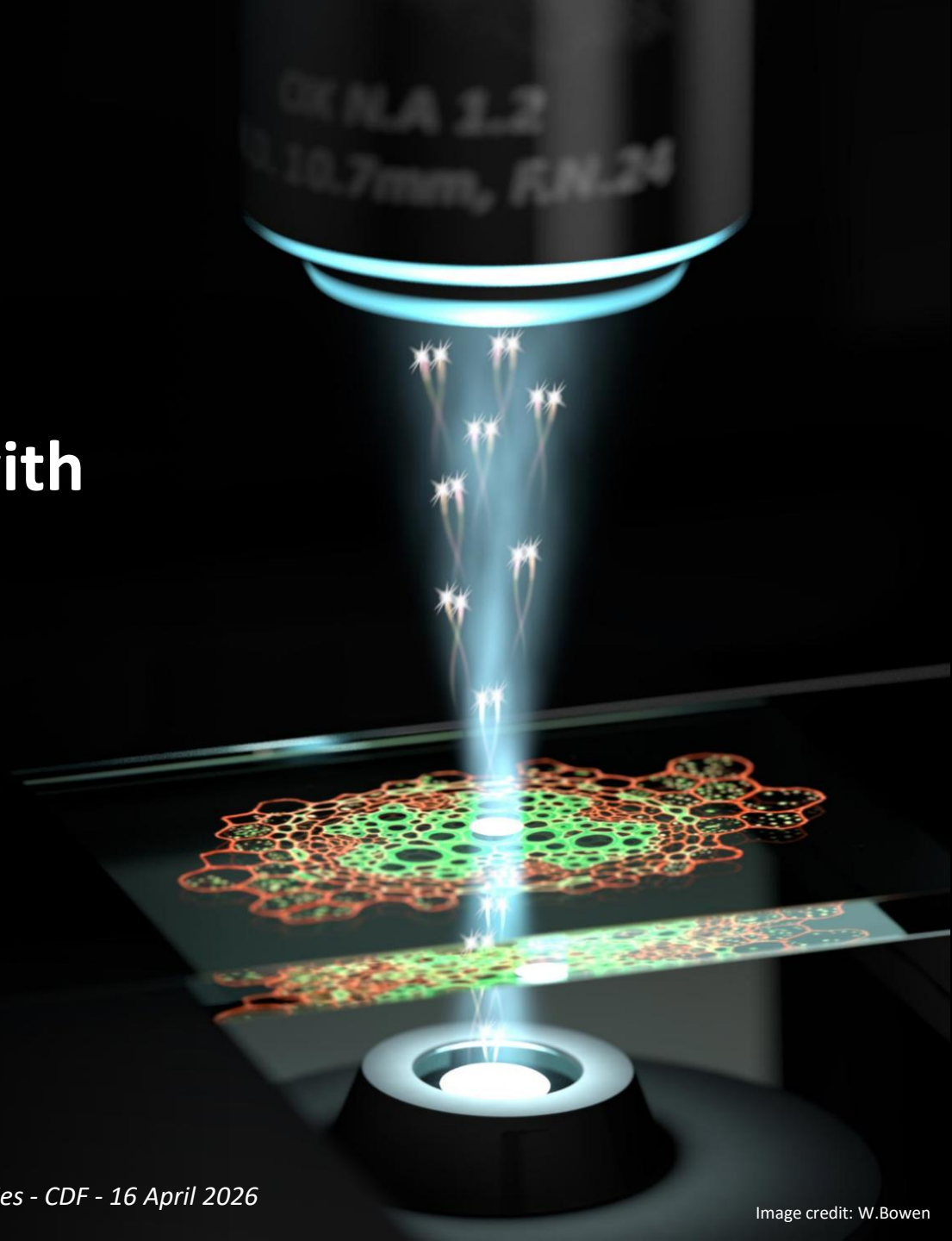
Quantum imaging with entangled photons

Hugo Defienne



Symposium Light-based quantum technologies - CDF - 16 April 2026

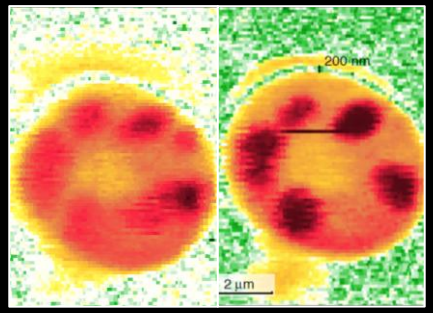
Image credit: W.Bowen

Quantum imaging: using non-classical light properties to improve imaging system performance beyond classical limits

Quantum imaging

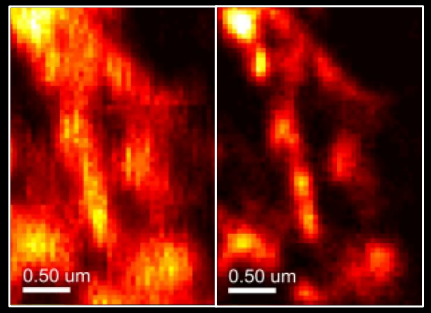
Improve imaging performance

↗ Signal-to-noise



Nature, 594 (2021)
Prof. Bowen's group

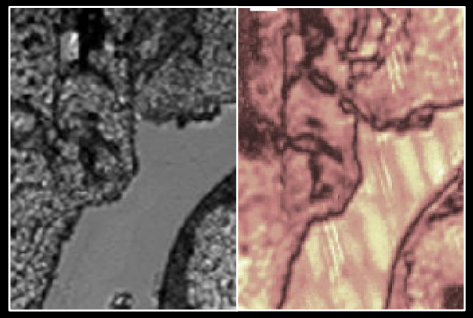
↗ Spatial resolution



Nat.Phot., 13(2) (2019)
Prof. Oron's group

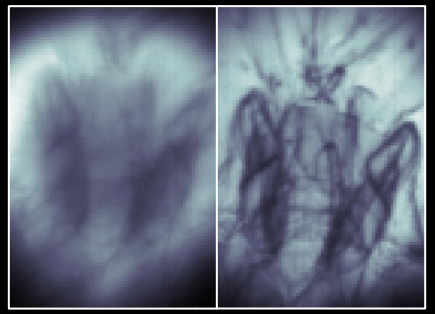
Develop new modalities

Illum. $\lambda_1 \neq \lambda_2$ detection



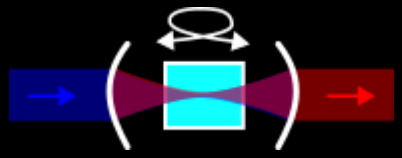
Opt.Expr.,4 (30) (2022)
Nature 512 (2014)
Prof. Ramelow | Prof. Zeilinger groups

Overcome aberrations



Science, 383 (2024)

Bright squeezed light



Single-photon emitters

Entangled photons pairs

+ Methods: Phase-enhanced imaging, Ghost imaging, …
+ Sources: Multiphoton state, bright squeezed vaccuum, …
+ Applications: Astronomy, detection and ranging, …

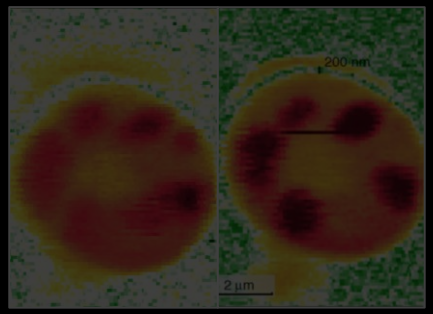
Goal: Beyond classical limits

***Review**: Defienne, Bowen, Chekhova, Lemos, Oron, Ramelow, Treps, Faccio. Advances in quantum imaging. Nat. Phot. 18, 1024-1036 (2024)*

Quantum imaging

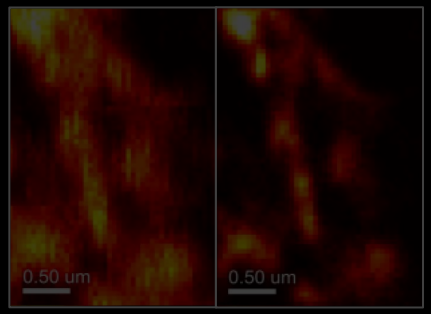
Improve imaging performance

↗ Signal-to-noise



Nature, 594 (2021)
Prof. Bowen's group

↗ Spatial resolution



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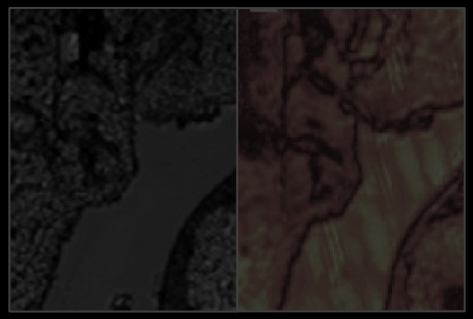

Opt.Expr.,4 (30) (2022)
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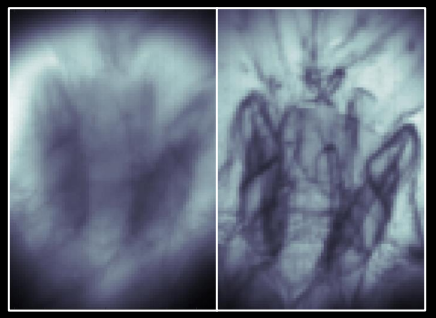
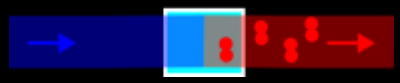


Science, 383 (2024)

Bright squeezed light

Single-photon emitters

Entangled photons pairs



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+ **Sources:** Multiphoton state, bright squeezed vaccuum, …
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***Review**: Defienne, Bowen, Chekhova, Lemos, Oron, Ramelow, Treps, Faccio. Advances in quantum imaging. Nat. Phot. 18, 1024-1036 (2024)*

Today's problem: Aberrations in microscopy

Sample

Microscope

Aberrations
Specimen
System

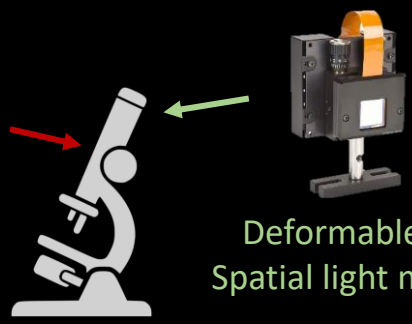
Diffraction-limited image

Aberrations

Scattering

Today's problem: Aberrations in microscopy

Aberrations
Specimen
System



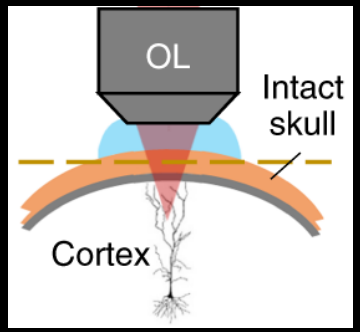
Microscope

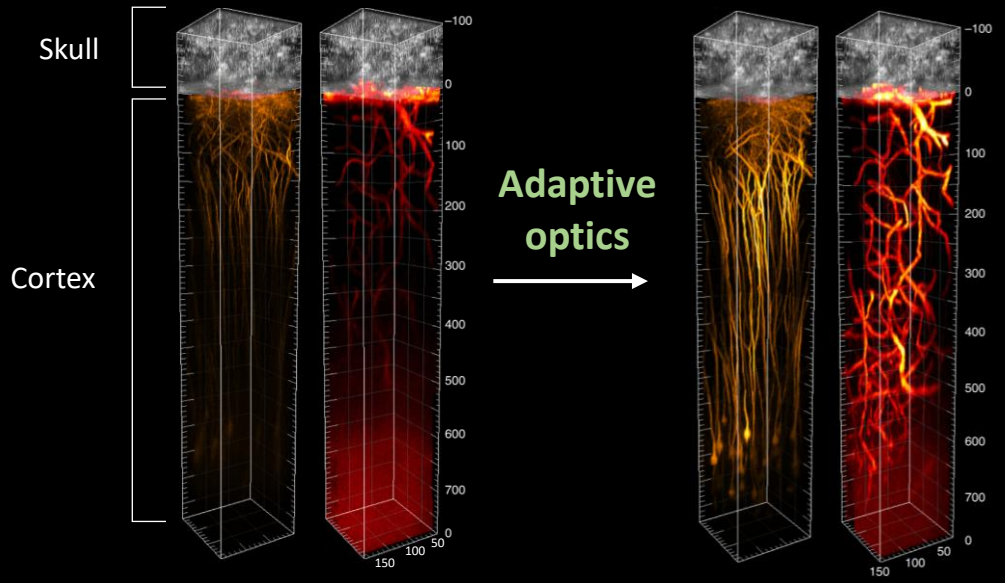
Deformable mirror
Spatial light modulator

Challenge in biology and medecine:
Non-invasive imaging at depth (>1mm) preserving optical resolution (<1µm)

Deep-tissue imaging

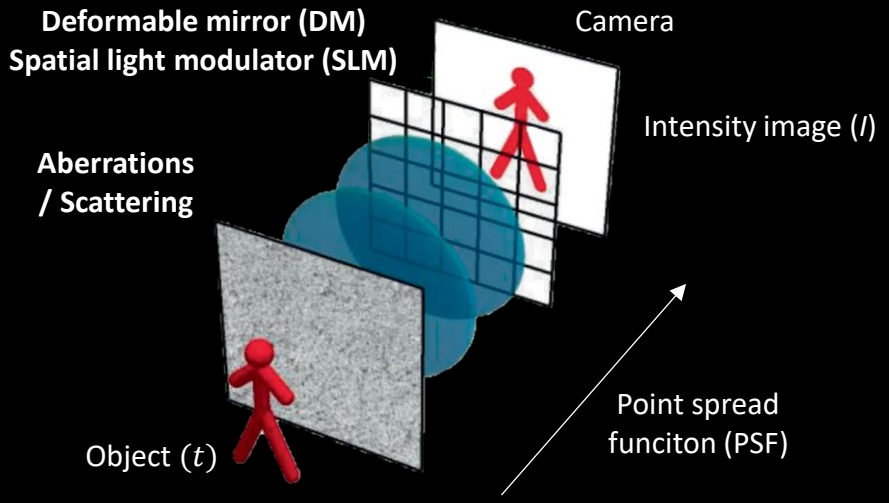
Three-photon microscope





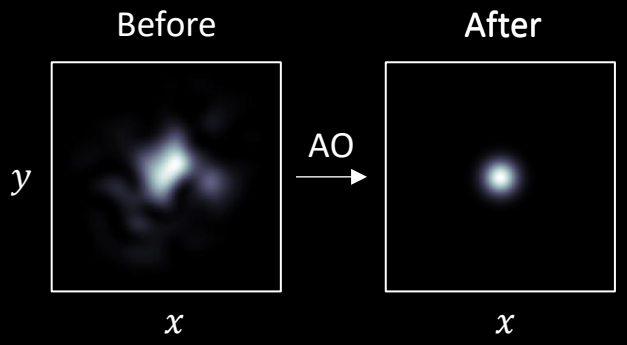
Qin et al. *Nature Biotechnology*, 40, 1663-1671 (2022)

Adaptive optics for microscopy



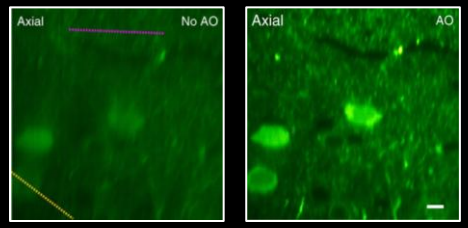
Bertolotti and Katz. Nat Phys, *18*(9), 1008-1017 (2022)

$$I = |t|^2 * |PSF|^2$$



Challenge: Finding the optimal SLM correction

Guide-star based AO (direct/indirect)



Nat. Meth., 11(10), 1037-1040 (2014)

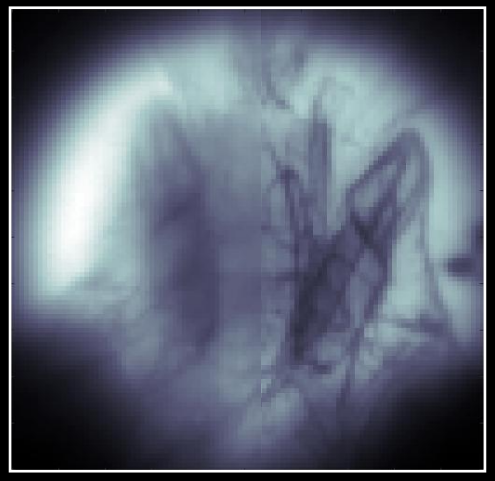
Need a guide-star
and/or Wavefront sensor

Image-based AO

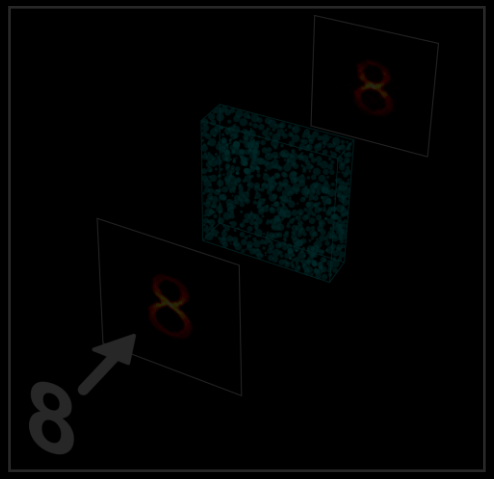
Opt. Expr., *15*(13), 8176-8190 (2007)

Object/contrast mechanism
dependant

Today's focus : Improving adaptive optics using entangled photons



Part 1. Overcome aberrations
using photon **correlations**



Part 2. Bypass scattering
with **entanglement**

The source: Spatially-entangled photon pairs

Spontaneous parametric down conversion (SPDC)

Energy conservation

$w_p = w_i + w_s$

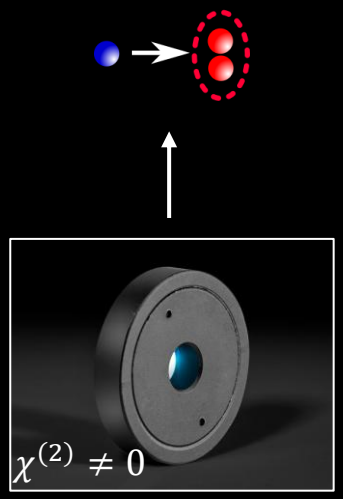
405nm $\rightarrow 2 \times 810nm$

Momentum conservation

$k_p = k_i + k_s$

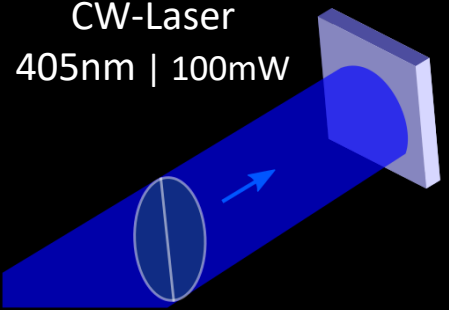
$0 \approx k_{iT} + k_{sT}$

$$|\Psi\rangle \approx |0\rangle + \eta \sum_{k} \hat{a}_{k}^{+} \hat{a}_{-k}^{+} |0\rangle$$



