Quantum Technologies
(Computing, Sensing & Simulation)
Torino, 7-9 Giugno 2023

# Quantum Imaging

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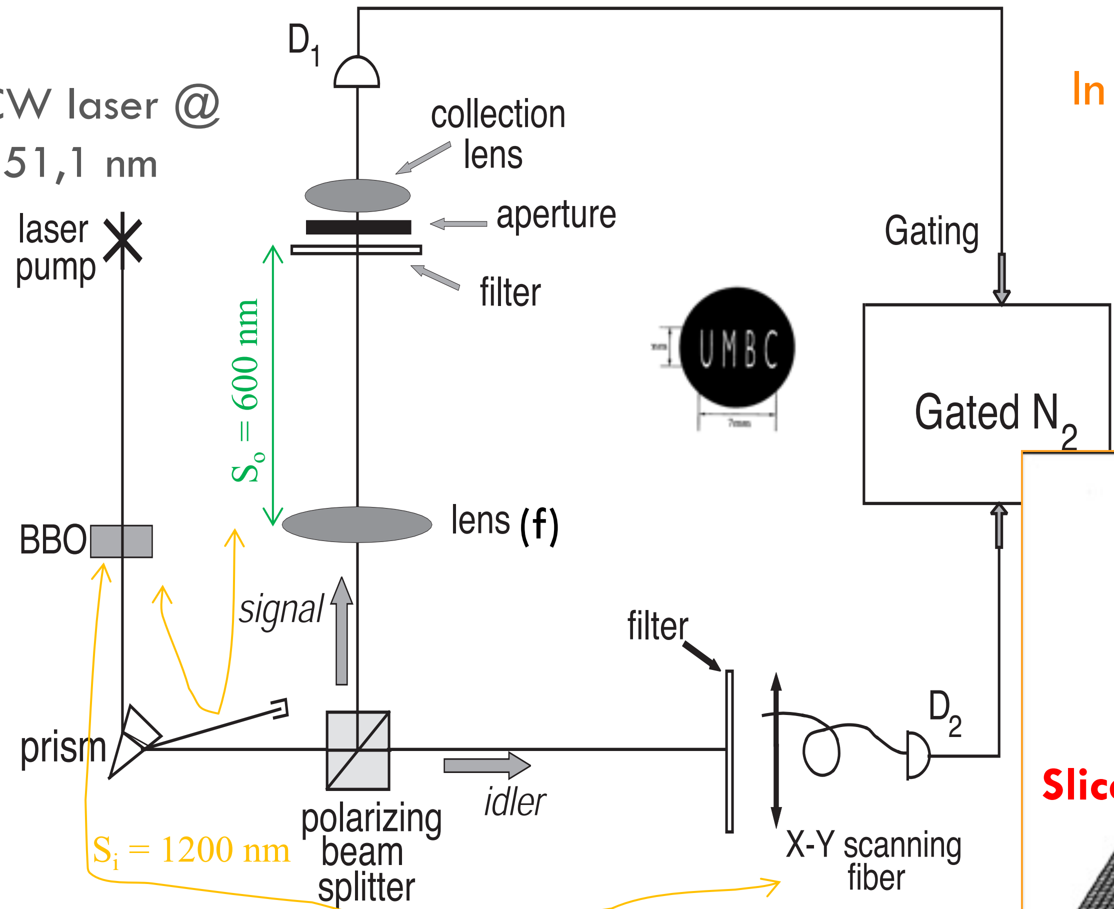
Università degli Studi di Bari – Dip. Interateneo di Fisica
INFN sez. Bari

# Quantum Imaging, the beginning

Pittman et al., PRA, 52, R3429 (1995).

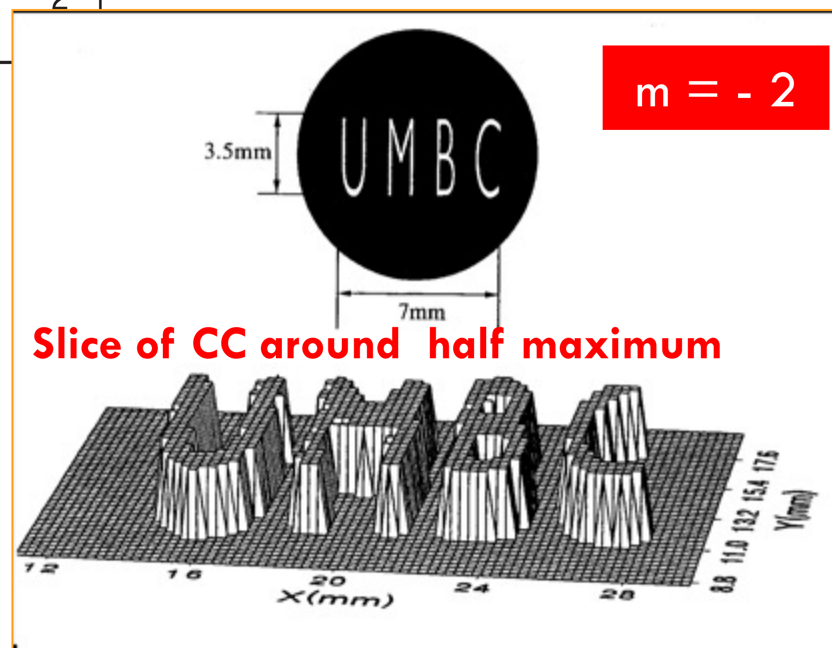
CW laser @ 351,1 nm

In collaboration with David Klyshko




$$\frac{1}{S_0} + \frac{1}{S_i} = \frac{1}{f}$$

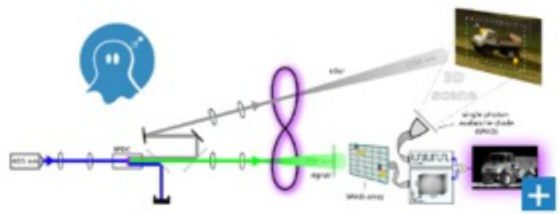
Scanning step of $D_2$: 0,25 mm



# Development in Quantum Imaging

Fraunhofer IOSB

Dr. Dominik Walter



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Published: 27 August 2014

## Quantum imaging with undetected photons

Gabriela Barreto Lemos, Victoria Borish, Garrett D. Cole, Sven Ramelow, Radek Lapkiewicz & Anton Zeilinger

Nature 512, 409–412 (2014) | Cite this art

## Detection and tracking of moving objects hidden from view

Genevieve Gariepy, Francesco Tonolini, Robert Henderson, Jonathan Leach & Daniele Faccio

University of Glasgow

Nature Photonics 10, 23–26 (2016) | Cite this article

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

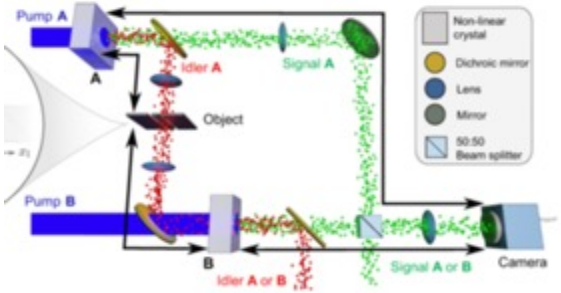
ABBE CENTER OF PHOTONICS

## Principles and prospects for single-pixel imaging

Matthew P. Edgar, Graham M. Gibson & Miles J. Padgett

Nature Photonics 13, 13–20 (2019) | Cite this article

ICFO



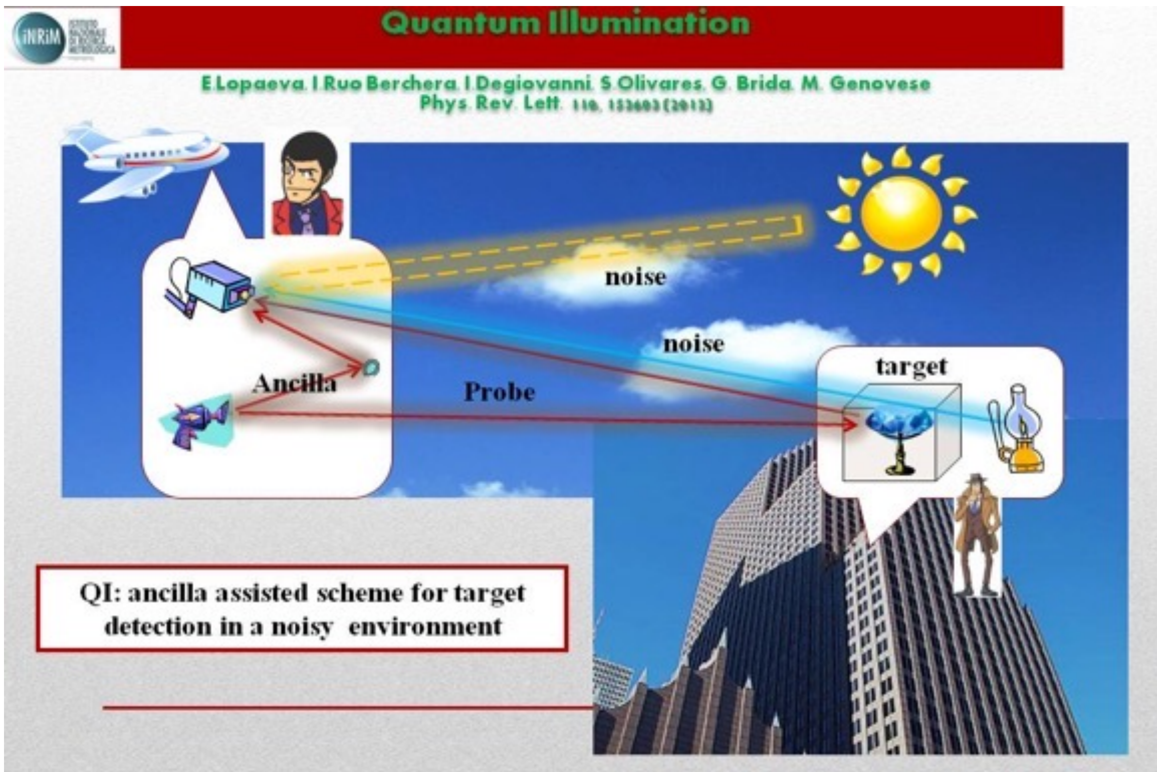
# Quantum target detection

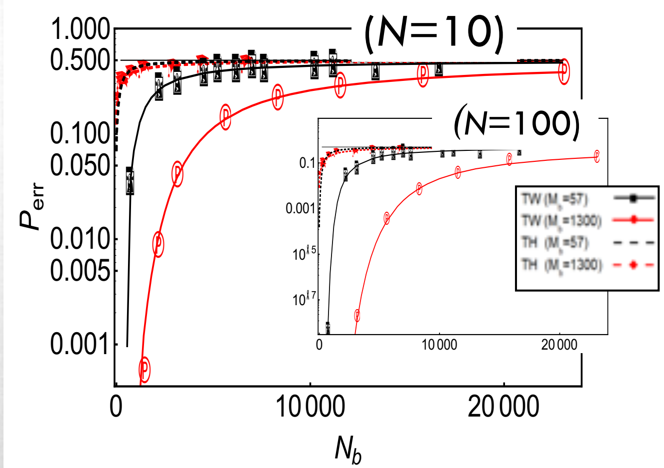
Science
AAAS
**Enhanced Sensitivity of Photodetection via Quantum Illumination**
Seth Lloyd
*Science* **321**, 1463 (2008);
DOI: 10.1126/science.1160627

PRL **101**, 253601 (2008) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2008

**Quantum Illumination with Gaussian States**

Si-Hui Tan,[1] Baris I. Erkmen,[2,*] Vittorio Giovannetti,[3] Saikat Guha,[2,†] Seth Lloyd,[2] Lorenzo Maccone,[4] Stefano Pirandola,[2] and Jeffrey H. Shapiro[2,‡]

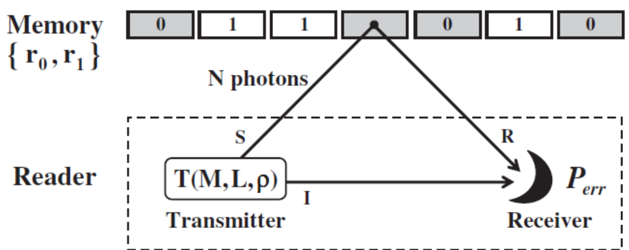


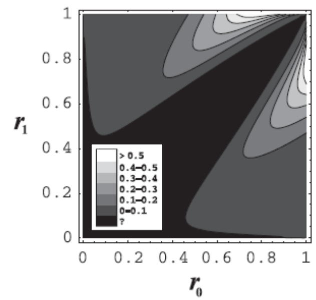



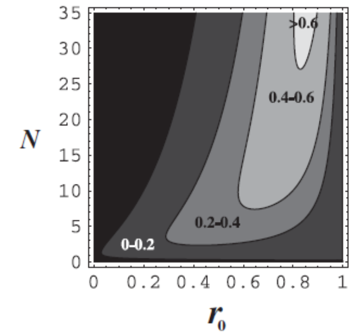
PRL 106, 090504 (2011) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2011

