# New Trends Towards Seismic Metamaterials

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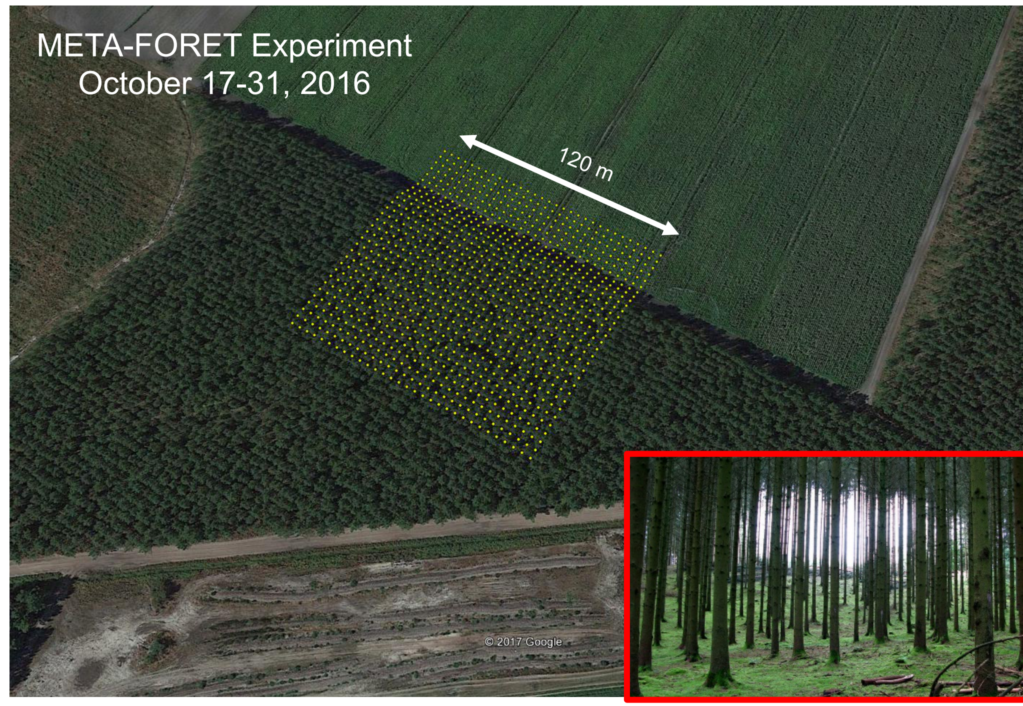
META-FORET




*In collaboration with M. Lott, P. Gueguen, S. Garambois, M. Rupin, **ISTerre**, 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:**

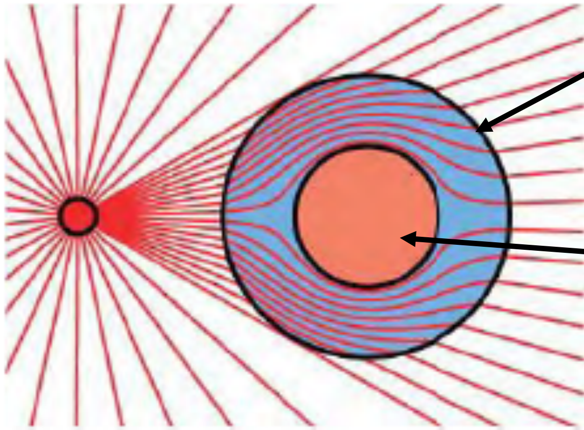
- **Predicting major seismic events** : dense seismic arrays and continuous ambient noise

- **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)



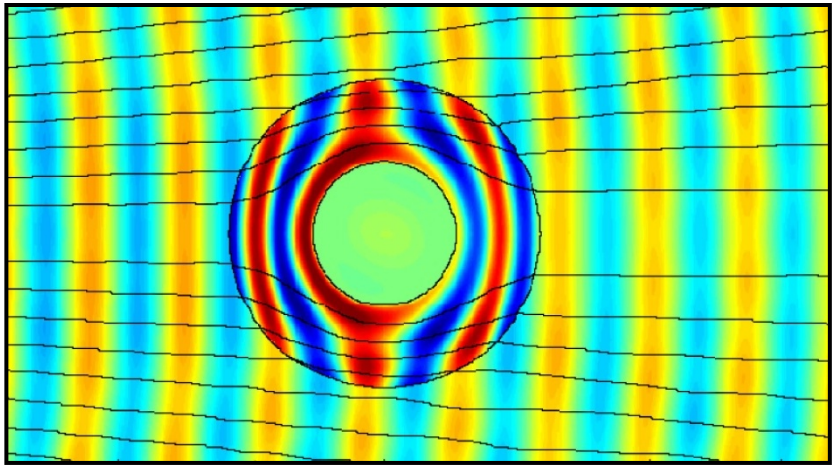

WIKIPEDIA

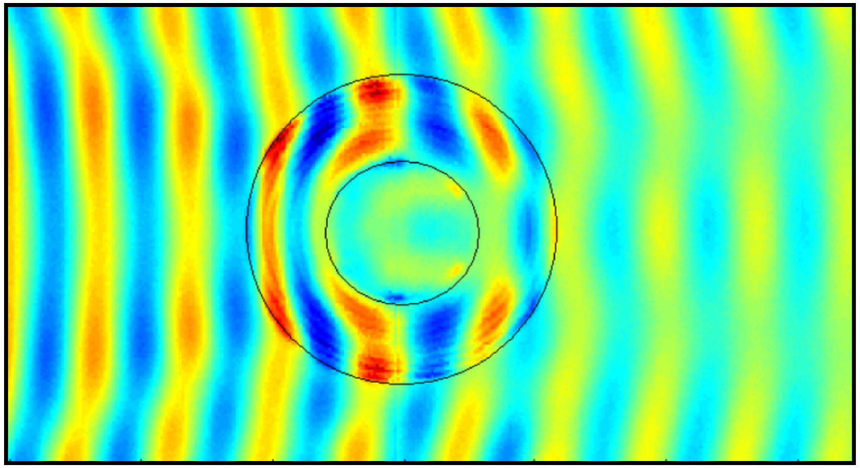
**Metamaterials** are artificial materials engineered to have properties that have not yet been found in nature.

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

# Concept : Manipulating the Wavefield (2)

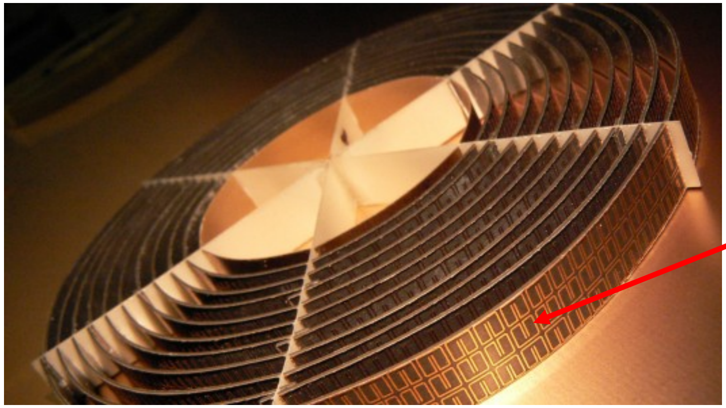
**Electromagnetic waves**





Simulation

Experiment



Unitary cell

*Schurig et al., Science (2006)*

WIKIPEDIA

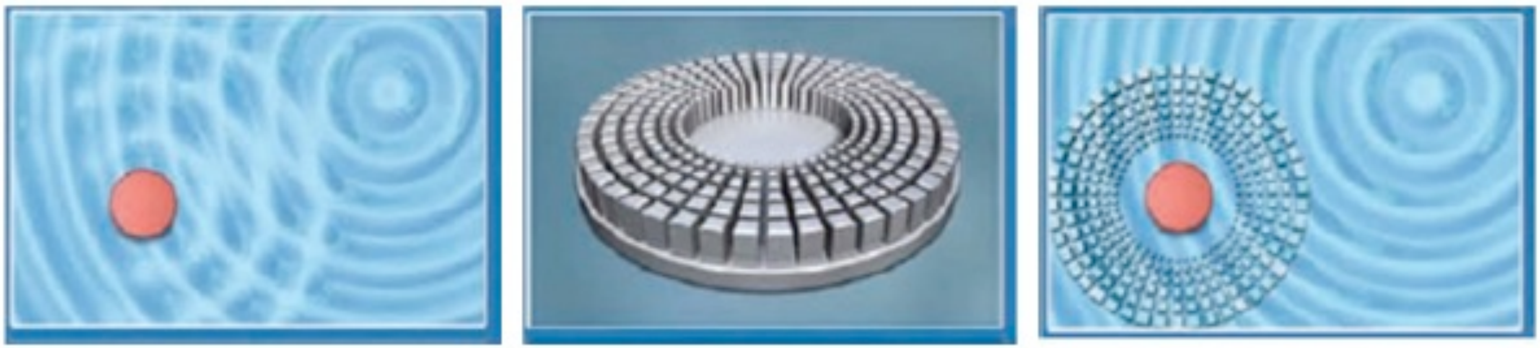
They are **assemblies of multiple individual elements** fashioned from conventional materials such as metals or plastics, but **the materials are usually constructed into repeating patterns**, often with microscopic structures.

# Concept : Manipulating the Wavefield (3)

**Acoustic waves**

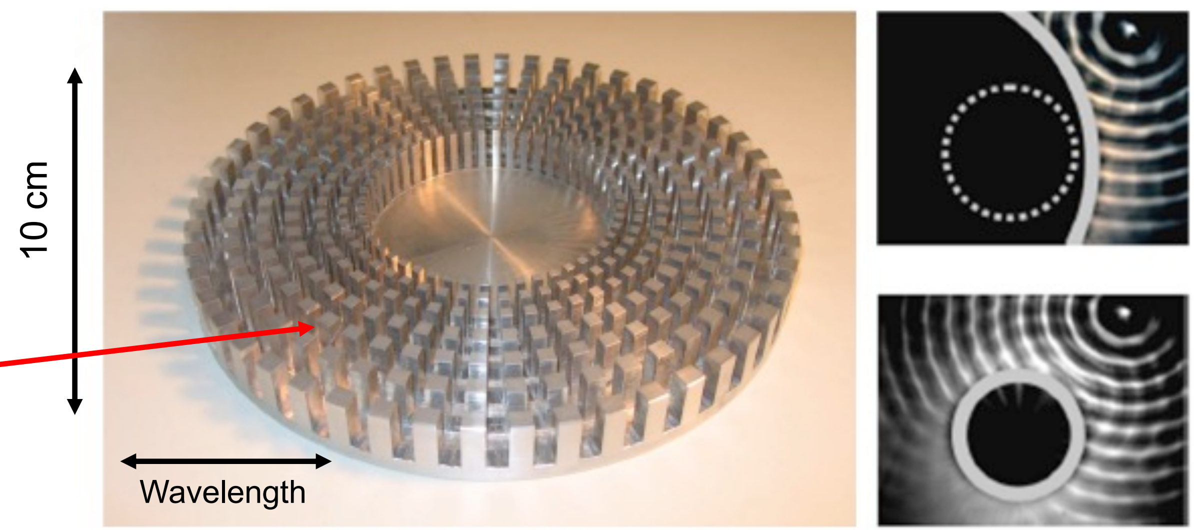
*Frahat et al, Institut Fresnel, Marseille*

Numerical simulation



Infographie La Recherche (Février 2012)

Laboratory experiment



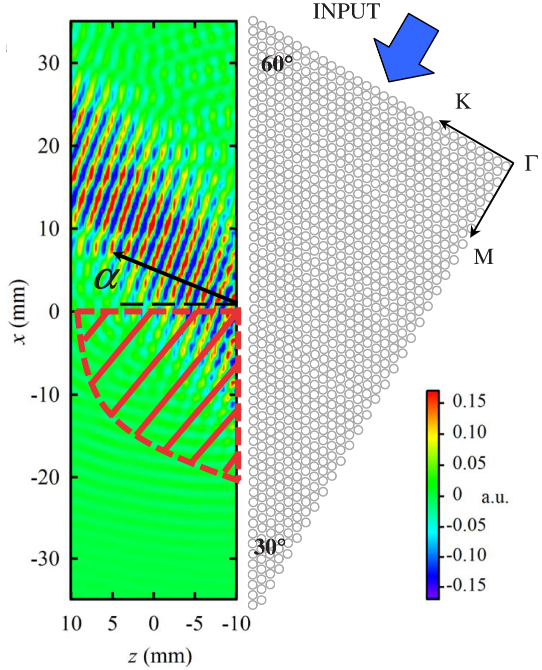

Physical Review Letters 101, 134501 (2008)

# How to Manipulate the Wavefield ?

1- Bragg scattering and Phononic crystals

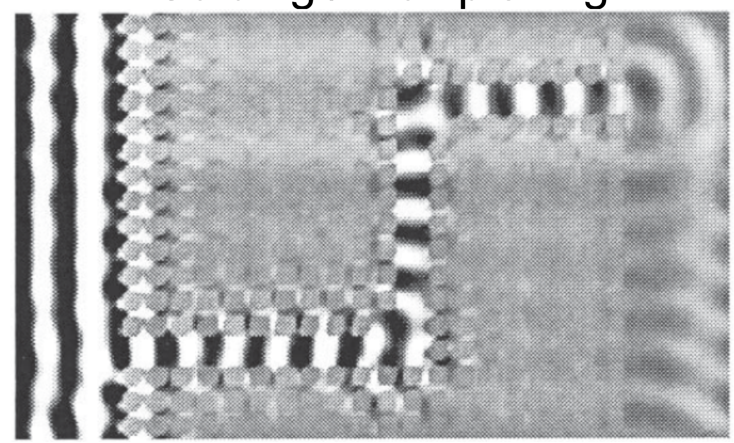
## Negative Index of Refraction

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.

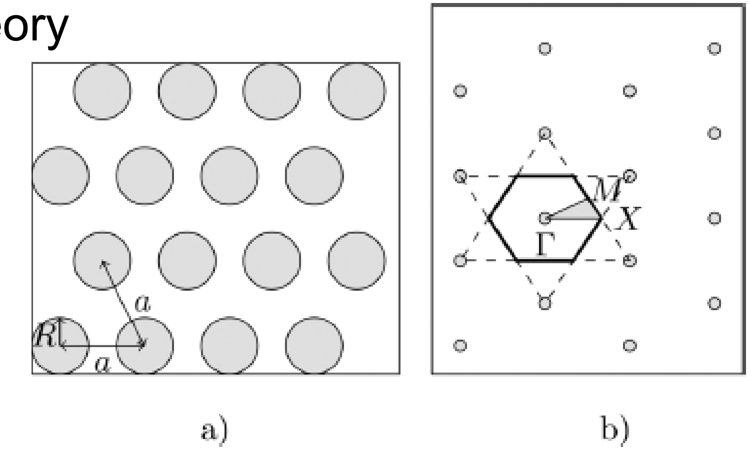



FIG. 1. Diagram of a triangular lattice for an ideal sonic crystal. (a) Direct space, where rods have a radius $r$ and a lattice constant $a$. (b) Reciprocal space with the irreducible Brillouin zone.

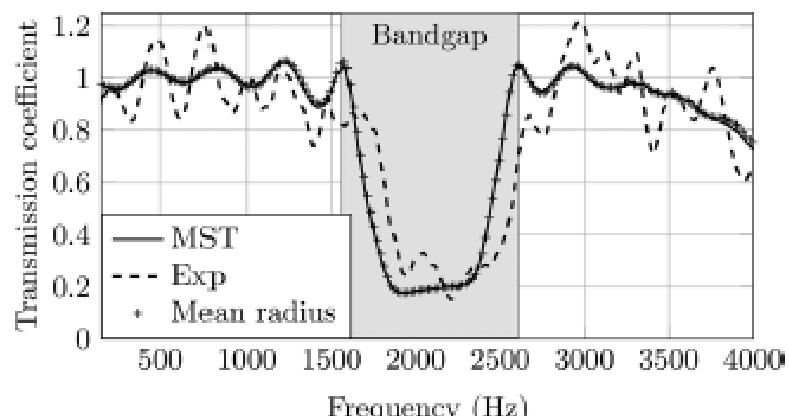



FIG. 6. Comparison between the transmission coefficient calculated by MST with all the radii accounted for (—), by MST with the mean radius (···), and mesured experimentally (– – –) for a triangular lattice sonic crystal of 9 × 5 rods of 4 cm of diameter.

*Lagarrigue et al., JASA (2012)*

# How to Manipulate the Wavefield ?

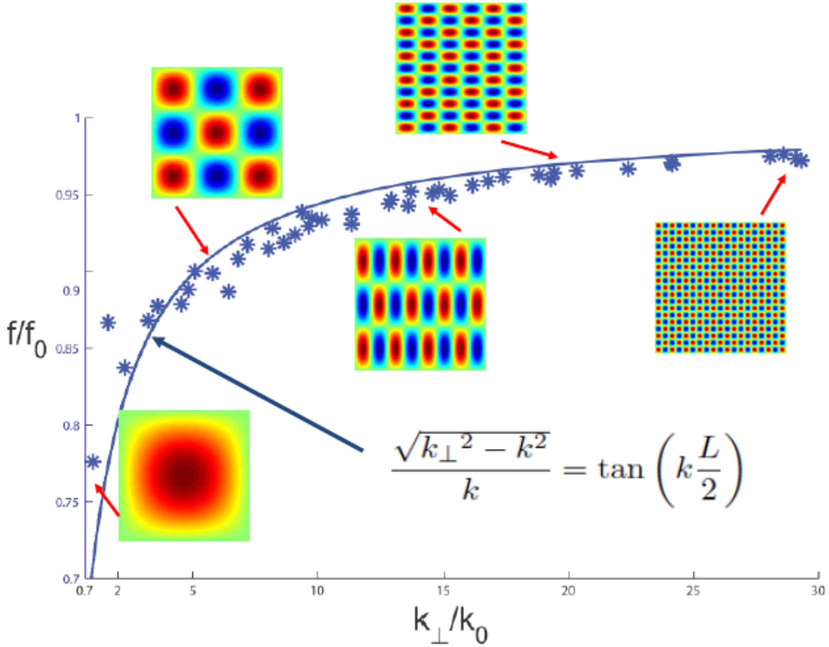
## 2- Multi-resonators at the sub-wavelength scale

Periodic arrangement of identical wires

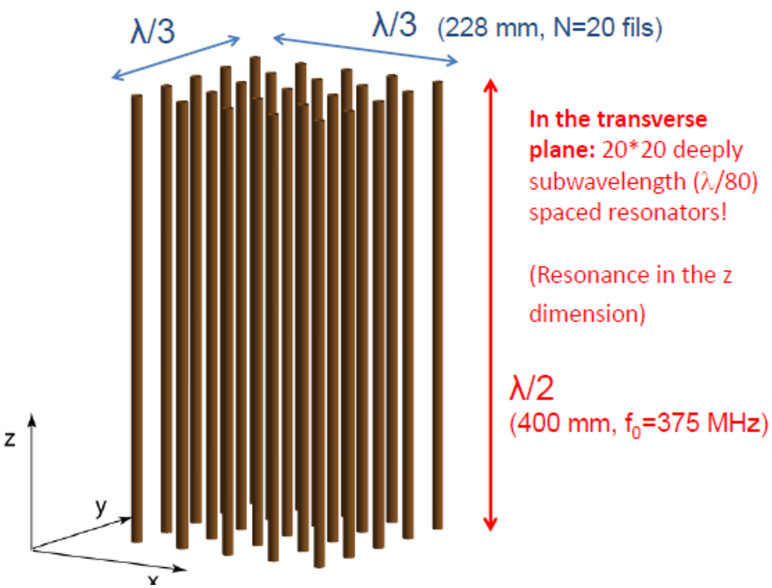
*Fabrice Lemoult, Geoffroy Lerosey, Julien de Rosny, Mathias Fink*
« Resonant Metalenses for Breaking the Diffraction Barrier »
Phys Rev Lett 104, 203901 (May 2010)

The closely spaced subwavelength resonators approach: « resonant metalens »

Dispersion relation theoretical derivation




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



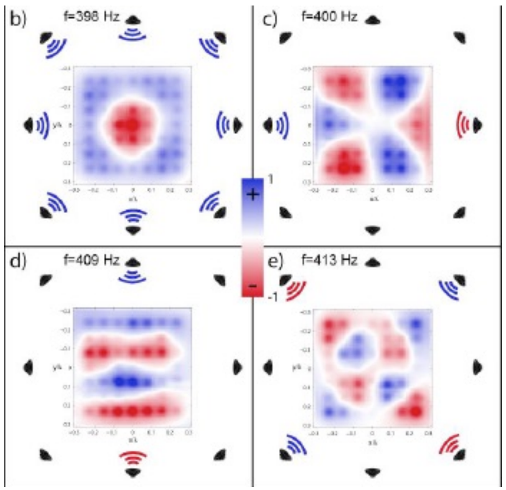

**In the transverse plane:** 20*20 deeply subwavelength (λ/80) spaced resonators!

(Resonance in the z dimension)

# How to Manipulate the Wavefield ?

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

*Lemoult et al, PRL, 2010*





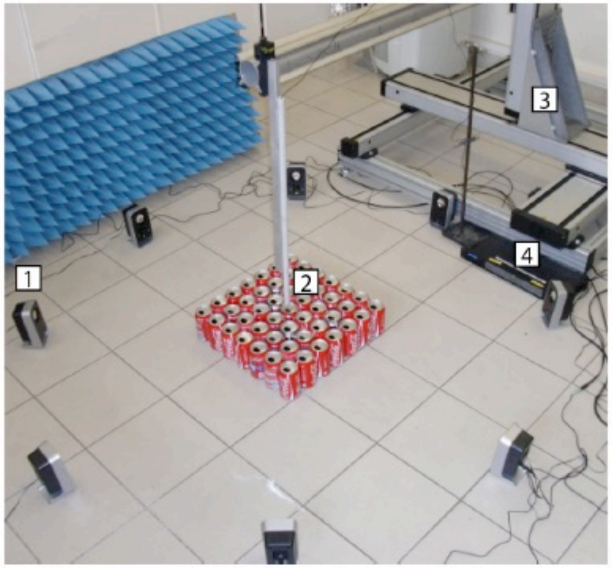
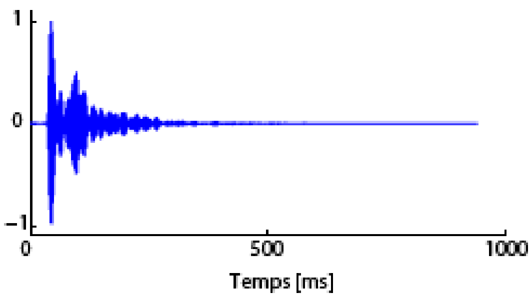
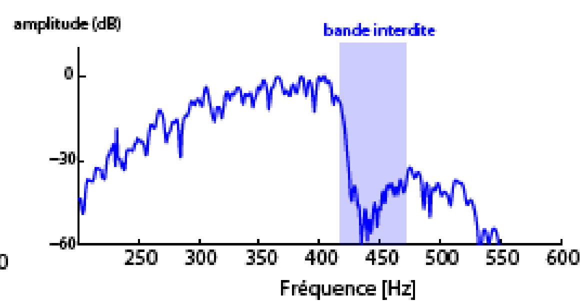
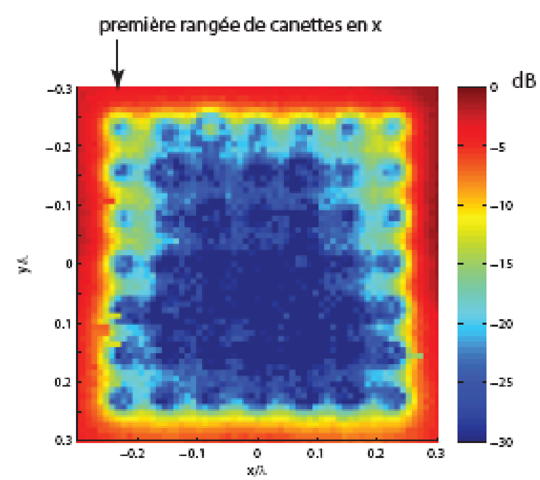



FIGURE IV.6 – Le réseau de 7 × 7 canettes et le dispositif expérimental : (1) 8 haut-parleurs commerciaux pré-amplifiés, (2) microphone monté sur (3) un banc de mesure motorisé, (4) carte son MOTU.

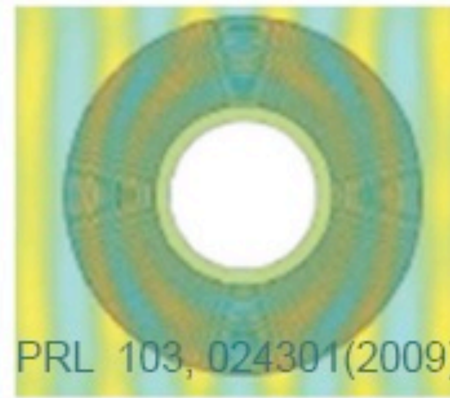


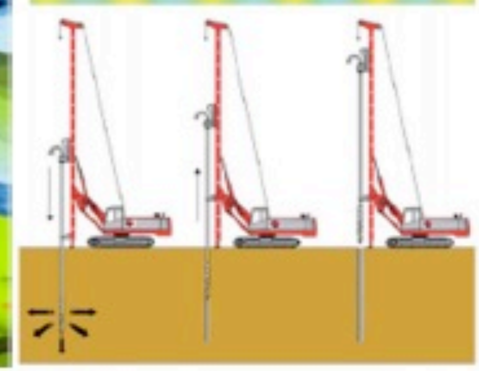



# At Larger Scale : Cancellation of Seismic Waves?

S. Guenneau, Institut Fresnel, Marseille



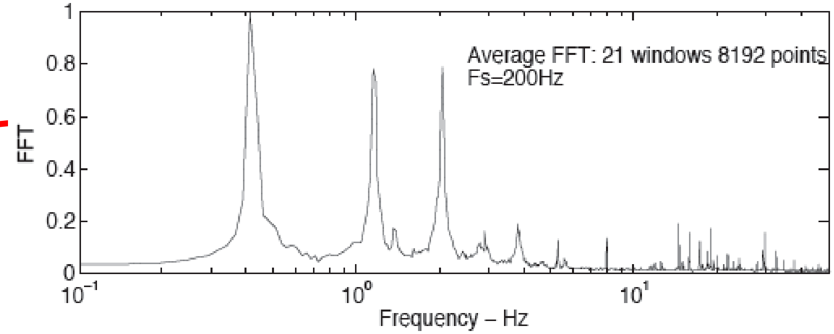



Infographie Popular Science Magazine (2009)

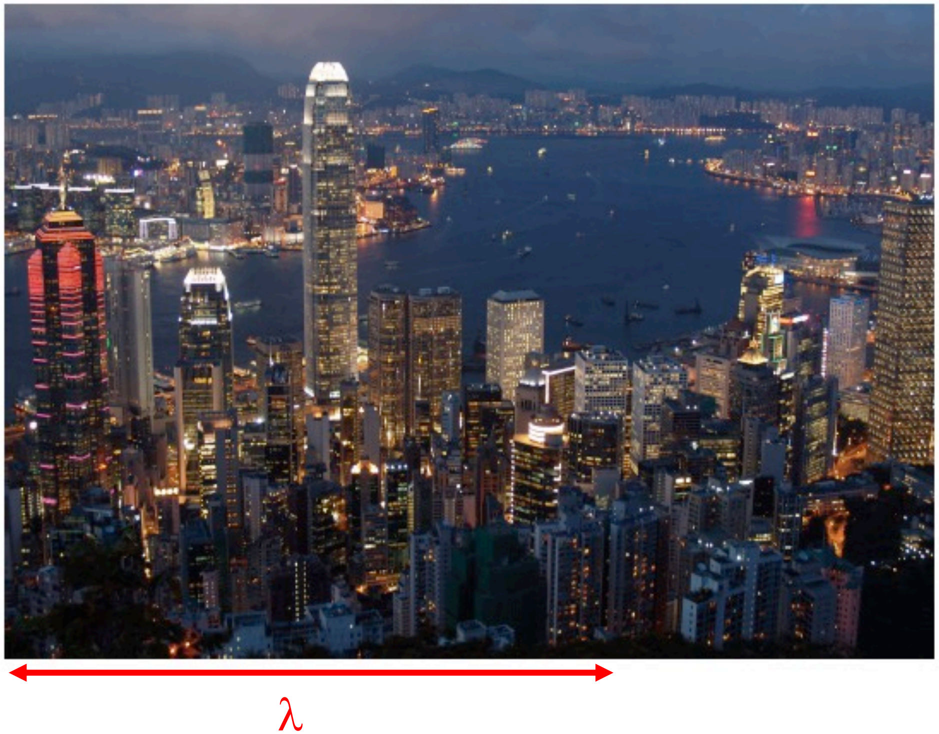
Infographie Ménard

# A City : Macroscopic Arrangement of Resonating Elements ?

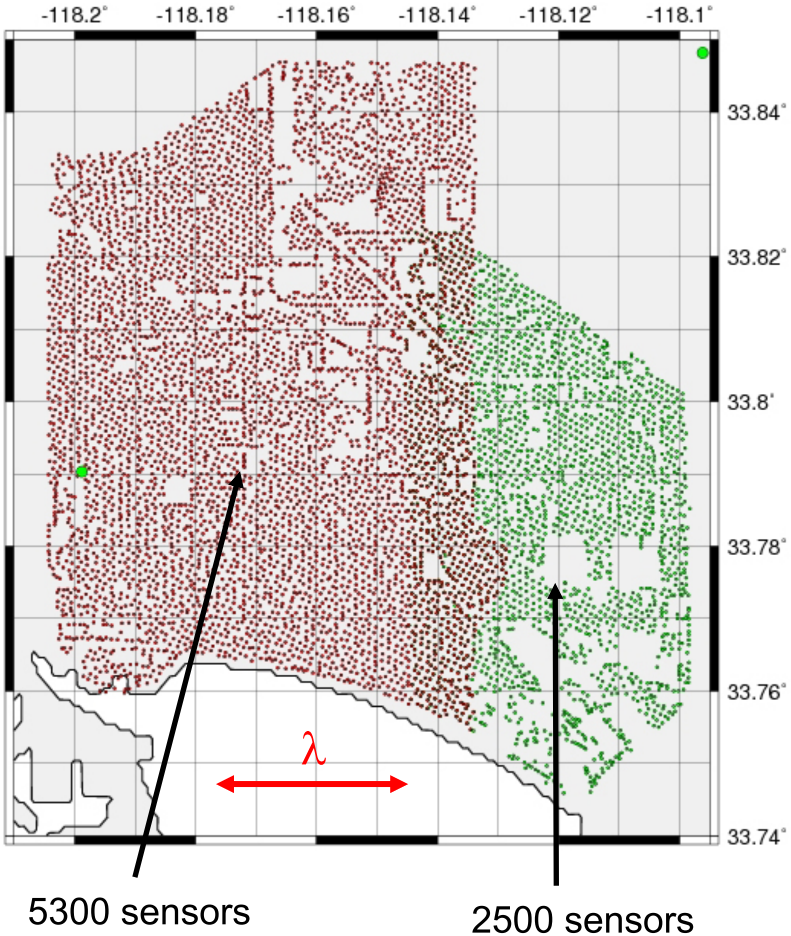
Tall building : subwavelength resonator for ~1 Hz seismic wave




Cluster of buildings : locally-resonant metamaterial?

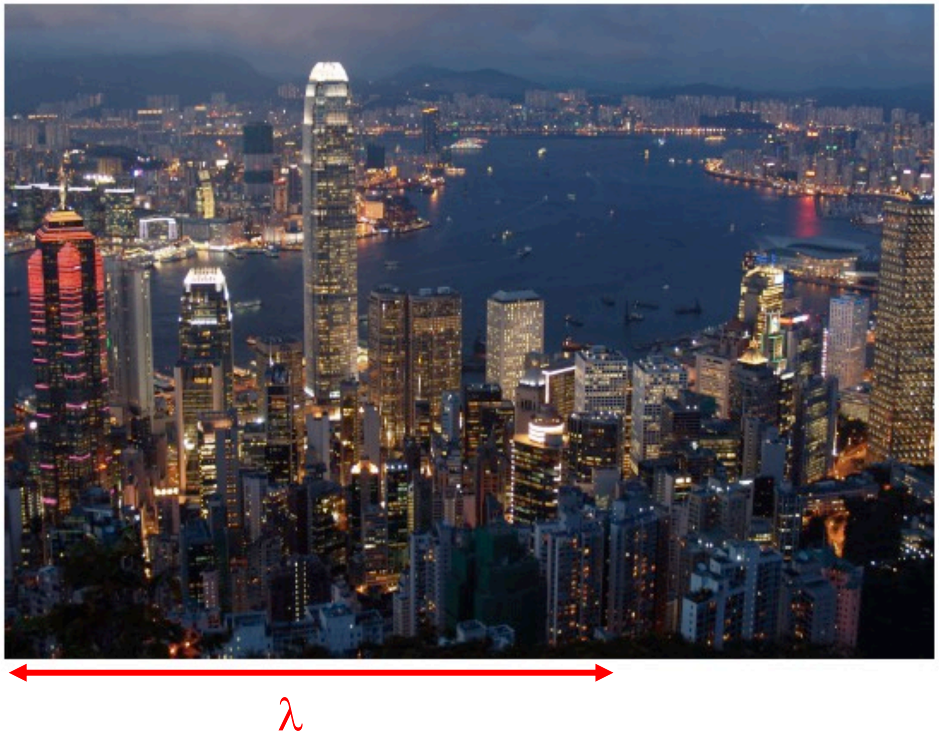


# A City : Macroscopic Arrangement of Resonating Elements ?




Density ~ 75 sensors per square-km

Cluster of buildings : locally-resonant metamaterial?

