Soft Acoustic Metamaterials

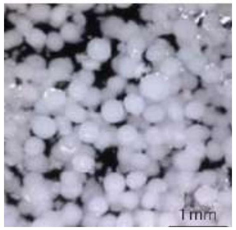
From locally resonant metafluids to soft gradient-index metasurfaces

Thomas Brunet
Institut de Mécanique et d'Ingénierie de Bordeaux

thomas.brunet@u-bordeaux.fr

Outline

- Context & motivations
  - Basis principles of metamaterials physics
- Locally resonant metafluids
  - Multi-resonant acoustic suspensions
  - Experimental demonstration of negative index



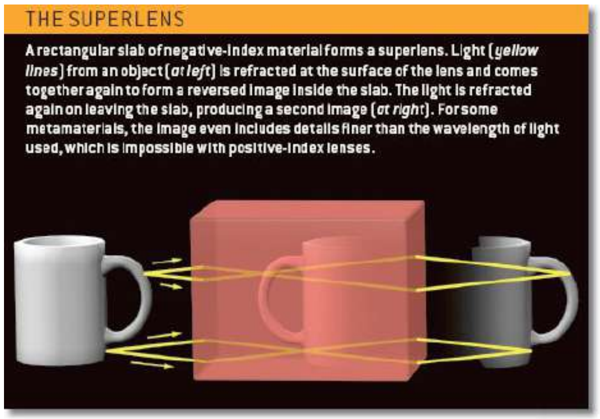
- Soft gradient-index metasurfaces
  - Soft porous silicone rubber lenses
  - Experimental demonstration of wavefront shaping

- Conclusion & perspectives
  - Soft acoustic metamaterials
  - Towards soft reconfigurable flat ultrasonic lenses

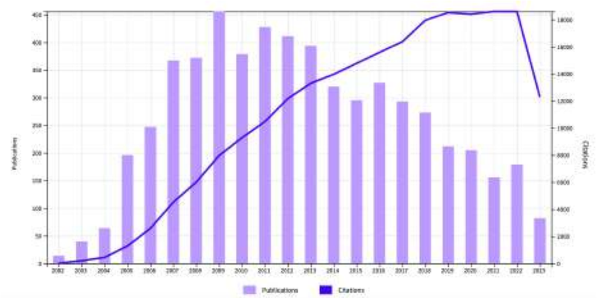
Context and motivations

- *Metamaterials* = artificial materials engineered to *control* wave propagation

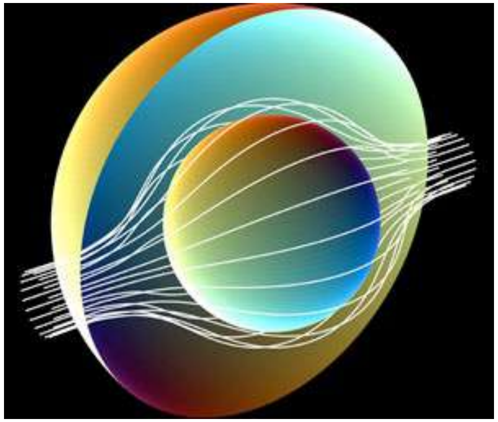
negative-index materials



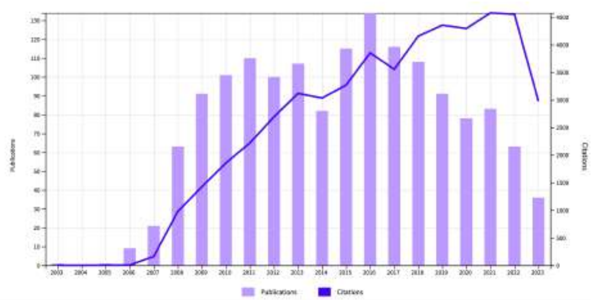
www.nature.com/scientificamerican/journal/…



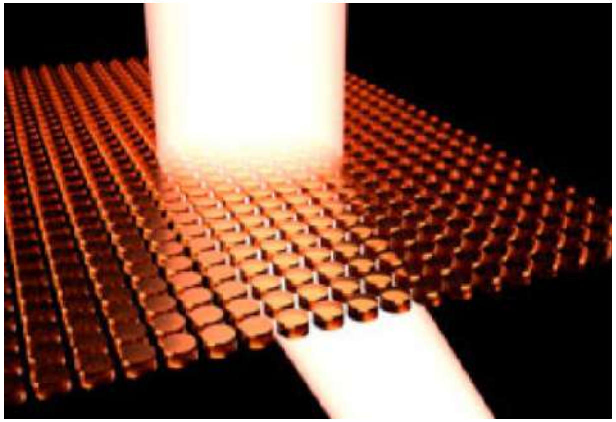
invisibility cloaks



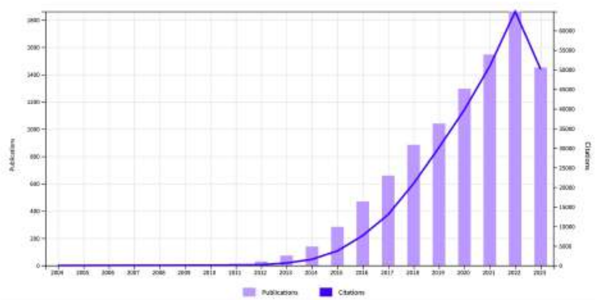
https://www.discoverymagazine.com/



metasurfaces



https://www.sciencedaily.com/



Context and motivations

- Double negativity, negative index and negative refraction

Double negativity concept

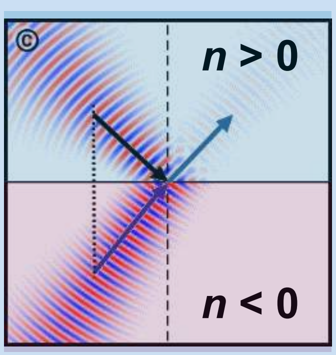
THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

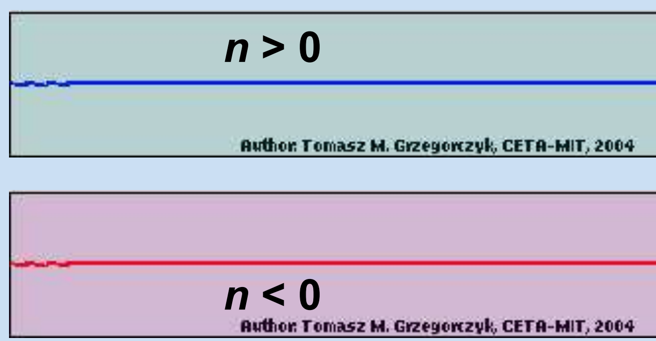
V. G. VESELAGO

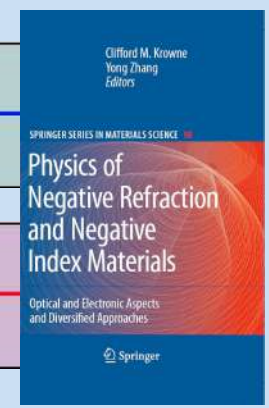
P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

Negative index and negative refraction



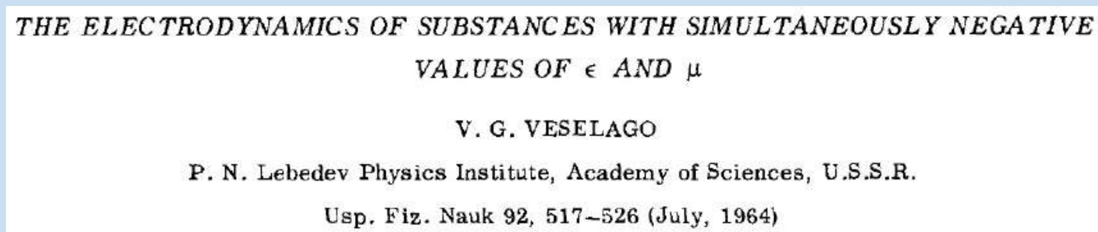




Context and motivations

- Double negativity, negative index and double negative refraction

Double negativity concept



THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ *AND* μ

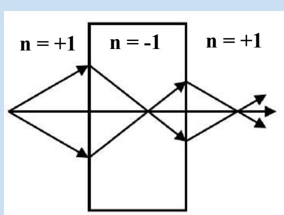
V. G. VESELAGO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

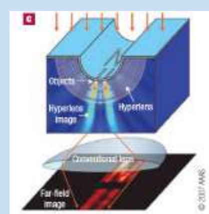
Negative index for high resolution imaging

Perfect lens



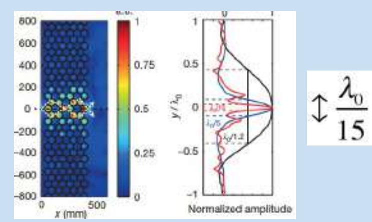
J. Pendry
Phys. Rev. Lett. **85**, 3966 (2000)

Optical superlens



N. Fang *et al.*
Science. **308**, 534 (2005)

Acoustic superlens

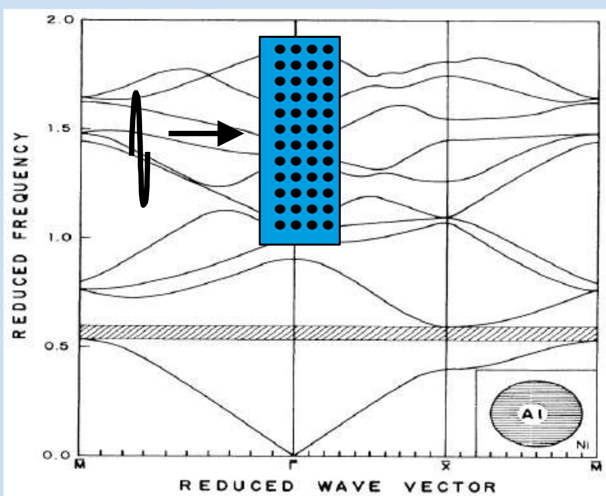


N. Kaina *et al.*
Nature **525**, 77 (2015)

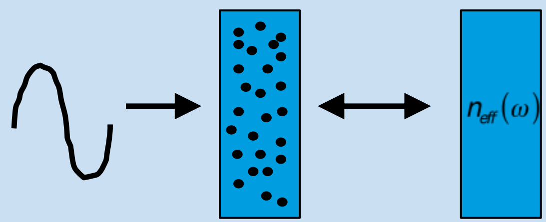
Context and motivations

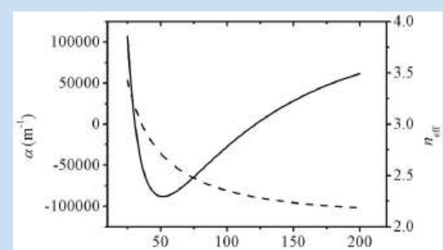
- "Ordered" phononic structures VS "disordered" resonant materials

Crystals (periodic structure)	**Metamaterials (random media)**
• λ ~ a (lattice constant) • negative group velocity comes from band folding, can get negative refraction • Bragg scattering • band structure description	• λ >> a • double negative constitutive parameters implies negative refraction • **local resonances scattering** • effective medium description



Kushwaha *et al.*, *Phys. Rev. Lett.* **71**, 2022 (1993)

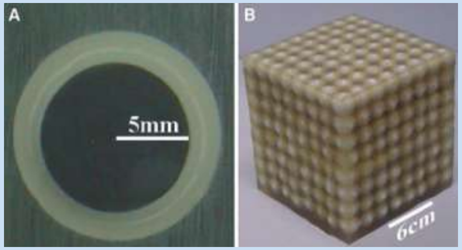




Liang *et al.*, *Sci. Rep.* **4**, 5015 (2014)

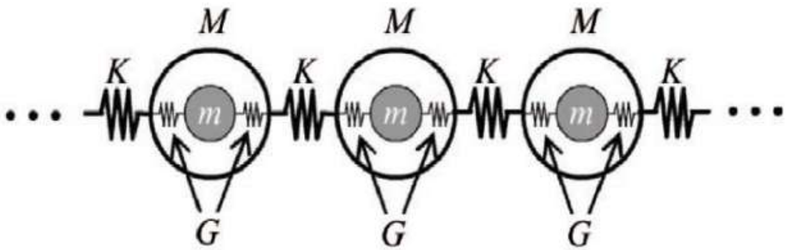
Locally resonant metamaterials

- Effective medium description and local resonances (ω)

Electromagnetic Metamaterials	**Acoustic Metamaterials**
effective permeability μ_{eff} ↓ $n_{\text{eff}}(\omega) = \pm\sqrt{\varepsilon_{\text{eff}}(\omega)\mu_{\text{eff}}(\omega)}$ ↑ effective permittivity ε_{eff}	effective mass density ρ_{eff} ↓ $n_{\text{eff}}(\omega) \equiv \pm\sqrt{\kappa_{\text{eff}}^{-1}(\omega)\rho_{\text{eff}}(\omega)}$ ↑ effective bulk modulus κ_{eff}
 Shelby *et al.*, *Science* **292**, 77 (2001)	 Liu *et al.*, *Science* **289**, 1734 (2000)

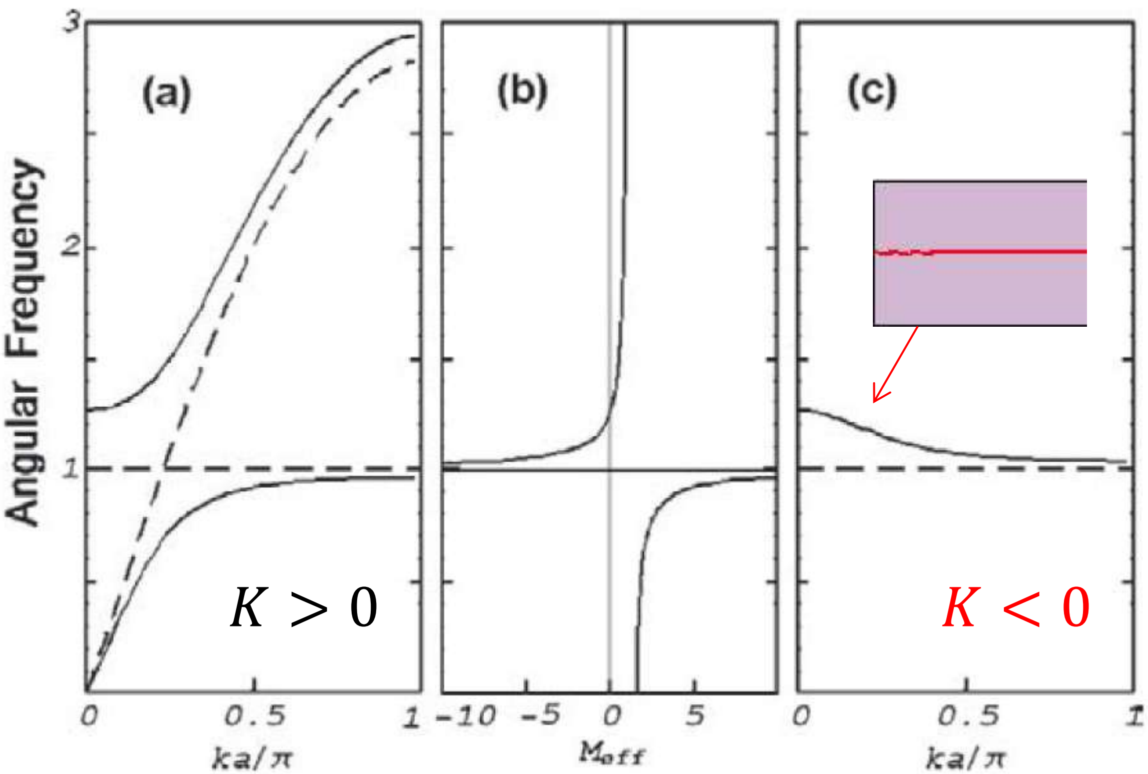
Li, Fung, Liu, Sheng and Chan (2007)
"Generalizing the concept of negative medium to acoustic waves"

Locally resonant metamaterials

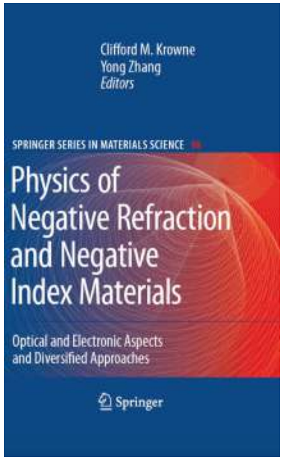


$$\omega^2\left(M+\frac{m\omega_0^2}{\omega_0^2-\omega^2}\right)=4K\sin^2\left(\frac{ka}{2}\right)$$

with $\omega_0=\sqrt{2G/m}$



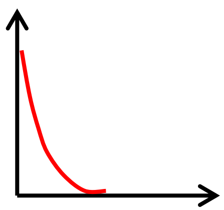
$$M_{\text{eff}}=M+\frac{m\omega_0^2}{\omega_0^2-\omega^2}$$



Acoustic metamaterials

ρ_{eff}

evanescent waves



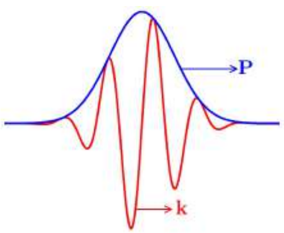
single negativity

$$n_{\text{eff}} \equiv \mathrm{i}\sqrt{\frac{\rho_{\text{eff}}}{|\kappa_{\text{eff}}|}}$$

double positivity

$$n_{\text{eff}} \equiv \sqrt{\frac{\rho_{\text{eff}}}{\kappa_{\text{eff}}}} > 0$$

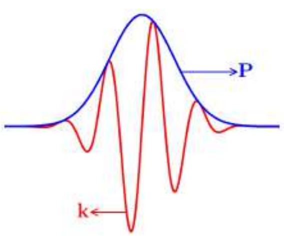
propagating (forward) waves



0

κ_{eff}

propagating (backward) waves



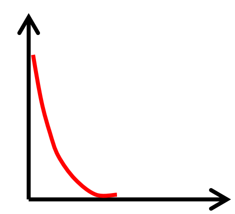
$$n_{\text{eff}} \equiv -\sqrt{\frac{\rho_{\text{eff}}}{\kappa_{\text{eff}}}} < 0$$

double negativity

$$n_{\text{eff}} \equiv \mathrm{i}\sqrt{\frac{|\rho_{\text{eff}}|}{\kappa_{\text{eff}}}}$$

single negativity

evanescent waves

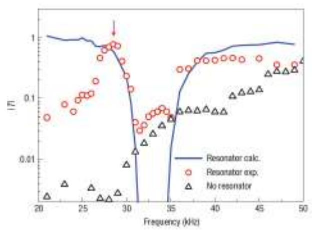


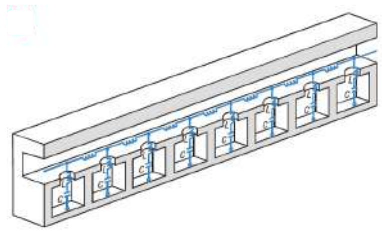
Kadic *et al., Rep. Prog. Phys.* **76**, 126501 (2013)

Mechanical 1D-2D locally resonant structures

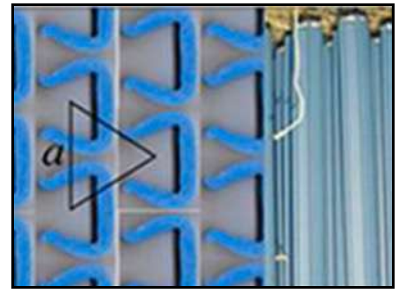
ρ_{eff}

evanescent waves



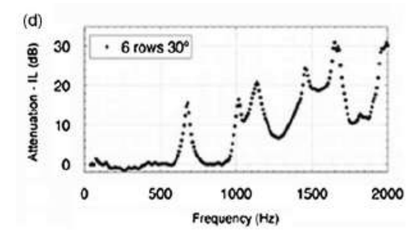


Fang *et al.*
Nat. Mater. **5**, 452 (2006)



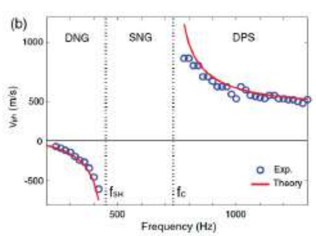
Romero-Garcia *et al.*
J. Sound Vibr. **332**, 184 (2013)

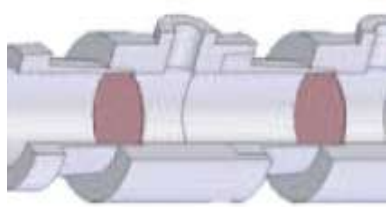
propagating (forward) waves



0 κ_{eff}

propagating (backward) waves

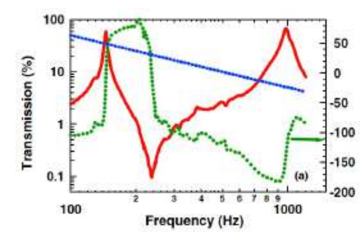




Lee *et al.*
Phys. Rev. Lett. **104**, 05301 (2010)

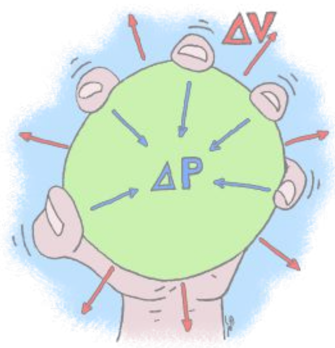
Yang *et al.*
Phys. Rev. Lett. **96**, 041906 (2008)

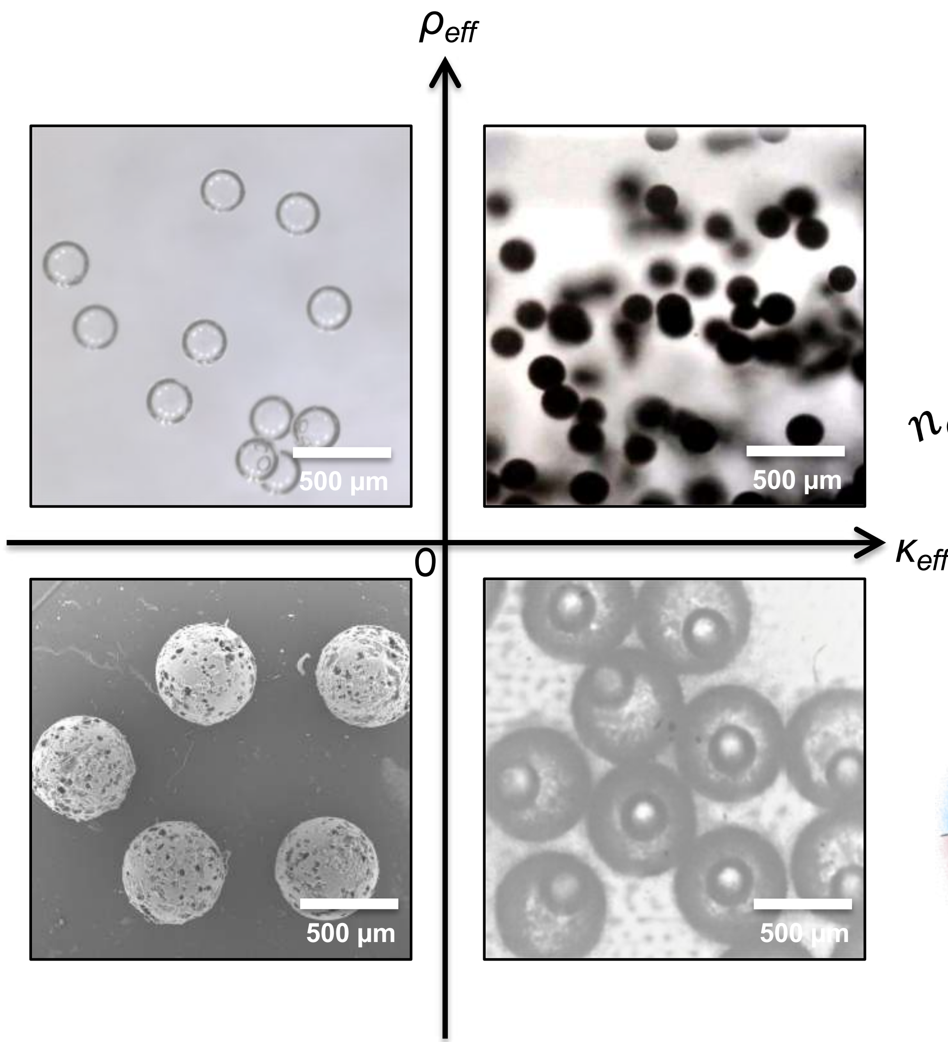
evanescent waves



Kadic *et al.*, *Rep. Prog. Phys.* **76**, 126501 (2013)

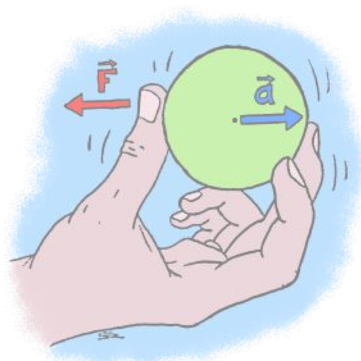
Locally resonant metafluids





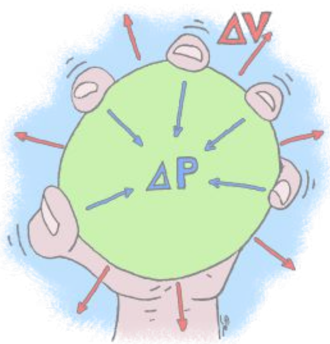
$n_{droplets} = 3\times n_{water}$

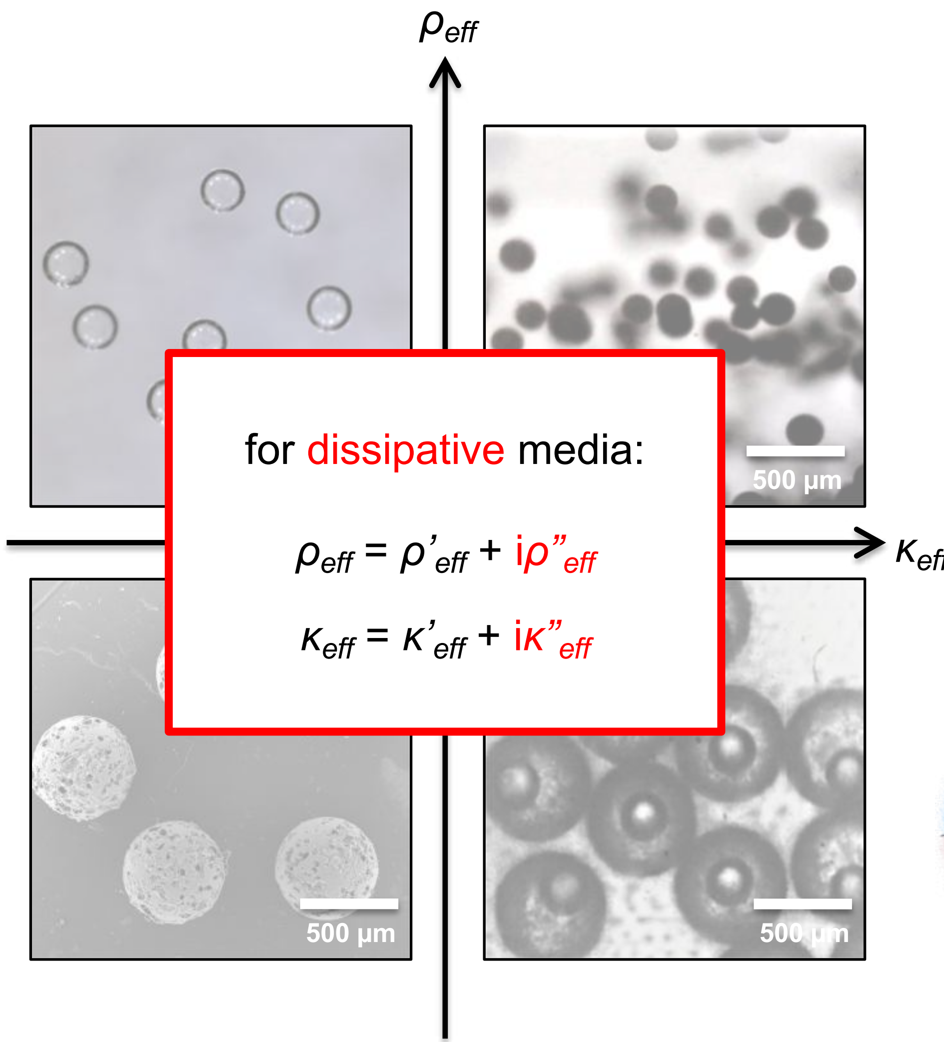
$n_{beads} = 40\times n_{water}$!!

