Shaped waves and speckle correlations: See the light inside

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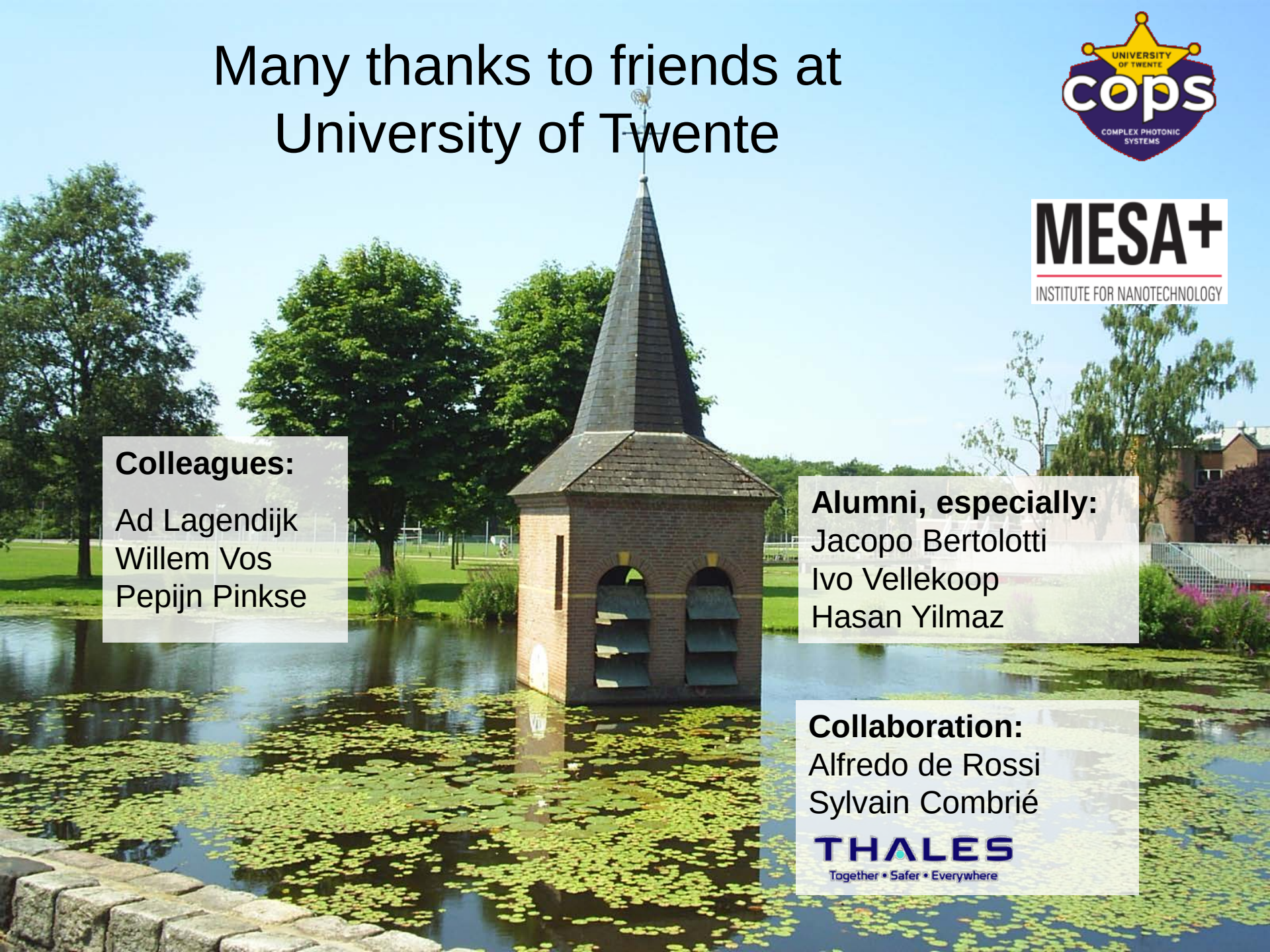
Many thanks to friends at University of Twente



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Collaboration:

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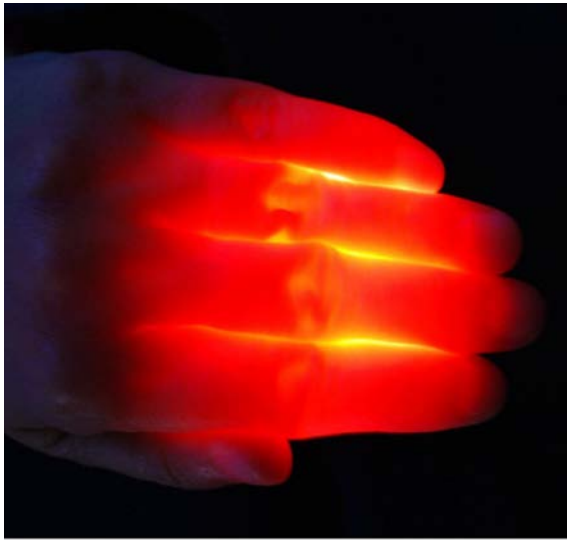
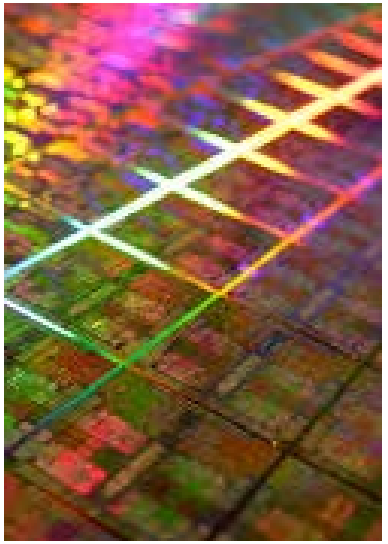
Sylvain Combrié

Plan

- Wavefront shaping
- Imaging
- Open and closed channels
- Secure authentication

Light scattering: A problem?

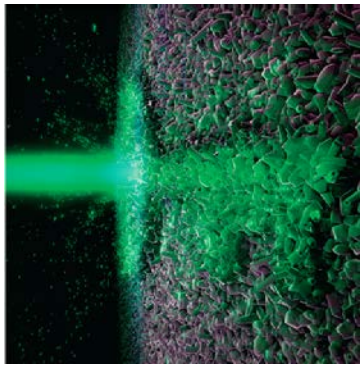




Counteract scattering

- Focus light through scattering media
- Image through scattering media
- *Nanophotonic resonator arrays*

Scattering is the key



- High resolution imaging
- *Nanopositioning*
- *Secure keys*

Introduction

BASICS OF LIGHT SCATTERING

Weak scattering

Weak refractive index variations

Light slightly changes direction

Can usually be corrected with adaptive optics

Nic MacBean, ABC News

Good books on adaptive optics: Tyson (3rd ed, 2010), Hardy (1998)

Scattered Light

Water drops fully randomize direction of light.

Scattered light outshines “ballistic”.

Filter ballistic light: **OCT, Coherent Imaging, gated imaging, …**

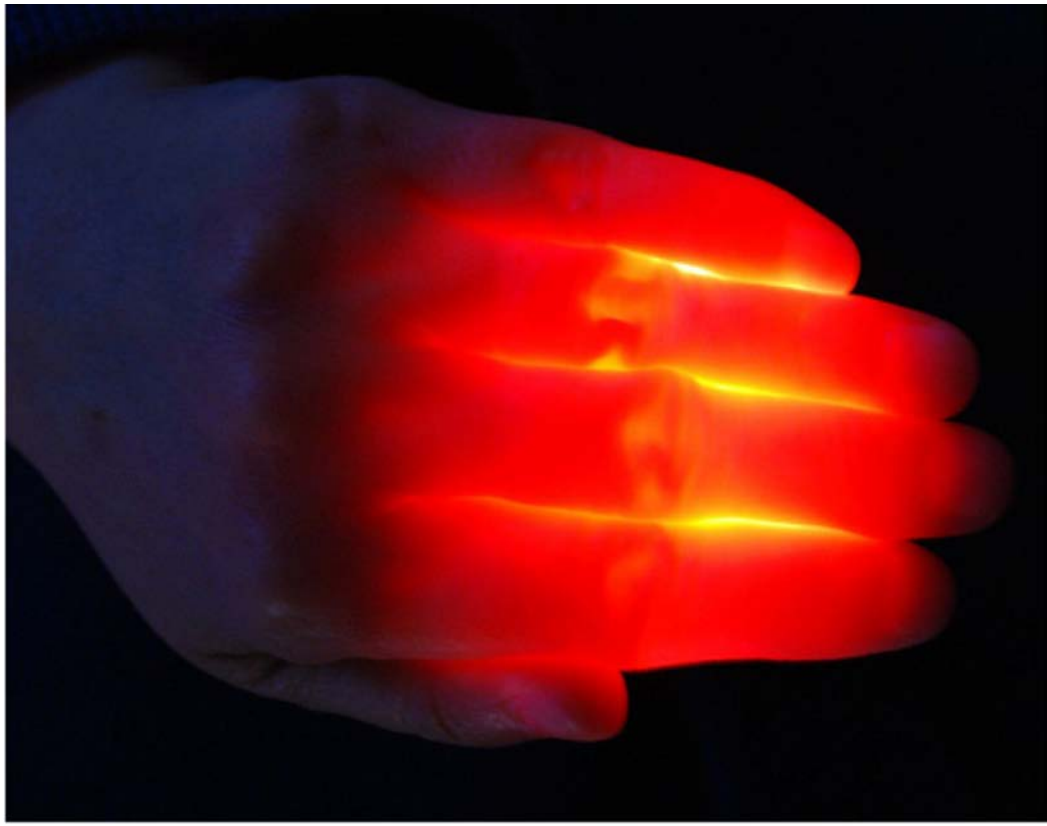
OCT: Huang *et al.,* Science **254** (1991)
Gated imaging: Wang *et al.*, Science **253** (1991)
Coherent imaging through smoke: Locatelli *et al.*,Opt. Expr. **21** 5379 (2013)

Scattered light only

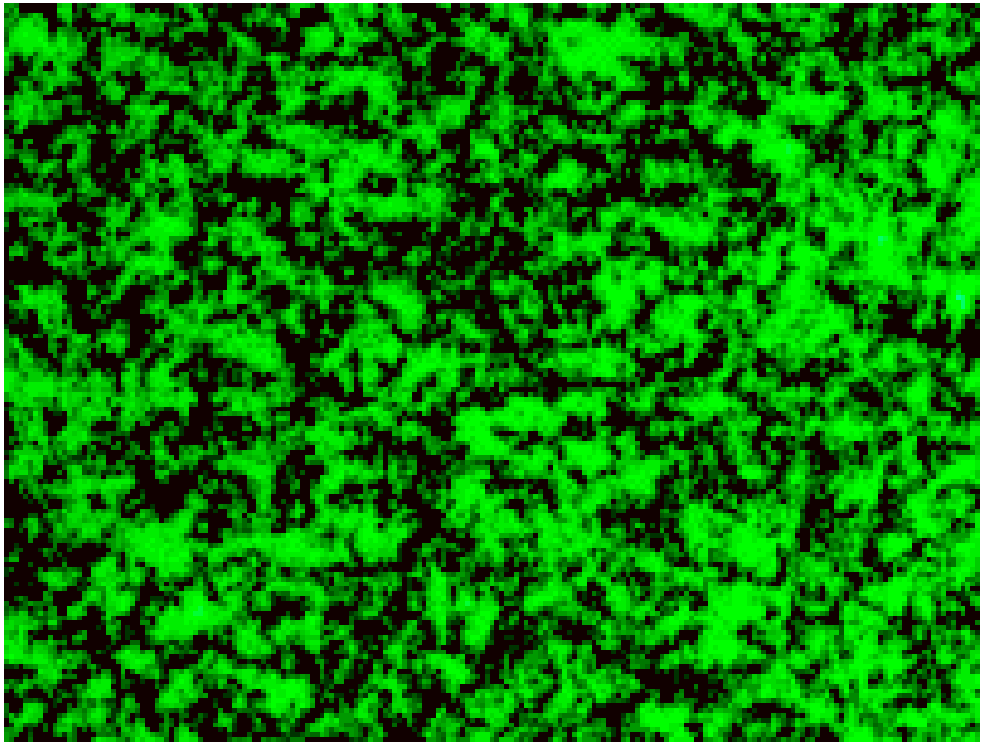
Multiple scattered light. No trace of ballistic light left.

- Other waves:
  Ultrasound,
  X-ray,
  THz

- Diffusive Tomography (low resolution).

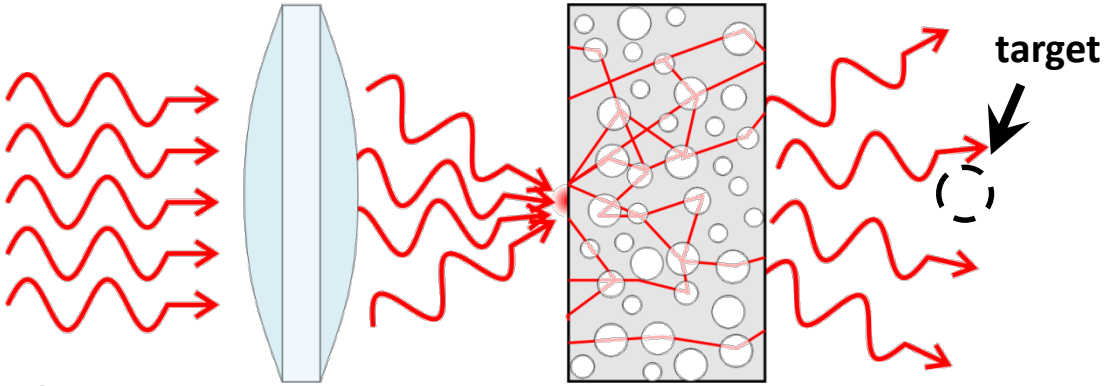


Laser light: Speckle

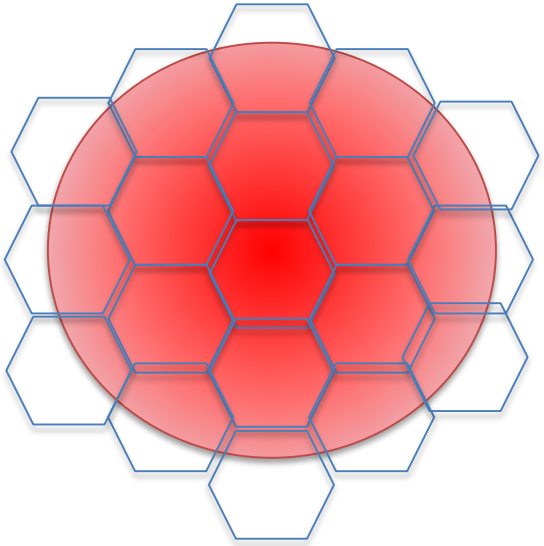


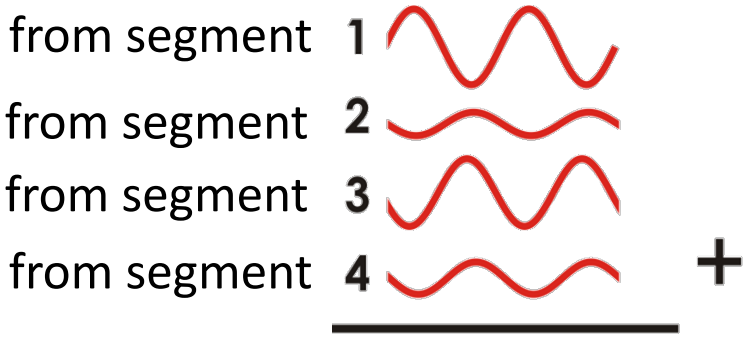
Even visible after 10000 scattering events

Speckle is random interference



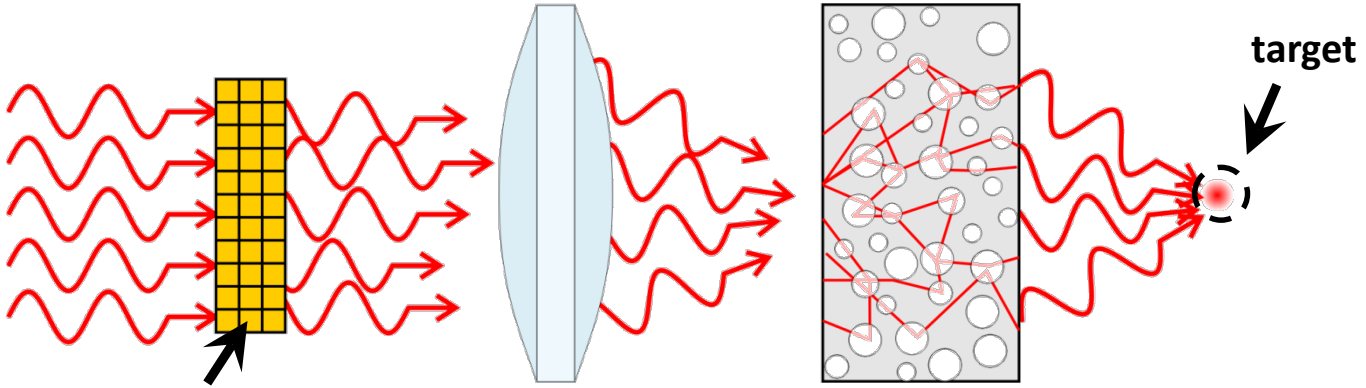
$$N \approx 2\pi \frac{A}{\lambda^2}$$



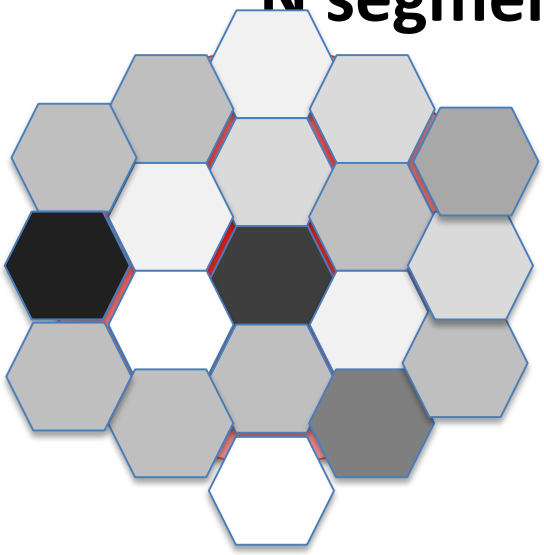


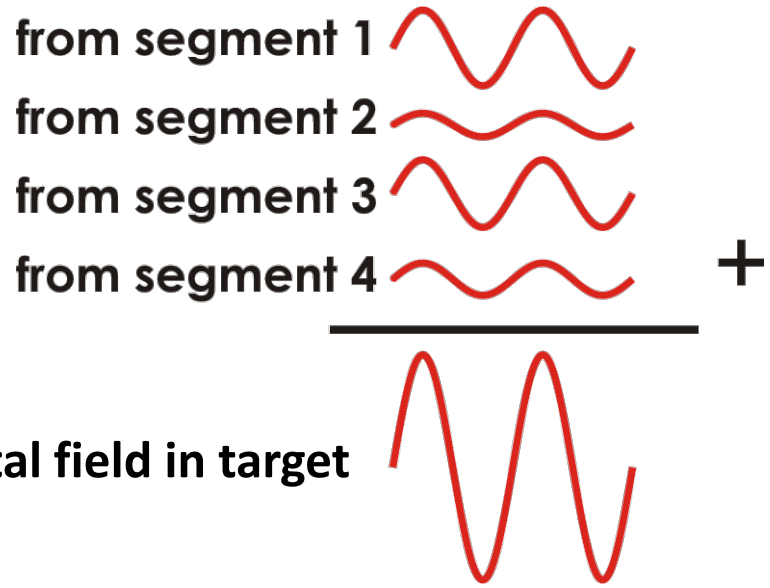
total field in target

Guide light by interference

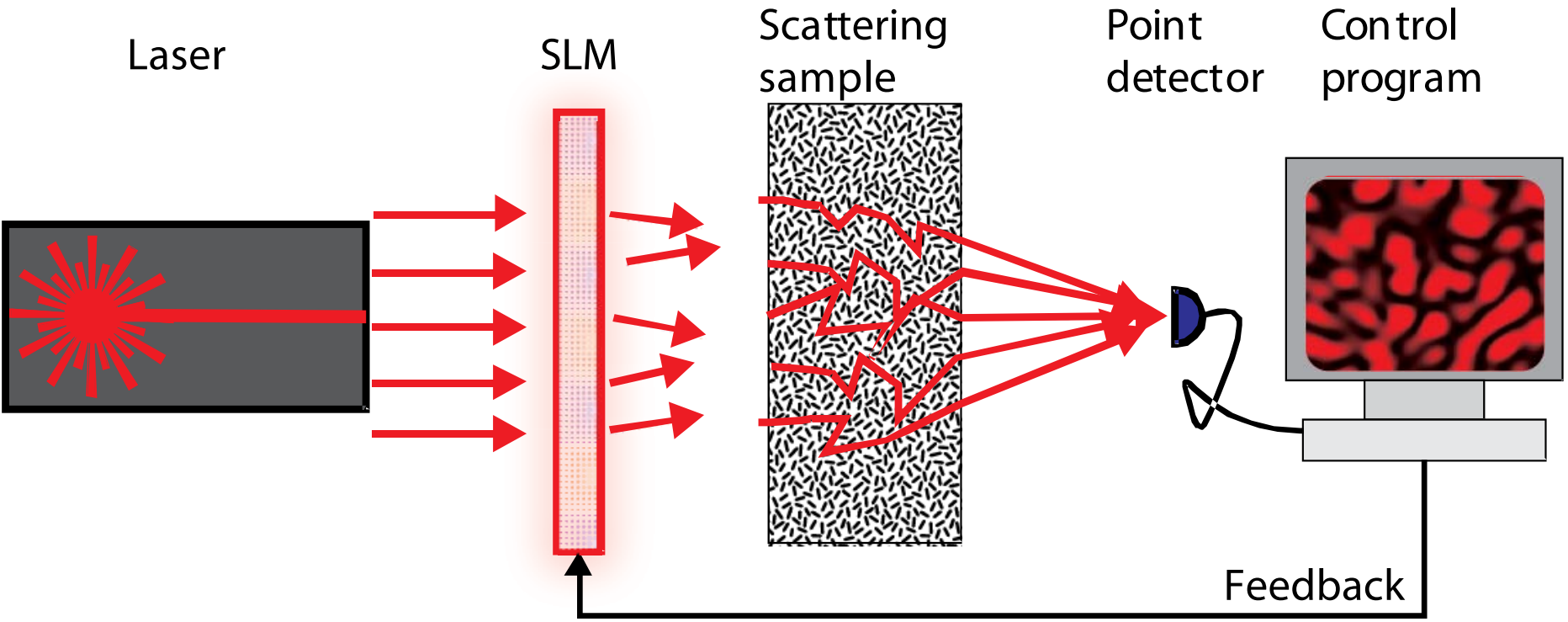


N segments



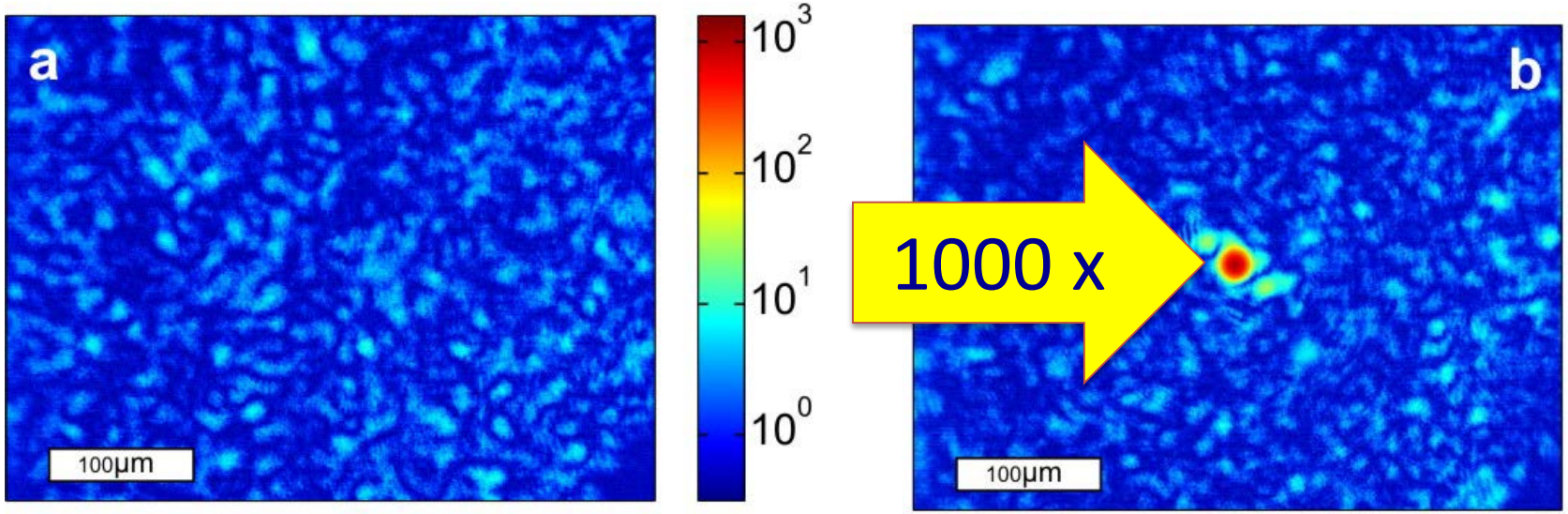


Wavefront shaping in scattering media



Vellekoop & APM, Opt Lett (2007);
Vellekoop, Lagendijk & APM,Opt Express(2008)

Result



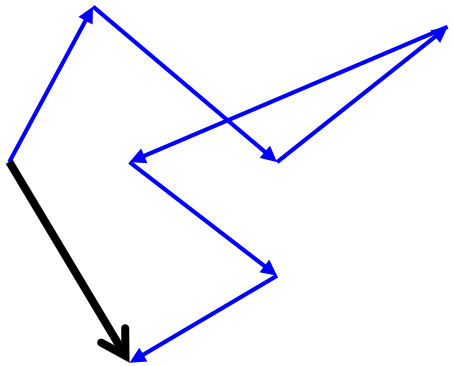
Sample: 10 µm titanium dioxide
Light source: He Ne laser

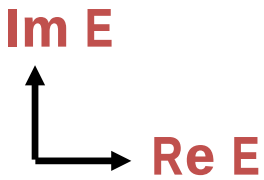
Speckle-scale focus
log color scale!