Type I BBO

CW-Laser 405nm | 100mW



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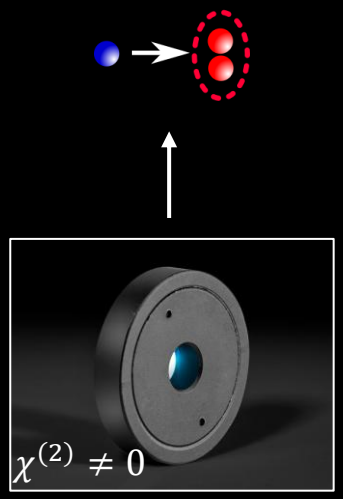

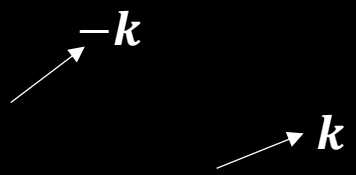

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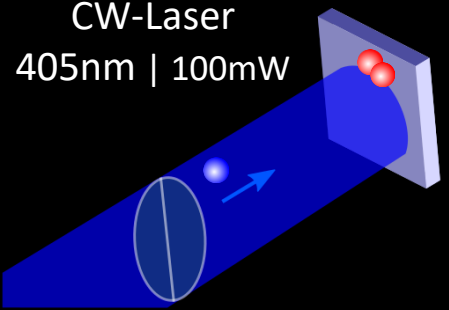

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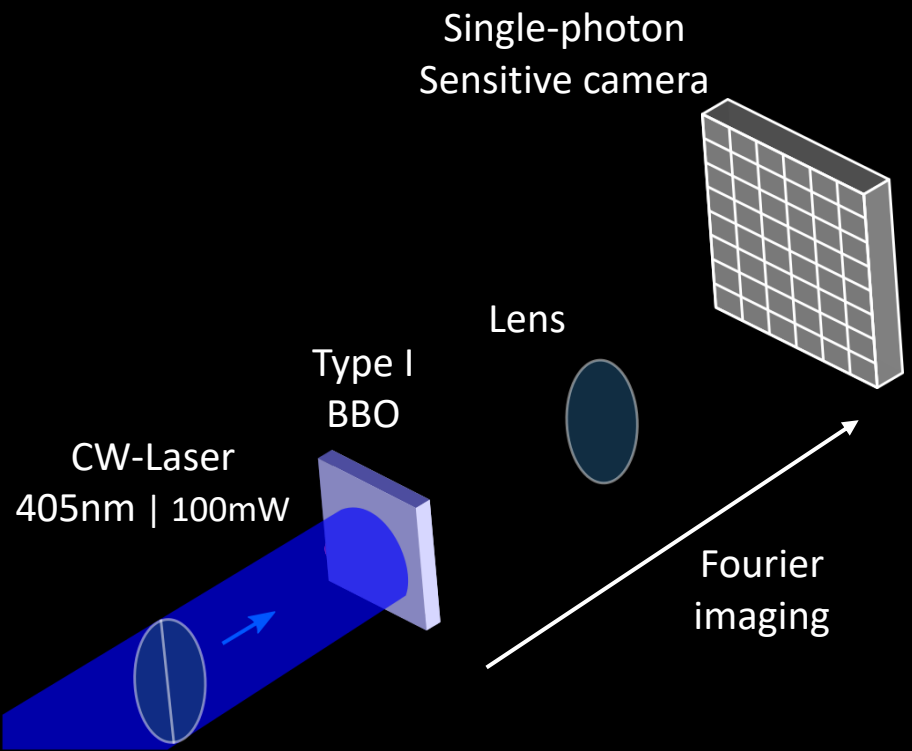
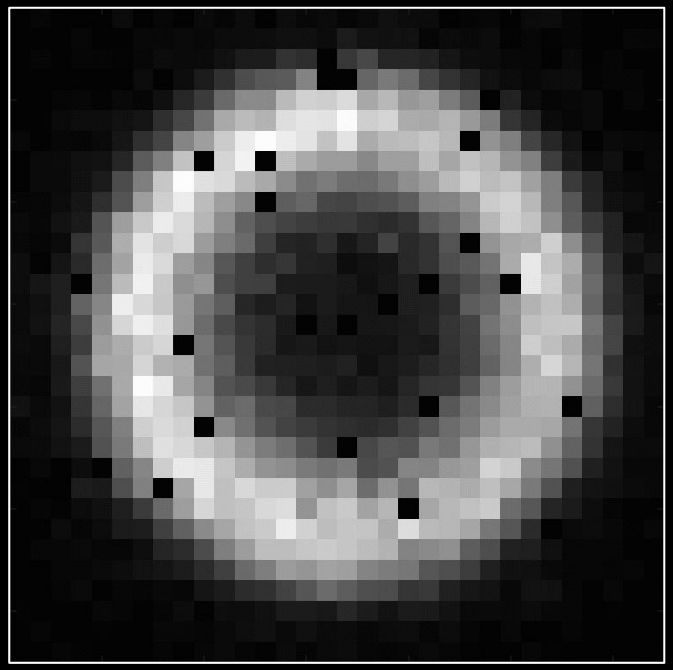


The source: Spatially-entangled photon pairs

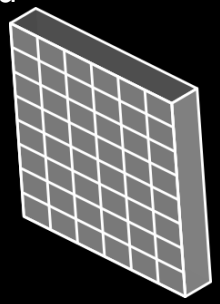
Single-photon Avalanche Diode (SPAD) array

Exposure time: **10ms**

Intensity image [singles]

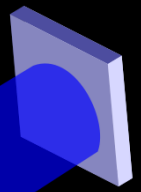


Single-photon Sensitive camera

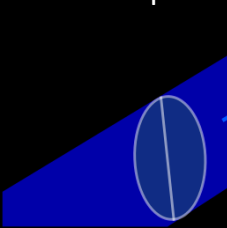


Lens

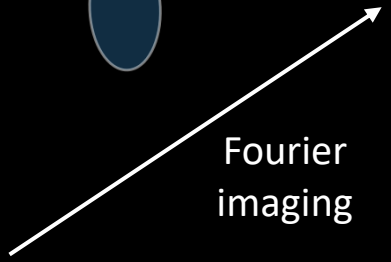
Type I BBO



CW-Laser 405nm | 100mW



Fourier imaging

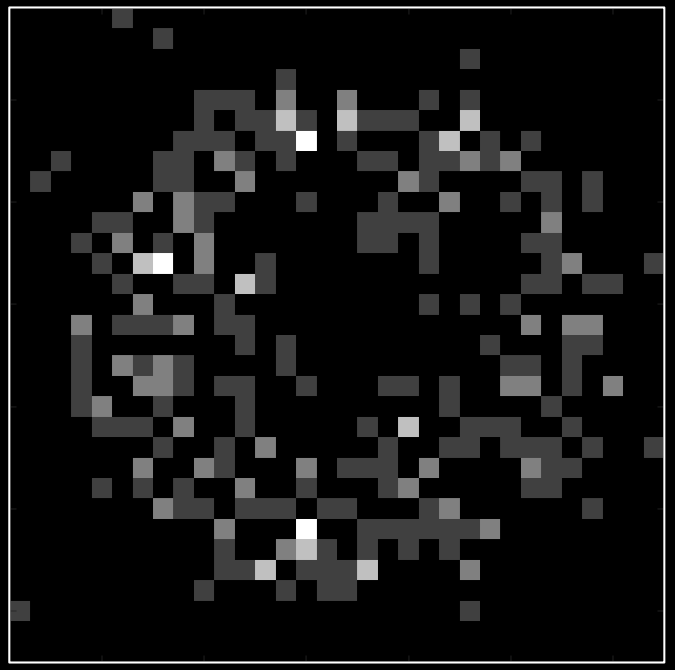


The source: Spatially-entangled photon pairs

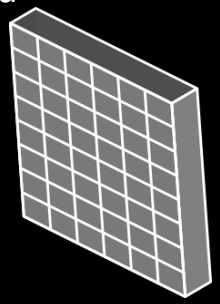
Single-photon Avalanche Diode (SPAD) array

Exposure time: **50µs**

Intensity image [singles]



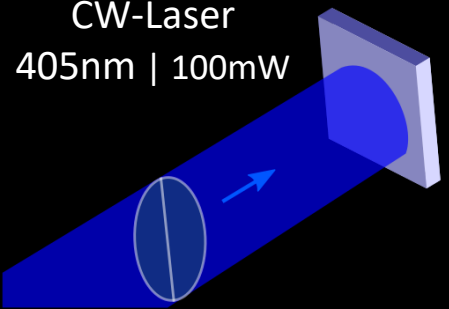
Single-photon Sensitive camera



Lens

Type I BBO

CW-Laser 405nm | 100mW



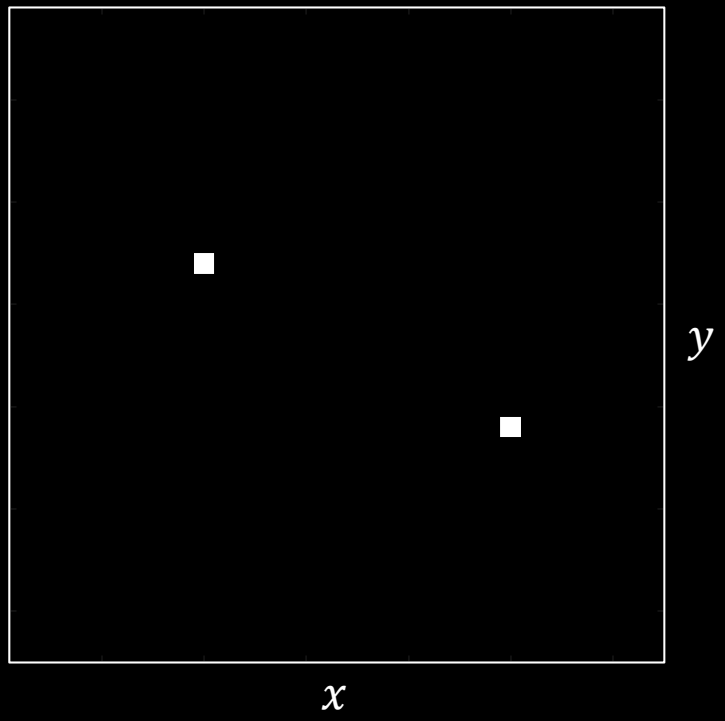
Fourier imaging

The source: Spatially-entangled photon pairs

Single-photon Avalanche Diode (SPAD) array

Exposure time: **10ns**

Intensity image [singles]



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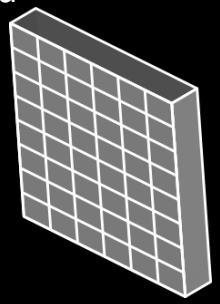

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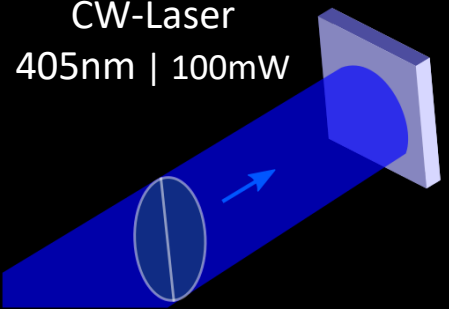


Fourier imaging

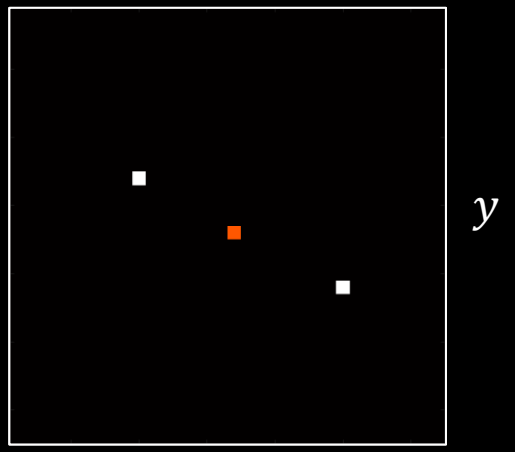
$\rightarrow G^{(2)}(x_1, y_1, x_2, y_2)$
Second-order intensity correlation matrix

The source: Spatially-entangled photon pairs

Single-photon Avalanche Diode (SPAD) array

Exposure time: **10ns**

Intensity image [singles]



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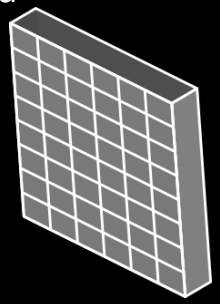
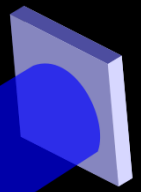


Lens

Type I BBO



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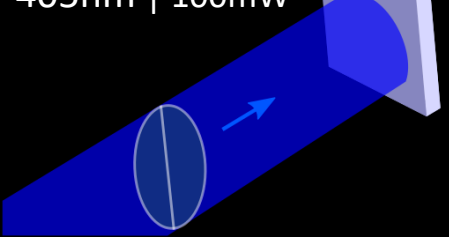

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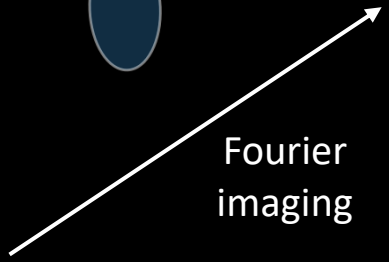
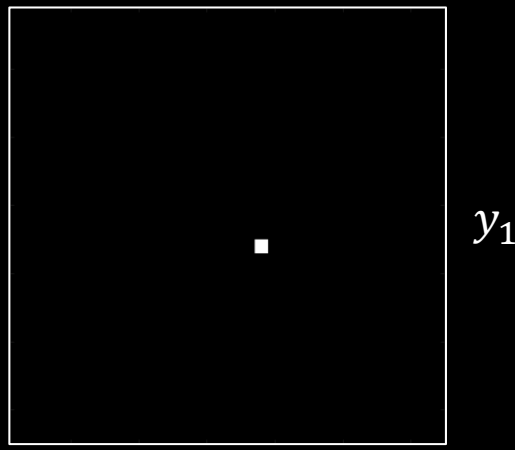


Correlation image ($G^{(2)}$) [coincidences]

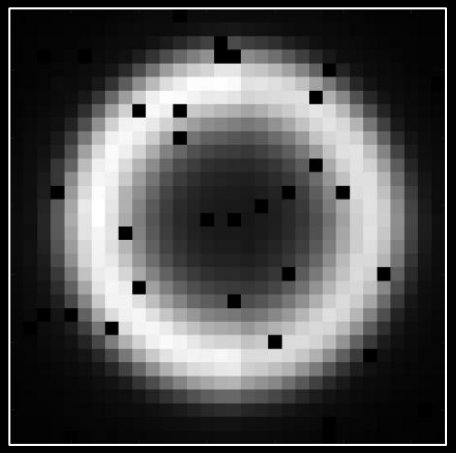


The source: Spatially-entangled photon pairs

Single-photon Avalanche Diode (SPAD) array

Exposure time: **1.3s**

Intensity image [singles]



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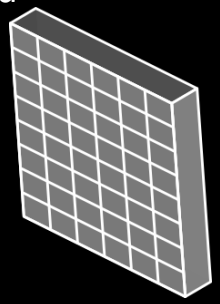
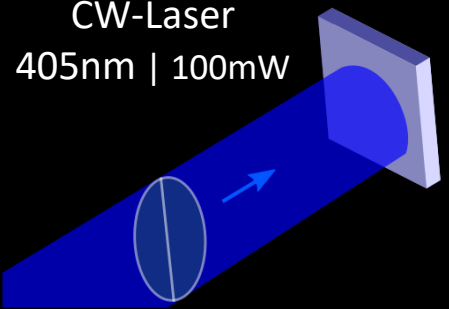


Lens

Type I BBO

CW-Laser 405nm | 100mW



Fourier imaging

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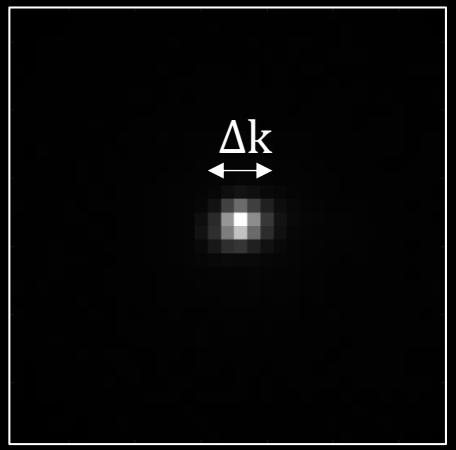
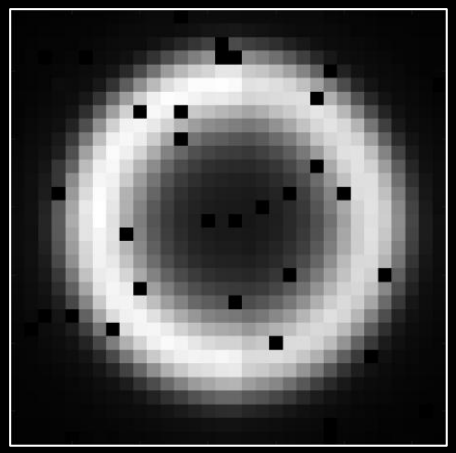


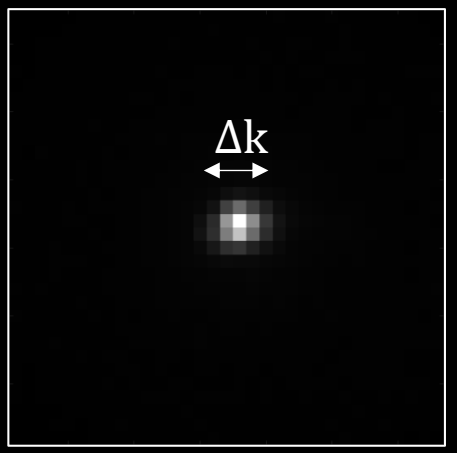
The source: Spatially-entangled photon pairs

Intensity image [singles]

