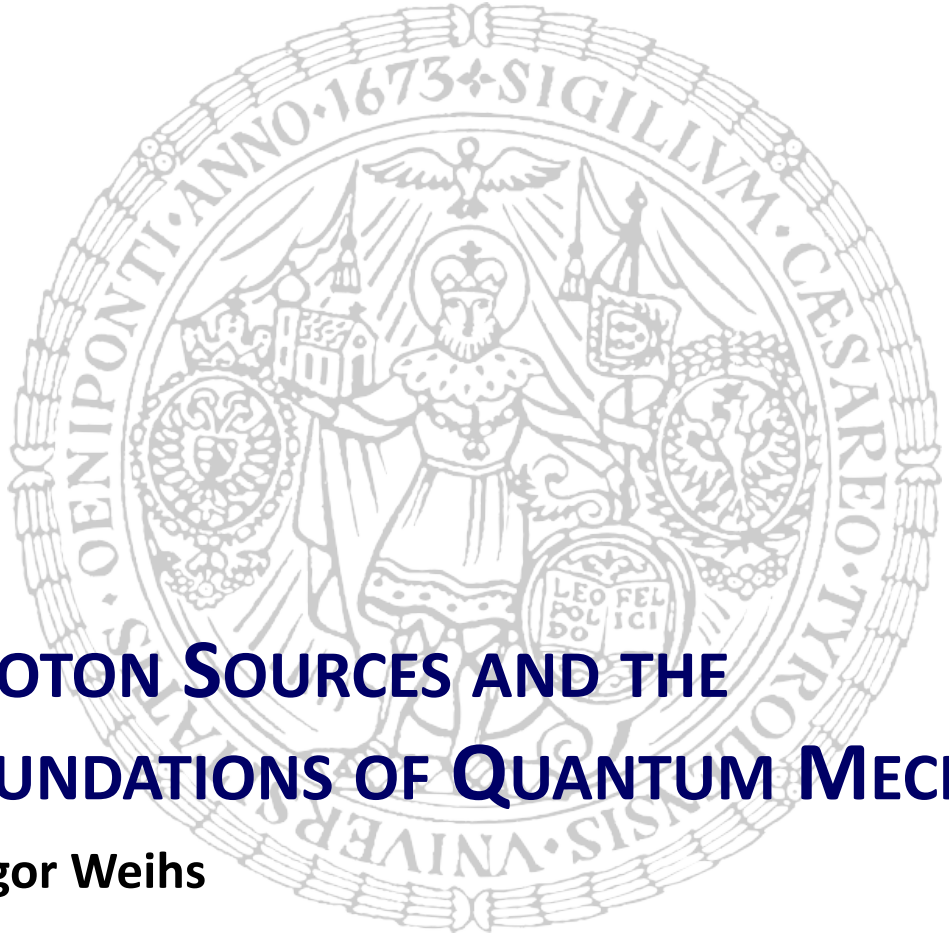
esf european social fund in the czech republic
EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT



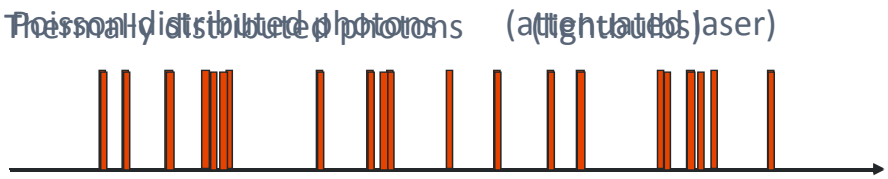
Photon Sources and the Foundations of Quantum Mechanics

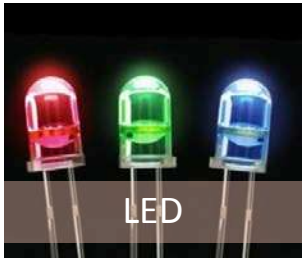
Gregor Weihs

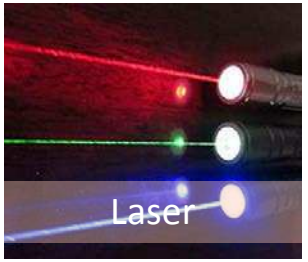
Institute for Experimental Physics - University of Innsbruck
Institute for Quantum Computing – University of Waterloo

Classical and Nonclassical Light

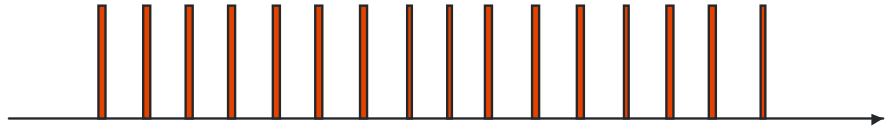
- Classical Light
  - Lightbulbs
  - LEDs
  - Lasers

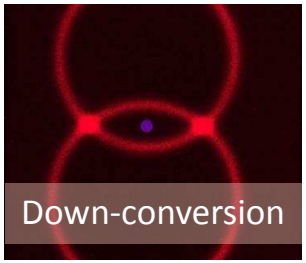


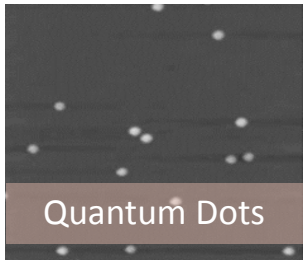




- Nonclassical light
  - Fock states (single photons,…)
  - Squeezed light
  - Entangled states



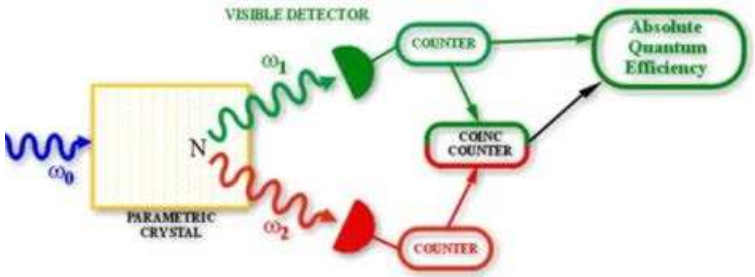




„Classical“ Applications of Nonclassical Light

Radiometry

Absolute detection efficiency measurement



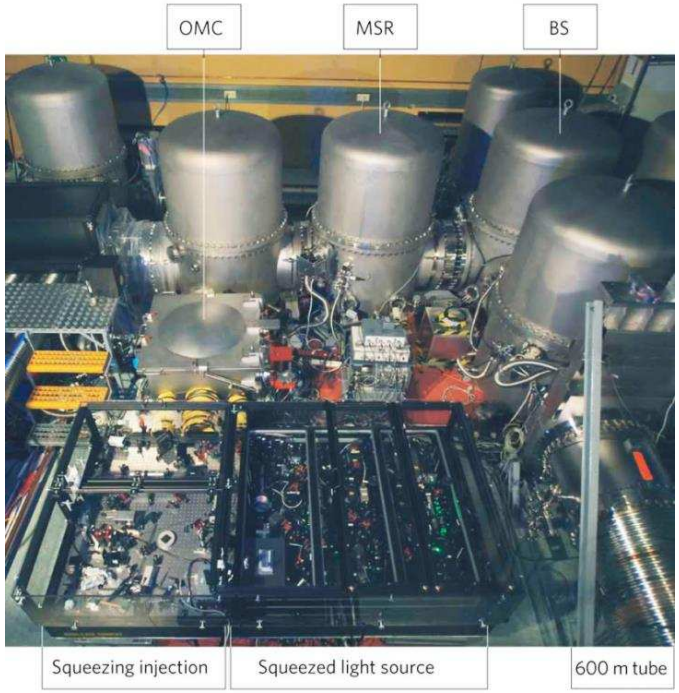
$N_1 = \eta_1 N \qquad N_2 = \eta_2 N \qquad N_C = \eta_1 \eta_2 N$

$$\eta_1 = \frac{N_C}{N_2}$$

www.nist.gov/pml/div684/grp03/quantum_correlated.cfm

Metrology

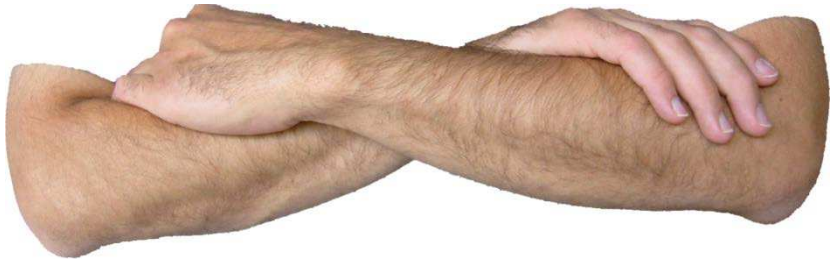
Sensitivity enhancement of gravitational wave detection



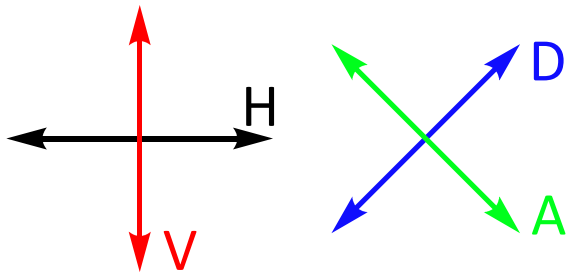
Nat Phys **7**, 962 (2011)

ENTANGLEMENT

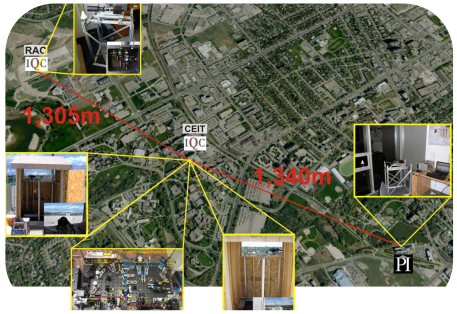
$$|\psi\rangle = \frac{1}{\sqrt{2}}[|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2]$$



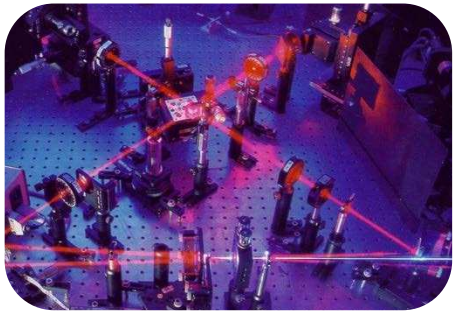
$$|H\rangle|H\rangle + |V\rangle|V\rangle = |D\rangle|D\rangle + |A\rangle|A\rangle$$



Applications of Entanglement

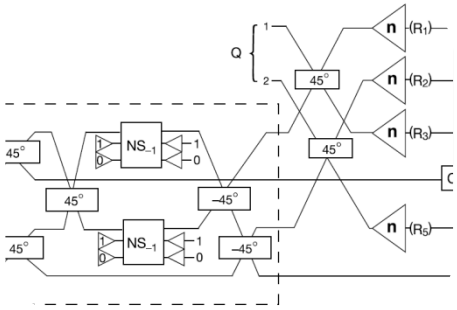


Quantum Cryptography

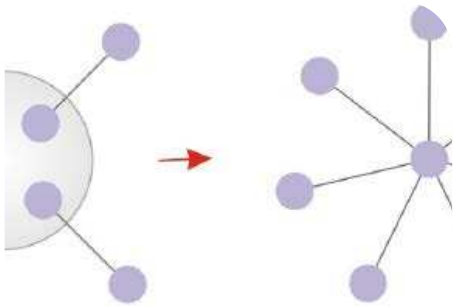


Teleportation

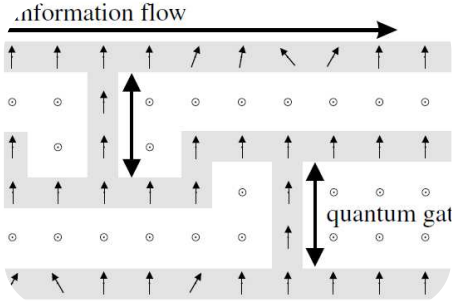
Purification



Linear Optical Quantum Computing



Multipartite Entanglement



Measurement-based Quantum Computing

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- GHZ
- Mermin inequality
- Loopholes and how to close them

Group

Waveguides
Rolf Horn, Kaisa Laiho
Thomas Günthner, Benedikt Pressl
Matthias Covi

Quantum dots
Ana Predojevic
Hari Jayakumar, Tobias Huber,
Lorenz Butschek

Multipath Interference
Robert Keit
Thomas Kauten, Benjamin
Gschösser, Thomas Kaufmann

Collaborations and funding

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(U. Waterloo)

Sven Höfling,
Christian Schneider
(U. Würzburg)

Stephan Reitzenstein
(TU Berlin)

Quantum dots

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(U. Innsbruck)

Hashem Zoubi
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(U. Olomouc)

H. Majedi, M. Koshnekar
(U. Waterloo)

Multipath Interference

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Urbasi Sinha
(RRI Bangalore)

Alex Szameit
(U. Jena)

erc

FWF
Der Wissenschaftsfonds.

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

ÖAW
Österreichische Akademie der Wissenschaften

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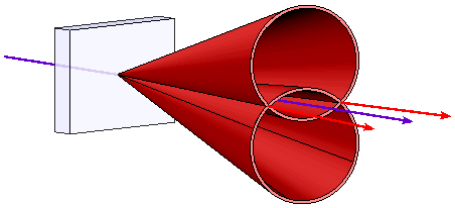
Semiconductor Sources for Integration

+



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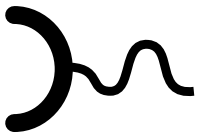
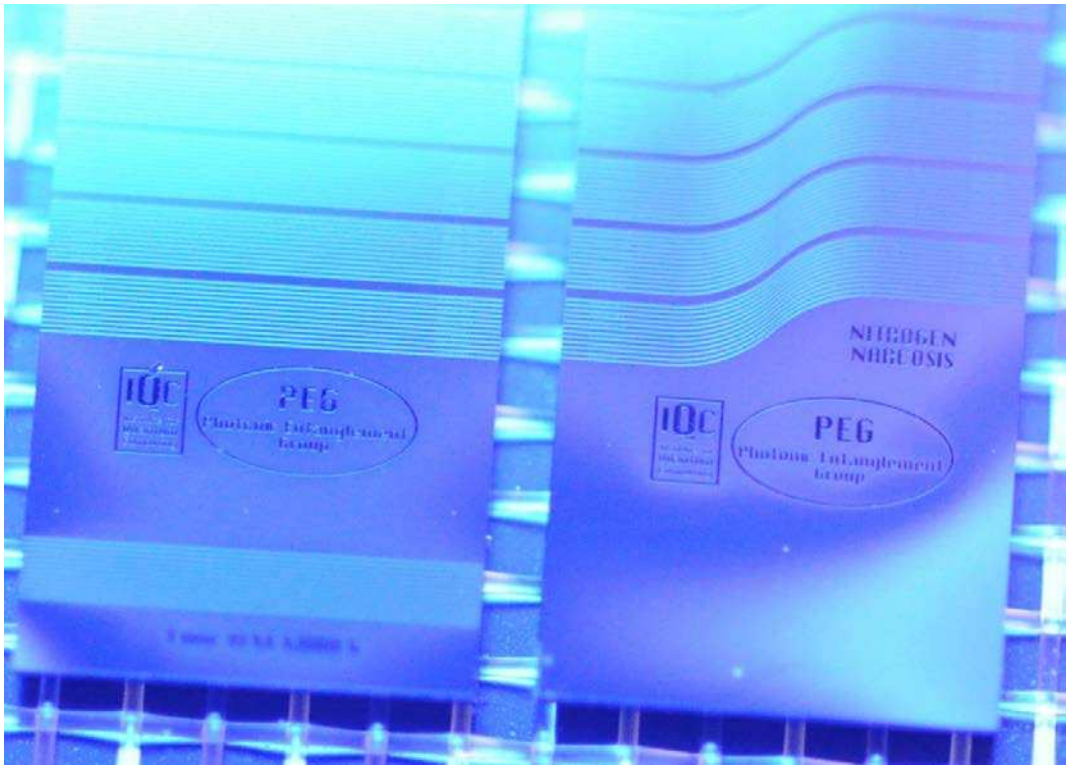
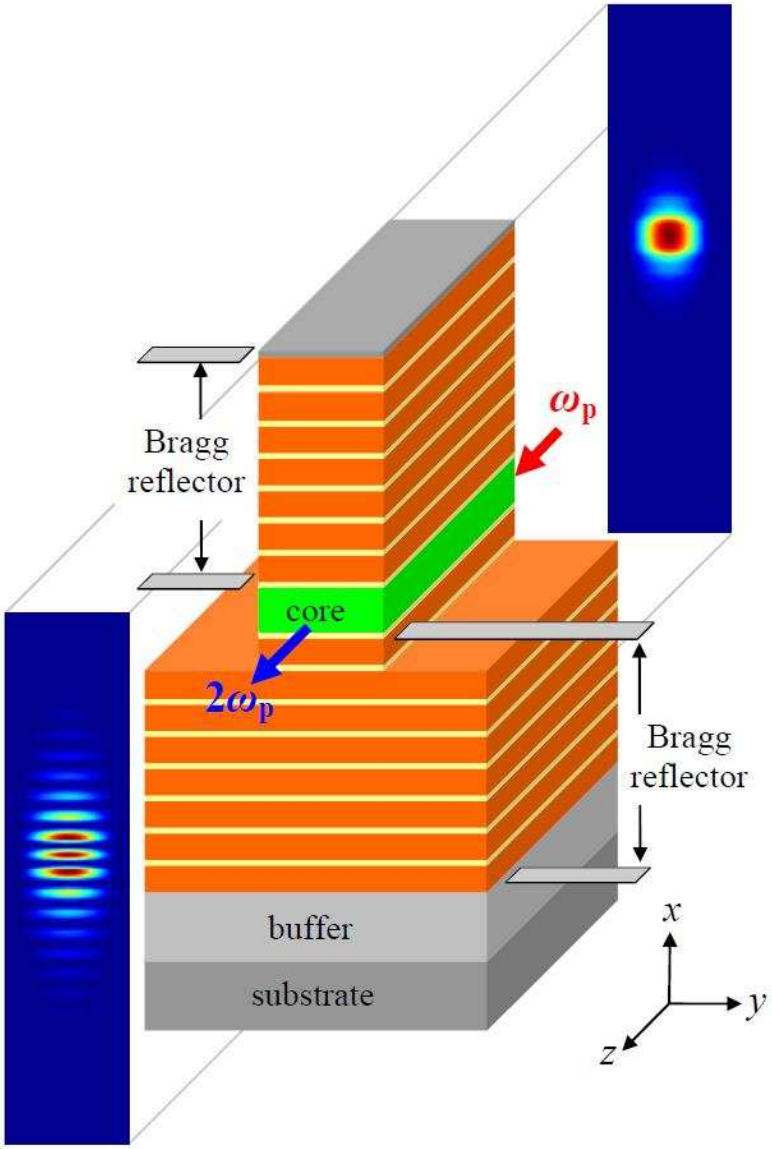
+



