2° Congresso della Sezione INFN e del Dipartimento di Fisica di Bari

Trasferimento tecnologico con focus sulle tecnologie ottiche quantistiche *2.0*

Milena D'Angelo

Quantum imaging:

from the foundations of quantum mechanics…

Franco Selleri

Augusto Garuccio

Yanhua Shih

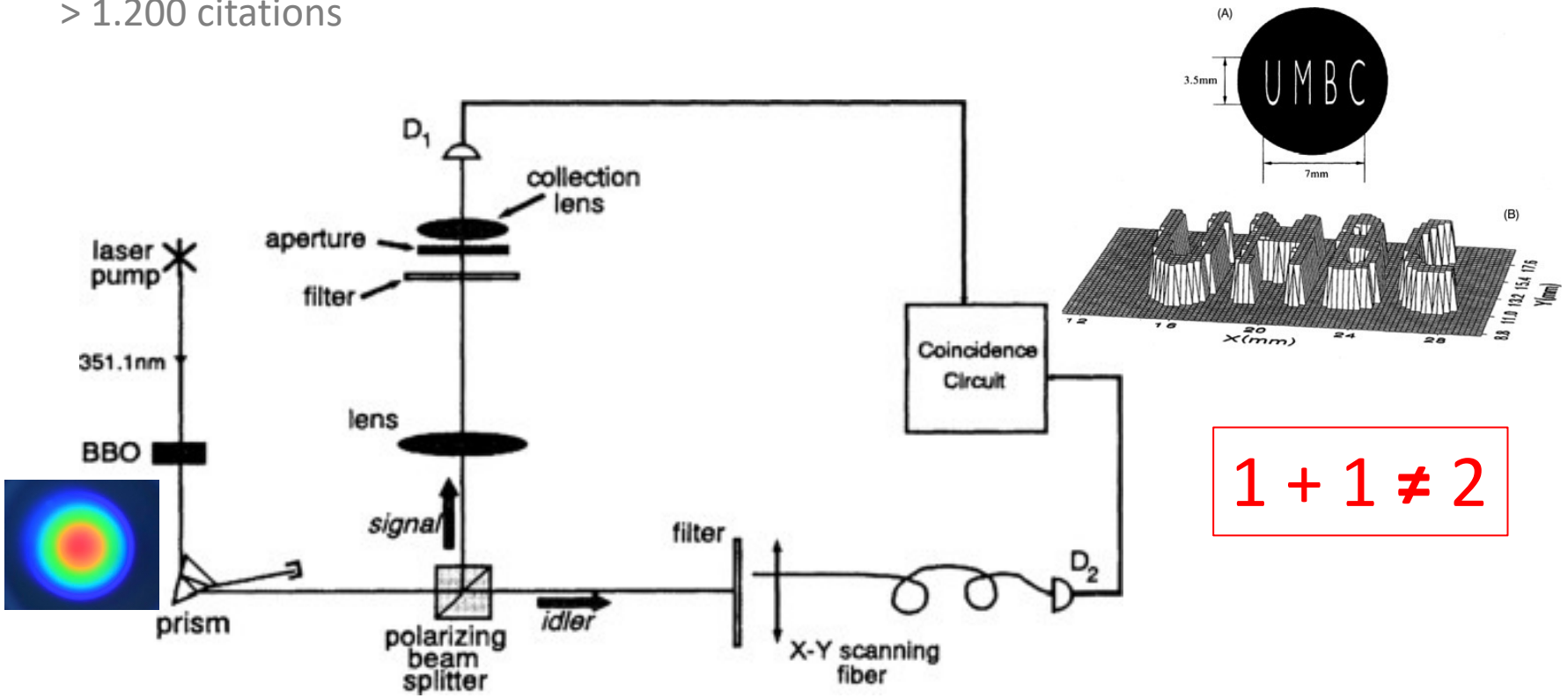
… to applications

Quantum imaging, the beginning

Ghost imaging with *entangled* photons

- Pittman, PRA 1995 «Optical imaging by means of two-photon quantum entanglement»

  > 1.200 citations



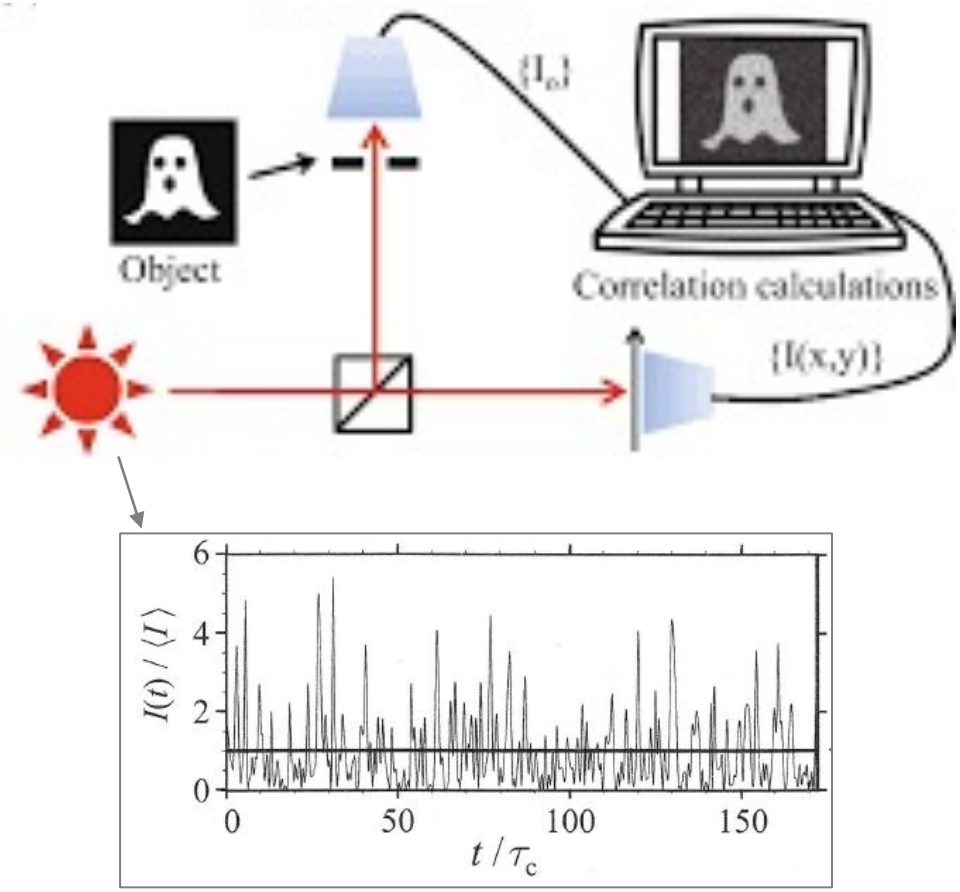
1 + 1 ≠ 2

Quantum imaging, 10 years later

Ghost imaging with *thermal* light

- Valencia, PRL 2005 «Two-photon imaging with thermal light»

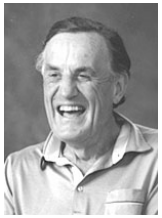
  > 500 citations

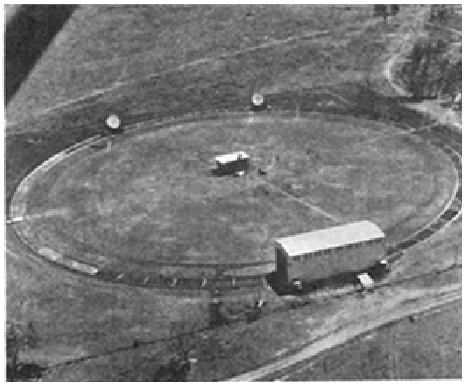


Liu, *Scient. Rep.* **10**, 14626 (2020)

Who are the parents?

