Quantum technologies within INFN: *current status* and perspectives
Padova, 20-21 Gen. 2020

Qu3D

Quantum 3D imaging at high speed and high resolution

Coordinator: Milena D'Angelo (Univ. Bari)

INFN
Istituto Nazionale di Fisica Nucleare

QUANTERA

The team of Qu3D

Optics

- **Milena D'Angelo (exp)**
- Francesco V. Pepe (th)
- 1 postdoc + 1 PhD (exp)

Lab of Quantum Optical Technologies 2.0 @ Università di Bari & INFN-Bari

Data analysis

- **Bohumil Stoklasa (exp)**
- Z. Hradil, J. Rehacek (th)
- L. Motka, 1 postdoc, 1 PhD

Quantum Optics Group @ *Palacky University Olomouc (CZ)*

Sensors

- **Claudioo Bruschini**
- Edoardo Charbon
- Samuel Burri

Advanced Quantum Architecture Lab @ *Ecole Polyt. Feder. de Lausanne (CH)*

Electronics

- **Maria Ieronymaki**
- Michele Jacobellis
- Ilias Ioannou

Aerospace SME (born in Puglia) @ Athens (GR)

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

Quantum technology: more security and improved imaging

21/Nov/2019

Targeted breakthrough of Qu3D

Design and implement *quantum plenoptic cameras* :

- ✓ refocusing out-of-focus pictures
- ✓ extending the DOF with high luminosity and SNR
- ✓ scanning-free 3D imaging

with unprecedented:

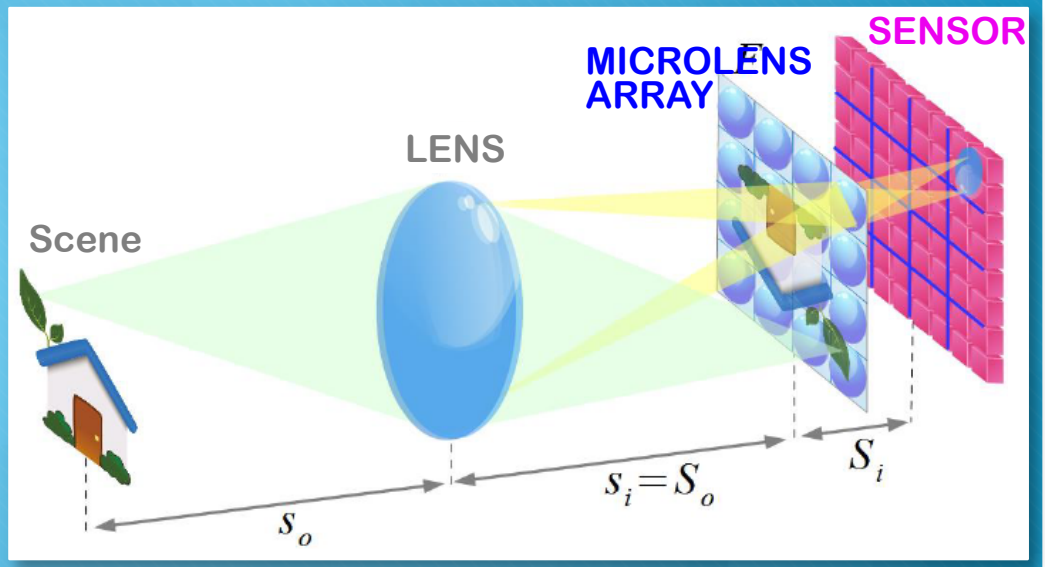
- ○ Resolution (diffraction-limited or better)
- ○ DOF (over 10 times larger than in standard imaging)
- ○ SNR advantage (weakly absorbing samples, stray light, …)

