# Elastography, tribo elastography and passive elastography

Stefan Catheline

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University of Lyon, INSERM, LabTAU, J-Y Chapelon

# Part I: Overview of elastography


*Reflection coefficient* $$R_a = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

*Impedance* $$Z = \rho\, C = \sqrt{\rho(\lambda + 2\mu)}$$

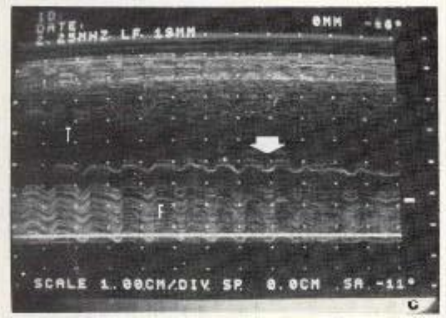
→ *Ultrasound devices give impedance variation imaging*

Years

Qualitatif

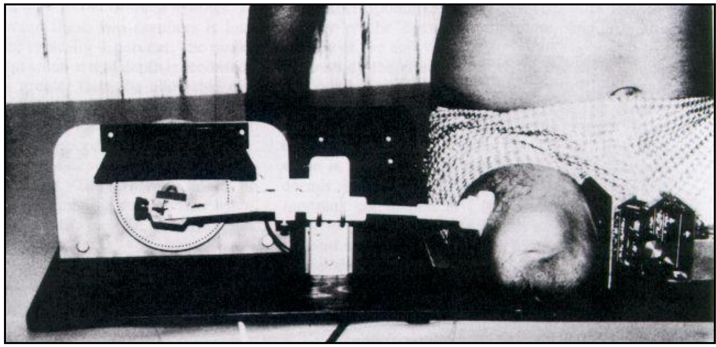
1981 Natural motion (Dickinson)

1983 Vibrator (Eisencher Echosismography)




Quantitatif

1987 **Monochromatic** + Doppler (Krouskop)



**Elastic, homogeneous, isotropic, linear**

$$(\lambda + 2\mu)\overrightarrow{grad}\, div(\vec{u}) - \mu\, \overrightarrow{rot}\, \overrightarrow{rot}\, \vec{u} - \rho \frac{\partial^2 \vec{u}}{\partial t^2} = \vec{0}$$

$$C_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} \approx \sqrt{\frac{\lambda}{\rho}} \qquad C_S = \sqrt{\frac{\mu}{\rho}}$$

*Soft tissues:*
*$\lambda$ = 2,5 Gpa*
*$\mu$ = 25 kPa* $\ll \lambda$

Water and soft tissues are incompressible

→ *Manual palpation reveals shear elasticity $\mu$*

Shear waves are slow.

Years

Qualitatif

1981 Natural motion (Dickinson)

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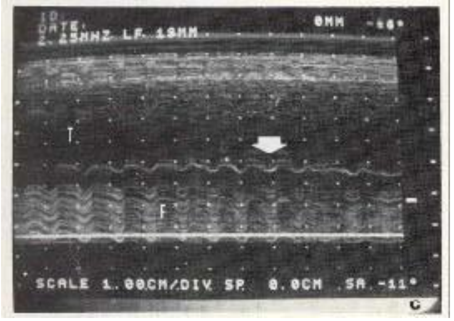
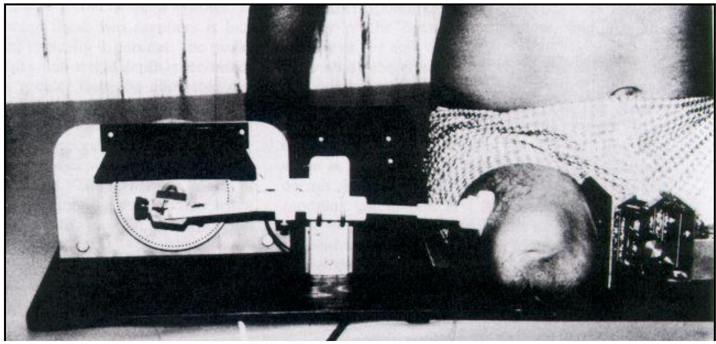



Quantitatif

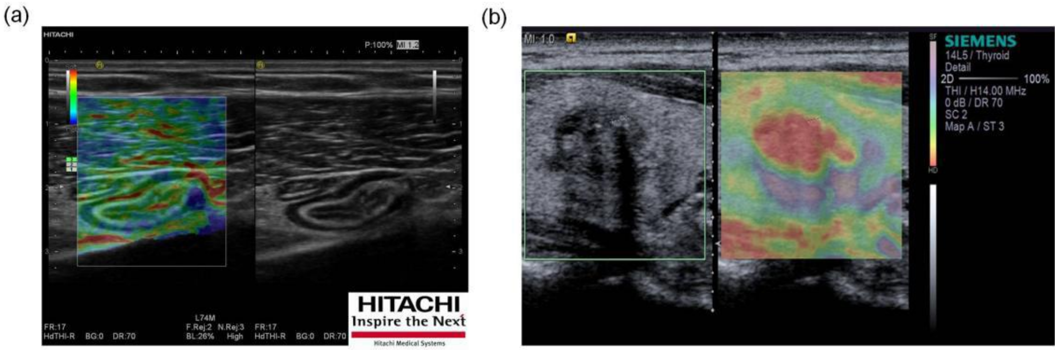
1987: **Monochromatic** + Doppler (Krouskop)



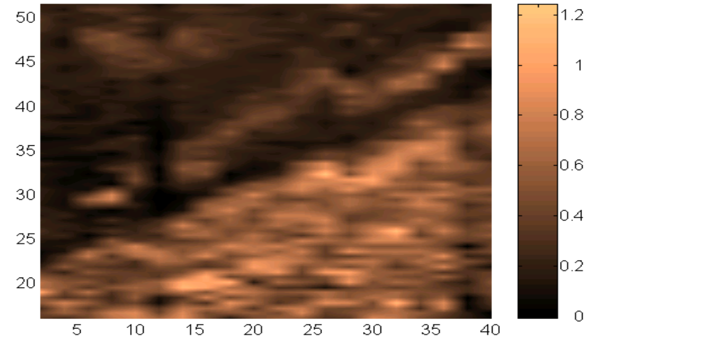
1991: **Static** (Ophir)

Hooke's law:

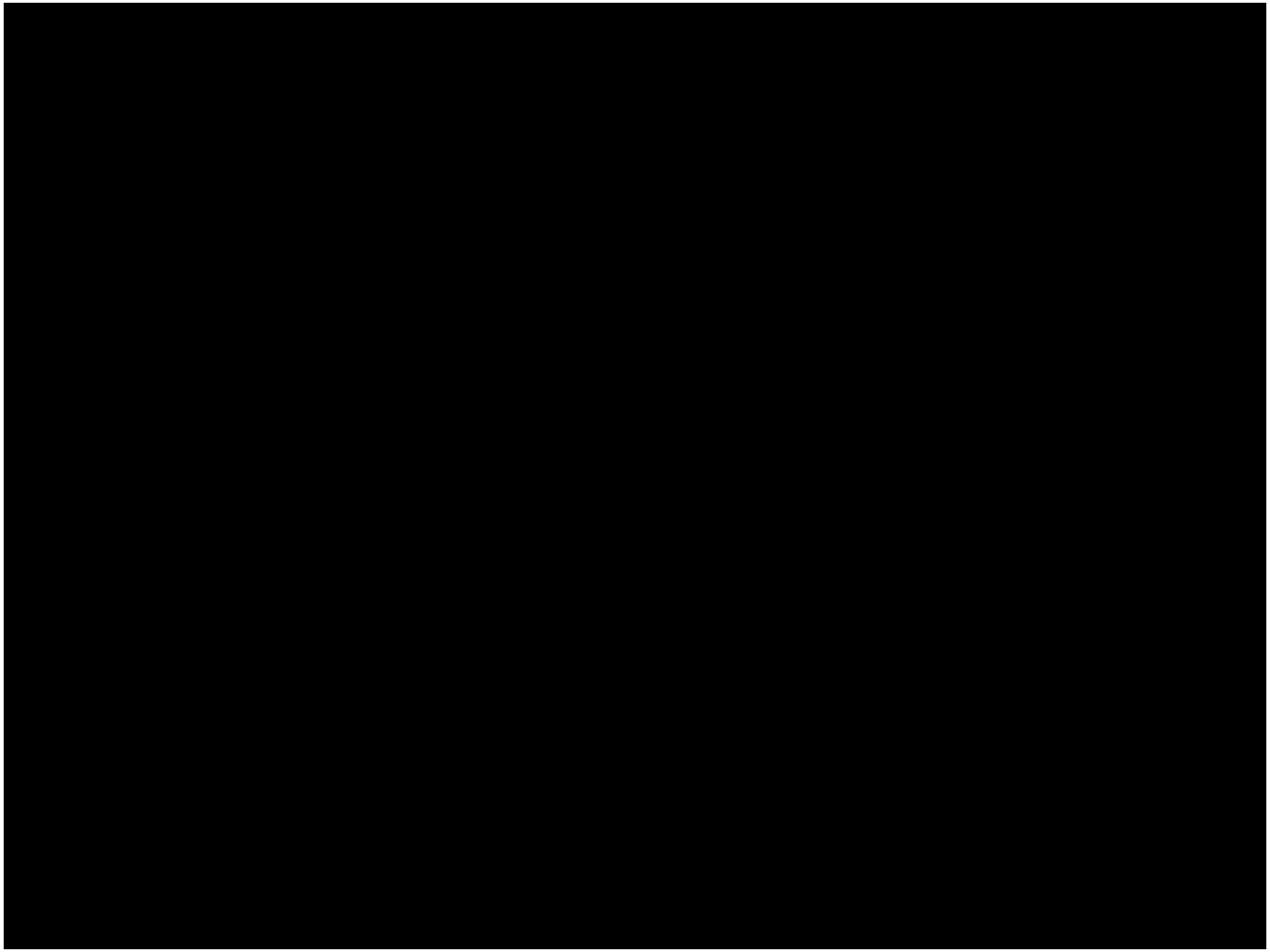
$$T_{ij} = C_{ijkl} S_{kl}$$



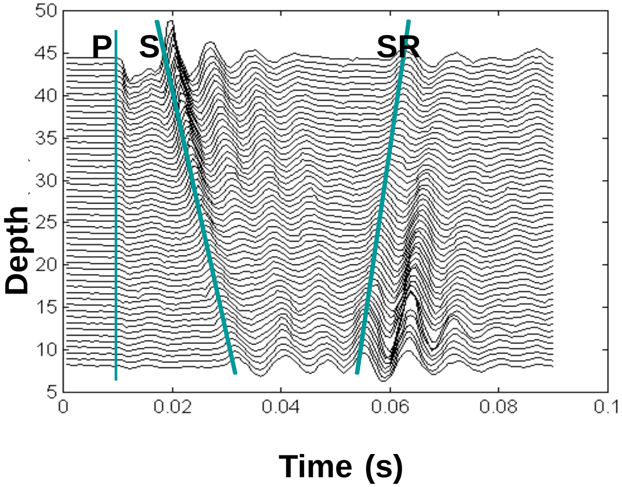

1998: **Pulse** (Fink, Catheline)



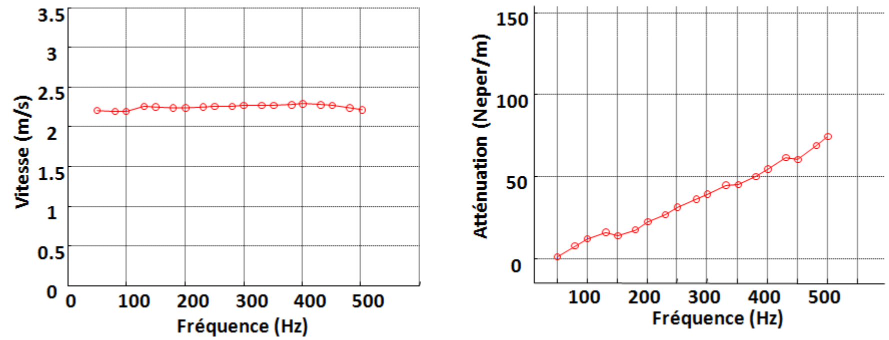
# I Elastography



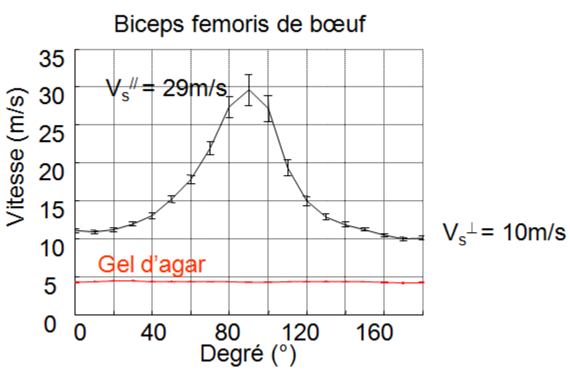
# Elastodynamic



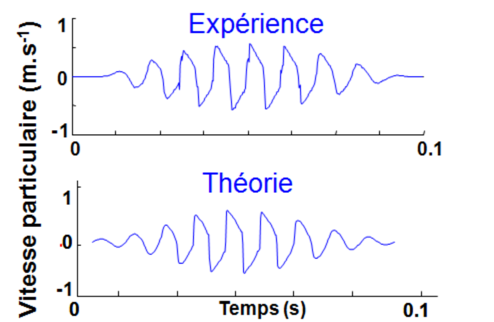

# Rheology



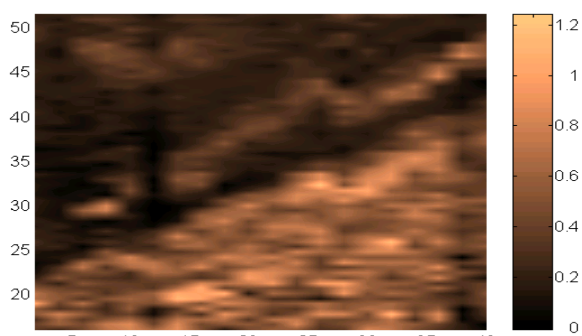

# Anisotropy



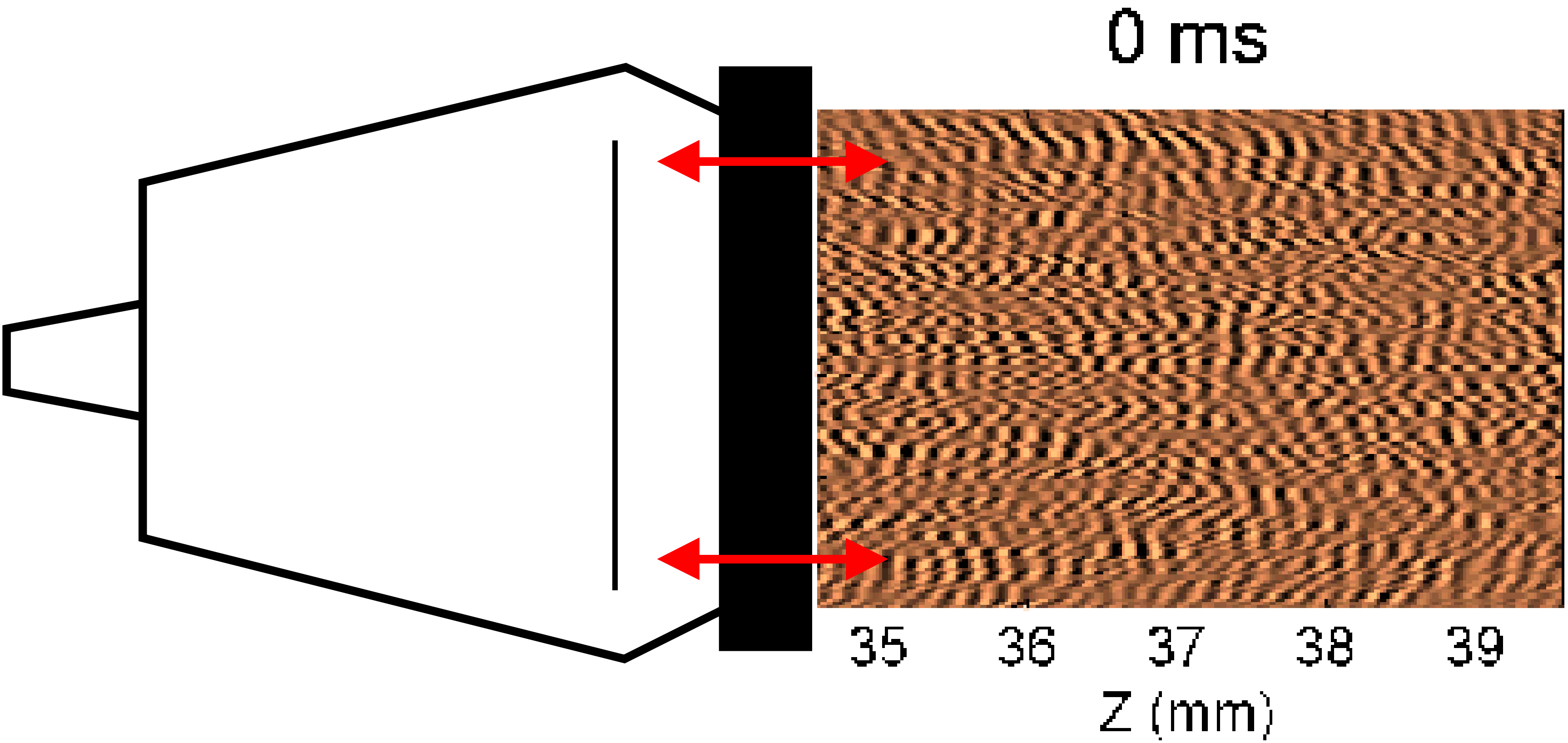

# Non linearity



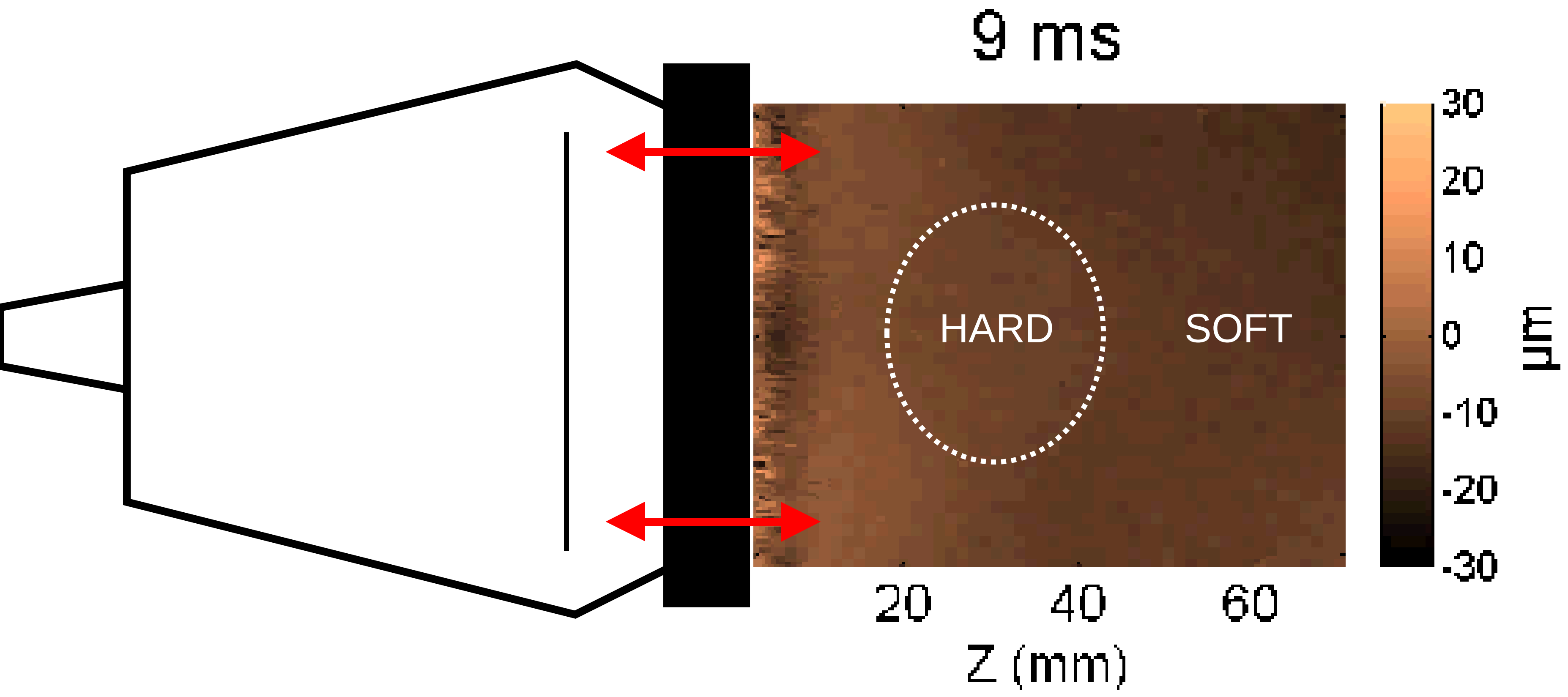

# Imaging



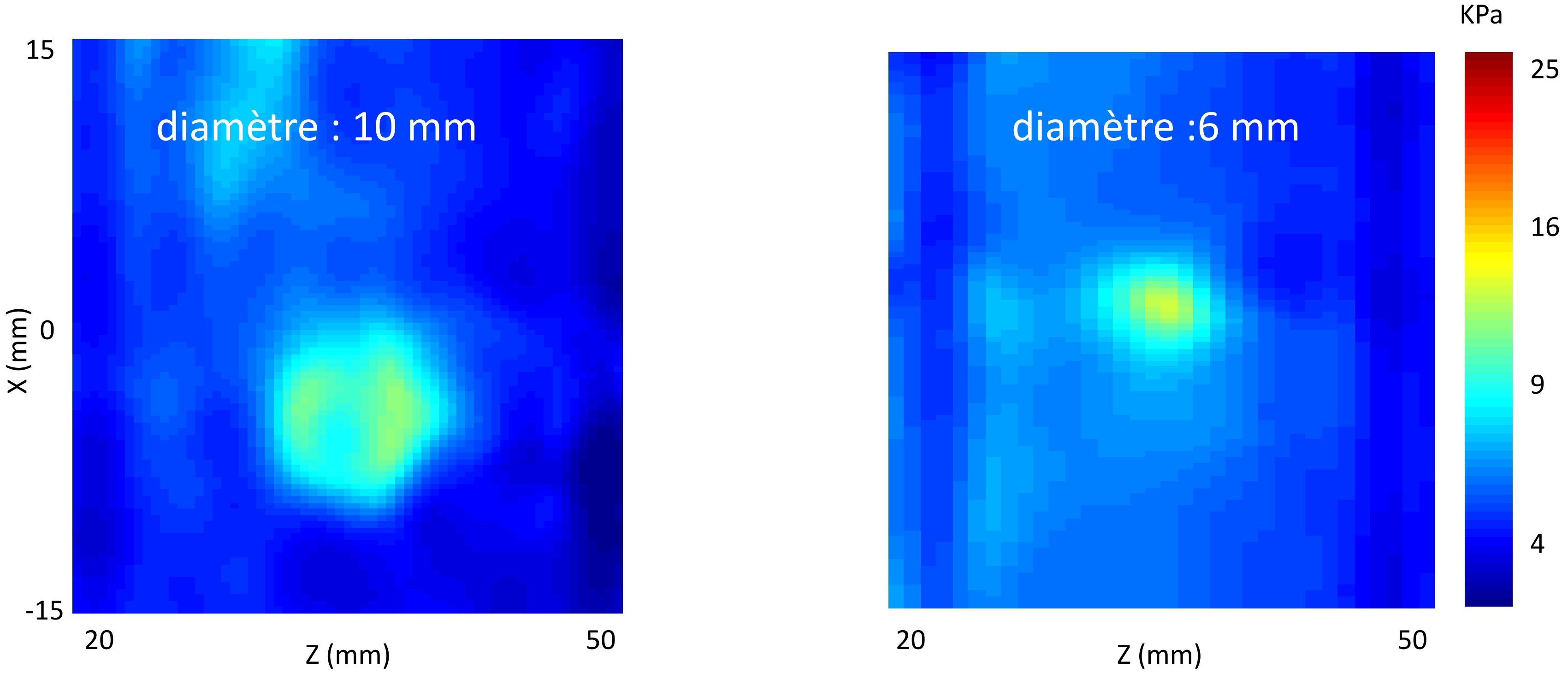
# Ultrasound speckle interferometry



Experimental movie of the z component of the displacements



# Example of inclusions in gels

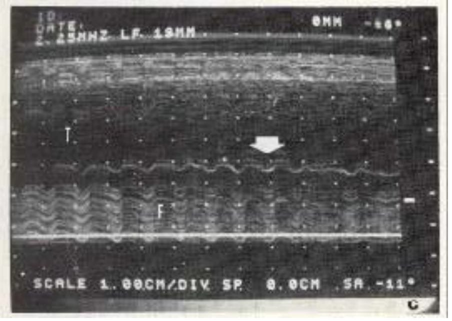



Brevet n° FR99 03157 déposé le 16 Mars 1999 : "Imagerie sismique des ondes de cisaillement", Laurent Sandrin, Mickael Tanter, Stefan Catheline, Mathias Fink

Years Qualitatif

1981 Natural motion (Dickinson)

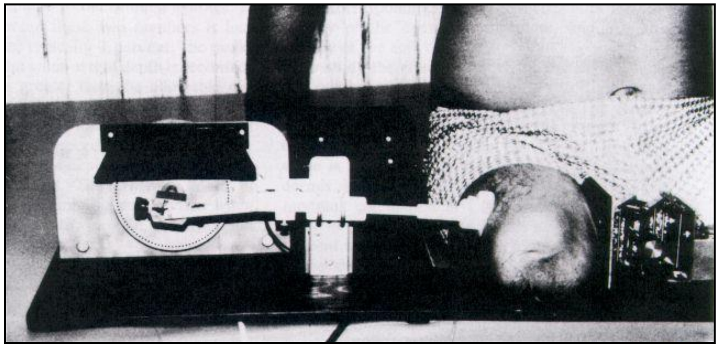
1983 Vibrator (Eisencher Echosismography)



Quantitatif

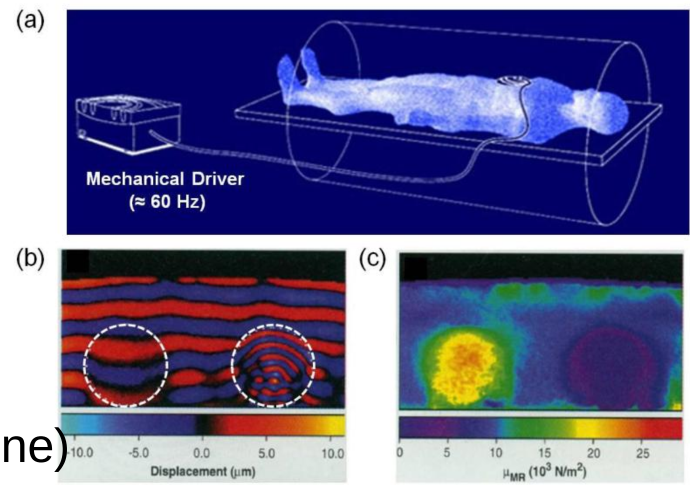
1987: **Monochromatic** + Doppler (Krouskop)