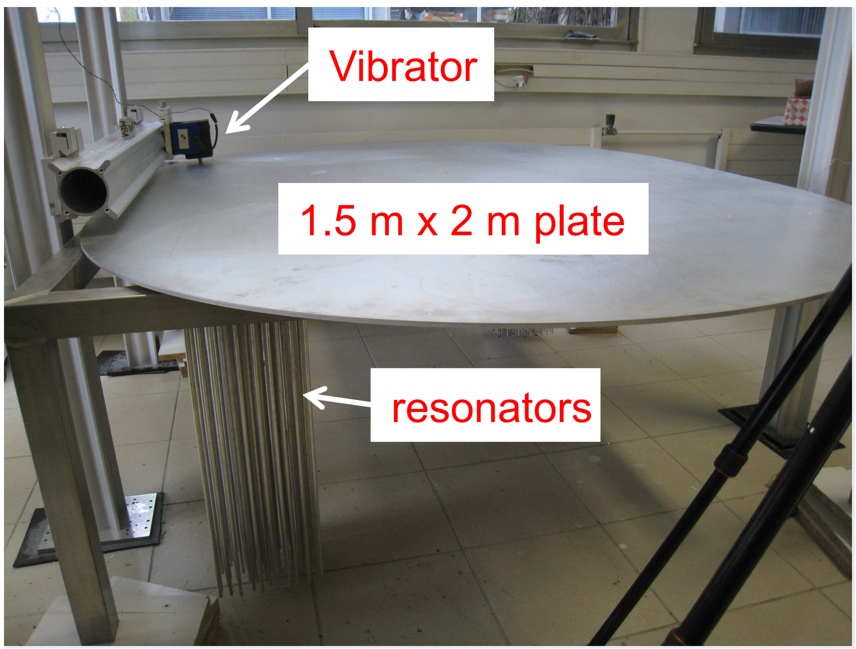


# Experimental / Theoretical / Numerical Approach at ISTerre

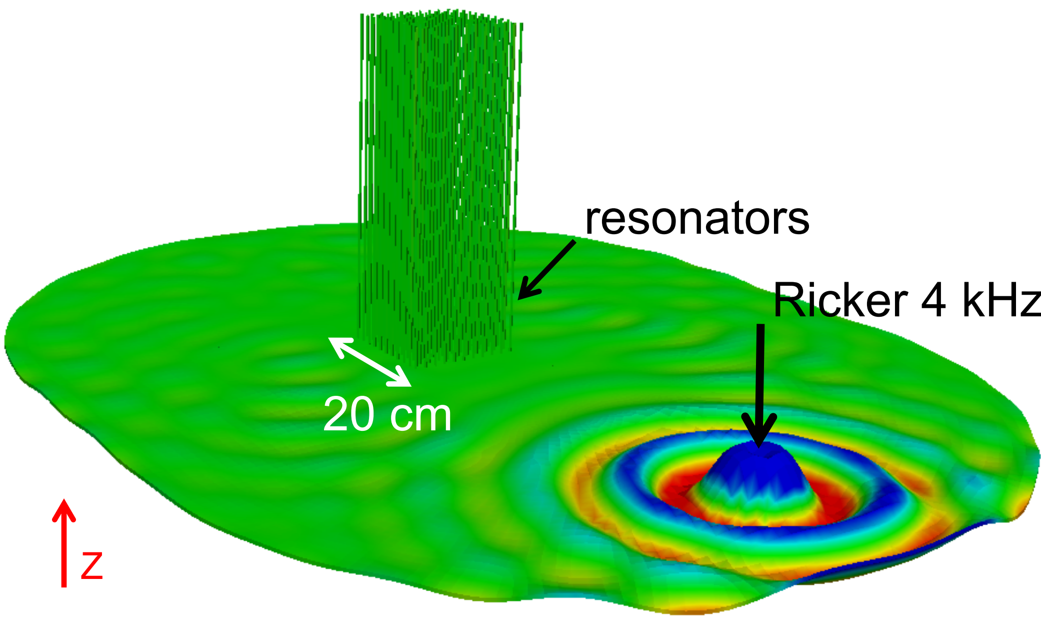
Coupling Surface wave (Geophysics)

and

Multi-Resonators (Acoustics)

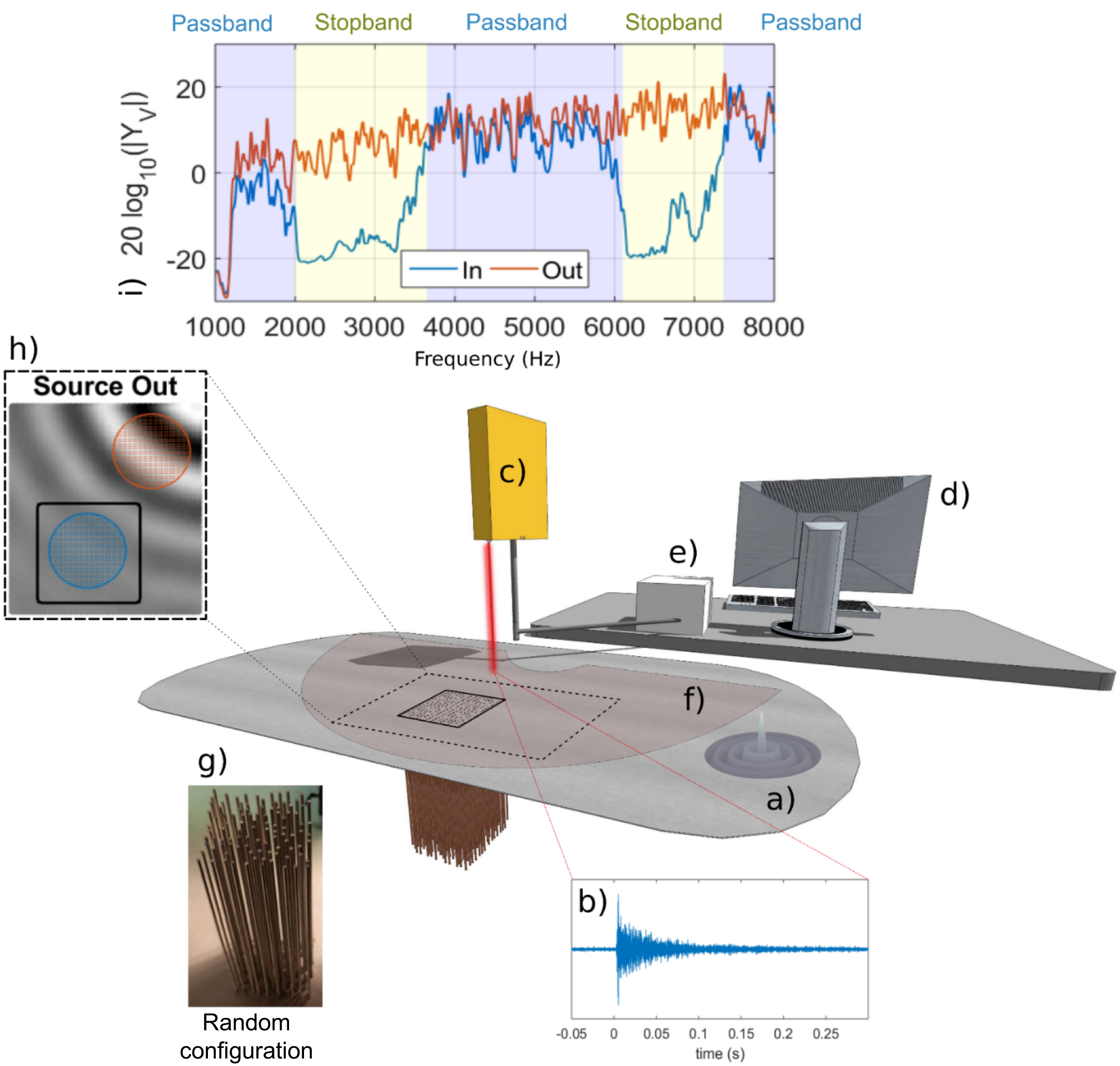



Laboratory set-up




Simulation setup

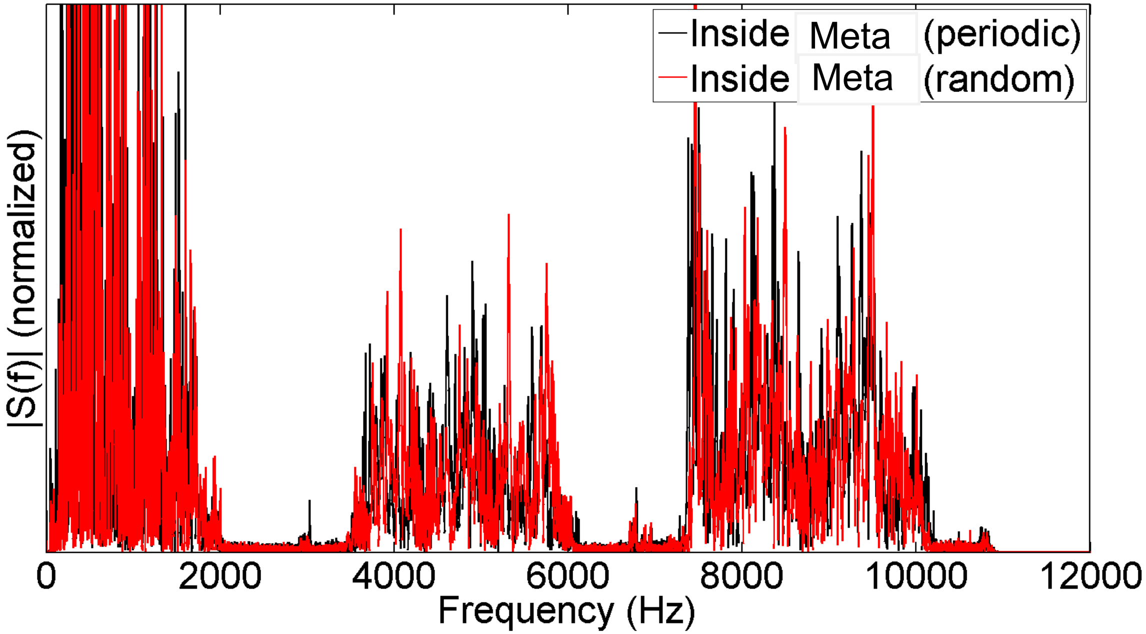
# Experimental Configuration



# Periodic / Random Distribution of Beams

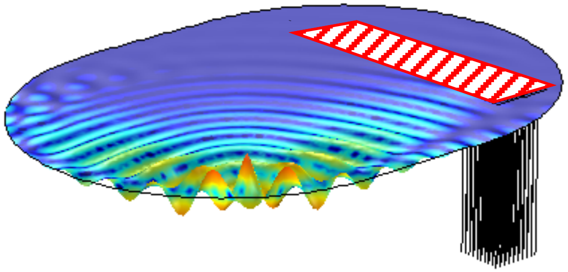
Periodic configuration

Random configuration

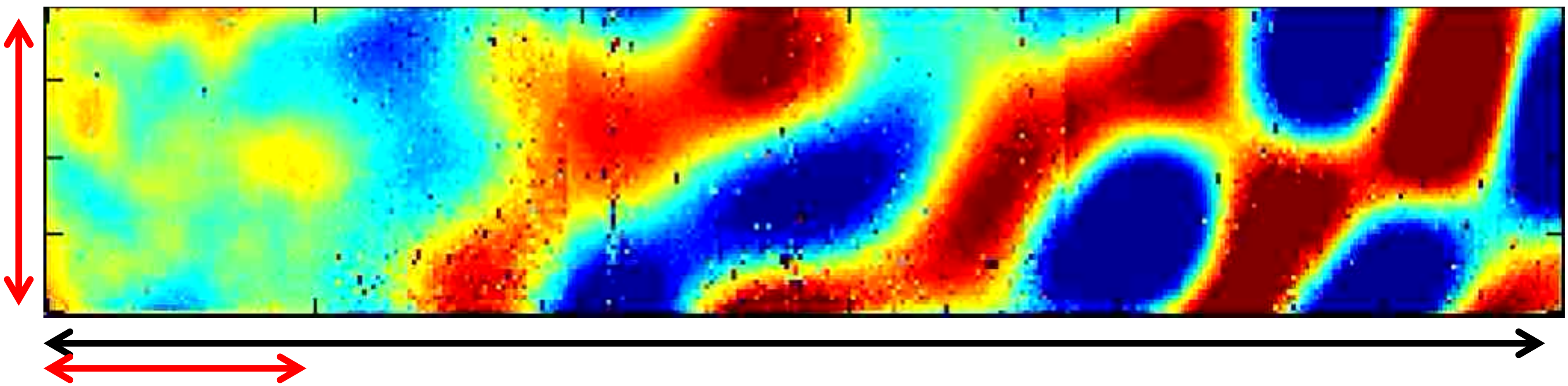



*Cowan et al. Phys. Rev. B, 2011*

# Temporal Evolution of the Wavefield

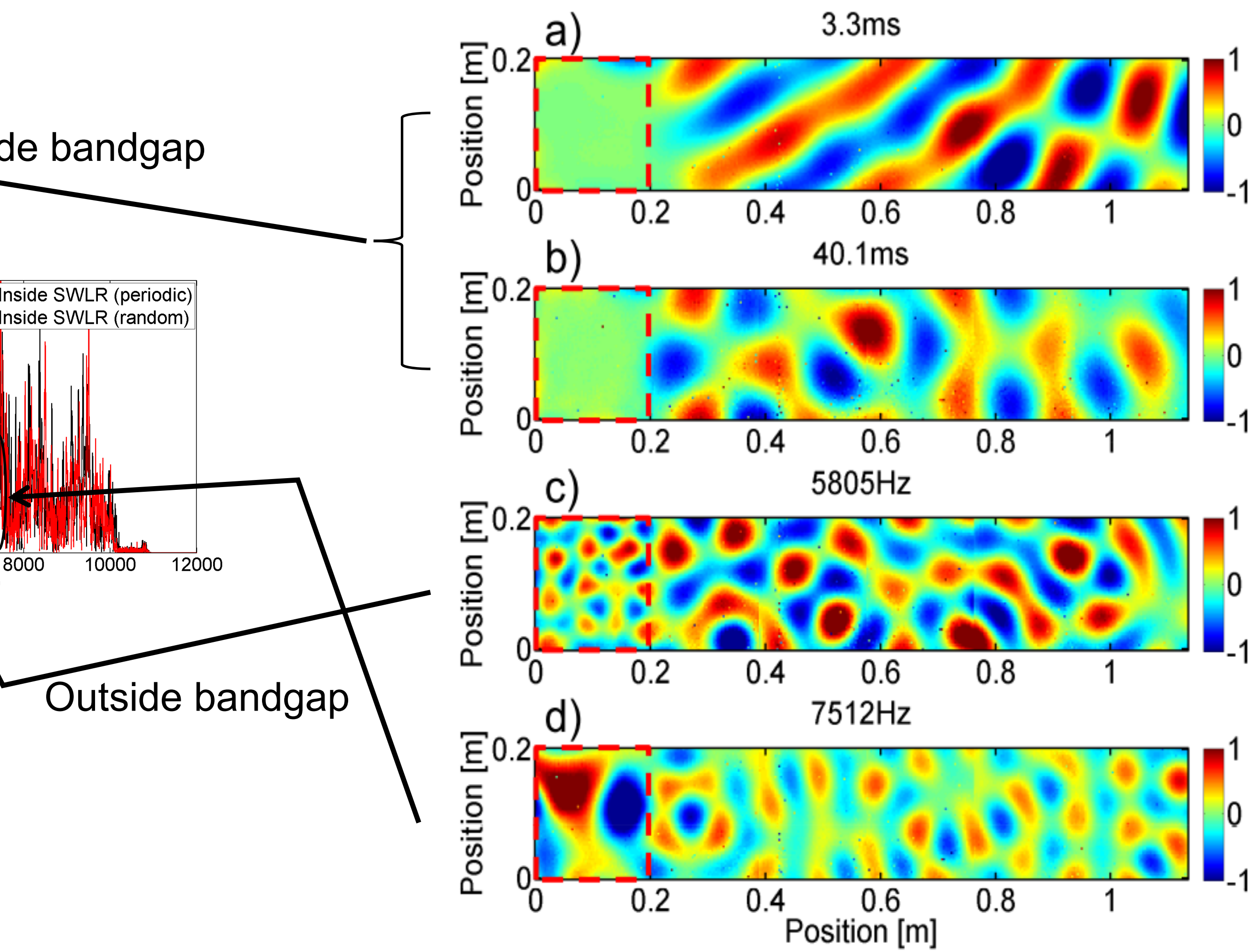


Vertical Displacement filtered in [2100Hz - 2800Hz]




*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

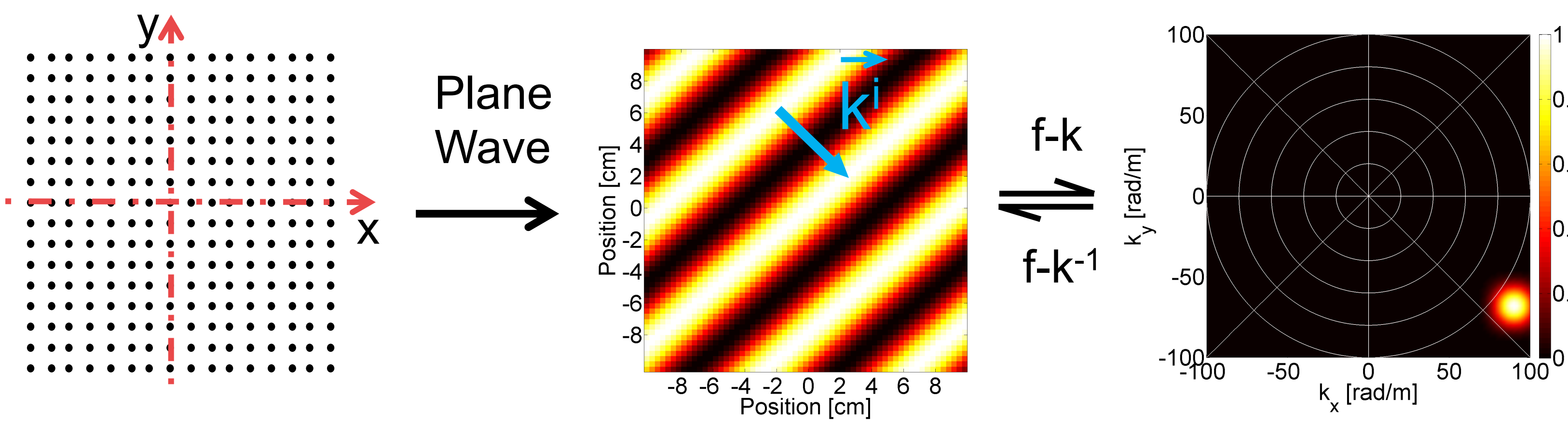




*Rupin et al., PRL 2014; APL, 2015*

# Metamaterial description through Dispersion relation

- 2-D Frequency-Wavenumber projection



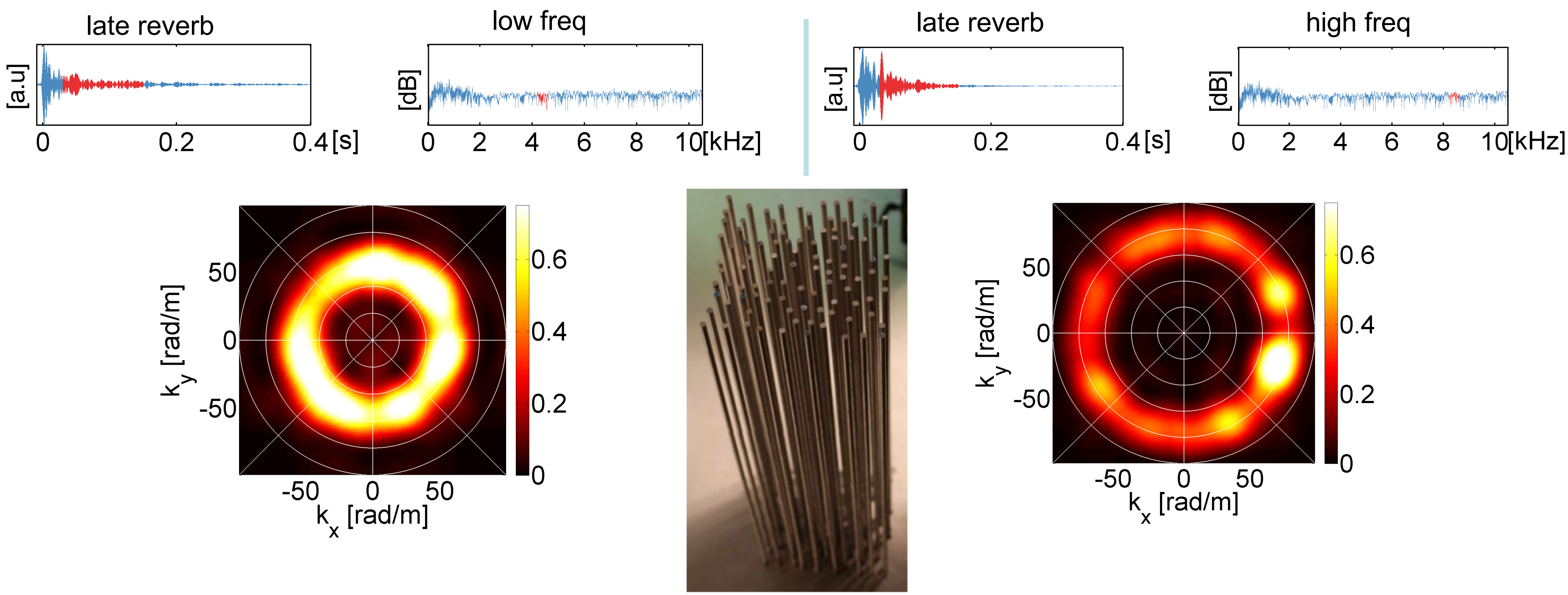

2D antenna
(NxN receivers)

x-y field
representation

$k_x$-$k_y$ field
representation

# Metamaterial description through Dispersion relation

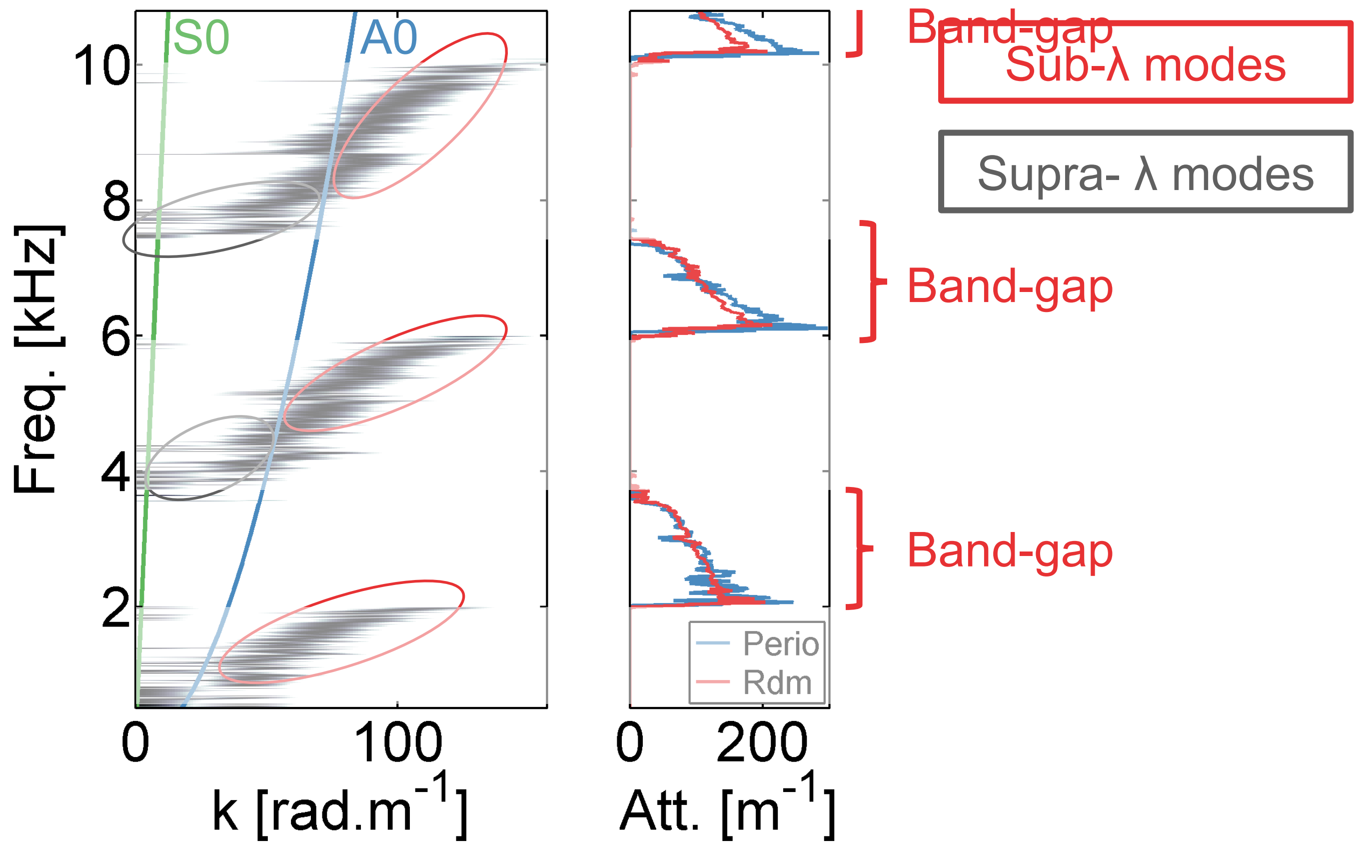
## Examples of experimental F-K




Isotropic Wavenumber Distribution = Diffuse Field

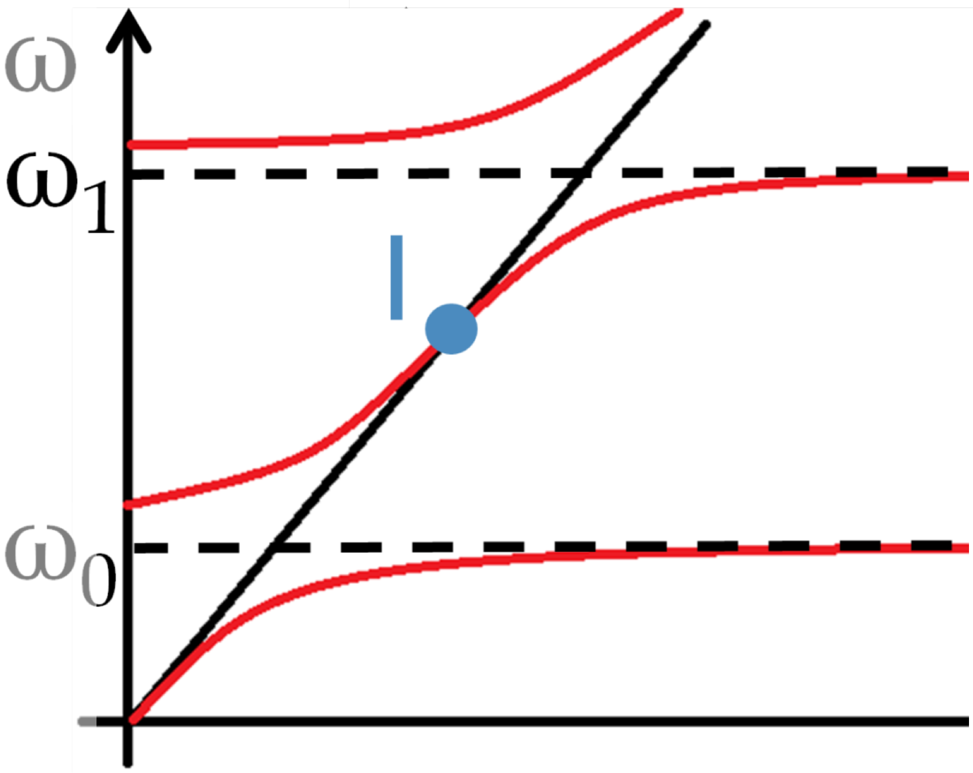
# Metamaterial description through Dispersion relation

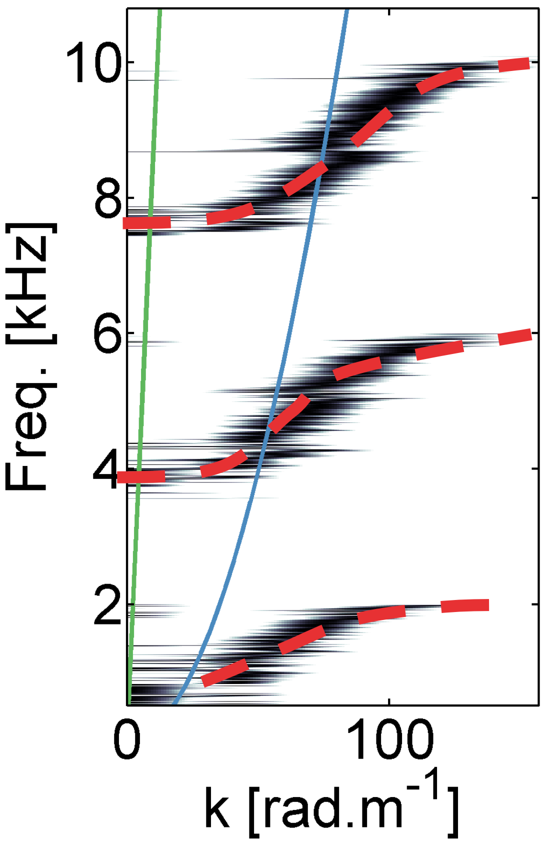
- Dispersion relation inside the Metamaterial



# Metamaterial description through Dispersion relation

Role of the resonances : the hybridation phenomenon



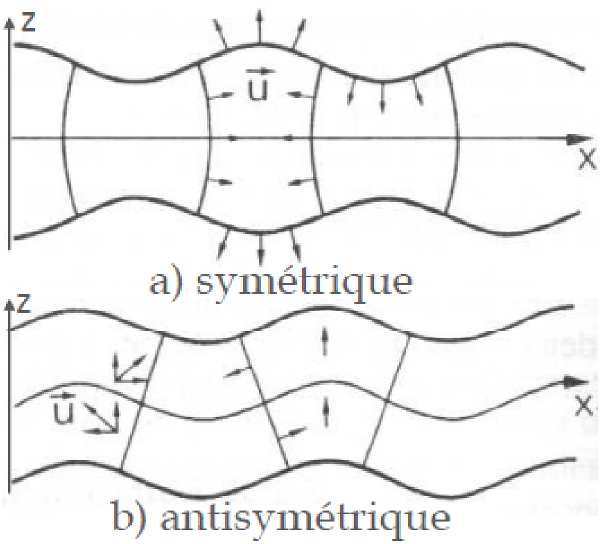
# Mutli-wave + Multi-resonance problem

In the plate…

In one resonator…

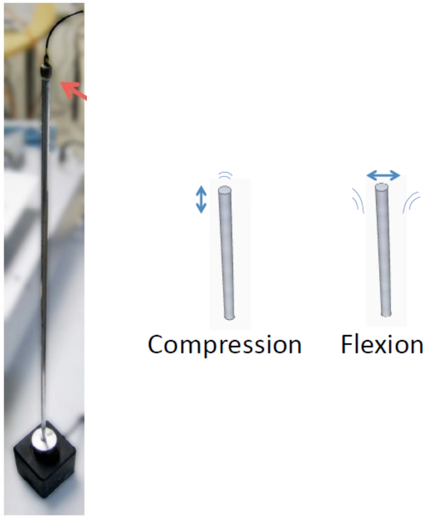
S0 wave

A0 wave




Displacement is mostly horizontal

Displacement is mostly vertical




Two types of waves

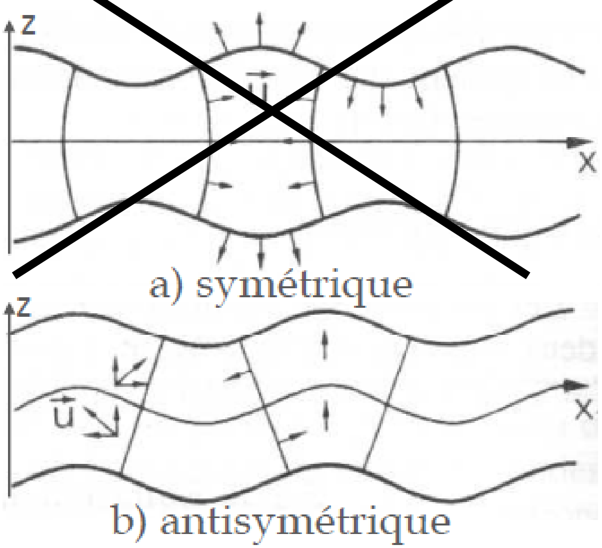
Two types of resonances

*Royer & Dieulesaint, 1996*

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

In the plate…

S0 wave



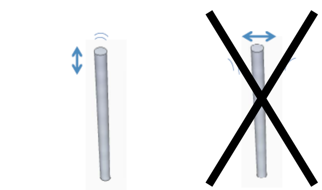

Displacement is mostly horizontal

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

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

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

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

Account for boundary conditions at the bar-plate interface

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

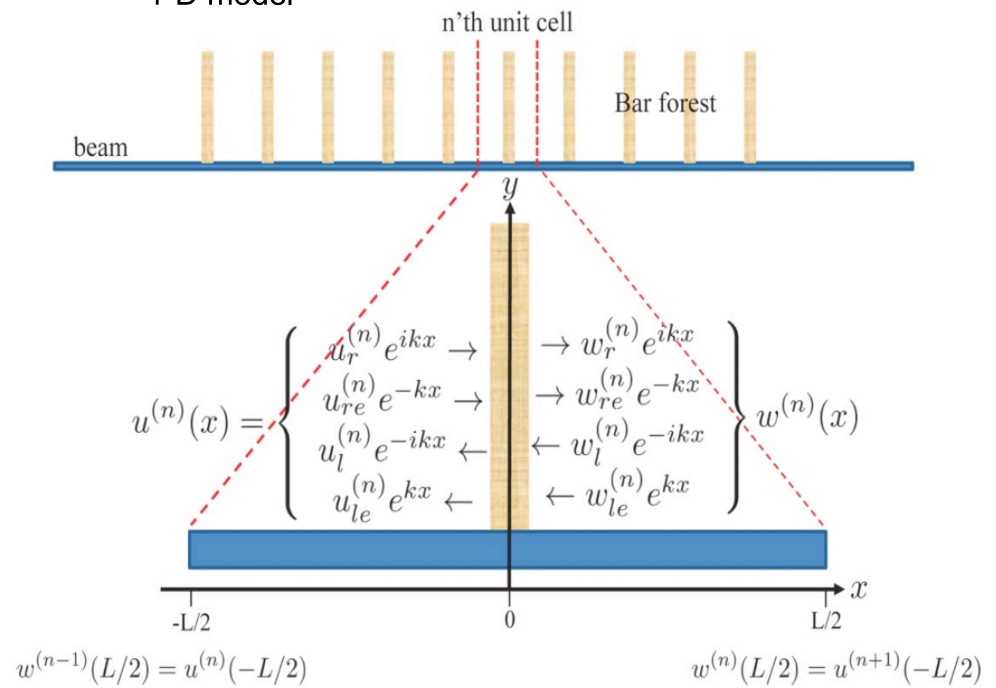
$$D \equiv \begin{bmatrix} e^{-ikL/2} & 0 & 0 & 0 \\ 0 & e^{kL/2} & 0 & 0 \\ 0 & 0 & e^{ikL/2} & 0 \\ 0 & 0 & 0 & e^{-kL/2} \end{bmatrix}$$

