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14. ABSTRACT The investigators are developing a free-space quantum communication system that improves both the photon efficiency (long term goal of 10 bits per photon) and communication rate (long term goal of 1 Gbit/s). To achieve these worldrecord results, the system will rely on hyperentanglement in which multiple degrees of freedom (polarization and time/frequency) of the photon are entangled to transmit multiple secret bits per photon and independent communication channels using the transverse spatial degree of freedom will be used to achieve high communication rates. The investigators have achieved a spatial heralding efficiency of >90% in the hyperentangled					
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Report Title

Final Report: Information on a Photon: Free-Space Quantum Communication (InPho: FSQC)

ABSTRACT

The investigators are developing a free-space quantum communication system that improves both the photon efficiency (long term goal of 10 bits per photon) and communication rate (long term goal of 1 Gbit/s). To achieve these worldrecord results, the system will rely on hyperentanglement in which multiple degrees of freedom (polarization and time/frequency) of the photon are entangled to transmit multiple secret bits per photon and independent communication channels using the transverse spatial degree of freedom will be used to achieve high communication rates. The investigators have achieved a spatial heralding efficiency of >90% in the hyperentangled source, distributed a quantum key with 8.3 bits/photon at a rate of 67 kbit/s and 2.2 bits/photon at a rate of 12.6 Mbits/s in a single channel, a source brightness of over 100 million photons/s into a single mode, developed single photon counting detectors with >80% quantum efficiency and jitter <120 ps and explored methods for reducing detector after pulsing, evaluated commercial time taggers for the system, devised an improved error correction protocol, improved the performance of a sorter for orbital angular momentum modes, developed a method for arbitrary sorting of spatial modes, assessed the strength of atmospheric turbulence over a 1 km horizontal path, assessed multi-pixel detectors for single-photon counting, and developed new method for securing time bin quantum states.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
10/05/2015 50.00	Michael A. Wayne, Alessandro Restelli, Joshua C. Bienfang, Paul G. Kwiat. Afterpulse Reduction Through Prompt Quenching in Silicon Reach-Through Single-Photon Avalanche Diodes, <i>Journal of Lightwave Technology</i> , (11 2014): 4097. doi: 10.1109/JLT.2014.2346736
10/05/2015 90.00	Ryan E. Warburton, Frauke Izdebski, Christian Reimer, Jonathan Leach, David G. Ireland, Miles Padgett, Gerald S. Buller. Single-photon position to time multiplexing using a fiber array, <i>Optics Express</i> , (01 2011): 2670. doi: 10.1364/OE.19.002670
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10/05/2015 88.00	Gregorius C. G. Berkhout, Martin P. J. Lavery, Miles J. Padgett, Marco W. Beijersbergen. Measuring orbital angular momentum superpositions of light by mode transformation, <i>Optics Letters</i> , (05 2011): 1863. doi: 10.1364/OL.36.001863
10/05/2015 87.00	Martin P J Lavery, Angela Dudley, Andrew Forbes, Johannes Courtial, Miles J Padgett. Robust interferometer for the routing of light beams carrying orbital angular momentum, <i>New Journal of Physics</i> , (09 2011): 93014. doi: 10.1088/1367-2630/13/9/093014
10/05/2015 86.00	J. Leach, R. E. Warburton, D. G. Ireland, F. Izdebski, S. M. Barnett, A. M. Yao, G. S. Buller, M. J. Padgett. Quantum correlations in position, momentum, and intermediate bases for a full optical field of view, <i>Physical Review A</i> , (01 2012): 13827. doi: 10.1103/PhysRevA.85.013827
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10/05/2015 84.00	F. M. Miatto, D. Giovannini, J. Romero, S. Franke-Arnold, S. M. Barnett, M. J. Padgett. Bounds and optimisation of orbital angular momentum bandwidths within parametric down-conversion systems, <i>The European Physical Journal D</i> , (07 2012): 178. doi: 10.1140/epjd/e2012-20736-x
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10/05/2015 82.00	Angela Dudley, Thandeka Mhlanga, Martin Lavery, Andre McDonald, Filippus S. Roux, Miles Padgett, Andrew Forbes. Efficient sorting of Bessel beams, <i>Optics Express</i> , (01 2013): 165. doi: 10.1364/OE.21.000165
10/05/2015 81.00	D. Giovannini, J. Romero, J. Leach, A. Dudley, A. Forbes, M. J. Padgett. Characterization of High-Dimensional Entangled Systems via Mutually Unbiased Measurements, <i>Physical Review Letters</i> , (04 2013): 143601. doi: 10.1103/PhysRevLett.110.143601
10/05/2015 80.00	Mhlambululi Mafu, Angela Dudley, Sandeep Goyal, Daniel Giovannini, Melanie McLaren, Miles J. Padgett, Thomas Konrad, Francesco Petruccione, Norbert Lütkenhaus, Andrew Forbes. Higher-dimensional orbital-angular-momentum-based quantum key distribution with mutually unbiased bases, <i>Physical Review A</i> , (09 2013): 32305. doi: 10.1103/PhysRevA.88.032305

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- 11/05/2013 30.00 David A. B. Miller. How complicated must an optical component be?, *Journal of the Optical Society of America A*, (01 2013): 0. doi: 10.1364/JOSAA.30.000238
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- 11/05/2013 45.00 B. G. Christensen, K. T. McCusker, J. B. Altepeter, B. Calkins, T. Gerrits, A. E. Lita, A. Miller, L. K. Shalm, Y. Zhang, S. W. Nam, N. Brunner, C. C. W. Lim, N. Gisin, P. G. Kwiat. Detection-Loophole-Free Test of Quantum Nonlocality, and Applications, *Physical Review Letters*, (9 2013): 0. doi: 10.1103/PhysRevLett.111.130406

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- 11/05/2013 48.00 Sebastian A. Schulz, Taras Machula, Ebrahim Karimi, Robert W. Boyd. Integrated multi vector vortex beam generator, Optics Express, (06 2013): 0. doi: 10.1364/OE.21.016130

TOTAL: 75

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Barnett

1. "Information security: from classical to quantum", Proc. SPIE 8542, Electro-Optical Remote Sensing, Photonic Technologies, and Applications VI, 85421I, Edinburgh, U.K., November 19, 2012.
2. "Quantum communications with highly entangled photons", Pecs workshop on Quantum Information and Quantum Optics, Pecs, Hungary, May 28-30, 2012.

Boyd

3. Quantum Aspects of the Transverse Degrees of Freedom of Photons, Presented at the OSA Structured Light in Structured Media Incubator, Washington DC, 29 September – 1 October 2013
4. Ghost Imaging and Quantum Imaging, Presented at the OSA Annual Meeting, Orlando, Florida, October 9, 2013
5. Weak Values and Direct Measurement of the Quantum Wavefunction, Presented at the APS/DLS Laser Science Annual Meeting, Orlando, Florida, October 9, 2013
6. Quantum Aspects of Light Beams Carrying Orbital Angular Momentum, Presented at the VIII Reunión Española de Optoelectrónica, Alcalá de Henares, Madrid, July 10-12, 2013.
7. Quantum Aspects of Light Beams Carrying Orbital Angular Momentum, Presented at International Workshop on "Singularities and Topological Structures of Light," ICTP Trieste. Italy, July 8-12, 2013.
8. Weak Values and Direct Measurement of the Quantum Wavefunction, ICSSUR, Nürnberg, June 24, 2013.
9. Weak Values and Direct Measurement of the Quantum Wavefunction, Presented at CQO/QIM, Rochester, New York, June 16-20, 2013.
10. Nonlinear Photonics (Encompassing nanophotonics and quantum nonlinear optics), presented at the LENS Workshop, Florence Italy, March 12, 2013
11. Multi-bit-per-photon QKD system based on encoding in orbital-angular-momentum states of light, SPIE Photonics West, February 6, 2013.
12. Orbital-Angular-Momentum Encoding for Free Space QKD, Presented at the Symposium on the Physics of Quantum Electronics, Snowbird Utah, January 7, 2013.
13. Encoding Information on Light Fields Using OAM States (Especially Quantum Information), presented at the New York State Center for Complex Light Workshop, CCN, October 22, 2012.
14. The Promise of Quantum Nonlinear Optics, presented at the APS-DLS – OSA Joint Annual Meeting, Rochester, NY, USA, October 16, 2012.
15. Research in Quantum Nonlinear Optics, presented at the IEEE Photonics Conference, San Francisco, September, 26, 2012.
16. Quantum Imaging: Enhanced Image Formation Using Quantum States of Light, presented at the 2012 Karles Invitational Conference on Quantum Information Science and Technology, Naval Research Laboratory Washington, DC 20375, August 27-28, 2012.
17. Quantum Imaging: Enhanced Image Formation Using Quantum States of Light, presented at the 21st International Laser Physics Workshop (LPHYS'12), Calgary, Alberta, Canada, July 23, 2012.
18. Research in Quantum Nonlinear Optics, presented at the Workshop on Novel Ideas in Optics, Purdue University, May 31-June 2, 2012.
19. Nonlinear Optics, Past Successes and Future Challenges, Plenary Talk presented at the Conference on Lasers and Electro-Optics and Quantum Electronics and Laser Science Conference (CLEO: 2012), San Jose, California, May 6-11, 2012.
20. Information in a Photon, Presented at Photonics West, San Francisco, January 25, 2012.
21. High-Order Entanglement for Quantum Information, presented at PQE, Snowbird Utah, January 3, 2012.
22. Promises and Challenges of Ghost Imaging, presented at the OSA Topical Meeting on Signal Recovery and Synthesis, July 11, 2011.
23. Information in a Photon, presented at the First International Workshop on High-Dimensional Entanglement, Como, Italy. June 20-24, 2011.
24. Quantum Imaging: Enhanced Image Formation Using Quantum States of light, Presented at Information Photonics, Ottawa, May 19, 2011.
25. Promises and Challenges in Quantum Nonlinear Optics, Presented at Photonics North, Ottawa, ON, May 16, 2011.
26. Information in a Photon, presented at the Winter Colloquium on the Physics of Quantum Electronics, January 5, 2011.

Gauthier

27. 'Observation of Elliptical Patterns in Type I Spontaneous Parametric Down Conversion', 2013 Frontiers in Optics/Laser Science XXIX (FiO/LS), Orlando FL, Oct. 6 - Oct. 10, 2013.
28. 'Achieving high-rate quantum key distribution by multiplexing orbital angular momentum transverse modes,' 43rd Colloquium on the Physics of Quantum Electronics 2103, Snowbird, Utah, Jan. 7, 2013.
29. 'Quantum Key Distribution Using Hyperentanglement,' Quantum Information and Measurement Conference, Berlin, Germany, Mar. 20, 2012.
30. 'High rate quantum key distribution,' 41st Colloquium on the Physics of Quantum Electronics, Snowbird, UT, Jan. 5, 2011.

Kwiat

31. "Higher-dimensional quantum cryptography", QCrypt 2013, 3rd international conference on quantum cryptography. August 5–9, 2013 in Waterloo, Canada
32. "La Morte de Realismo locale", Paul G. Kwiat, Quantum Information Processing and Communication, Florence, IT, June 30-July 5, 2013.
33. "The Death of Nonlocality", Paul G. Kwiat, Conference on Quantum Information and Quantum Control (CQIQC-V), Fields Institute,

Toronto, Canada, 12 Aug 2013 - 16 Aug 2013

34. "Loopholes -- Be Gone!", Paul Kwiat, Single Photon Workshop 2013, Oak Ridge National Laboratory, October 15-18, 2013
35. "Implementation and Applications of a Loophole-free Test of Quantum Nonlocality", Brad Christensen and Paul Kwiat, Quantum Communications and Photonics, Waikoloa, Hawaii, July 8-10, 2013.
36. "Information Reconciliation in Higher Dimensional Quantum Cryptography", Quantum Information and Measurement 2013, Rochester, New York United States, June 17-20, 2013
37. "The End of Local Realism", Quantum Information and Measurement 2013, Rochester, New York United States, June 17-20, 2013
38. "Advanced Quantum Communication via Hyperentanglement," Quantum Information and Measurement (QIM) 19 March - 21 March 2012, Laser Optics Berlin, Berlin, Germany.
39. "Hyperentanglement: More IS better," 11th Annual Meeting of the Fitzpatrick Institute for Photonics (FIP), Duke University, October 10-11, 2011, Durham, NC.

Miller

40. "Nanometallic concentration for enhanced photodetection," IEEE Photonics conference, Arlington VA, October 13, 2011, Paper ThA1
41. "Device Challenges and Opportunities for Optical Interconnects," (invited tutorial), OSA Frontiers in Optics conference, San Jose, CA, October 18, 2011, Paper FTuV1
42. "Optical Interconnects – Why We Will Have To Use Them," ISSCC, San Francisco, CA, Feb. 20, 2012, Session ES4
43. "Optical Interconnects to Chips," (Invited Tutorial talk), European Conference on Integrated Optics, Sitges, Spain, April 19, 2012
44. "Optical Interconnects to Chips," (Invited Tutorial talk), IEEE International Interconnect Technology Conference, San Jose, June 3, 2012
45. "The Roles of Optics in Information Processing," (Plenary talk), OSA Nonlinear Photonics and Integrated Photonics Research conferences, Colorado Springs, Colorado, June 18, 2012
46. "The Heat Death of Information Processing and Why Interconnects Are More Important Than Logic," Future Trends in Microelectronics 2012, Corsica, June 28, 2012
47. "Why Interconnects Are More Important Than Logic," Royal Society e-Futures Meeting, Royal Society, London, UK, May 14, 2013
48. "Attojoule Optoelectronics?" Royal Society e-Futures Kavli Meeting, Royal Society Kavli Centre, Chicheley Hall, Newport Pagnell, UK, May 16, 2013
49. "Attojoule optoelectronics – why and how," (Plenary talk) IEEE Photonics Society Summer Topical Meetings, Micro- and Nano-Cavity Integrated Photonics, Kona, Hawaii, July 9, 2013, Paper TuA2.1
50. "Requirements and novel devices for optical interconnects," IEEE Photonics Conference, Bellevue, Washington, Sept. 9, 2013
51. "Low-energy optoelectronics for interconnects," (Invited tutorial) OSA Frontiers in Optics, Orlando, Florida, October 8, 2013, Paper FM3B.2
52. "Designing arbitrary optical components without calculations," 9th National Conference on Laser Technology and Optoelectronics and the International Forum on Laser and Optics Technology, Shanghai, China, March 18, 2014
53. "Low energy optoelectronics for interconnects," The Tenth International Nanotechnology Conference on Communications and Cooperation (INC 10), NIST, Gaithersburg, Maryland, May 15, 2014
54. "Limits and opportunities of electrical and optical interconnects," OSA Incubator Nanophotonic Devices: Beyond Classical Limits, Washington, D.C., May 15, 2014
55. "Nanophotonics and Interconnects – Status and Future Directions," 2014 IEEE International Interconnect Technology Conference, May 21, 2014, San Jose, California
56. "Establishing optimal optical channels automatically," OSA Frontiers in Optics, Orlando, Florida, October 7, 2014, Paper FM3B.2

Padgett

57. The nonlinear meeting, Edinburgh, UK, 2014.
58. SPIE Defense and Security, Baltimore, USA, 2014.
59. Quantum Information and Measurement, Berlin, Germany, 2014.
60. Physics of Quantum Electronics, Snowbird, USA, 2014.
61. Plenary Speaker Australia - New Zealand Optics & Photonics, Perth Australia, 2013.
62. Structured Light in Structured Media, OSA Incubator, Washington, USA, 2013.
63. Keynote Speaker, SPIE Security and Defense, Dresden, Germany, 2013.
64. Summer School, New Frontiers on Smart Sensing, Otranto, Italy, 2013.
65. Winter School on Quantum Information Processing, Paraty, Brazil, 2013.
66. Plenary Lecture Physics of Quantum Electronics, Snowbird, USA, 2013.
67. Workshop on Singular Optics, ICTP, Trieste, Italy, 2012.
68. Plenary Lecture Rochester Coherence Conference, Rochester, USA, 2012.
69. Spin-Orbit Interaction for Light and Matter waves, Dresden, Germany, 2012.
70. Plenary Lecture SPIE Photonics West, San Francisco, USA, 2012.
71. National Meeting on Condensed Matter Physics, Águas de Lindóia, Brazil, 2012.
72. Conference on Lasers and Electro Optics, OSA, San Jose, USA, 2012.
73. Workshop on Orbital Angular Momentum and Applications, Vienna, Austria, 2012.
74. SPIE Photonics West, Complex Light, San Francisco, USA, 2012.
75. Physics of Quantum Electronics, Snowbird USA, 2012.

76. "Efficient measurement of orbital angular momentum using refractive optical elements," FIO Oct. 16-21 (2011), San Jose, CA.
77. "Measuring the orbital angular momentum of light with high optical efficiency," ICQI June 6-8, (2011), Ottawa, Canada.
78. "Measuring the orbital angular momentum of light," Invited talk, Photonics West, San Francisco, CA, Jan. 26, 2011.
79. "Sorting optical angular momentum states based on a geometric transformation," Frontiers in Optics 2010, Rochester, NY, Oct. 24, 2010.
80. "Optically efficient separation of orbital angular momentum states," Photon 10, Southampton, UK, Aug. 23-26, 2010.

Number of Presentations: 80.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
10/05/2015 52.00	Daniel J. Gauthier, Mario Stipcevic. Precise Monte Carlo simulation of single-photon detectors, SPIE Defense, Security, and Sensing. 29-APR-13, Baltimore, Maryland, USA. : ,
10/05/2015 60.00	Stephen M. Barnett, Thomas Brougham. Information security: from classical to quantum, SPIE Security + Defence. 24-SEP-12, Edinburgh, United Kingdom. : ,
10/05/2015 54.00	Kevin T. McCusker, Venkat Chandar, Daniel J. Gauthier, Paul G. Kwiat, Daniel Kumor, Bradley G. Christensen. Information Reconciliation in Higher Dimensional Quantum Cryptography, Quantum Information and Measurement. 19-JUN-13, Rochester, New York. : ,
10/05/2015 53.00	Daniel J. Gauthier, Christoph F. Wildfeuer, Hannah Guilbert, Mario Stipcevic, Bradley G. Christensen, Daniel Kumor, Paul Kwiat, Kevin T. McCusker, Thomas Brougham, Stephen Barnett. Quantum Key Distribution Using Hyperentangled Time-Bin States, Quantum Information and Measurement. 19-JUN-13, Rochester, New York. : ,
10/06/2015 91.00	David A. B. Miller. Separating arbitrary overlapping spatial modes losslessly and without calculations, 2013 IEEE Photonics Society Summer Topical Meeting Series. 08-JUL-13, Waikoloa, HI, USA. : ,
11/05/2013 26.00	Mohammad Mirhosseini, Mehul Malik, Martin Lavery, Jonathan Leach, Miles Padgett, Robert W. Boyd. Photon efficient wavefront sensing using an SLM for polarization-based weak measurements, Frontiers in Optics. , Rochester, NY. : ,
11/05/2013 3.00	Robert Boyd, Heedeuk Shin, Mehul Malik, Colin O'Sullivan, Kam Wai Clifford Chan, Hye Jeong Chang, Daniel J. Gauthier, Anand Jha, Jonathan Leach, Sangeeta Murugkar, Brandon Rodenburg. Applications of Nonlinear Optics in Quantum Imaging and Quantum Communication, Nonlinear Optics: Materials, Fundamentals and Applications. 17-JUL-11, Kauai, Hawaii. : ,
11/05/2013 5.00	Robert W. Boyd, Anand Jha, Mehul Malik, Colin O'Sullivan, Brandon Rodenburg, Daniel J. Gauthier, Zameer U. Hasan, Philip R. Hemmer, Hwang Lee, Charles M. Santori. Quantum key distribution in a high-dimensional state space: exploiting the transverse degree of freedom of the photon, SPIE OPTO. 11-FEB-11, San Francisco, California. : ,
11/05/2013 10.00	Eliot Bolduc, Jonathan Leach, Robert Boyd. The Secure Information Capacity of Photons Entangled in High Dimensions, Quantum Information and Measurement. , Berlin, Germany. : ,
11/05/2013 9.00	Bradley G. Christensen, Kevin T. McCusker, Daniel J. Gauthier, Paul G. Kwiat. High-Speed Quantum Key Distribution Using Hyper-Entangled Photons, CLEO: Applications and Technology. , San Jose, California. : ,
11/05/2013 11.00	Jonathan Leach, Megan Agnew, Melanie McLaren, Stef Roux, Robert Boyd. Quantum State Characterization of High-dimensionally Entangled Photons, Quantum Information and Measurement. , Berlin, Germany. : ,
11/05/2013 12.00	Daniel Gauthier, Hannah Guilbert, Yunhui Zhu, Meizhen Shi, Kevin McCusker, Bradley Christensen, Paul Kwiat, Thomas Brougham, Stephen M. Barnett, Venkat Chandar. Quantum Key Distribution Using Hyperentanglement, Quantum Information and Measurement. , Berlin, Germany. : ,

- 11/05/2013 16.00 Brandon Rodenburg, Mehul Malik, Malcolm O'Sullivan, Mohammad Mirhosseini, Robert Boyd. Influence of Atmospheric Turbulence on the Performance of a High Dimensional Quantum Key Distribution System using Spatial Mode Encoding, Quantum Information and Measurement. , Berlin, Germany. : ,
- 11/05/2013 17.00 Brandon Rodenburg, Mehul Malik, Malcolm O'Sullivan, Mohammad Mirhosseini, Nicholas K. Steinhoff, Glenn A. Tyler, Robert W. Boyd. Influence of thick atmospheric turbulence on the propagation of quantum states of light using spatial mode encoding, CLEO: Applications and Technology. , San Jose, California. : ,
- 11/05/2013 42.00 David A. B. Miller. Separating arbitrary overlapping spatial modes losslessly and without calculations, 2013 IEEE Photonics Society Summer Topical Meeting Series. 08-JUL-13, Waikoloa, HI, USA. : ,

TOTAL: 15

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
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- | | |
|------------------|---|
| 10/05/2015 57.00 | Thomas Brougham, Christoph F Wildfeuer, Stephen M Barnett, Daniel J Gauthier. The information of high-dimensional time-bin encoded photons, arXiv:1506.0442v2 (06 2015) |
|------------------|---|

TOTAL: 1

Number of Manuscripts:

Books

<u>Received</u>	<u>Book</u>
-----------------	-------------

TOTAL:

Received

Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Robert Boyd, Canada Excellence Research Chair in Quantum Nonlinear Optics

Robert Boyd, Fellow of the SPIE

Daniel Gauthier, Robert C. Richardson Professorship

David Miller, Fellow of the Electromagnetics Academy

David Miller, Carnegie Millennium Professorship

Miles Padgett, Fellow of the Optical Society of America

Miles Padgett, Fellow of the SPIE

Miles Padgett, Research Fellow of the Royal Society

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Martin Lavery	1.00	
Meizhen Shi	0.78	
Hannah Guilbert	1.00	
Branden Rodenburg	1.00	
Bradley Christensen	1.00	
Kevin McCusker	0.40	
Anand Jha	0.13	
Daniel Giovannini	0.13	
Collin O'Sullivan	1.00	
Mehul Malik	0.13	
Mohammad Mirhosseini	0.78	
Heedueuk Shin	0.13	
Filippo Miatto	0.13	
FTE Equivalent:	7.61	
Total Number:	13	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	
Allison Yao	0.10	
Christoph Wildfeuer	0.40	
Hugo Cavalcante	0.13	
Thomas Brougham	0.80	
Jonathan Leach	0.50	
FTE Equivalent:	1.93	
Total Number:	5	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Steve Barnett	0.08	
Daniel Gauthier	0.08	
Robert Boyd	0.08	
Paul Kwiat	0.08	
David Miller	0.16	Yes
Miles Padgett	0.08	
FTE Equivalent:	0.56	
Total Number:	6	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Yu-Po Wong	0.20	Physics
Daniel Kumor	0.20	Physics
FTE Equivalent:	0.40	
Total Number:	2	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 2.00

Names of Personnel receiving masters degrees

<u>NAME</u>	
Meizhen Shi	
Total Number:	1

Names of personnel receiving PhDs

<u>NAME</u>
Mehul Malik
Hannah Guilbert
Kevin McCusker
Martin Lavery
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Glenn Tyler	0.09
Nicholas Steinhoff	0.28
FTE Equivalent:	0.37
Total Number:	2

Sub Contractors (DD882)

1 a. Stanford University

1 b. 3160 Porter Drive

Suite 100

Palo Alto

CA

943041222

Sub Contractor Numbers (c): 11-DARPA-1021

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Undertake fundamental limits of optical components for transforming the transverse profi

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 6/30/14 12:00AM

1 a. Stanford University

1 b. 3160 Porter Drive

Suite 100

Palo Alto

CA

943058445

Sub Contractor Numbers (c): 11-DARPA-1021

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Undertake fundamental limits of optical components for transforming the transverse profi

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 6/30/14 12:00AM

1 a. the Optical Sciences Company

1 b. 1341 South Sunkist St

PO Box 25309

Anaheim

CA

92806

Sub Contractor Numbers (c): 11-DARPA-1023

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Undertake measurements of turbulence on a 1 km horizontal path and develop mitigation

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 11/11/13 12:00AM

1 a. University of Rochester

1 b. ORPA

518 Hylan Building

Rochester

NY

146270140

Sub Contractor Numbers (c): 11-DARPA-1025

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Develop a quantum key distribution systems based on transverse spatial modes of optical

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 6/30/14 12:00AM

1 a. University of Rochester

1 b. 518 Hylan Bldg.

Rochester

NY

146113847

Sub Contractor Numbers (c): 11-DARPA-1025

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Develop a quantum key distribution systems based on transverse spatial modes of optical

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 6/30/14 12:00AM

1 a. University of Illinois - Urbana - Champaign

1 b. 1901 S. First St., Suite A

Champaign

IL

618207406

Sub Contractor Numbers (c): 11-DARPA-1025

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Develop high-rate quantum key distribution system using high-dimensional encoding

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 6/30/14 12:00AM

1 a. University of Illinois - Urbana - Champaign

1 b. 1901 S. First Street, Suita A, MC-68

Champaign

IL

618207406

Sub Contractor Numbers (c): 11-DARPA-1025

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Develop high-rate quantum key distribution system using high-dimensional encoding

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 6/30/14 12:00AM

1 a. University of Glasgow

1 b. Research Enterprise

10 The Square

Glasgow

Scotland G12 8QQ

Sub Contractor Numbers (c): 11-DARPA-1022

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Develop optical systems for sorting spatial modes, investigate high-dimensional quantum

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 6/30/14 12:00AM

1 a. University of Strathclyde

1 b. University of Strathclyde

Glasgow

Sub Contractor Numbers (c): 11-DARPA-1022

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Undertake theoretical research on high-dimensional quantum key distribution identifying

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 8/11/13 12:00AM

1 a. University of Strathclyde

1 b. University of Strathclyde

106 Rottenrow

Glasgow, G4 0NW UK 00000

Sub Contractor Numbers (c): 11-DARPA-1022

Patent Clause Number (d-1): 37 CFR 401

Patent Date (d-2):

Work Description (e): Undertake theoretical research on high-dimensional quantum key distribution identifying

Sub Contract Award Date (f-1): 8/12/10 12:00AM

Sub Contract Est Completion Date(f-2): 8/11/13 12:00AM

Inventions (DD882)

Scientific Progress

See attached.

Technology Transfer

Quantum Key Distribution Using Hyperentanglement

InPho: FSQC



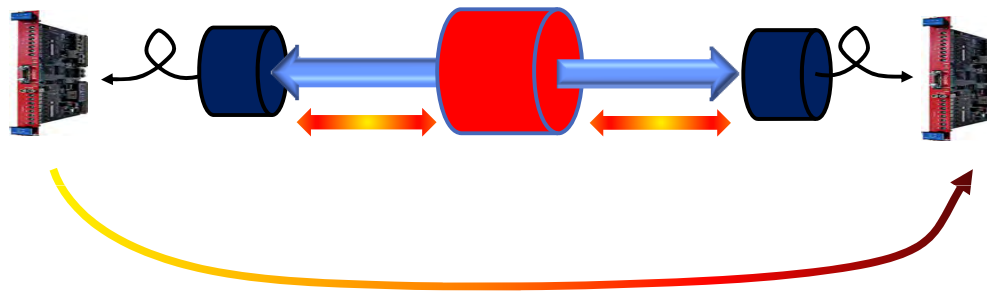
Question: What are the fundamental limits of encoding/decoding information on a photon?

Goal: Develop a free-space, entanglement-based quantum key distribution (QKD) system that achieves >10 bits/photon received and >1 Gb/s

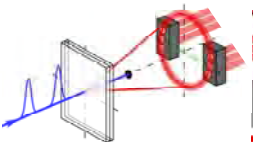
Steve Barnett, Strathclyde, **Robert Boyd**, Ottawa,
Daniel Gauthier, Duke, **Paul Kwiat**, UIUC, **David Miller**, Stanford,
Miles Padgett, Glasgow, **Glenn Tyler**, tOSC

Advisors/Partners:

Venkat Chandra, MIT Lincoln Labs, **Norbert Lütkenhaus**, U. Waterloo
Sae-Woo Nam, NIST



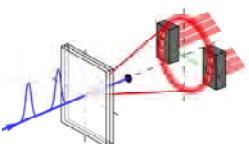
Duke InPho Site Visit, June 6, 2014



Primary Duke InPho Quantum Key Distribution System

Paul Kwiat
University of Illinois, Urbana-Champaign

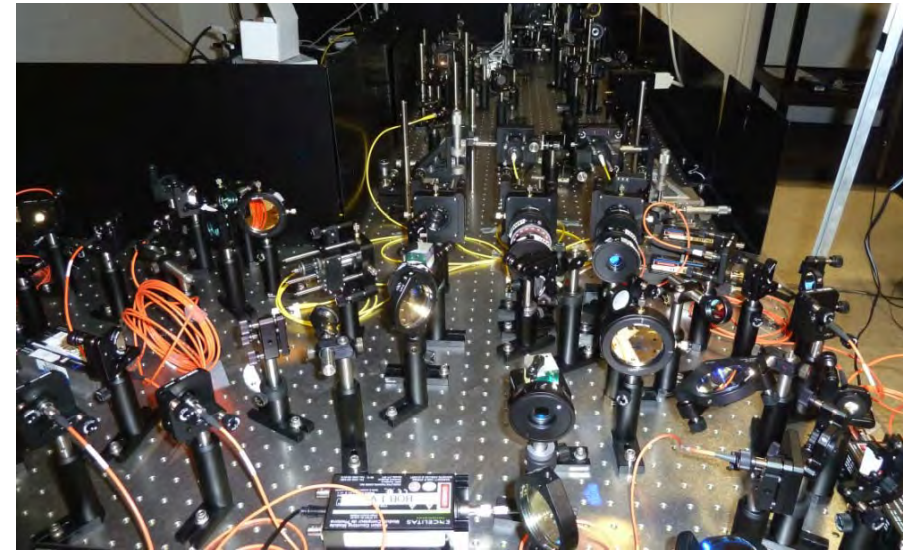
Daniel Gauthier
Duke University



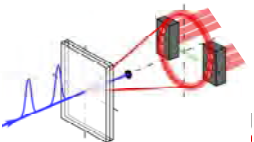


***Accomplishment:* Set up 2-channel hyper-entanglement-based QKD system, with time-bin PPM secured using simultaneous polarization entanglement.**

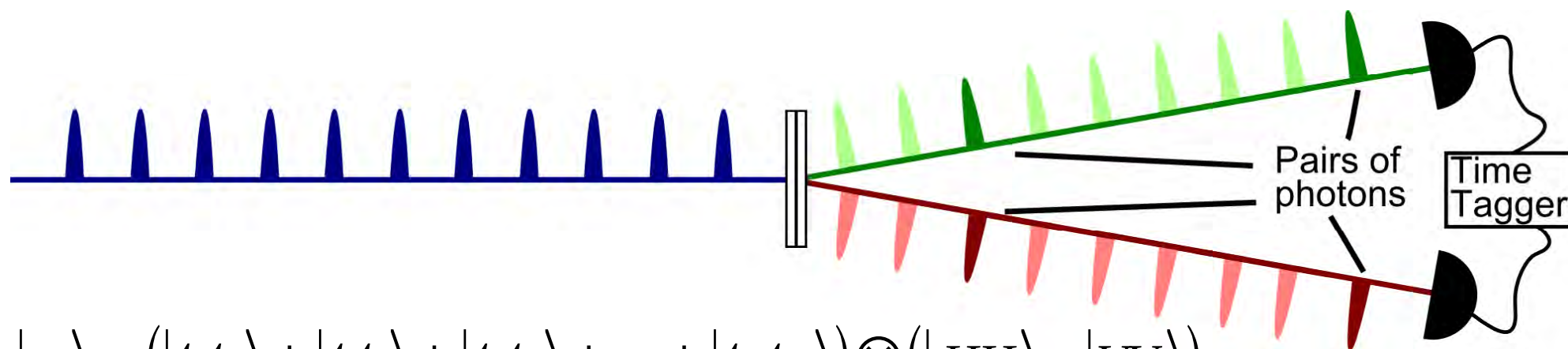
- Low jitter detectors (average 158-ps FWHM)
- x32 repetition-rate multipliers increase pulse frequency to 3.84 GHz
- Reduced detector deadtime (~ 25 ns) allows for high saturation
- Still photon-number limited
 - Use few-mode fibers ($\sim x7$ brightness)
 - Polarization decoherence issues with few-mode fiber
- Assumes intercept-resend attacks, and no polarization-independent QND measurements



June 2014	Low Power	High Power
Singles	50 kHz	10.1 MHz
Coincidences	8 kHz	2.9 MHz
Average BER	0.4 %	0.9 %
“Secure” bit/coincidence	8.3 bits	2.2 bits
“Secure” bit/second	67 kbits	6.3x2 Mbits 12.6 Mbits



Central Concept: Encode in time, verify in polarization



$$|\psi\rangle \propto (|t_0 t_0\rangle + |t_1 t_1\rangle + |t_2 t_2\rangle + \dots + |t_N t_N\rangle) \otimes (|HH\rangle + |VV\rangle)$$

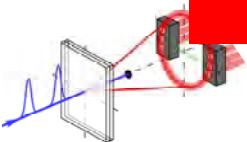
Alice and Bob use which time bin they detect a photon in to generate multiple bits per click, e.g., 1 pair in 1024 bins (2^{10}) $\rightarrow$ ~10 bits

Get extra 0.5 bpp from BB84 w. polarization.

