Measuring the Quadrature Coherence Scale on Borealis

Aaron Z. Goldberg[1,2], Guillaume S. Thekkadath[1], Khabat Heshami[1,2,3]

[1]National Research Council of Canada, [2]University of Ottawa, [3]University of Calgary

(photonics experiments on the cloud)
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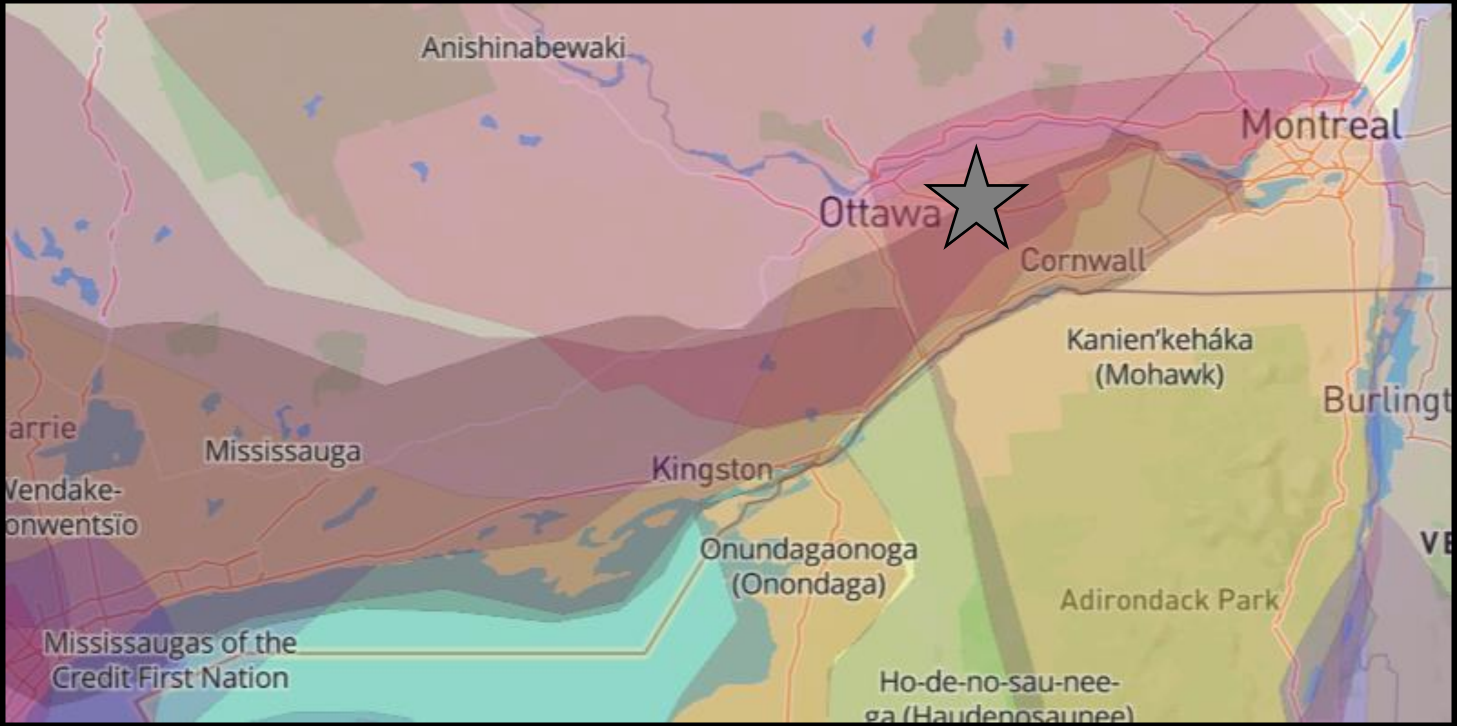
Land Acknowledgment

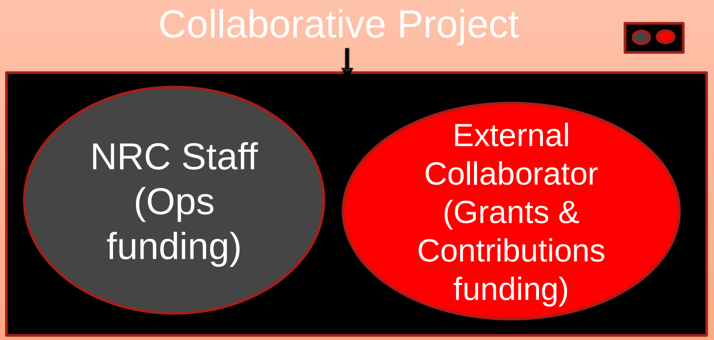
The NRC headquarters is located on the traditional, unceded territory of the Algonquin Anishinaabe and Mohawk peoples



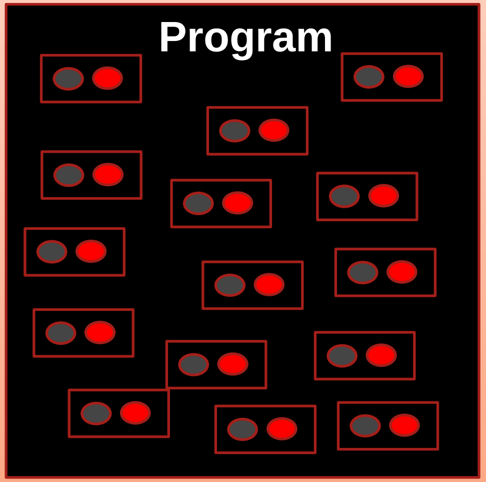
https://native-land.ca/

NRC QUANTUM SENSORS CHALLENGE PROGRAM

Vision: To support Canada's ambition to be a global leader in quantum technologies.

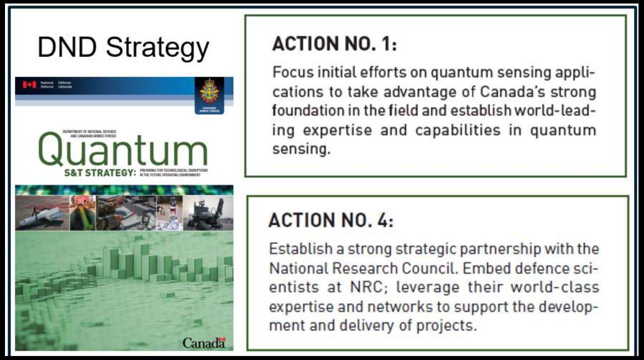


Challenge Programs consist of a portfolio of projects that address an over-arching challenge



Alignment with National and Federal Policies:

a) Defence Quantum S&T Strategy



ACTION NO. 1:

Focus initial efforts on quantum sensing applications to take advantage of Canada's strong foundation in the field and establish world-leading expertise and capabilities in quantum sensing.

ACTION NO. 4:

Establish a strong strategic partnership with the National Research Council. Embed defence scientists at NRC; leverage their world-class expertise and networks to support the development and delivery of projects.

b) National Quantum Strategy

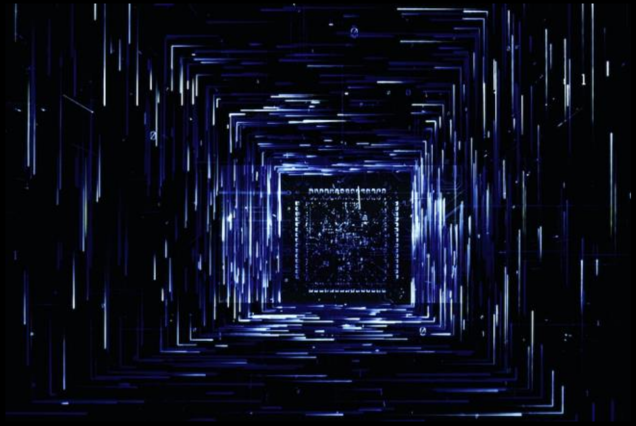
New collaborative funding opportunities launching this summer!

c/o Aimee Gunther, Deputy Director QSP

Resources for Continuous-Variable Quantum Computing

- Sources of light
  - Squeezing
  - Single photons, Fock states
  - Entanglement, nonclassicality, non-Gaussianity, …
- Manipulations
  - Phase shifters, beam splitters
  - Displacement, squeezing
- Measurements
  - Homodyne
  - Photon counting