Vellekoop & APM; Opt Lett. (2007)

Target field in complex plane

before



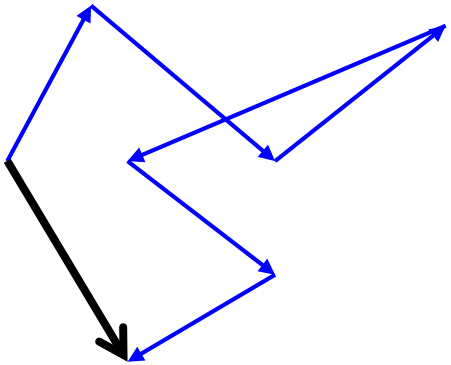


Measure phase of N transmission coefficients

Vellekoop & APM
Opt. Comm. **281**, 3071 (2008)

Target field in complex plane

before



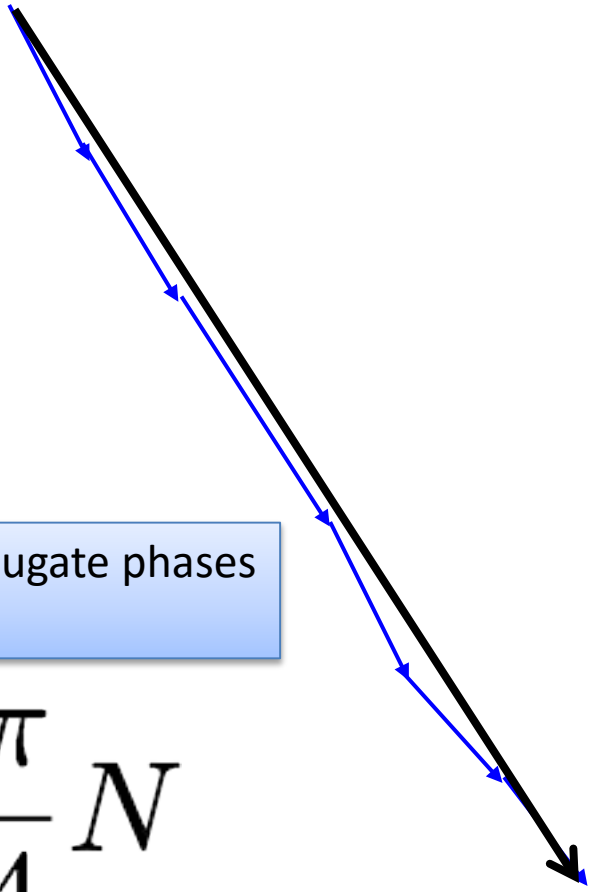
Im E

Re E

Measure phase of N transmission coefficients

after

Apply conjugate phases to SLM

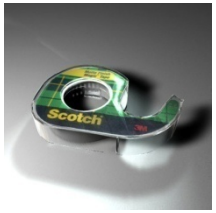


enhancement $\eta = \frac{\pi}{4} N$

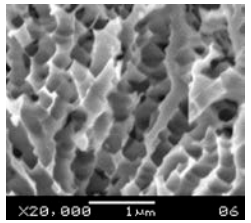
Vellekoop & APM
Opt. Comm. **281**, 3071 (2008)

Everything is a lens!

Teeth



Scotch tape



porous

semi-conductor

paint

(dry)

egg shell

daisy petals

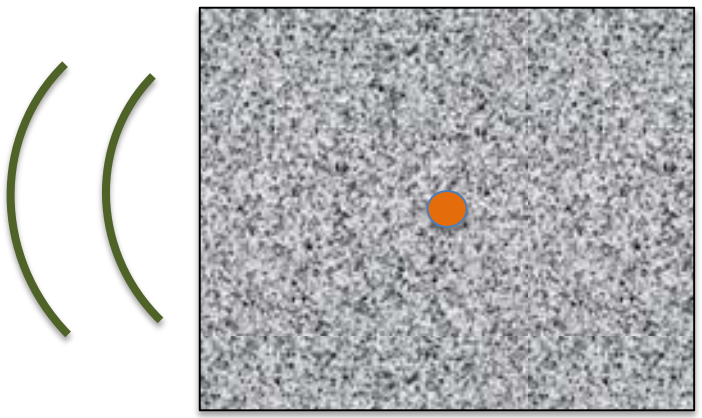
(fresh)

Tissue

Cui *et al.,* Opt. Express 18, 25 (2010)

IMAGING

Focusing on a guide star

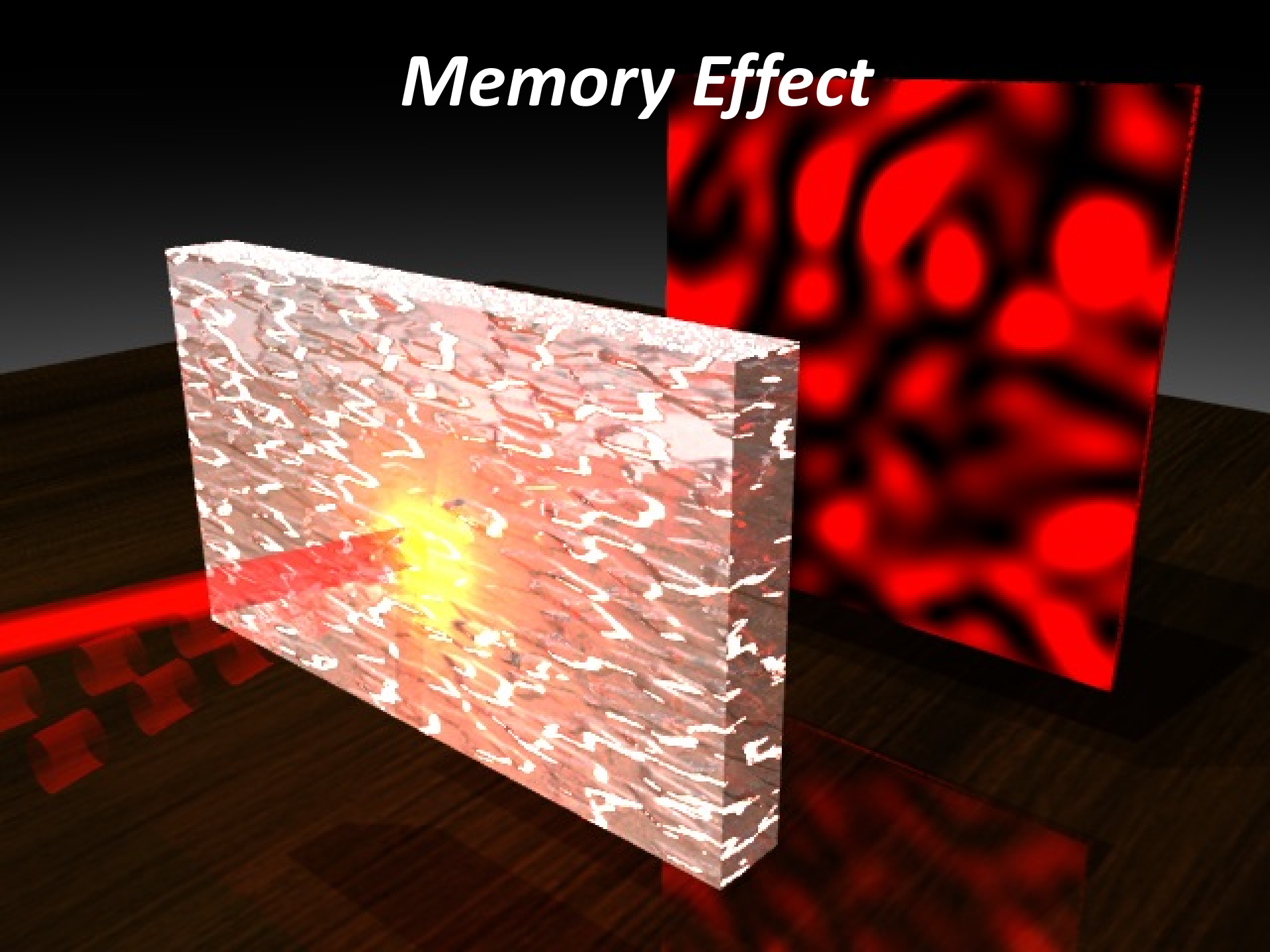


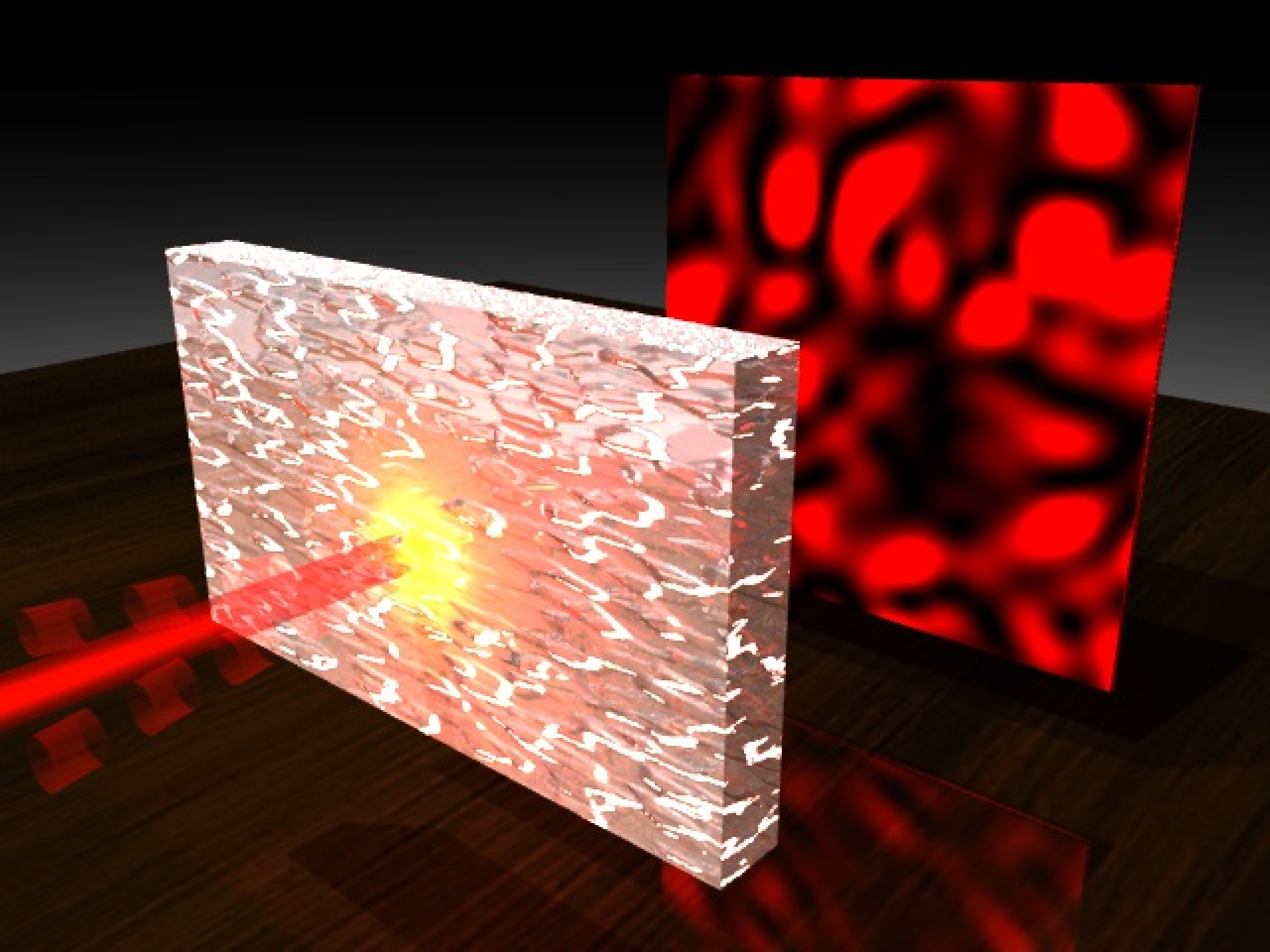
A *guide star* can be used to make a focus:

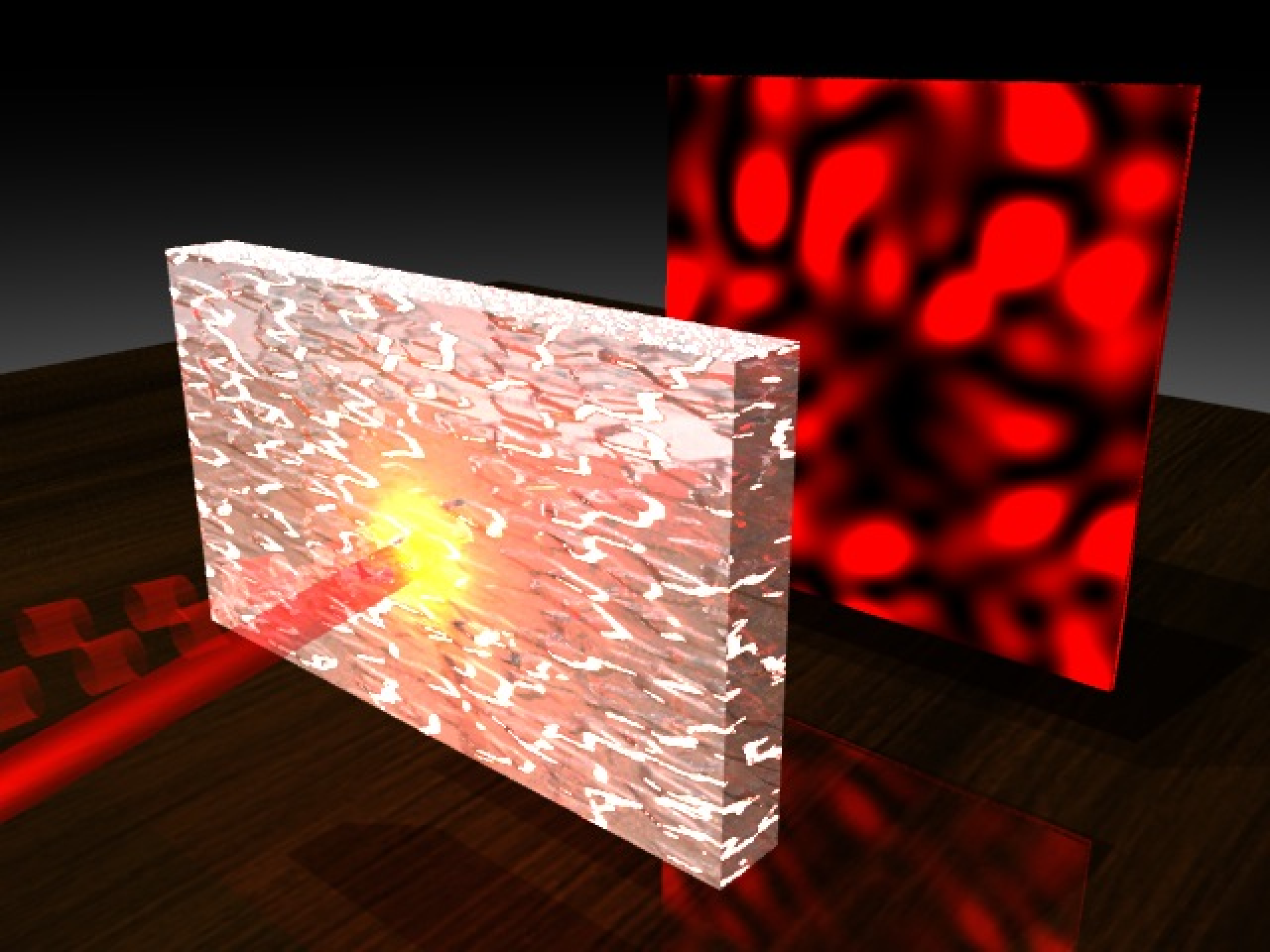
- *Probe particle*
- *Acoustic focus*
- *Nonlinear conversion*

Vellekoop *et al.*, Opt. Expr. **16**, 67 (2008)
Hsieh *et al,* Opt. Expr (2010)
Van Putten *et al*., JOSA B **28**, 1200 (2011)
Xu *et al.*, Nat. Photon (2011)

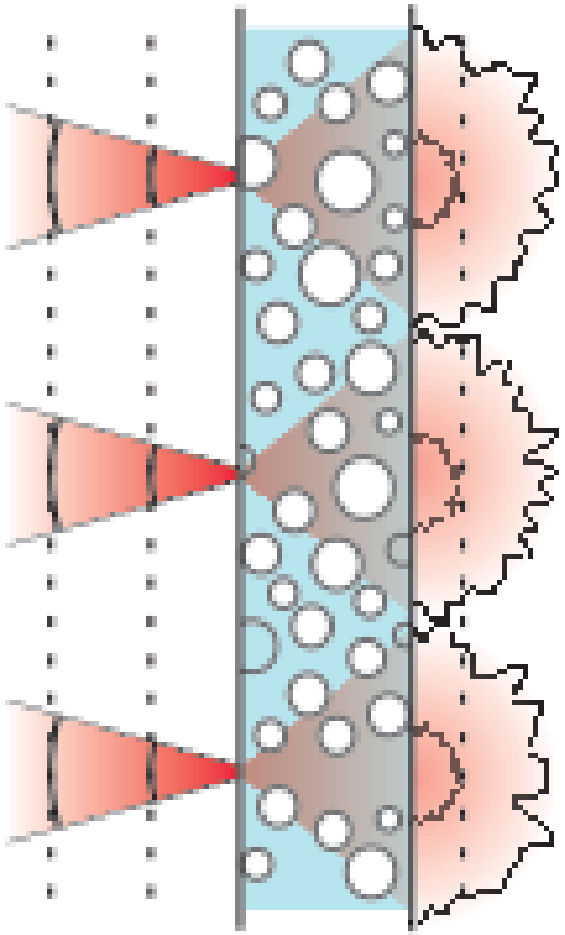
Memory Effect







Memory Effect



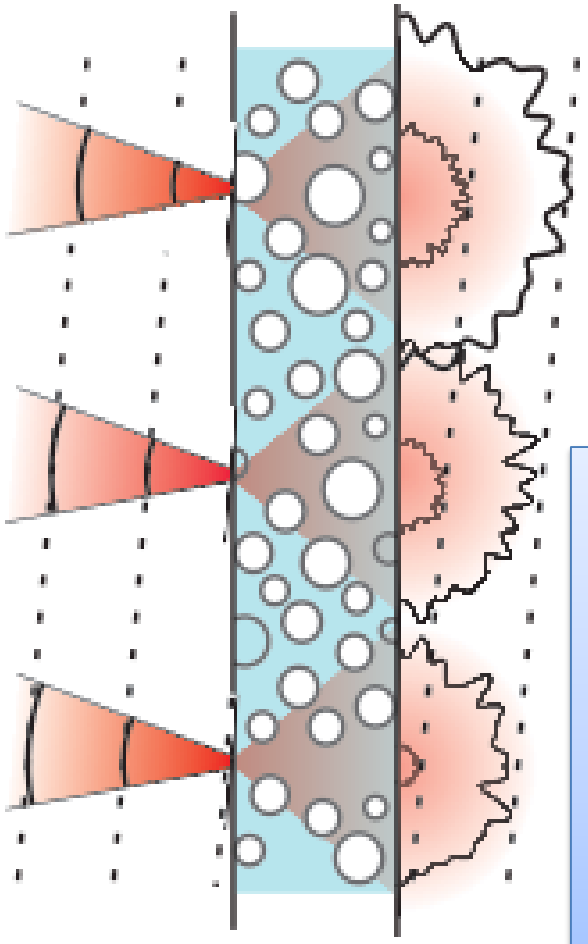
Feng et al., Phys. Rev. Lett. **61**, 834 (1988)
Freund et al., Phys. Rev. Lett. **61**, 2328 (1988)
Li & Genack (1994)
Mosk, Lerosey, Lagendijk & Fink, Nat. Phot. (2012)

Memory Effect

Correlation

Angle

λ/d

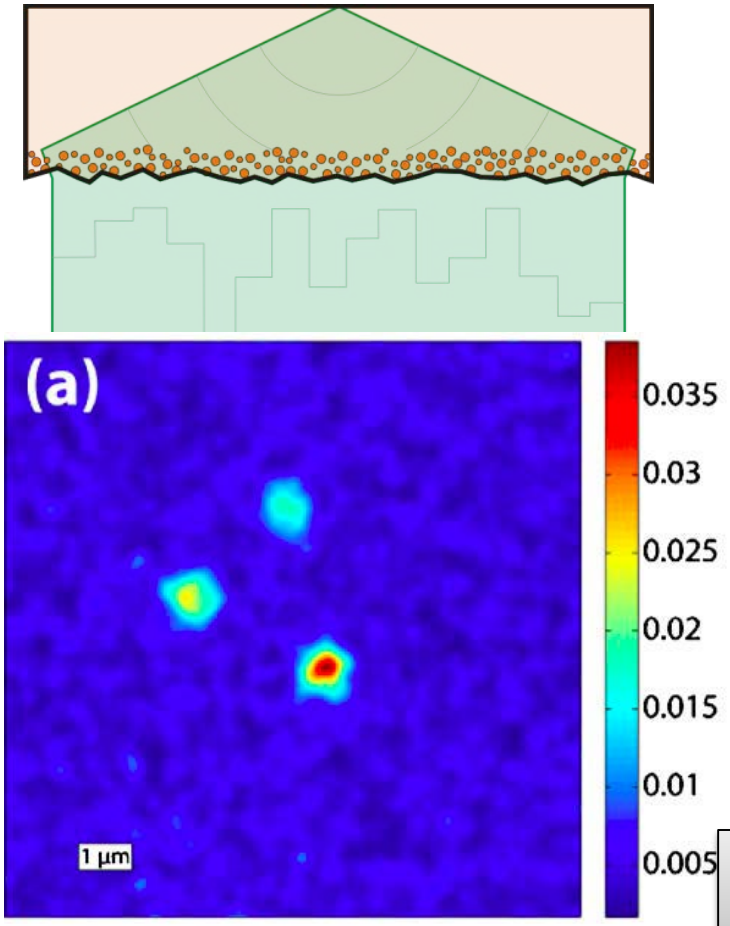


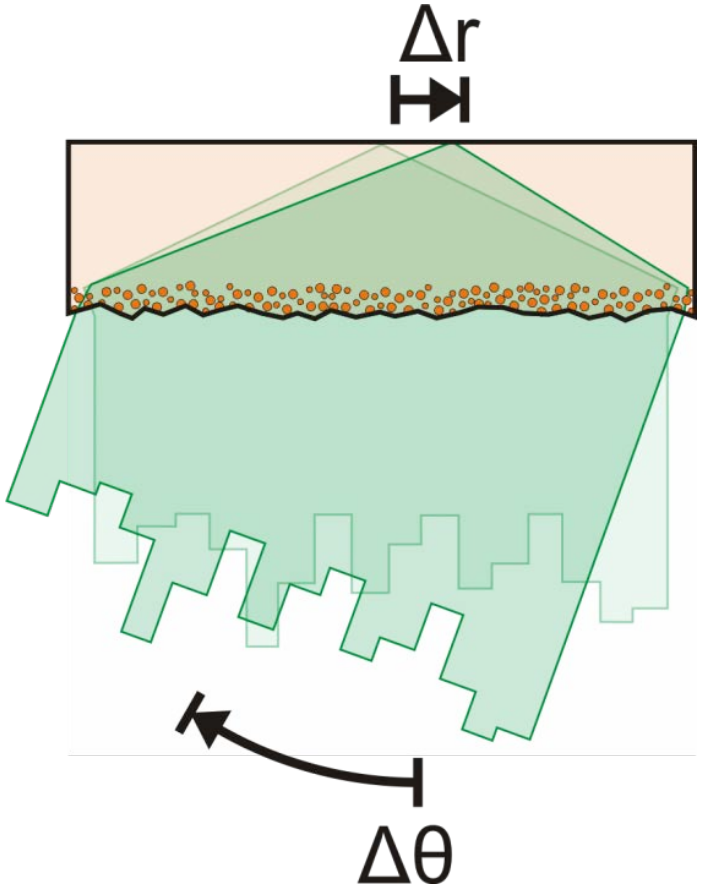
Memory effect in tissue:

Judkewitz et al, Nat. Physics, 2015
Schott et al., Opt. Expr. (2015)

Image: E.G. van Putten, Ph.D. Thesis (Twente, 2011)