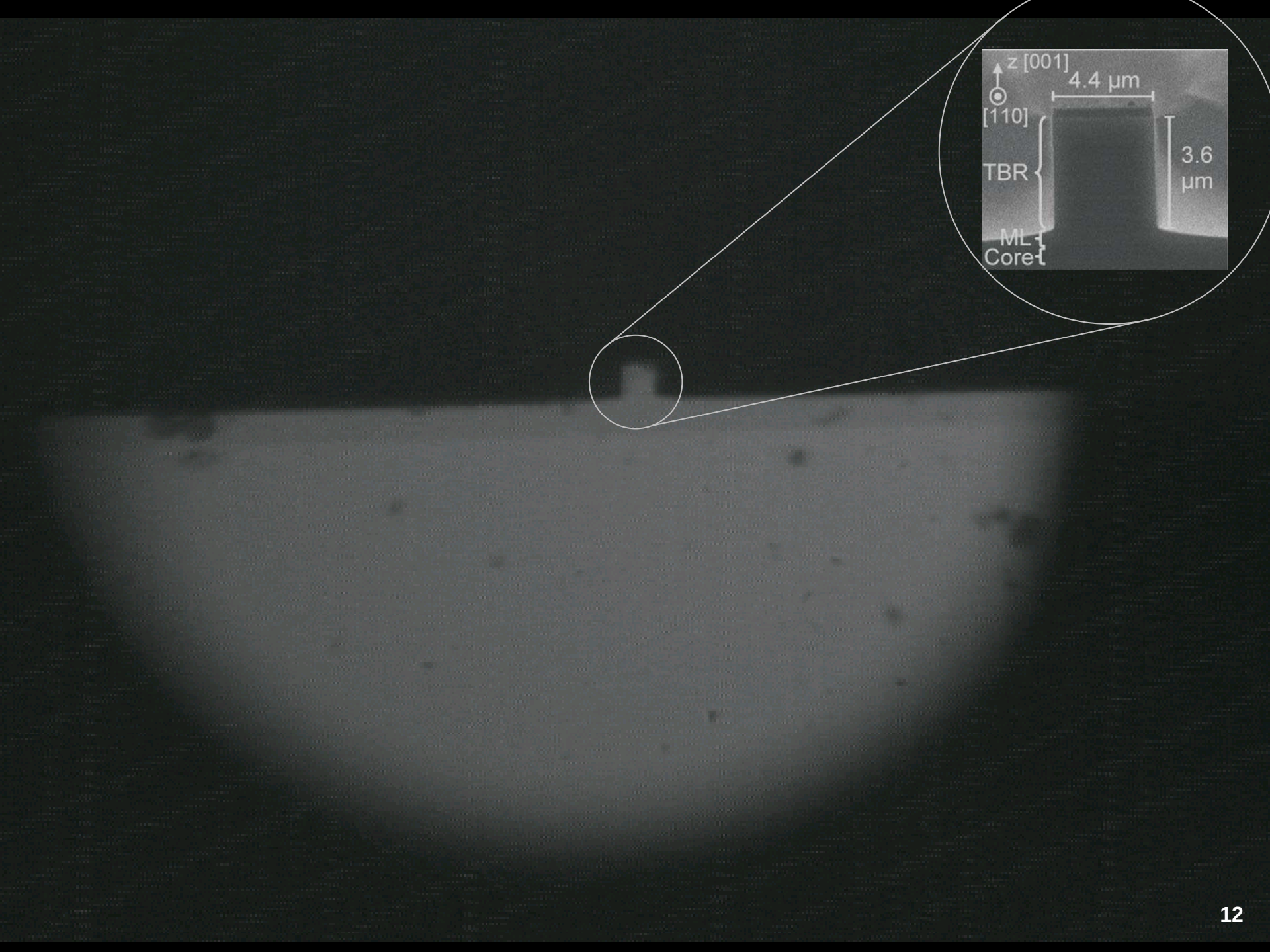


Bragg-Reflection Waveguides

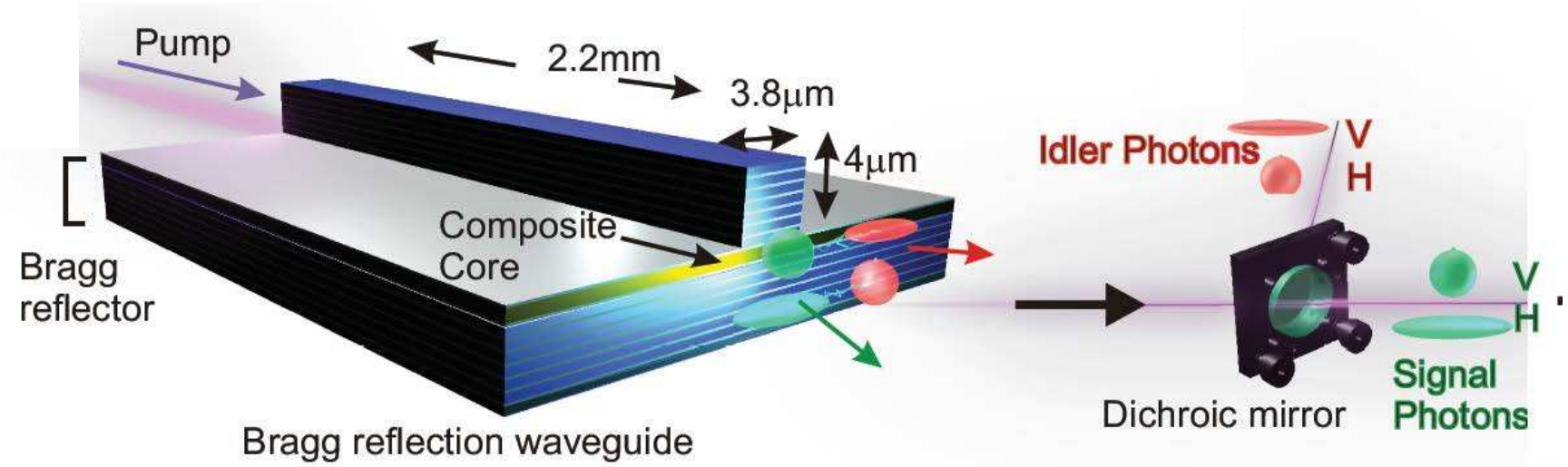


- Transverse Bragg reflector introduces additional guided mode with much lower effective index
- Bragg mode at 2ω can match regular index guided mode at ω
- No periodicity in propagation direction, i.e. no QPM

Yeh & Yariv, Opt. Comm. **19,** 427 (1976);
Helmy et al., Opt. Lett. **32,** 2399 (2007);
Abolghasem et al., IEEE Photon. Tech. Lett. **21,** 1462 (2009).


z [001]
[110]
4.4 µm
3.6 µm
TBR
ML
Core

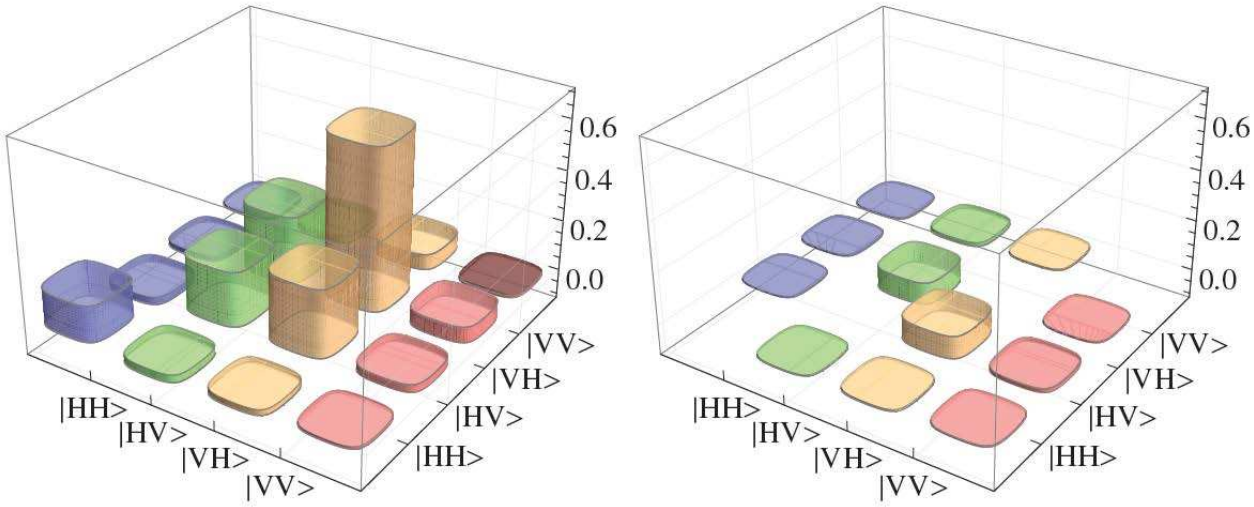
EXPERIMENT



- Produce non-degenerate polarization entanglement
- Use dichroic splitter near central wavelength

R. Horn et al., Sci. Rep. **3**, 2314 (2013).

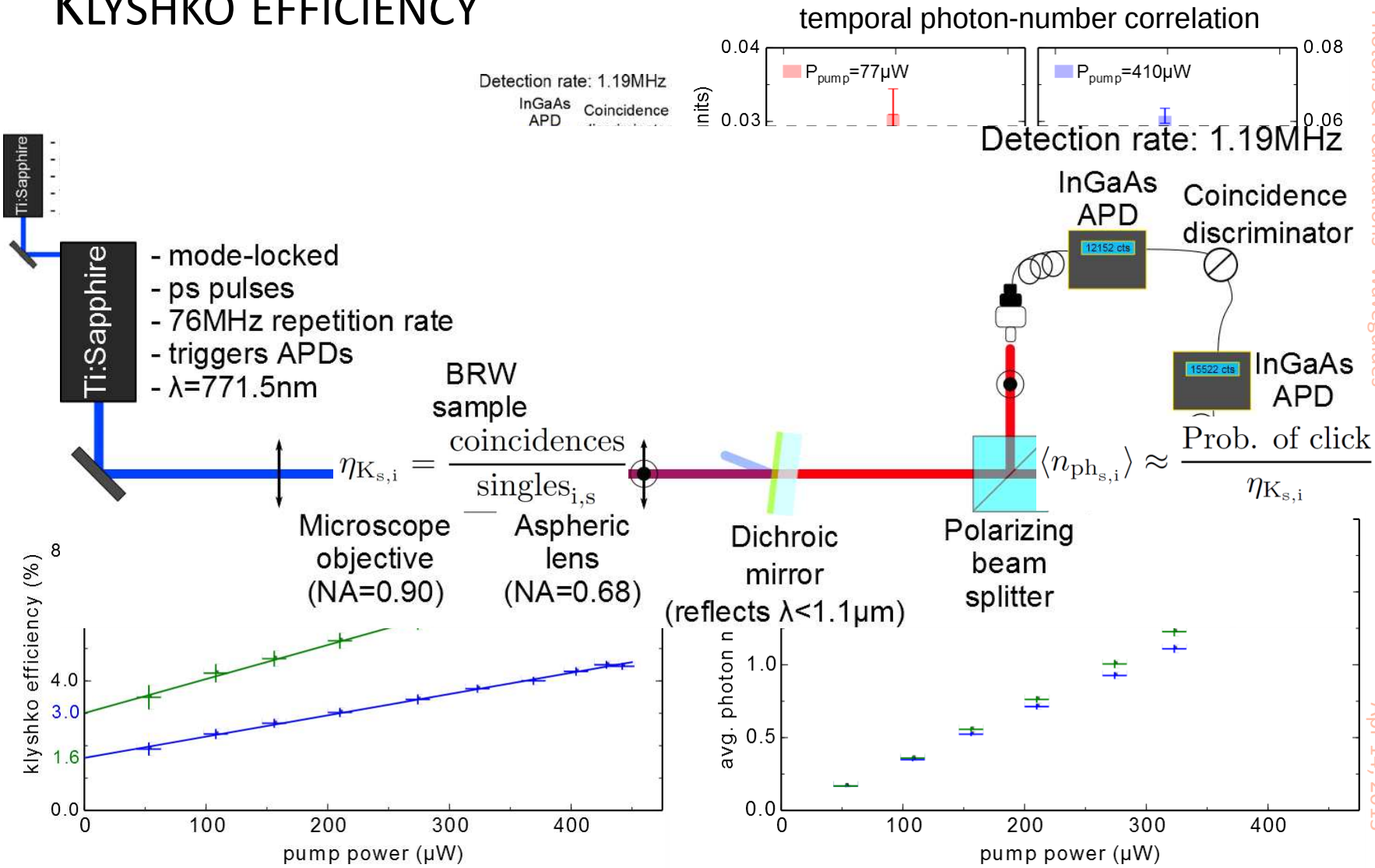
Polarization entanglement



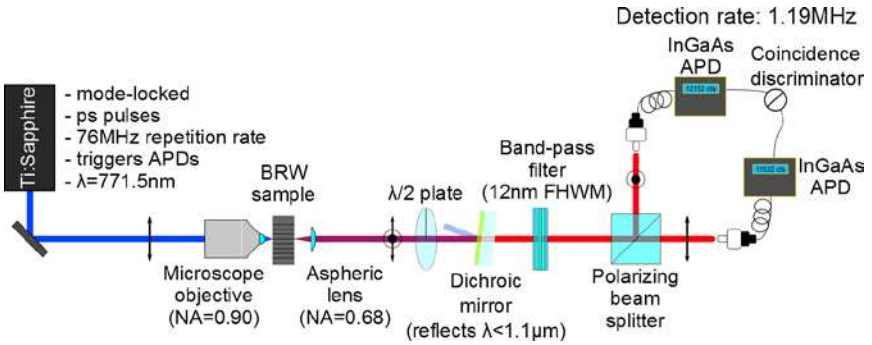
- Pronounced HH background
- Concurrence 0.52
- Fidelity to Ψ^+: 0.83

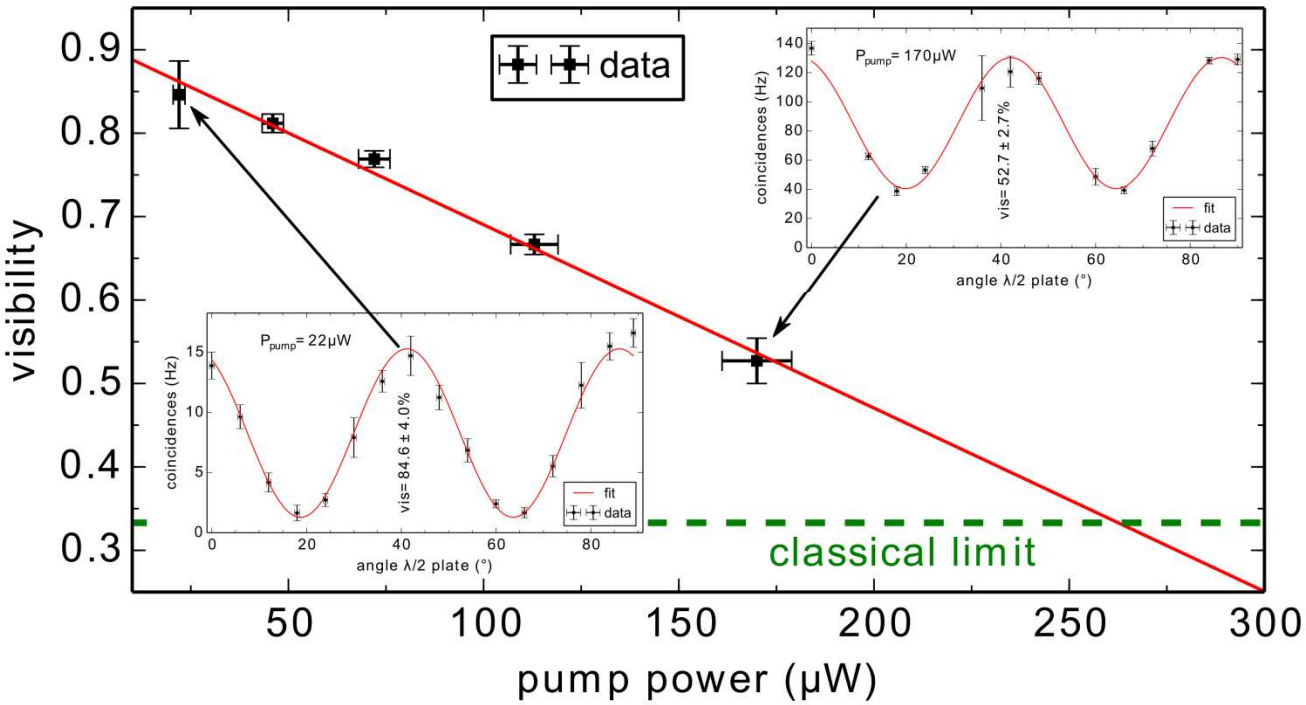
R. Horn et al., Sci. Rep. **3**, 2314 (2013).

KLYSHKO EFFICIENCY



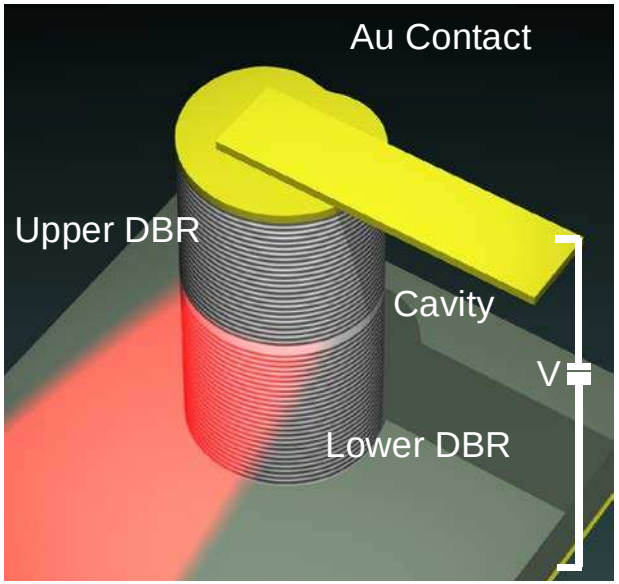
POLARIZATION HONG-OU-MANDEL

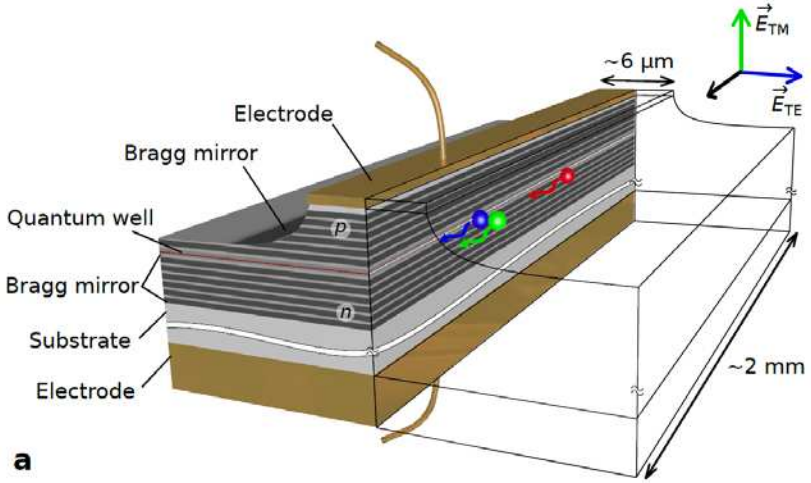




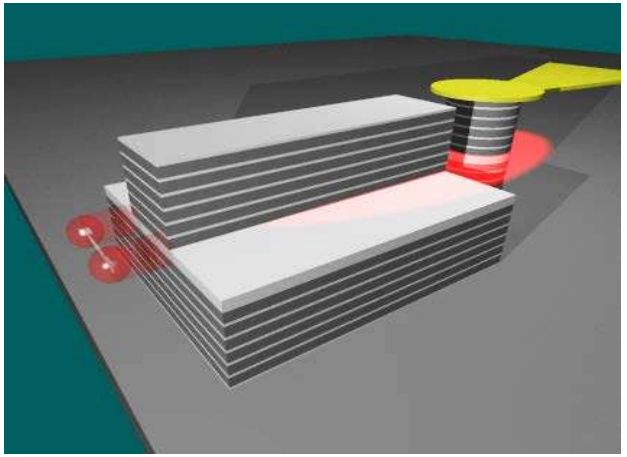
Integrating a laser on the chip

- Whispering Gallery Mode lasers
  - Limaçon shape for directed emission
  - Quantum dots or wells as gain medium
- Fabry-Perot laser + SPDC demonstrated (Paris)





From Boitier et al., arXiv:1312.6137



Pictures C. Schneider, S. Reitzenstein

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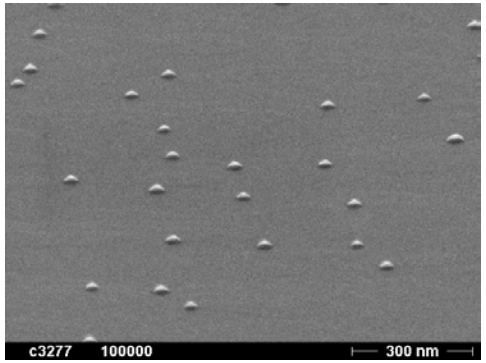
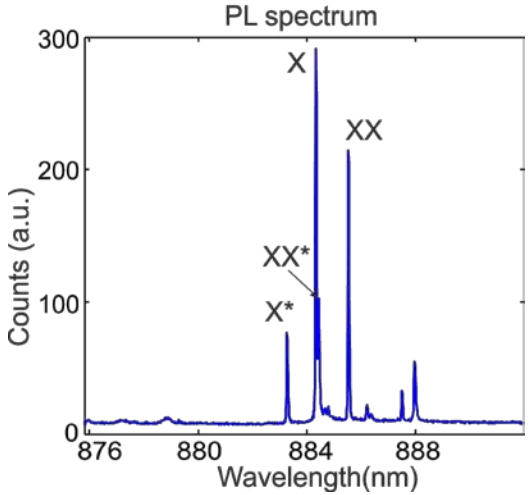
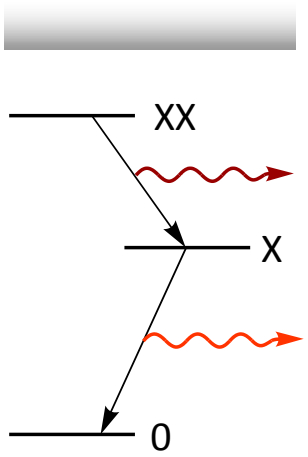
InAs on GaAs dots

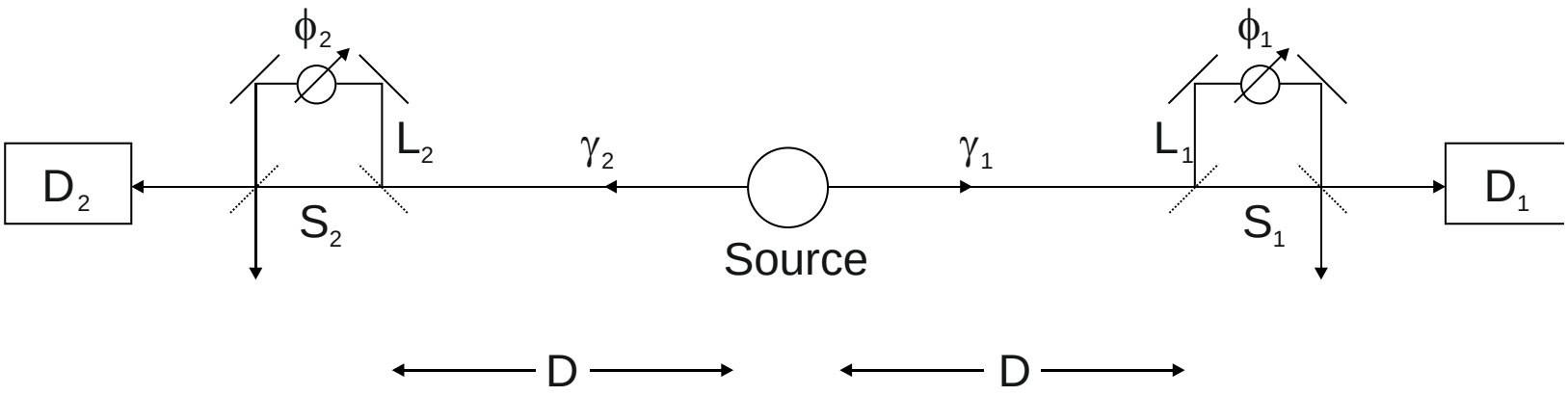
- Convenient emission wavelength
  - around 920 nm (as grown)
  - around 880 nm (annealed)
- High photon detection efficiency
- Lithographic selection possible