'60: Hanbury-Brown & Twiss stellar interferomenter (the 1° intensity interferomenter → quantum optics !)

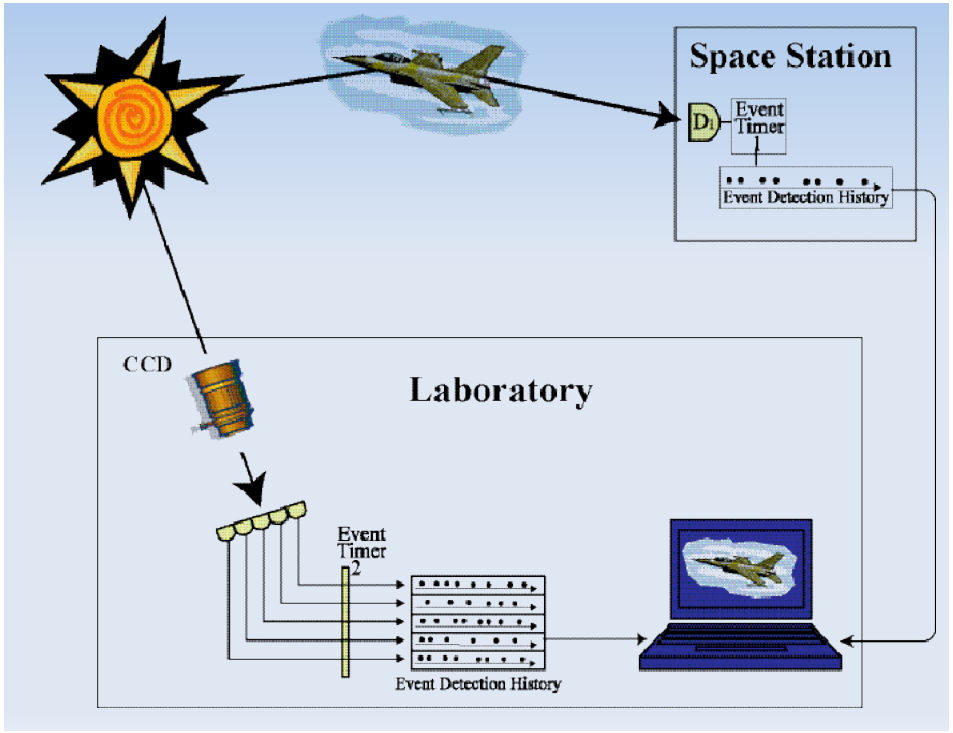




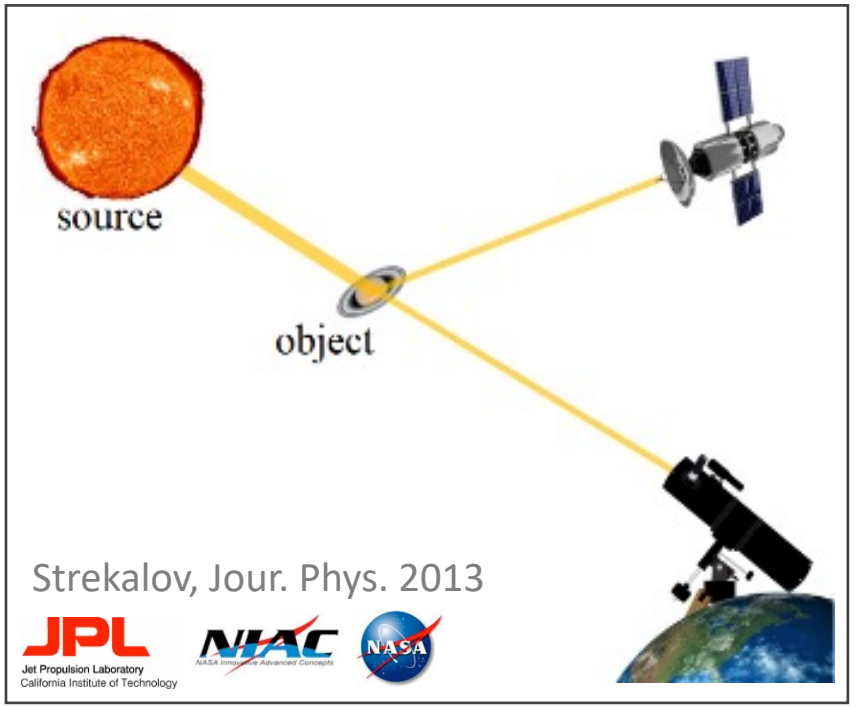
Introduction

Quantum imaging, the promises

Ghost imaging

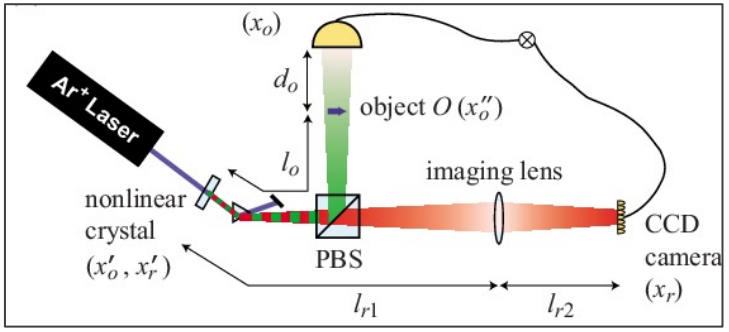


Yanhua Shih

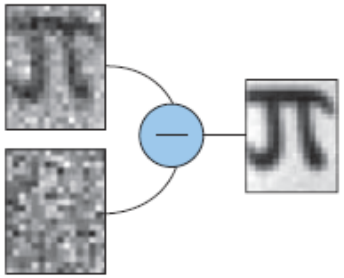


Quantum imaging, the advantages

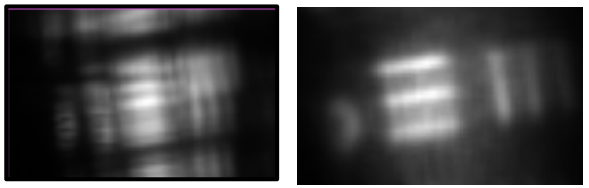
- Two-color ghost imaging [Boyd 2008]



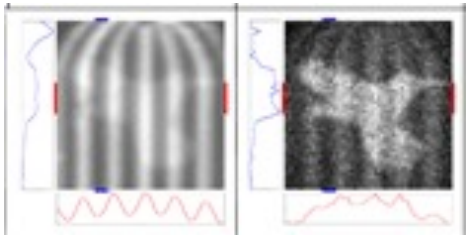
- Sub-shot-noise imaging and microscopy [Brida 2010]



- Imaging with undetected photons [Zeilinger 2014]
- **Correlation plenoptic imaging** [D'Angelo 2016]



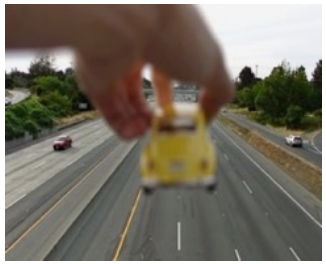
- Imaging through noise [Padgett 2020]



