Sensing with Quantum Light 2020
Berlin + zoom, Sept. 6-9 2020

QUANTUM PLENOPTIC IMAGING

Milena D'Angelo
Physics Dept. - University of Bari (Italy)
& INFN Bari

PICS4ME

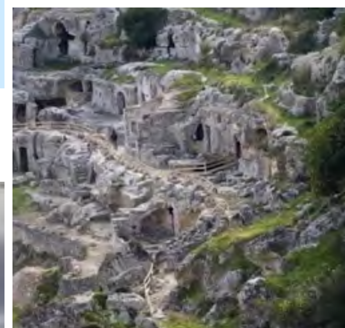
CLOSE

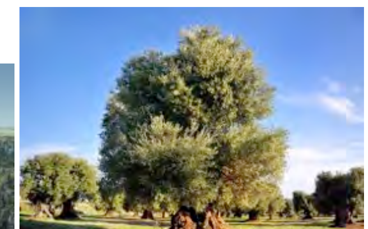
Qu3D

UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO

INFN Istituto Nazionale di Fisica Nucleare

Where is Bari ?





QuOT Lab @ UniBA

- Students :
  - Emiliana De Scisciolo, Alessio Scagliola, Alessandro Lupo
  - Giovanni Scala, Davide Giannella, Gianlorenzo Massaro
- Post-docs:
  - Francesco Di Lena
  - Sergii Vasiukov
  - Francesco V. Pepe
- Permanent:
  - Milena D'Angelo
  - Augusto Garuccio

CLOSE – Close to Earth

PON RICERCA E INNOVAZIONE

PICS4ME - Plenoptic Imaging with CorrelationS for Microscopy Enhancement

Partners

M. Genovese, I. P. Di Giovanni (INRIM, Torino - IT)

J. Forneris, P. Olivero (Università di Torino - IT)

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

Partners:

E. Charbon, C. Bruschini (EPFL - CH)

B. Stoklasa, Z. Hradil, J. Rehacek (Olomouc University - CZ)

M. Iacobellis, F. Santoro, L. Amoruso (Planetek Hellas - GR)

QUANTERA

FNSNF
Swiss National Science Foundation

QUANTERA

Qu3D

Quantum technology: more security and improved imaging

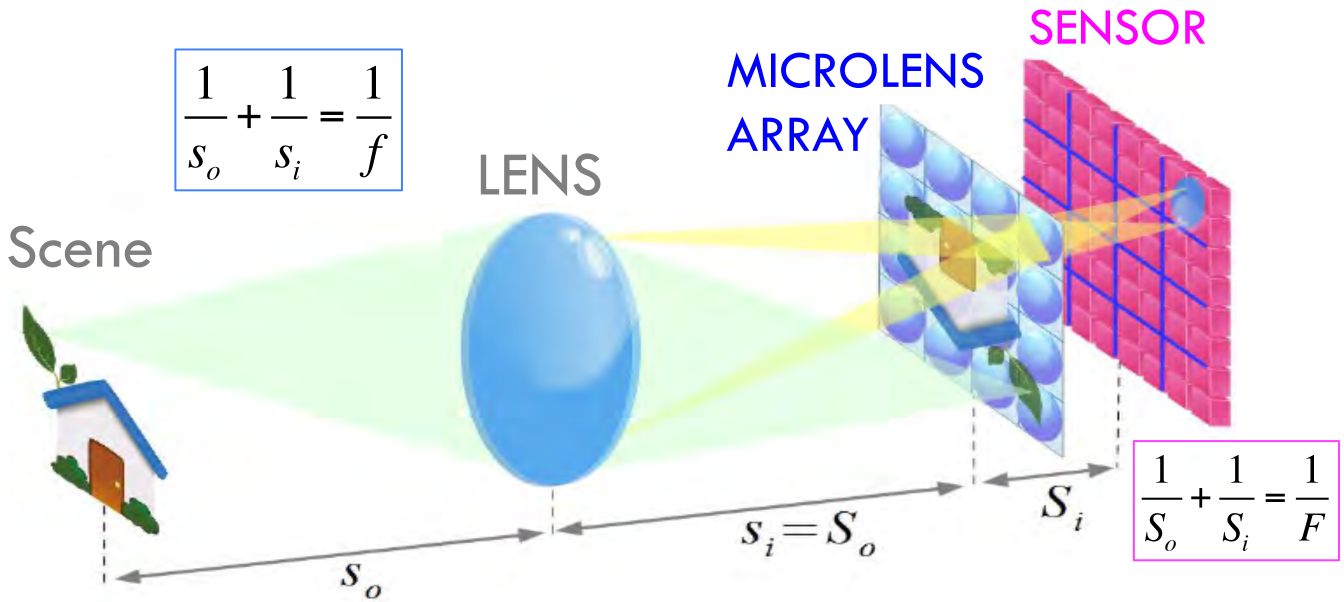
21/Nov/2019

Conventional plenoptic imaging

Lippman [1908] and Ives [1930]

Adelson and Wang [1992]

Ng [2005]

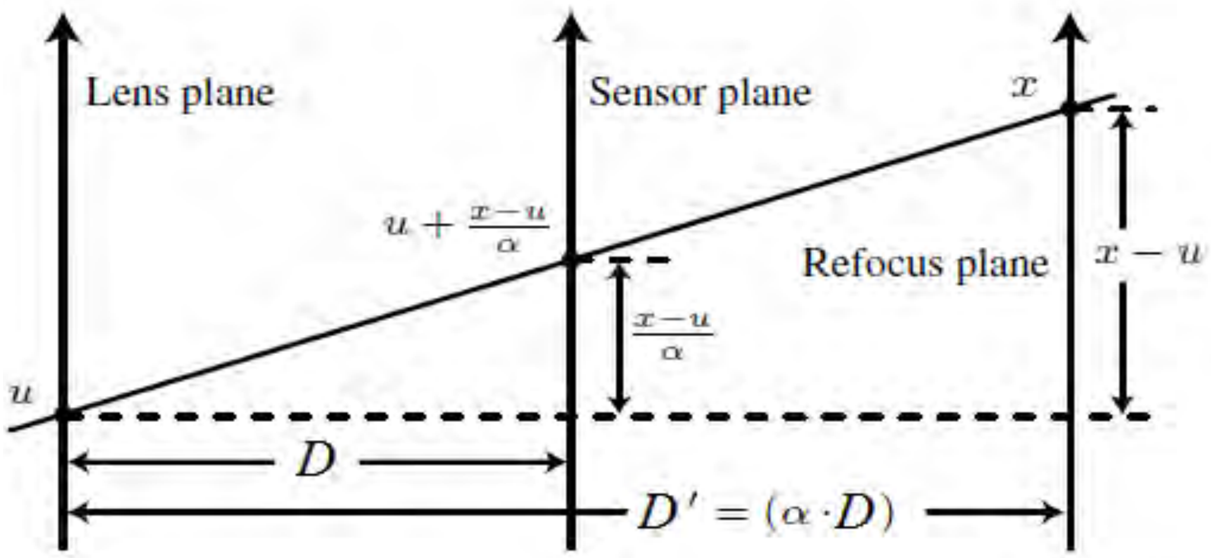


Enables to retrieves BOTH
the **image** AND the **propagation direction** of light

What for?

Ray tracing → *Re*focusing !

Ng et al., Tech. Rep. 2005



Refocusing = rescaling the acquired radiance

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

Why plenoptic imaging?

Lippman [1908] Adelson and Wang [1992] Ng [2005]

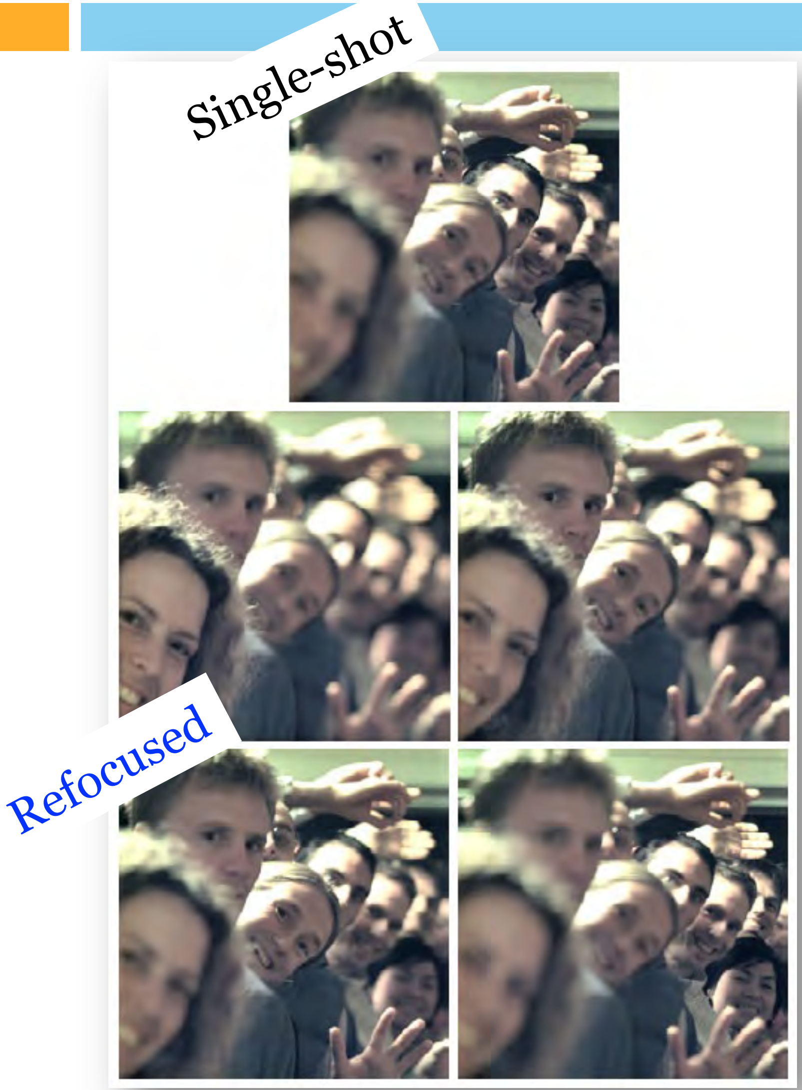
Refocusing out-of-focus pictures

Shot

Refocused (post-proc.)

From refocusing to extended DOF

https://illum.lytro.com/illum



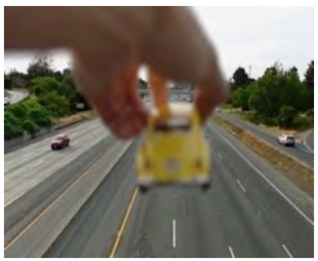
Same DOF of a smaller lens,
but higher SNR :

Simplifies low light shooting,
auto-focus …

Why plenoptic imaging?

Shot

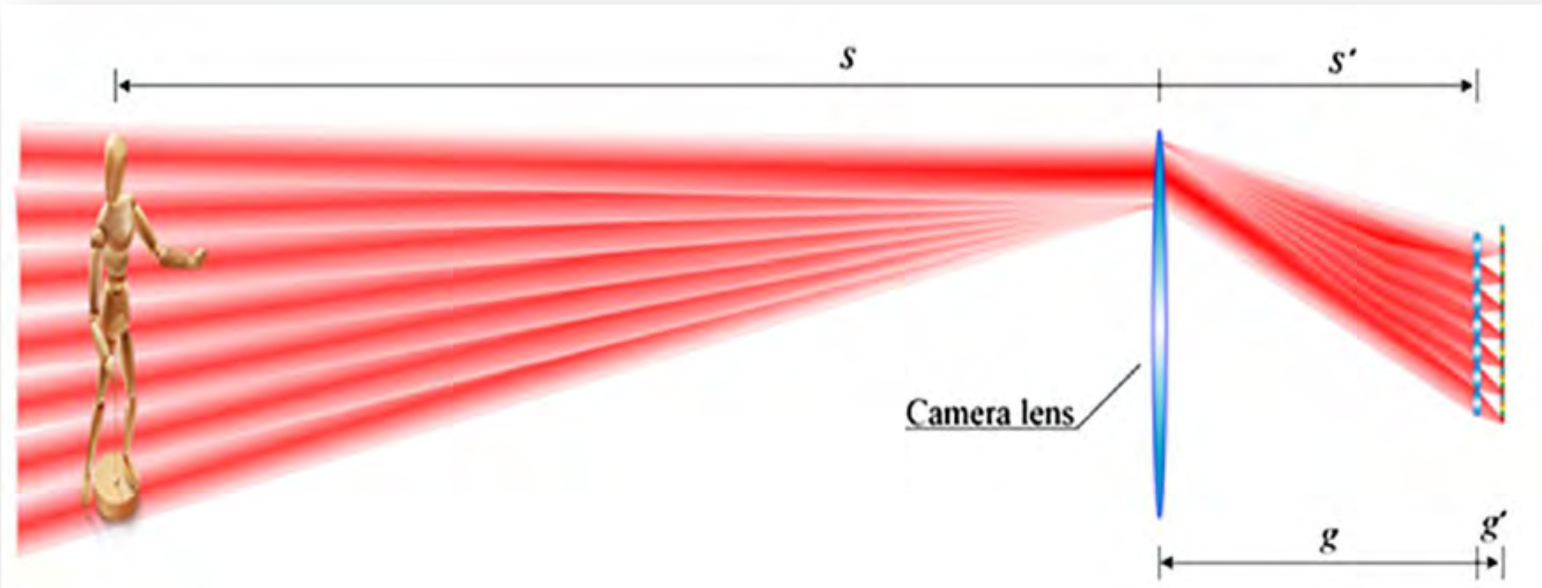
Refocused (post-proc.)

