Time-Reversed Waves and Subwavelength Focusing

Mathias Fink, Geoffroy Lerosey, Fabrice Lemoult, Julien de Rosny
Arnaud Tourin, Arnaud Derode, Philippe Roux, Ros-Kiri Ing, Carsten Draeger

Institut Langevin
Ecole Supérieure de Physique et de Chimie Industrielles de la Ville de Paris, CNRS, Paris, FRANCE

Ultrasound, Microwaves and Optics: The Source/Detector Problem

Ultrasound

Microwave

Each antenna (ultrasound or microwave) is able to record the temporal modulation of the wave field and to emit any temporal waveform.

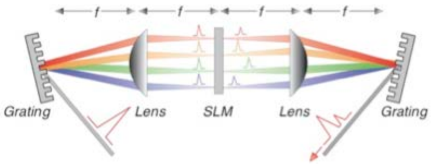
Optics

Spatial shaping

Liquid crystals SLM

Optics

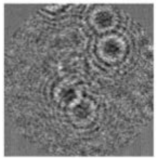
Temporal shaping



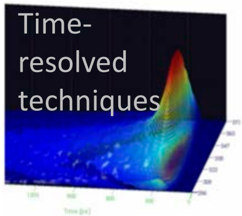
Femtosecond Coherent control

Optics

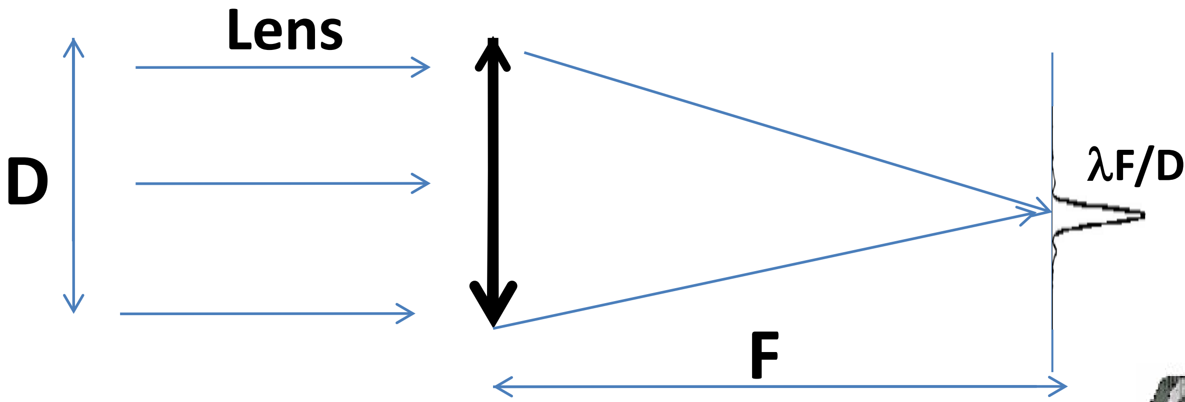
Interferometry/detection



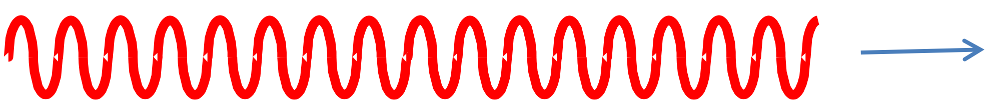
holography

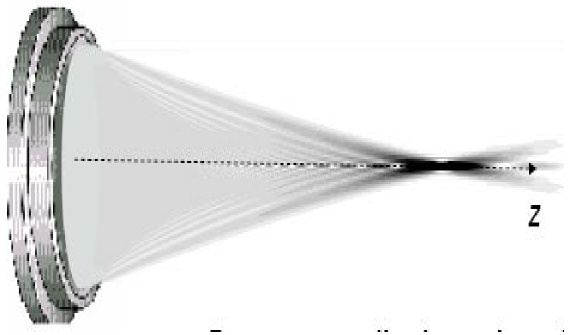


Wave Focusing in homogeneous medium

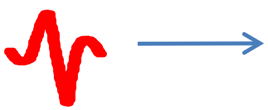


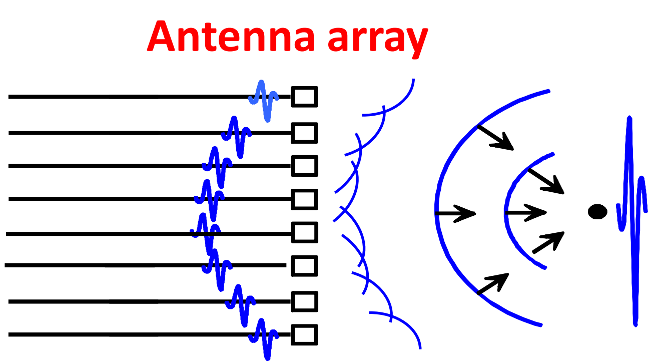
Lenses work both for **monochromatic** and **pulsed** waves





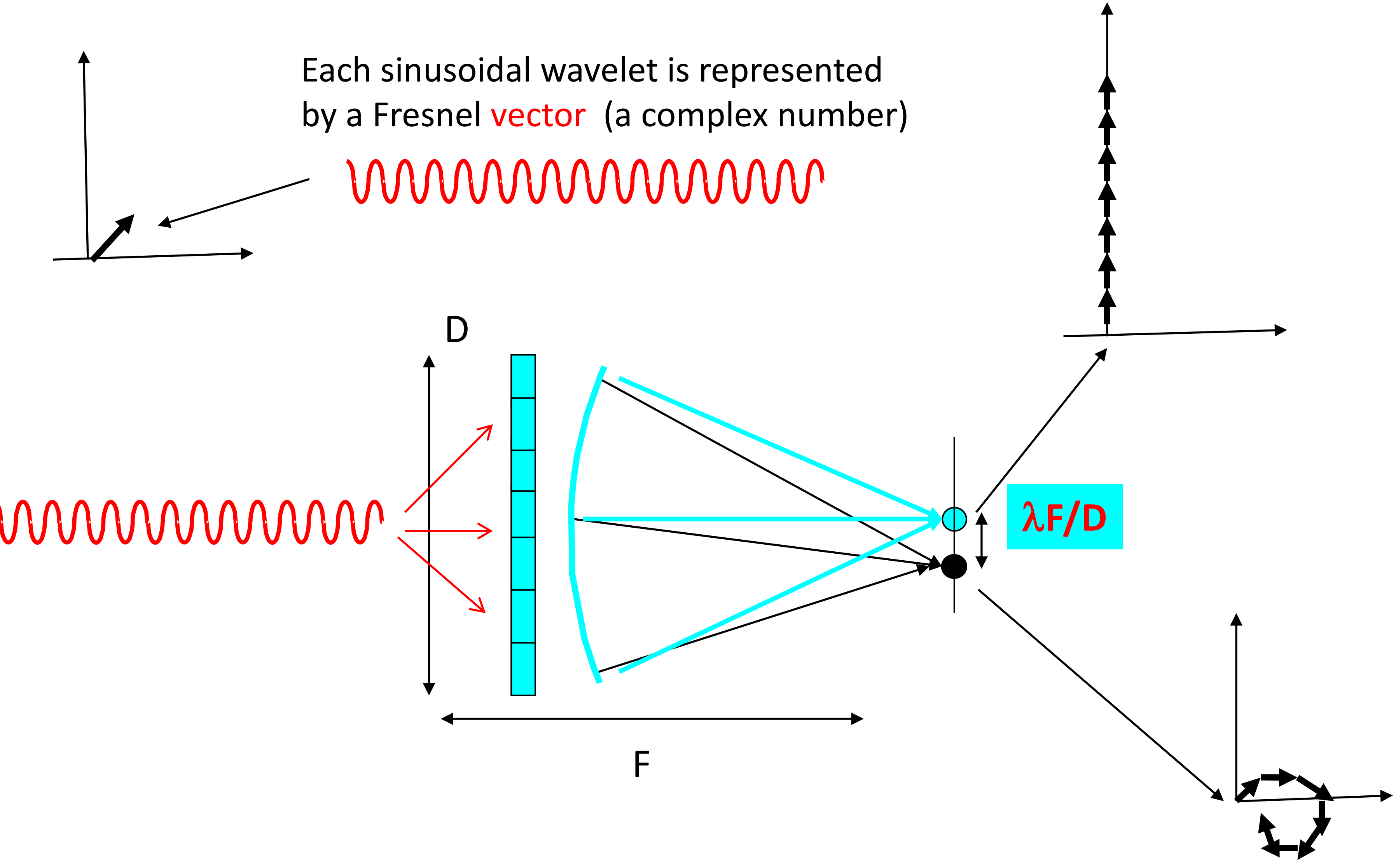
- **focusing energy** (Hyperthermia - Therapy)
- **imaging** in stationnary mode





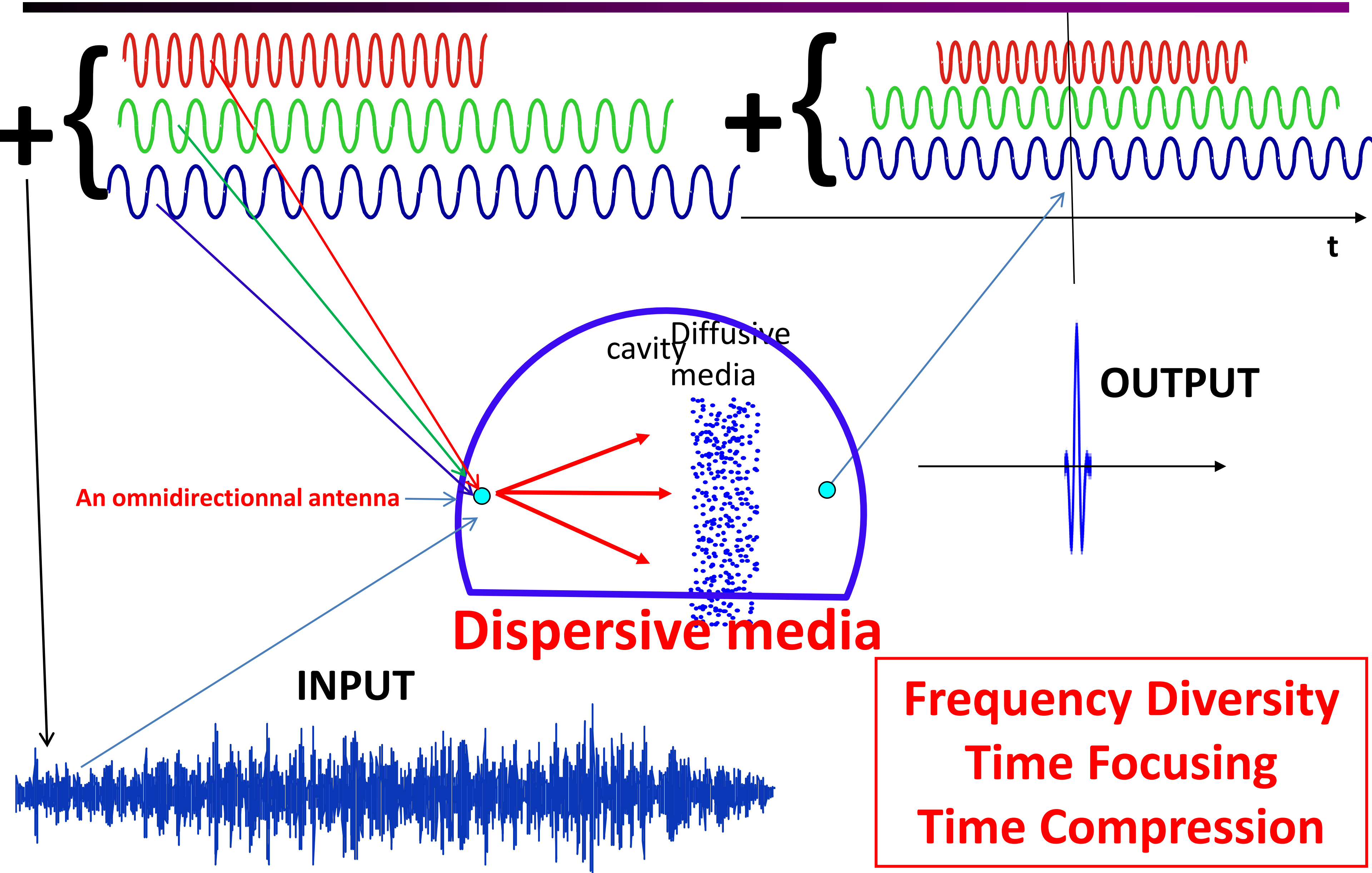
- **Imaging** in pulsed mode
  (radar, sonar)
- **Focusing shock waves or electromagnetic pulses**
  (therapy or defense)
- **Telecommunications**
  discrete broadband telecommunications