ENERGY-TIME-ENTANGLEMENT



VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

Bell Inequality for Position and Time

J. D. Franson

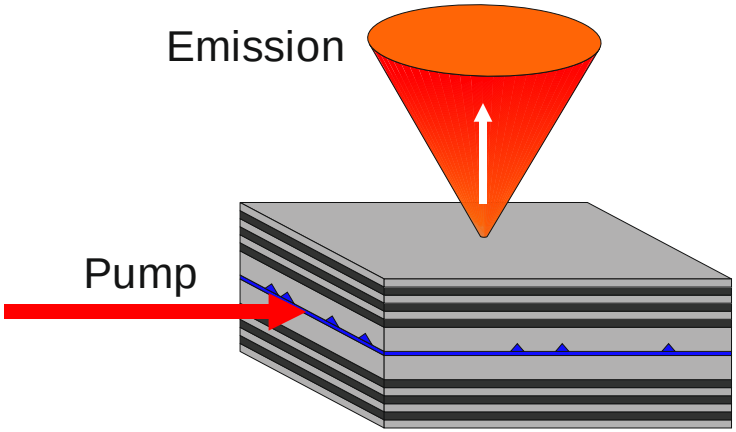
Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland 20707-6099

(Received 24 October 1988)

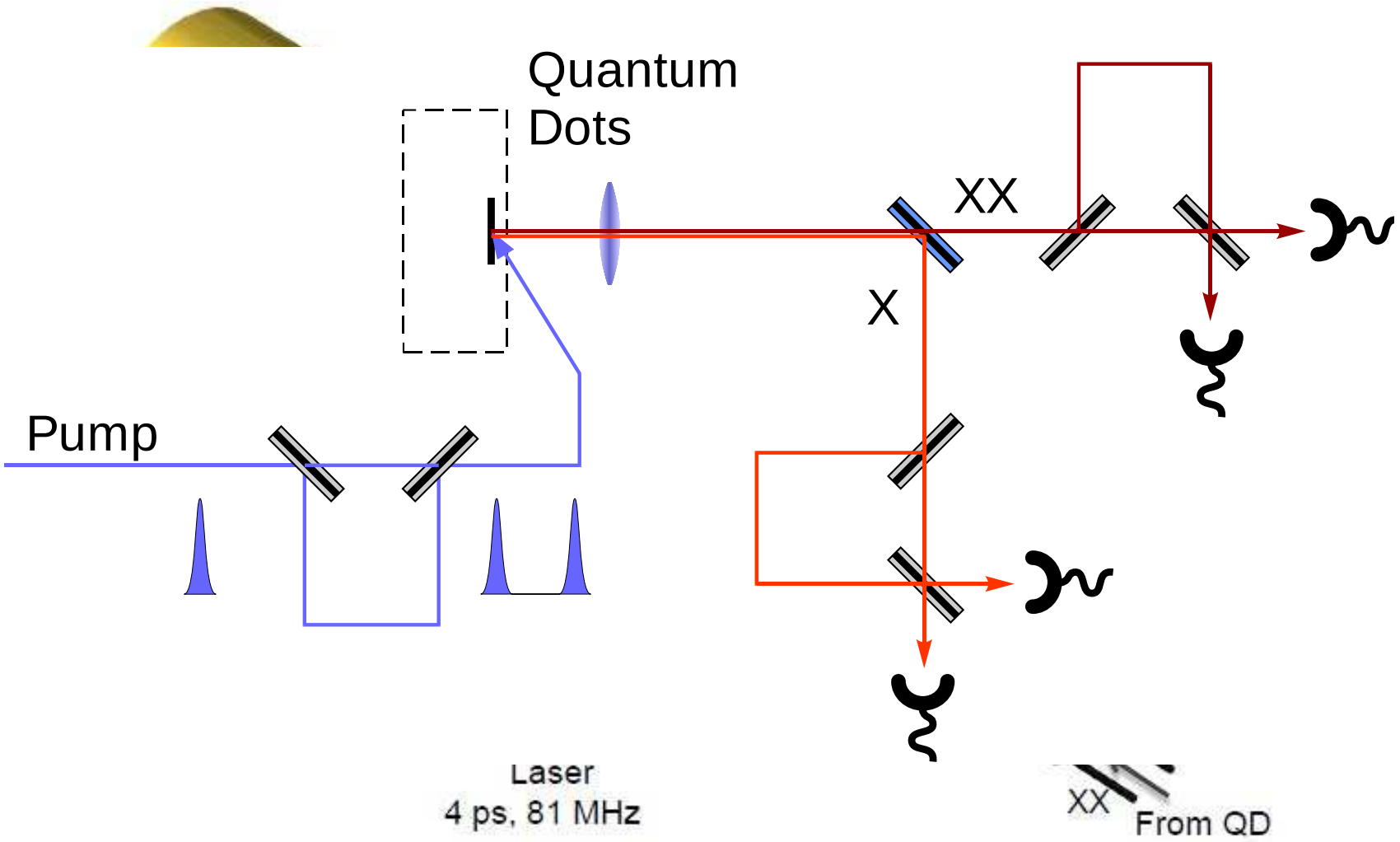
The quantum-mechanical uncertainty in the position of a particle or the time of its emission is shown to produce observable effects that are inconsistent with any local hidden-variable theory. A new experimental test of local hidden-variable theories based on optical interference is proposed.

Side pumping

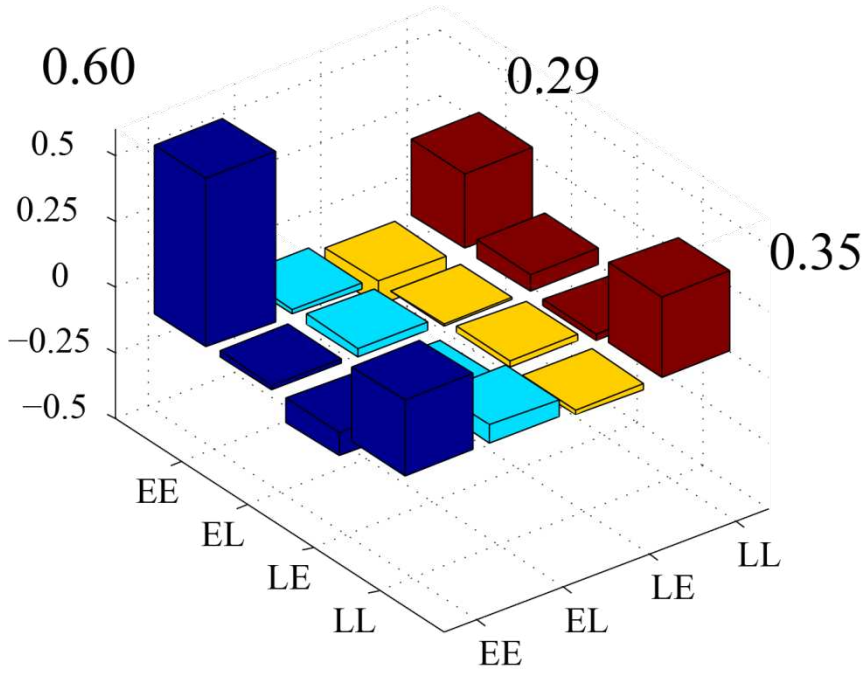
- Planar cavity acts as waveguide for pump
- No masking required
- Focusing difficult



Time-bin Entanglement



Improving collection & interferometer



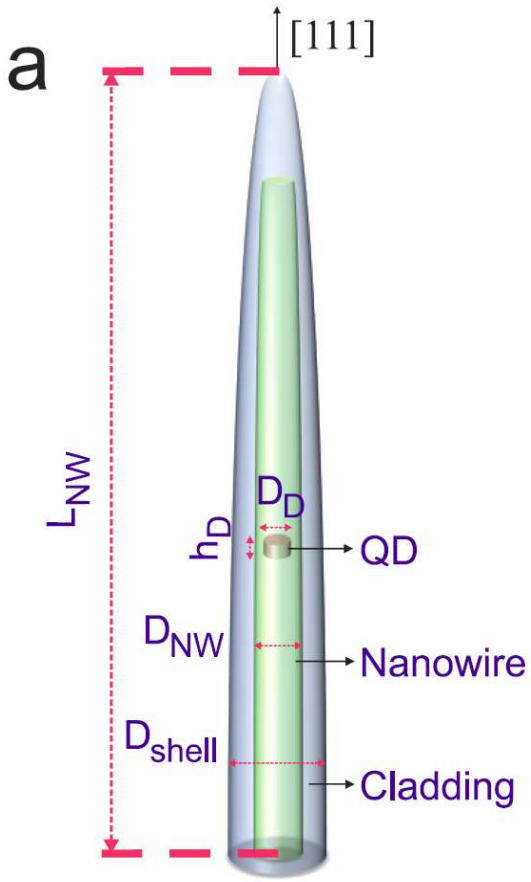
Before:

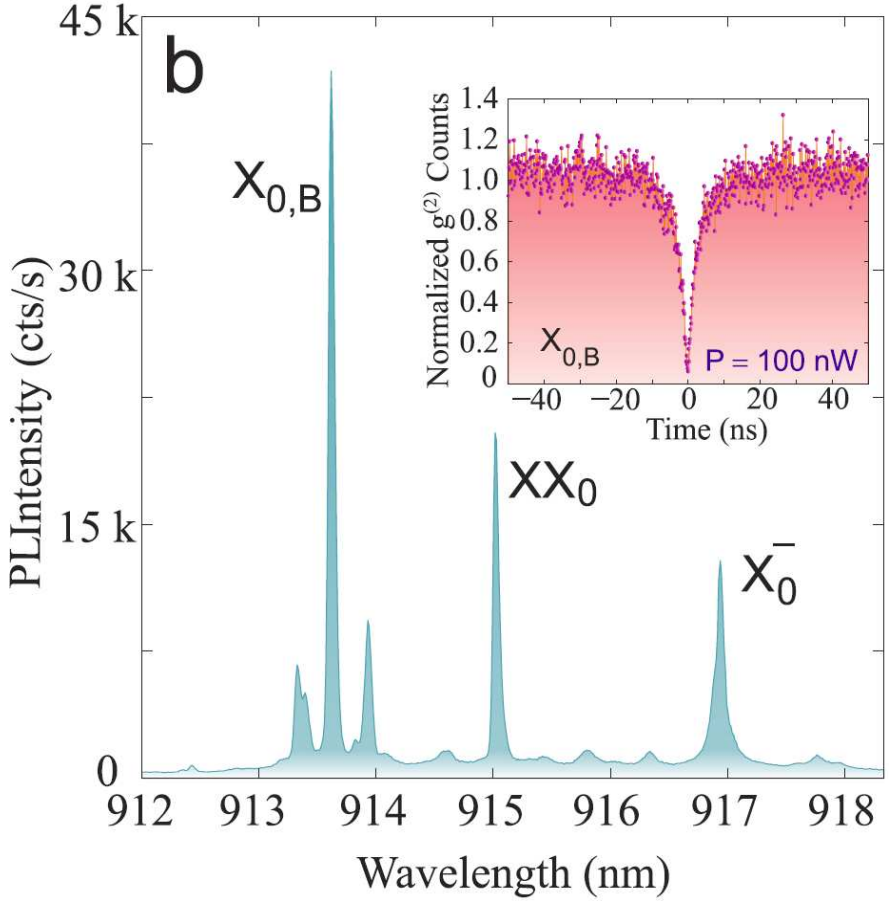
Concurrence	0.41(6)
Tangle	0.17(6)
Fidelity	0.69(3)

Now:

Concurrence	**0.62(7)**
Tangle	**0.38(7)**
Fidelity	**0.76(4)**

Outlook: Nanowire Quantum Dots





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I.2 ON THE QUANTUM MECHANICS OF COLLISIONS

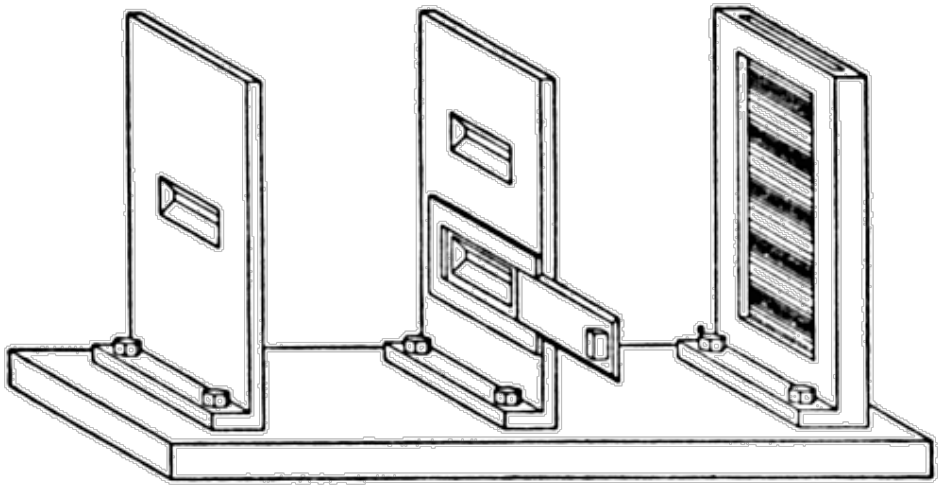
[Preliminary communication]†

MAX BORN

If one translates this result into terms of particles, only one interpretation is possible. $\Phi_{n_\tau m}(\alpha, \beta, \gamma)$ gives the probability* for the electron, arriving from the z-direction, to be thrown out into the direction designated by the angles α, β, γ, with the phase change δ. Here its energy τ has increased by one quantum $h\nu^0_{nm}$ at the

* Addition in proof: More careful consideration shows that the probability is proportional to the square of the quantity $\Phi_{n_\tau m}$.

INTERFERENCE



From N. Bohr 1949/1983: Discussions with Einstein on Epistemological Problems in Atomic Physics, p. 27

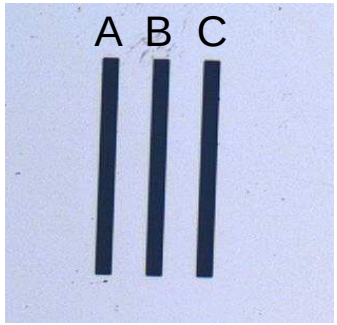
Two possible paths $|\psi\rangle = |\psi_A\rangle + |\psi_B\rangle$

Probability

$$P_{AB} = |\psi_A + \psi_B|^2 =$$
$$= |\psi_A|^2 + |\psi_B|^2 + \psi_A^* \psi_B + \psi_B^* \psi_A =$$
$$= P_A + P_B + I_{AB}$$

Interference $\boxed{I_{AB} = P_{AB} - P_A - P_B}$

Three Slits



$$P_{ABC} = |\psi_A + \psi_B + \psi_C|^2 =$$
$$= |\psi_A|^2 + |\psi_B|^2 + |\psi_C|^2 + \psi_A^*\psi_B + \psi_B^*\psi_A + \psi_A^*\psi_C + \psi_C^*\psi_A + \psi_B^*\psi_C + \psi_C^*\psi_B =$$
$$= P_A + P_B + P_C + I_{AB} + I_{AC} + I_{BC}$$

$$P_{ABC} = P_A + P_B + P_C + P_{AB} - P_A - P_B + P_{AC} - P_A - P_C + P_{BC} - P_B - P_C$$

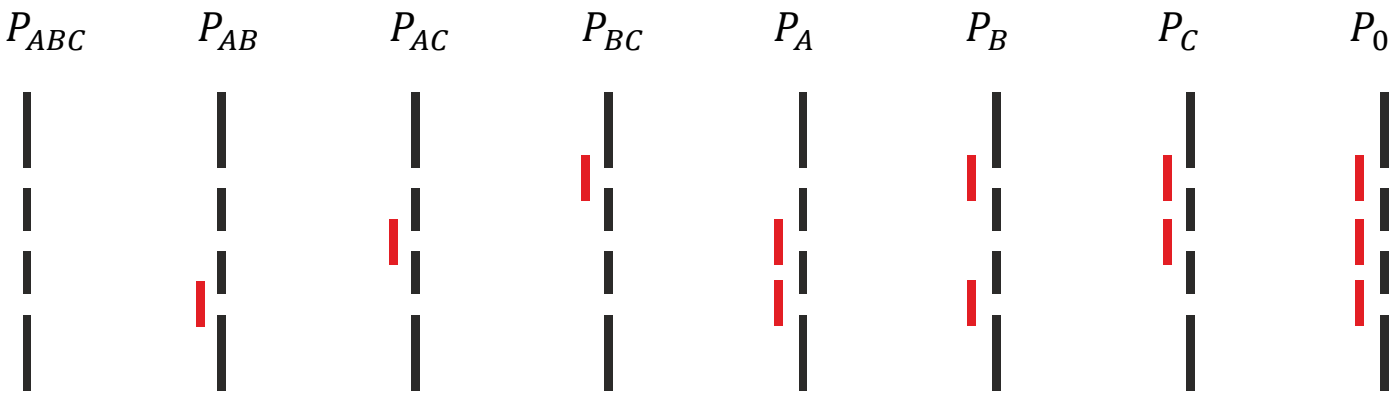
$$P_{ABC} = P_{AB} + P_{AC} + P_{BC} - P_A - P_B - P_C$$

Hypothetical three-path (second order) interference term:

$$I_{ABC} = P_{ABC} - P_{AB} - P_{AC} - P_{BC} + P_A + P_B + P_C$$

Rafael D. Sorkin,
Quantum Mechanics as Quantum Measure Theory,
Modern Physics Letters A ***9,*** 3119-3127 (1994).

Testing for higher-order interference



$$\epsilon = P_{ABC} - P_{AB} - P_{AC} - P_{BC} + P_A + P_B + P_C - P_0$$

$$\delta = |I_{AB}| + |I_{AC}| + |I_{BC}|$$

$$\kappa = \frac{\epsilon}{\delta}$$

Second order interference

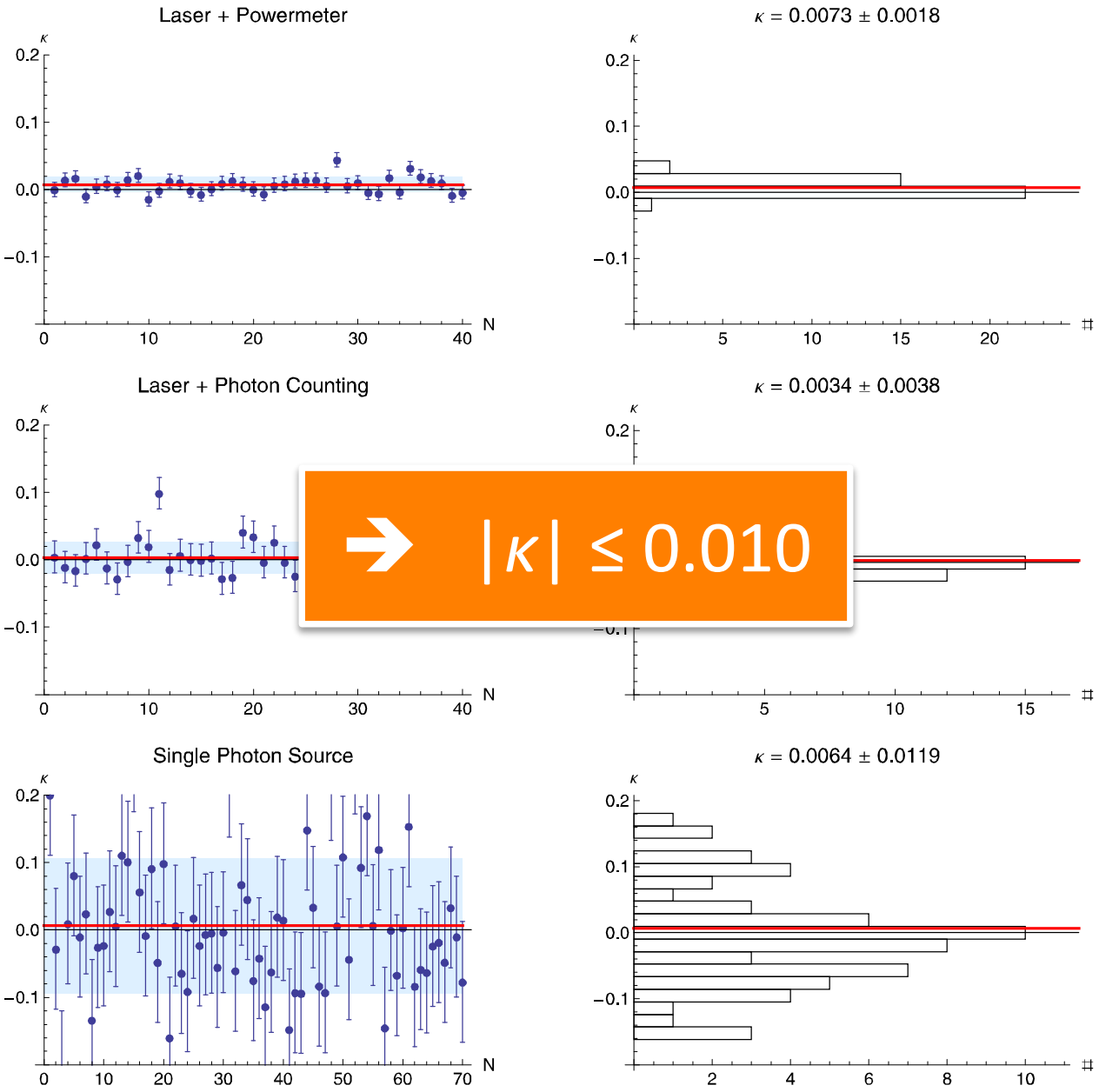
First order interference

U. Sinha, et al., in *FPP-5,* AIP Conference Proceedings **1101,** 200 (2009).

What if …?

