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Opaque lenses

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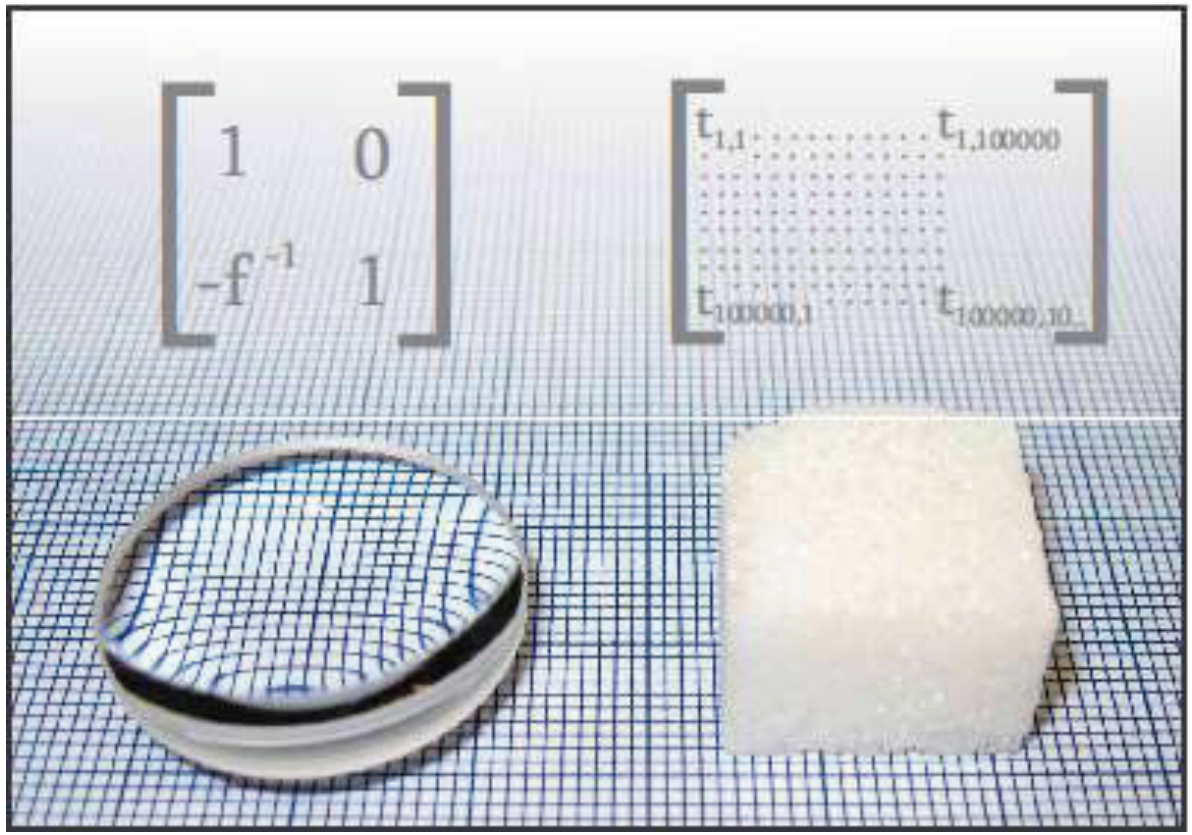

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Disclaimer

This document is an adaptation of slides used for a workshop presentation, and its main purpose is educational. Many details are presented in a simplified way.

Please refer to the original published papers (citations given on the slides) for full information on the scientific results and more complete reference to related work.

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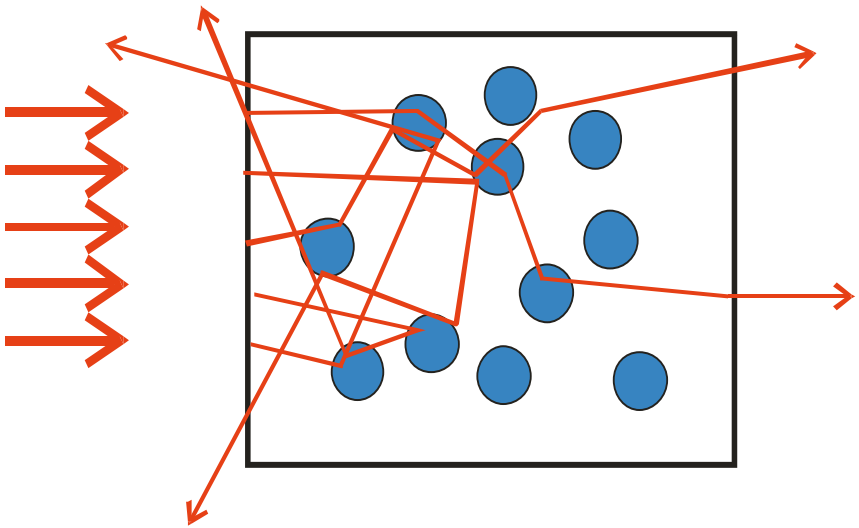
Willem Vos	*- Chair of COPS group*

Outline

- Wavefront control of light
- Focusing *through* opaque materials
- Focusing *inside* opaque materials
- Universal optimal transmission
- Conclusion

Scattering

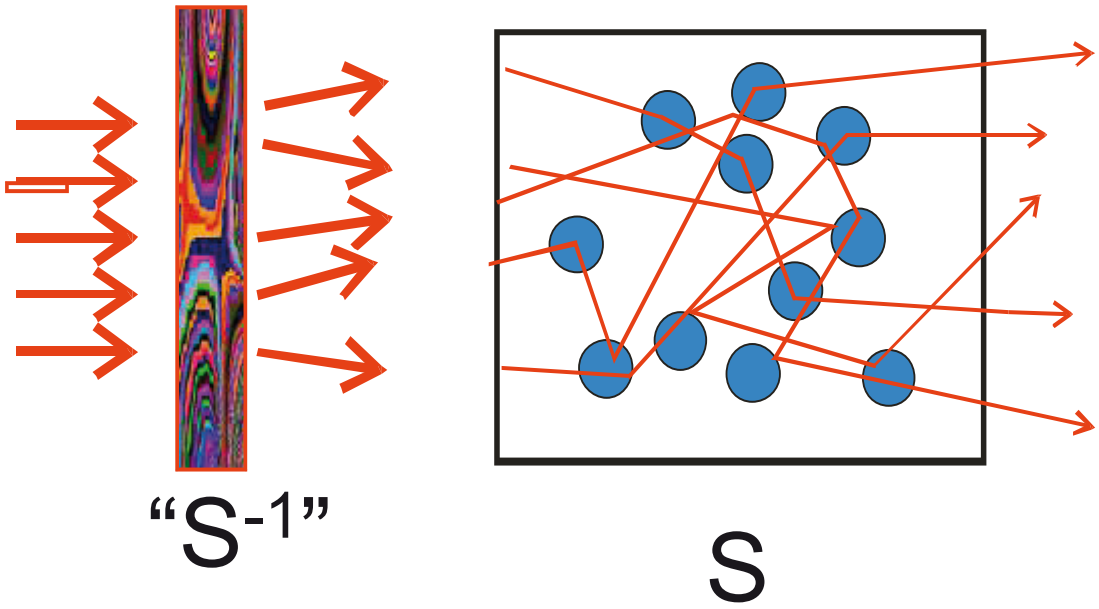
- A propagating light field has a large but *finite* number of degrees of freedom.
- Scattering is described by a matrix S.



S

Control scattering?

- If we know S, how well can we control the scattered light ?



How many matrix elements ?

Number of degrees of freedom in a wavefront

DOF = # TE + TM modes in waveguide of same area

= 2 Area/Diffr. limited spot size

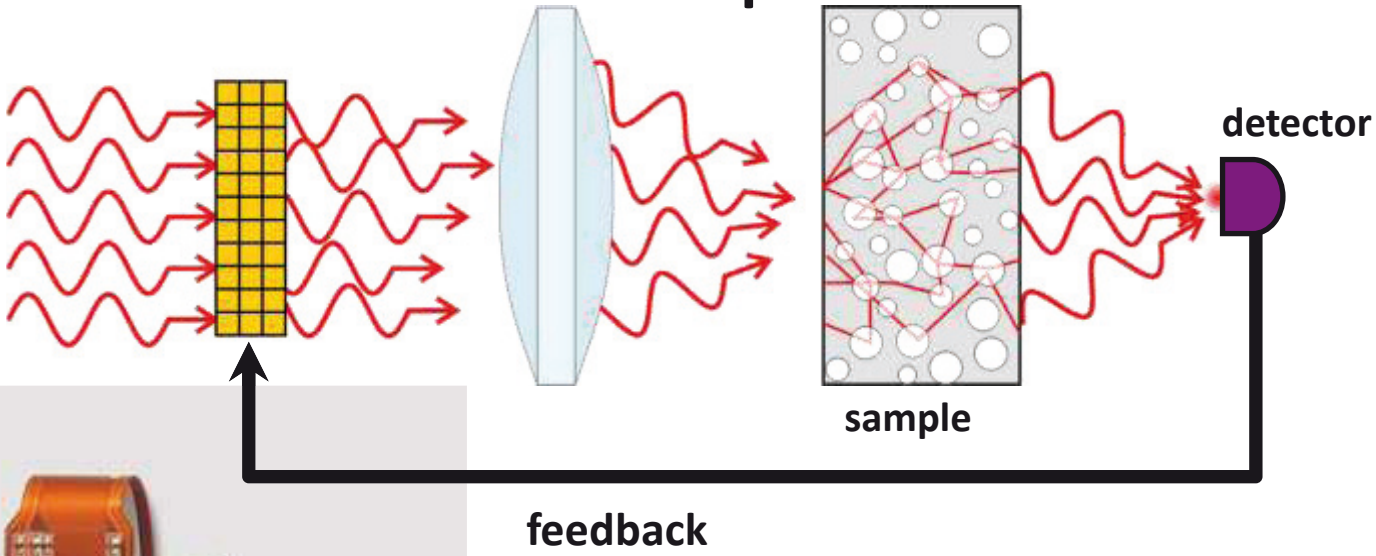
= $2 \pi A/\lambda^2$

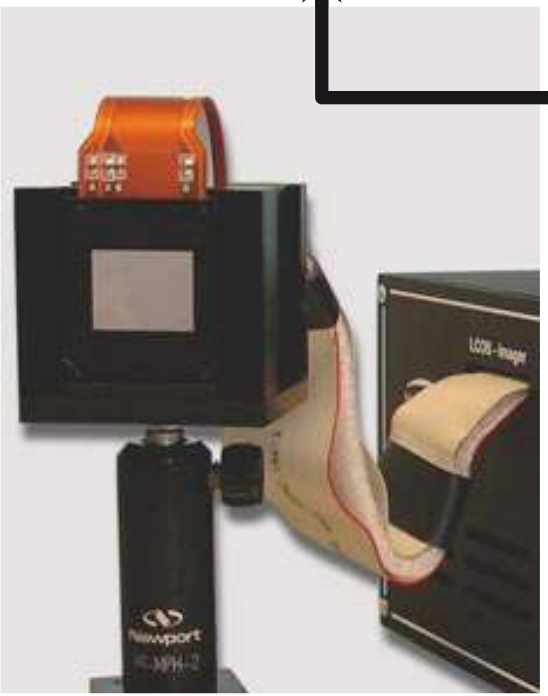
matrix elements = $(DOF)^2$

Number of degrees of freedom in a light field

$(10\ \mu m)^2$	1 600 DOF; $2.5\ 10^6$ matrix elements (5 MB; one mp3 song)
$(100\ \mu m)^2$	160 000 DOF; $2.5\ 10^{10}$ matrix elements (50 GB; a blu-ray disc)
$(1\ mm)^2$	16 000 000 DOF; $2.5\ 10^{14}$ matrix elements (500 TB; monthly uploads to YouTube)

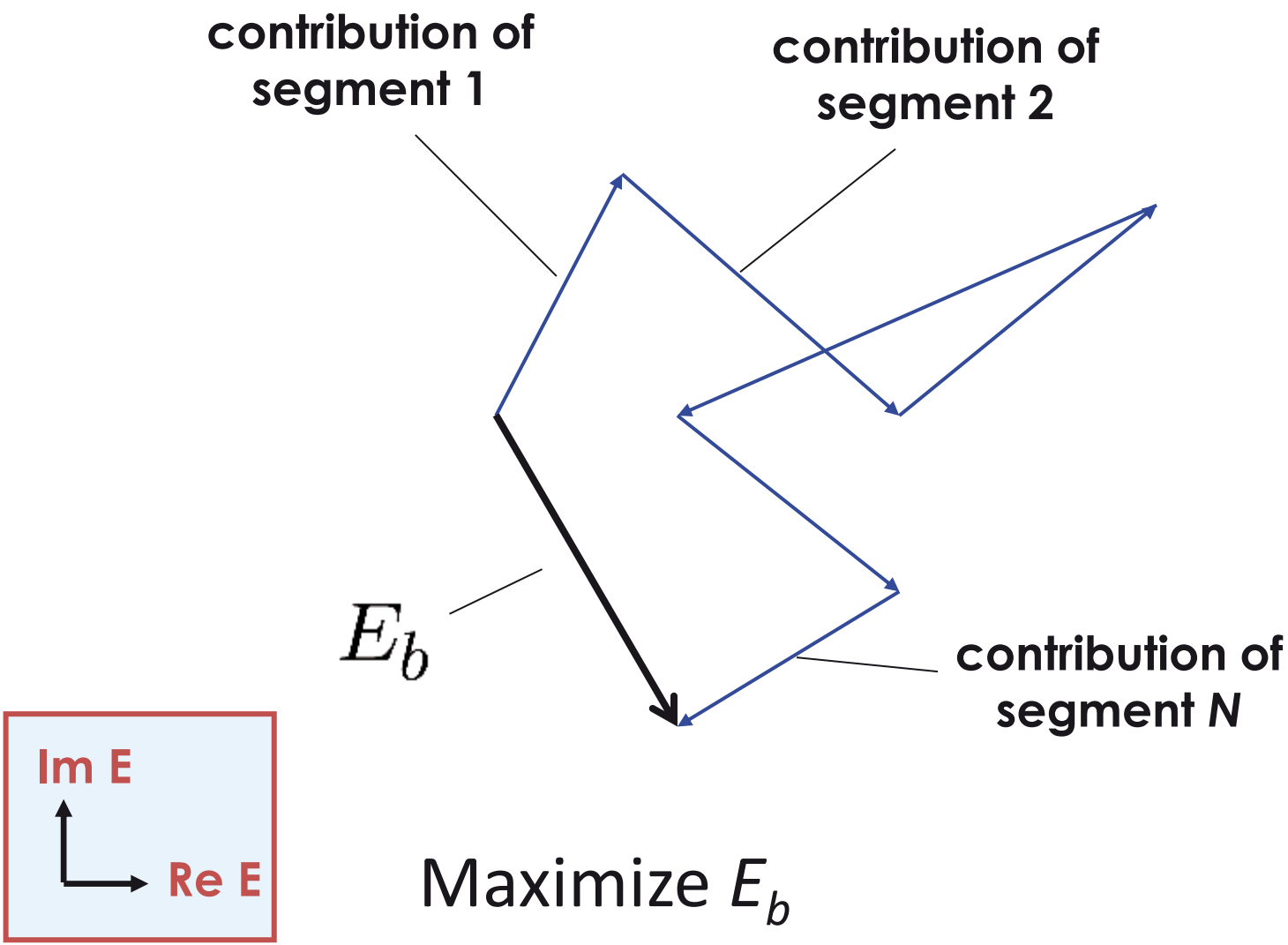
Easiest approach: Feedback optimization





Spatial amplitude and phase modulation using commercial TN LCDs
van Putten, Vellekoop & Mosk,
Appl. Opt. **47,** 2076 (2008).

