Institut Langevin
ONDES ET IMAGES

Physique et Mécanique
des Milieux Hétérogènes
UMR 7636

Elastograhy in deformed viscoelastic strips

A. DELORY[1,2], D. KIEFER[1], M. LANOY[1,3], A. EDDI[2], C. PRADA[1] & F. LEMOULT[1]

GdR MecaWave – May 9, 2022

[1] Institut Langevin, ESPCI Paris, Université PSL, CNRS, Paris, France
[2] PMMH, ESPCI Paris, Université PSL, Sorbonne Université, Paris
[3] LAUM, IA-GS, CNRS, Le Mans Université, Le Mans, France

ESPCI PARIS PSL SIMONS FOUNDATION cnrs

From a static measurement: Palpation ...

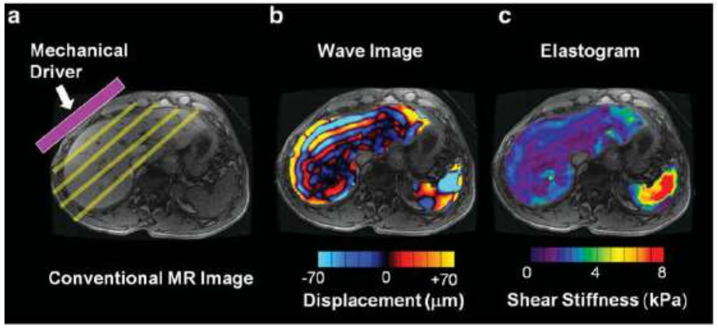
Evaluating the body resistance (Young's modulus E)

From Wikipedia *"Doctor Murai Kinzan's teachings (alias Genshinkan, 1733-1815)"* Collection W. Michel (Fukuoka, Japon)
Sandrin et al. *"Non-Invasive Assessment of Liver Fibrosis by Vibration-Controlled Transient Elastography (Fibroscan®)"* (2011)
Formation Pole Therapeutes "*L'*importance de la palpation abdominale et des fascias au cœur de la formation techniques-manuelles"

… to a dynamic one: Elastography

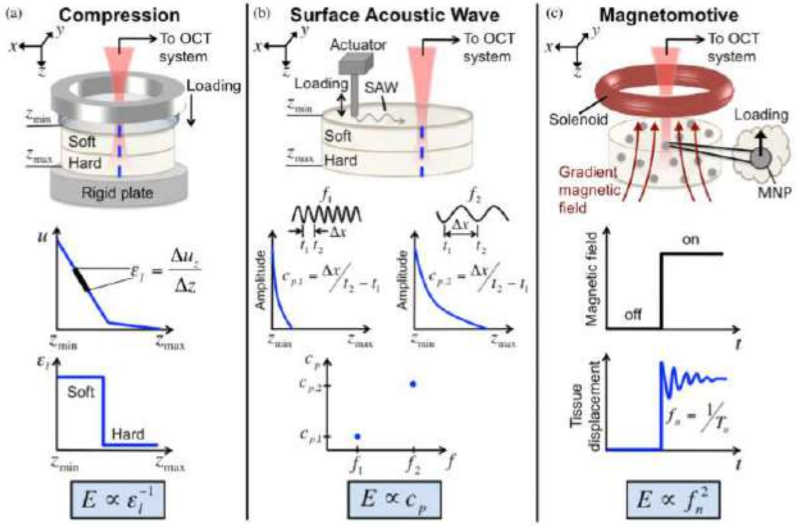
Field of view

Measuring shear wave velocity:
$$E = 3 \times \rho V^2$$



MRE

OCE



Spatial resolution

Venkatesh et al "*Magnetic resonance elastography of liver: Technique, analysis, and clinical applications*" in JMRI, **37** (2013)
Kennedy et al. "*A Review of Optical Coherence Elastography: Fundamentals, Techniques and Prospects*" in IEEE JSTQE, **20**, 2 (2014)
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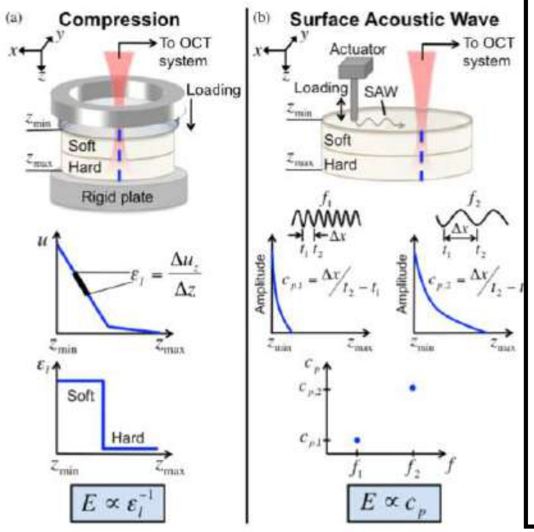
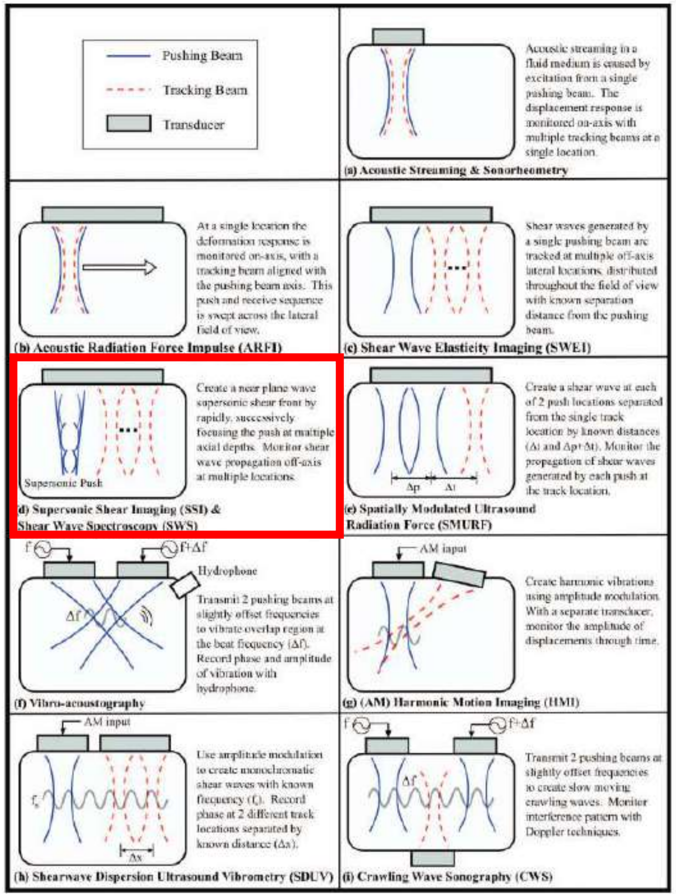




(a) Acoustic Streaming & Sonorheometry

Acoustic streaming in a fluid medium is caused by excitation from a single pushing beam. The displacement response is monitored on-axis with multiple tracking beams at a single location.

(b) Acoustic Radiation Force Impulse (ARFI)

At a single location the deformation response is monitored on-axis, with a tracking beam aligned with the pushing beam axis. This push and receive sequence is swept across the lateral field of view.

(c) Shear Wave Elasticity Imaging (SWEI)

Shear waves generated by a single pushing beam are tracked at multiple off-axis lateral locations distributed throughout the field of view with known separation distance from the pushing beam.

(d) Supersonic Shear Imaging (SSI) & Shear Wave Spectroscopy (SWS)

Create a near plane wave supersonic shear front by rapidly, successively focusing the push at multiple axial depths. Monitor shear wave propagation off-axis at multiple locations.

(e) Spatially Modulated Ultrasound Radiation Force (SMURF)

Create a shear wave at each of 2 push locations separated from the single track location by known distances (Δt and Δp+Δt). Monitor the propagation of shear waves generated by each push at the track location.

(f) Vibro-acoustography

Transmit 2 pushing beams at slightly offset frequencies to vibrate overlap region at the beat frequency (Δf). Record phase and amplitude of vibration with hydrophone.

(g) (AM) Harmonic Motion Imaging (HMI)

Create harmonic vibrations using amplitude modulation. With a separate transducer, monitor the amplitude of displacements through time.

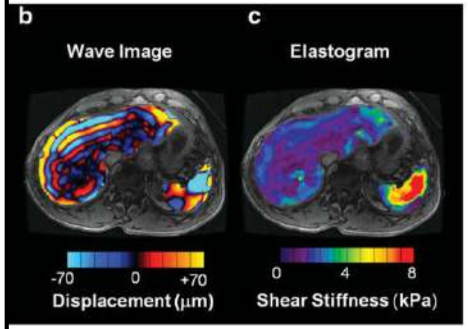
(h) Shearwave Dispersion Ultrasound Vibrometry (SDUV)

Use amplitude modulation to create monochromatic shear waves with known frequency (f_s). Record phase at 2 different track locations separated by known distance (Δx).

(i) Crawling Wave Sonography (CWS)

Transmit 2 pushing beams at slightly offset frequencies to create slow moving crawling waves. Monitor interference pattern with Doppler techniques.

UE



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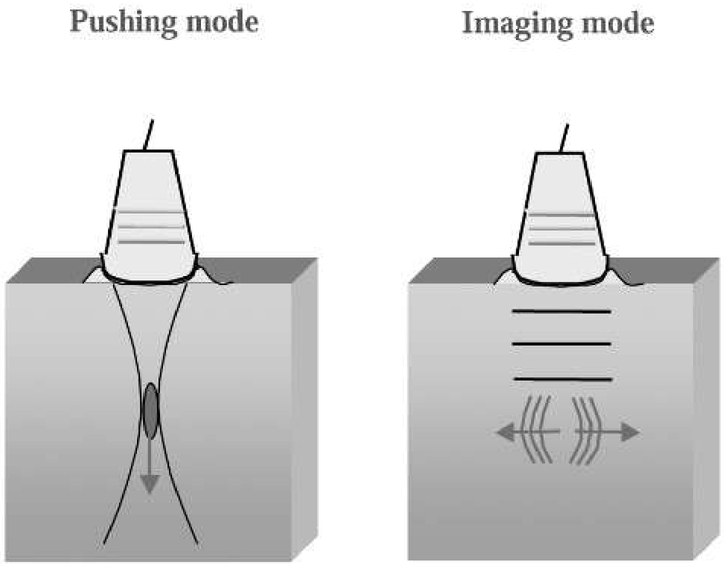
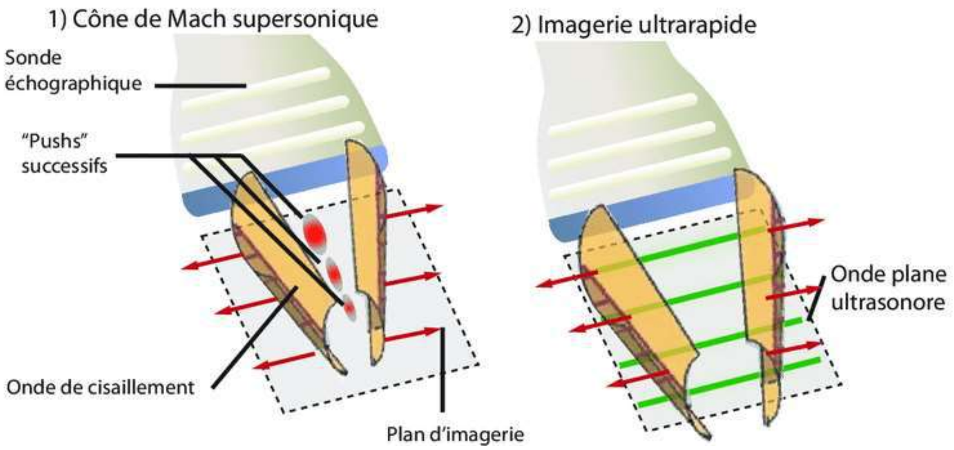
Doherty et al. "*Acoustic radiation force elasticity imaging in diagnostic ultrasound*" in IEEE TUFFC, **60**, 4 (2013)

