From Dark to Light

how looking for dark
matter led to photonic
tests of local realism

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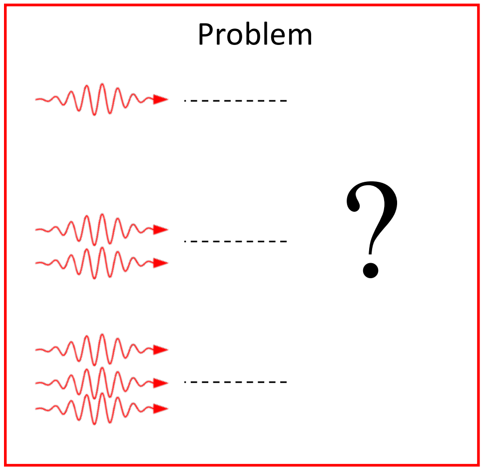
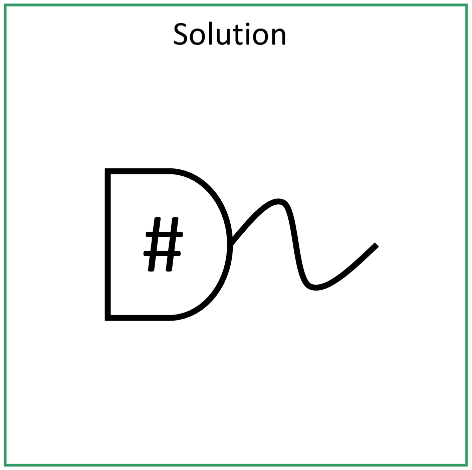
~late 1990's early 2000's





Faint Photonics

Sae Woo Nam
(Richard Mirin)
NIST
Boulder, CO

- NIST
  - Faint Photonics and Quantum Nanophotonics
- Components
  - Detectors
  - Sources
  - Characterization
- Quantum Metrology
  - Standard Quantum Limit / Heisenberg Limit

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- UIUC
- Univ. Waterloo
- MIT, MIT-LL
- BBN
- Dule

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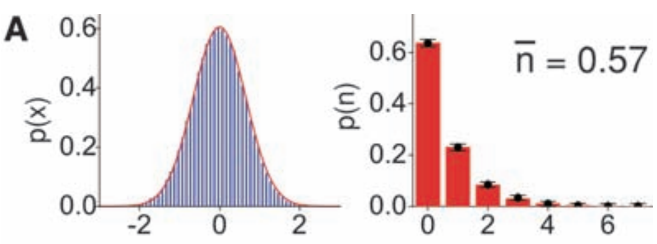
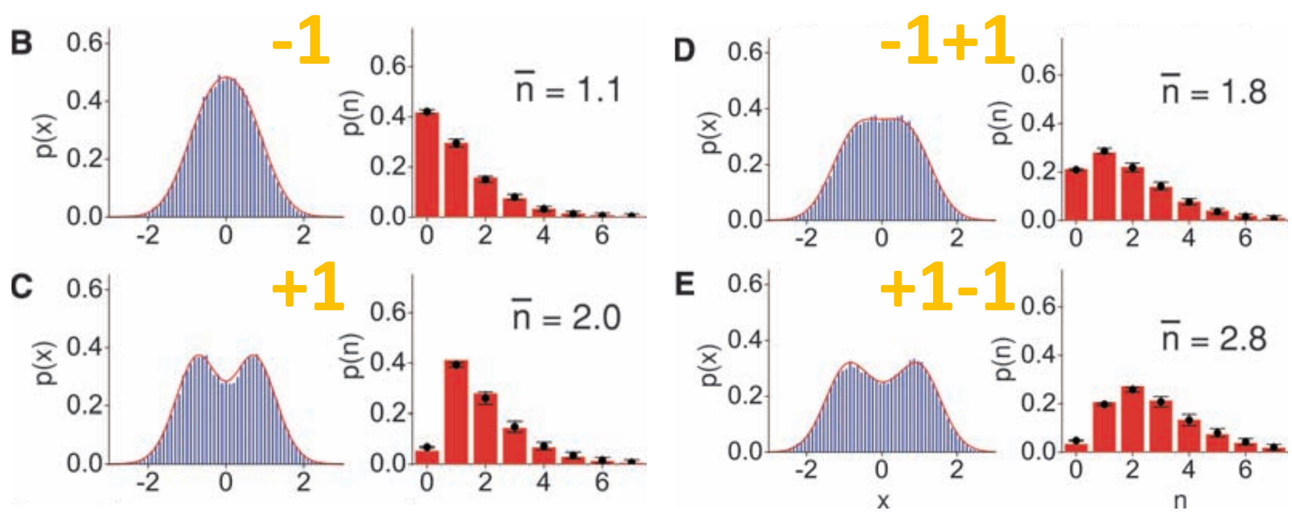
NIST mission, values, competencies

- **NIST's mission:**
  - To promote U.S. innovation and industrial competitiveness by **advancing measurement science, standards, and technology** in ways that enhance economic security and improve our quality of life.
- **NIST's vision:**
  - NIST will be the world's leader in creating critical measurement solutions and promoting equitable standards. Our efforts stimulate innovation, foster industrial competitiveness, and improve the quality of life.
- **NIST's core competencies:**
  - Measurement science, good at measuring quanta (ions, atoms, electrons, photons)
  - Rigorous traceability
  - Development and use of standards

Probing Quantum Commutation Rules by Addition and Subtraction of Single Photons to/from a Light Field

Valentina Parigi,[1] Alessandro Zavatta,[2] Myungshik Kim,[3] Marco Bellini[1,4]*





Nature is confusing

Can we take advantage of this?

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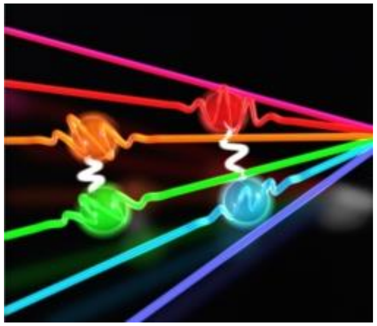
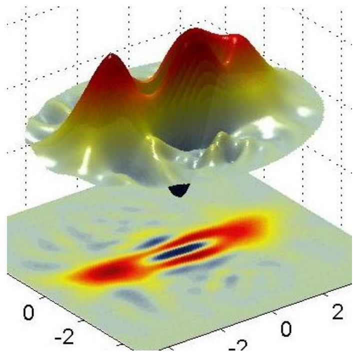
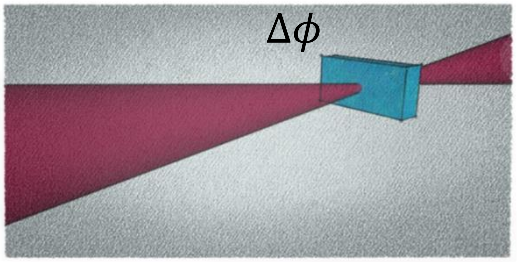
SCIENCE, vol 317, 28 SEPTEMBER 2007

Faint Photonics and Quantum Nanophotonics group:



- Generation and manipulation of quantum states of light (non-classical)
- Characterization of light
- Demonstration in novel imaging and metrology applications