Account for propagation accross the unit cell

$$W_+^{(n)} = DCDW_+^{(n-1)}$$

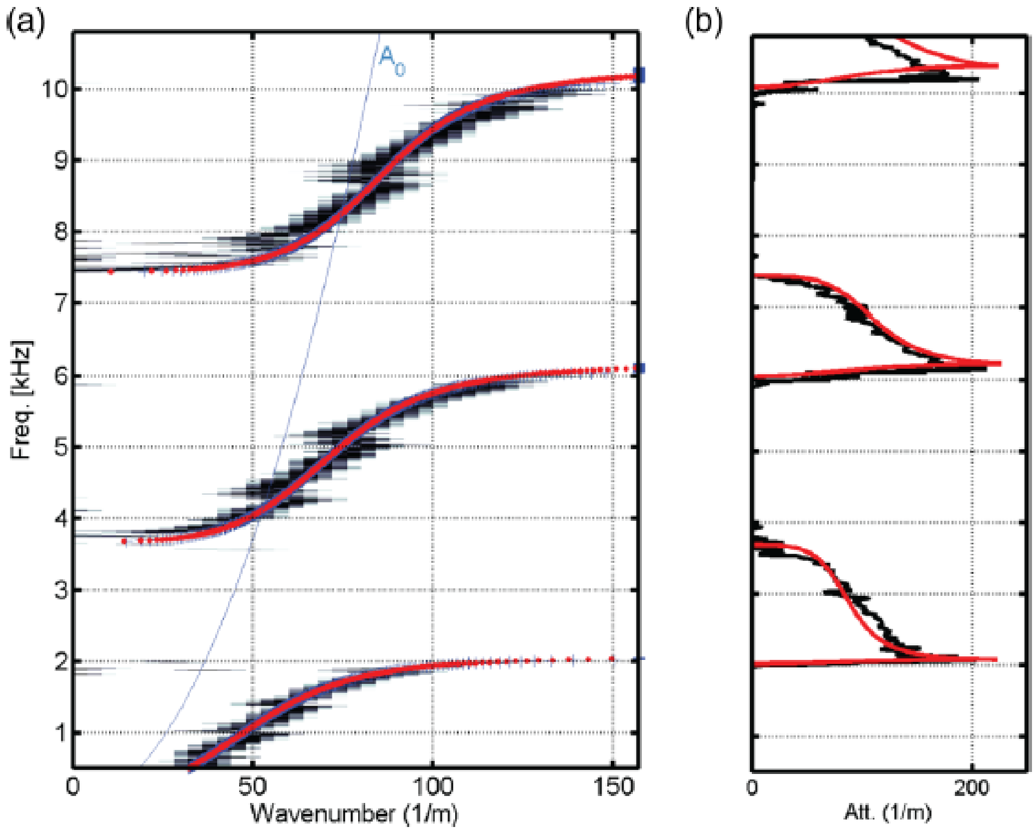
Transfer matrix between two cells

1-D model




Dispersion curves are obtained from the solution of an eigenvalue problem

# Theoretical (scalar) approach through Bloch Theorem



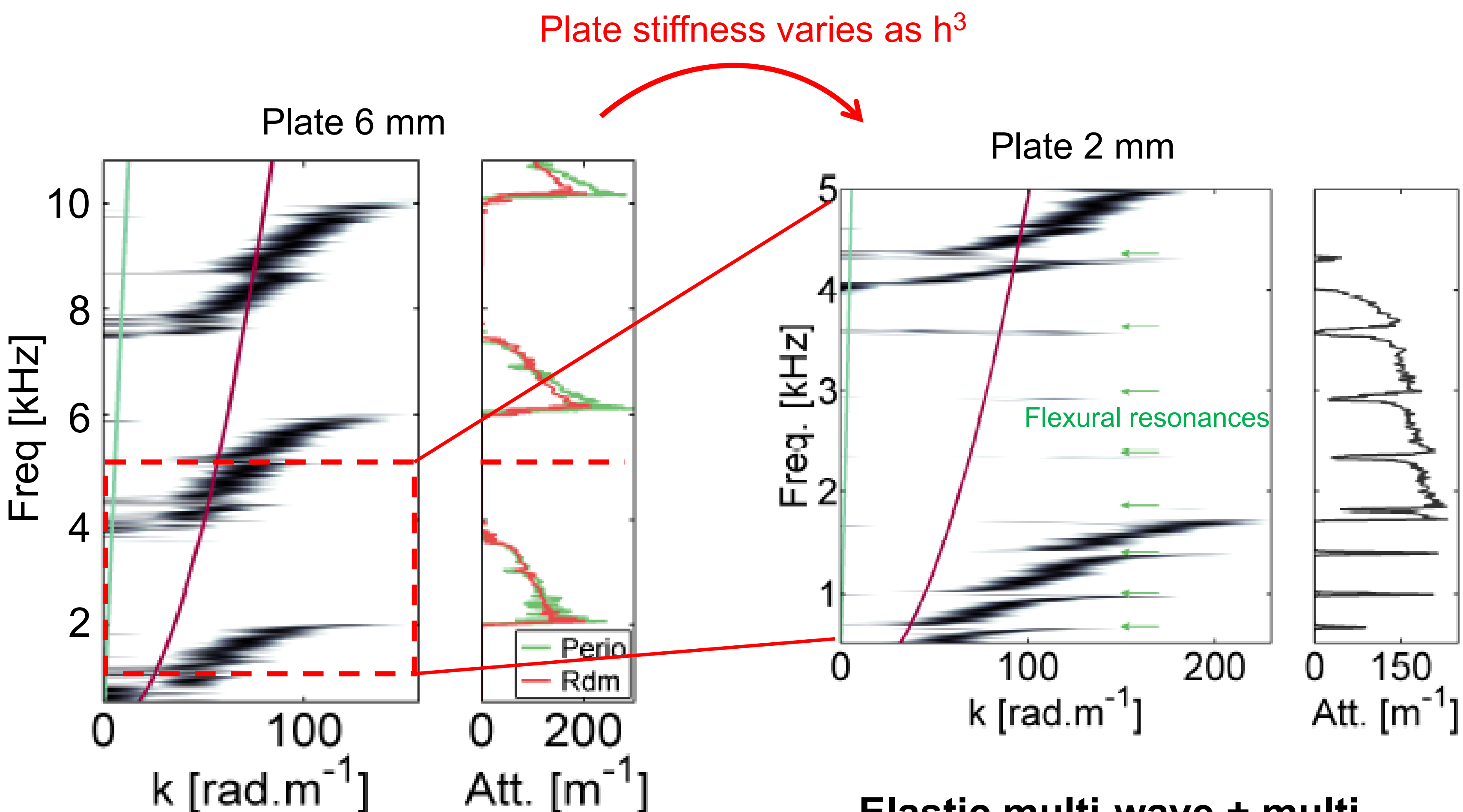

$$c_{\mathrm{eff}}/c_p = \left[\frac{M_b}{M}\frac{\tan(k_b L_b)}{k_b L_b} + 1\right]^{-1/4}$$

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

*$M_b$ = 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?

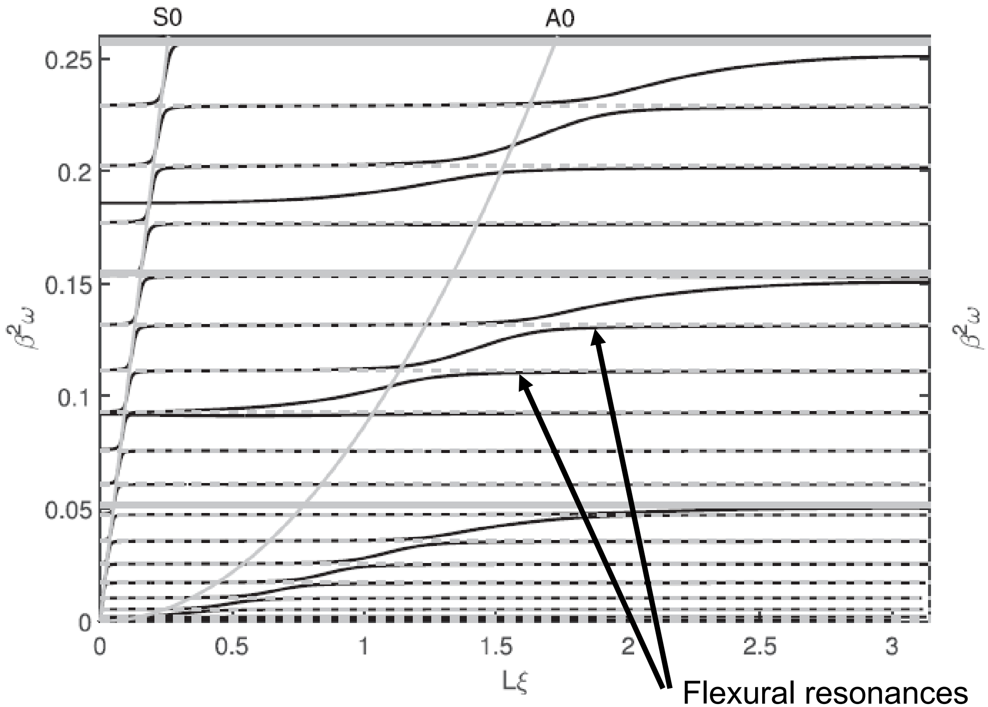


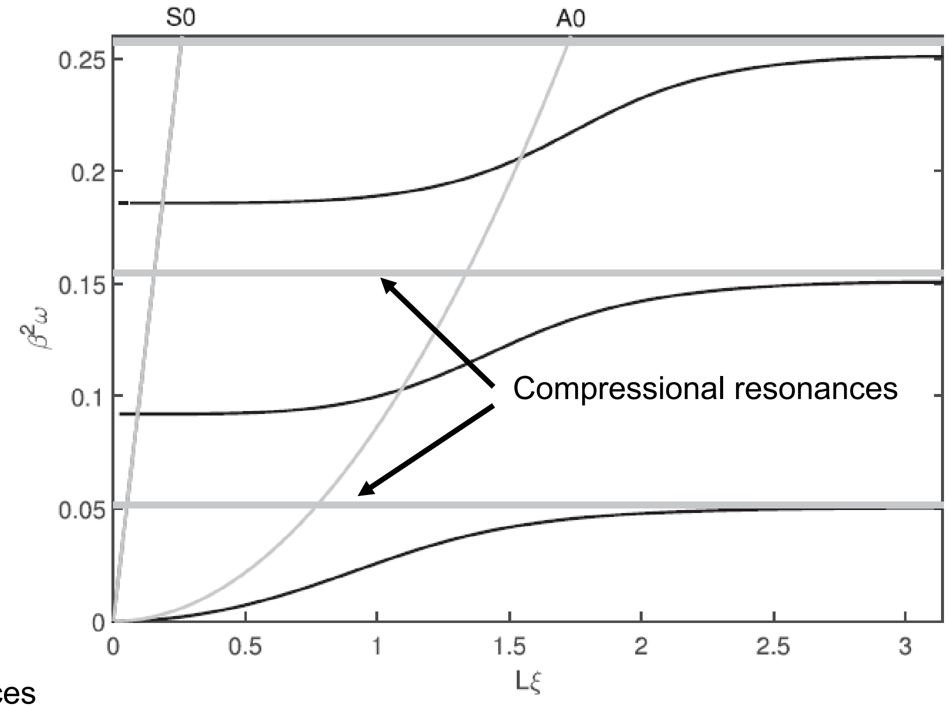

**Scalar wave + resonator interaction**

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

*Rupin et al., Scientific Reports, 2016*

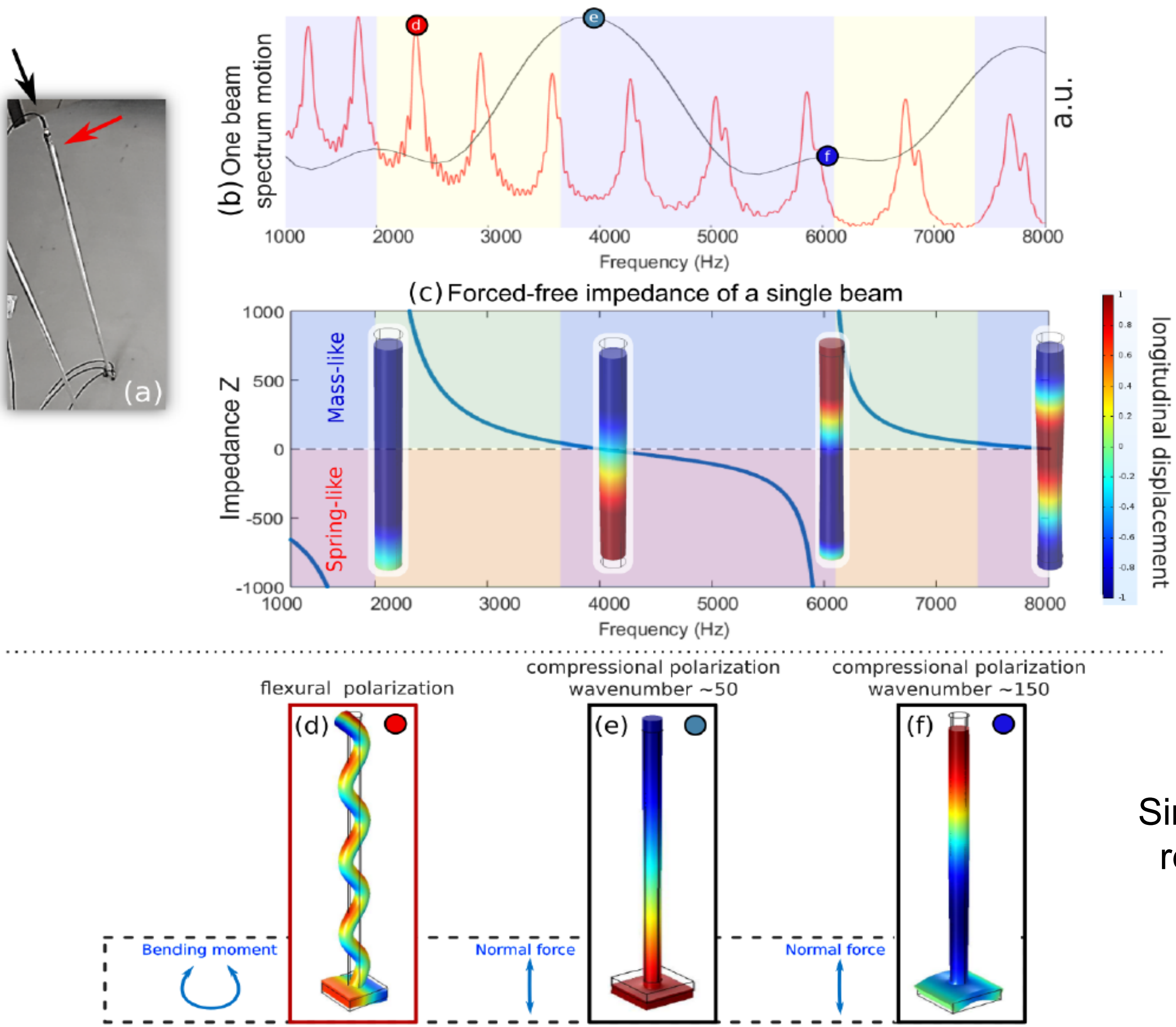
# The dispersion curves for the plate + rod system




*Colquitt et al., JMPS, 2017*

# Impedance and mechanical coupling of a single rod attached to the plate



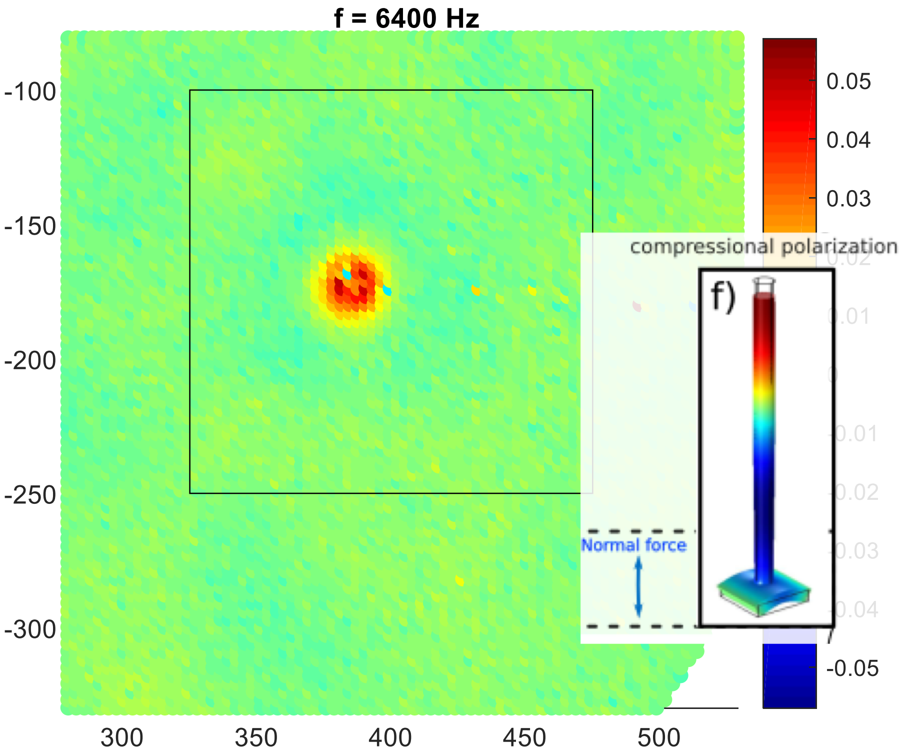

Single-rod motion spectrum

Single-rod impedance model

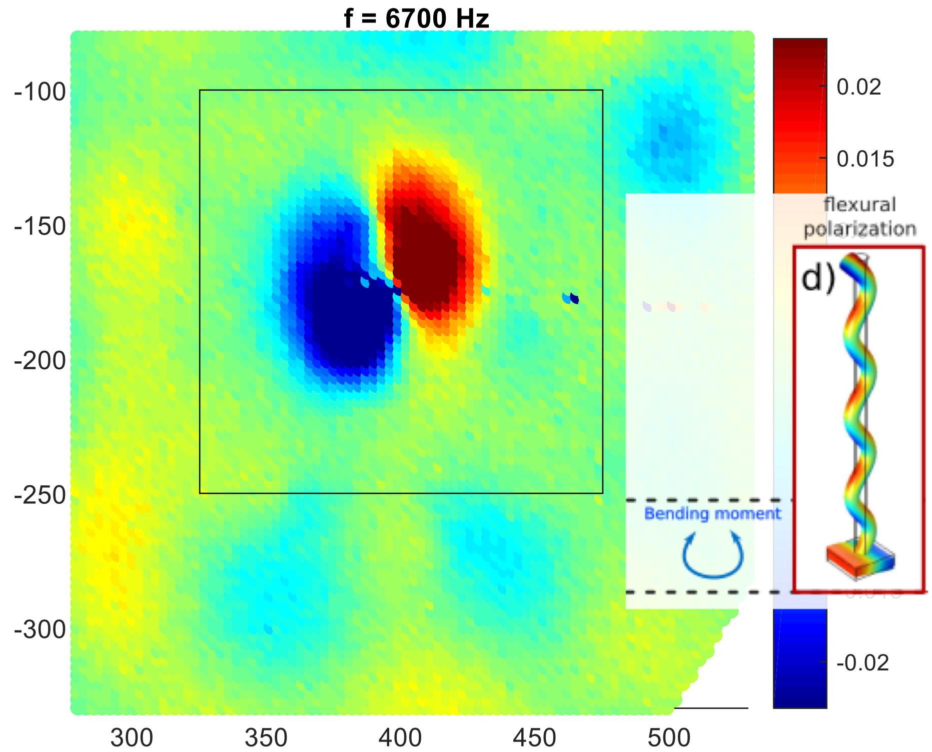
Single-rod modal representation (COMSOL)