** Lippman (1908), Adelson & Wang (1992), Ng (2005)

Starting point of Qu3D

Correlartion plenoptic imaging (CPI)*

- Conventional plenoptic imaging**



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

*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

** Adelson & Wang (1992), Ng (2005)

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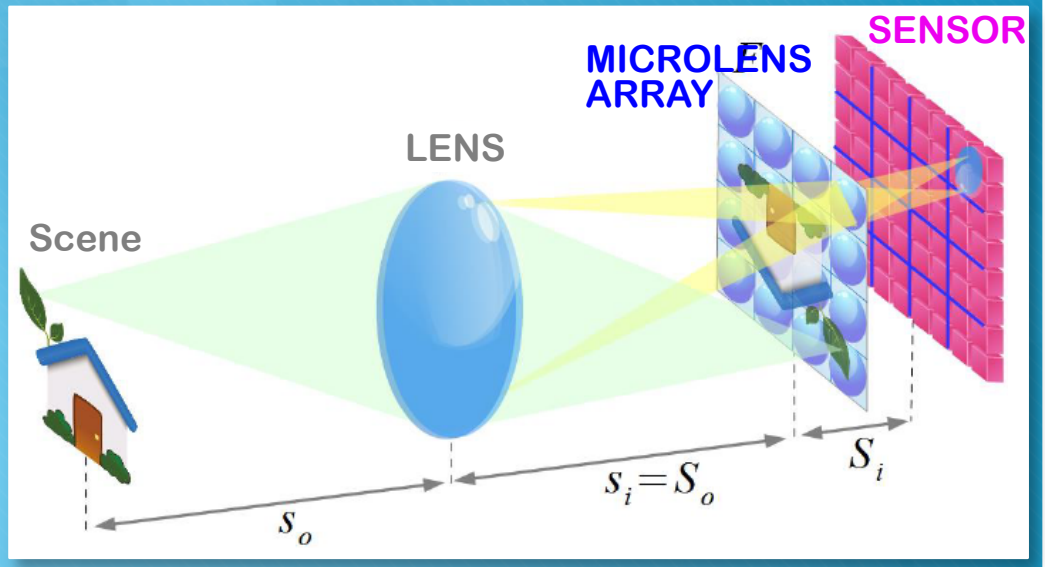
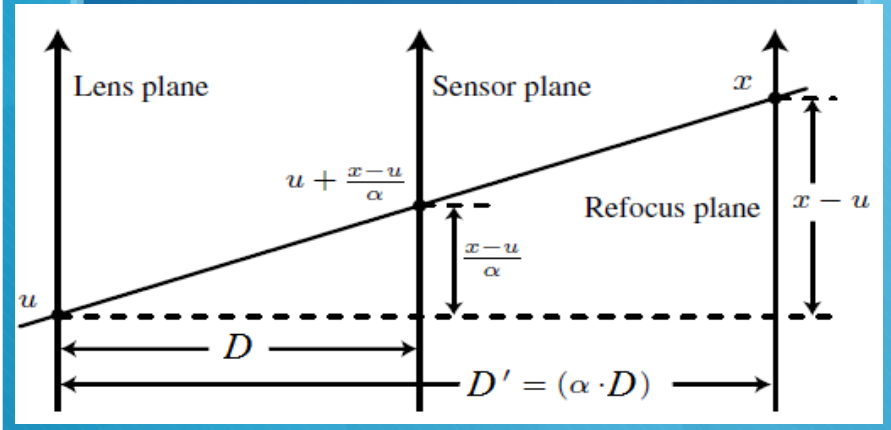
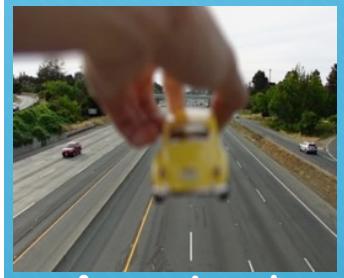
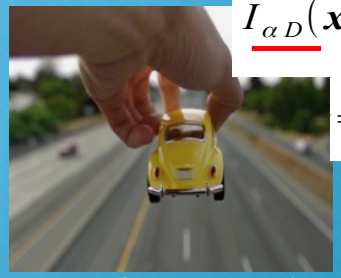


Refocusing capability





Acquired



Refocused

$$I_{\alpha D}(\boldsymbol{x}) \propto \int L_{\alpha D}(\boldsymbol{x}, \boldsymbol{u})\, d^2u$$
$$= \int L_D\left(\frac{\boldsymbol{x}}{\alpha} + \left(1 - \frac{1}{\alpha}\right)\boldsymbol{u}, \boldsymbol{u}\right)$$

*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

** Ng (2005)

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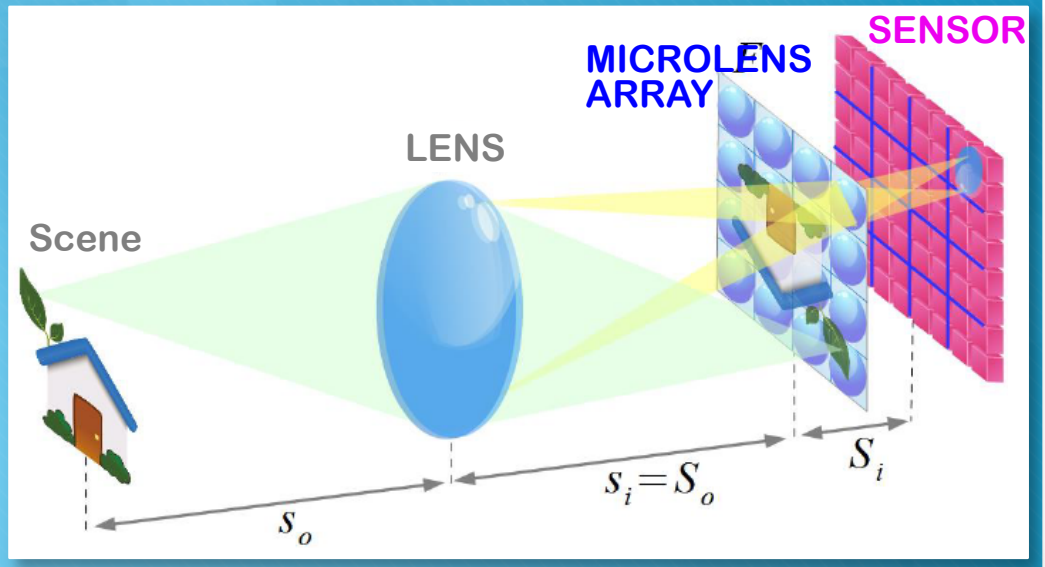