Focusing a monochromatic wave



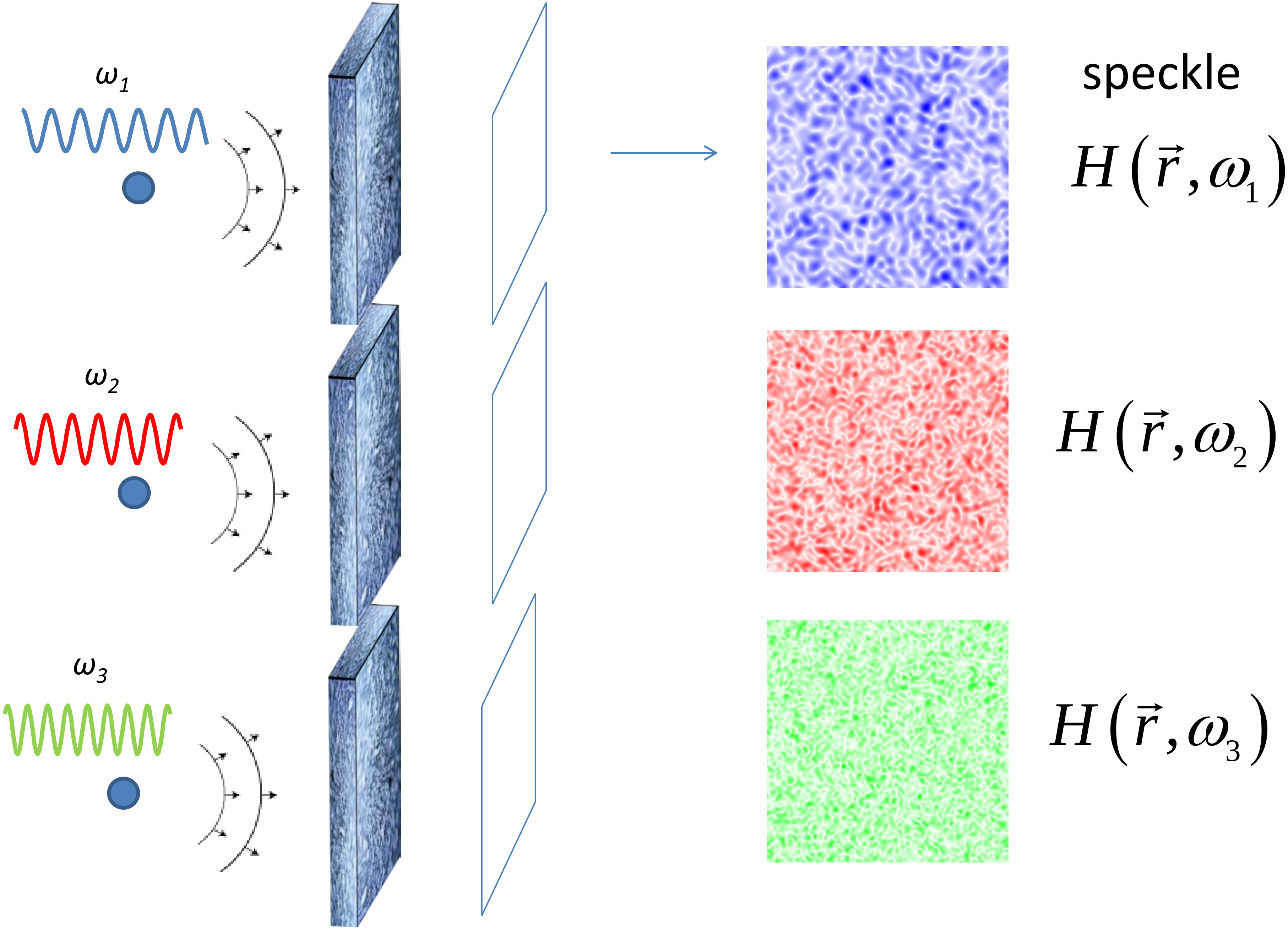
Spatial Diversity

Focusing a Polychromatic Wave through dispersive media

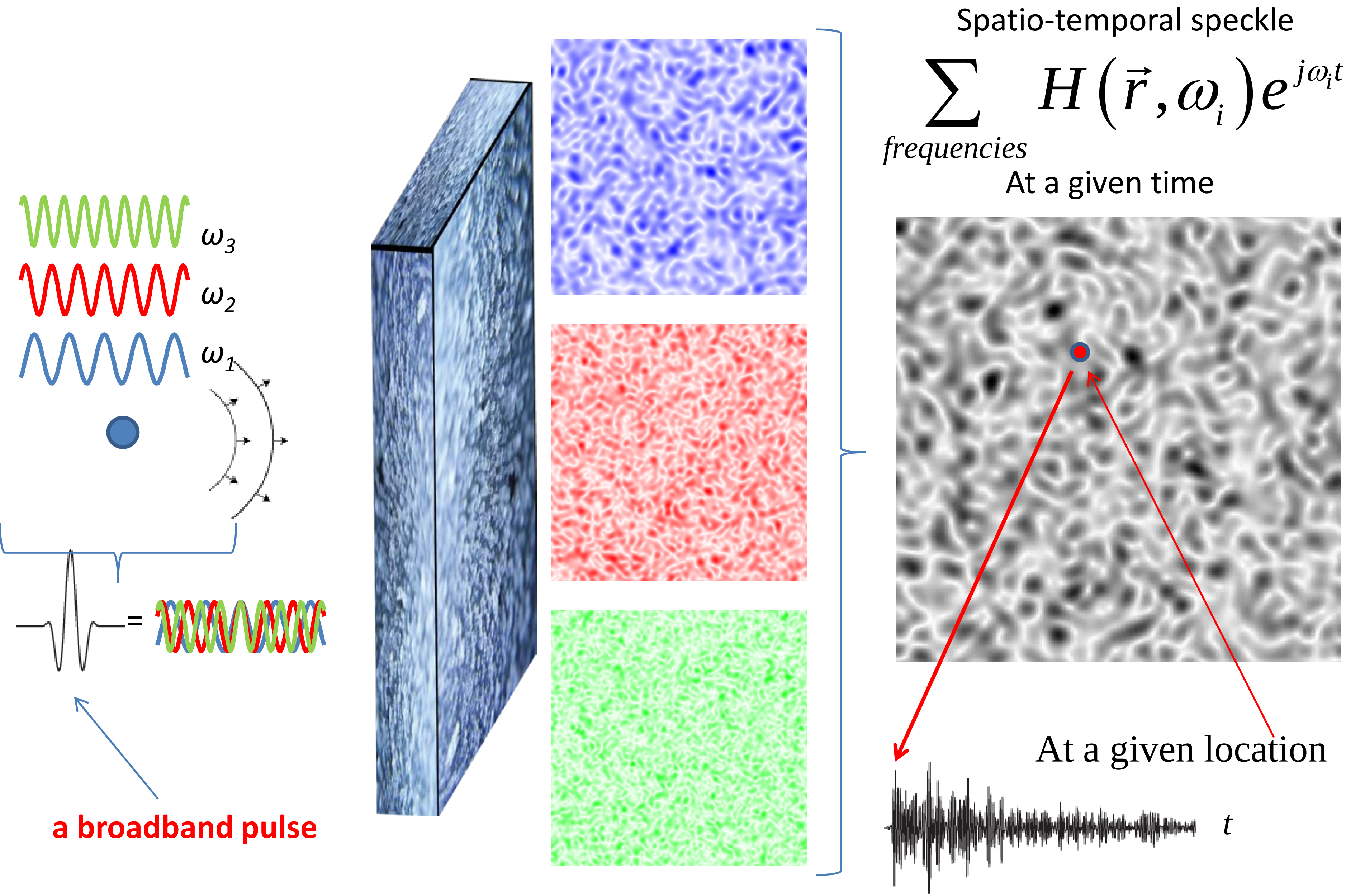


Frequency Diversity
Time Focusing
Time Compression

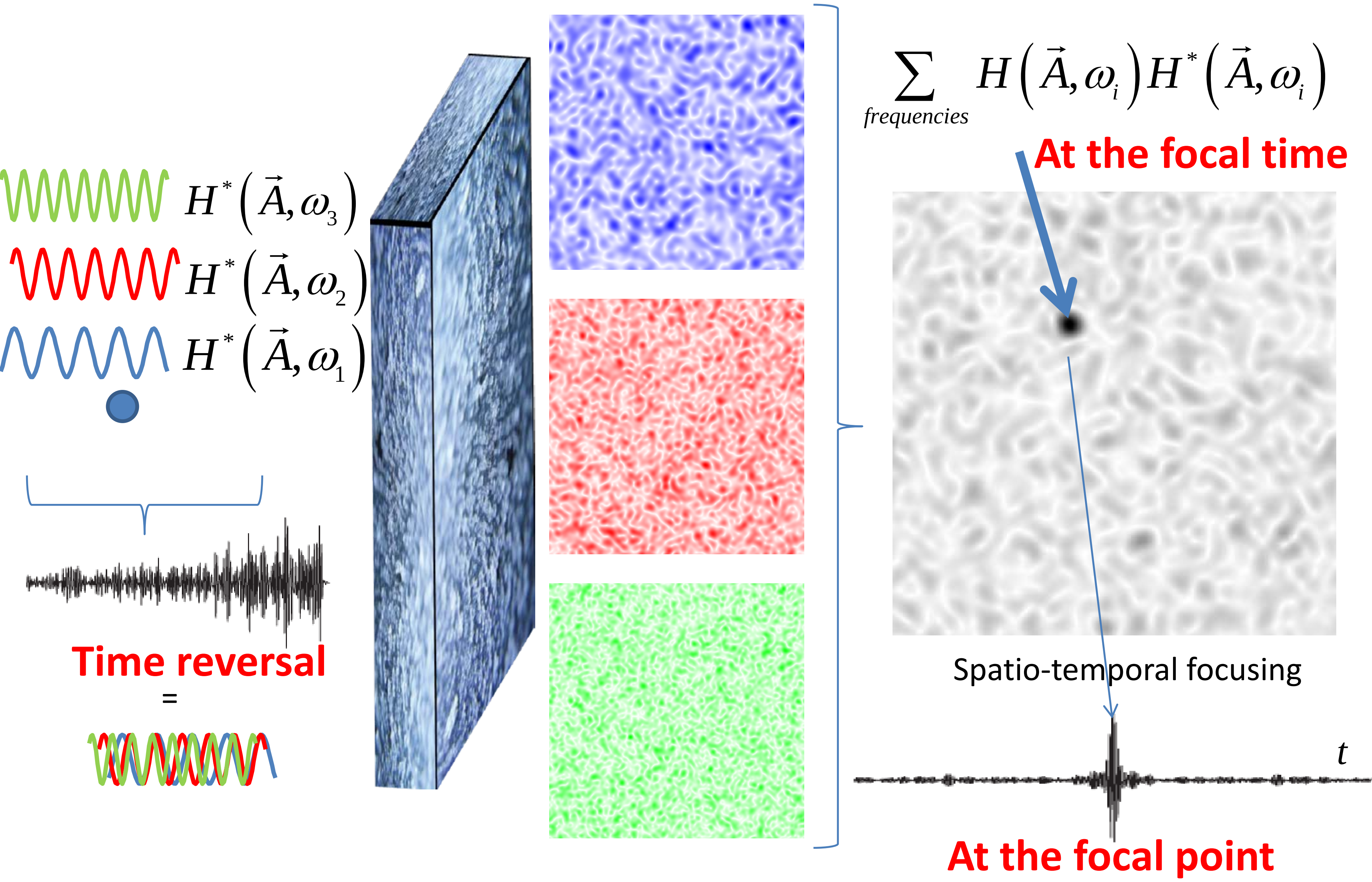
Spatial focusing with temporal degrees of freedom (frequential)



Spatial focusing with temporal degrees of freedom (frequential)



Phase Conjugation and Time Reversal



Focusing quality and diffraction limits: the connection with time-reversed waves

Focusing a broadband wave in an heterogeneous medium

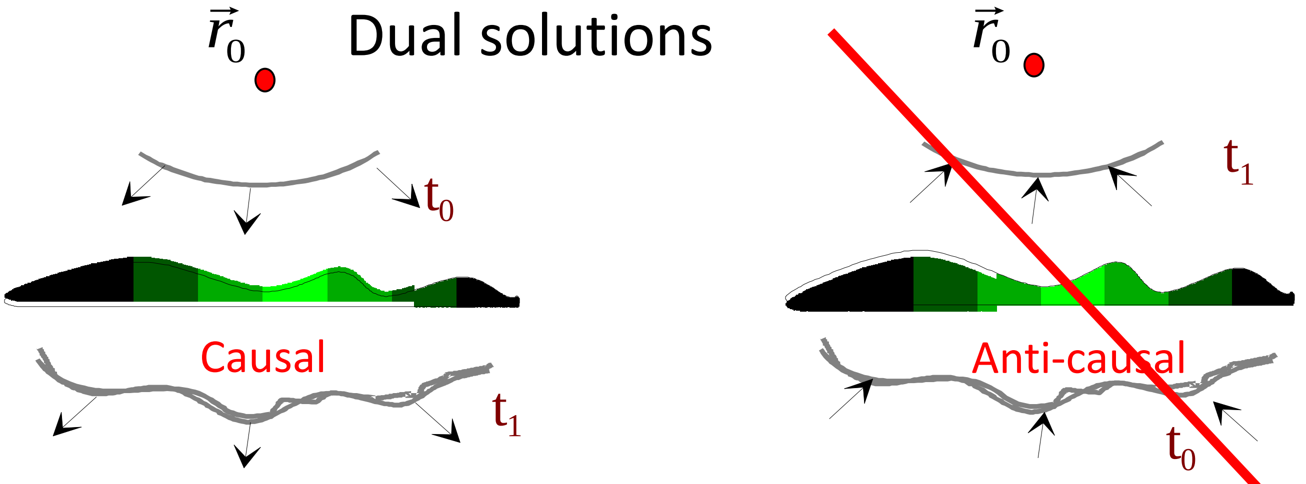
A solution : building a time-reversed wave (causality Pb)

The acoustic case : **non dissipative heterogeneous** medium with a ponctual source

$$\left\{\Delta - \frac{1}{c^2(\vec{r})}\frac{\partial^2}{\partial t^2}\right\} G(\vec{r},\vec{r}_0;t) = -\delta(\vec{r}-\vec{r}_0)\,\delta(t)$$

Green's function

Dual solutions



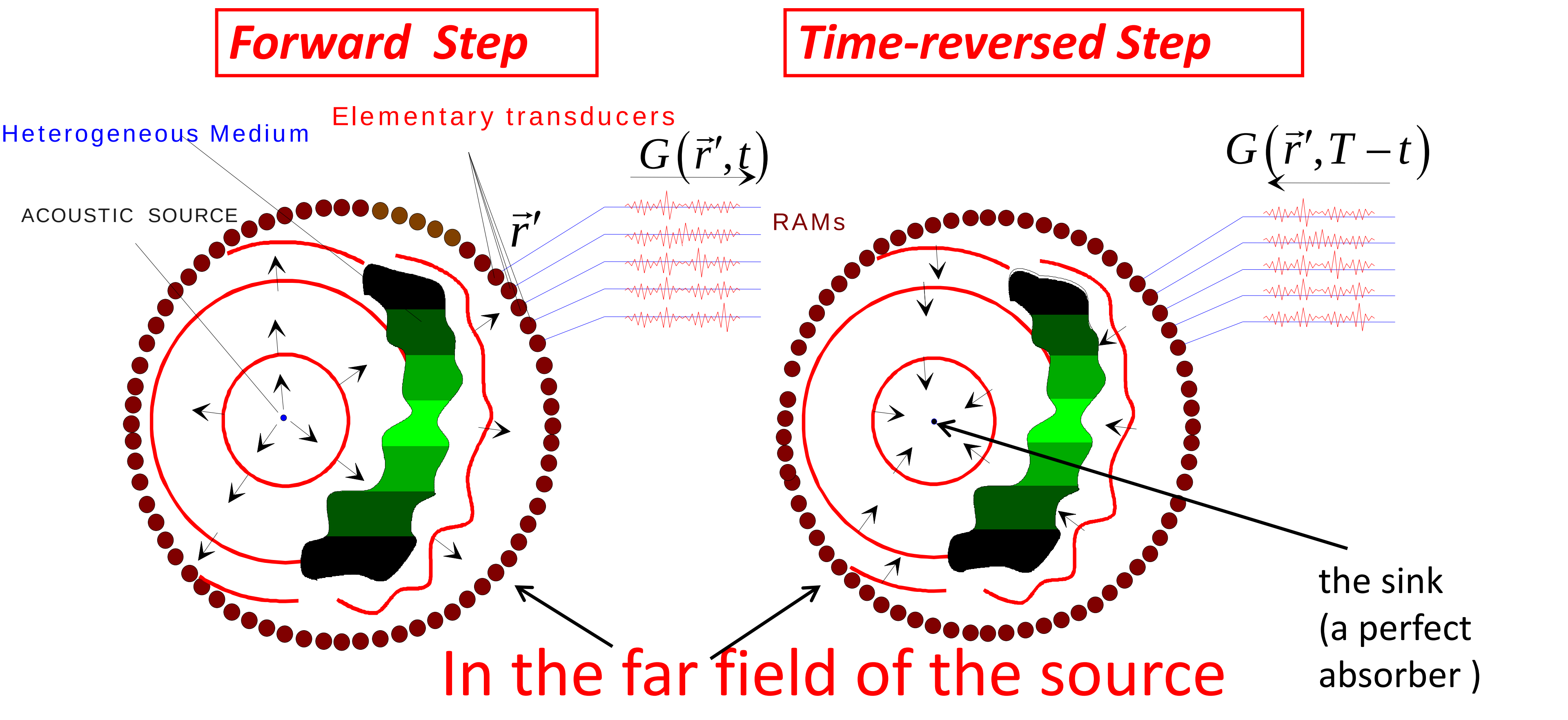
$G_{ret}(\vec{r},\vec{r}_0;t)$

$G_{ret}(\vec{r},\vec{r}_0;-t) = G_{adv}(\vec{r},\vec{r}_0;t)$

To build the TR field : Time reversed the causal field on the boundary : the time reversal cavity

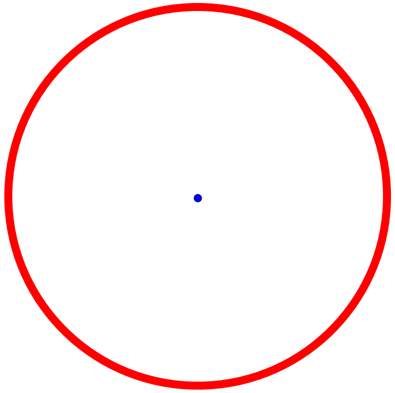
TR on the boundary : the TR Cavity

- record on the boundary $G(\vec{r}',\vec{r}_0;t);\partial_n G(\vec{r}',\vec{r}_0;t)$
- transmit from the boundary $G(\vec{r}',\vec{r}_0;T-t);\partial_n G(\vec{r}',\vec{r}_0;T-t)$

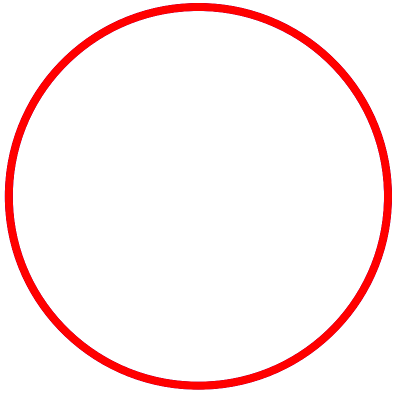


What is the focal spot size ?

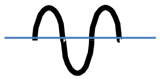
Initial step

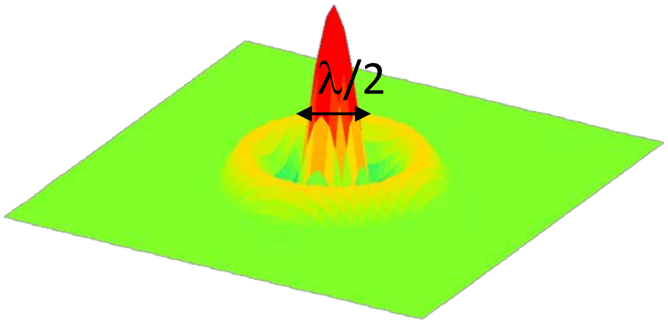


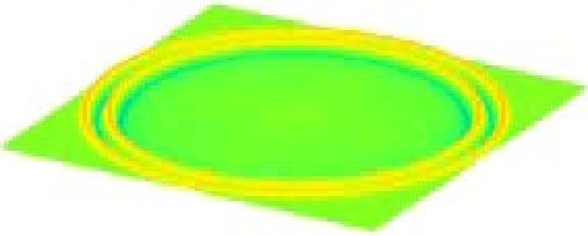
Time-reversed step



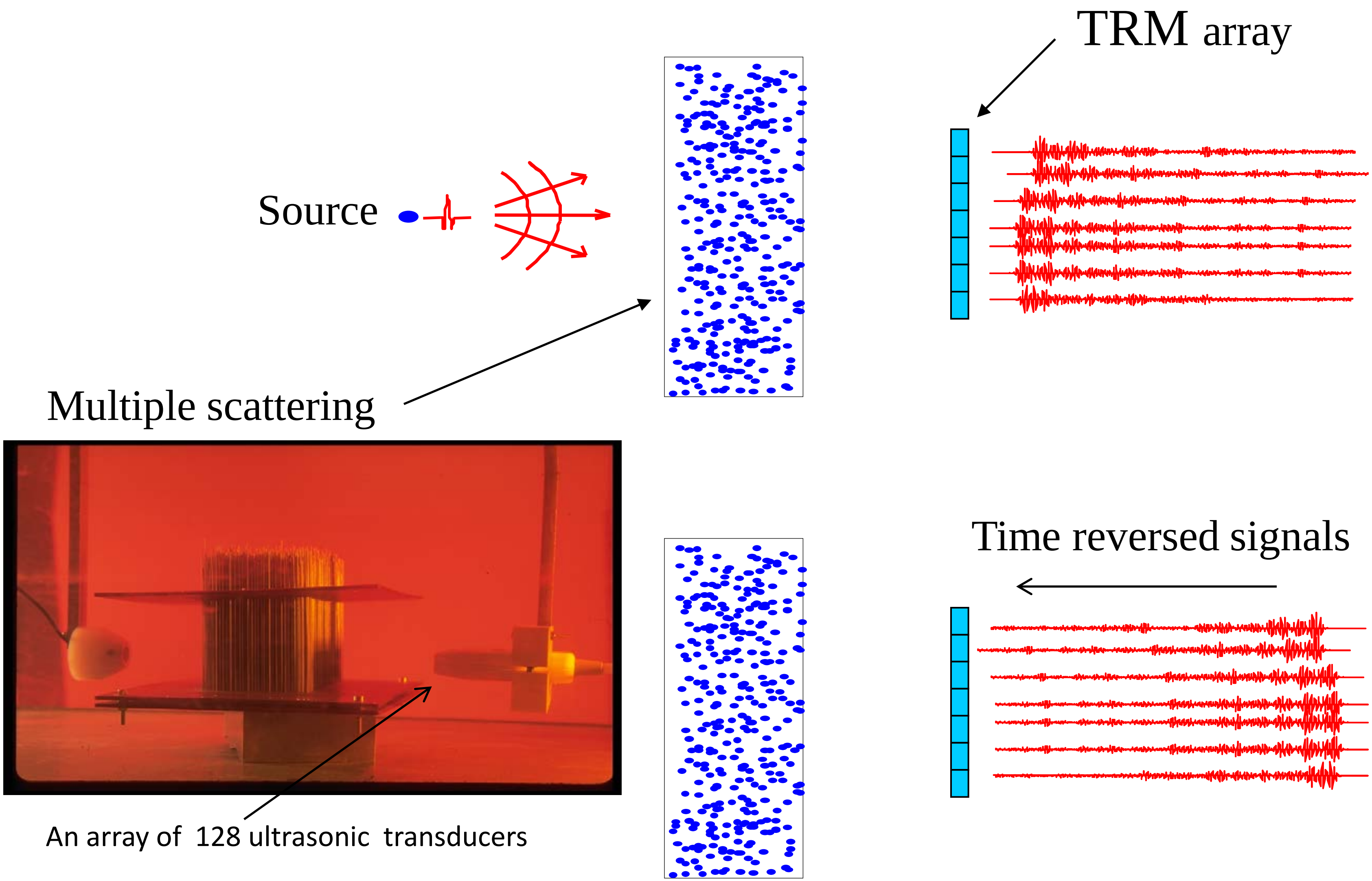
wavelength λ







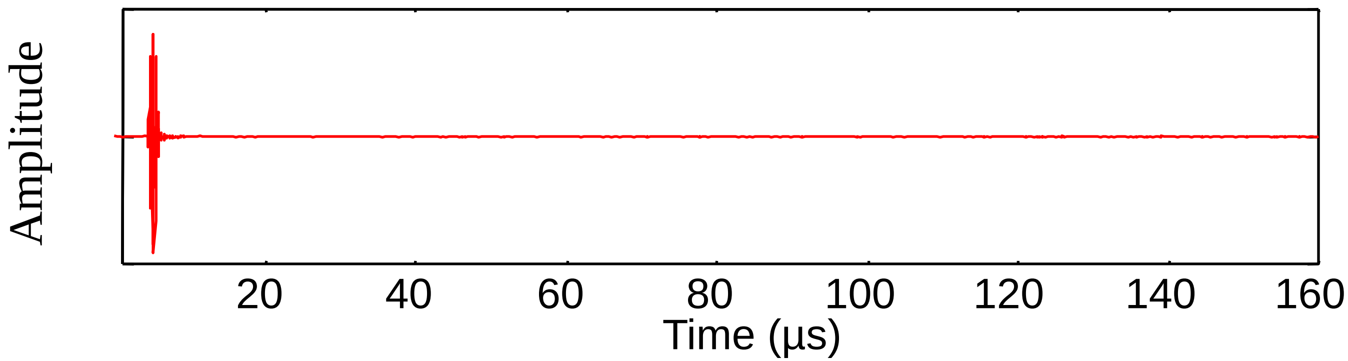
Finite aperture TR through a diffusive medium



