A sneak peek with light into opaque materials

from Imaging to Computing

Sylvain Gigan

Optica Webinar

Photonic Metamaterial Technical Group

Nov. 17th 2022

Laboratoire Kastler Brossel
Physique quantique et applications
ENS
SORBONNE UNIVERSITÉ
COLLÈGE DE FRANCE
cnrs

Team – Collaborators - Funding

Our Goal :
Understand and exploit the complexity of light propagation in complex media

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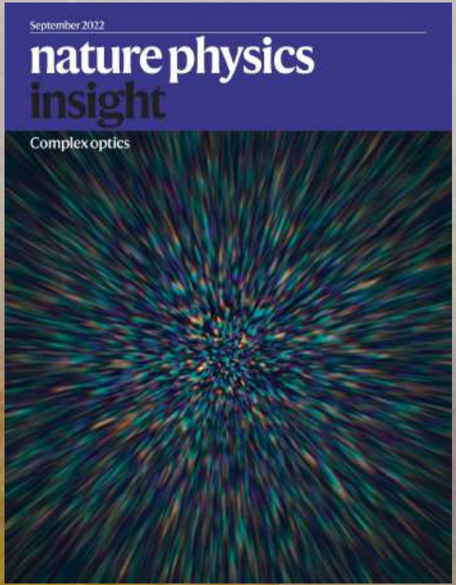
Fundings
DARPA, erc, ANR, NIH, FET-Open, HFSP, CZ



Review Article | Published: 08 September 2022

Shaping the propagation of light in complex media

Hui Cao, Allard Pieter Mosk & Stefan Rotter

Nature Physics **18**, 994–1007 (2022) | Cite this article

Review Article | Published: 08 September 2022

Physics of highly multimode nonlinear optical systems

Logan G. Wright, Fan O. Wu, Demetrios N. Christodoulides & Frank W. Wise

Perspective | Published: 08 September 2022

Quantum light in complex media and its applications

Ohad Lib & Yaron Bromberg

Nature Physics **18**, 986–993 (2022) | Cite this article

Comment | Published: 08 September 2022

Controlling random lasing action

Riccardo Sapienza

Nature Physics **18**, 976–979 (2022) | Cite this article

Review Article | Published: 08 September 2022

Imaging in complex media

Jacopo Bertolotti & Ori Katz

Nature Physics **18**, 1008–1017 (2022) | Cite this article

Perspective | Published: 08 September 2022

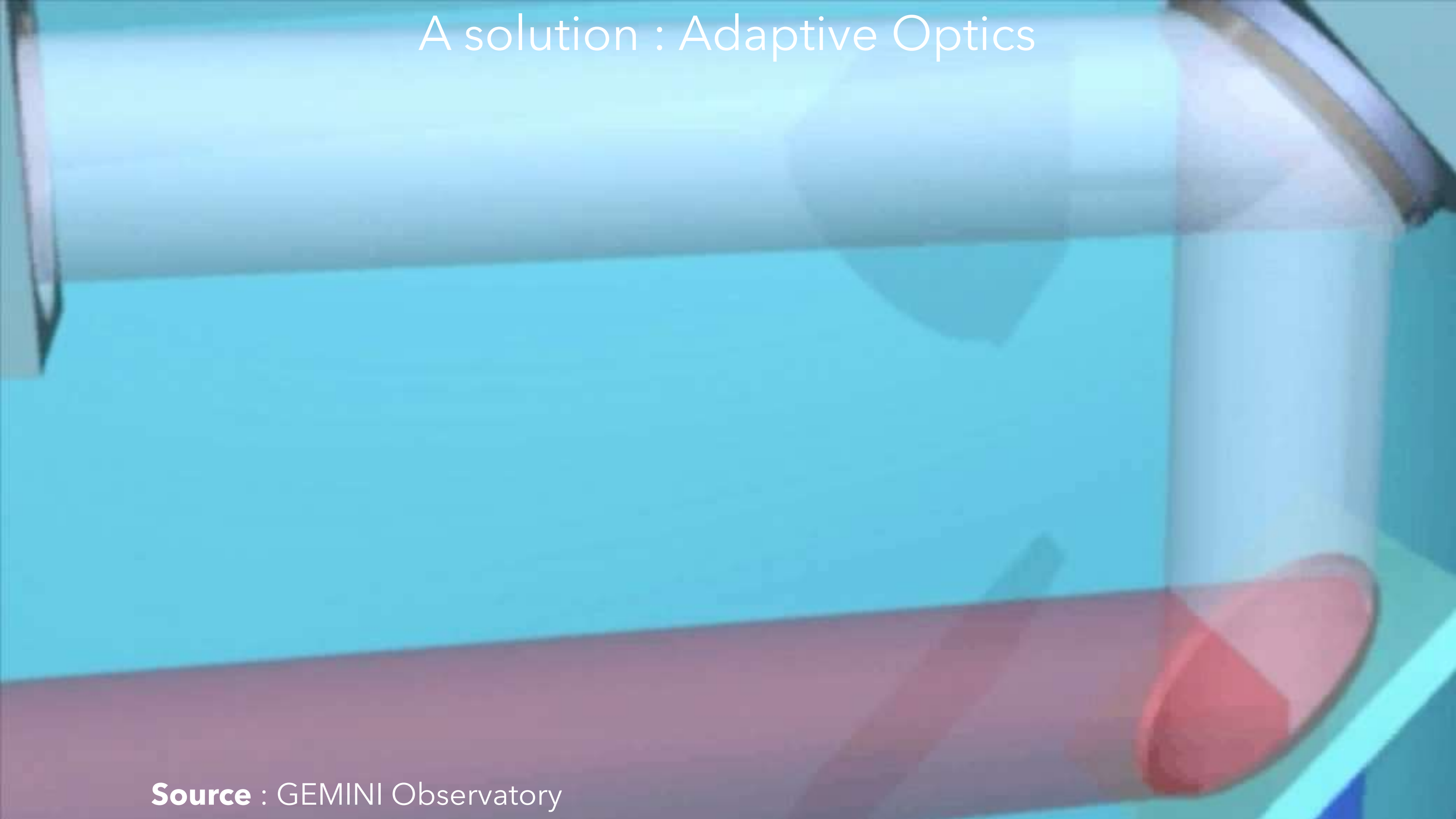
Imaging and computing with disorder

Sylvain Gigan

Nature Physics **18**, 980–985 (2022) | Cite this article

Imaging through turbulence

A solution : Adaptive Optics

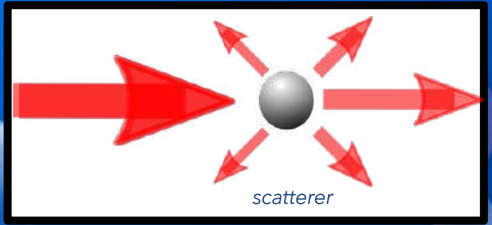


Source : GEMINI Observatory

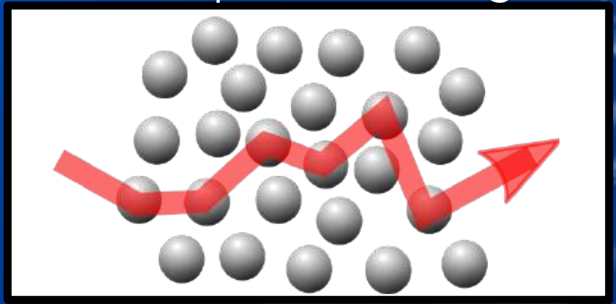
Scattering

Ballistic Light

Single scattering



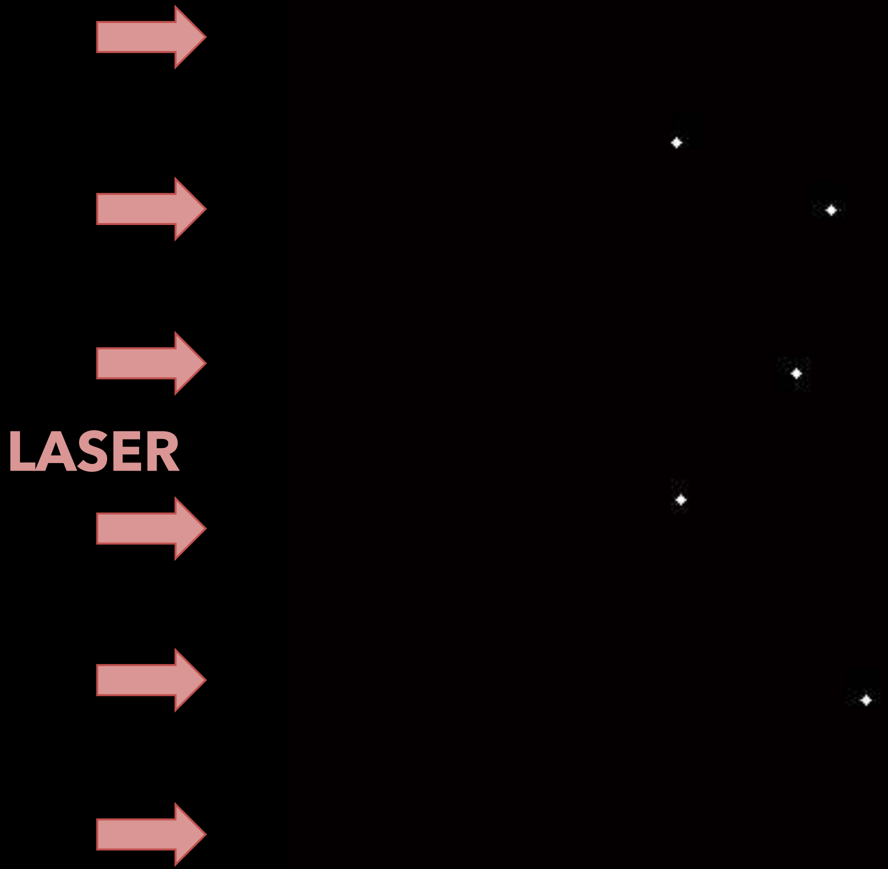
Multiple Scattering



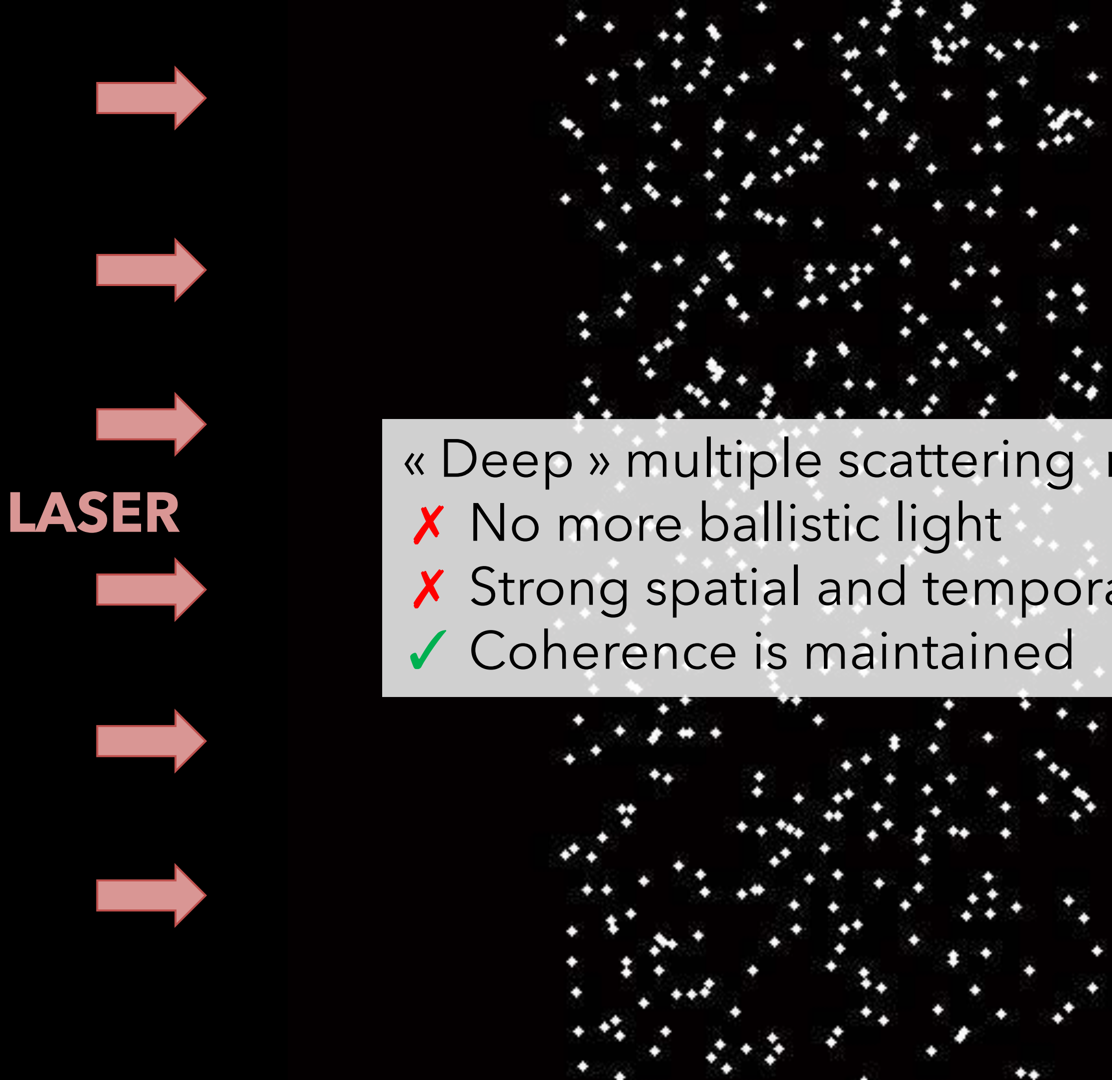
Biological tissues are scattering

typical biological tissues

- ➢ **scattering mean free path** $l_s \simeq 50 - 100 \mu m$
- ➢ **transport mean free path** $l^* \simeq 1 mm$

