Dottorato in Fisica – XXXI ciclo

Presentazione attività di dottorato
II anno

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Tutor: *Milena D'Angelo*
Saverio Pascazio

Why Correlation Plenoptic Imaging (CPI)?

- Traditional optical imaging: unavoidable trade-off between resolution and depth of field

$$\Delta x = \frac{0.61\lambda}{\mathrm{NA}} \qquad DOF \propto \frac{\lambda}{\mathrm{NA}^2}$$

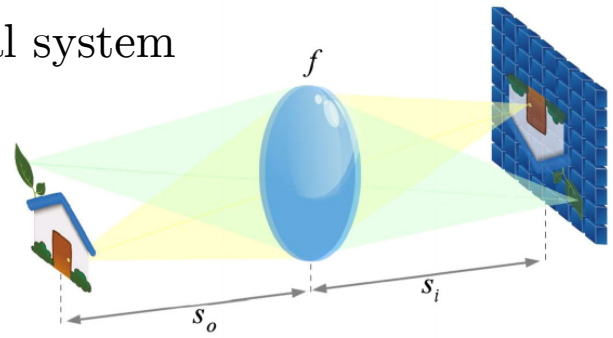
- Standard plenoptic: refocusing and 3D imaging capability, but DOF improvement offered is practical and not fundamental

$$\Delta x = \frac{0.61\lambda}{\mathrm{NA}} N_u \qquad DOF \propto \frac{\lambda}{\mathrm{NA}^2} N_u^2$$

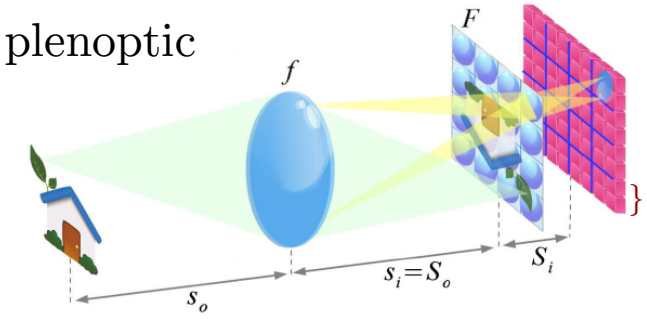
- CPI: refocusing and 3D capability without loosing resolution