Simpson (2019), unsplash



Patricola (2019), unsplash

Resources for Continuous-Variable Quantum Computing

- Sources of light
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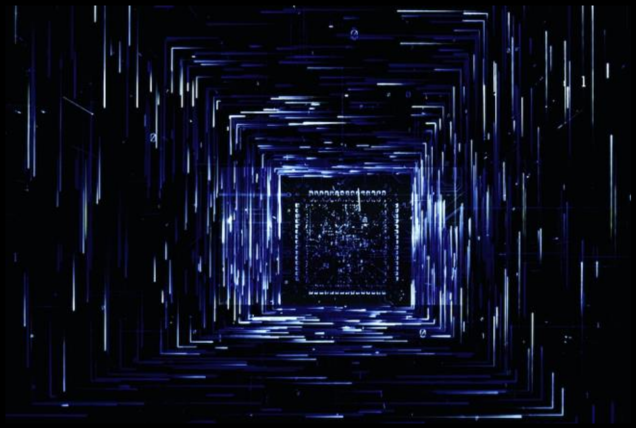
- Manipulations
  - Phase shifters, beam splitters
  - Displacement, squeezing
- Measurements
  - Homodyne
  - Photon counting
- Available from Xanadu via the cloud!

Simpson (2019), unsplash

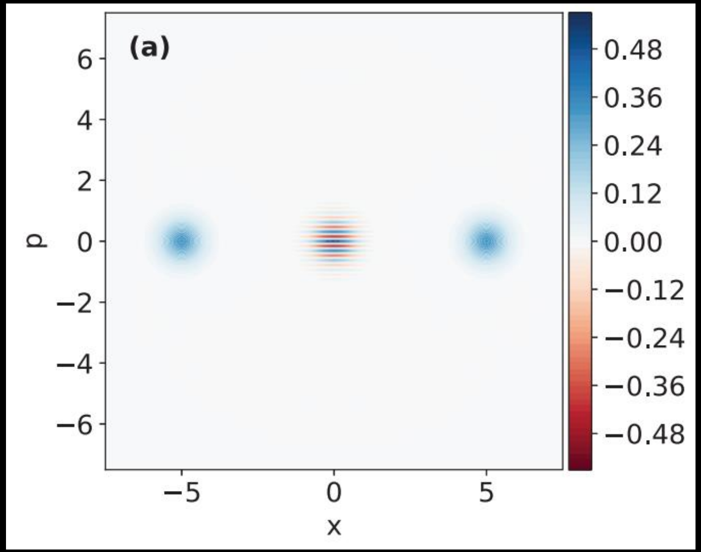


Patricola (2019), unsplash

First Story: Quantify Quantumness

- Superpositions of macroscopically different things are quantum
  - Look at $|\langle x|\rho|x'\rangle|^2$. If it's large, state has some component $|x\rangle + |x'\rangle$
  - The larger $(x-x')^2$ is, the more macroscopic
- Quadrature coherence scale: average over any two quadratures

$$C^2 \propto \int dx\, dx'\, (x-x')^2 |\langle x|\rho|x'\rangle|^2 + \int dp\, dp'\, (p-p')^2 |\langle p|\rho|p'\rangle|^2$$



AZG & KH (2021) PRA

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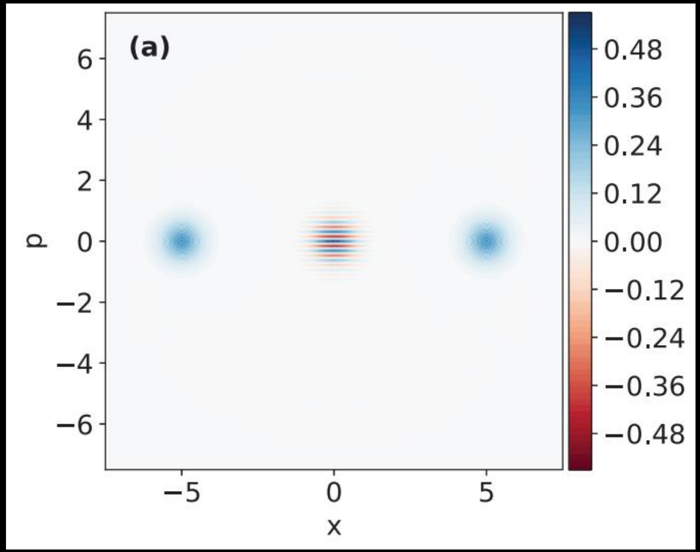
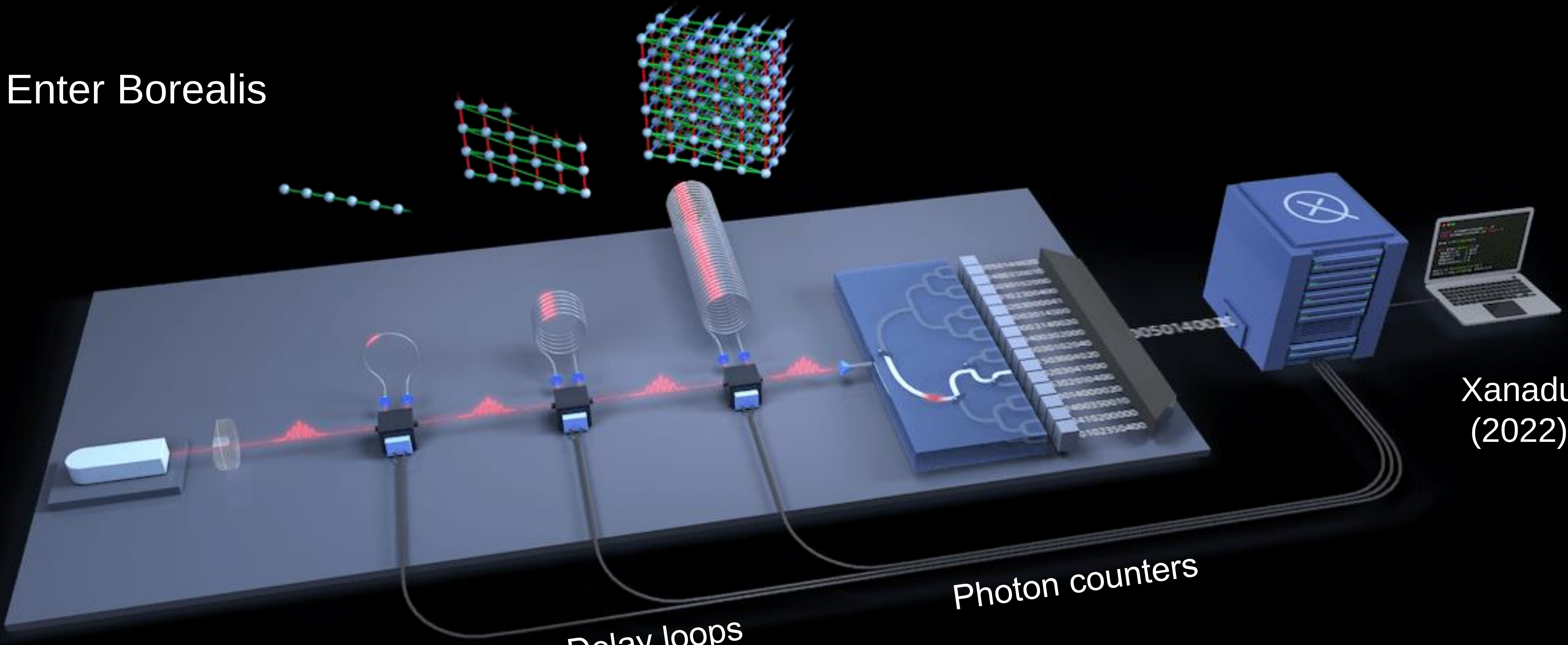
- Witness quantumness and macroscopicity
  - Original applications for quantum chaos
  - Measure decoherence
- Can be measured with (Griffet *et al*. PRA 2023)
  - Two copies of a state, one beam splitter, photon counting



AZG & KH (2021) PRA

First Story: Quantify Quantumness

- Enter Borealis



Xanadu
(2022)

