Dottorato in Fisica – XXXI ciclo

Advances in Correlation Plenoptic Imaging

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Tutor: *Saverio Pascazio*
Milena D'Angelo

Contents

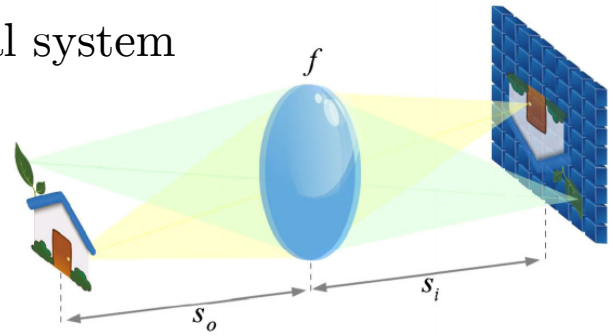
Why Correlation Plenoptic Imaging?

- **Traditional optical imaging:** unavoidable trade-off between resolution and depth of field (DOF)

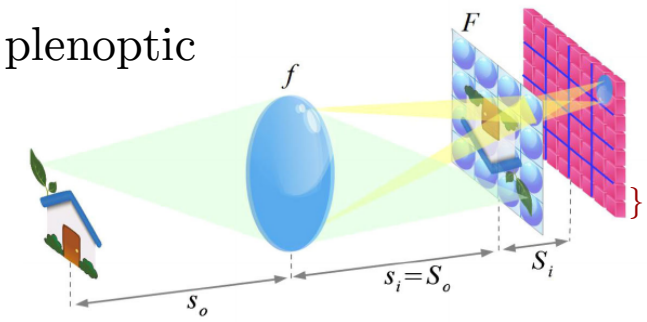
- **Standard plenoptic:** refocusing and 3D imaging capability, but DOF improvement is at the expenses of the resolution

- **CPI:** refocusing and 3D capability **without losing resolution**

Traditional system

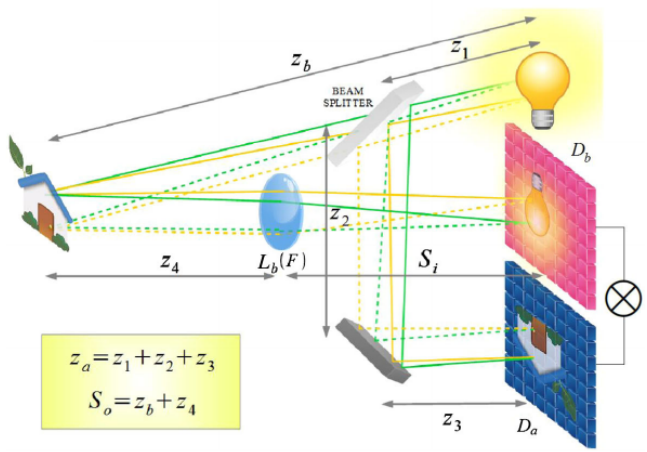


Standard plenoptic



$N_u = 2$

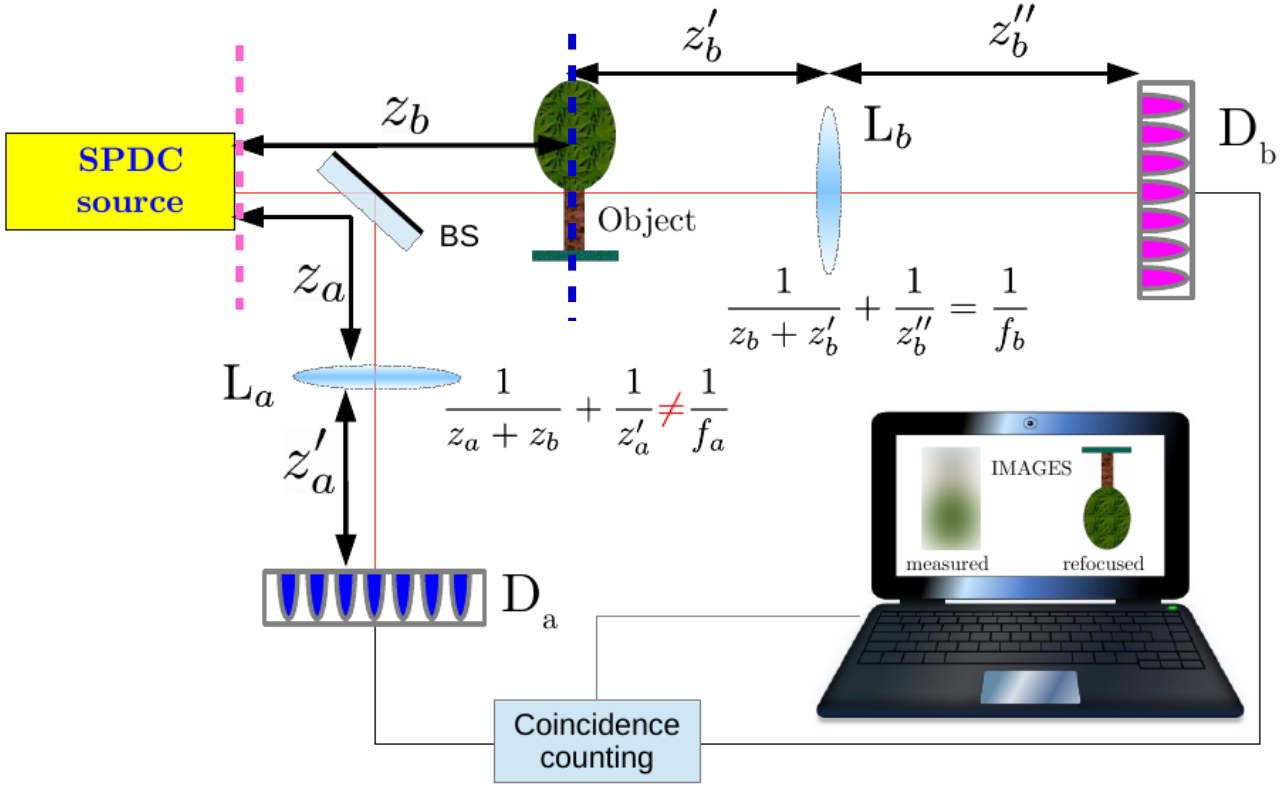
CPI

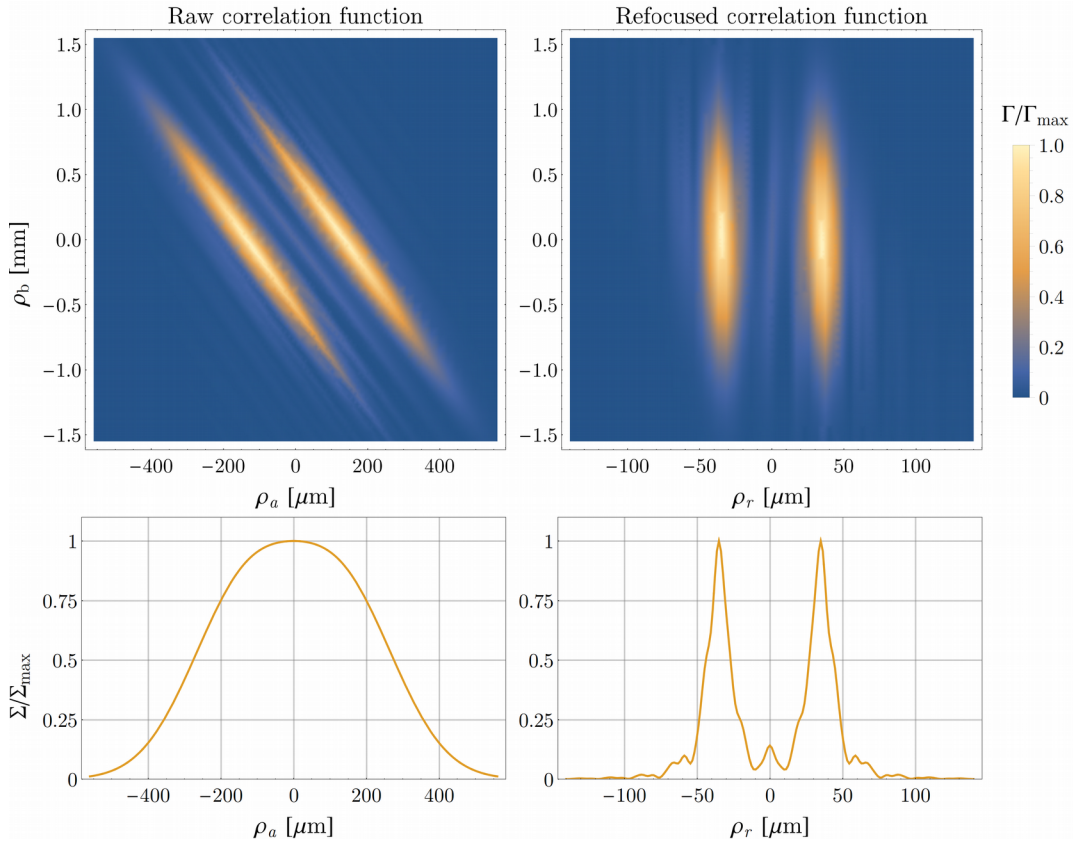


1. CPI with entangled photons

1. CPI with entangled photons

Working principle





The second order correlation function is characterized by plenoptic properties

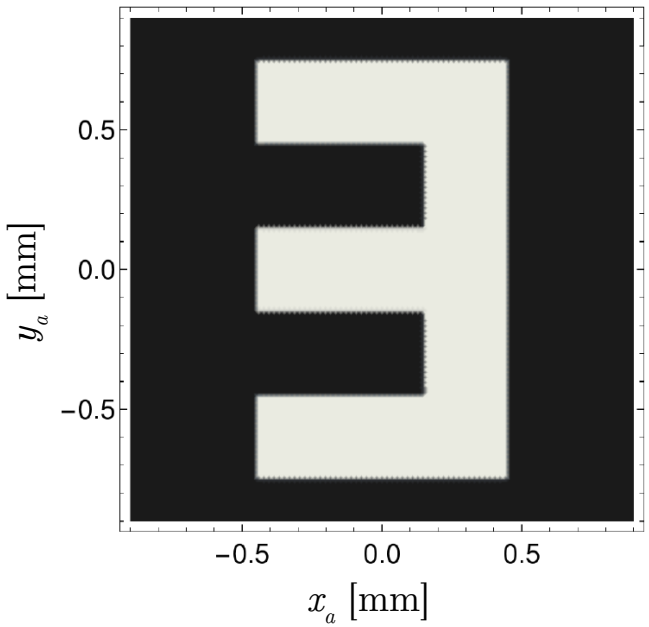
$$G^{(2)}(\rho_a, \rho_b; t_a, t_b) = < E_a^{(-)}(\rho_a, t_a) E_b^{(-)}(\rho_b, t_b) E_a^{(+)}(\rho_a, t_a) E_b^{(+)}(\rho_b, t_b) >$$

- F. V. Pepe, F. Di Lena, A. Garuccio, G. Scarcelli, and M. D'Angelo, Technologies, vol. 4, no. 2, p. 17, 2016