$$\Delta x = \frac{0.61\lambda}{\mathrm{NA}} N_u \qquad DOF \propto \ldots$$

Traditional system

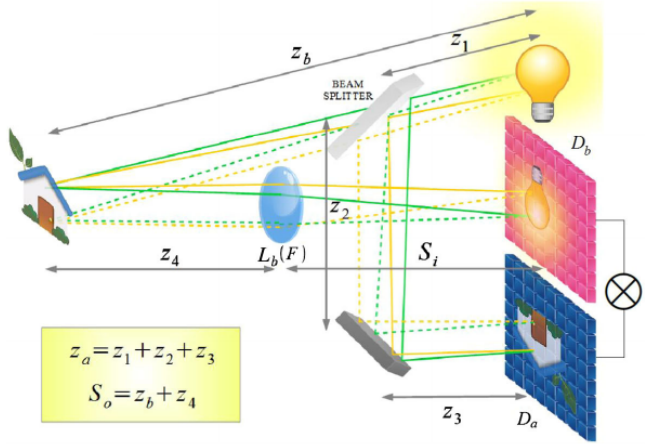


Standard plenoptic



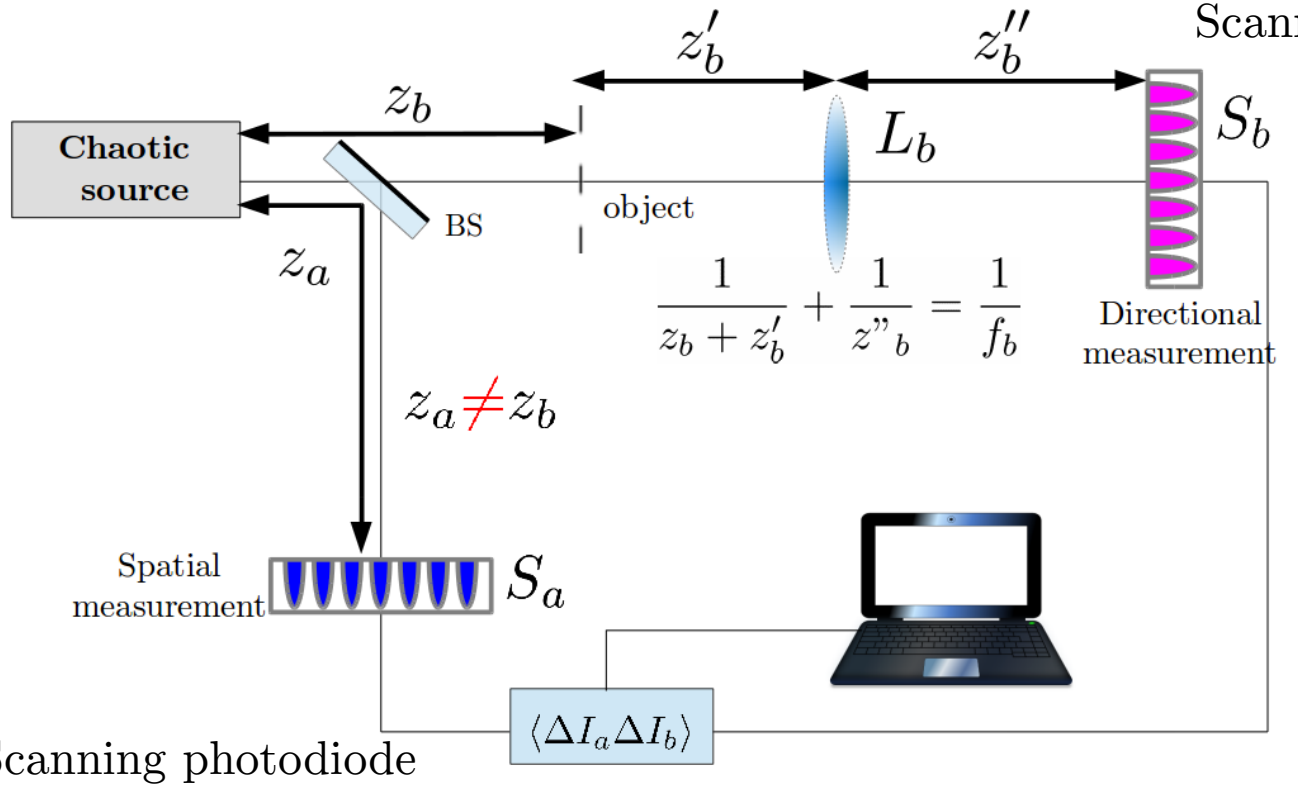
$N_u = 2$

CPI



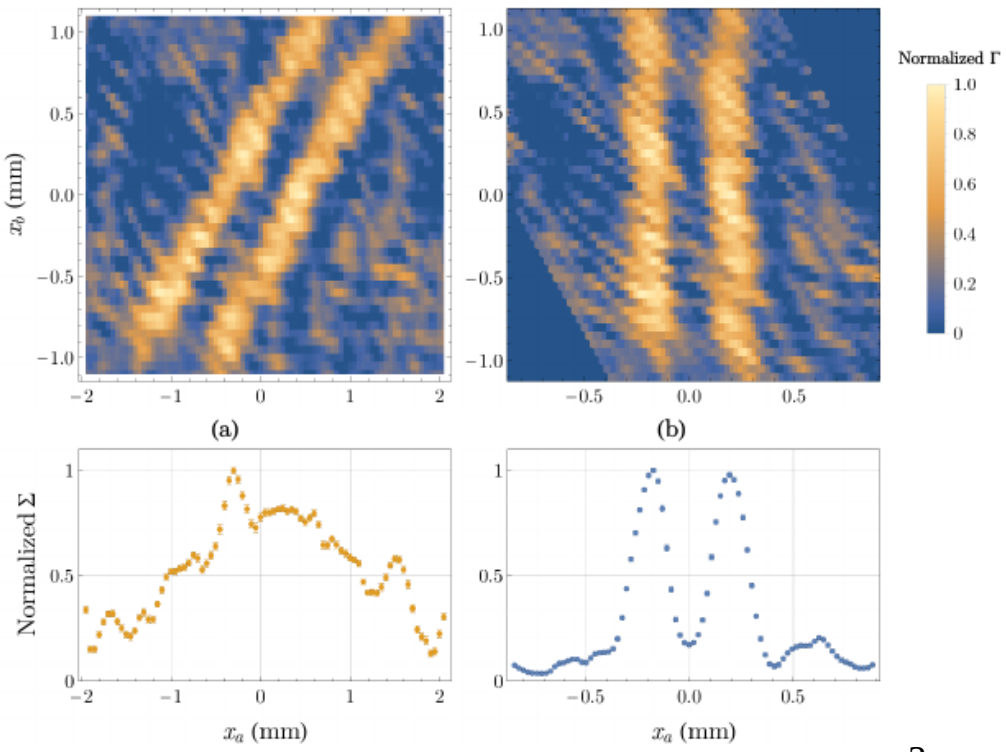
First experiment

Resolution:
$\Delta x^f = 120\ \mu m$



Scanning photodiode
(Thorlabs PDA36A-EC)

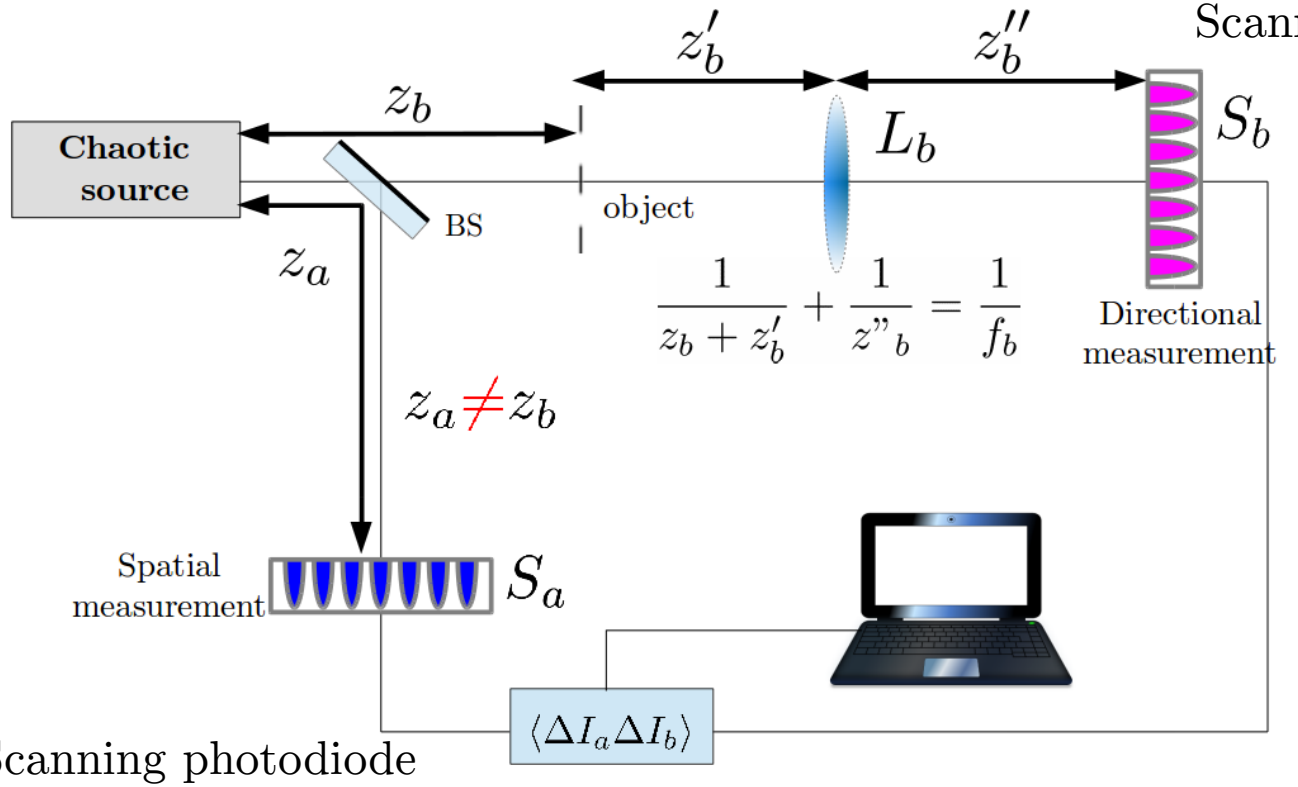
RAW data → Refocus



CPI has both refocusing capability
and diffraction limited resolution!

Toward 2D images

Resolution:
$\Delta x^f = 40\ \mu m$

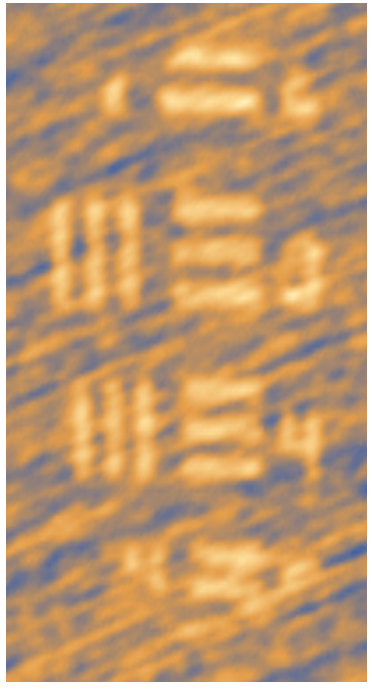


Scanning photodiode
(Thorlabs PDA36A-EC)

