Quantum Mechanics

in Measurement, Control and Computation

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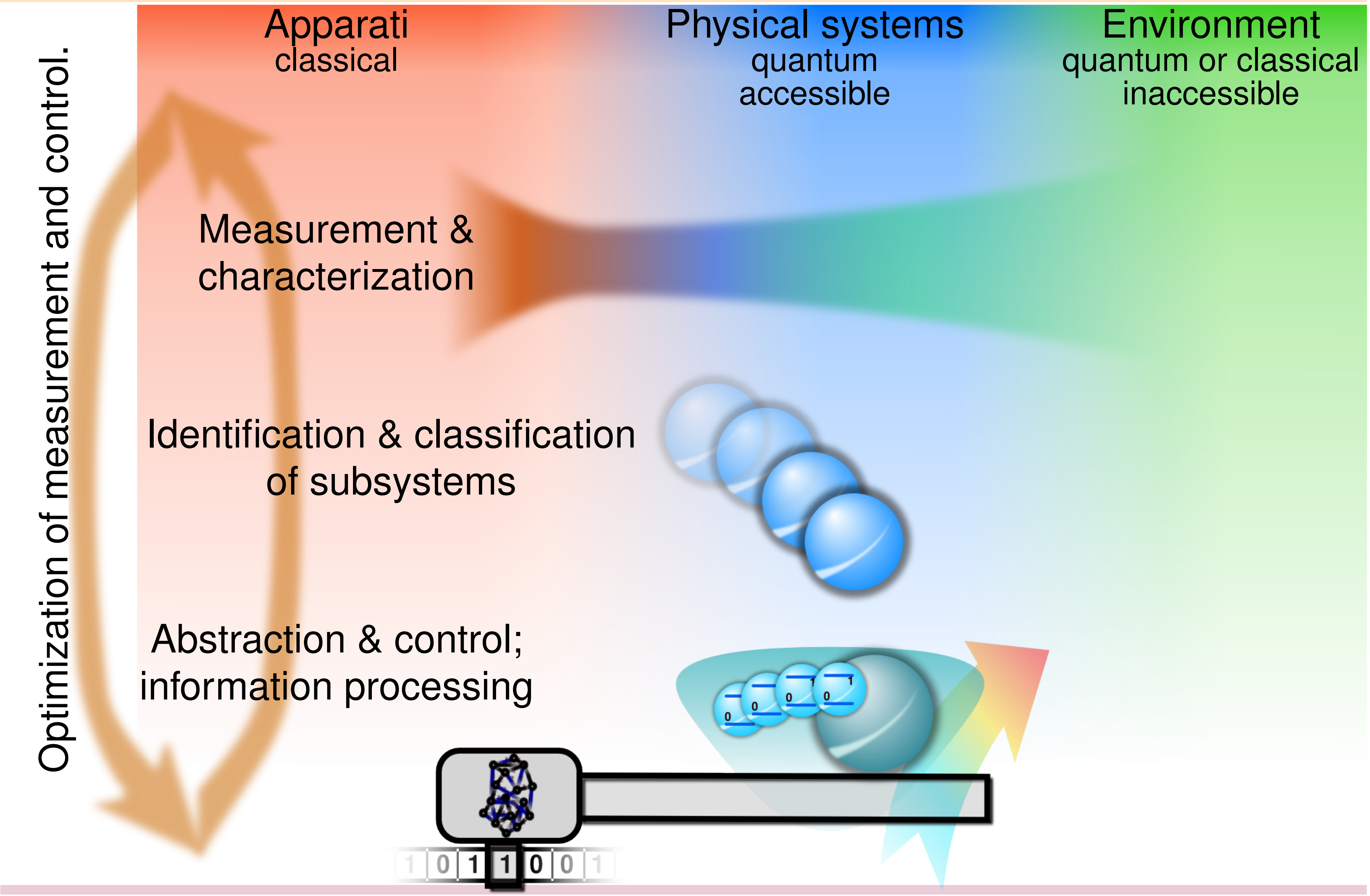
- The quantum information perspective.
- Quantum systems everywhere:
  Simple, composite, emergent.
- Surprises and highlights.

> Quantum phenomena that were once thought to limit measurement capabilities are now being harnessed to enhance them...
> H. Batelaan, A. Tonomura, *Physics Today*, Sept. 2009

E. "Manny" Knill: knill@boulder.nist.gov

Quantum Information Perspective



A QI View of Research Areas

- Requires quantum physics to develop and understand.
  Ex: Apps. of neutron interference, superconductivity.

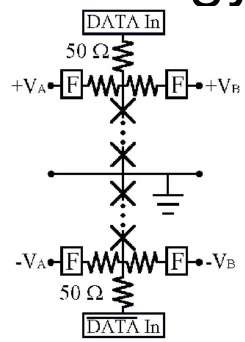
- Involves quantum control of one system.
  Ex: Spectroscopy. Nuclear magnetic resonance.

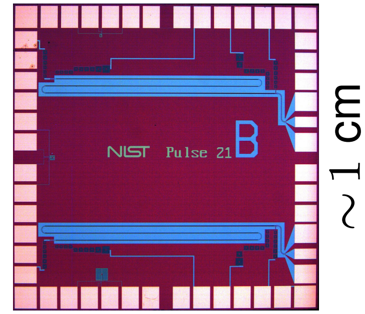
- Uses QI concepts for motivation or implementation.
  Ex: Photon pair sources.

- Aims for universal quantum control of many systems.
  Ex: Ion, j.j, . . . , photonic quantum computing.

