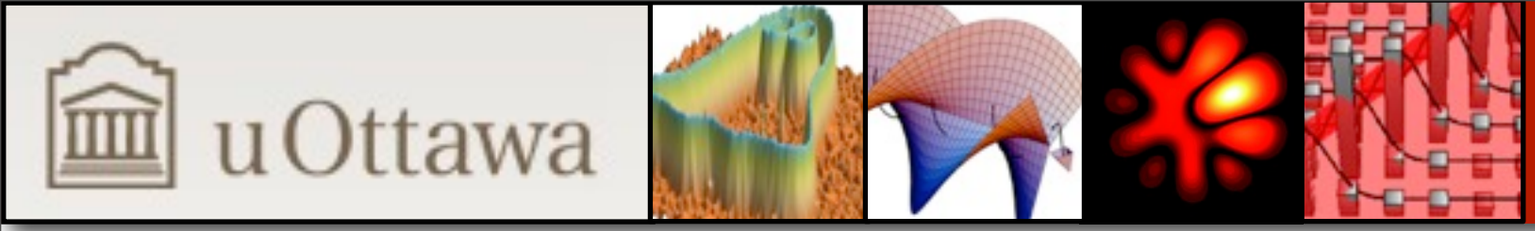
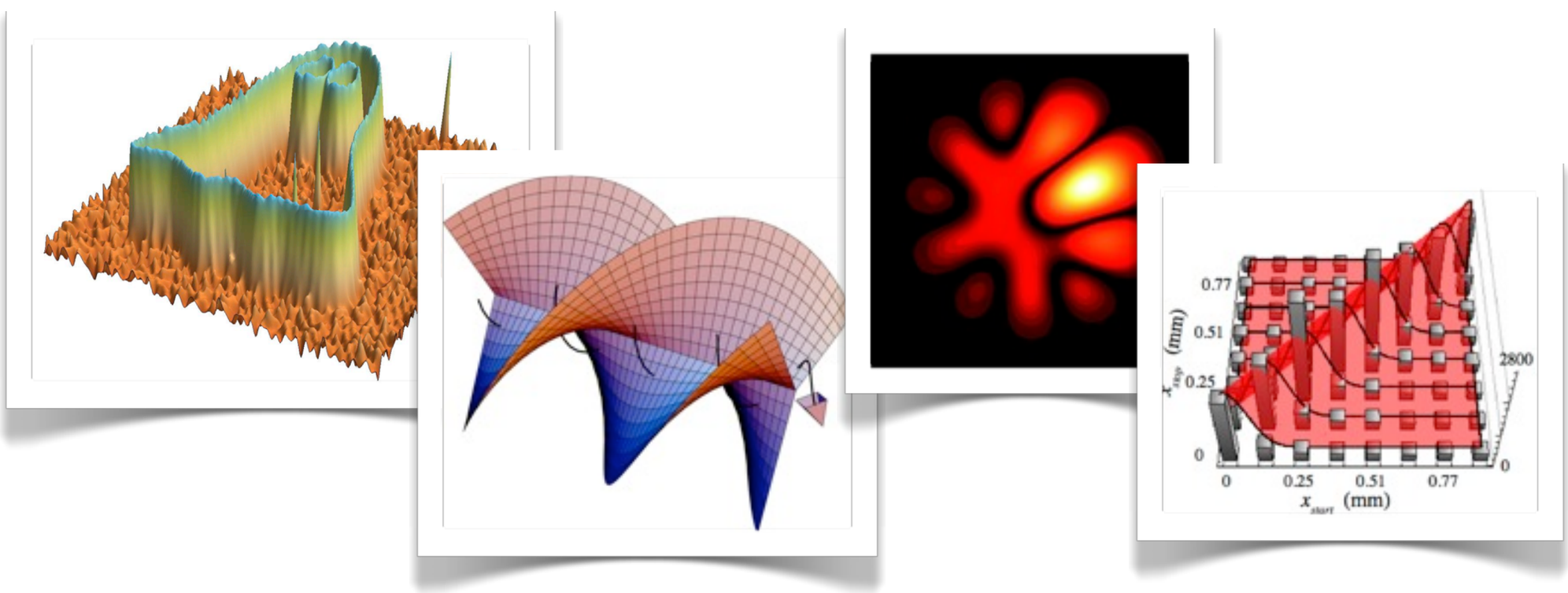


High-dimensional Quantum Entanglement and Holographic Ghost Imaging

Jonathan Leach, University of Ottawa



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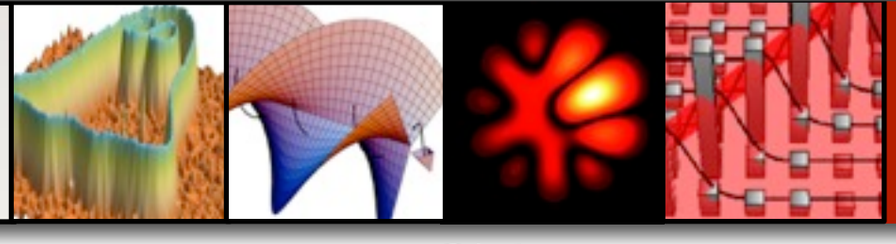


Ottawa

Megan Agnew Eliot Bolduc

Jake Larsson

Robert Boyd

Rochester

Anand Jha

Glasgow

Jacqui Romero

Miles Padgett

Barry Jack

Steve Barnett

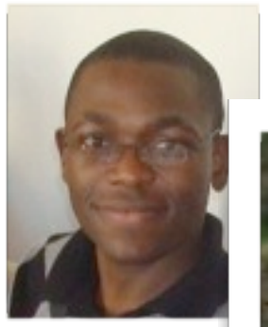
Sonja Franke-Arnold

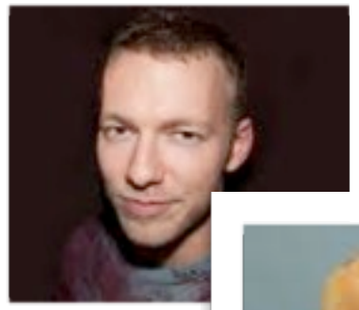
Dave Ireland

Edinburgh

Ryan Warburton

Tunmise Dada

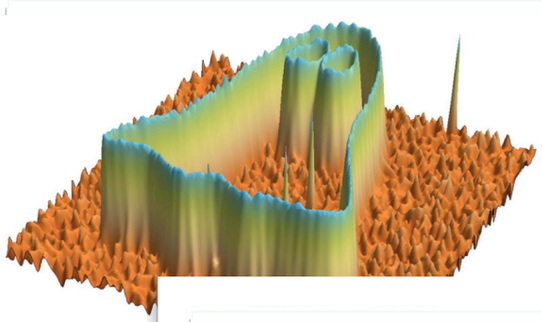




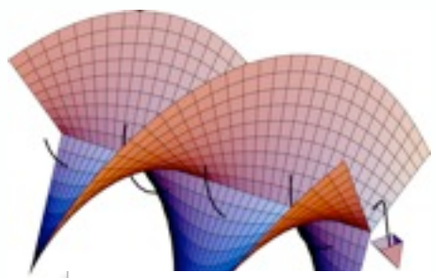
Erika Andersson

Gerald Buller

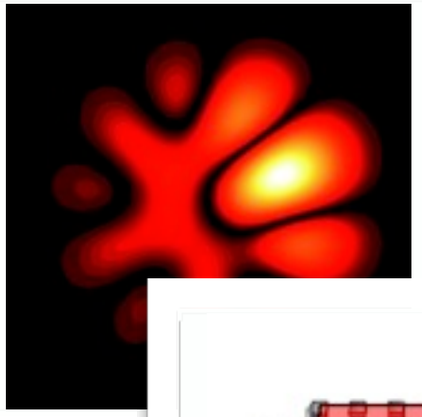
uOttawa



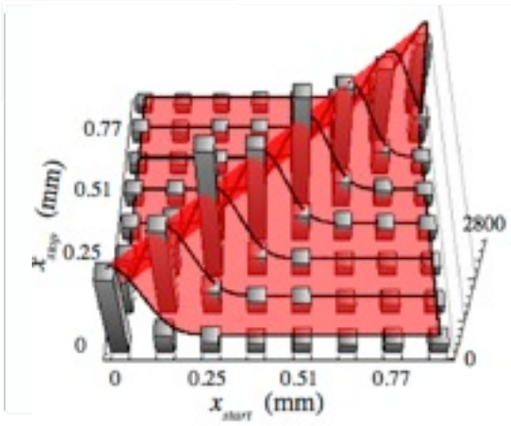
Holographic ghost imaging



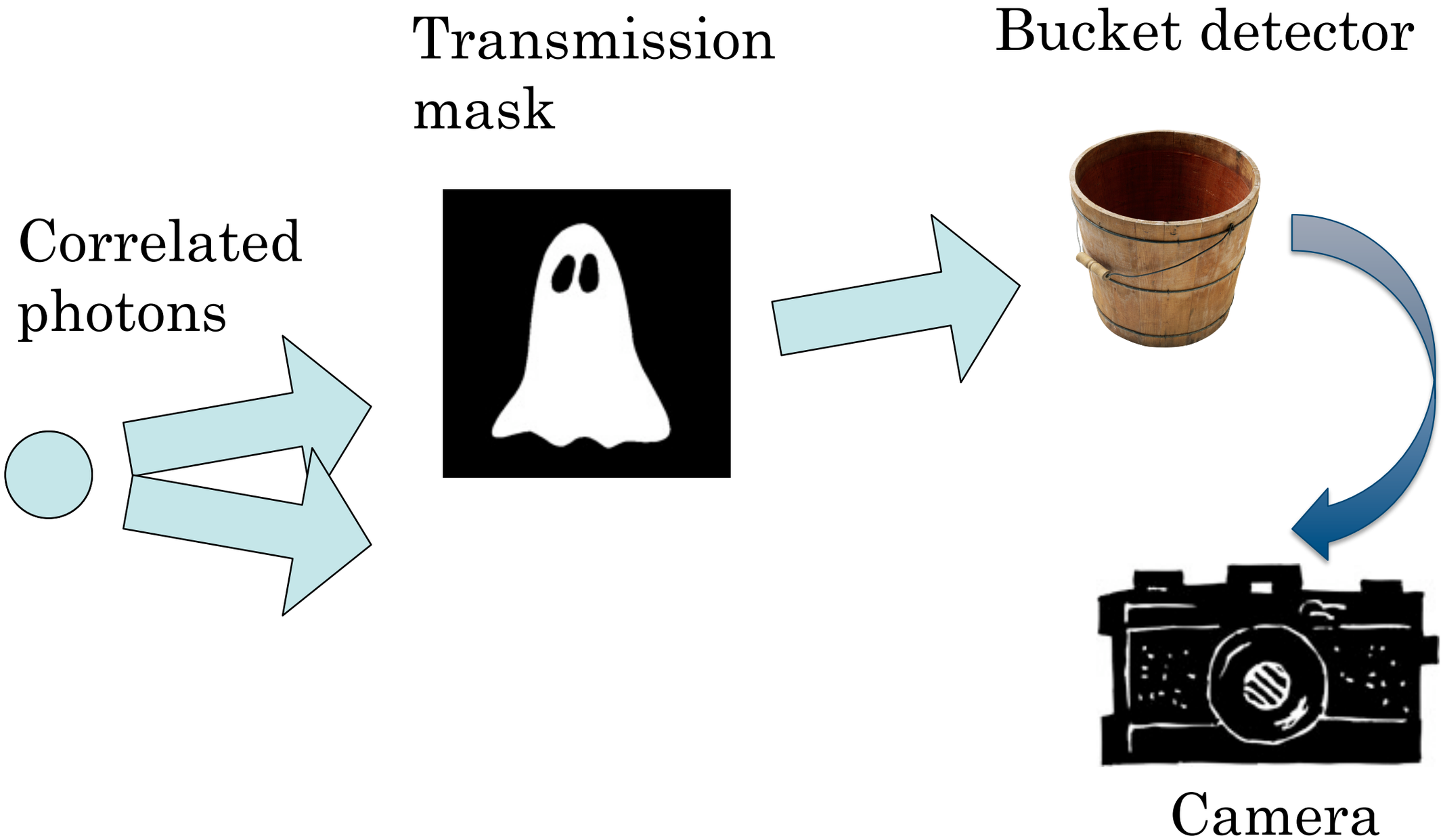
EPR correlations in the OAM/angle basis

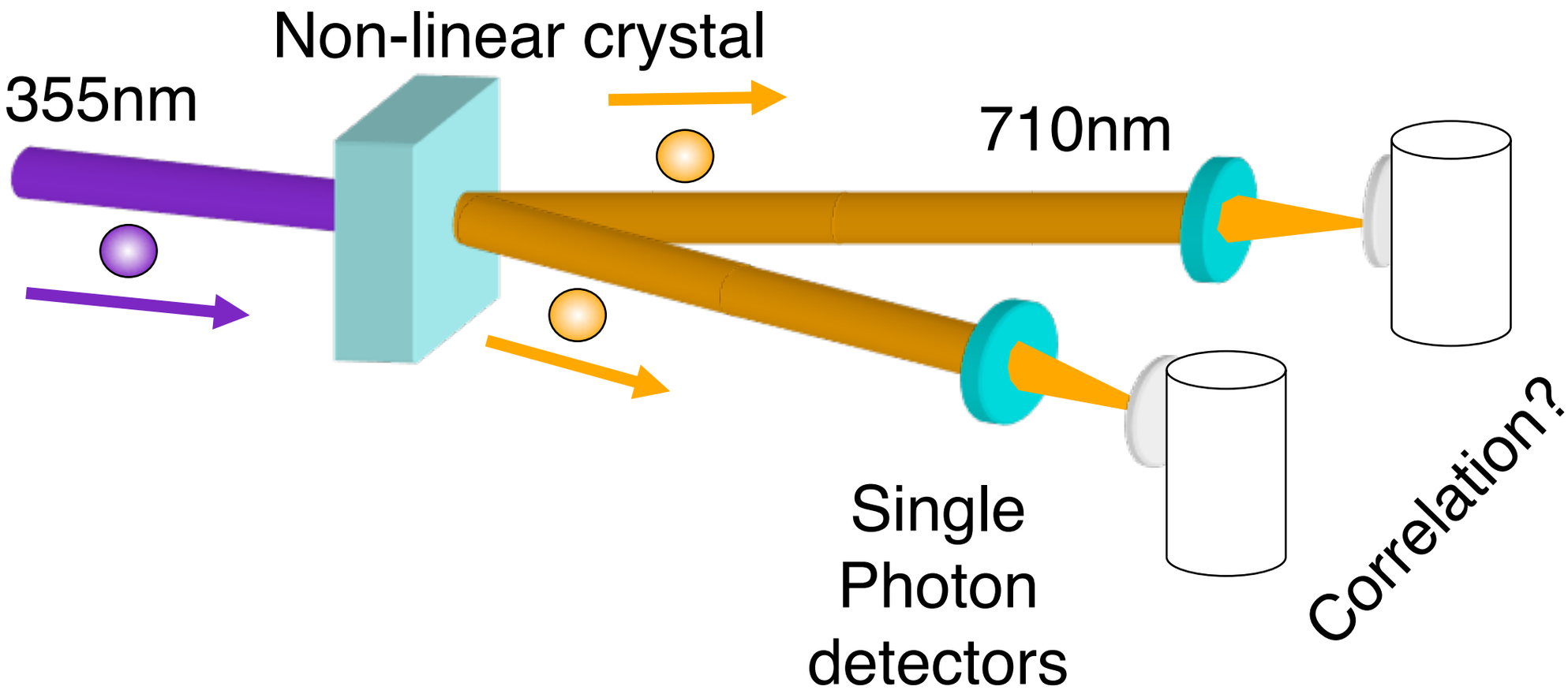


Violations of generalized Bell inequalities

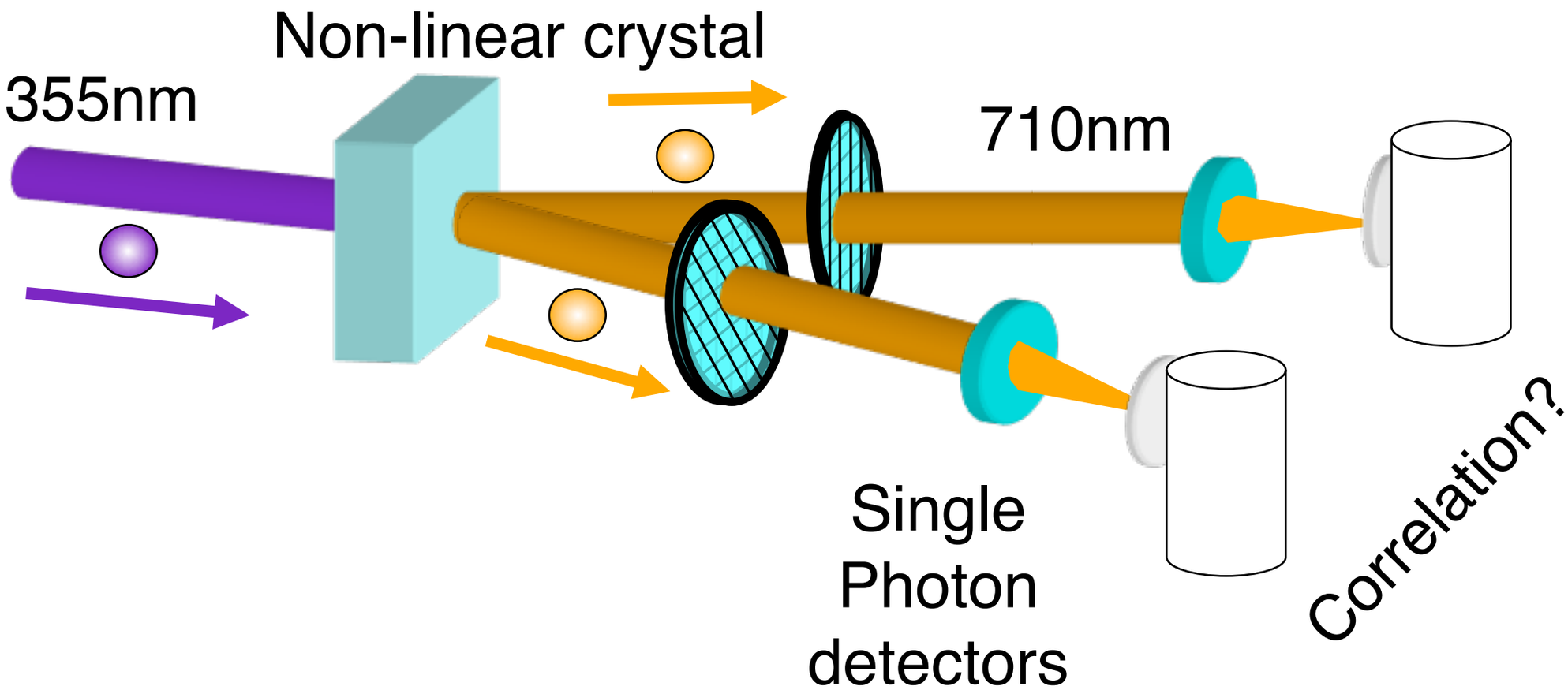


Full-field quantum measurements

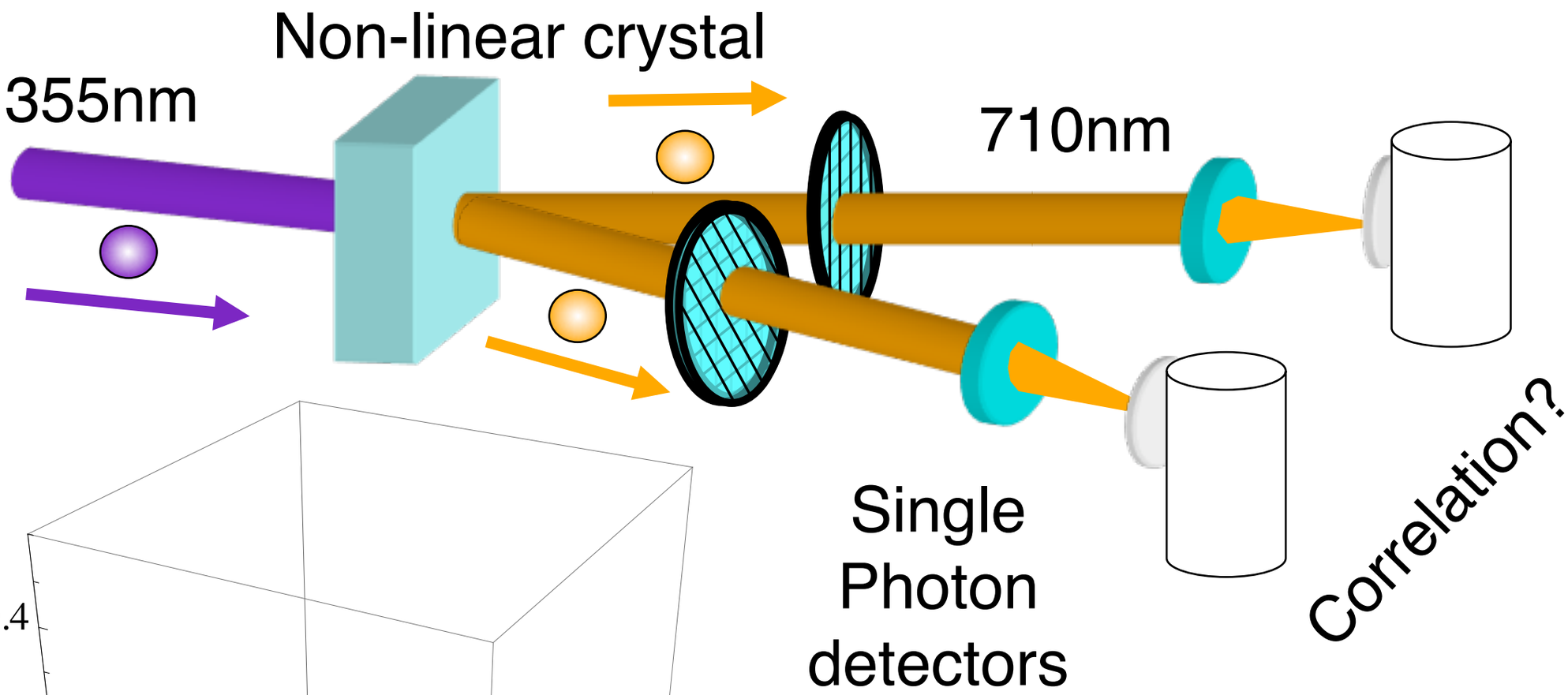

Transmission mask
Bucket detector
Correlated photons
Camera

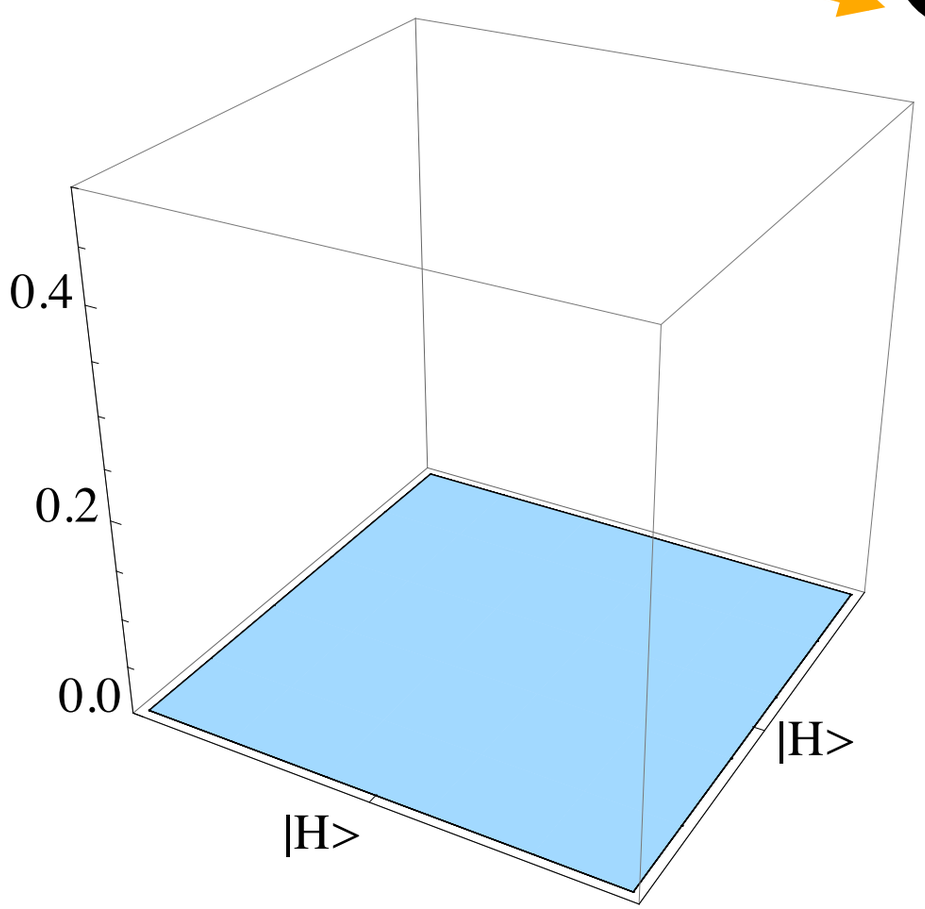


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\right)$$

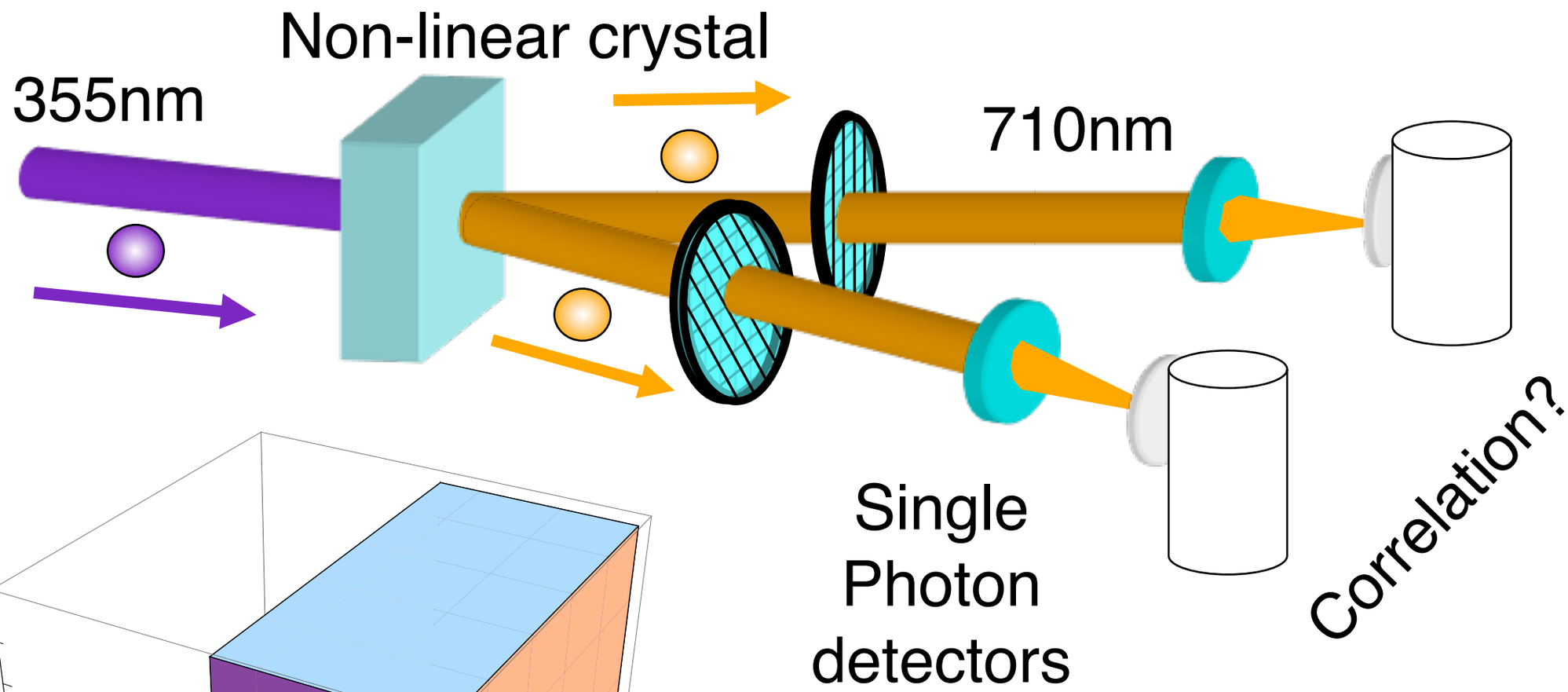


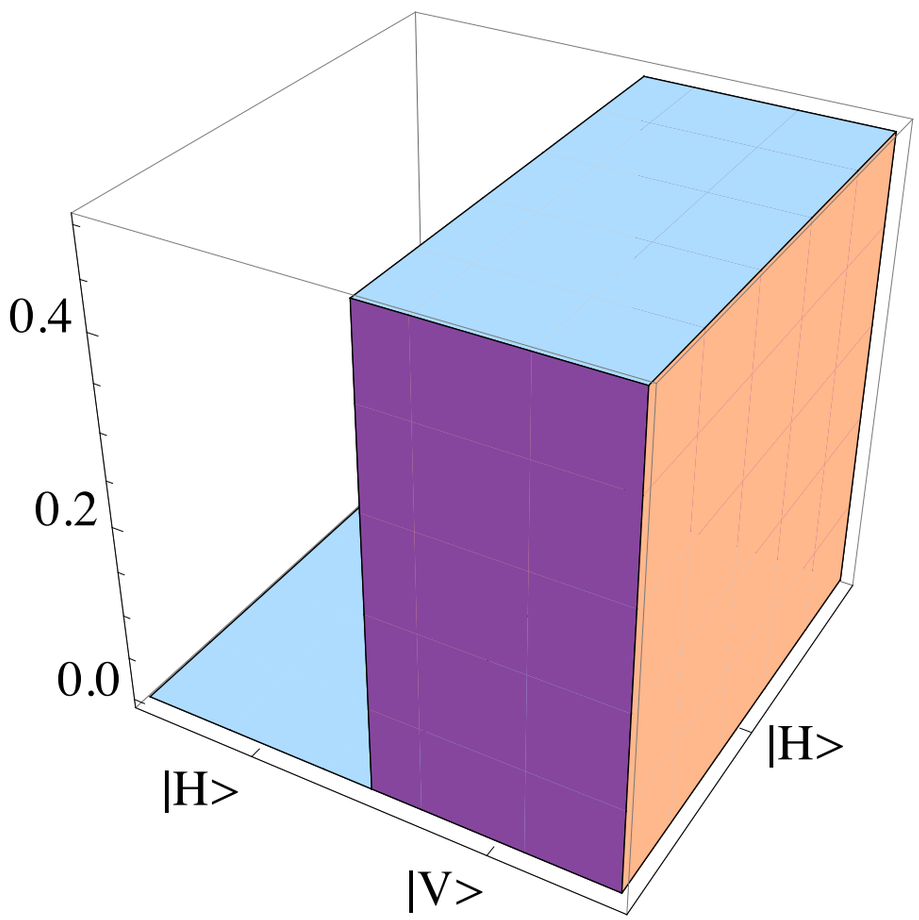
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\right)$$



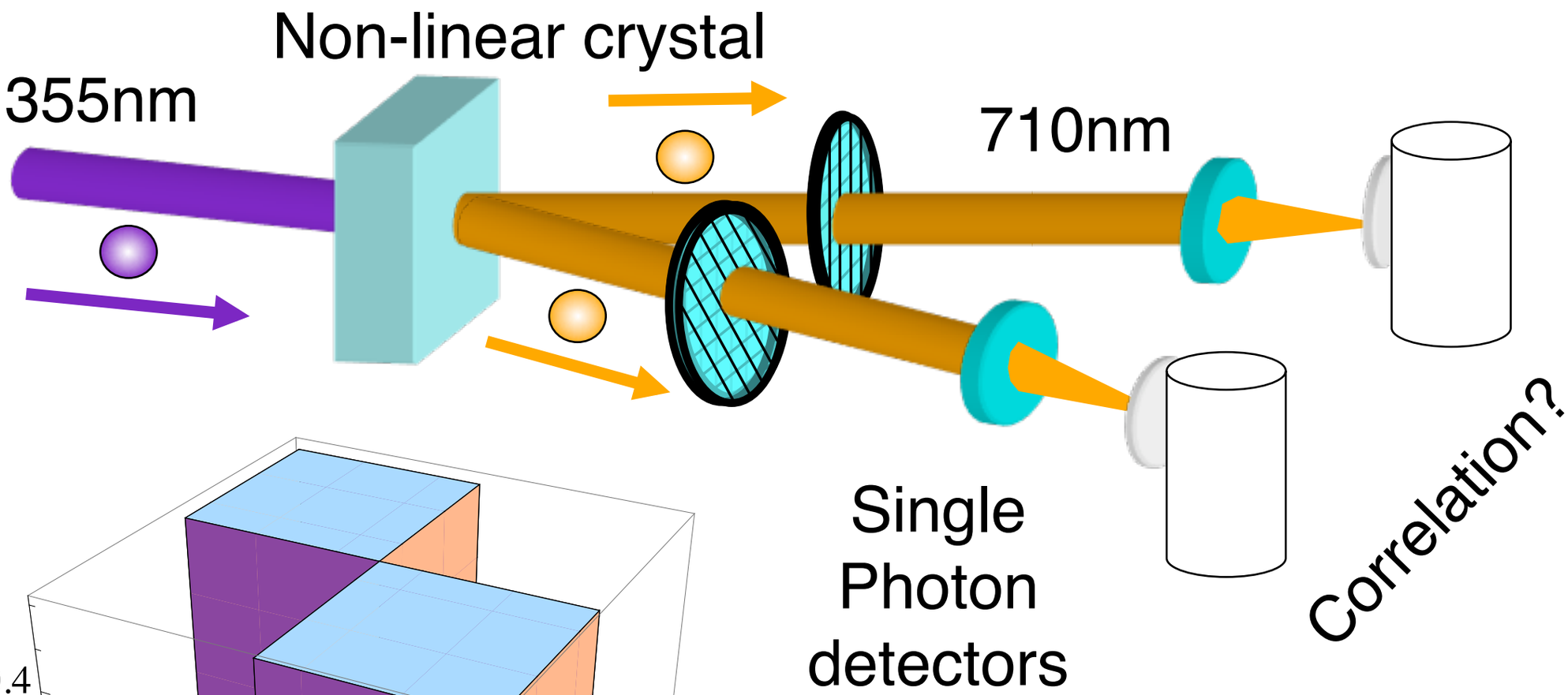


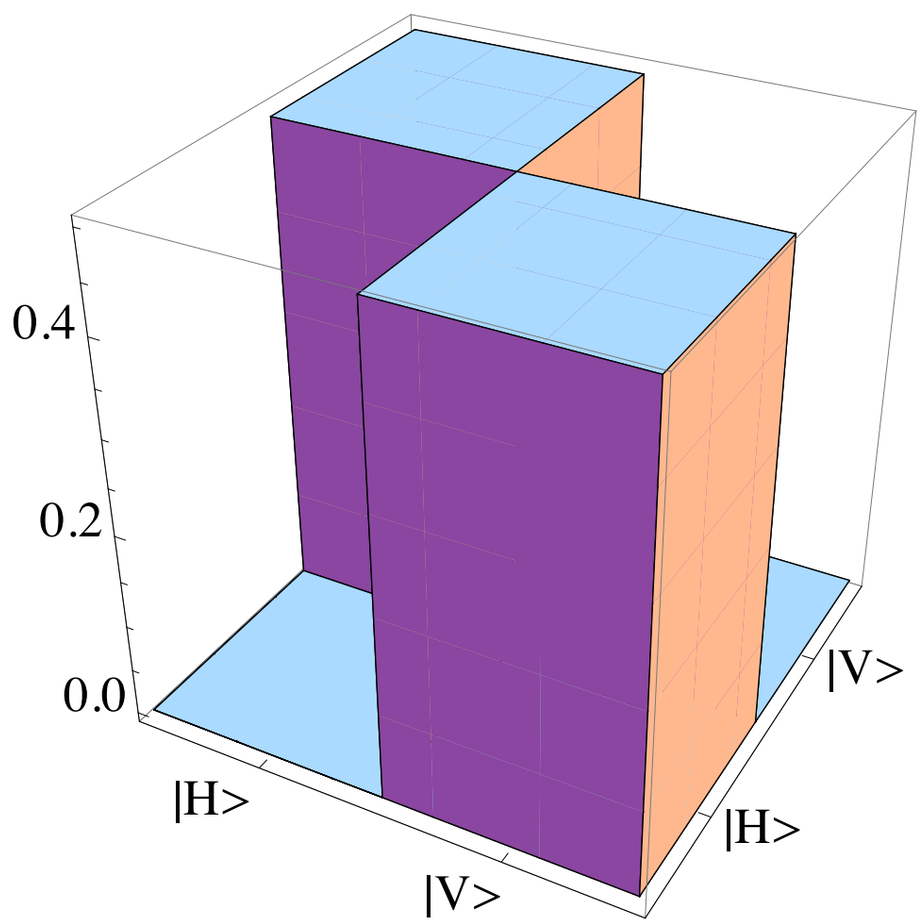
Is this enough to show entanglement?



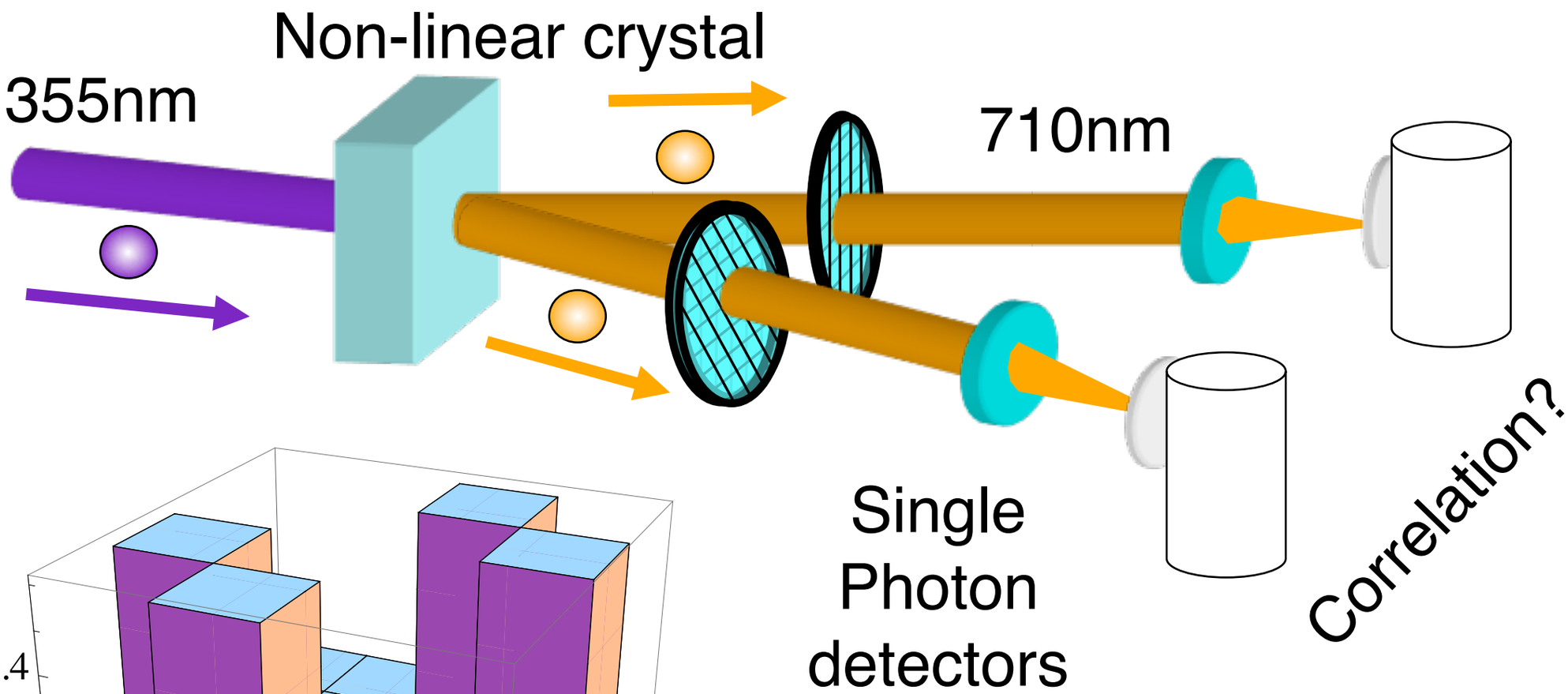


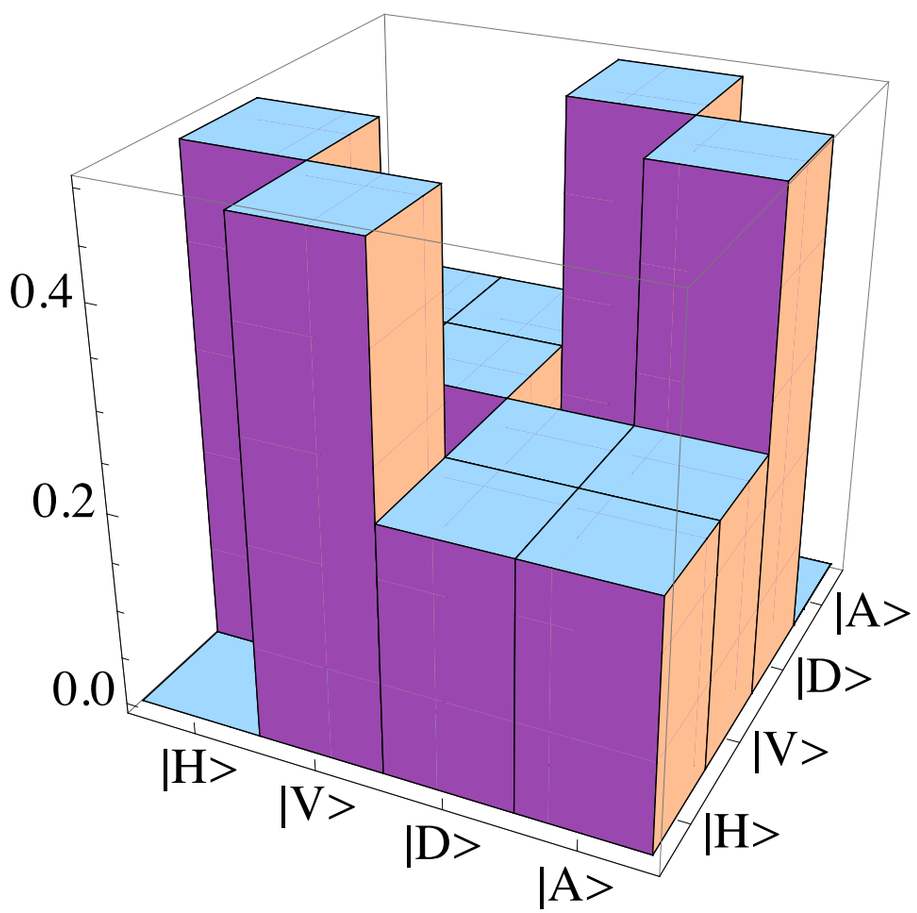
Is this enough to show entanglement?