- Would we need to modify the dynamics?
  - Probability preserved?
- What about classical physics?
  - Photon electrical field energy density
- Superquantum computing?
  - D. Meyer [arXiv:1004.1434]
  - S. Aaronson [Proc. R. Soc. A **461,** 3473 (2005)]
- Other consequences
  - C. Ududec, et al. [Found. Phys. (2010)]: higher tomography
  - G. Niestegge (arXiv:1104.0091): Tsirelson violation

Three slit results

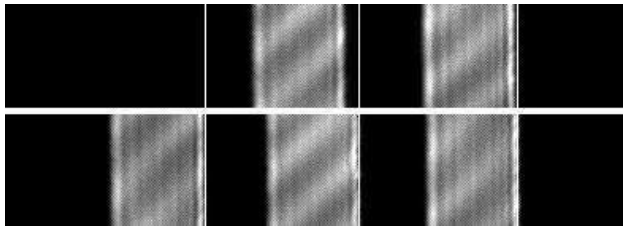


➔ $|\kappa| \leq 0.010$

U. Sinha, C. Couteau, T. Jennewein, R. Laflamme & G. Weihs, Science **329,** 418-421 (2010).

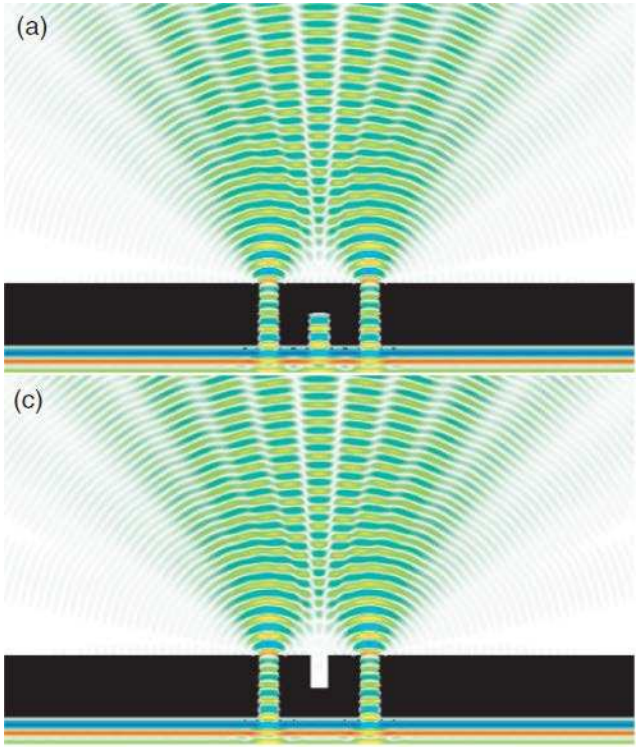
Slit Problems

- Manufacturing error



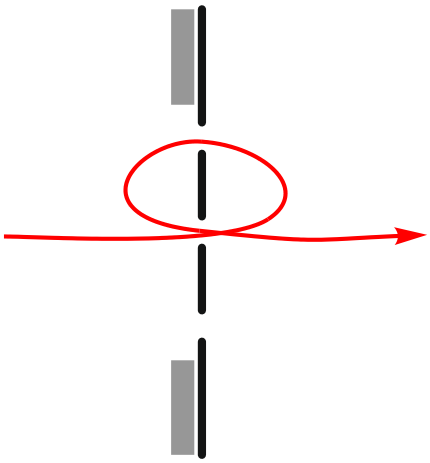
- Cross-talk

H. De Raedt, et al. PRA **85,** 012101 (2012)



- Loops

R. Sawant et al.,
ICQIQC conference,
Bangalore (2013)



11.8.2010

View Cottage, High Street
Lyndham, Oxfordshire OX7 4QX.
Tel/Fax: 01993 830 492

Dear Dr. Sinha,

I thought I would like to tell you of the great surprise and pleasure your paper in the July issue of Science has given me. I am the son of Max Born, and am greatly gratified that theoretical work he did in 1926 (when I was five) should now receive experimental confirmation,

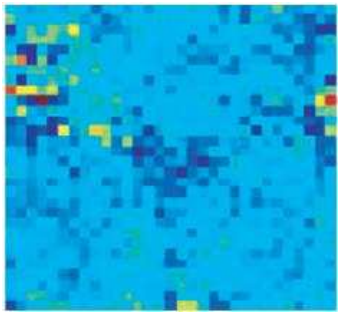
3/4 of a century later. I am a biomedical scientist, far from properly understanding your work – and my father's either, of course. But he and I were very close in every way, and so you can imagine my gladness when a physicist friend of mine drew my attention to your clearly excellent work. Please let me know of any follow-up papers on this.

With best wishes, Yours sincerely, Gustav Born.

Other Experiments

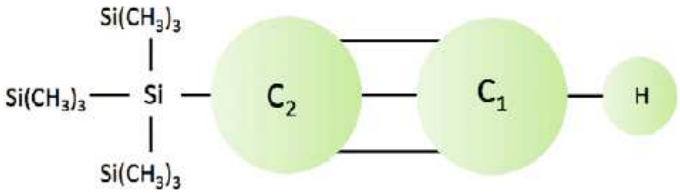
- Spatial light modulators: $\kappa \leq 0.004 \pm 0.030$

  J. M. Hickmann, E. J. S. Fonseca, A. J. Jesus-Silva,
  Born's rule and the interference of photons with orbital angular momentum by a triangular slit,
  Europhysics Letters **96,** 64006 (2011).



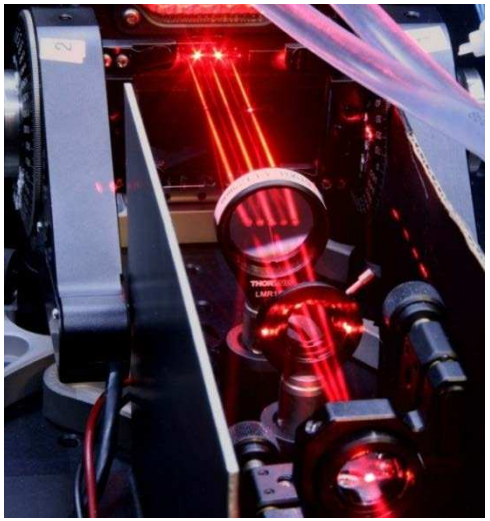
- NMR: $\kappa \leq 0.001 \pm 0.003$

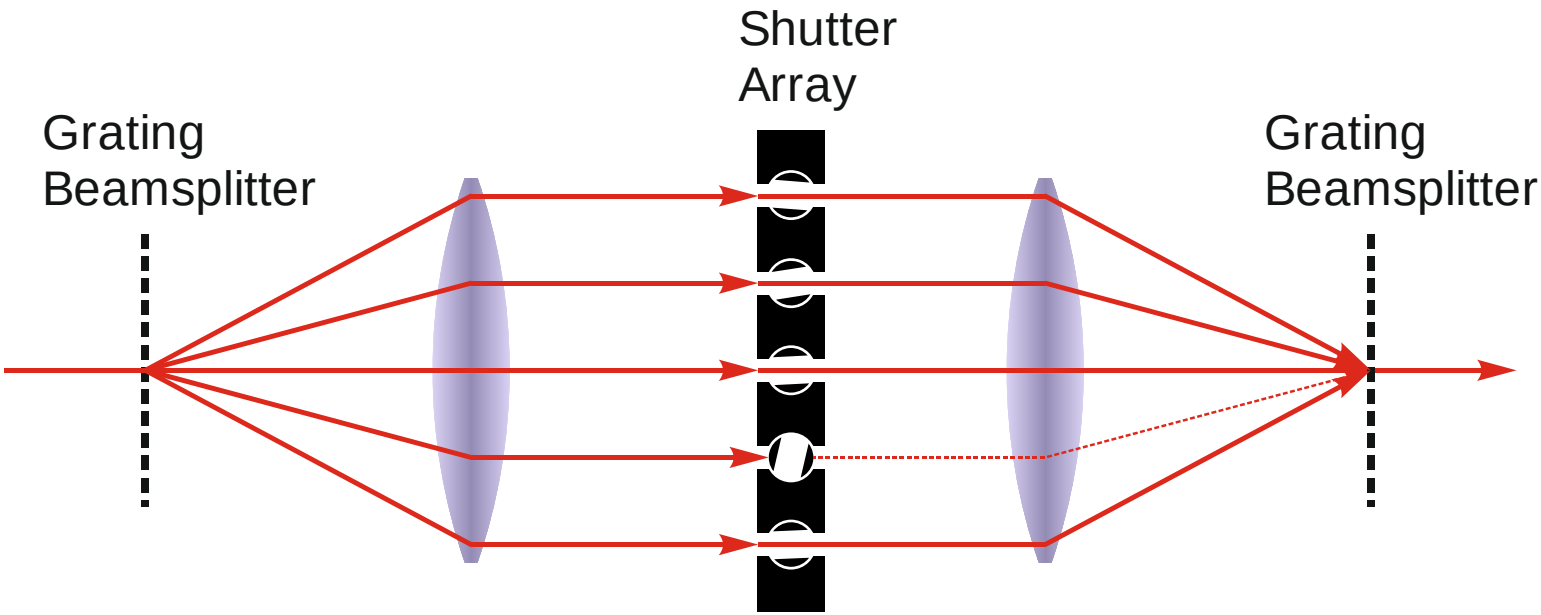
  D. K. Park, O. Moussa & R. Laflamme,
  Three path interference using nuclear magnetic resonance: a test of the consistency of Born's rule
  New Journal of Physics **14,** 113025 (2012).



Interferometers

- Improve throughput
- Shutter paths independently
- Access entire phase space

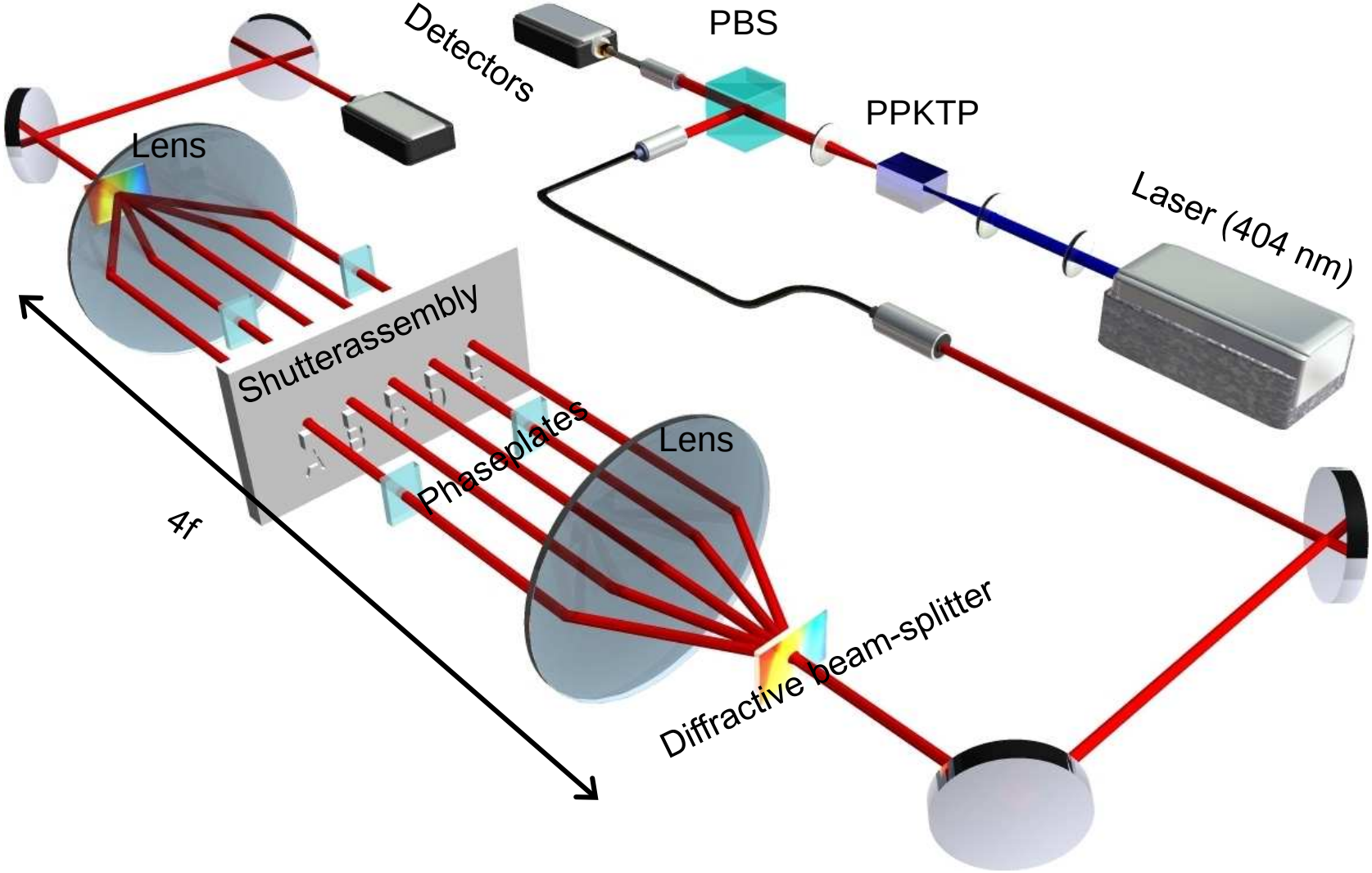




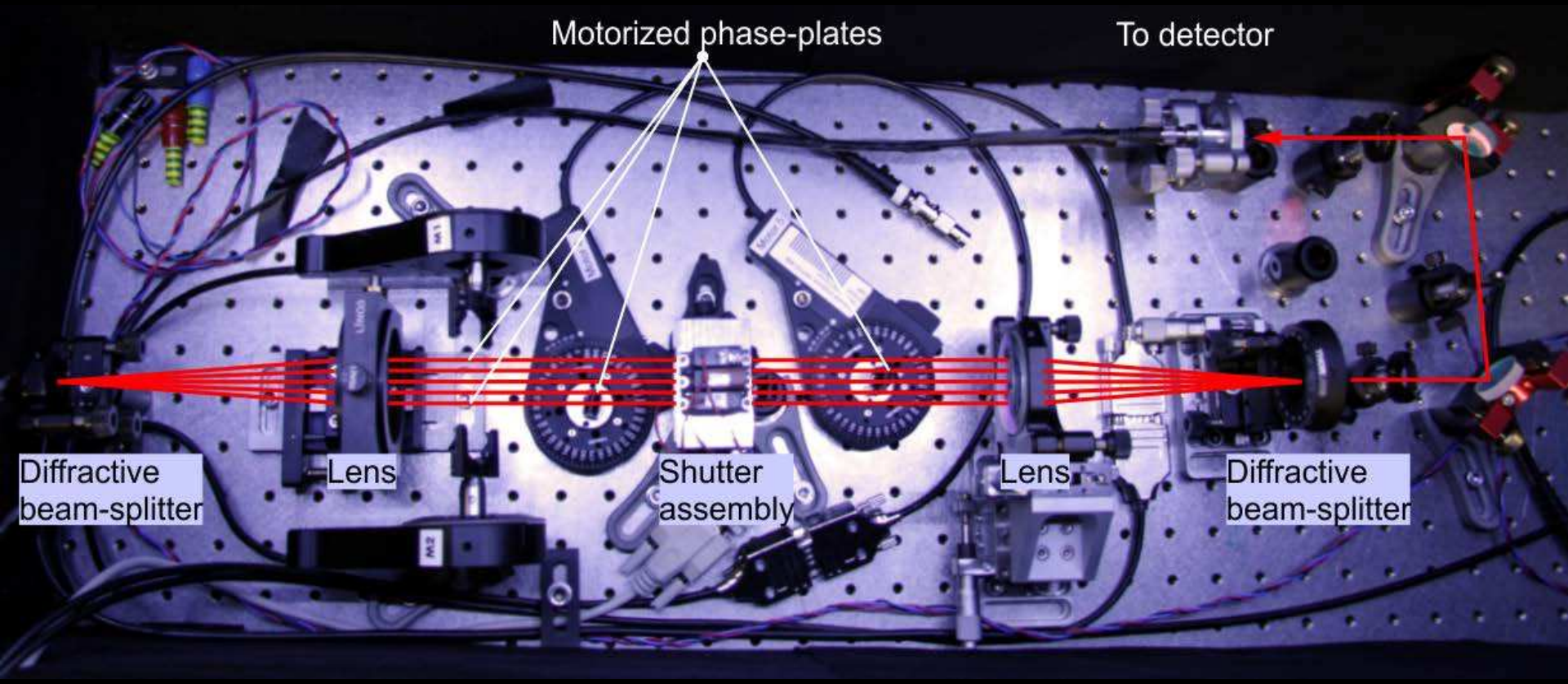
More than 3 paths?

- Measure 4 and 5 path terms
- Reduce systematics
  - Contains five 4-path, ten 3-path, and ten 2-path sub-interferometers!
- Born's rule modification
  - Power series: $P = |\psi|^2 + c_4|\psi|^4 + c_6|\psi|^6 + \cdots$
  - Modified exponent: $P = |\psi|^p$
- Test explicit models
  - Khrennikov
  - Brukner