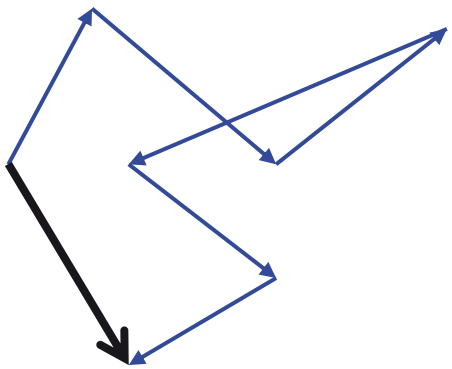
Graphical representation



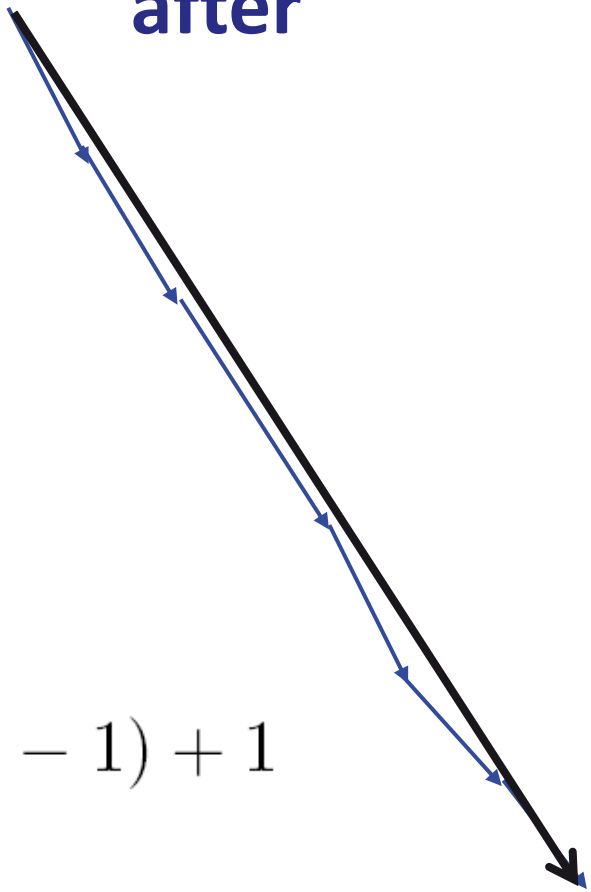
Maximize E_b

Phase of incident wavefront is conjugate of transmission matrix elements

before

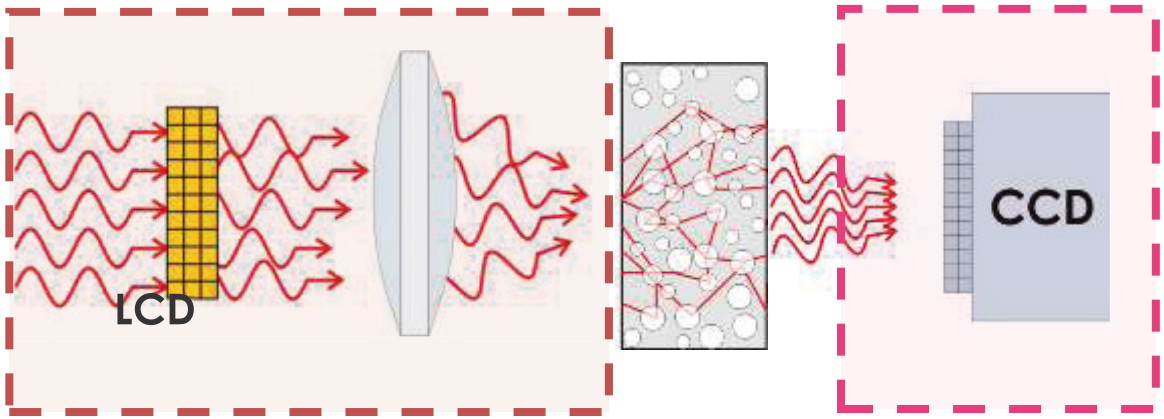


after



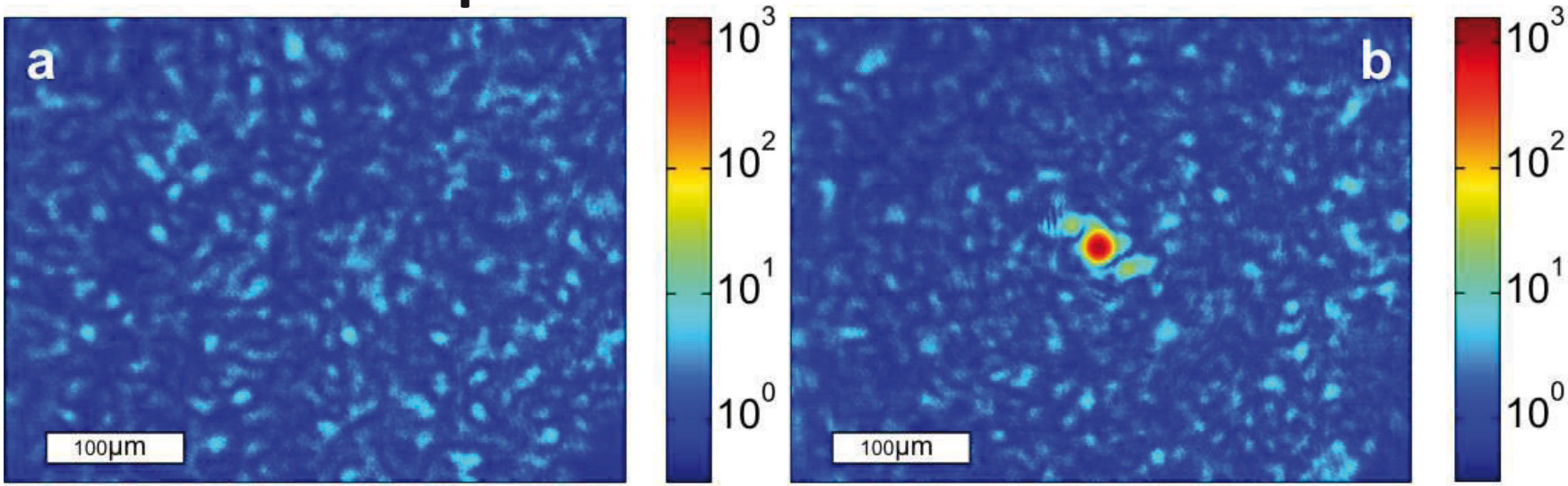
global maximum $\eta = \frac{\pi}{4}(N-1)+1$

Experimental setup



Sample: 10 µm layer of TiO2 pigment.
Light source: 633 nm HeNe laser.
Detection : 1 pixel of CCD camera.

Experimental results

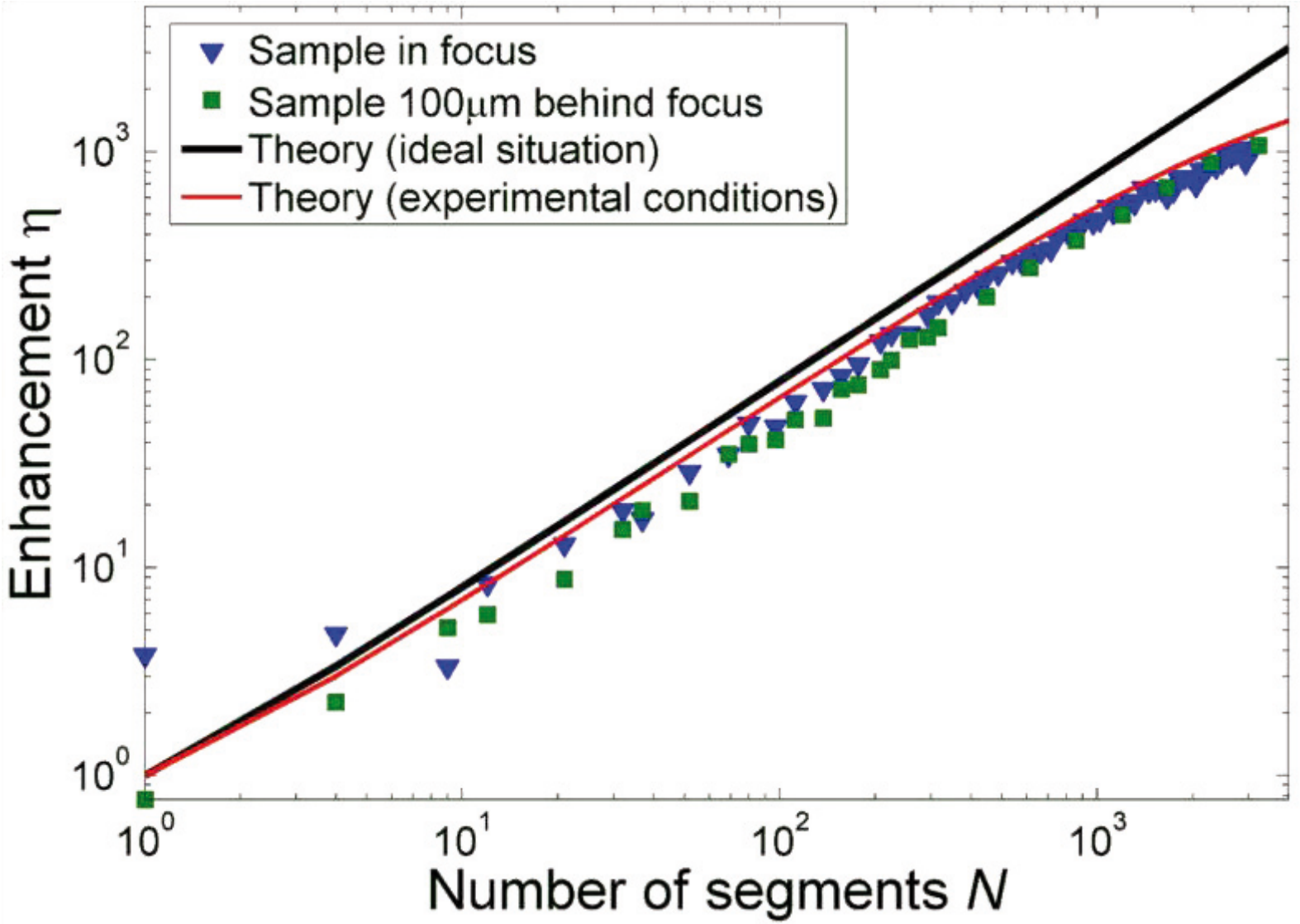


measured transmission (normalized by average diffuse intensity)

Opaque objects focus light: Opaque lens

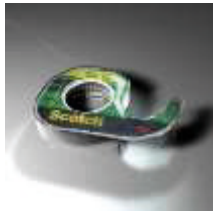
Vellekoop & Mosk. Opt. Lett. **32**, 2309 (2007)

Intensity of focus

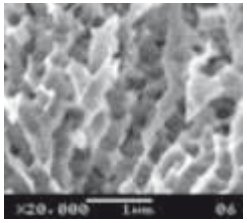


Opaque lenses

teeth (ex vivo)



Scotch tape



porous semi-conductor

paint (dry)

egg shell

daisy petals (fresh)

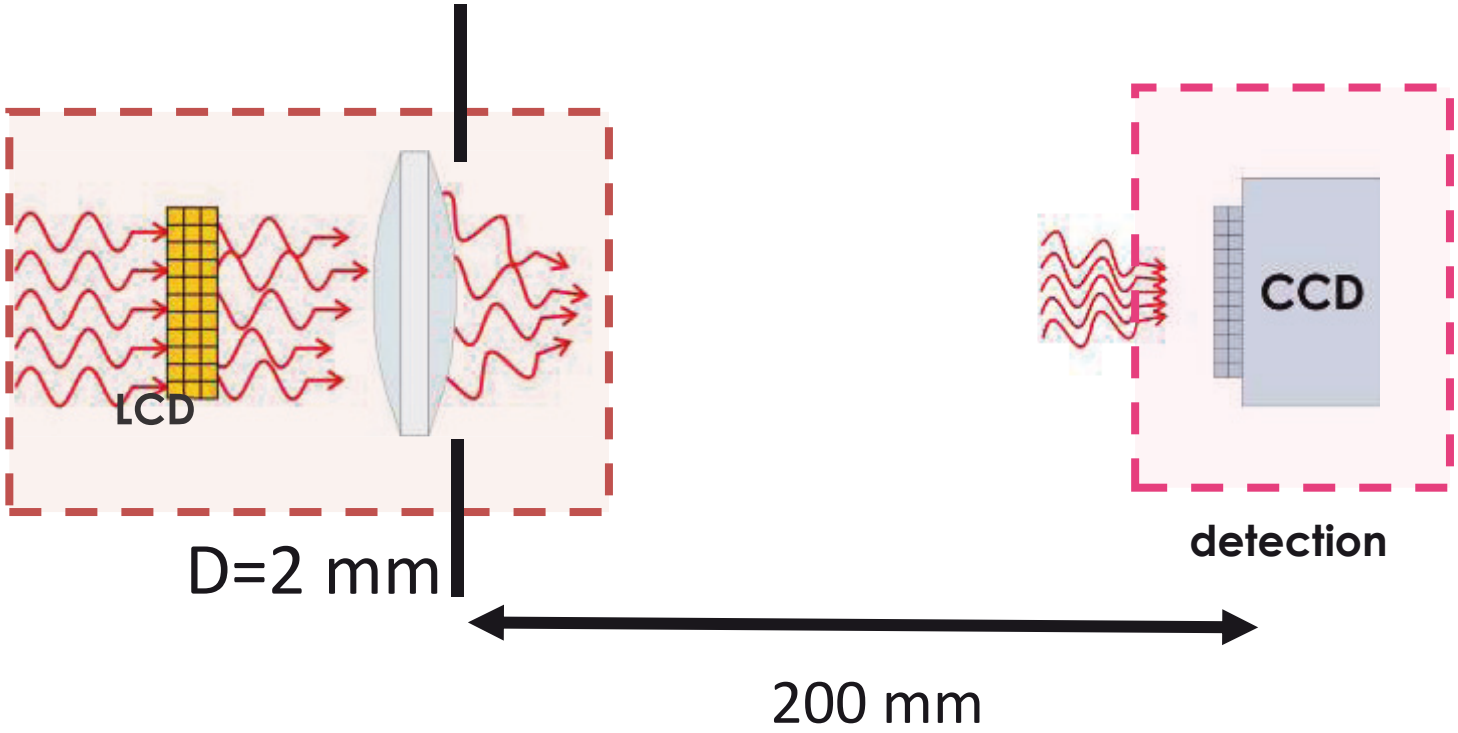
chicken breast (prepared)

Living tissue ? (Cui, Mc. Dowell,Yang ,Opt Expr. 2010)

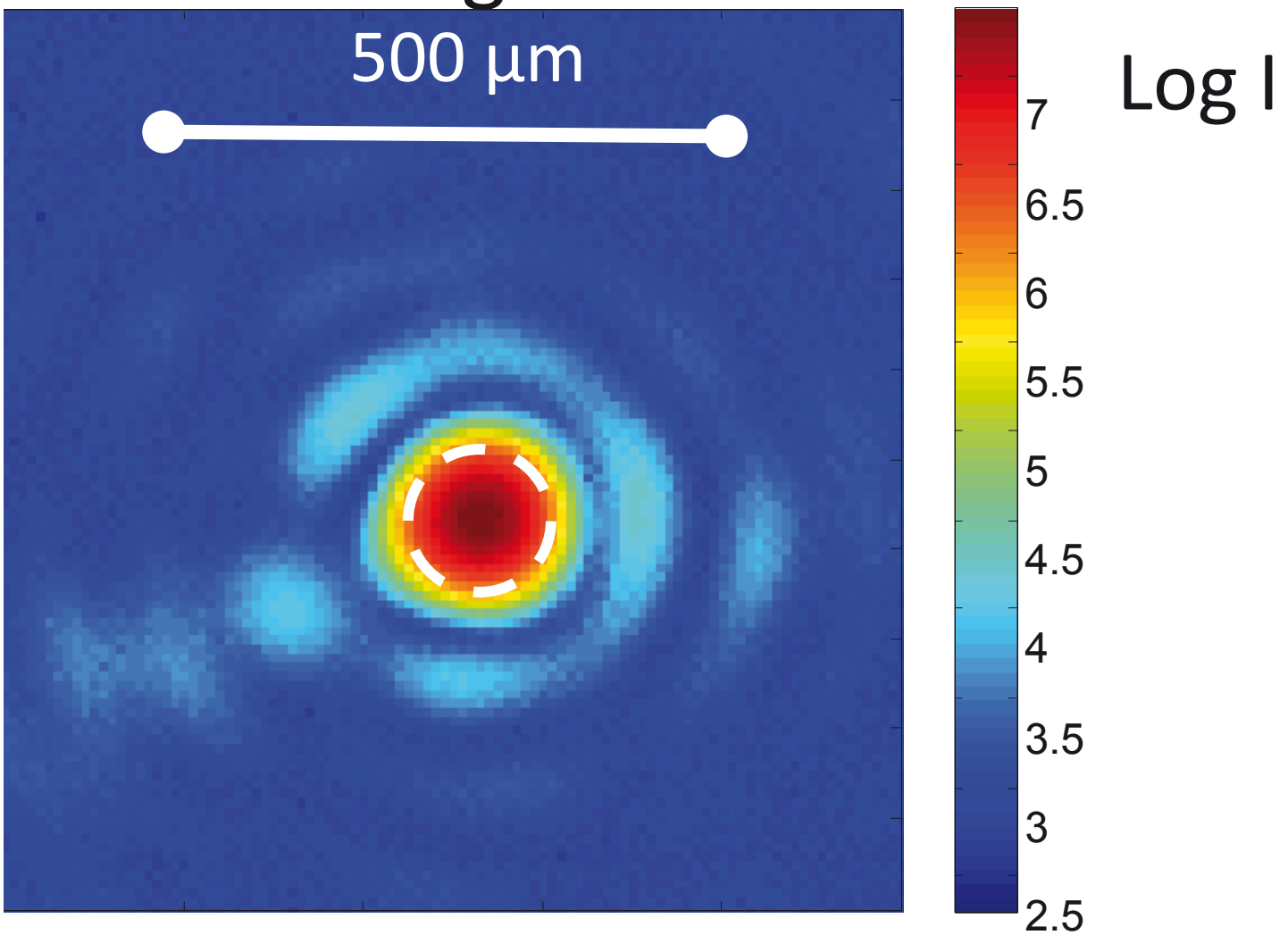
Influence of scattering on focusing resolution

Traditional view:
Scattering degrades resolution
Acoustical work by Fink group:
Scattering can sometimes improve resolution
Does this work in optics?