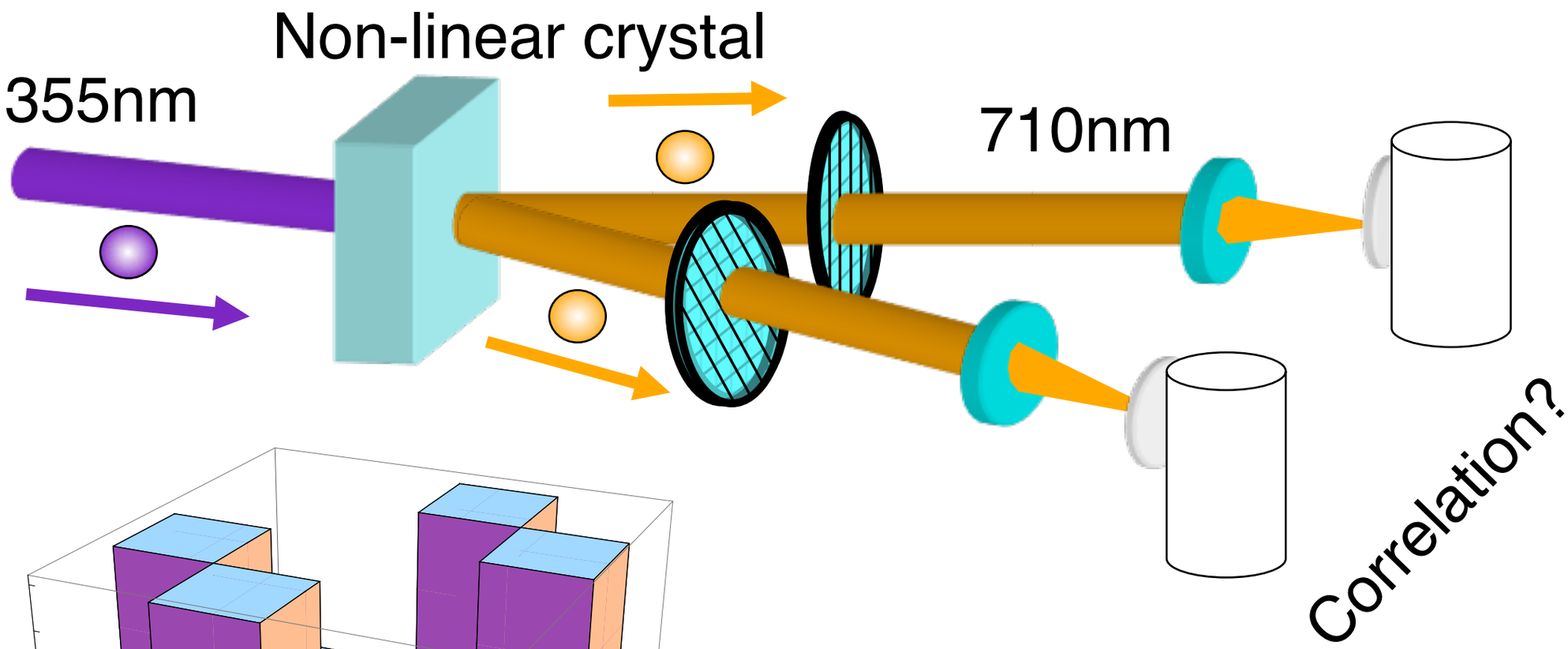


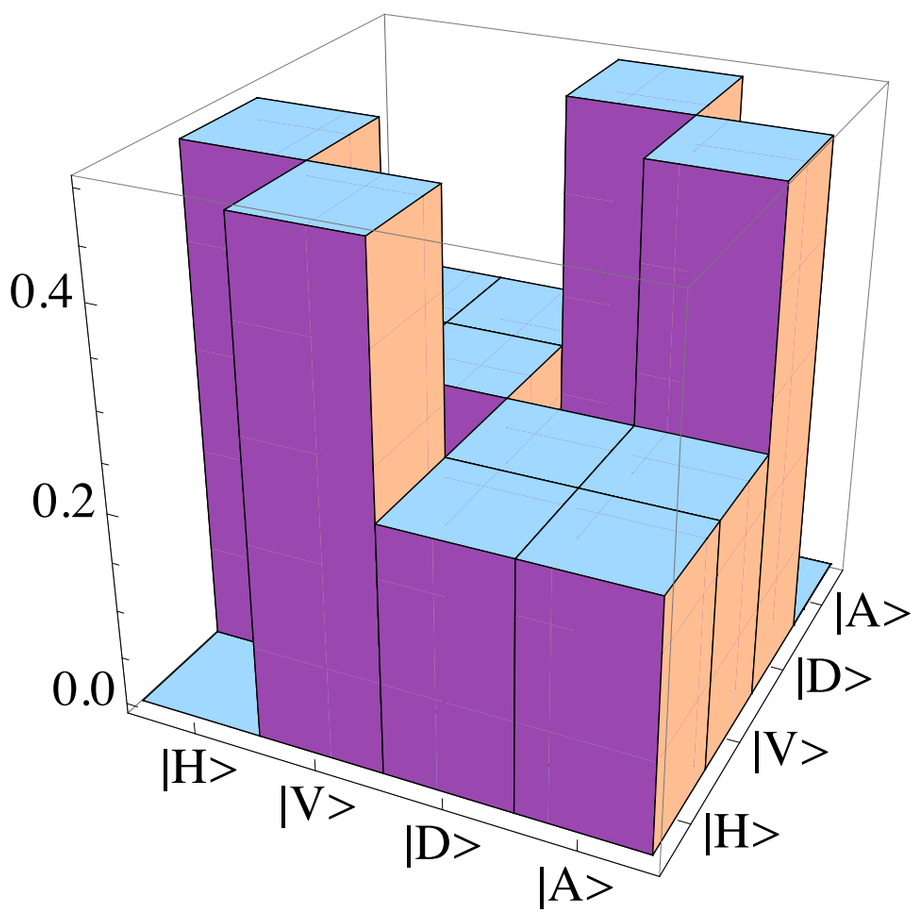
Is this enough to show entanglement?



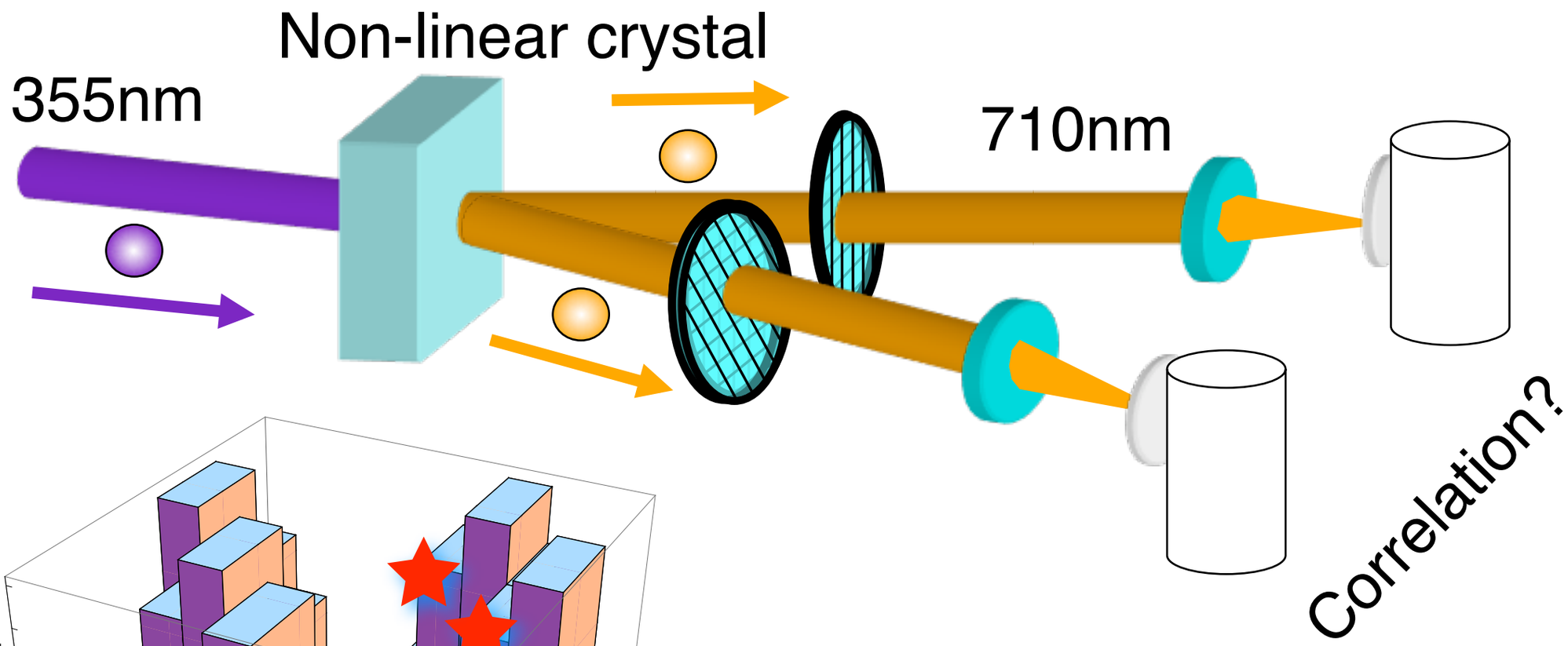


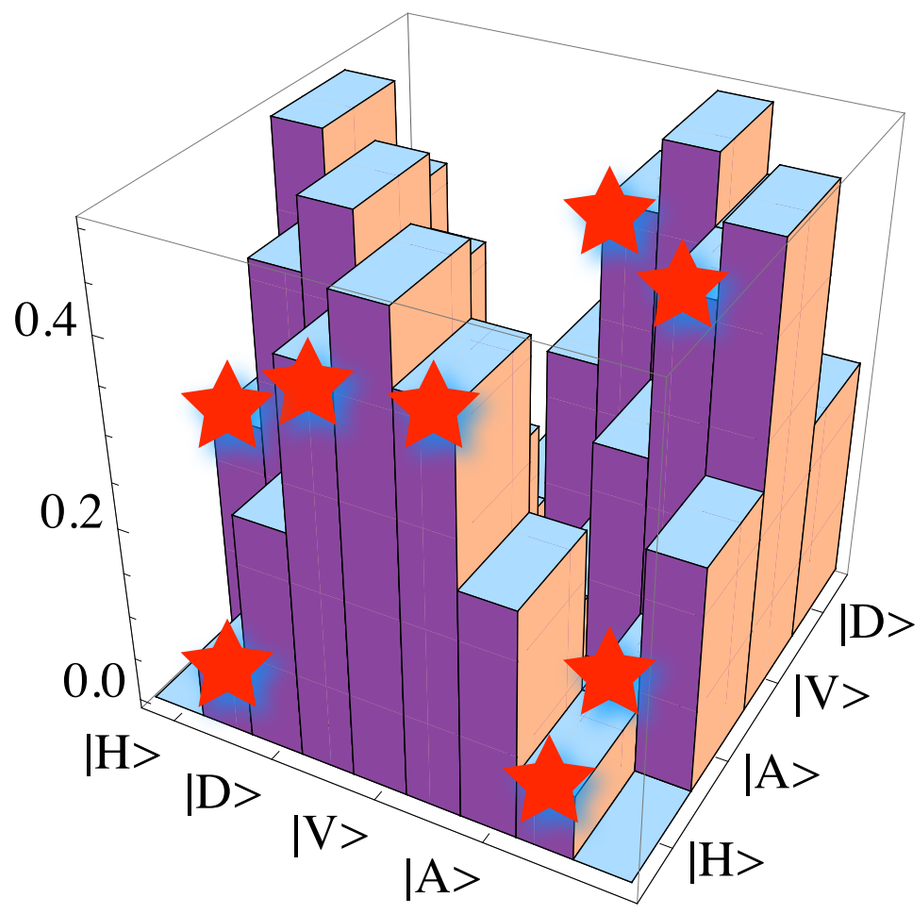
Is this enough to show entanglement?





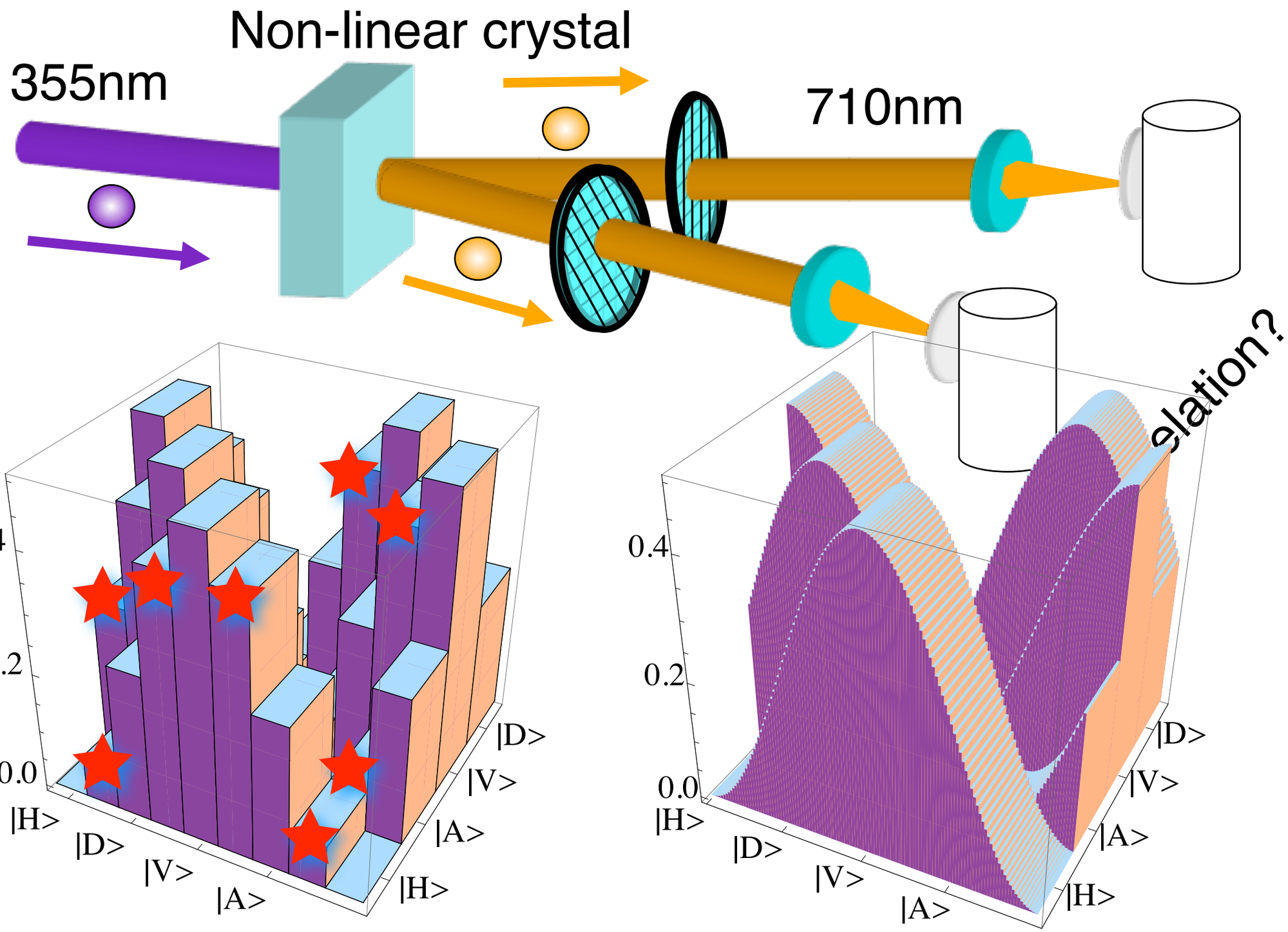
Does this result rule out local hidden variables?



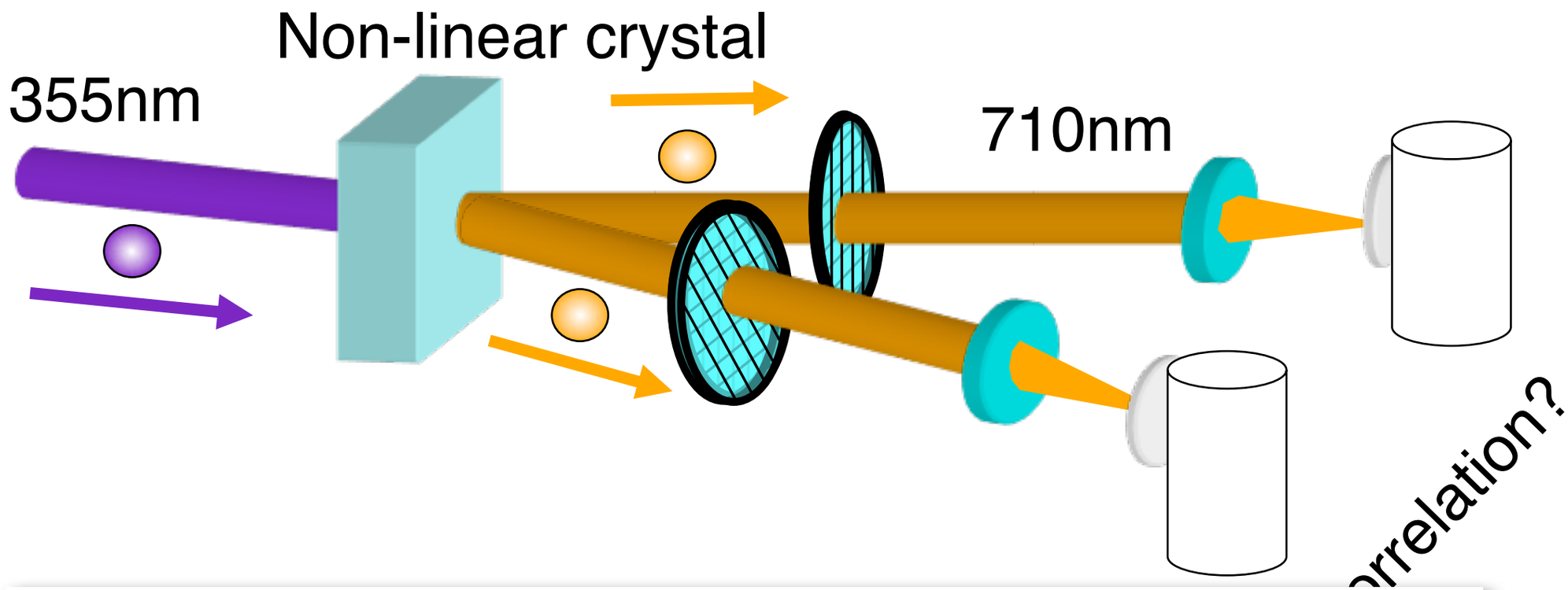


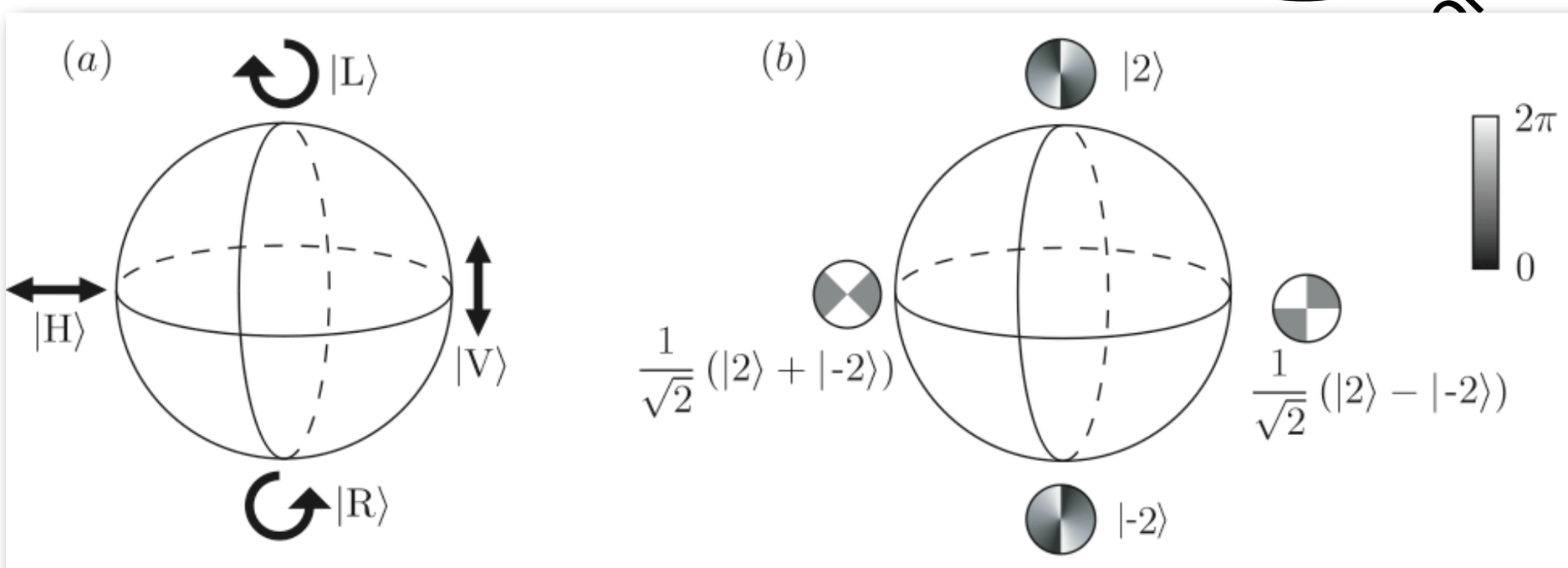
Does this result rule out local hidden variables?

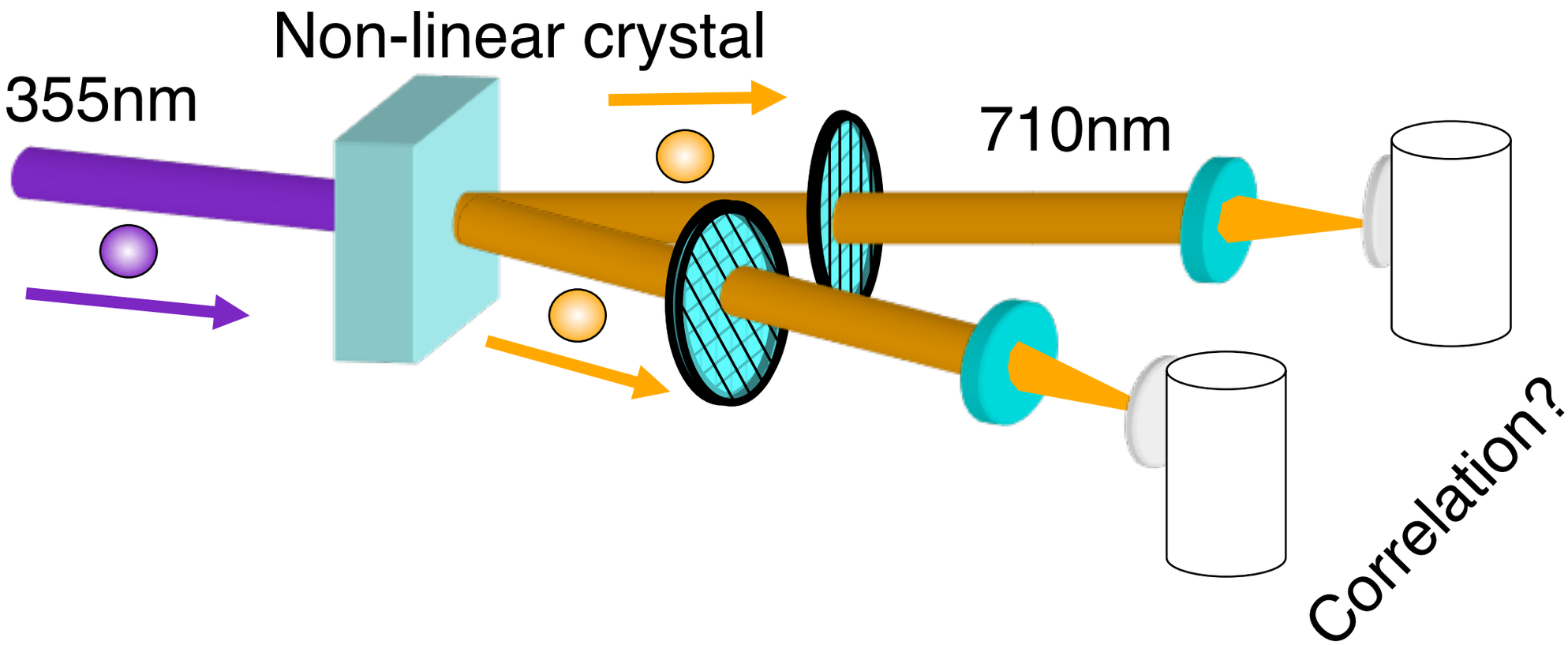
★ x16 Measurements


Non-linear crystal
355nm
710nm
0.4
0.2
0.0
|H>
|D>
|V>
|A>
|D>
|V>
|A>
|H>
0.4
0.2
0.0
|H>
|D>
|V>
|A>
|D>
|V>
|A>
|H>

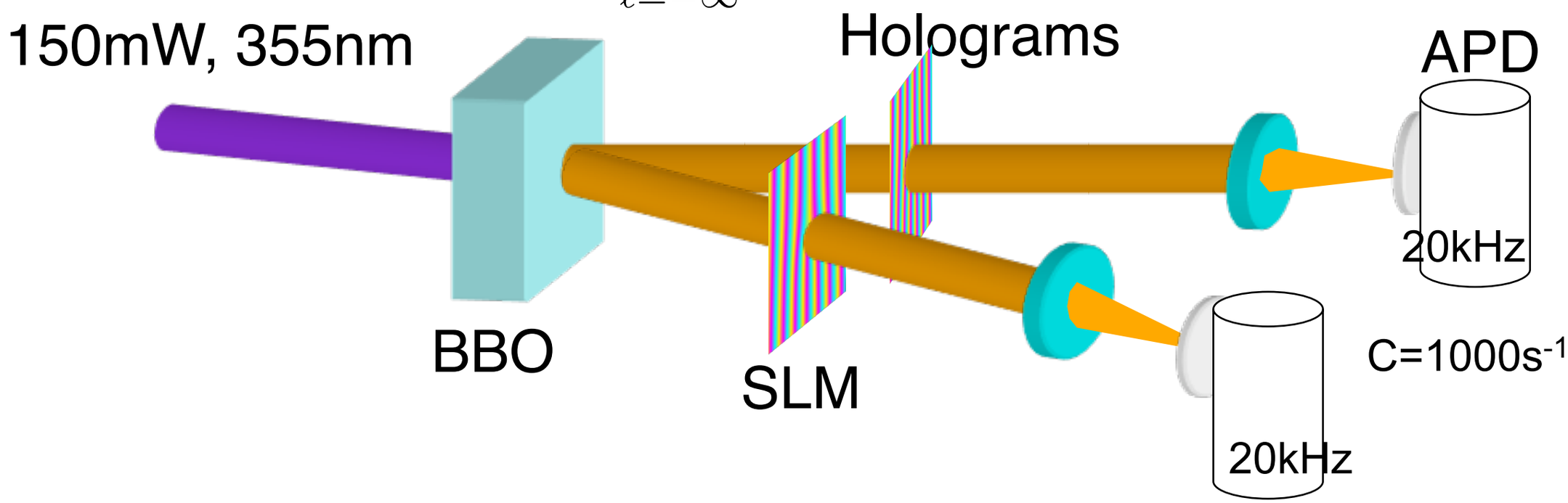
elation?

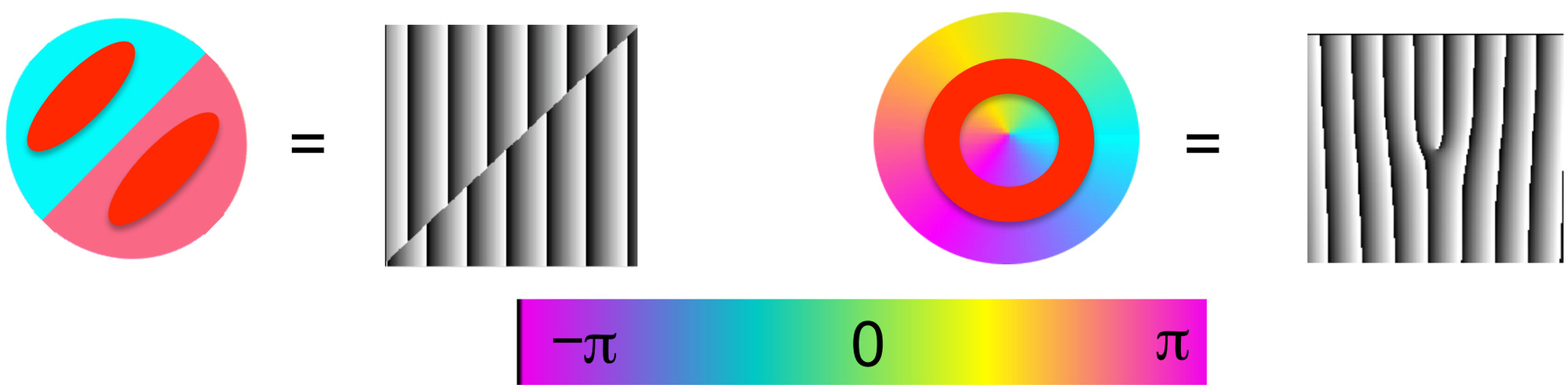

Non-linear crystal
355nm
710nm
correlation?


(a)
|L⟩
|H⟩
|V⟩
|R⟩
(b)
|2⟩
2π
0
$\frac{1}{\sqrt{2}}(|2\rangle + |\text{-}2\rangle)$
$\frac{1}{\sqrt{2}}(|2\rangle - |\text{-}2\rangle)$
|-2⟩

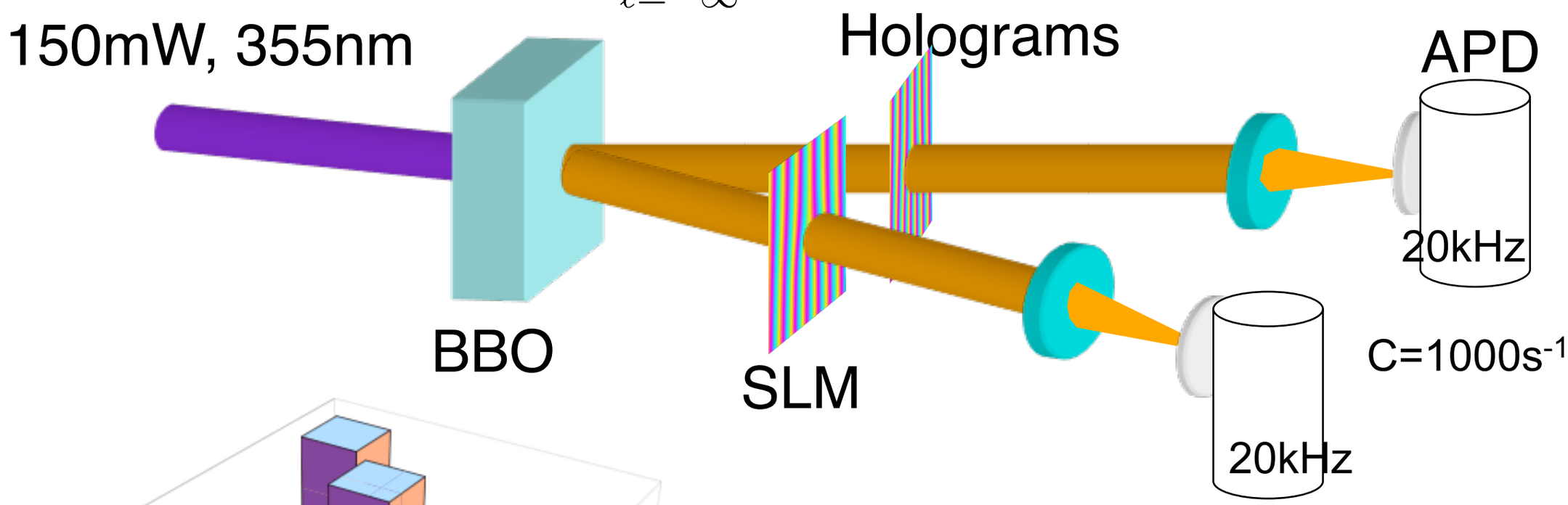

Non-linear crystal
355nm
710nm
Correlation?

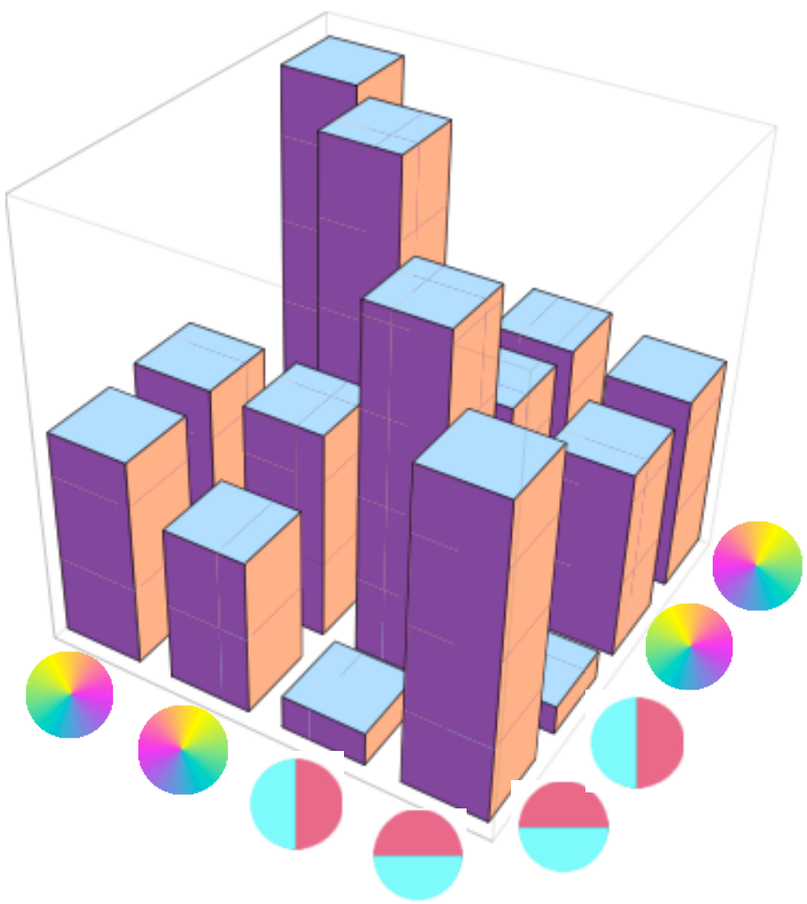
$$|\psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} c_\ell |-\ell\rangle|\ell\rangle$$

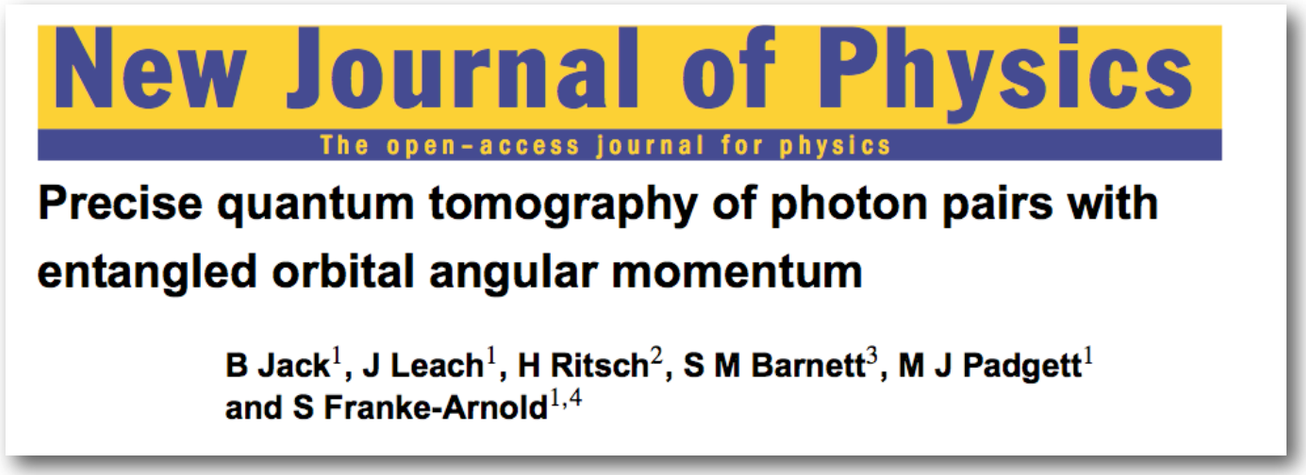




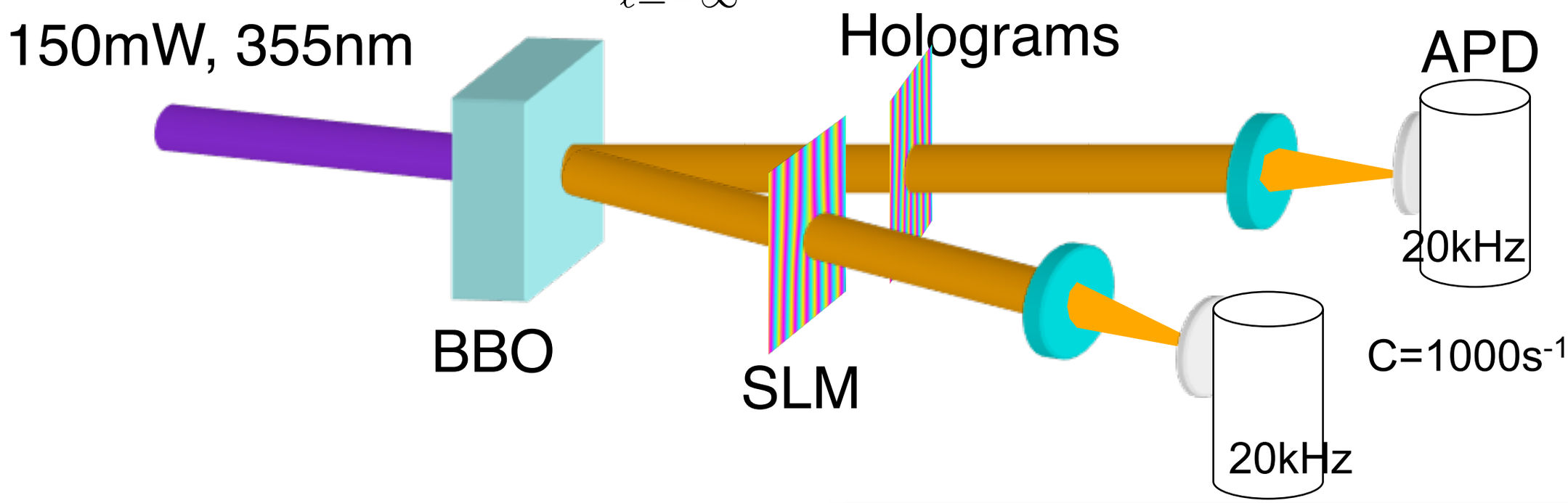
$$|\psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} c_\ell |-\ell\rangle|\ell\rangle$$





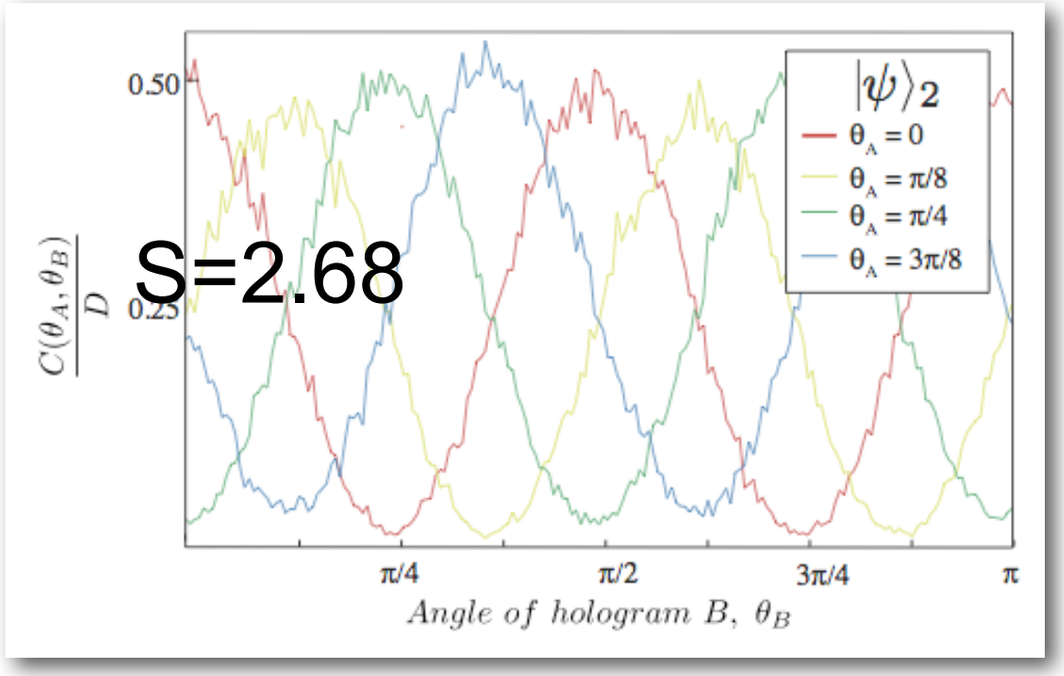

New Journal of Physics
The open-access journal for physics
Precise quantum tomography of photon pairs with entangled orbital angular momentum
B Jack[1], J Leach[1], H Ritsch[2], S M Barnett[3], M J Padgett[1] and S Franke-Arnold[1,4]

$$|\psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} c_\ell |-\ell\rangle|\ell\rangle$$

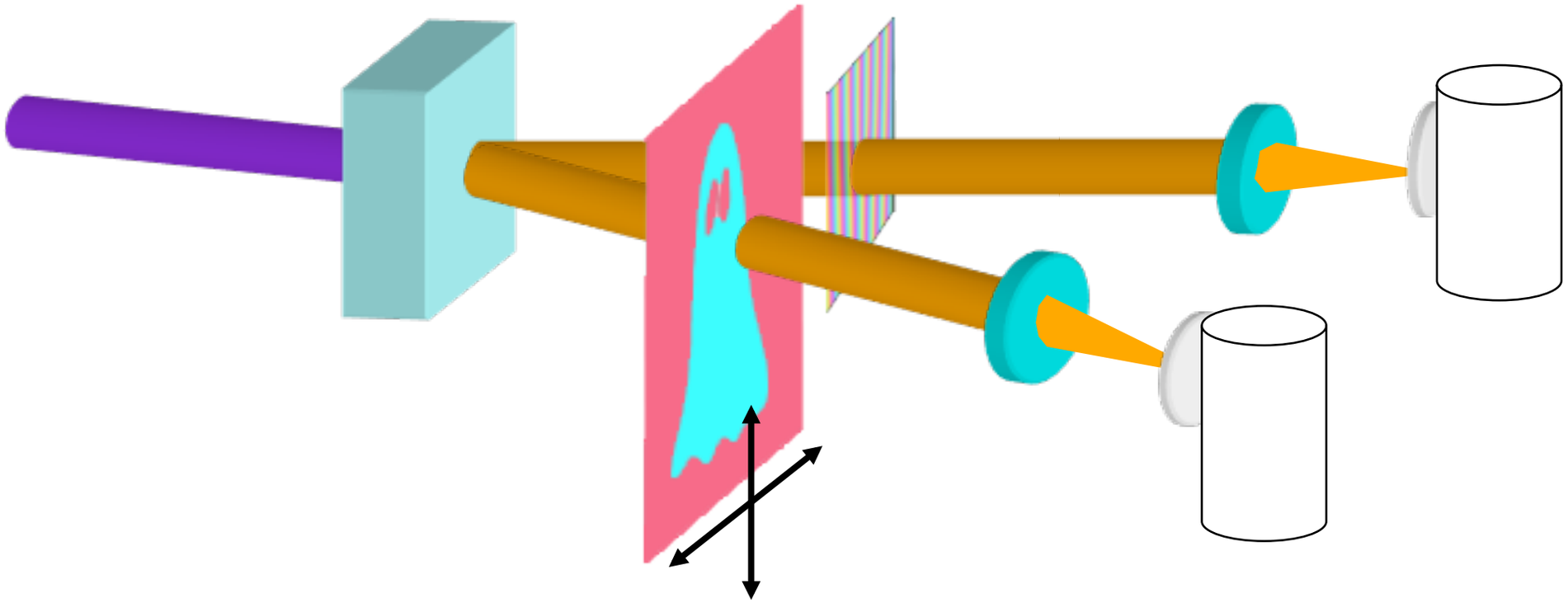


Violation of a Bell inequality in two-dimensional orbital angular momentum state-spaces

J. Leach[1], B. Jack[1], J. Romero[1], M. Ritsch-Marte[2], R. W. Boyd[3], A. K. Jha[3], S. M. Barnett[4], S. Franke-Arnold[1] and M. J. Padgett[1]

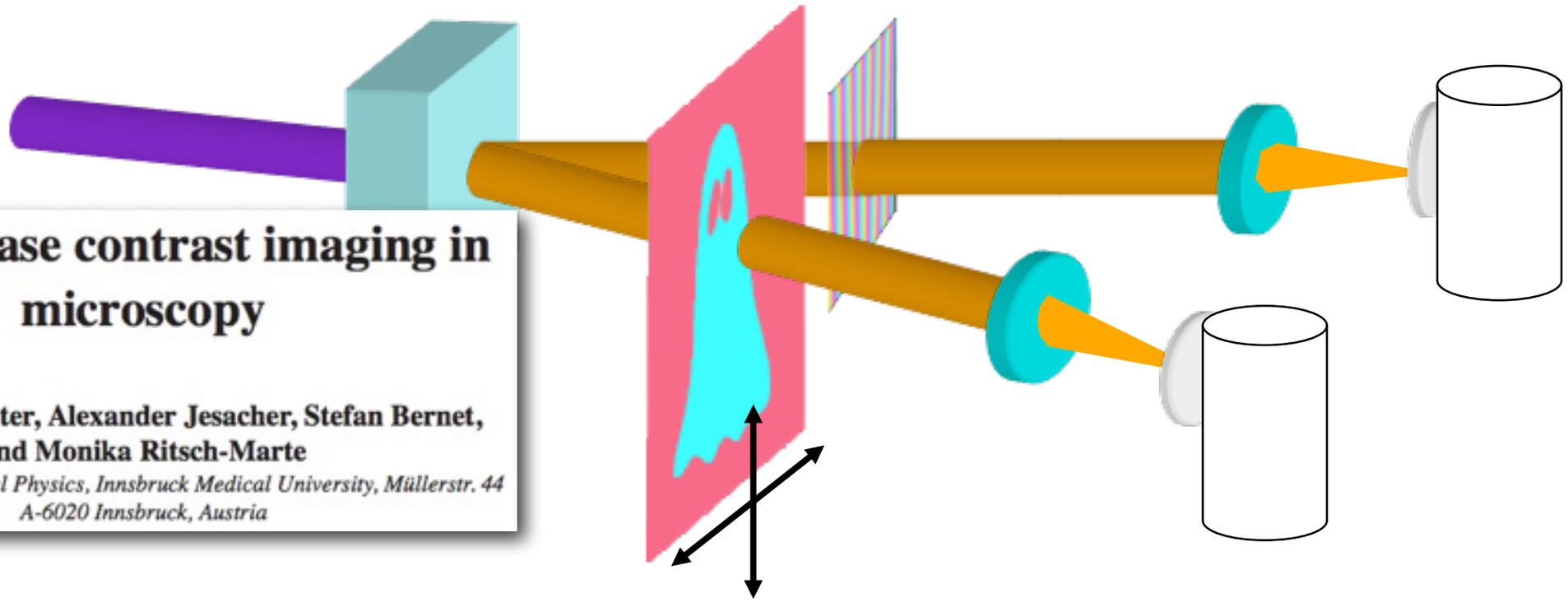


$$|\psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} c_\ell |-\ell\rangle|\ell\rangle$$



?