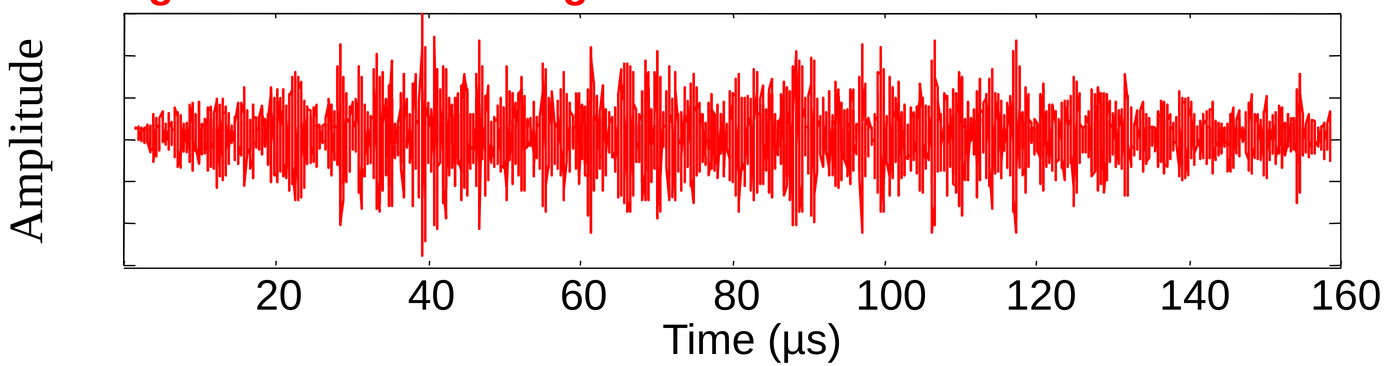
A. Derode, P. Roux, M. Fink, « Robust Acoustic Time reversal with high order multiple scattering» Phys Rev Let , 25(23,) 4206-4209 , 1994

Time Focusing

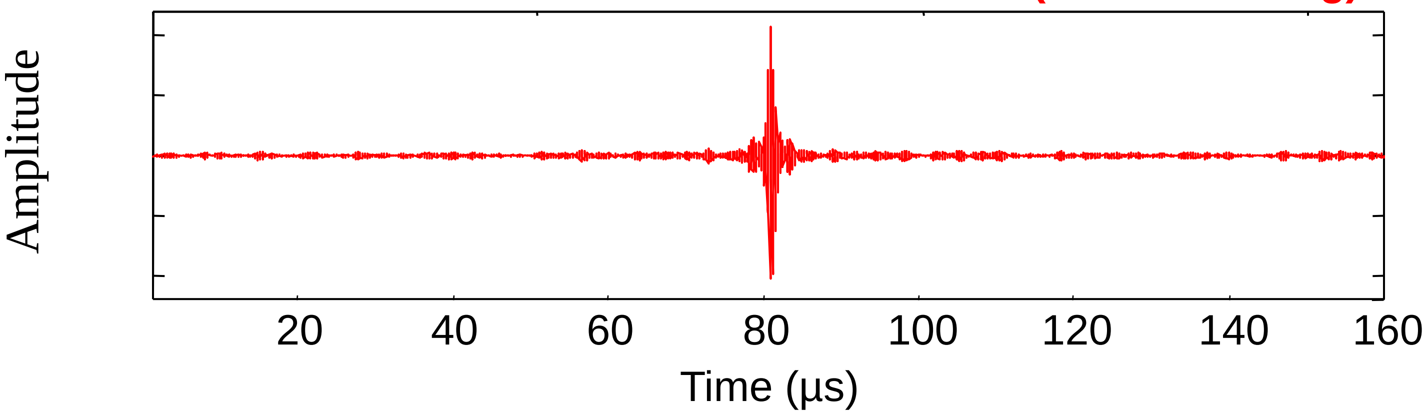
Transmitted signal



Signal recorded through the diffusive medium on transducer 64

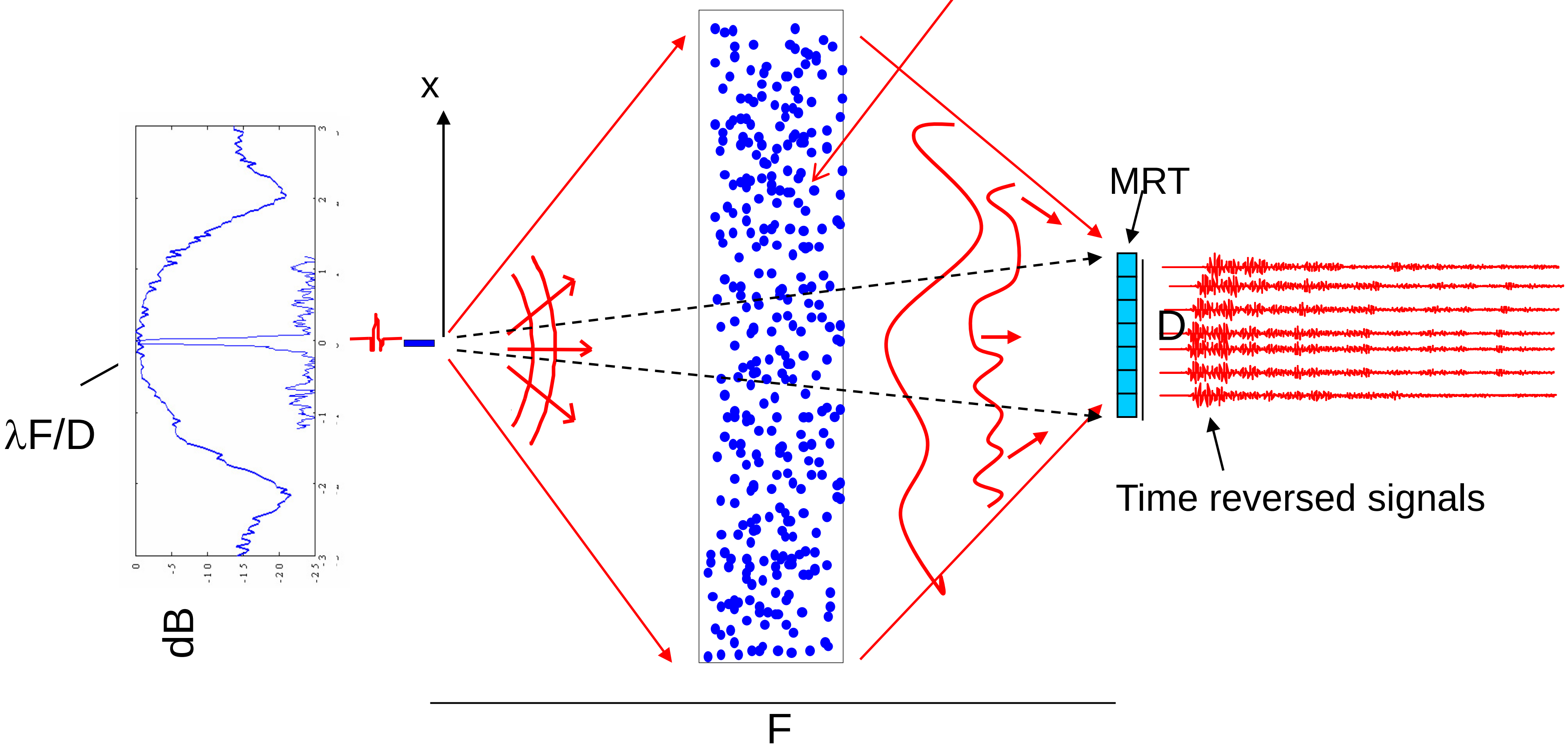


Time reversed wave at the source location (Time Focusing)



Spatial Focusing

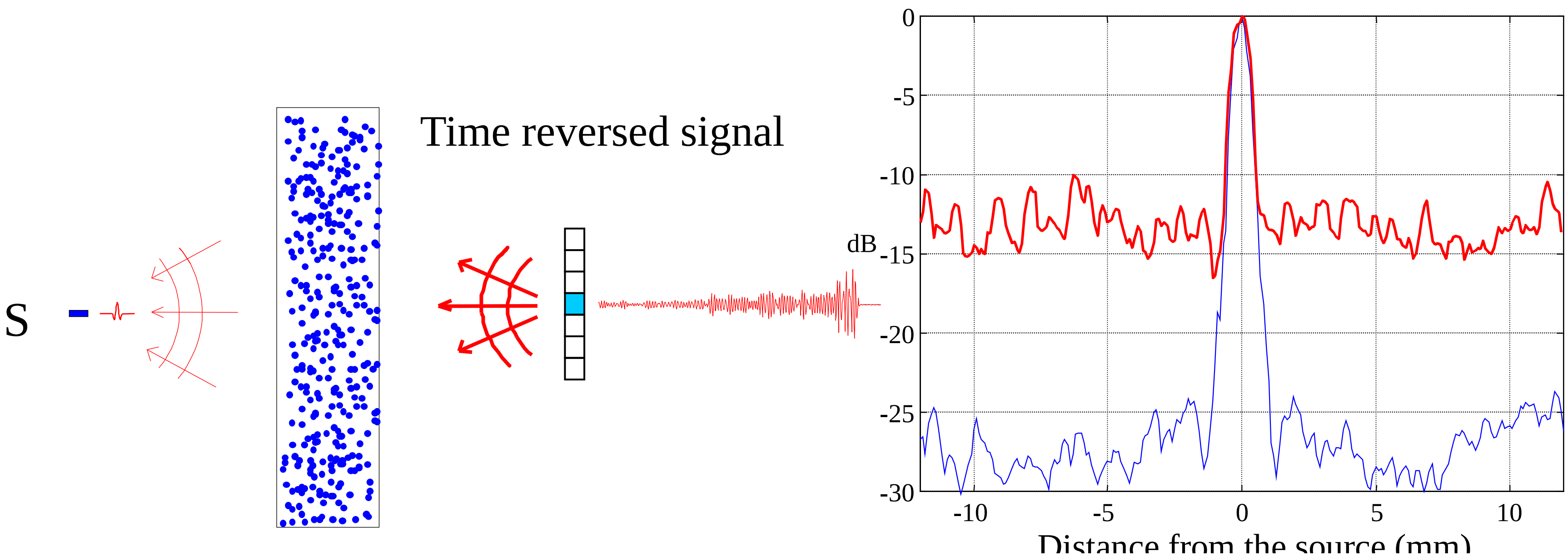
The medium is the Lens



Focal spot : beamwidth at -6 dB : **35 mm / 1 mm**

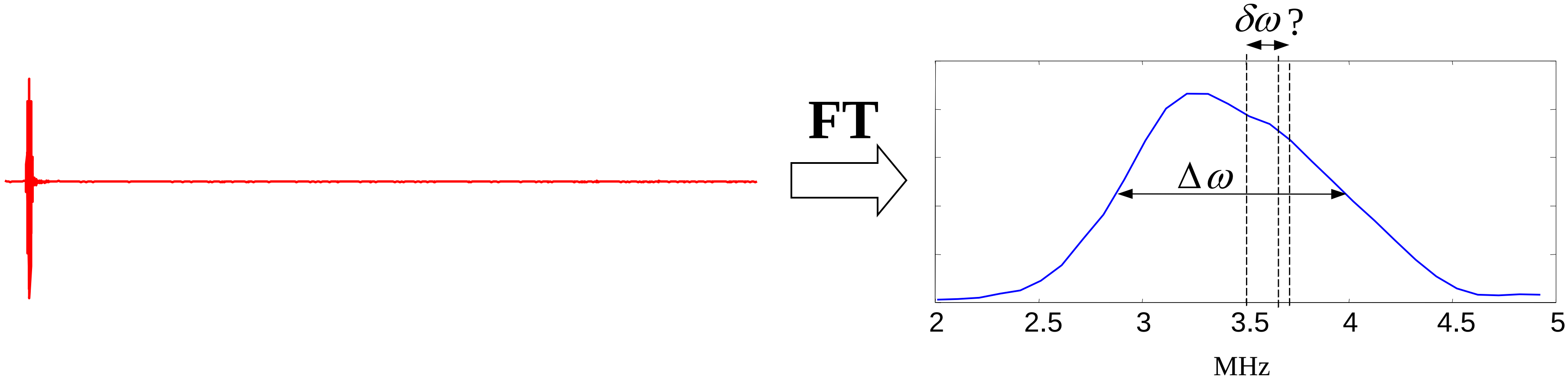
Spatial resolution does not depend on the array aperture !!!

One channel time reversal mirror

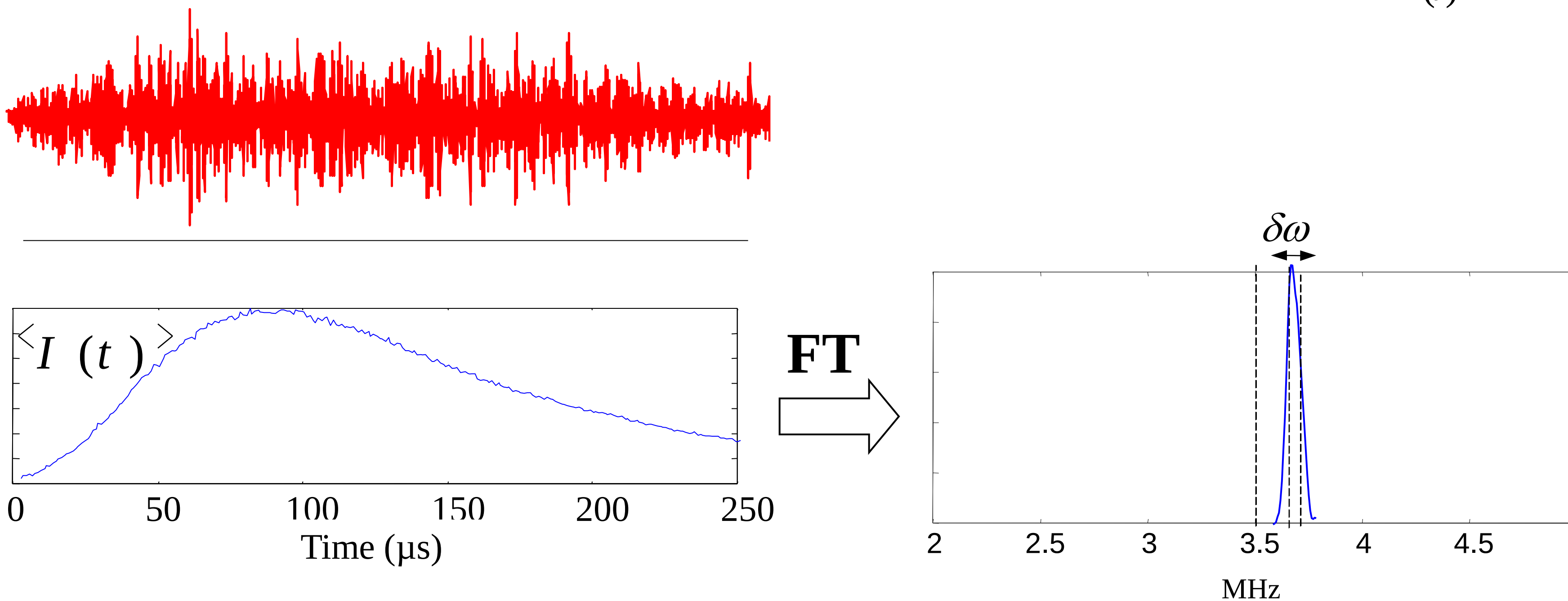


Directivity patterns of the time-reversed waves around the source position with 128 transducers (blue line) and 1 transducer (red line).

How many uncorrelated speckles ? (temporal degrees of freedom)



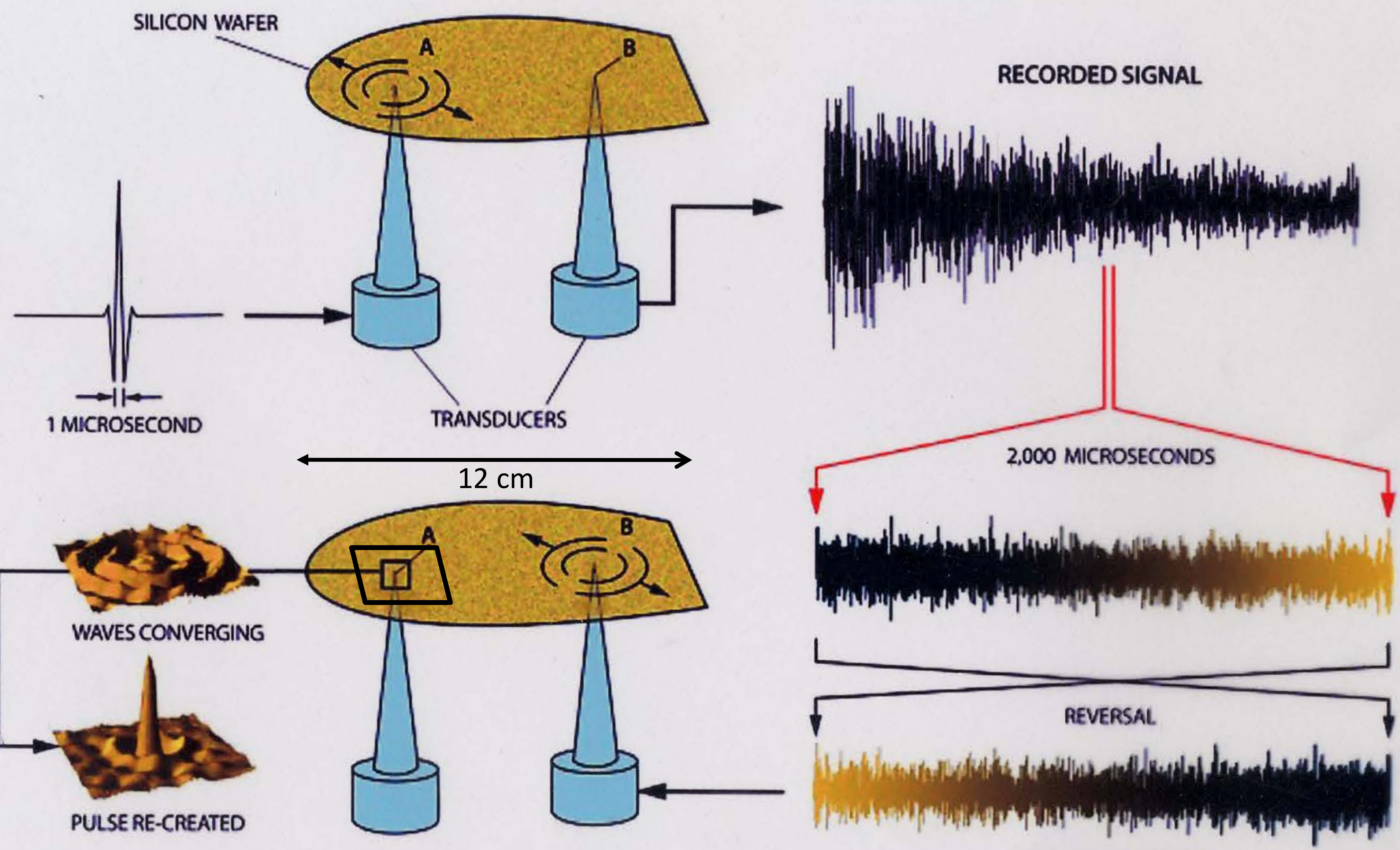
Spectral Field-field correlation = fourier transform of the travel time distribution $\langle I(t) \rangle$