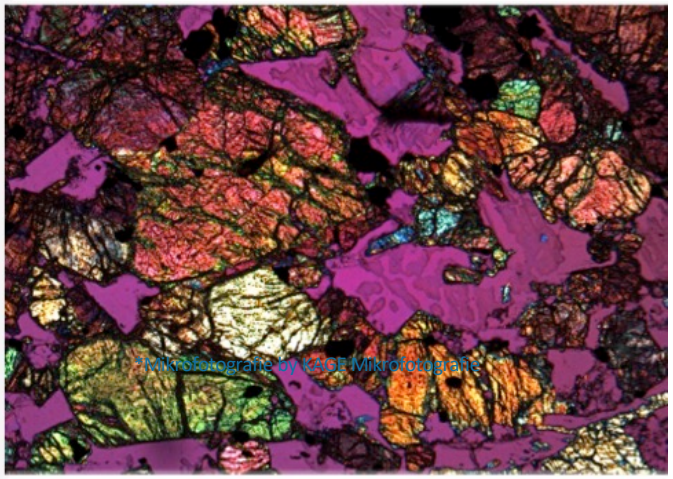
Plenoptic cameras

www.raytrix.de/

What: Refocusing acquired pictures, in post-processing,
+ Single-shot 3D imaging



Why: EO, microscopy, security monitoring,..



Mars meteorite*

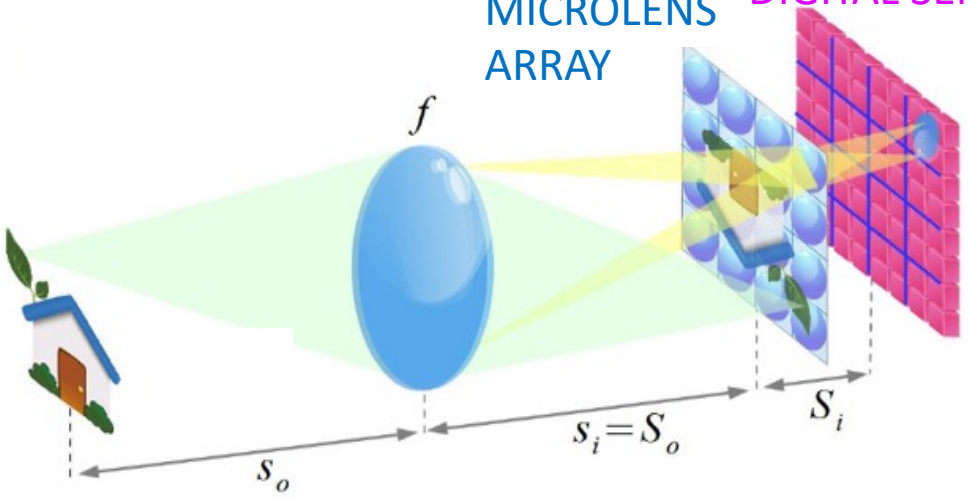
Microsatellites, drones

Quadrocopter, 3D Aerial Imaging

How: by measuring the propagation direction of light

Plenoptic imaging: working principle

Ng 2005



DIGITAL SENSOR: retrieves BOTH the image AND the ***propagation direction*** of light

↓

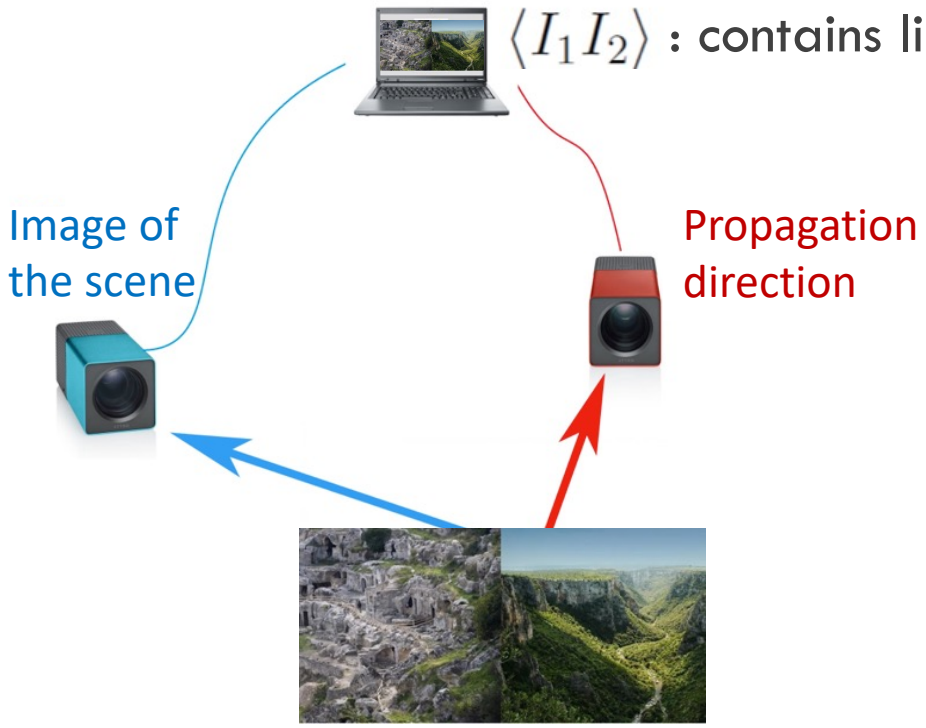
A 16 Megapixel camera, behaves as a 4 Megapixel

- Trade-off between resolution and depth-of-field → NO diffraction-limited resolution
- Sacrificed change of perspective limits the 3D imaging capability

Can quantum imaging help?

Correlation plenoptic imaging, the idea

Exploit spatio-temporal correlations of light to decouple image acquisition from direction measurement



3D imaging

&

refocusing, in post-processing

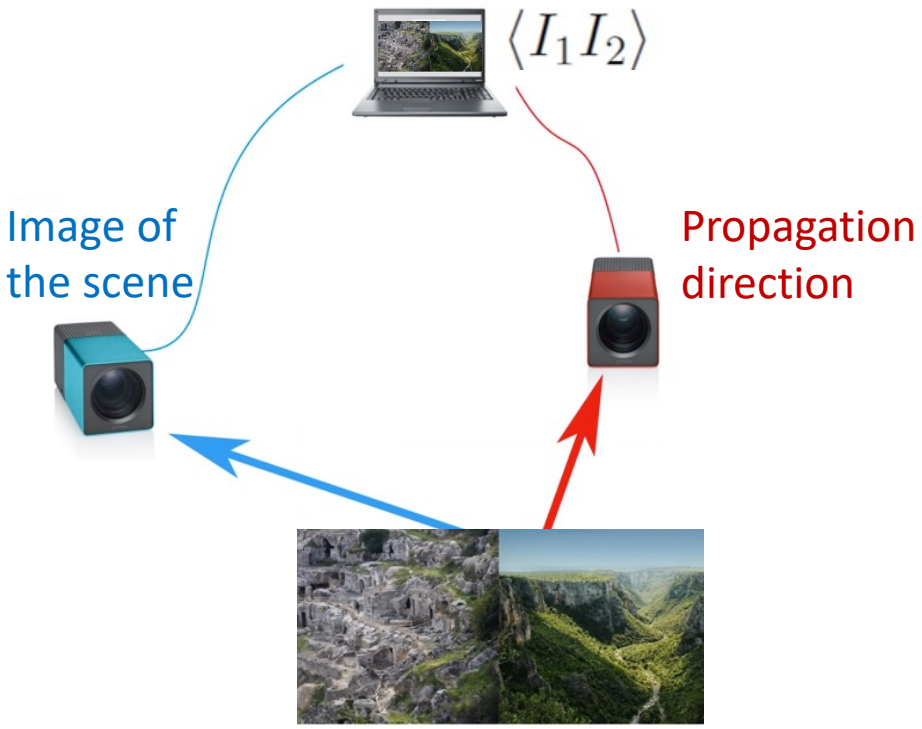
with

an unprecedented combination of resolution and depth of field

Quantum imaging in Bari

Correlation plenoptic imaging, TT

IDEA: Exploit spatio-temporal correlations of light to decouple image acquisition from direction measurement