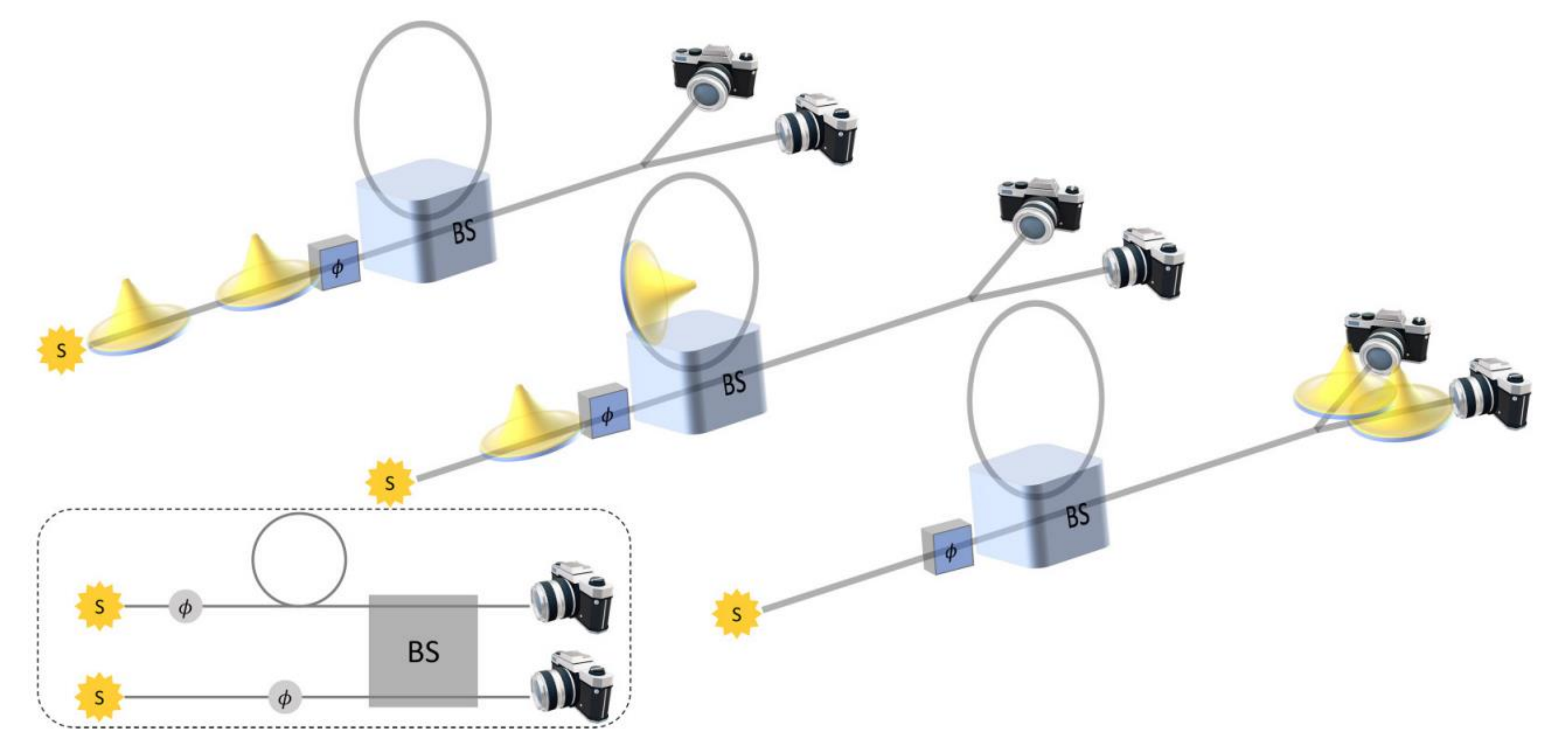
Photon counters

Delay loops

Source: Train of squeezed light pulses

First Story: Quantify Quantumness

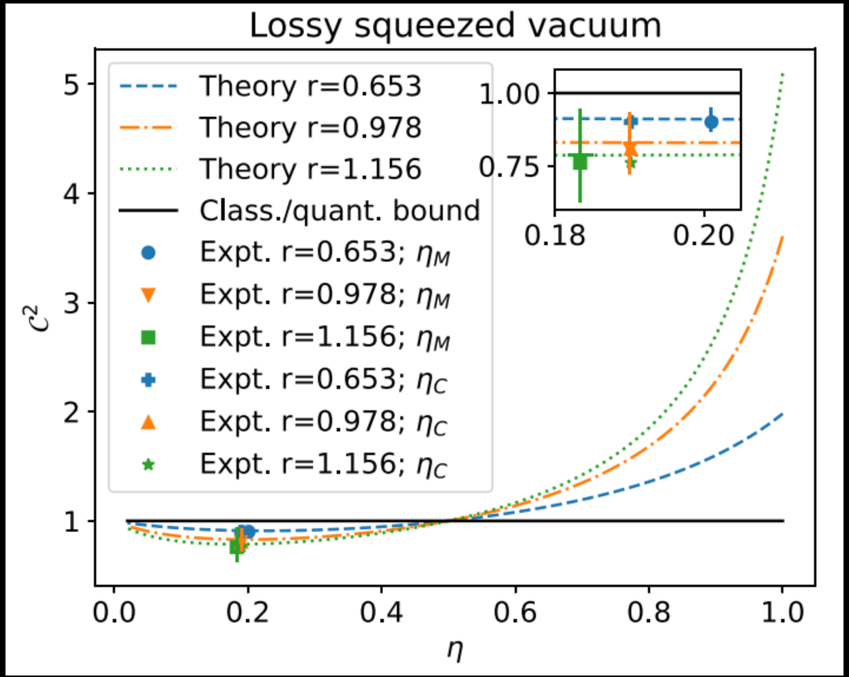
- Delay one copy of squeezed vacuum to interact with another, then count photons



AZG, GST, KH (2023) PRA

First Story: Quantify Quantumness

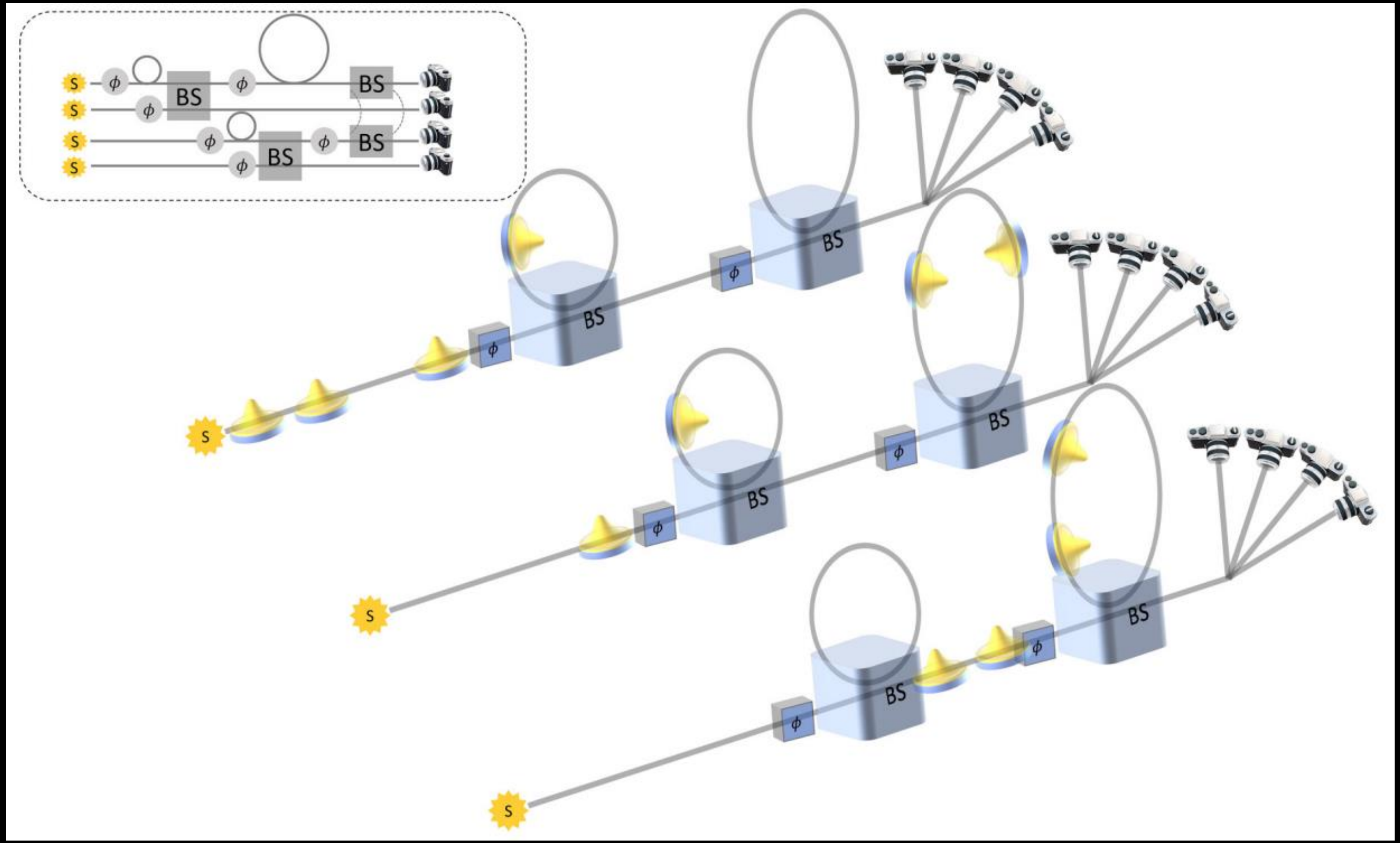
- Delay one copy of squeezed vacuum to interact with another, then count photons
- But: there's loss, so effectively started with a lossy state
- Correct result, can't certify quantumness



