UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO
DIPARTIMENTO INTERATENEO DI FISICA "MICHELANGELO MERLIN"

Dottorato in Fisica – XXXI ciclo

Presentazione attività di dottorato
I anno

Dottorando: *Francesco Di Lena*

Tutor: *Milena D'Angelo*
Saverio Pascazio

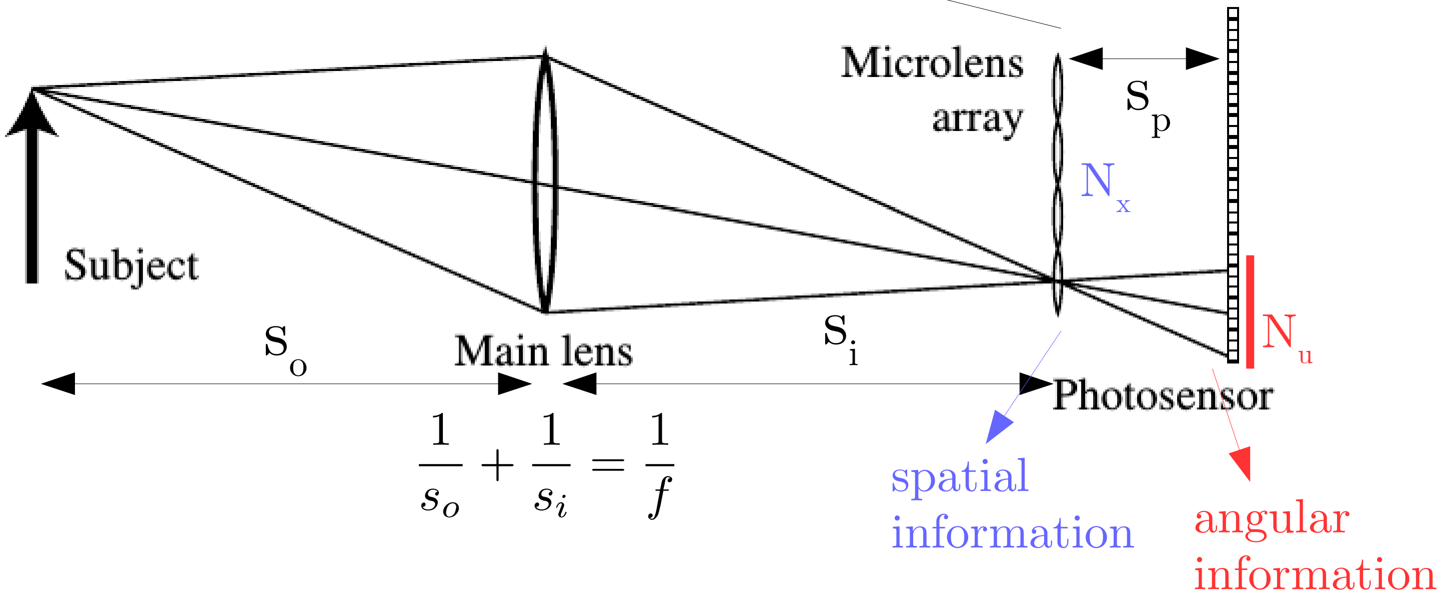
Summary

- Basic concepts:
  - Plenoptic imaging
  - Correlation imaging
- Activities:
  - Correlation plenoptic imaging (CPI) with entangled photons
  - Correlation plenoptic imaging with chaotic light
- Second year objectives
- Publications, conferences, exams

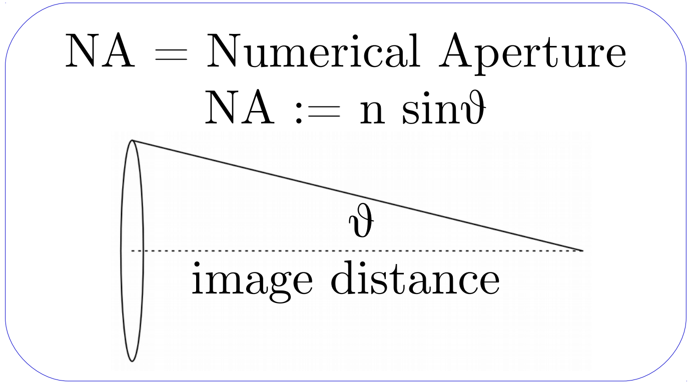
Basic concepts

plenoptic imaging

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



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



N_x = number of microlenses

N_u = number of pixel for each microlens

- 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/

Basic concepts

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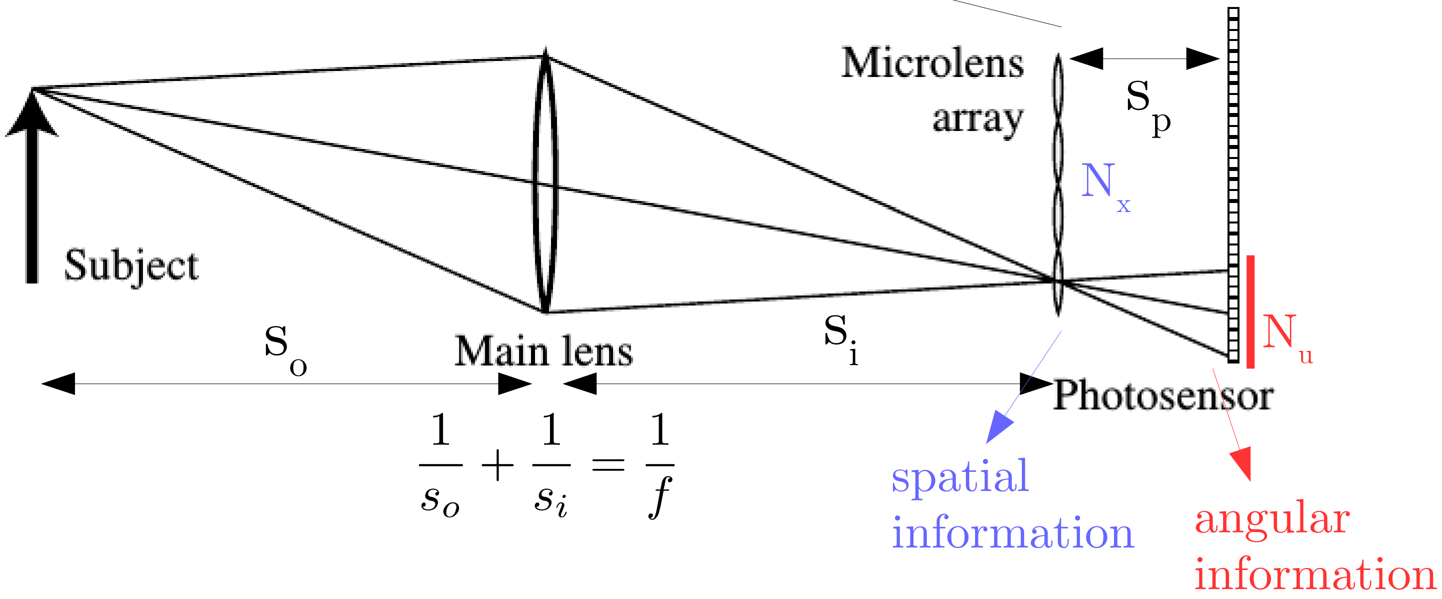