# What happens inside the bandgap at a flexural resonance?

Source inside the Meta




Monopole source away from flexural resonances



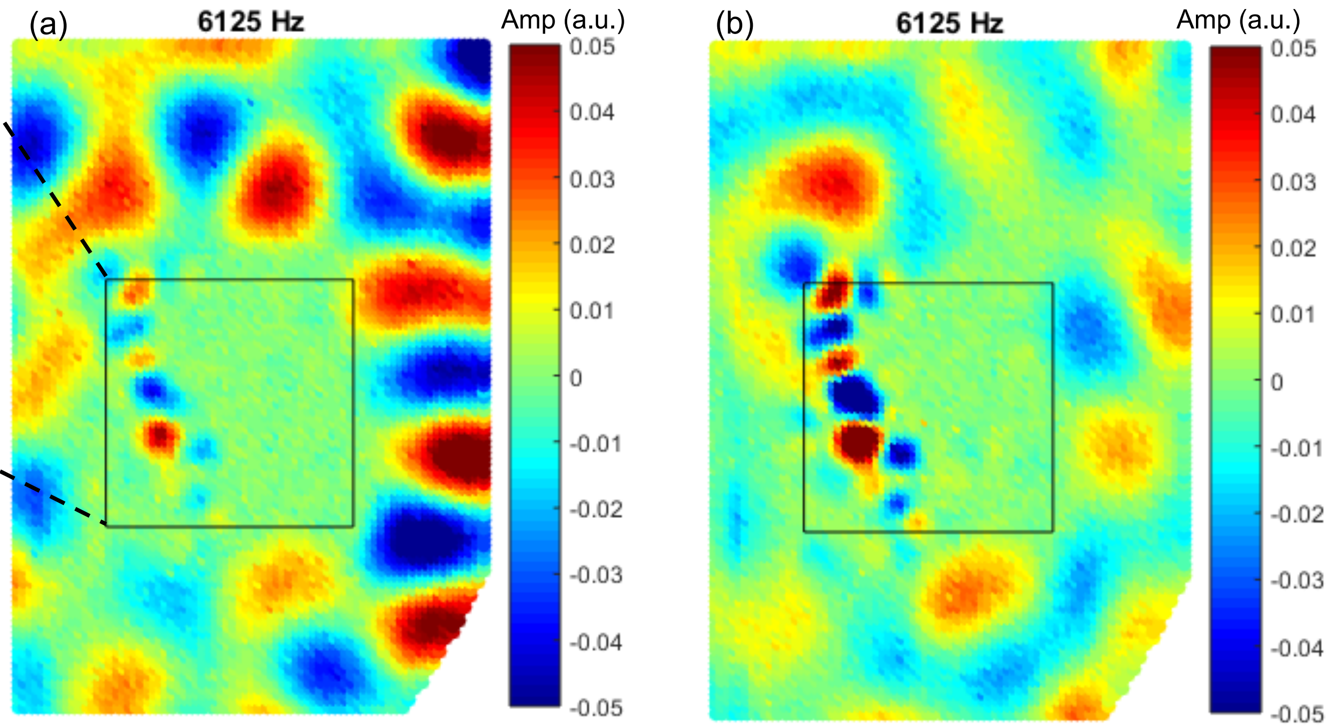

Dipole source at a flexural resonance

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

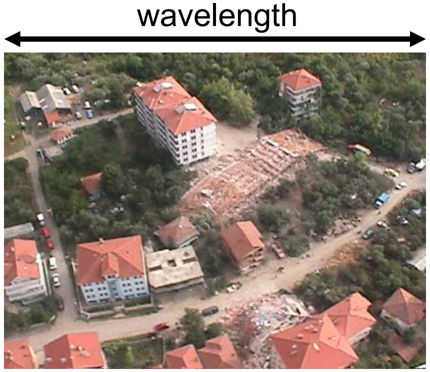
Random Metamaterial

Source outside of the metamaterial

Source inside the metamaterial



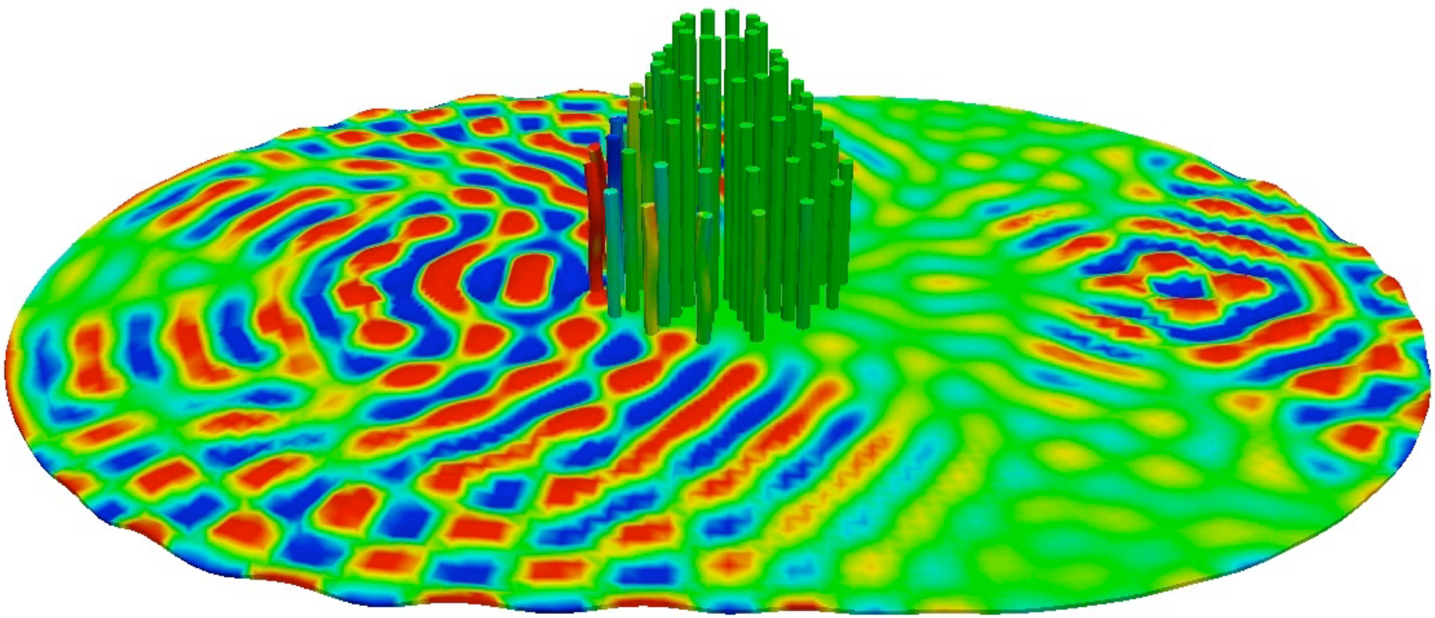

wavelength



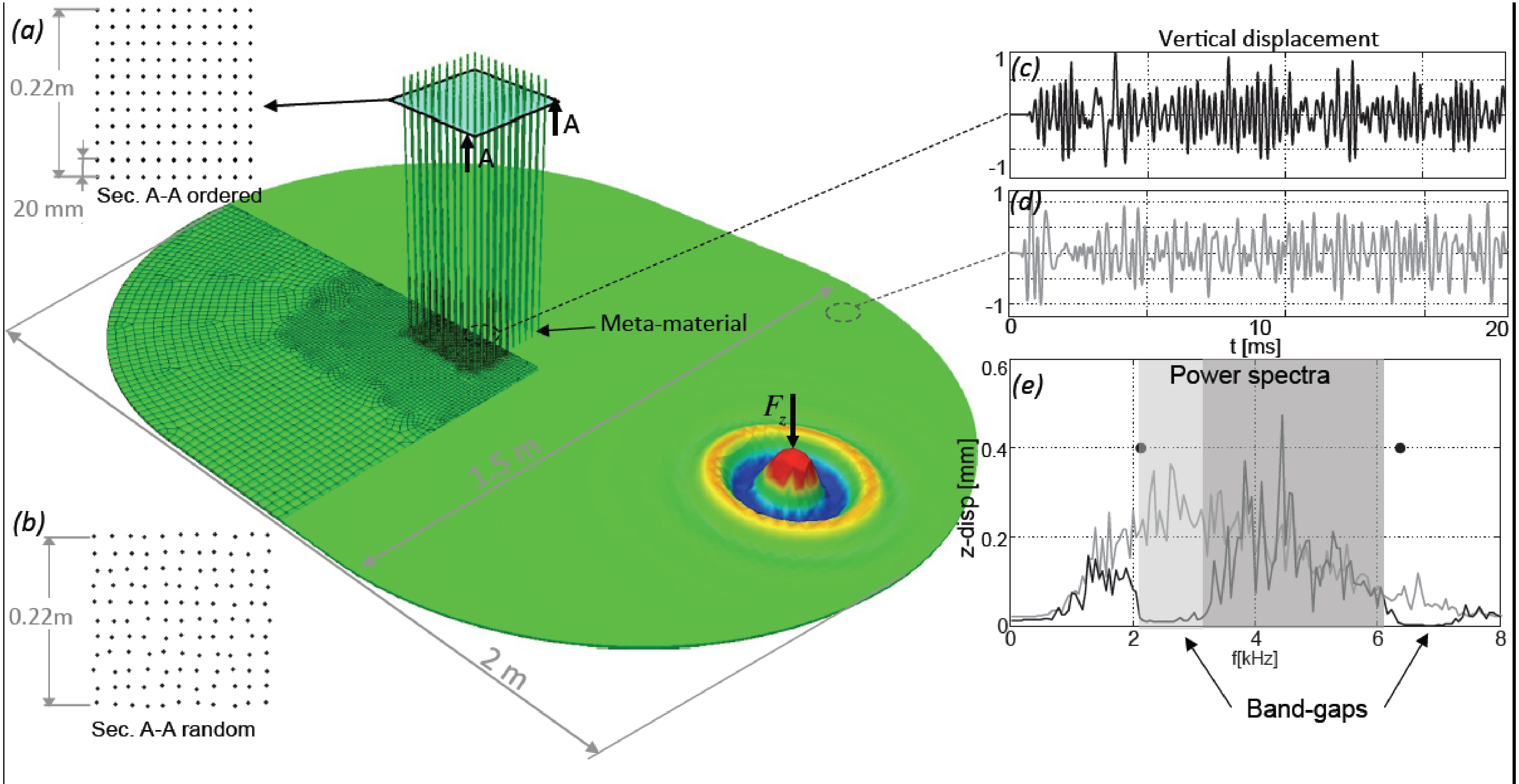
Localized mode

# Seismo-Acoustic Cloaking using a numerical approach

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

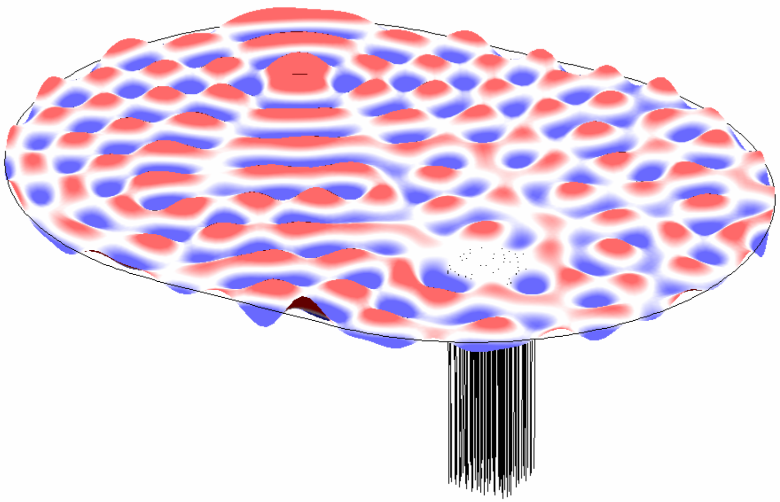


# Numerical approach : Spectral Element Method with 3-D Adaptive Meshing

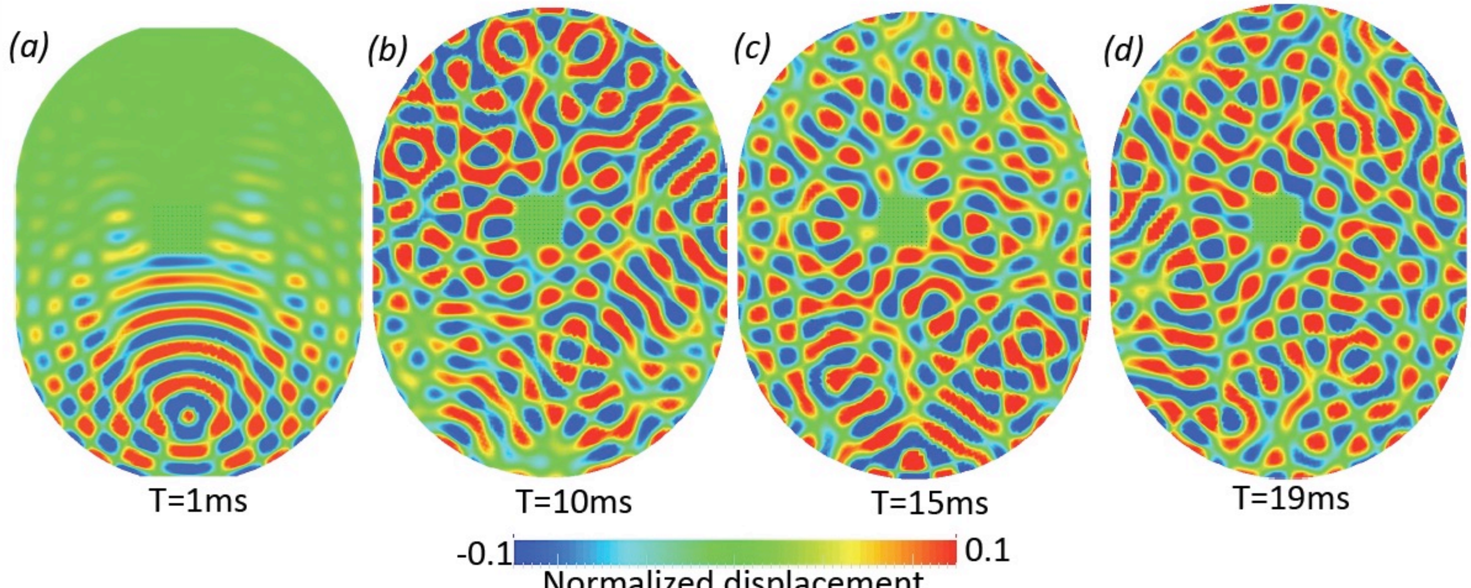



*Colombi et al., JASA-EL, 2014*

# Numerical Results (Filtered in the Bangap)

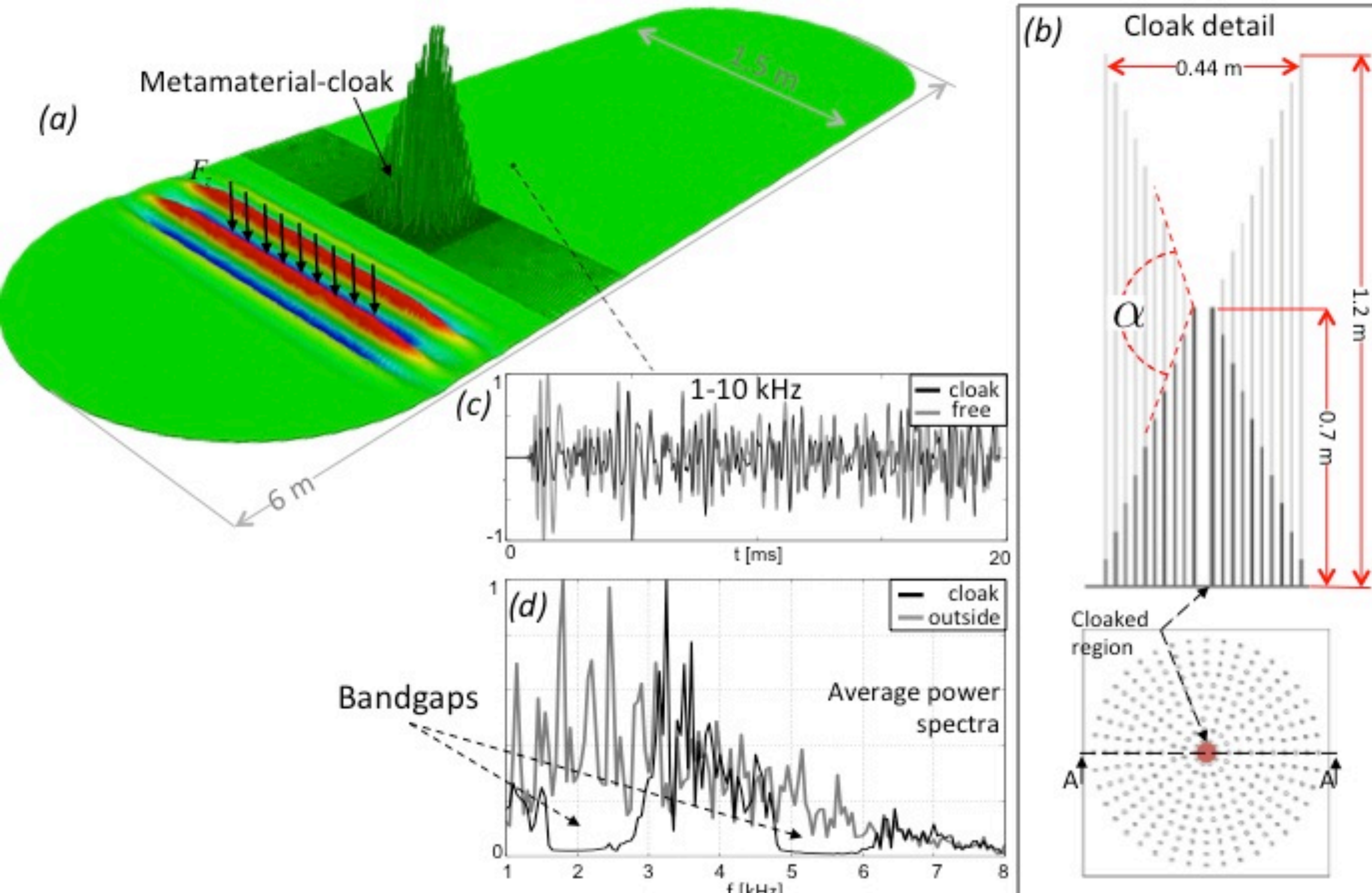


A few snapshots of the wavefield…

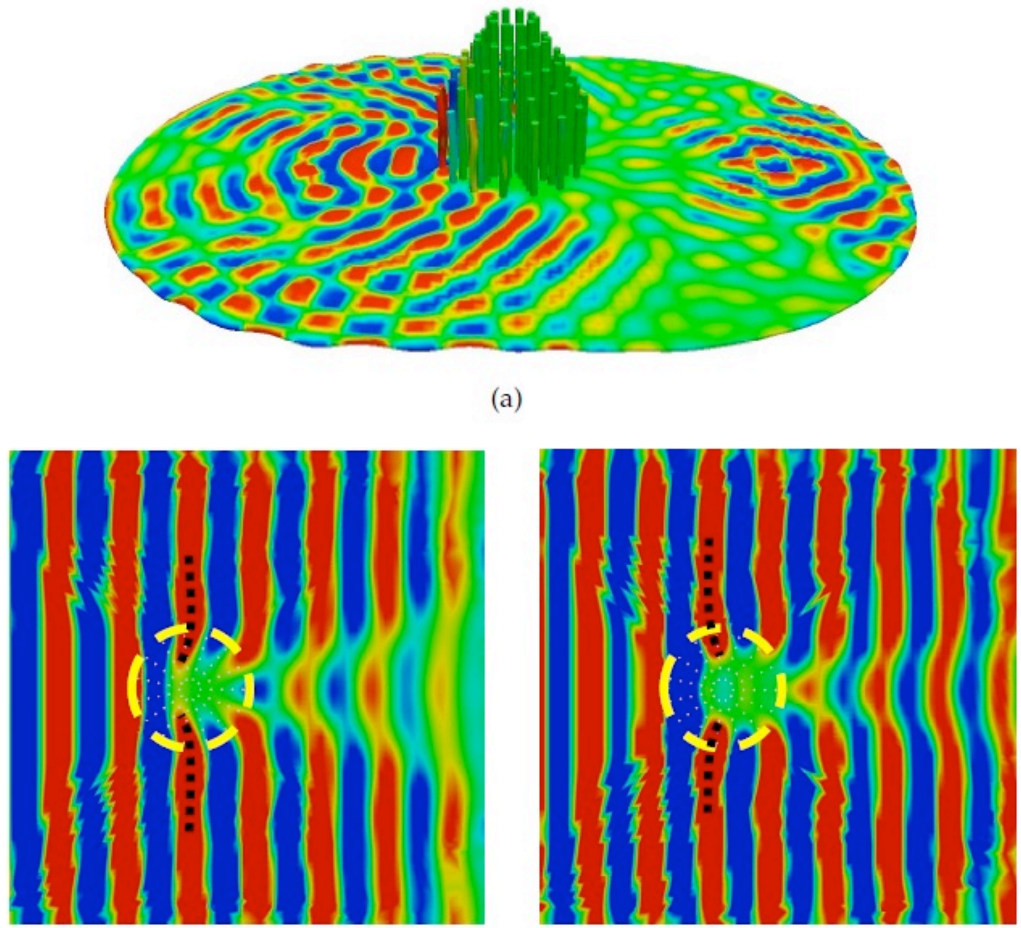



*Roux et al., Handbook of Metamaterial, 2017*

# Toward Acoustic Cloaking (Numerical Results)



# Effective Speed inside the Meta-Material



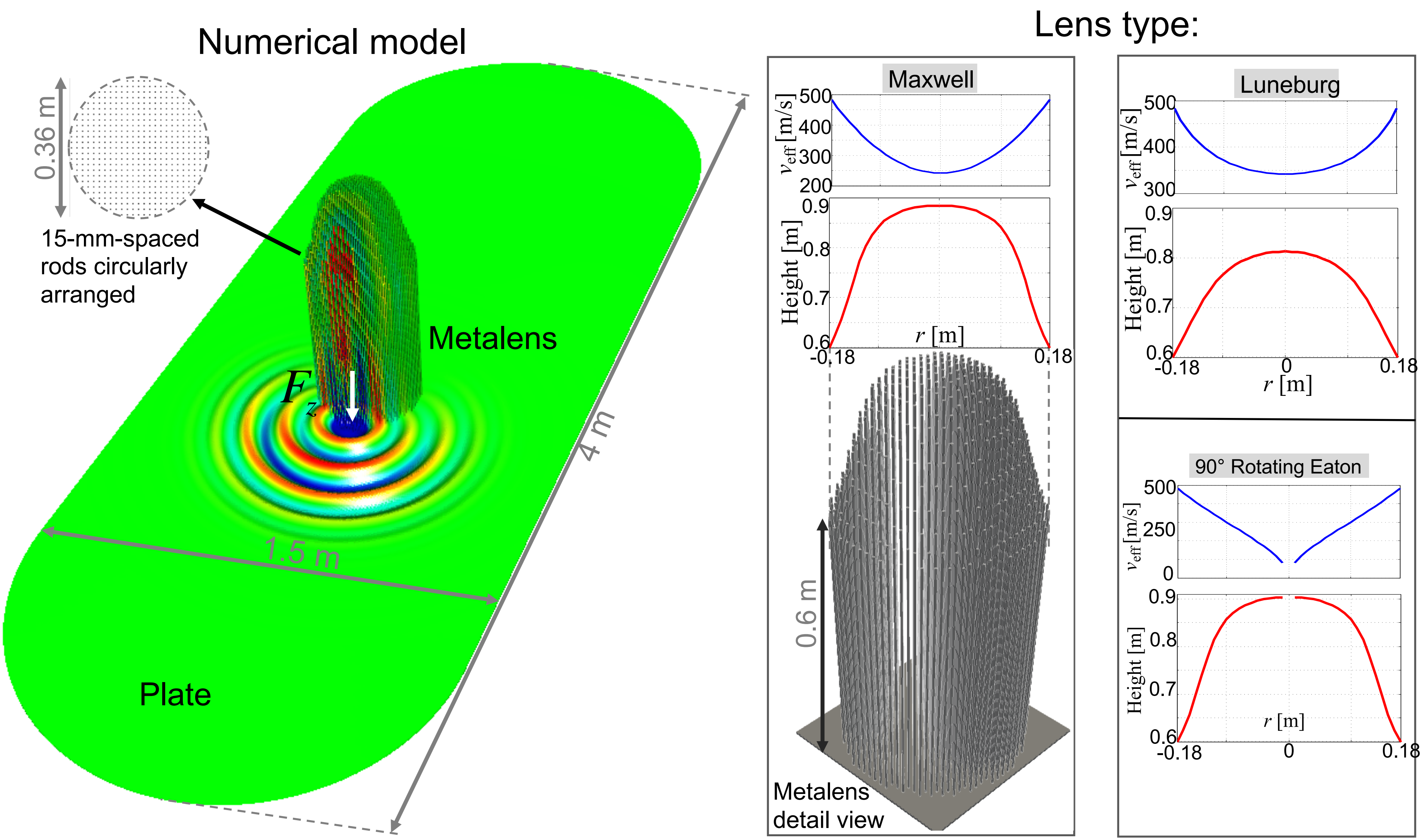
(a)

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

(c) 4,2kHz - 5kHz

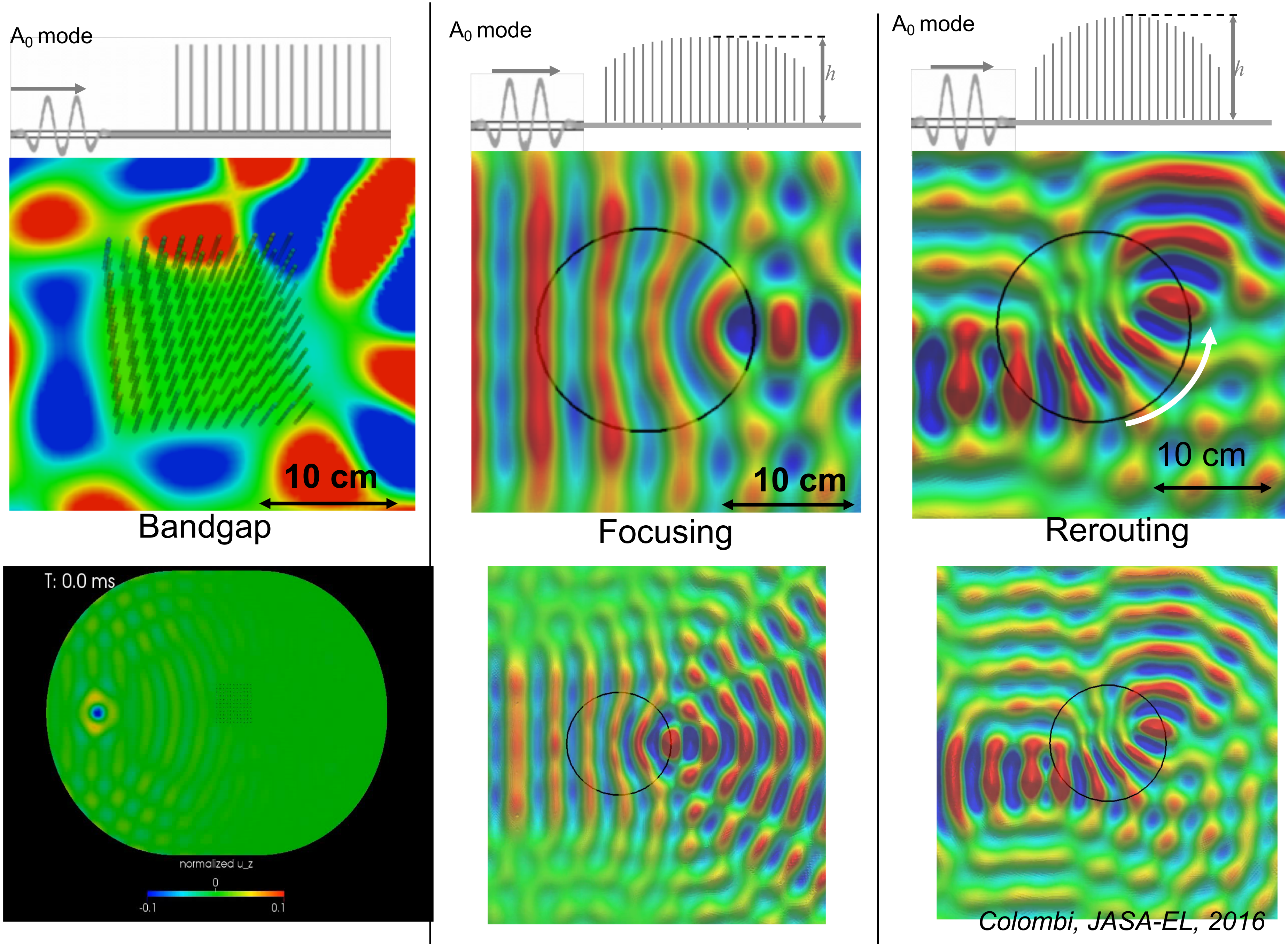
FIGURE 3.36 – *Illustration des travaux en cours de développement pour la mise au point d'une cape d'invisibilité pour les ondes de Lamb A0. a) Exemple de configuration étudiée : un ensemble de tiges de différentes longueurs disposées en étoile. b-c) Allure du champ d'ondes (vitesses verticales) au dessus 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




*Colombi, JASA-EL, 2016*

# Plate Wave Manipulation with Gradient Index Lenses



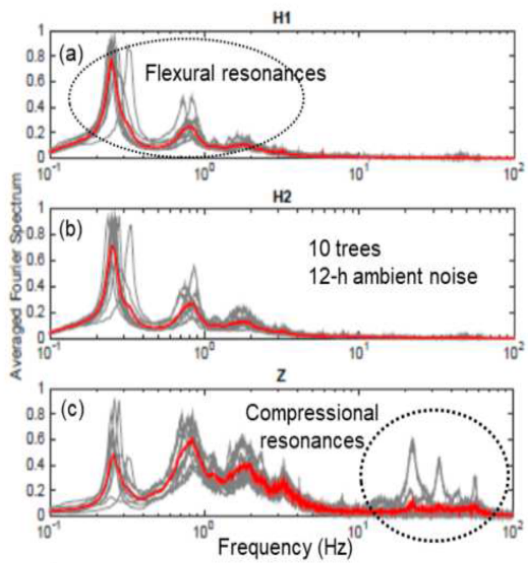

Colombi, JASA-EL, 2016

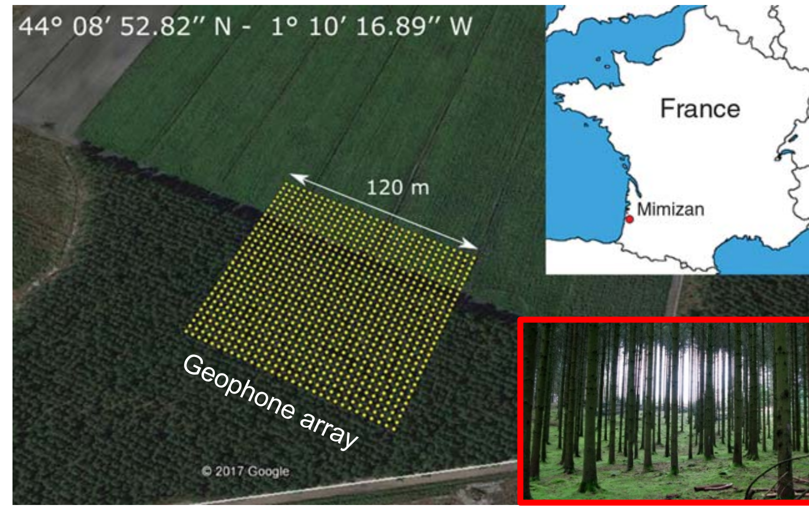
# Application at the geophysics scale : can we consider a forest as a natural Metamaterial?

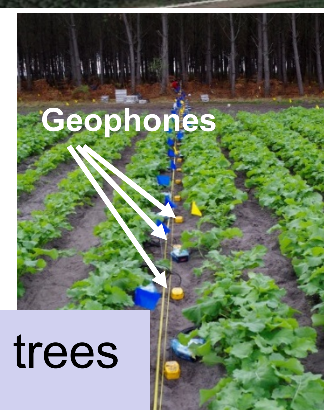
*Roux et al., SRL, 2018*

META-FORET

Trees as resonators

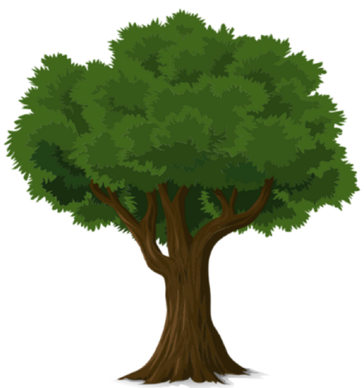


- Compressional and Flexural motion for the trees
- Sources inside and outside the forest

# Transposition from Laboratory study to Geohysics

Compression/flexion

Tree



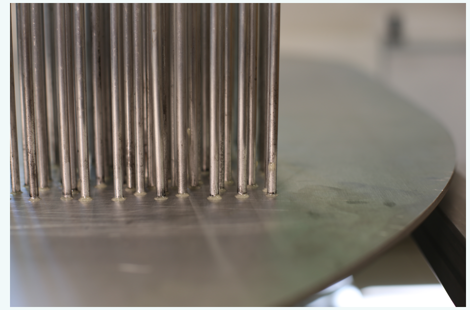
Beam

ground

plate

Surface waves
*Freq* : 10-100 Hz

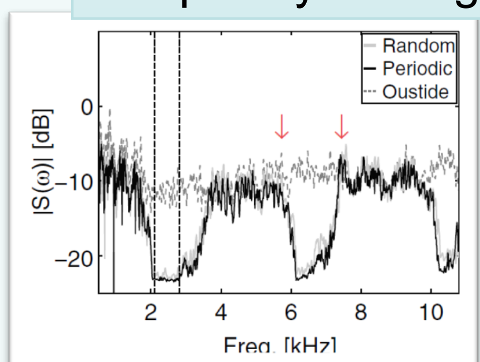
A0 Lamb waves
Freq : 1-10 kHz

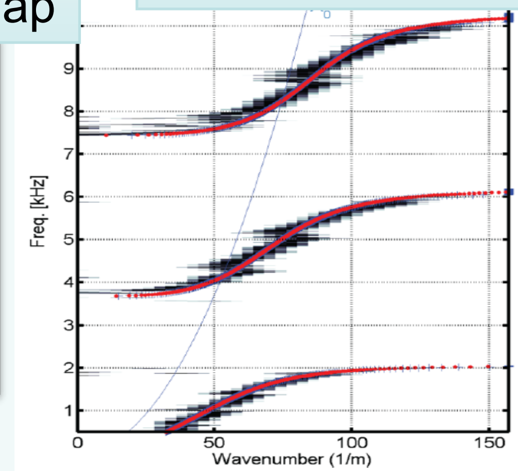


Forest of rods on
A0 Lamb wave

Hybridization-like
dispersion curve

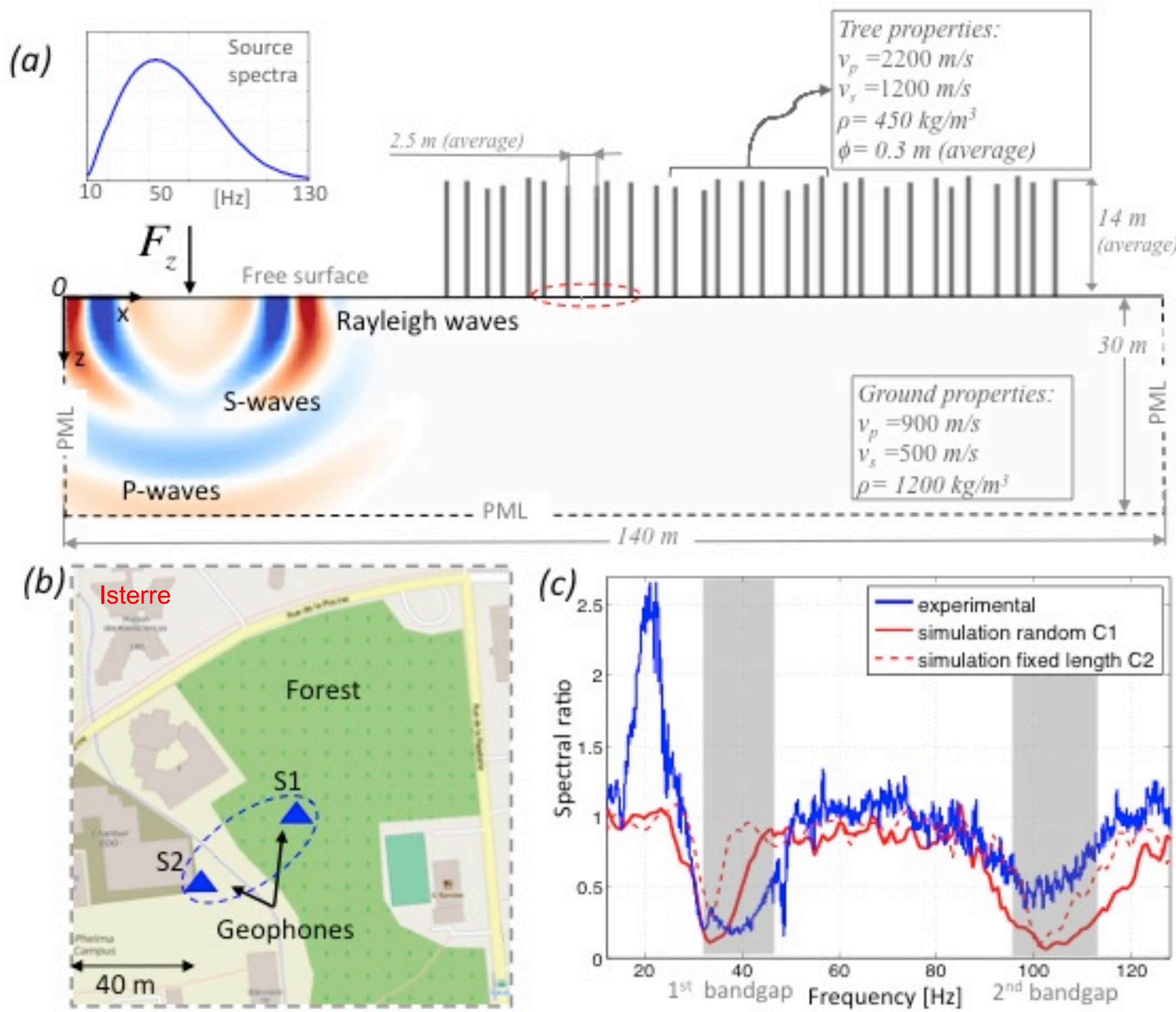
Frequency band-gap



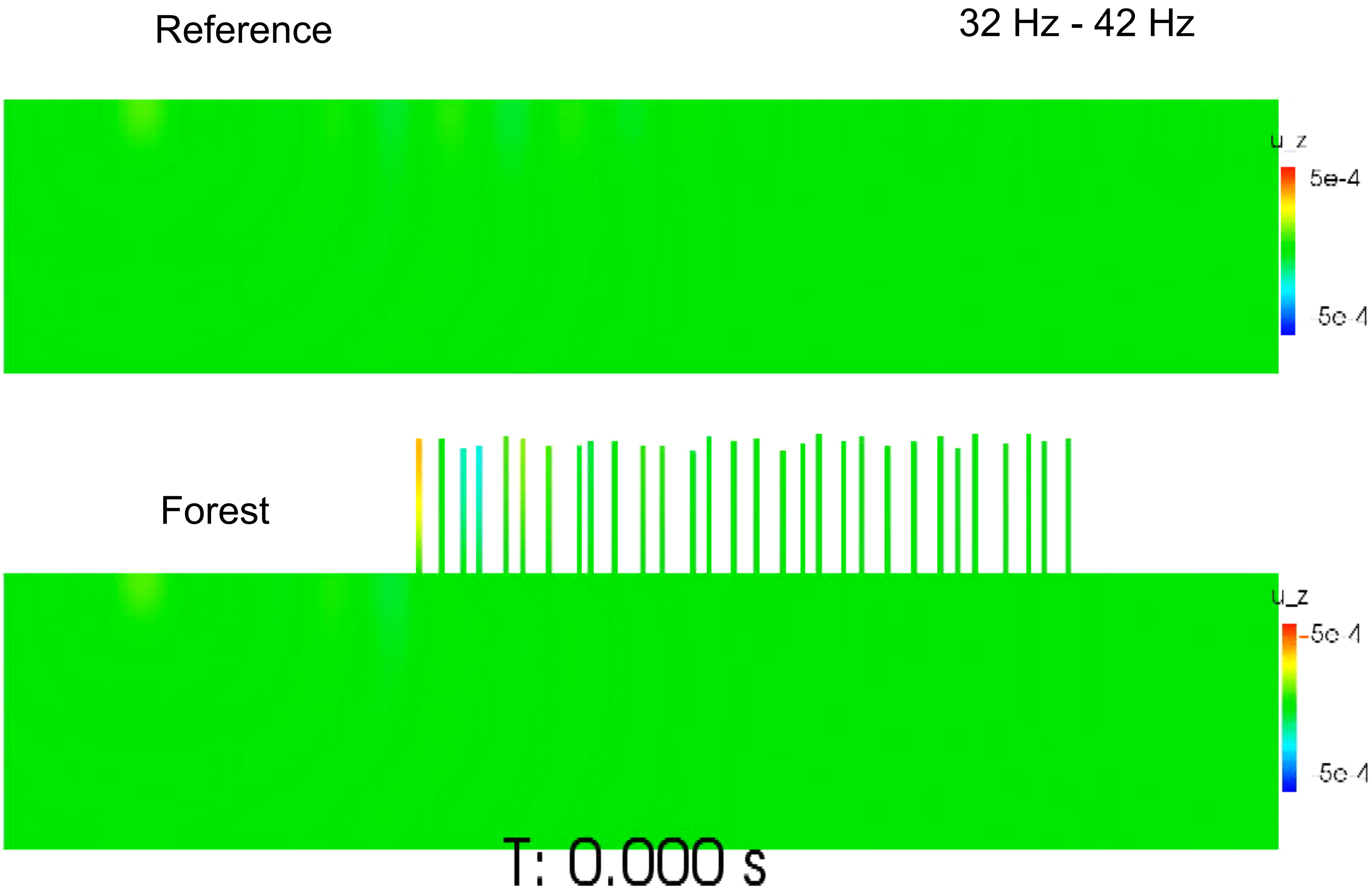

*Rupin et al. PRL 2014*

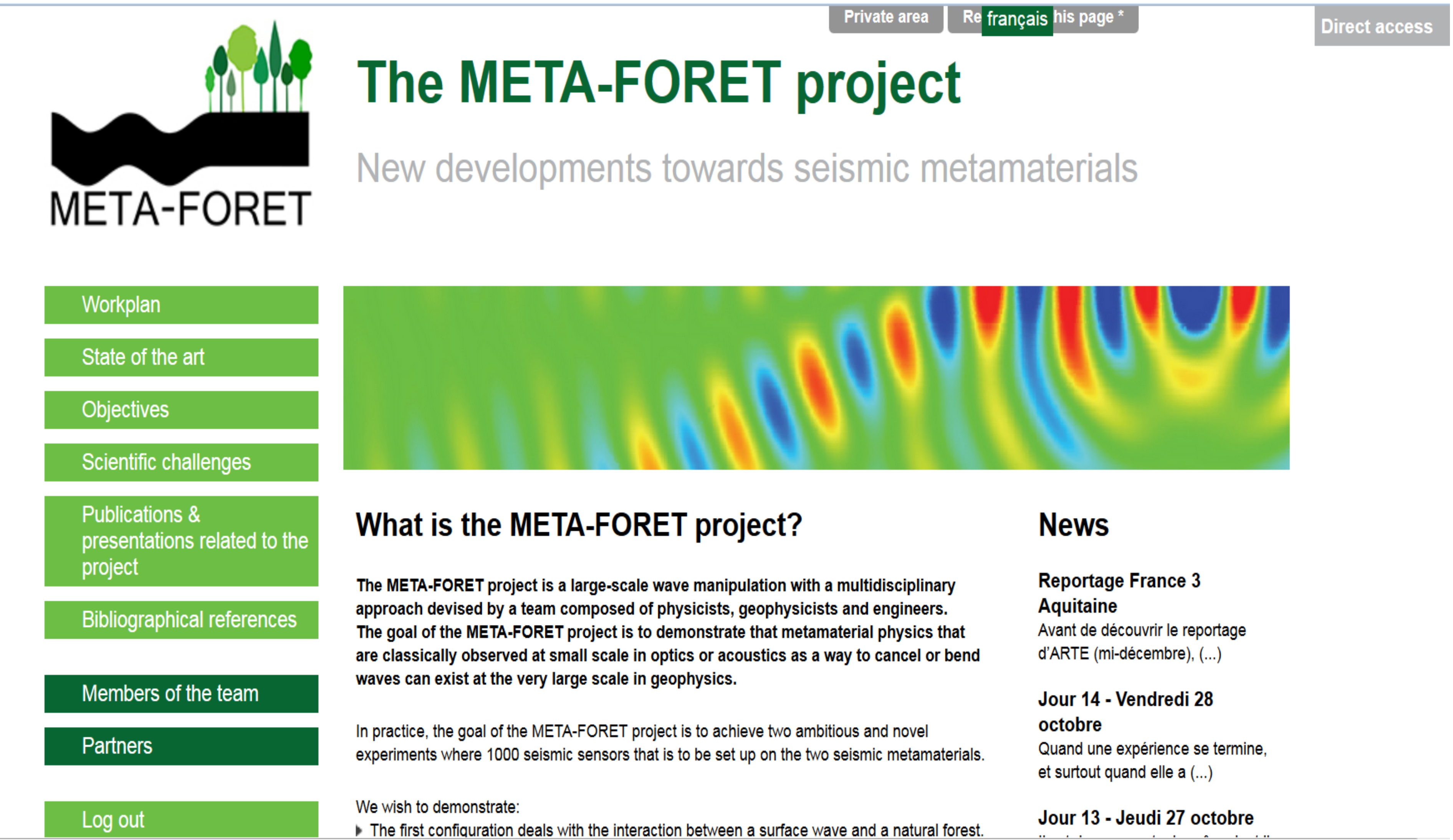
# First experimental / numerical demonstration at the geophysics scale (2015)