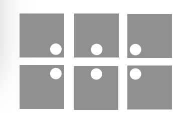


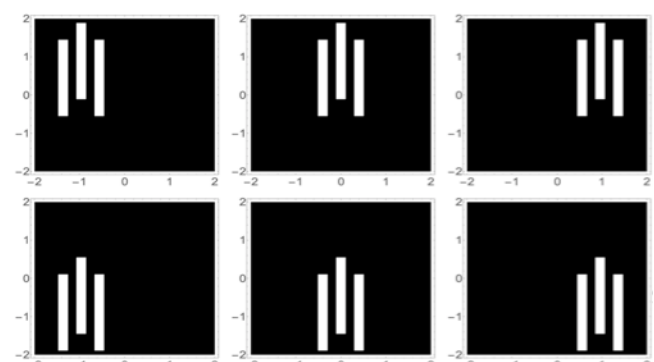
Extending the depth of field,
with high luminosity & SNR

www.raytrix.de/

Plenoptic imaging for multi-perspective view



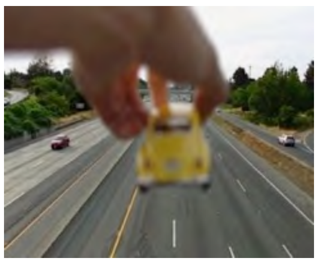




Why plenoptic imaging?

Shot

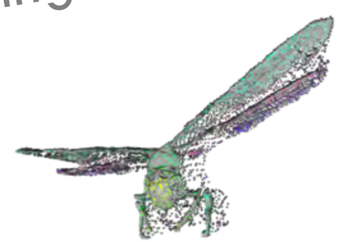
Refocused (post-proc.)

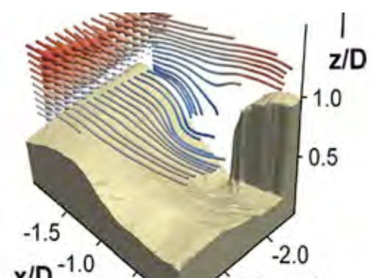


Extending DOF with high luminosity & SNR

www.raytrix.de/

Parallel acquisition of multi-perspective images → Single-shot 3D imaging

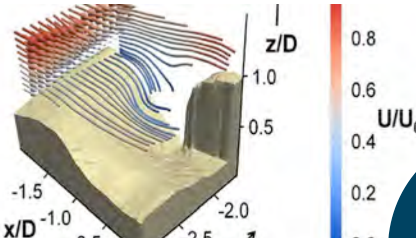


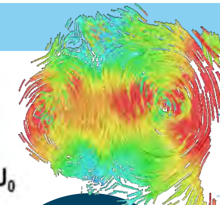


www.raytrix.de/

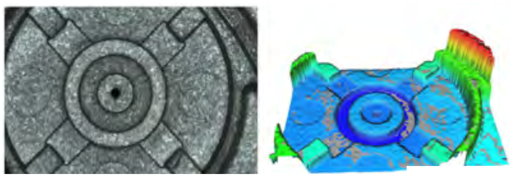
PI: The most promising method for 3D imaging

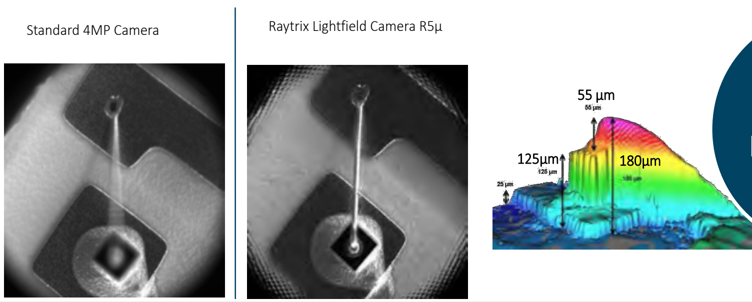
www.raytrix.de/

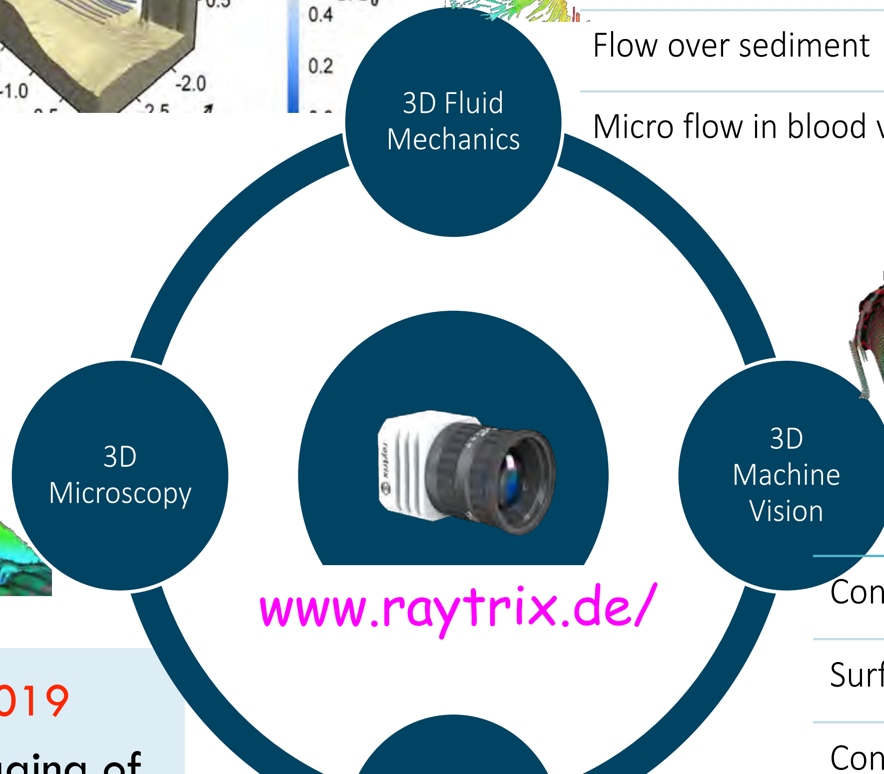


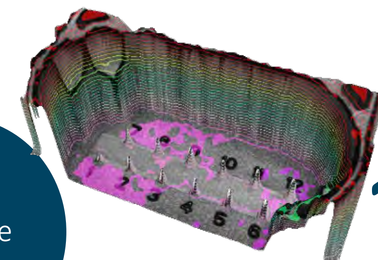


- Petrol injection
- Flow over sediment
- Micro flow in blood vessels



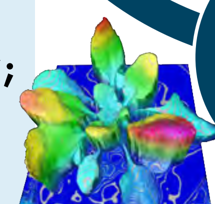






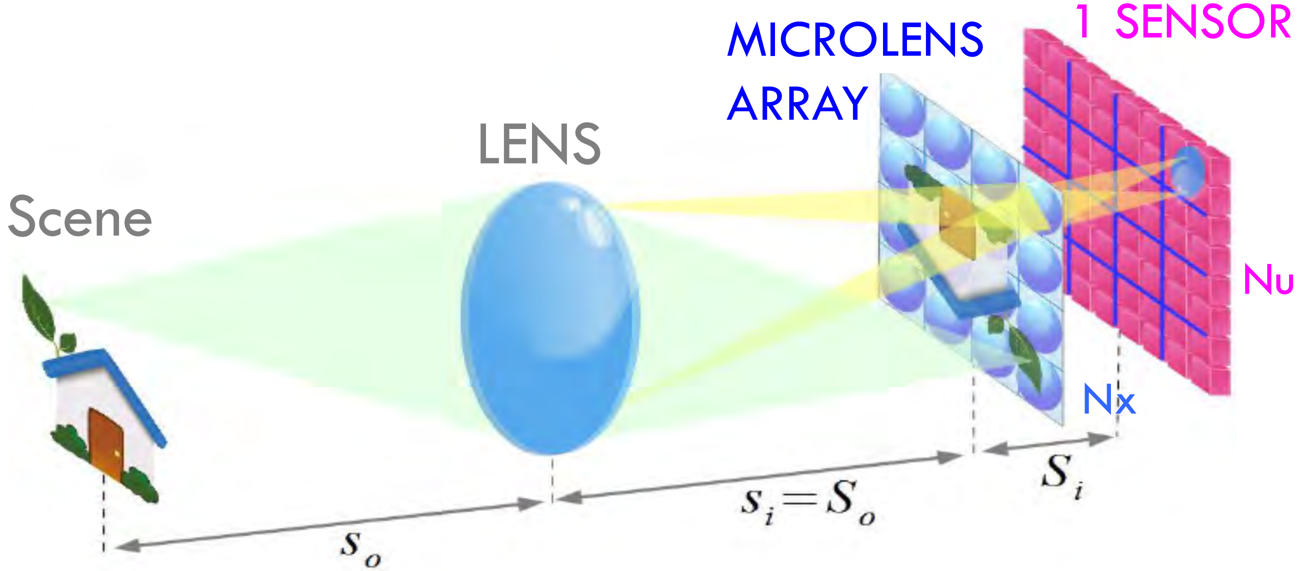
- Connector pin inspection
- Surface inspection
- Contaminations in Glass

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



- Plant breeding
- Picking
- Weeding

Limits of conventional plenoptic imaging



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

A 16 Megapixel camera, behaves as a 4 Megapixel ☹

Intrinsic limits of conventional PI :

- Strong trade-off between resolution and depth-of-field (Nx Nu = Ntot)

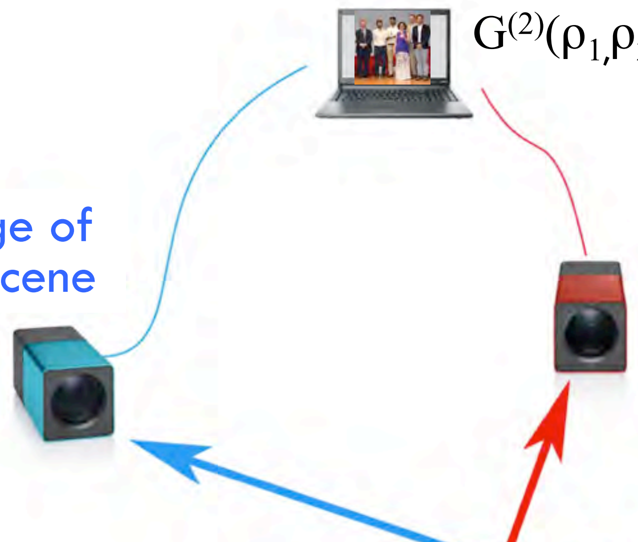
  → No diffraction limited resolution !
- Highly sacrificed change of perspective limits the 3D imaging capability