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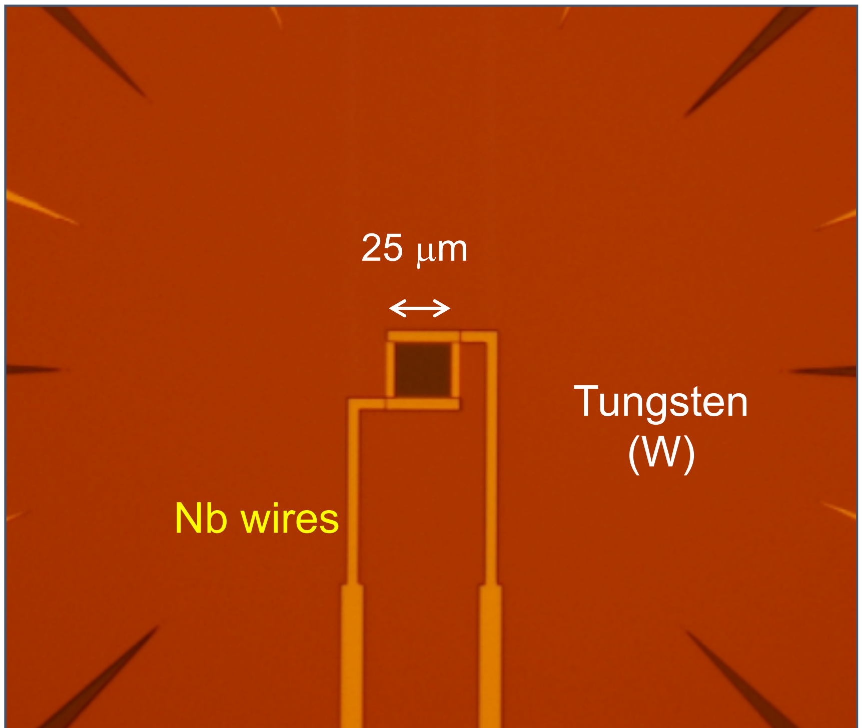
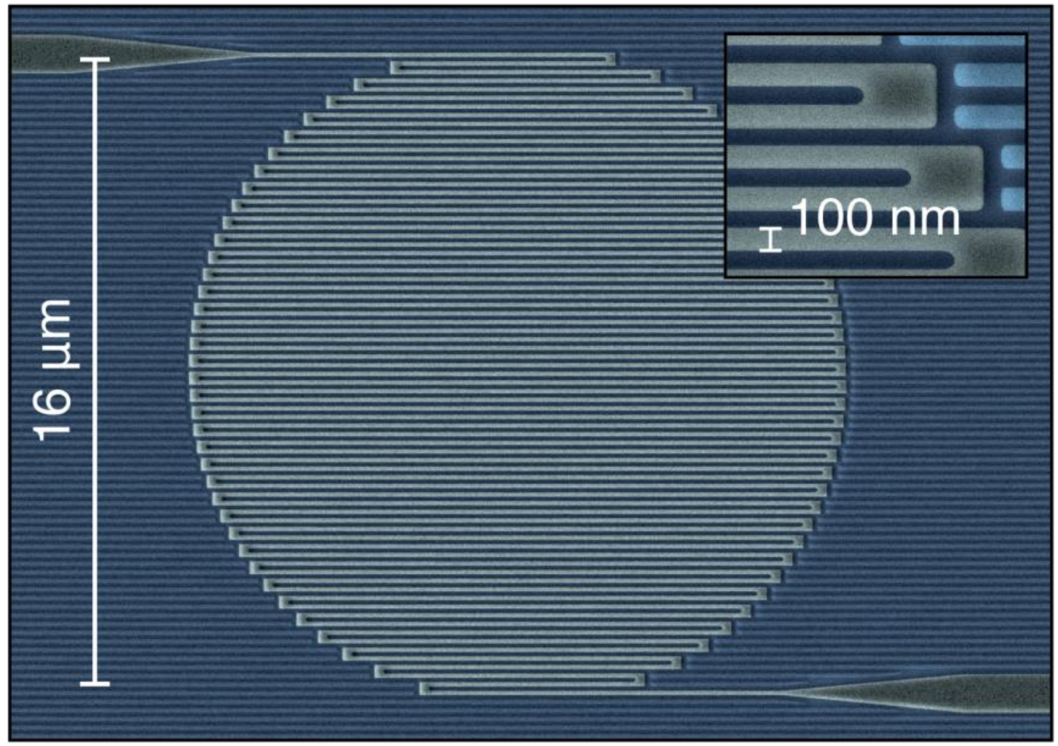
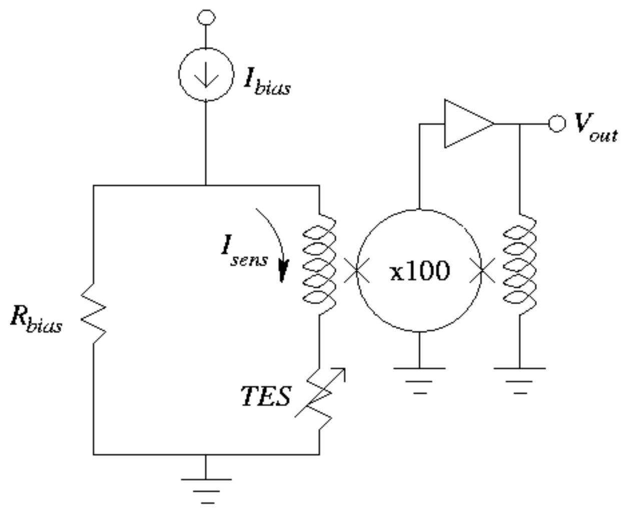
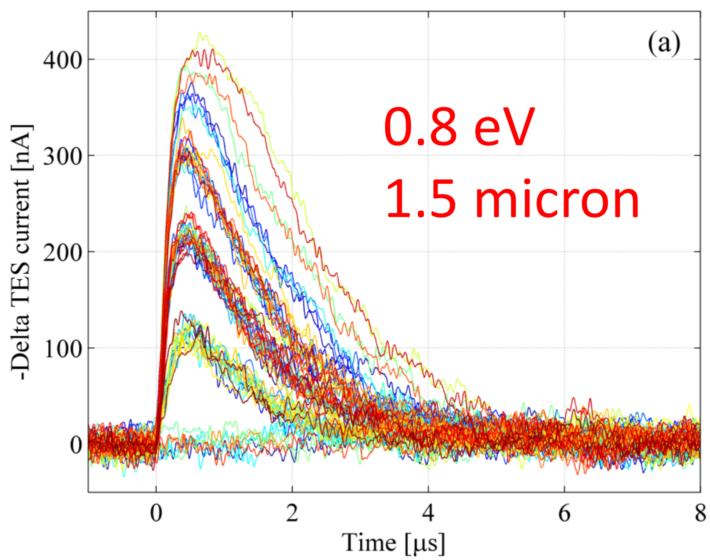
Superconducting Detectors: TES and SNSPD





TES Signal





- Device is voltage biased
- Current through device is pre-amplified using a cryogenic SQUID array amplifier