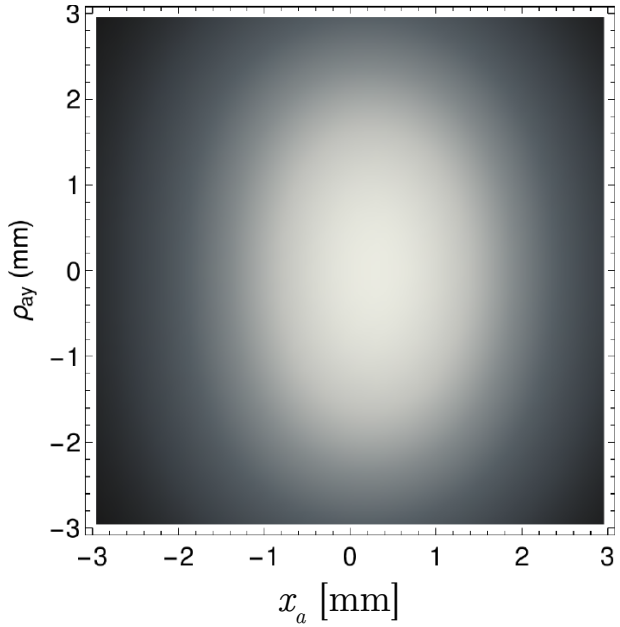
1. CPI with entangled photons

Numerical simulation

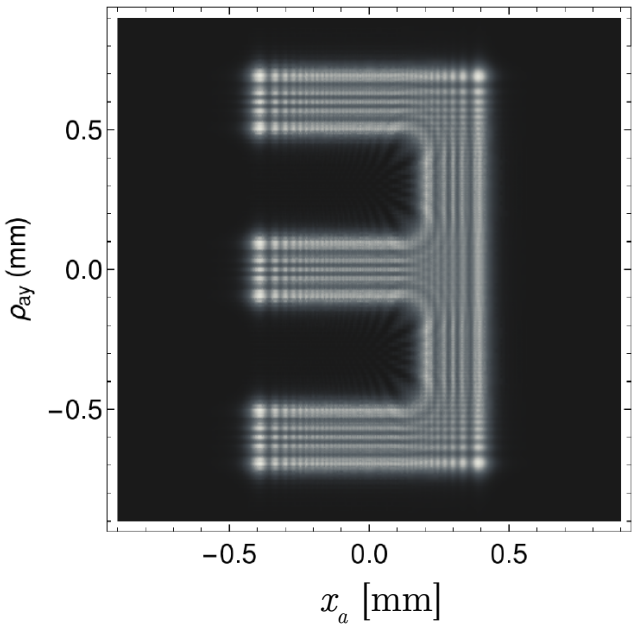
Focused image

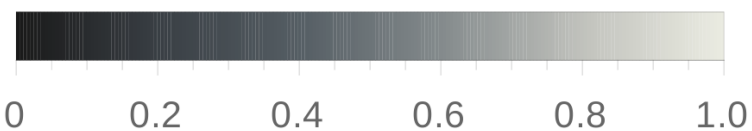


Out-of-focus image



Refocused image

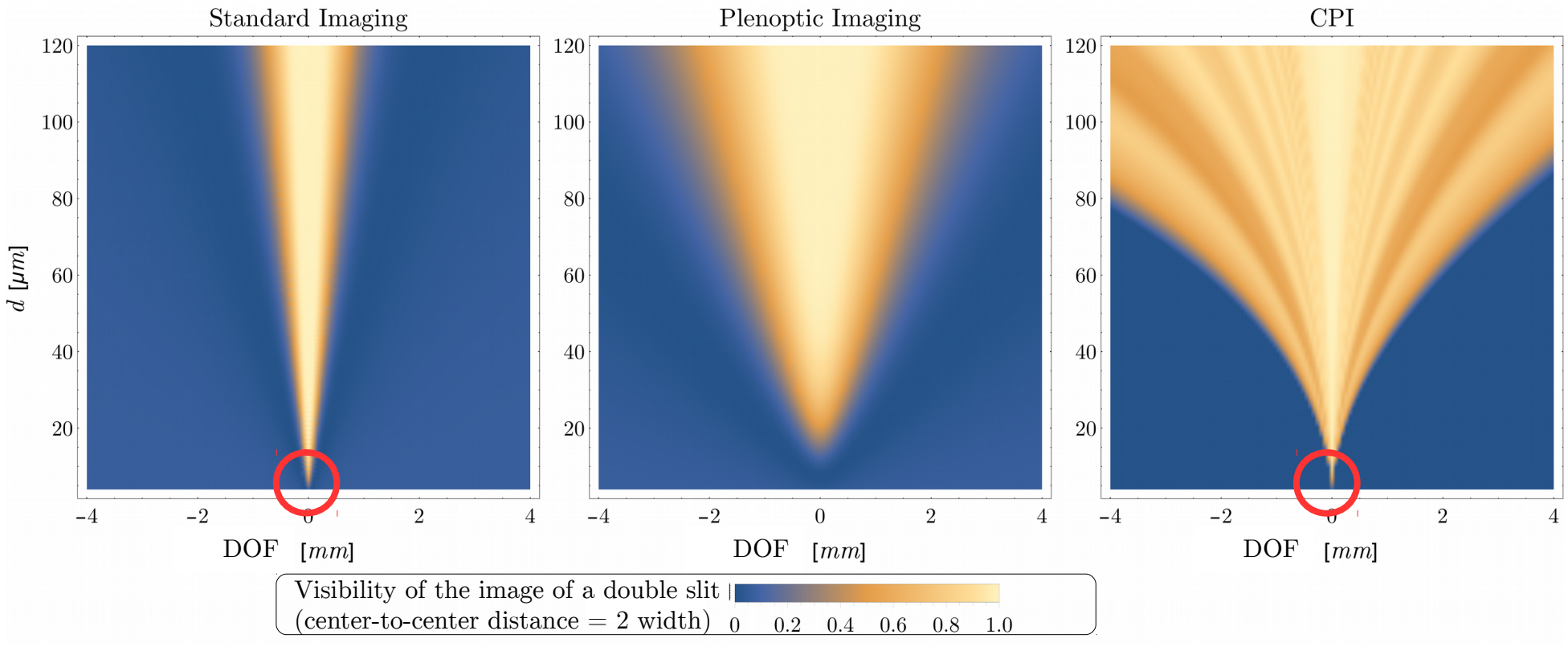




- F. V. Pepe, F. Di Lena, A. Garuccio, G. Scarcelli, and M. D'Angelo, Technologies, vol. 4, no. 2, p. 17, 2016

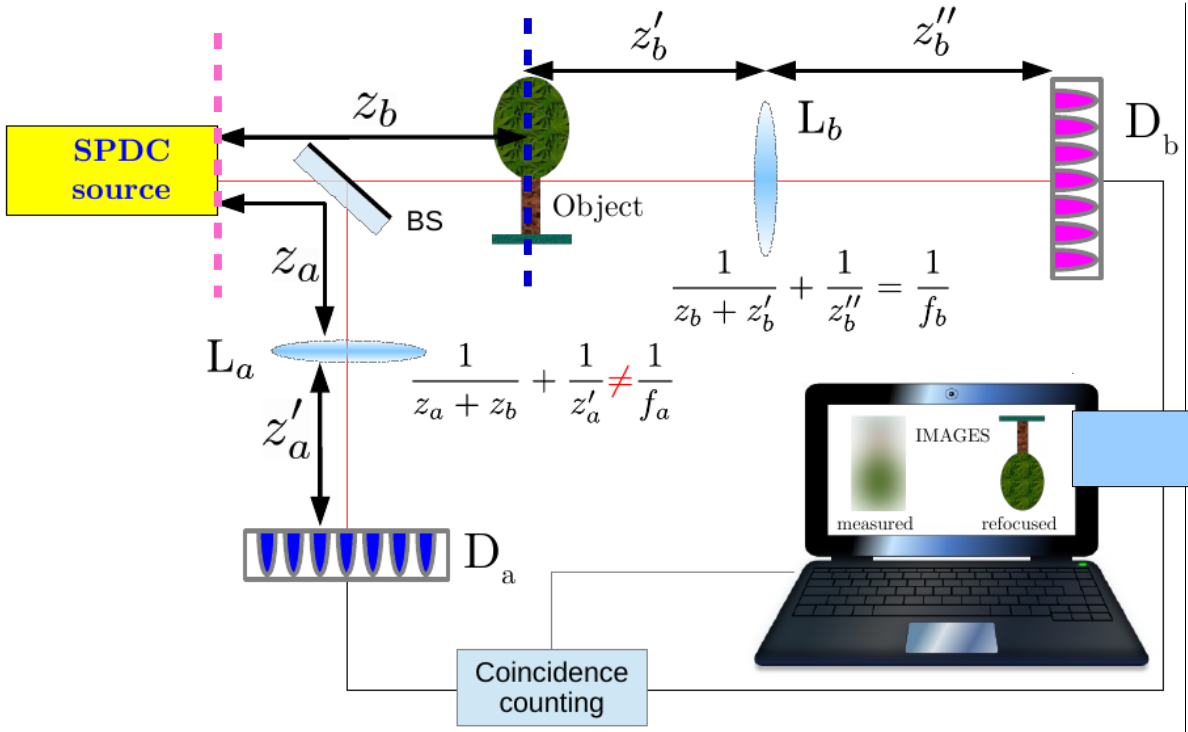
1. CPI with entangled photons

DOF vs. resolution trade-off

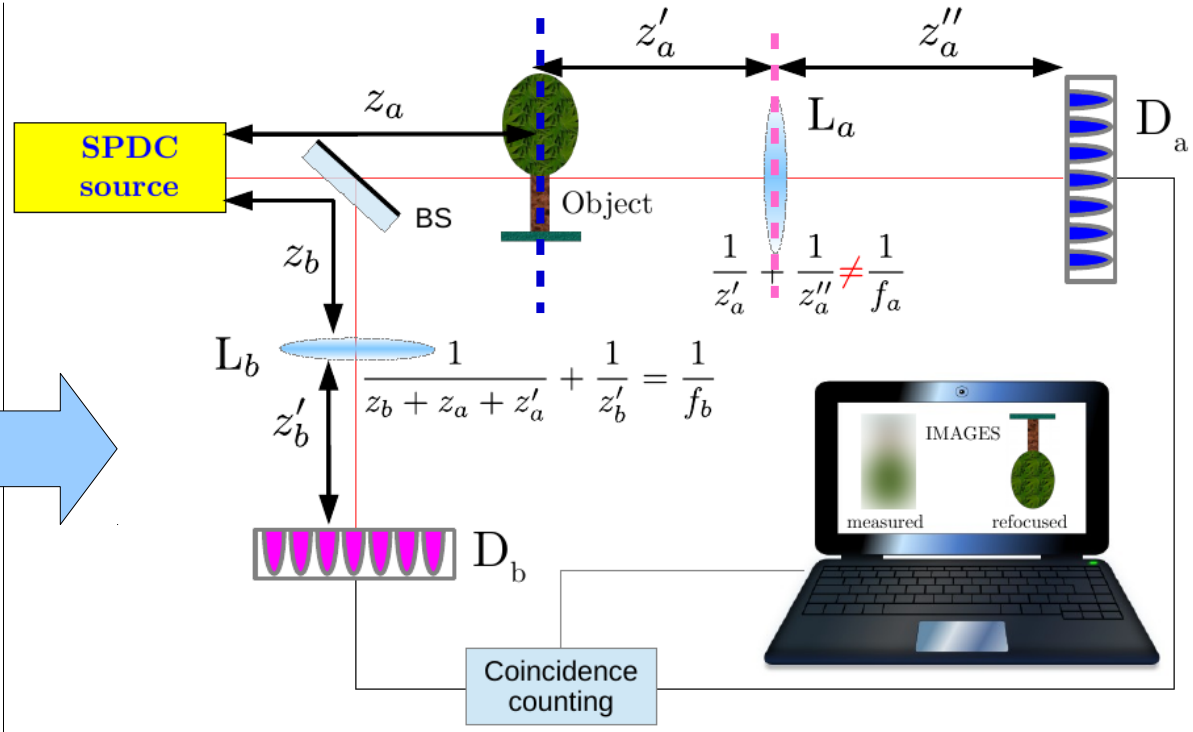


CPI enables refocusing in a much wider range than standard imaging and PI, while keeping the resolution of standard imaging!

