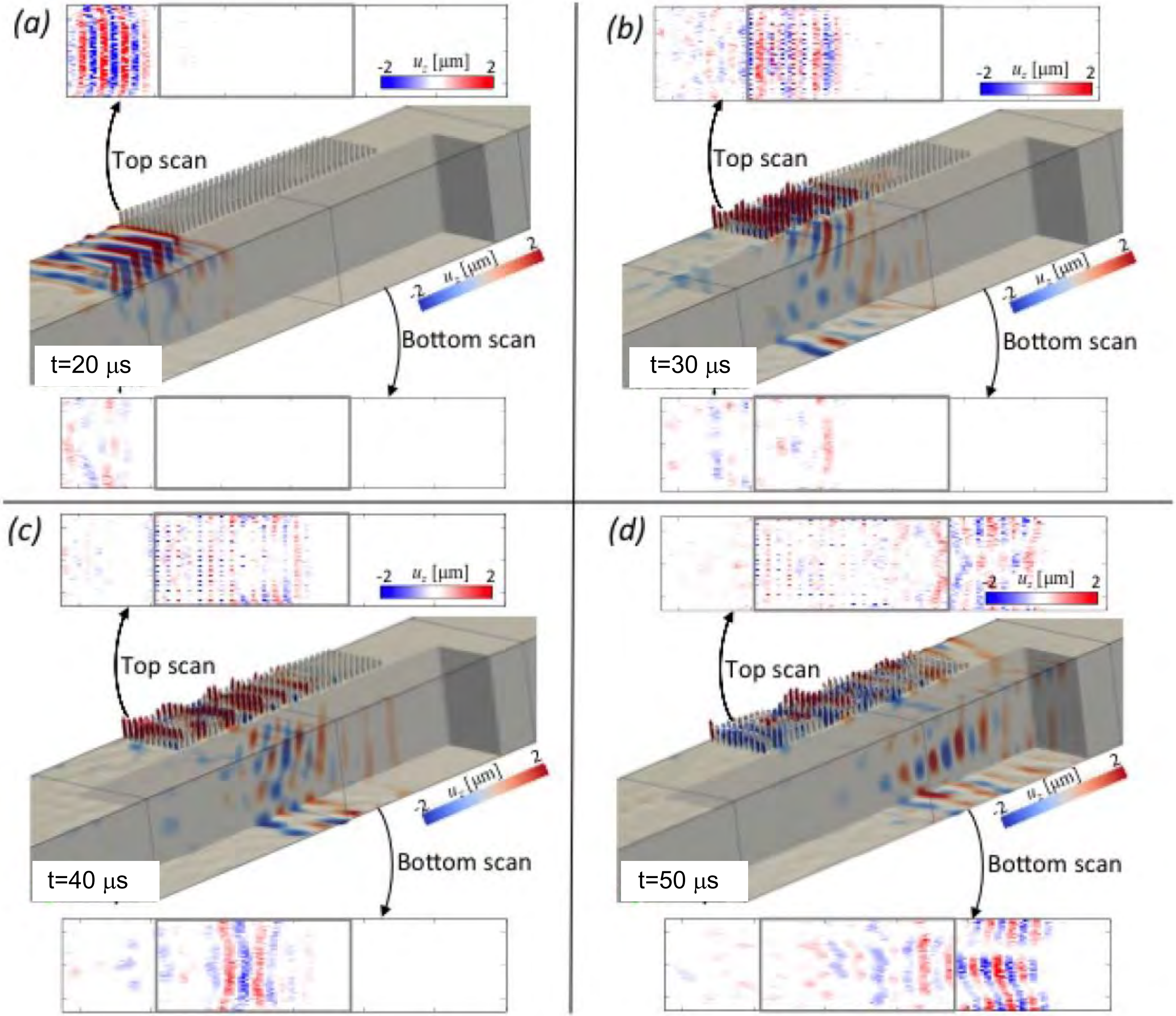
*Colombi et al., Scientific Reports, 2017*