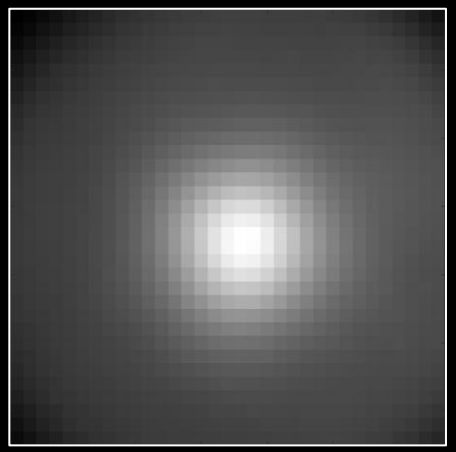


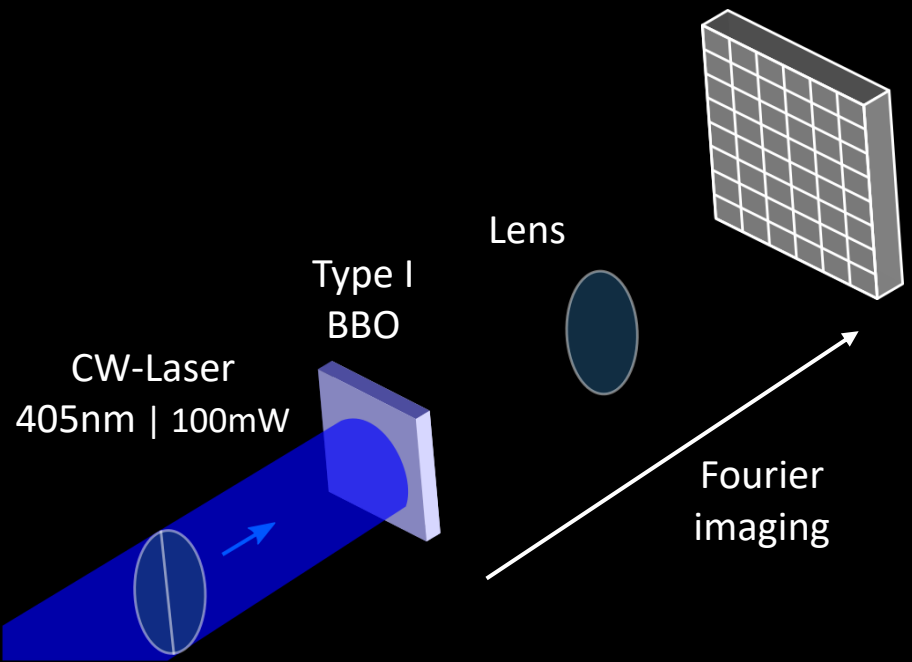
Exposure time: **1.3s**

Correlation image ($G^{(2)}$) [coincidences]



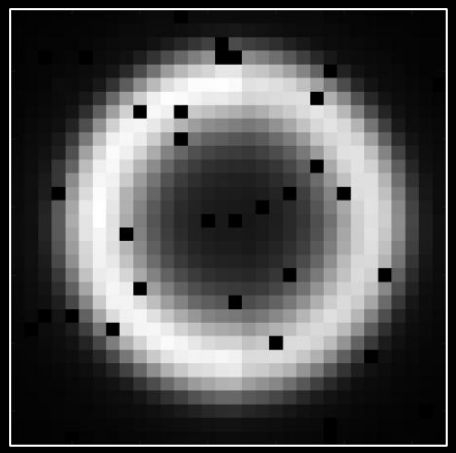
$G^{(2)}$ Uncorrelated photons



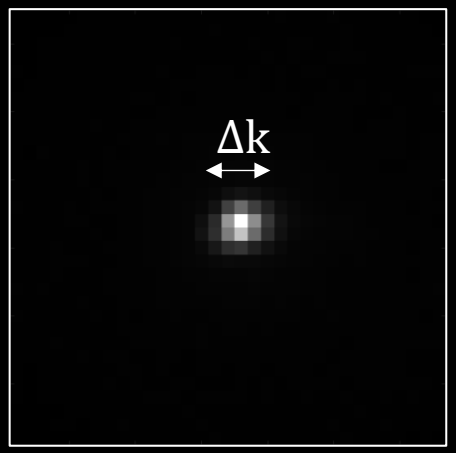


The source: Spatially-entangled photon pairs

Intensity image [singles]



Correlation image ($\boldsymbol{G^{(2)}}$) [coincidences]



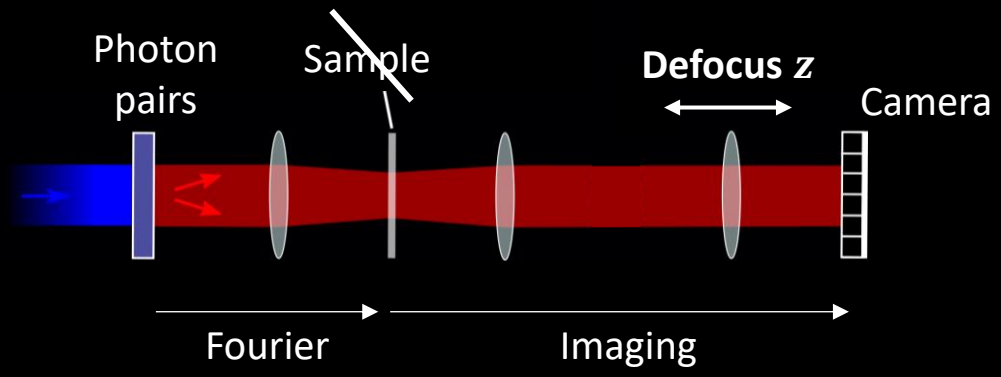
SPAD array

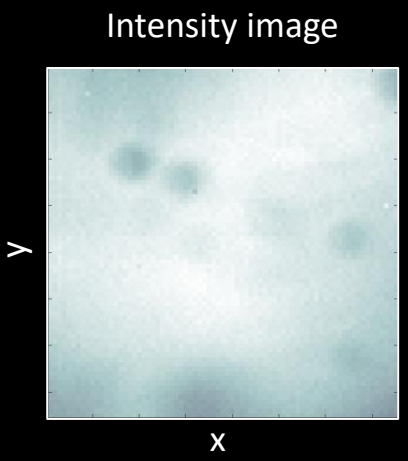
EMCCD

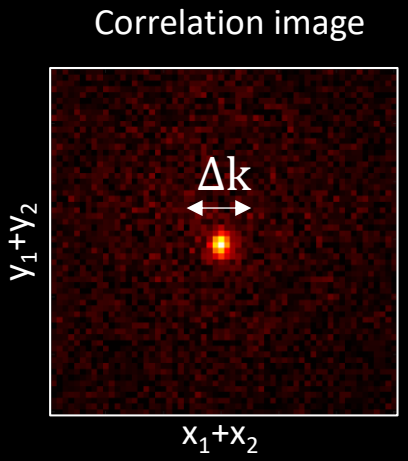
Tpx3cam

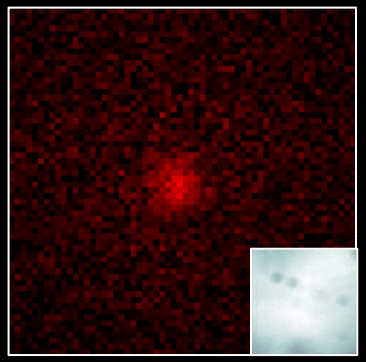
Moreau et al. PRA 86,010101 (2012) | Tasca et al. Nat.Com.3,984 (2012) | Defienne et al. PRL 120(20),203604 (2018)

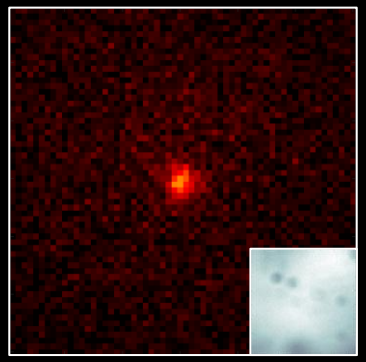
Photon correlations ↔ Optical aberrations