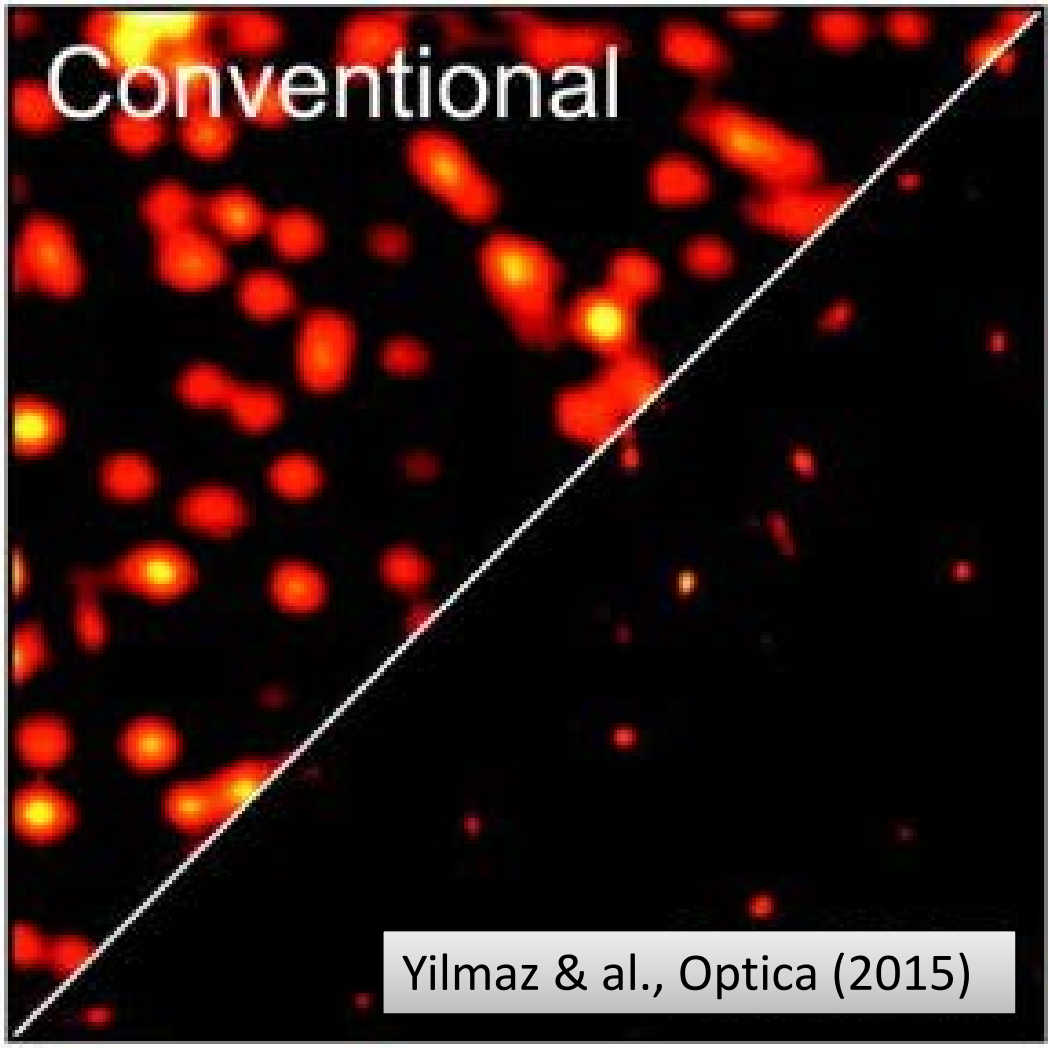
Imaging using scanning focus





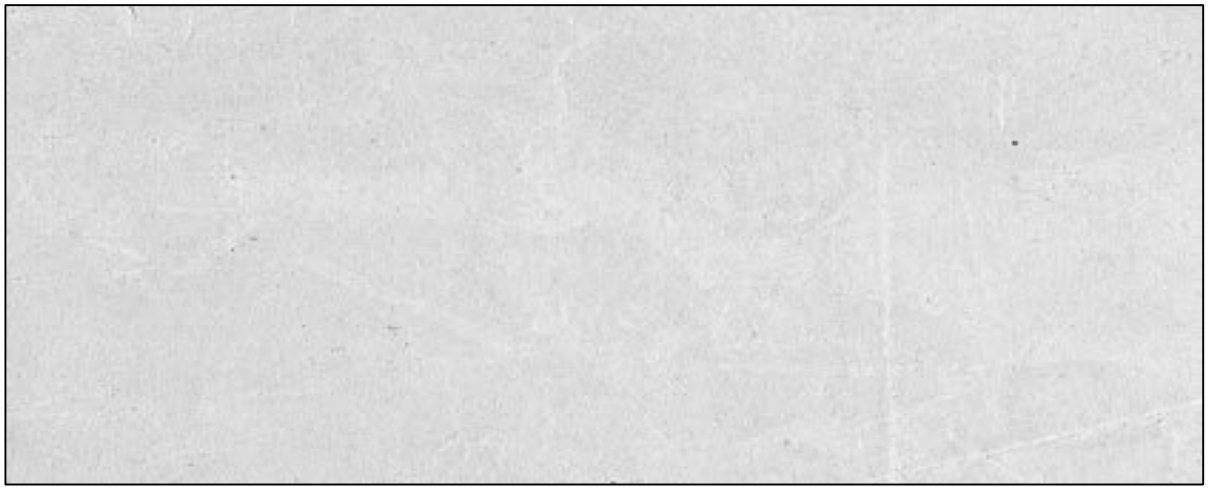
(a):Vellekoop&Aegerter, Opt. Lett. (2010)
also: Hsieh *et al.*, Opt. Express **18**, 20723 (2010)

High resolution & Wide field



NONINVASIVE IMAGING

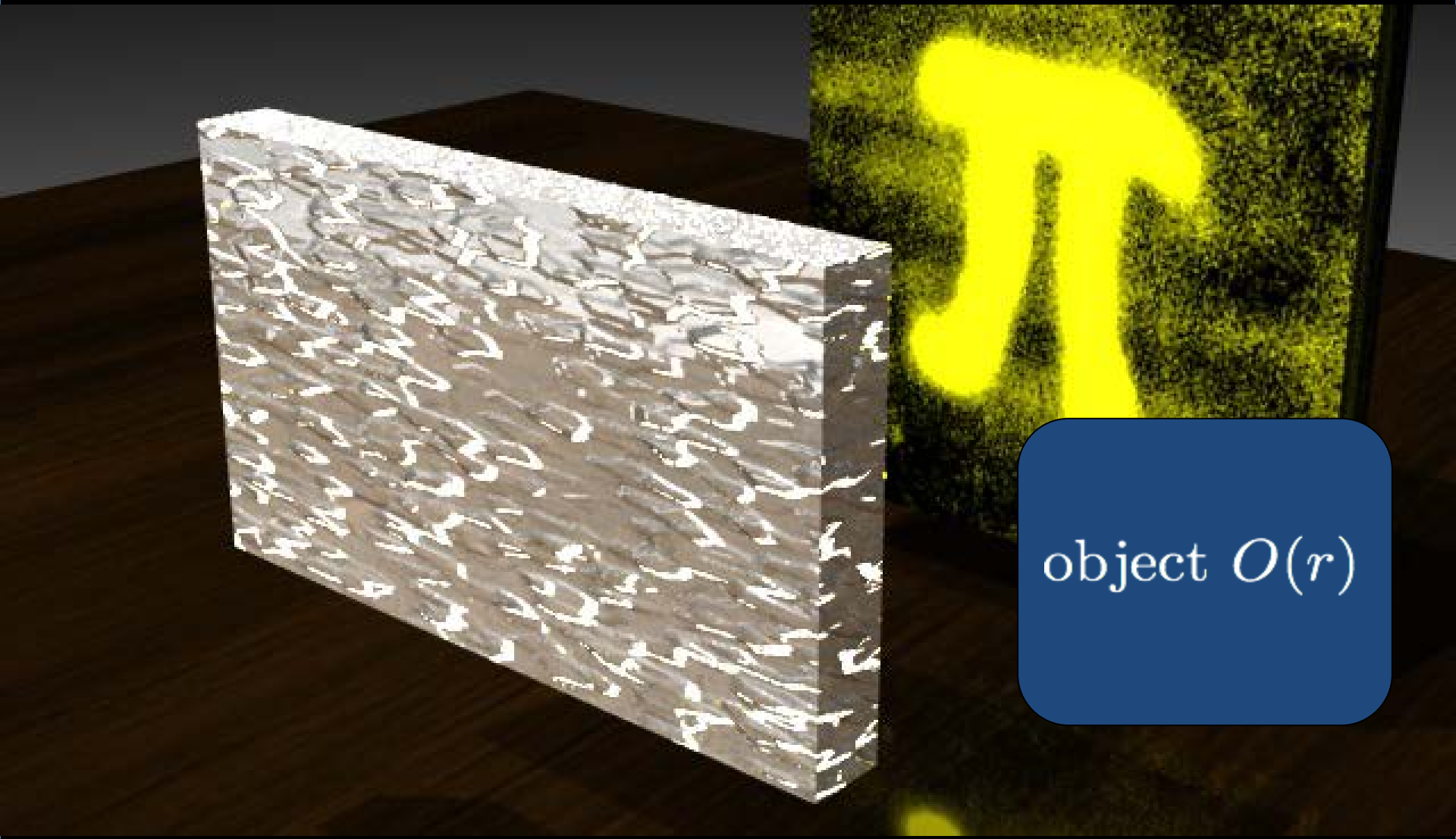
Non-invasive optical imaging



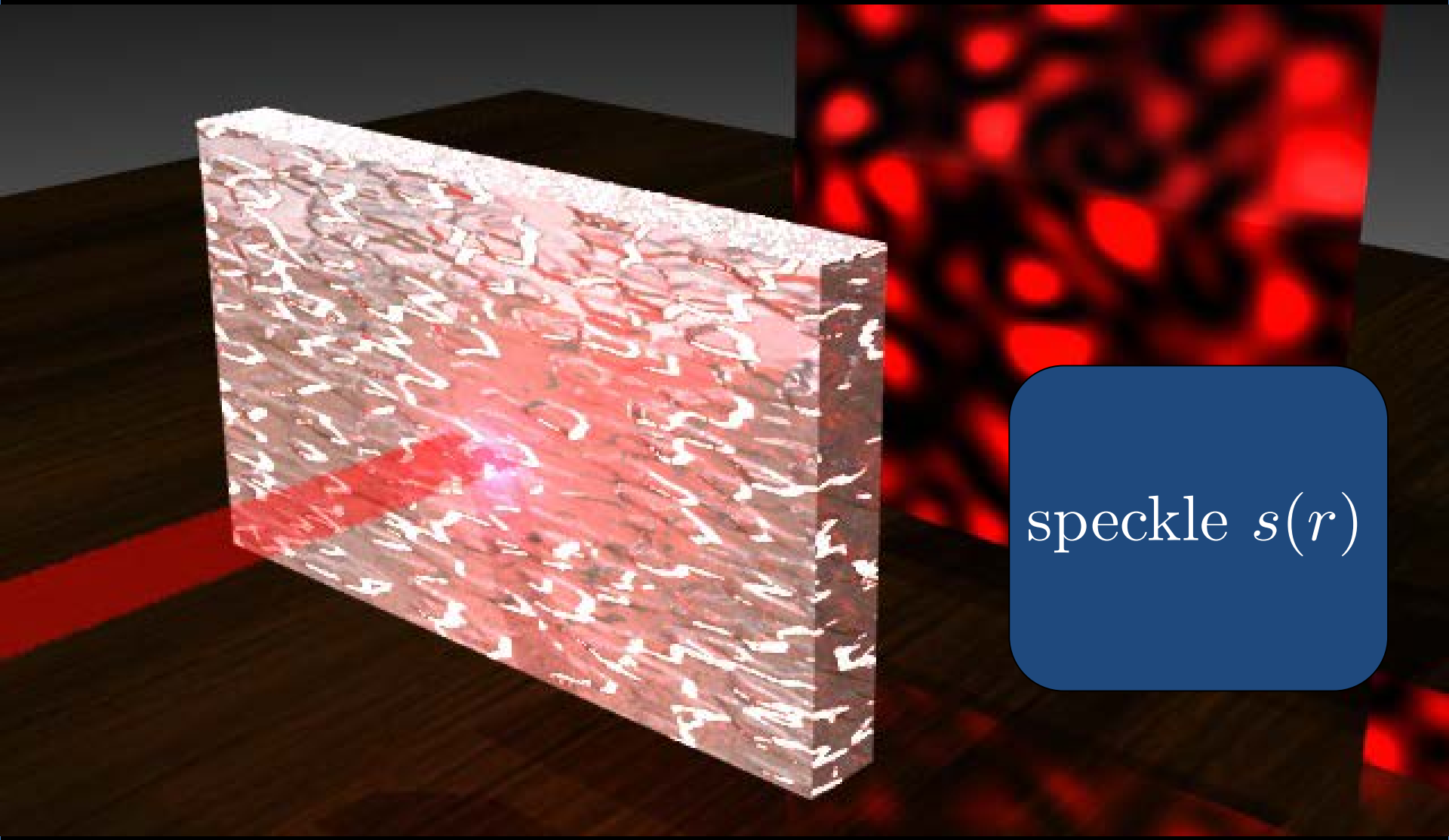
What is hidden behind the screen?

No equipment behind the screen allowed.

