Quantum Optical Simulations of Scattering Observables

Olivier Pfister

U. of Virginia

Quantum computing vs. lattice-gauge QCD calculations?

Collaboration funded by a JLab LDRD award (2021-2023)


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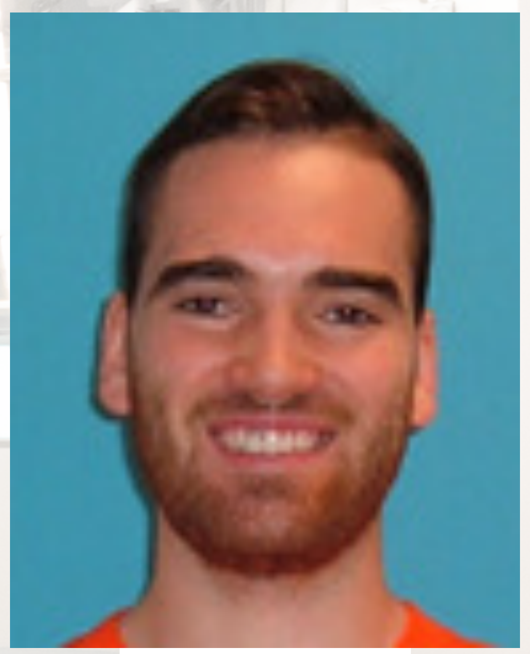
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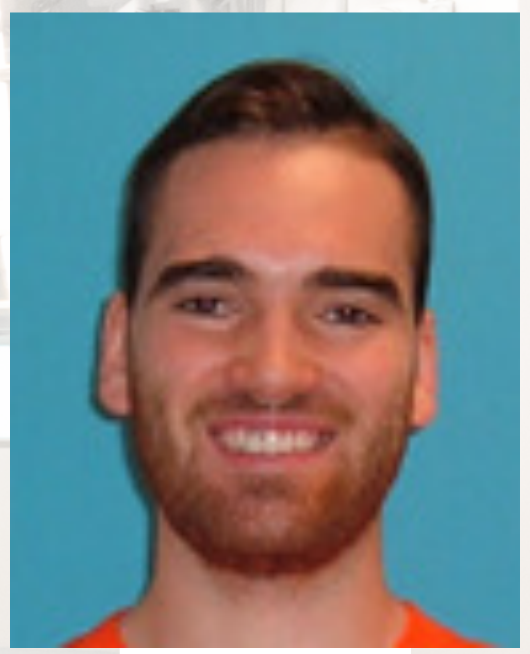
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Toward coherent quantum computation of nuclear physics with a measurement-based photonic quantum processor

arXiv:2312.12613

Raúl A. Briceño*
Department of Physics, University of California, Berkeley, CA 94720, USA and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Robert G. Edwards†
Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA

Miller Eaton, Carlos González-Arciniegas, and Olivier Pfister‡
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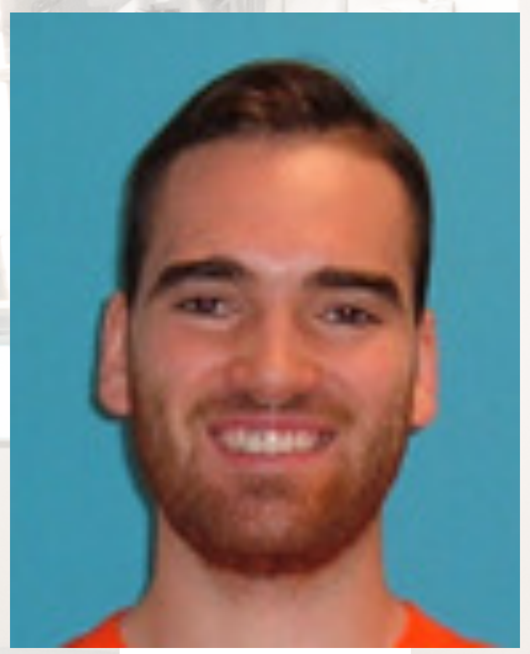
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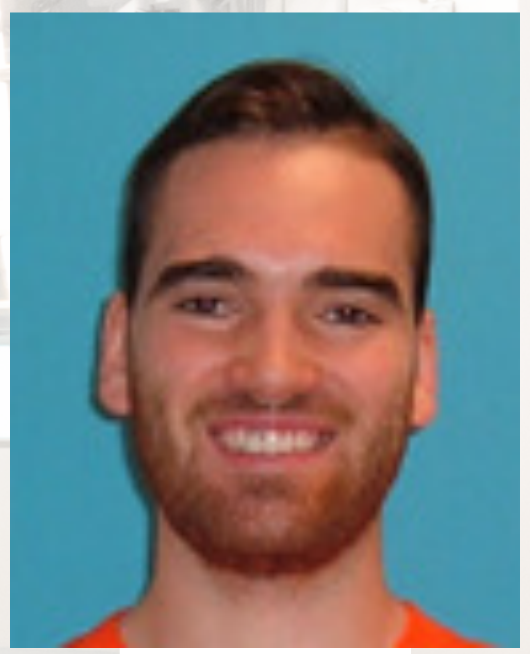