2016: our 1° step toward TT

IT patent application

Intellectual property Award 2019 MISE-UIBM

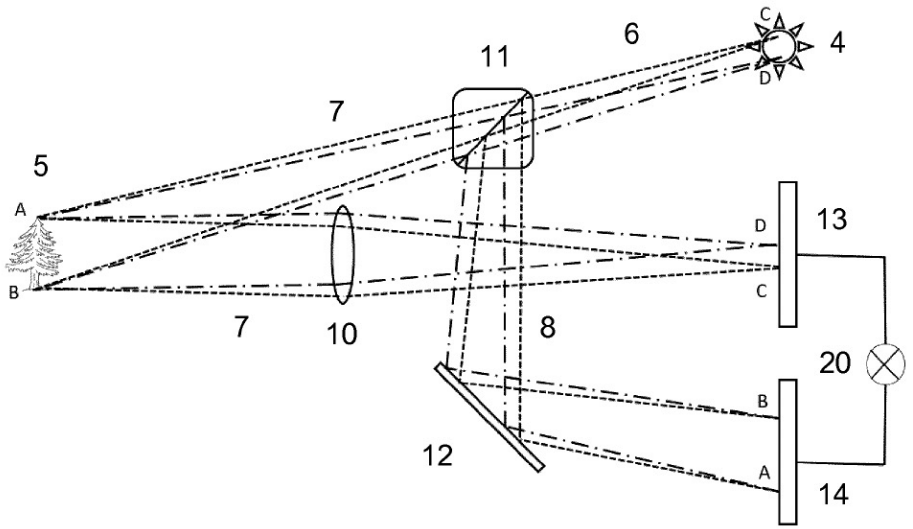
D'Angelo et al., PRL 2016

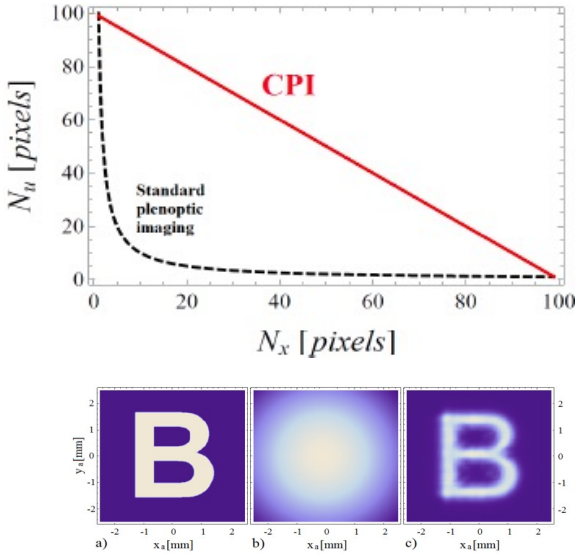
Quantum imaging in Bari

Lessons from our 1° patent application

DEVICE AND PROCESS FOR THE PLENOPTIC CAPTURE OF IMAGES

- The patent covers the invention of a ***device*** and ***process***
- **No one expects the «device and process» to really work** .. It is ok if it requires technological dveelopments that are not yet available





- The TT office of the institution hires a private company for writing the patent application and follow the entire iter .. Still, frequent interactions are indispesable at different levels (writing, replying to examiners, etc.)

The adventure in TT

IP needs to be «valorized»

1° patent → «**Borsa della ricerca**», Salerno 2017

Lesson 1: IT patent is useless, go for **International patent**

Lesson 2: «come back next year with a **prototype»**

Lesson 3: search for a ***killer application*** - study the *mom's test*

Lesson 4: protect your patent with many «daughter patents»

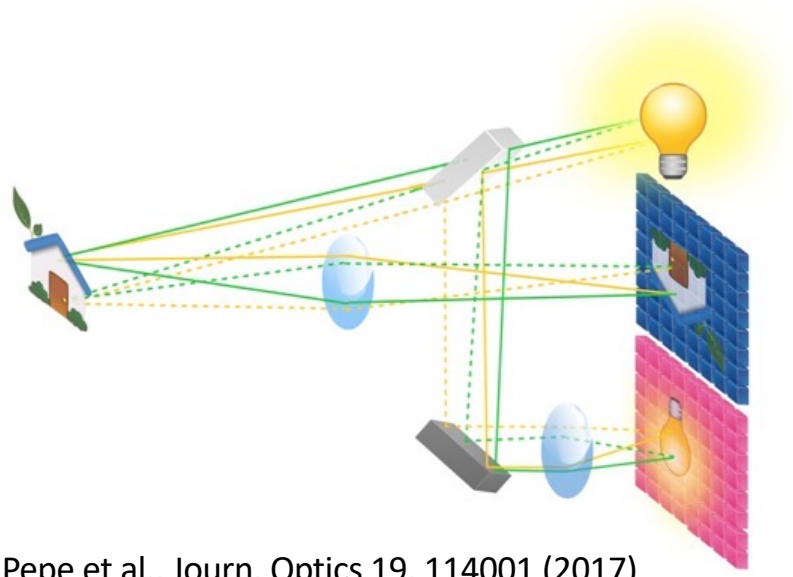
Young researcher project - INFN CSN5: PICS (PI: Francesco Pepe)
Main goals:

- Develop CPI in the framework of **microscopy**, for 3D imaging of particle tracks in emulsions and biomed applications
- Design of the **prototype** of a CPI microscope
- Protect INFN **IP** → 3° patent application

The first daughter

DEVICE AND PROCESS FOR THE CONTEMPORARY CAPTURE OF STANDARD AND PLENOPTIC IMAGES

PCT/2017 → Europe, USA and Cina



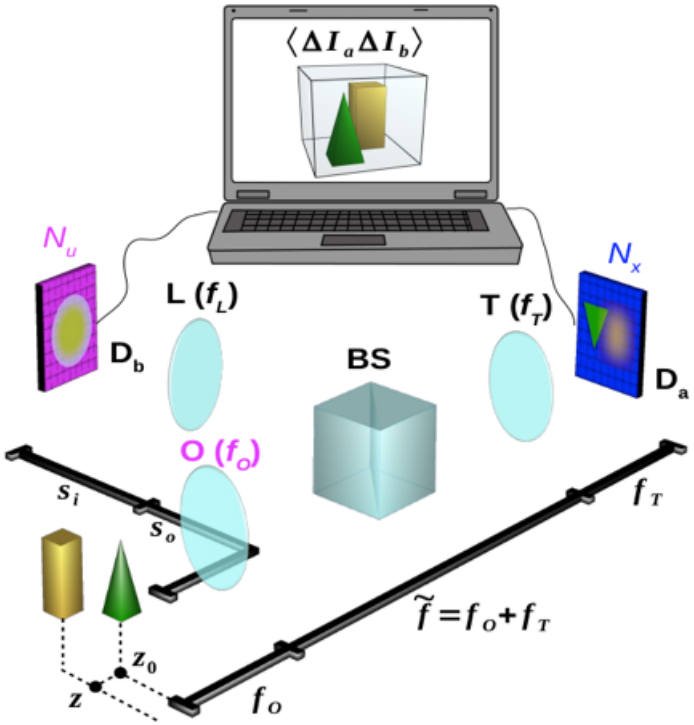
Pepe et al., Journ. Optics 19, 114001 (2017)
Di Lena et al., Applied Sciences 2018
Pepe, PRA 99, 053808 (2019)