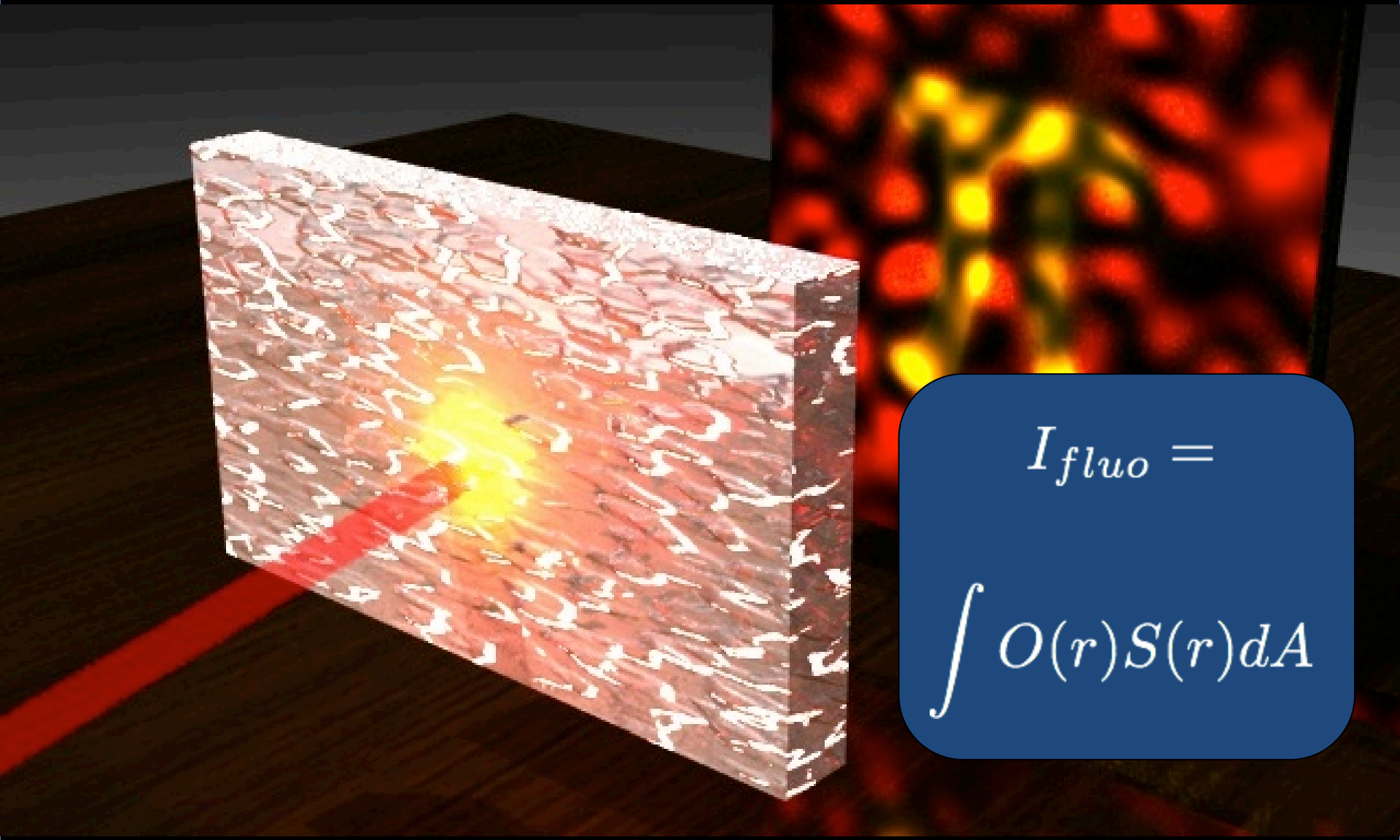
Object behind screen



Speckle illumination

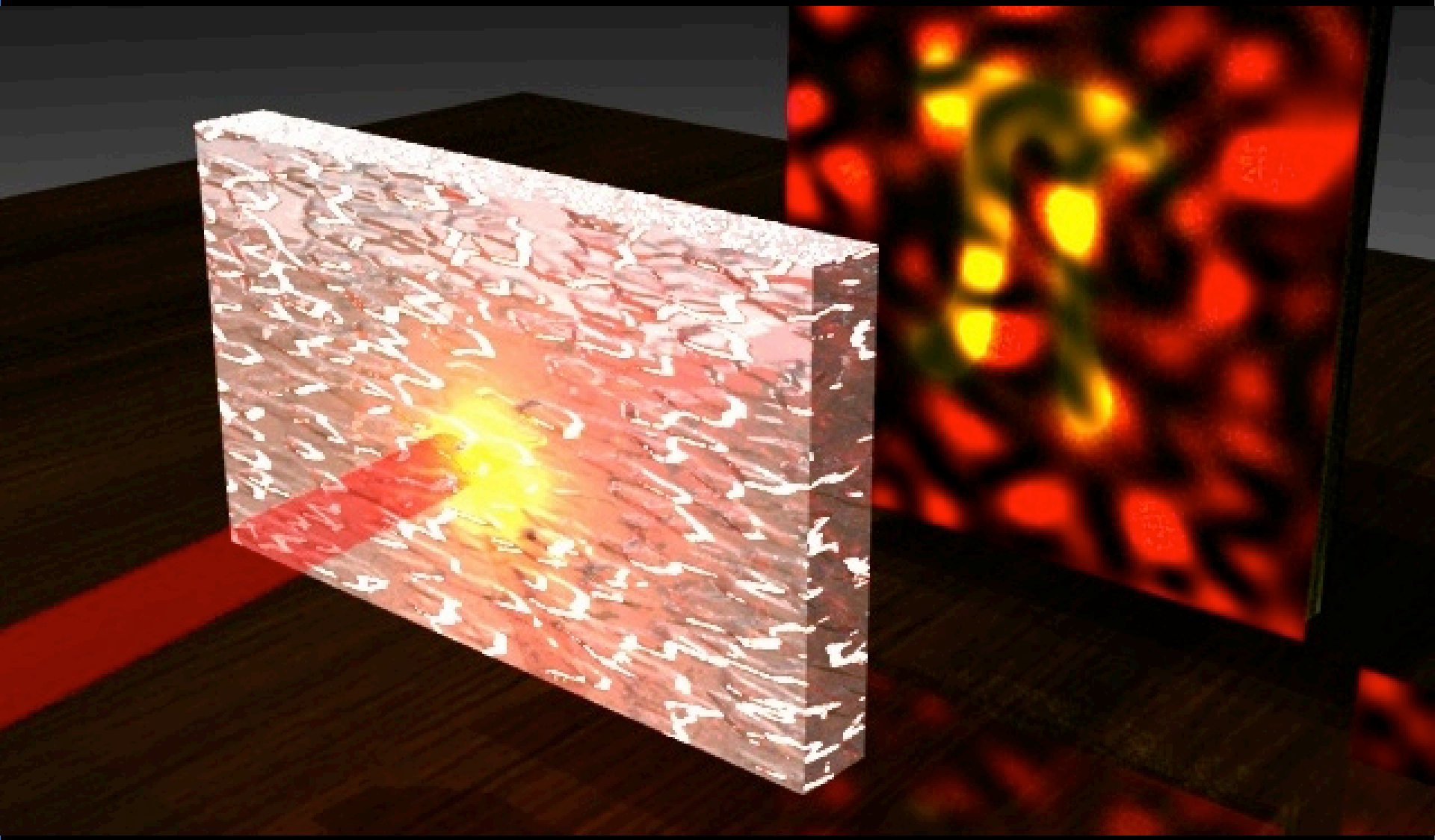


Speckle illuminates object

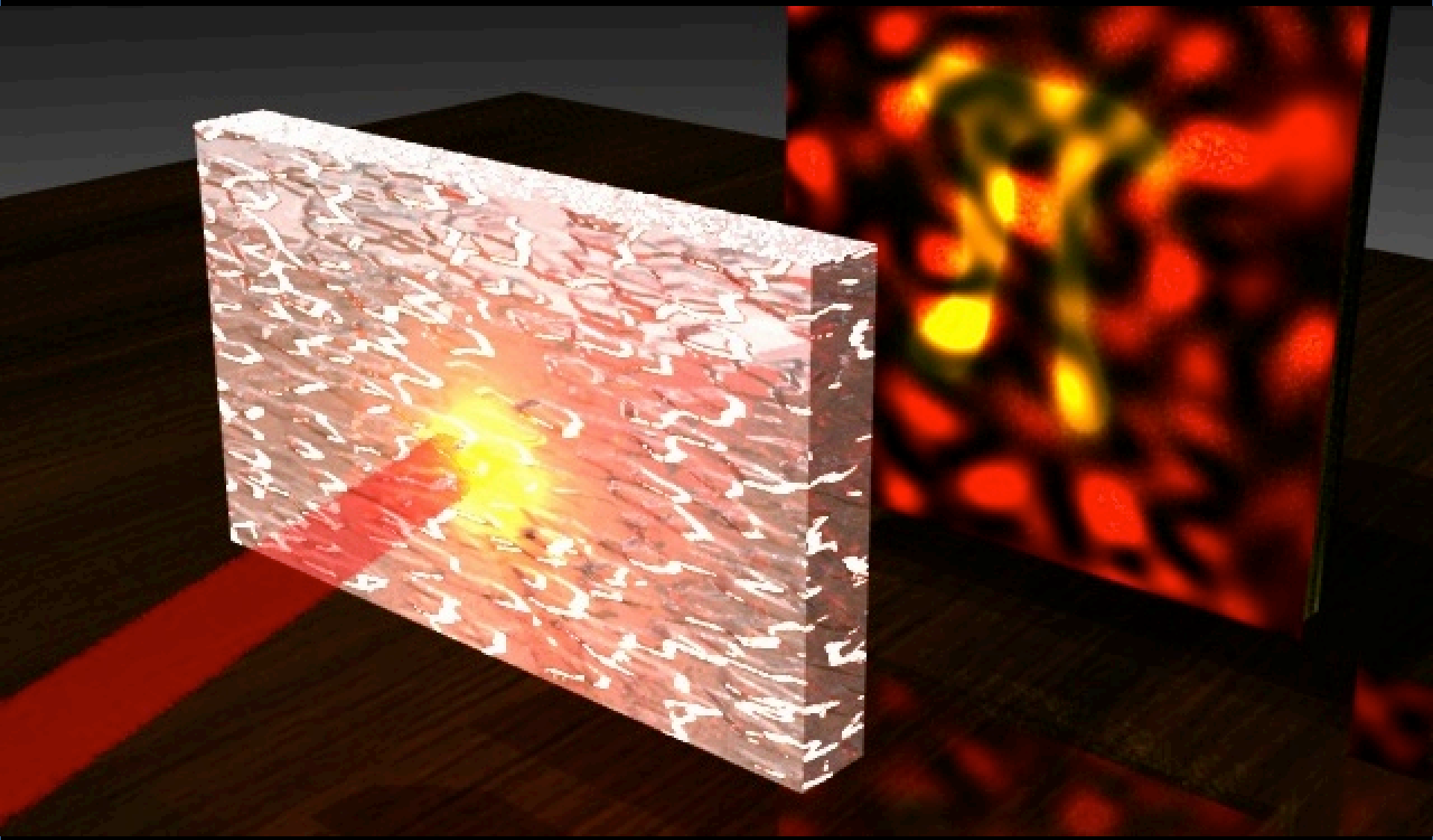


$$I_{fluo} = \int O(r)S(r)dA$$

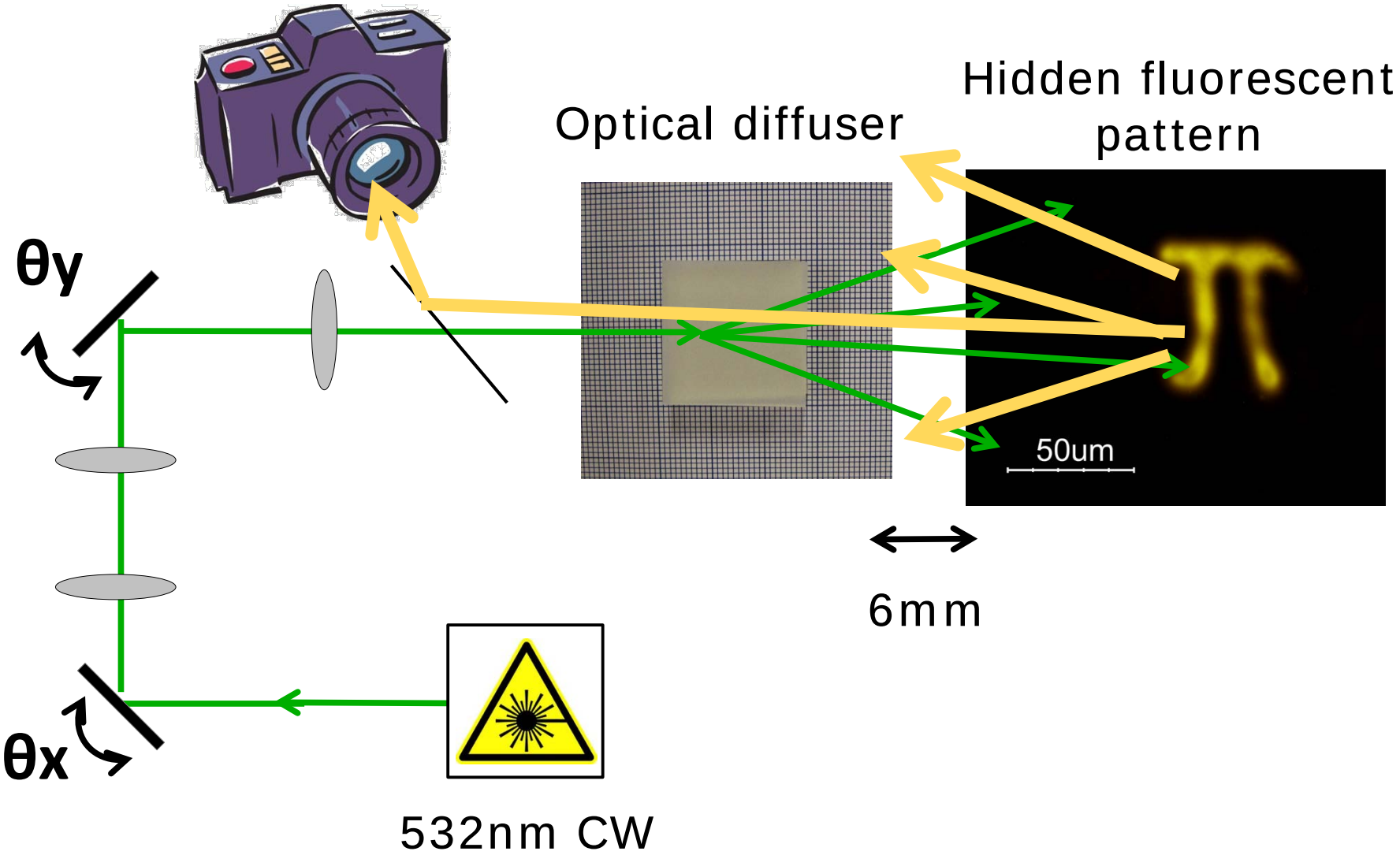
Scan incident beam



Speckles remain correlated

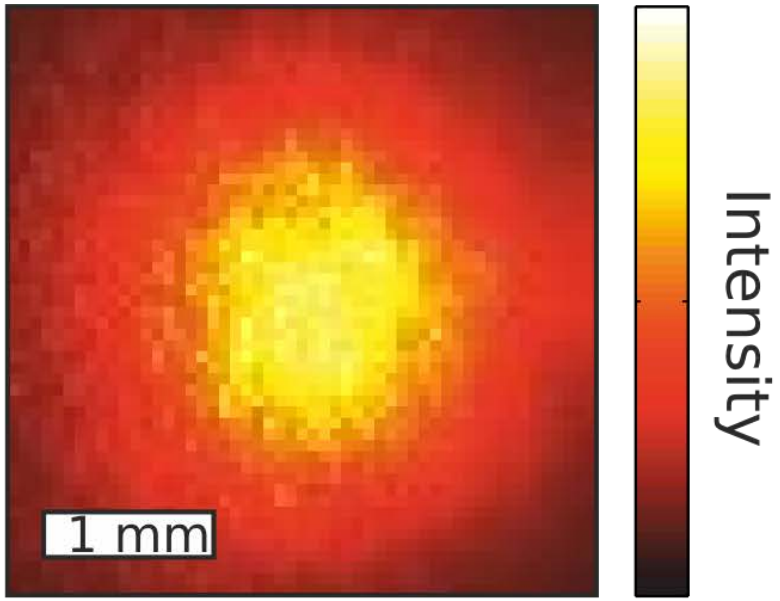


Set-up


Optical diffuser
Hidden fluorescent pattern
θy
θx
50um
6mm
532nm CW

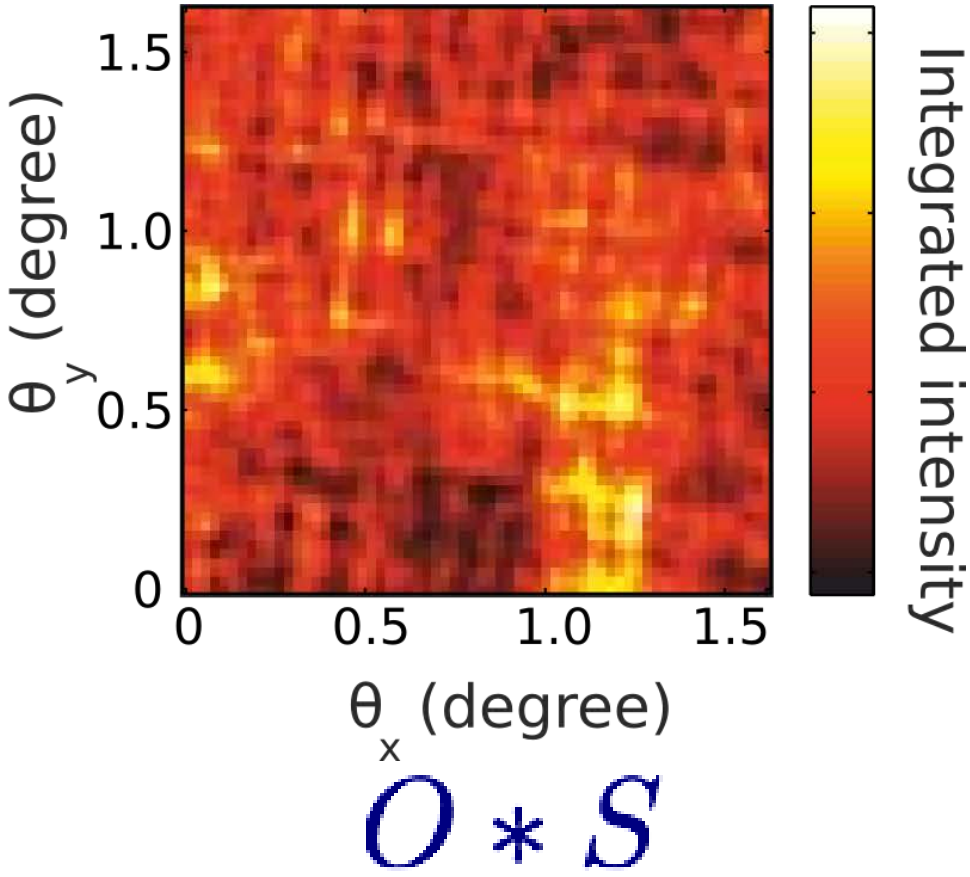
Measured Signal

Signal on Camera



For fixed laser angle

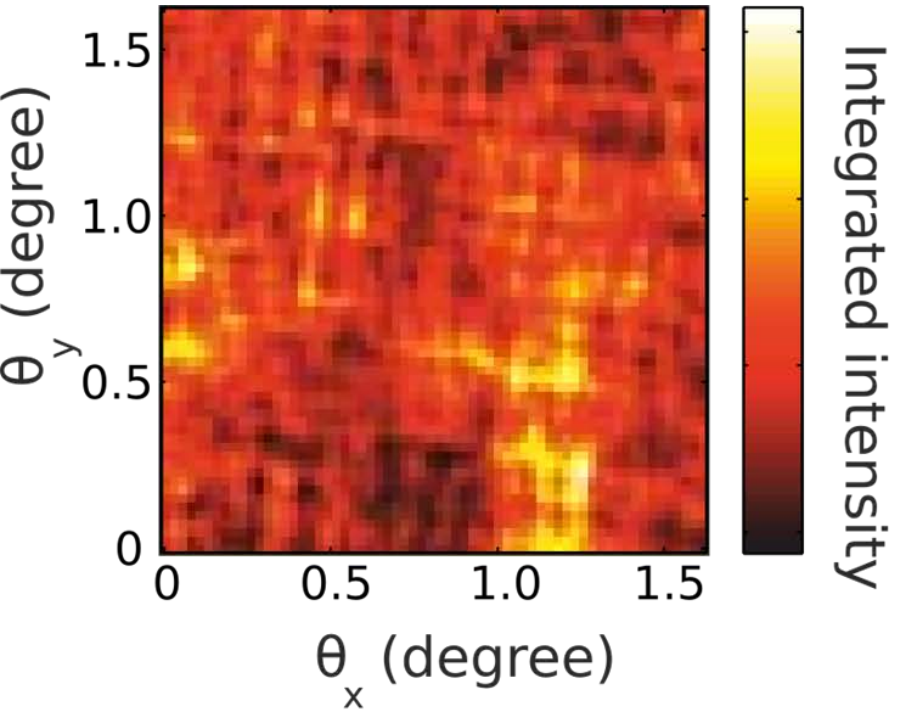
Intensity vs Angle



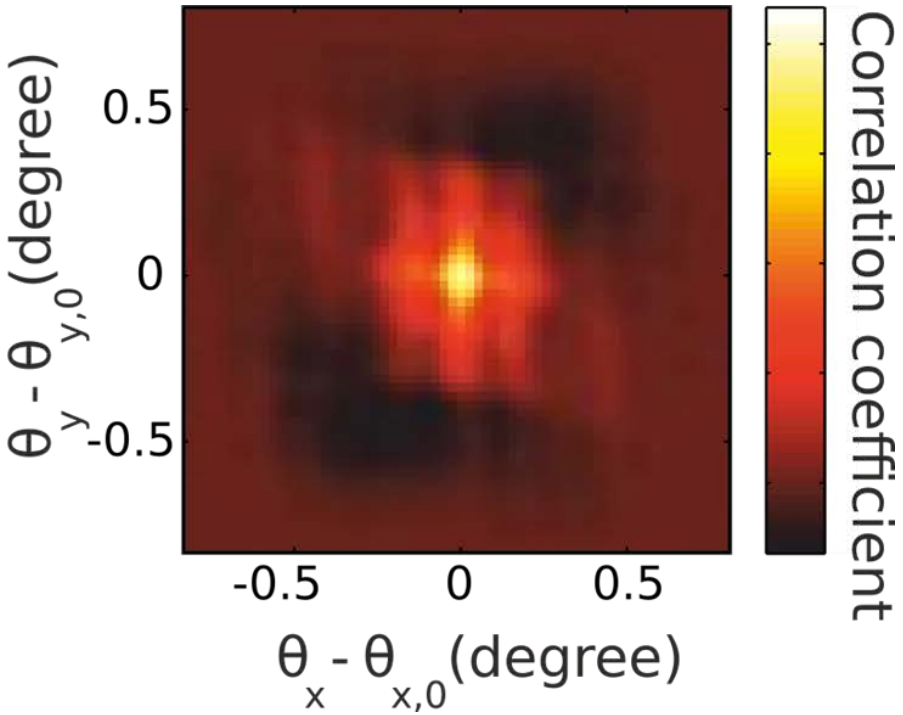
$$O * S$$

Autocorrelations

Intensity vs Angle



Autocorrelation



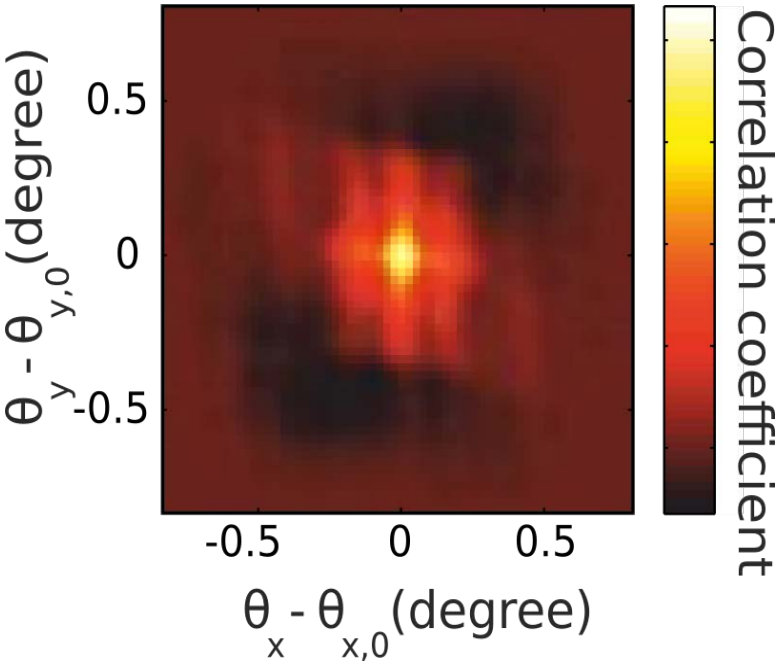
$$(O * s) \star (O * s) = (O \star O) * (s \star s)$$

Goodman, J. W. *Statistical Optics* (Wiley, 2000)

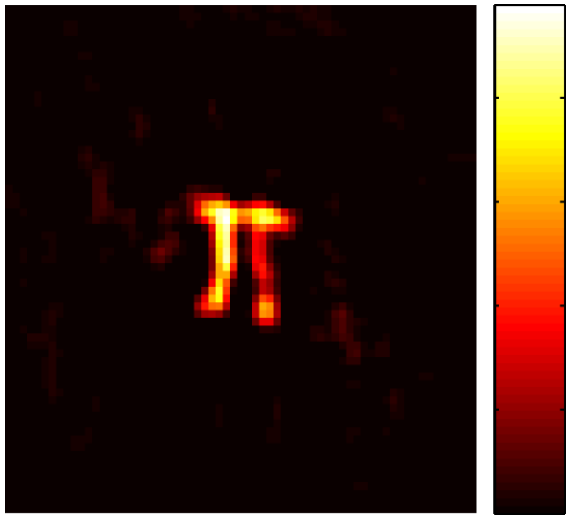
Idell et al., Opt Lett. **14**, 154, (1989)

Inversion of autocorrelate

The autocorrelate contains less information than the picture.
Still a reconstruction is possible.



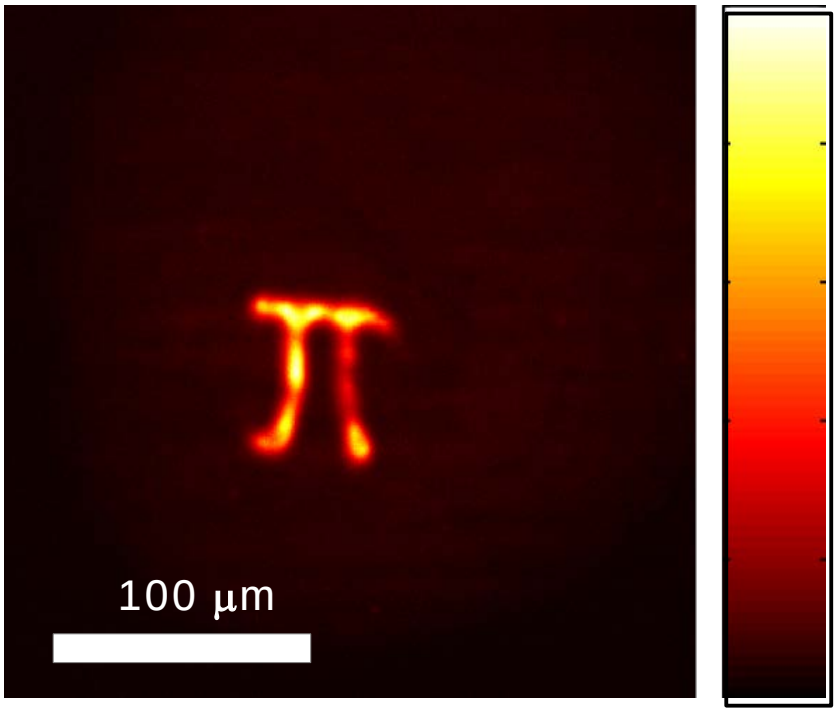
~10 s



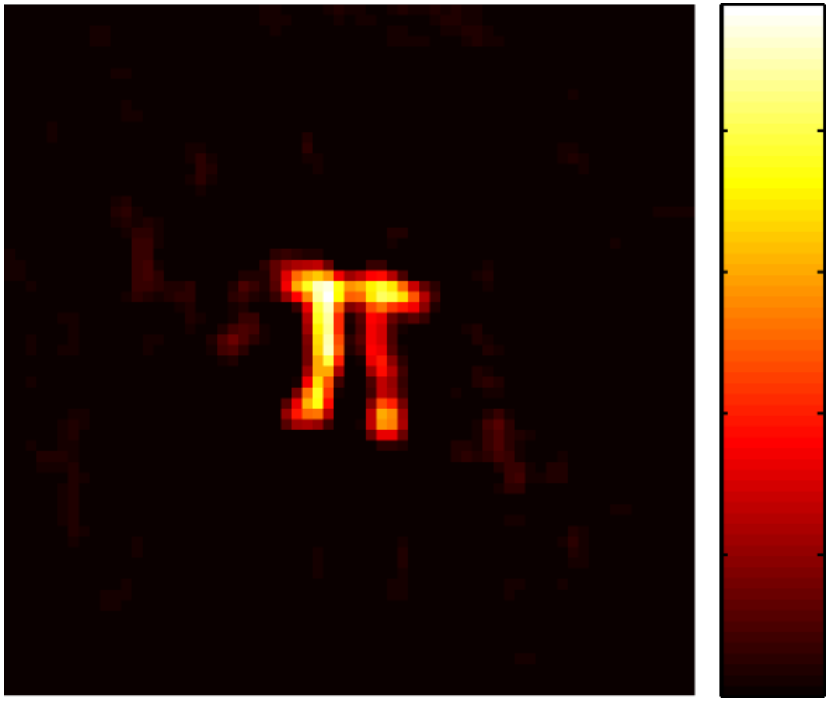
Iterative algorithms developed for astronomy, X-ray crystallography, holography

Labeyrie, Astron. Astrophys. **6**, 85 (1970)
Fienup, *Appl. Opt.* **21**, 2758 (1982)
Dainty, *Laser Speckle & related phenomena* (1984)
Miao, Charalambous, Kirz & Sayre, *Nature* **400**, 342 (1999)
Abbey *et al.*, *Nat. Photon*. **5** (2011)

Object seen through screen



Object
(taken before the experiment)

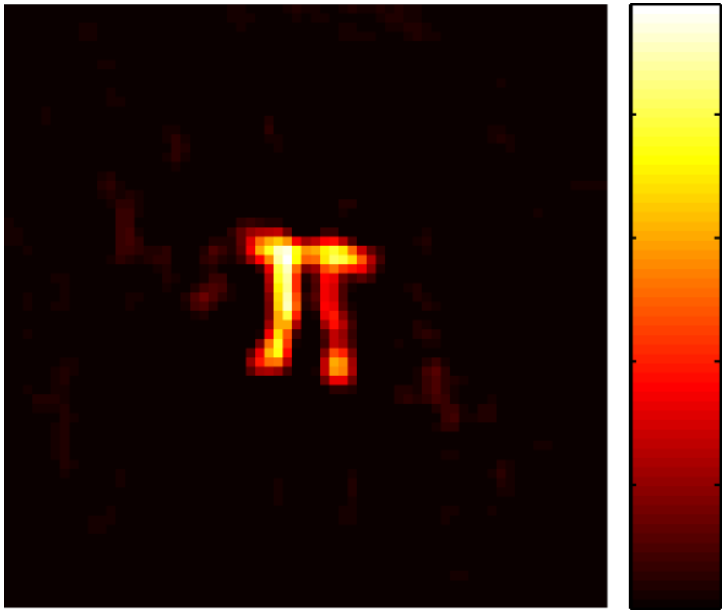


Recovered object

J. Bertolotti, E.G. van Putten, C. Blum, A.Lagendijk, W.L. Vos and APM, Nature **491**, 232-234 (2012)

Conclusion 1

Shaped wavefronts and speckle correlations can be used for imaging through strongly scattering layers.

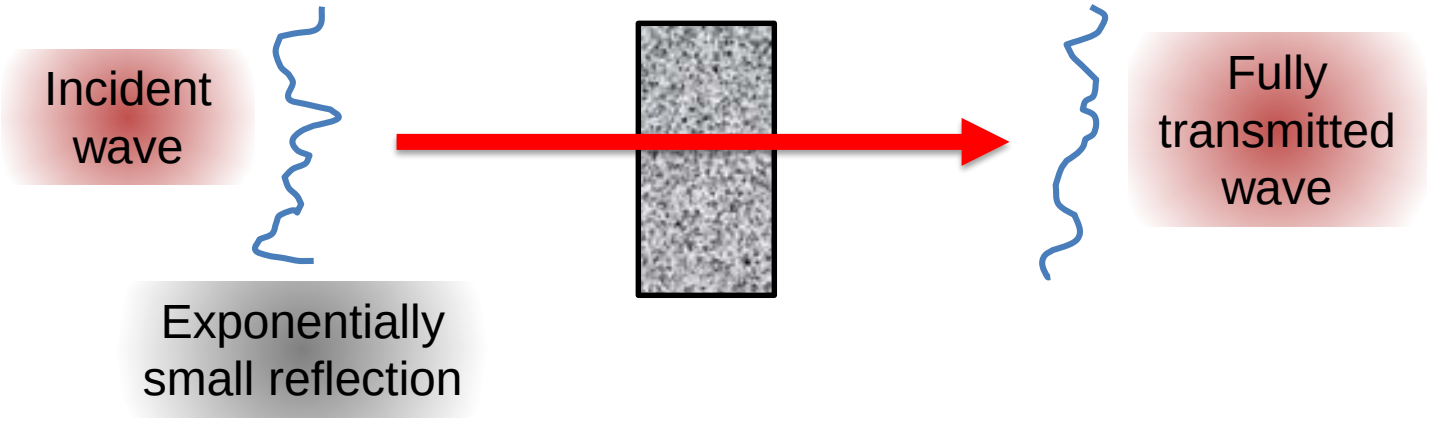


Many groups reporting progress in this area:

Gigan group (Paris)
Psaltis Group (EPFL)
Changhuei Yang group (Cal Tech)
Lihong Wang group (St. Louis)
Park group (Seoul)
Katz group (Jerusalem)
Cizmar group (Dundee UK)
Dholakia group (St. Andrews)
....

OPEN AND CLOSED CHANNELS

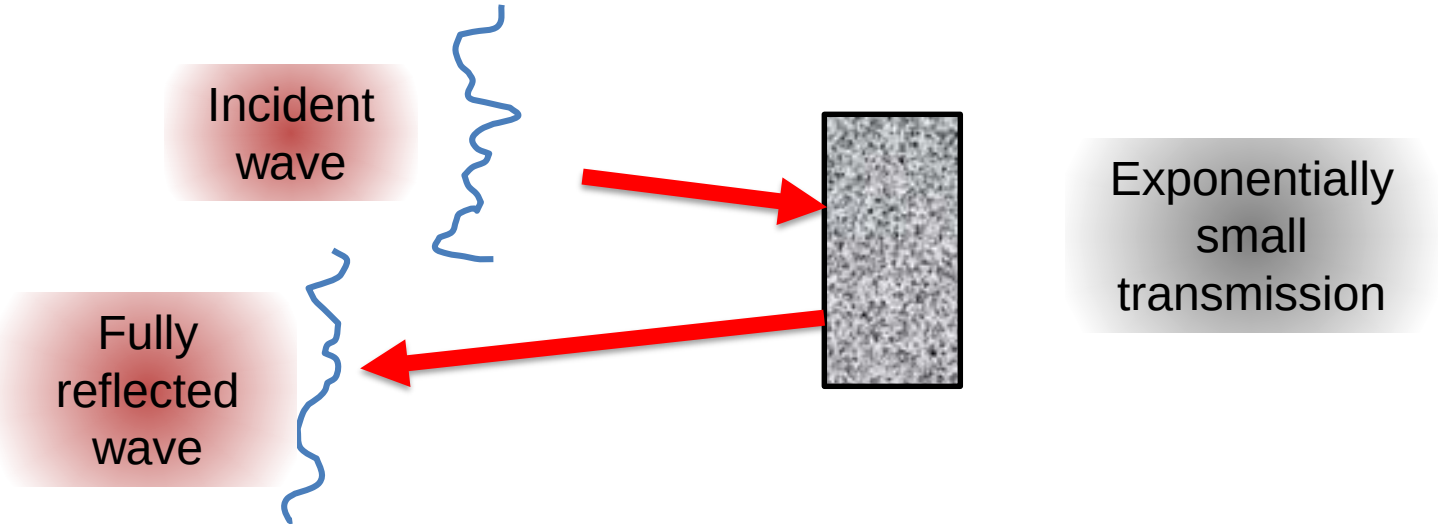
Open channels



- Open channels: completely diffusely transmitted.
- Fraction of open channels $\approx \ell / L$

Dorokhov, Sol. St. Comm. **51**, 381 (1984).
Mello, Pereyra, Kumar, Ann. Phys.(N.Y.) **181**, 290 (1988)
Pendry, Mackinnon & Prêtre, Physica A **168**, 400 (1990).
Beenakker, Rev. Mod. Phys. **69**, 731 (1997).
Muttalib, Pichard, and Stone, Phys. Rev. Lett. 59, 2475 (1987).
Pendry, Physics **1**, 20 (2008).