✓ DOF extension

www.illum.lytro.com

*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

** Adelson & Wang (1992), Ng (2005)

Starting point of Qu3D

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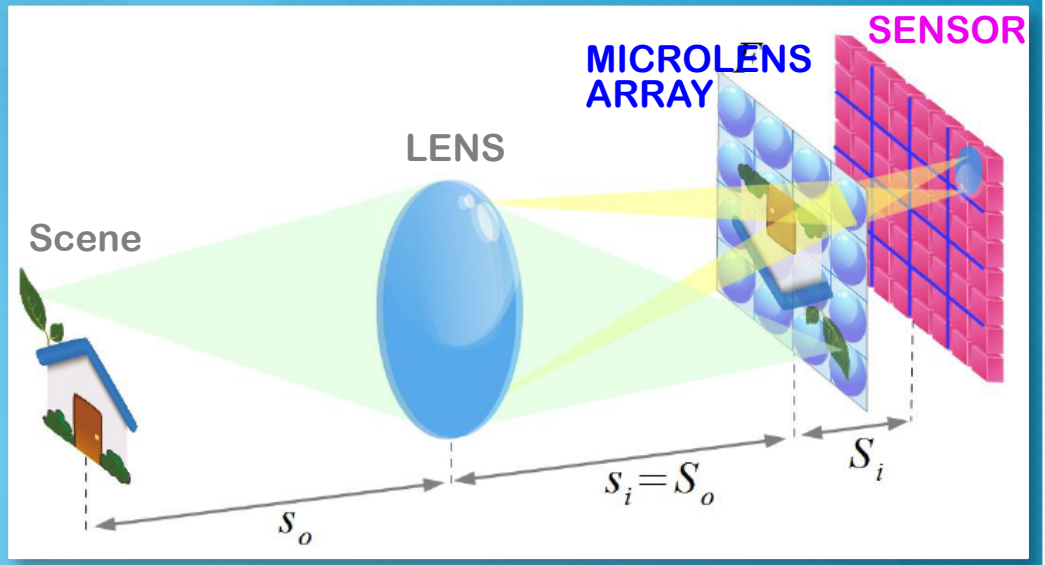
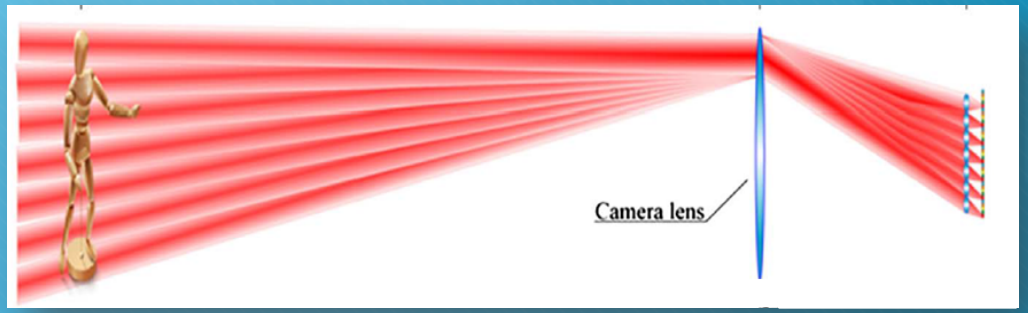


✓ Single-shot 3D imaging



Parallel acquisition of multiple perspectives

*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

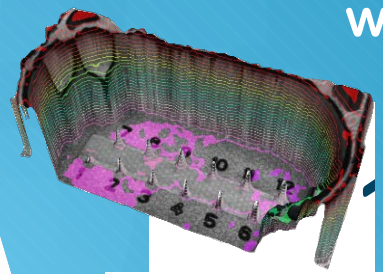
Starting point of Qu3D

Correlartion plenoptic imaging (CPI)*

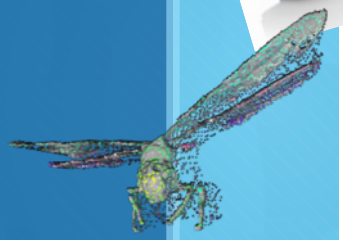
Commercial plenoptic cameras

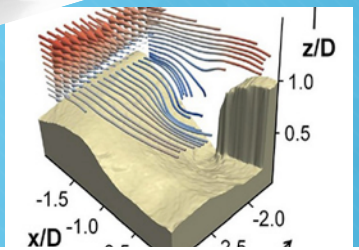
www.raytrix.de

Microscopy, inspection



2-3 um pixel, 2-3 Mpixel; 7 fps





5 um pixel, 3 Mpixel; 180 fps

Real-time imaging

R. Prevedel et al., Nature Meth. 2014 & 2019

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

*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

Commercial plenoptic cameras

www.raytrix.de

Starting point of Qu3D

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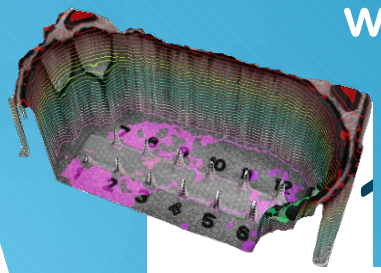
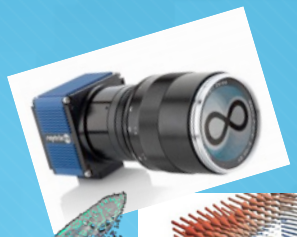
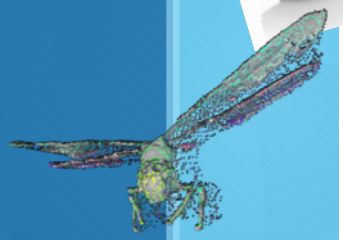
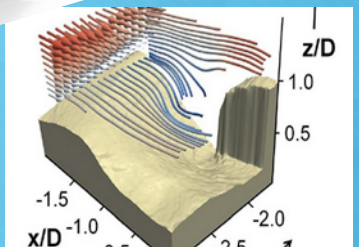
Microscopy, inspection