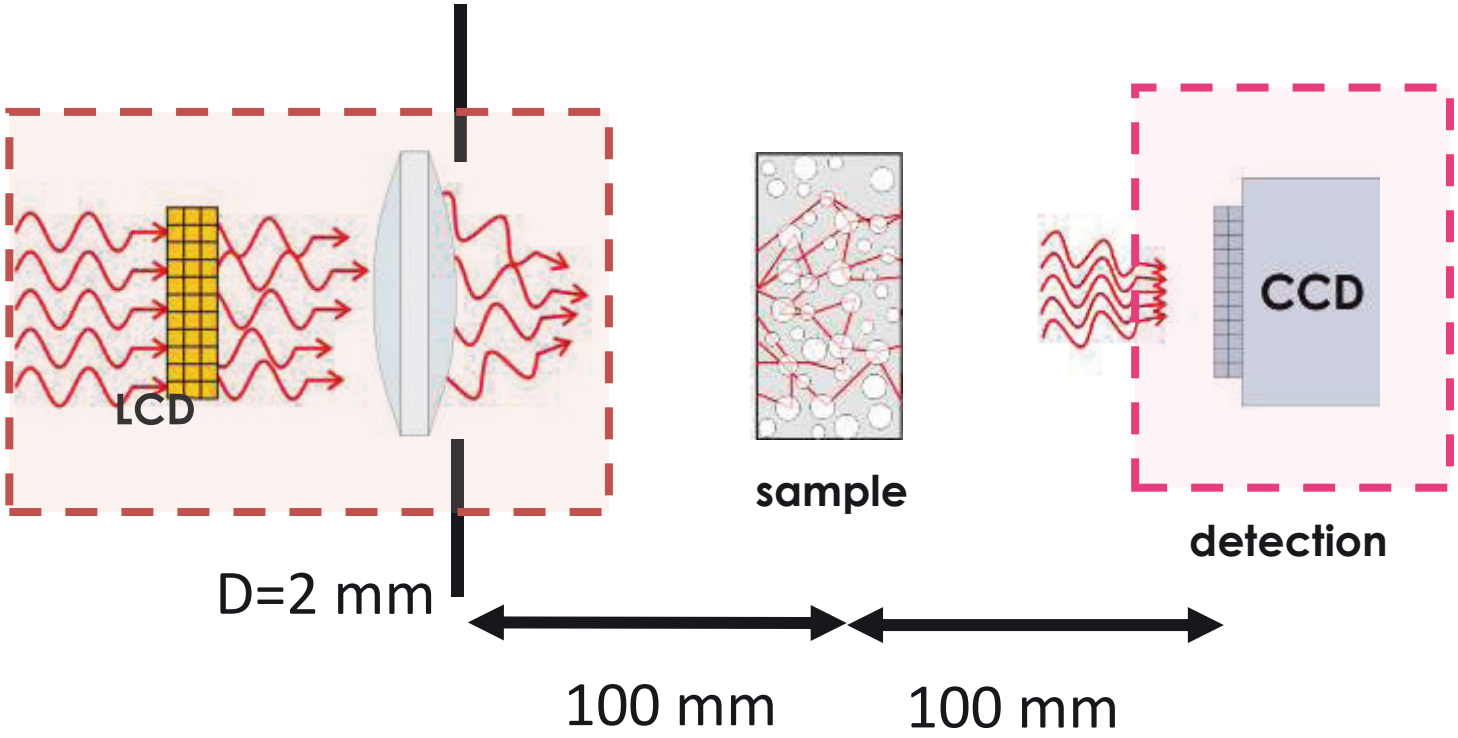
Reference measurement:
No scattering



No scattering: Diffraction limit of the glass lens

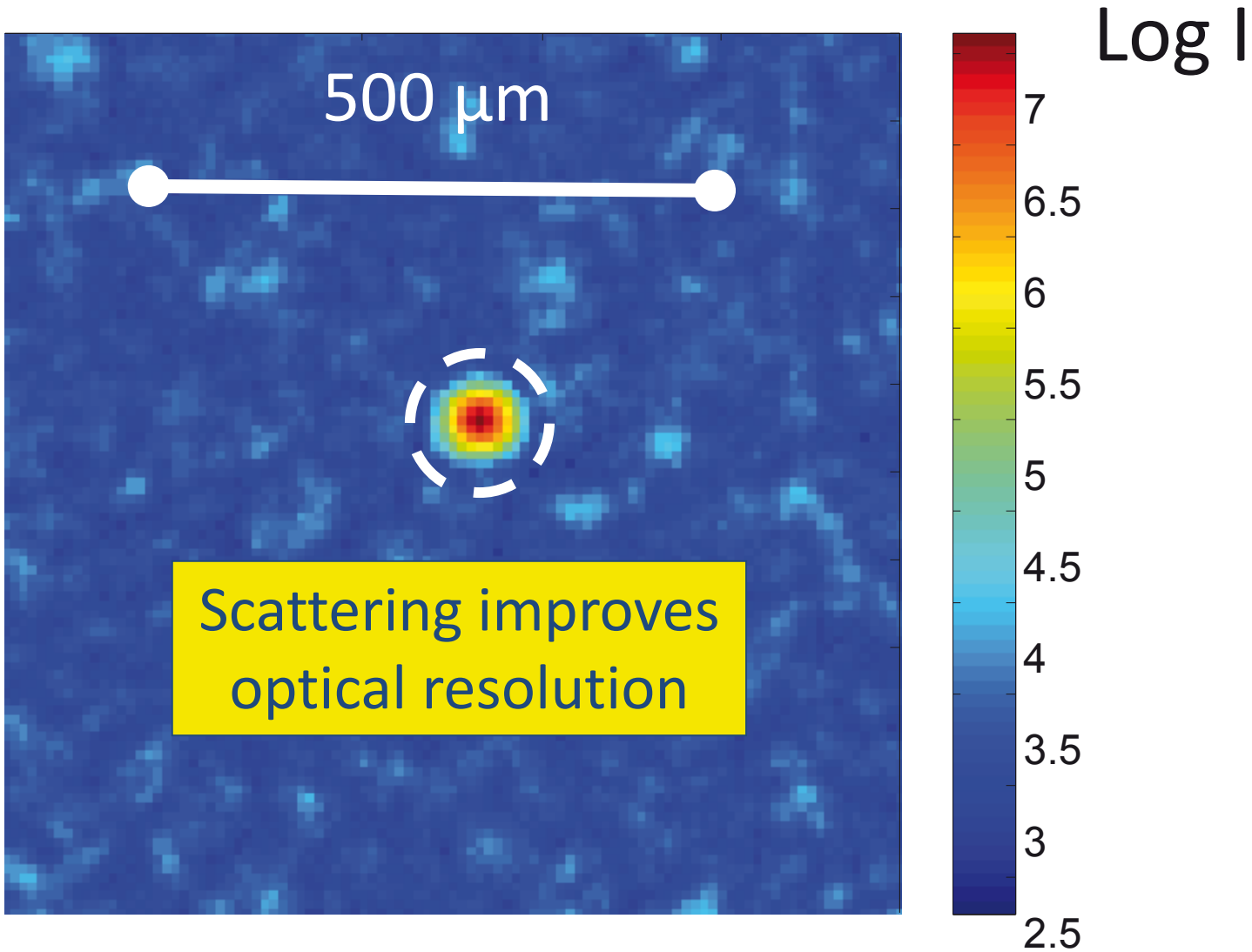


Scattering sample at 100 mm

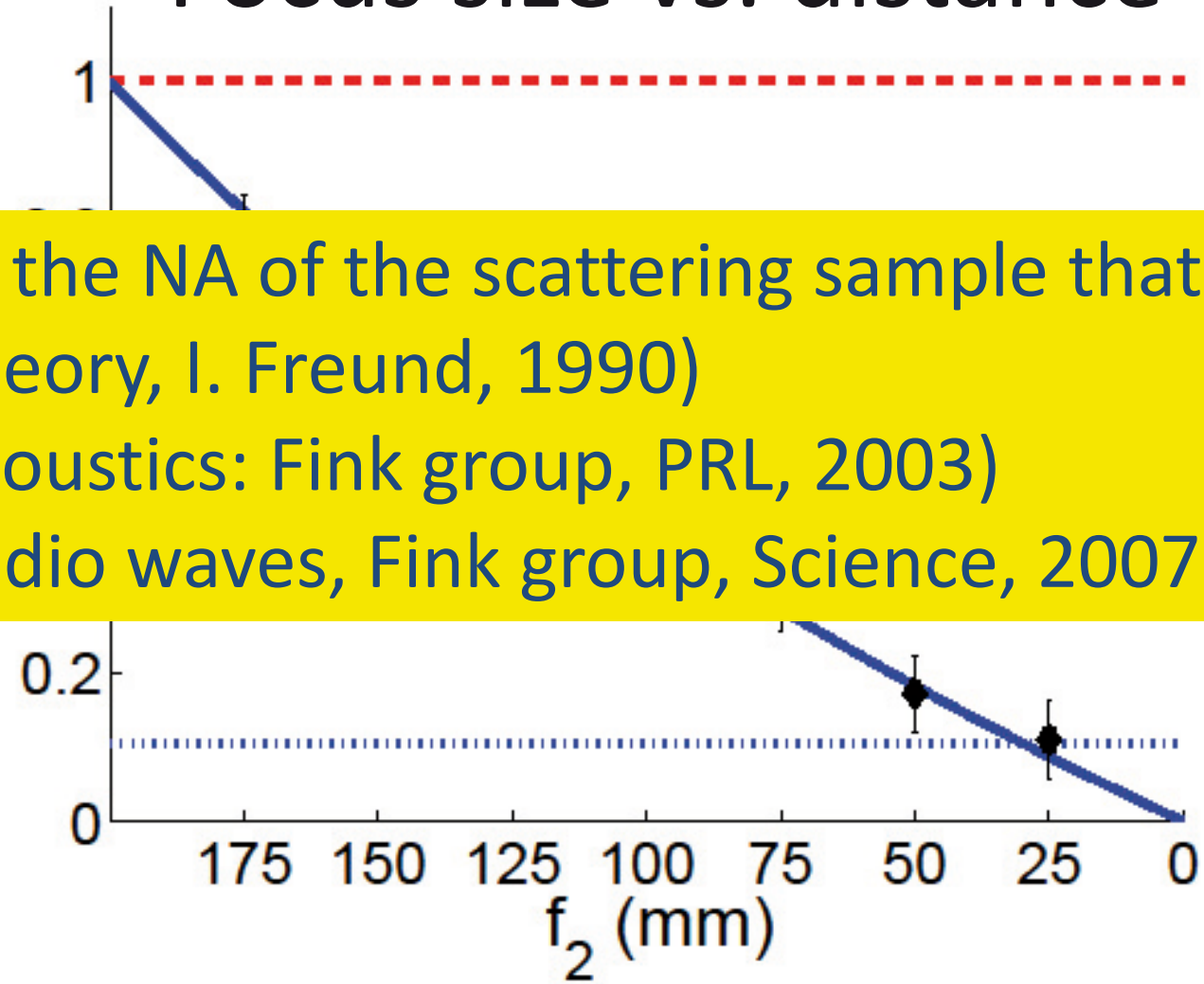


Optimize intensity

With scattering: Smaller focus



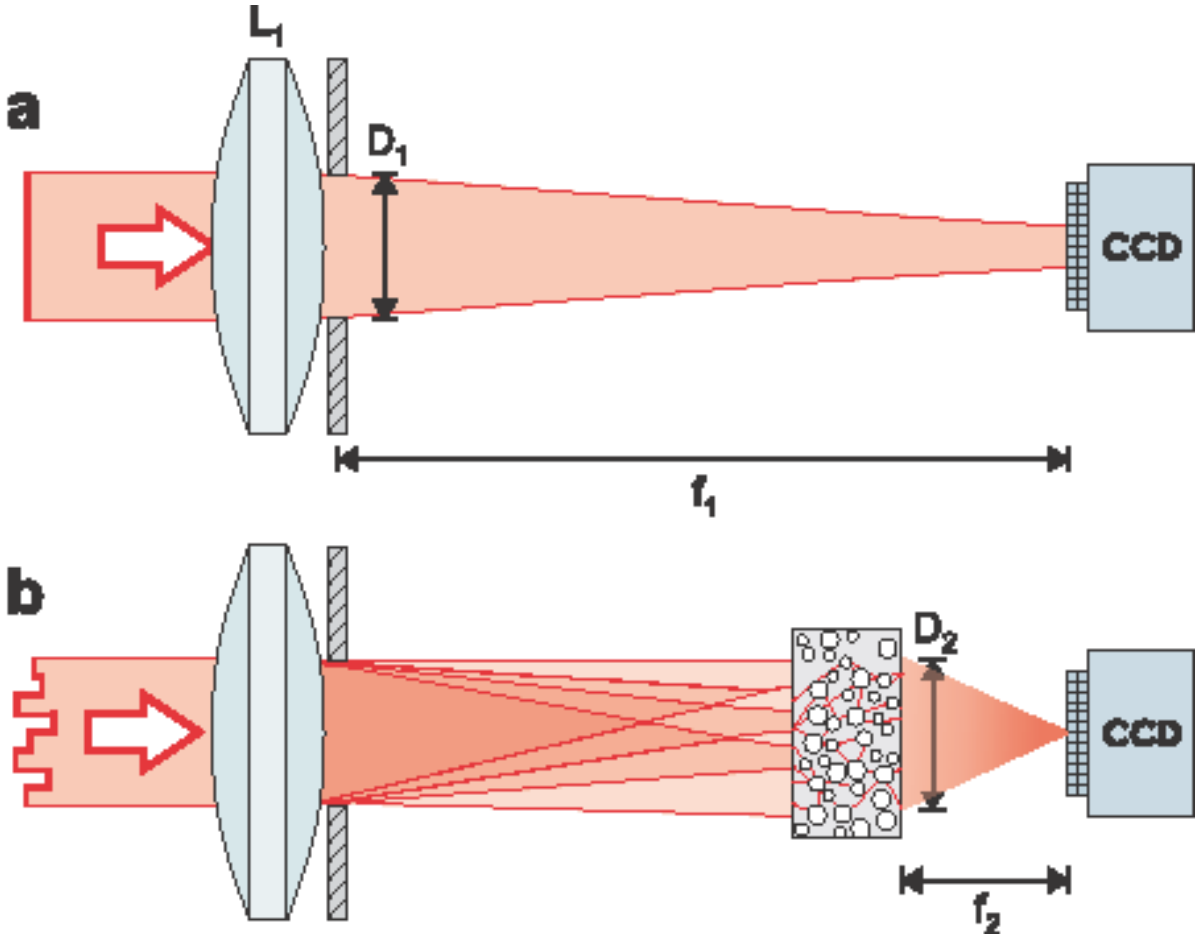
Focus size vs. distance



It's the NA of the scattering sample that counts
(Theory, I. Freund, 1990)
(Acoustics: Fink group, PRL, 2003)
(Radio waves, Fink group, Science, 2007)

I.M. Vellekoop, A.P. Mosk, A. Lagendijk Nat. Photon. (May 2010)

Opaque lens



Resolution and contrast

Normal lens / adaptive optics:

Wavefront error deteriorates focus size

Opaque lens:

Wavefront error scattered into background

(deteriorates focus contrast)

Focus size unaffected.