Closed channels

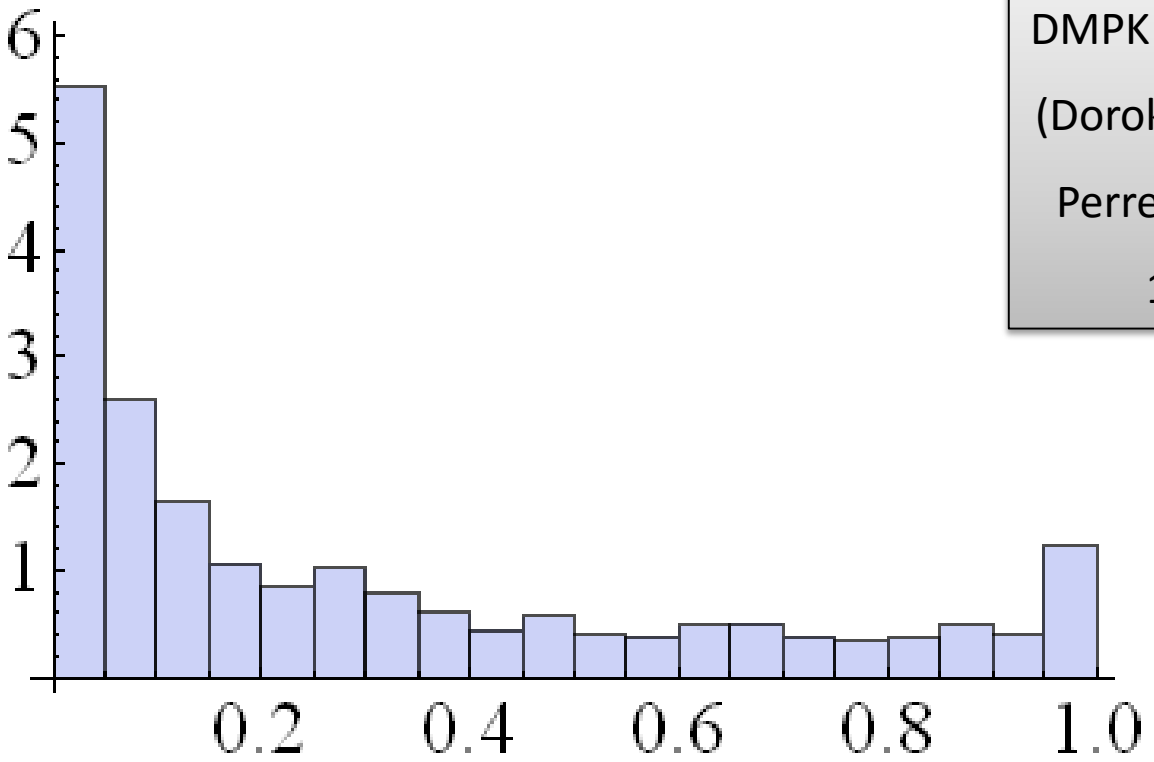


- Closed channels: completely diffusely reflected.
- Fraction of closed channels $\approx \ell/L$

Dorokhov, Sol. St. Comm. **51**, 381 (1984).
Mello, Pereyra, Kumar, Ann. Phys.(N.Y.) **181**, 290 (1988)
Pendry, Mackinnon & Prêtre, Physica A **168**, 400 (1990).
Beenakker, Rev. Mod. Phys. **69**, 731 (1997).
Muttalib, Pichard, and Stone, Phys. Rev. Lett. 59, 2475 (1987).
Pendry, Physics **1**, 20 (2008).

Channel transmission histogram

counts



Transmission singular value $\tau^{1/2}$

DMPK distribution (Dorokhov, Mello, Perreira, Kumar 1980's

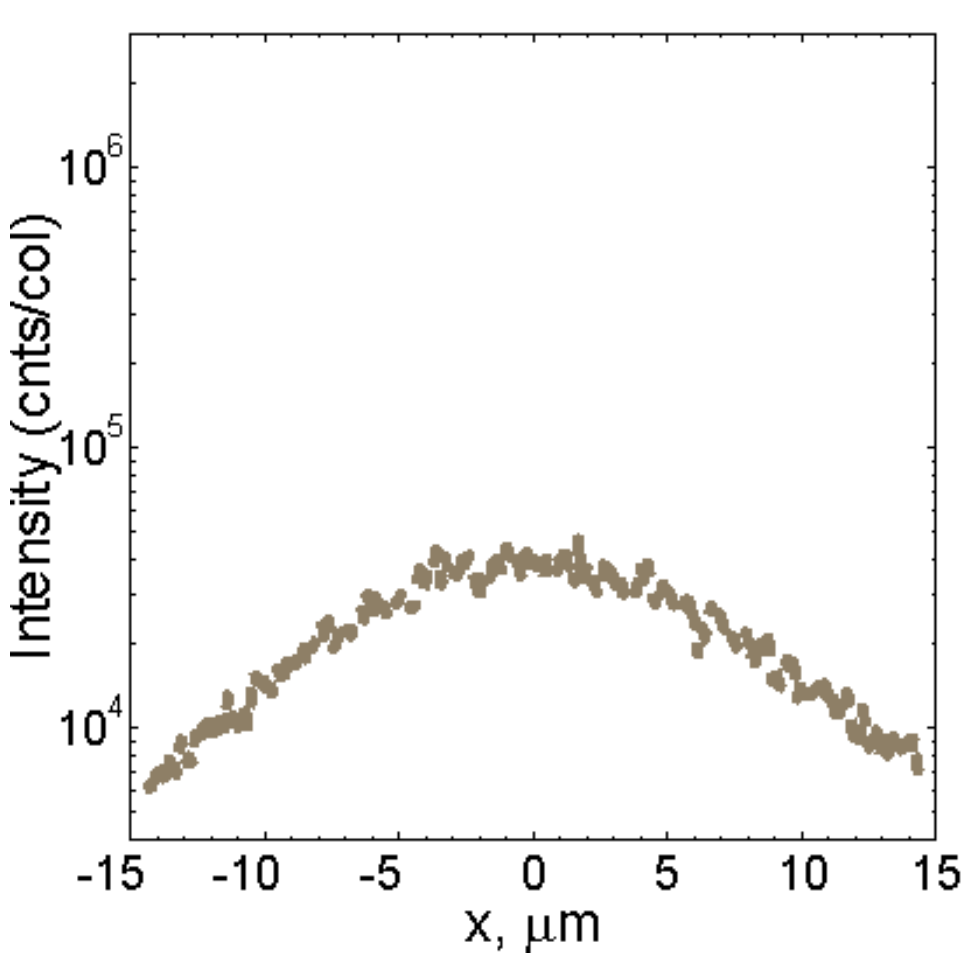
Microwaves (Shi & Genack, PRL, 2012)
Ultrasound (Gerardin *et al.*, PRL, 2014)

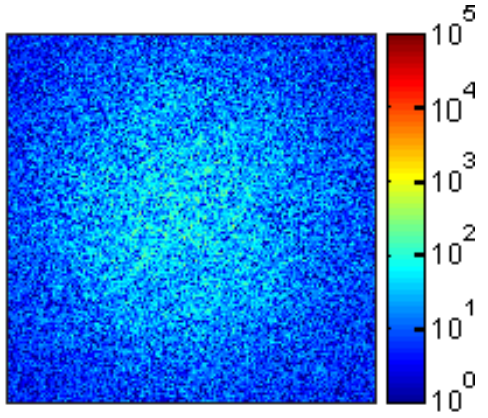
Wavefront shaping & open channels

- Uncorrelated matrix elements?
  - *Only focus intensity enhanced.*

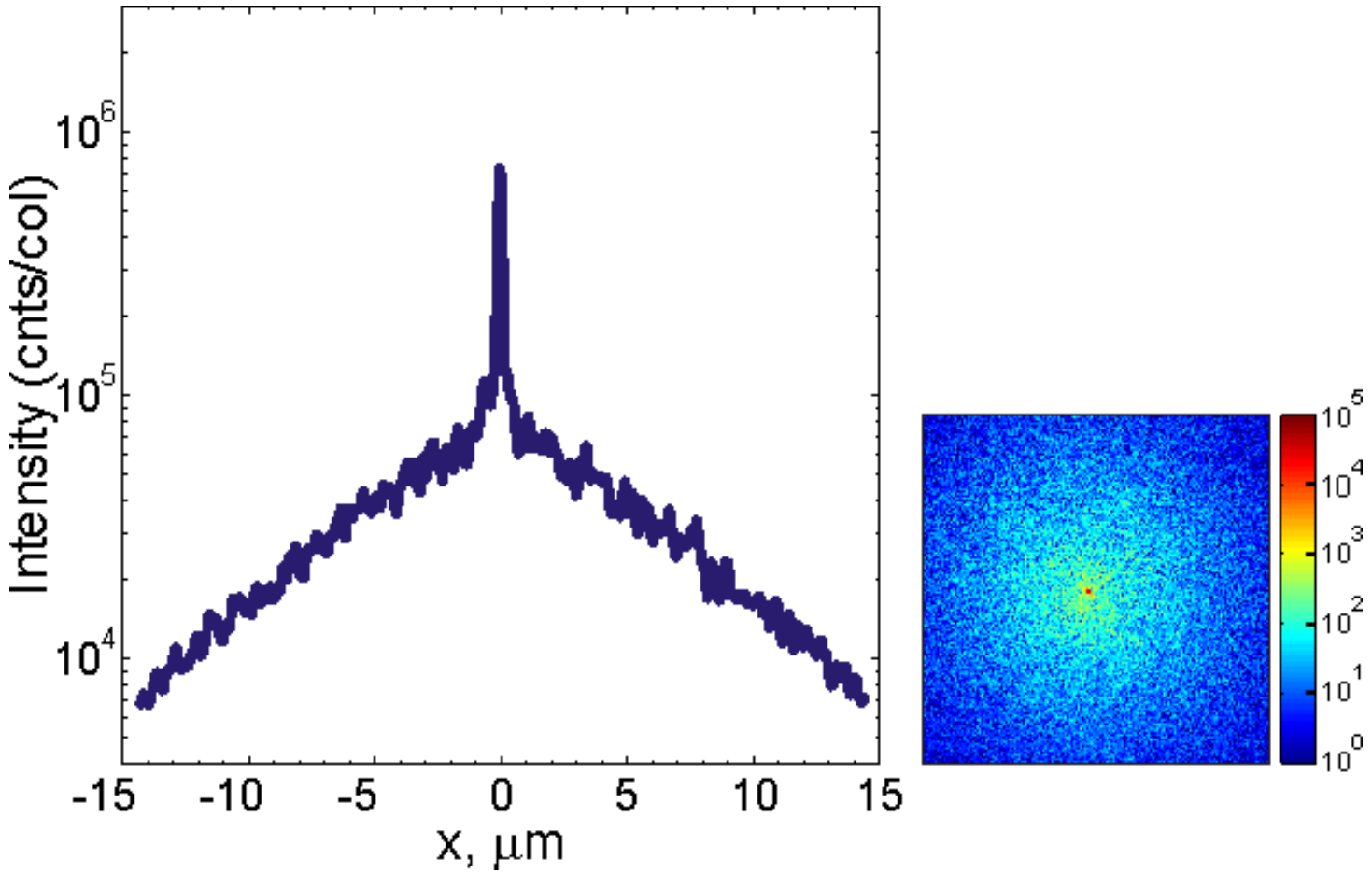
- Open channels present?
  - *Intensity injected into open channels.*
  - *Background speckle also enhanced.*

Before optimization



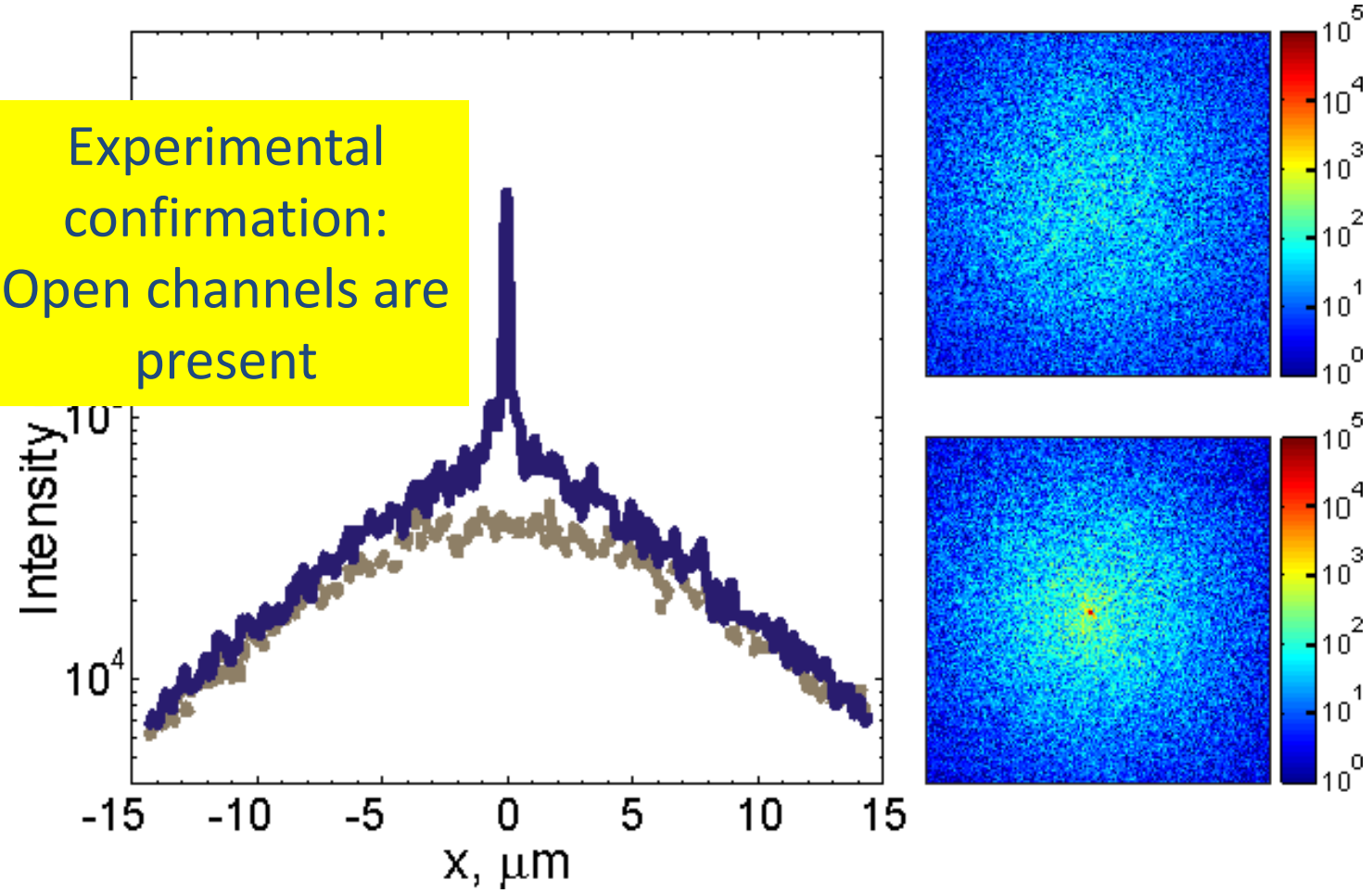


After optimization



Before and After

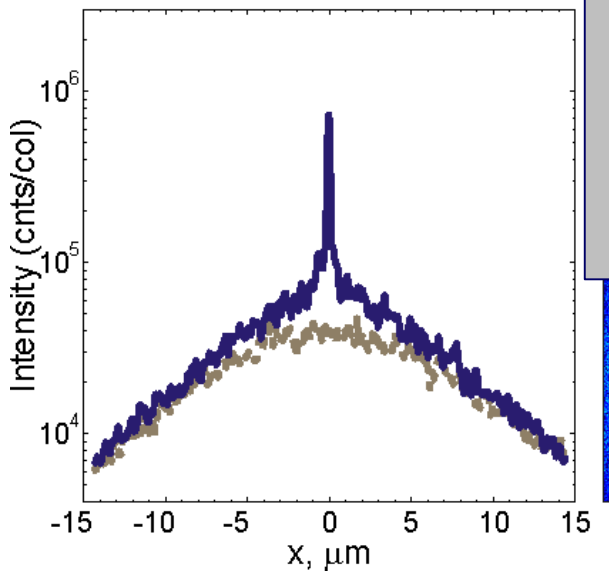
Experimental confirmation: Open channels are present

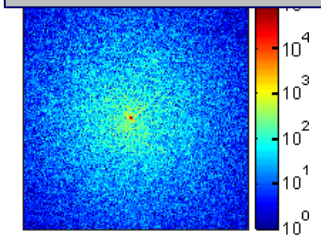


Vellekoop & APM, PRL **101** (2008).

Conclusion 2

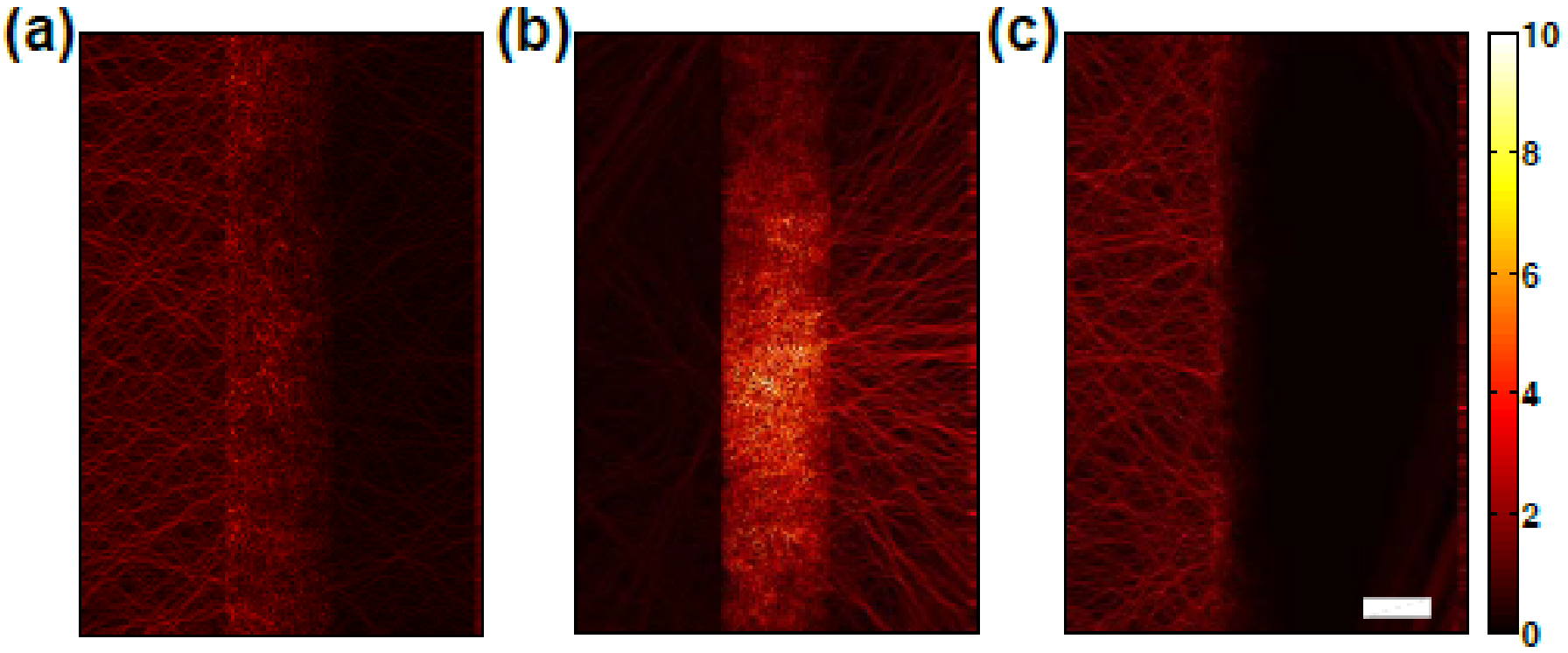
Open channels determine transport of light





Vellekoop & APM, PRL **101** (2008).
Microwaves (Shi & Genack, PRL, 2012)
Ultrasound (Gerardin *et al.*, PRL, 2014)
Light (Yu et al., PRL 153902, 2013)
APM, Lerosey, Lagendijk & Fink, Nat. Phot. (2012)

Energy density in open and closed channels



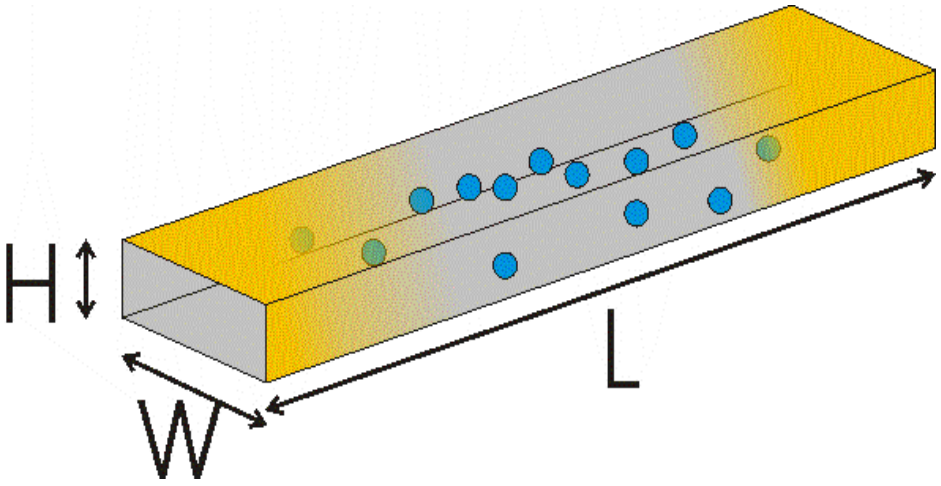
FDTD simulation by Choi et al, PRB, 2011
(Korea University)

Simulations of energy density

Simulate transport in a waveguide

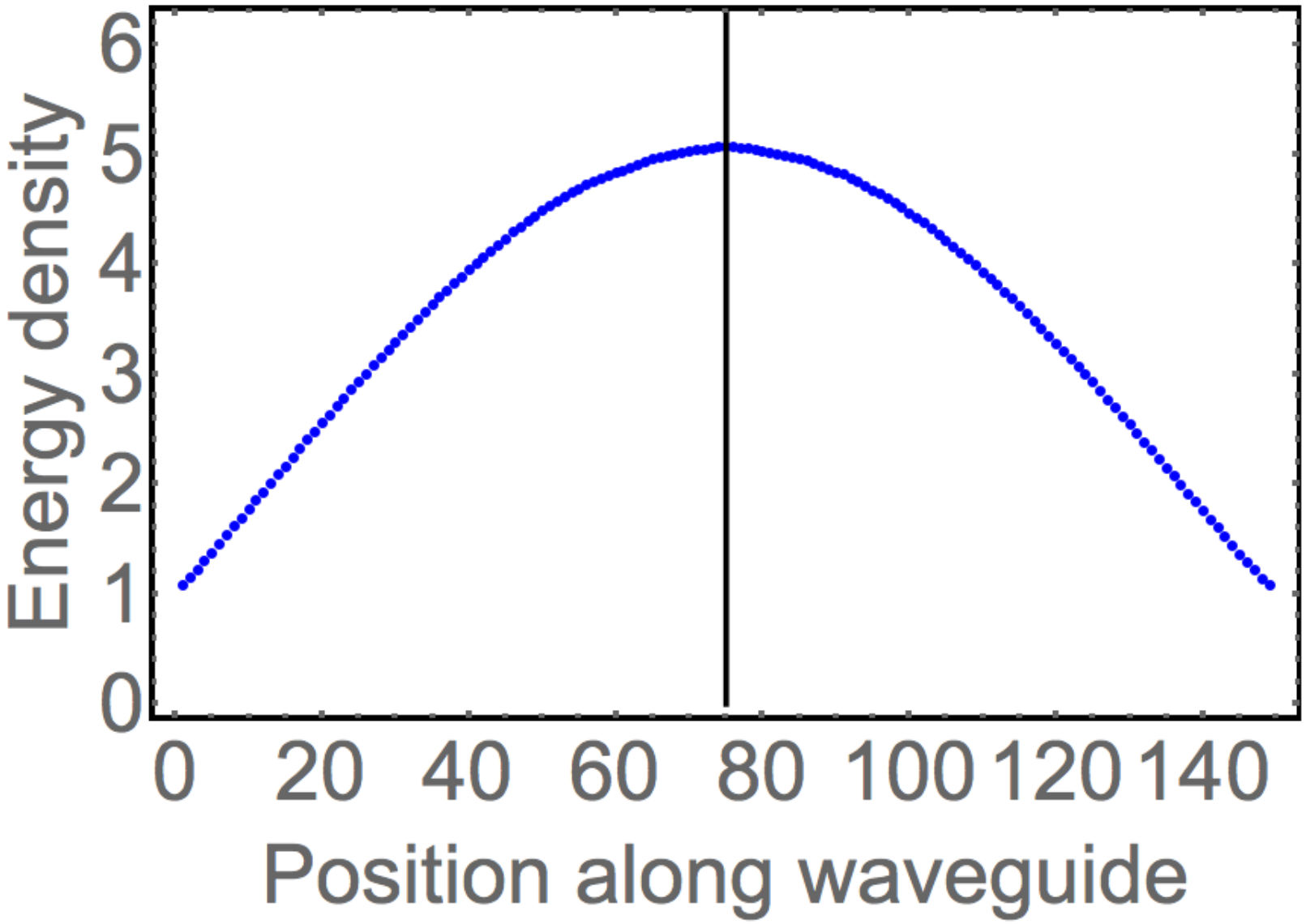
S-Matrix composition

(Ko & Inkson, 1998)