AZG, GST, KH (2023) PRA

First Story: Quantify Quantumness

- Create thermal state from two squeezed vacua, repeat, interact, count



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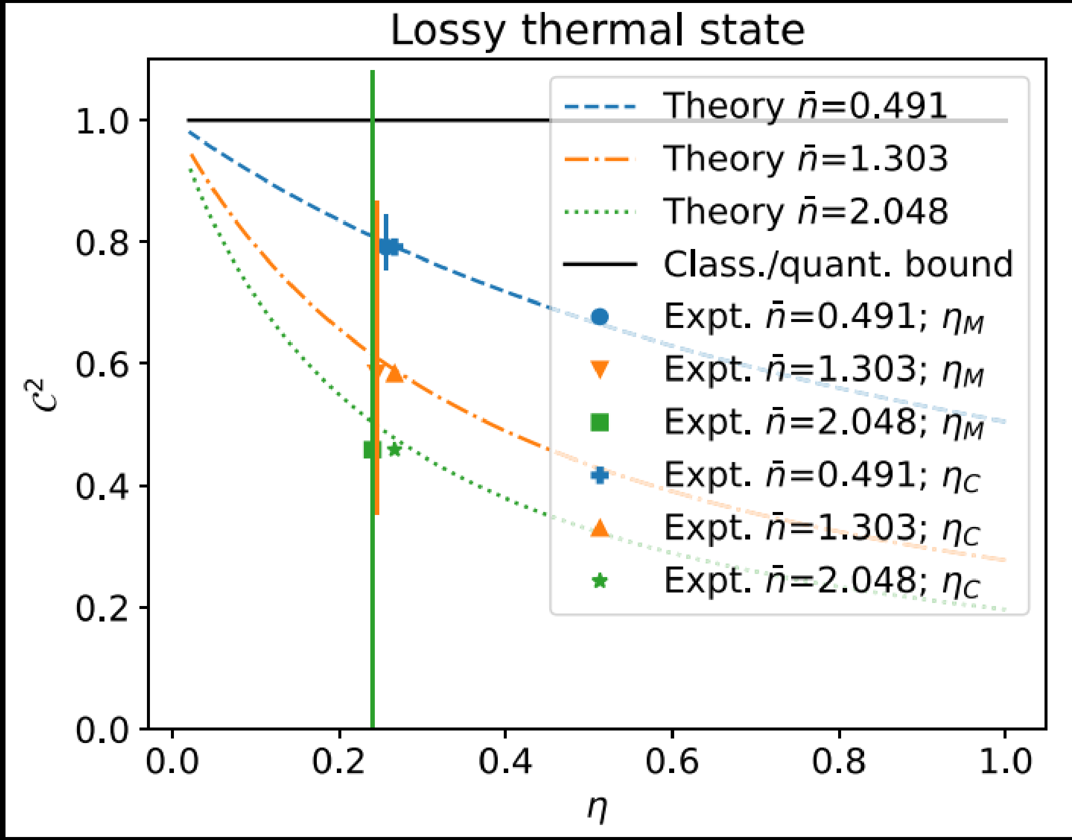
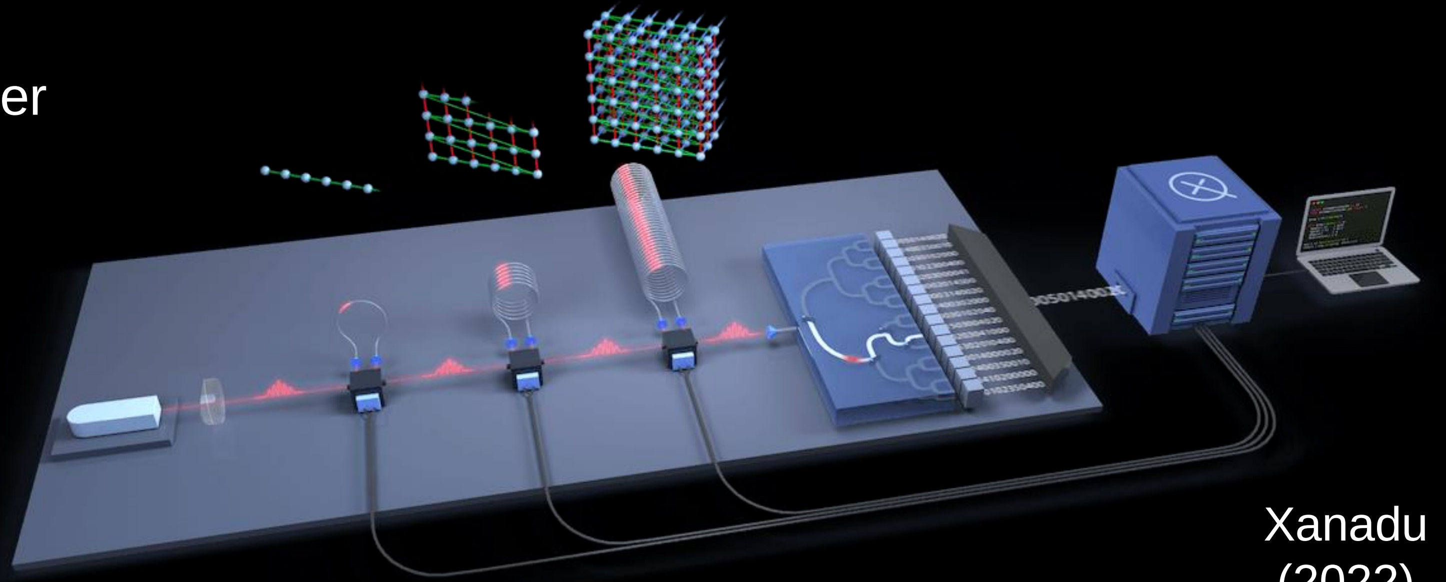


AZG, GST, KH (2023) PRA

Second Story: Teleamplification

- Dream of phase-insensitive amplification $|\alpha\rangle \rightarrow |g\alpha\rangle$
  - Must be imperfect or probabilistic
- Recent scheme for $\sum_{n=0}^{\infty} \psi_n |n\rangle \rightarrow \sum_{n=0}^{N} g^n \psi_n |n\rangle$ requires (Guanzon *et al*. PRL 2022)
  - Fock state $|N\rangle$
  - Photon-number counting
  - Fourier-transform interferometer
  - Programmable beam splitter



