Acoustic devices based on Acoustic Metamaterials with positive parameters

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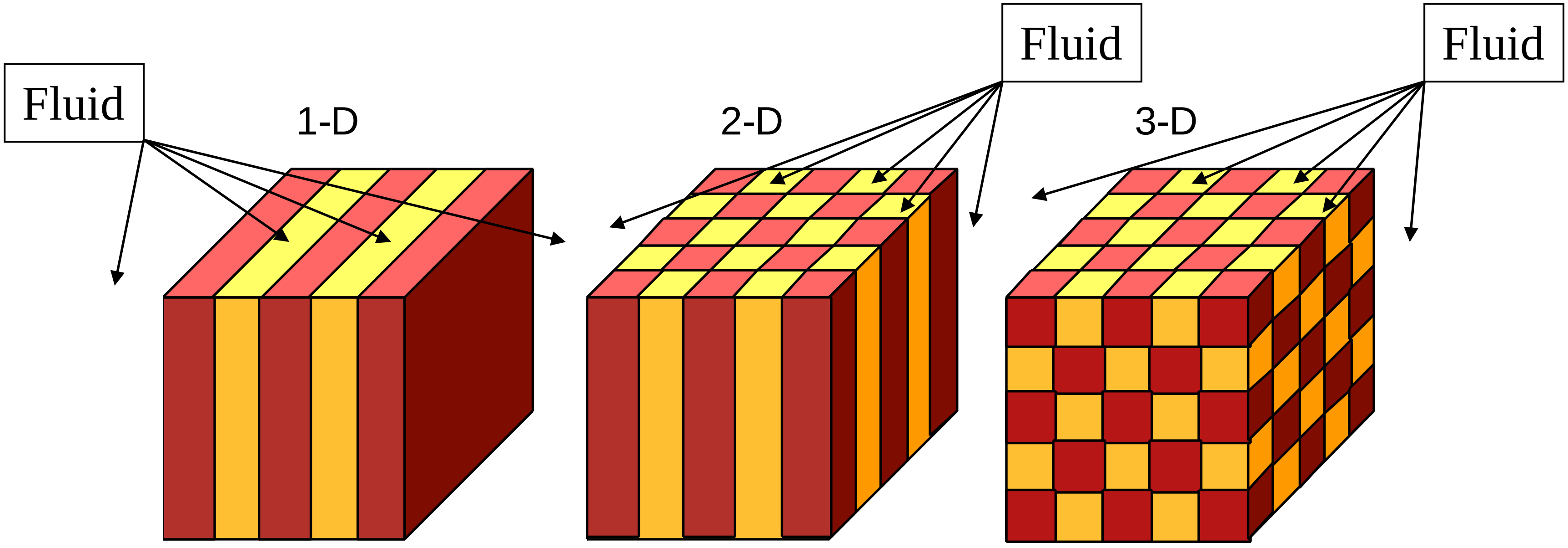
Universitat Politècnica de València, Spain

Outline:

1. **Sonic crystals / Phononic crystals**
2. **Acoustic metamaterials based on Sonic crystals**
3. **Acoustic lenses**
4. **Acoustic cloaks**
5. **Acoustic Black holes**

Sonic/Phononic Crystals

periodic media made of (at least!) two elastic or fluid materials



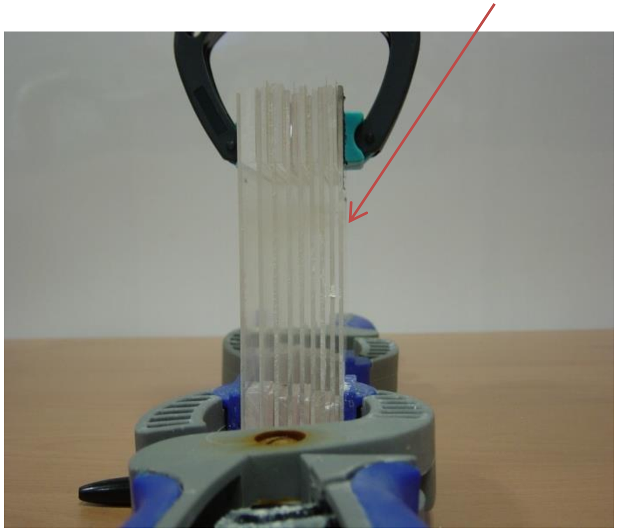
periodic in
one direction

periodic in
two directions

periodic in
three directions

Phononic Crystals

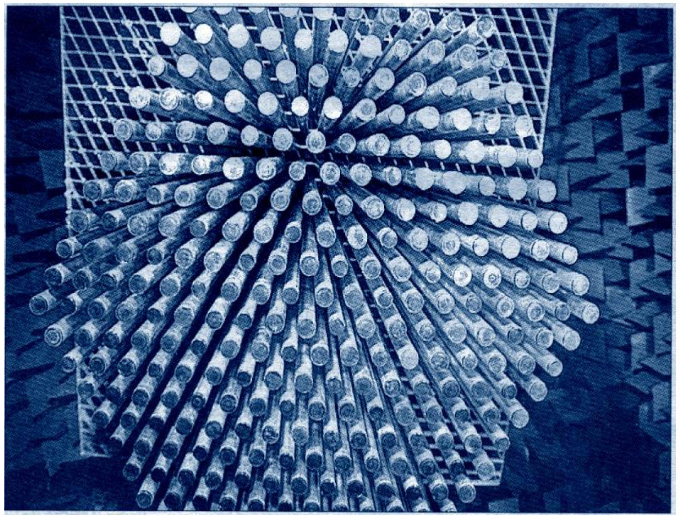
1D



plexiglass

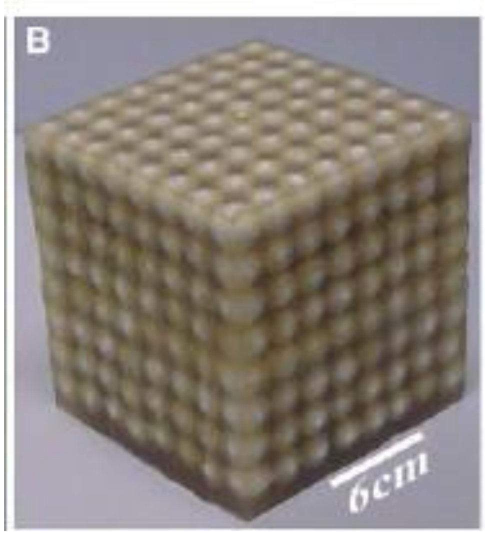
PRL, **98**, 134301 (2007)

2D



PRL, **80**, 5325 (1998)

3D



Science, **289**, 1739 (2000)

Pioneering work on Phononic Crystals

ACOUSTICAL PROPERTIES OF A THINLY LAMINATED MEDIUM*

Sov. Phys. Acoustics (1958)

S. M. Rytov

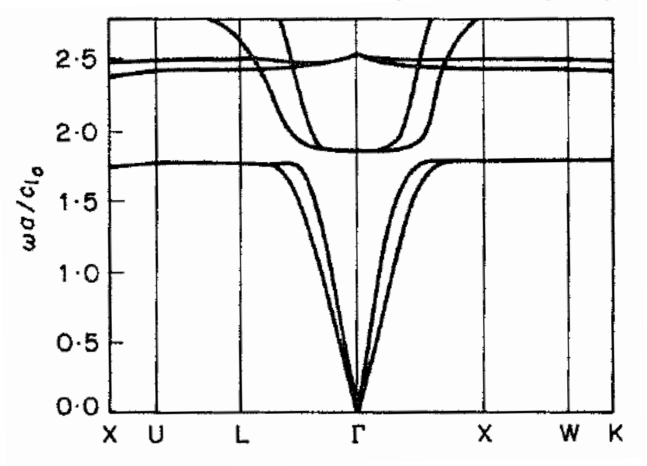
$$\boxed{\cos k(a+b) = \cos k_l a \cos \bar{k}_l b - \frac{1+\varkappa^2}{2\varkappa} \sin k_l a \sin \bar{k}_l b,}$$

ELASTIC AND ACOUSTIC WAVE BAND STRUCTURE

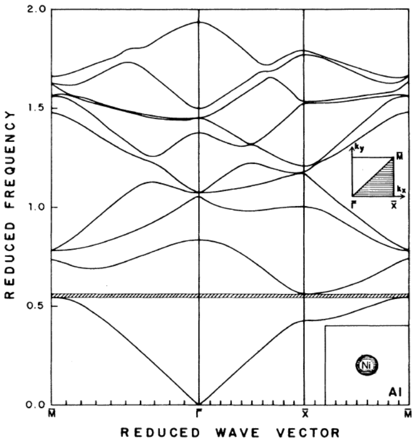
M. M. SIGALAS
Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, U.S.A.
AND
E. N. ECONOMOU
Department of Physics, University of Crete, 714 09, Crete, Greece

J. Sound and Vibration (1992)

FCC lattice of spheres (**3D**)



Square lattice of Ni cylinders in Al (**2D**)

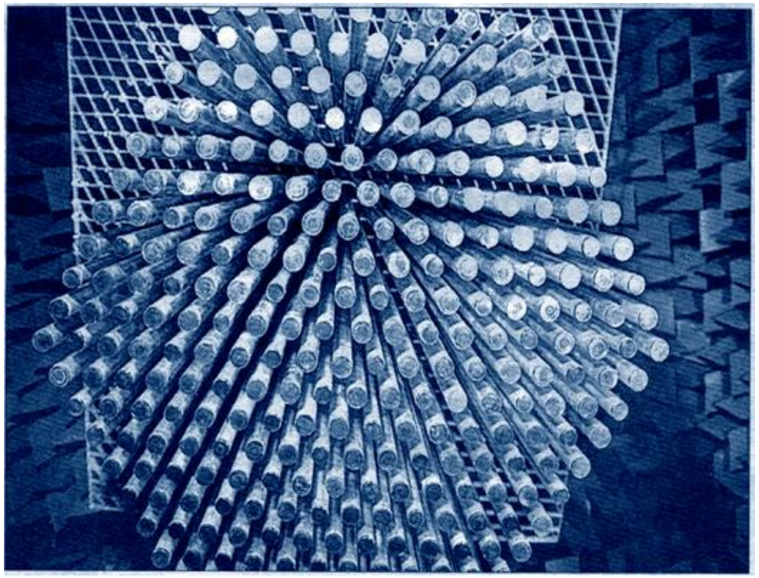


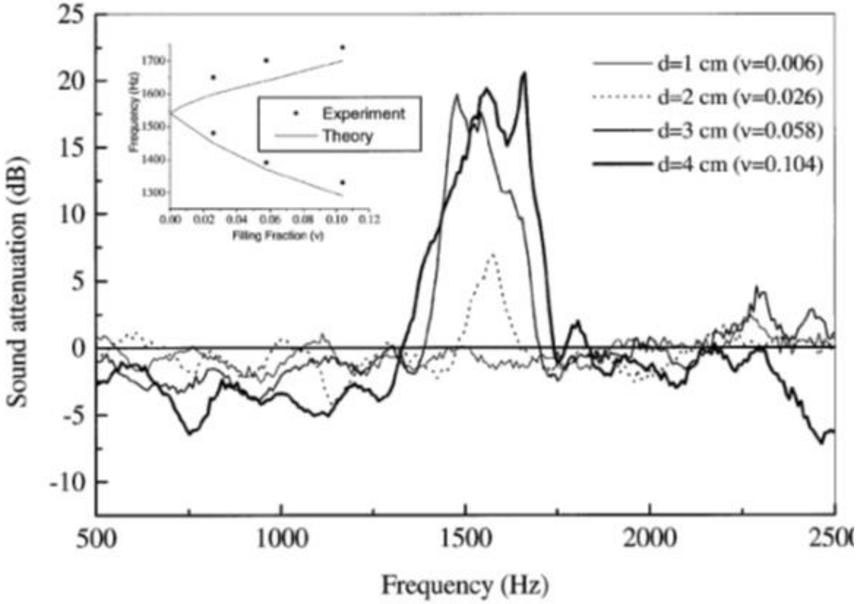
Phys. Rev. Lett. (1993)

Acoustic Band Structure of Periodic Elastic Composites

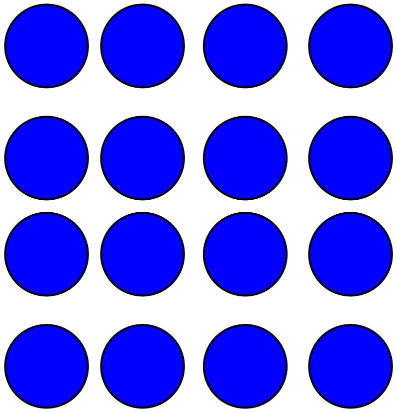
M. S. Kushwaha,[1] P. Halevi,[1,2] L. Dobrzynski,[3] and B. Djafari-Rouhani[3]
[1]*Instituto de Física de la Universidad Autónoma de Puebla, Apdo. Post. J-48, Puebla, Puebla 72570 México*
[2]*Centro de Investigación en Física de la Universidad de Sonora, Apdo. Post. 5-088, Hermosillo, Sonora 83190, México*
[3]*Laboratoire de Dynamique et Structure des Materiaux Moleculaires, Centre National de la Recherche Scientifique, Université de Lille I, Unité Fondamentale de Recherche de Physique, Bâtiment P5, 59655 Villeneuve D'Ascq Cedex, Franc*

Transmission features of sonic crystals

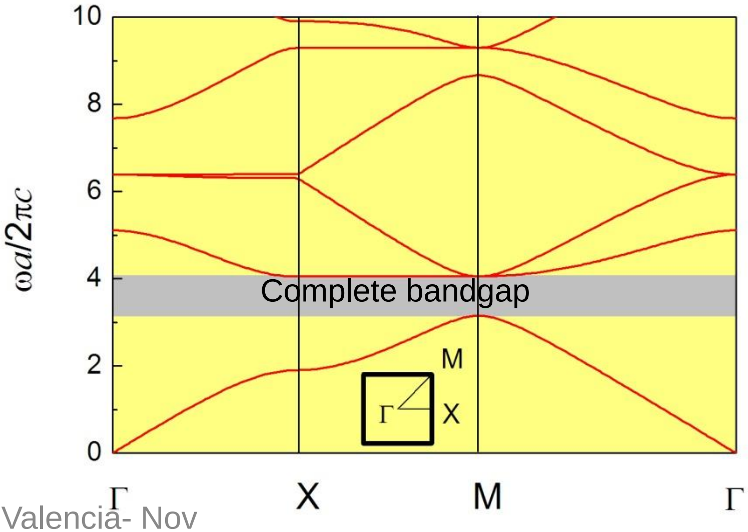




f=0.4

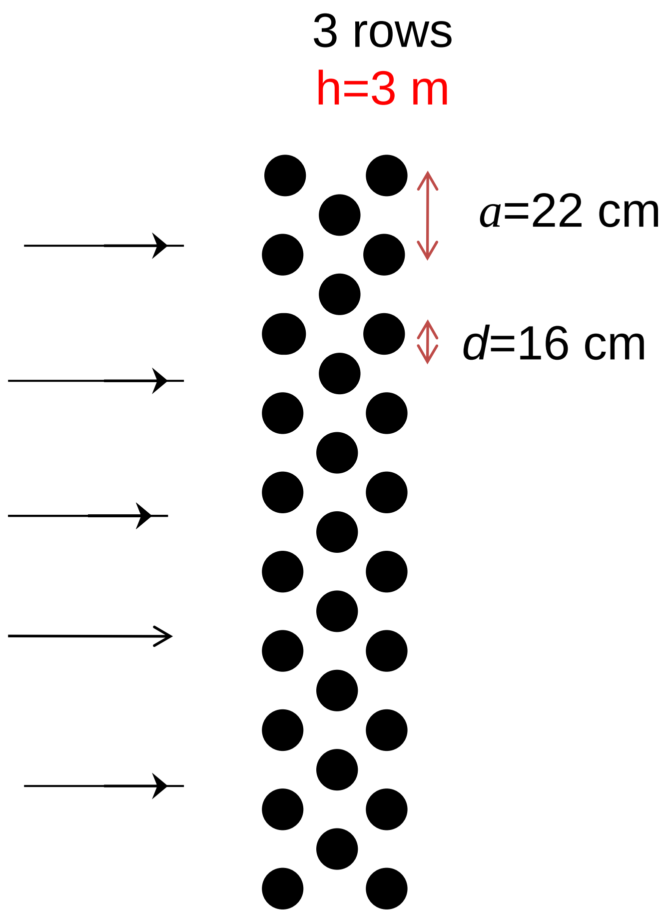


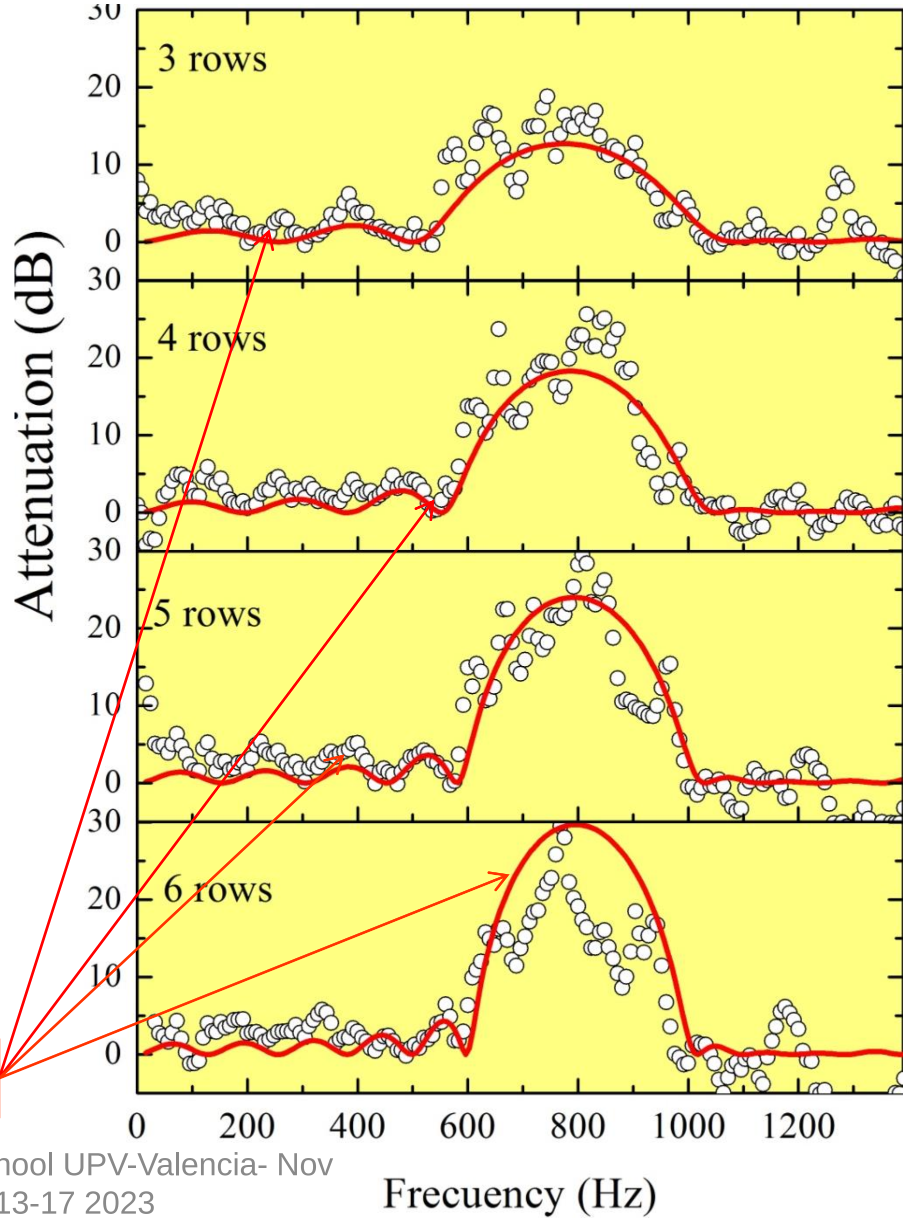
$\omega(\mathbf{k})$



Phys. Rev. Lett. **80**, 5325 (1998)

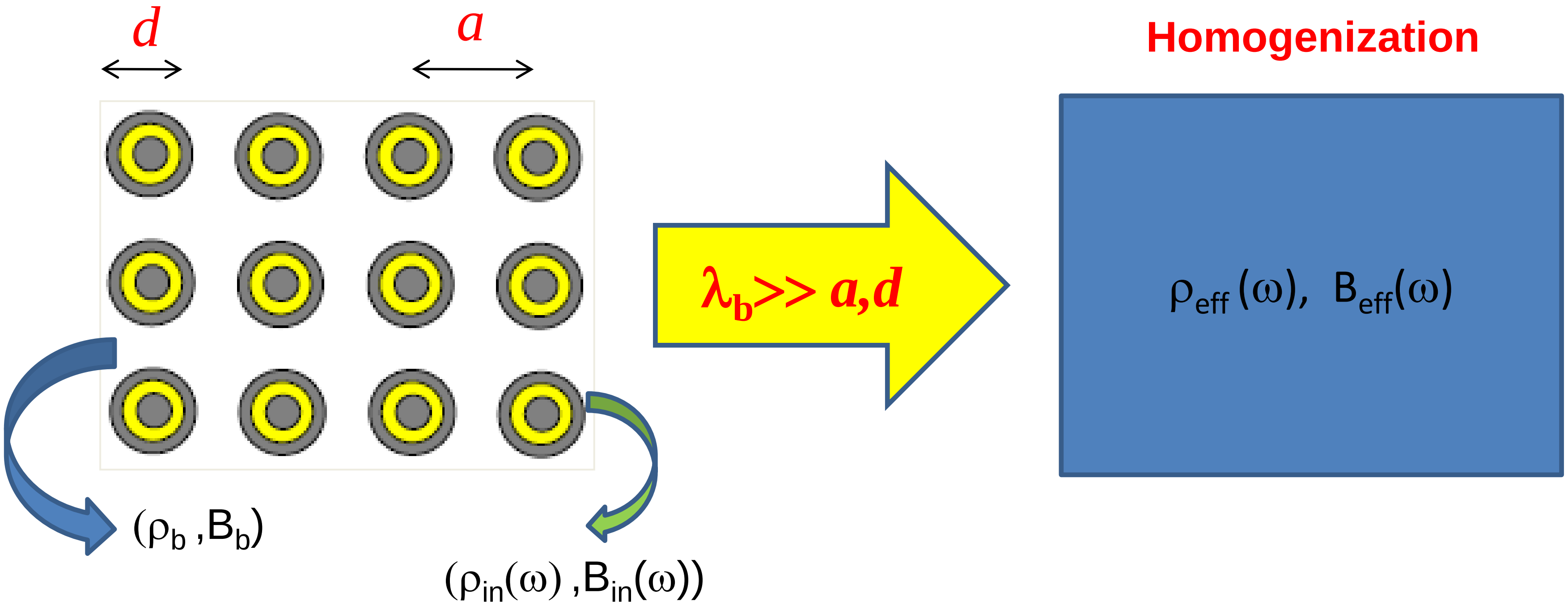
What is the minimum number of rows?