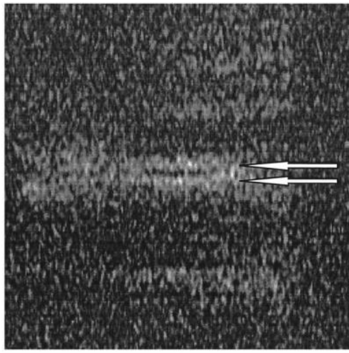
1990: **Monochromatic** + Doppler (Levinson, Parker, Sato)



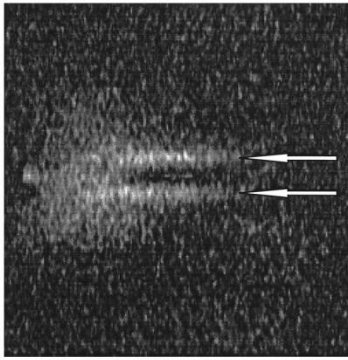
1991: **Static** +Ultrasound (Ophir)

1995: **Monochromatic**+MRI (Greenleaf)



(a)



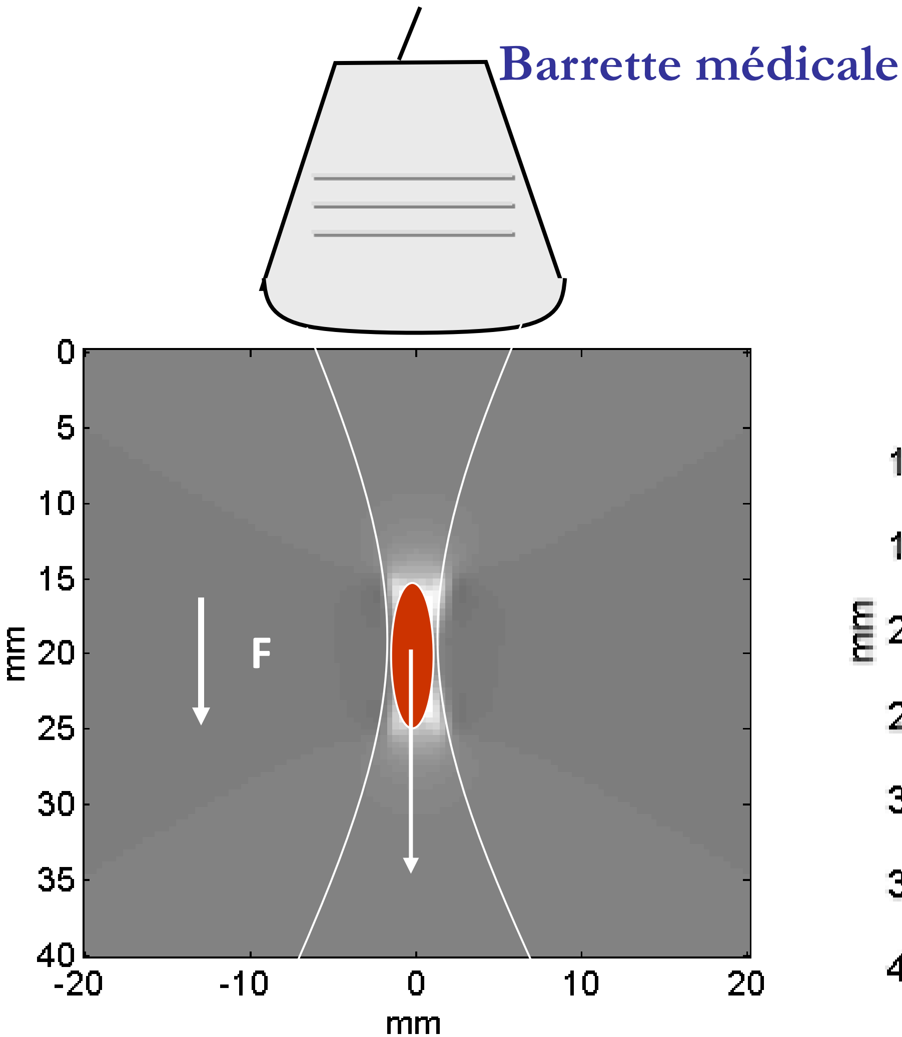
(b)

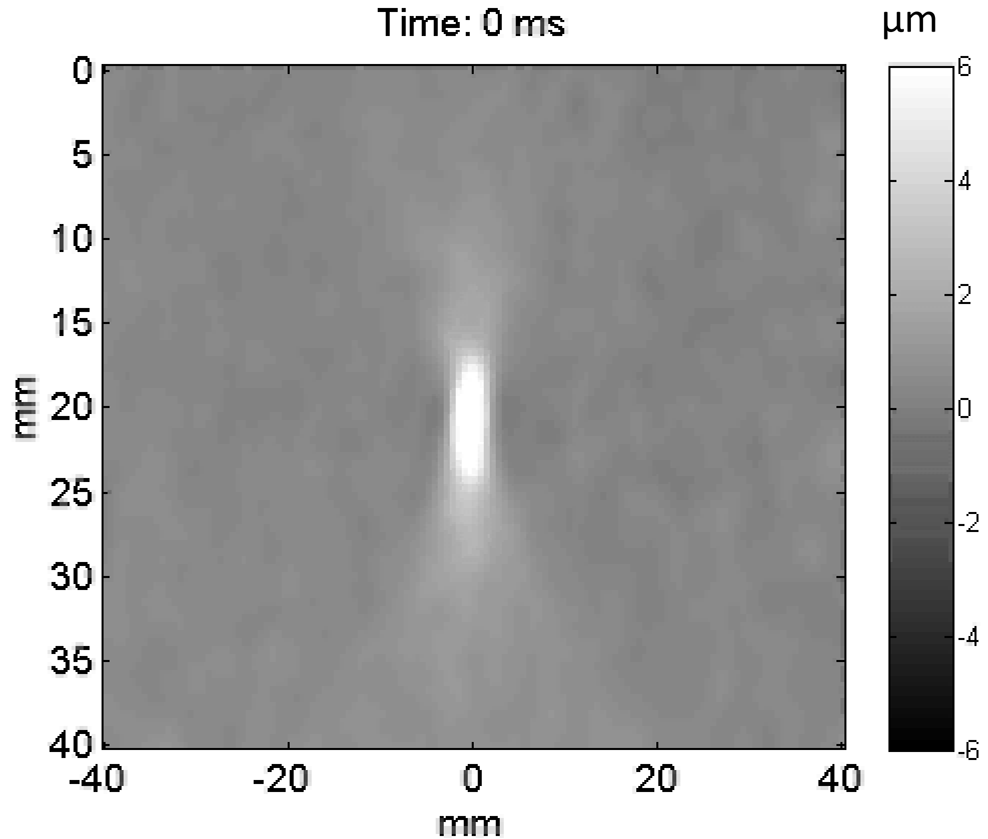
1998: **Pulse**+ultrasound (Fink, Catheline)

1998: **Pulse**+MRI+Radiation pressure (Sarvazian)

2004: **Pulse**+ultrasound (Fink, Tanter, Bercoff)

# La pression de radiation



## Echosens (2003): le Fibroscan


## Supersonic Imagine (2008): l'Aixplorer

# Part II: From Medical Imaging to seismology

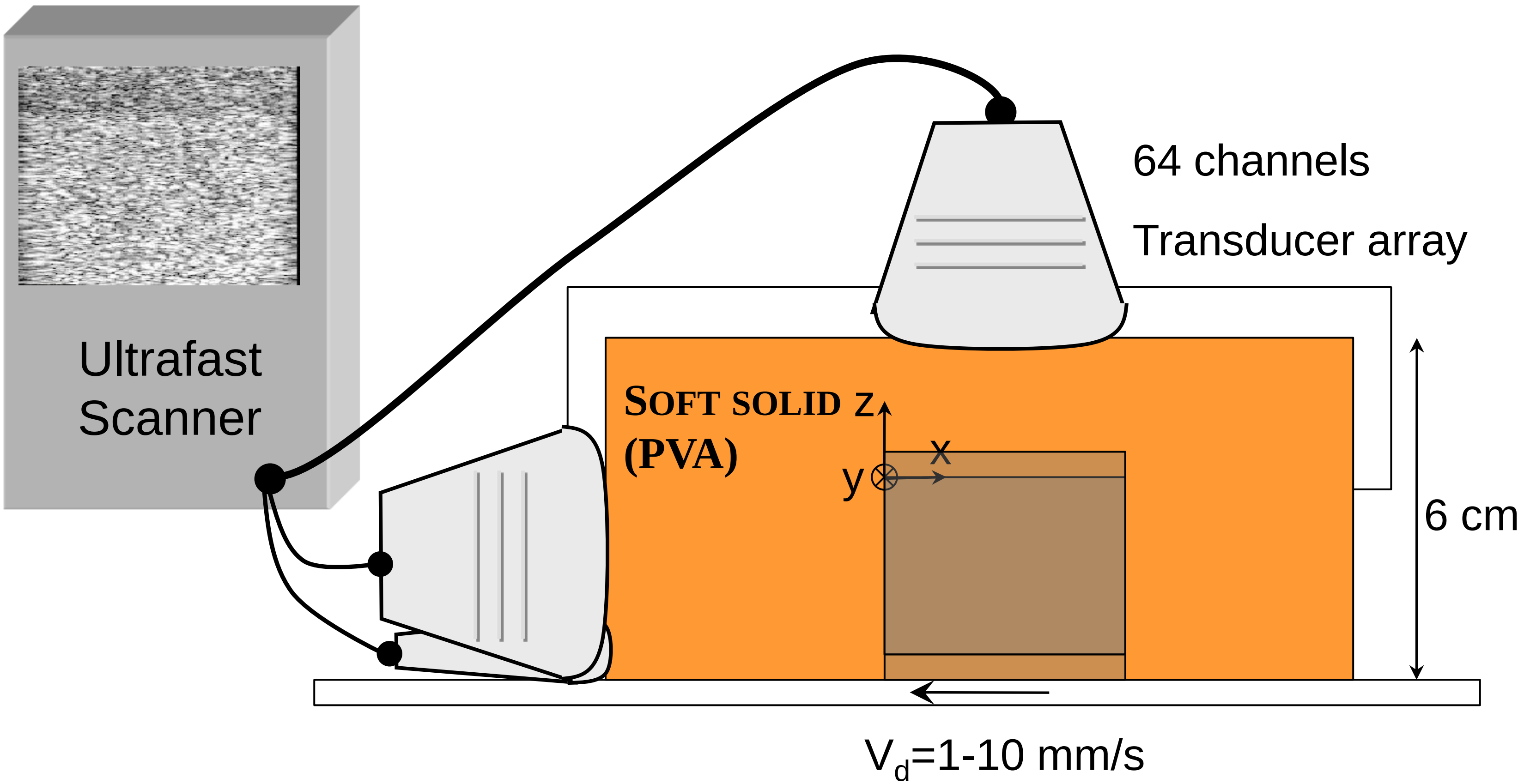
# -Sliding dynamic studies by use of elastography-

Stefan CATHELINE
Soumaya LATOUR
Thomas GALLOT
Francois RENARD
Christophe VOISIN
Michel CAMPILLO
Eric LAROSE

Earth Institute (ISTerre),
University of Grenoble

S. Latour *et al*,
« Ultrafast ultrasonic imaging of dynamic sliding friction in soft solids: the slow slip and the super shear regimes »
Europhysics Letter, EPL, 96 (2011) 59003.

# Friction experimental set-up: the basic principle

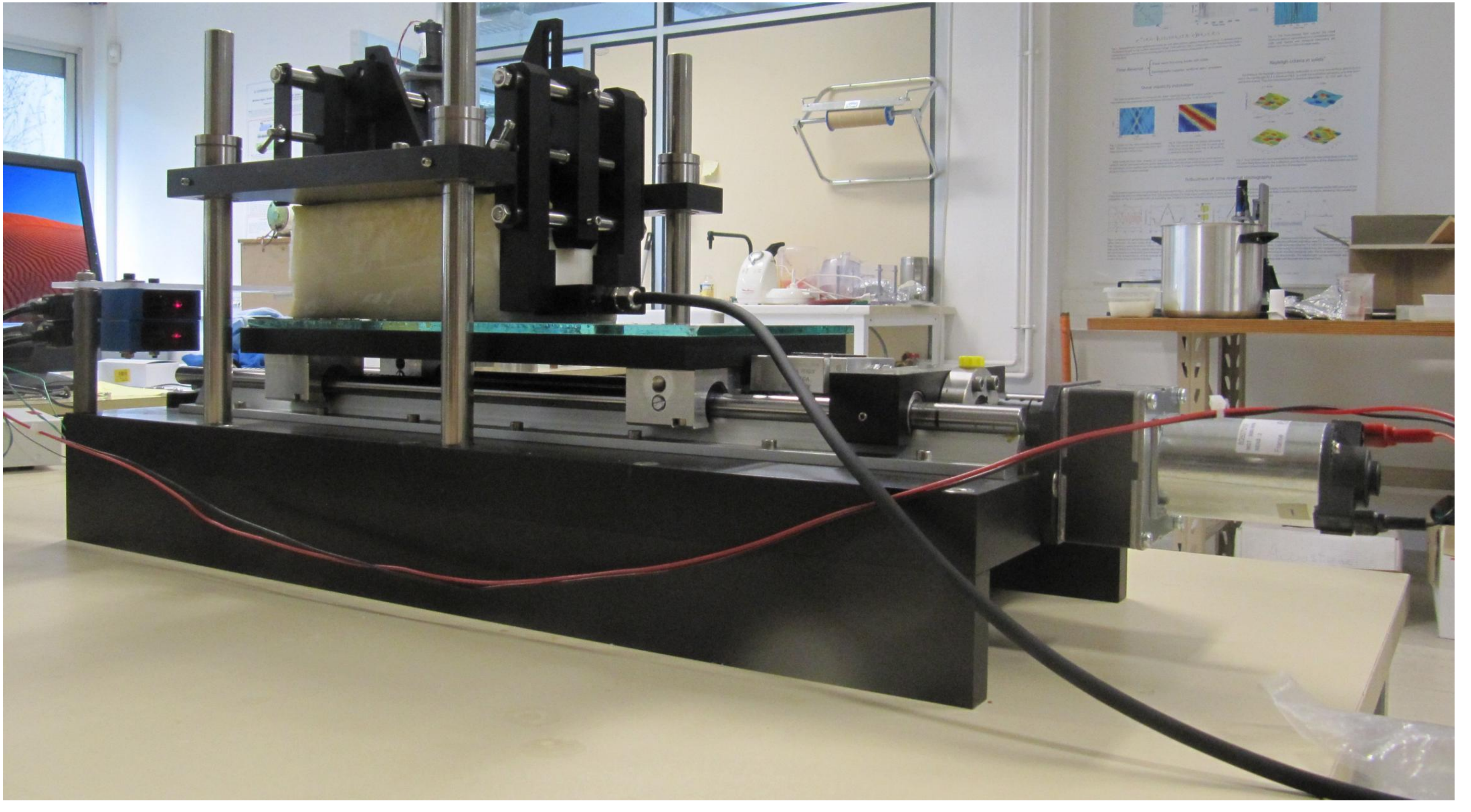



Soft: $V_S \sim$ 4m/s, $V_P$=~ 1500 m/s

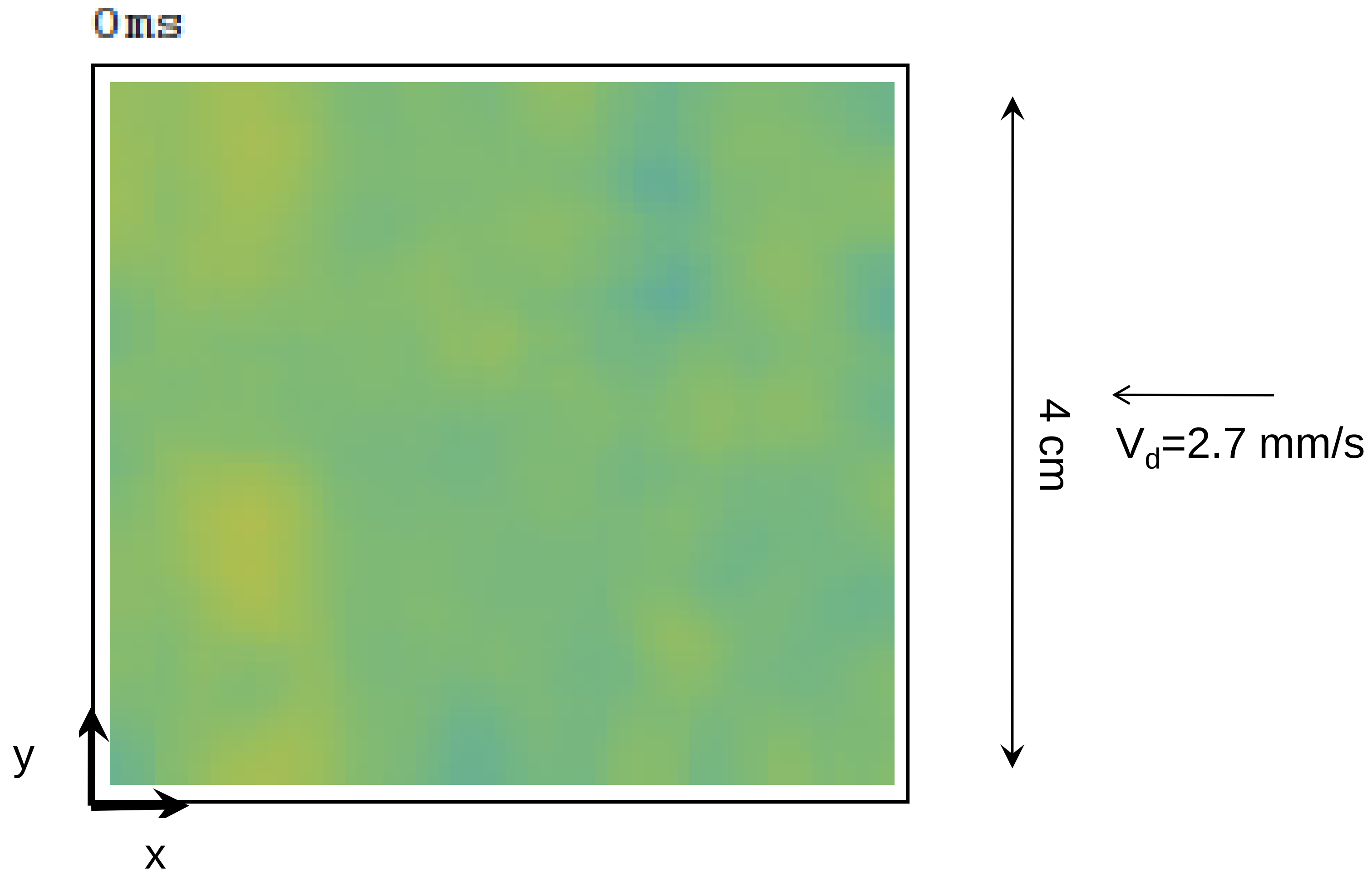

L. Sandrin, S. Catheline, M.Tanter, X Hennekin, M. Fink, « Time-resolved pulsed elastography with ultra fast imaging », Ultrasonic Imaging Vol. 13, pp.111-134, 1999.

Baumberger *et al.*, « Self-healing slip pulses and the friction of gelatin gels »,The European Physical Journal E, Vol.11, pp.85, 2003.

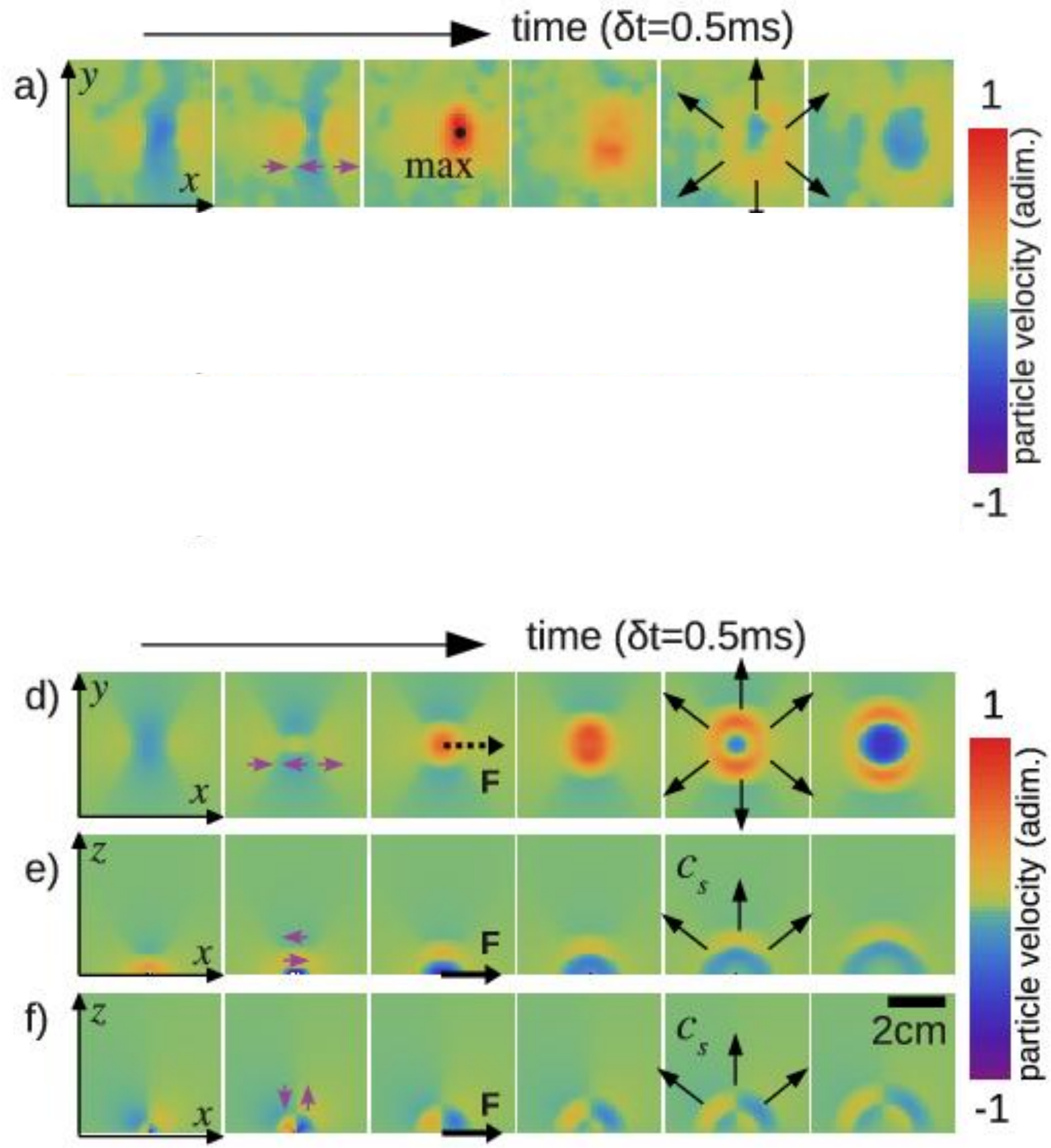
# Experimental set-up



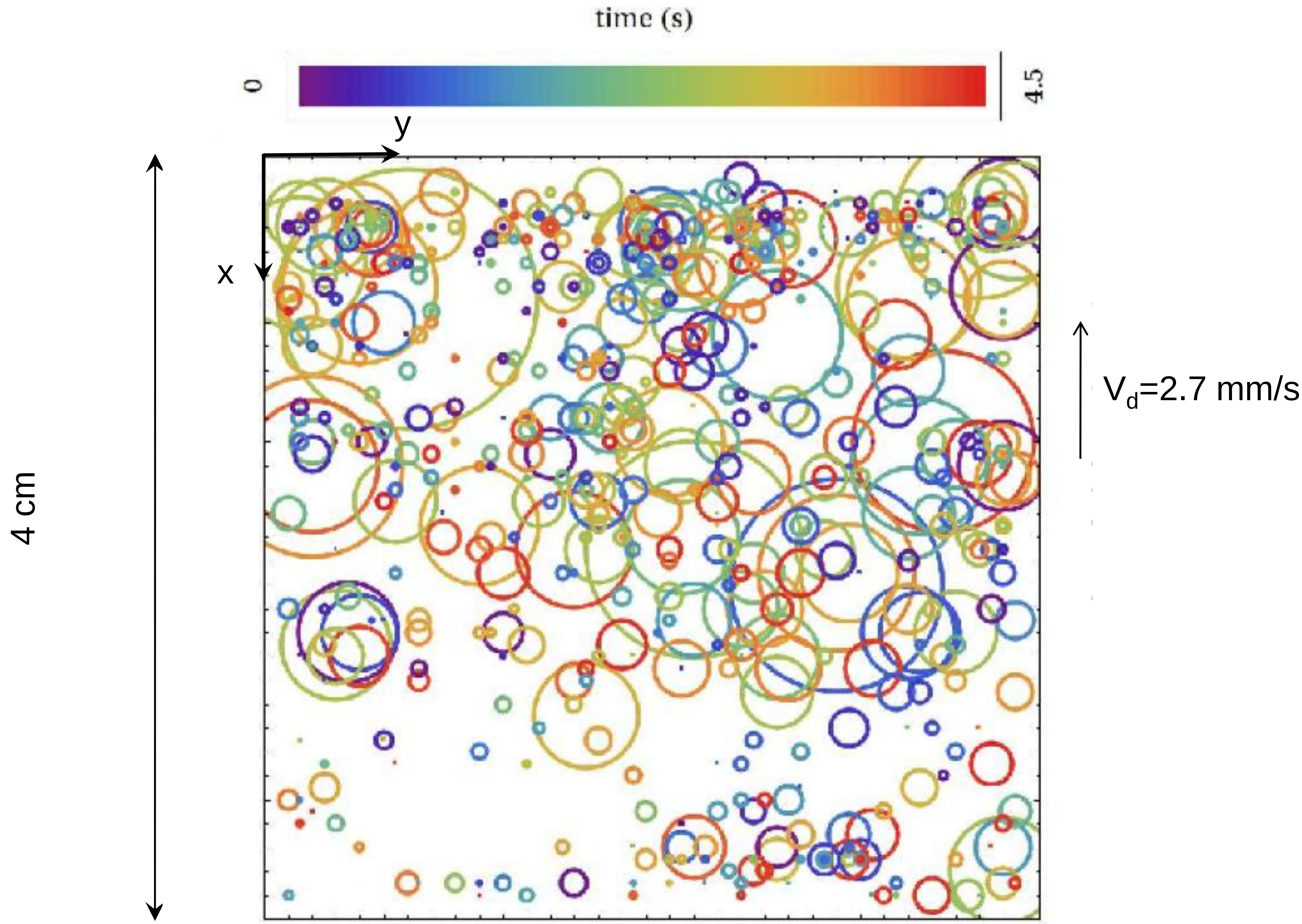
# Strong friction configuration: PVA-sand paper interface