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

RAW data

- E. H. Adelson and J. Y. Wang, vol. 14, no. 2, pp. 99–106, 1992.
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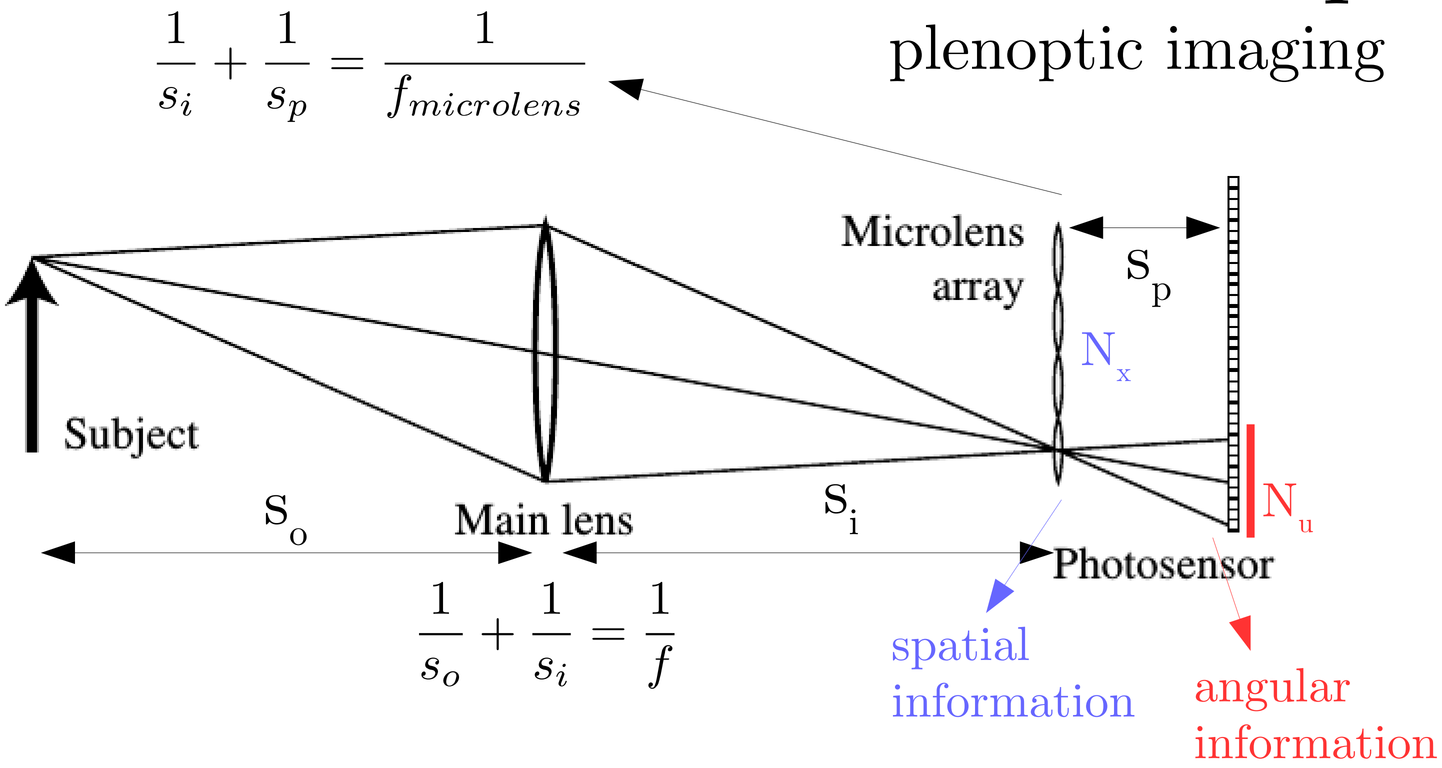
Basic concepts

plenoptic imaging



refocus on the nearest subject

- 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
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Basic concepts

plenoptic imaging

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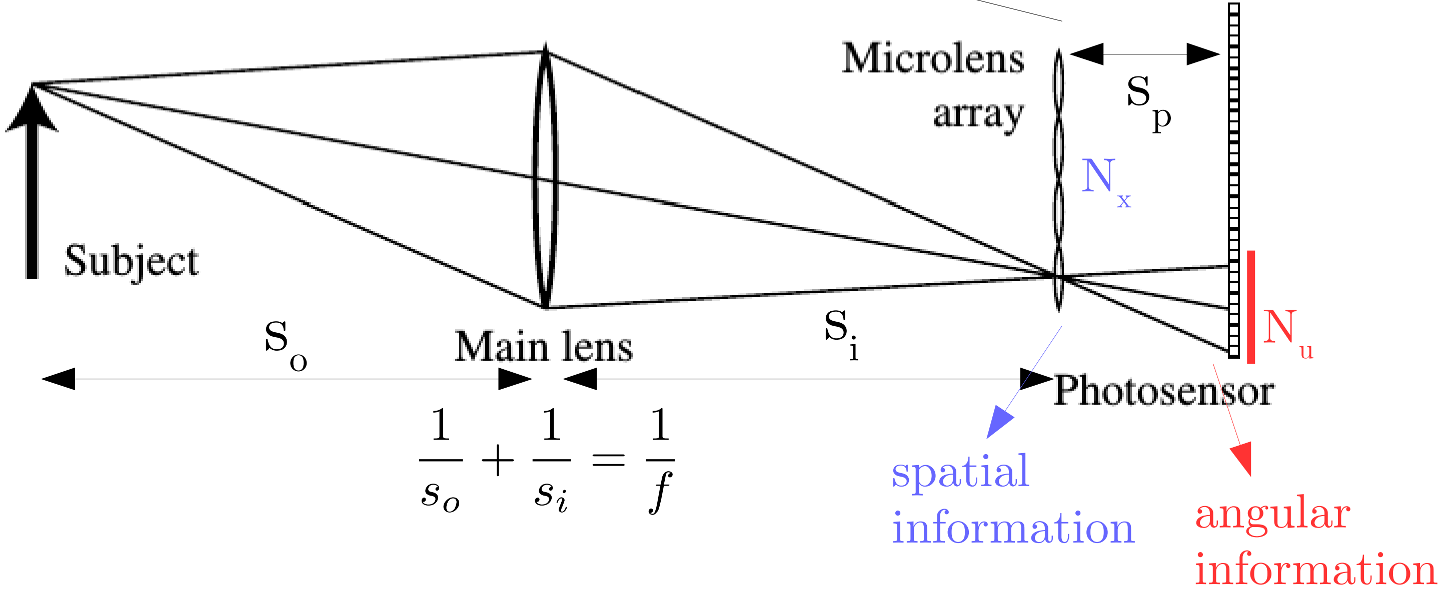

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

refocus on the farthest subject

- 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/

Basic concepts

plenoptic imaging

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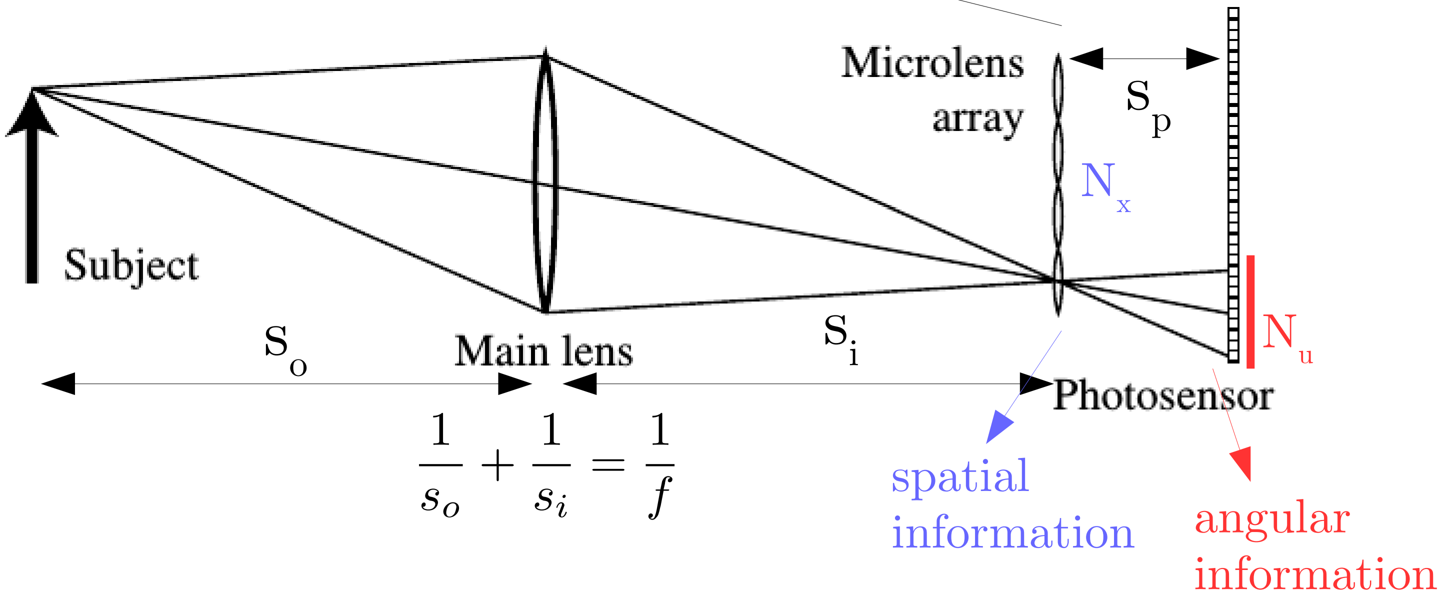