1 um pixel, 40 Mpixel; 7 fps







5 um pixel, 3 Mpixel; 180 fps

Space, science, army (drones, microsat, …)

Security moitoring (Quadrocopter, 3D aerial Imaging)

*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

** Adelson & Wang (1992), Ng (2005)

Starting point of Qu3D

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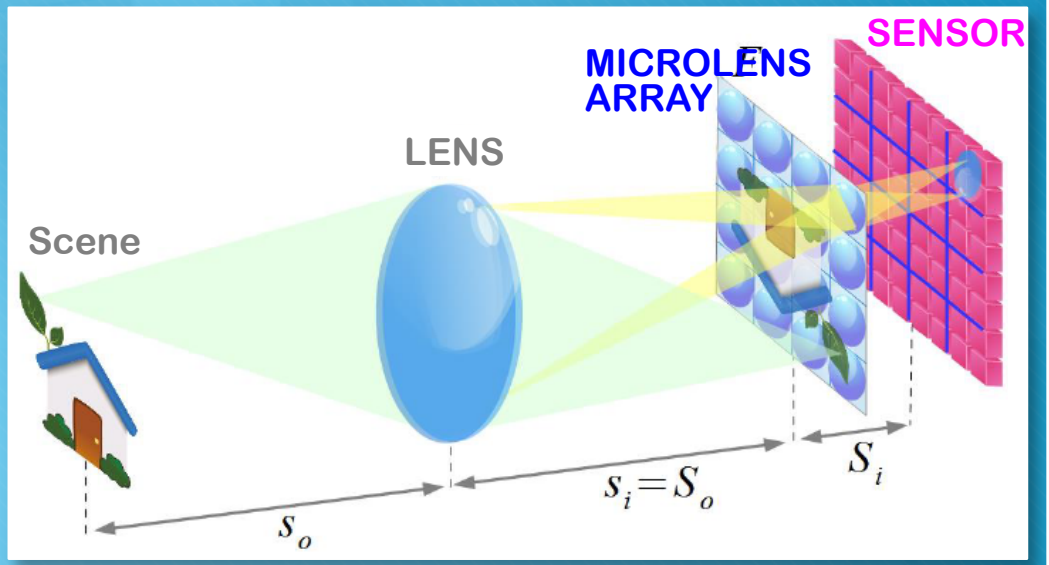


Intrinsic limitations:

- Strong trade-off resolution vs. DOF
  → **no diffraction-limited resolution**
- sacrificed change of perspective

... both defined by the microlens size!

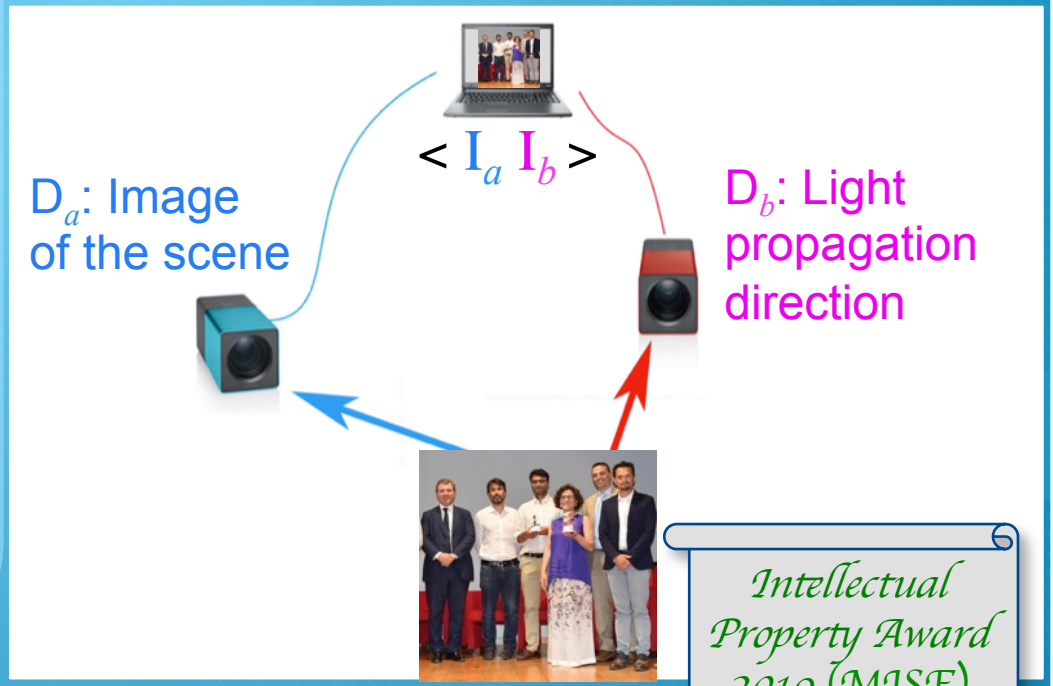
*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

Starting point of Qu3D

Correlartion plenoptic imaging (CPI)*

Correlation plenoptic imaging *

Exploiting momentum-position correlations of light to decouple image acquisition and direction measurement !