Test Target

d = 88 μm

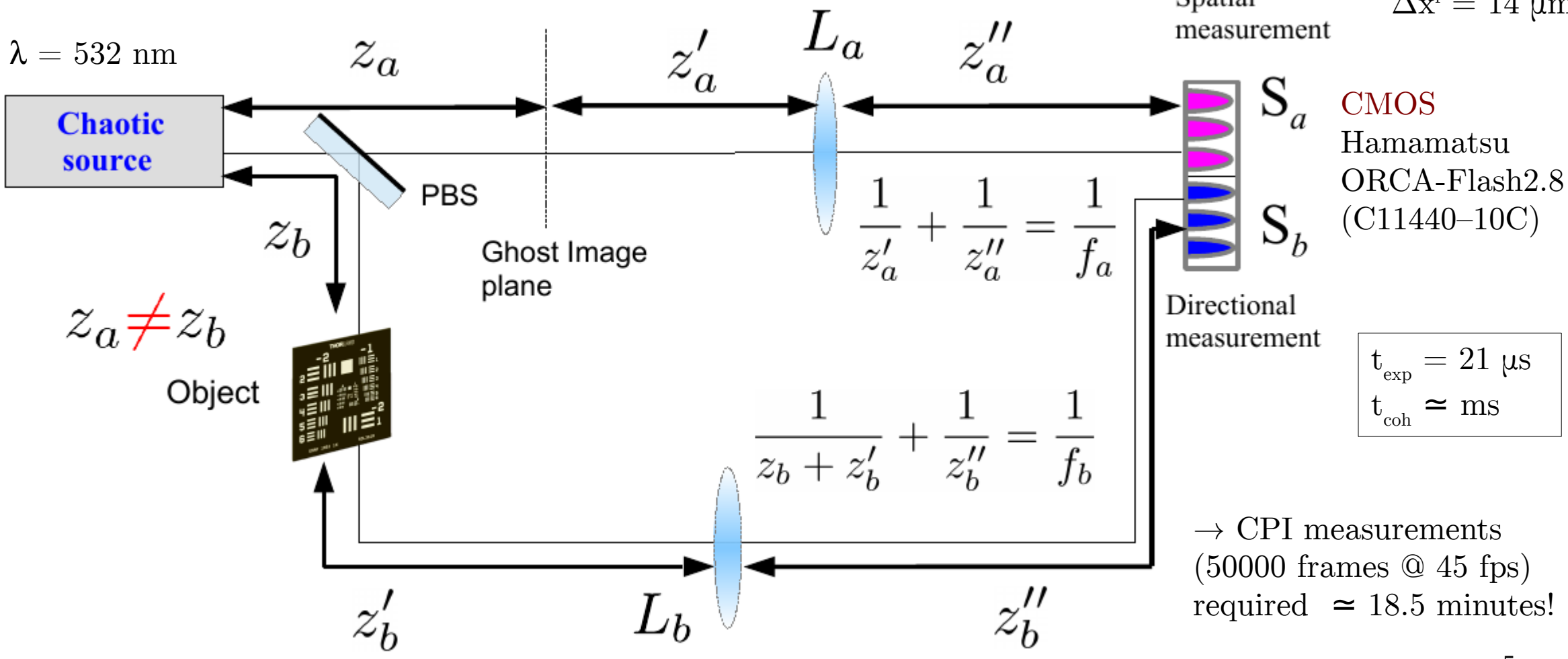
Ghost Image



Required ≃ 13 hours scanning.

CPI of 2D objects

Resolution:
$\Delta x^f = 14\ \mu m$

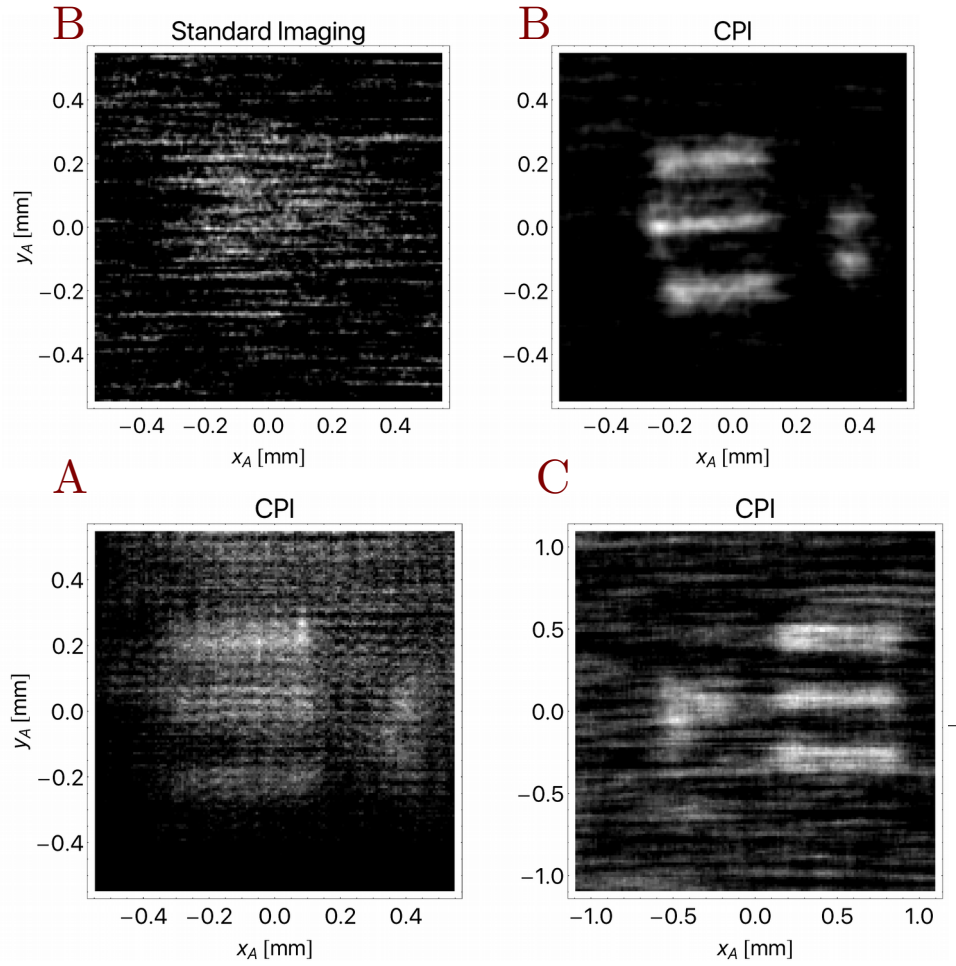


CMOS
Hamamatsu
ORCA-Flash2.8
(C11440–10C)

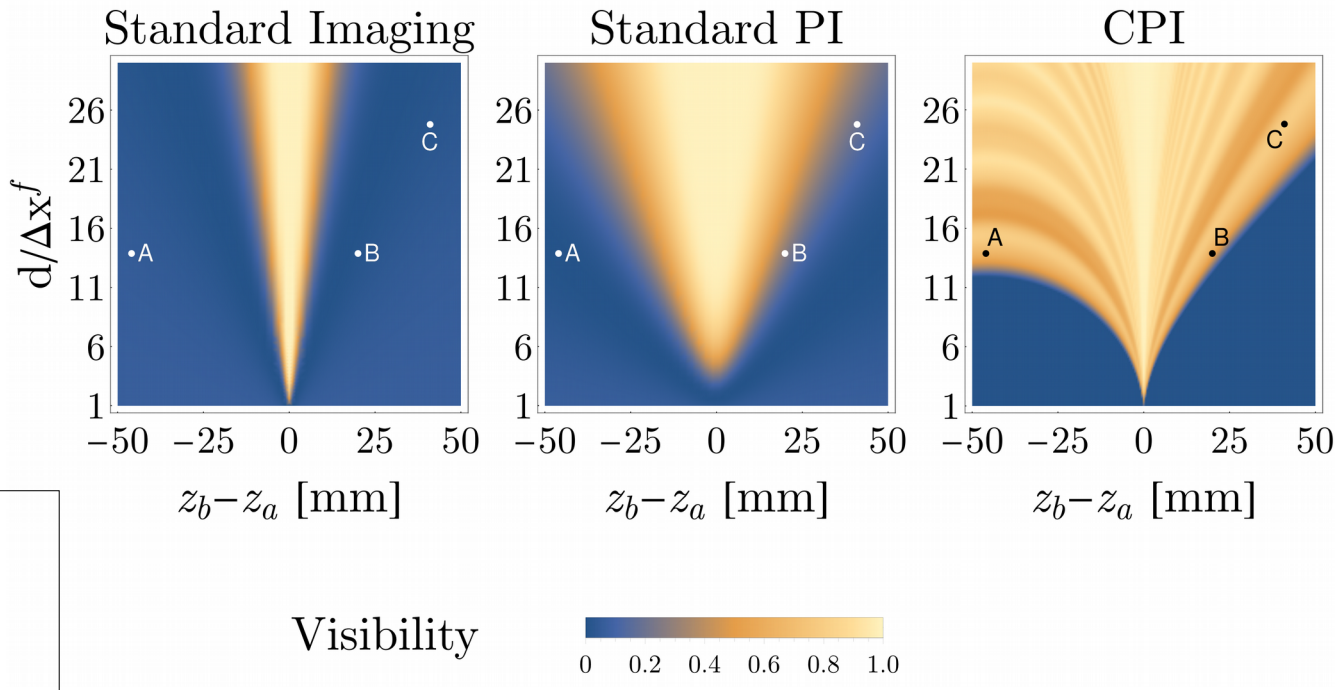
$t_{exp} = 21\ \mu s$
$t_{coh} \simeq$ ms

→ CPI measurements
(50000 frames @ 45 fps)
required ≃ 18.5 minutes!