*Colombi et al., Scientific Reports, 2016*

# Rayleigh wave interacting with resonating trees?




Private area

Re français his page *

Direct access

META-FORET

# The META-FORET project

New developments towards seismic metamaterials

- Workplan
- State of the art
- Objectives
- Scientific challenges
- Publications & presentations related to the project
- Bibliographical references
- Members of the team
- Partners
- Log out

## 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*

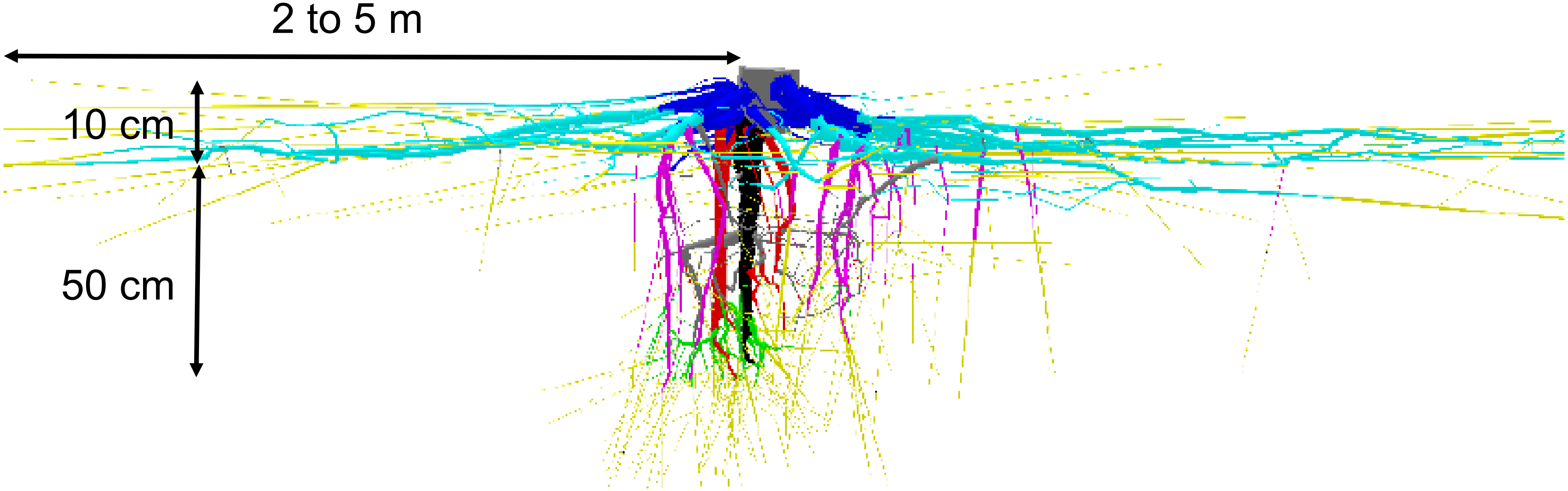
# Preparation of the METAFORET Experiment (2016)

Choice of the forest area

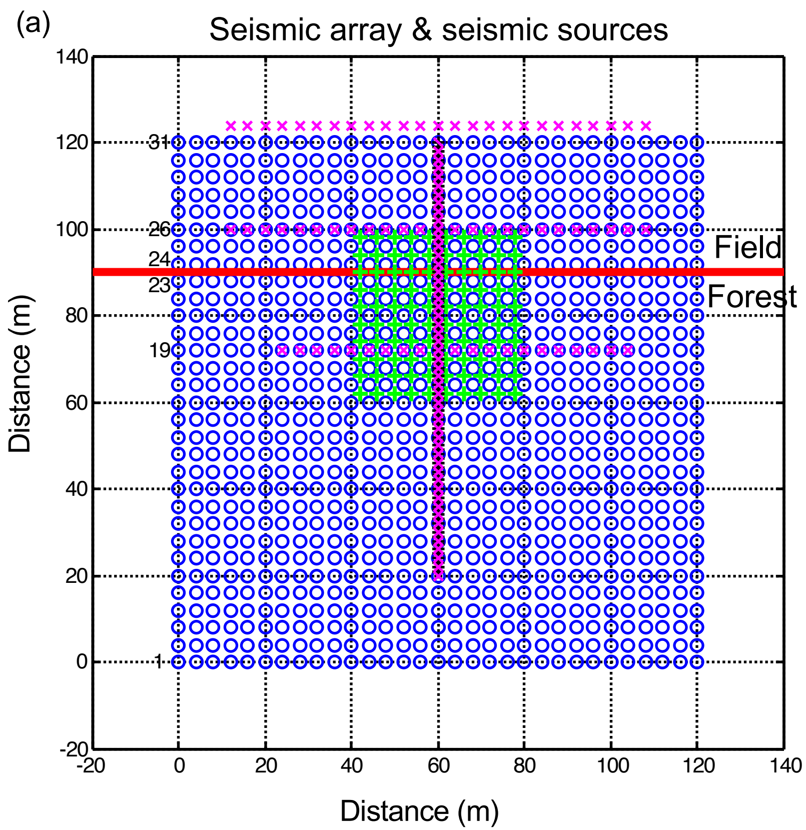
Collaborations with CNPF,

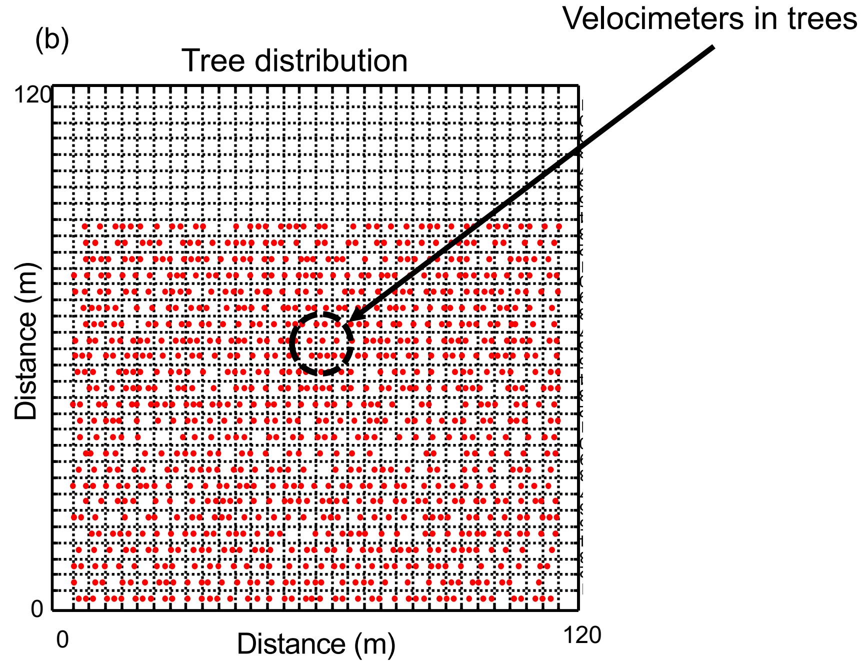
INRA BIOGECO & ISPA

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

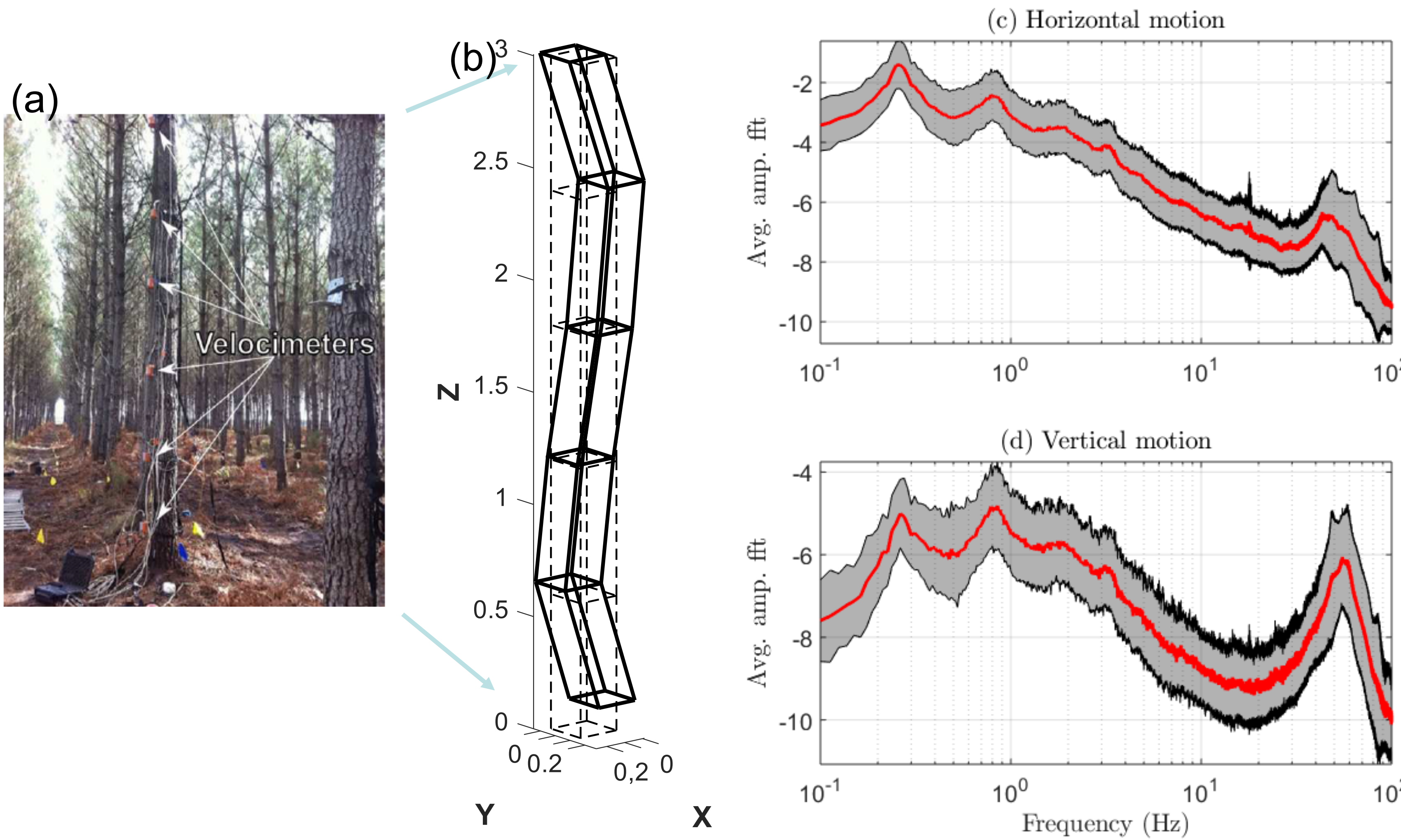
(c) Vibrometer source (> 15 Hz)

# The METAFORET experiment

(a) Tree instrumented with 6 velocimeters

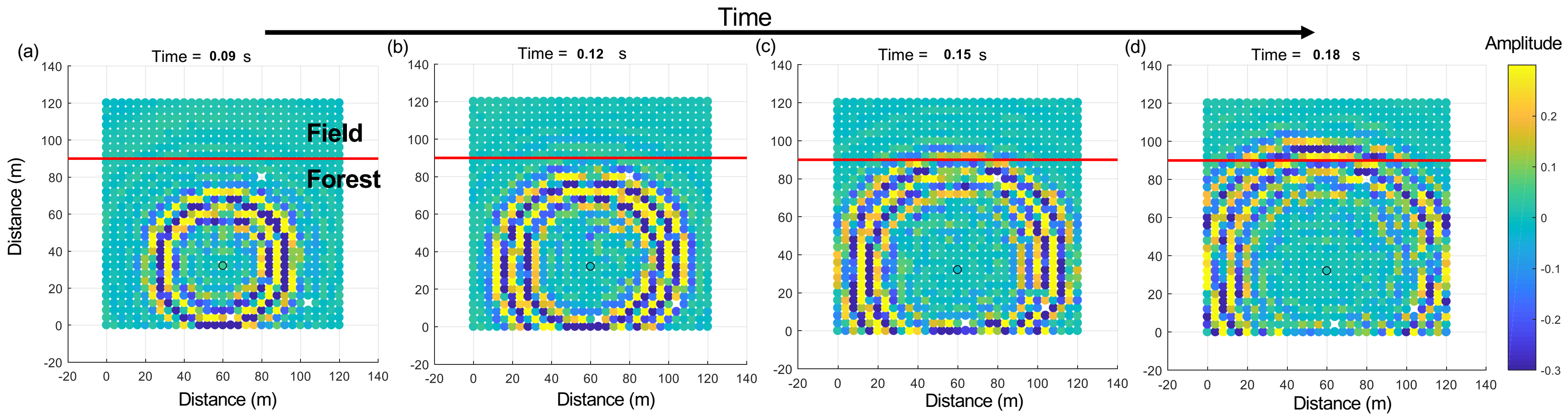
(b) Ground Penetrating Radar survey

# The METAFORET data : The tree spectral response

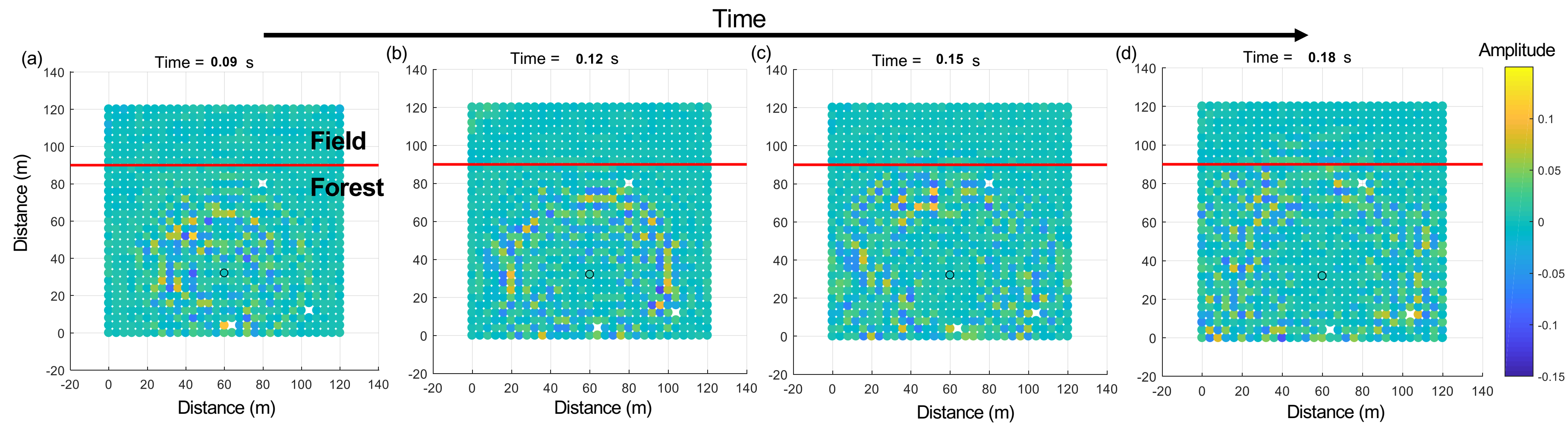


# The METAFORET data : Active Source on 2-D Surface Array

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

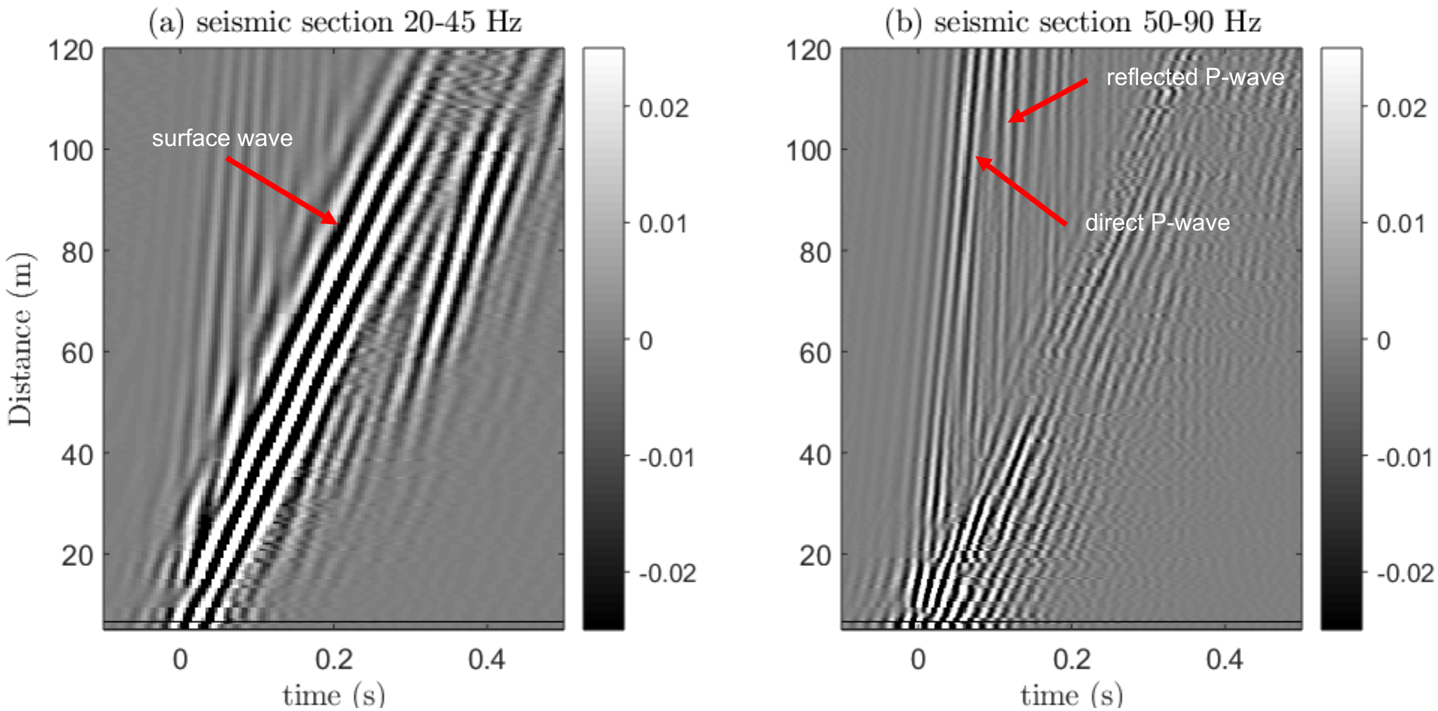



Frequency : 50 Hz - 80 Hz : above the tree compressionnal resonances



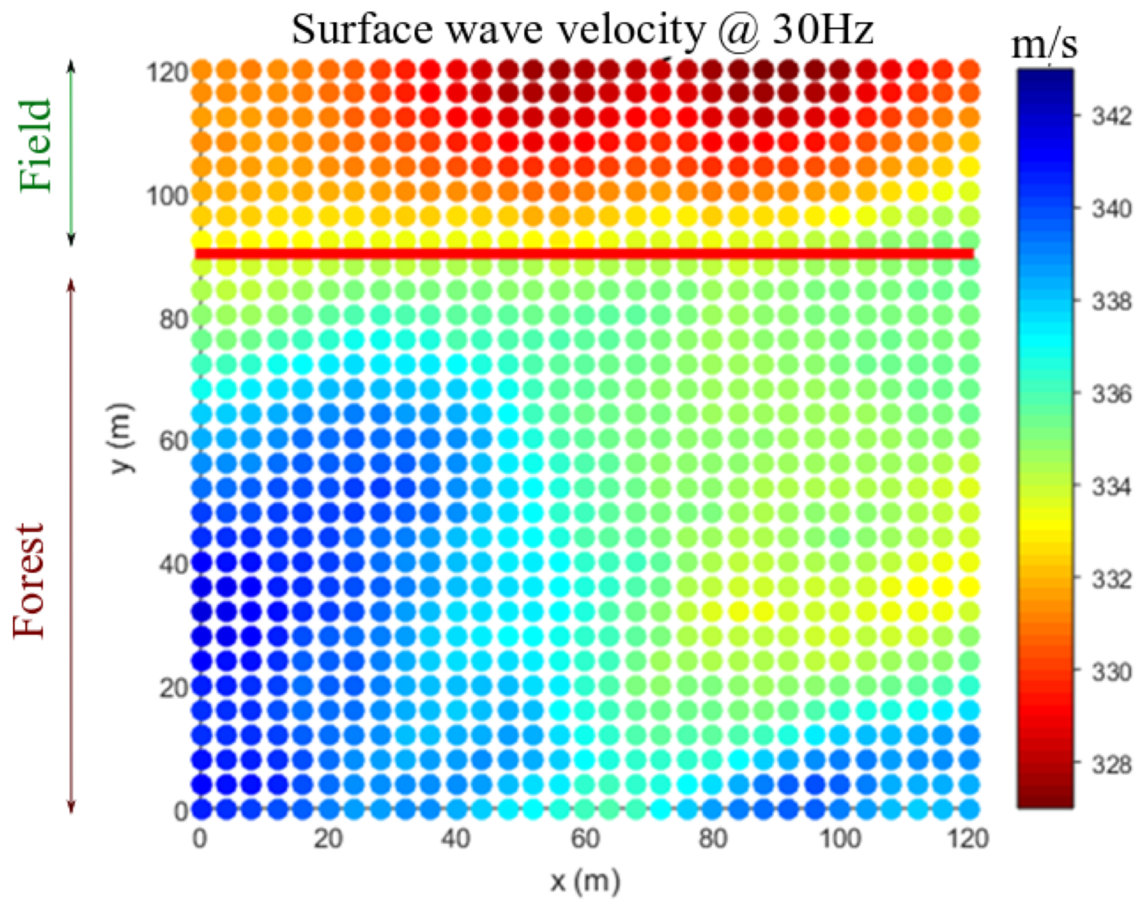
# The METAFORET data :

# Active Source for Average Seismic Section



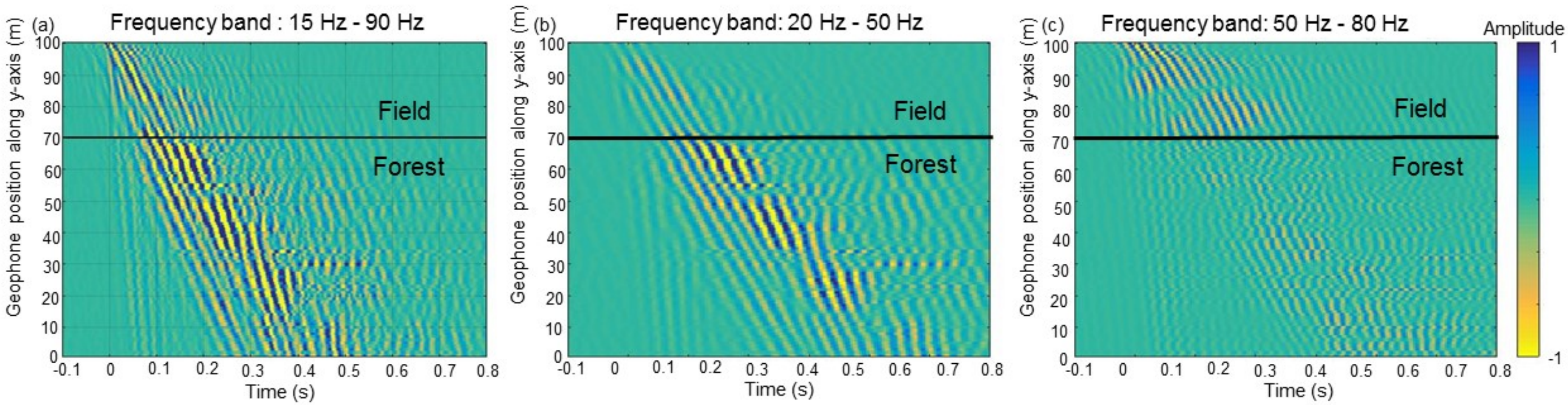
# The METAFORET data :

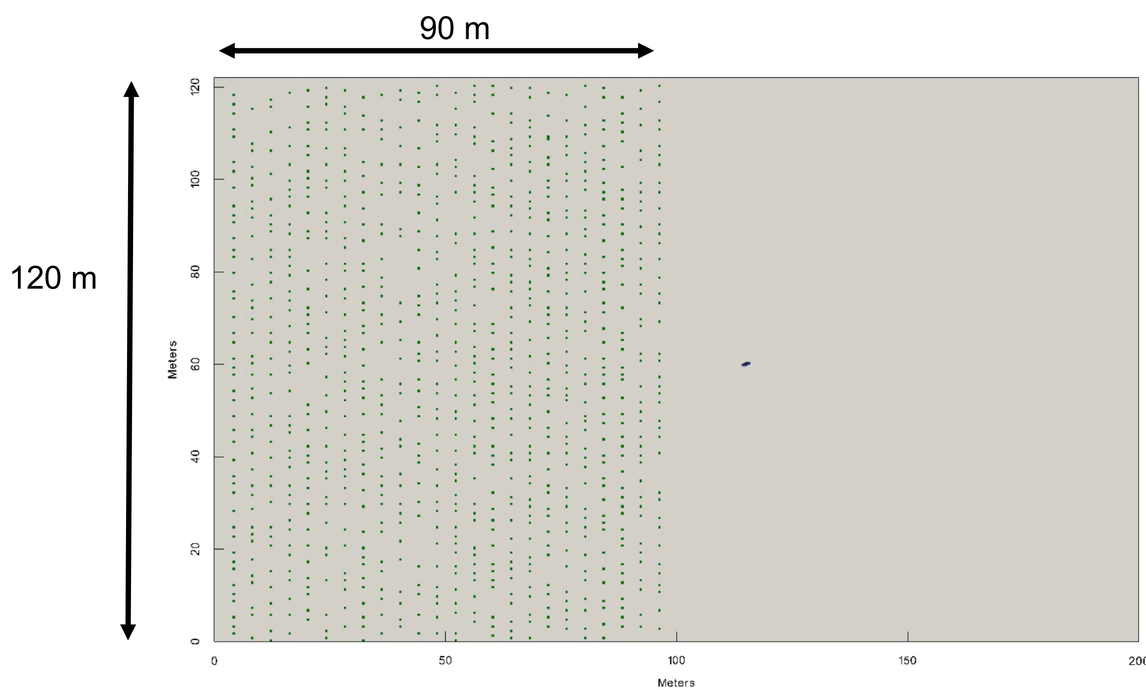
# Active Source for Surface Wave Tomography



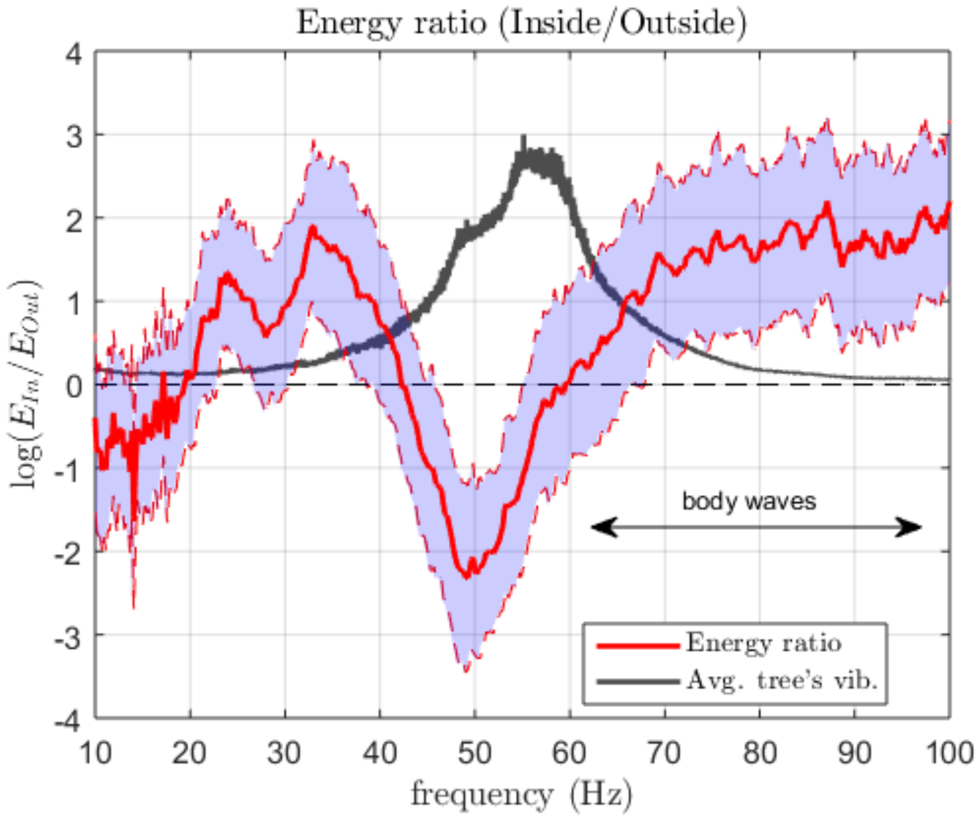

Role of the tree roots ?