Quantum Physics Required

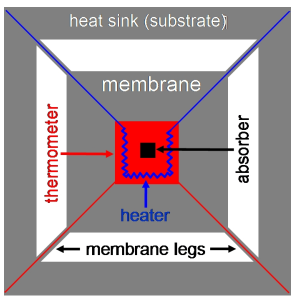
- Quantum-based electrical metrology. NIST-EEEL [1, 2, 3, 4]
  - Johnson noise thermometry, q. metrological triangle.

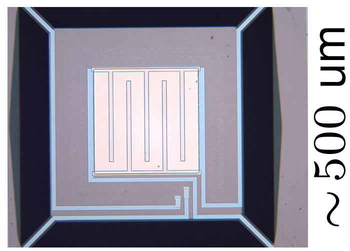




S. Benz, NIST-PL

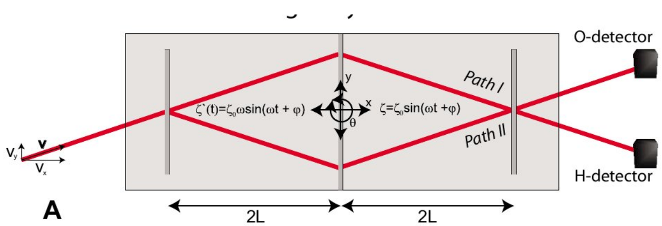
- Phase-transition-based measurements. NIST-EEEL [5, 6]
  - Quantum candela, transition edge sensors, photon counters.





S. W. Nam, NIST-EEEL

- Neutron scattering and interference to probe matter. NIST-NCNR [7]
  - Decoherence-free neutron interferometry.



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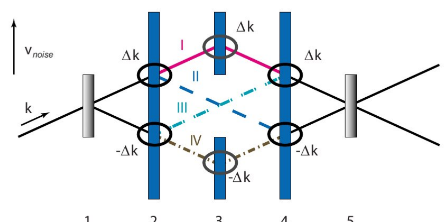
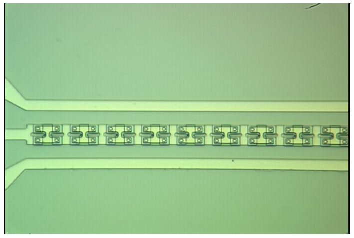


D. Pushin, M. Arif, D. Cory, NIST-PL, MIT

Based on Simple Quantum Control

- Sub-quantum limited parametric amplification. NIST-EEEL,-PL(JILA)
  - Josephson-junction microwave amplifiers. [8, 9]



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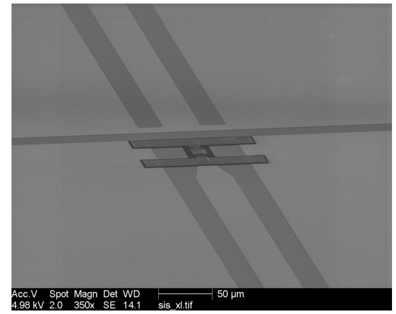
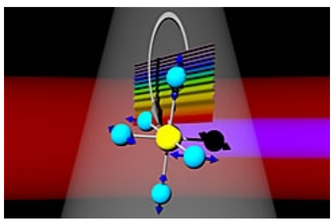
K. Lehnert, M. Castellanos-Beltran, C. Regal, NIST-PL(JILA)

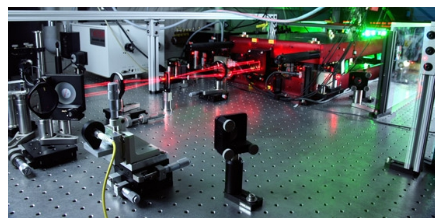


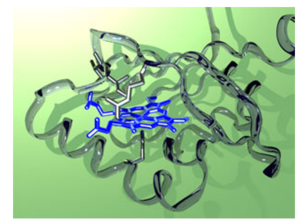
~ 300 um

J. Aumentado, L. Spietz&al., NIST-EEEL

- Pulse-probe spectroscopy. NIST-PL(JILA)
  - Single-molecule dynamics with femtosecond laser pulses. [10, 11, 12, 13]

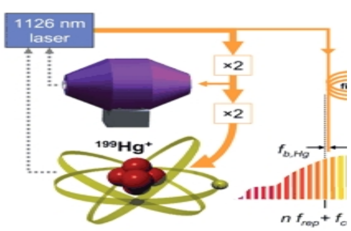


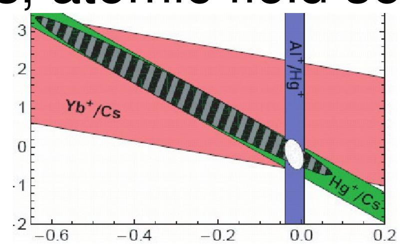




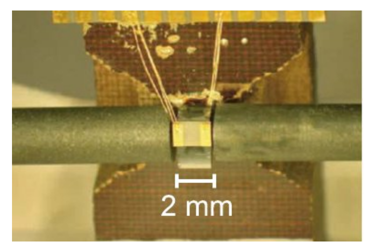
H. Kapteyn, M. Murnane, S. Cundiff, R. Jimenez, NIST-PL(JILA)

- Atomic transitions for precision measurement. NIST-PL(JILA)
  - Atom and ion clocks, atomic field sensing. [14, 15, 16, 17]





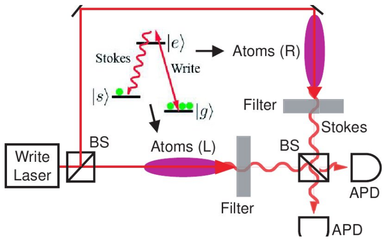
C. Oates, J. Berquist, T. Rosenband&al., NIST-PL