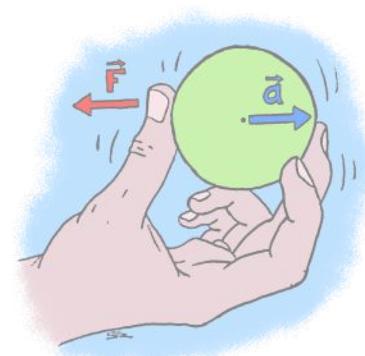


Brunet, Leng and Mondain-Monval, *Science* **342**, 323 (2013)

Locally resonant metafluids

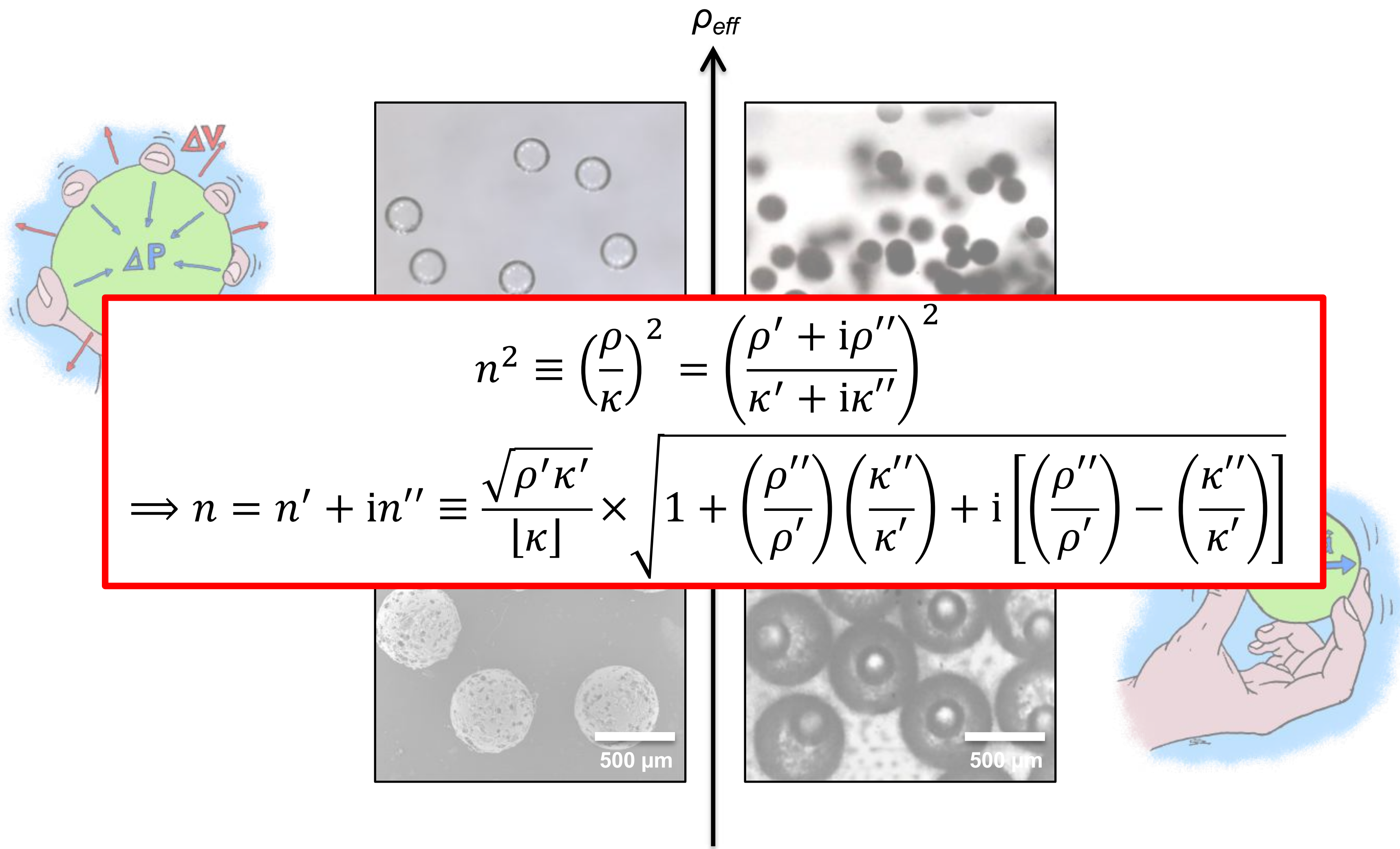






Brunet, Leng and Mondain-Monval, *Science* **342**, 323 (2013)

Locally resonant metafluids

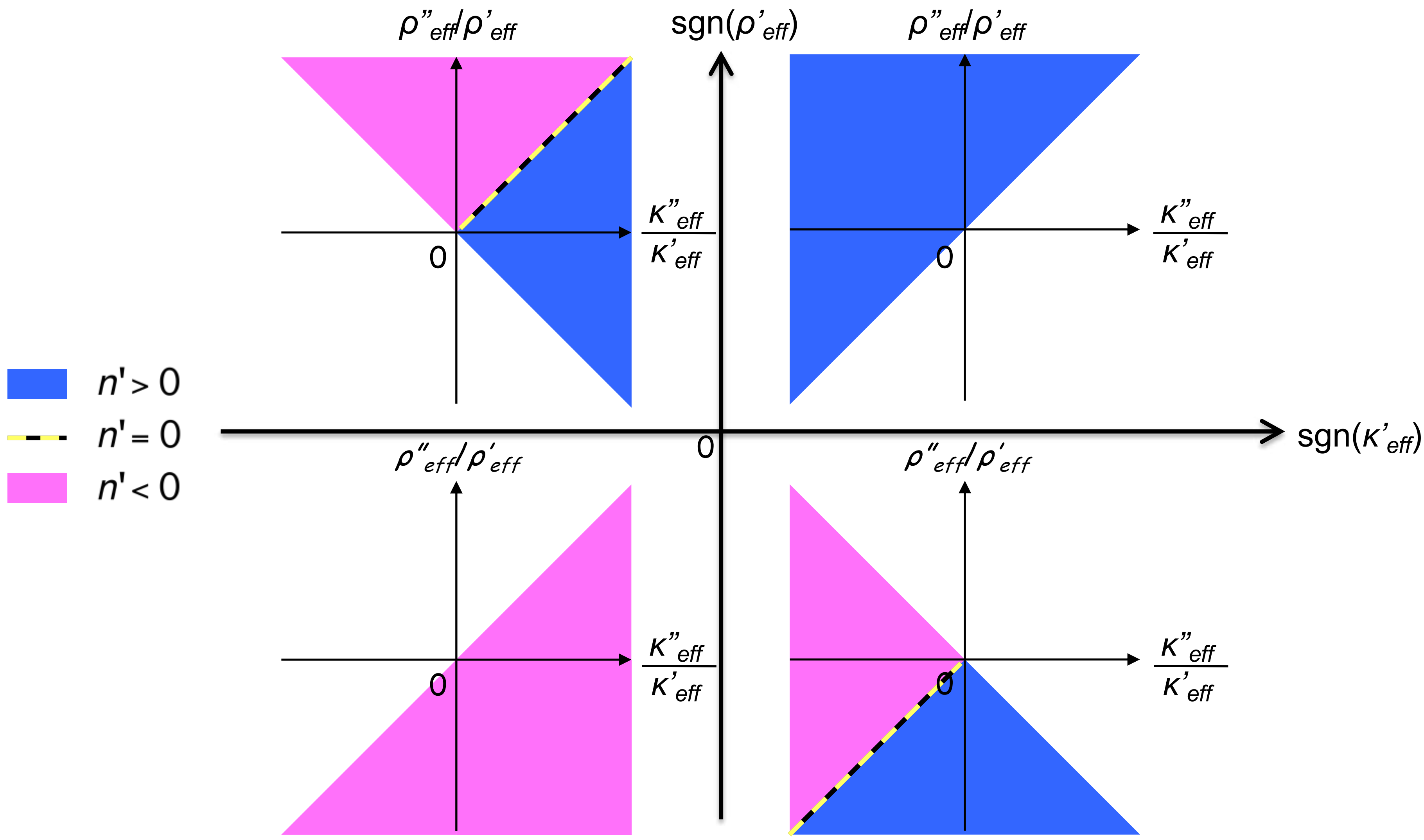


$$n^2 \equiv \left(\frac{\rho}{\kappa}\right)^2 = \left(\frac{\rho' + \mathrm{i}\rho''}{\kappa' + \mathrm{i}\kappa''}\right)^2$$

$$\Longrightarrow n = n' + \mathrm{i}n'' \equiv \frac{\sqrt{\rho'\kappa'}}{|\kappa|} \times \sqrt{1 + \left(\frac{\rho''}{\rho'}\right)\left(\frac{\kappa''}{\kappa'}\right) + \mathrm{i}\left[\left(\frac{\rho''}{\rho'}\right) - \left(\frac{\kappa''}{\kappa'}\right)\right]}$$

Brunet, Leng and Mondain-Monval, *Science* **342**, 323 (2013)

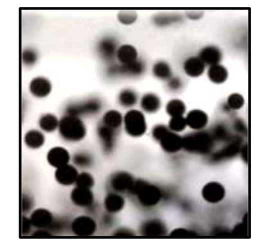
Acoustic metamaterials



Brunet *et al., EPJ Appl. Metamat.* **2**, 3 (2015)

Outline

- Context & motivations
  - Basis principles of metamaterials physics
- Locally resonant metafluids
  - Multi-resonant acoustic suspensions
  - Experimental demonstration of negative index



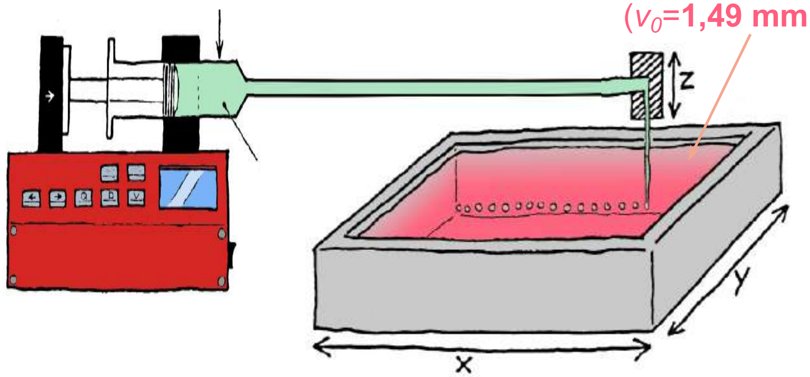
- Soft gradient-index metasurfaces
  - Soft porous silicone rubber lenses
  - Experimental demonstration of wavefront shaping

- Conclusion & perspectives
  - Soft acoustic metamaterials
  - Towards soft reconfigurable flat ultrasonic lenses

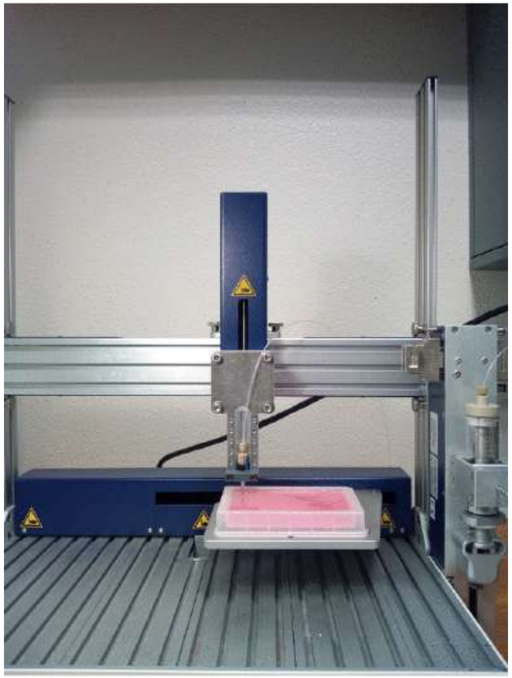
Multi-resonant acoustic suspensions

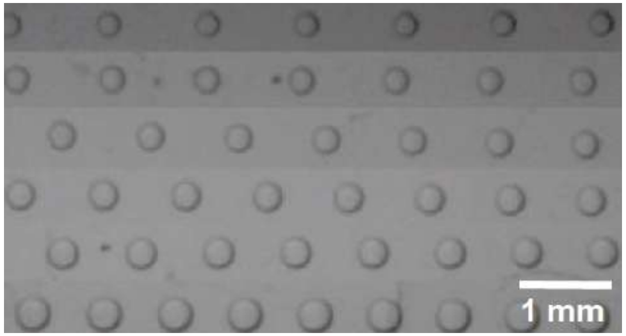
Fluorinated oil FC40®
(v_1=**0,64 mm.µs^{-1}** & ρ_1=1,855)

water-based yield-stress gel
(v_0=**1,49 mm.µs^{-1}** & ρ_0=1,005)

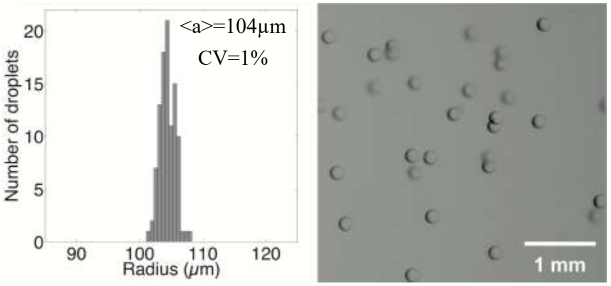


Leroy *et al.*, J. *Acoust. Soc. Am.* **123**,1931 (2008)



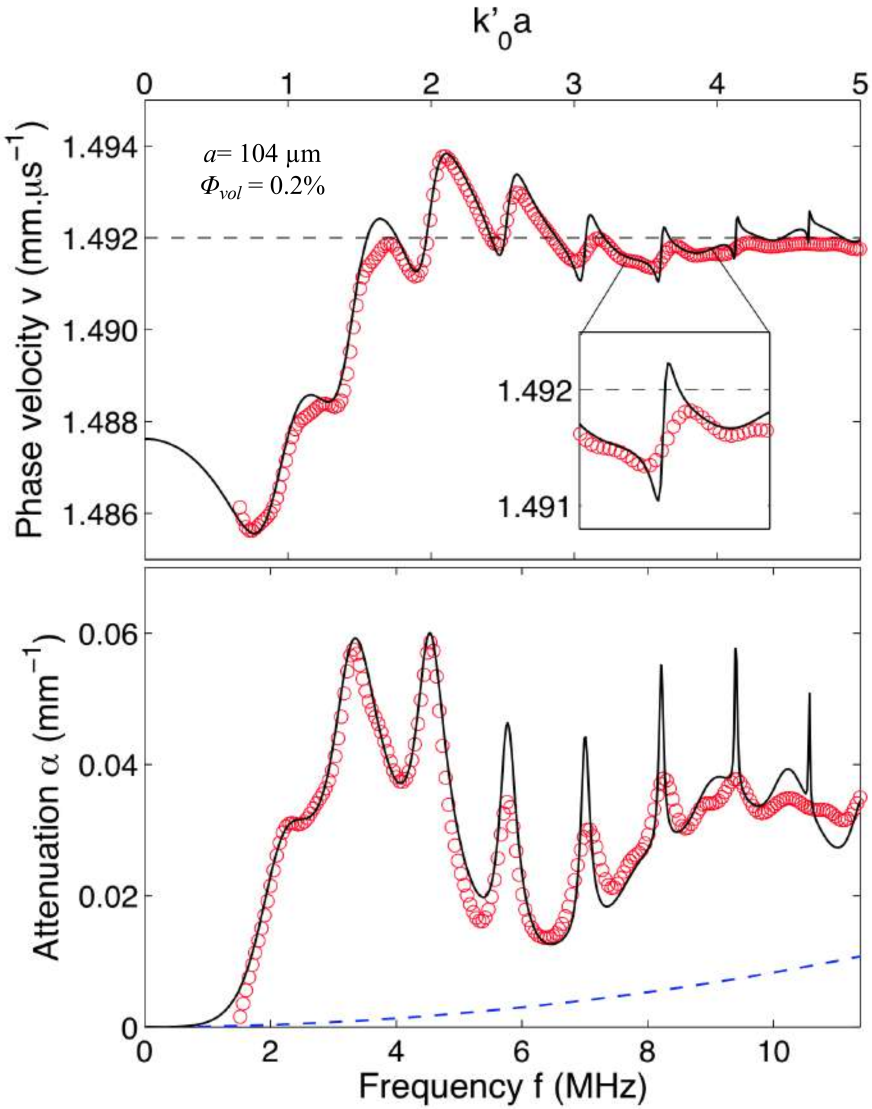


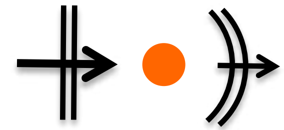
mixing



Brunet *et al., Appl. Phys. Lett.* **101**, 011913 (2012)

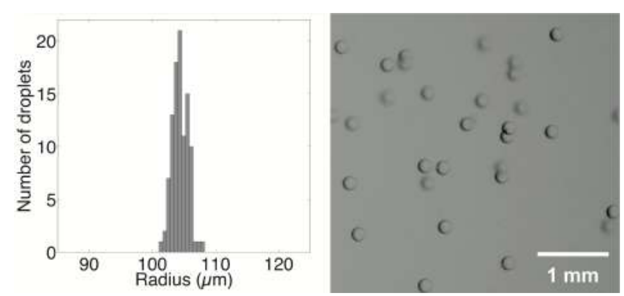
Multi-resonant acoustic suspensions





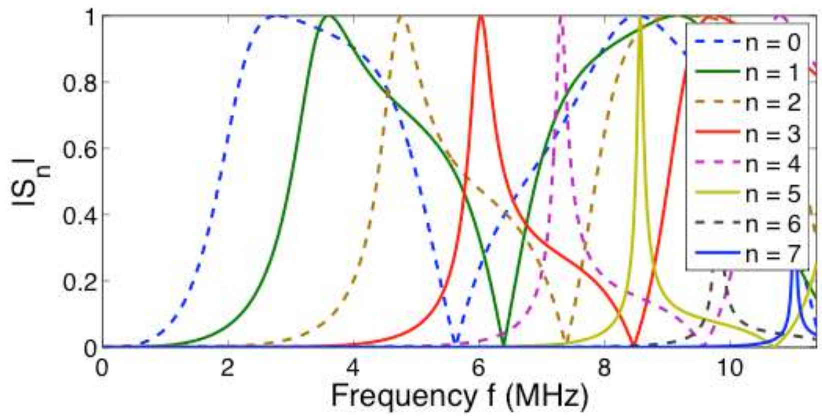
Lax
Rev. Mod. Phys. **23**, 287 (1951)

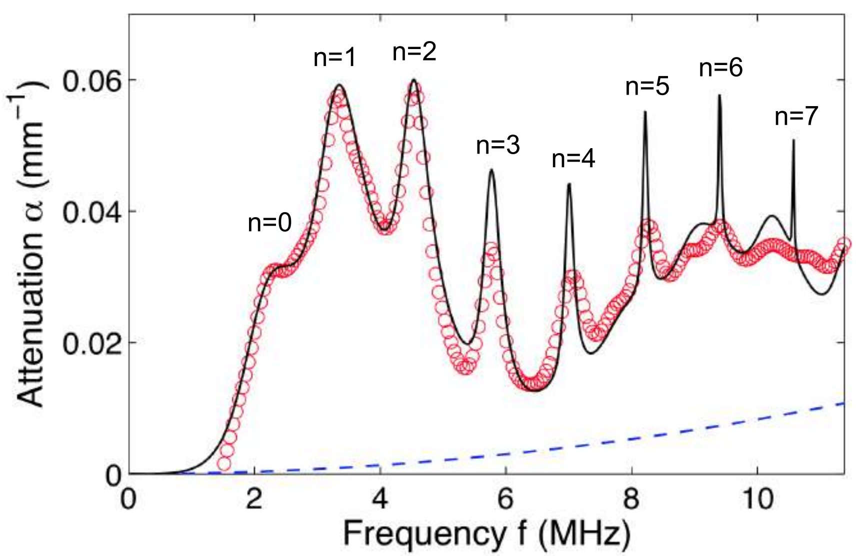
$$\begin{cases} k^2 = \left(\dfrac{\omega}{v} + \mathrm{i}\alpha\right)^2 = k_0^2 + 4\pi\eta f_\mathrm{a}(0) \\ \text{with } f_\mathrm{a}(0) = \dfrac{1}{ik_0}\displaystyle\sum_{n=0}^{\infty}(2n+1)S_n(k_0 a) \\ \text{and } \phi_{vol} = \dfrac{4}{3}\pi a^3 \eta \end{cases}$$

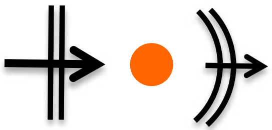


Brunet *et al., Appl. Phys. Lett.* **101**, 011913 (2012)

Multi-resonant acoustic suspensions

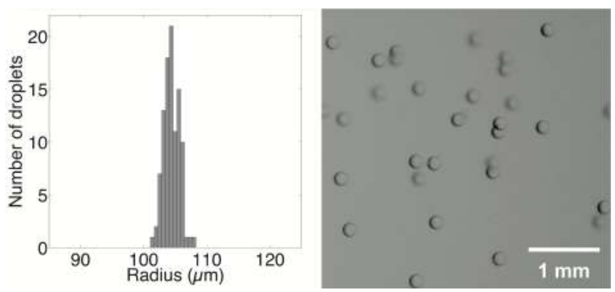






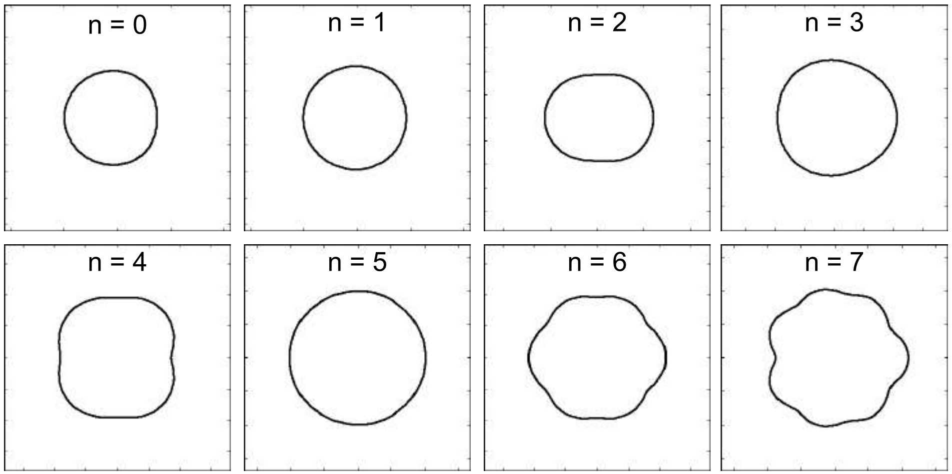
Lax
Rev. Mod. Phys. **23**, 287 (1951)

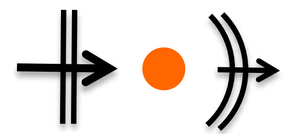
$$\begin{cases} k^2 = \left(\frac{\omega}{v} + \mathrm{i}\alpha\right)^2 = k_0^2 + 4\pi\eta f_\mathrm{a}(0) \\ \text{with } f_\mathrm{a}(0) = \frac{1}{ik_0}\sum_{n=0}^{\infty}(2n+1)S_n(k_0 a) \\ \text{and } \phi_{vol} = \frac{4}{3}\pi a^3 \eta \end{cases}$$



Brunet *et al., Appl. Phys. Lett.* **101**, 011913 (2012)

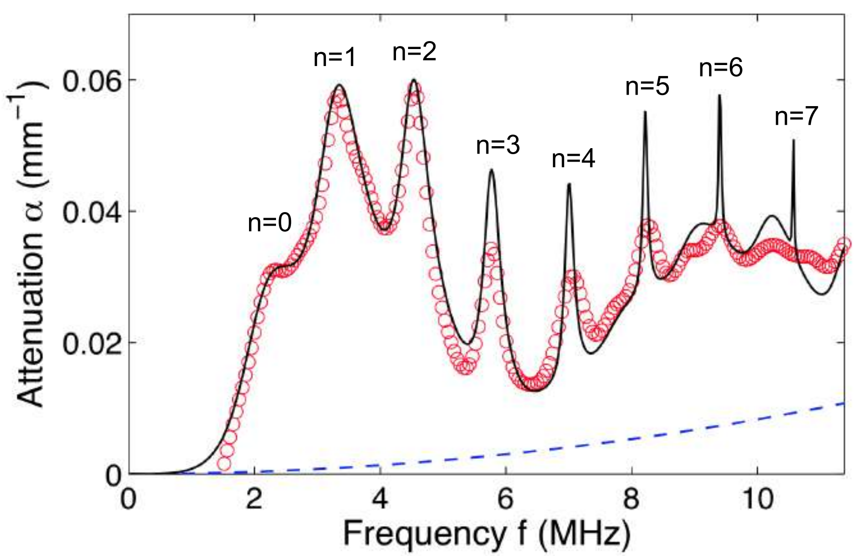
Multi-resonant acoustic suspensions

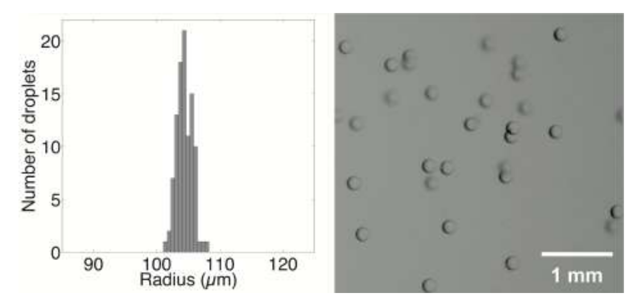




Lax
Rev. Mod. Phys. **23**, 287 (1951)

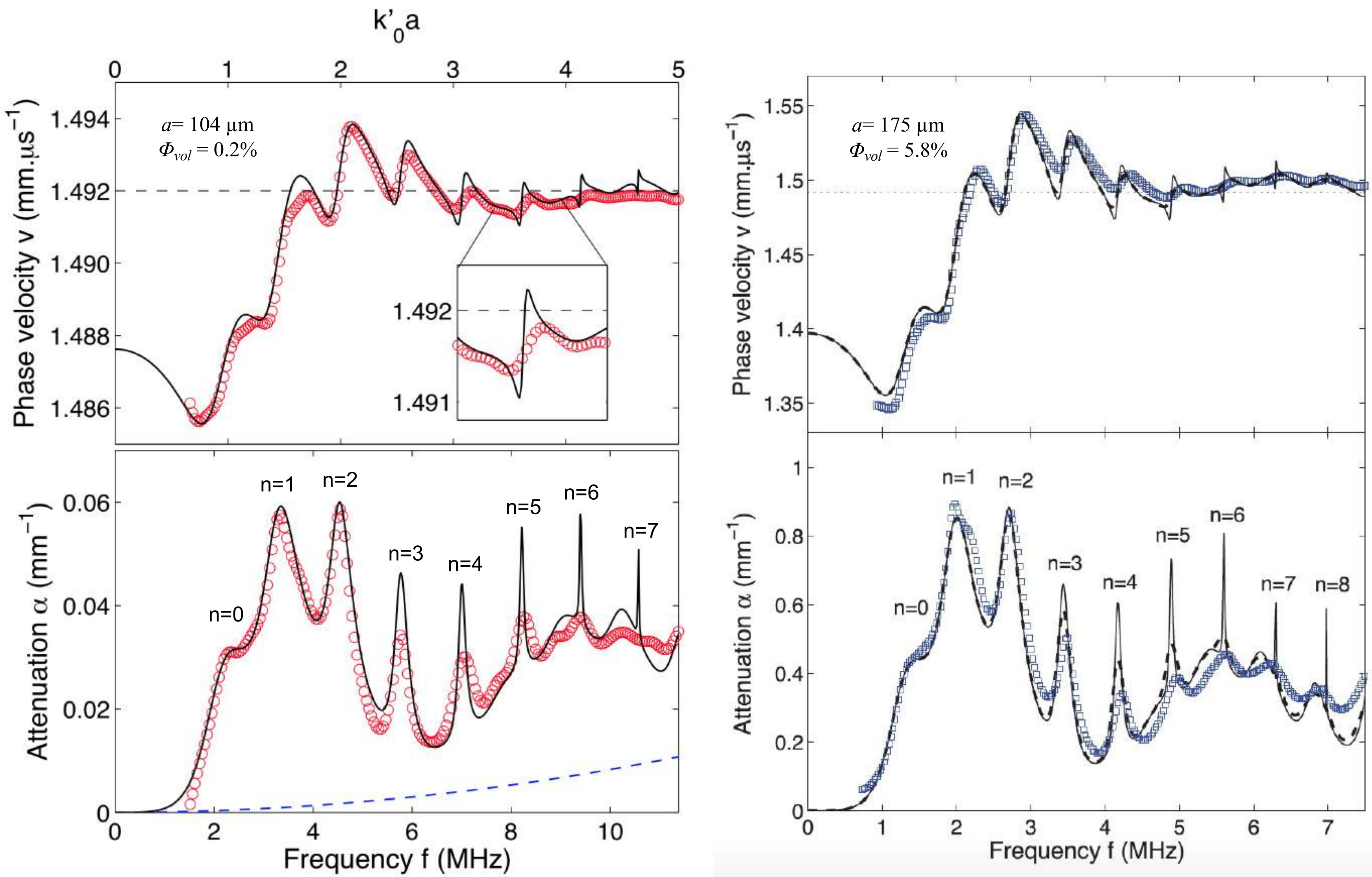
$$\begin{cases} k^2 = \left(\frac{\omega}{v} + \mathrm{i}\alpha\right)^2 = k_0^2 + 4\pi\eta f_a(0) \\ \text{with } f_a(0) = \frac{1}{ik_0}\sum_{n=0}^{\infty}(2n+1)S_n(k_0 a) \\ \text{and } \phi_{vol} = \frac{4}{3}\pi a^3\eta \end{cases}$$