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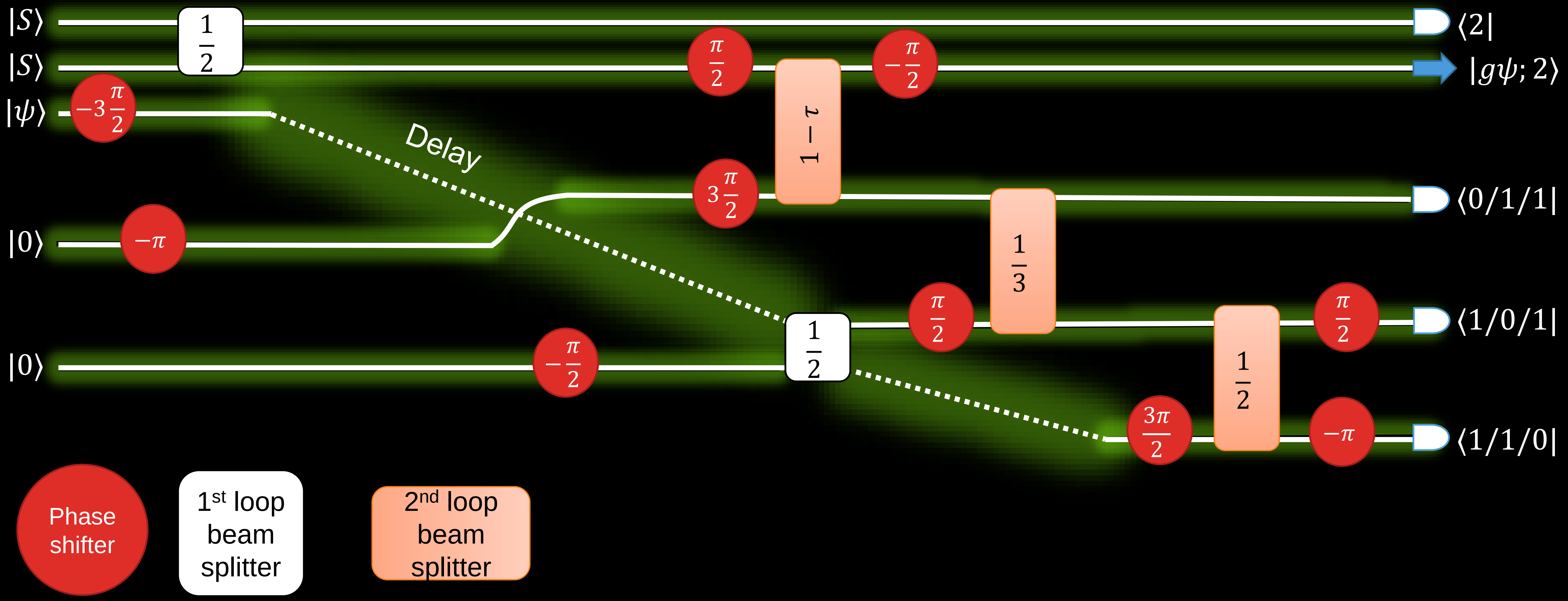

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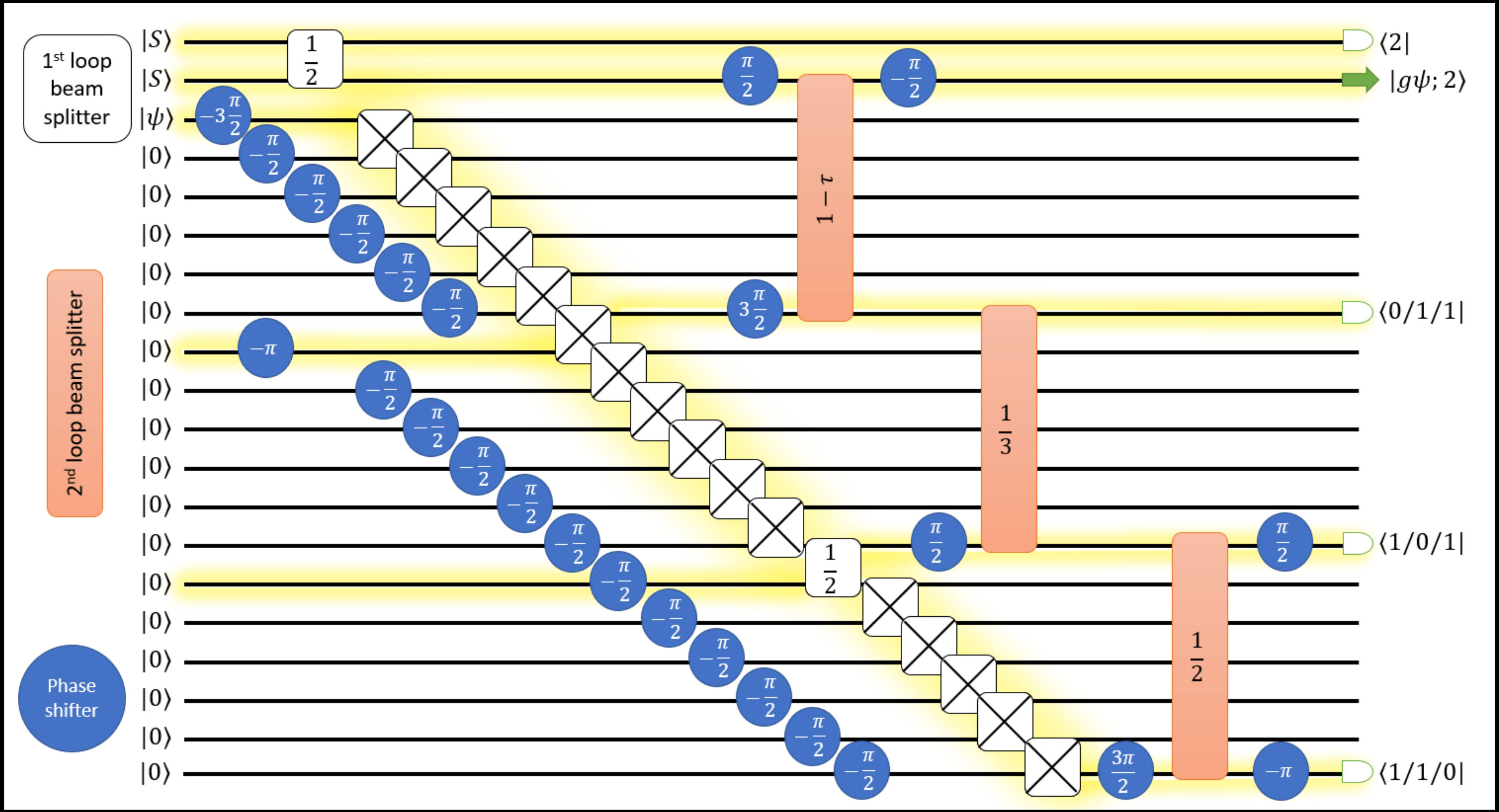

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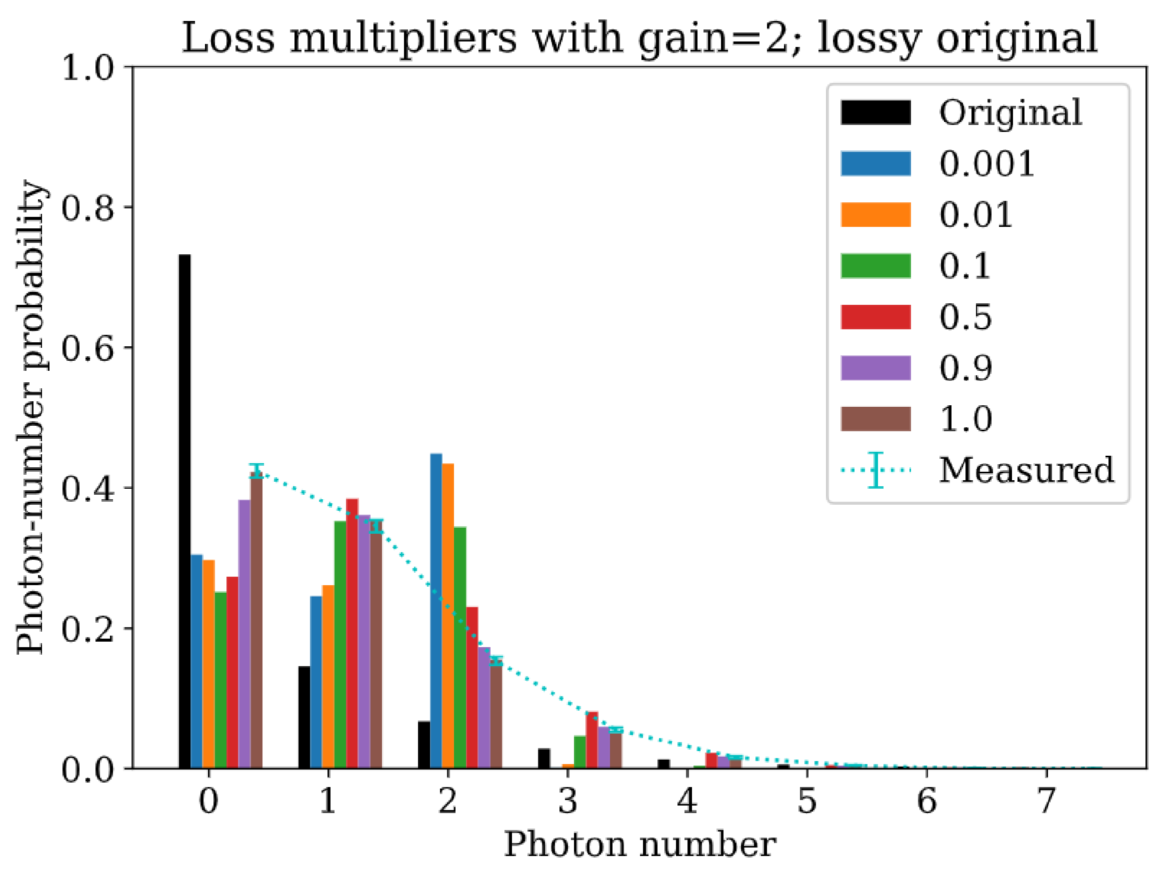