Supersonic Shear Imaging + Limits





Measuring shear wave velocity:

$$E = 3 \times \rho V^2$$

Some limitations for robust quantitative elastography:

- Waveguide geometry
- Anisotropy
- Viscoelasticity
- Prestress

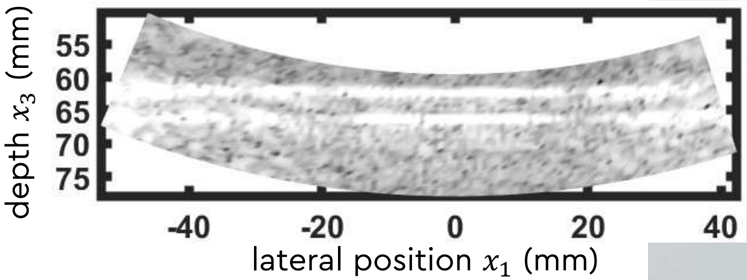
Bercoff et al. "*Supersonic shear imaging*" IEEE TUFFC, **51**, 4 (2004)
Deffieux PhD (2008)

Bilston, NMR in Biomedicine, **31**, 10 (2018)
Sigrist et al., Theranostics, **7**, 5 (2017)

Experimental setup

EcoFlex® = silicon gel

Typical reconstructed image



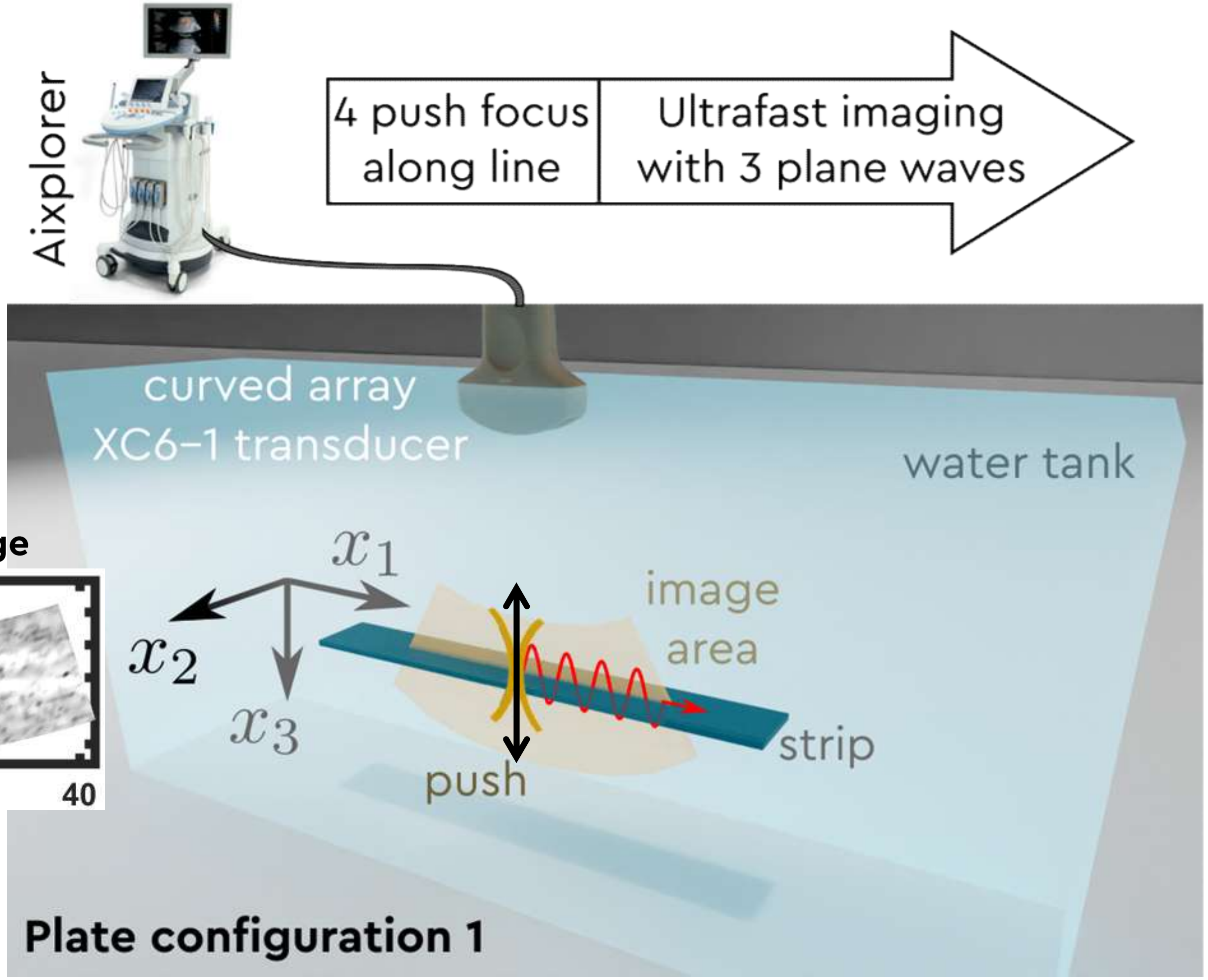
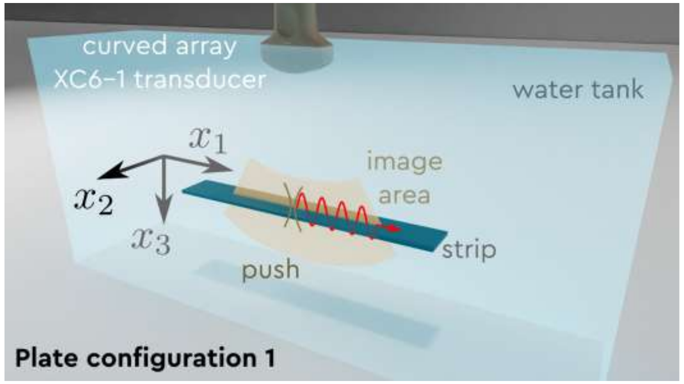
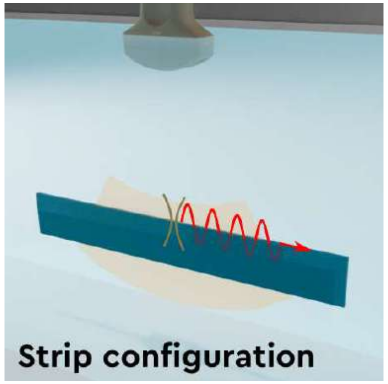
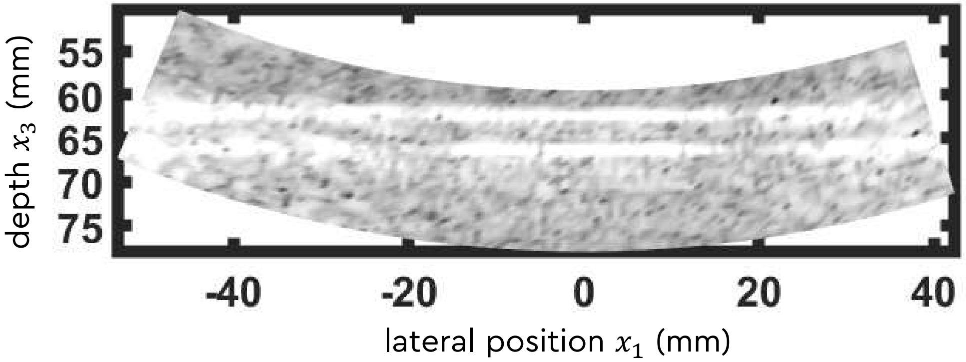