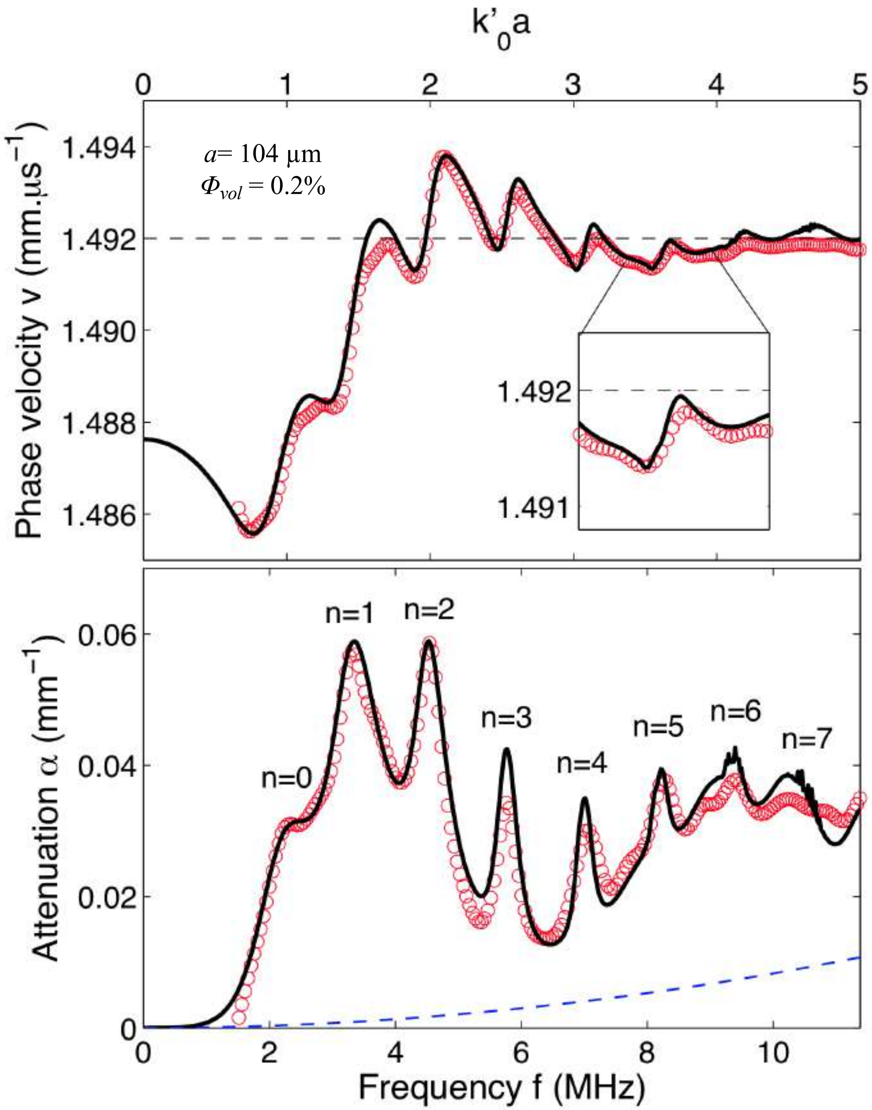


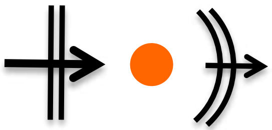
Brunet *et al.*, *Appl. Phys. Lett.* **101**, 011913 (2012)

Impact of droplet size on Mie-type resonances



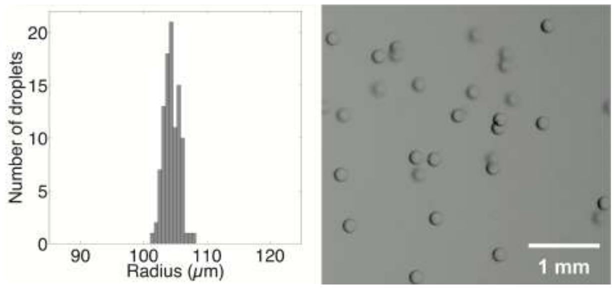
Impact of size dispersion on Mie-type resonances





Lax
Rev. Mod. Phys. **23**, 287 (1951)

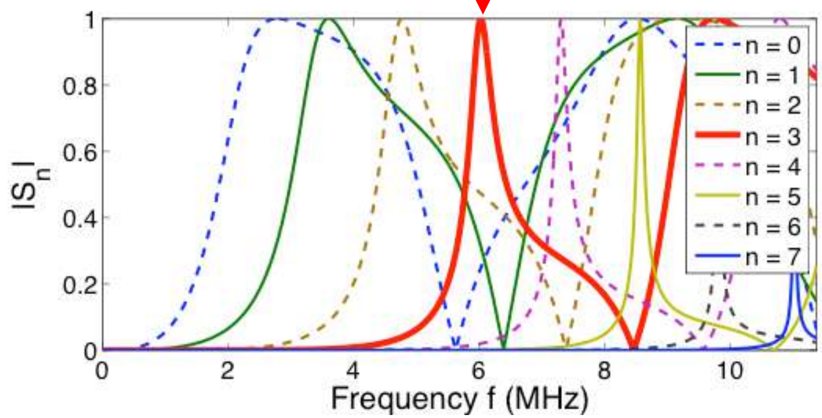
$$\begin{cases} k^2 = \left(\dfrac{\omega}{v} + \mathrm{i}\alpha\right)^2 = k_0^2 + \displaystyle\int_a 4\pi\eta(a) f_{\mathrm{a}}(0)\mathrm{d}a \\ \text{with } f_{\mathrm{a}}(0) = \dfrac{1}{ik_0}\displaystyle\sum_{n=0}^{\infty}(2n+1)S_n(k_0 a) \\ \text{and } \phi_{vol} = \displaystyle\int_a \dfrac{4}{3}\pi a^3 \eta(a)\mathrm{d}a \end{cases}$$

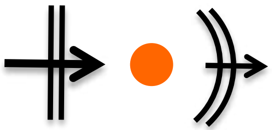


Brunet *et al., Appl. Phys. Lett.* **101**, 011913 (2012)

Impact of size dispersion on Mie-type resonances

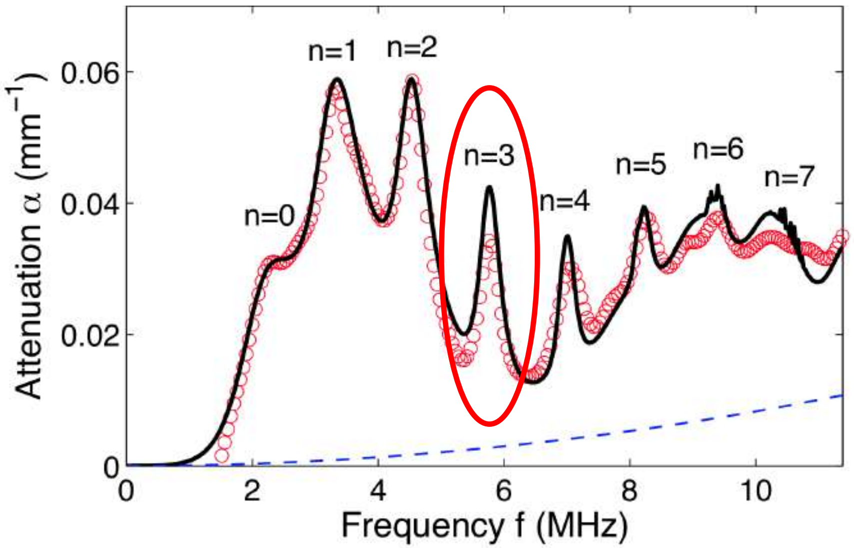
$Q_{res}(n=3) = f_{res}/\Delta f_{res} \approx 10$

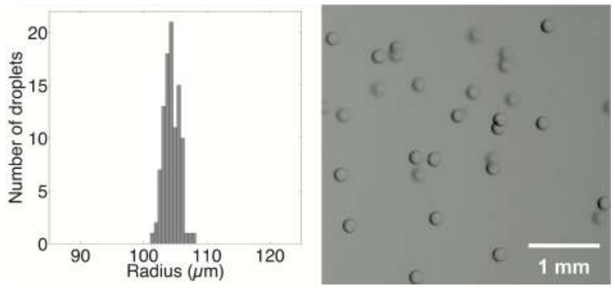




Lax
Rev. Mod. Phys. **23**, 287 (1951)

$$\begin{cases} k^2 = \left(\frac{\omega}{v} + \mathrm{i}\alpha\right)^2 = k_0^2 + \int_a 4\pi\eta(a) f_{\mathrm{a}}(0)\mathrm{d}a \\ \text{with } f_{\mathrm{a}}(0) = \frac{1}{ik_0}\sum_{n=0}^{\infty}(2n+1)S_n(k_0 a) \\ \text{and } \phi_{vol} = \int_a \frac{4}{3}\pi a^3 \eta(a)\mathrm{d}a \end{cases}$$





Brunet *et al., Appl. Phys. Lett.* **101**, 011913 (2012)

Impact of size dispersion on Mie-type resonances

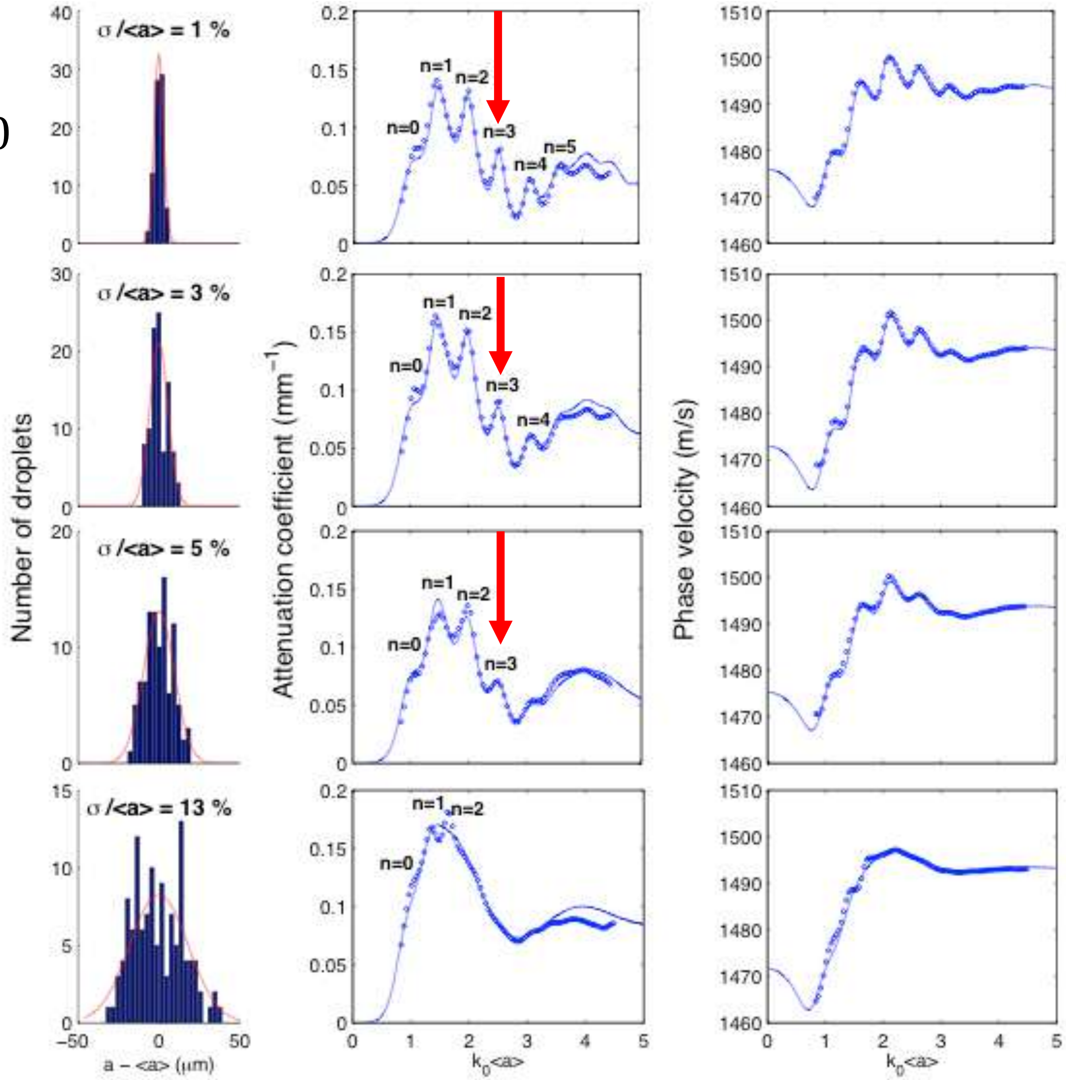
$Q_{\text{res}}(n=3) = f_{\text{res}}/\Delta f_{\text{res}} \approx 10$

$Q_{\text{PSD}} \approx 100$

$Q_{\text{PSD}} \approx 33$

$Q_{\text{PSD}} \approx 20$

$Q_{\text{PSD}} \approx 7$



Criterion on the PSD
for the emergence
of acoustic resonances

$$\frac{<a>}{\sigma} = Q_{\text{PSD}} > Q_{\text{res}} = \frac{f_{\text{res}}}{\Delta f_{\text{res}}}$$

Mascaro *et al.*
J. Acoust. Soc. Am. **133**, 1996 (2013)

Impact of droplet shape on Mie-type resonances

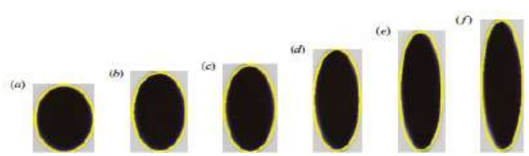
droplet under shear

Taylor, *Proc. Roy Soc. A* **146**, 501 (1934)

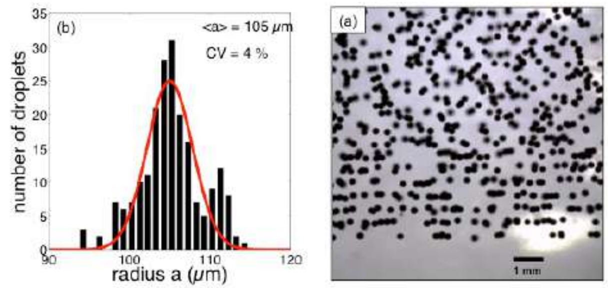
droplet under an electric field

Vizika *et al.*, *J. Fluid Mech.* **239**, 1 (1992)

droplet under a magnetic field

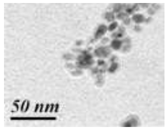


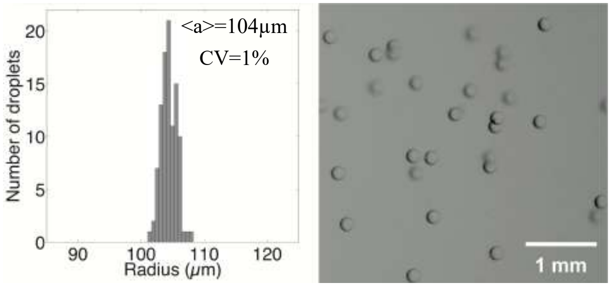
Afkhami *et al.*, *J. Fluid Mech.* **663**, 3 (2010)



Brunet *et al.*, *Phys. Rev. Lett.* **111**, 264301 (2013)

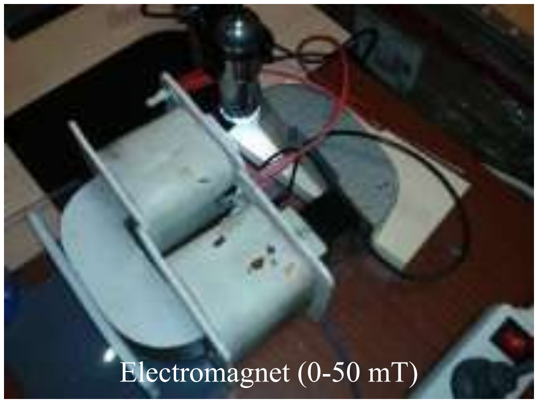
+ superparamagnetic γ-Fe_2O_3 nanoparticles



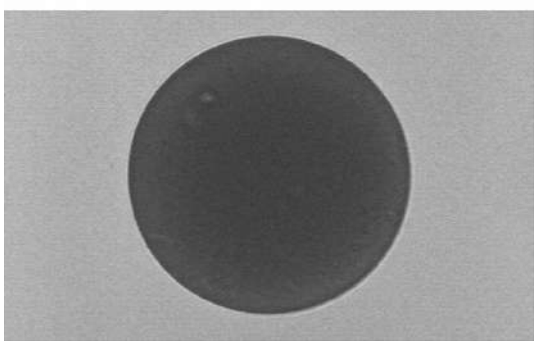


Brunet *et al.*, *Appl. Phys. Lett.* **101**, 011913 (2012)

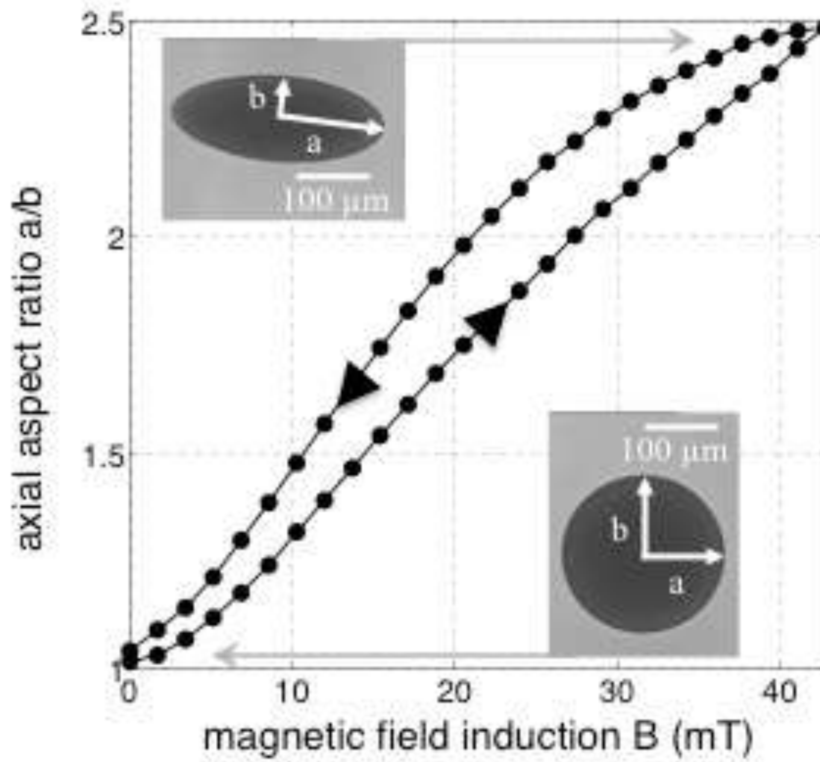
Impact of droplet shape on Mie-type resonances

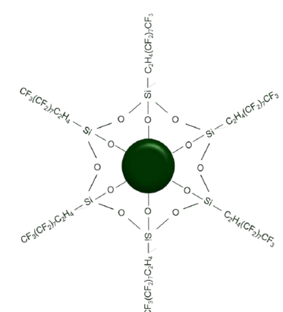


B = 0 G

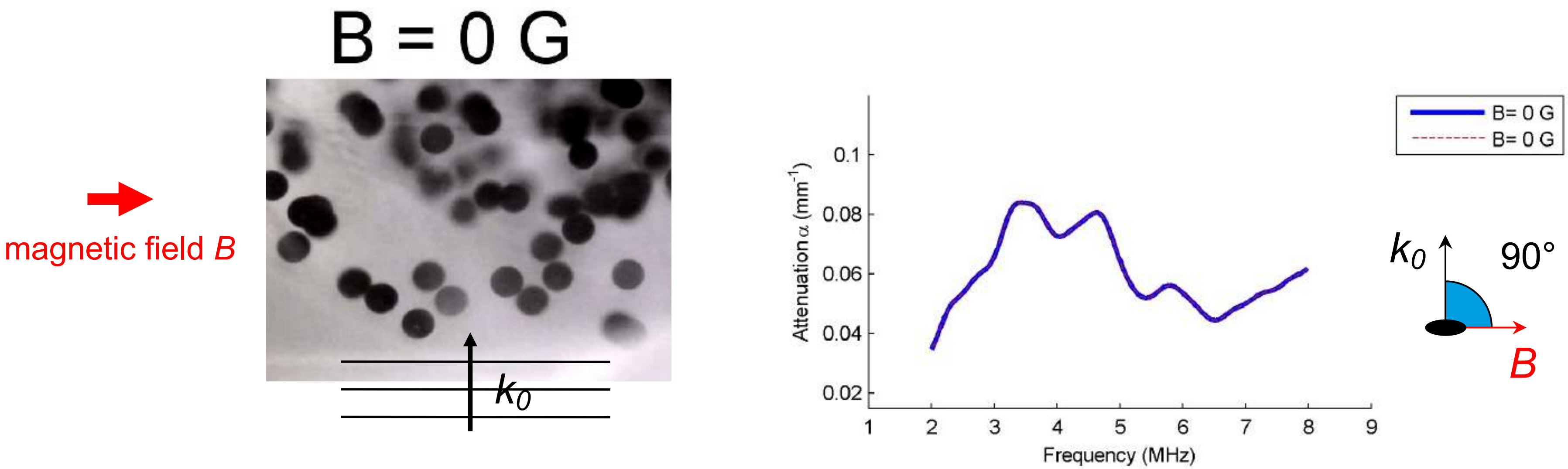


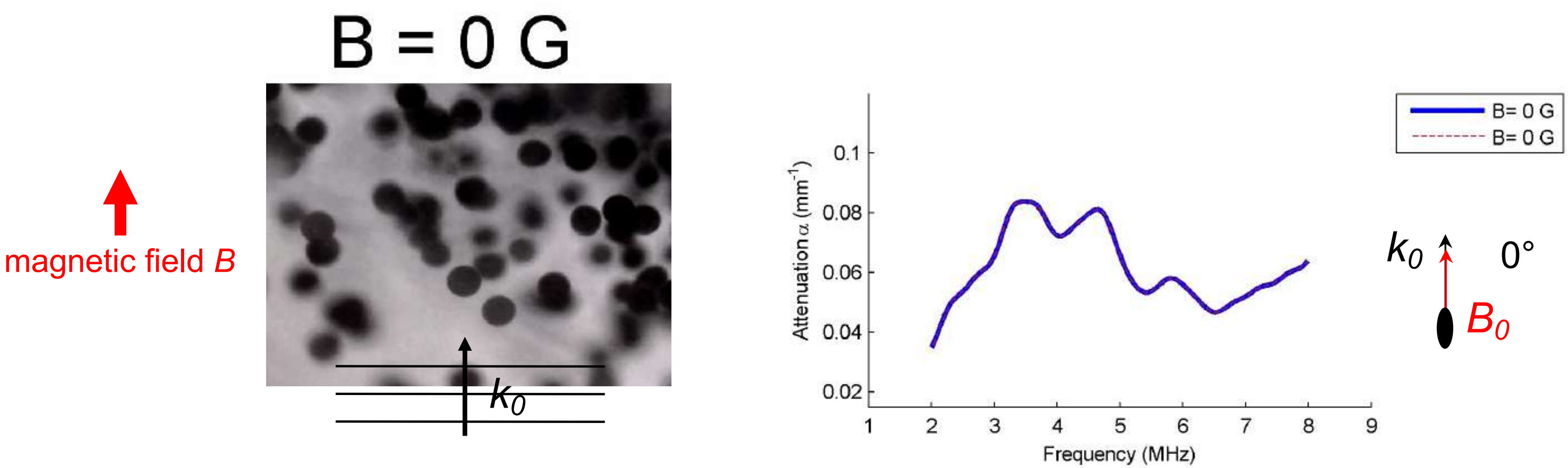
single fluorinated ferrofluid droplet
under an external magnetic field *B*





Impact of droplet shape on Mie-type resonances





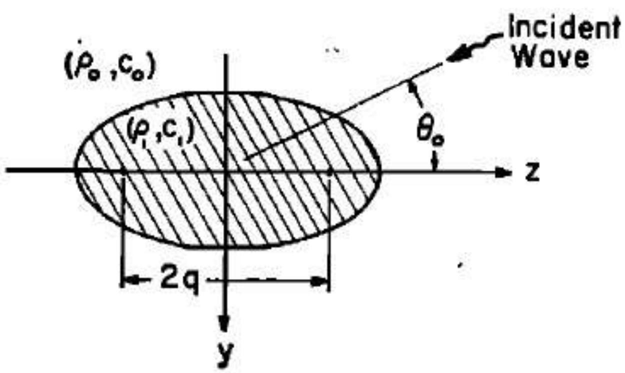
Impact of droplet shape on Mie-type resonances

Received 17 April 1967 11.2, 11.7; 13.4, 13.6

Scattering of Acoustic Waves by a Penetrable Prolate Spheroid. I. Liquid Prolate Spheroid*

C. YEH

Electrical Engineering Department, University of Southern California, Los Angeles, California 90007



PRL **111**, 264301 (2013) PHYSICAL REVIEW LETTERS week ending 27 DECEMBER 2013

Tuning Mie Scattering Resonances in Soft Materials with Magnetic Fields

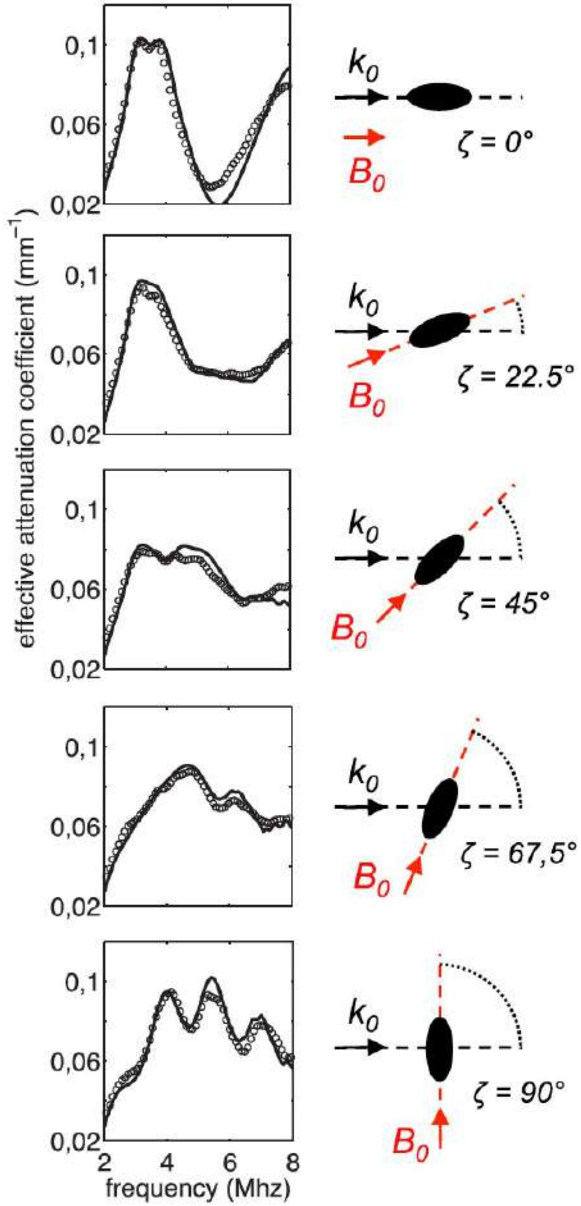
Thomas Brunet,[1,*] Kevin Zimny,[2,3] Benoit Mascaro,[1] Olivier Sandre,[2] Olivier Poncelet,[1] Christophe Aristégui,[1] and Olivier Mondain-Monval[3]

[1]*Université de Bordeaux, CNRS, UMR 5295, Institut de Mécanique et d'Ingénierie, 351 cours de la Libération, 33405 Talence, France*

[2]*Université de Bordeaux, CNRS, UMR 5629, Laboratoire de Chimie des Polymères Organiques, 16 avenue Pey Berland, 33607 Pessac, France*

[3]*Université de Bordeaux, CNRS, UPR 8641, Centre de Recherche Paul Pascal, 115 avenue du Docteur Schweitzer, 33600 Pessac, France*

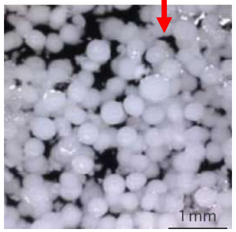
(Received 15 October 2013; published 27 December 2013)



Outline

- Context & motivations
  - Basis principles of metamaterials physics
- Locally resonant metafluids
  - Multi-resonant acoustic suspensions
  - Experimental demonstration of negative index
- Soft gradient-index metasurfaces
  - Soft porous silicone rubber lenses
  - Experimental demonstration of wavefront shaping
- Conclusion & perspectives
  - Soft acoustic metamaterials
  - Towards soft reconfigurable flat ultrasonic lenses

Need for particles with a very low speed of sound!