$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

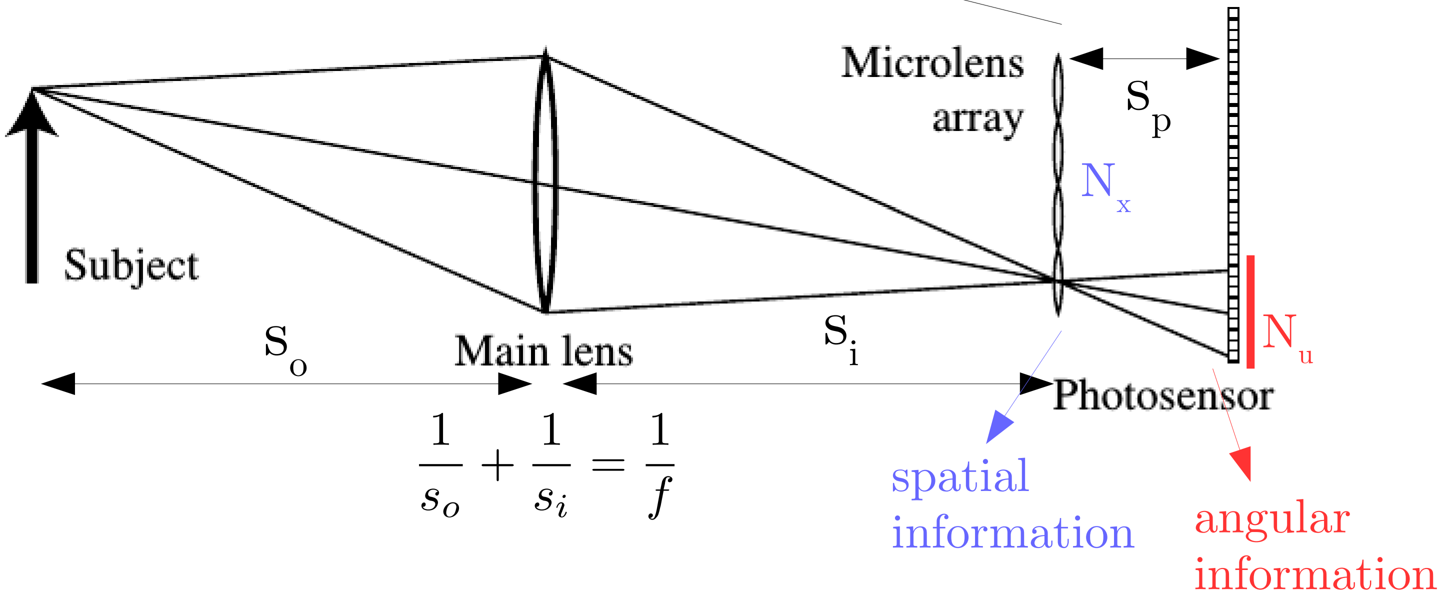
extended depth of field image

- 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/

Basic concepts

plenoptic imaging

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



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

Strong trade off between resolution and depth of field:

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

extended depth of field image

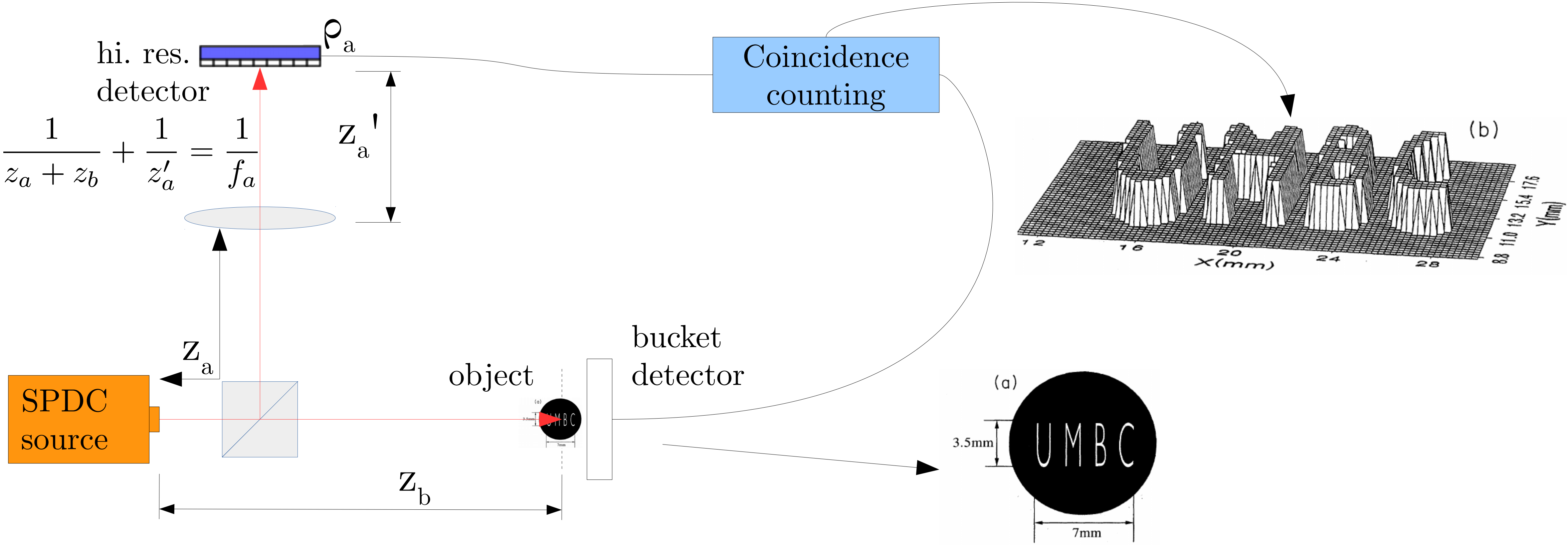
Application:

- 3D optical inspection
- Capture both 3D particle positions and 3D particle velocities in a volume
- 3D Microscopy

- 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/

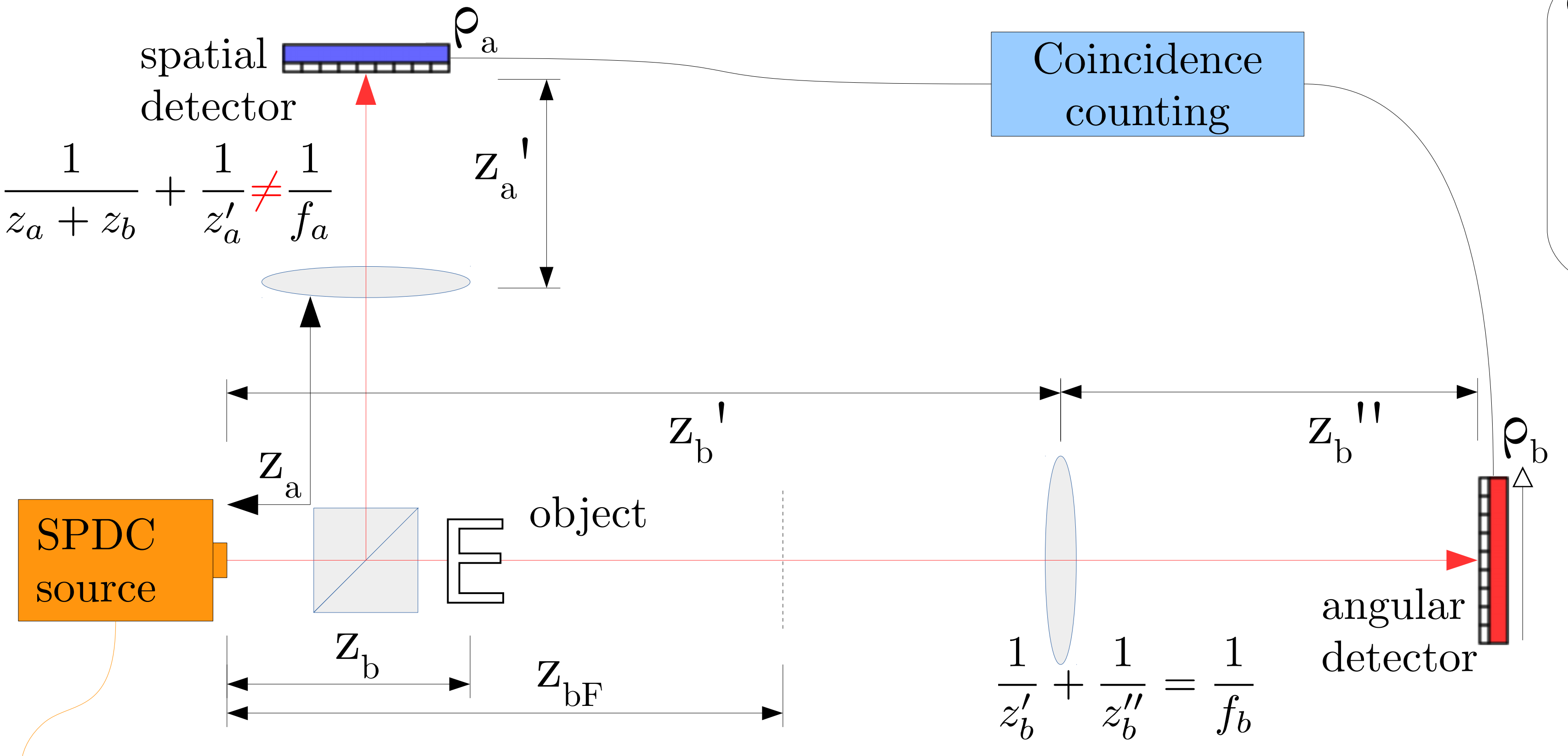
Basic concepts:

correlation (ghost) imaging



➢ T. Pittman, Y. Shih, D. Strekalov, and A. Sergienko, Physical Review A, vol. 52, no. 5, p. R3429, 1995.
➢ T. Pittman, D. Strekalov, D. Klyshko, M. Rubin, A. Sergienko, and Y. Shih, Physical Review A, vol. 53, no. 4, p. 2804, 1996.