Results: CPI refocus capabilities



Visibility of the image of a double slit
(distance d = 2 width)

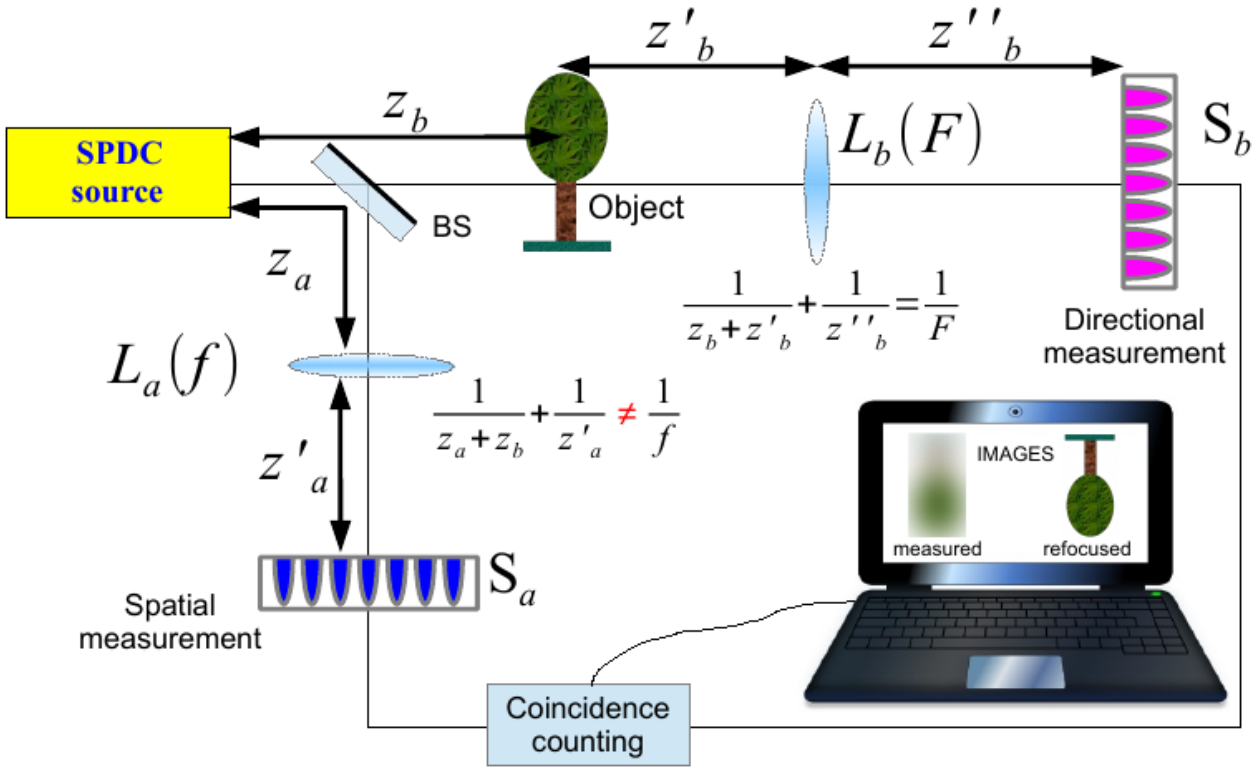


for d = 0.189 mm (A and C):

$$\frac{DOF_{CPI}}{DOF_{SI}} \simeq 7 \qquad \frac{DOF_{CPI}}{DOF_{SI}} \simeq 2.5$$

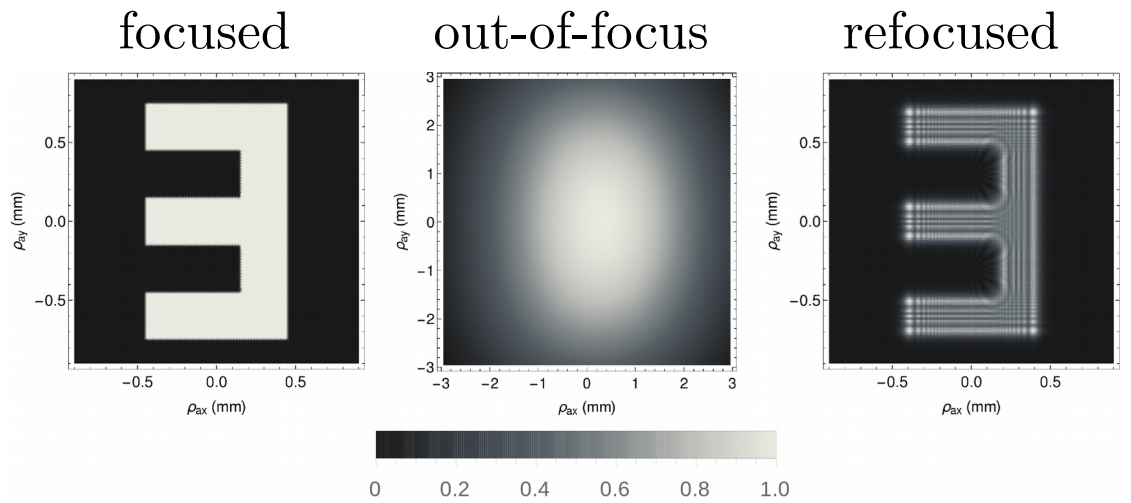
CPI enables refocusing in a much wider range than standard imaging and PI, while keeping the resolution of standard imaging!

CPI with entangled photons



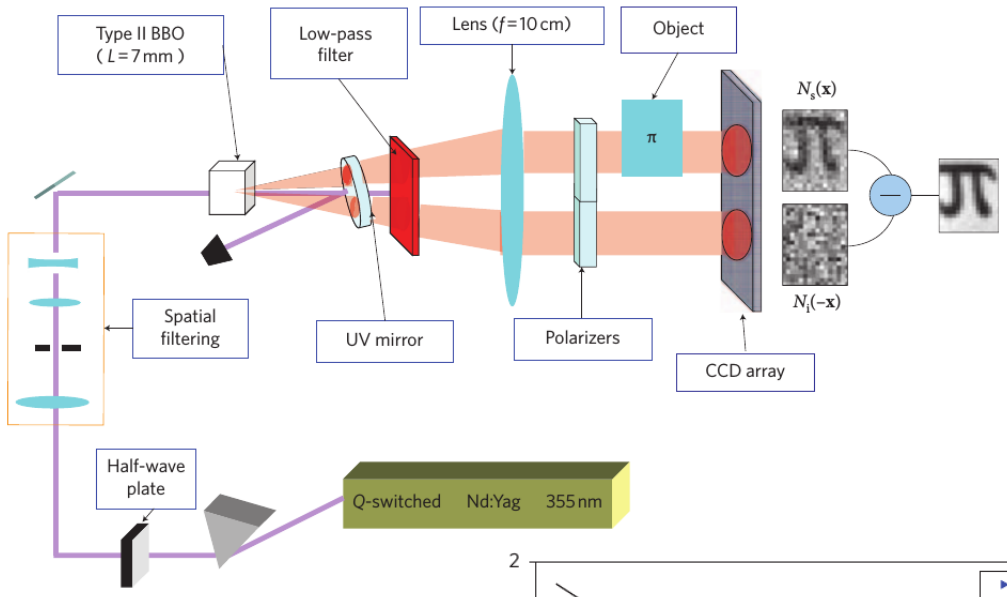
Numerical simulation

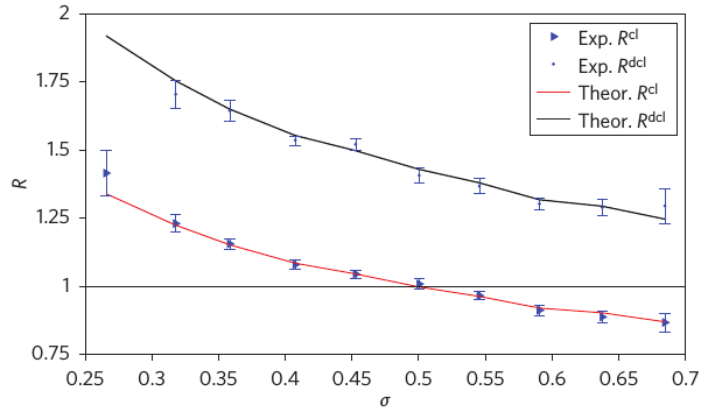
- $\lambda_p = 500$ nm
- $\Delta x^f = 6$ μm
- E thickness $= 0.2$ mm
- $z_b = z_{bF}/3$



F. V. Pepe, F. Di Lena, A. Garuccio, G. Scarcelli, and M. D'Angelo, "Correlation plenoptic imaging with entangled photons," Technologies, vol. 4, no. 2, p. 17, 2016

Why entangled photons?