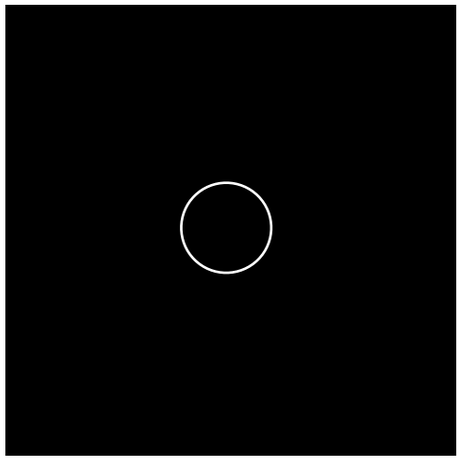
$$|\psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} c_\ell |-\ell\rangle|\ell\rangle$$



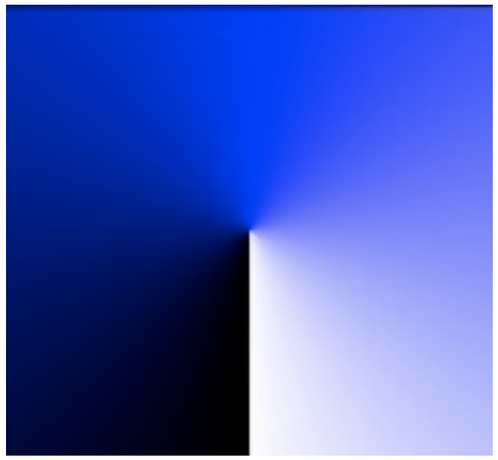
Spiral phase contrast imaging in microscopy

Severin Fürhapter, Alexander Jesacher, Stefan Bernet, and Monika Ritsch-Marte
Division for Biomedical Physics, Innsbruck Medical University, Müllerstr. 44 A-6020 Innsbruck, Austria

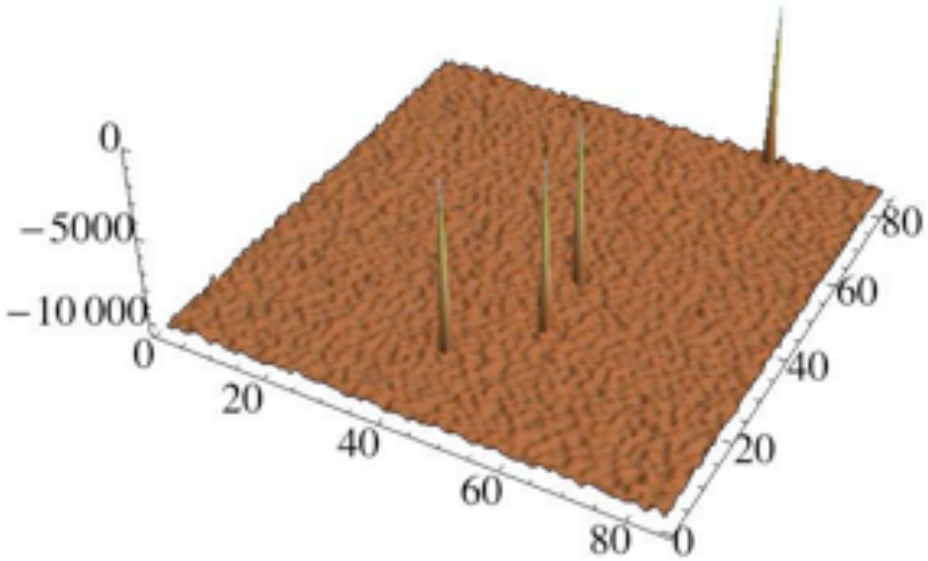
Object



Filter



Coincidence



Scanned image from reference arm

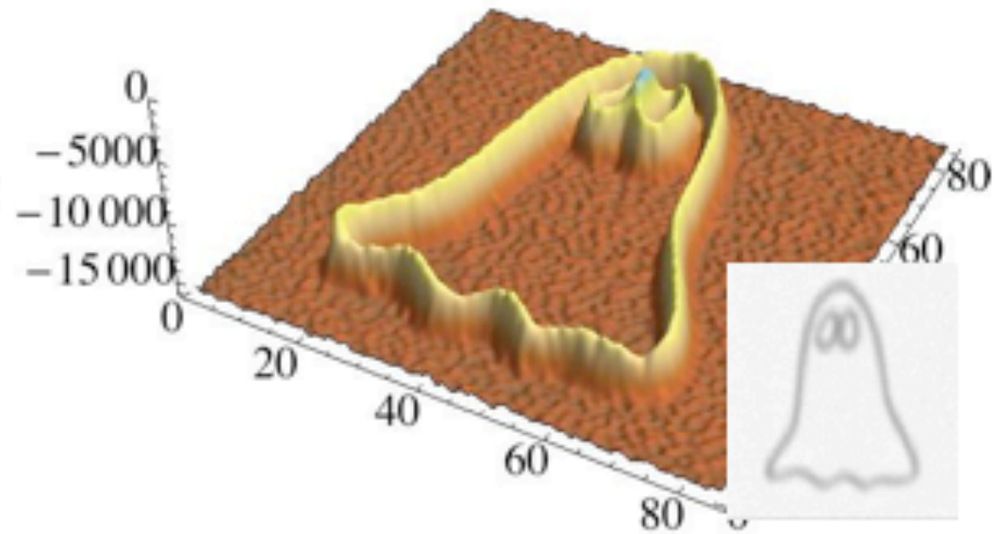
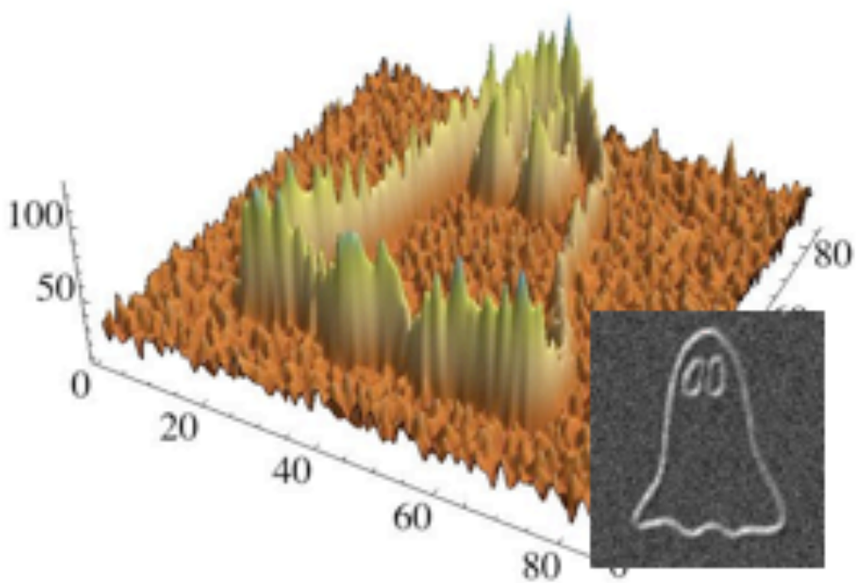
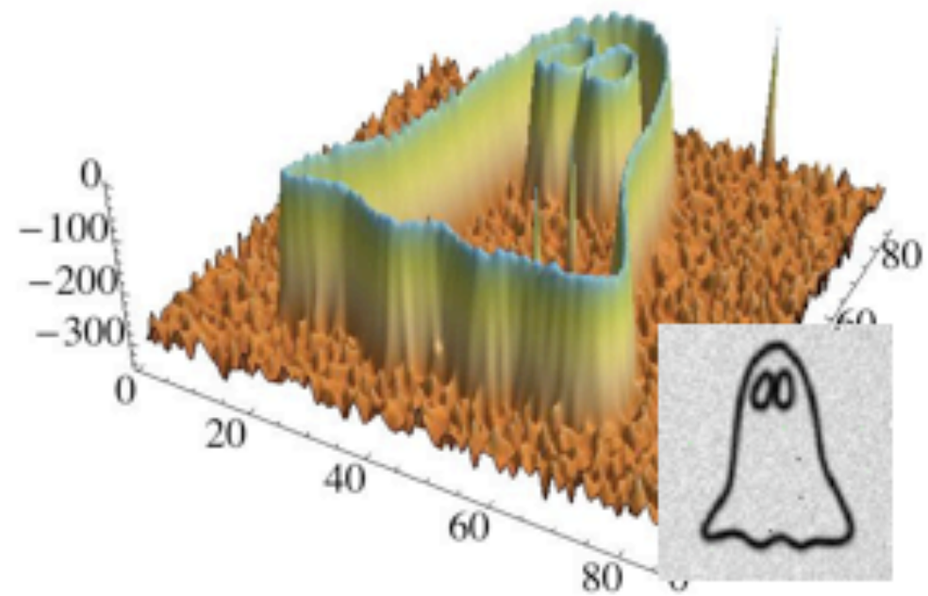


Image from arm containing phase object (Scale reversed)

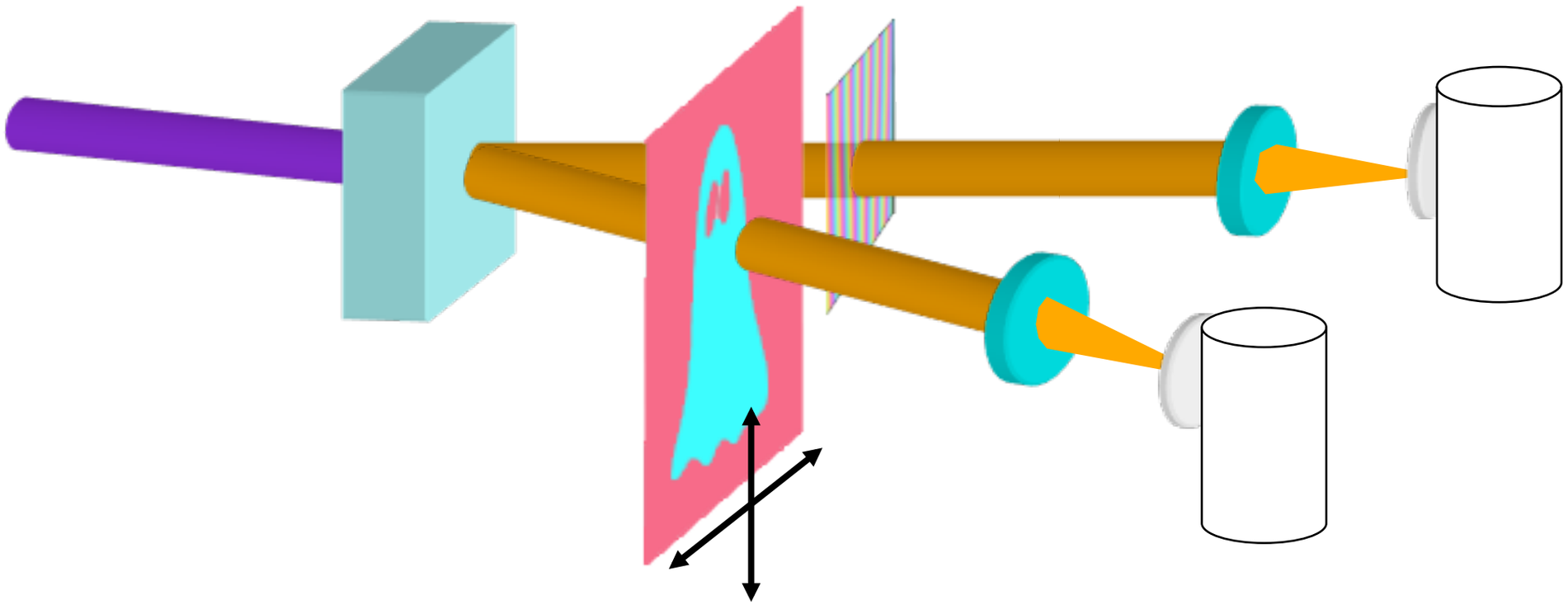


Coincident image with $\ell_{ref} = +1$

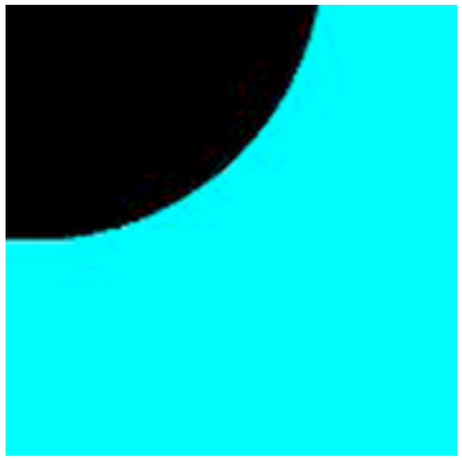


Coincident image with $\ell_{ref} = 0$ (Scale reversed)

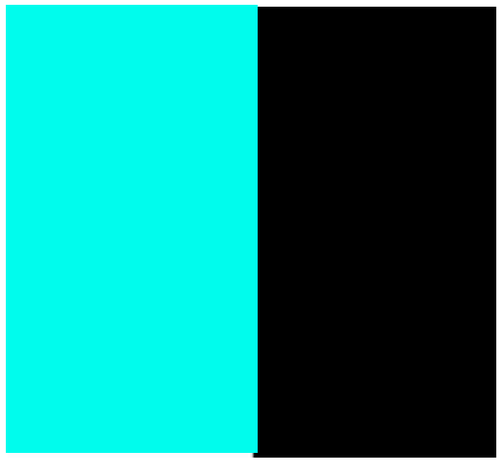
$$|\psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} c_\ell |-\ell\rangle|\ell\rangle$$



Object



Filter



Coincidence

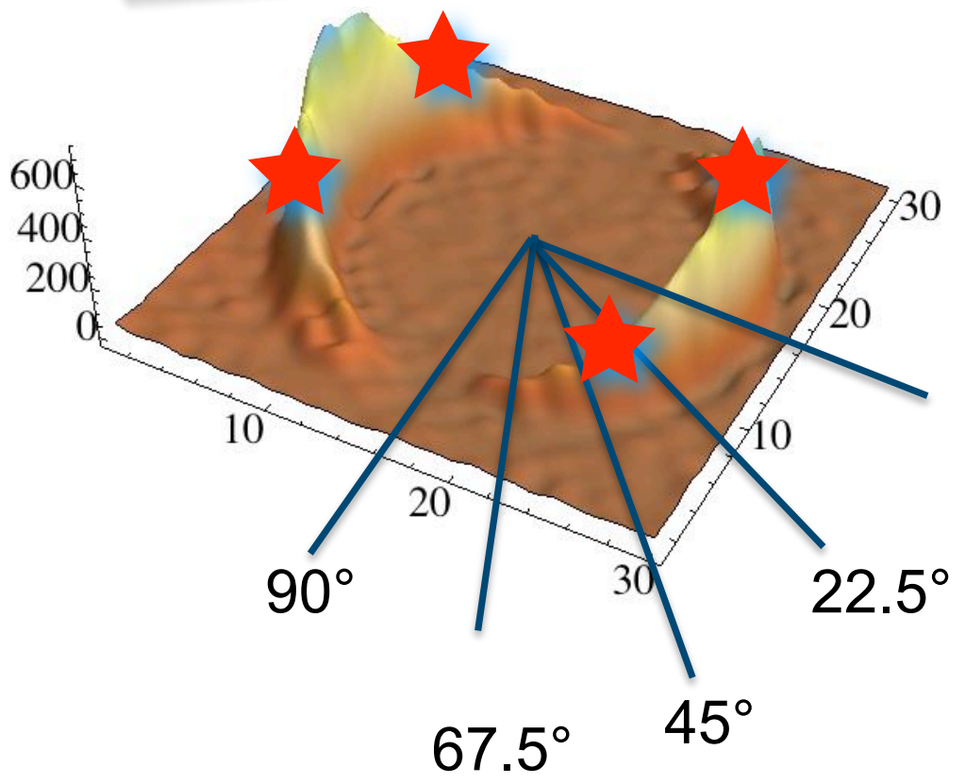
PRL 103, 083602 (2009) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2009

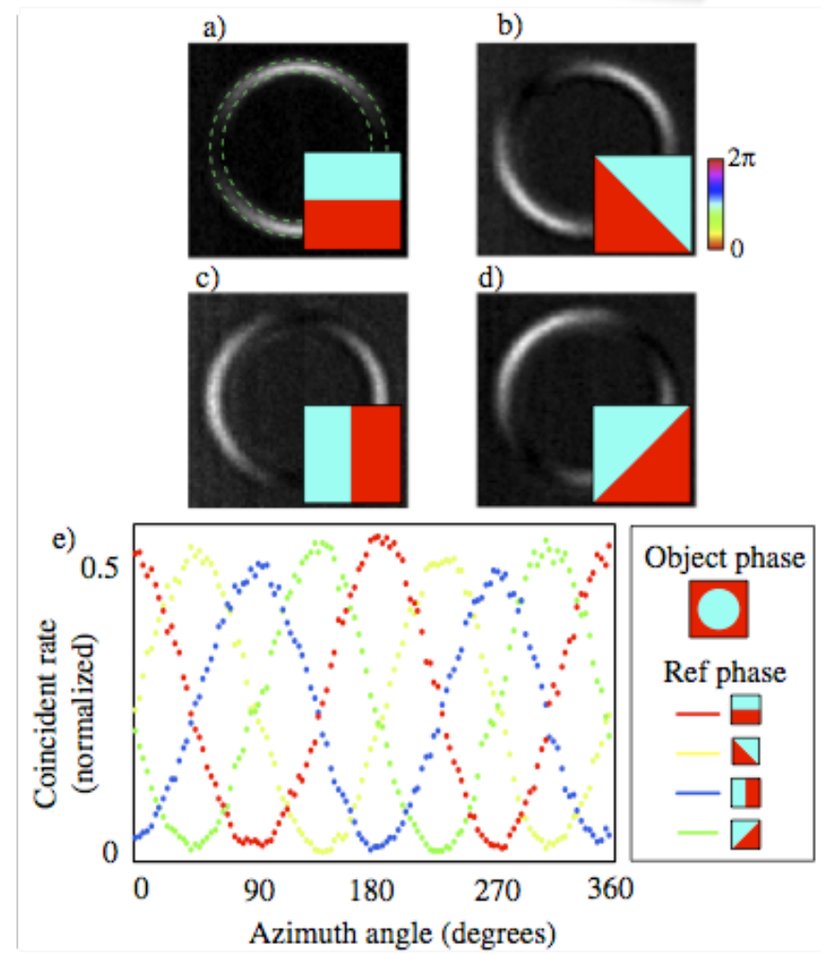
Holographic Ghost Imaging and the Violation of a Bell Inequality

B. Jack,[1] J. Leach,[1] J. Romero,[1] S. Franke-Arnold,[1] M. Ritsch-Marte,[2] S. M. Barnett,[3] and M. J. Padgett[1]

[1]*Department of Physics and Astronomy, SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[2]*Division for Biomedical Physics, Innsbruck Medical University, A-6020 Innsbruck, Austria*
[3]*Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, United Kingdom*

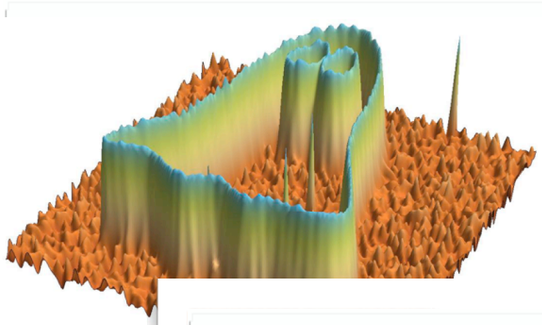
(Received 11 May 2009; published 20 August 2009)



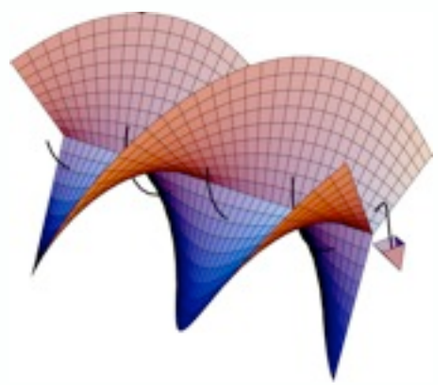


x16 Measurements

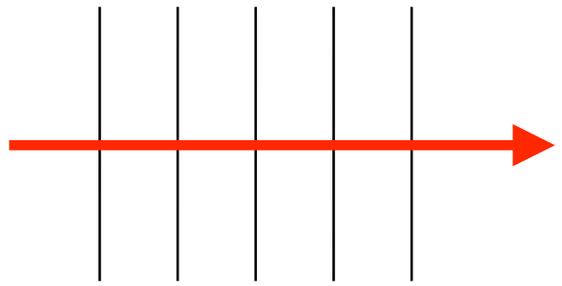
uOttawa



Holographic ghost imaging

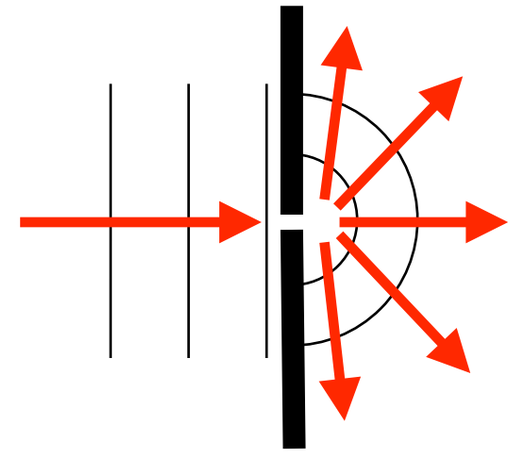


EPR correlations in the OAM/angle basis



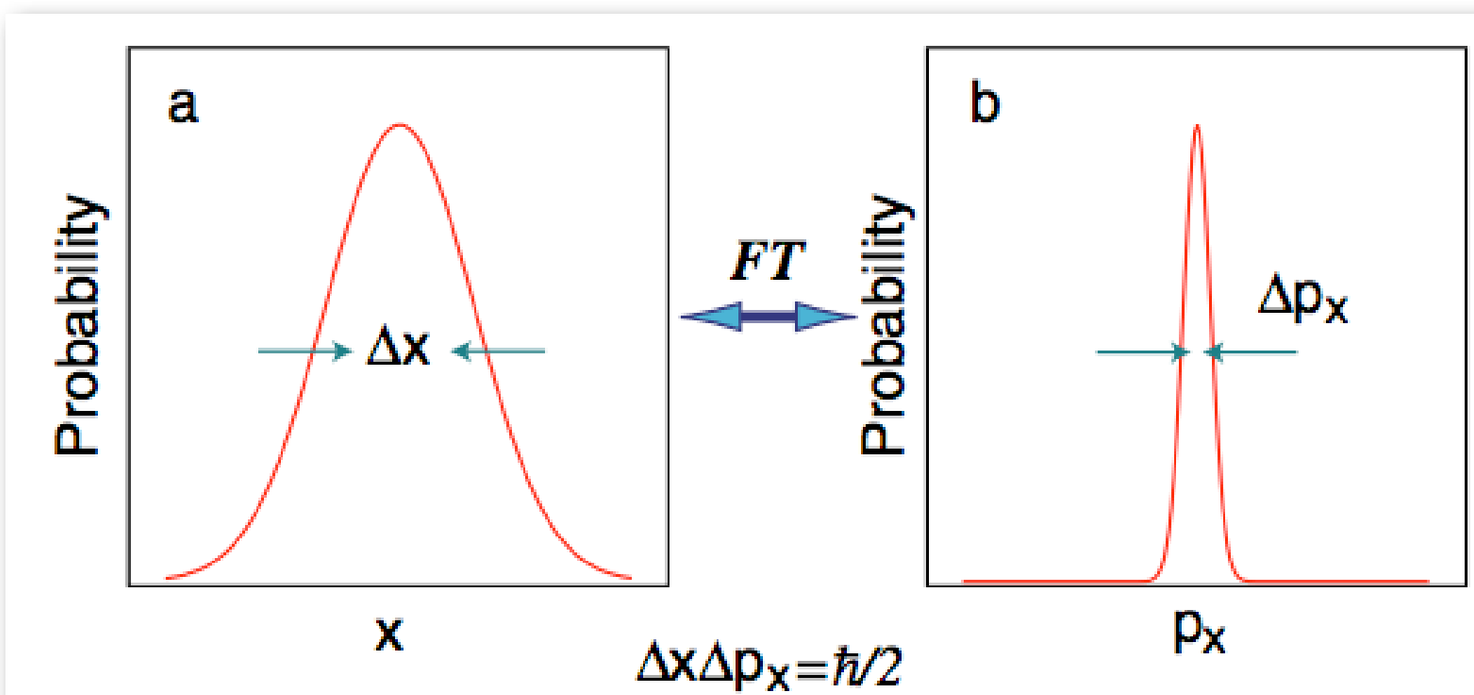
Momentum ✓

Position ✗



Momentum ✗

Position ✓



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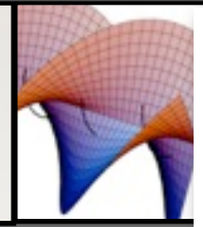
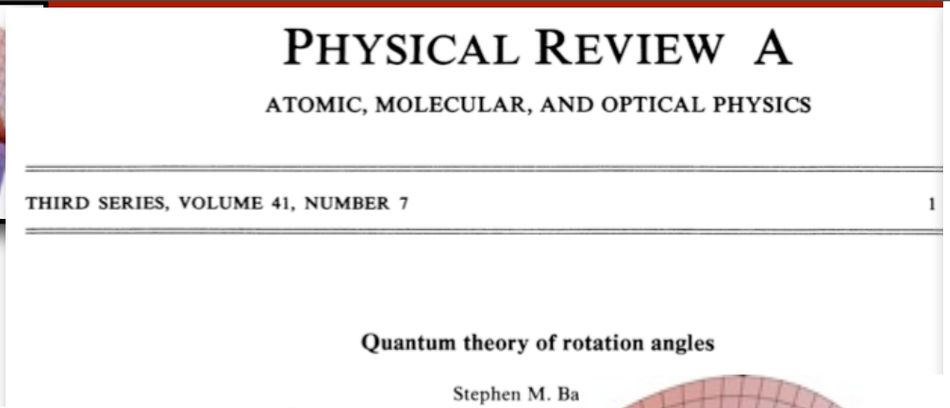
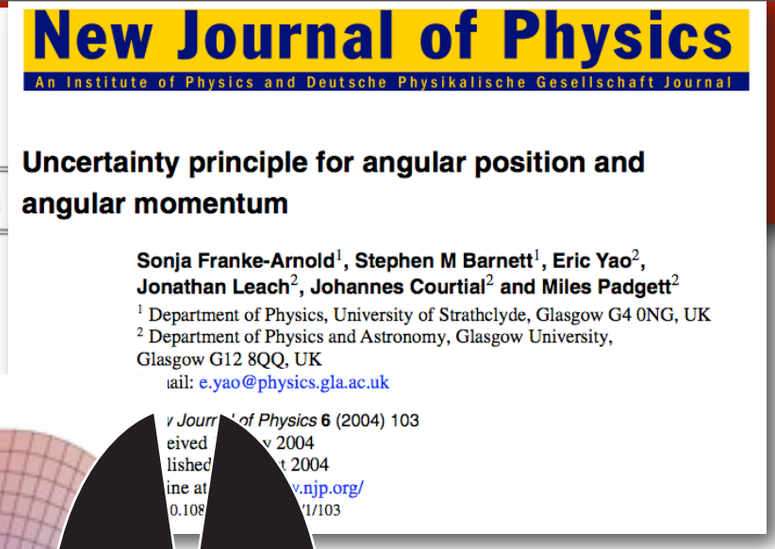



PHYSICAL REVIEW A
ATOMIC, MOLECULAR, AND OPTICAL PHYSICS
THIRD SERIES, VOLUME 41, NUMBER 7
Quantum theory of rotation angles
Stephen M. Ba
partment of Engineering Science, University of Oxf
D. T. Peg
School of Science, Griffith University, Nathan, E
(Received 25 Septem


New Journal of Physics
An Institute of Physics and Deutsche Physikalische Gesellschaft Journal
Uncertainty principle for angular position and angular momentum
Sonja Franke-Arnold[1], Stephen M Barnett[1], Eric Yao[2], Jonathan Leach[2], Johannes Courtial[2] and Miles Padgett[2]
[1] Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[2] Department of Physics and Astronomy, Glasgow University, Glasgow G12 8QQ, UK
ail: e.yao@physics.gla.ac.uk
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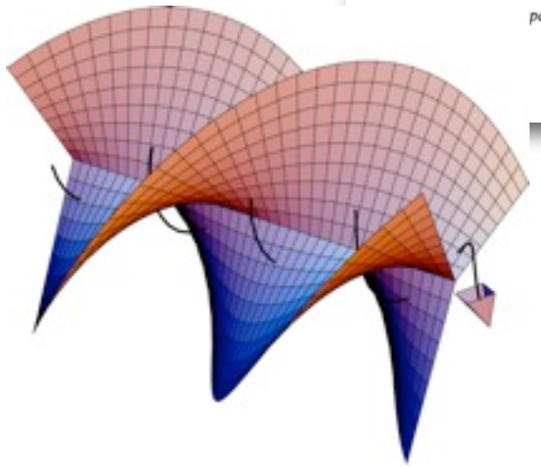
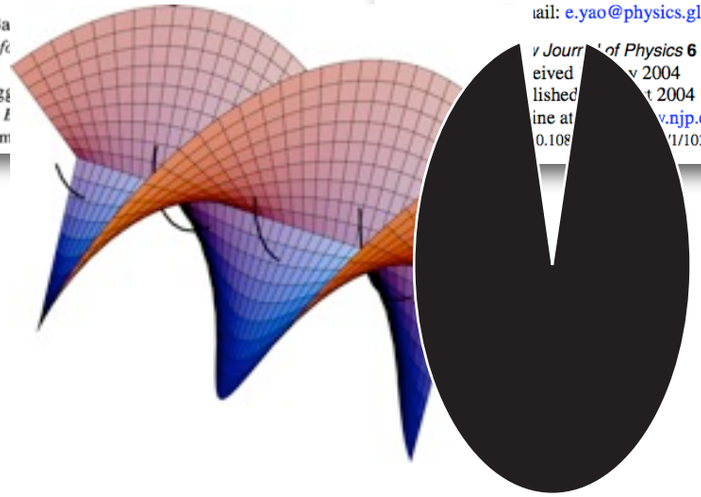
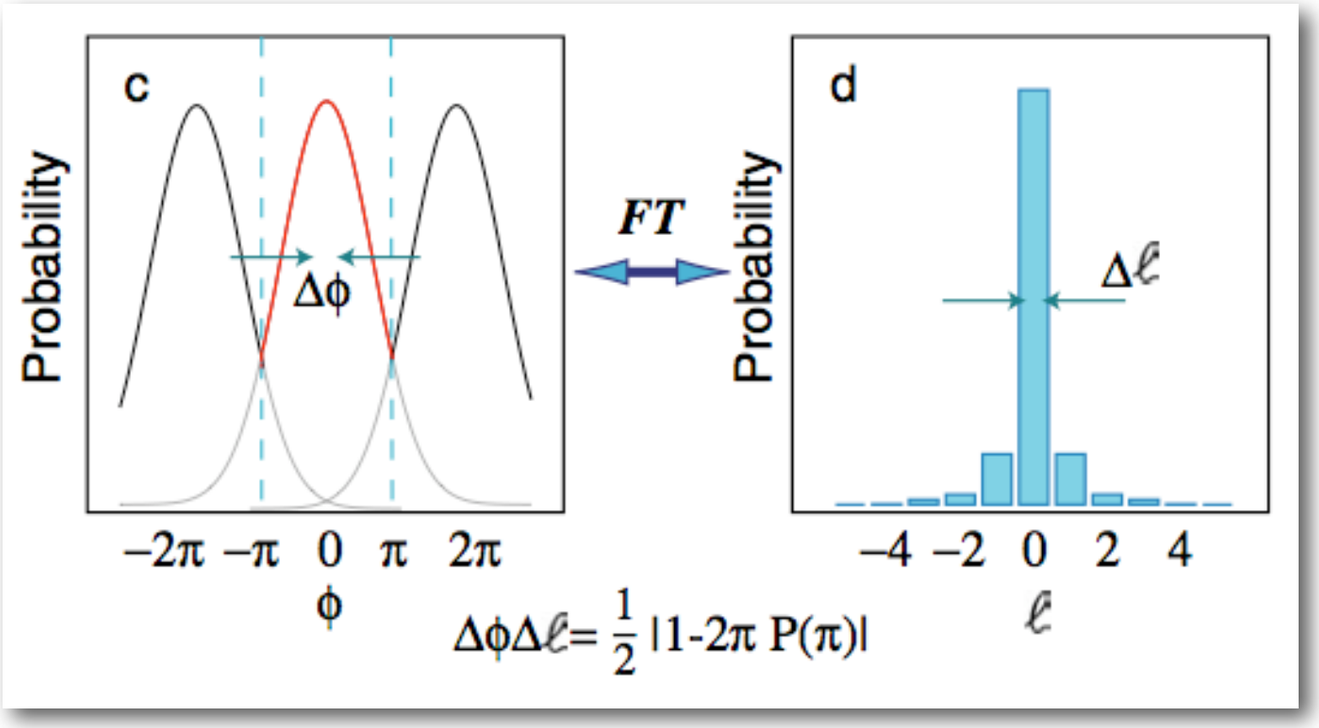




Angular momentum ✓ Angular momentum ✗

Angular position ✗ Angular position ✓



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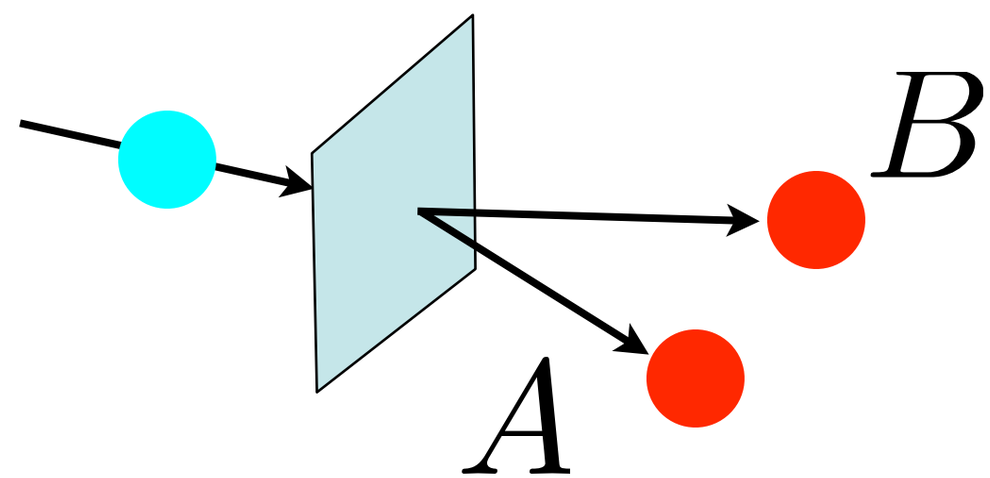
MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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)

If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.



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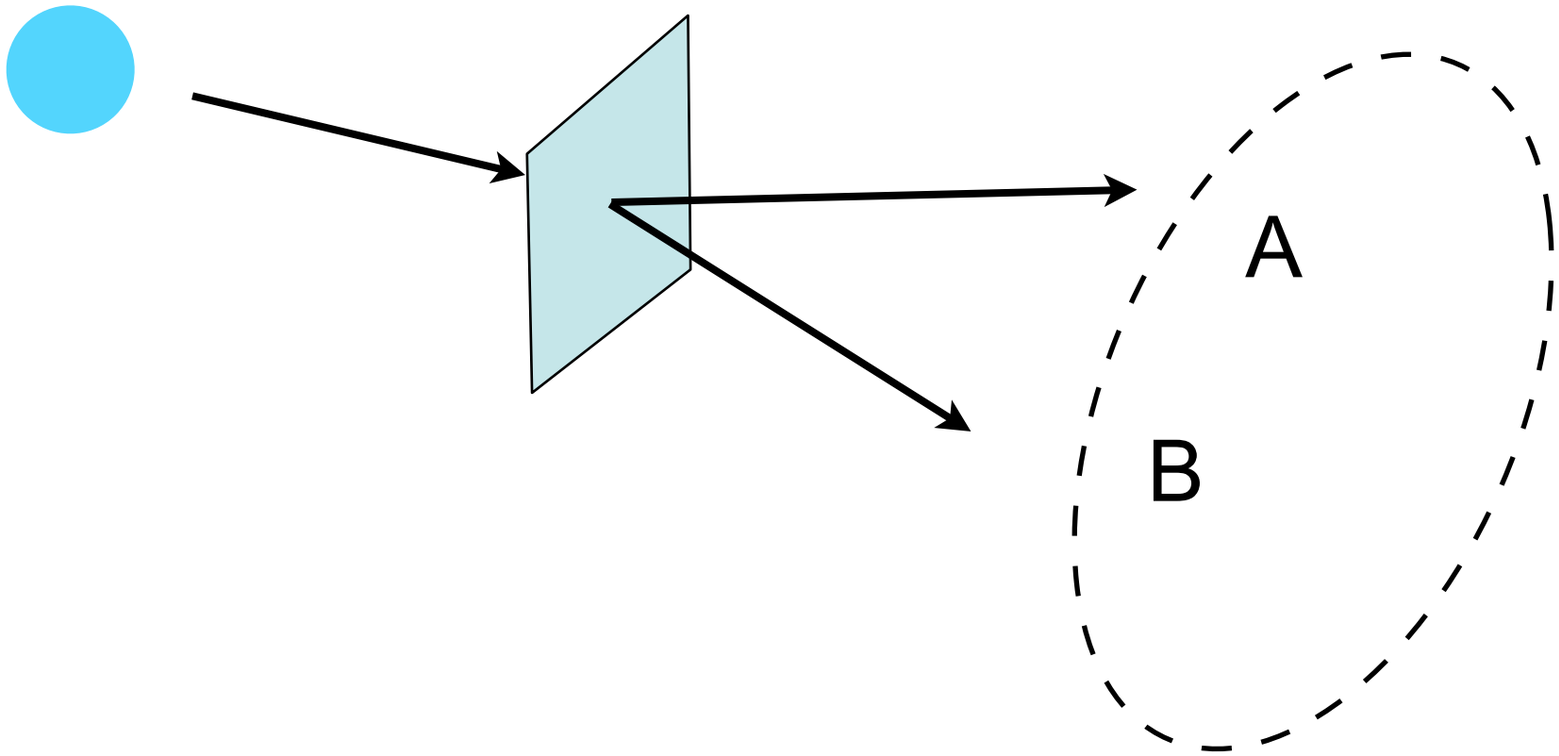
If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.



Spatially separated entangled photons

Can we measure the momentum of photon A and infer the momentum of photon B?