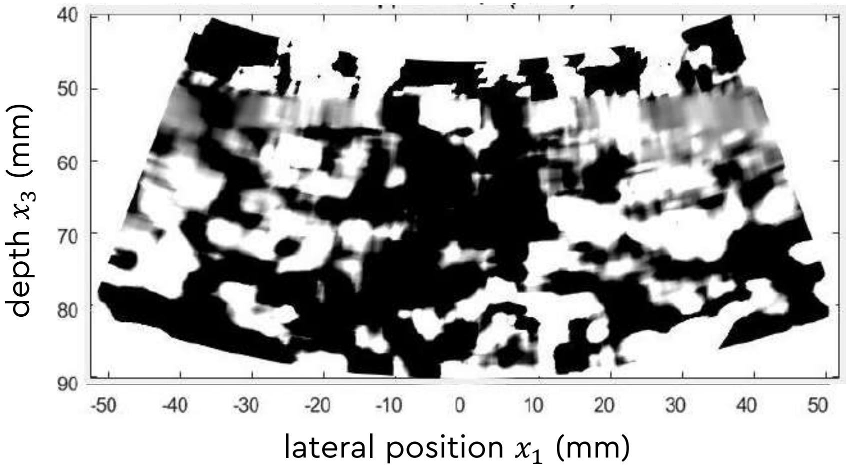
Plate configuration 1

First observations

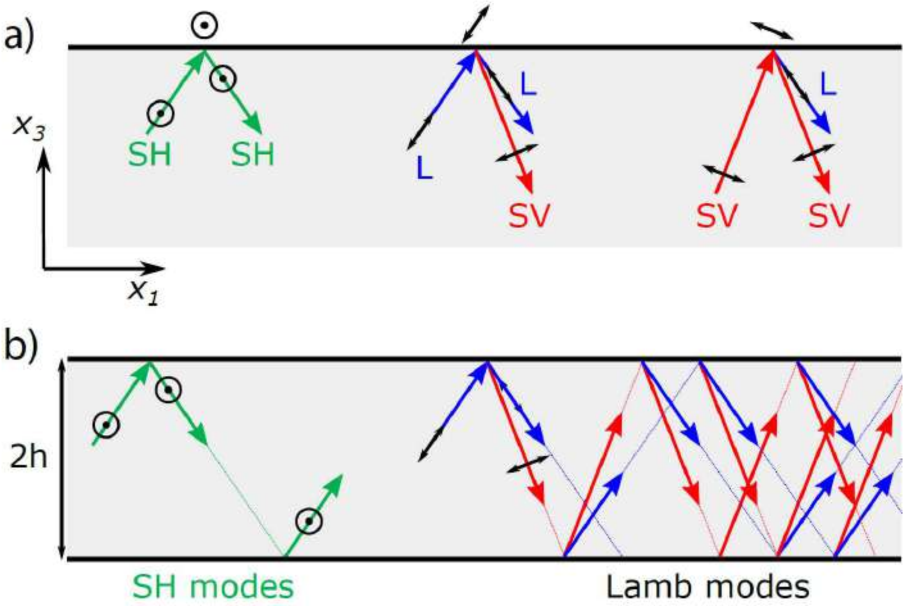


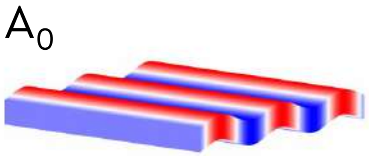




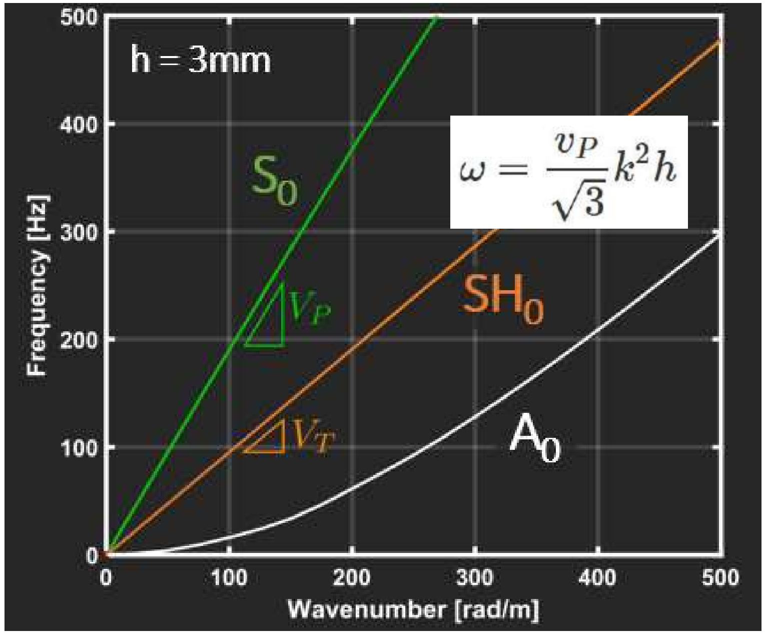


Guided elastic waves in a plate



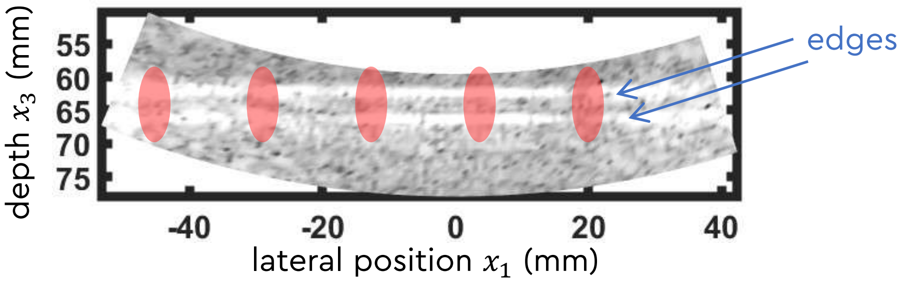


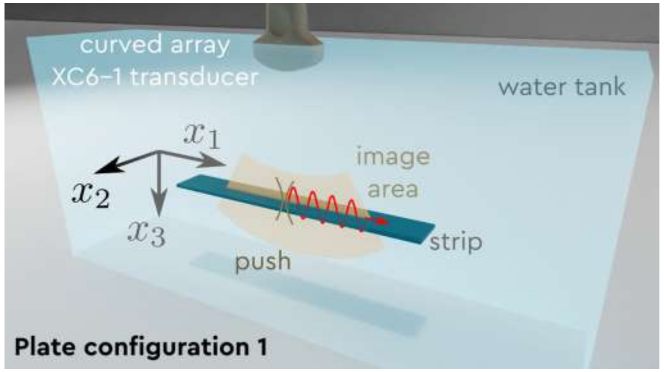
Theoretical dispersion curves



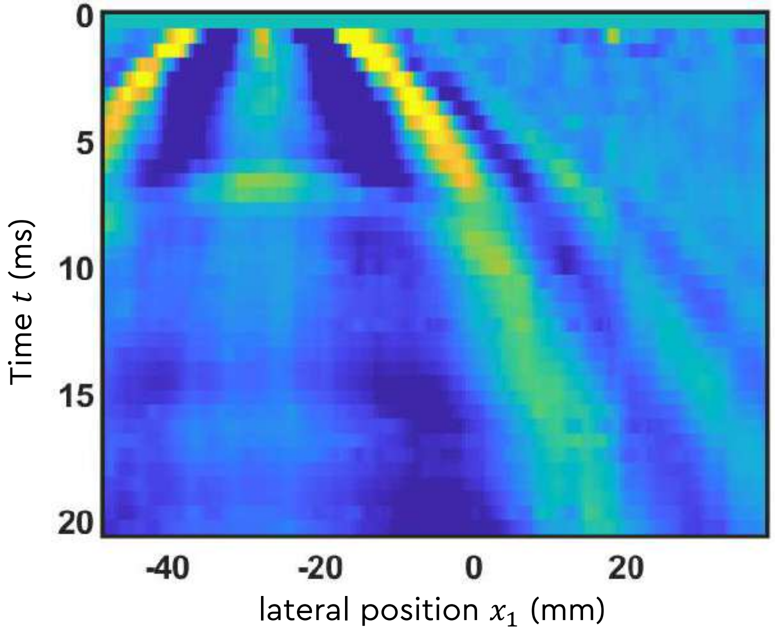
Delory, Lemoult, Lanoy, Eddi & Prada. "*Soft elastomers: A playground for guided waves*", JASA **151** (2022)

