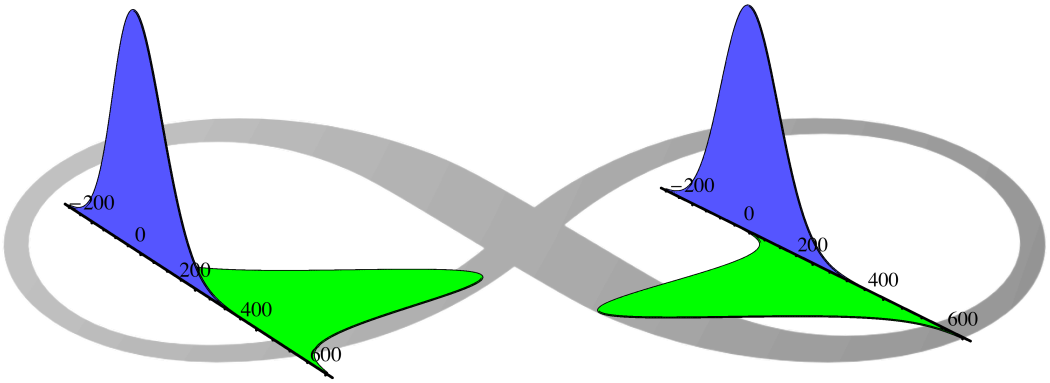
Laboratoire Kastler Brossel
Physique quantique et applications

ENS cnrs UPMC SORBONNE UNIVERSITÉS

Quantum Information and Quantum Metrology: from Fundamental Physics to Start-up(s)

Nicolas Treps

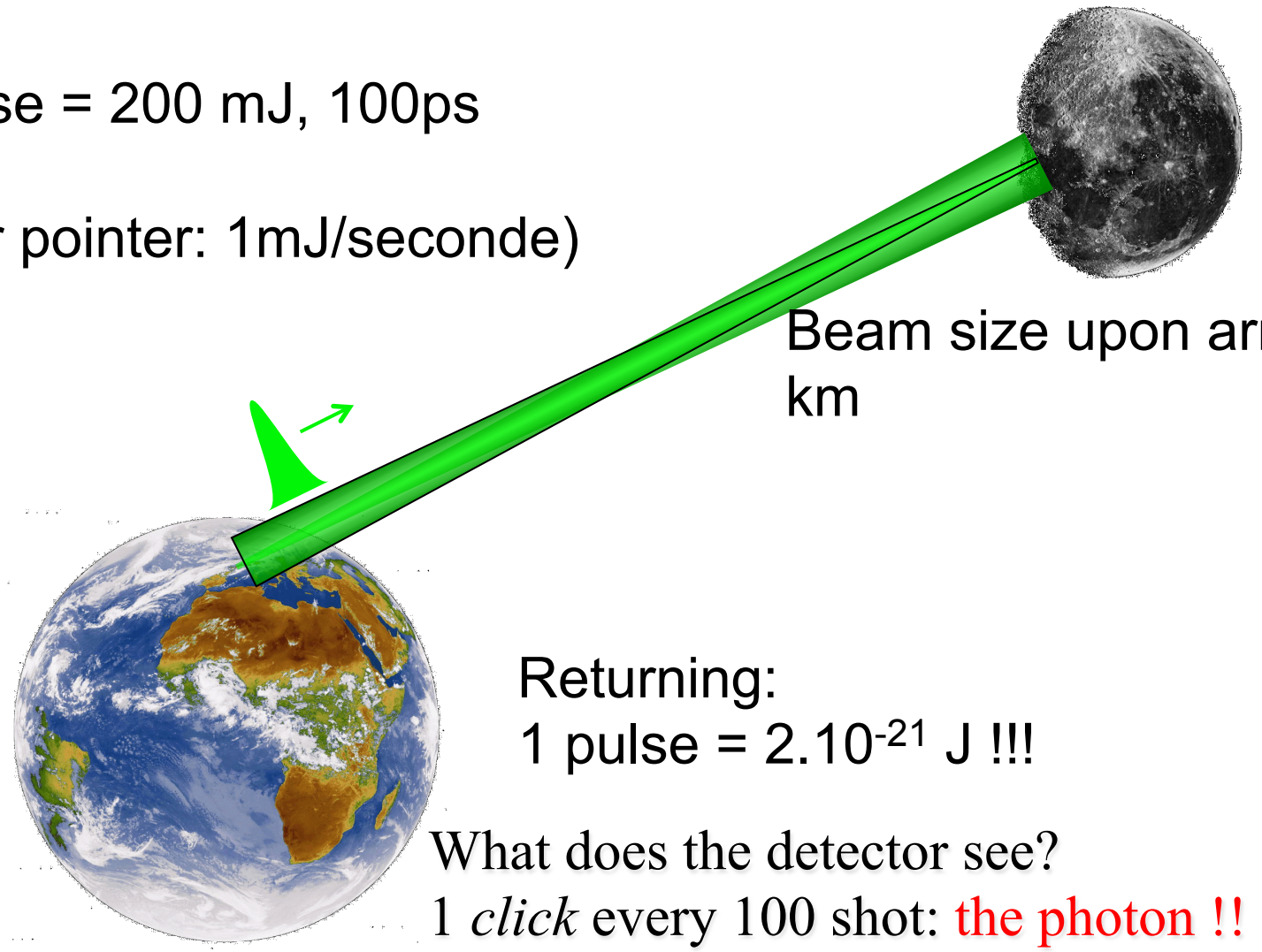
ANR erc



Earth – Moon distance measurement

1 pulse = 200 mJ, 100ps

(laser pointer: 1mJ/seconde)

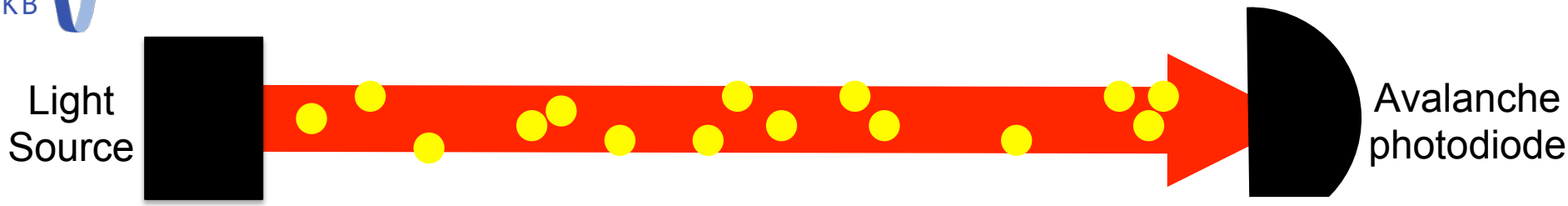


Beam size upon arrival ≈ km

Returning:
1 pulse = 2.10^{-21} J !!!

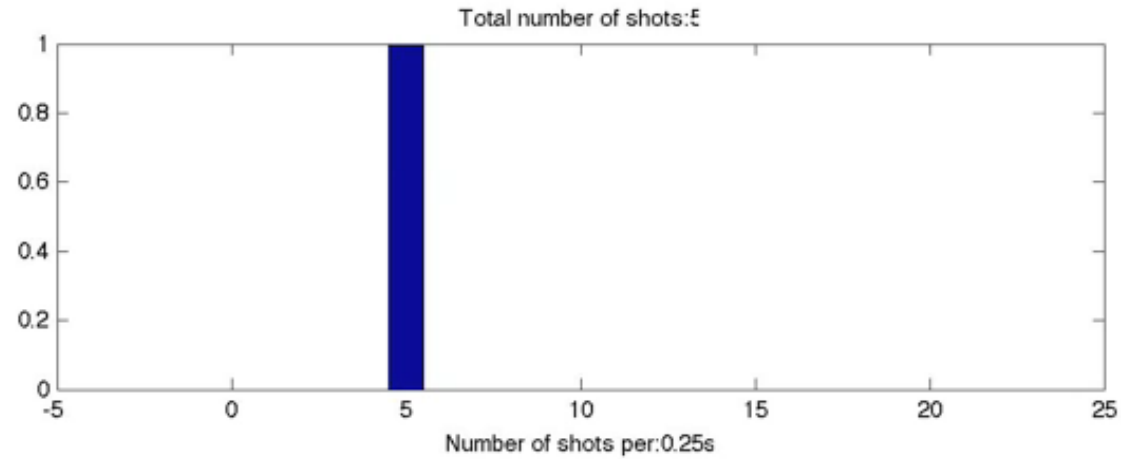
What does the detector see?
1 *click* every 100 shot: the photon !!
Probabilistic nature of measurement in quantum physics

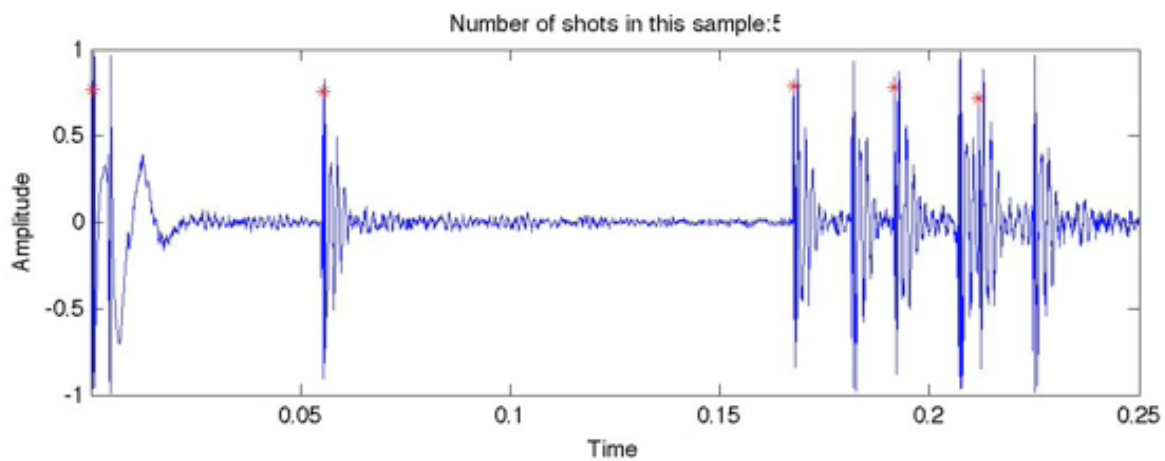
Random arrival times of photons



$$\Delta N = \sqrt{\langle N \rangle}$$

Arrival times of photons follow a Poissonian law: Shot Noise





« standard quantum limit for absorption measurement:

$$a_{\min} = \frac{1}{\sqrt{\langle N \rangle}}$$

Quantum Description of Light

Classical: solutions of Maxwell's equations

Amplitude

Optical modes

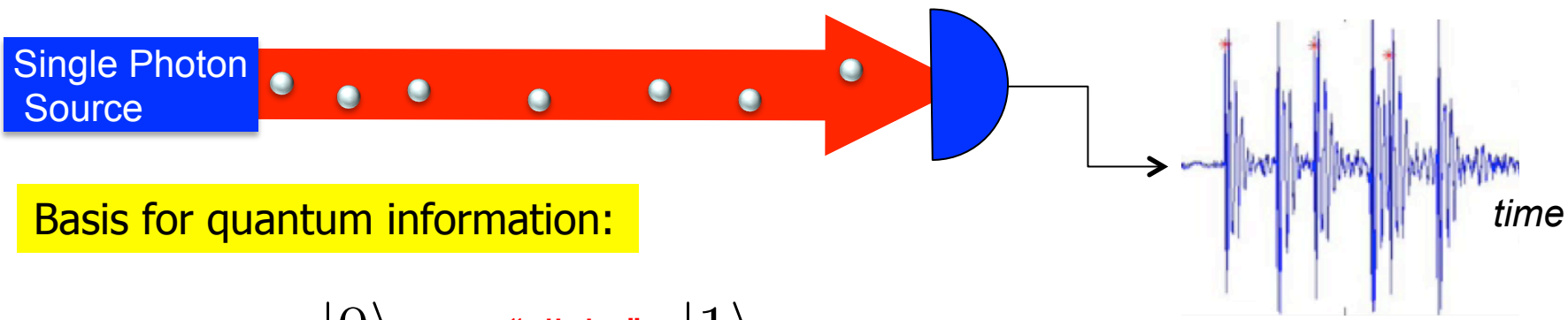
$$E^{(+)}(\vec{r},t) = i\sum_l \mathcal{E}_l \alpha_l e^{i(\vec{k}_l\cdot\vec{r}-\omega_l t)}$$

$$\mathcal{E}_l = \sqrt{\frac{\hbar\omega_l}{2\varepsilon_0 L^3}}$$

Quantum description: $\hat{E}^{(+)}(\vec{r},t) = i\sum_l \mathcal{E}_l \hat{a}_l e^{i(\vec{k}_l\cdot\vec{r}-\omega_l t)}$

Photon numbers: $\hat{N} = \hat{a}^\dagger \hat{a}$

Photon's events



Basis for quantum information:

vacuum $|0\rangle$ or "clicks" $|1\rangle$

Discrete regime

Single photon regime :
"clicks" on a photon counter

Quantum Description of Light

Amplitude

Optical modes

Classical: solutions of Maxwell's equations

$$E^{(+)}(\vec{r},t) = i\sum_l \mathcal{E}_l \alpha_l e^{i(\vec{k}_l\cdot\vec{r}-\omega_l t)}$$

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Quantum Description of Light

Quantum description: $\hat{E}^{(+)}(\vec{r},t) = i\sum_l \mathcal{E}_l \hat{a}_l e^{i(\vec{k}_l\cdot\vec{r}-\omega_l t)}$

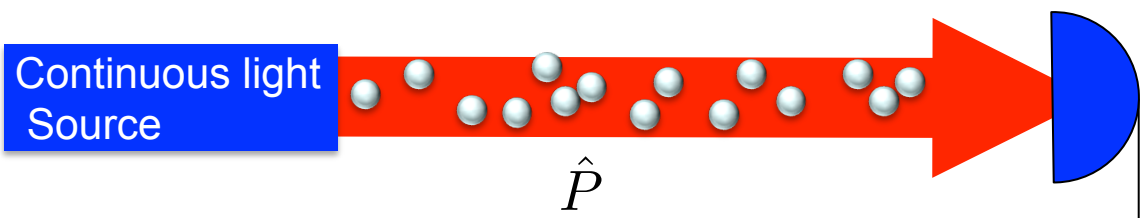
Photon numbers: $\hat{N} = \hat{a}^\dagger \hat{a}$

Continuous variable regime
Single mode

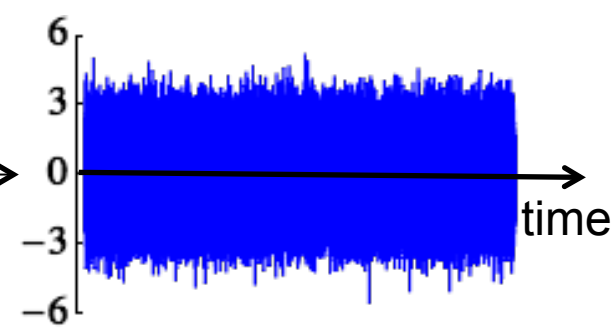
Position and momentum of a particle

$$\hat{x} \propto \hat{a} + \hat{a}^\dagger$$

$$\hat{p} \propto i(\hat{a}^\dagger - \hat{a})$$



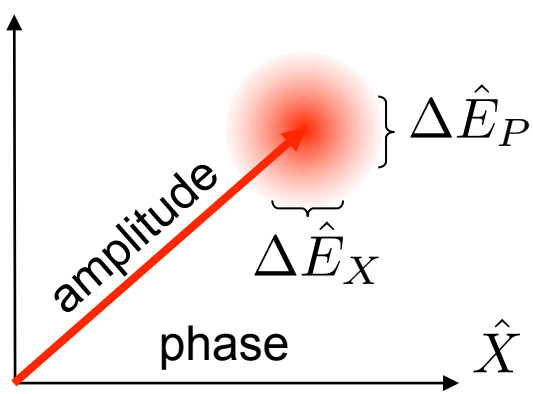
Light fluctuations: noise on the detection



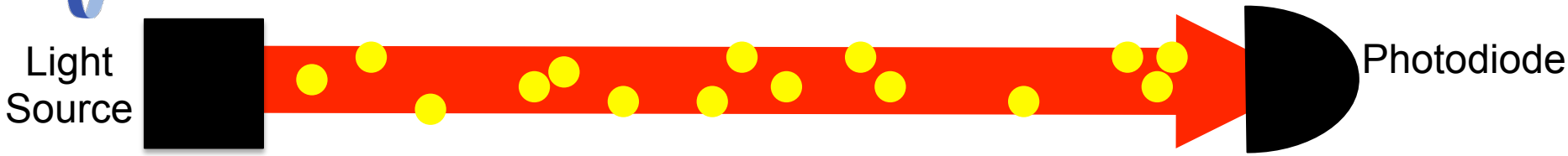
Quadrature representation

$$\hat{E}_X \propto \hat{a} + \hat{a}^\dagger$$

$$\hat{E}_P \propto i(\hat{a}^\dagger - \hat{a})$$

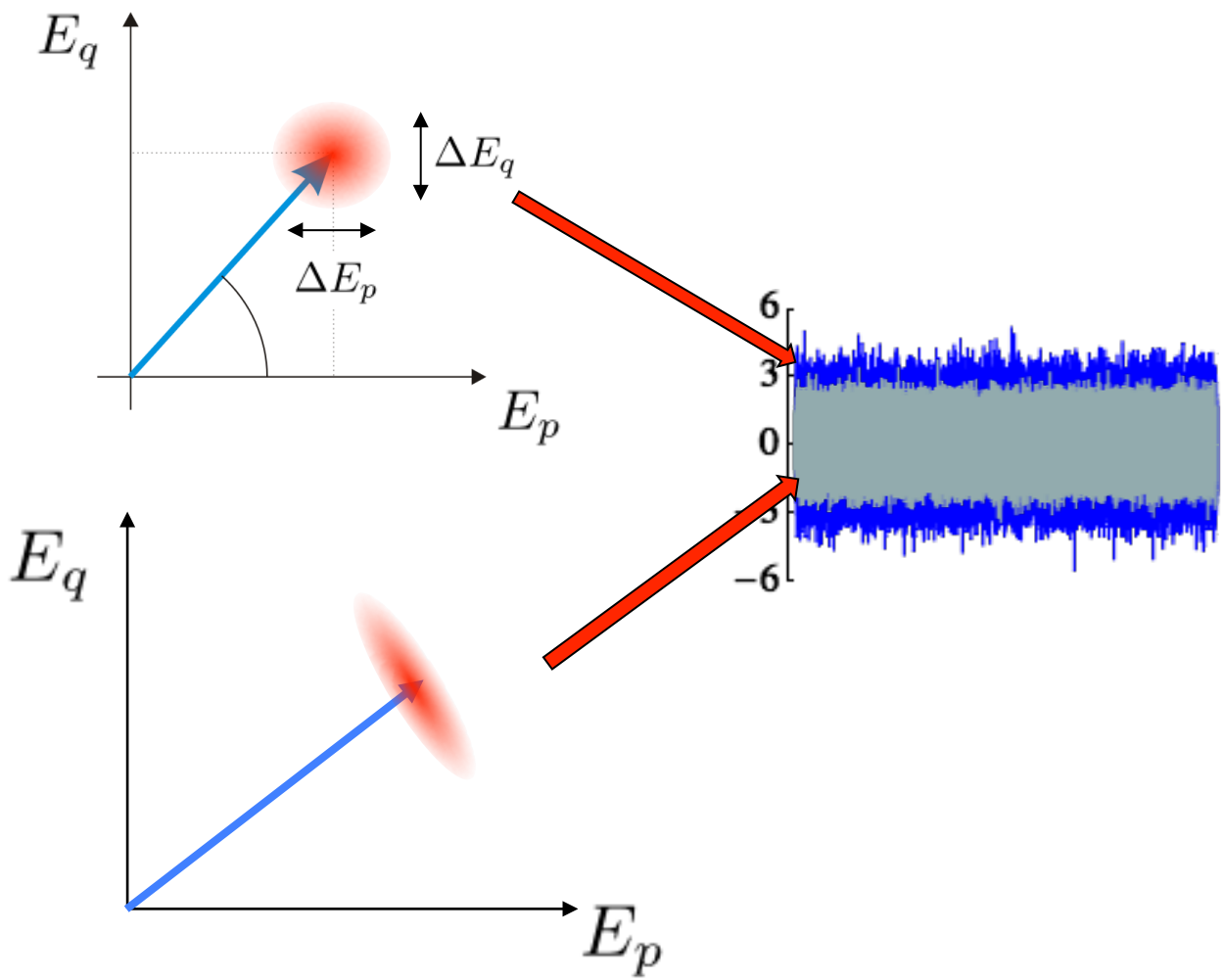


Can we go further than shot noise?



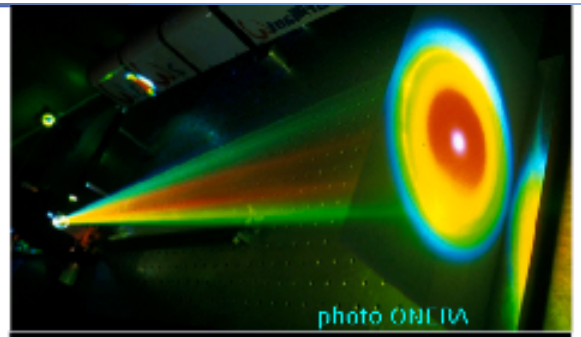
$$\Delta E_p \Delta E_q = 1$$

Glauber states !