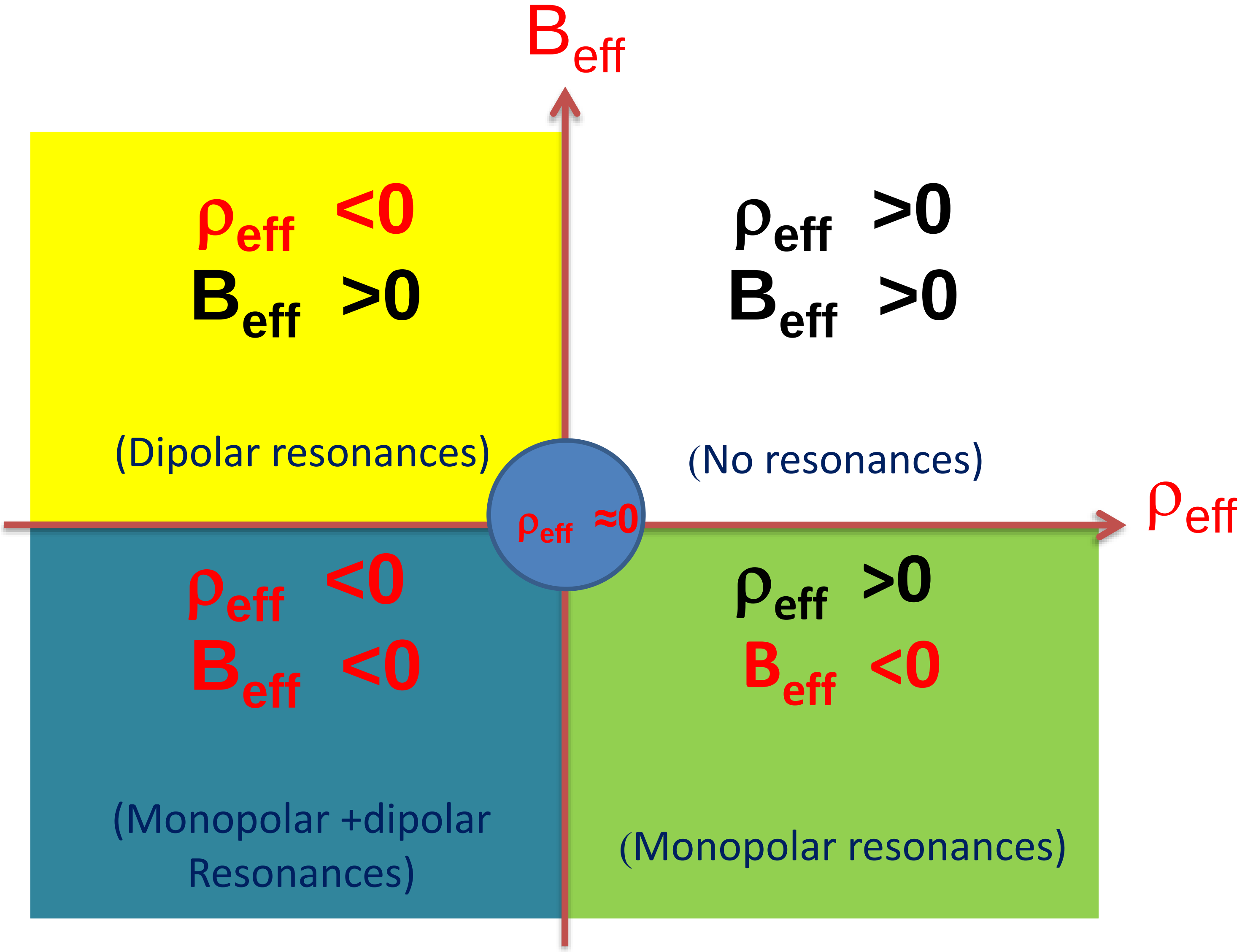
Multiple scattering simulations

Acoustic metamaterials / metafluids



Acoustic metamaterials are artificial structures made of subwavelength units such that their acoustic properties are NEW in comparison with that of the building units

Acoustic metamaterials



B_{eff}

ρ_{eff}

$\rho_{eff} < 0$
$B_{eff} > 0$

(Dipolar resonances)

$\rho_{eff} > 0$
$B_{eff} > 0$

(No resonances)

$\rho_{eff} \approx 0$

$\rho_{eff} < 0$
$B_{eff} < 0$

(Monopolar +dipolar Resonances)

$\rho_{eff} > 0$
$B_{eff} < 0$

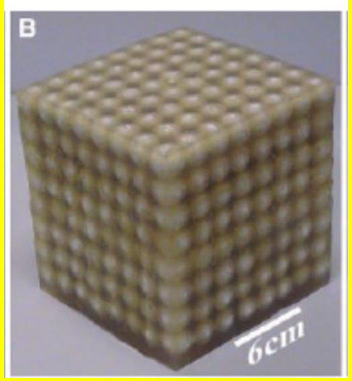
(Monopolar resonances)

Li and Chan, PRE (2004)

Acoustic metamaterials / Metafluids

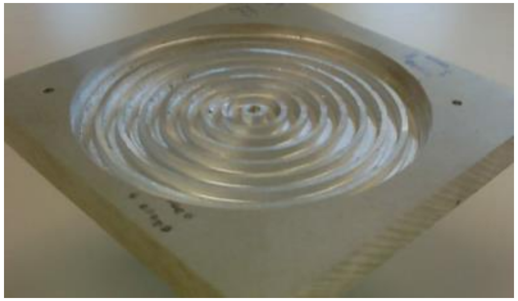
B_{eff}

ρ_{eff} <0



Liu et al. Science (2000)

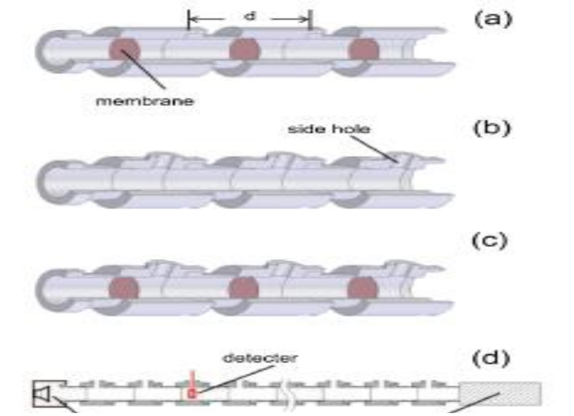
ρ_{eff} >0; B_{eff} >0



Torrent & JSD, PRL (2010)

ρ_{eff}

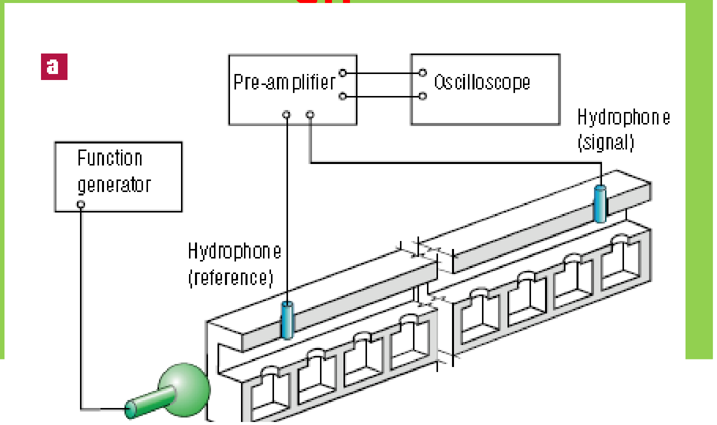
ρ_{eff} <0 B_{eff} <0



s)

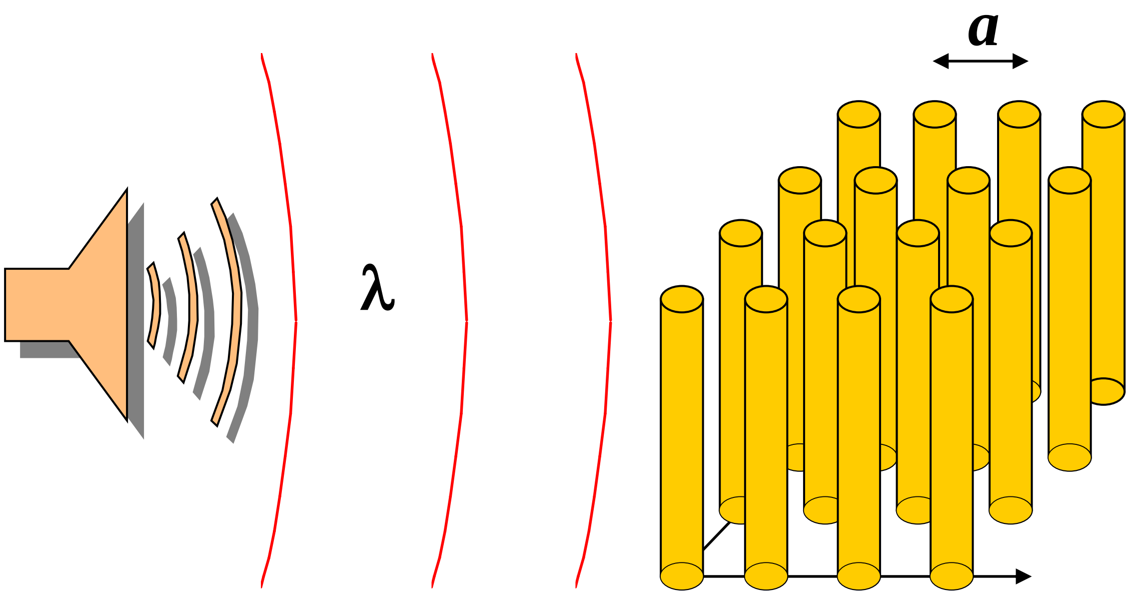
S.H. Lee et al. PRL (2010)

B_{eff} <0



N. Fang et al. Nat. Mat (2006)

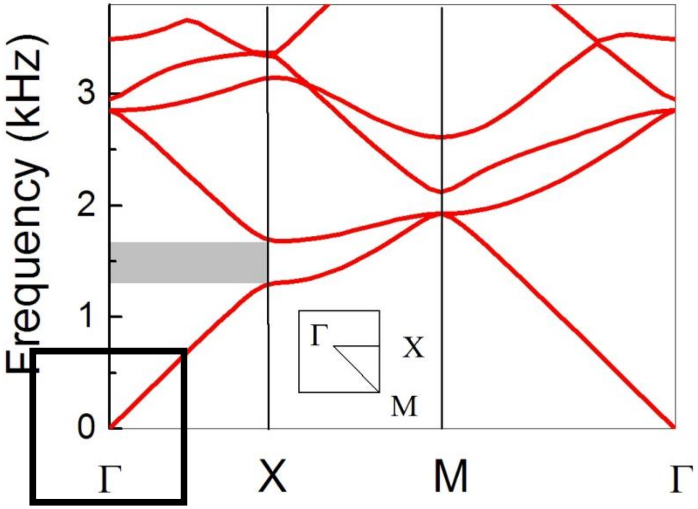
HOMOGENIZATION = LIMIT ω $0\rightarrow$

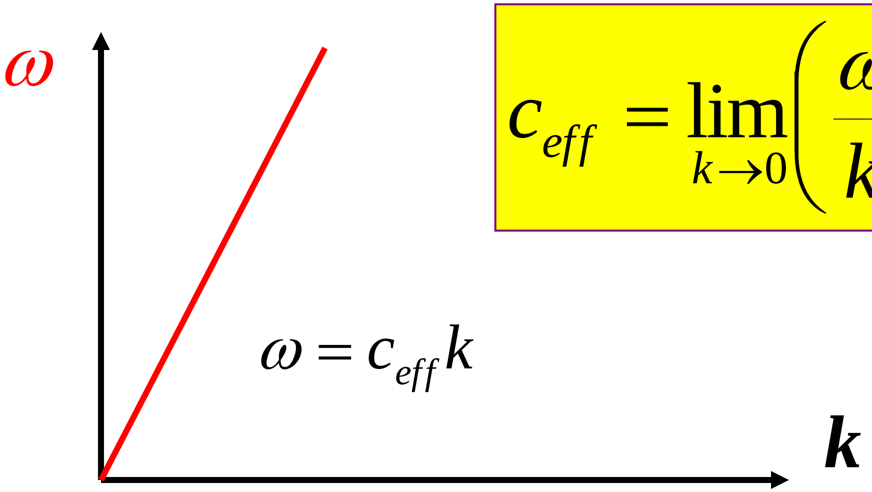


$\lambda >> a$

=

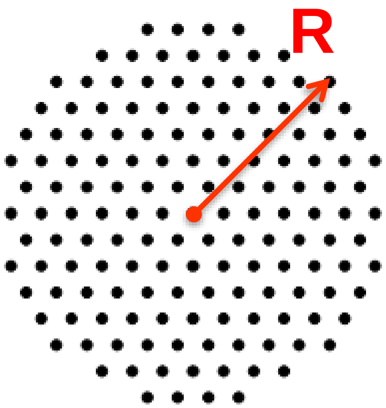
Effective medium



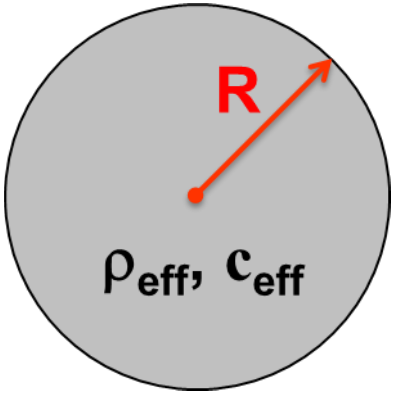


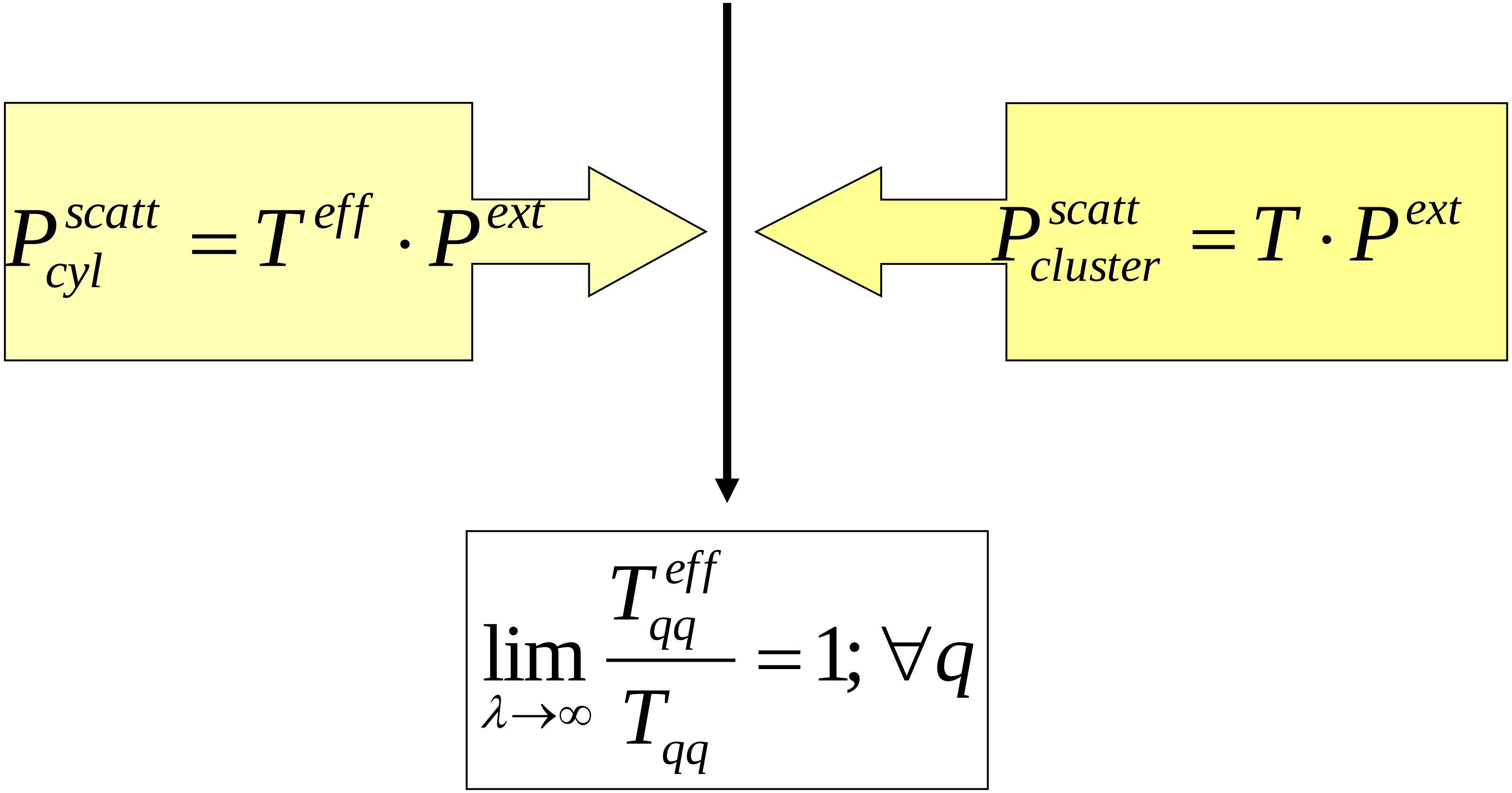
$$c_{eff} = \lim_{k \to 0} \left(\frac{\omega}{k} \right)$$

The homogenization method: a MS approach



$$\lim_{\lambda\to\infty}\frac{P^{scatt}_{cluster}-P^{scatt}_{cyl}}{P^{scatt}_{cluster}}=0$$





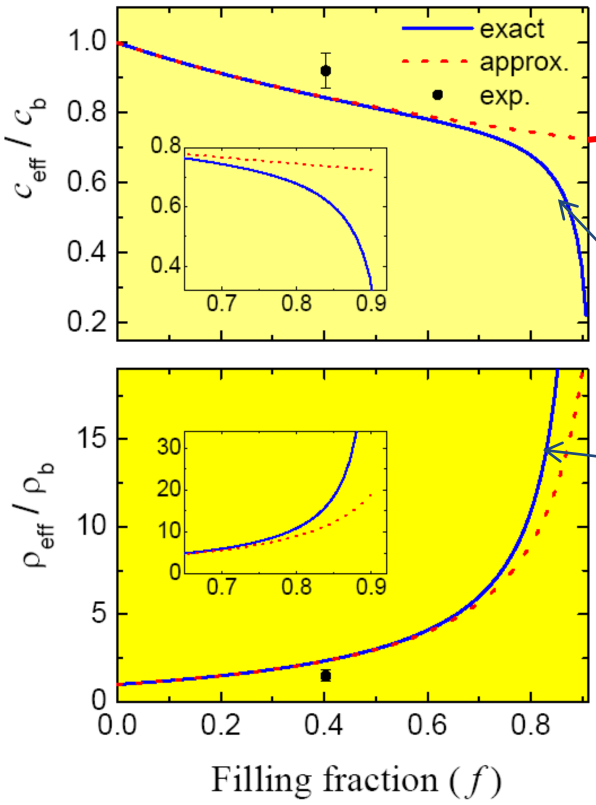
$$P^{scatt}_{cyl}=T^{eff}\cdot P^{ext}$$

$$P^{scatt}_{cluster}=T\cdot P^{ext}$$

$$\lim_{\lambda\to\infty}\frac{T^{eff}_{qq}}{T_{qq}}=1;\ \forall q$$

Homogenization of lattices of rigid cylinders (MST)

2D solid(rigid)-fluid structures (hexagonal)



$$\rho_{eff} = \frac{1+f}{1-f}\rho_b ; c_{eff} = \frac{c_b}{\sqrt{1+f}}$$

For *Δ=1 (f→0)*

$$\rho_{eff} = \frac{\Delta+f}{\Delta-f}\rho_b$$

$$c_{eff} = \sqrt{\frac{\Delta-f}{1-f}}\frac{c_b}{\sqrt{\Delta+f}}$$

$$\frac{1}{\Delta} = \frac{1}{N}\sum_{\alpha,\beta}\left(\hat{M}^{-1}_{\alpha\beta}\right)_{11}$$

$$\Delta \xrightarrow[f\to 0]{} 1$$

Effective parameters are robust against small displacement of the scatterers!!