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nature photonics

Article

https://doi.org/10.1038/s41566-022-01105-9

Resolution of 100 photons and quantum generation of unbiased random numbers

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Could QC beat lattice-gauge QCD calculations?

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Quantum Algorithms for Quantum Field Theories

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1 JUNE 2012 VOL 336 **SCIENCE** www.sciencemag.org

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Quantum simulation of quantum field theory using continuous variables

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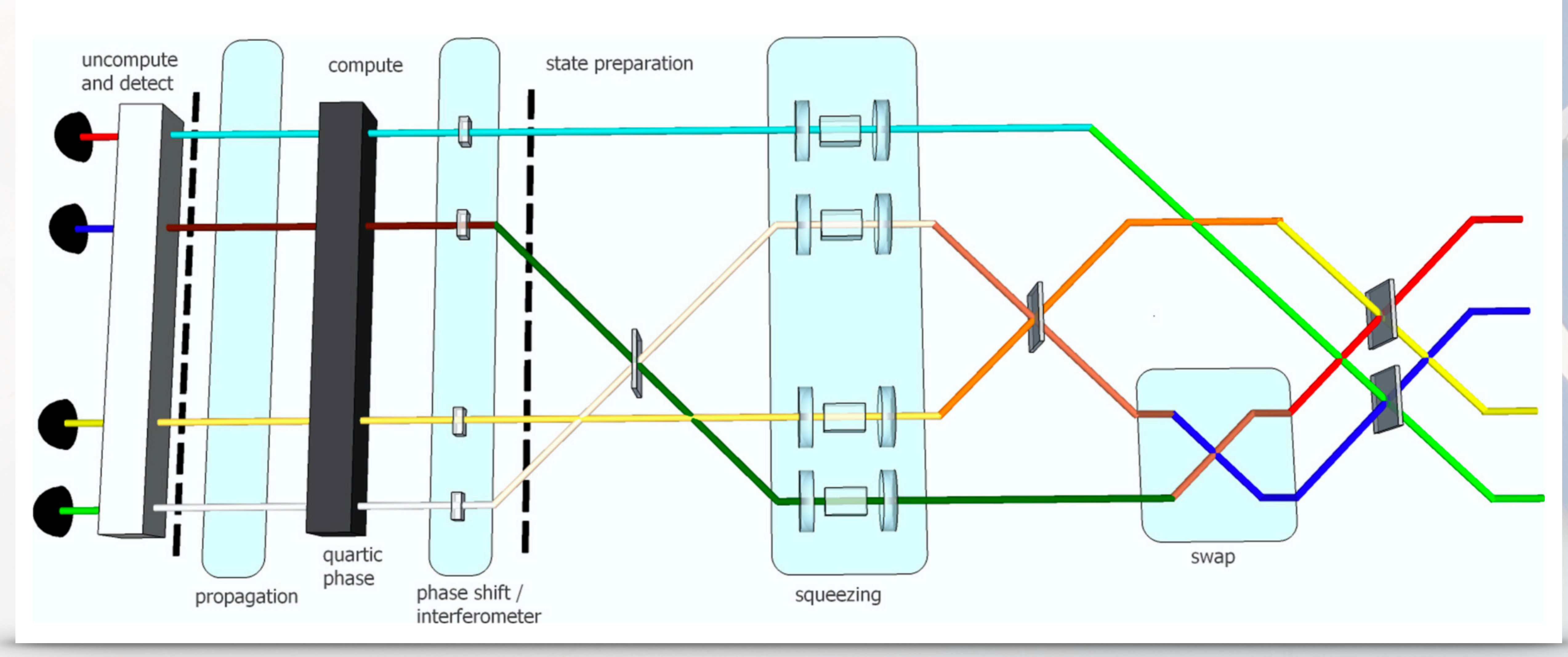