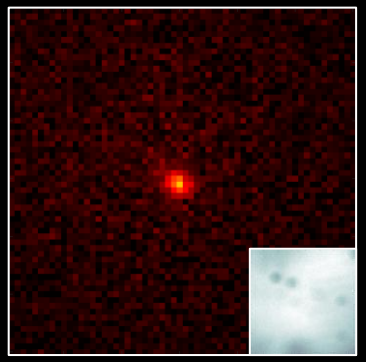


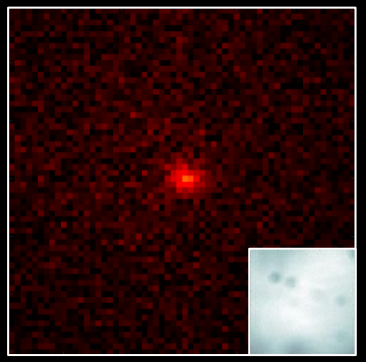





-0,3mm

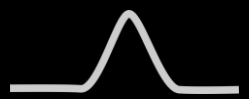

-0,1mm


+0,2mm

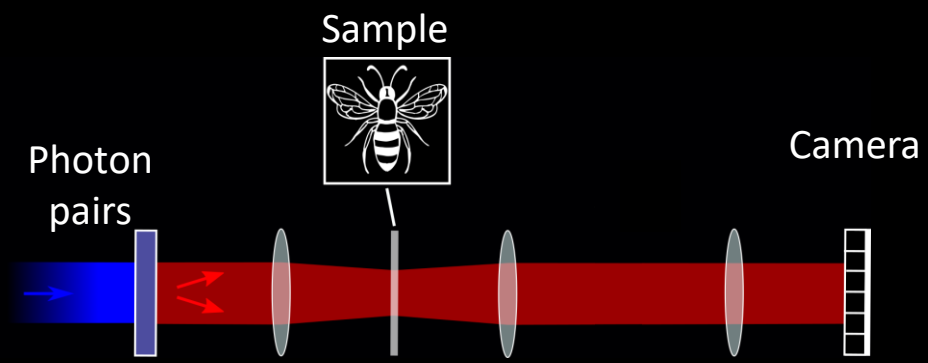

+0,4mm

Δk ↗ Signal ↘

$$G^{(2)} \approx K\,|[\boldsymbol{PSF} * \boldsymbol{PSF}]|^2$$

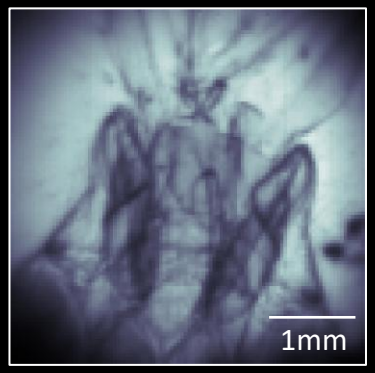

PSF

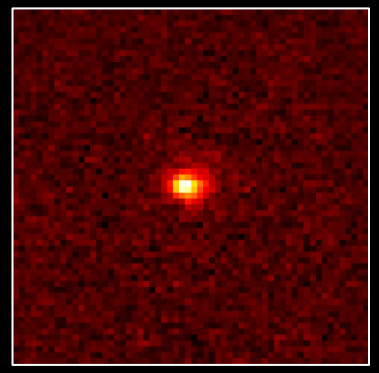
Adaptive optics with correlated photons



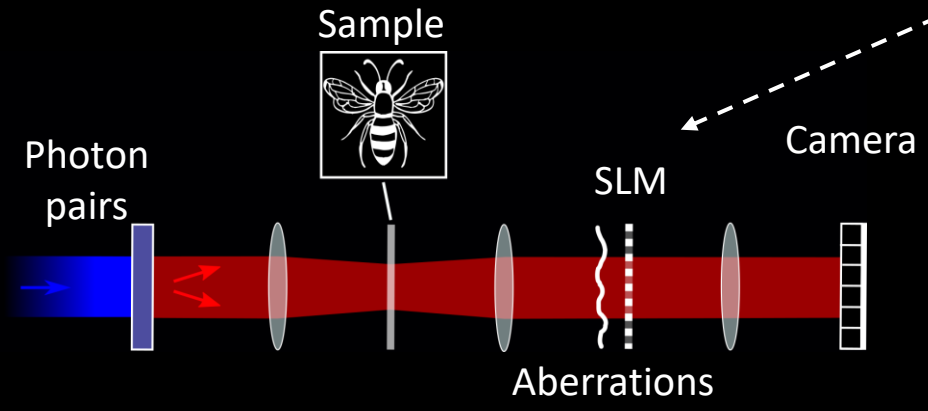
Intensity

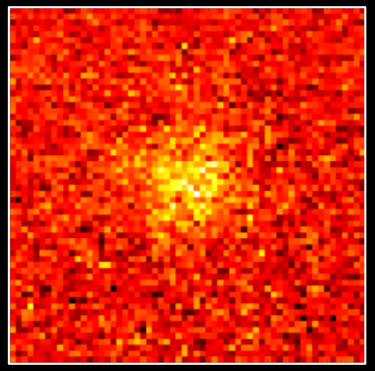
Correlations





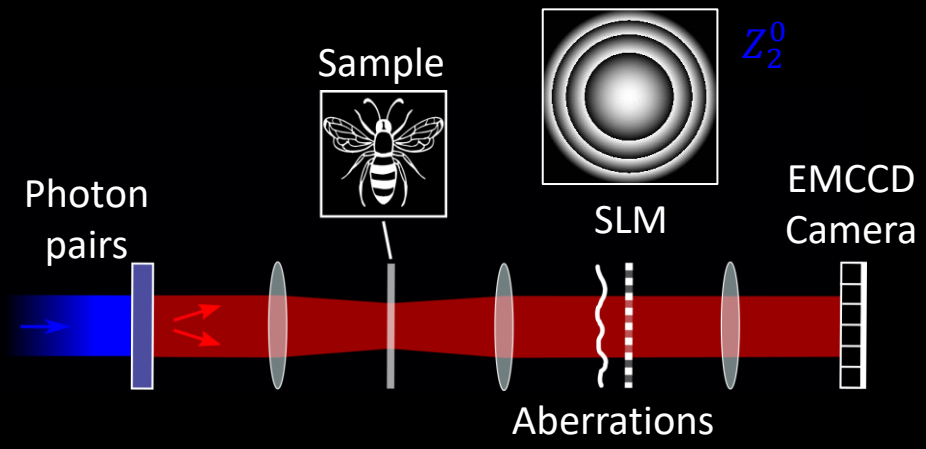
Adaptive optics



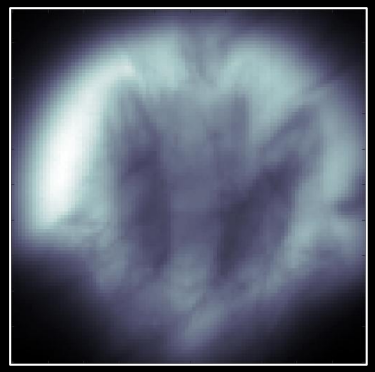


$$G^{(2)} \approx K\,|[\boldsymbol{PSF} * \boldsymbol{PSF}]|^2$$

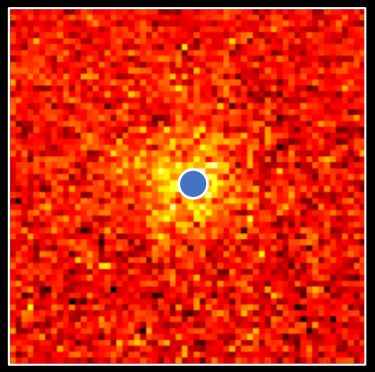
Adaptive optics with correlated photons

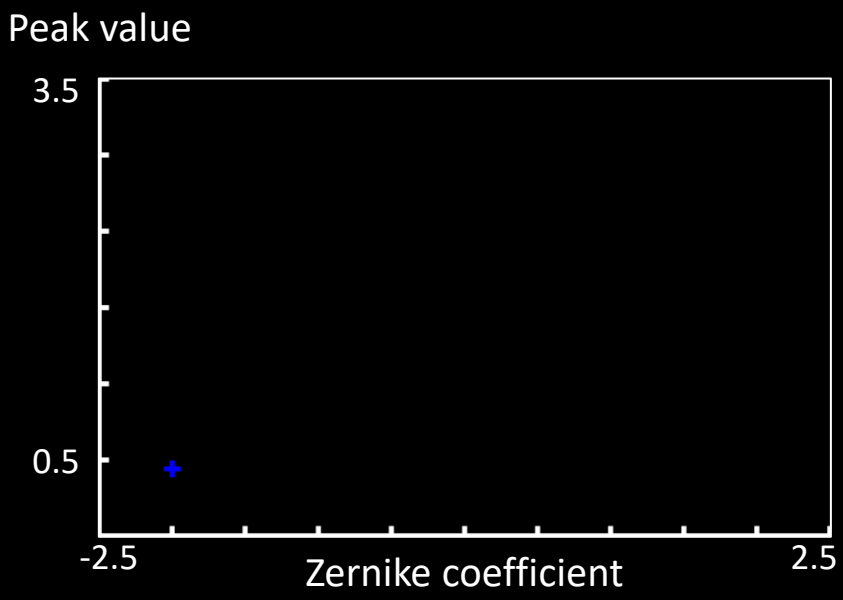


Intensity

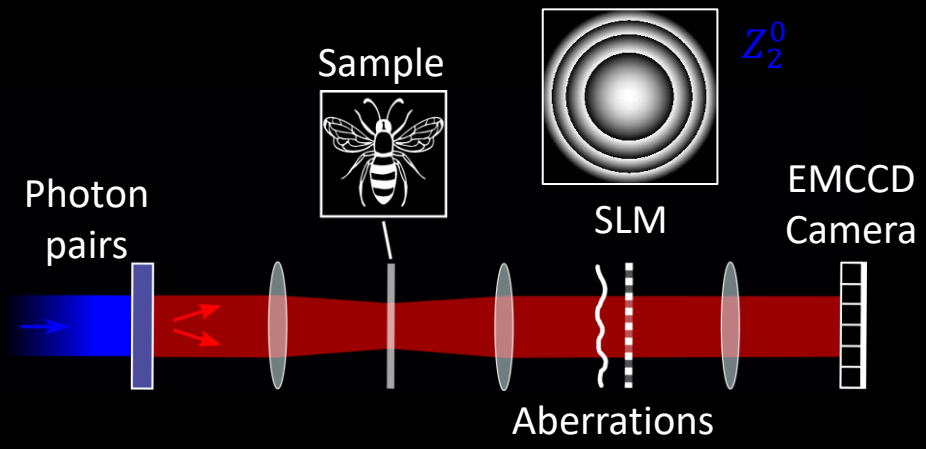


Correlations

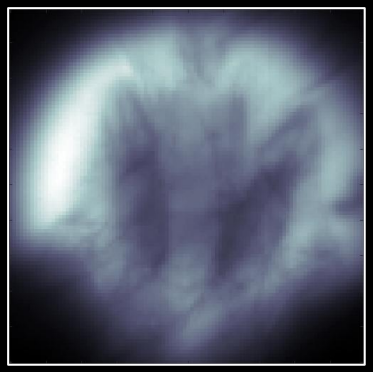




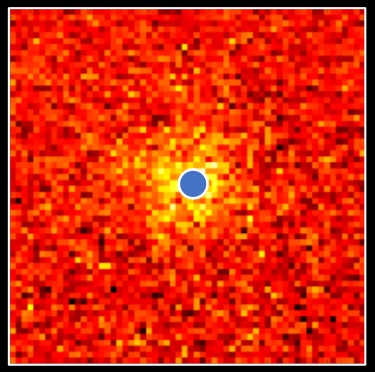
Adaptive optics with correlated photons

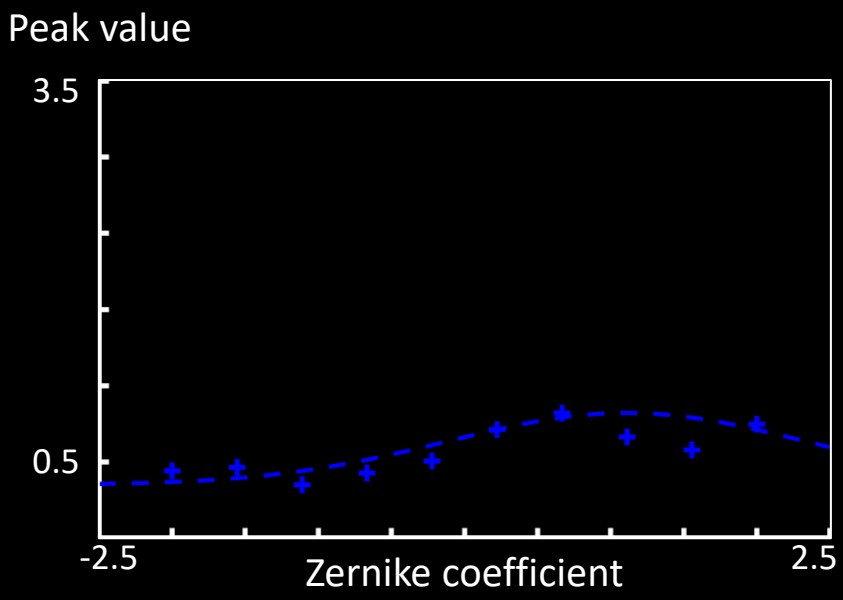


Intensity

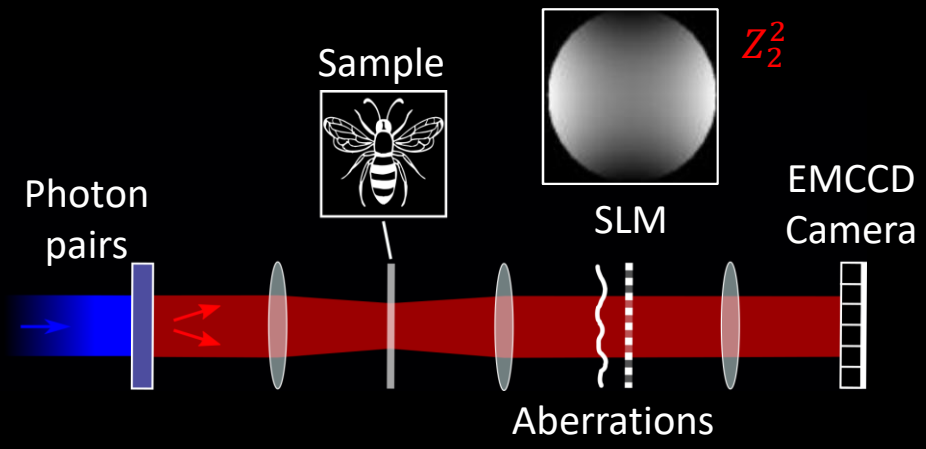


Correlations

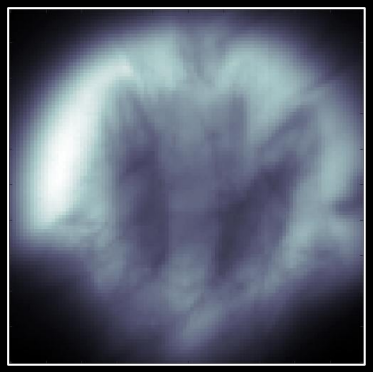




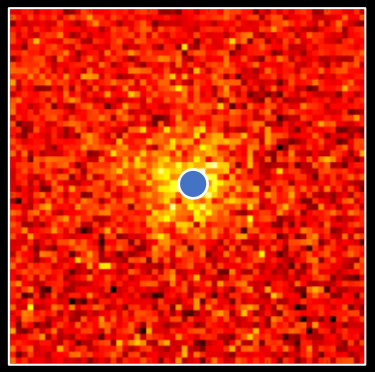
Adaptive optics with correlated photons

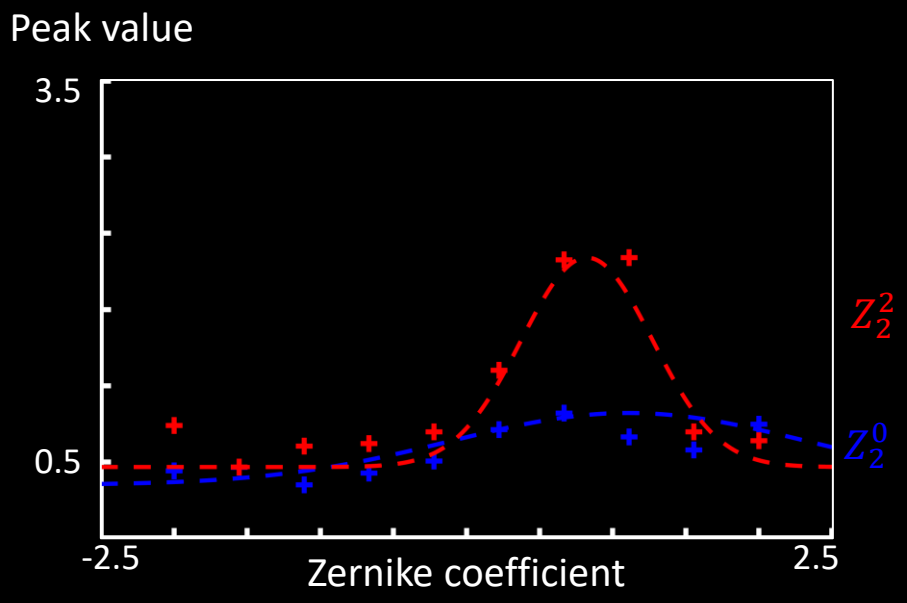


Intensity

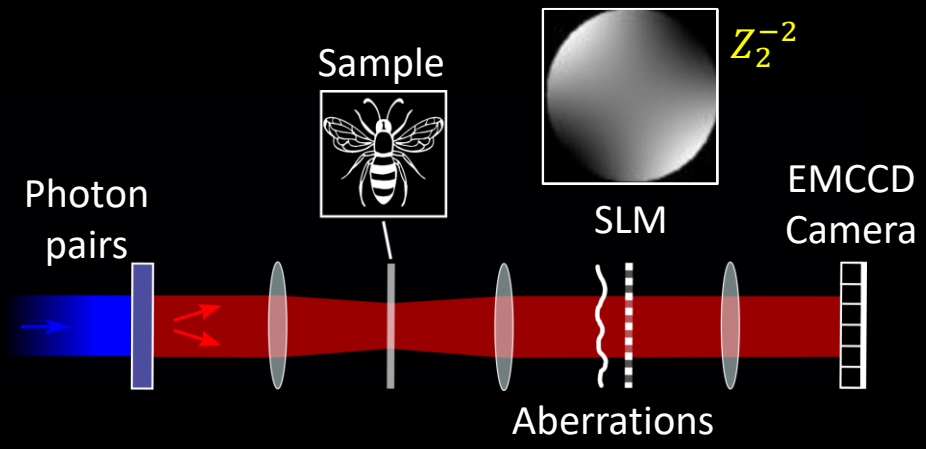


Correlations

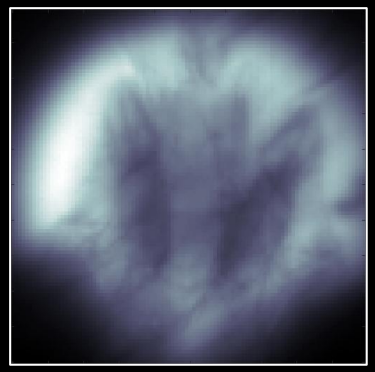




Adaptive optics with correlated photons



Intensity



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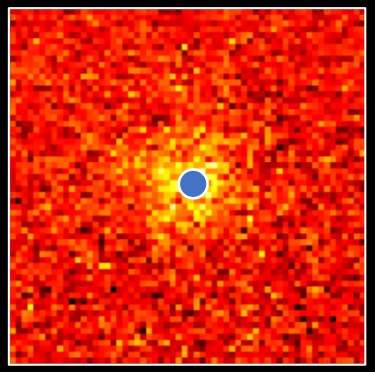
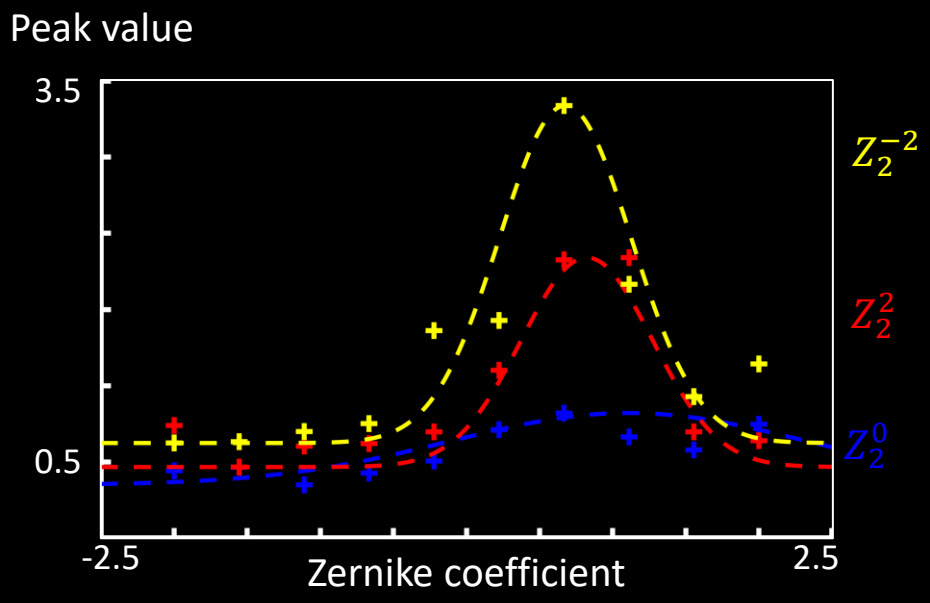
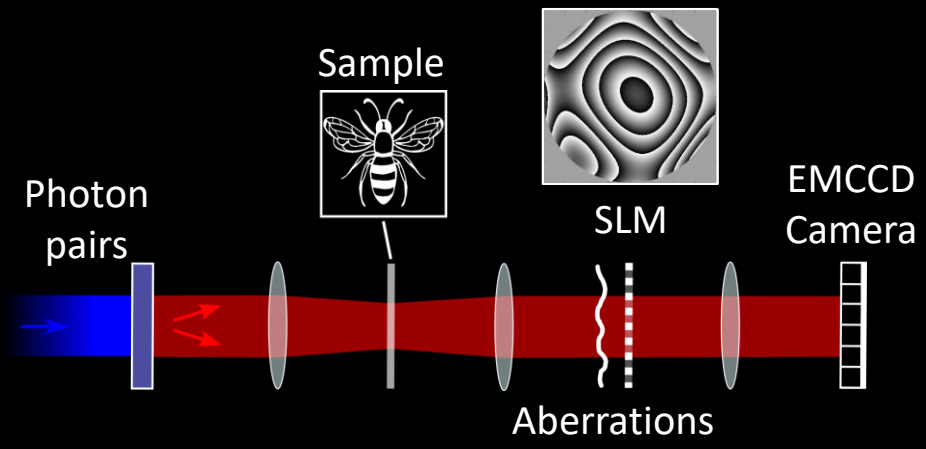
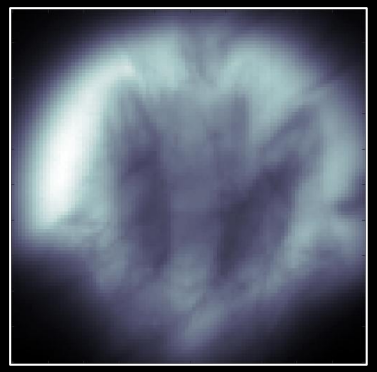




