ISSW 2022

The International SPAD Sensor Workshop

online conference

JUNE 13 - 15, 2022

CORRELATION PLENOPTIC IMAGING BASED ON SPAD TECHNOLOGY

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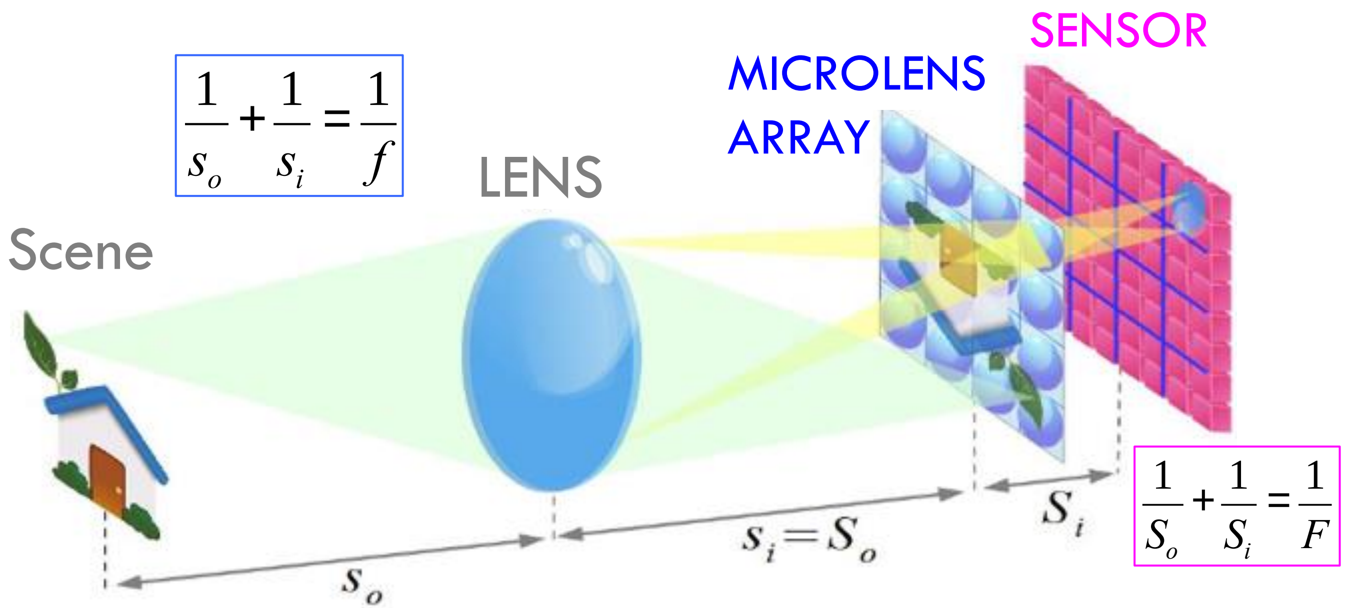
Plenoptic/light-field imaging

Lippman [1908] and Ives [1930] Adelson and Wang [1992] Ng [2005]

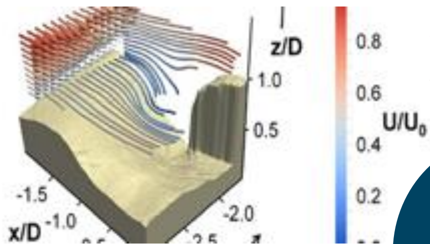


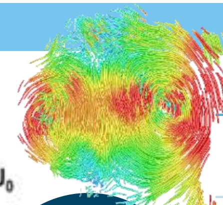
Enables to retrieves BOTH
the **image** AND the **propagation direction** of light

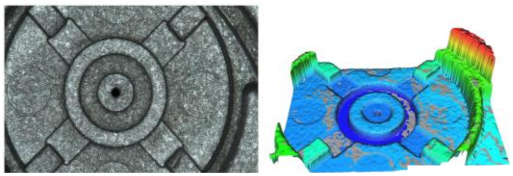
⬇

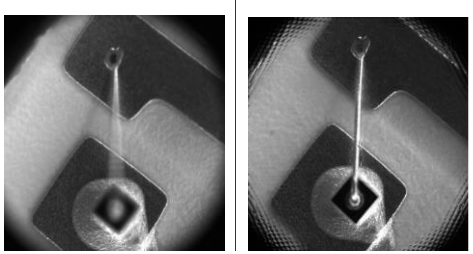
Refocusing & single-shot 3D imaging

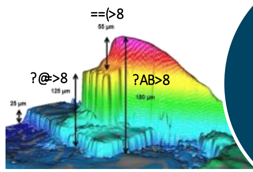
Light-field cameras for fast 3D imaging

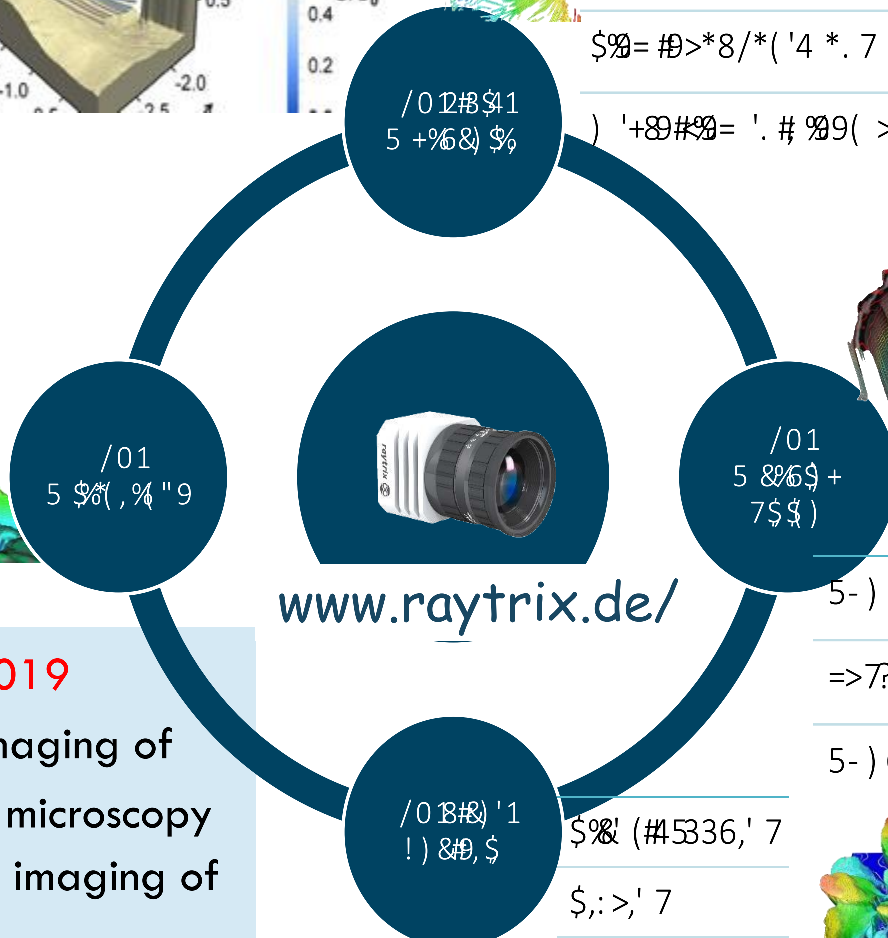


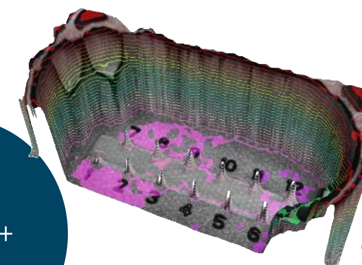


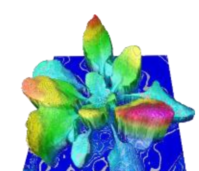








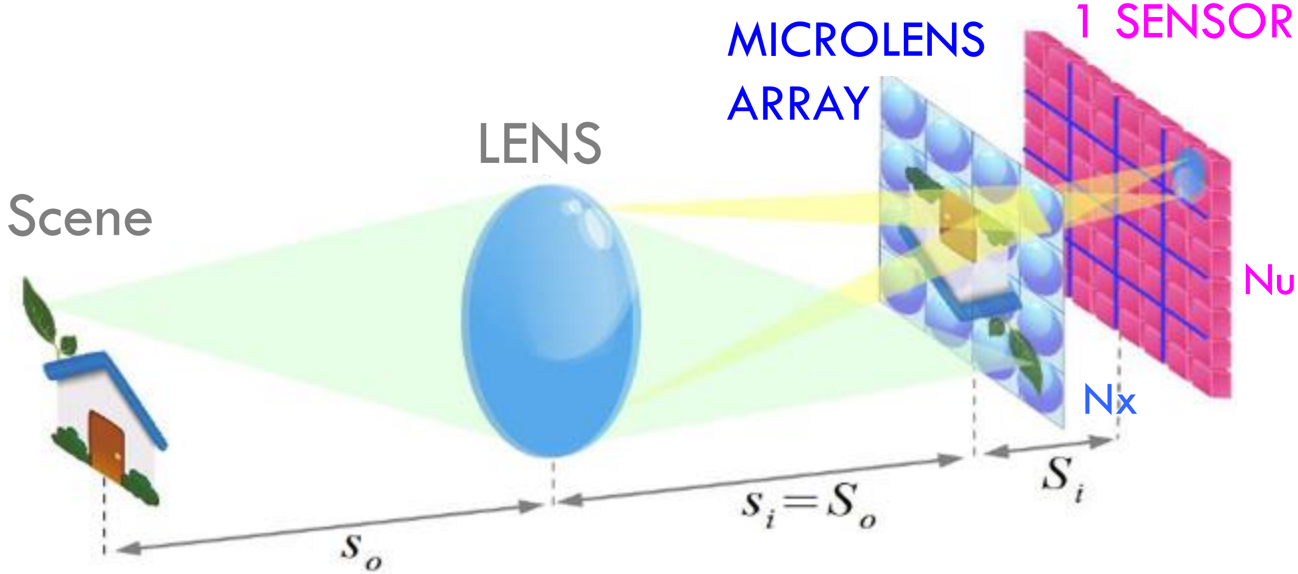




R. Prevedel: Nature Meth. 2014 & 2019

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

Intrinsic limits of conventional light-field cameras



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

↓

A 16 Megapixel camera, behaves as a 4 Megapixel ☹

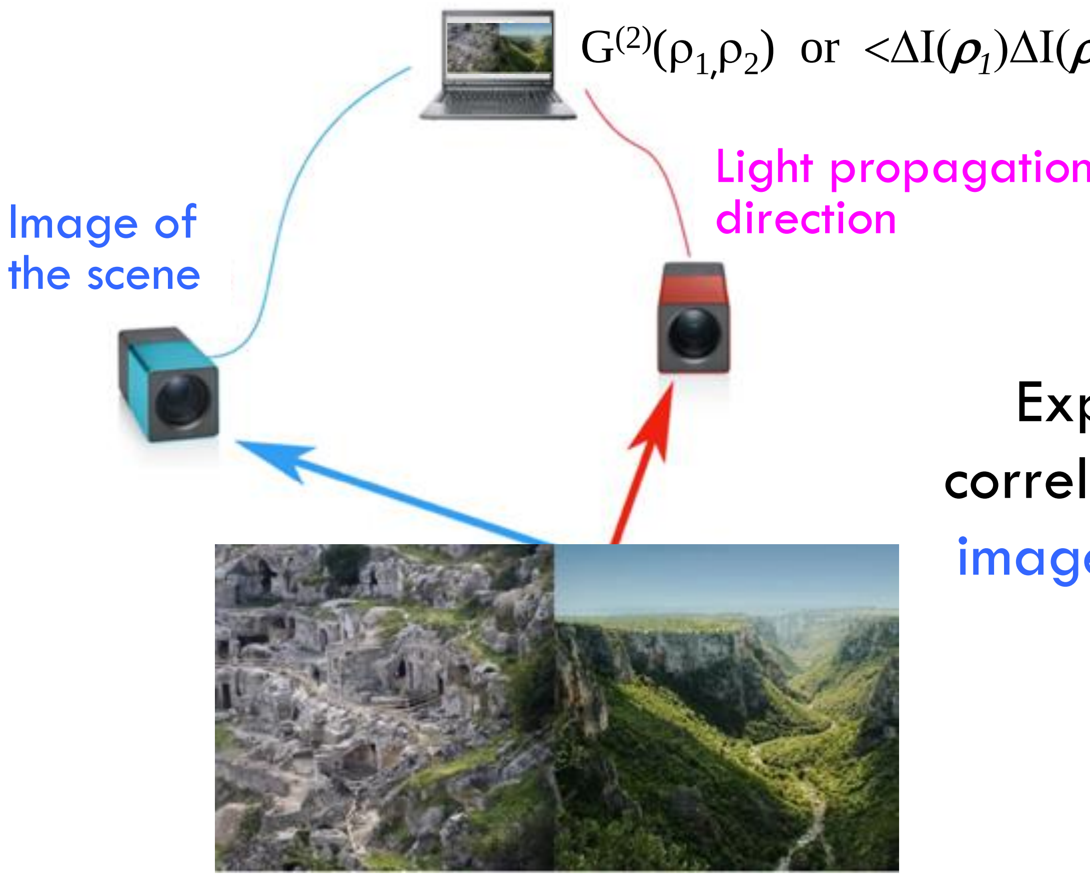
- Strong trade-off between resolution and depth-of-field (Nx Nu = Ntot)
  → No diffraction limited resolution !
- Sacrificed change of perspective limits the 3D imaging capability

… both defined by the microlens array !