Wave transport and Random Matrices

Two regimes of wave transport

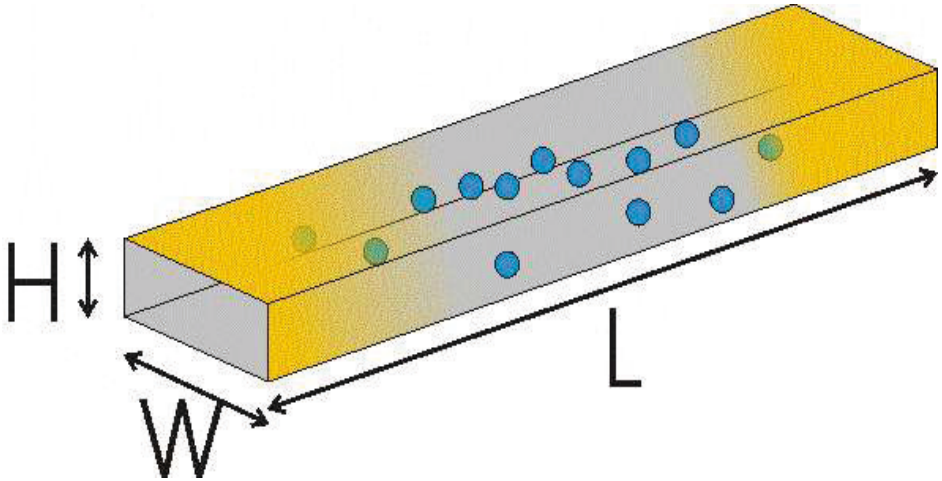
Waveguide geometry

Fixed number of propagating modes. Losses and leaks under control.

Open geometry

Real-world case. Most intensity leaks out of system.

Transport in lossless waveguide

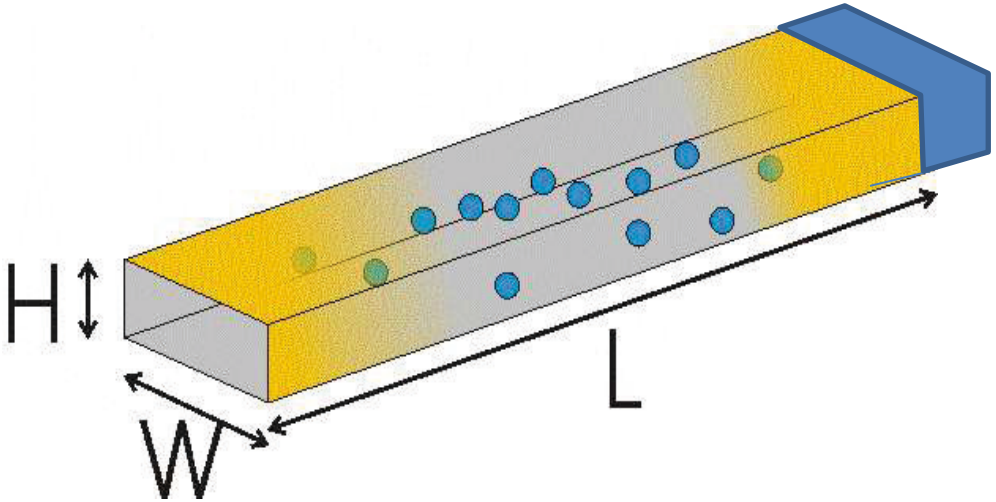


The random sample is modeled as a waveguide with disorder.

Transmission matrix t_{ab} : coupling between $2\pi\,(HW)/\lambda^2$ channels, on left and right sides of the waveguide. We look for the eigenvalues of $tt^\dagger$

Strong parallels exist with transport of electrons (Anderson, John, Pendry, Beenakker, Soukoulis)

Waveguide geometry



What happens to the matrix *t* when we add a thin disordered slice to the sample?

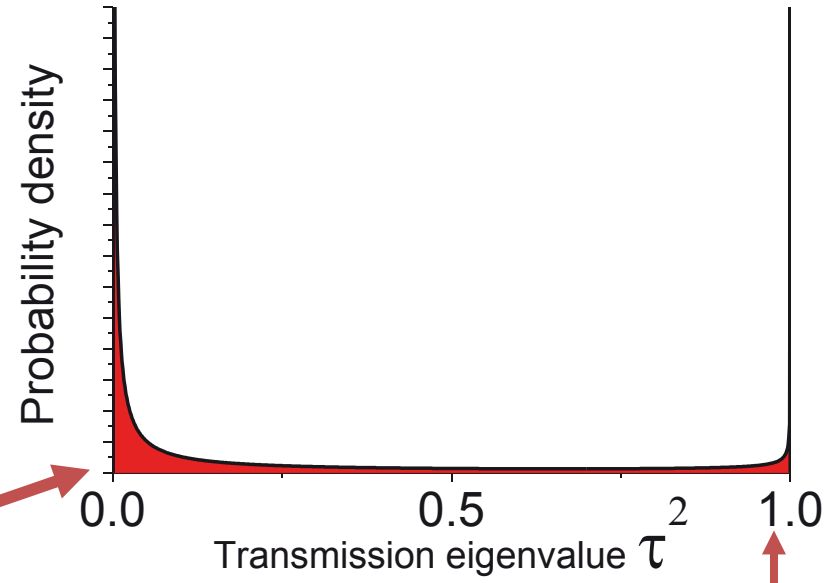
$$t_{1+2} = t_1 t_2 + t_1 r_2 r_1 t_2 + \ldots$$

Thin slice has transmission matrix close to unity.
Eigenvalues only slightly perturbed: $\tau \rightarrow \tau + \delta\tau$
"Brownian motion of eigenvalues"

Bimodal transparency distribution

- Dorokhov, Mello, Perreyra, Kumar: DMPK distribution of eigenvalues (1980s).

$$P(\tau^2) \propto \frac{1}{\tau^2\sqrt{1-\tau^2}}$$

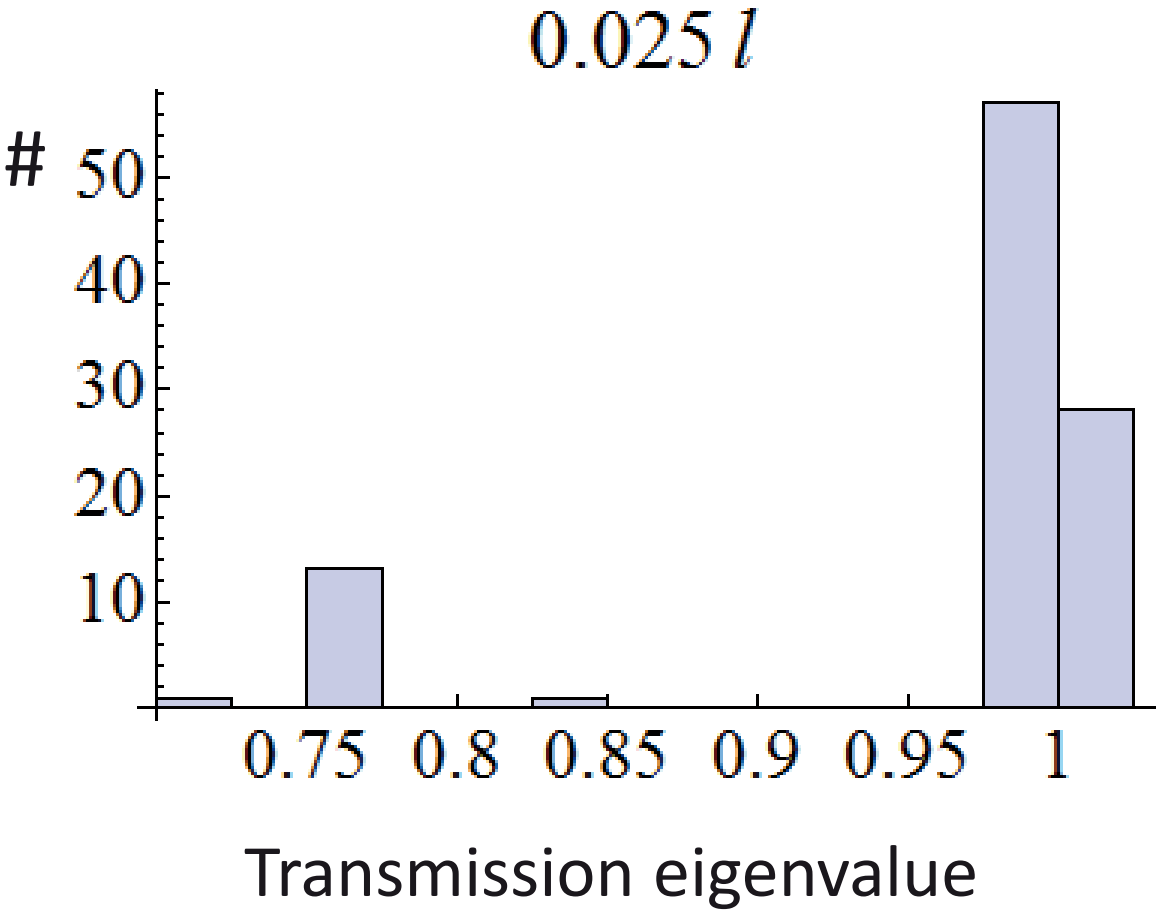


MANY closed channels
Transparency eigenvalues 0

FEW open channels

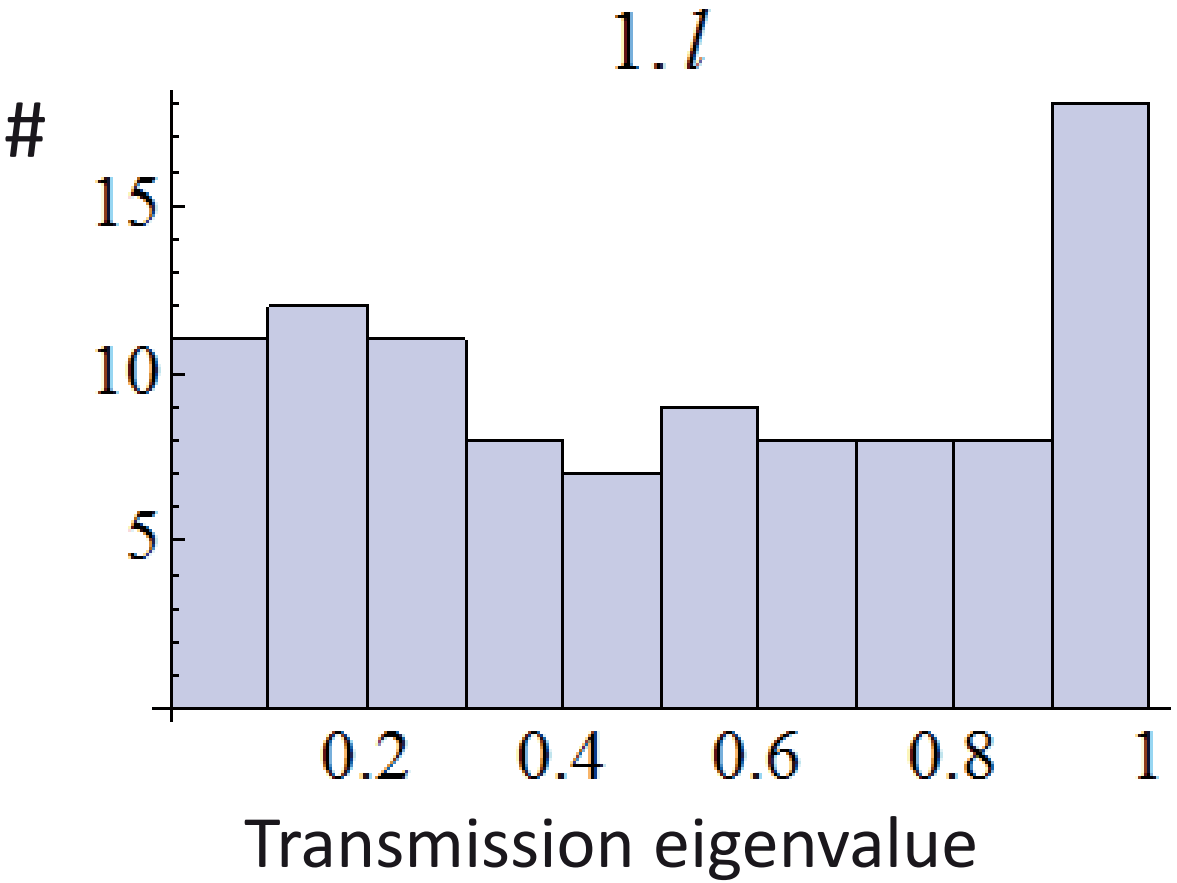
Pendry (1990): "Maximal Fluctuations"