Phys. Rev. Lett., **96**, 204302 (2006)
Phys. Rev. B, **74**, 224305 (2006)

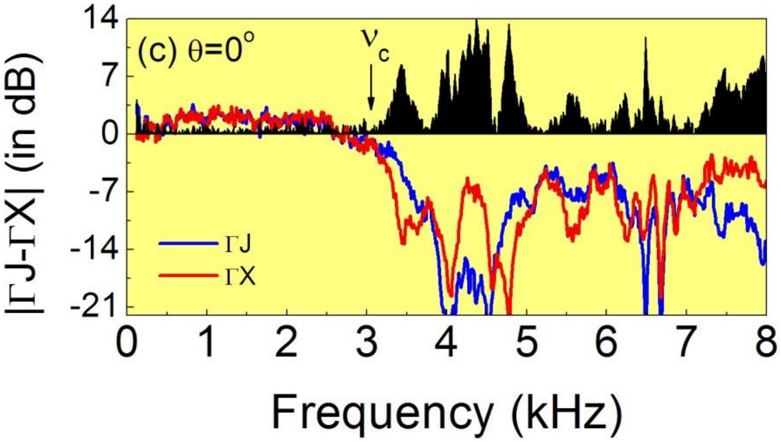
Homogenization (Experimental)

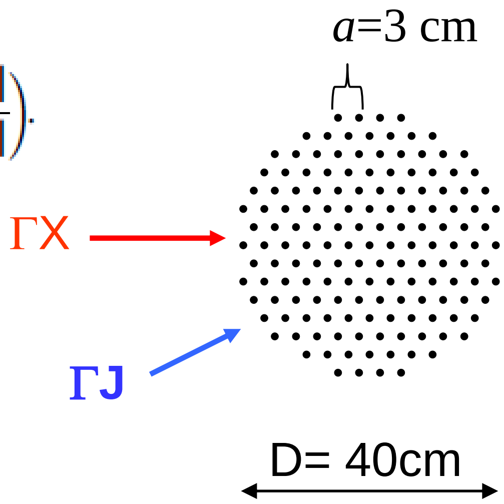
Number of cylinders: 151

Filling fraction: 0.4

Sound amplification map

$$\mathrm{SA}\,(r_0, \theta, \nu)(\mathrm{dB}) = 20\log_{10}\left(\frac{|P_{\mathrm{rms}}(r_0, \theta, \nu)|}{|P^{\mathrm{ext}}_{\mathrm{rms}}(r_0, \theta, \nu)|}\right).$$



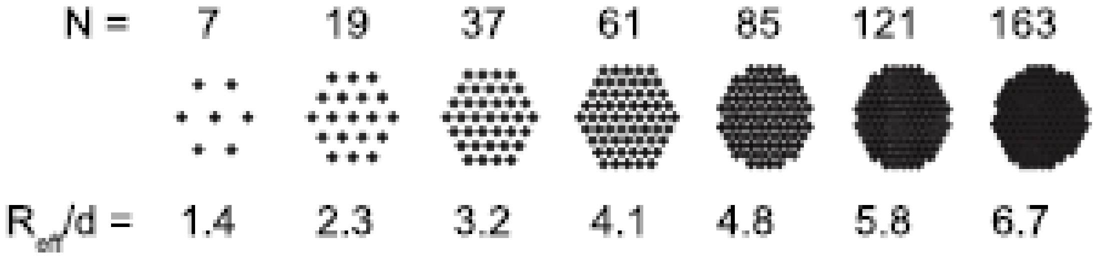


The homogenization is valid below 3 kHz or **$\lambda \geq 4a$ (=¼ D)**

Effective parameters (f = 0.4): ρ_{eff}=1.92 ± 0.40 Kg/m^3; c_{eff}= 316 ± 17 m/s

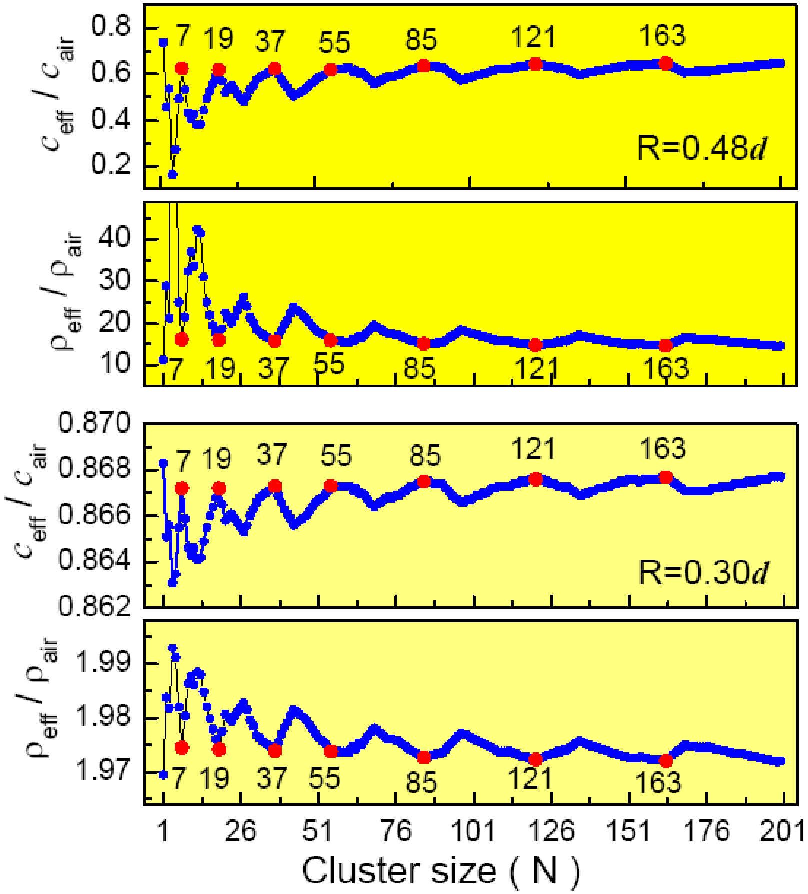
The wooden cluster dynamically behaves as a cylinder of Kripton gas!!
(ρ_{kr}=1.6 Kg/m^3; c_{Kr}= 319 m/s at 25^{O} C)

Homogenization of 2D clusters by MST: Magic clusters



f = 0.81

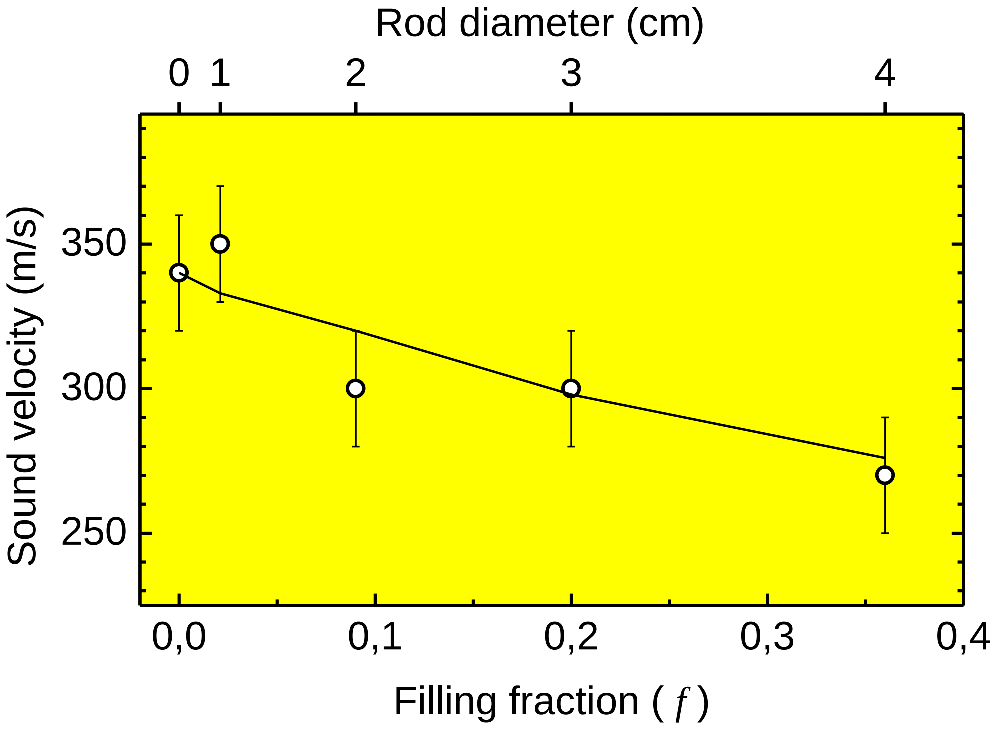
f = 0.31



PRB 75, 24140R (2007)

Sound propagation through lattices of rigid cylinders in air

Hexagonal lattice (a=6.35)



$$c_{eff} = c_{air}/n \approx c_{air}/\sqrt{(1+f)}$$

Refractive devices based on SONIC CRYSTALS: lenses

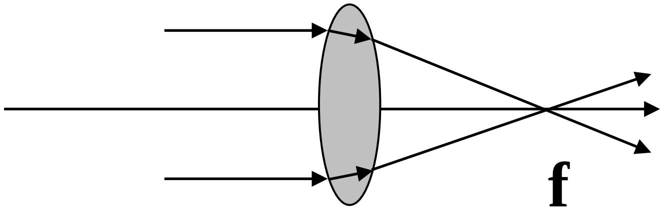
Why optical lenses are possible?

a) Light velocity is lower in solids than in air:

$c_{solid} < c_{air}$ ($n_{solid} > n_{air}$)

b) Dielectric materials exist that are transparent to light :

$n_{solid} \approx n_{air}$



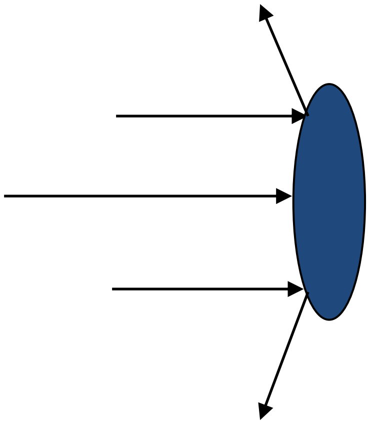
Why sonic lenses did not exist?

a) Sound velocity is larger in solids than in air:

$v_{solid} > v_{air}$ (≈340 m/sec))

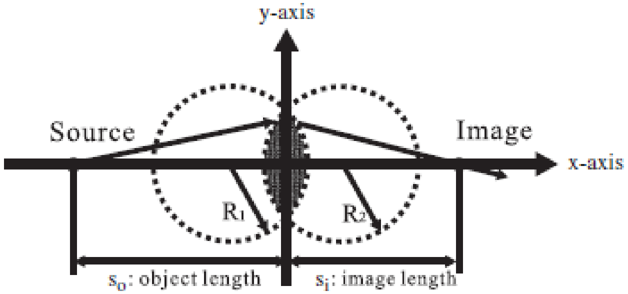
b) Solids materials <u>are not transparent</u> to sound:

$Z_{solid} >> Z_{air}$



Acoustic lenses in the audible based on SONIC CRYSTALS

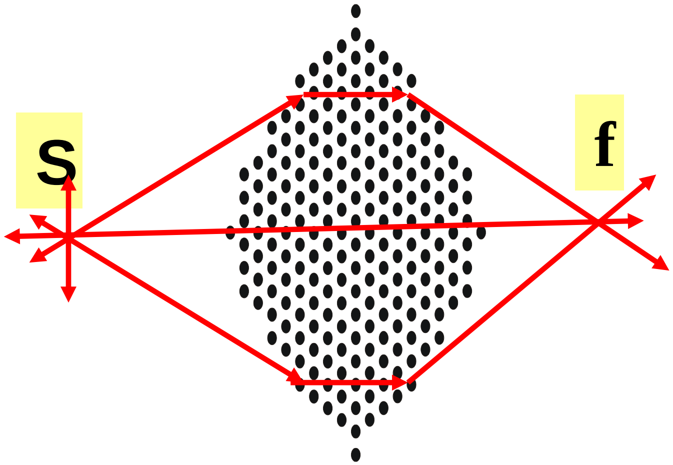
Lensmaker’s formula:



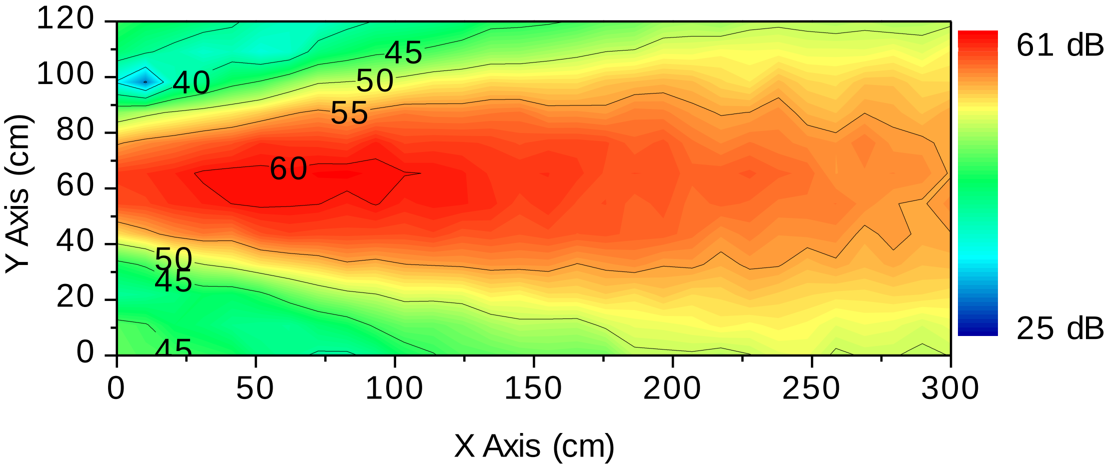
$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}.$$

(thin lenses)

$$\frac{1}{s_o} + \frac{1}{s_i} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right),$$



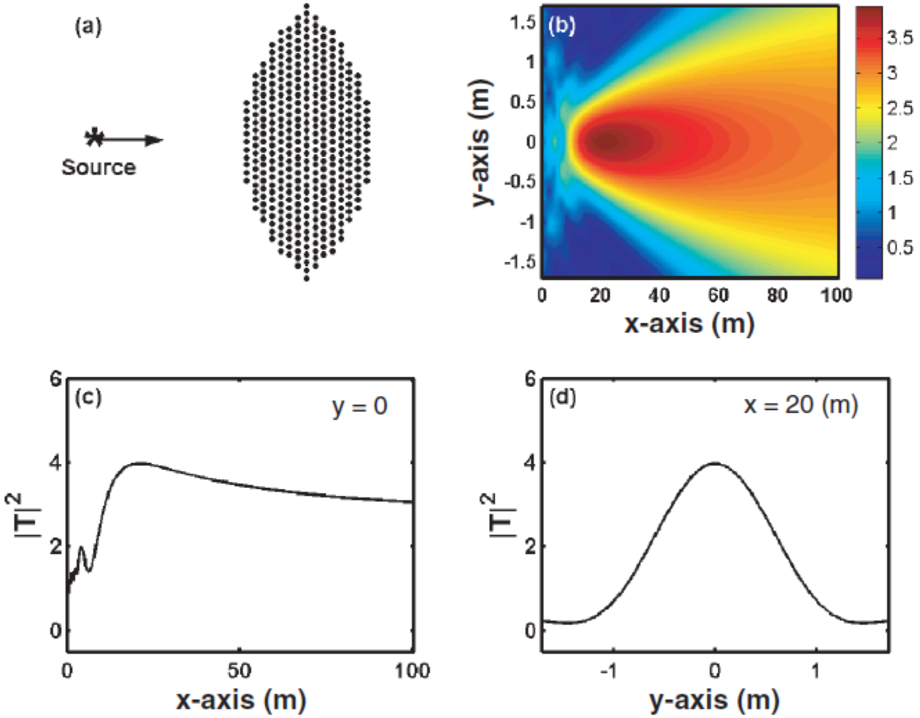
1700 Hz



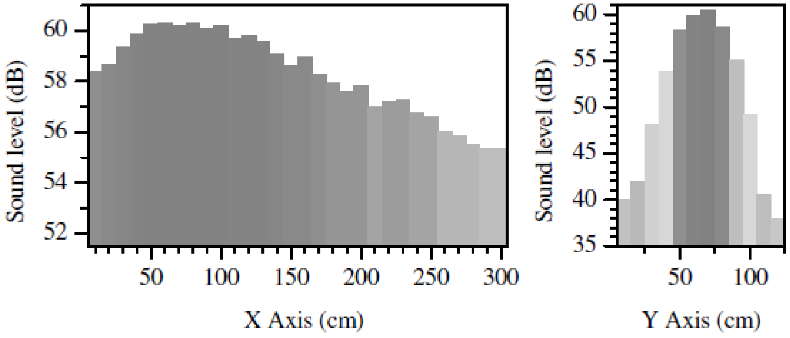
Phys. Rev. Lett. (2002)

Acoustic lenses in the audible based on SONIC CRYSTALS

Theoretical simulations based on MST:

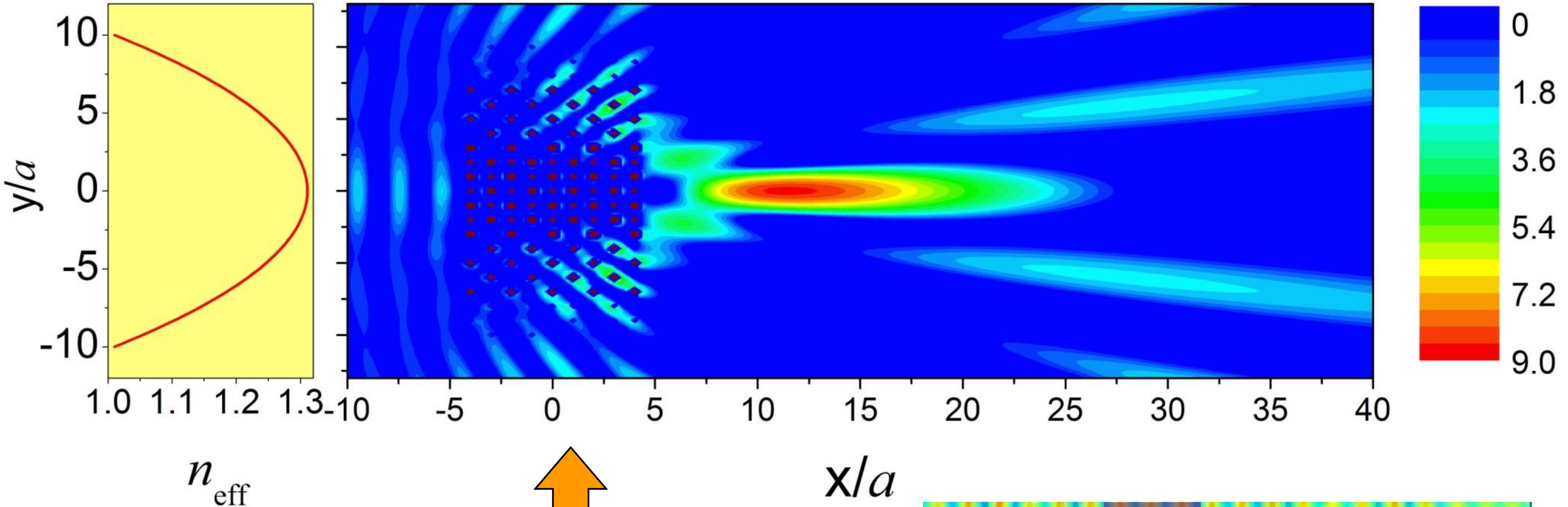


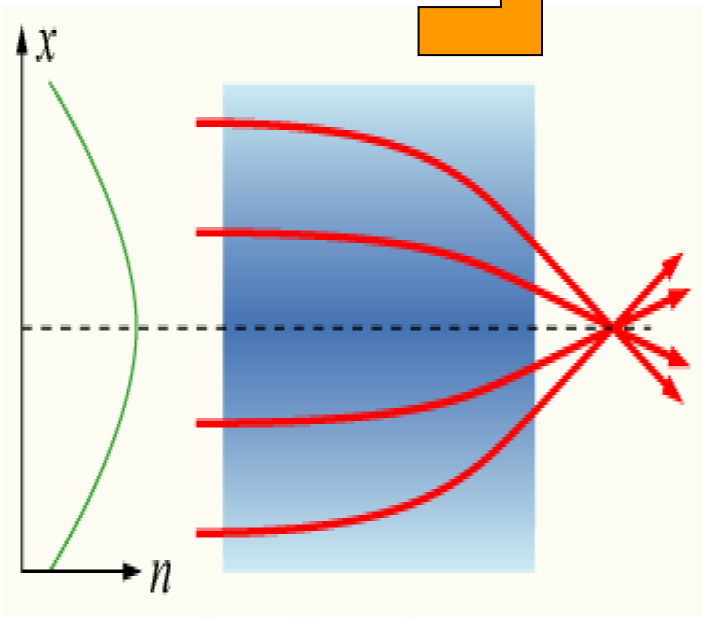
Experimental profiles:

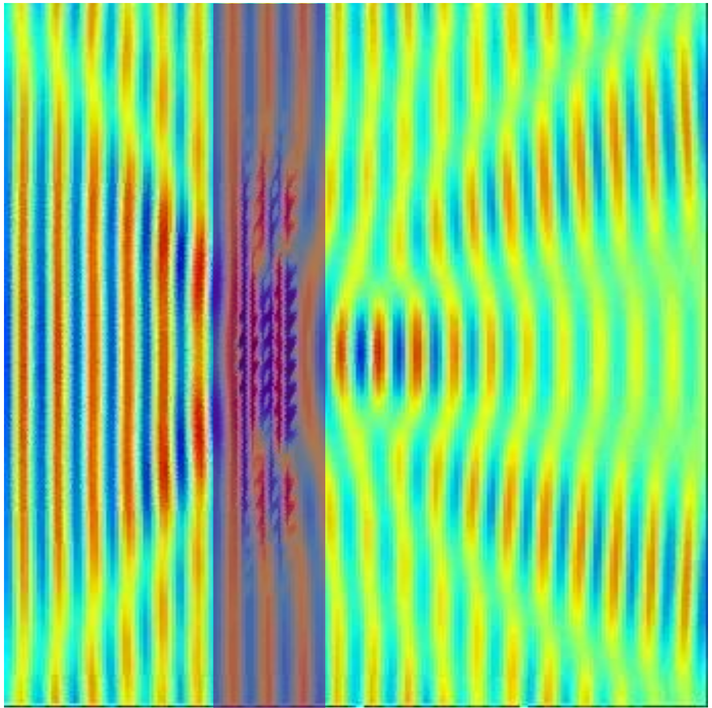


Gupta & Ye Phys.Rev. E (2003)
Kuo & Ye J.Phys.D:AppPhys (2004)

A gradient index sonic lens



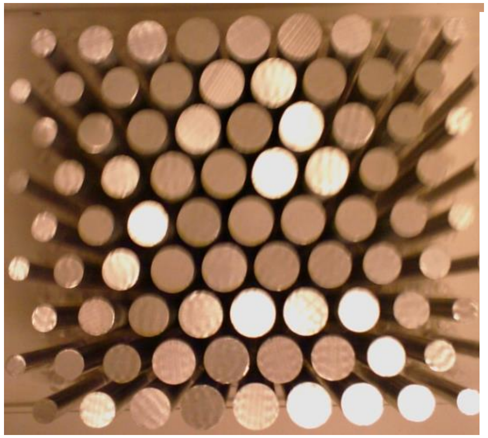


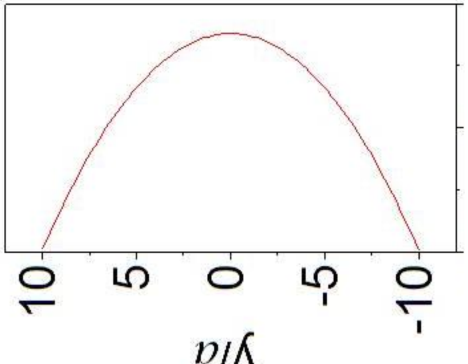


2D Gradient Index Acoustic Lenses

Airborne sound:
hexagonal array of Al cylinders in air (*a*=2cm)

SOUND AMPLIFICATION (3.5 kHz-4.5 kHz)

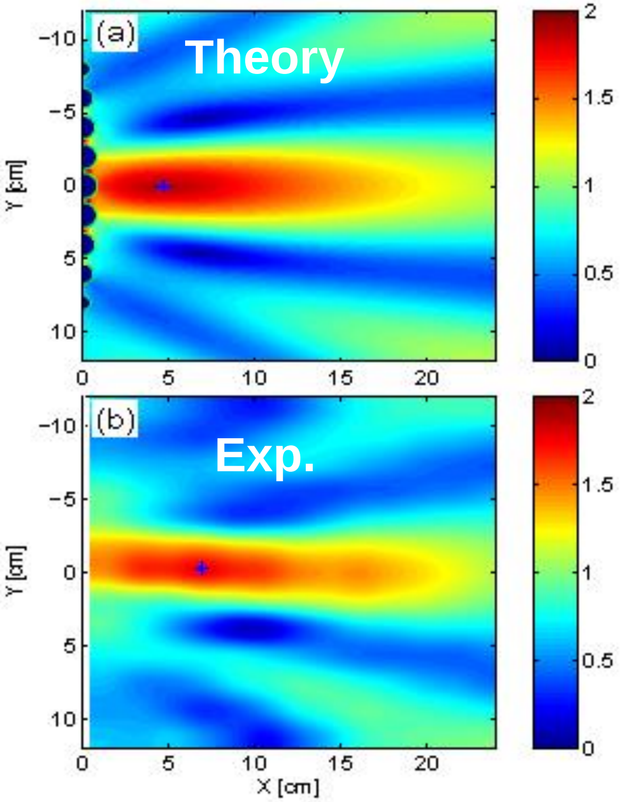




$$n(y) = n_0 \,\mathrm{sech}(\alpha y)$$

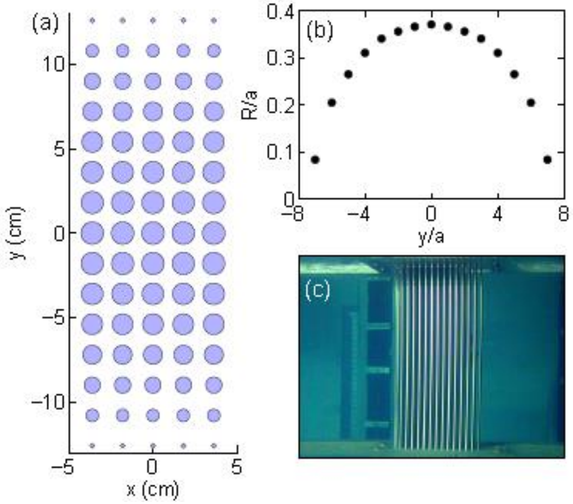
$$\alpha = \frac{1}{h}\cosh^{-1}\left(\frac{n_0}{n_h}\right)$$

Focusing at 4.5 kHz

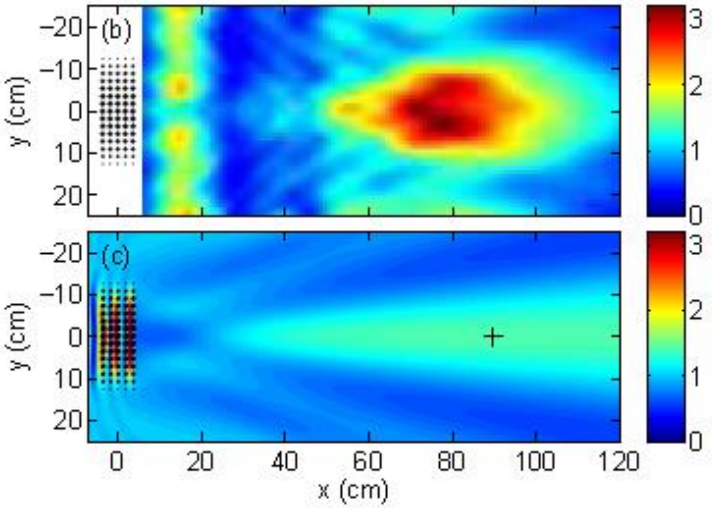


Appl. Phys. Lett. **97**, 104103 (2010)

underwater sound



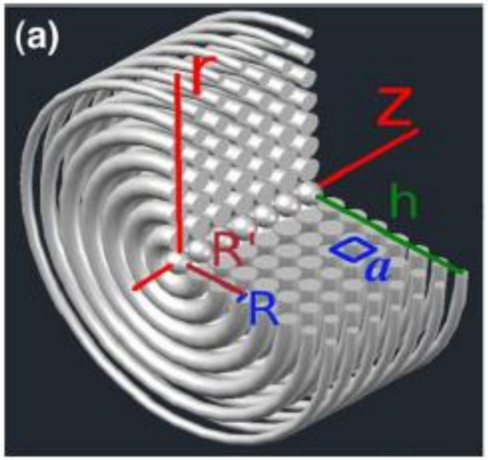
Focusing at 20 kHz (λ≈4*a*)

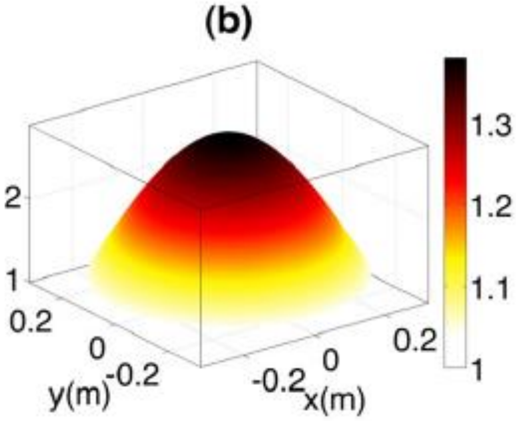


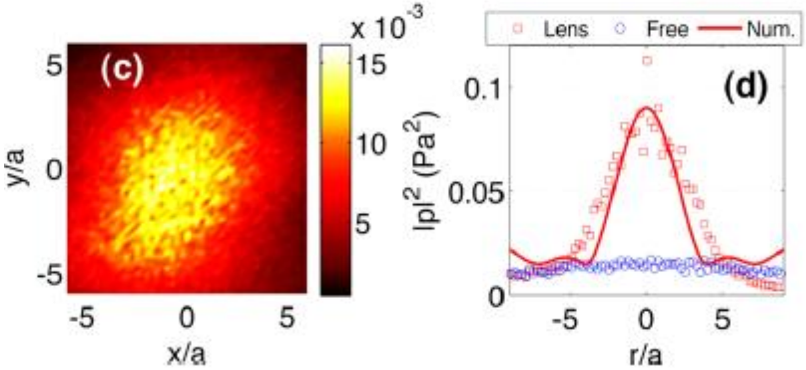
Appl. Phys. Lett. **97**, 113503 (2010)

3D Gradient Index Acoustic Lens (Axisymmetric)

Airborne sound:
Multilayer array of toroidal scatterers







Sound Amplification≈ 8.24dB

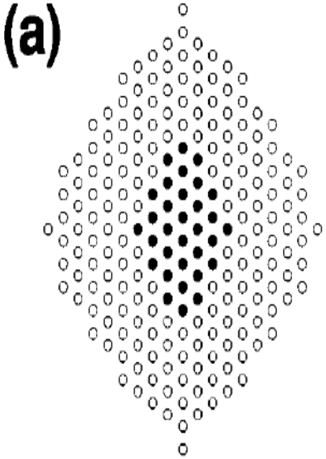
Appl Phys Lett **103**, 264106 (2010)

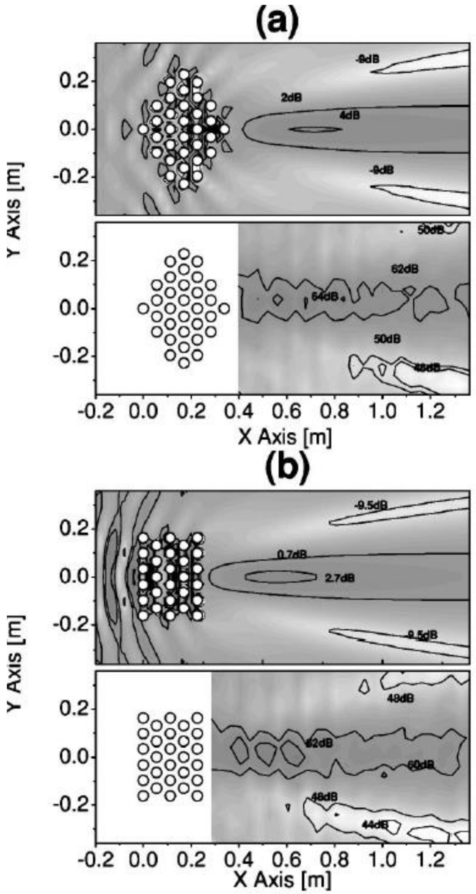
Diffraction versus refraction

PHYSICAL REVIEW E **71**, 018601 (2005)

Comment on "Theory of tailoring sonic devices: Diffraction dominates over refraction"

32 rods



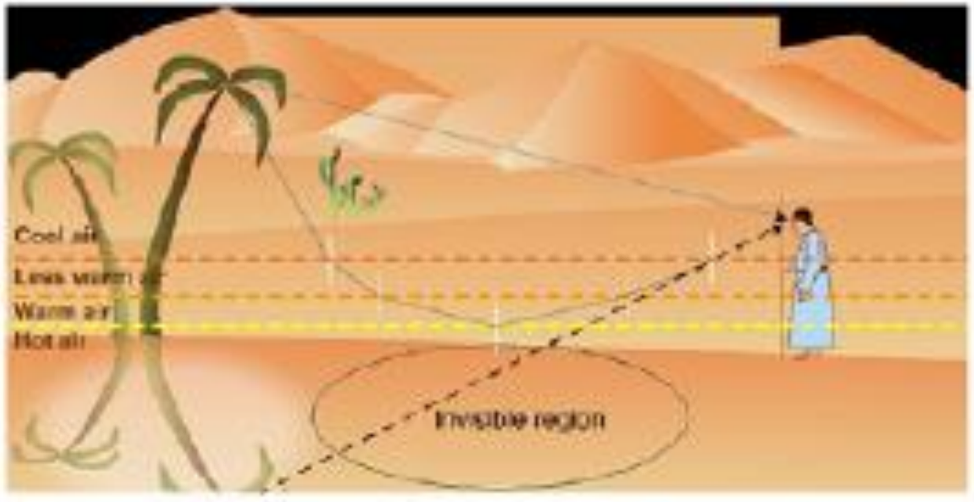


Wave manipulation using metafluids

Guide the sound as desired

Acoustic cloaking:

- Inspired by the similar phenomenon previously demonstrated for EM waves
- Principle like mirage

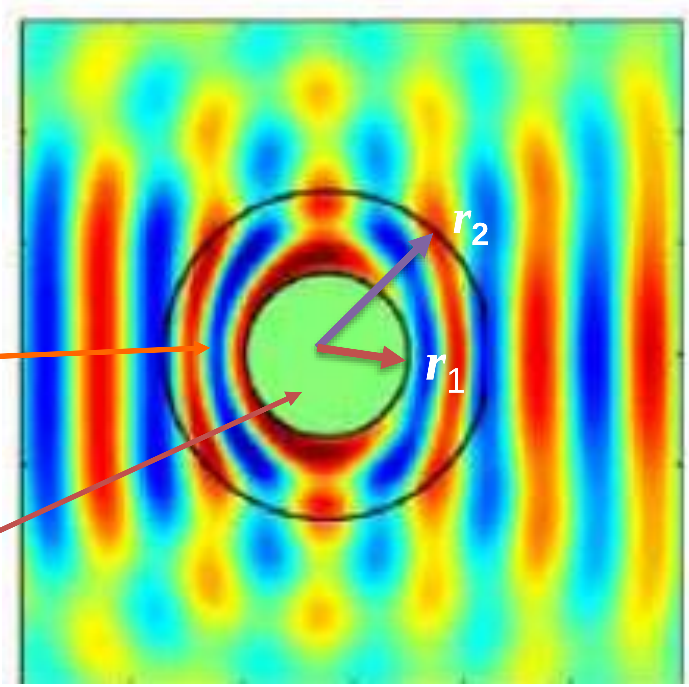


Wave manipulation by using metafluids: Acoustic cloaking

2D Acoustic cloaking

Acoustic metamaterial:

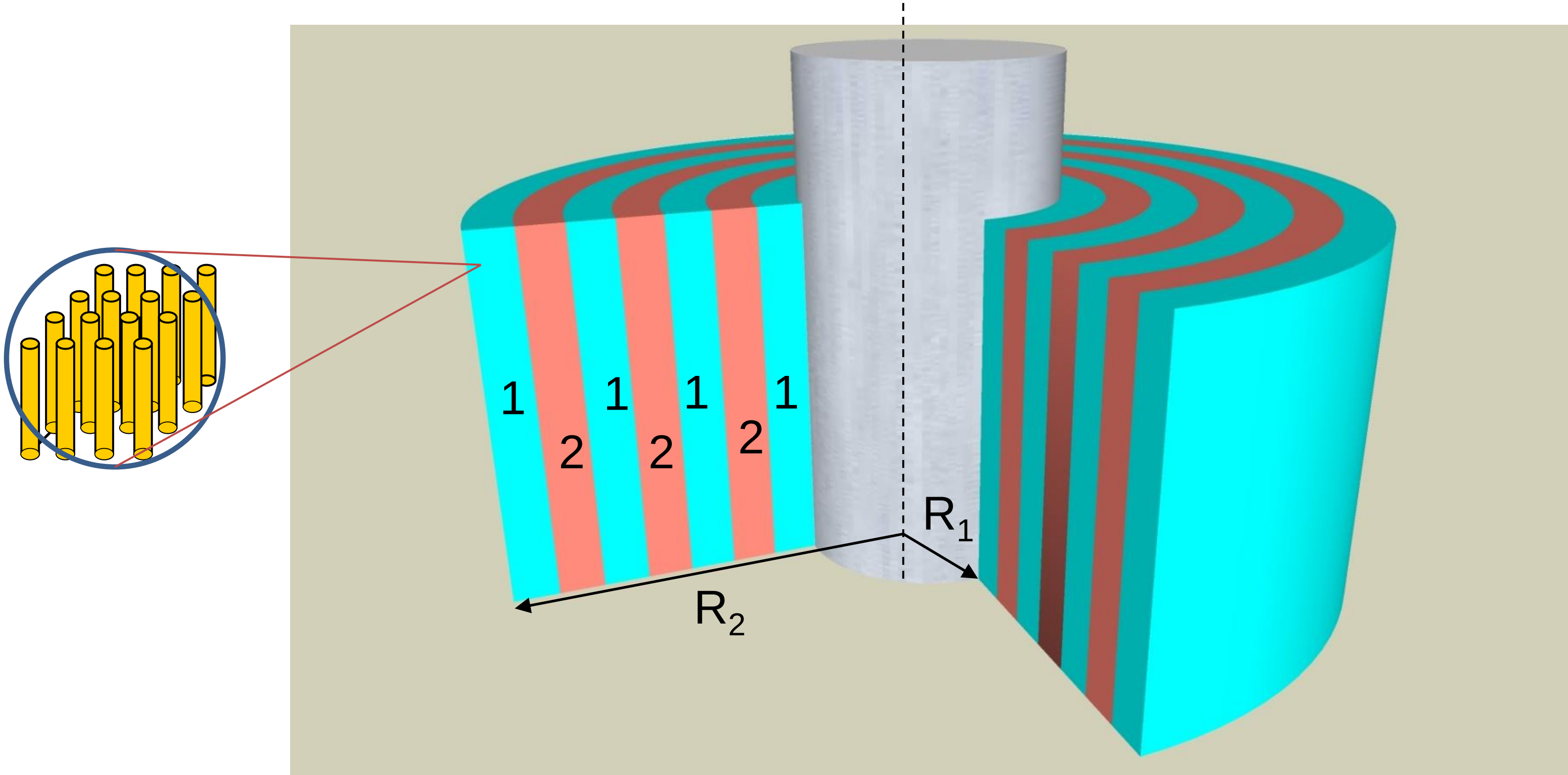
$$\frac{\rho_r}{\rho_0} = \frac{r}{r - r_1}, \quad \frac{\rho_\theta}{\rho_0} = \frac{r - r_1}{r}, \quad \frac{\lambda_c}{\lambda_0} = \left(\frac{r_2}{r_2 - r_1}\right)^2 \frac{r}{r - r_1},$$



This region is “invisible” to sound!

Cummer and Schurig
New J. Phys. **9**, 45 (2007)

Acoustic cloaking: a proposal based on SC



$$\rho_1(r) = \rho_r(r) + \sqrt{\rho_r^2(r) - \rho_b^2} = \frac{r + R_1\sqrt{2r/R_1 - 1}}{r - R_1}\rho_b$$

$$c_1(r) = \sqrt{\frac{B^*\rho_r}{\rho_b^2}} = \frac{R_2 - R_1}{R_2}\frac{r}{r - R_1}c_b$$

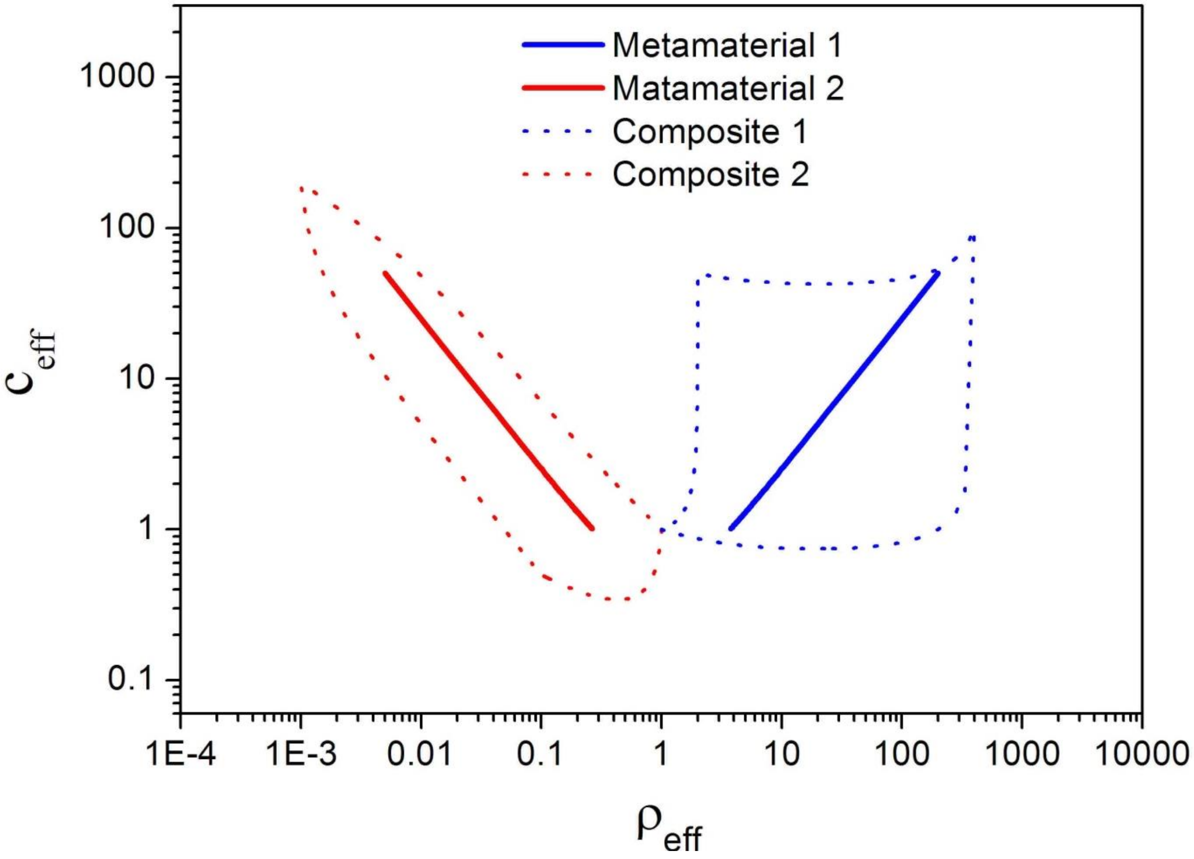
$$\rho_2(r) = \rho_b^2/\rho_1 = \frac{r - R_1}{r + R_1\sqrt{2r/R_1 - 1}}\rho_b$$

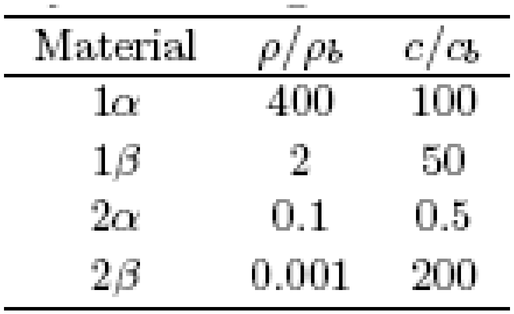
$$c_2(r) = c_1(r) = \frac{R_2 - R_1}{R_2}\frac{r}{r - R_1}c_b$$

New J. Phys. (2008)

4. Acoustic cloaking: a proposal based on SC

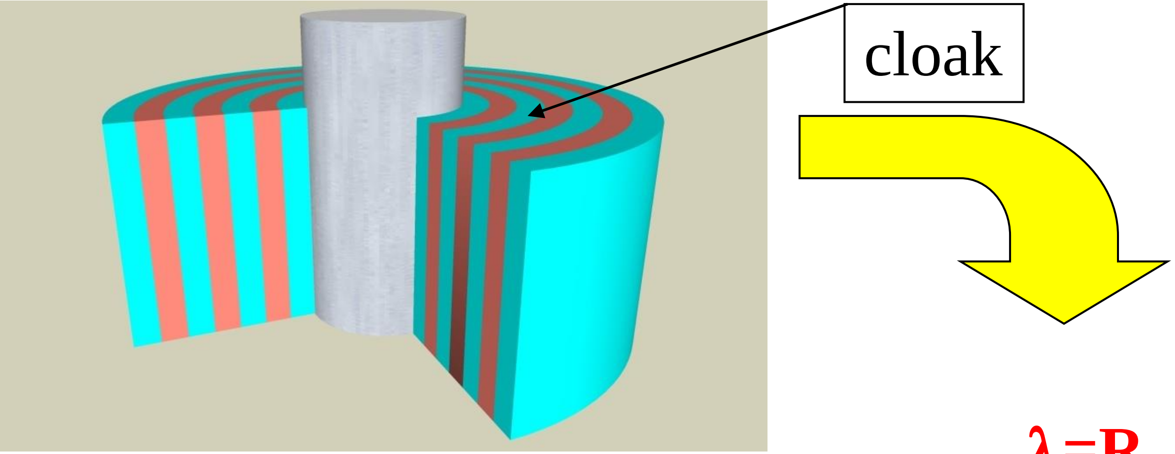
Each layer is an acoustic metamaterial based on a sonic crystal made of 2 type of elastic solids



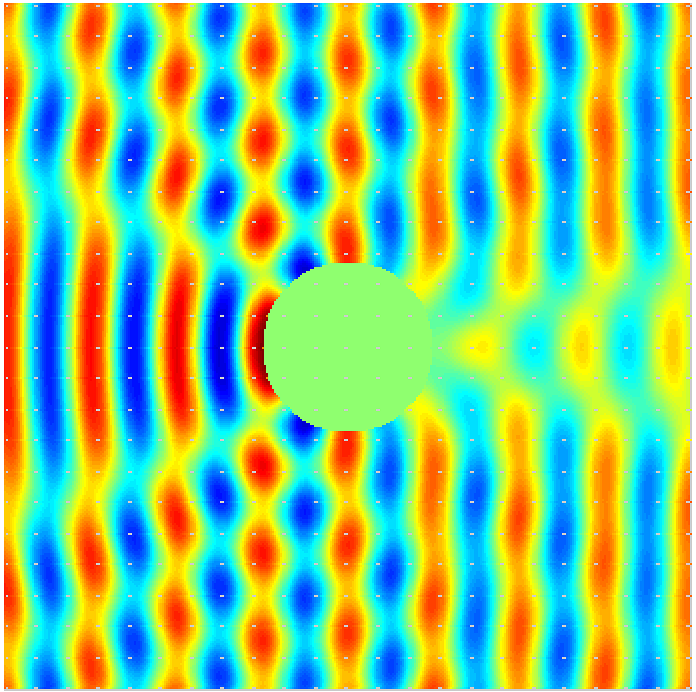


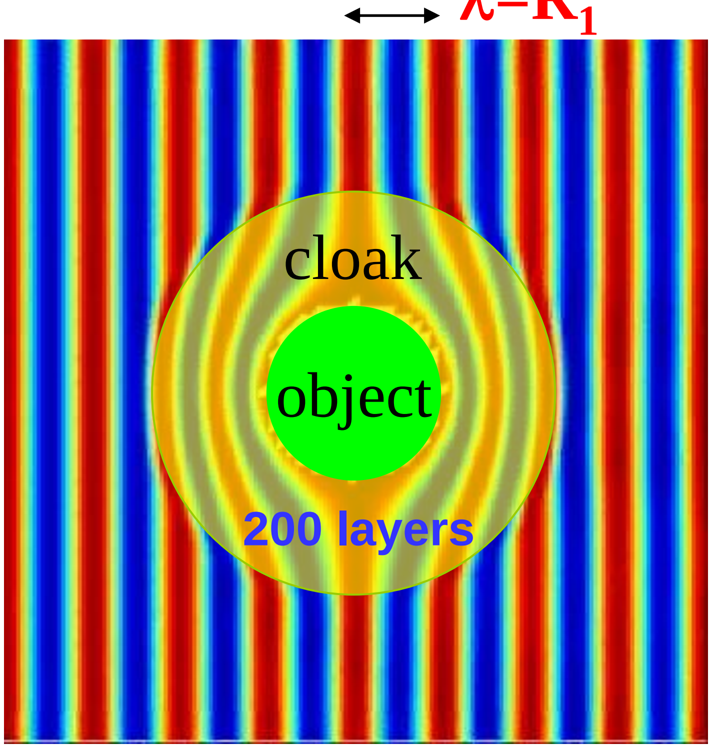
Material	ρ/ρ_b	c/c_b
1α	400	100
1β	2	50
2α	0.1	0.5
2β	0.001	200

Acoustic cloaking: a proposal based on SC

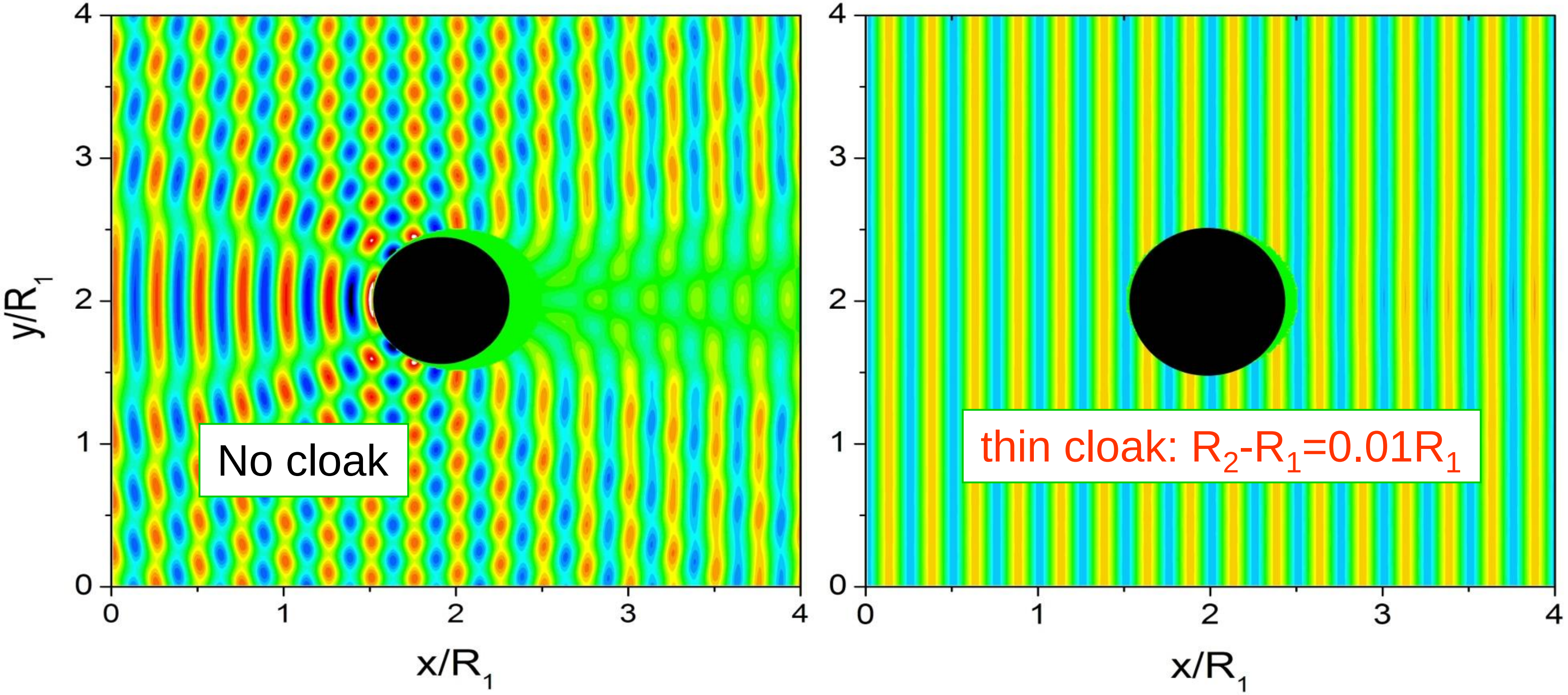


No Cloak





Wave manipulation using metafluids: acoustic cloaks



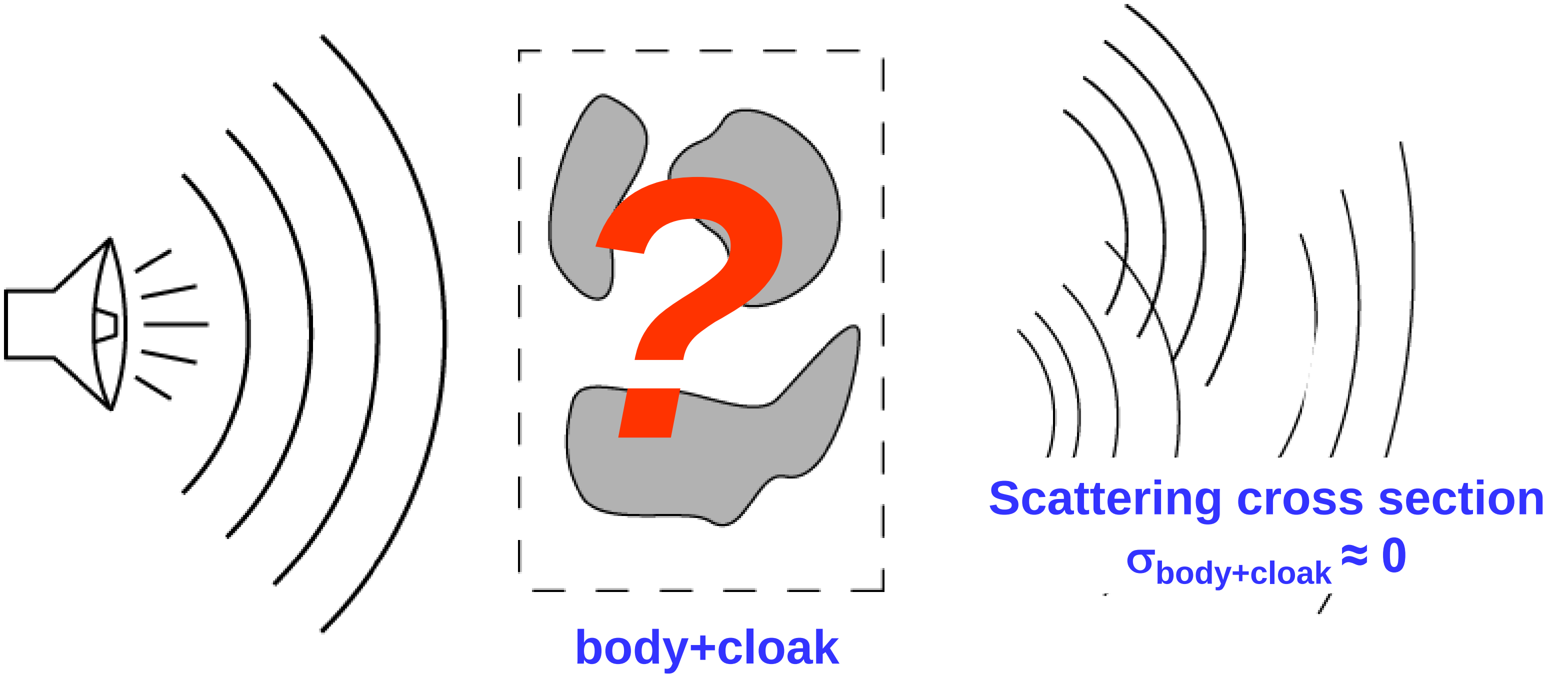
Potentials applications:

- noise reduction in buildings
- Inhibition of echoes in rooms
- To make objects undetectable by sound

Acoustic cloaks based on scattering cancellation

Inverse design of cloaks

Wave source (s)	Material dist. (m)	Performance $d=[G(m)]_s$



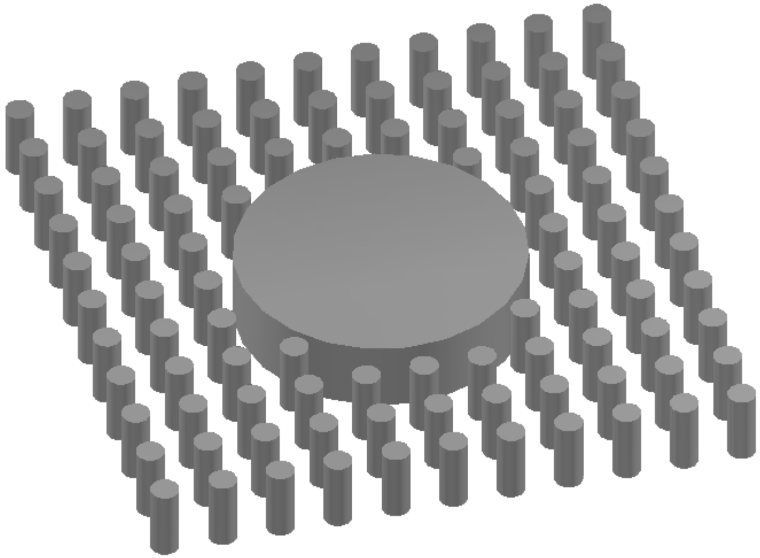
body+cloak

Scattering cross section

$\sigma_{body+cloak} \approx 0$

2D cloak based on scattering cancellation

- We propose to hide a rigid cylinder by means of a set of small rigid cylinders surrounding it.
- The cylinders have the same radius and their positions are obtained through an optimization procedure.