Combination of CPI and standard imaging



Standard image of the source



Ghost image of the lens L_a

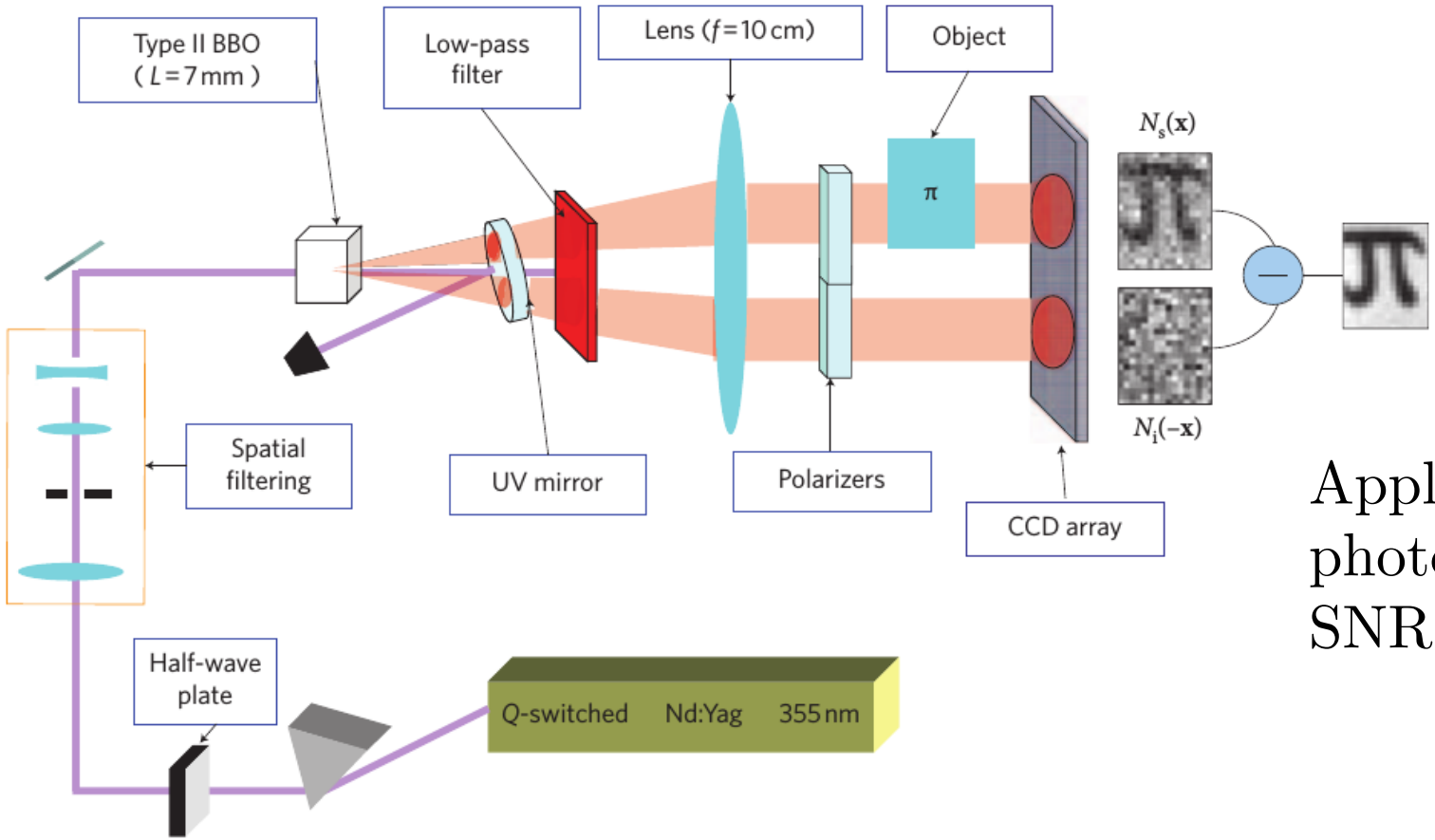
Pantent request
PCT/IB2017/055842

Advantages:
- Availability of the standard image (quick check of the object)
- Larger control of image resolution defined by NA of the lens L_a

Advantage of entangled photons

Entangled photons enable sub-shot imaging

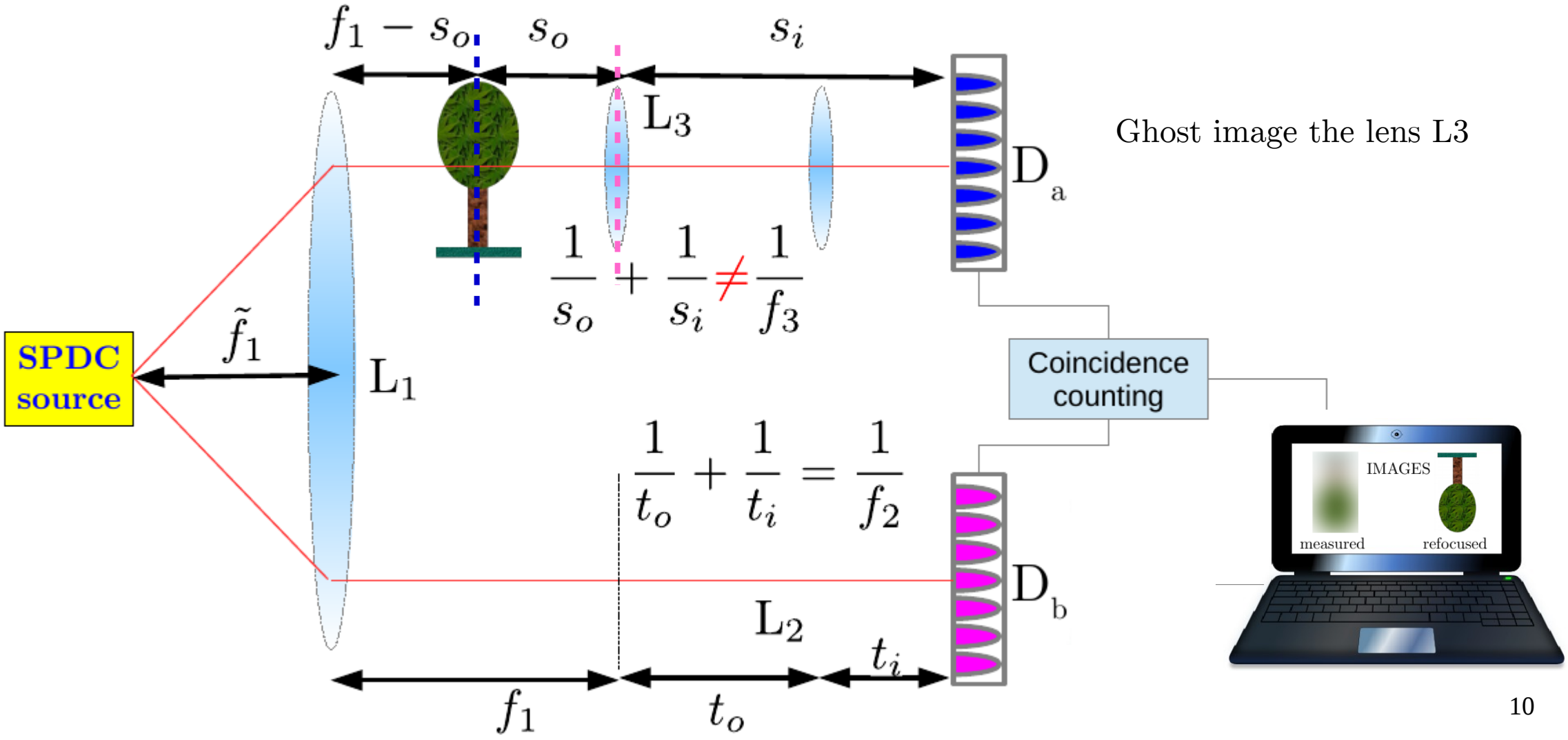
G. Brida, M. Genovese, and I. R. Berchera Nature Photonics, vol. 4, no. 4, pp. 227–230, 2010 @INRiM.



Application of entangled photons to optimize the SNR of CPI

1. CPI with entangled photons

SNR enhancement

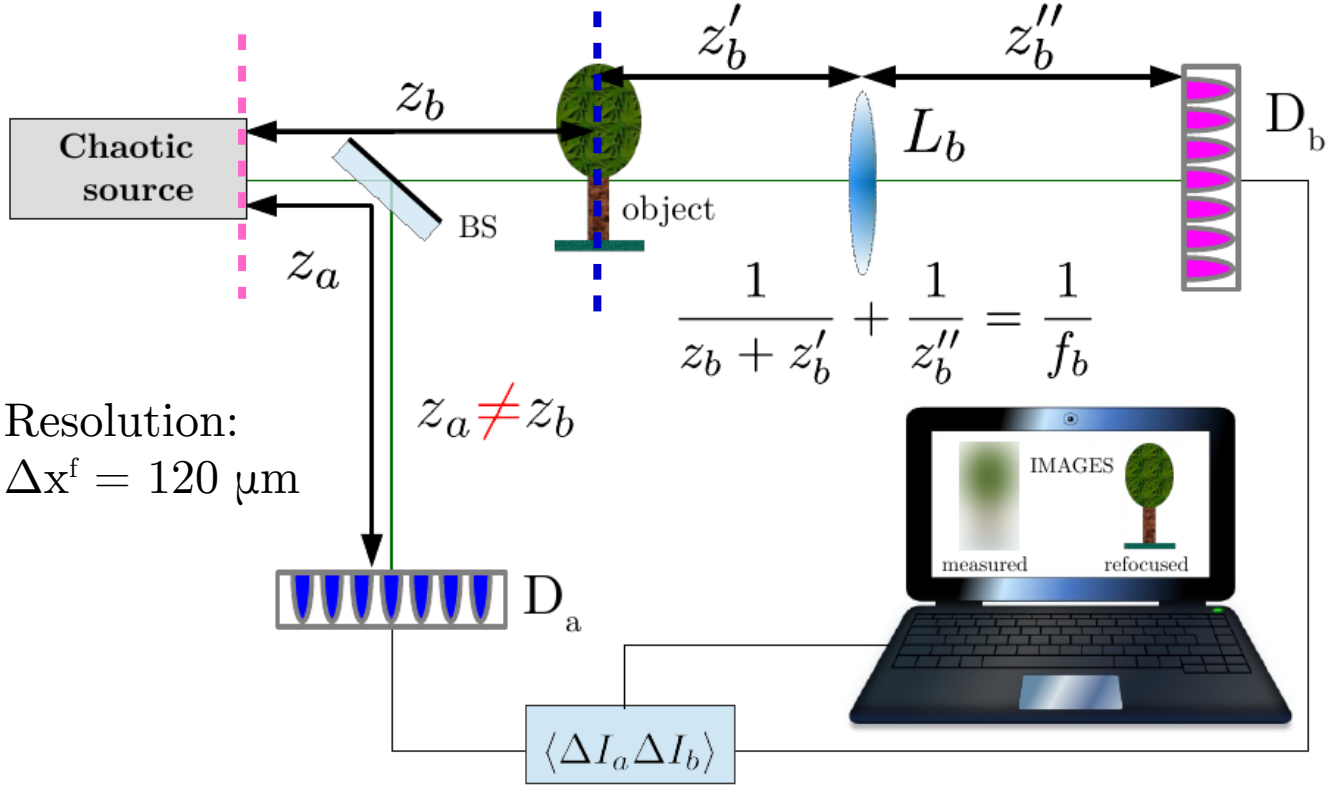


Ghost image the lens L3

2. CPI with chaotic light

2. CPI with chaotic light

Experimental setup for 1D images



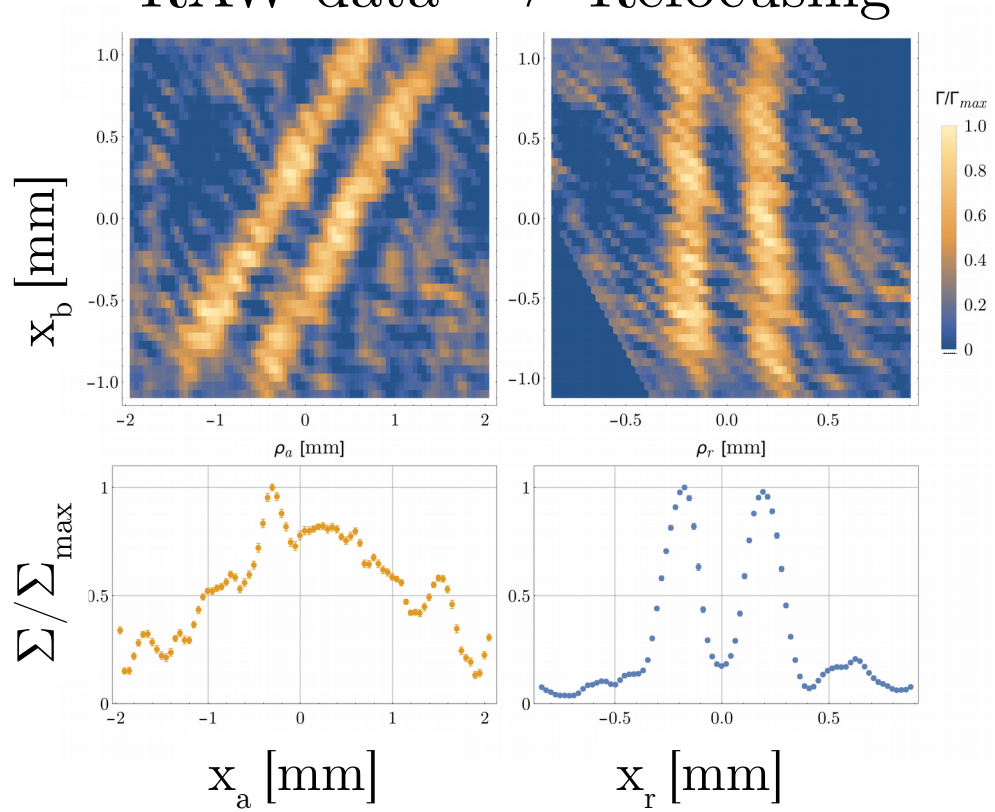
Resolution:
$\Delta x^f = 120\ \mu m$

$N_u^{PI} \leq 4 \rightarrow N_u^{CPI} = 45 \Rightarrow 10\times$ DOF enhancement with same NA