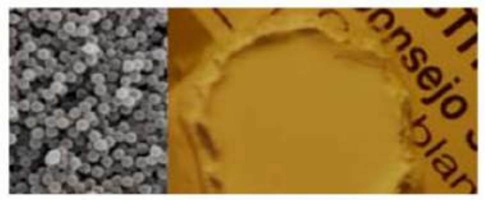


Film courtesy of Emmanuel Bossy (Univ. Grenoble) - SIMSONIC software



« Deep » multiple scattering regime :

- ✗ No more ballistic light
- ✗ Strong spatial and temporal perturbation
- ✓ Coherence is maintained

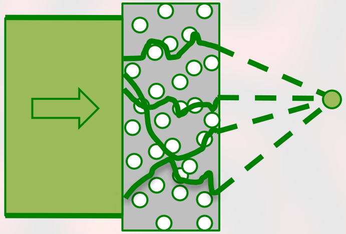


3D random Sample
« white paint »

Film courtesy of Emmanuel Bossy (Univ. Grenoble) - SIMSONIC software

The speckle pattern

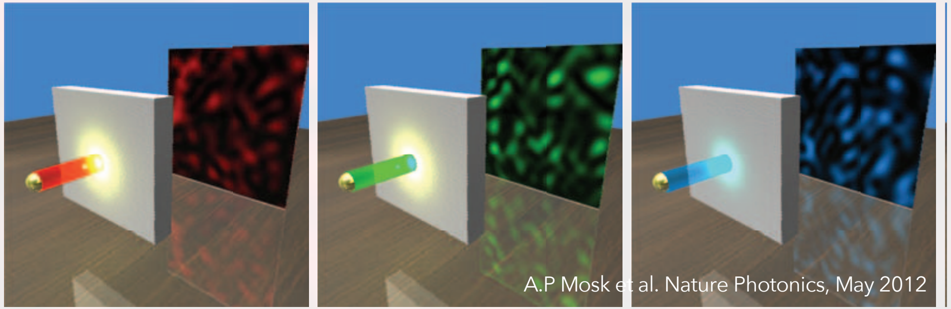
Monochromatic regime



A speckle grain =

- Sum of different paths with random phases
  = random walk in the complex plane
- Size limited by diffraction
- unpolarized speckle = 2 independent speckles

Polychromatic (i.e. dispersion)



A.P Mosk et al. Nature Photonics, May 2012

Spectral dependence
=
confinement time of light in the medium

SPECKLE : complex distribution … but coherent and deterministic

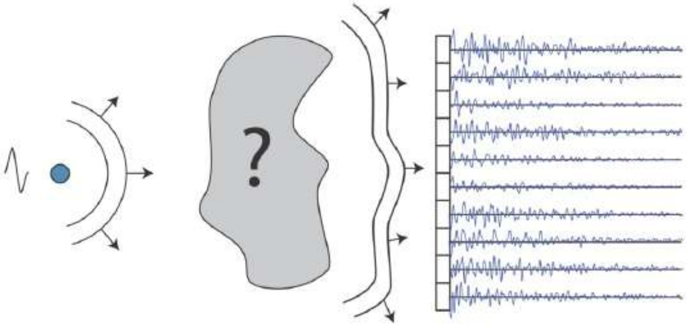
Imaging through scattering

MISSION: IMPOSSIBLE
(Until 2007)

« EASY »
(ballistic)

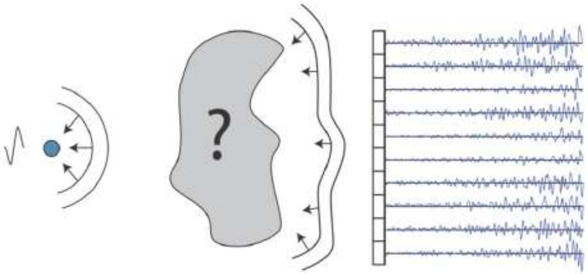
HARD
(OCT, multiphoton,confocal)

Hypothesis : linearity, reversibility of wave equation



Step 1: record

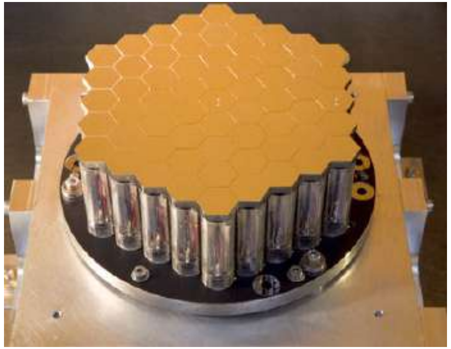
Step 2: playback



Spatial and temporal focusing

A. Derode, P. Roux et M. Fink, *Phys. Rev. Lett.*, 75, 4206 (1995)

Spatial shaping tools in optics



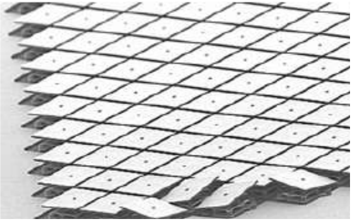
Deformable Mirrors :

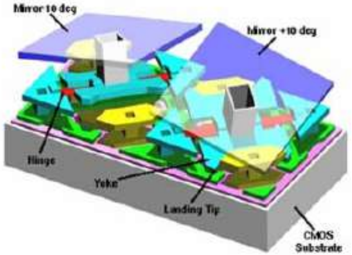
10-100 actuators typical
course : 10-20 microns
Speed > kHz

Not good !

Liquid crystals
Spatial Light Modulators :
>1 million pixel
Phase modulation
course : 1 microns
limited speed : 50Hz

Tool of choice
…until now!





MEMS
Spatial Light Modulators :
Texas DLP/DMD
>8 million pixel
binary ON/OFF
very fast speed : 24kHz

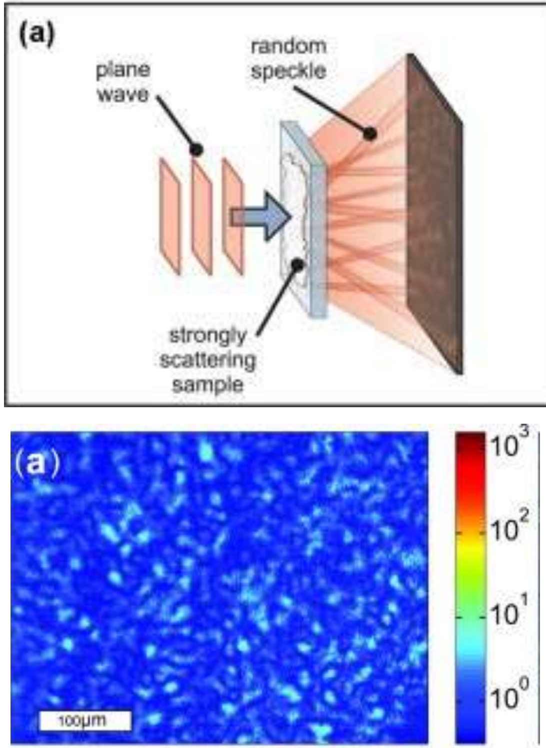
Very promising…
…but need tweeking

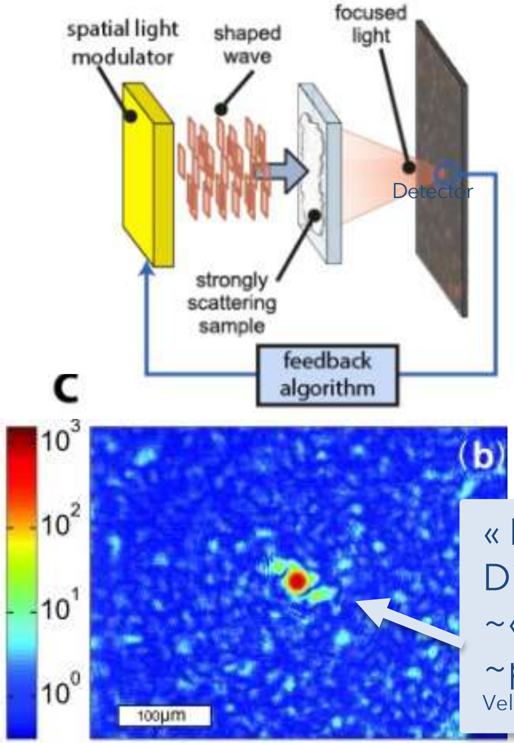
Wavefront shaping with CW light

Iterative optimization algorithm

No shaping

Optimized Wavefront



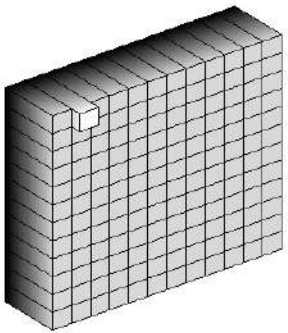


« Perfect » focus
Diffraction-limited
~« Extreme » AO
~phase conjugation
Vellekoop et al., Nat. Photonics (2010)

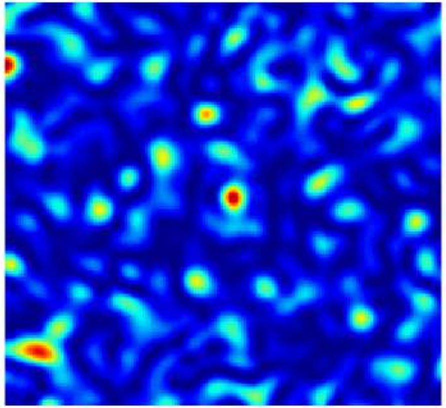
Vellekoop and Mosk, *Optics Letter, 2007*

Iterative approach:
→ Optical feedback optimization

Spatial Light Modulator



Output speckle

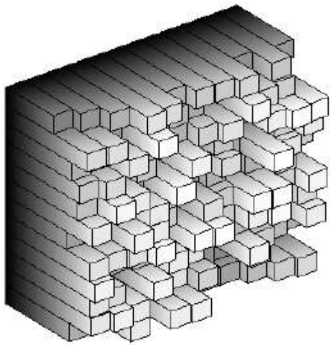


Optimization of optical intensity

(Simulations)

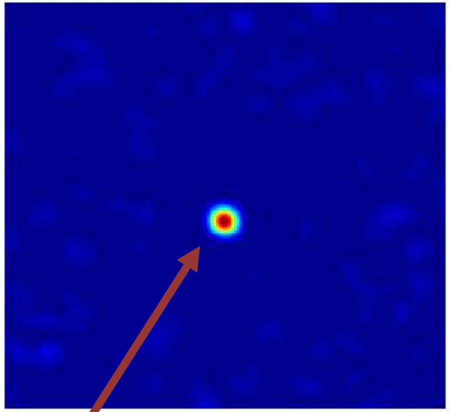
Iterative approach:
→ Optical feedback optimization

Spatial Light Modulator

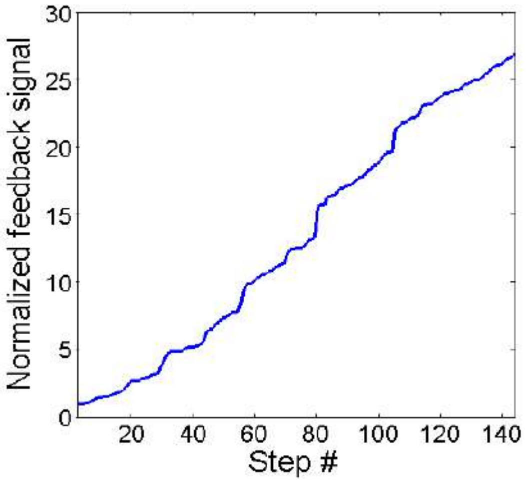


(Simulations)