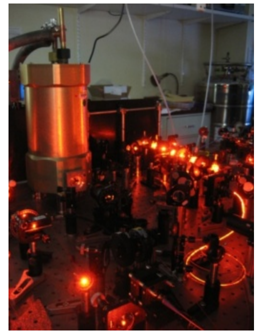


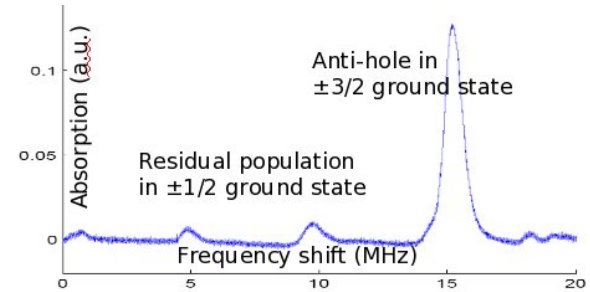
J. Kitching&al., NIST-PL

Connected to Quantum Information

- Light storage in atomic media. NIST-PL(JQI)
  - Spectral hole burning. [18]

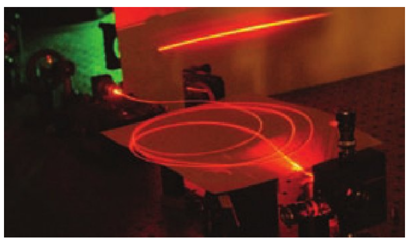




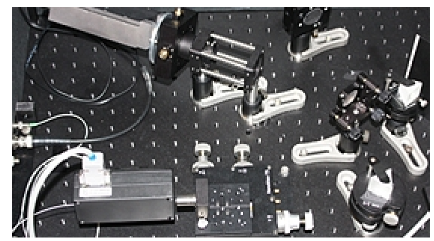


M. Eisaman&al. NIST-PL(JQI)

- Quantum optical metrology. NIST-EEEL,-PL,-ITL
  - Apps. of entangled photons, upconversion. [19, 20, 21, 22, 23, 24, 25]

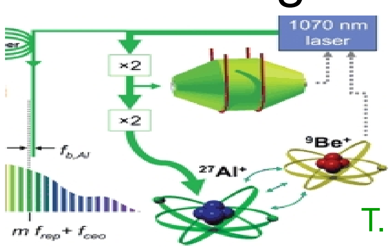


J. Fan, A Migdall, L. Wang. NIST-PL

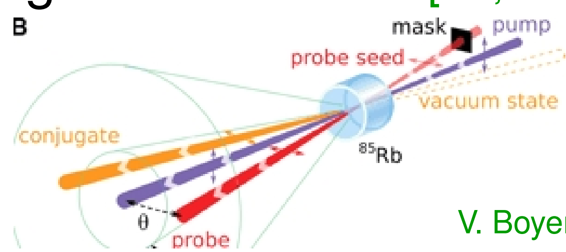


L. Ma, O. Slattery, X, Tang. NIST-ITL

- Quantum-enhanced measurement strategies. NIST-PL,-ITL
  - Quantum logic clock. Quantum imaging. [15, 14, 26, 27, 28, 29]



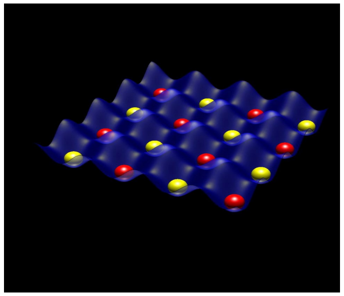
T. Rosenband&al., NIST-PL



V. Boyer&al. NIST-PL

Aiming for Universal Quantum Control

- Atoms in optical lattices. NIST-PL(JQI)
  - Addressable atoms in a lattice. [30, 31, 32, 33]



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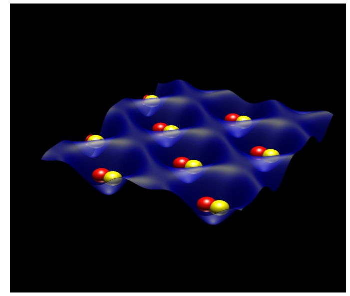
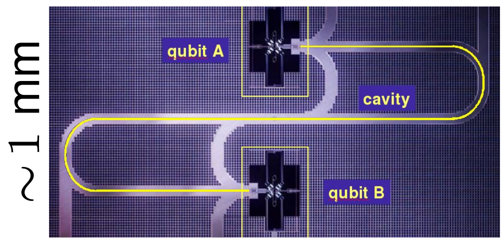
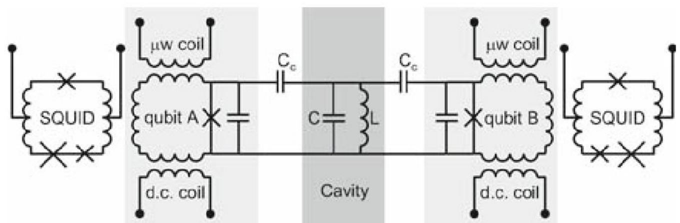
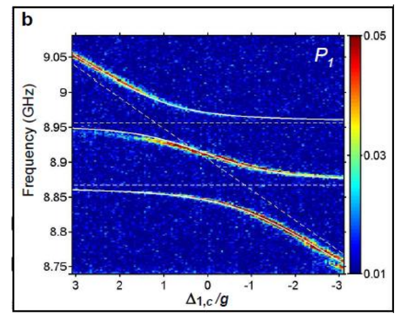


N. Lundblad, T. Porto&al. NIST-PL

- Qubits in superconducting circuits. NIST-EEEL
  - Phase qubits and stripline cavities. [34, 35]