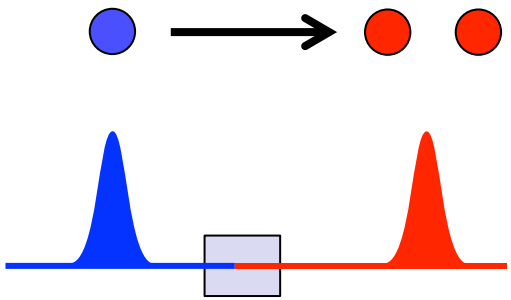
Quantum resource: squeezed states !

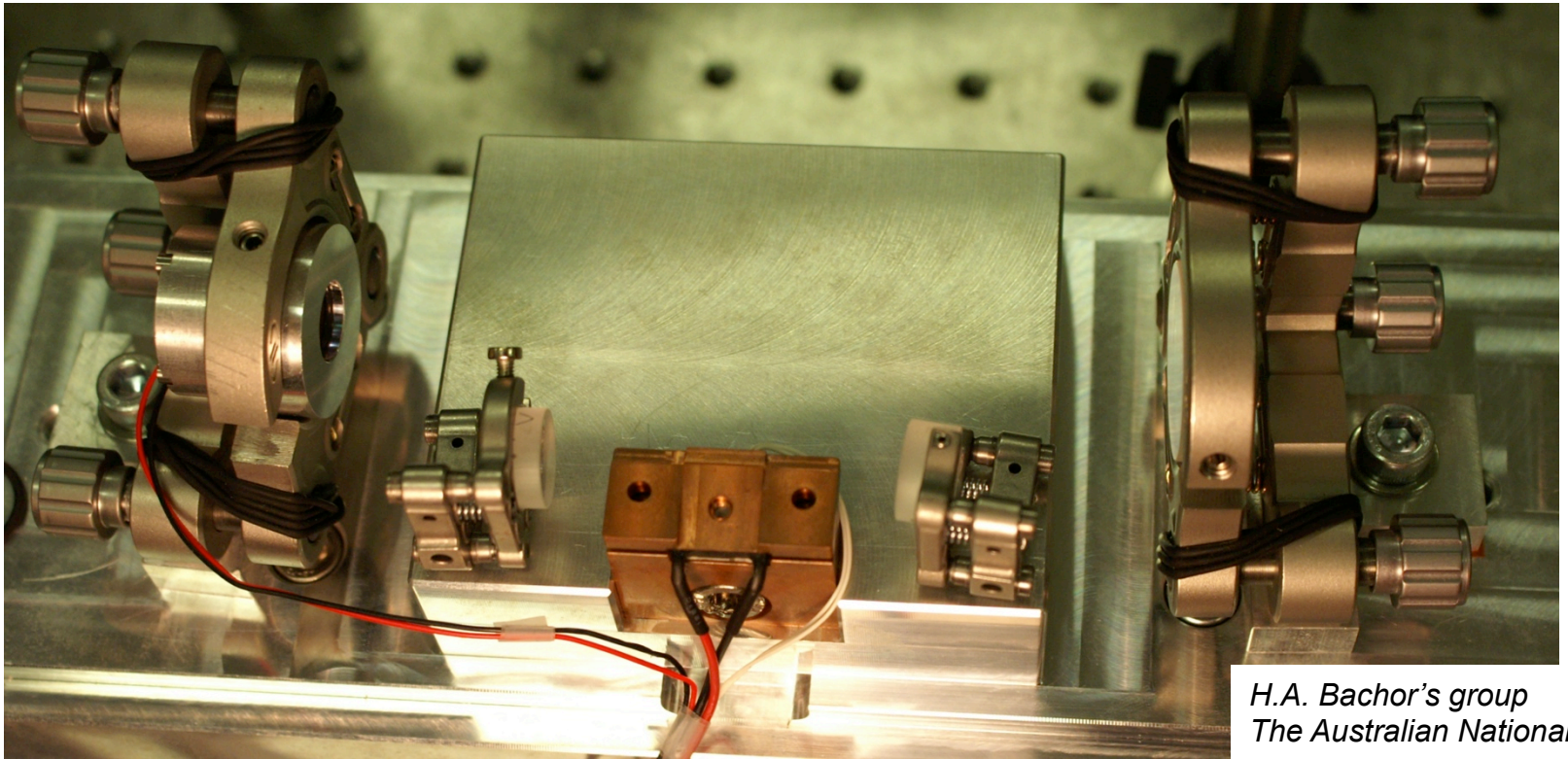
Squeezed light generation



$$\omega_p = \omega_s + \omega_i$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

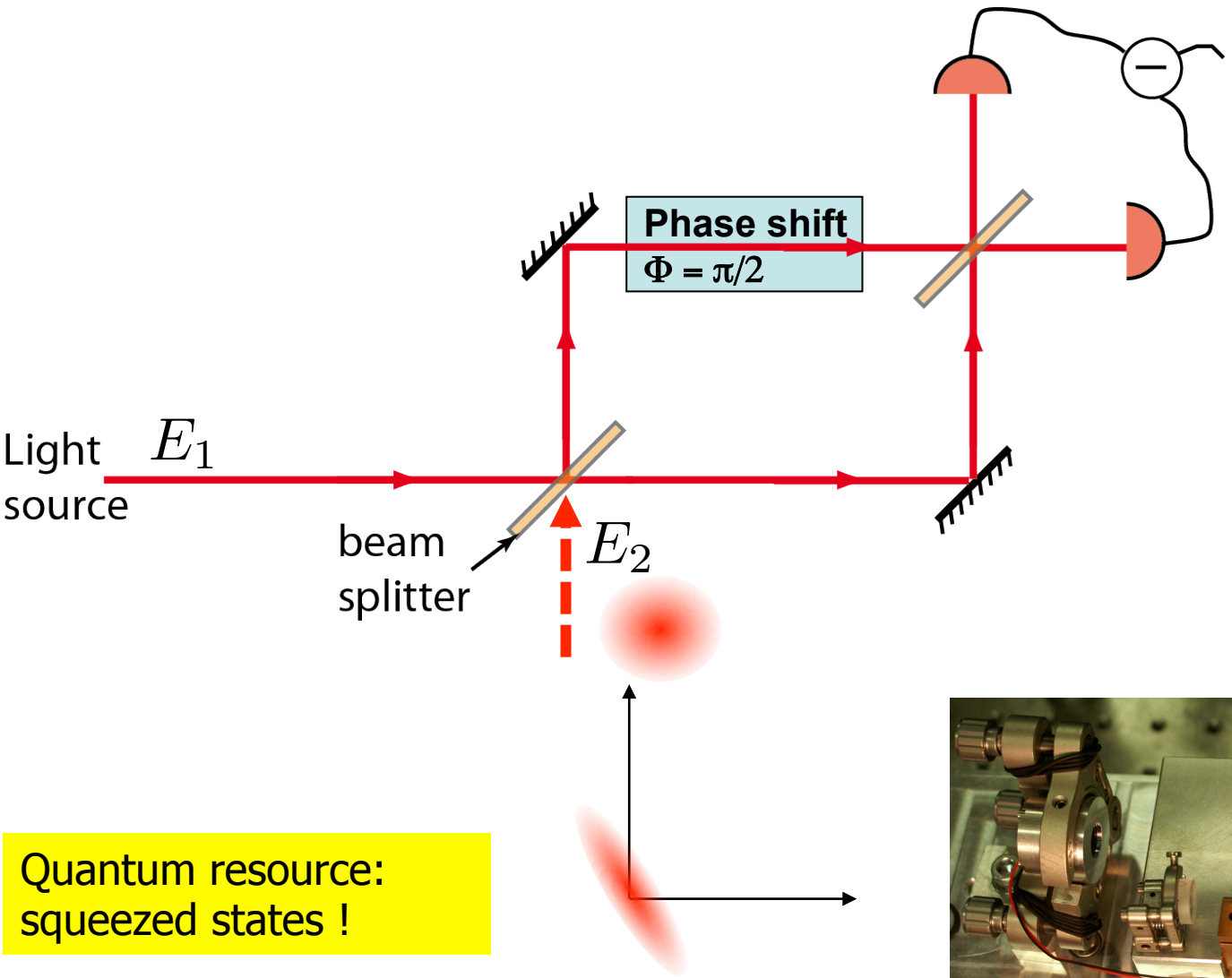
Non-linear optics

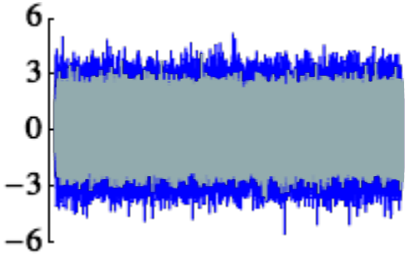




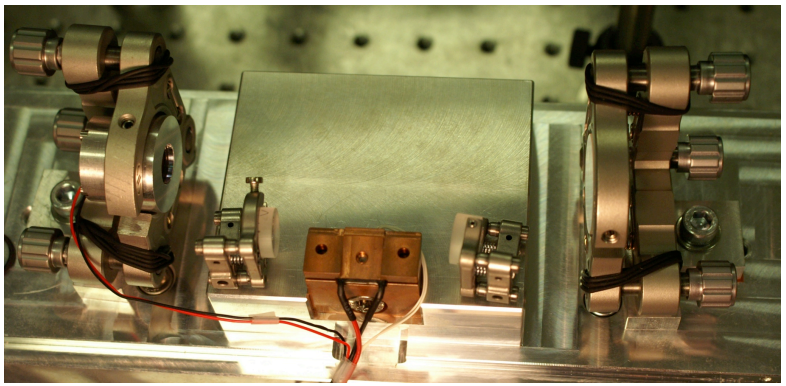
H.A. Bachor's group
The Australian National University

Improved phase measurement





Quantum resource: squeezed states !