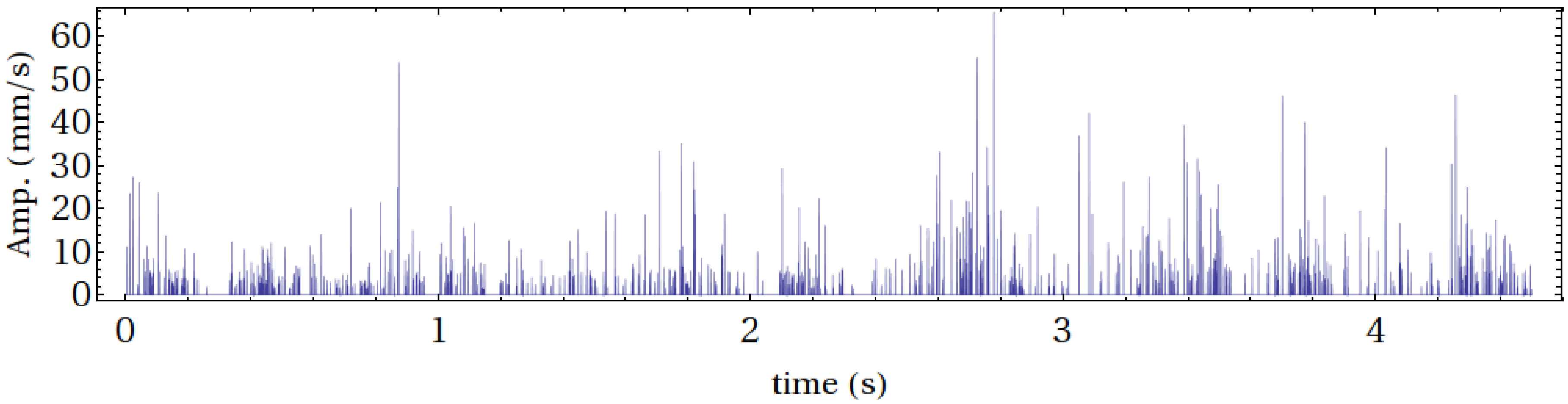
# Strong friction configuration: Single depinning event analysis