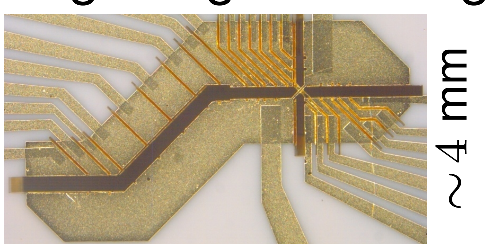


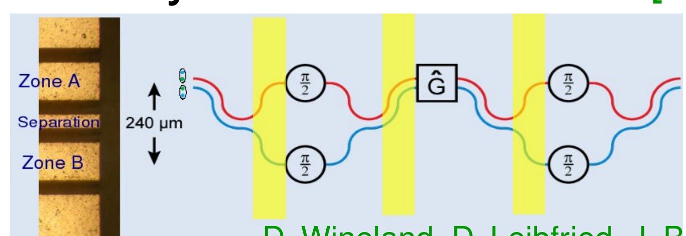




R. Simmonds&al. NIST-PL

- Trapped ions. NIST-PL,-ITL
  - Integrating technologies toward scalability. [36, 37, 38, 39]





D. Wineland, D. Leibfried, J. Bollinger&al. NIST-PL

Aside: Quantum Collaborations

- Collaborators' institutions, from above references only:

  U. Twente (Netherlands), MSL (New Zealand), METAS (Switzerland), Immetro (Brazil), U. Neuchatel (Switzerland), Albion Coll., MIT, CU Boulder, NRC (Canada), CU Denver, UC. Berkeley, LBNL, Princeton, U. Innsbruck, INRM (Italy), SRS, Oberlin Coll., U. Maryland, Harvard U., Texas A&M U., Williams Coll., U. A. Barcelona (Spain), U. Ulm (Germany), INFN (Italy), Sc. Norm. Sup. (Italy), Bates Coll., Helsinki U. (Finland), LPS, Weizman (Israel), Lockheed Martin.

- Notable NIST-Boulder workshops:
  - International workshop on dynamical decoupling. Oct 5–6, 2009. M. Biercuk (NIST), T. Ladd (Stanford U.), H. Uys (NIST).
  - Single Photon workshop.
    Nov. 3–6, 2009. A. Migdall (NIST).

Coherence in Superconducting Circuits

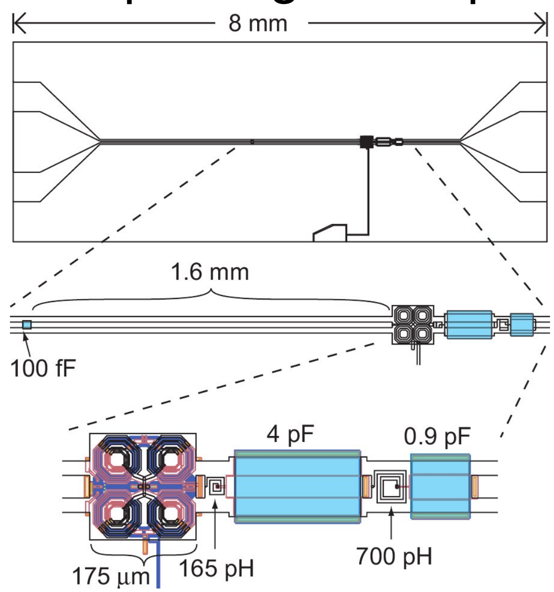
- Surprise: Super conducting q. systems yield plausible qubits!
- Highlight: Superconducting low-noise amplifiers.
  - Low noise cryogenic μwave amplifiers needed for fast and precise
    - characterization or use of cold devices and nano-structures;
    - Heisenberg-limited position and force sensing;
    - quantum optics with microwaves;
    - measurements of solid state qubits.
  - Status quo.
    - Conventional HEMT amplifiers add $40+$ quanta of noise to the source.
    - Theory, some experiments by B. Yurke and others, '80s, '90s.
  - Principal NIST researchers.

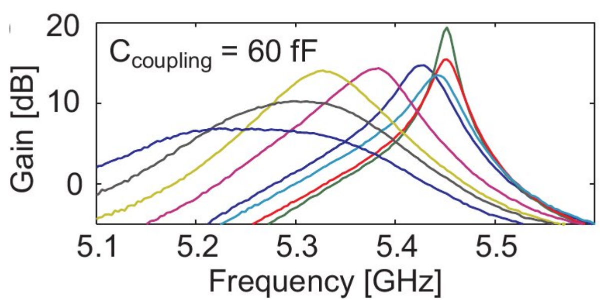
    José Aumentado, Kent Irwin, Minhyea Lee, Lafe Spietz, NIST-EEEL
    Manuel Castellanos-Beltran, Konrad Lehnert, NIST-PL(JILA)
    Scott Glancy, Emanuel Knill. NIST-ITL

$+\$$(IARPA, DARPA, NSF)

Coherence in Superconducting Circuits

- Highlight: Superconducting low-noise amplifiers. (cont.)
  - Recent progress at NIST.
    - Towards “packageable” phase-preserving amps. Aumentado group [40, 41]