They can constantly check for an eavesdropper using the polarization DOF (assuming no QND capability for Eve).

Perform NON-standard error detection/correction and privacy amp.

First experiment to use one DOF to secure another.



World-Record Heralding Efficiency

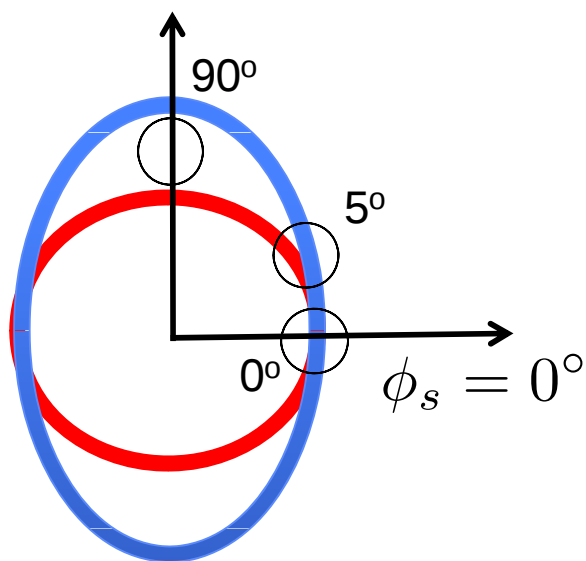
Source Quality:

- $\eta = \eta_{\text{spatial}} * \eta_{\text{spectral}} * \eta_{\text{optics}}$
 $= 0.9 * 0.95 * 0.95 = 0.81$
- Used in detection-loop-hole-free Bell test
- Visibility in all bases >99.7% using temporal compensation,
- World-record (?) pair production rate of 30 MHz into a single mode (over a >20 nm bandwidth at 710 nm)
- Other improvements possible (e.g., achromatic coupling)

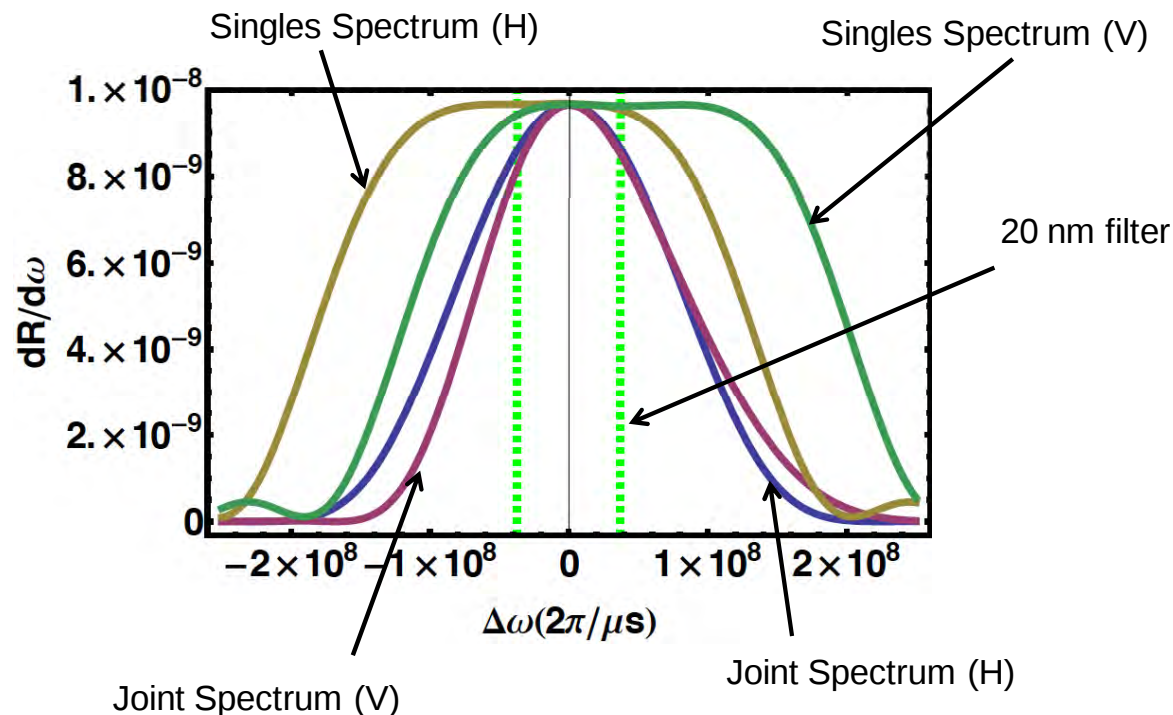
Developed one of the world's best entanglement sources.

Heralding Efficiency for BiBO source

InPho Breakthrough – Develop complete model for coupling bi-photons into single mode fibers. Accounts for elliptical shape of down-conversion ring, spatial-spectral coupling



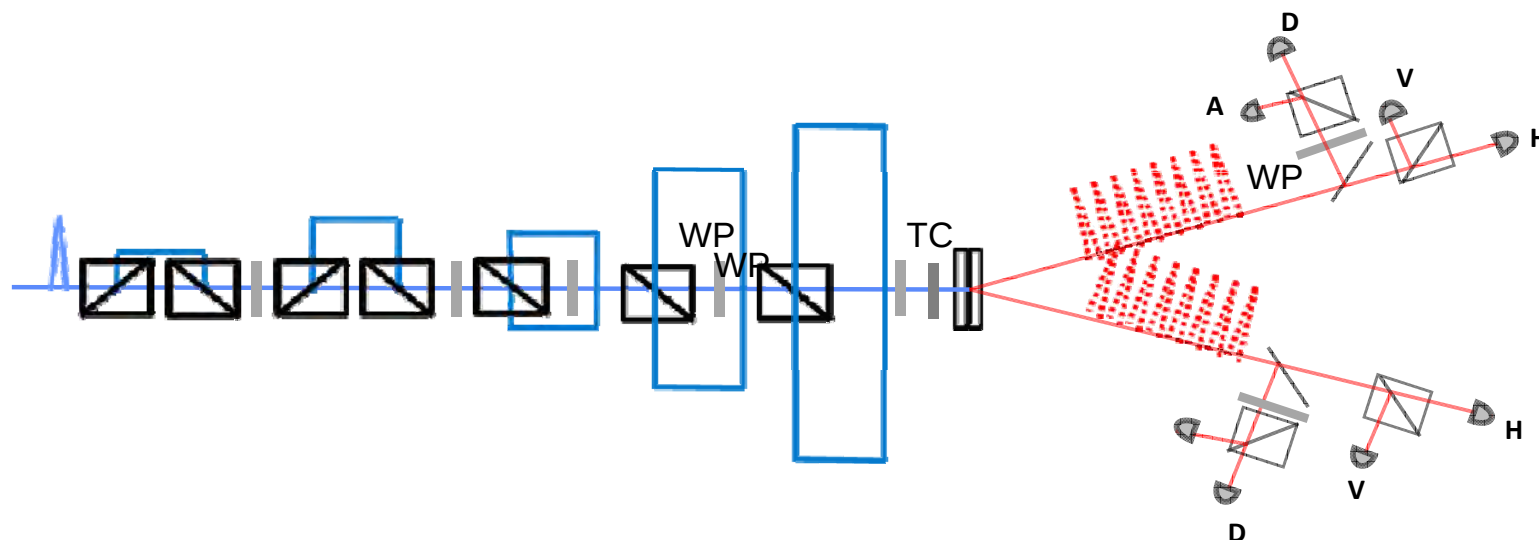
Note: Eccentricity exaggerated in drawing



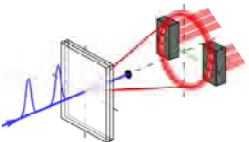
	Visibility	HE (H)	HE (V)
0°	99.986%	96.44%	95.71%
5°	99.982%	95.62%	96.23%
90°	99.971%	96.64%	95.84%

Predicted polarization visibility
spatial/spectral heralding efficiency
(20 nm bandwidth)

Implemented rep-rate multiplication system (x32) to achieve detector-jitter limited system.

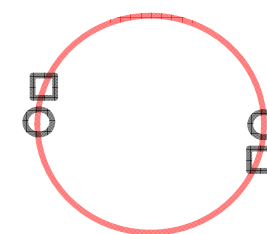
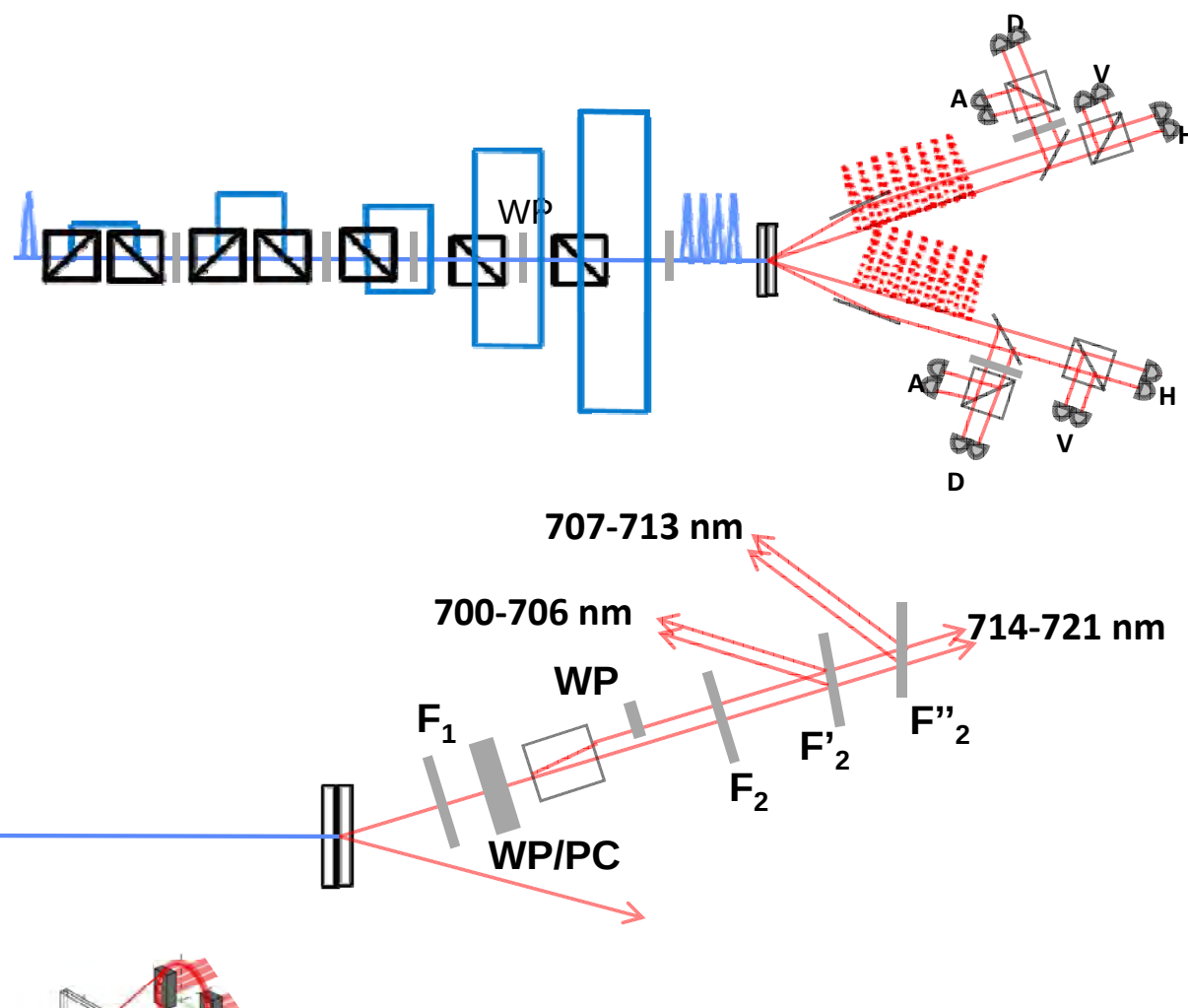


- Repetition-rate multipliers increase pulse frequency from 120 MHz $\rightarrow$ 3.8 GHz
- Time-bins (~ 260 ps) comparable to combined detector/time-tagger jitter
- Use spectrum-analyzer and high-speed detector to $\sim$ match path lengths (necessary for eventual mutually-unbiased basis checking)



Multiple Spatial/Spectral Channels

Demonstrated/will demonstrate methods to achieve multiple independent spatial and spectral channels



End view of
SPDC cone

- Up to 10 sets of spatial pairs possible/practical
- Sequential tilted filters allow x3 WDM (~x20 possible)
- Collection into few-mode fiber allows saturation of each channel
- Key rates above ~60 MHz (with 2 spatial channels)
- 10 channels + few-mode fiber → >1 GHz key rate!

Demonstrate all technologies to achieve milestones!

High-Efficiency, Low-Jitter, High-Saturation Rate Single-Photon-Counting Detectors

InPho: FSQC

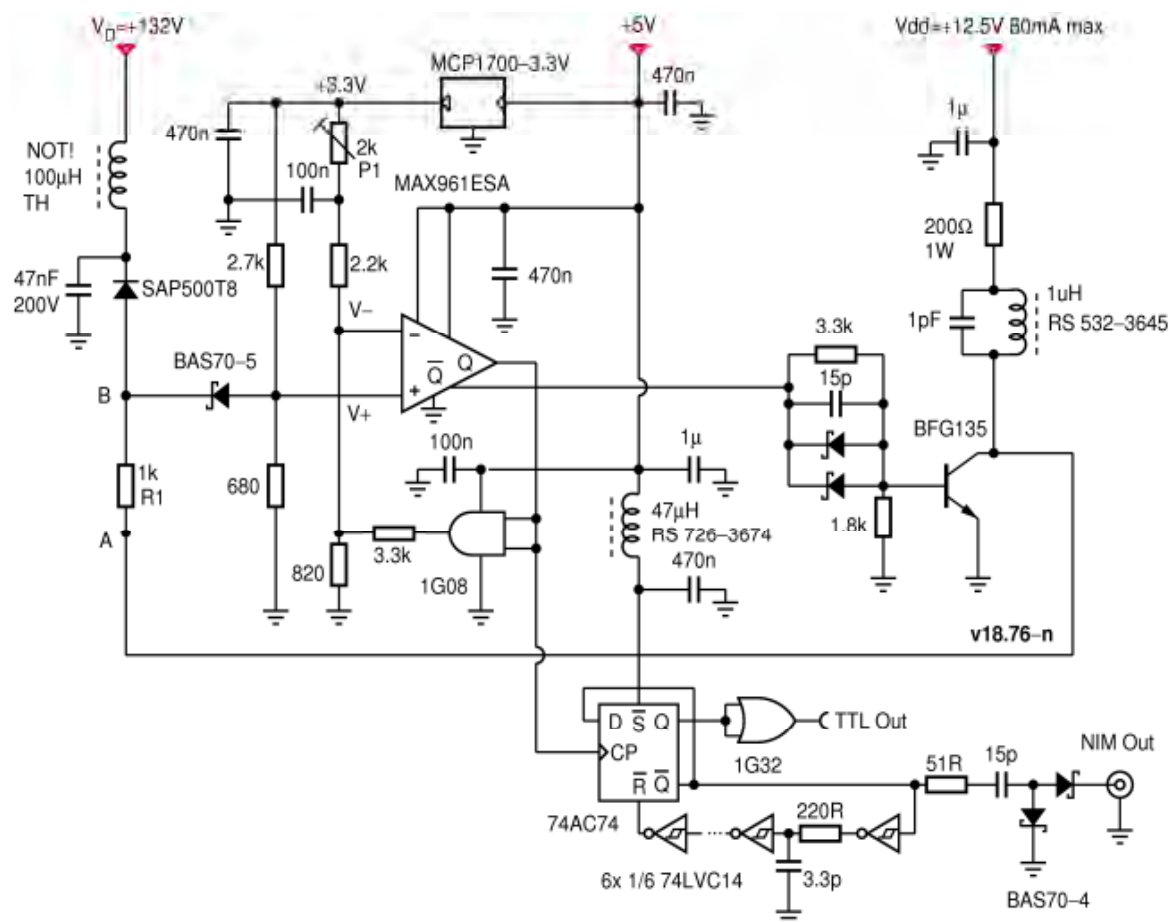


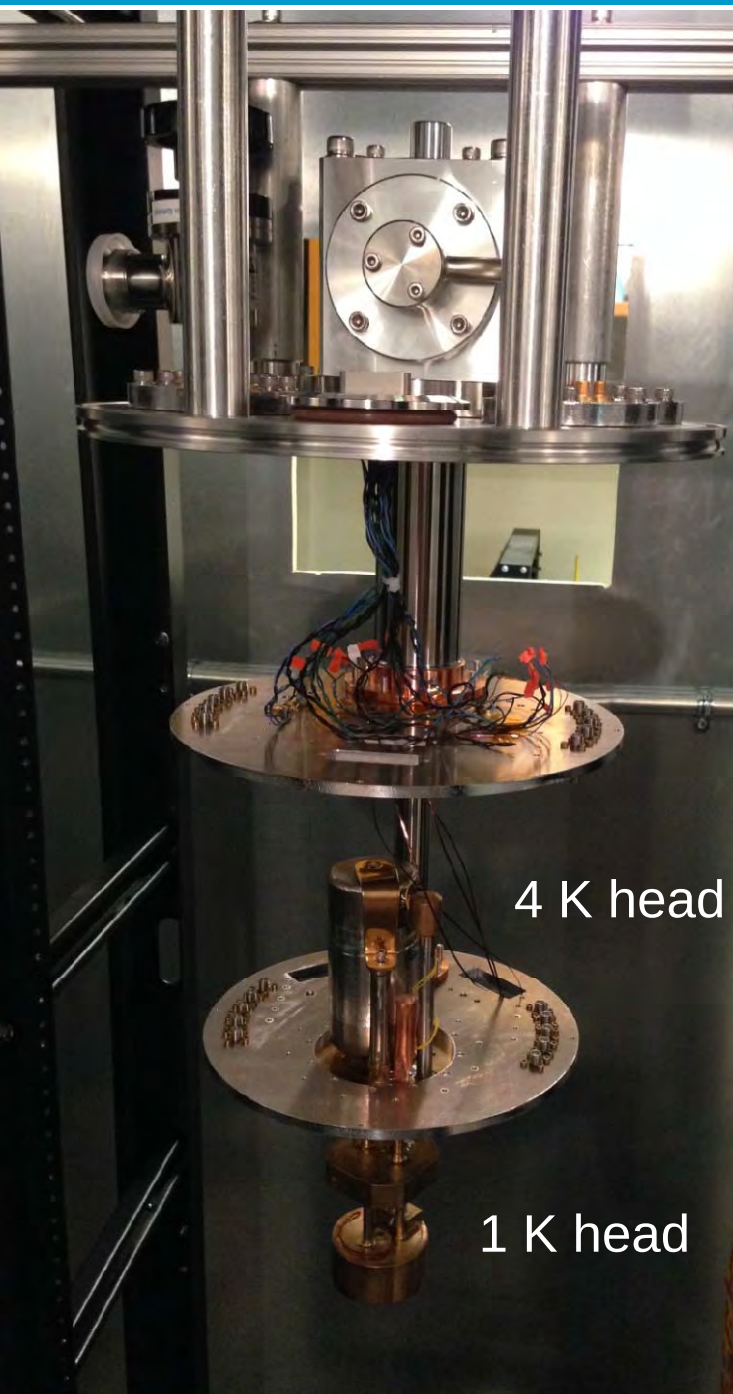
InPho Breakthrough – Develop custom electronics mated with Laser Components SAP-500 SPAD

Quantum Efficiency @ 710 nm: ~70%

Deadtime: 24.5 ns (41 MHz saturation rate) Afterpulsing probability: <0.1%

Jitter: 158 ps average for 15 detectors Dark Count Rate: ~3.5 kHz





InPho Breakthrough – Develop 8 channel SiW superconducting nanowire detectors optimized for 710 nm in collaboration with NIST

Status report (6/4/14): Cryostat constructed, chill-down tests, detectors fabricated, undergoing testing

Anticipated performance:

Quantum Efficiency: >90%

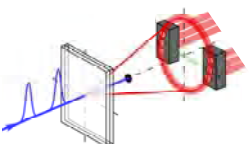
Jitter: 100 ps

Deadtime: <20 ns

InPho Breakthrough – Assess and qualify time-taggers for time-bin QKD. Developed high-throughput custom time-tagger.

	Agilent	IQC	UIUC/NIST
Max count rate:	80 MHz (20 MHz continuous)	12 MHz	200 MHz (400 MHz possible)
Resolution (jitter):	50 ps (60 ps)	156 ps (180 ps)	50-100 ps (10 ps)
Channels:	6	12	4

- The Agilent timetagger can run up to 80 MHz in “burst mode” where only a few milliseconds of data are taken at a time.
- Custom UIUC/NIST timetagger count rate limited by hard drive write speed. At high rates, less bits per count (currently 32 bits) can be used allowing up to 400 MHz continuous. Resolution limited by the FPGA clock, the current board has a 100 ps resolution. A better board could allow for a 50 ps time bin size.



Mutual Information of the quantum key distribution system including error correction, privacy amplification, and security analysis

Steve Barnett

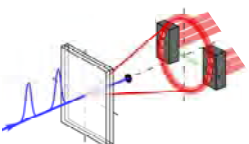
University of Strathclyde/Glasgow University

Paul Kwiat

University of Illinois, Urbana-Champaign

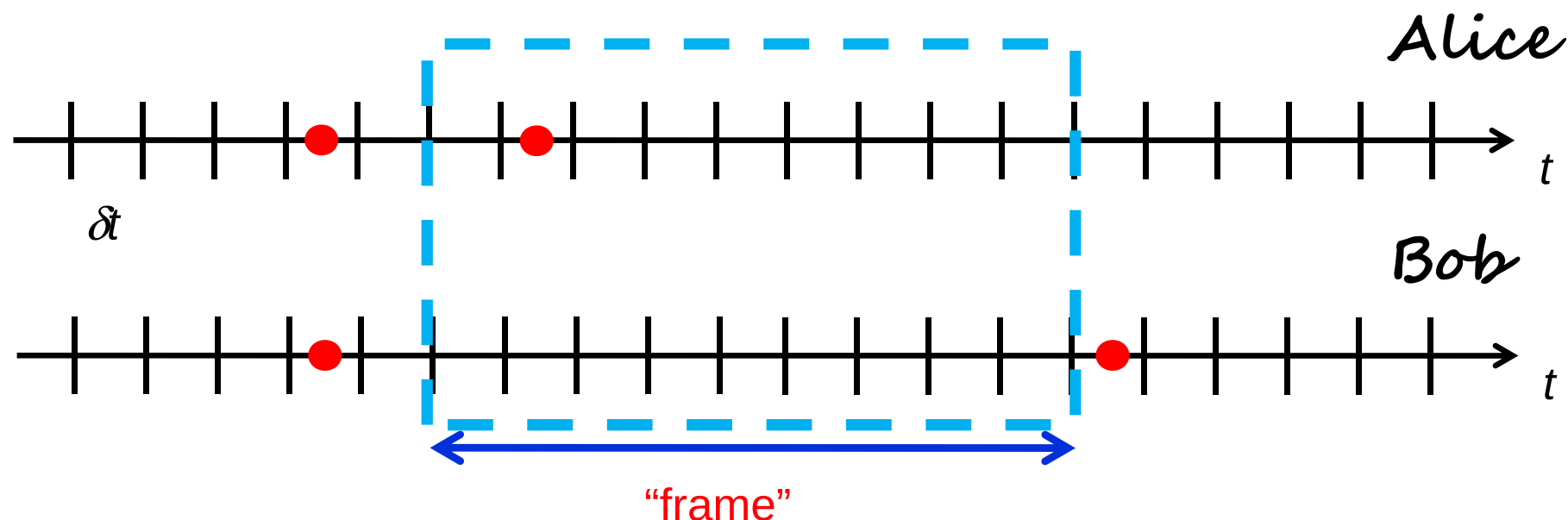
Daniel Gauthier

Duke University

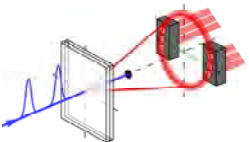


The information per photon pair

- Number bits / photon depend on errors. Typical errors are *finite efficiency*, *channel losses*, *dark counts*, *after-pulsing*, *jitter*, etc.



- Even with errors, we can get **>10 bits per detected photon pair^{*}**.
- InPho break through**:- developed new model, takes account of *frame-encoding*, *losses*, *dark counts*, *jitter*, *multiple photons in each frame* and *dead-time*.
- Very general, applies to other high-D QKD setups.

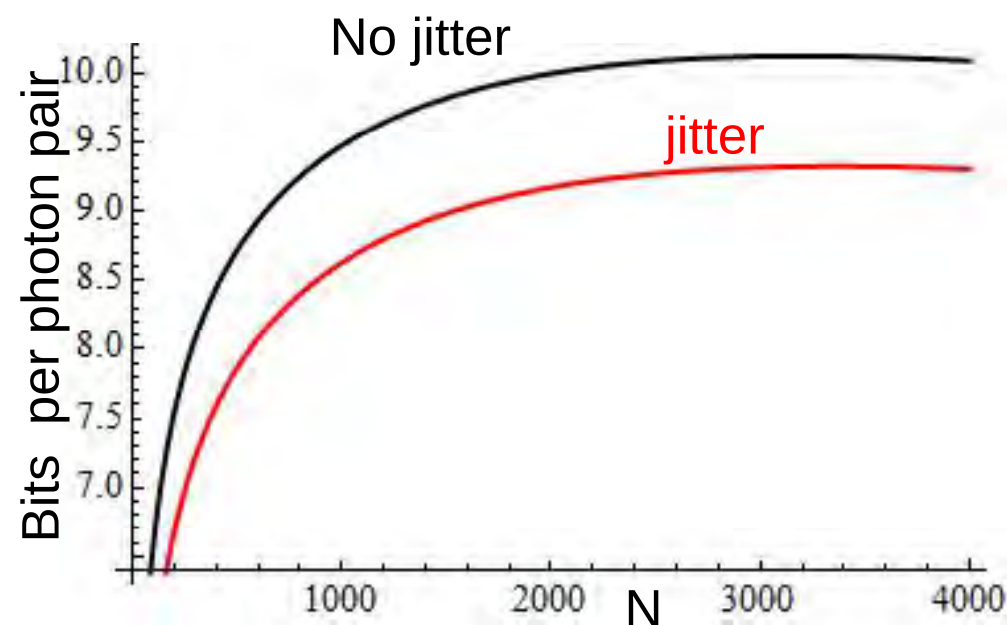


^{*} Brougham & Barnett, PRA **85**, 032322 (2012).

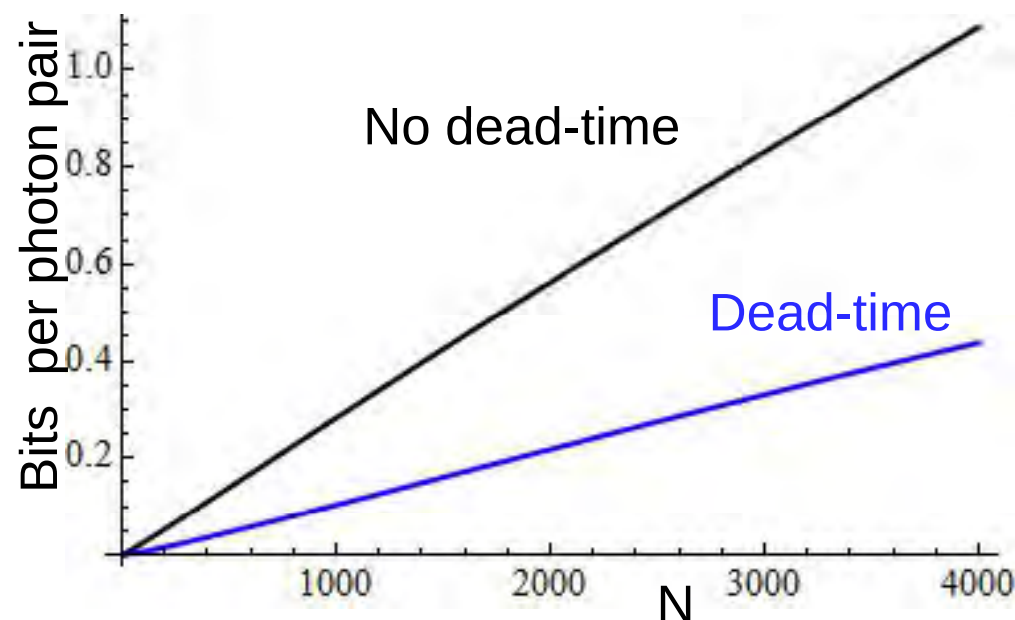
Information in frame-encoded photons

Can optimize frame size, N , in presence of realistic errors

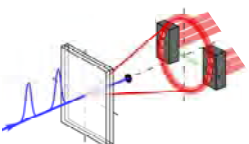
Information in 1,1-frames



Information in 2,2-frames



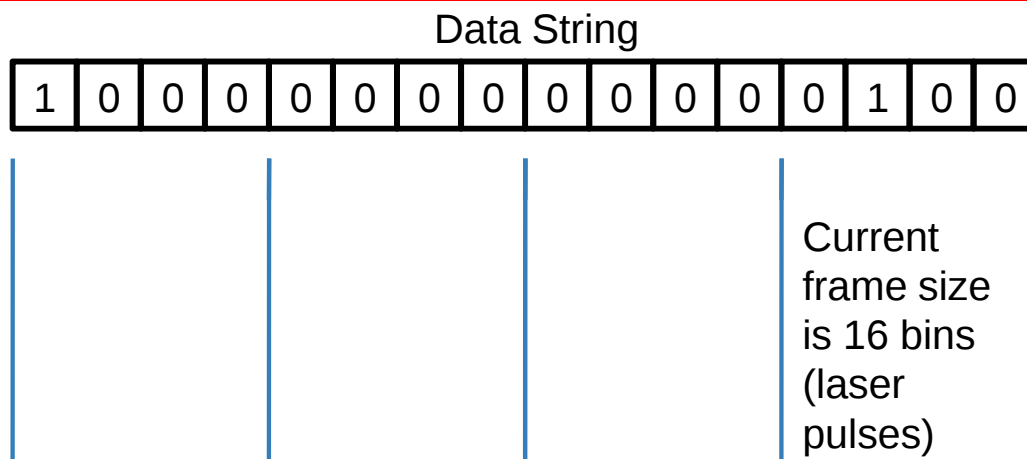
$\eta = 0.3$, $\lambda = 6.0 \times 10^{-5}$, Pulse rate = 1ns,
 jitter probability = 0.1, Dead-time = 1 time-bin
 dark count rate = 300/s, After-pulsing rate = 1000/s



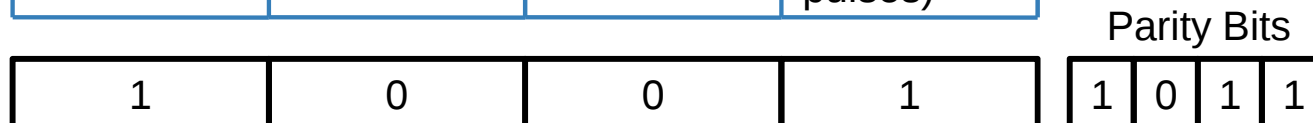
T. Brougham, C. F. Wildfeuer, S. M. Barnett and
 D. J. Gauthier, manuscript in preparation.

Implemented novel Slepian-Wolf-based error correction (both 'non-binary' and 'binary' levels, to cope with sparse data sets).

A data string is generated with the QKD source



The data string is broken into two data strings: an occupancy string and a letter string.