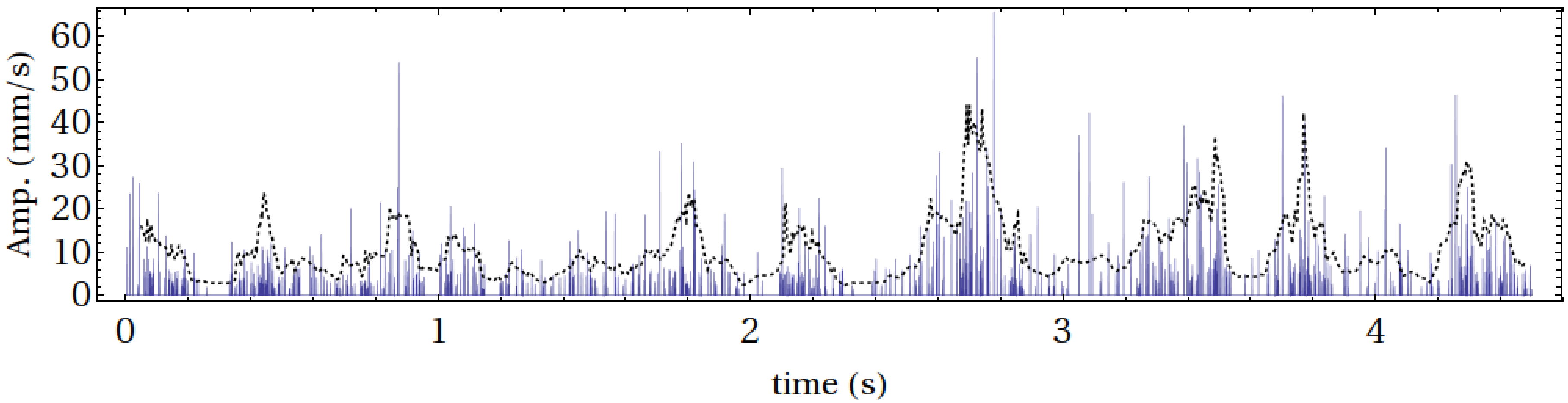

$V_d$=2.7 mm/s

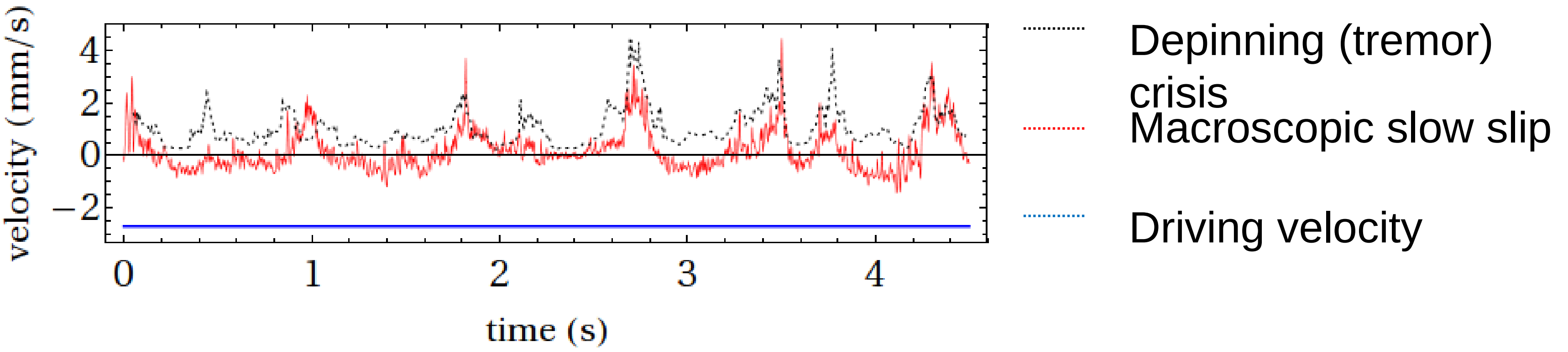

time (s)
0
4.5
y
x
4 cm
$V_d$=2.7 mm/s

# Strong friction configuration: Statistic analysis

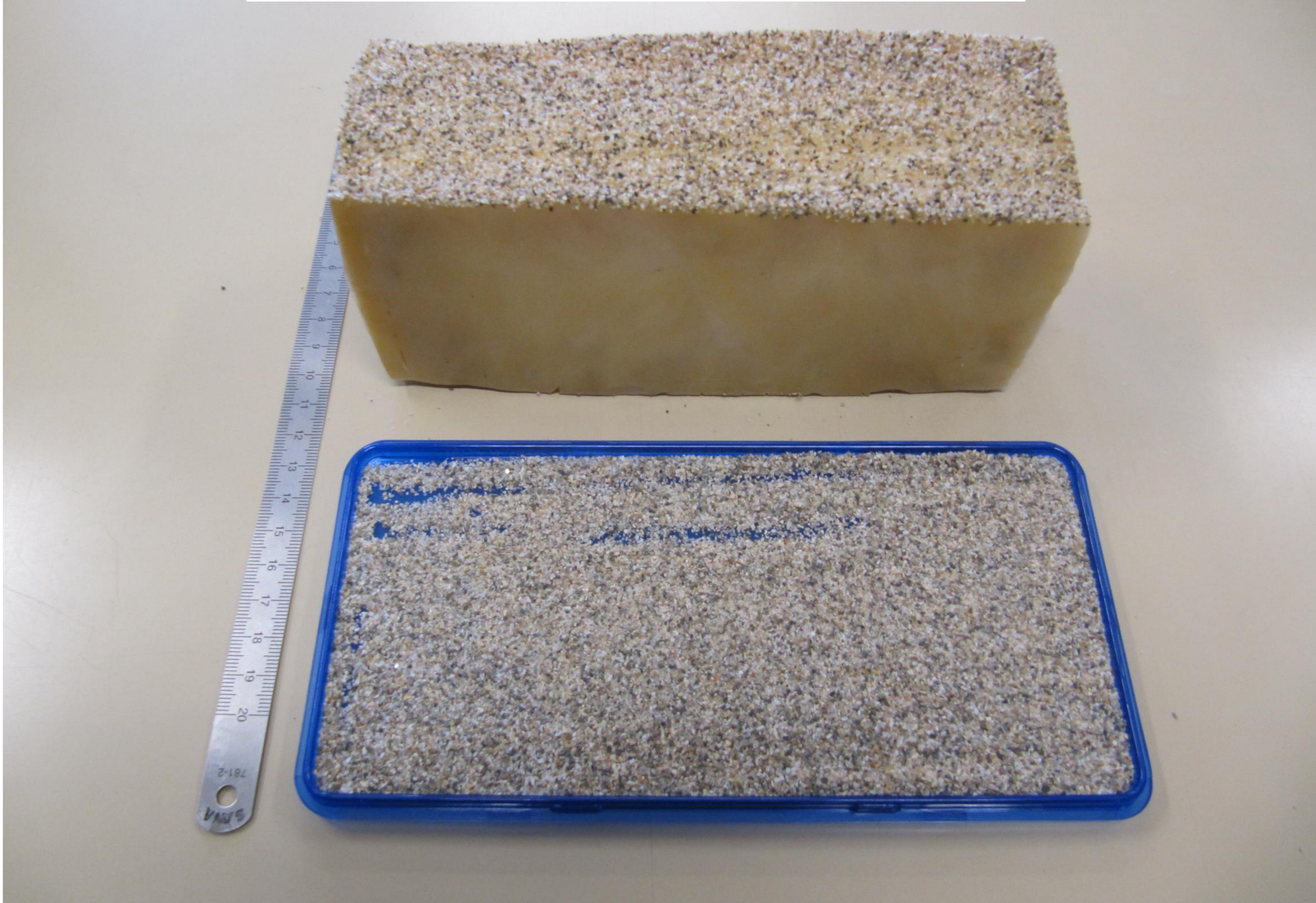


# Part I: PVA-sand paper interface - Statistic analysis

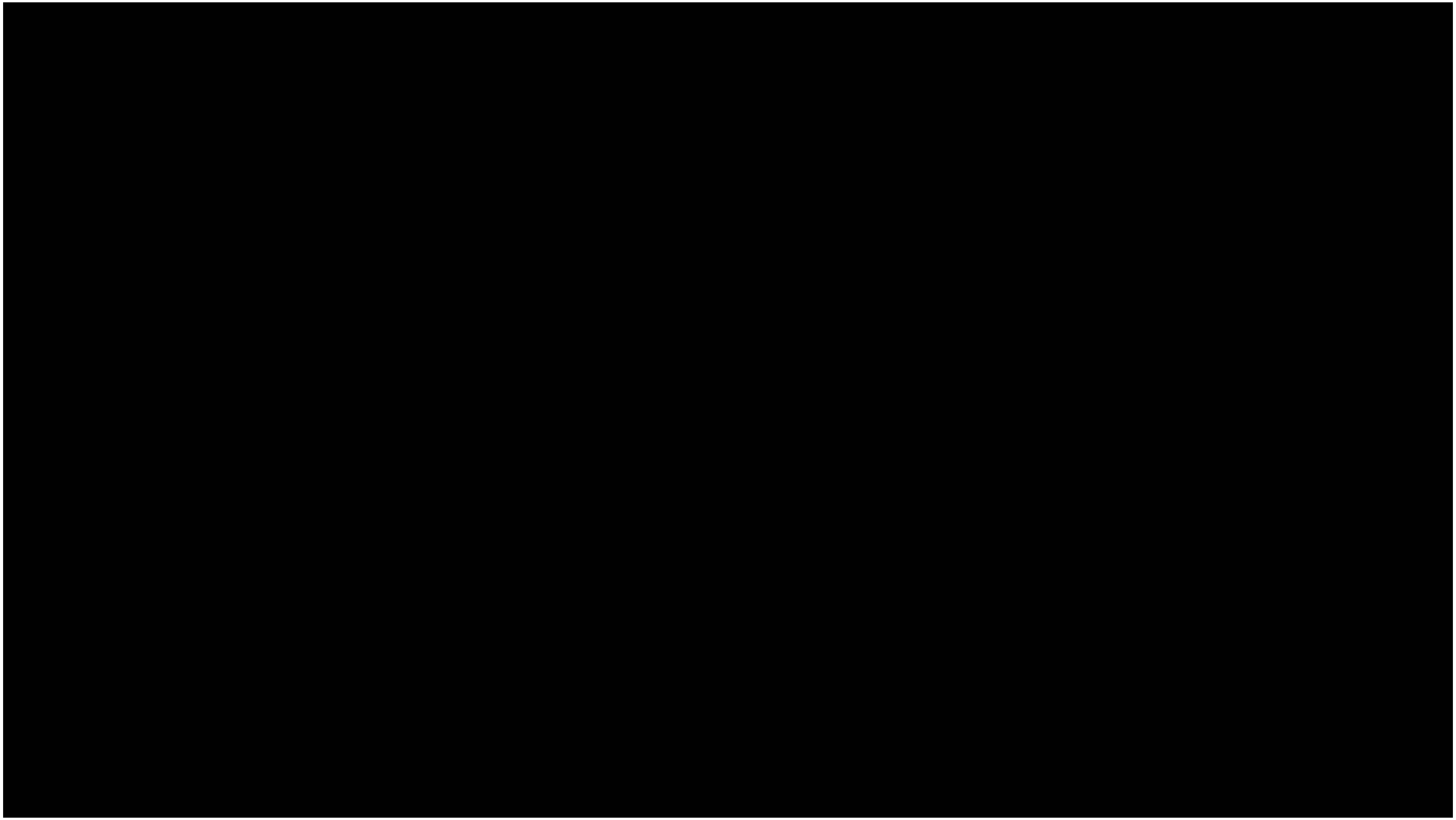


# Weak friction configuration : Sand/glass interface

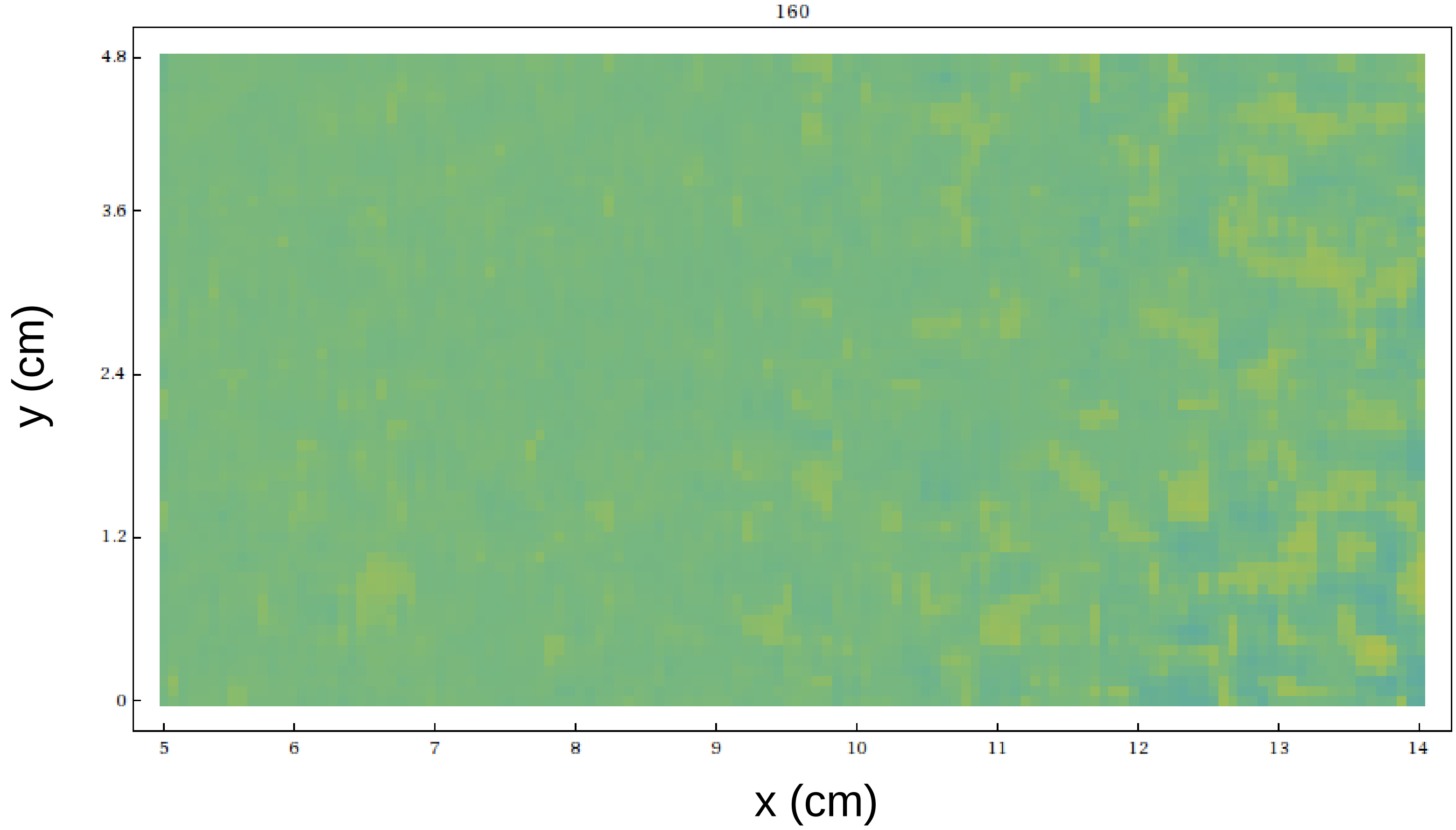


# Weak friction configuration : Sand/glass interface

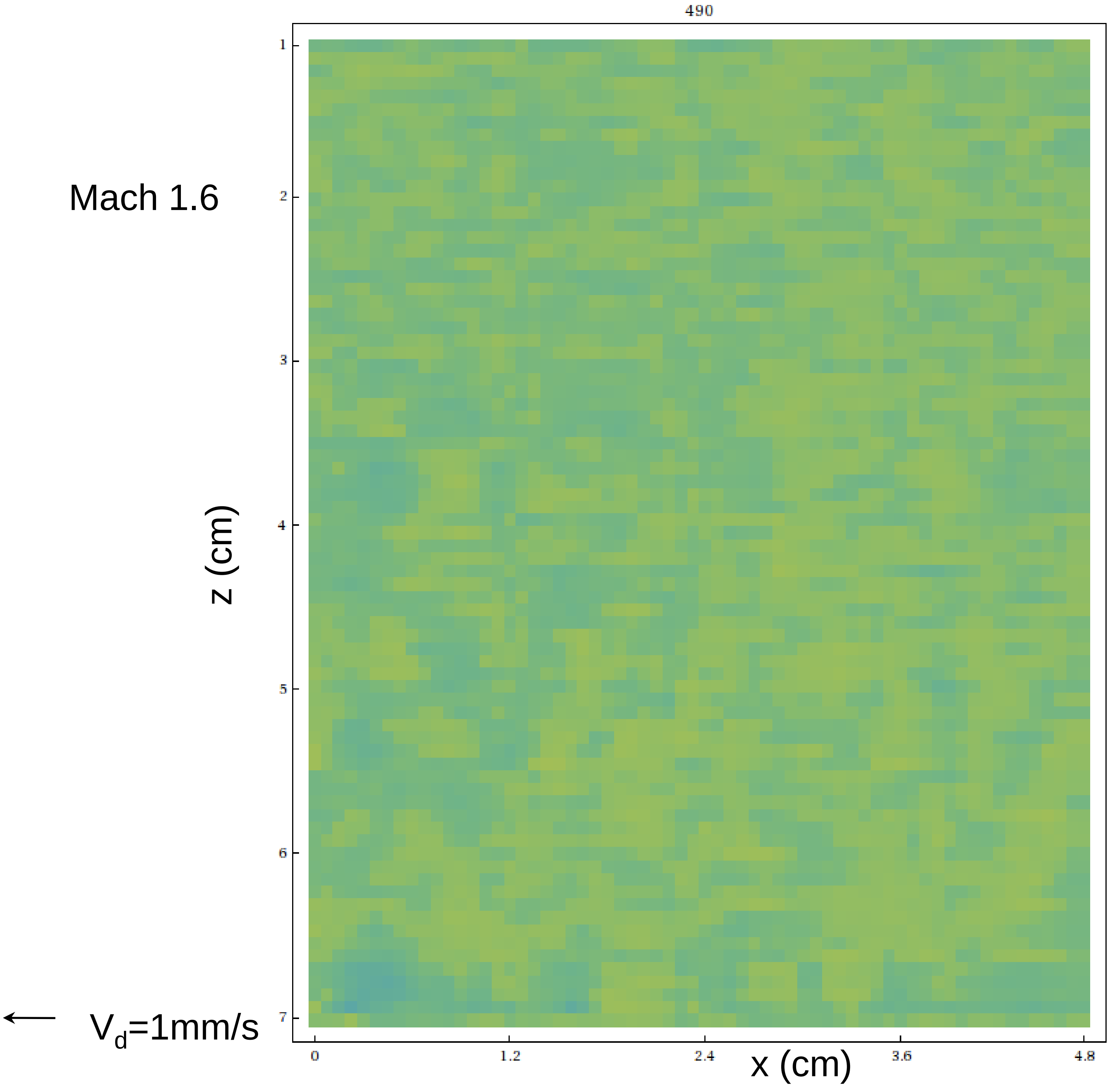


# Weak friction configuration : super shear regime

Mach 2.5

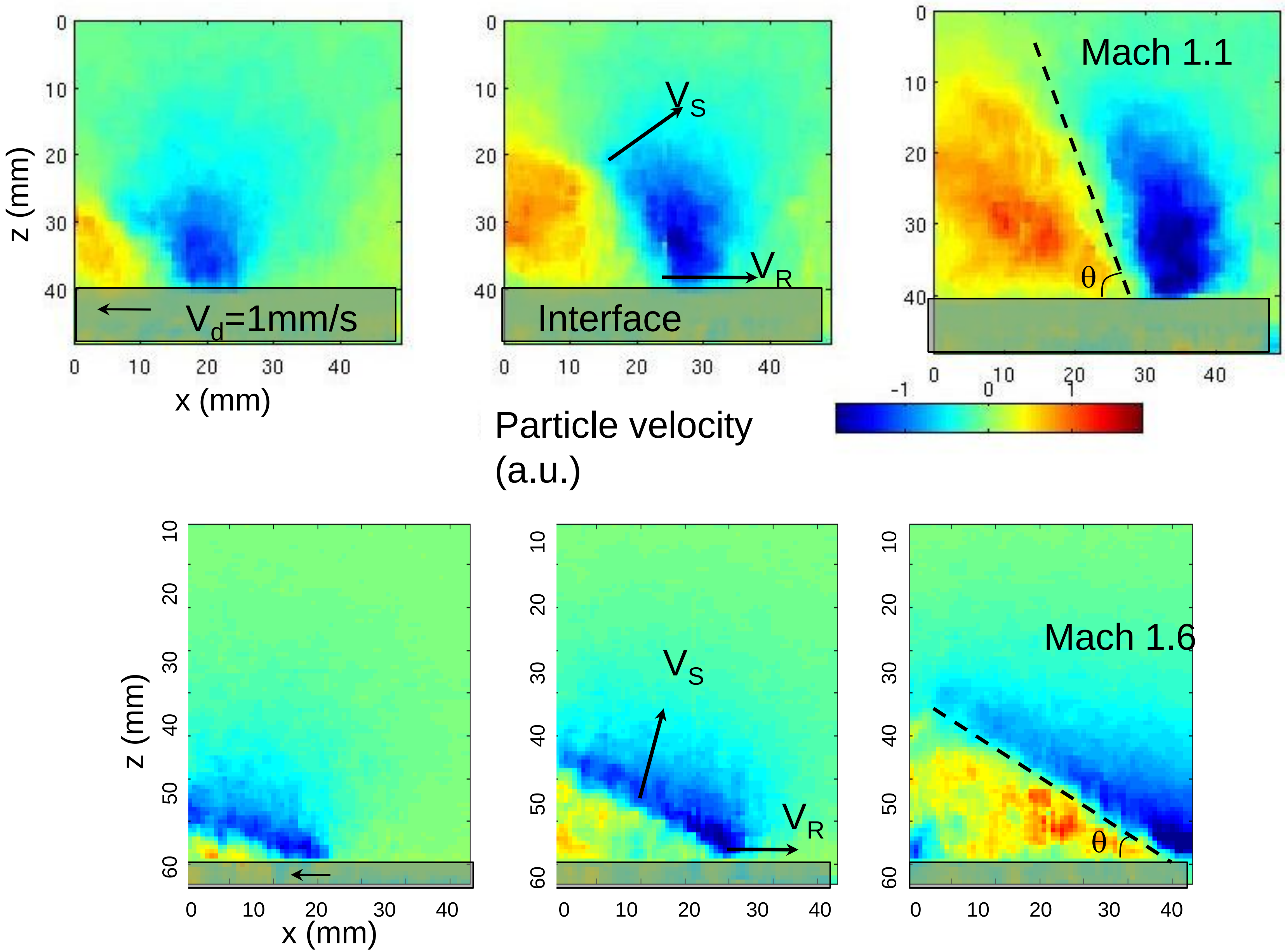



← $V_d$=1mm/s

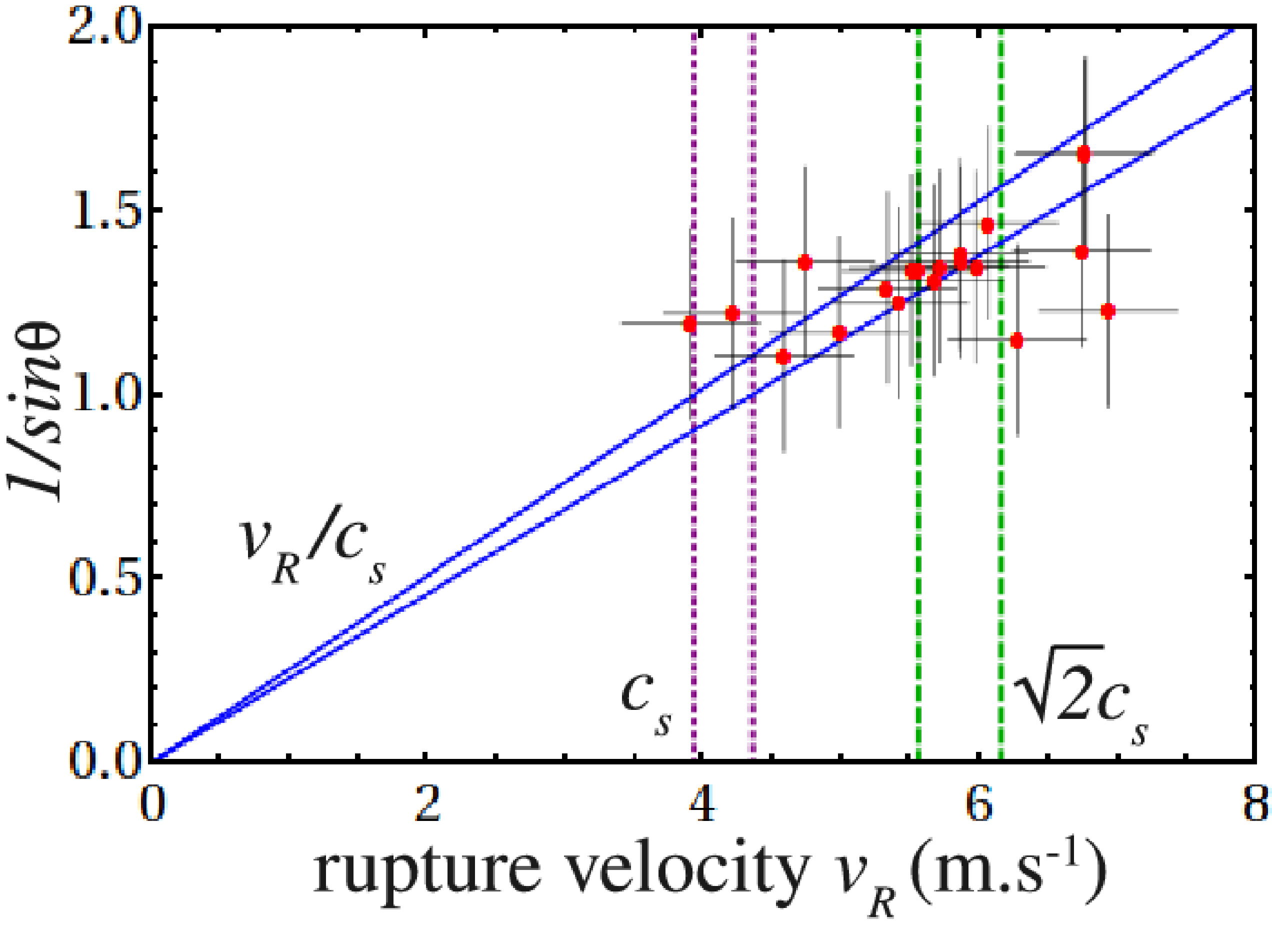


Mach 1.6
490
z (cm)
1
2
3
4
5
6
7
0
1.2
2.4
3.6
4.8
x (cm)
V_d=1mm/s

# Weak friction configuration : super shear regime



# Weak friction configuration : super shear regime

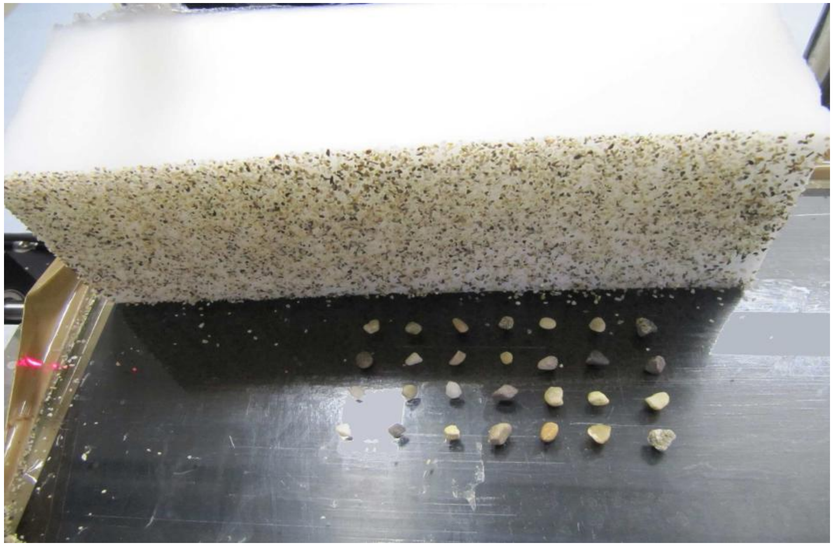




Mott (1945), Burridge (1973).
Archuleta R., Journal of Geophysical Research, Vol.89, pp.4559, 1984. 1979 Imperial Valley earthquake
A. Rosakis *et al*., « Cracks faster than the shear wave speed »,Science, Vol.284, pp.1337, 1999.

# Effect of heterogeneities

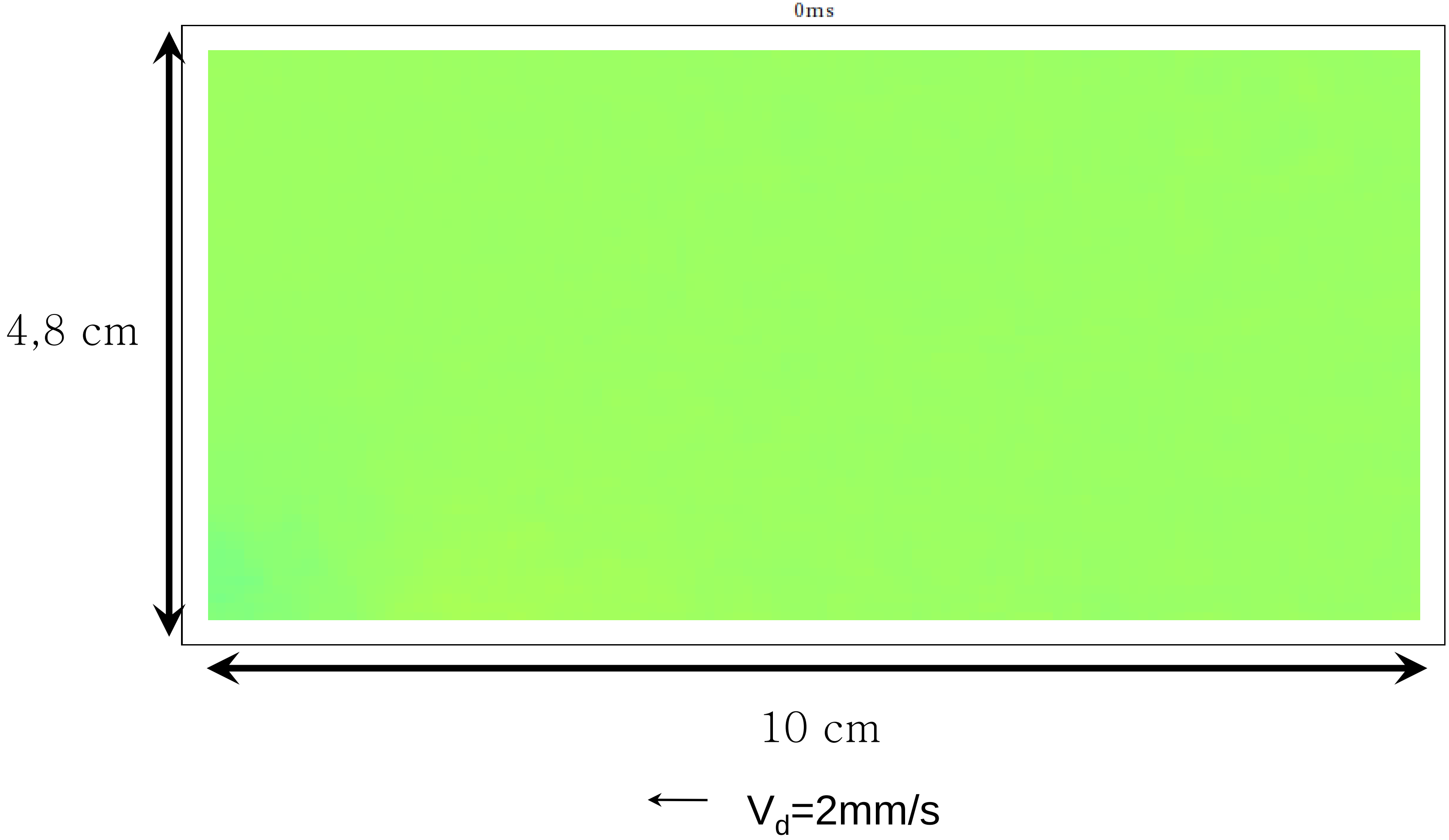
Mixed friction configuration: Sand+Pebles(higher cohesive resistance)



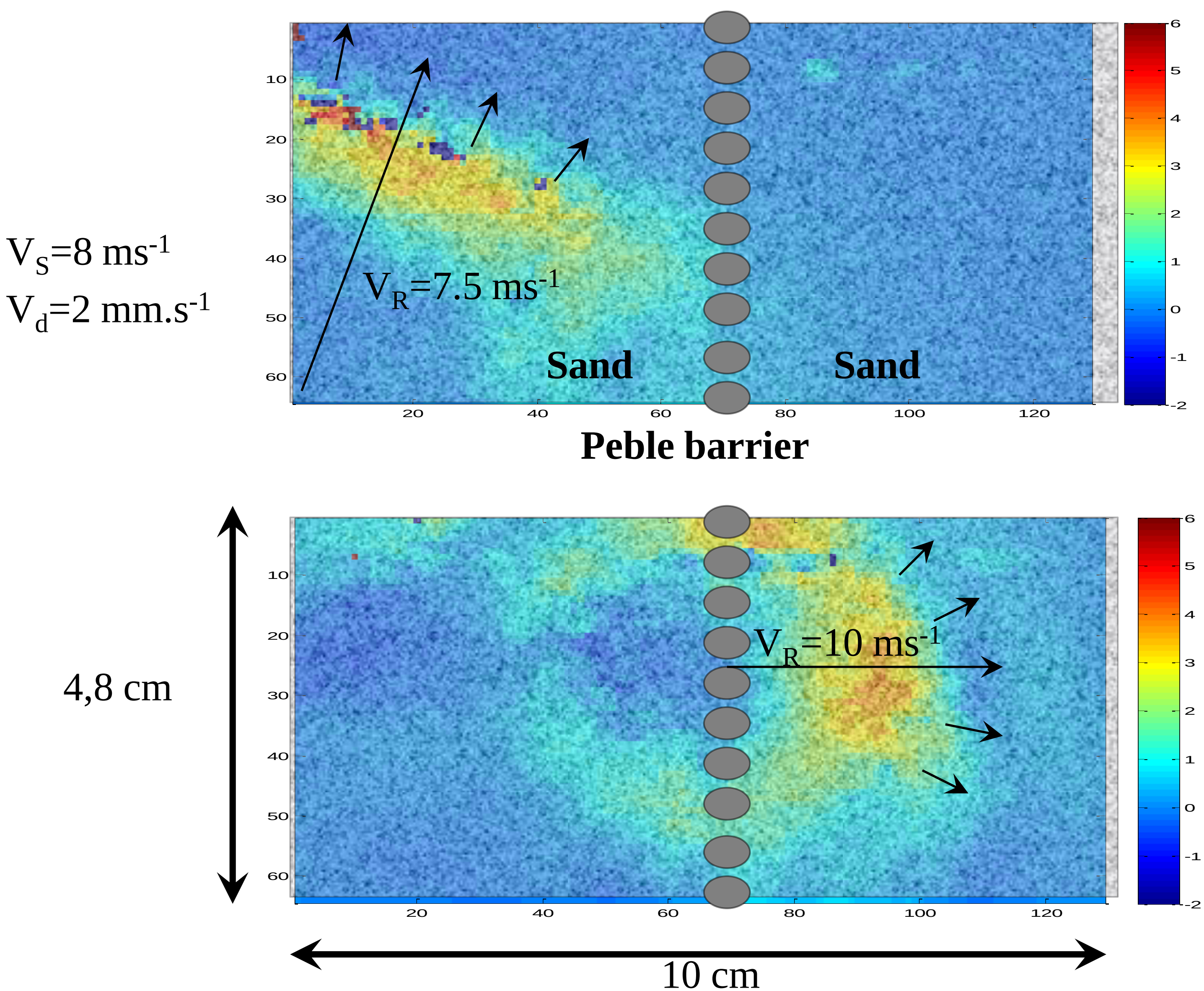
O. Ben David *et al*., « The dynamics of the onset of frictional slip »,Science, Vol.330, pp.211, 2010.

E. M. Dunham *et al*., « A supershear transition mechanism for cracks »,Science, Vol.299, pp.1557, 2003.

# Effect of barriers



# Mixed friction configuration



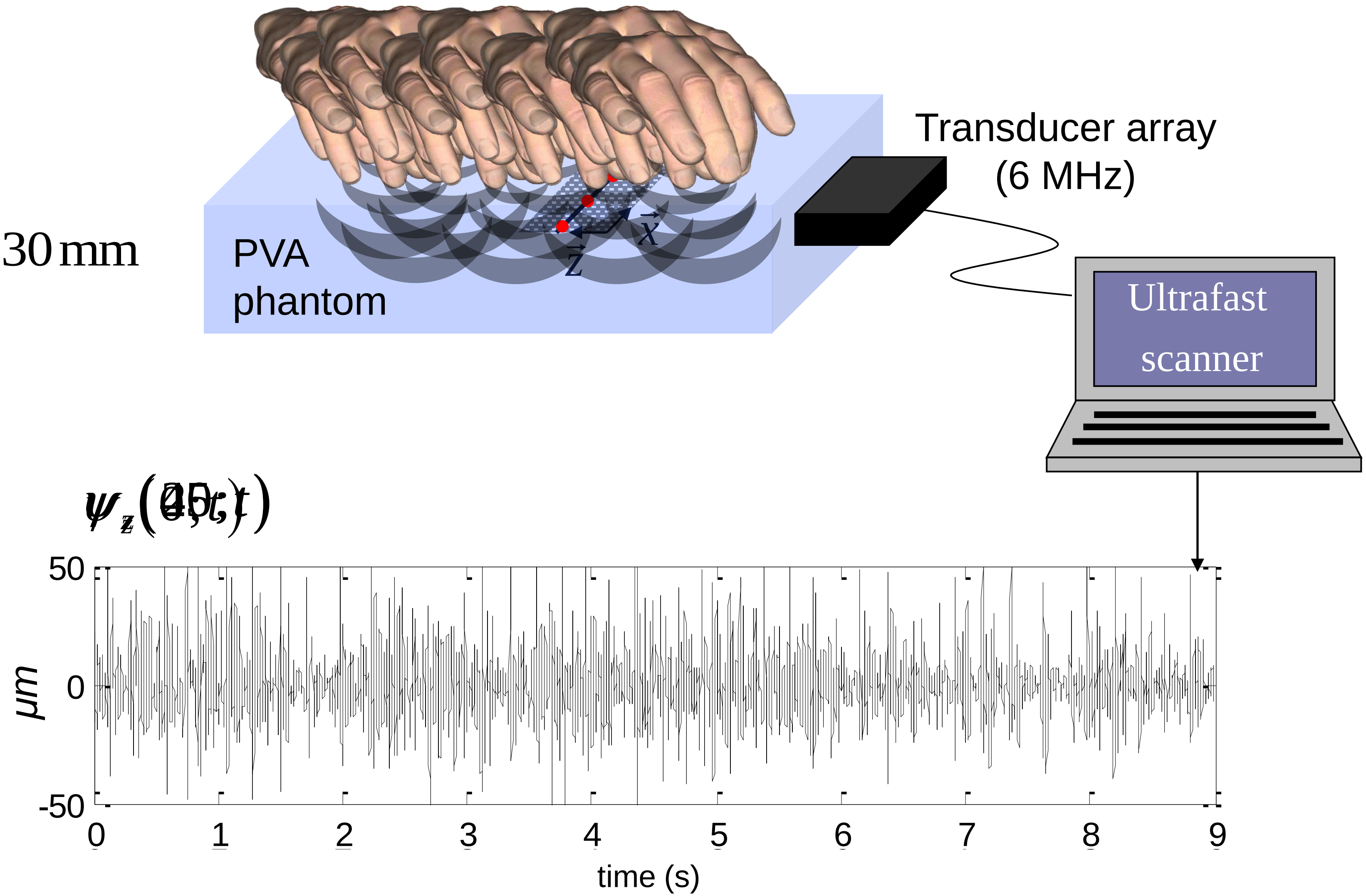

Latour et al. « Effect of fault heterogenity on rupture dynamics: an experimental approach using ultrafast ultrasound imaging », submitted Journal of Geophys. Reasearch.

**Non deterministic behaviour (memory effect?)**

# Part III: From seismology to medical imaging

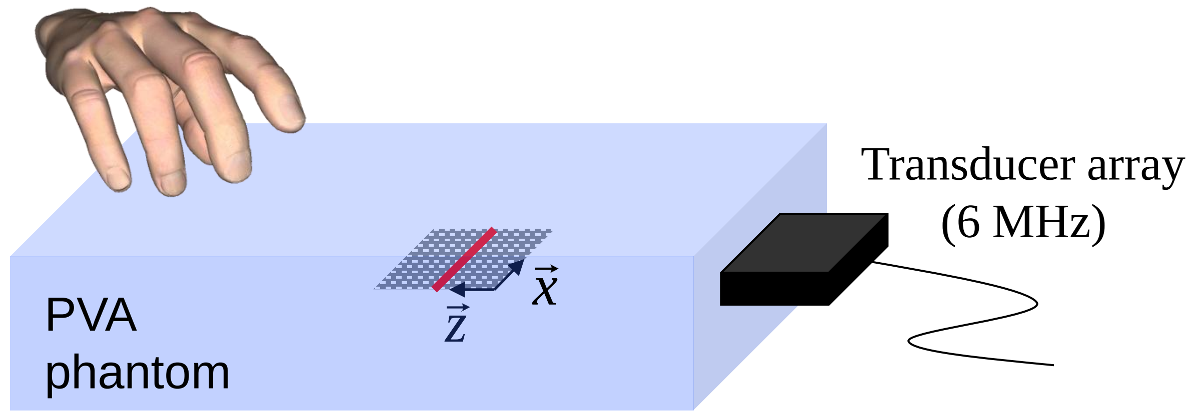
## -Noise correlation technique in passive elastography-

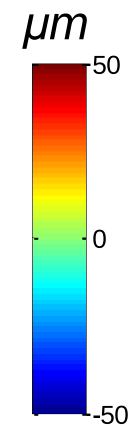
$z = 30\,\mathrm{mm}$



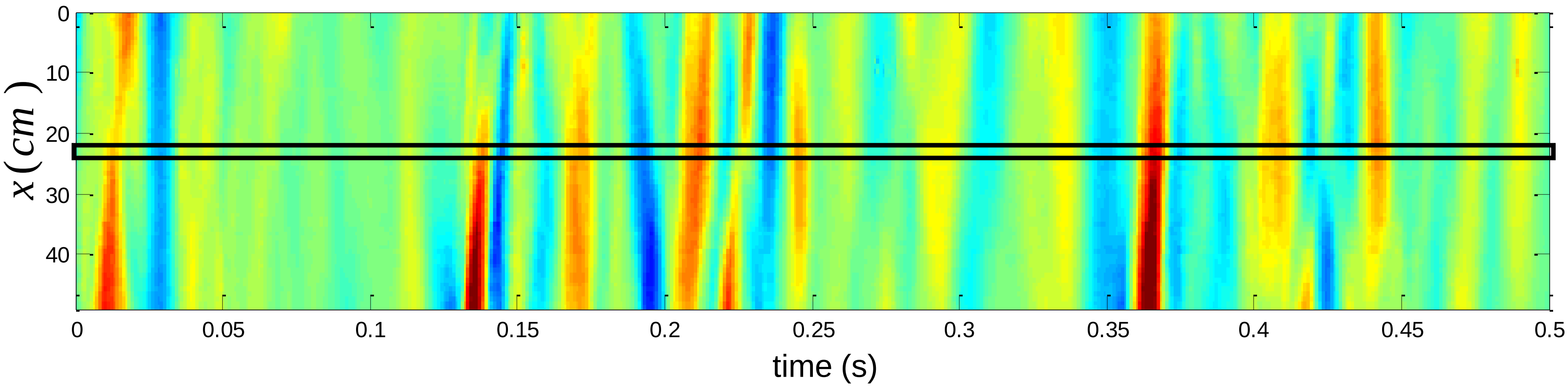
# Displacement field allong the *x*-axis

$z = 30\,\text{cm}$



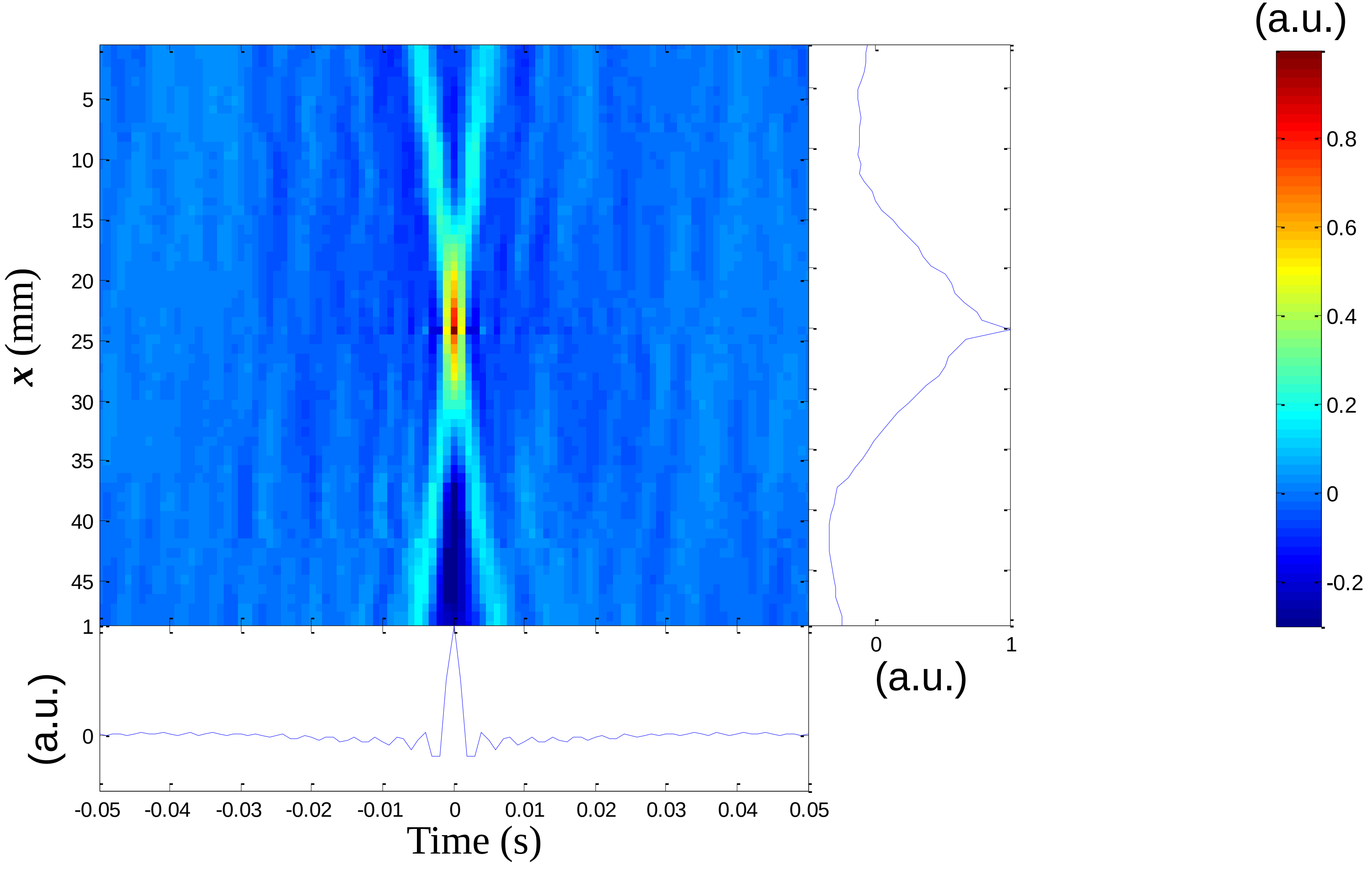




Zoom of half a second of $\psi_z(x;t)$ along *x*-axis

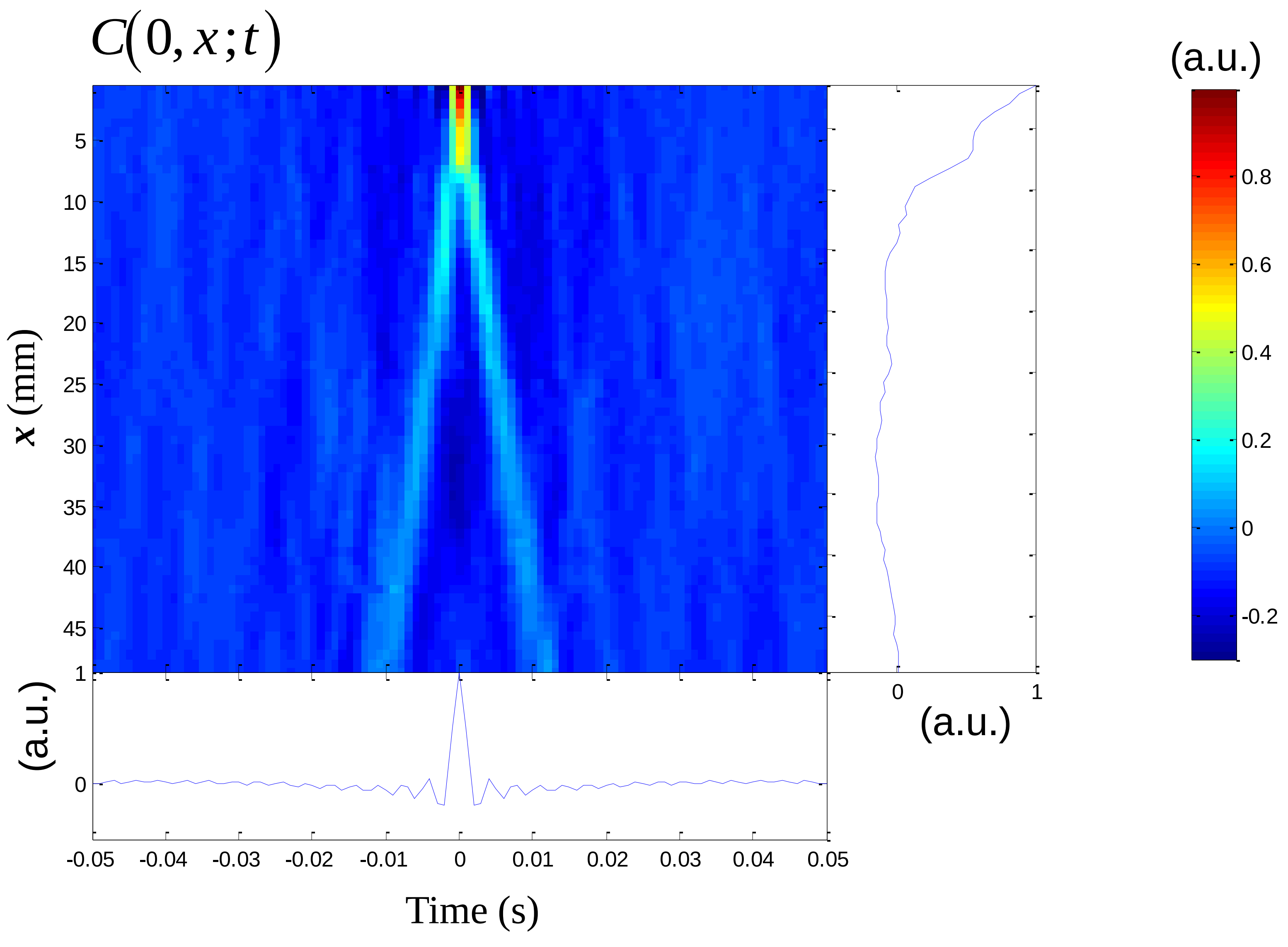


# TR field from noise cross-correlation

$$C(x_0, x; t) = \psi_z(x_0, T-t) \otimes \psi_z(x, t) \qquad \begin{cases} x_0 = 24\text{mm} \\ x \in [0; 49] \end{cases}$$