Thoules time, $\delta\tau = L^2/D \sim 150\ \mu s$ ⟶ $\delta\omega = 8$ kHz $\Delta\omega/\delta\omega = 150$

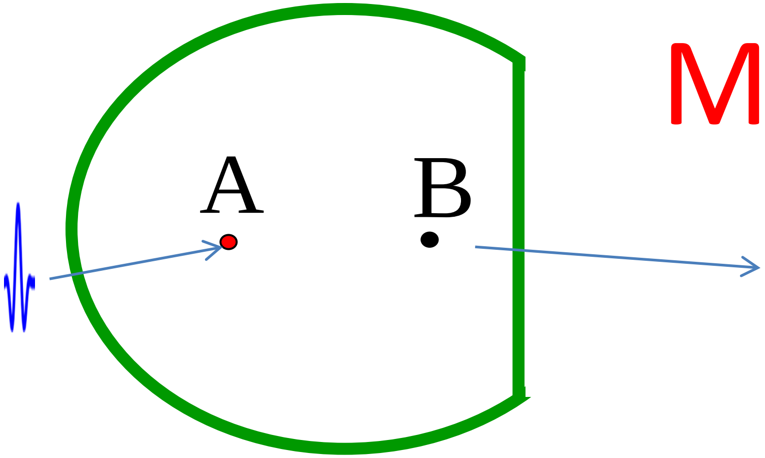
How to transform a closed cavity in a lens

A one channel time-reversal antenna

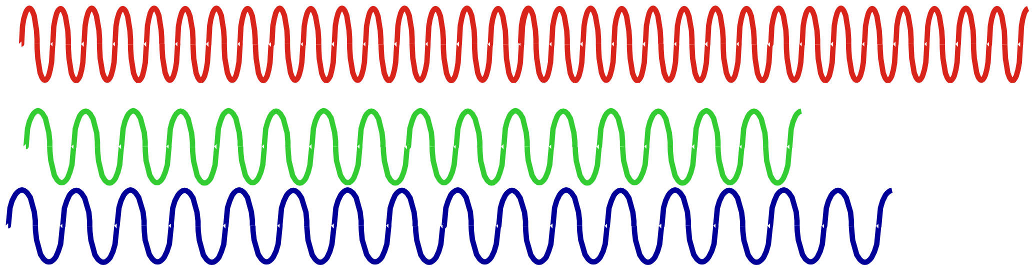


C. Draeger, M. Fink, « One channel time-reversal of elastic waves in a chaotic 2D-silicon cavity »
Physical Review Letters ,**79** (3), 407-410,1997

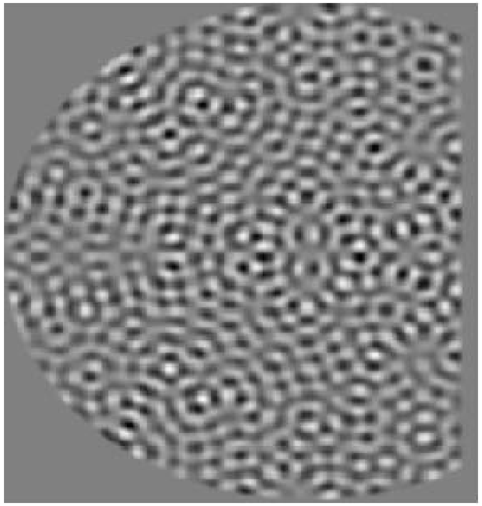
Multi-modal Focusing



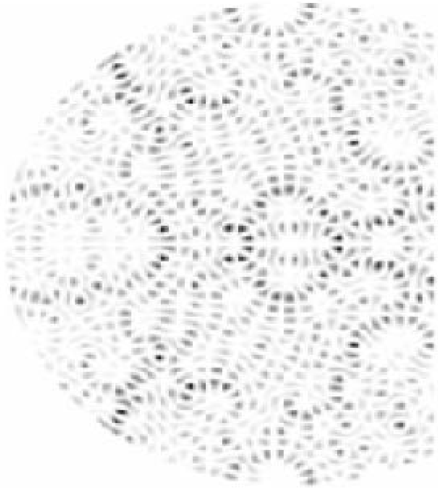
The signal recorded in B is the summation of <u>all the eigenfrequencies excited by the source in A</u>



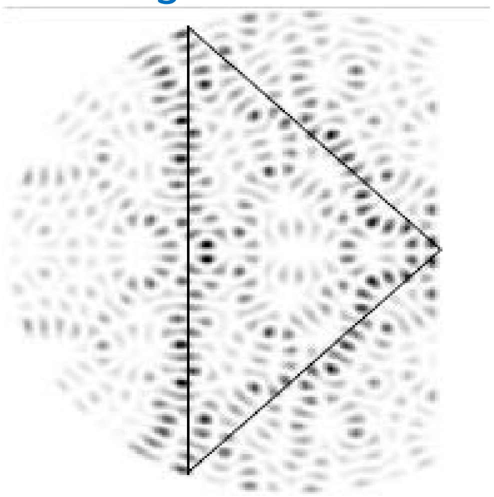
ω_1 mode 1



ω_2 mode 2

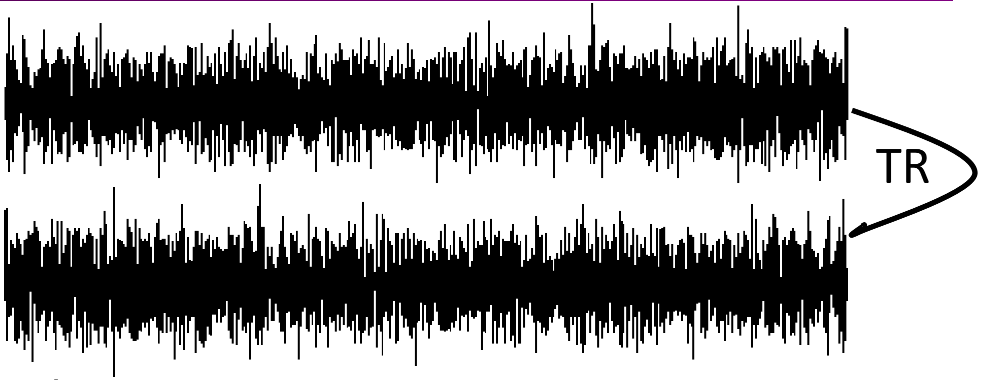


ω_3 mode 3

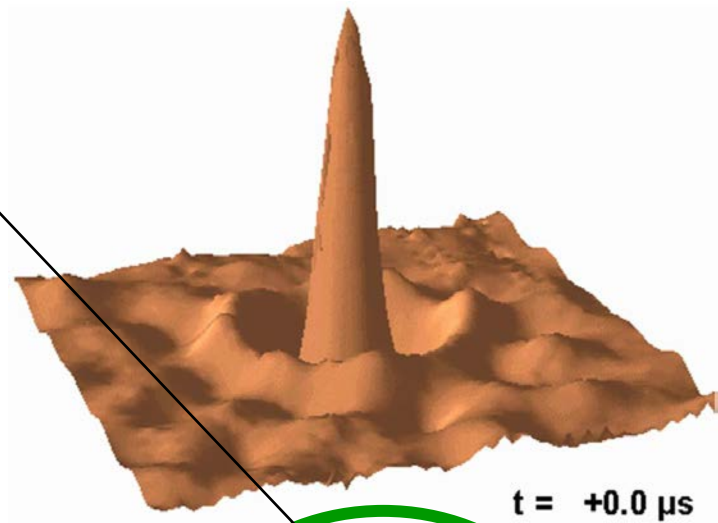


The time-reversed wave opticaly detected (surface wave)

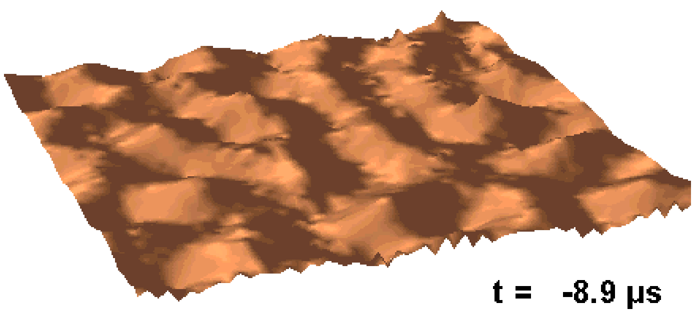
A 2 ms duration signal
transmitted by point B :

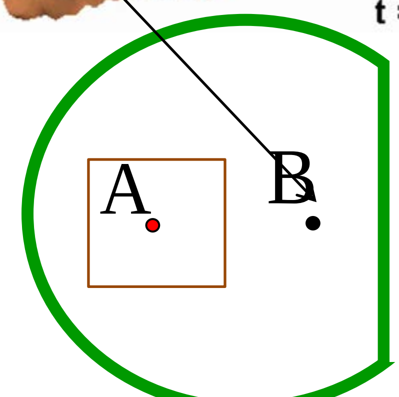


A time Hologram

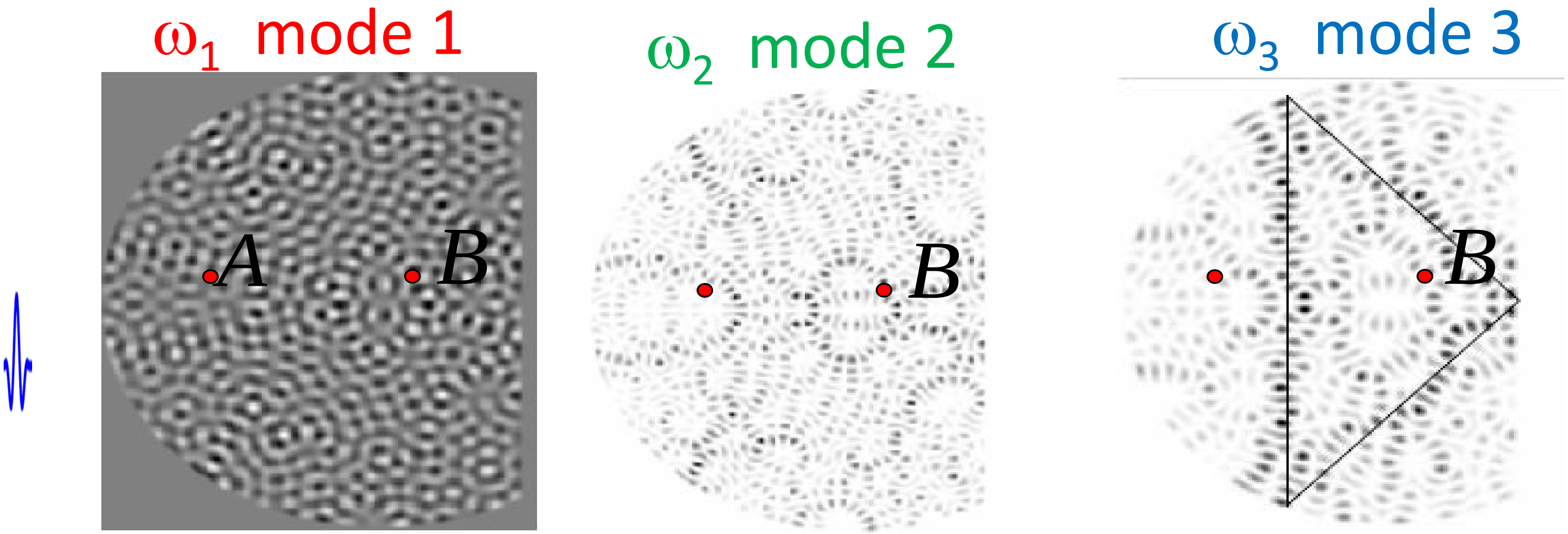


Displacement
field recorded
on a square
15 x15 mm^2





Multi-modal Focusing

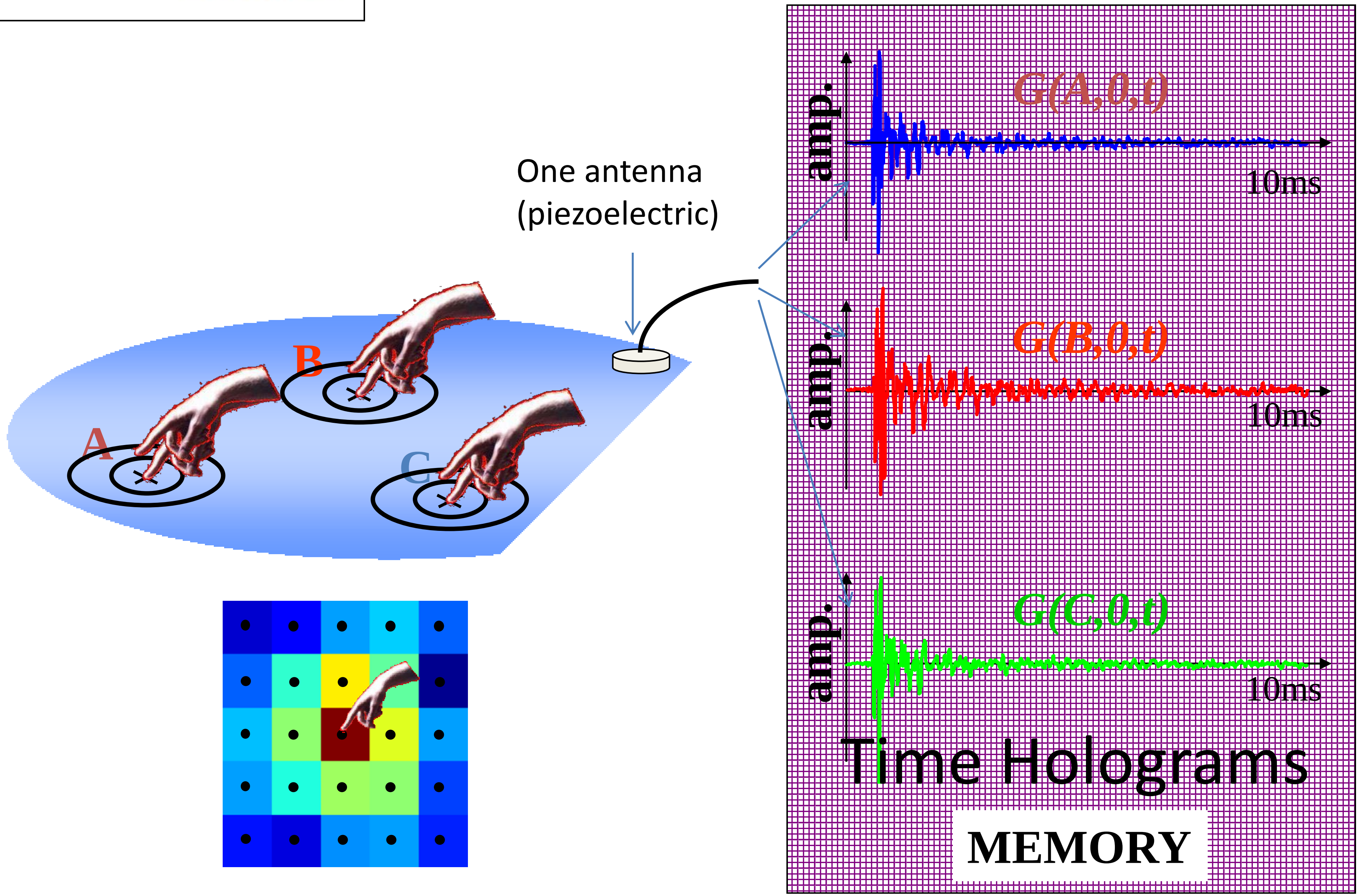


During the time-reversed step from point B , 400 uncorellated eigenmodes are excited with perfect phase matching at point A