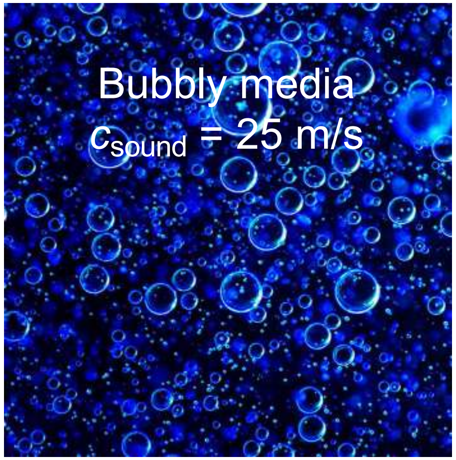


Materials with very low sound speeds?

- In **solids**, the sound speed is of the order of a few thousand m/s:
  - from 1.000 m/s (polymers) to 10.000 m/s (heavy metals)
- In **liquids**, the sound speed is of the order of a few hundred m/s:
  - from 500 m/s (fluorinated oils) to 1.500 m/s (water)
- How to reach sound speeds of the order of a few tens of m/s ?

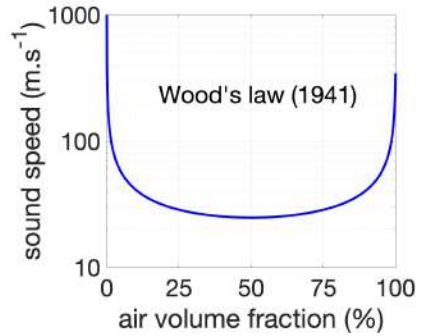
Materials with very low sound speeds?

- In **solids**, the sound speed is of the order of a few thousand m/s:
  - from 1.000 m/s (polymers) to 10.000 m/s (heavy metals)
- In **liquids**, the sound speed is of the order of a few hundred m/s:
  - from 500 m/s (fluorinated oils) to 1.500 m/s (water)
- How to reach sound speeds of the order of a few tens of m/s ?



$$\begin{cases} \rho_{\text{bubbly}} = (1-\Phi)\rho_{\text{w}} + \Phi\rho_{\text{air}} \approx (1-\Phi)\rho_{\text{w}} \\ \dfrac{1}{\kappa_{\text{bubbly}}} = \dfrac{1-\Phi}{\kappa_w} + \dfrac{\Phi}{\kappa_{\text{air}}} \approx \dfrac{\Phi}{\kappa_{\text{air}}} \end{cases}$$

$$\Longrightarrow c_{\text{bubbly}} = \sqrt{\frac{\kappa_{\text{bubbly}}}{\rho_{\text{bubbly}}}} \approx \sqrt{\frac{\kappa_{\text{air}}}{\Phi(1-\Phi)\rho_{\text{w}}}}$$

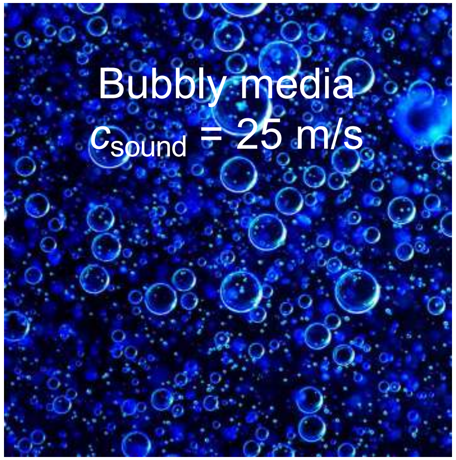


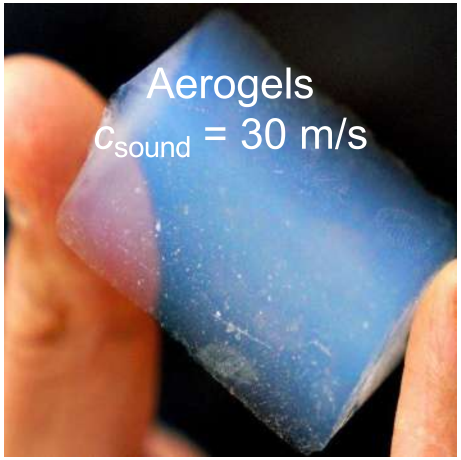
Materials with very low sound speeds?

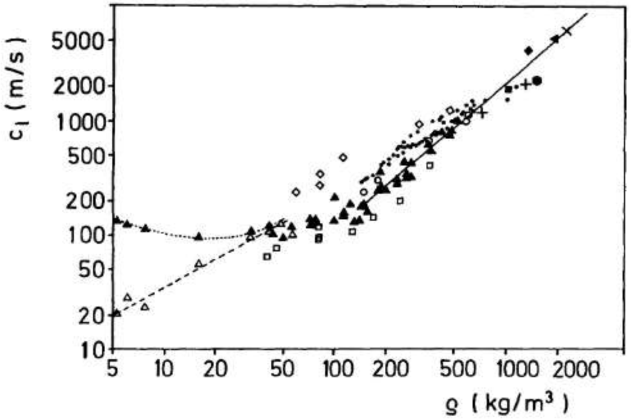
- In **solids**, the sound speed is of the order of a few thousand m/s:
  - from 1.000 m/s (polymers) to 10.000 m/s (heavy metals)

- In **liquids**, the sound speed is of the order of a few hundred m/s:
  - from 500 m/s (fluorinated oils) to 1.500 m/s (water)

- How to reach sound speeds of the order of a few tens of m/s ?



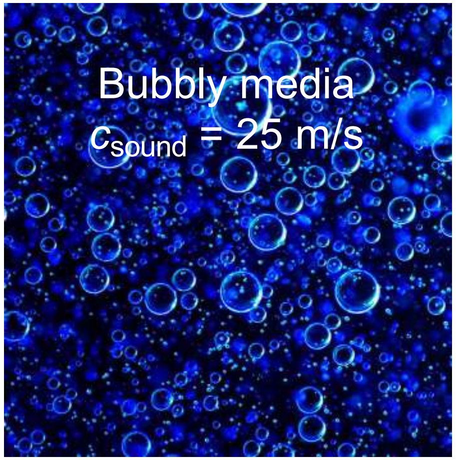


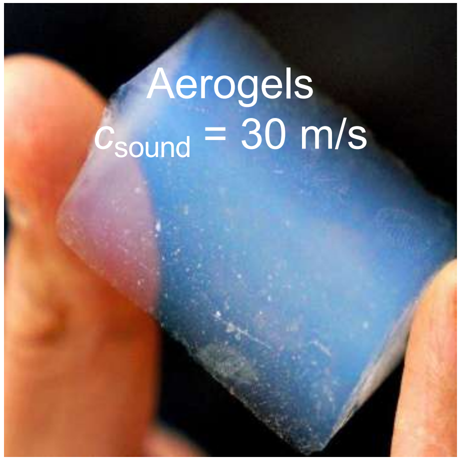


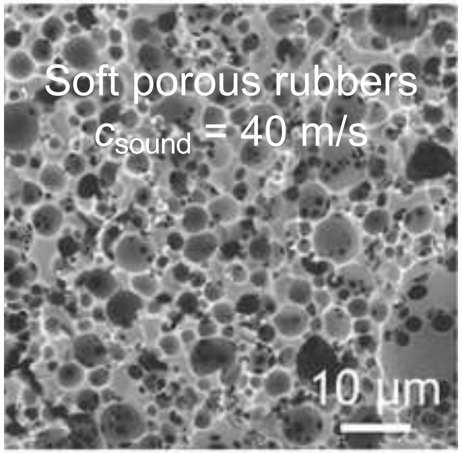
Gross *et al.*
Phys. Rev. B **45**, 12774 (1992)

Materials with very low sound speeds?

- In **solids**, the sound speed is of the order of a few thousand m/s:
  - from 1.000 m/s (polymers) to 10.000 m/s (heavy metals)
- In **liquids**, the sound speed is of the order of a few hundred m/s:
  - from 500 m/s (fluorinated oils) to 1.500 m/s (water)
- How to reach sound speeds of the order of a few tens of m/s ?





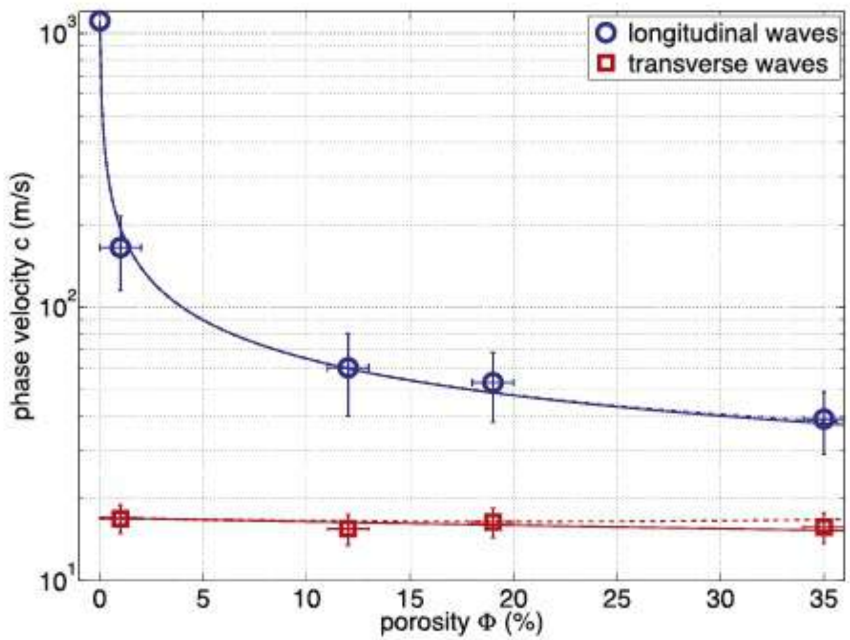


Soft porous silicone rubbers

For soft porous silicone rubbers:

$K_0 \approx 1\ \text{GPa} \gg G_0 \approx 1\ \text{MPa}$

and $K_{\text{air}} \approx 0.1\ \text{MPa} \gg G_{\text{air}} = 0$



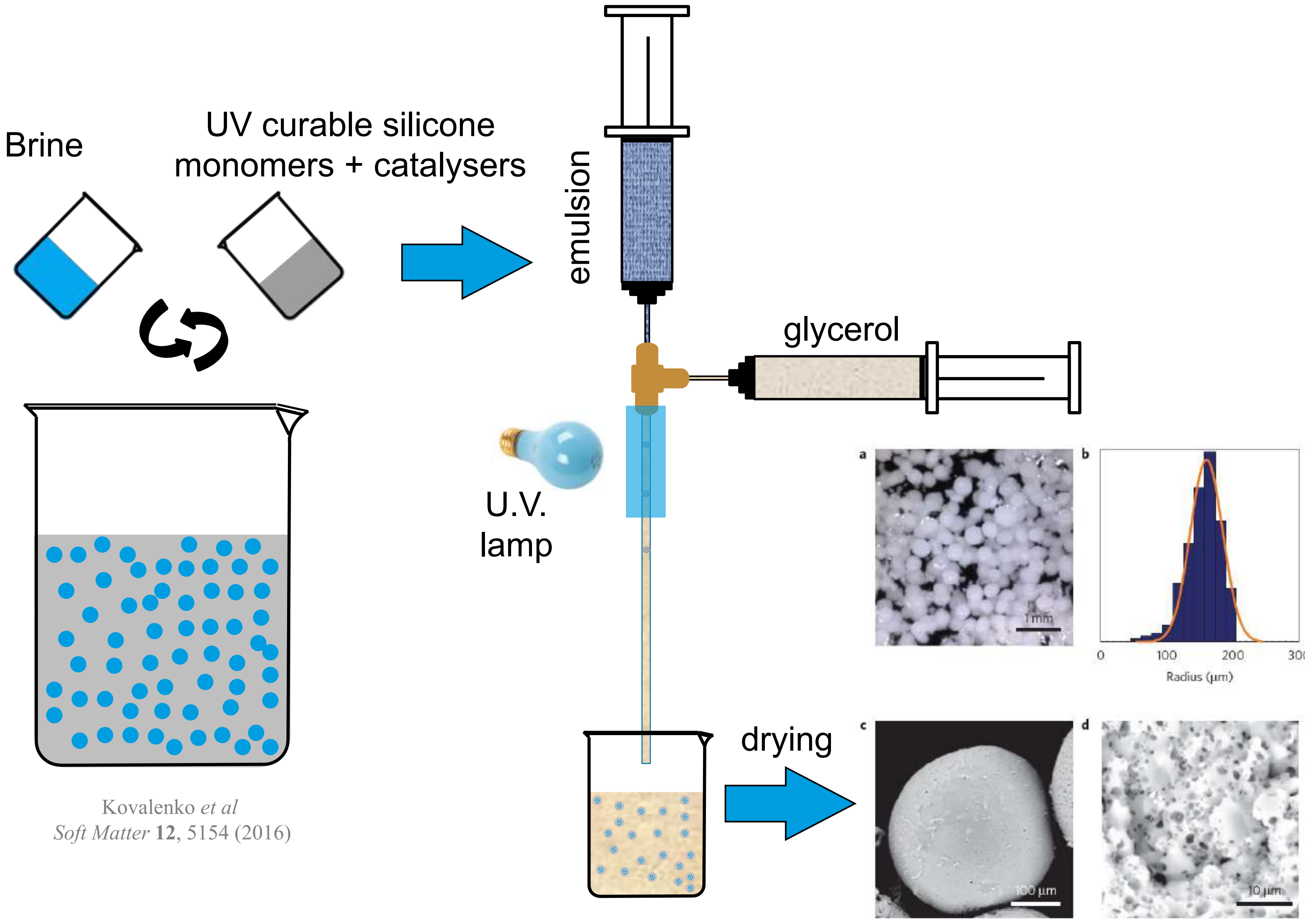
From the single scattering theory derived in the long-wavelength limit, we have:

$$\begin{cases} \rho_{\text{porous}} = (1-\Phi)\rho_0 + \Phi\rho_{\text{air}} \\ \dfrac{K_{\text{porous}} - K_0}{3K_{\text{porous}} + 4G_0} = \Phi \dfrac{K_{\text{air}} - K_0}{3K_{\text{air}} + 4G_0} \\ \dfrac{G_{\text{porous}} - G_0}{6G_{\text{porous}}(K_0 + 2G_0) + G_0(9K_0 + 8G_0)} \\ = \dfrac{\Phi(G_{\text{air}} - G_0)}{6G_{\text{air}}(K_0 + 2G_0) + G_0(9K_0 + 8G_0)} \end{cases} \Rightarrow \begin{cases} c_{\text{L}} = \sqrt{\dfrac{K_{\text{porous}} + \left(\frac{4}{3}\right) G_{\text{porous}}}{\rho_{\text{porous}}}} \approx \dfrac{c_{L,0}}{\sqrt{1 + \frac{3K_0}{4G_0}\phi}} \\ c_{\text{T}} = \sqrt{\dfrac{G_{\text{porous}}}{\rho_{\text{porous}}}} \approx \dfrac{c_{T,0}}{\sqrt{1 + \frac{2}{3}\phi}} \end{cases}$$

Kuster & Toksöz, *Geophysics* **39**, 587 (1974)

Ba *et al.* *Sci. Rep.* **7**, 40106 (2017)

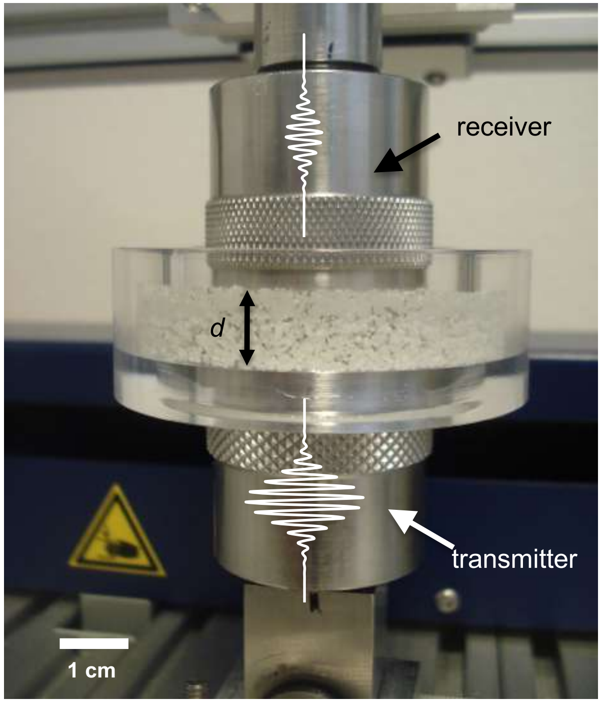
Soft porous silicone rubber beads

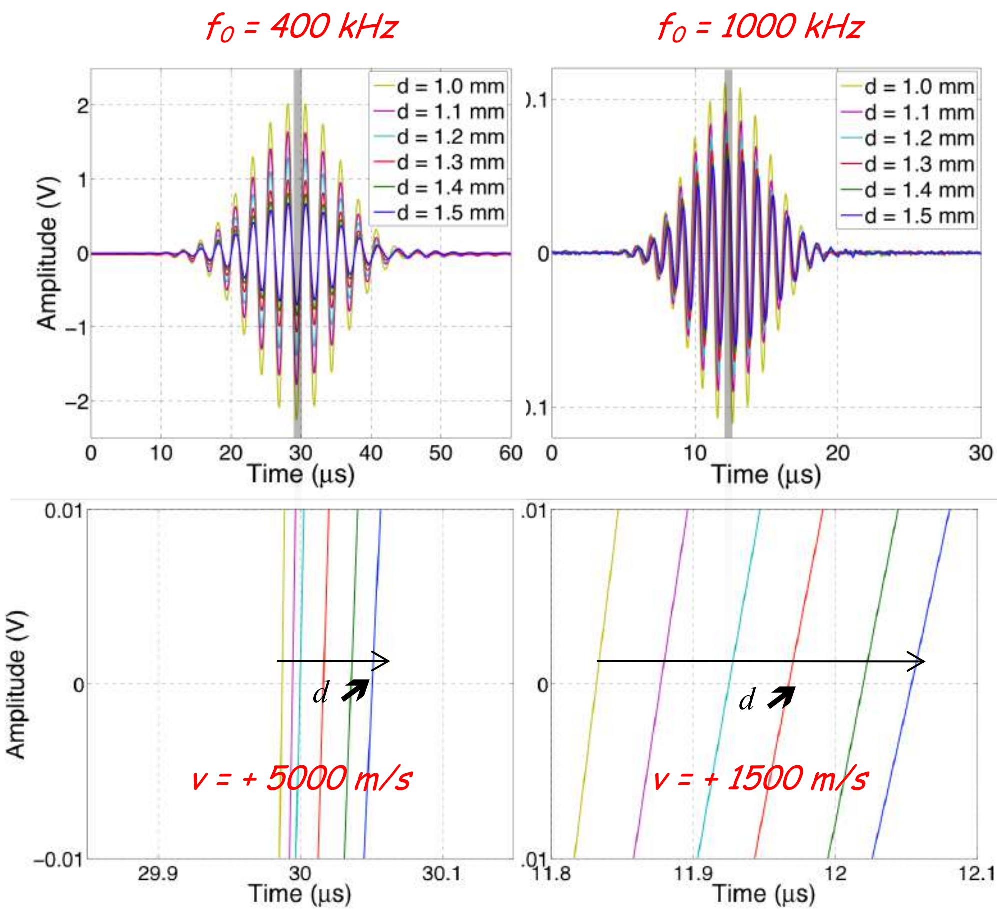


Kovalenko *et al*
Soft Matter **12**, 5154 (2016)

Ultrasound measurements

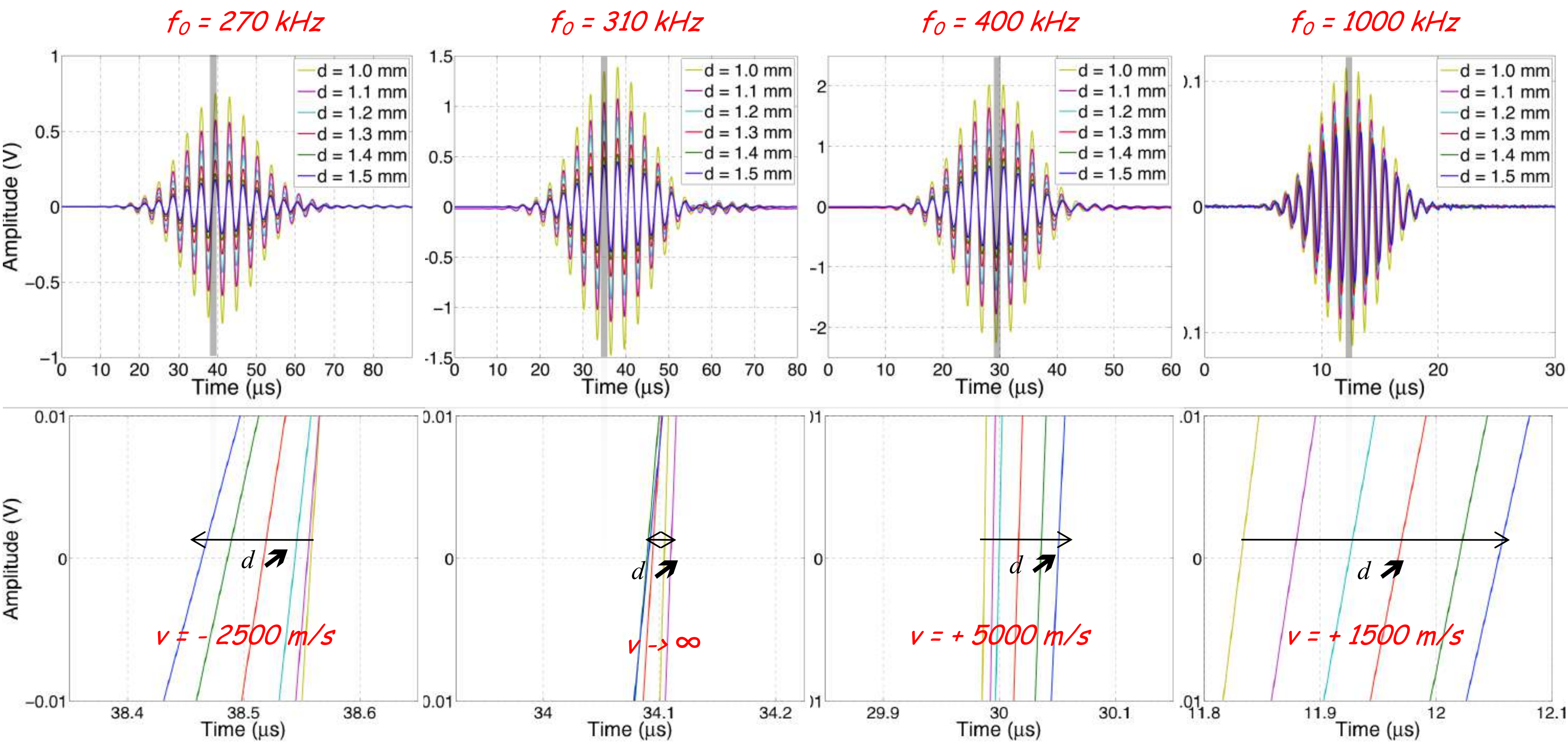
direct-contact pitch/catch experiments





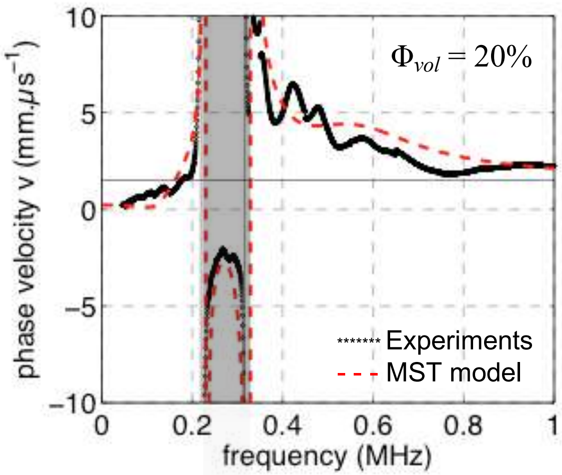
retrieval of the effective phase velocity v and the acoustic attenuation α over a broad ultrasonic frequency range [100 – 1000 kHz]

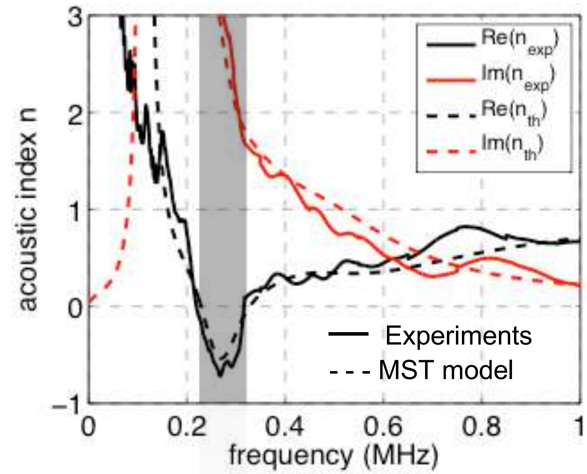
Ultrasound measurements

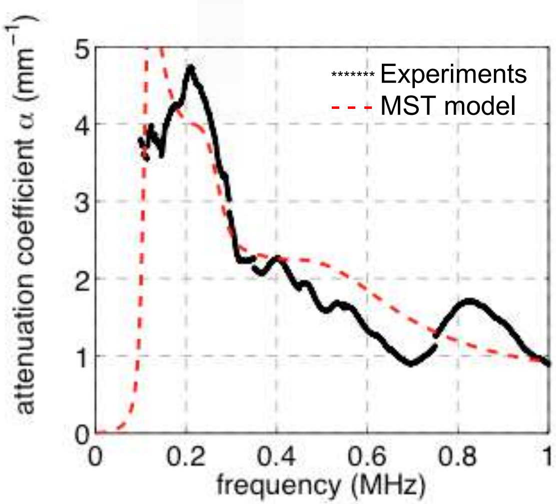


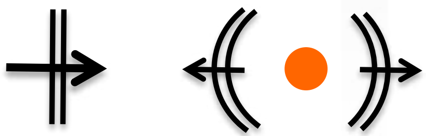
retrieval of the effective phase velocity v and the acoustic attenuation α
over a broad ultrasonic frequency range [100 – 1000 kHz]