- The fitness function for this process is defined in terms of the scattering cross section; i.e., $\sigma_{cyl+cloak}=0$

Cloaks based on scattering cancellation

Experimental realizations using discrete units

2D

App. Phys. Lett. (2011)

3D

Phys. Rev. Lett. (2013)

Advantages:

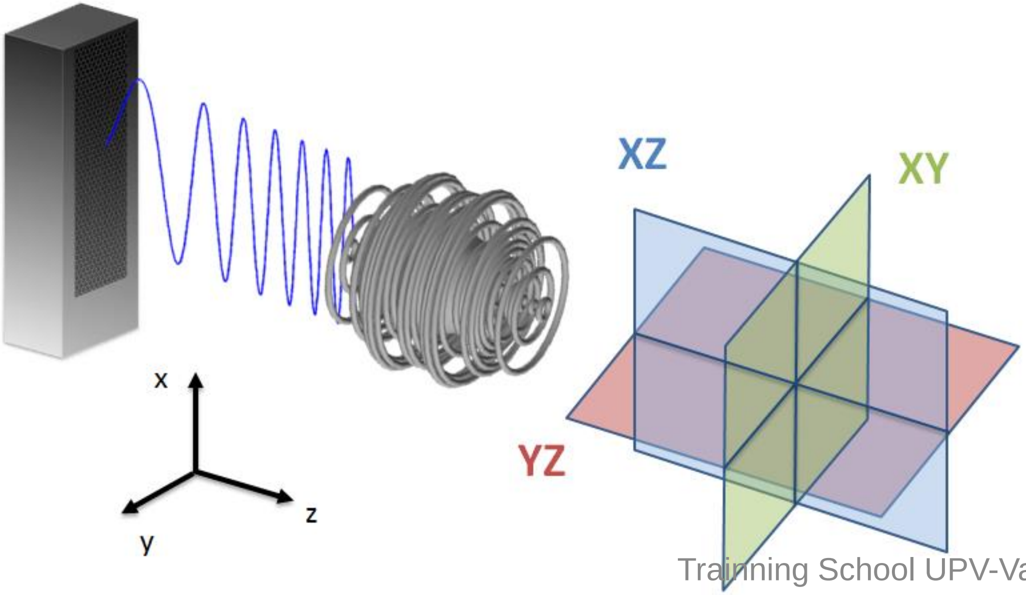
- Easy design and construction
- Scalable
- Low loss

Drawbacks:

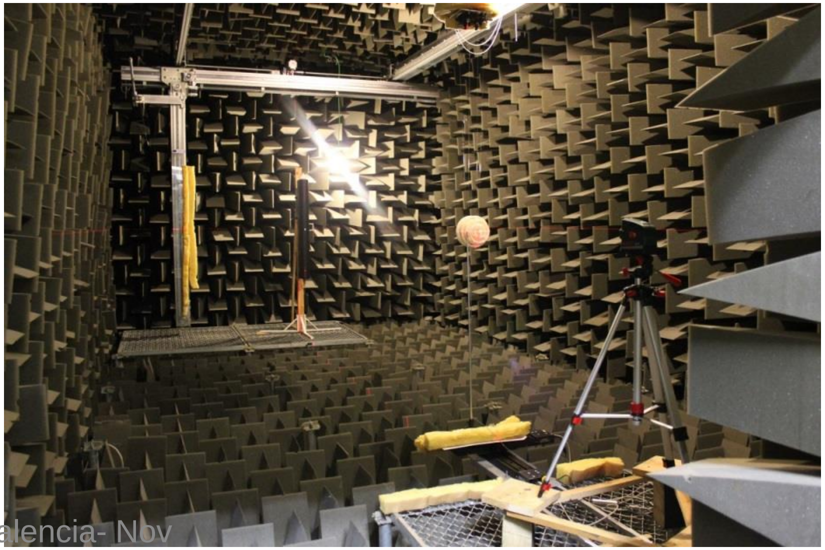
- One directional
- Depend of the shape of the cloaked objects
- Narrowband

3D cloak: Experimental setup

- Acoustic field is recorded on three perpendicular planes
- Each plane covers an area 0.2×0.2m^2, with 5mm of resolution.
- At each point a chirp in the range 7.5-9.5kHz was emitted, received and processed.



Inside the anechoic room:



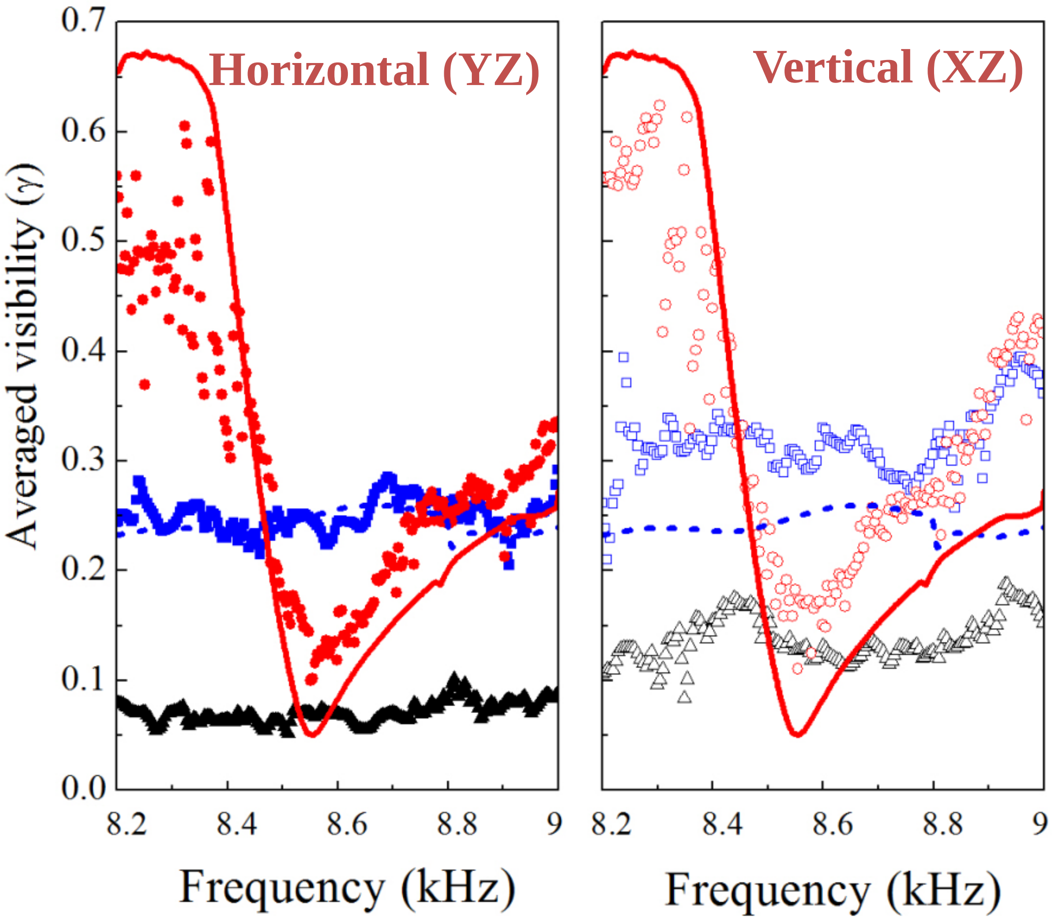
3D cloak: theory + experiment

- Best performance obtained at 8.55kHz.
- A 90% of scattering reduction is achieved

Average visibility index:

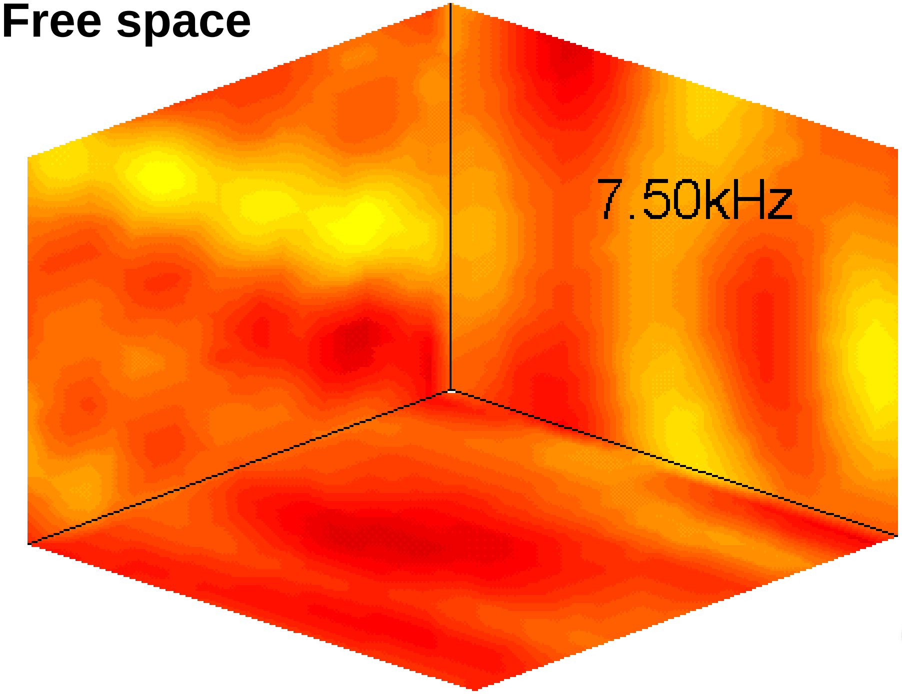
$$\gamma = \frac{1}{N}\sum_{j}\frac{|P_{max,j}| - |P_{min,j}|}{|P_{max,j}| + |P_{min,j}|}$$

N= number of wavefronts

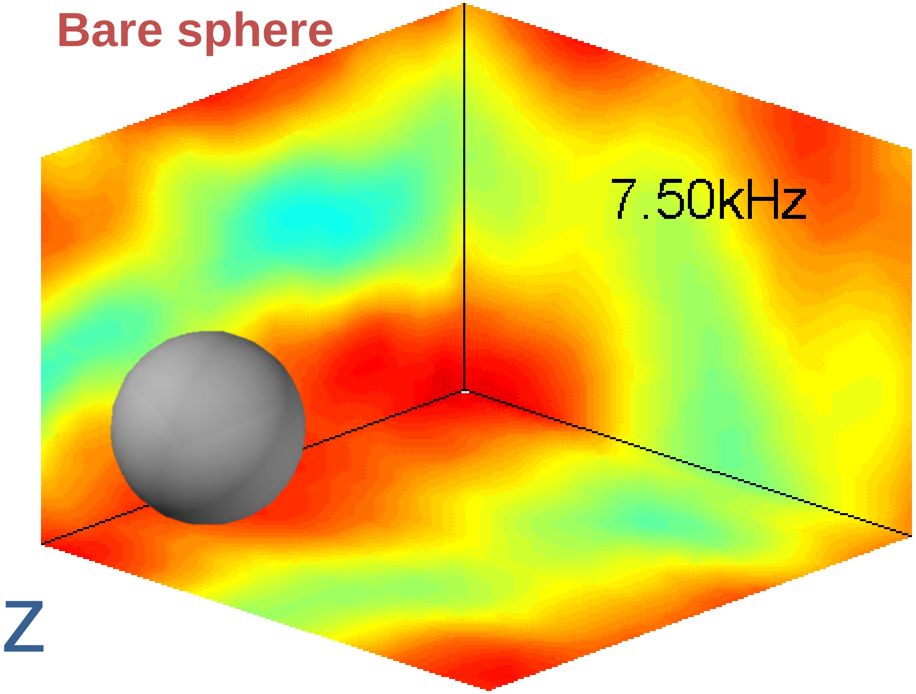


PRL. **110**, 124301 (2013)