The size of the focal spot is of the order of the size of one modal cell = λ/2

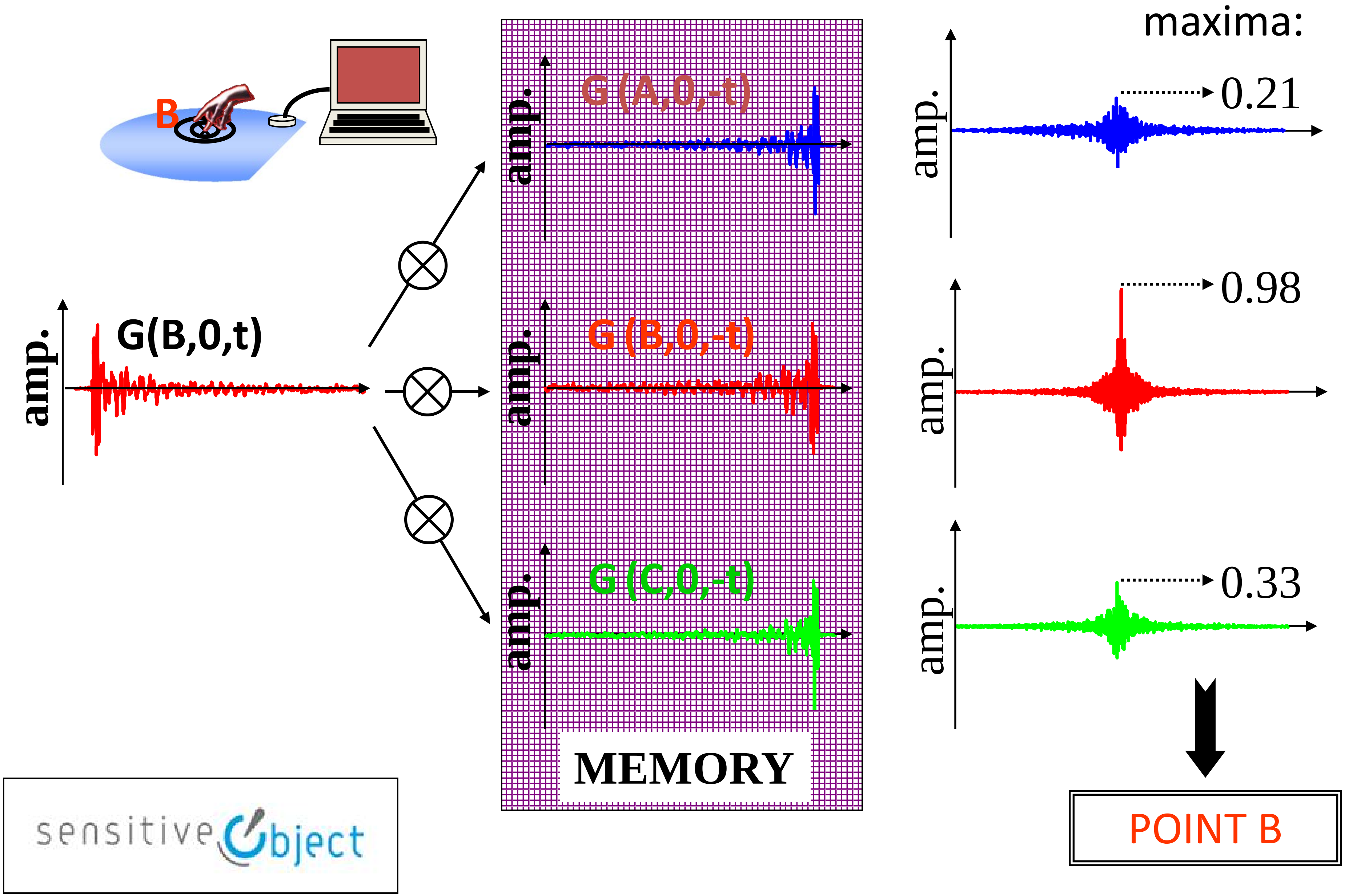
sensitive Object

Tactile Objects

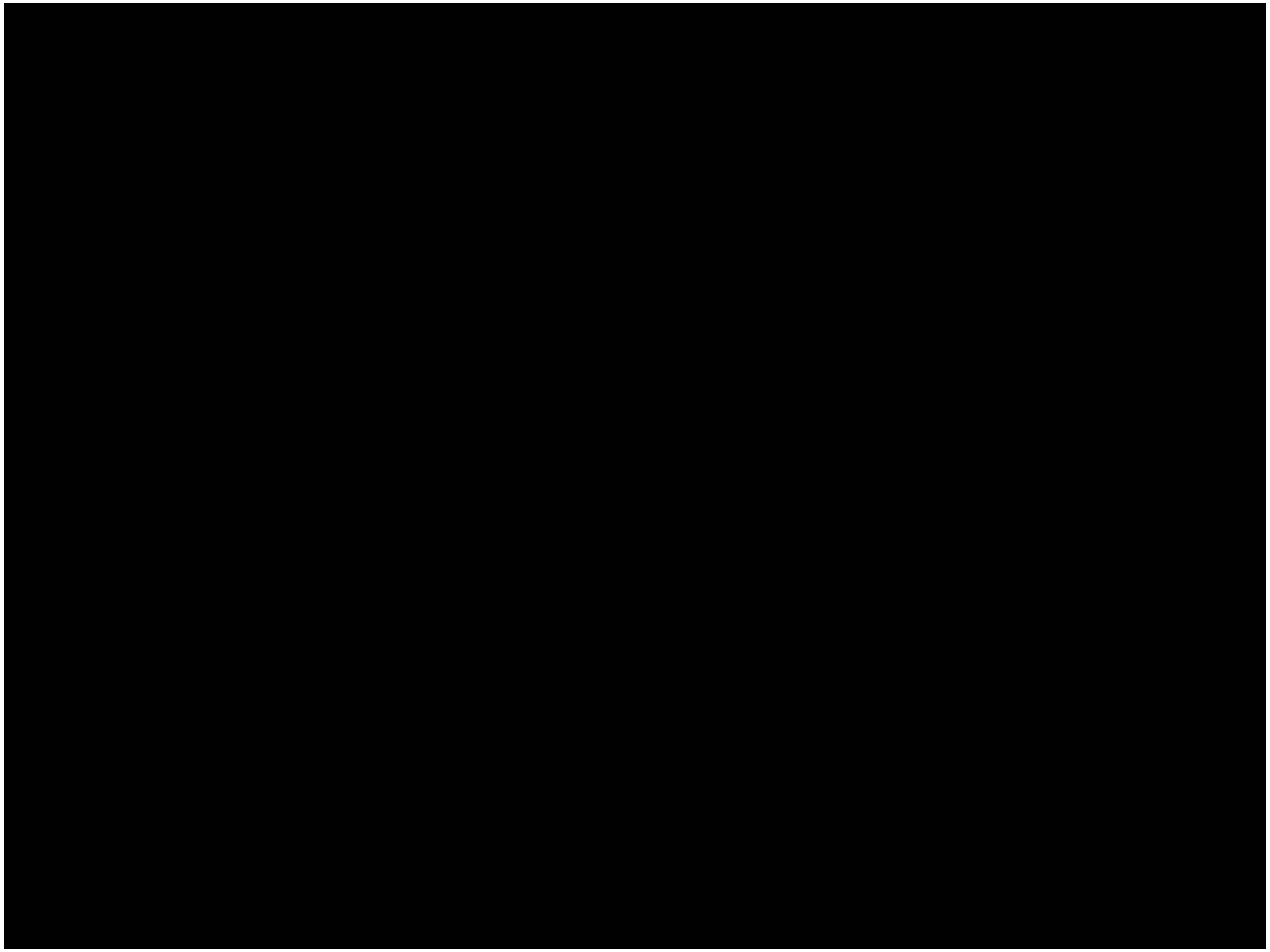


Rk Ing, N Quieffin, S Catheline, M Fink. “In solid localization of finger impacts using acoustic time-reversal process”, *Applied Physics Letters* 87 (20): Art. No. 204104, 2005

Source localisation by cross-correlation, mimicking a time-reversal experiment in the computer



Products : Tactile Objects



The noise radiated by the finger is enough to follow the trajectory

Sensitive Object , 35 employees Now Tyco Electronics

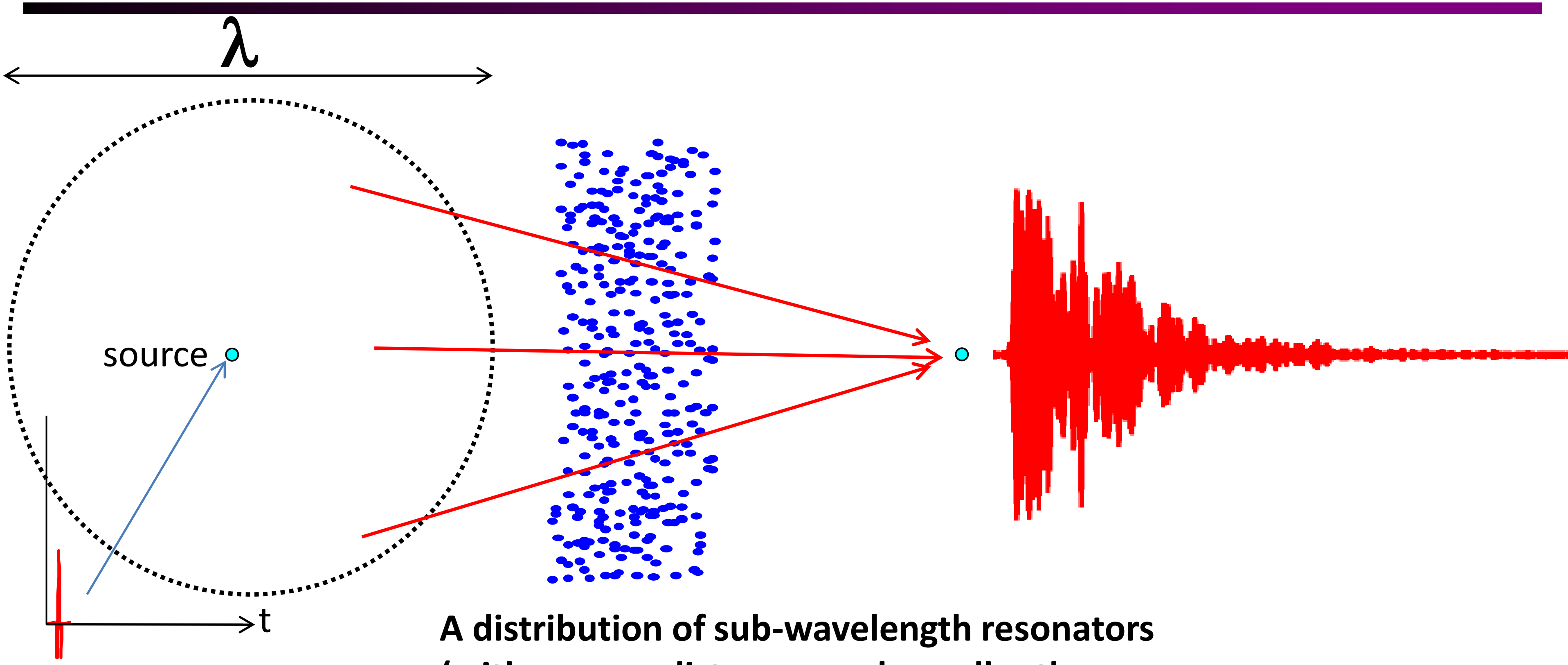
Subwavelength Focusing with TR

Two different approaches :

- distribution of sub-wavelength resonators in the near field of the source

- the sink (a perfect absorber), introducing dissipation

How to build a dispersive medium with subwavelength scale ?



A distribution of sub-wavelength resonators (with a mean distance much smaller than the wavelength)

Near field and multiple scattering

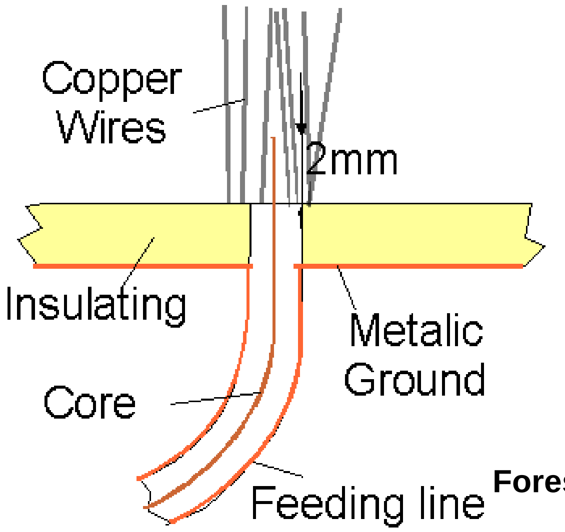
Frequency Diversity

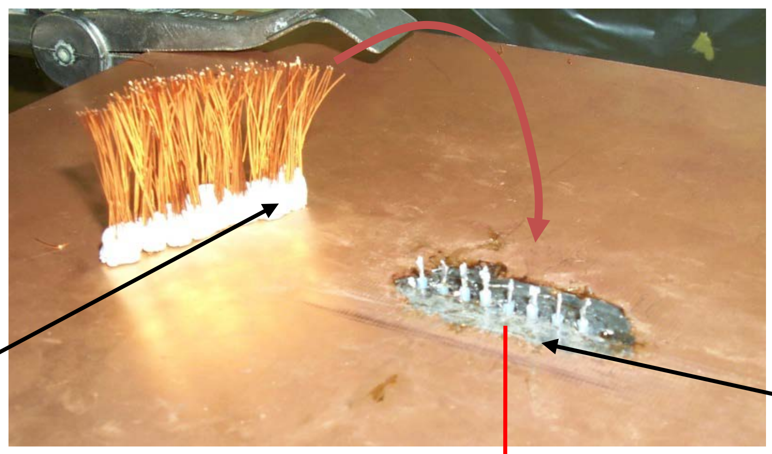
G Lerosey, J de Rosny, A Tourin, M Fink Science, **315**, 1120- 2007

Super-resolution

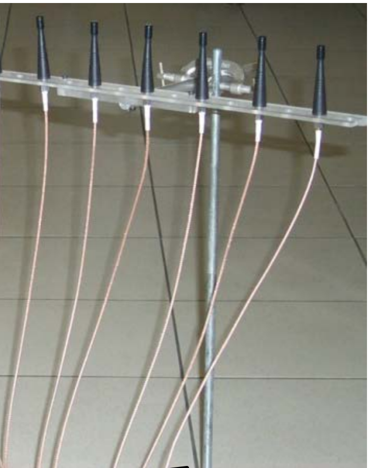
Electromagnetic Waves : wavelength 12 cm at 2.44 GHz- WiFi Frequency)

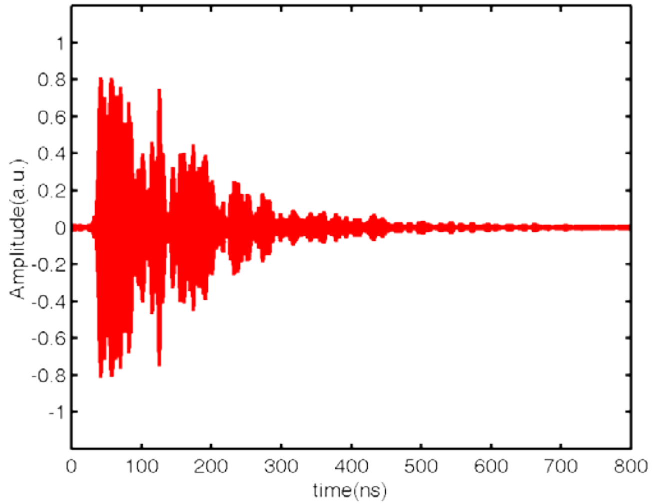
You have to locate in the near field of the source (less than a wavelength) a distribution of resonating scatterers

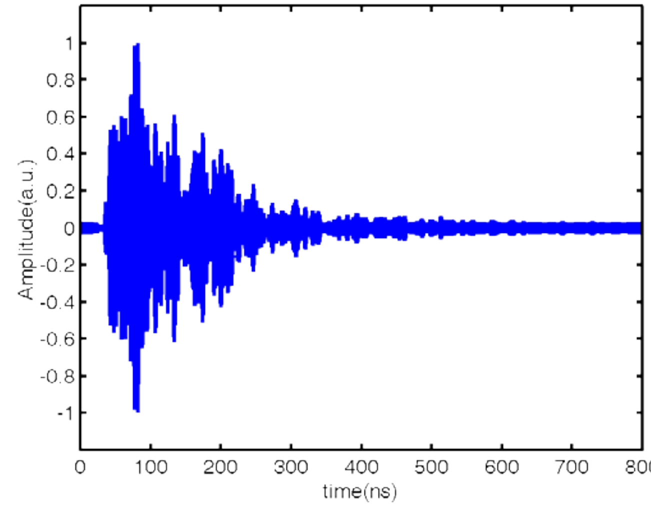




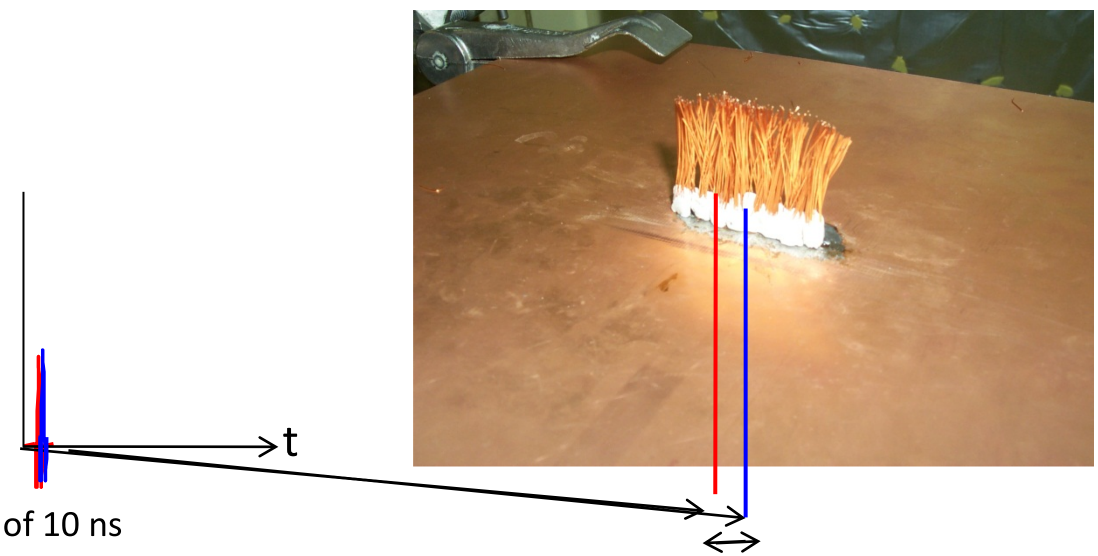
G Lerosey, J de Rosny, A Tourin, M Fink, Science, **315**, 1120- 2007







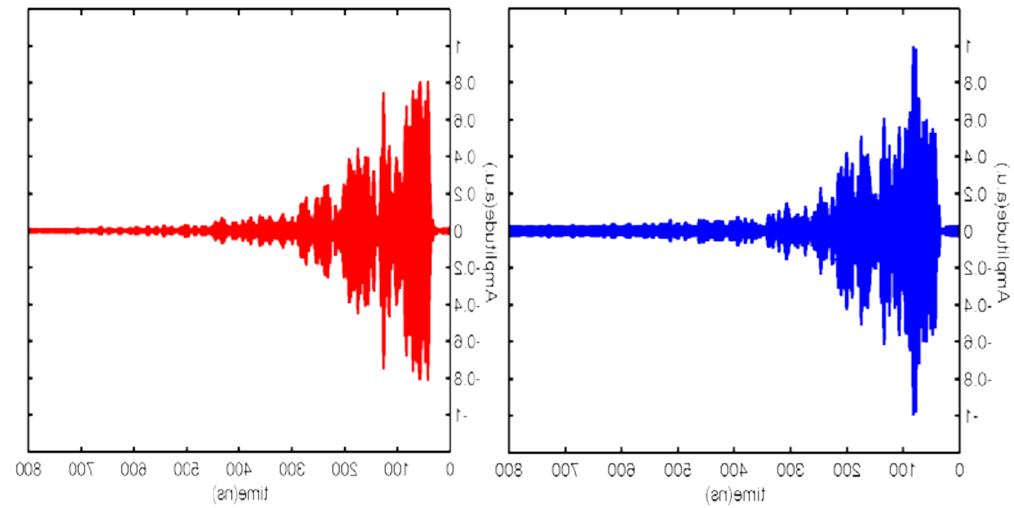
Signal recorded in the far field by one TRM antenna