Negative index ultrasonic metafluids





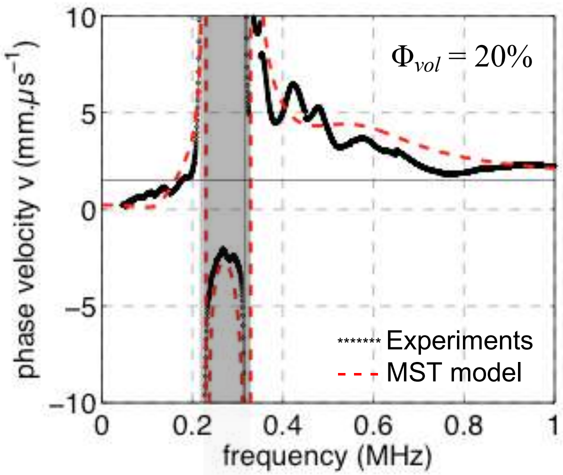


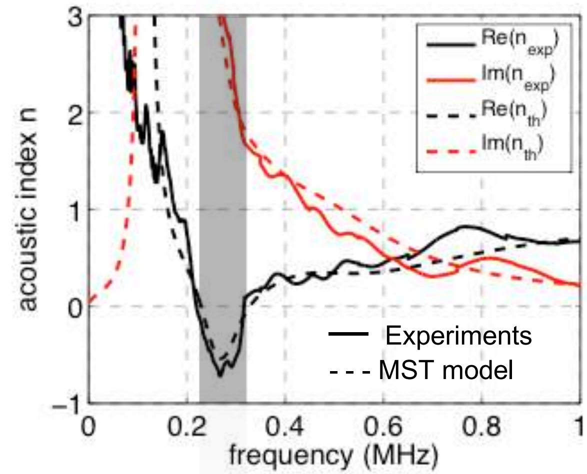


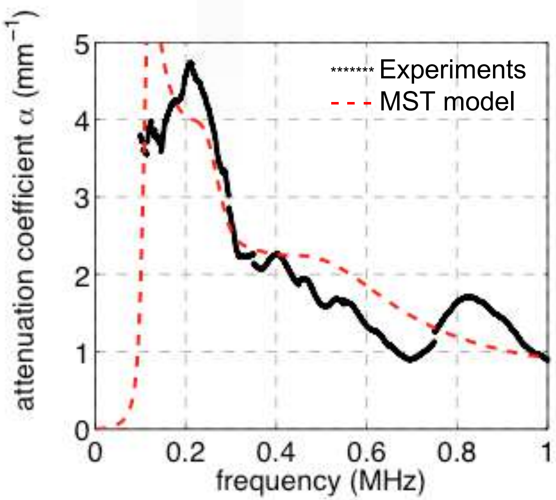
Waterman and Truell
J. Math. Phys. **2**, 512 (1961)

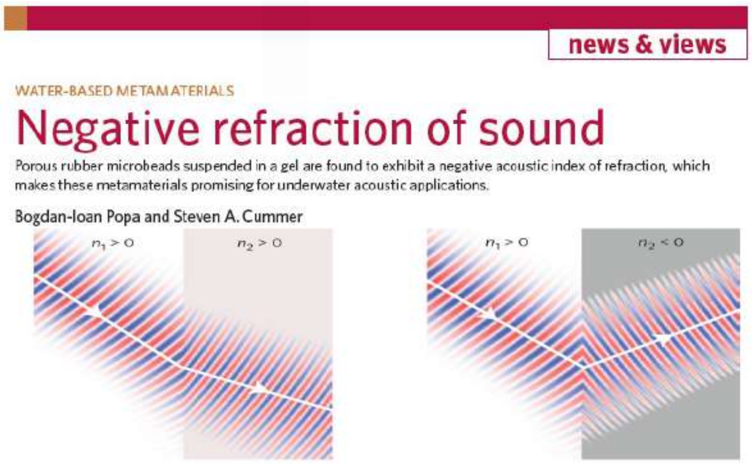
$$\begin{cases} k^2 = k_0^2 + \int_a \left(4\pi\eta(a) f_a(0) + \frac{4\pi^2\eta^2(a)}{k_0^2}\{[f_a(0)]^2 - [f_a(\pi)]^2\}\right) \mathrm{d}a \\ \text{with} \quad \phi_{vol} = \int_a \frac{4}{3}\pi a^3 \eta(a) \mathrm{d}a \end{cases}$$

Negative index ultrasonic metafluids









news & views

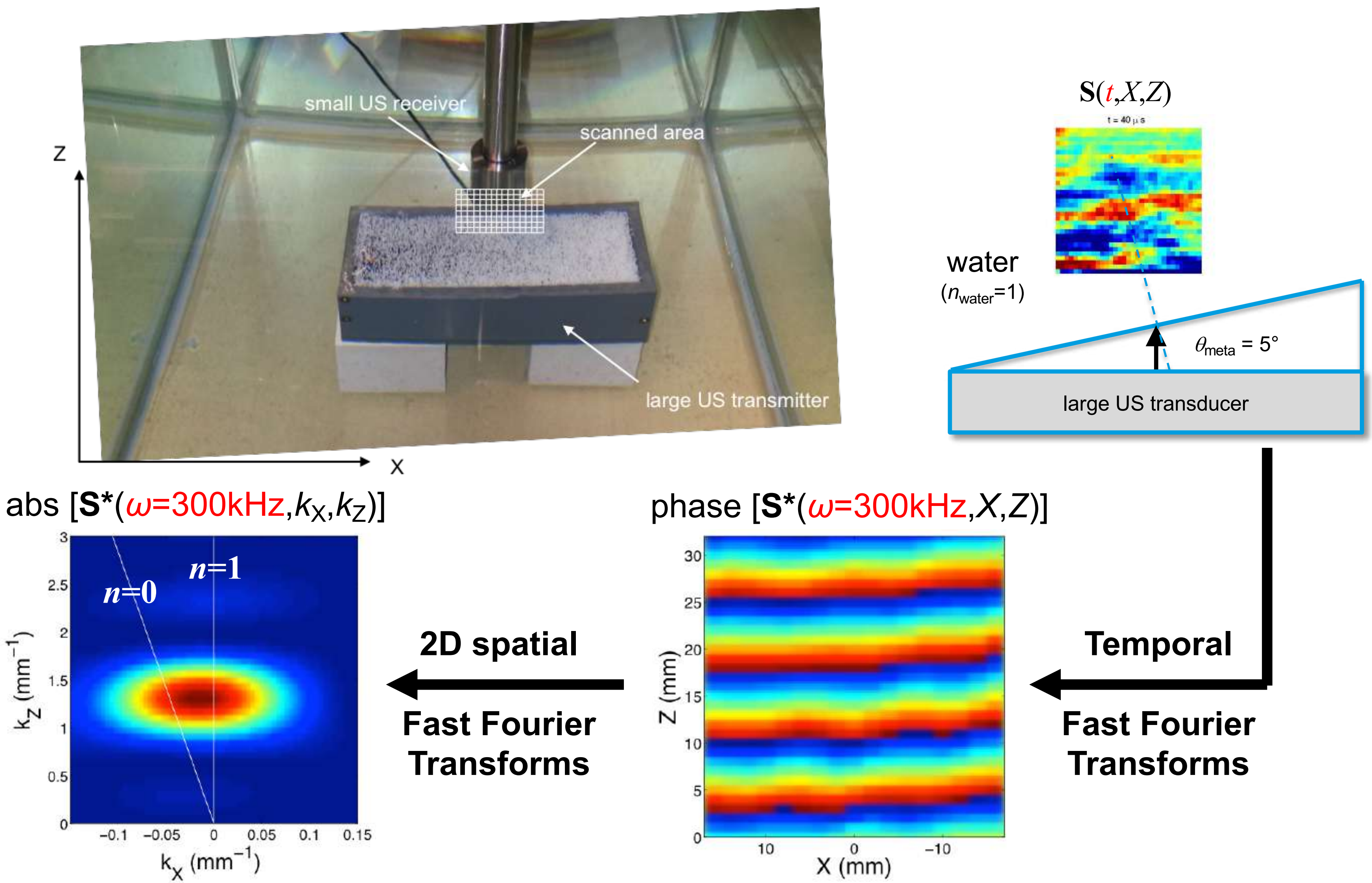
WATER-BASED METAMATERIALS

Negative refraction of sound

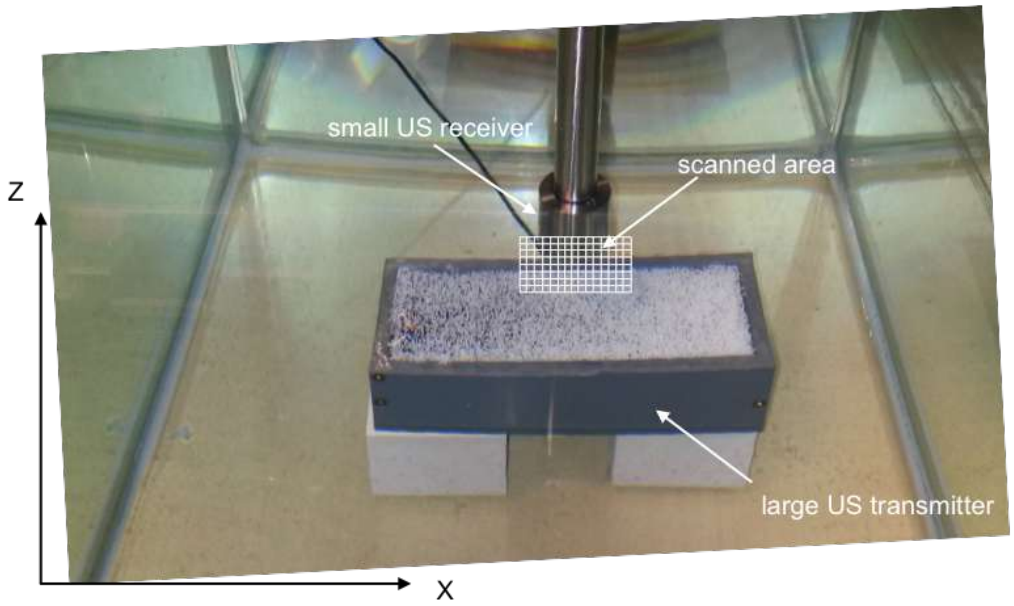
Porous rubber microbeads suspended in a gel are found to exhibit a negative acoustic index of refraction, which makes these metamaterials promising for underwater acoustic applications.

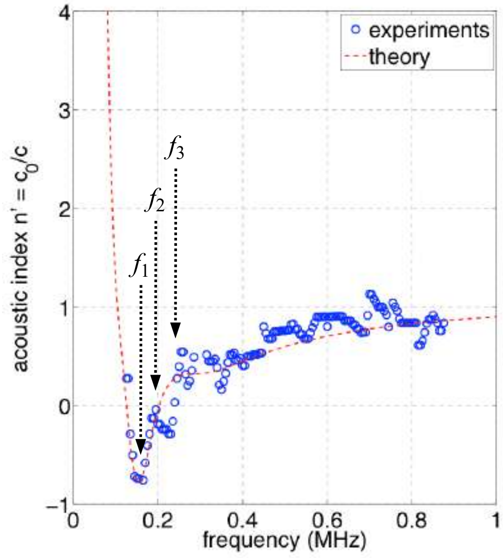
Bogdan-Ioan Popa and Steven A. Cummer

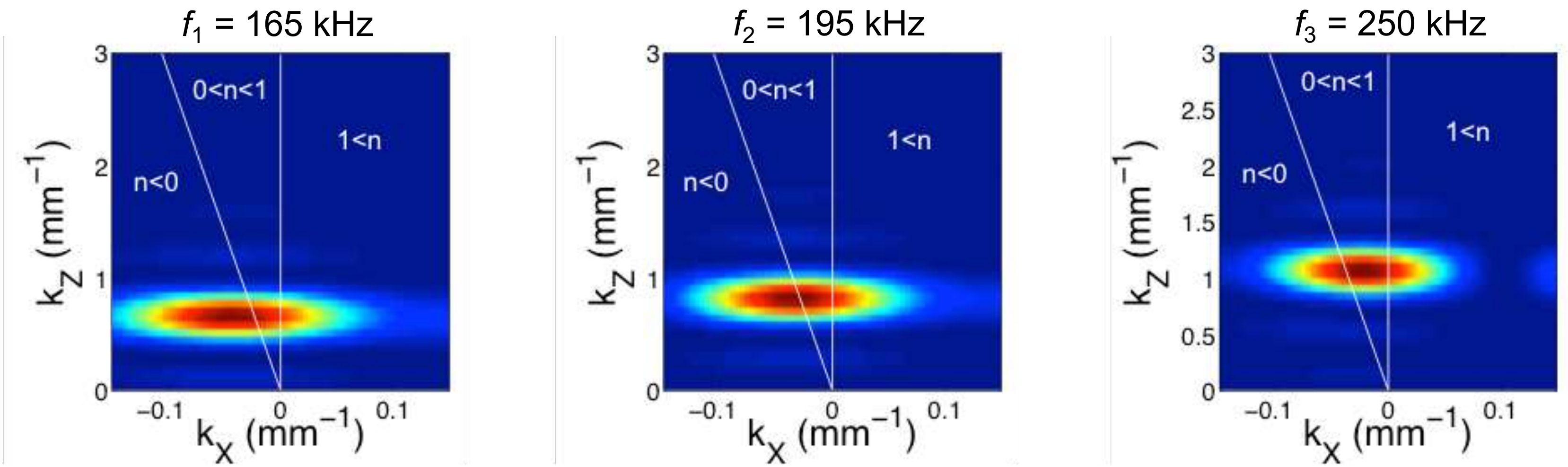
Negative refraction experiments



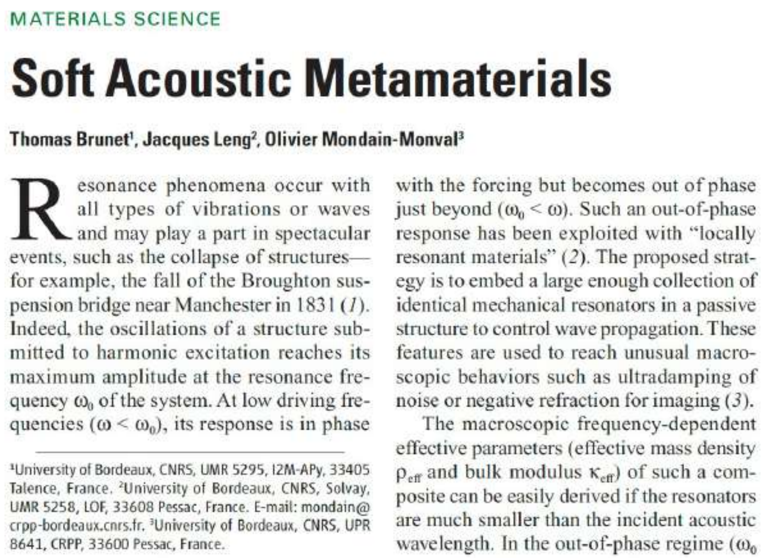
Negative refraction experiments







Conclusion



MATERIALS SCIENCE

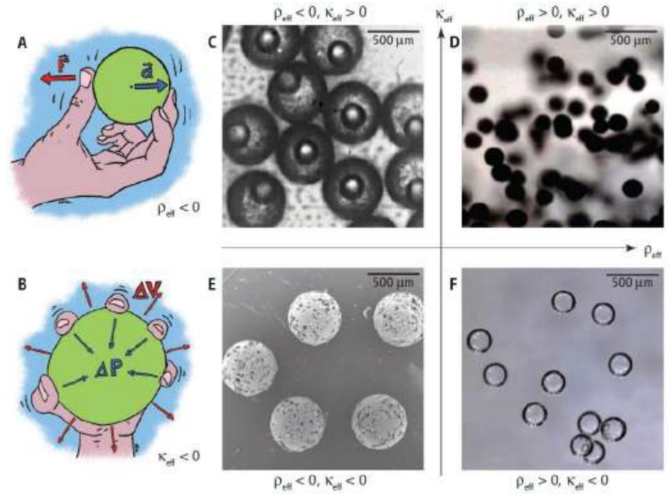
Soft Acoustic Metamaterials

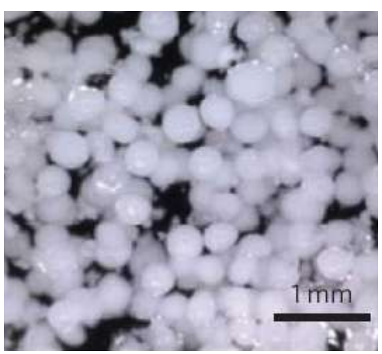
Thomas Brunet[1], Jacques Leng[2], Olivier Mondain-Monval[3]

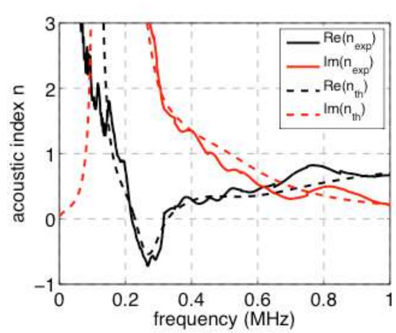
Resonance phenomena occur with all types of vibrations or waves and may play a part in spectacular events, such as the collapse of structures—for example, the fall of the Broughton suspension bridge near Manchester in 1831 (1). Indeed, the oscillations of a structure submitted to harmonic excitation reaches its maximum amplitude at the resonance frequency ω_0 of the system. At low driving frequencies ($\omega < \omega_0$), its response is in phase with the forcing but becomes out of phase just beyond ($\omega_0 < \omega$). Such an out-of-phase response has been exploited with "locally resonant materials" (2). The proposed strategy is to embed a large enough collection of identical mechanical resonators in a passive structure to control wave propagation. These features are used to reach unusual macroscopic behaviors such as ultradamping of noise or negative refraction for imaging (3).

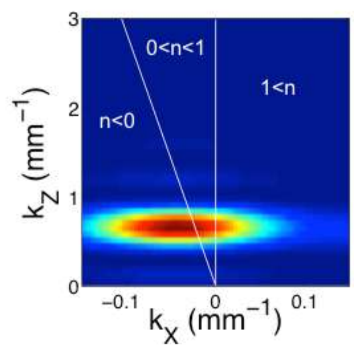
The macroscopic frequency-dependent effective parameters (effective mass density ρ_{eff} and bulk modulus κ_{eff}) of such a composite can be easily derived if the resonators are much smaller than the incident acoustic wavelength. In the out-of-phase regime (ω_0

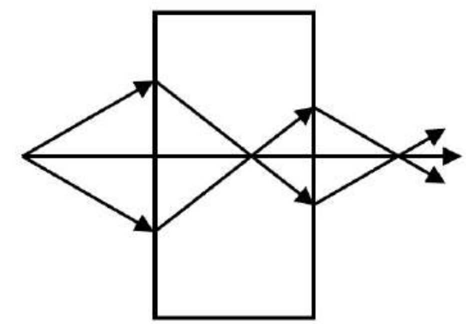
[1]University of Bordeaux, CNRS, UMR 5295, I2M-APy, 33405 Talence, France. [2]University of Bordeaux, CNRS, Solvay, UMR 5258, LOF, 33608 Pessac, France. E-mail: mondain@crpp-bordeaux.cnrs.fr. [3]University of Bordeaux, CNRS, UPR 8641, CRPP, 33600 Pessac, France.











Acoustic metafluids | Negative Index ✓ | Negative Refraction ✓ | Perfect lens ✖

Conclusion

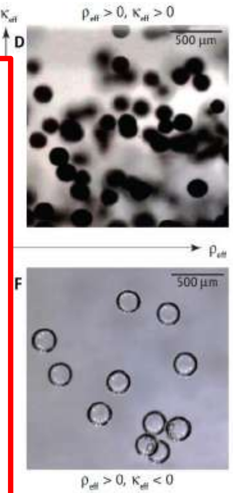
MATERIALS SCIENCE

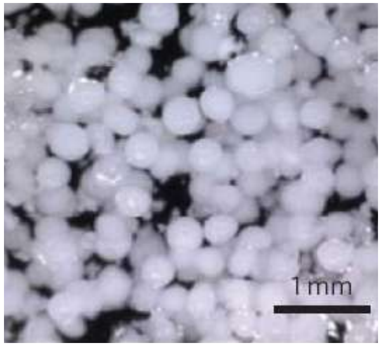
Soft Acoustic Metamaterials

Thomas Brunet[1], Jacques Leng[2], Olivier Mo

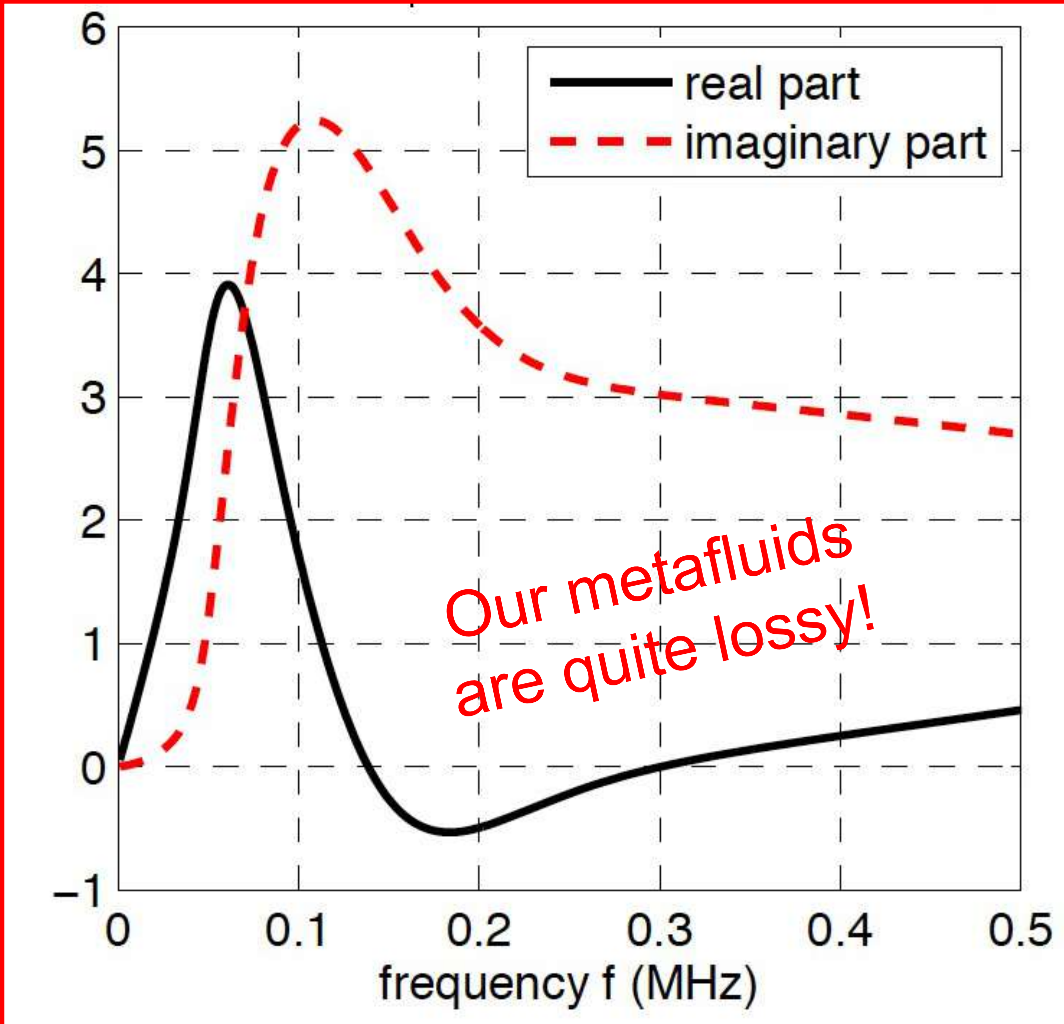
Resonance phenomena occur w all types of vibrations or wav and may play a part in spectacu events, such as the collapse of structures for example, the fall of the Broughton s pension bridge near Manchester in 1831 (Indeed, the oscillations of a structure su mitted to harmonic excitation reaches maximum amplitude at the resonance f quency ω_0 of the system. At low driving f quencies ($\omega < \omega_0$), its response is in pha

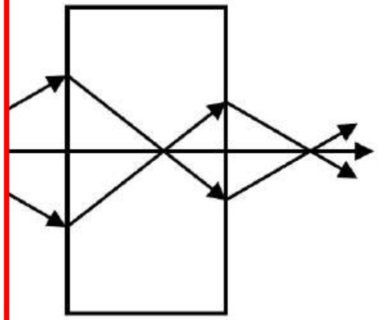
[1]University of Bordeaux, CNRS, UMR 5295, I2M-APy, 33 Talence, France. [2]University of Bordeaux, CNRS, Sol UMR 5258, LOF, 33608 Pessac, France. E-mail: mondai crpp-bordeaux.cnrs.fr. [3]University of Bordeaux, CNRS, 8641, CRPP, 33600 Pessac, France.





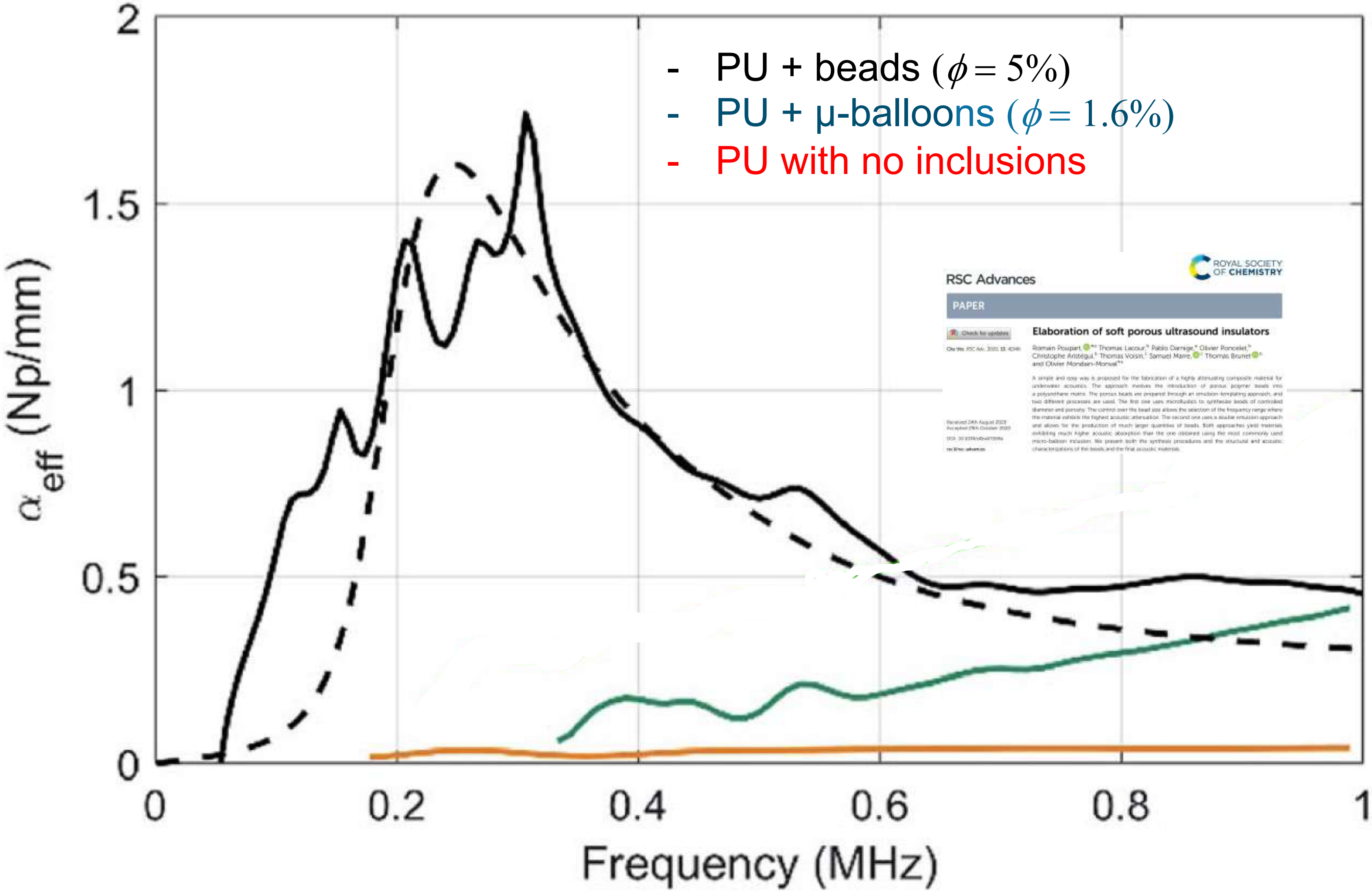
Acoustic metafluids





Perfect lens ✖

Perspective: soft ultrasound insulators



RSC Advances

ROYAL SOCIETY OF CHEMISTRY

PAPER

Elaboration of soft porous ultrasound insulators

Romain Poupart, Thomas Lacour, Pablo Darnige, Olivier Poncelet, Christophe Aristégui, Thomas Voisin, Samuel Marre, Thomas Brunet and Olivier Mondain-Monval

A simple and easy way is proposed for the fabrication of a highly attenuating composite material for underwater acoustics. The approach involves the introduction of porous polymer beads into a polyurethane matrix. The porous beads are prepared through an emulsion-templating approach, and two different processes are used. The first one uses microfluidics to synthesize beads of controlled diameter and porosity. The control over the bead size allows the selection of the frequency range where the material exhibits the highest acoustic attenuation. The second one uses a double emulsion approach and allows for the production of much larger quantities of beads. Both approaches yield materials exhibiting much higher acoustic absorption than the one obtained using the most commonly used micro-balloon inclusion. We present both the synthesis procedures and the structural and acoustic characterizations of the beads and the final acoustic materials.

