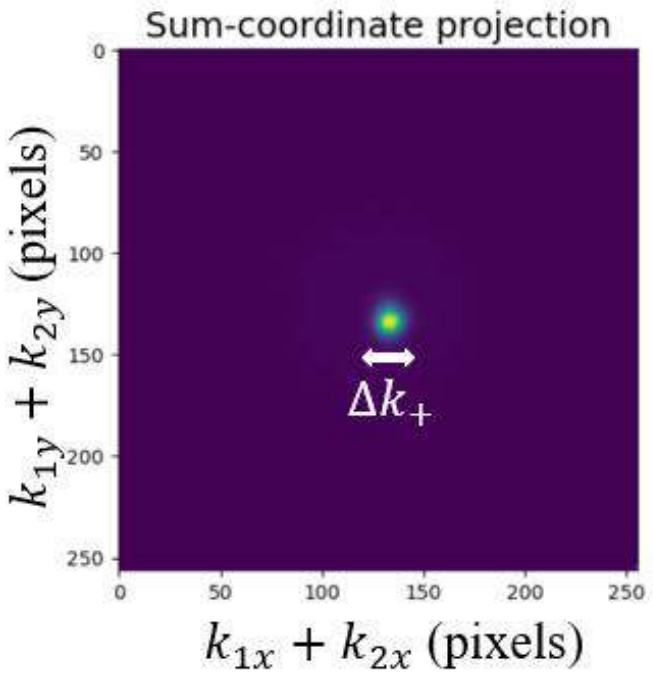
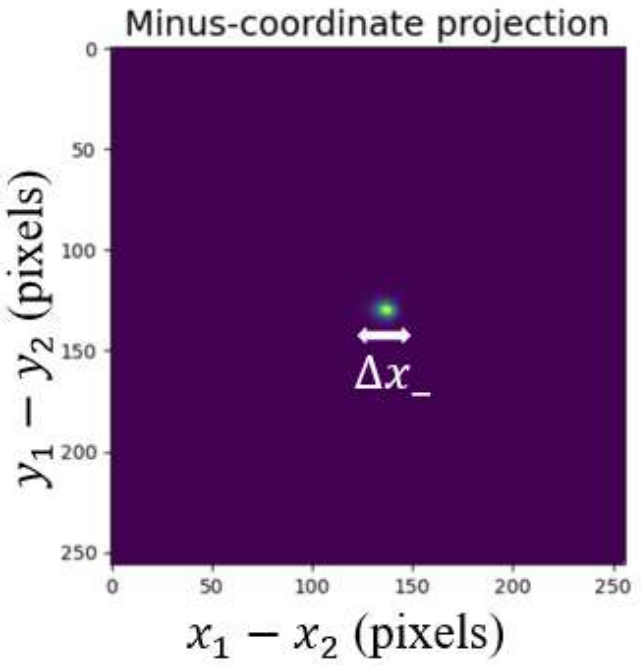
# Certifying high-dimensional quantum entanglement using a time-stamping camera