Numerical example



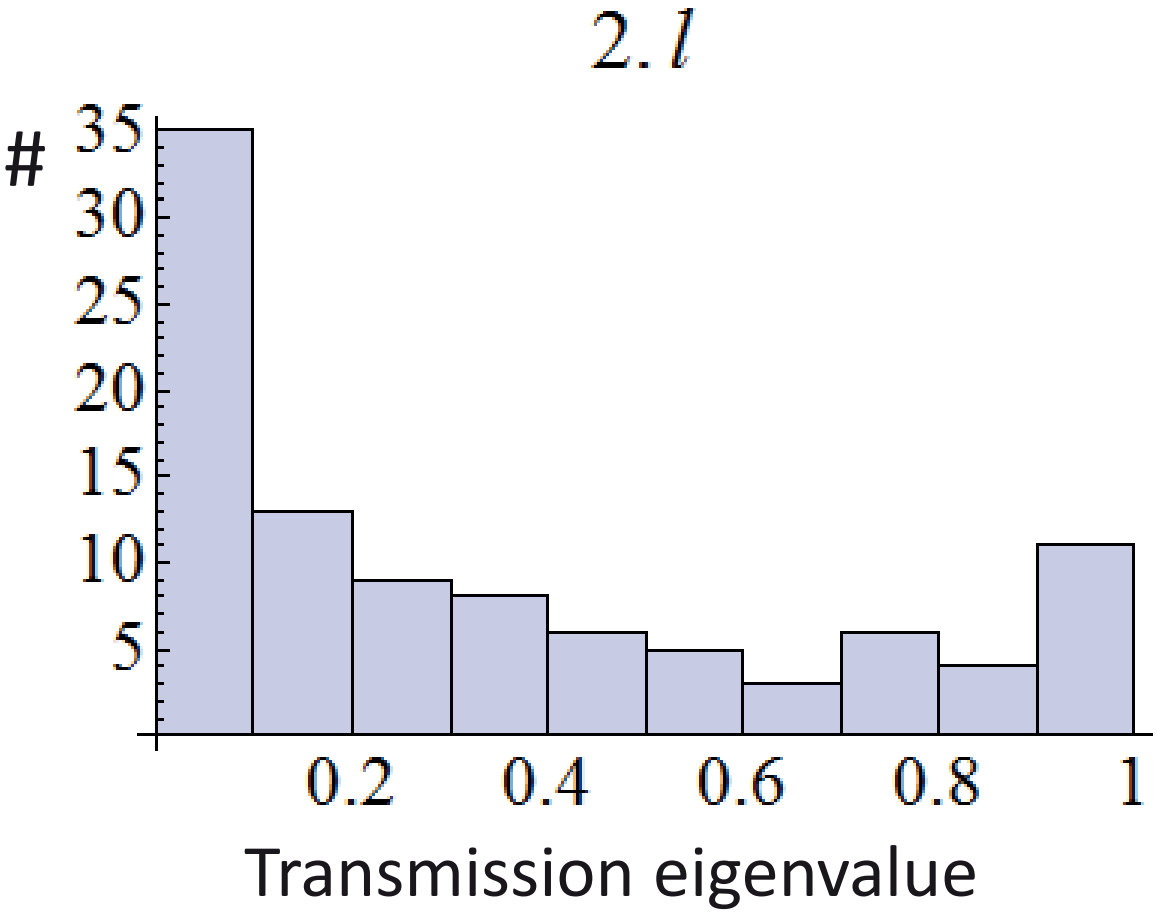
2D waveguide
width 75 λ

Numerical example



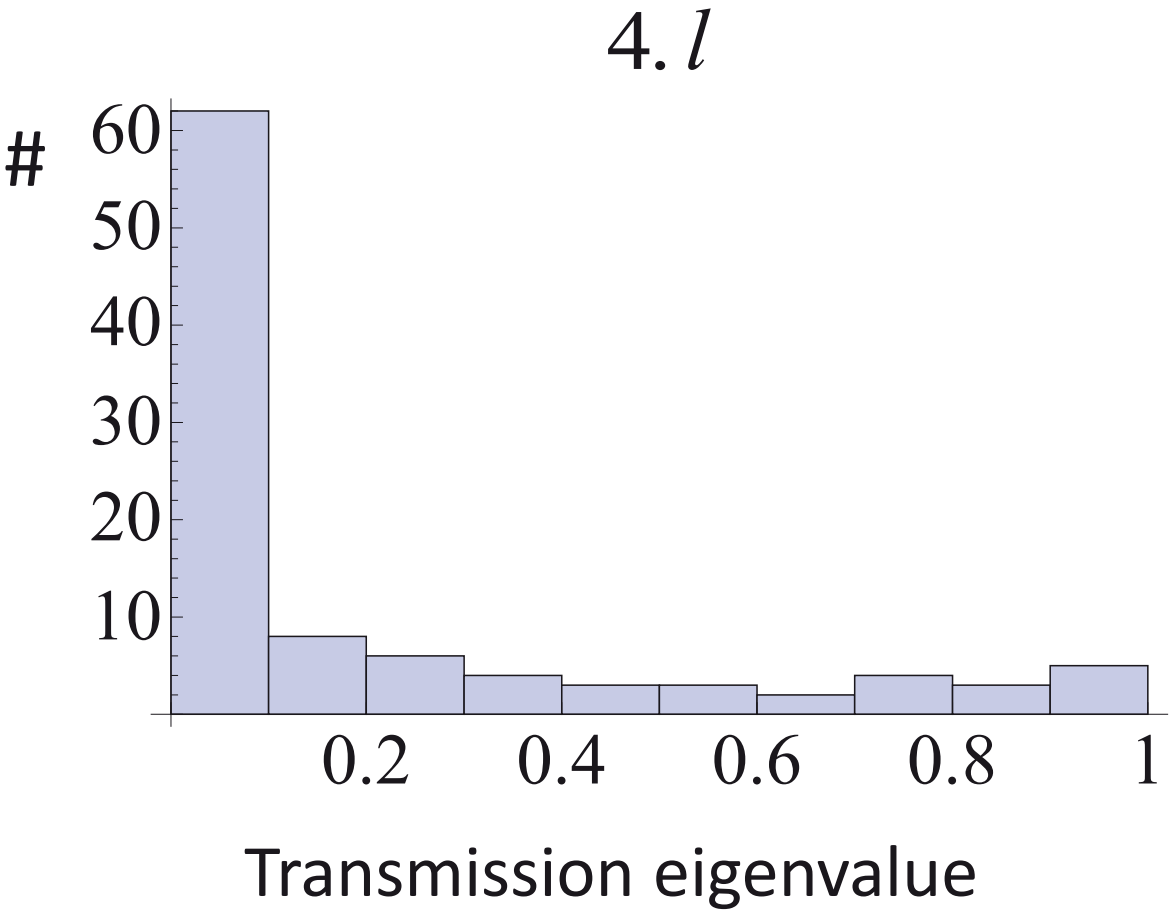
2D waveguide
width 75 λ

Numerical example



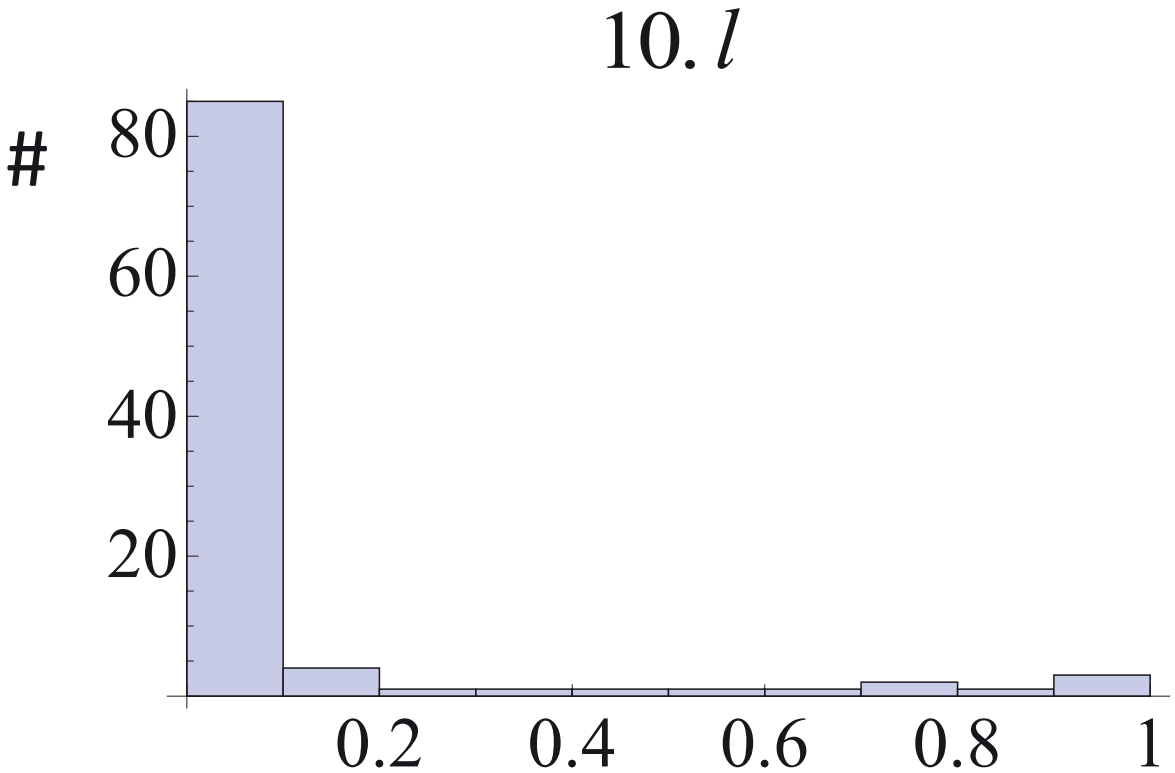
2D waveguide
width 75 λ

Numerical example



2D waveguide
width 75 λ

Numerical example



Transmission eigenvalue

How about the open geometry

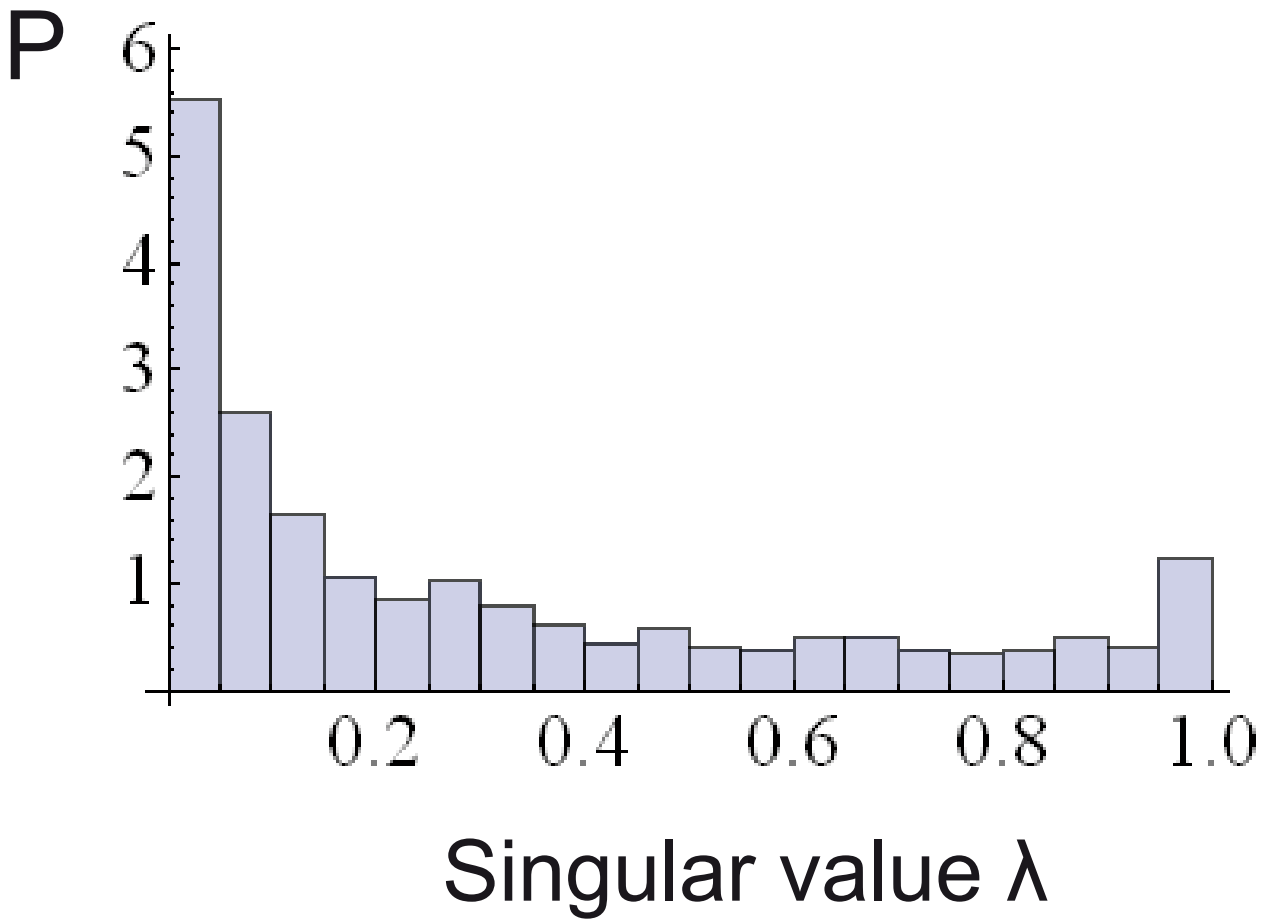
Same as closed geometry, but we are not observing all of the input/output channels.

We look at a submatrix of T

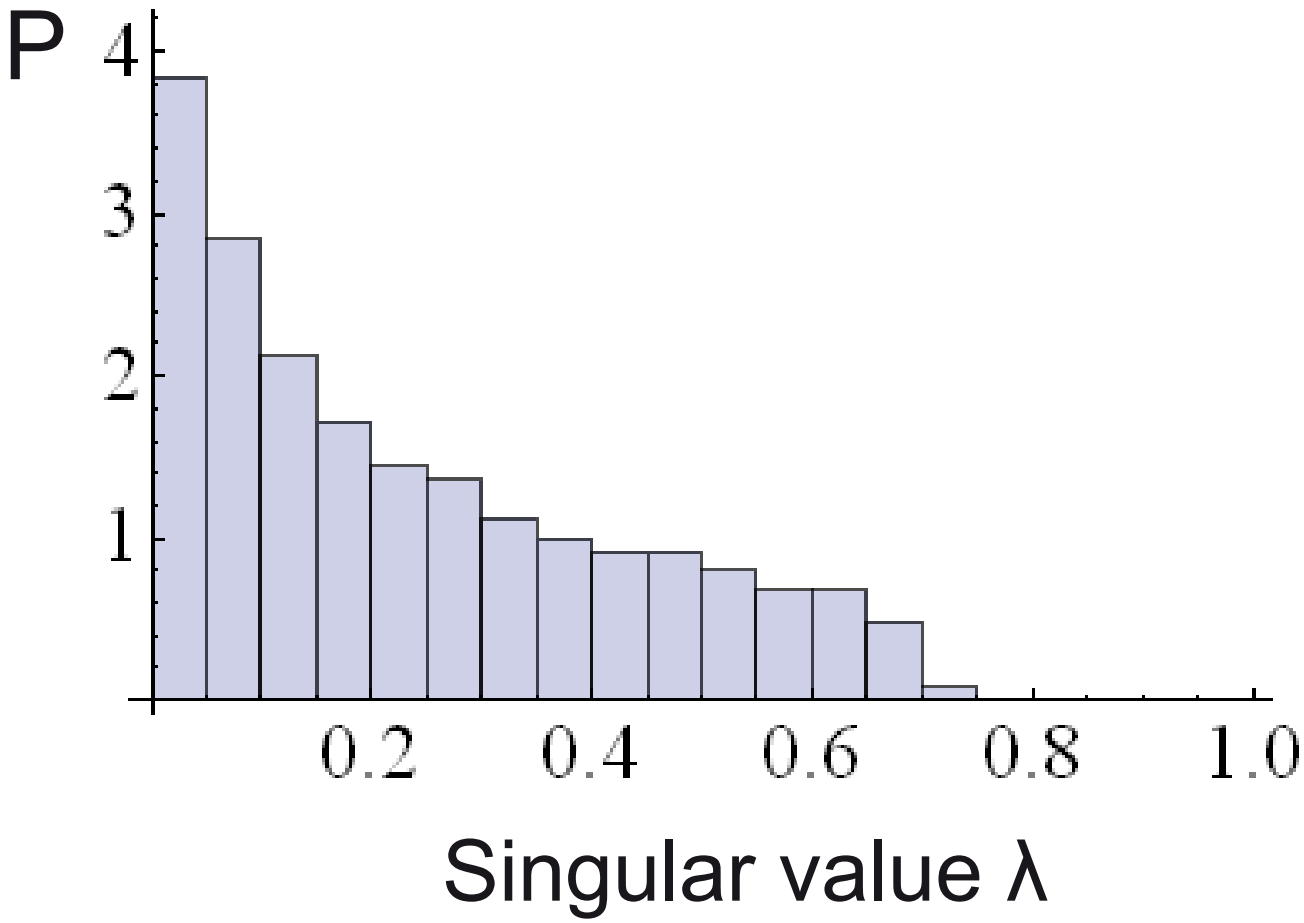
Famous result by Marchenko & Pastur:

Singular values of a small submatrix have quarter circle distribution.