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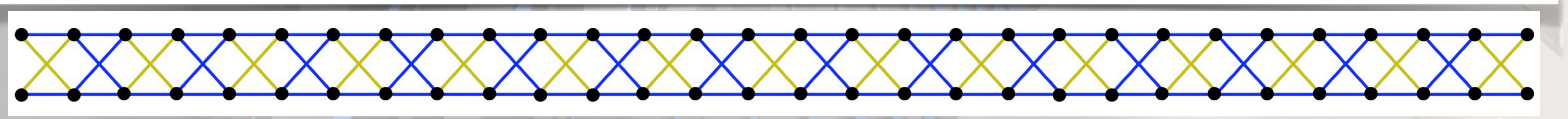
PRL **112,** 120505 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Experimental Realization of Multipartite Entanglement of 60 Modes of a Quantum Optical Frequency Comb

Moran Chen,[1] Nicolas C. Menicucci,[2,*] and Olivier Pfister[1,†]
[1]*Department of Physics, University of Virginia, Charlottesville, Virginia 22903, USA*
[2]*School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*



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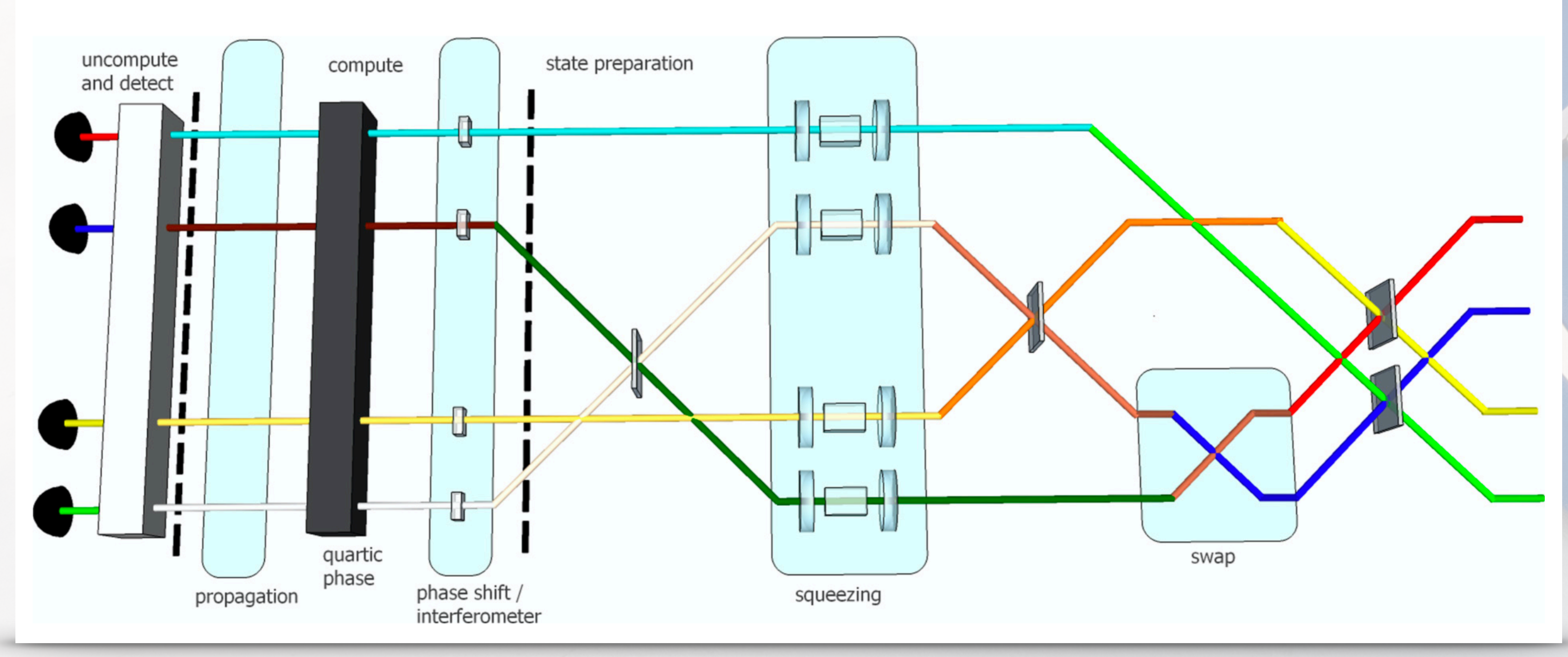