Correlation Plenoptic Imaging (CPI) with entangled photons



Glauber correlation function

$$G^{(2)}(\rho_a, \rho_b; t_a, t_b) = \langle E_a^{(-)}(\rho_a, t_a) E_b^{(-)}(\rho_b, t_b) E_a^{(+)}(\rho_a, t_a) E_b^{(+)}(\rho_b, t_b) \rangle$$

↓

The second order correlation function is characterized by plenoptic property

↓

It enables refocusing

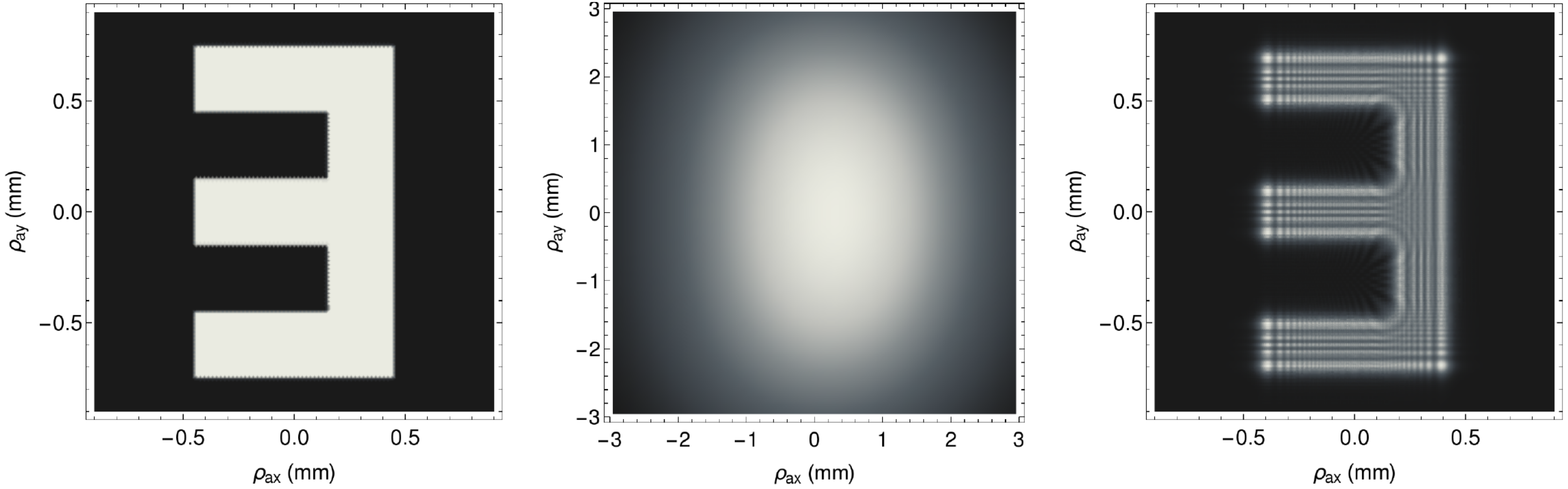
$$|\Psi\rangle = \mathcal{N} \int d\nu s(LD\nu) \int d\boldsymbol{\kappa}_i d\boldsymbol{\kappa}_s h_{\text{tr}}(\boldsymbol{\kappa}_i + \boldsymbol{\kappa}_s) a^\dagger_{\boldsymbol{k}_i} a^\dagger_{\boldsymbol{k}_s} |0\rangle$$

- 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

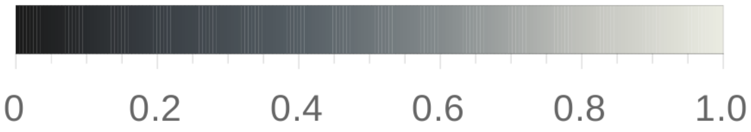
CPI with entangled photons

our numerical results

focused $z_b = z_{bF}$ — out-of-focus $z_b = z_{bF}/3$ — refocused $z_b = z_{bF}/3$



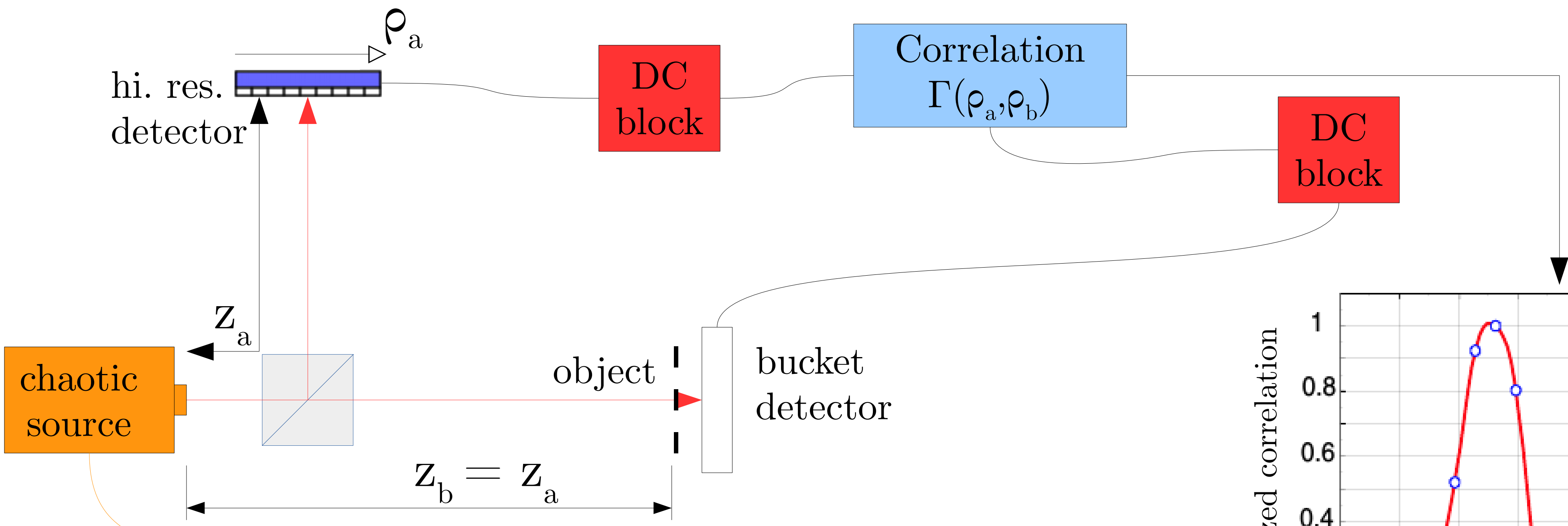
E thickness = 0.2 mm

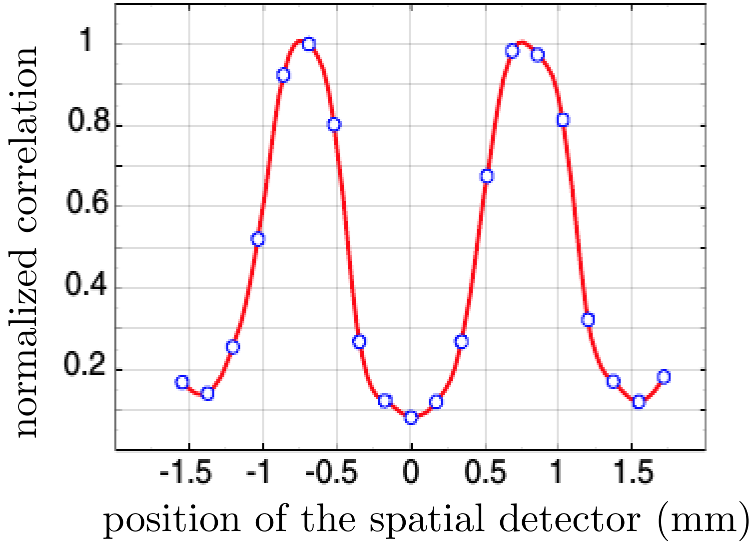


➢ F. V. Pepe, F. Di Lena, A. Garuccio, G. Scarcelli, and M. D'Angelo, "Correlation plenoptic imaging with entangled photons," Technologies, vol. 4, no. 2, p. 17, 2016