Output speckle

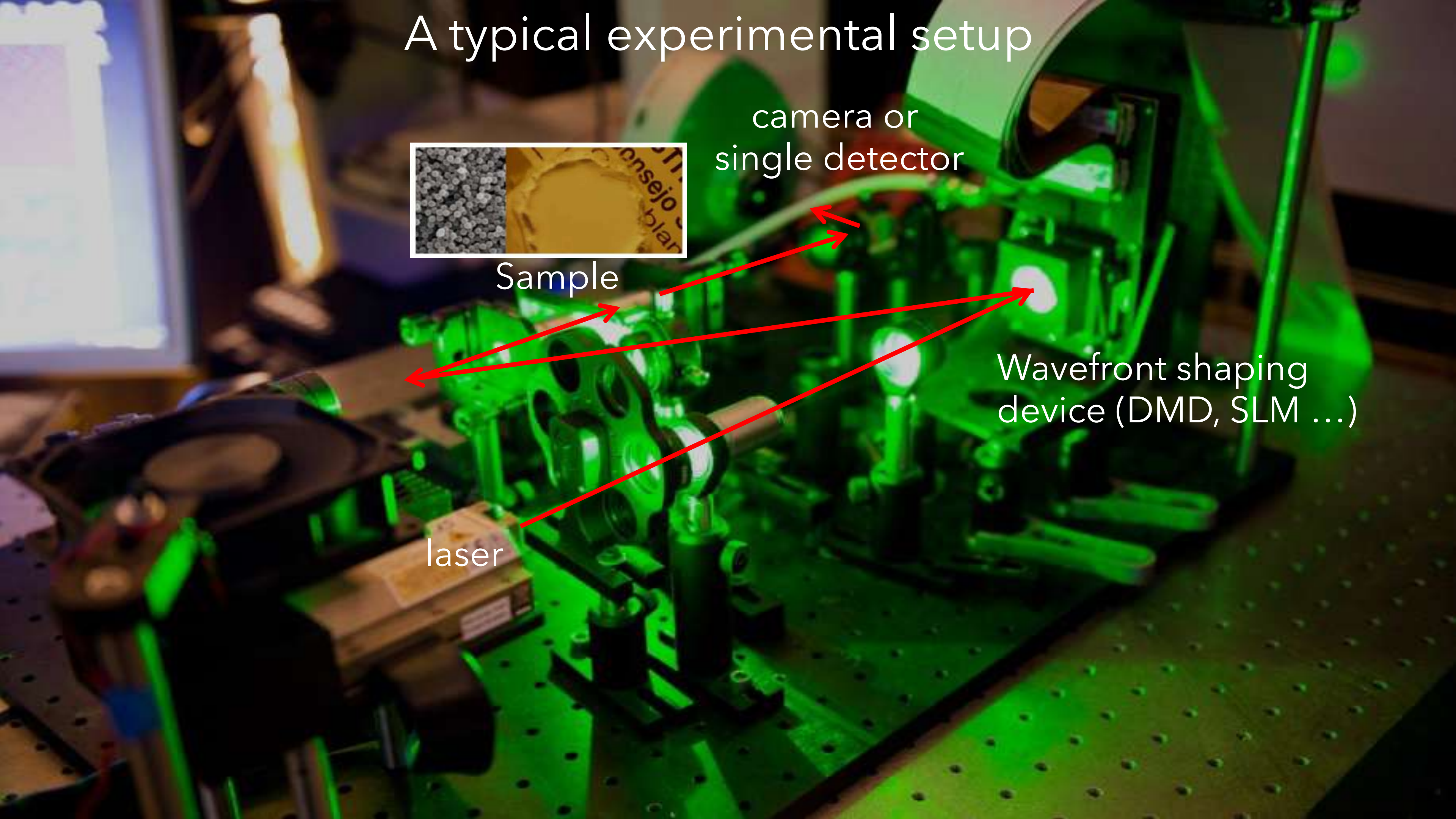


Optimization of optical intensity

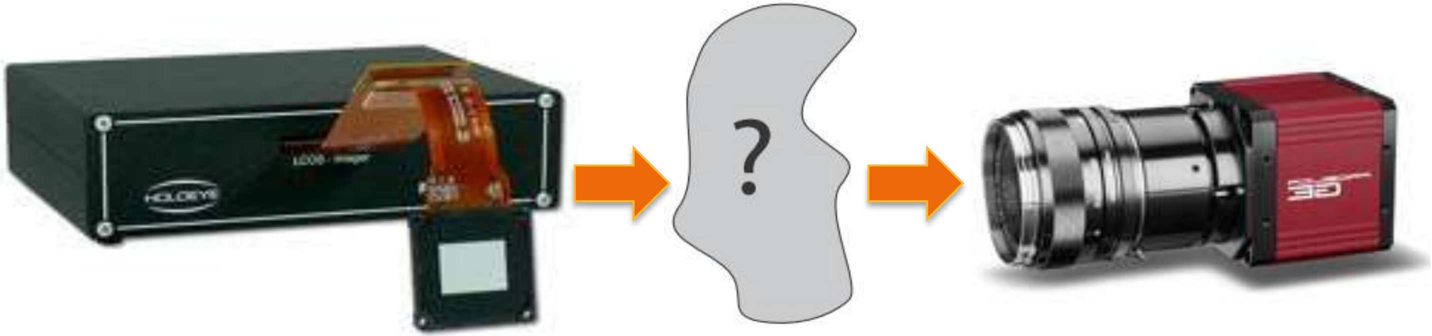


« Perfect » Point spread function Vellekoop et al., Nat. Photonics (2010)

A typical experimental setup

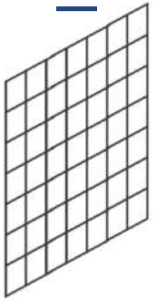


A general formalism : the transmission matrix

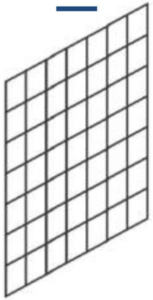


SLM : array of pixels Linear system CCD camera : array of pixels

= = =

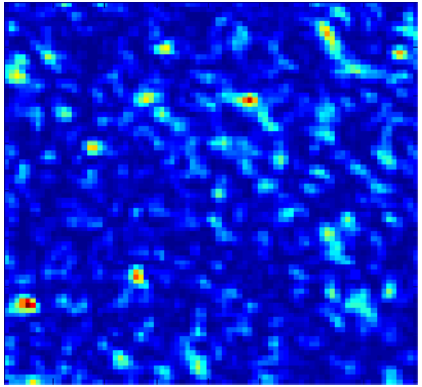


$$H = \begin{pmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N} \\ \vdots & & \ddots & \vdots \\ h_{M,1} & h_{M,2} & \dots & h_{M,N} \end{pmatrix}$$



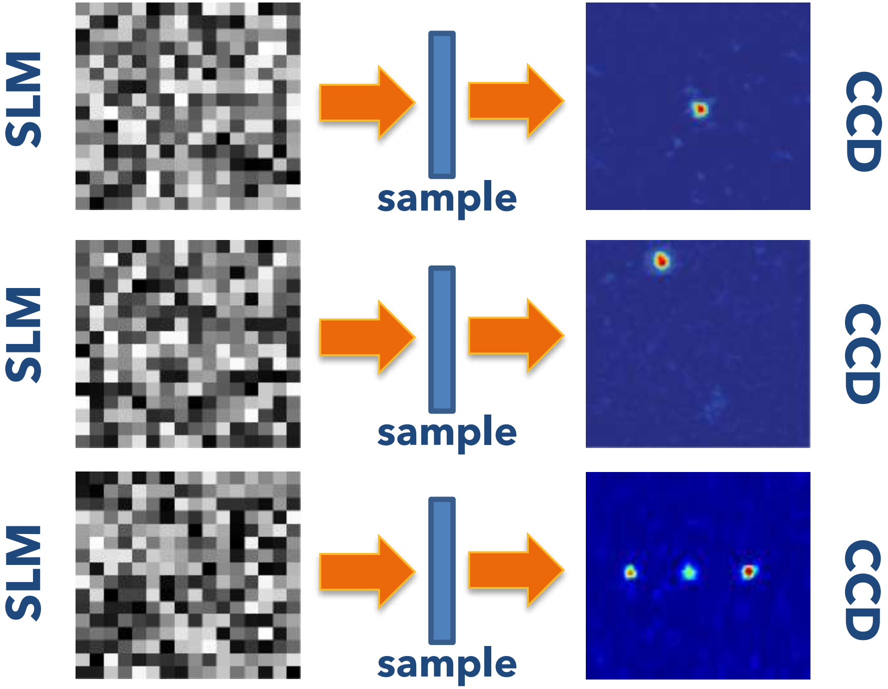
measurement of the TM : see Popoff et al. Phys. Rev. Lett. 104,100601 (2010)

Exploiting the TM : focusing



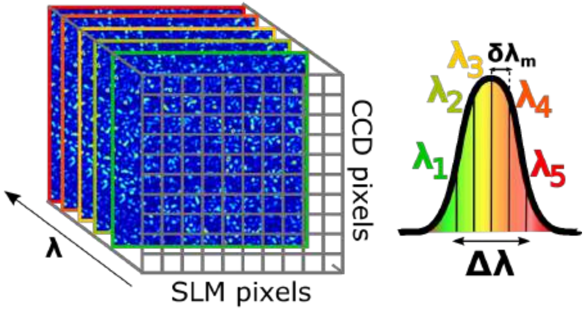
Plane wave illumination

Computational "Phase-conjugation"



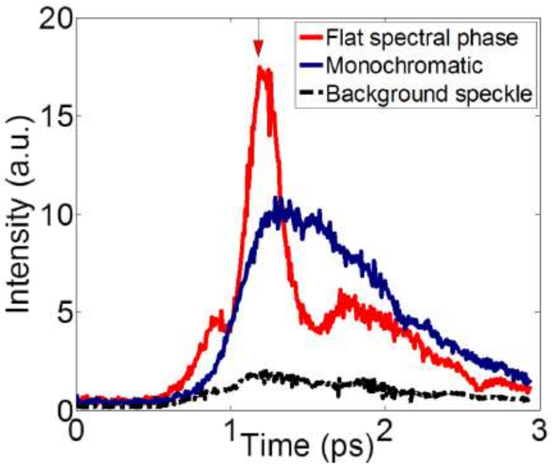
Popoff et al. Phys. Rev. Lett. 104,100601 (2010)

Controlling polychromatic / pulsed light?

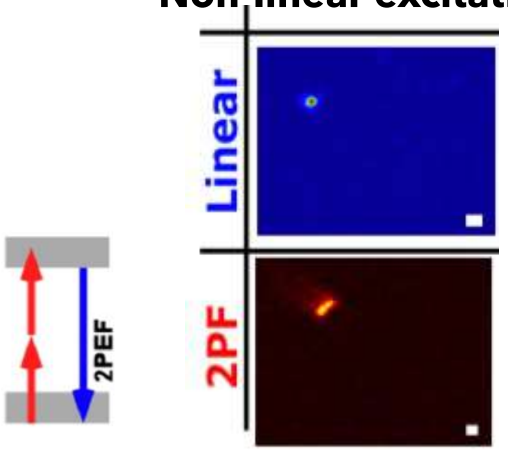


Spatiospectral matrix / time-resolved matrix

- •Broadband – femtosecond pulse
- •Temporal control +focusing
- •Coherent control
- •Multiphoton microscopy

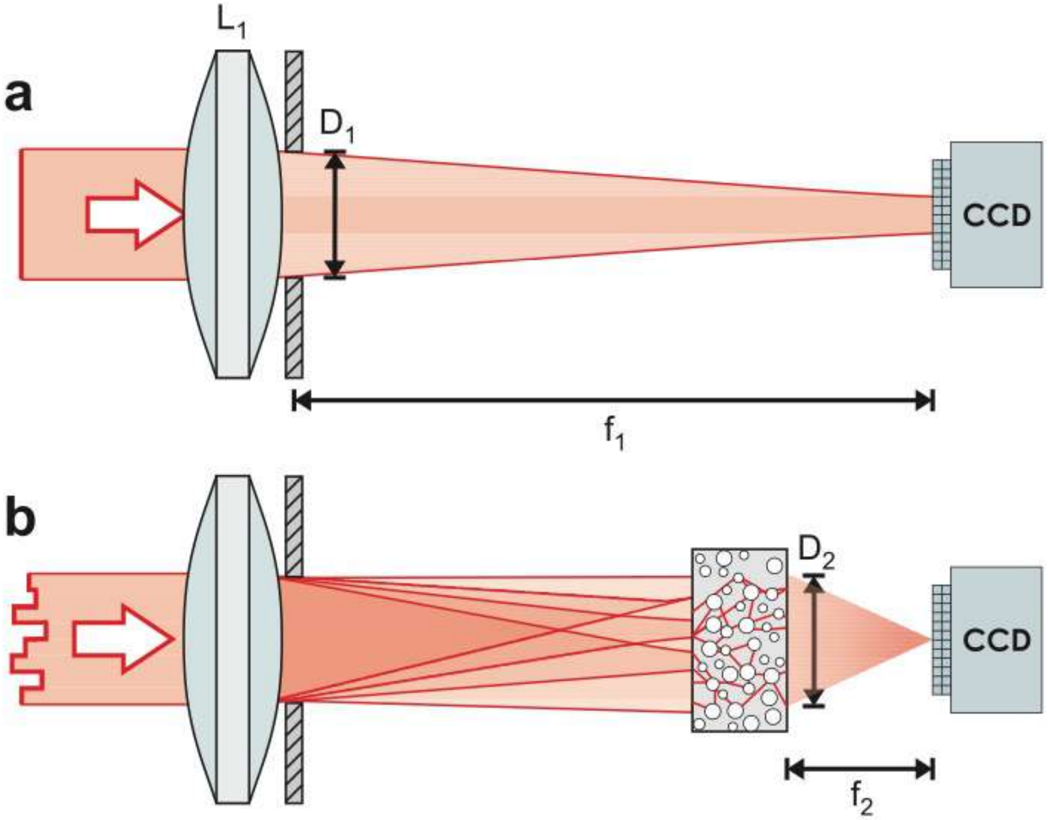


Non-linear excitation



Mounaix et al. , Phys. Rev. Lett. 116, 253901 (2016)
Phys. Rev. A 94, 041802 (2016) Optica 4, 1289-1292 (2017)

Why « lensless » imaging ?