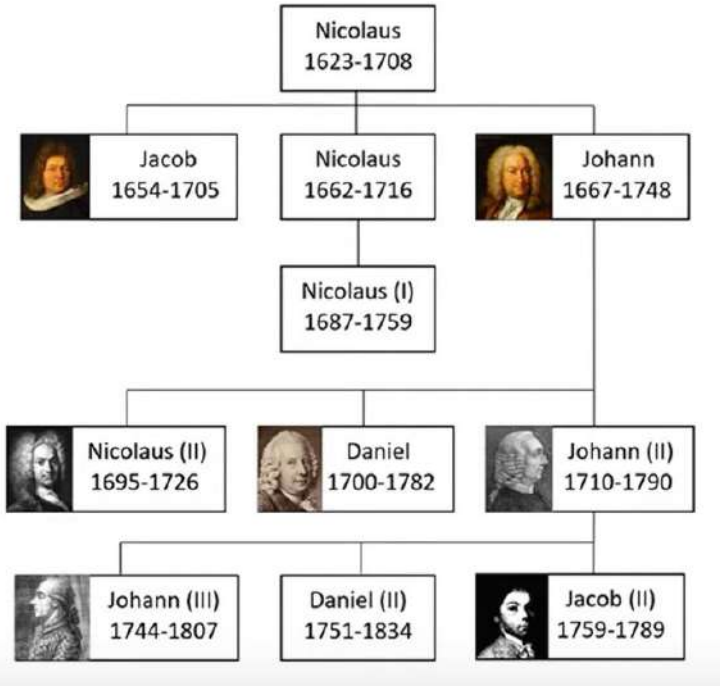
Raphaël GUITTER



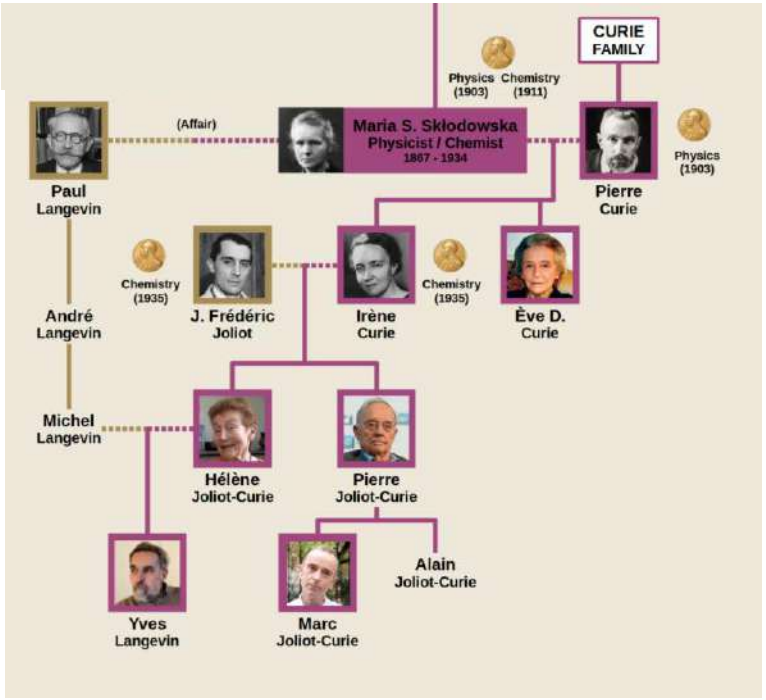



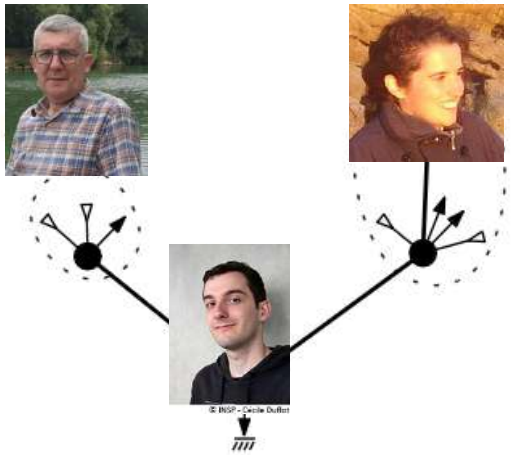
# Heredity in Physics

## Bernoullis

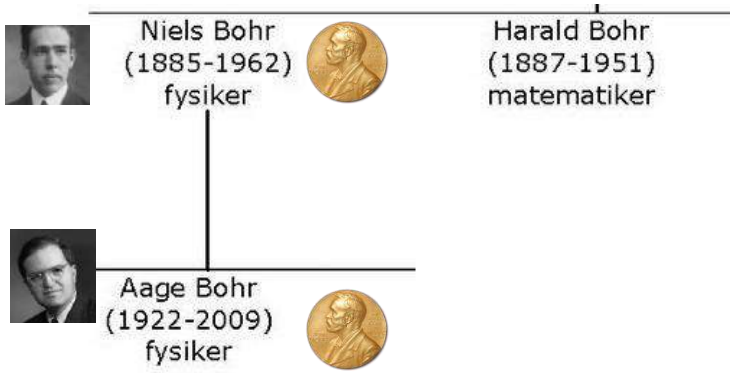



## Curies



## Bohrs

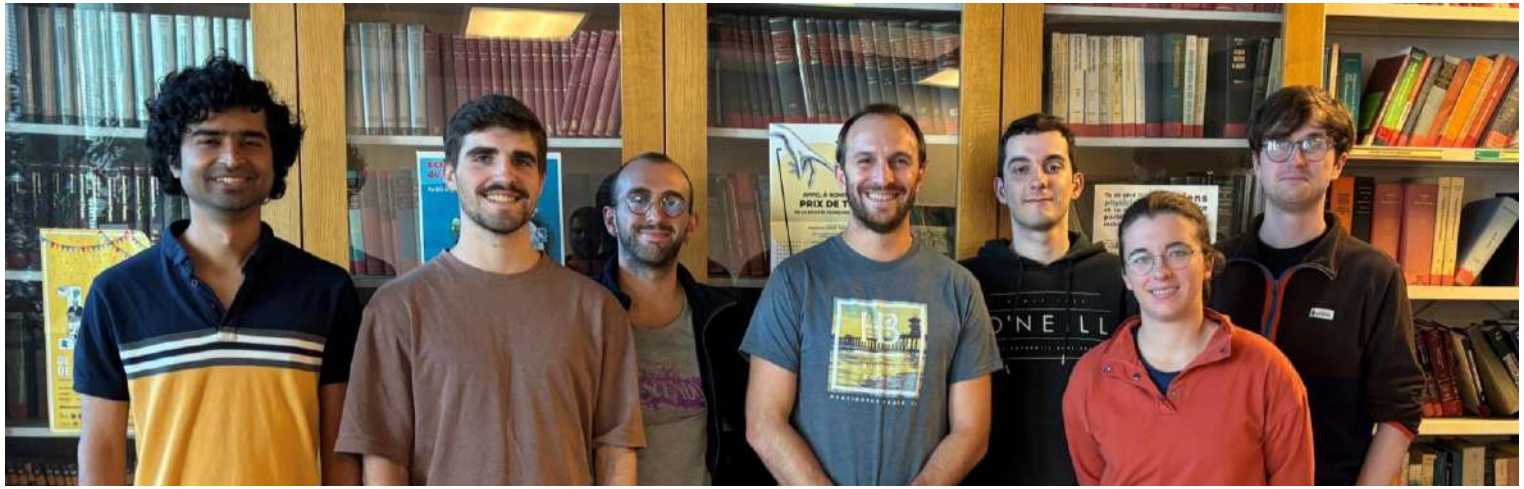


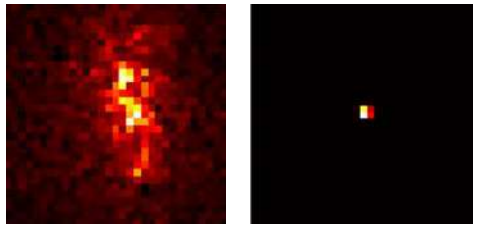

**And many others…**

Machs
Thomsons
Raman & Chandrasekhar
Bardeens
Braggs
Siegbahns
…

# Institute of NanoSciences of Paris

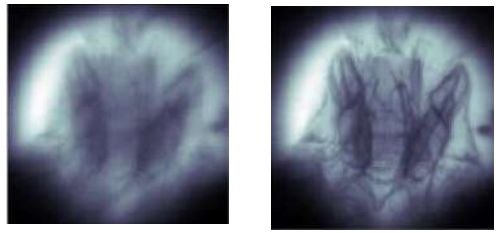
## Quantum Imaging Team :