Our solution:
Plenoptic imaging with correlated beams

D'Angelo et al., PRL 116, 223602 (2016) + Pepe et al., PRL 119, 243602 (2017) + 5 patents

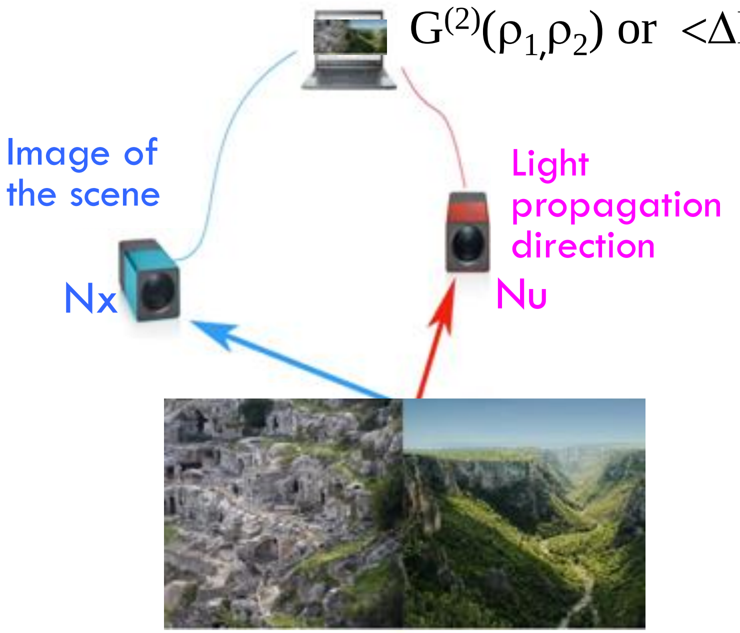
$G^{(2)}(\rho_1,\rho_2)$ or $\langle \Delta I(\rho_1) \Delta I(\rho_2) \rangle$: contains light-field properties !

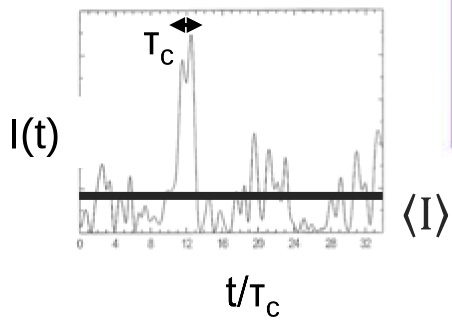


Exploiting spatio-temporal correlations of light to **decouple** image acquisition and direction measurement !!

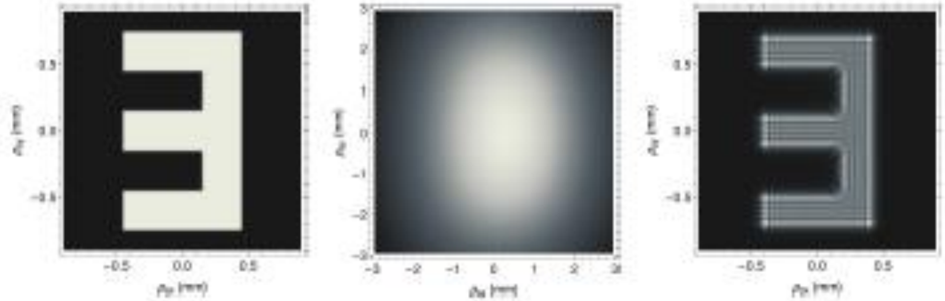
Sources for Correlation Plenoptic Imaging

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





Entangled photons

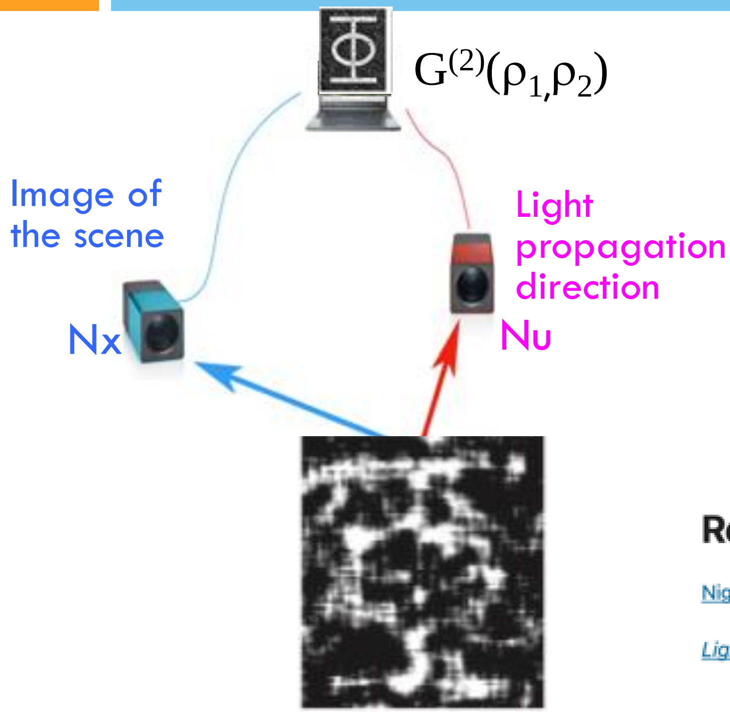


F.V. Pepe et al., Technologies 4, 17 (2016)

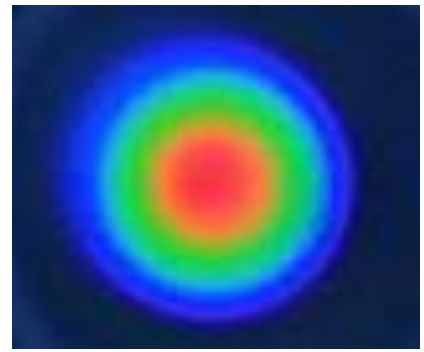
Chaotic light

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

Sources for Correlation Plenoptic Imaging



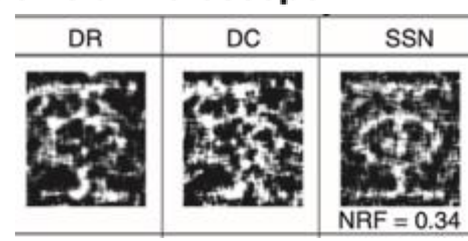
Entangled photons



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

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

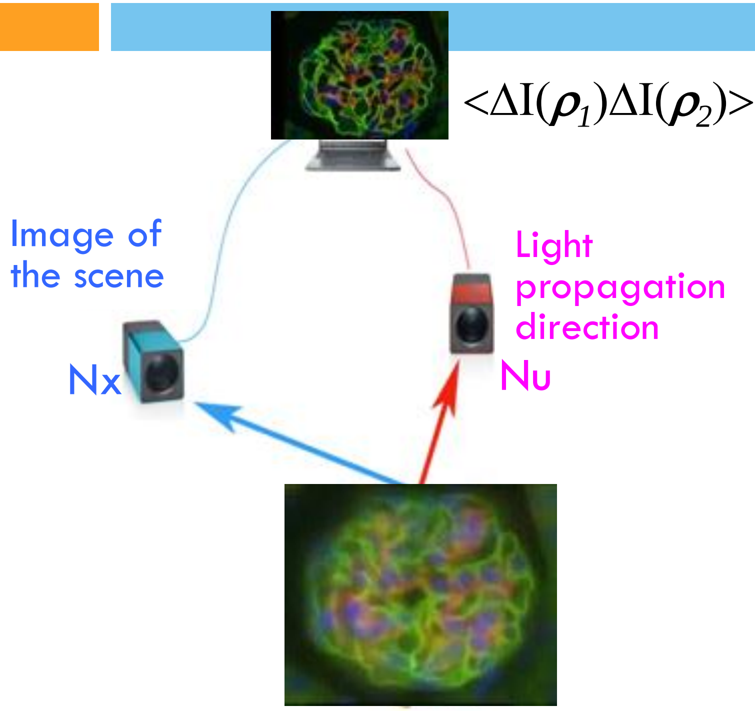
Light: Science & Applications **6**, e17005 (2017) | Cite this article



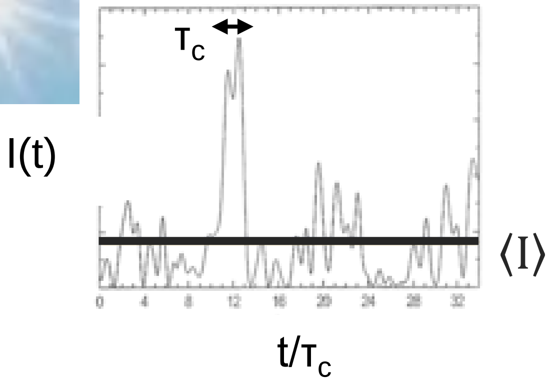
Ultra-low-noise (shot-noise limit or below) → imaging of low-absorping objects

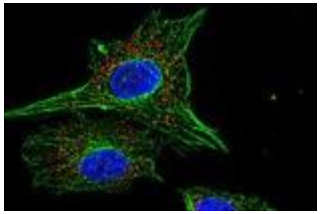
SPAD arrays → speed

Sources for Correlation Plenoptic Imaging



Chaotic light





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

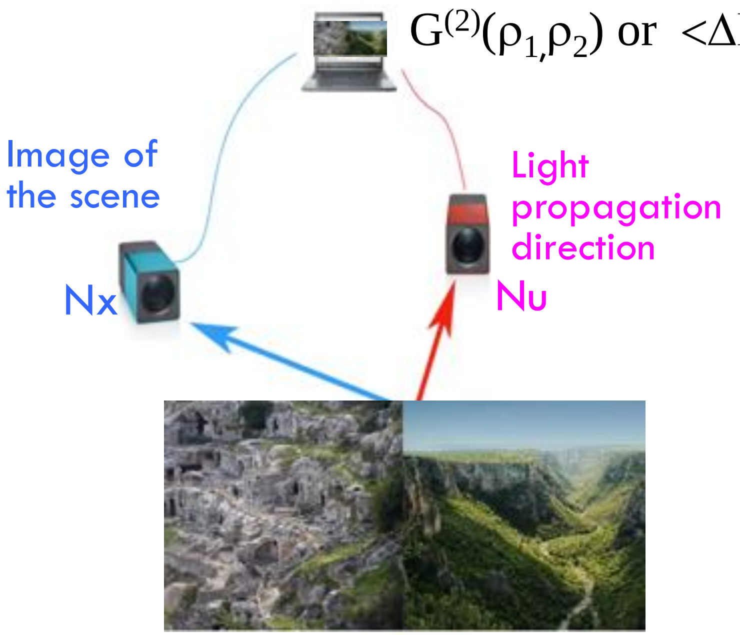
No chaos → no image !!!
Chaos = intensity fluctuations
… Detectors need to follow them!

SPAD arrays → temporal resolution

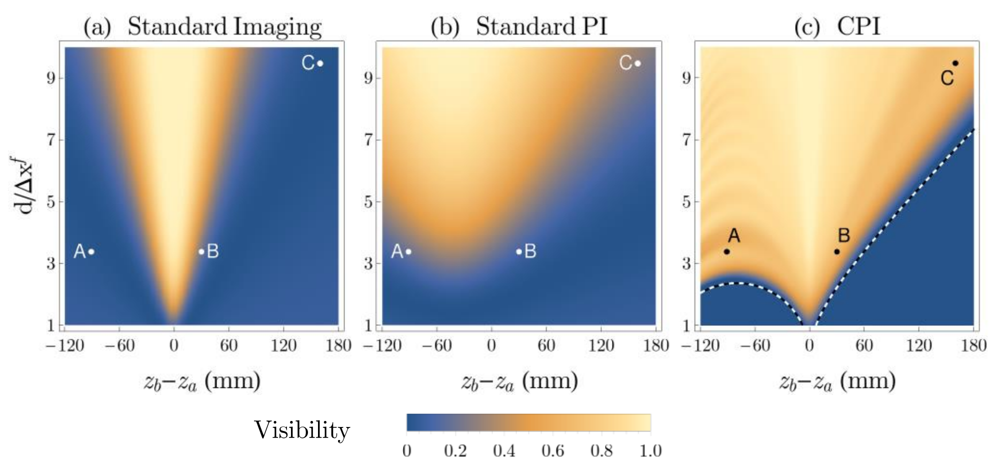
Resolution vs. DOF improvement

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 vs. DOF improvement

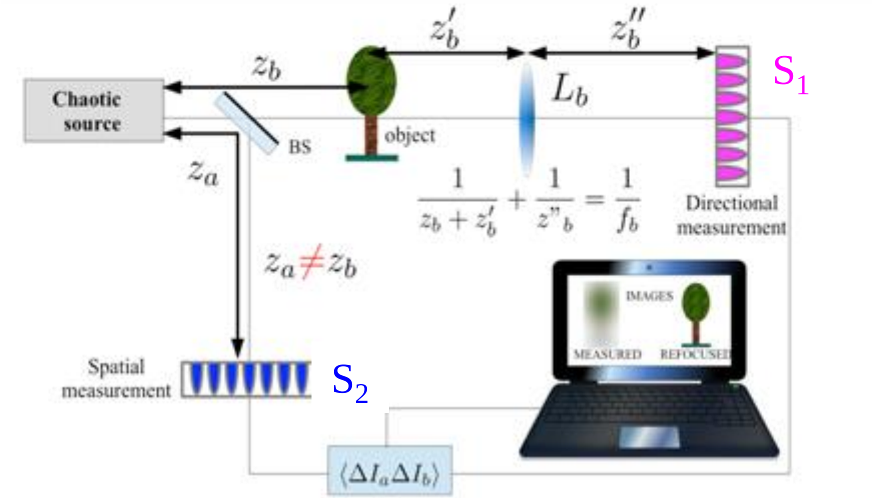


Diffraction-limited resolution
is combined with a much larger DOF
than in standard imaging