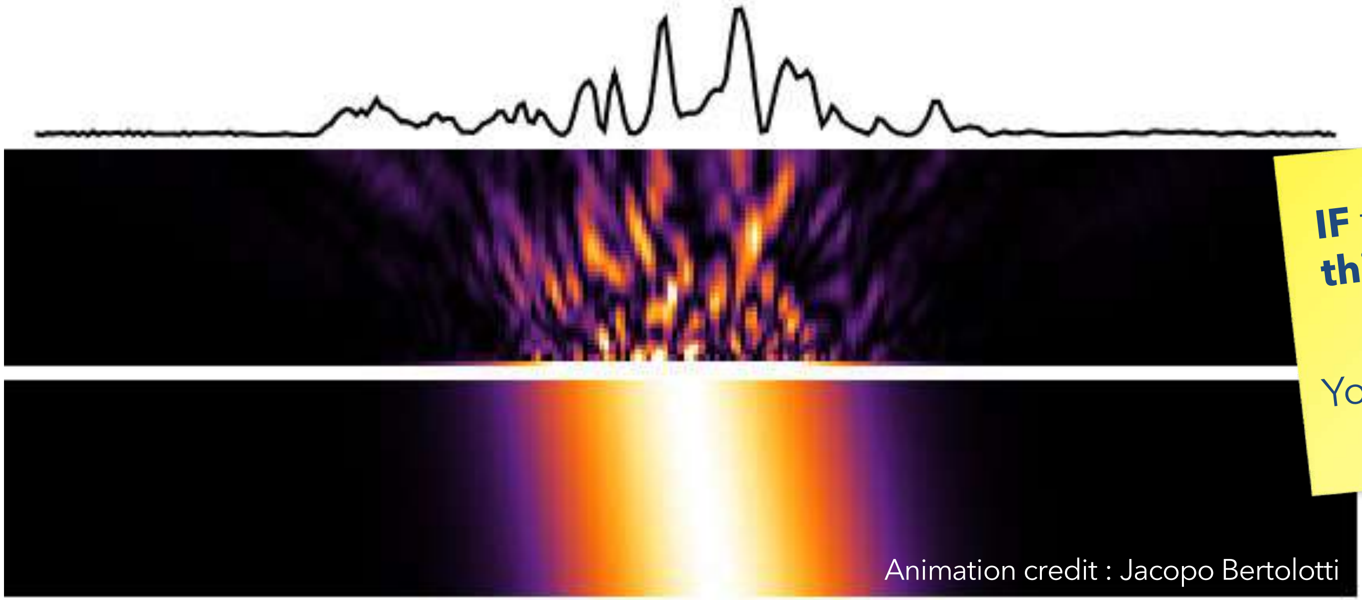


Resolution given by the scattering medium

The lens is irrelevant!

Vellekoop, Ivo M., Aart Lagendijk, and A. P. Mosk. "Exploiting disorder for perfect focusing." *Nature photonics* 4.5 (2010): 320-322.

Why « lensless » imaging : The optical memory effect



IF the medium is **thin** or **forward-scattering**

You have « some » field of view

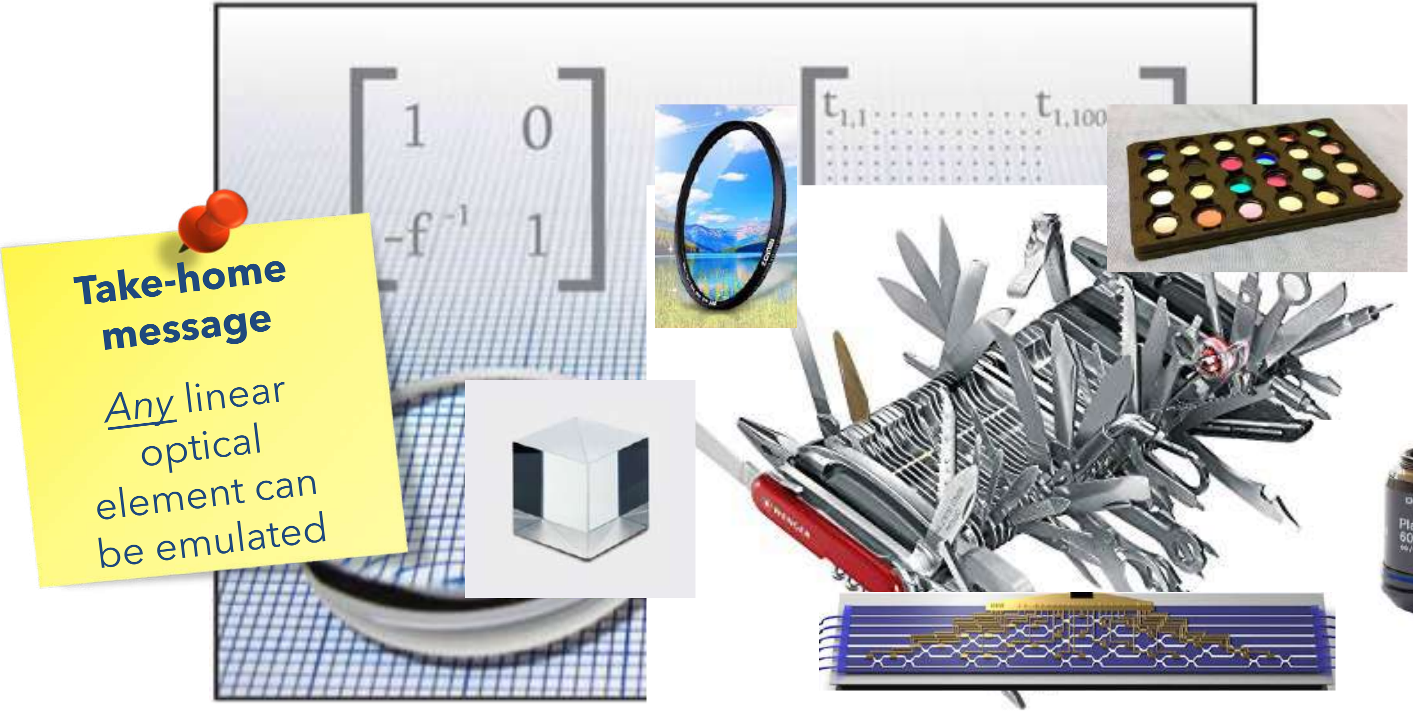
- Osnabrugge, G., et al. "Generalized optical memory effect." *Optica* 4.8 (2017): 886-892.
- Judkewitz, B., et al. "Translation correlations in anisotropically scattering media." Nature physics 11.8 (2015): 684-689
- Schott, S et al. (2015). Characterization of the angular memory effect of scattered light in biological tissues. *Optics express*, *23*(10), 13505-13516.
- Vellekoop, I. M., & Aegerter, C. M. (2010). Scattered light fluorescence microscopy: imaging through turbid layers. *Optics letters*, *35*(8), 1245-1247.

Viewpoint Physics

Physics **3**, 22 (2010)

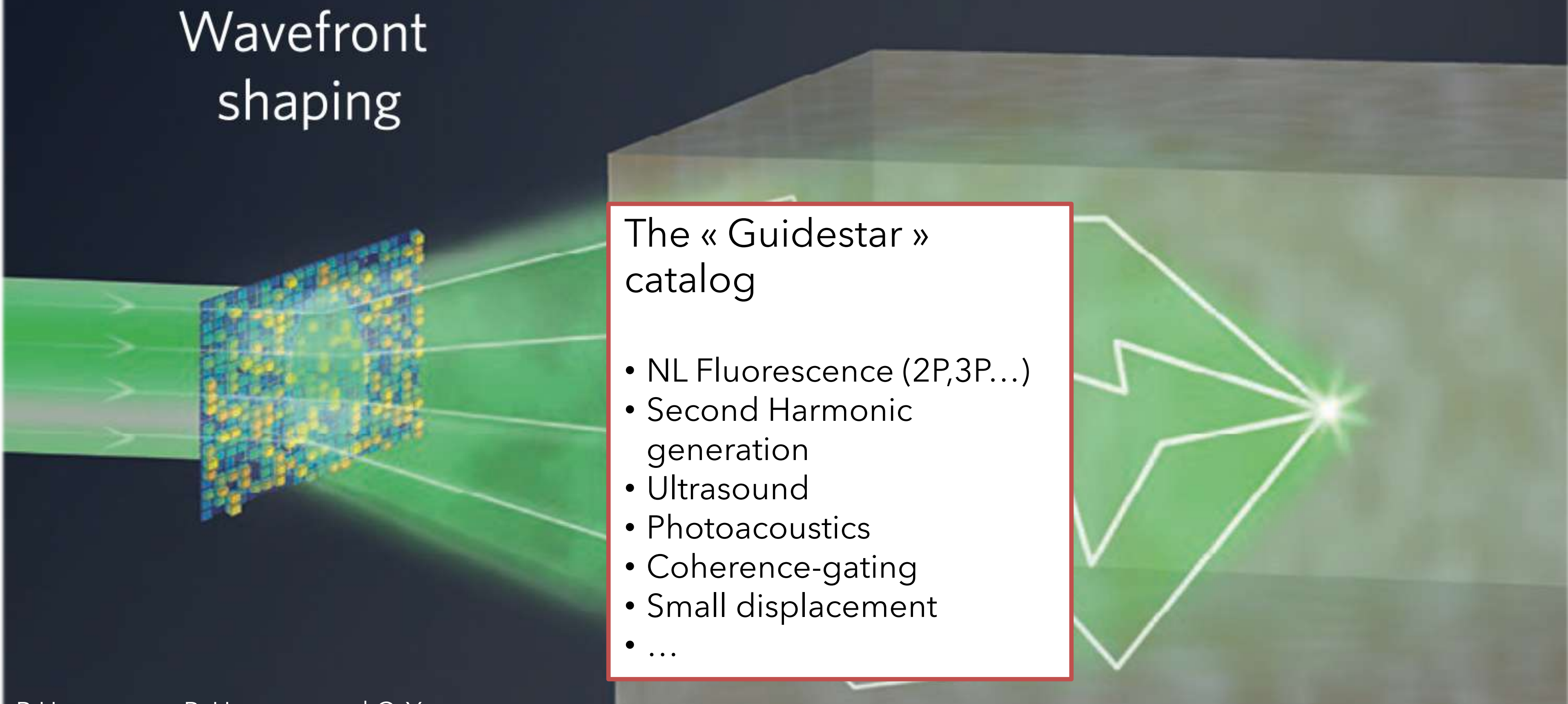
The information age in optics: Measuring the transmission matrix

Elbert G. van Putten and Allard P. Mosk



See : Mosk, Allard P., et al. "Controlling waves in space and time for imaging and focusing in complex media." *Nature photonics* 6.5 (2012): 283-292.

Which feedback to go inside?



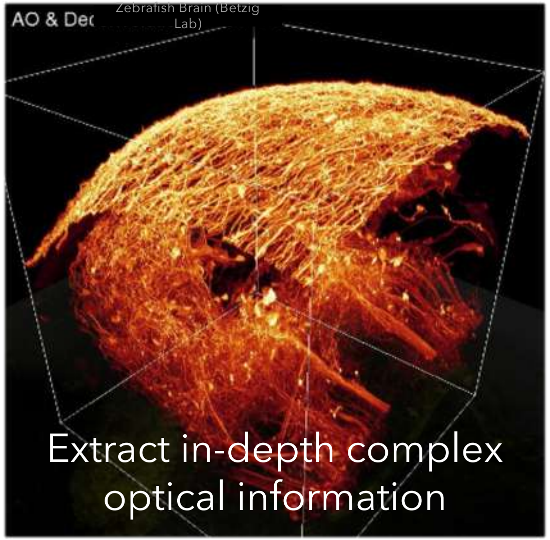
The « Guidestar » catalog

- NL Fluorescence (2P,3P…)
- Second Harmonic generation
- Ultrasound
- Photoacoustics
- Coherence-gating
- Small displacement
- …

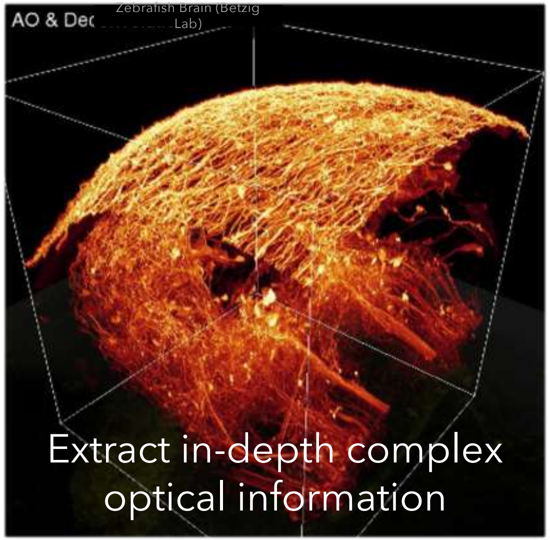
R.Horstmeyer,R. Haowen, and C. Yang
Guidestar-Assisted Wavefront-Shaping Methods for Focusing Light Into Biological Tissue
Nature Photonics 9 (9): 563–71. (2015)