Standard image of the source

D_a and D_b scanning photodiodes

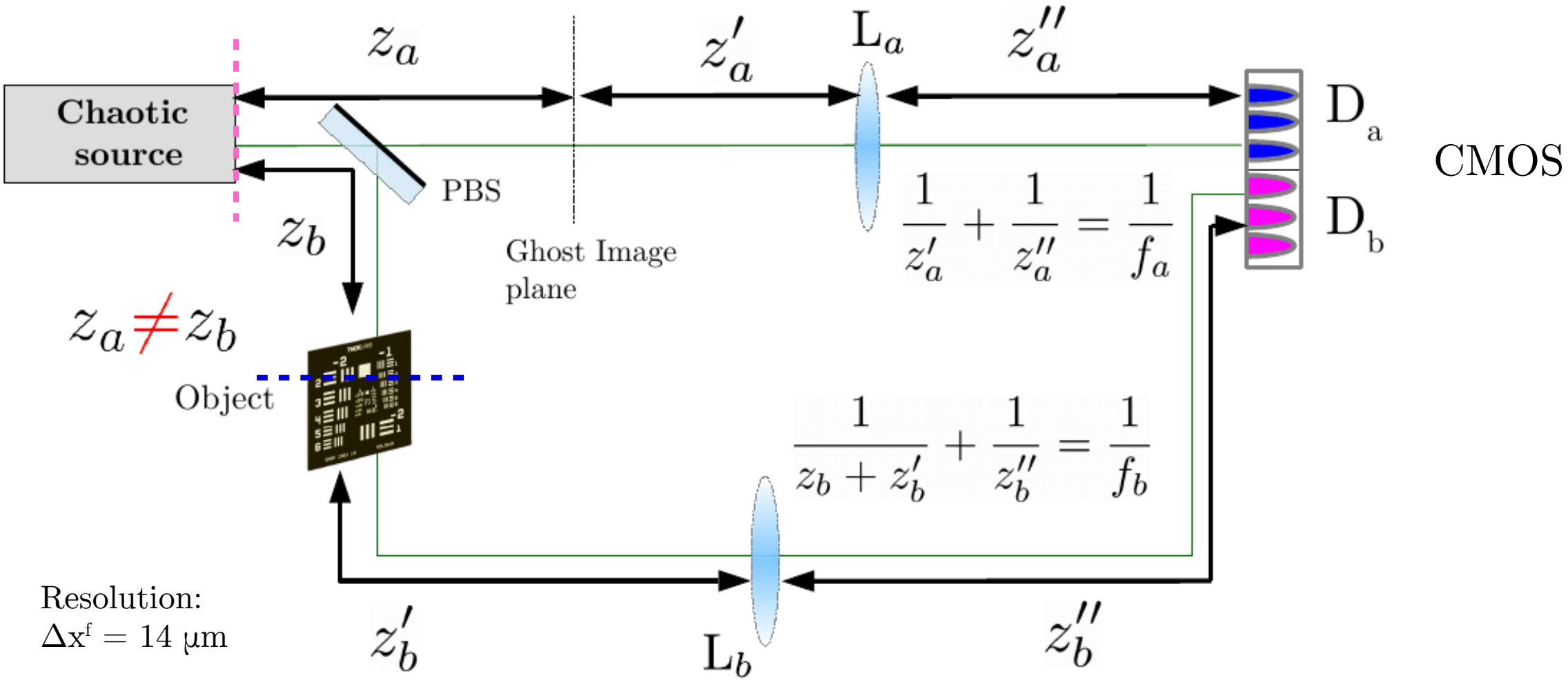
RAW data $\rightarrow$ Refocusing



- F. Di Lena, F. Pepe, A. Mazzilli, A. Garuccio, G. Scarcelli and M. D'Angelo, Nuovo Cimento C (in production).

2. CPI with chaotic light

Experimental setup for 2D images

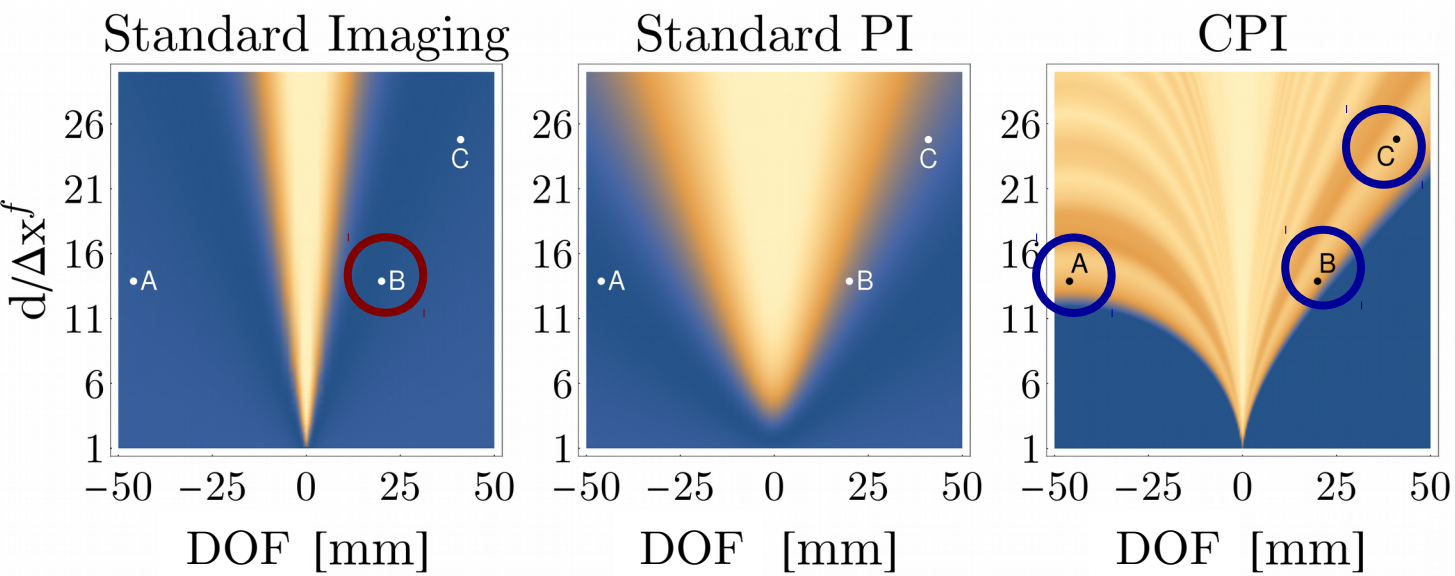


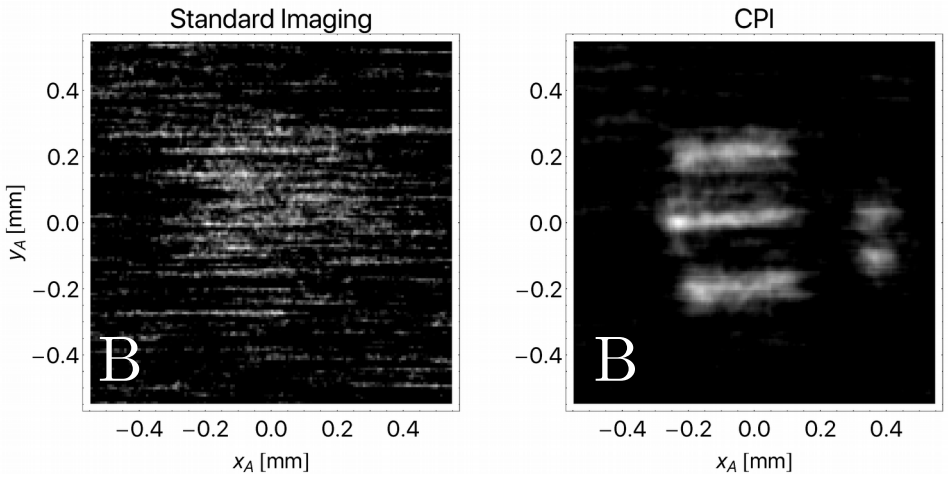
Resolution:
$\Delta x^f = 14\ \mu m$

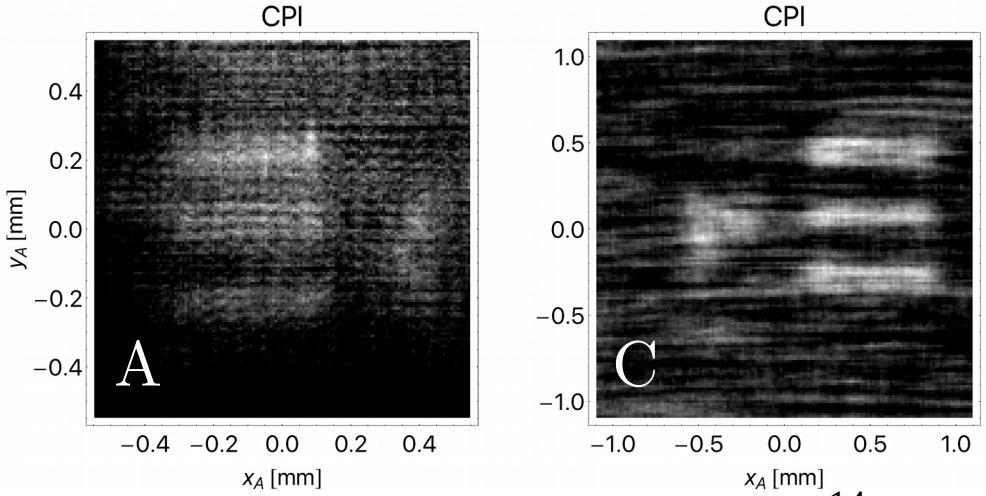
F. V. Pepe, F. Di Lena, A. Mazzilli, E. Edrei, A. Garuccio, G. Scarcelli, and M. D'Angelo, PRL, vol. 119, no. 24, p. 243602, 2017.