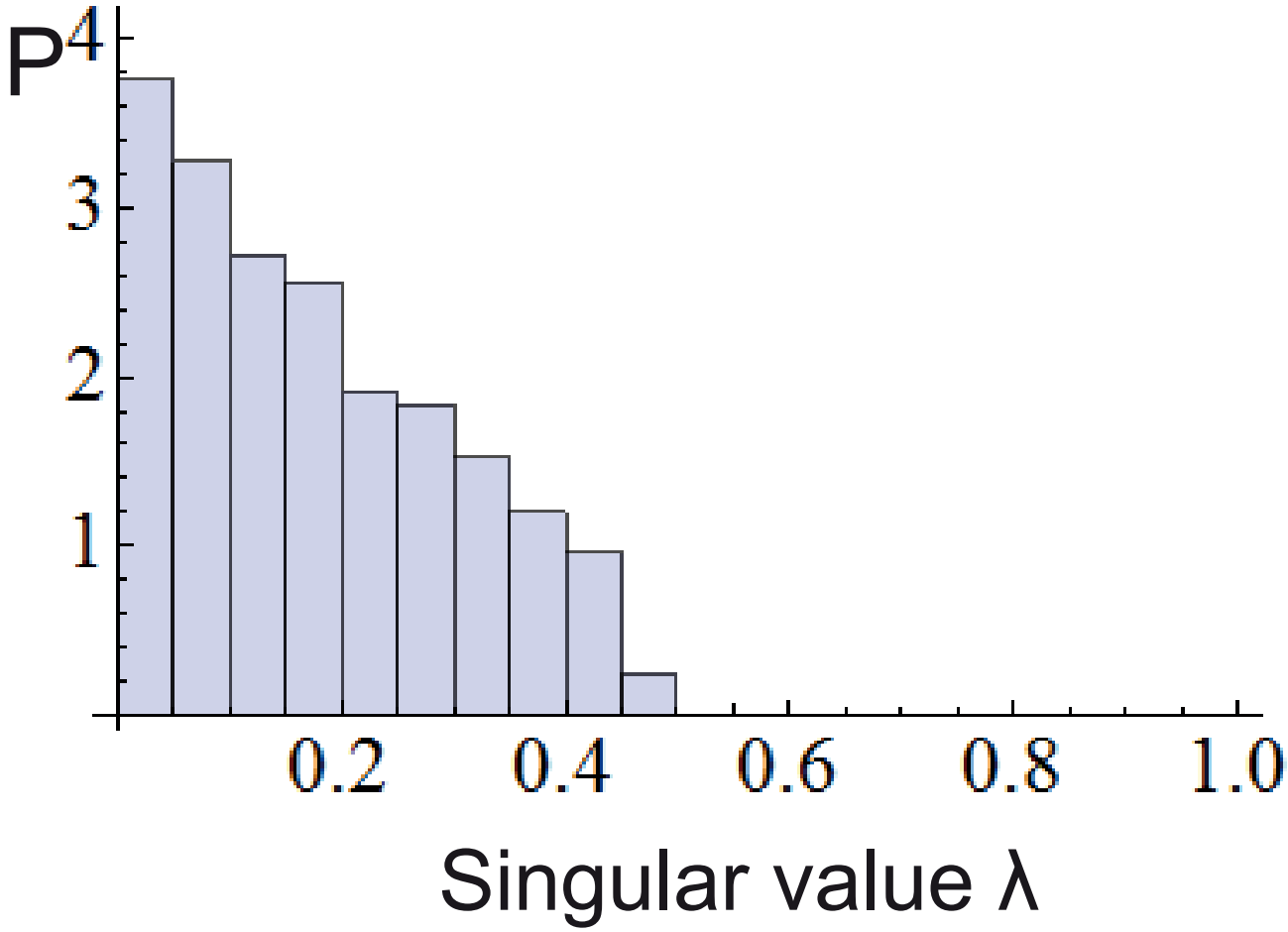
Full N x N matrix



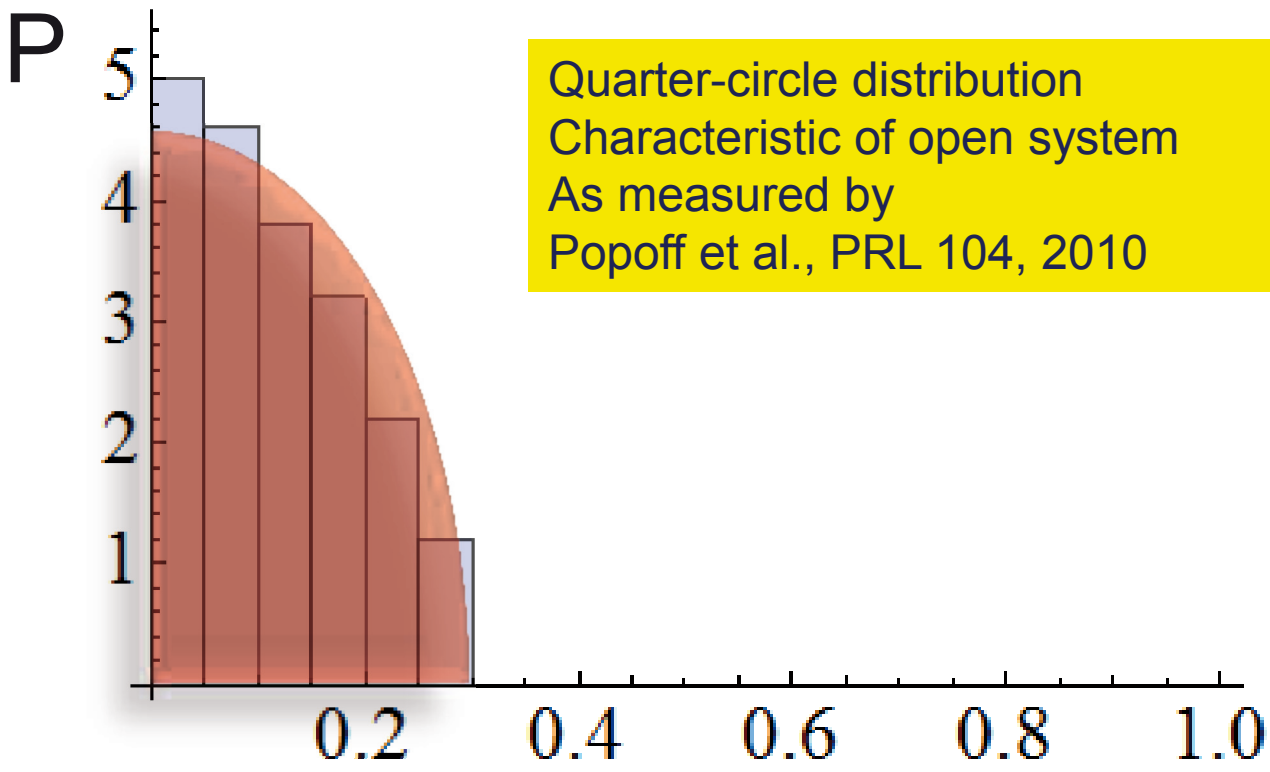
N/2 x N/2



N/4 x N/4



N/10 x N/10



Quarter-circle distribution
Characteristic of open system
As measured by
Popoff et al., PRL 104, 2010

Singular value λ

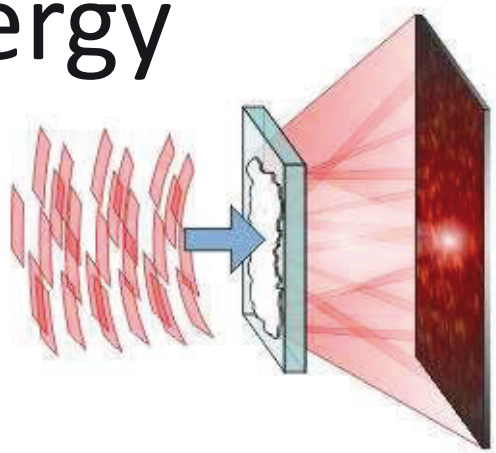
Towards perfect wavefronts

Perfect wavefront control:

- control all $2\pi A/\lambda^2$ incident modes
- Power in focus of order integrated background
- Light transmission strongly modified

Conservation of Energy

- *If we optimize and make a focus:*

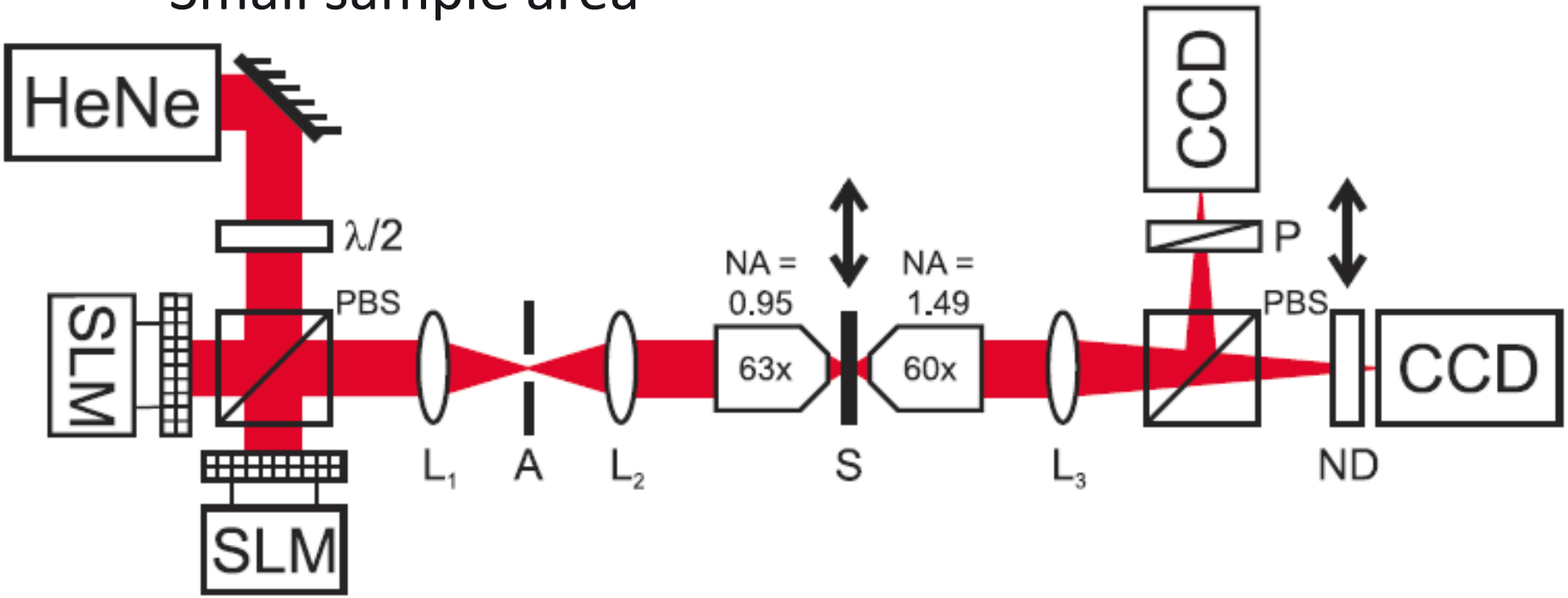


If open channels not present:
Background transmission stays the same.
(all speckles uncorrelated)

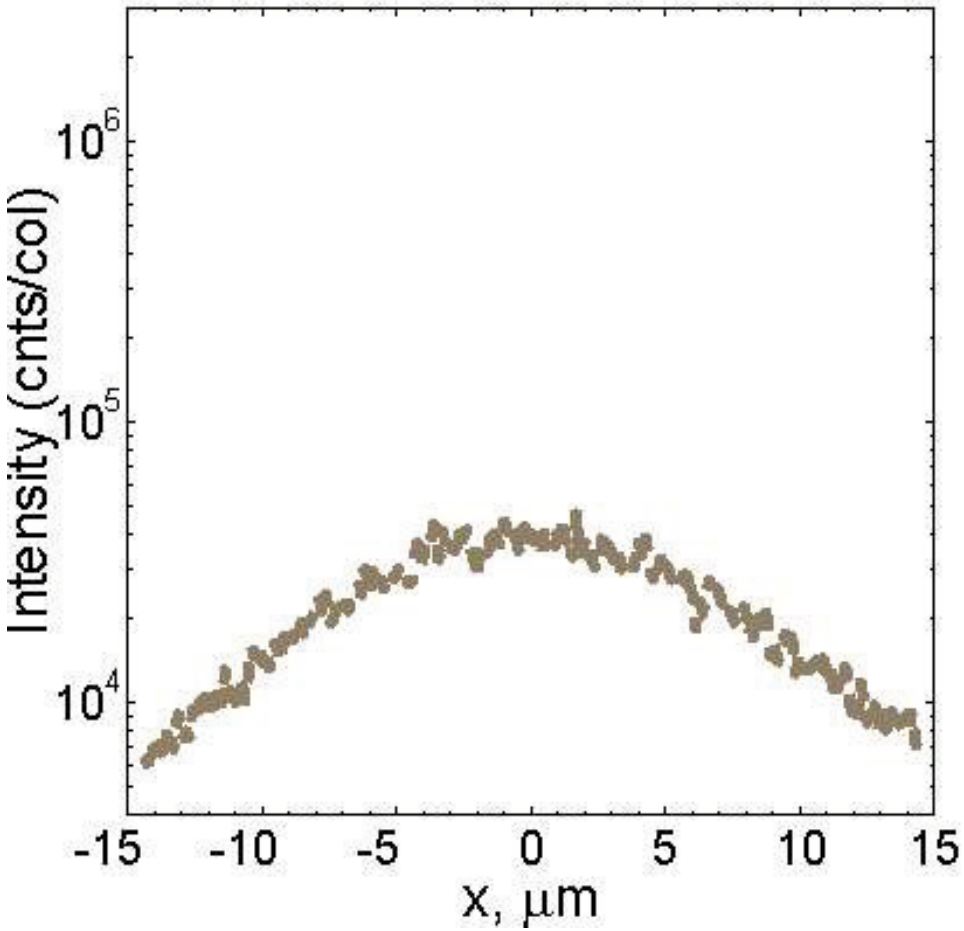
If open channels present:
Background transmission grows
(Intensity is moved into open channels)