# TR field from noise cross-correlation



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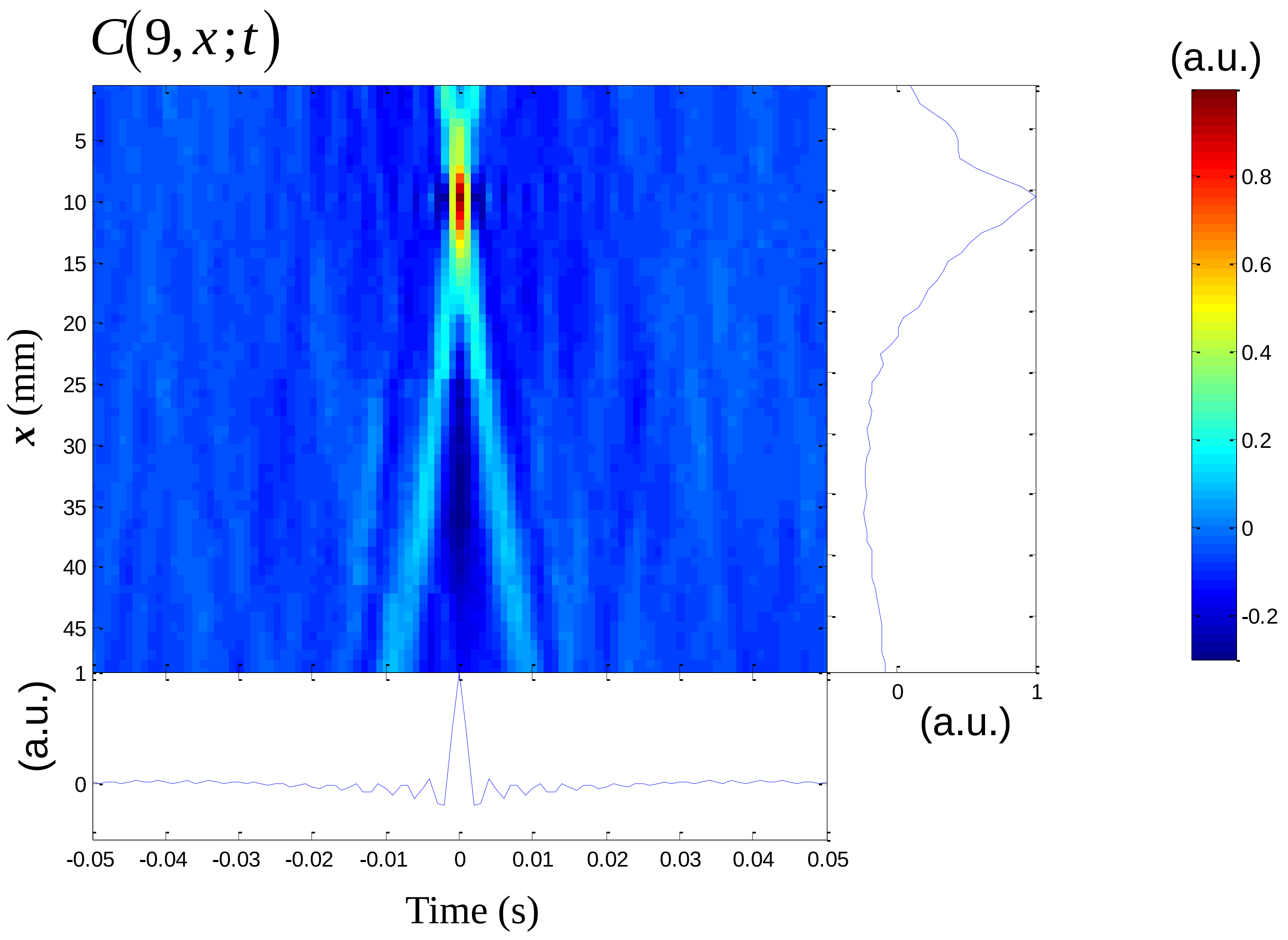
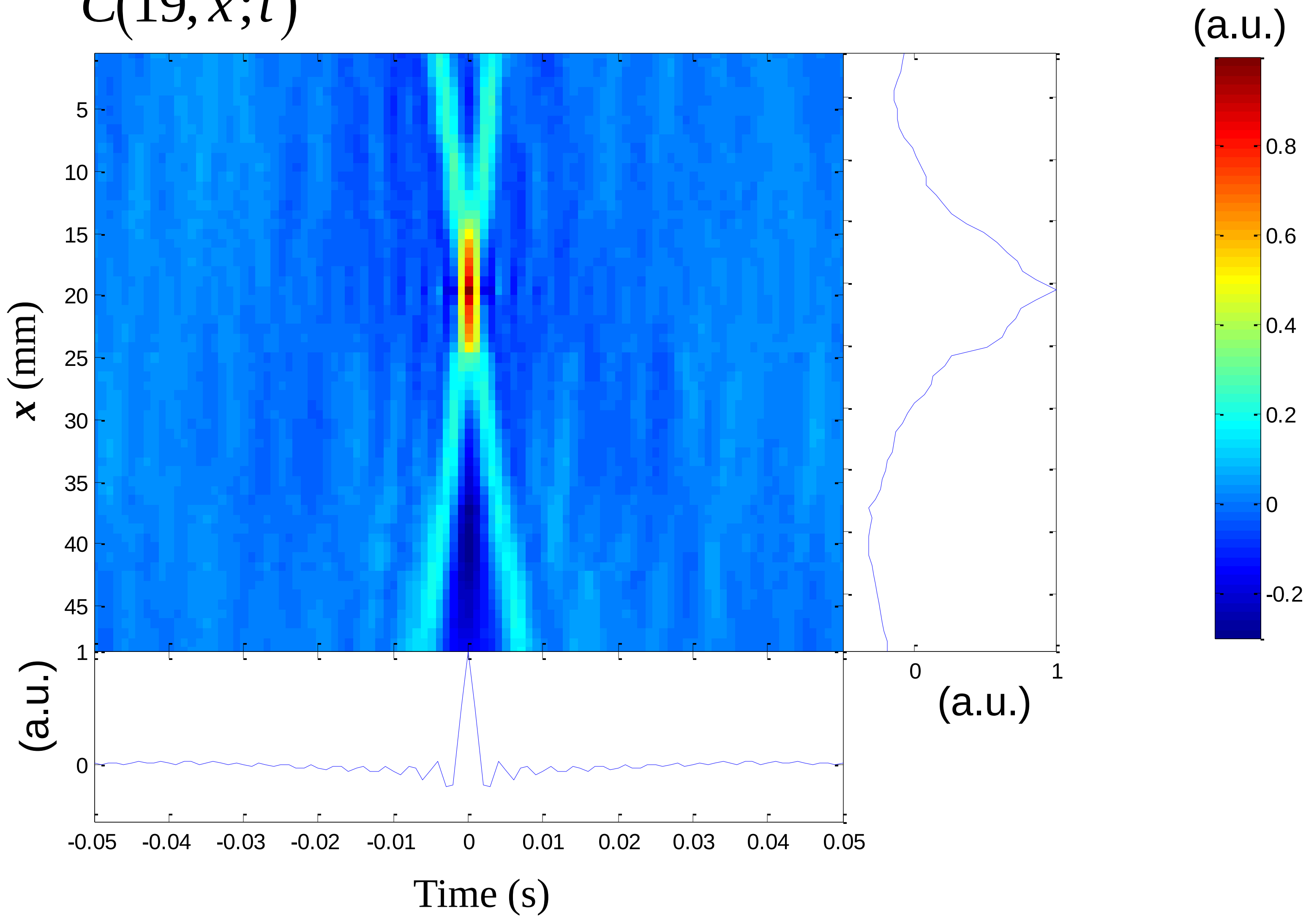


# TR field from noise cross-correlation

$C(19, x; t)$



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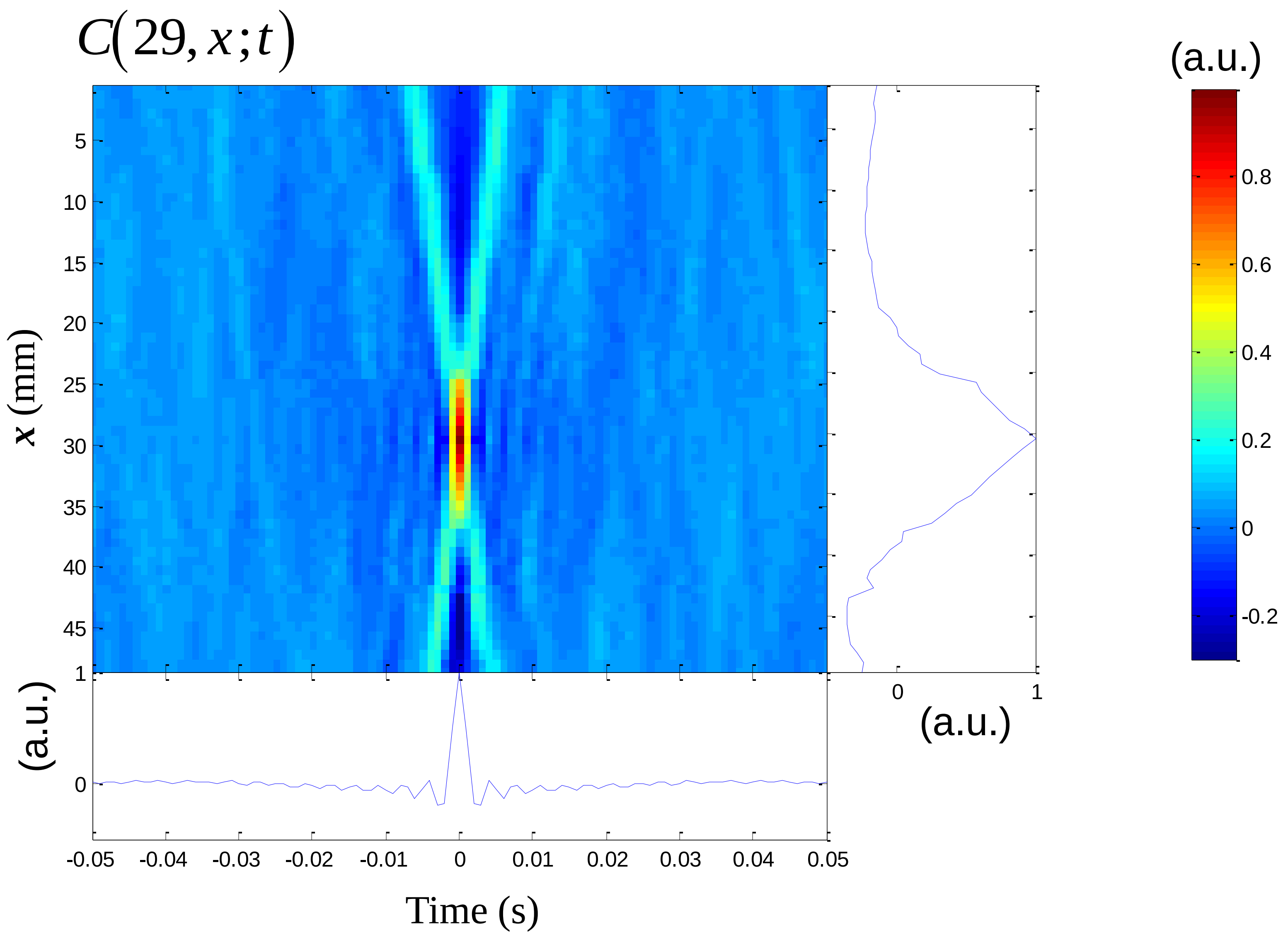

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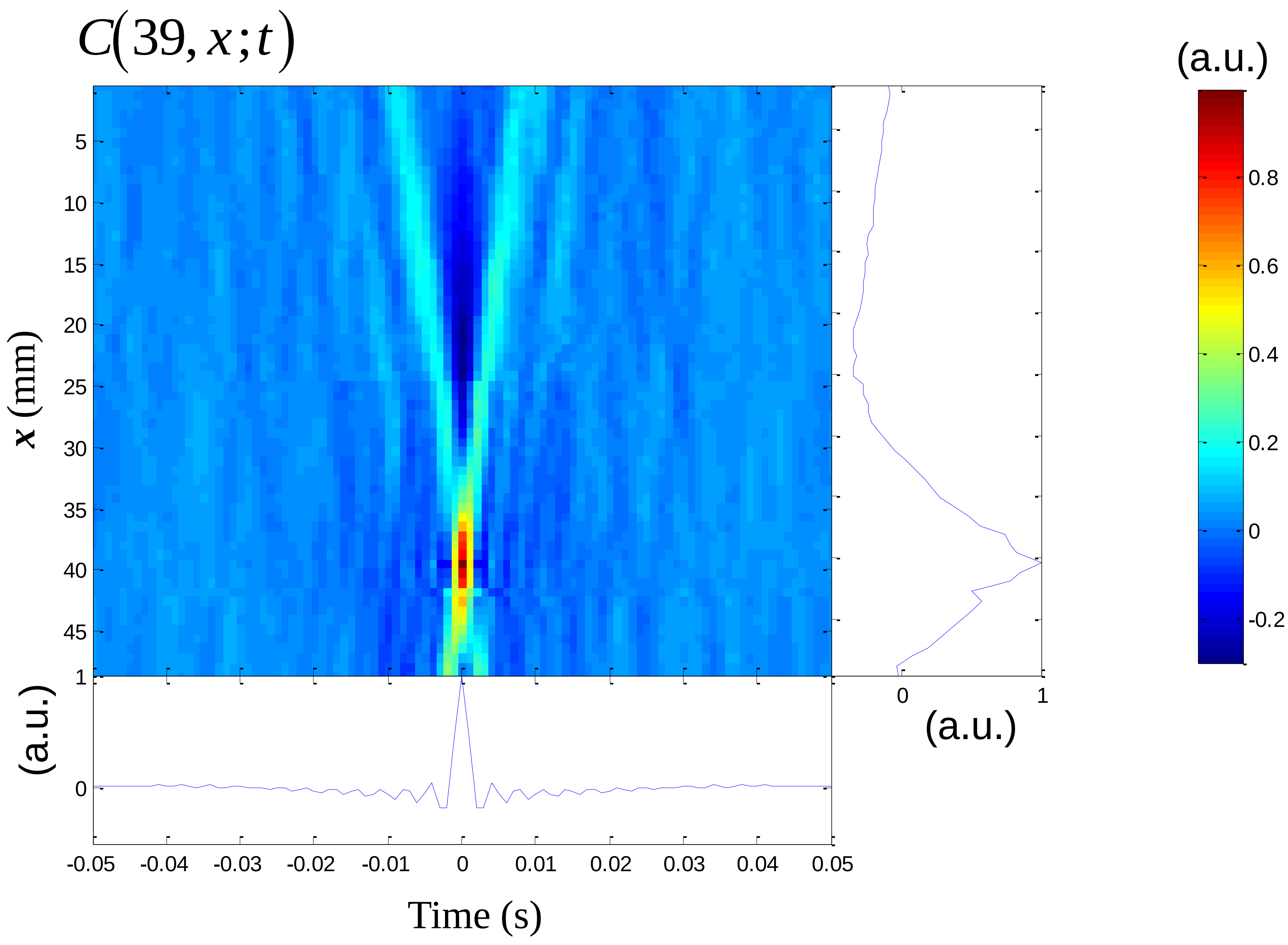

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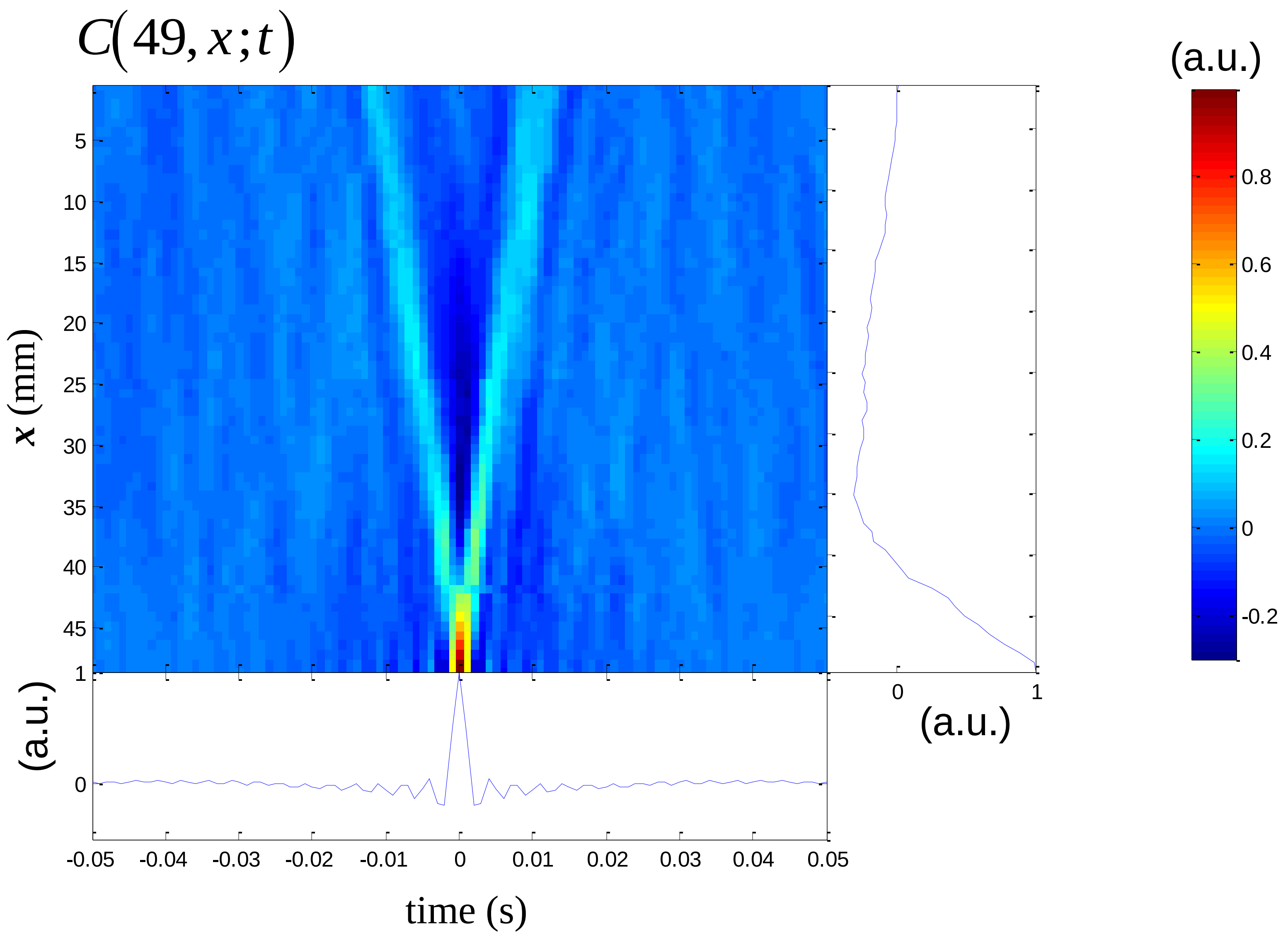
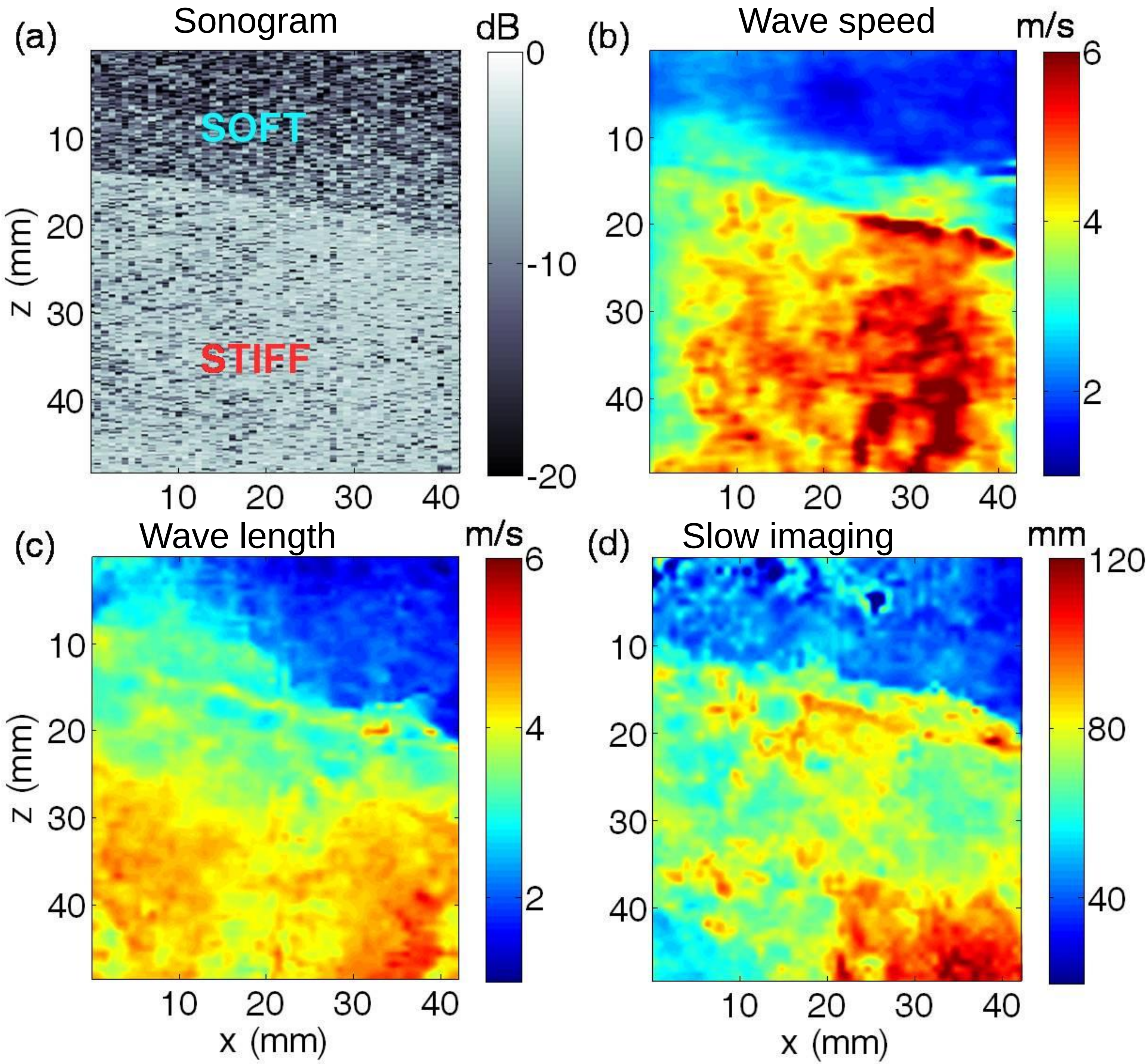
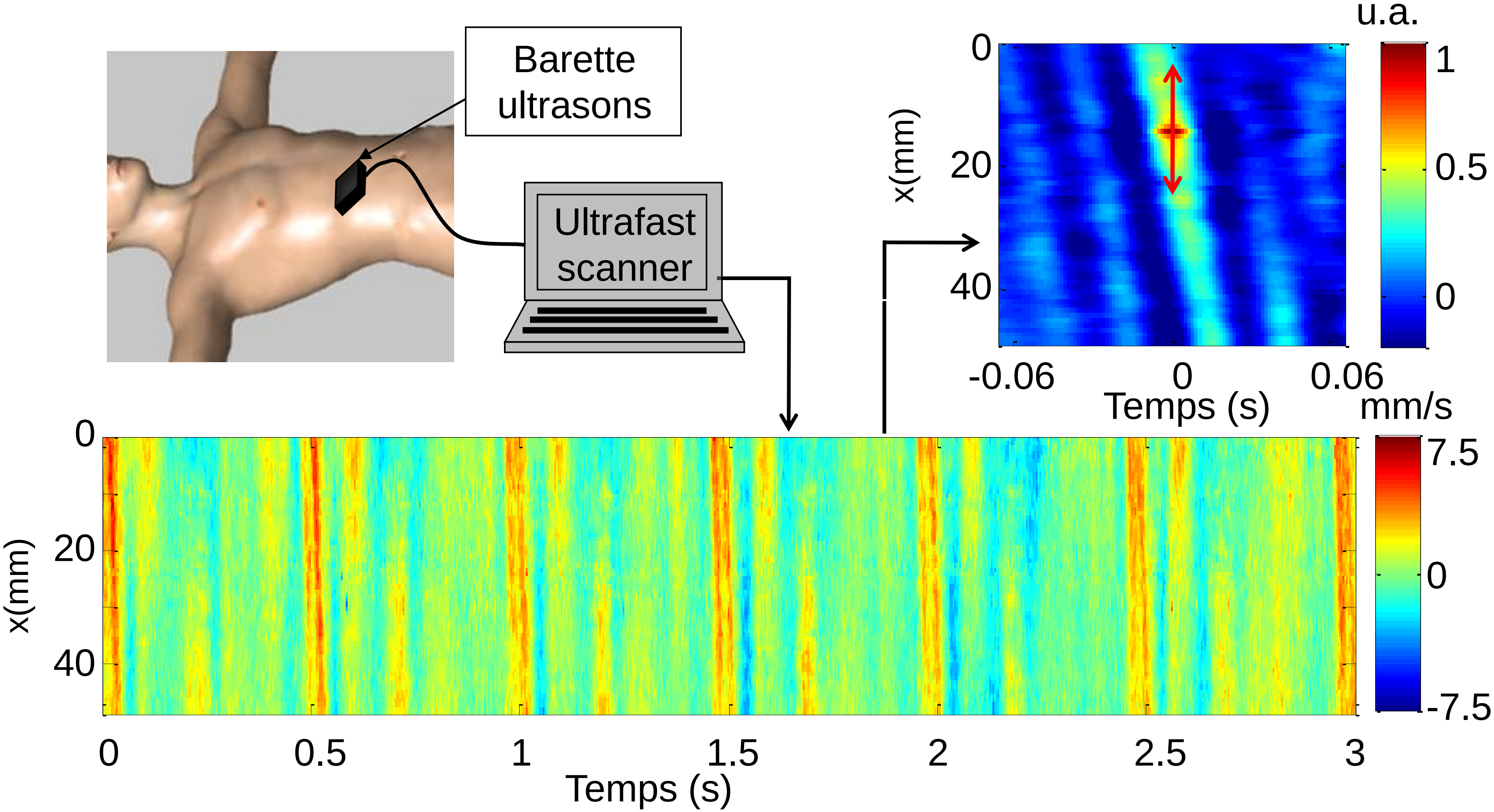