Intellectual Property Award 2019 (MISE)

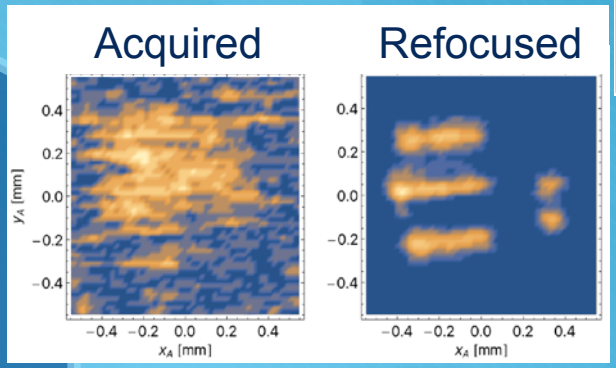
*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

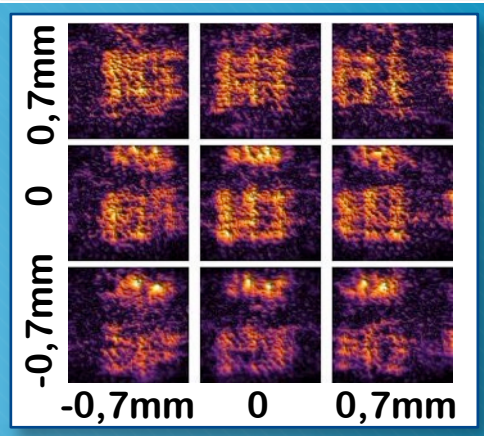
Starting point of Qu3D

Correlartion plenoptic imaging (CPI)*:

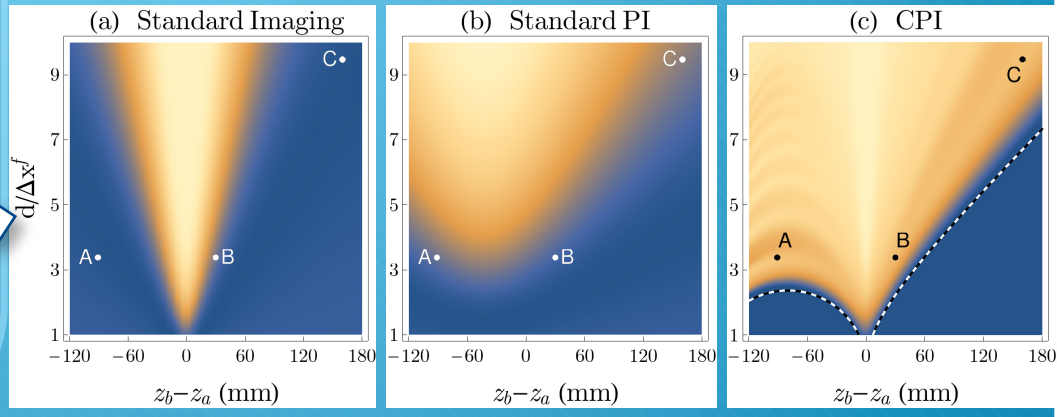
- ✓ Refocusing capability
- ✓ DOF extension
- ✓ Scanning-free 3D imaging

with dramatically enhanced DOF & resolution at the diffraction limit !





Resolution vs. DOF



*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

Quantum plenoptic cameraS

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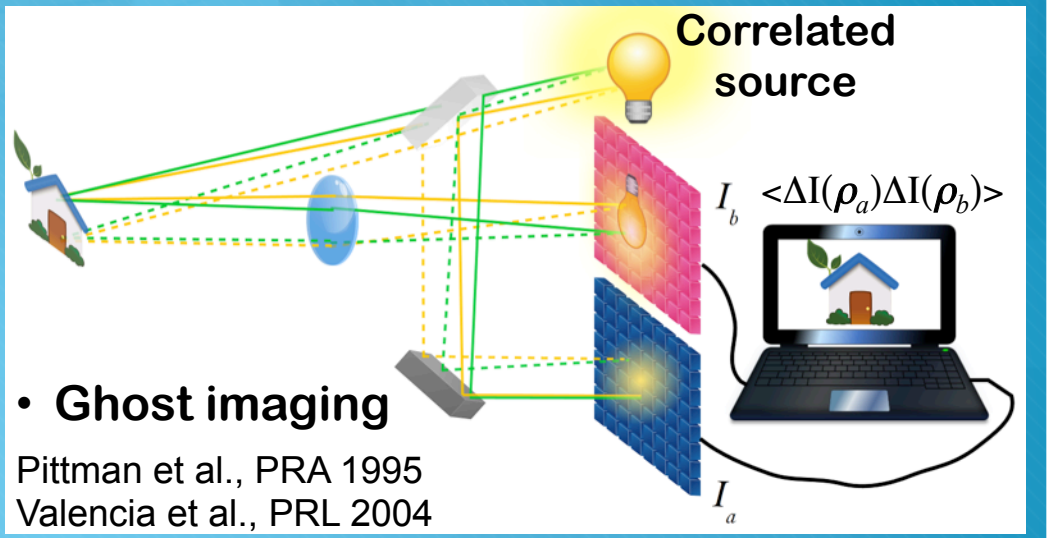


- **Ghost imaging**

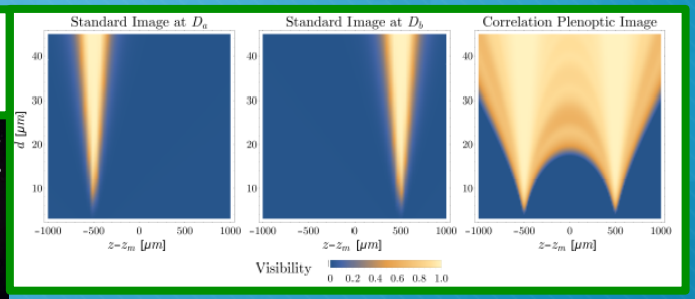
Pittman et al., PRA 1995
Valencia et al., PRL 2004