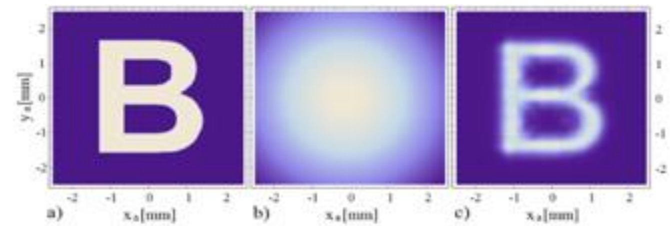
Intellectual Property
Award 2019 (MISE)

Proof-of-principle demonstration

PRL 116, 223602 (2016), PRL 119, 243602 (2017)



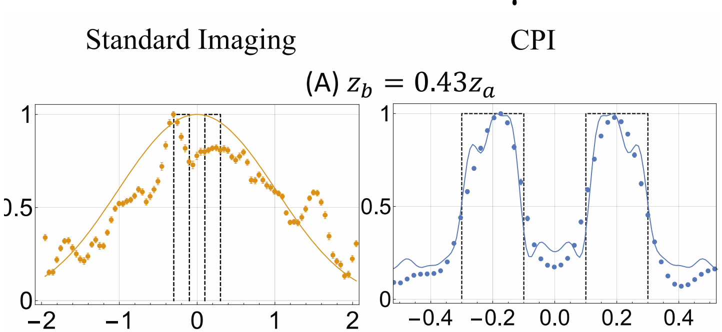
Same resolution, but 40 times larger DOF !!!



$$\frac{\mathrm{DOF}^{(\mathrm{cp})}}{\mathrm{DOF}^{(\mathrm{p})}} = \frac{N_u^{(\mathrm{cp})}}{(N_u^{(\mathrm{p})})^2} = 40 \text{ !!!}$$

Diffraction-limited CPI

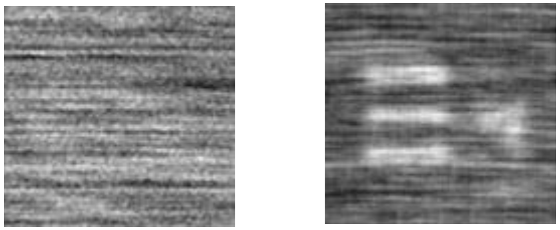
Double-slit: d = 400 μm



$z_b = 0{,}4\ z_a$

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

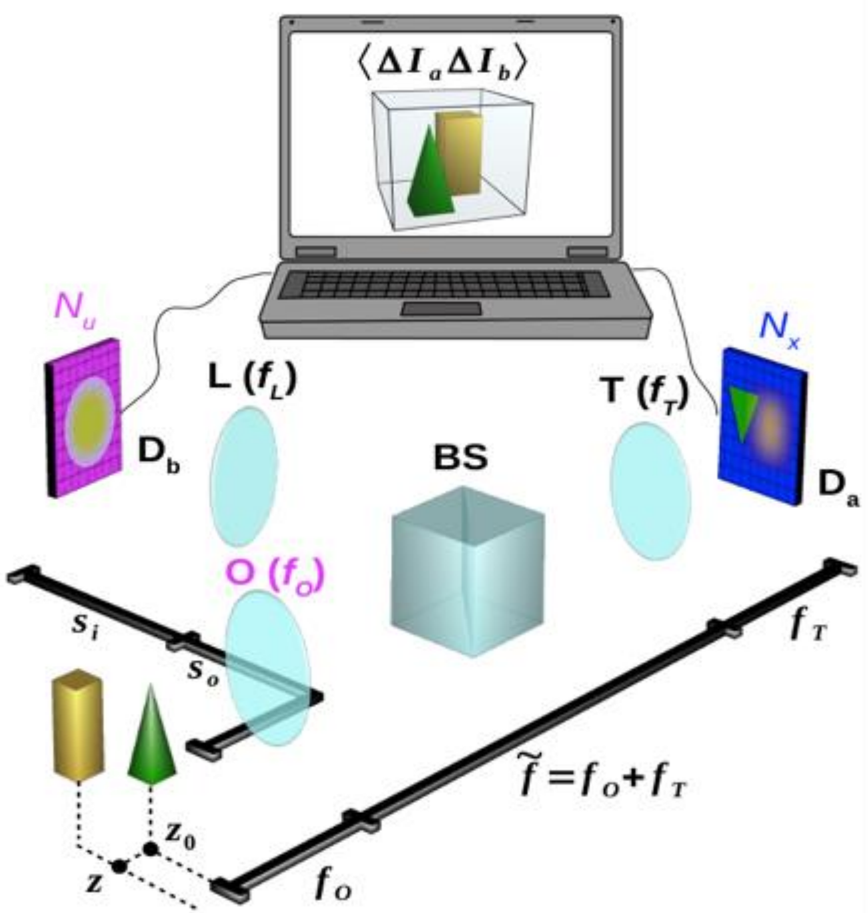
Ghost image CPI



$z_b = 1{,}5\ z_a$

Plenoptic Microscopy with correlated beams

PCT/2018 (INFN) + PLA 2020 + arXiv:2110.00807

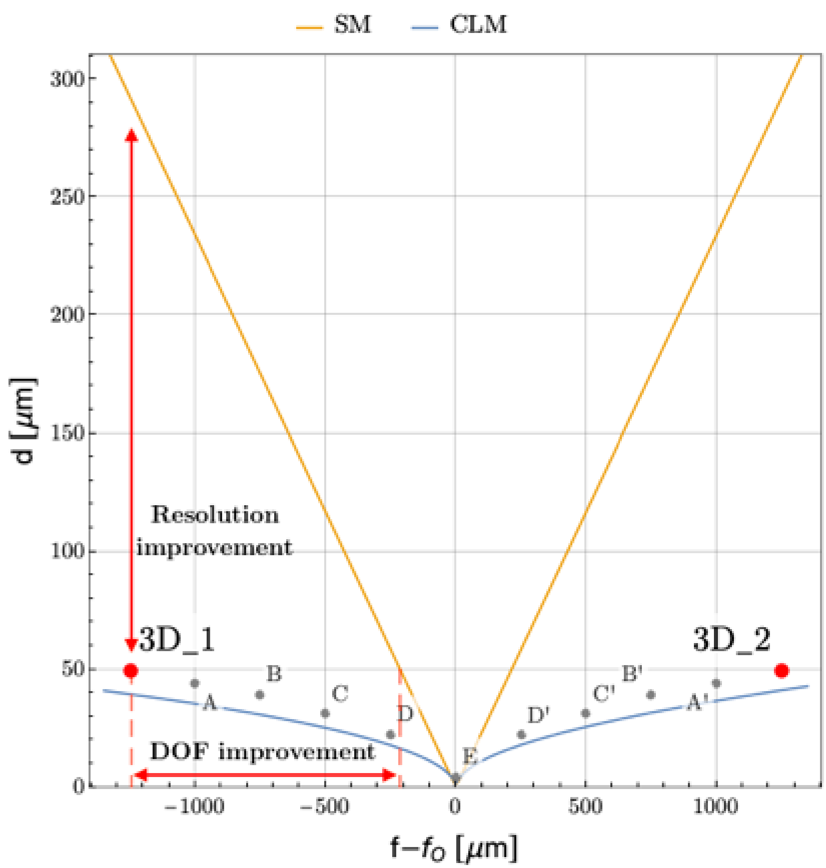


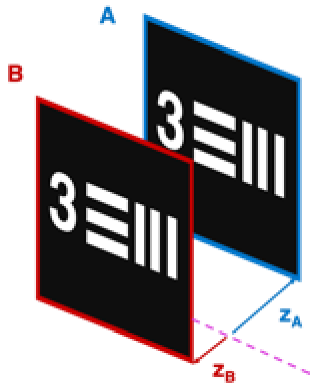
Measure correlations between

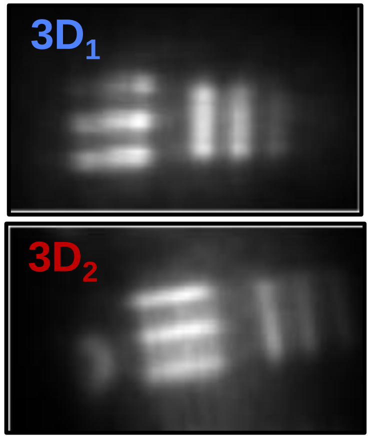
- the *image of the sample* (formed by an ordinary microscope: lenses O & T)
- the *image of the objective lens* (formed by lens L)

Plenoptic Microscopy with correlated beams

3D Sample | Acquired | REFOCUSED







6 times higher resolution,at fixed DOF

6 times larger DOF, at fixed resolution

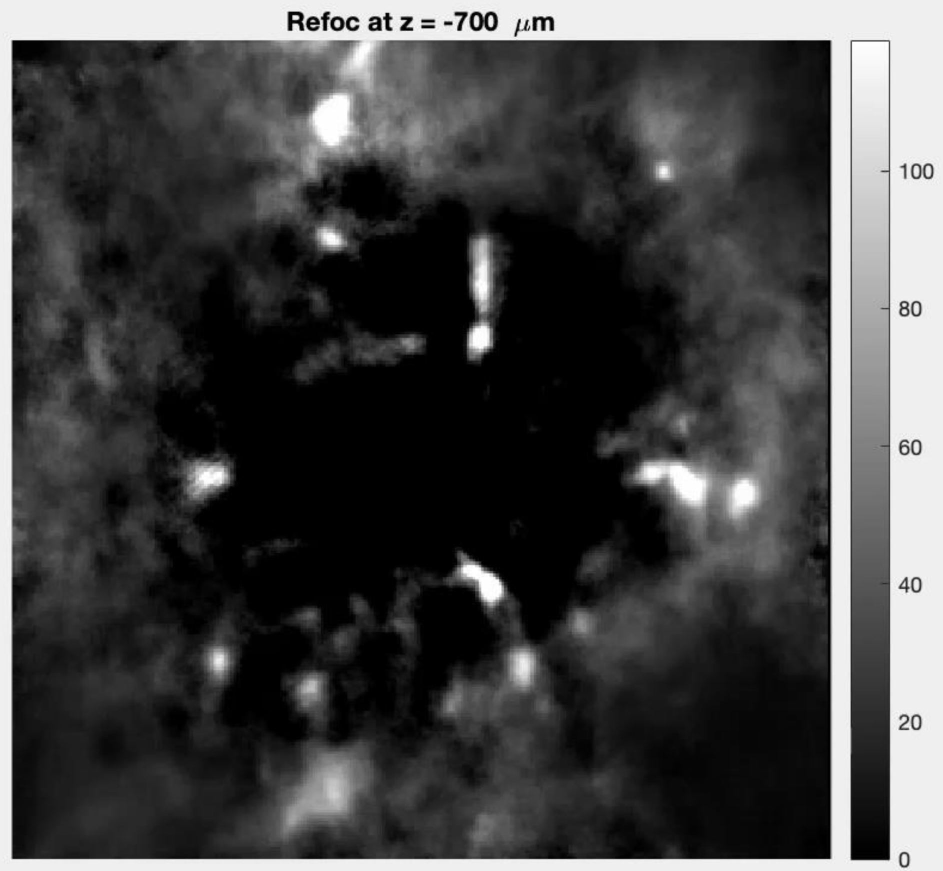
G. Massaro, et al., *Light-field microscopy with correlated beams for extended volumetric imaging at the diffraction limit* arXiv:2110.00807

Plenoptic Microscopy with correlated beams

3D sample:
STARCH IN GEL

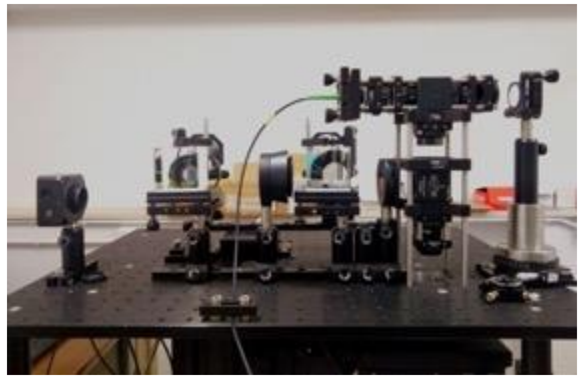
Grain size: 20 um

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



CPM protoype

TOPMICRO
MISE - Proof of concept



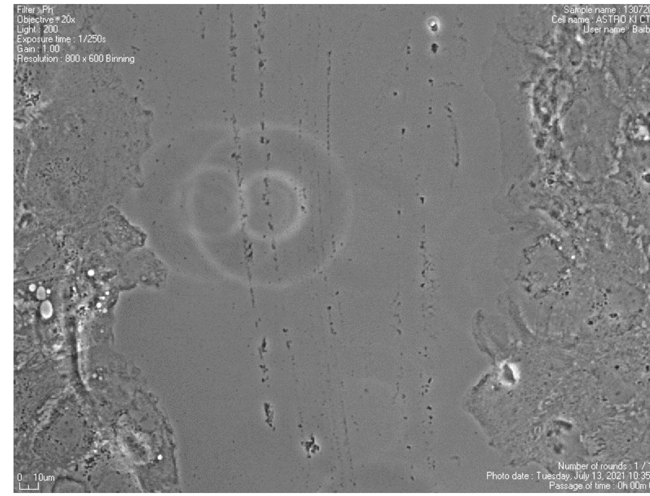
Potential applicaitons:

- Study of cell aggregation → glioma

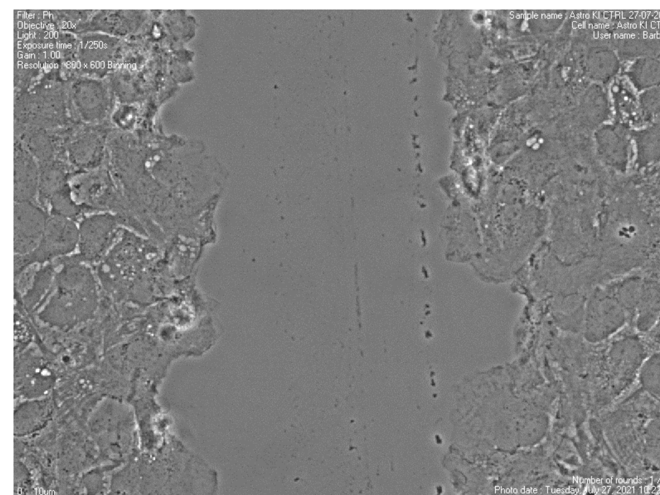
~ 30-100 um diameter
~ 3-5 um height

Brain cells (astrocytes) during 24-hours migration

In focus



Out of focus ~3hrs later



CPM protoype

TOPMICRO
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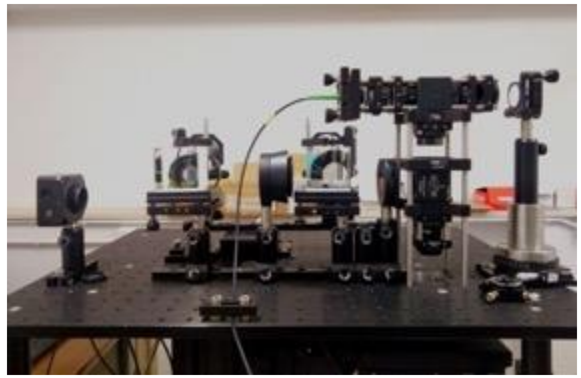
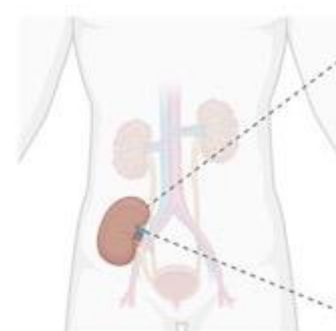
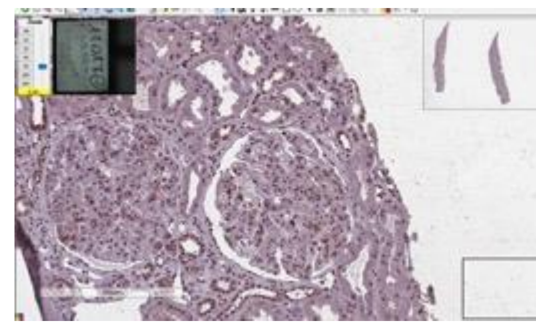
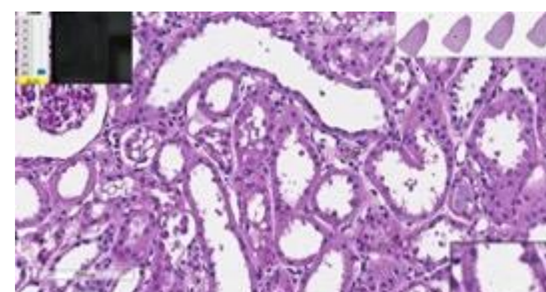




Potential applicaitons:

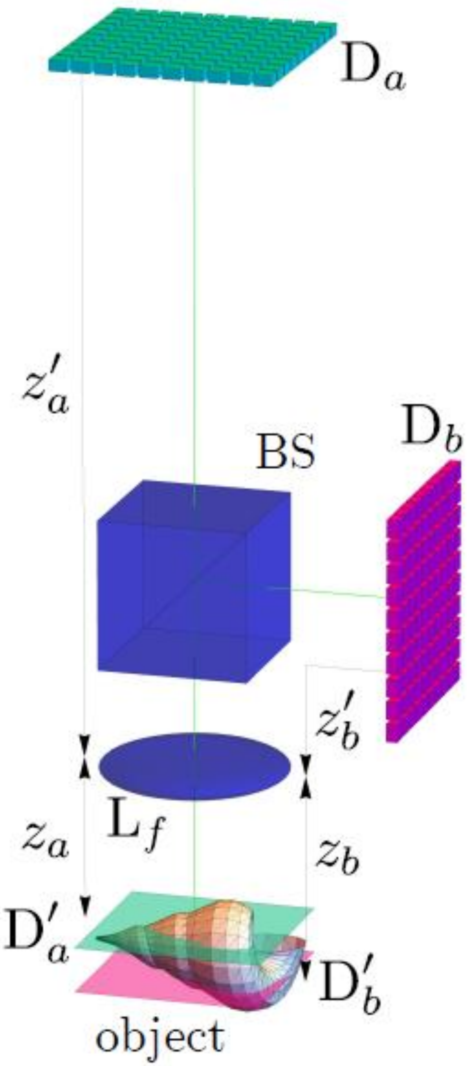
- 3D analysis of diagnostic biopsies during organ transplants / perfusion..
- Ophalmoscopy
- Particle tracks in nuclear emulsions
- Recycled fabrics…





CPI between arbitrary planes

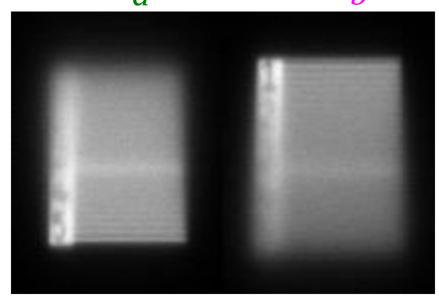
F. Di Lena, PhD thesis (2019) + PCT 2019 + F. Di Lena, et al, Opt. Exp. 2020



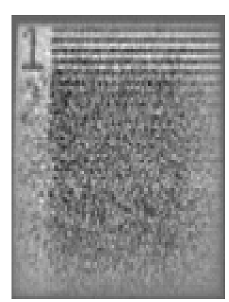
2 different arbitrary planes within the 3D object are focused by 1 lens on the two disjoint sensors

Acquired images

D_a D_b



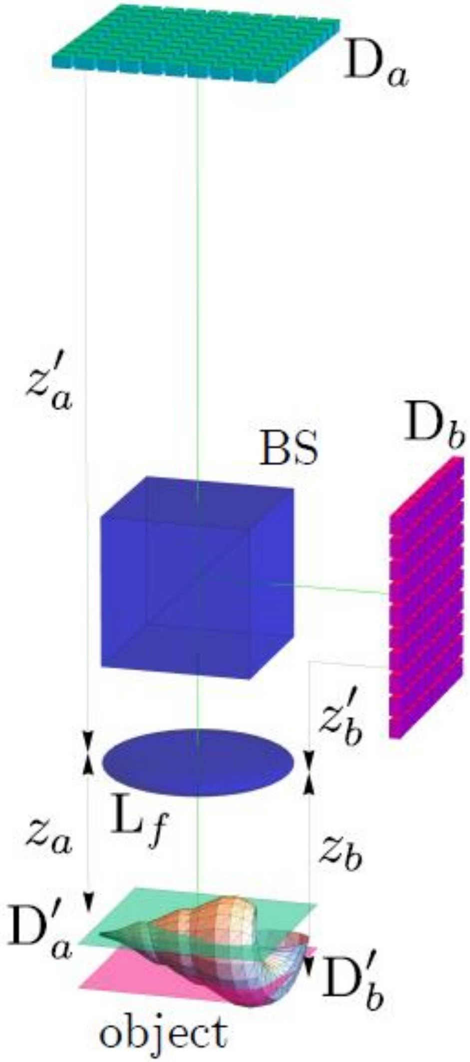
Refocusing

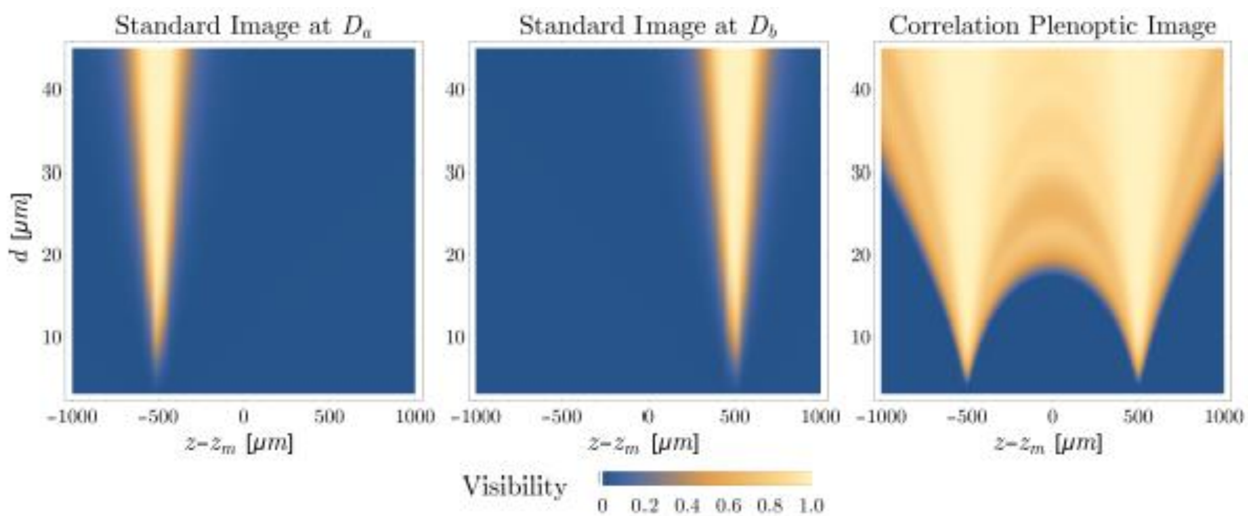


Stacked refocused image

CPI between arbitrary planes

F. Di Lena, PhD thesis (2019) + PCT 2019 + Opt. Exp. 2020



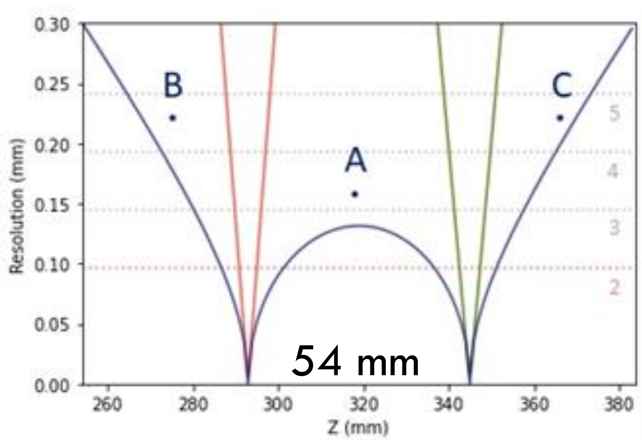


Single-lens CPI with highly improved DOF, & diffraction-limited resolution

CPI-AP with SwissSPAD2

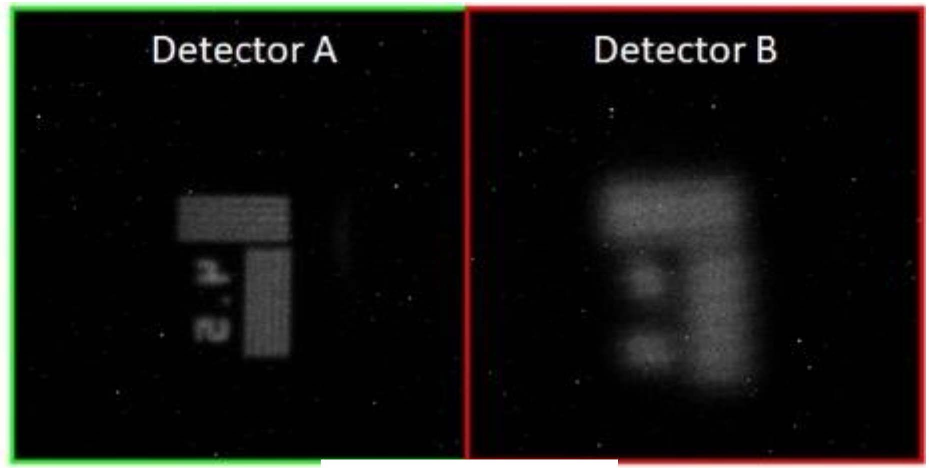
87 kfps , $N_{frames} = 8 \times 10^3$

→ CPI acquisition: 10 fps

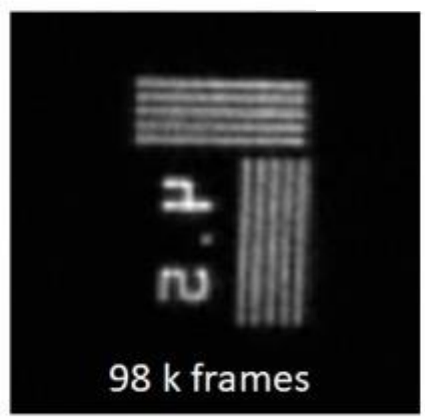


DOF enhancement: 12 x

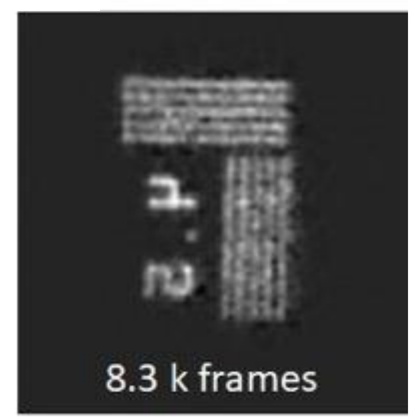
Acquired



Refocused



Max SNR



60% SNR

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

Swiss National Science Foundation

Quantum technology: more security and improved imaging

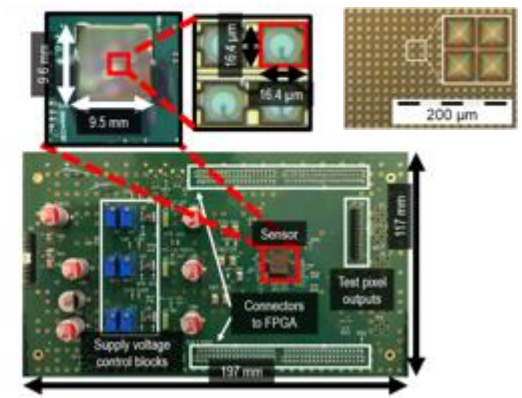
21/Nov/2019

QUANTERA

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

INFN – Istituto Nazionale di Fisica Nucleare	Milena D'Angelo
planetek hellas	Maria Ieronymaki
EPFL	Claudio Bruschini
Palacký University Olomouc	Bohumil Stoklasa