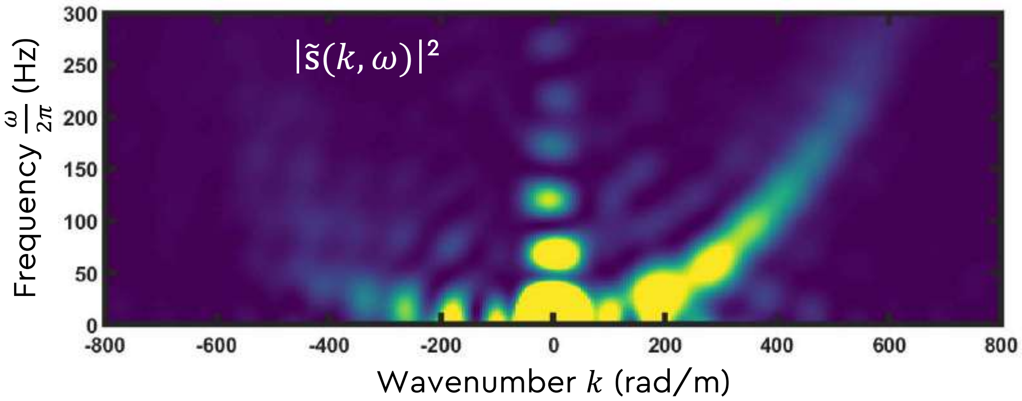
Method in the plate configuration


Typical reconstructed image



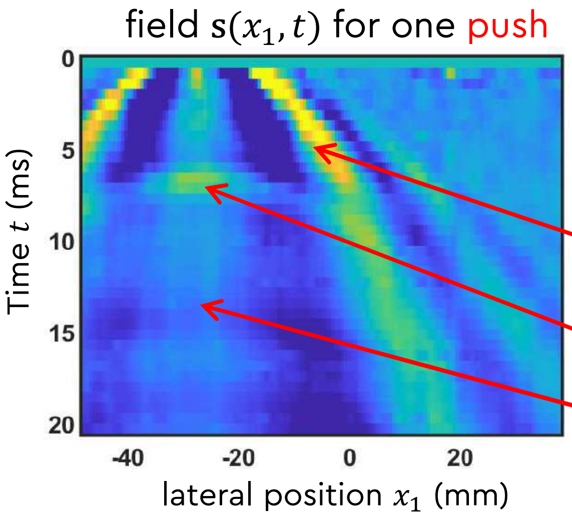
field $s(x_1, t)$ for one push

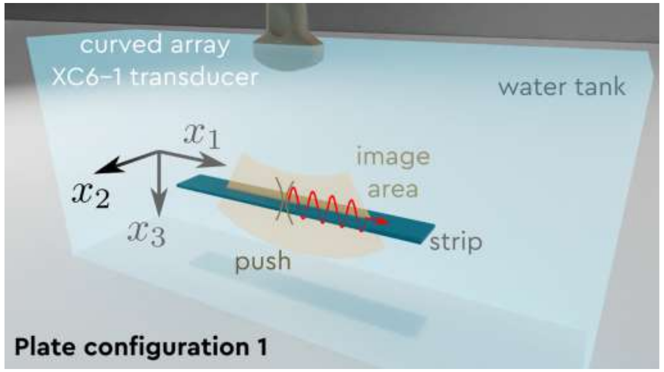




→ Push at different locations and superimpose dispersion curves

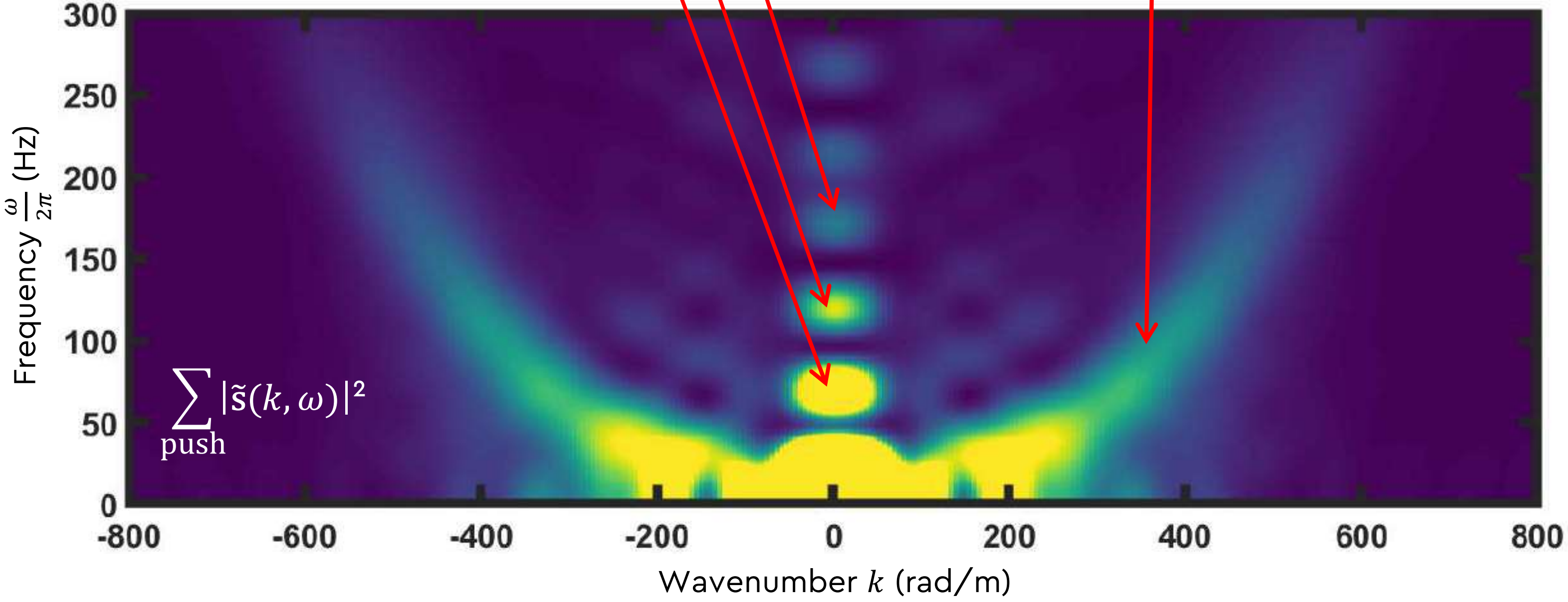
Results in the undeformed strip



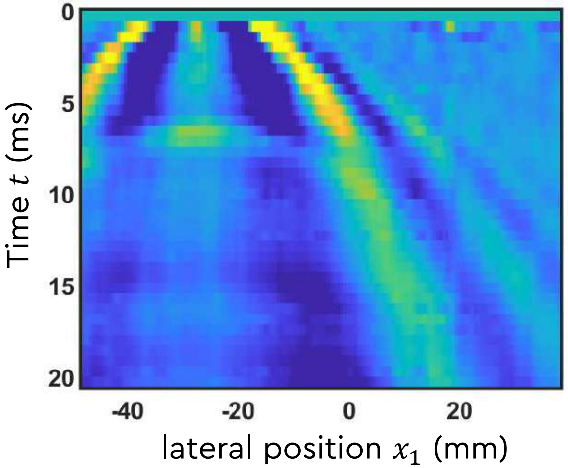


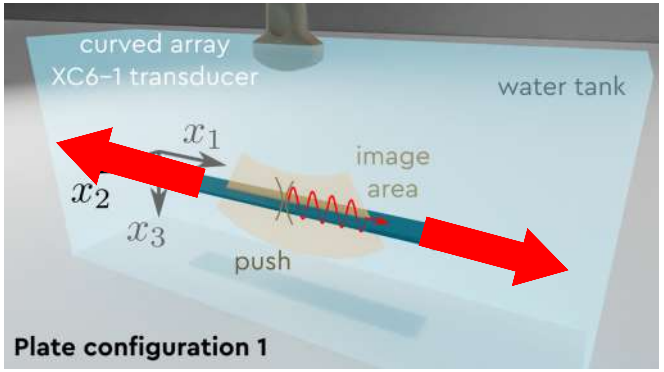
Back and forth along the width x_2

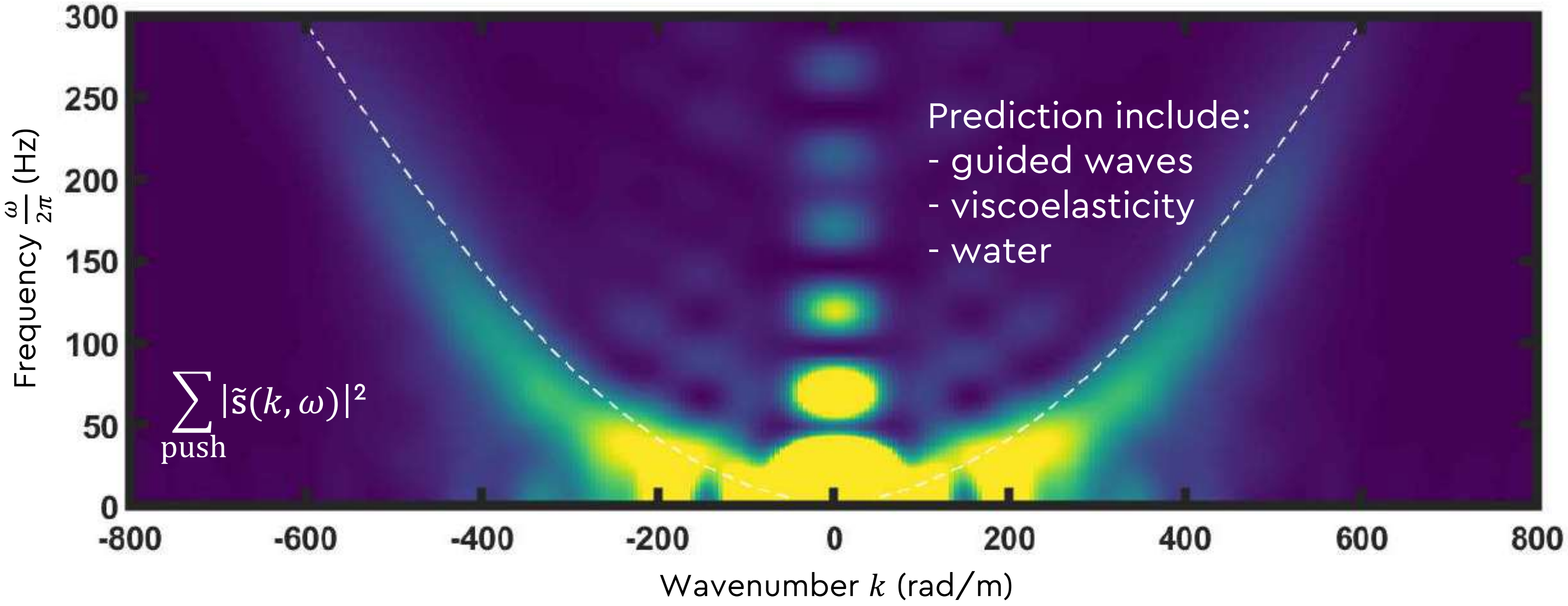
Propagation of quasi-A_0 (in water)



Results in the **stretched** strip

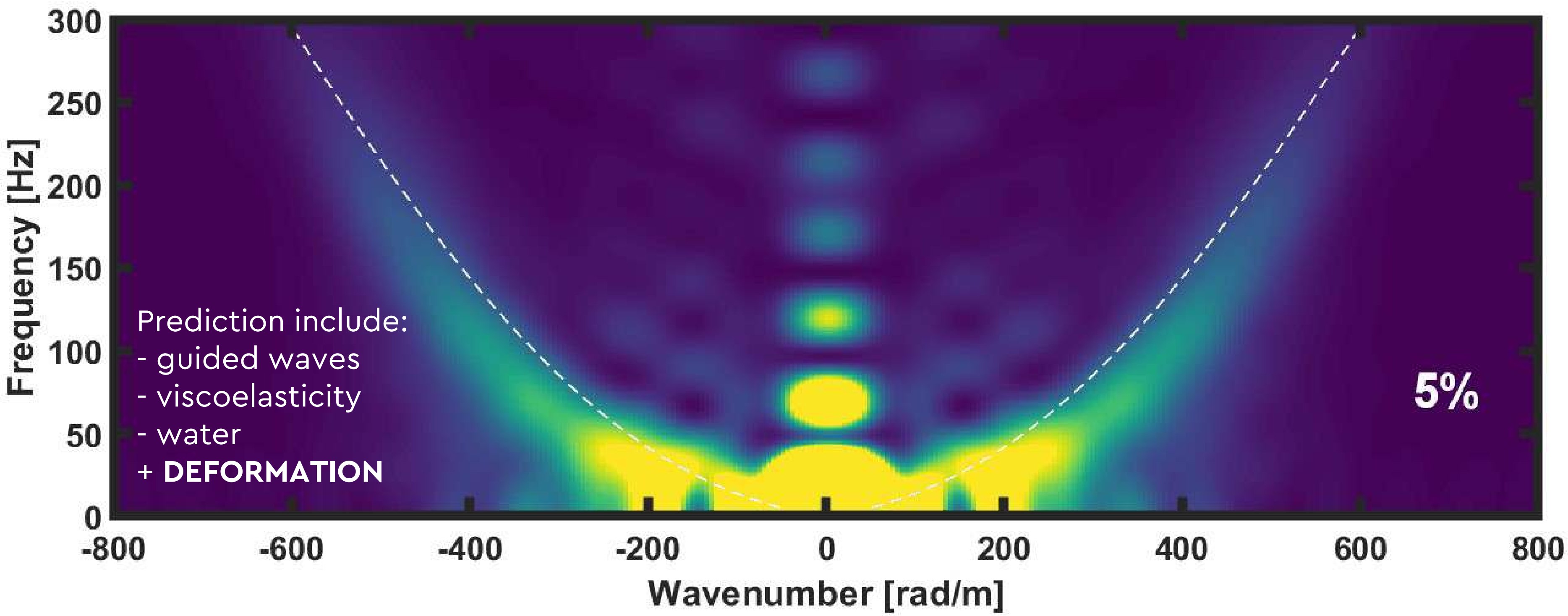

field $s(x_1,t)$ for one push




Prediction include:

- guided waves
- viscoelasticity
- water

Results in a **stretched** strip



Prediction include:
- guided waves
- viscoelasticity
- water
+ **DEFORMATION**

5%

To take deformation into account, use an equivalent elasticity tensor:

$$C^{\omega}_{jikl}\frac{\partial^2 u'_l}{\partial x_j \partial x_k} = \rho \frac{\partial^2 u'_i}{\partial t^2}$$

$$C^{\omega}_{ijkl} = C^{0}_{ijkl} + (\delta_{ik}\delta_{jl} + \delta_{il}\delta_{kj})\left(\nu + \beta\,\frac{\lambda_i^2+\lambda_j^2}{2}\right)(\mathrm{i}\omega)^n$$