Basic concept

correlation (ghost) imaging with chaotic light



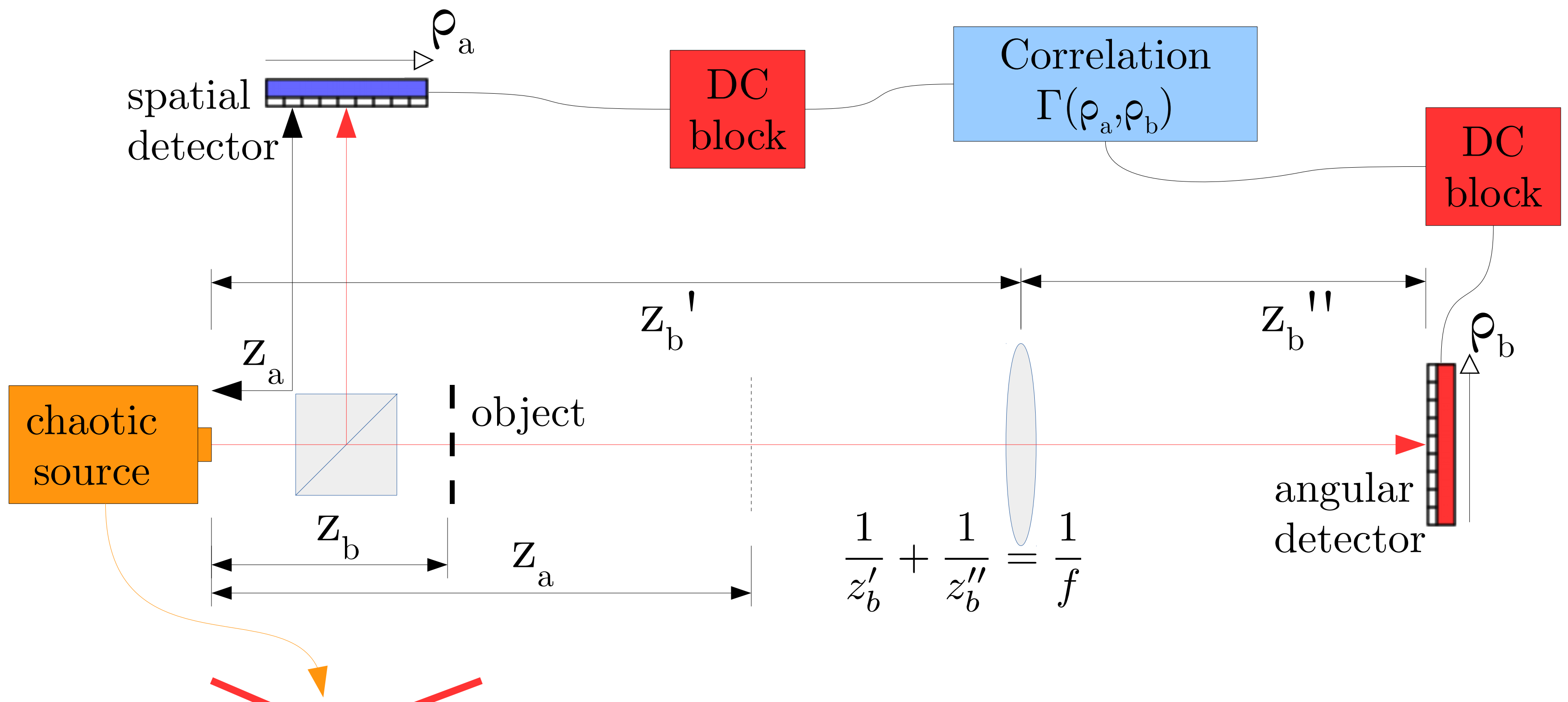


$$G^{(2)}(\rho_a, \rho_b) = I_a(\rho_a) I_b(\rho_b) + \Gamma(\rho_a, \rho_b)$$

- 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

CPI with chaotic light

working principle

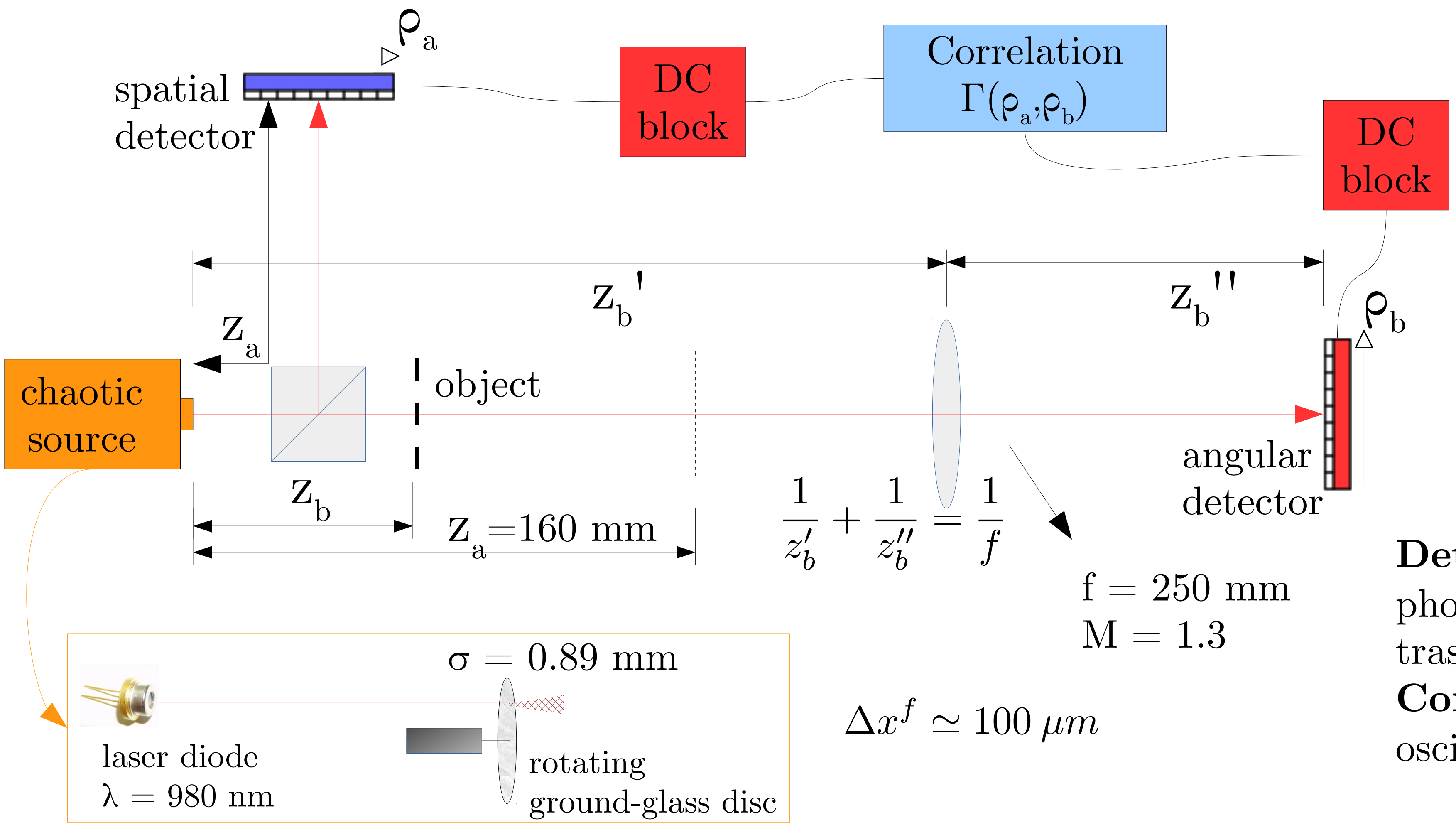


$$G^{(2)}(\rho_a, \rho_b) = I_a(\rho_a) I_b(\rho_b) + \Gamma(\rho_a, \rho_b)$$

➢ M. D'Angelo, F. V. Pepe, A. Garuccio, and G. Scarcelli, "Correlation plenoptic imaging", Physical Review Letters, vol. 116, no. 22, p. 223602, 2016.