28% of the entropy is primarily lost due to multi-events per frame

5% of the Shannon-limit entropy

67% of the Shannon-limit entropy

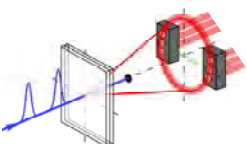
We keep 0% of the Shannon-limit entropy.

We keep 62% of the Shannon-limit entropy.



Goes into a non-binary Slepian-Wolf Code

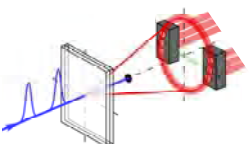
Goes into a binary Slepian-Wolf Code



Detecting Eve and leaked information I

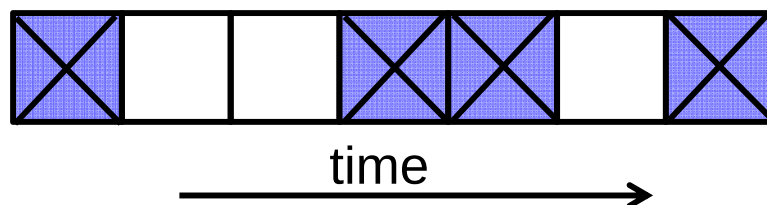
- **InPho breakthrough**:- Bound information leaked to Eve for reasonable attacks (not QND). Standard results don't work for our setup.
 - **Direct attack**: Eve measures time by making as general a POVM, with constrain that she *absorbs and possibly re-emits photons*.
 - Photons in state $|\psi\rangle \propto (|HH\rangle + |VV\rangle) \otimes [|11\rangle + |22\rangle + \dots + |dd\rangle]$
- Polarization is *entangled*.
- Eve's attack must disturb polarization (as it is not a QND measurement).
 - Detect Eve by checking *polarization correlation* within two mutually unbiased bases.
 - Example: $\eta=0.3$, $\lambda=5.33 \times 10^{-5}$, D.C =300/s and a bit error rate of $P_E = 0.02$

$$I_{AB} = 10.3 \text{ bits / photon pair} \quad \& \quad I_{Eve} = 0.82 \text{ bits / photon pair}$$



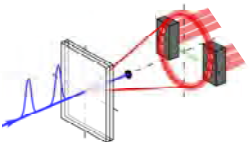
Detecting Eve and leaked information II

- **Blocking attack**: Eve randomly blocks several, *non-contiguous*, time-bins.
- Eve knows photons not found in certain time-bins. ***This reduces her uncertainty and thus she gains information.***



- Eve can also ***partially block*** time-bins, reduces probability that photons found within those time-bins.
- **InPho breakthrough**:- Developed new methods to detect ***sophisticated blocking attacks***
- Detect attacks using '***decoy***' pulses.
- From detection statistics for pulses, we estimate blocked and partial blocking time-bins.
- Example: $\eta=0.3$, $\lambda=5.33 \times 10^{-5}$, D.C = 300/s and *fully* blocking $\frac{1}{2}$ of all time-bins

$$I_{AB} = 10.3 \text{ bits / photon pair} \quad \& \quad I_{Eve} = 0.74 \text{ bits / photon pair}$$



- Setup still vulnerable to QND attacks

Security against QND attacks: Franson interferometers

- Franson interferometer secure in the limit of 3-4 bits per photon (8 to 16 time-bins), PRL **112**, 120506 (2014).

- **InPho breakthrough**:- Showed **single** interferometers insecure in **high-dimensions** ~ 10 bits per photon*. Would need visibility $> 99.8\%$.

- **InPho breakthrough**:- Developed bounds for Eve's information gain for **multiple** interferometers.

- Bounds valid for collective attacks[#].

* J. Phys. B **46**, 104010 (2013).

[#] Manuscript in preparation.

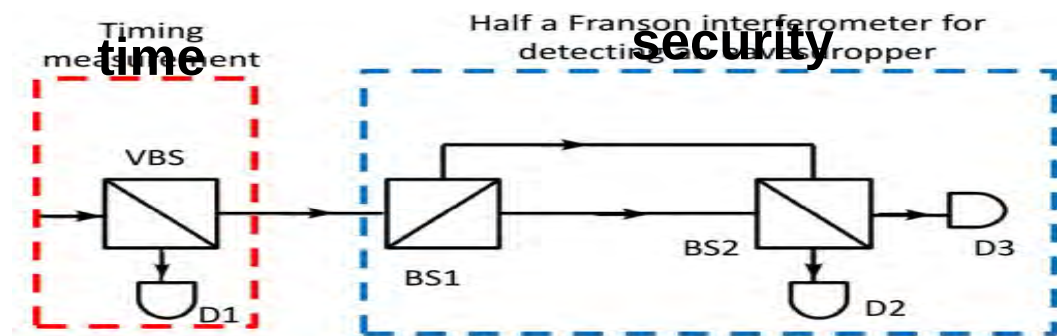
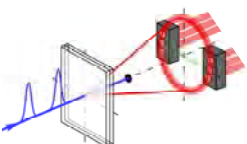
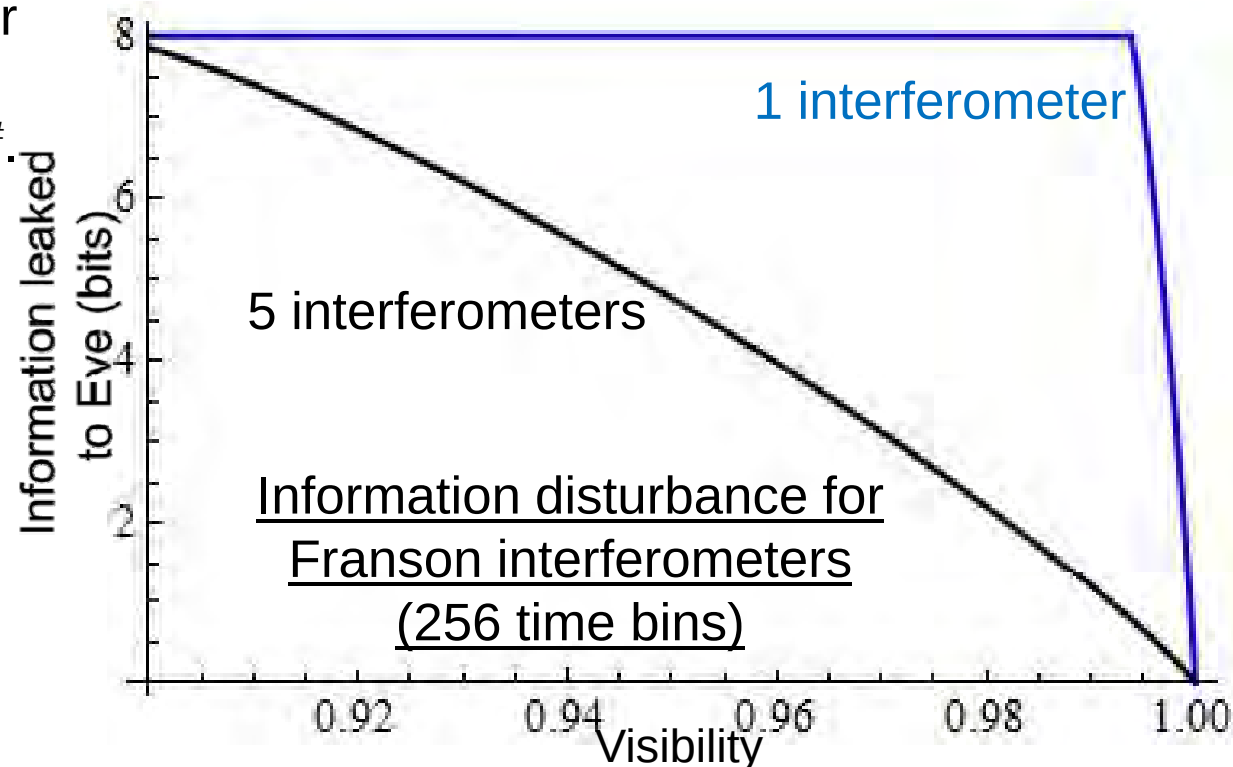


Figure 1. One half of the optical setup that Alice and Bob would each have. VBS is a variable beam splitter, while BS1 and BS2

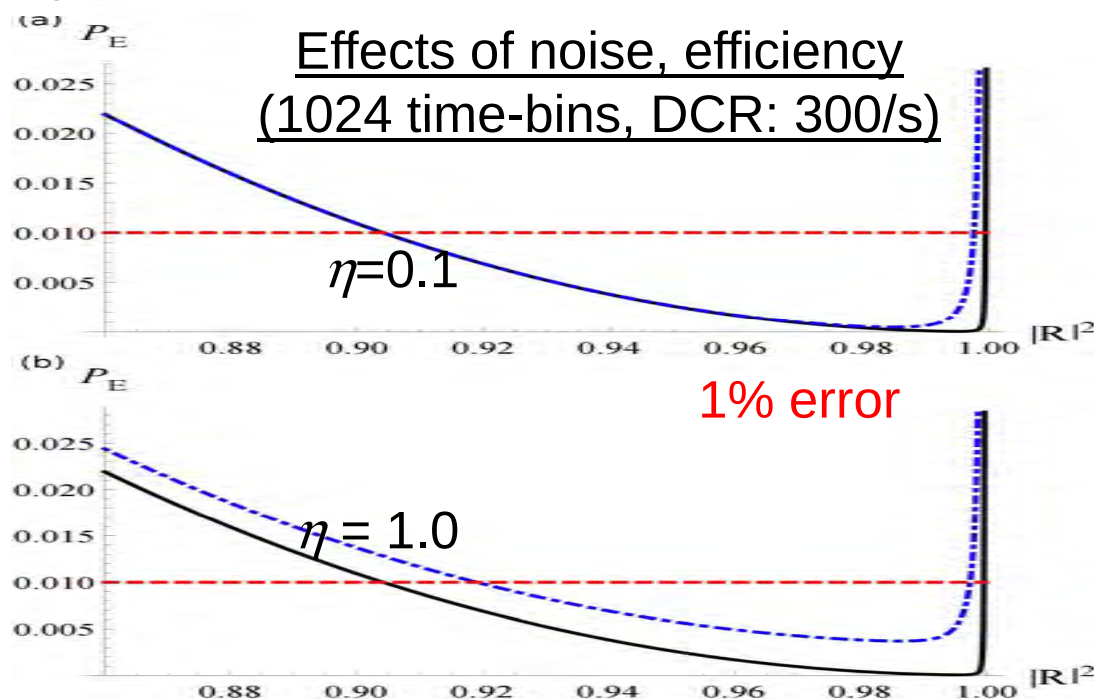
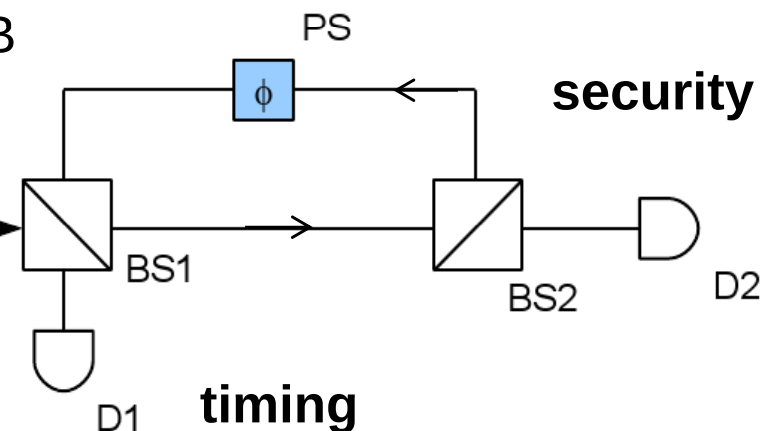


Security against QND attacks: implementing MUBs using a cavity

- **InPho breakthrough**:- Scheme that uses cavity to project onto **very high-dimensional** MUB states.
- Detection at D2 is projects onto the approximate MUB state

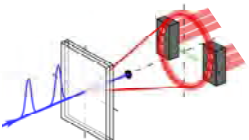
$$\sum_{m=0}^{N-1} |R_1|^m |R_2|^m e^{im(\phi+\pi)} |N-m\rangle$$
 where $R_1 \approx R_2 \approx 1$
- Different values for ϕ correspond to different MUBs.
- Setup robust to errors for 1024 time-bins (~10 bits per photon pair).

Alice and Bob's setup

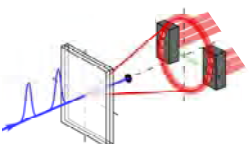


Brougham & Barnett, EPL **104**, 30003 (2013).

Brougham & Barnett, to appear in J. Phys. B



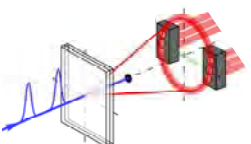
*Technological Developments
for Quantum Key Distribution
Systems using Spatial Modes
including
Turbulence Mitigation*



Generating, Sorting, and Characterizing Orbital Angular Momentum States

Robert Boyd
University of Rochester

Miles Padgett
Glasgow University

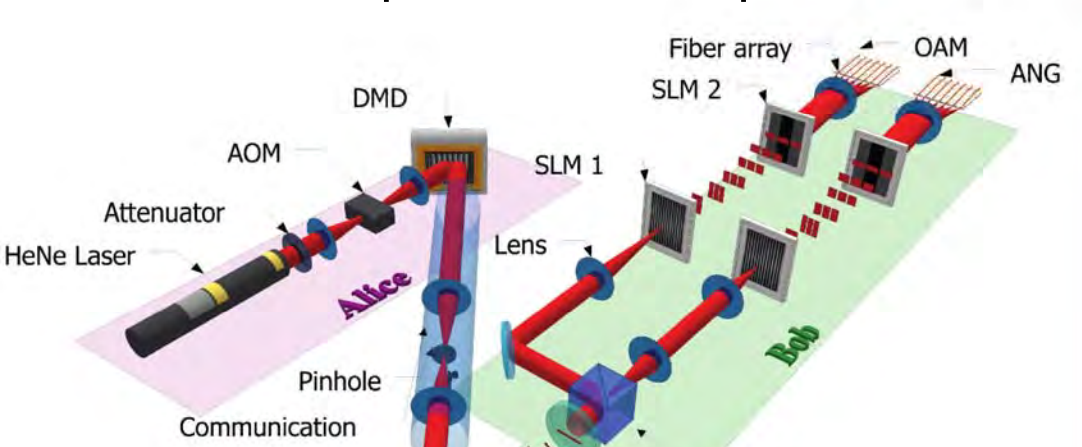


Quantum Cryptography with More Than One Bit Per Photon

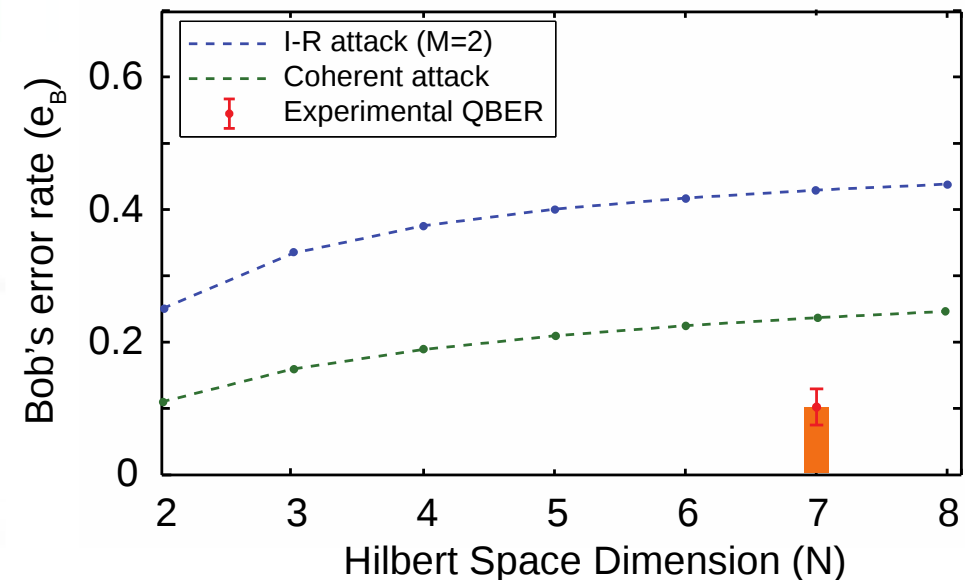
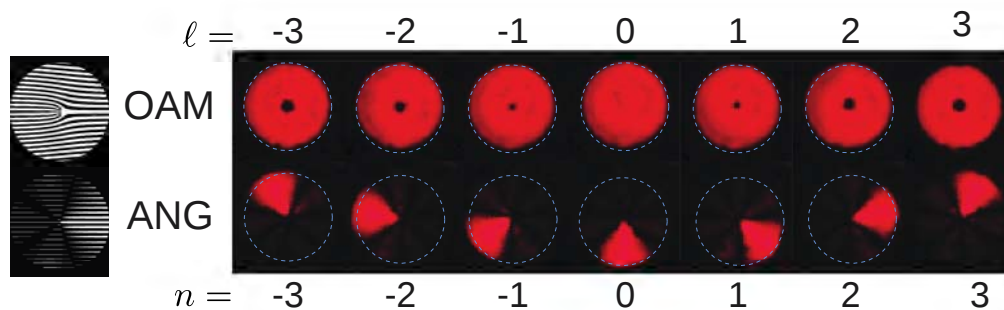
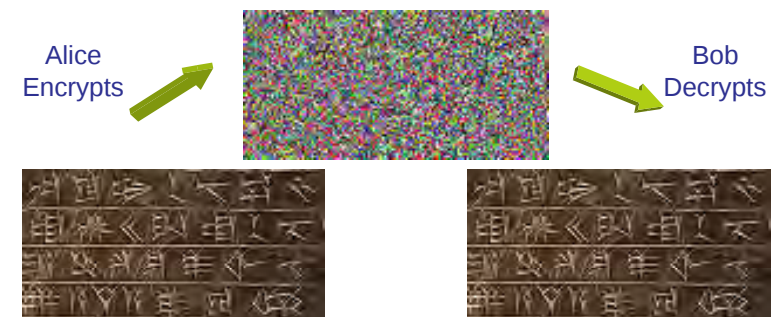
We have constructed a QKD system that can transmit more than one bit (2.1 bits at present) per sifted photon.

We have demonstrated that this system is secure against even coherent attacks

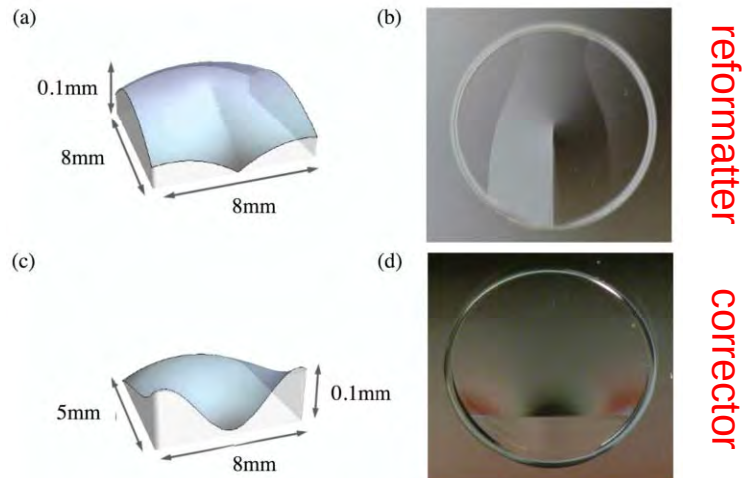
The experimental setup



Some results



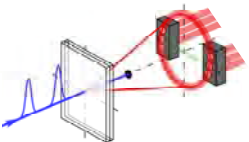
Measuring OAM, a multi-output beam splitter



- Two bespoke optical components transform any OAM state to a single spot.
- The displacement of the spot is proportional to the OAM

Refractive elements for the measurement of the orbital angular momentum of a single photon

30 January 2012 / Vol. 20, No. 3 / OPTICS EXPRESS 2110



Mode-sorters enabled further inPho successes

- Boyd Group
- Willner Group

The first reported method for efficient sorting of OAM state, beating the $1/N$ limit of previous approaches

Direct Measurement of a Statevector in a Very Large Hilbert Space

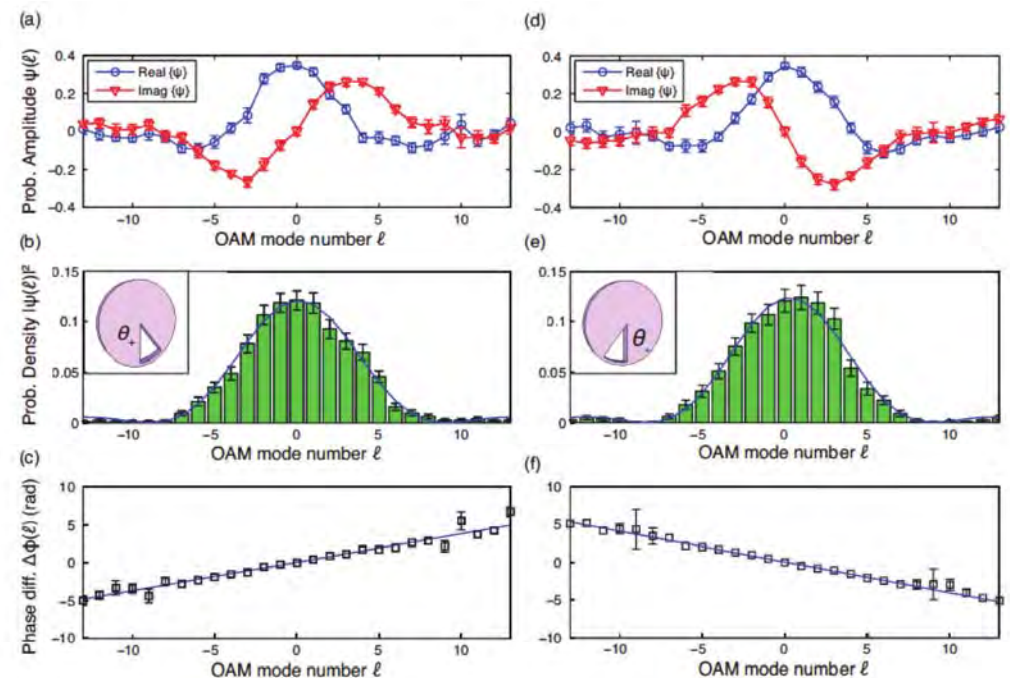
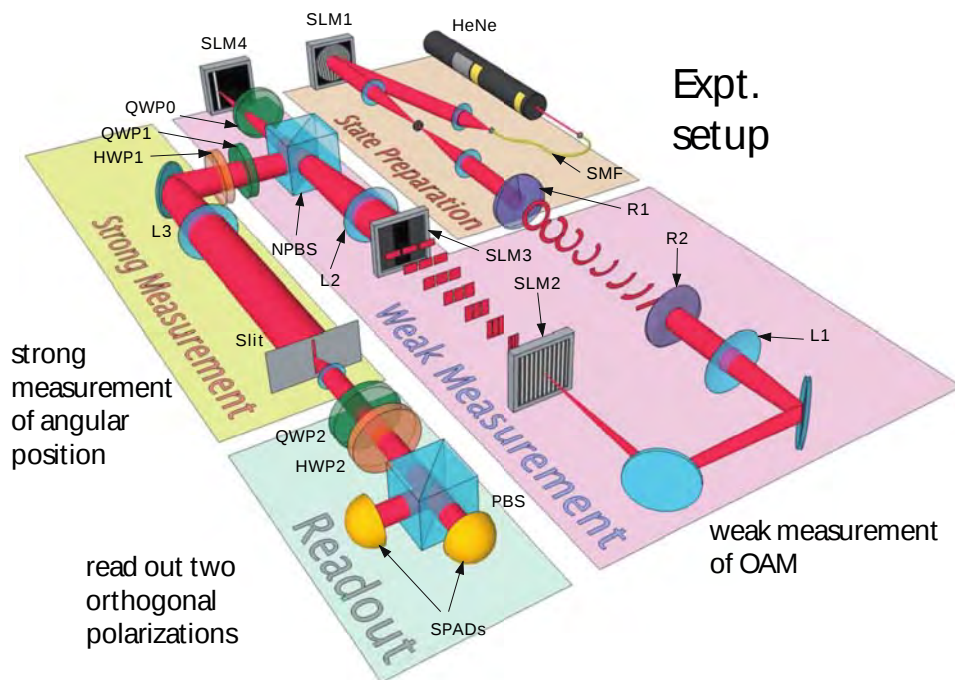
We have measured the state vector of a state imbedded in a very large (27-dimensional) Hilbert space. Procedure is based on Aharonov's "weak values" as developed by Lundeen et al. for state determination. The concept of "direct measurement" based on "weak values" can successfully be applied even to quantum states embedded in a very high dimensional discrete state space.

OAM states $\ell = -13, \dots, 13$

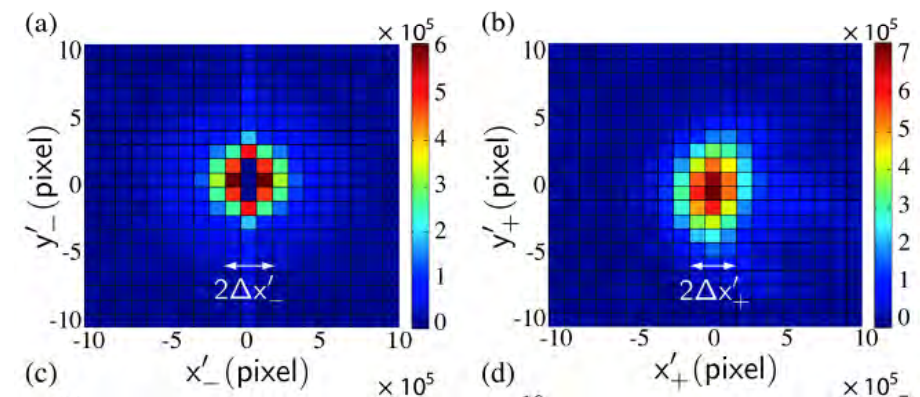
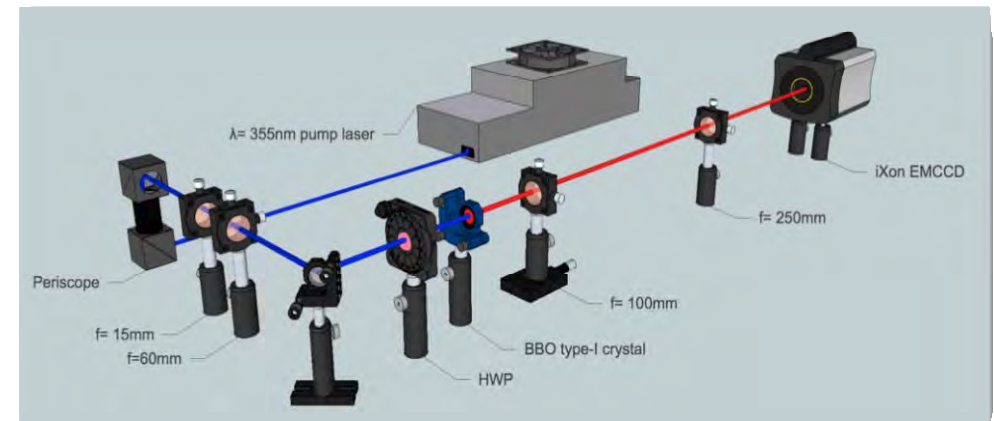


We measure the statevector of the light transmitted through a pie-shaped wedge

Note that the two cases have the same probability density but different phase structures



- EMCCD using to measure entanglement.
- Hilbert space >2000 modes
- Observation of position OR momentum correlation (i.e. EPR)
- EMCCD Cameras CAN be used high dimensional entanglement



EMCCD demonstration

The first Camera-based demonstration of EPR (cameras are multi-dimension detectors, scanning detectors are not)

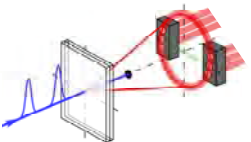


ARTICLE

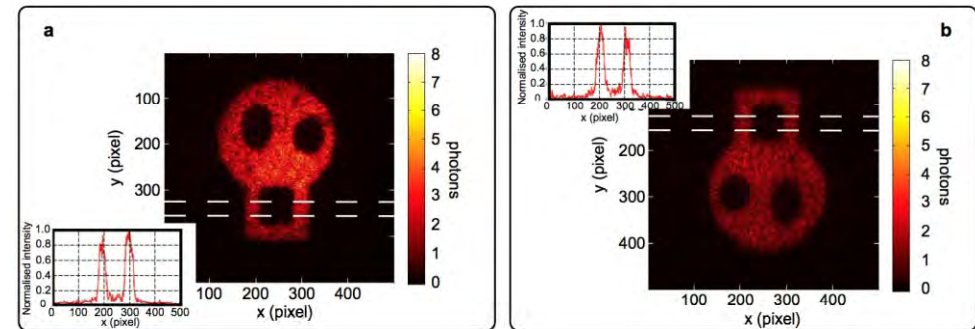
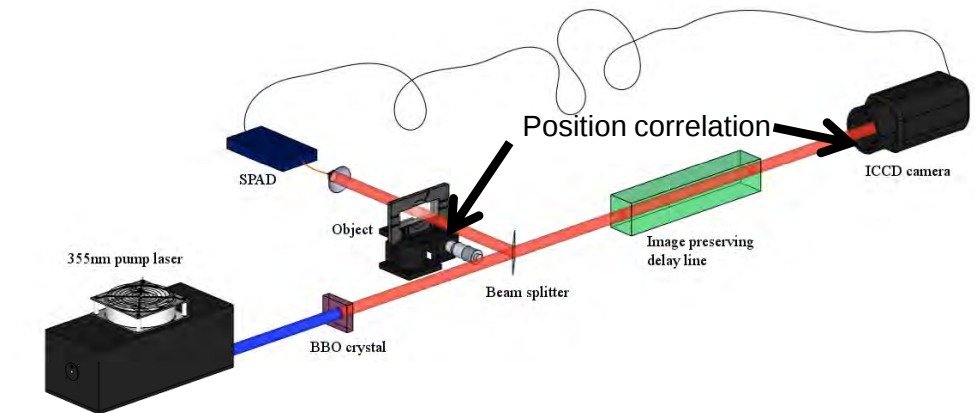
Received 14 May 2012 | Accepted 4 Jul 2012 | Published 7 Aug 2012

DOI:10.1038/ncomms1988

Imaging high-dimensional spatial entanglement with a camera



- Time-gated ICCD camera used for single photon imaging.
- ≈ 10 bits/photon
- Ghost image obtained from position OR momentum correlation (i.e. EPR)
- ICCD cameras CAN be used to measure high dimensional entanglement



New Journal of Physics
The open access journal for physics

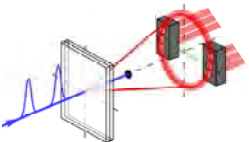
EPR-based ghost imaging using a
single-photon-sensitive camera

New Journal of Physics **15** (2013) 073032 (11pp)

ICCD demonstration enabled further inPho
successes

- Boyd Group

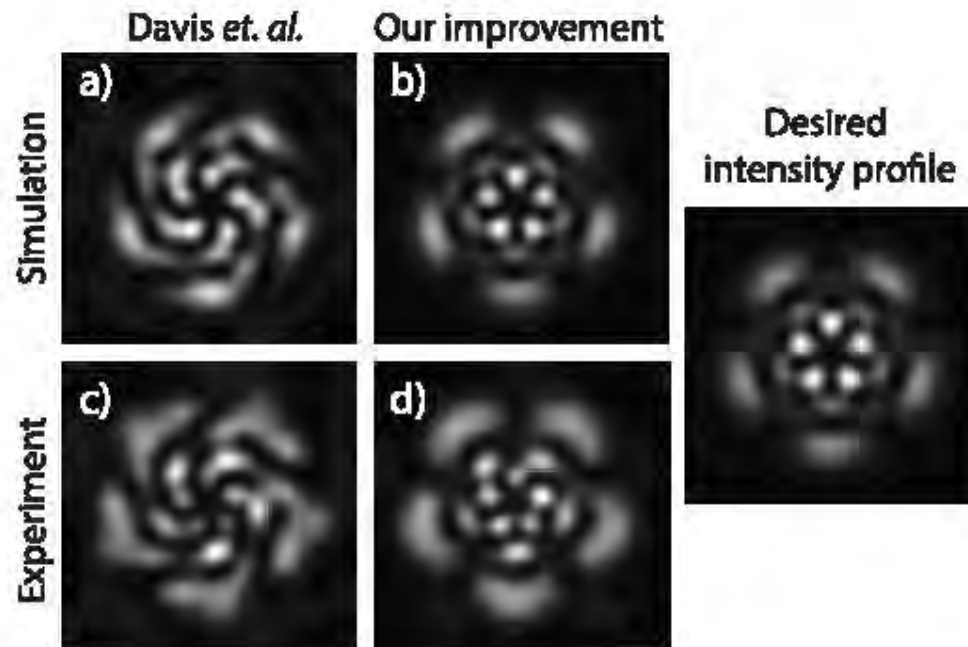
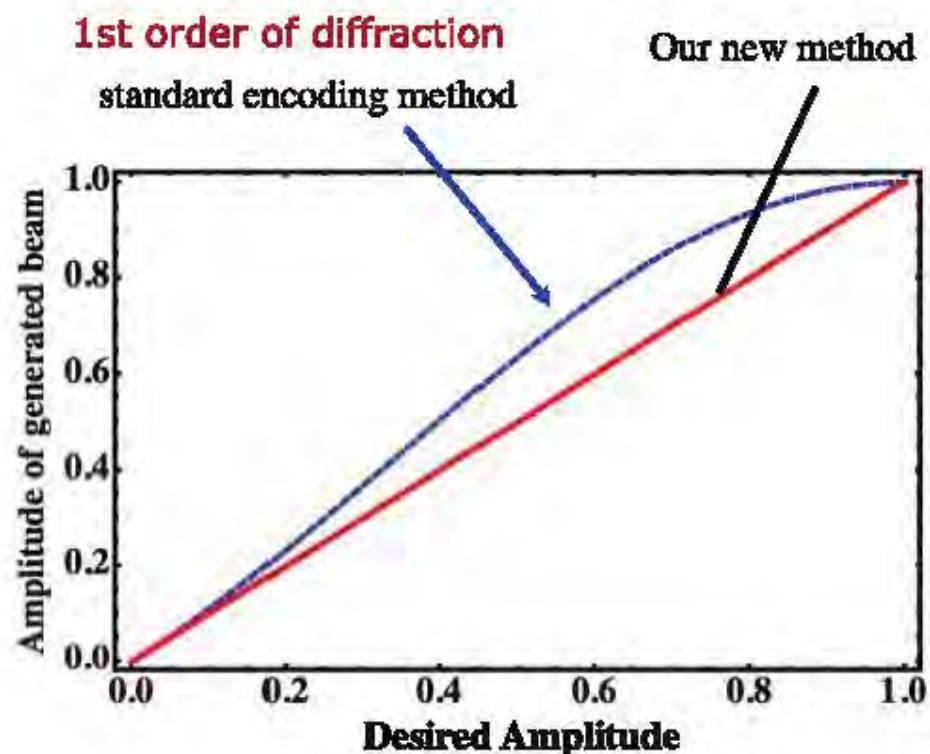
The first Camera-based quantum ghost
imaging (cameras are multi-dimension
detectors, scanning detectors are not)



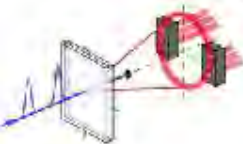
Improved Method for Encoding Computer-Generated Holograms onto an SLM

Previously workers used good but only approximate algorithms to encode holograms onto SLMs.