- Absorption events show good distinguishability
- Much slower than APDs

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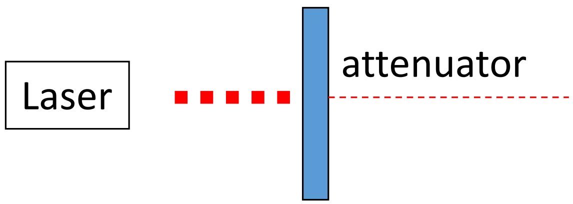
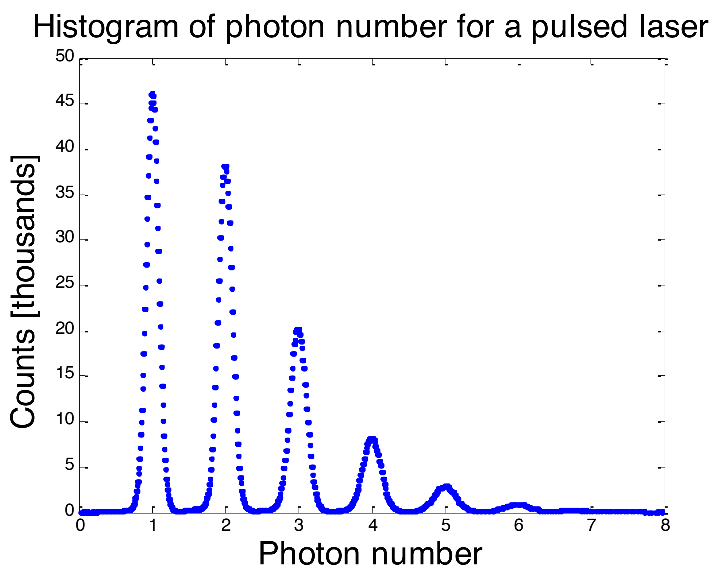
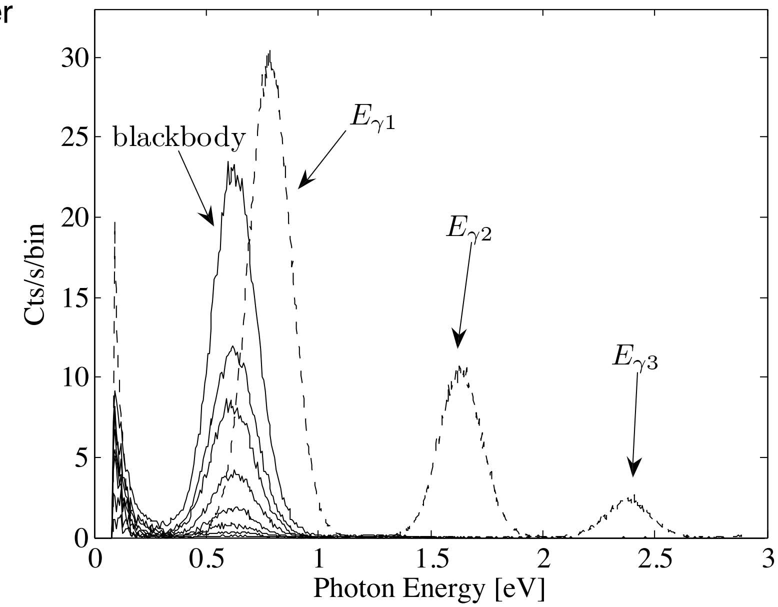
Photon Statistics