2. CPI with chaotic light

Experimental 2D images







Visibility of the image of a double slit

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

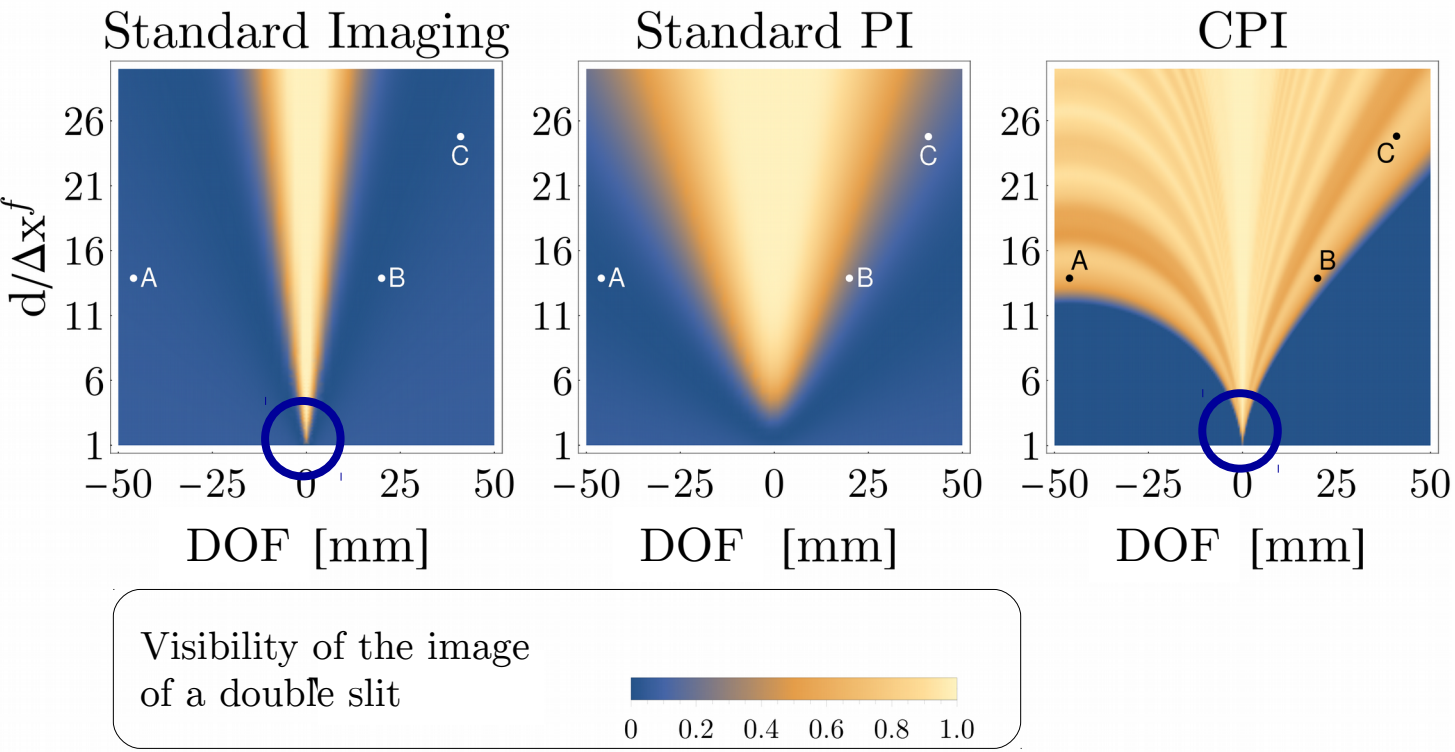
$$\frac{DOF_{CPI}}{DOF_{PI}} \simeq 2.5$$

CPI enables refocusing in a much wider range than standard imaging and PI

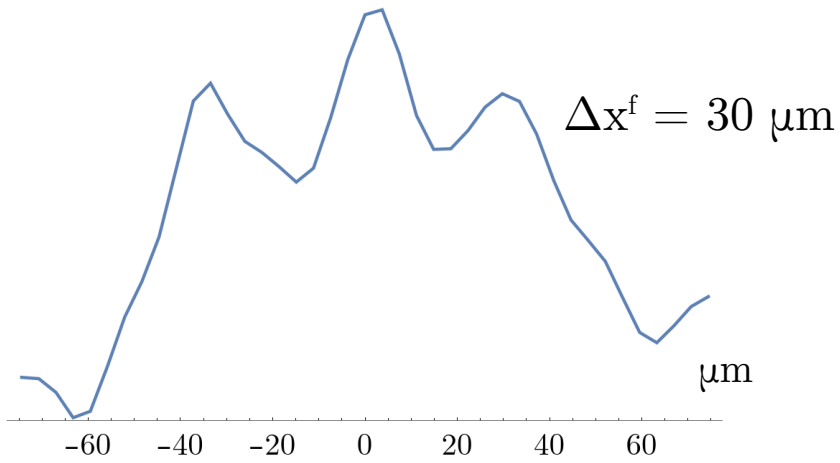
- F. V. Pepe, F. Di Lena, A. Mazzilli, E. Edrei, A. Garuccio, G. Scarcelli, and M. D'Angelo, PRL, vol. 119, no. 24, p. 243602, 2017.

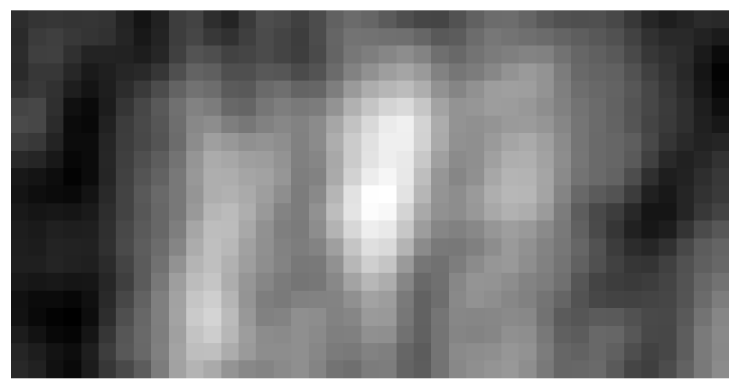
2. CPI with chaotic light

Experimental 2D images



Diffraction limited resolution



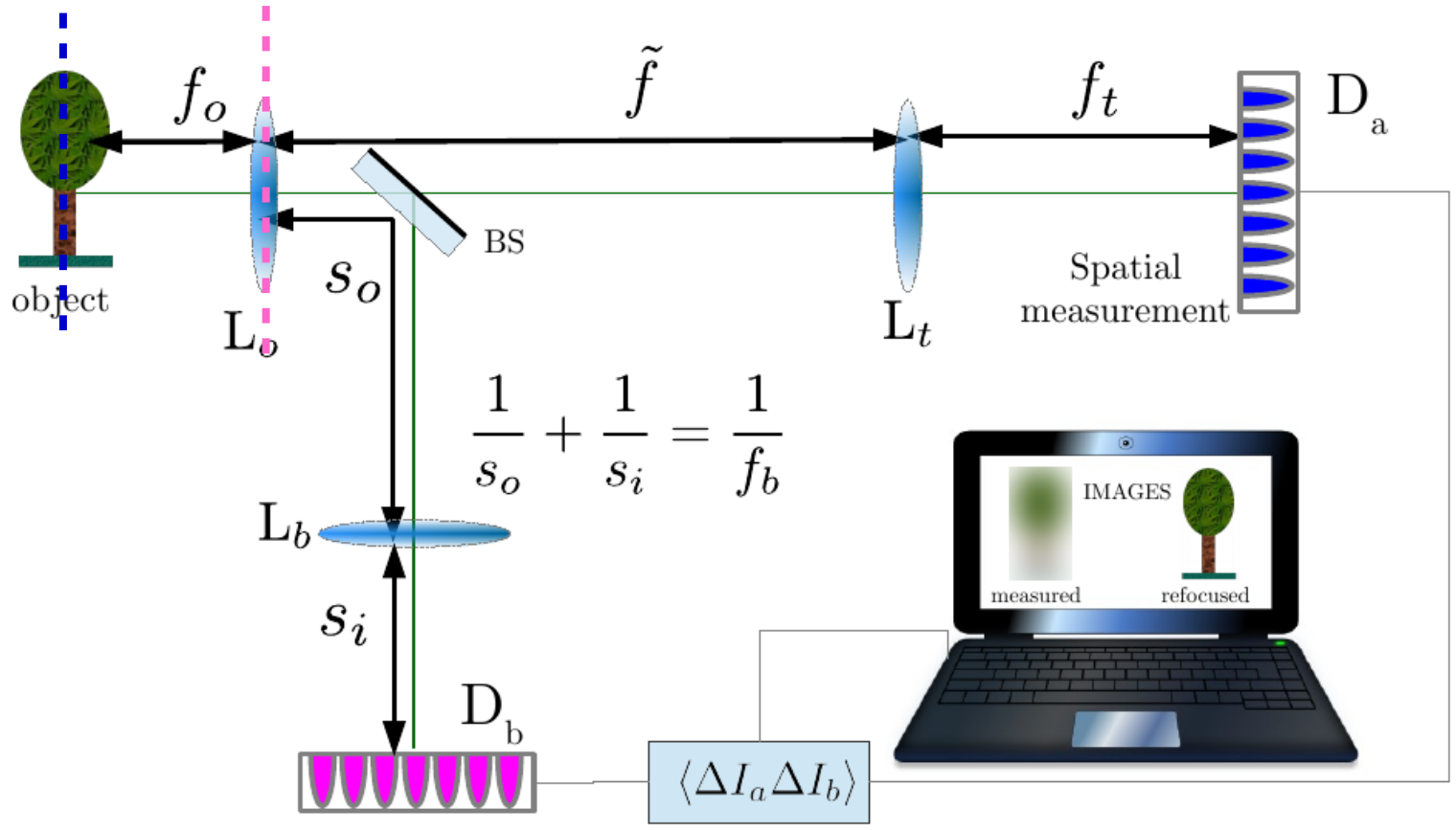


CPI enables refocusing in a much wider range than standard imaging and PI, **while keeping the resolution of standard imaging!**

F. V. Pepe, F. Di Lena, A. Mazzilli, E. Edrei, A. Garuccio, G. Scarcelli, and M. D'Angelo, PRL, vol. 119, no. 24, p. 243602, 2017.

3. Correlation Plenoptic Microscopy

Experimental setup



Standard image of the lens L_o (objective)

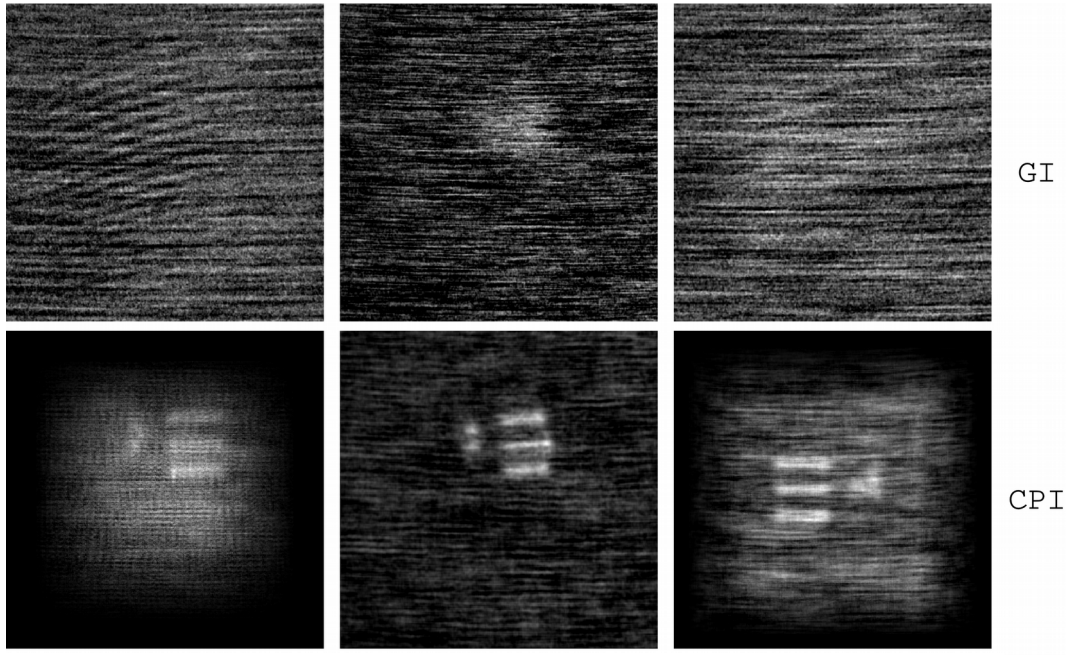
Basic idea: using chaotic light emitted by the sample as a correlated source

Turbulence attenuation expected

Patent request n. 102018000007857
M. D'Angelo, F. Di Lena, A. Garuccio, F. V. Pepe, A. Scagliola.