We have developed a protocol for encoding holograms onto an SLM that avoids the problems of earlier designs and that is in fact mathematically exact.

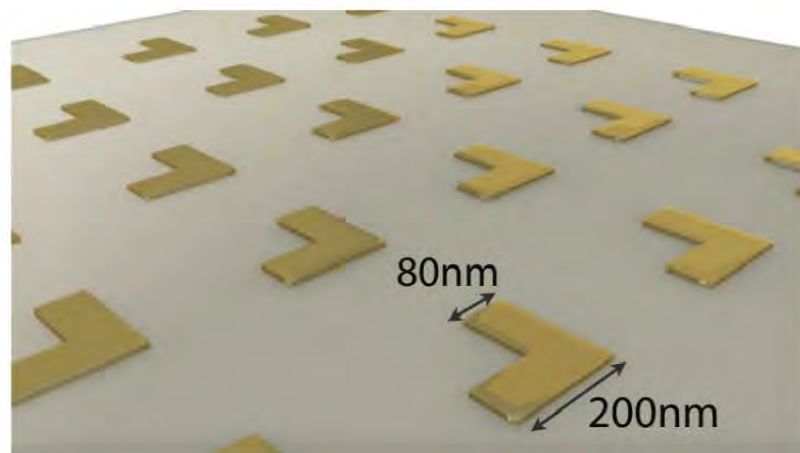


Bolduc et al., Optics Lett. 38, 3546 (2013)

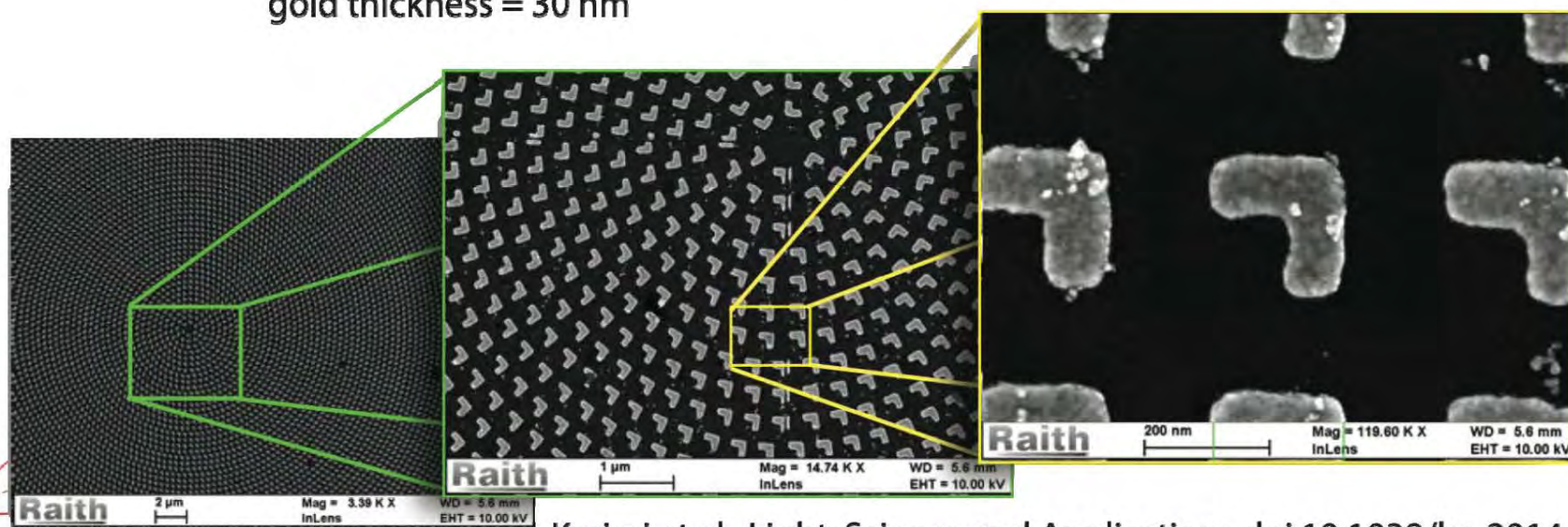
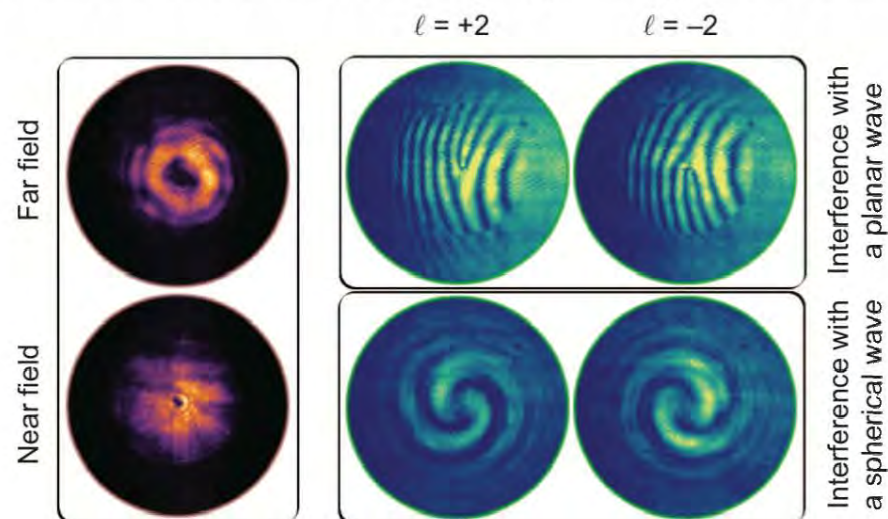


Development of a Nano-Structured Q-plate

- A q-plate is a device that converts spin angular momentum into orbital angular momentum.
- It functions as a quantum interface.
- Have shown ability to construct a spin-angular-momentum to orbital-angular-momentum converter in a structure only 30-nm-thick and thus suitable for use in integrated photonic circuits.



gold thickness = 30 nm

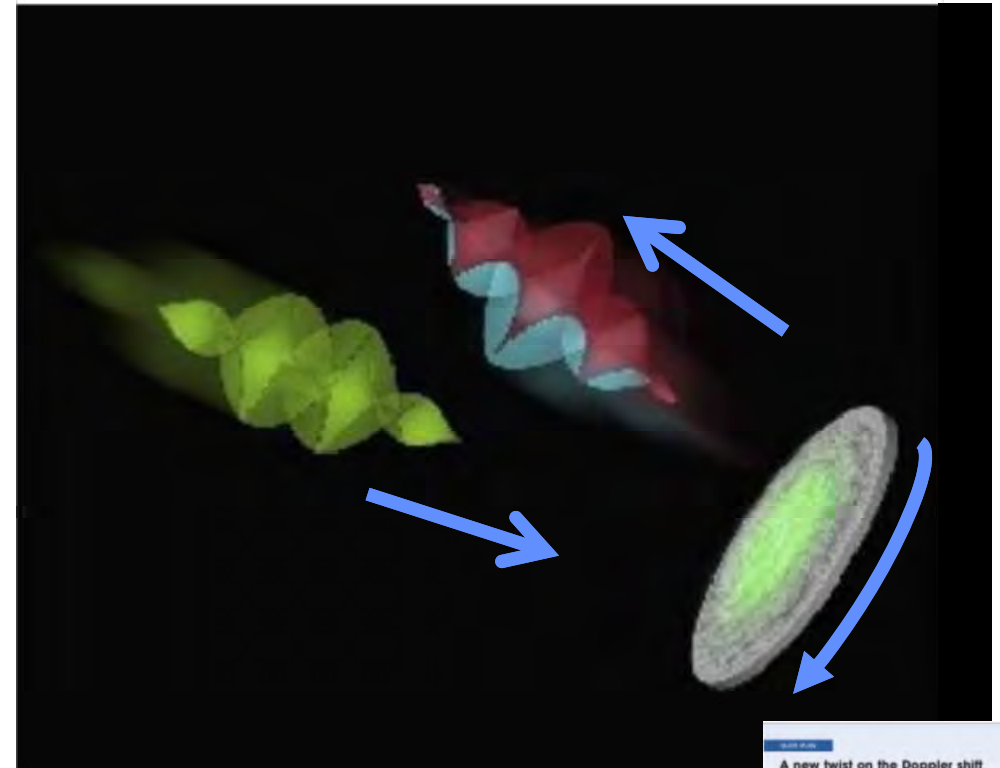


Remote detection of a spinning object

InPho: FSQC

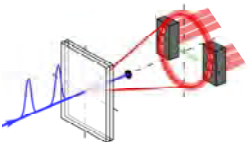


- Light scattered from a spinning object is shifted in frequency even when the linear Doppler shift is zero.
- The shift is proportional to the product of the OAM and the rotation speed



Detection of a Spinning Object Using Light's Orbital Angular Momentum

SCIENCE VOL 341 2 AUGUST 2013



Featured in Physics Today

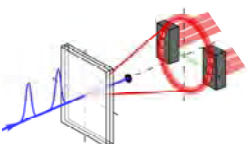


A new form of the Doppler effect, observable even when the traditional Doppler shift is zero

Designing arbitrary mode converters and linear optical components with no calculations

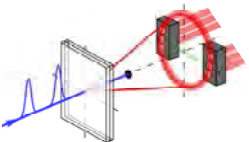
David Miller
Stanford University

Robert Boyd
University of Rochester



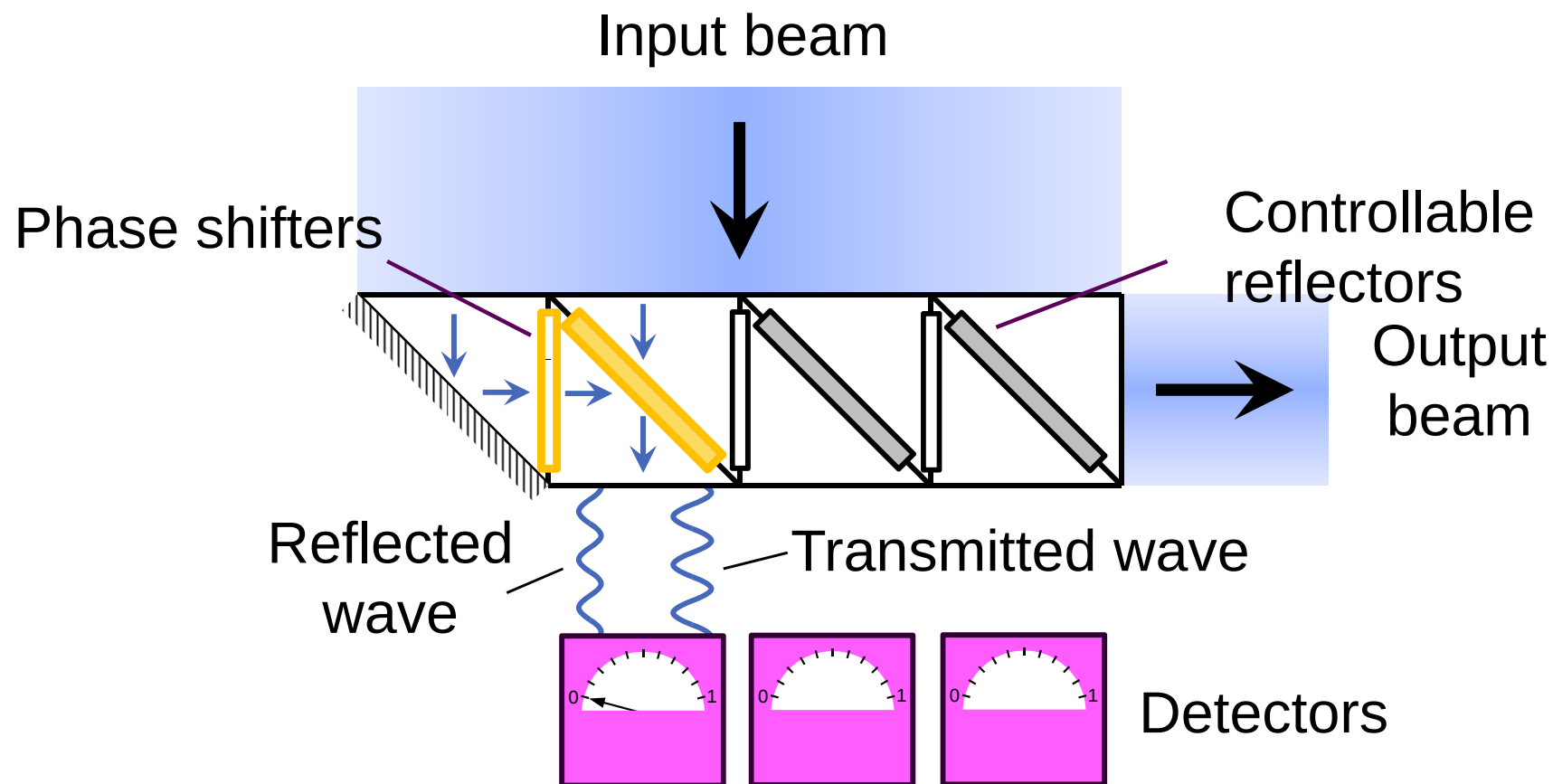
Mode converters and arbitrary optical design

- Major previously-unsolved problem in optics
 - How can separate arbitrary orthogonal but overlapping beams
 - Without fundamental splitting loss?
- **Breakthrough - We have solved this problem**
 - **and** we can prove any linear optical component satisfying basic physical laws can be made in principle
 - with at least one progressive (i.e., non-iterative) way of designing it
- **Breakthrough - We can also perform the design**
 - in real-time in simple hardware, **with no calculations!**
- Additionally
 - We can reduce any linear optical component to a mode converter
 - We can calculate how complicated a component has to be
 - **Breakthrough** - We can automatically find optimum optical channels in linear optics
 - **Breakthrough** - We can design arbitrary spatial add-drop multiplexers

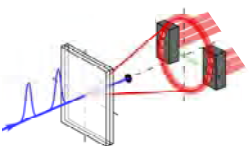


Work also funded in part by AFOSR MURIs
FA9550-10-1-0264 and FA9550-09-0704

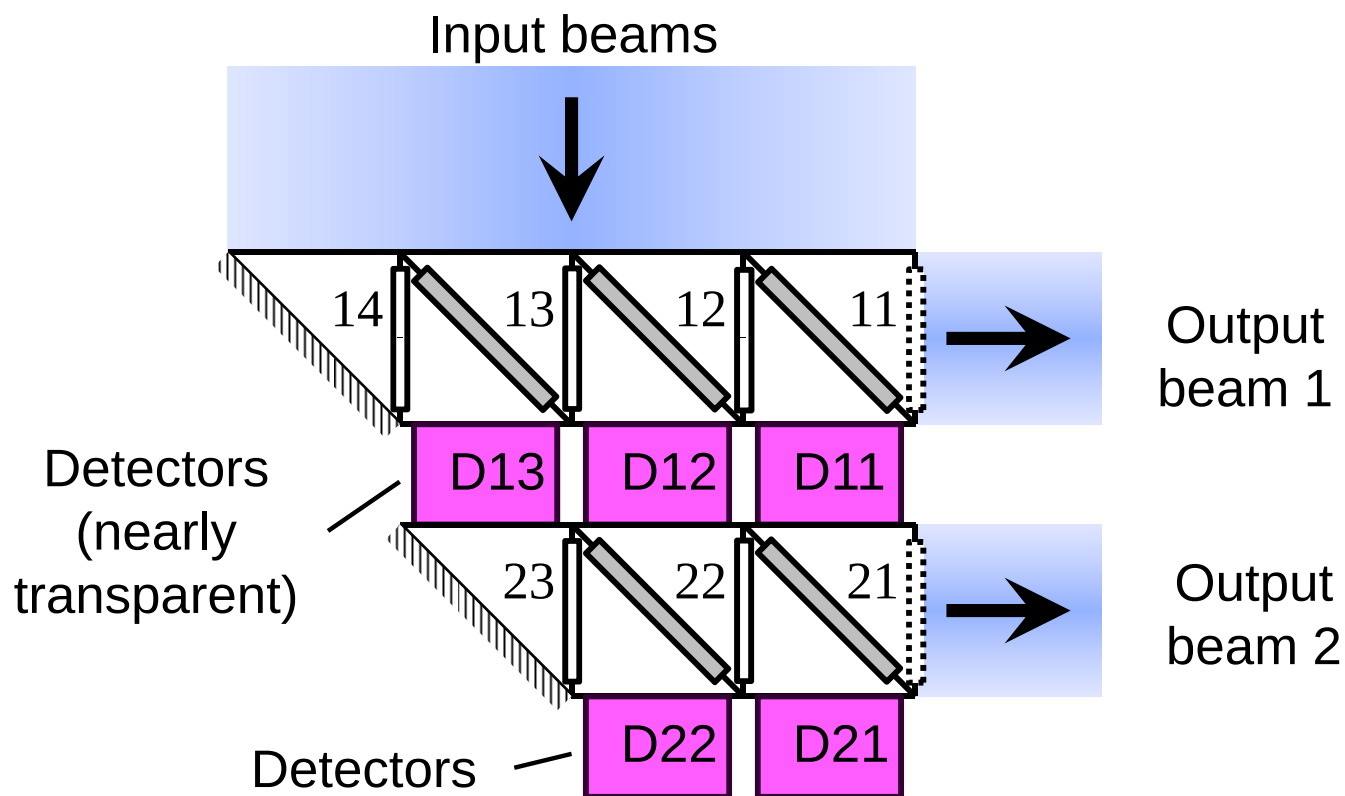
David Miller, Stanford



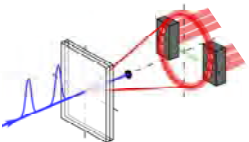
- Suppose a beam can be adequately represented by a finite number of segments
 - Adjust phase shifter in first block to minimize power in first detector
 - Then adjust reflectivity in first block to minimize power again in first detector
 - Repeat for each block
 - Leaves no power in detectors, all input power in output beam
 - Automatically aligns any beam



Self-aligning multiple orthogonal beams

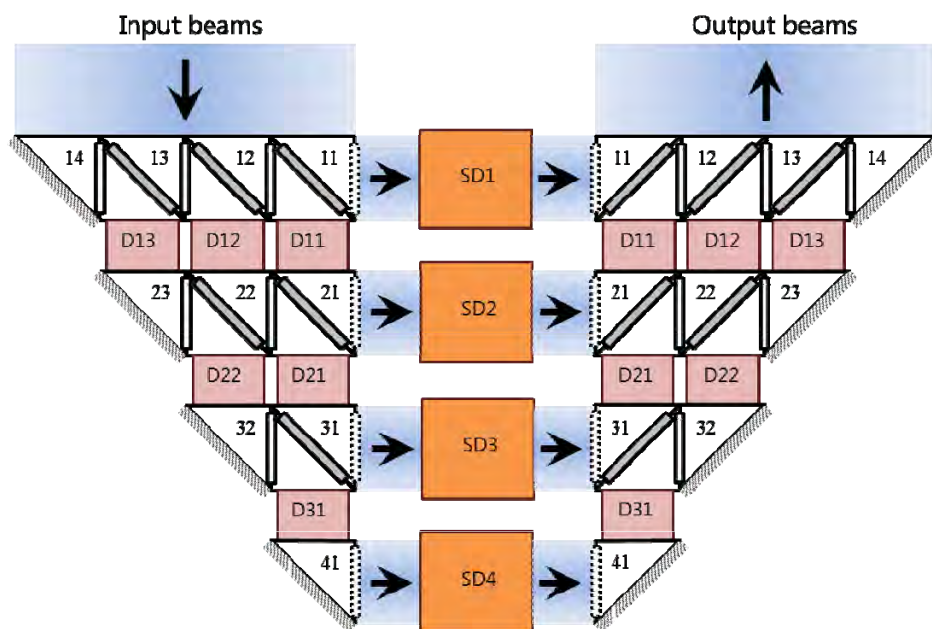


- Once we have aligned beam 1 using detectors D11 – D13
 - An orthogonal input beam 2 passes through the nearly transparent detectors to the second row
 - Where we can self-align it using detectors D21 – D22
- Separating two overlapping orthogonal beams to separate outputs
- Can continue, here up to four separated beams

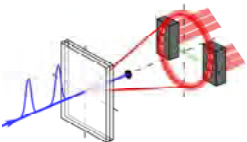


Corollaries and extensions

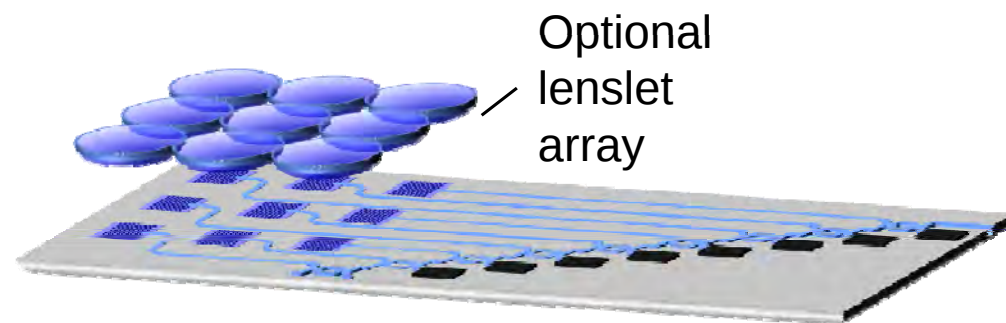
- Make arbitrary beam mode converter (including polarization conversion) by training an output section with desired output beams



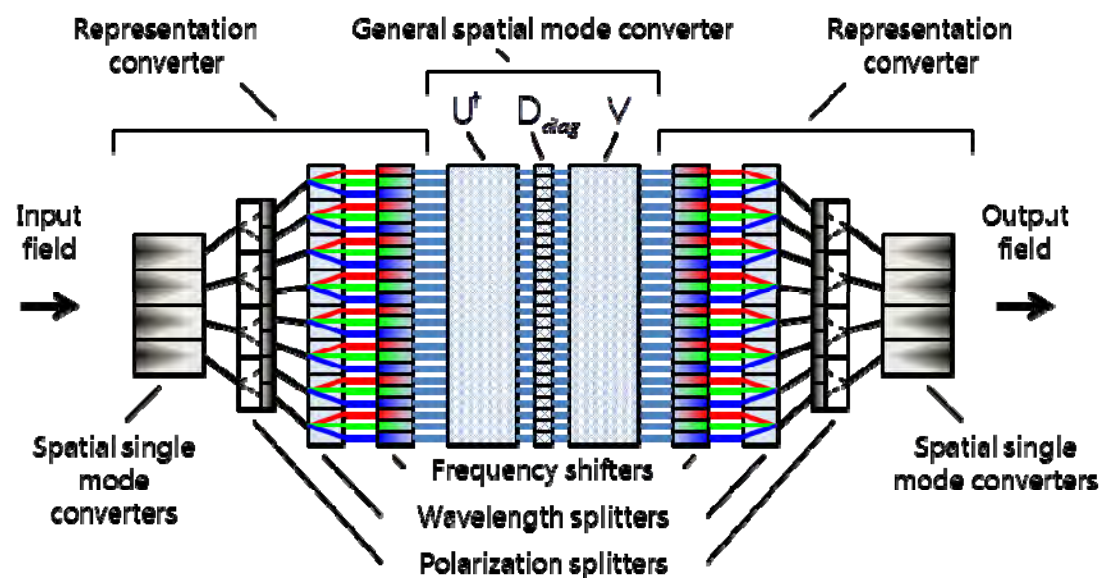
- Establish the optimum channels through arbitrary and changing scattering media
- Arbitrarily add and drop spatial modes losslessly



- Implement in silicon photonics with grating couplers and Mach-Zehnders



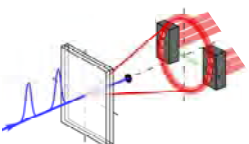
- Make any linear optical component in principle



Turbulence simulation and mitigation

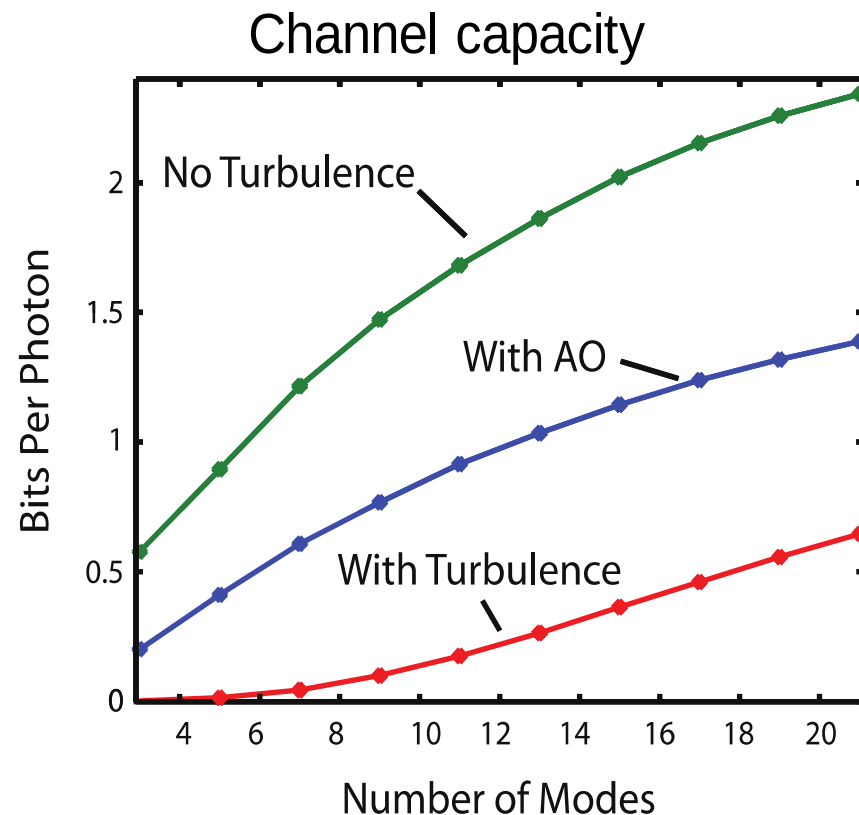
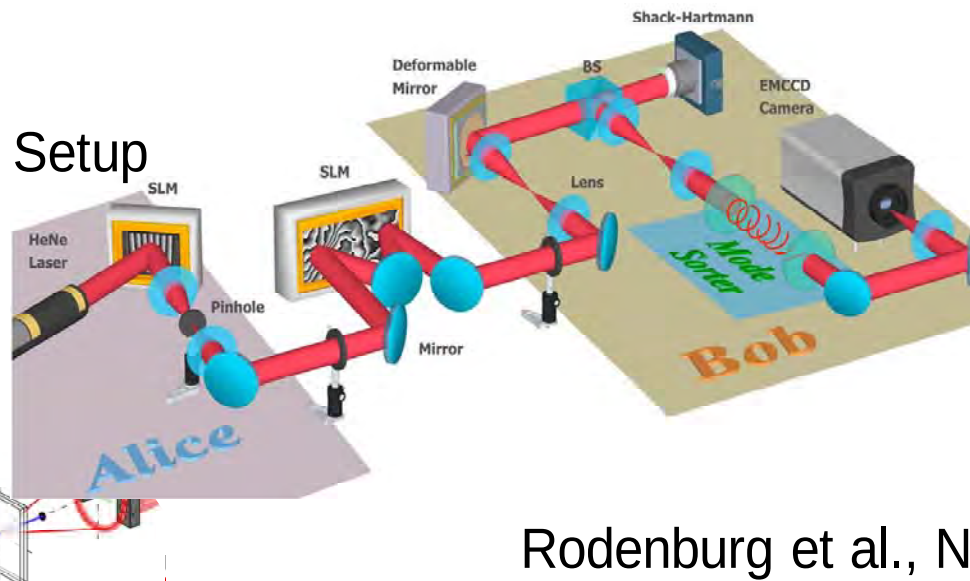
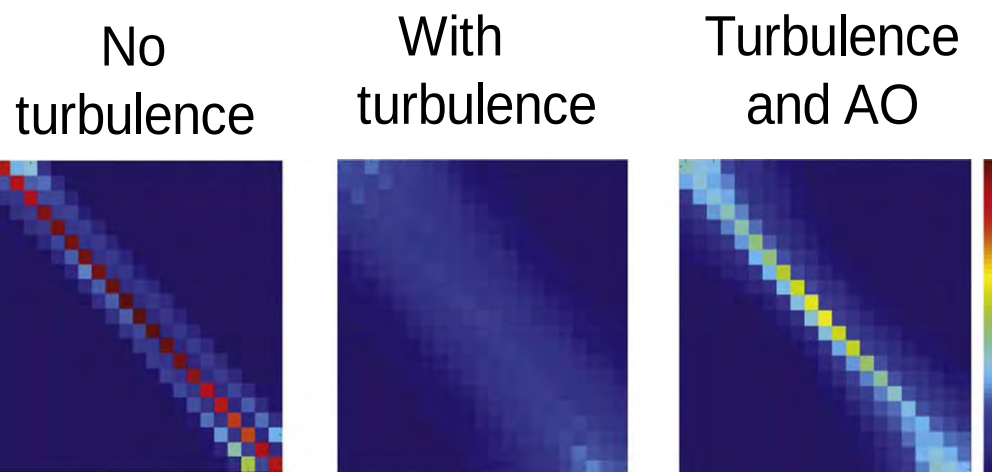
Robert Boyd
University of Rochester

Glenn Tyler
the Optical Sciences Corporation

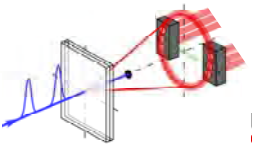


Accurate Simulation of Atmospheric Turbulence using Two Phase Screens

- A single Kolmogorov phase screen cannot model thick turbulence
- But only two phase screens are needed for realistic horizontal paths!
- Results given for 1 km path and $C_n^2 = 1.8 \times 10^{-14} \text{ m}^{-2/3}$
- By reversibility, only two deformable mirrors required to perform adaptive optics.