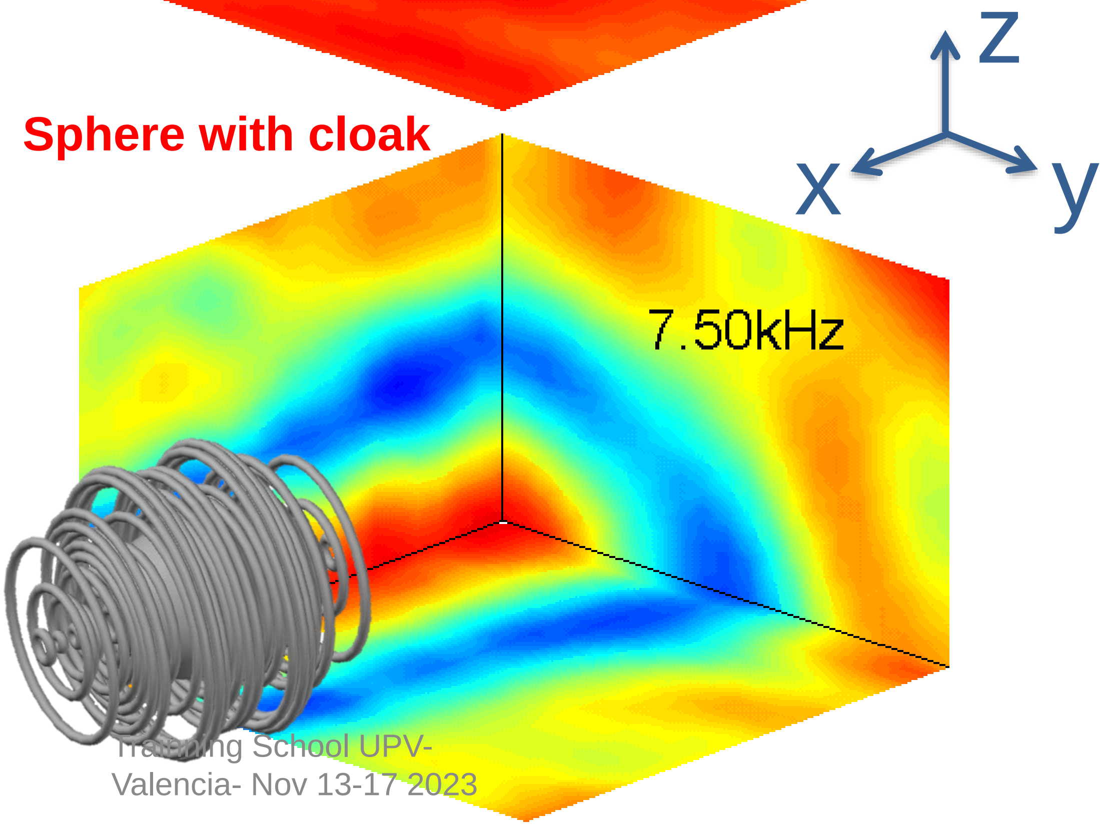
Free space



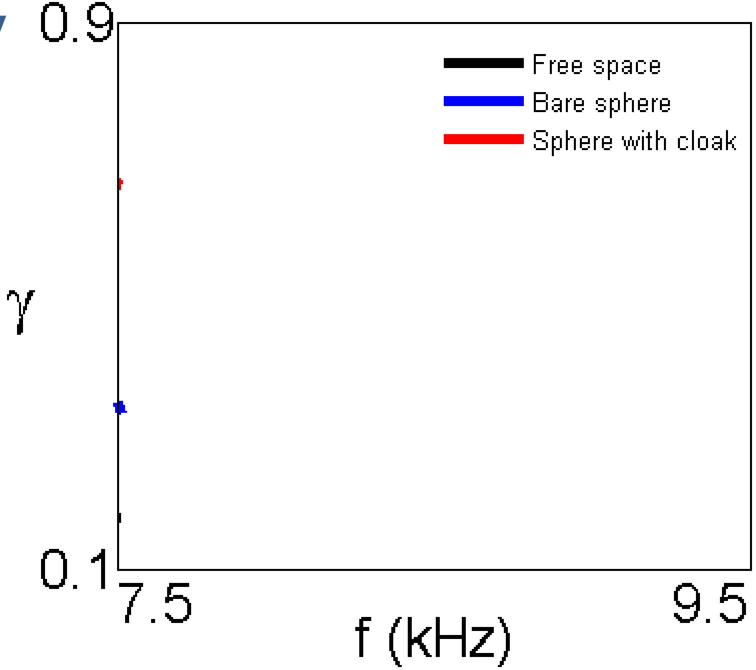
Bare sphere



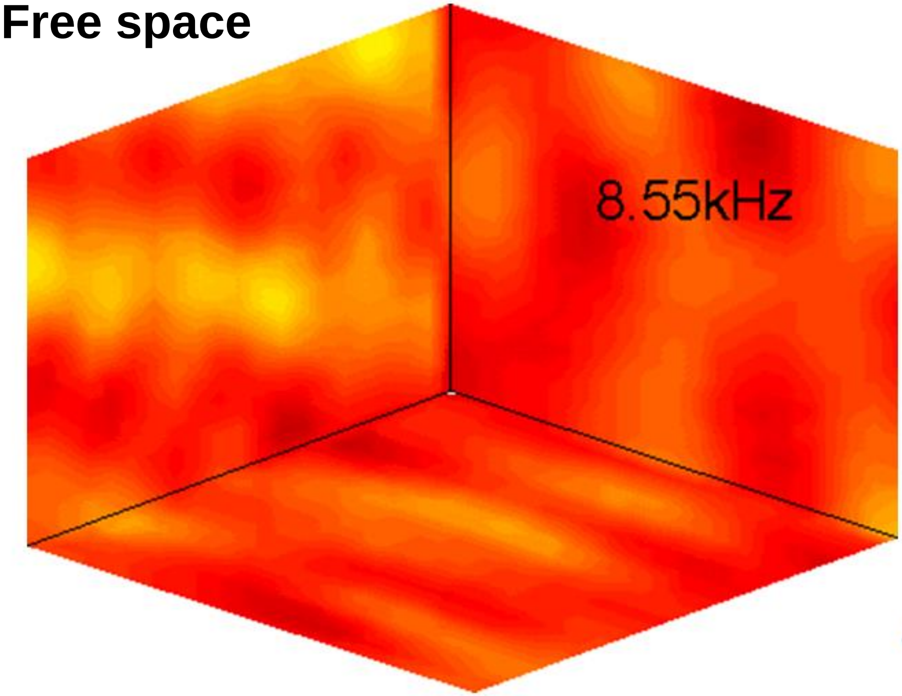
Sphere with cloak



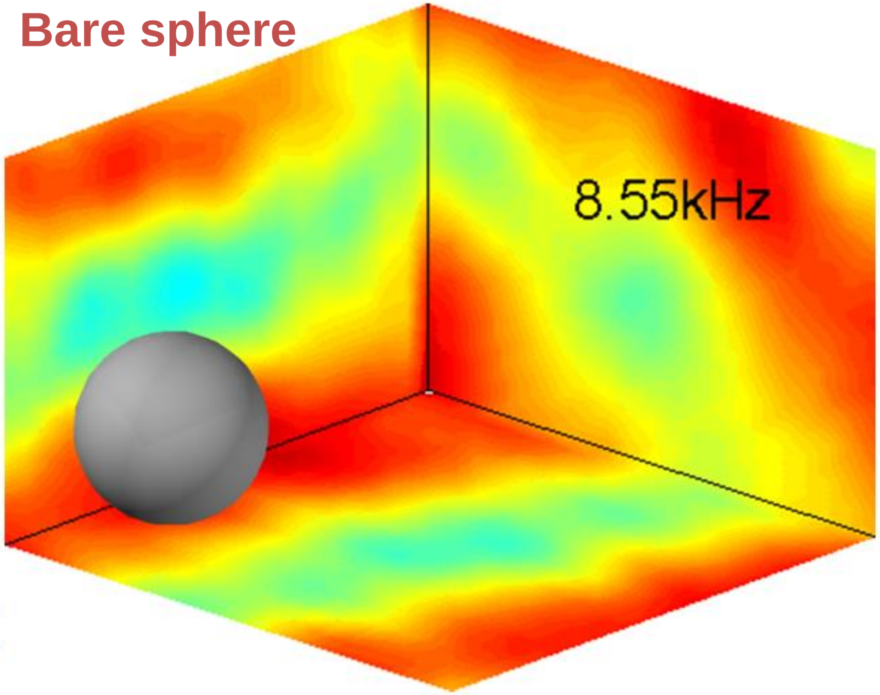
Victor M. García-Chocano



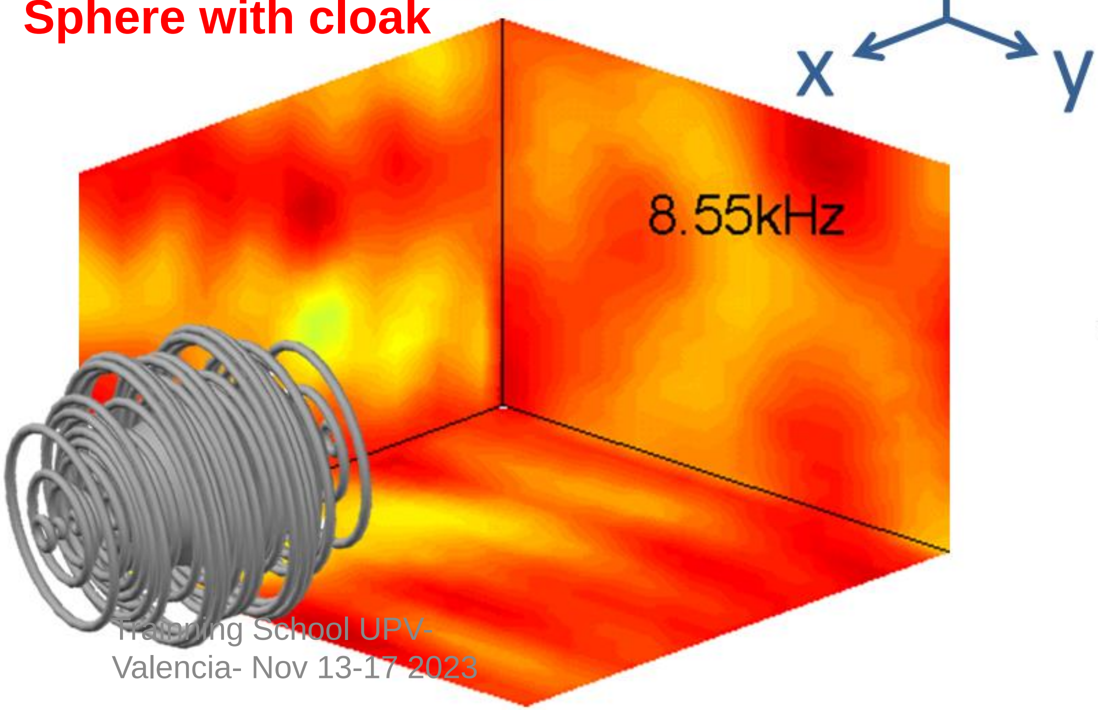
Free space



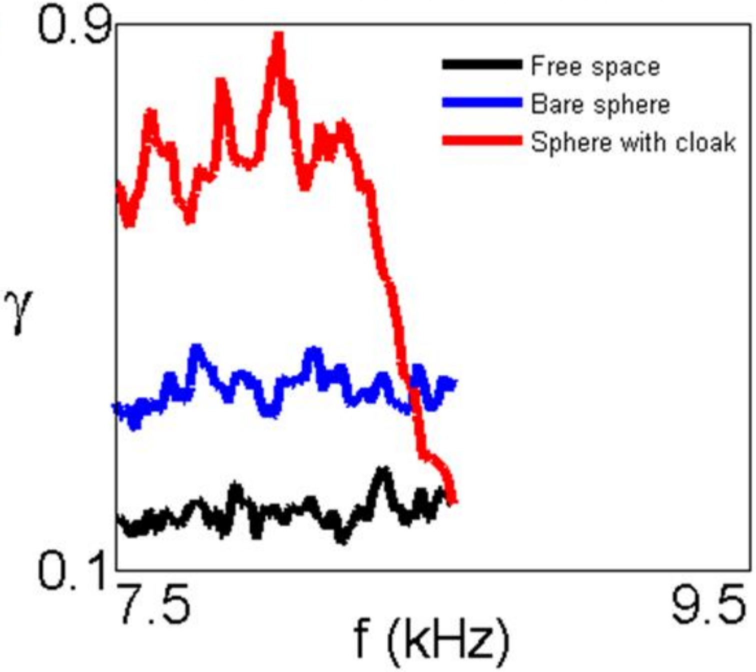
Bare sphere



Sphere with cloak



Victor M. García-Chocano



Acoustic black hole: an omnidirectional acoustic absorber

Narymanov & Kildishev,

Optical black hole: Broadband Omnidirectional light absorber (2009).

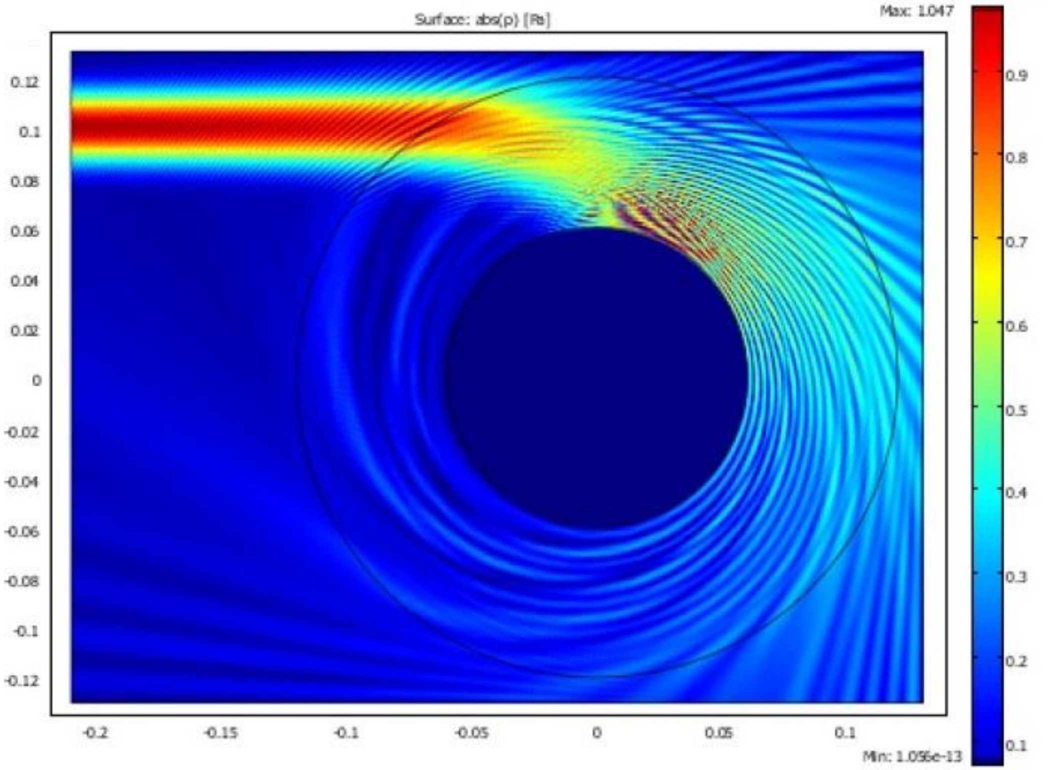
$$R_{\min} \geq \frac{\lambda}{2}$$

$$R_{\max} = R_{\min} \frac{n_a}{n_b}$$

$$n(r) = \begin{cases} n_b & r > R_{\max} \\ n_b \left(\frac{R}{r}\right) \rightarrow & R_{\max} > r > R_{\min} - \\ n_a + i\gamma & R_{\min} > r \end{cases}$$

λ	3 mm
R_{min}	6 cm
R_{max}	12.6 cm
n_a	2.1
n_b	1
$rho_b = rho_r = rho_a$	1.25
c_b	347
c_a	$c_b/n-\alpha^*i$
alpha	2000

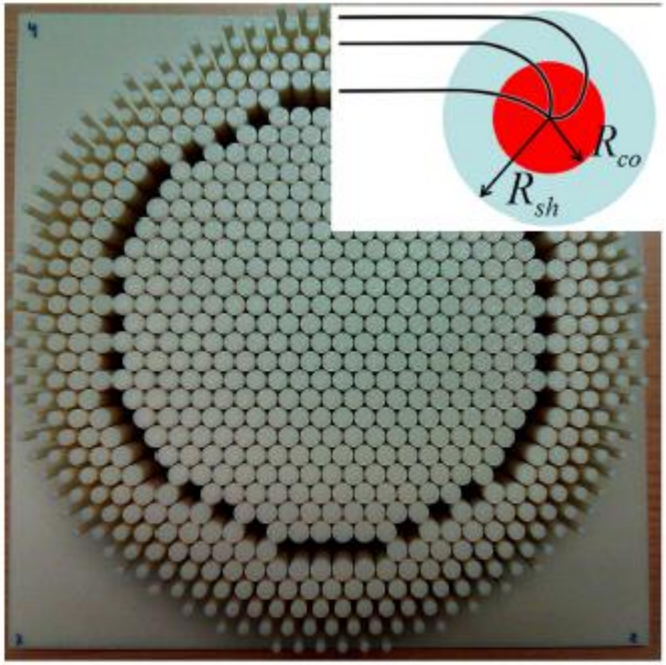
Acoustic black hole (COMSOL simulation)



Acoustic black hole: A practical realization in 2D

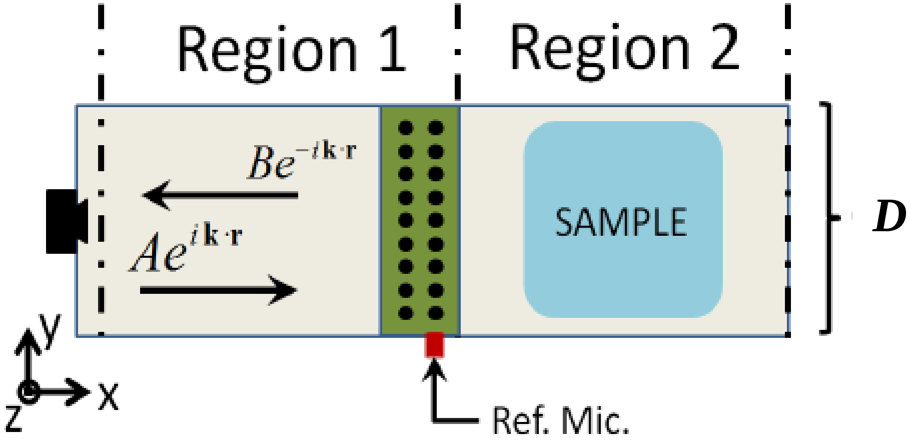
Omnidirectional acoustic absorber (disipative core + GRIN shell)

$$n(r) = \begin{cases} n_b & R_s < r \\ \frac{R_s}{r} n_b & R_c < r < R_s\,, \\ n_c + i\gamma & r < R_c \end{cases}$$



Appl. Phys. Lett. **100**, 144103 (2012)

Experimental setup



$$P(x,y) = \sum_{m=0}^{\infty} [A_m e^{i\beta_m x} + B_m e^{-i\beta_m x}] \cos\left(\frac{m\pi}{D} y\right)$$

$$\Phi_A = \frac{Dh}{4\omega\rho_b} \sum_{m=0}^{M} \beta_m |A_m|^2$$

$$\Phi_B = \frac{Dh}{4\omega\rho_b} \sum_{m=0}^{M} \beta_m |B_m|^2$$

$$\mathcal{R} = \Phi_B / \Phi_A\,;$$

$$\boxed{\alpha(\omega) = 1 - \Phi_B / \Phi_A}$$

Chamber width D = 29.6 cm

Chamber length L = 148 cm

Acoustic black hole: an omnidirectional acoustic absorber

Quality factor: $$Q_\alpha = \frac{1}{\Delta_\upsilon} \int_{\upsilon_i}^{\upsilon_f} \alpha(\upsilon) d\upsilon$$

$\vartheta_i = 580Hz;$
$\vartheta_f = 3400Hz$

Core R=80mm:

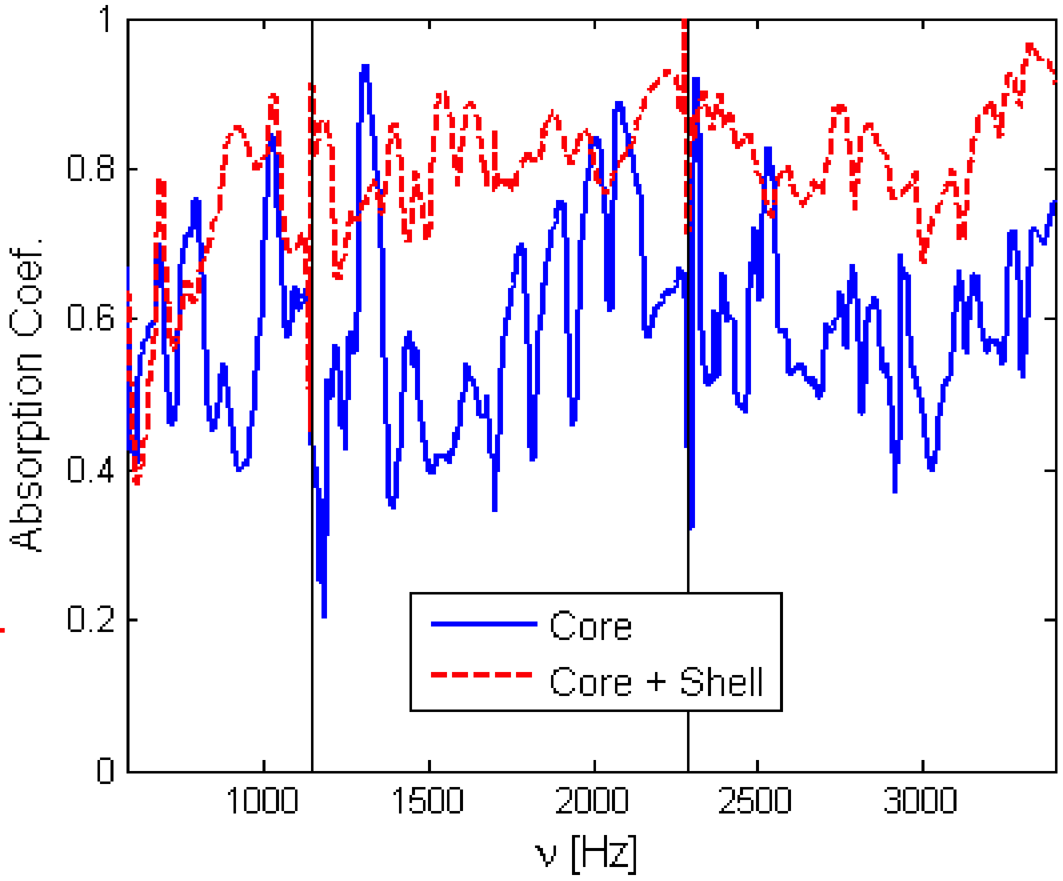
$$Q_{N1} = 59.0\%$$

Core R=120mm:

$$Q_{N2} = 62.7\%$$

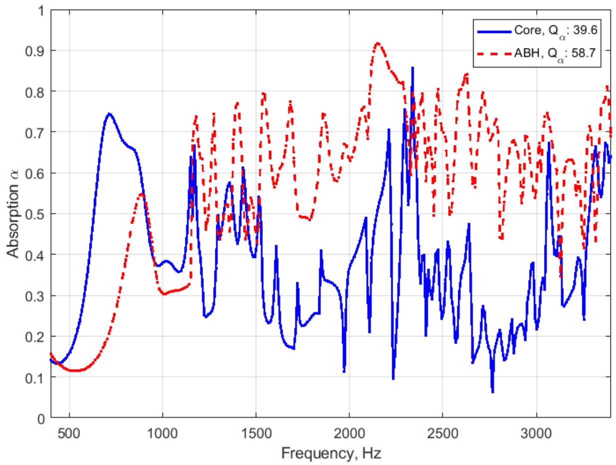
Core+Shell (Black Hole):

$$Q_{BH} = 79.6\%$$

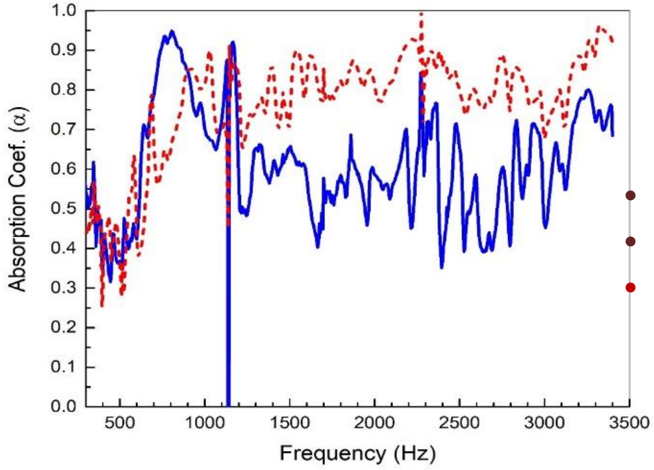


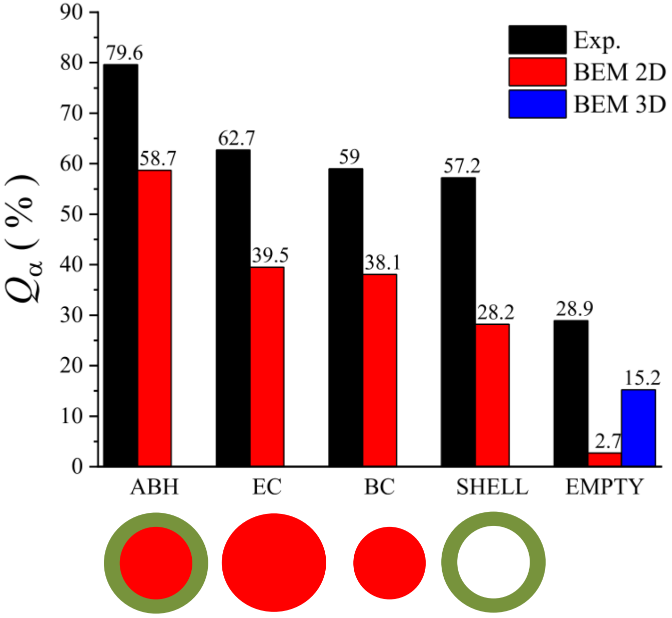
Viscothermal effects in a two-dimensional acoustic black hole:
A boundary element approach

BEM, numerical (2021)



Experimental (2012)





- *The experiments show higher absorption than simulations, due to chamber leakage*
- *The 2D simulations also miss some loss happening in the 3D chamber walls*
- *The results, however, present very similar relative differences*

Phys. Rev. Appl., **15**, 064057 (2021)

Summary

1. **Sonic crystals / Phononic crystals**
2. **Acoustic metamaterials based on Sonic crystals**
3. **Acoustic lenses**
4. **Acoustic cloaks**
5. **Acoustic Black holes**

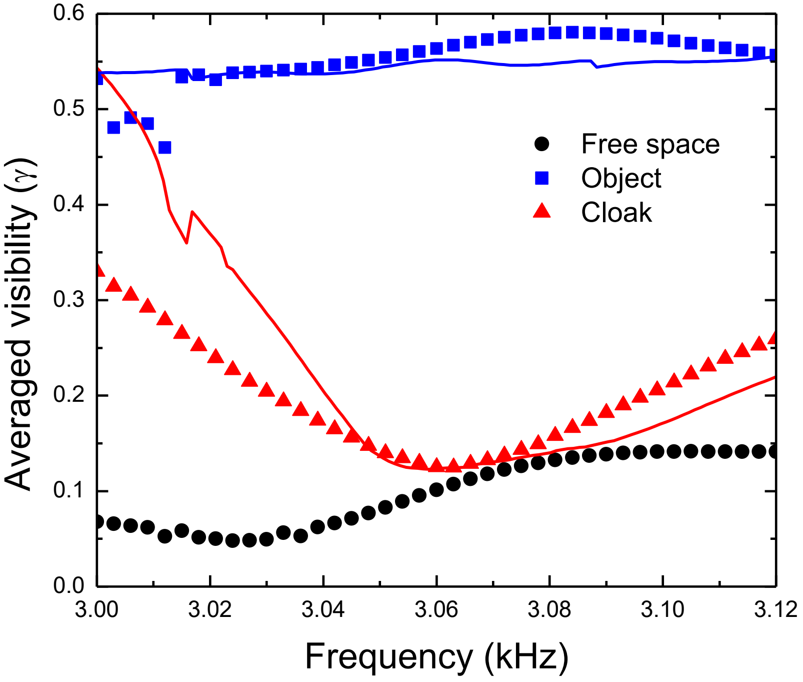
Thanks for your attention!!