# Quantum Reading of a Classical Digital Memory

Stefano Pirandola

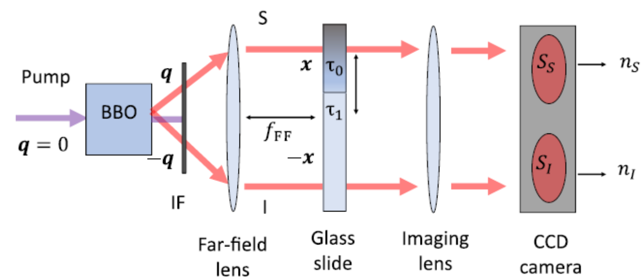


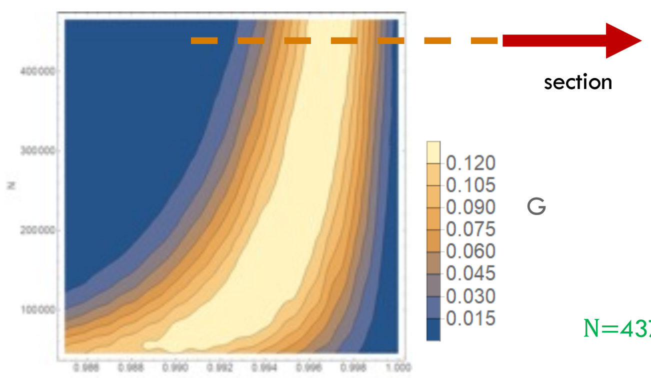



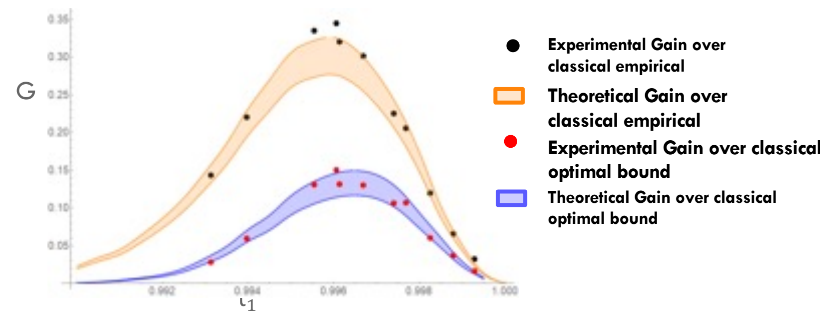

Number of bits per cell gained by an EPR transmitter

G.Ortolano, E.Losero, S.Pirandola, MG , I.Ruo Berchera
Sci. Adv. (2021) 7, eabc7796




$\tau_1 = 1$ $\eta_p = 0.76$ $\eta_r = 0.76$



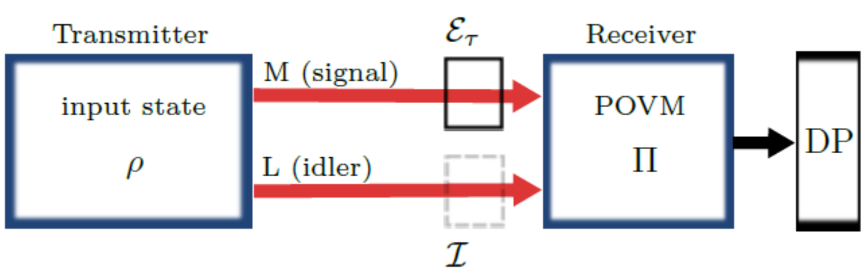

N=437559 $\tau_1 = 1$ $\eta_p = 0.7608$ $\eta_r = 0.7573$

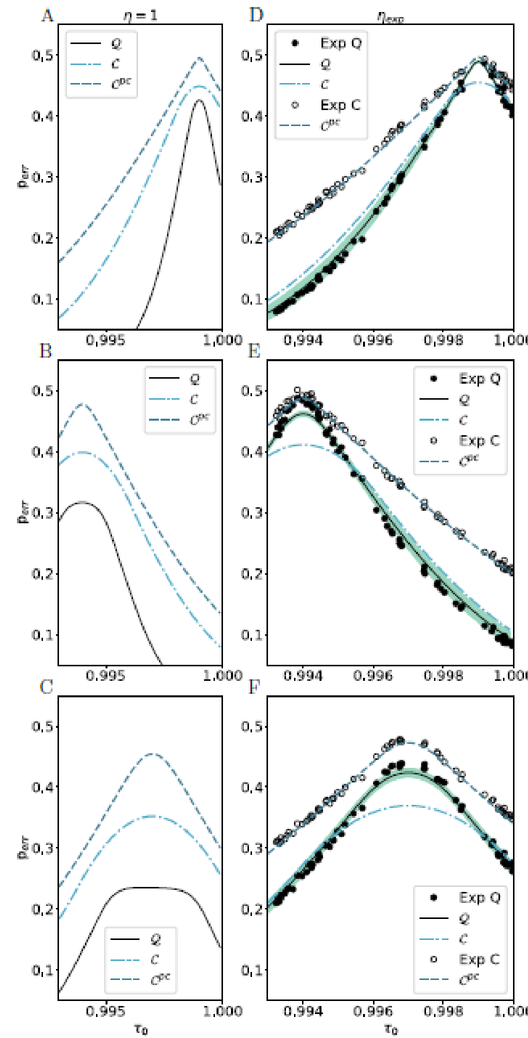
# The Quantum Conformance Test

G.Ortolano, P.Boucher, I.Degiovanni, E.Losero1, M.Genovese1, I.Ruo-Berchera,

Sci. Adv.7, eabm3093 (2021)

The **conformance test** is the discrimination between two processes: a “reference" process and a “defective" process, $P_1$. The task is **to decide whether an unknown object has been generated by $P_0$ or $P_1$.**



# Quantum Imaging @ INFN

## INFN Bari (UniBA)

- Milena D'Angelo
- Francesco V. Pepe
- Francesco Scattarella
- Sergio De Gioia
- Davide Giannella
- Gianlorenzo Massaro
- Giuseppe Lerario


CSN5 - QUISS


## INFN Torino (INRIM, UniTo)

- Marco Genovese
- Ivo P. Degiovanni
- Paolo Olivero
- Jacopo Forneris
- Ivano R. Berchera
- Alessio Avella
- Alice Meda
- Alberto Paniate

# QI within INFN in pills

Quantum [**INFN CSN4**, PI: S. Pascazio…] → Activity on Quantum Imaging @ sez. Bari / UniBA

PICs – Plenoptic Imaging wthrough Correlations [**INFN CSN5** progetto giovani 2018-19, PI: F. V. Pepe, sez. Bari] → brevetto

PICS4ME – Plenoptic Imaging through Correlations for Microscopy Enhancement [**INFN CSN5** 2020-22, PI: M. D'Angelo]
Partners: M. Genovese, I. P. Di Giovanni (INRIM, Torino), J. Forneris, P. Olivero (Univ. Torino)

TOPMICRO – Toward the prototype of a Correlation Plenoptic Microscope [**INFN PoC MISE INTEFF**, 2021-22, PI: M. D'Angelo]

Qu3D – Qunatum 3D imaging at high speed and high resolution [**QuantERA 2019**, PI: M. D'Angelo]
Partners: C. Bruschini (EPFL - CH), B. Stoklasa (Olomouc Univ. - CZ), M. Jero (Planetek - GR)

QUISS – Quantum Imaging with new Sources and Sensors [**INFN** CSN5 '23-'25, PI: M. D'Angelo]
Partners: M. Genovese, I. P. Di Giovanni (INRIM, Torino), J. Forneris, P. Olivero (Univ. Torino)

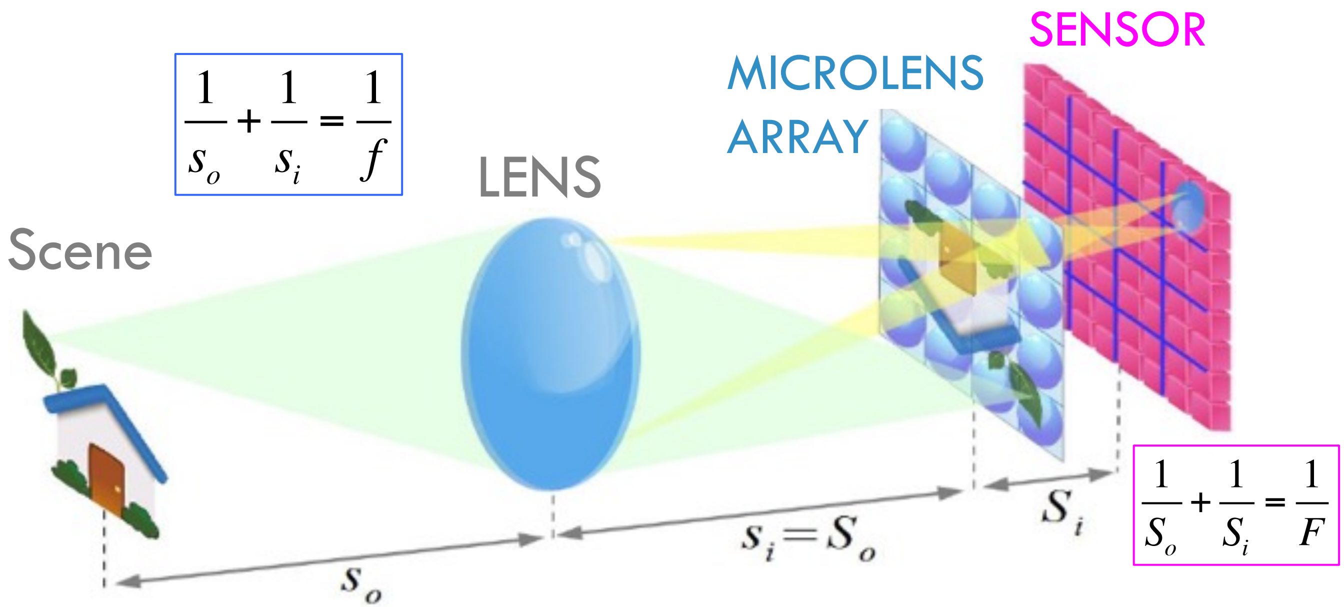
NQSTI (PNRR), ADEQUADE (EDF), QUASIMODO (MUR)

# Plenoptic imaging

Lippman [1908] and Ives [1930]

Adelson and Wang [1992]

Ng [2005]




Enables

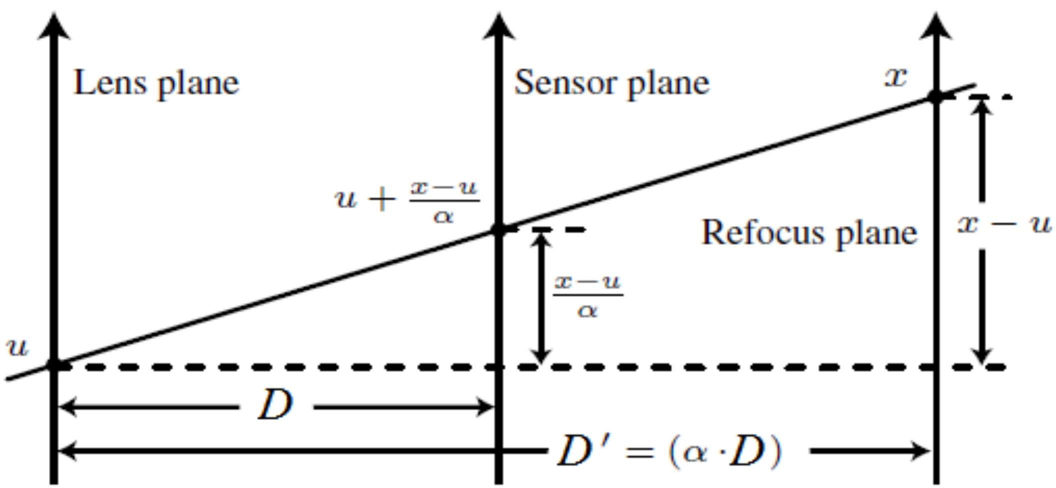
scanning-free 3D imaging & refocusing / DOF extension

by retrieving

both the image and the propagation direction of light

# Ray tracing → Refocusing !

Ng et al., Tech. Rep. 2005




Shot

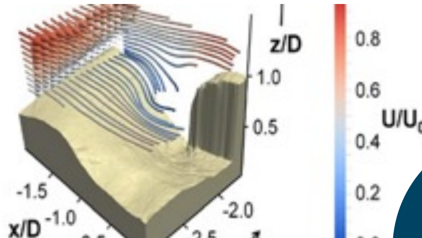
Refocused (post-proc.)