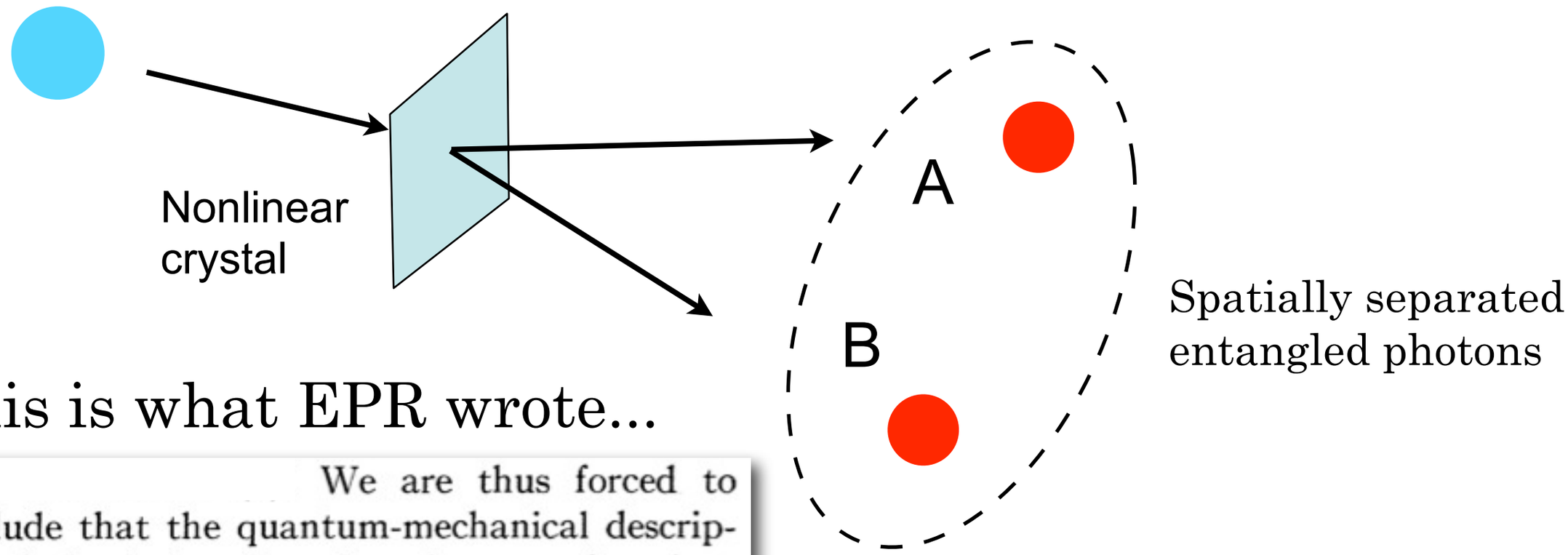
If yes, photon B has reality of momentum

Can we measure the position of photon A and infer the position of photon B?

If yes, photon B has reality of position

Photon B has simultaneous reality of position and momentum!!!

Photon B has simultaneous reality of position and momentum!!!



This is what EPR wrote...

> We are thus forced to conclude that the quantum-mechanical description of physical reality given by wave functions is not complete.

What is the resolution to EPR's thoughts?

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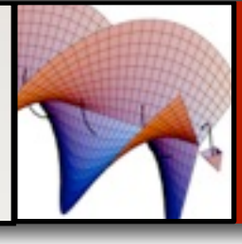
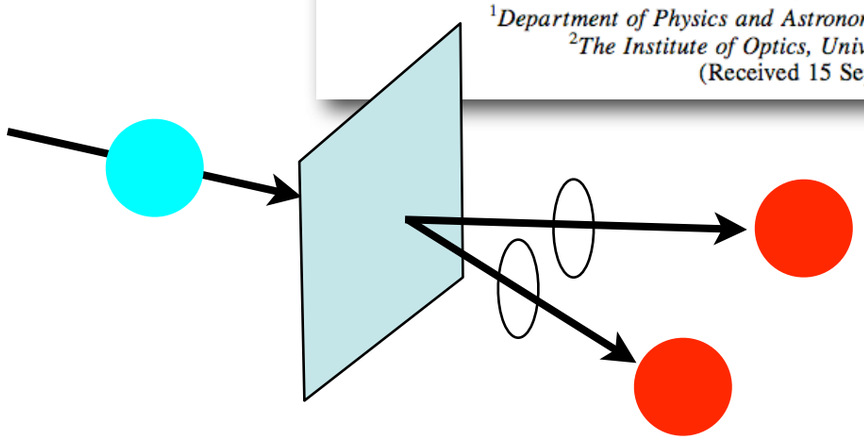


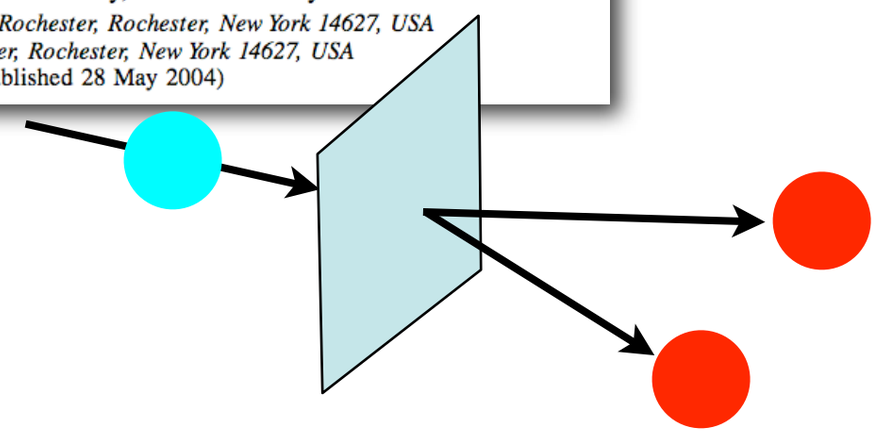
VOLUME 92, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 28 MAY 2004

Realization of the Einstein-Podolsky-Rosen Paradox Using Momentum- and Position-Entangled Photons from Spontaneous Parametric Down Conversion

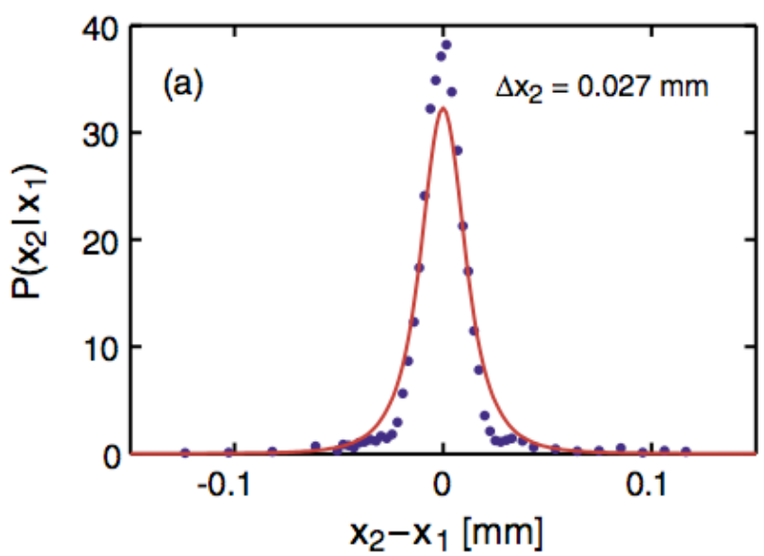
John C. Howell,[1] Ryan S. Bennink,[2] Sean J. Bentley,[2,*] and R.W. Boyd[2]
[1]*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA*
[2]*The Institute of Optics, University of Rochester, Rochester, New York 14627, USA*
(Received 15 September 2003; published 28 May 2004)

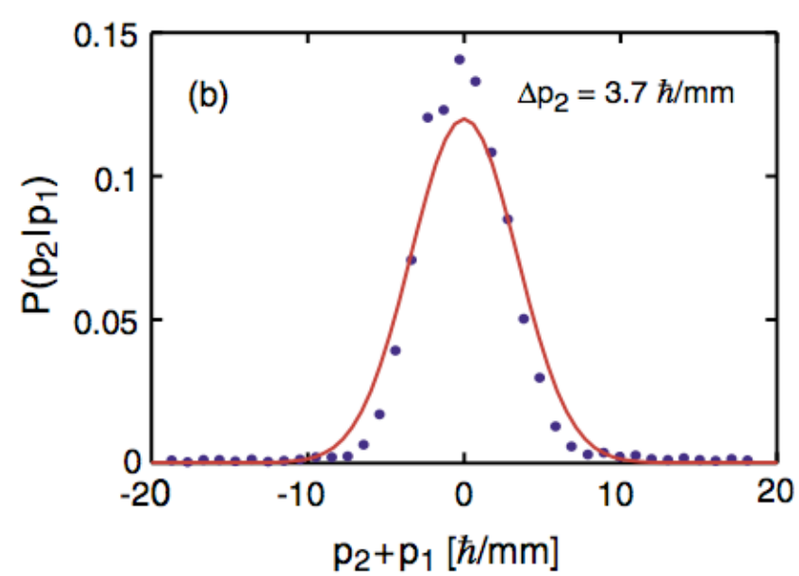


Position correlations



Momentum correlations





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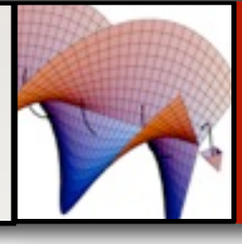

Journal of Modern Optics
Vol. 53, Nos. 5–6, 20 March–15 April 2006, 627–645

Taylor & Francis
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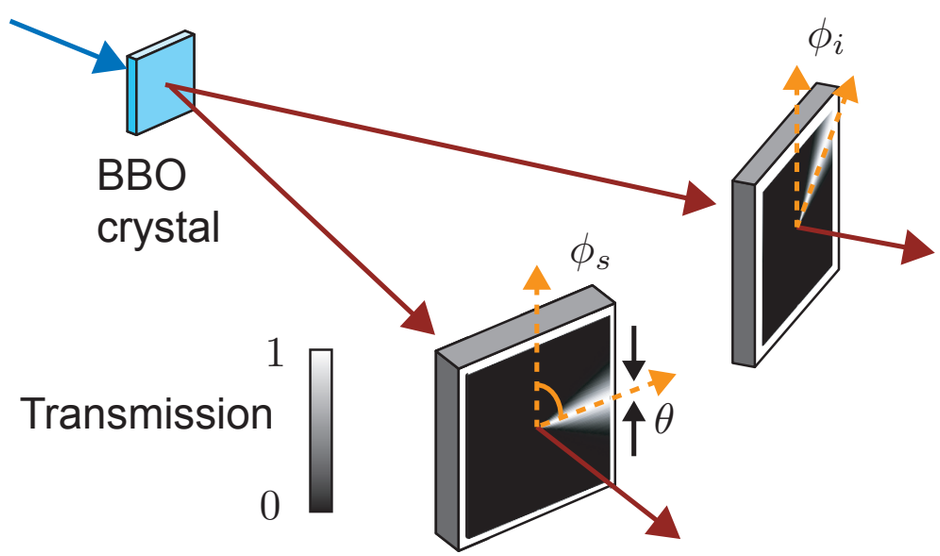
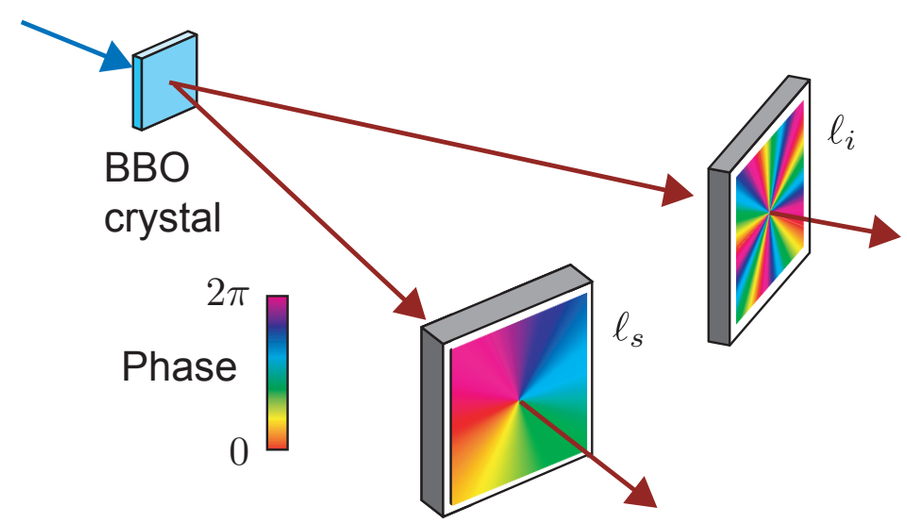
Angular EPR paradox

J. B. GÖTTE*, S. FRANKE-ARNOLD and STEPHEN M. BARNETT
Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK

Angular position correlations



Angular momentum correlations



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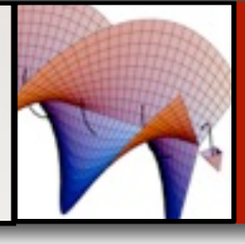
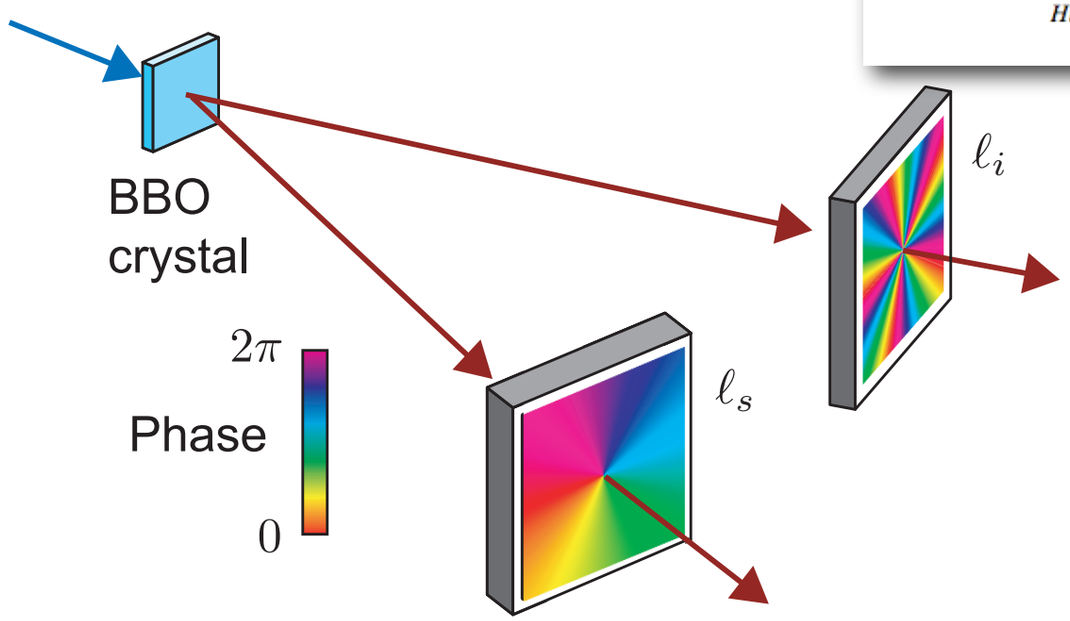


PRL **95**, 240501 (2005) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2005

Experimental Demonstration of Fractional Orbital Angular Momentum Entanglement of Two Photons

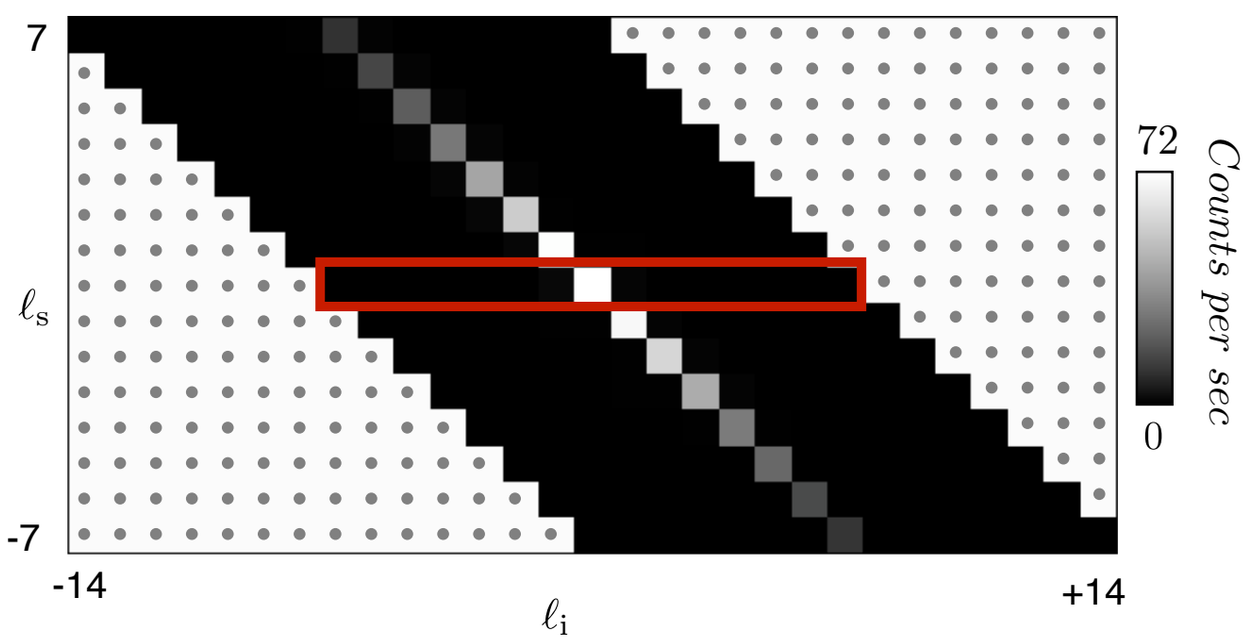
S. S. R. Oemrawsingh,* X. Ma, D. Voigt, A. Aiello, E. R. Eliel, G. W. 't Hooft,† and J. P. Woerdman
Huygens Laboratory, Leiden University, Post Office Box 9504, 2300 RA Leiden, The Netherlands
(Received 29 April 2005; published 8 December 2005)

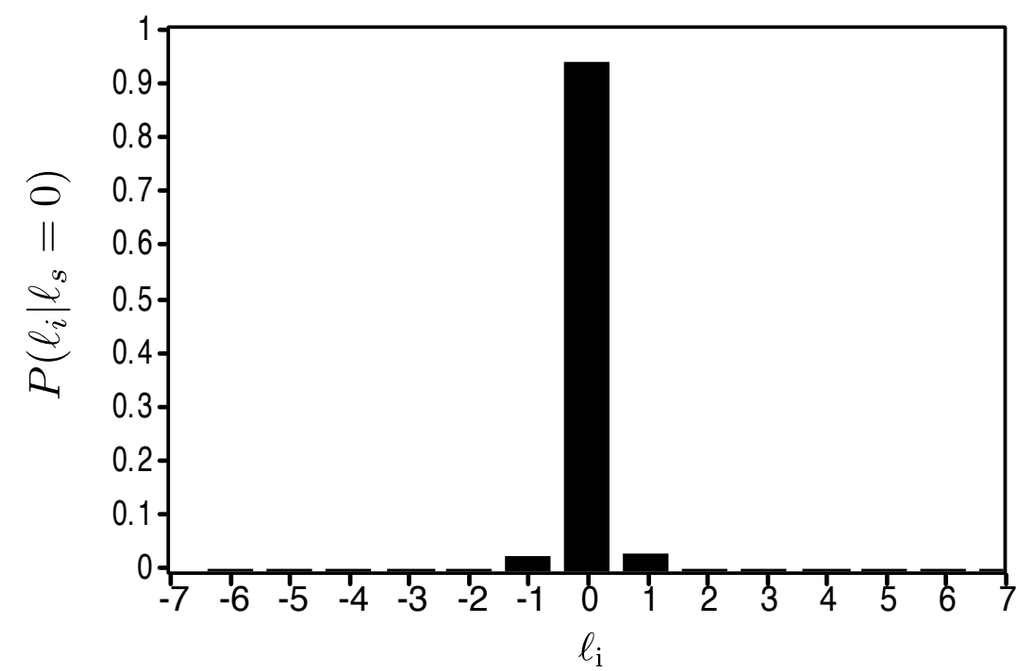


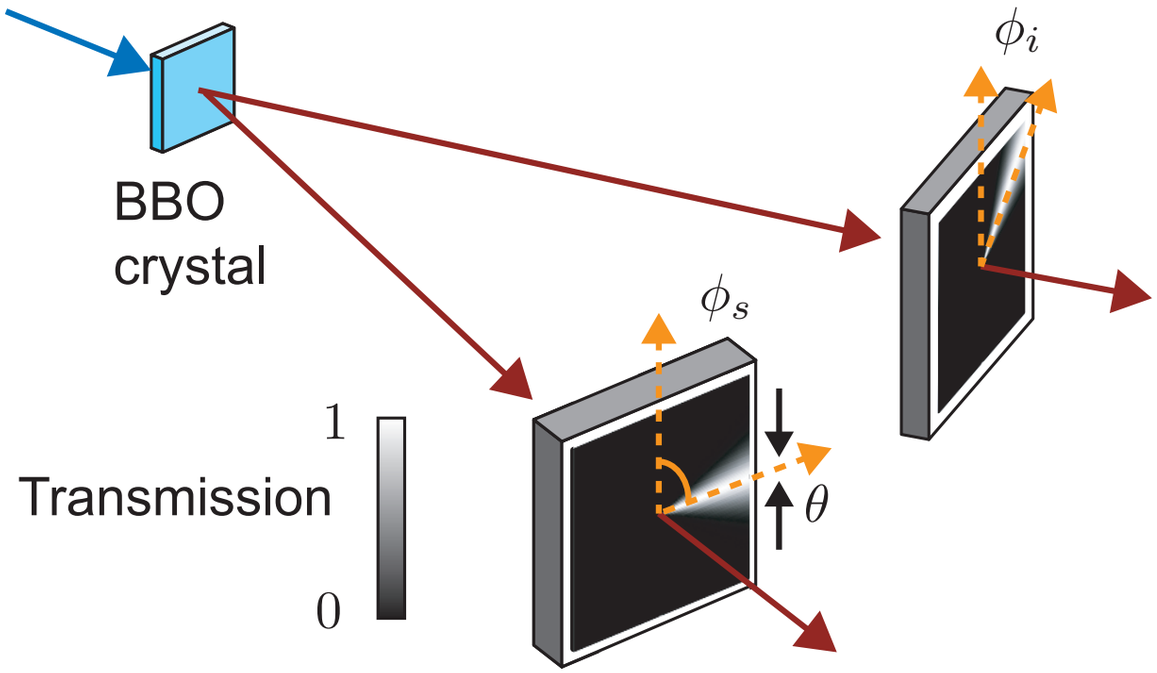
Entanglement of the orbital angular momentum states of photons

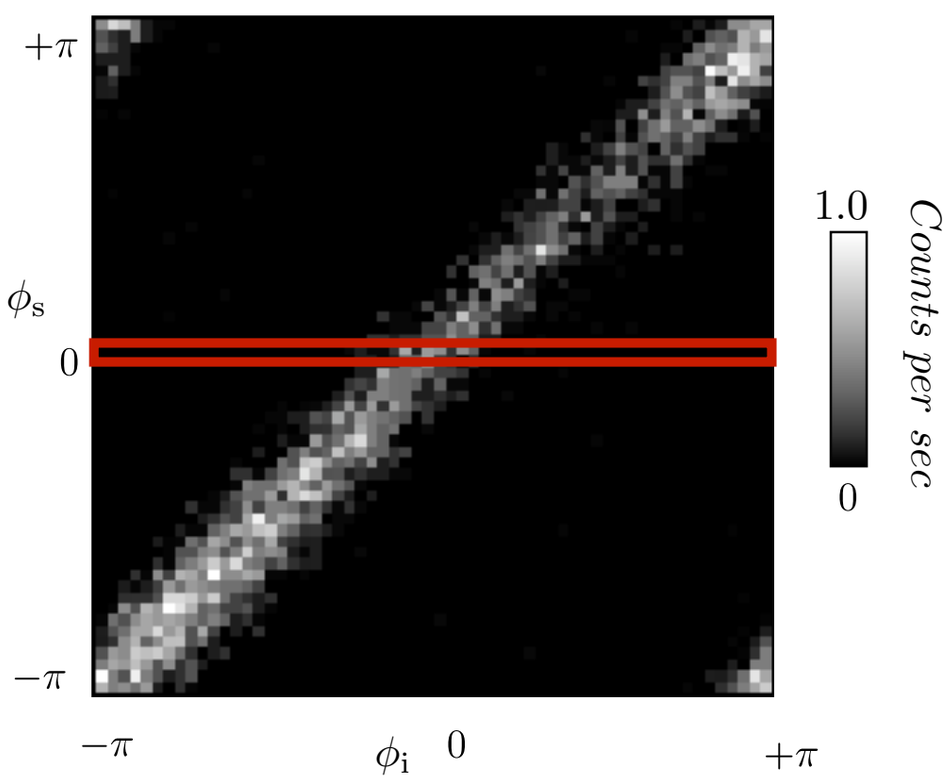
Alois Mair*, Alipasha Vaziri, Gregor Weihs & Anton Zeilinger

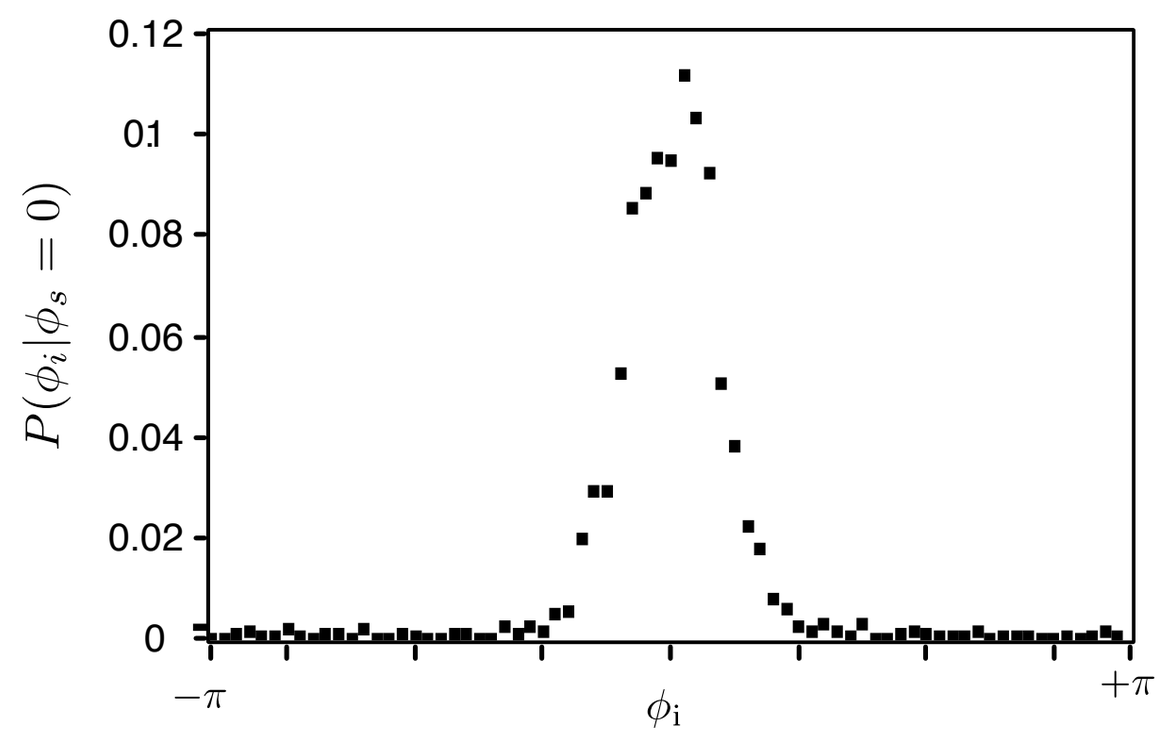
Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, 1090 Wien, Austria

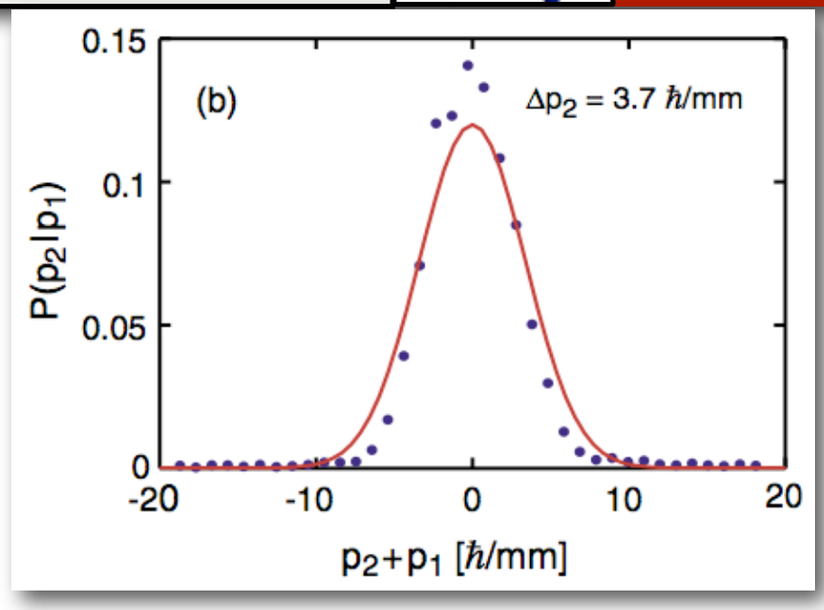


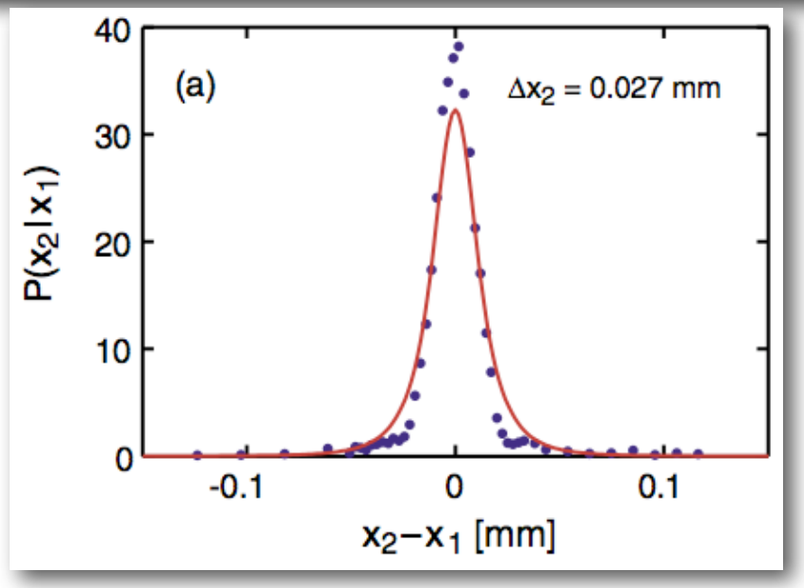


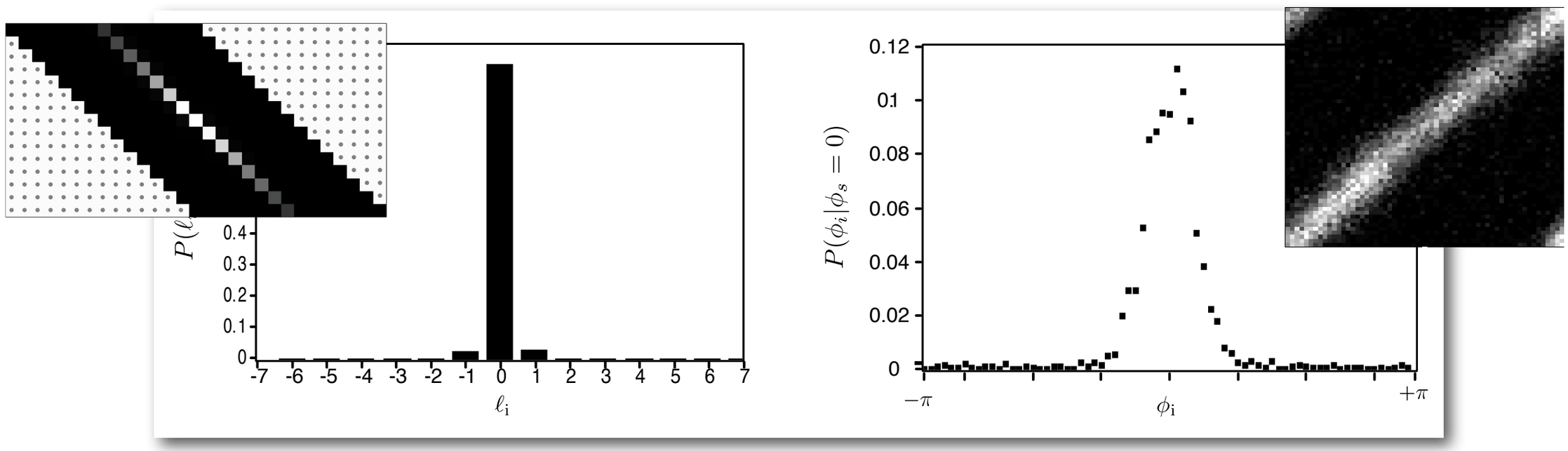

BBO
crystal
ϕ_i
ϕ_s
θ
Transmission
1
0


$+\pi$
ϕ_s
0
$-\pi$
$-\pi$
ϕ_i
0
$+\pi$
1.0
0
Counts per sec

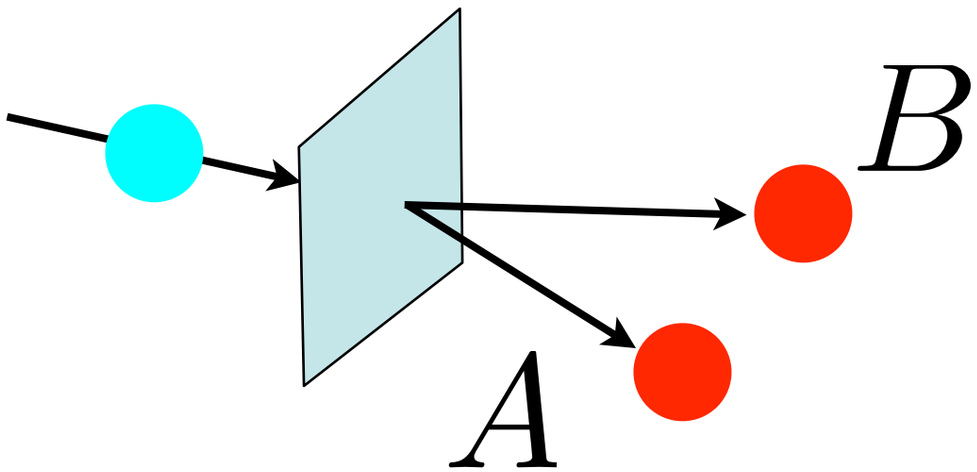

0.12
0.1
0.08
0.06
0.04
0.02
0
$P(\phi_i|\phi_s = 0)$
$-\pi$
ϕ_i
$+\pi$







$$[\Delta\phi_i|\phi_s]^2[\Delta\ell_i|\ell_s]^2 \geq \frac{1}{4} \qquad [\Delta\phi_i|\phi_s]^2[\Delta\ell_i|\ell_s]^2 = 0.024$$



Entropy is a measure of the uncertainty associated with a random variable.

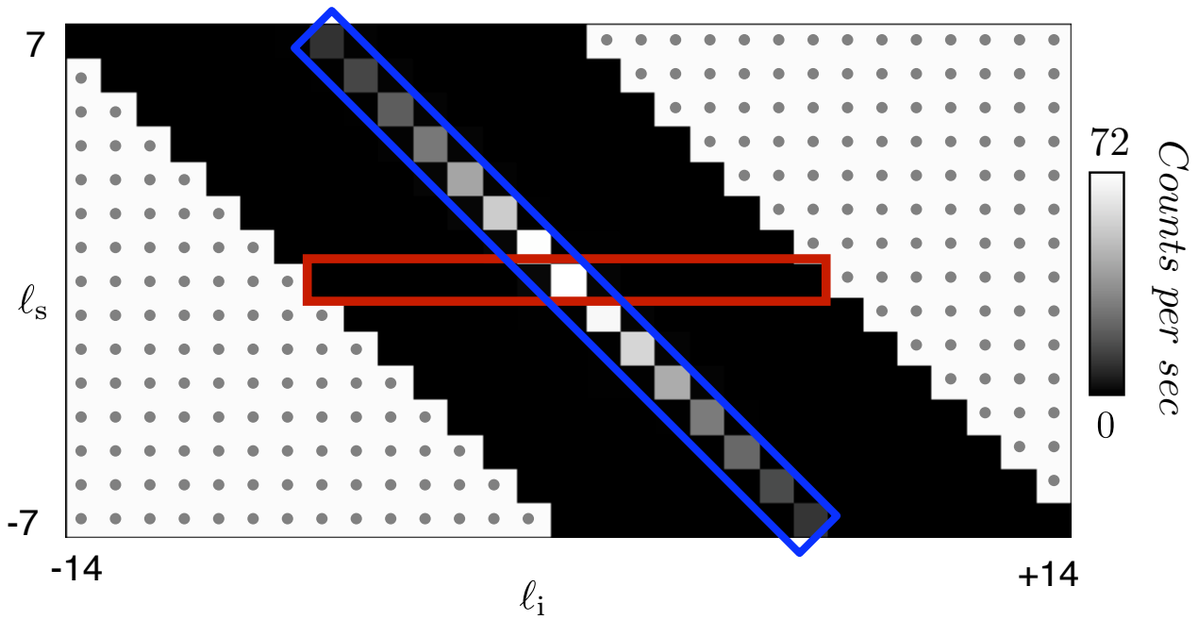
Entanglement requires a degree of certainty about the **inferred** outcome of a measurement on B, given a measurement on A, and vice versa

Entropy = 0

Entanglement requires uncertainty about the outcome of the measurements at A and B

Entropy is > 0

$$|\psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} c_\ell |-\ell\rangle|\ell\rangle$$



Entropy is low,
number of modes is low

Entropy is high,
number of modes is high

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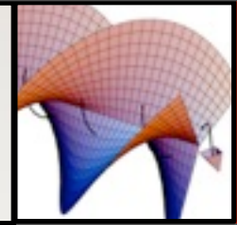
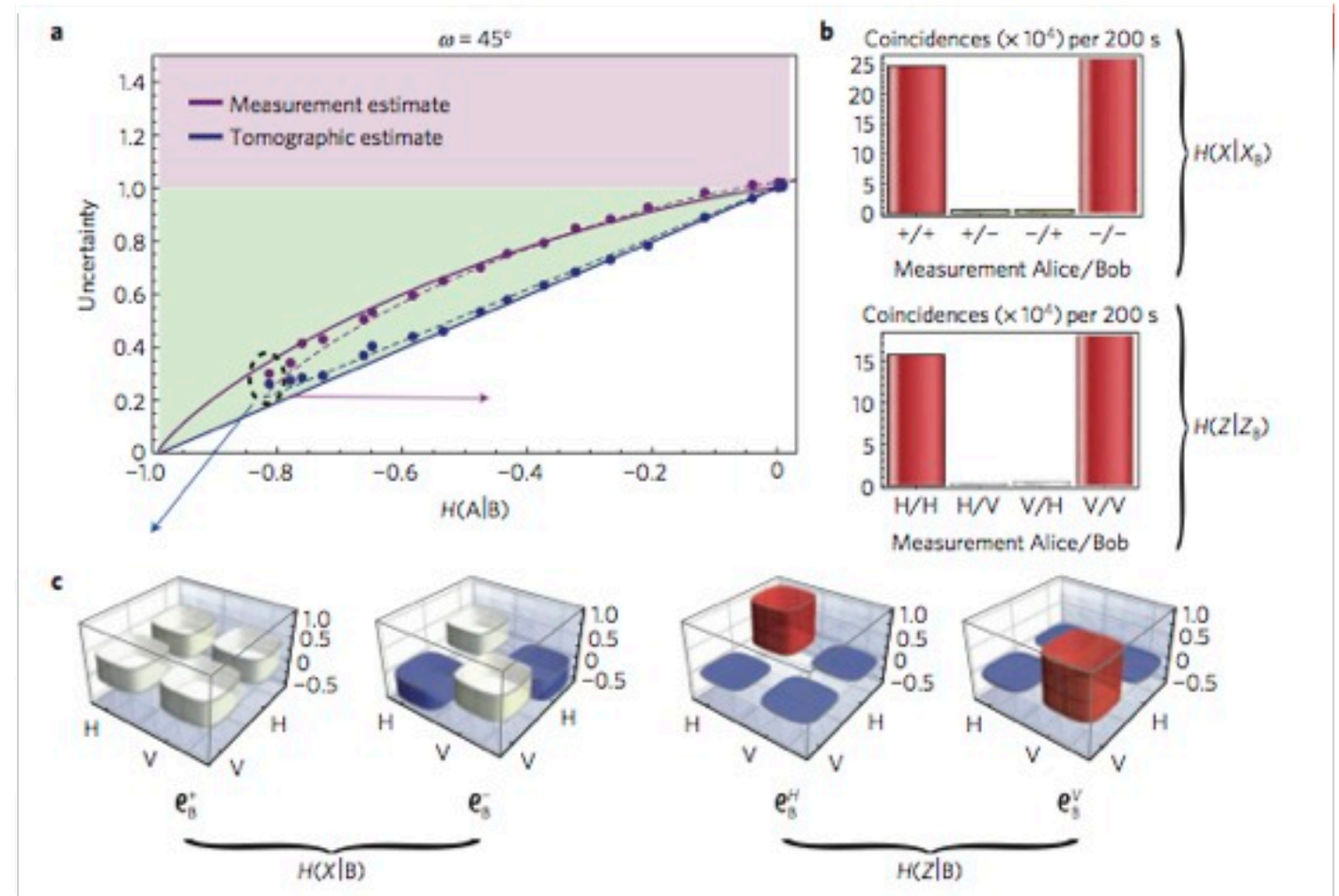


nature physics

The uncertainty principle in quantum memory

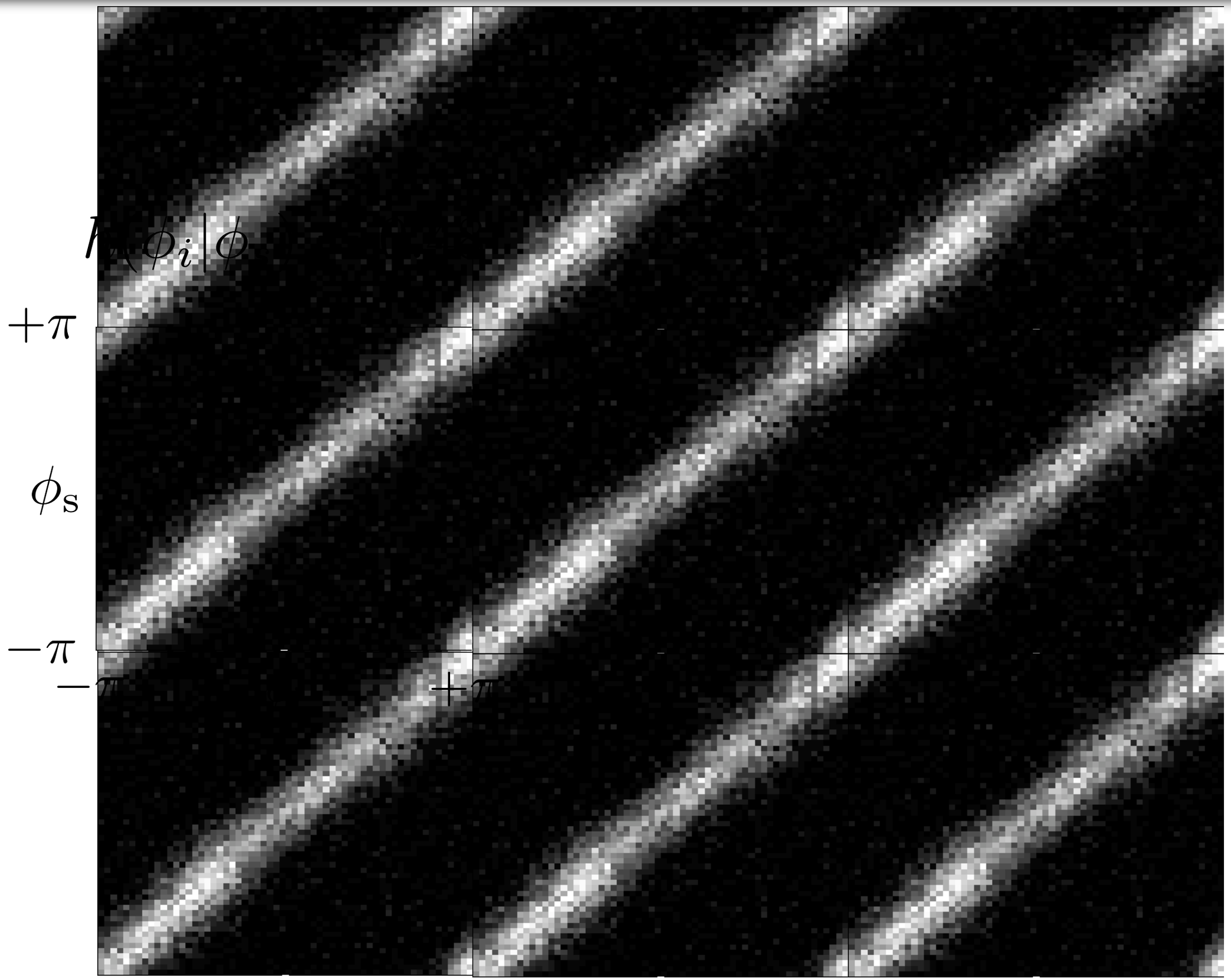
Mario Berta[1,2], Matthias Christandl[1,2], Roger Colbeck[1,3]