# Classic Metawedge

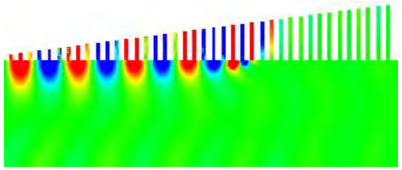


# Inverse Meta-wedge



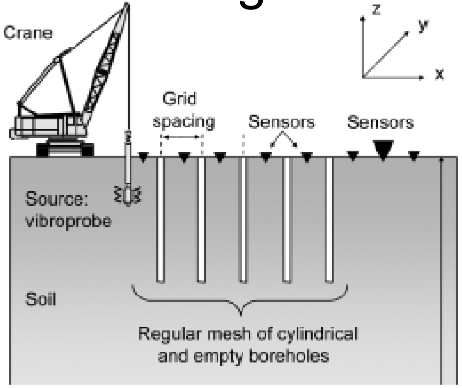
# Other Attempts with Seismic Metamaterials:

- The Metawedge configuration



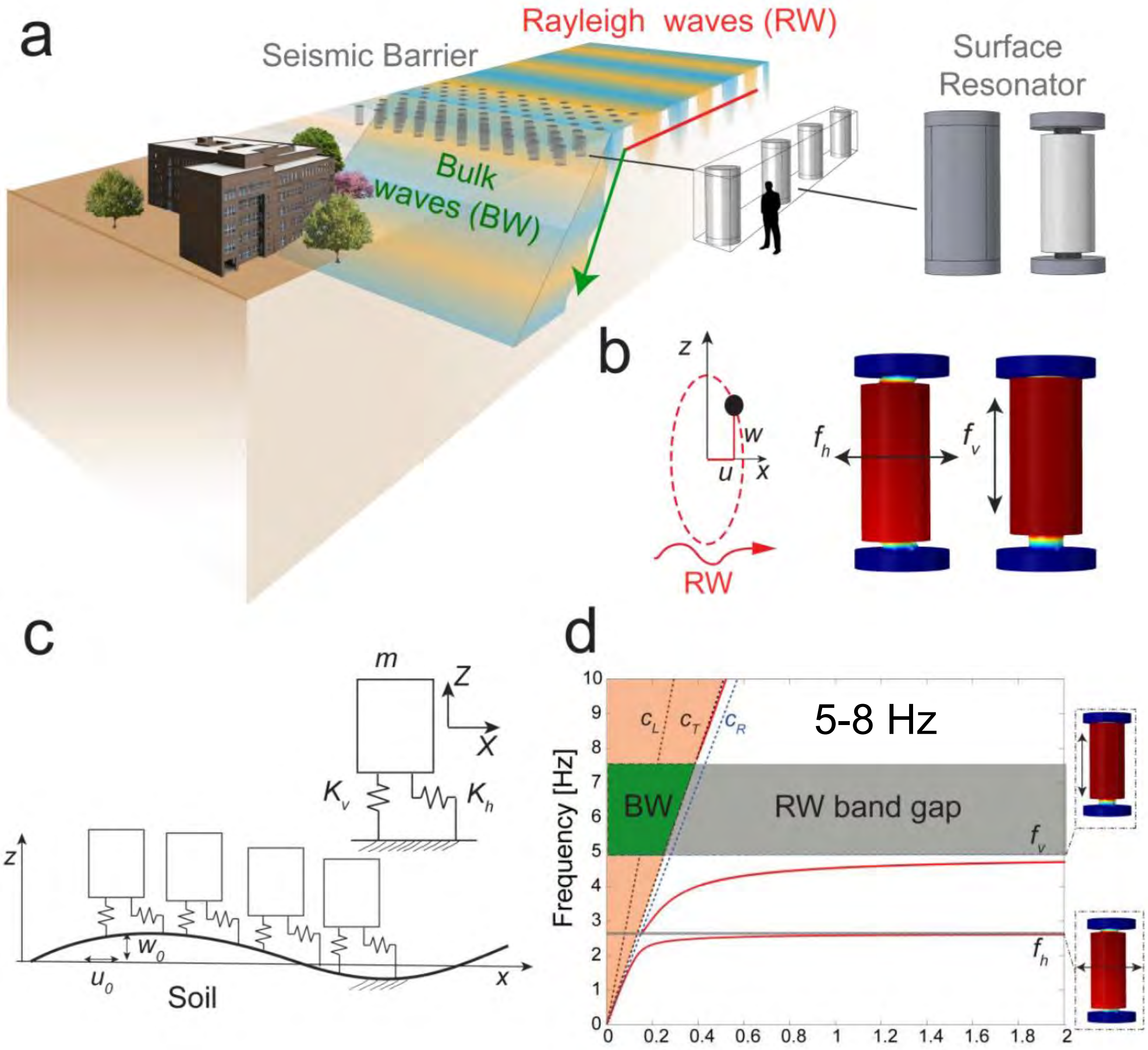
- Seismic wave cancellation using buried resonators