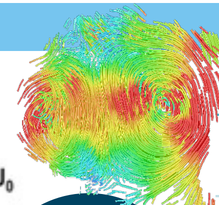
Refocusing = rescaling the acquired radiance

$$L_{\alpha D}(\boldsymbol{x}, \boldsymbol{u}) = L_D\left(\frac{\boldsymbol{x}}{\alpha} + \left(1 - \frac{1}{\alpha}\right)\boldsymbol{u}, \boldsymbol{u}\right)$$

# PI: The most promising method for 3D imaging

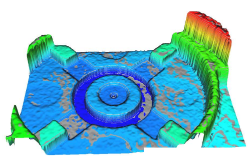
www.raytrix.de/



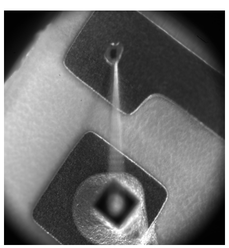



3D Fluid Mechanics

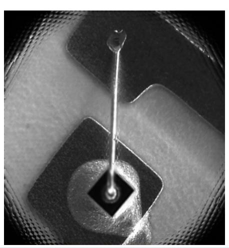
- Petrol injection
- Flow over sediment
- Micro flow in blood vessels

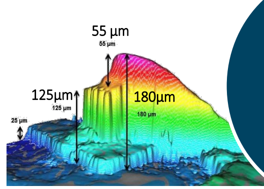


Standard 4MP Camera



Raytrix Lightfield Camera R5µ

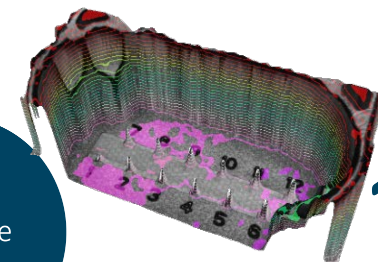




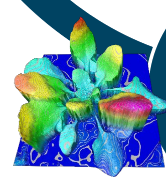

3D Microscopy

www.raytrix.de/

3D Machine Vision



- Connector pin inspection
- Surface inspection
- Contaminations in Glass



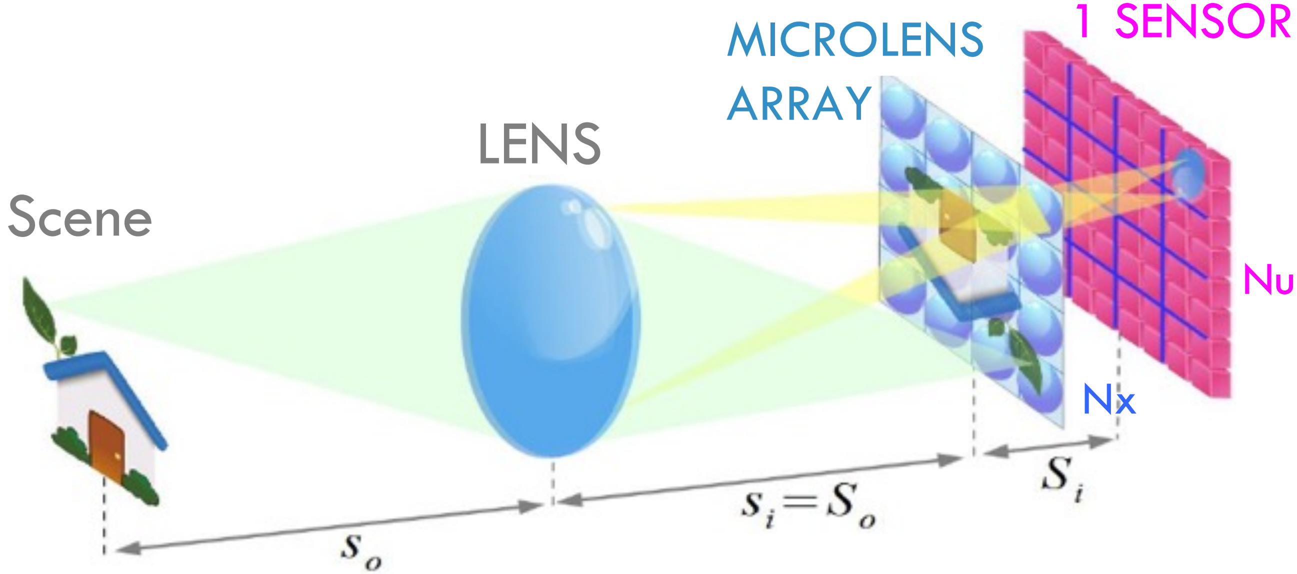
3D Plant Analysis

- Plant breeding
- Picking
- Weeding

*R. Prevedel: Nature Meth.* 2014 & 2019

- Simultaneous whole-animal 3D imaging of neuronal activity using light-field microscopy;
- Instantaneous isotropic volumetric imaging of fast biological processes

# *Intrinsic Limits* of conventional PI




1 SENSOR retrieves BOTH the image AND the ***propagation direction*** of light

↓

A 16 Megapixel camera, behaves as a 4 Megapixel ☹

- Strong trade-off between resolution and depth-of-field (Nx Nu = Ntot)
  → No diffraction limited resolution !
- Highly sacrificed change of perspective limits the 3D imaging capability

# Our solution: Correlation Plenoptic Imaging

7 patents

NO microlenses

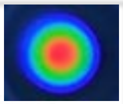
$G^{(2)}(\rho_1,\rho_2)$ or $\langle \Delta I(\rho_1)\Delta I(\rho_2)\rangle$ : Contains plenoptic properties !

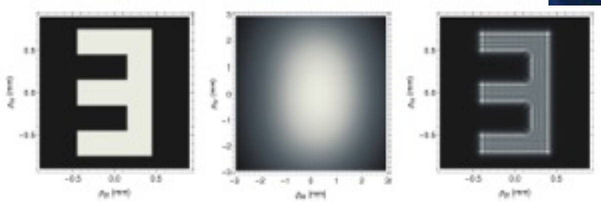
Image of the scene

Propagation direction

Intellectual Property Award 2019 (MISE)

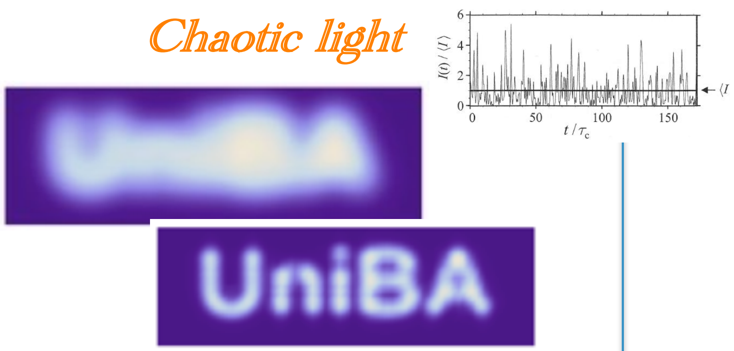
*Entangled photons*





F.V. Pepe et al., Technologies 4, 17 (2016)

*Chaotic light*

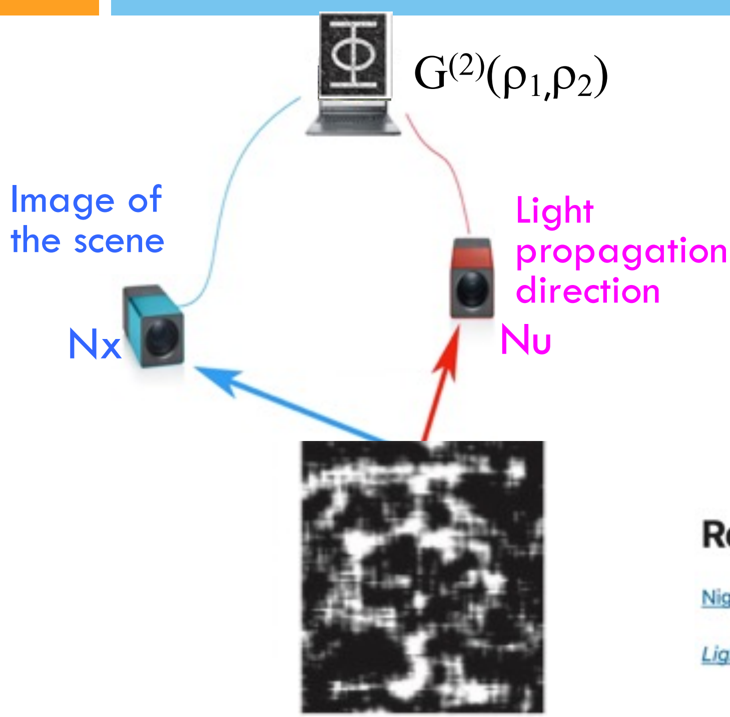




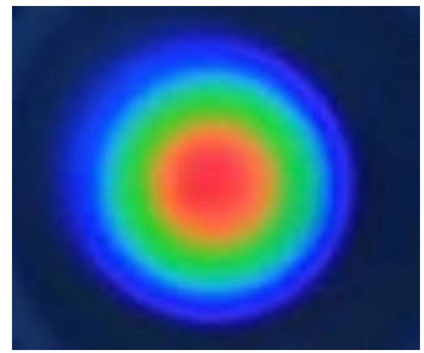
D'Angelo et al., PRL 116, 223602 (2016)

Decouples image acquisition from direction measurement to enable diffraction-limited PI and 3D imaging with a wide change of perspective

# Sources for Correlation Plenoptic Imaging



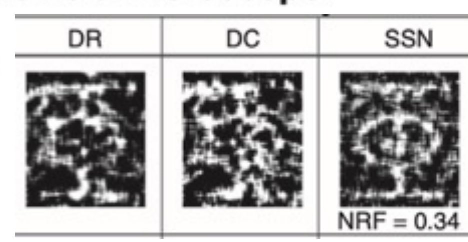

**Entangled photons**



**Realization of the first sub-shot-noise wide field microscope**

Nigam Samantaray, Ivano Ruo-Berchera, Alice Meda & Marco Genovese

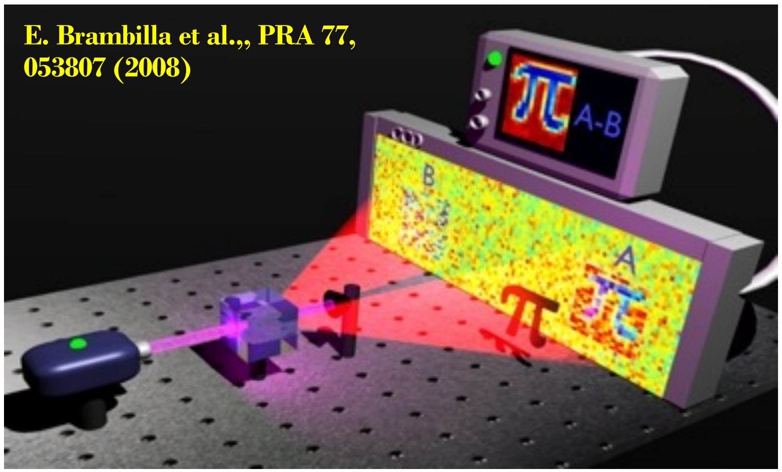
*Light: Science & Applications* **6**, e17005 (2017) | Cite this article