CPI with chaotic light

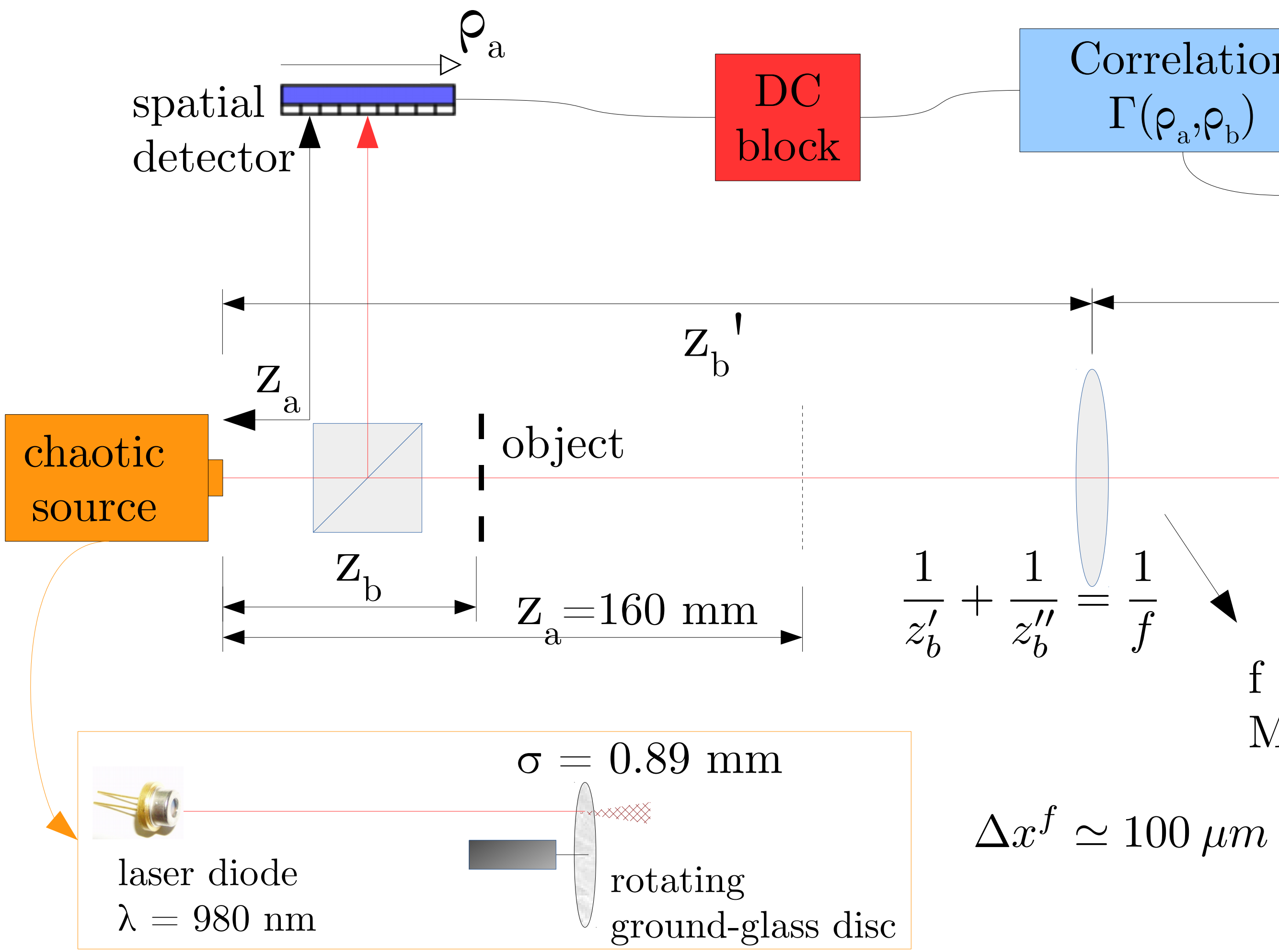
our experiment



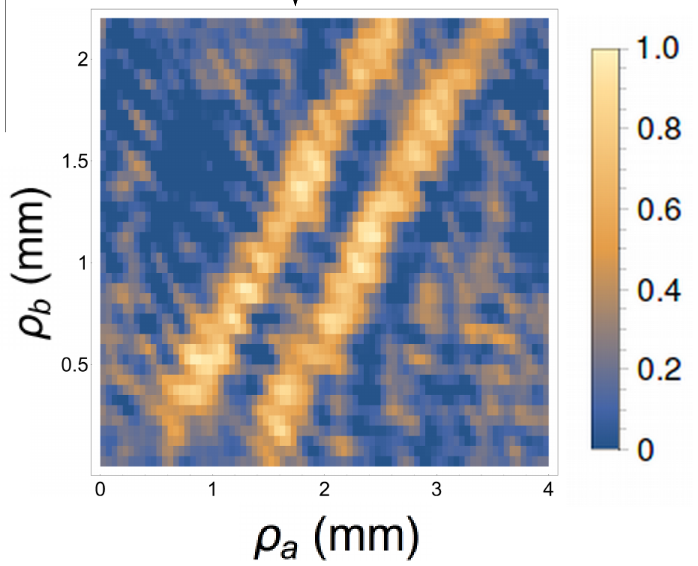
Detectors: amplified photodiodes on motorized traslational stage
Correlation measurement: oscilloscope + LabView