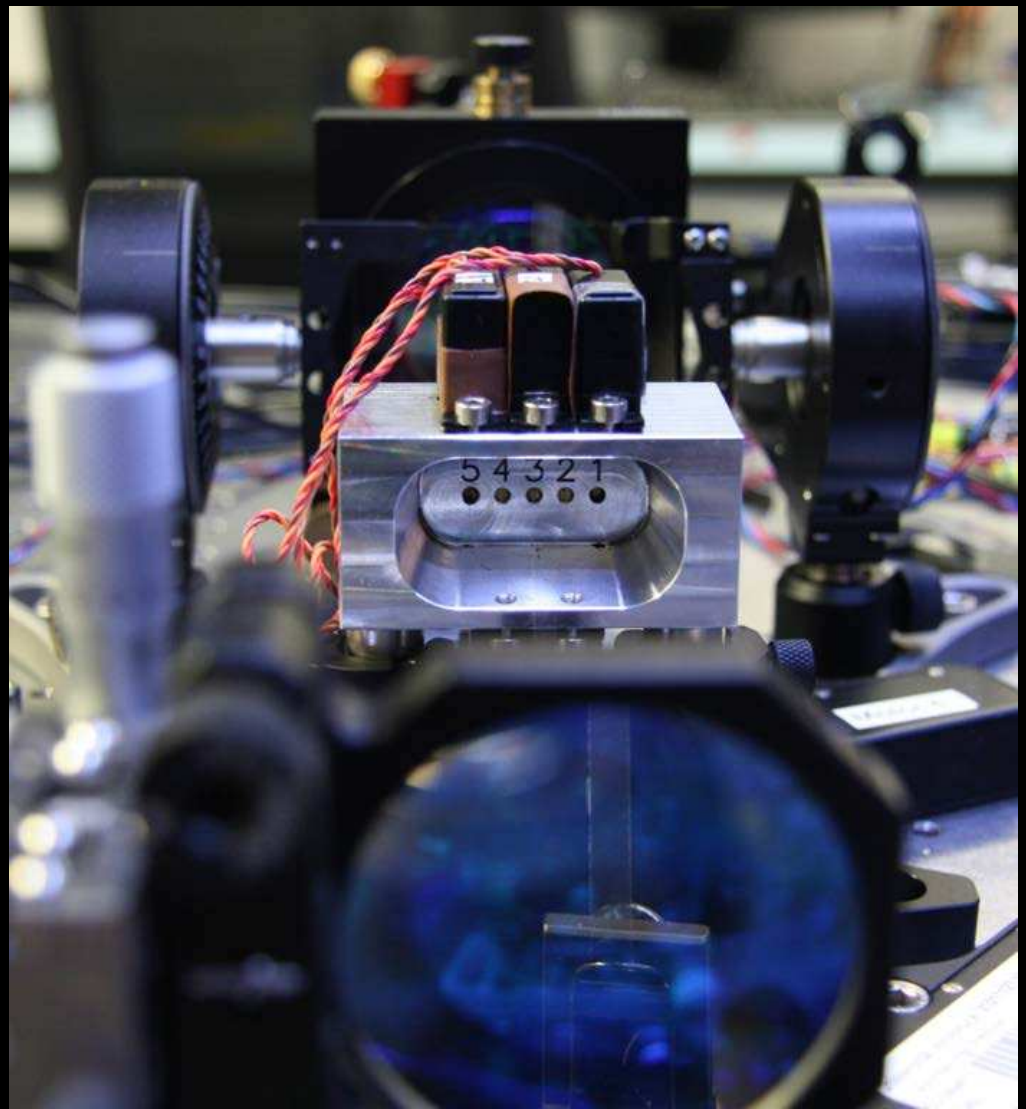
Experimental Setup



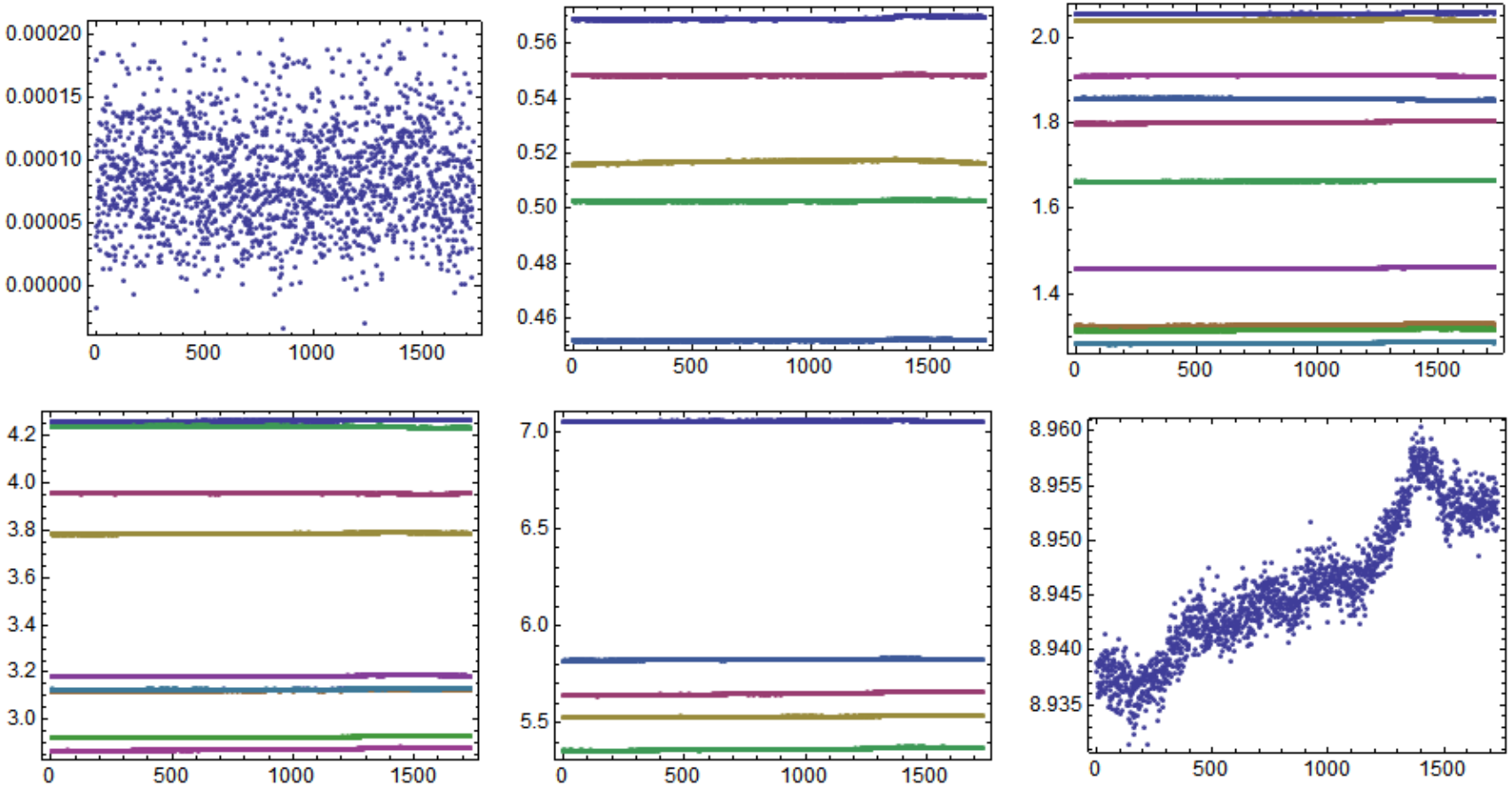
The 5-path interferometer



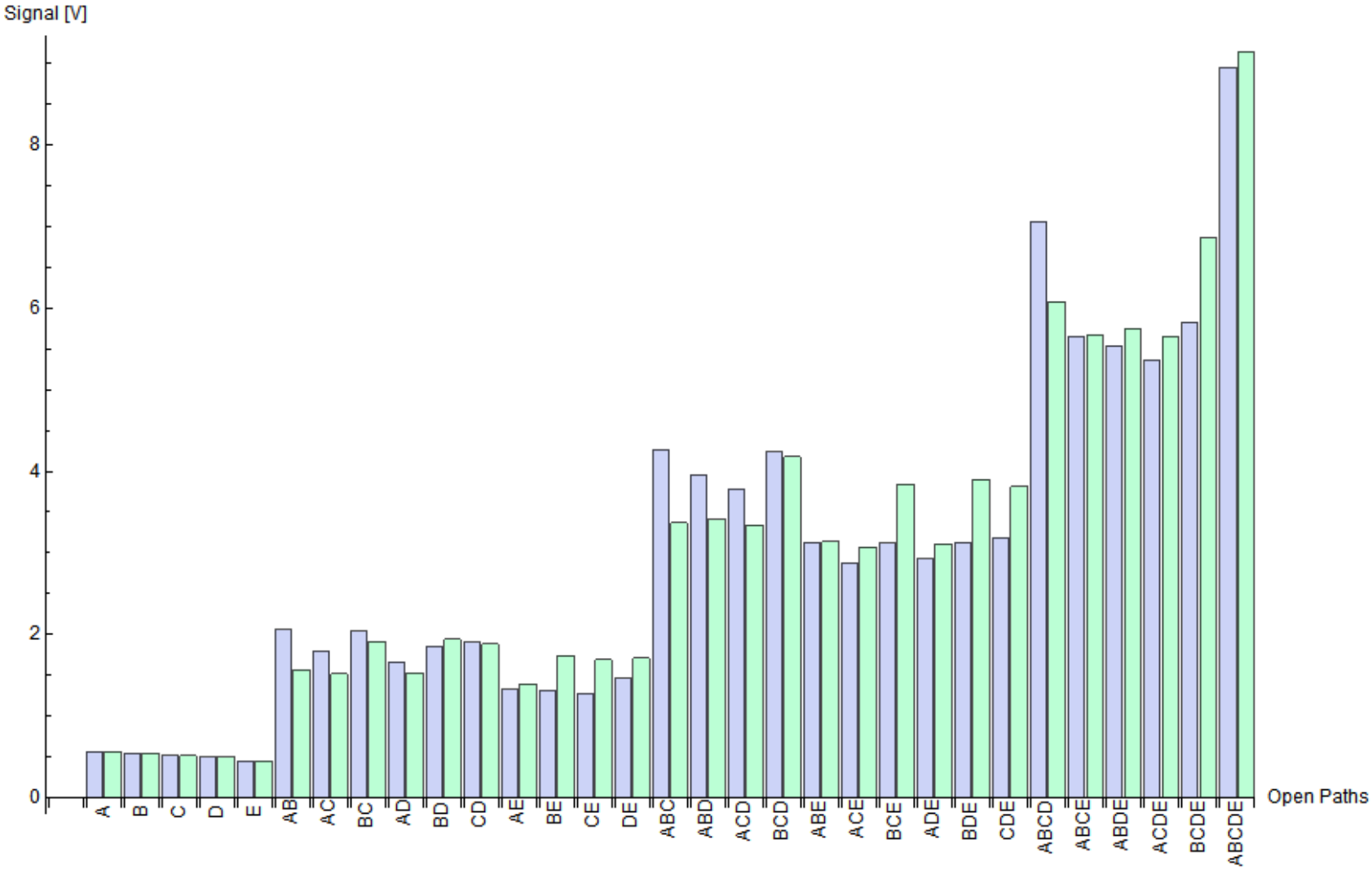
The 5-path interferometer



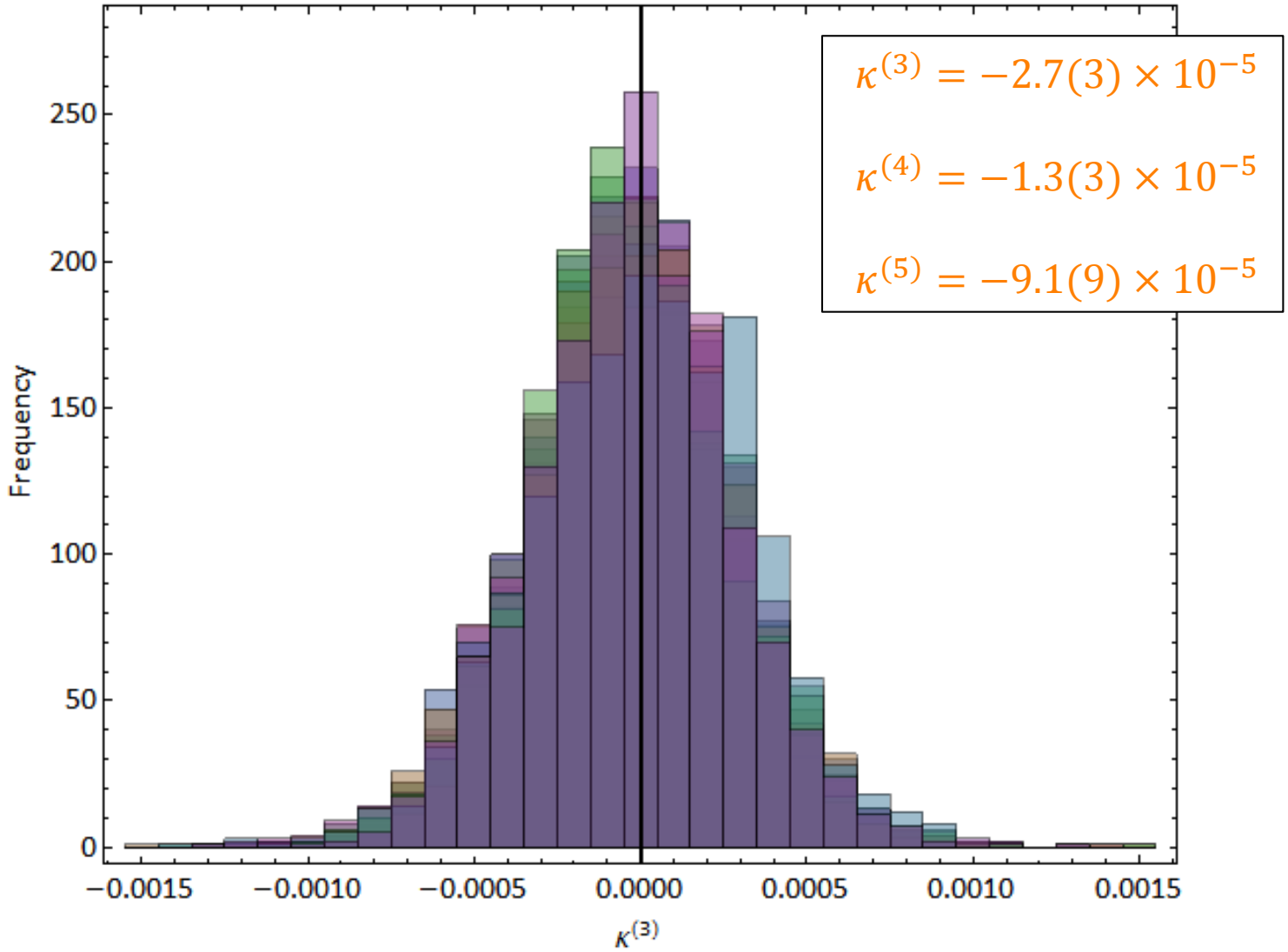
Interferometer stability



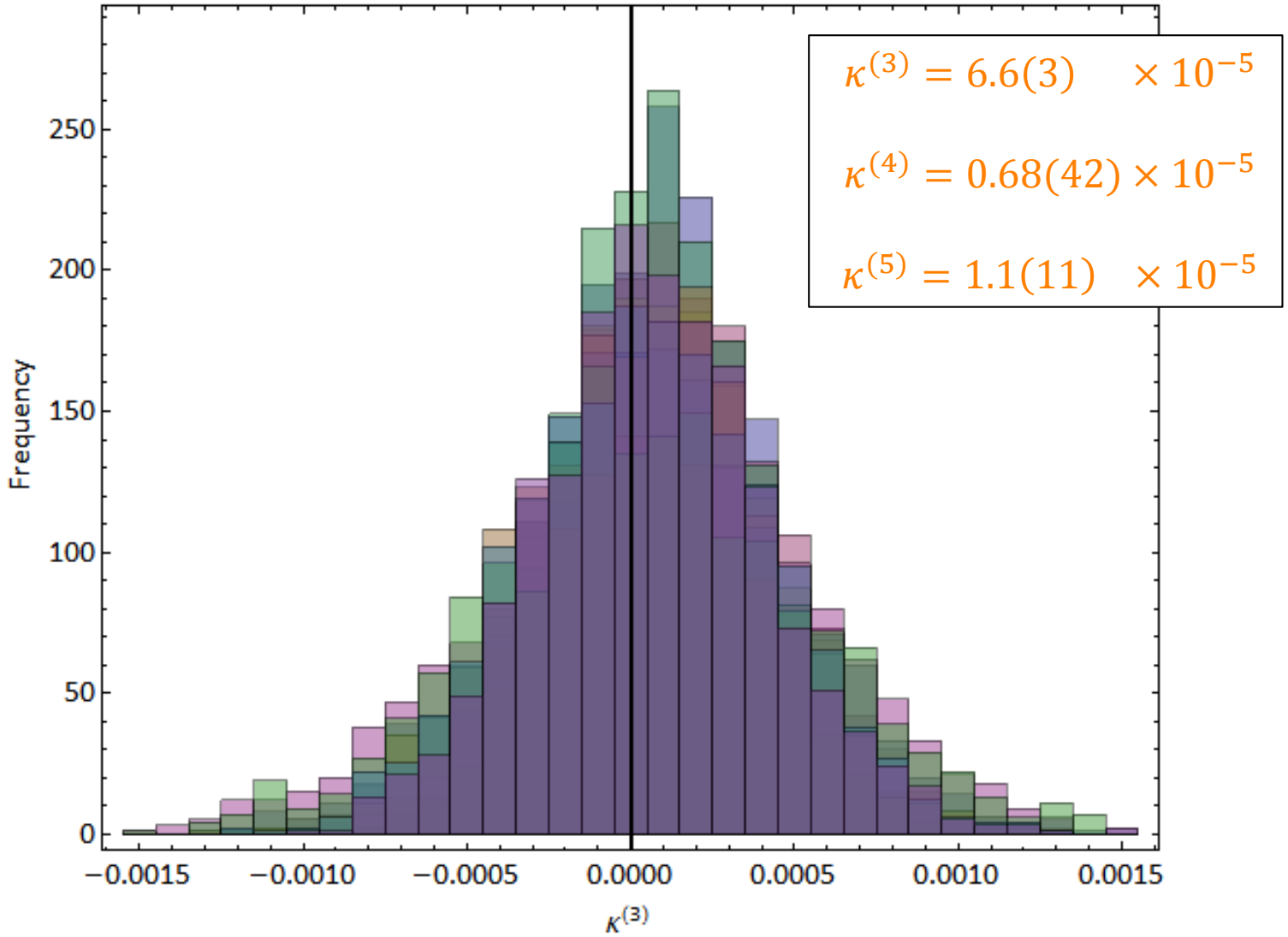
Analysis


Signal [V]
0
2
4
6
8
A
B
C
D
E
AB
AC
BC
AD
BD
CD
AE
BE
CE
DE
ABC
ABD
ACD
BCD
ABE
ACE
BCE
ADE
BDE
CDE
ABCD
ABCE
ABDE
ACDE
BCDE
ABCDE
Open Paths

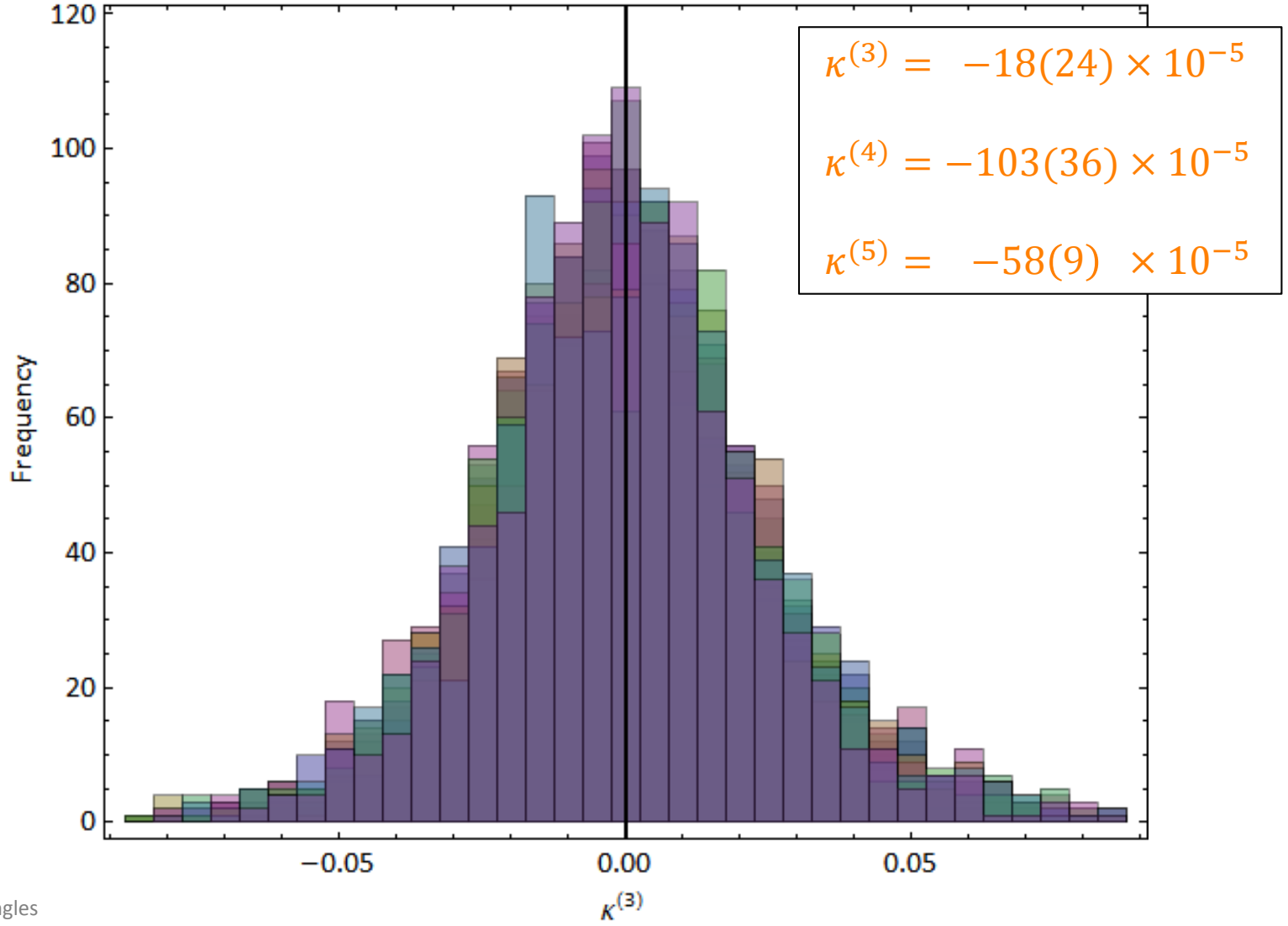
Results – Photodiode 1



Results – Photodiode 2



Results – Photon Counting



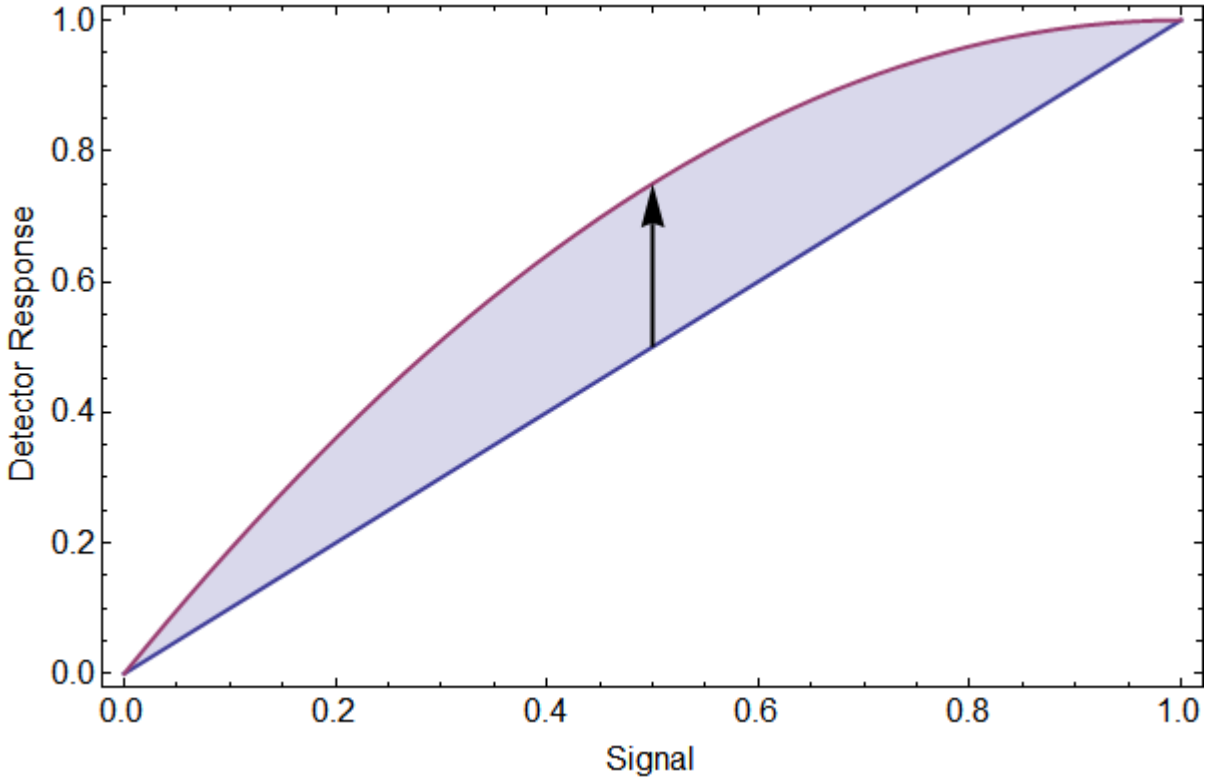
$$\kappa^{(3)} = -18(24) \times 10^{-5}$$

$$\kappa^{(4)} = -103(36) \times 10^{-5}$$

$$\kappa^{(5)} = -58(9) \times 10^{-5}$$

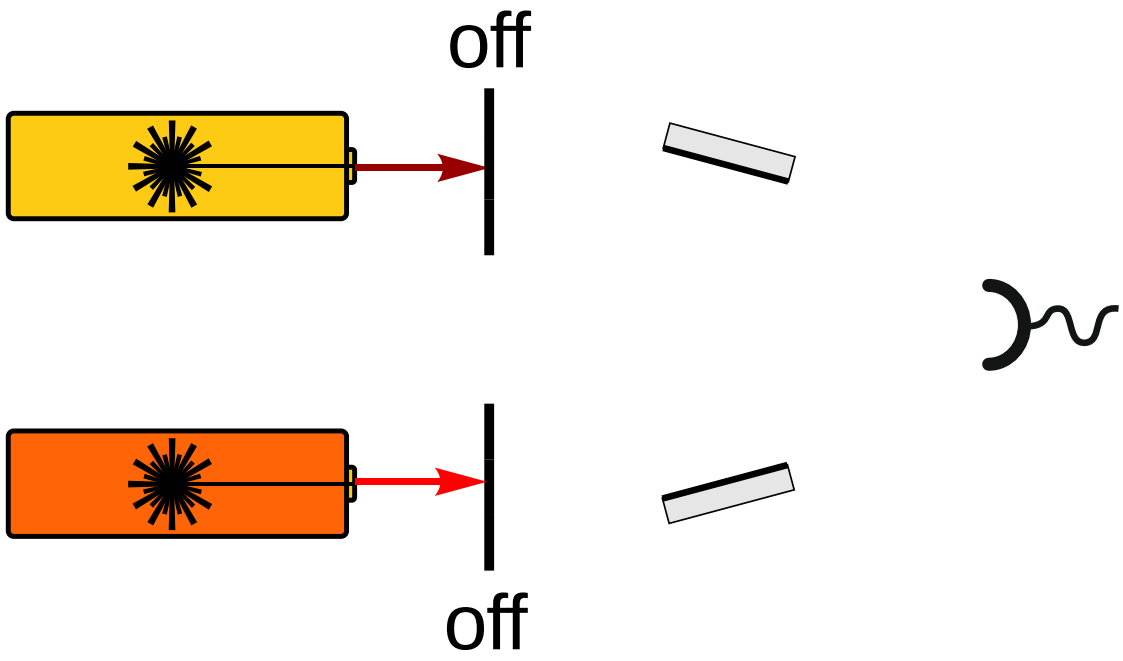
Detector nonlinearity

- Every real detector has nonlinearity
  - Photon counting: dead time
  - Photodiodes: feedback resistor