Motivation:

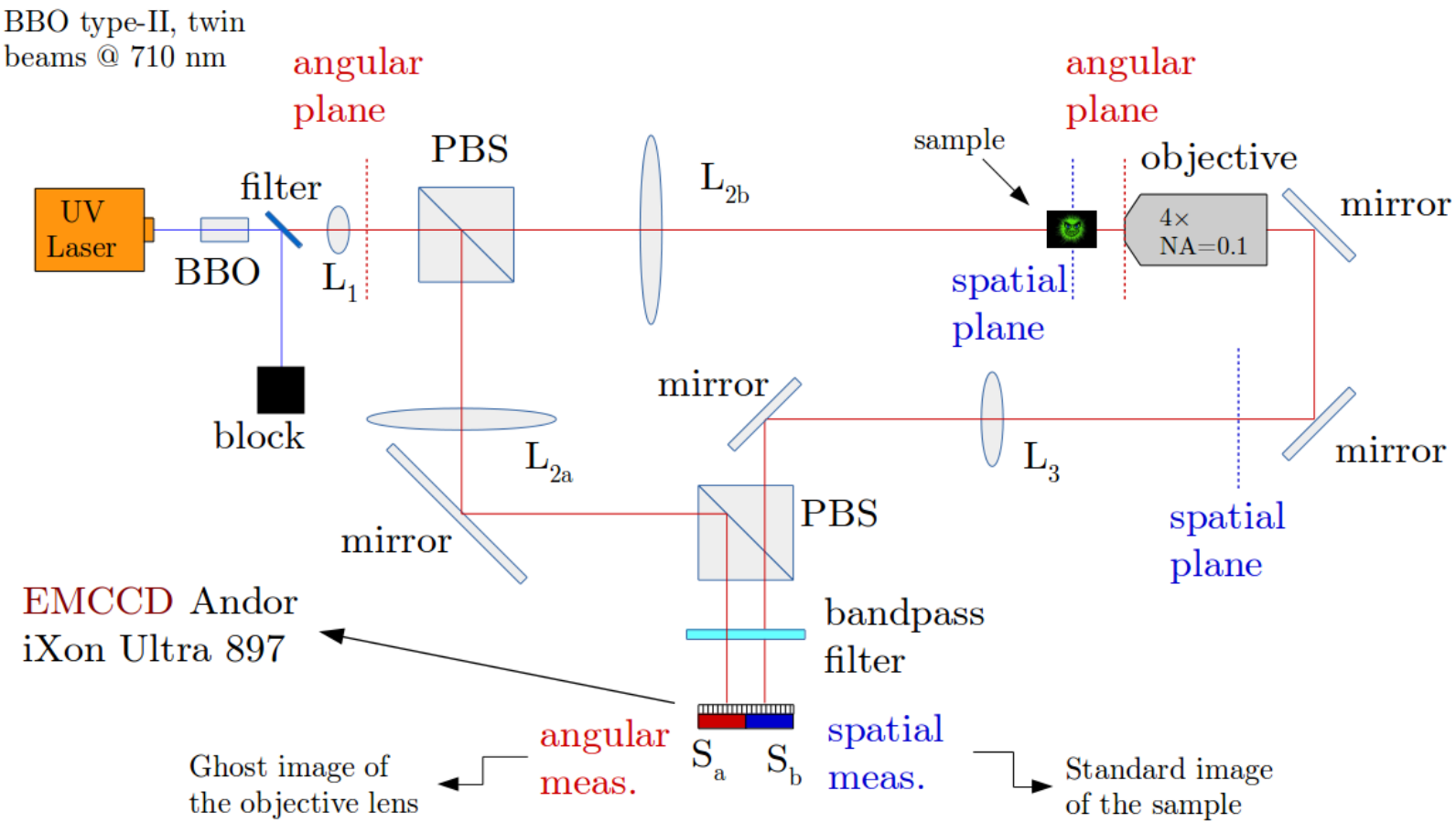
→ Entangled enables subshot noise imaging.

→ We aim at optimizing the SNR of CPI

→ Collaboration with INRiM

G. Brida, M. Genovese, and I. R. Berchera Nature Photonics, vol. 4, no. 4, pp. 227–230, 2010 @INRiM.

Setup CPI – SPDC



L_1: reproduces in its focal plane ("angular plane") the FT of the signal and idler beams ($f_1 = 10$ mm)

L_{2a} and L_{2b}: images the focal plane on the camera sensor S_a and objective lens respectively. ($f_2 = 50$ mm, $M_2 = 2$)

Objective (and L_3): reproduce the image of the sample on the camera (side S_b).

Resolution: $\Delta x^f = 9\ \mu m$

Plan of the exp measurements

Out-of-focus resolution

Standard Imaging:

$$\Delta x(s_o) \propto \frac{s_o\, D}{\sqrt{2}} \left| \frac{1}{s_o} - \frac{1}{s_o^f} \right|$$

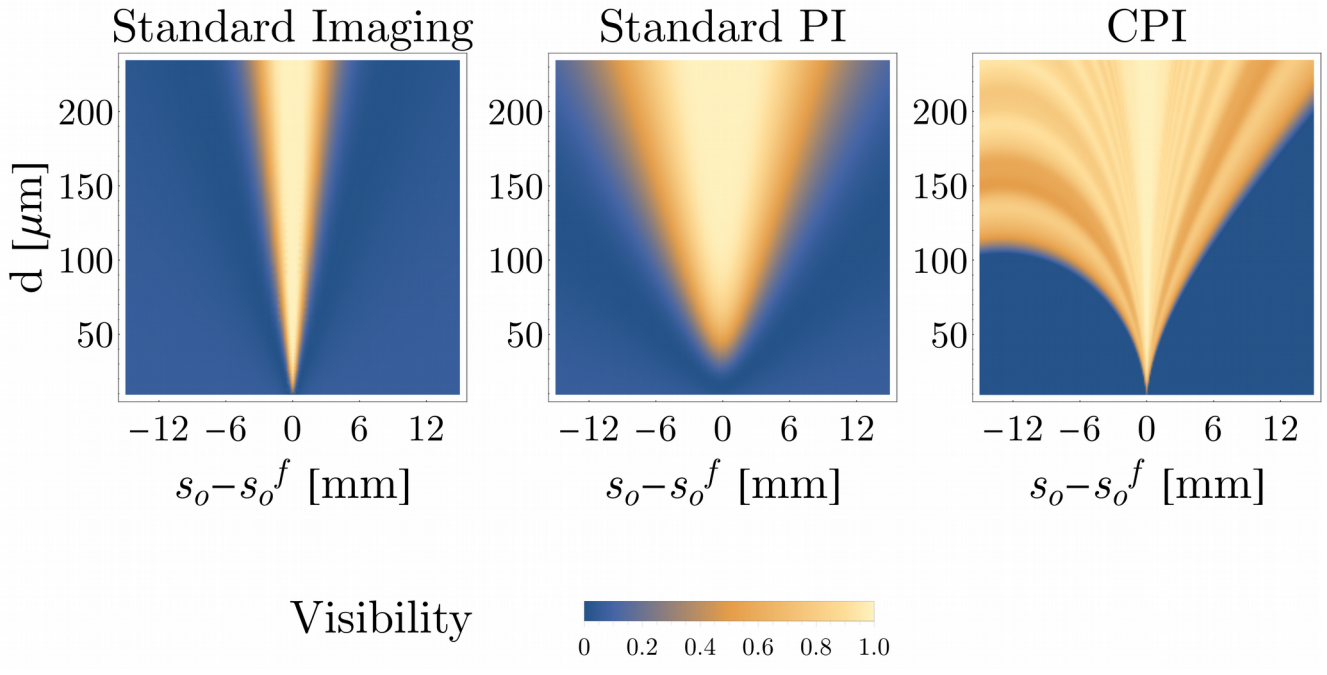
Plenoptic Imaging:

$$\Delta x(s_o) \propto \frac{s_o\, D}{\sqrt{2} N_u} \left| \frac{1}{s_o} - \frac{1}{s_o^f} \right|$$

CPI:

$$\Delta x(s_o) \propto s_o \sqrt{\frac{\lambda}{\pi} \left| \frac{1}{s_o} - \frac{1}{s_o^f} \right|}$$

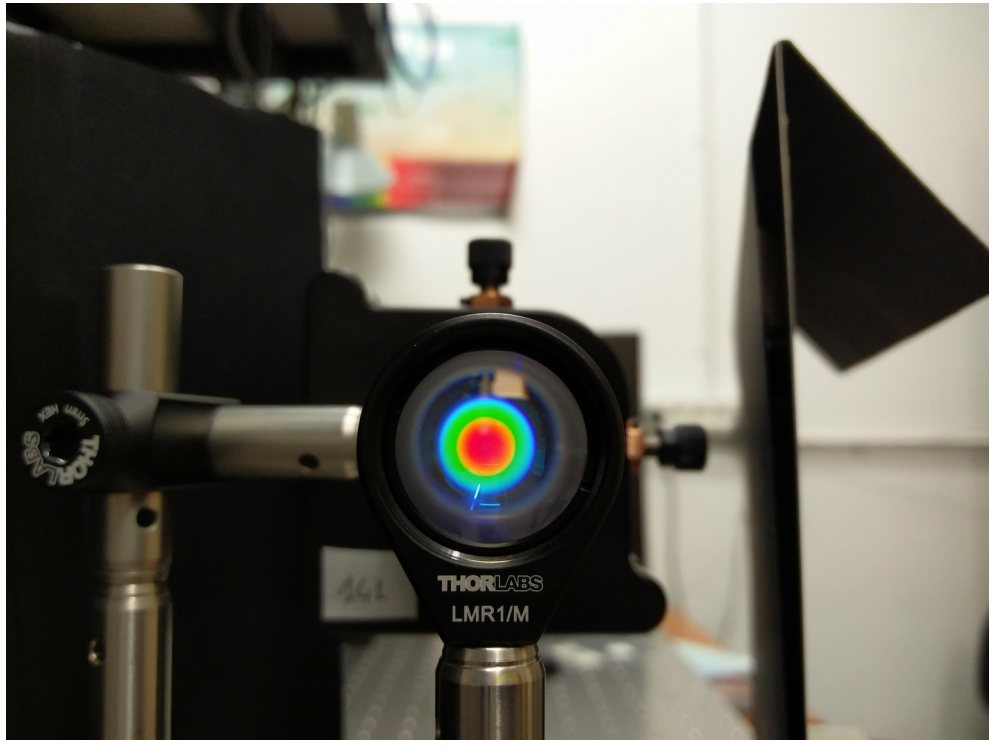
Visibility of the image of a double slit
Distance (d) = 2 width



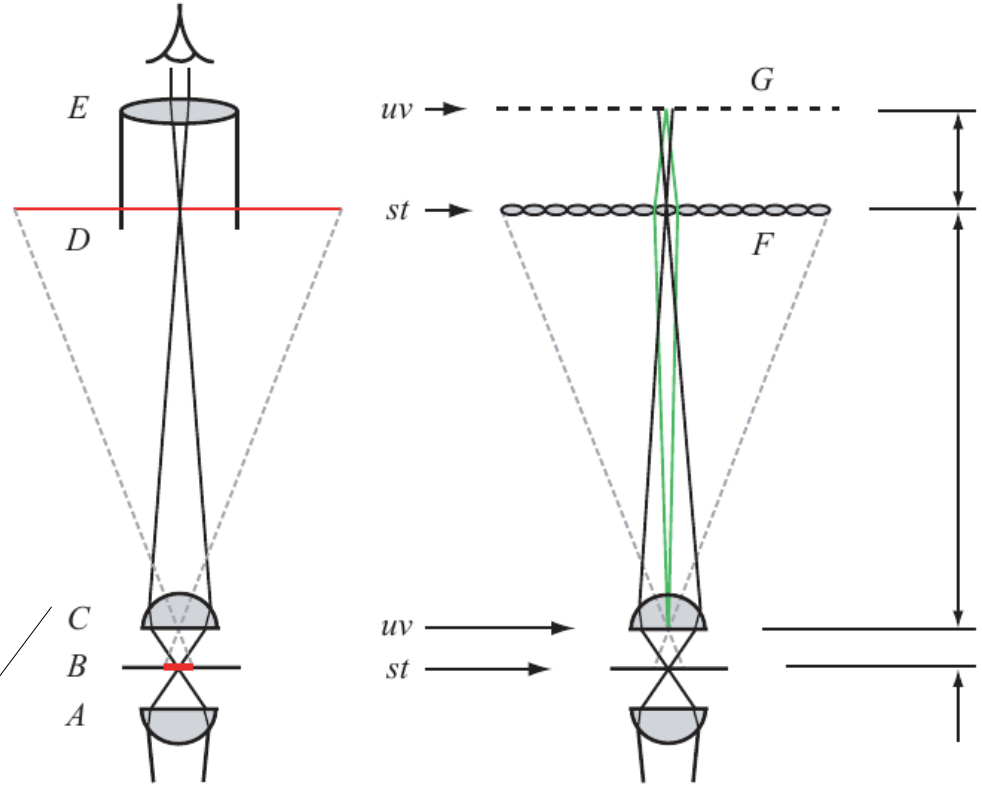
Expected DOF of the CPI is considerably better than standard imaging and better than standard PI.
Unlike standard PI the CPI keeps the resolution of standard imaging.