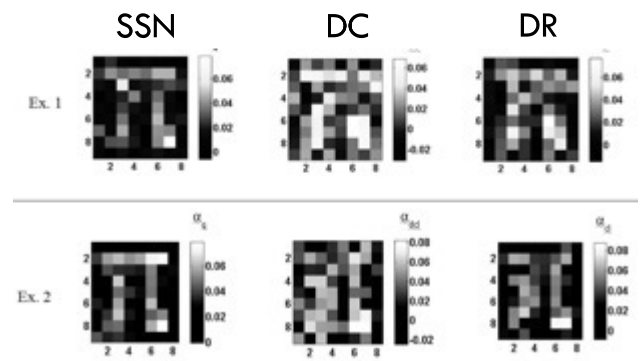



*Ultra-low-noise* (shot-noise limit or below)
→ imaging of low-absorping objects

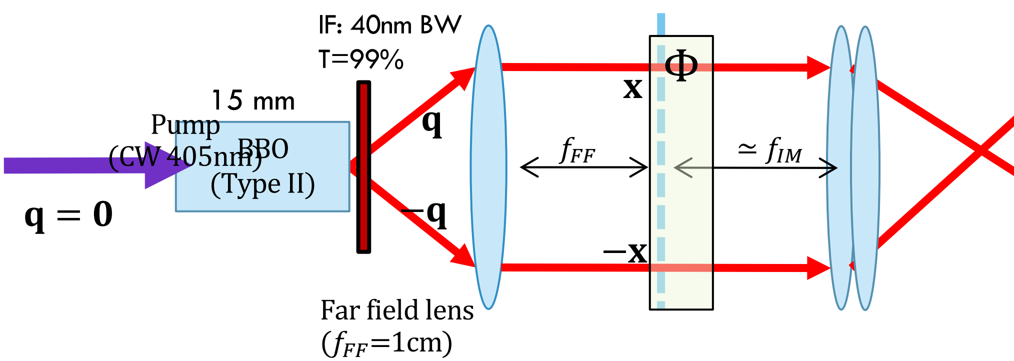
# Sub-shot noise imaging & microscopy (INRIM)

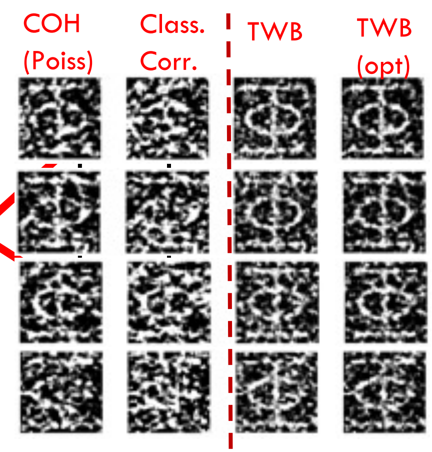
G. Brida *et al*, Nat. Phot. **4**, 227 (2010). PRA **83**, 033811 (2011)



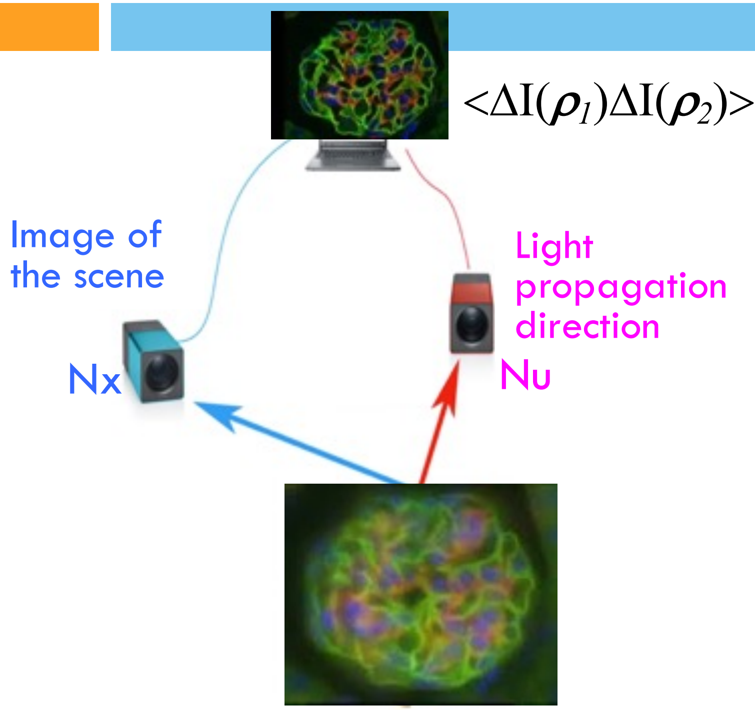




N.Samantaray, et al.,Light: Science & doi: 10.1038/lsa.2017.5

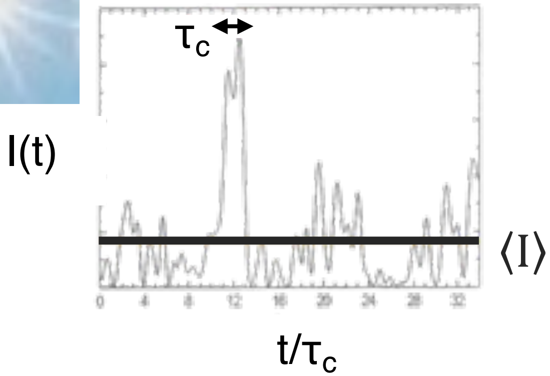


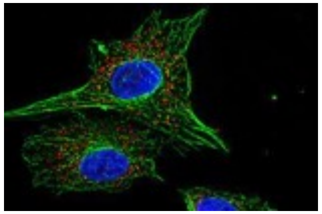



# Sources for Correlation Plenoptic Imaging




## Chaotic light



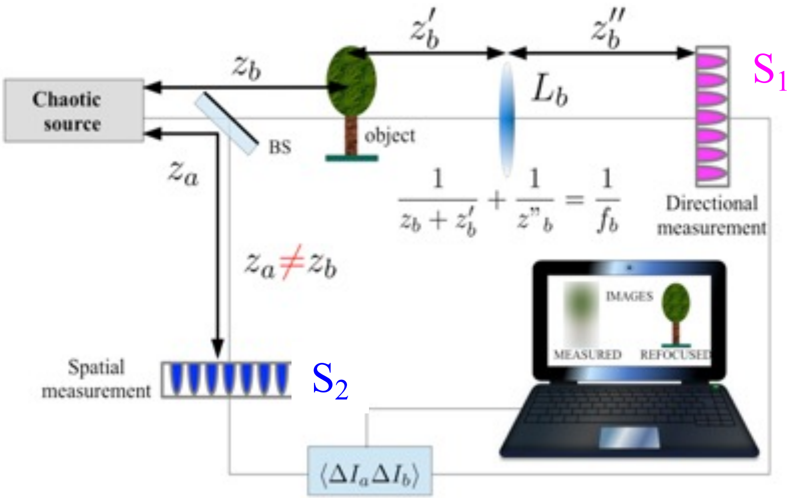



- *Entanglement is unfeasible …*
- *Passive imaging (photography, security,..)*
- *Fluorescence microscopy*
- *From single photon to mesoscopic light*

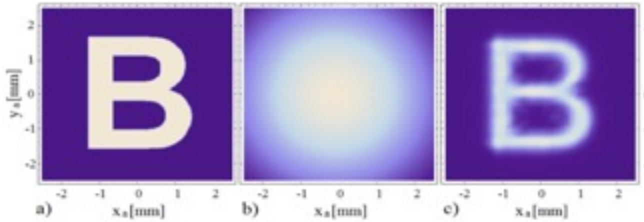
No chaos → No image !!!
Chaos = intensity fluctuations
… Detectors need to follow them!

# $1^{st}$ CPI experiment: ghost-imaging based

PRL 116, 223602 (2016)




Same resolution, but 40 times larger DOF !!!




$N_x^{(p)} = 150,$

$N_x^{(cp)} = N_u^{(cp)} = 150.$

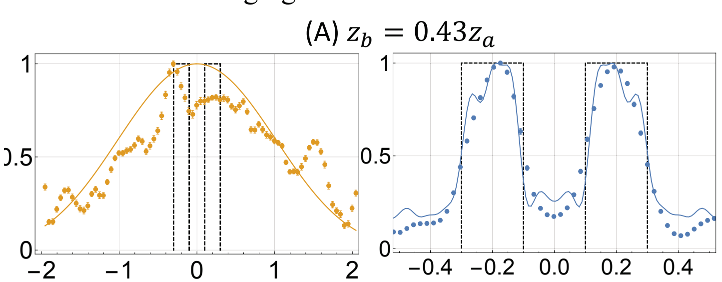
$N_u^{(p)} = N_{tot}/N_x^{(p)} = 2.$

$$\frac{\mathrm{DOF}^{(cp)}}{\mathrm{DOF}^{(p)}} = \frac{N_u^{(cp)}}{(N_u^{(p)})^2}$$

= 40 !!!

PRL 119, 243602 (2017) Exp diffraction-limited CPI

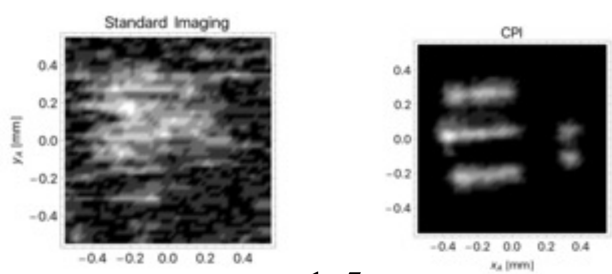
Double-slit: d = 400 μm




$z_b = 0{,}4\ z_a$

Test target (gr. 1, el. 4): $d$ = 354 μm

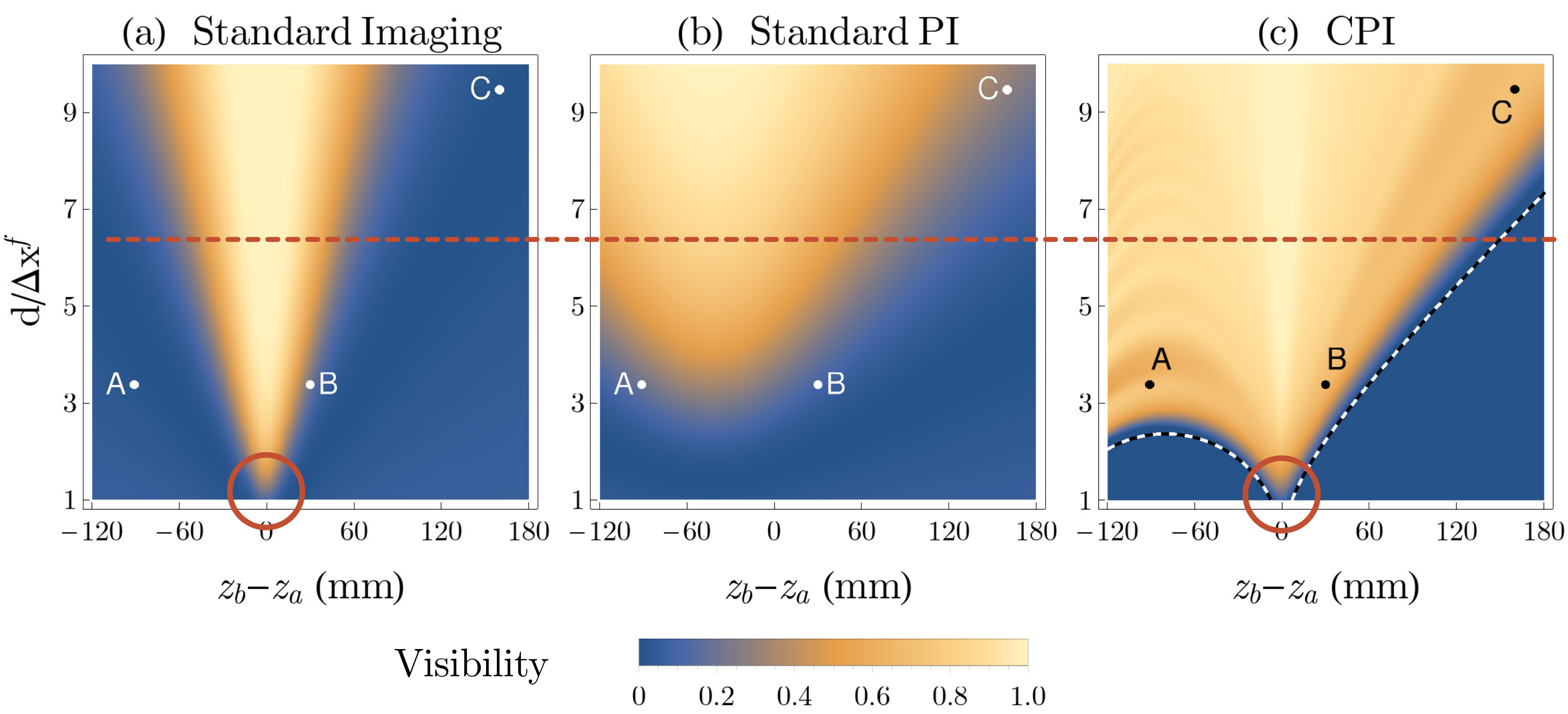
Ghost image CPI




$z_b = 1{,}5\ z_a$

# Resolution vs DOF improvement

Pepe et al., PRL 119, 243602 (2017)




By decoupling spatial and angular detection, CPI yields larger depth of focus than both standard imaging and conventional plenoptic imaging (PI), while maintaining diffracton-limited resolution

# Advances in CPI

Pepe et al., Journ. Optics 19, 114001 (2017) + Di Lena et al., Applied Sciences 2018 + PCT/2017

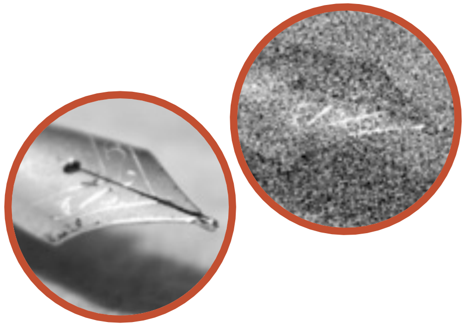
In the 1° scheme, the **direction of light before and after the object** must change in a predictable way (transmission, mirror-like reflection) !!