Nonlinearity Measurement

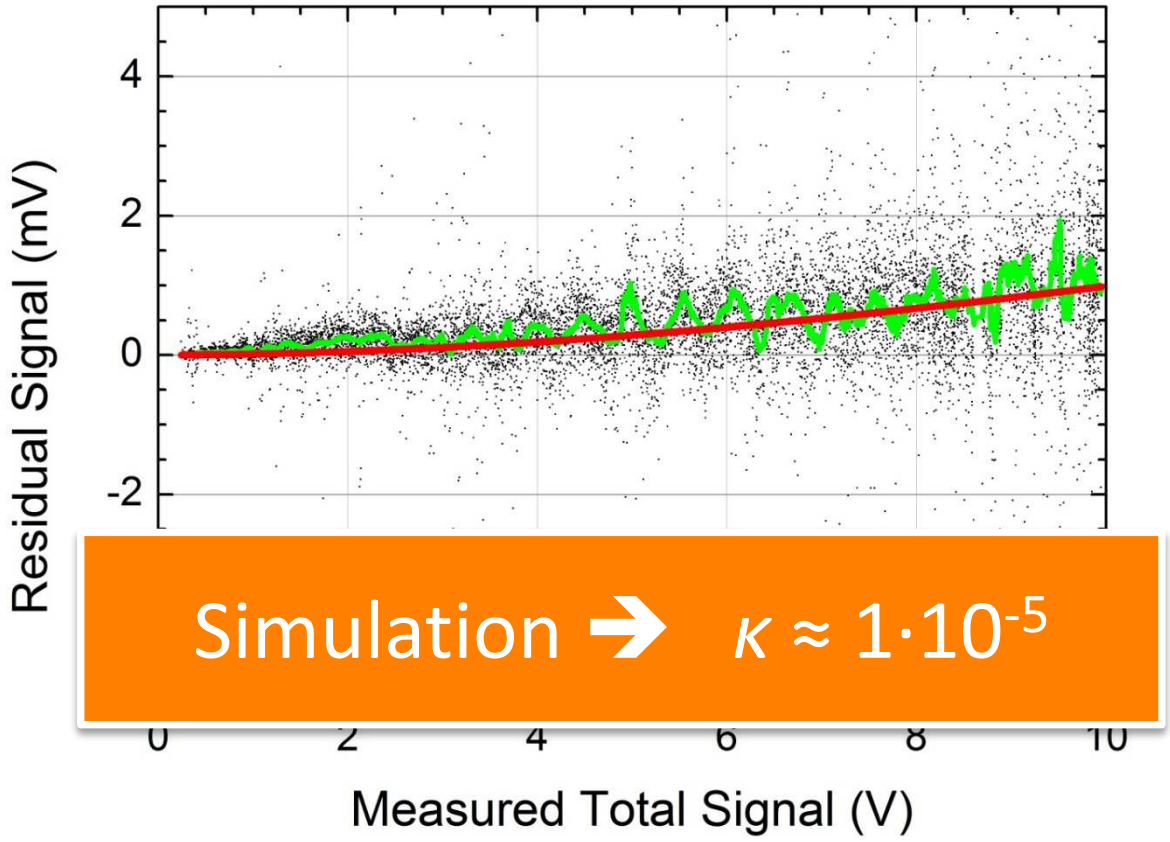
- Measurement using incoherent beam combination



Söllner et al. Found. Phys. **42,** 742 (2012).

Photodiode Nonlinearity

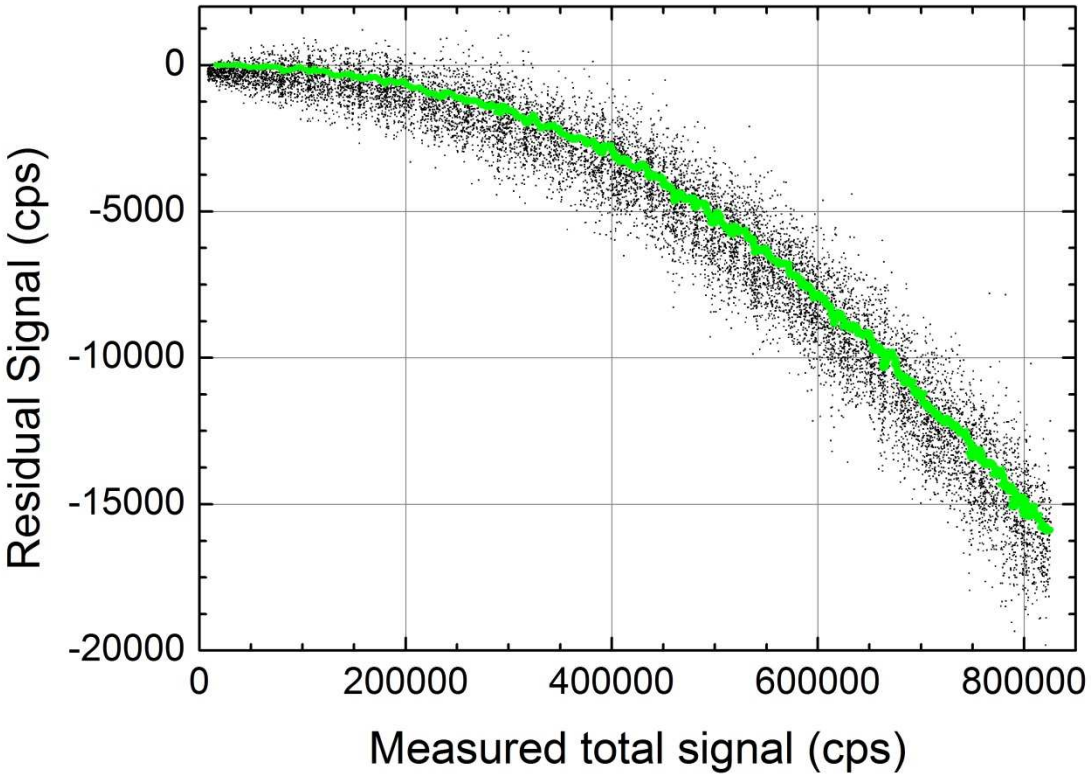
- Low-nonlinearity photoreceiver
- Polynomial fit ➔ 25 ppm nonlinearity



Kauten et al., arXiv:1311.1629 , to appear in Rev. Sci. Instr.

Photon Counting Nonlinearity

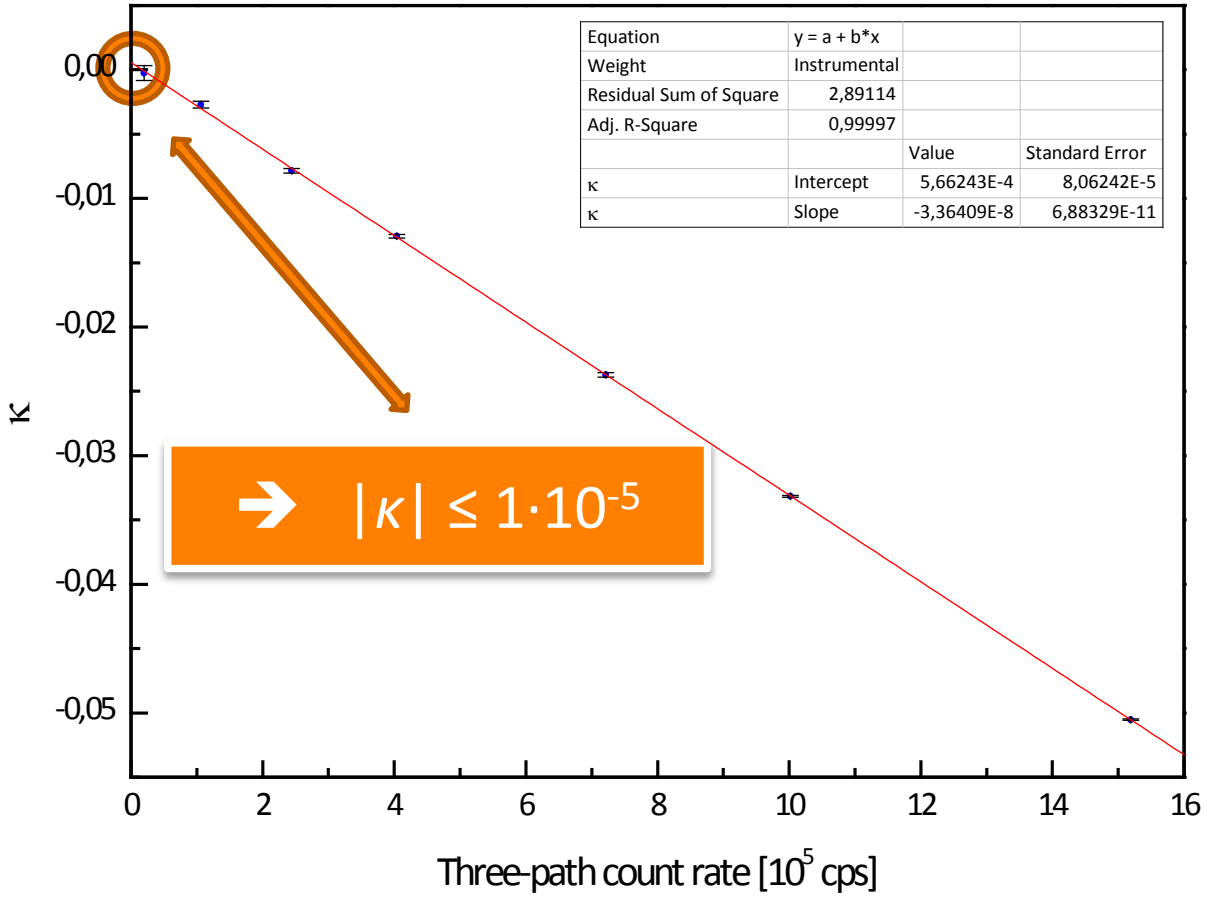
- Dead-time limits count rate



- Improve with pulsed single photon source

Photon Counting Results

- Extrapolate to zero count rate



QUATERNIONS

$$z = a \cdot 1 + b \cdot i + c \cdot j + d \cdot k$$

$$i^2 = j^2 = k^2 = ijk = -1$$

$$ij = k \qquad ji = -k$$

Quaternion plaque on Brougham (Broom) Bridge, Dublin

PERES TEST FOR QUATERNIONIC QUANTUM MECHANICS

Proposed Test for Complex versus Quaternion Quantum Theory

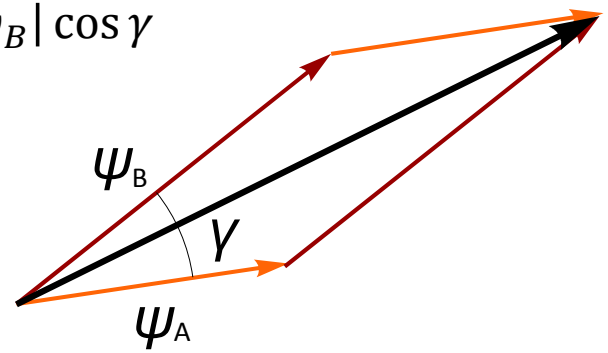
Asher Peres
Department of Physics, Technion–Israel Institute of Technology, Haifa, Israel
(Received 7 December 1978)

If scattering amplitudes are ordinary complex numbers (not quaternions) then there is a universal algebraic relationship between the six coherent cross sections of any three scatterers (taken singly and pairwise). A violation of this relationship would indicate either that scattering amplitudes are quaternions, or that the superposition principle fails. Some experimental tests are proposed, involving neutron diffraction by crystals made of three different isotopes, neutron interferometry, and K_S-meson regeneration.

PRL **42,** 683 (1979).

$$|\psi_{AB}|^2 = |\psi_A + \psi_B|^2 = |\psi_A|^2 + |\psi_B|^2 + 2|\psi_A||\psi_B|\cos\gamma$$

$$\cos\gamma = \frac{P_{AB} - P_A - P_B}{2\sqrt{P_A P_B}}$$

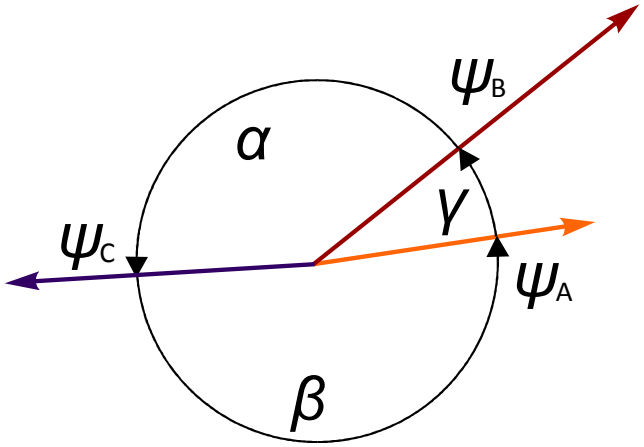


PERES CRITERION

$$\cos\alpha = \frac{P_{BC} - P_B - P_C}{2\sqrt{P_B P_C}}$$

$$\cos\beta = \frac{P_{AC} - P_A - P_C}{2\sqrt{P_A P_C}}$$

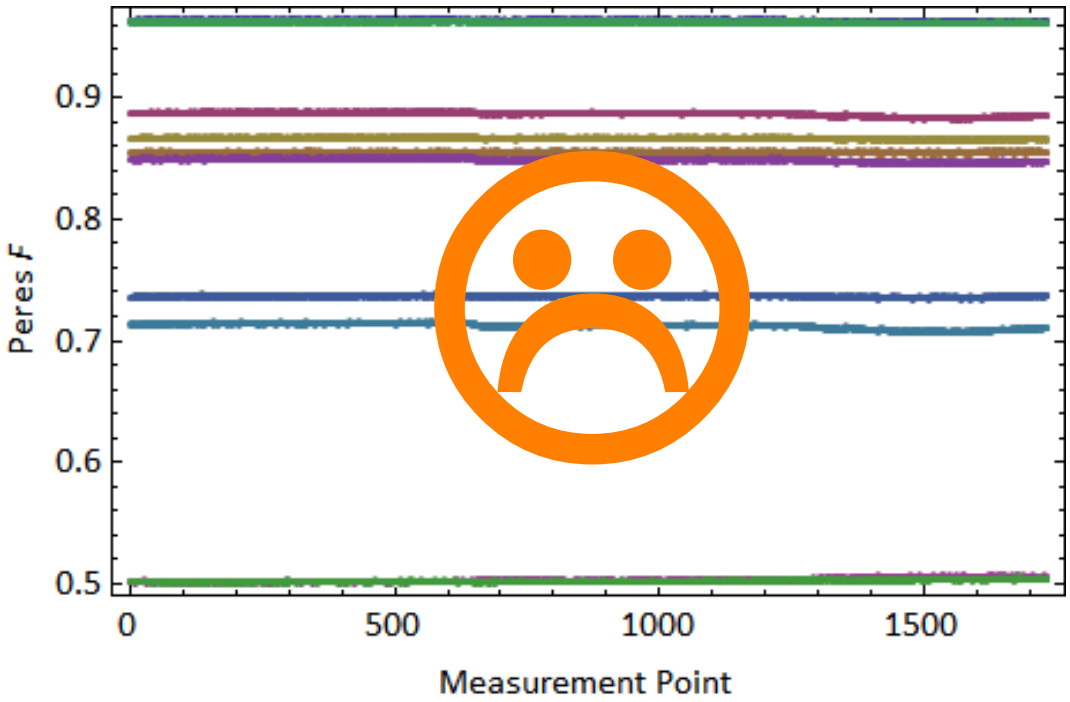
$$\cos\gamma = \frac{P_{AB} - P_A - P_B}{2\sqrt{P_A P_B}}$$



$$F = \cos^2\alpha + \cos^2\beta + \cos^2\gamma - 2\cos\alpha\cos\beta\cos\gamma$$

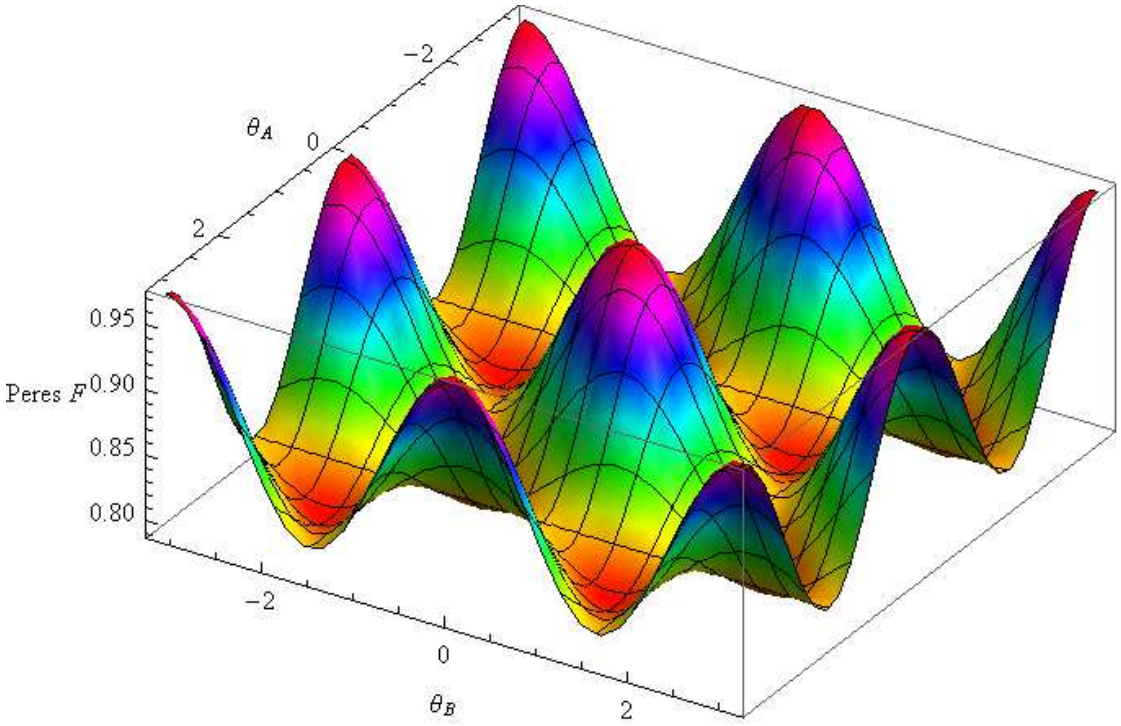
ψ quaternion – non-coplanar: $F \leq 1$

Results

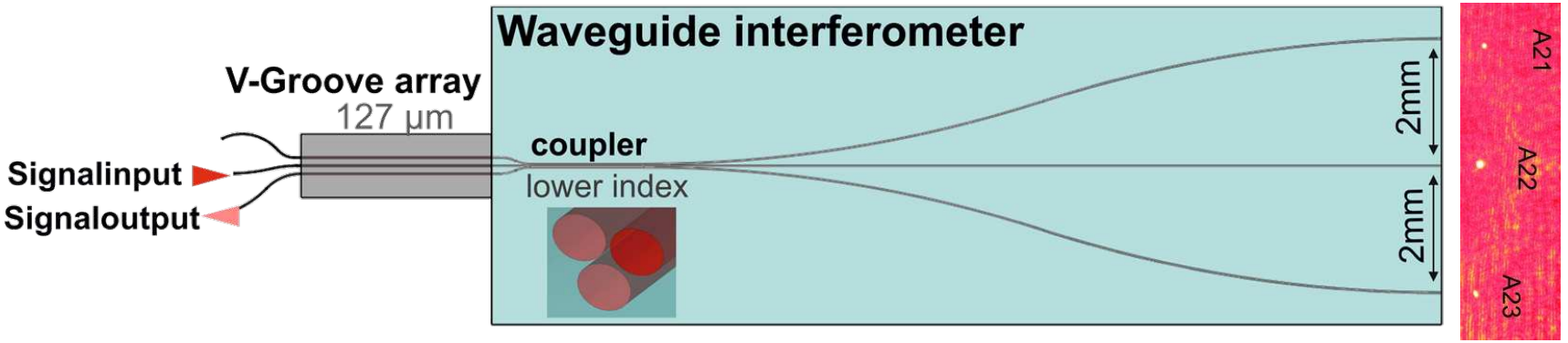


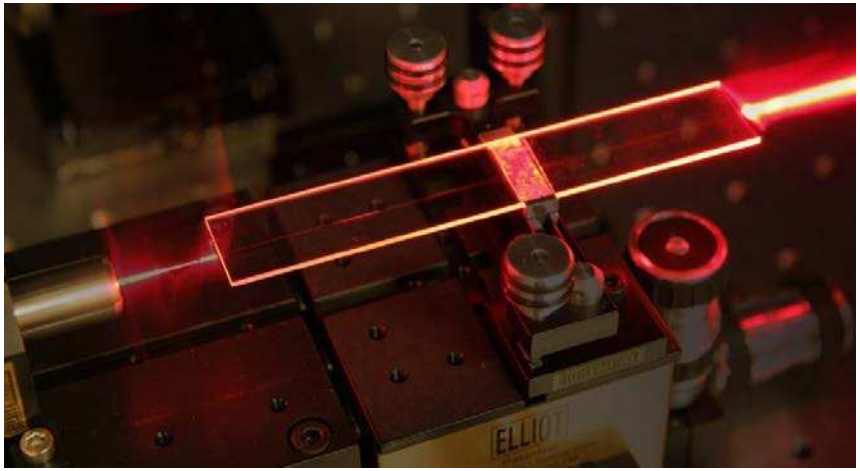
Need for a more robust criterion

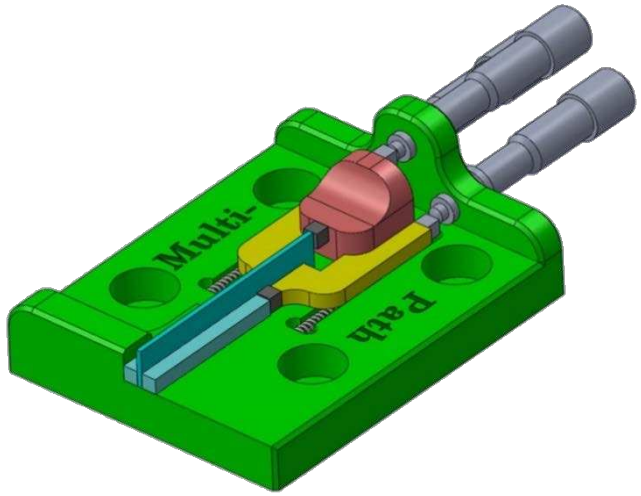
- The culprit: finite coherence / indistinguishability
- $\cos\gamma = \frac{P_{AB}-P_A-P_B}{2\sqrt{P_A P_B}}$ ➔ $\frac{\langle P_{AB}\rangle-\langle P_A\rangle-\langle P_B\rangle}{2\sqrt{\langle P_A\rangle\langle P_B\rangle}}$



Outlook – Waveguide interferometer







CONTENTS

Photon sources: new developments

- Bragg-reflection waveguides
- Quantum dots

Multipath Interference Tests of Quantum Mechanics

- Born‘s rule
- Sorkin tests
- Quaternion quantum mechanics?