Outline

- Context & motivations
  - Basis principles of metamaterials physics
- Locally resonant metafluids
  - Multi-resonant acoustic suspensions
  - Experimental demonstration of negative index

- **Soft gradient-index metasurfaces**
  - Soft porous silicone rubber lenses
  - Experimental demonstration of wavefront shaping

- Conclusion & perspectives
  - Soft acoustic metamaterials
  - Towards soft reconfigurable flat ultrasonic lenses

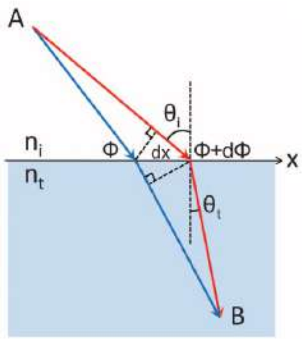
Soft gradient-index metasurfaces

RESEARCH ARTICLE

Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction

Nanfang Yu[1], Patrice Genevet[1,2], Mikhail A. Kats[1], Francesco Aieta[1,3], Jean-Philippe Tetienne[1,4], Federico Capasso[1,*], Zeno...
+ See all authors and affiliations

Science 21 Oct 2011:
Vol. 334, Issue 6054, pp. 333-337
DOI: 10.1126/science.1210713



$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_o}{2\pi n_i}\frac{d\Phi}{dx}$$

$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \frac{\lambda_o}{2\pi}\frac{d\Phi}{dx}$$

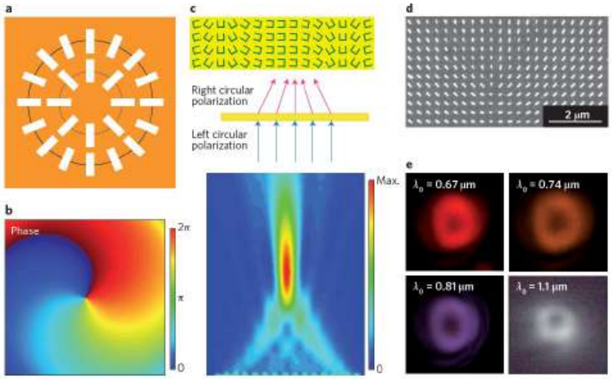
nature materials

Review Article | Published: 23 January 2014

Flat optics with designer metasurfaces

Nanfang Yu & Federico Capasso

Nature Materials **13**, 139–150 (2014) | Download Citation



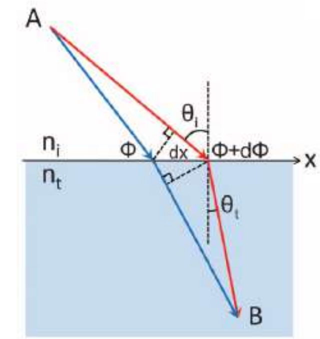
Soft gradient-index metasurfaces

Review Article | Published: 17 October 2018

Acoustic metasurfaces

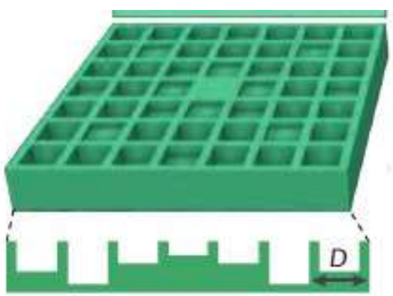
Badreddine Assouar, Bin Liang, Ying Wu, Yong Li, Jian-Chun Cheng & Yun Jing

Nature Reviews Materials **3**, 460–472 (2018) | Download Citation

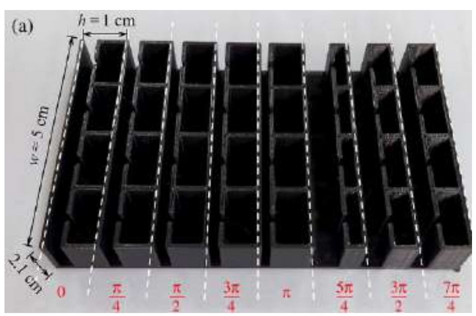


$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_o}{2\pi n_i}\frac{d\Phi}{dx}$$

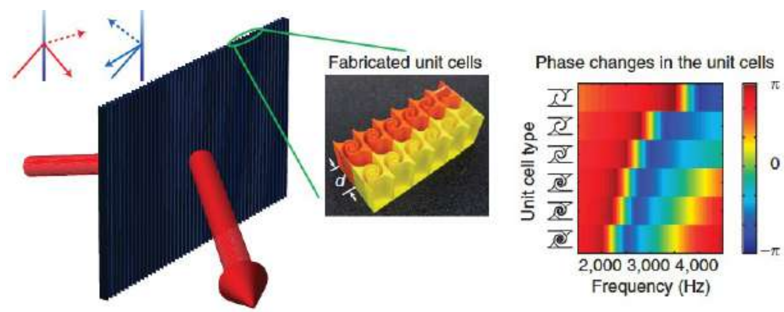
$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \frac{\lambda_o}{2\pi}\frac{d\Phi}{dx}$$



Zhu *et al.*
Physical Review X 7, 021034 (2017)

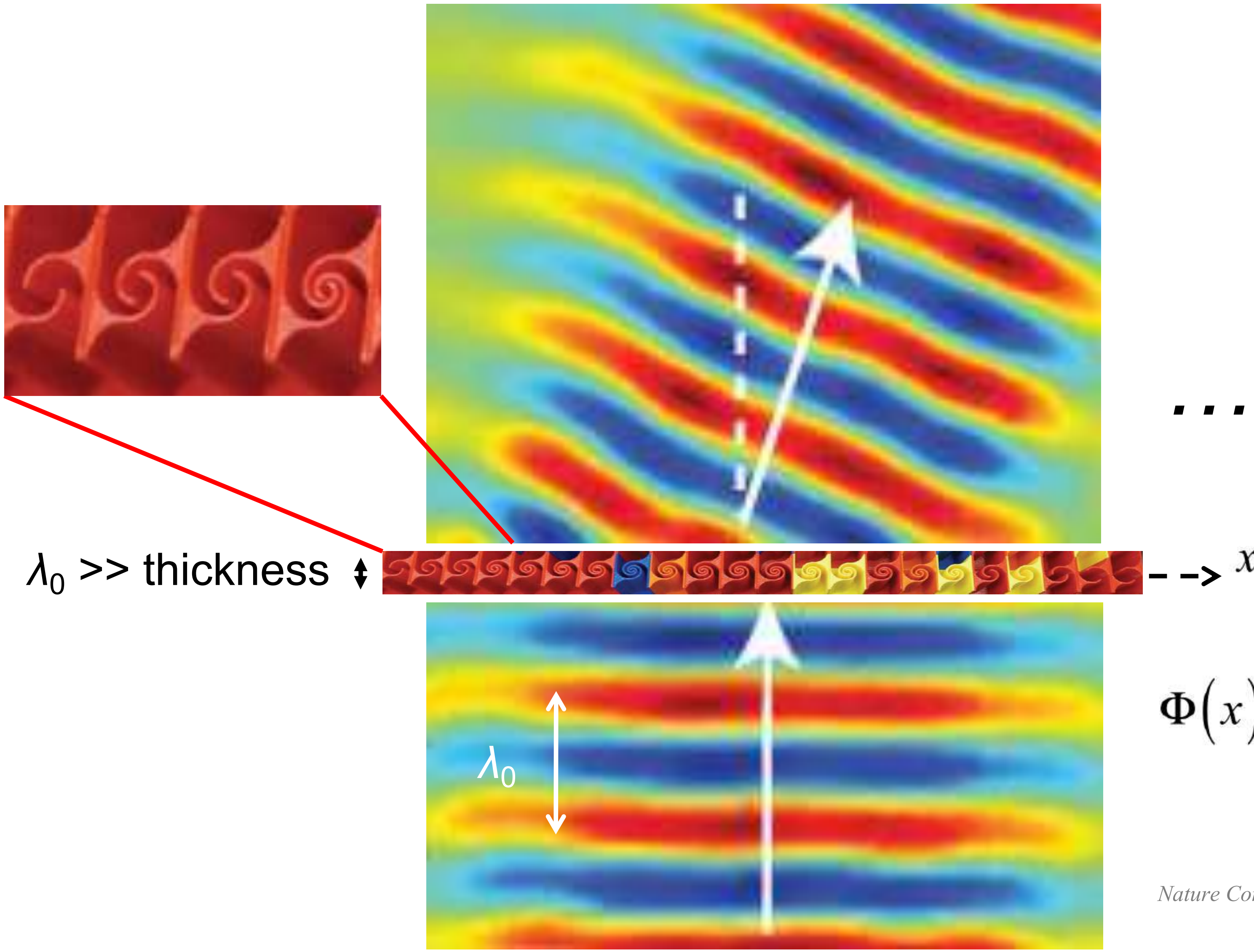


Li *et al.*
Physical Review Applied **5**, 024003 (2015)



Xie *et al.*
Nature Communications **5**, 5553 (2014)

Soft gradient-index metasurfaces

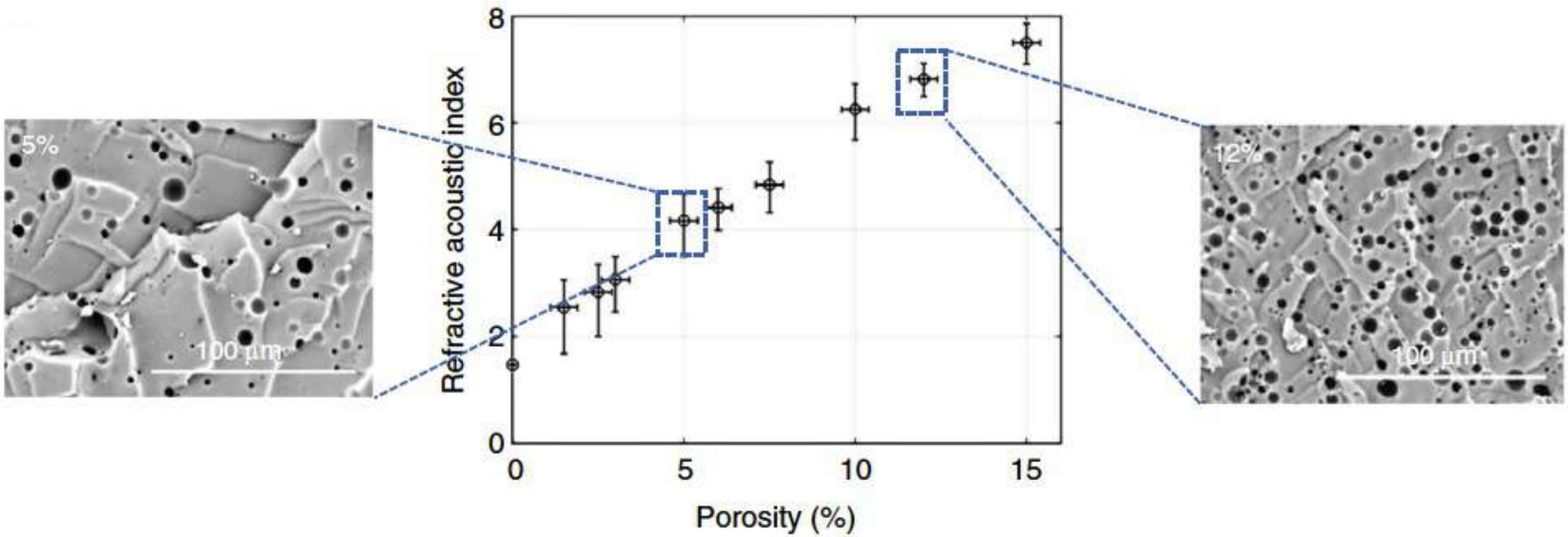


$$\ldots = \frac{\lambda_0}{2\pi}\frac{d\Phi}{dx}$$

$$\Phi(x) = \frac{2\pi}{\lambda_0} n d(x)$$

Xie *et al.*
Nature Communications **5**, 5553 (2014)

Soft porous silicone rubbers

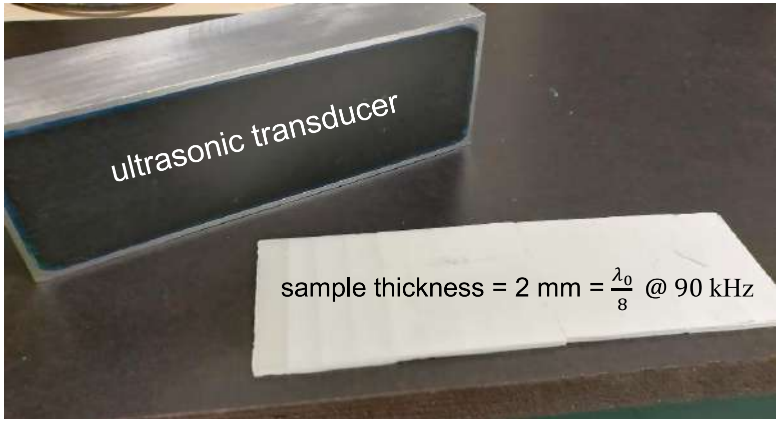


Article | OPEN | Published: 11 January 2019

Flat acoustics with soft gradient-index metasurfaces

Yabin Jin, Raj Kumar, Olivier Poncelet, Olivier Mondain-Monval & Thomas Brunet

Nature Communications **10**, Article number: 143 (2019) | Download Citation



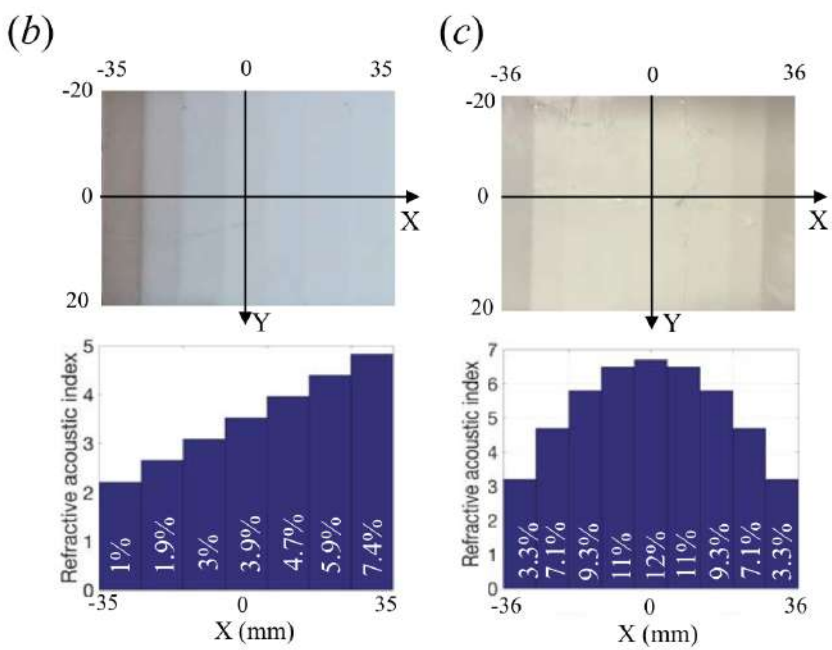
Soft porous silicone rubbers

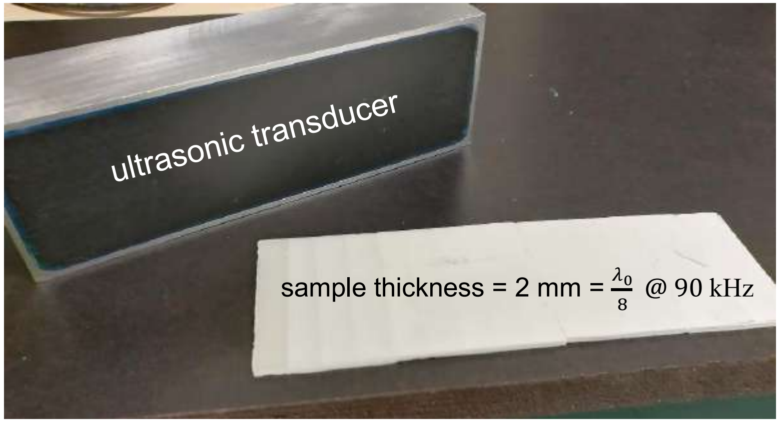
$$(b): \quad n(X) = n(X=0) + \frac{\sin(\theta) X}{d}$$

$\Rightarrow$ linear gradient of index for deflection

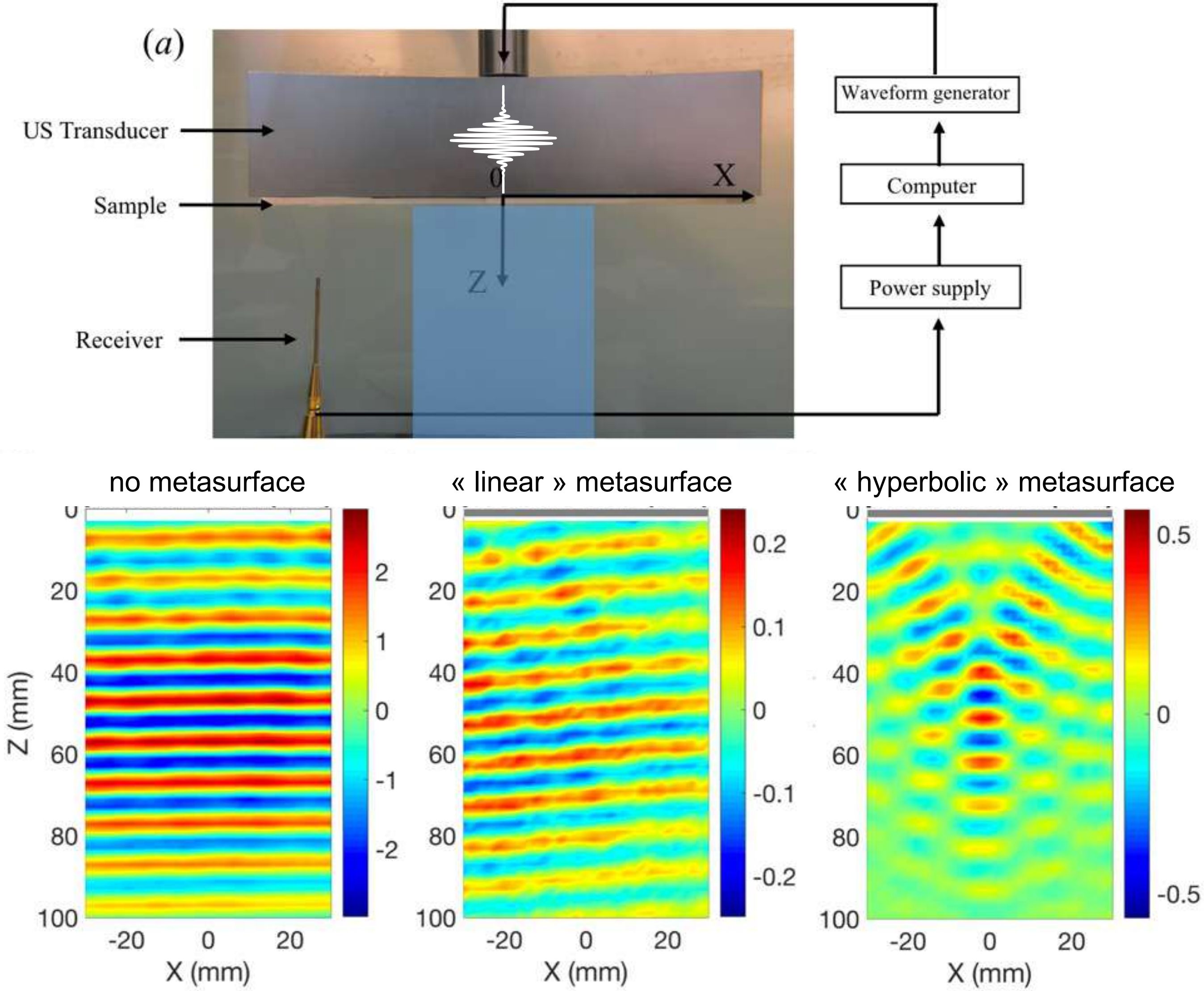
$$(c): \quad n(X) = n(X=0) - \frac{\sqrt{X^2 + F^2} - F}{d}$$