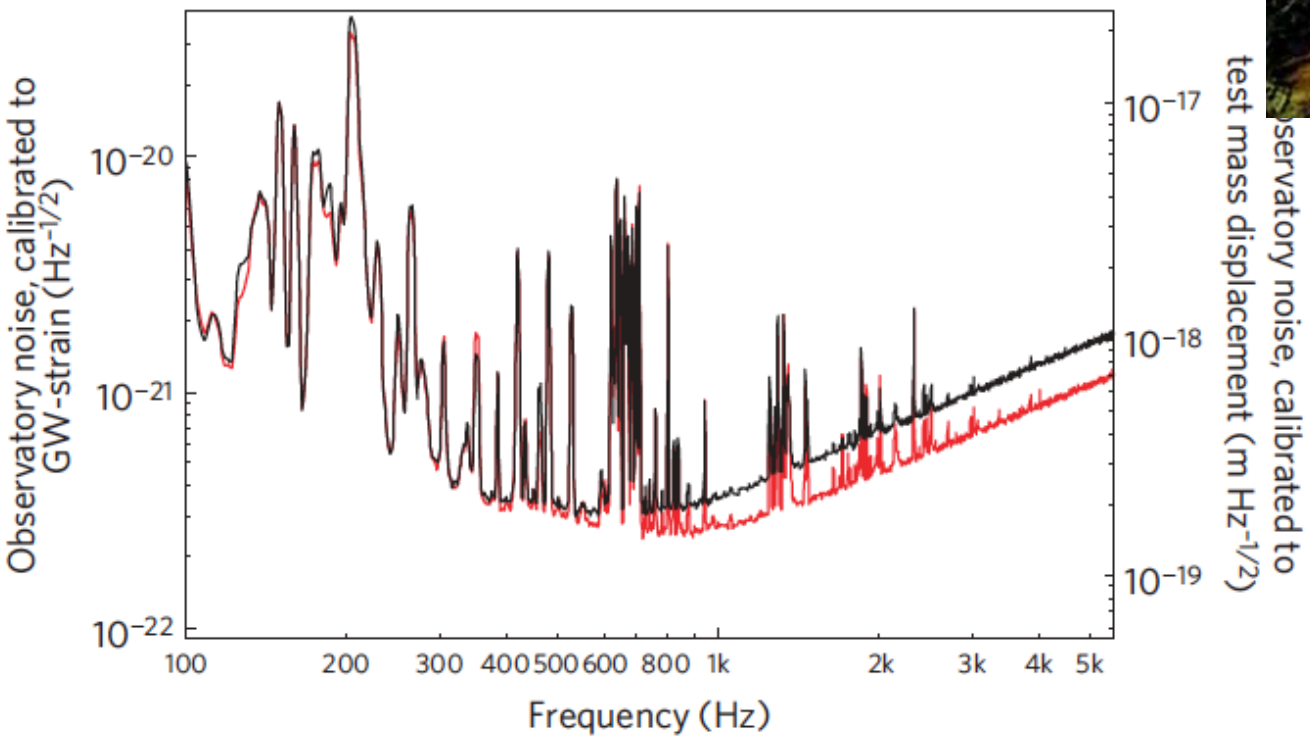


Gravitational waves measurement

LETTERS
PUBLISHED ONLINE: 11 SEPTEMBER 2011 | DOI: 10.1038/NPHYS2083
nature physics

A gravitational wave observatory operating beyond the quantum shot-noise limit

The LIGO Scientific Collaboration †*



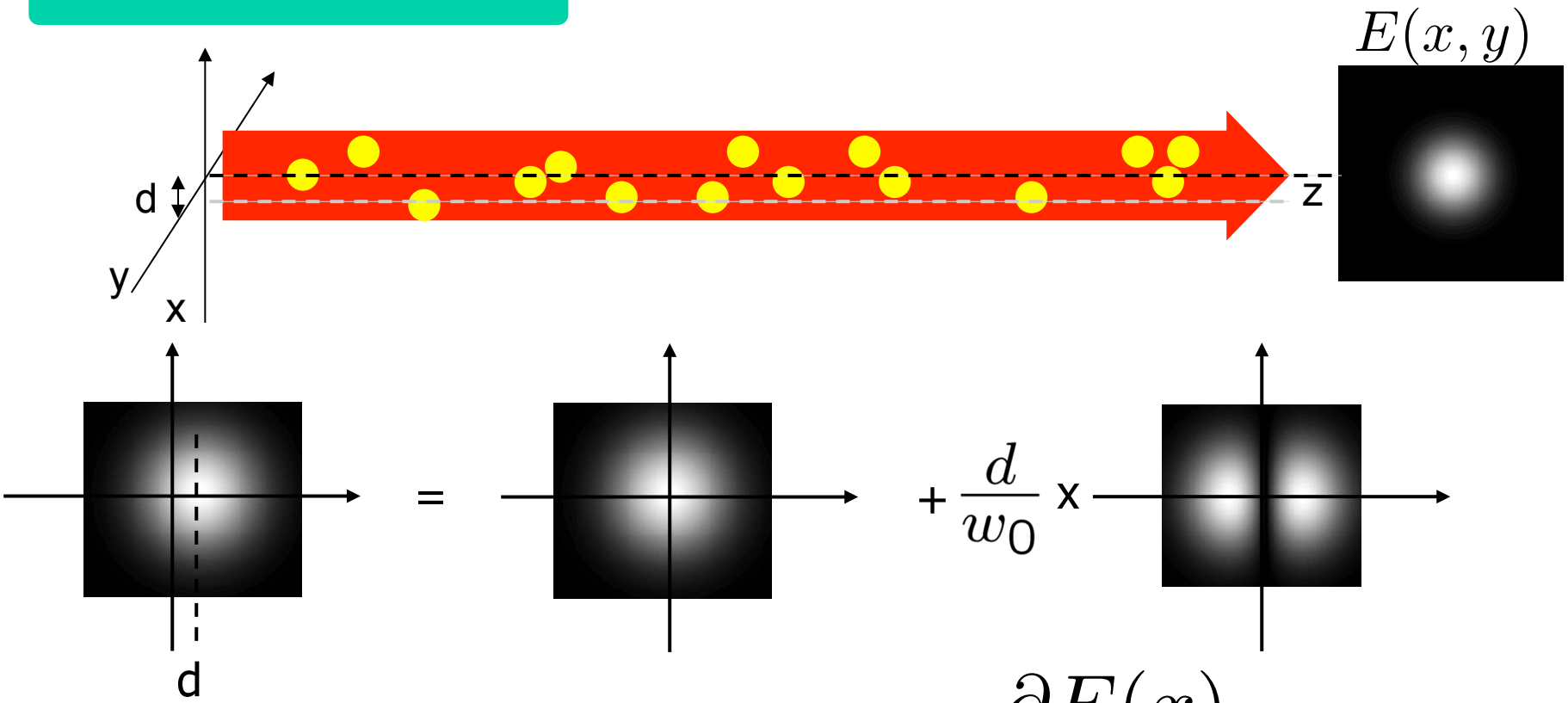
Menu

- Quantum metrology
- Quantum information

- CAILabs company

Beam positioning

Gaussian laser beam



$$E(x+d) = \underbrace{E(x)} + \underbrace{d \times \frac{\partial E(x)}{\partial x}}$$

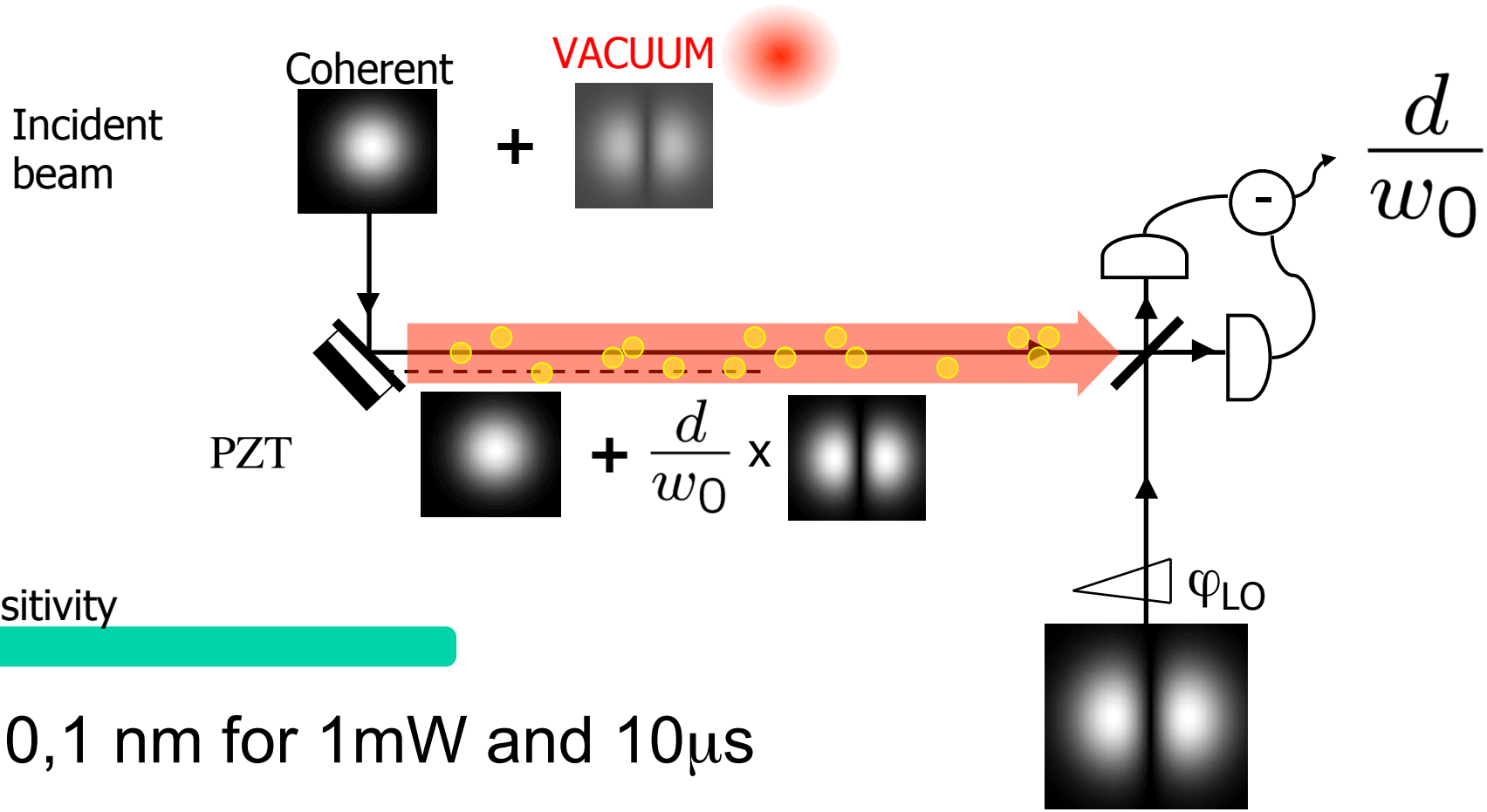
1er order (Taylor)