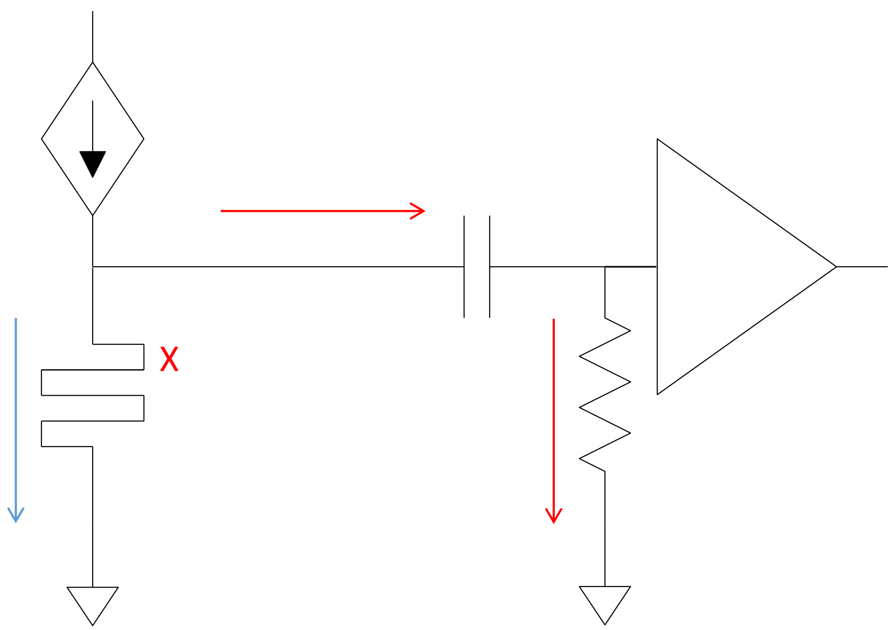
$$P(n) = \frac{\mu^n}{n!} e^{-\mu}$$

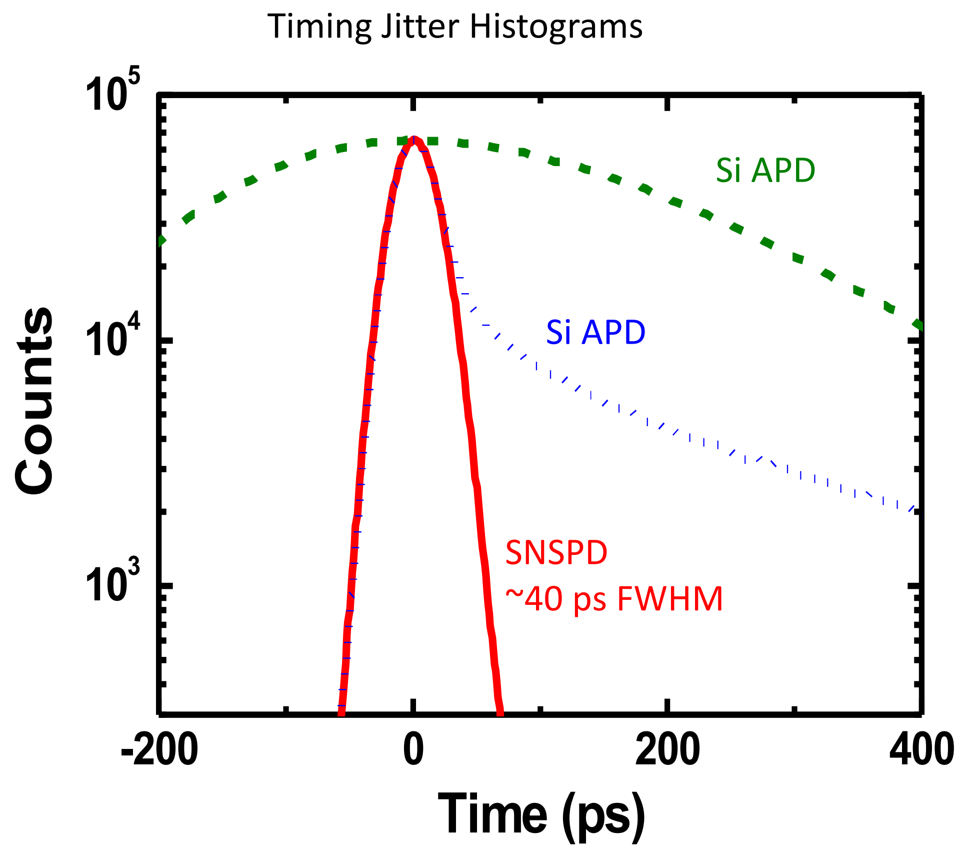
$$|\alpha\rangle$$





SNSPD: Superconducting Nanowire Single-Photon Detector





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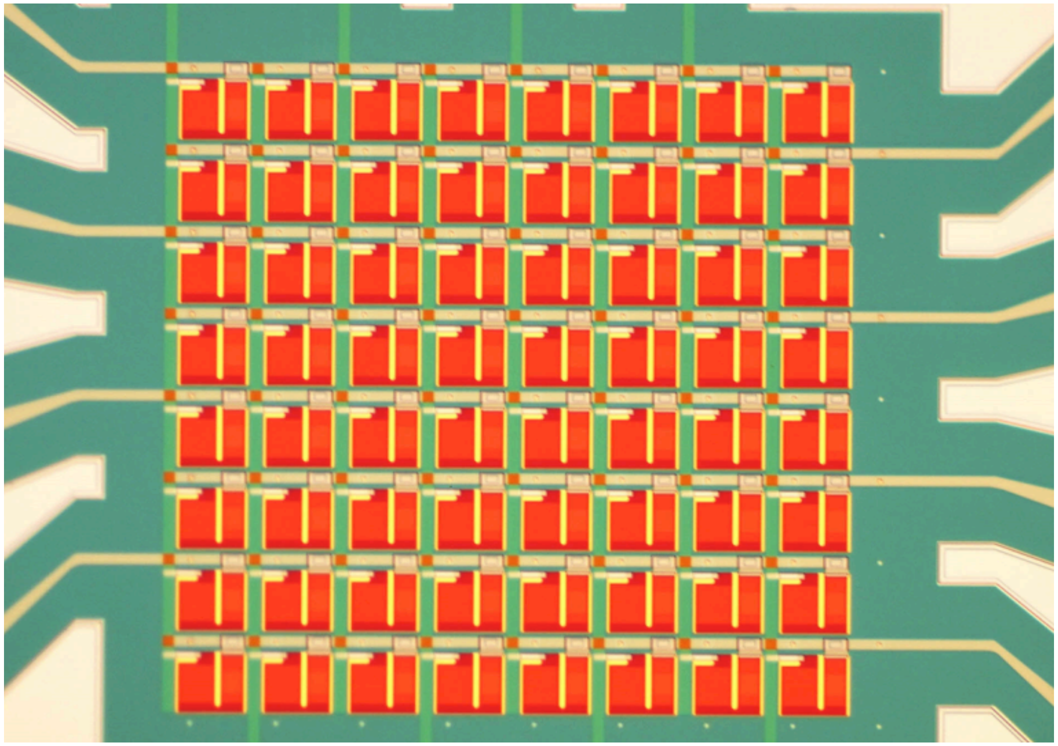
Real-time single-photon imaging



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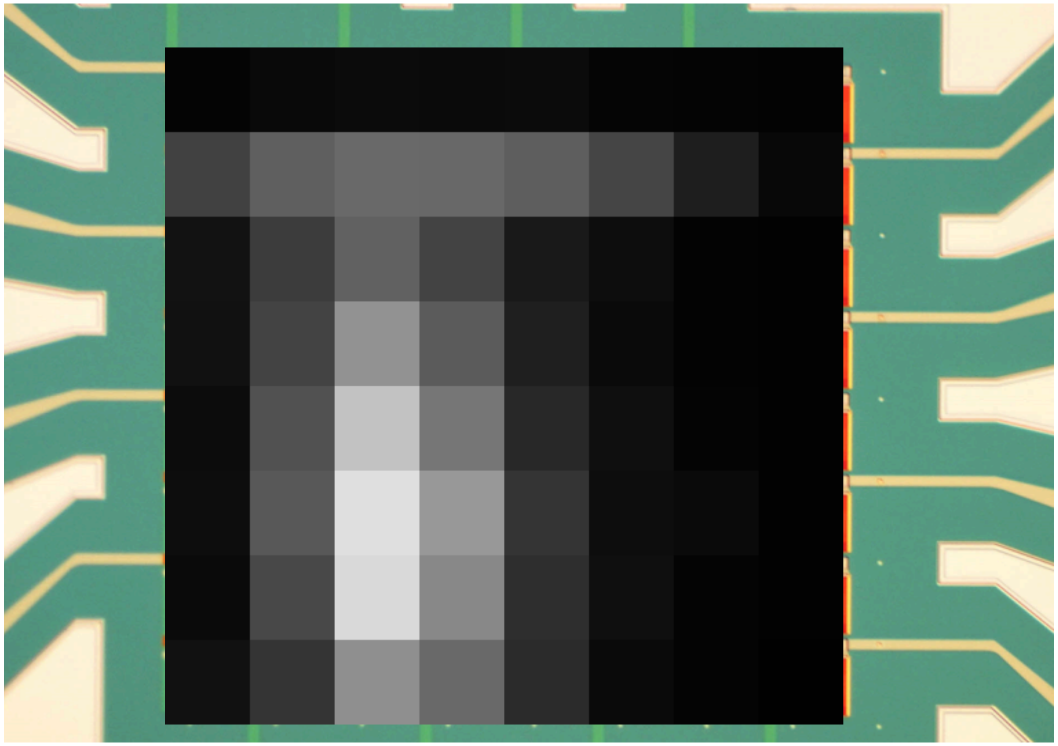
Real-time single-photon imaging



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Single-Photon Detectors

- Key metrics:
  - Wavelength range   (10 microns to 100nm)
  - Device quantum efficiency /system detection efficiency (>90%)
  - Dark count rate (none)
  - Maximum count rate (100Mhz unclocked, 625Mbps clocked)
  - Timing jitter (<10ps – SNSPD, ~10ns TES)
  - Arrays (100's)
- Other considerations:
  - Size
  - Operating temperature
  - Photon-number resolution / Energy

Quantum States of Light

- Lots of options
- Lasers
- Squeezed Light
- Atoms / Ions
- Artificial Atoms: Quantum Dots, Defects in Diamond, Silicon Carbide
- Four-wave mixing, Spontaneous Parametric Downconversion
- Photon Subtraction / Addition

Nonlinear Quantum Optics

Four-wave mixing

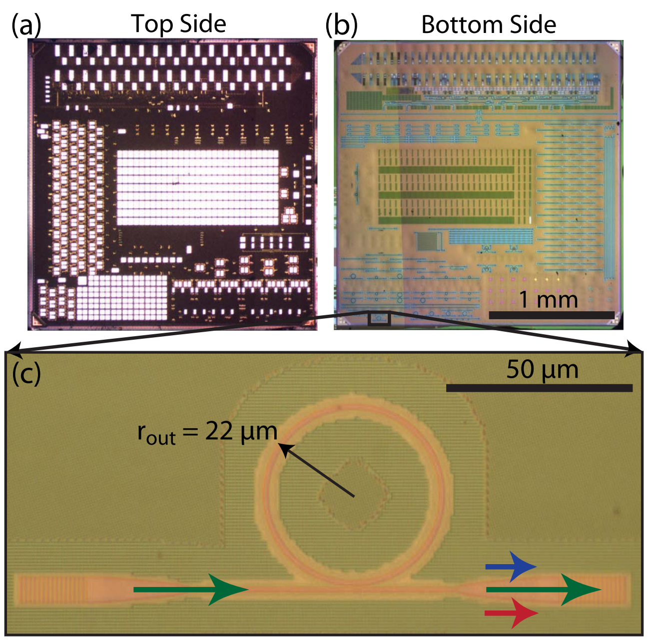
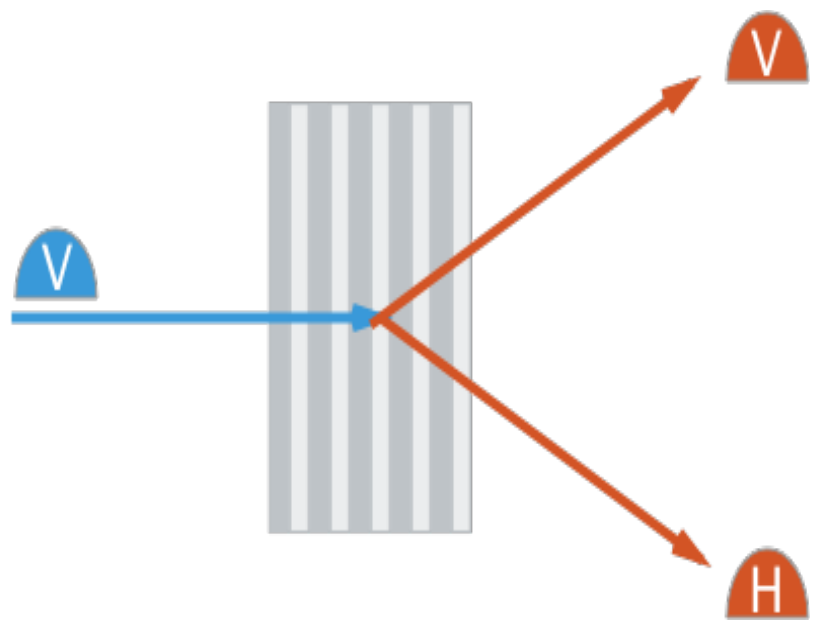


Fig. 1. Optical micrograph of the (a) top and (b) bottom of the CMOS chip with (c) zoom-in of the ring resonator pair source and grating couplers.