$\Rightarrow$ hyperbolic gradient of index for focusing

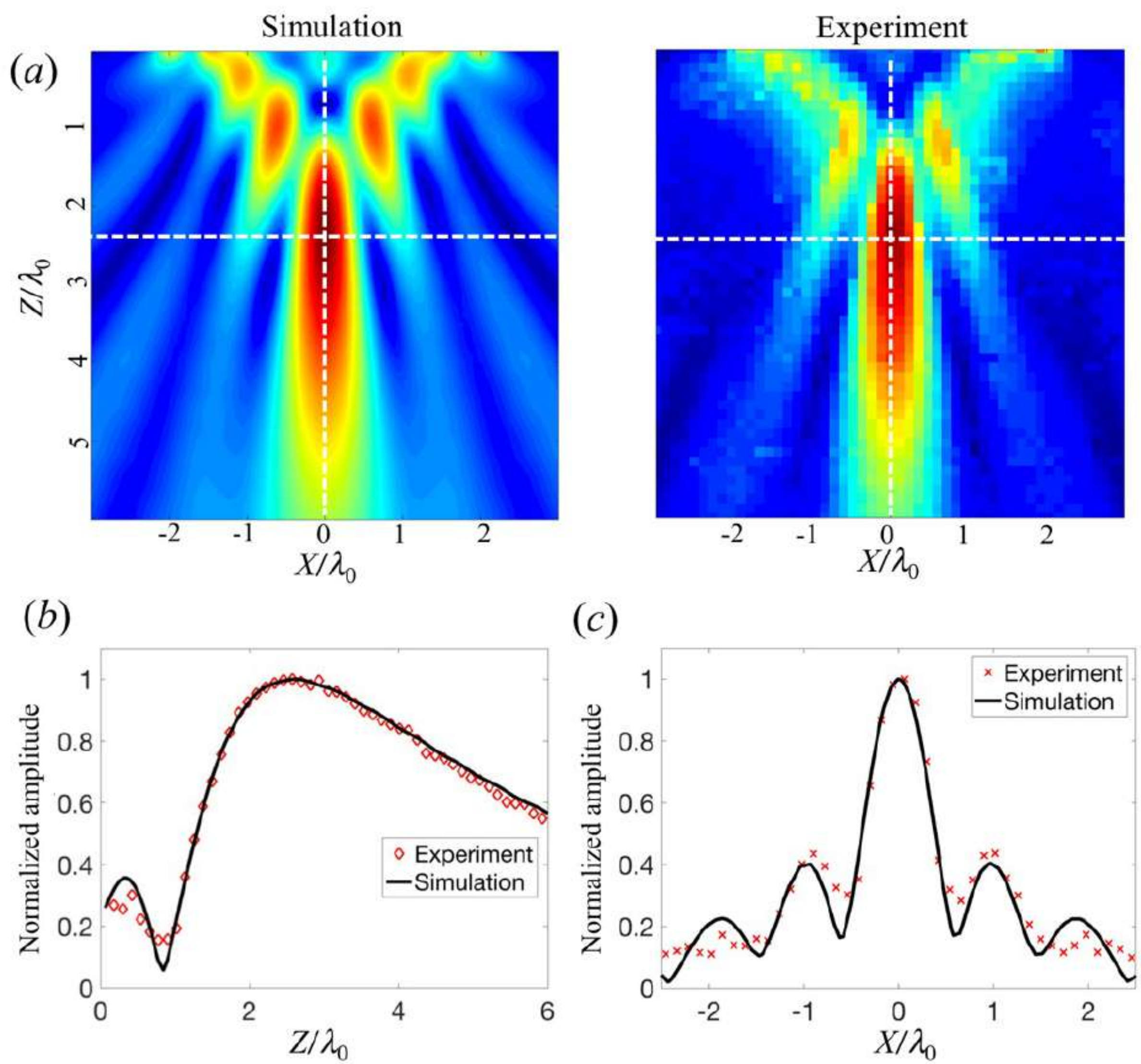




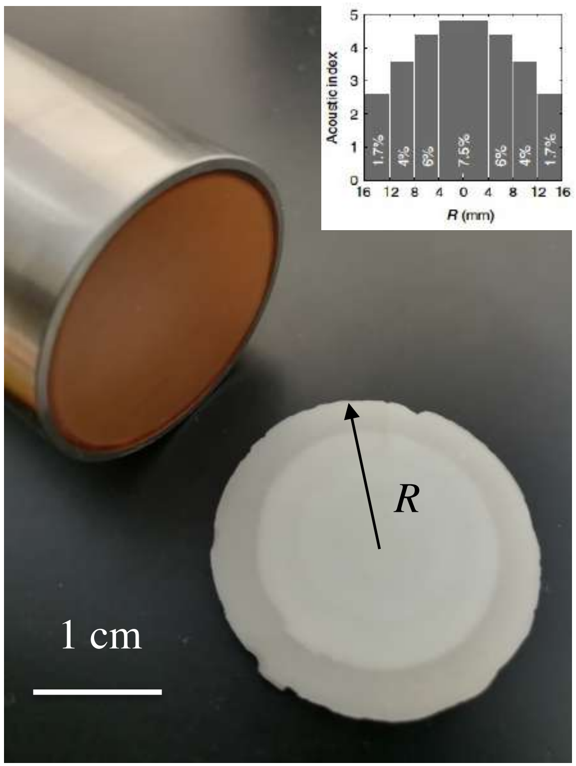
2D wavefront shaping



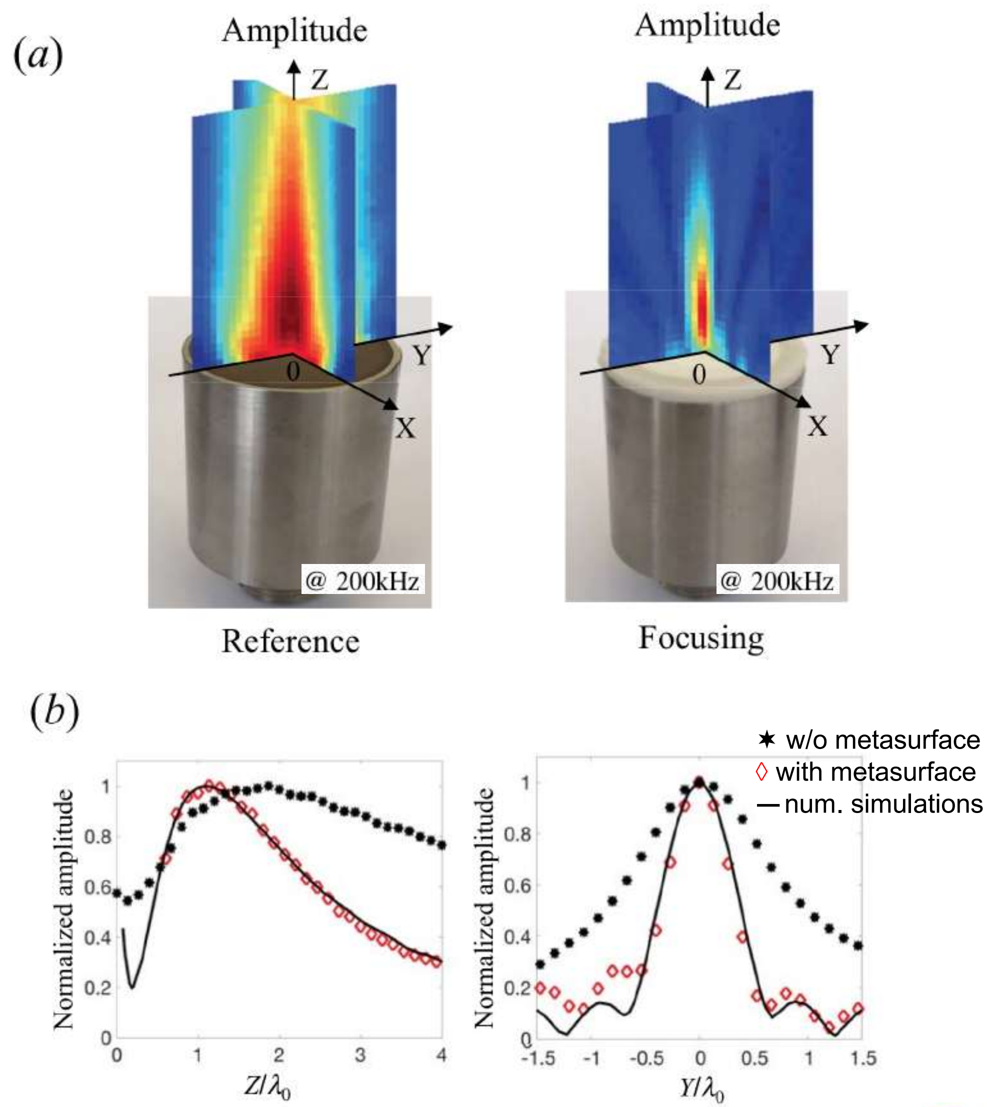
2D wavefront shaping



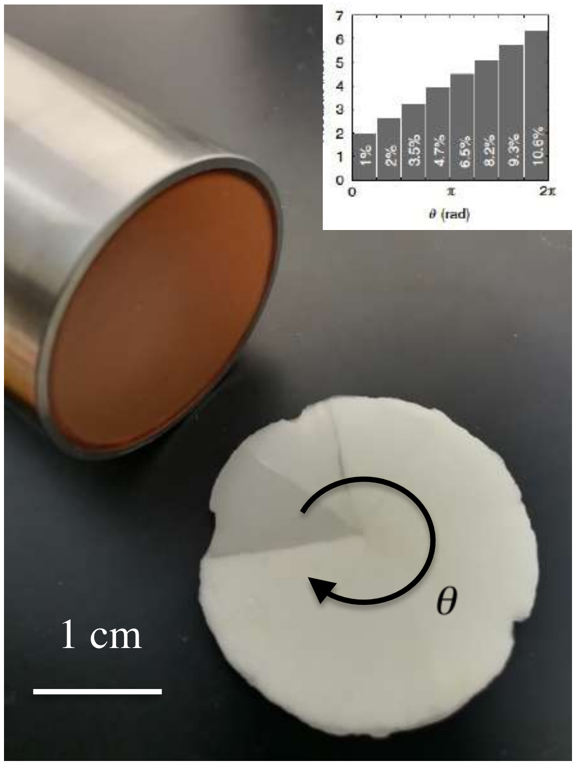
3D wavefront focusing



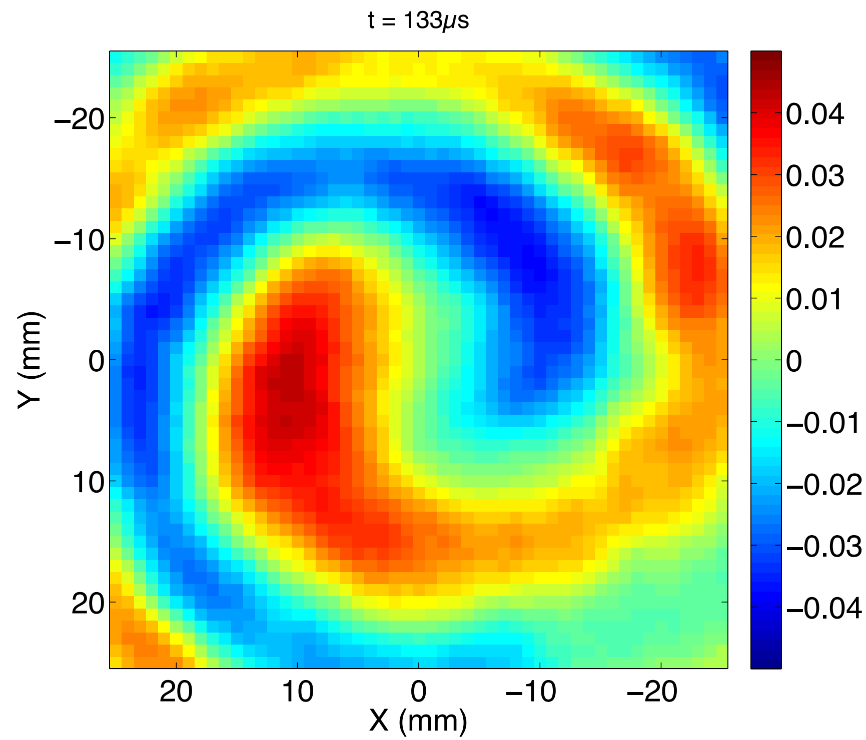
Radially graded flat lens



3D wavefront twisting

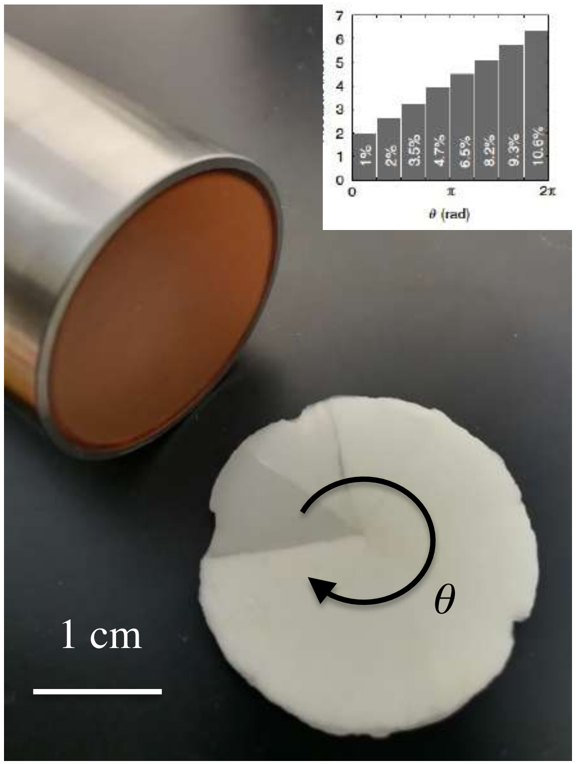


Azimuthally graded flat lens

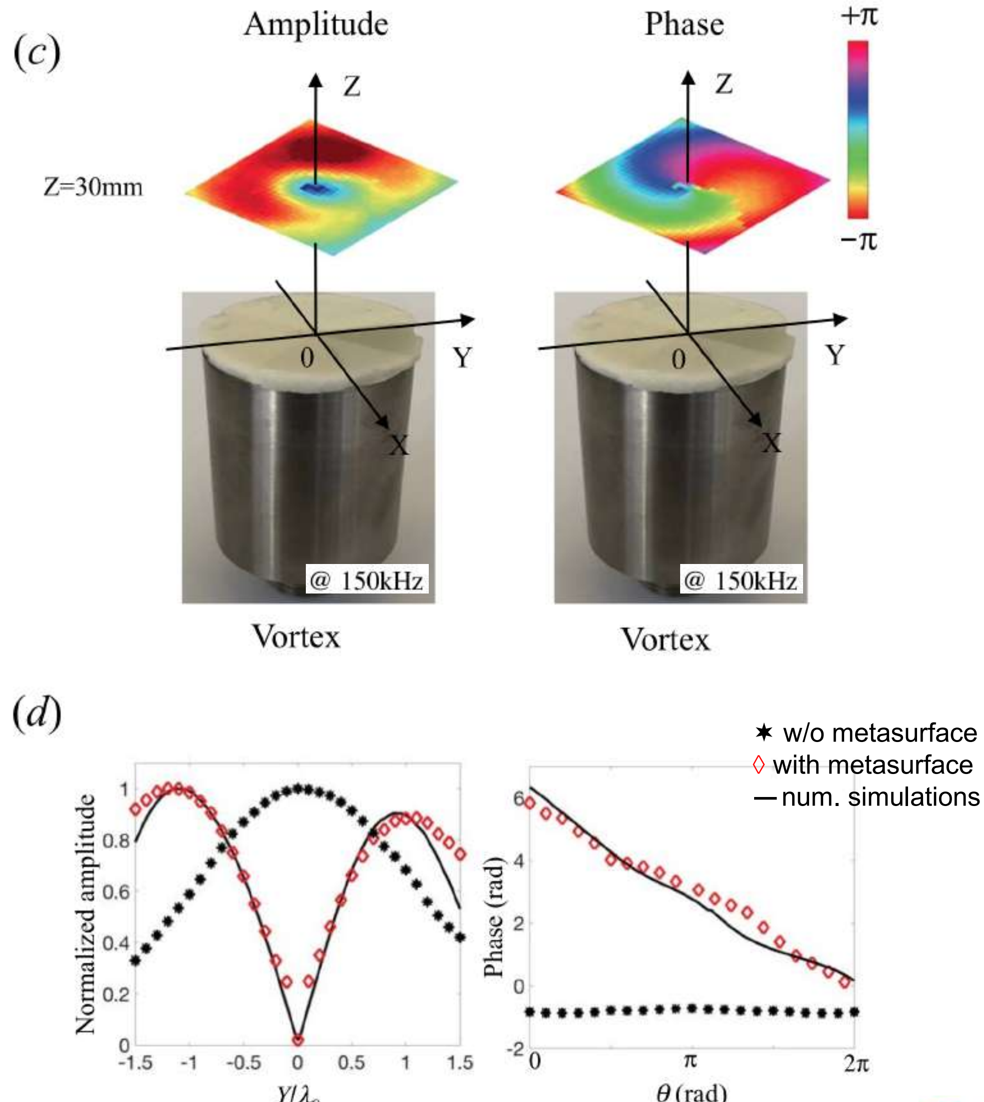


Instantaneous pressure field
measured in the transverse *XY*-plane,
the acoustic wave propagating along the *Z*-axis.

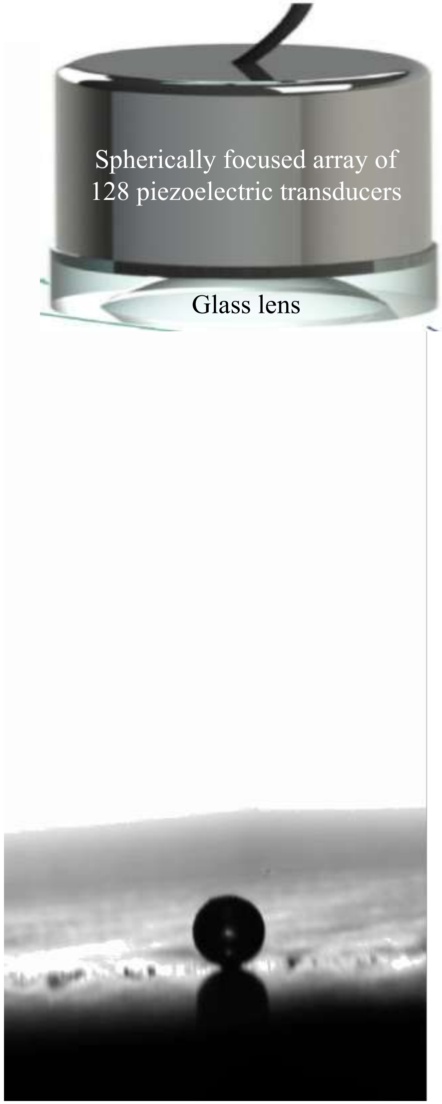
3D wavefront twisting

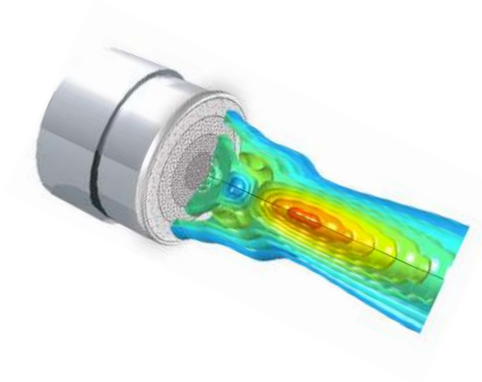


Azimuthally graded flat lens

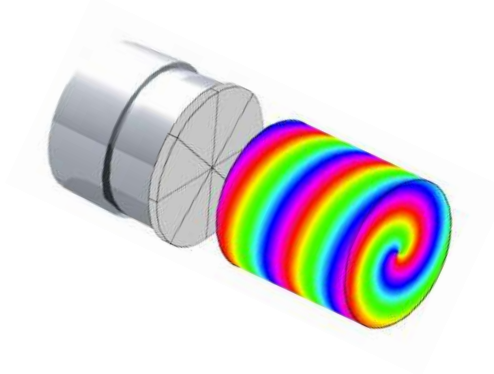


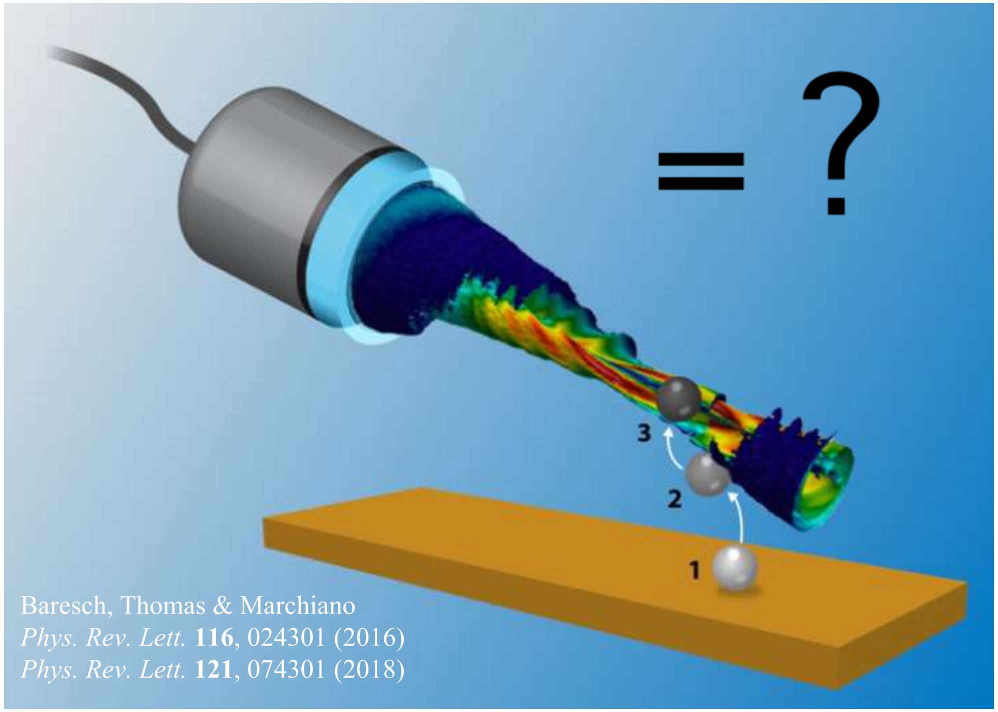
Towards “soft acoustic tweezers” ?





+

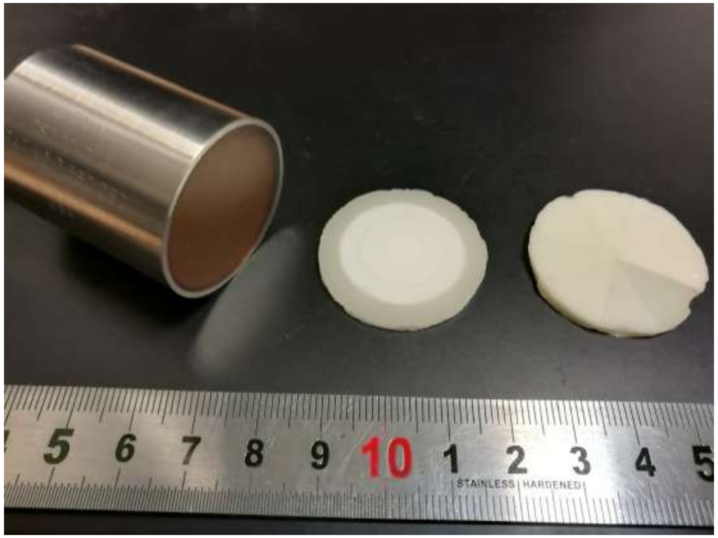


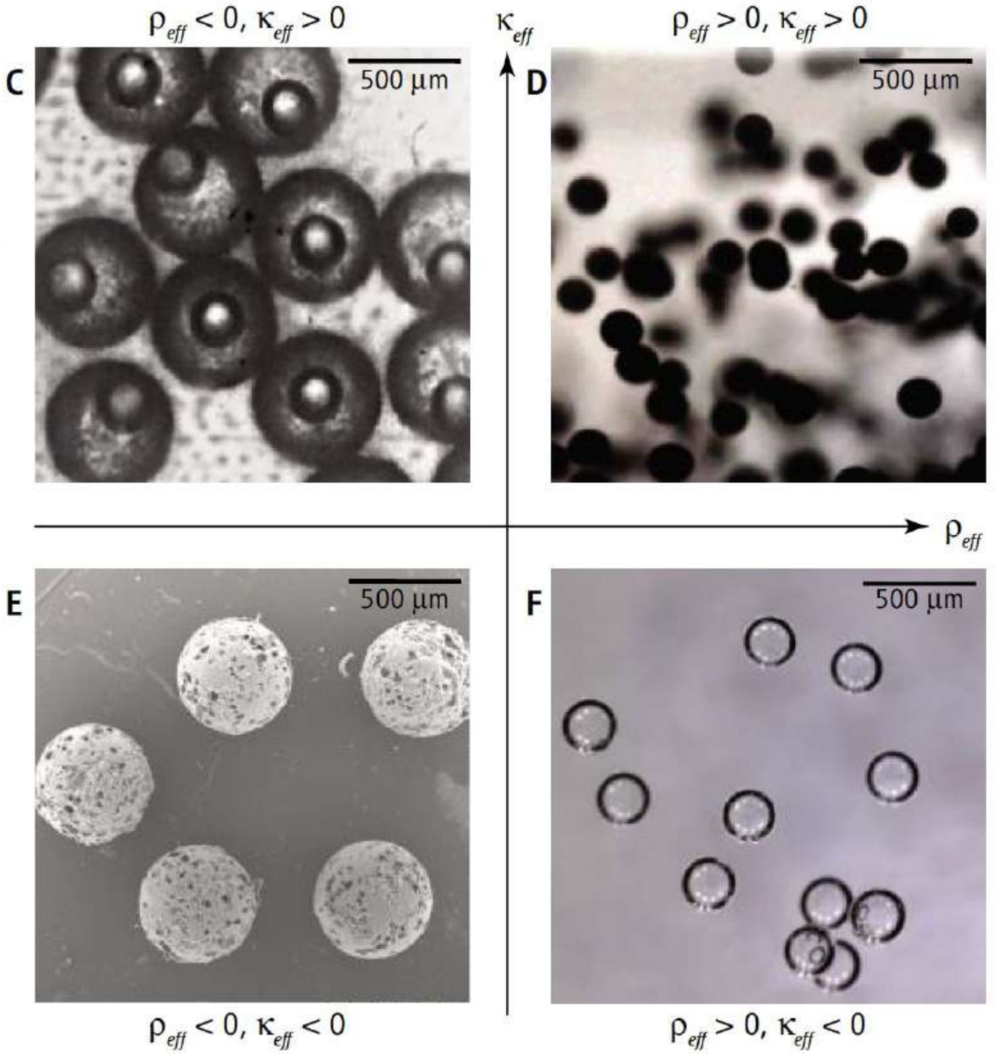


Baresch, Thomas & Marchiano
Phys. Rev. Lett. **116**, 024301 (2016)
Phys. Rev. Lett. **121**, 074301 (2018)

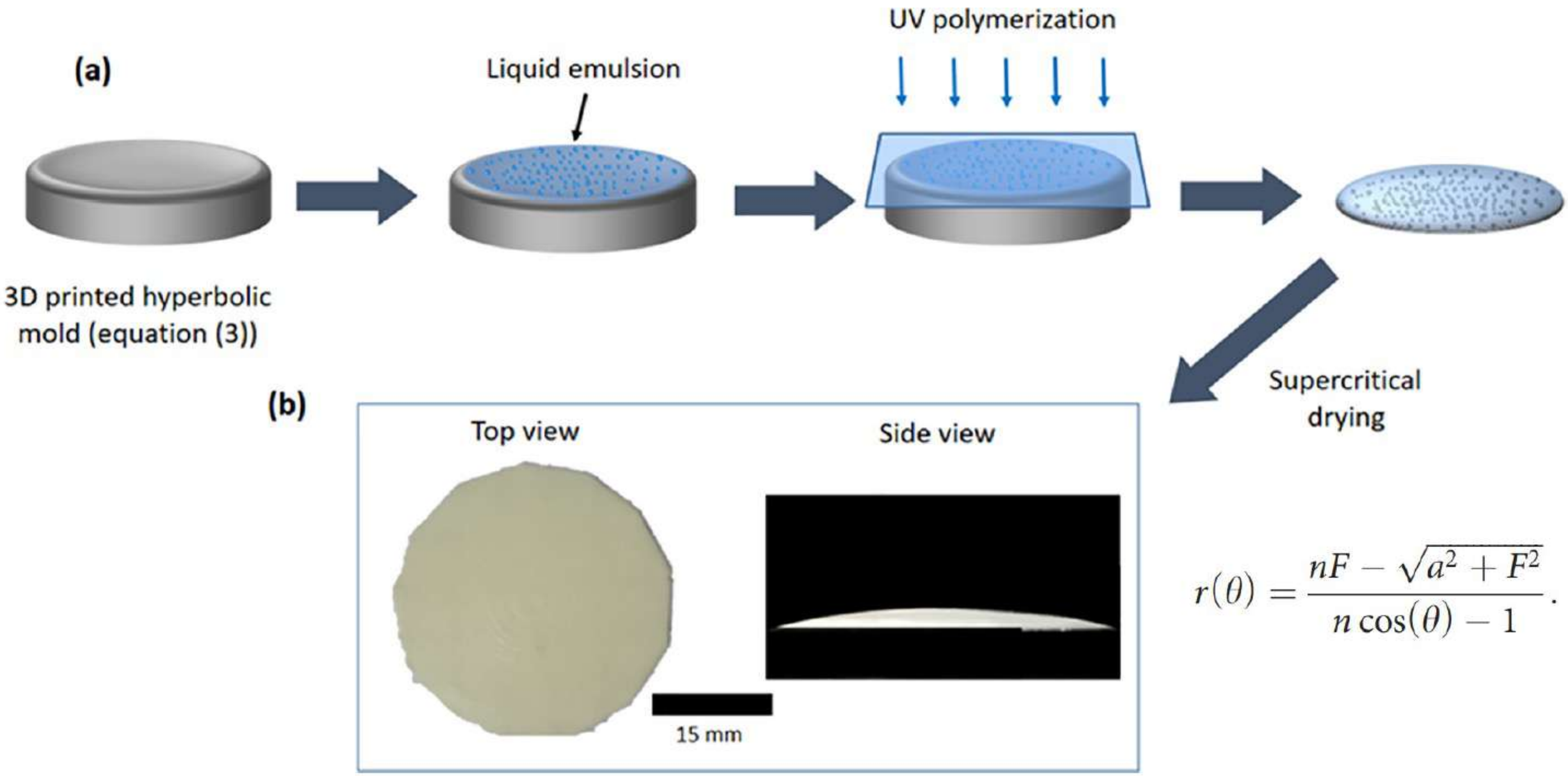
Conclusion

Controlling (ultra)sound with soft acoustic metamaterials!