- Seismic wave cancellation using buried beams

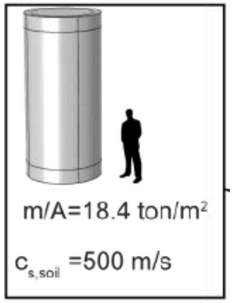


# Engineered Metabarrier as Shield from Seismic Surface Waves

*Palermo et al., Scientific Reports, 2017*

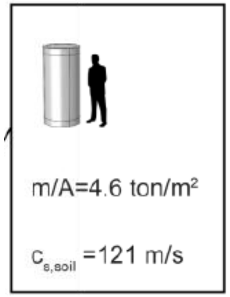


5-8 Hz



m/A=18.4 ton/m²

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

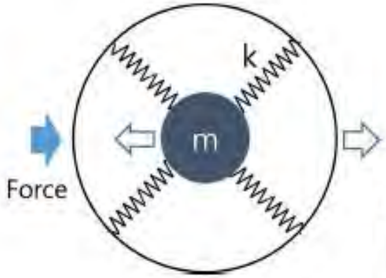


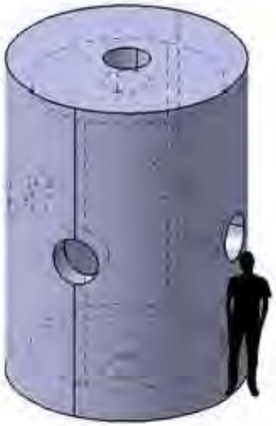
m/A=4.6 ton/m²

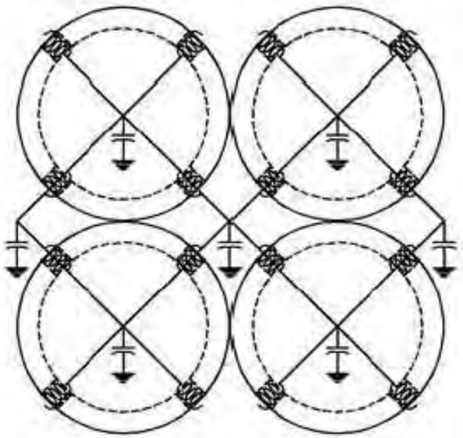
$c_{s,soil}$ =121 m/s

# Engineered Metabarrier as Shield from Seismic Surface Waves

m ~ 1000 kg







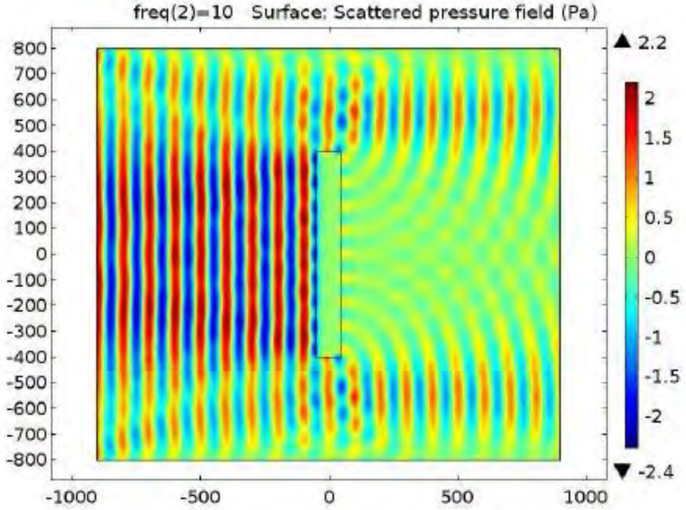
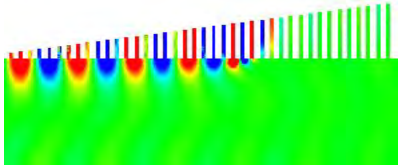


FIG. 3: Pressure distribution by a negative belt. Acoustic wave comes from the left side. Freq.= $10Hz$. The units are m.