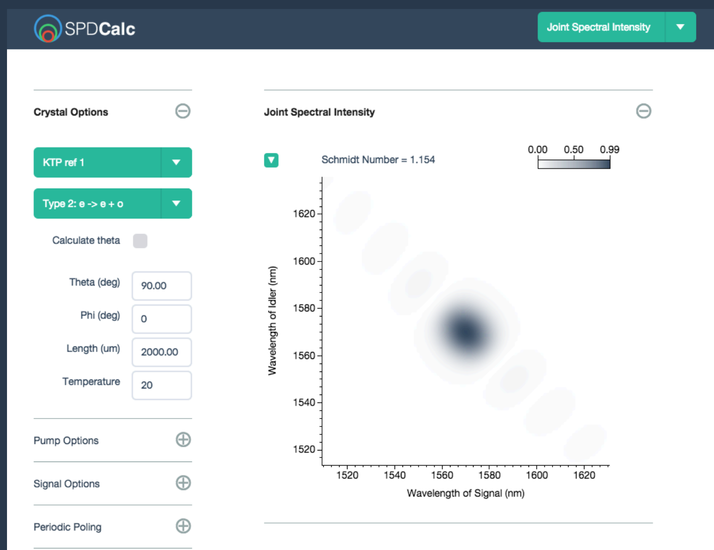
Spontaneous Parametric Downconversion



Krister Shalm

SPDCalc www.spdcalc.org

Web app for designing photon pair sources



Handles / Calculates:

χ^2

Phasematching

Periodic Poling

Noncollinear geometries

Fiber coupling

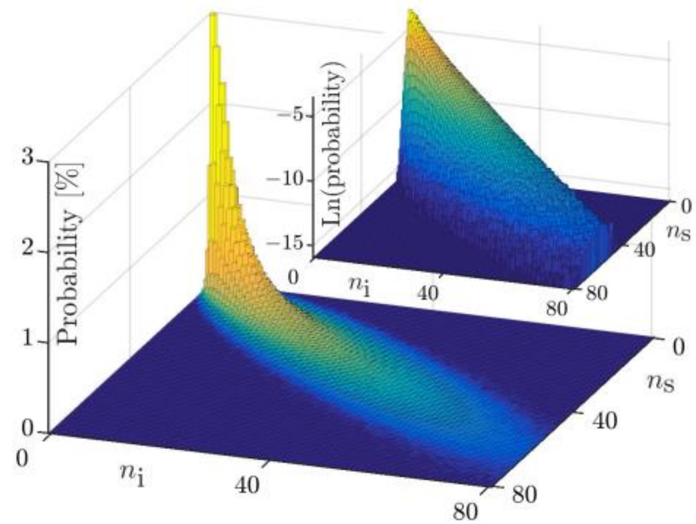
Heralding efficiency

Spectral Purity

2 and 4 photon Hong-Ou-Mandel

Development led by NIST-Boulder with contributions from experts from around the world

Single-Mode Parametric-Down-Conversion States with 50 Photons as a Source for Mesoscopic Quantum Optics



G. Harder et al., PRL 116, 143601 (2016)

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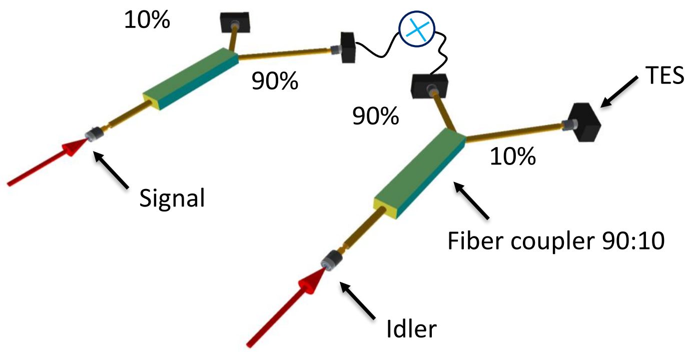
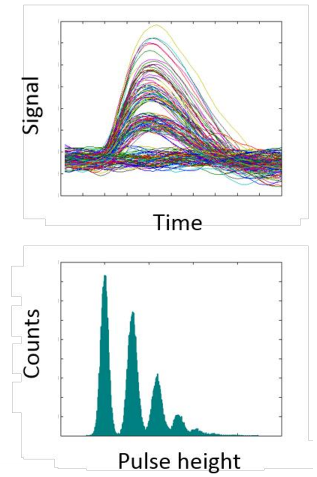
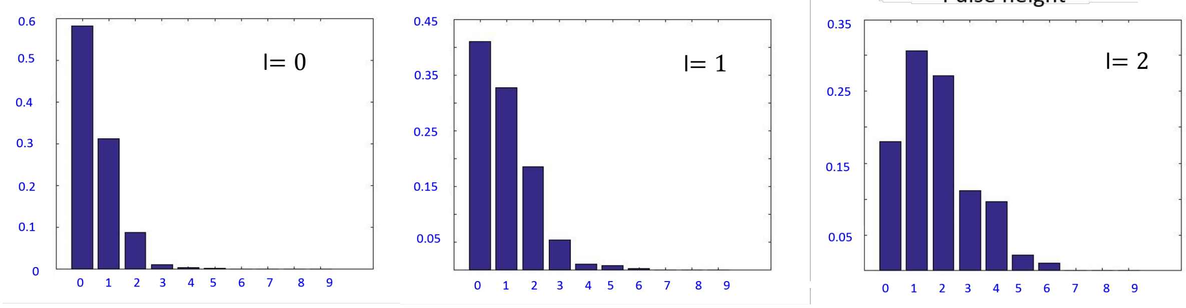
EXPERIMENTAL GENERATION OF ENTANGLED PHOTON-SUBTRACTED STATES

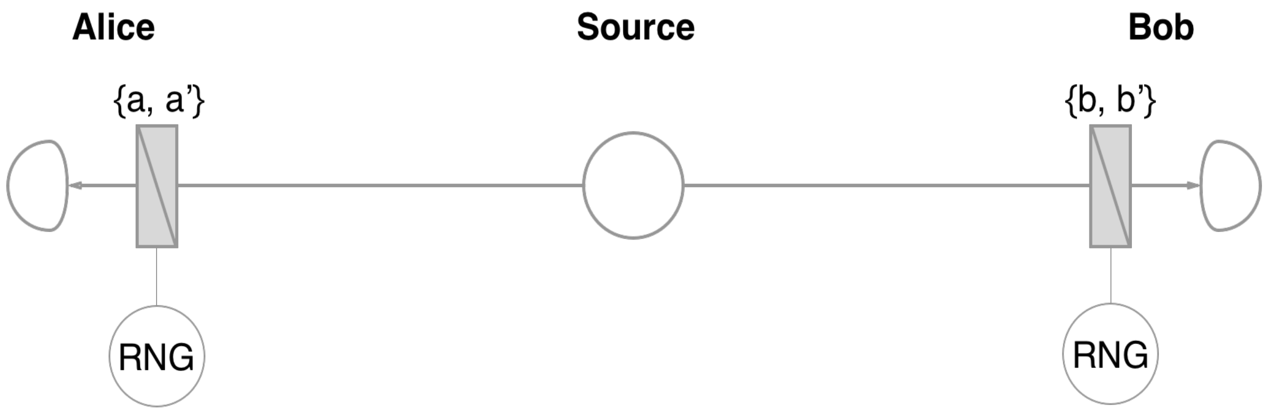




Experimental results (one arm)



Loophole-free Bell Tests



B. Hensen *et al.*, "Loophole-free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres," **Nature 526, 682 (2015).**

M. Giustina *et al.*, "Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons," **Phys. Rev. Lett. 115, 250401 (2015).**

L. K. Shalm *et al.*, "Strong Loophole-Free Test of Local Realism," **Phys. Rev. Lett. 115, 250402 (2015).**

PRL, December 18th 2015 cover

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As I have said so many times, God doesn't play dice with the world.