Eulerian elasticity tensor
for a Mooney-Rivlin solid

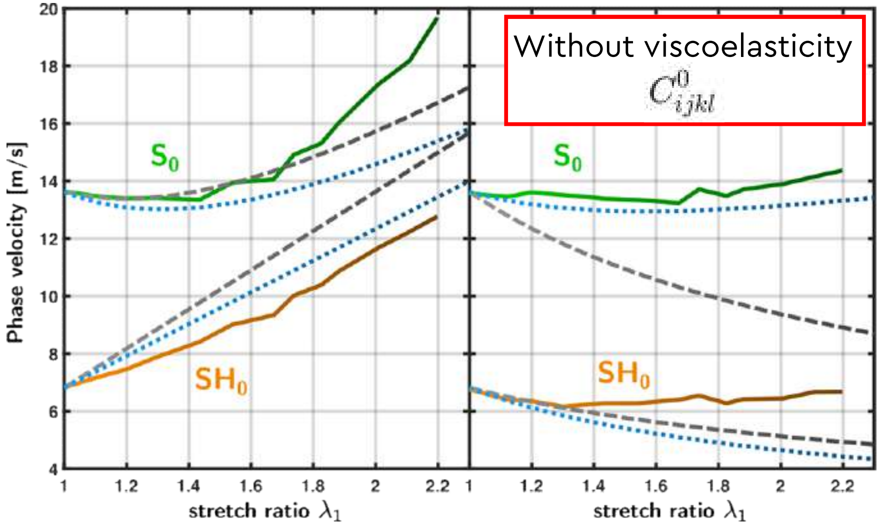
Shear motion

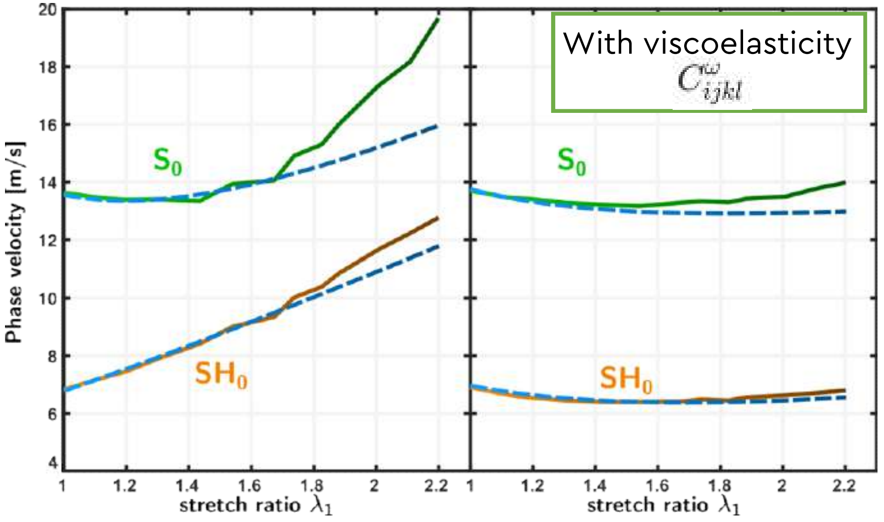
Viscoelastic non-linearity

Fractionnal
KV model

Delory, Lemoult, Eddi & Prada. "*Guided elastic waves in a highly-stretched soft plate* ", EML **61** (2023)

Brief parenthesis about this model





Taking into account the viscoelastic model of our material:

$$\mu(\omega) = \mu_0 [1 + (\mathrm{i}\omega\tau)^n]$$

↓

Fitting for β' and α

Delory, Lemoult, Eddi & Prada. "*Guided elastic waves in a highly-stretched soft plate* ", EML **61** (2023)

First observations in the strip configuration

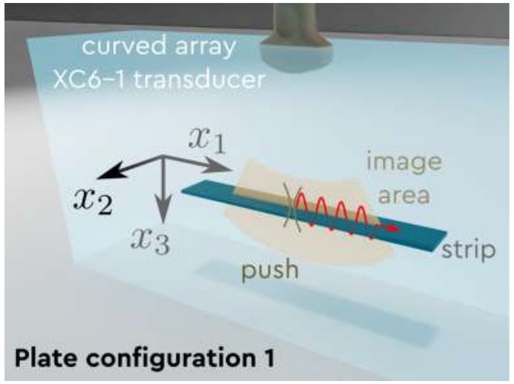
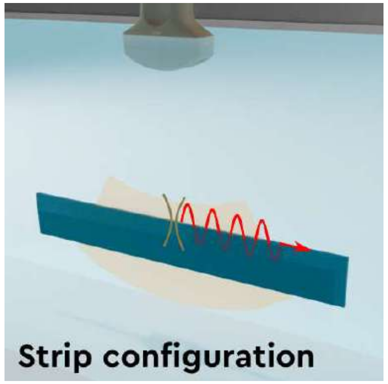
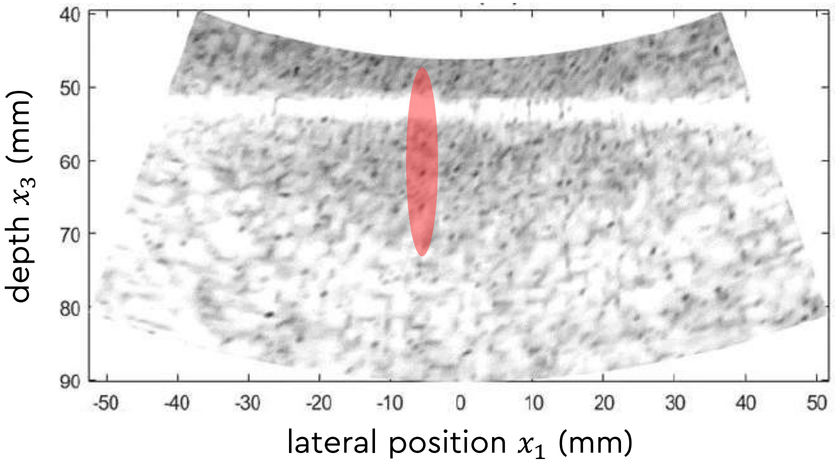
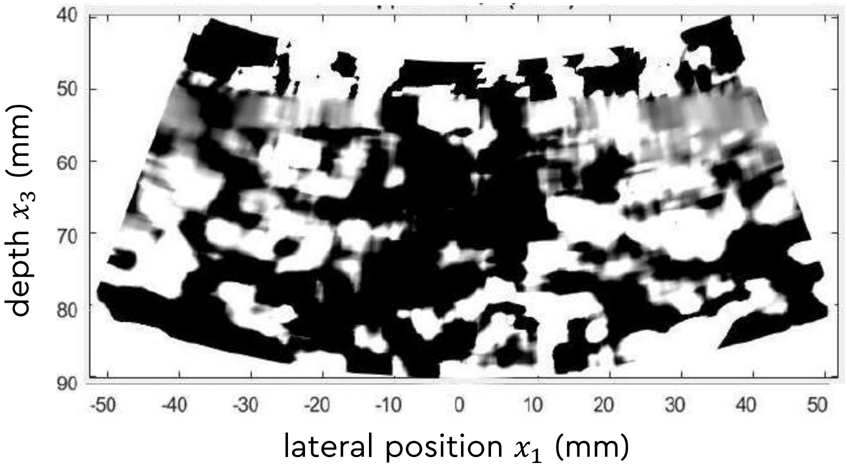


Plate configuration 1



Strip configuration





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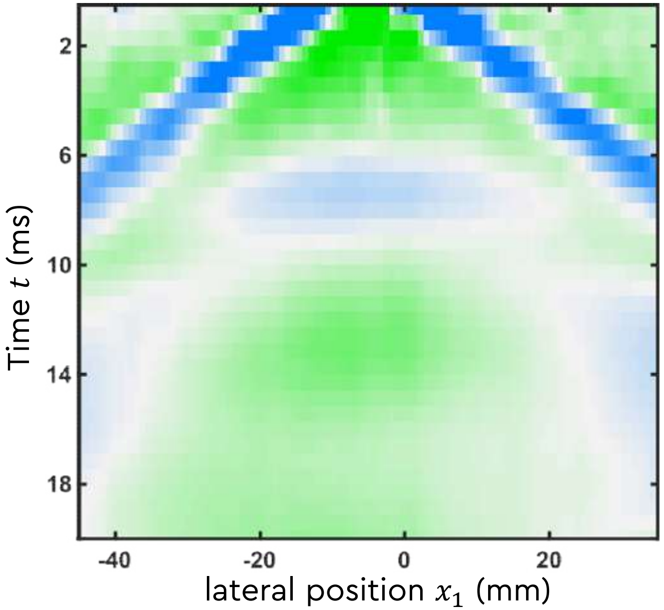
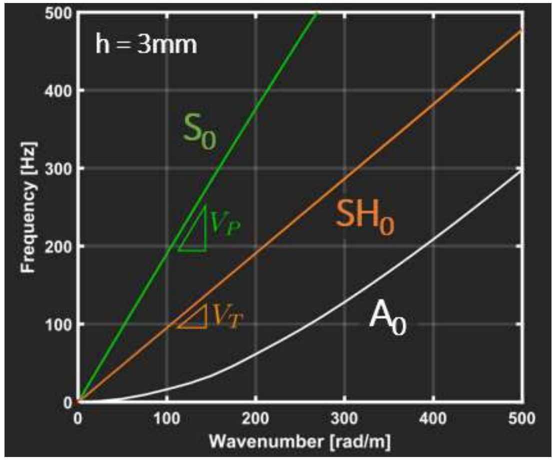
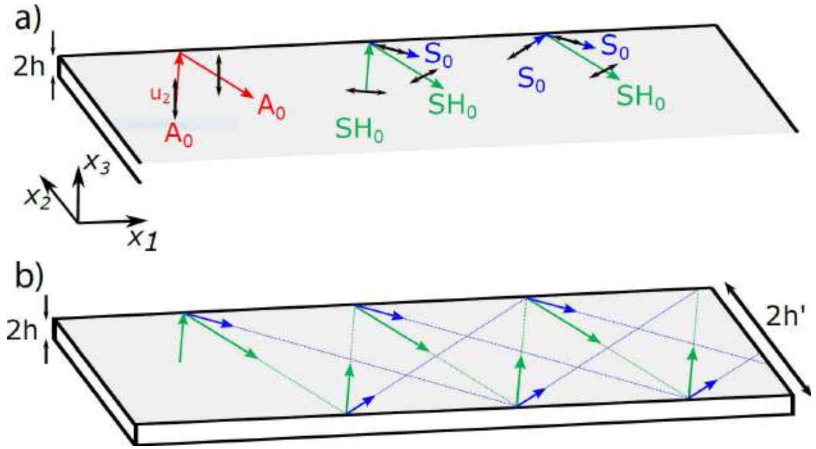
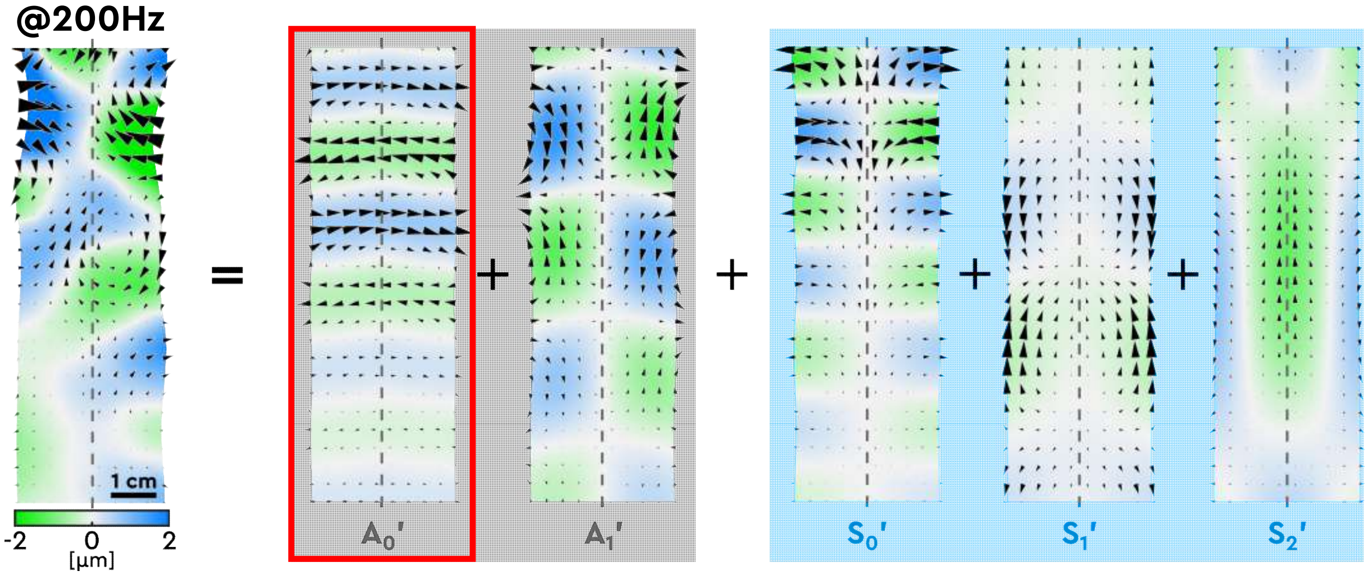