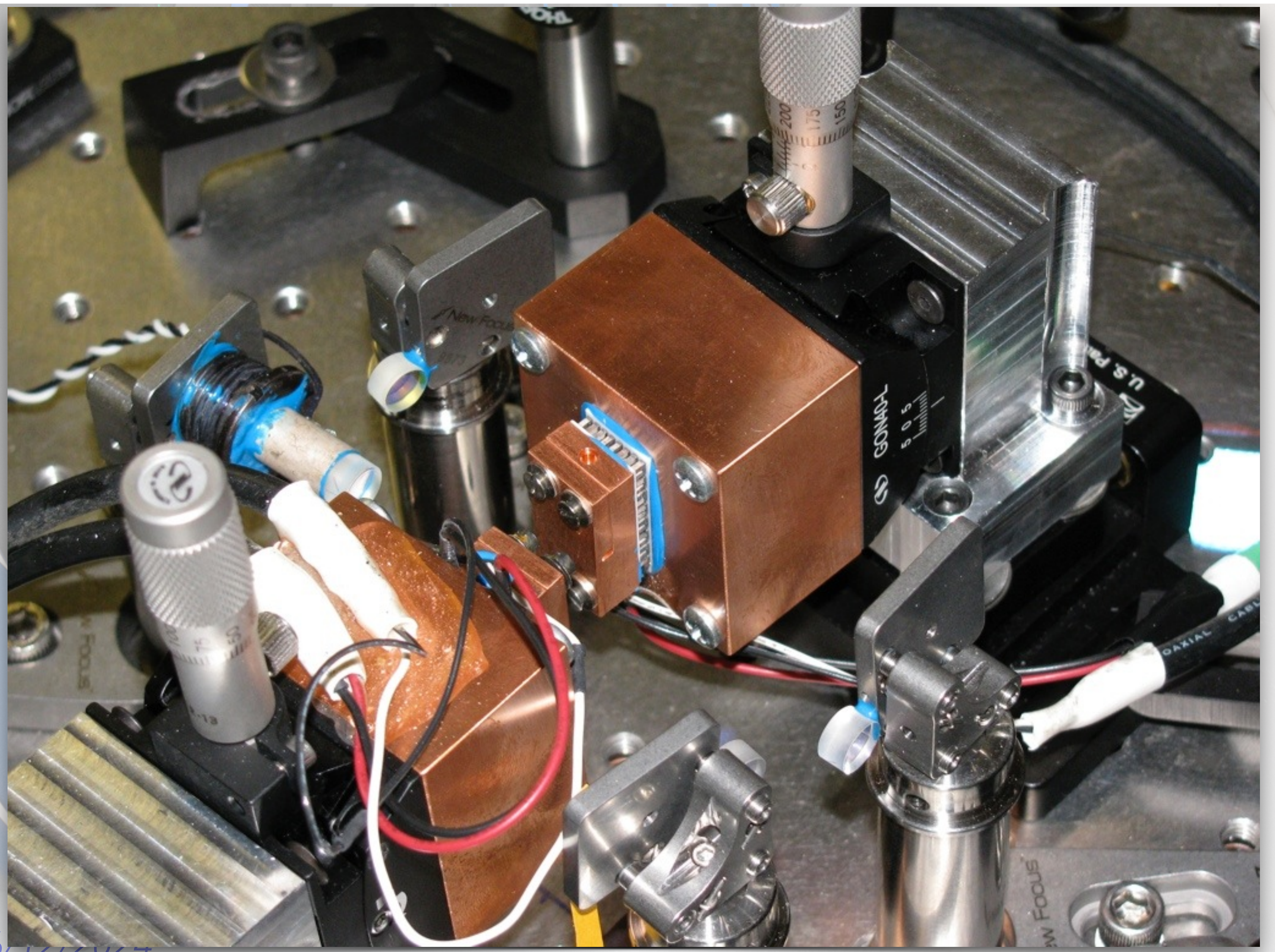

Quantum simulation of fields with fields

- Consider complex scalar fields $[\phi(x), \pi(x')] = i\delta(x - x')$ and a ϕ^4 QFT Hamiltonian

$$H = \sum_{x=0}^{L-1} \left[\pi^\dagger(x)\pi(x) + \nabla\phi^\dagger(x)\nabla\phi(x) + m_0^2\phi^\dagger(x)\phi(x) + \frac{\lambda}{4}(\phi^\dagger(x)\phi(x))^2 \right]$$

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Non-Gaussian quantum optics