Hardware speed-up



SwissSPAD2. Ultra-fast SPAD array

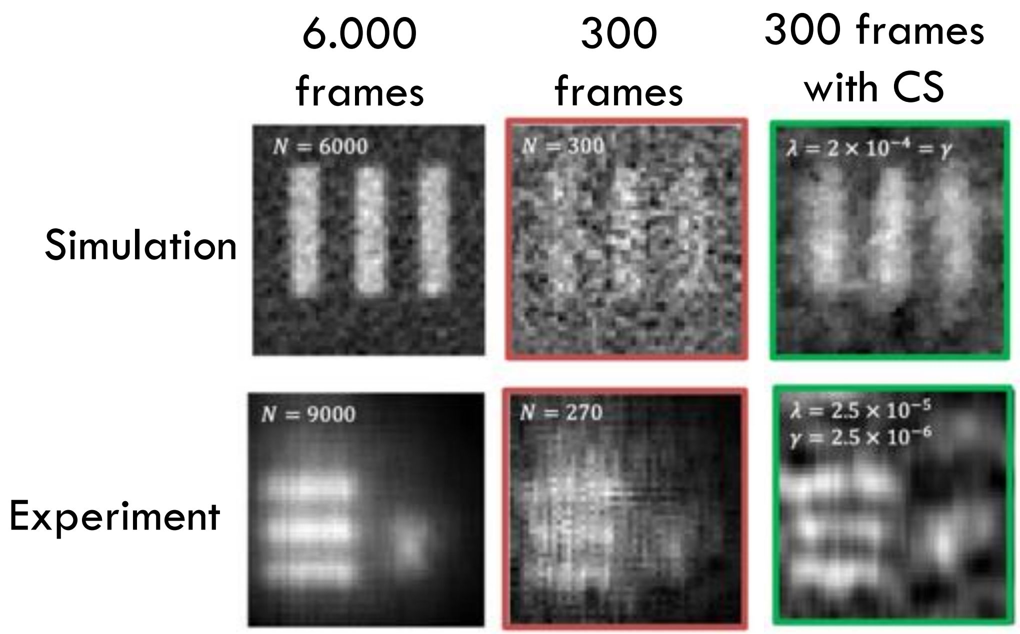
- Array of 512 x 512 SPAD
- Records binary frames at 100 KHz
- Minimum gate length of 10.8 ns
- Fill factor ~ 60% (with microlenses)
- On-board FPGA for control, redout and logic operations

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

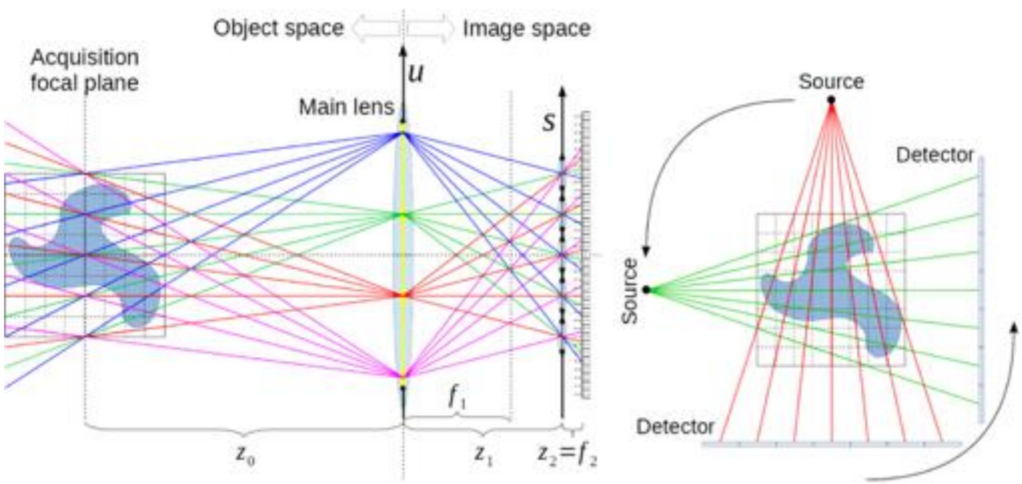


Quantum Fisher Information

- Super-resolution and/or frame number optimization

Processing optimization

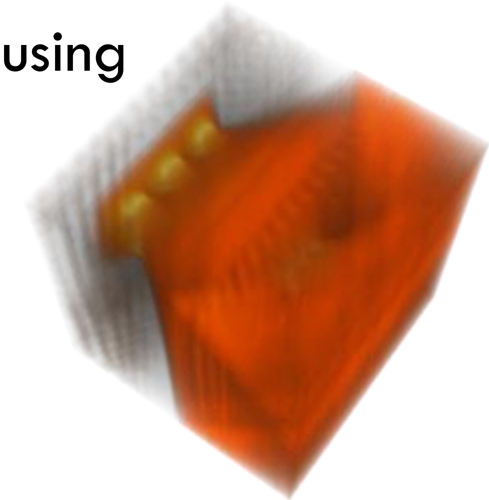
Quantum tomography



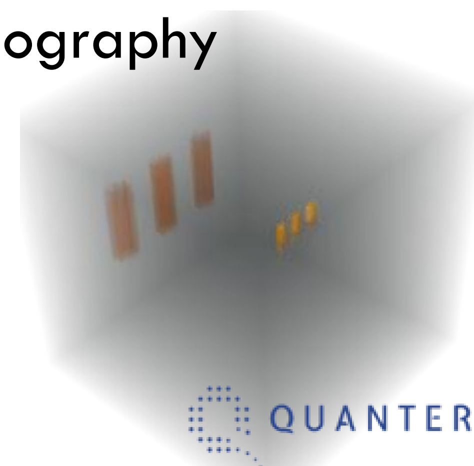
(a) Compound plenoptic camera.

(b) Cone-beam tomography.

CPI refocusing



QPI Tomography



Advantages of CPI

Scanning-free refocusing of 3D samples

Parallel acquisition of multiple perspectives → 3D imaging

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

Perspectives

- Correlation Light-filed 3D Microscope

  DMD, filtered LED/lamps … fluorescence

INTEFF-ToPMicro

PICS4ME

- 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

QuOT Lab @ UniBA

Milena D'Angelo

- Researchers:
  - Francesco Scattarella
  - Francesco V. Pepe
- Post-docs:
  - Francesco Di Lena
  - Sergii Vasiukov
- Students:
  - Davide Giannella,
  - Gianlorenzo Massaro,
  - Germano Borreggine

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

QUANTERA

Partners:

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

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

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

TOPMICRO – TOward the Prototype of a correlation plenoptic MICROscope

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)

Close – Close to the Earth

Where is Bari ?

Quantum 2022 - Summer School on Quantum Optical Technologies in Apulia

https://agenda.infn.it/e/quantum2022

Trani (Bari), 18-24 Sept. 2022

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.

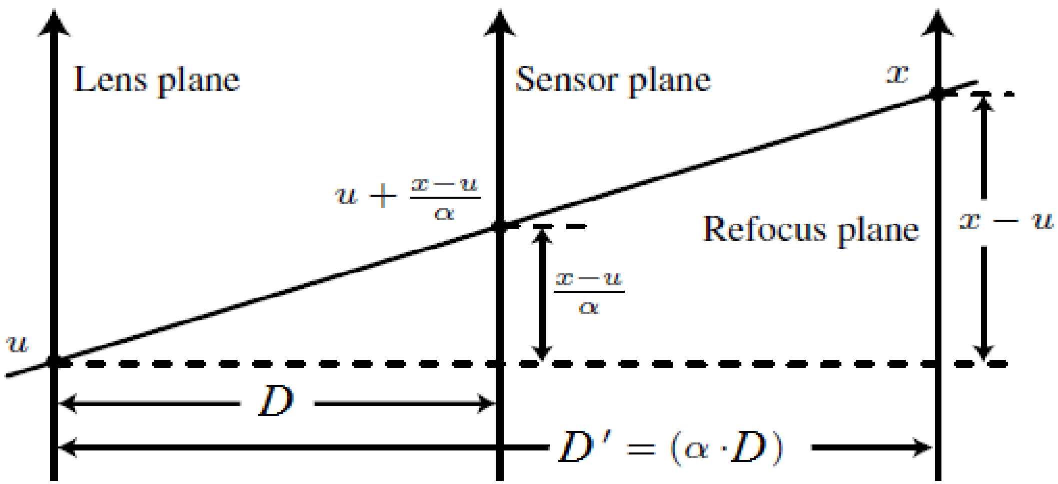
Lecturers: Gunnar Björk, Edoardo Charbon, Maria Chekhova, Milena D'Angelo, Ivo Pietro Degiovanni, Paolo Facchi, Daniele Faccio, John Howell, Zdenek Hradil, Simone Montangero (to be confirmed), Ivano Ruo-Berchera, Fabio Sciarrino, Bohumil Stoklasa, Paolo Villoresi, Hugo Zbinden

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

PhD & post-doc positions available !!! For details, contact: milena.dangelo@uniba.it

Ray tracing → Refocusing

Ng et al., Tech. Rep. 2005



Shot

Refocused (post-proc.)

Rescaling the acquired radiance = Refocusing

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

Refocused image:

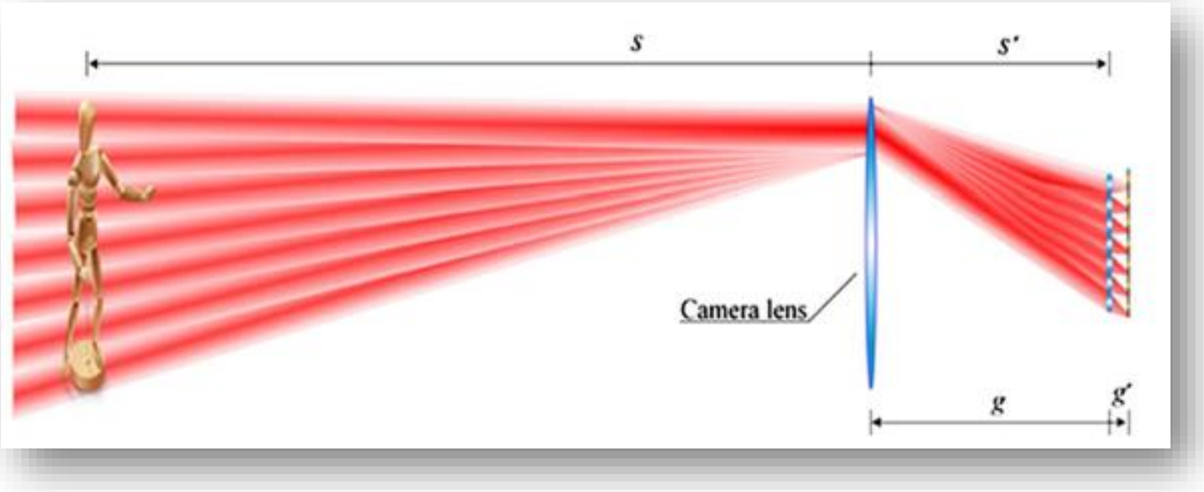
$$\underline{I_{\alpha D}}(\boldsymbol{x}) \propto \int \underline{L_{\alpha D}}(\boldsymbol{x},\boldsymbol{u})\, d^2 u$$

From refocusing to extended DOF

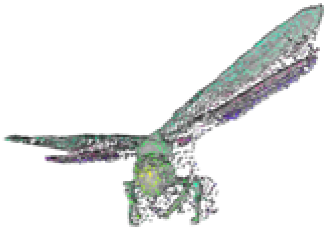
Ng et al., Tech. Rep. 2005 https://illum.lytro.com/illum

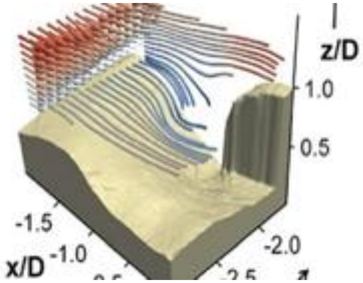
Same DOF of a smaller NA, but higher luminosity and SNR