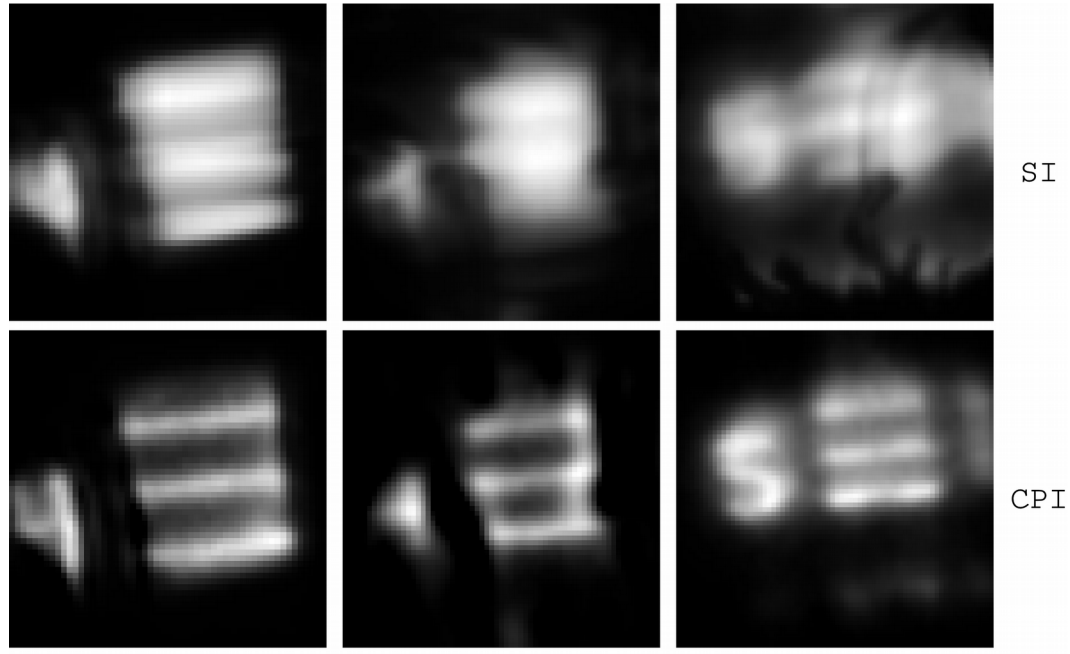
Preliminary results

CPI (PRL 2017)



(A) 198 μm (B) 198 μm (D) 354 μm

CPM (in preparation)



(A) 44 μm (B) 44 μm (D) 39 μm

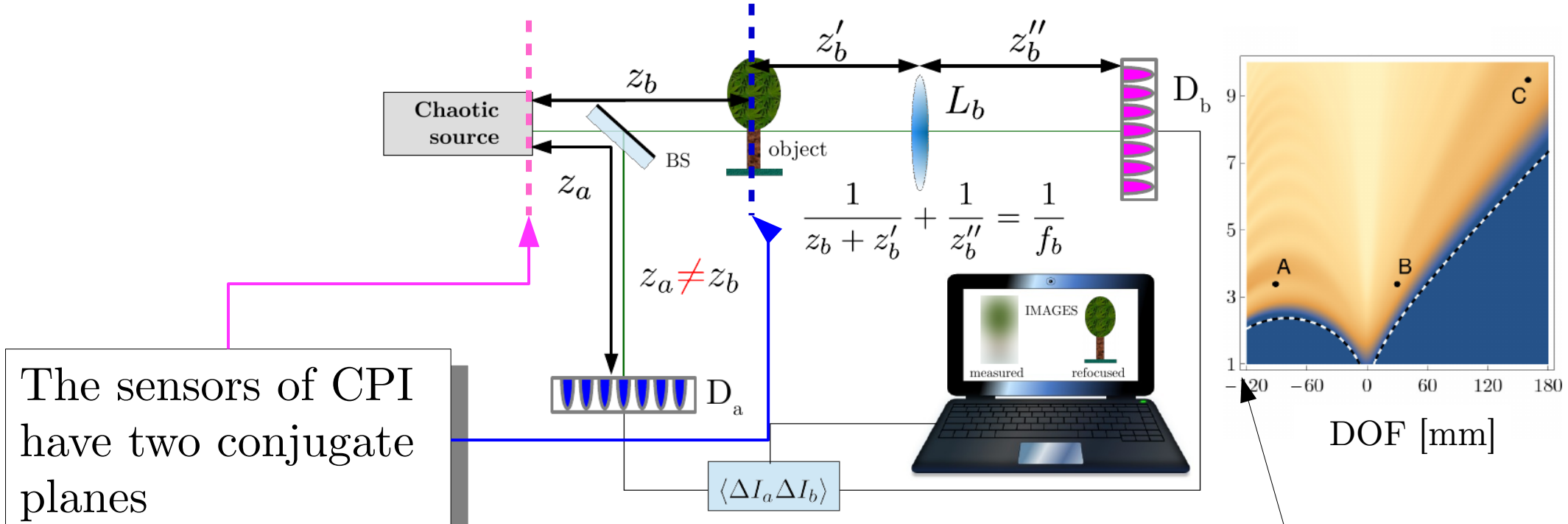
- ✔ Microscopic resolution
- ✔ Image of the sample directly avaliable

- SNR improvement
- Turbulence mitigation (work in progress)

4. Correlation Plenoptic Imaging between Arbitrary Planes

4. Correlation Plenoptic Imaging between Arbitrary Planes

Basic idea

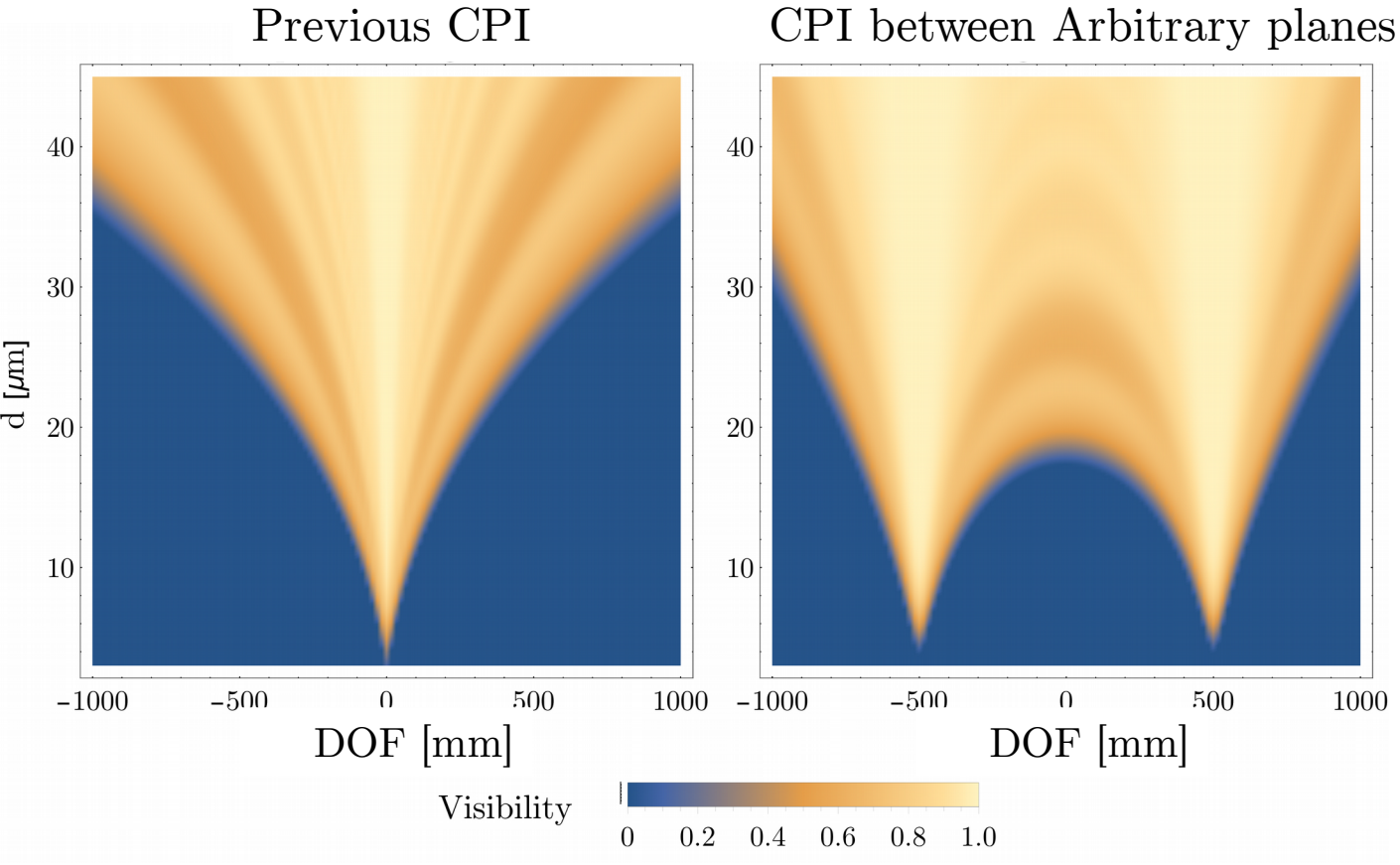


The sensors of CPI have two conjugate planes

There is a second focus!
How can we effectively use it?

Patent request
under preparation

Advantages



1. Further DOF enhancement
2. No image of the focusing element
3. Beam splitter 50:50 (if Ma ≃ Mb)

Works with both chaotic light and entangled photons

Conclusions

Results:

1. Theoretical proof of CPI with entangled photons
2. Experimental proof of CPI with chaotic light
3. CPM: preliminary experimental results
4. A new CPI scheme
5. Plot of RES. vs. DOF: a tool for designing and comparing setups

Work in progress:

1. Experment
2. SNR analysis
3. Proof of turbolence mitigation
4. 3D image of biological sample
5. Implemented in the ongoing experiment of CPI with entangled photons
6. Under implementation in CPM

Summary of the activities

- Publications:
  - Pepe, F.V.; Di Lena, F.; Garuccio, A.; Scarcelli, G.; D'Angelo, M. "Correlation Plenoptic Imaging with Entangled Photons" Technologies 2016, 4, 17.
  - Pepe, F.V.; Di Lena, F.; Mazzilli, A.; Edrei, E.; Garuccio, A.; Scarcelli, G.; D'Angelo, M. "Diffraction-limited plenoptic imaging with correlated light" Phys. Rev. Lett. 2017, 119, 243602.
  - F. Di Lena, F. Pepe, A. Garuccio, and M. D'Angelo, "Correlation plenoptic imaging: An overview" Applied Sciences, vol. 8, no. 10, p. 1958, 2018.
  - F. Di Lena, F. Pepe, A. Mazzilli, A. Garuccio, G. Scarcelli and M. D'Angelo, "Plenoptic imaging through correlation measurement" Nuovo Cimento C - Colloquia and Communications in Physics (in production).
- Proocedings
  - Pepe, F.V.; Di Lena, F.; Garuccio, A.; D'Angelo, M. "Correlation plenoptic imaging" Proc. SPIE 2017, 10333.
  - F. V. Pepe, F. Di Lena, A. Mazzilli, A. Garuccio, G. Scarcelli, and M. D'Angelo, "Correlation plenoptic imaging," in Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC, 2017 Conference on), pp. 1–1, IEEE, 2017.
  - F. V. Pepe, F. Di Lena, A. Mazzilli, E. Edrei, A. Garuccio, G. Scarcelli, and M. D'Angelo, "Experimental demonstration of diffraction-limited plenoptic imaging" Proc. SPIE 2018, 10677.
  - Di Lena, F.; Pepe, F.V.; Avella, A.; Ruo-Berchera, I.; Scarcelli, G.; Garuccio, A.; D'Angelo, M. "Correlation plenoptic imaging with entangled photons" Proc. SPIE 2018, 10674.
  - F. V. Pepe, F. Di Lena, A. Mazzilli, E. Edrei, A. Garuccio, G. Scarcelli and M. D'Angelo, "Experimental demonstration of diffraction-limited plenoptic imaging" in Computational Optical Sensing and Imaging, pp. CTh2D-1, Optical Society of America, 2018.
  - F. V. Pepe, F. Di Lena, O. Vaccarelli, A. Garuccio, G. Scarcelli, and M. D'Angelo, "Exploring plenoptic properties of correlated light," Proc. SPIE 2018
- Patents
  - Device and process for the acquisition of microscopic plenoptic images with turbulence mitigation, request n. 102018000007857 of 3 August 2018 to the Italian Patent Office (pending); inventors: Milena D'Angelo, Francesco Di Lena, Augusto Garuccio, Francesco V. Pepe, Alessio Scagliola.