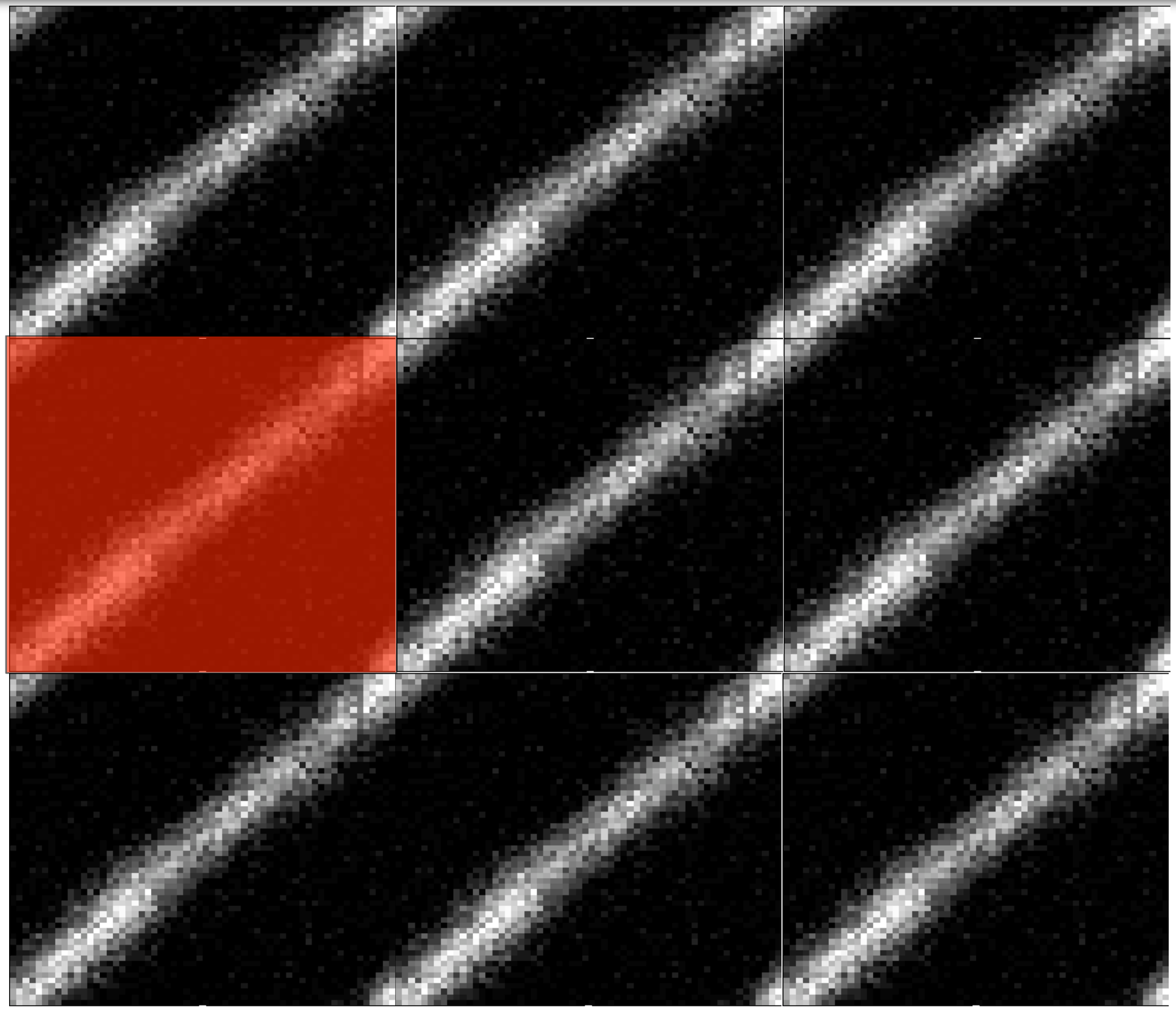


nature physics

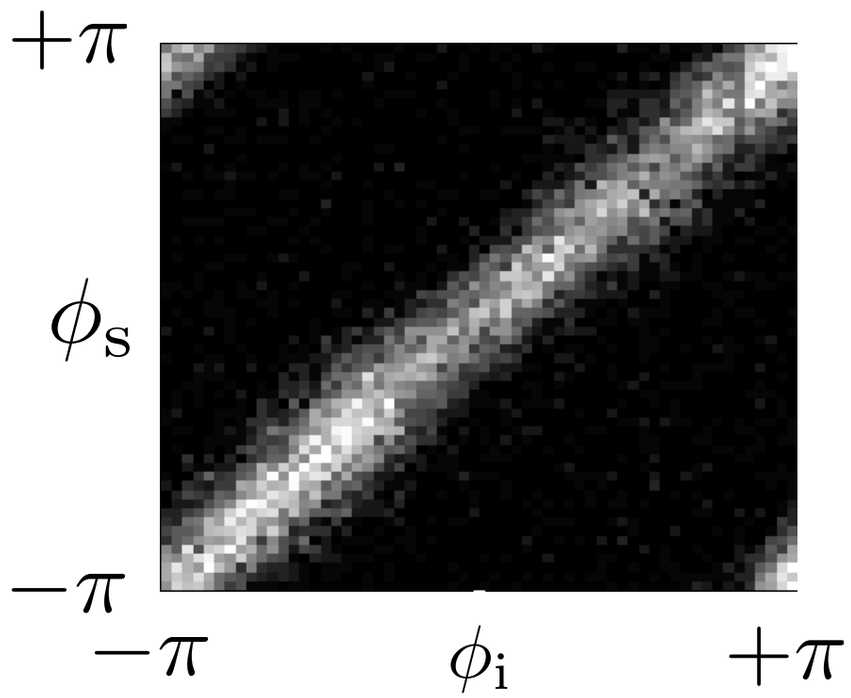
Experimental investigation of the uncertainty principle in the presence of quantum memory and its application to witnessing entanglement

Robert Prevedel[1]*, Deny R. Hamel[1], Roger Colbeck[2], Kent Fisher[1] and Kevin J. Resch[1]

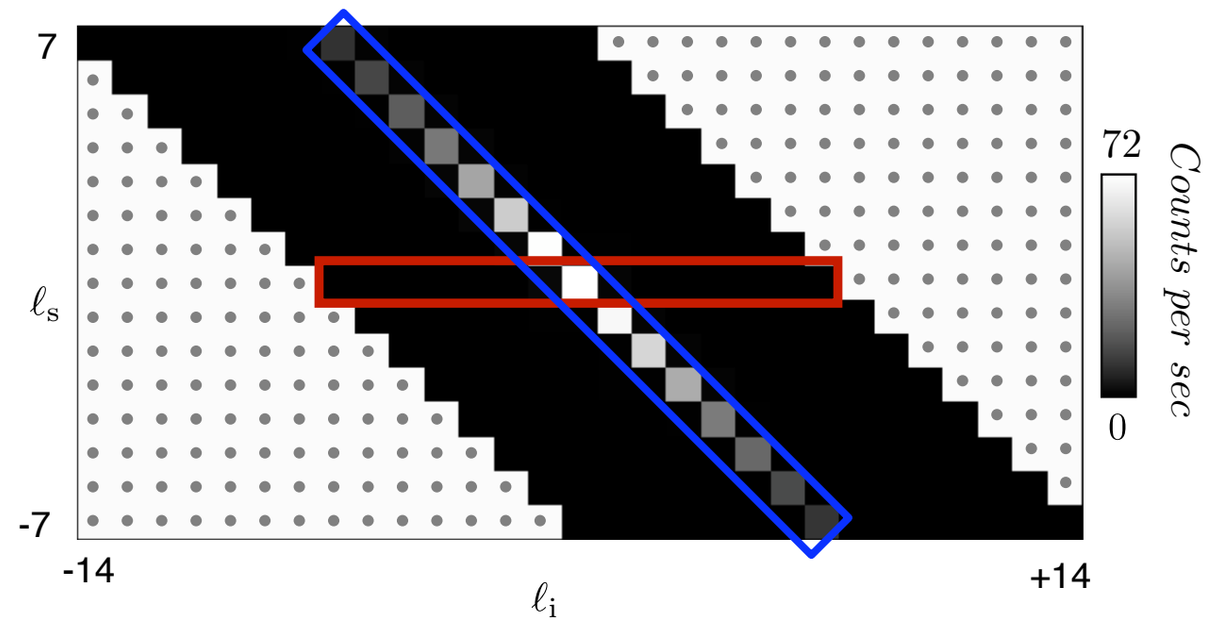

$\phi_i|\phi$
$+\pi$
ϕ_s
$-\pi$
$-\pi$
$+\pi$



$$h(\phi_i|\phi_s) = 0.48$$

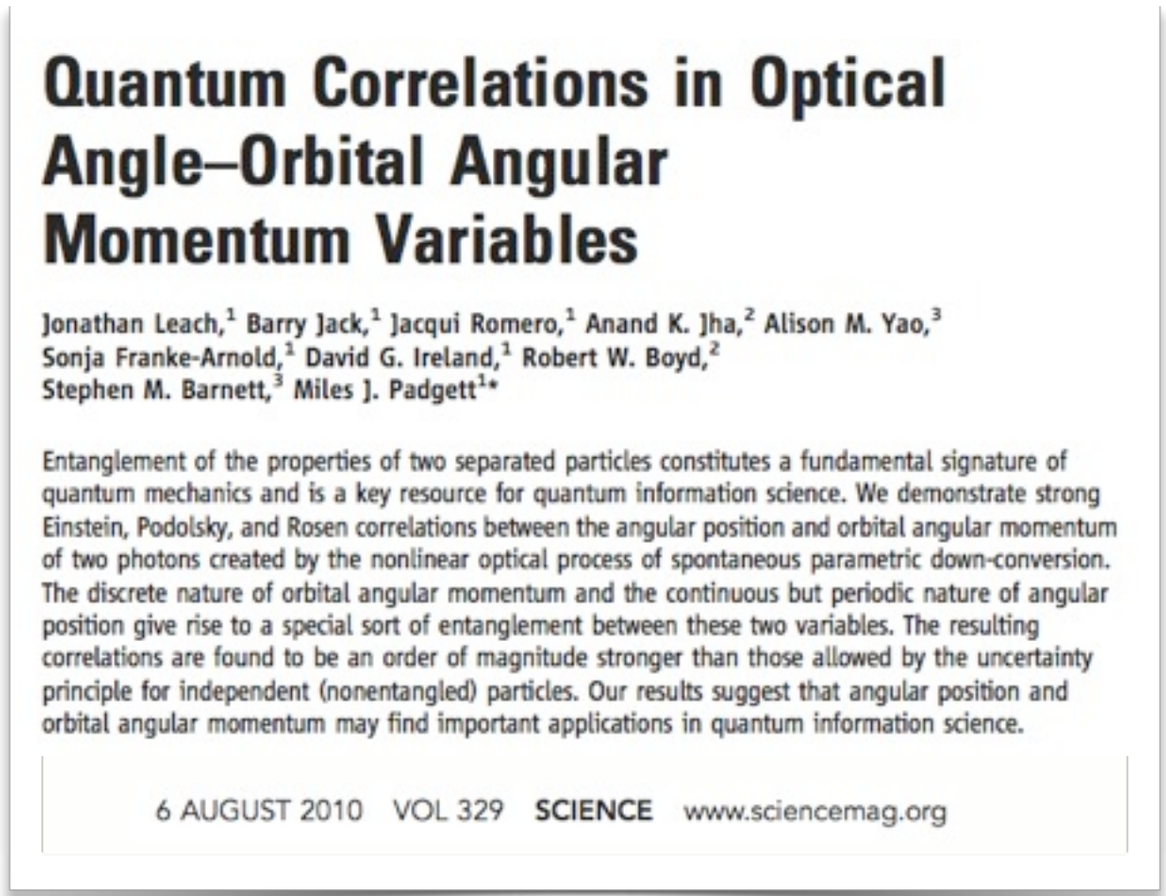


$$h(\ell_i|\ell_s) = 0.41$$



$$h(\ell_i|\ell_s) + h(\phi_i|\phi_s) \geq \log_2(2\pi) = 2.65$$

$$h(\ell_i|\ell_s) + h(\phi_i|\phi_s) = 0.89$$



Quantum Correlations in Optical Angle–Orbital Angular Momentum Variables

Jonathan Leach,[1] Barry Jack,[1] Jacqui Romero,[1] Anand K. Jha,[2] Alison M. Yao,[3] Sonja Franke-Arnold,[1] David G. Ireland,[1] Robert W. Boyd,[2] Stephen M. Barnett,[3] Miles J. Padgett[1*]

Entanglement of the properties of two separated particles constitutes a fundamental signature of quantum mechanics and is a key resource for quantum information science. We demonstrate strong Einstein, Podolsky, and Rosen correlations between the angular position and orbital angular momentum of two photons created by the nonlinear optical process of spontaneous parametric down-conversion. The discrete nature of orbital angular momentum and the continuous but periodic nature of angular position give rise to a special sort of entanglement between these two variables. The resulting correlations are found to be an order of magnitude stronger than those allowed by the uncertainty principle for independent (nonentangled) particles. Our results suggest that angular position and orbital angular momentum may find important applications in quantum information science.

6 AUGUST 2010 VOL 329 SCIENCE www.sciencemag.org

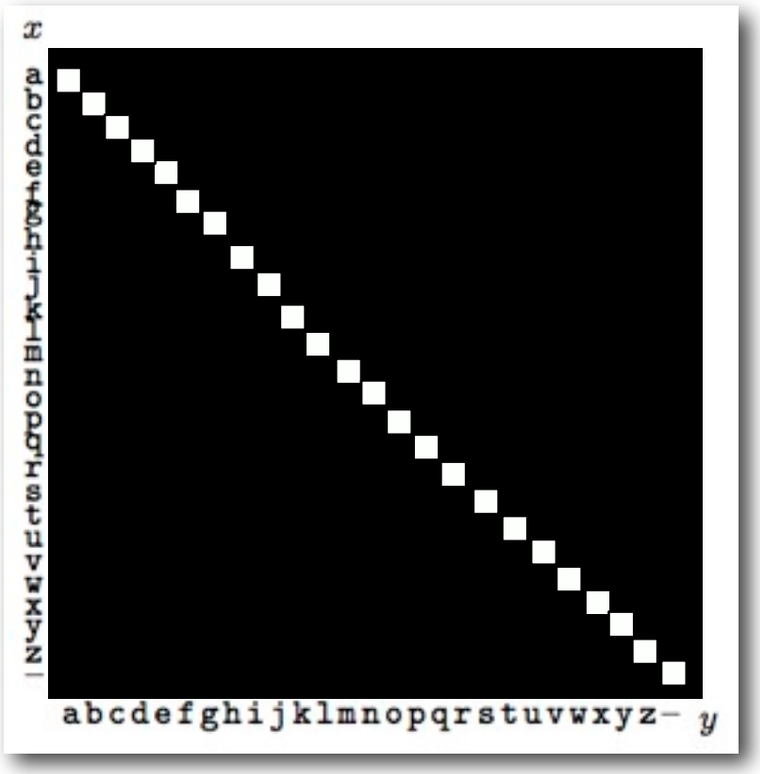
Work provides a clear picture for angles/angular momentum

Both entropy calculation and inferred variances show EPR correlations

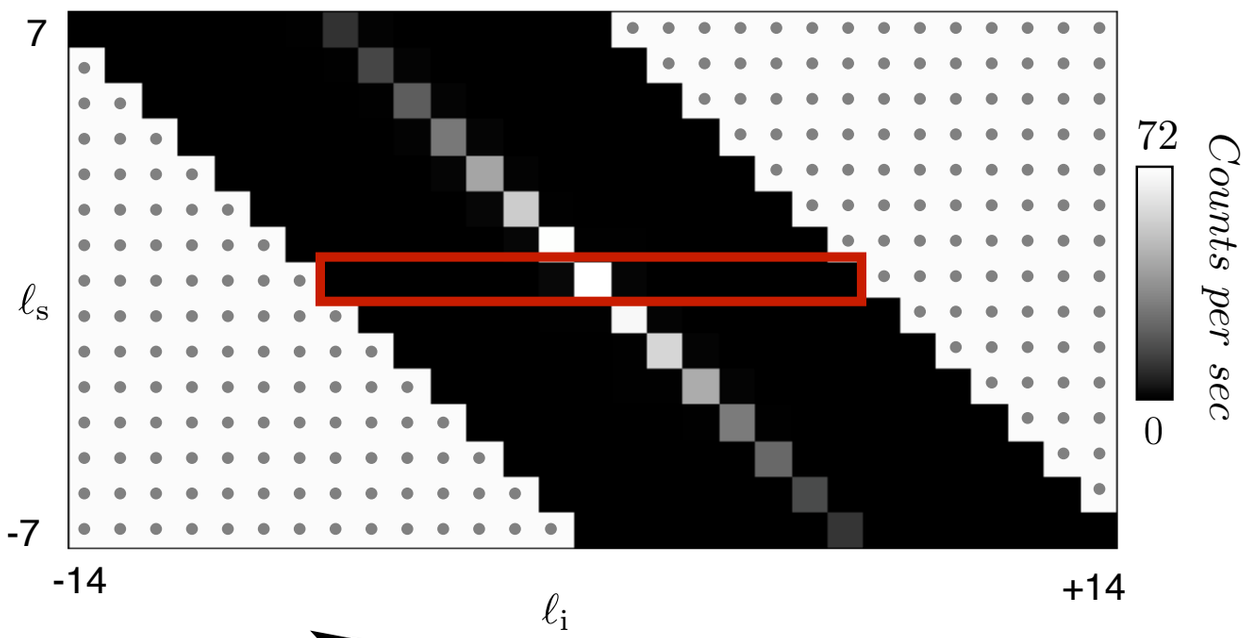
Entropy calculation is not effected by cyclic nature of angles

Can use for quantum cryptography, quantum imaging etc

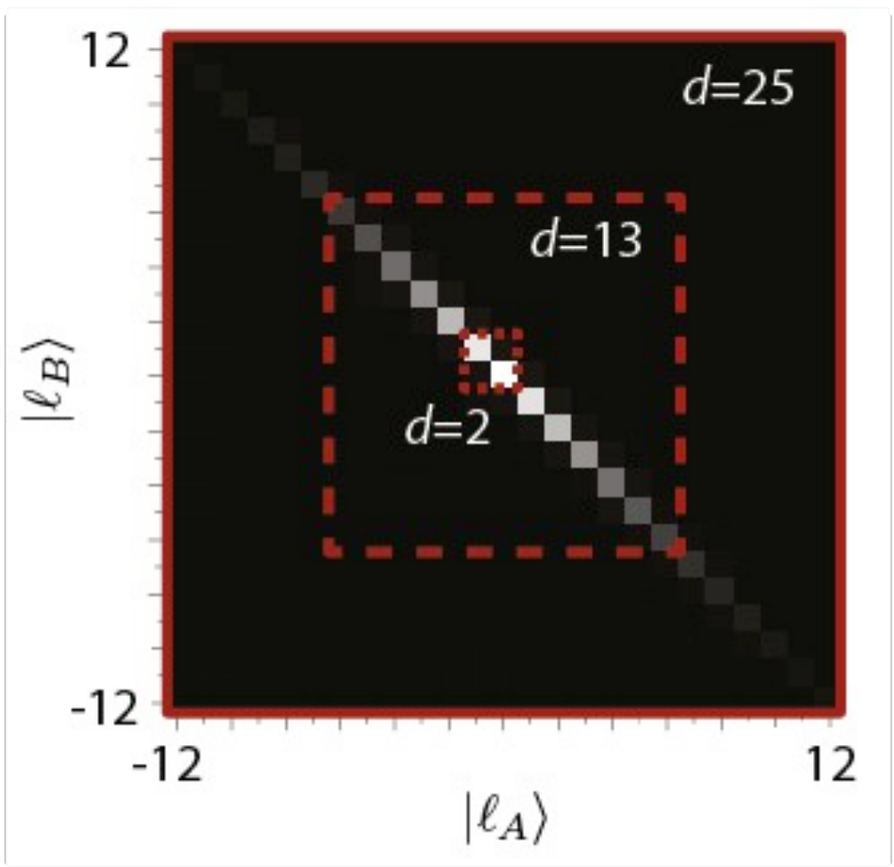
Classical communication

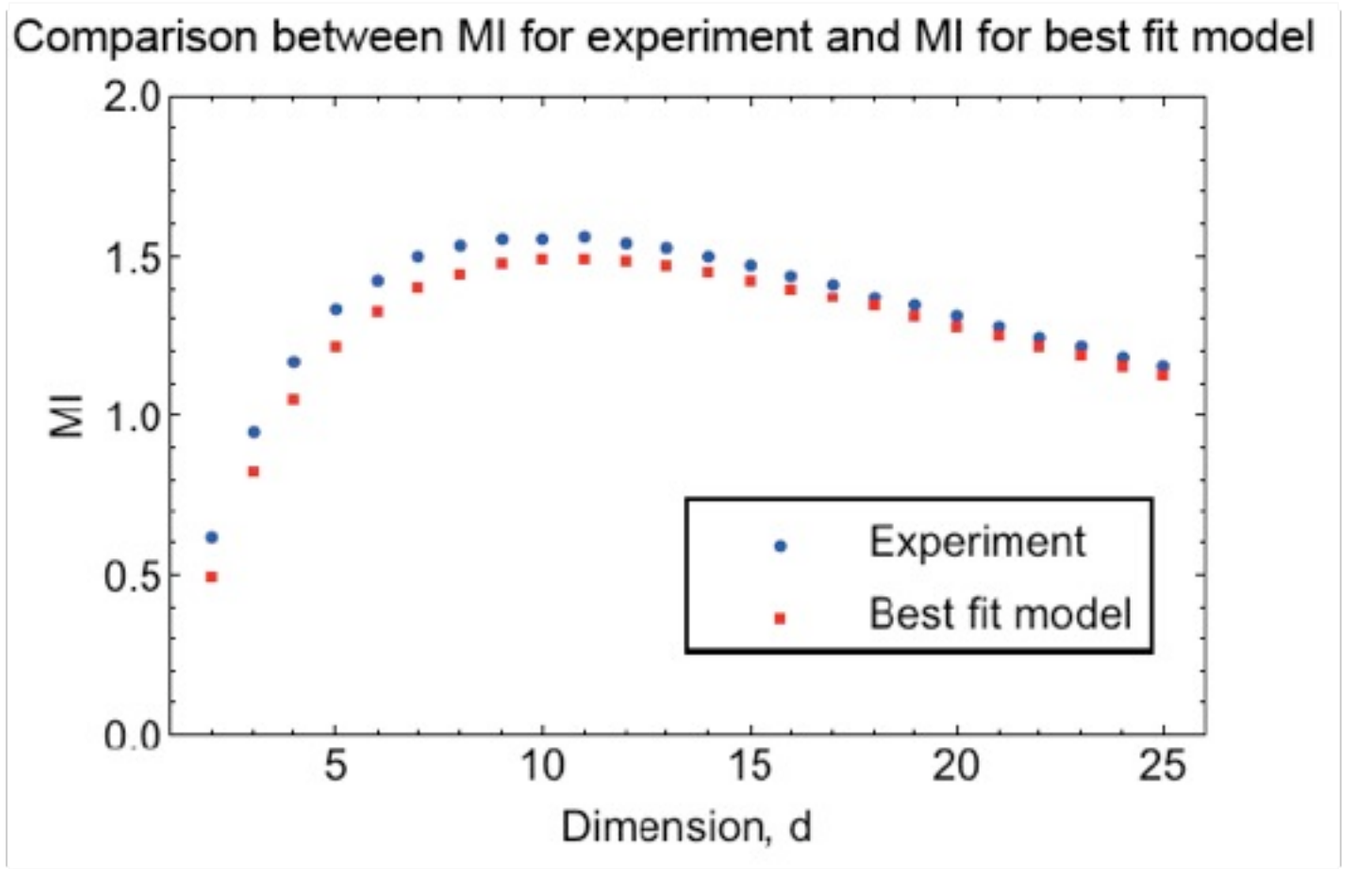


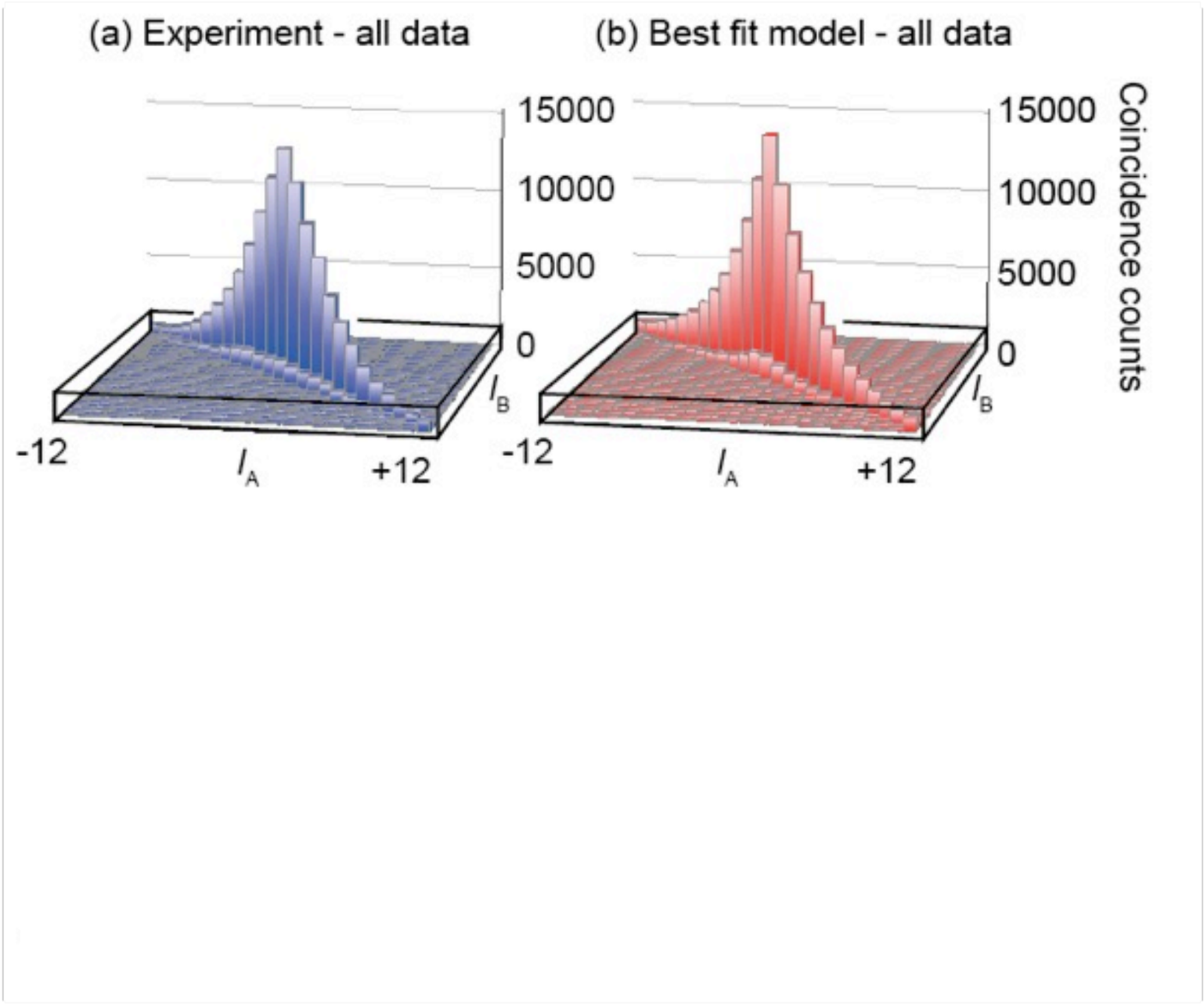
Quantum measurements

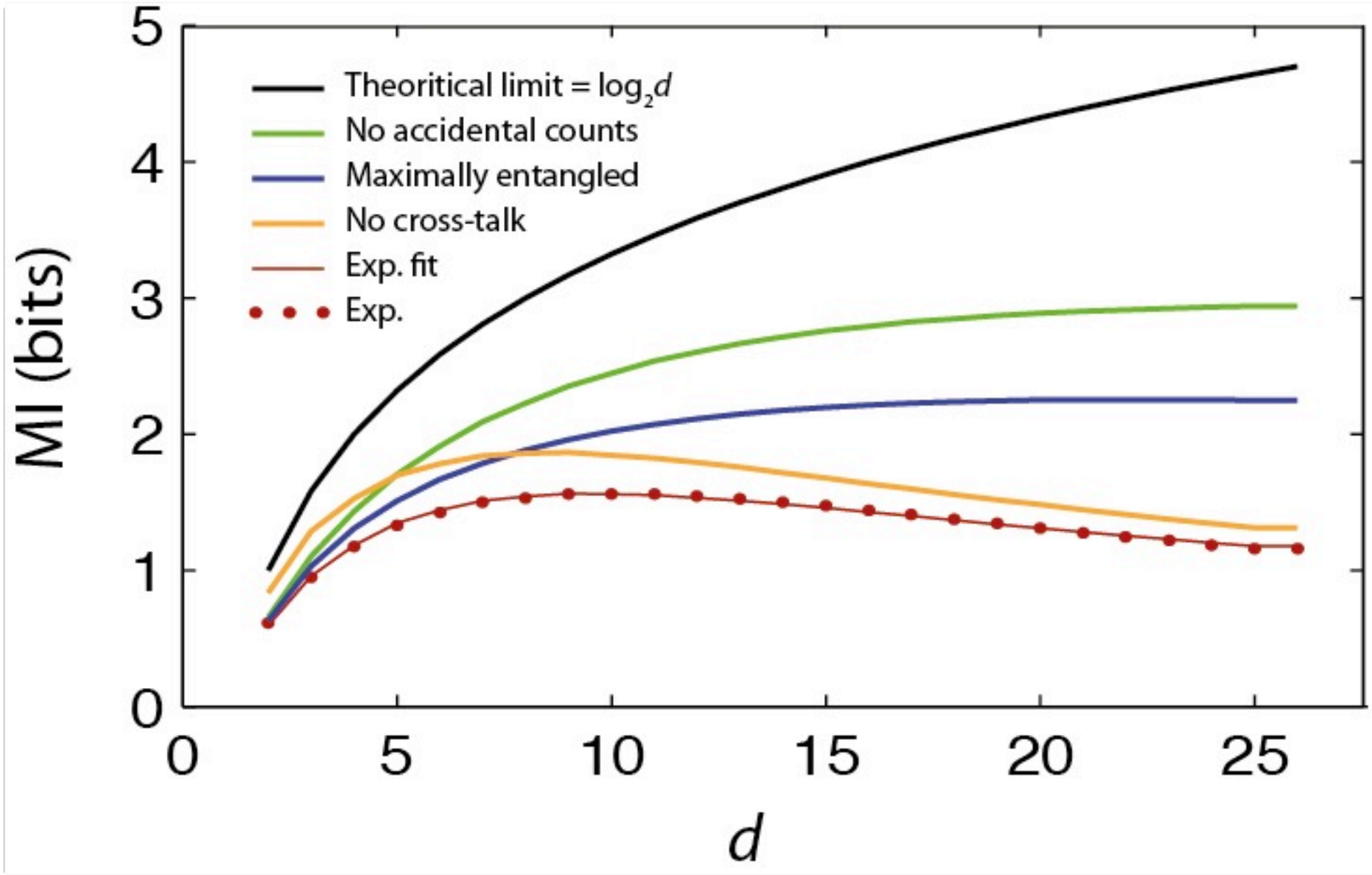


$$I(A;B) \quad = \quad H(A) - H(A|B) = H(B) - H(B|A)$$


12
-12
-12
12
d=25
d=13
d=2
$|\ell_B\rangle$
$|\ell_A\rangle$


Comparison between MI for experiment and MI for best fit model
2.0
1.5
1.0
0.5
0.0
MI
5
10
15
20
25
Dimension, d
Experiment
Best fit model


(a) Experiment - all data
(b) Best fit model - all data
15000
10000
5000
0
Coincidence counts
l_B
-12
l_A
+12


Theoritical limit = $\log_2 d$
No accidental counts
Maximally entangled
No cross-talk
Exp. fit
Exp.
MI (bits)
d
0
1
2
3
4
5
0
5
10
15
20
25

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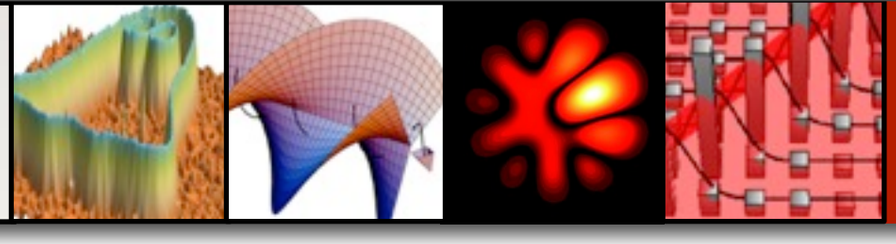
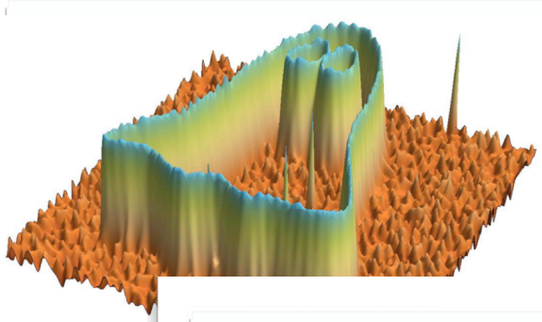
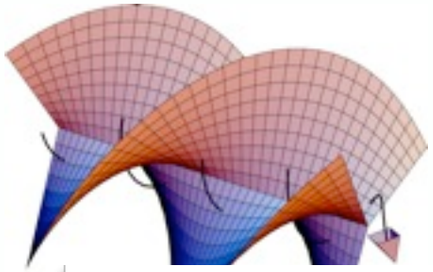
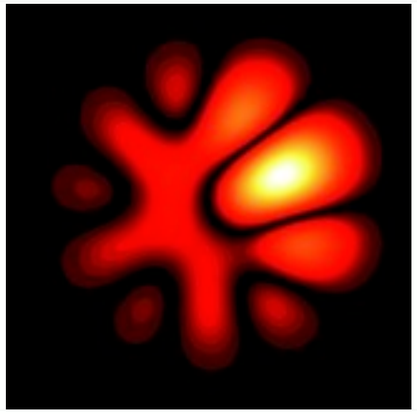




Holographic ghost imaging

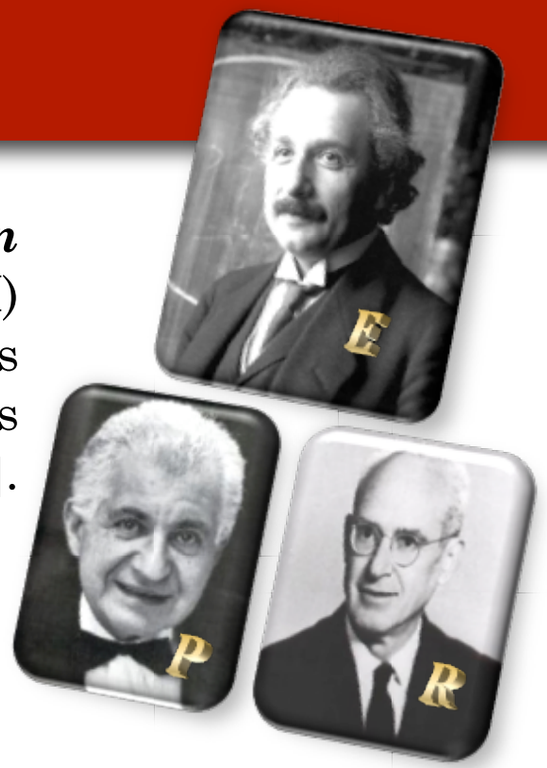


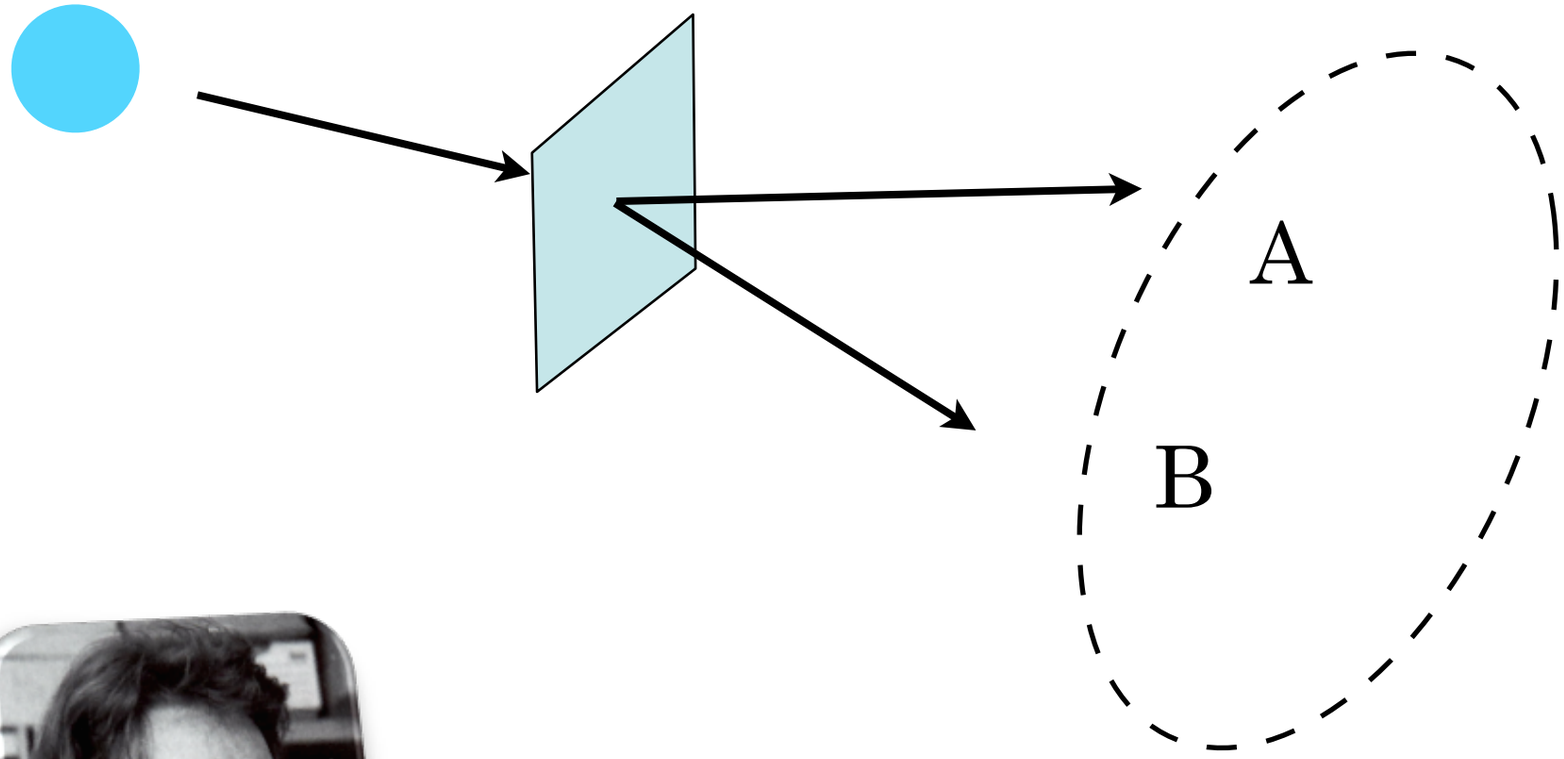
EPR correlations in the OAM/angle basis



Violations of generalized Bell inequalities

Einstein, ***Podolsky*** and ***Rosen*** argued that Quantum Mechanics (QM) was an incomplete theory because of its description of entangled systems [EPR, Phys. Rev. **47**, 777 (1935)].





Spatially separated entangled photons

Bell proposed a method of testing local realism.

Bell's theorem: no classical theory based on local-hidden variables can ever fully reproduce quantum mechanical predictions [Bell, Physics **1**, 195 (1964)].