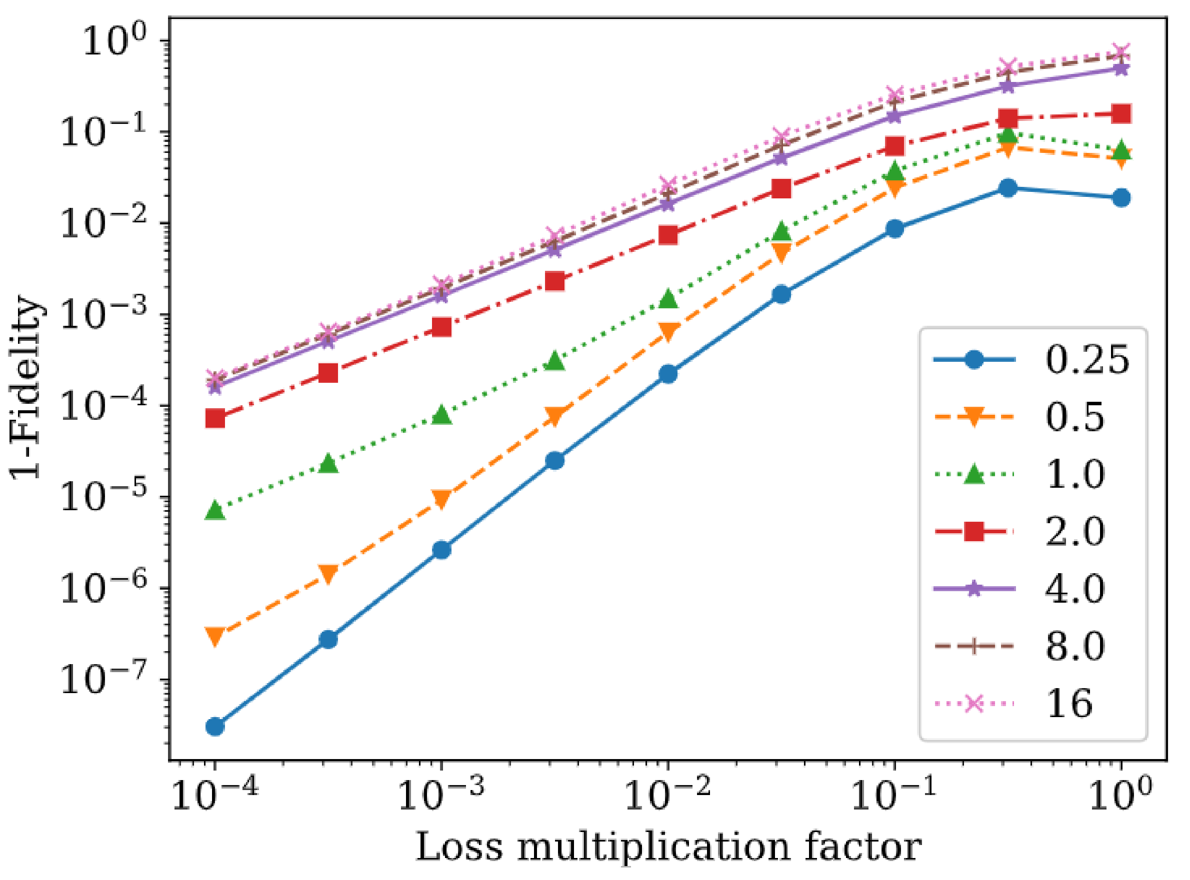

Takeaways

- Photonics, chip-based systems designed for quantum computing
  - Can be used for metrology
  - Can be used for state characterization
  - Can be used to quantity quantumness
  - Can be used for phase-insensitive amplification
- Run experiments on the cloud!
- Still in the era of noisy devices – for photonics, that’s the era of lossiness
  - Excellent characterization – can predict the lossy results

What’s Next?

- Borealis recently retired – not before we took some data – stay tuned
- More metrology experiments on X8

- What else can you do with squeezed light? Photon counting?
  - Fault tolerant quantum computing, eventually

- With sufficiently robust chip-based systems…
  - … portable quantum sensors!

Propaganda 1

On the operator bases underlying Wigner's, Kirkwood's and Glauber's phase space functions

Berthold-Georg Englert

JPhysA 1989

- Wigner functions and operators interconvert with a kernel

$$2\exp(2ip;q) = 2\exp(-2iq;p) = 2\exp\left(-2a^\dagger;a\right) = 2\sum_n \frac{\left(-2a^\dagger\right)^n a^n}{n!}$$

$$F_W(q',p') = \mathrm{Tr}\{F(q,p)2\exp[-2i(q-q');(p-p')]\}$$

$$F(q,p) = \int \frac{dq'\,dp'}{2\pi} F_W(q',p') 2\exp[2i(p-p');(q-q')]$$

- Change the 2, get KD or Glauber families (limit at 1)

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- Change the 2, get KD or Glauber families (limit at 1)
- What if you want to know the coefficient of a particular term, like $a^{\dagger m}a^n$?

Propaganda 1

- What if you want to know the coefficient of a particular term, like $\mathrm{T_{Kq}} = a^{\dagger K+q} a^{K-q}$?

Covariant operator bases for continuous variables

Aaron Z. Goldberg[1,2], Andrei B. Klimov[3], Gerd Leuchs[4], and Luis L. Sánchez-Soto[4,5]

$$\mathrm{Tr}(\hat{\mathfrak{T}}_{Kq}\hat{T}_{K'q'}) = \delta_{KK'}\delta_{Kq'}.$$

$$\hat{\mathfrak{T}}_{Kq} = \frac{(-1)^{K+q}}{(K+q)!\,(K-q)!}\frac{1}{\pi}\int d^2\beta\, e^{-\frac{|\beta|^2}{2}}\,\hat{D}(\beta)\,\beta^{K+q}\beta^{*K-q}.$$