*S-H Kim and M. Das, in press, 2017*

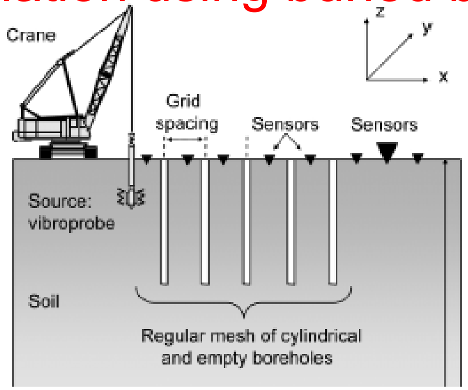
# Other Attempts with Seismic Metamaterials:

- The Metawedge configuration



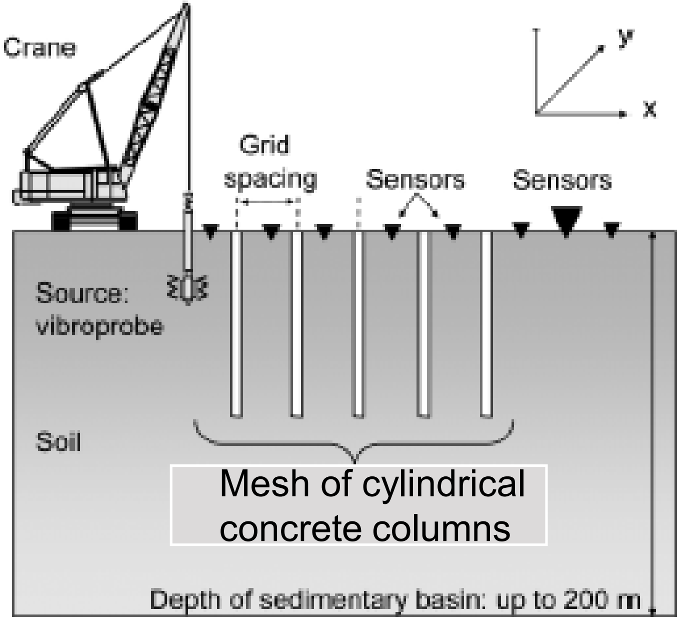
- Seismic wave cancellation using buried resonators

- Seismic wave cancellation using buried beams



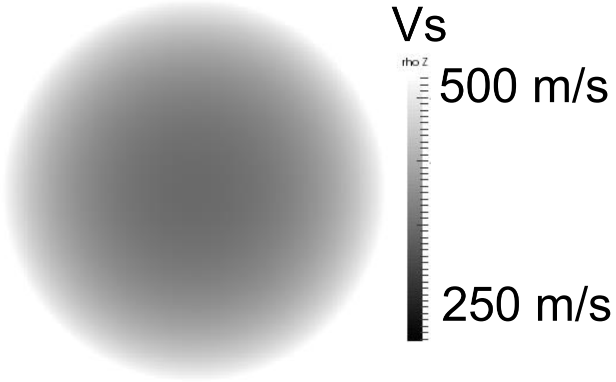
# Soil Reinforcement using Buried Vertical Concrete Beams