CPI with chaotic light

our experiment

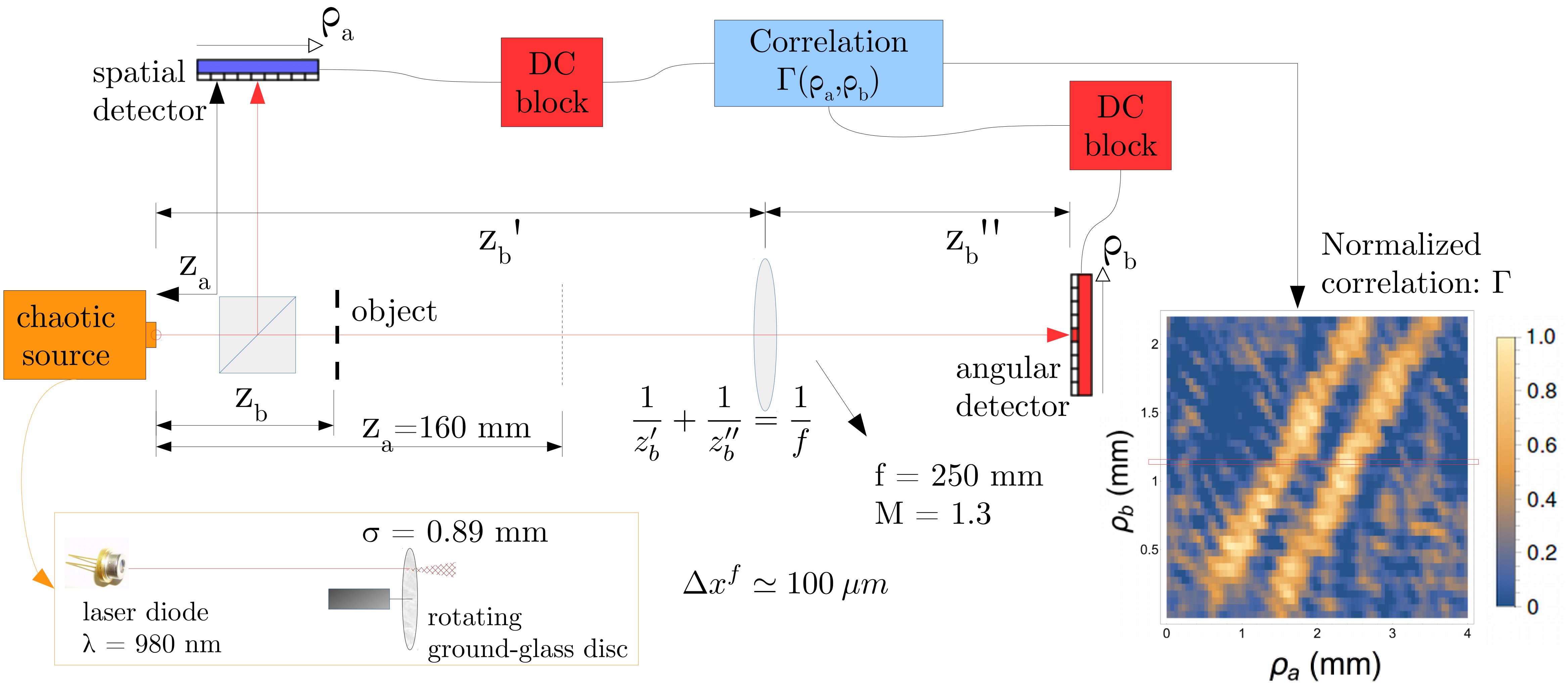


Normalized correlation: Γ



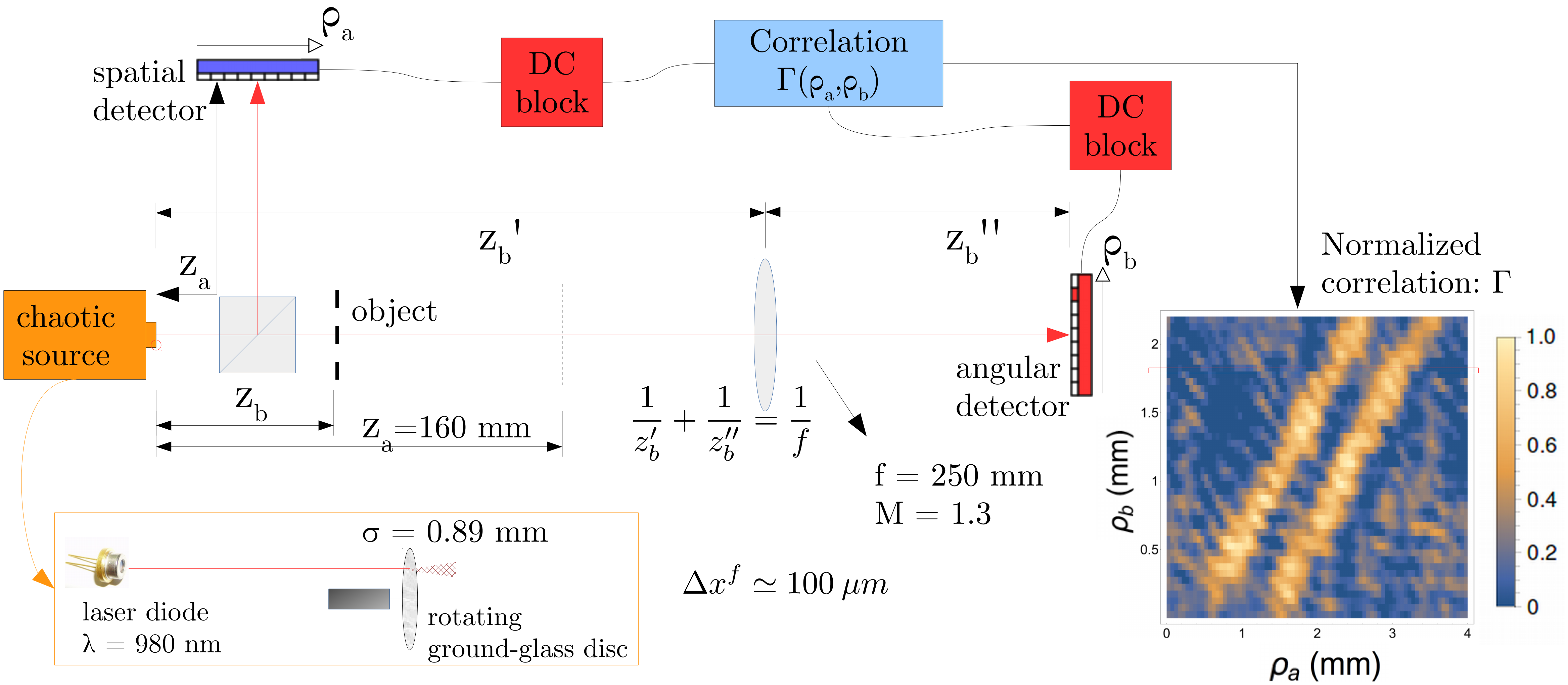
CPI with chaotic light

our experiment



CPI with chaotic light

our experiment



$$\frac{1}{z_b'} + \frac{1}{z_b''} = \frac{1}{f}$$

$$\Delta x^f \simeq 100\,\mu m$$

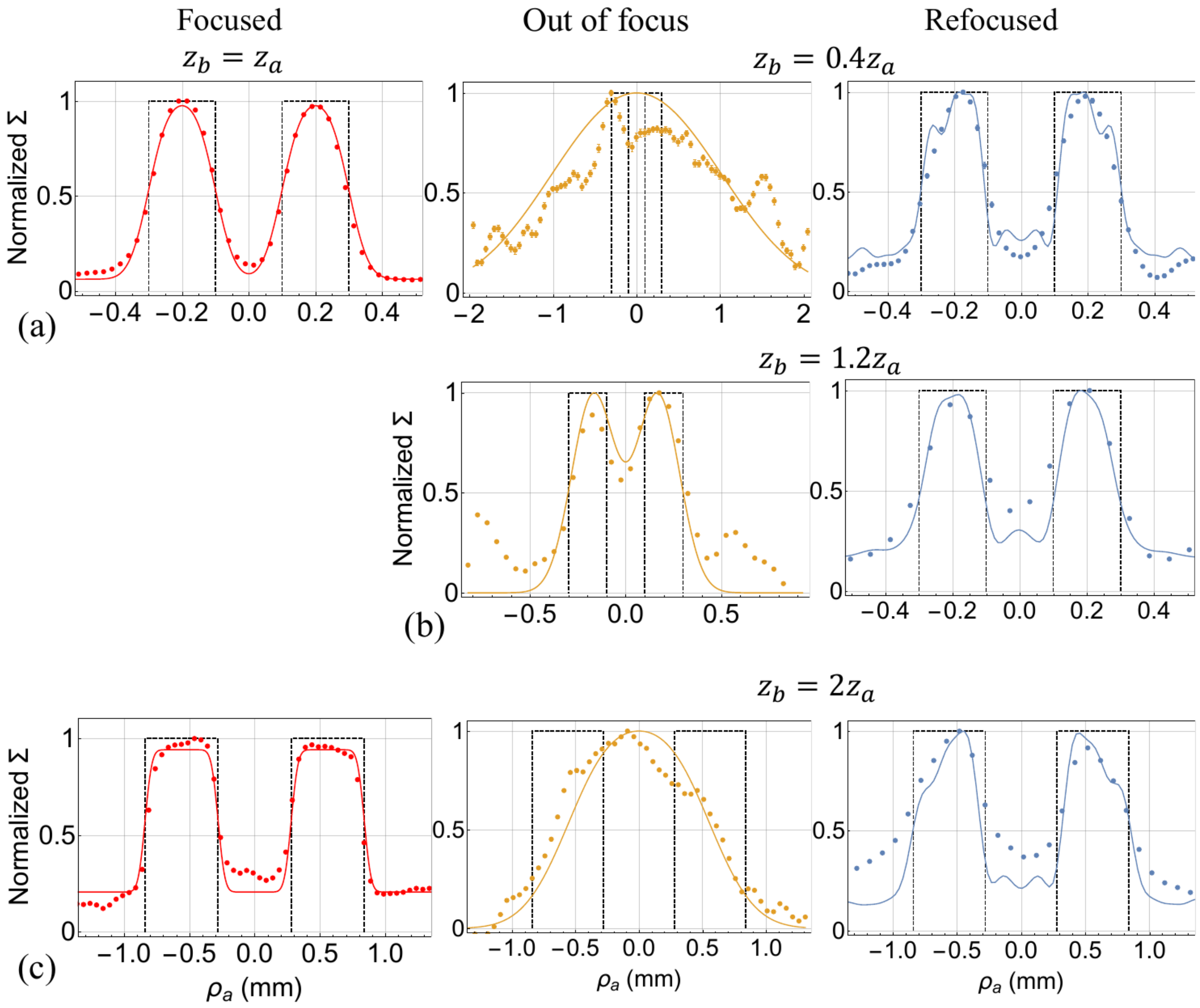
CPI with chaotic light

our experimental results

(A) d = 0.4 mm

(B) d = 0.4 mm

(C) d = 1.12 mm



Out-of-focus

$$\Sigma(\rho_a) = \int \Gamma(\rho_a, \rho_b) d\rho_b$$

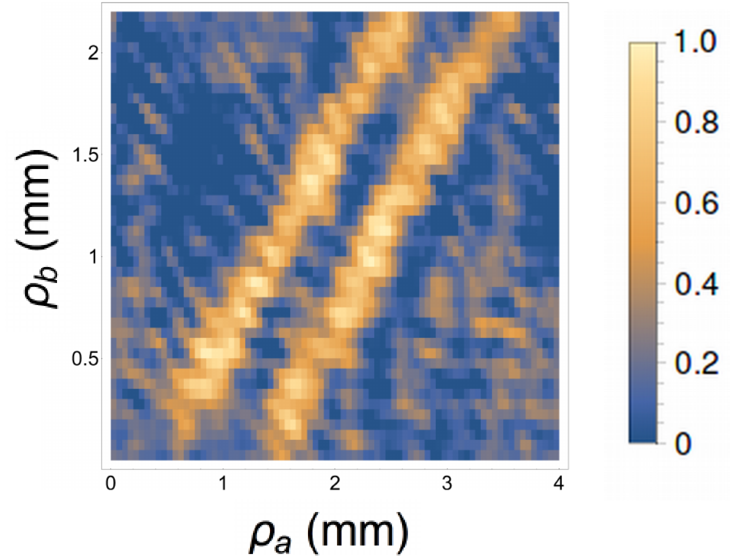
Refocused

$$\Sigma_{ref}(\rho_a) = \int \Gamma_{ref}(\rho_a, \rho_b) d\rho_b$$

CPI with chaotic light

explanation of the refocusing

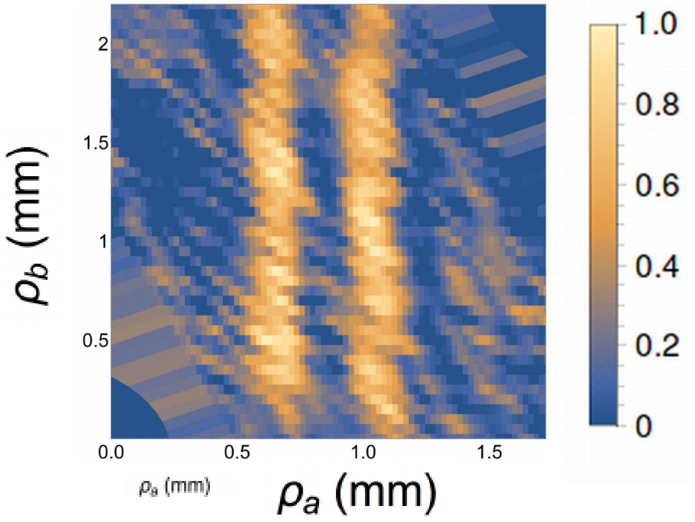
RAW data



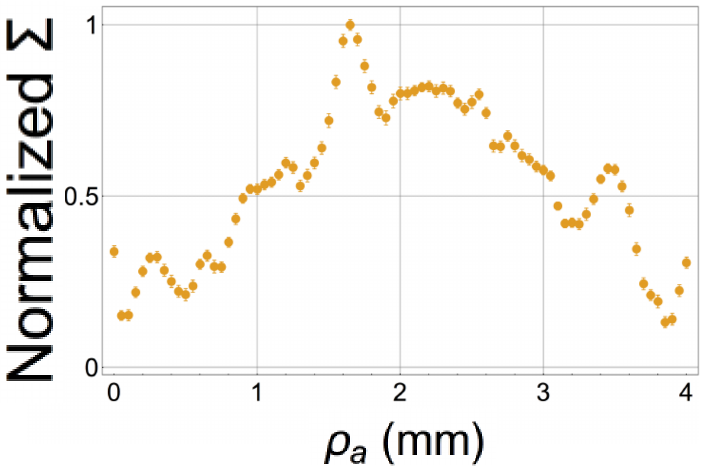
REFOCUS

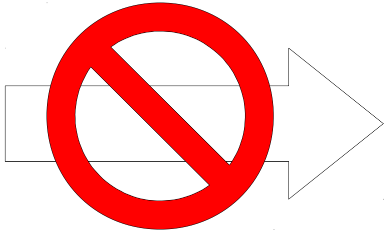
$$\rho_a \to \frac{z_b}{z_a}\rho_a + \left(\frac{z_b}{z_a} - 1\right)\frac{\rho_b}{M}$$