- **CPM prototype:**

No need for ghost imaging → **larger SNR, emitting samples, turbulence attenuation, …**

PON RICERCA E INNOVAZIONE

CLOSE (DTA Puglia)



*1 EU patent, 3 PCT applications (INFN + UniBA), PRL 2016 & 2017. Progetto giovani: F.Pepe -PICS

The challenges addressed by Qu3D

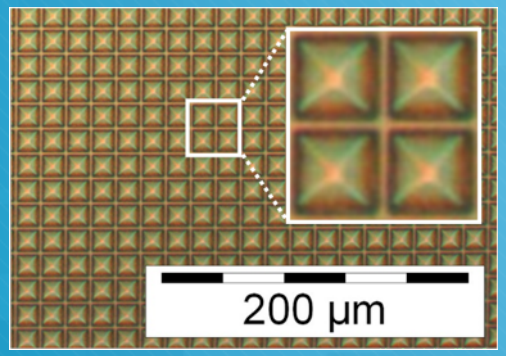
Need for 5-30 x 10^3 high resolution frames (2.5-15 GB)* for proper reconstruction of the correlation $\langle \Delta i_a \, \Delta I_B \rangle$

- Acquisition time (sCMOS @ 50 fps): 3 - 10 min
- Data transfer (USB 3.0) + saving: 1 - 30 min
- Elaboration time for calculating the point-by-point correlation function (Mathematica): > 10 hours