*Brule et al, PRL, 2014*

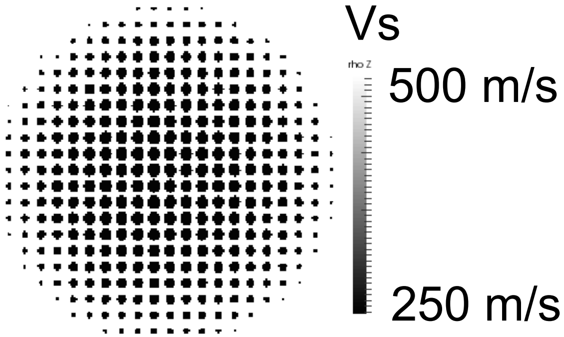


→ Local change of refraction index

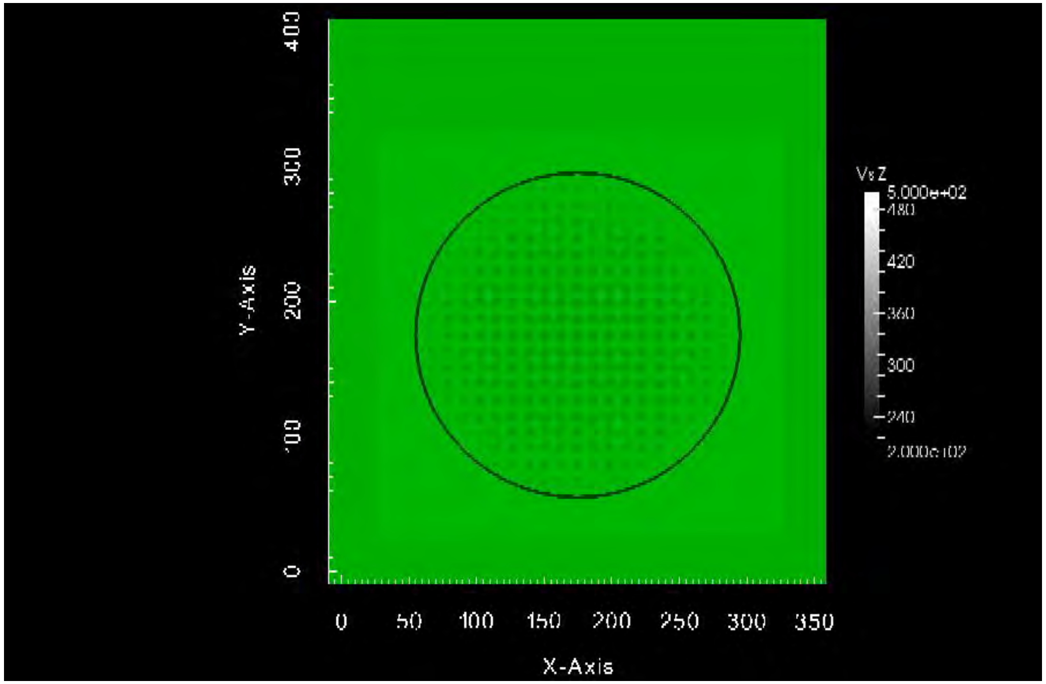
# Luneberg Lens applied to Geophysics