Third year objectives

Experimental realization of
CPI with entangled photons



Toward CPI microscope



Ordinary microscope Plenoptic microscope

M. Levoy, R. Ng, A. Adams, M. Footer, and M. Horowitz, ACM Trans. Graph. 25, 924 (2006).

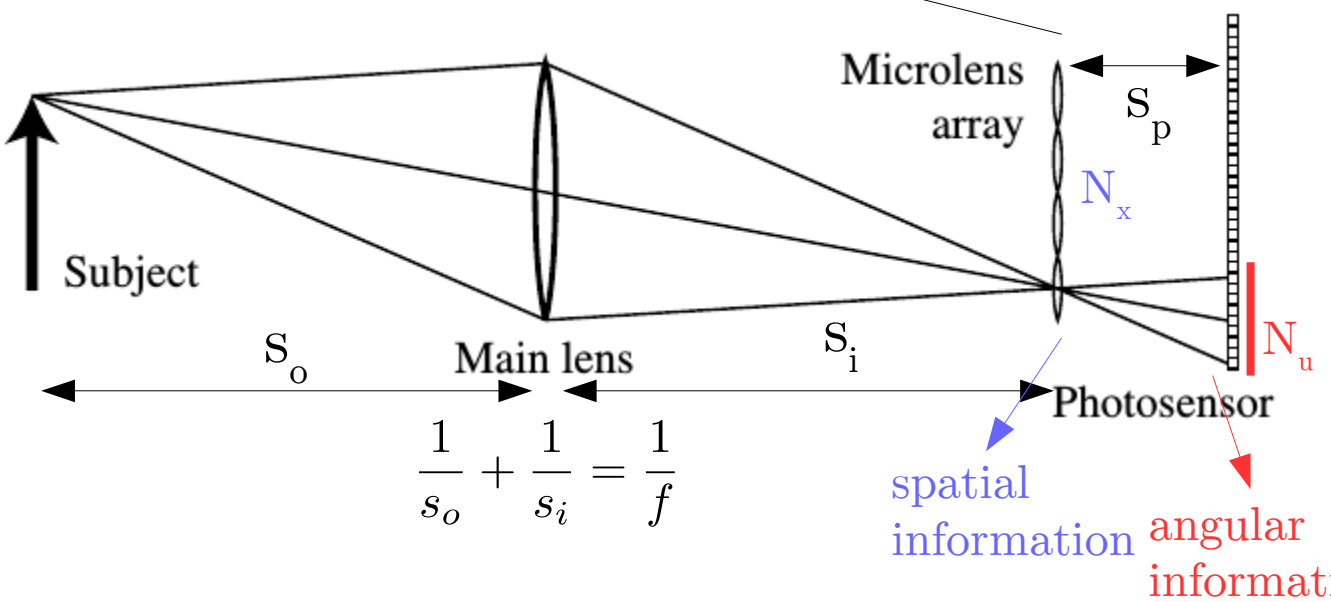
2nd year publications, schools and conferences

- Publications:
  - Francesco V. Pepe, Francesco Di Lena, Augusto Garuccio, Milena D'Angelo, "Correlation Plenoptic Imaging", Proc. SPIE 10333, 26 June 2017.
  - Francesco V. Pepe, Francesco Di Lena, Aldo Mazzilli, Eitan Edrei, Augusto Garuccio, Giuliano Scarcelli, and Milena D'Angelo, "Diffraction-limited plenoptic imaging with correlated light " under review (Physical Review Letters).
- Schools:
  - "International Training School - Beyond Conventional Tissue Imaging", Bari, february 22th – 24th 2017. "Correlation Plenoptic Imaging" (poster).
  - "9th Optoelectronics and Photonics Winter School" Folgaria (TN), march 26th – april 1th 2017. "Correlation Plenoptic Imaging" (poster).
- Conferences:
  - 103° congresso nazionale della SIF, Trento, september 14th – 15th 2017. "Imaging plenottico con misure di correlazione" (oral).
  - 37° congresso SISFA, Bari, september 26th – 29th 2017.
- Other activities
  - Guided tour at Quantum Optics lab, Conferenza Italiana Studenti di Fisica, Bari, may 11th – 12th 2017.
  - Exams completed.

Thank you for your attention!

Plenoptic imaging

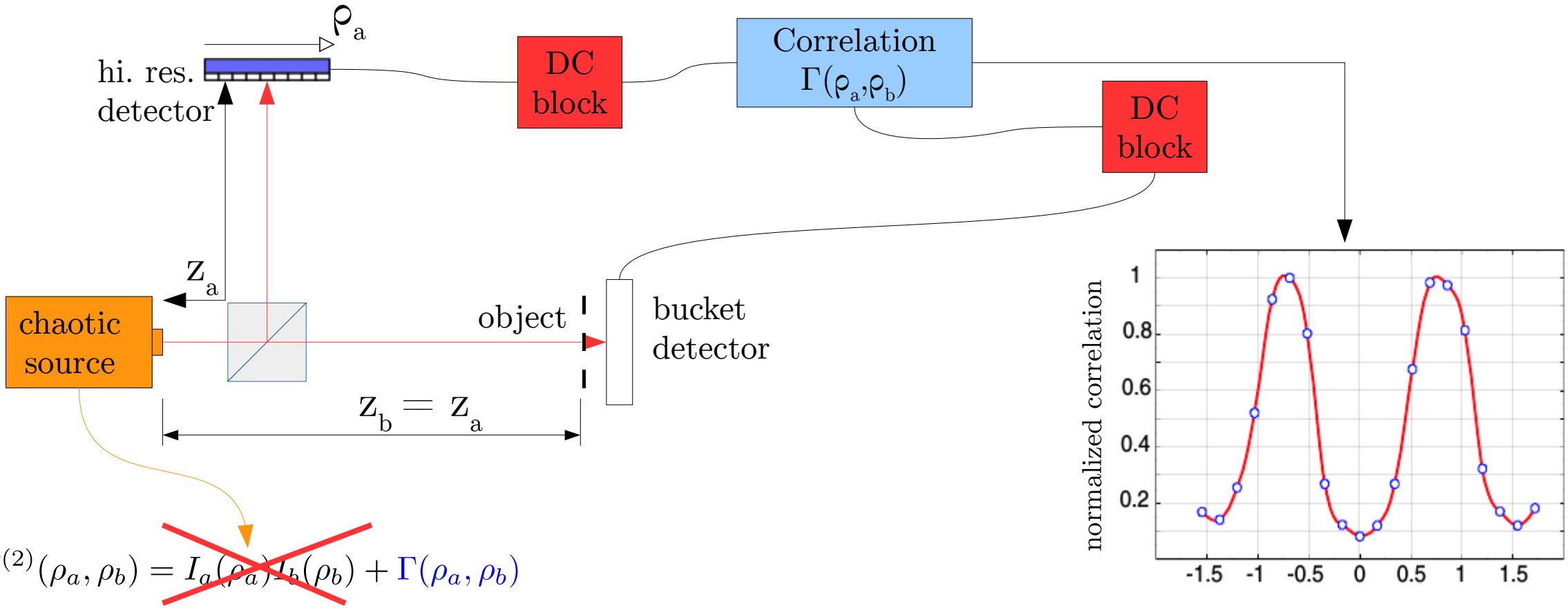
$$\frac{1}{s_i} + \frac{1}{s_p} = \frac{1}{f_{microlens}}$$



$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

- E. H. Adelson and J. Y. Wang, vol. 14, no. 2, pp. 99–106, 1992.
- R. Ng, M. Levoy, M. Brédif, G. Duval, M. Horowitz, and P. Hanrahan, vol. 2, no. 11, pp. 1–11, 2005
- https://www.raytrix.de/

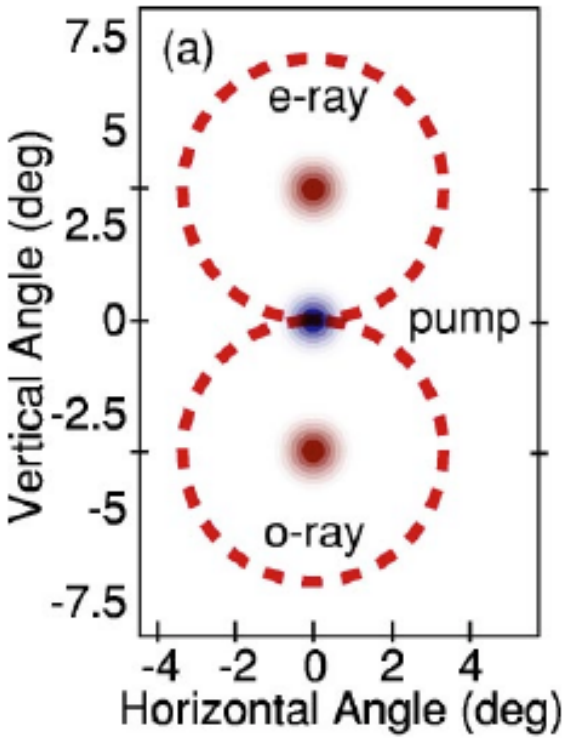
Ghost Imaging



$$G^{(2)}(\rho_a, \rho_b) = I_a(\rho_a) I_b(\rho_b) + \Gamma(\rho_a, \rho_b)$$

- A. Valencia, G. Scarcelli, M. D'Angelo, and Y. Shih, Physical Review Letters, vol. 94, no. 6, p. 063601, 2005.
- G. Scarcelli, V. Berardi, and Y. Shih, Physical Review Letters, vol. 96, no. 6, 2006