Do not depend on d

proportional to d

Beam positioning

Homodyne detection

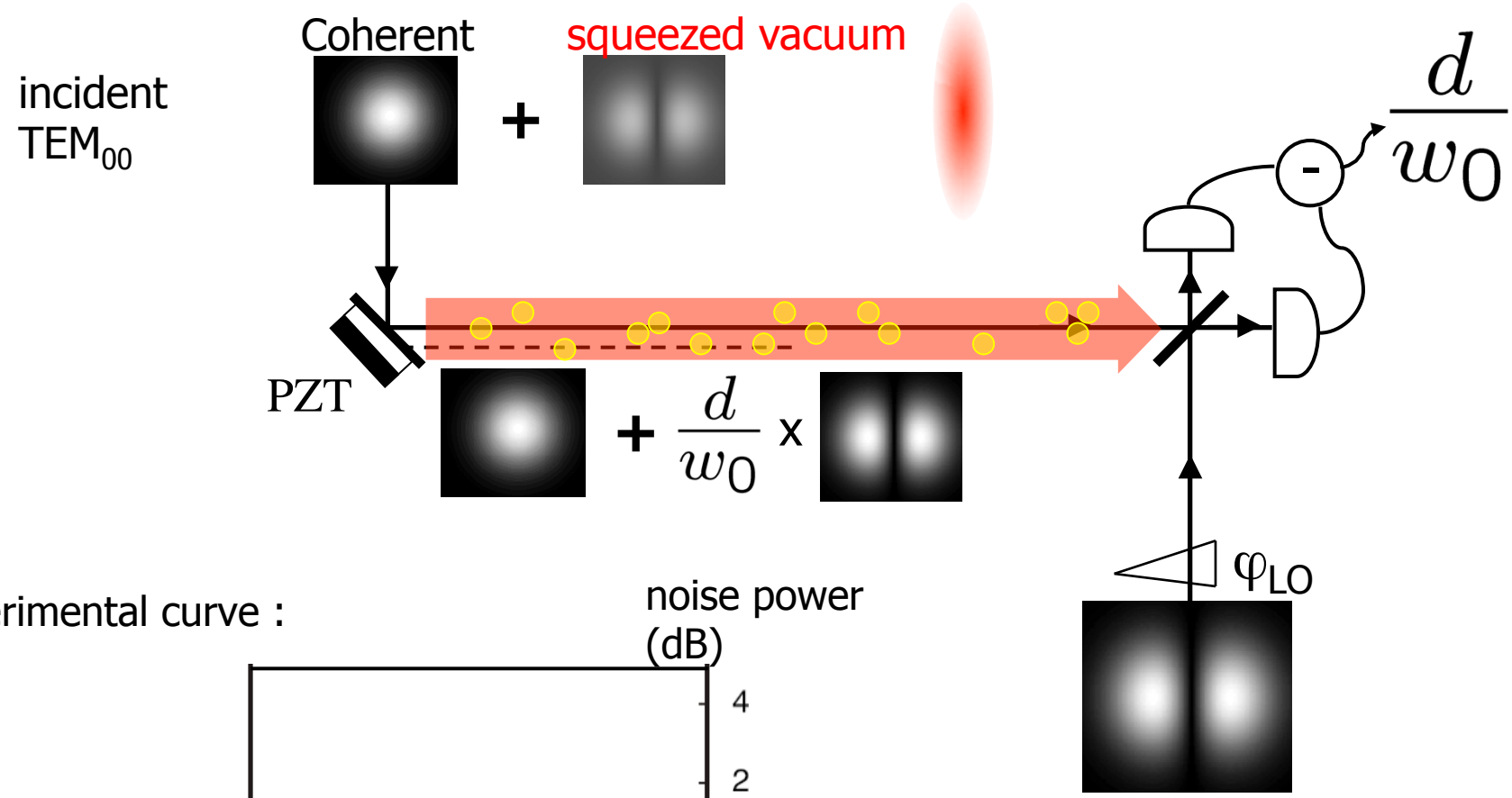


Sensitivity

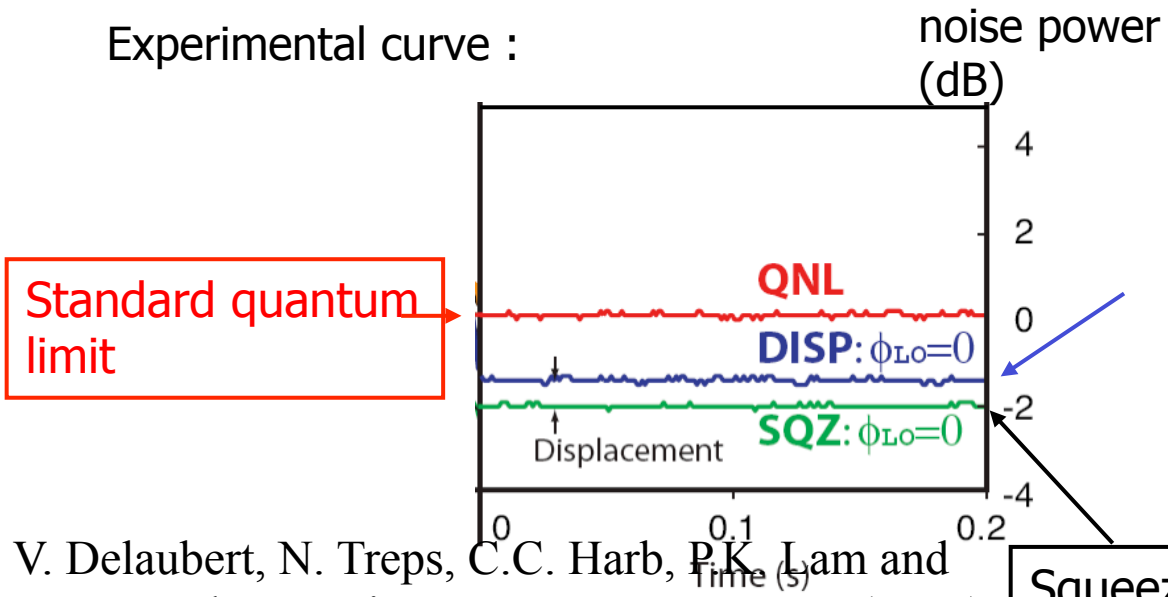
0,1 nm for 1mW and 10μs

Limiting noise : vacuum noise of the derivative of the incident beam

Measurement at Cramér Rao bound



Experimental curve :



Standard quantum limit

Displacement smaller than standard quantum limit

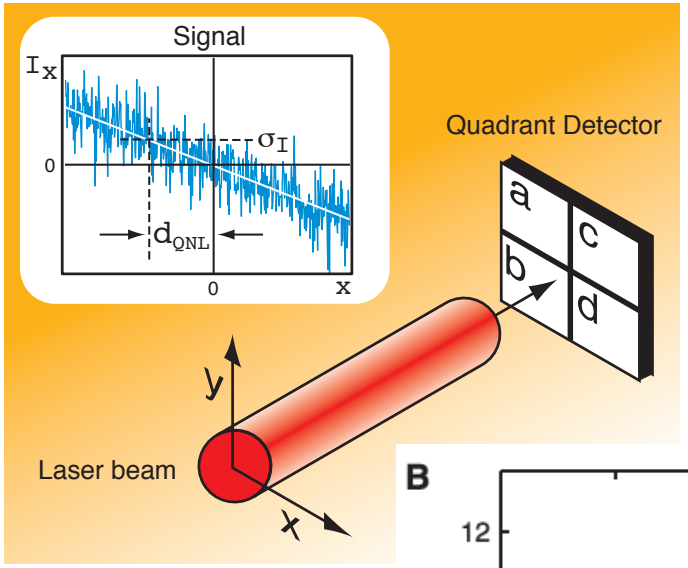
Squeezed background noise on TEM_{10}

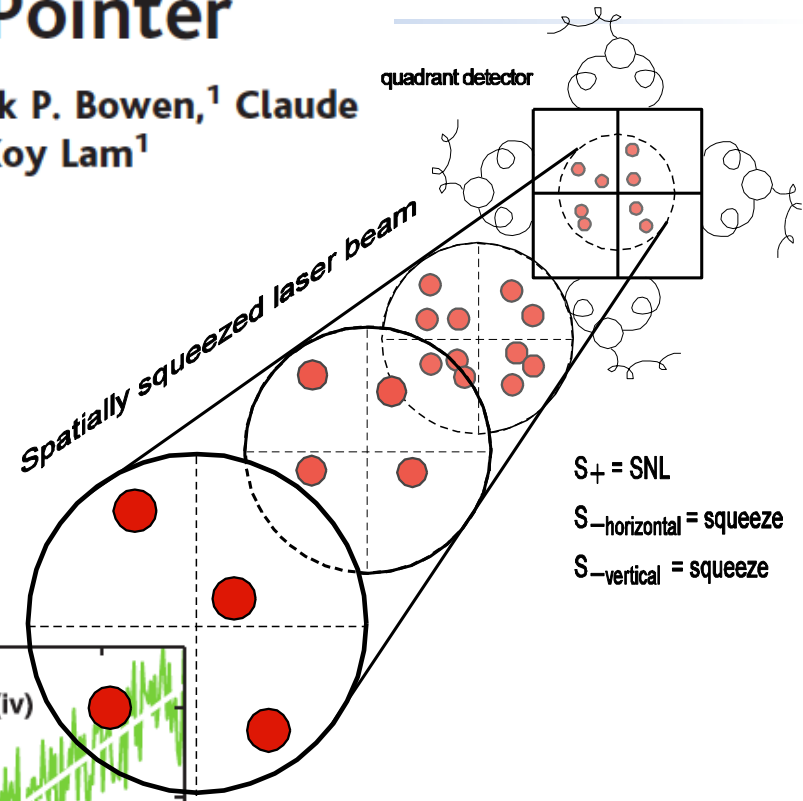
V. Delaubert, N. Treps, C.C. Harb, P.K. Lam and H.-A. Bachor, Optics Letters **31** 1537-1539 (2006)

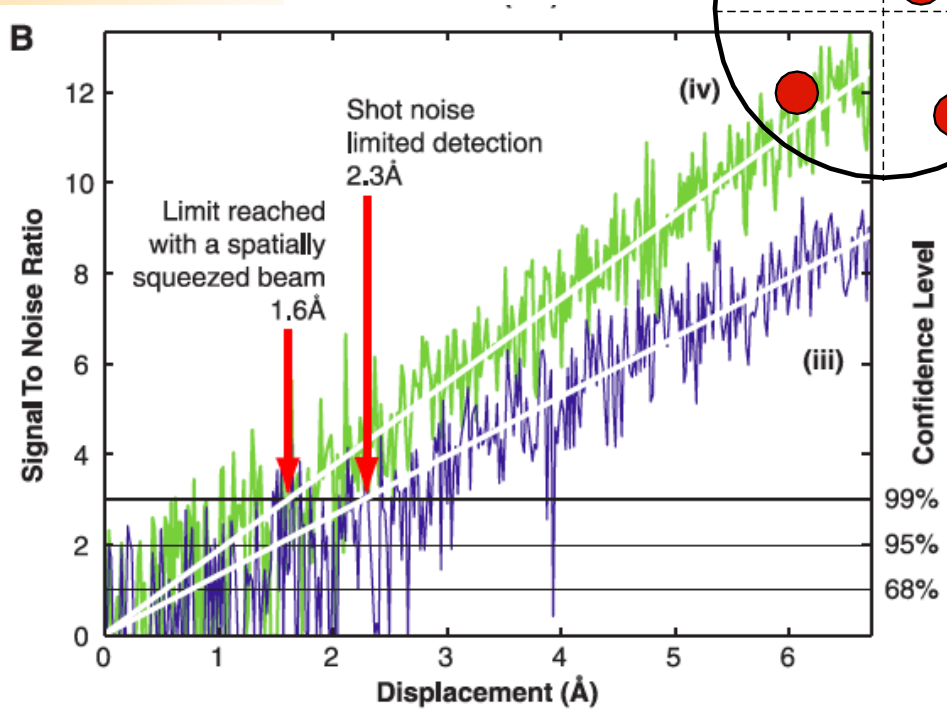
15 AUGUST 2003 VOL 301 SCIENCE www.sciencemag.org