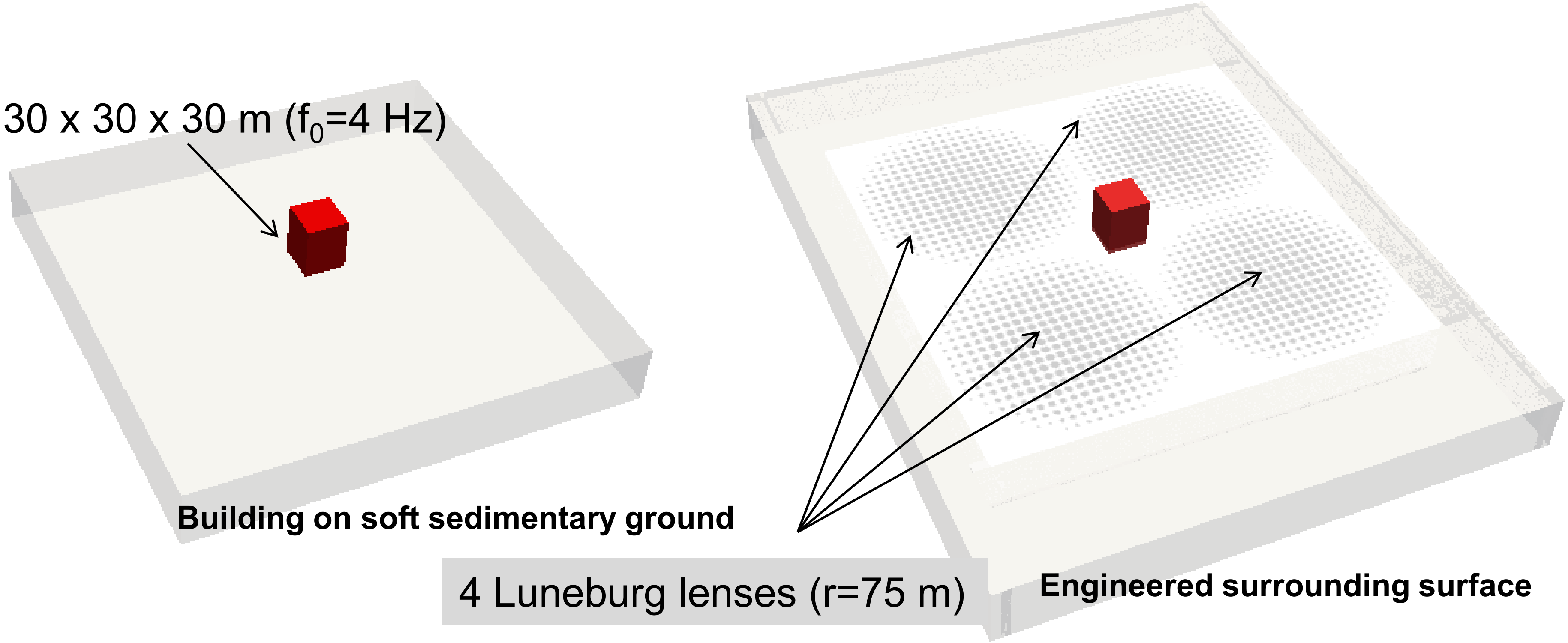
Continuous version



Discrete version



# Application to Seismic Protection



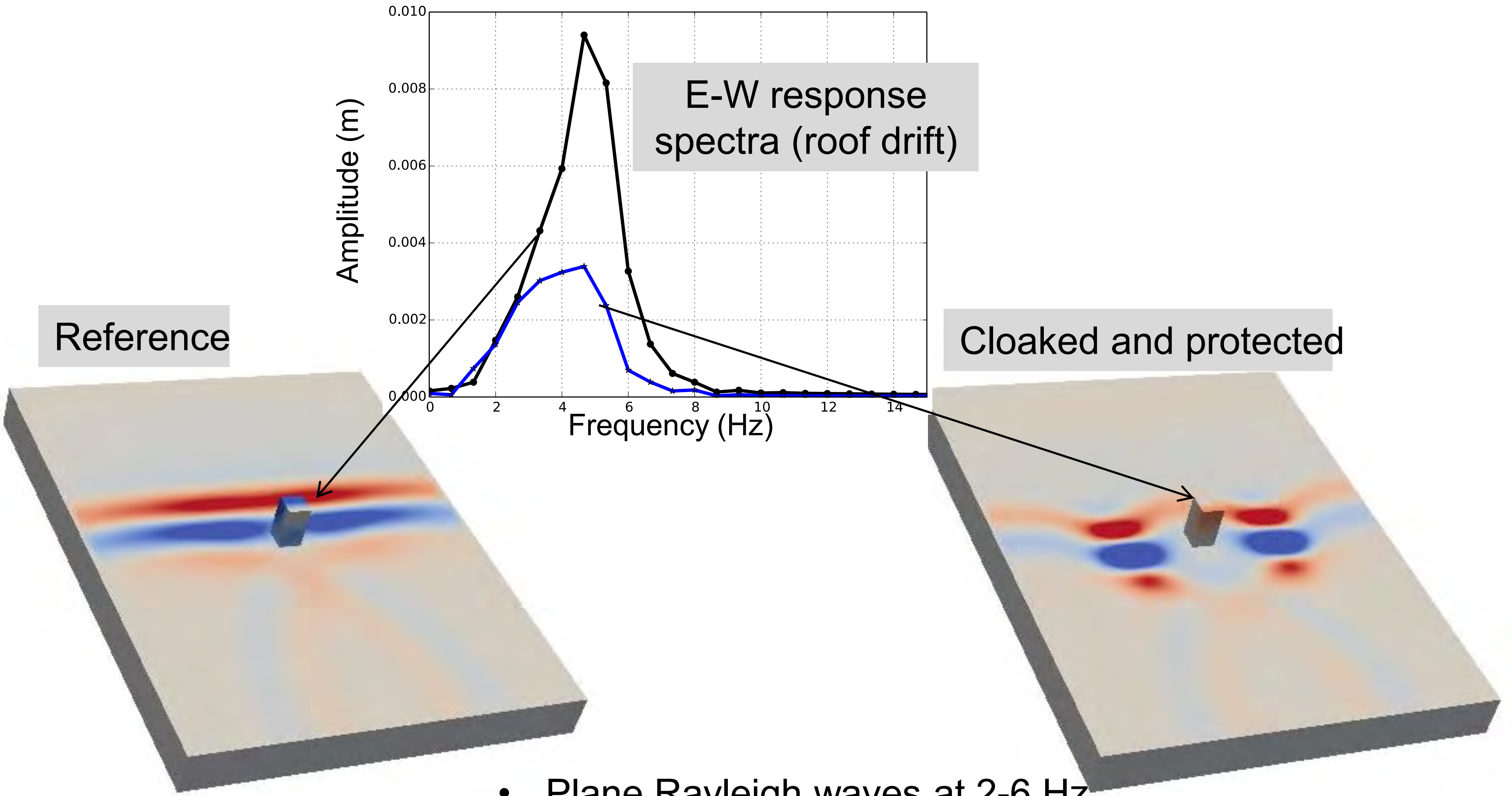
30 x 30 x 30 m ($f_0$=4 Hz)