Experimental result indicating two photon superpositions in OAM [A. Mair *et al.*, Nature 412, 313 (2001)]

letters to nature

NATURE | VOL 412 | 19 JULY 2001 | www.nature.com

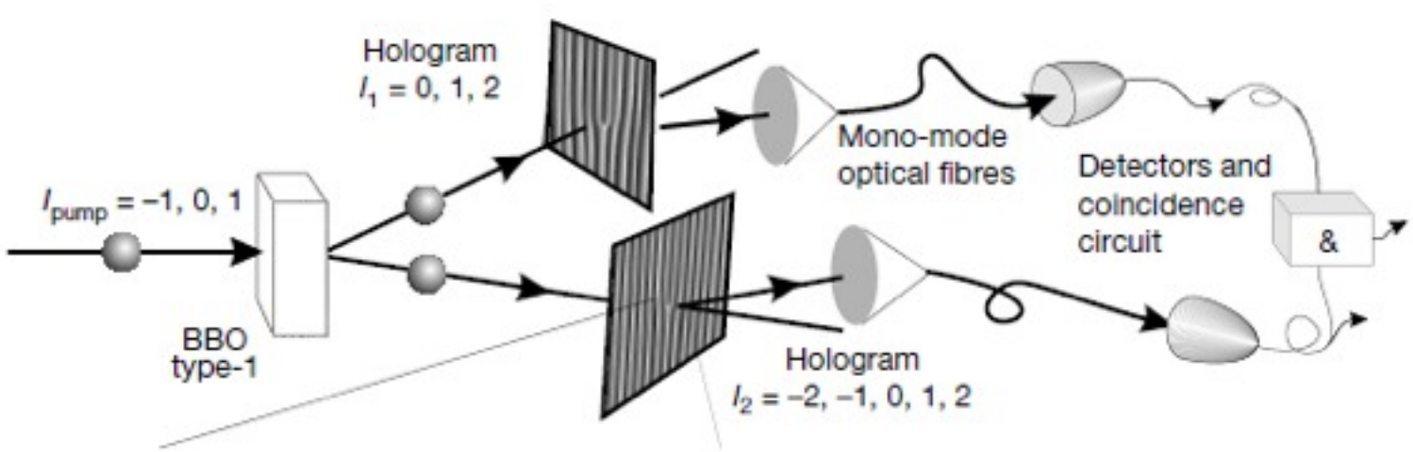
Entanglement of the orbital angular momentum states of photons

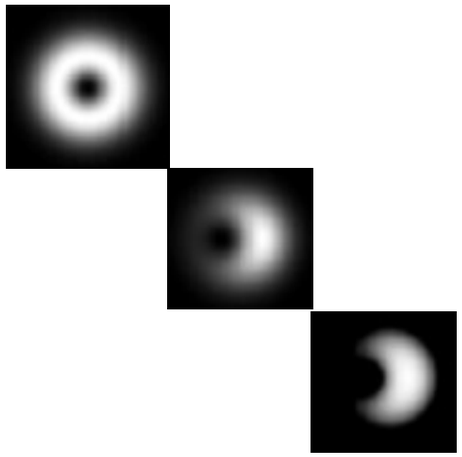
Alois Mair*, Alipasha Vaziri, Gregor Weihs & Anton Zeilinger

Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, 1090 Wien, Austria

in a coincidence pattern not containing any intensity zeroes. Such a coincidence pattern would also be observed if a shifted hologram together with a mono-mode detector were not able to analyse for superposition states.

An entangled state represents correctly both the correlation of the eigenmodes and the correlations of their superpositions. Having experimentally confirmed the quantum superposition for $l = 0$ and $l = \pm 2$, it is reasonable to expect the quantum superposition will also occur for the other states. Nevertheless, ultimate confirmation of entanglement will be a Bell inequality experiment generalized to more states[25]. Such an experiment will be a major experimental challenge, and we are preparing to perform it.





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VOLUME 88, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JANUARY 2002

Bell Inequalities for Arbitrarily High-Dimensional Systems

Daniel Collins,[1,2] Nicolas Gisin,[3] Noah Linden,[4] Serge Massar,[5] and Sandu Popescu[1,2]

[1]*H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, United Kingdom*
[2]*BRIMS, Hewlett-Packard Laboratories, Stoke Gifford, Bristol BS12 6QZ, United Kingdom*
[3]*Group of Applied Physics, University of Geneva, 20, rue de l'Ecole-de-Médecine, CH-1211 Geneva 4, Switzerland*
[4]*Department of Mathematics, Bristol University, University Walk, Bristol BS8 1TW, United Kingdom*
[5]*Service de Physique Théorique, Université Libre de Bruxelles, CP 225, Boulevard du Triomphe, B1050 Bruxelles, Belgium*
(Received 23 July 2001; published 10 January 2002)

We develop a now
by local variable the
quantum systems of
our work gives an a
high dimensionality.

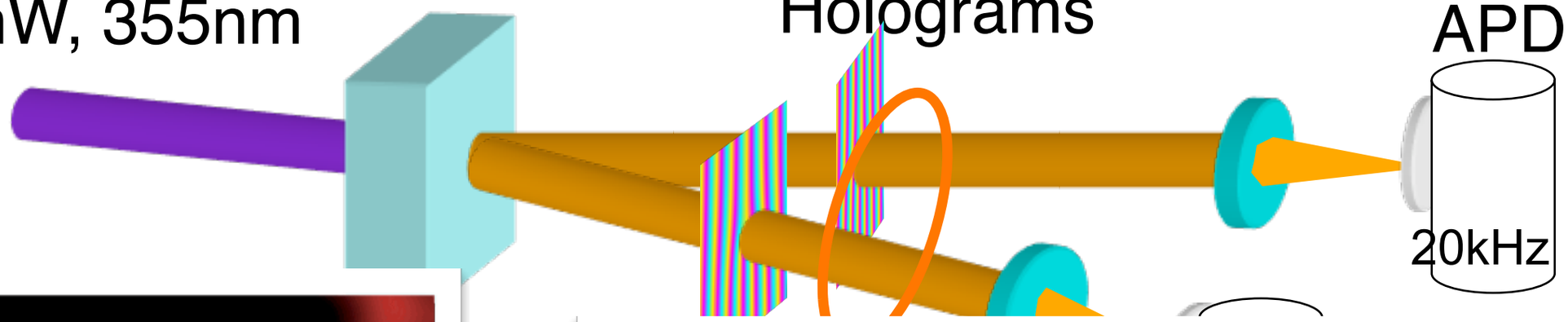
PRL **104,** 060401 (2010) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2010

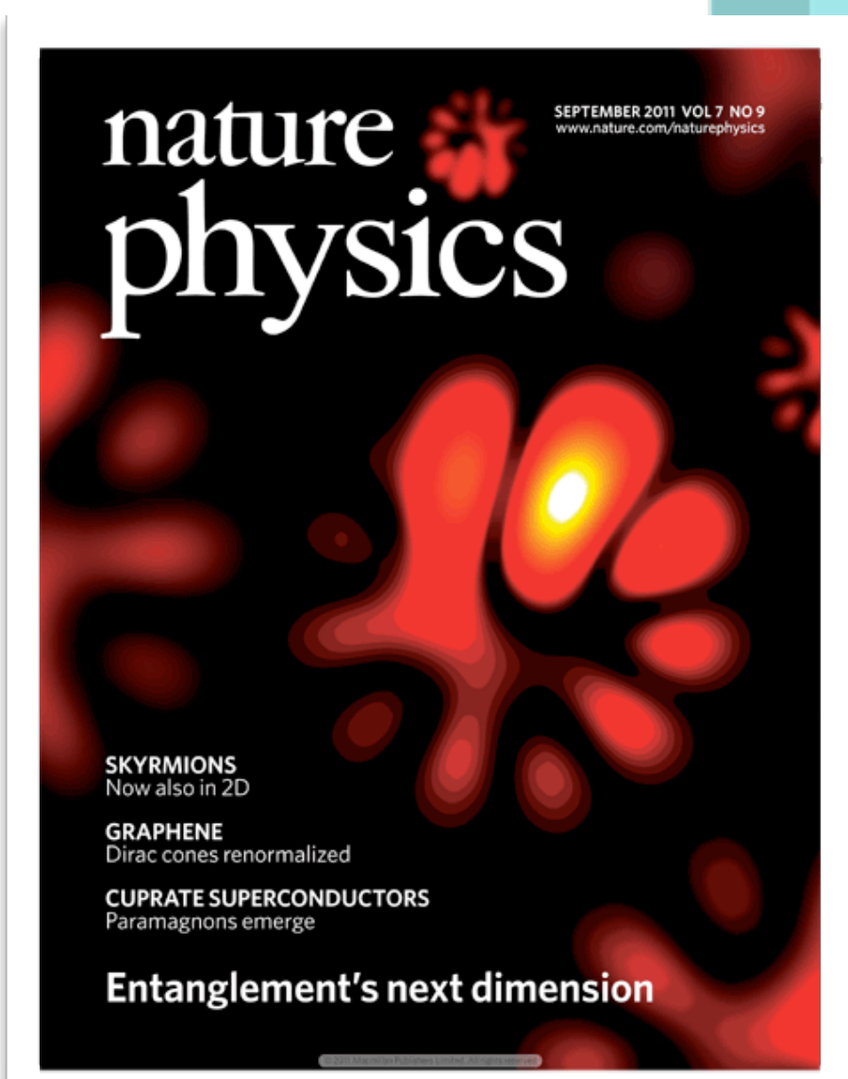
Closing the Detection Loophole in Bell Experiments Using Qudits

Tamás Vértesi,[1] Stefano Pironio,[2] and Nicolas Brunner[3]

[1]*Institute of Nuclear Research of the Hungarian Academy of Sciences, H-4001 Debrecen, P.O. Box 51, Hungary*
[2]*Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland*
[3]*H.H. Wills Physics Laboratory, University of Bristol, Bristol, BS8 1TL, United Kingdom*
(Received 8 October 2009; published 11 February 2010)

We show that the detection efficiencies required for closing the detection loophole in Bell tests can be significantly lowered using quantum systems of dimension larger than two. We introduce a series of asymmetric Bell tests for which an efficiency arbitrarily close to $1/N$ can be tolerated using N-dimensional systems, and a symmetric Bell test for which the efficiency can be lowered down to 61.8% using four-dimensional systems. Experimental perspectives for our schemes look promising considering recent progress in atom-photon entanglement and in photon hyperentanglement.





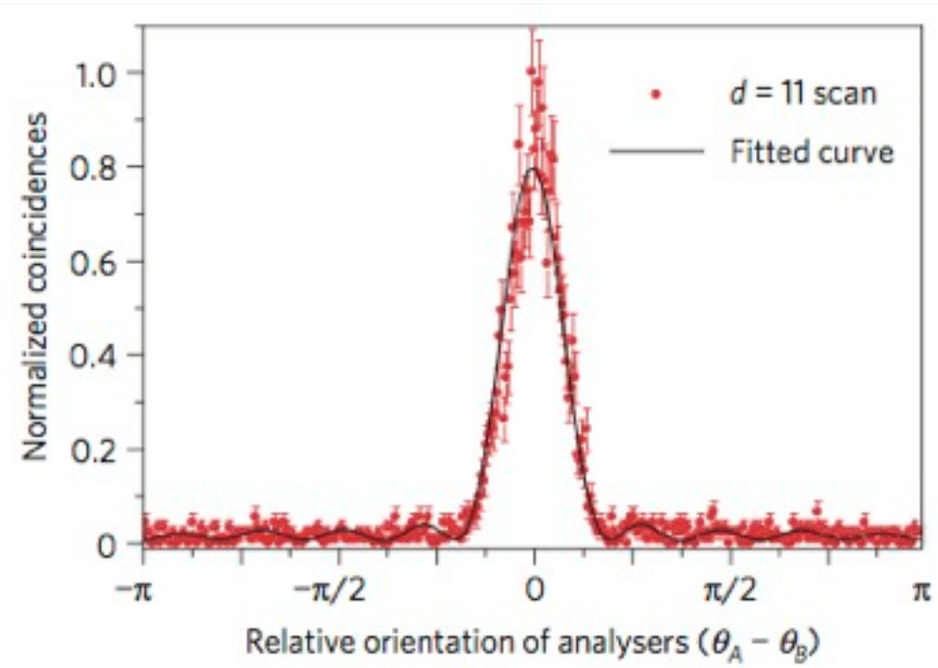


Figure 2 | Coincidence count rate (self-normalized) as a function of the relative orientation angle between state analysers ($\theta_A - \theta_B$). Equation (5) for a state with maximal 11-dimensional entanglement is fitted to the experimental data with the vertical offset and amplitude left as free parameters. Errors were estimated assuming Poisson statistics.

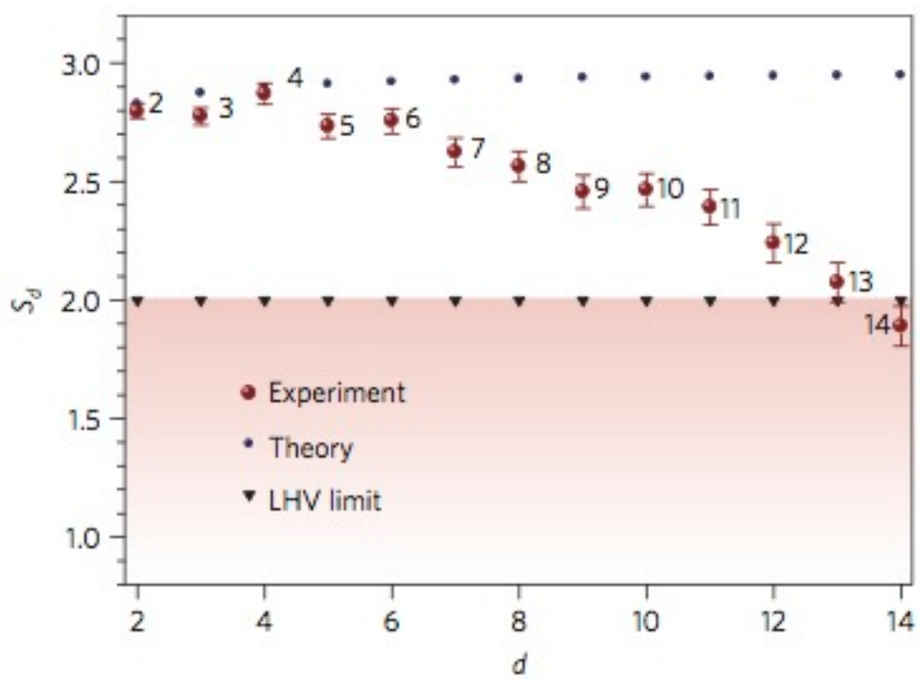


Figure 3 | Experimental Bell-type parameter S_d versus number of dimensions d. $S_d > 2$ violates local realism for any $d \geq 2$. The plot compares the theoretically predicted violations by a maximally entangled state and the LHV limit with the experiments. Violations are observed for up to $d = 12$. Errors were estimated assuming Poisson statistics.

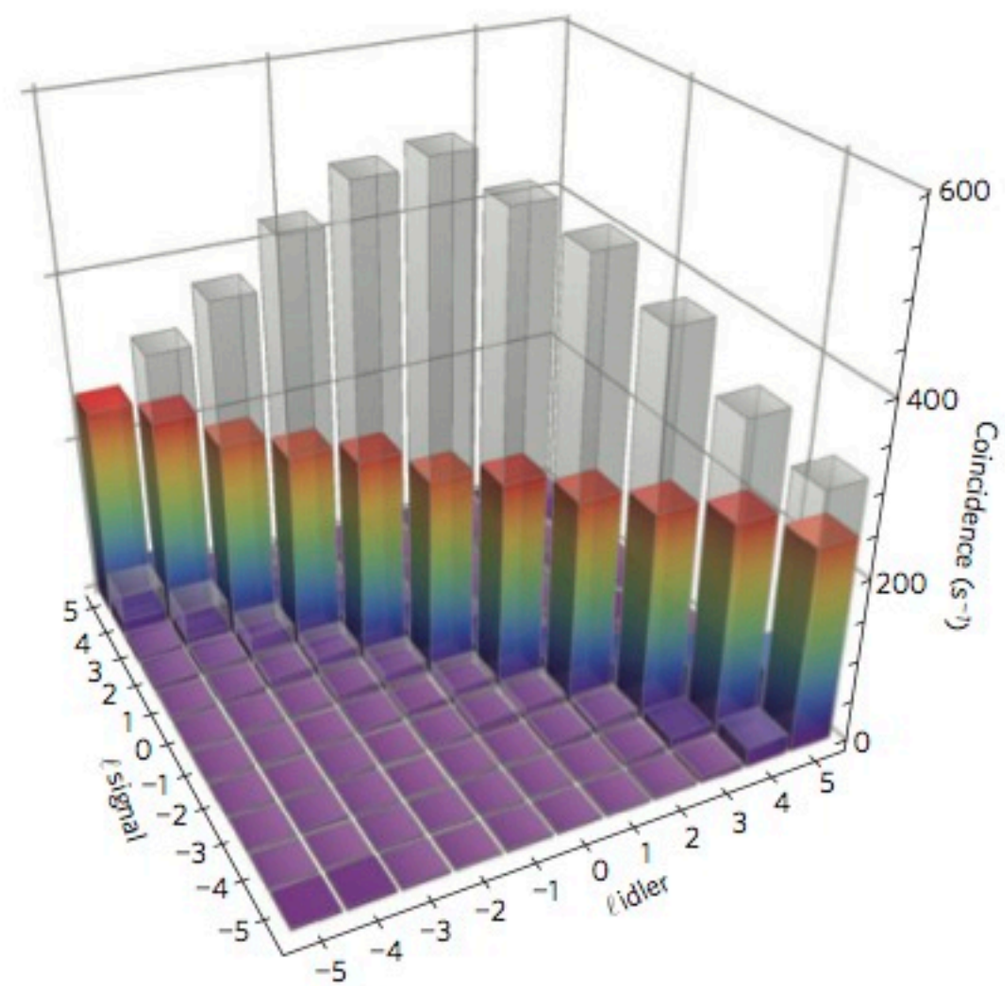


Figure 4 | Experimental coincidence rates proportional to the probability of measuring the state $|\ell_s\rangle \otimes |\ell_i\rangle$ with $\ell_s, \ell_i = -5, \ldots, +5$. The coloured and greyed-out bars depict the measurement results with and without the application of Procrustean filtering respectively. The measurement time was 20 s for each combination of ℓ_s and ℓ_i.

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Measurement of qubits

Daniel F. V. James,[1,*] Paul G. Kwiat,[2,3] William J. Munro,[4,5] and Andrew G. White[2,4]
[1]*Theoretical Division T-4, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[2]*Physics Division P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[3]*Department of Physics, University of Illinois, Urbana-Champaign, Illinois 61801*
[4]*Department of Physics, University of Queensland, Brisbane, Queensland 4072, Australia*
[5]*Hewlett-Packard Laboratories, Filton Road, Stoke Gifford, Bristol BS34 8QZ, United Kingdom*
(Received 20 March 2001; published 16 October 2001)

We describe in detail the theory underpinning the measurement of density matrices of a pair of quantum two-level systems ("qubits"). Our particular emphasis is on qubits realized by the two polarization degrees of freedom of a pair of entangled photons generated in a down-conversion experiment; however, the discussion applies in general, regardless of the actual physical realization. Two techniques are discussed, namely, a tomographic reconstruction (in which the density matrix is linearly related to a set of measured quantities) and a maximum likelihood technique which requires numerical optimization (but has the advantage of producing density matrices that are always non-negative definite). In addition, a detailed error analysis is presented, allowing errors in quantities derived from the density matrix, such as the entropy or entanglement of formation, to be estimated. Examples based on down-c

DOI: 10.1103/PhysRevA.64.052312

PHYSICAL REVIEW A **66**, 012303 (2002)

Qudit quantum-state tomography

R. T. Thew*
Center for Quantum Computer Technology, University of Queensland, QLD 4072, Brisbane, Australia and Group of Applied Physics, University of Geneva, 20 rue de l'Ecole-de-Médecine, CH-1211 Geneva 4, Switzerland

K. Nemoto
School of Informatics, University of Wales, Bangor LL57 1UT, United Kingdom

A. G. White
Center for Quantum Computer Technology, University of Queensland, QLD 4072, Brisbane, Australia

W. J. Munro
Hewlett-Packard Laboratories, Filton Road, Stoke Gifford, Bristol BS34 8QZ, United Kingdom
(Received 14 January 2002; published 16 July 2002)

Recently quantum tomography has been proposed as a fundamental tool for prototyping a few qubit quan-
te produced from a given input into the device.
rmation quantities such as the degree of entangle-
easurements have been discussed for this tomog-
hic reconstruction technique to two new regimes.
reconstruction of the state of the system provided
quantum-state tomography can be performed for
ve this in one- and two-qutrit systems.

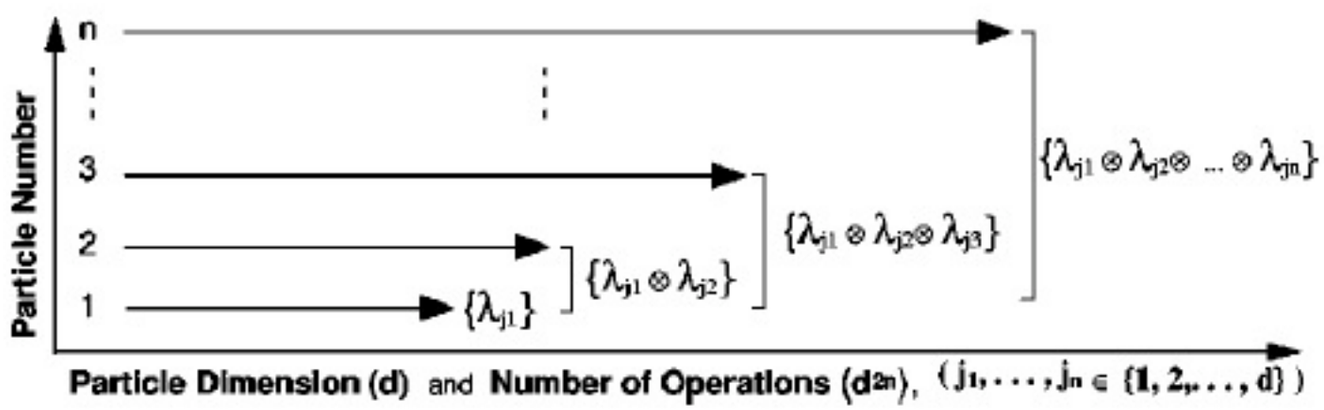

FIG. 2. The measurement scaling for tomography on n qudits results from the necessity to measure every basis state on every subsystem in every permutation. The measurements scale as $d^{2n}-1$, where d is the *particle dimension*, e.g., $d=2$ for a qubit and n is the number of particles.

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VOLUME 93, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 30 JULY 2004

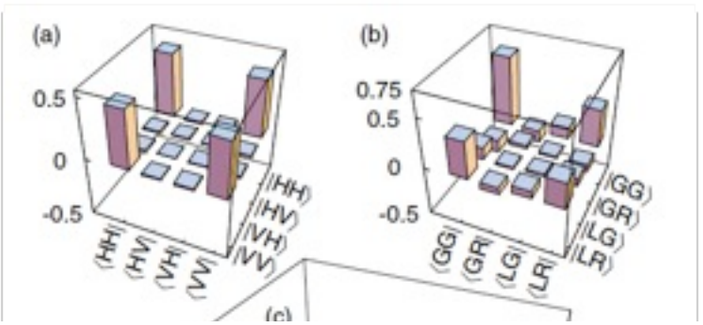
Measuring Entangled Qutrits and Their Use for Quantum Bit Commitment

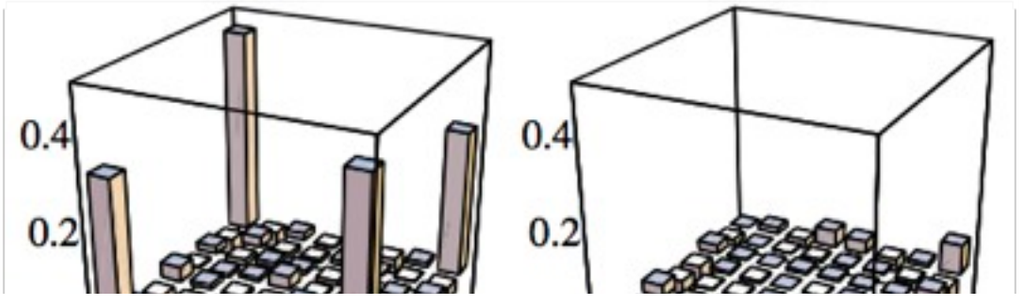
N. K. Langford,* R. B. Dalton, M. D. Harvey, J. L. O'Brien, G. J. Pryde, A. Gilchrist, S. D. Bartlett, and A. G. White

PRL 94, 070402 (2005) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2005

Full Characterization of a Three-Photon Greenberger-Horne-Zeilinger State Using Quantum State Tomography

K. J. Resch,[1,*] P. Walther,[1,*] and A. Zeilinger[1,2]





New Journal of Physics
The open-access journal for physics

Precise quantum tomography of photon pairs with entangled orbital angular momentum

B Jack[1], J Leach[1], H Ritsch[2], S M Barnett[3], M J Padgett[1] and S Franke-Arnold[1,4]

[1] Department of Physics and Astronomy, SUPA, University of Glasgow, Glasgow, UK
[2] Institute of Theoretical Physics, University of Innsbruck, Austria
[3] Department of Physics, SUPA, University of Strathclyde, Glasgow, UK
E-mail: s.franke-arnold@physics.gla.ac.uk

New Journal of Physics **11** (2009) 103024 (12pp)
Received 29 May 2009
Published 12 October 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/10/103024

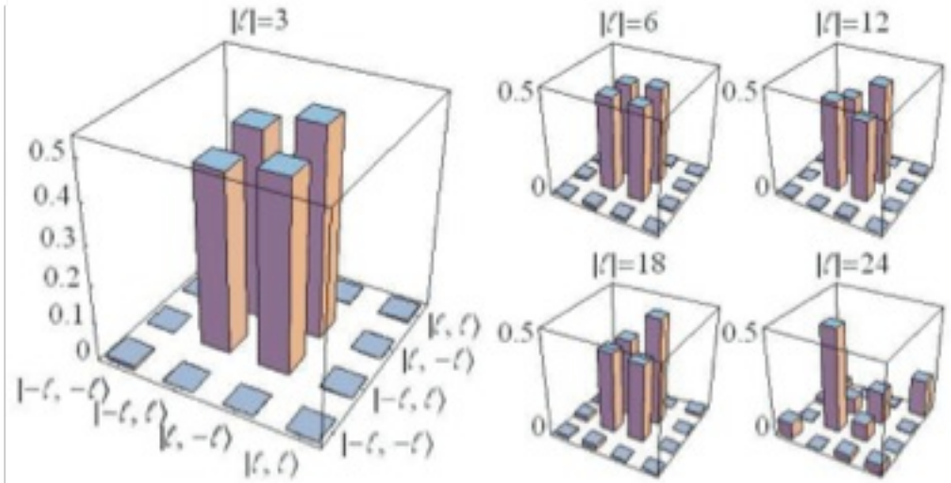


Figure 5. Graphical representation of the real part of the density matrix for various $|\ell|$ subspaces. For subspaces of $|\ell| \leqslant 22$ the four central entries of the density matrix dominate, indicating quantum entanglement. For larger ℓ the coincidence counts become comparable to the noise background and quantum correlations deteriorate.

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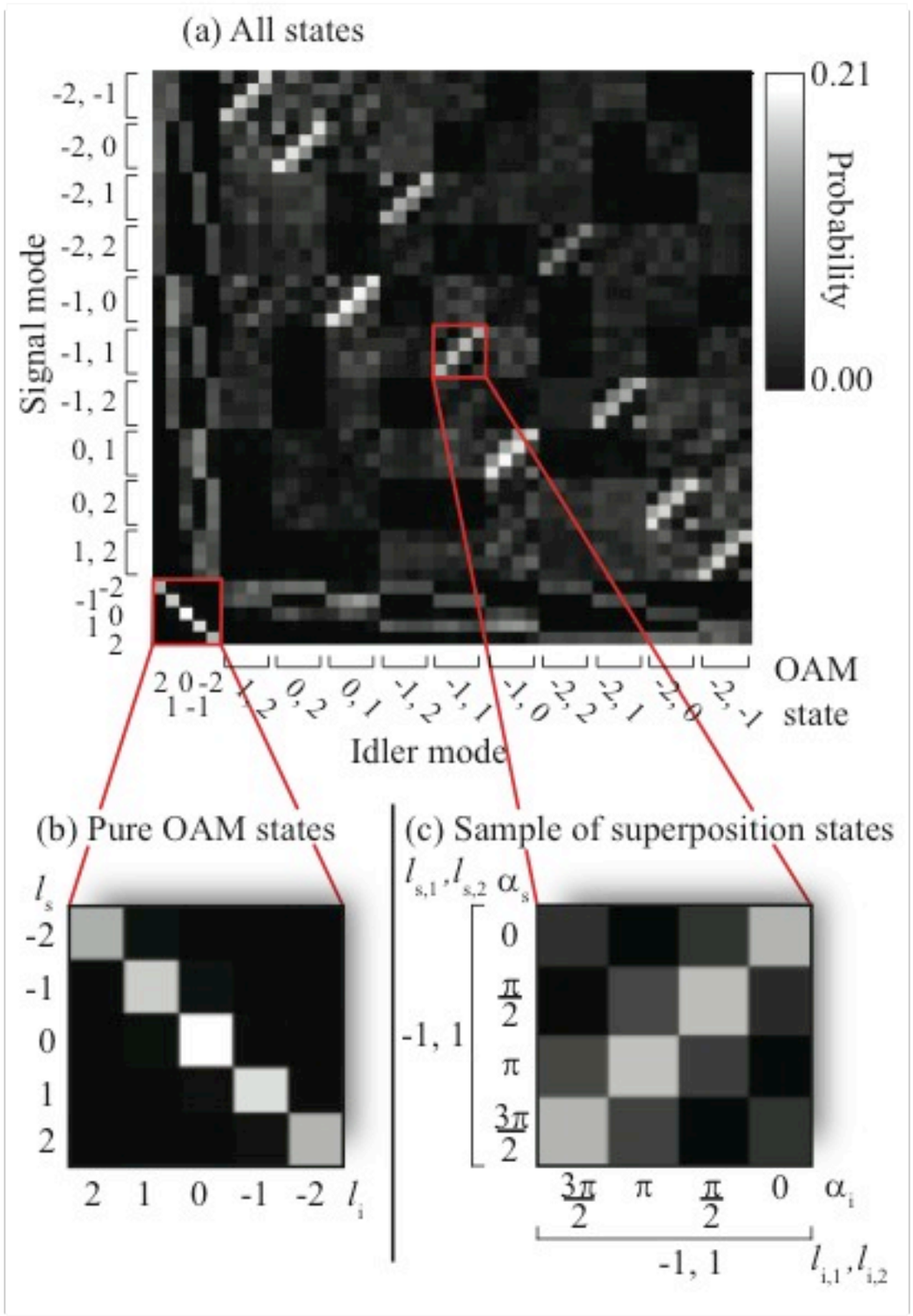
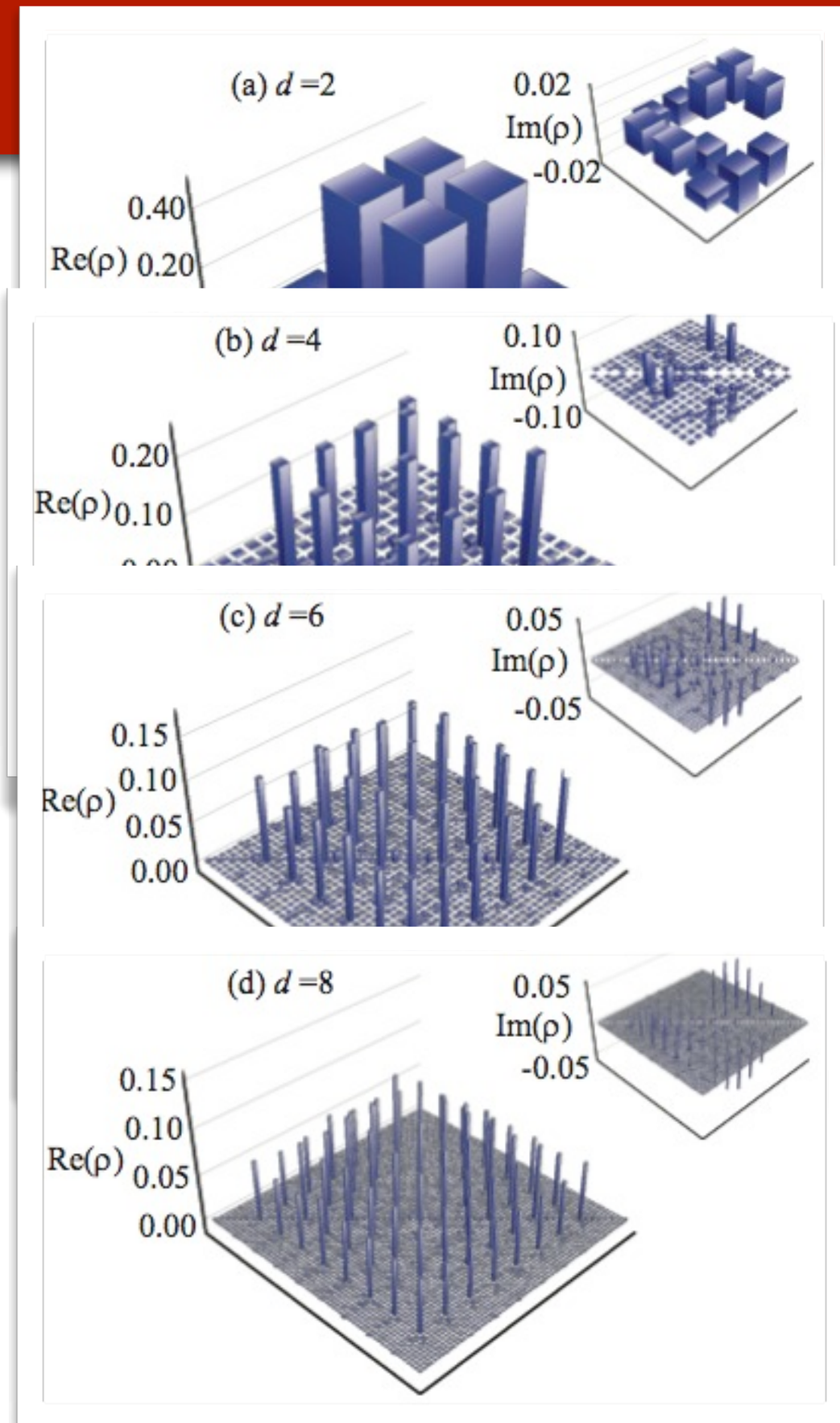
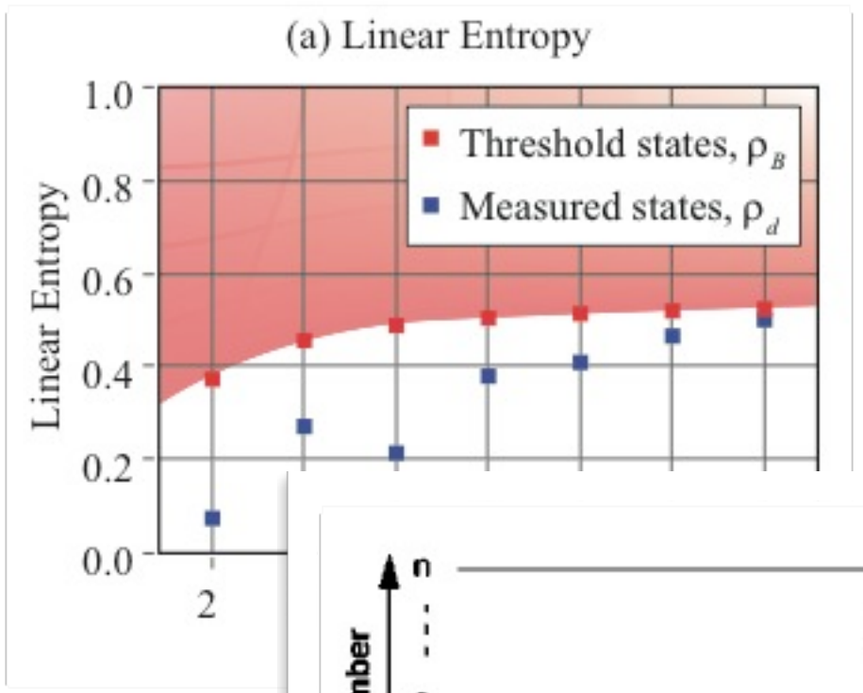
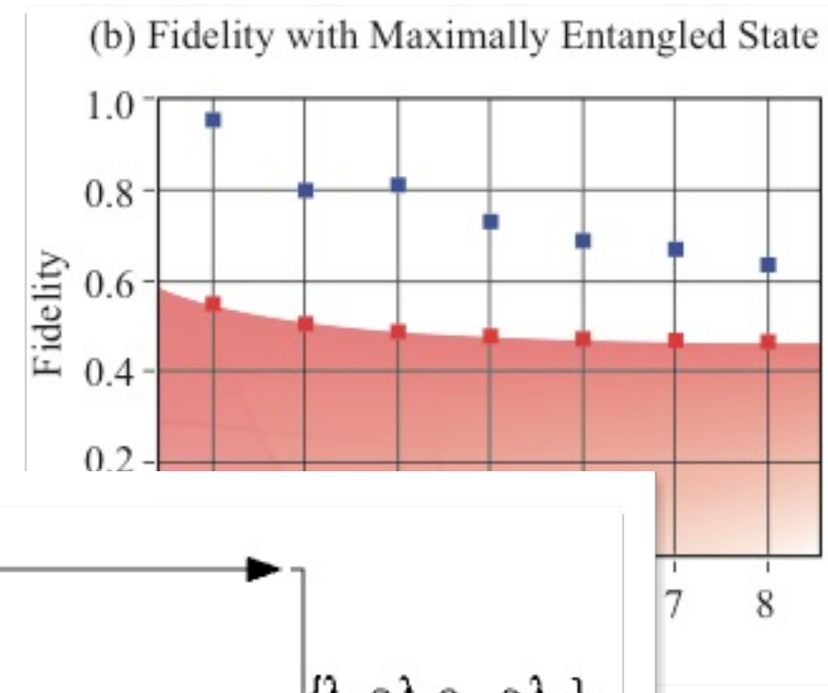

(a) All states
Signal mode
-2, -1
-2, 0
-2, 1
-2, 2
-1, 0
-1, 1
-1, 2
0, 1
0, 2
1, 2
Idler mode
OAM state
Probability
0.21
0.00
(b) Pure OAM states
(c) Sample of superposition states
-1, 1


(a) d =2
(b) d =4
(c) d =6
(d) d =8
Re(ρ)
Im(ρ)





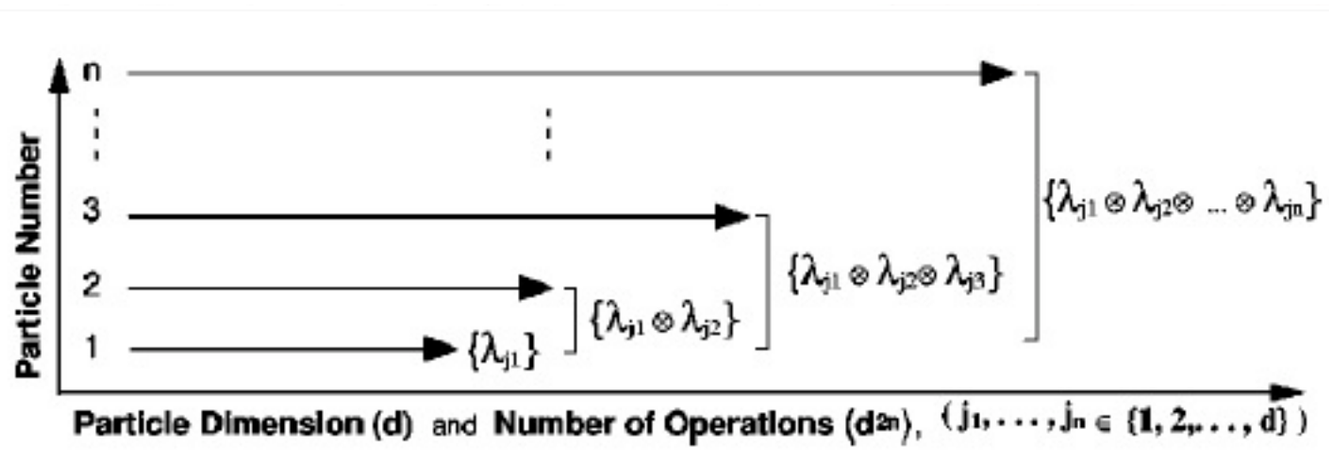


FIG. 2. The measurement scaling for tomography on n qudits results from the necessity to measure every basis state on every subsystem in every permutation. The measurements scale as $d^{2n} - 1$, where d is the *particle dimension*, e.g., $d = 2$ for a qubit and n is the number of particles.