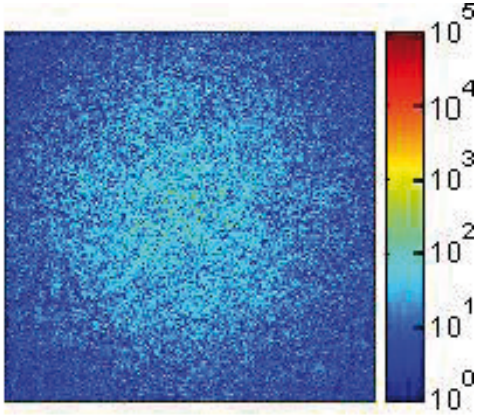
Setup for perfect wavefront control

- 2 polarizations
- High NA
- Small sample area

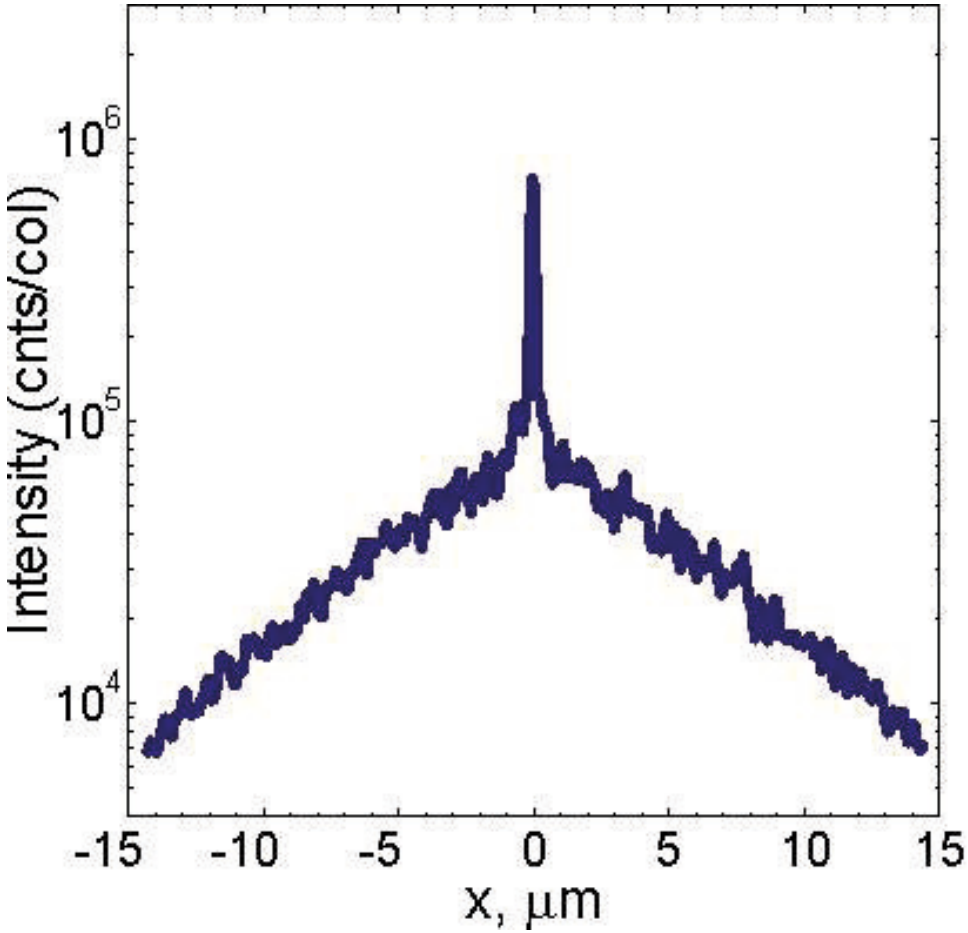


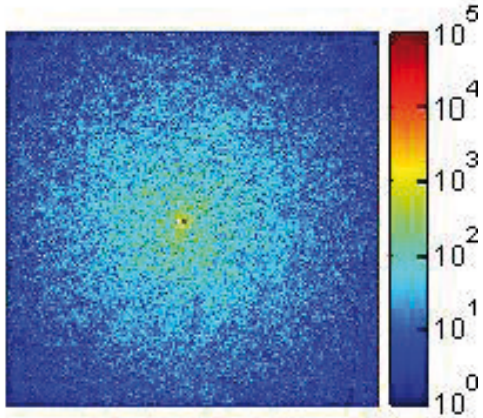
Before optimization



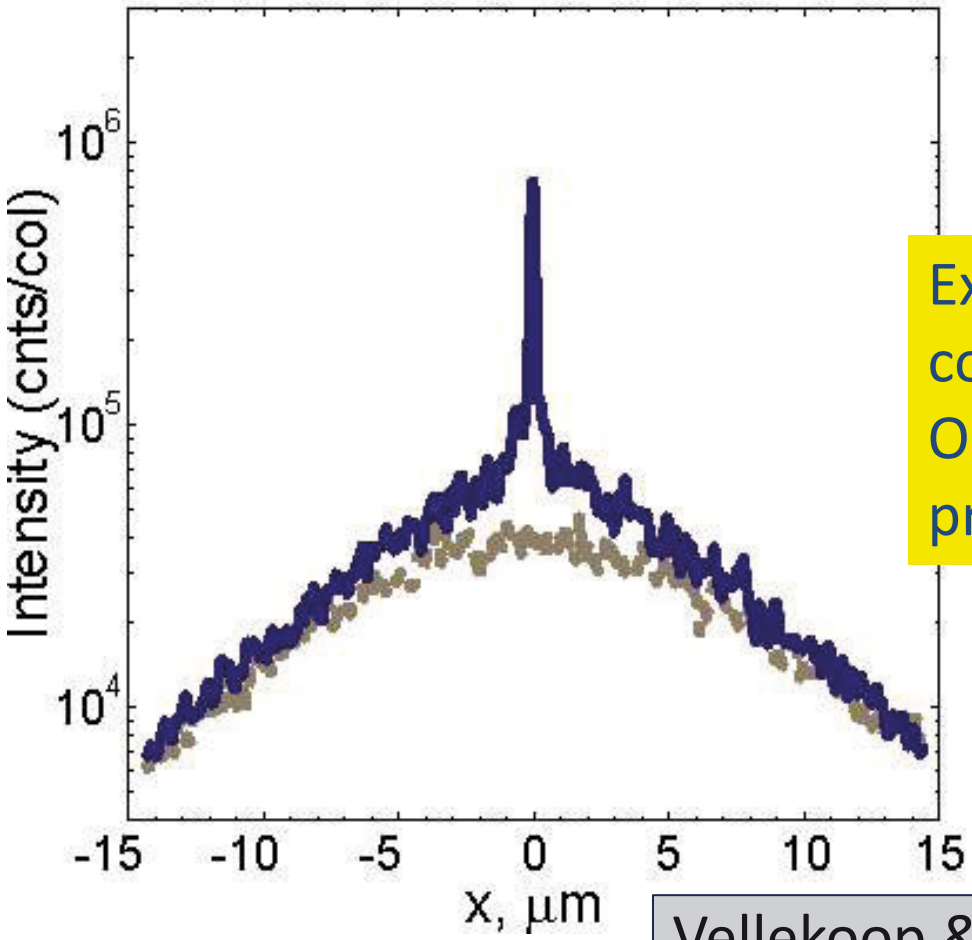


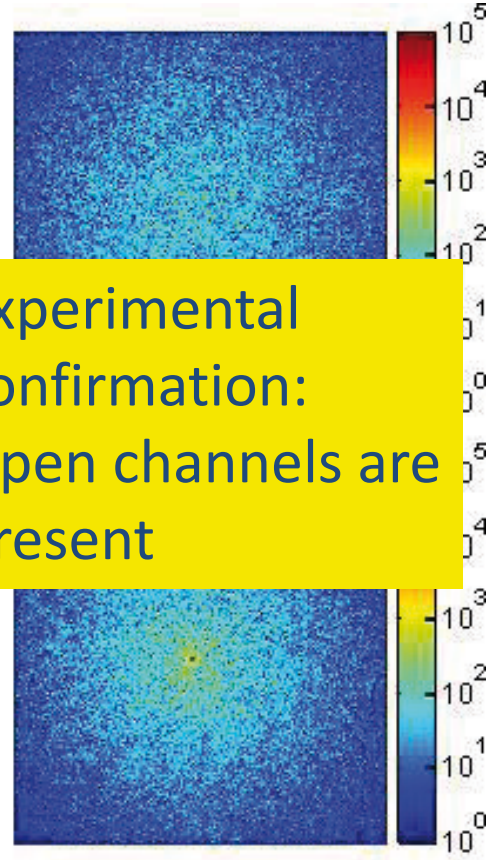
After optimization





Before and After





Experimental confirmation: Open channels are present

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

Optimal transmission

Transmission of a perfect phase conjugate wavefront

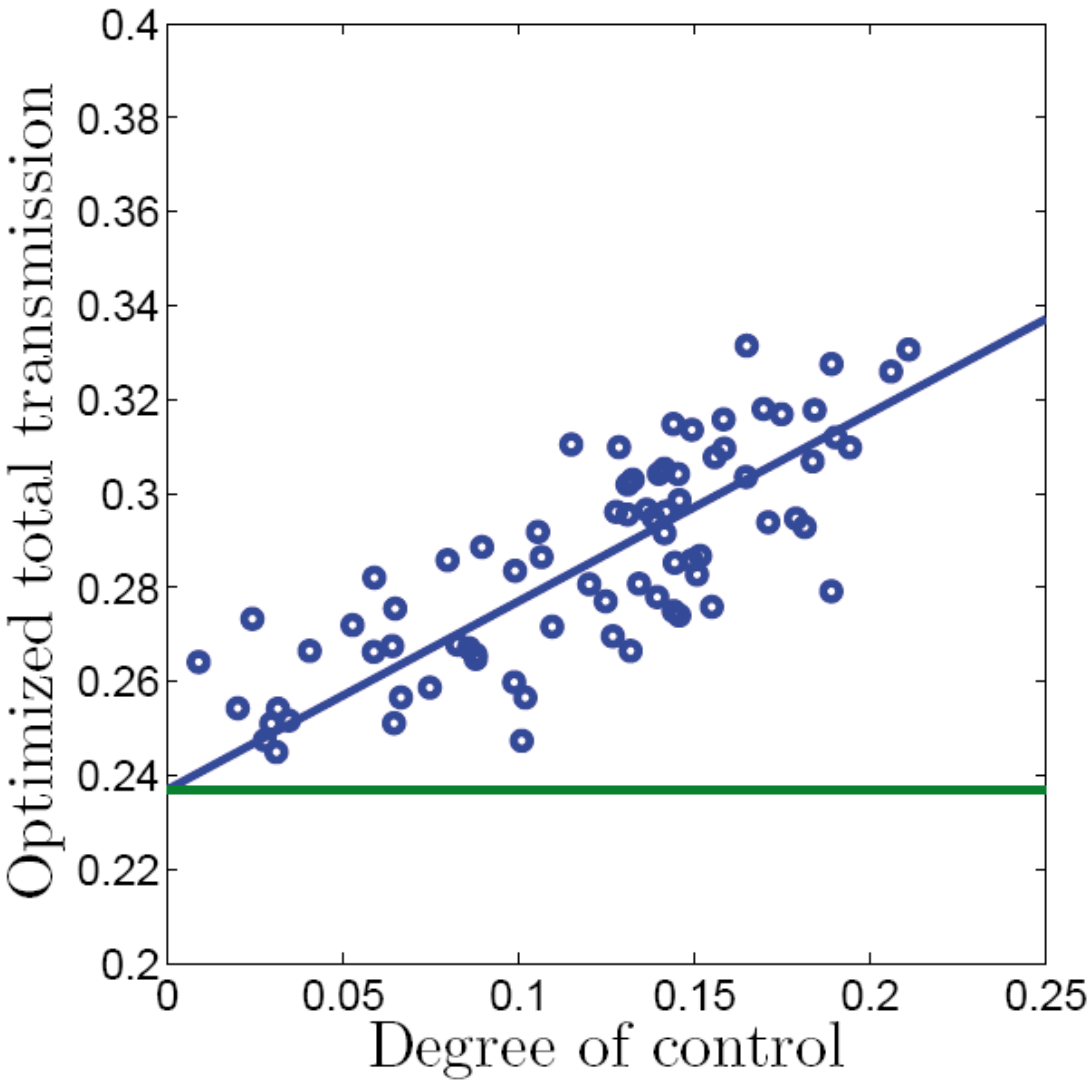
$$T_\varphi = \langle t^4 \rangle / \langle t^2 \rangle$$

2/3 for bimodal distribution,
2<T> for quarter circle.

However, wavefront is not perfect.
The focus intensity is a measure for its quality.

Degree of control =
(Measured Intensity in focus)/(Ideal intensity)
=
(# controlled DOF)/ (# total DOF)

More control, more transmission



Line extrapolates to T=0.64(7)

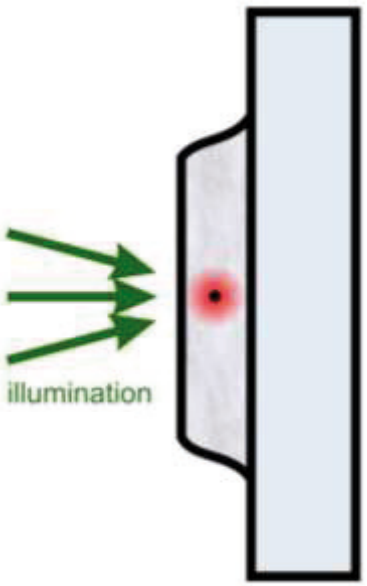
We find 0.67(17) for thicker samples

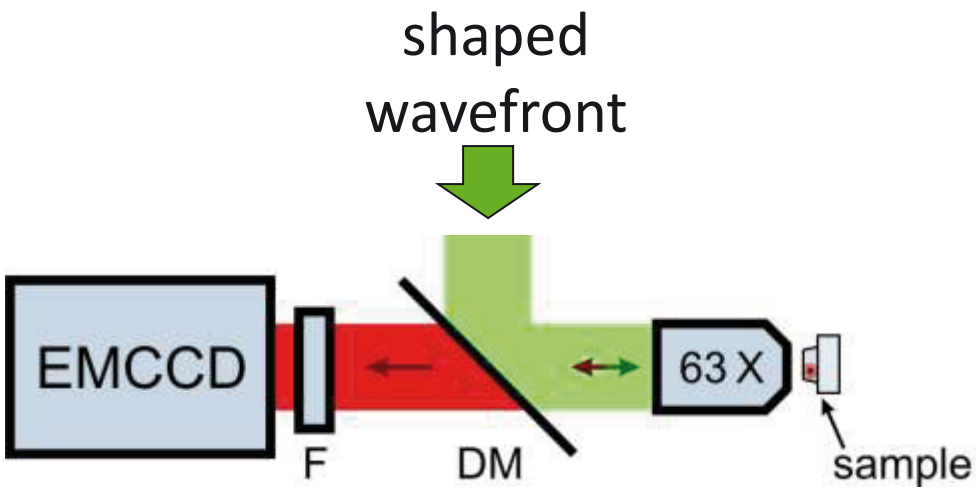
Direct evidence for bimodal distribution of transmission coefficients

Focusing *inside* opaque materials

Focusing inside

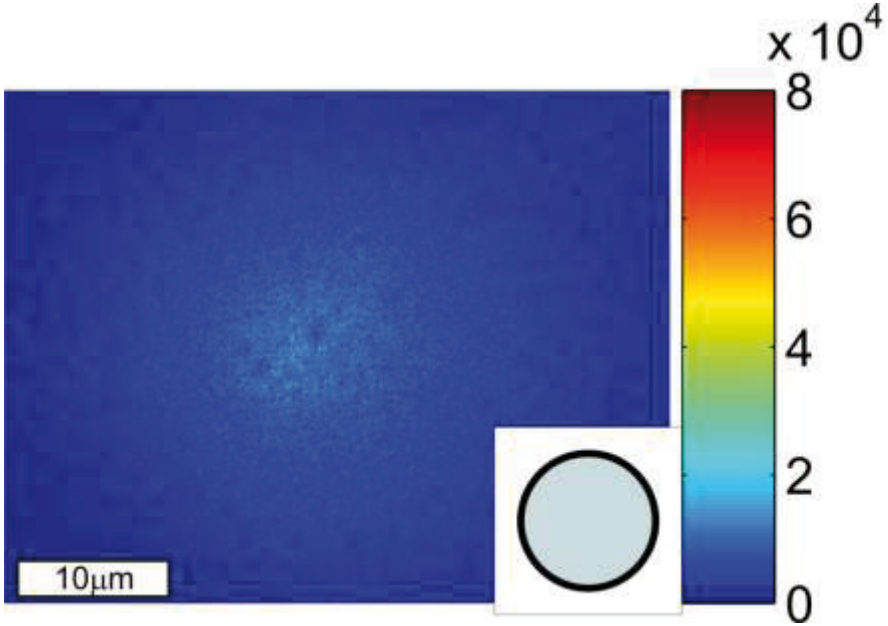
- First method to accomplish this!
- Use fluorescent probe particle for feedback.