Guided elastic waves in a strip







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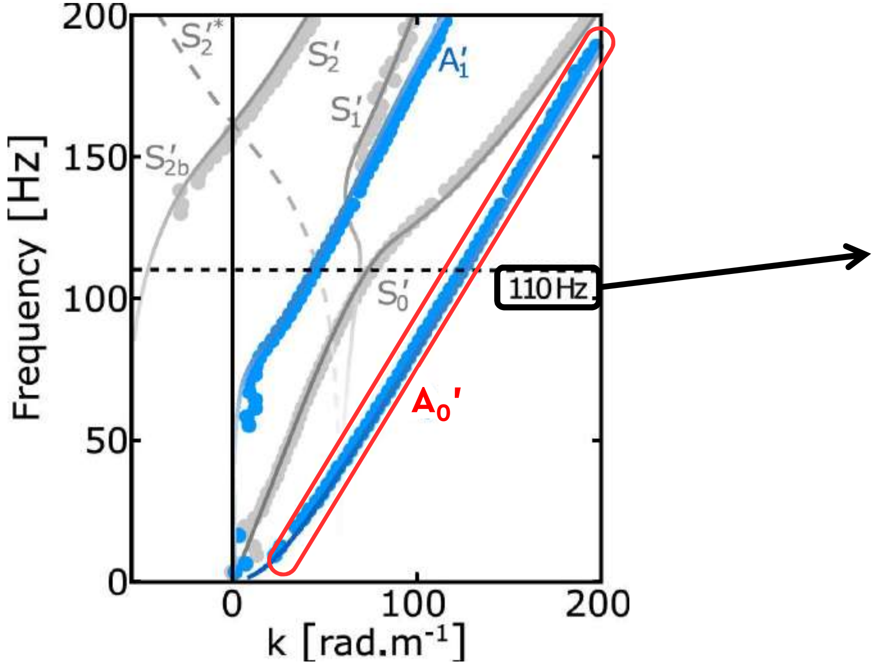
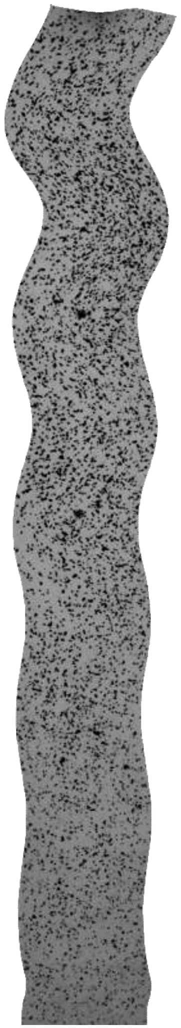
Delory, Kiefer, Lanoy, Eddi, Prada & Lemoult. "*Guided elastic waves in deformed viscoelastic strips*", Soft Matter **in prep** (2023)

Dispersion curves for in-plane guided waves





At low frequency:
  Flexural wave

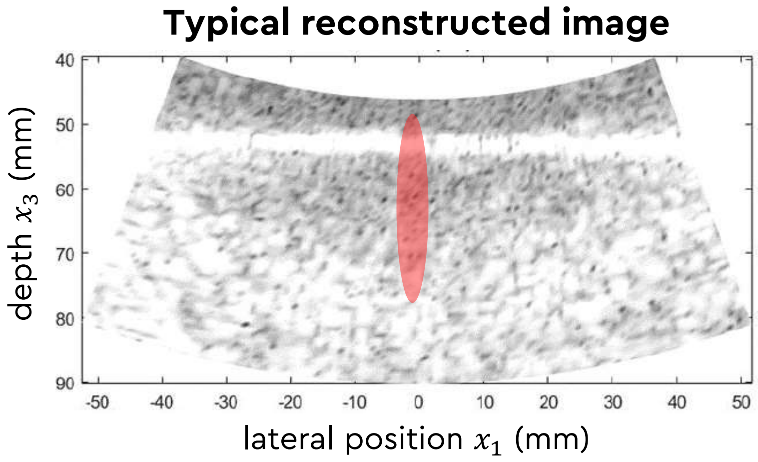
At high frequency:
  Pseudo-Rayleigh wave

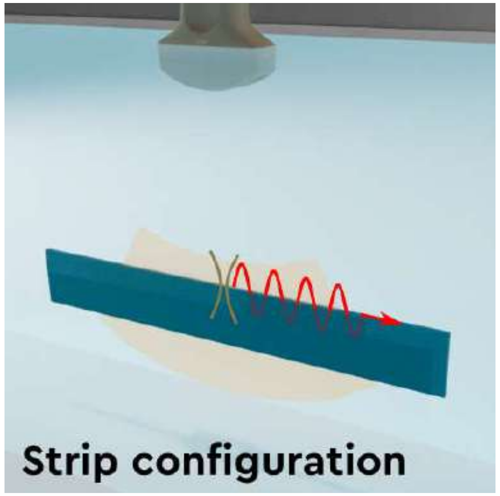
Many interesting waves features ! Such as:
- backward waves
- linear crossing at $k = 0$
- ZGV in a viscoelastic solid

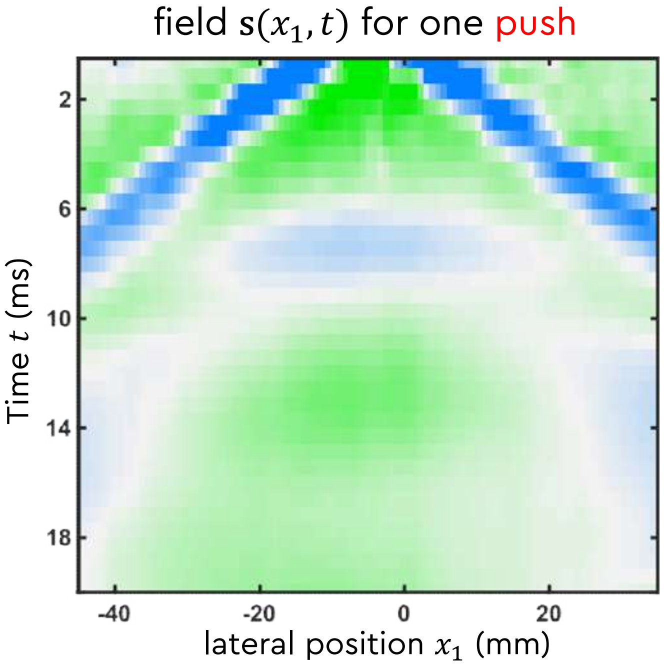
…

Lanoy, Lemoult, Eddi & Prada. *“Dirac cones and chiral selection of elastic waves in a soft strip”*, PNAS **117**, 48 (2020)
Delory, Lemoult, Lanoy, Eddi & Prada. *"Soft elastomers: A playground for guided waves"*, JASA **151** (2022)