A Quantum Laser Pointer

Nicolas Treps,[1,2]* Nicolai Grosse,[1] Warwick P. Bowen,[1] Claude Fabre,[2] Hans-A. Bachor,[1] Ping Koy Lam[1]







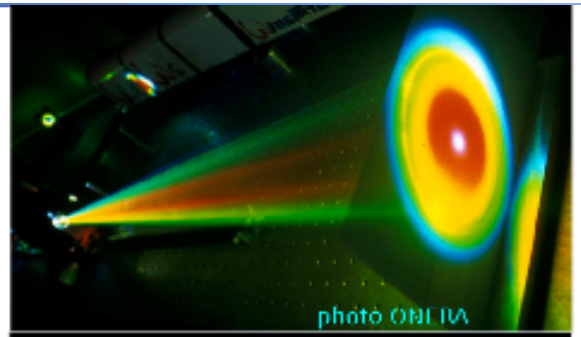
Partenaire

THE AUSTRALIAN NATIONAL UNIVERSITY

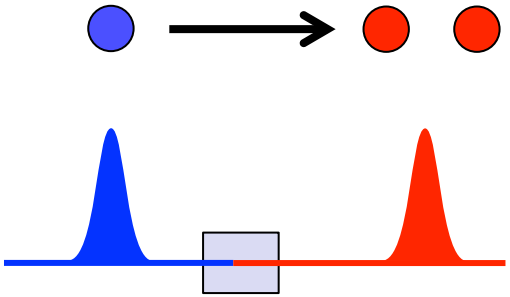
Menu

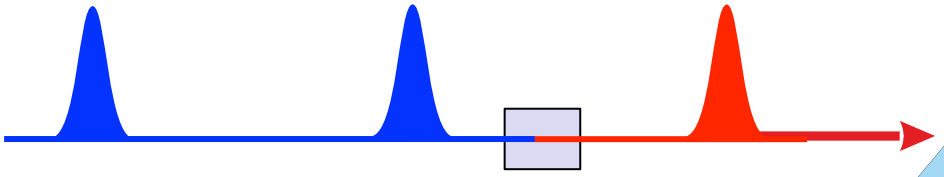
- Quantum metrology
- Quantum information
- CAILabs company

Optical Frequency Combs

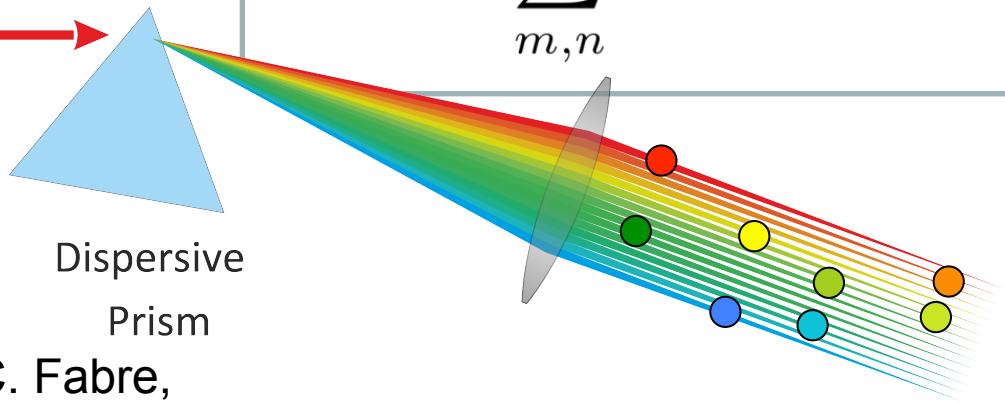


$$\omega_p = \omega_s + \omega_i$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$





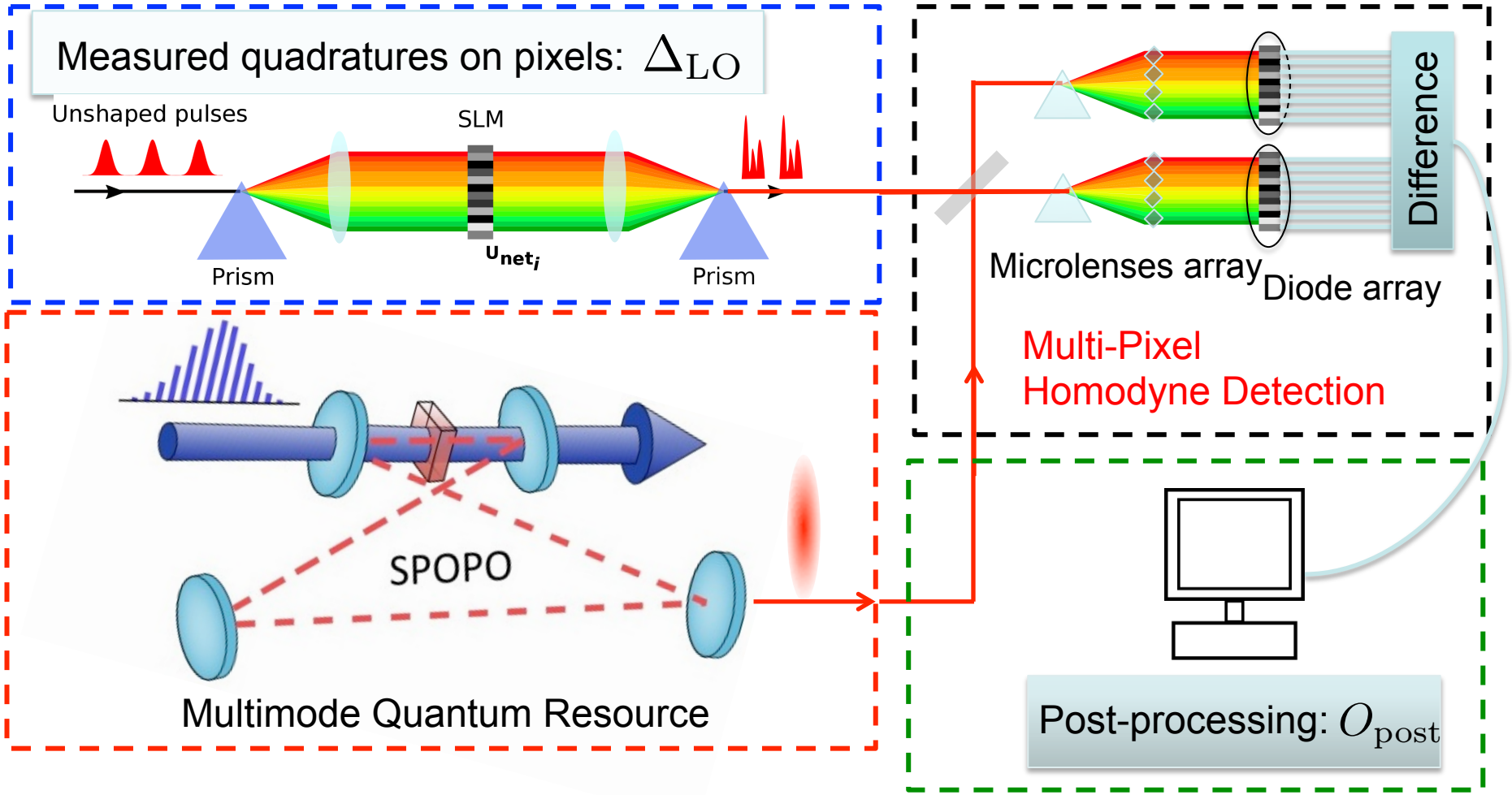
$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^\dagger_{-m}\, \hat{a}^\dagger_n$$



J. Roslund, R. M. de Araújo, S. Jiang, C. Fabre, and N. Treps, Nature Photonics **8**, 109 (2014).

Maximally entangled state

Quantum computing



Final result

$$\vec{a}_{\mathrm{out}} = O_{post} \Delta_{LO} U_{lin} \vec{a}_{\mathrm{pix}}$$

A classical company based on quantum-inspired technologies

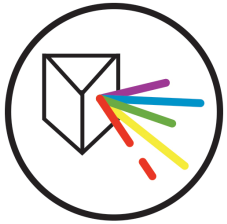
Space division multiplexing

C. Kao prix Nobel 2009

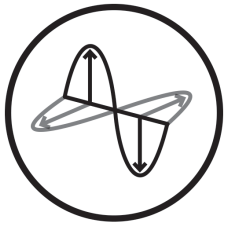
Demand for bandwidth is growing globally:

- IP traffic grows **20% - 90% annually**, led by IP video traffic
- Cloud and virtualization drive **LAN traffic increase**