**Building on soft sedimentary ground**

4 Luneburg lenses (r=75 m)

**Engineered surrounding surface**

# Application to Seismic protection



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

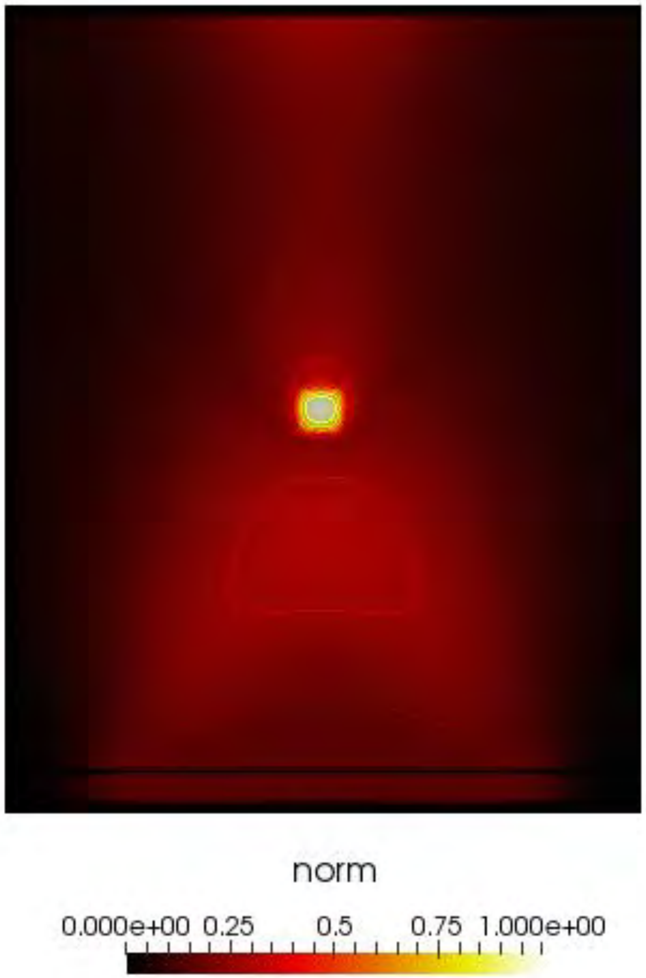
*Colombi et al., Scientific Reports, 2016*