(1) Computational imaging

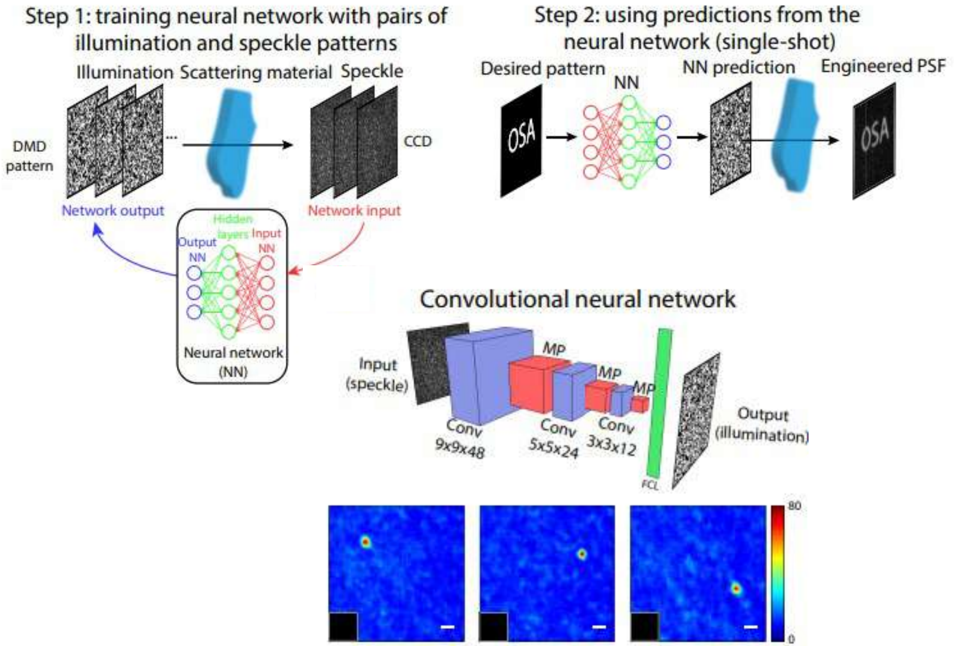
(2) Optical Computing



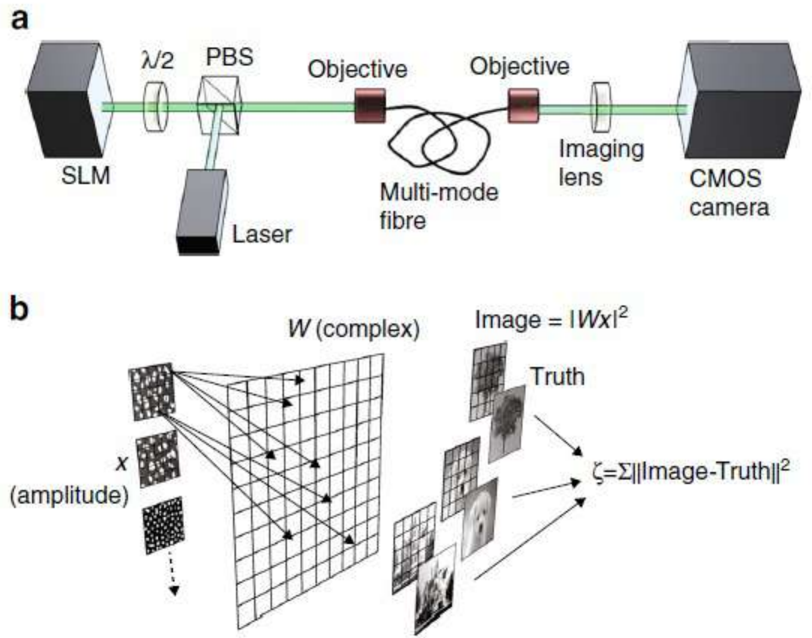
(1) Computational imaging



Neural networks for imaging through scattering media



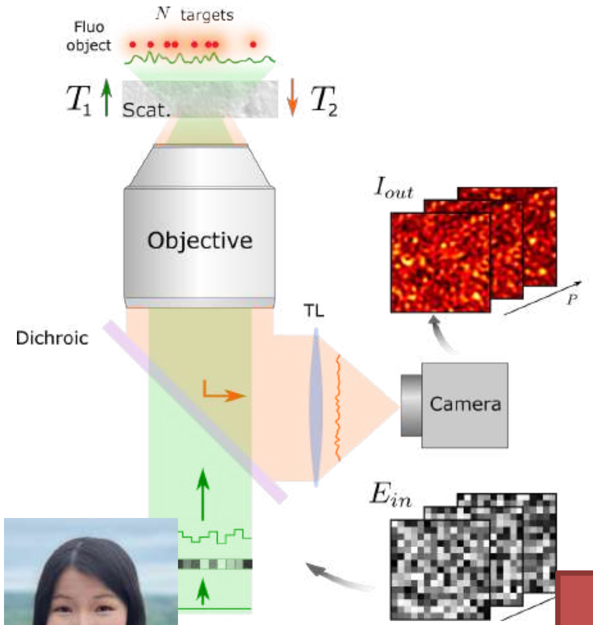
A.Turpin, I. Vishniakou, and J. d. Seelig, 132 *Opt. Express* 26, 30911 (2018)

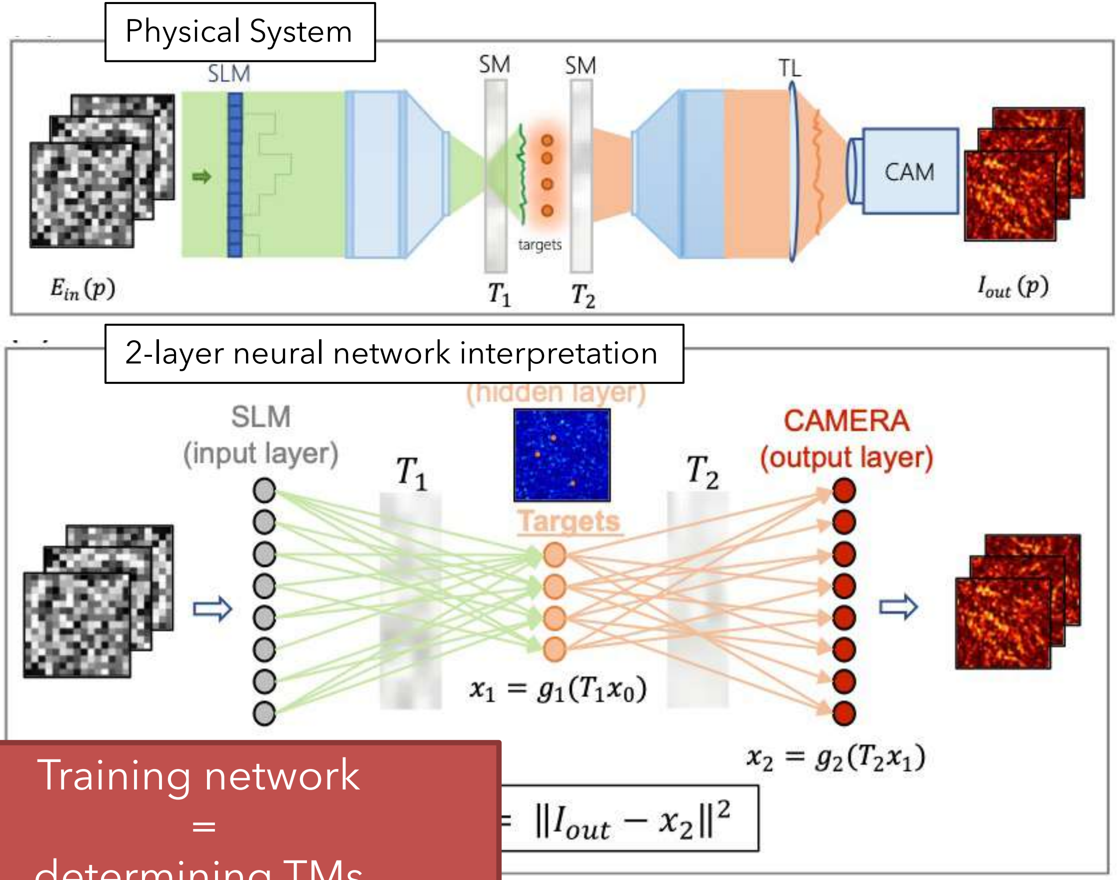


P. Caramazza, O. Moran, R. Murray-Smith and D. Faccio, *Nat. Commun*. (2019)

Only to see « **through** » scattering media

Physics-based 2-layer neural network





Training network
=
determining TMs

Arco, F. Xia, et al. Optics Express (2022)

(2) Improve computing with optics

Machine Learning

The deep Learning revolution

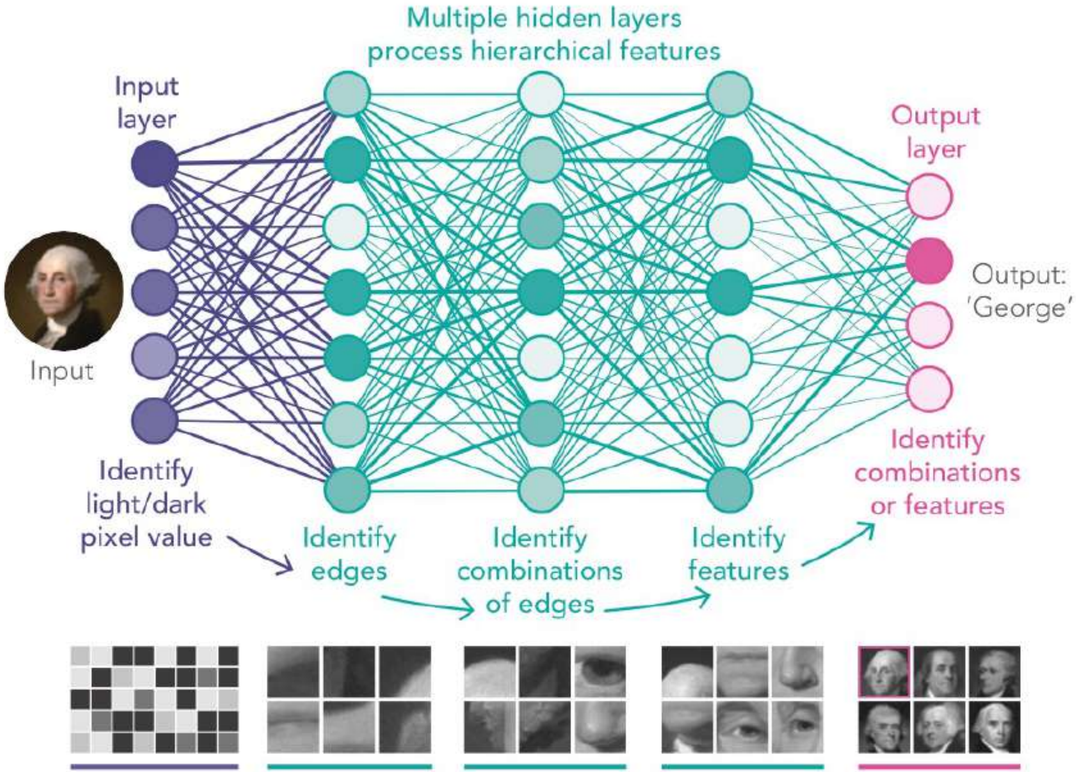


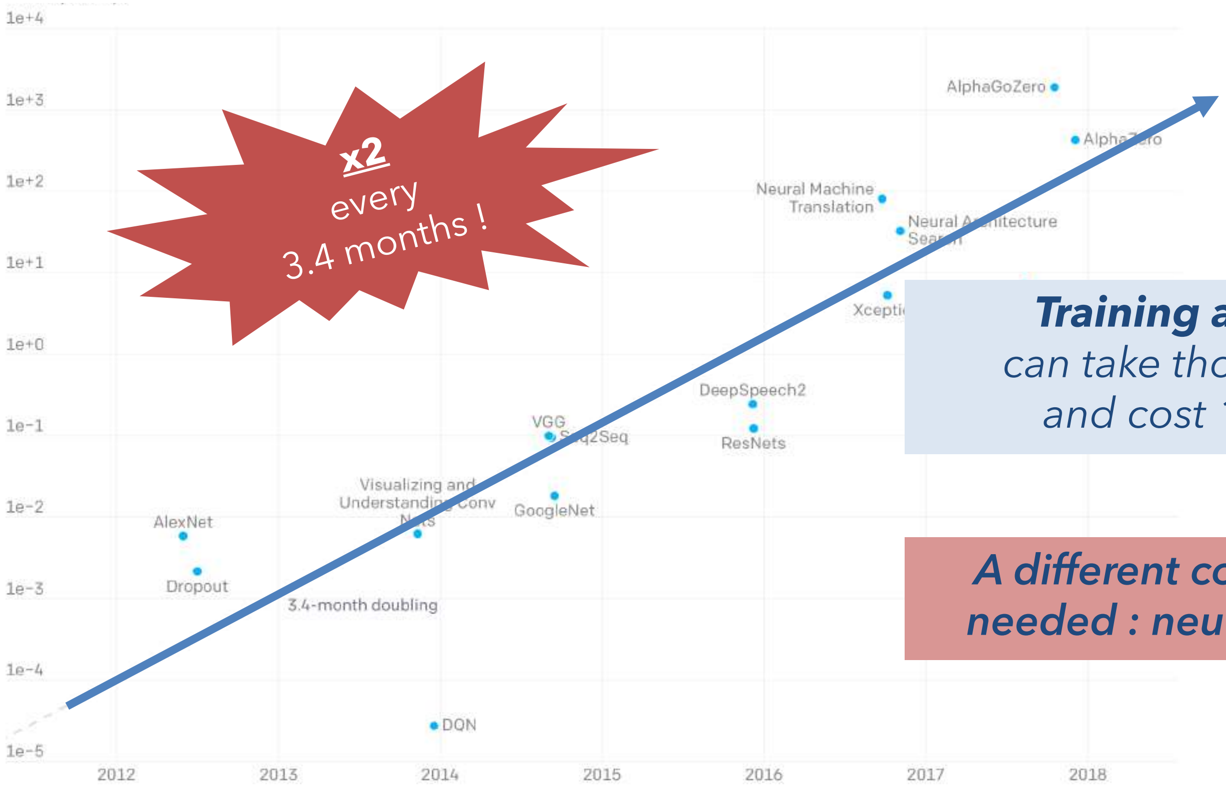
Image: Waldrop, PNAS (2019)

- Many (10s to 100s) Layers
- Each layer = a matrix multiplication
- 10s BILLIONS weights / parameters
- Huge datasets
- **Training** and **Inference** are extremely demanding

See: Deep learning, LeCun, Bengio & Hinton, Nature 521, 436 (2015)

AI and Compute

PetaFlop/s.days



x300.000
(Moore: x7)

Training a single AI Models
can take thousands of GPU.days
and cost 10s of millions of $

A different computing paradigm is needed : neuromorphic approach ?