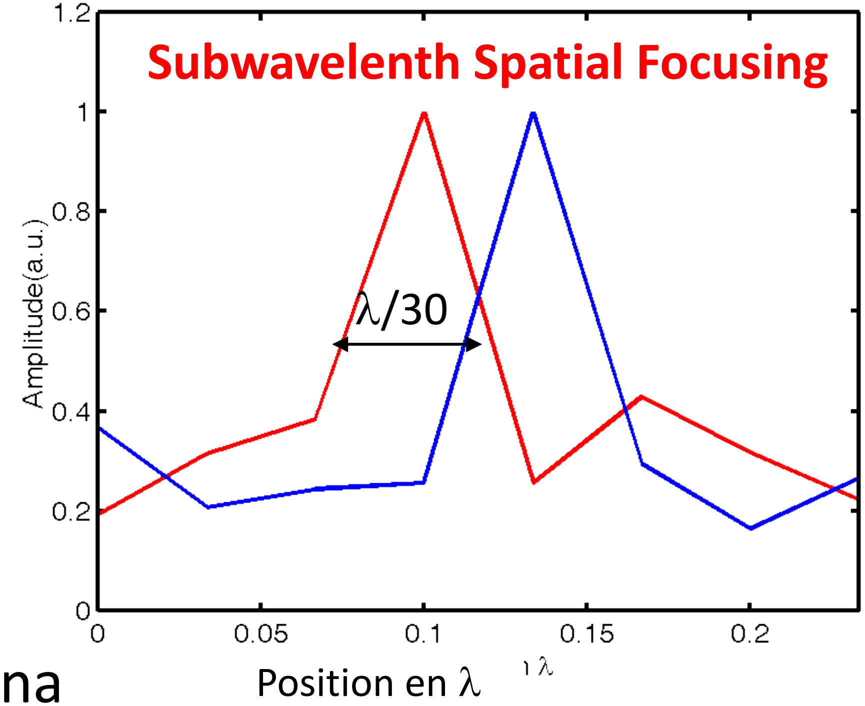


Pulse of 10 ns

4mm = $\lambda/30$

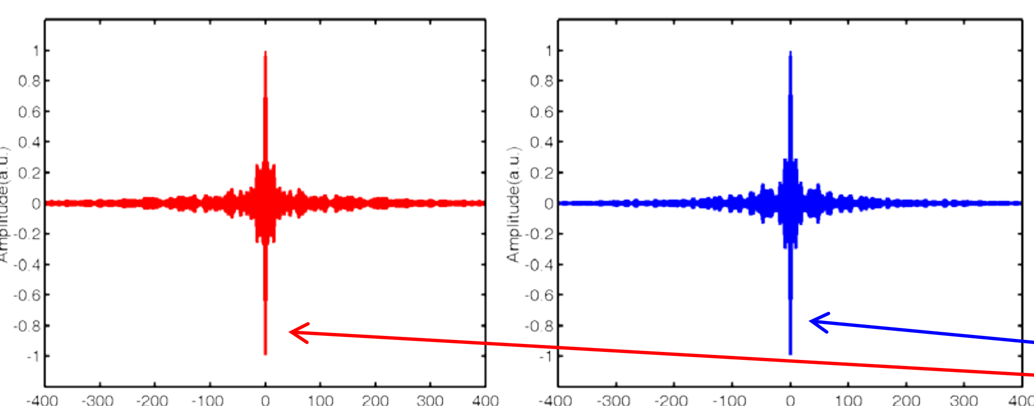
Sub-wavelength resolution by a far field TRM

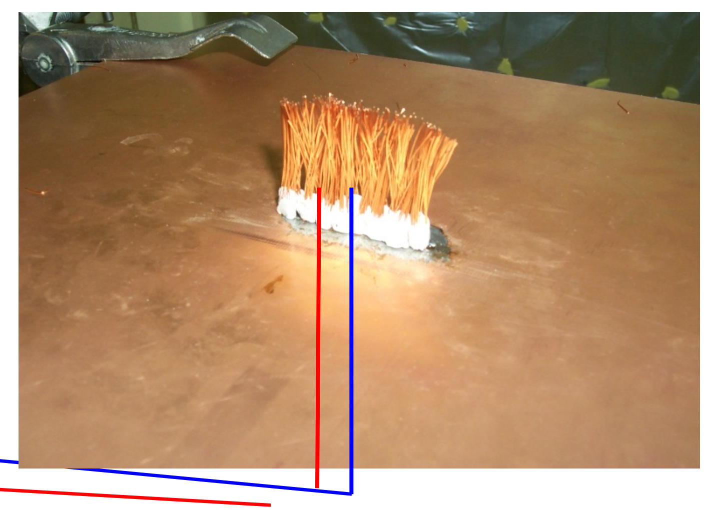




Time-reversed signals transmitted and observed by the red or blue wire antenna

Time-Focusing

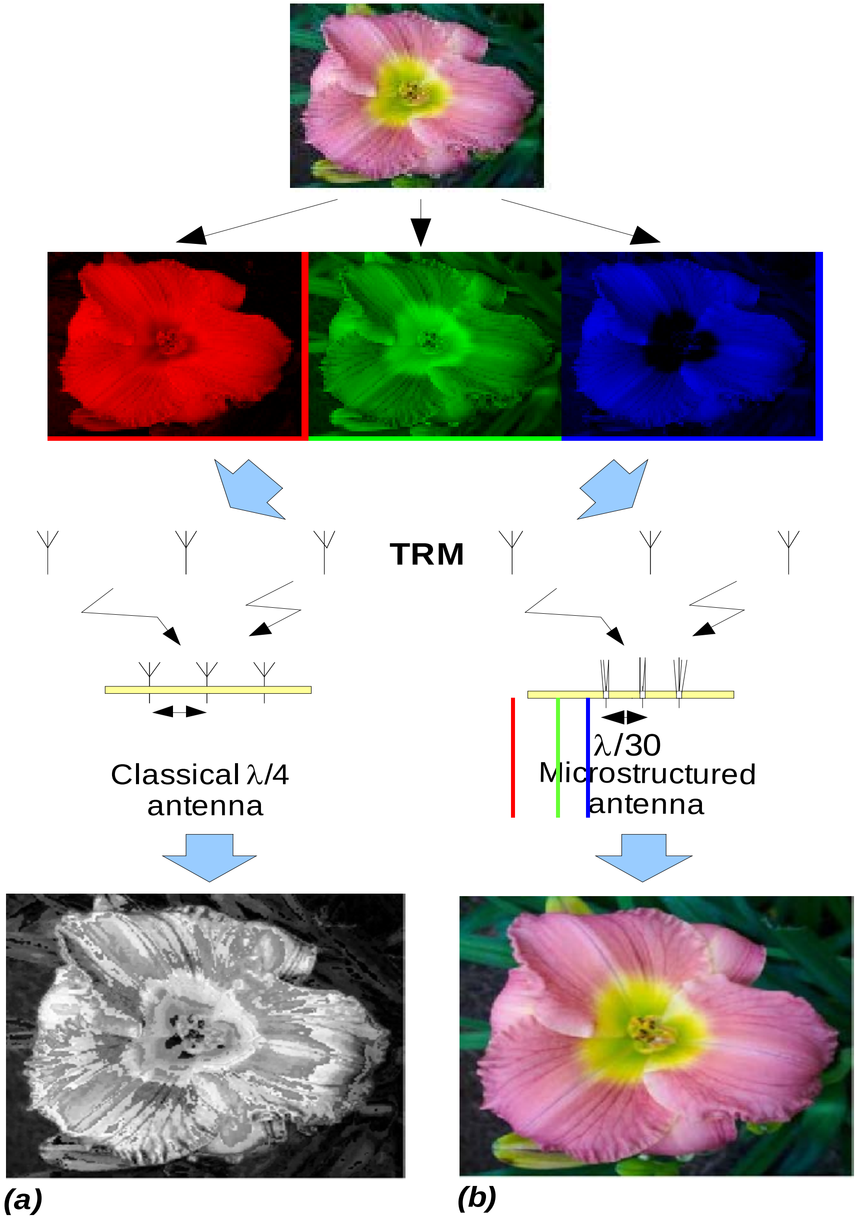




Telecommunications

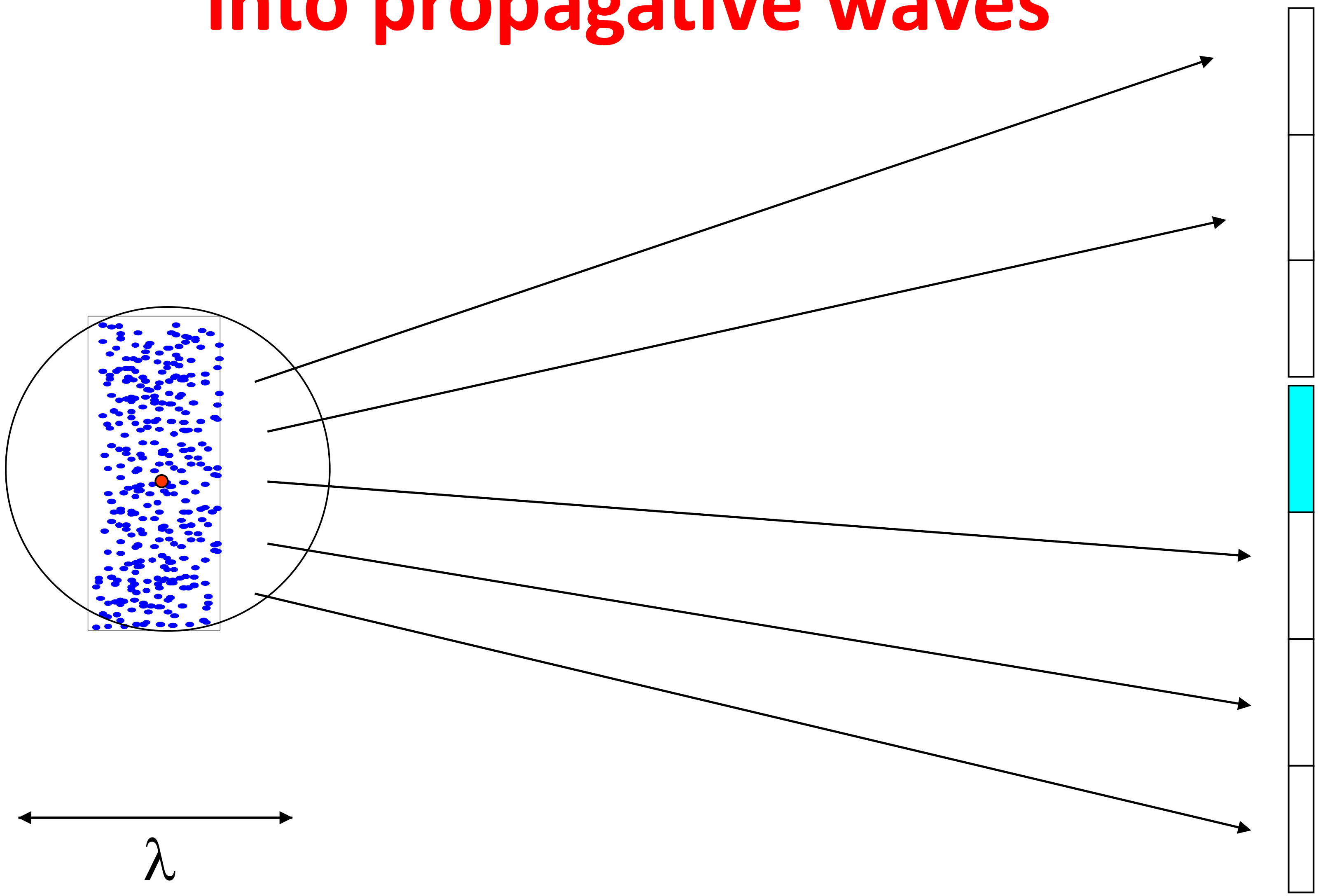
3 bitstreams (RGB) with 50 Mbits/s.
The total rate transfer is 150 Mbits/s.

The TRM was made of 3 antenna with 2.45 GHz center frequency and 180 MHz bandwidth

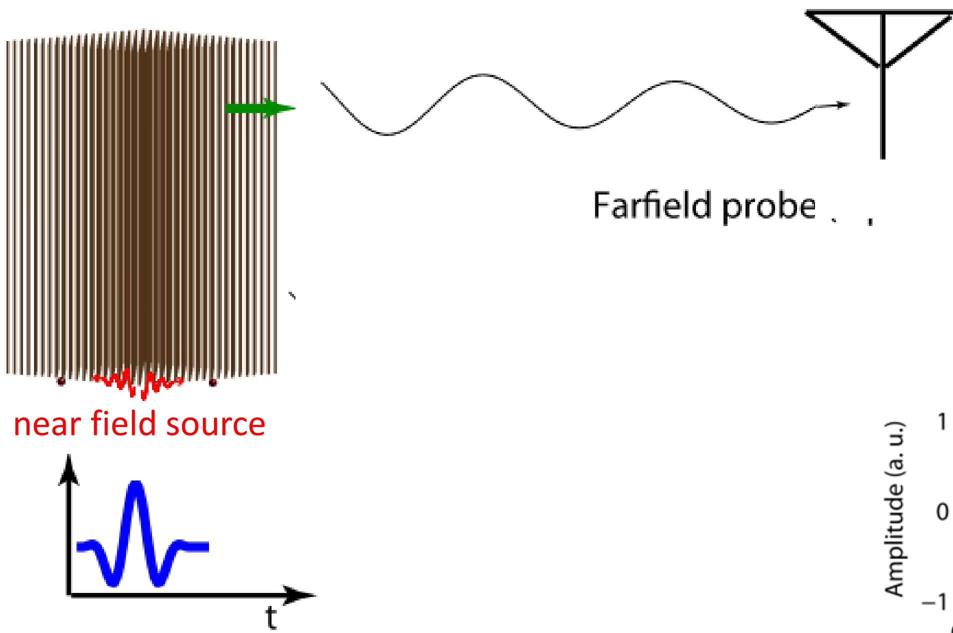


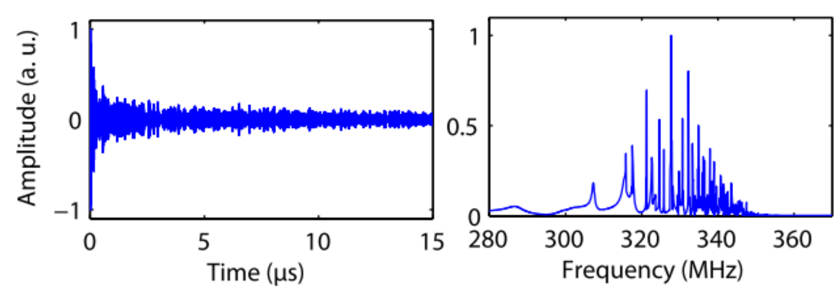
Start-up Time-Reversal Communications (40 employees, now Bull)

The evanescent field is converted into propagative waves



What mecanism transforms evanescent waves into propagative waves ?
The multi-modal Board





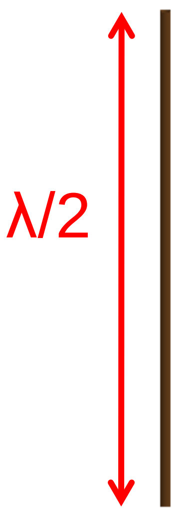
F. Lemoult, G. Lerosey, J. de Rosny, M.Fink, Phys. Rev. Lett., 104, p 203901, 2010

F. Lemoult, M. Fink, G. Lerosey, Waves in random and Complex media, 21 (4) 614-627 , 2011

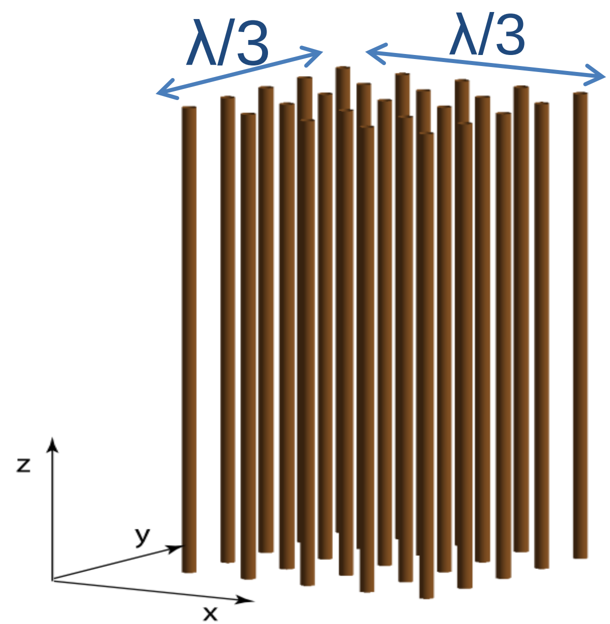
F. Lemoult, M. Fink, G. Lerosey ,Waves in random and Complex media, 21 (4) 591-613 , 2011

Two key points :

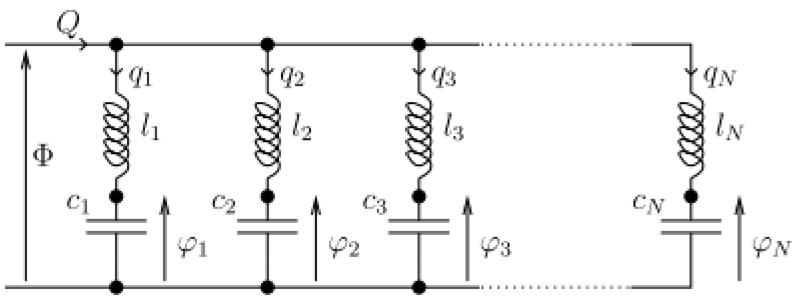
1. **The medium is made of coupled subwavelength resonators**
2. **The medium must be of finite lateral size**



1 copper wire
⇔ 1 resonator
for EM waves at
frequency f_0

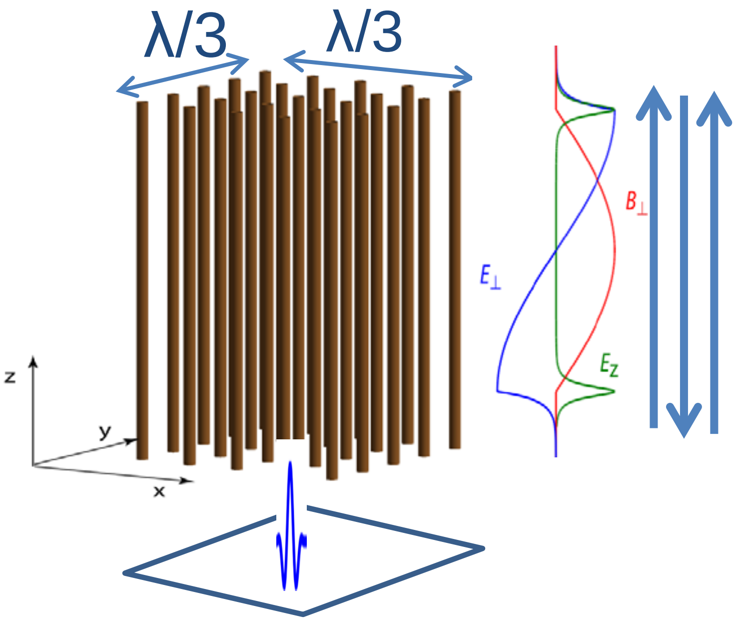


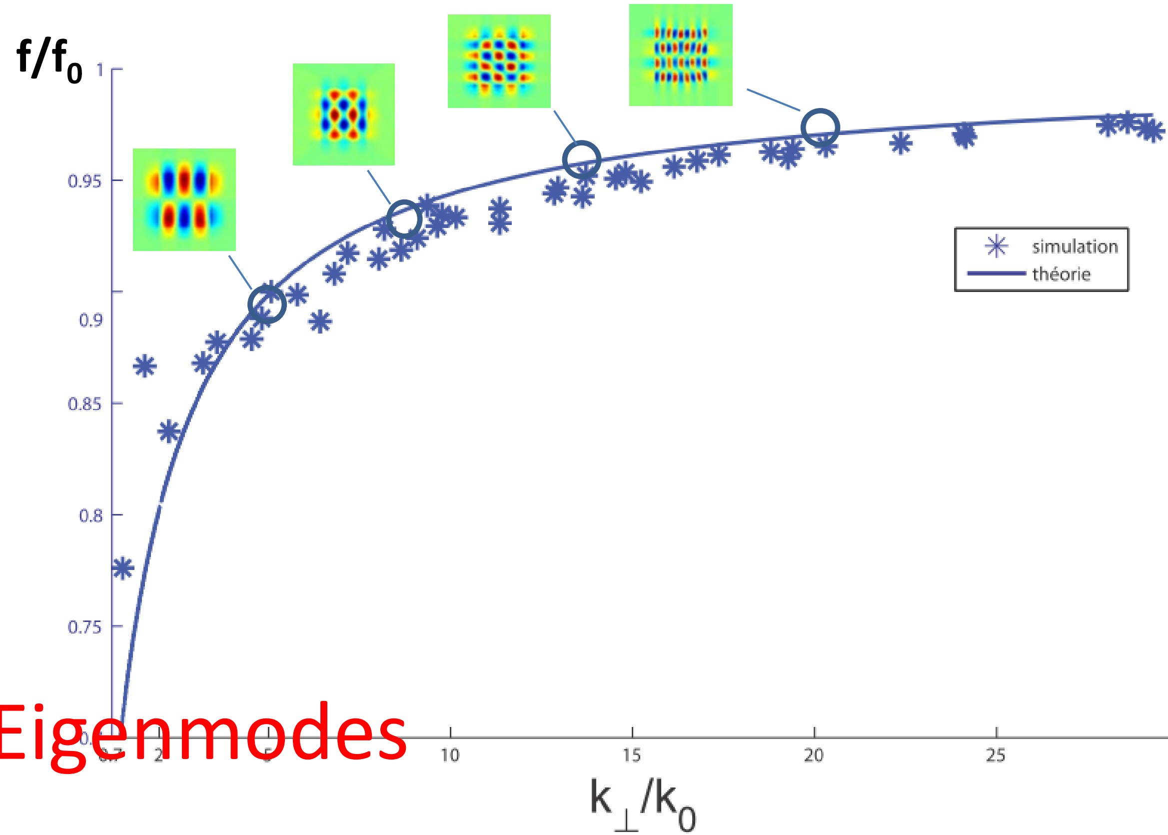
An example : (λ/80) spaced resonators in a periodic structure (or random)