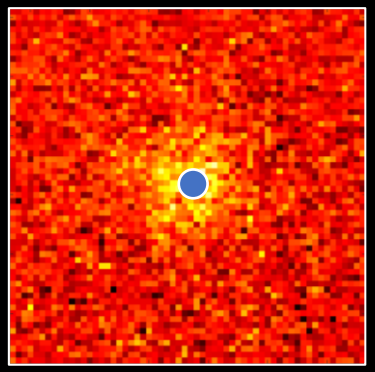
Adaptive optics with correlated photons

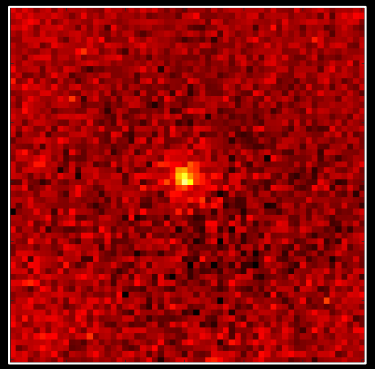


Intensity

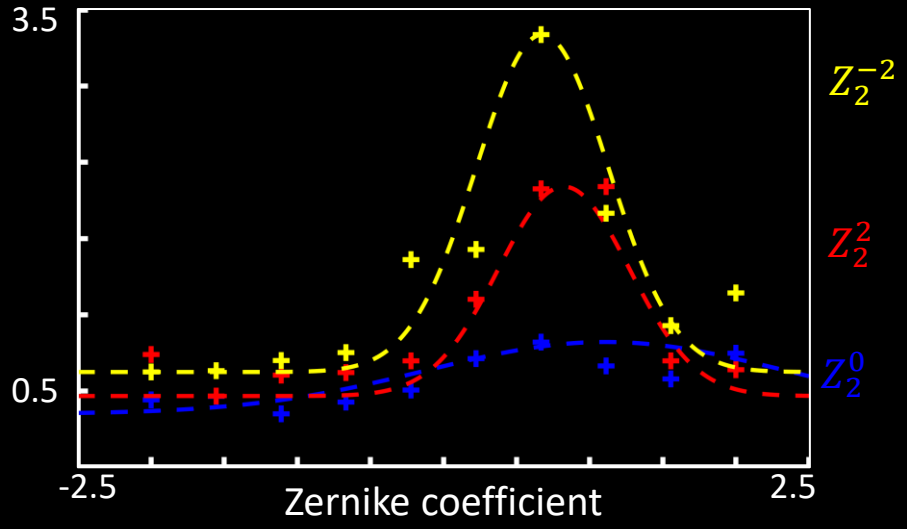


Correlations

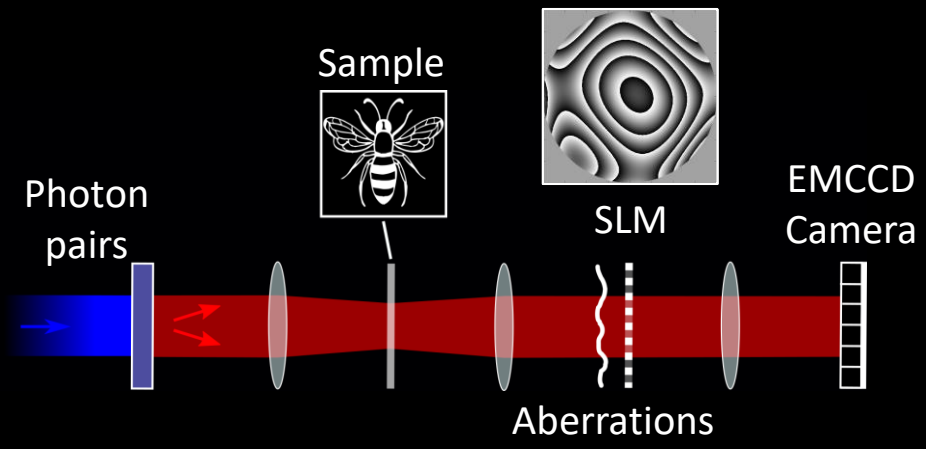


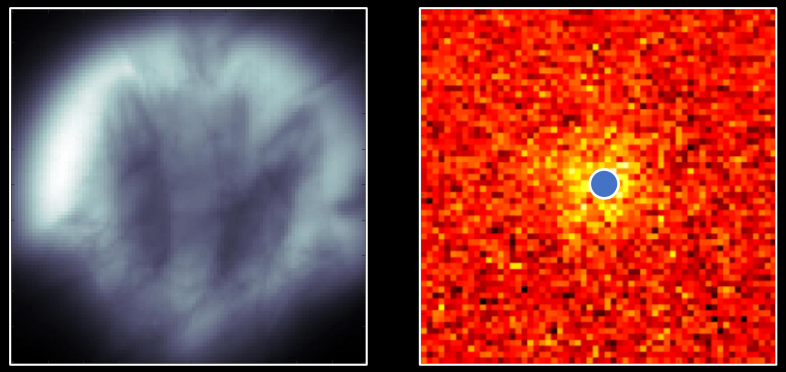


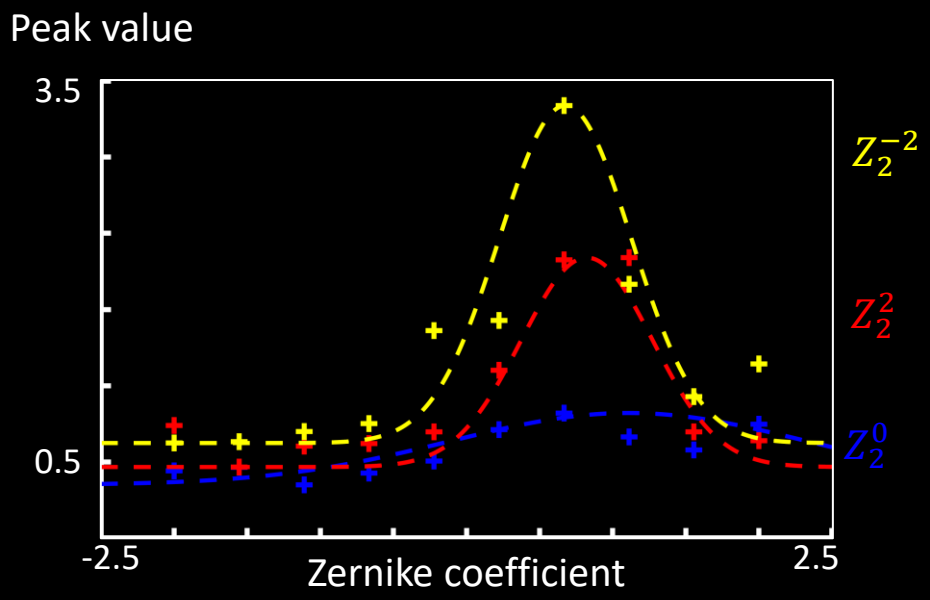
Peak value

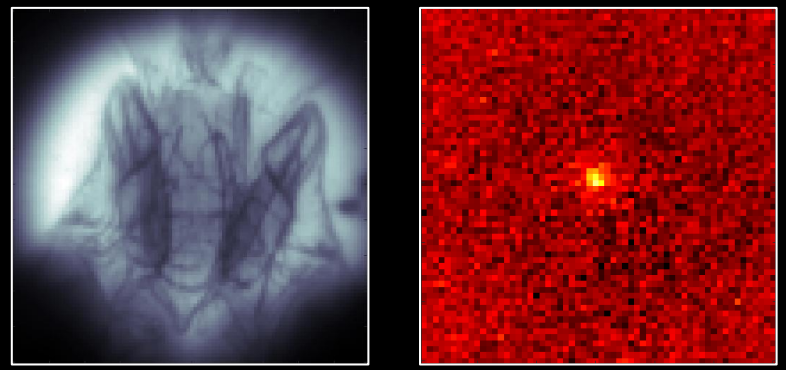


Adaptive optics with correlated photons



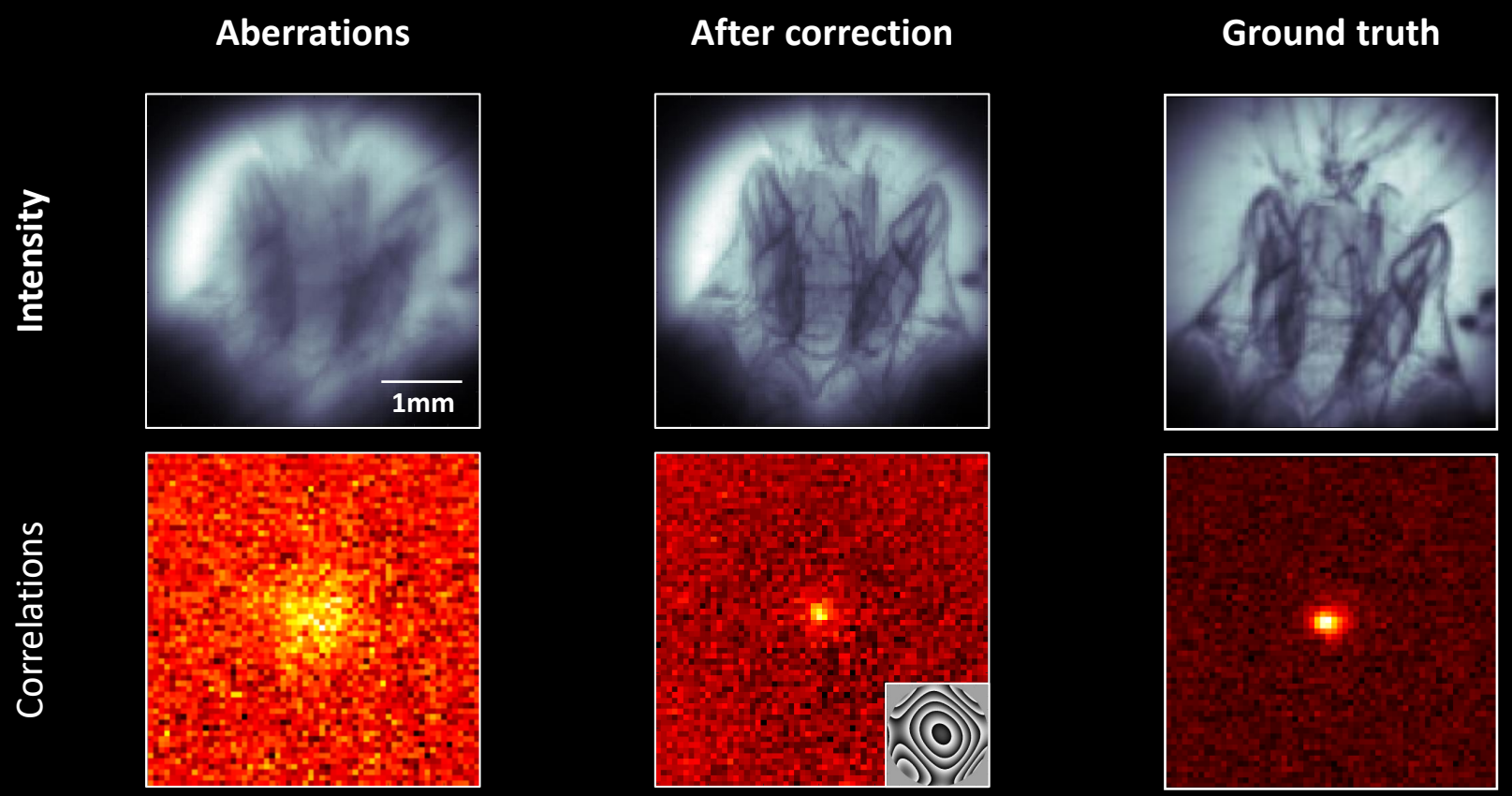






Cameron, Courme, Vernière, Pandya, Faccio, Defienne Science 383, 1142-1148 (2024)

Application to microscopy



Universal aberrations metric

Direct PSF access

No guidestar

No contrast/ specimen dependent

No wavefront sensor

Practical drawbacks

Slow iterative process

Very weak flux

Needs entangled photon pair

Cameron, Courme, Vernière, Pandya, Faccio, Defienne Science 383, 1142-1148 (2024)

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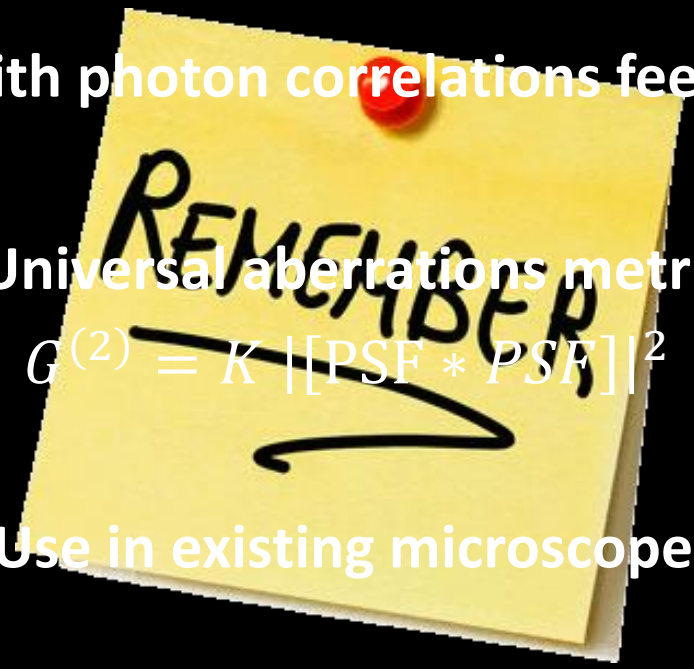
Cameron, Courme, Vernière, Pandya, Faccio, Defienne Science 383, 1142-1148 (2024)

AO with photon correlations feedback



Universal aberrations metric

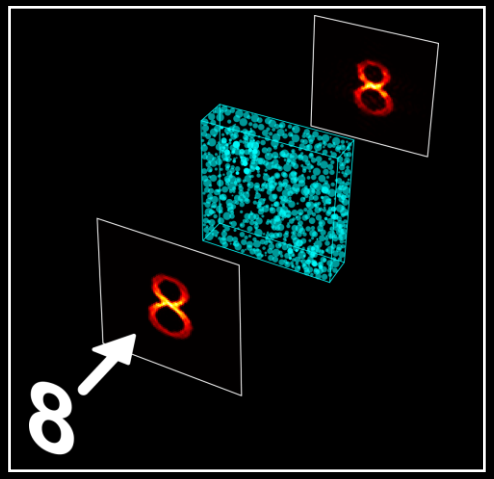
$$G^{(2)} = K\,|[\mathrm{PSF} * PSF]|^2$$

Use in existing microscopes

Cameron, Courme, Vernière, Pandya, Faccio, Defienne Science 383, 1142-1148 (2024)

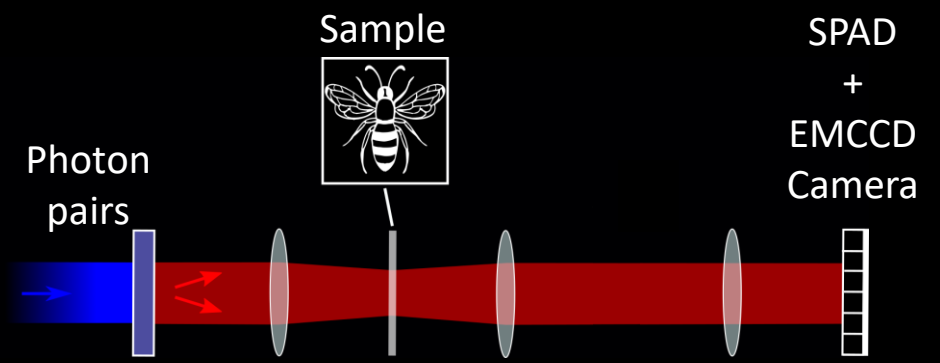
Today's focus : Improve adaptive optics using entangled photons

Part 1. Overcome aberrations
using photon **correlations**

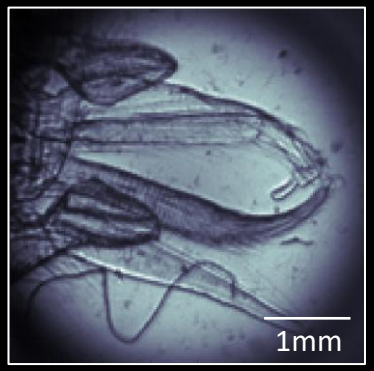


Part 2. Bypass scattering
with **entanglement**

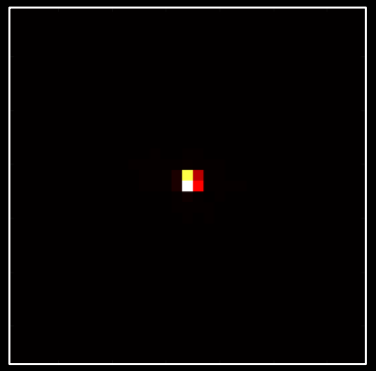
Imaging through scattering



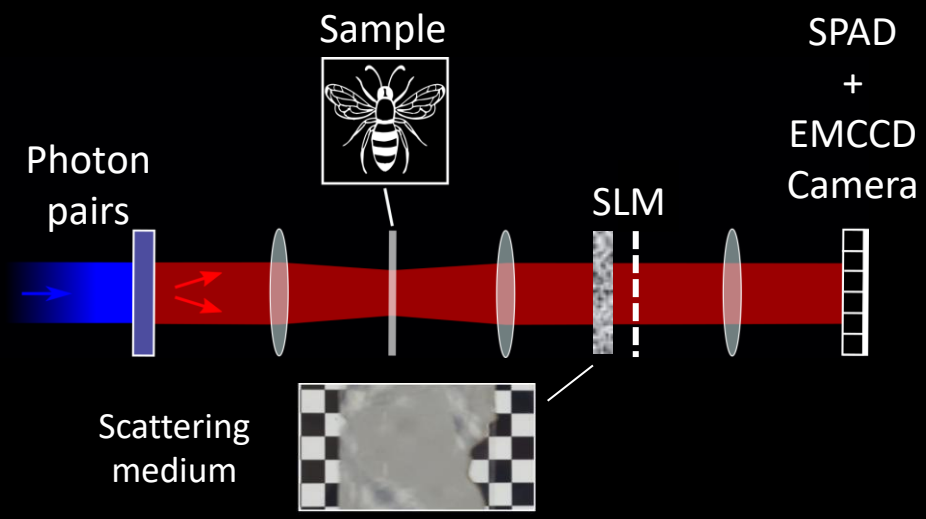
Intensity

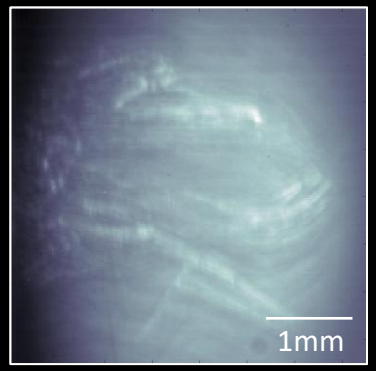


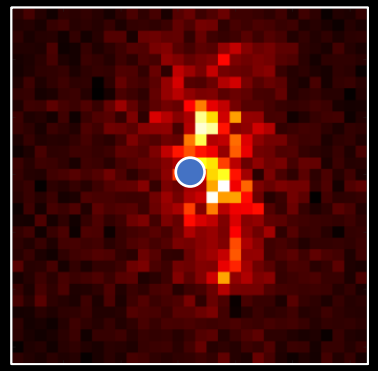
Correlations



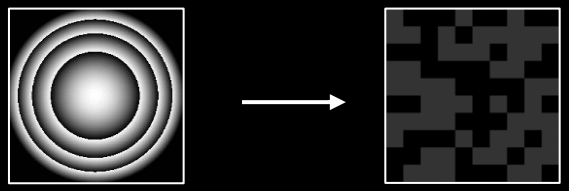
Imaging through scattering



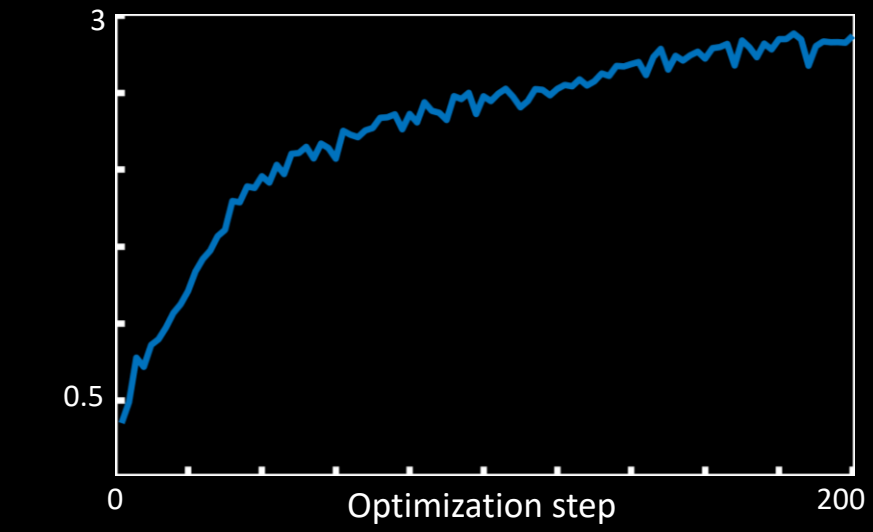




Optimization basis

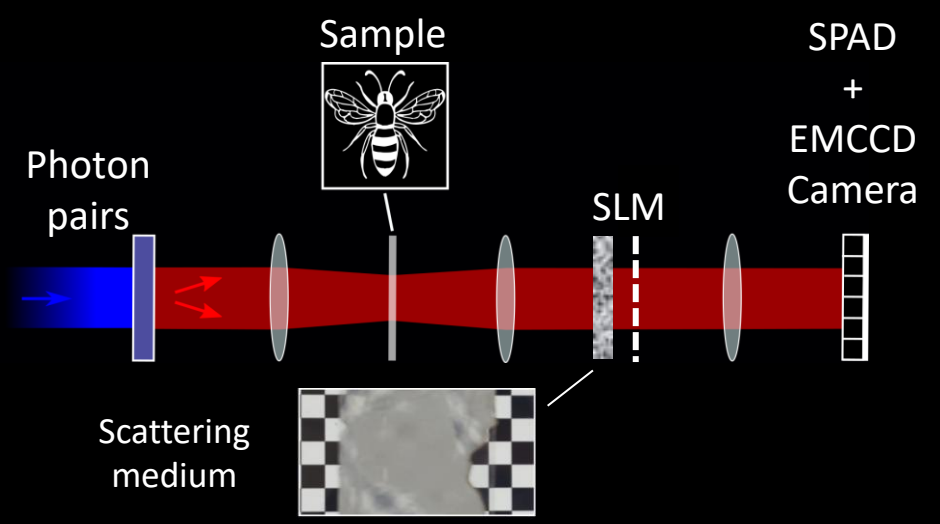


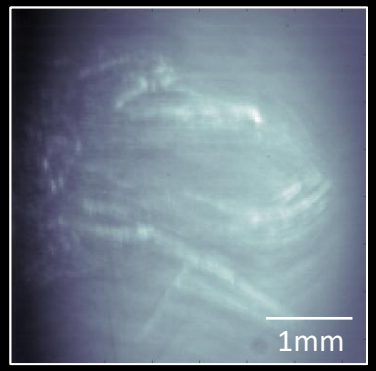
Optimization curve

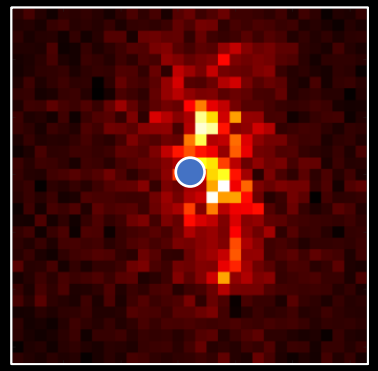


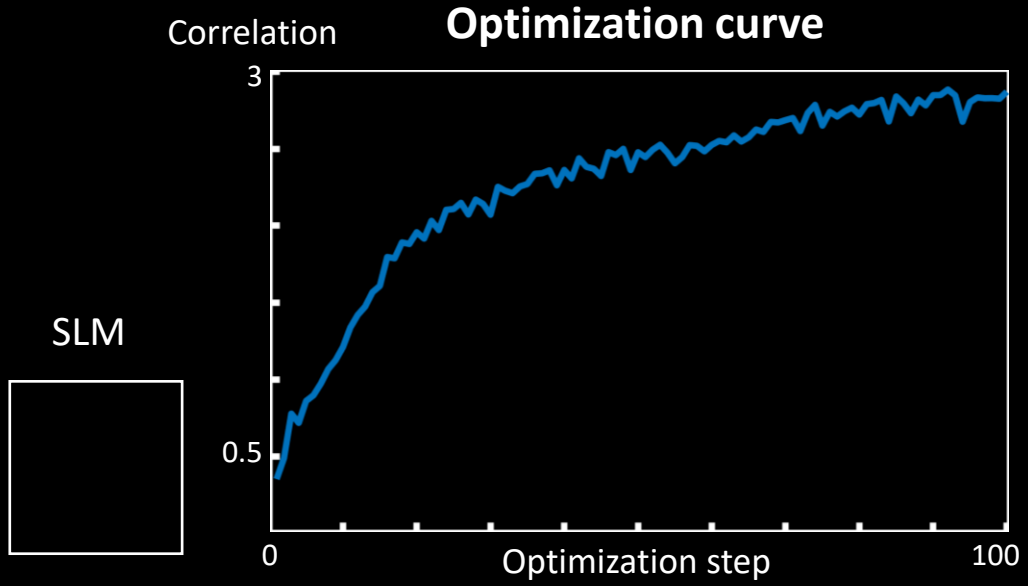
Vellekoop, Mosk. Optics letters, 32(16), 2309-2311 (2007)