- Can be done for any member of the family

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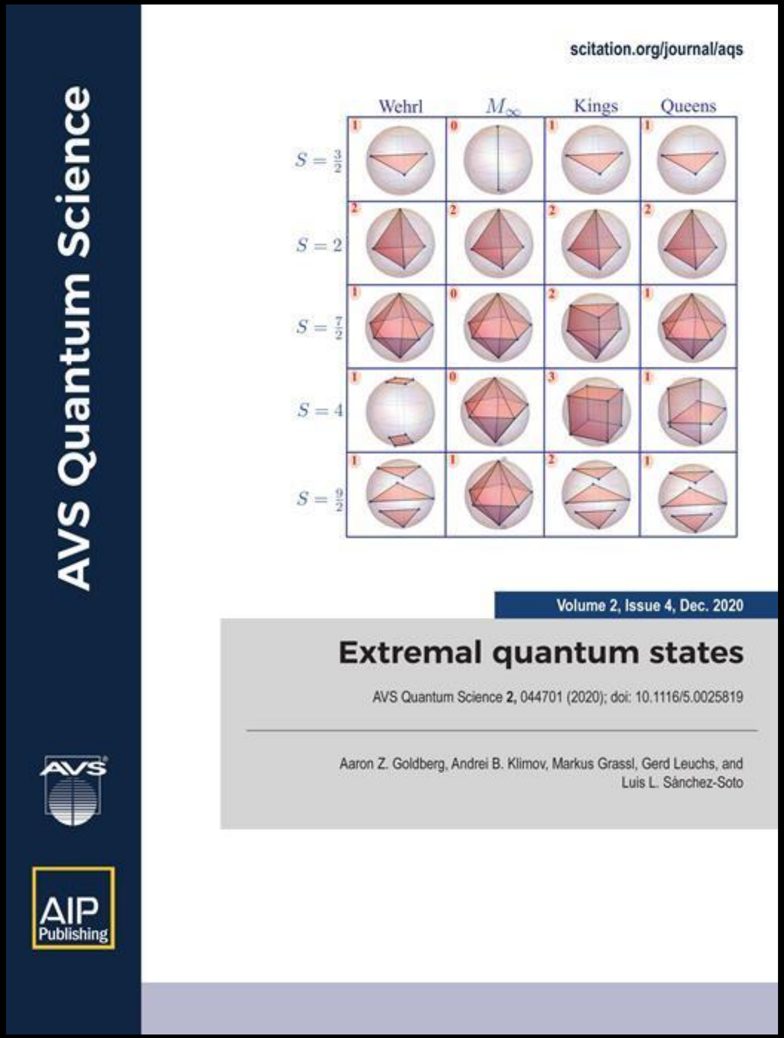
- Can be done for any member of the family
- Characterize “state multipoles” and their transformations

$$\hat{\varrho} = \sum_{Kq}\langle\hat{\mathfrak{T}}_{Kq}\rangle\;\hat{T}_{Kq}$$

Propaganda 2

- Insights from continuous variables can be misleading!
- CV:
  - Different quantifiers agree on which states are the least/most quantum
- Spins:
  - Different quantifiers agree on which states are the least quantum; disagree on which are the most quantum

- (What is Gaussianity on a sphere?)



Thanks and Thank You For Listening

NSERC
CRSNG

XANADU

National Research Council Canada

Conseil national de recherches Canada

QSP FINGERPRINT: TECHNOLOGIES AND APPLICATIONS

New collaborative funding opportunities launching this summer!

Sensing what?

Optical fields
- 7 projects
  - Single-photon sources
- 9 projects
  - Imaging and Single-photon detection

Microwave fields
- 2 projects

Temperature
- 2 projects

Charge/current
- 1 project

Magnetic fields
- 2 projects

Timing & Positioning
- 1 project

For what?

Quantum technologies
- 5 projects
- For Comms or Computing

Probing materials
- 2 projects

Biological or molecular
- 4 projects

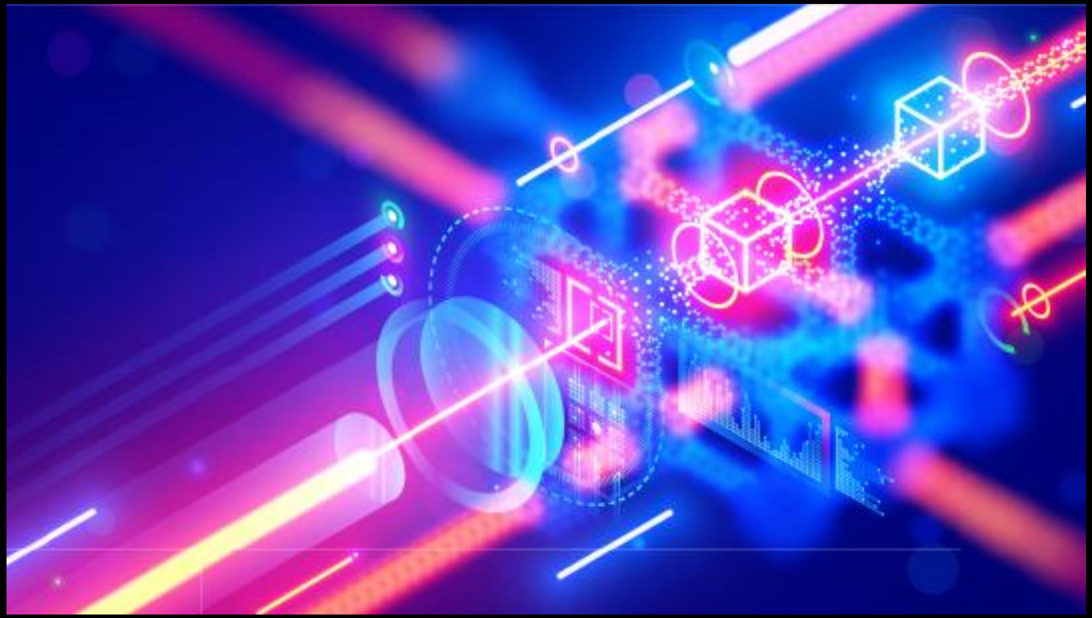
Environment
- 4 projects

Defence, Safety, and Security
- 11 projects

Quantum Sensors Challenge program

- Strengthening of the Canadian quantum technology innovation ecosystem, including increased IP portfolio
- Advancement of quantum sensing technologies towards adoption and commercialization

- Current areas of focus:
  - Quantum photonics
  - Chip-based quantum systems
  - Quantum metrology



Applications: The Usual Suspects

- Fault tolerant quantum computation
- Quantum state preparation
  - Metrology
  - Communication
- Quantum measurements
  - Metrology
  - Communication

Applications: The Usual Suspects

- Fault tolerant quantum computation
- Quantum state preparation
  - Metrology
  - Communication
- Quantum measurements
  - Metrology
  - Communication
- Unusual suspects:
  - Quantum engines, quantum batteries, …

Third Story: Transmission Estimation

- Spectroscopy, ellipsometry, loss estimation: “How much light got through?”

$$\hat{a}^\dagger \rightarrow \eta \hat{a}^\dagger + \sqrt{1-\eta^2}\hat{v}^\dagger$$

- Best done with Fock states and photon counting

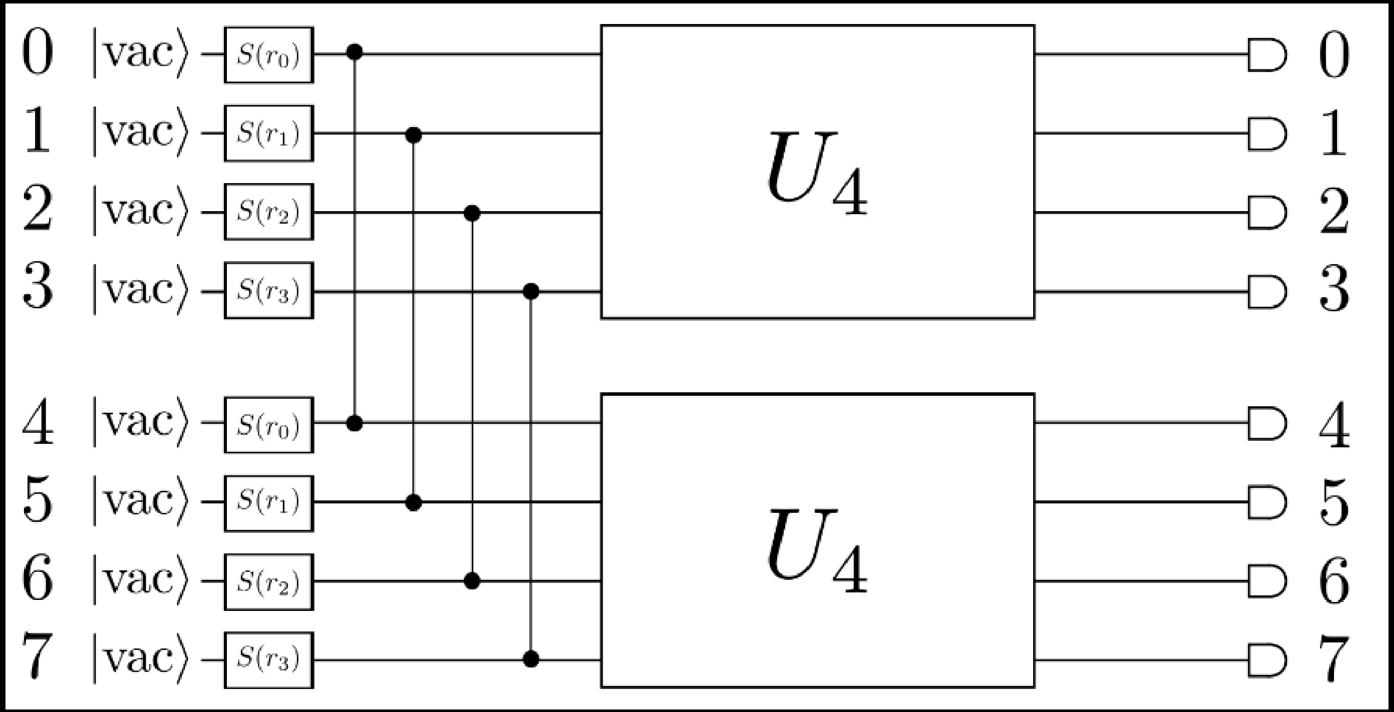
“3…4…8”