Processed data



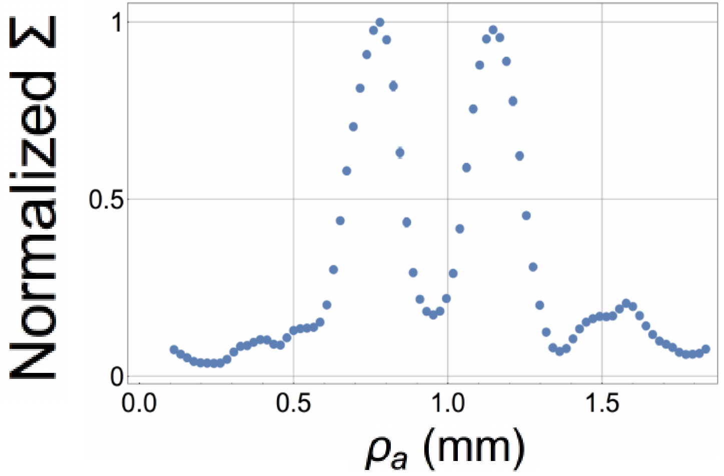
$\int \Gamma(\rho_a,\rho_b)d\rho_b$





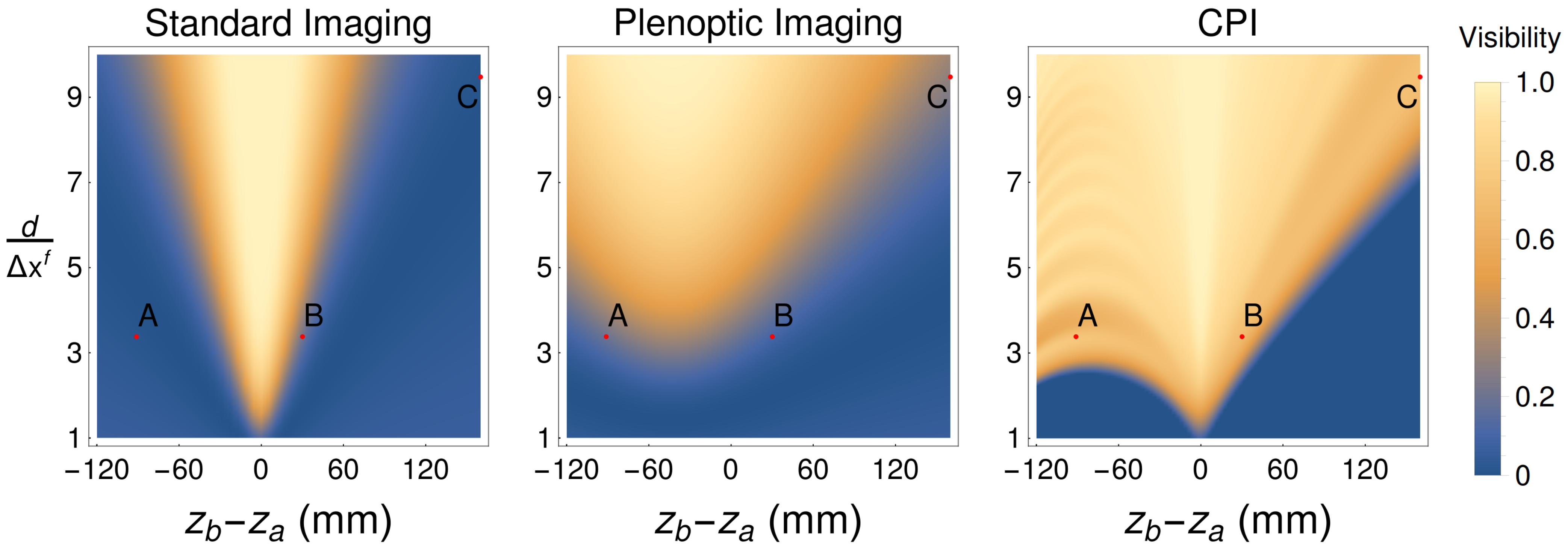
Not enough information!

$\int \Gamma_{ref}(\rho_a,\rho_b)d\rho_b$



CPI with chaotic light

comparison with standard imaging and PI

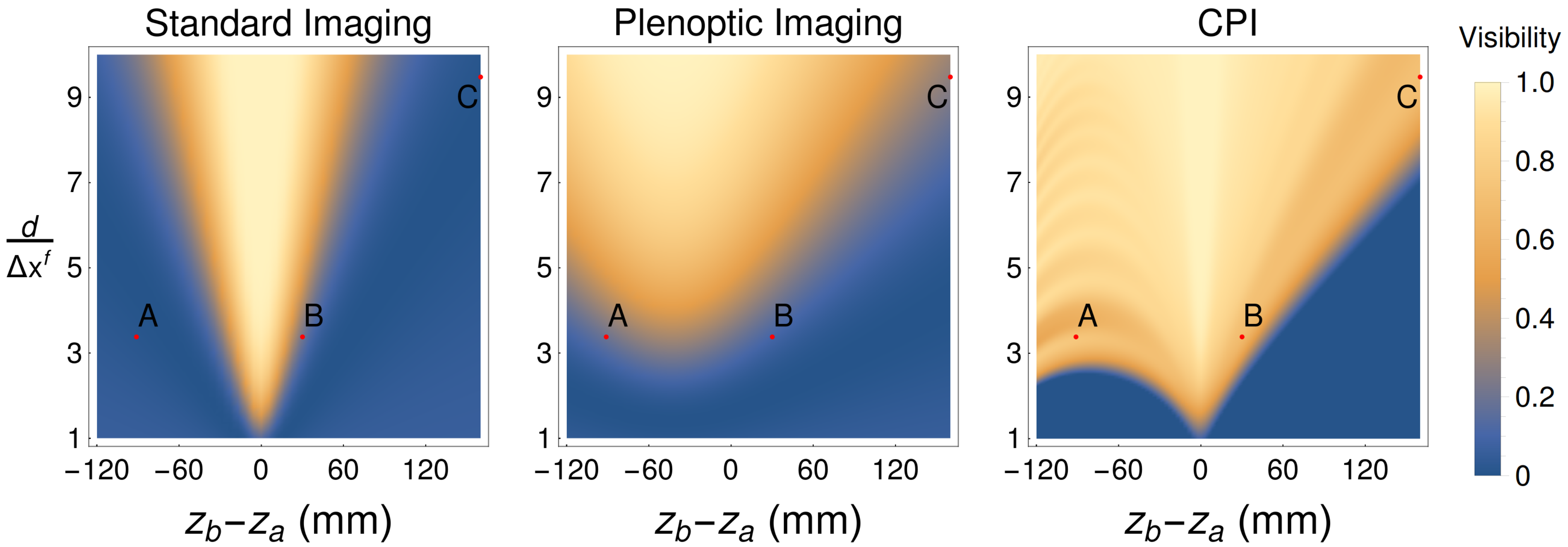


A, B and C previous measurements

Impossible without correlation

CPI with chaotic light

comparison with standard imaging and PI



A B and C previous measurements

Impossible without correlation

Manifest improvement due to correlation photons, only limited by diffraction.

Second year objectives

- CPI with bi-dimensional and tri-dimensional objects
  - $\rightarrow$ Building a setup with CCD
- Setup improvement
  - $\rightarrow$ Alternative configurations towards CPI microscopy
- CPI whit a single detector
  - $\rightarrow$ Computational ghost imaging
- Sub-shot Noise CPI
  - $\rightarrow$ Replacing the chaotic source with entangled photons source

- Y. Bromberg, O. Katz, and Y. Silberberg, Physical Review A, vol. 79, no. 5, p. 053840, 2009.
- G. Brida, M. Genovese, and I. R. Berchera, Nature Photonics, vol. 4, no. 4, pp. 227–230, 2010.

Publication, conferences and exams

- Publications:
  - ✔ 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.
  - M. D'Angelo, F. Di Lena, A. Garuccio, A. Mazzilli, F. V. Pepe, G. Scarcelli, "Experimental demonstration of correlation plenoptic imaging at the diffraction limit". *In preparation (Nature Physics).*
- Conferences:
  - "Correlation Plenoptic Imaging" (poster), "Quantum Roundabout 2016", University of Nottingham, July 6th - 8th 2016.
  - "Imaging Plenottico con Misure di Correlazione" (oral), 102 congresso nazionale della SIF, Padova Sept. 26th - 30th 2016.
- Exams:
  - ✔ Management and knowledge of European research model and promotion of research results
  - ✔ How to prepare a technical speech in English
  - ✔ LabView introductory Course
  - ✔ Programming FPGA with LabView
  - ✔ Optical sensors
  - Complex Systems (by November 2016)
  - Gaseous detector (December 15th 2016)
  - Analysis of experimental data (by December 2016)

Thank you for your attention!