Imaging through scattering

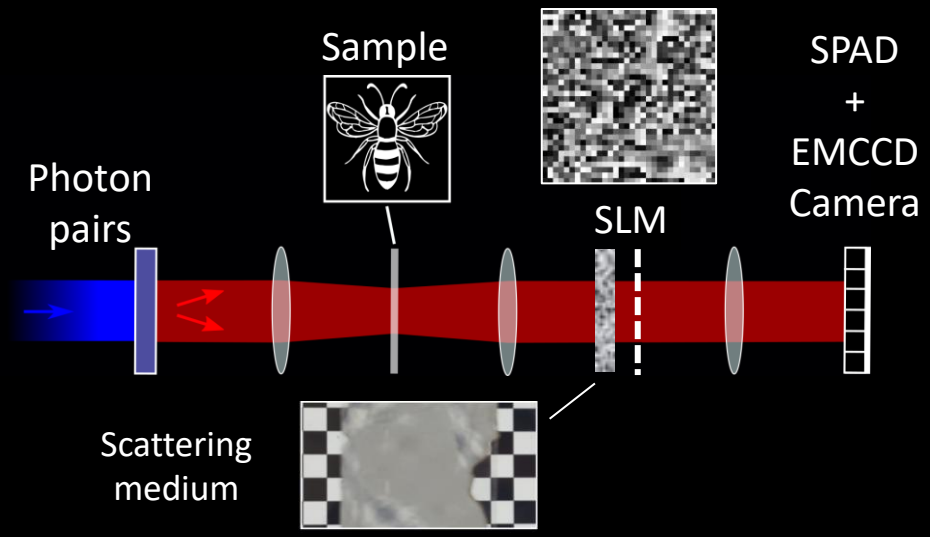


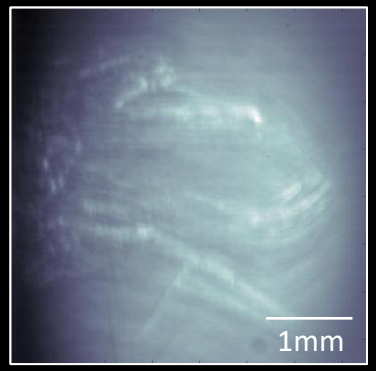


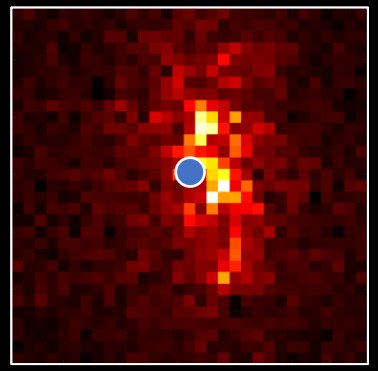




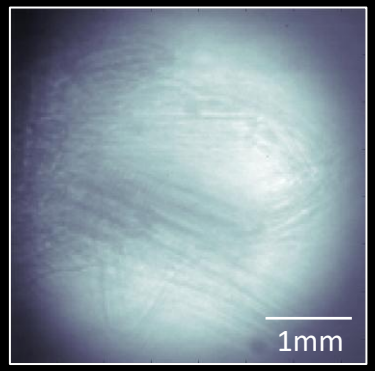
Imaging through scattering

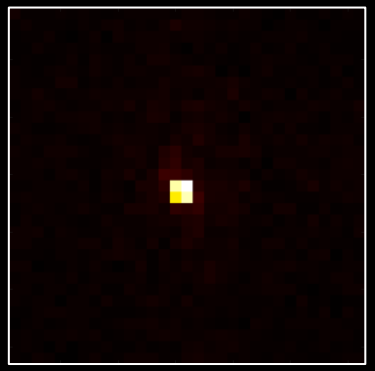


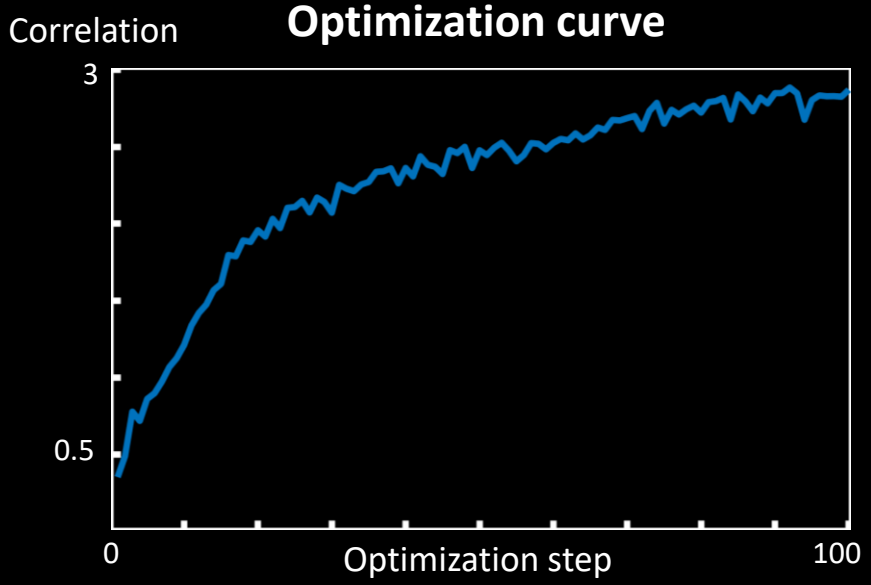




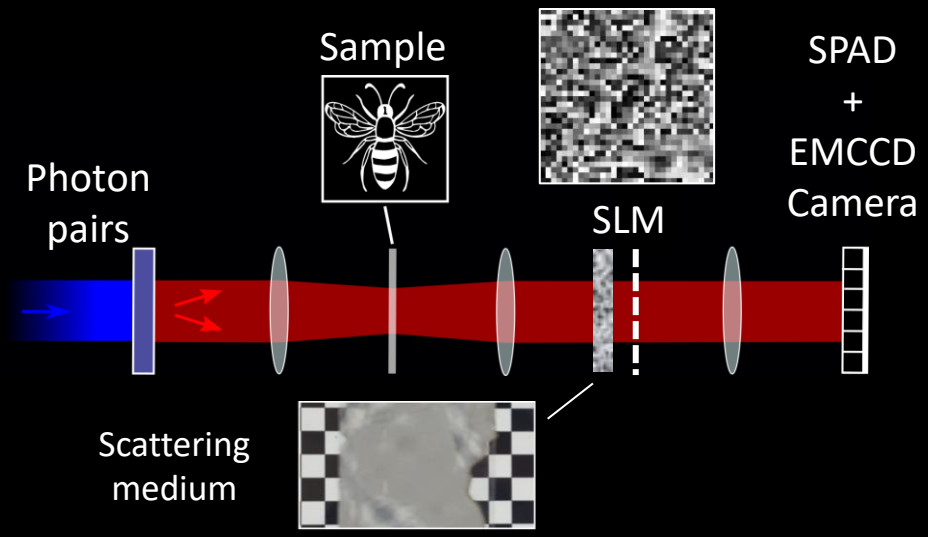
Correction

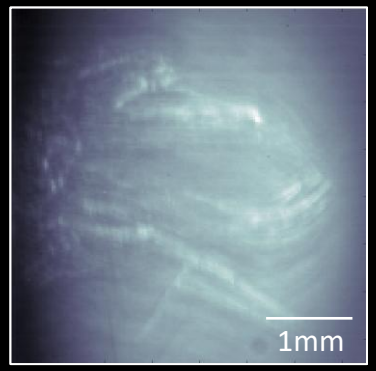


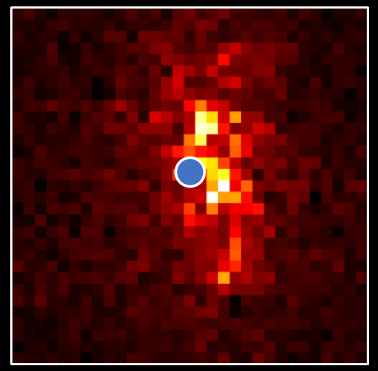




Imaging through scattering







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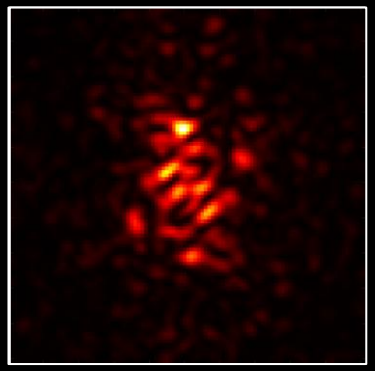
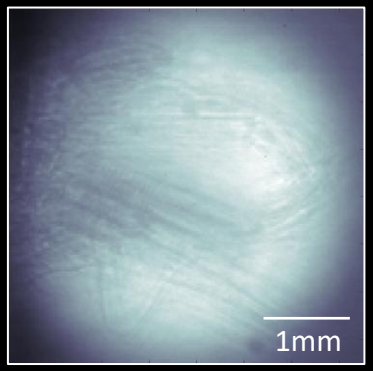
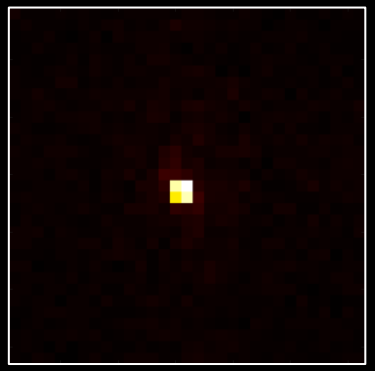


$h(\boldsymbol{r}', \boldsymbol{0})$

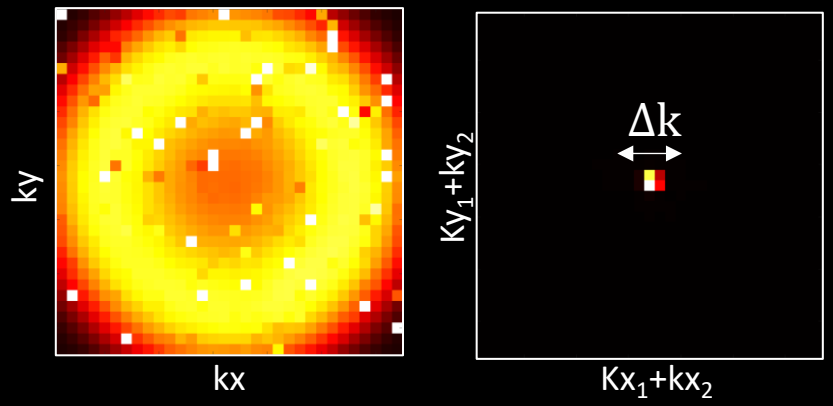




Correlations and entanglement

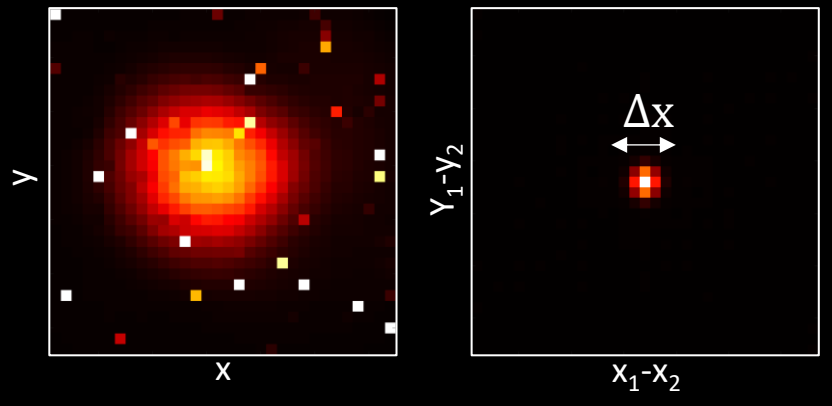
Correlations in the **momentum basis** $\{k_x, k_y\}$

$$|\Psi\rangle \approx |0\rangle + \eta \sum_{\boldsymbol{k}} \hat{a}^{+}_{\boldsymbol{k}} \hat{a}^{+}_{-\boldsymbol{k}} |0\rangle$$

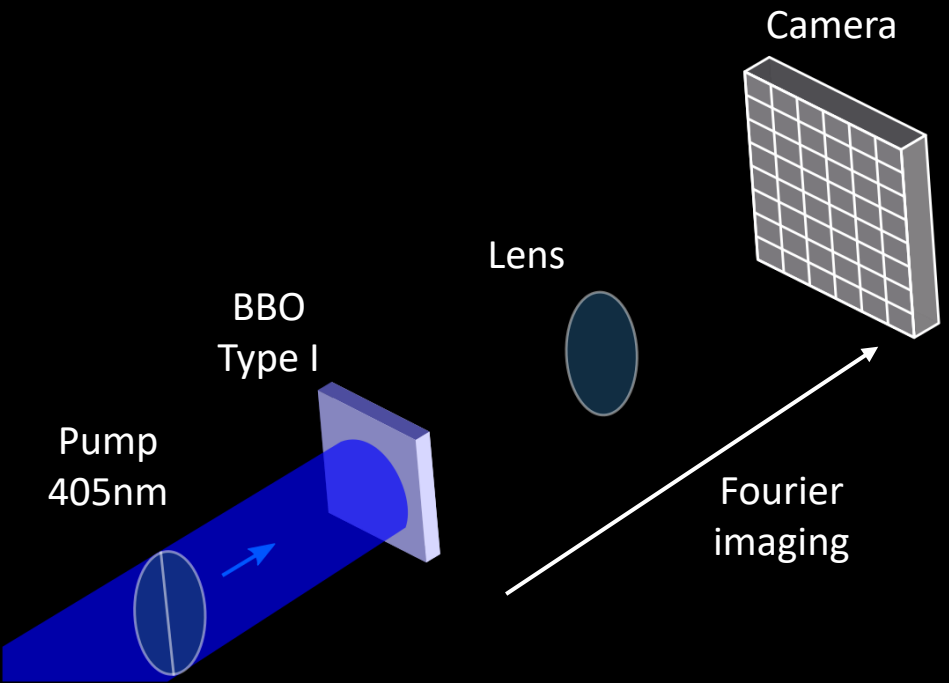


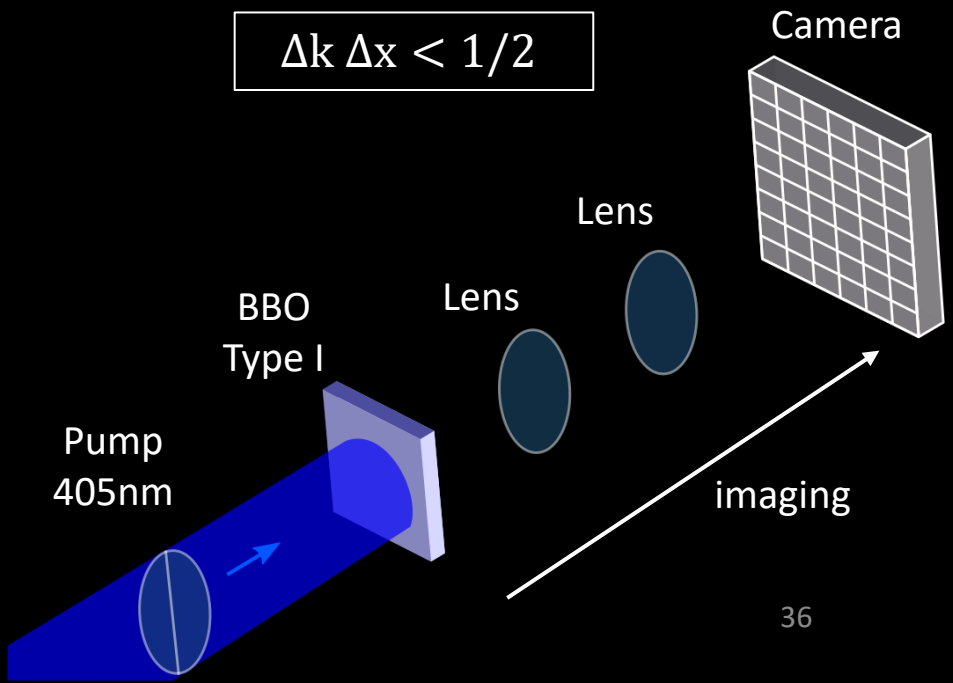
Correlations in the **position basis** $\{x, y\}$

$$|\Psi\rangle \approx |0\rangle + \eta \sum_{\boldsymbol{k}} \hat{a}^{+}_{\boldsymbol{r}} \hat{a}^{+}_{\boldsymbol{r}} |0\rangle$$

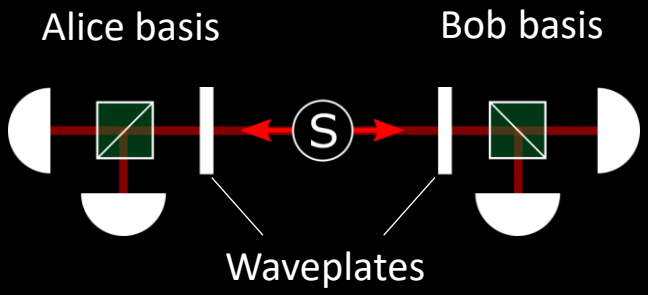


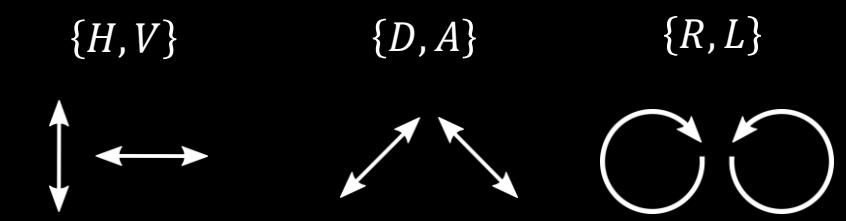
$$\Delta k \, \Delta x < 1/2$$





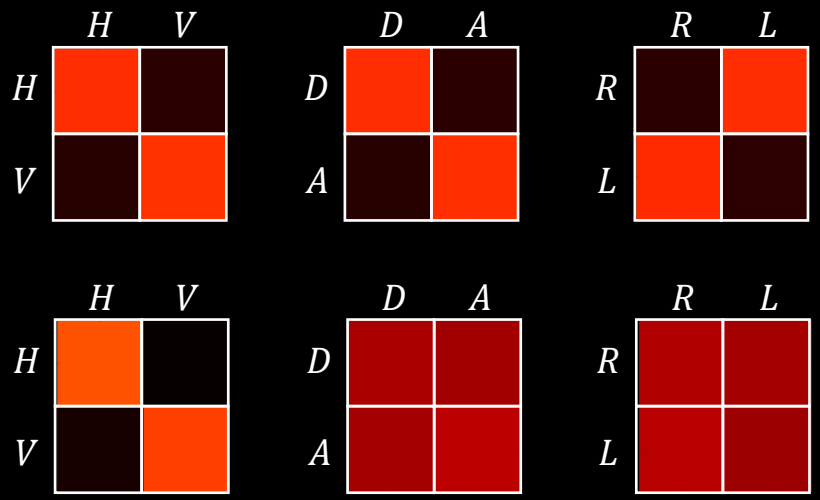
Correlations and entanglement





$$|\psi\rangle = \frac{1}{\sqrt{2}}[|HH\rangle + |VV\rangle]$$

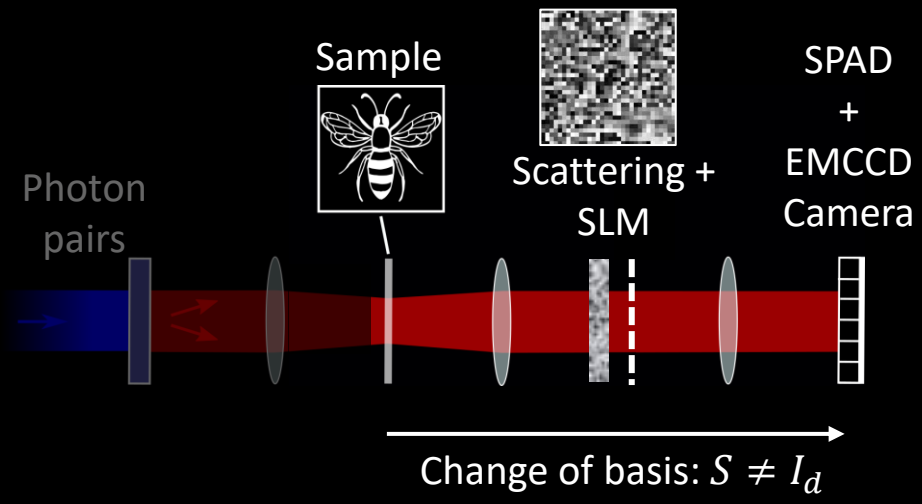
$$\rho = \frac{1}{2}[|HH\rangle\langle HH| + |VV\rangle\langle VV|]$$

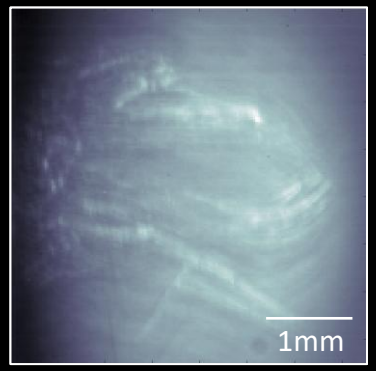


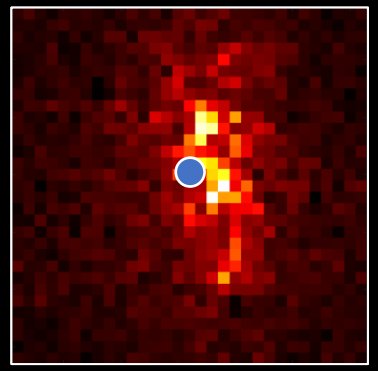
"Quantum correlations are **more resistant against changes of the basis** than ordinary correlations in separable states."