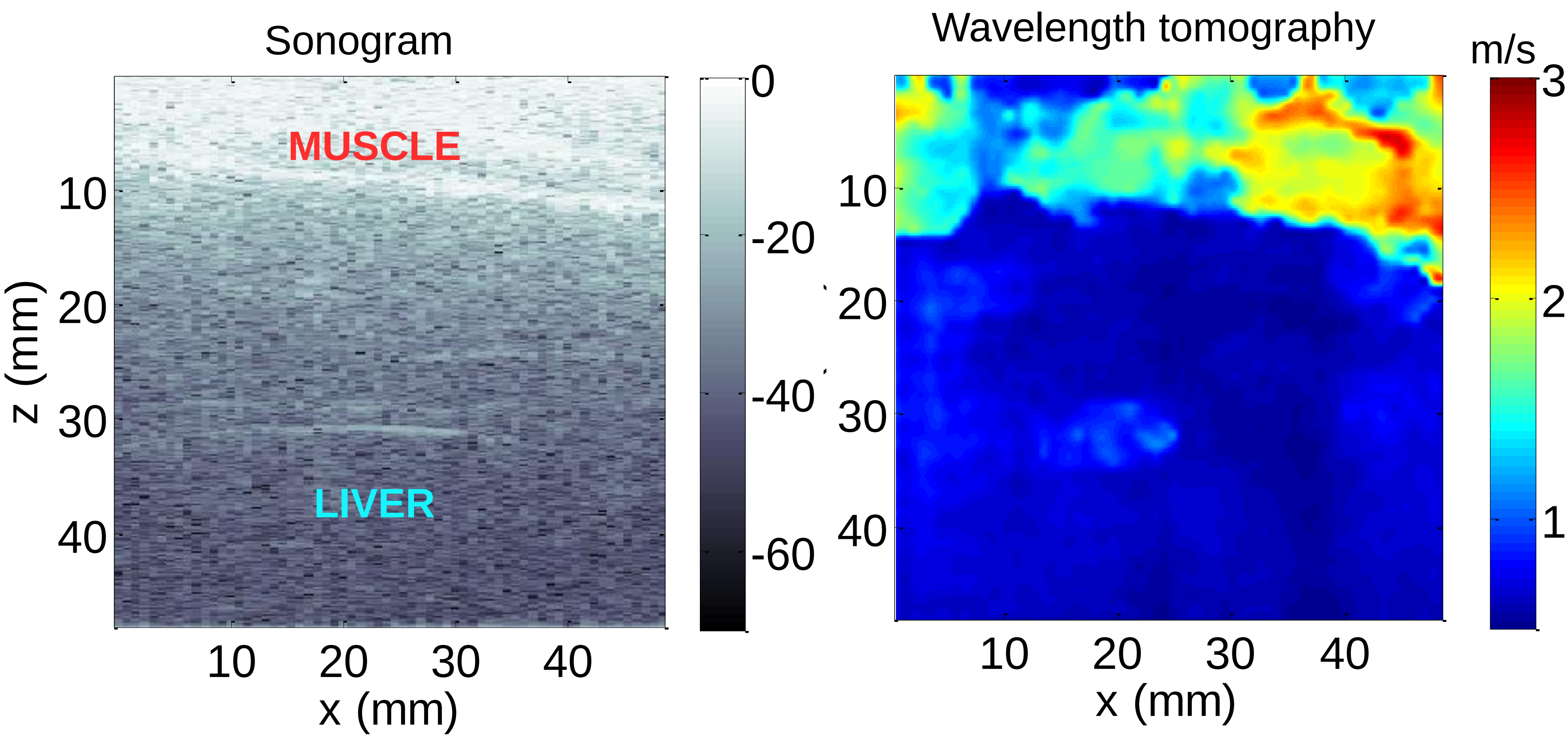
(a)
Sonogram
dB
0
-10
-20
SOFT
STIFF
(b)
Wave speed
m/s
6
4
2
(c)
Wave length
m/s
6
4
2
(d)
Slow imaging
mm
120
80
40
z (mm)
x (mm)
10
20
30
40

# The physiologic noise correlation by use of elastography




K. Sabra, S. Conti, P. Roux, and W. Kuperman, “Passive in vivo elastography from skeletal muscle noise,” Appl. Phys. Lett. **901–3, 194101,** 2007.

# The physiologic noise correlation by use of elastography



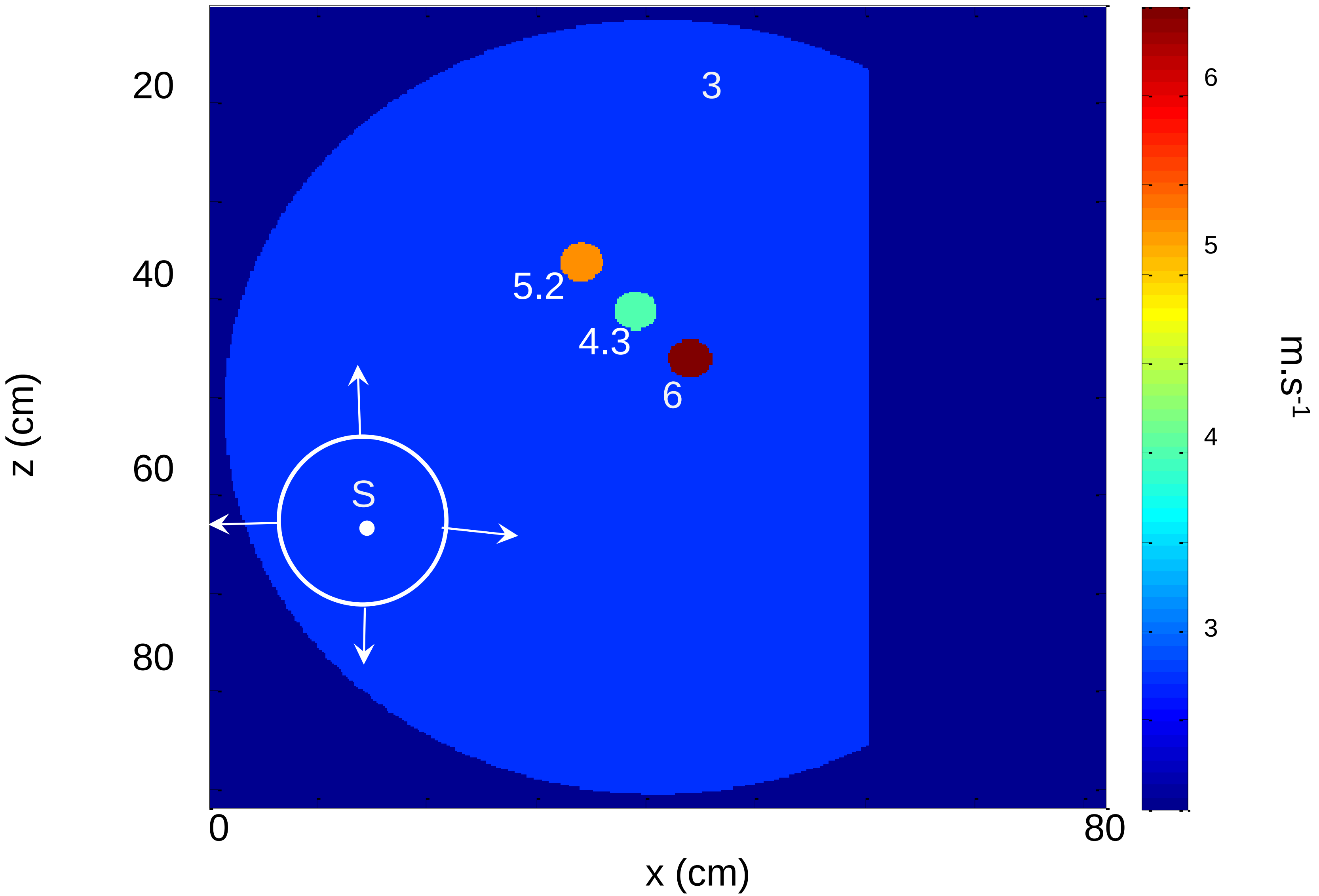

T. Gallot, S. Catheline, P.Roux, J.Brum, N.Benech, C.Negreira« Passive elastography: shear wave tomography  from physiological noise correlation in soft tissues » IEEE transaction on UFFC, Vol.58 N°6, June 2011.

# Shear wave imaging with a conventional scanner: the passive elastography approach

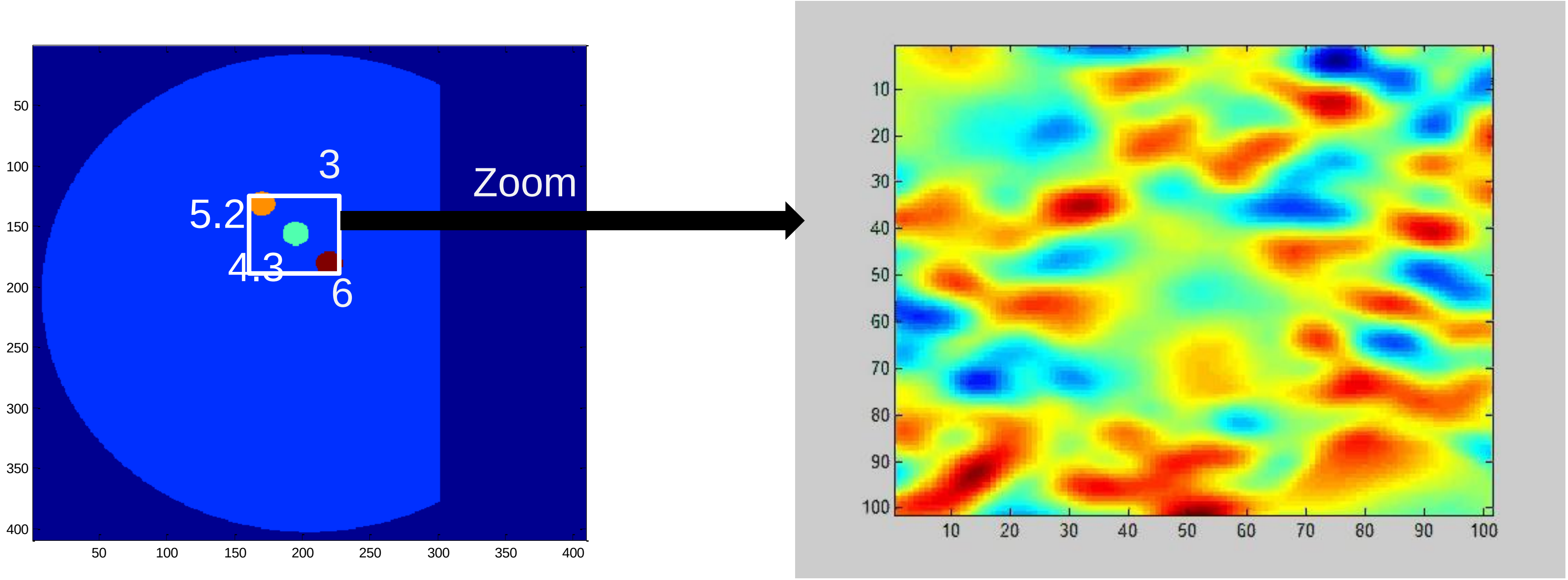
S.Catheline, R.Souchon, A. Hoang-Dinh and J-Y Chapelon

INSERM U1032, LabTAU, University of Lyon

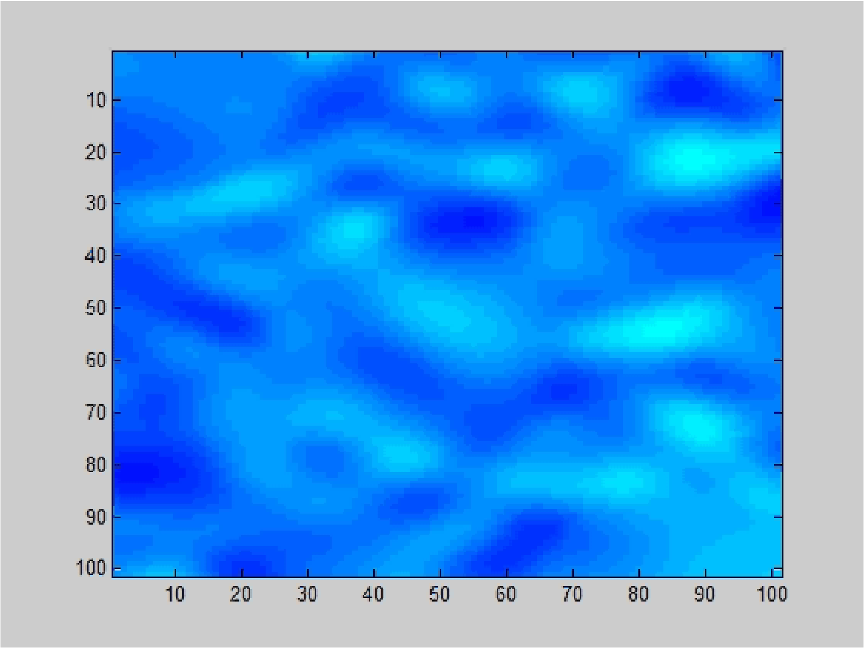
# The diffuse field approach: finite difference



# The diffuse field approach



# Time reversal




Key for speed extraction=TR

TR=spatio-temporal correlation (coda wave interferometry)

S.Catheline, N. Benech, X. Brum, and C. Negreira, *Phys.Rev.Letter.* **100**, 064301 (2008).

T.Gallot, S. Catheline, P. Roux, J. Brum, N. Benech, C. Negreira, *IEEE UFFC*, vol.58,6,p.1122 (2011)

$$\Delta\Phi - \frac{1}{c^2}\frac{\partial^2\Phi}{\partial t^2} = 0 \rightarrow \psi^{RT} = \Phi(\vec{r},t)\otimes\Phi(\vec{r}_0,-t) = \int \Phi\,\Phi^*\,dt$$

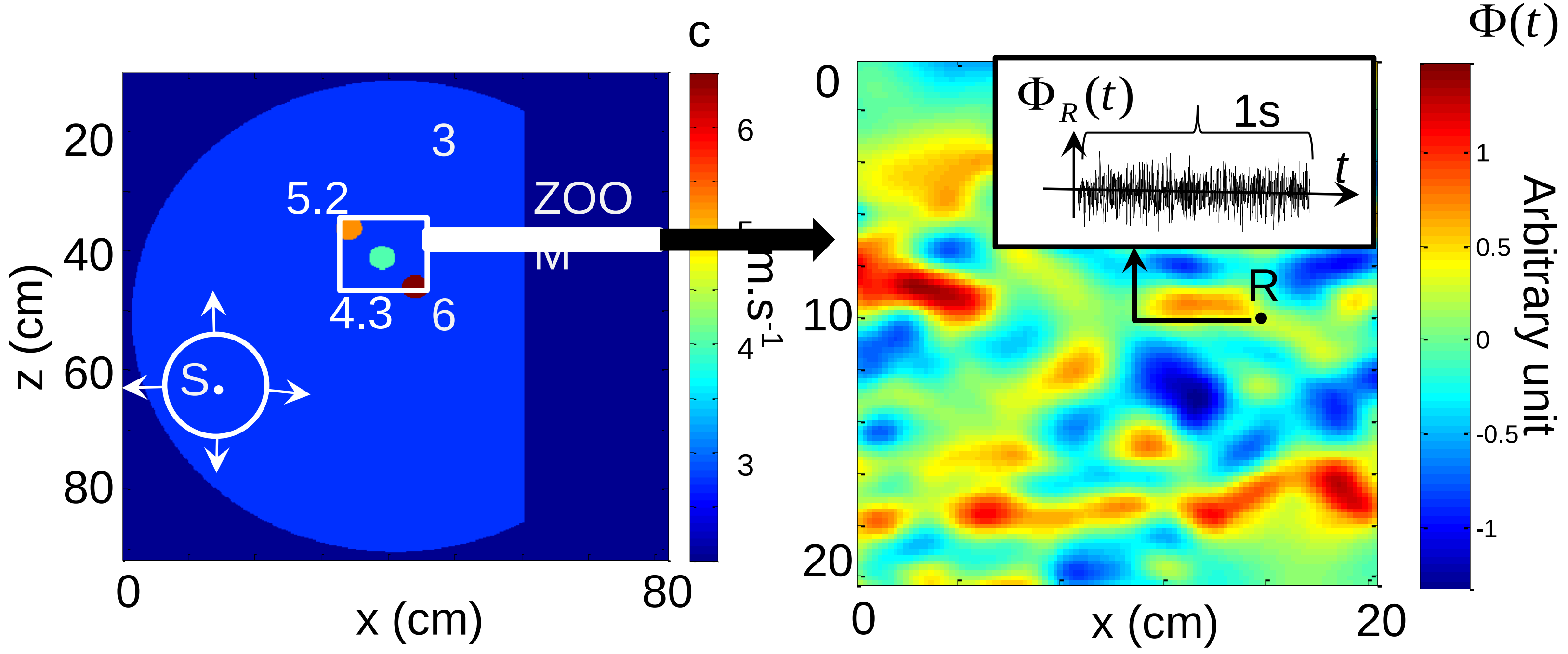
$$\varepsilon_z = \frac{\partial\Phi}{\partial z} \rightarrow \Delta\varepsilon_z - \frac{1}{c^2}\frac{\partial^2\varepsilon_z}{\partial t^2} = 0 \rightarrow \xi^{RT} = \int \varepsilon_z\varepsilon_z^*\,dt$$

Plane wave

$$\rightarrow \xi^{RT} \approx -k^2\psi^{RT}$$

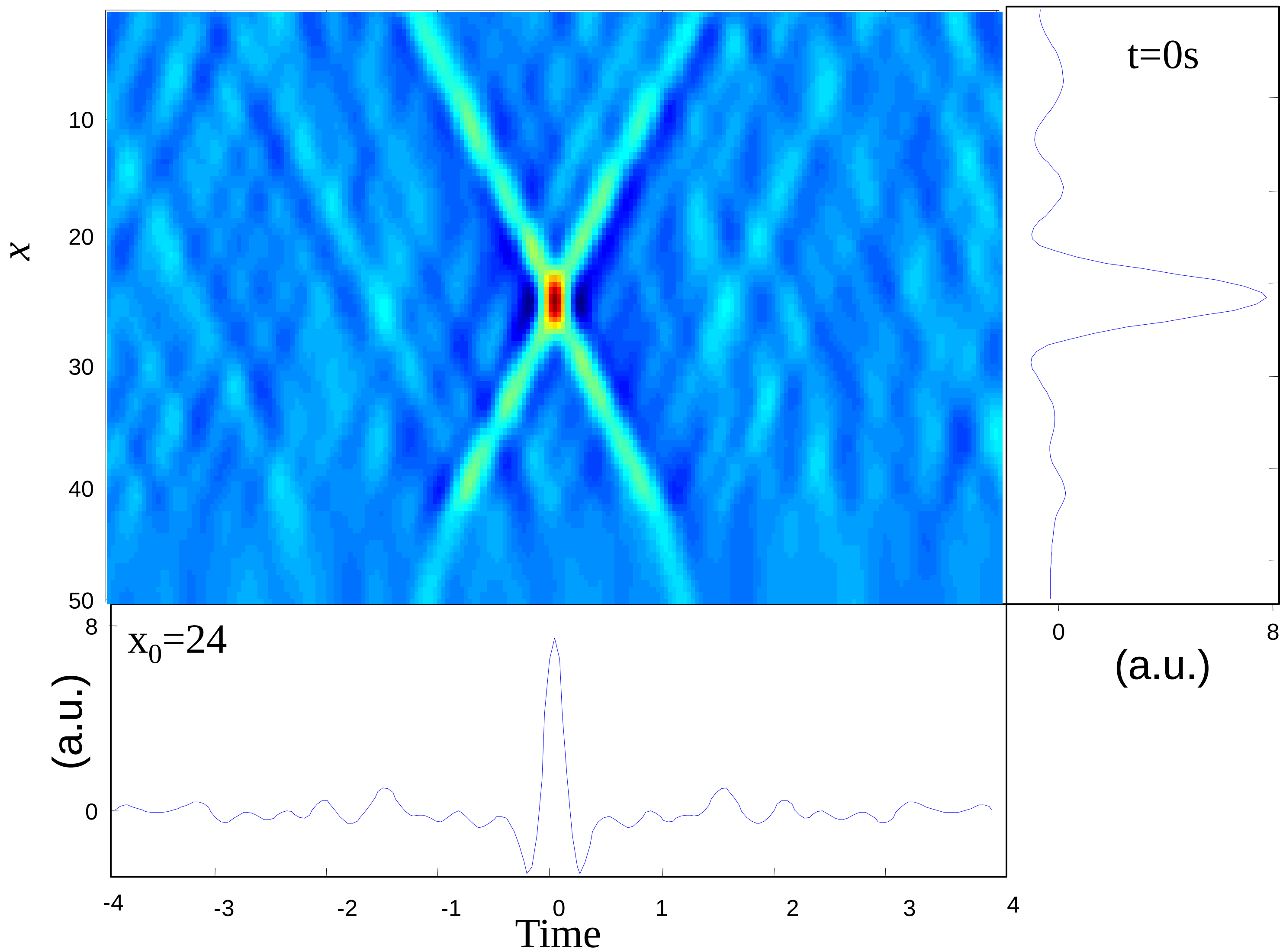
$$v = \frac{\partial\Phi}{\partial t} \rightarrow \Delta v - \frac{1}{c^2}\frac{\partial^2 v}{\partial t^2} = 0 \rightarrow V^{RT} = \int v v^*\,dt \rightarrow V^{RT} \approx -\omega^2\psi^{RT}$$