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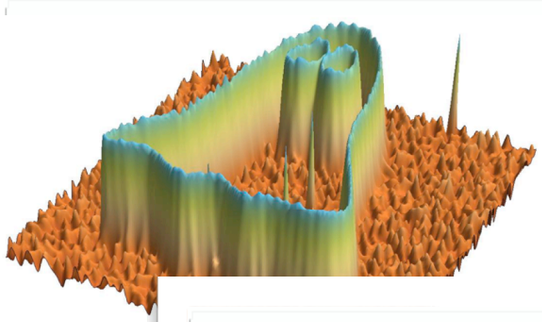
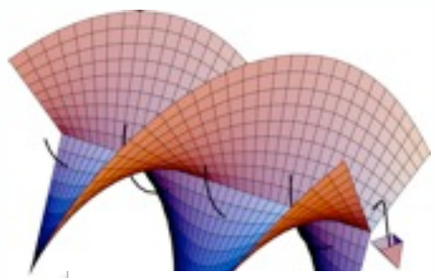
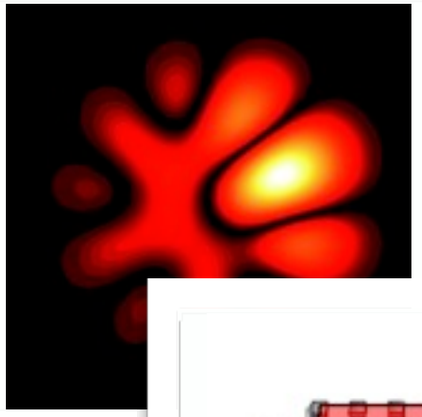


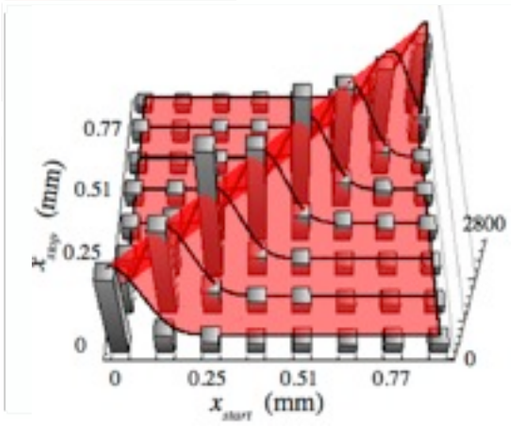
Holographic ghost imaging



EPR correlations in the OAM/angle basis



Violations of generalized Bell inequalities



Full-field quantum measurements

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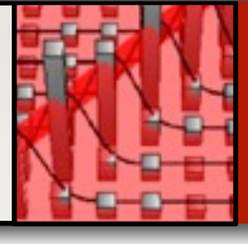
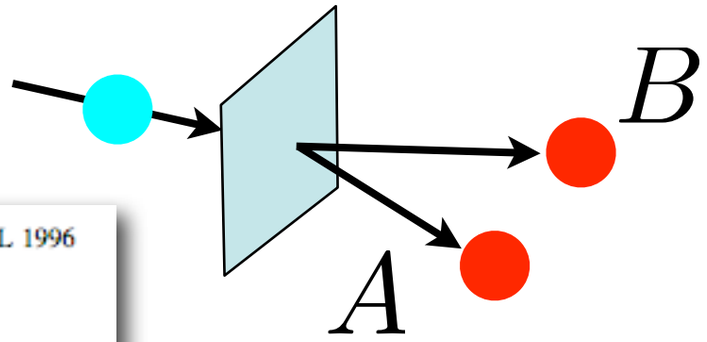




1935

1996

2004

2005

2009

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

PHYSICAL REVIEW A VOLUME 53, NUMBER 4 APRIL 1996

Two-photon geometric optics

T. B. Pittman, D. V. Strekalov, D. N. Klyshko,* M. H. Rubin, A. V. Sergienko, and Y. H. Shih

VOLUME 92, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 28 MAY 2004

Realization of the Einstein-Podolsky-Rosen Paradox Using Momentum- and Position-Entangled Photons from Spontaneous Parametric Down Conversion

John C. Howell,[1] Ryan S. Bennink,[2] Sean J. Bentley,[2,*] and R.W. Boyd[2]

PRL 94, 220501 (2005) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2005

Pixel Entanglement: Experimental Realization of Optically Entangled $d = 3$ and $d = 6$ Qudits

Malco

[2]The De

PHYSICAL REVIEW A 79, 033801 (2009)

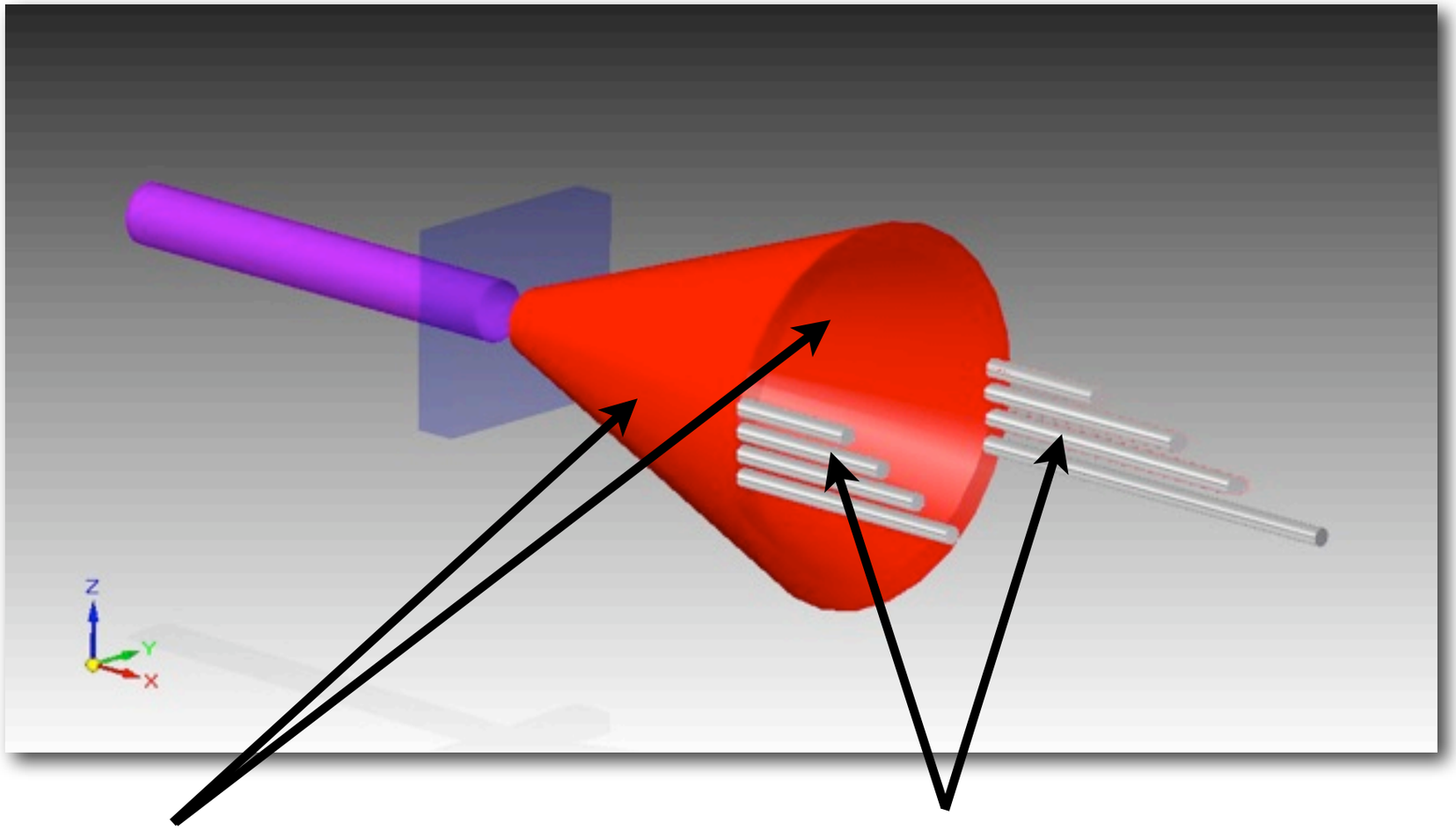
Propagation of transverse intensity correlations of a two-photon state

D. S. Tasca,* S. P. Walborn, and P. H. Souto Ribeiro†
Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postale 68528, Rio de Janeiro 21941-972, Brazil

F. Toscano
Fundação Centro de Ciências e Educação Superior a Distância do Estado do Rio de Janeiro, Rio de Janeiro 20943-001, Brazil and Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postale 68528, Rio de Janeiro 21941-972, Brazil

P. Pellat-Finet
Groupe d'Optique Théorique et Appliquée, LMAM, Université de Bretagne Sud, BP 92116, Lorient Cedex, France and Département d'Optique, UMR CNRS 6082, École Nationale Supérieure des Télécommunications de Bretagne, CS 833813 29238 BREST cedex 3, France

(Received 22 August 2008; published 4 March 2009)

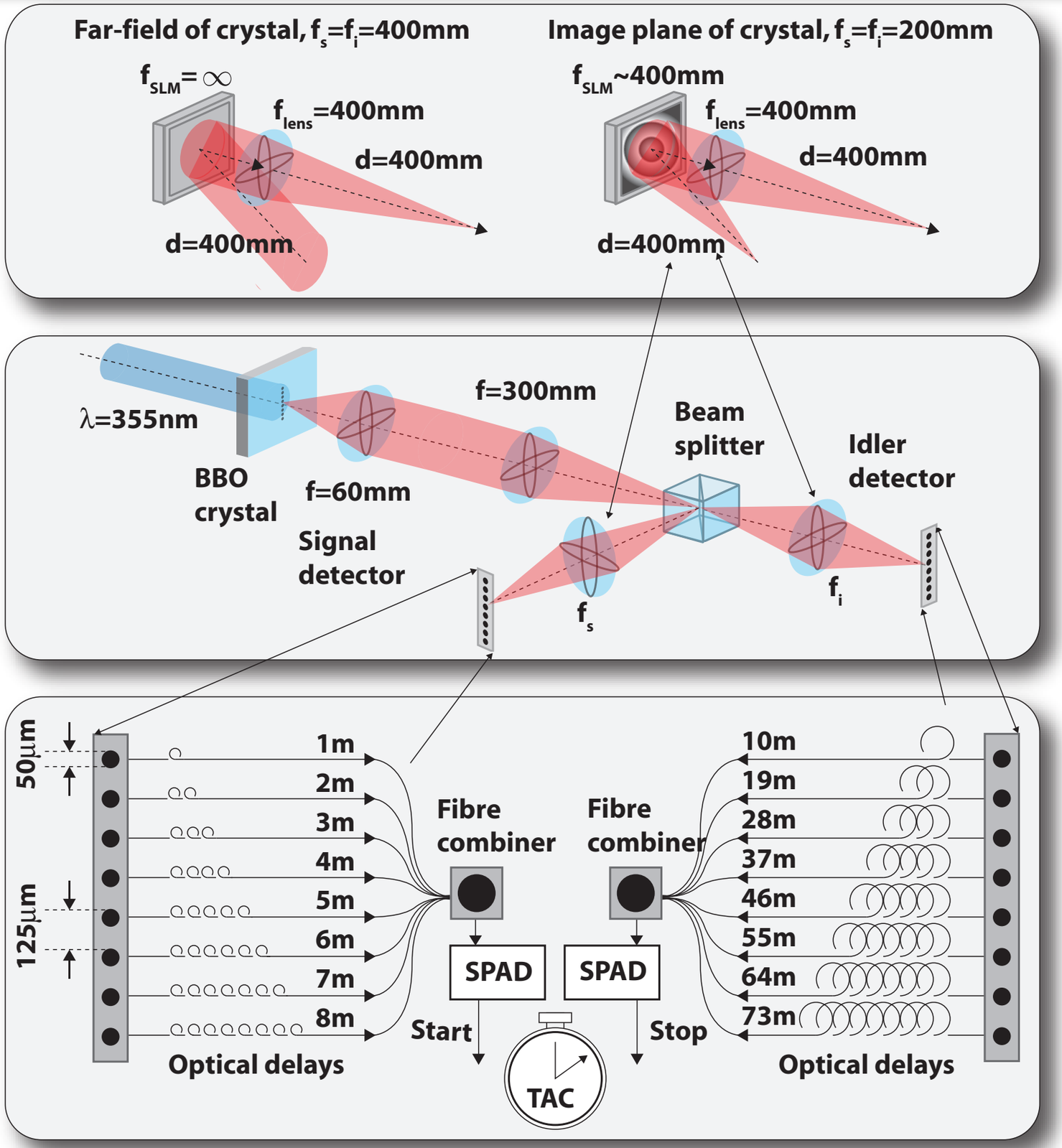


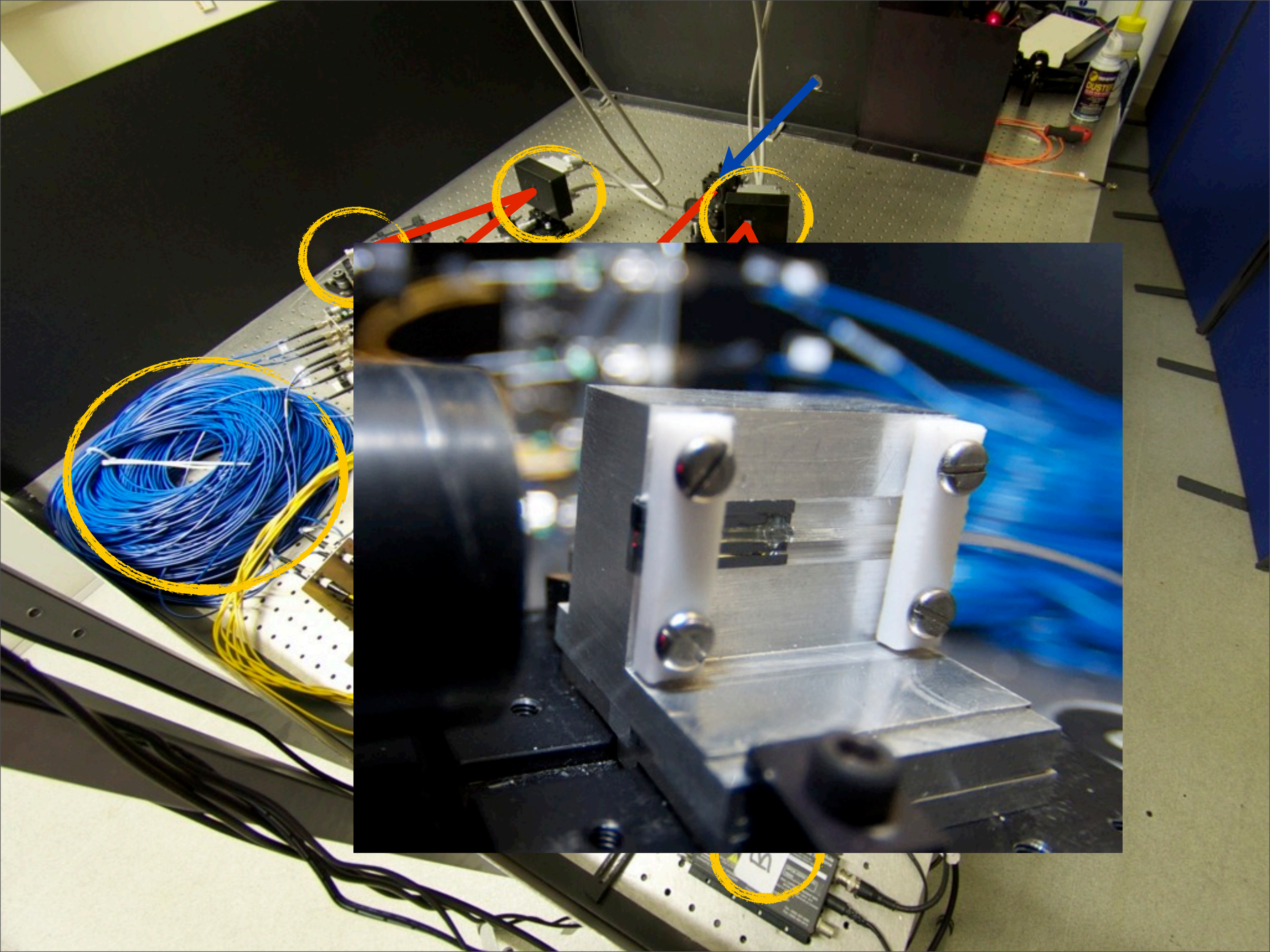
1. SLMs in signal/idler arms (not shown in picture)

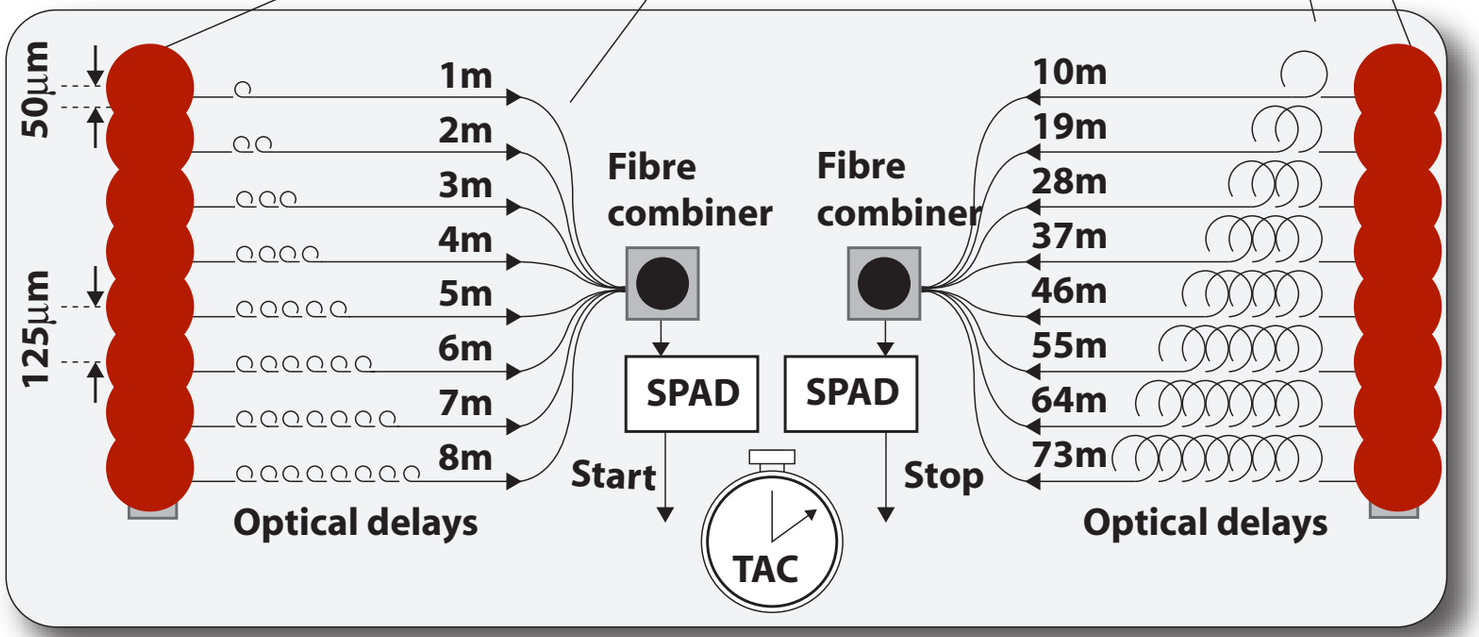
   We can detect coincidences for near-field/far-field/ intermediate-fields

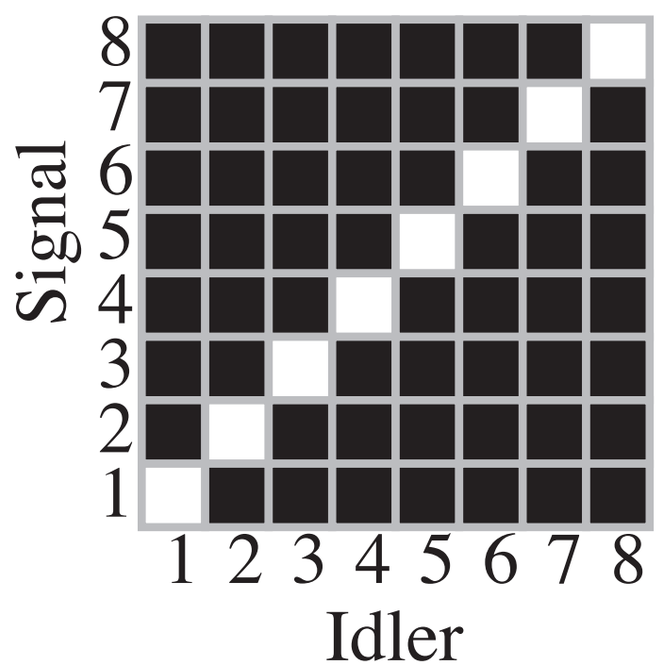
2. Multi-pixel detector array (converts position to time)

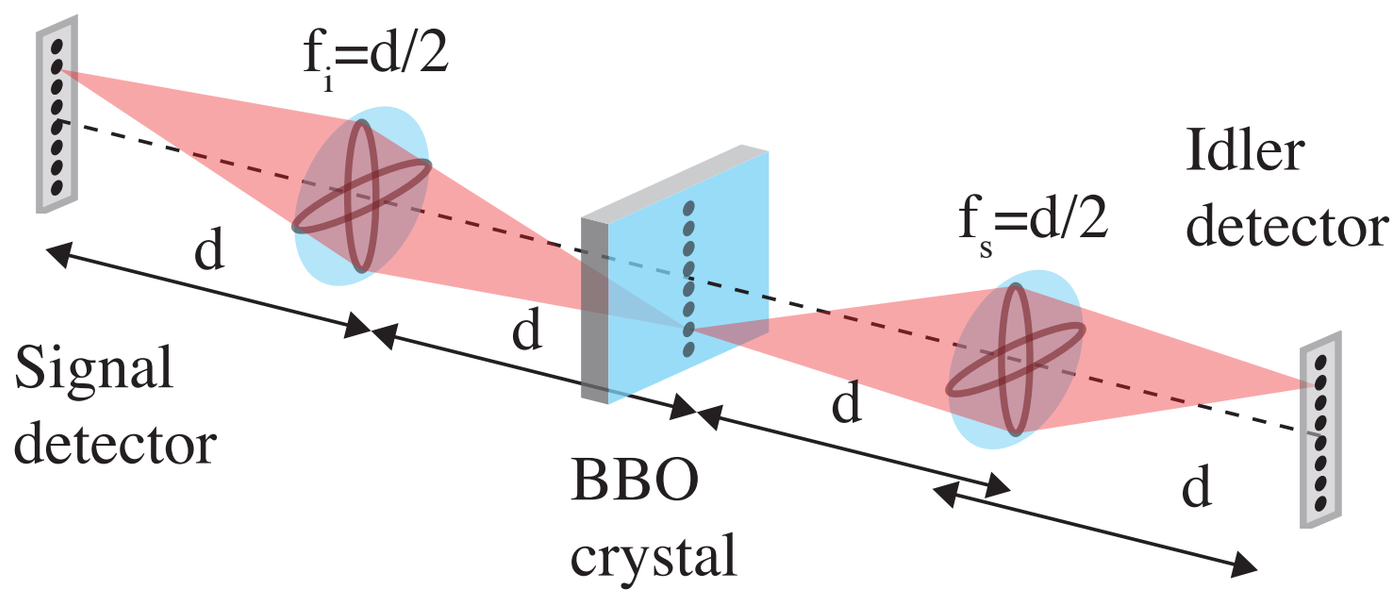
   We can simultaneously measure 8 quantum states with no scanning

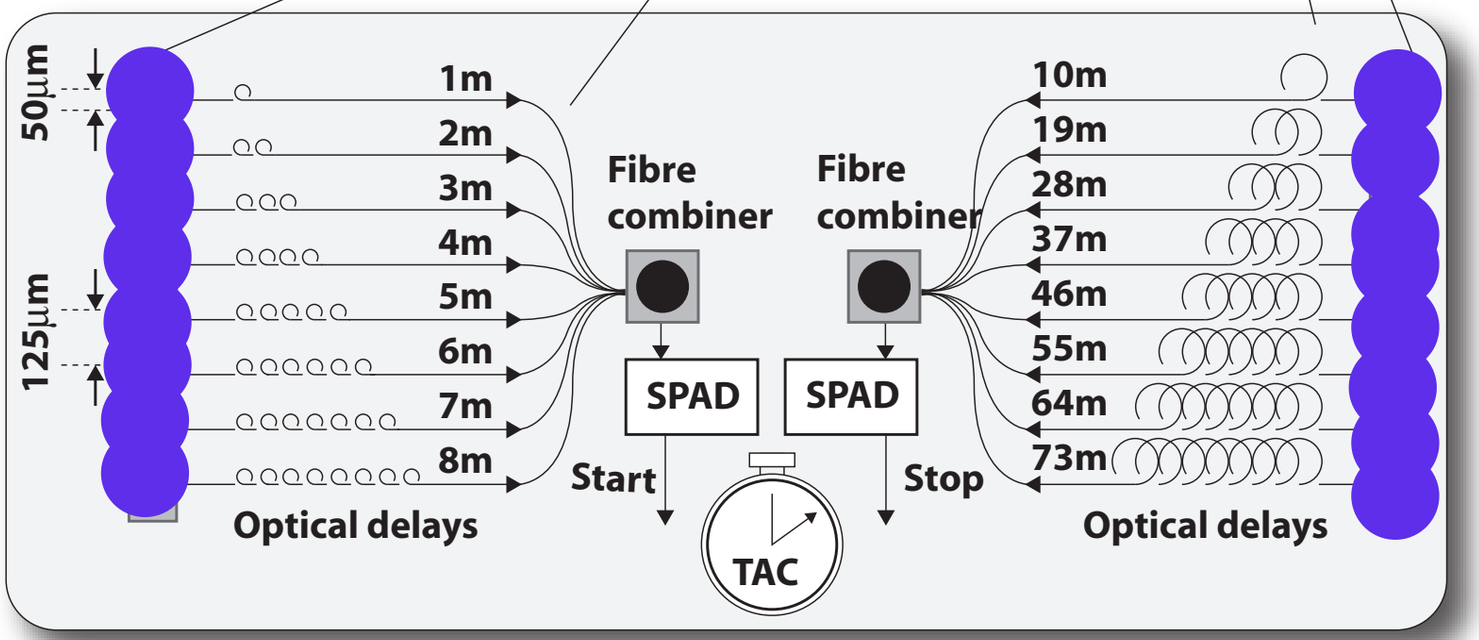

Far-field of crystal, f_s=f_i=400mm
f_{SLM}= ∞
f_{lens}=400mm
d=400mm
d=400mm
Image plane of crystal, f_s=f_i=200mm
f_{SLM}~400mm
f_{lens}=400mm
d=400mm
d=400mm
λ=355nm
BBO crystal
f=60mm
f=300mm
Beam splitter
Idler detector
Signal detector
f_s
f_i
50μm
125μm
1m
2m
3m
4m
5m
6m
7m
8m
Optical delays
Fibre combiner
Fibre combiner
SPAD
SPAD
Start
Stop
TAC
10m
19m
28m
37m
46m
55m
64m
73m
Optical delays

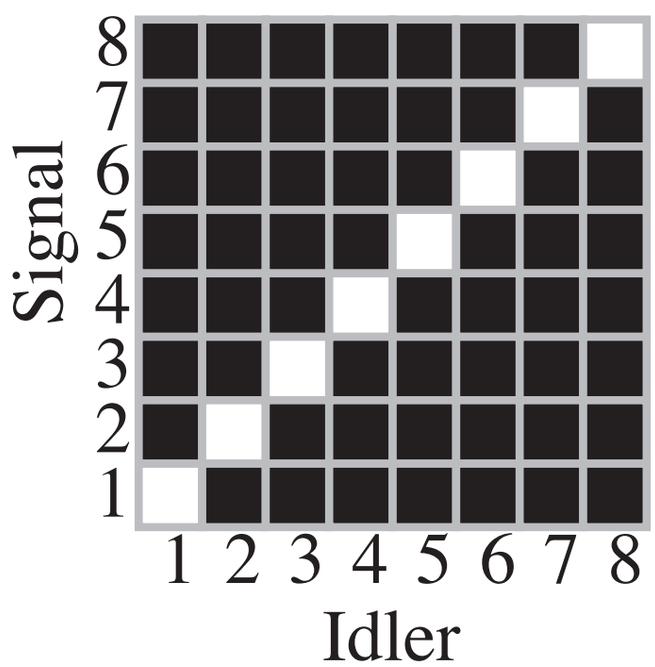


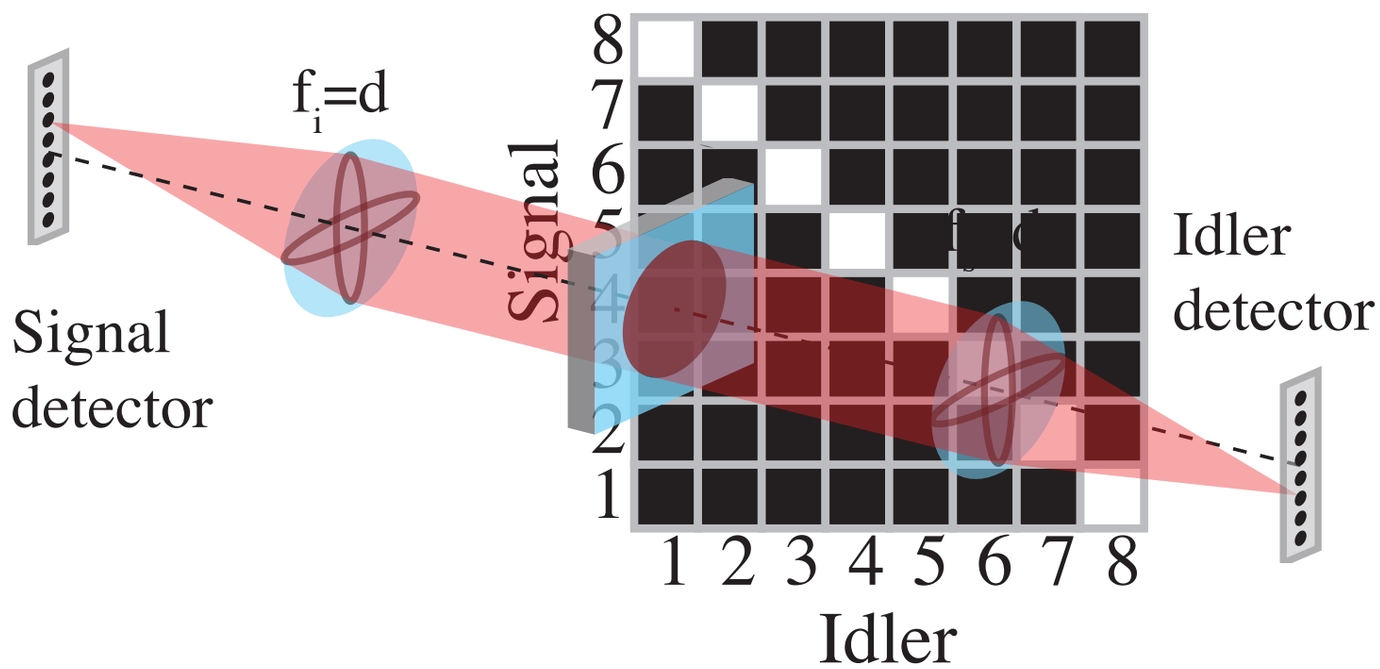

50µm
125µm
1m
2m
3m
4m
5m
6m
7m
8m
Optical delays
Fibre combiner
Fibre combiner
SPAD
SPAD
Start
Stop
TAC
10m
19m
28m
37m
46m
55m
64m
73m
Optical delays

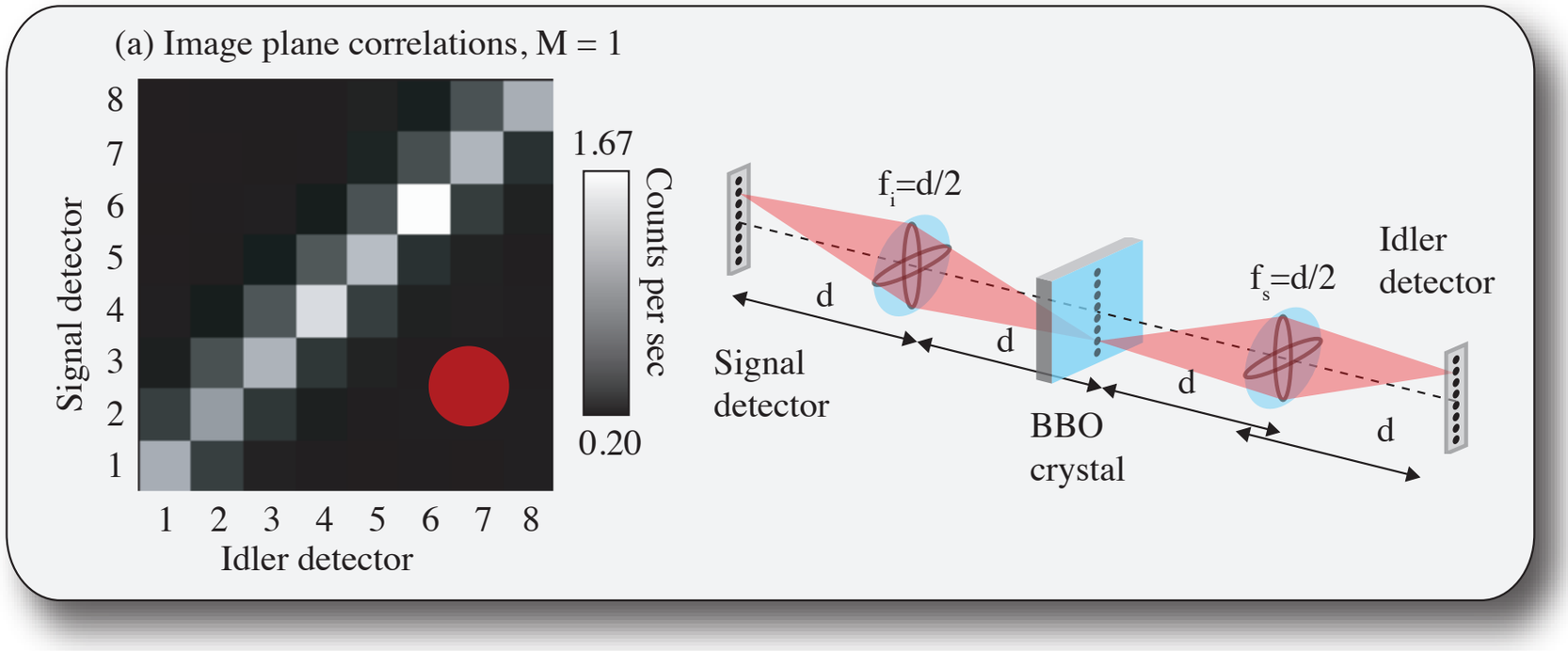

Signal
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7 8
Idler

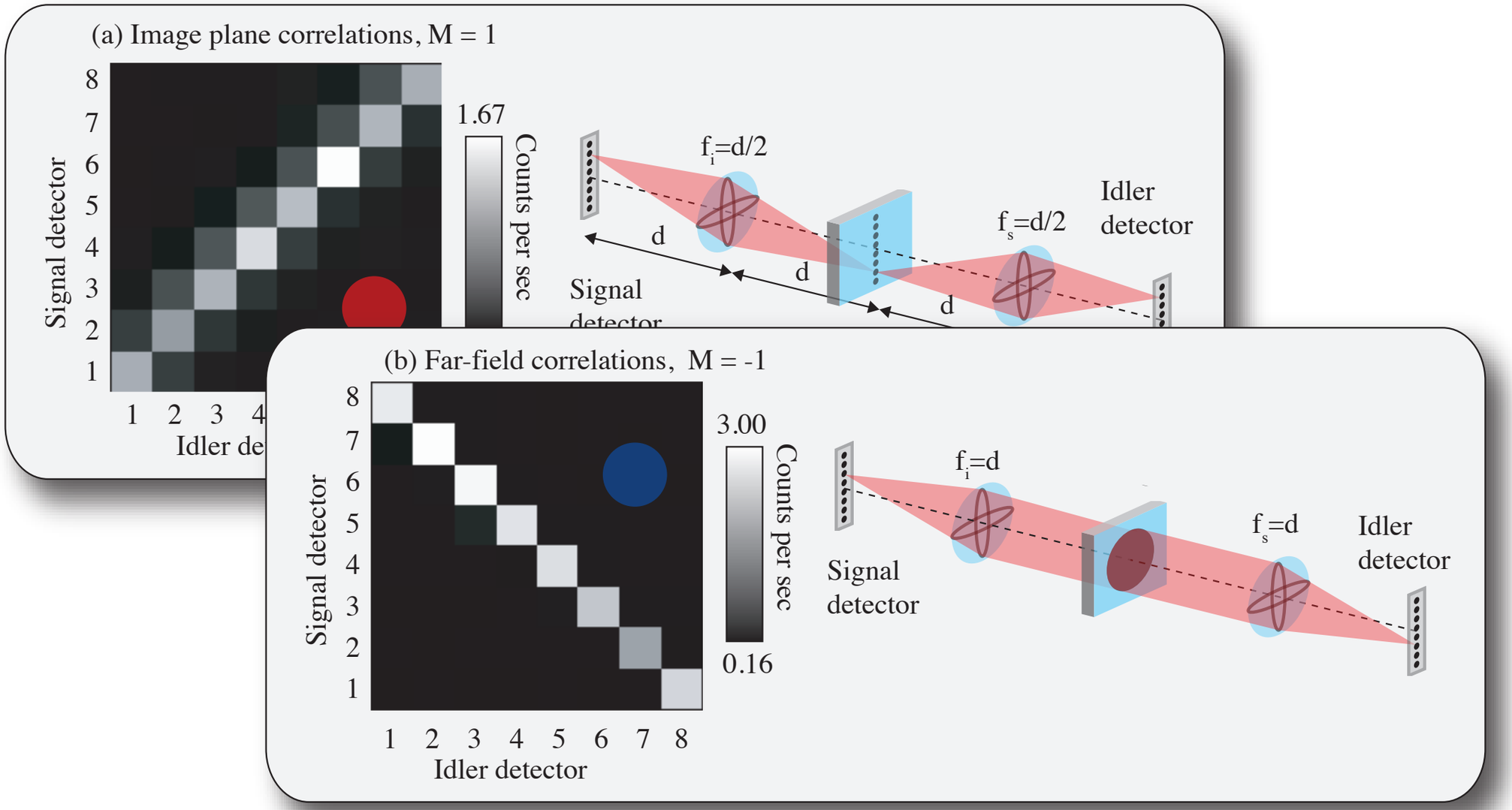

f_i=d/2
f_s=d/2
Idler detector
d
d
d
d
Signal detector
BBO crystal

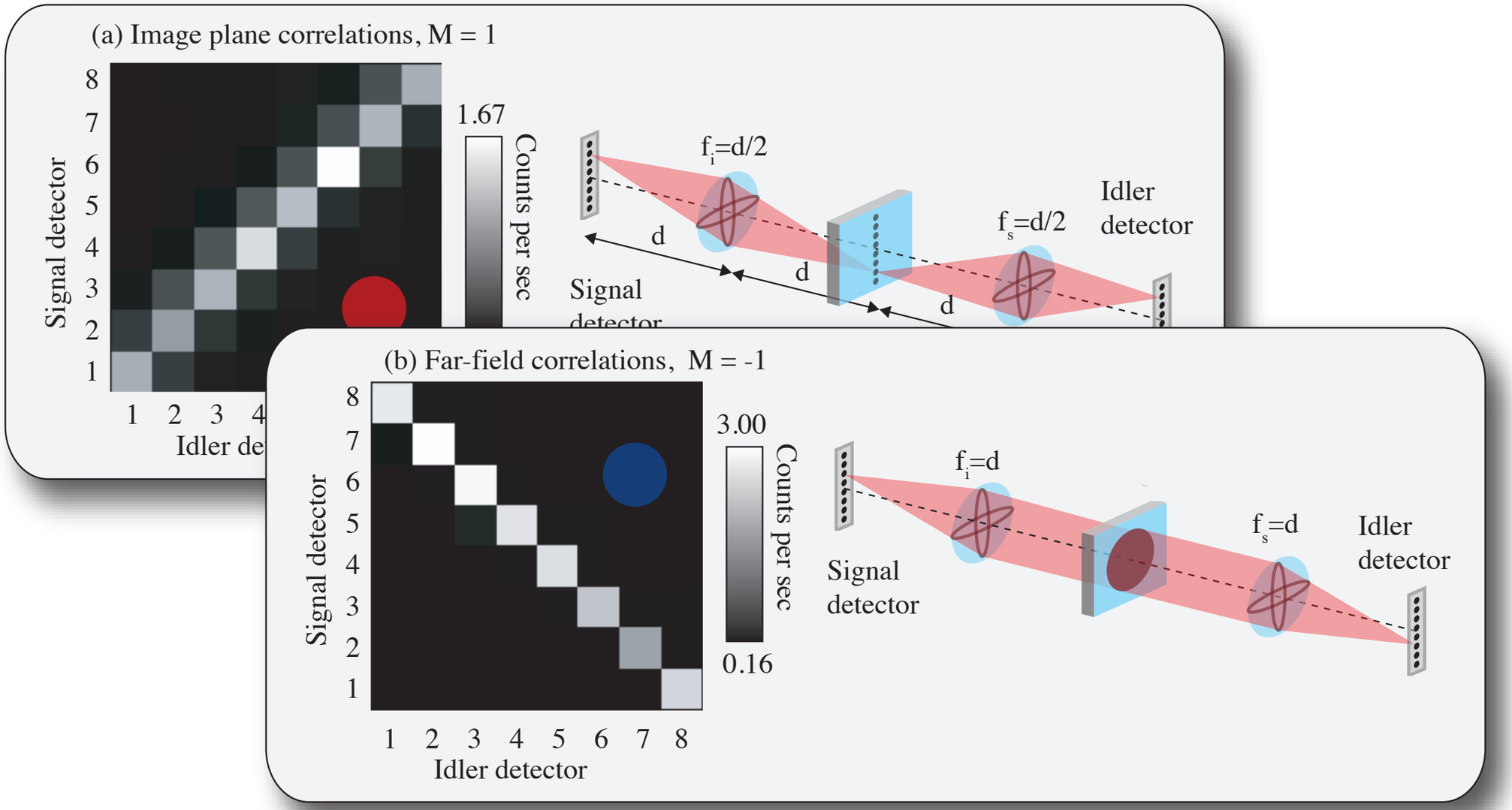

50µm
125µm
1m
2m
3m
4m
5m
6m
7m
8m
Optical delays
Fibre combiner
Fibre combiner
SPAD
SPAD
Start
Stop
TAC
10m
19m
28m
37m
46m
55m
64m
73m
Optical delays


Signal
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7 8
Idler

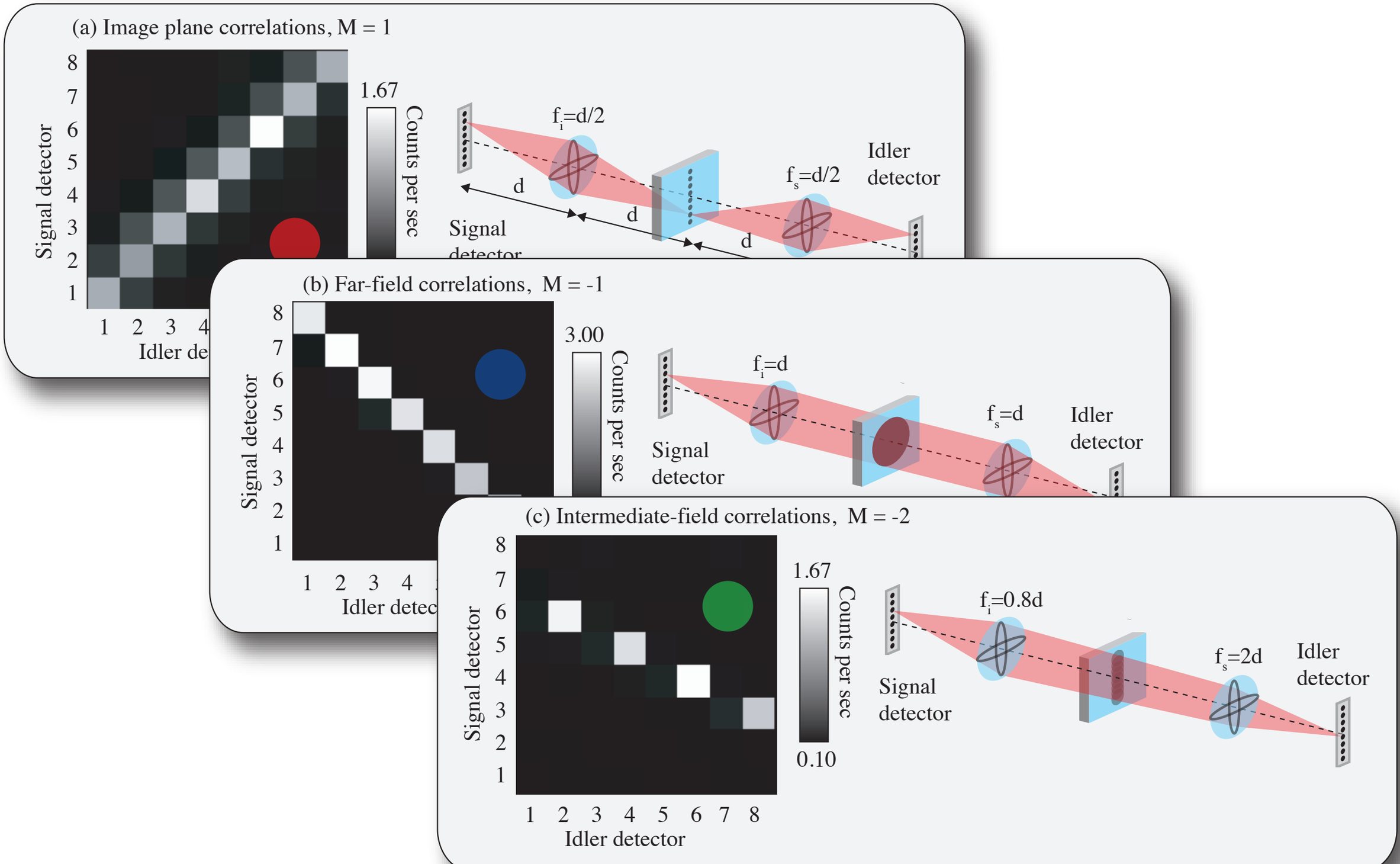

f_i=d
Signal detector
Signal
8
7
6
1
1 2 3 4 5 6 7 8
Idler
Idler detector


(a) Image plane correlations, M = 1
Signal detector
Idler detector
1.67
0.20
Counts per sec
f_i=d/2
f_s=d/2
d
Signal detector
BBO crystal
Idler detector