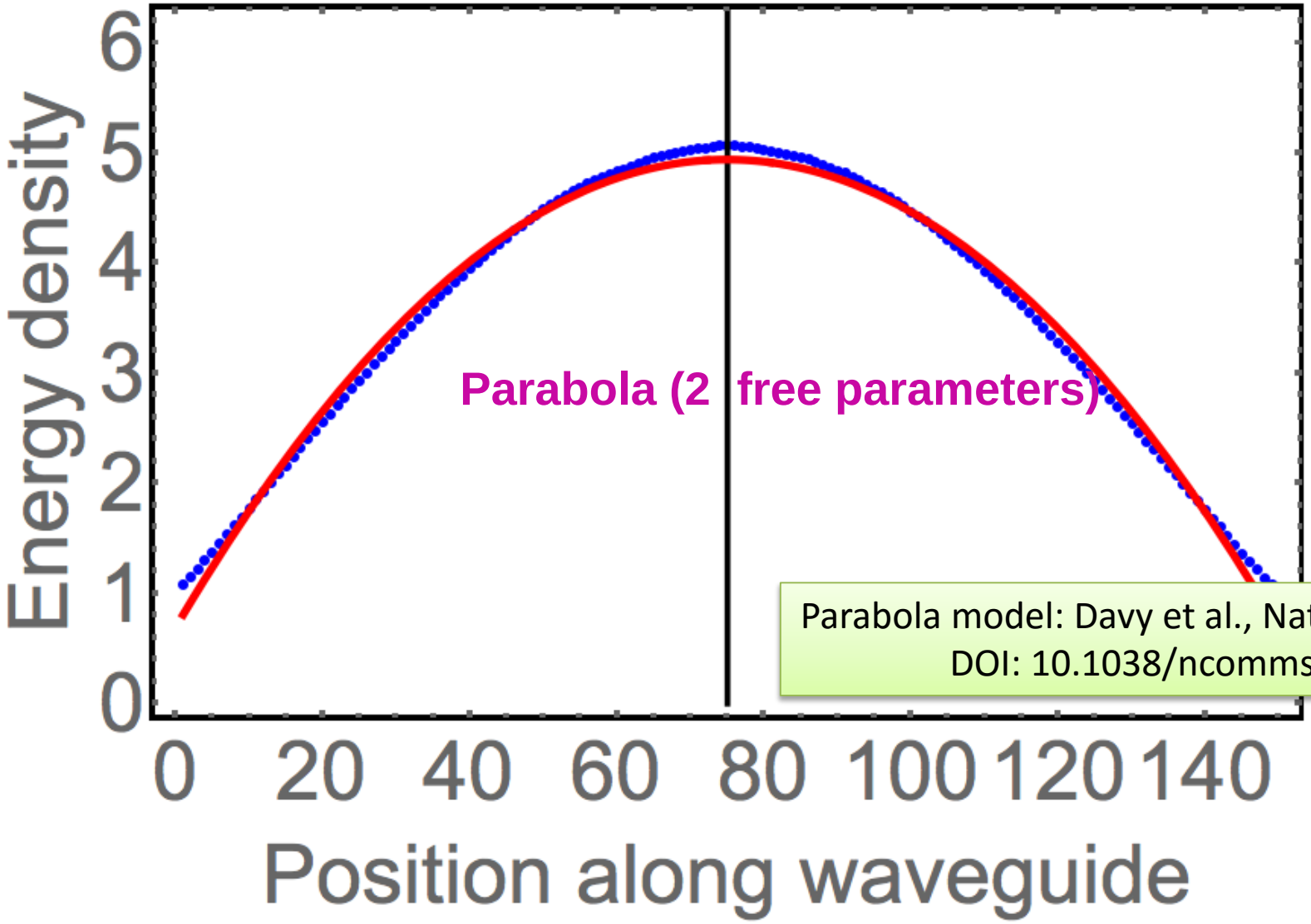


- Calculate eigenchannels by SVD, select T>0.99
- Average over 100000 samples
- Plot internal energy density

Energy density of open channels

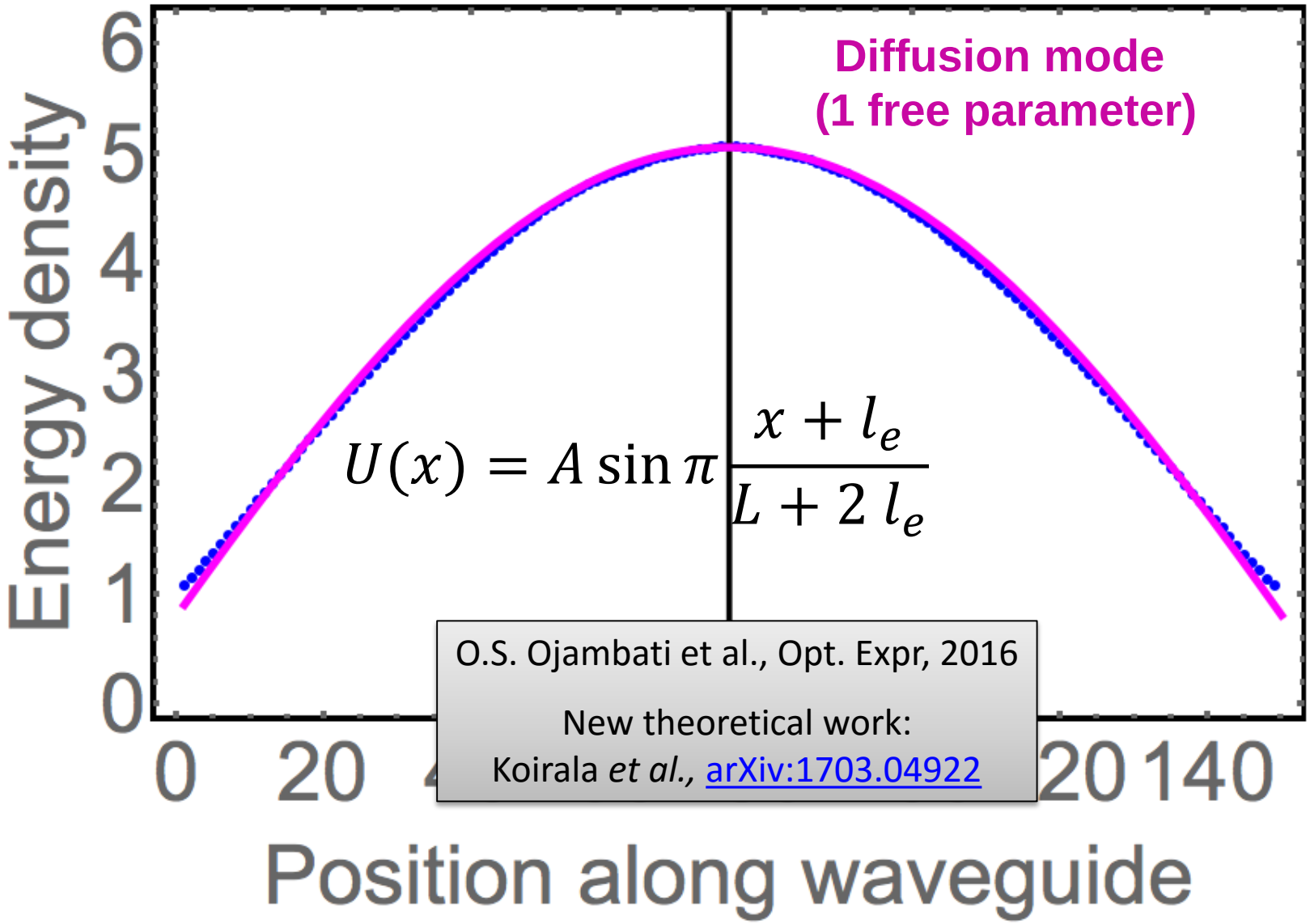


Energy density of open channels

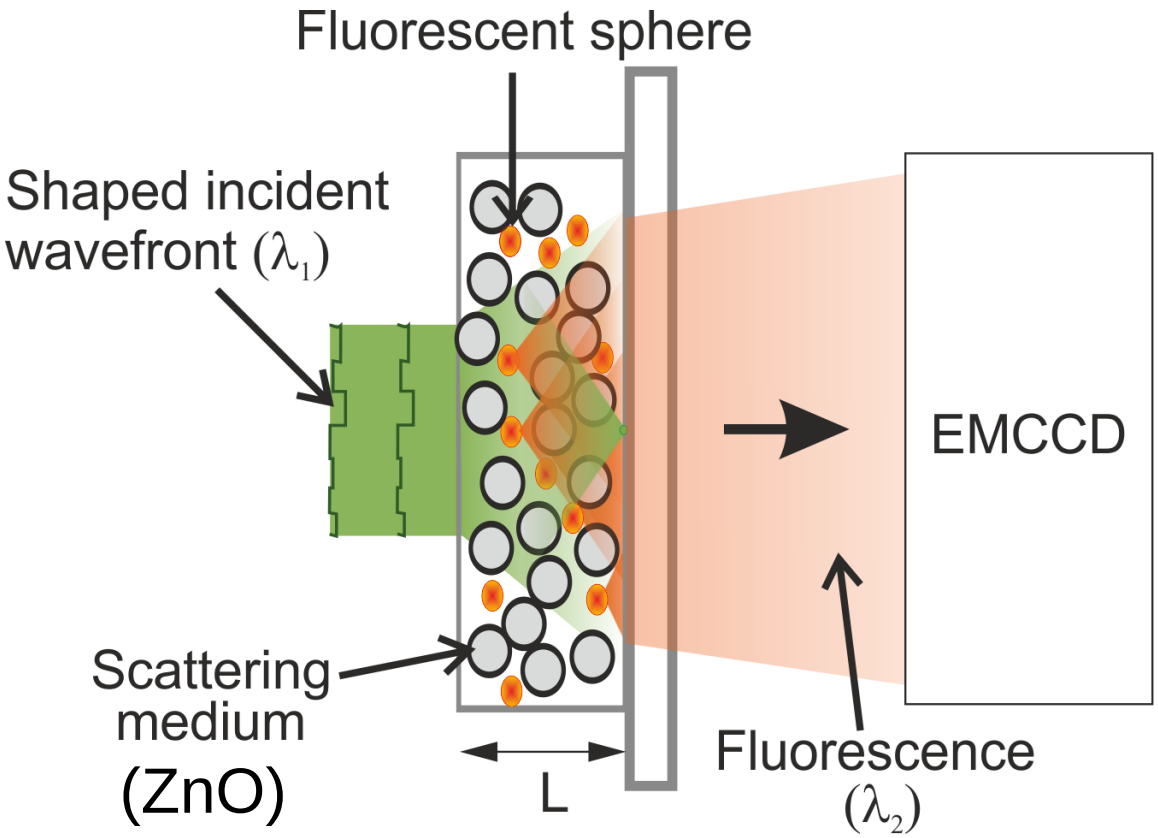


Parabola model: Davy et al., Nat. Comm. 2015, DOI: 10.1038/ncomms7893

Energy density of open channels

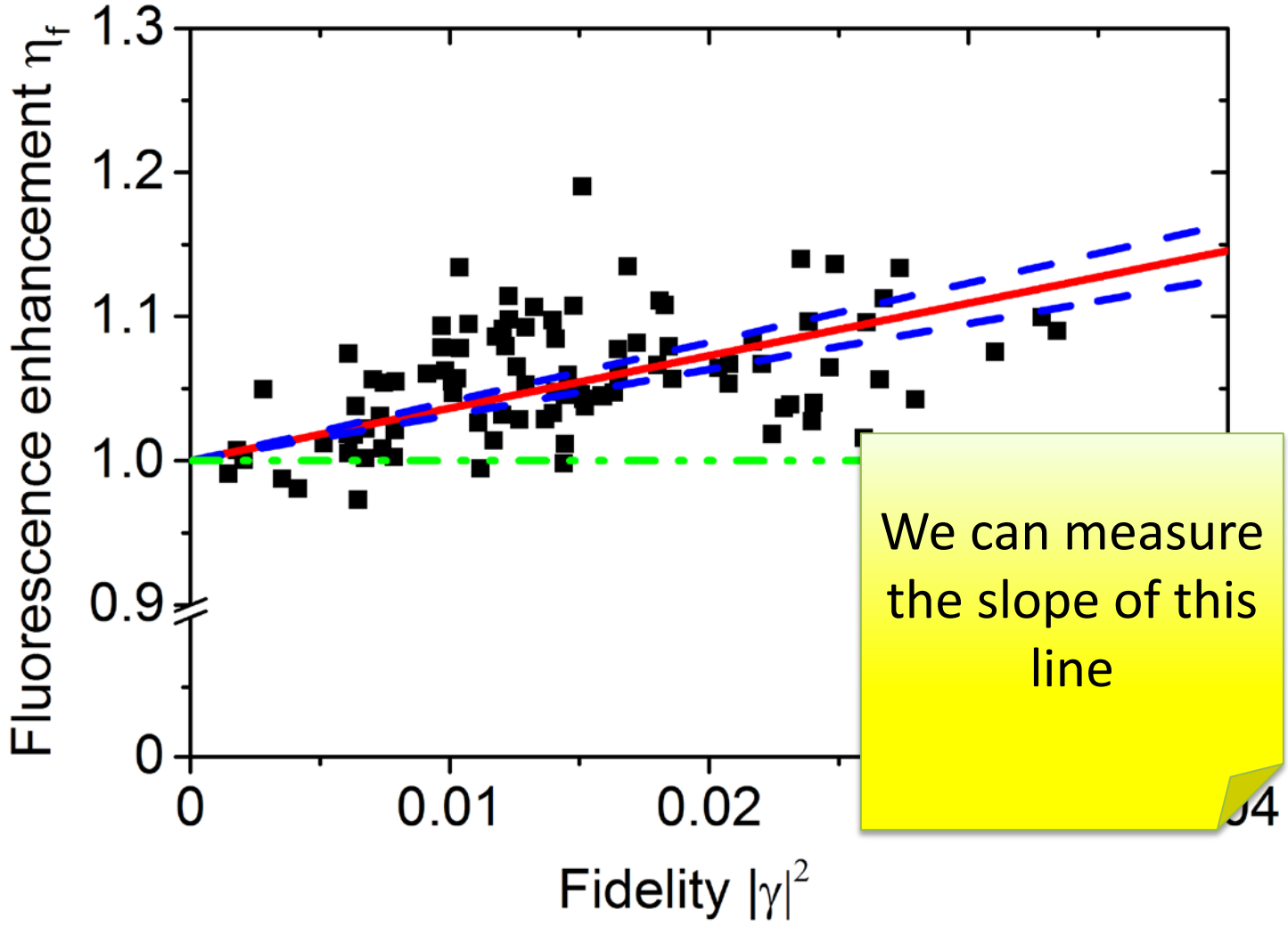


Probing the internal energy density



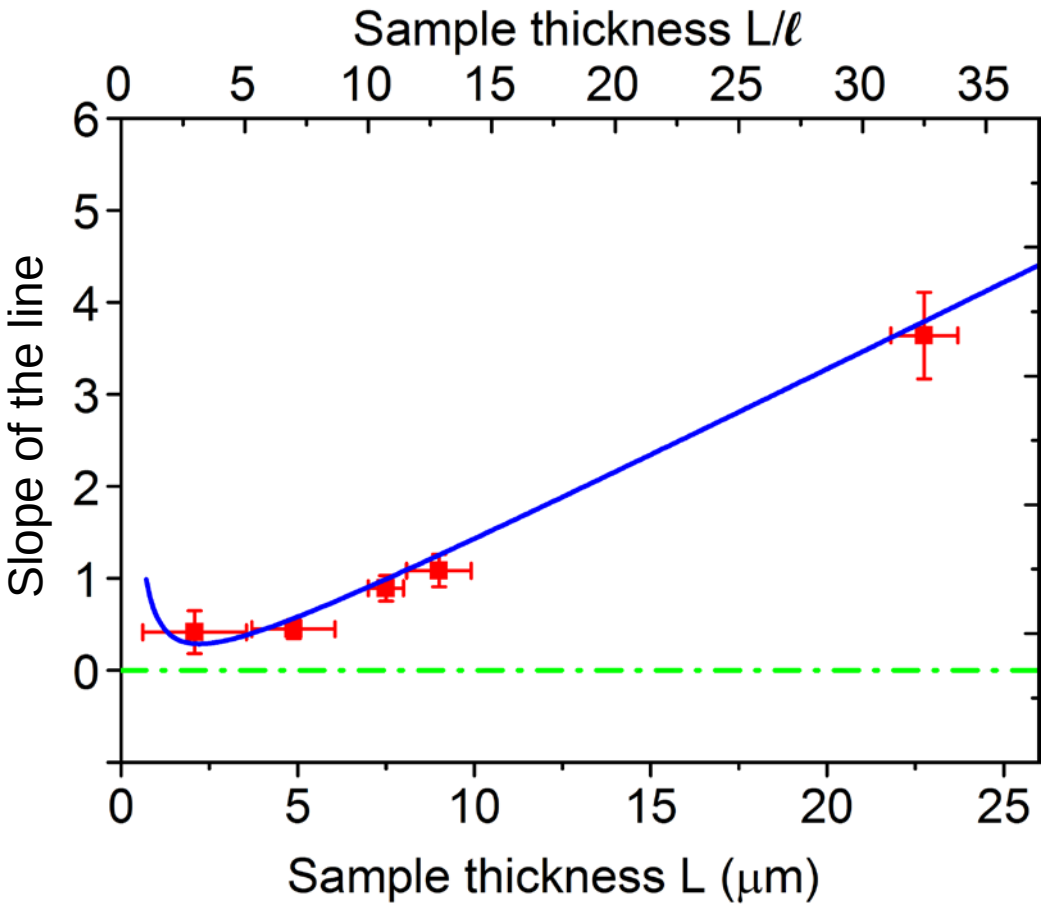
If we optimize *transmission*, does *fluorescence* change?

Fluorescence is enhanced



"successfully optimized part of the intensity"

Quantitative match

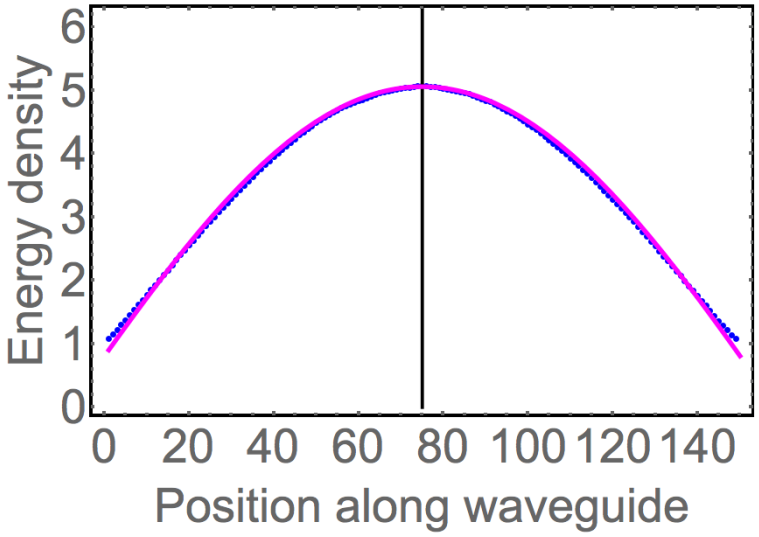


Model: the optimized light follows the m=1 solution of the diffusion equation

O.S. Ojambati *et al*, New J. Phys, 2016

Conclusion 3

The energy density profile of open channels resembles the fundamental diffusion mode.

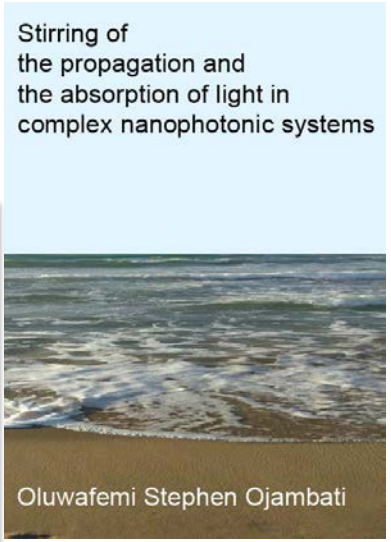


O.S. Ojambati *et al*,

New J. Phys, 2016

Opt. Expr. 2016

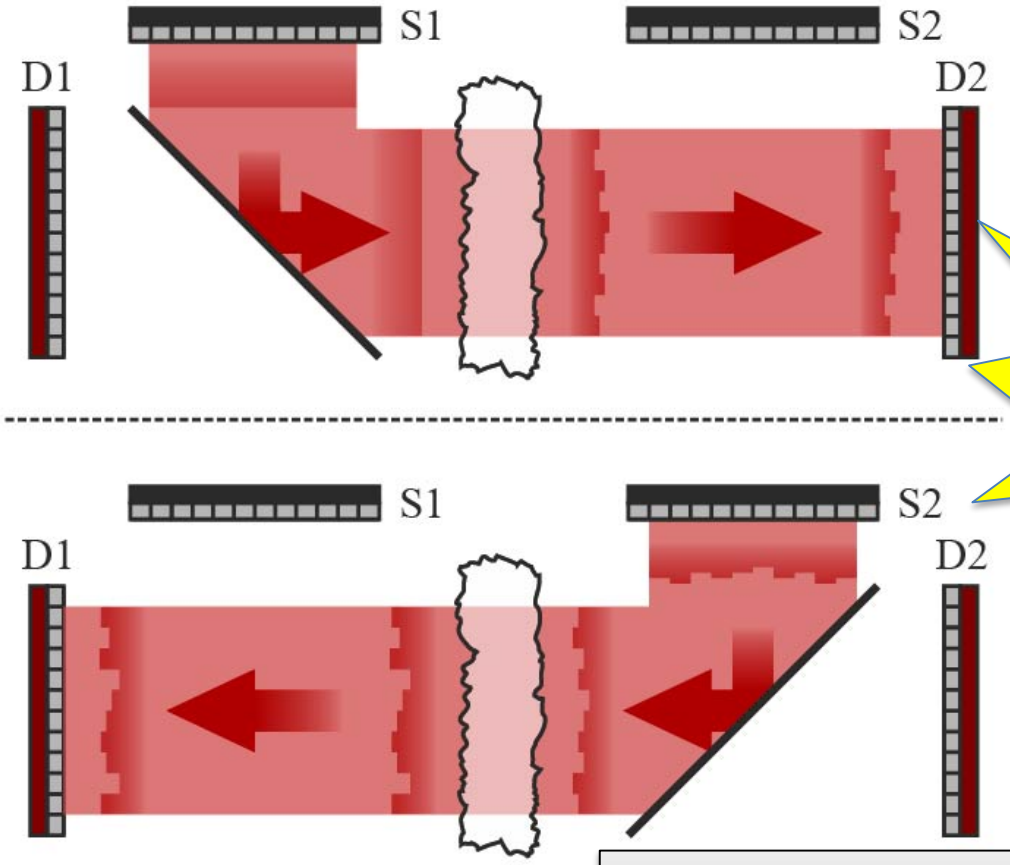
Ph.D. thesis 2016

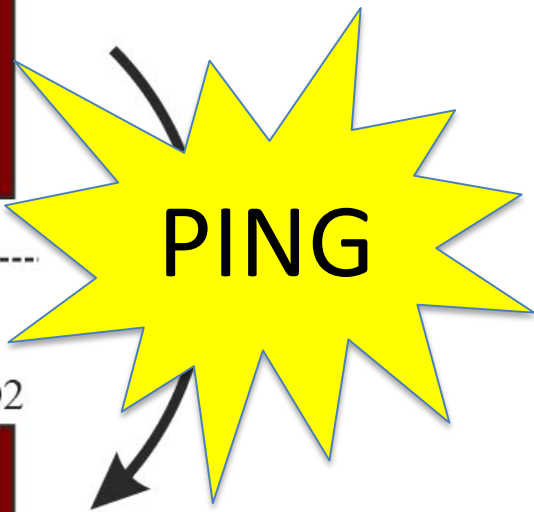


Open channels vs. resonant modes

- For resonant modes high energy density correlates with narrow frequency width
- This is corroborated by observations in localized quasi-1D waves (Shi & Genack, 2015)
- How about the diffusive regime?
- Approach: Find an approximate open channel then measure its frequency width

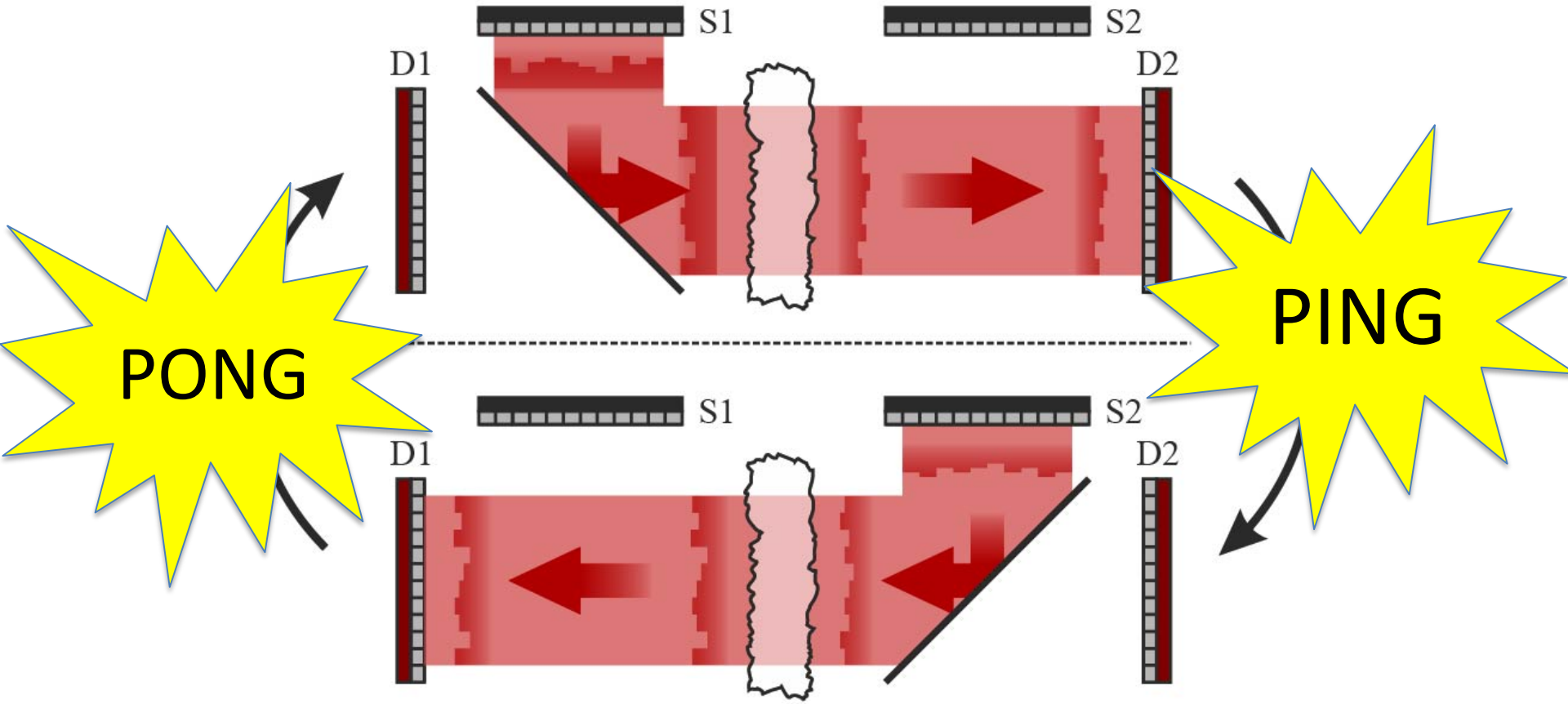
Method: Iterative digital phase conjugation