$$c = \frac{\omega}{k} = \sqrt{\frac{V^{RT}}{\xi^{RT}}}$$

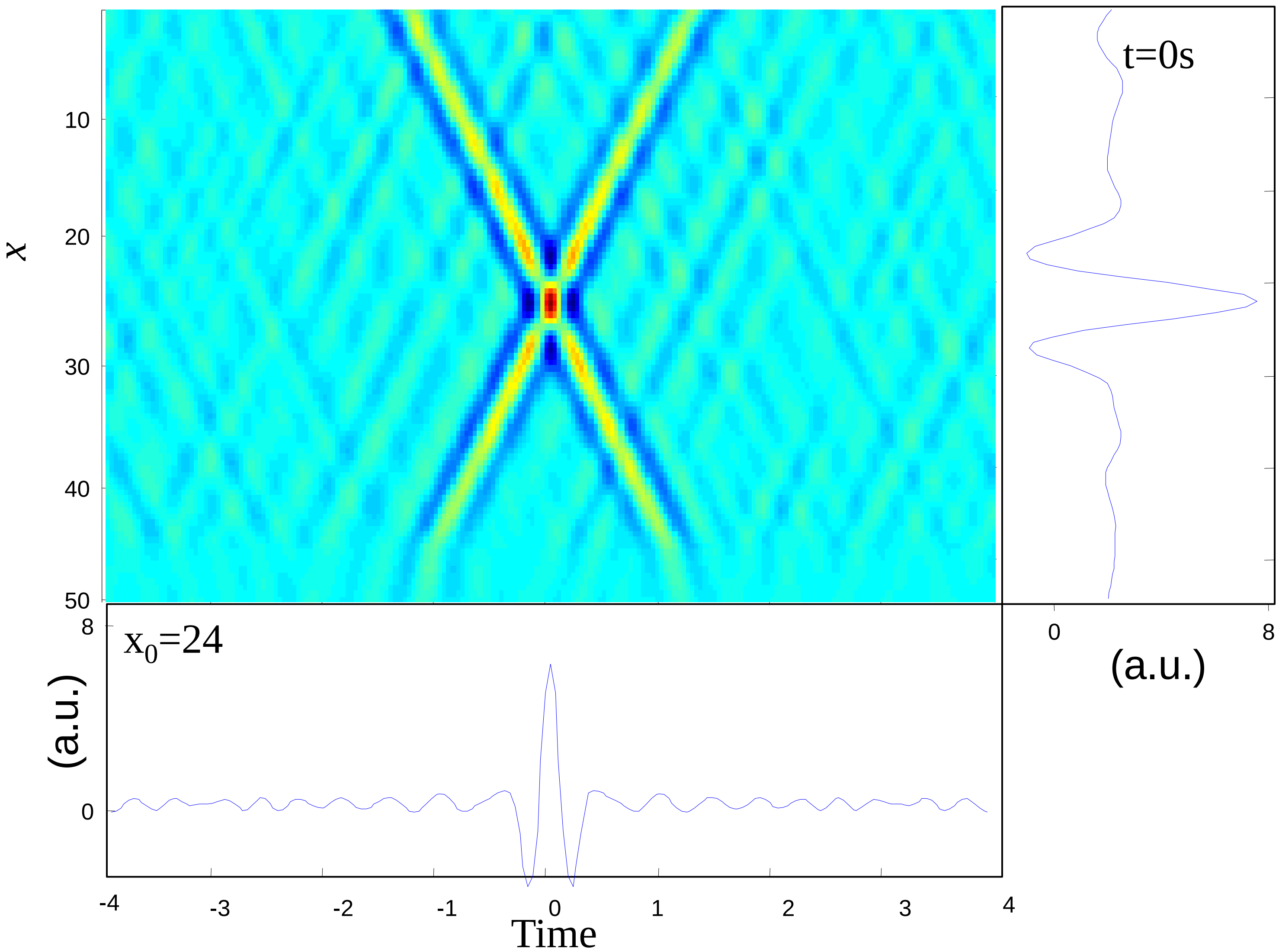


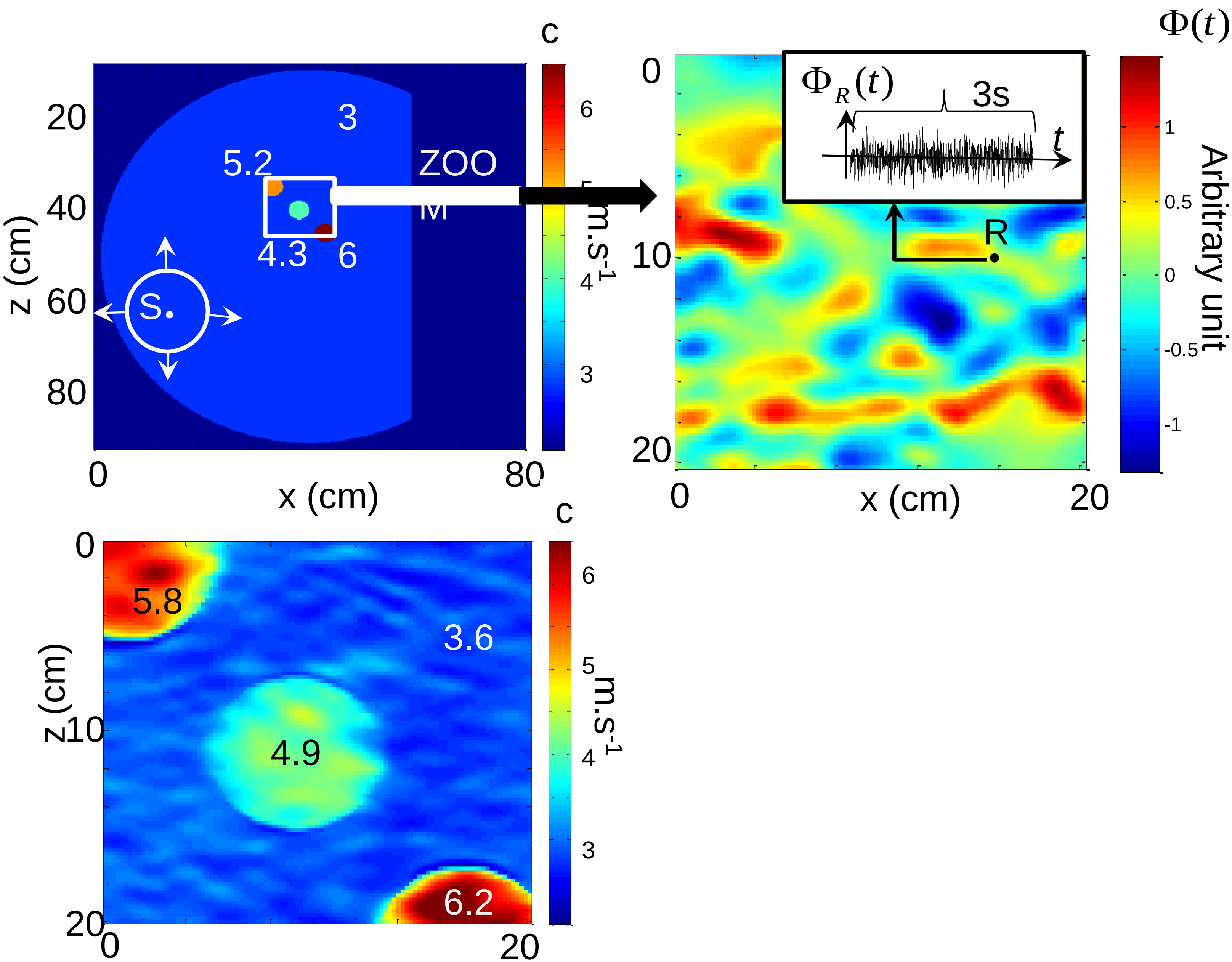

$F_{sampling}$=1000Hz

# Over sampling

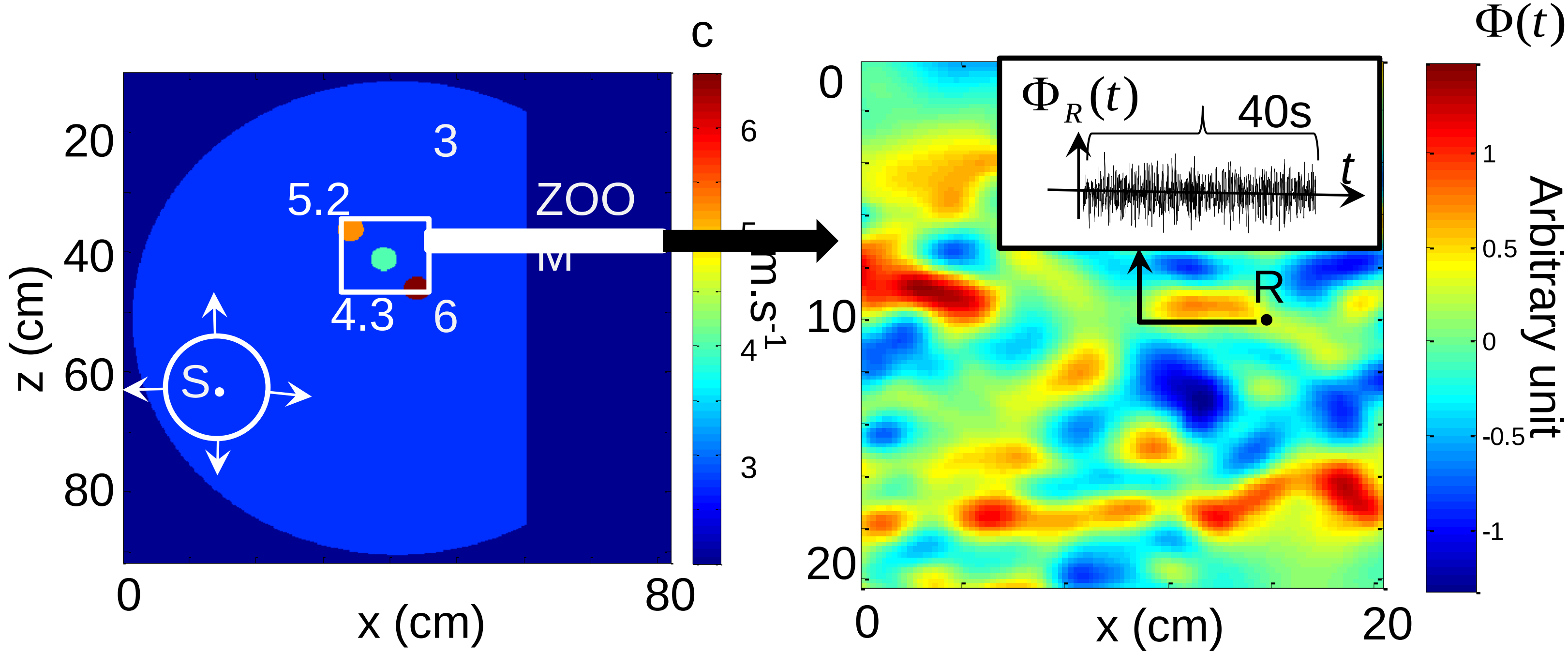


# Over sampling



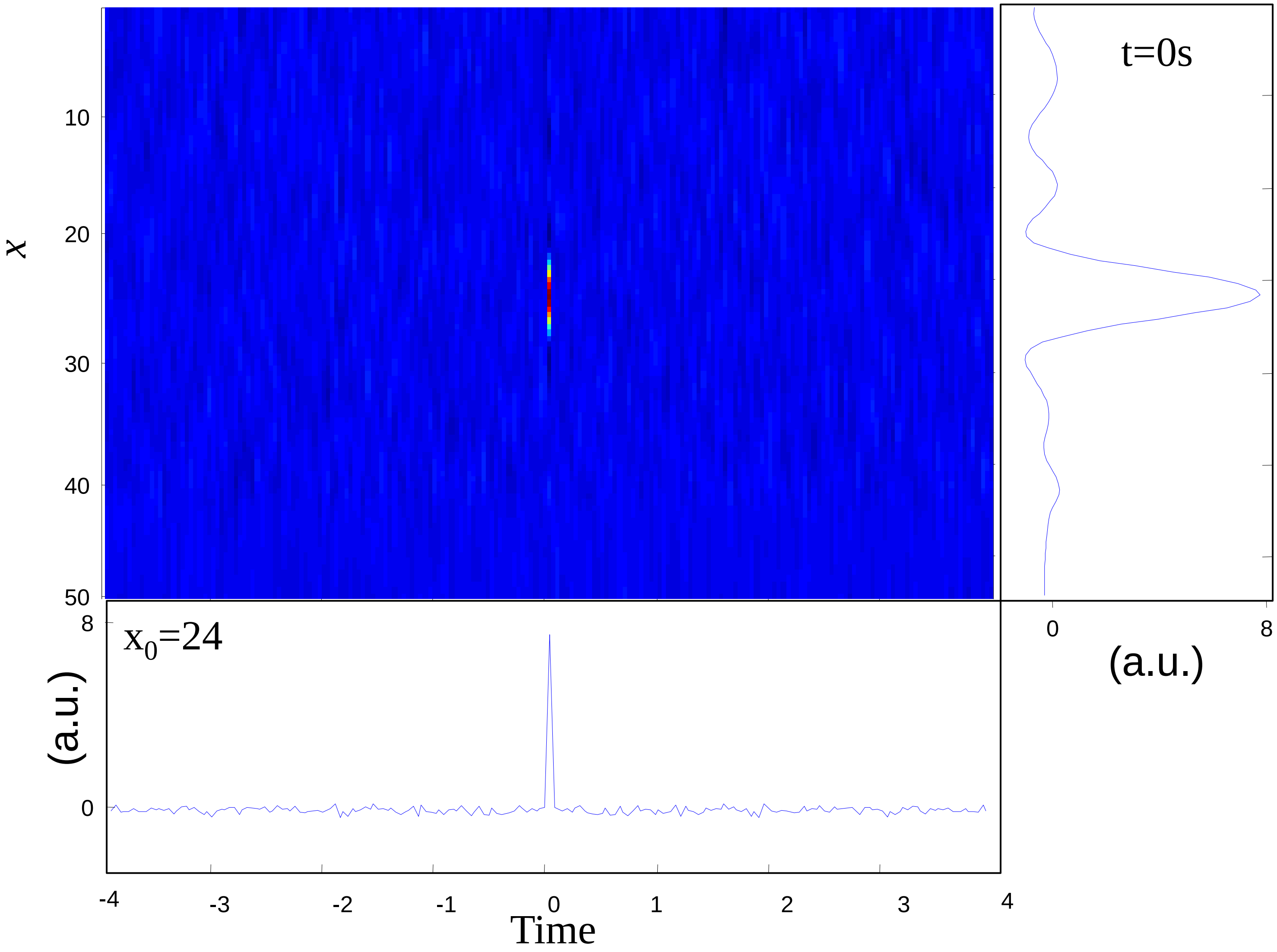



$$c = \frac{\omega}{\mathrm{Re}(k)} = \sqrt{\frac{V^{RT}}{\xi^{RT}}}$$



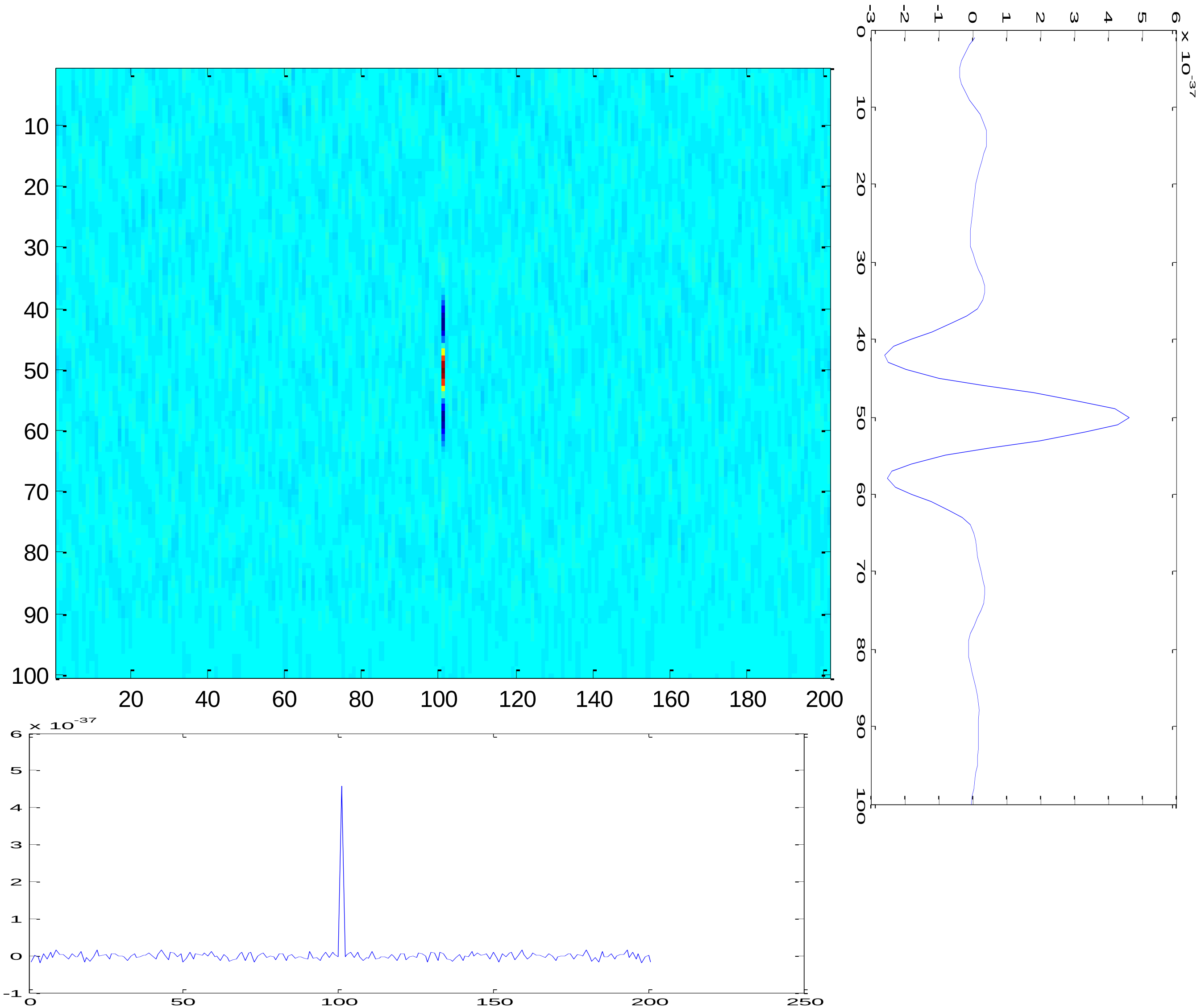

$F_{sampling}$=25Hz

# Under sampling

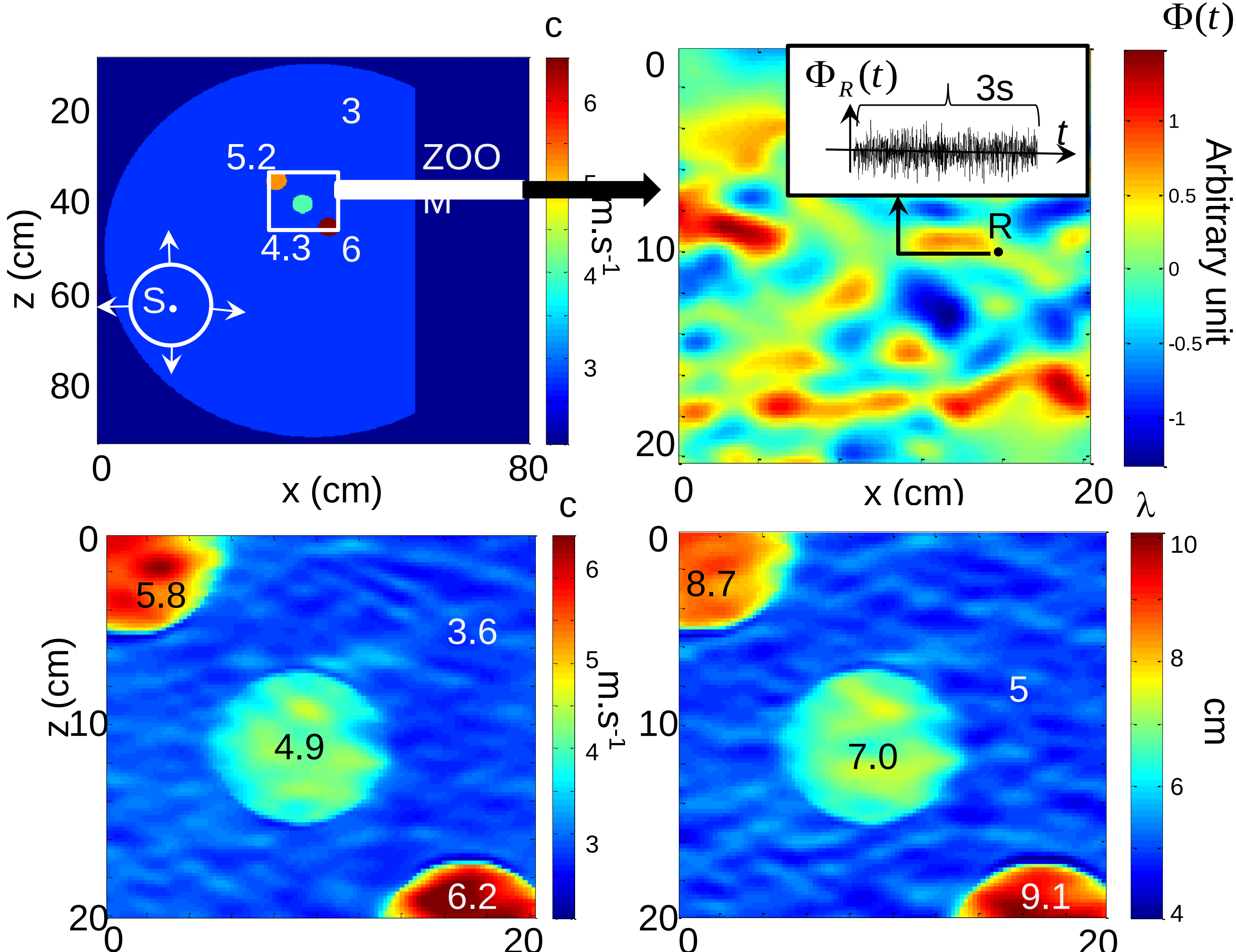



$$C(\vec{r}_0, \vec{r}; 0) = \int_0^T \psi_z(\vec{r}_0, \tau) \cdot \psi_z(\vec{r}, \tau) \mathrm{d}\tau.$$

$$C_\phi(\vec{r}_0, \vec{r}; 0) = \int_0^T \psi_z(\vec{r}_0, \phi(\tau)) \cdot \psi_z(\vec{r}, \phi(\tau)) \mathrm{d}\tau.$$



x 10^-37
x 10^-37

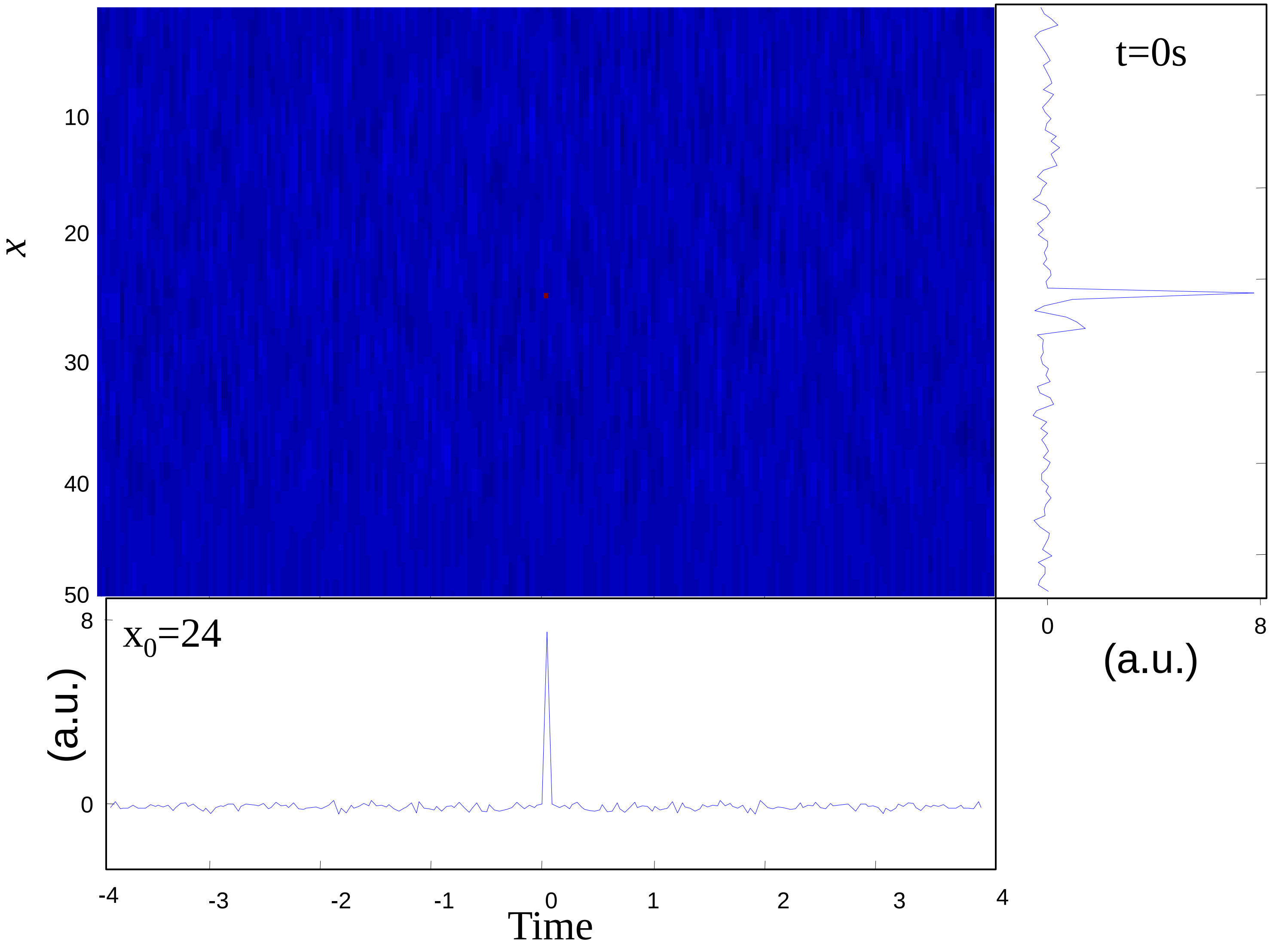


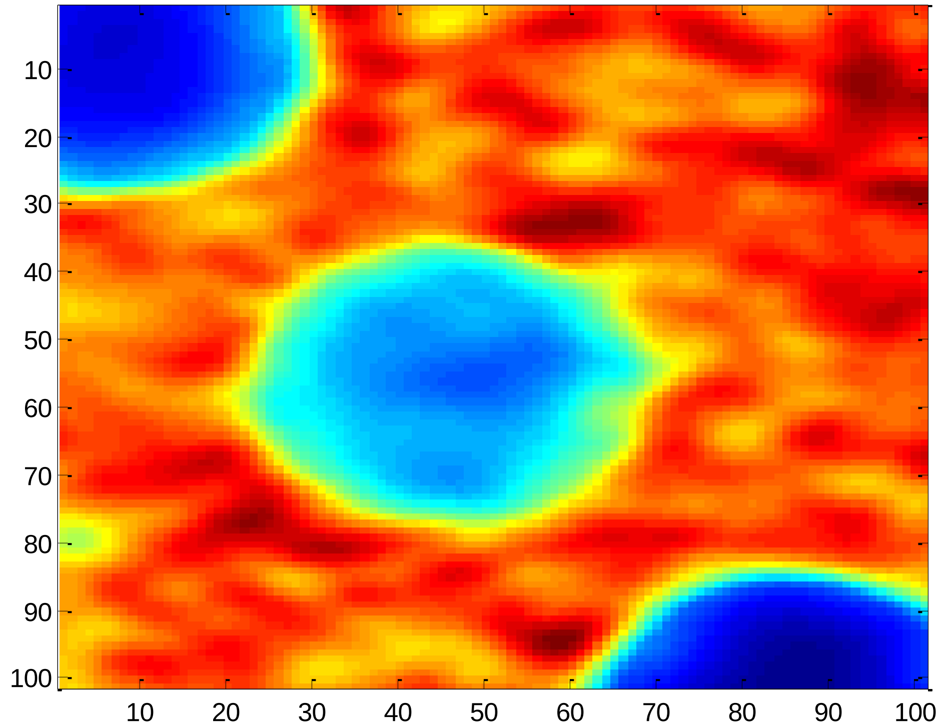

$$c = \frac{\omega}{\mathrm{Re}(k)} = \sqrt{\frac{V^{RT}}{\xi^{RT}}}$$

$$k = \sqrt{\frac{\xi^{RT}}{\psi^{RT}}}$$

Infos spatiales uniquement
Pas d'info temporelle

# Elasticity imaging: under sampling experiments






$$\mathrm{Im}\left[G_{mn}(\mathbf{0},\mathbf{r})\right] = \frac{k}{12\pi\mu}\left\{\left[\left(\frac{\beta}{\alpha}\right)^3\left(j_0(qr)+j_2(qr)\right)+2j_0(kr)-j_2(kr)\right]\delta_{mn}+\left[3j_2(kr)-3\left(\frac{\beta}{\alpha}\right)^3 j_2(qr)\right]\gamma_m\gamma_n\right\}$$

$$\mathrm{Im}\left[G_{mn}(0,0)\right] = \frac{k}{12\pi\mu}\left[\left(\frac{\beta}{\alpha}\right)^3+2\right] \cong \frac{k}{6\pi\mu} = \frac{f}{3\rho c_S^3}$$

The softer, the higher the amplitude

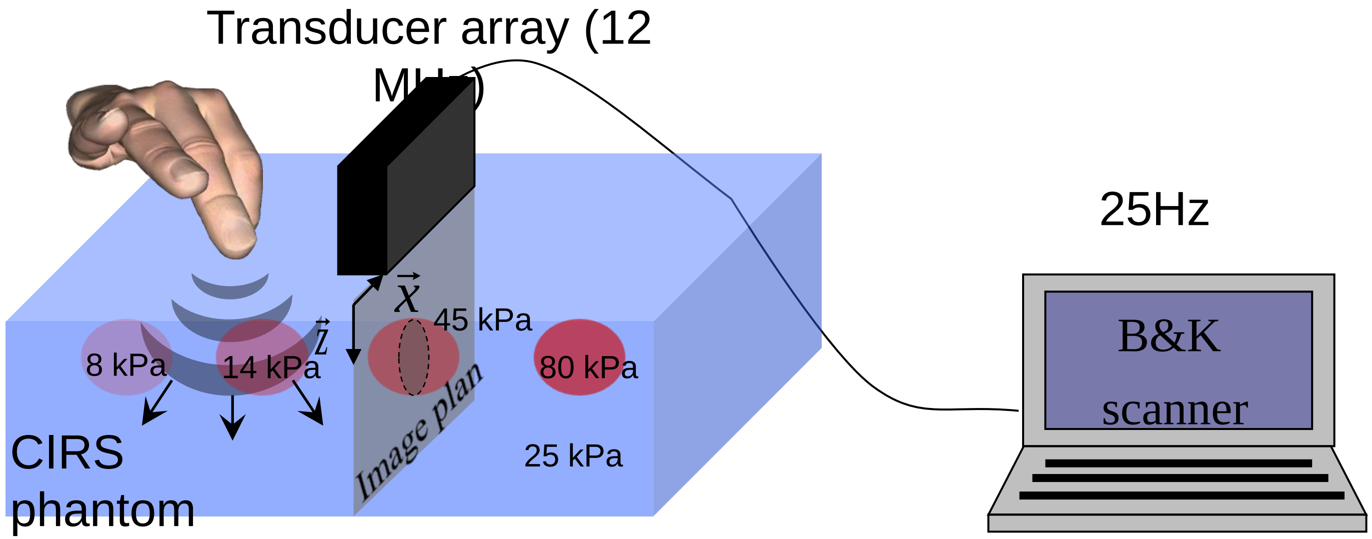
Is it always true? Not sure. Bar, plate, string