- Object can be monitored with standard imaging (no ghost imaging required)
- Higher SNR: no trade-off SNR vs. resolution & trasmissive area of the object

Lesson learned:
Trusting the company is not enough, what matters is who writes the patent application

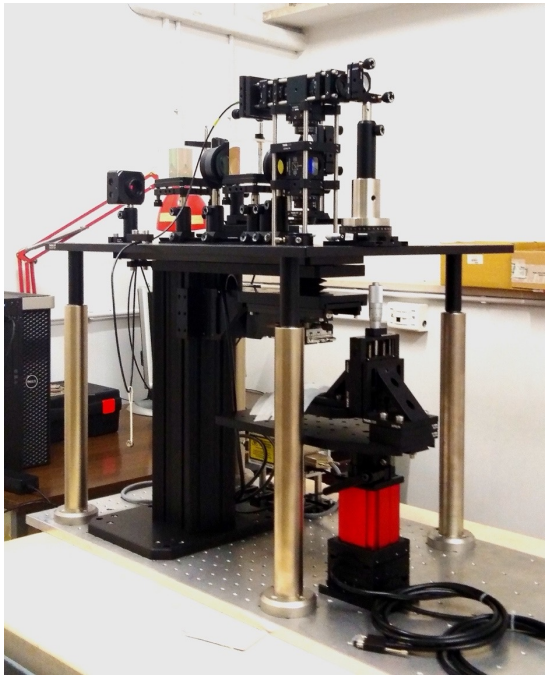
The fruits of PICS

1) PCT/2018: DEVICE AND PROCESS FOR CAPTURING **MICROSCOPIC** PLENOPTIC IMAGES WITH ***TURBULENCE ATTENUATION*** → Europe, USA, Cina, Japan



2) Our 1° **prototype**

(Davide Giannella, Laurea thesis)



3) PICS4ME – INFN CSN5

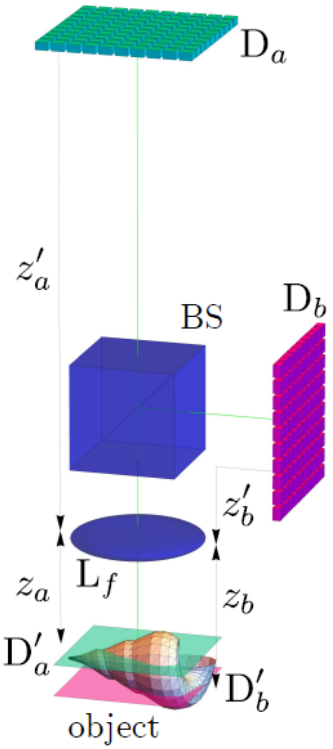
4) MISE - Proof of Concept: TOPMICRO (12 month, 40k€)

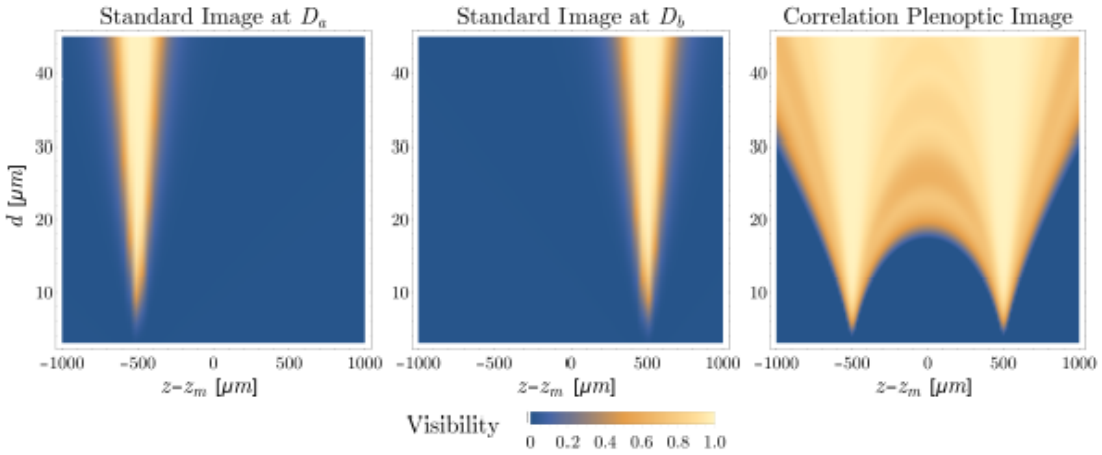
The adventure in TT

Two more patents

PCT/2019: **CPI –AP** (original idea by Francesco Di Lena, PhD thesis)

NEW agency for patent application





- Born within project PON ARS Close
- Basis of **EU project** Qu3D (**QuantERA 2019**)

PCT/2020: Hyperstecral imaging by correlations (G. Massaro, PhD thesis)

??? Basis of **QEO**, ind. partner: Planetek (RIPARTI, Reg. Puglia '21)

The adventure in TT

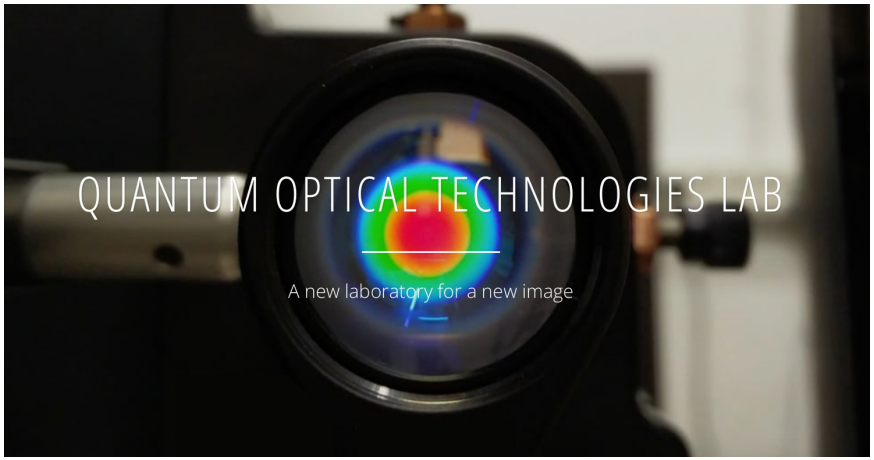
Plans for the future

Joint INFN-UniBA spin-off (expected @ Sept. 2022): currently looking for

- investors / public or private financing
- motivated young physicist/engineer
- «killer application» in both microscopy, EO, automotive, ..