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



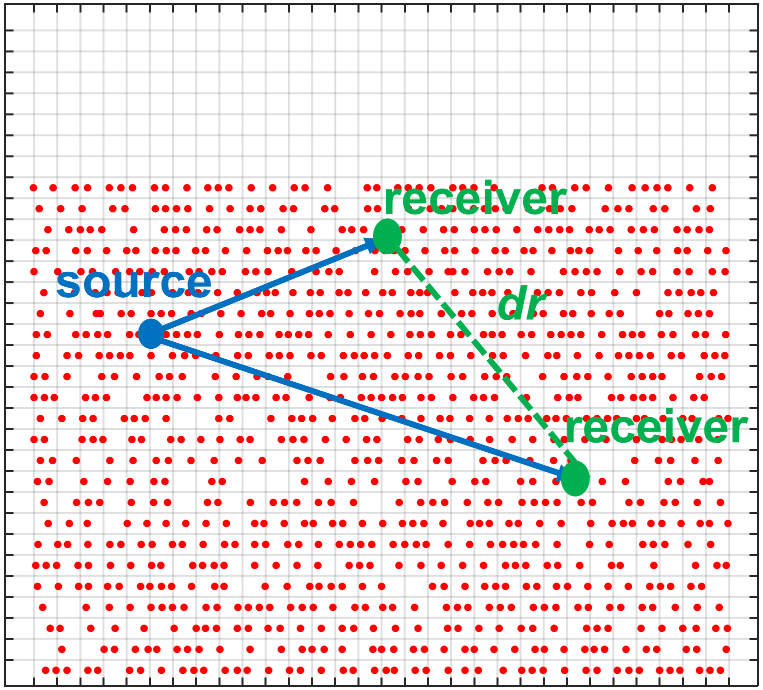



# The METAFORET data : Spectral ratio in / out of the forest



# The METAFORET data : Two-point correlation analysis

125 sources
961 receivers

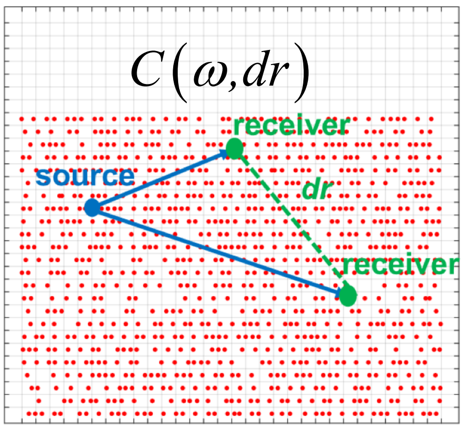


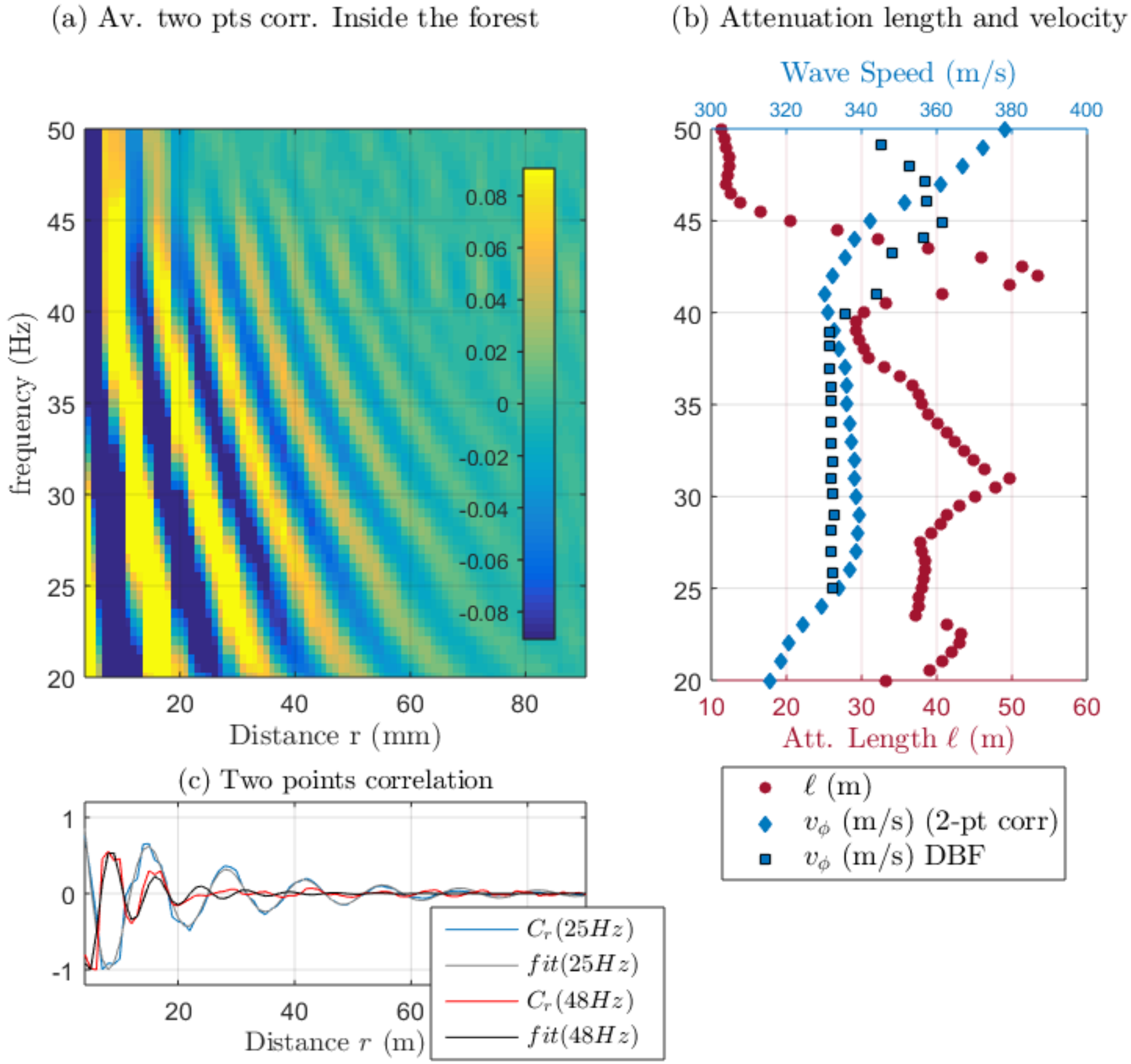

$$C\left(\omega,d\vec{r}\right)=\frac{\left\langle \Psi\left(\omega,\vec{r}\right)\Psi^{*}\left(\omega,\vec{r}+d\vec{r}\right)\right\rangle_{\vec{r}}}{\left\langle \left|\Psi\left(\omega,\vec{r}\right)\right|^{2}\right\rangle_{\vec{r}}}$$

$$C\left(\omega,dr\right)=\left\langle C\left(\omega,d\vec{r}\right)\right\rangle_{\theta}$$

Effective medium approximation

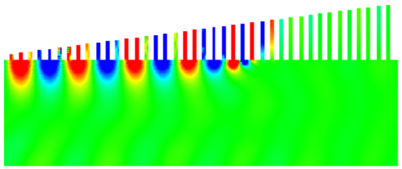
# The METAFORET data : Two-point correlation



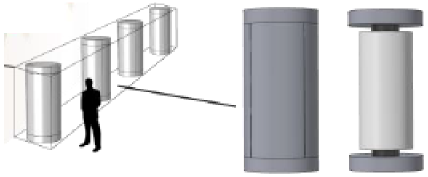



# Other Attempts with Seismic Metamaterials

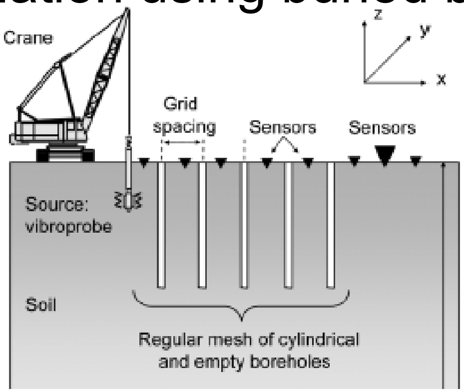
- The Metawedge configuration



- Seismic wave cancellation using buried resonators



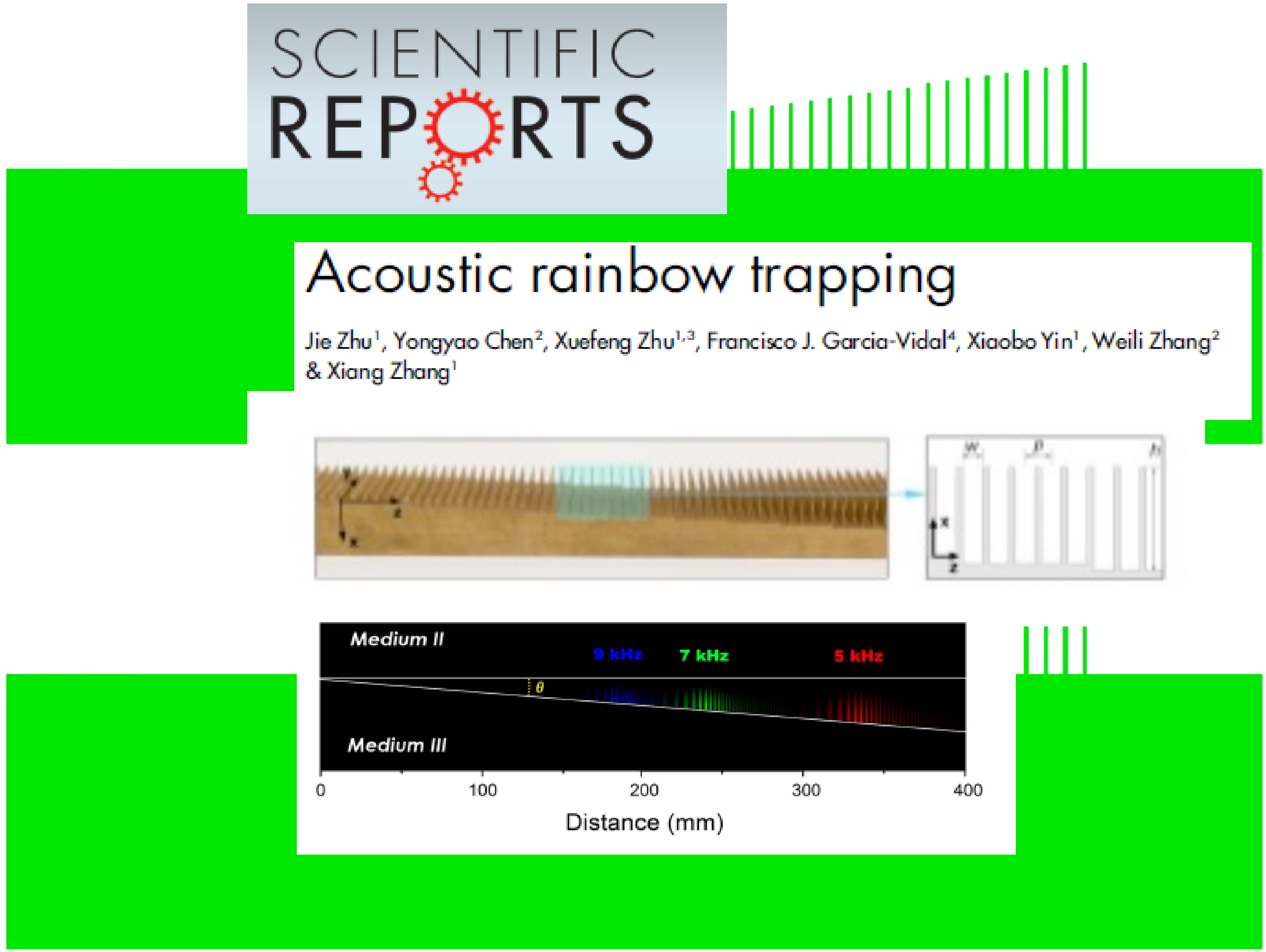
- Seismic wave cancellation using buried beams



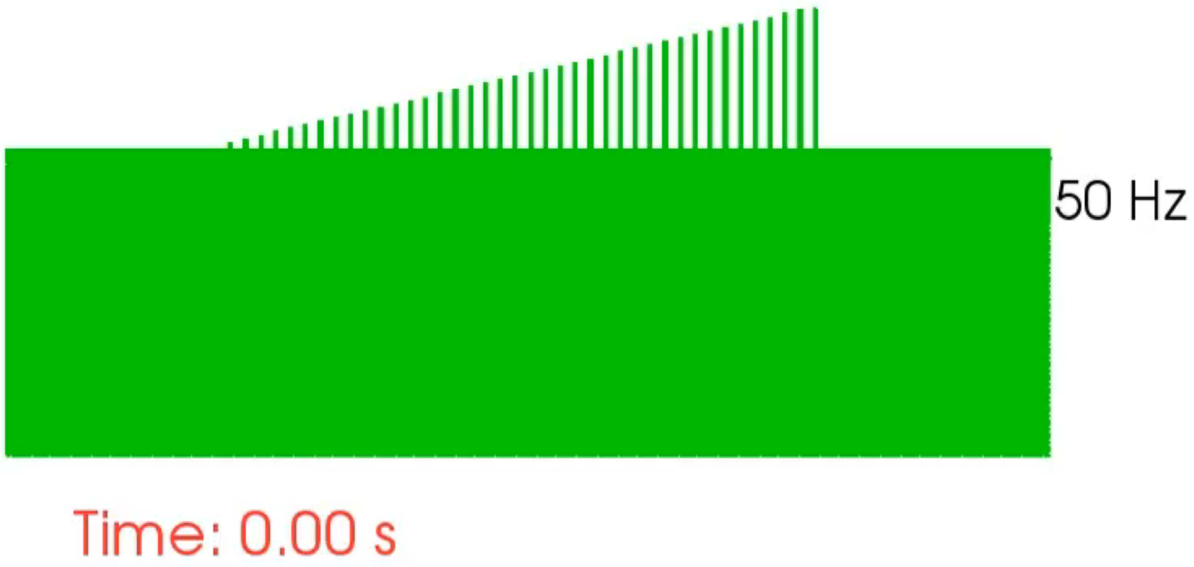
# Trees with different height : The seismic rainbow

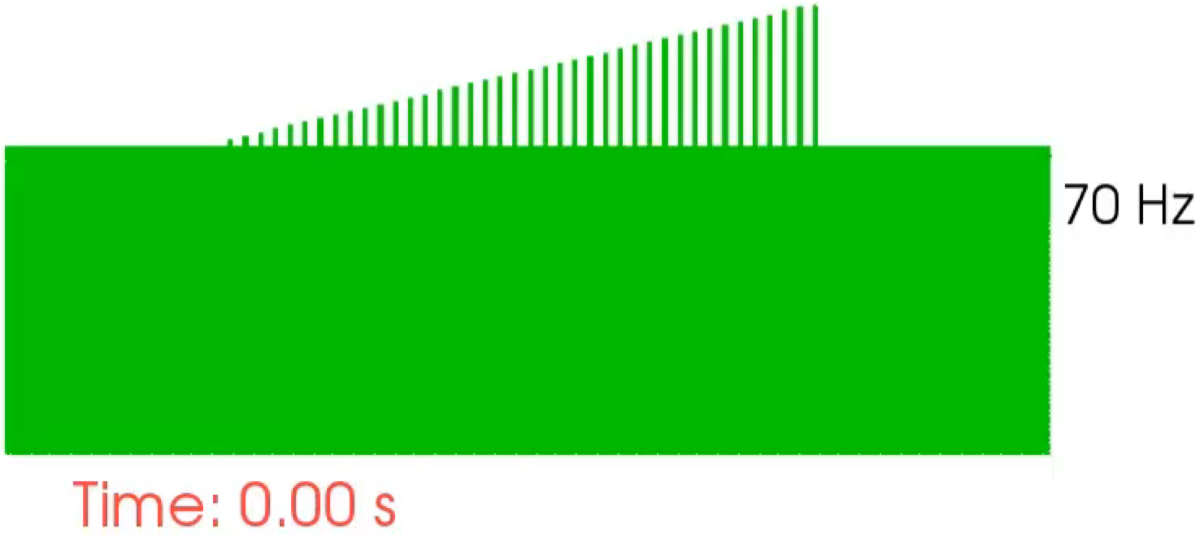
40 Hz

70 Hz



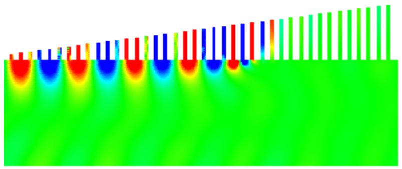
# Trees with different height : The inverse wedge effect



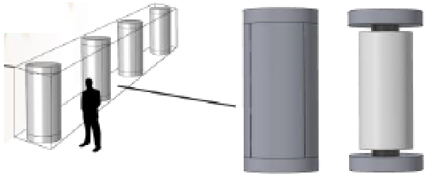



# Other Attempts with Seismic Metamaterials:

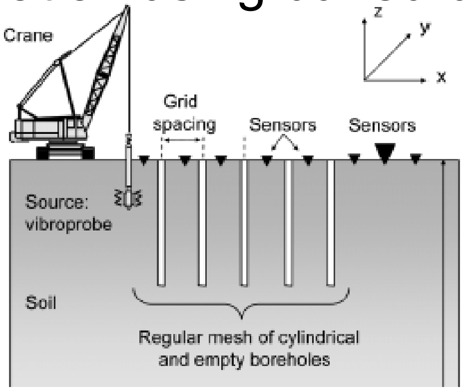
- The Metawedge configuration



- Seismic wave cancellation using buried resonators

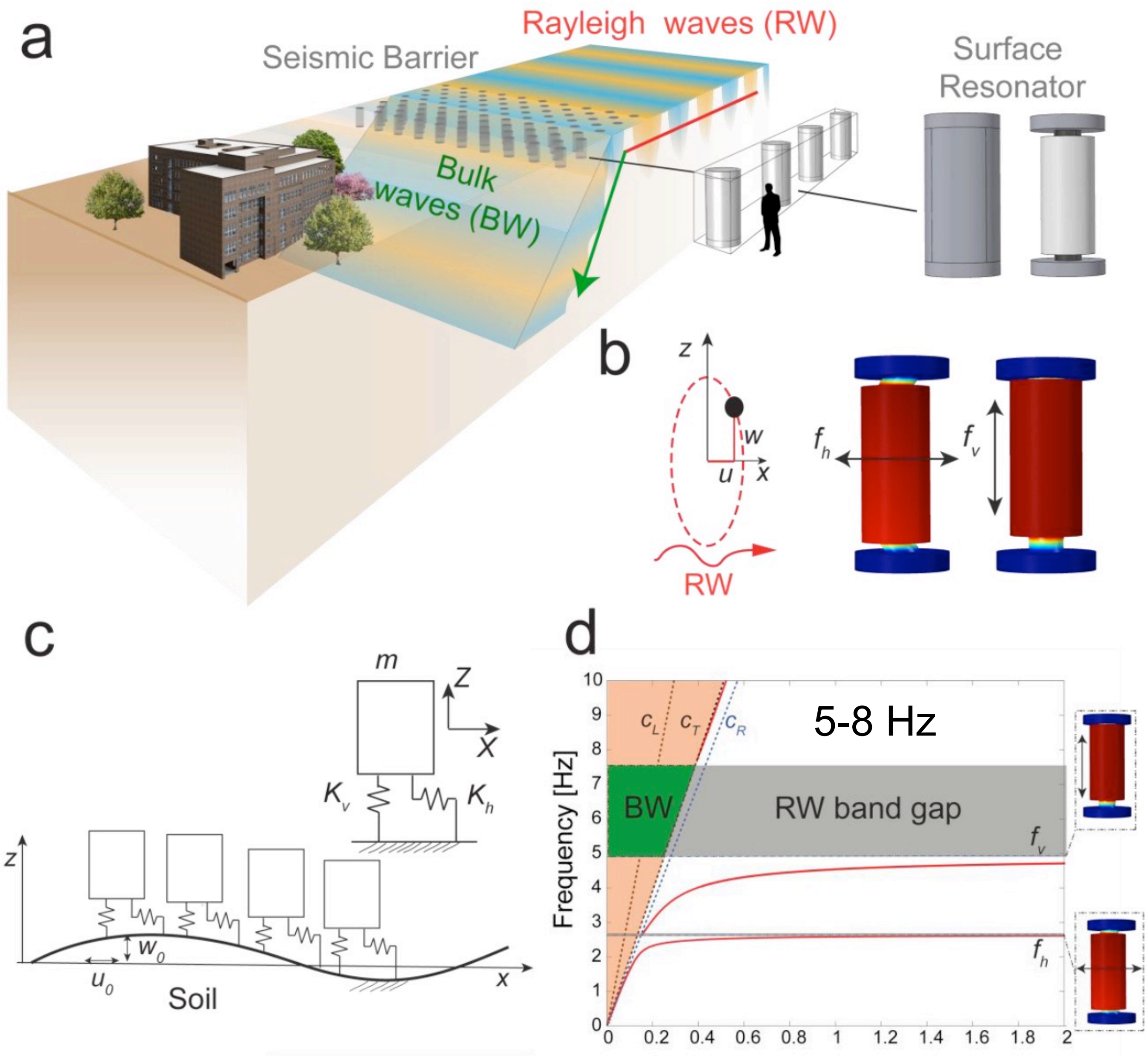


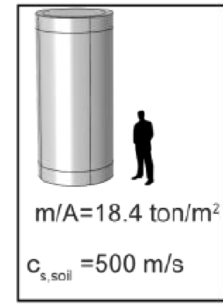
- Seismic wave cancellation using buried beams

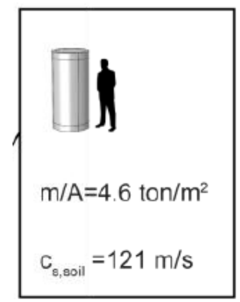


# Engineered Metabarrier as Shield from Seismic Surface Waves (1)

*Palermo et al., Scientific Reports, 2017*

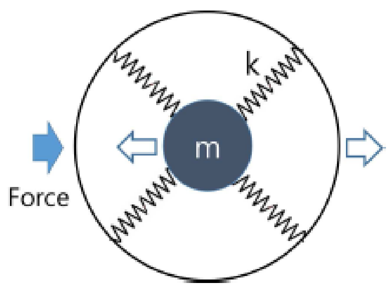


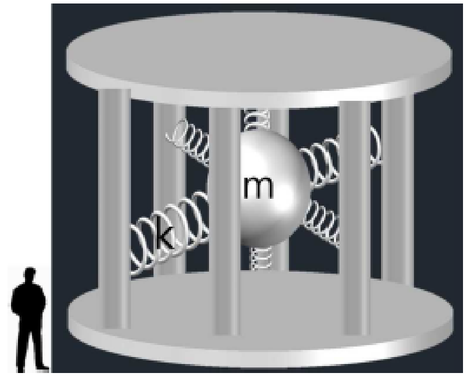



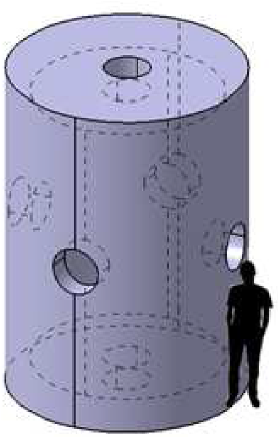



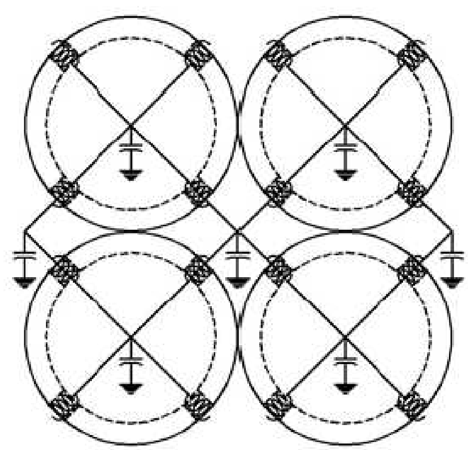
# Engineered Metabarrier as Shield from Seismic Surface Waves (2)

m ~ 1000 kg





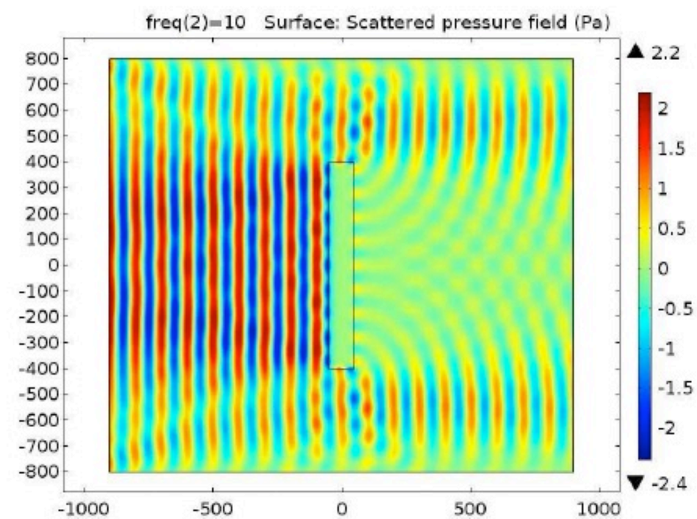
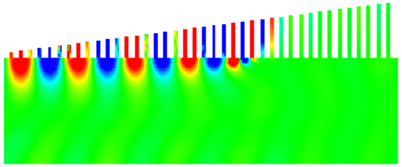



FIG. 3: Pressure distribution by a negative belt. Acoustic wave comes from the left side. Freq.= $10Hz$. The units are m.

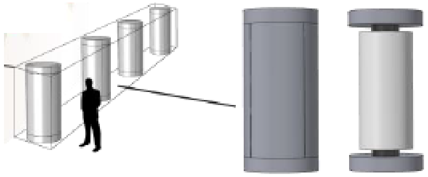
*S-H Kim and M. Das, 2017*

# Other Attempts with Seismic Metamaterials:

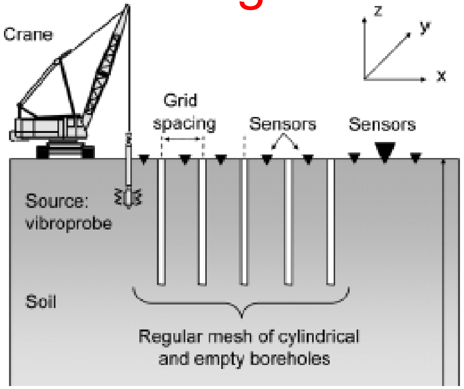
- The Metawedge configuration



- Seismic wave cancellation using buried resonators

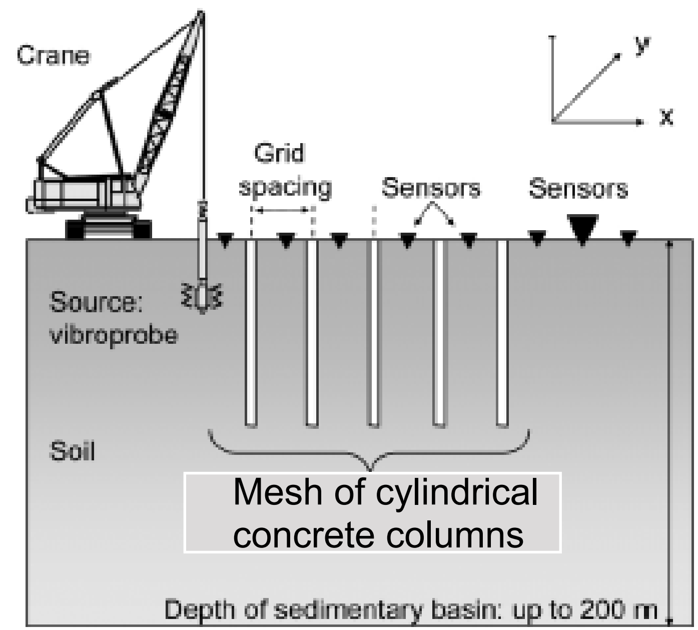


- Seismic wave cancellation using buried beams



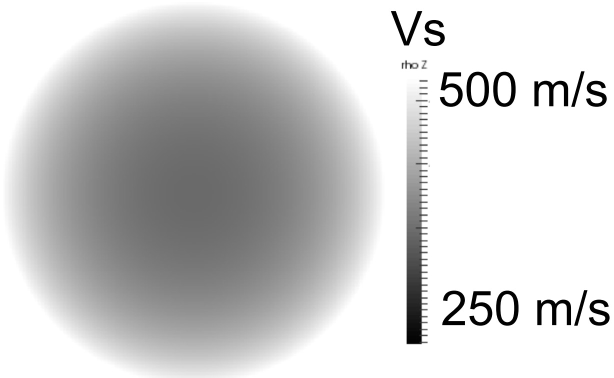
# Soil Reinforcement using Buried Vertical Concrete Beams