Spengler, Huber, Brierley, Adaktylos, Hiesmayz. PRA, 86(2), 022311 (2012)

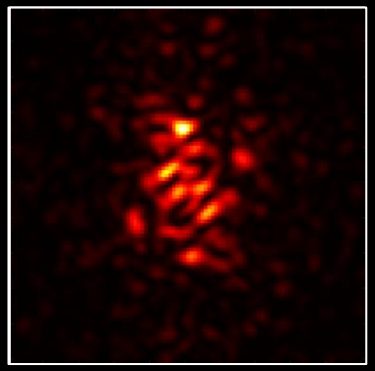
Imaging through scattering



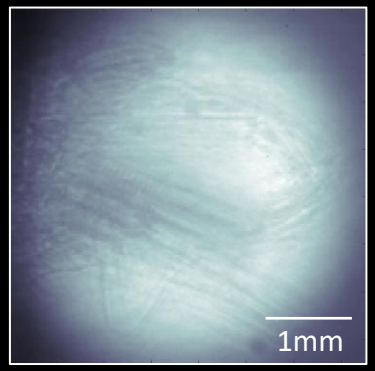


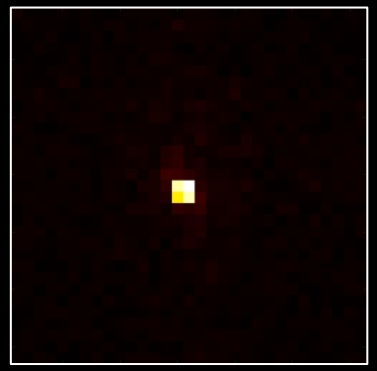


Correction

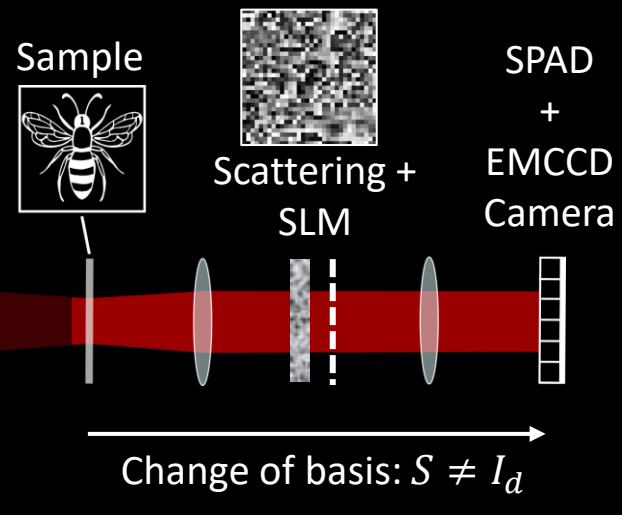


$h(\boldsymbol{r}', \boldsymbol{0})$

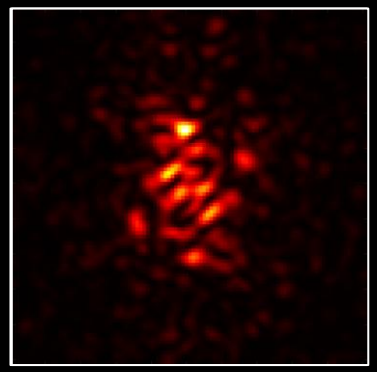




Imaging through scattering

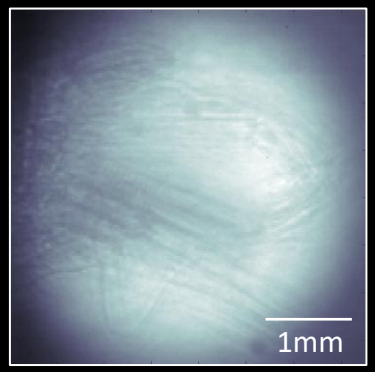


PSF after correction

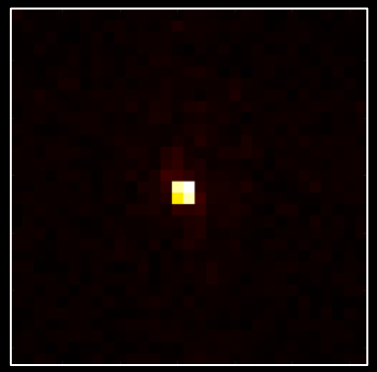


$h(\boldsymbol{r}', \mathbf{0})$

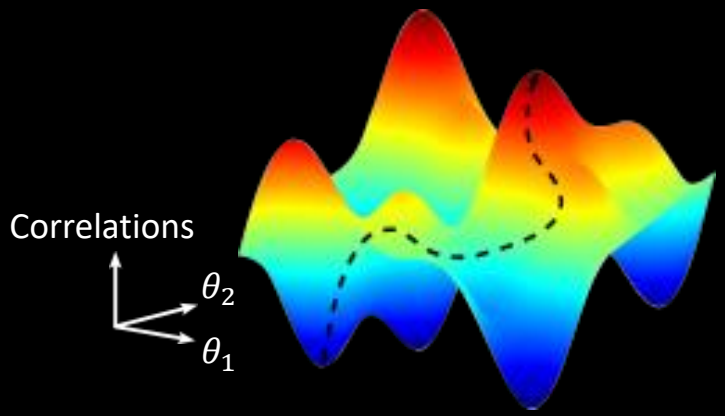
Intensity



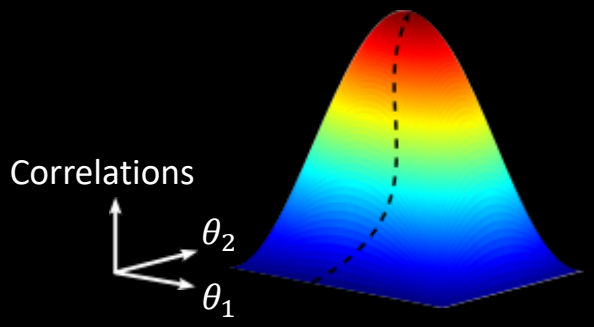
Correlations



Non-classical optimization

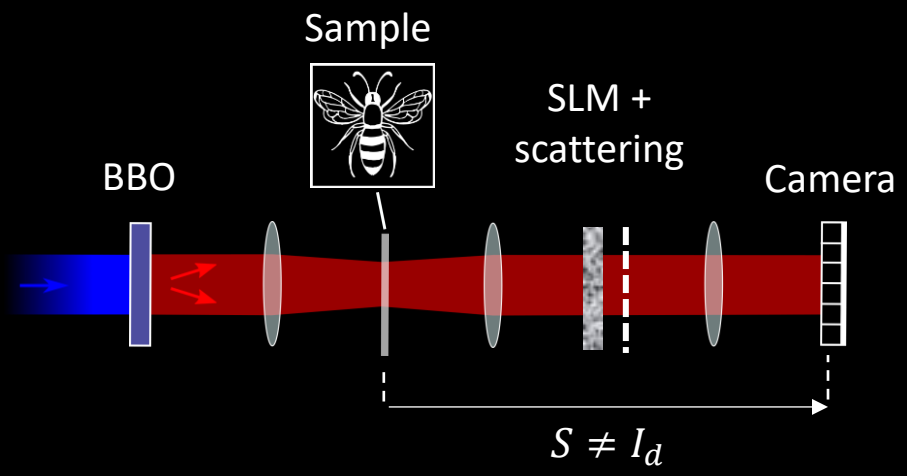


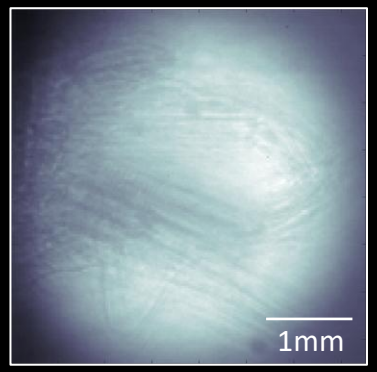
Classical optimization

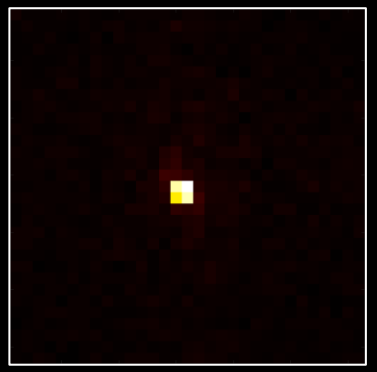


Courme, Vernière, Joly, Faccio, Gigan, Defienne. Optica (2026, in press)

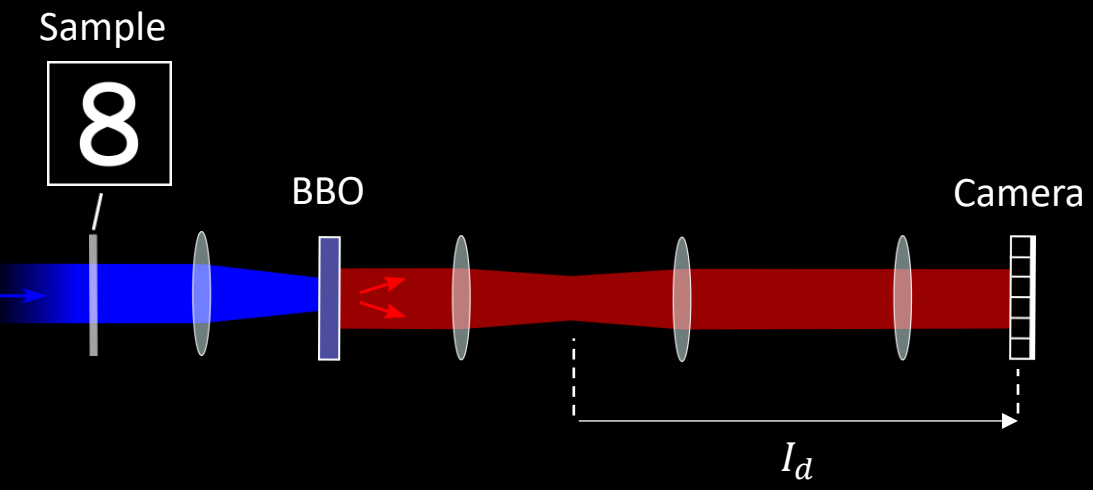
Entanglement-based imaging through scattering

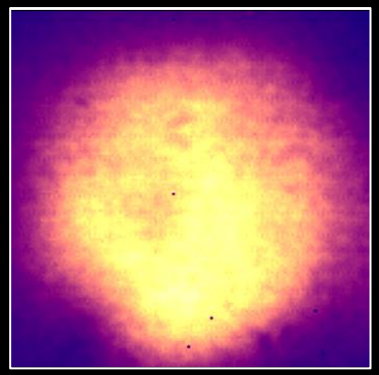






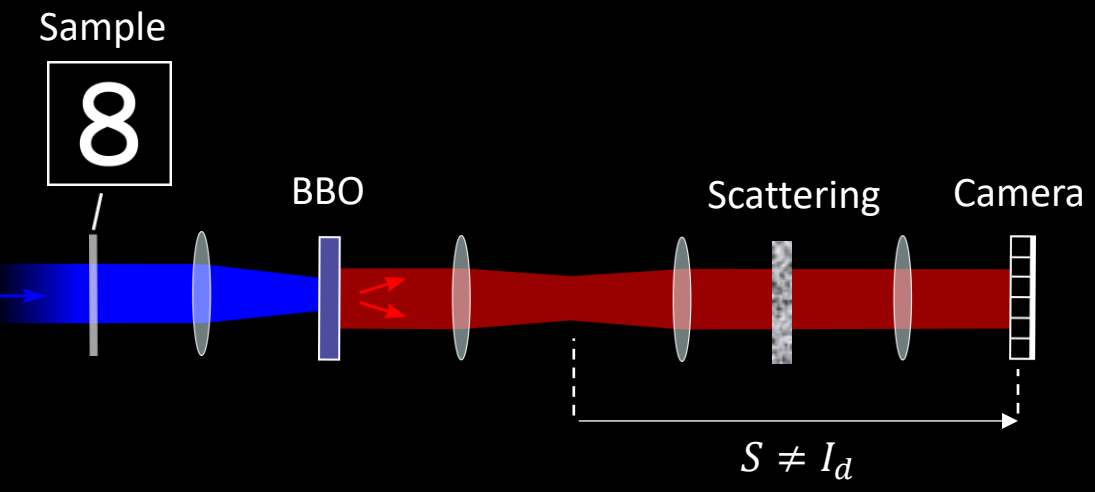
Entanglement-based imaging through scattering

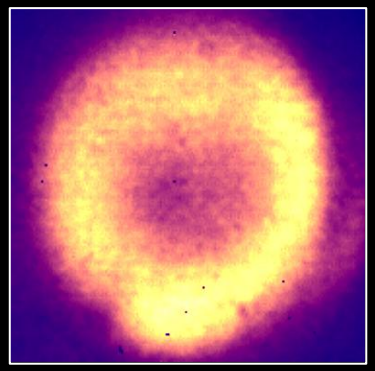


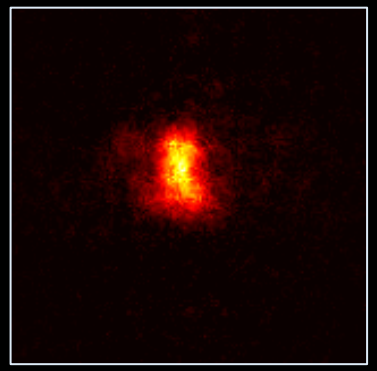


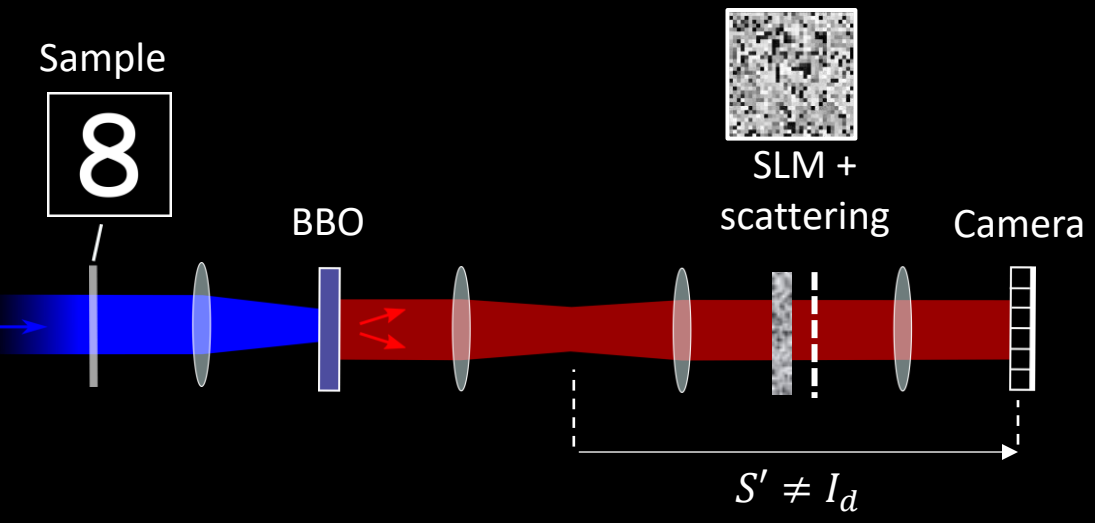
Vernière, Defienne. PRL 133, 093601 (2024)

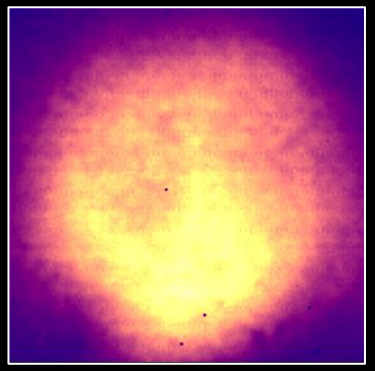
Entanglement-based imaging through scattering