Our solution: Correlation Plenoptic Imaging

D'Angelo et al., PRL 116, 223602 (2016) + 4 patents

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

Image of the scene



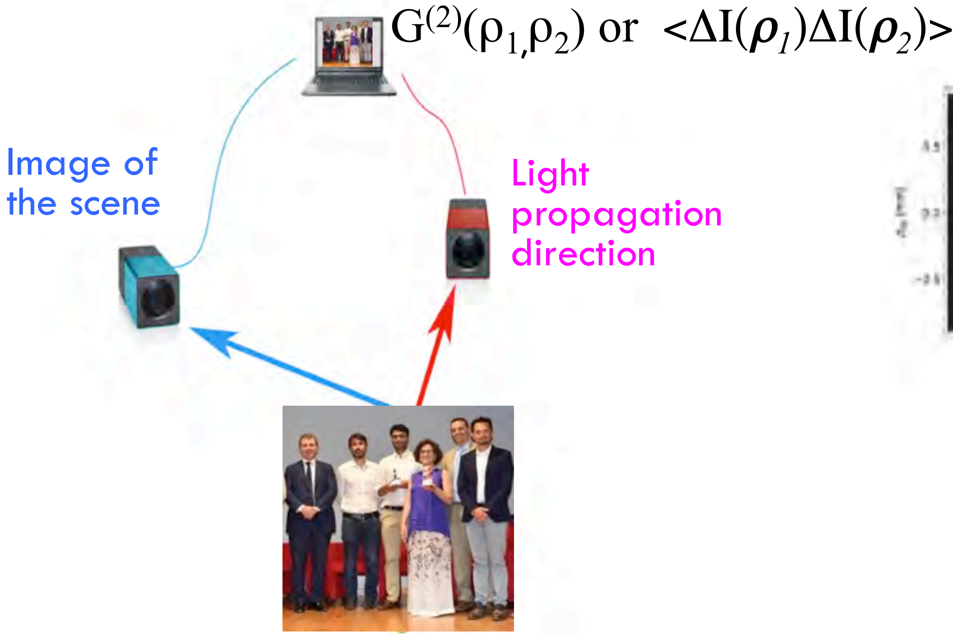
Light propagation direction

- Take **two correlated light beams**: at least one of them interacts with the object
- **Follow in time their number of photons/ intensitites** with <u>two</u> <u>*spatially resolving*</u> detectors
- Time-average to evaluate the point-to-point **coincidences / correlations of intensity fluctuations**

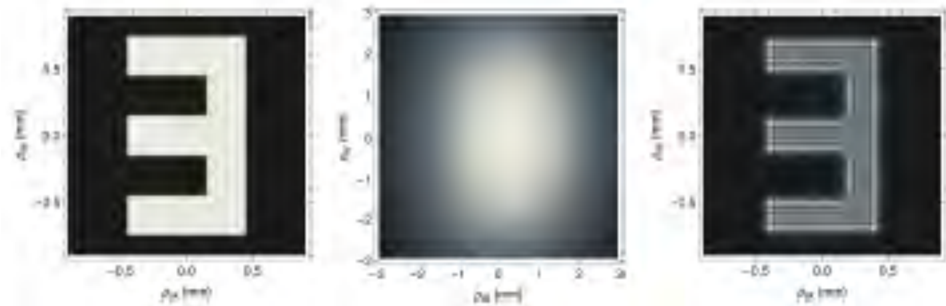
Intellectual Property Award 2019 (MISE)

Exploiting spatio-temporal correlations of light to decouple image acquisition and direction measurement !!

Sources for Correlation Plenoptic Imaging



Entangled photons



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

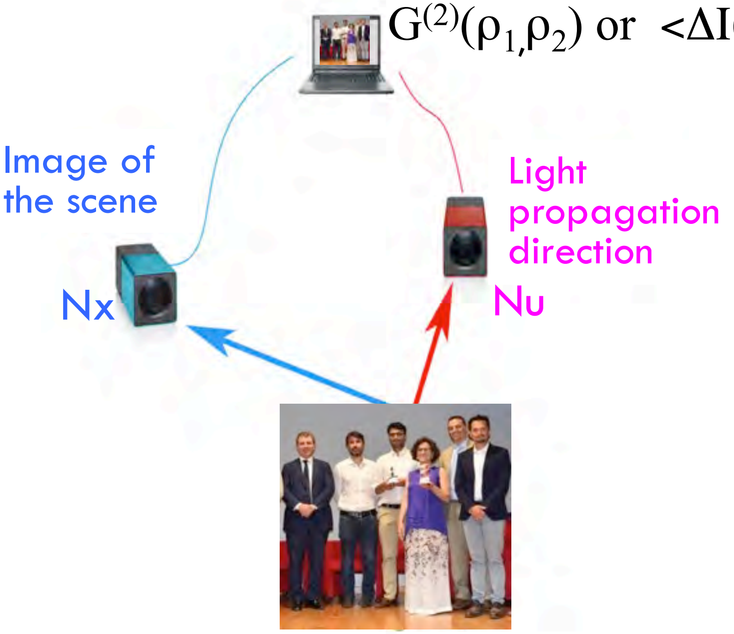
Chaotic light

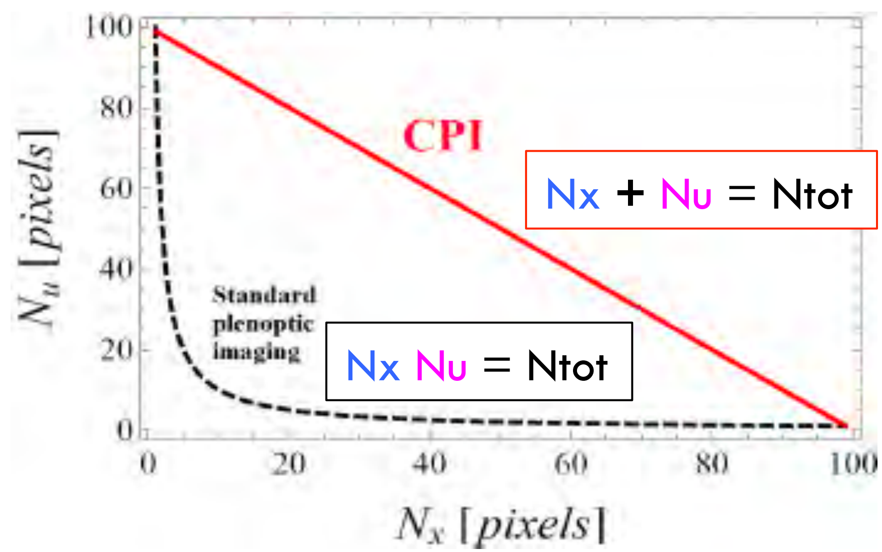
D'Angelo et al., PRL 116, 223602 (2016)

Resolution vs. DOF improvement

D'Angelo et al., PRL 116, 223602 (2016) + patent 102016000027106 (2016)

$G^{(2)}(\rho_{1,}\rho_2)$ or $\langle\Delta I(\boldsymbol{\rho}_1)\Delta I(\boldsymbol{\rho}_2)\rangle$

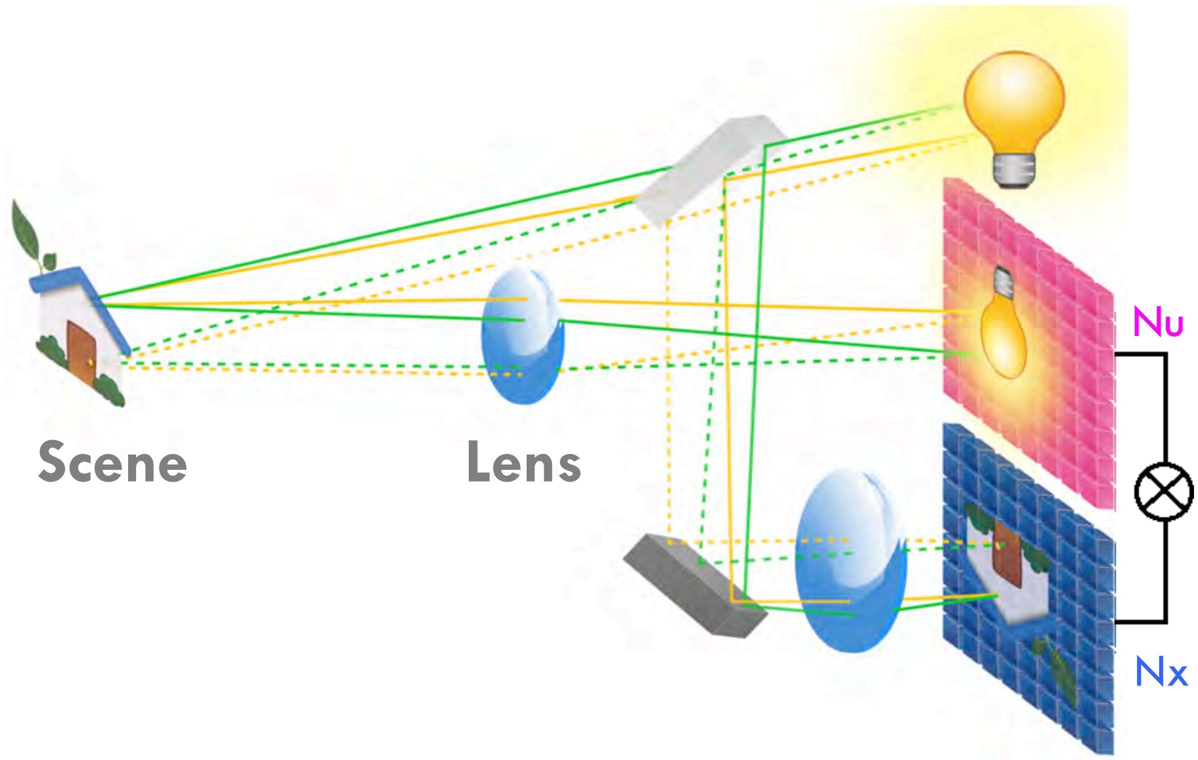




Resolution and maximum achievable DOF
scale linearly
rather than hyperbolically !!

Working principle of the 1st CPI scheme

D'Angelo et al., PRL 116, 223602 (2016) + patent 102016000027106 (2016)



CORRELATED Light Source

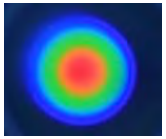
SENSOR 1: retrieves the direction of light rays

$G^{(2)}(\rho_1,\rho_2)$ or $\langle \Delta I(\boldsymbol{\rho}_1)\Delta I(\boldsymbol{\rho}_2)\rangle$

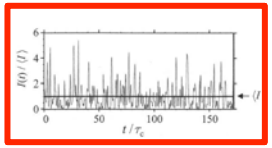
SENSOR 2: retrieves the image of the scene

Summing correlations over the entire *Sensor 1* yields the incoherent **ghost image** of the object

Pittman et al., PRA 1995

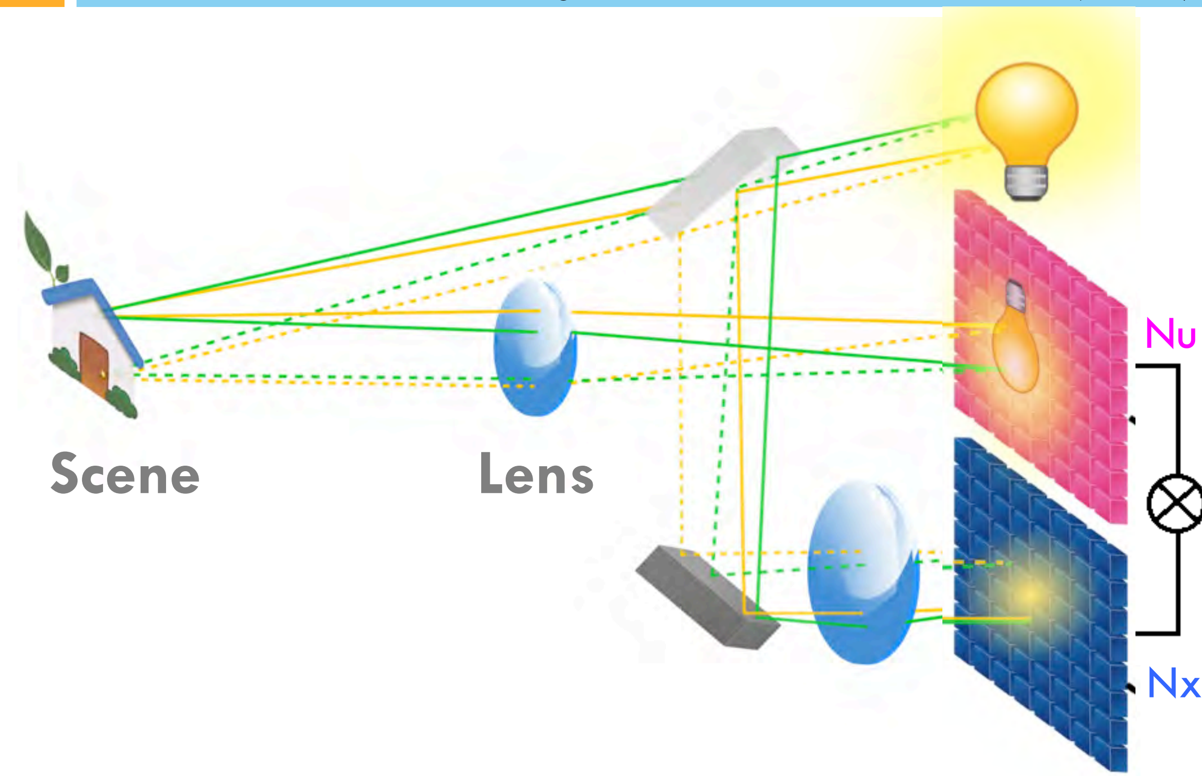


Valencia et al, PRL 2004



Working principle of the 1st CPI scheme

D'Angelo et al., PRL 116, 223602 (2016) + patent 102016000027106 (2016)