GHZ experiment under strict locality

- GHZ
- Mermin inequality
- Loopholes and how to close them

A GHZ Test under Strict Locality

E. Meyer-Scott K. Fisher J. Lavoie B. Higgins Z. Yan C. Pugh J.P. Bourgoin

L. Richards

K. Shalm N. Gigov R. Prevedel R. Laflamme G. Weihs T. Jennewein K. Resch

GHZ States and Local Realism

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|\mathrm{H}\rangle_1|\mathrm{H}\rangle_2|\mathrm{H}\rangle_3 - |\mathrm{V}\rangle_1|\mathrm{V}\rangle_2|\mathrm{V}\rangle_3]$$

- Local hidden variables setup
  - YYX measurement ➔ Product +1
  - YXY measurement ➔ Product +1
  - XYY measurement ➔ Product +1
- For any LHV model all observables are now assigned
- XXX measurement: LHV predict +1
- Quantum mechanics: XXX = -1

Mermin's inequality

- Mermin's Inequality for three particles

$$M = |E(a,b,c) - E(a,b',c') - E(a',b,c') - E(a',b',c)| \leq 2$$

- Inequality can be maximally violated to 4 with the GHZ states

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|\mathrm{H}\rangle_1|\mathrm{H}\rangle_2|\mathrm{H}\rangle_3 \pm i|\mathrm{V}\rangle_1|\mathrm{V}\rangle_2|\mathrm{V}\rangle_3]$$

and for measurement bases a, b, c (linear)

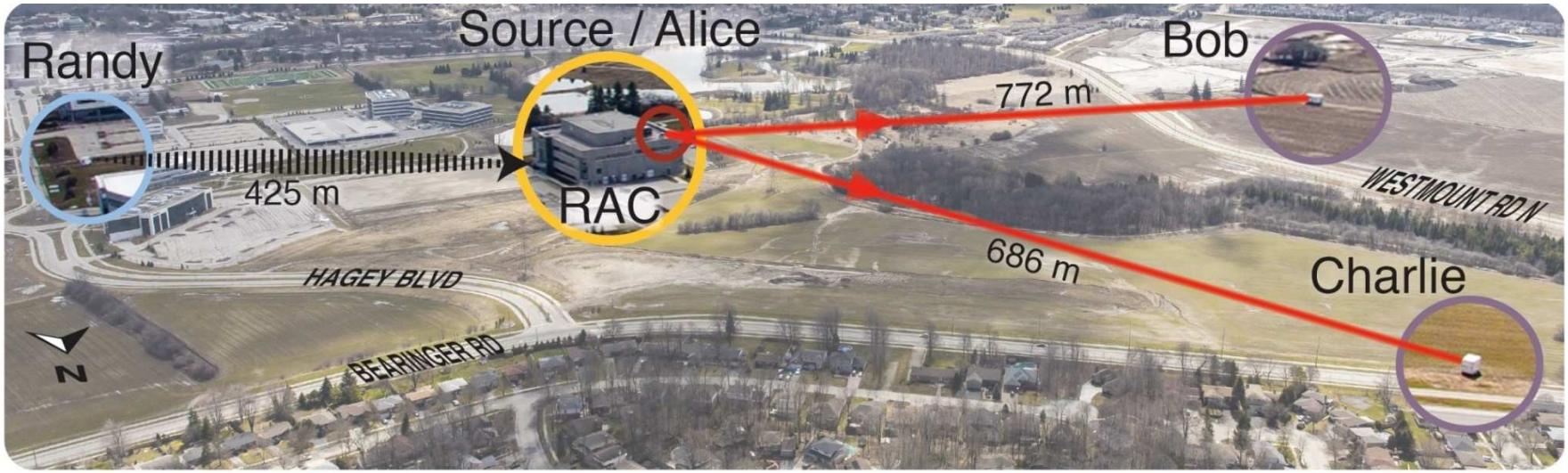
a, b, c: $|\mathrm{D}\rangle = \frac{1}{\sqrt{2}}[|\mathrm{H}\rangle + |\mathrm{V}\rangle]$ and $|\mathrm{A}\rangle = \frac{1}{\sqrt{2}}[|\mathrm{H}\rangle - |\mathrm{V}\rangle]$

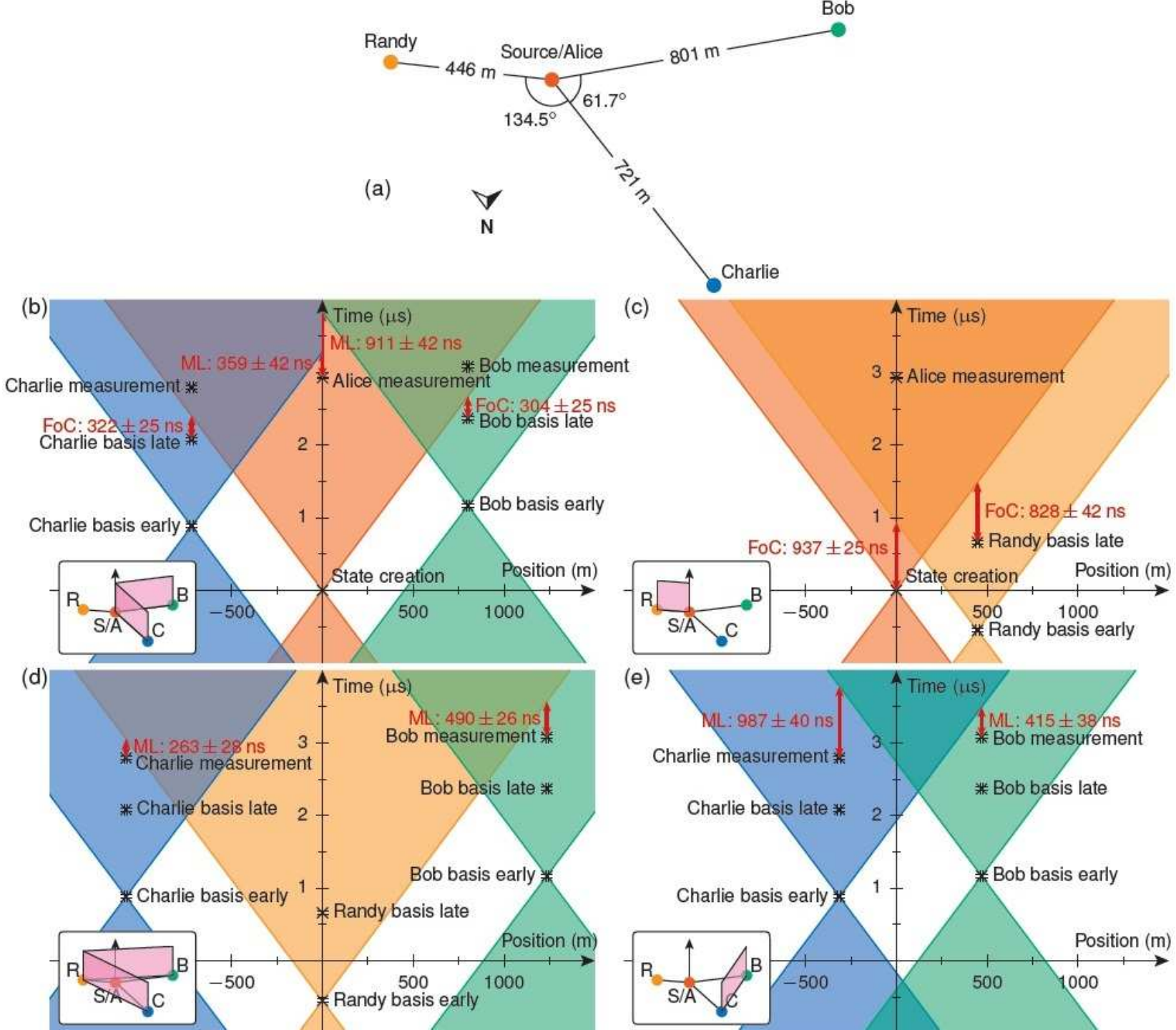
a', b', c': $|\mathrm{R}\rangle = \frac{1}{\sqrt{2}}[|\mathrm{H}\rangle + i|\mathrm{V}\rangle]$ and $|\mathrm{L}\rangle = \frac{1}{\sqrt{2}}[|\mathrm{H}\rangle - i|\mathrm{V}\rangle]$

LOOPHOLES

Measurement Locality

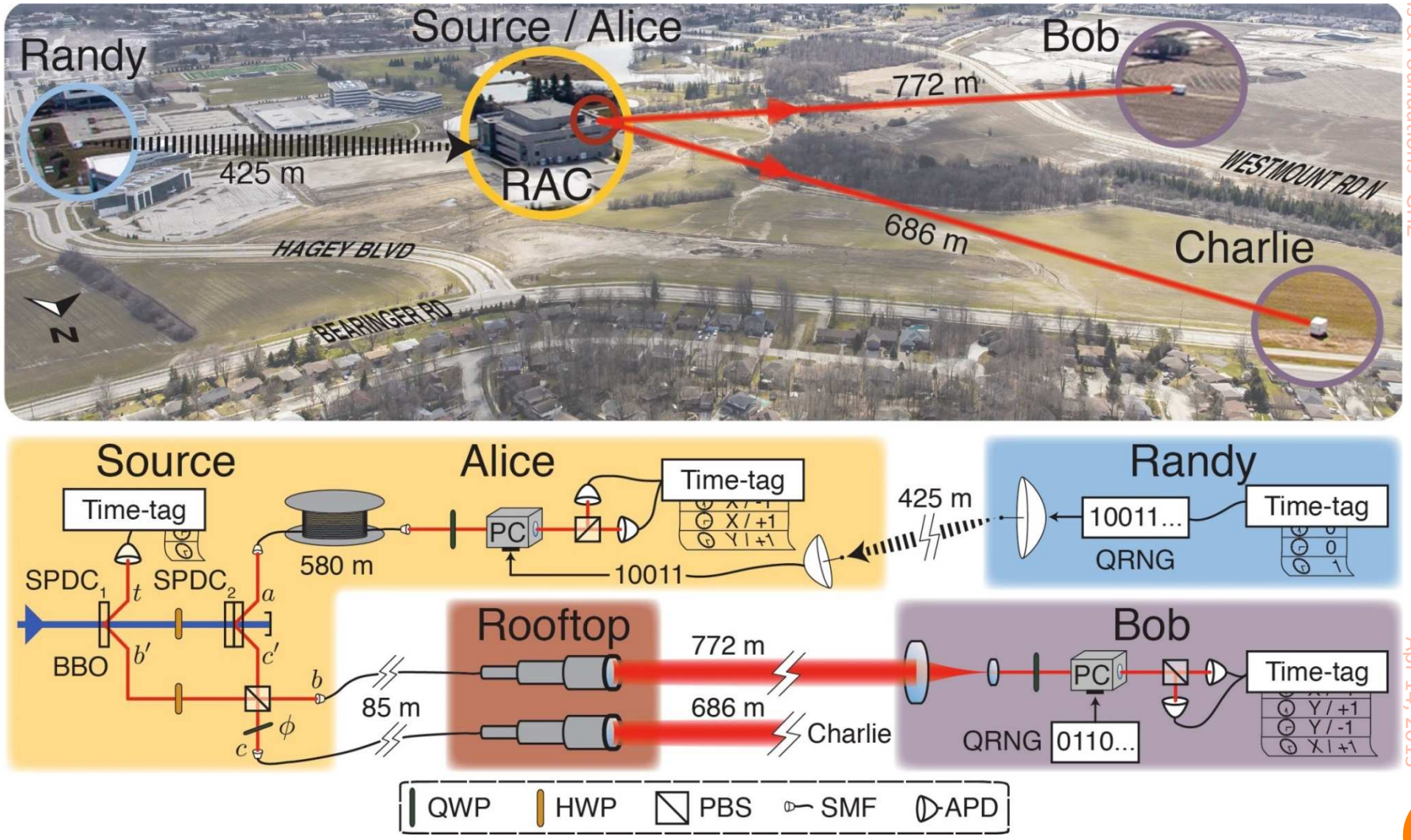
Freedom-of-Choice



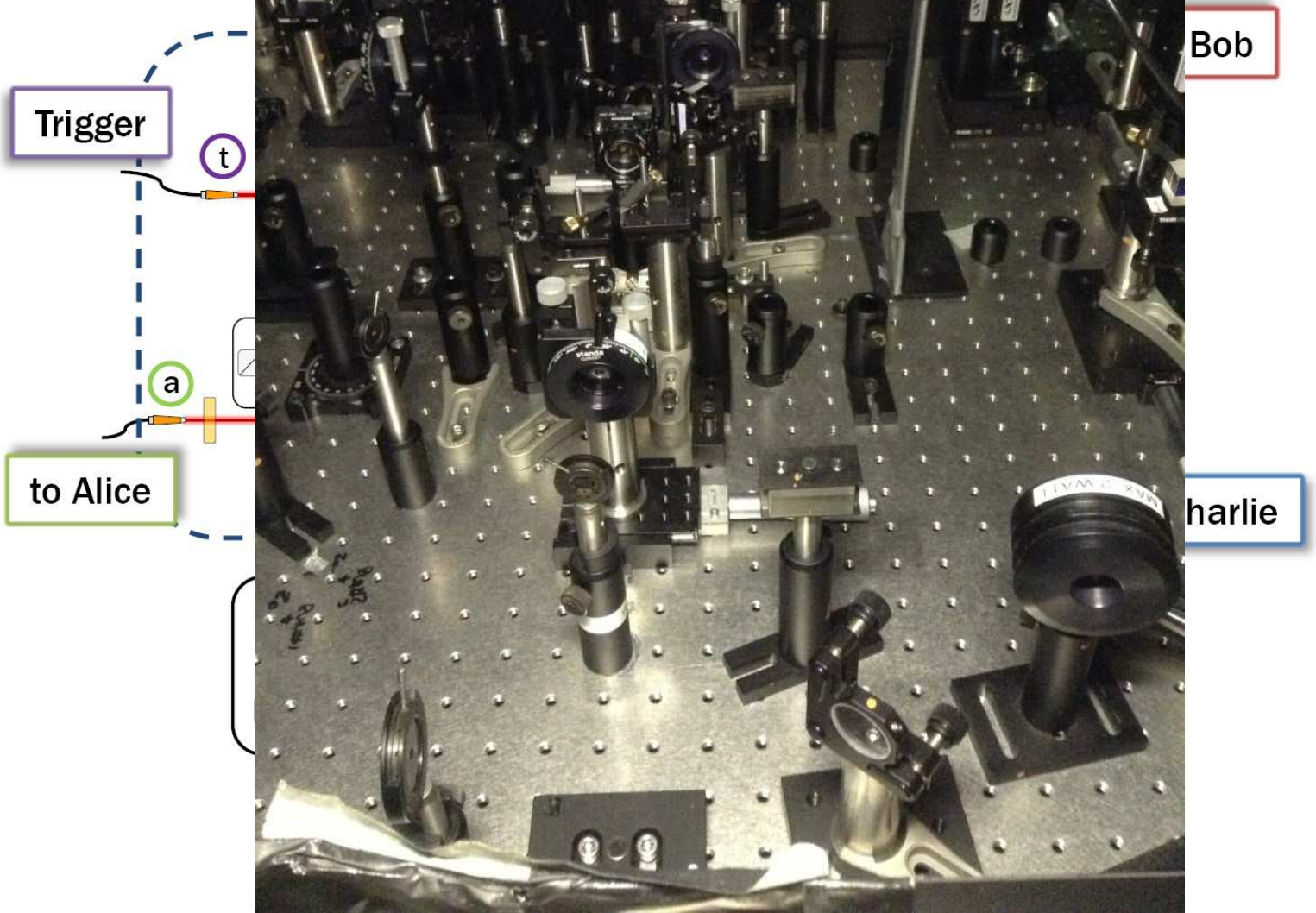

Randy
Source/Alice
Bob
446 m
801 m
61.7°
134.5°
721 m
Charlie
(a)
N
(b)
Time (μs)
ML: 911 ± 42 ns
ML: 359 ± 42 ns
Alice measurement
Bob measurement
Charlie measurement
FoC: 304 ± 25 ns
Bob basis late
FoC: 322 ± 25 ns
Charlie basis late
Bob basis early
Charlie basis early
State creation
Position (m)
R
B
S/A
C
−500
500
1000
(c)
Time (μs)
Alice measurement
FoC: 828 ± 42 ns
Randy basis late
FoC: 937 ± 25 ns
State creation
Position (m)
Randy basis early
(d)
Time (μs)
ML: 490 ± 26 ns
ML: 263 ± 28 ns
Bob measurement
Charlie measurement
Bob basis late
Charlie basis late
Bob basis early
Charlie basis early
Randy basis late
Position (m)
Randy basis early
(e)
Time (μs)
ML: 987 ± 40 ns
ML: 415 ± 38 ns
Bob measurement
Charlie measurement
Bob basis late
Charlie basis late
Bob basis early
Charlie basis early
Position (m)

Impressions

SCHEMATIC

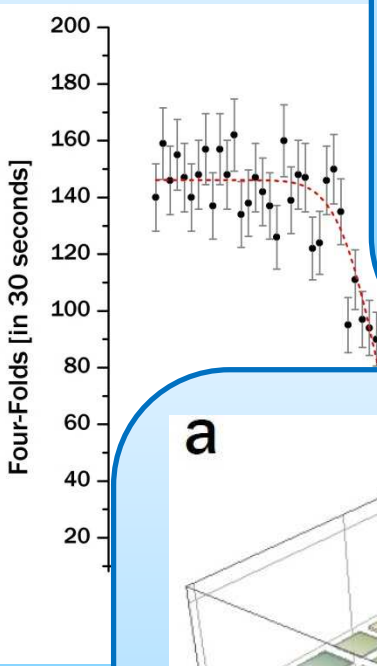

Randy
Source / Alice
Bob
425 m
RAC
772 m
WESTMOUNT RD N
686 m
Charlie
HAGEY BLVD
BEARINGER RD
N
Source
Time-tag
SPDC1
SPDC2
BBO
t
a
b′
c′
b
ϕ
c
580 m
Alice
PC
Time-tag
X / +1
Y / +1
10011
425 m
Randy
10011...
QRNG
Time-tag
0
1
Rooftop
772 m
686 m
85 m
Charlie
Bob
PC
Time-tag
Y / +1
Y / -1
X / +1
QRNG
0110...
QWP
HWP
PBS
SMF
APD