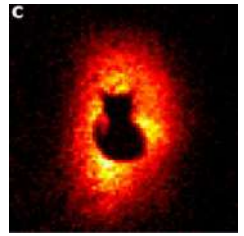
**Focusing Correlations through Scattering Media**

Baptiste Courme, Chloé Vernière et al., arXiv:2503.24283



**Quantum-enhanced Adaptative Optics**

Patrick Cameron, Baptiste Courme et al., Science 2024 Mar 8;383(6687):1142-1148



**Hiding Images in Quantum Correlations**

Chloé Vernière, Hugo Defienne, Phys. Rev. Lett. **133**, 093601

# Entanglement Certification

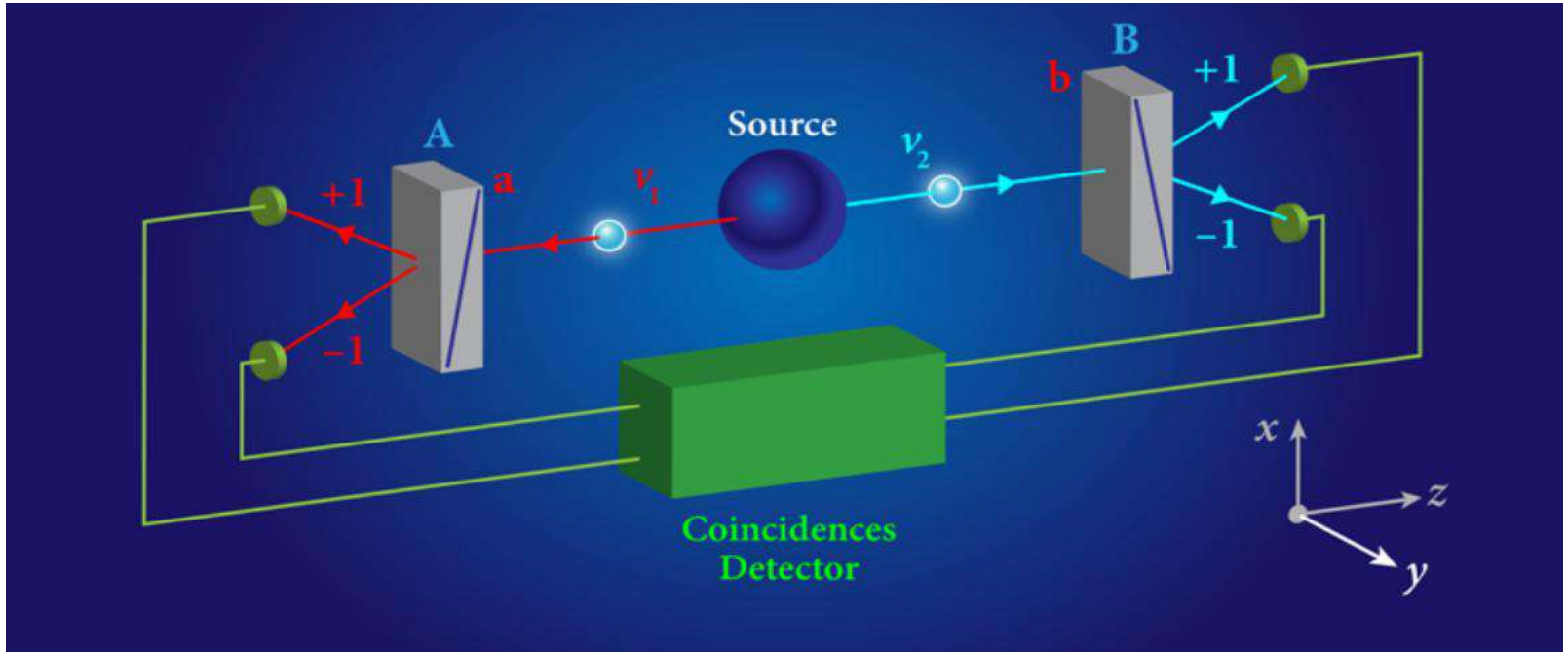
Entangled Bell State:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$$

Separable State:

$$|\Psi'\rangle = \frac{1}{\sqrt{2}}|H\rangle \otimes (|H\rangle + |V\rangle)$$

Alain Aspect Experiment




Stonebraker Design

John S. Bell

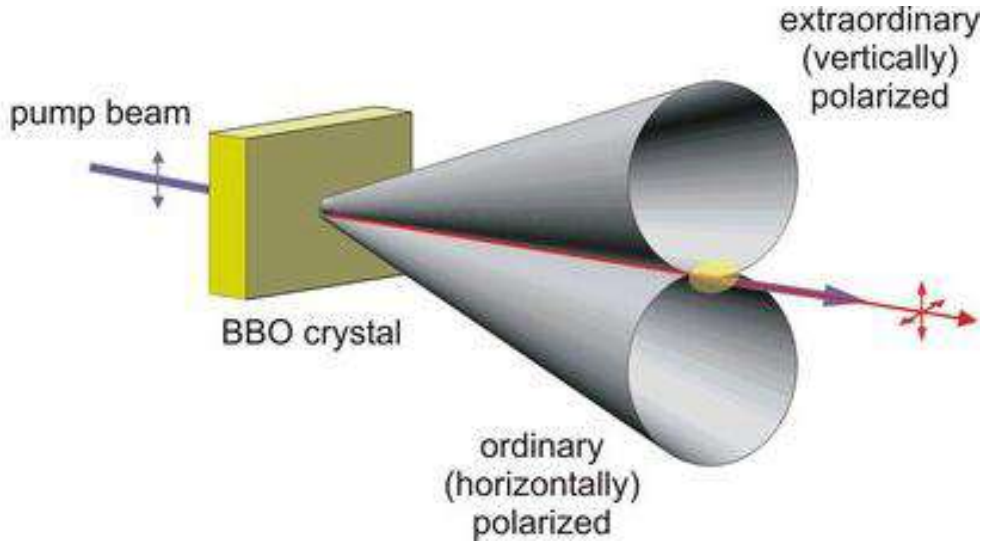
Alain Aspect

Applications : Quantum Key Distribution,
Quantum Computations,...