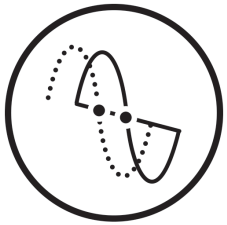
Power



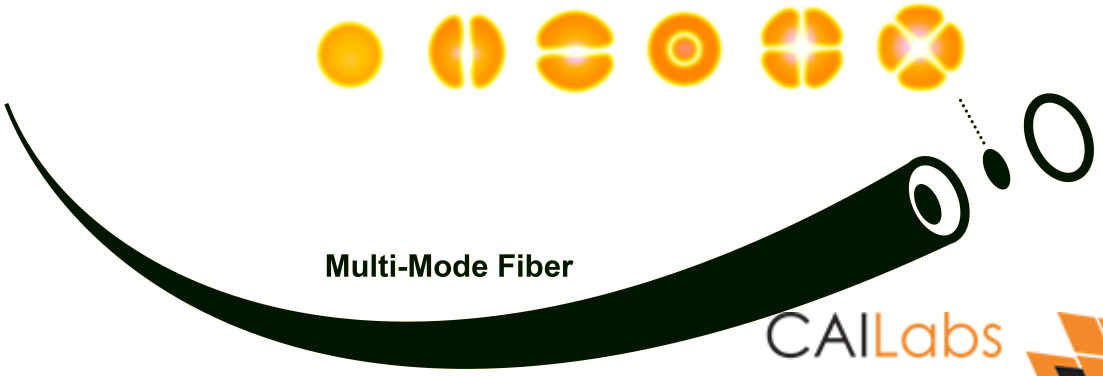
Wavelength



Polarization



Phase

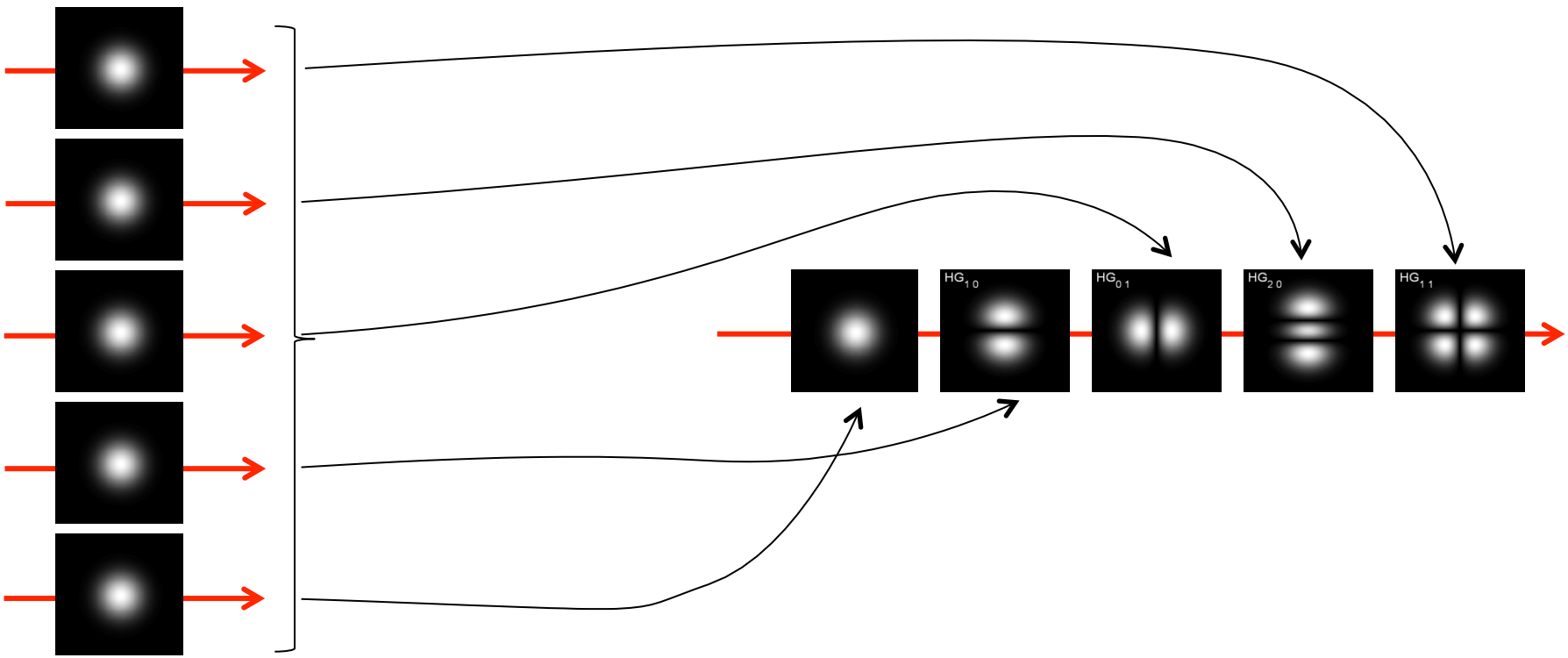


CAILabs
Shaping the light

Quantum to classical technology

Each mode: an information channel (quantum or classical)

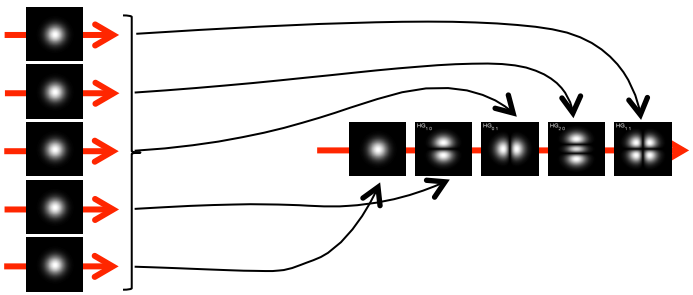
One needs lossless mode mixing



Mode (information channel) changes, not the information itself

Possible ? Yes: it is a unitary transformation

Unitary transformation on light



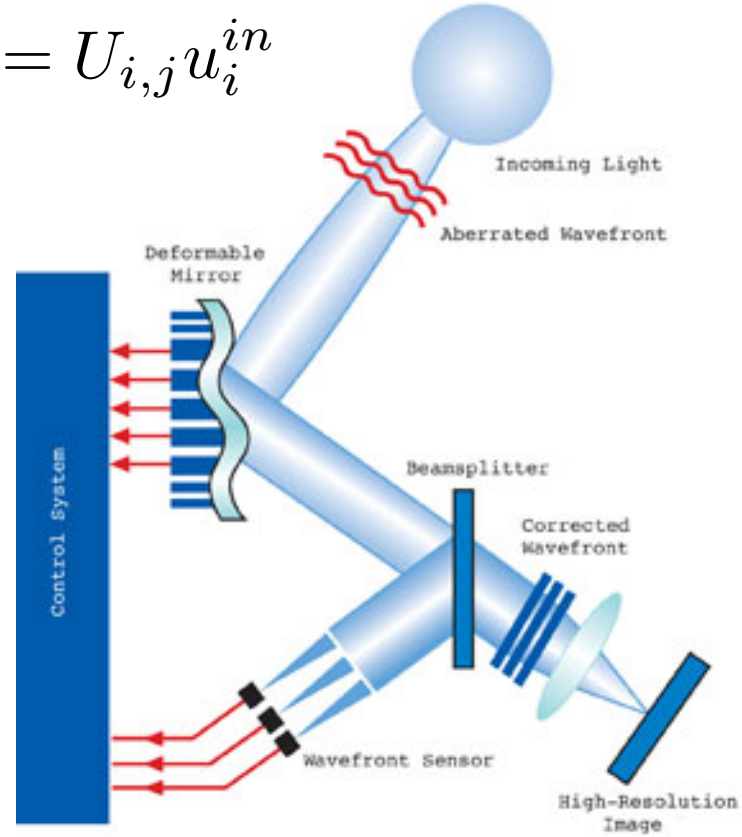
N modes in

-> N modes out

$$v_j^{out} = U_{i,j} u_i^{in}$$

Needs to be unitary

-> only local phase modulation



Adaptative optics

Phase and amplitude transformation

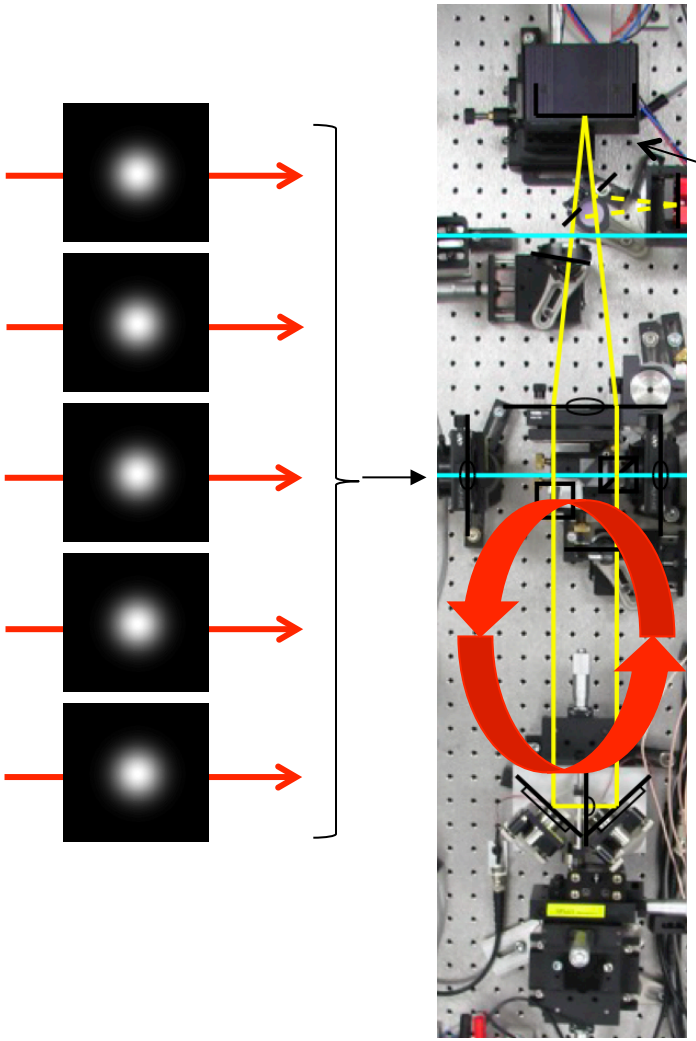
Same dimension of the number of modes

-> **a unique phase plane is not enough**

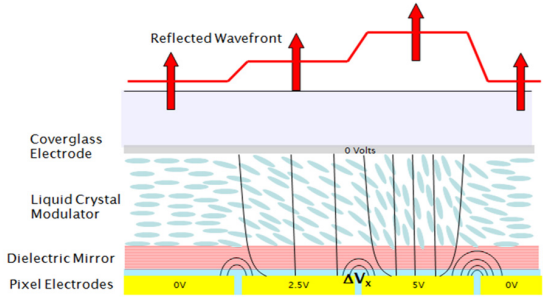
Quantum to classical technology

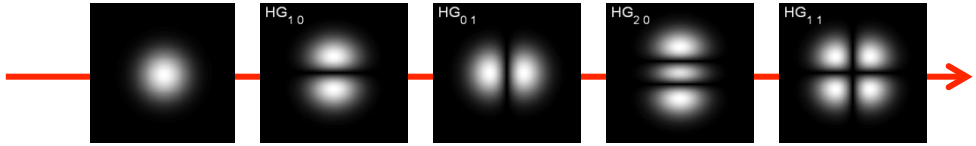
Each mode: an information channel (quantum or classical)