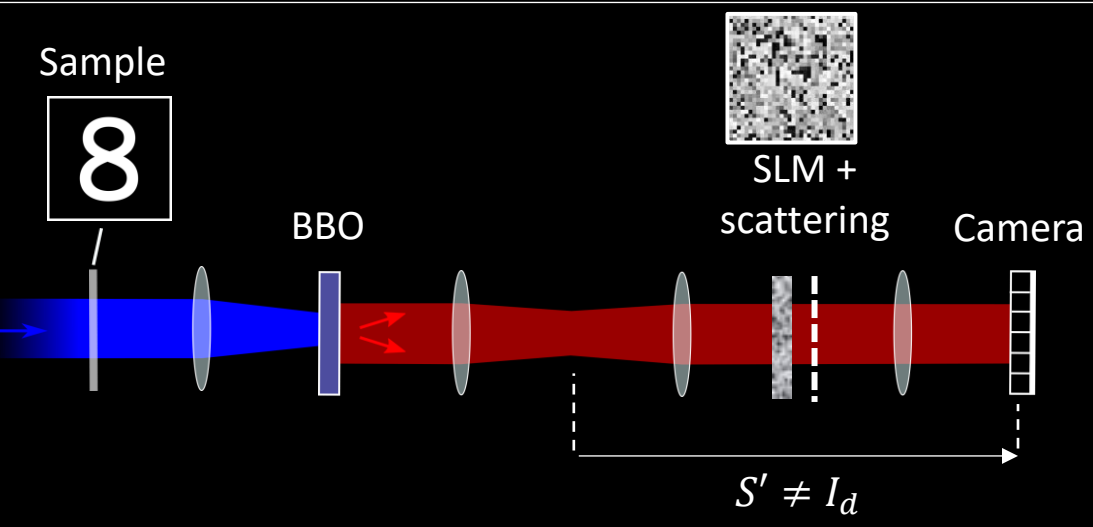


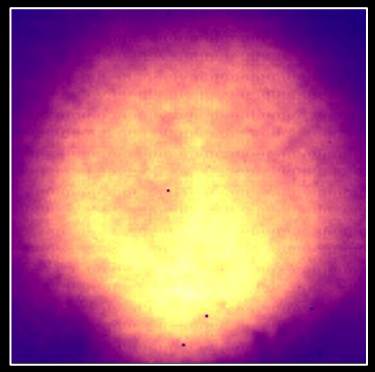


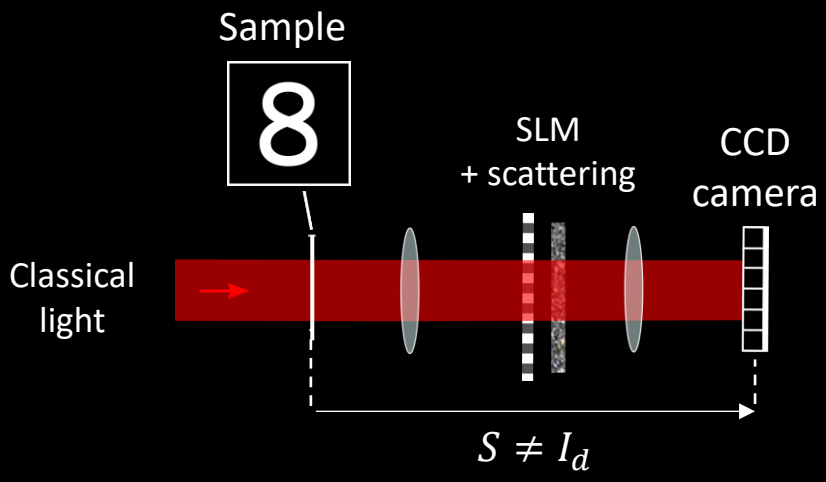


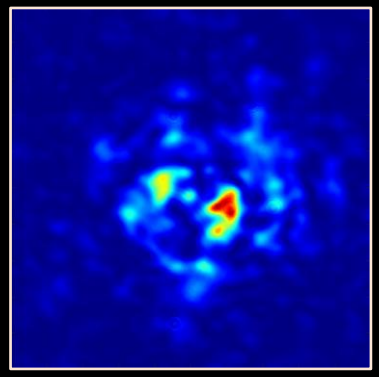


Entanglement-based imaging through scattering

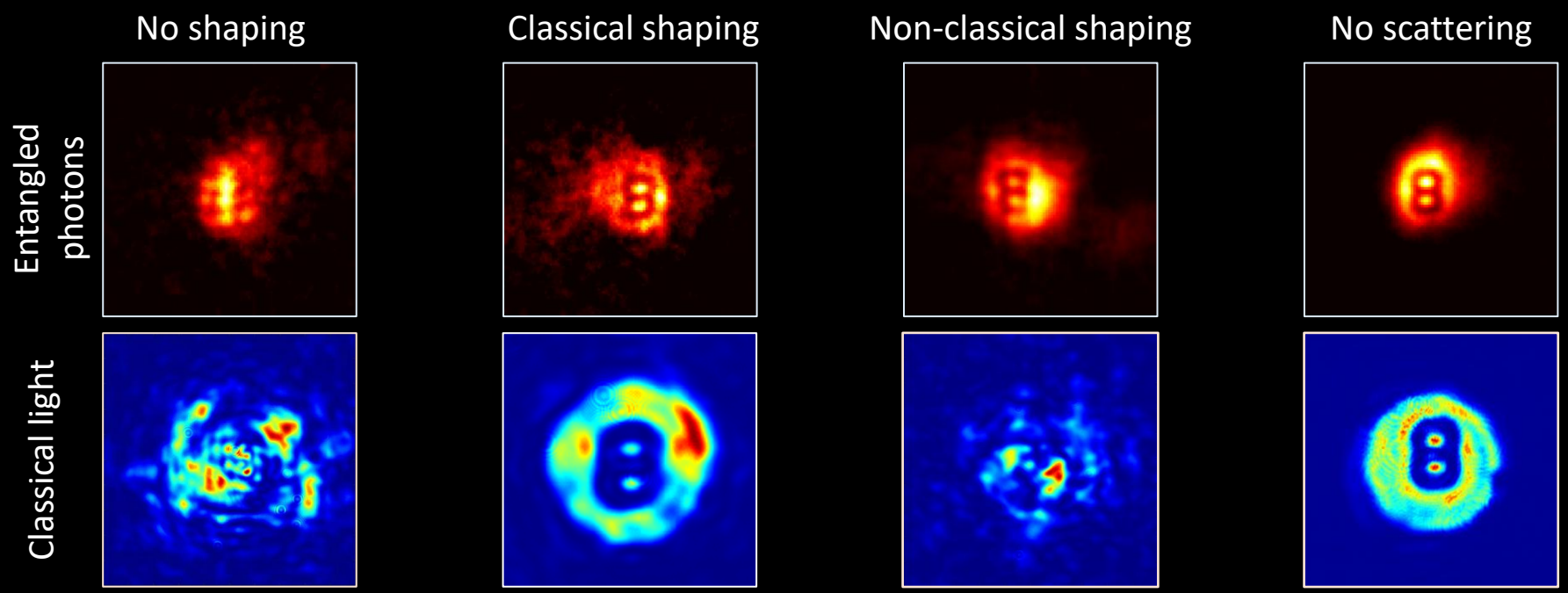


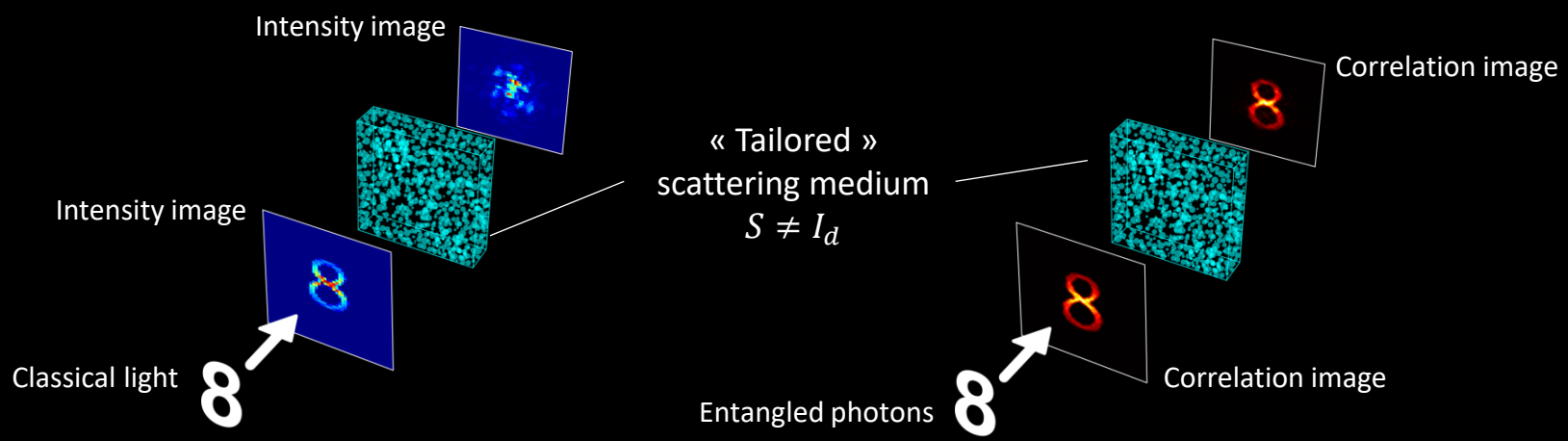






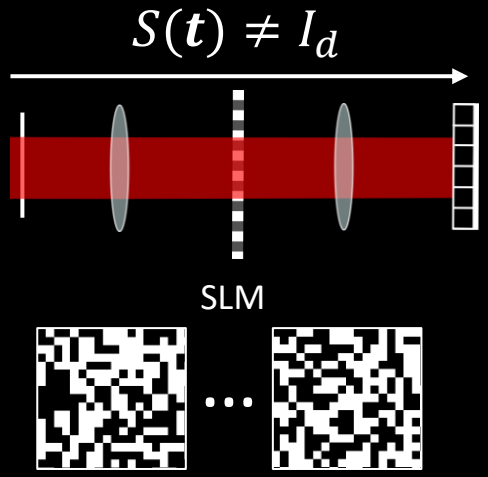
Entanglement-based imaging through scattering

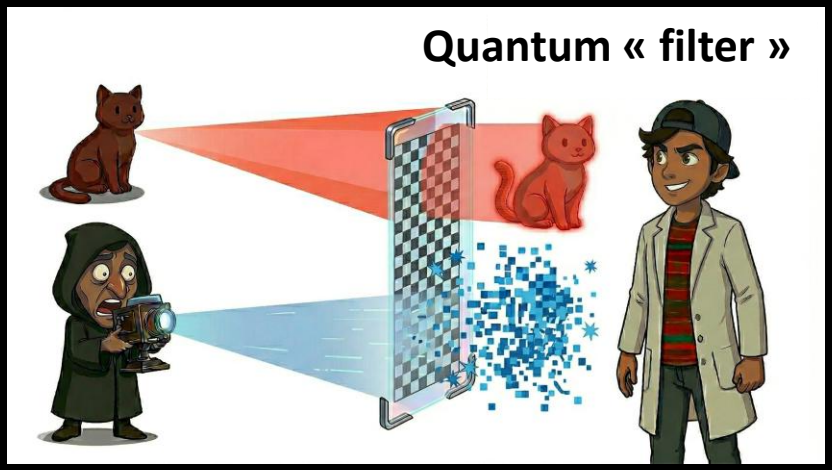




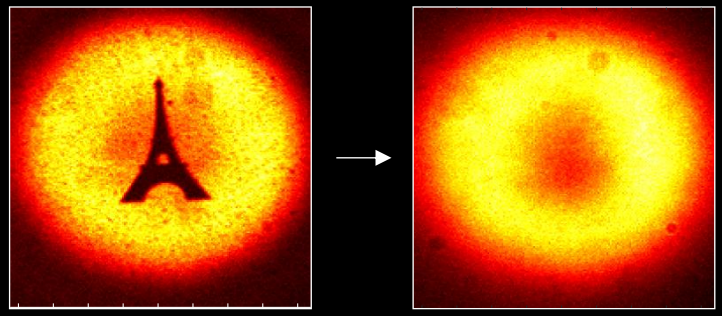
Vernière, Guitter, Courme, Defienne. Nature Physics (2026, in press)

Application: a quantum-classical filter

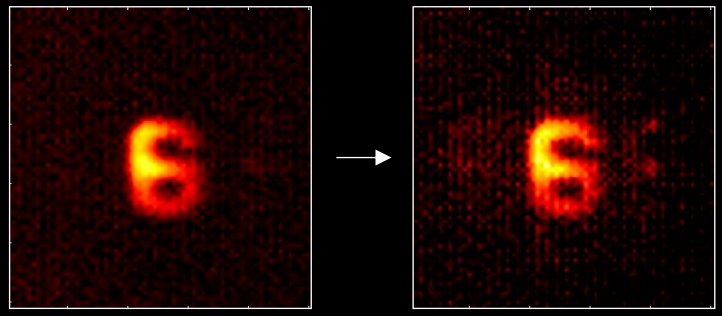




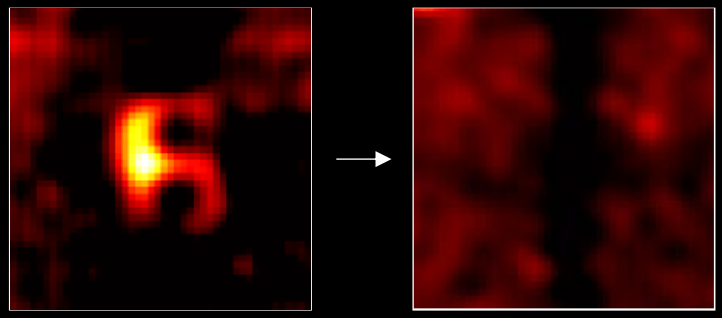
Classical light



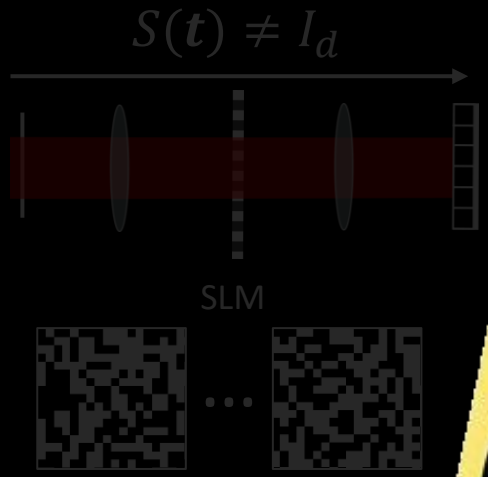
Entangled photons



Classically-correlated photons

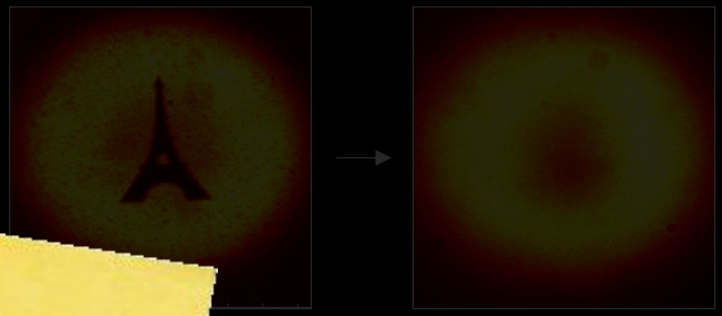


Application: a quantum-classical filter

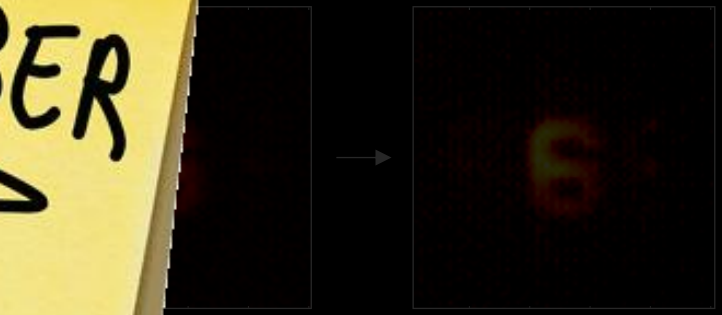


Dr. Xin Huang

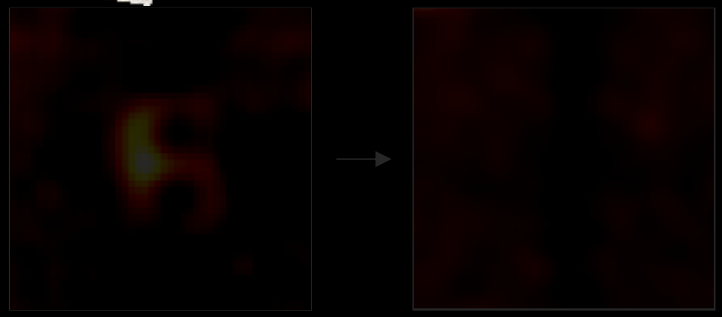
Classical light

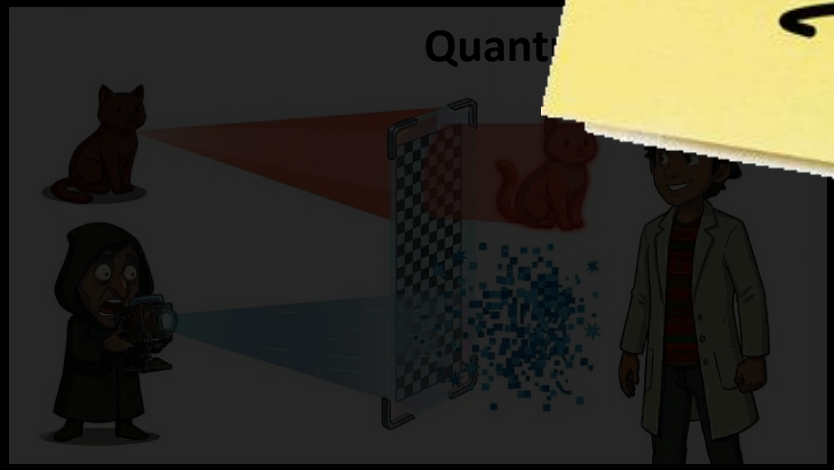


ntangled photons



sically-correlated photons





Transmit images through scattering media using non-classical optimization

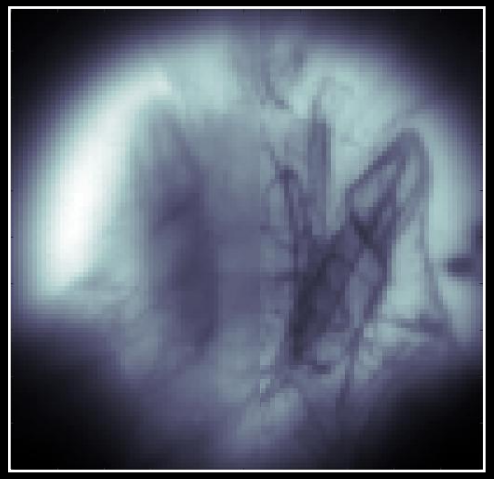
Entanglement is crucial

A quantum-classical filter

Courme, Vernière, Joly, Faccio, Gigan, Defienne. Optica (2026, in press) | Vernière, Guitter, Courme, Defienne. Nature Physics (2026, in press)

Conclusion: Light-based quantum technology → Imaging

Overcome aberrations using photon correlations



Quantum idea

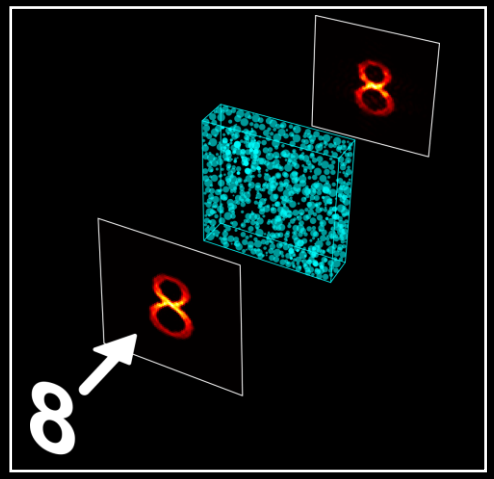
↓

New technique:
correlation-based adaptive optics

↓

Application to Microscopy

Bypass scattering with entanglement



Quantum idea

↓

New concept/technique: **quantum-classical information filter**

↓

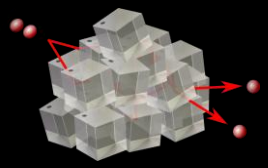
Application ?

Thank you

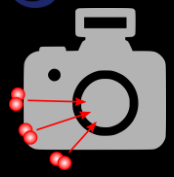
Quantum Imaging Paris

SORBONNE UNIVERSITÉ

Quantum imaging



Complex media



High-dimensional entangled states

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Related papers:

Vernière, Guitter, Courme, Defienne. Nature Physics (2026, in press) - ArXiv 2508.14616
Courme, Vernière, Joly, Faccio, Gigan, Defienne. Optica (2026, in press) - ArXiv 2503.24283
Vernière and Defienne. PRL 133, 093601 (2024)
Cameron, Courme, Vernière, Pandya, Faccio, Defienne. Science 383, 1142-1148 (2024)
Review: Defienne, Bowen, Chekhova, Lemos, Oron, Ramelow, Treps, Faccio. Nature Photonics 18, 1024–1036 (2024)