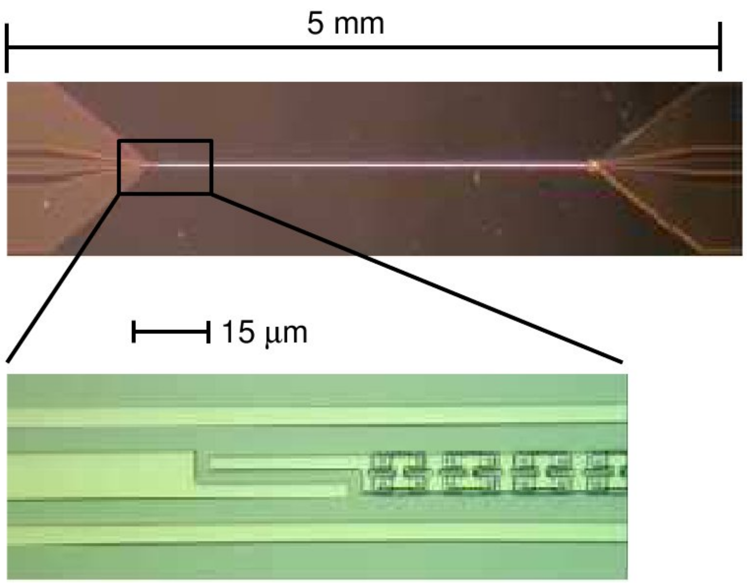


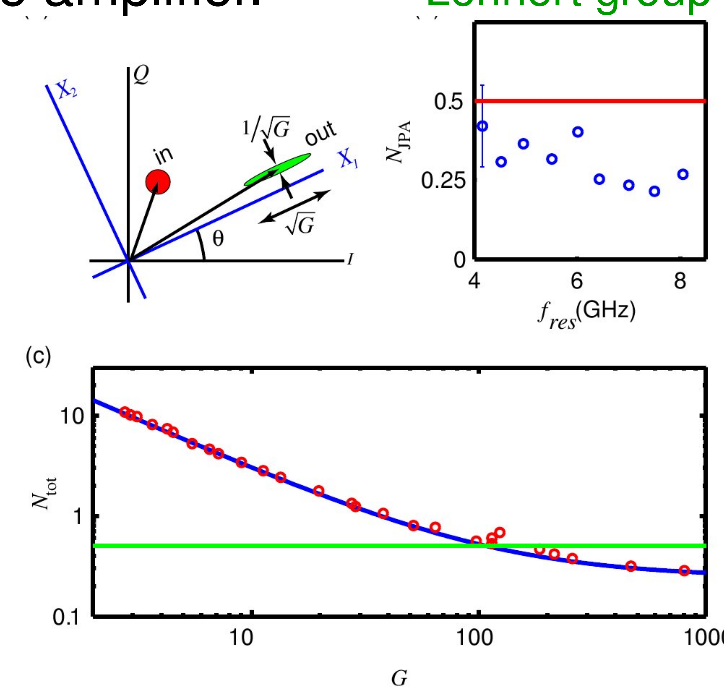
Gain*Bandwidth = 27 GHz.

Noise(HEMT)/Noise(SQUID amp) $\approx$ 15.

Coherence in Superconducting Circuits

- Highlight: Superconducting low-noise amplifiers. (cont.)
  - Recent progress at NIST.
    - Towards "packageable" phase-preserving amps. Aumentado group [40, 41]
    - Josephson metamaterial phase-sensitive amplifier. Lehnert group [8]





Noise(JP amp @ $\phi = 0$) $\approx$ 0.23.
Squeezing factor of $\approx$ 10.

Coherence in Superconducting Circuits

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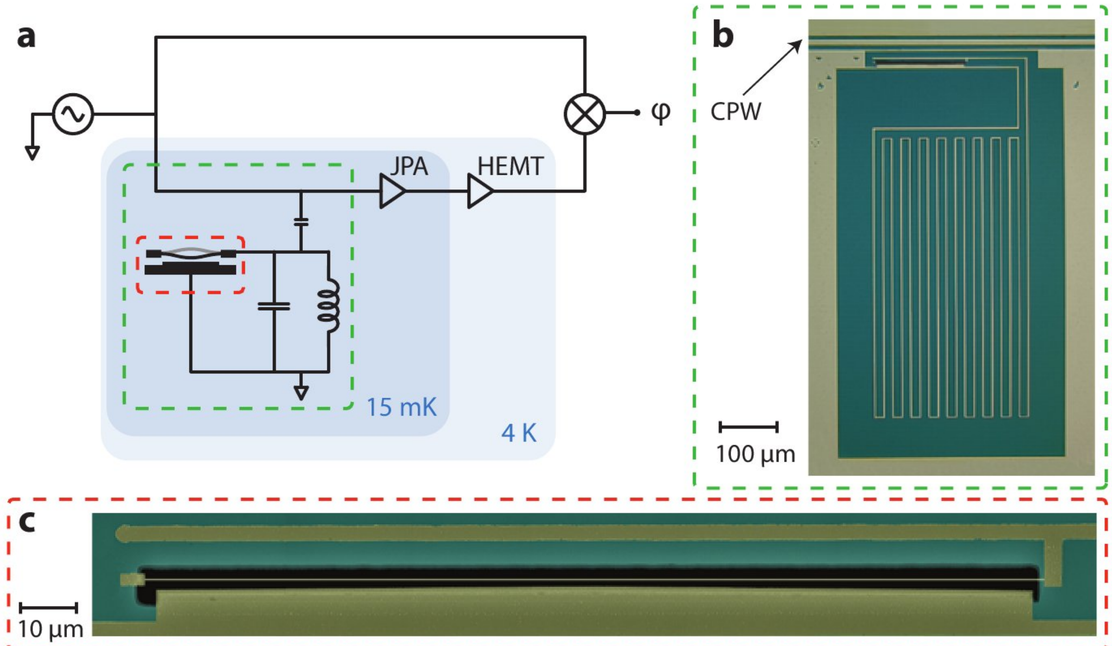
  - Recent progress at NIST.
    - Towards “packageable” phase-preserving amps. Aumentado group [40, 41]
    - Josephson metamaterial phase-sensitive amplifier. Lehnert group [8]
    - Ultrasensitive force sensing. Lehnert group [9]



  - Next steps.
    - Higher bandwidth, improved noise measurement, multi-mode control.
    - Entangled microwave photons on a chip, state tomography.