**What if we have :**

- Diffusive objects
- Objects surrounded by turbulence
- Randomly emitting samples ???

**Relevant categories for microscopy, space objects, …**

SNR analysis

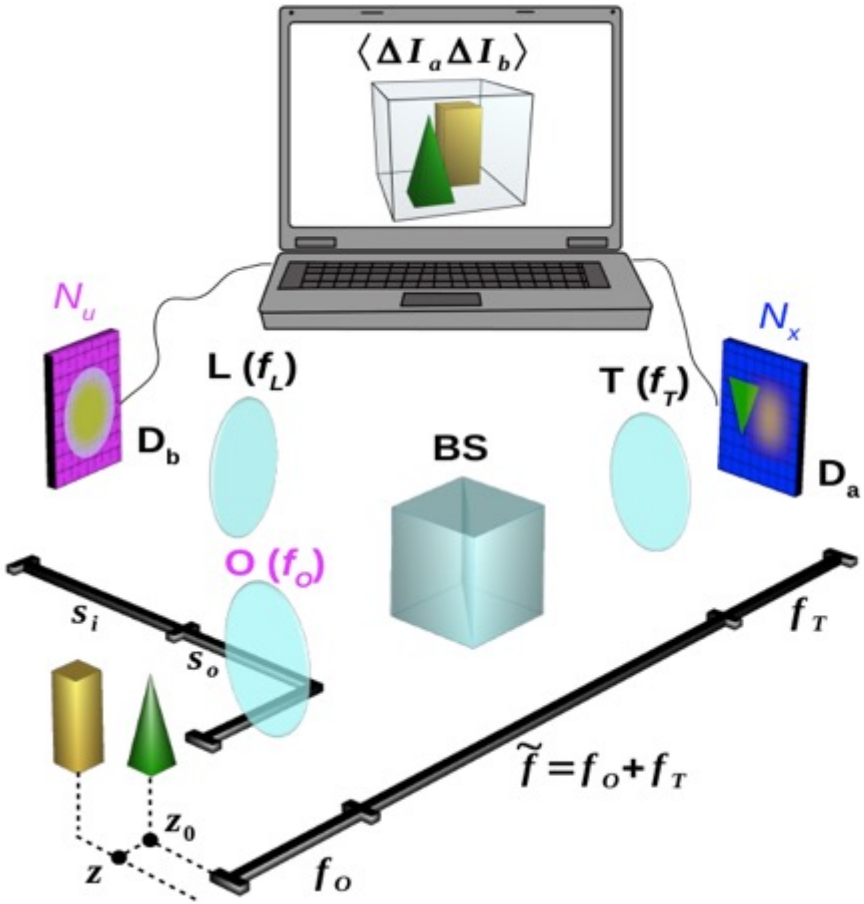


PRA 2019

EPJ Plus 2022

# 1) Correlation Plenoptic Microscopy

PCT/2018 (INFN) + PLA 2020 + Scientific Reports 2022




**Basic idea:**

Measuring correlations between

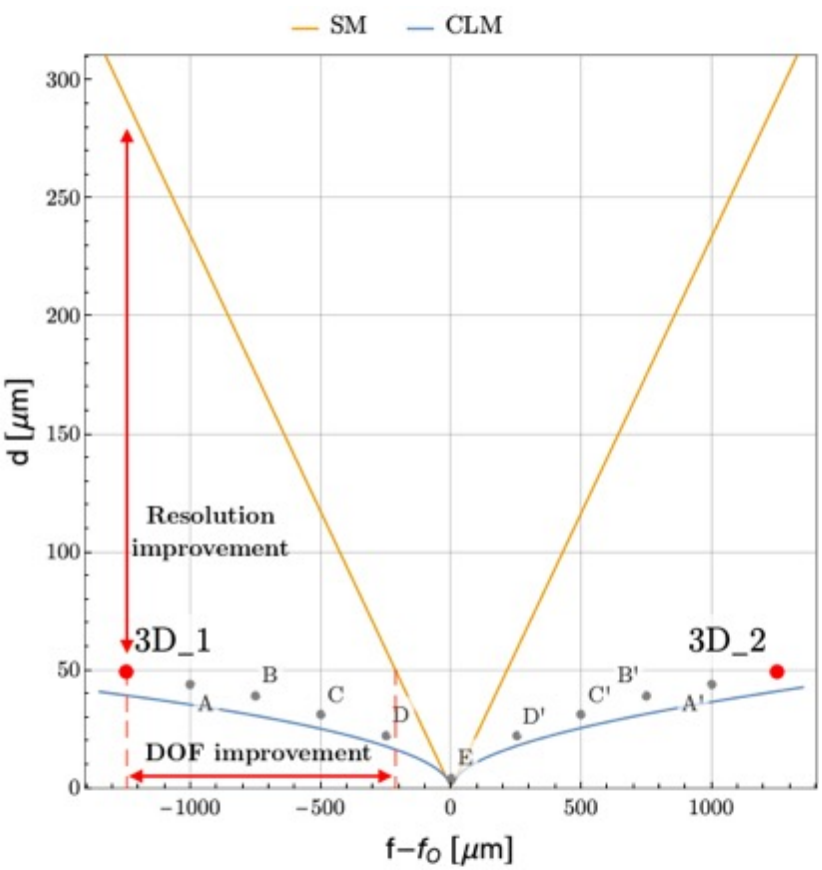
- the *image of the sample* formed by the ordinary microscope (O & T)

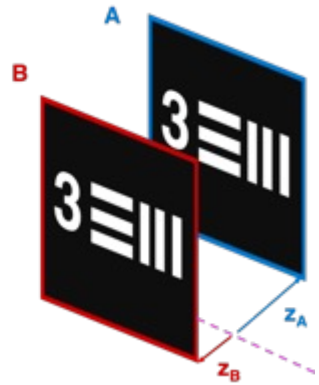
and

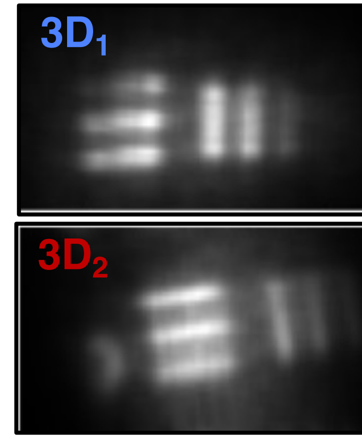
- the *image of the objective lens*, formed by lens L

# 1) Correlation Plenoptic Microscopy

3D Sample    Acquired    REFOCUSED




**6 times higher resolution**, at fixed DOF

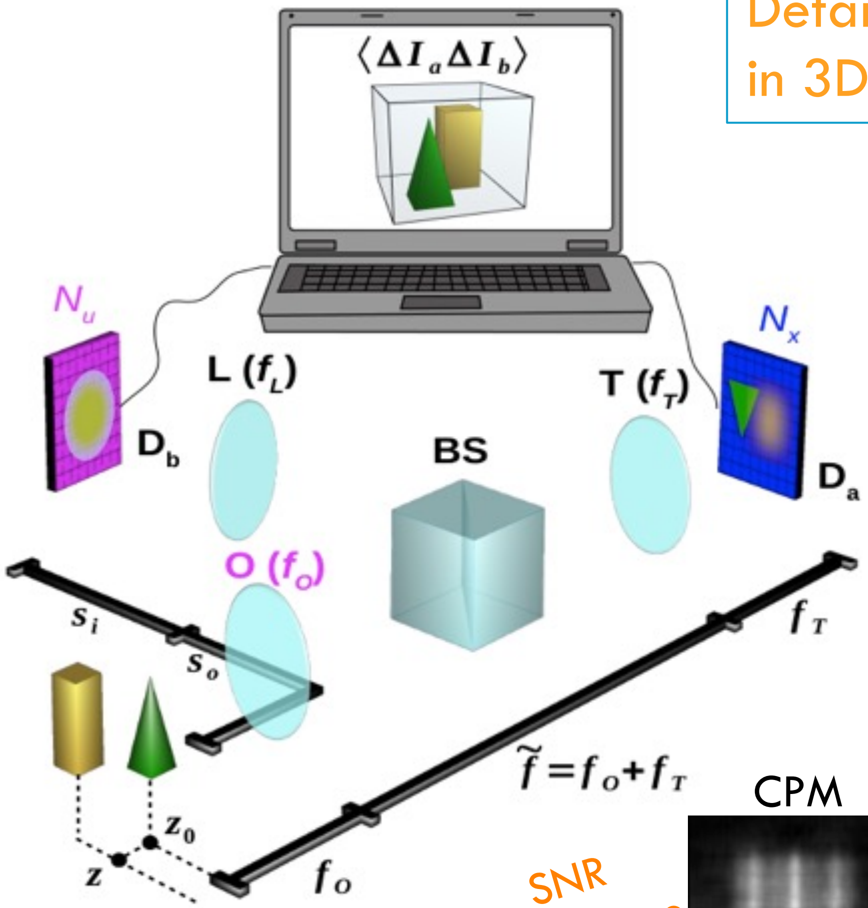
**6 times larger DOF**, at fixed resolution

G. Massaro, et al., *Light-field microscopy with correlated beams for extended volumetric imaging at the diffraction limit* , **Scietific Reports 2022**