Multi-perspective view



Parallel acquisition of multi-perspective images → Scanning-free 3D imaging





www.raytrix.de/

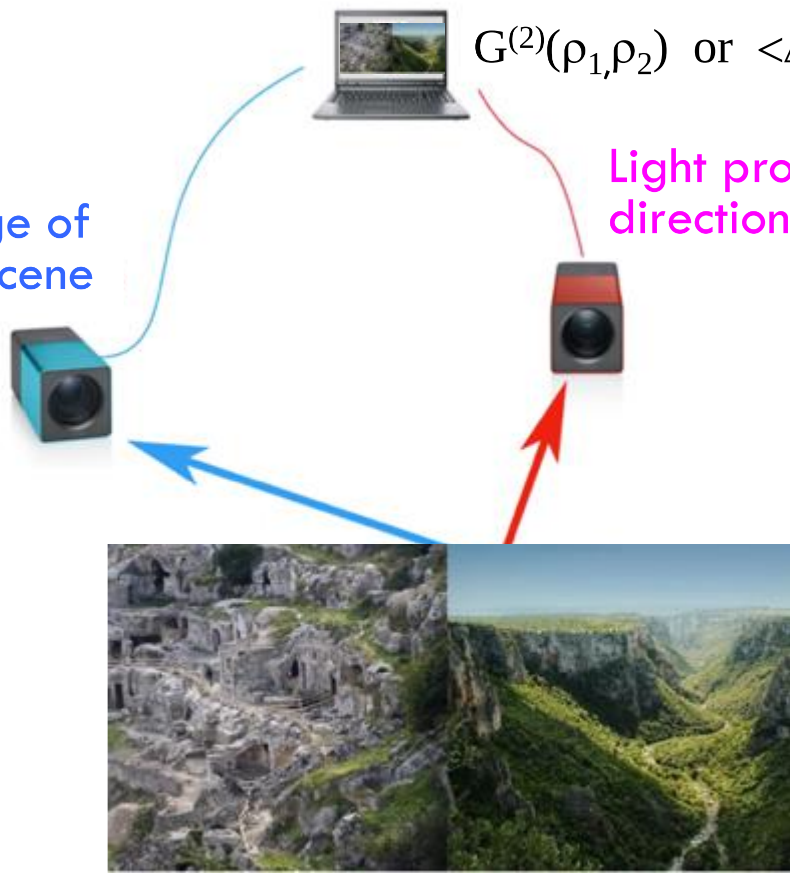
Our solution:
Plenoptic imaging with correlated beams

D'Angelo et al., PRL 116, 223602 (2016) + Pepe et al., PRL 119, 243602 (2017) + 5 patents

$G^{(2)}(\rho_{1},\rho_{2})$ or $\langle \Delta I(\boldsymbol{\rho}_1)\Delta I(\boldsymbol{\rho}_2)\rangle$: contains plenoptic properties !

Light propagation direction

Image of the scene

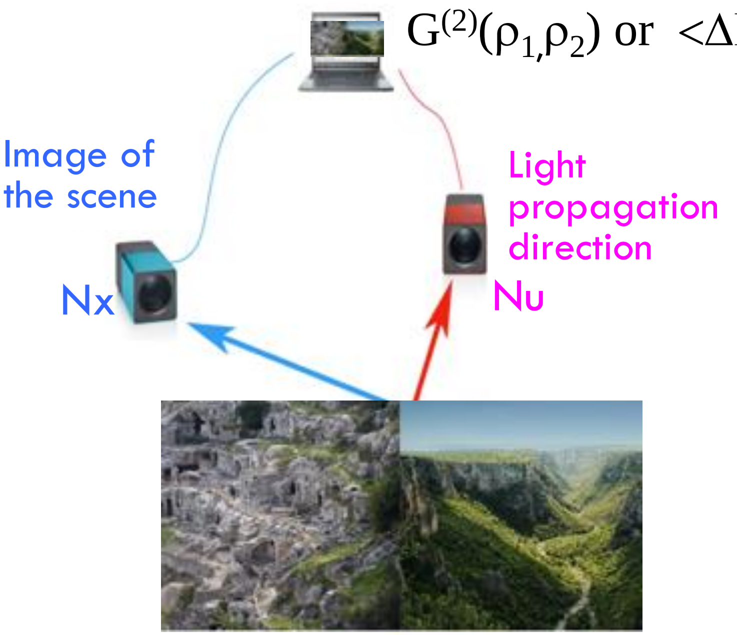


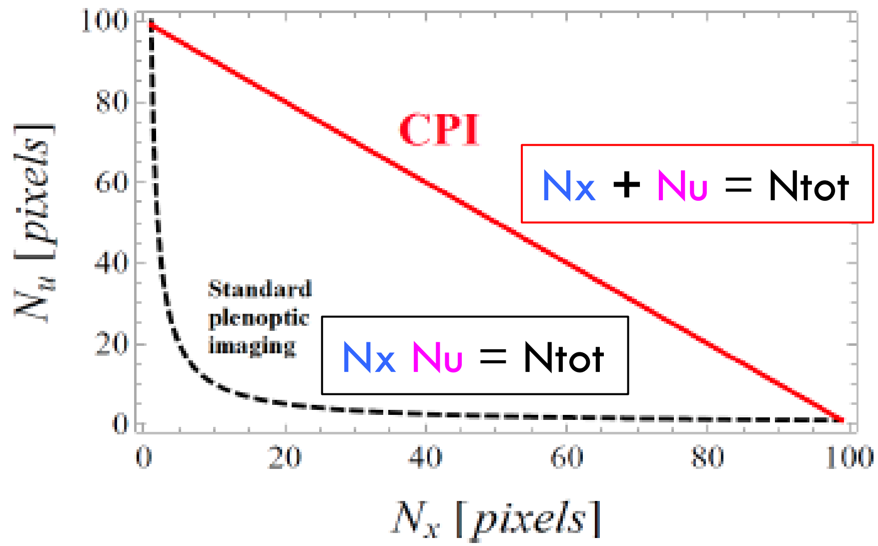
- Take **two correlated light beams**: at least one of them interacts with the object
- **Follow in time the number of photons/intensitites** with *two high resolution* detectors
- Time-average to evaluate the point-to-point **coincidences / correlations of intensity fluctuations**

Resolution vs. DOF improvement

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

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





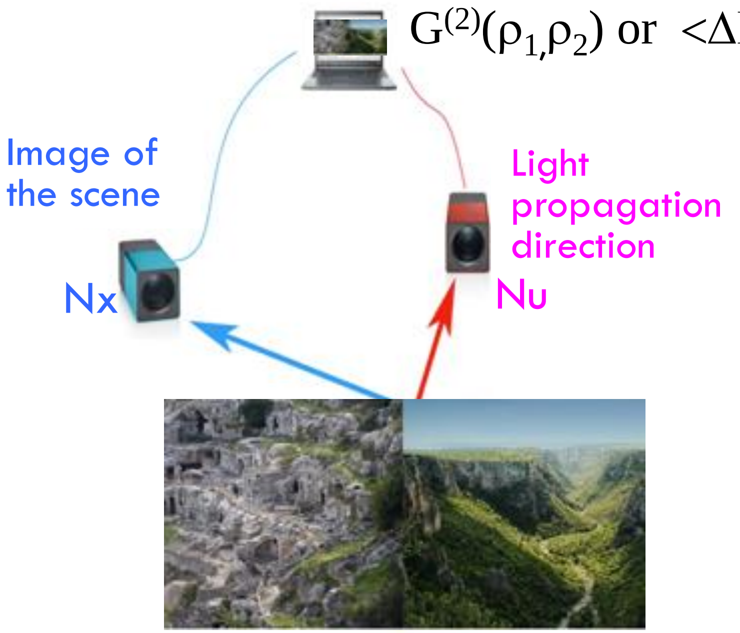
Intellectual Property Award 2019 (MISE)

Resolution and maximum achievable DOF
scale linearly
rather than hyperbolically

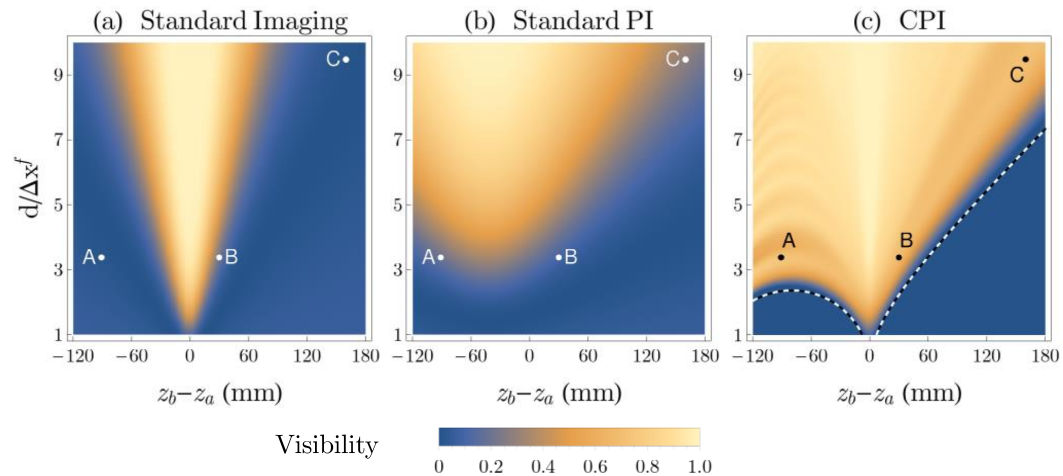
Advantages of Correlation Plenoptic Imaging

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

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



Resolution vs. DOF improvement



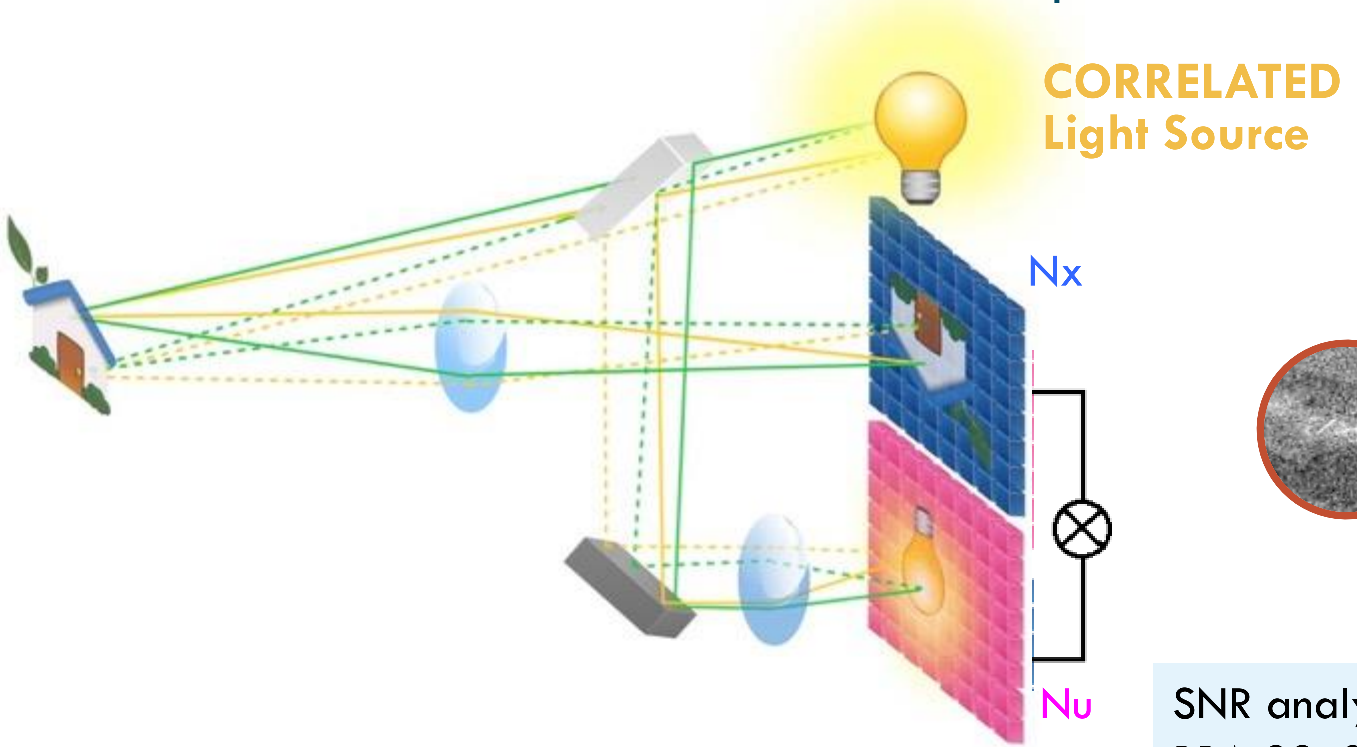
Diffraction-limited resolution
is combined with a much larger DOF
than in standard imaging

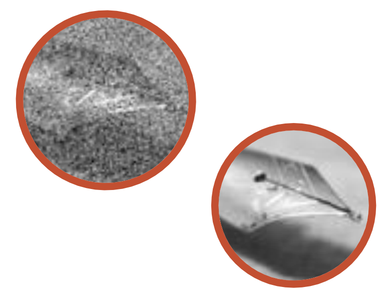
Advances in CPI

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 by conventional imaging
- Higher SNR: no trade-off SNR vs. resolution & object trasmission area !