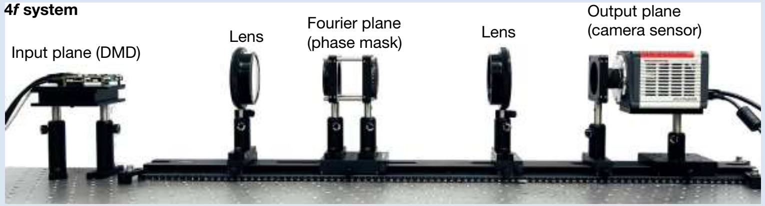
https://openai.com/blog/ai-and-compute/

Optics has distinct advantages…

- Low energy consumption
- Easy interconnect – Multiplexing
- Low latency + blazing speed

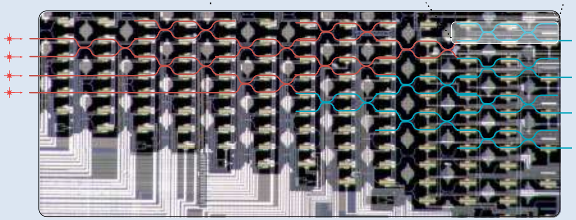
… and some disadvantages:

- Bulky
- Tricky non-linearities
- Storage



Sci. Rep. **8**, 12324 (2018).

Free space vs Integrated optics



Sci. Adv. **5**, eaay6946 (2019).

Nature Photonics 15, 10 (2021)

Photonics for artificial intelligence and neuromorphic computing

REVIEW ARTICLE | FOCUS
https://doi.org/10.1038/s41566-020-00754-y

Bhavin J. Shastri[1,2,7], Alexander N. Tait[2,3,7], T. Ferreira de Lima[2], Wolfram H. P. Pernice[4], Harish Bhaskaran[5], C. D. Wright[6] and Paul R. Prucnal[2]

Nature 588, 39 (2020)

Perspective

Inference in artificial intelligence with deep optics and photonics

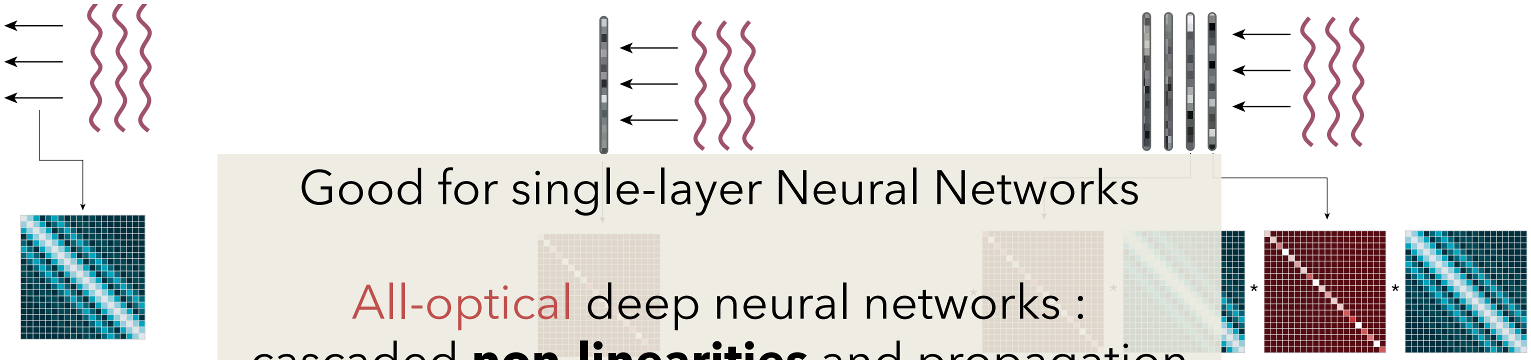
https://doi.org/10.1038/s41586-020-2973-6
Received: 28 November 2019

Gordon Wetzstein[1], Aydogan Ozcan[2], Sylvain Gigan[3], Shanhui Fan[1], Dirk Englund[4], Marin Soljačić[4], Cornelia Denz[5], David A. B. Miller[1] & Demetri Psaltis[6]

Matrix multiplication in free space optics

Basic building blocks:

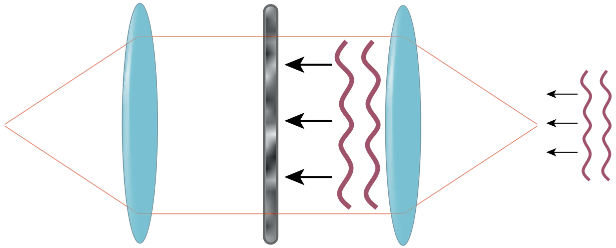
Free space — Thin mask — layered scatterer



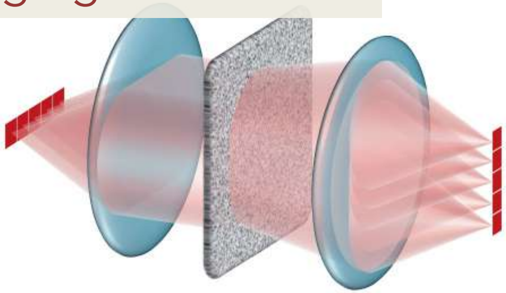
Good for single-layer Neural Networks

All-optical deep neural networks :
cascaded **non-linearities** and propagation
remains challenging

Advanced functions



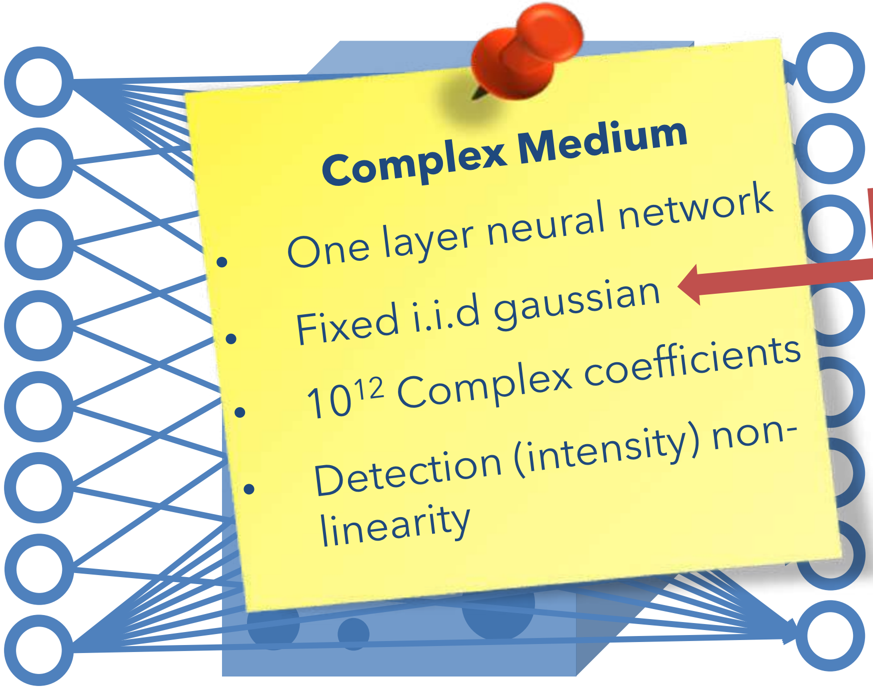
2D convolutions



1D vector-matrix multiplier

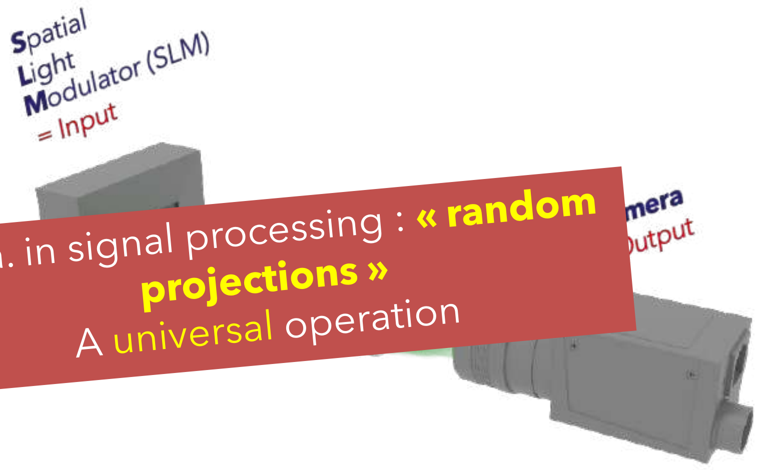
Adapted from *Nature* 588, 39 (2020)

Optical computing with a complex medium ?



Complex Medium

- One layer neural network
- Fixed i.i.d gaussian
- 10^{12} Complex coefficients
- Detection (intensity) non-linearity



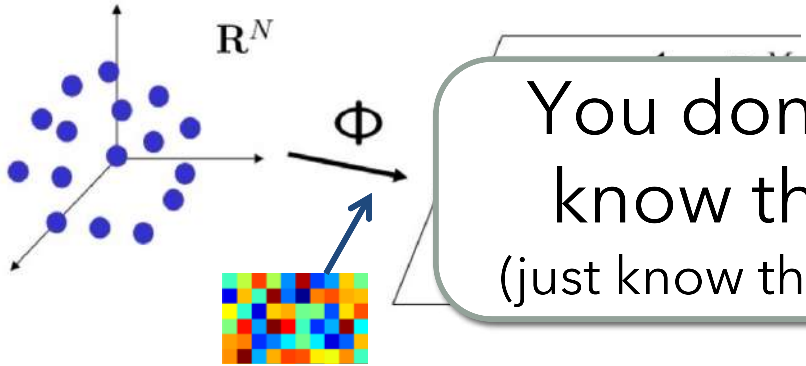
a.k.a. in signal processing : **« random projections »**

A universal operation

Using disorder for computation in Machine Learning?

What are « random projections » good for?