- We have developed a complete QKD system that operates at a
- record rate (on a table top)
 - record efficiency
 - encodes information in photon arrival time and polarization
 - partial security obtained by checking polarization (assumes no QND attack possible that does not disturb polarization)
 - a single channel operates at a “secure” rate over 10 Mbit/s
 - multiplex many spatial and spectral channels to achieve 1 Gbit/s rate
 - achieve > 4 bits/detected photon pair at high rate
 - achieve > 8 bits/detected photon pair at low rate (maintain coherence in a very high dimension Hilbert space!)
 - developed a wide range of new quantum technologies that will have an impact beyond this immediate project



Quantum Key Distribution Using Hyperentanglement

InPho: FSQC



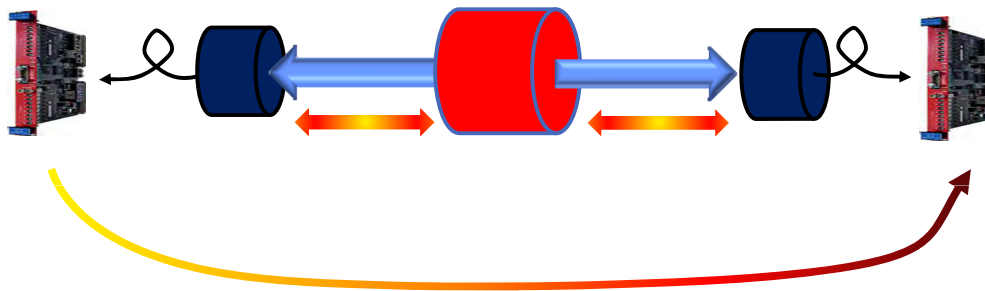
Question: What are the fundamental limits of encoding/decoding information on a photon?

Goal: Develop a free-space, entanglement-based quantum key distribution (QKD) system that achieves >10 bits/photon received and >1 Gb/s

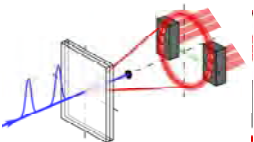
Steve Barnett, Strathclyde, **Robert Boyd**, Ottawa,
Daniel Gauthier, Duke, **Paul Kwiat**, UIUC, **David Miller**, Stanford,
Miles Padgett, Glasgow, **Glenn Tyler**, tOSC

Advisors/Partners:

Venkat Chandra, MIT Lincoln Labs, **Norbert Lütkenhaus**, U. Waterloo
Sae-Woo Nam, NIST



Duke InPho Site Visit, June 6, 2014



Primary Duke InPho Quantum Key Distribution System: Details for Site Visit

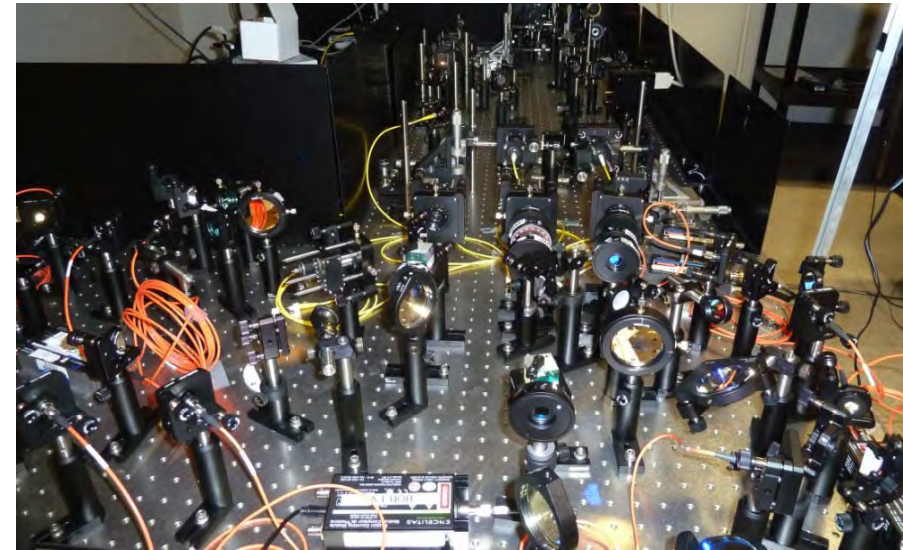
Paul Kwiat
University of Illinois, Urbana-Champaign

Daniel Gauthier
Duke University



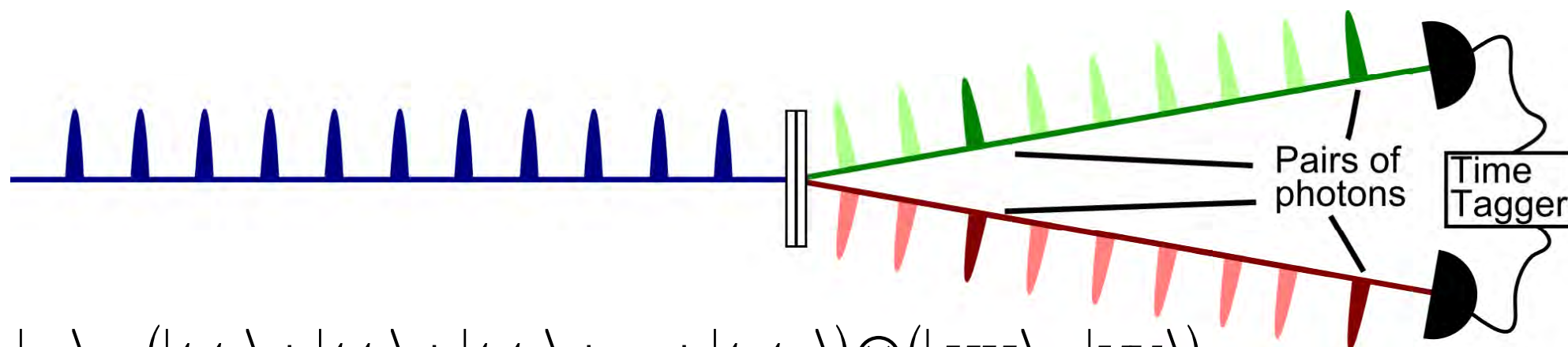
Accomplishment: Set up 2-channel hyper-entanglement-based QKD system, with time-bin PPM secured using simultaneous polarization entanglement.

- Low jitter detectors (average 158-ps FWHM)
- x32 repetition-rate multipliers increase pulse frequency to 3.84 GHz
- Reduced detector deadtime (~ 25 ns) allows for high saturation
- Still photon-number limited
 - Use few-mode fibers ($\sim x7$ brightness)
 - Polarization decoherence issues with few-mode fiber
- Assumes intercept-resend attacks, and no polarization-independent QND measurements



June 2014	Low Power	High Power
Singles	50 kHz	10.1 MHz
Coincidences	8 kHz	2.9 MHz
Average BER	0.4 %	0.9 %
“Secure” bit/coincidence	8.3 bits	2.2 bits
“Secure” bit/second	67 kbits	6.3x2 Mbits 12.6 Mbits

Central Concept: Encode in time, verify in polarization



$$|\psi\rangle \propto (|t_0 t_0\rangle + |t_1 t_1\rangle + |t_2 t_2\rangle + \dots + |t_N t_N\rangle) \otimes (|HH\rangle + |VV\rangle)$$

Alice and Bob use which time bin they detect a photon in to generate multiple bits per click, e.g., 1 pair in 1024 bins (2^{10}) $\rightarrow$ ~10 bits

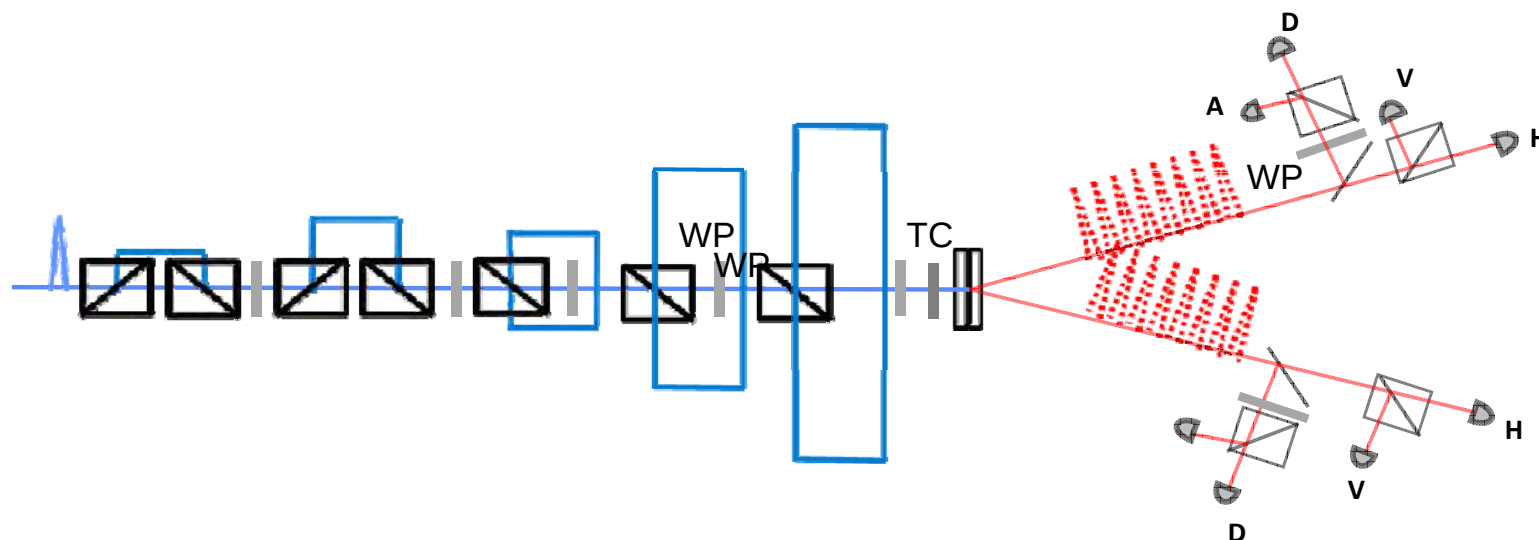
Get extra 0.5 bpp from BB84 w. polarization.

They can constantly check for an eavesdropper using the polarization DOF (assuming no QND capability for Eve).

Perform NON-standard error detection/correction and privacy amp.

First experiment to use one DOF to secure another.

Implemented rep-rate multiplication system (x32) to achieve detector-jitter limited system.



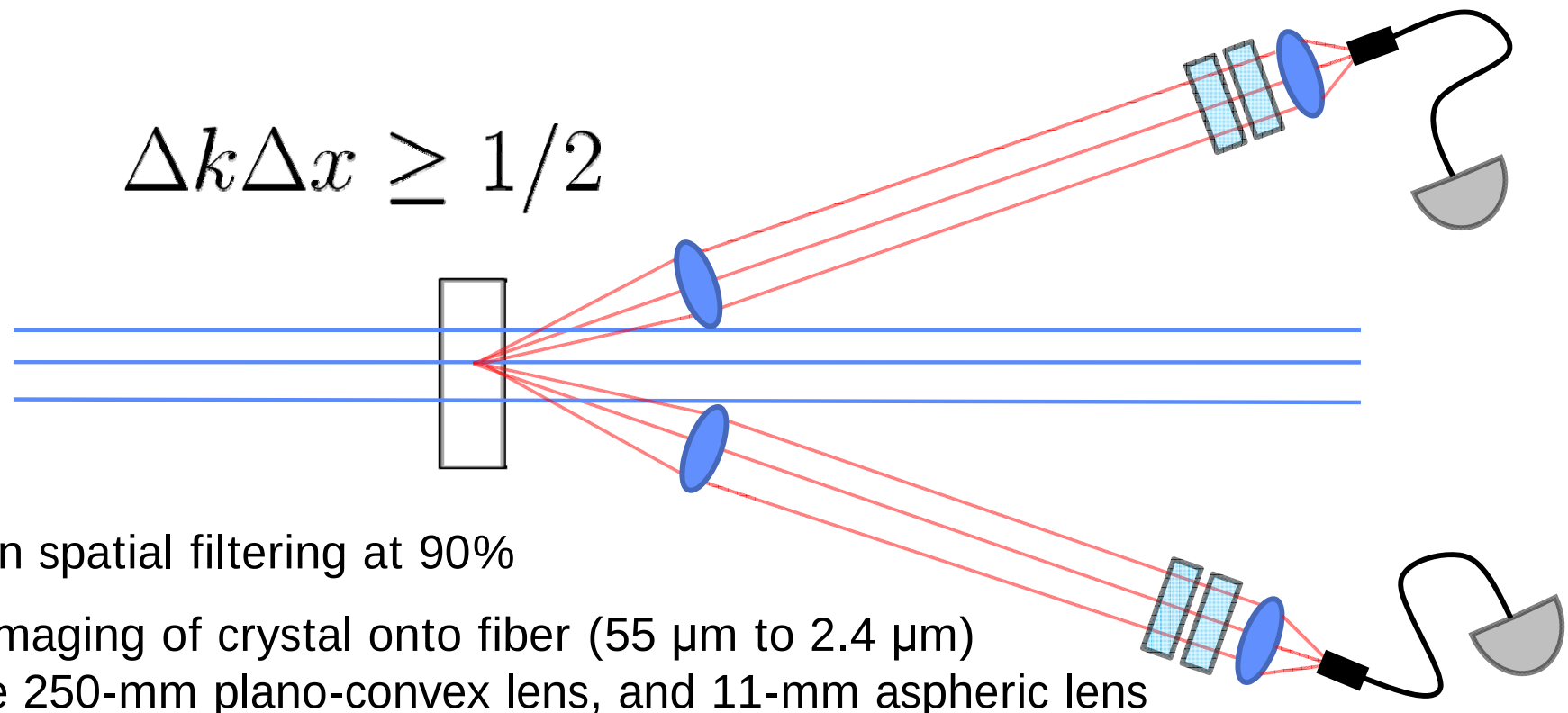
- Repetition-rate multipliers increase pulse frequency from 120 MHz $\rightarrow$ 3.84 GHz
- Time-bins (~ 260 ps) comparable to combined detector/time-tagger jitter
- Use spectrum-analyzer and high-speed detector to $\sim$ match path lengths (necessary for eventual mutually-unbiased basis checking)

World-Record Heralding Efficiency

Source Quality:

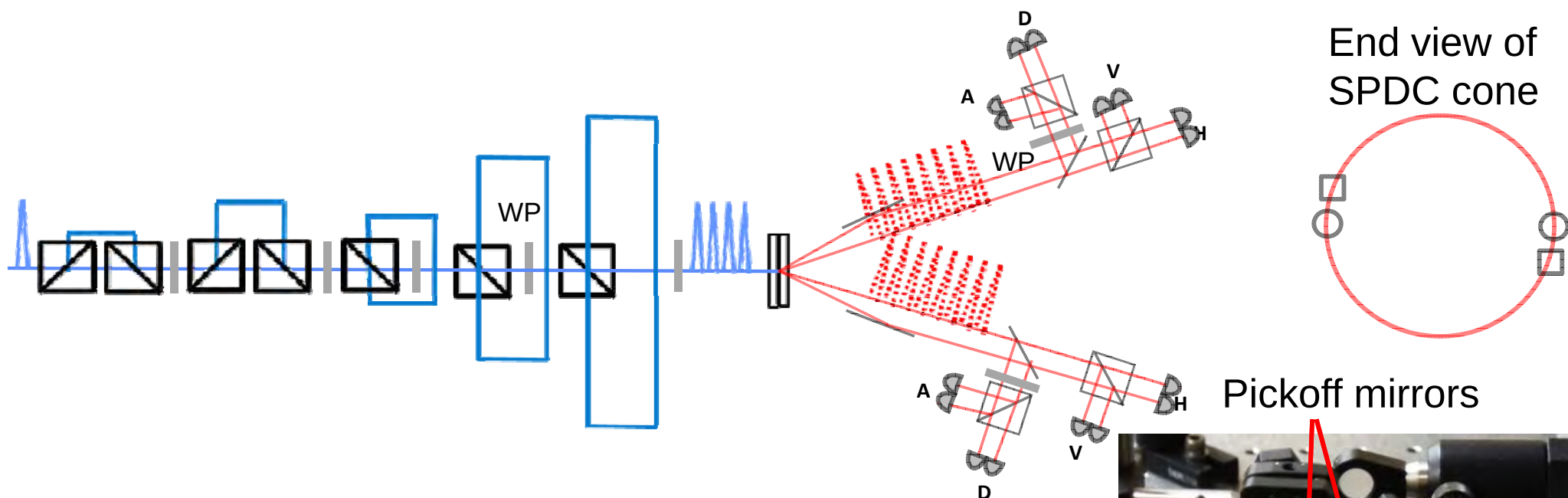
- $\eta = \eta_{\text{spatial}} * \eta_{\text{spectral}} * \eta_{\text{optics}}$
 $= 0.9 * 0.95 * 0.95 = 0.81$
- Used in detection-loop-hole-free Bell test
- Visibility in all bases >99.7% using temporal compensation,
- World-record (?) pair production rate of 30 MHz into a single mode (over a >20 nm bandwidth at 710 nm)
- Other improvements possible (e.g., achromatic coupling)

Developed one of the world's best entanglement sources.

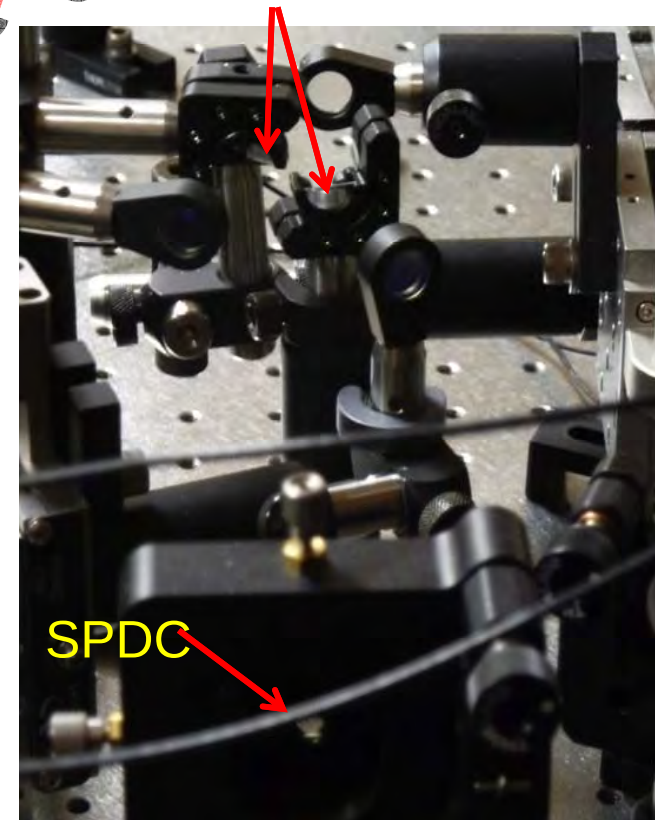


- Gaussian spatial filtering at 90%
- ~23:1 imaging of crystal onto fiber (55 μm to 2.4 μm)
 - Use 250-mm plano-convex lens, and 11-mm aspheric lens
- Pump radius of ~150 μm
 - Optimizes heralding efficiency over brightness
- 600- μm crystal
 - Reduced efficiency with two-crystal collection (90 $\rightarrow$ 78%) primarily from birefringent walk-off
 - Correctable using second birefringent 'stitching' crystal
- Chromatic aberration in collection lenses adds ~3% coupling loss
 - Optimized lenses should improve spatial collection efficiency 90 $\rightarrow$ 93%

Add a second channel...

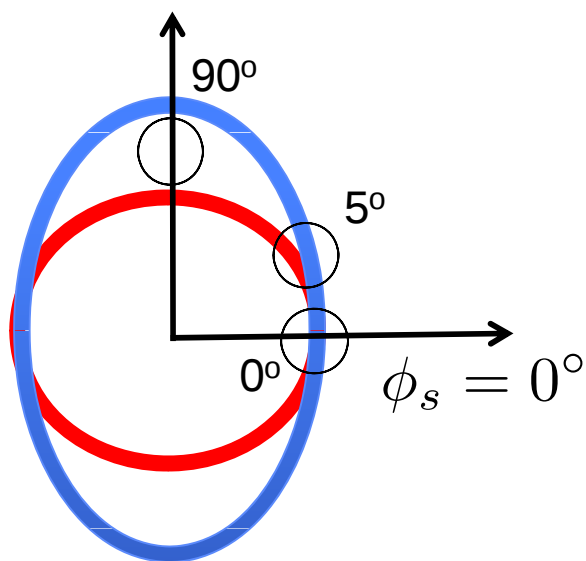


- 2nd-channel C/S ~47% (more constraints)
- Intrinsic pol BER still < 0.8%
- Currently 'time-sharing' time-taggers with Channel 1
- GOAL: 10 pairs around the cone
(20 is feasible)

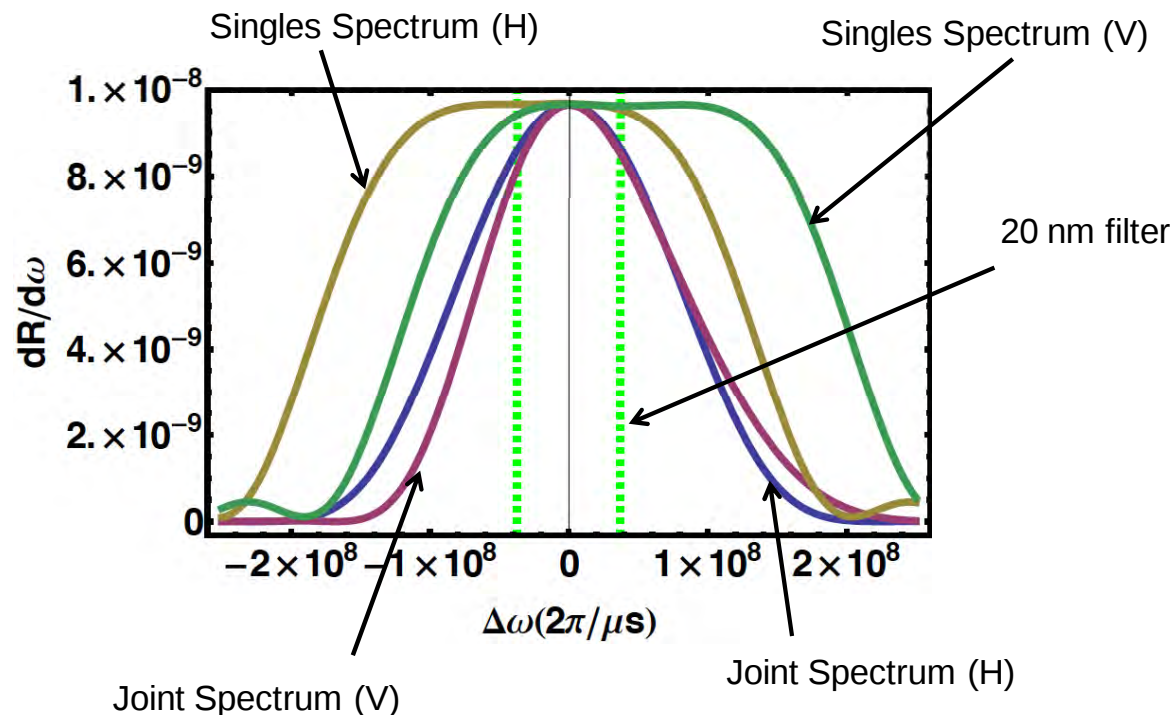


Heralding Efficiency for BiBO source

InPho Breakthrough – Develop complete model for coupling bi-photons into single mode fibers. Accounts for elliptical shape of down-conversion ring, spatial-spectral coupling

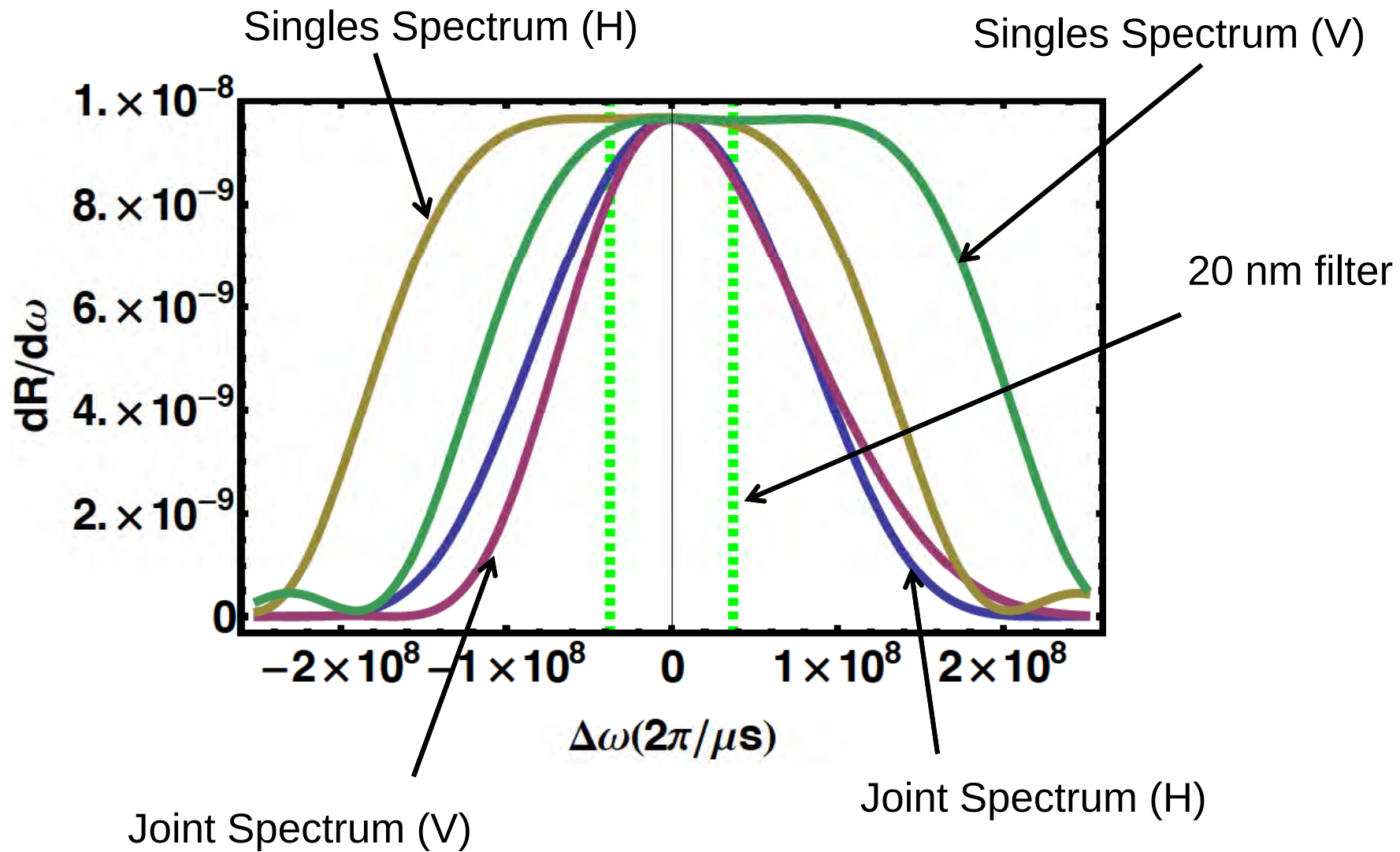


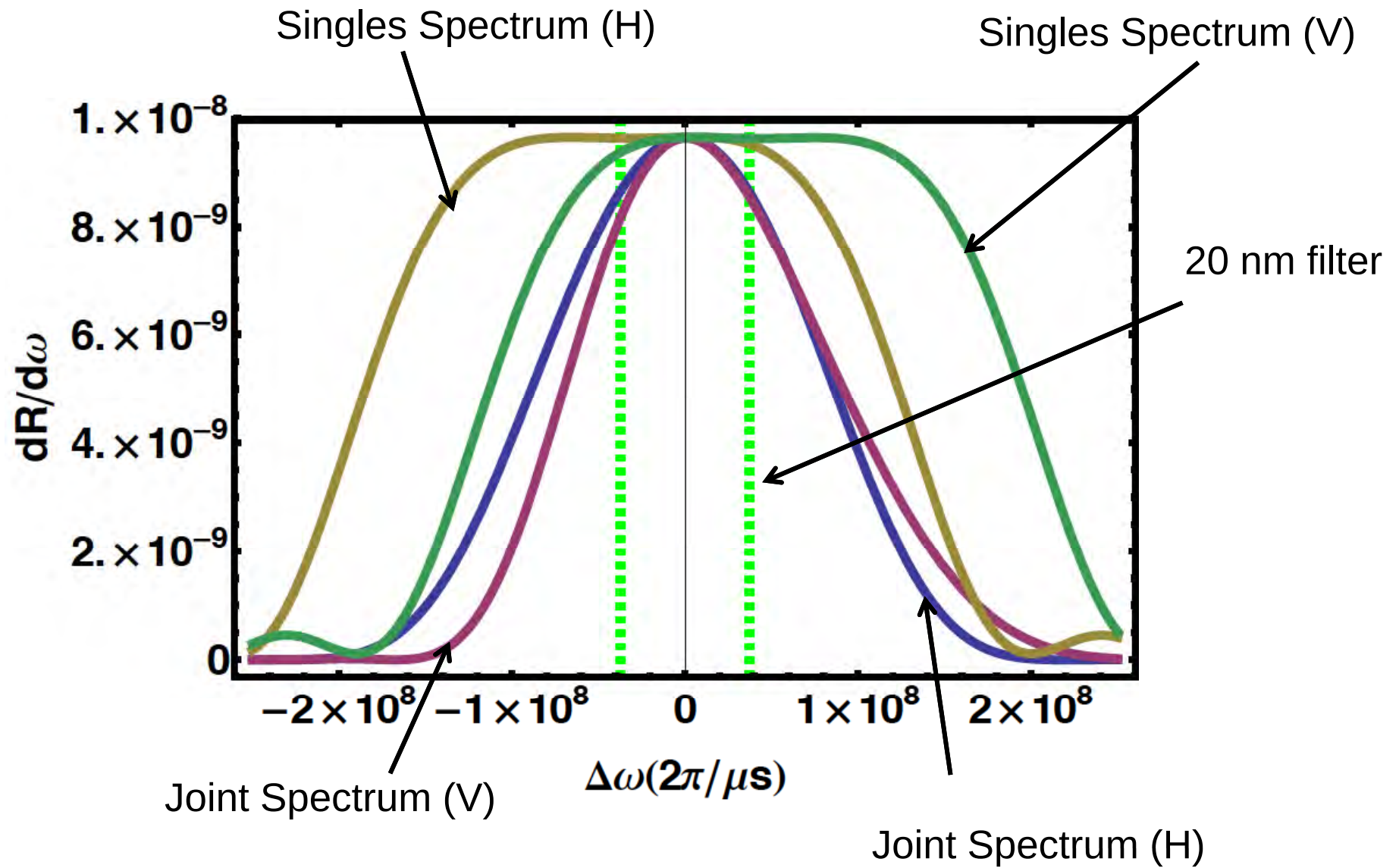
Note: Eccentricity exaggerated in drawing

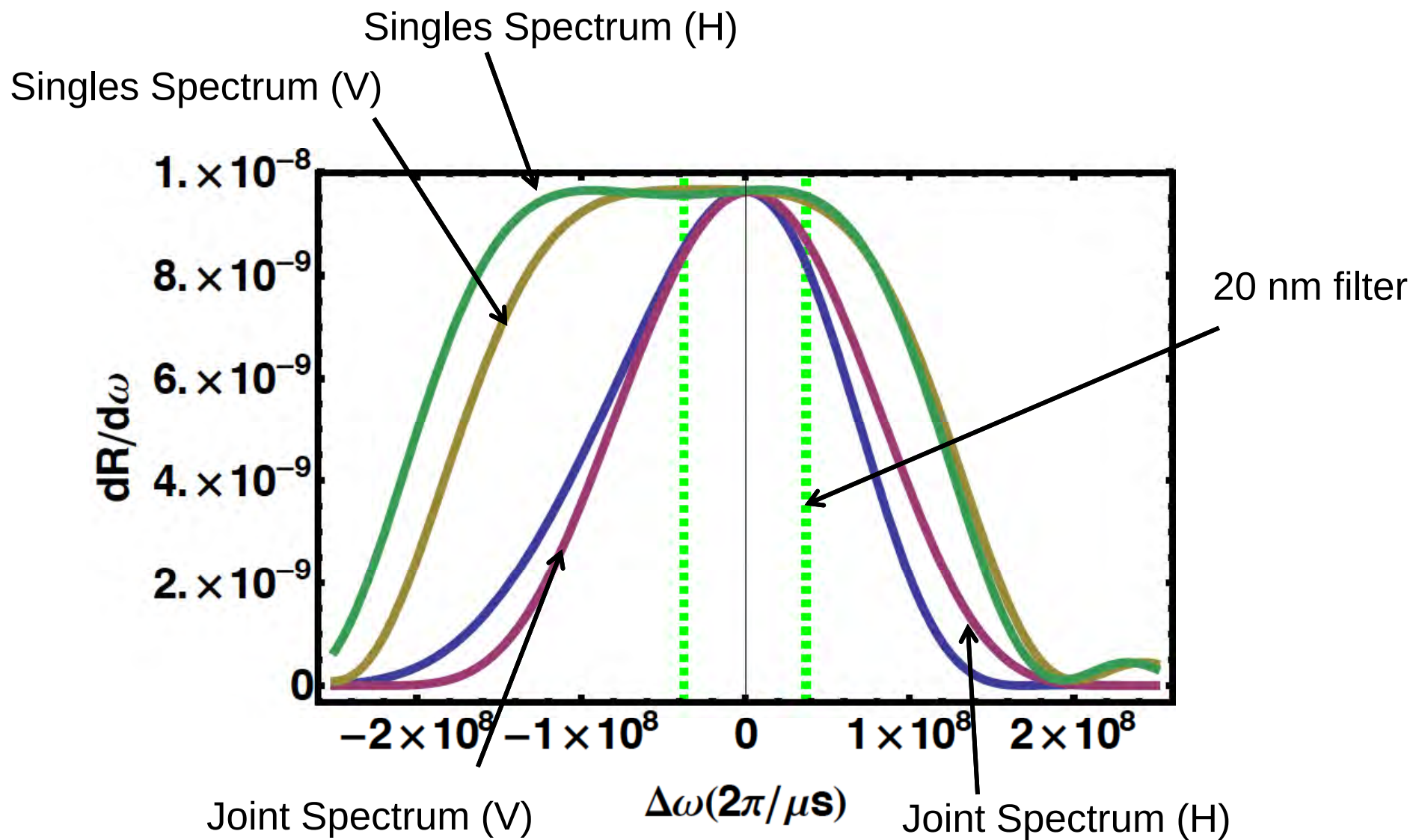


	Visibility	HE (H)	HE (V)
0°	99.986%	96.44%	95.71%
5°	99.982%	95.62%	96.23%
90°	99.971%	96.64%	95.84%