# 1) Correlation Plenoptic Microscopy

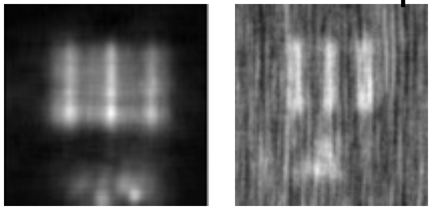
Scientific Reports 2022

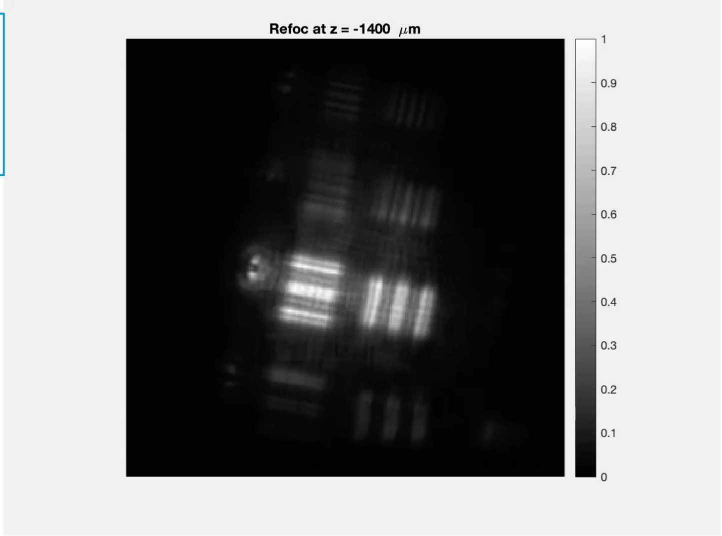
Detail recovery in 3D samples

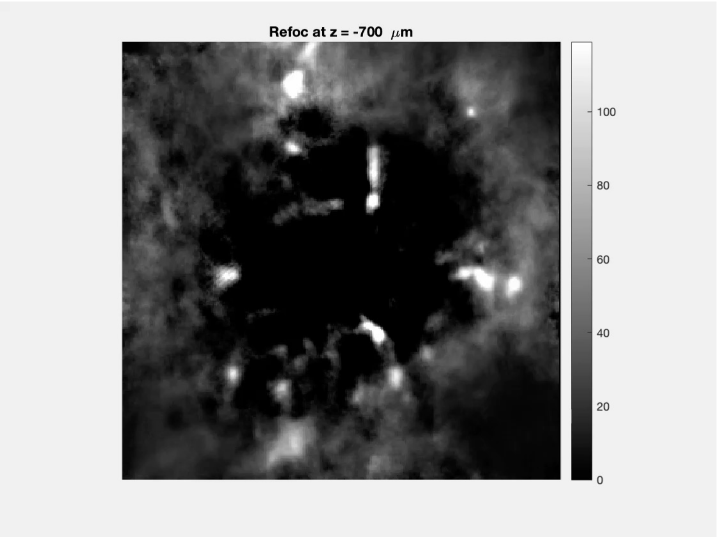



SNR advantage

CPM Old setup

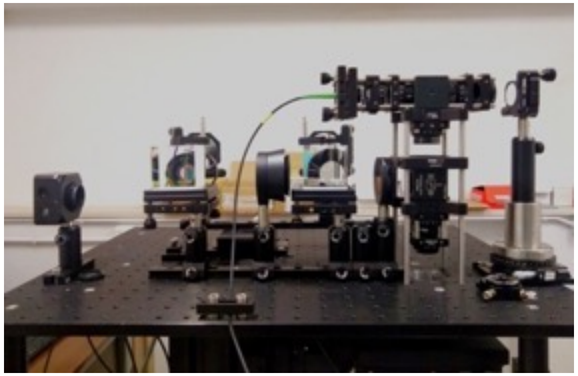




# CPM protoype

TOPMICRO
MISE - Proof of Concept



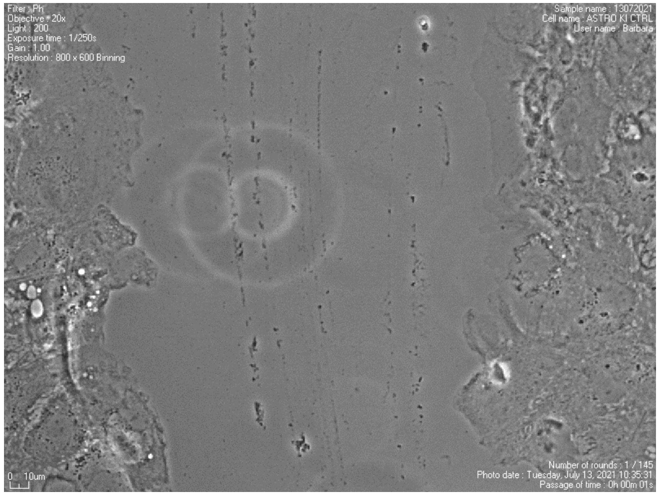
Potential applicaitons:

- Study of cell aggregation → glioma

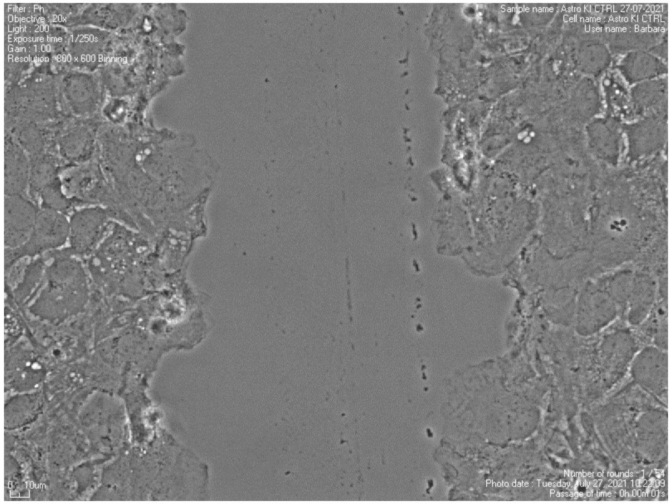
~ 30-100 um diameter
~ 3-5 um height

Brain cells (astrocytes) during 24-hours migration

In focus

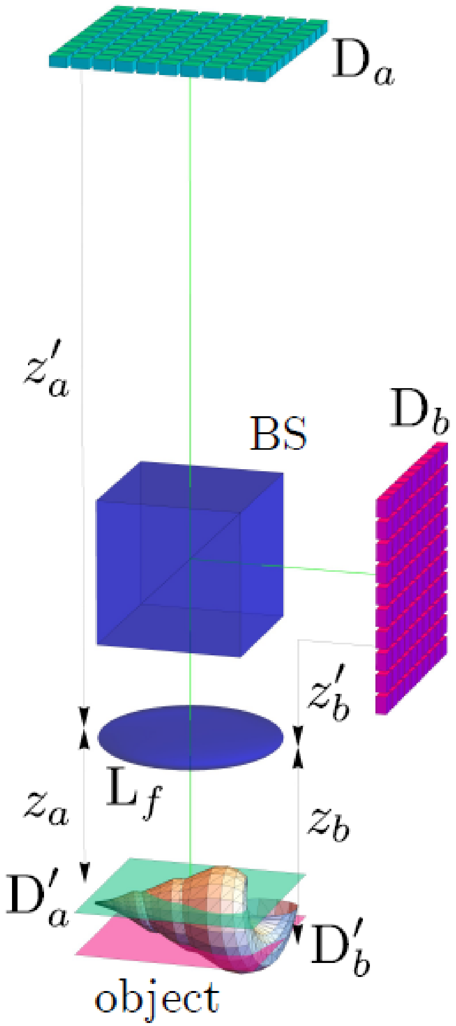


Out of focus ~3hrs later

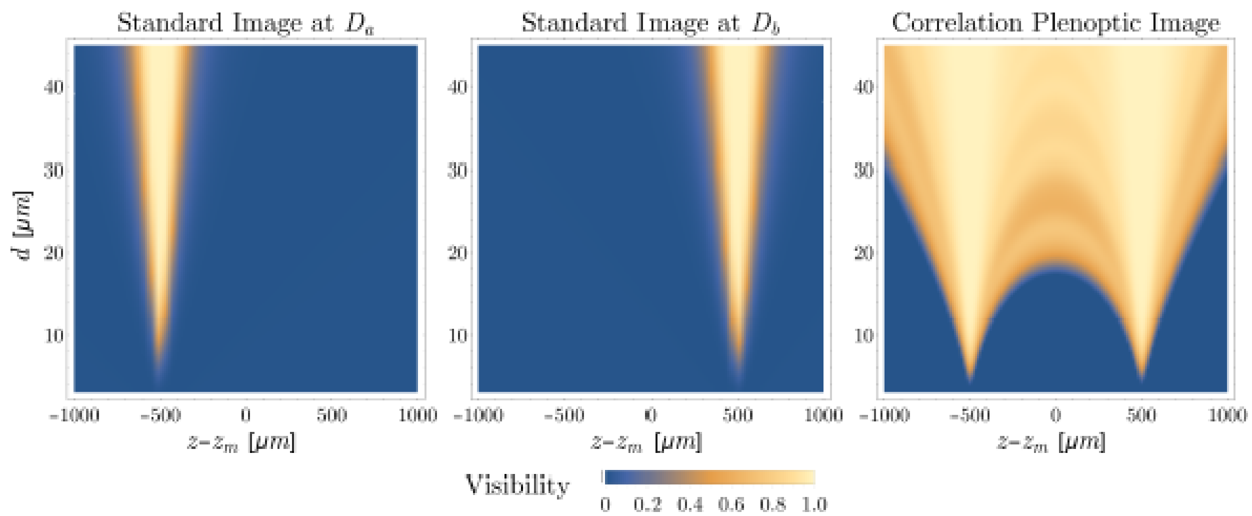


# 2) CPI between arbitrary planes

PCT 2019 + Opt. Exp. 2020 + arXiv:2007.12033

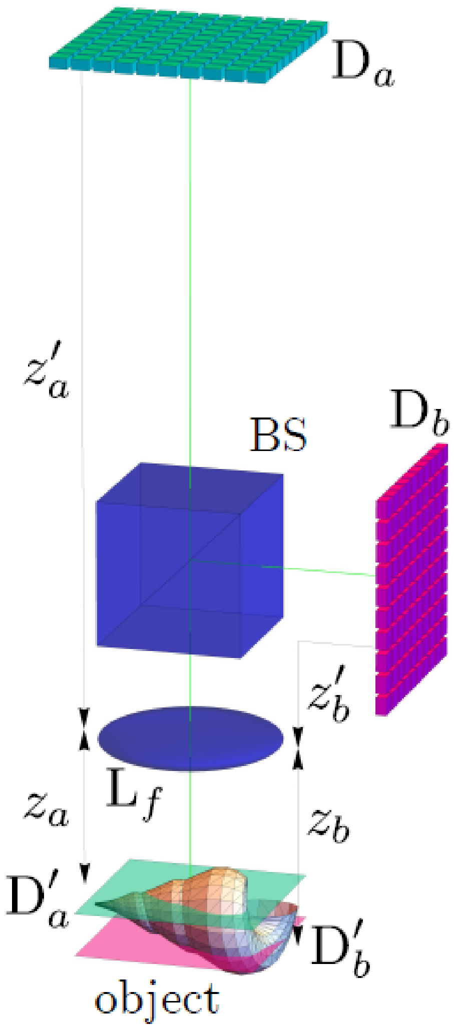



**Single-lens CPI device**: 2 different arbitrary planes within the 3D object are focused by the lens on the two disjoint sensors