CORRELATED Light Source

SENSOR 1: retrieves the direction of light rays

$G^{(2)}(\rho_1,\rho_2)$ or $<\Delta I(\boldsymbol{\rho}_1)\Delta I(\boldsymbol{\rho}_2)>$

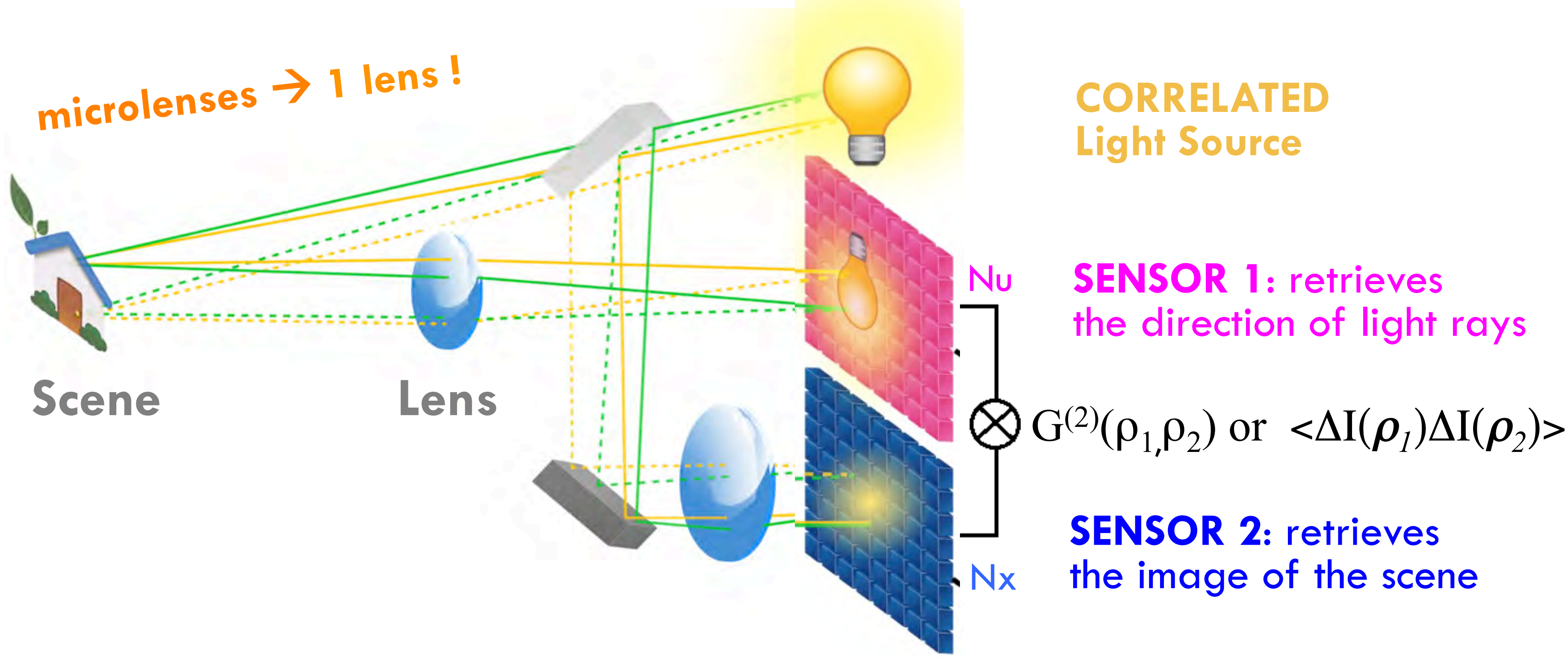
SENSOR 2: retrieves the image of the scene

If the "2-photon thin lens equation" is NOT satisfied (i.e., the ghost image is blurred) → **Multiple images of the object** : one for each pixel of Sensor 1 !

→ **Combined to refocus and change the point of view**

Working principle of the 1st CPI scheme

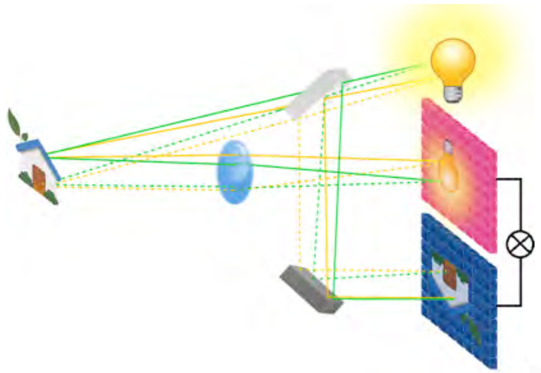
D'Angelo et al., PRL 116, 223602 (2016) + patent 102016000027106 (2016)

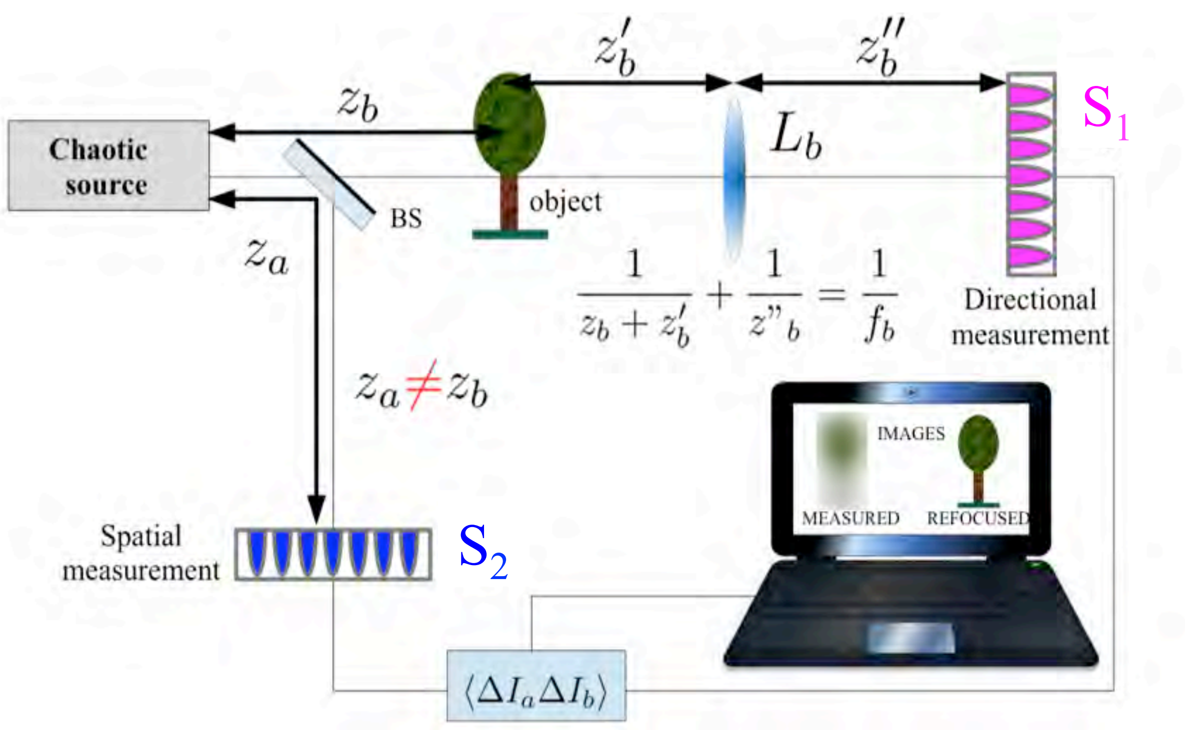


Refocusing out-of-focus images + **3D imaging**, with **diffraction-limited resolution** & a **wide change of perspective**

1st CPI experiment

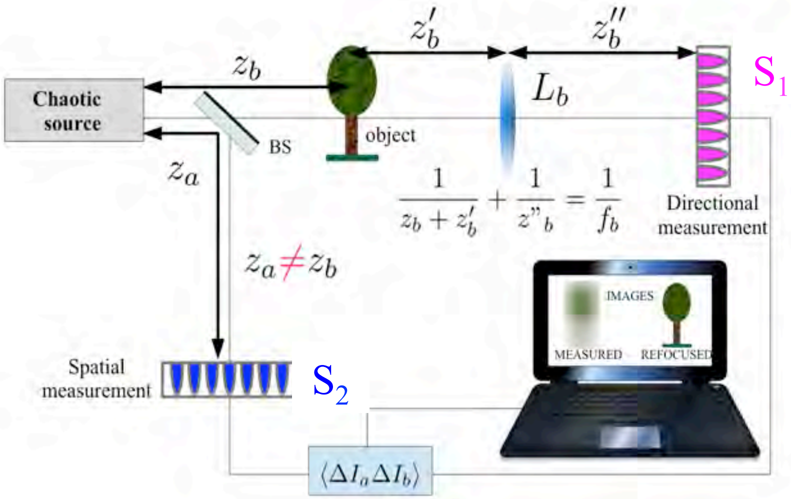
Pepe et al., PRL 119, 243602 (2017)



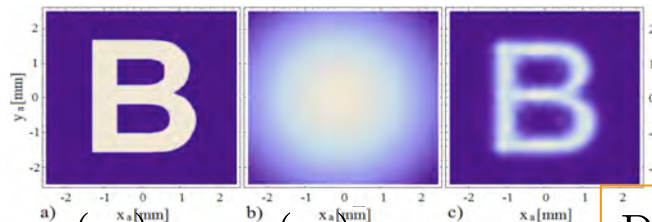


1 st CPI experiment

PRL 116, 223602 (2016)



Same resolution, but 40 times larger DOF !!!



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

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

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

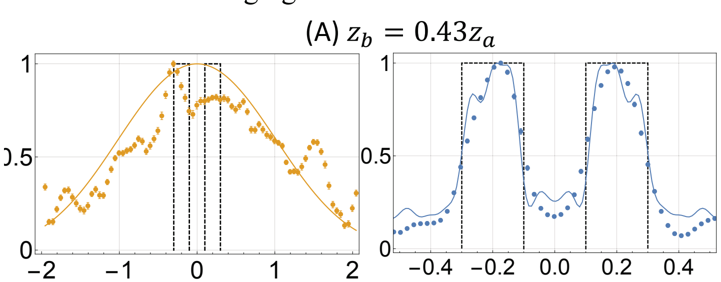
$$\frac{\mathrm{DOF}^{(\mathrm{cp})}}{\mathrm{DOF}^{(\mathrm{p})}} = \frac{N_u^{(\mathrm{cp})}}{(N_u^{(\mathrm{p})})^2}$$

= 40 !!!