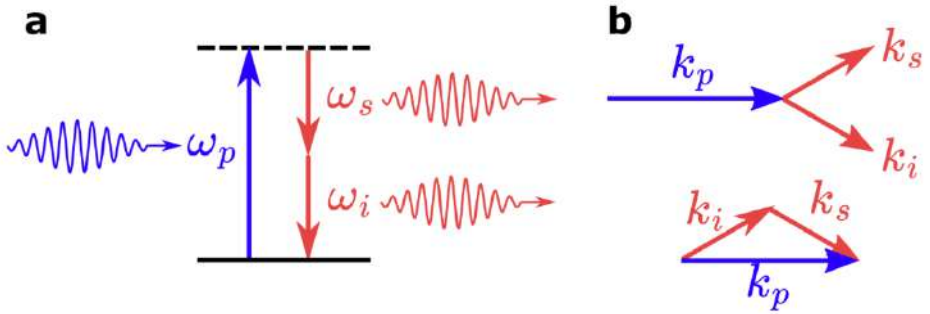
# States entangled in high dimensions

$$d = 2: \quad |\Psi\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle) \quad \Rightarrow \quad d > 2: \quad |\Psi\rangle = \sum_{1 \le k \le d} |a_k, b_k\rangle$$

Generation :




Kiesel, Nikolai. Experiments on Multiphoton Entanglement.




Why ?

Quantum Cryptography using larger alphabets

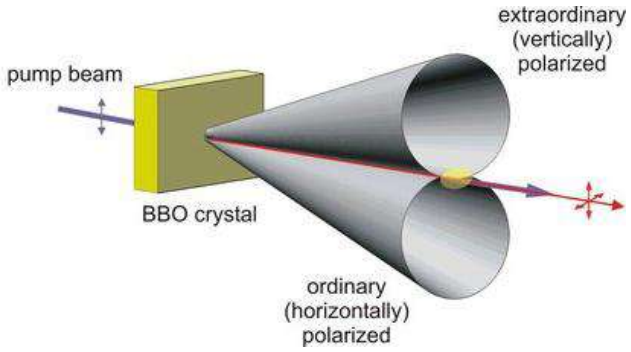
H. Bechmann-Pasquinucci and W. Tittel
*Group of Applied Physics, University of Geneva, CH-1211, Geneva 4, Switzerland*

**Overcoming Noise in Entanglement Distribution**

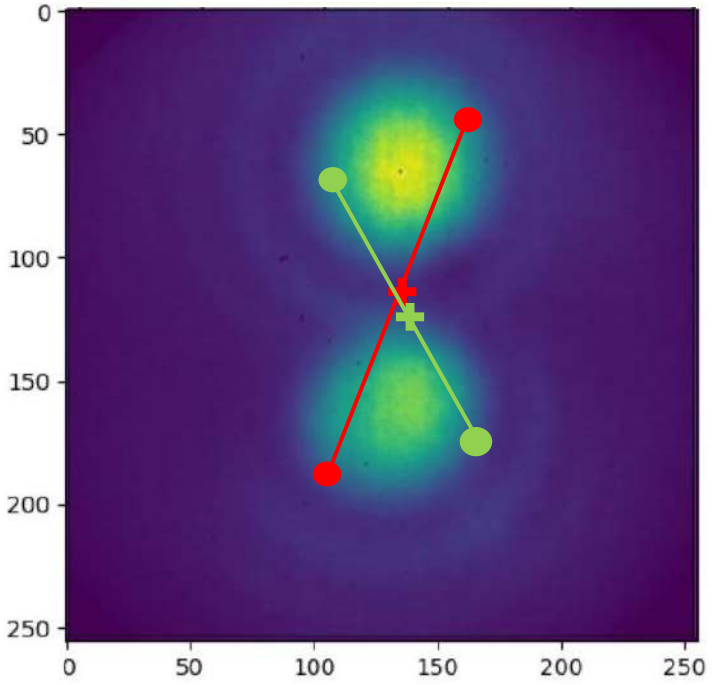
Sebastian Ecker,[1,2,*] Frédéric Bouchard,[3] Lukas Bulla,[1,2] Florian Brandt,[1,2] Oskar Kohout,[1,2] Fabian Steinlechner,[1,2,4,5] Robert Fickler,[1,2,6,†] Mehul Malik,[1,2,7,‡] Yelena Guryanova,[1,2,§] Rupert Ursin,[1,2,¶] and Marcus Huber[1,2,**]

SPDC : $|\Psi\rangle = \sum_k |k, -k\rangle = \sum_x |x, x\rangle$

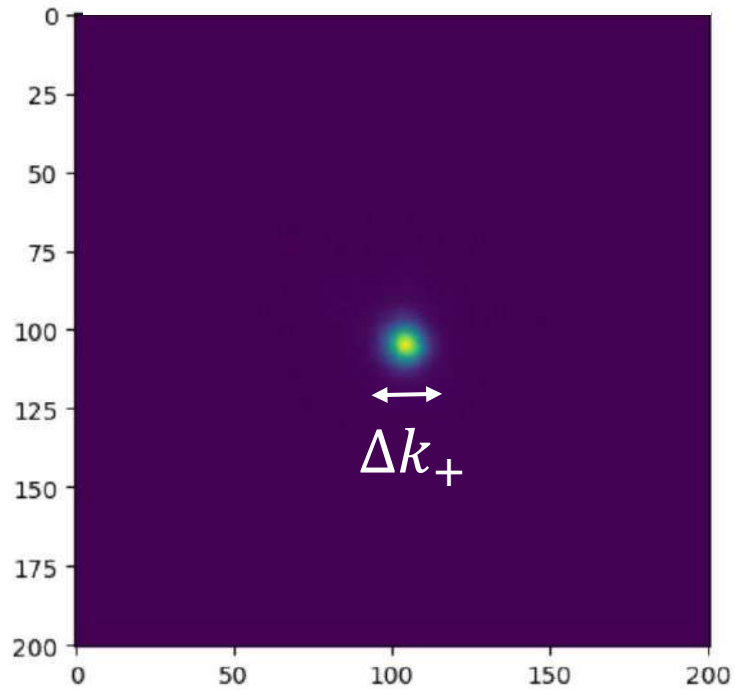
# Certifying entanglement with a camera : EPR criterion