Strenghtening collaboration with companies (Leonardo, Planetek) through joint projects

Quantum optical technologies group



quotlab.uniba.it

- Milena D'Angelo: group leader
- Francesco V. Pepe: RTDb – theory
- Francesco Scattarella: RTDa – image analysis
- Sergii Vasiukov: post-doc - exp
- Francesco Di Lena: post-doc – models, algorithms, exp
- Gianlorenzo Massaro: PhD student – theory, exp, models, algorithm
- Davide Giannella: PhD student – exp, prototype engineering
- Germano Borreggine: Laureando - theory

Thanks for your attention

QPI Systems

Tecnologie quantistiche
per immagini

MILENA D'ANGELO
CSO & co-founder

Problema

In un’immagine sfocata e mossa l’informazione è definitivamente persa.

Soluzione

Con le tecnologie quantistiche forniamo immagini nitide a una velocità almeno 10 volte superiore*.

5 brevetti europei ed internazionali

Prodotto

Quantum
Plenoptic
Imaging

1 Immagine acquisita

Prodotto

Quantum
Plenoptic
Imaging

2 QPI: rifocalizza tutti i piani

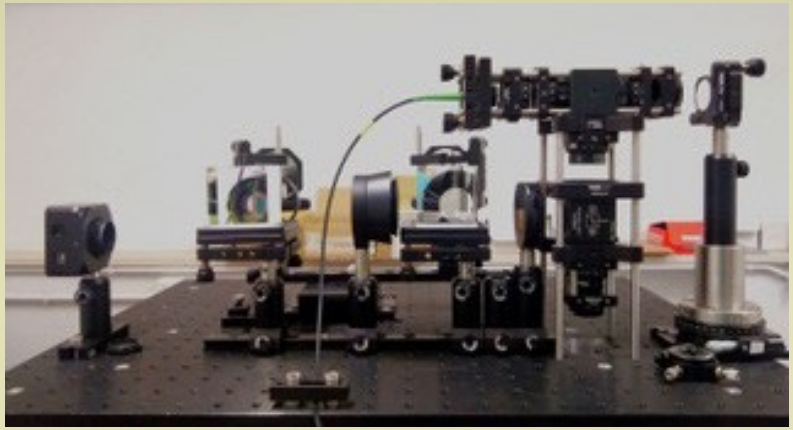
Prodotto

Quantum
Plenoptic
Imaging

3 QPI: cambio del punto di vista

1° prototipo

TRL 4



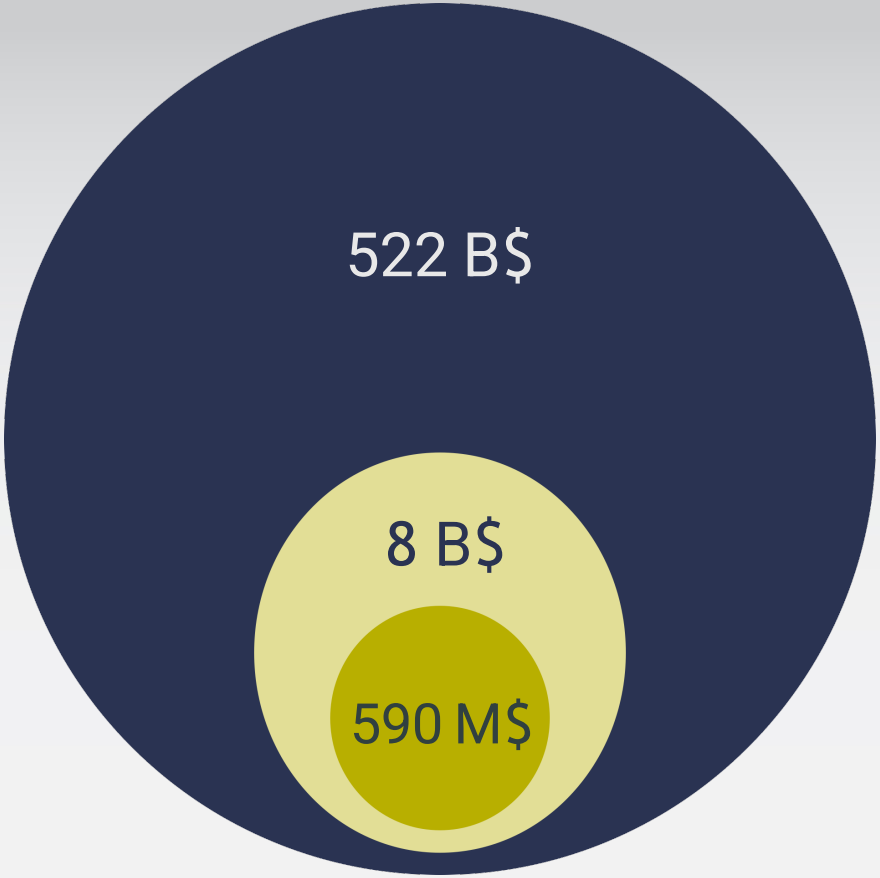
Sfrutta le correlazioni quantistiche della luce per fornire immagini 3D nitide, ad elevata velocità

Mercato

TAM Dispositivi per produrre immagini

SAM Microscopia

SOM Microscopi confocali



Competitors

Team

Milena D'Angelo
CSO

Progettazione di dispositivi quantistici

Augusto Garuccio
CEO

Gestione scientifica e amministrativa

Gianluca Scarcelli
CFO

Amministrazione, finanza e controllo

Francesco V. Pepe
CTO

Sviluppo di dispositivi quantistici

Collaboratori :
Francesco Mezzapesa
Davide Giannella

Disegno e sviluppo dei prototipi

Roadmap

OGGI
5 brevetti, TRL 4,
messa a punto 1° prototipo

GIUGNO 2022
Validazione prototipo
Costituzione startup

OTTOBRE 2022
Perfezionamento prototipo

FEBBRAIO 2023
Avvio B2B
Avvio 2° prototipo

GIUGNO 2023
Concessione know-how
Validazione nuovo prototipo

Funding Needs

R&D

- 25% Prototypes
- 40% Scient & tech developer
- 10% Patents

Adm

- 10% Administrative staff
- 10% General costs

Mar

- 5% Marketing

Call to Action

Team qualificato, motivato e coeso

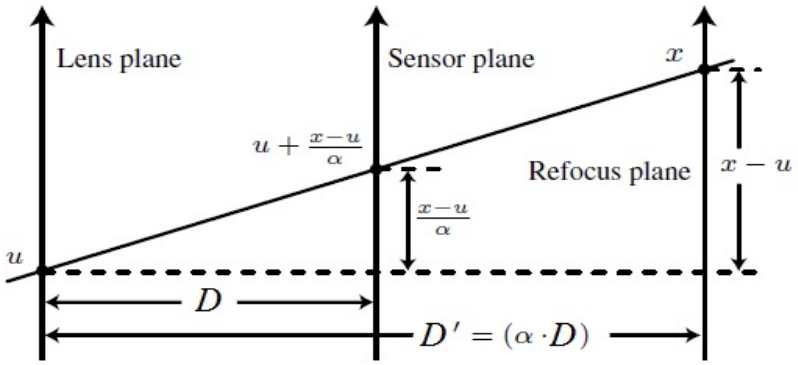
Tecnologia innnovativa

Vantaggio competitivo

- **QPI Systems**
- Tecnologie quantistiche per immagini

Ray acing → *Re*focusing

Ng et al., Tech. Rep. 2005



Shot

Refocused (post-proc.)