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

Double-slit: d = 400 μm

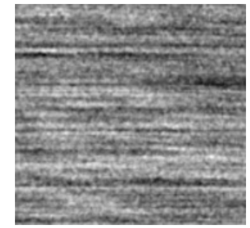
Standard Imaging CPI



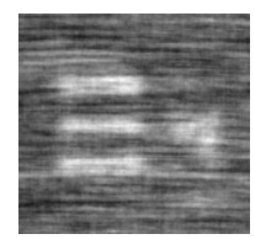
$z_b = 0{,}4\ z_a$

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

Ghost image



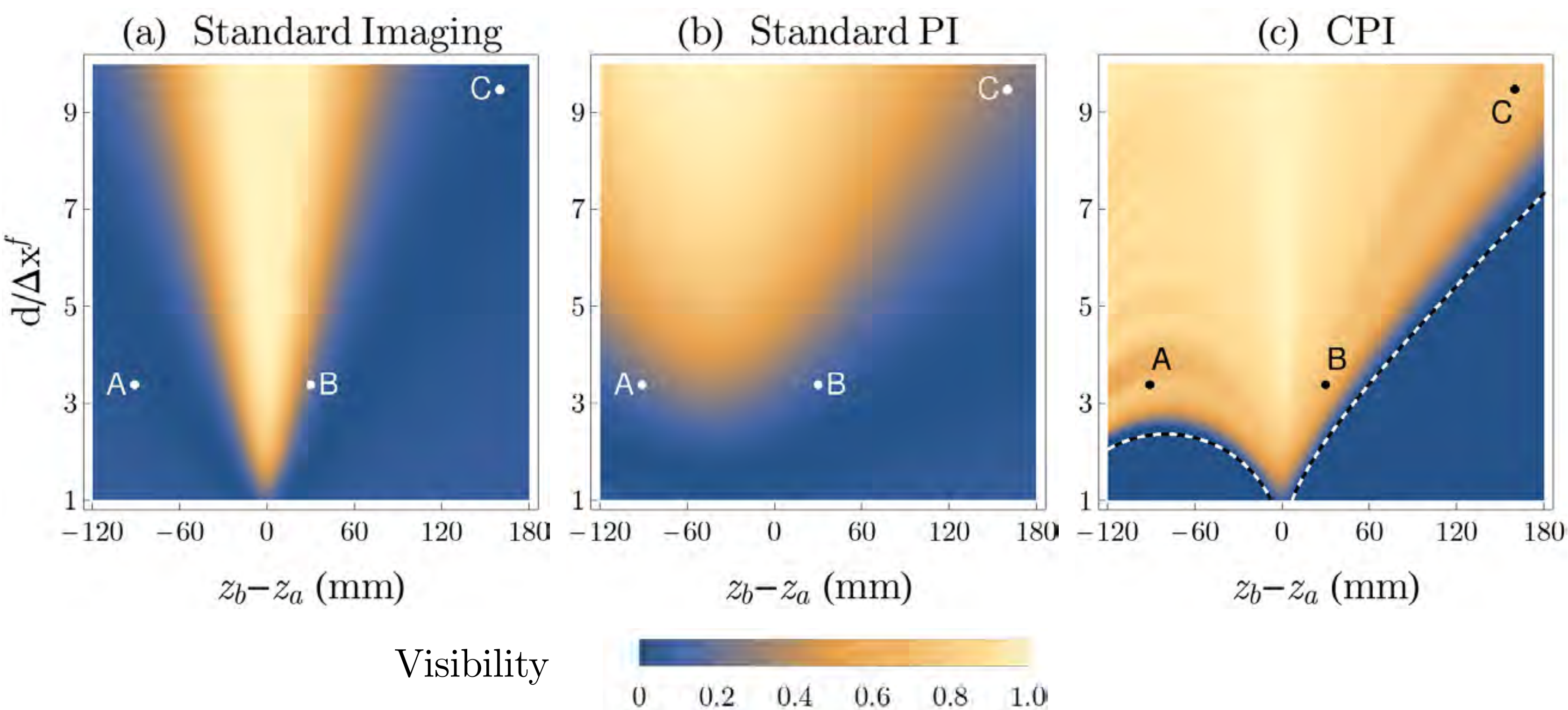
CPI



$z_b = 1{,}5\ z_a$

Resolution vs DOF improvement

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



When the image is focused:

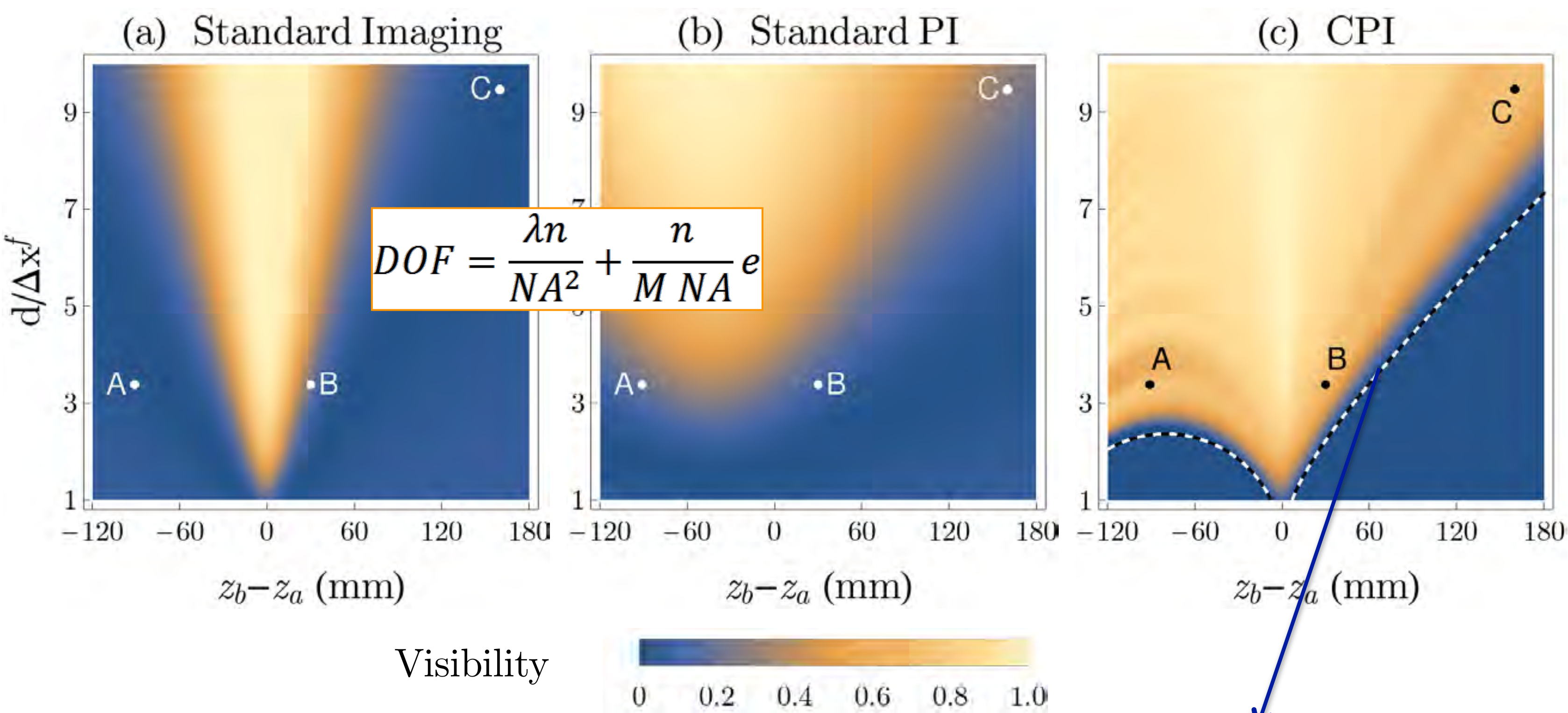
→ Resolution: λ/NA

→ Depth of field: λ/NA^2

NA = Numerical Aperture of the imaging lens / source

Resolution vs DOF improvement

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



$$DOF = \frac{\lambda n}{NA^2} + \frac{n}{M\,NA}e$$

Geometrical prediction:

$$\left|1-\frac{z_a}{z_b}\right| < \frac{\Delta x}{\Delta u} = \frac{d z_a/z_b}{\max[\lambda z_b/a,\ 2\lambda/(M_b \mathrm{NA}_b),\ 2\delta u/M]}$$

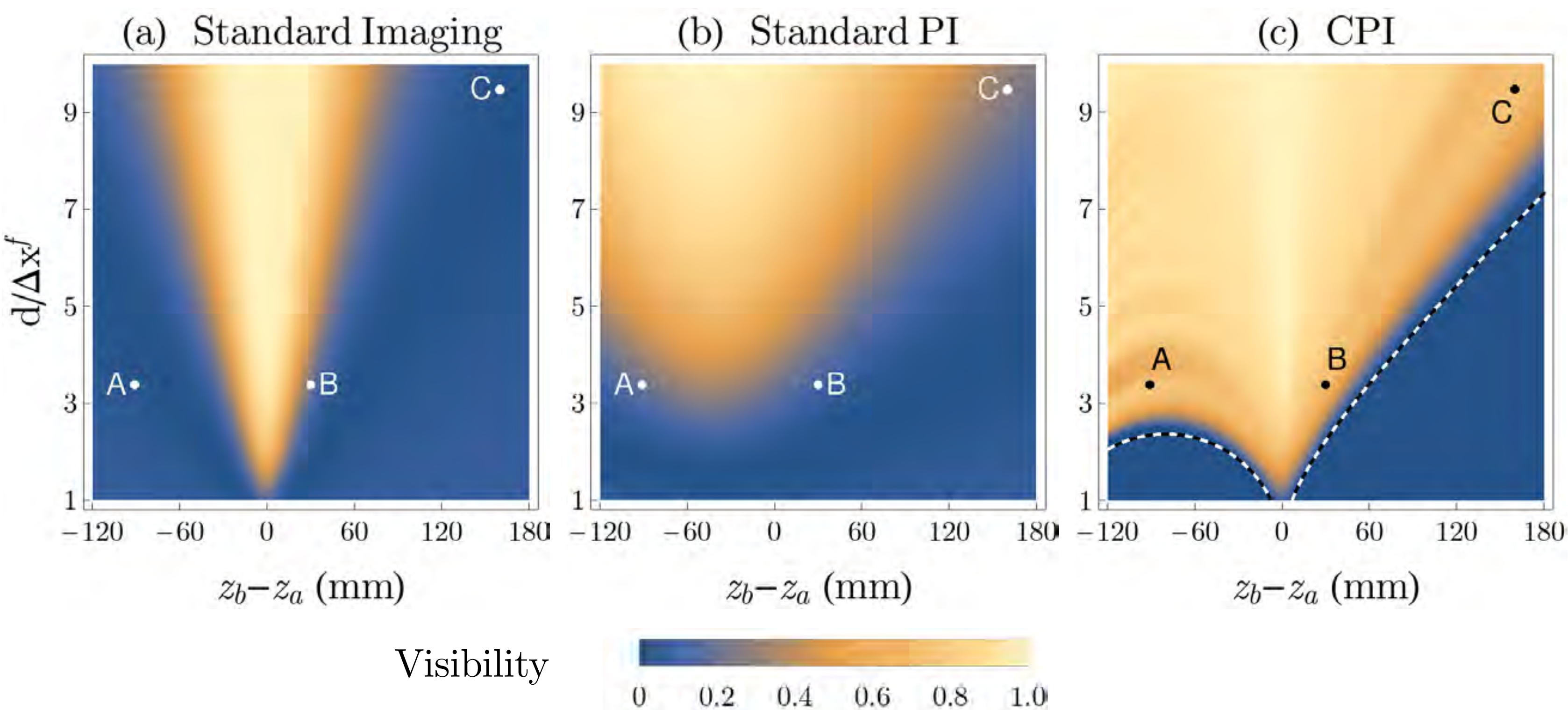
Diffraction at the object — Lens aperture — Pixel size

Δx: resolution on the <u>image</u> plane

Δu: resolution on the <u>source</u> plane

Resolution vs DOF improvement

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



By decoupling spatial and angular detection, CPI yields refocusing at higher resolution and larger depth of focus than both standard imaging and conventional plenoptic imaging (PI)

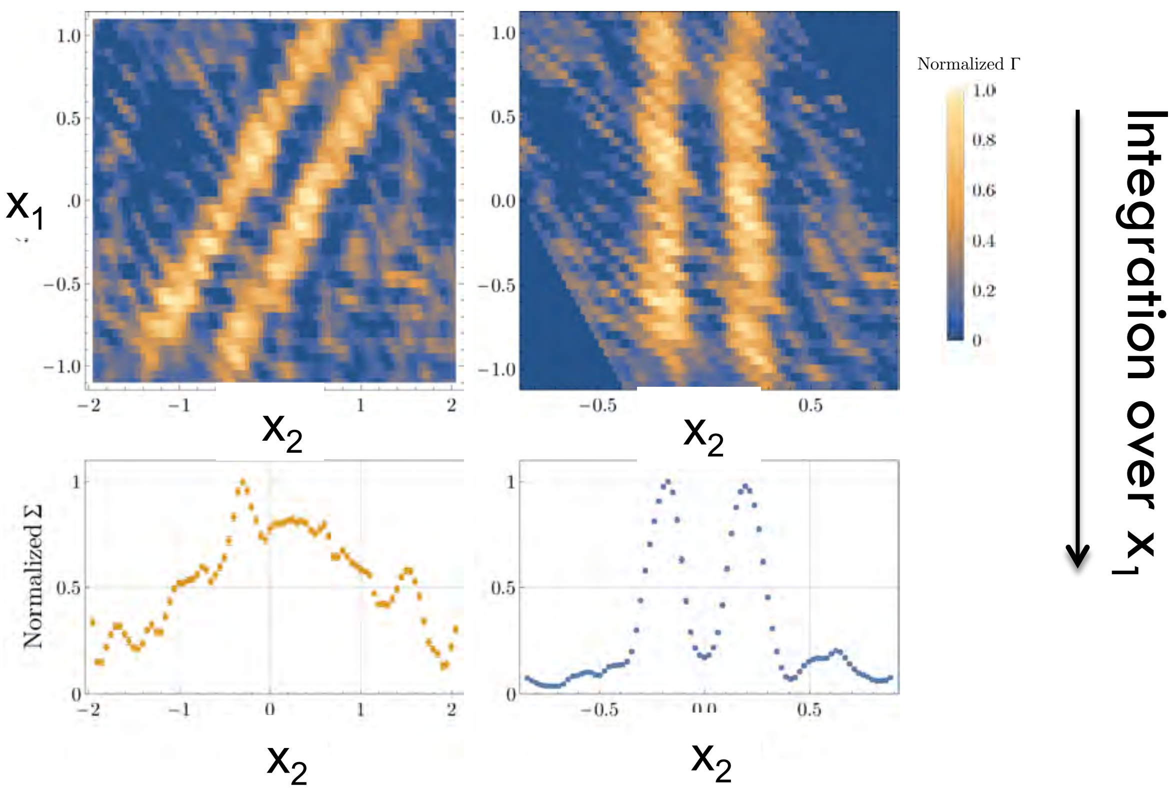
What makes refocusing possible ?