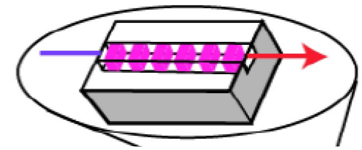
Generation and Metrology of Nonclassical Light

- Surprise: Photon-count-based heralding is powerful!
- Highlight: Pairs, squeezing and cats.
  - Some motivation.
    - High rate of photon pairs needed for q. radiometry.
    - Squeezed light for sensitive position measurements.
    - Entangled pairs for tests of q. mechanics, communication.
    - Extensive control needed for reliable q. communication.
  - Status quo.
    - Mode indistinguishability lacking, squeezing limited, lossy optics.
    - Typical single photon source, detector efficiencies $\ll 10\ \%, < 60\ \%$.
  - Principal NIST researchers.

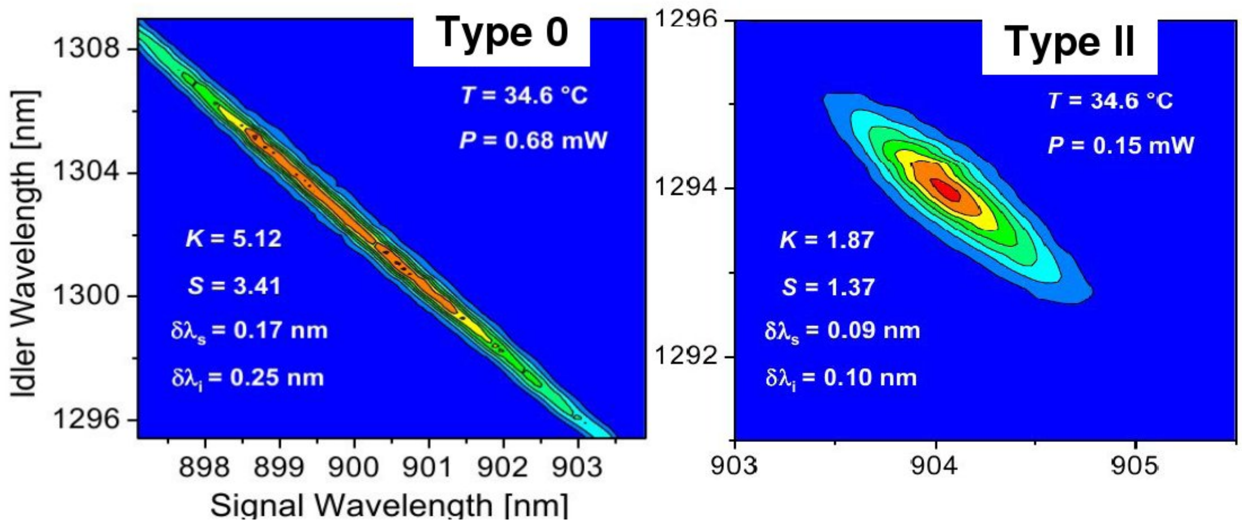
Jingyun Fan, Paul Lett, Alan Migdall, Sergey Polyakov	NIST-PL(JQI)
Tracy Clement, Thomas Gerrits, Rich Mirin,	NIST-EEEL
Shelly Dyer, Sae Woo Nam,	NIST-EEEL
Scott Glancy, Emanuel Knill, Xiao Tang.	NIST-ITL
	$+\$$(IARPA,ARO)

Generation and Metrology of Nonclassical Light

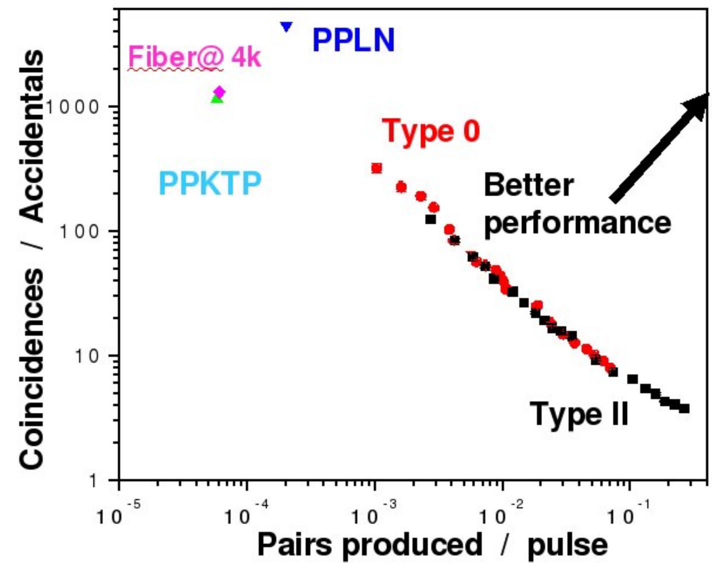
- Highlight: Pairs, squeezing and cats. (cont.)
  - Some recent progress at NIST.
    - Characterization of waveguide pair source.