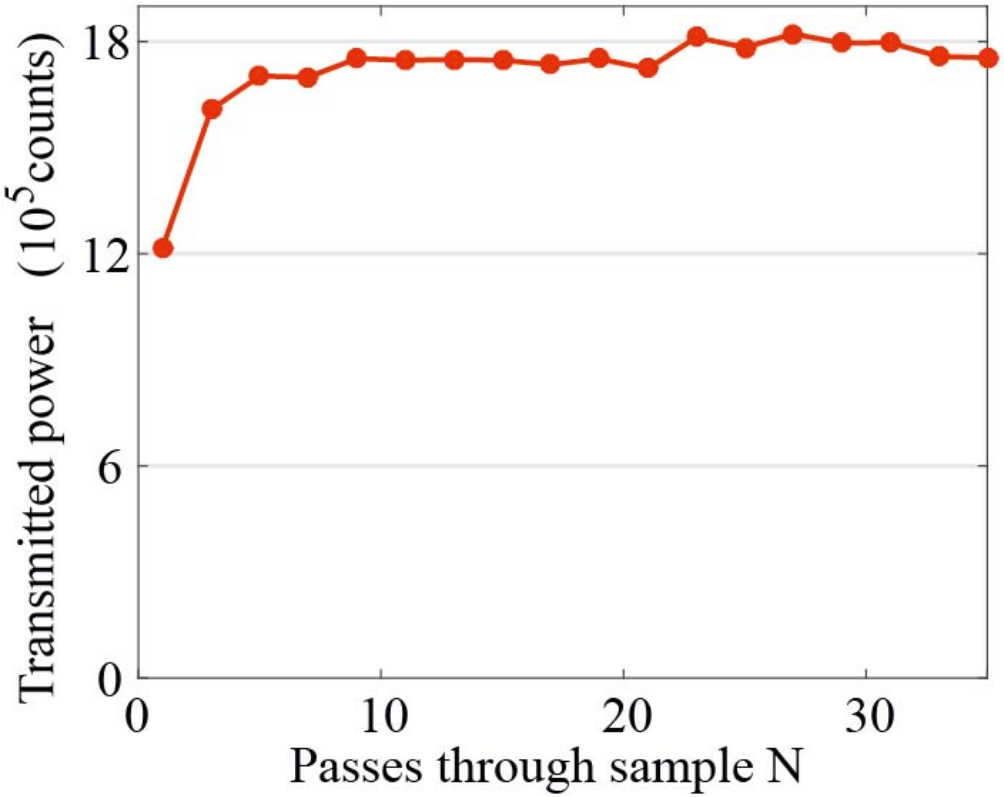
Von Mises, 1929
Hao et al., Sci Rep 2014
Bosch, Goorden & APM, Opt. Expr. 2016

Method: Iterative digital phase conjugation



Result: Iterative phase conjugation

Initially ~10% transmission

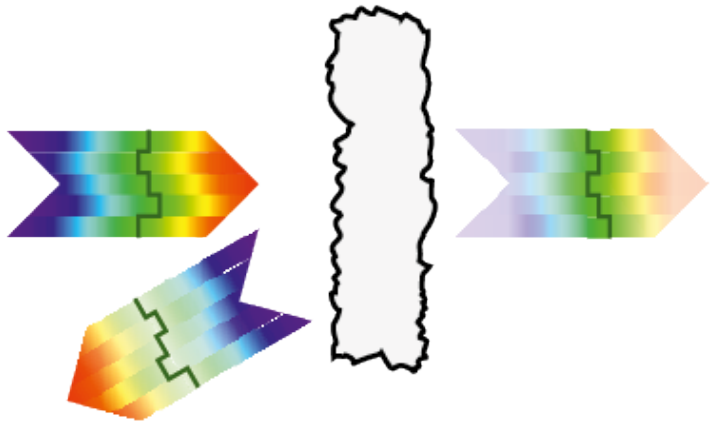


Sample: 20 micrometer-thick ZnO particles

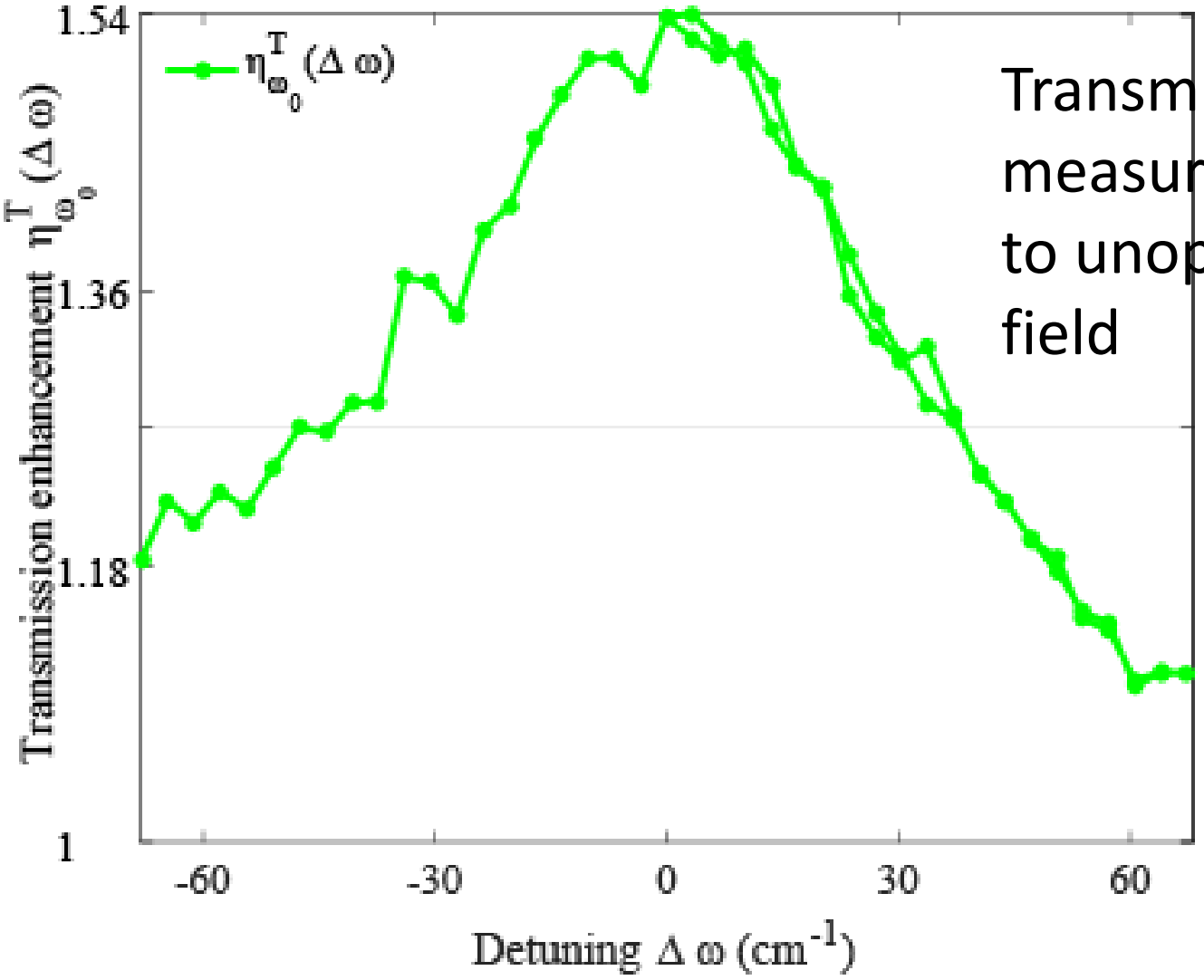
J. Bosch, S.A. Goorden & APM, Opt. Expr. **24**, 26472 (2016)

Spectral width of a transmission channel

- Optimise for a single wavelength
- scan wavelength while keeping wavefront constant

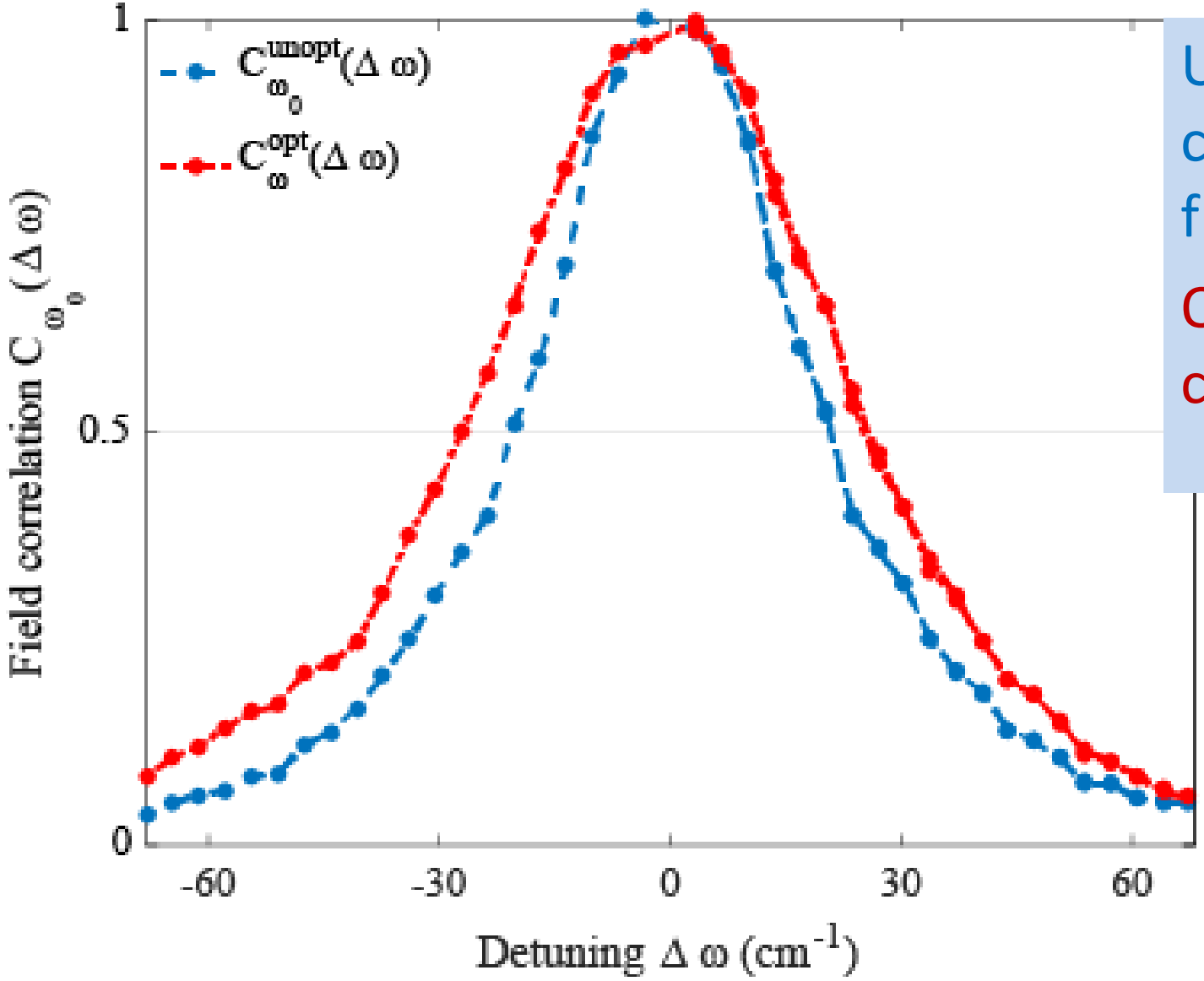


Results: Transmission enhancement



Transmission measured relative to unoptimized field

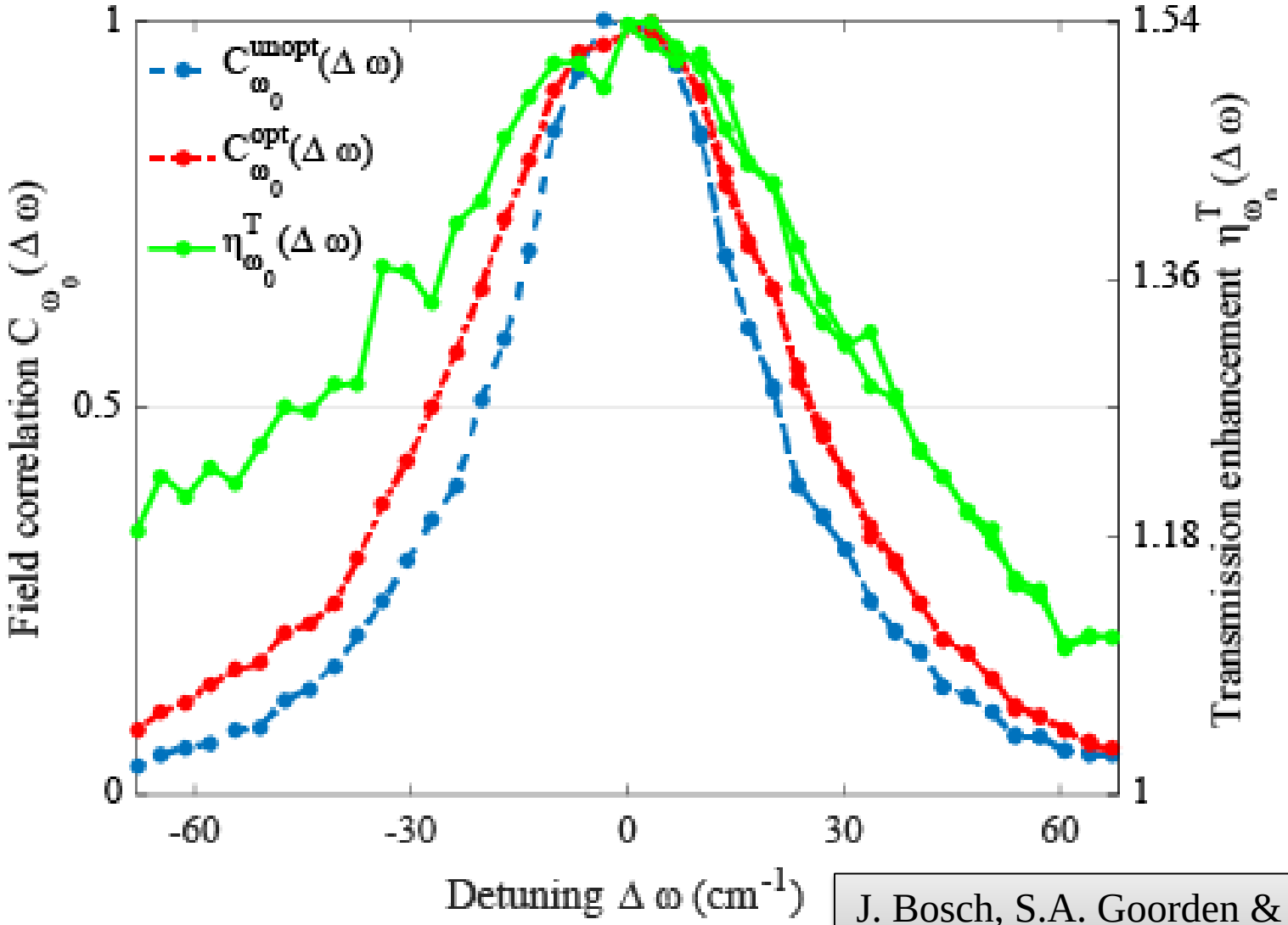
Measured field correlation



Unoptimized correlation function C_1

Optimized correlation

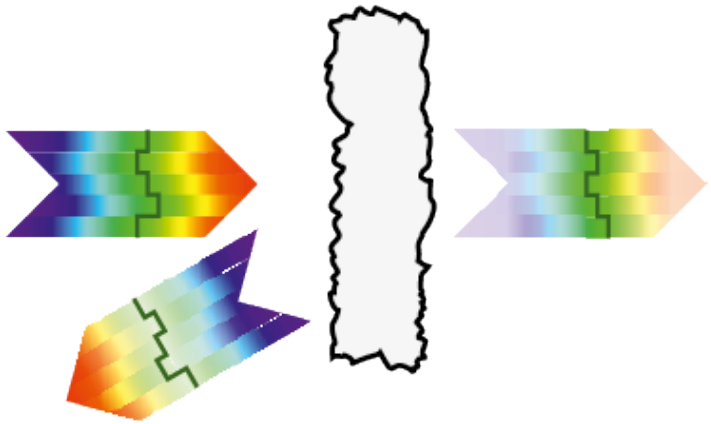
Results



J. Bosch, S.A. Goorden & APM, Opt. Expr. **24**, 26472 (2016)

Conclusion 4

Open channels have a larger frequency width than the speckle correlation function.



J. Bosch, S.A. Goorden & APM, Opt. Expr. **24**, 26472 (2016)

SECURE AUTHENTICATION

Authentication Keys

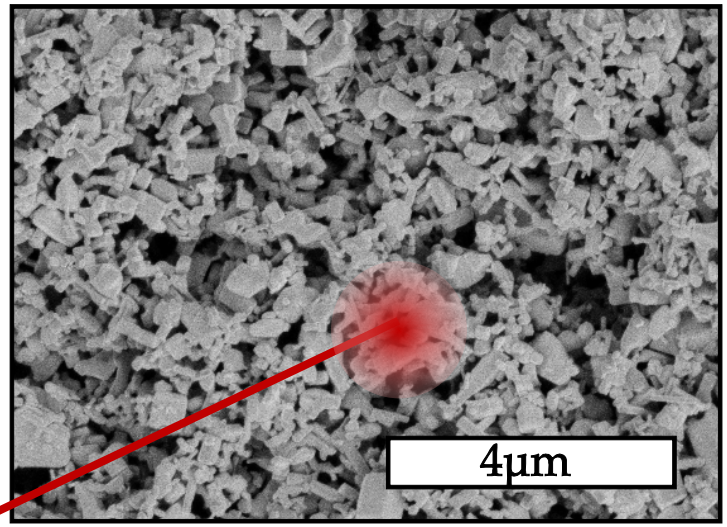
1) Code keys

Code can be distributed without you knowing it

2) Physical keys

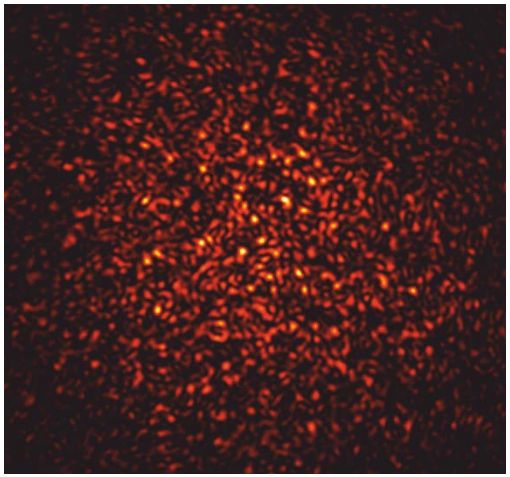
Key can be copied without you knowing it

Unclonable key: Scattering



"Challenge"

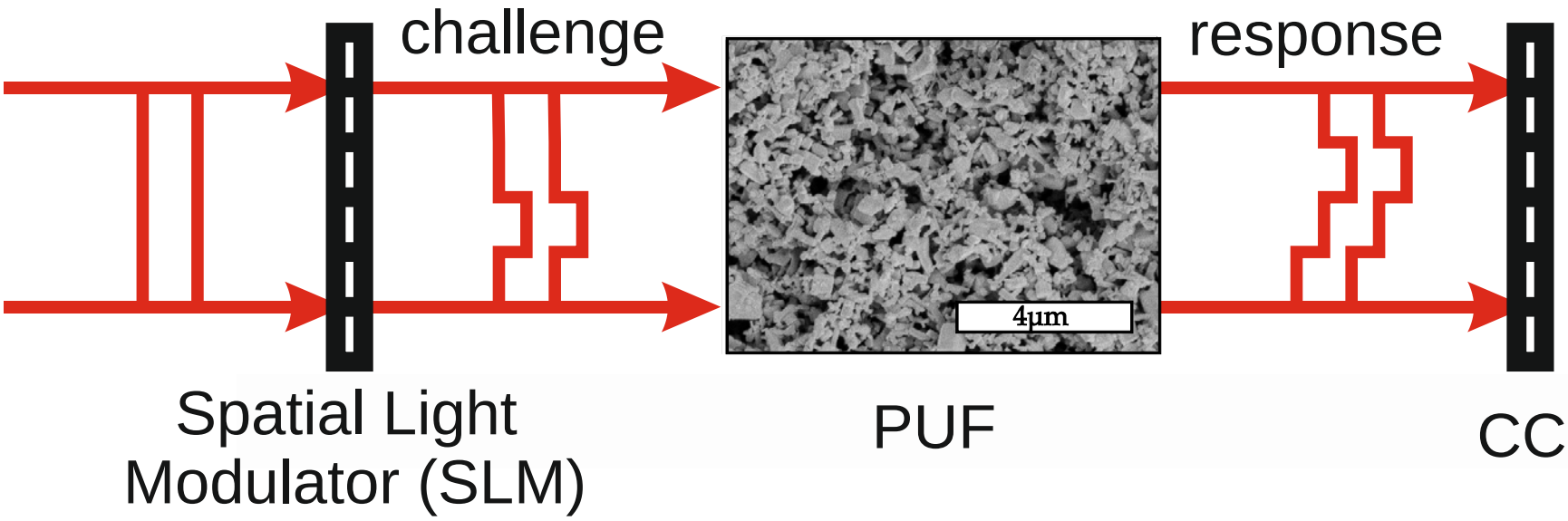
"Response"



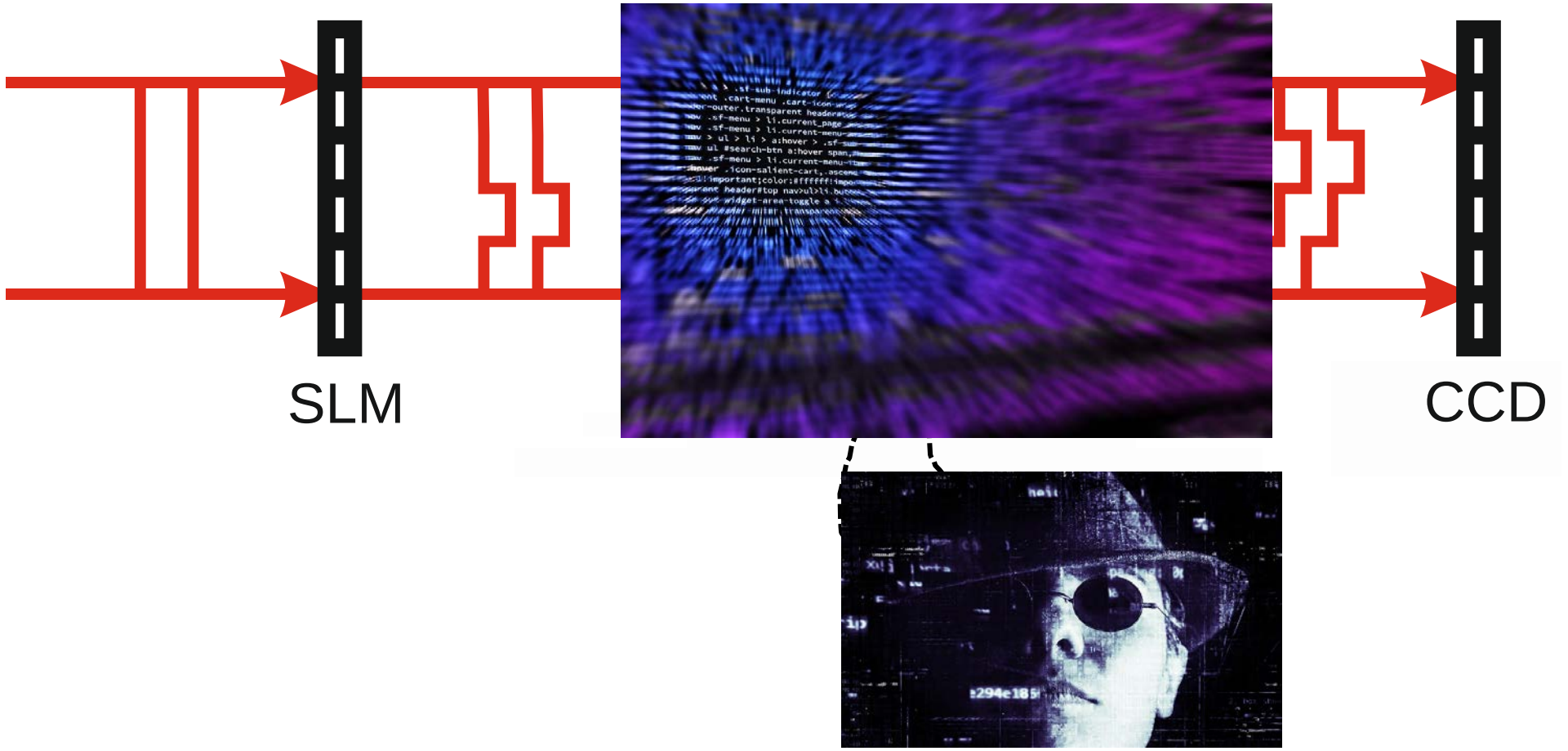
depends critically on uncontrollable aspects of manufacturing

Physical Unclonable Function
(Pappu et al, Science 2002)