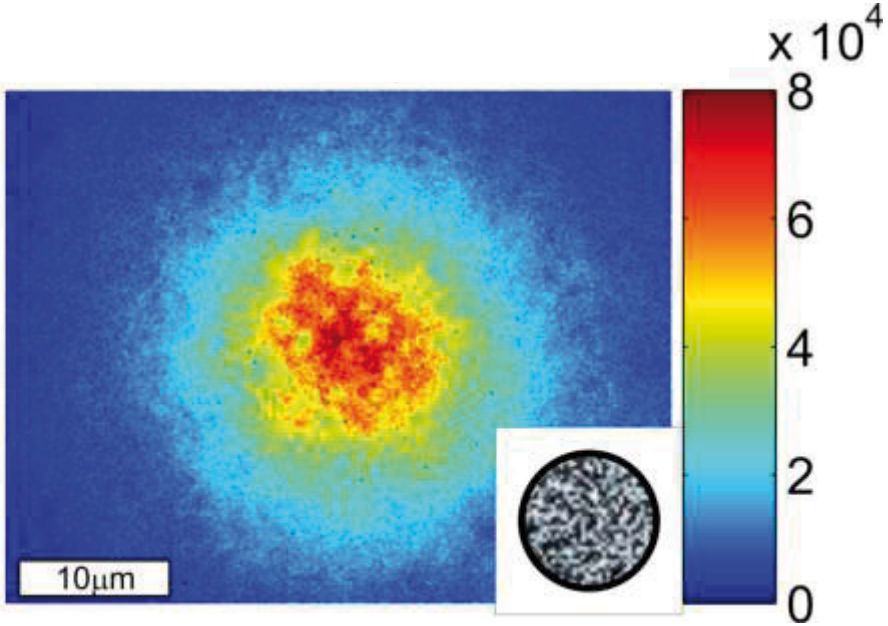


First focusing deep in turbid material

Fluorescence from embedded 300 nm sphere



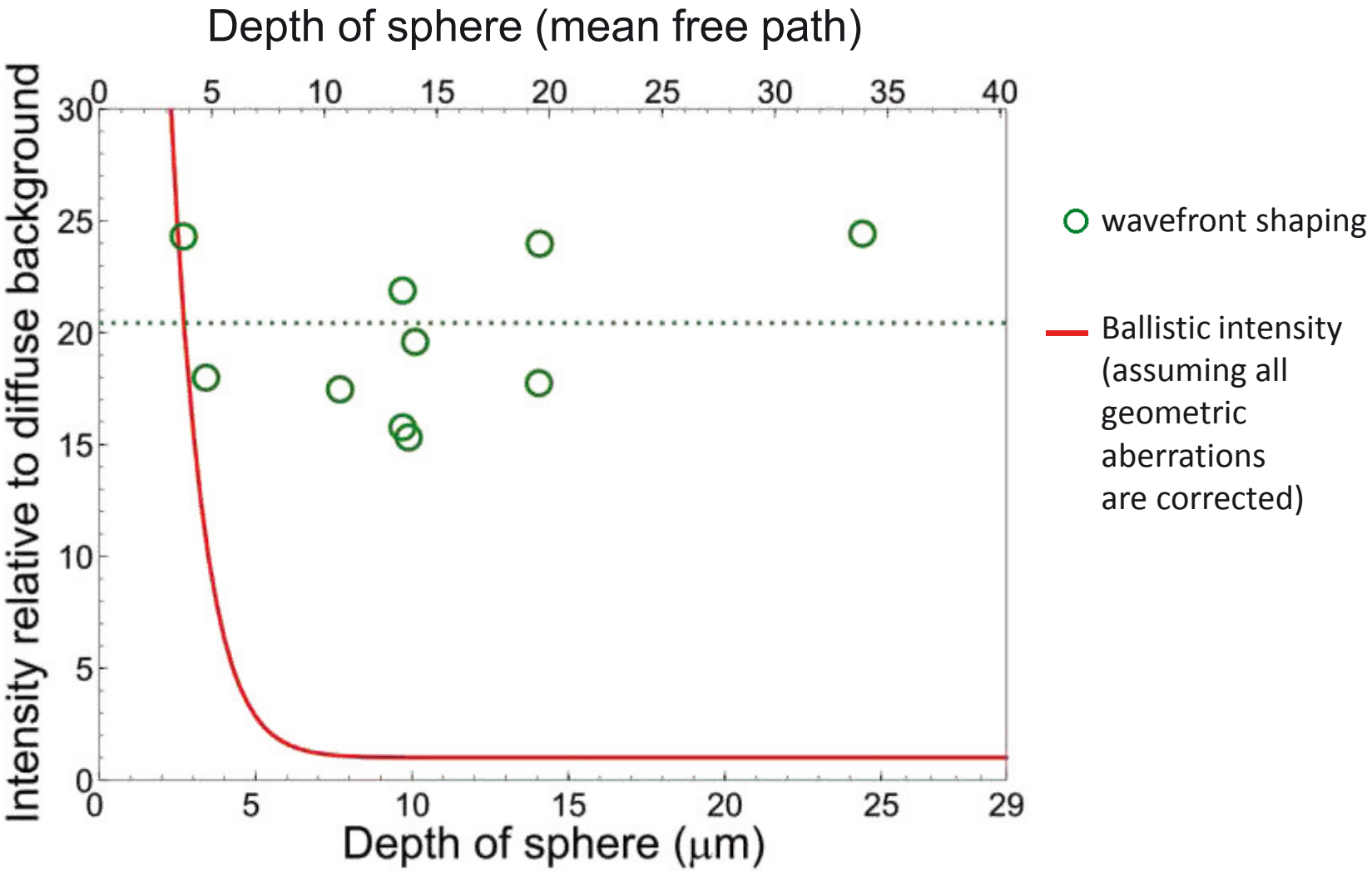
plane wave



shaped wave

Vellekoop, van Putten, Lagendijk & Mosk. Opt. Expr. **16**, 67 (2008)

Deep focussing



New development

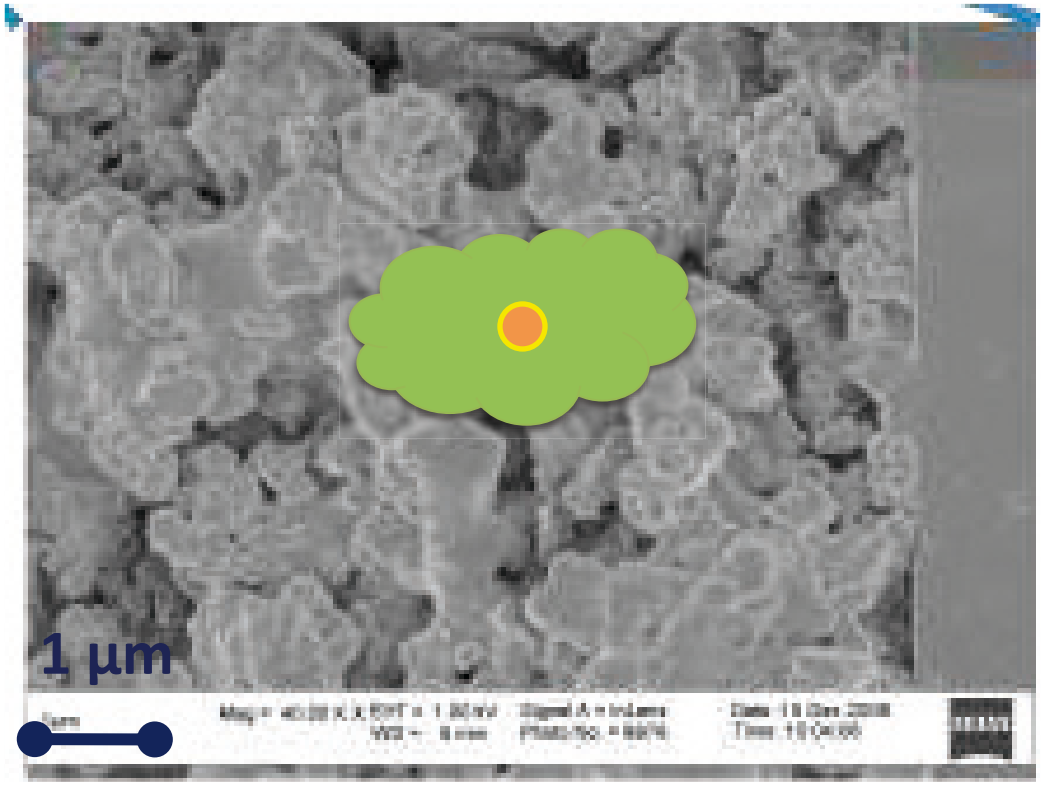
Lausanne Group (Hsieh et al, Opt Expr. 2010)

use a nanoprobe with nonlinear response

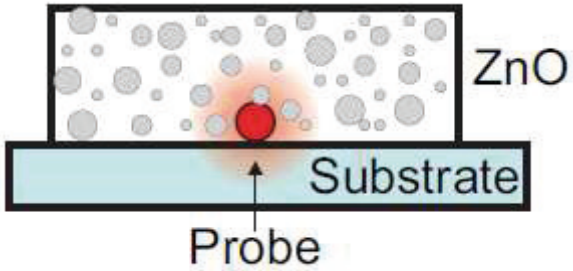
+ digital optical phase conjugation.

This allows one-shot focusing on an embedded particle. Intensity enhancement factor 30.

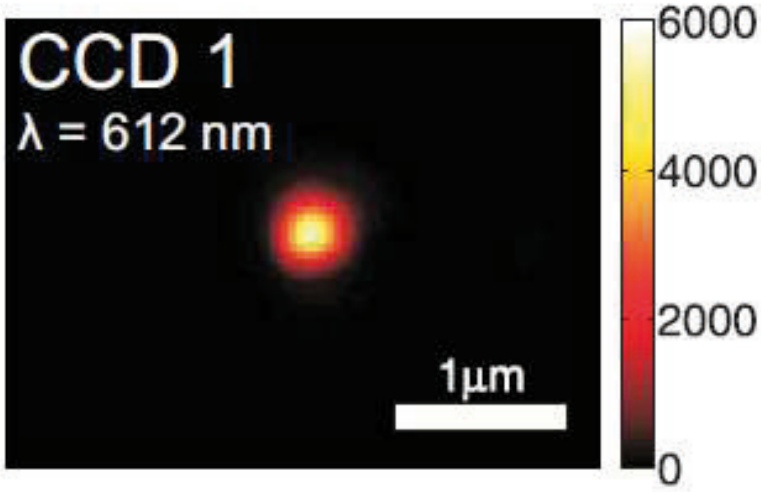
What is the size of the focus?

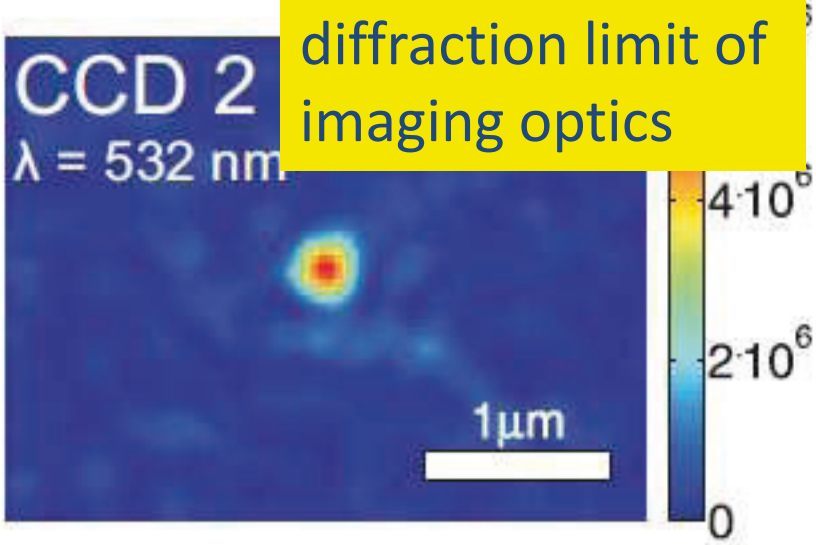


What is the size of the focus?



Probe emission



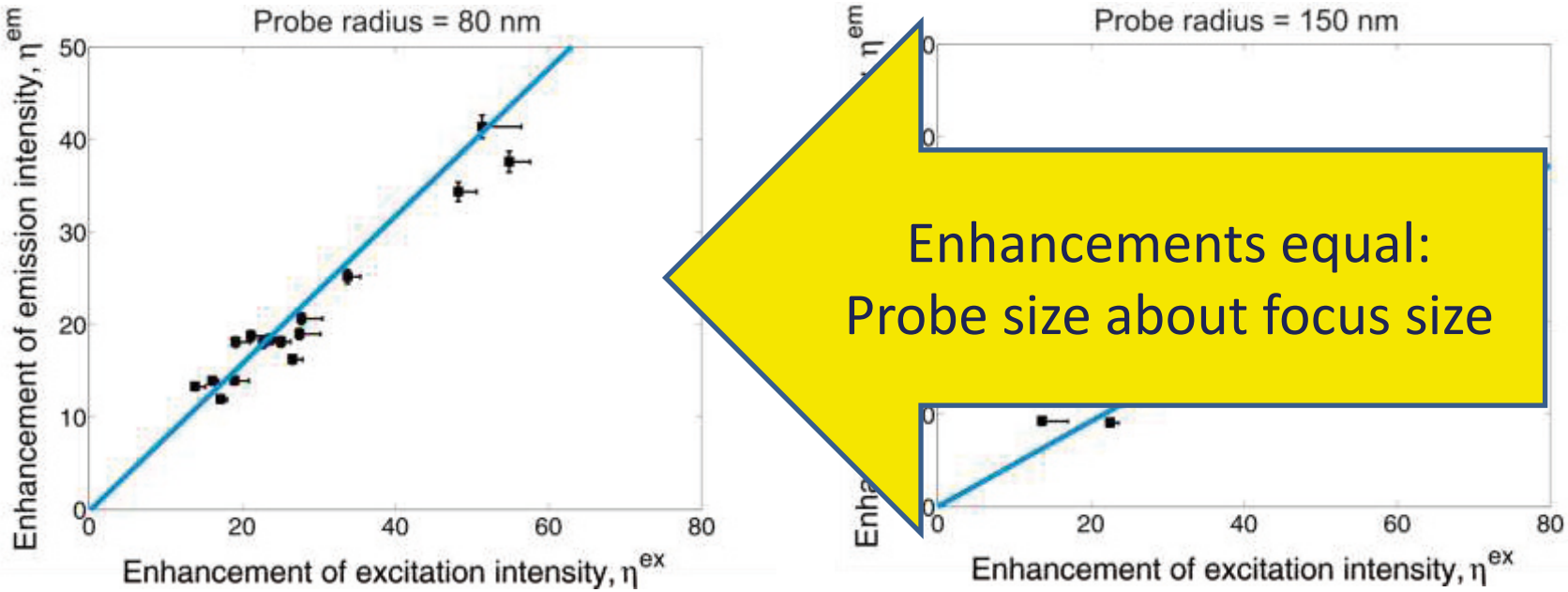


Focus of excitation light is at diffraction limit of imaging optics

van Putten, Lagendijk, & Mosk, submitted (2010)

Spot too small for our microscope

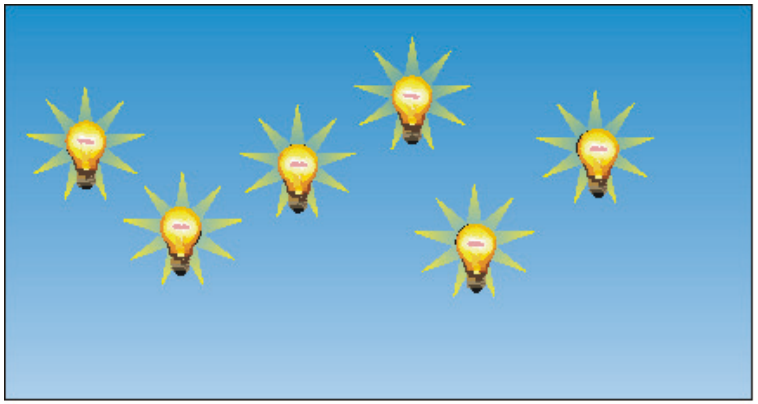
Infer spot size from ratio of excitation and emission enhancements

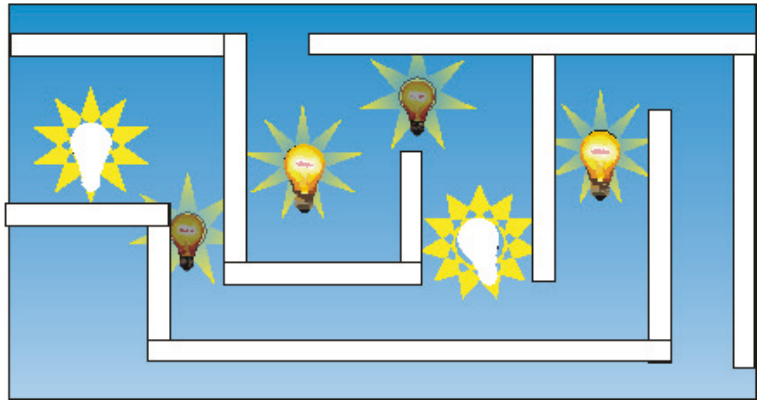


Enhancements equal:
Probe size about focus size

Blue lines: assume spot is optimally concentrated

Fluctuations of emission rate





C0 fluctuation
predicted by
B. Shapiro (PRL 1999)

Experiment: Birowosuto, Skipetrov, Vos, Mosk, PRL 2010 (accepted)

Vacancies for Ph.D students!

- New method for bringing light to a focus
  - Focus light through variety of materials
  - Focus light deep inside opaque objects
  - Universal transmission observed
  - Improved focusing observed
  - Fluctuations of LDOS observed

cops.tnw.utwente.nl for all our papers and recent M.Sc/ Ph.D. theses

Related work emerging in several groups:

C.H. Yang (CalTech), presented at FiO 2009
K. Dholakia (St. Andrews), presented at SPIE OP 2009
Boccara/Fink Group (ESPCI Paris), arXiv:0910.5436v1 (2009).
Xiang Zhang group, Phys. Rev. B 79, 201103(R) (2009)