F. Di Lena et al, Nuovo Cimento C 41, 106 (2018)

$$\Gamma_{(z_a,z_b)}(\boldsymbol{\rho}_a,\boldsymbol{\rho}_b) \sim F\left(-\frac{\boldsymbol{\rho}_b}{M}\right)^2 \left| A\left[\frac{z_b}{z_a}\boldsymbol{\rho}_a - \frac{\boldsymbol{\rho}_b}{M}\left(1-\frac{z_b}{z_a}\right)\right]\right|^2$$

refocusing →

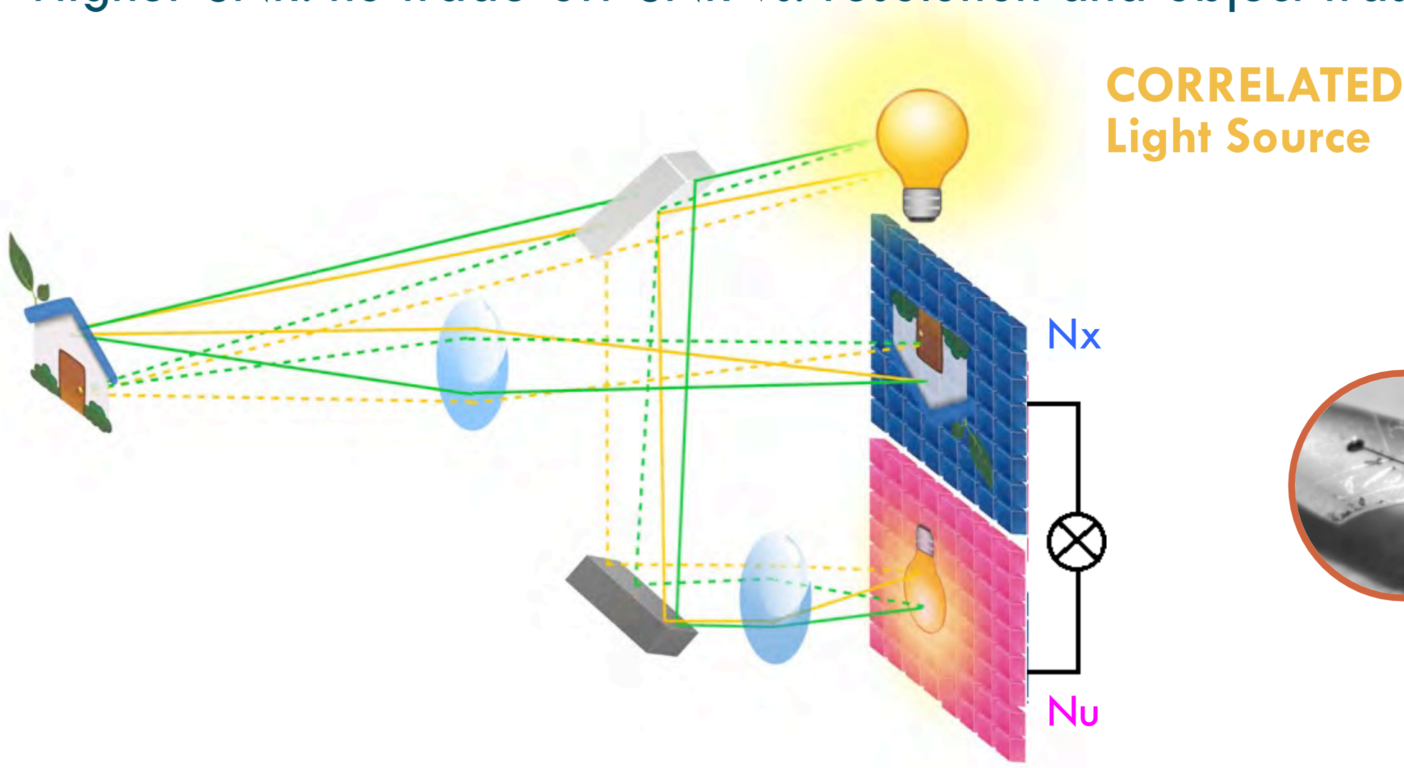
$$\Gamma_{(z_a,z_b)}\left(\frac{z_a}{z_b}\boldsymbol{\rho}_a - \frac{\boldsymbol{\rho}_b}{M}\left(1-\frac{z_a}{z_b}\right), \boldsymbol{\rho}_b\right) \sim F\left(-\frac{\boldsymbol{\rho}_b}{M}\right)^2 \left|A(\boldsymbol{\rho}_a)\right|^2$$

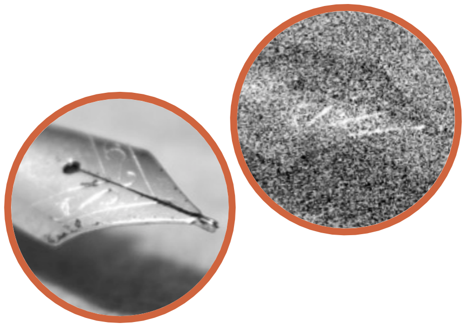


Alternative schemes for CPI

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

- No ghost imaging of the object → monitor object with conventional techniquies
- Higher SNR: no trade-off SNR vs. resolution and object trasmission area !!



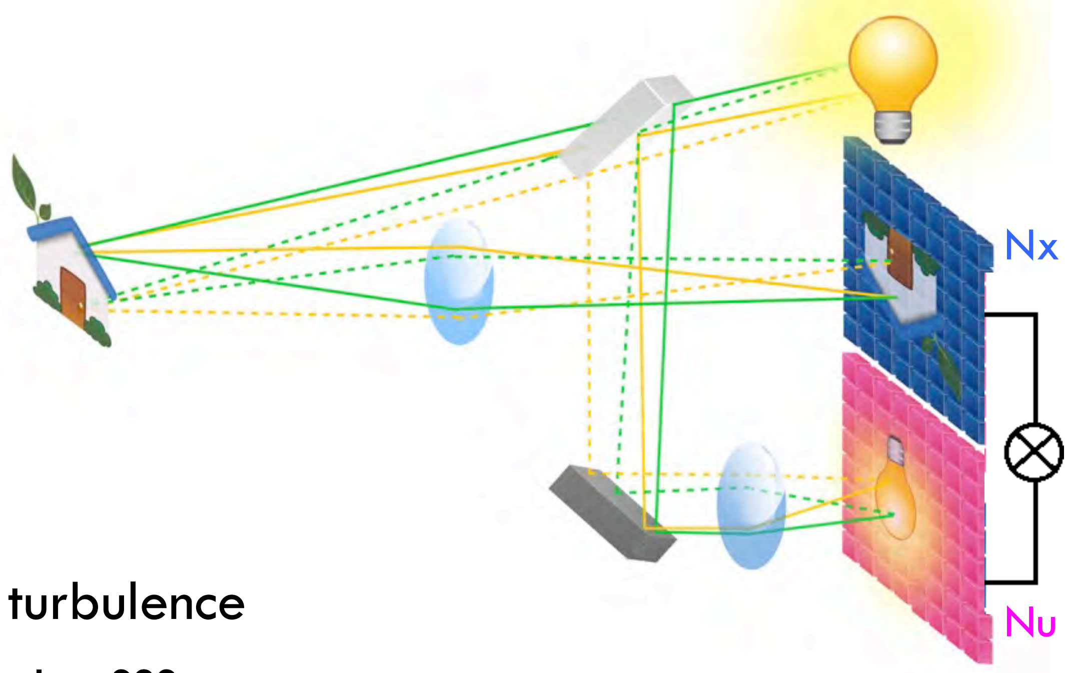


SNR analysis: Scala *et al*, PRA 99, 053808 (2019)

Need for more flexible CPI schemes

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

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



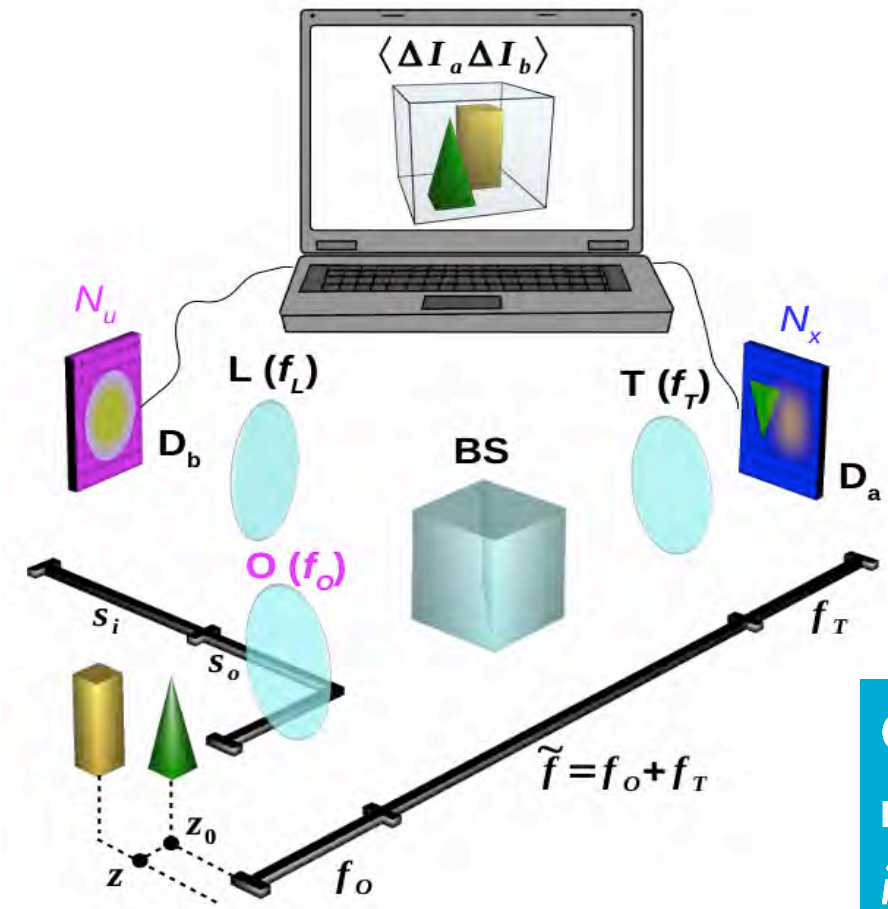
What if we have :

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

Relevant categories for microscopy, space objects, ...