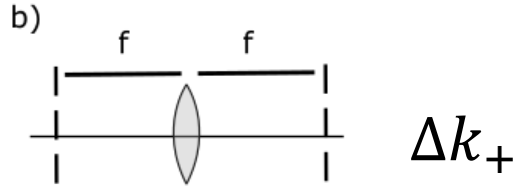

Total Intensity




Sum-Coordinate Projection




Fourier Imaging:

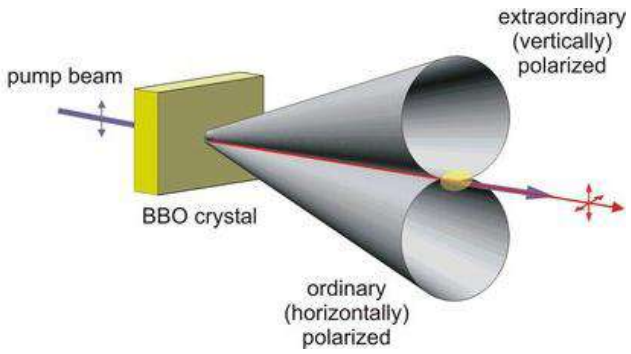



$\Delta k_+$

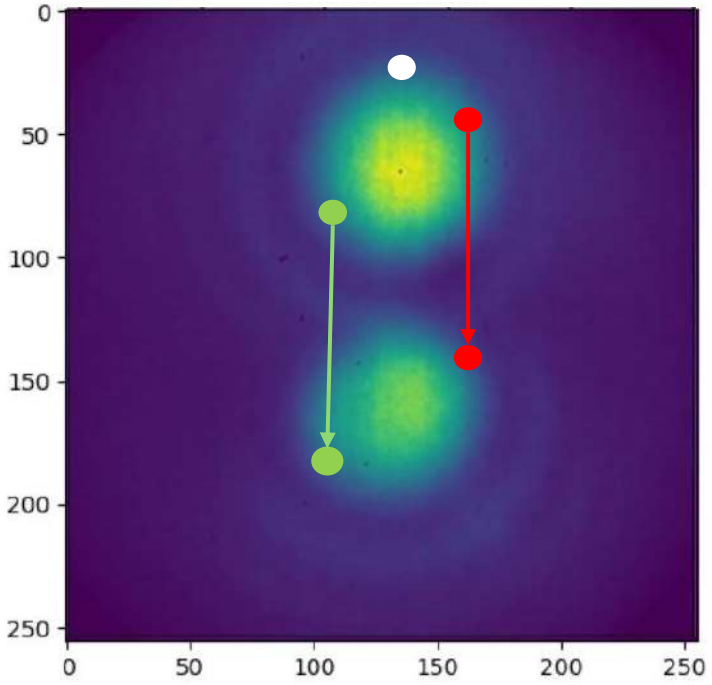
Input plane

Output plane

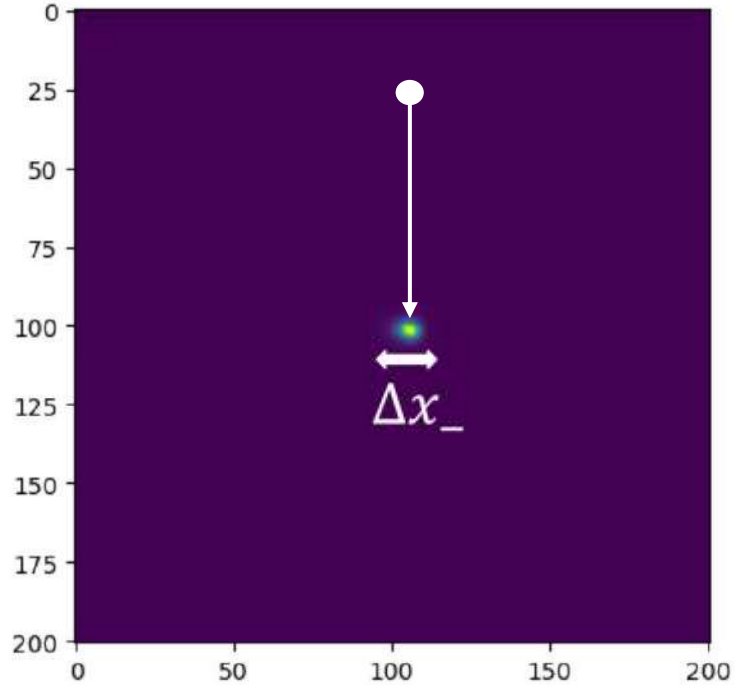
# Certifying entanglement with a camera : EPR criterion



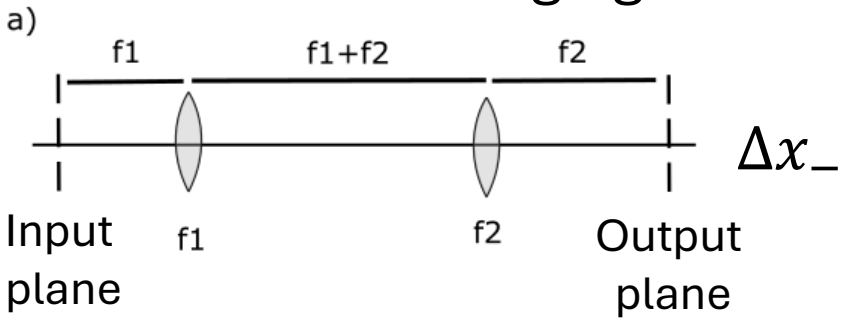

Total Intensity




Minus-Coordinate Projection




Standard imaging:



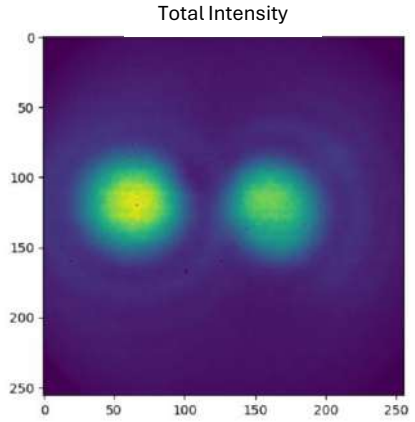

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

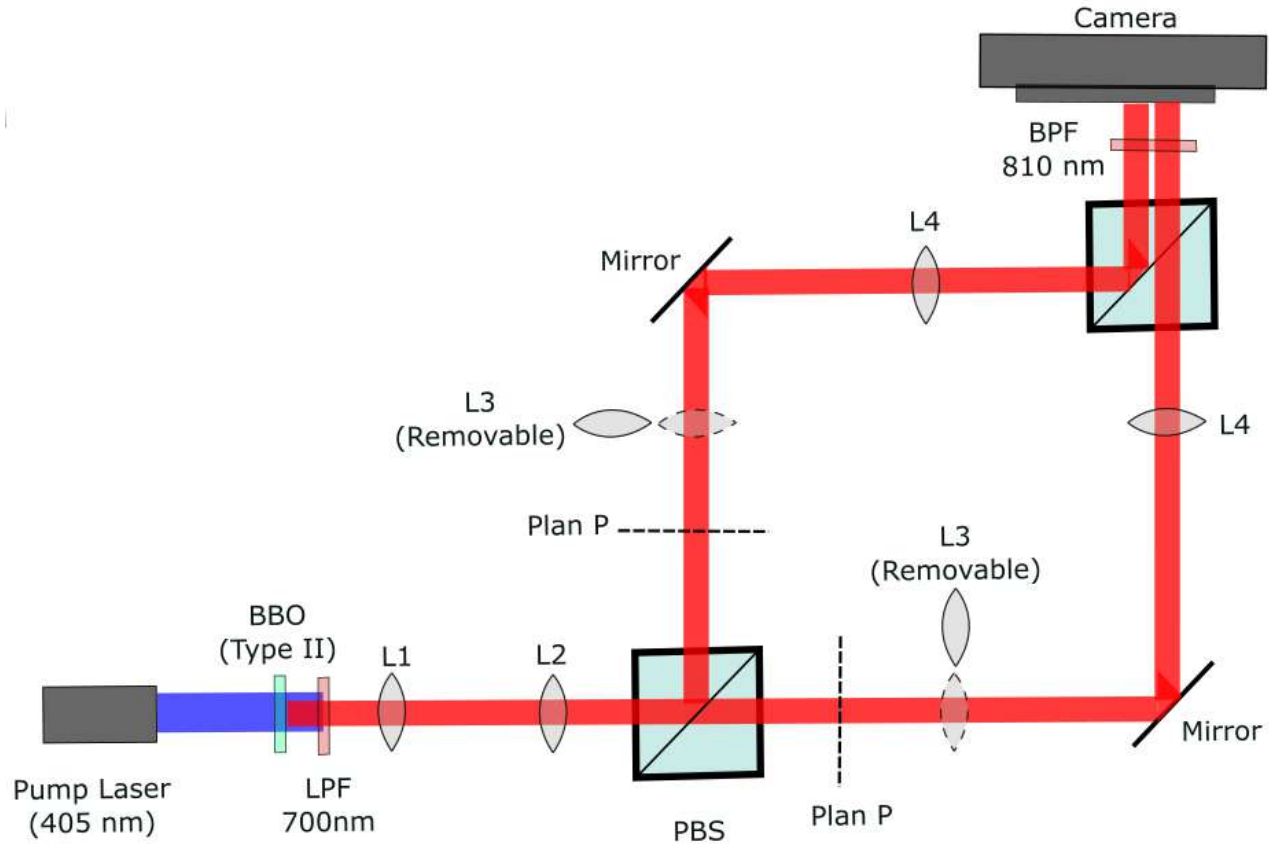
A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