*Brule et al, PRL, 2014*

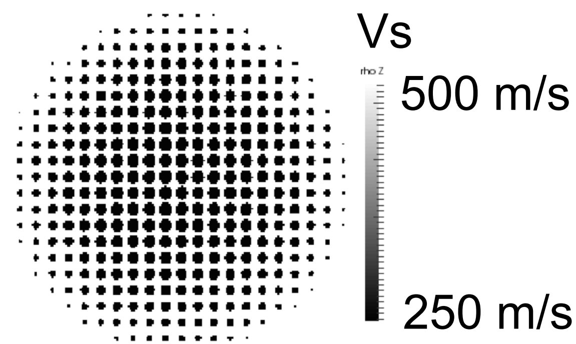



→ Local change of refraction index

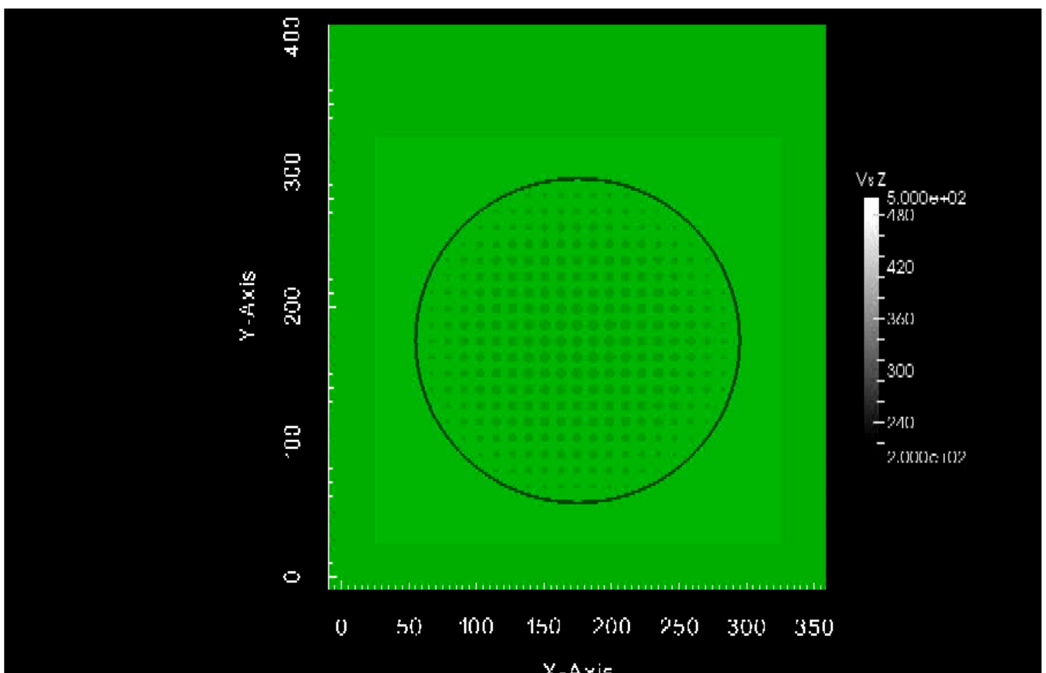
# Luneberg Lens applied to Geophysics



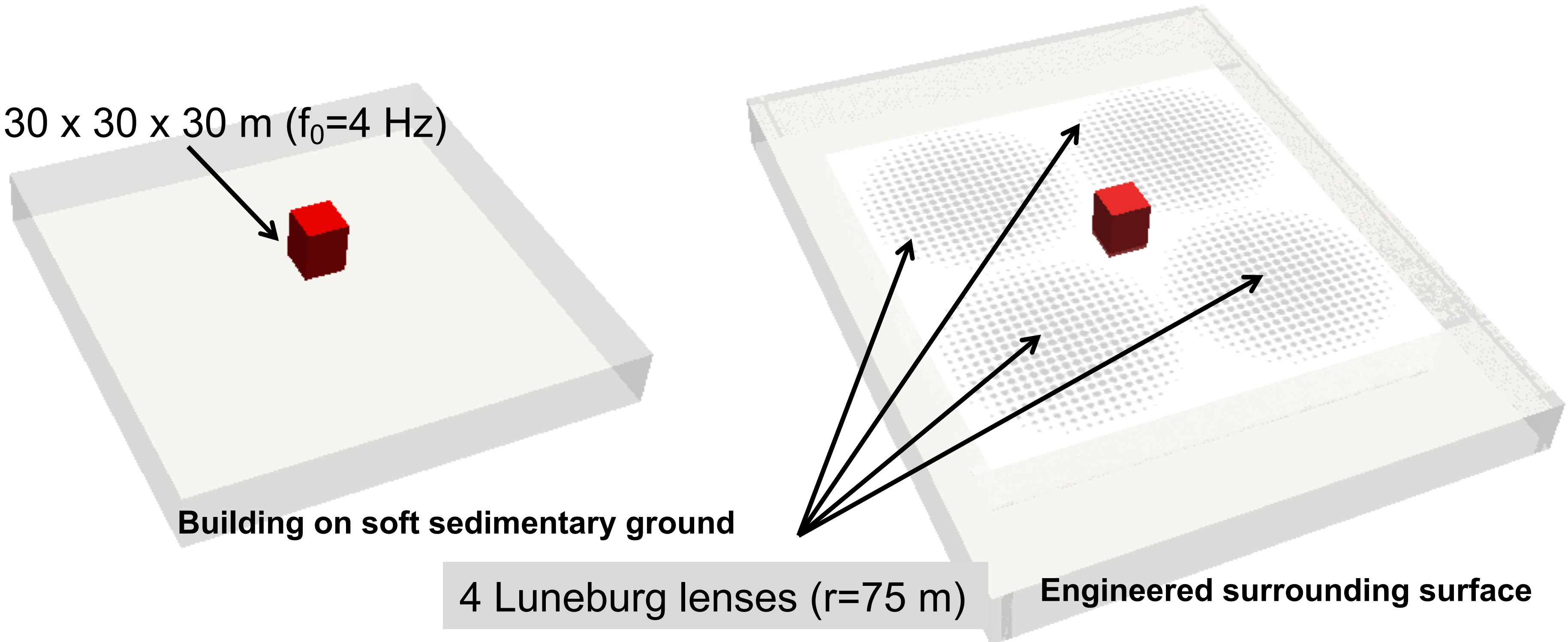

Continuous version



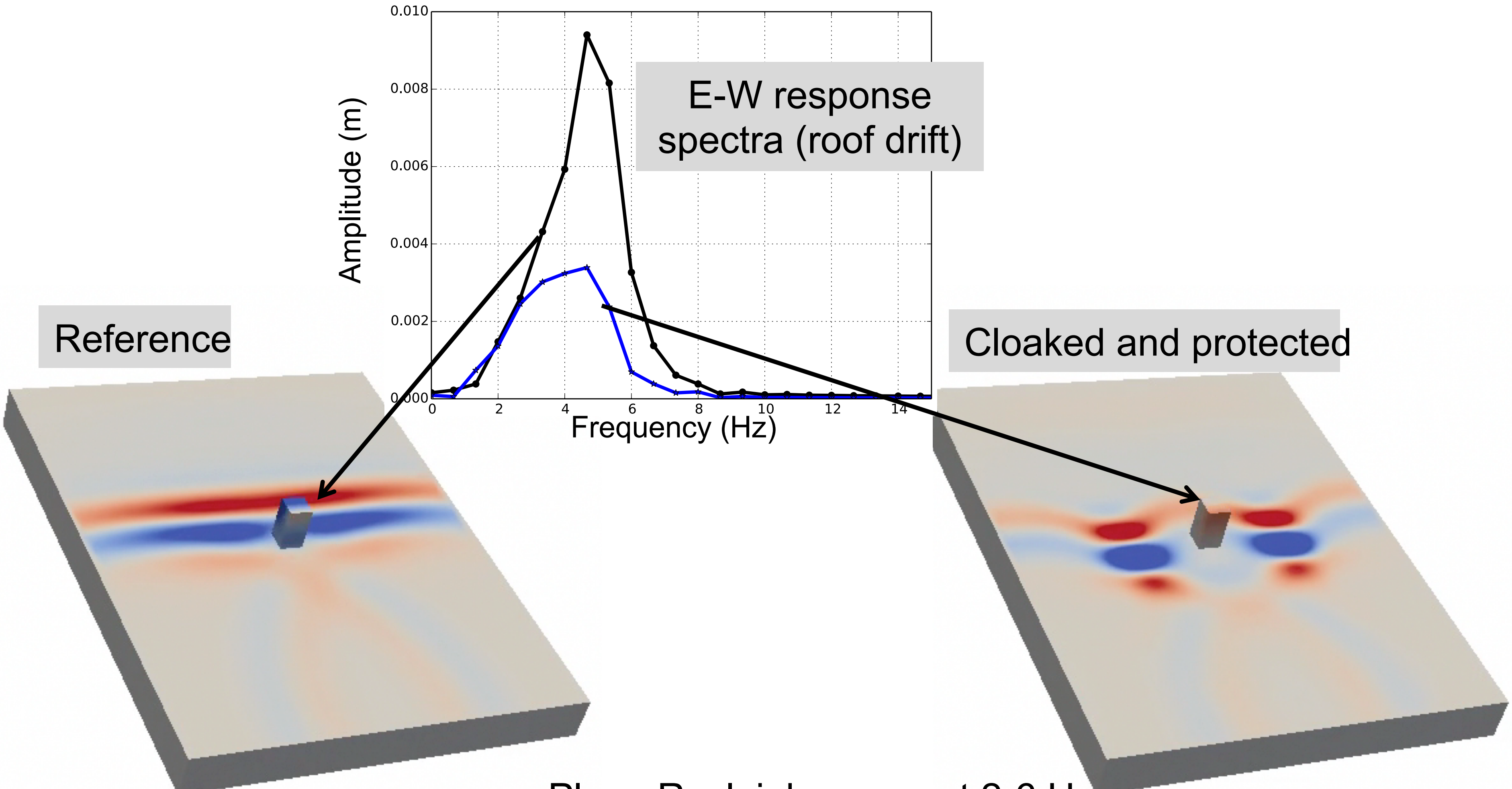

Discrete version



# Application to Seismic Protection (1 – 5 Hz)



# Application to Seismic protection (1 – 5 Hz)

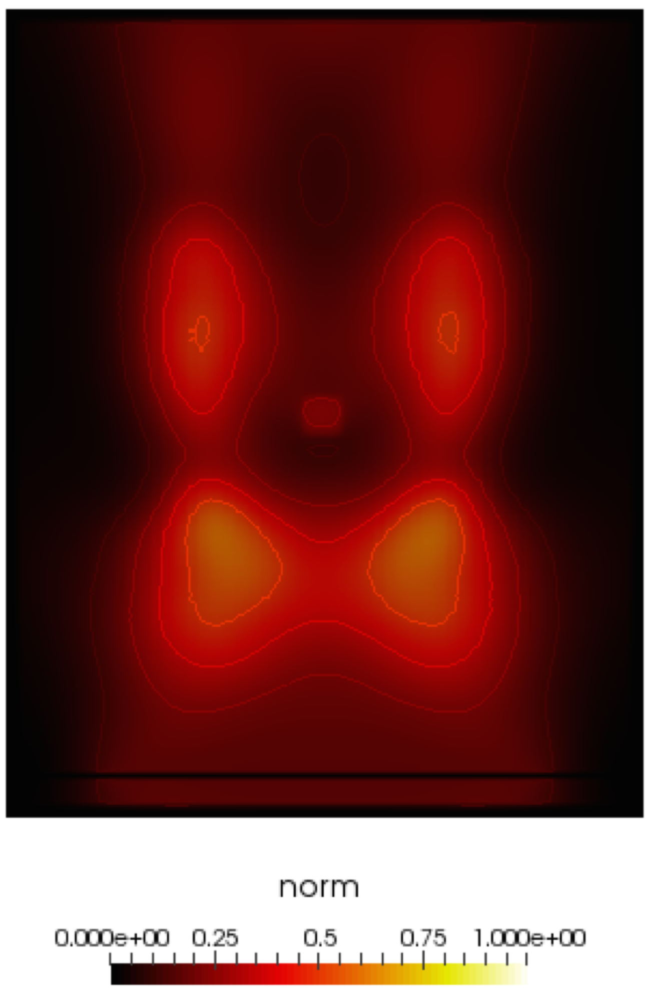



- Plane Rayleigh waves at 2-6 Hz
- Soft sedimentary soil

*Colombi et al., Scientific Reports, 2016*

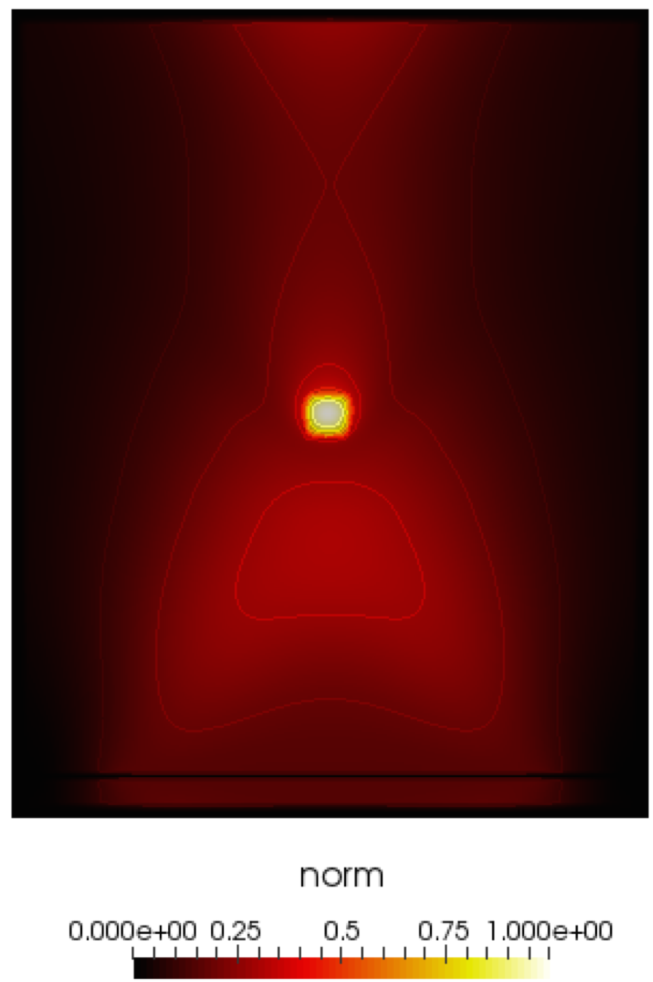
# Application to Seismic protection (1 – 5 Hz)

Cloaked and protected



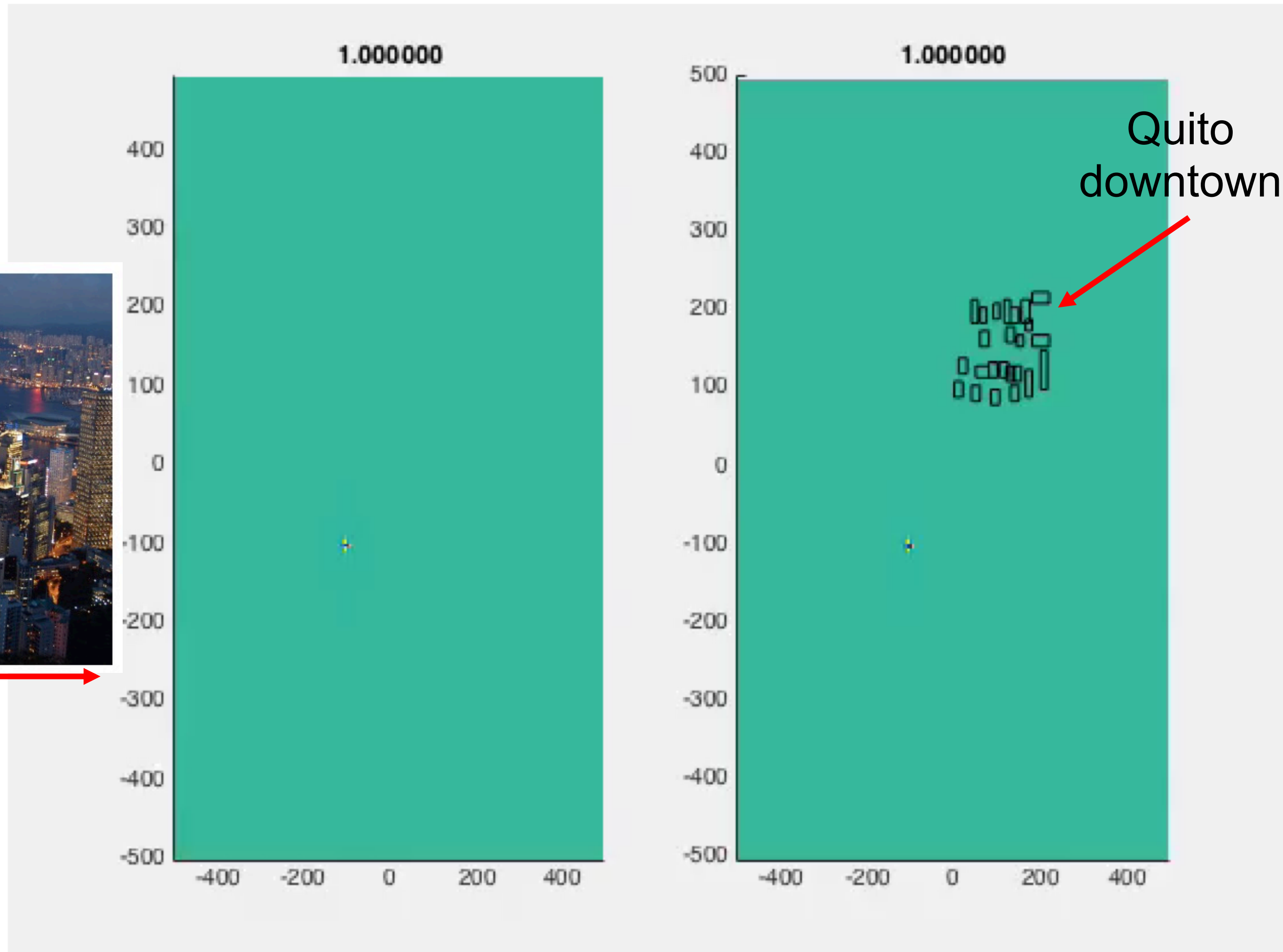

**Energy distribution**

Reference



# Work for the Future

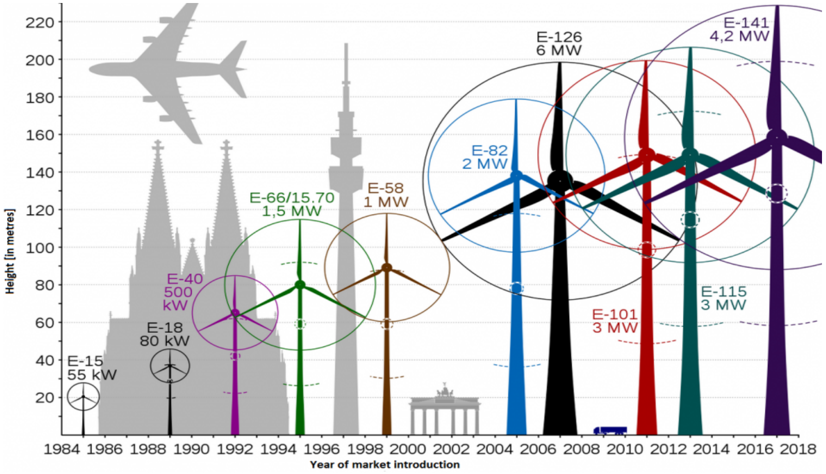
## A City : Macroscopic Arrangement of Resonating Elements ?

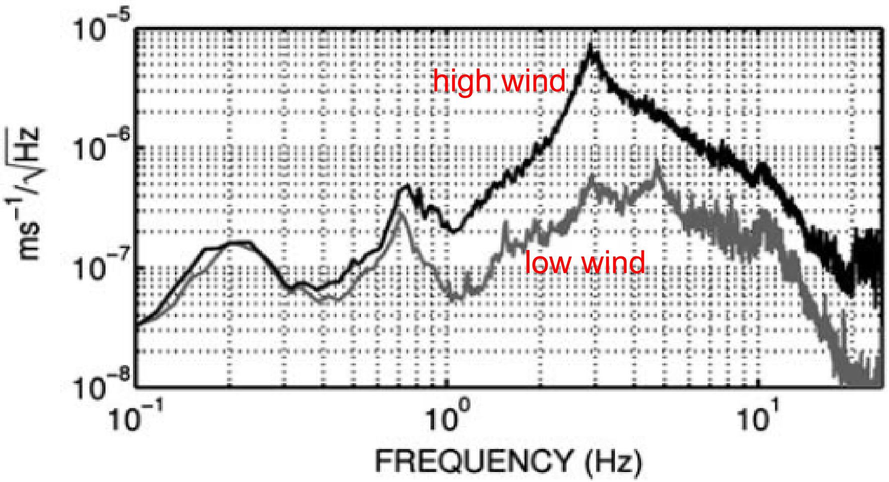

*Colombi et al., BSSA, 2017*

# Perspectives for Seismic Metamaterial (2020)

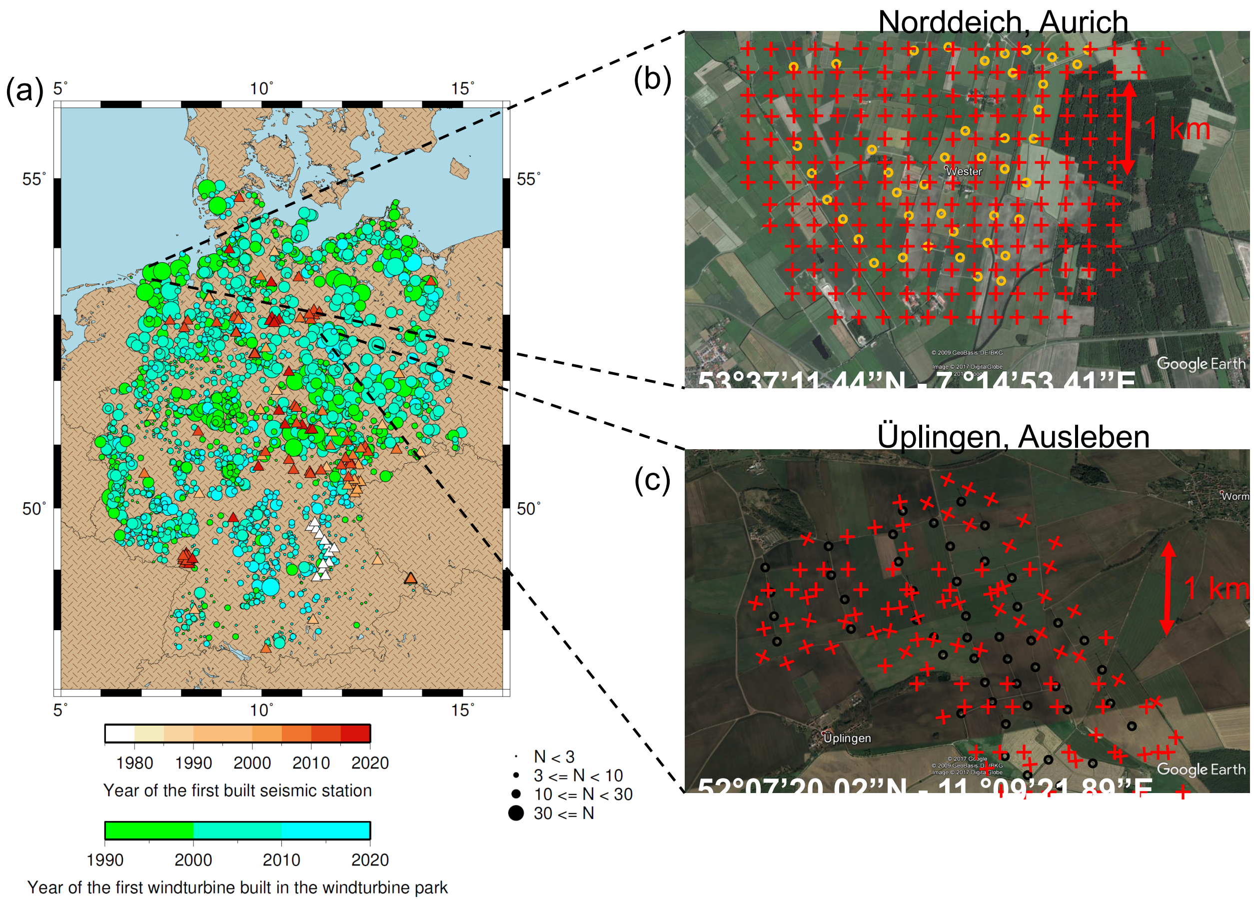
Wind turbine fields

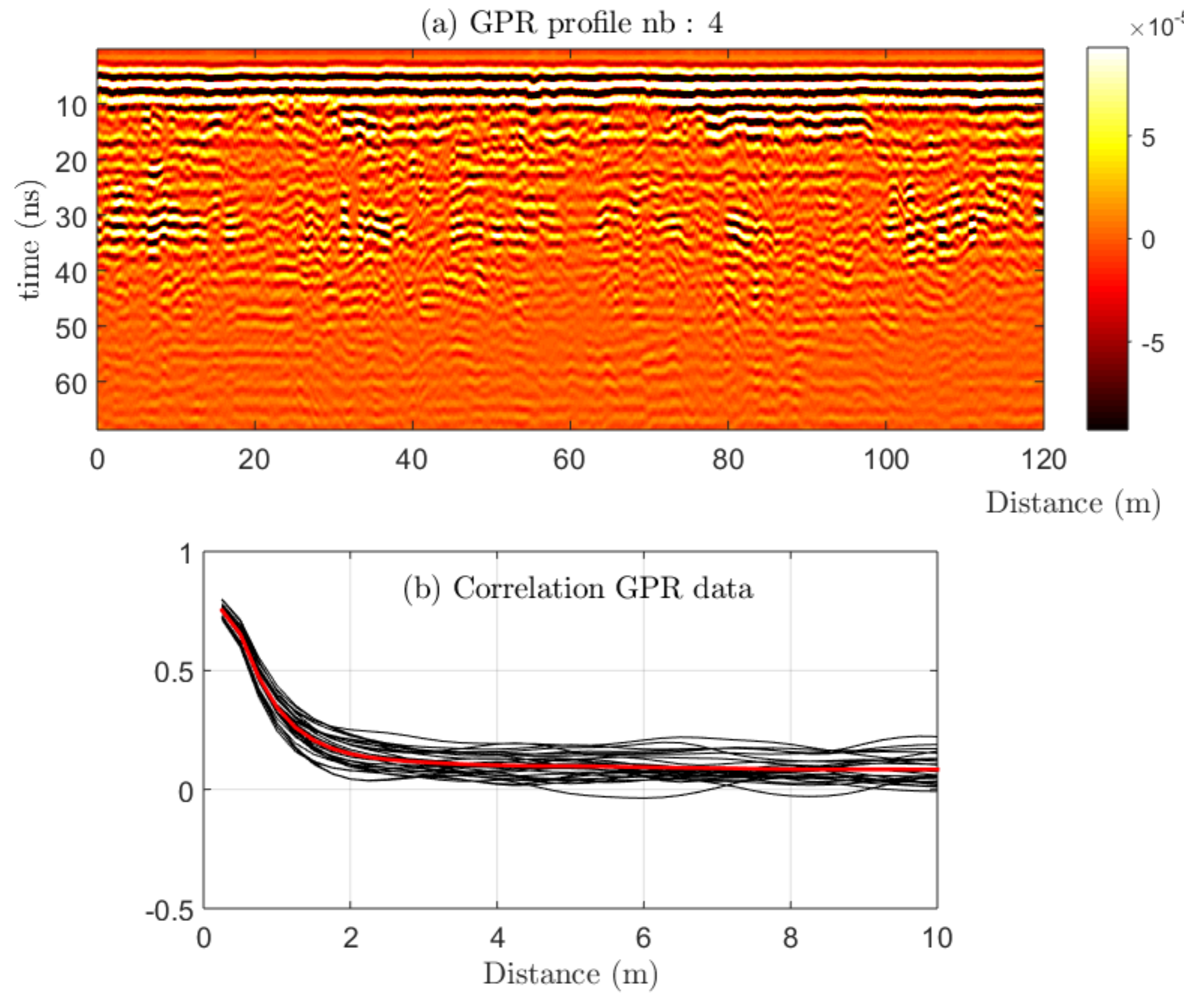



Saccorotti et al., 2011

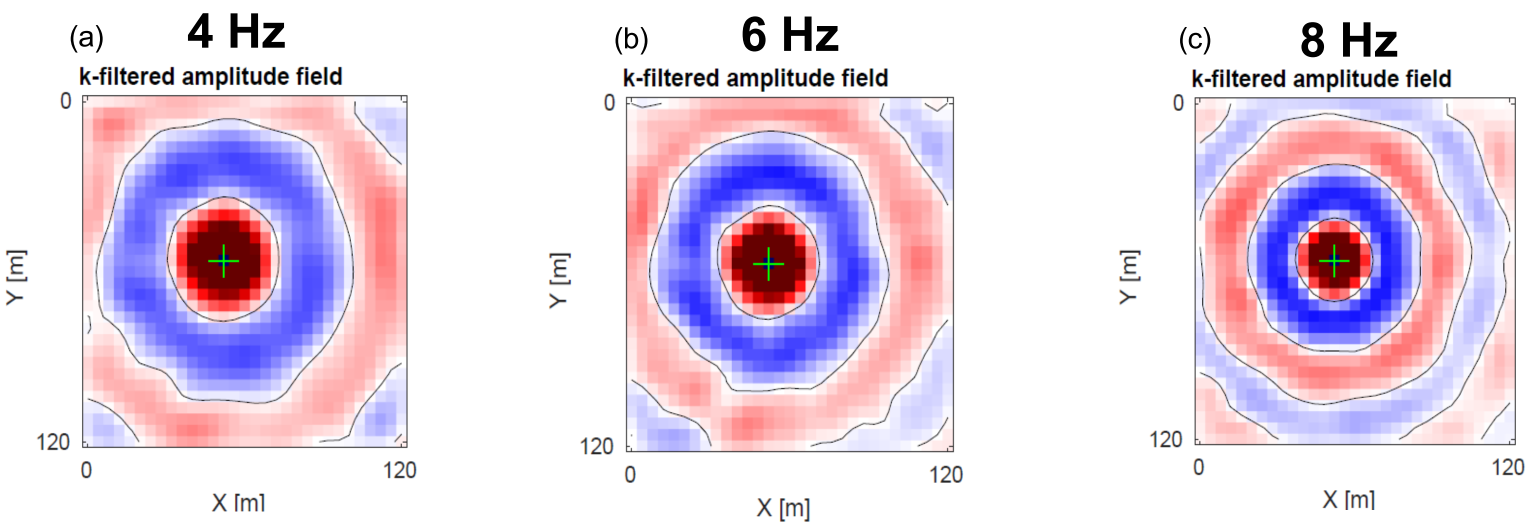


# META-WT project
# (submitted to ANR – DFG)




(a) GPR profile nb : 4
time (ns)
10
20
30
40
50
60
0
20
40
60
80
100
120
Distance (m)
×10^-5
5
0
-5
(b) Correlation GPR data
1
0.5
0
-0.5
0
2
4
6
8
10
Distance (m)

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




Dispersion curve from ambient noise (<20 Hz)

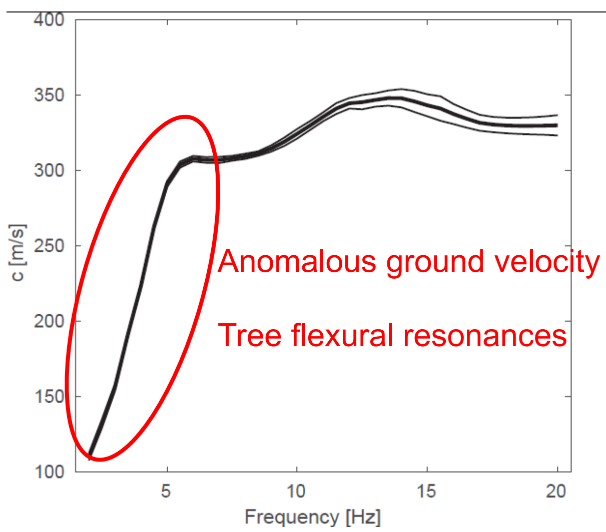
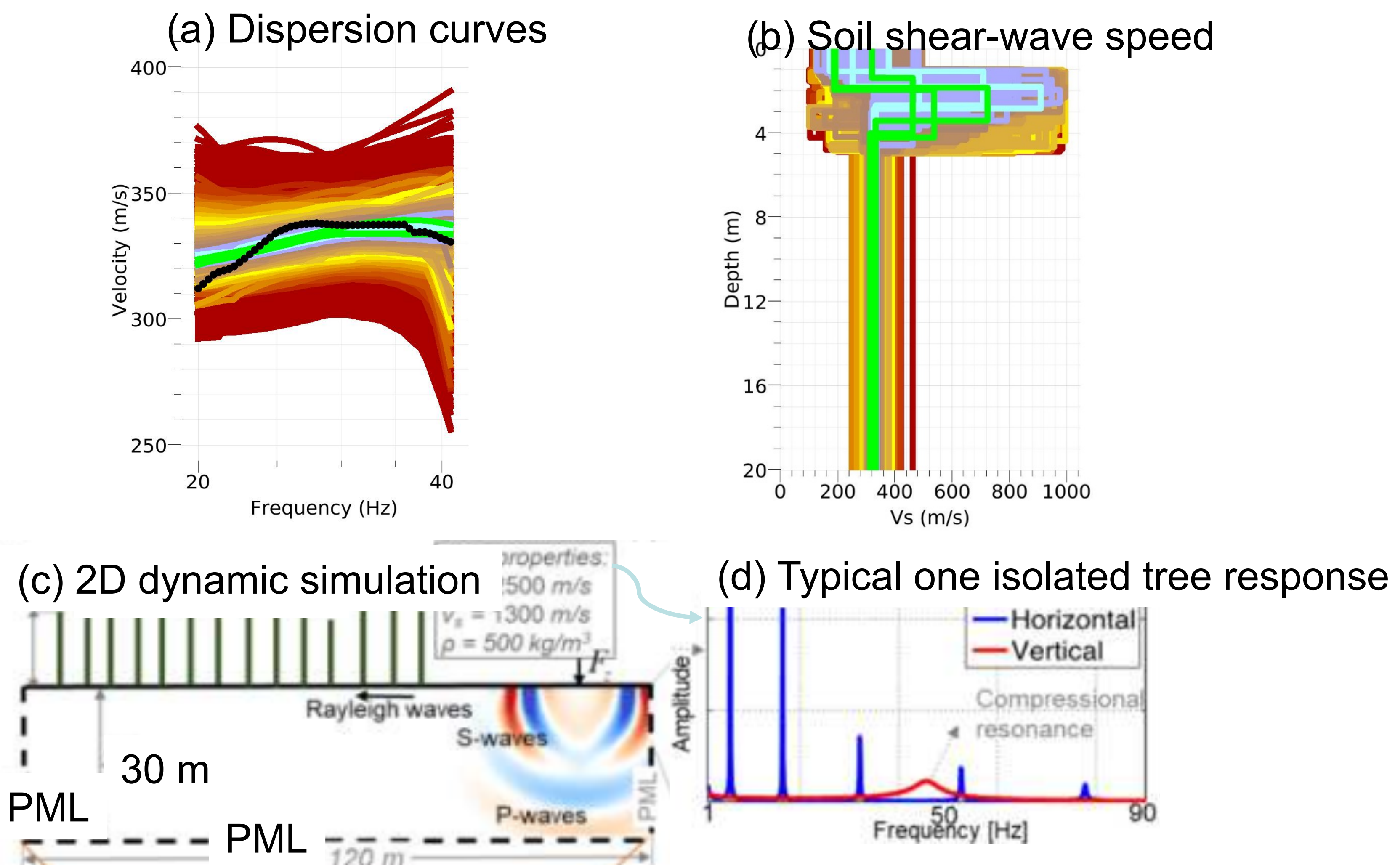


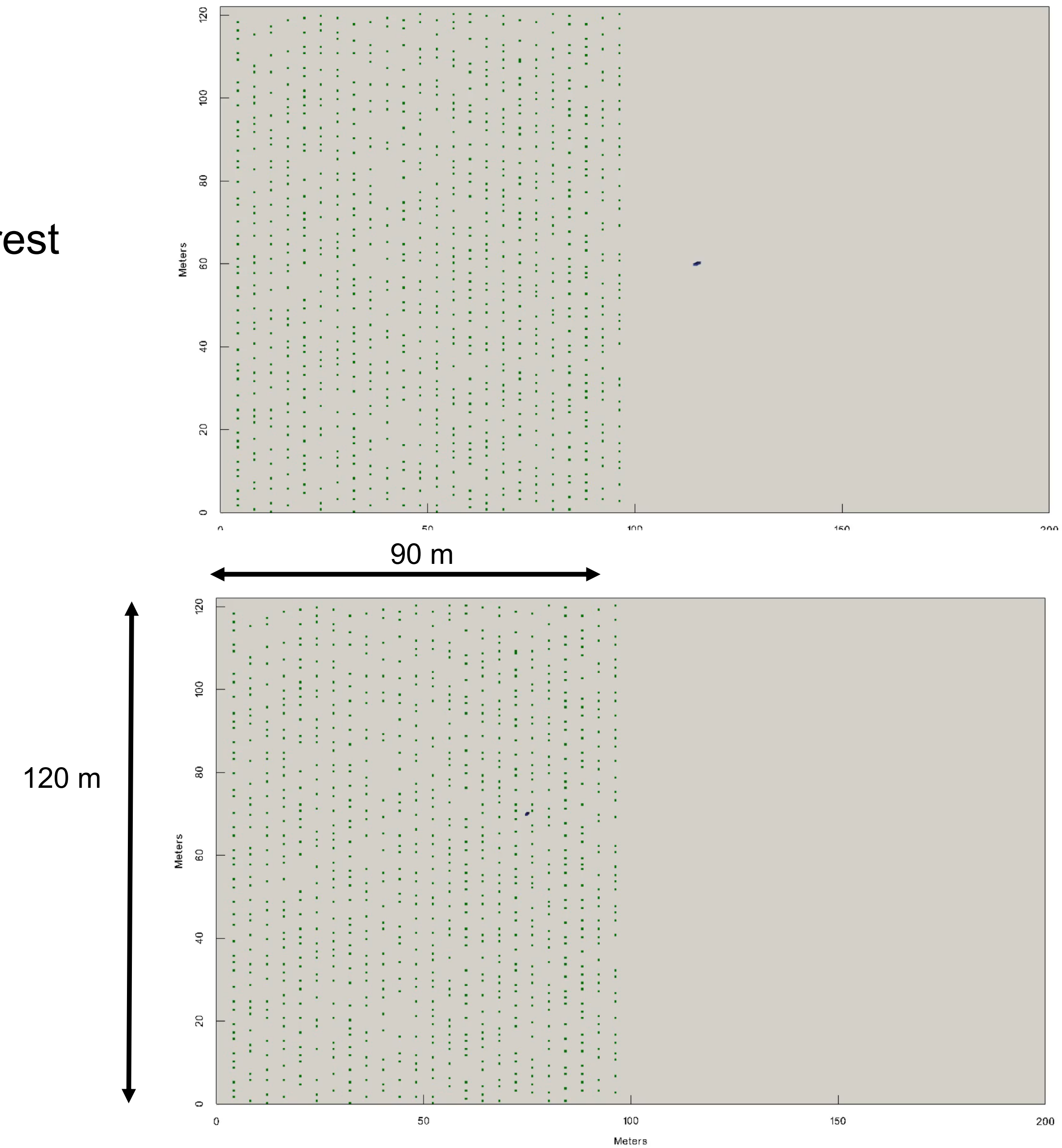
Fig. 9

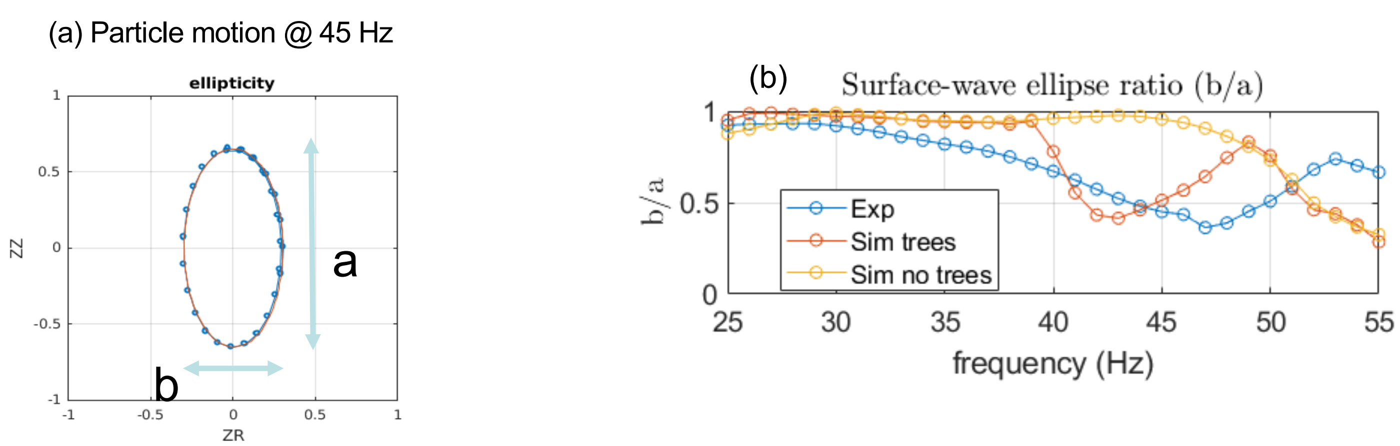


(a) Dispersion curves
Velocity (m/s)
400
350
300
250
20
40
Frequency (Hz)
(b) Soil shear-wave speed
Depth (m)
0
4
8
12
16
20
0
200
400
600
800
1000
Vs (m/s)
(c) 2D dynamic simulation
Rayleigh waves
S-waves
P-waves
30 m
PML
PML
PML
120 m
(d) Typical one isolated tree response
Horizontal
Vertical
Compressional
resonance
Amplitude
1
50
90
Frequency [Hz]