–Albert Einstein

(1943)

God’s Dice / Random number beacon

http://beacon.nist.gov

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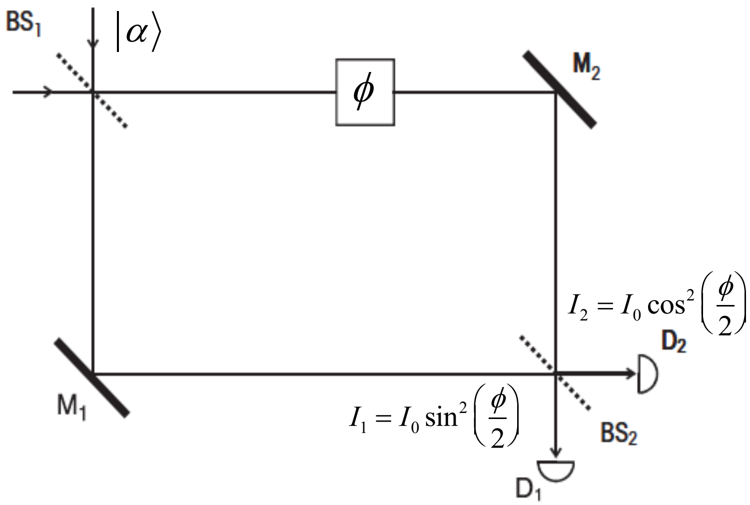
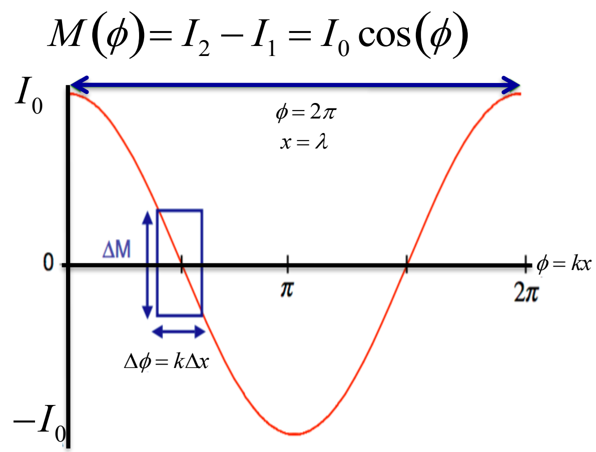
"Standard Quantum Limit"





J. P. Dowling, Contemp. Phys. 49, 125-143 (2008)

$$\Delta\phi = \frac{\Delta M}{\partial M / \partial\phi} = \frac{\Delta M}{I_0 \sin(\phi)}$$

$$\Delta\phi_{SNL} \propto \frac{1}{\sqrt{I_0}}$$

”Heisenberg” limit

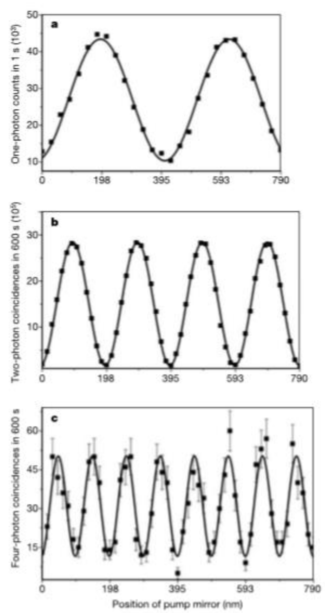
De Broglie wavelength of a non-local four-photon state

Philip Walther[1], Jian-Wei Pan[1]*, Markus Aspelmeyer[1], Rupert Ursin[1], Sara Gasparoni[1] & Anton Zeilinger[1,2]

nature (2004)

Super-resolving phase measurements with a multiphoton entangled state

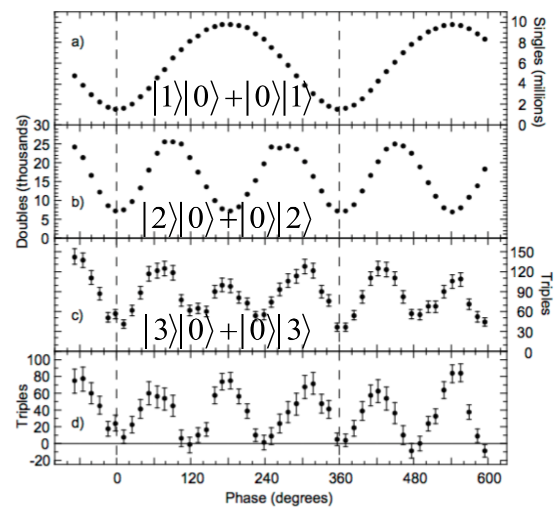
M. W. Mitchell, J. S. Lundeen & A. M. Steinberg