Quasi-flat high-index acoustic lenses



$$r(\theta) = \frac{nF - \sqrt{a^2 + F^2}}{n\cos(\theta) - 1}.$$

Quasi-flat high-index acoustic lenses

Applied Physics Letters ARTICLE scitation.org/journal/apl

Quasi-flat high-index acoustic lens for 3D underwater ultrasound focusing

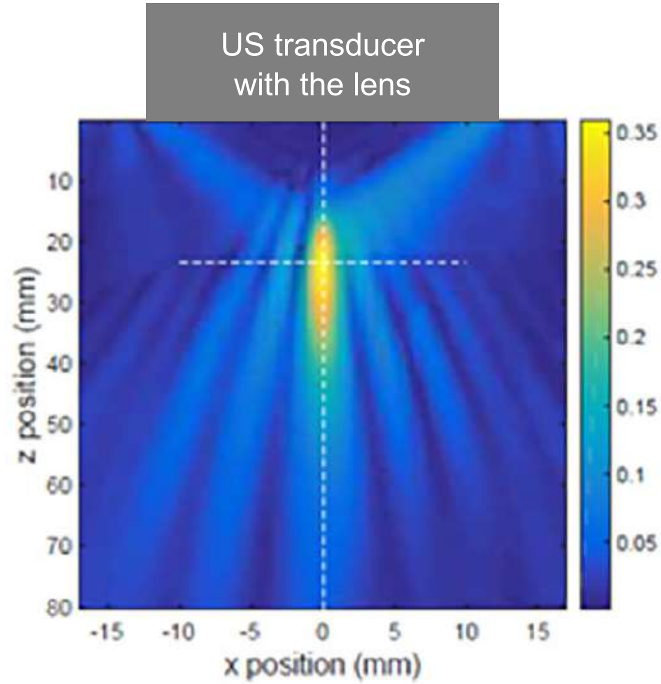
Cite as: Appl. Phys. Lett. **120**, 221701 (2022); doi: 10.1063/5.0088503
Submitted: 17 February 2022 · Accepted: 12 May 2022
Published Online: 31 May 2022

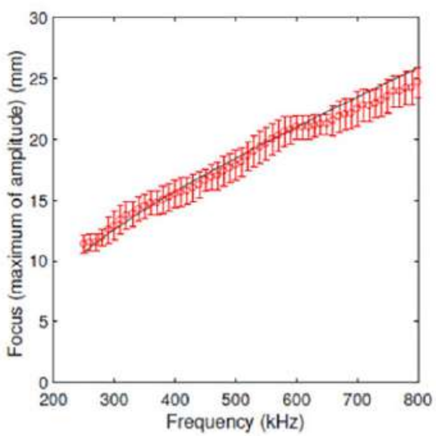
Olivier Lombard,[1,a)] Raj Kumar,[2] Olivier Mondain-Monval,[2,b)] Thomas Brunet,[1,b)] and Olivier Poncelet[1]

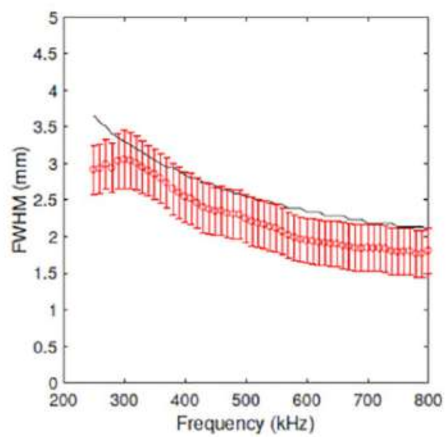
AFFILIATIONS

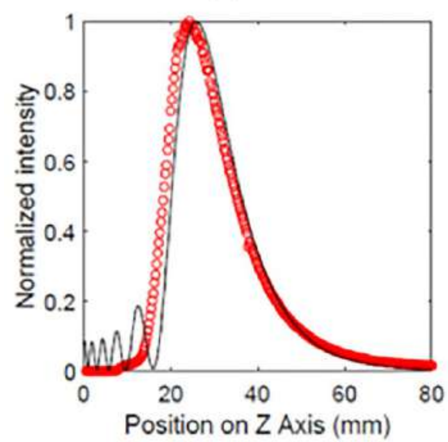
[1]University Bordeaux, CNRS, Bordeaux INP, ENSAM, UMR 5295 I2M, F-33405 Talence, France
[2]University Bordeaux, CNRS, UMR 5031 CRPP, F-33600 Pessac, France

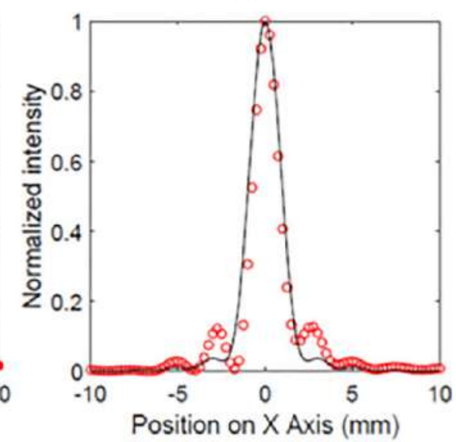
Note: This paper is part of the APL Special Collection on Acoustic and Elastic Metamaterials and Metasurfaces.
[a)]**Present address:** University Avignon, UMR 1114 EMMAH, Avignon, France.
[b)]**Authors to whom correspondence should be addressed:** olivier.mondain@crpp.cnrs.fr and thomas.brunet@u-bordeaux.fr









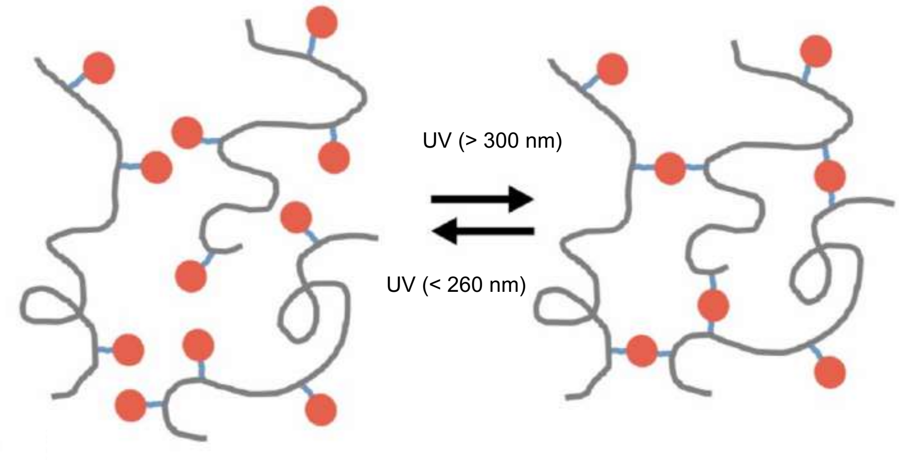


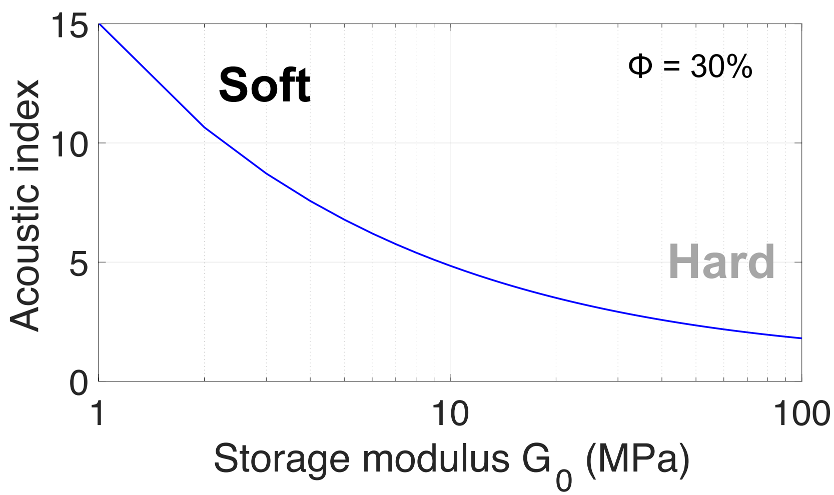
Perspectives: towards soft reconfigurable lenses

For soft porous silicone rubbers:

$$K_0 \approx 1 \text{ GPa} \gg G_0$$

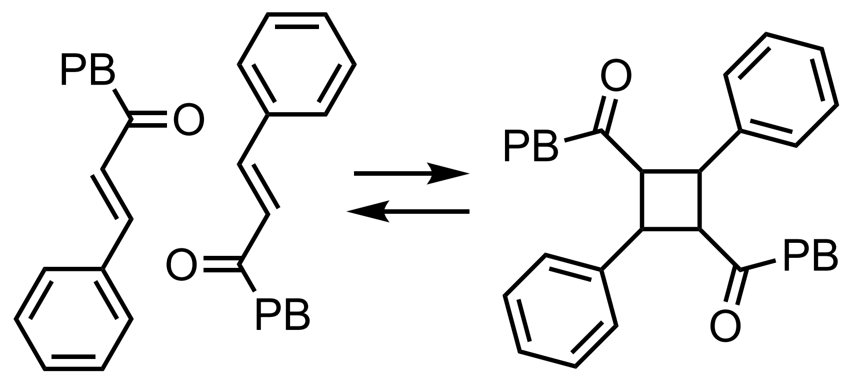
$$\Rightarrow n \approx n_0 \sqrt{1 + \frac{3K_0}{4G_0}\phi}$$





Soft

Hard



Acknowledgements

Benoit Mascaro
Post-Doc Acoustics
(2011-2015)

Simon Raffy
PhD Materials
(2011-2014)

Kevin Zimny
Post-Doc Materials
(2012-2014)

Aurore Merlin
Post-Doc Materials
(2012-2015)

Abdoulaye Ba
PhD Acoustics
(2013-2016)

Artem Kovalenko
Post-Doc Materials
(2015-2017)

Yabin Jin
Post-Doc Acoustics
(2017-2018)

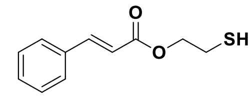
Raj Kumar
PhD Materials
(2016-2019)

DGA

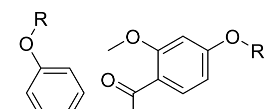
AMADEus
Advanced MAterials by DEsign
labEx
Initiatives d'excellence

EUROPEAN OFFICE AEROSPACE R&D

Agence Nationale de la Recherche
ANR



Simon Colanges
PhD in Chemistry
(2021-2024)



Arthur Lamouroux
Post-Doc in Chemistry
(2022-2024)

Acknowledgements

Jacques Leng (LOF)
Microfluidics

Thomas Vidil (LCPO)
Chemistry

Christophe Aristégui (I2M)
Multiple scattering

Acoustics

Soft Matter

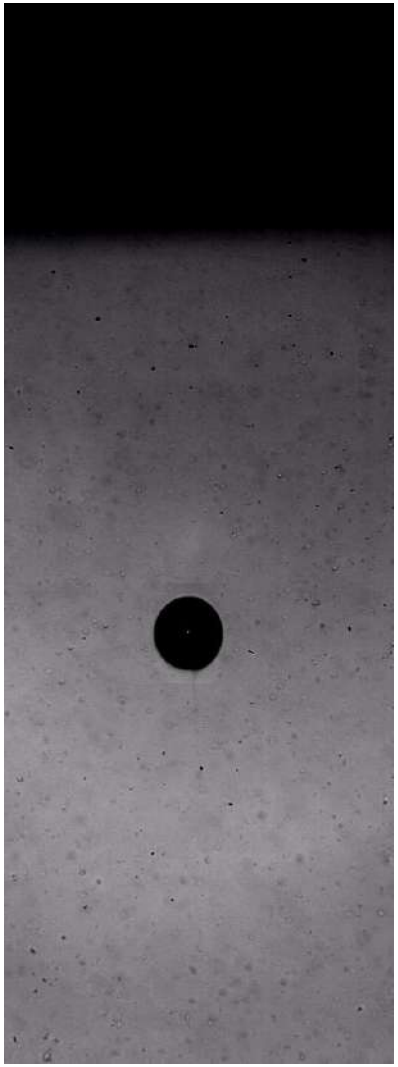
Olivier Sandre (LCPO)
Magnetic nanoparticles

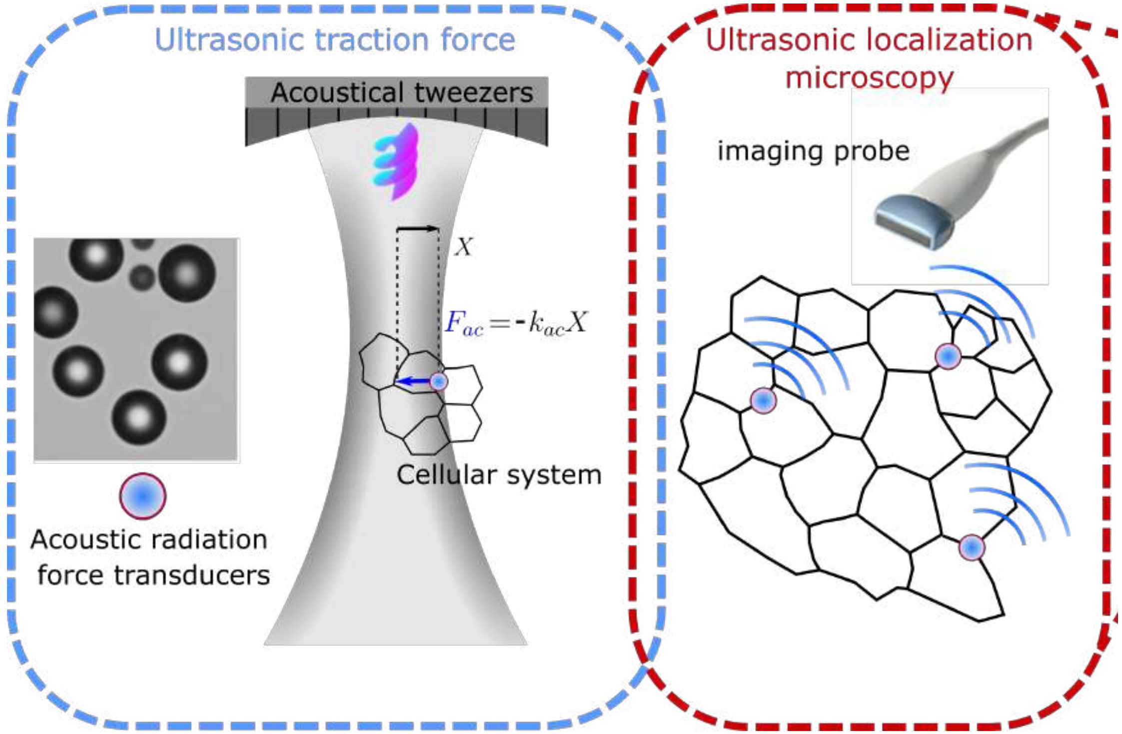
Olivier Poncelet (I2M)
Wave propagation

Olivier Mondain-Monval (CRPP)
Physico-Chemistry

Samuel Marre (LCPO)
Supercritical fluids

A 2-year Postdoc position is available in our team!

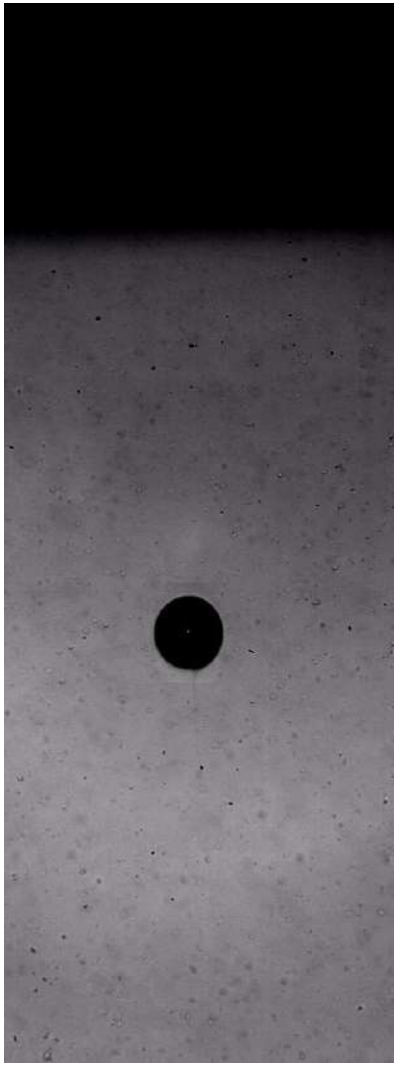




Acoustical tweezers for the life sciences

Contact: diego.baresch@u-bordeaux.fr

A 2-year Postdoc position is available in our team!



Acoustic trapping and manipulation techniques that use the radiation force of ultrasound are emerging as mature experimental tools in the fields of applied physics, material science and physical biology. They are proving increasingly relevant **wherever materials are to be probed or handled with large forces, large penetration depths and biocompatibility**, which are situations that preclude the use of laser light and more conventional optical trapping methods [1]. The main aim of our research group is to prove the suitability of acoustic trapping to explore a range of interesting phenomena in the **mechanics of soft and biological materials**. Our approach is based on the trapping and manipulation of micrometric radiation force transducers **with single-beam acoustical tweezers** [2-3]. We will pursue our efforts in developing the trapping methodology, and explore the capability of these transducers to non-invasively measure local and subtle mechanical properties of a range of soft and biological materials.

Job Description

The candidate will be in charge of implementing **manipulation and imaging strategies** of the radiation force transducers used in the lab. He/she will use our acoustic trapping setup and imaging protocols to explore the force transducers' response to ultrasound, calibrate their sensitivity and confront the experimental data to the models we have developed in the lab. Activities and methods include:

- **Instrumentation**, experimental design and signal processing for ultrasound.
- Basics of optical imaging (macro) and image analysis.
- **Ultrasonic imaging**.
- **Data analysis and basic programming** with Python/Matlab.

The Lab and working environment

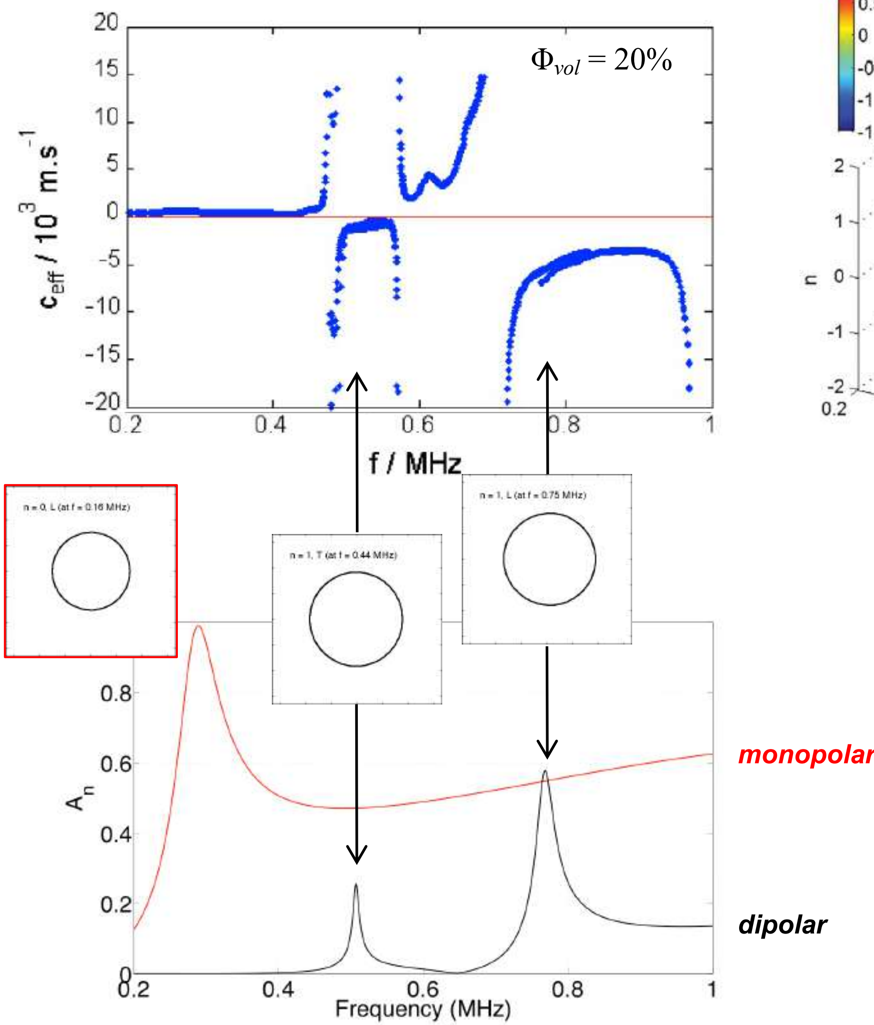
The research group is located in the Physical Acoustics department of the Mechanical engineering Institute (I2M, Instut de Mécanique et d'ingénierie) in the exceptional environment offered by the city of Bordeaux. The postdoc will work in close collaboration with the PI and a 2nd year graduate student. He/she will also closely collaborate with our scientific partners located in the bioengineering department.

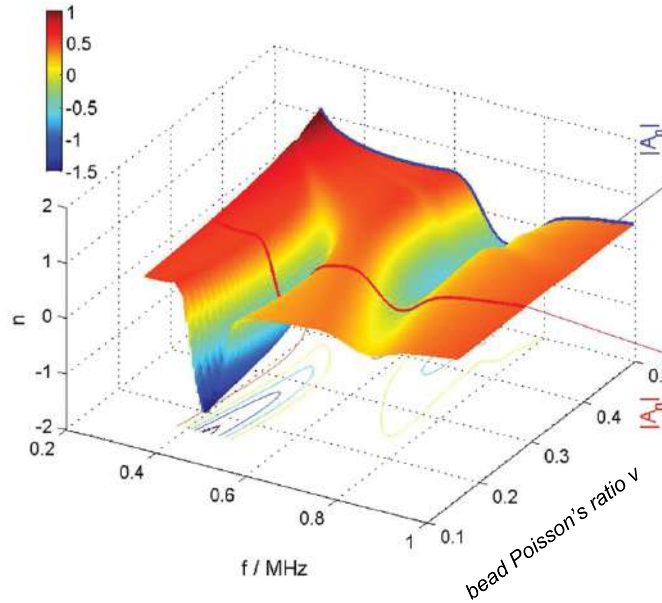
Application and other information

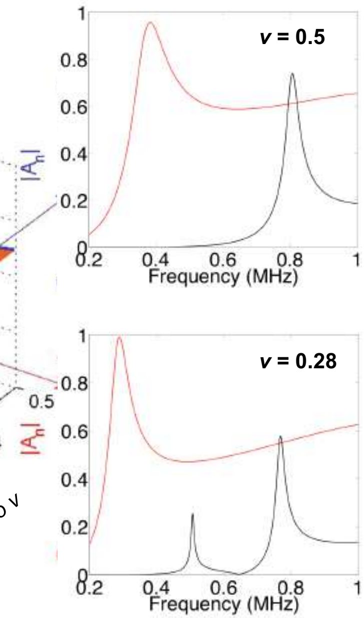
Application: directly by email to diego.baresch@u-bordeaux.fr
Expected starting date: Fev. March 2024 for 2 years.
Salary 2800 to 4000€ gross per month (depending on experience)
Funding: ANR young researcher program, includes funds for travels & conferences.

Dual-band negative index ultrasonic metafluids

Micro-porous *silica-xerogel* micro-beads







criteria for emergence of two “negative bands” :

- low size dispersion
- high volume fraction
- not too high absorption
- Poisson ratio *ν* less than 0.4

Raffy *et al.*, *Advanced Materials* **28**, 1760 (2016)

Effective constitutive parameters

for dissipative media:

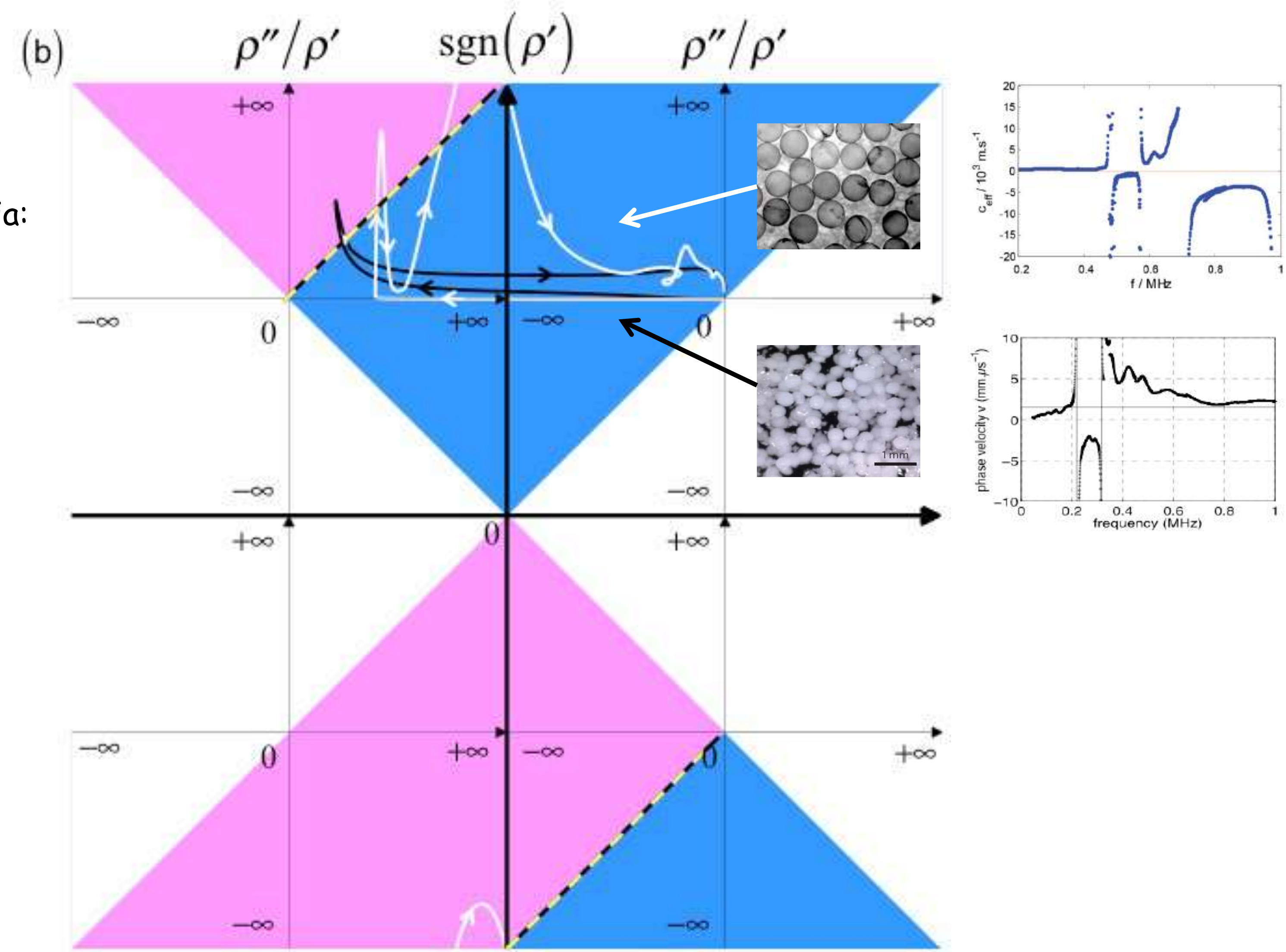
$$\rho_{eff} = \rho'_{eff} + i\rho''_{eff}$$

$$\kappa_{eff} = \kappa'_{eff} + i\kappa''_{eff}$$

$v_{eff} > 0$

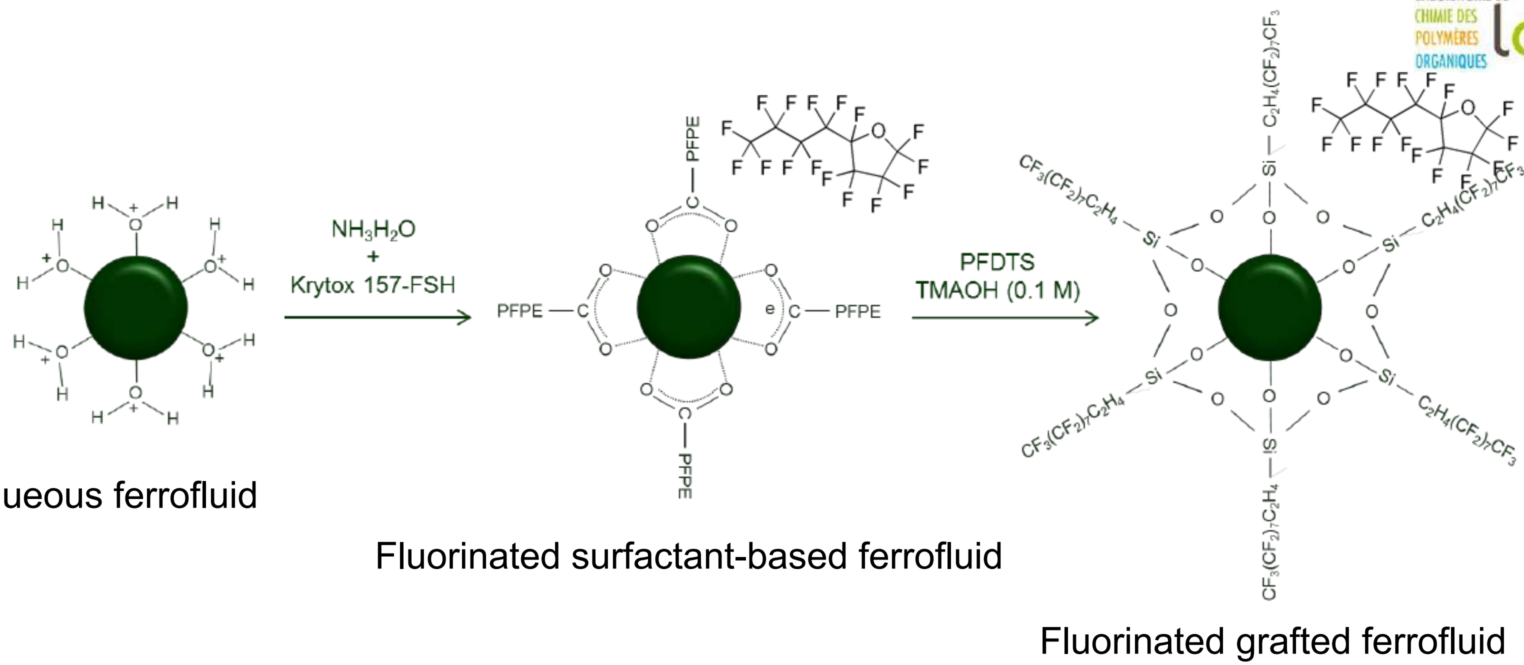
$v_{eff} = \infty$

$v_{eff} < 0$



Brunet, Poncelet and Aristégui., *EPJ Appl. Metamat.* **2**, 3 (2015)

Production of a stable fluorinated ferrofluid



- Preparation of aqueous ferrofluid : $Fe^{2+} + 2Fe^{3+} + 8OH^{-} \longrightarrow Fe_3O_4 + 4H_2O$
- Coating with a perfluoropolyether functionalized with a carboxylic acid
- Ligand exchange: fluorosilane covalently bonds on the surface of the MNPs

Zimny *et al.*
J. Mater. Chem. B **2**, 1285 (2014)