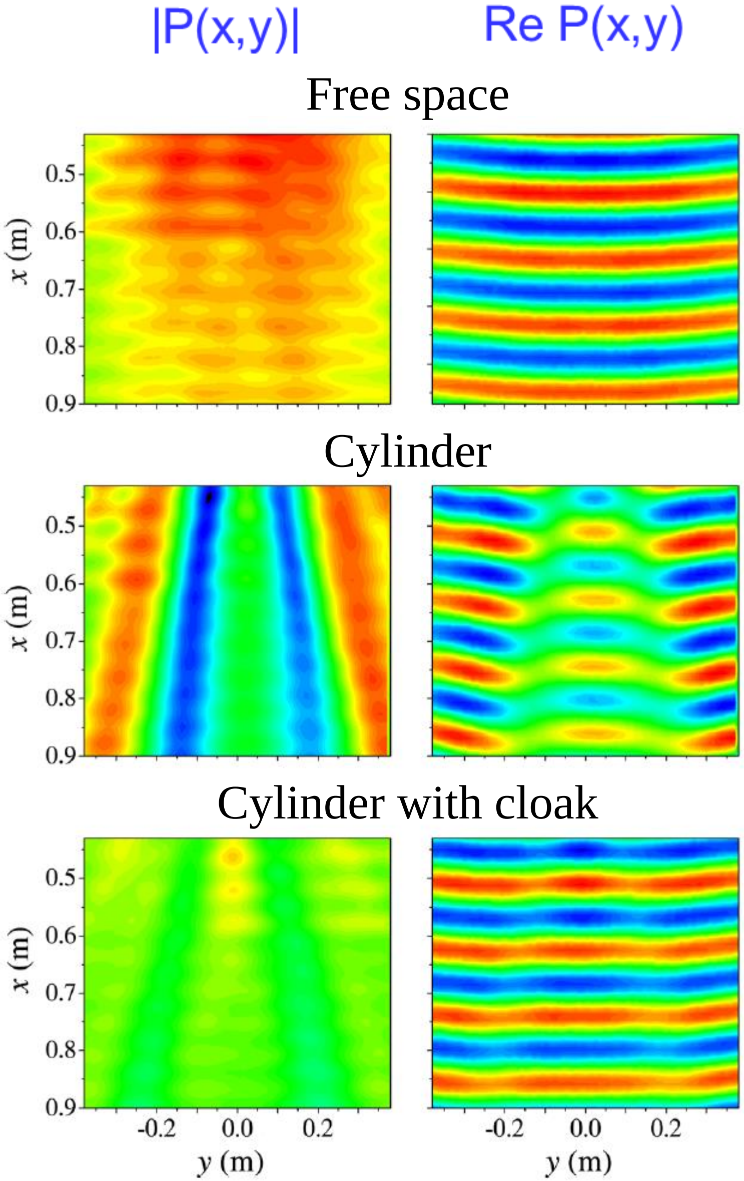
Practical realization: 2D cloak based on scatt. cancellation

- Experimental results:

$$\gamma = \frac{1}{N}\sum_j \frac{|P_{max,j}| - |P_{min,j}|}{|P_{max,j}| + |P_{min,j}|}$$

N= number of wavefronts

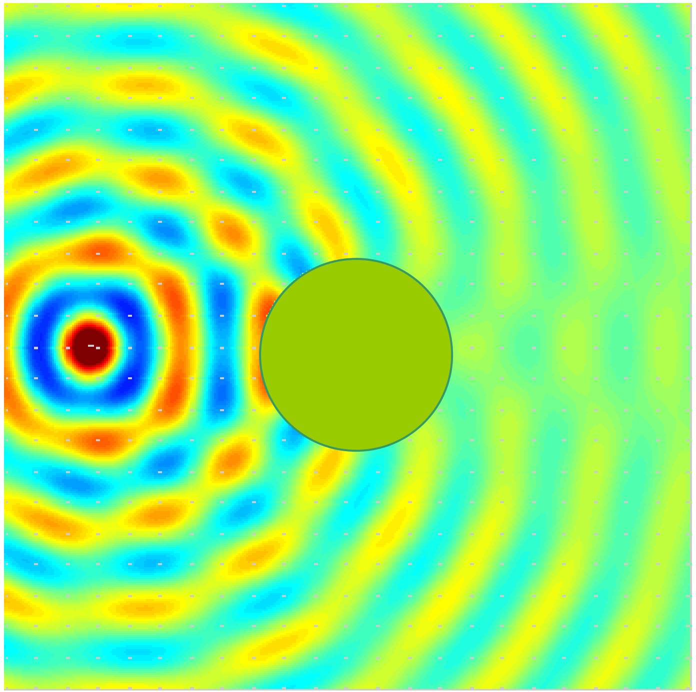


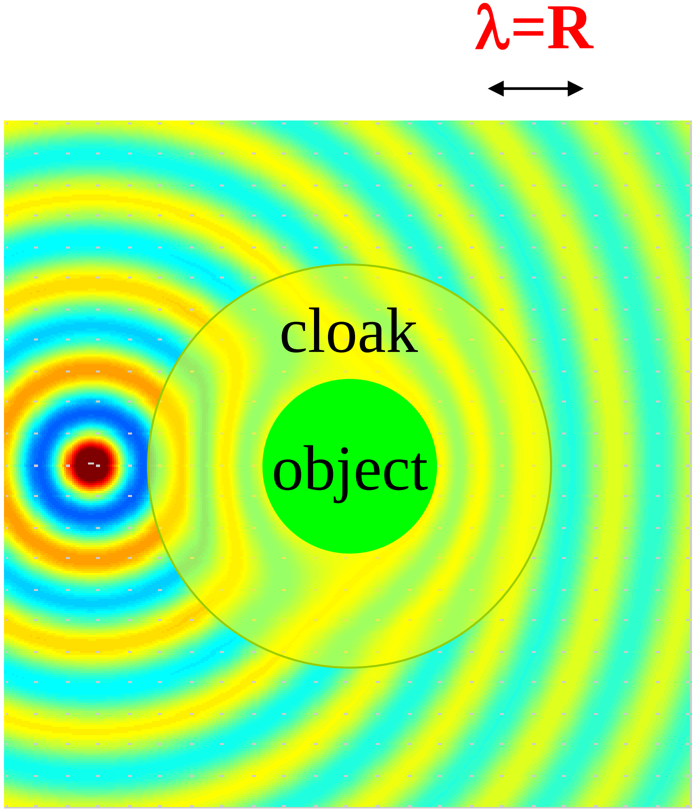


Appl. Phys. Lett. **99**, 074102 (2011)

Acoustic cloak

Punctual source interacting with a cylindrical object





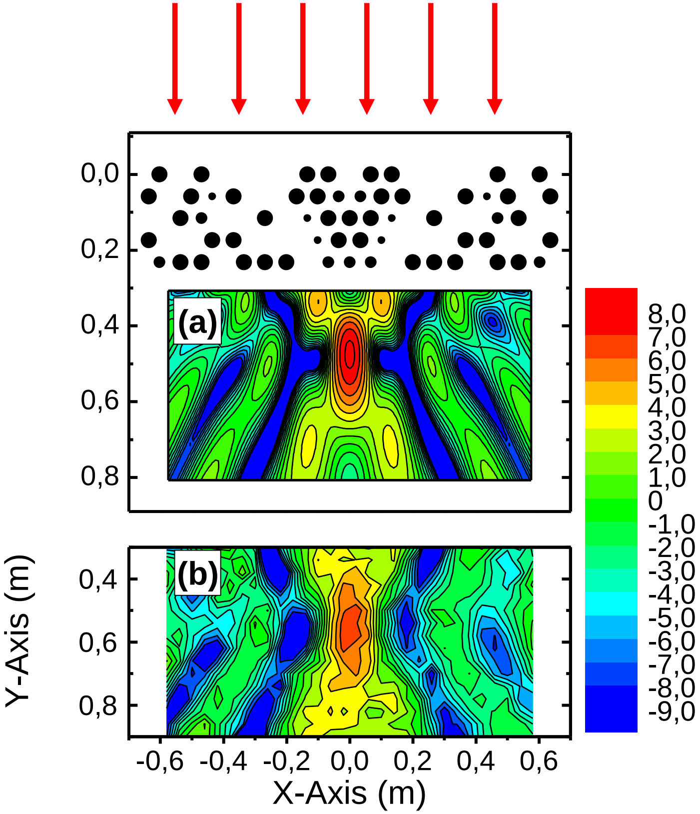
Inverse design of sonic lenses

Theory

Experiment

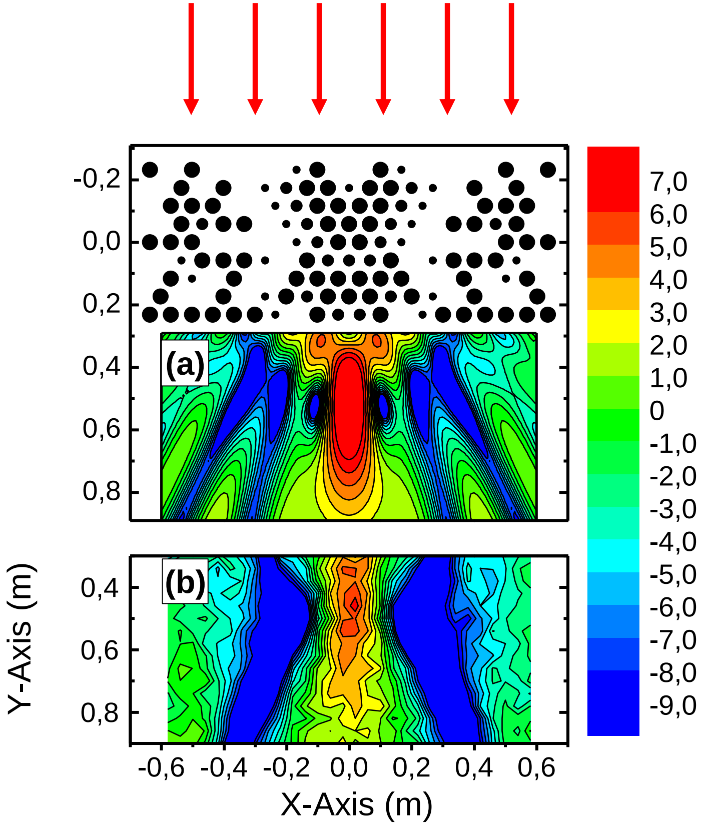
5 layers lens

(1700 Hz)



9 layers lens

(1700 Hz)



Phys. Rev. B **70**, 214302 (2004)

Appl. Phys. Lett. **86**, 054102 (2005)

Metamaterials with anisotropic effective mass density

Isotropic fluids:

$$\boxed{c^2 = B/\rho}$$

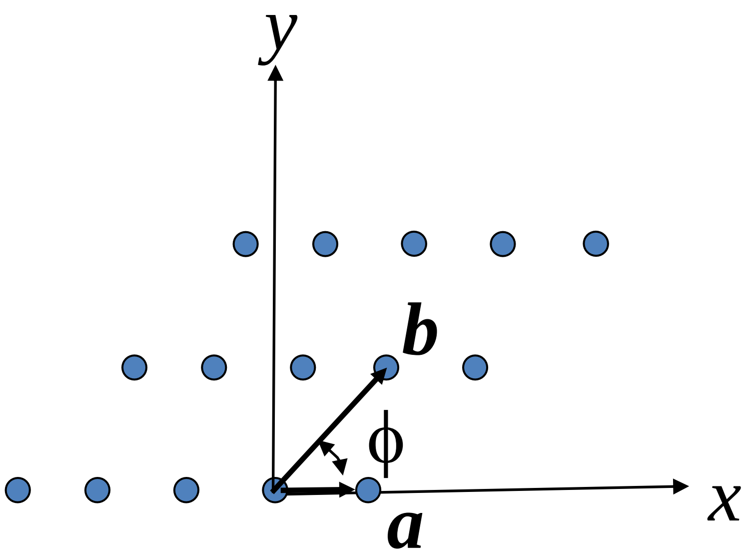
(Square and hexagonal lattices)

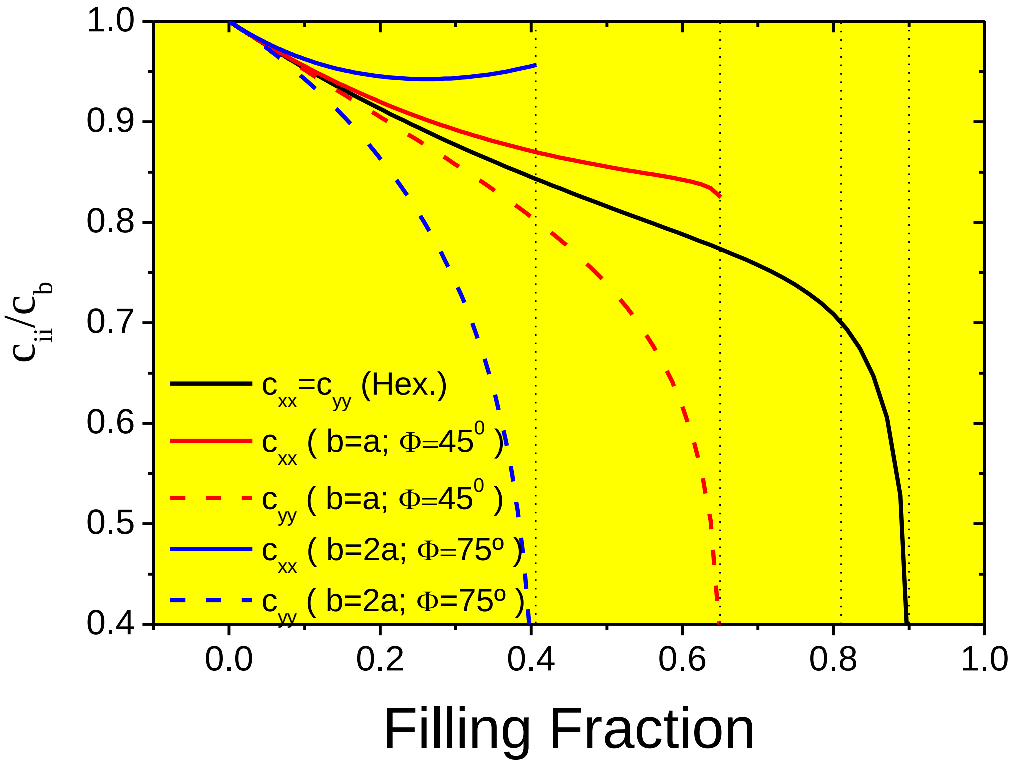
Anisotropic fluids:

$$\boxed{c_{ij}^2 = B\rho_{ij}^{-1}}$$

Components of the sound speed tensor
(Rigid cylinders)

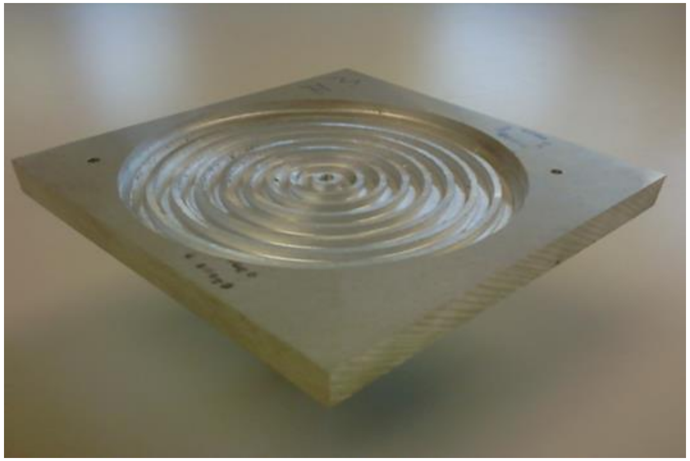
Non-isotropic lattices:





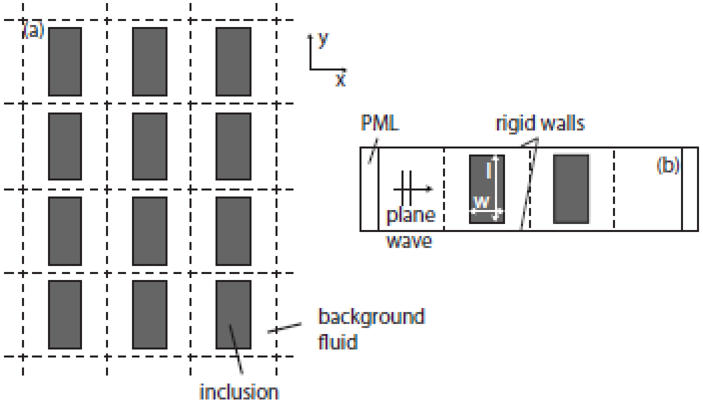
New J Phys **10**, 023004 (2008)

Anisotropic mass density tensor



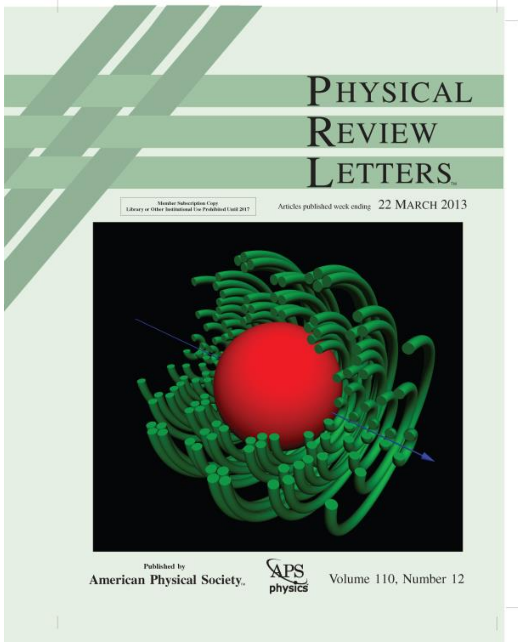
Phys. Rev. Lett., **105,** 174301 (2010)

Appl. Phys. Lett., **98**, 244102 (2011)



Cummer's group: PRB **108**, 174303 (2009); JAP**109,** 054906 (2011)

3D Cloak based on scattering cancellation



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APS physics

Volume 110, Number 12

Sanchis et al., PRL. **110**, 124301 (2013)

- **Parameters:**
  - 60 tori with minor radius 2.67mm
  - Sphere with radius R_{sph}= 4cm
  - Frequency of operation: f_0=8.62kHz ($R_{sph}= \lambda_0$)
- **Range of operation:**
  - Bandwidth: 120Hz
  - Angle of incidence: ±2.25º