# Application to Seismic protection

Cloaked and protected

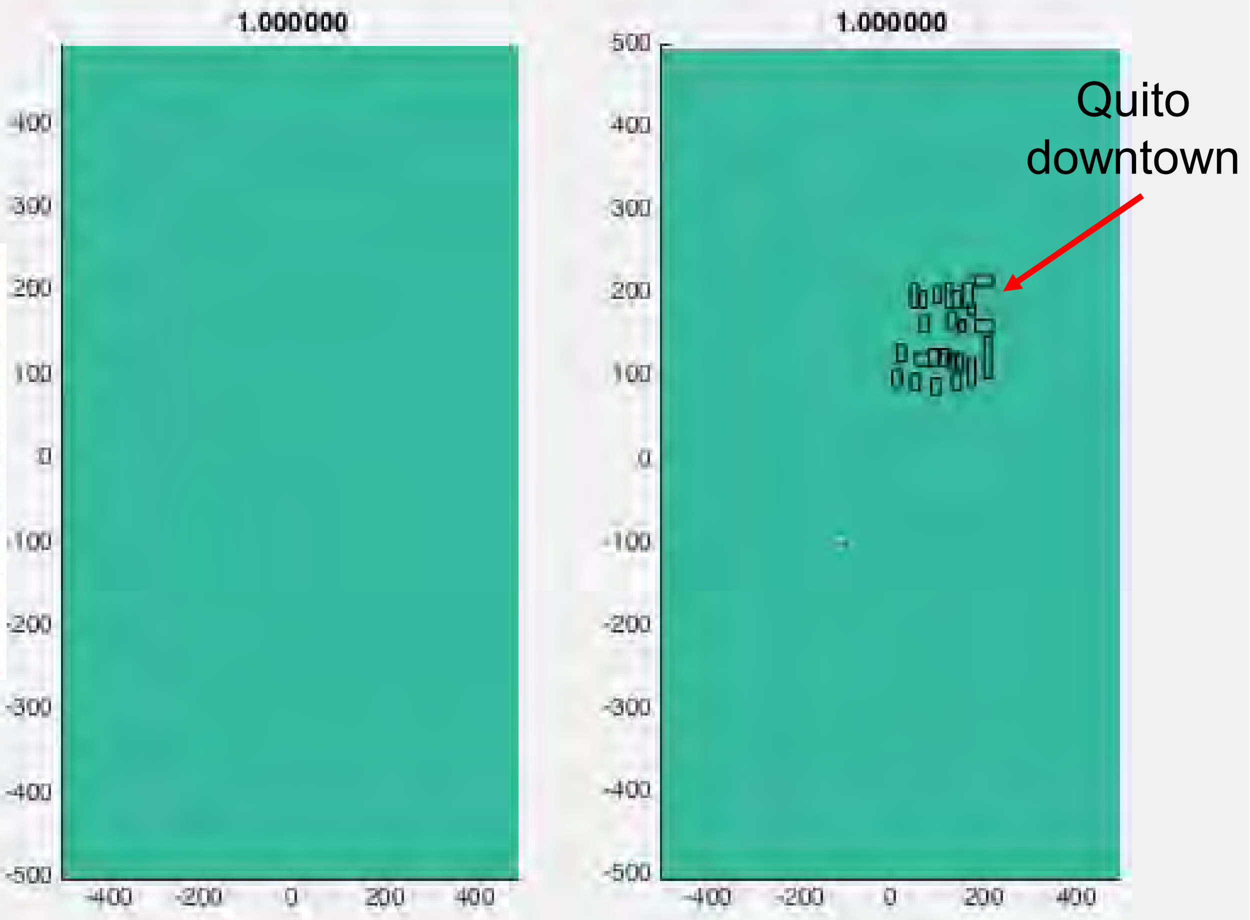
**Energy distribution**

Reference



# Work for the Future

## A City : Macroscopic Arrangement of Resonating Elements ?



*Colombi et al., BSSA, 2017*