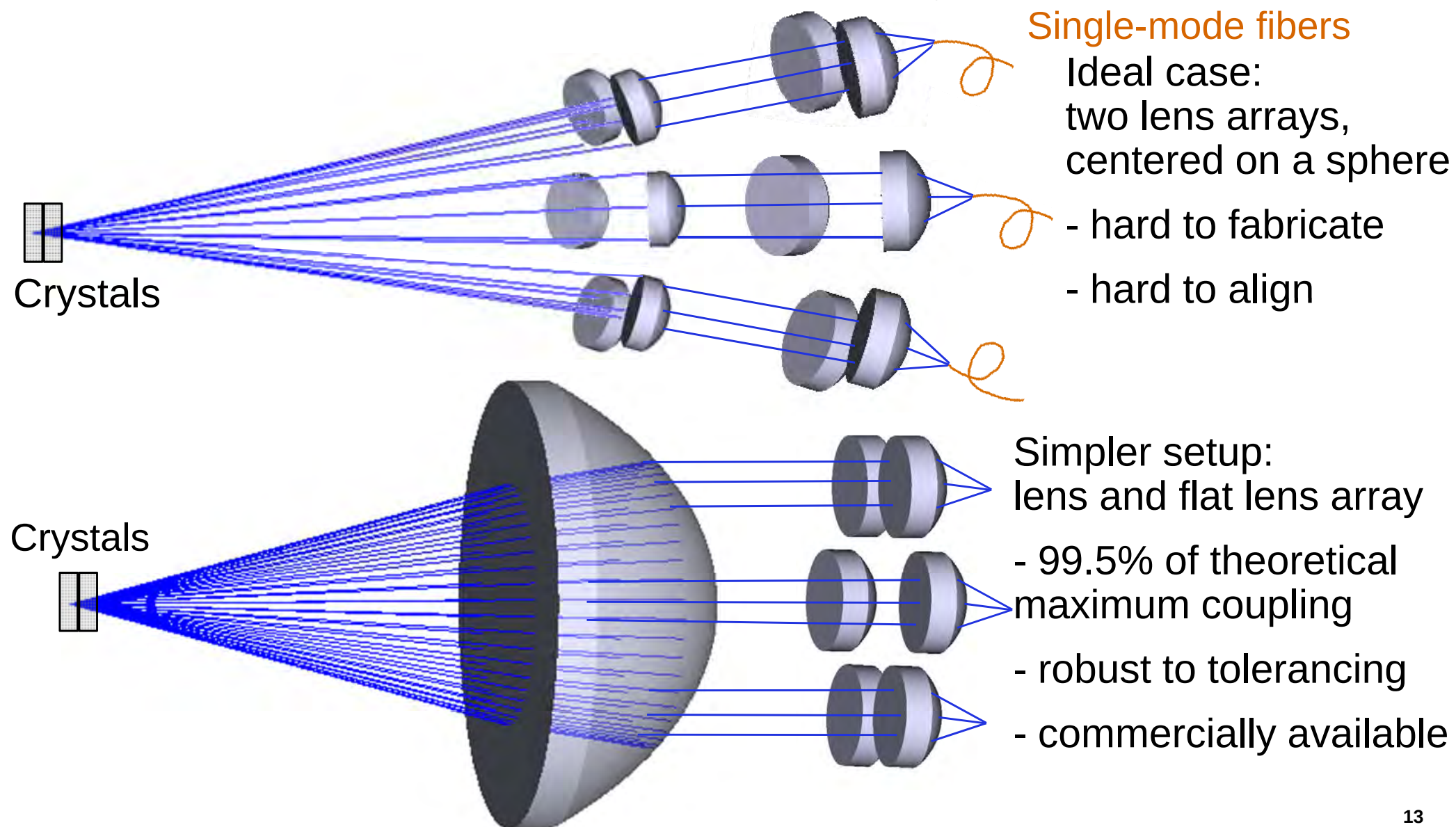
Predicted polarization visibility
spatial/spectral heralding efficiency
(20 nm bandwidth)





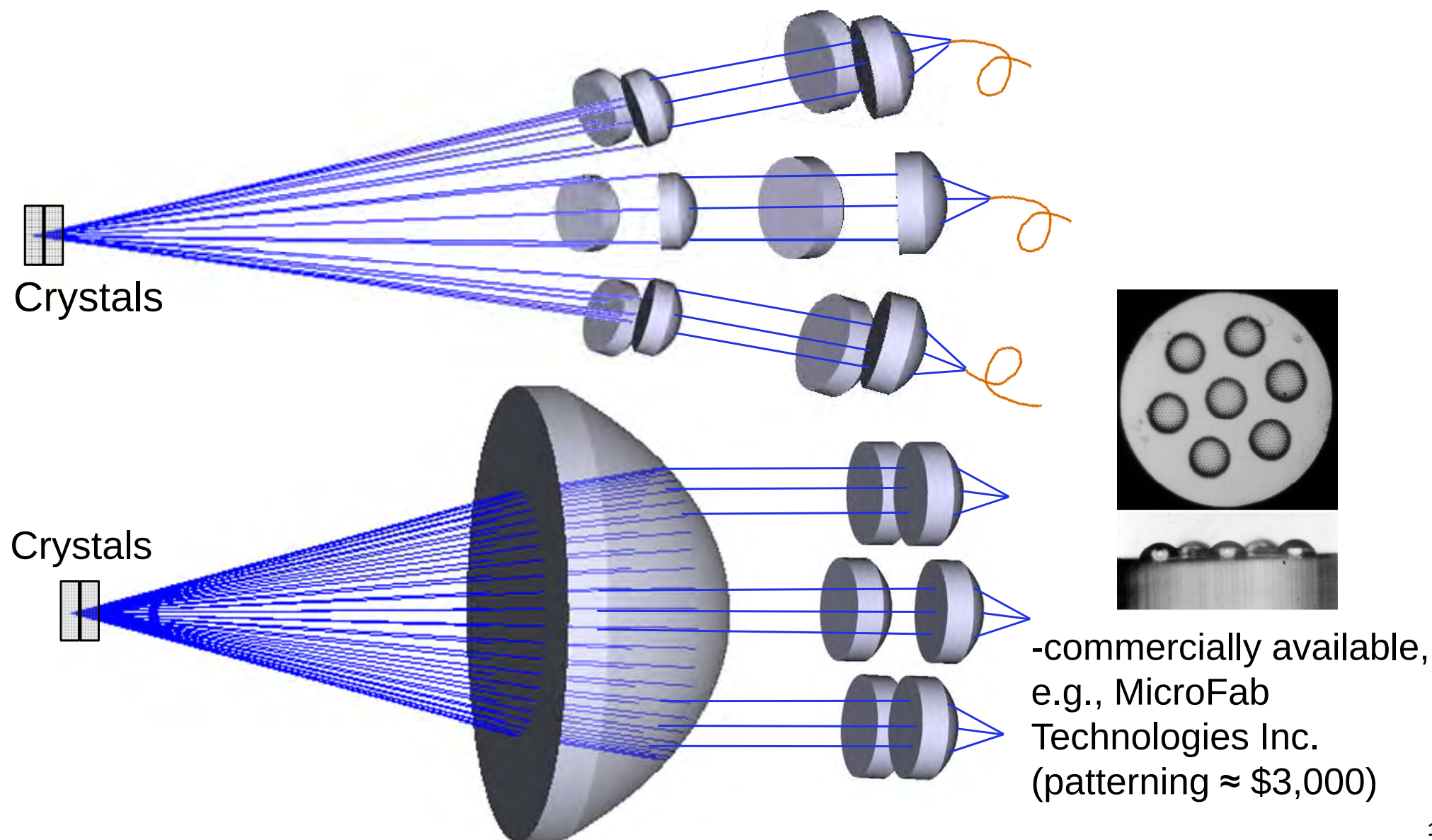


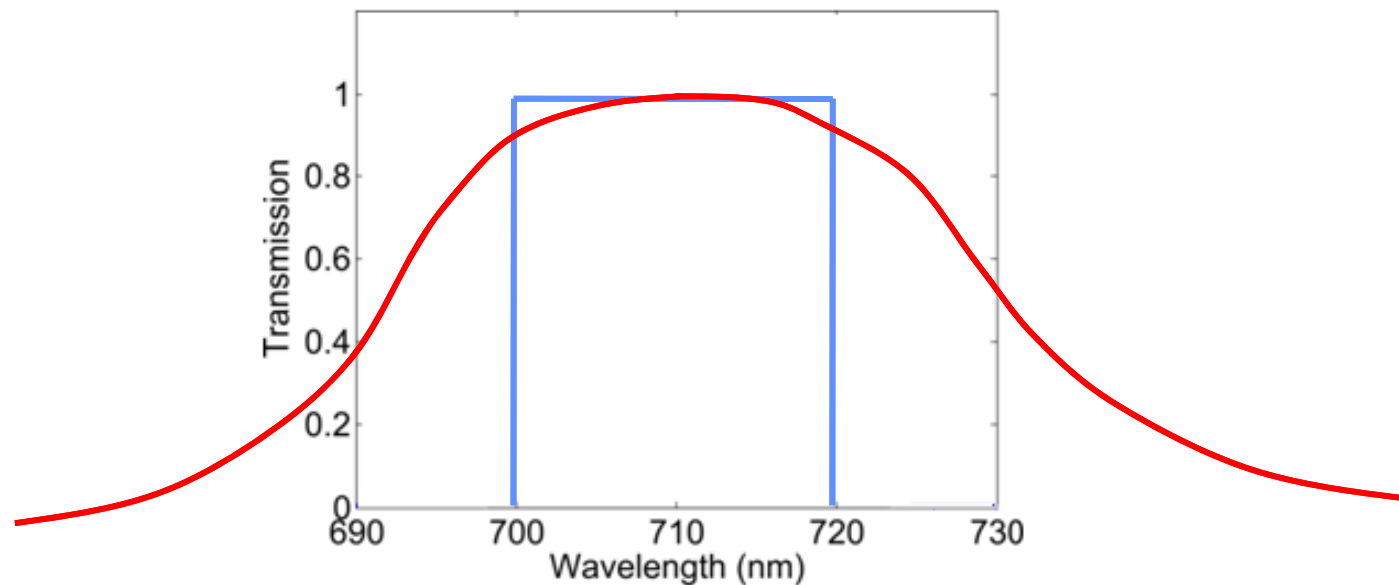
By collecting from multiple paired locations, count rates are directly increased.



Multi-channel collection optics

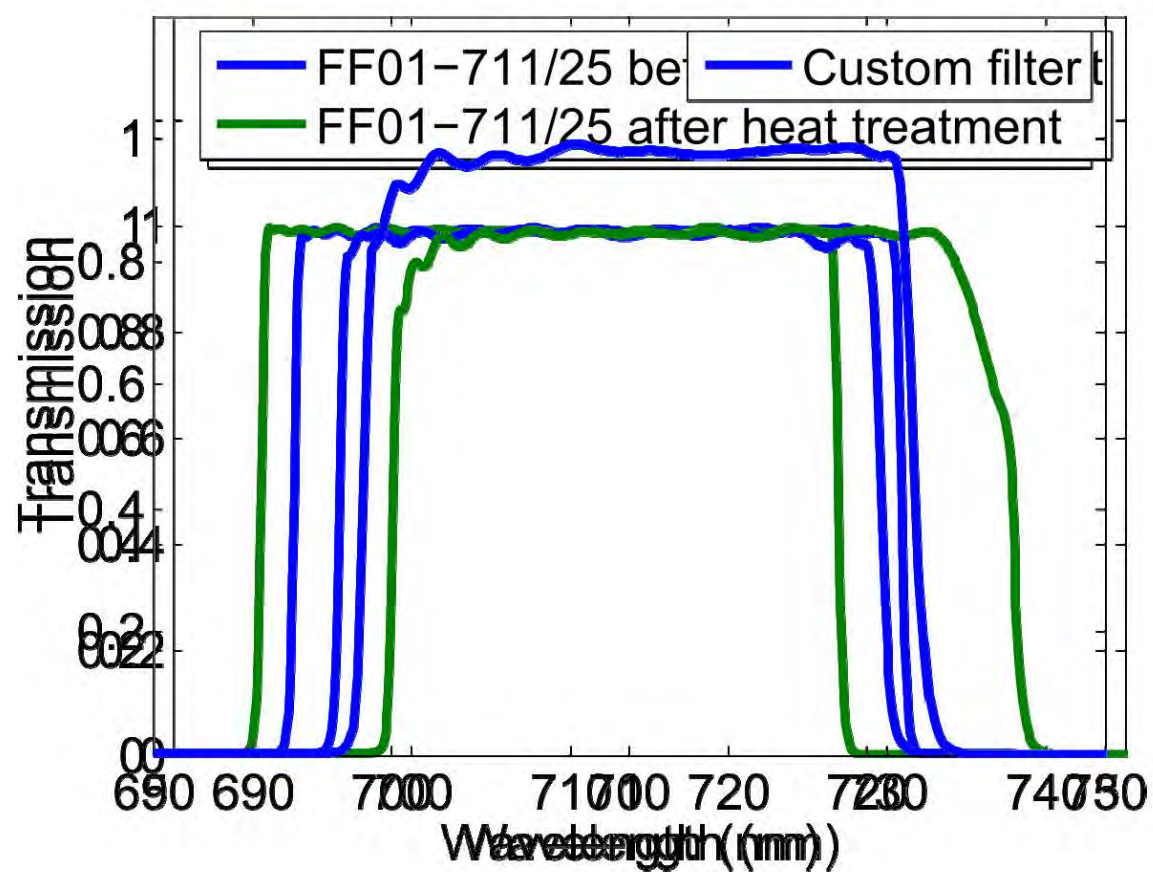
By collecting from multiple paired locations, count rates are directly increased.





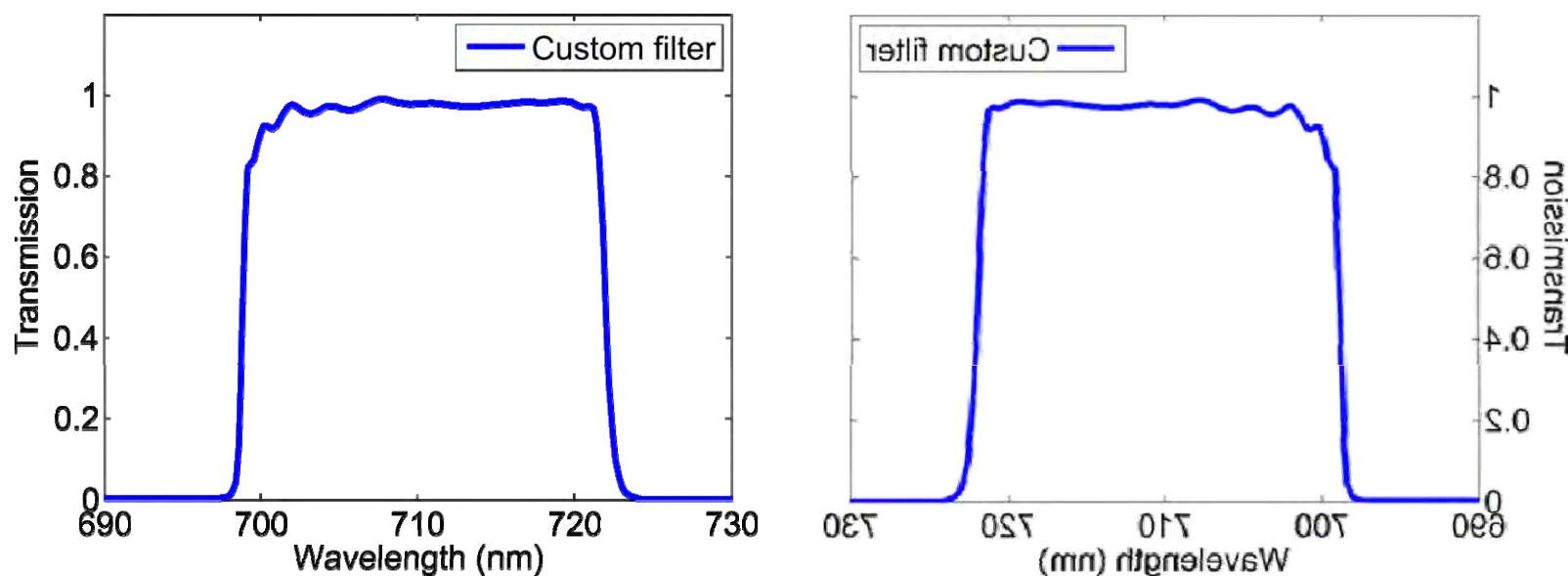
- For high heralding efficiency, want to pick off only part of the collected spectrum (the tail edges produce loss)
- Keep only the peak of the SMF-implied Gaussian filter (~ 70 -nm FWHM)
- Want steep edges, symmetric about 710 nm

Spectral Heralding Efficiency



355 nm $\rightarrow$ 710 nm + 710 nm

Spectral Heralding Efficiency



- Spectral filter is decoupled from spatial filtering by picking out a top-hat spectrum
- We use two different filters to set the two edges of the top-hat filter
 - Lower wavelength edge is temperature tuned (permanent)
 - Upper edge is tilted, and used to match the temperature-tuned filter edge of the conjugate side
- Tilted filters are polarization dependant and cause polarization decoherence in the A/D basis → need the filters *after* the polarization analysis
- Spectral heralding efficiency is 95%

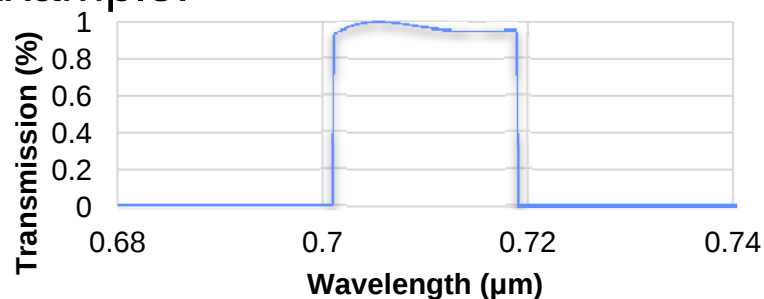
Grating-based spectral filtering:

Wavelength-dependent transmission

Goals:

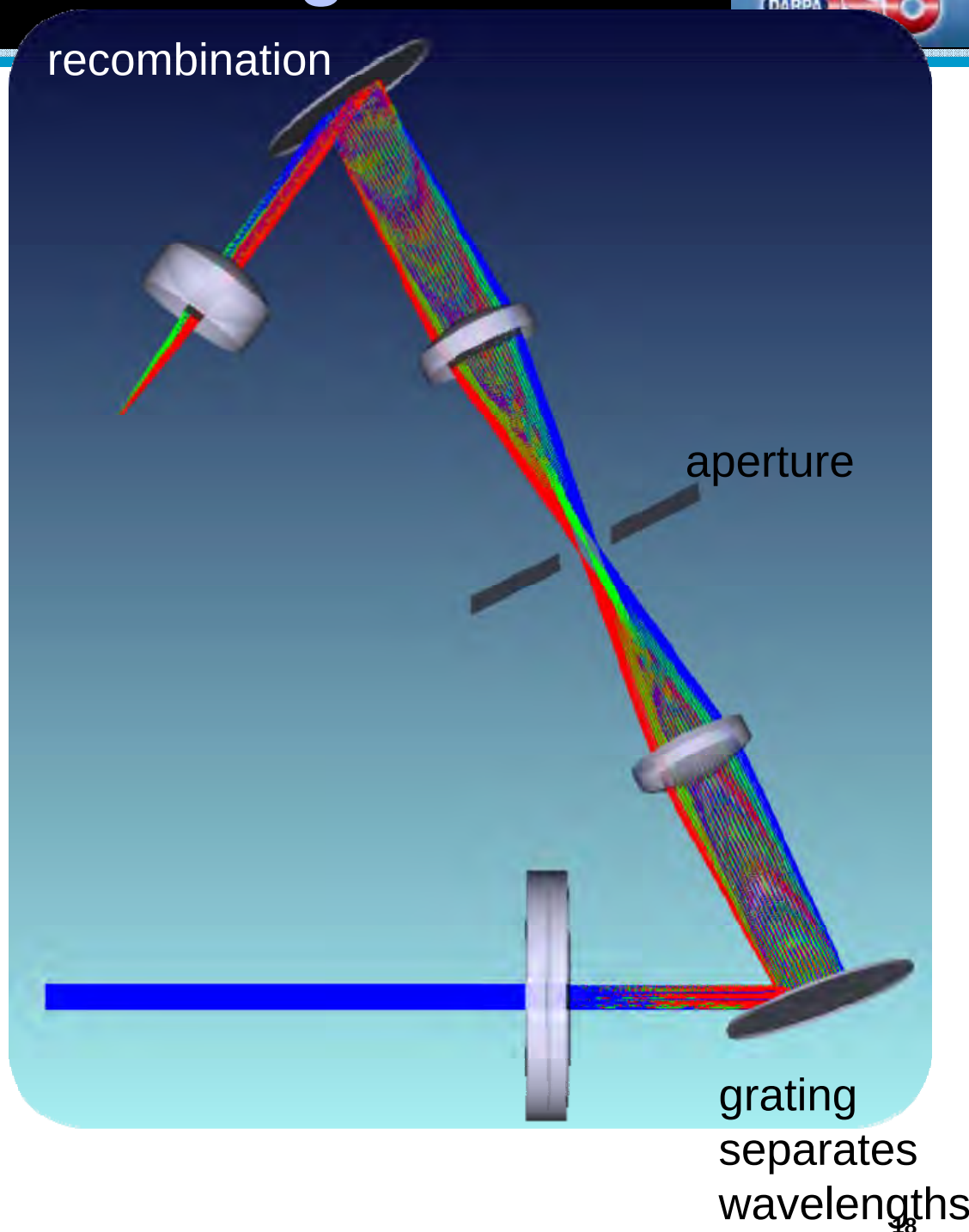
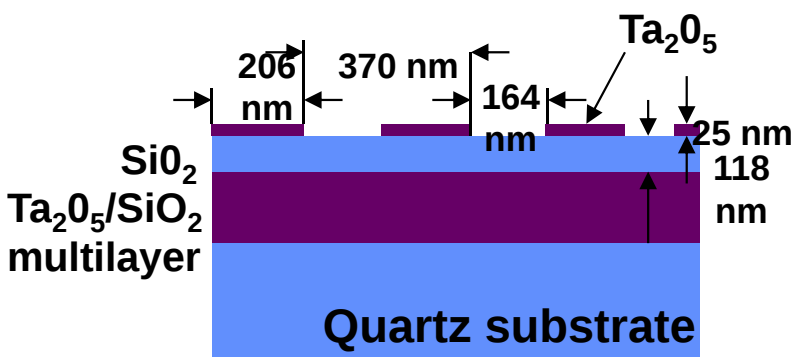
- high total transmission
- sharp edges

Example:



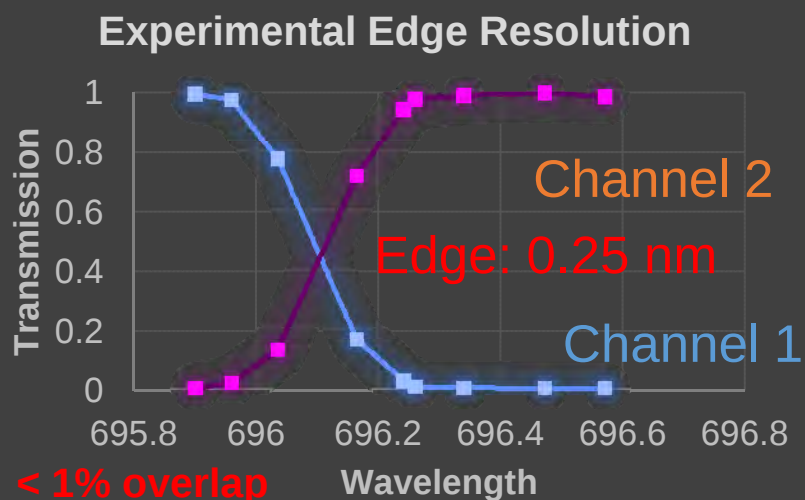
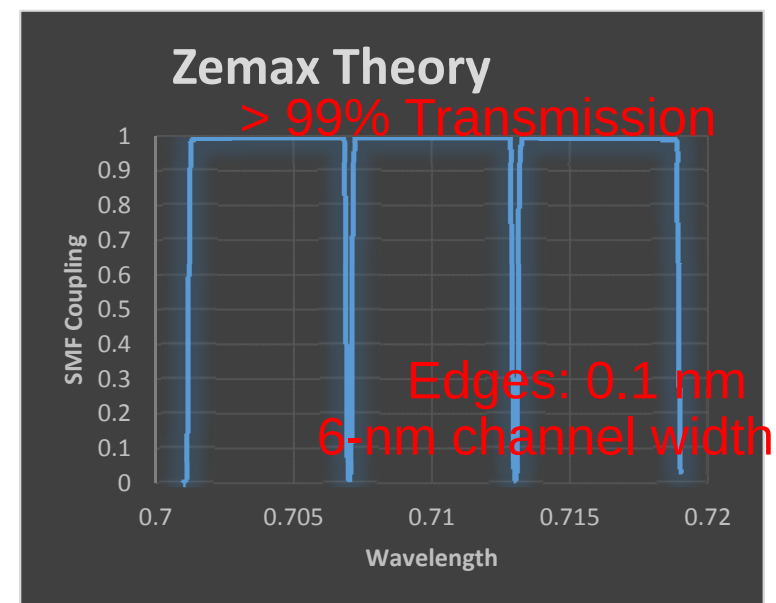
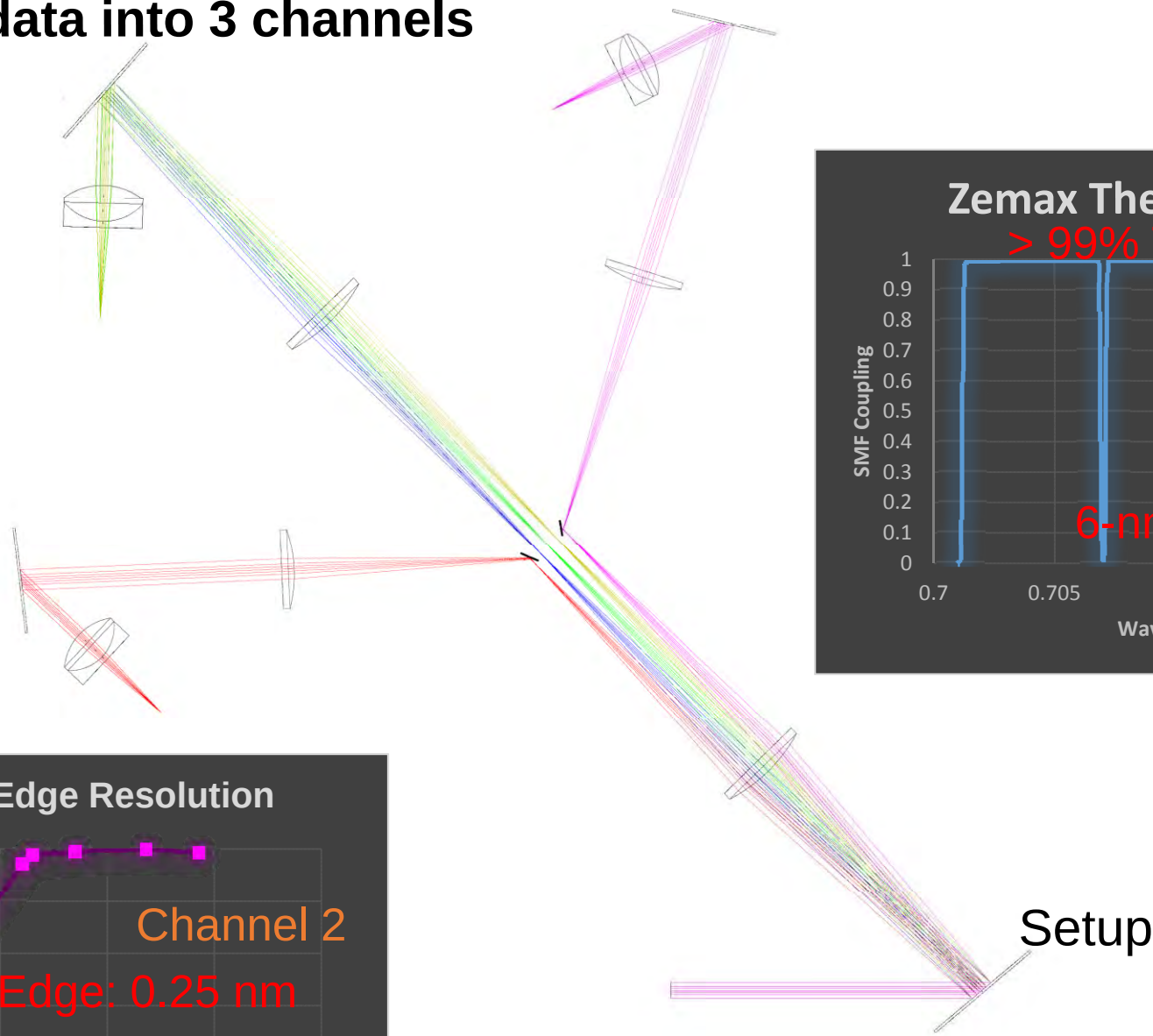
Plasmon-enhanced Grating

(Destouches et al., Opt. Exp. 13, 3230 (2005))



High-efficiency spectral multiplexing

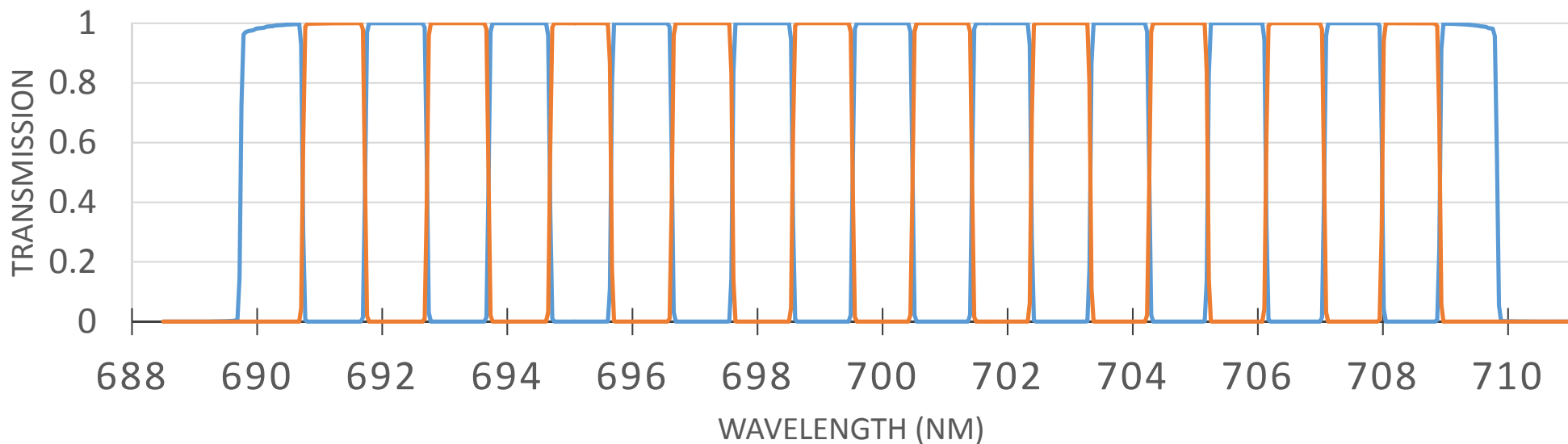
-separate data into 3 channels



Ideal case: 3 “top hat” profiles
 -minimal overlap between channels

Many-bin multiplexing

21-NM BANDWIDTH



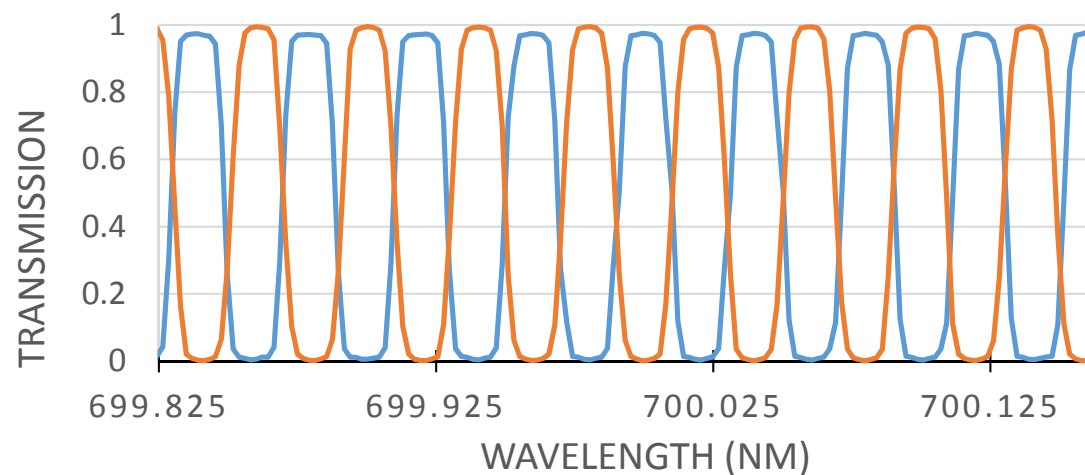
21 1-nm wavelength channels

Could be saturated using:

- longer crystals
- higher power
- few-mode collection

What's the limit?