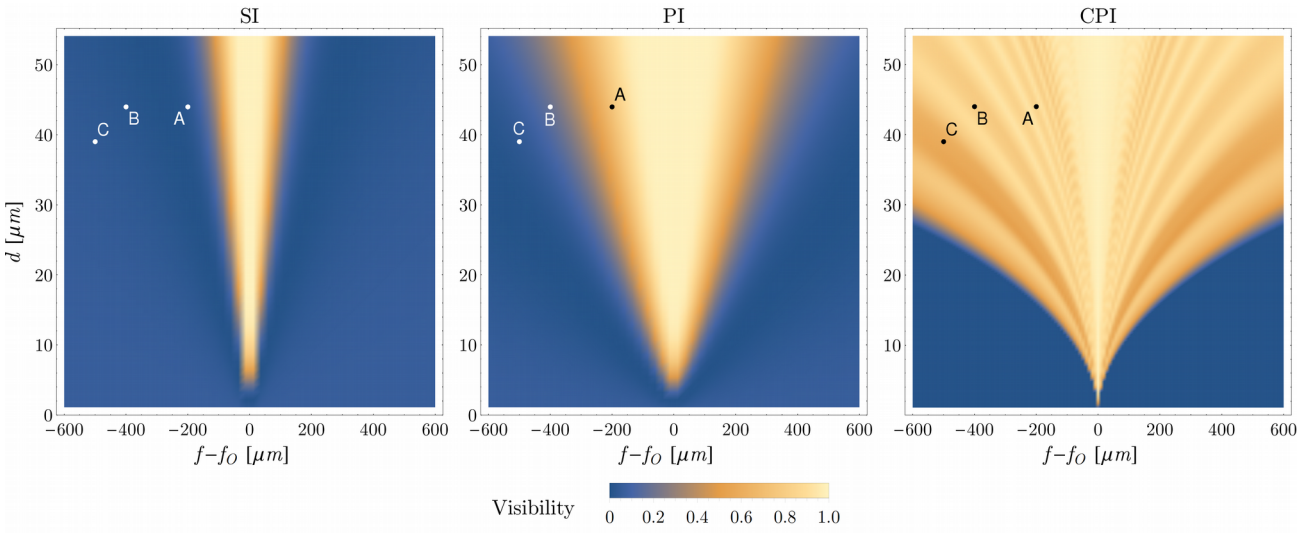
Summary of the activities

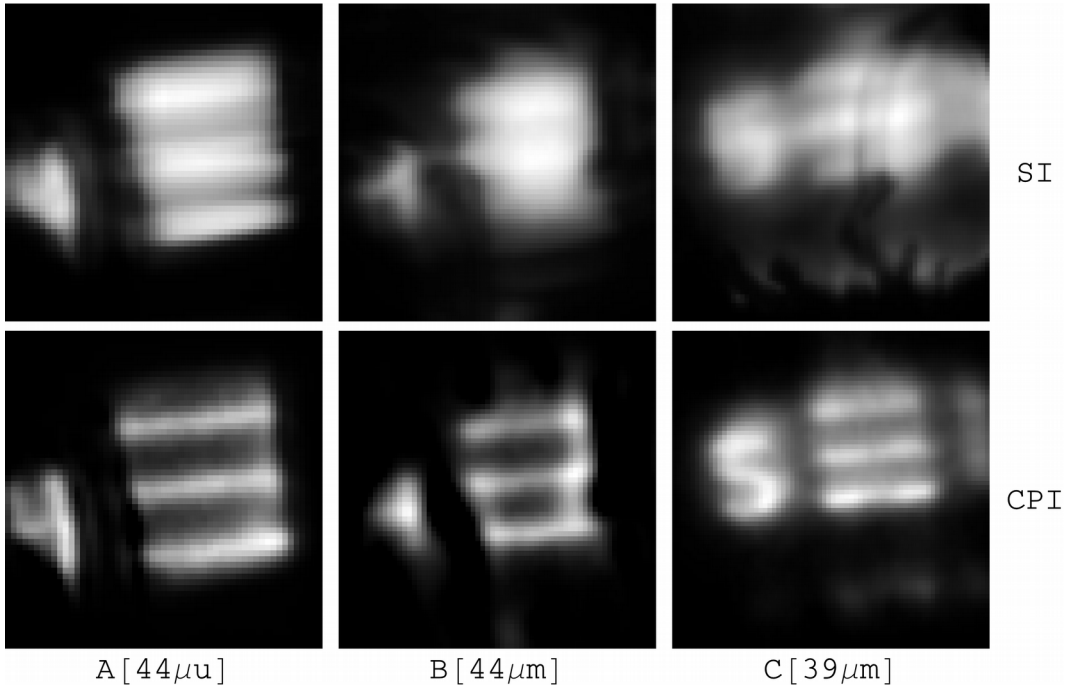
- Talks
  - "Imaging plenottico con misure di correlazione" 102° Congresso nazionale della SIF, Padova, September 26th - 30th 2016.
  - "Imaging plenottico con misure di correlazione" 103° Congresso nazionale della SIF, Trento, September 14th – 15th 2017 (awarded talk).
  - "Plenoptic imaging at the diffraction imit" (invited speaker), The 48th Winter Colloquium of the Physics of Quantum Electronics 2018 (PQE-2018), Snowbird, Utah, USA, January 07th – 12th 2018.
  - "Correlation plenoptic imaging with entangled photons", in Quantum Technologies, SPIE Photonics Europe 2018, Strasbourg, France 22th – 26th aprile 2018.
- Other conferences:
  - "Quantum Roundabout 2016", University of Nottingham, July 6th - 8th 2016 (poster).
  - 37° Congresso SISFA, Bari, September 26th – 29th 2017.
- 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 (poster).
- Other activities
  - Guided tour at Quantum Optics lab, Conferenza Italiana Studenti di Fisica, Bari, May 11th – 12th 2017.
  - Teaching assistant "Laboratorio di ottica moderna" Academic year: 2017 – 2018.

Thank you for your attention!

Appendix

Correlation Plenoptic Microscopy DOF

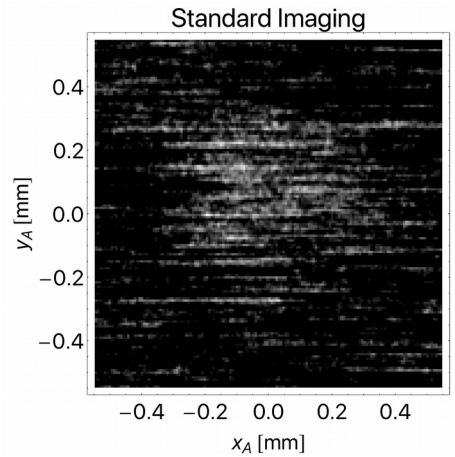




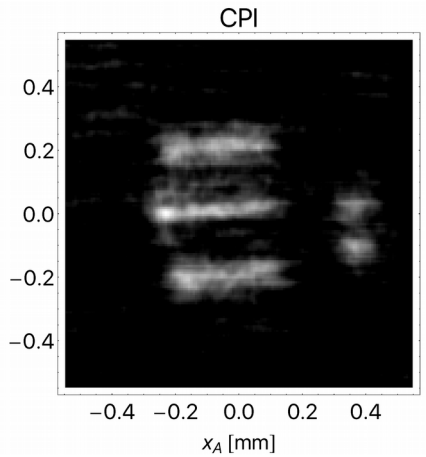
2. CPI with chaotic light

Experimental 2D images

B

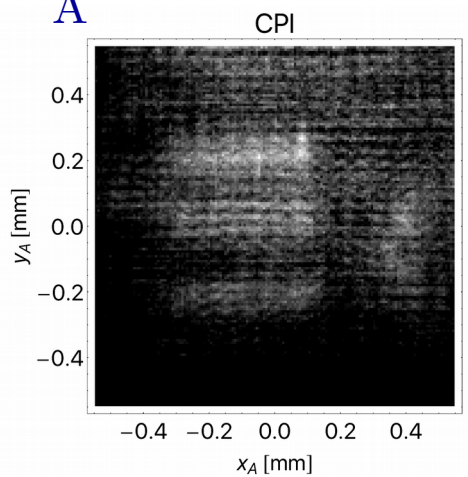


B

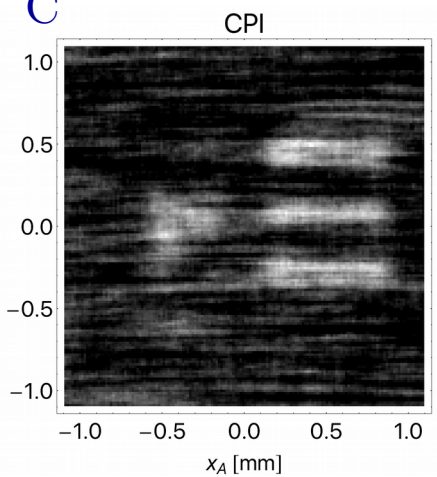


Visibility of the image of a double slit
(distance d = 2 width)