1) Correlation Plenoptic Microscopy

PCT/2018 (INFN) + PLA 2020

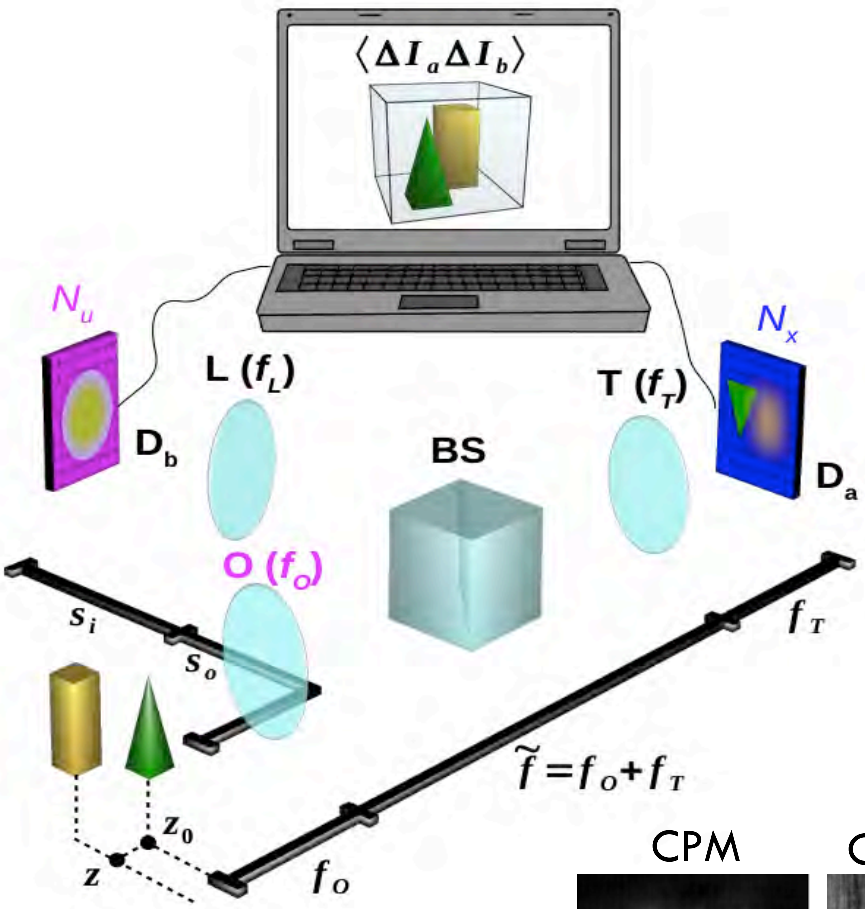


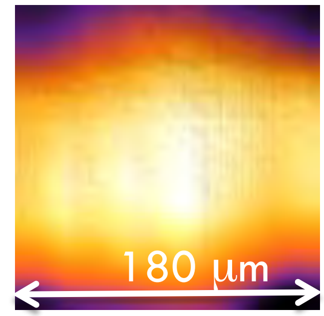
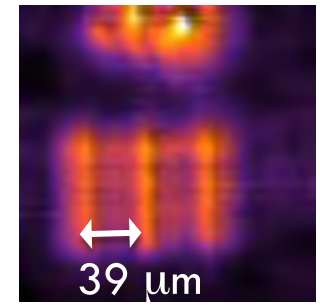
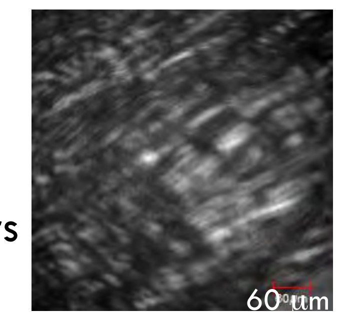
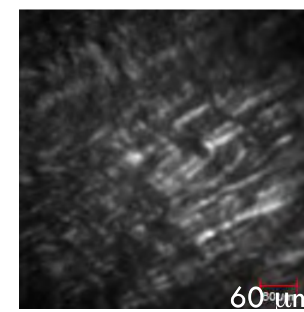
Ordinary microscope: sample in the focal plane of an objective (O) of focal length f_O, sensor (D_a) in the focal plane of a tube lens (T) of focal length f_T

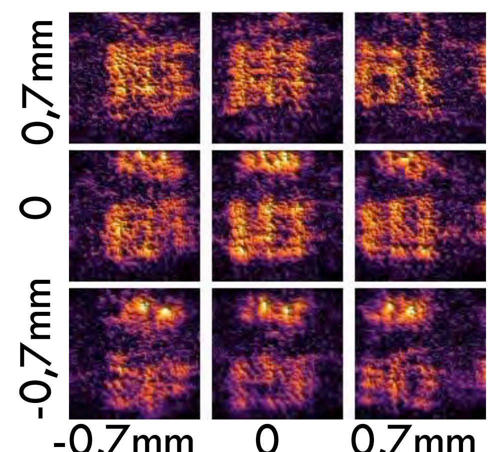
Correlation Plenoptic Microscope: measures correlations between the *image of the sample* (formed by the ordinary microscope) and the *image of the objective lens* (formed by lens L)

1) Correlation Plenoptic Microscopy

PCT/2018 (INFN) + PLA 2020



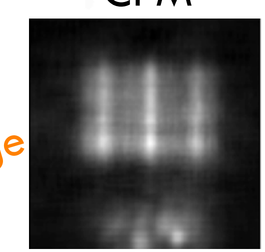
	SHOT	REFOCUSED
TEST TARGET (1 mm)		
BOVINE CORNEA: birifringent collagene fibers (100 um)		



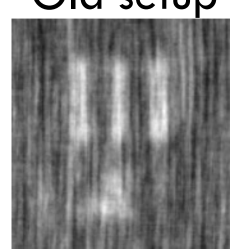
CHANGE OF PERSPECTIVE

SNR advantage

CPM

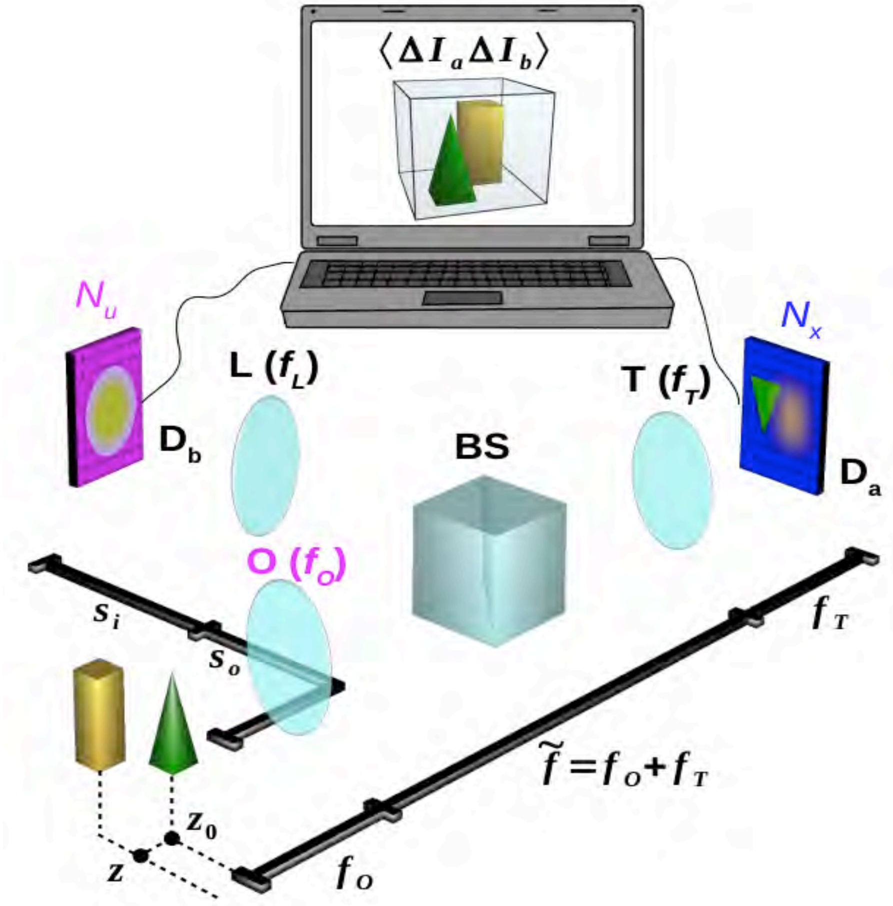


Old setup



1) Correlation Plenoptic Microscopy

PCT/2018 (INFN) + PLA 2020

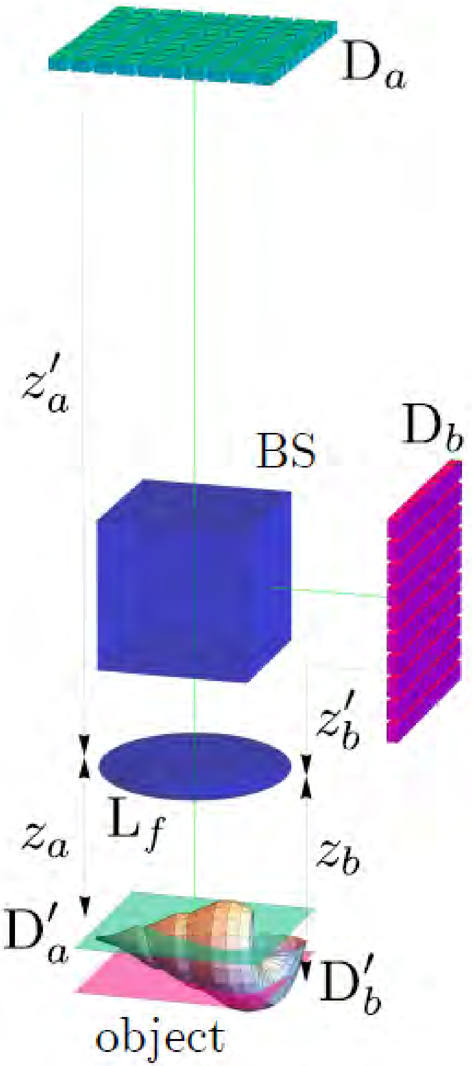


STARCH IN GEL (3D sample): Change of refocusing plane

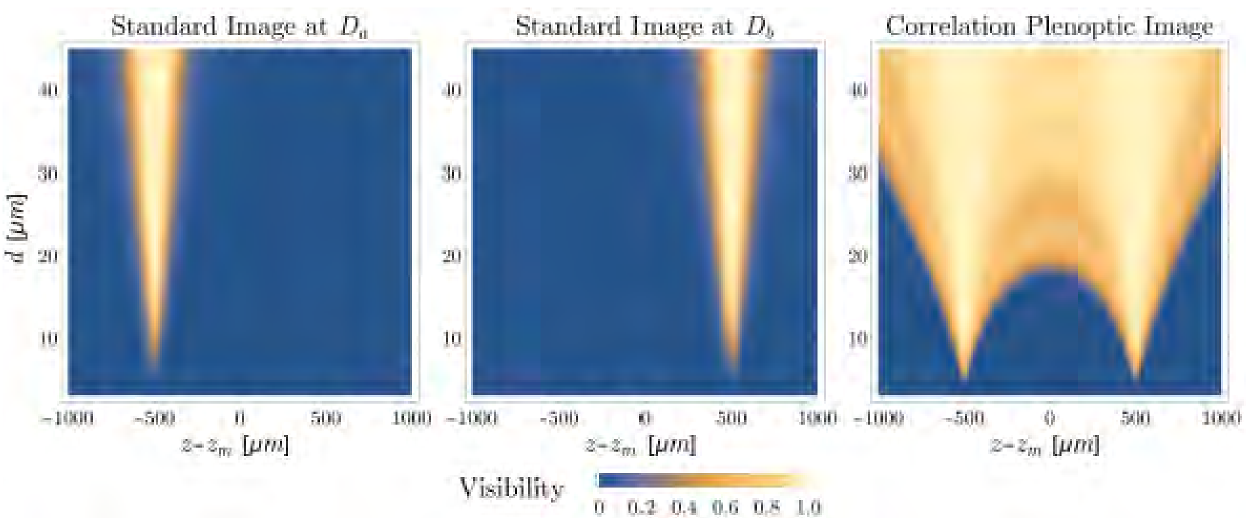
- **Detail recovery**
- **3D rendering**