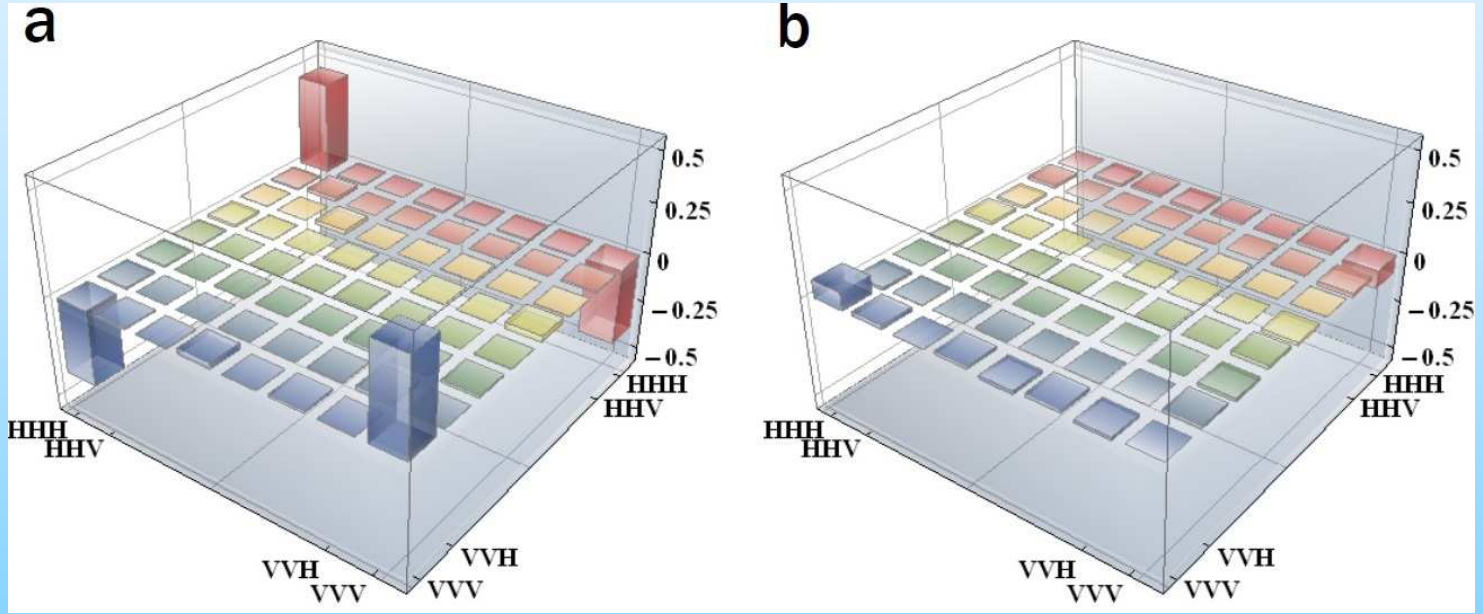
GHZ Sour



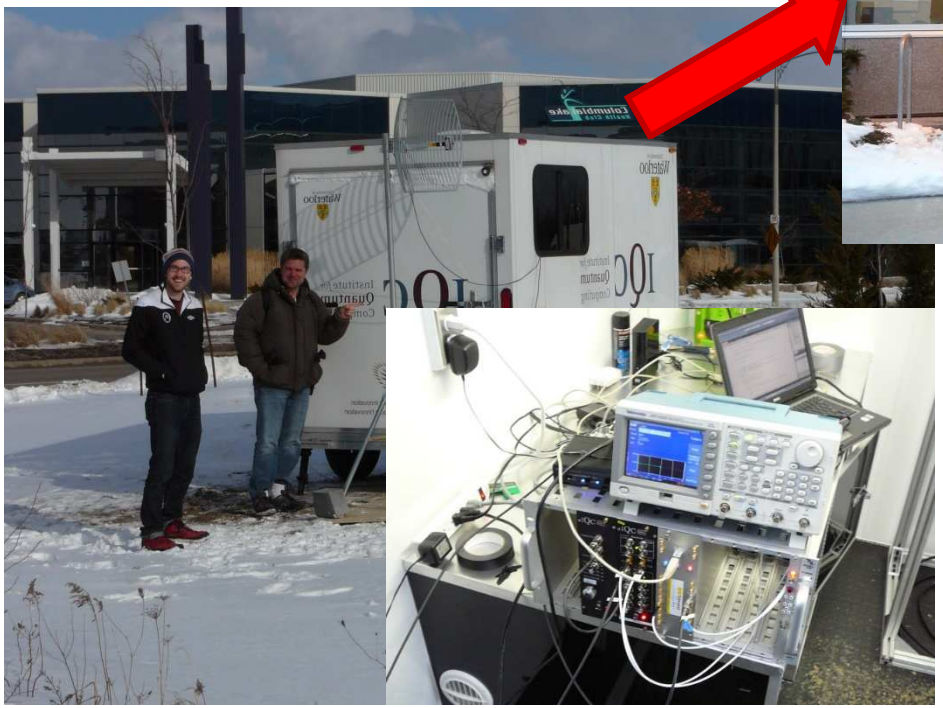
Source Pe

Measurement Settings (ABC)	Counts	Measurement Settings (ABC)	Counts
HHH	**775**	DDD	60
HHV	31	**DDA**	**384**
HVH	37	**DAD**	**370**
HVV	12	DAA	66
VHH	19	**ADD**	**339**
VHV	34	ADA	42
VVH	23	AAD	45
VVV	**765**	**AAA**	**340**
H/V Visibility	**81.60%**	**D/A Visibility**	**74.12%**



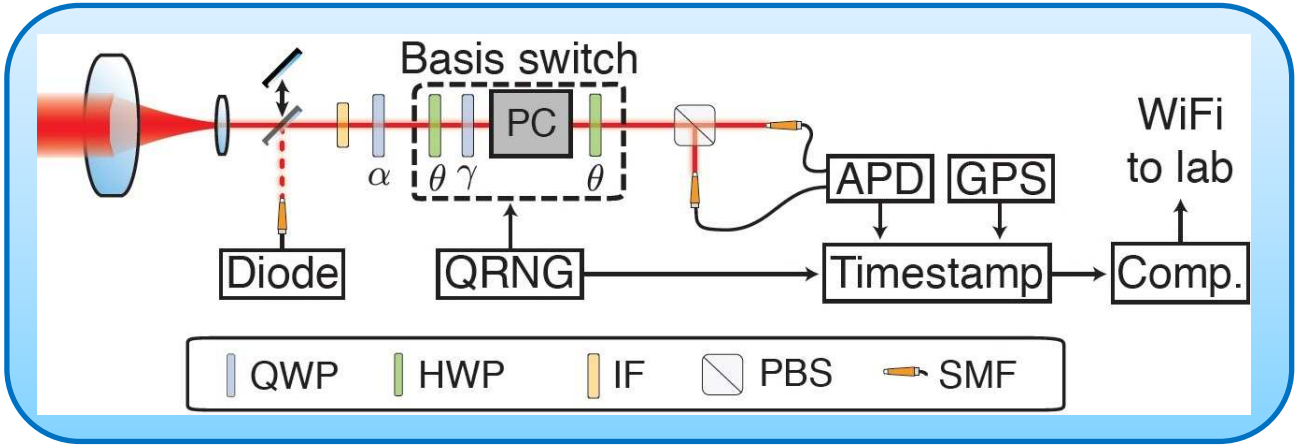


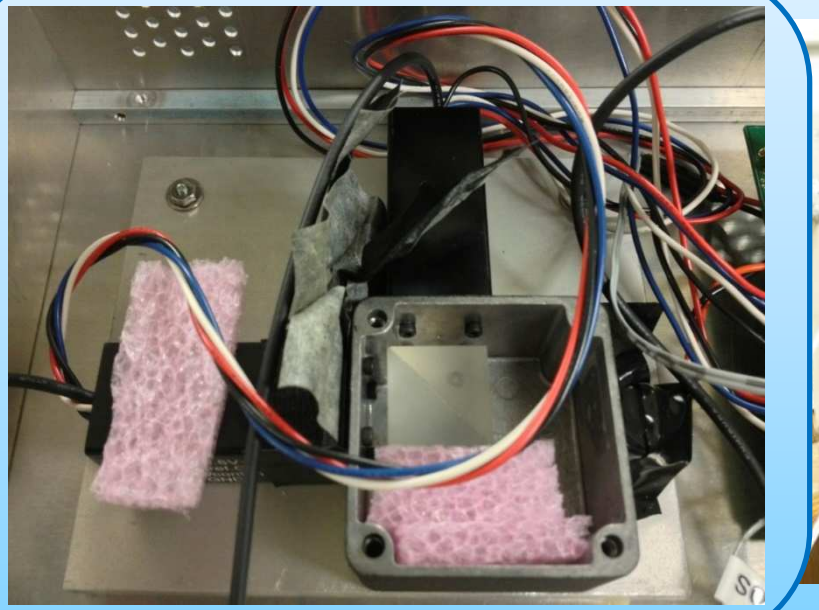
Randy's QRNG and RF Link

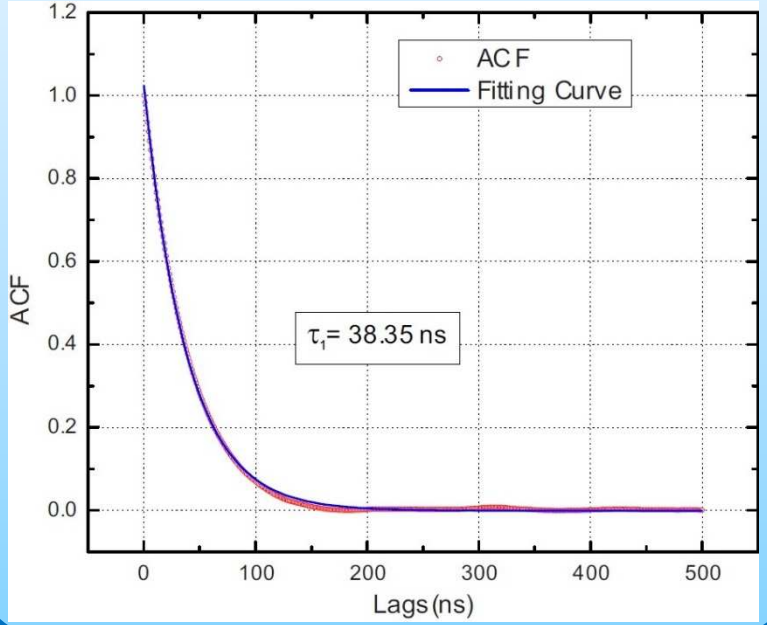


Rooftop Sending Telescopes

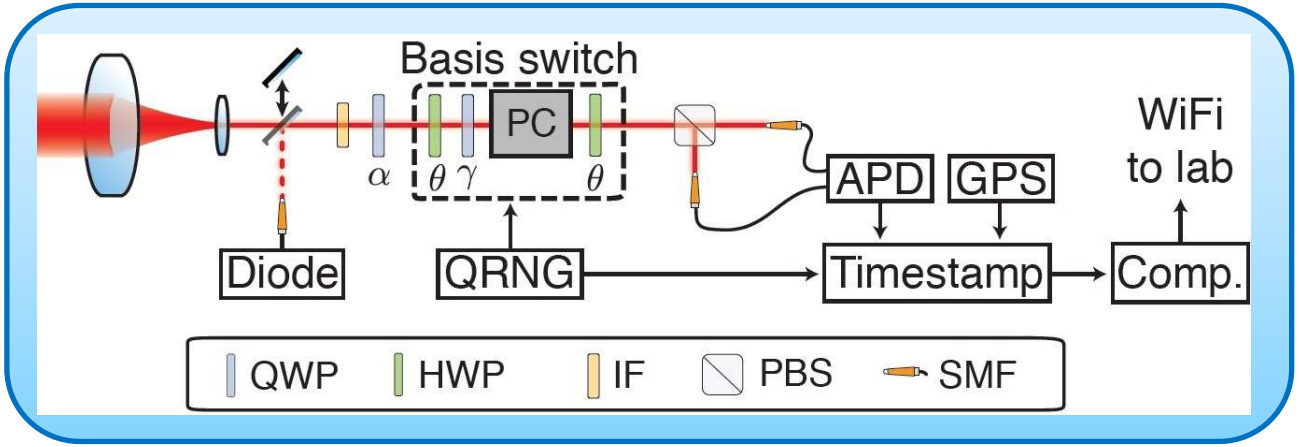
QRNGs & Timing Electronics







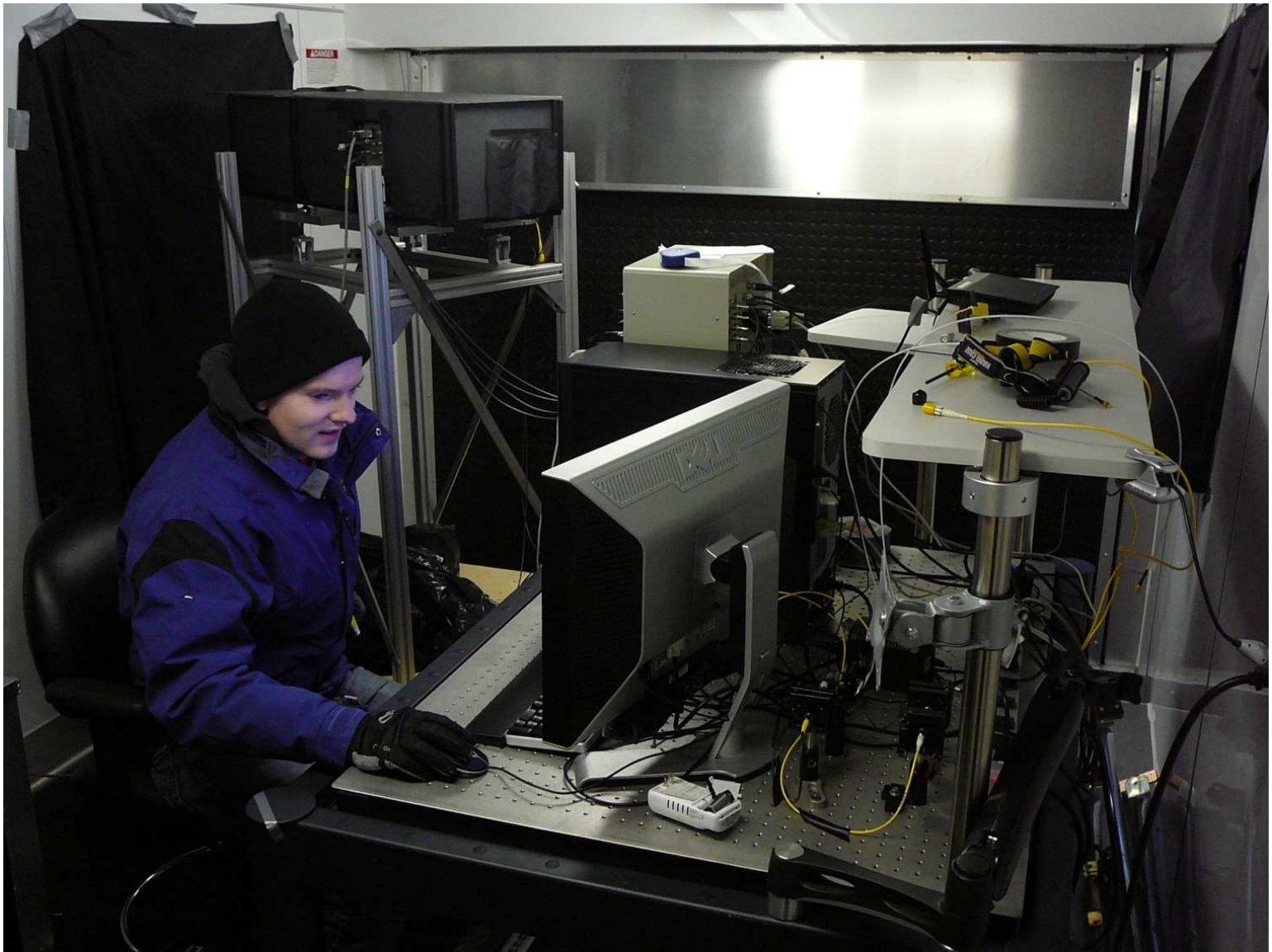
POCKELS CELL SWITCHING



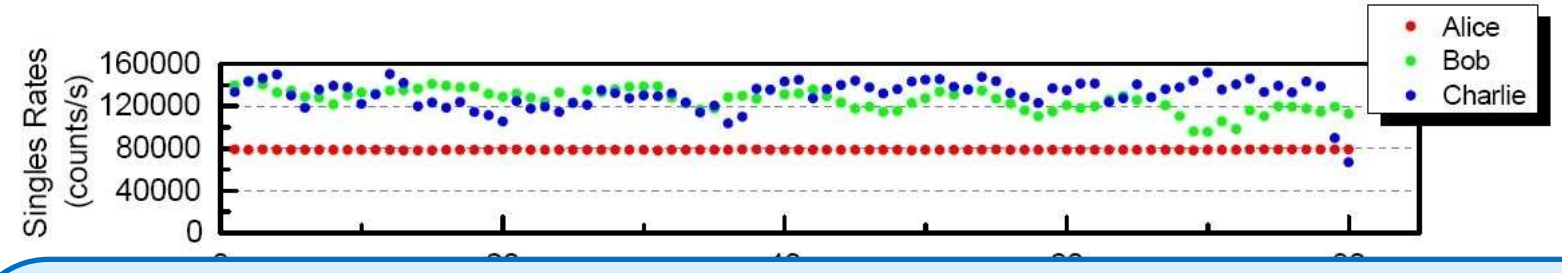
Contrasts > 100:1!

Vibration Isolation

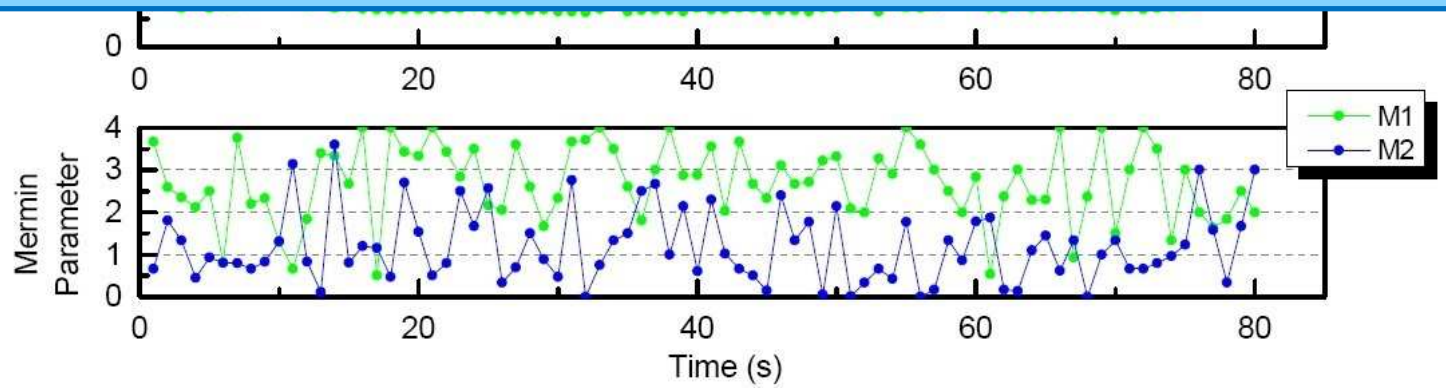
Chez Bob



RESULTS

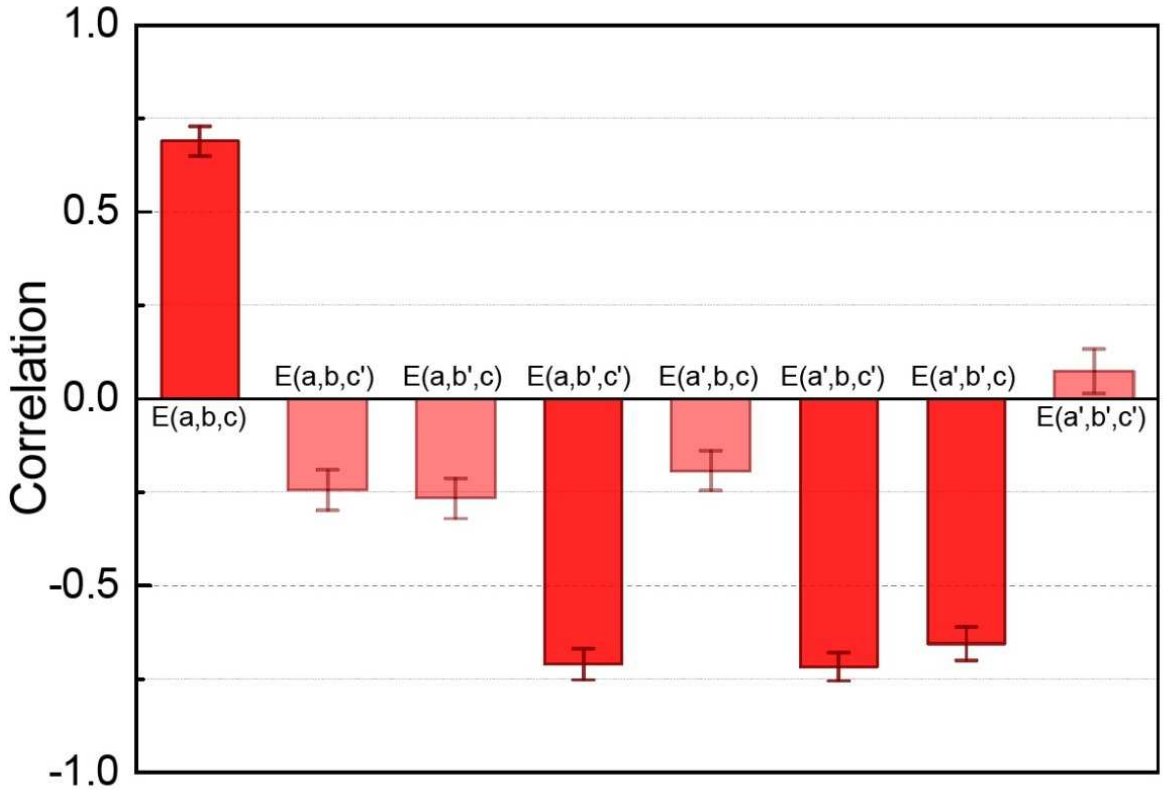


	Singles Rates				Twofold Rates		Fourfold Rates
	Alice	Bob	Charlie	Trigger	AB	AC	
Local	576,000	386,000	417,000	476,000	33,700	45,400	39
Free-Space	78,480	125,673	130,619	504,692	12,938	12,594	0.51
Efficiency	13.6%	32.6%	31.3%				



Results

- 2,475 fourfold detections between 00:49 and 02:08
- M = 2.7720 ± 0.0824, violating LHV by 9.36σ



Erven et mult. al., Nature Photonics AOP, 10.1038/NPHOTON.2014.50

Conclusions

- Pair sources needed for
  - Heralding
  - Higher entanglement
  - …
- Multi-path interference tests
- Multipartite entanglement tests