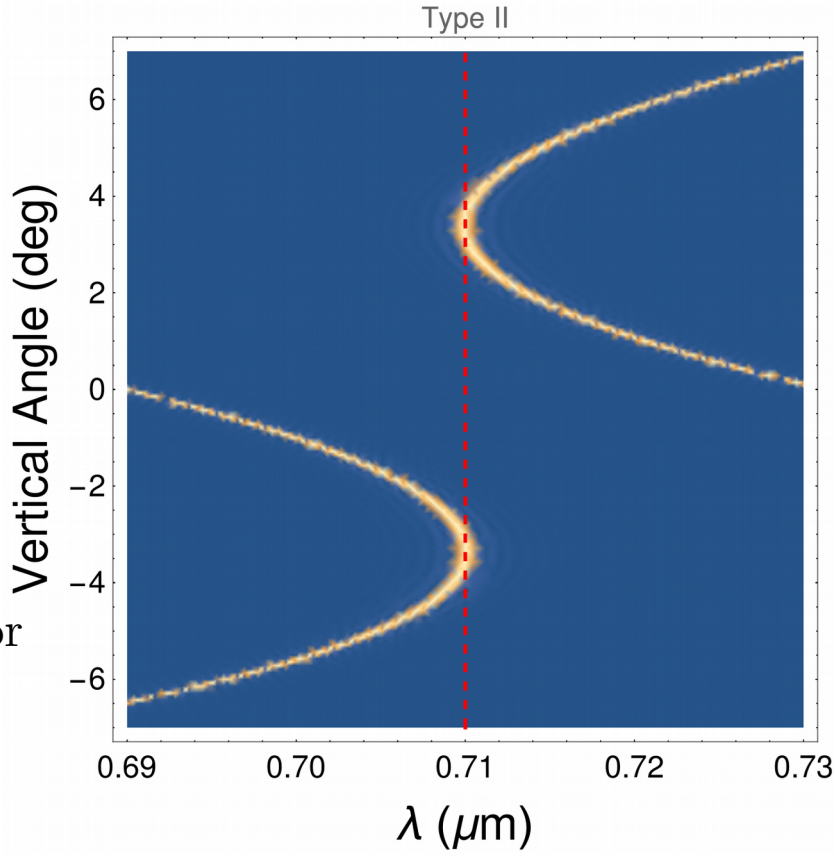
SPDC – type II beam like



$$\omega_p = \omega_s + \omega_i$$

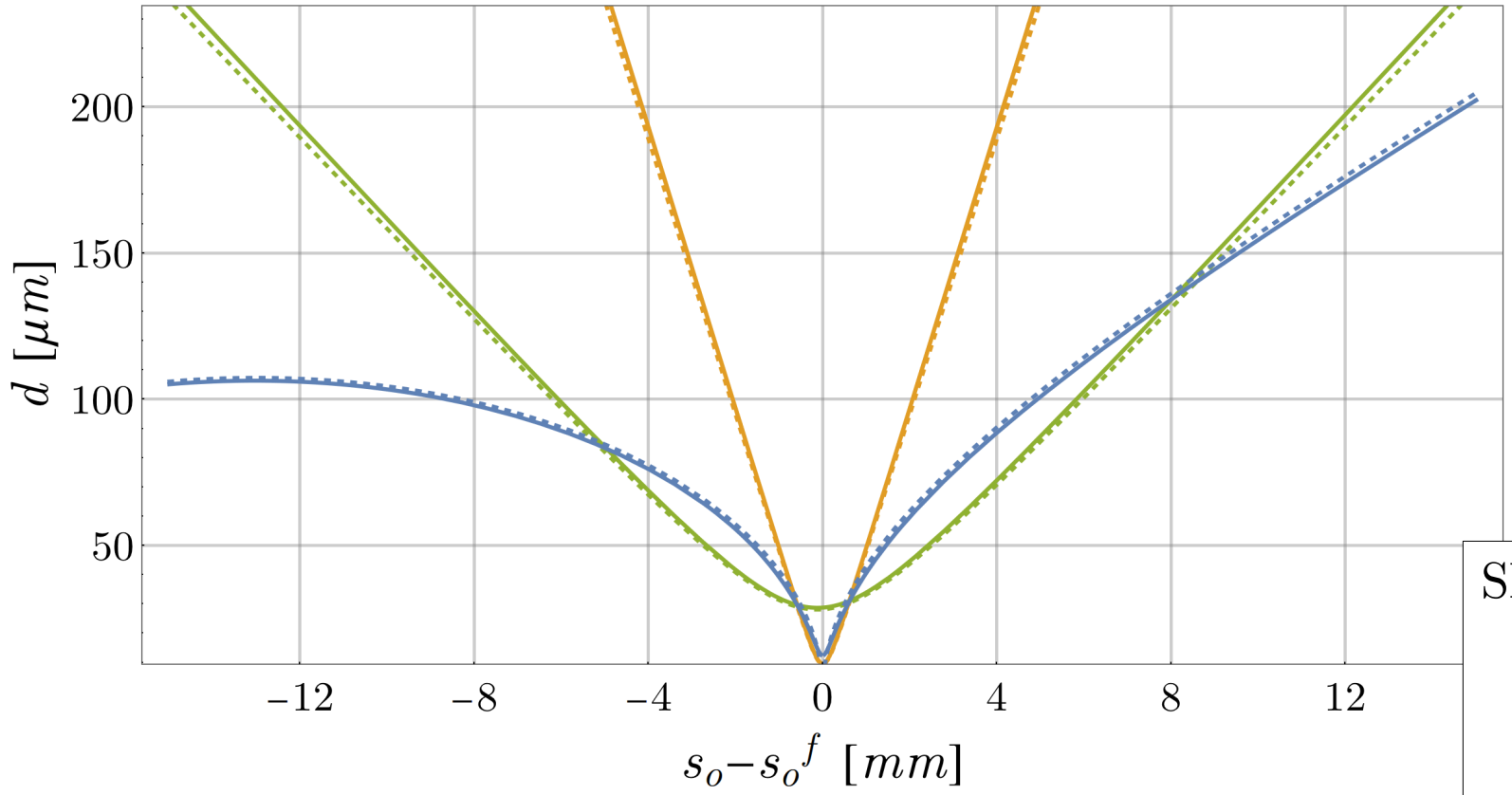
$$\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_i$$

Barium Borate (BBO) crystal (7 mm thick) cut for $\lambda = 355$ nm, type II collinear degenerate SPDC + additional tilt



Y.-H. Kim, Physical Review A, vol. 68, no. 1, p. 013804, 2003.

Depth of field comparison



Dotted line
→ simulation
continuous line
→ PSF width

Out-of-focus resolution

SI:

$$\Delta x(s_o) \propto \frac{s_o\, D}{\sqrt{2}} \left| \frac{1}{s_o} - \frac{1}{s_o^f} \right|$$

CPI:

$$\Delta x(s_o) \propto s_o \sqrt{\frac{\lambda}{\pi} \left| \frac{1}{s_o} - \frac{1}{s_o^f} \right|}$$

Expeted DOF of the CPI is considerably better than standard imaging (SI) and better than standard PI. The latter has no diffraction limited resolution in focus.