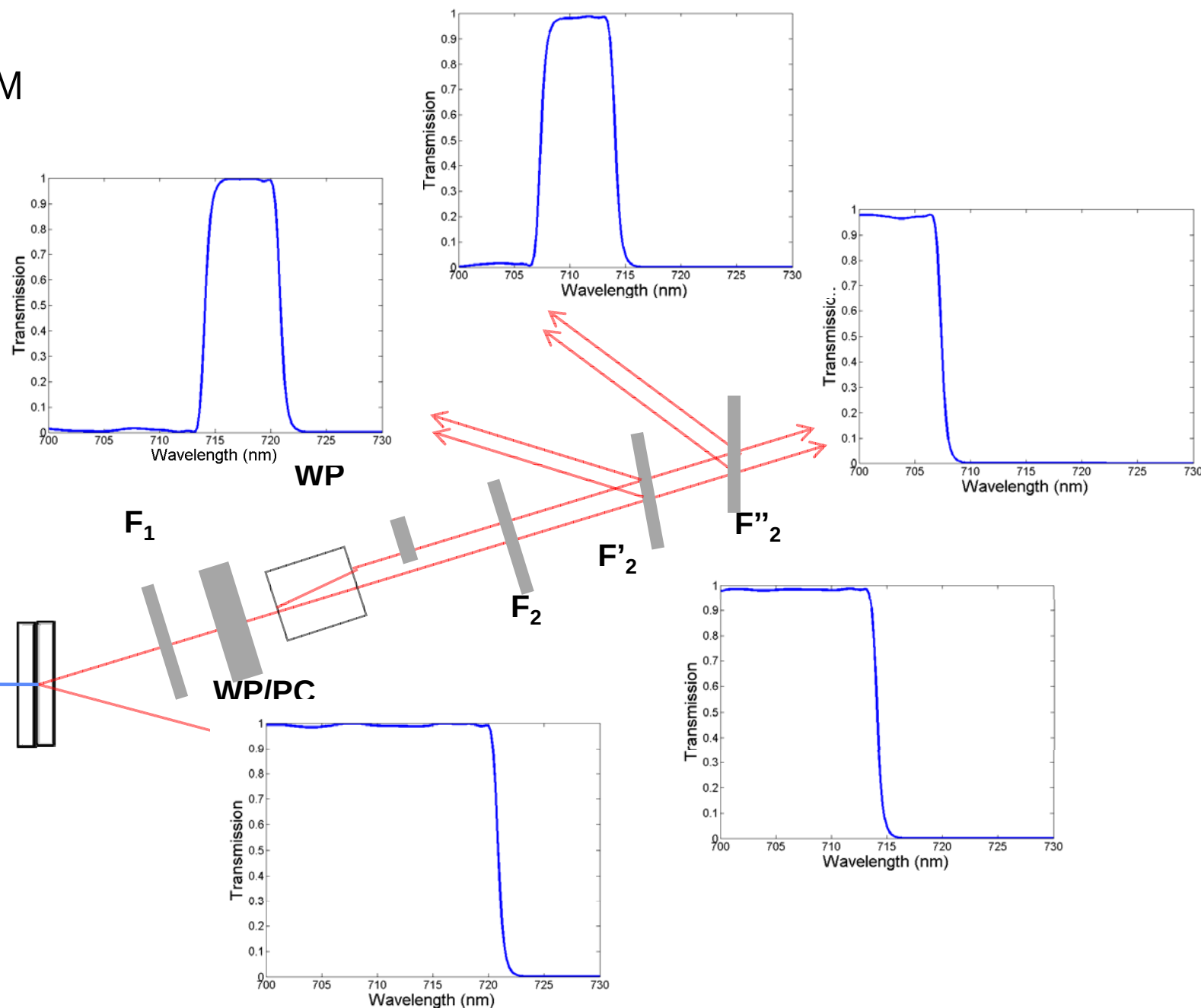
20-PICOMETER BINS



Note: No point in having spectral bin widths less than pump bandwidth (currently ~ 0.1 nm)

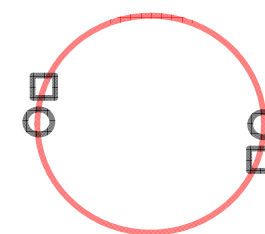
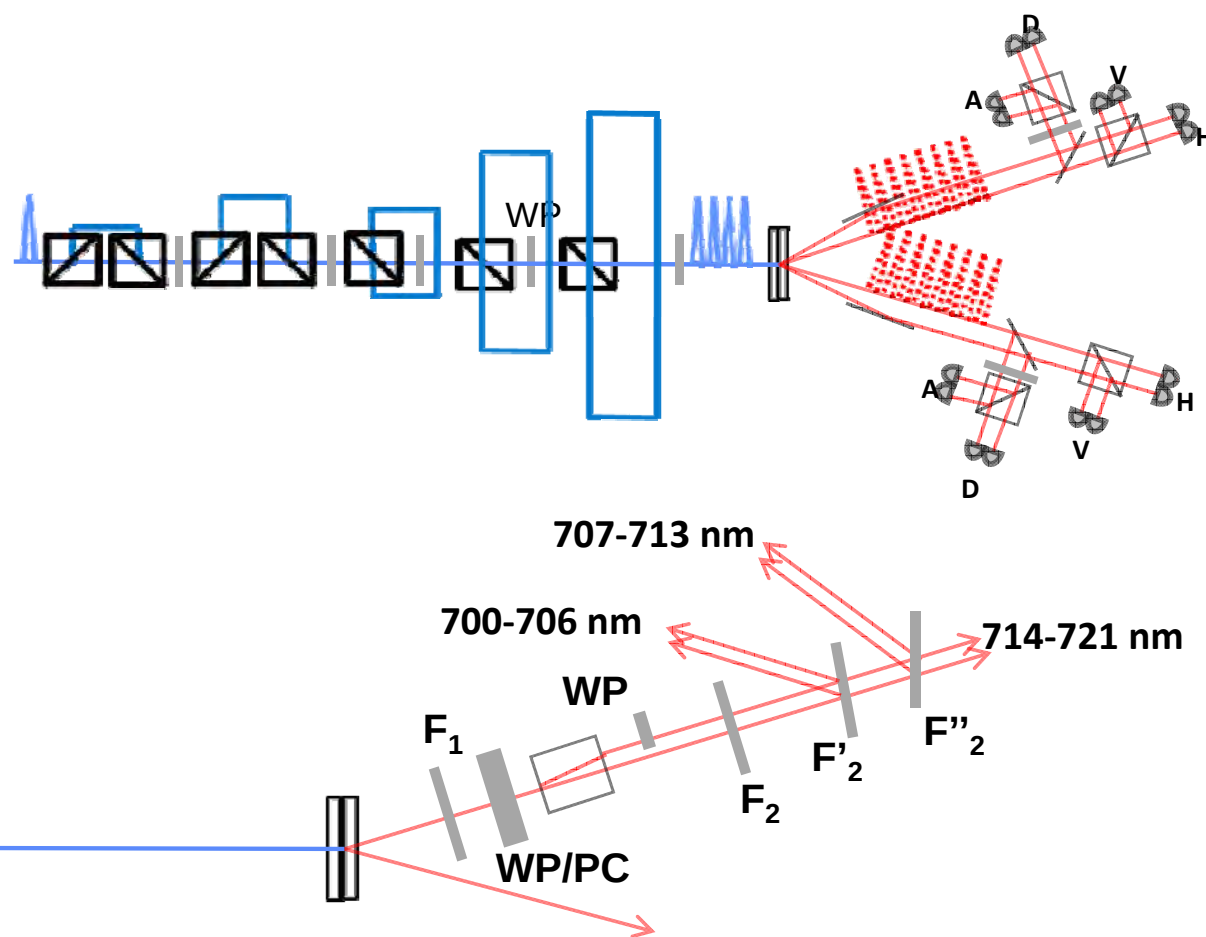
Multiple Spatial/Spectral Channels

- Sequential tilted filters allow x3 WDM (~x20 possible)
- PC would allow for asymmetric basis checking
- Collection into few-mode fiber allows saturation of each channel
- Key rates above ~60MHz (with 2 spatial channels)



Summary: Multiple Spatial/Spectral Channels

Demonstrated/will demonstrate methods to achieve multiple independent spatial and spectral channels



End view of
SPDC cone

- Up to 10 sets of spatial pairs possible/practical
- Sequential tilted filters allow x3 WDM (~x20 possible)
- Collection into few-mode fiber allows saturation of each channel
- Key rates above ~60 MHz (with 2 spatial channels)
- 10 channels + few-mode fiber → >1 GHz key rate!

Demonstrate all technologies to achieve milestones!

High-Efficiency, Low-Jitter, High-Saturation Rate Single-Photon-Counting Detectors

InPho: FSQC



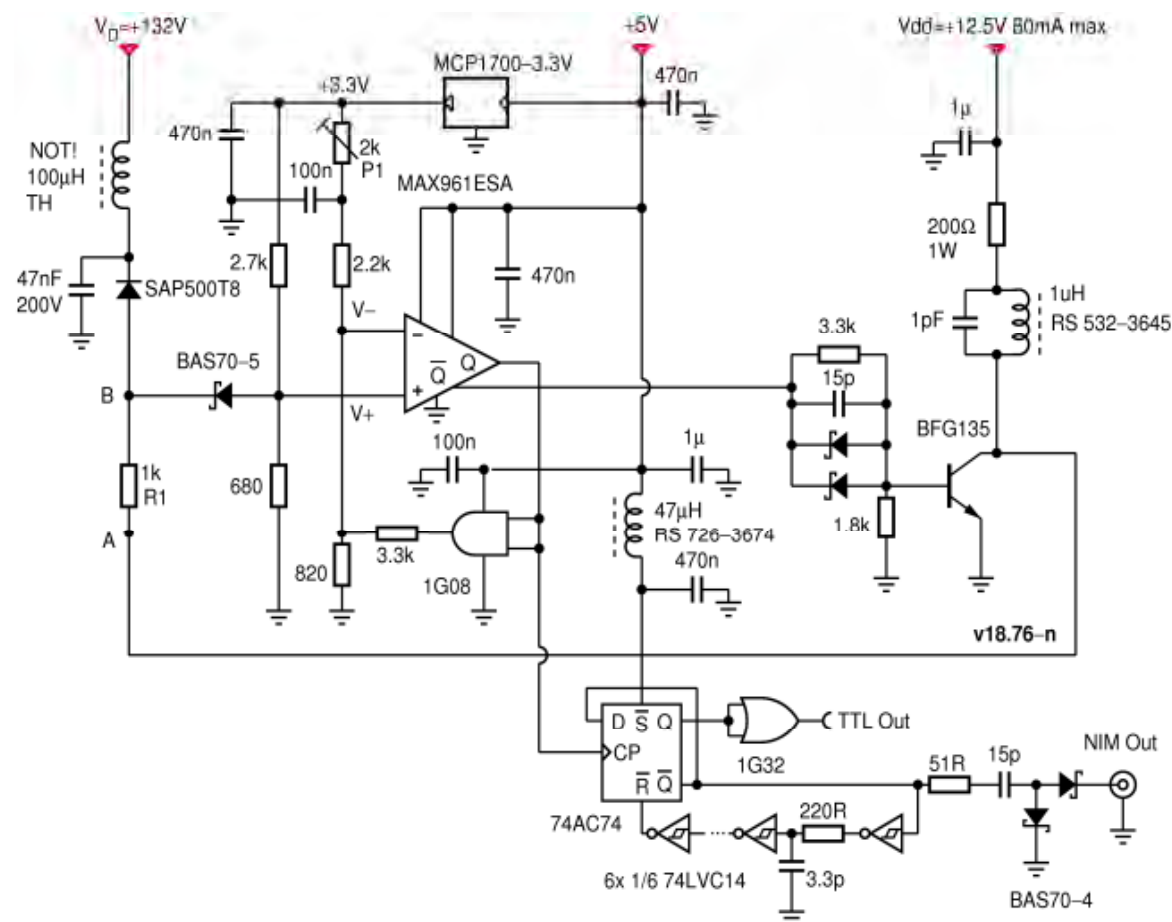
Develop custom electronics mated with Laser Components SAP-500 SPAD

Quantum Efficiency @ 710 nm: ~70%

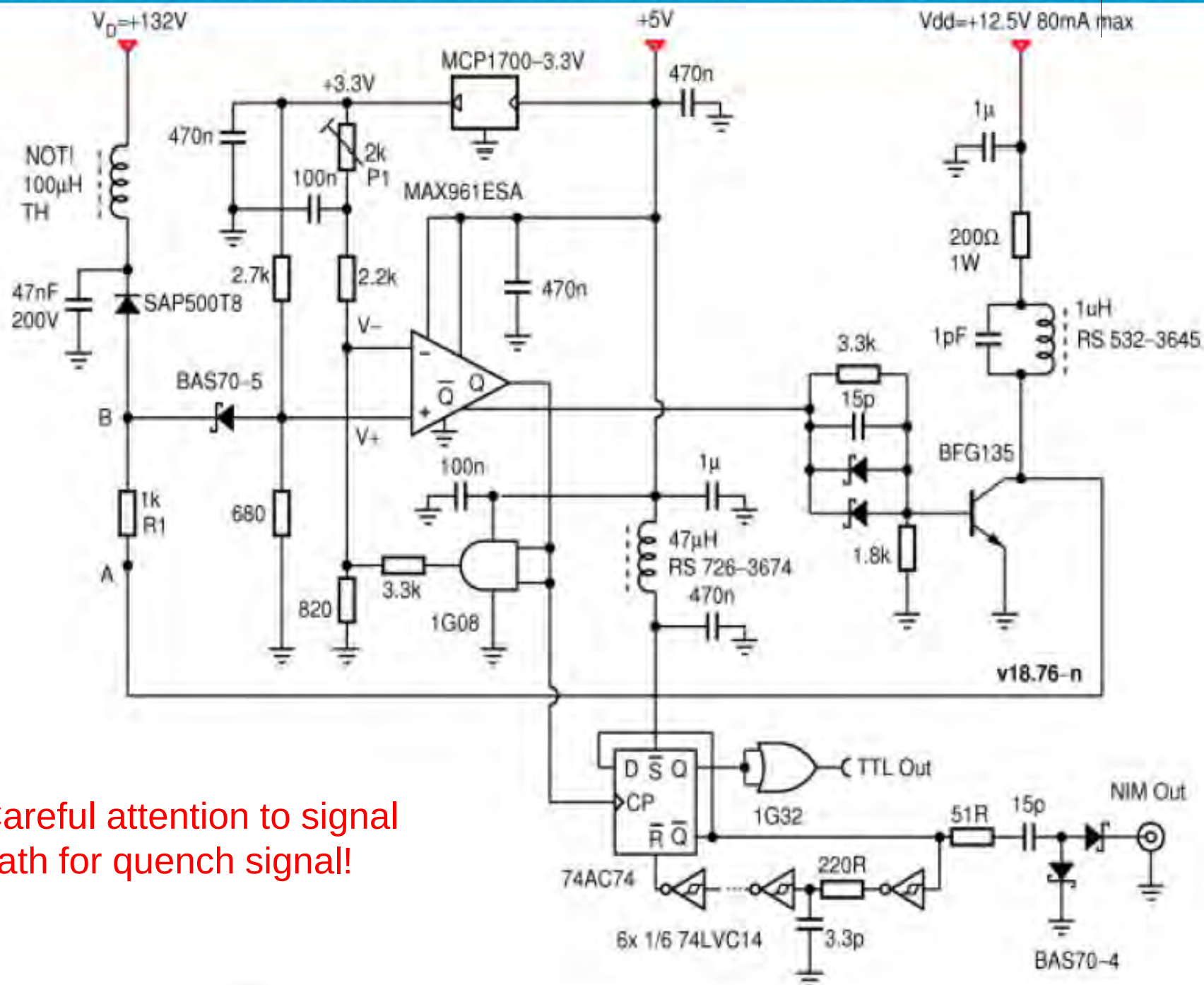
Deadtime: 24.5 ns (41 MHz saturation rate) Afterpulsing probability: <0.1%

Jitter: 158 ps average for 15 detectors

Dark Count Rate: ~3.5 kHz



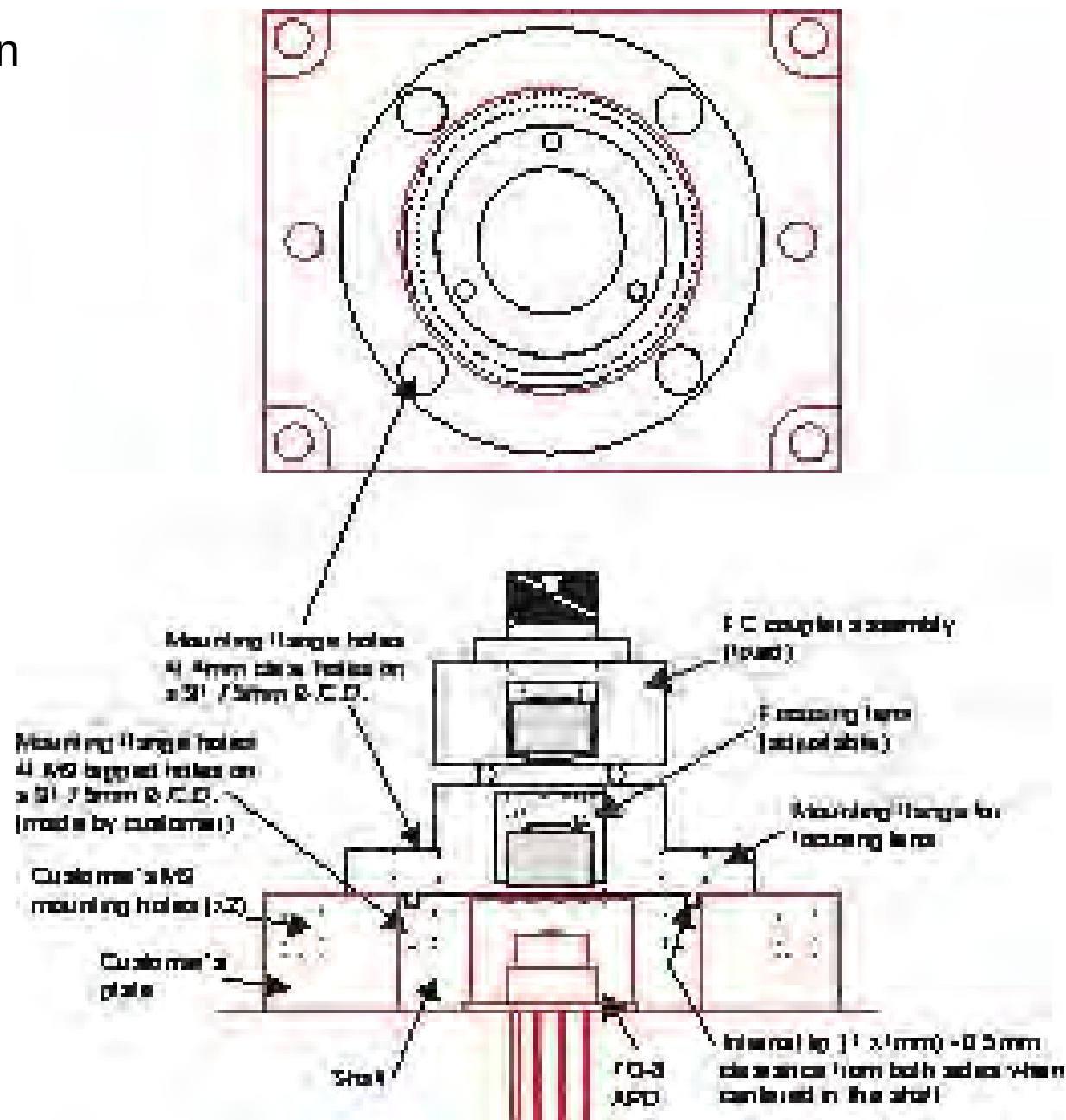
Active Quenching Circuit



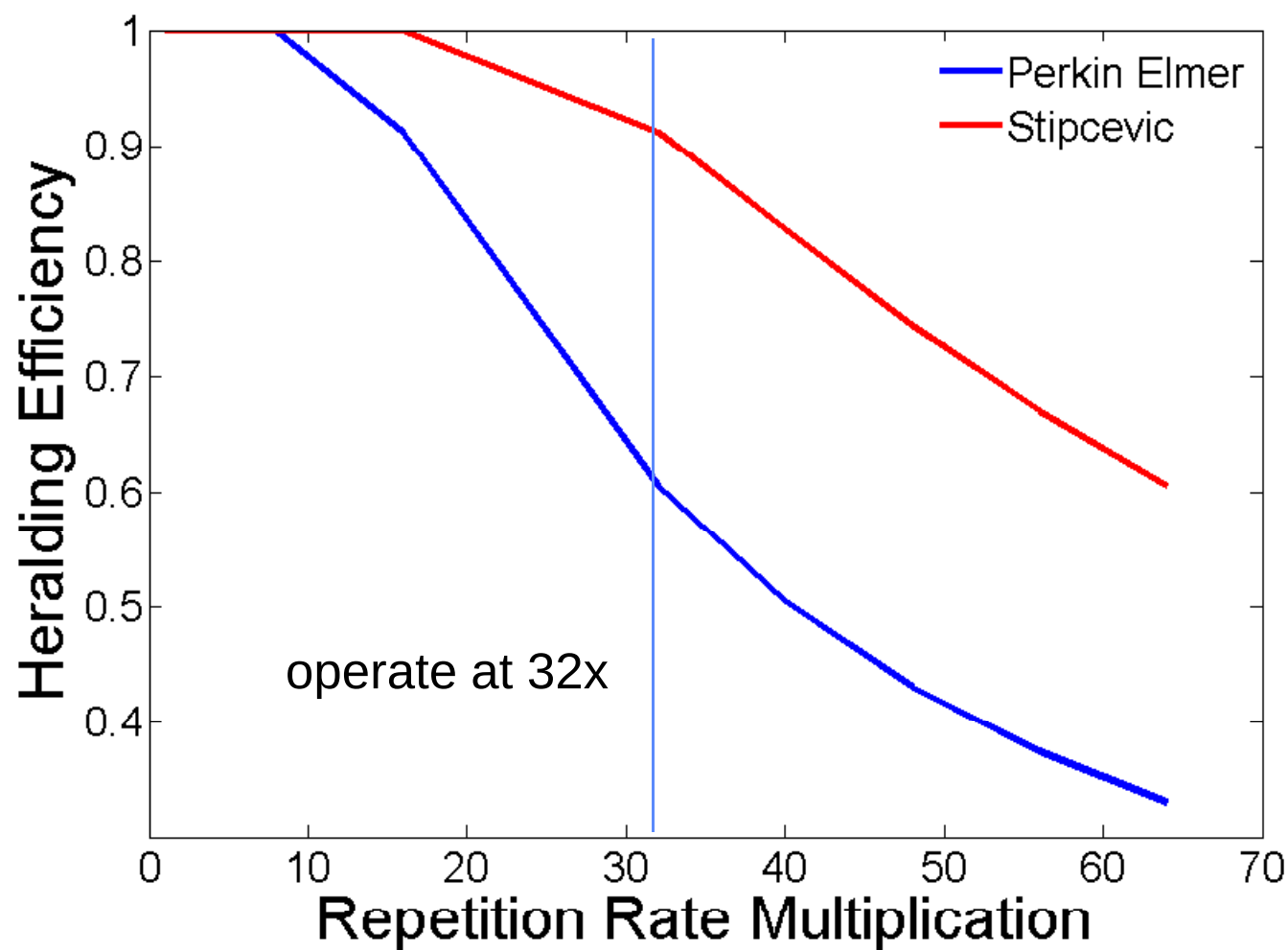
Careful attention to signal path for quench signal!

High fiber coupling efficiency for APDs

- Partner with OZ Optics to design fiber coupler with XYZ translation of the beam
- Adjust to achieve highest efficiency
- Lowest jitter requires finer adjustment
- 15 fiber-coupled detectors with custom quench circuit delivered to UIUC in April 2014

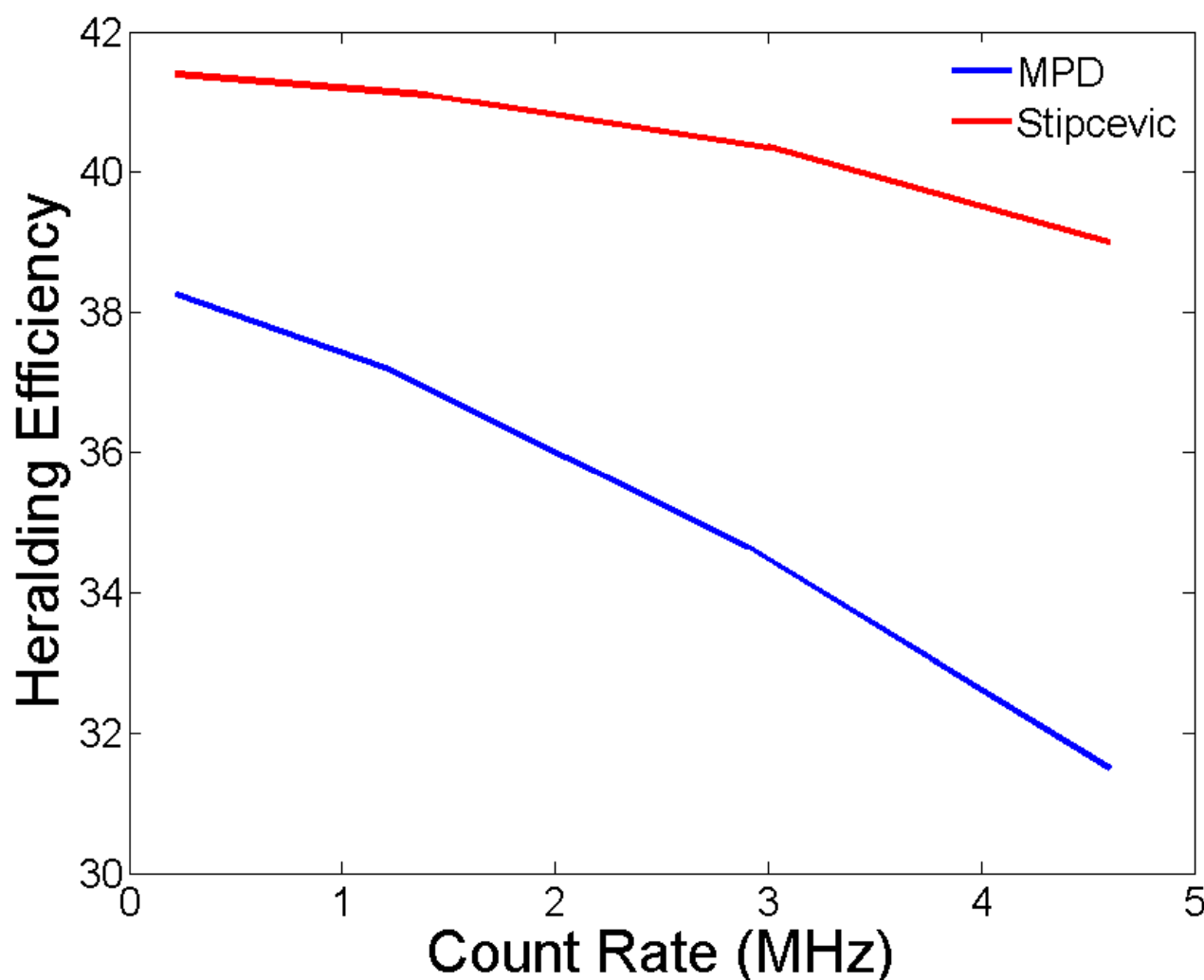


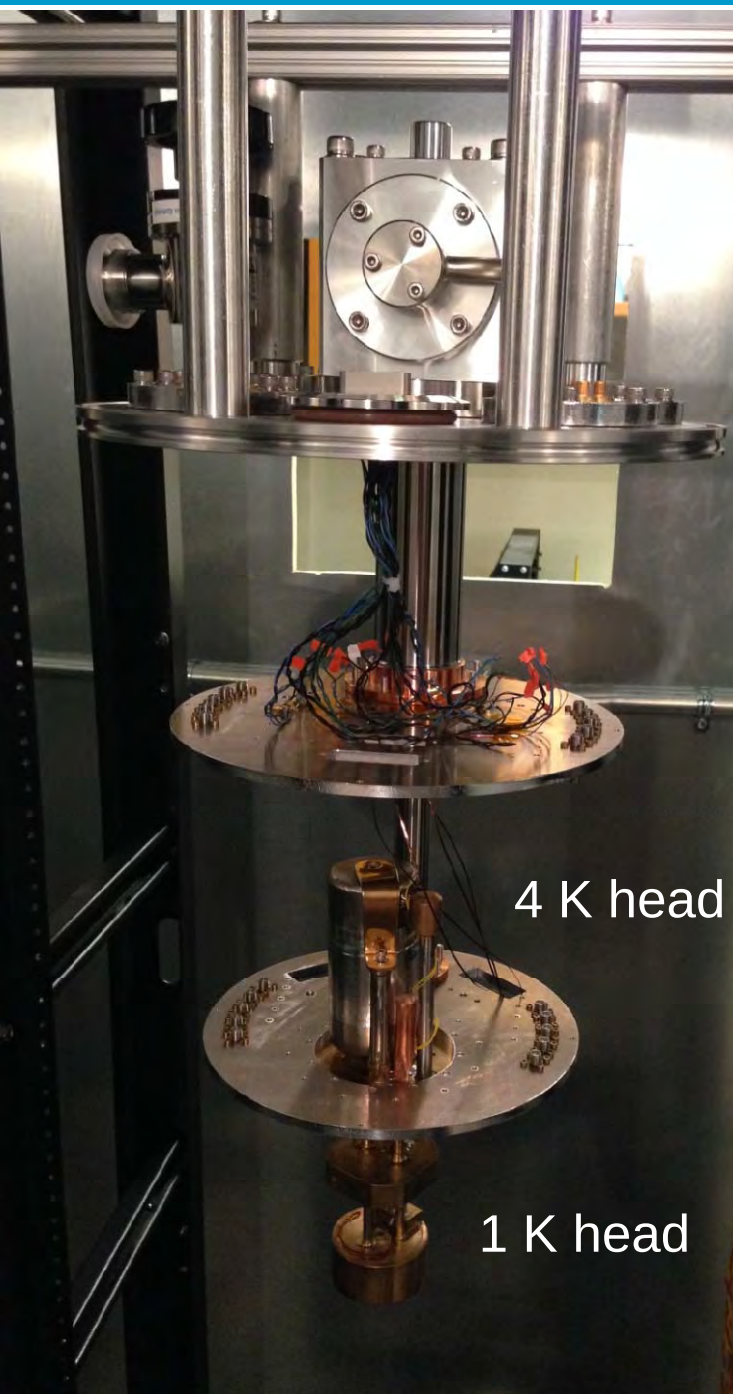
Improved jitter in custom quench circuit allows for greater repetition-rate multiplication and higher photon efficiency



Saturation characteristics: MPD vs. custom quench circuits

Higher saturation rate with similar jitter with custom circuit vs. MPD circuit allows for higher key rate and photon efficiency





Develop 8 channel SiW superconducting nanowire detectors optimized for 710 nm in collaboration with NIST

Status report (6/4/14): Cryostat constructed, chill-down tests, detectors fabricated, undergoing testing

Anticipated performance:

Quantum Efficiency: >90%

Jitter: 100 ps

Deadtime: <20 ns

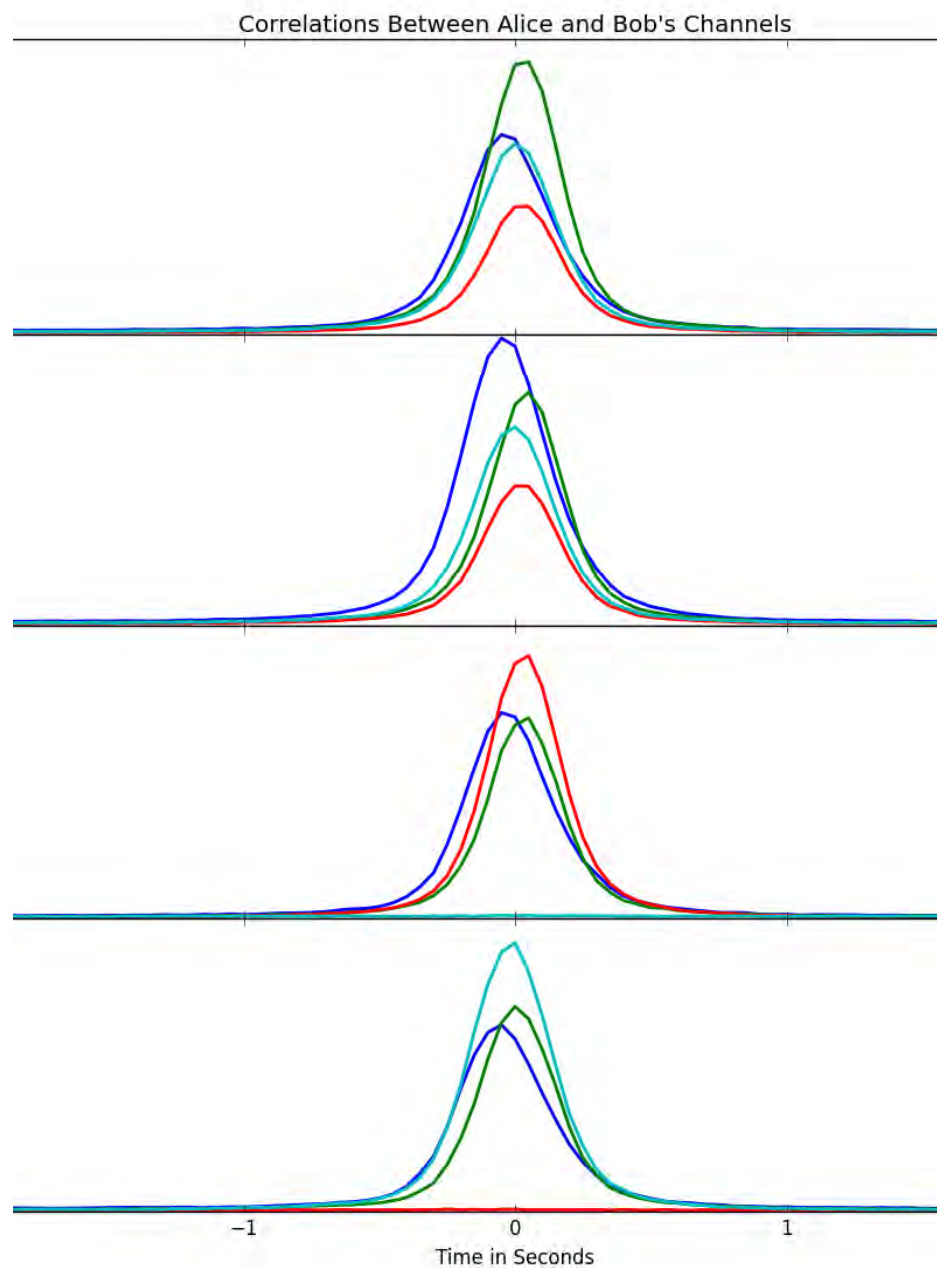
Assess and qualify time-taggers for time-bin QKD.
Developed high-throughput custom time-tagger.