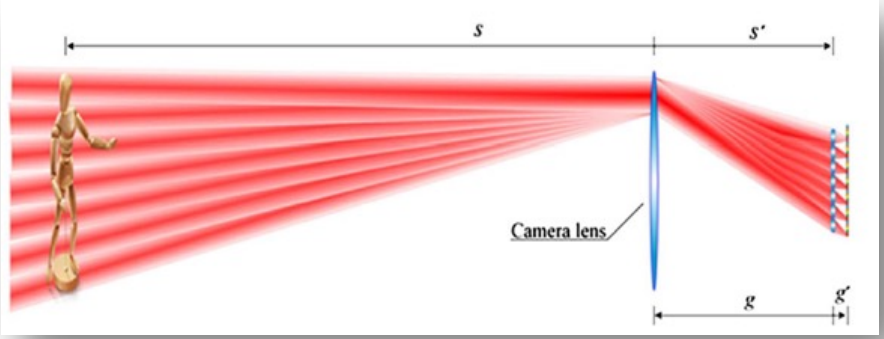
Rescaling the acquired radiance = Refocusing

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

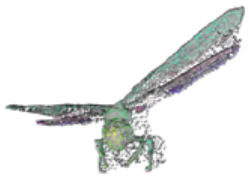
Refocused image:

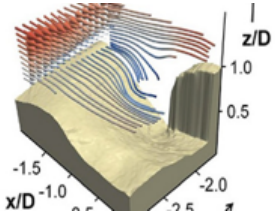
$$I_{\alpha D}(\boldsymbol{x}) \propto \int L_{\alpha D}(\boldsymbol{x},\boldsymbol{u})\, d^2u$$

Multi-perspective view



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

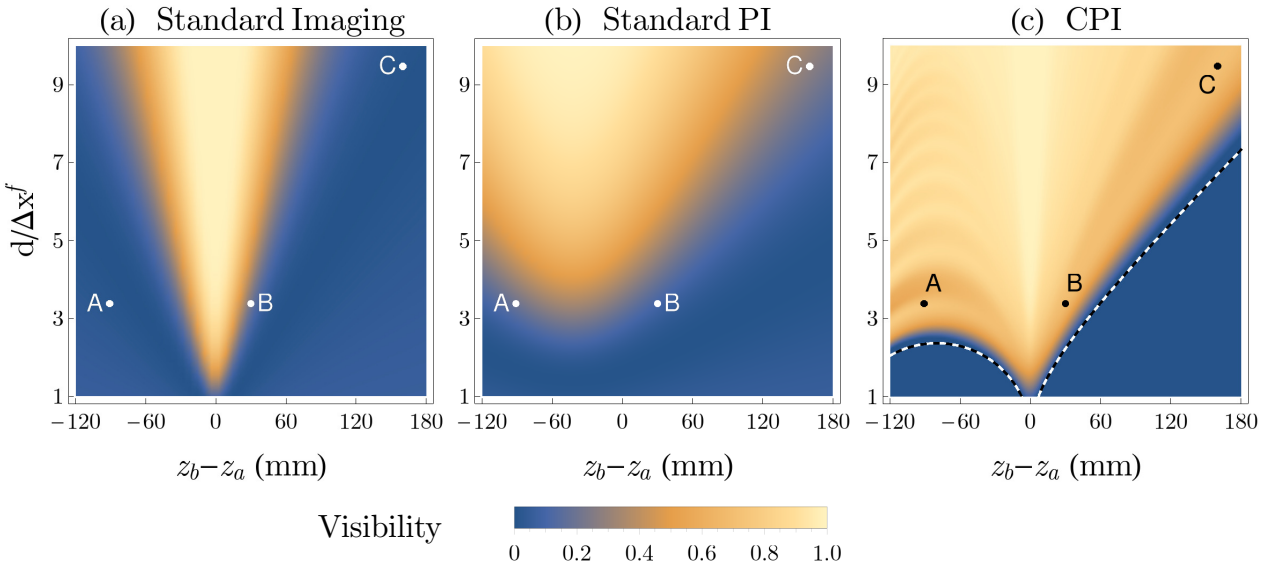




www.raytrix.de/

Resolution vs DOF improvement

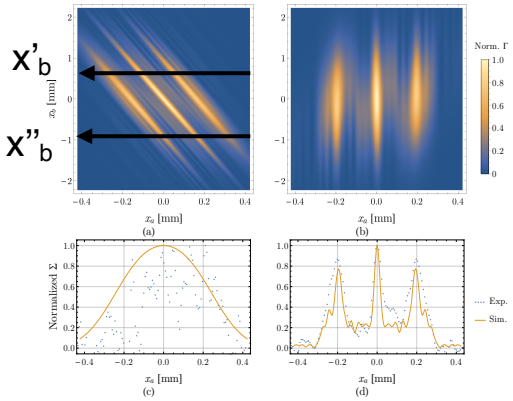
Pepe et al., PRL 119, 243602 (2017)



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

The physics behind QPI

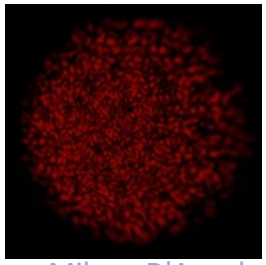
1) What makes refocusing possible:

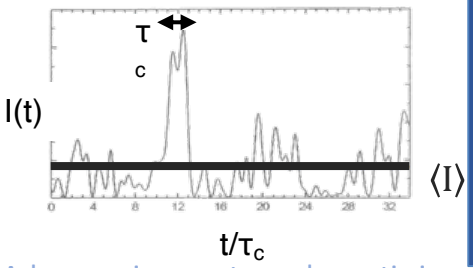


2) Numerical Aperture (NA) of the source/lens
→ Transverse resolution: λ/NA
→ Axial resolution: λ/NA^2

3) No chaos → no image !!!

Chaos = intensity fluctuations … Detectors need to follow them!

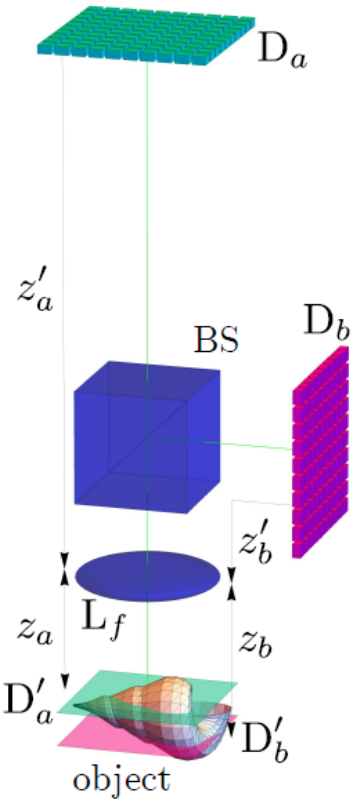




Need for:
- **Fast cameras**, with small exp. time !
- **Controllable sources** / spectrally filtered, …
- **Multiple acquisitions** (10^2-10^3 frames)
  → *Compressive Sensing & co.*

CPI between arbitrary planes

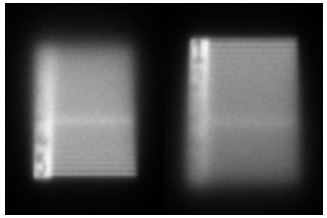
F. Di Lena, PhD thesis (2019) + PCT 2019 + F. Di Lena, et al, Opt. Exp. 2020