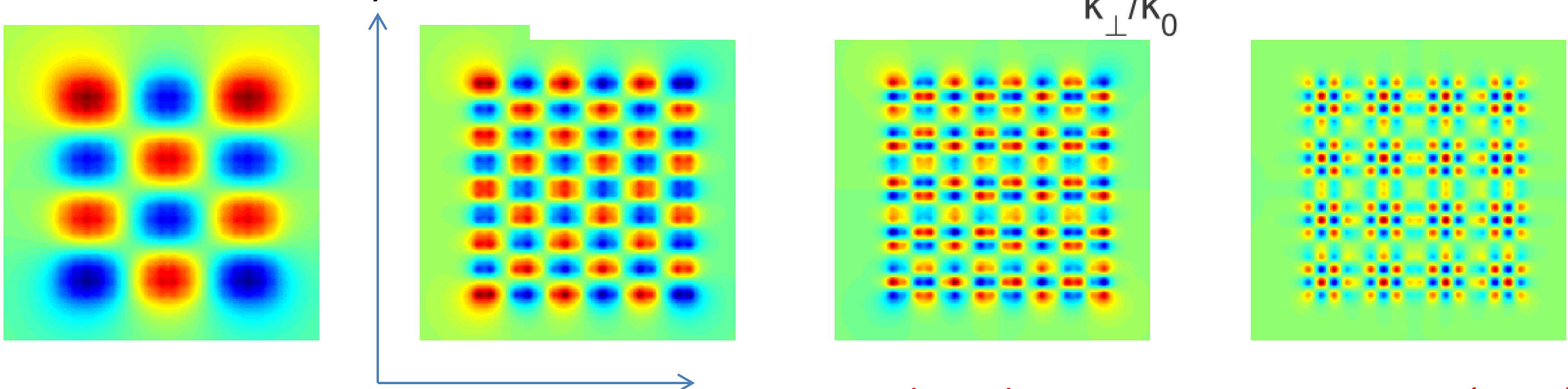
N electrical coupled oscillators
=> N eigenmodes and
N eigenfrequencies

Dispersion of TEM Waves





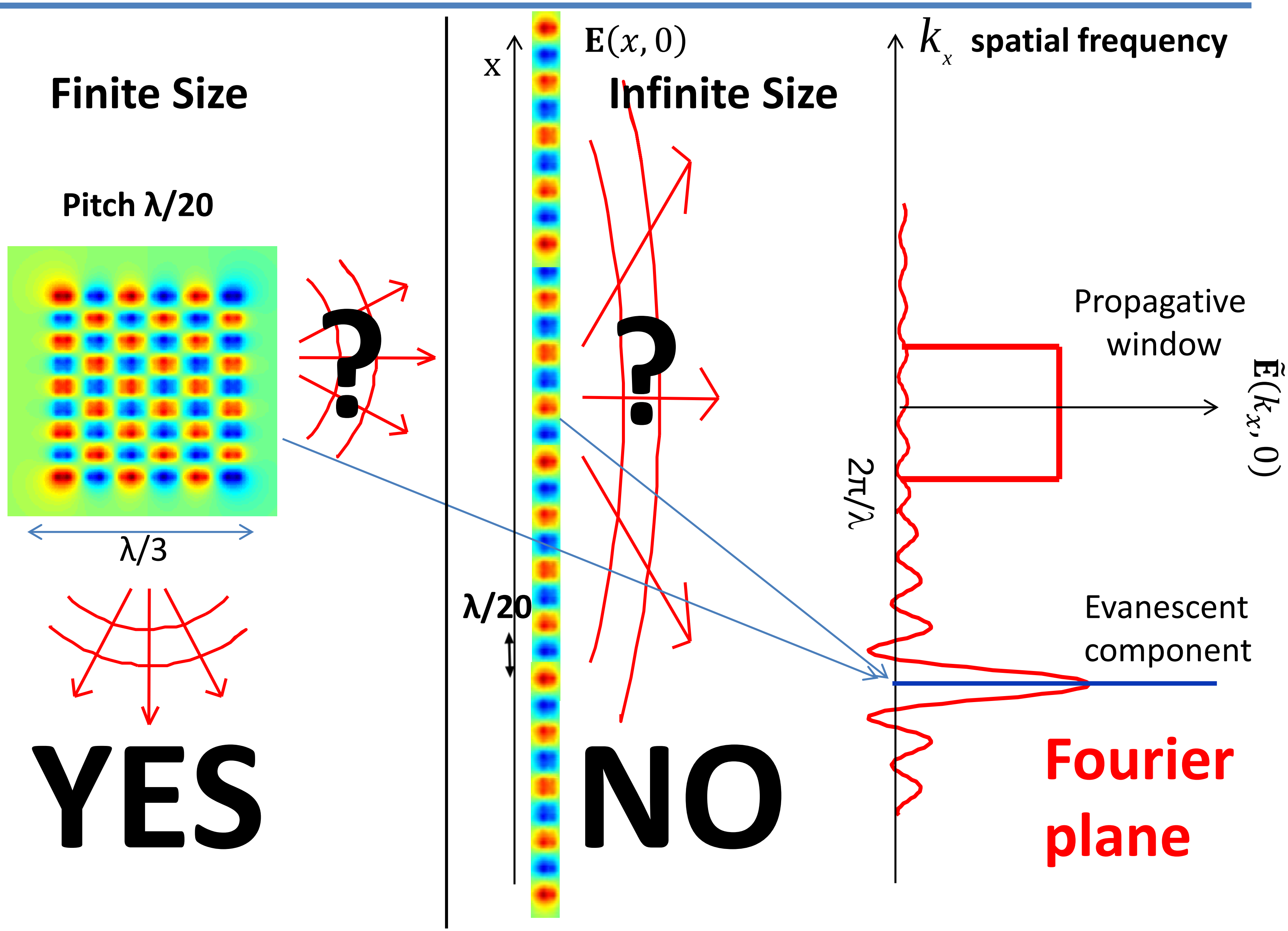
Some Evanescent Eigenmodes



Lemoult, Fink, Lerosey , WRCM 21, 591 (2011)

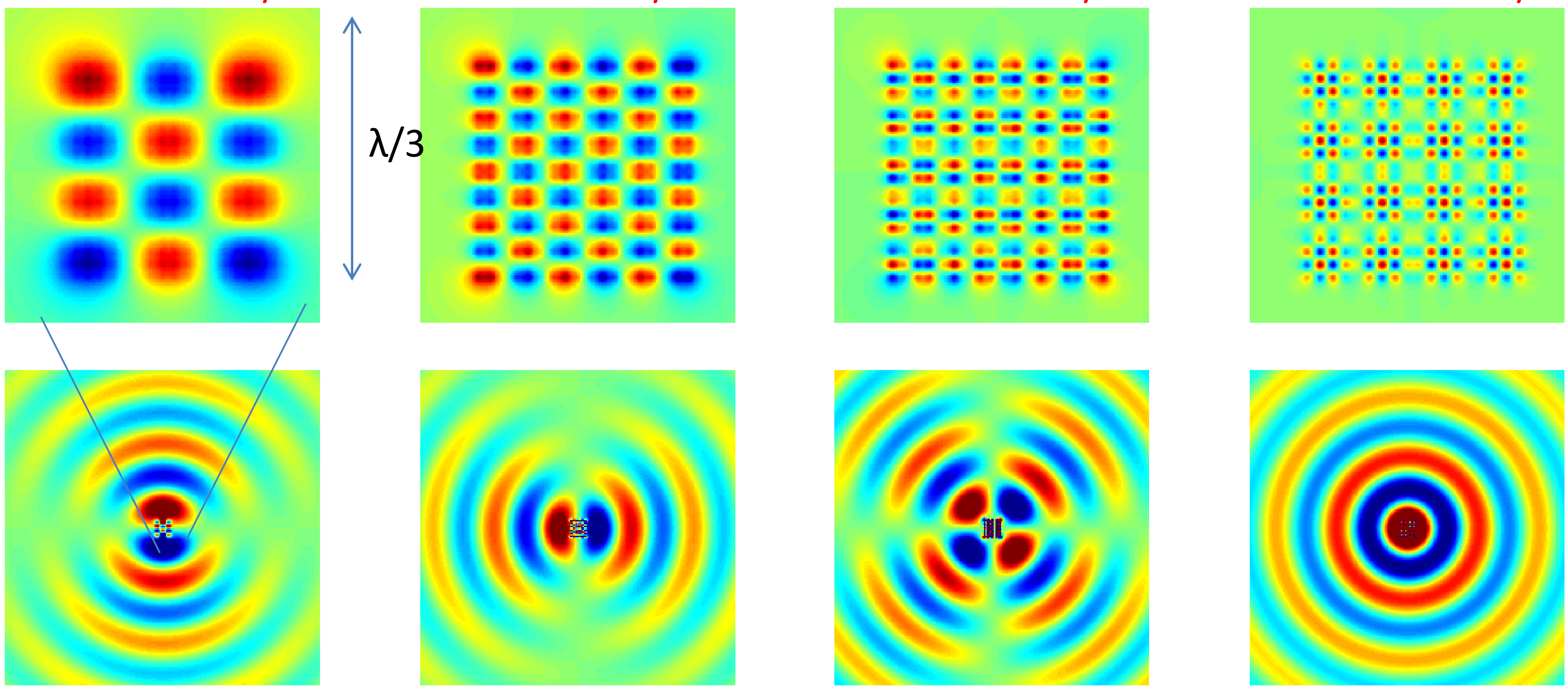
Why evanescent eigenmodes can radiate in the far field ???

Because the wire medium is bounded



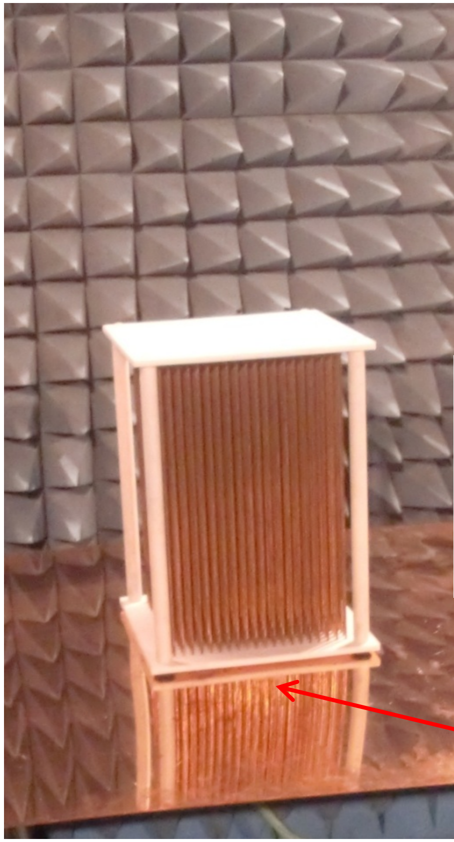
Is it Efficient ? Yes : Resonant amplification

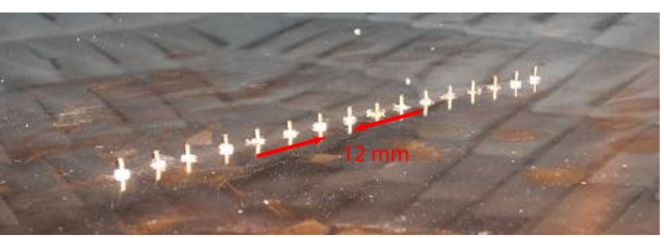
For f_0 = 375 MHz

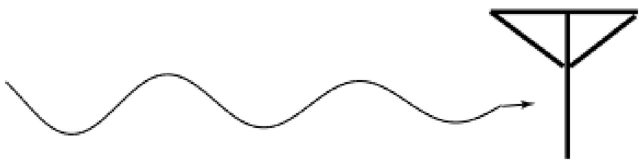


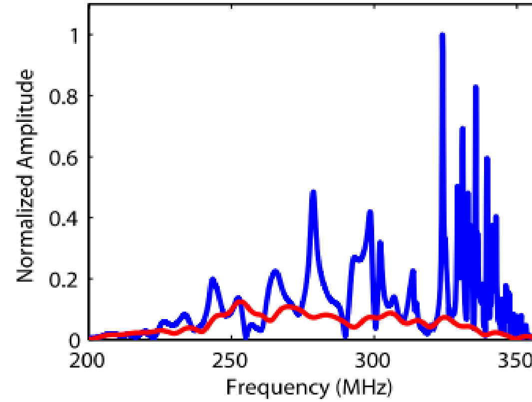
Resonant Amplification : When a mode radiates slowly, the energy is trapped and there is a strong resonant amplification inside the structure: **Purcell Effect**

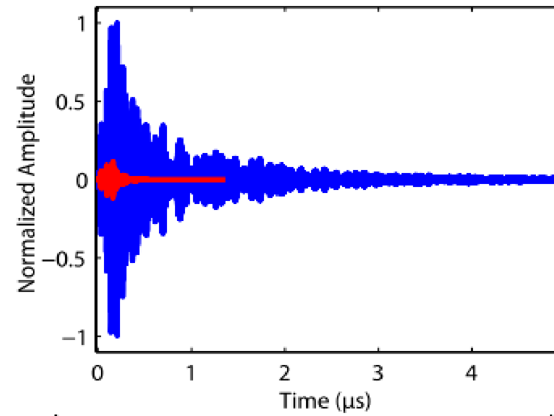
Subwavelength focusing from the far field



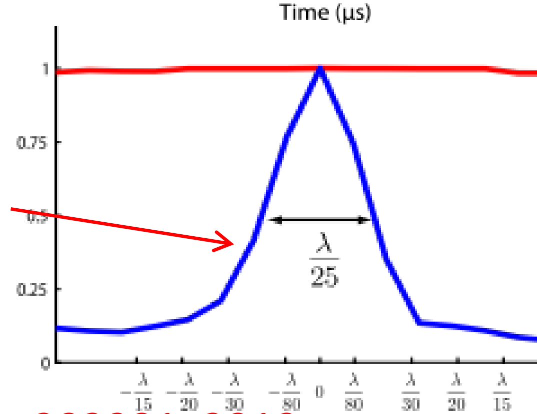








Subwavelenth Focusing



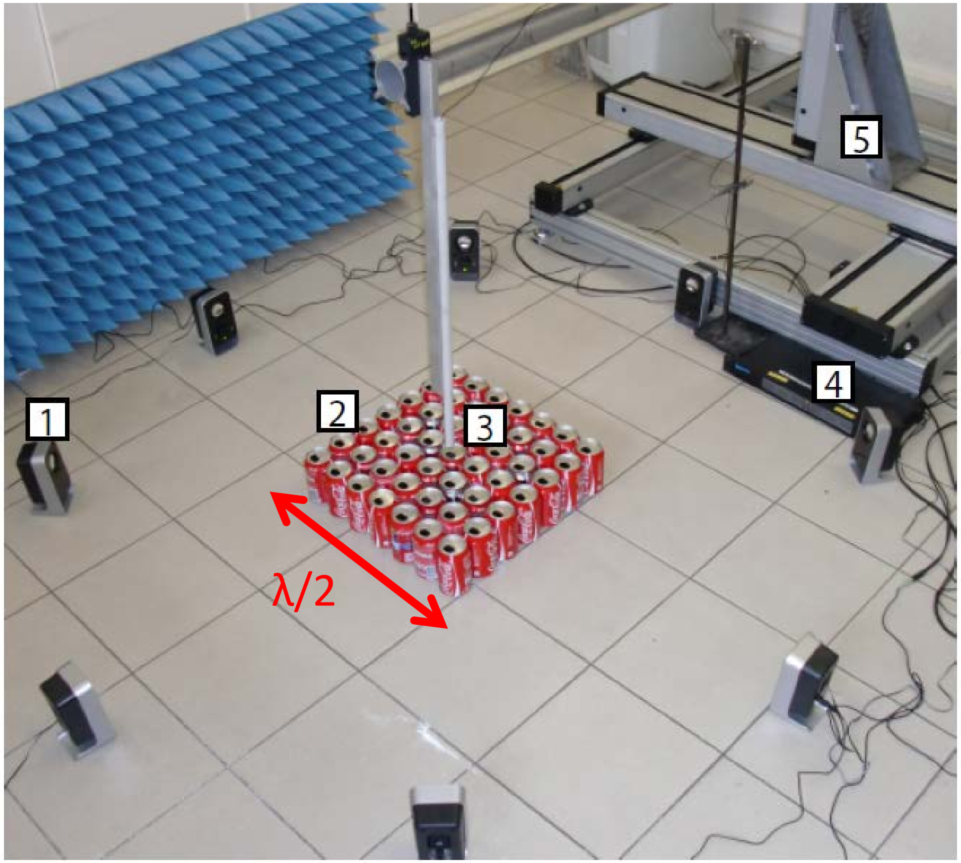
F. Lemoult, G. Lerosey, J. de Rosny, M.Fink, Phys. Rev. Lett., 104, p 203901, 2010