	Agilent	IQC	UIUC/NIST
Max count rate:	80 MHz (20 MHz continuous)	12 MHz	200 MHz (400 MHz possible)
Resolution (jitter):	50 ps (60 ps)	156 ps (180 ps)	50-100 ps (10 ps)
Channels:	6	12	4

- The Agilent timetagger can run up to 80 MHz in “burst mode” where only a few milliseconds of data are taken at a time.
- Custom UIUC/NIST timetagger count rate limited by hard-drive write-speed. At high rates, less bits per count (currently 32 bits) can be used allowing up to 400 MHz continuous. Resolution limited by the FPGA clock, the current board has a 100-ps resolution. A better board could allow for a 50-ps time-bin size.

Mysterious rate-dependent jitter in one time tagger

Alice-Bob cross correlation



time in ns

*Mutual Information of the quantum key distribution system
including error correction, privacy amplification,
and security analysis*

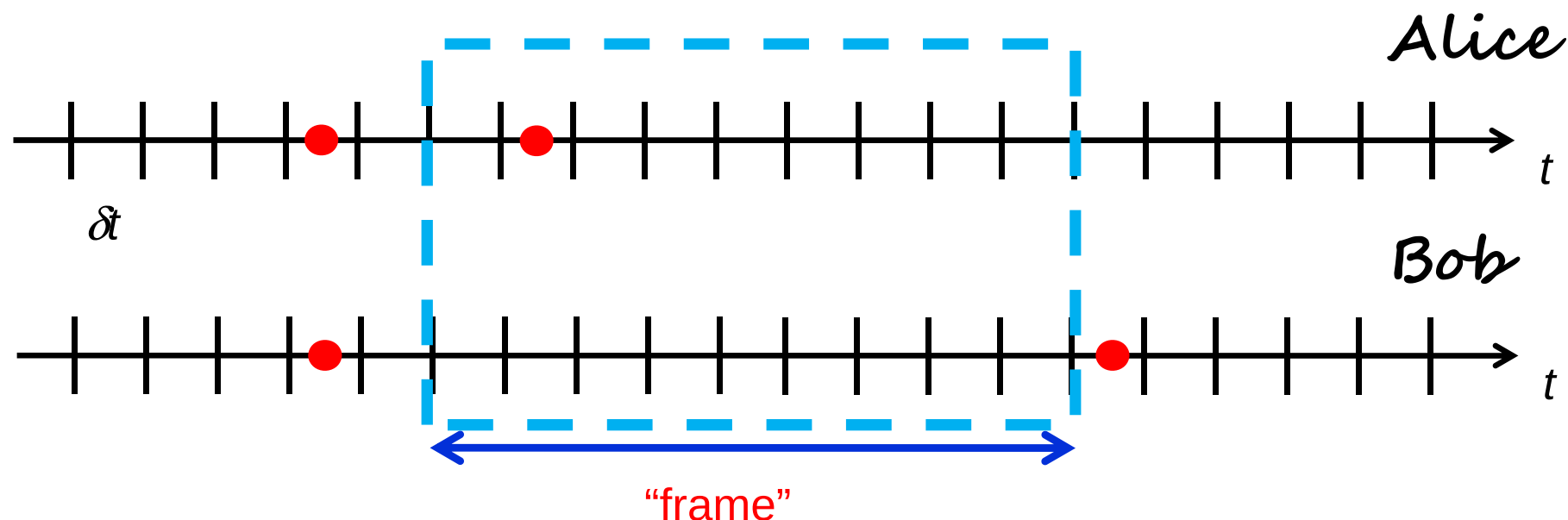
Steve Barnett
University of Strathclyde/Glasgow University

Paul Kwiat
University of Illinois, Urbana-Champaign

Daniel Gauthier
Duke University

The information per photon pair

- Number bits / photon depend on errors. Typical errors are *finite efficiency*, *channel losses*, *dark counts*, *after-pulsing*, *jitter*, etc.



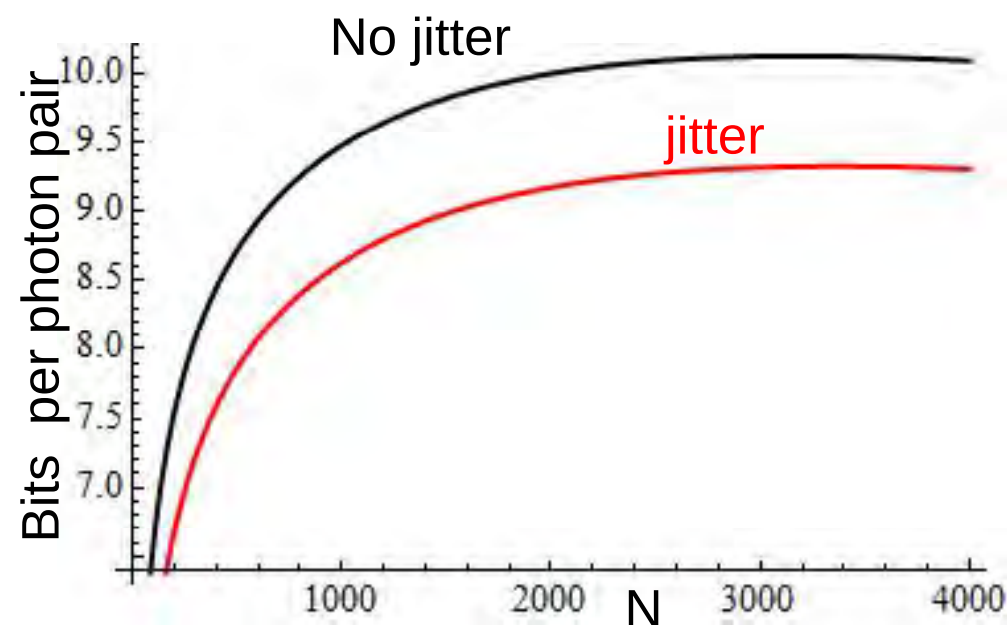
- Even with errors, we can get **>10 bits per detected photon pair^{*}**.
- InPho Breakthrough**: Developed new model, takes account of *frame-encoding*, *losses*, *dark counts*, *jitter*, *multiple photons in each frame* and *dead-time*.
- Very general, applies to other high-D QKD setups.

^{*} Brougham & Barnett, PRA **85**, 032322 (2012).

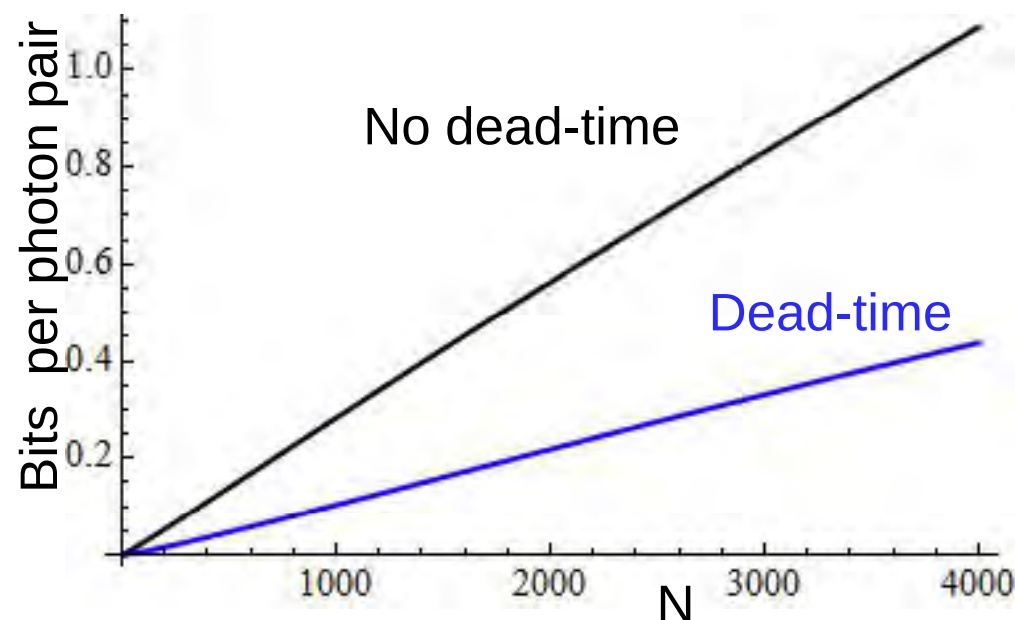
Information in frame-encoded photons

Can optimize frame size, N , in presence of realistic errors

Information in 1,1-frames



Information in 2,2-frames



$\eta = 0.3$, $\lambda = 6.0 \times 10^{-5}$, pulse interval = 1 ns,
 jitter probability = 0.1, dead-time = 1 time-bin
 dark count rate = 300/s, after-pulsing rate = 1000/s

T. Brougham, C. F. Wildfeuer, S. M. Barnett and
 D. J. Gauthier, manuscript in preparation.

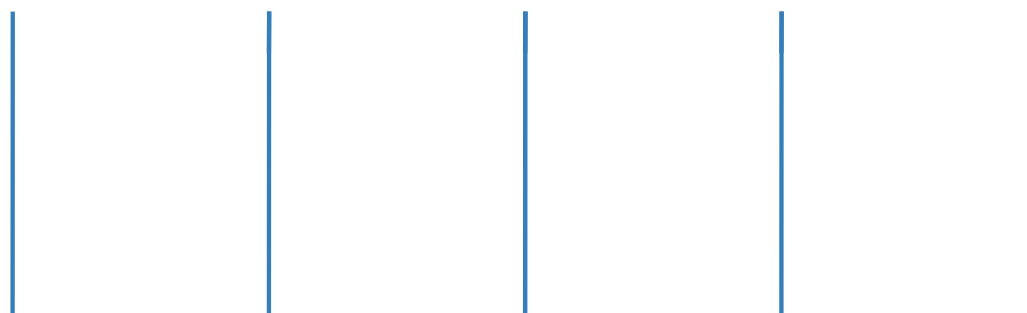
Implemented novel Slepian-Wolf-based error correction to cope with sparse data sets

A data string is generated with the QKD source

Data String

1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

The data string is broken into two data strings: an occupancy string and a letter string.



Numbers below assume 16-bin frame size, high-power data

1	0	0	1
---	---	---	---

occupancy

occupancy 50% of the Shannon-limit entropy

10% of the entropy is primarily lost due to jitter, frame edge effects, and location entropy from multi-events per frame

location

1	2
---	---

location (1:1 frames): 40% of the Shannon-limit entropy

Both occupancy and location data go into separate non-binary Slepian-Wolf codes



Slepian-Wolf codes retain ~65% of the Shannon-limit entropy for both occupancy and location

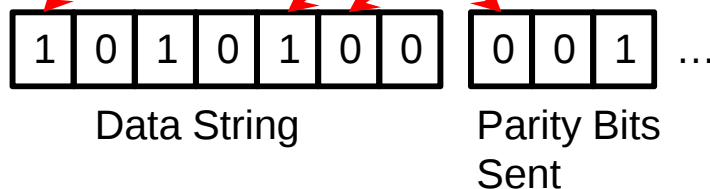
Shared sparse pseudo-random matrix to define the parity checks

$$\begin{pmatrix} 1 & 0 & 1 & . & . & . \\ 0 & 0 & 1 & . & . & . \\ 0 & 1 & 0 & . & . & . \\ 0 & 0 & 0 & . & . & . \\ 1 & 1 & 0 & . & . & . \\ 1 & 0 & 0 & . & . & . \\ 0 & 0 & 1 & . & . & . \end{pmatrix}$$

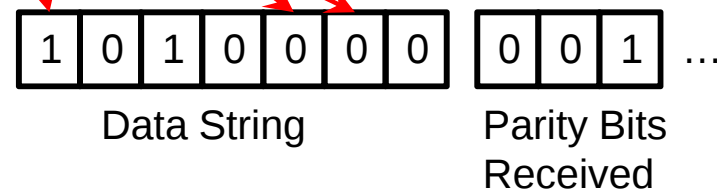
Matrices have to be generated such that the encoding system works well and does not get caught in a parity check loop (larger data sets also help to prevent this).

$$1+1+0 = 0 \text{ mod } 2$$

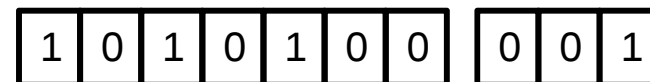
a) $1+0+0=1(\text{ERR})$
b) $1+0=1(\text{ERR})$
 $\Rightarrow$ Most likely bit 5 is flipped



ALICE



After looping over all parity checks, all the errors are corrected if enough bits are sent



BOB

Binary SW code is same, except mod(N) instead of mod(2) for the parity checks

Probabilities and jitter corrections are based upon data statistics

Alphabet of 4	...	0	...	2	...	1	...
p0	...	.40	...	.16	...	.22	...
p1	...	.28	...	.22	...	.40	...
p2	...	.16	...	.40	...	.22	...
p3	...	.16	...	.22	...	.16	...

Bit X

Bit Y

Bit Z

Jitter correction

Parity Check
A=0

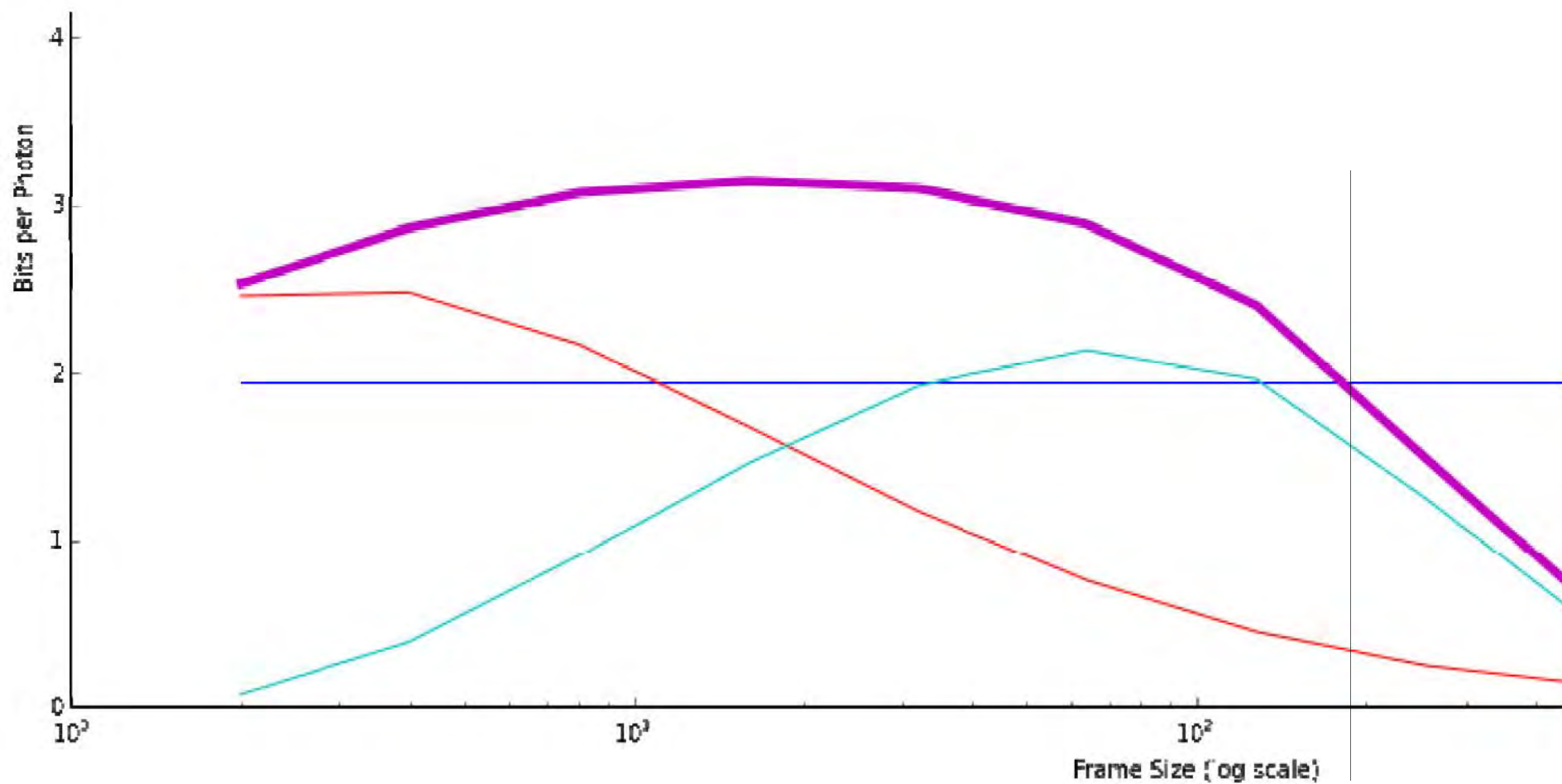
Example of Parity Check A's correction to bit X's probability of being 1

$$P(\text{Bit X is 1 given A}) = P(\text{Bits Y and Z mod 4 add up to } 4-1=3)$$

$$\begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \end{pmatrix} + \begin{pmatrix} 3 \\ 2 \\ 1 \\ 0 \end{pmatrix} \pmod{4} = \begin{pmatrix} 3 \\ 3 \\ 3 \\ 3 \end{pmatrix} \quad \text{so} \quad P(\text{X}=1|\text{A}) = \text{sum} \begin{pmatrix} p0 \\ p1 \\ p2 \\ p3 \end{pmatrix} \otimes \begin{pmatrix} p3 \\ p2 \\ p1 \\ p0 \end{pmatrix}$$

Y Z

Example “extractable” entropy



Detecting Eve and leaked information I

- **InPho breakthrough**: Bound information leaked to Eve for reasonable attacks (not QND). Standard results don't work for our setup.
- **Direct attack**: Eve measures time by making as general a POVM, with constrain that she *absorbs and possibly re-emits photons*.

- Photons in state $|\psi\rangle \propto (|HH\rangle + |VV\rangle) \otimes [|11\rangle + |22\rangle + \dots + |dd\rangle]$

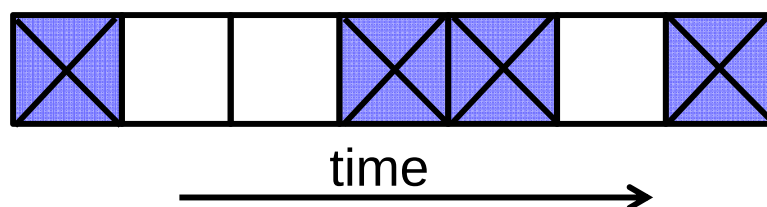
Polarization is *entangled*.

- Eve's attack must disturb polarization (as it is not a QND measurement).
- Detect Eve by checking *polarization correlation* within two mutually unbiased bases.
- Example: $\eta=0.3$, $\lambda=5.33 \times 10^{-5}$, D.C =300/s and a bit error rate of $P_E = 0.02$

$$I_{AB} = 10.3 \text{ bits / photon pair} \quad \& \quad I_{Eve} = 0.82 \text{ bits / photon pair}$$

Detecting Eve and leaked information II

- **Blocking attack**: Eve randomly blocks several, *non-contiguous*, time-bins.
- Eve knows photons not found in certain time-bins. ***This reduces her uncertainty and thus she gains information.***



- Eve can also ***partially block*** time-bins, reduces probability that photons found within those time-bins.
- **InPho breakthrough**: Developed new methods to detect ***sophisticated blocking attacks***
- Detect attacks using ***‘decoy’ pulses***.
- From detection statistics for pulses, we estimate blocked and partial blocking time-bins.
- Example: $\eta=0.3$, $\lambda=5.33 \times 10^{-5}$, D.C = 300/s and *fully* blocking $\frac{1}{2}$ of all time-bins

$$I_{AB} = 10.3 \text{ bits / photon pair} \quad \& \quad I_{Eve} = 0.74 \text{ bits / photon pair}$$

- Setup still vulnerable to QND attacks

Security against QND attacks: Franson interferometers

- Franson interferometer secure in the limit of 3-4 bits per photon (8 to 16 time-bins), PRL **112**, 120506 (2014).

- **InPho breakthrough**:- Showed **single** interferometers insecure in **high-dimensions** ~ 10 bits per photon*. Would need visibility $> 99.8\%$.

- **InPho breakthrough**:- Developed bounds for Eve's information gain for **multiple** interferometers.

- Bounds valid for collective attacks#.

* J. Phys. B **46**, 104010 (2013).

Manuscript in preparation.

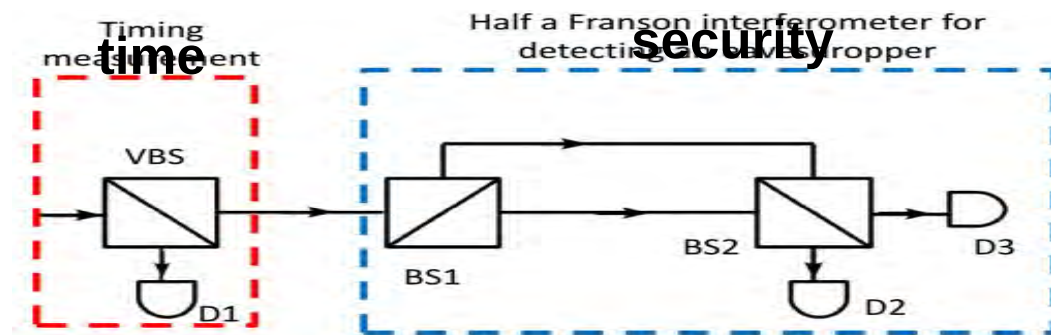
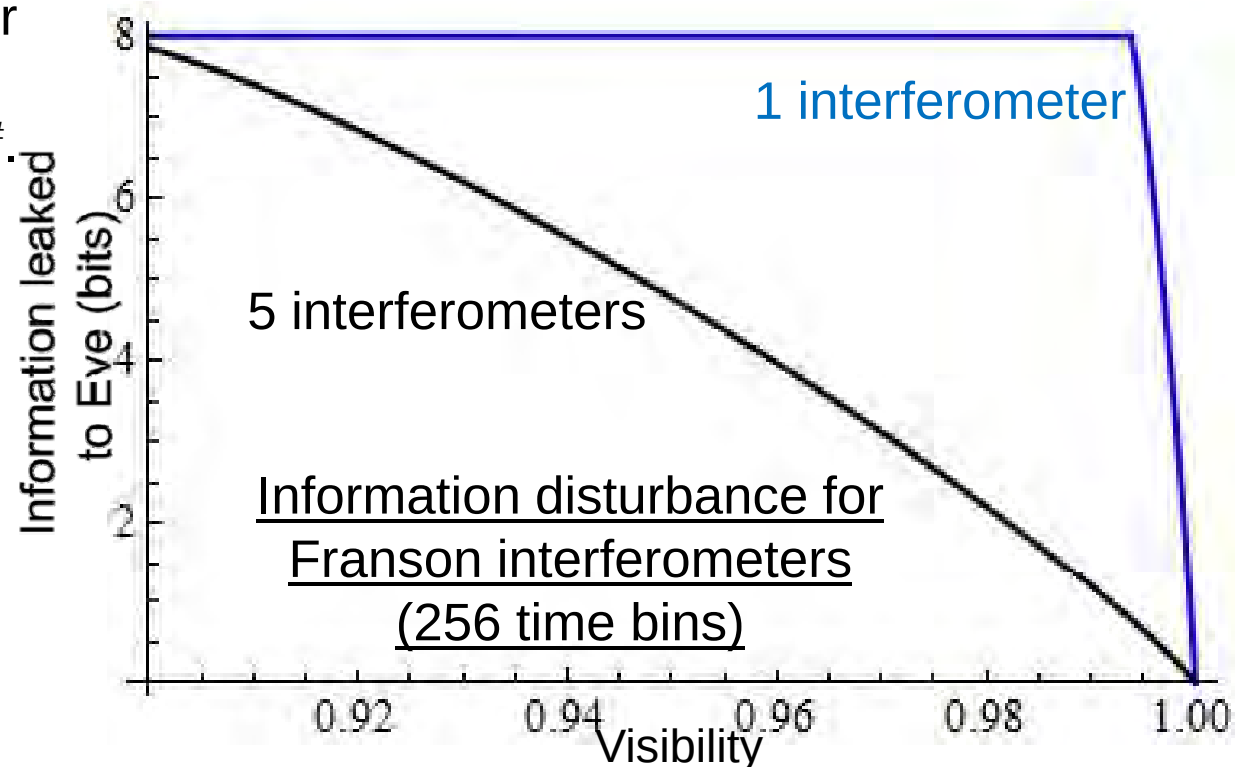


Figure 1. One half of the optical setup that Alice and Bob would each have. VBS is a variable beam splitter, while BS1 and BS2



Security against QND attacks: implementing MUBs using a cavity

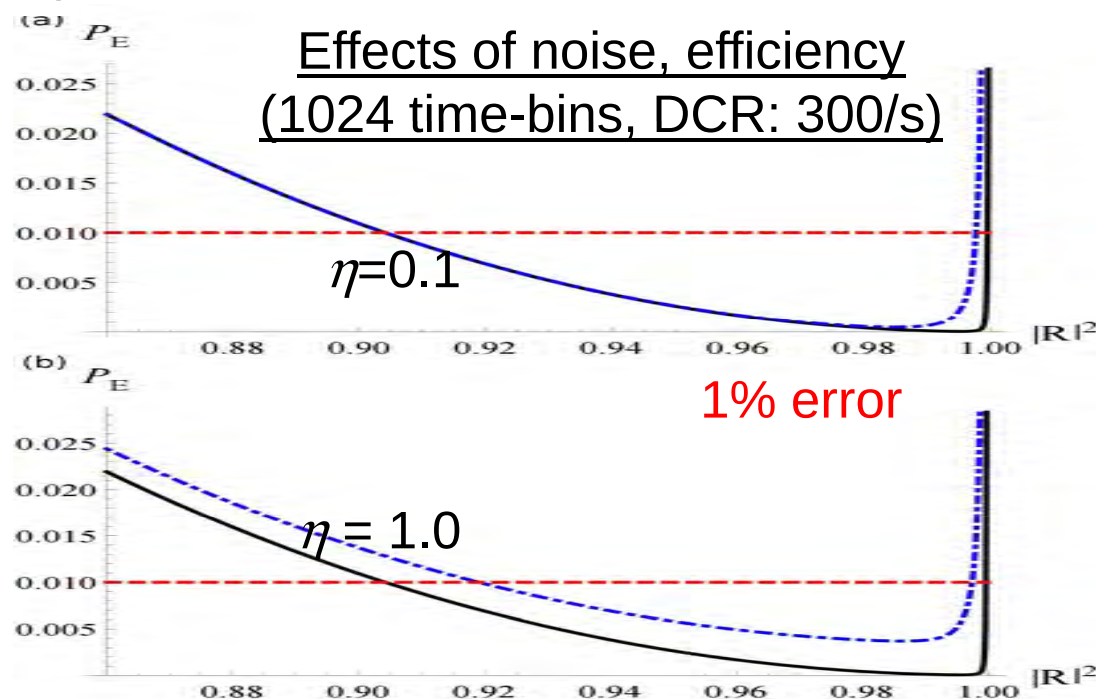
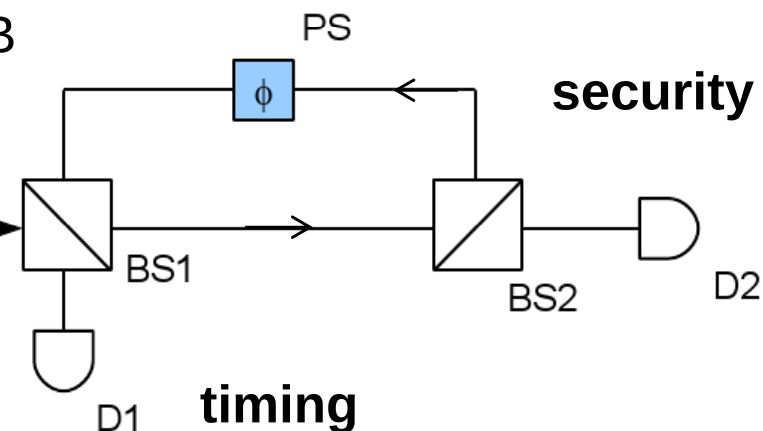
- **InPho breakthrough**:- Scheme that uses cavity to project onto **very high-dimensional** MUB states.

- Detection at D2 is projects onto the approximate MUB state

$$\sum_{m=0}^{N-1} |R_1|^m |R_2|^m e^{im(\phi+\pi)} |N-m\rangle \text{ where } R_1 \approx R_2 \approx 1$$

- Different values for ϕ correspond to different MUBs.
- Setup robust to errors for 1024 time-bins (~10 bits per photon pair).

Alice and Bob's setup



Brougham & Barnett, EPL **104**, 30003 (2013).

Brougham & Barnett, to appear in J. Phys. B

- We have developed a complete QKD system that operates at a
- record rate (on a table top)
 - record efficiency
 - encodes information in photon arrival time and polarization
 - partial security obtained by checking polarization (assumes no QND attack possible that does not disturb polarization)
 - a single channel operates at a “secure” rate over 10 Mbit/s
 - multiplex many spatial and spectral channels to achieve 1 Gbit/s rate
 - achieve > 4 bits/detected photon pair at high rate
 - achieve > 8 bits/detected photon pair at low rate (maintain coherence in a very high dimension Hilbert space!)
 - developed a wide range of new quantum technologies that will have an impact beyond this immediate project