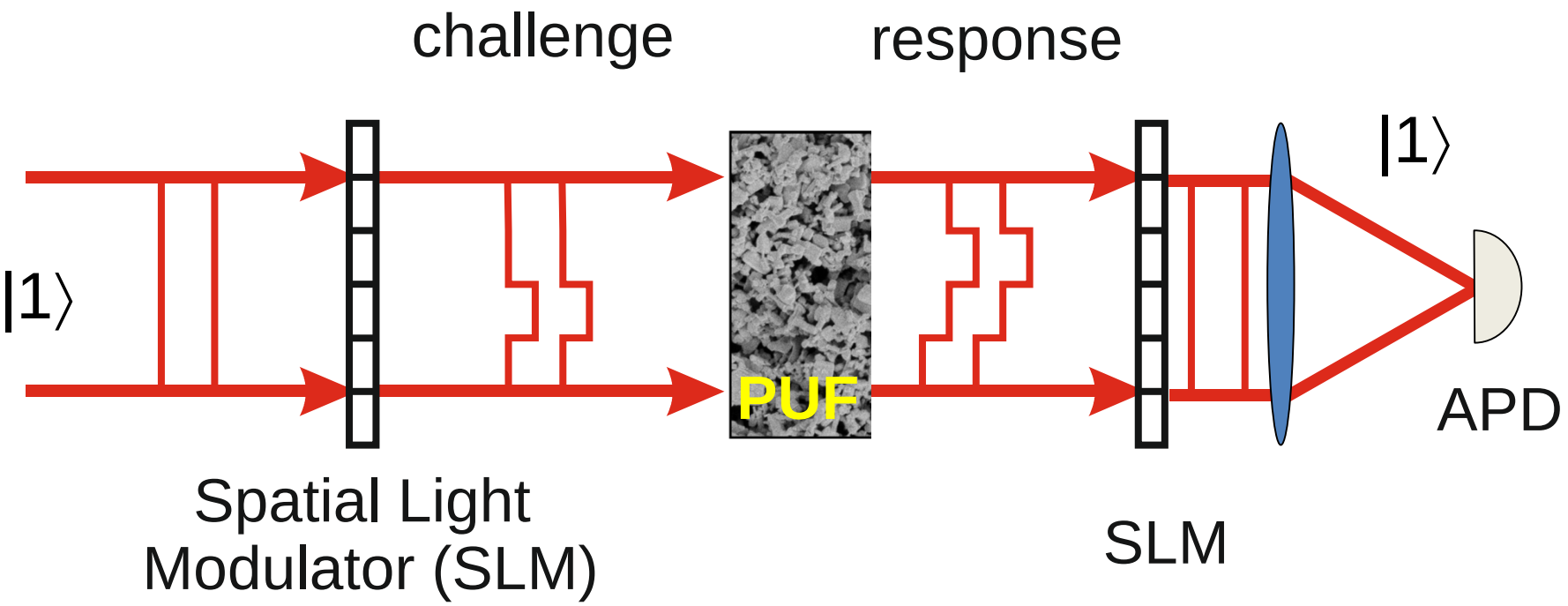
High-dimensionalOptical Readout



Vulnerability: Emulation



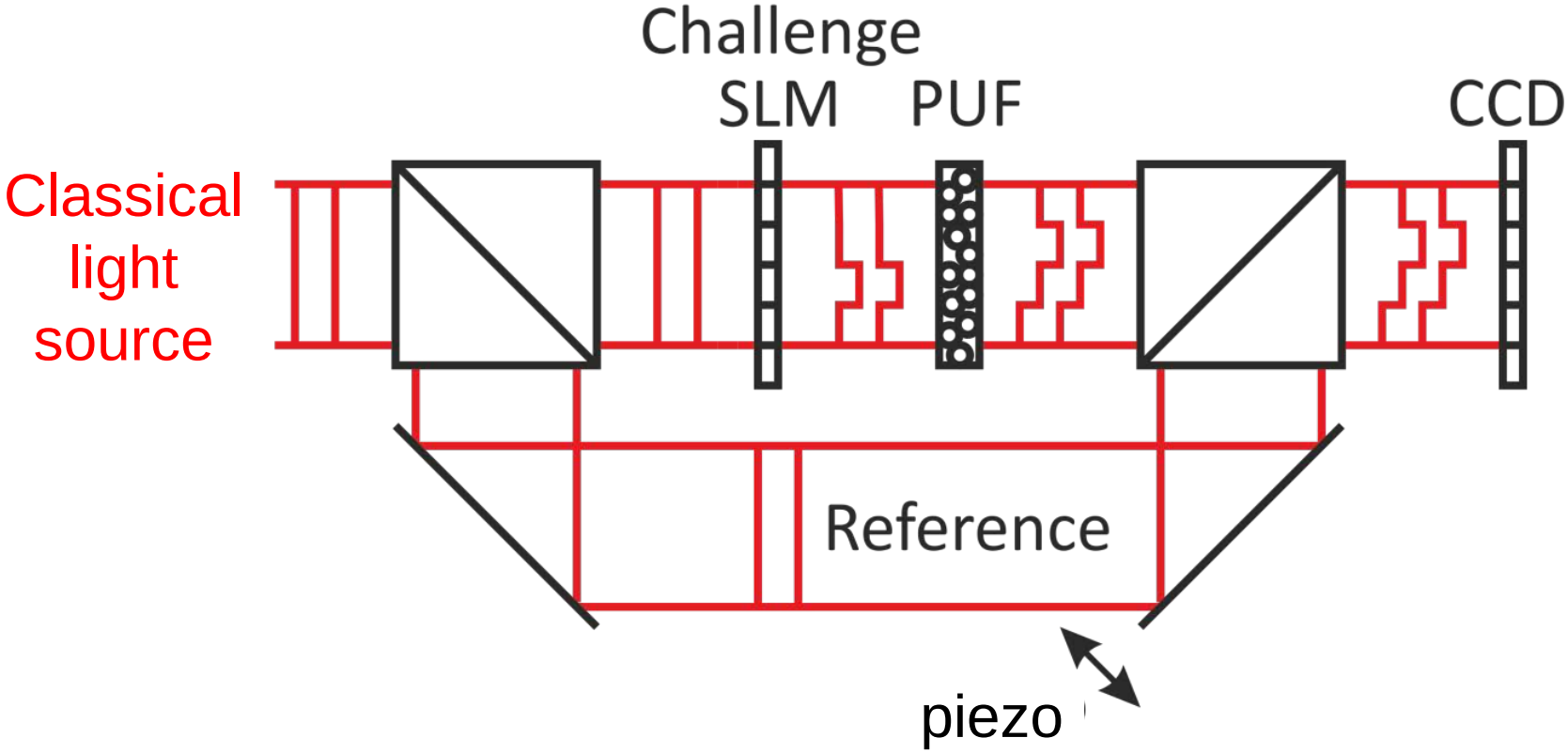
Single-Mode Projection Readout



The challenge state could be a one photon state $|1\rangle$, shaped in a complex wavefront (1000s of classical bits)

Škorić, APM & Pinkse, Int. J. Quantum Inf. **11**, 135401: 1-15 (2013)

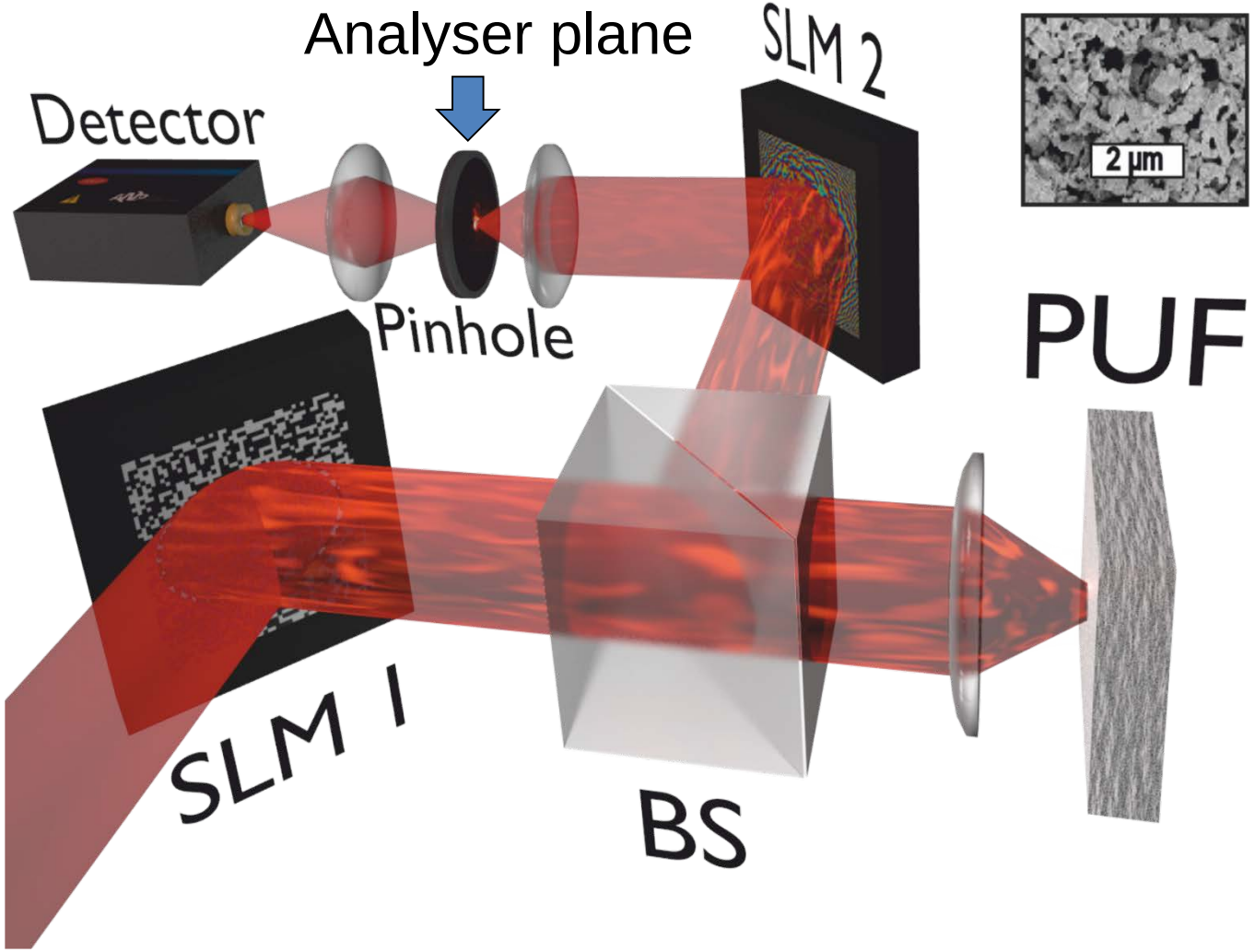
Enrollment



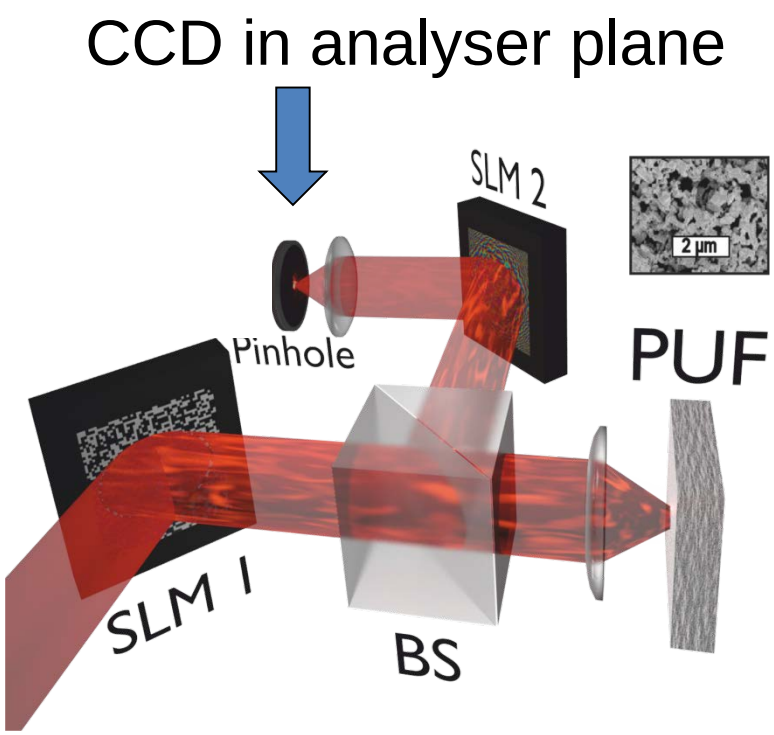
- Holographic method to read out responses

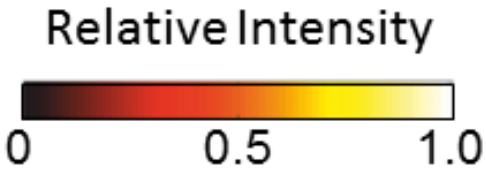
⟹ Make challenge-response database

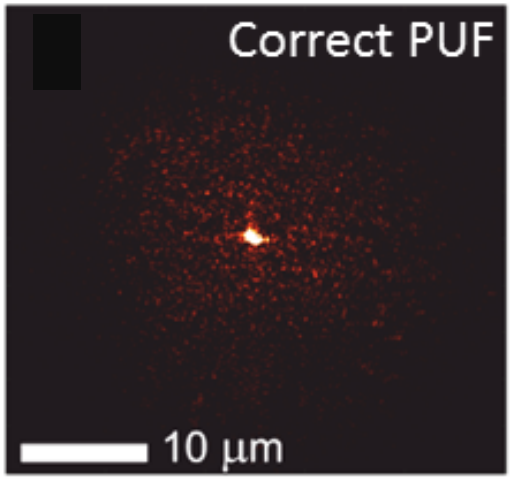
Readout Setup

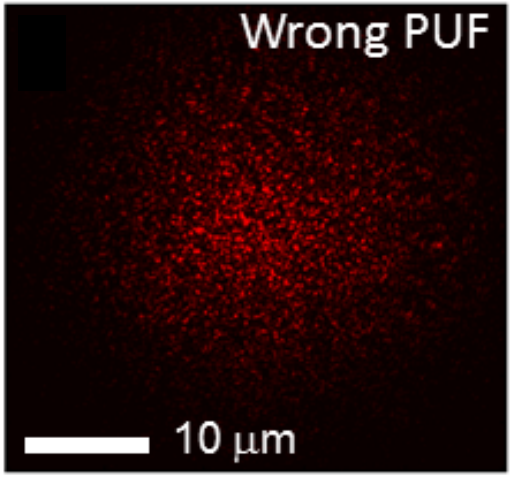


Classical Light Example





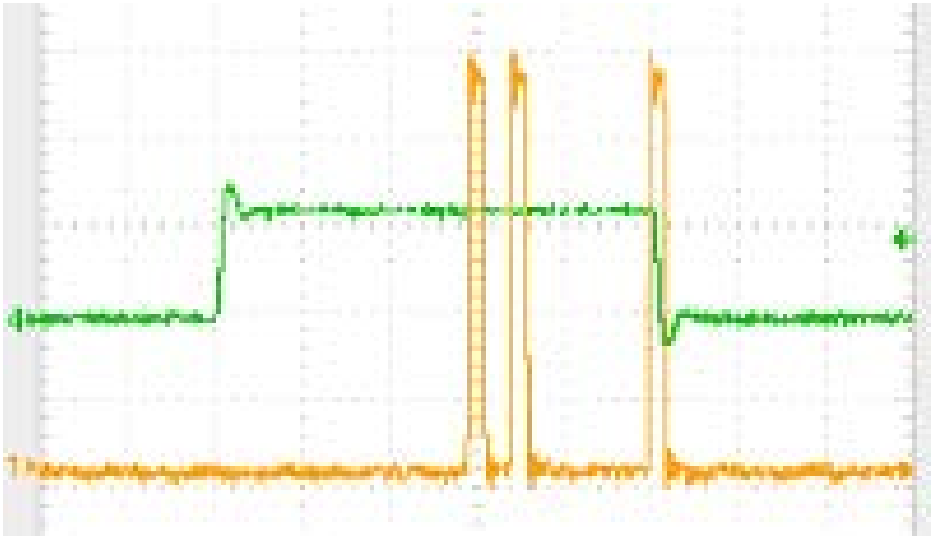




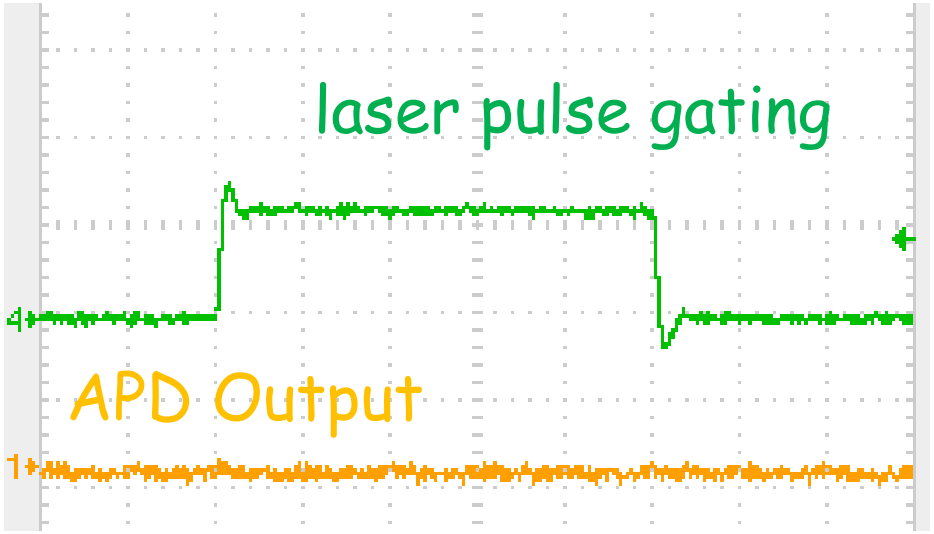
Counting Photons with APD

Result of firing weak coherent pulses

Correct PUF

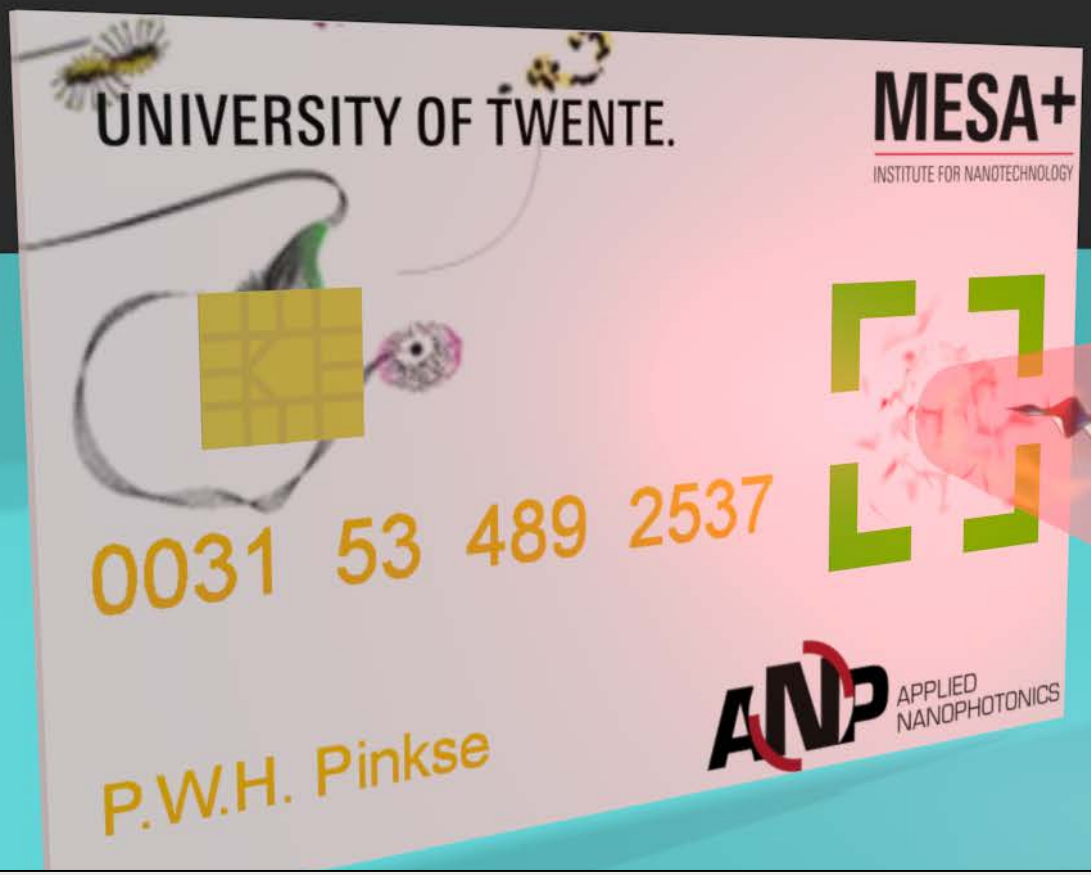


Wrong PUF



Time [100 ns / div]

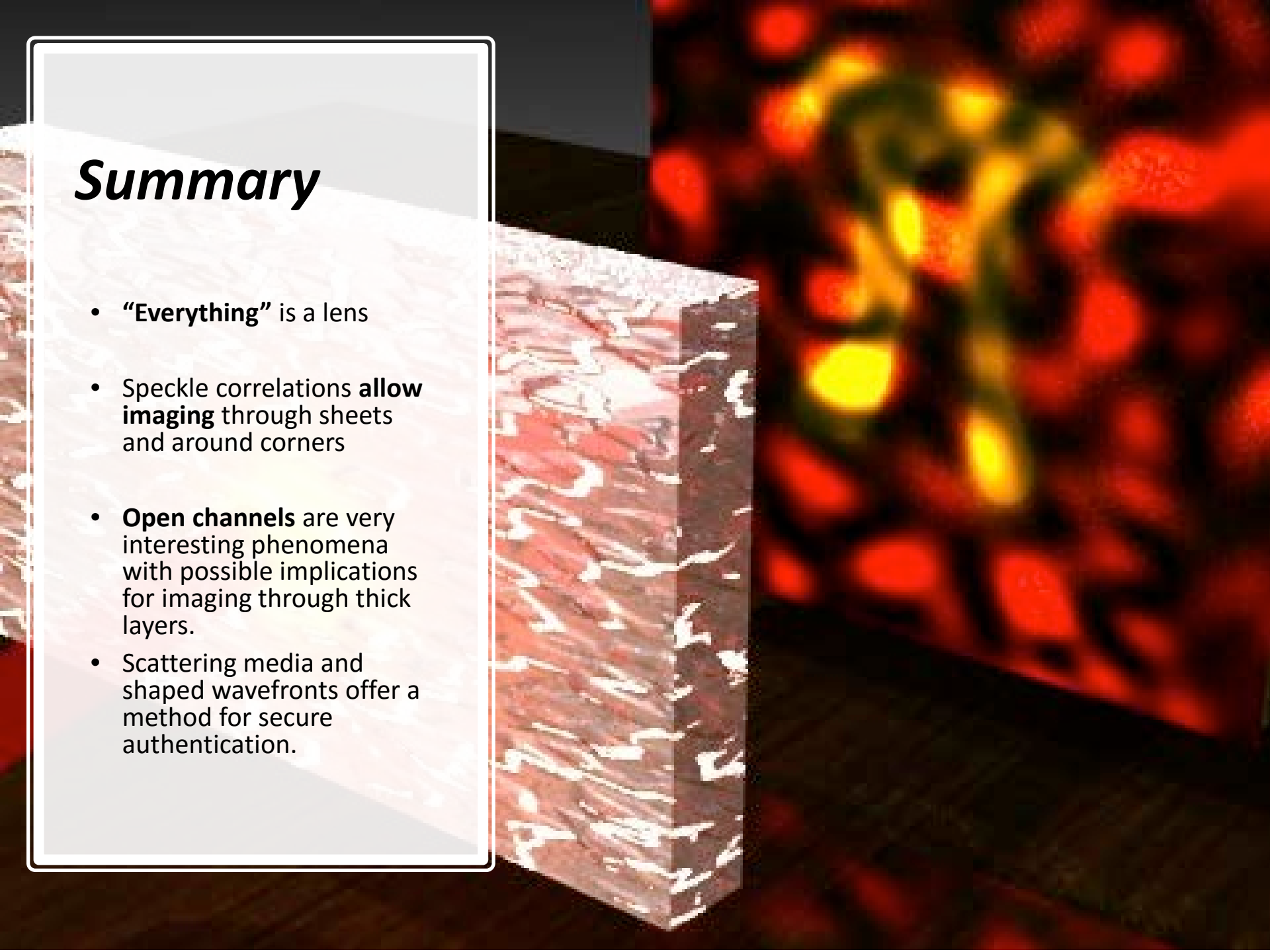
The Quantum Credit Card



S.A. Goorden, M. Horstmann, APM, B. Škorić, and P.W.H. Pinkse, *Quantum-Secure Authentication with a Physical Key*, Optica 1, 421-424 (2014). Patent pending

B. Škorić, APM & P.W.H. Pinkse, Int. J. Quantum Inf. 11, 135401: 1-15 (2013)

B. Škorić, P. W. H. Pinkse, and APM, Quantum Inf. Process. **16**, 200, (2017)



Summary

- **“Everything”** is a lens
- Speckle correlations **allow imaging** through sheets and around corners
- **Open channels** are very interesting phenomena with possible implications for imaging through thick layers.
- Scattering media and shaped wavefronts offer a method for secure authentication.

Future

- Use open channels for imaging
  (e.g. inside brain tissue)
- Study *single* open channels
  (J. Bosch e.a., Opt. Expr. **24**, 26472, 2016)
- Find time-delay eigenchannels
  (see also theoretical work by S. Rotter)

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