Method in the strip configuration


Typical reconstructed image

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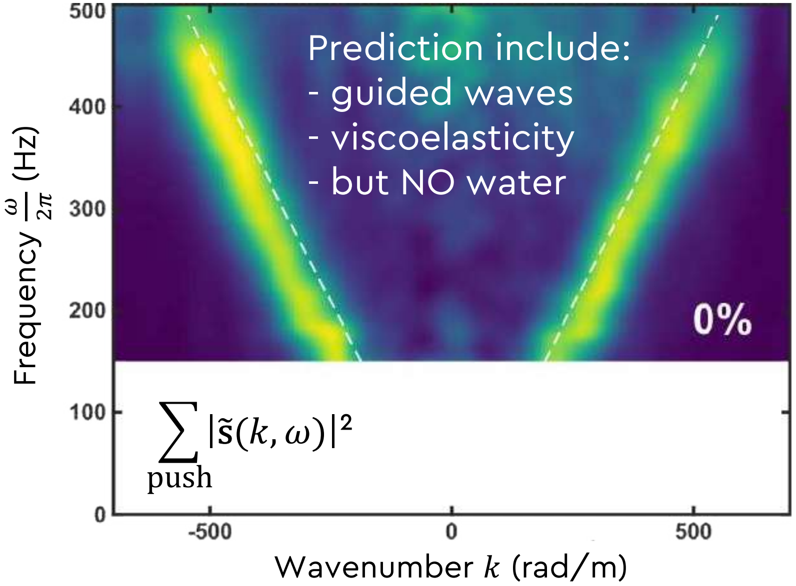
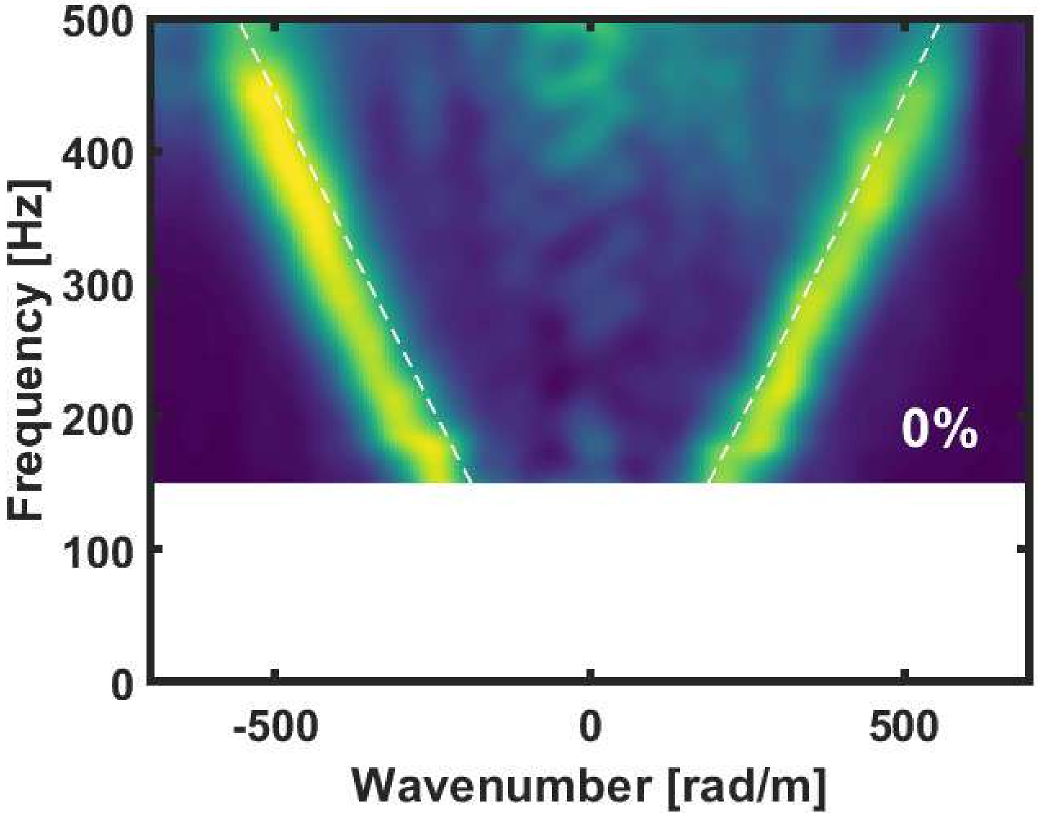


Prediction include:
- guided waves
- viscoelasticity
- but NO water

$$\sum_{\text{push}} |\tilde{s}(k,\omega)|^2$$

And if the strip is deformed ?



Prediction include:
- guided waves
- viscoelasticity
- but NO water
- deformation

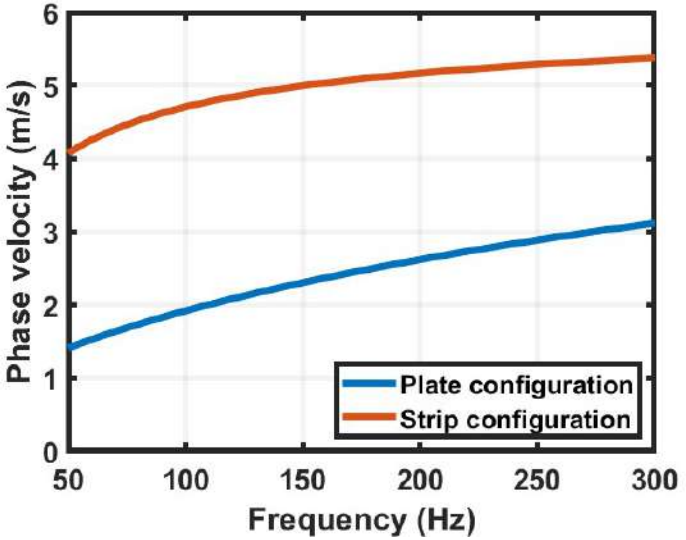
To sum up, in the **SAME STRIP**, we measured velocities:
- at different frequencies
- with different orientations
- for different deformations

→ Let's now compare everything

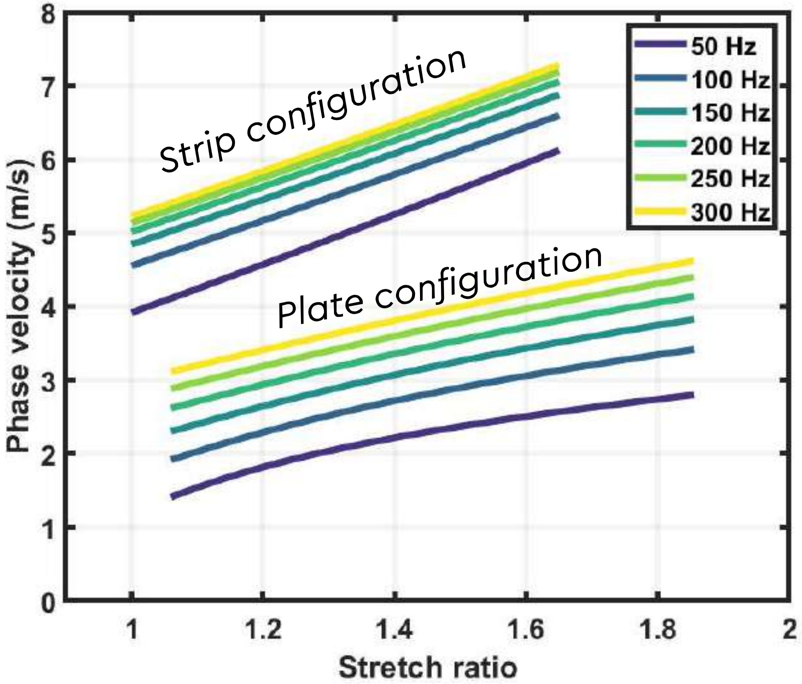
Delory, Kiefer, Lanoy, Eddi, Prada & Lemoult. "*Guided elastic waves in deformed viscoelastic strips*", Soft Matter **in prep** (2023)

Comparing all those velocities

Effect of the frequency and orientation



Effect of the deformation



CONCLUSIONS:

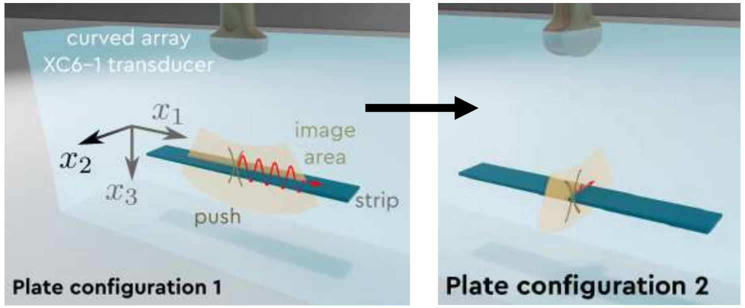
From a <u>physical</u> point of view:

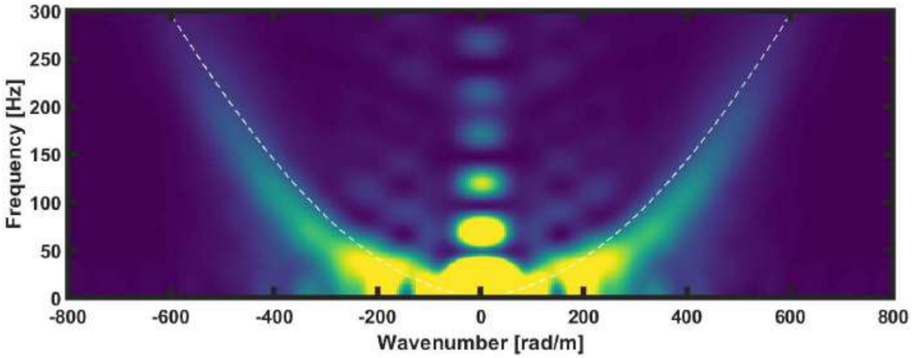
An efficient method to observe and study
(guided) elastic waves in deformed soft solids

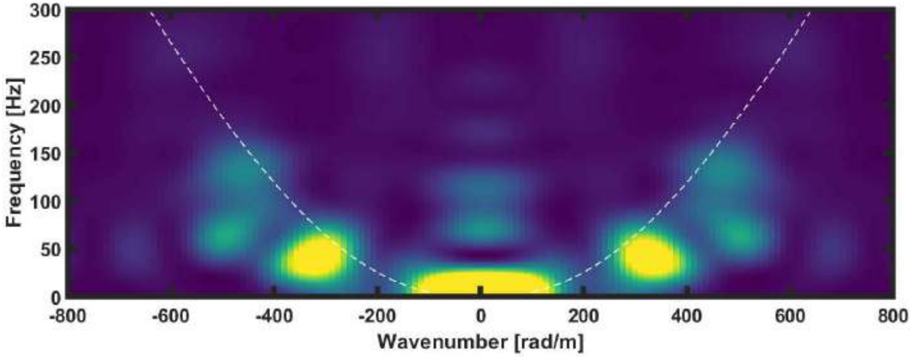
From a <u>medical</u> point of view:

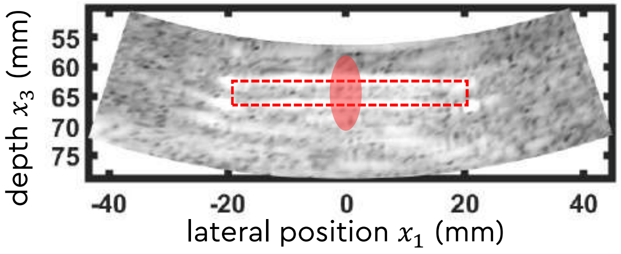
The initial assumption leads to differences of
up to a factor **20** in the evaluation of Young Modulus