Active source
outside of the forest

Active source
inside the forest





(a) Particle motion @ 45 Hz
ellipticity
ZZ
ZR
a
b
1
0.5
0
-0.5
-1
(b)
Surface-wave ellipse ratio (b/a)
b/a
frequency (Hz)
25
30
35
40
45
50
55
Exp
Sim trees
Sim no trees

# Localization of Ultrasound in a Three-Dimensional Elastic Network*

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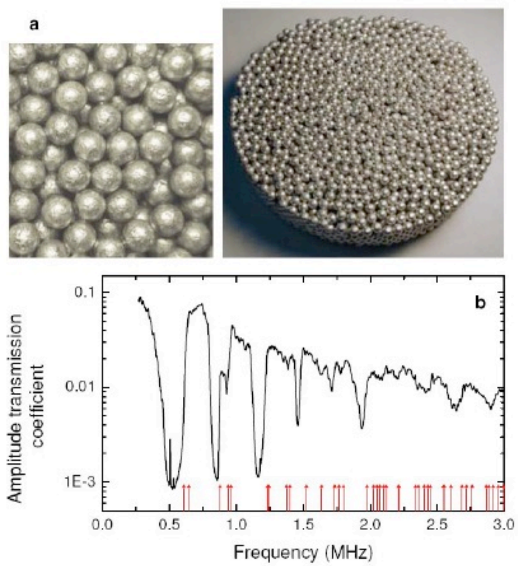
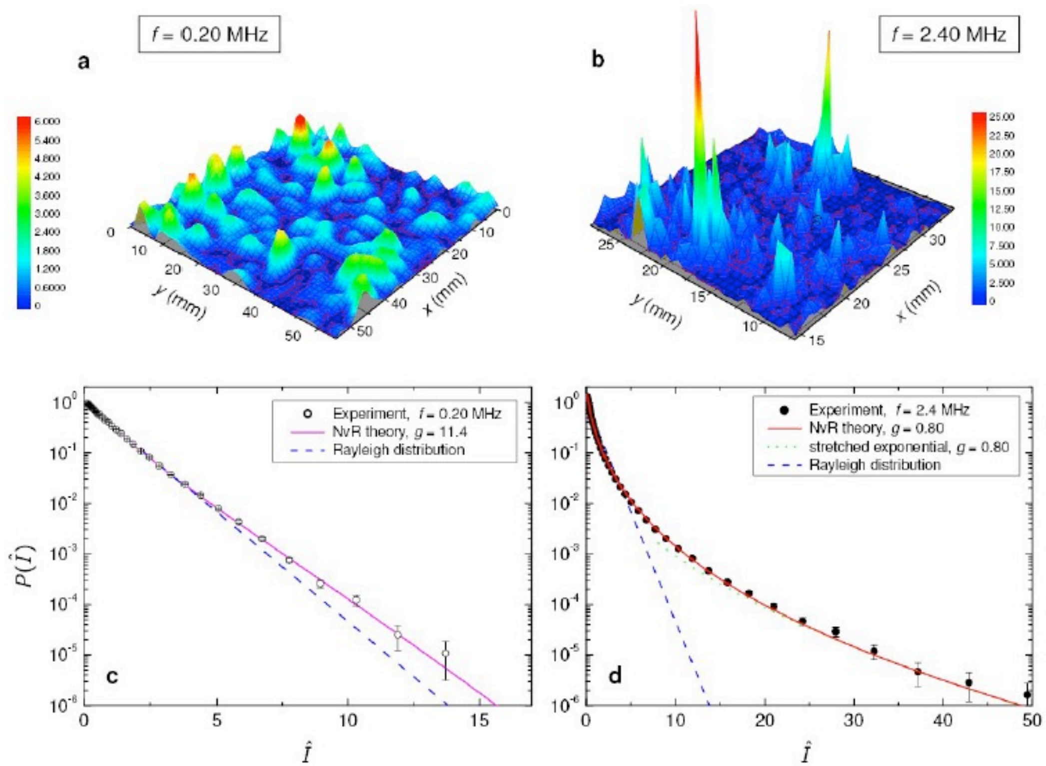
[2] *Université Joseph Fourier, Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS, 25 Rue des Martyrs, BP 166, 38042 Grenoble, France*

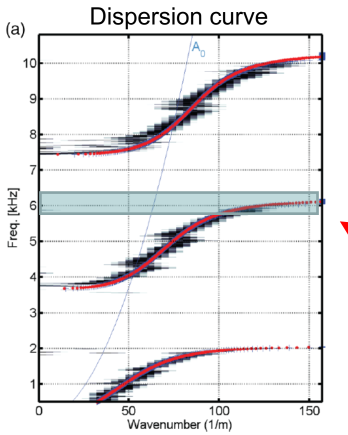
(Dated: June 18, 2009)

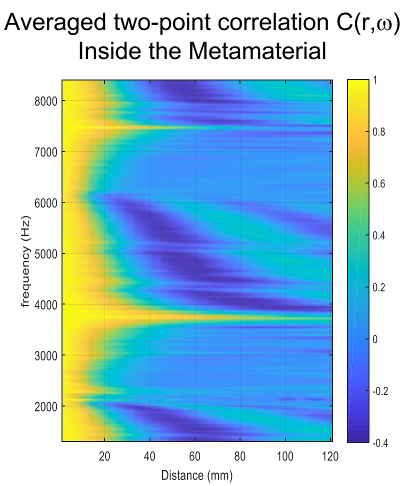


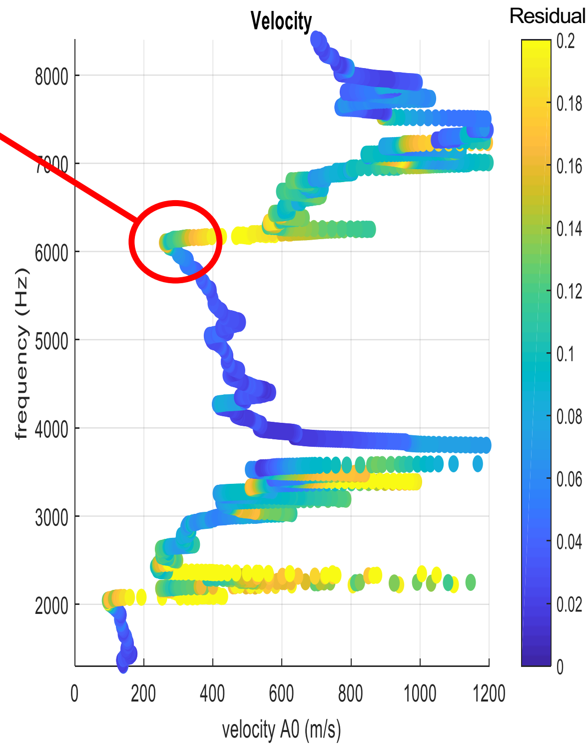



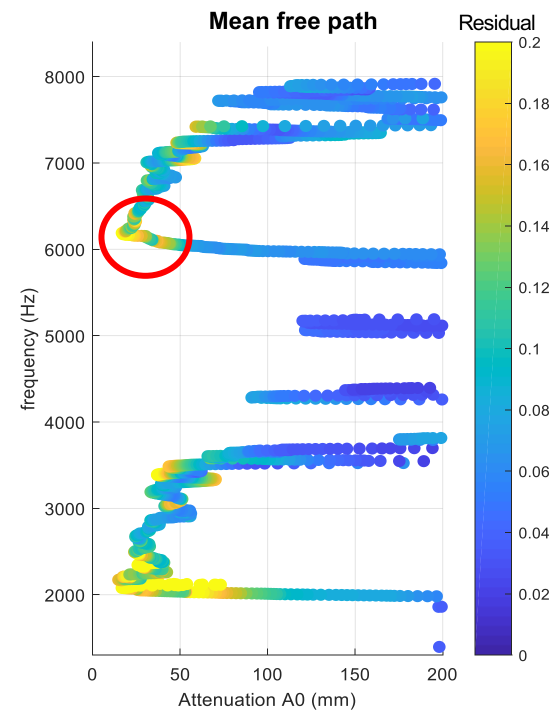
# Field-Field correlation inside the Metamaterial

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



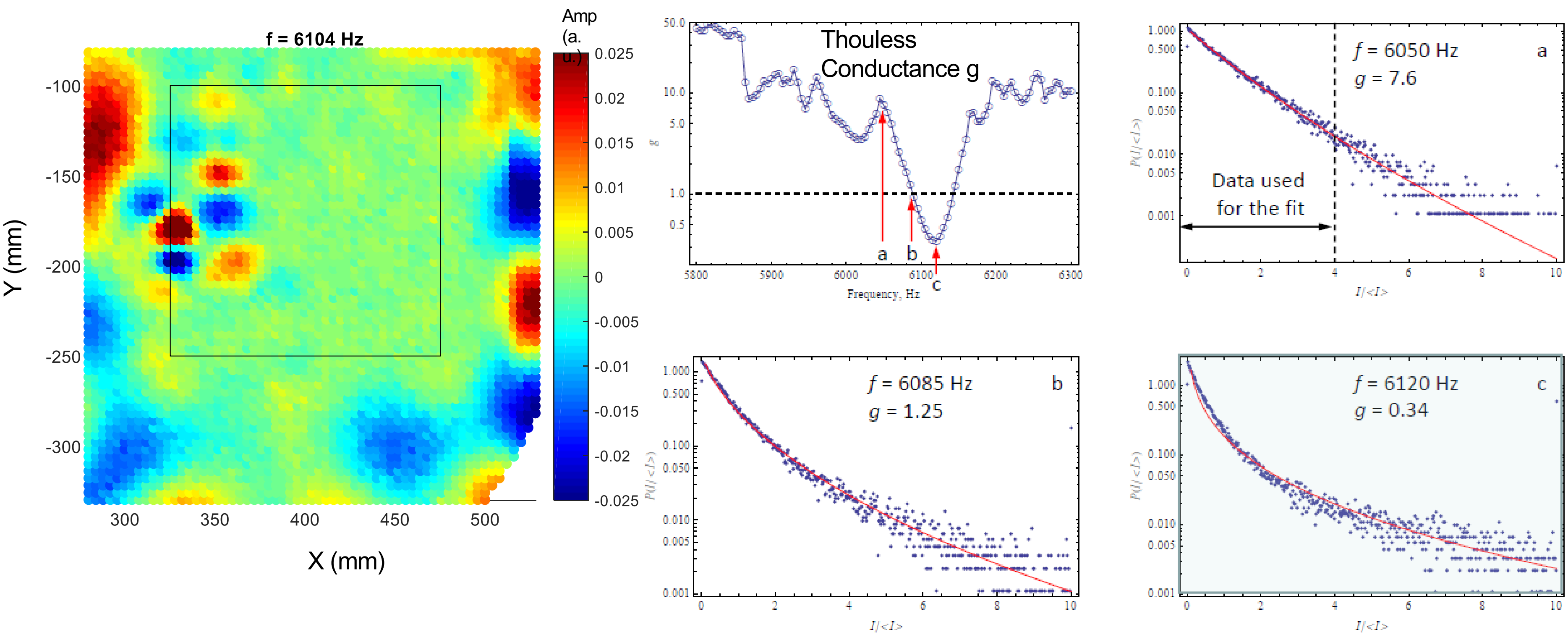



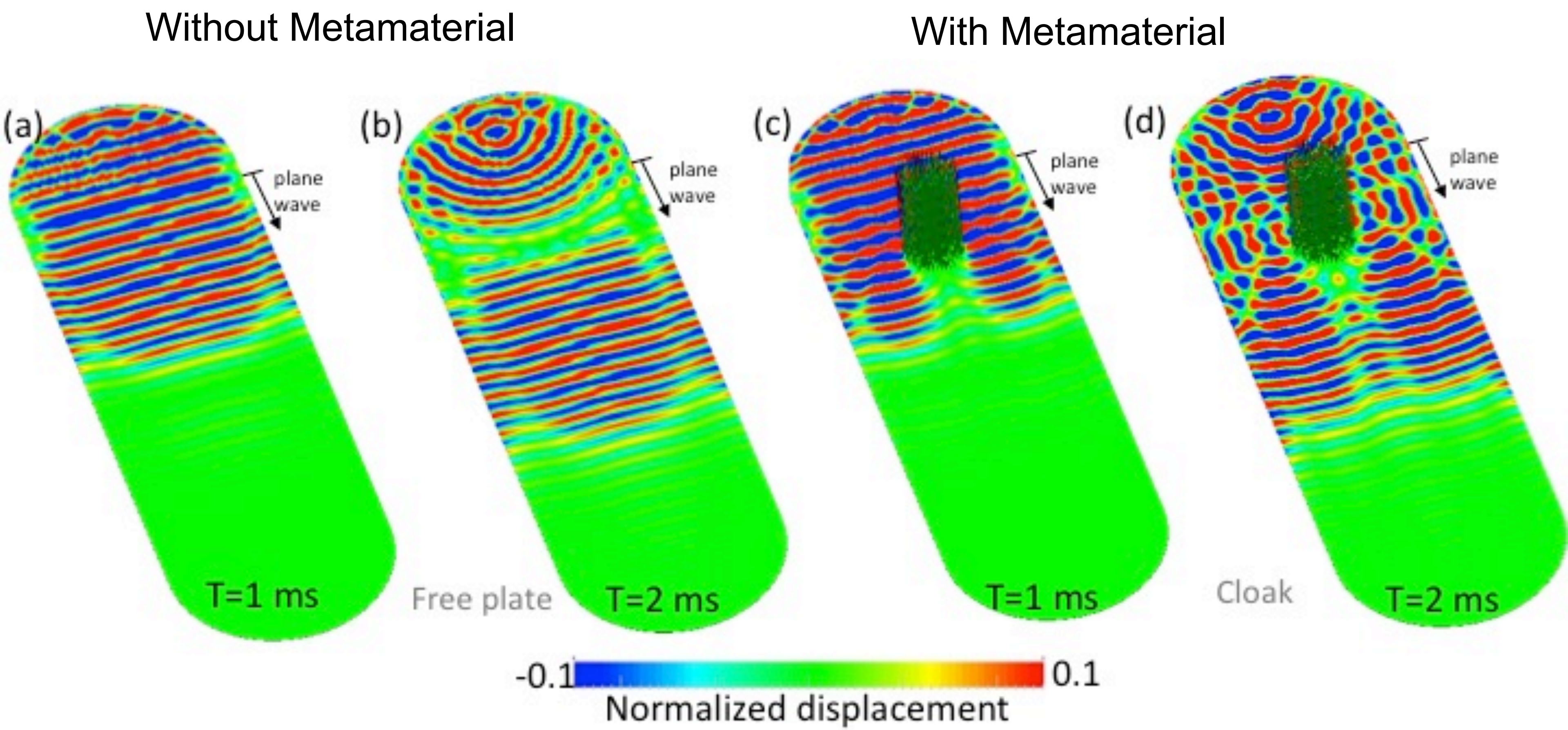




⇨ λ ~ l (mean free path) ~ 2a (distance between rods) = 4 cm

# Signature of Anderson localization inside the Metamaterial

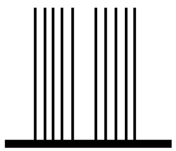


# Toward Acoustic Cloaking (Numerical Results)

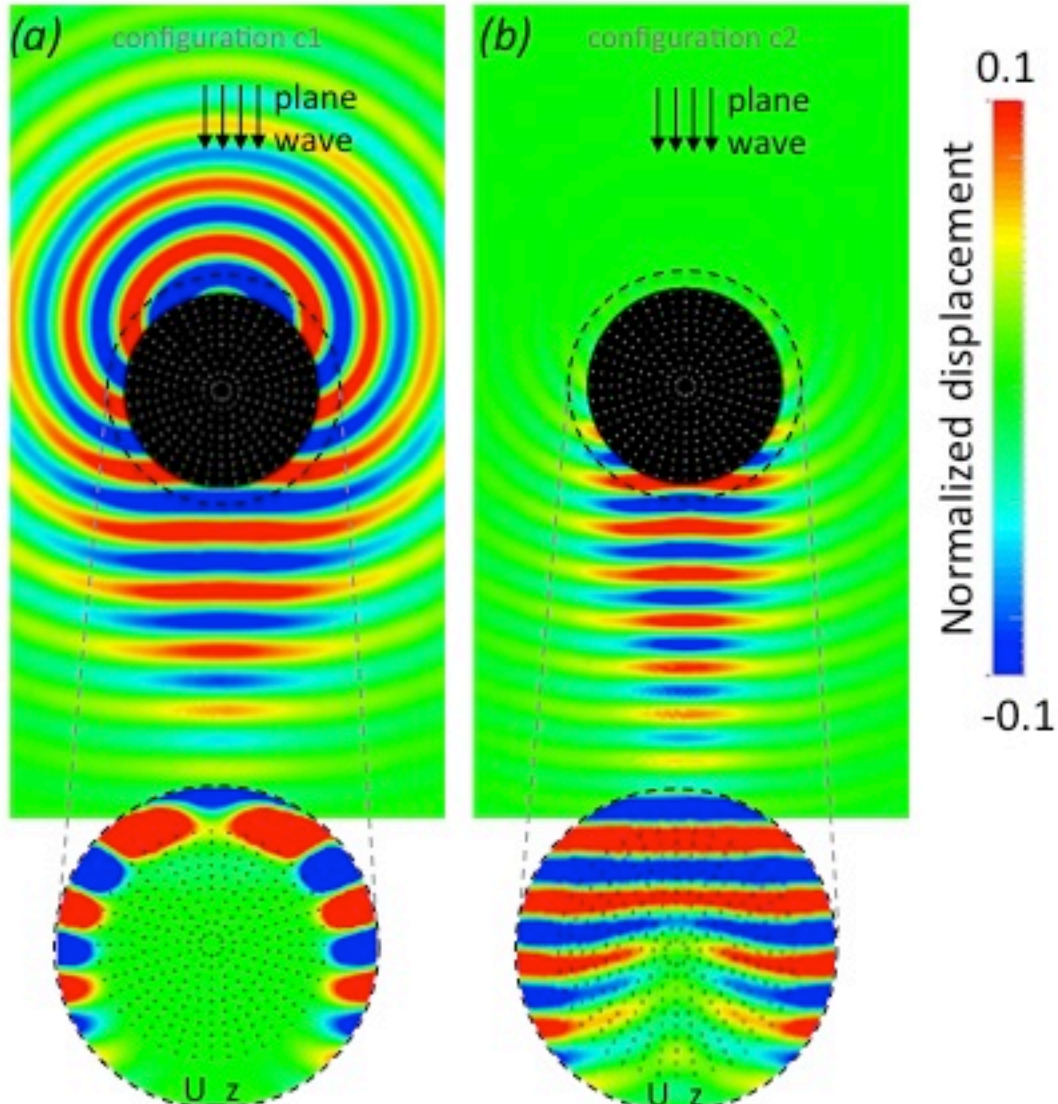


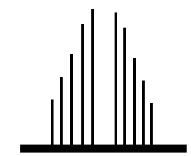
# Intermediate Result : optimal Cloak for Backscattered field

**Scattered Field**



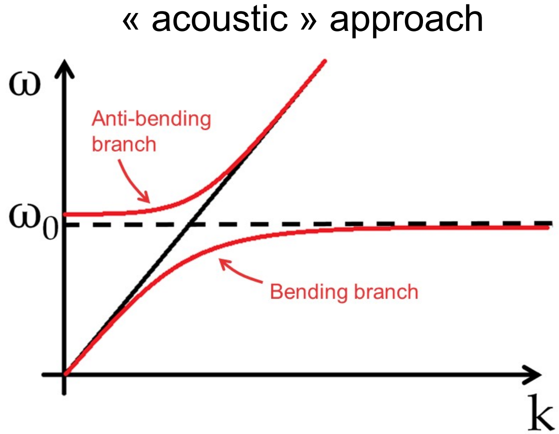
Configuration c1

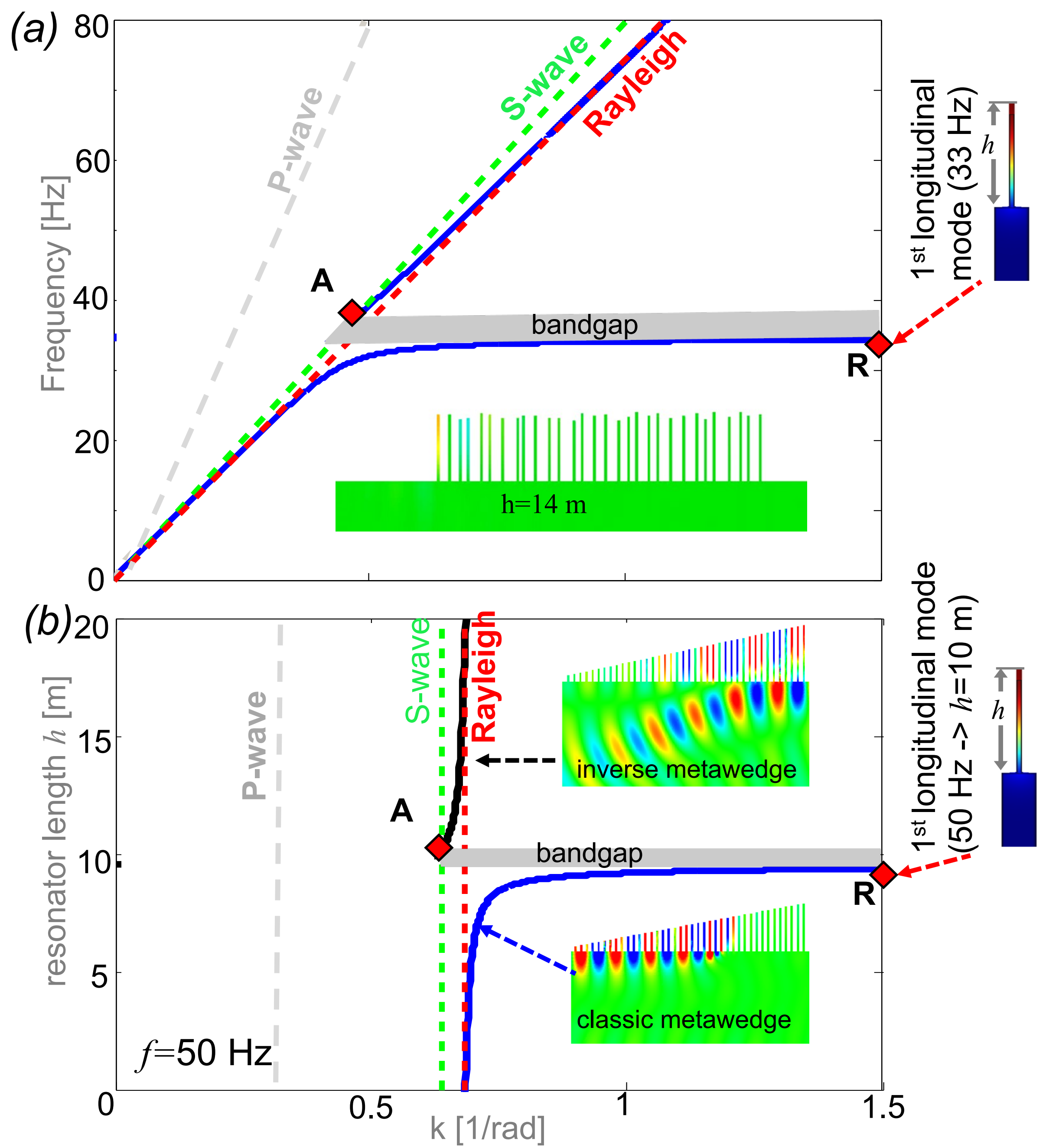


Configuration c2

*Colombi et al., JASA, 2015*



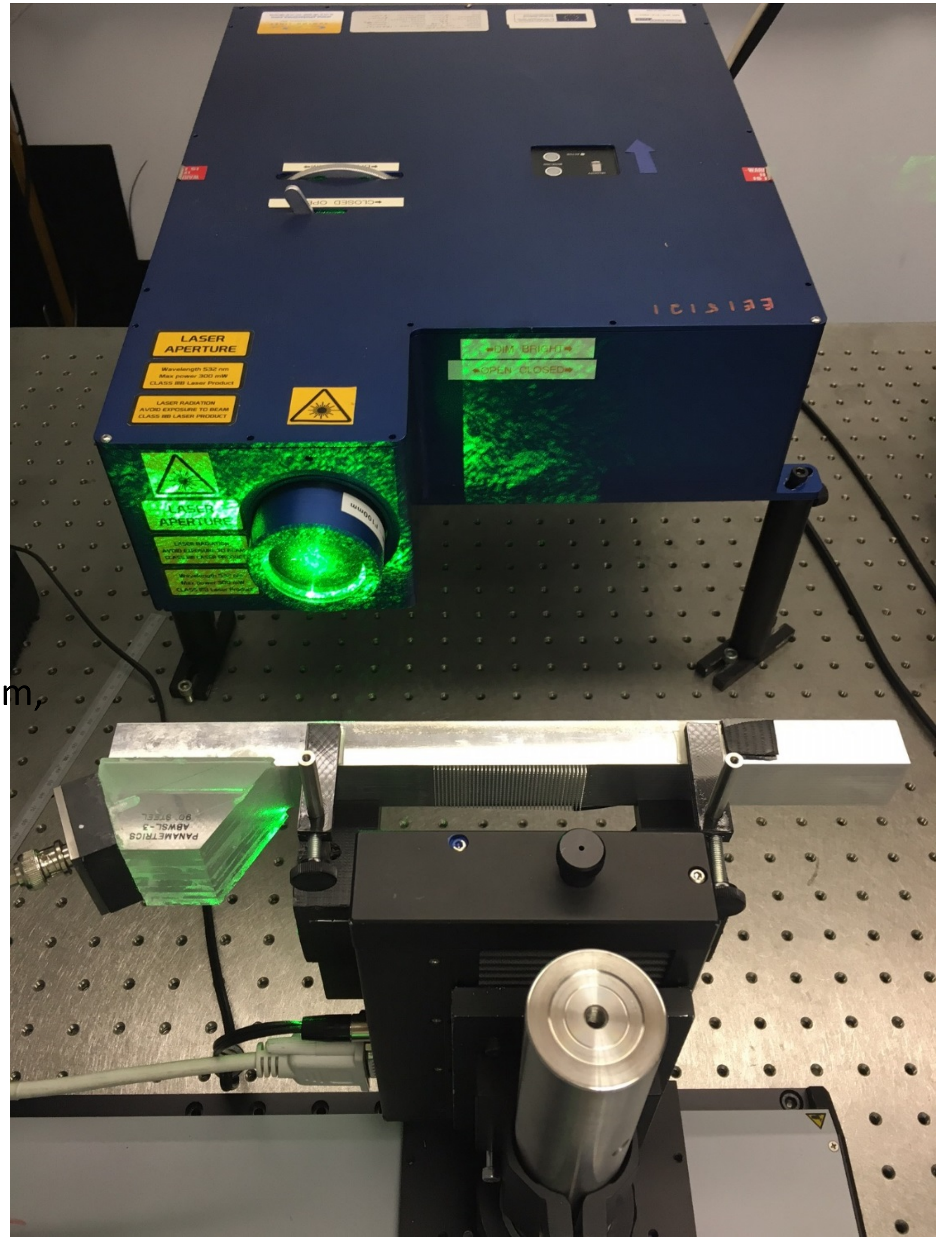

*Colombi et al., Scientific Reports, 2016*

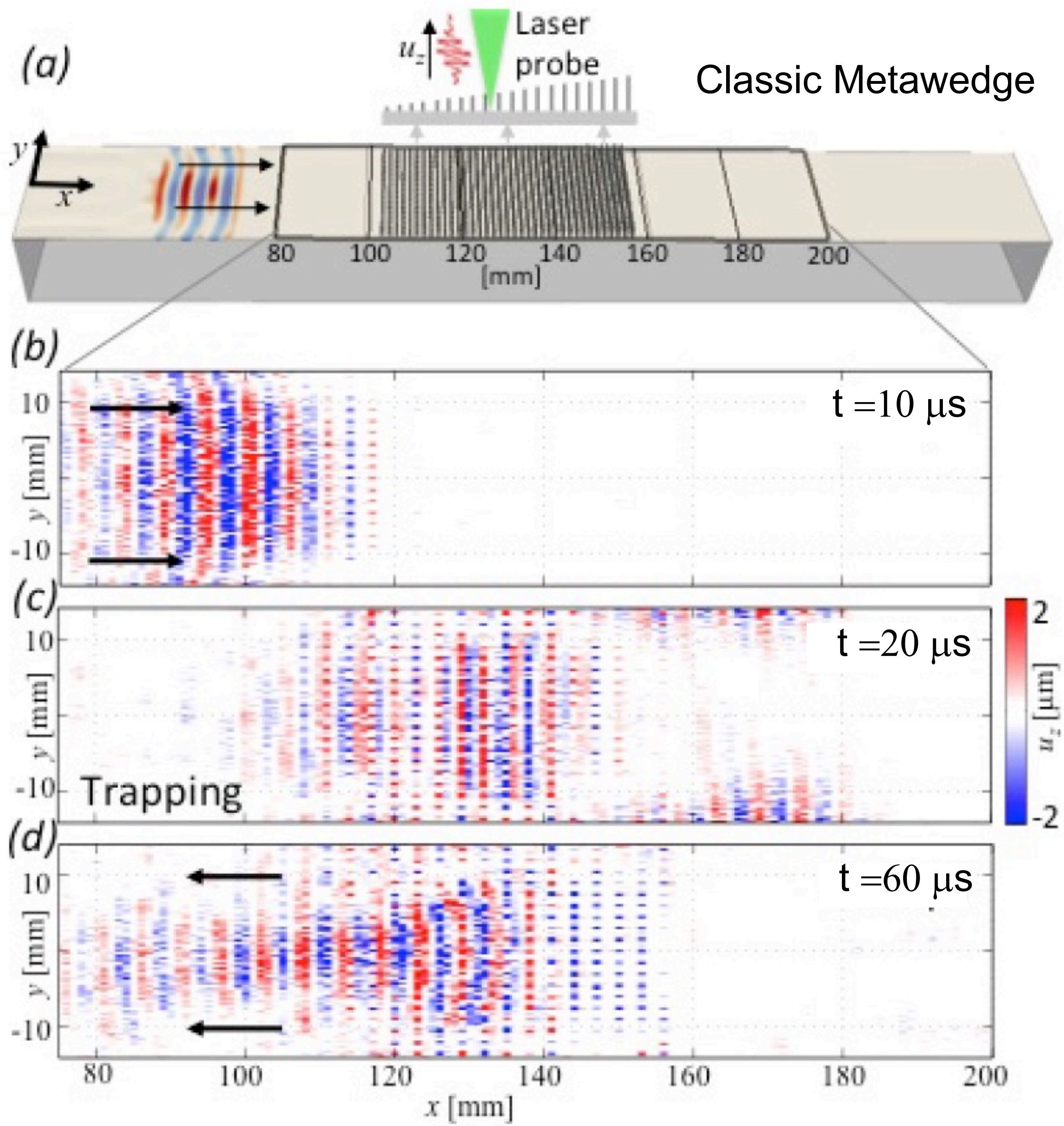
# Experimental Demonstration of the Resonant Meta-Wedge at the Ultrasonic Scale (~500 kHz)

**Matt Clark's group**

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

*Colombi et al., Scientific Reports, 2017*





(a)
Laser
probe
$u_z$
Classic Metawedge
y
x
80
100
120
140
160
180
200
[mm]
(b)
t =10 μs
(c)
t =20 μs
Trapping
(d)
t =60 μs
y [mm]
10
-10
x [mm]
$u_z$ [μm]
2
-2

# Inverse Meta-wedge