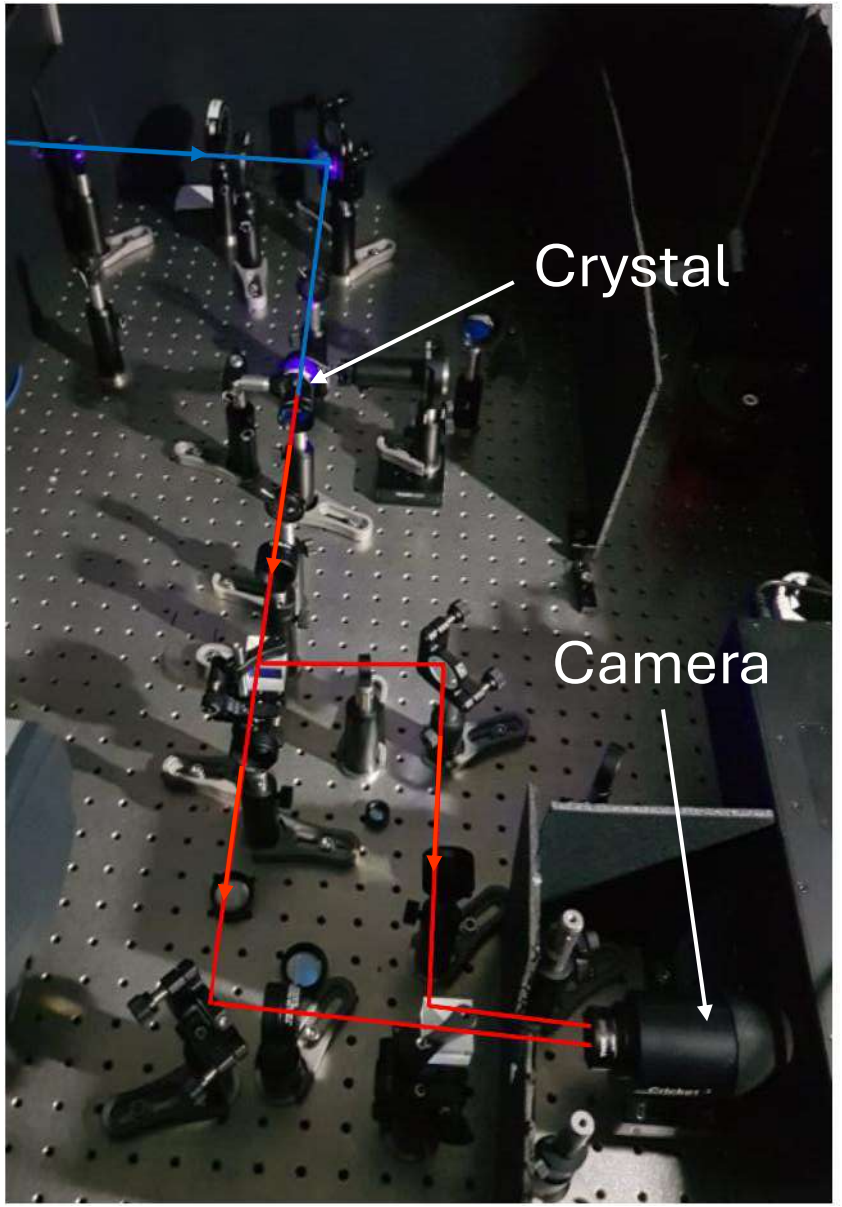
Entanglement certification:
$\Delta x_- \, \Delta k_+ < 1/2$