Dimensional Reduction
« Johnson & Lindenstrauss »

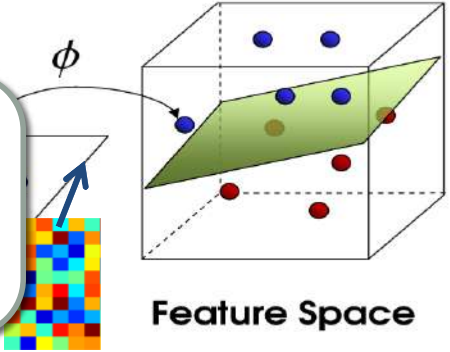


You don't need to know the matrix!
(just know that it is random)

- Random matrix : reduction in dimension
- **conserve distances** even for M<<N

Reference : Johnson, W. B., & Lindenstrauss, J. Extensions of Lipschitz mappings into a Hilbert space. *Contemporary mathematics*, 26,189(1984)

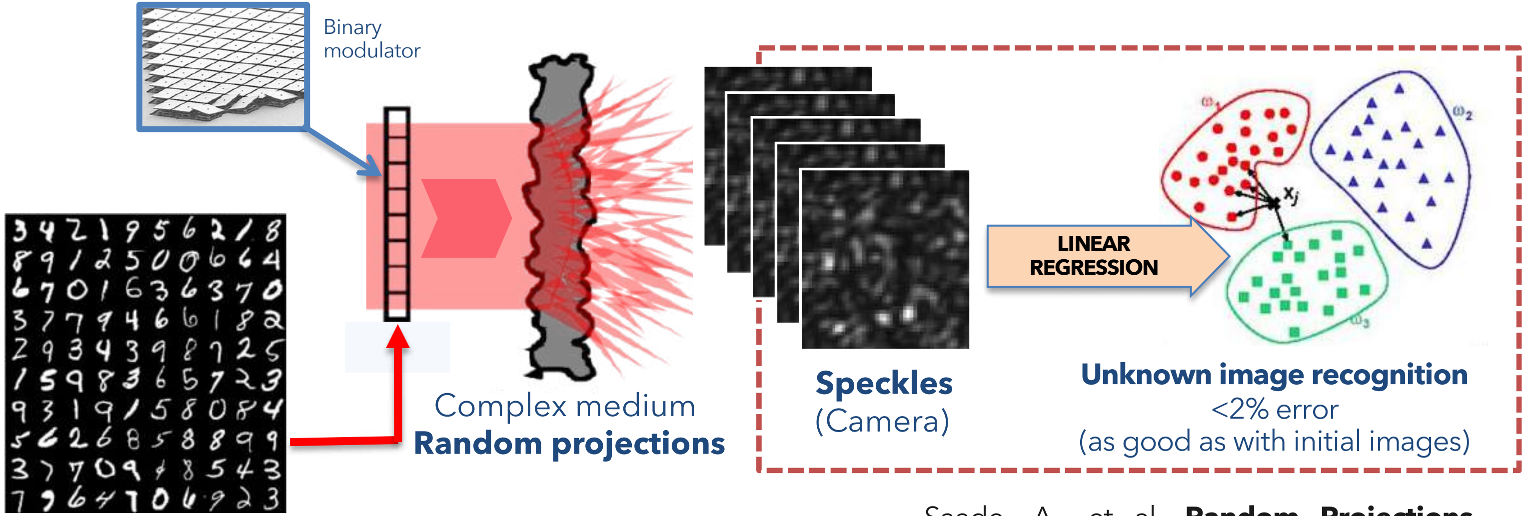
Dimensional expansion: The "kernel Trick" « Rahimi & Recht »



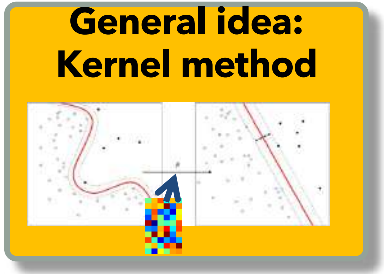
- Make a **non-linear** regression problem **linear**
- Random projections are **efficient** and **universal**

Reference : Rahimi, A., & Recht, B. (2007). Random features for large-scale kernel machines. In *Advances in neural information processing systems* (pp. 1177-1184).

Optical computing : image classification



Images Database :
Handwritten numbers



Saade, A., et al. **Random Projections through multiple optical scattering: Approximating kernels at the speed of light.** *IEEE (ICASSP) (2016)*

Collaboration : Igor Carron, Florent Krzakala, Laurent Daudet

optical computing revisited?

Why is it interesting ?

EXTRA-LARGE **&** **SUPER-FAST**

H of size higher than 10^6 x 10^6 (TBs of memory)

kHz operation $\rightarrow 10^3$ such multiplies / s

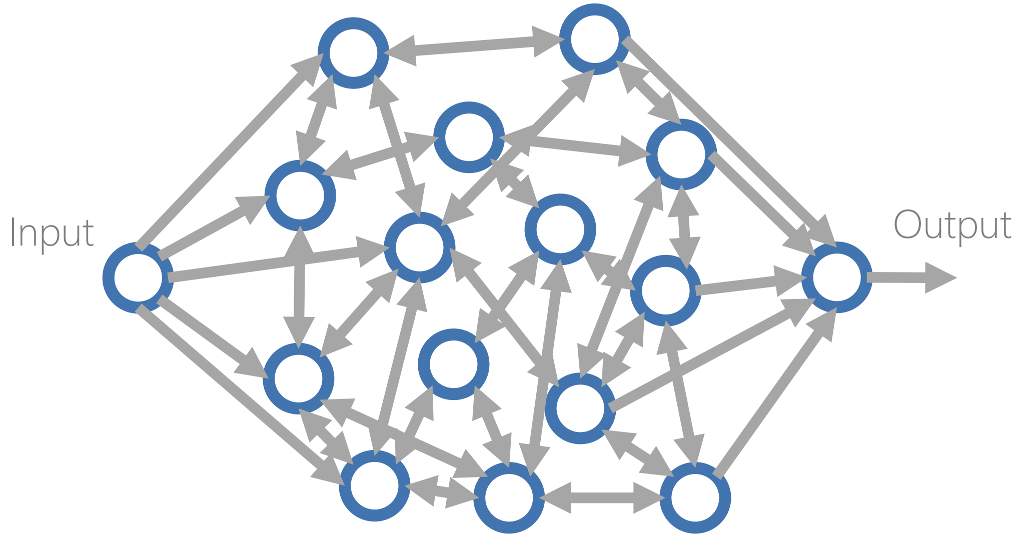
Equivalent 10^{15} operations / s : You would need a *Peta-scale* computer to do the same !

LightOn

We bring Light to AI

- **many, many use cases (inference, training, linear algebra…)**
- **already at scale for modern machine learning**
- **you can buy it already (1st commercial optical processor)**

(CoI disclosure: S.G. acknowledges financial interest in LightOn)



Recurrent Neural Networks are notoriously hard to train

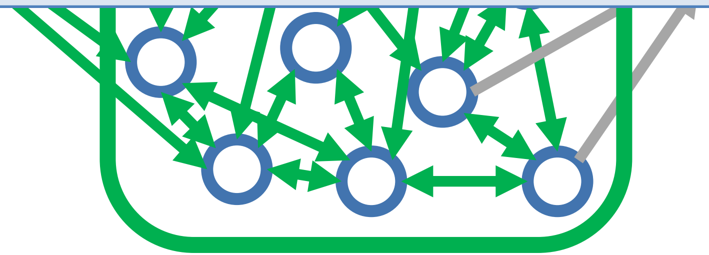
Jaeger & Haas (2004). *Science*

Particularly well suited for physical implementations

- Dedicated electronics
- Exotic architectures
- Integrated & free space photonics

Van der Sande, Guy, Daniel Brunner, and Miguel C. Soriano. "Advances in photonic reservoir computing." Nanophotonics 6.3 (2017): 561-576.

Input



Reservoir

orks
train
s all
nly

Only the output weights are trained

Random matrices

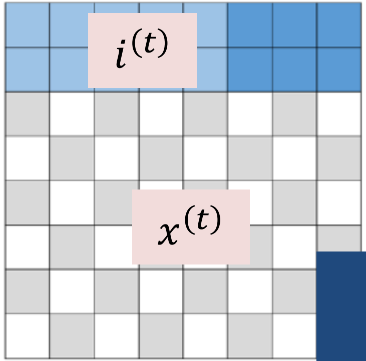
$$x^{(t+1)} = f\left(W_r\, x^{(t)} + W_i\, i^{(t)}\right)$$

next reservoir — current reservoir — current input

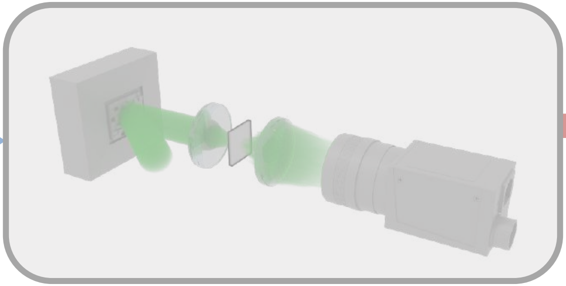
Jaeger & Haas (2004). *Science*

Reservoir computing with a complex medium ?

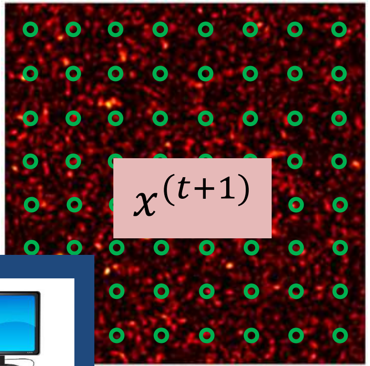
Input



Reservoir state



$$x^{(t+1)} = f\left(W_r\, x^{(t)} + W_i\, i^{(t)}\right)$$



utput speckle
ratic non-linearity)

$f = |.|^2$

Last stage / off-line

Predict output with a linear model

$$o^{(t)} = W_o x^{(t)}$$

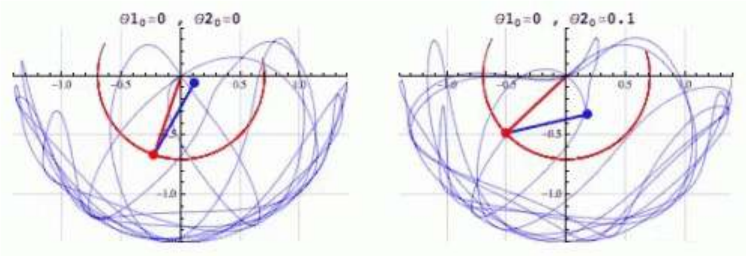
(done on a CPU or GPU - Typically not the bottleneck)

Dong, Rafayelyan, Krzakala, Gigan (2019). *IEEE Journal of Selected Topics in Quantum Electronics*

chaotic systems

LKB ENS SORBONNE UNIVERSITÉ COLLEGE DE FRANCE cnrs

Double-rod pendulum

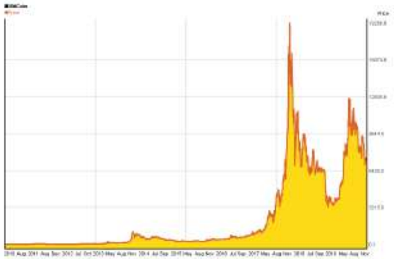


System becomes unpredictable after a characteristic time : **the Lyapunov time**

Turbulence

Weather and climate

Financial markets



…

Model equations for chaotic systems

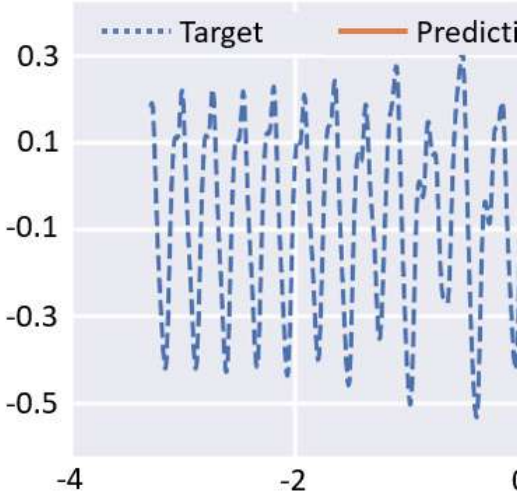
The Mackey-Glass equation (1D):

$$\frac{dx}{dt} = \frac{\beta x_\tau}{1 + x_\tau^n} - \gamma x$$

The Kuramoto-Sivashinsky equation (2D):

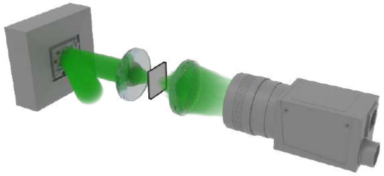
$$\frac{\partial u}{\partial t} + \nabla^4 u + \nabla^2 u + \frac{1}{2}|\nabla u|^2 = 0$$

Mackey-Glass prediction (1D)



1. Compute the reservoir states

$$x^{(t+1)} = \frac{1}{\sqrt{N}} f\left(W_r\, x^{(t)} + W_i\, i^{(t)}\right)$$

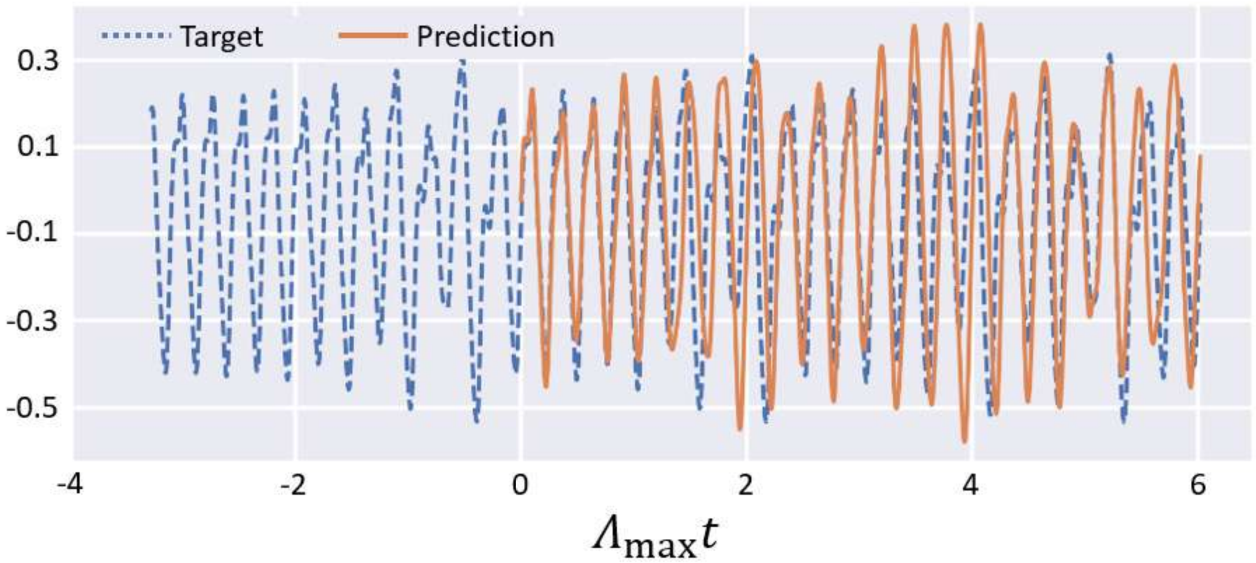


2. Output with a linear model

$$o^{(t)} = W_o x^{(t)}$$

Dong, Rafayelyan, Krzakala, Gigan (2019). *IEEE Journal of Selected Topics in Quantum Electronics*