A



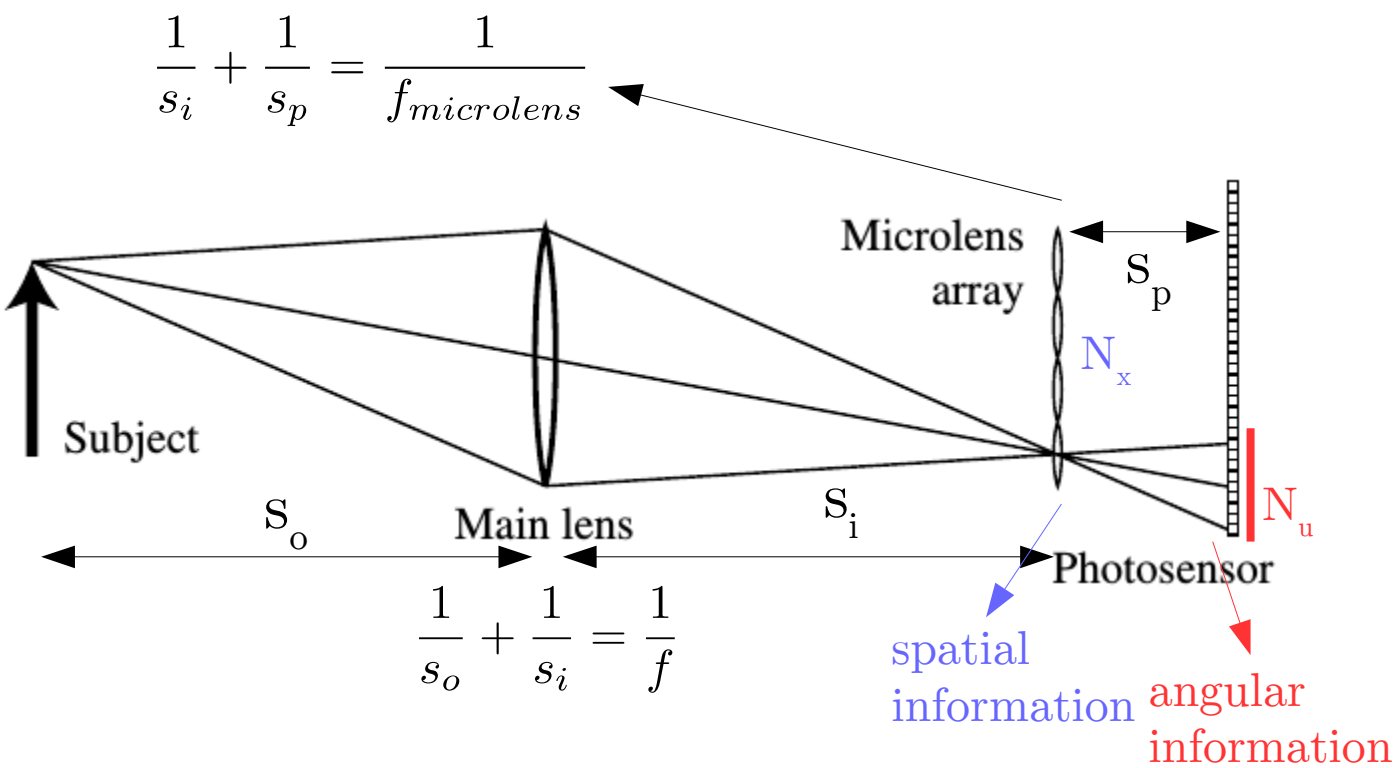
C



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

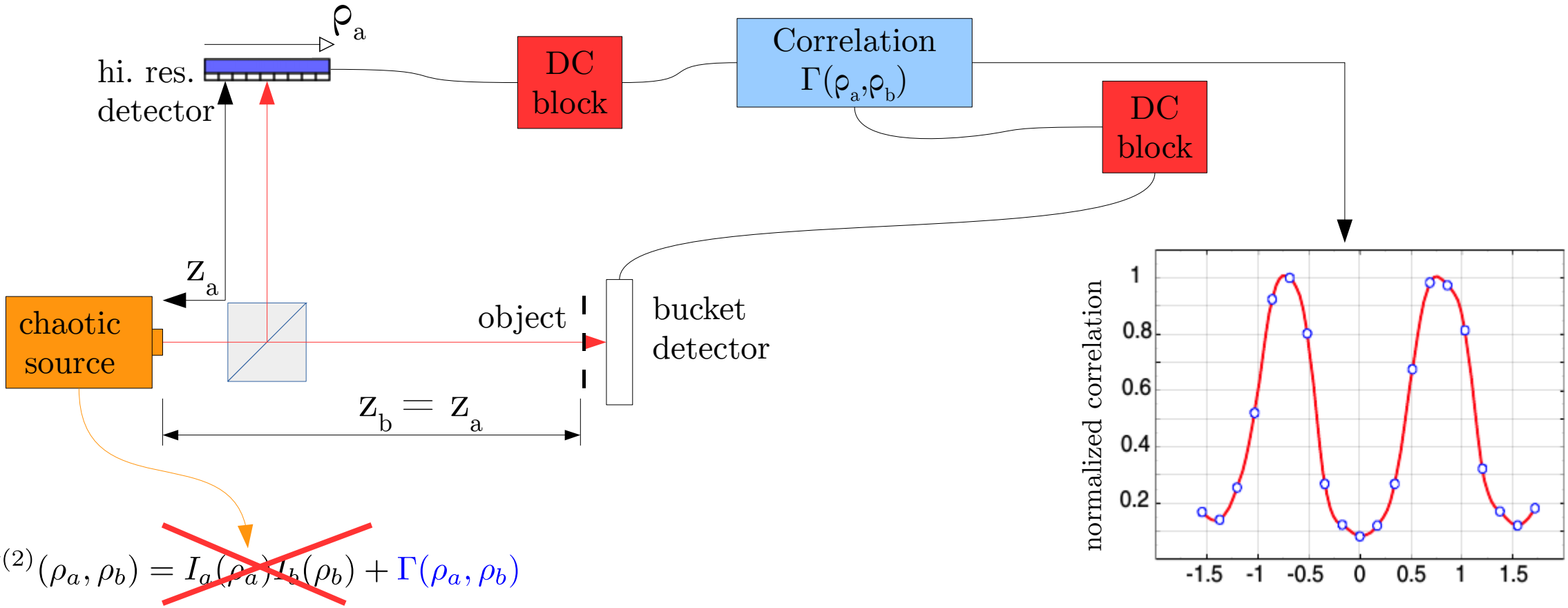
CPI enables refocusing in a much wider range than standard imaging and PI, while keeping the resolution of standard imaging!

Plenoptic imaging



- 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/

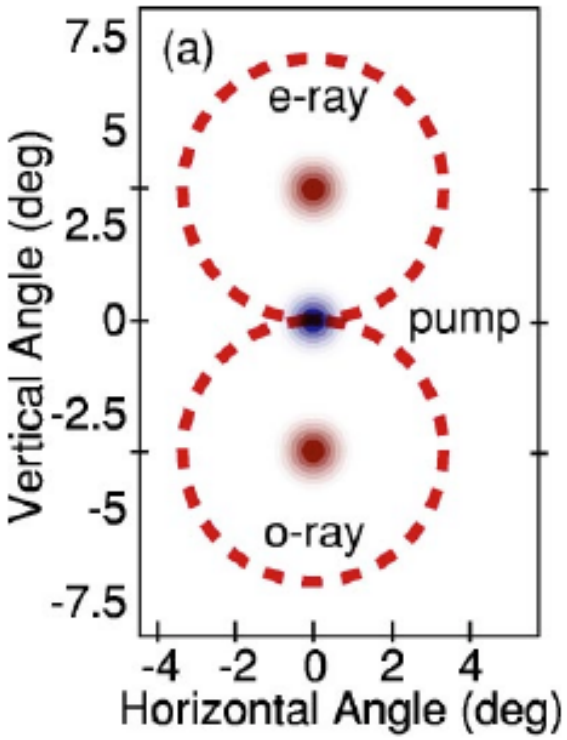
Ghost Imaging



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

- 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

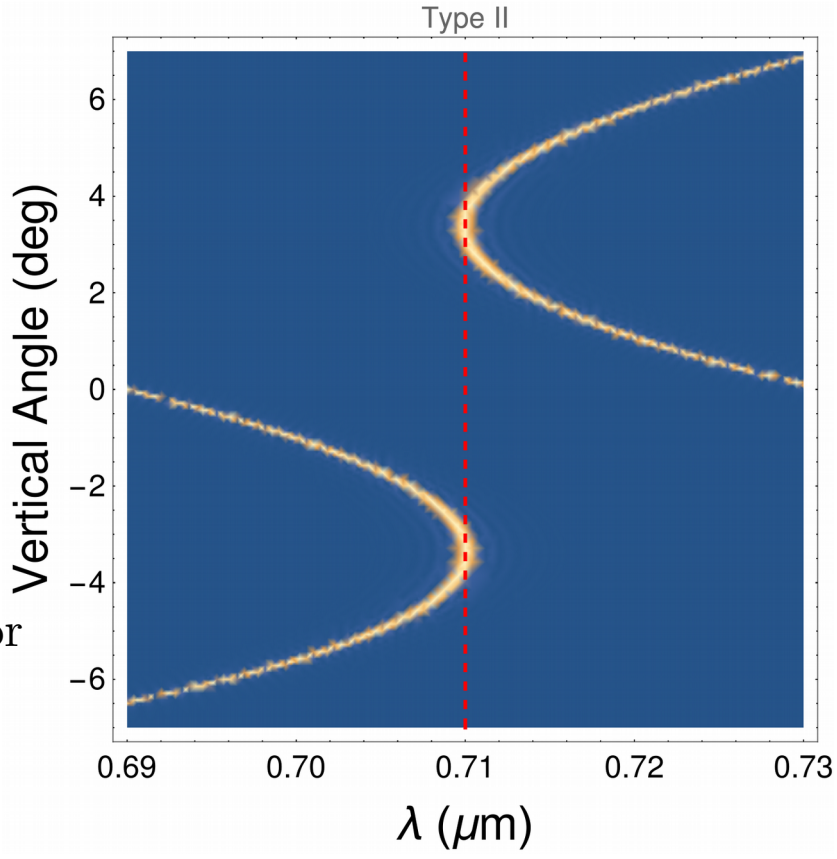
SPDC – type II beam like



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

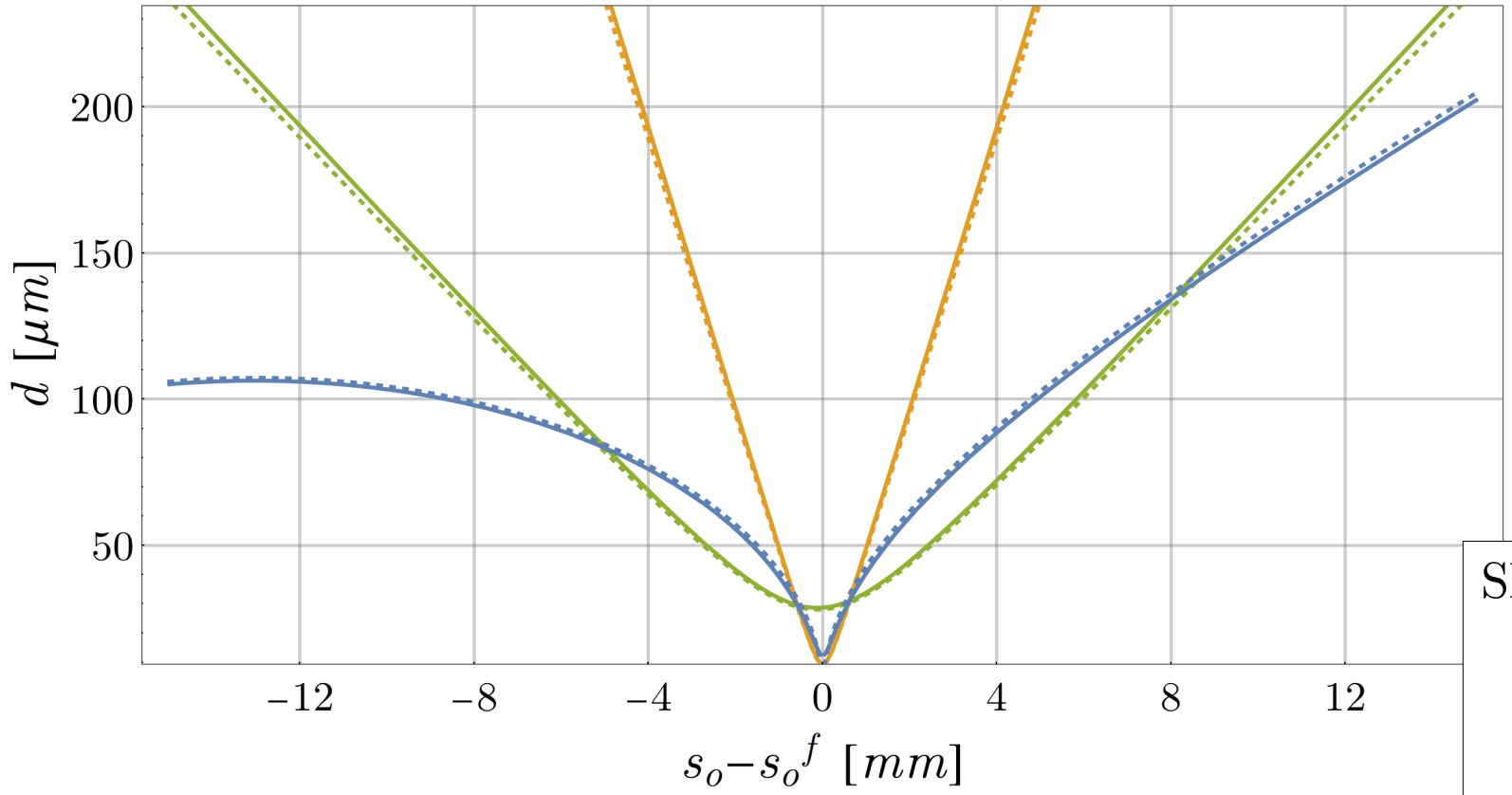
$$\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_i$$

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.