Migdall group [20]

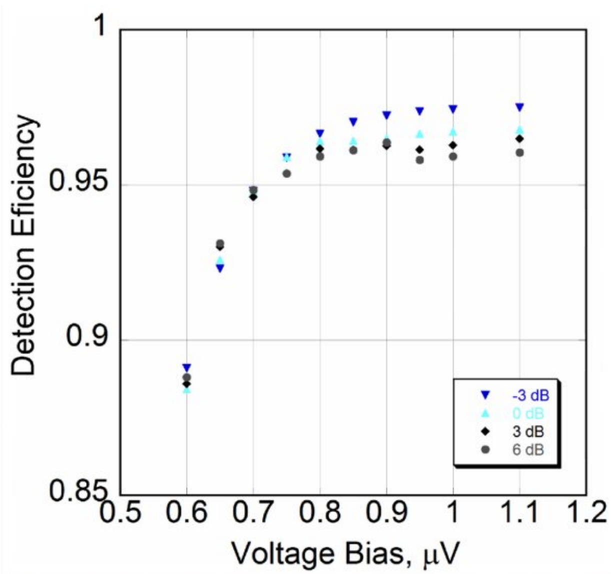


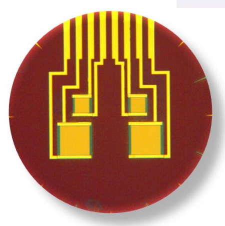
Source comparison.

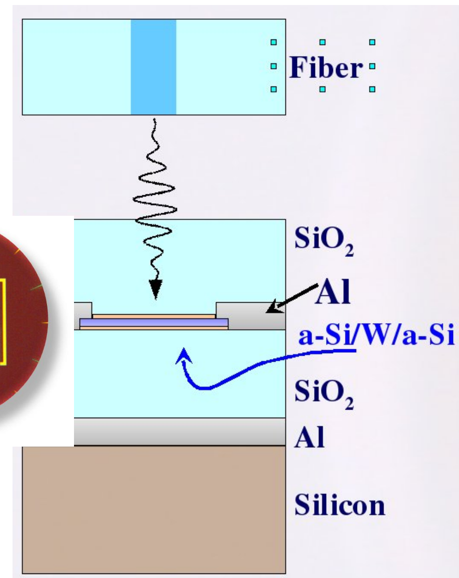


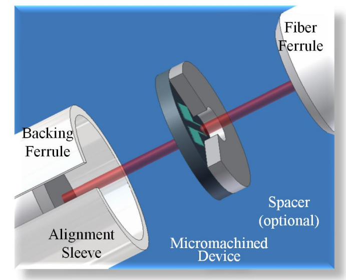
Generation and Metrology of Nonclassical Light

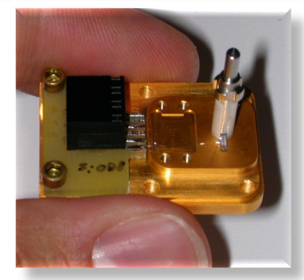
- Highlight: Pairs, squeezing and cats. (cont.)
  - Some recent progress at NIST.
    - Characterization of waveguide pair source. Migdall group [20]
    - Packagable, very efficient ($> 95\ \%$) photon counters. Nam group [6]





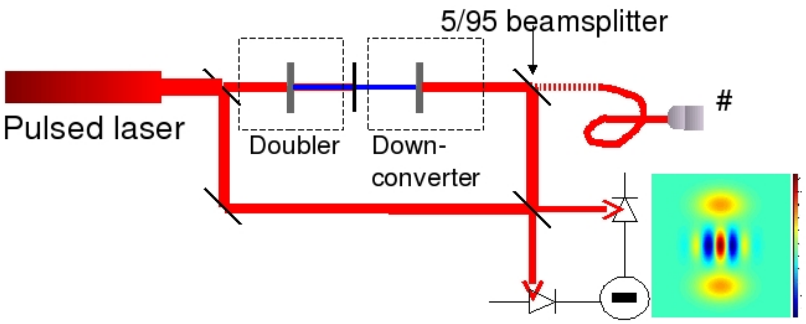




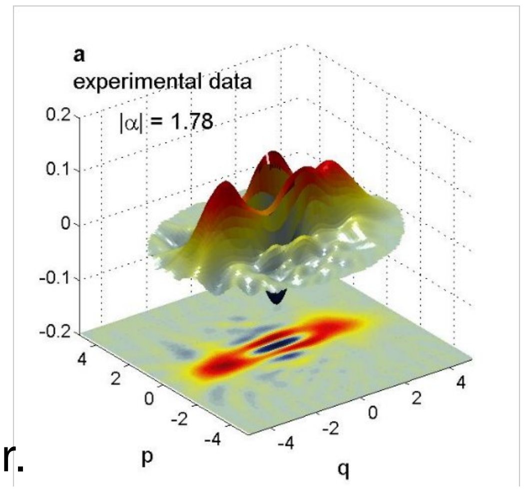


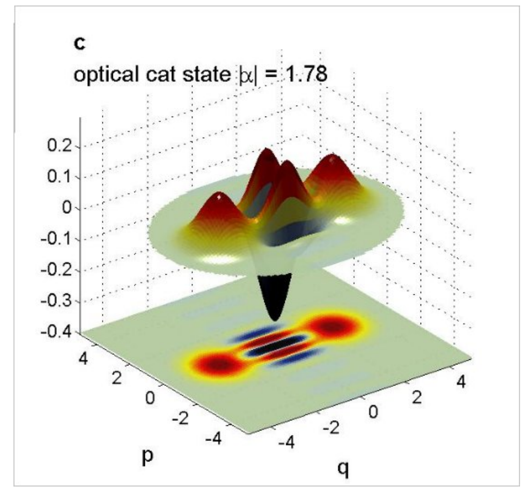
Generation and Metrology of Nonclassical Light

- Highlight: Pairs, squeezing and cats. (cont.)
  - Some recent progress at NIST.
    - Characterization of waveguide pair source. Migdall group [20]
    - Packagable, very efficient ($> 95\ \%$) photon counters. Nam group [6]
    - Quantum kittens by ≥ 2-photon subtraction. Mirin/Nam group



Heralded by transition-edge sensor.