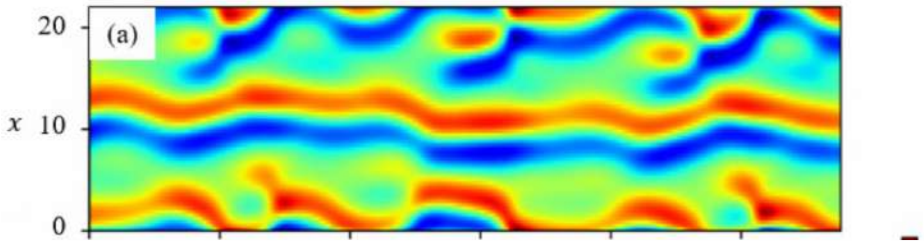
Mackey-Glass prediction (1D)



Dong, Rafayelyan, Krzakala, Gigan (2019). *IEEE Journal of Selected Topics in Quantum Electronics*

Kuramoto-Sivashinsky prediction - results

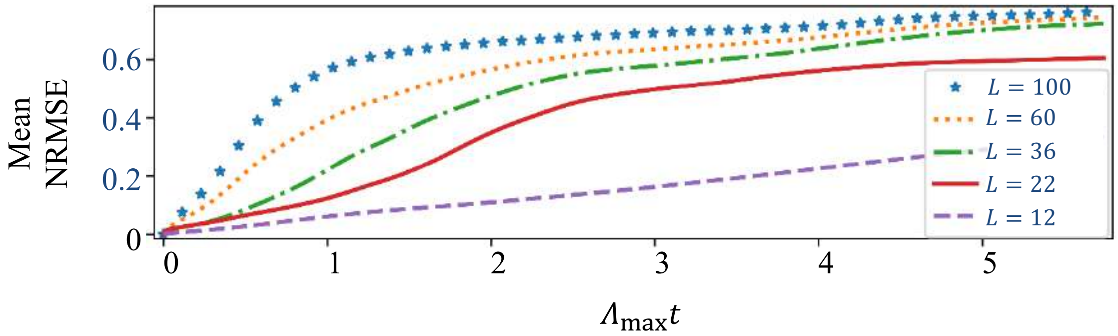
Ground truth



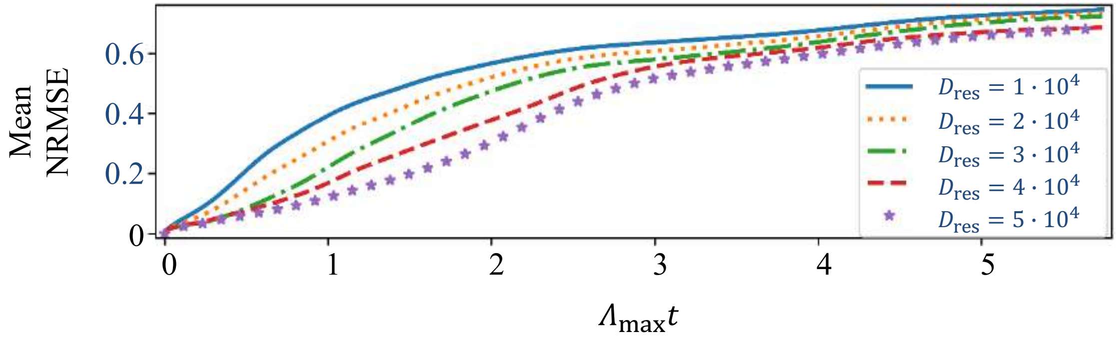
Rafayelyan, Dong, Tan, Krzakala, Gigan (2020). *Physical Review X*

Scaling behavior

Reservoir size is fixed, $D_{\mathrm{res}} = 10000$



Spatial domain size is fixed, $L = 60$



Larger networks can predict better larger chaotic systems

Rafayelyan, Dong, Tan, Krzakala, Gigan (2020). *Physical Review X*

Optical computing efficiency

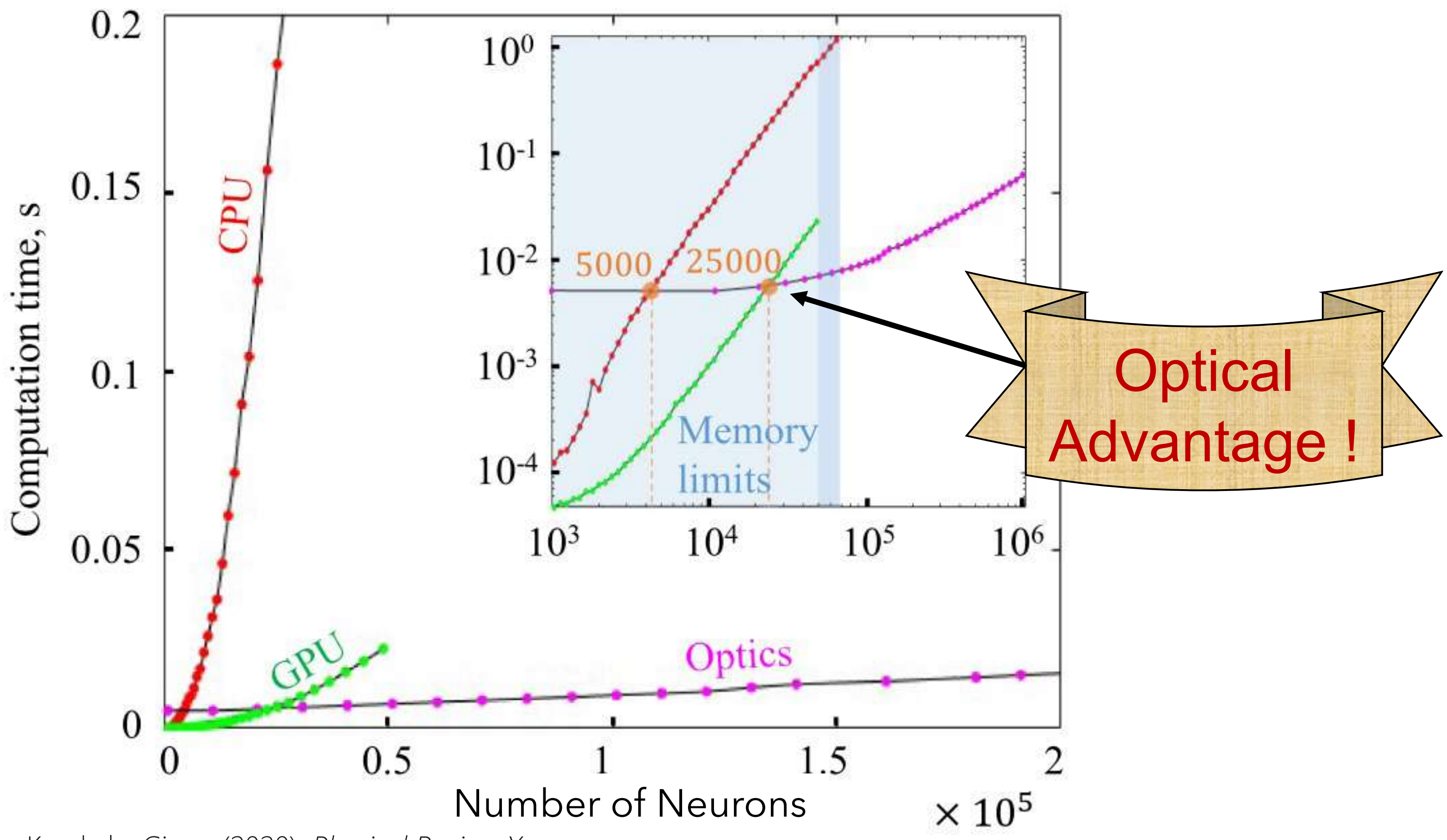
Speed

	Electronics	**Optics**
Speed	$\mathcal{O}(n^2)$	$\mathcal{O}(1)$
Energy efficiency	~150 W	~30 W
Dimensionality	Memory limit (~ GB)	Resolution limit (~ TB)

Energy efficiency

Dimensionality

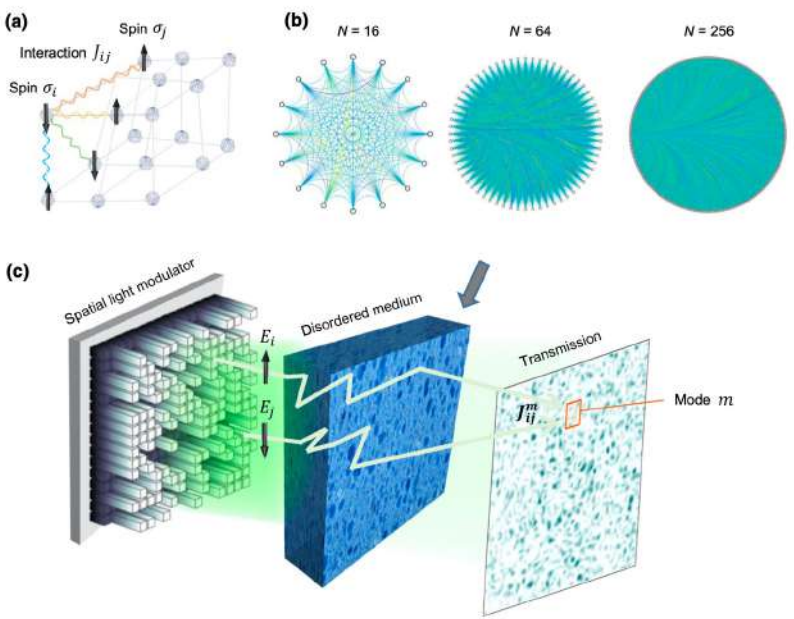
Computation time versus reservoir size (one iteration)



Rafayelyan, Dong, Tan, Krzakala, Gigan (2020). *Physical Review X*

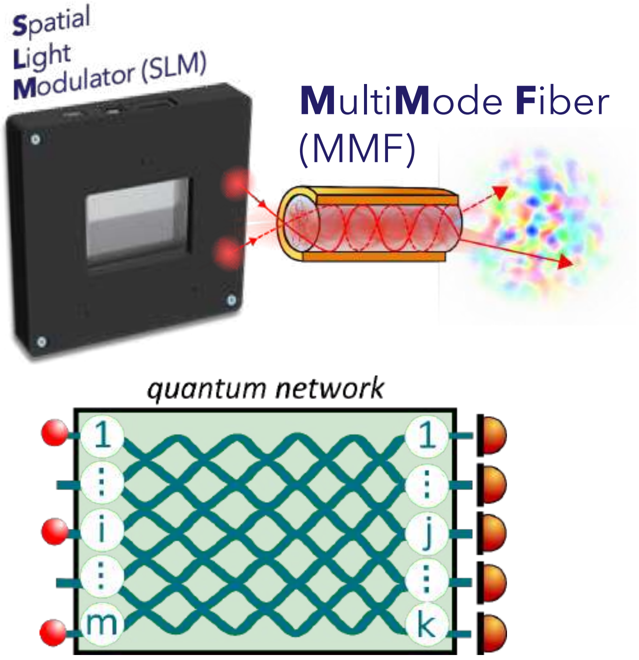
Other recent works on computing with disorder

Scalable Spin-Glass Optical Simulator



Pierangeli et al. Phys. Rev. Applied 15, 034087 (2021)
Collaboration : Claudio Conti (Roma)

Programmable linear circuits in a multimode fiber



Leedumrongwatthanakun, S.. et al.,
Nature Photonics 14, 139–142 (2020).

Take-home message

LKB

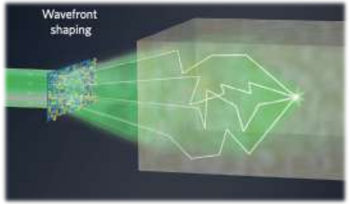
Light in complex media

- Complex media are ubiquitous
  …scattering can exploited
- Shaping can “undo” scattering

Transformative concept for many fields (imaging, sensing, spectroscopy…)

Computational imaging

- Algorithms joins force with hardware
- Leverages modern ML frameworks



Challenges

- Low signals
- Speed
- …

optical computing

- All-to-all connectivity
- Large scale
- Low power consumption

Challenges

- Engineering disorder
- Non-linearities

Thanks to my coworkers and collaborators

Thank you for your attention !

Sylvain.gigan@lkb.ens.fr
@comedialkb

If you are interested in the field :

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Sylvain Gigan

Nature Physics **18**, 980–985 (2022) | Cite this article

Perspective | Published: 02 December 2020

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Gordon Wetzstein, Aydogan Ozcan, Sylvain Gigan, Shanhui Fan, Dirk Englund, Marin Soljačić, Cornelia Denz, David A. B. Miller & Demetri Psaltis

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