(a) Image plane correlations, M = 1
Signal detector
Idler de
1.67
Counts per sec
f_i=d/2
f_s=d/2
d
d
d
Idler detector
Signal detector
(b) Far-field correlations, M = -1
Signal detector
Idler detector
3.00
0.16
Counts per sec
f_i=d
f_s=d
Signal detector
Idler detector



$$(\Delta_{\text{inf}} x_s)^2 (\Delta_{\text{inf}} p_{x_s})^2 = 0.023\hbar$$


(a) Image plane correlations, M = 1
Signal detector
Idler de
1.67
Counts per sec
f_i=d/2
f_s=d/2
d
d
d
Signal detector
Idler detector
(b) Far-field correlations, M = -1
Signal detector
Idler detec
3.00
Counts per sec
f_i=d
f_s=d
Signal detector
Idler detector
(c) Intermediate-field correlations, M = -2
Signal detector
Idler detector
1.67
0.10
Counts per sec
f_i=0.8d
f_s=2d
Signal detector
Idler detector

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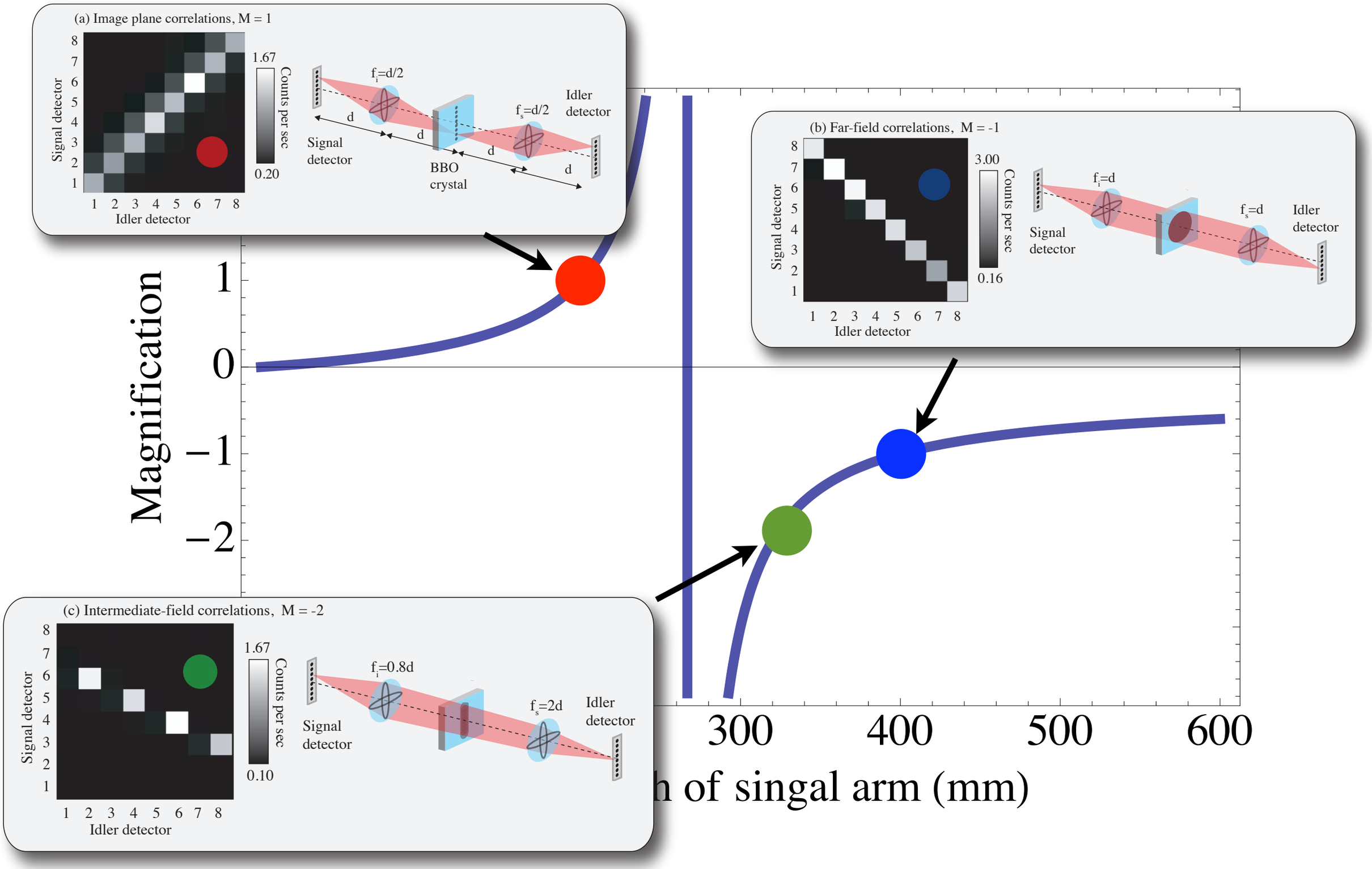
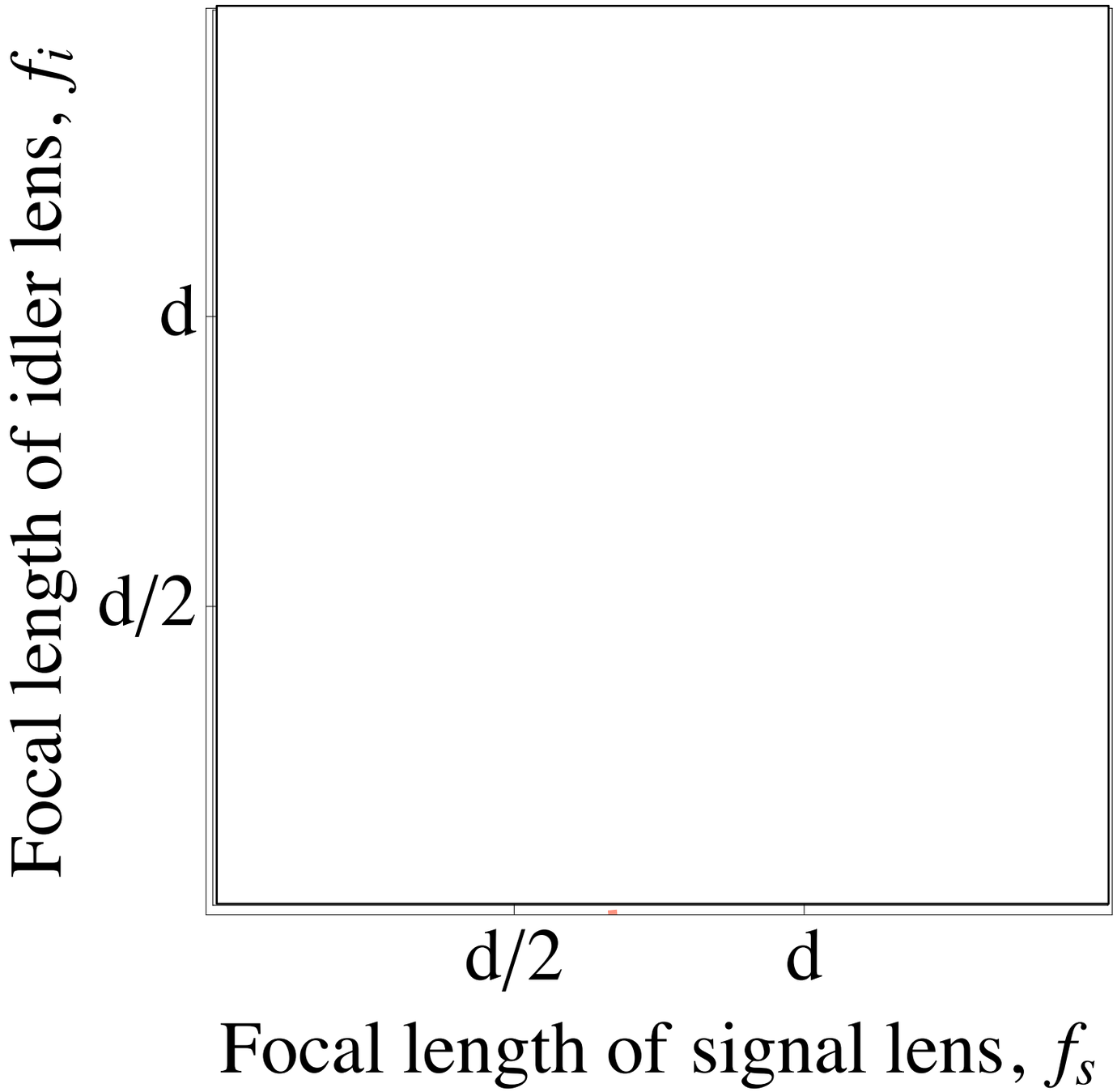
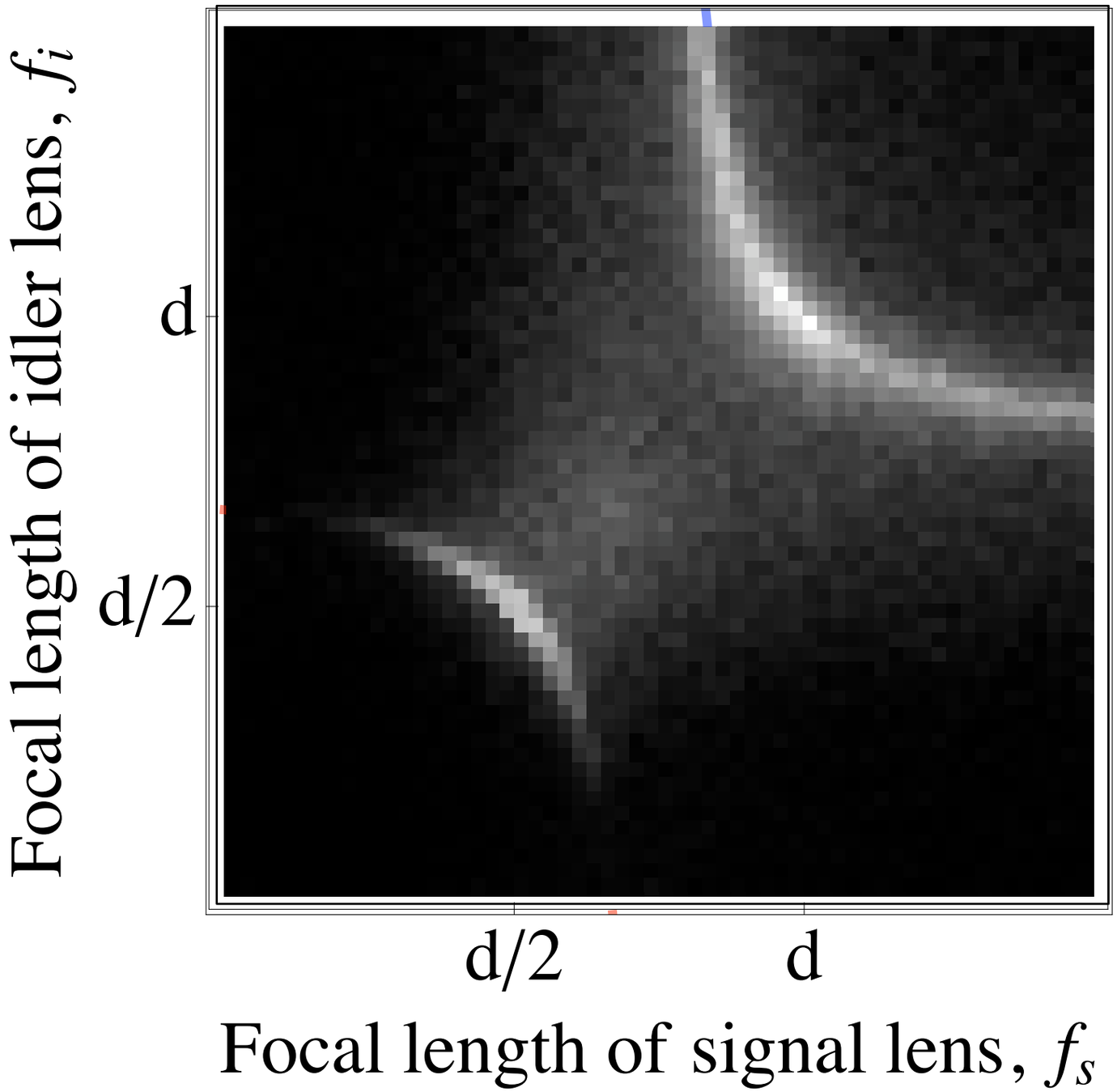
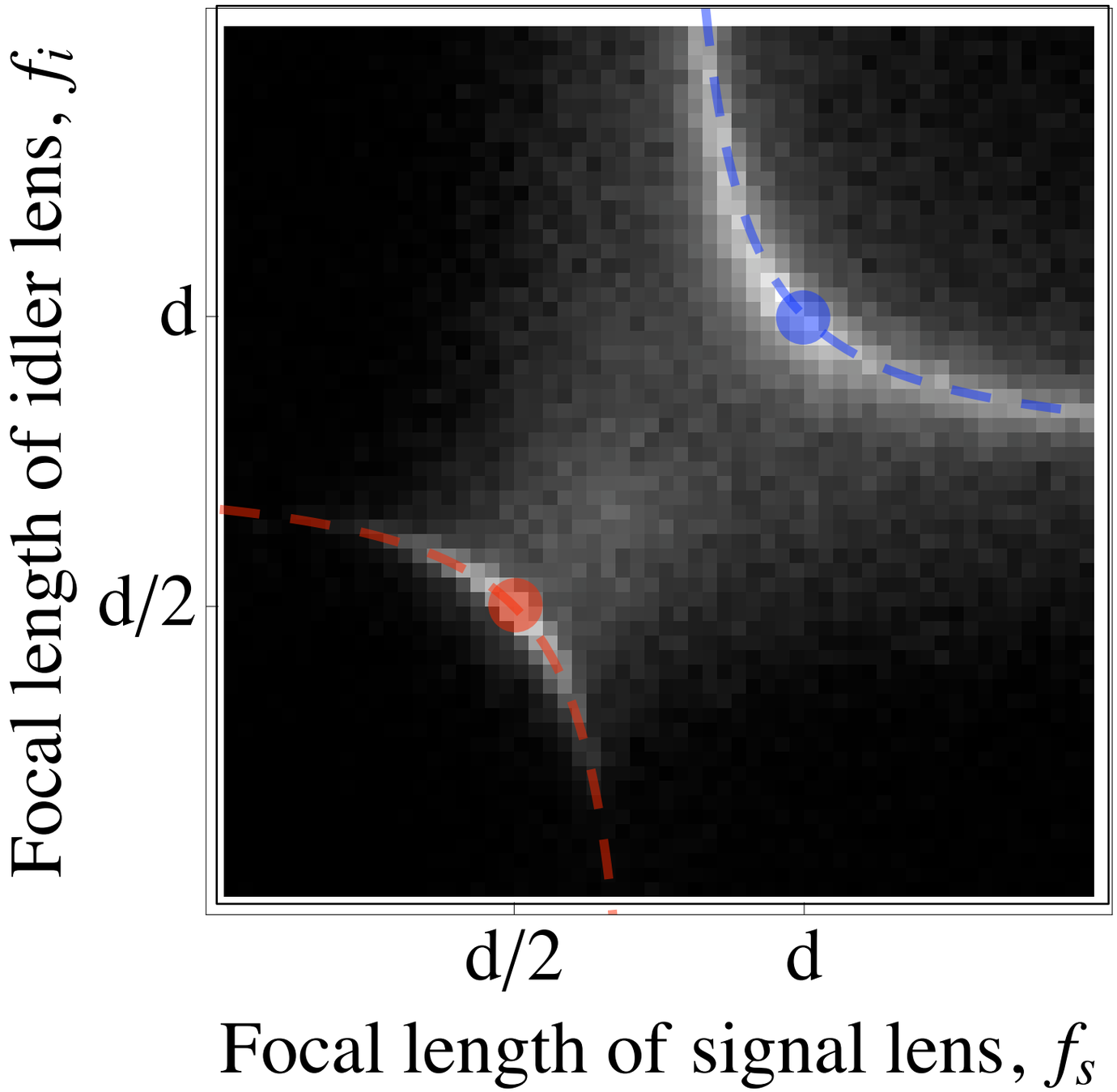
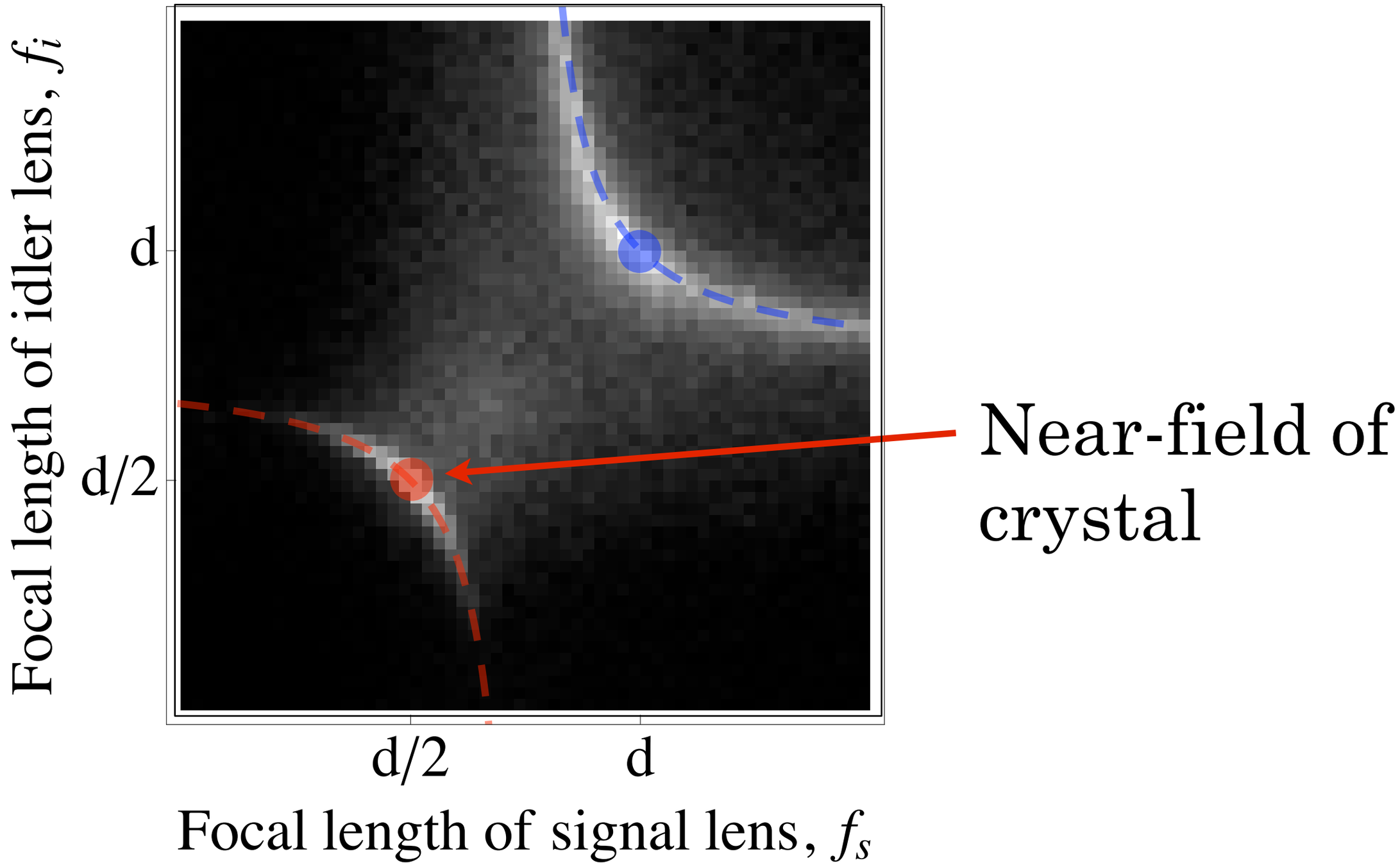
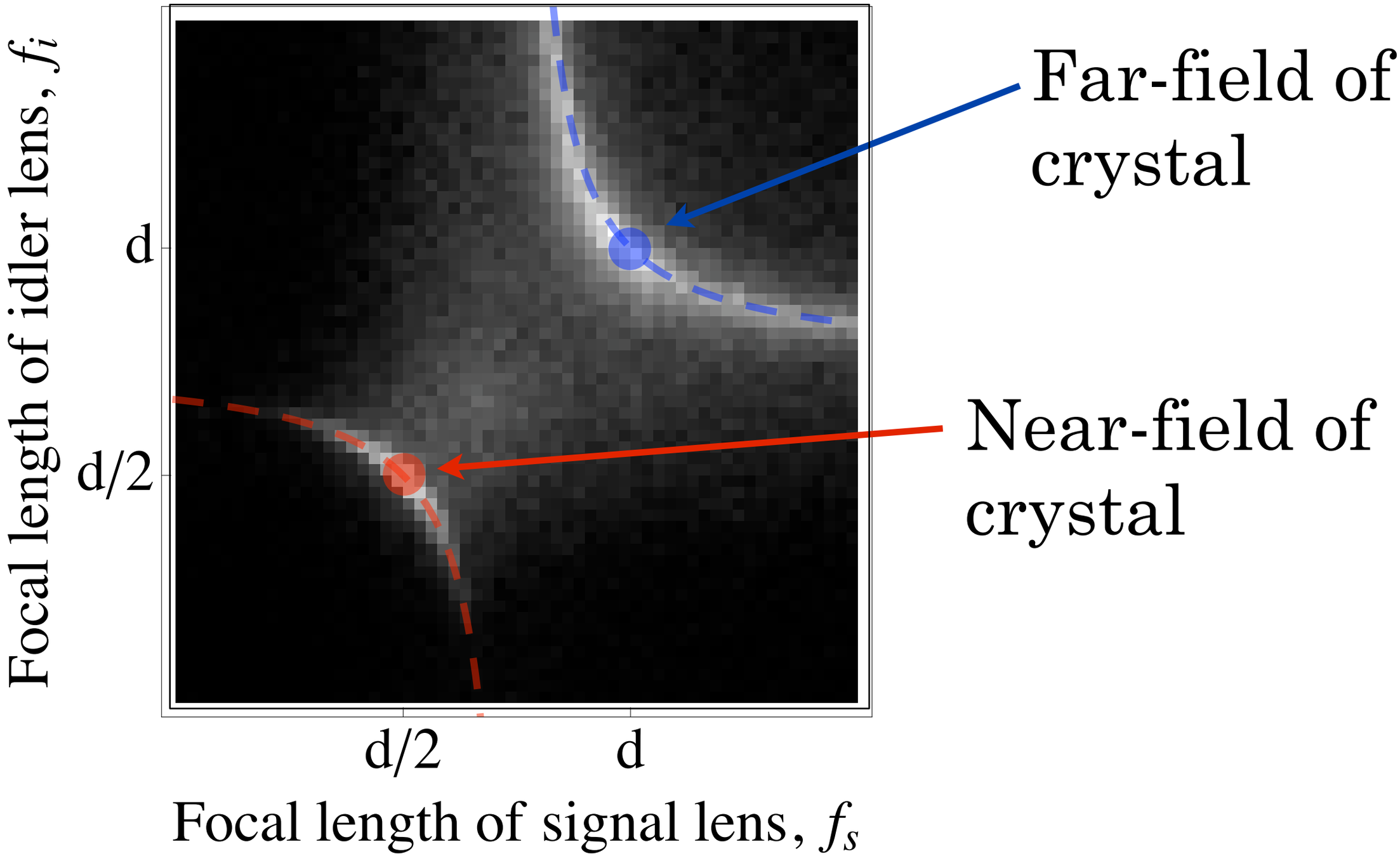

(a) Image plane correlations, M = 1
Signal detector
Idler detector
1.67
0.20
Counts per sec
f_i=d/2
f_s=d/2
Signal detector
BBO crystal
Idler detector
d
(b) Far-field correlations, M = -1
3.00
0.16
f_i=d
f_s=d
(c) Intermediate-field correlations, M = -2
1.67
0.10
f_i=0.8d
f_s=2d
Magnification
1
0
−1
−2
300
400
500
600
h of singal arm (mm)

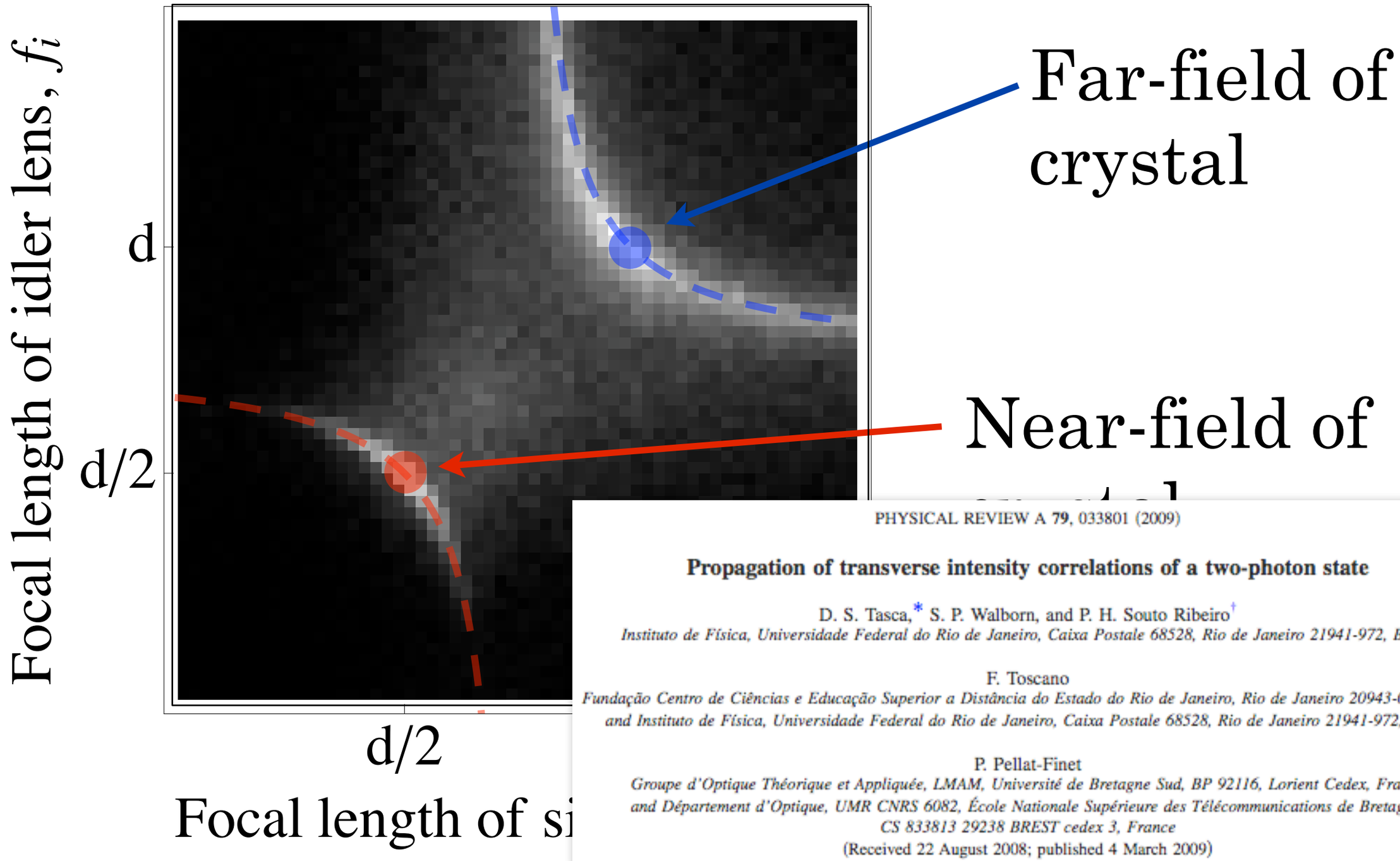

Focal length of idler lens, f_i
d
d/2
d/2
d
Focal length of signal lens, f_s


Focal length of idler lens, f_i
d
d/2
d/2
d
Focal length of signal lens, f_s


Focal length of idler lens, f_i
d
d/2
d/2
d
Focal length of signal lens, f_s


Focal length of idler lens, f_i
d
d/2
d/2
d
Focal length of signal lens, f_s
Near-field of crystal


Far-field of crystal
Near-field of crystal
Focal length of idler lens, f_i
d
d/2
d/2
d
Focal length of signal lens, f_s



PHYSICAL REVIEW A **79**, 033801 (2009)

Propagation of transverse intensity correlations of a two-photon state

D. S. Tasca,* S. P. Walborn, and P. H. Souto Ribeiro†
Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postale 68528, Rio de Janeiro 21941-972, Brazil

F. Toscano
Fundação Centro de Ciências e Educação Superior a Distância do Estado do Rio de Janeiro, Rio de Janeiro 20943-001, Brazil and Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postale 68528, Rio de Janeiro 21941-972, Brazil

P. Pellat-Finet
Groupe d'Optique Théorique et Appliquée, LMAM, Université de Bretagne Sud, BP 92116, Lorient Cedex, France and Département d'Optique, UMR CNRS 6082, École Nationale Supérieure des Télécommunications de Bretagne, CS 833813 29238 BREST cedex 3, France
(Received 22 August 2008; published 4 March 2009)

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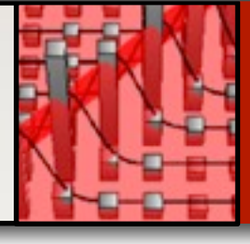
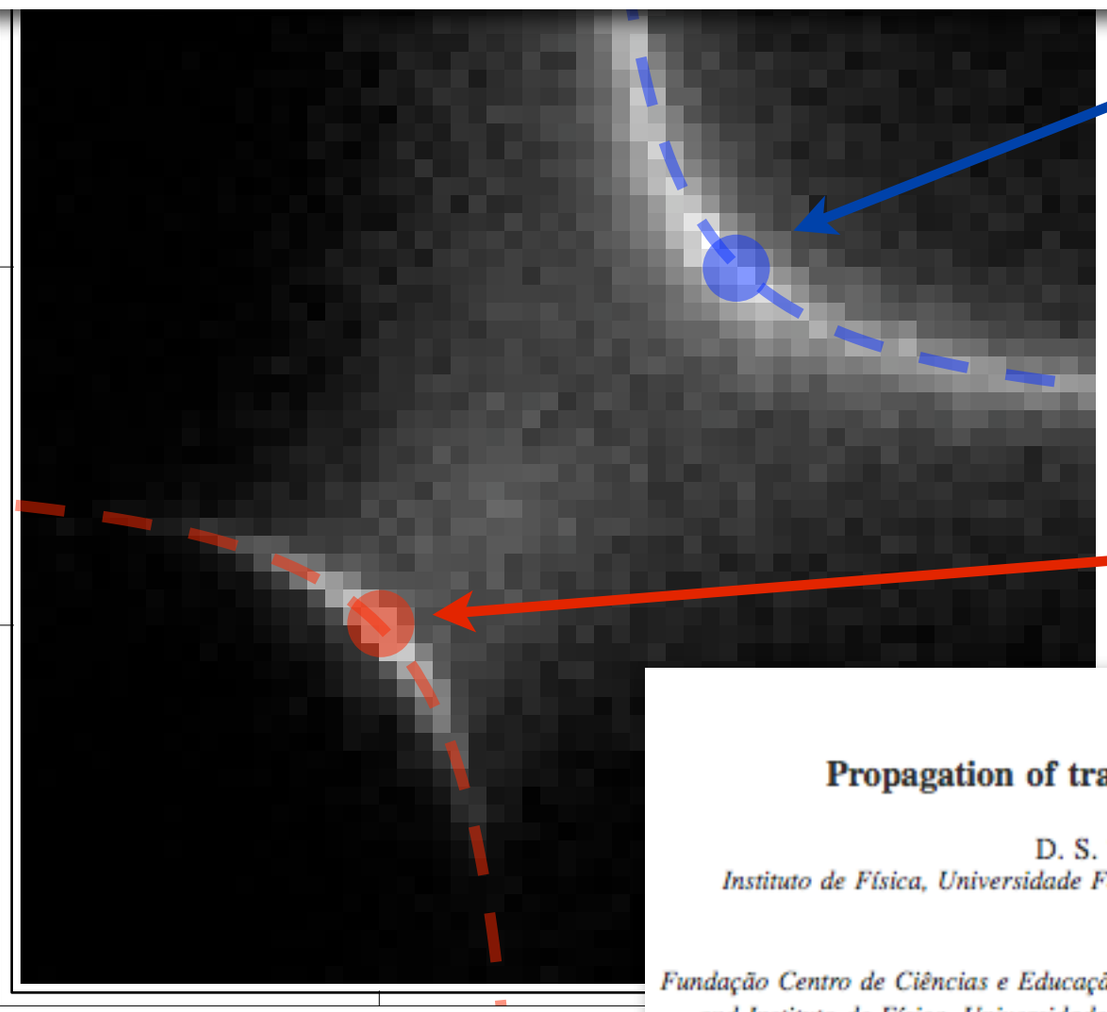


PHYSICAL REVIEW A VOLUME 53, NUMBER 4 APRIL 1996

Two-photon geometric optics

T. B. Pittman, D. V. Strekalov, D. N. Klyshko,* M. H. Rubin, A. V. Sergienko, and Y. H. Shih
Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228
(Received 10 October 1995)



Far-field of crystal

Near-field of

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Fundação Centro de Ciências e Educação Superior a Distância do Estado do Rio de Janeiro, Rio de Janeiro 20943-001, Brazil and Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postale 68528, Rio de Janeiro 21941-972, Brazil

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Groupe d'Optique Théorique et Appliquée, LMAM, Université de Bretagne Sud, BP 92116, Lorient Cedex, France and Département d'Optique, UMR CNRS 6082, École Nationale Supérieure des Télécommunications de Bretagne, CS 833813 29238 BREST cedex 3, France
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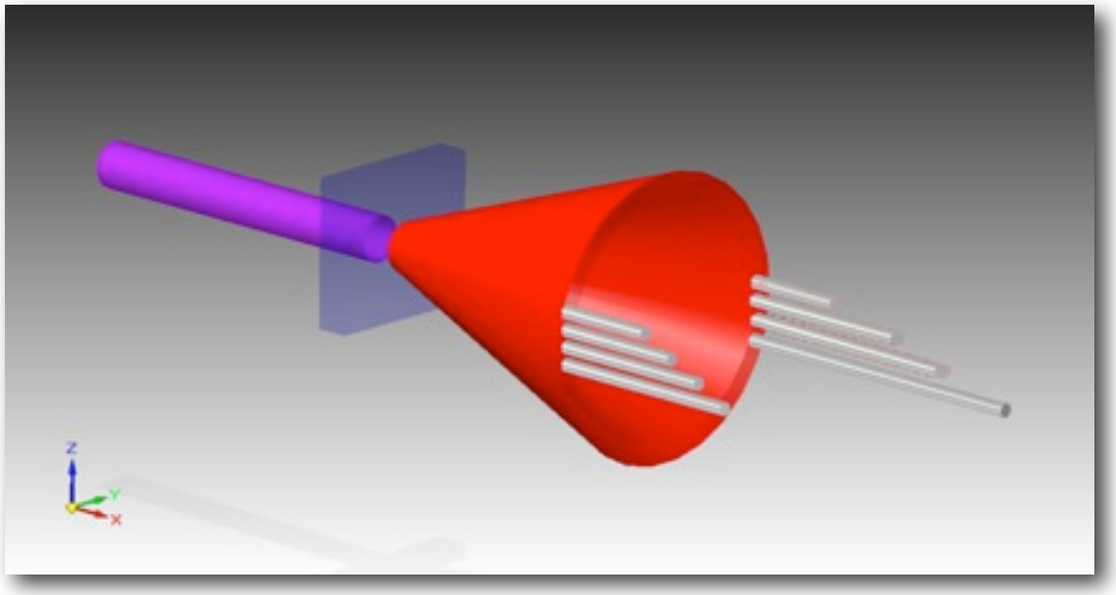
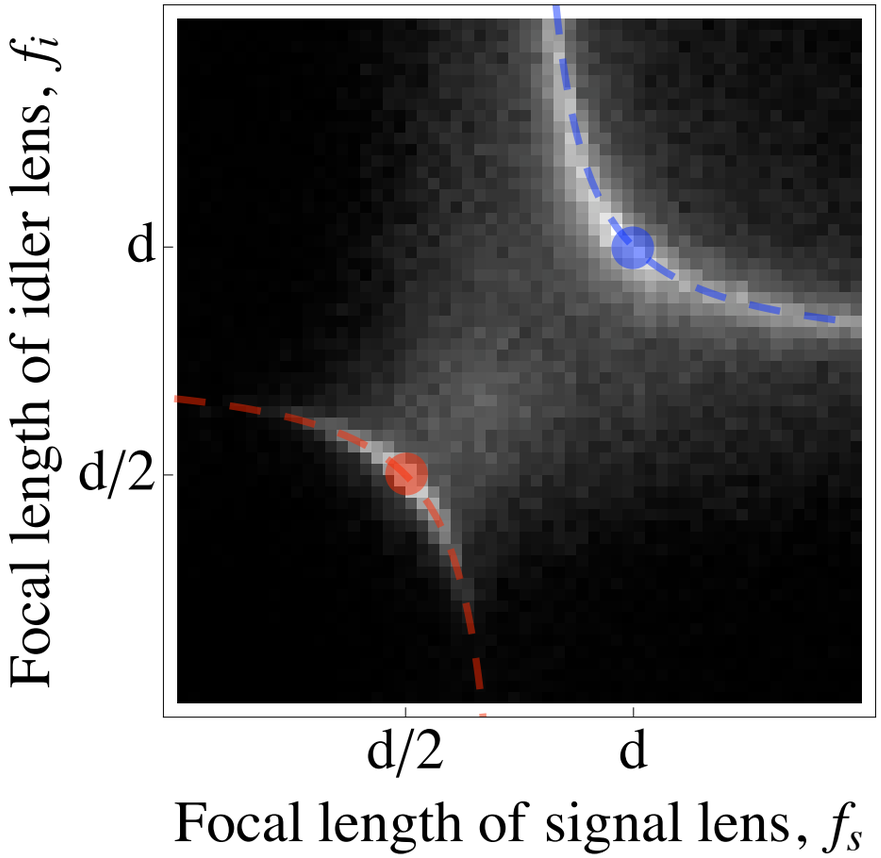
Our multi-pixel linear array, single photon detector allows to make.....

- a demonstration of spatial EPR in which the strength of the position or momentum is measured without scanning any of the optical or electronic system
- measure the correlations in the near-field, far-field and intermediate planes

What is the significance of how the correlations change as we move from the near-field to the far-field?

- the polarisation analogy has implications for locality and hidden variable theories





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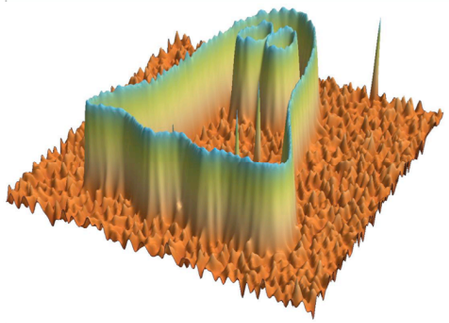
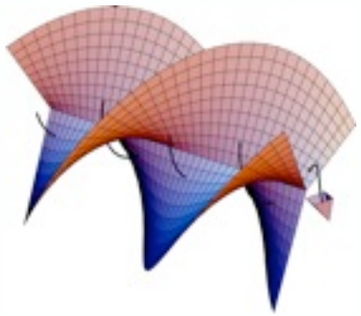


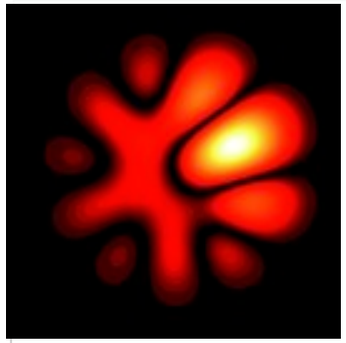
Holographic ghost imaging

Violations of Bell's inequality
Can a single image violate this?



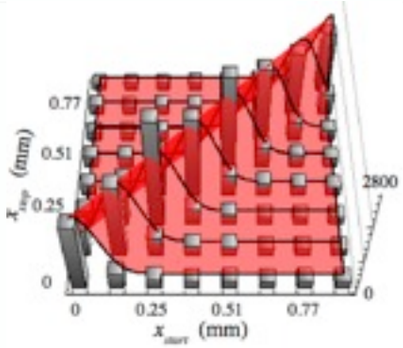
EPR correlations in the OAM/angle basis

QKD with spatial states
How best to maximise bit/photon?
Optimal basis for measurements?



Violations of generalized Bell inequalities

Differences between EPR/Bell?
How best to characterise states?



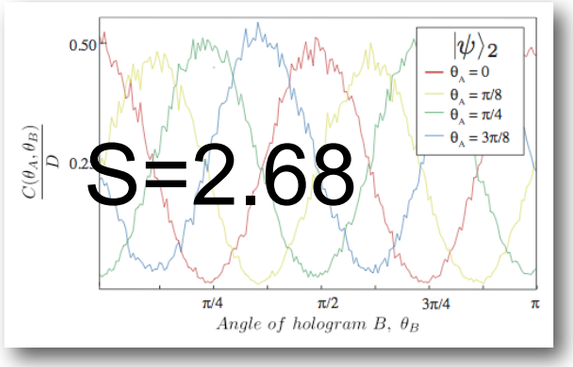
Full-field quantum measurements

Power of SLM for quantum optics
Implications for Bell's inequalities?

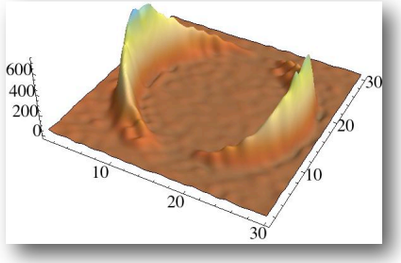
Questions

What is ghost imaging?
Is this a quantum effect?

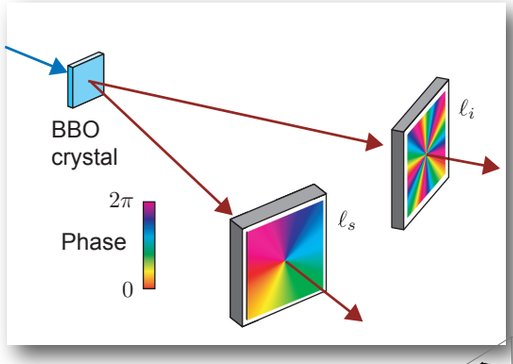
What is required to show a non-local quantum effect?



Is our image the result of a quantum effect?



What is the angular EPR paradox?
What is required to demonstrate this?



What is the difference between
- violating a Bell-type inequality
- demonstrating EPR correlations?