$|1\rangle|0\rangle+|0\rangle|1\rangle$

$|2\rangle|0\rangle+|0\rangle|2\rangle$

$|4\rangle|0\rangle+|0\rangle|4\rangle$

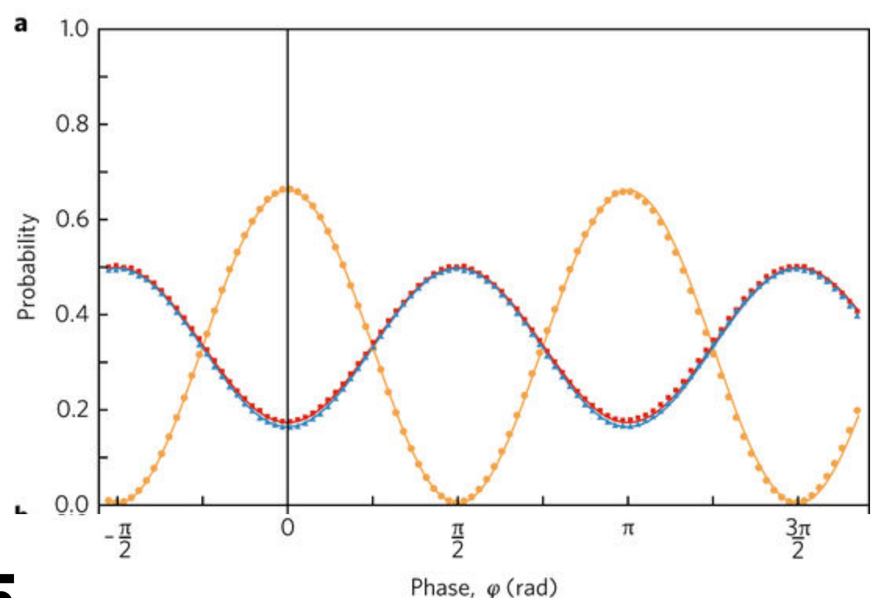


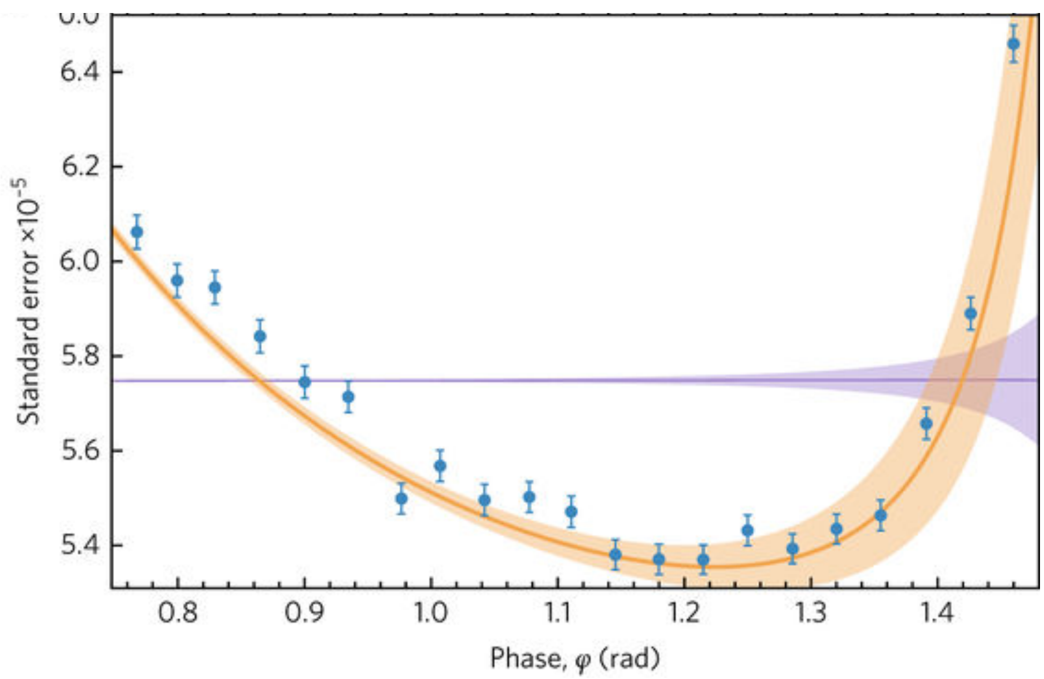
J. Xiong, et al., Experimental Observation of Classical Subwavelength Interference with a Pseudothermal Light Source, Physical Review Letters, **94**, 173601 (2005).

Unconditional violation of the shot-noise limit in photonic quantum metrology

Sergei Slussarenko[1], Morgan M. Weston[1], Helen M. Chrzanowski[1,2], Lynden K. Shalm[3], Varun B. Verma[3], Sae Woo Nam[3] and Geoff J. Pryde[1*]

Nature Photonics **11**, 700–703 (2017)





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Quantum Advantage with Photonic States ???

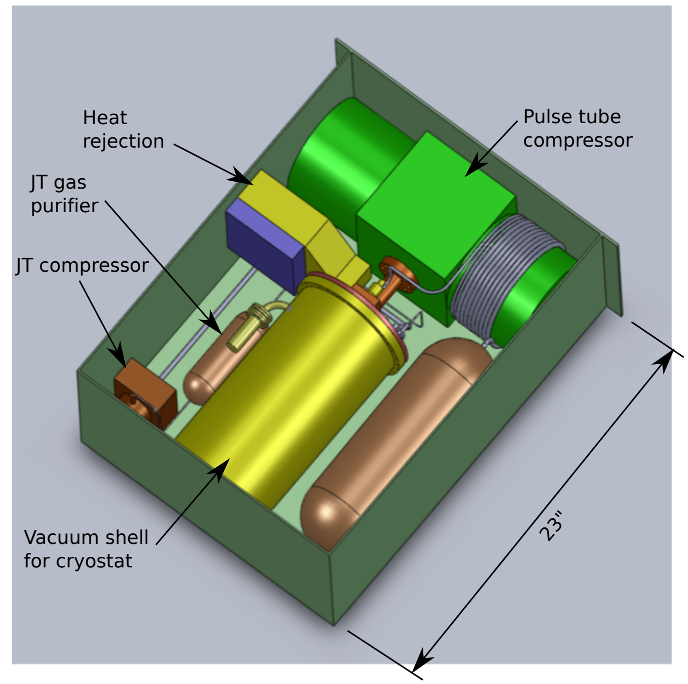
- Very challenging for Quantum Metrology
- Quantum states of light are fragile (loss)
- Photons don't interact with each other (usually)
- Light Matter interactions are important… Future relies on this
- Routing / coupling of light efficiently remains a challenge

Future / Partnerships?

- Superconducting detectors for ”optical” photon are unmatched in performance
  - How do we scale to Megapixel and beyond?
  - Infrastructure needs to be addressed:
    - Supply of people
    - SWaP: packaging
  - Addressing needs / finding a match

“Invisible Cryogenics”

- 6U high, 2ft deep
- <300 Watts
- <100 lbs
- <2.5K (He4), <1.5K (He3)
- Sufficient to run at many nanowire detectors
- 30 Hz compressor
- Funded by LTS, DARPA, Quantum Opus



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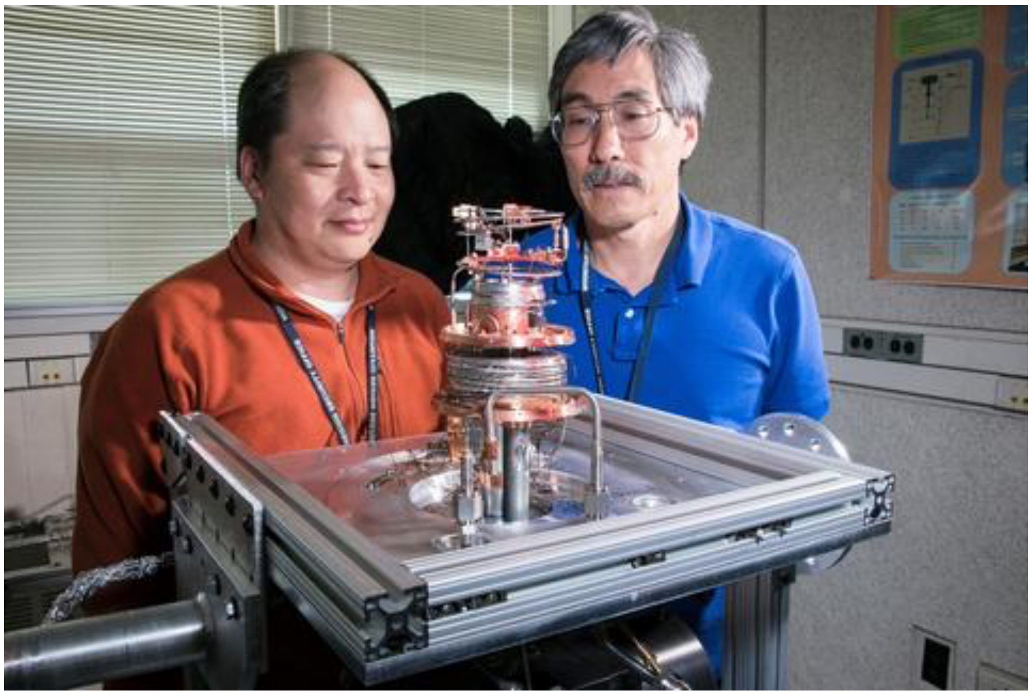
Dilution Refrigerator on your desk… I think so.