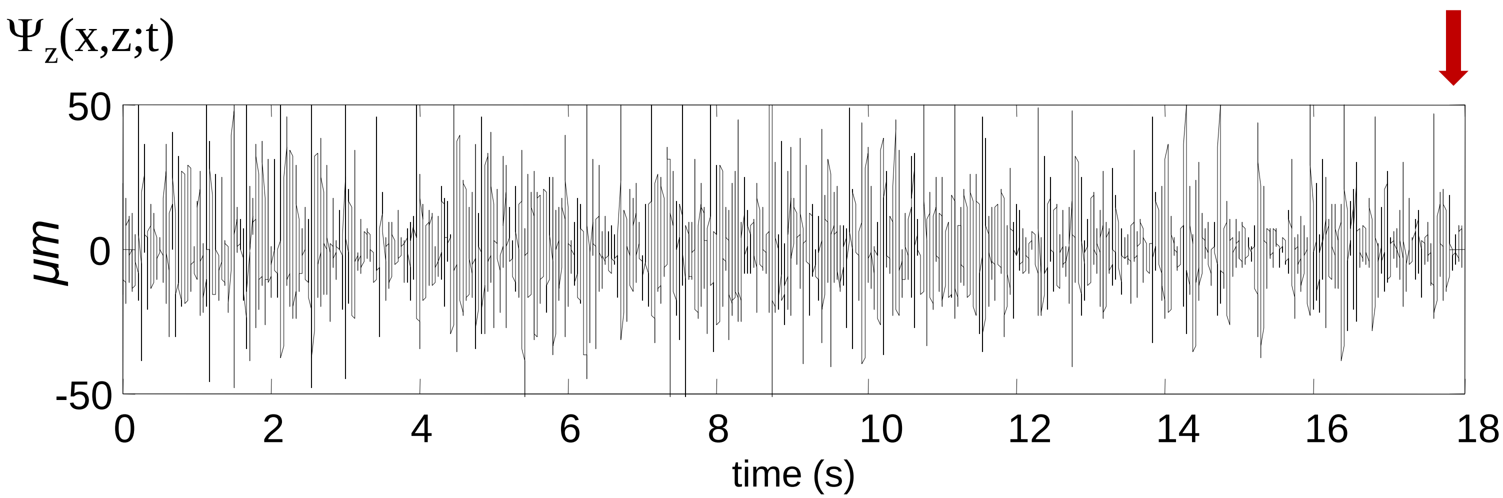
$$G^{plate}(0,x) = \frac{ic^2}{8\omega^2}[j_0(kr)+N_0(kr)-j_0(i\gamma r)-iN_0(i\gamma r)]$$

$$G^{bar}(0,x) = \frac{ic^3}{4\omega^3}e^{ikx}$$

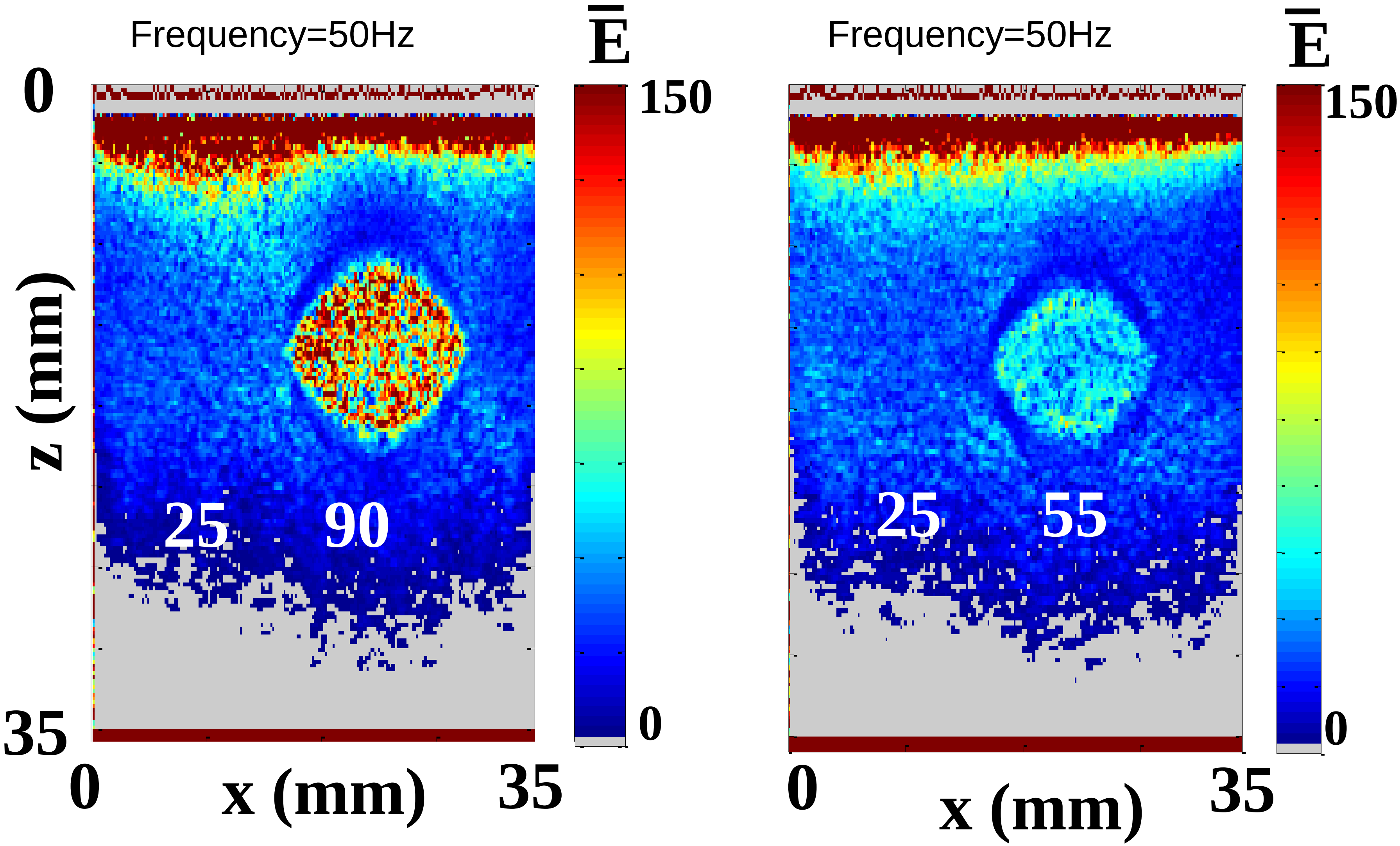
$$G^{string}(0,x) = i\frac{c}{2\omega}e^{ikx}$$

# Phantom experiment



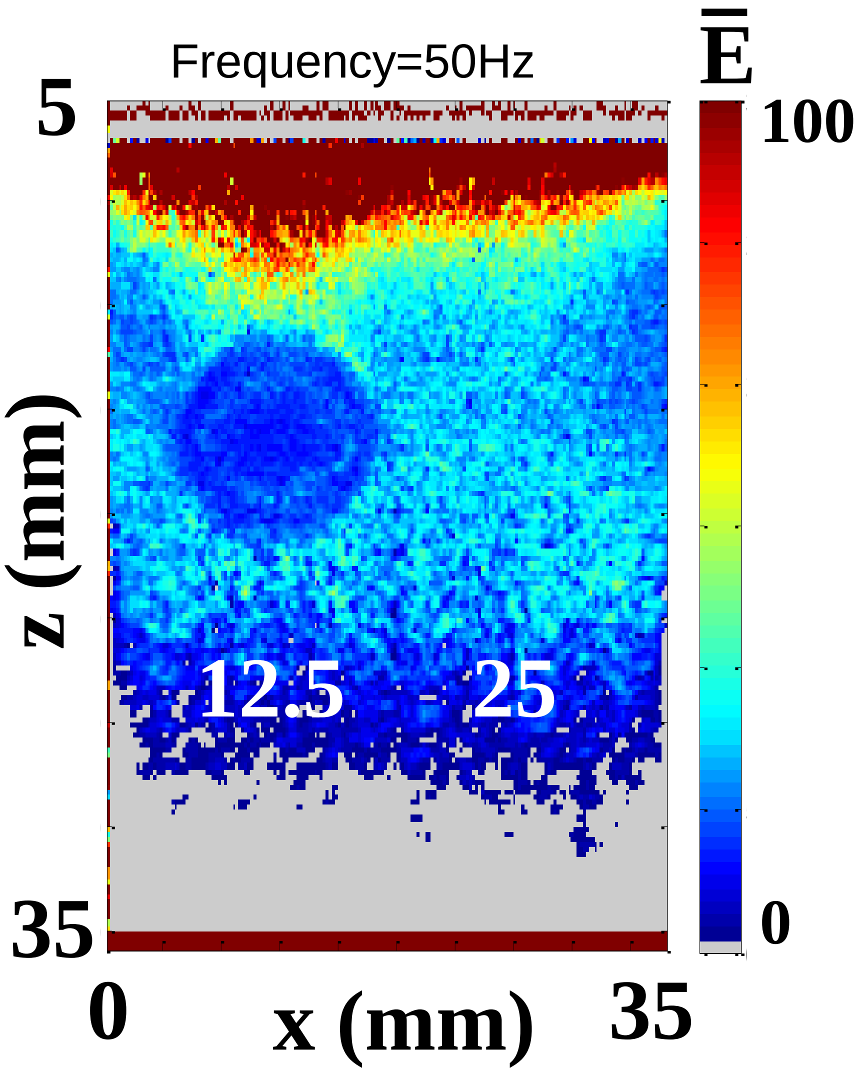
## Phantom experiment



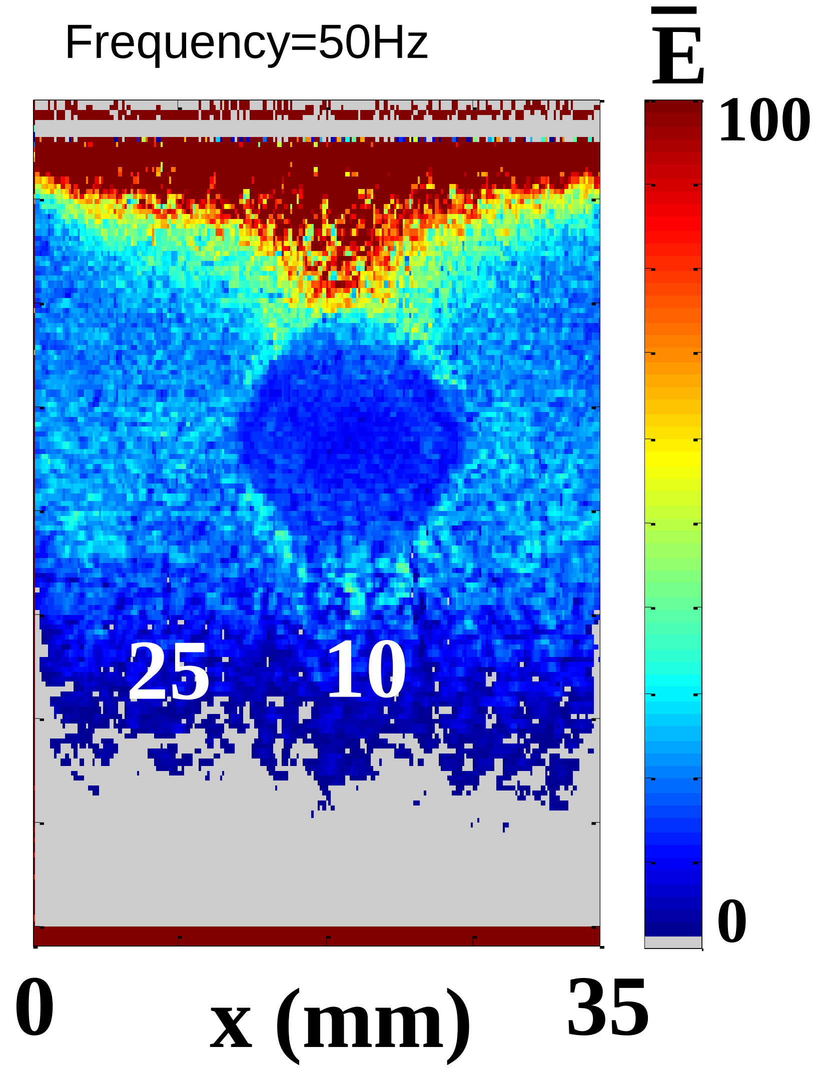

**Constructor: 80kPa**

**Constructor: 45kPa**

## Phantom experiment



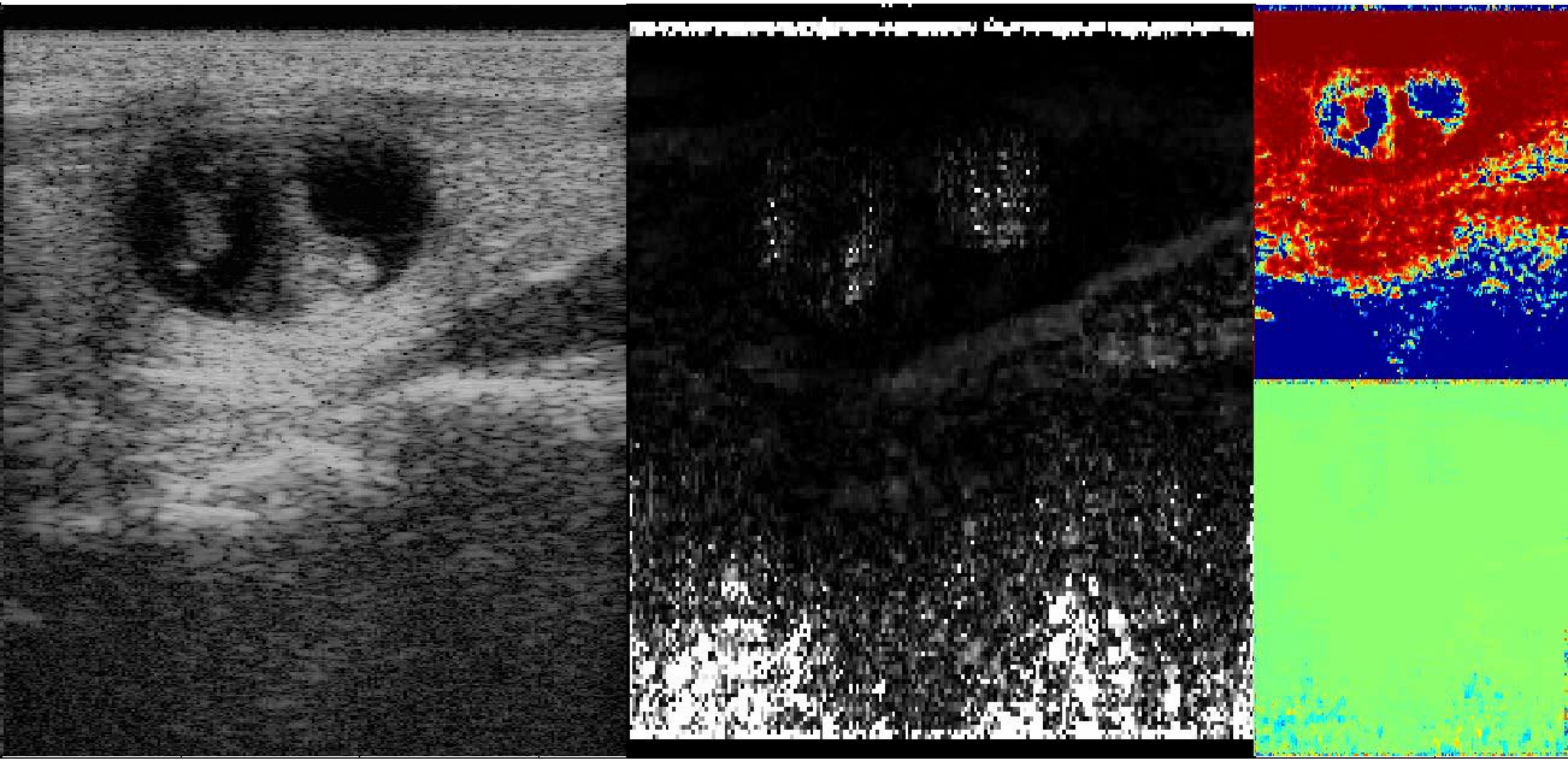

Constructor: 14kPa



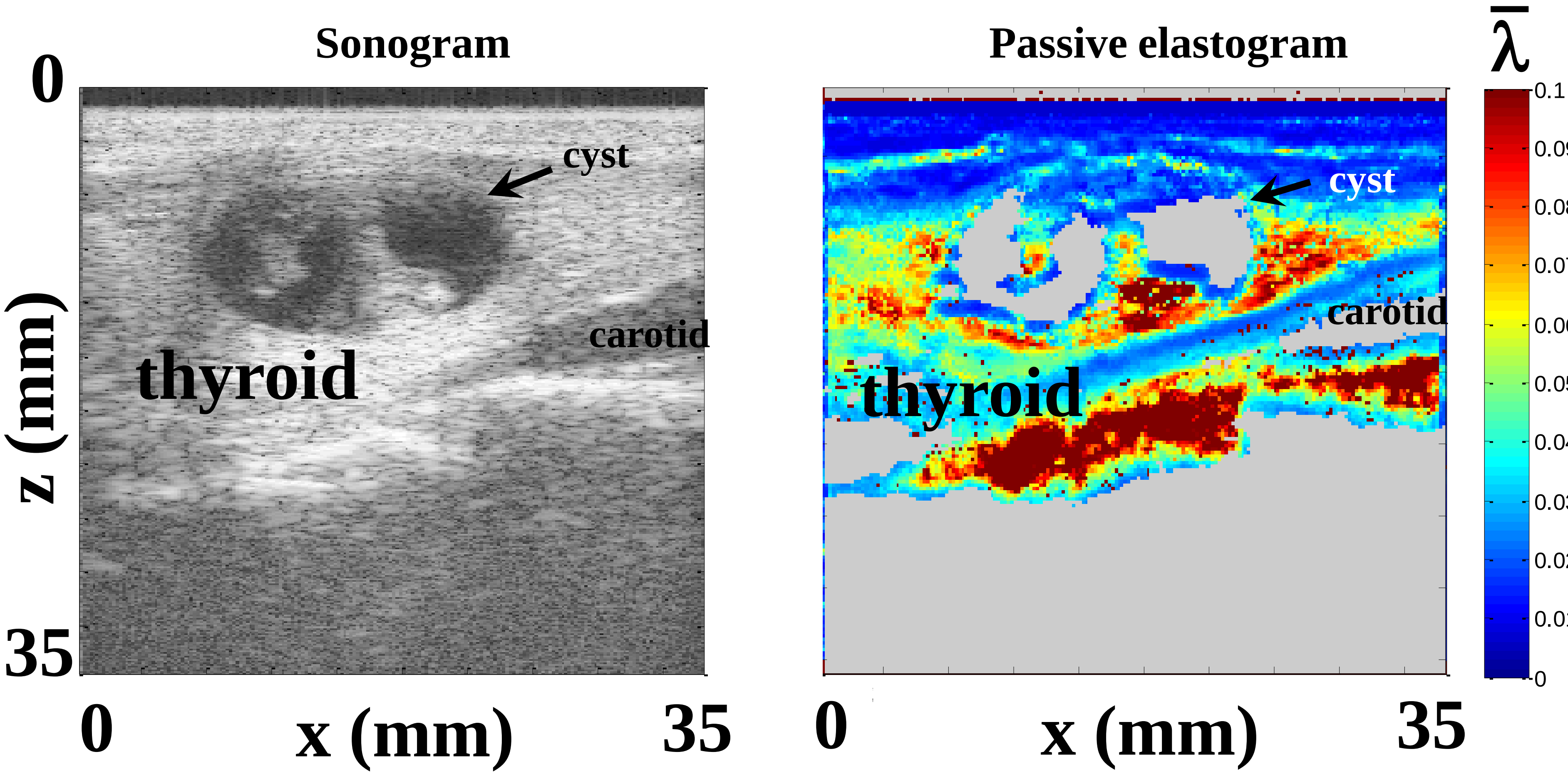

Constructor: 8kPa

# Preliminary *in-vivo*

# Preliminary *in-vivo*



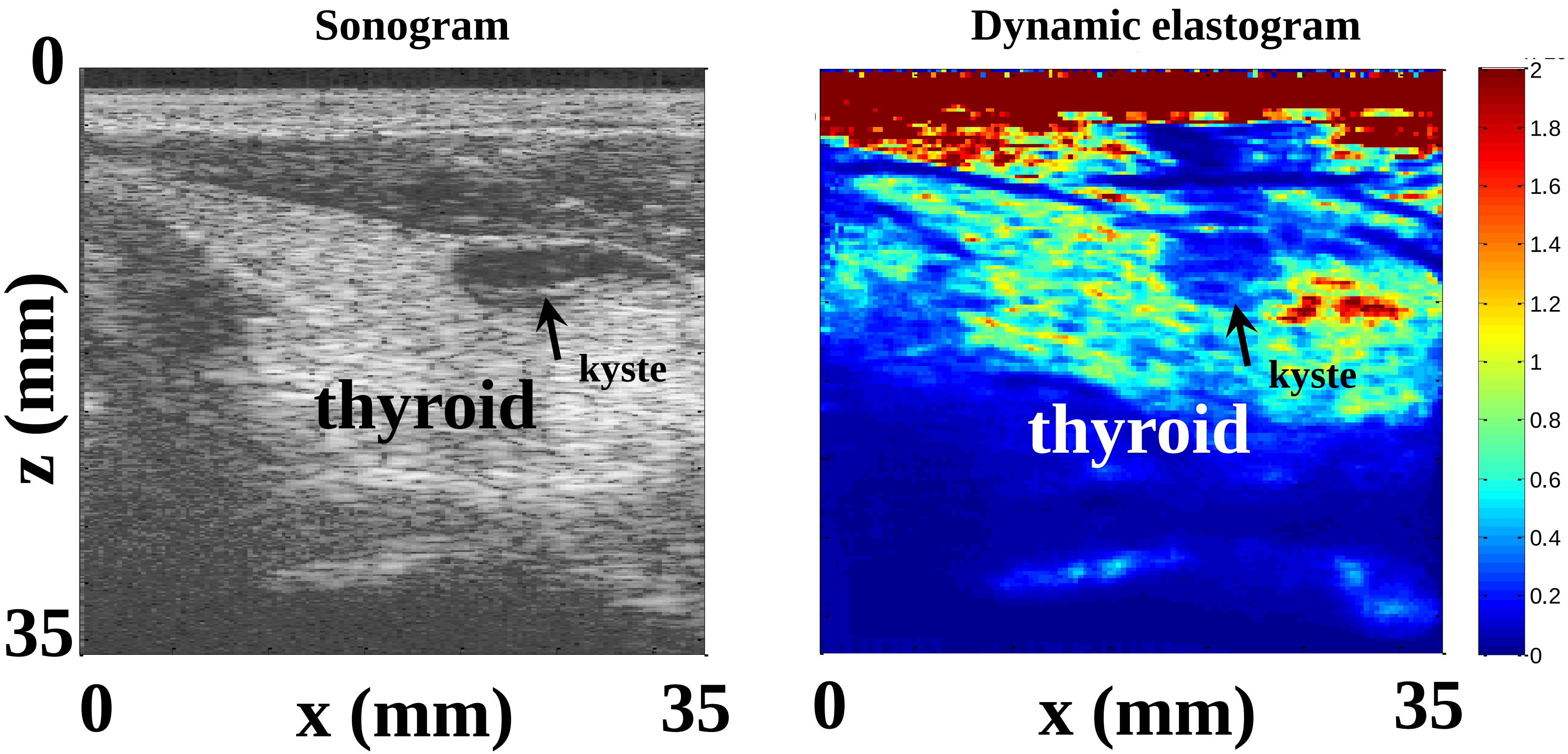
**800 images @ 25Hz**




$$k = \sqrt{\frac{\xi^{RT}}{\psi^{RT}}}$$

S. Catheline, R.Souchon, J. Brum, A.H. Dinh, J-Y Chapelon «Tomography from diffuse waves: passive shear wave imaging using low frame rate scanners» accepted Applied Physics Letter.

## *In vivo* experiment



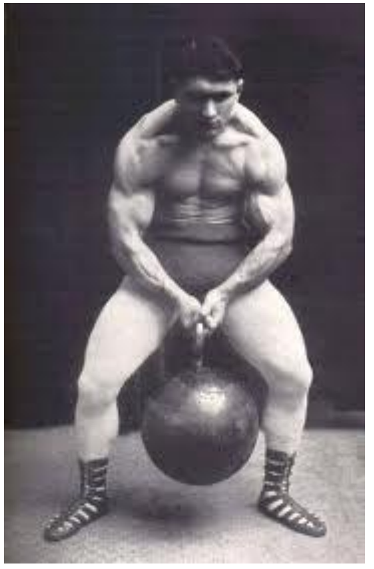

S. Catheline, R.Souchon, J. Brum, A.H. Dinh, J-Y Chapelon «TOMOGRAPHY FROM DIFFUSE WAVES: PASSIVE SHEAR WAVE IMAGING USING LOW FRAME RATE SCANNERS» accepted Applied Physics Letter.

**Milieux elastique, homogène, isotrope, linéaire**

$$(\lambda + 2\mu)\overrightarrow{grad}\, div(\vec{u}) - \mu\, \overrightarrow{rot}\, \overrightarrow{rot}\, \vec{u} - \rho \frac{\partial^2 \vec{u}}{\partial t^2} = \vec{0}$$

$$C_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} \approx \sqrt{\frac{\lambda}{\rho}} \qquad C_S = \sqrt{\frac{\mu}{\rho}}$$

*Soft tissues:*
*$\lambda$ = 2,5 Gpa*
*$\mu$ = 25 kPa $\ll \lambda$*



$$\sigma = \frac{Mg}{S} = \frac{130.10}{10^{-4}} = 0.013GPa$$

*Manual palpation reveals shear elasticity $\mu$*