  - Some next steps.
    - Efficiency sufficient for loop-hole free tests of q. mechanics.
    - Improve squeezing purity.
    - Solid state optical memory.

Q. Computing, Simulation with Ions and Atoms

- Surprise: Rapid progress toward analog q. simulation!
- Highlights: Growing control of ions and atoms.
  - Some motivation.
    - Quantum control $\Rightarrow$ quantum algorithms.
    - Quantum properties of many interacting systems?
    - The virtual quantum physics lab.
  - Status quo.
    - One-system control achieved, approaching full two-system control.
    - Most components of scalability tested in ion traps.
    - Growing diversity of trapped atom experiments.
  - Principal NIST researchers.

    John Bollinger, Didi Leibfried, Dave Wineland, NIST-PL

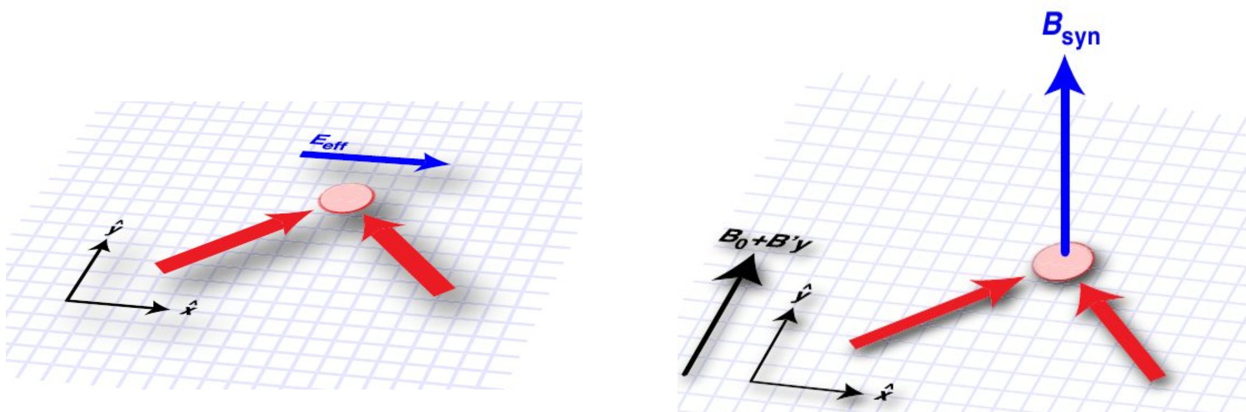
    Emanuel Knill, NIST-ITL

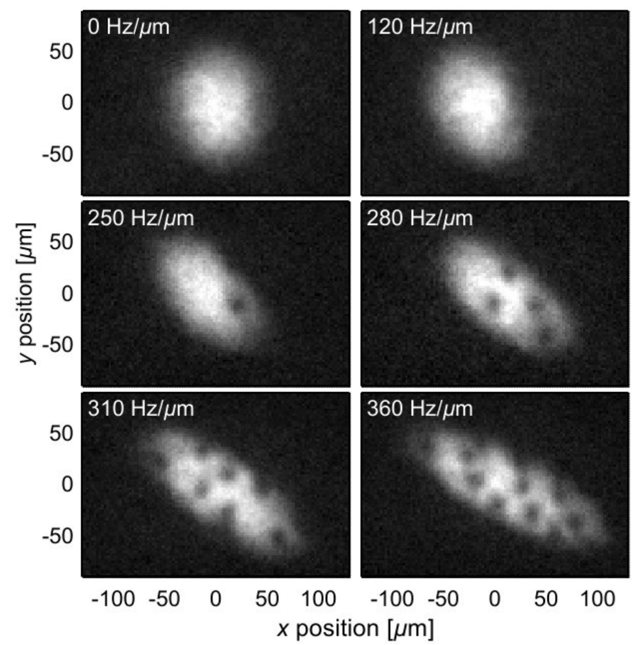
    Ian Spielman, Trey Porto, Bill Phillips. NIST-PL,-PL(JQI)

    +\$(ONR,DARPA,IARPA,NSF)

Q. Computing, Simulation with Ions and Atoms

- Highlights: Growing control of ions and atoms.
  - Some recent progress at NIST.
    - Benchmarks for one-qubit control. Ion Storage group [39]
    - Demonstration of components of scalability. Ion Storage group [42, 36, 37]
    - Synthetic vector potentials for atoms. Spielman group [30, 43]





⇒ Synthetic E and B fields generated.

  - Some next steps.
    - Two-qubit benchmarks.
    - Integration of ion railyard features.
    - Improved atom addressing in optical lattices.

The Future of Quantum Simulation

- Surprise: Potential speedups for modeling!
- Highlight: Digital quantum simulations.
  - Motivation:
    - Direct simulations have exponential complexity.
    - Monte Carlo simulations suffer "sign" problems.
    - ... how to reach the "thermodynamic limit"?
  - Status quo:
    - Analog but not digital quantum simulations becoming possible.
    - Concrete problem lacking?
    - Cannot clearly speedup determination of "groundstate energy", "spectrum"...
  - Principal NIST researcher: Emanuel Knill. NIST-ITL
  - Recent progress.
    - Improved state preparation (with CALTECH, Perimeter). [44]
  - Next steps?

Contents

References

[1] J. Qu, S. P. Benz, H. Rogalla, and D. R. White. Reduced non-linearities and improved temperature measurements for the NIST Johnson noise thermometer. *Metrologia*, 46:512–524, 2009.

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