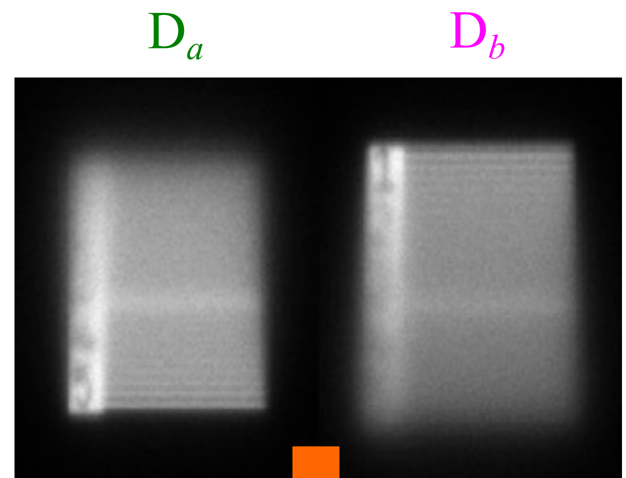
# 2) CPI between arbitrary planes

PCT 2019 + Opt. Exp. 2020

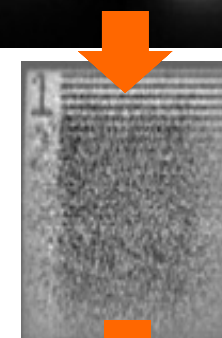



**Simulation**

**Acquired images**



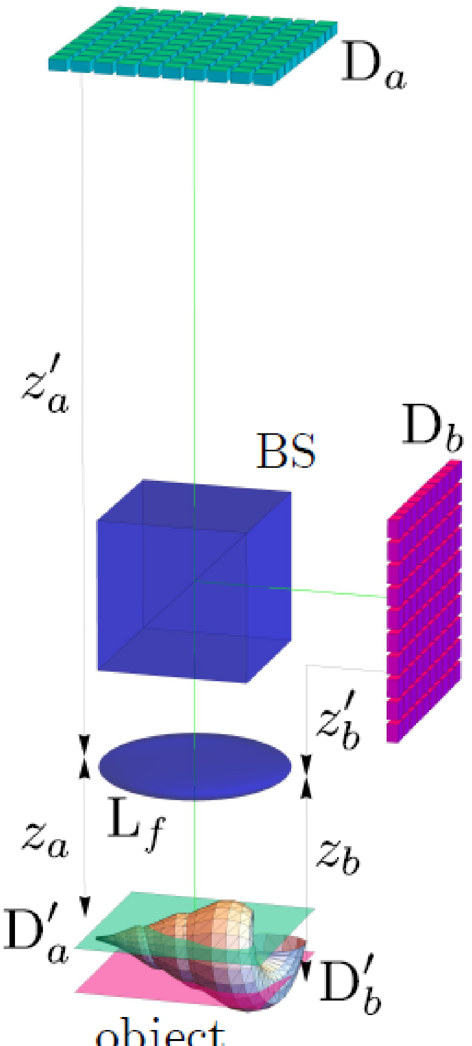

**CPI Refocusing**



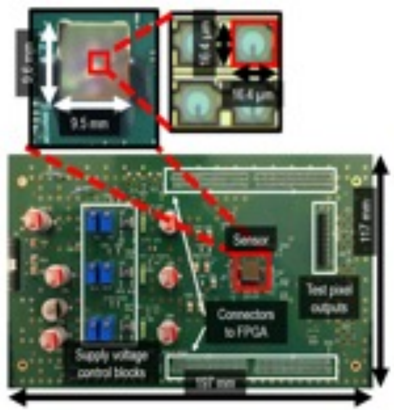
**Stacked refocused image**

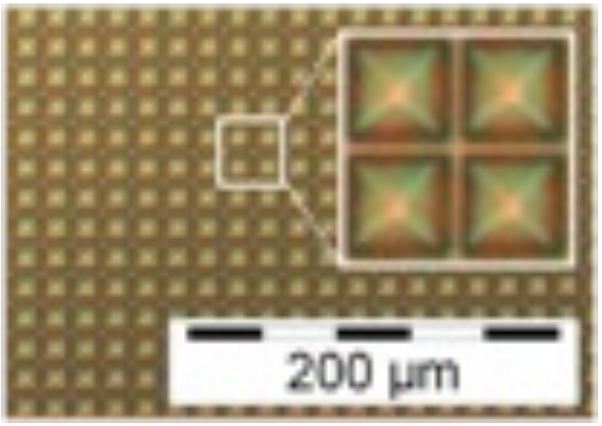
# 2) CPI-AP with SPAD arrays

PCT 2019 + Opt. Exp. 2020 + arXiv:2007.12033




Developed by AQUA group at EPFL – E. Charbon and C. Bruschini



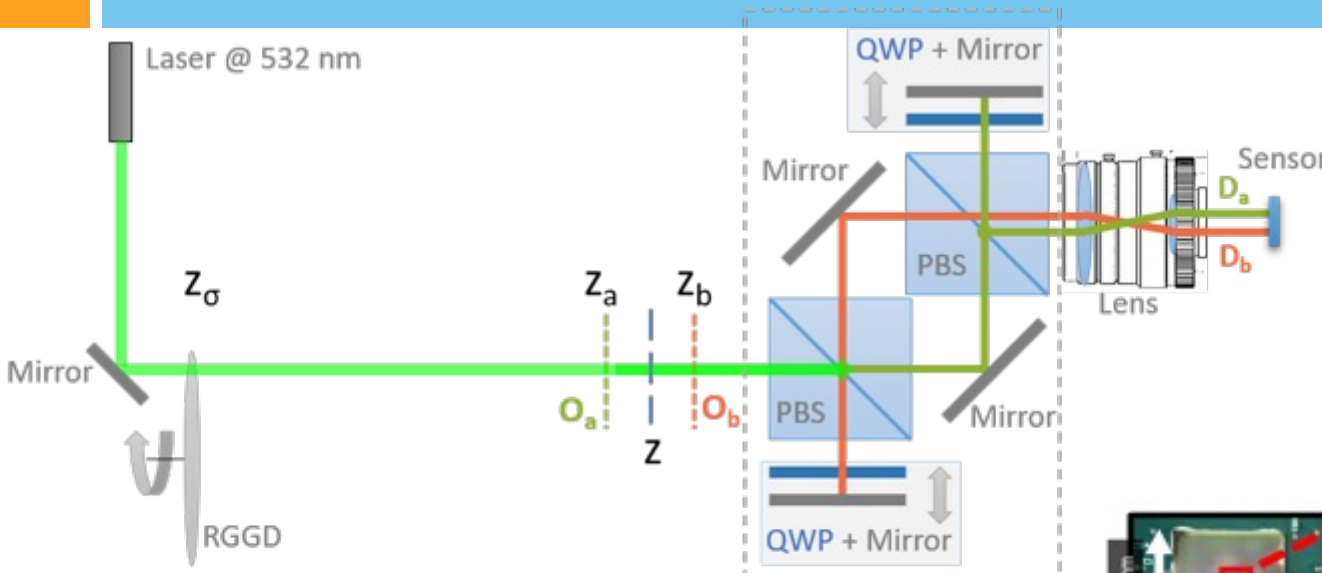




512 x 512 SPAD array, 100.000 fps (EPFL)

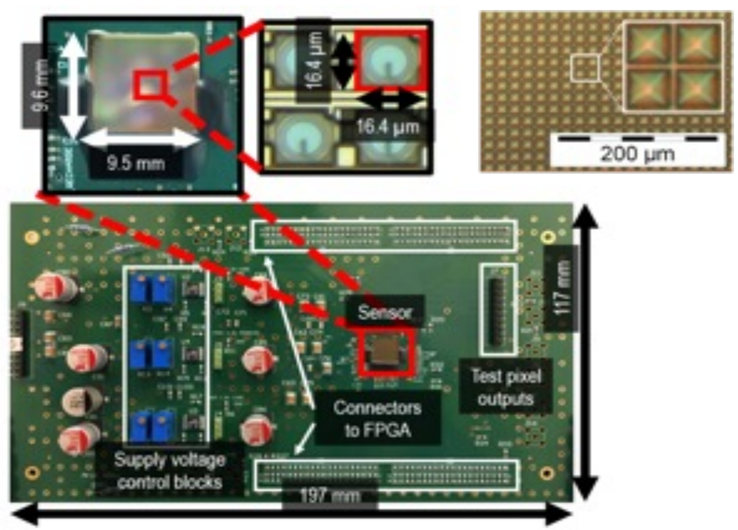
→ **Volumetric imaging @ 10 Hz**

Full-frame refocusing from a $256^4$ correlation function

# Correlated photon imaging at 10 volumetric images per second




- Single-lens design
- CPI-AP for extended refocusing range
- Ultra-fast and high-res SPAD array



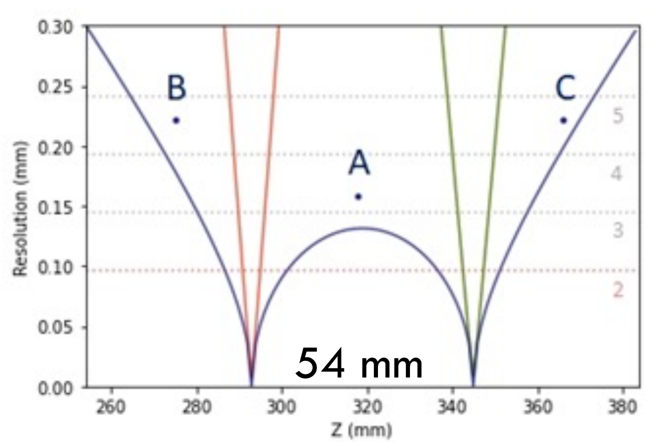

AQUA group at EPFL – E. Charbon and C. Bruschini

# Correlated photon imaging at 10 volumetric images per second

CPI with SPAD arrays

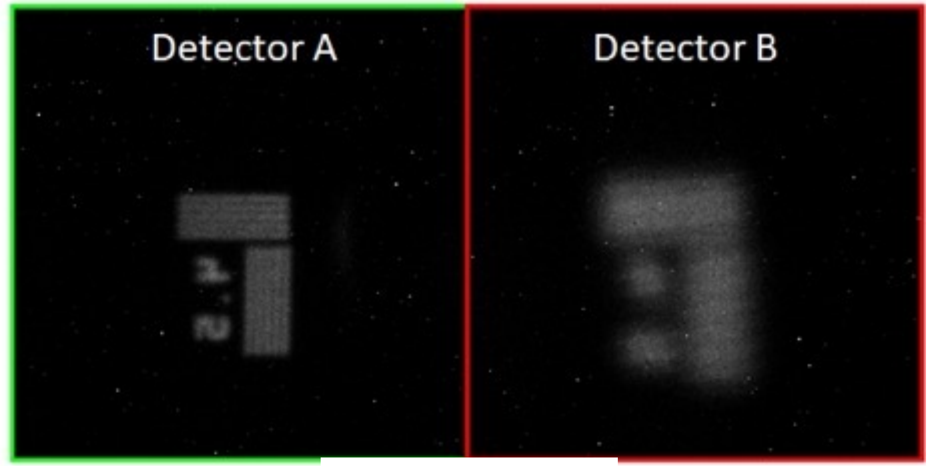
87 kfps , $N_{frames}$= 8 x$10^3$

→ CPI acquisition: 10 Hz

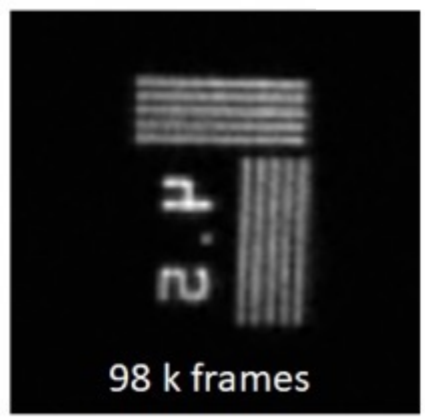



DOF enhancement: 12 x

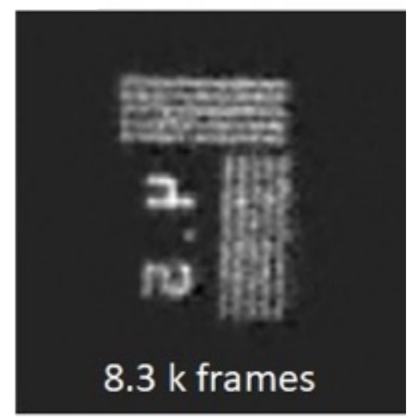
Acquired




Refocused




Max SNR




60% SNR

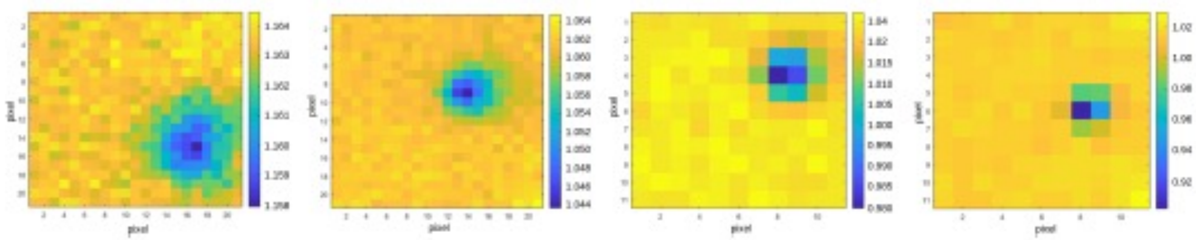
# Quantum CPI-AP

F. Di Lena, PhD thesis (2019) + PCT 2019 + IJQI 17, 1941017 (2020)

## Is sub-shot-noise CPI possible?

- **Experiment:** noise reduction factor (<1!!)

$$\sigma = \frac{\langle \Delta^2(\hat{n}_i - \hat{n}_s) \rangle}{\langle \hat{n}_i + \hat{n}_s \rangle}$$ Noise reduction factor



(a) No binning (b) $2 \times 2$ binning (c) $4 \times 4$ binning (d) $8 \times 8$ binning

σ = 1,16

σ =0,9

- **Theory:** NRF does not contain plenoptic info!! → Investigation of different correlation protocols (e.g. differential CPI), SNR anaysis, …
- **Exp:** work in progress

# Qu3D – Qunatum 3D imaging at high speed and high resolution

Swiss National Science Foundation

Quantum technology: more security and improved imaging

21/Nov/2019

QUANTERA

http://www.ba.infn.it/qu3d/index.html

INFN – Milena D'Angelo

planetek hellas – Maria Ieronymaki

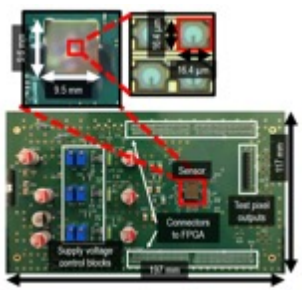
EPFL – Claudio Bruschini

Palacký University Olomouc – Bohumil Stoklasa

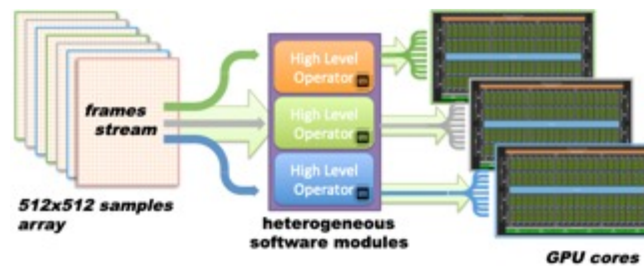
# **Qu3D** – Quantum 3D imaging at high speed and high resolution