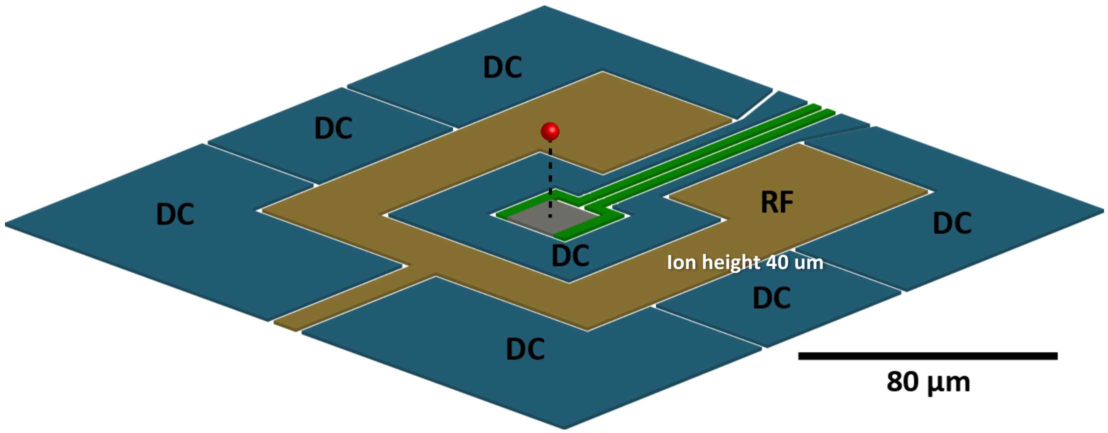


- How far can we push the technology?
- Mechanical Engineering
- Cryogenic Engineering
- Reliability Engineering

Outlook

- Photonics will always be a part of Quantum Communications / Cryptography
- The potential of quantum based protocols is unprecedented
- Requires development of techniques and technology of unprecedented precision and accuracy (will need NIST to verify)
- Requires integration of work from a variety of mathematical, science, and engineering disciplines

Ion Traps + SNSPDs in the UV

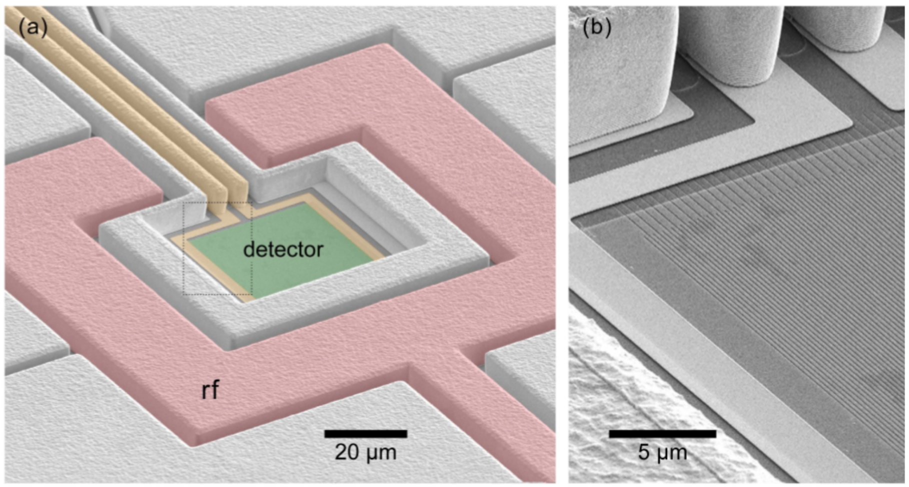


Collaboration with D. Wineland's group to develop integrated ion traps and detectors

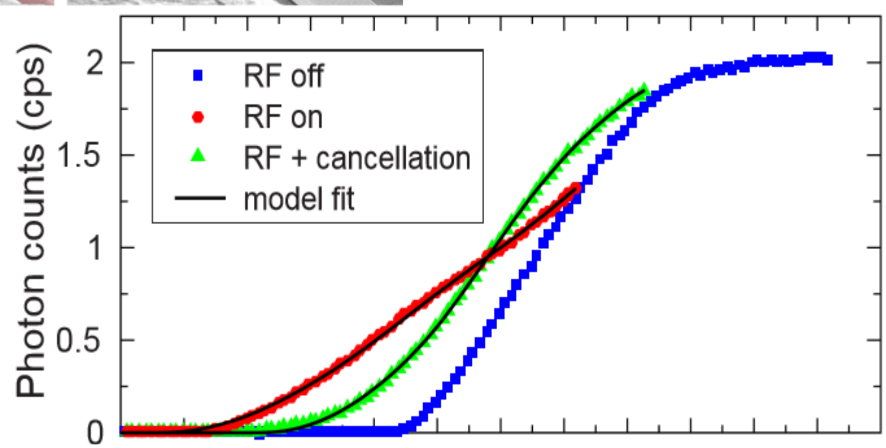
313nm
Detector: 1.1% of solid angle (0.8% of light)
RF amplitude: 0.5-3 V @ 30 MHz
DC: +/- 10 VDC max

D. H. Slichter, Opt. Express 25, 8705-8720 (2017)

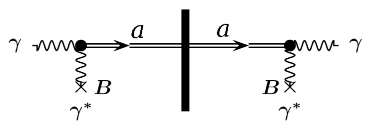
Ion trap integration with SNSPD



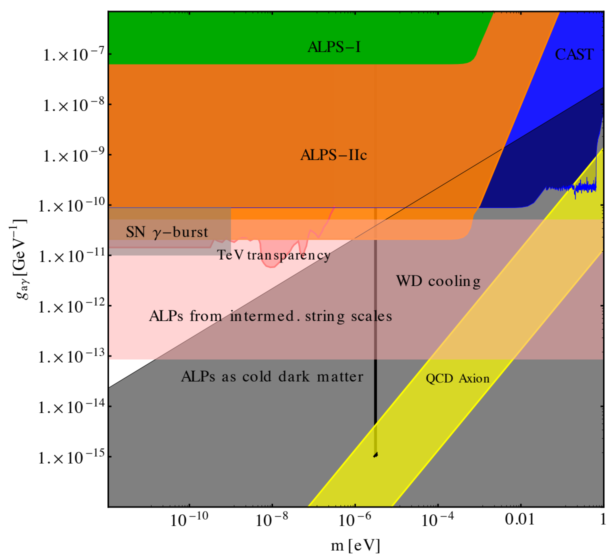
D. H. Slichter, Opt. Express 25, 8705-8720 (2017)



Any Light Particle Search (ALPS) at DESY – Light-Shining-through-a-Wall?

ALPS-I: $\gamma_{\text{in}} \sim 10^{21}\,1/\text{s}$  $\gamma_{\text{meas}} = (2 \pm \mathbf{13}) \times 10^{-3}\,1/\text{s}$

K. Ehret, et al., Physics Letters B 689 (2010) 149



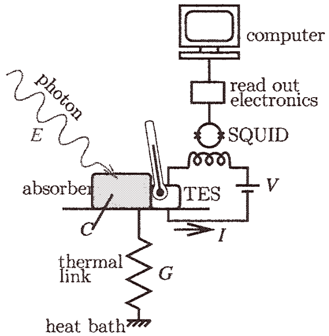
Axion-like particle specs:

- sub-eV mass, weakly interacting with SM
- could explain:
  - TeV transparency (Horns group, UHH)
  - CDM candidate
  - ...
- $g_{a\gamma} < \frac{1}{BL}\sqrt[4]{\frac{\gamma_{\text{out}}}{\gamma_{\text{in}} \times \epsilon}}\frac{1}{F(\dots)}$

Setting up a TES detector for ALPS

Very brief history

- 2011: gaining experience (Trieste, Camerino, Berlin, . . .) and connecting to small TES-community
- 2012: 30 mK in ALPS-IIa lab, DESY
- 2013: 1064 nm single photons and more. . .



TES detector for ALPS:

- **Sensor:** high-efficient fiber-coupled TES from NIST
- **Read-out:** low-noise SQUIDs from PTB
- **mK-cryogenis:** cryostat from Entropy GmbH

NIST

PTB

ENTROPY