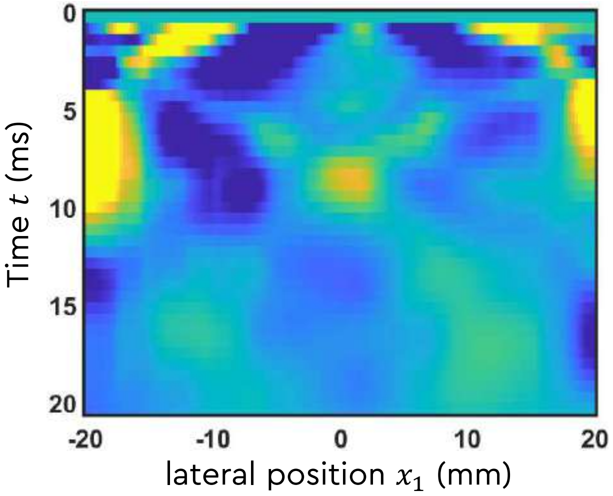
Another surprising result











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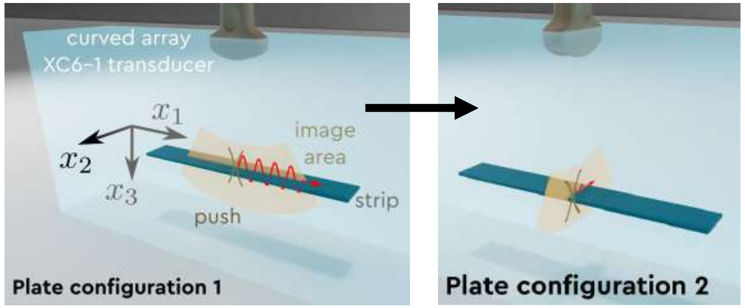
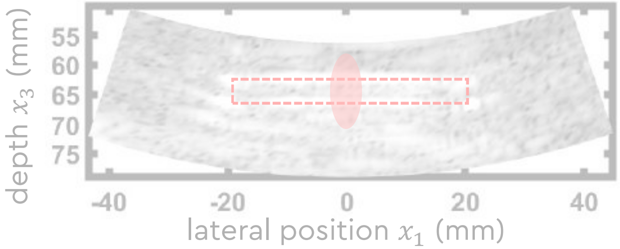
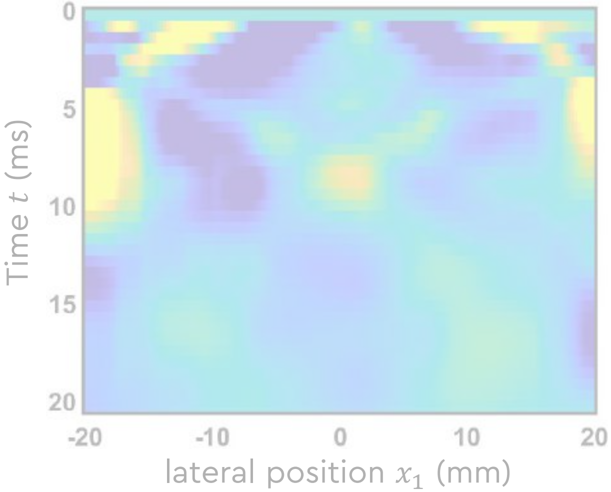
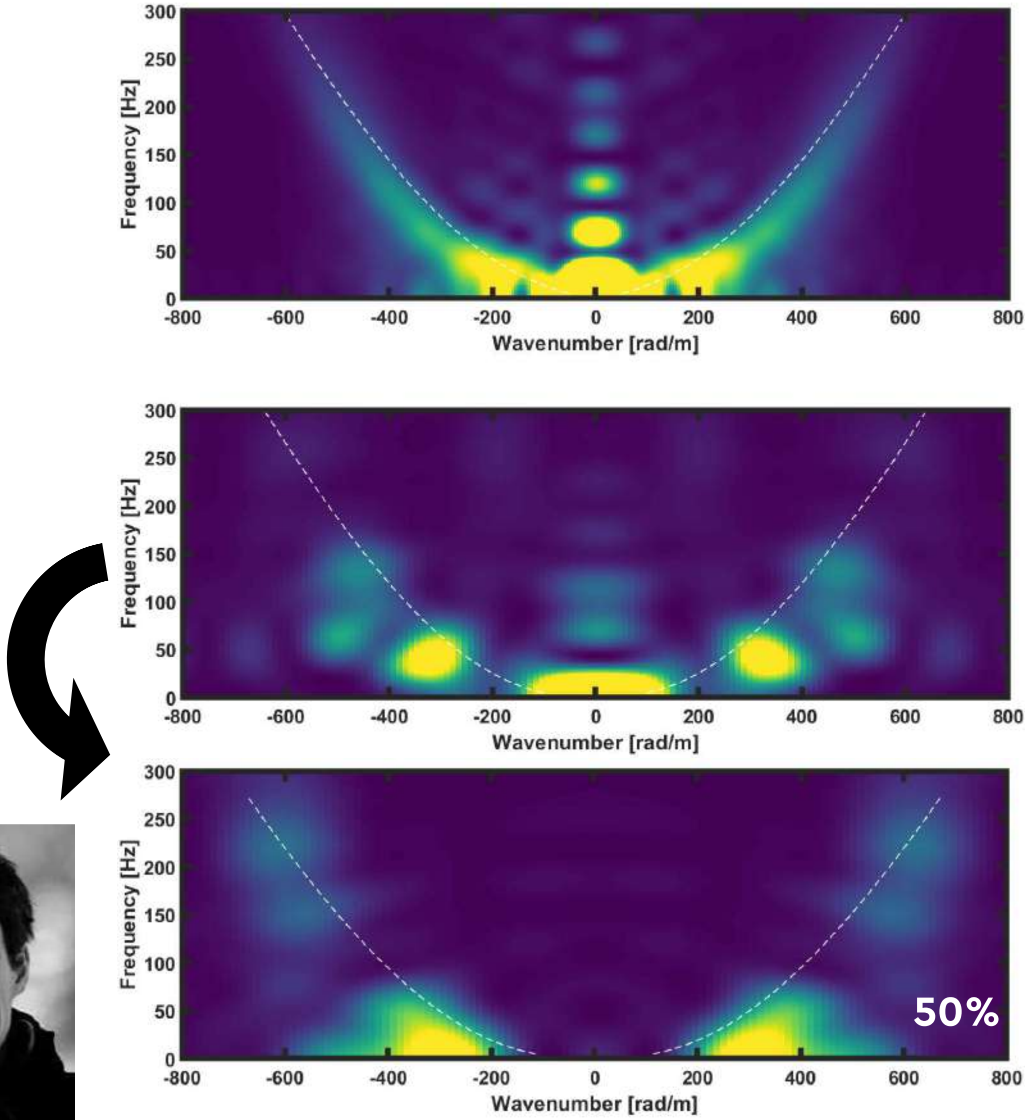




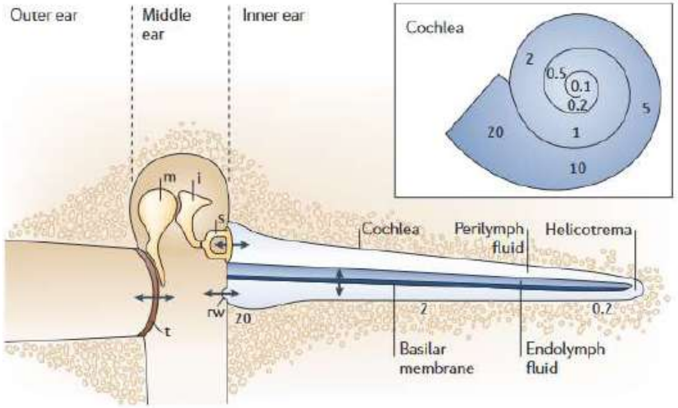


Pierre Chantelot

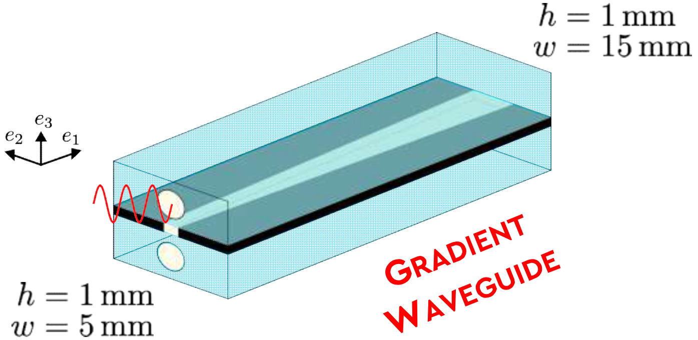


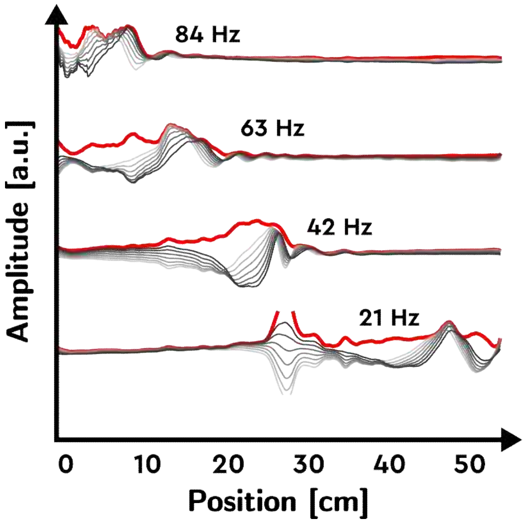
Cut-off wavenumber: elastic instability ?

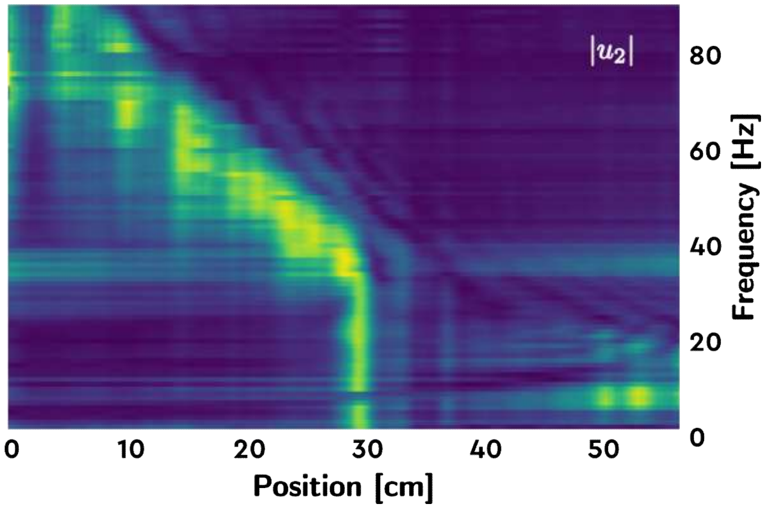
Other project: the Cochlea



Our macroscopic cochlea model:







Samuel Croquette

Institut Langevin
ONDES ET IMAGES

Physique et Mécanique
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Elastograhy in deformed viscoelastic strips

Thank you for your attention !

A. DELORY[1,2], D. KIEFER[1], M. LANOY[1,3], A. EDDI[2], C. PRADA[1] & F. LEMOULT[1]

GdR MecaWave – May 9, 2022

[1] Institut Langevin, ESPCI Paris, Université PSL, CNRS, Paris, France
[2] PMMH, ESPCI Paris, Université PSL, Sorbonne Université, Paris
[3] LAUM, IA-GS, CNRS, Le Mans Université, Le Mans, France

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