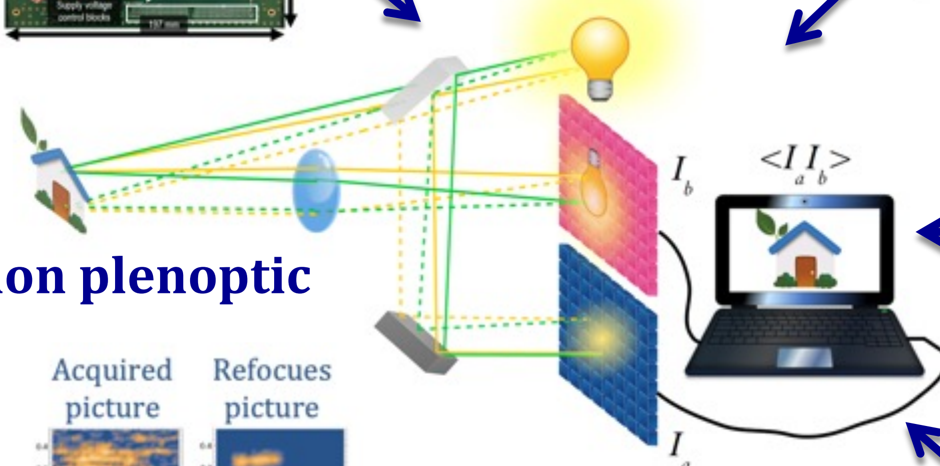
*Coordinatore:* **Milena D'Angelo** (INFN sez. Bari)
*Partners:* EPFL, Olomouc Univ., Planetek Hellas epe

✓ Ultra-fast sensors

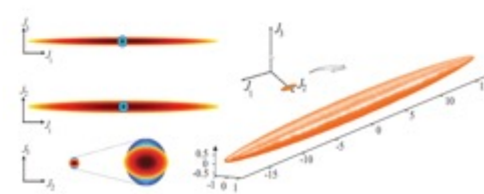



✓ Fast computing



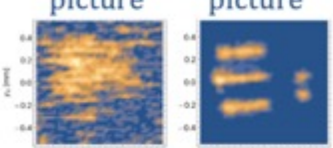

✓ Quantum tomography



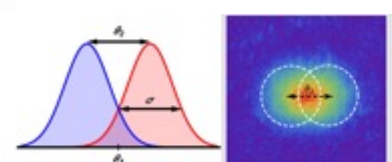
✓ **Correlation plenoptic imaging**

Acquired picture

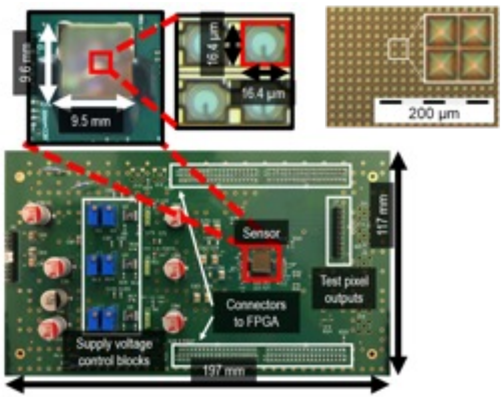
Refocues picture



✓ Super-resolution



# Hardware speed-up

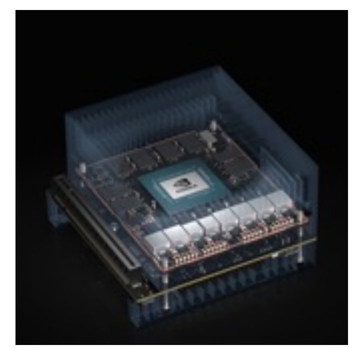



## SwissSPAD2. Ultra-fast SPAD array

- Array of 512 x 512 SPAD
- Records binary frames at 100 KHz
- Minimum gate length of 10.8 ns
- Fill factor ~ 60% (with microlenses)
- On-board FPGA for control, redout and logic operations

## High-performance computing

- Development of high-bandwitdth bus connection (required ~ 25 Gb/s)
- On-board GPU for parallel data pre-processing
- Taking advantage of the 1 images for faster calculations



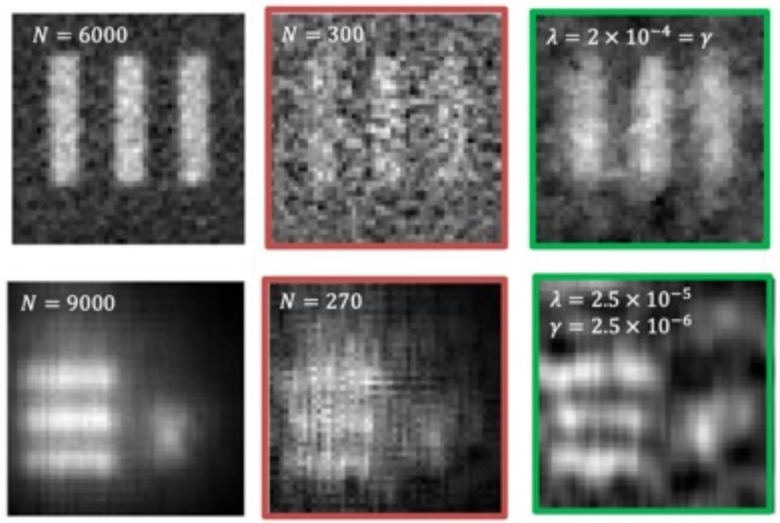
# Processing optimization

## Compressive sensing

6.000 frames | 300 frames | 300 frames with CS

Simulation

Experiment

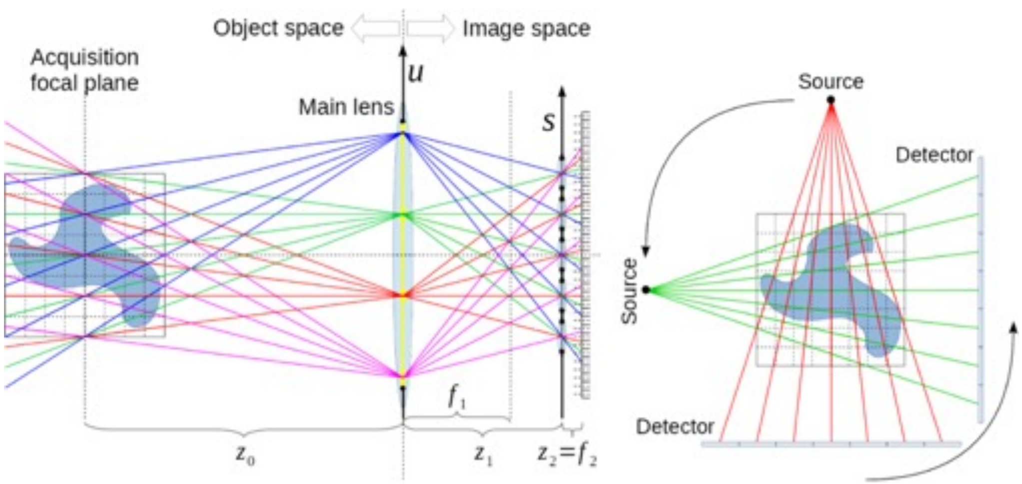



## Quantum Fisher Information

- Super-resolution and/or frame number optimization

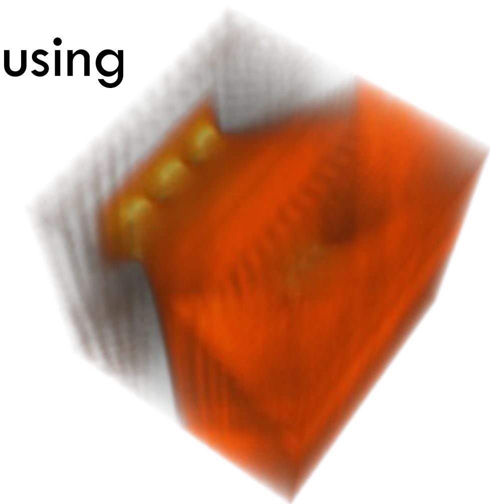
# Processing optimization

## Quantum tomography

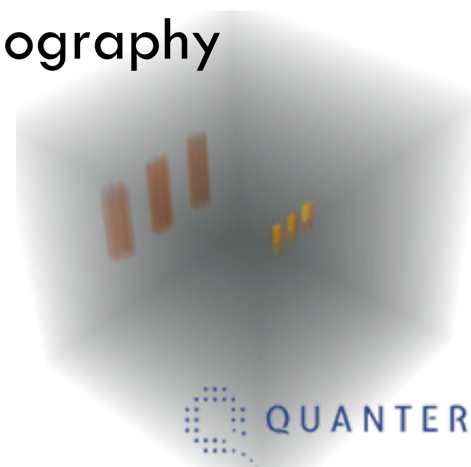



(a) Compound plenoptic camera. (b) Cone-beam tomography.

CPI refocusing



QPI Tomography



# Advantages of CPI

Scanning-free 3D imaging → high speed volumetrici imaging

Refocusing out-of-focus images → simplifies optomechanics

with

Diffraction-limited resolution

Unprecedented DOF , at fix given resolution

Turbulence/scattering attenutation capability … work in progress

SNR advantage: attenuation of stray light, source fluctuations, detector aging… work in progress

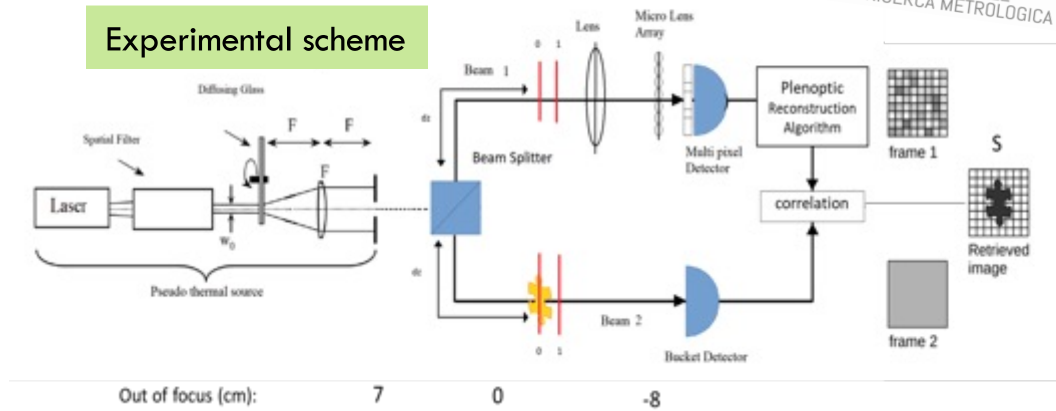
**Can be realized with natural sources**

# Plenoptic ghost imaging

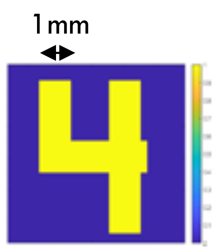
In Ghost Imaging (GI), the focalization of the object is hard and time consuming, unless its distance is precisely known.

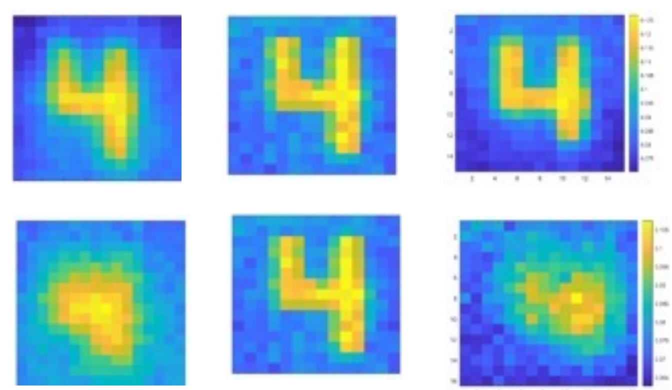
**PGI can refocus the ghost image a posteriori for a wider range of object positions, also enabling 3D GI.**

Experimental scheme




Refocusing capability



Plenoptic GI

Conventional GI

Out of focus (cm): 7 0 -8

# Work in progress

- Correlation Light-filed 3D Microscope

INTEFF-ToPMicro

PICS4ME

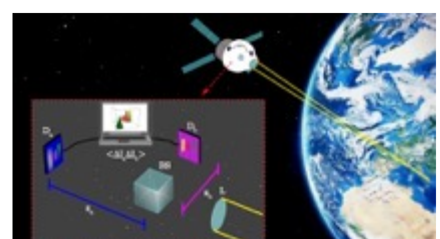
DMD, filtered LED/lamps … fluorescence

- Speed-up & Super resolution … both through ***software*** & ***hardware***

Qu3D

- SNR enhancement by optimizing setups, sources (e.g., entangled photons) and measurement protocols (e.g., differential, compressive, machine learning,…)
- Exploring different use cases: target detection, space imaging, hyperspectral imaging

CLOSE



Leonardo

EPJ Plus – Focus point

Quantum Sensing, metrology and imaging

Master di I livello in Quantum Computing & Artificial Inteligence @ Dip. Fisica - UniBa

milena.dangelo@uniba.it


# Grazie


Ready for 2024 edition

SPIN-OFF QPI Systems (work in progress)