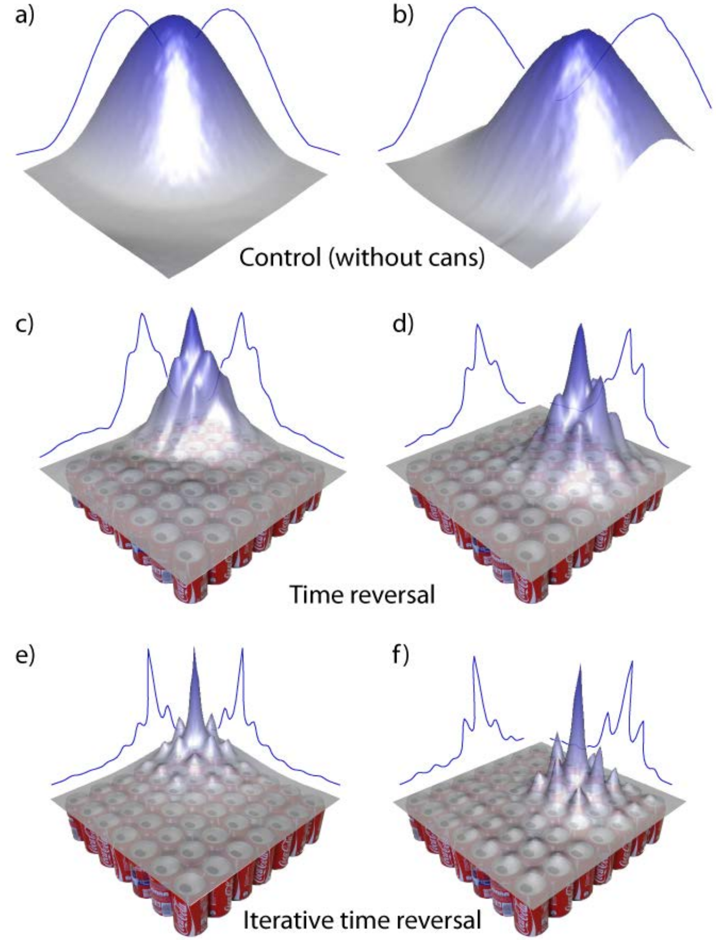
Sub-wavelenth acoustic resonators

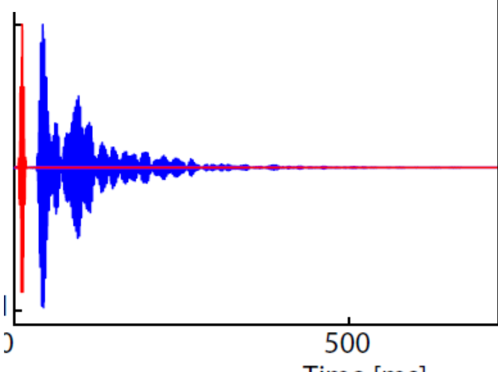
Resonance in air @ 420 Hz (λ=0.8m) , Helmoltz sub-λ resonator (diameter = 6,5 cm), Low loss

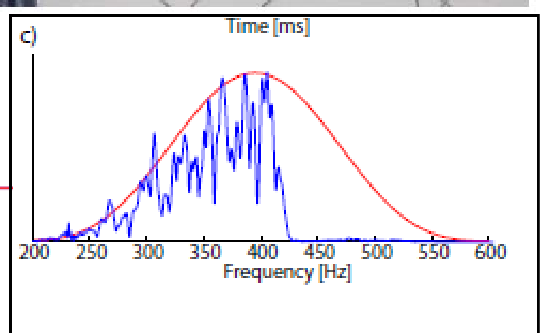
F. Lemoult, M. Fink and G. Lerosey, Phys. Rev. Lett. 107, 064301 (2011).

Sound Focusing and Soda Cans





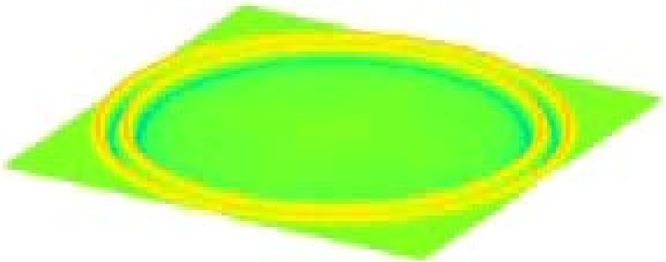




F. Lemoult, M. Fink and G. Lerosey, Phys. Rev. Lett. 107, 064301 (2011).

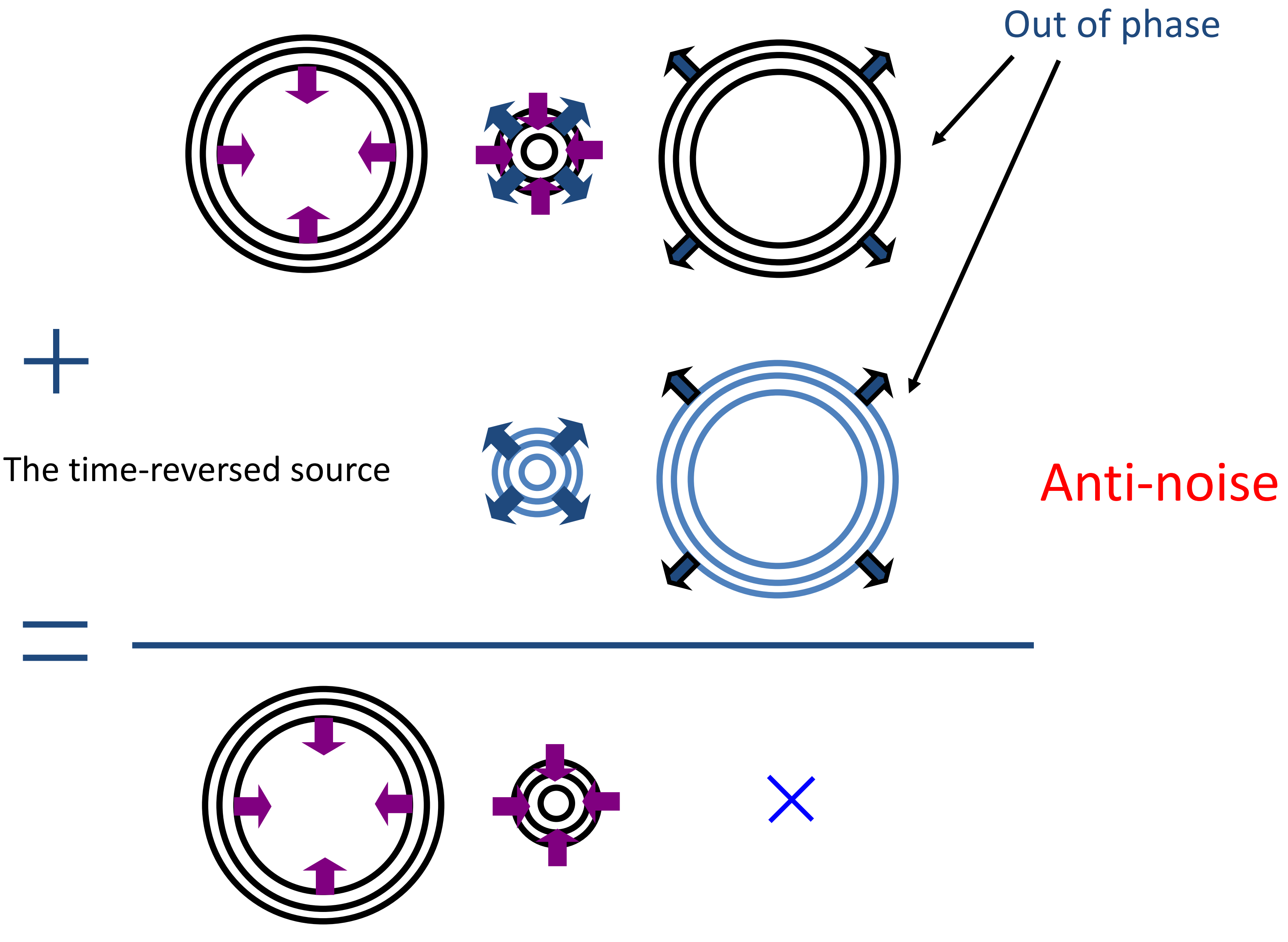
Another Way to Super-Resolution
Introducing the Sink - a Perfect Absorber -

Origin of the diffraction limit in free space



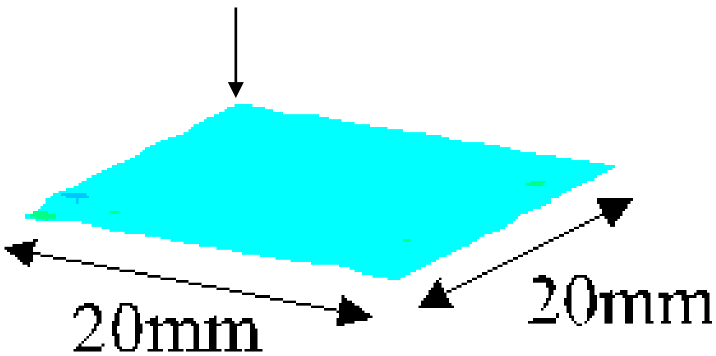
In free space, we cannot create only a converging wave, even with 4π aperture lens (a TR cavity or a Maxwell fish eye)

Principle of an active acoustic sink

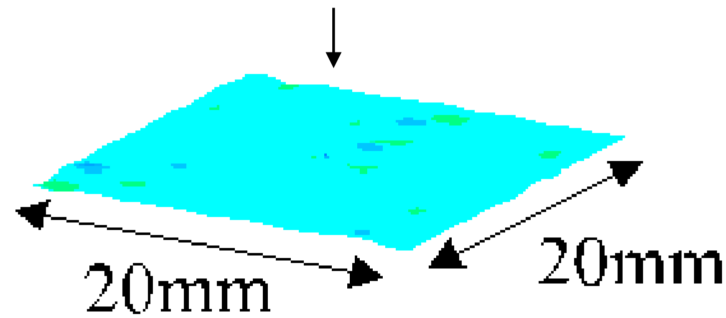


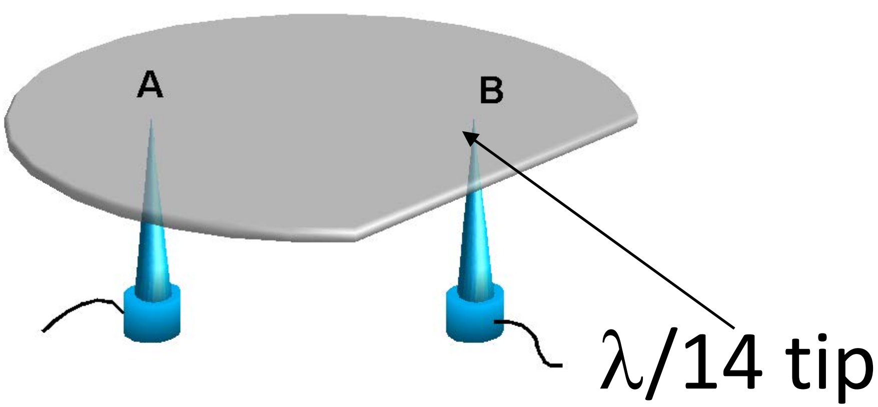
Experimental Acoustic Sink

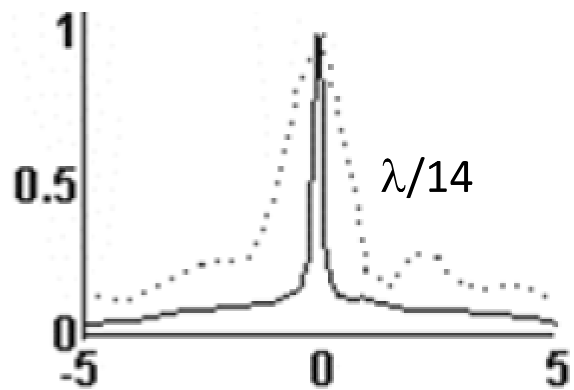
Wavefield Time Reversal



WaveField and Source Time Reversal

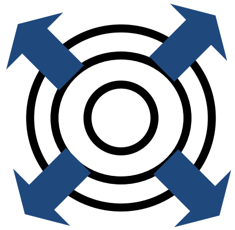






J. De Rosny, M.Fink, "Overcoming the diffraction limit in wave physics using a time-reversal mirror and a novel acoustic sink" *Physical Review Letters* 89 (12), p 124301, 2002

To create only a **converging wave** requires to time-reversed also the source : the Sink (drain)



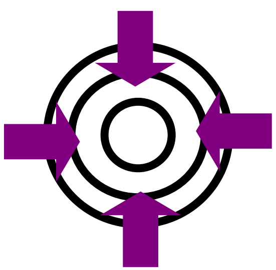
$$\left(\Delta - \frac{1}{c^2}\frac{\partial}{\partial t^2}\right)\varphi(\vec{r},t) = f(t)\delta(\vec{r}-\vec{r}_0)$$

The causal field : diverging wave

Point-like source

To create a perfect anti-causal field : a **converging wave** only

You have to replace ***t*** by ***–t*** in the wave equation



$$\left(\Delta - \frac{1}{c^2}\frac{\partial}{\partial t^2}\right)\varphi(\vec{r},-t) = f(-t)\delta(\vec{r}-\vec{r}_0)$$

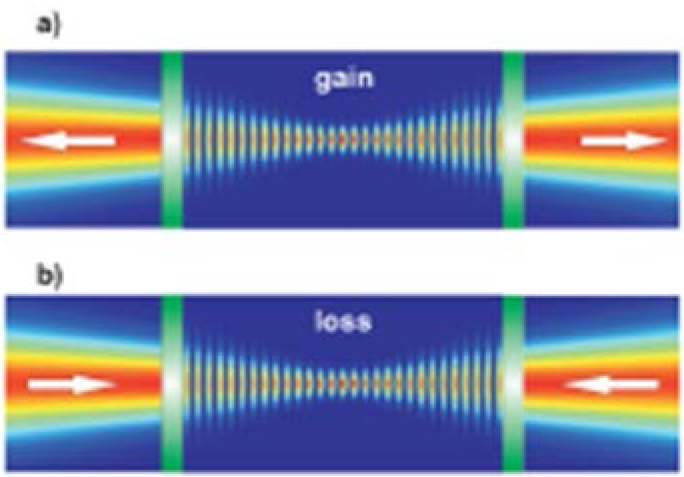
Converging wave

The time-reversed source is modulated by *f(-t)*

J. De Rosny, M.Fink, " Overcoming the diffraction limit in wave physics using a time-reversal mirror and a novel acoustic sink " *Physical Review Letters* 89 (12), p 124301, 2002

Is it possible to build a passive Sink ?
Introducing Dissipation (loss)

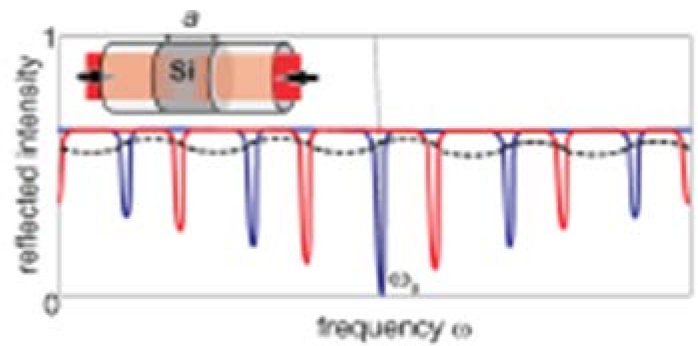
The coherent perfect absorber : the **time-reversed Laser**
: a sink for monochromatic wave (Loss is the time reversal of Gain**)**



Selected for a Viewpoint in *Physics*
PRL **105**, 053901 (2010) PHYSICAL REVIEW LETTERS week ending 30 JULY 2010

Coherent Perfect Absorbers: Time-Reversed Lasers

Y. D. Chong,* Li Ge, Hui Cao, and A. D. Stone



A Fabry Perot Resonator with gain is tranformed <u>in TR</u> operation in a Fabry Perot with loss

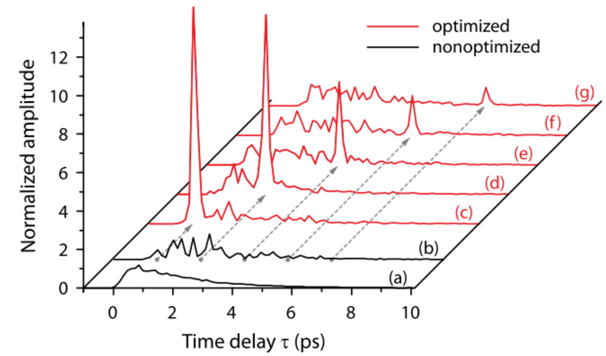
Is it possible to build a blackbody (broadband) of size smaller than the wavelengths ?

Time-reversal of visible light

Control of light transmission through opaque scattering media in space and time

Jochen Aulbach,[1,2,*] Bergin Gjonaj,[1] Patrick M. Johnson,[1] Allard P. Mosk,[3] and Ad Lagendijk[1]

Optical time reversal was still a dream 2 years ago…

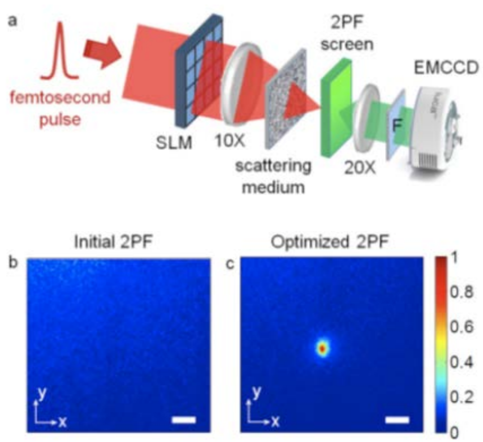


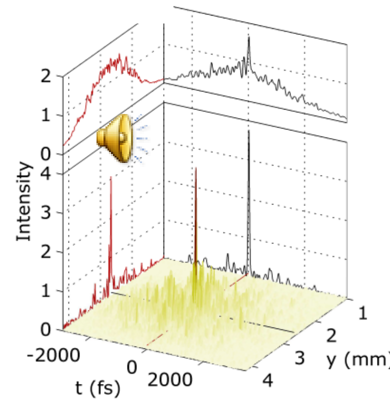
Controlled Spatiotemporal Focusing Through Turbid Media

Ori Katz*, Yaron Bromberg, Eran Small, Yaron Silberberg

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

**ori.katz@weizmann.ac.il*





Shaping speckles: spatio-temporal focussing of an ultrafast pulse through a multiply scattering medium

David J. McCabe,[1,*] Ayhan Tajalli,[1] Dane R. Austin,[2] Pierre Bondareff,[3] Ian A. Walmsley,[2] Sylvain Gigan,[3] and Béatrice Chatel[1]

[1] *CNRS-Université de Toulouse, UPS, Laboratoire Collisions, Agrégats Réactivité, IRSAMC, F-31062 Toulouse, France*

[2] *Clarendon Laboratory, Department of Physics, University of Oxford, Oxford, OX1 3PU, United Kingdom*

[3] *Institut Langevin, ESPCI ParisTech, CNRS UMR 7587, Universités Paris 6 & 7, INSERM, ESPCI, 10 rue Vauquelin, Paris, 75005, France*

nature photonics

REVIEW ARTICLE

PUBLISHED ONLINE: XX MAY 2012 | DOI: 10.1038/NPHOTON.2012.88

Controlling waves in space and time for imaging and focusing in complex media

Allard P. Mosk[1], Ad Lagendijk[1,2], Geoffroy Lerosey[3] and Mathias Fink[3]