2) CPI between arbitrary planes

F. Di Lena, PhD thesis (2019) + PCT 2019 + arXiv:2007.12033

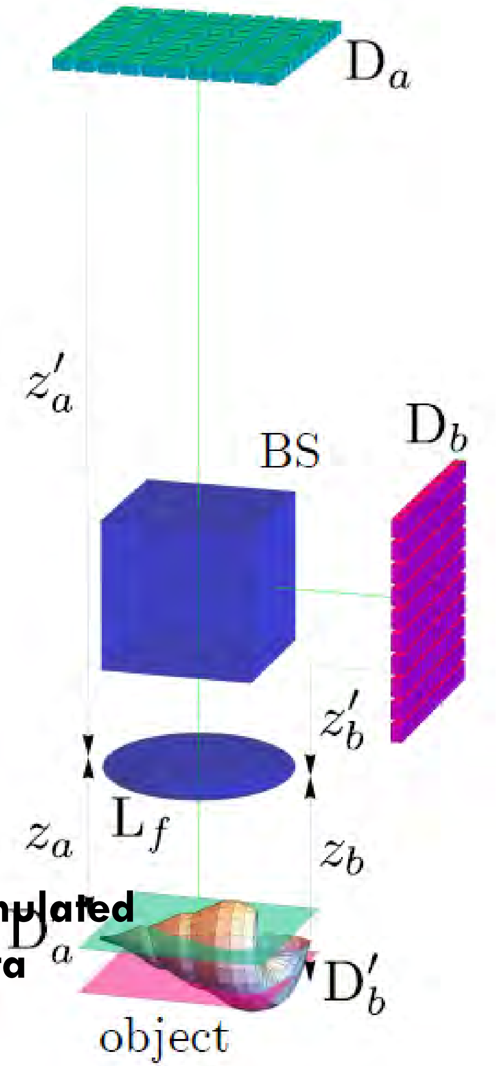


Single-lens CPI device: 2 different arbitrary planes within the 3D object are focused by the lens on the two disjoint sensors



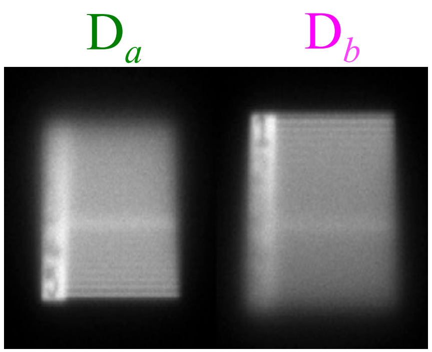
2) CPI between arbitrary planes

F. Di Lena, PhD thesis (2019) + PCT 2019 + arXiv:2007.12033

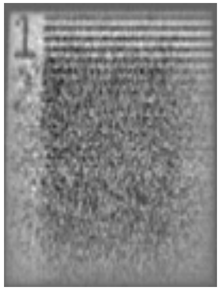


Simulated data

Acquired images



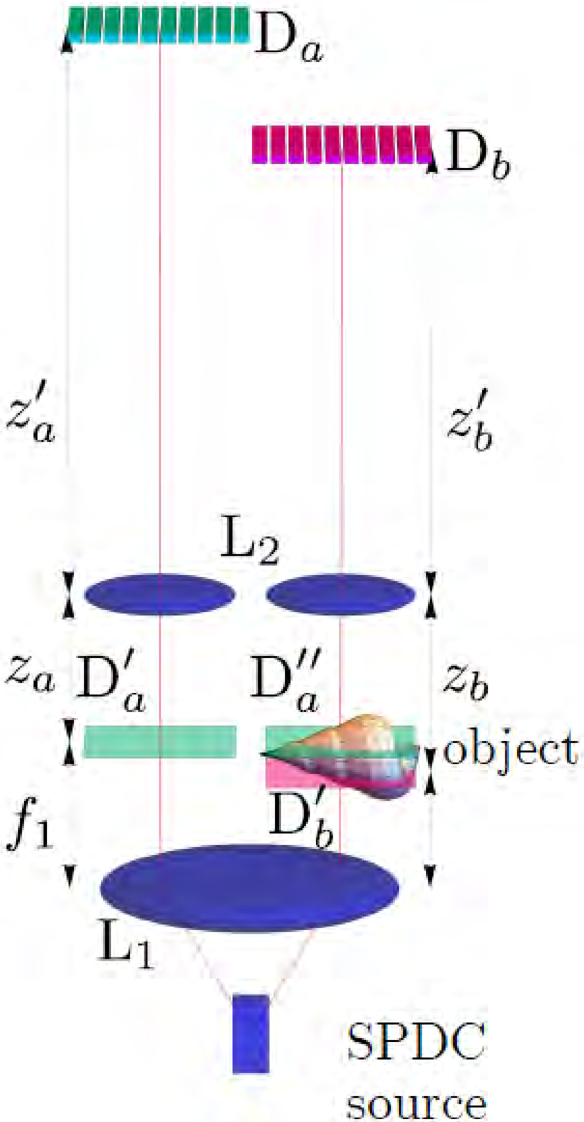
CPI Refocusing



Stacked refocused image

Quantum PI between arbitrary planes

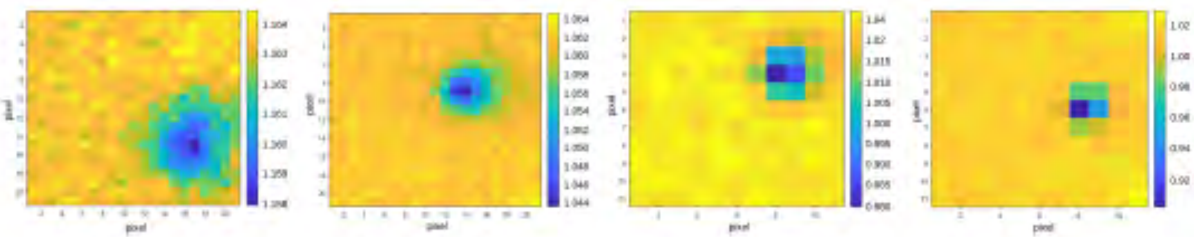
F. Di Lena, PhD thesis (2019) + PCT 2019 + IJQI 17, 1941017 (2020)



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 × 2 binning (c) 4 × 4 binning (d) 8 × 8 binning

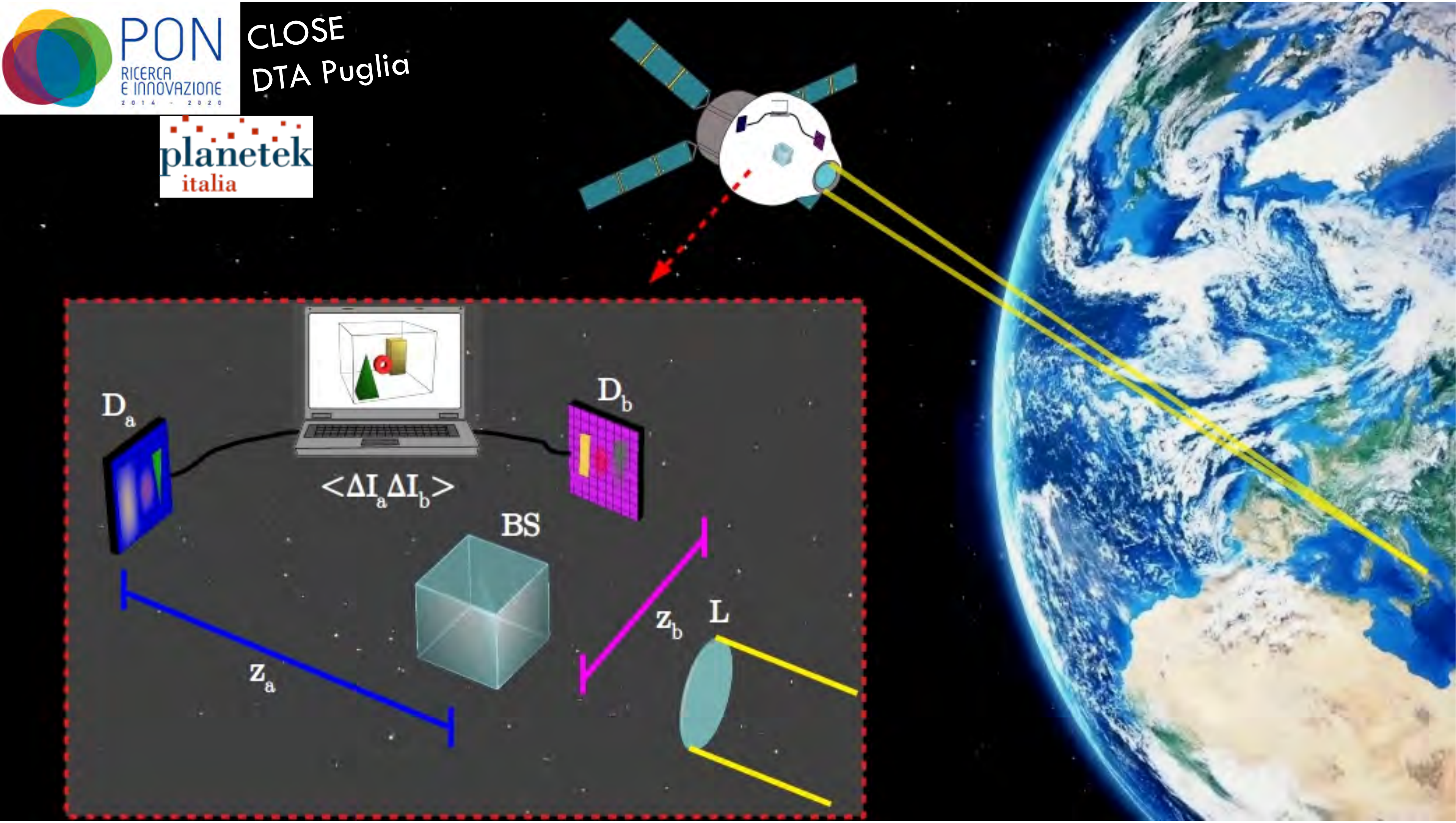
σ = 1,16 σ =0,9

- **Theory:** SNR anaysis, investigation of different correlation protocols (e.g. differential correlation imaging), ...

Correlation Plenoptic Imaging for EO

PCT/2018 (INFN)

CLOSE
DTA Puglia



Advantages of CPI

Refocusing out-of-focus pictures → simplifies optomechanics

Extending the depth of field with high luminosity & SNR

Parallel acquisition of multiple perspectives → 3D imaging

with

Diffraction-limited resolution

Unprecedented DOF with respect to standard imaging

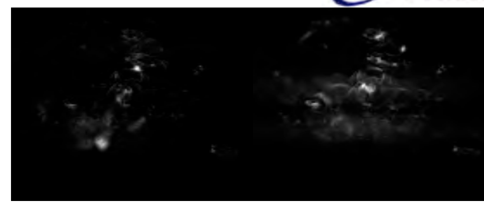
Turbulence attenutation capability … work in progress

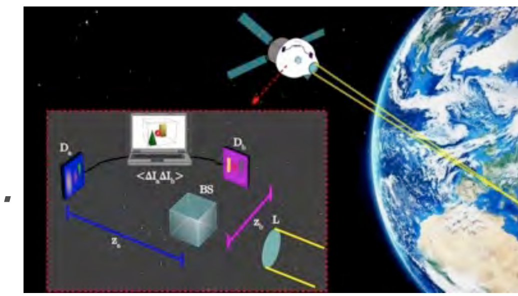
SNR advantage: attenuation of stray light, source fluctuations, detector aging… work in progress

Can be realized with natural sources

Perspectives

→ Correlation Plenoptic 3D Microscopy





→ *Other applications: Earth/Space imaging, medical imaging, industrial inspection, …*

- Noise reduction by optimizing setups, sources (e.g., entangled photons) and measurement protocols (e.g., differential imaging)

QUANTERA

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

Quantum 2021 - Summer School on Quantum Optical Technologies in Apulia

https://agenda.infn.it/e/quantum2020

Trani (Bari), 19-25 Sept. 2021

Partners

The school is oriented to PhD students, master students and young researchers, and aims to provide **a privileged vision of quantum optical technologies** from both a theoretical and an experimental perspective. The lecture topics will include: quantum imaging; quantum information; quantum cryptography; quantum simulation; quantum communication in space; detectors, sources and measurements for quantum technologies.

Lecturers: Gunnar Björk, Edoardo Charbon, Maria Chekhova, Milena D'Angelo, Ivo Pietro Degiovanni, Paolo Facchi, Daniele Faccio, John Howell, Zdenek Hradil, Simone Montangero (to be confirmed), Ivano Ruo-Berchera, Fabio Sciarrino, Bohumil Stoklasa, Paolo Villoresi, Hugo Zbinden

Scientific Committee: Milena D'Angelo, Paolo Facchi, Augusto Garuccio, Saverio Pascazio (UniBA and INFN), Marco Genovese (INRIM), Fabio Sciarrino (Sapienza Roma)

Thank you