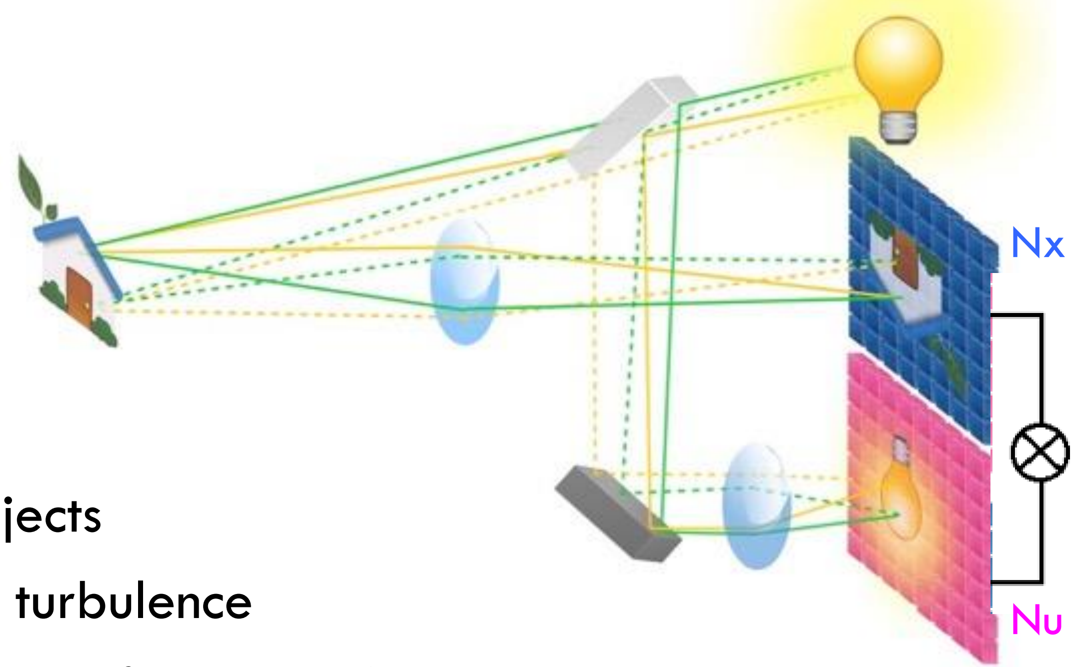


SNR analysis: Scala *et al*, PRA 99, 053808 (2019)

Need for more flexible CPI schemes

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

Still, 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, scattering objects
- Objects surrounded by turbulence
- Self-emitting samples (e.g., fluorescent)

Relevant categories for microscopy, space objects, …

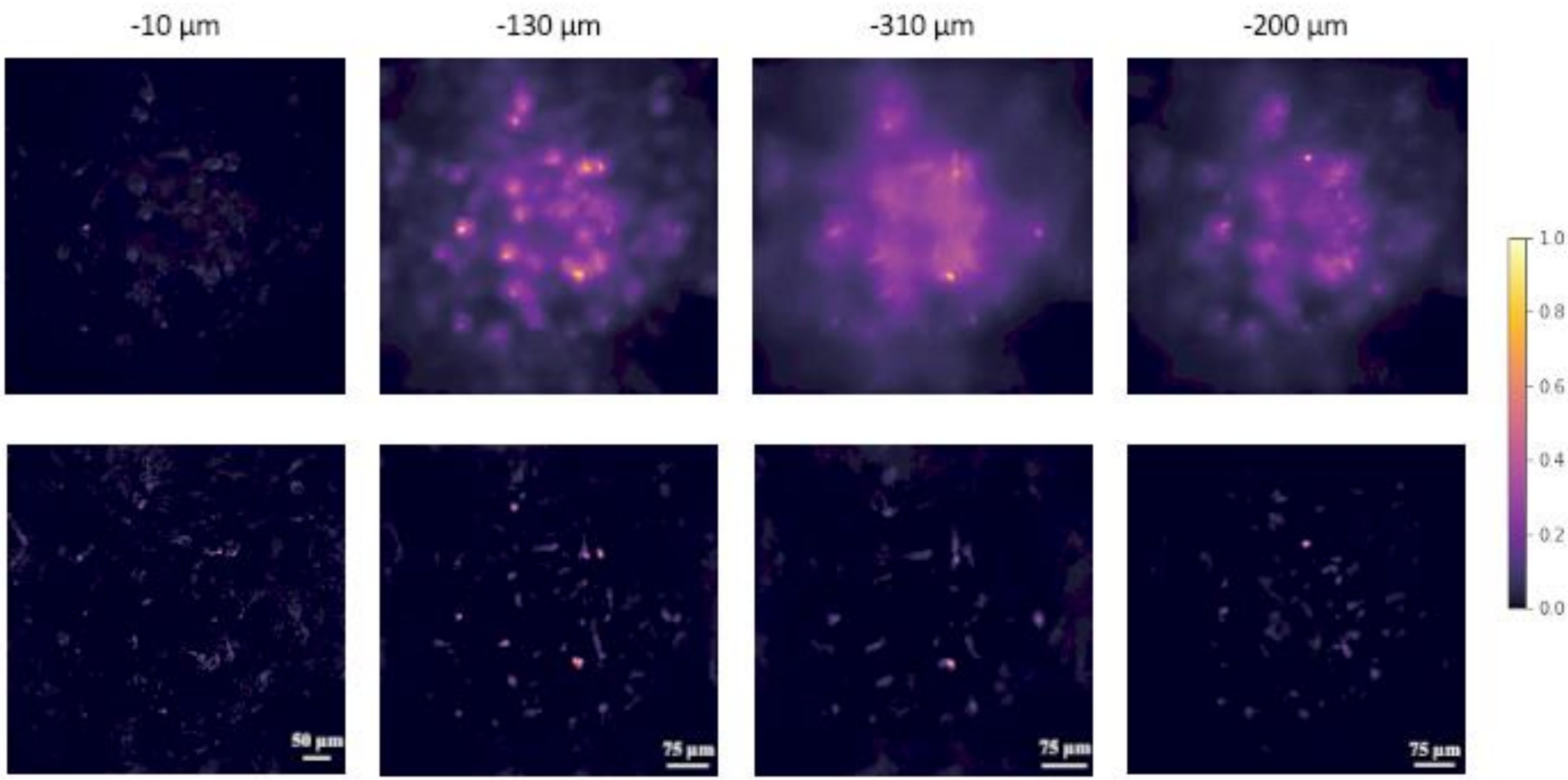
Differential CPM

Inspired by Ferri et al., PRL 104, 253603 (2010) Paper under preparation

$$\widetilde{\Gamma}(\rho_a, \rho_b) = \langle \Delta I_a(\rho_a) \left(\Delta I_b(\rho_b) - K(\rho_a, \rho_b) \Delta I_a^{\mathrm{TOT}} \right) \rangle,$$

Standard refocusing

Differential approach



Minimization of the statistical noise & background suppression

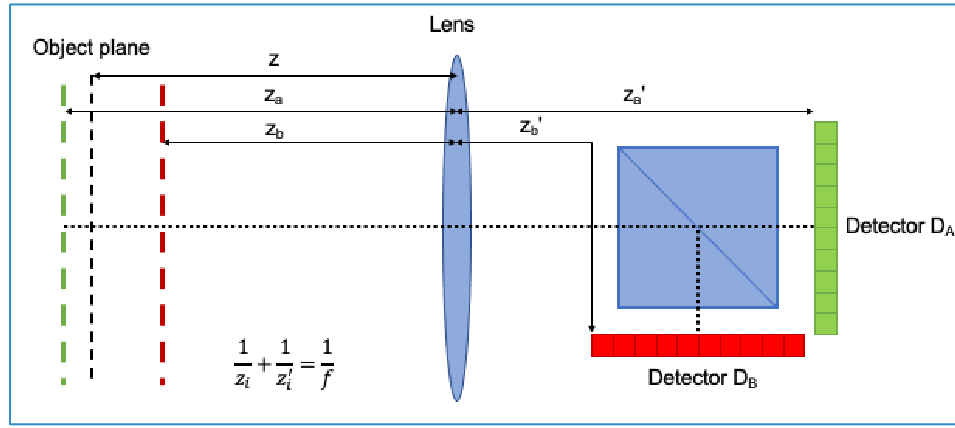
The physics behind CPI

- Conventional imaging

$$I(\boldsymbol{\rho}_{A,B}) = \int |A(\boldsymbol{\rho})|^2 \left|\Phi_{A,B}(\boldsymbol{\rho},\boldsymbol{\rho}_{A,B})\right|^2 d^2\rho$$

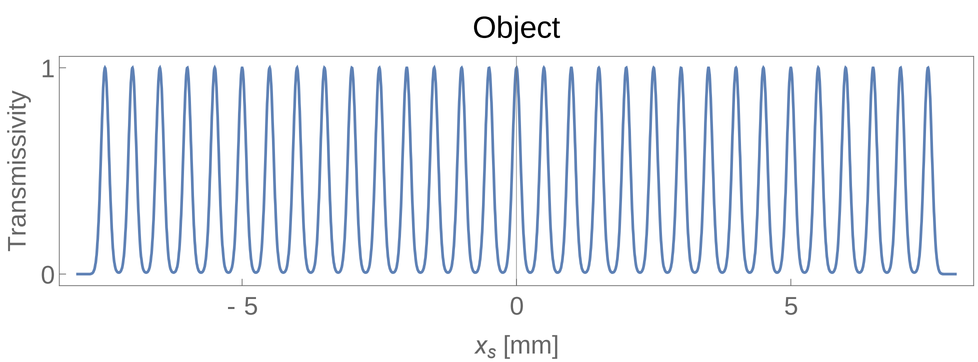
- In geometrical optics

$$I(\boldsymbol{\rho}_{A,B}) = \int \left|A(\alpha\, \boldsymbol{\rho}_{A,B} + \beta\boldsymbol{\rho})\right|^2 d^2\rho$$

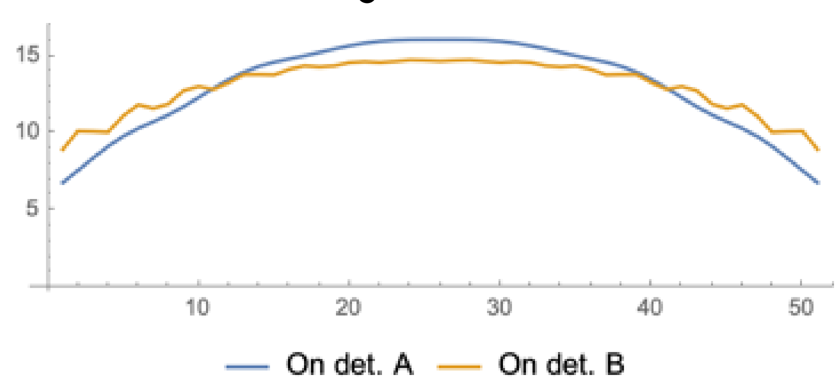


→ Object is resolved only if $\beta = 0$ (at focus) !

→ Ghost imaging would give similar results



Blurred image on the two detectors



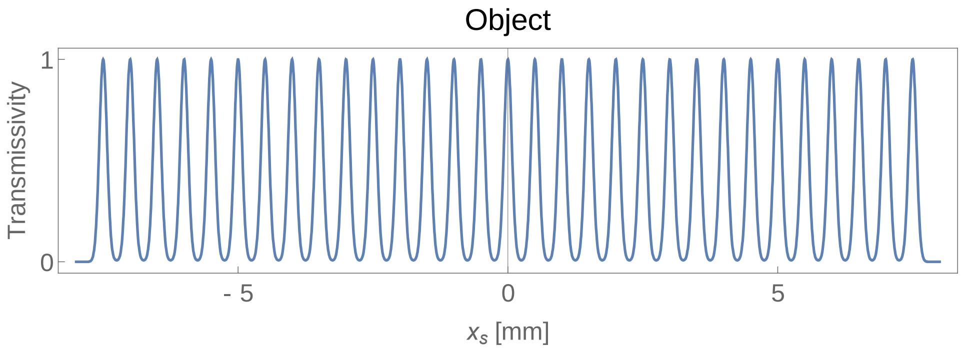
The physics behind CPI

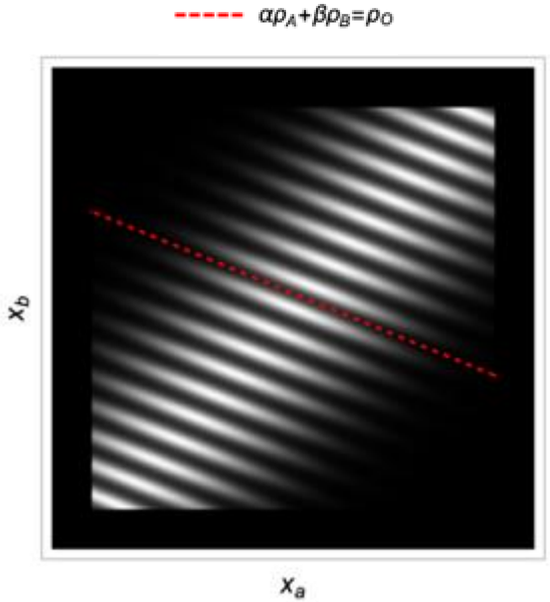
- Information about the 2D sample A is encoded in

$$G^{(2)}(\boldsymbol{\rho_A},\boldsymbol{\rho_B}) = \left|\int\int A(\boldsymbol{\rho_o})A^*(\boldsymbol{\rho'_o})\Phi(\boldsymbol{\rho_o},\boldsymbol{\rho'_o},\boldsymbol{\rho_A},\boldsymbol{\rho_B})\, d^2\rho_O\, d^2\rho'_O\right|^2$$

- In geometrical optics

$$G^{(2)}(\boldsymbol{\rho_A},\boldsymbol{\rho_B}) \simeq |A(\alpha\boldsymbol{\rho_A}+\beta\boldsymbol{\rho_B})|^2$$



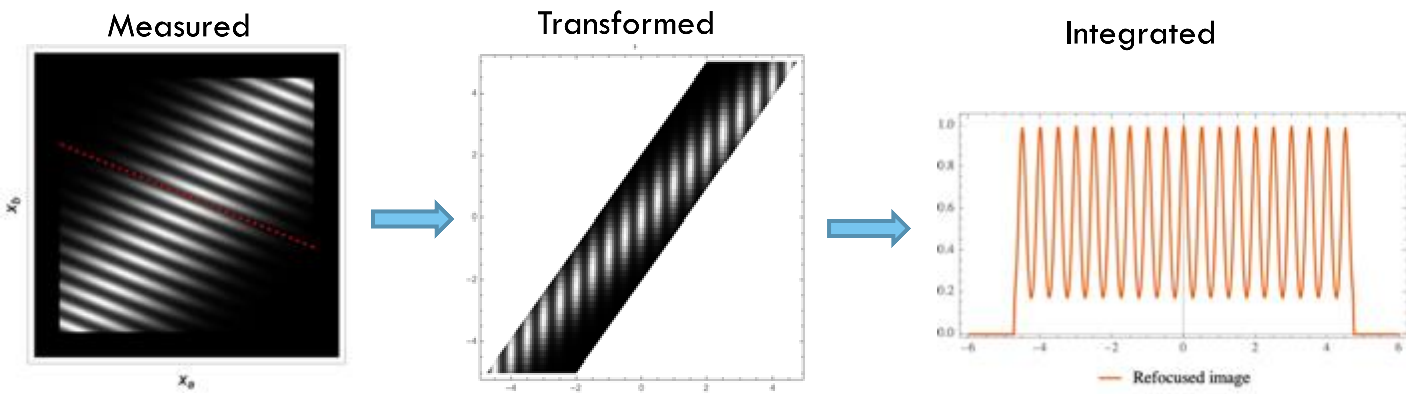


Sample details are available and spread along lines !