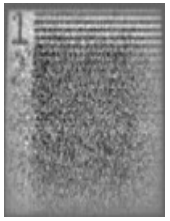
2 different arbitrary planes within the 3D object are focused by the lens on the two disjoint sensors

Acquired images

D_a D_b



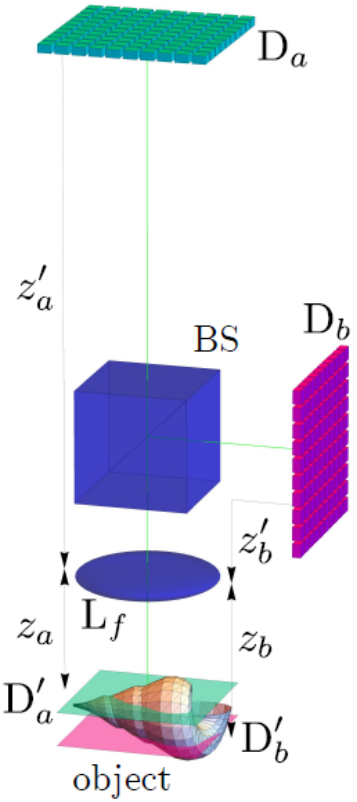
Refocusing

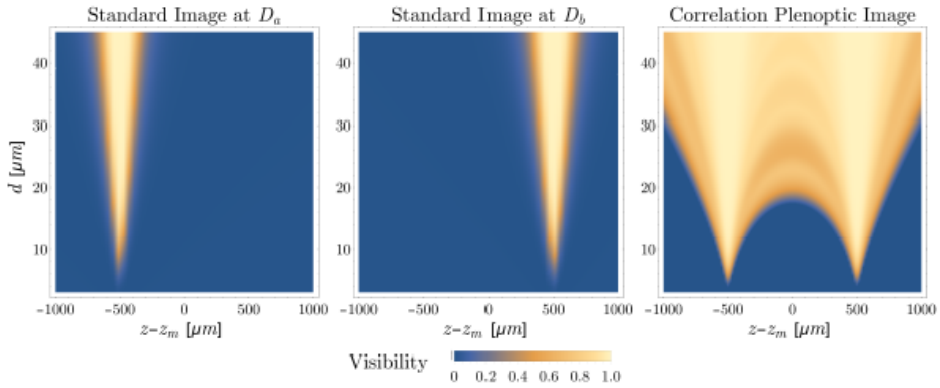


Stacked refocused image

CPI between arbitrary planes

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

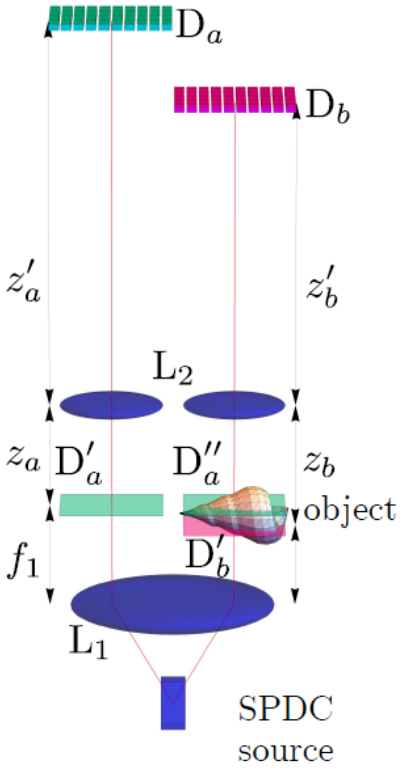




Single-lens CPI with highly improved DOF, & diffraction-limited resolution

Quantum CPI between arbitrary planes

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

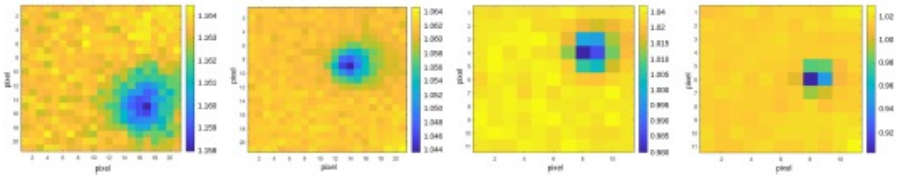


Is sub-shot-noise CLI possible?

Noise reduction factor (<1 for entangled light)

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

Noise reduction factor



σ = 1,16

σ =0,9

NRF does not carry plenoptic properties ! → searching for optimal measurements (e.g., differential CPI)

Advantages of QPI

- Refocusing out-of-focus images → simplifies optomechanics
- Depth of field extension, with high luminosity and SNR
- Parallel acquisition of multiple perspectives → 3D imaging

with

- Diffraction-limited resolution
- Unprecedented combination of resolution & depth of field
- 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

QUANTERA

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

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

Quantum technology: more security and improved imaging

21/Nov/2019

INFN Istituto Nazionale di Fisica Nucleare — Milena D'Angelo

planetek hellas — Maria Ieronymaki

EPFL — Claudio Bruschini

PALACKÝ UNIVERSITY OLOMOUC — Bohumil Stoklasa

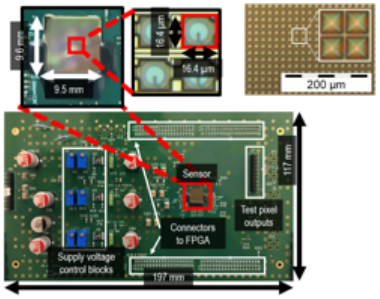
http://www.ba.infn.it/qu3d/index.html

C. Abbattista, et al., ***Towards Quantum 3D Imaging Devices,*** Appl. Sci. 2021, 11, 6414.

QUANTERA

Hardware speed-up

EPFL planetek hellas



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

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Processing optimization

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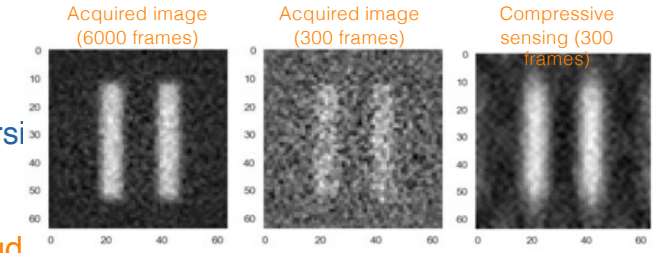
Compressive sensing

- Successfully applied to ghost imaging
- Recostruction of sub-sampled signal through sparsi the data
- Reducing number of frames by 1 order of magnitud



Quantum Fisher Information

- Exploits similarities between wave propagation and q. mechanics
- Maximum amount of information about relevant parameters
- Super-resolution and/or frame number optimization

Quantum tomography

- Recasting CPI as absorption tomography
- Absorption coefficient of 3D *voxels* is reconstructed through Maximum Likelihood
- Lack of artifacts from background

Exploring new CPI schemes

Single-lens CPI

- Performing CPI with only one lens
- Designed around a commercially available camera lens
- First steps towards a handheld device

CPI with entangled photons

- Exploits quantum correlations of entangled photon pairs
- Non-classical properties of light increase signal-to-noise ratio
- Aiming at sub-shot noise imaging with plenoptic properties
- Ideal for biomedical applications due to low photon-flux