* 500 x 500 pixels on both D_a and D_b

The solutions of Qu3D: *hardware* speed-up

Sensors: SwissSPAD2



Speed-up by 3 orders of magnitude

The largest SPAD array

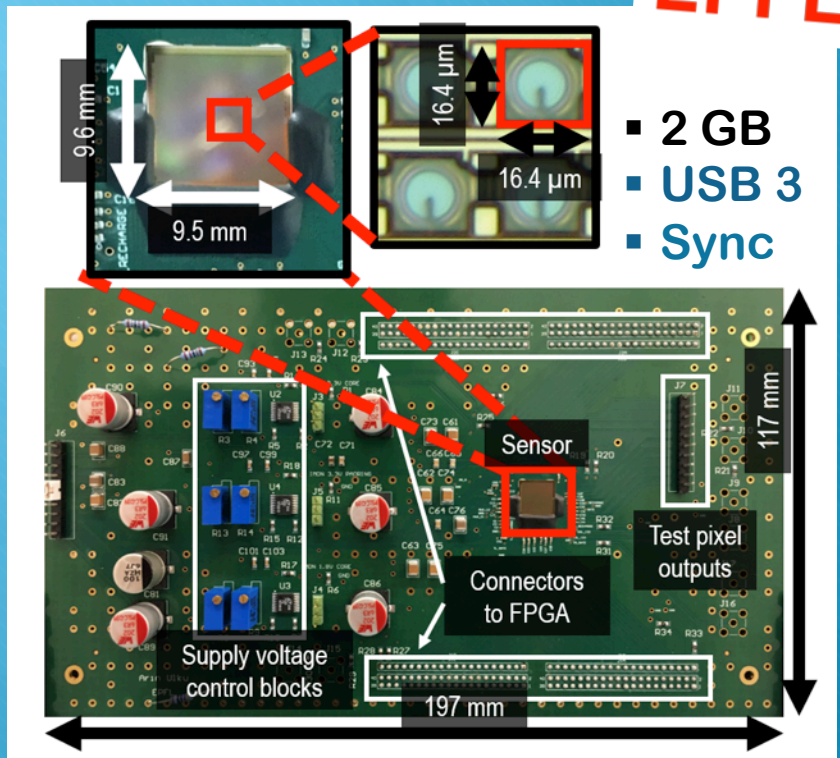
100 kfps

512 x 512 pixels with 16 um pitch

PDE 50% @ 532 nm

Dark counts: 100 cps

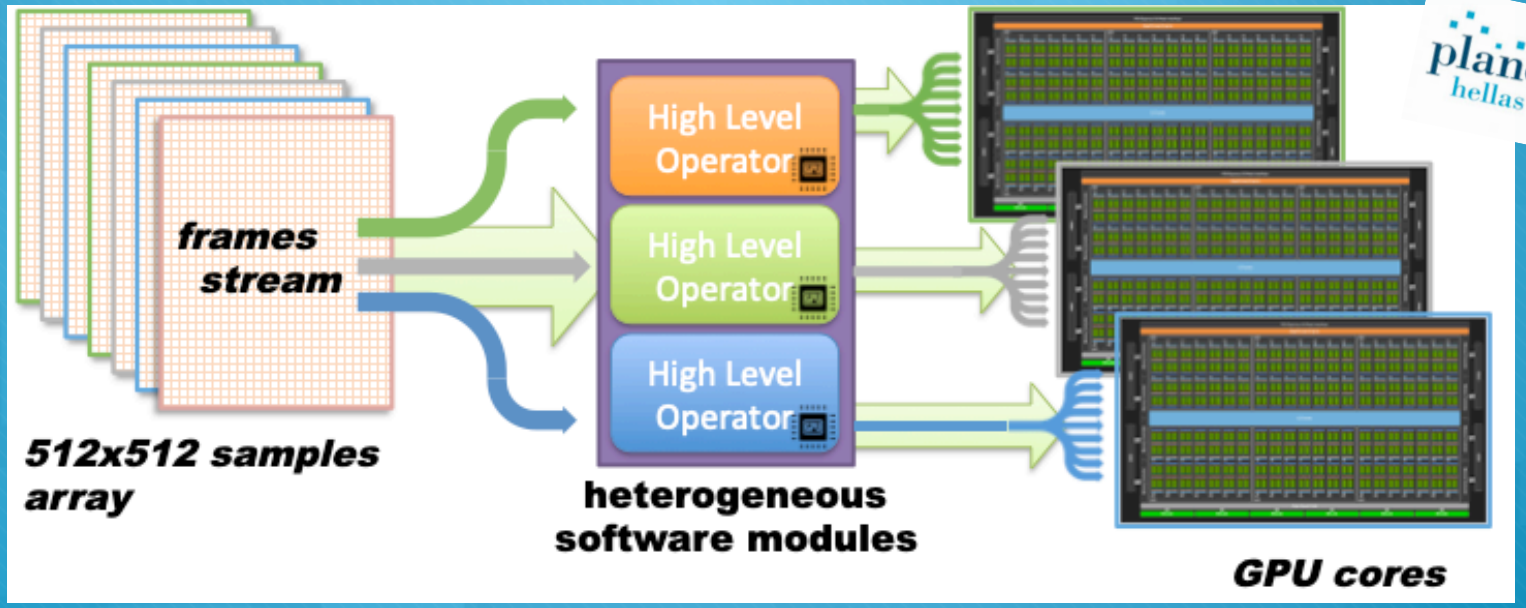
EPFL



A.C. Ulku et al., IEEE J. Sel. Top. Quantum Electron. **25** (2019) + Proc. SPIE, **10882** (2019)

The solutions of Qu3D: *hardware* speed-up

- PCI-express streaming interface & parallel computing (GPU,…)



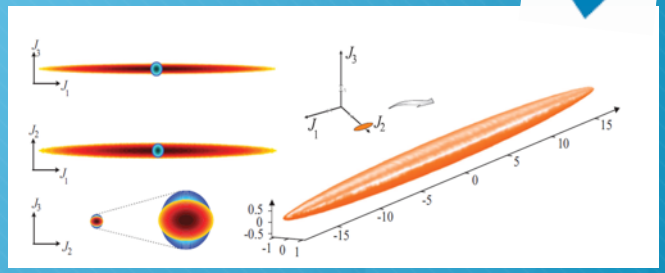
→ QPI @ 1 - 10 fps & elaboration times of a few minutes !

> 1 order of magnitude data reduction!

The solutions of Qu3D: *software* speed-up

- **Quantum tomography**

Advanced statistical inference methods inspired by quantum tomography (e.g., maximum-likelihood, maximum-entropy methods) for optimal image reconstruction protocols



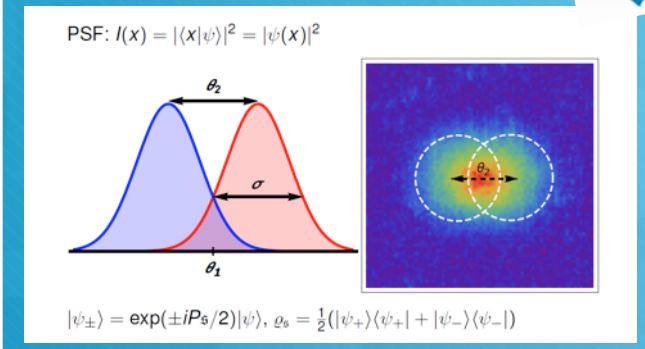
- **Compressive sensing**

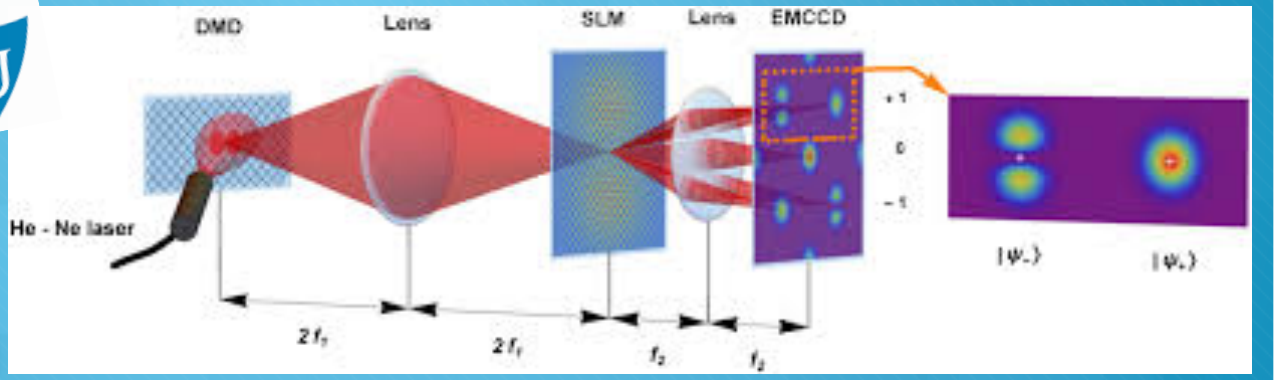
- **Machine learning, neural networks, …**