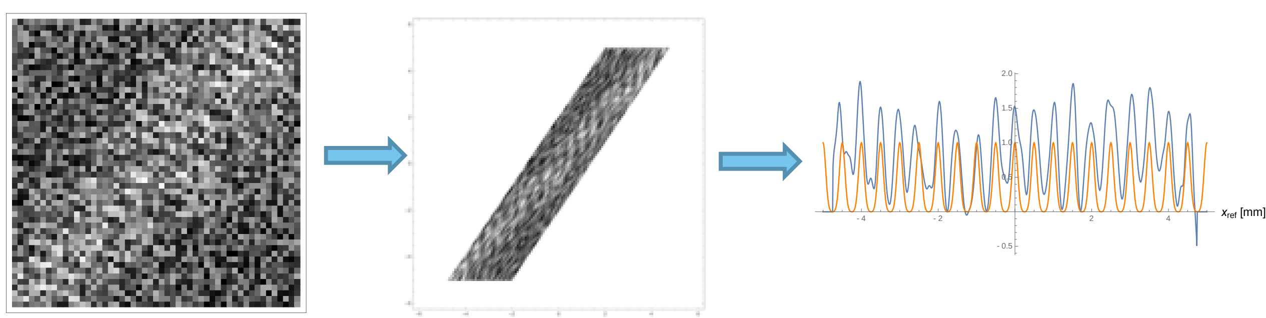
The physics behind CPI

Sample is recovered through line integrals:

$$\Sigma(\boldsymbol{\rho_O}) = \int_{\gamma(\boldsymbol{\rho_O})} G^{(2)}(\boldsymbol{\rho_A}, \boldsymbol{\rho_B}) dl \simeq |A(\boldsymbol{\rho_O})|^2$$



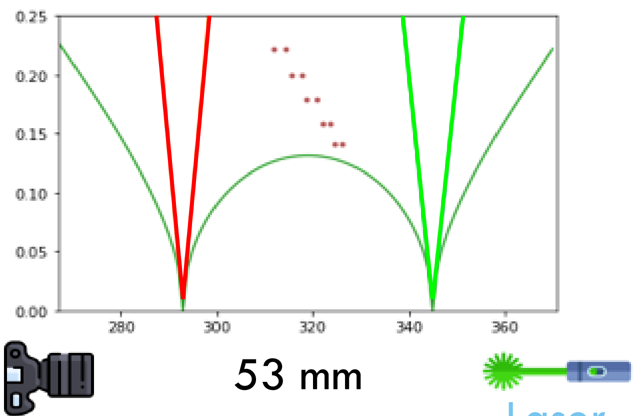
NOTE:
SNR is greatly increased



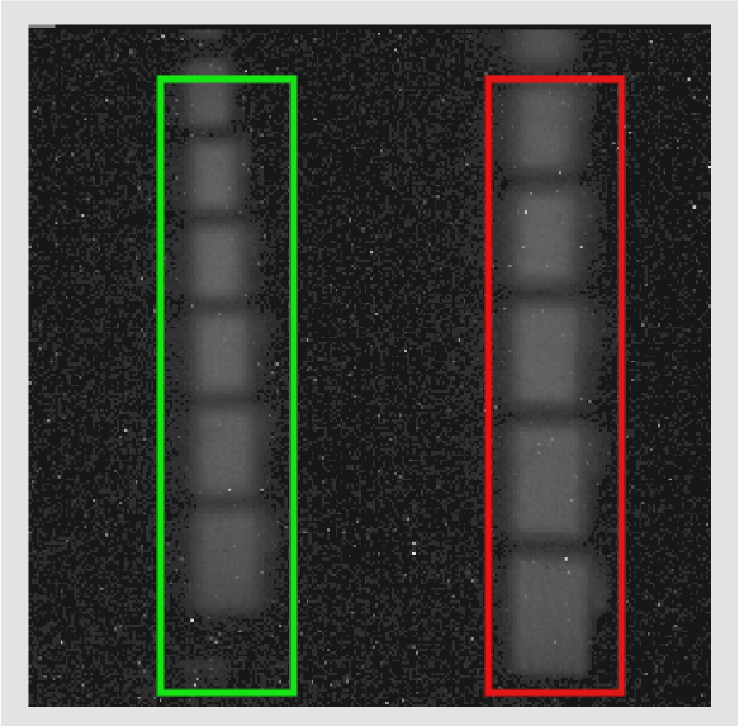
CPI-AP with SwissSPAD2

50-60 kframes @ 90 kHz

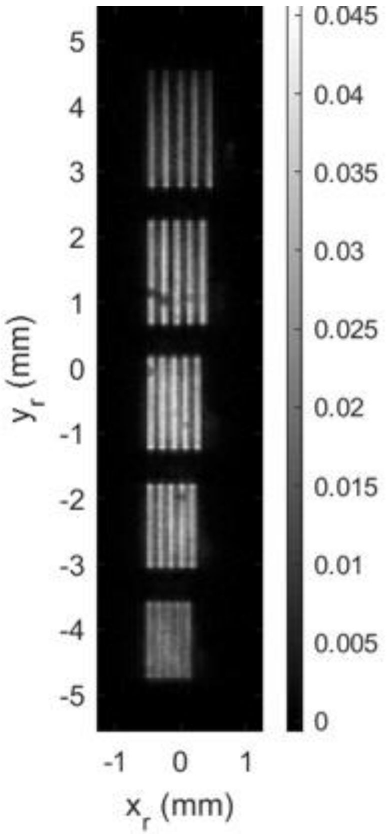
Total capture time: 0,6 sec



DIRECT IMAGES



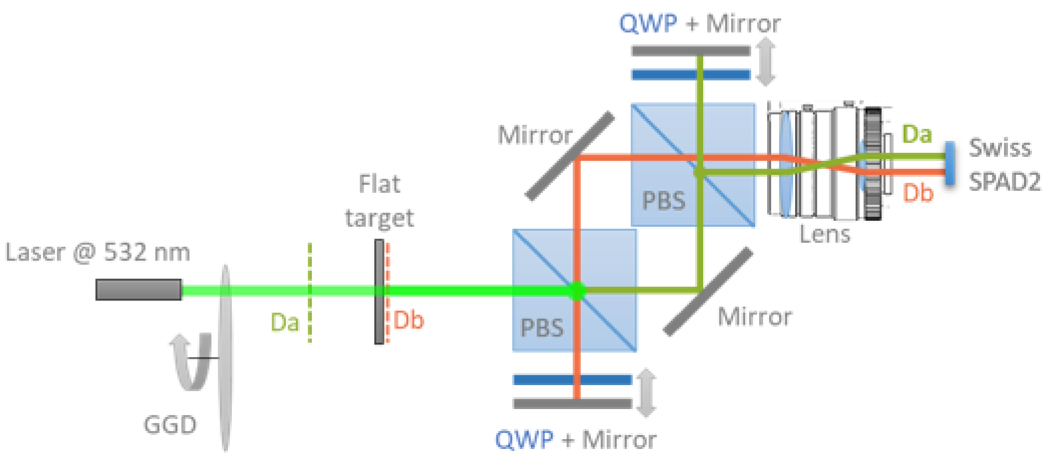
CPI REFOCUSED IMAGE

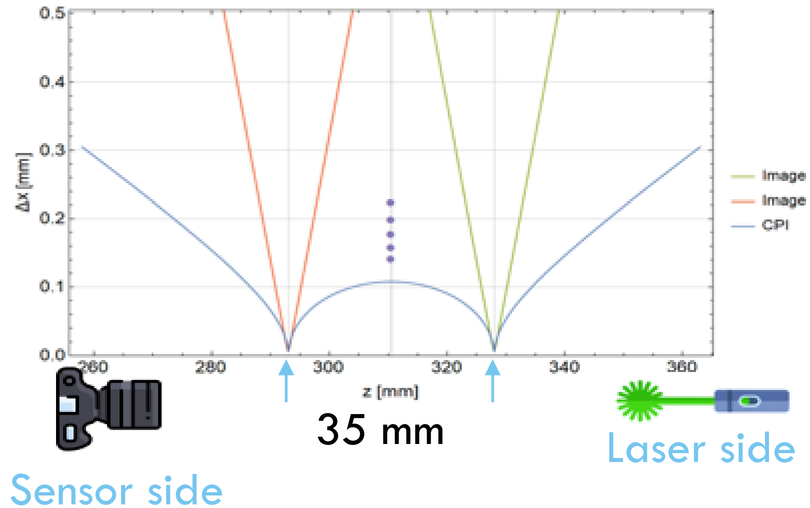


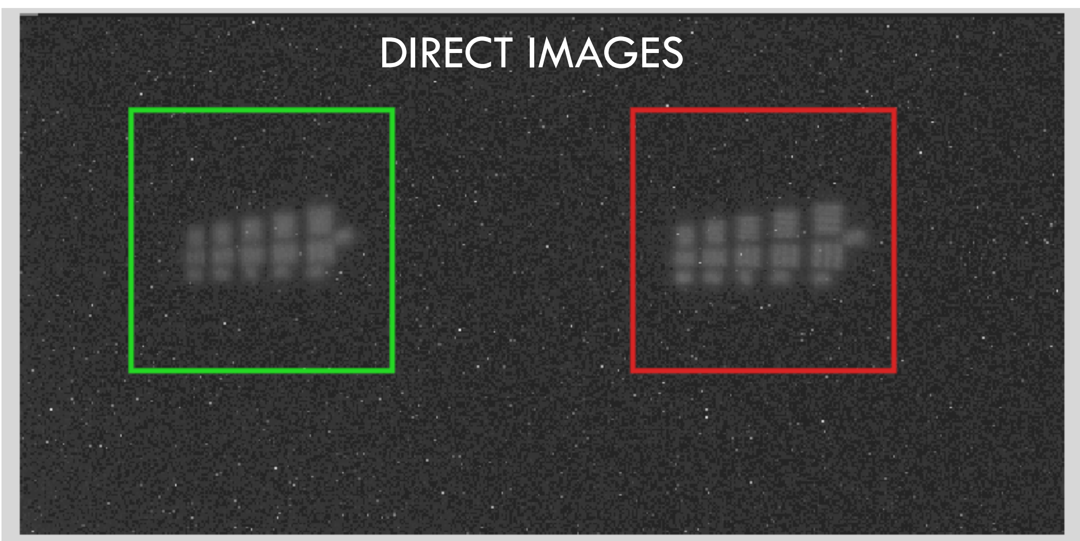
CPI-AP with SwissSPAD2

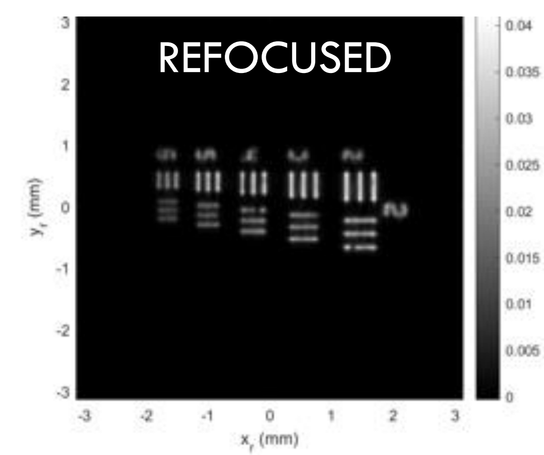
50 kframes @ 90 kfps

Total capture time: 0,6 sec





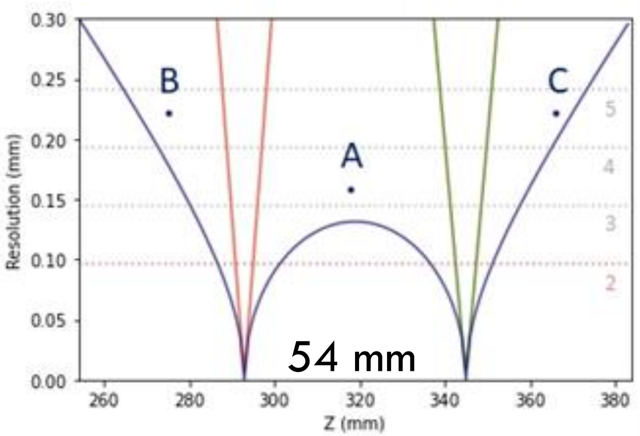




CPI-AP with SwissSPAD2

87 kfps , N_{frames}= 100 kf

CPI acquisition: 1 fps



DOF enhancement: 11-12 x