# Tpx3Cam : Setup

Measurement bases:
- Position
- Momentum

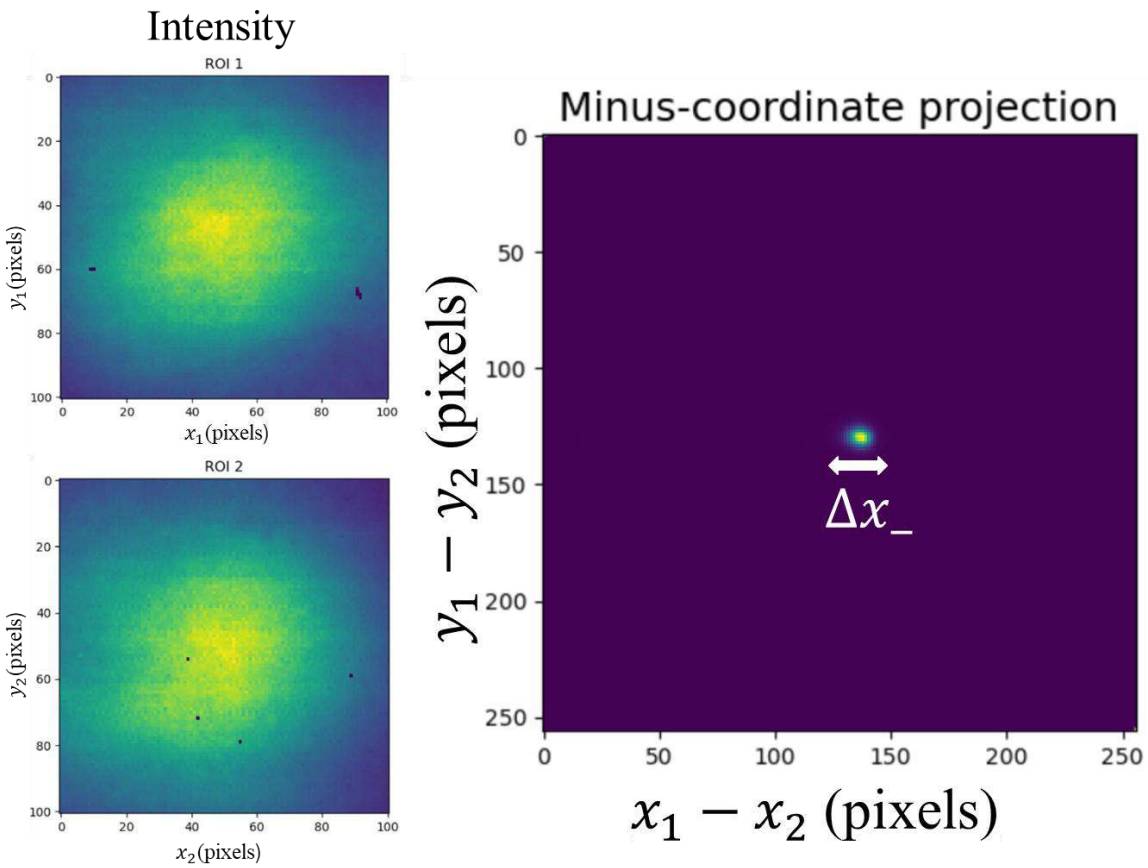


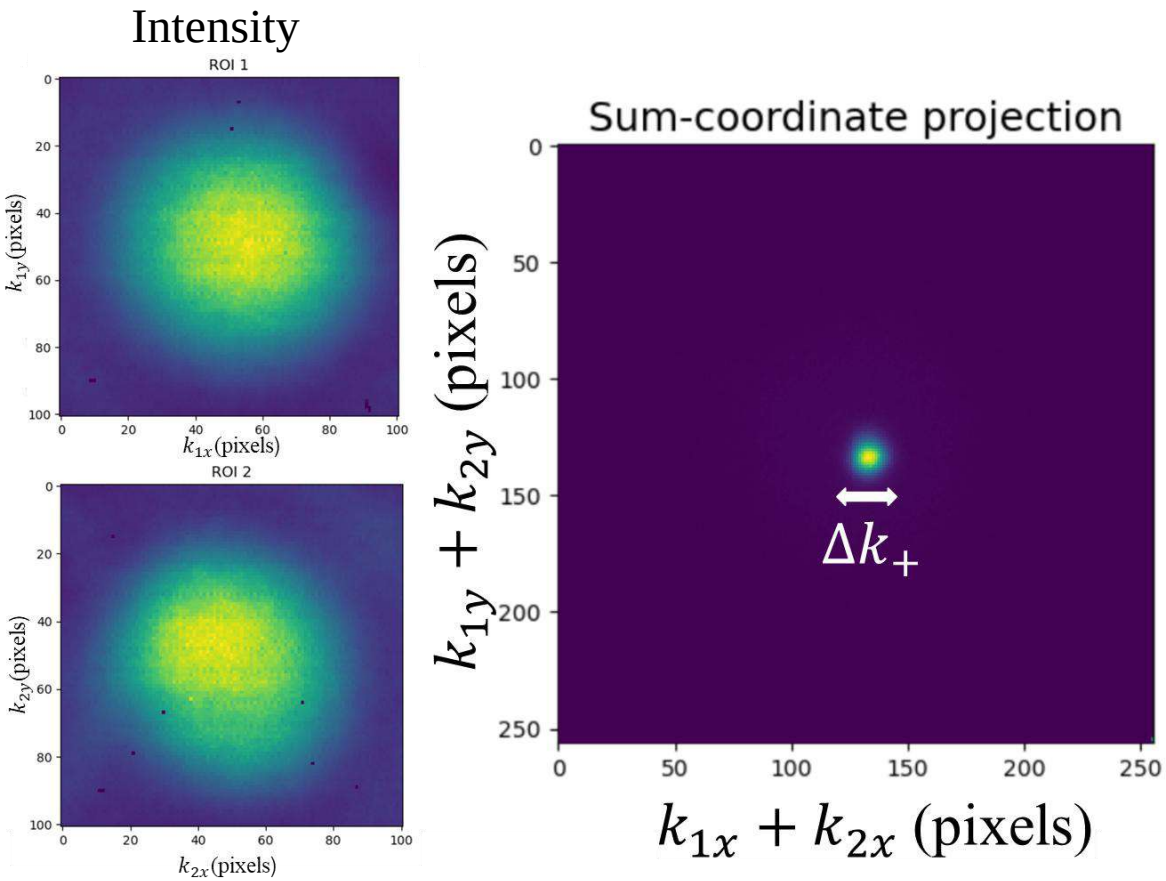
# Tpx3Cam : Results

## Standard Imaging:




$$\Delta x_- = (3.22 \pm 0.01) \times 10^{-5} m$$

## Fourier Imaging:



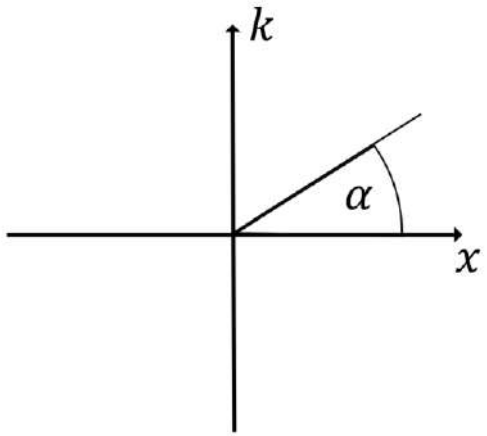

$$\Delta k_+ = 4113 \pm 2\, m^{-1}$$

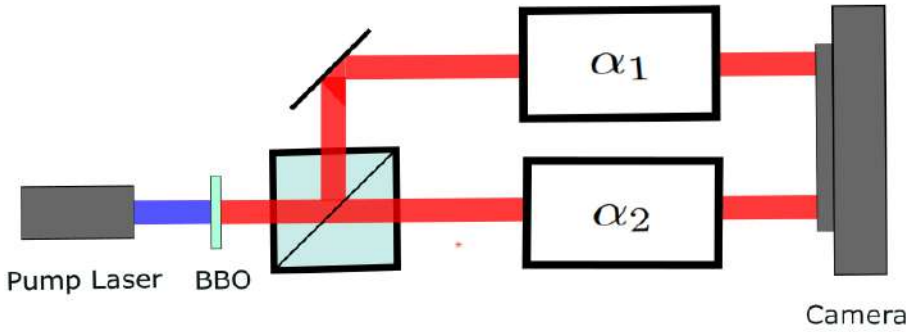
$$\Delta x_- \times \Delta k_+ = 0.132 \pm 0.001 < 1/2$$

Entanglement Certification

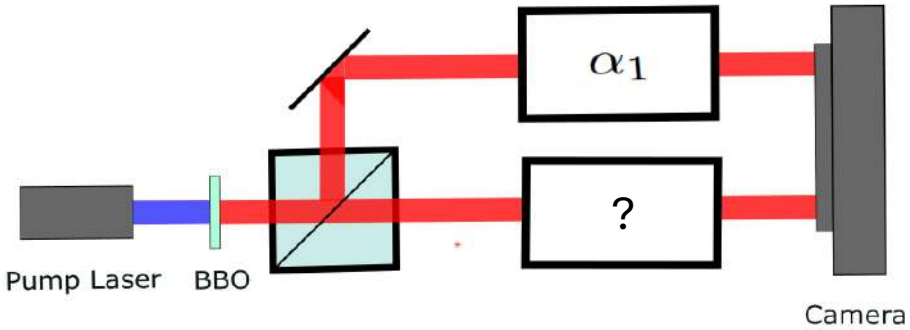
# Introducing additional measurement basis

Fractional Fourier Transform :




Certifying entanglement with an unknown arm




2 Bases → N bases

- More information on the state
- Entanglement criteria more robust to noise