Further challenges for Qu3D

- **Beating the diffraction limit**

  → The proposed solution: *Quantum Fisher information*





M. Paúr et al., Optica 3 (2016) + Optica 5 (2018)
J. Řehaček et al., PRA 96 (2017)

- **Minimizing noise in correlation measurments**

  → The proposed solution: novel measuring protocols (e.g., differential imaging)

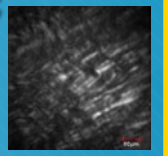
Transformational role in technology and society … toward new scientific and technological routes

Qu3D outputs

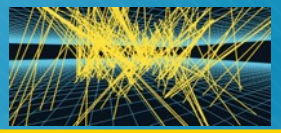
- Prototype of a compact 3D camera @ 100 fps
  [chaotic light]
- Ultra-low noise 3D imaging of low absorption samples
  [twin beams]

with ultra-high resolution & over 10 times larger DOF than standard imaging.

Novel imaging and diagnostic devices:



- *Quantum plenoptic microscopes and endoscopes*: biophotonics, biomedical applications, clinical imaging
- *Quantum space imaging devices*
- *Quantum 3D cameras* for particle tracking, security, industrial inspection, wavefront sensing, …



Perspectives

Extending quantum imaging to:

- → X-rays
- → muons

X-ray quantum imaging

ESRF (Grenoble)

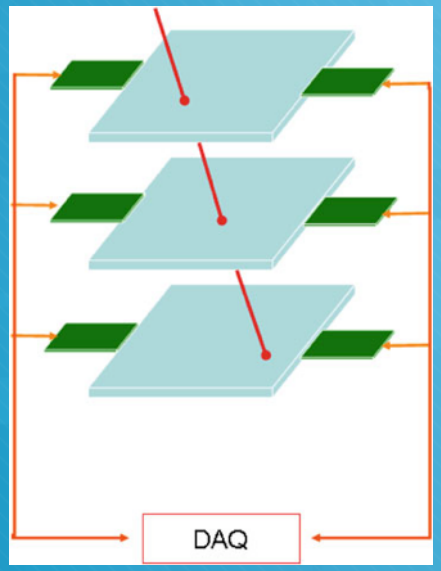
- "Experimental x-ray ghost imaging", Pelliccia et al., PRL 117 (2016)
  → mitigation of radiation damage

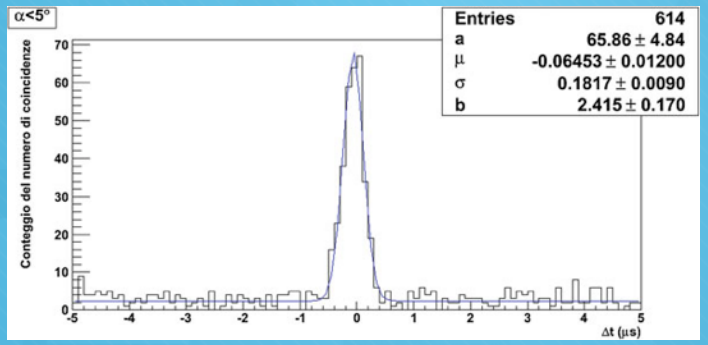
SSRF (Shanghai)

- "Fourier-Transform ghost imaging with hard x-ray", Yu et al., PRL 117 (2016)
  Retrieving Fourier Transform of the object in the Fresnel zone, with incoherent sources → NO NEED for coherent sources, huge distances or lenses !!!
  → Extension of x-ray crystallography to nanocrystals (molecular materials, difficult to grow into macroscopic cystals; samples in their natural states)
  → Avoids problems of standard Coherent Diffractrion Imaging: missing low-frequency, due to beamstop; need for high coherence & brightness → no high quaility imaging with x-ray lab sources.

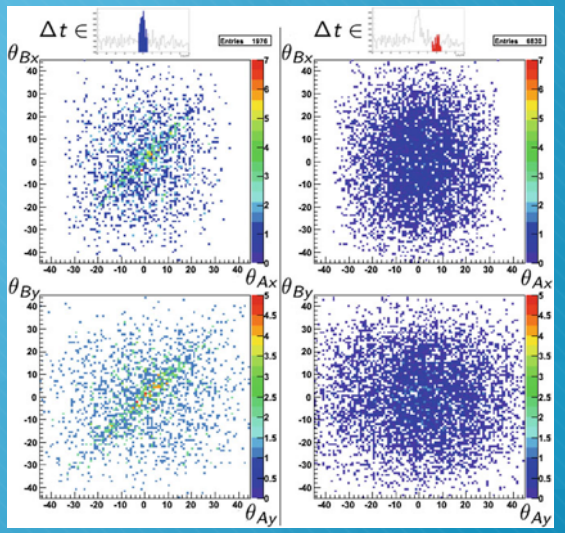
M. D'Angelo, Nuovo Cimento C 35, 243 (2012)

Quantum imaging with cosmic ray muons





EEE project (L'Aquila – LNGS)



Milena D'Angelo (BARI)

Advertisements

Quantum 2020 - Summer School on Quantum Optical Technologies in Apulia

Trani (BA), 21-25 Sett. 2020

Ad memoriam of *Franco Selleri*

In continuity with the Quantum workshops of Turin (May 2021)

Open Postdoc position

milena.dangelo@uniba.it