One needs lossless mode mixing



Spatial light modulator (or deformable mirror)
Boston nonlinear systems





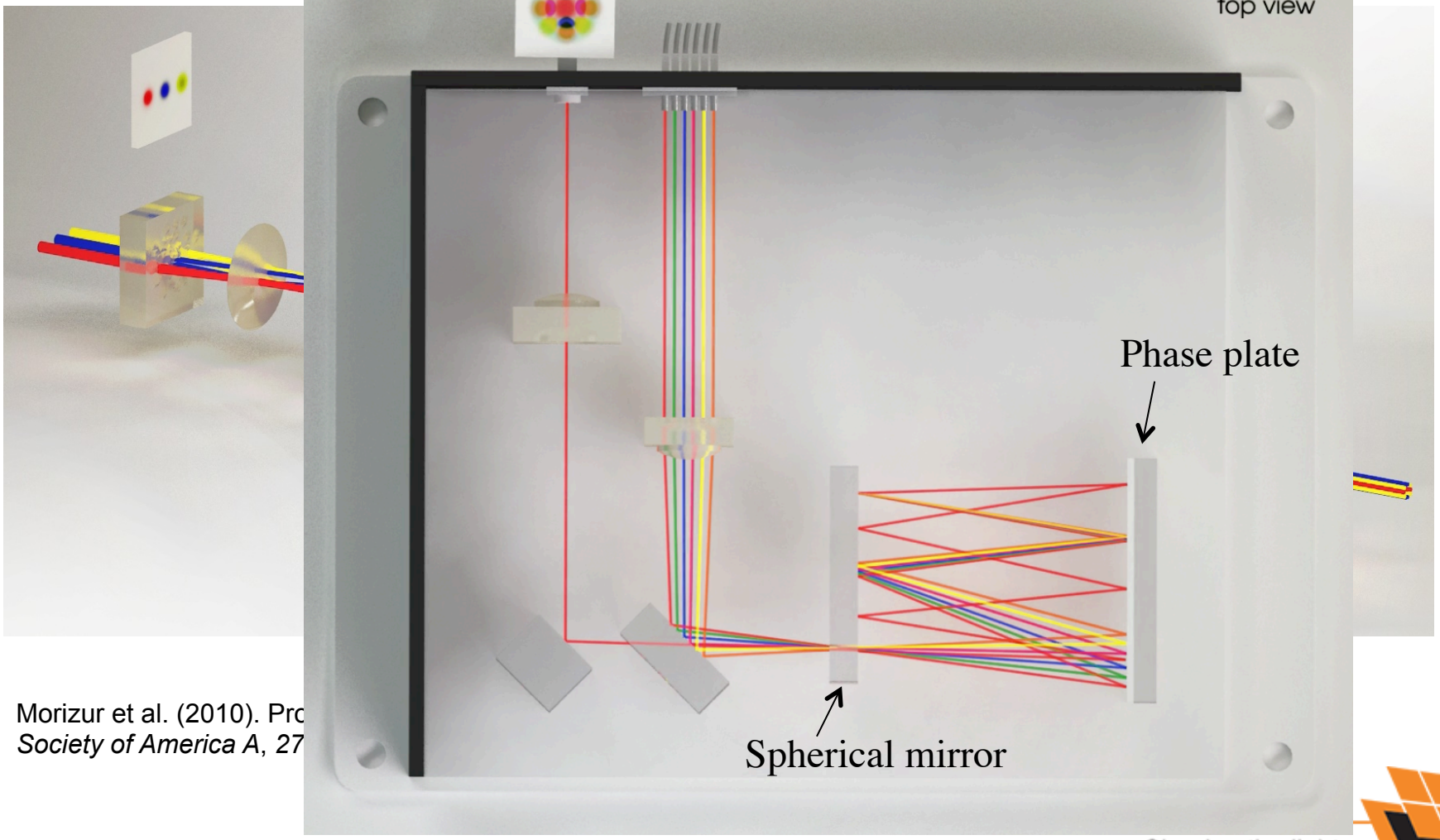
Optical Fourier transform

J.-F. Morizur, L. Nicholls, P. Jian, S. Armstrong, N. Treps, B. Hage, M. T. L. Hsu, W. Bowen, J. Janousek, and H.-A. Bachor, *Programmable unitary spatial mode manipulation* JOSA A **27**, 2524 (2010).

J. F. Morizur, S. Armstrong, N. Treps, J. Janousek, and H. A. Bachor, *Spatial reshaping of a squeezed state of light*, Eur Phys J D **61**, 237 (2011).

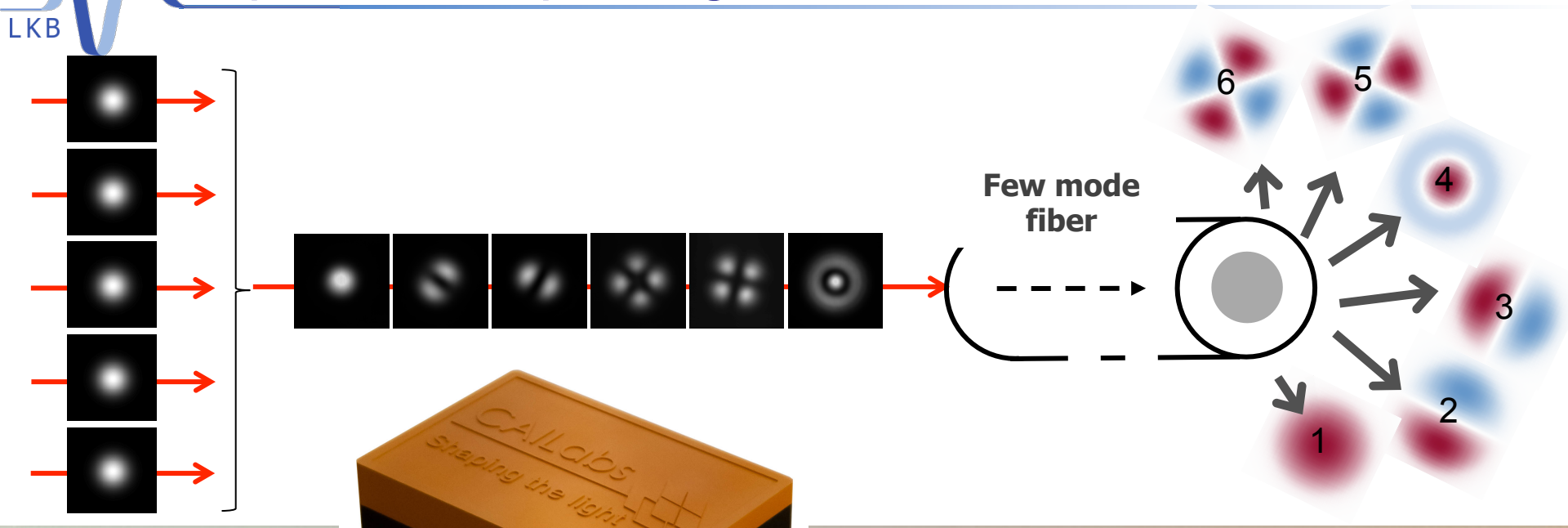
Multi-Plane light conversion

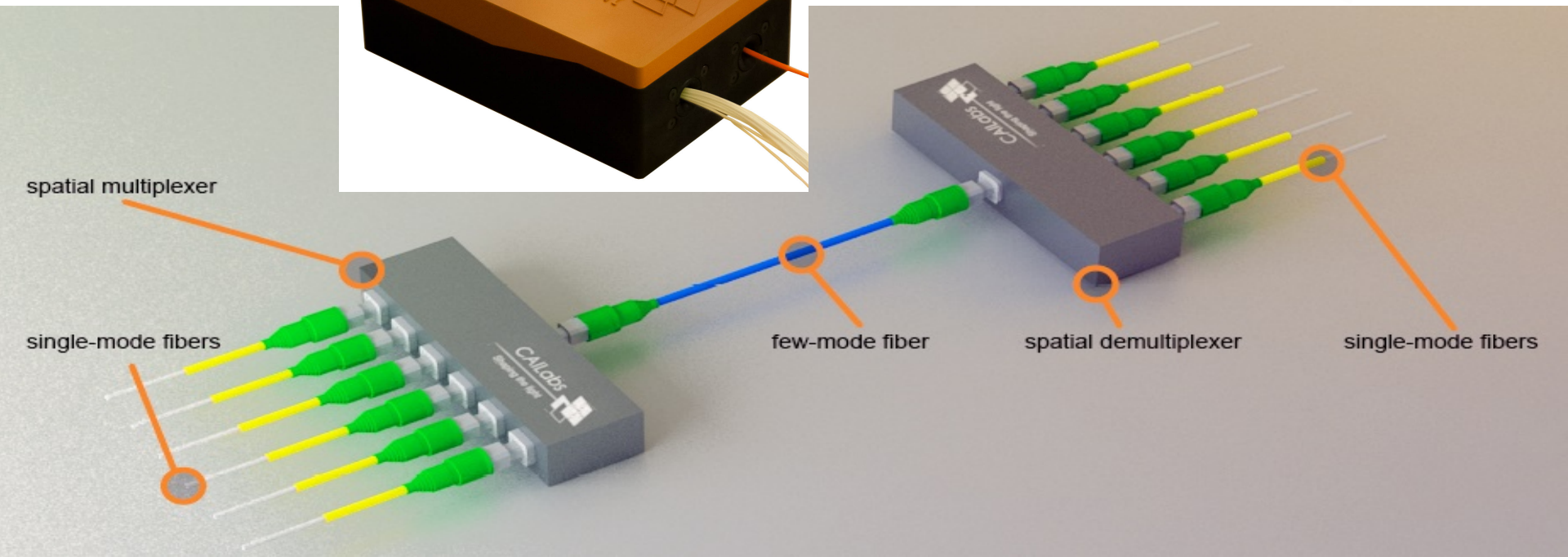
Convert any orthogonal basis of transverse modes into any other
No intrinsic losses



Morizur et al. (2010). Pro
Society of America A, 27

Spatial multiplexing





CAILabs company

Jean-François Morizur, PhD (Australia and UPMC - LKB), consulting: **CEO**
Guillaume Labroille, PhD (X - LOB), Post Doc (UPMC - LKB): **CTO**

CAILabs is a photonic start-up …

- Spin-off of the Laboratoire Kastler Brossel (Nobel prizes in '66, '97 and '12)
  - Research project started in 2008
- Seed round in November 2013
  - 1,6 M€, leading French VCs

… with a world-class team

- 16 employees, 7 PhDs, recognized expertise in spatial mode manipulation

Rennes (2h west of Paris), 340m^2

PRIX JEAN JERPHAGNON

CAILabs
Shaping the light

www.cailabs.com

People

Claude Fabre
Valentina Parigi
Nicolas Treps

Francesco Arzani
Syamsundar De
Adrien Dufour
Clément Jacquard
Young-Sik Ra
Valérian Thiel
Luca La Volpe

Pauline Boucher
Alexandre Brieussel
Vanessa Chille

Valentin Averchenko
Giulia Ferrini
Renné Medeiros
Jonathan Roslund
Roman Schmeissner
Cai Yin
Zhan Zheng