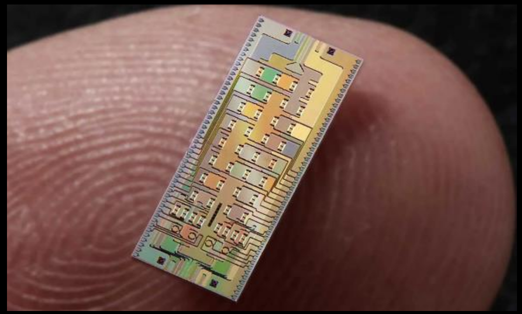
- We herald creation of Fock states using two-mode squeezed vacuum

$$|\psi\rangle \propto \sum_{n=0}^{\infty} t^n |n\rangle \otimes |n\rangle$$

Third Story: Transmission Estimation

- We herald creation of Fock states using two-mode squeezed vacuum… on X8

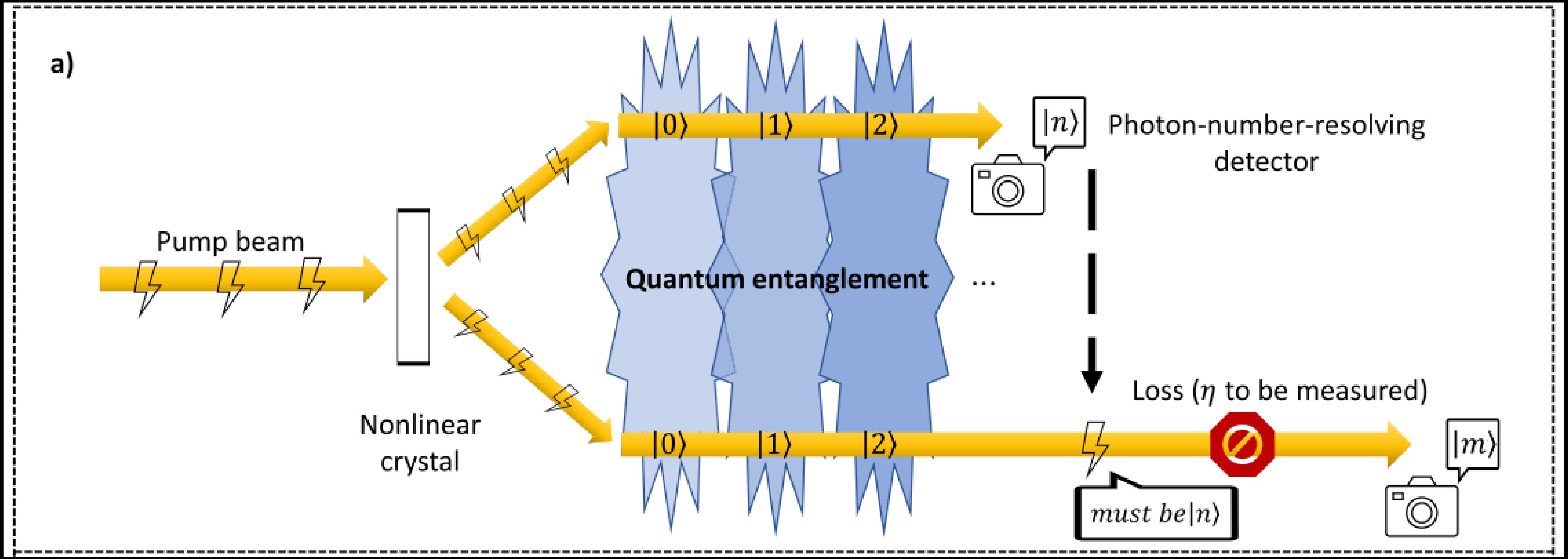




Xanadu

Third Story: Transmission Estimation

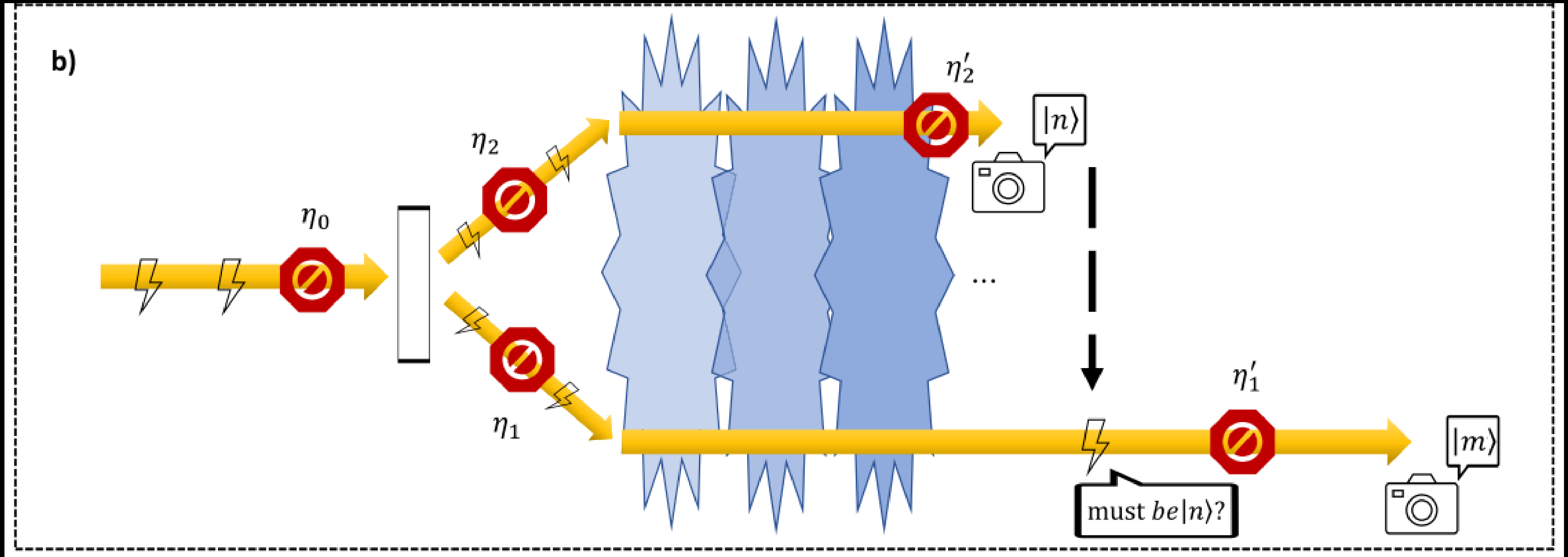
- Herald a Fock state $|n\rangle$, use it to probe η, count photons



Goldberg & Heshami (2022), NJP

Third Story: Transmission Estimation

- But there can also be loss in other places!
  - Multiparameter estimation



Third Story: Transmission Estimation

- Large squeezing $t = \tanh r$
- Transmission too small for quantum advantage; uncertainties at the ultimate statistical limit for this setup