The quantum optics toolbox: leveraging MBQC

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- the universal gate set of quantum computing (i.e., any quantum gate)
- quantum error correction

can all be implemented using measurement-based quantum computing

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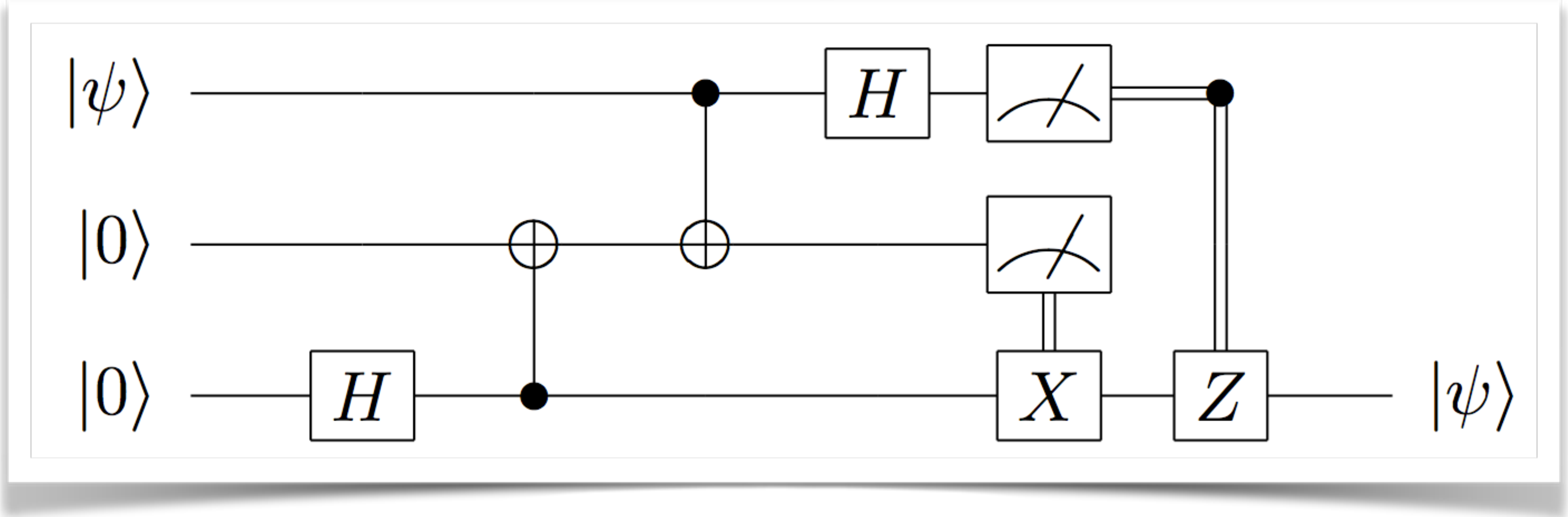

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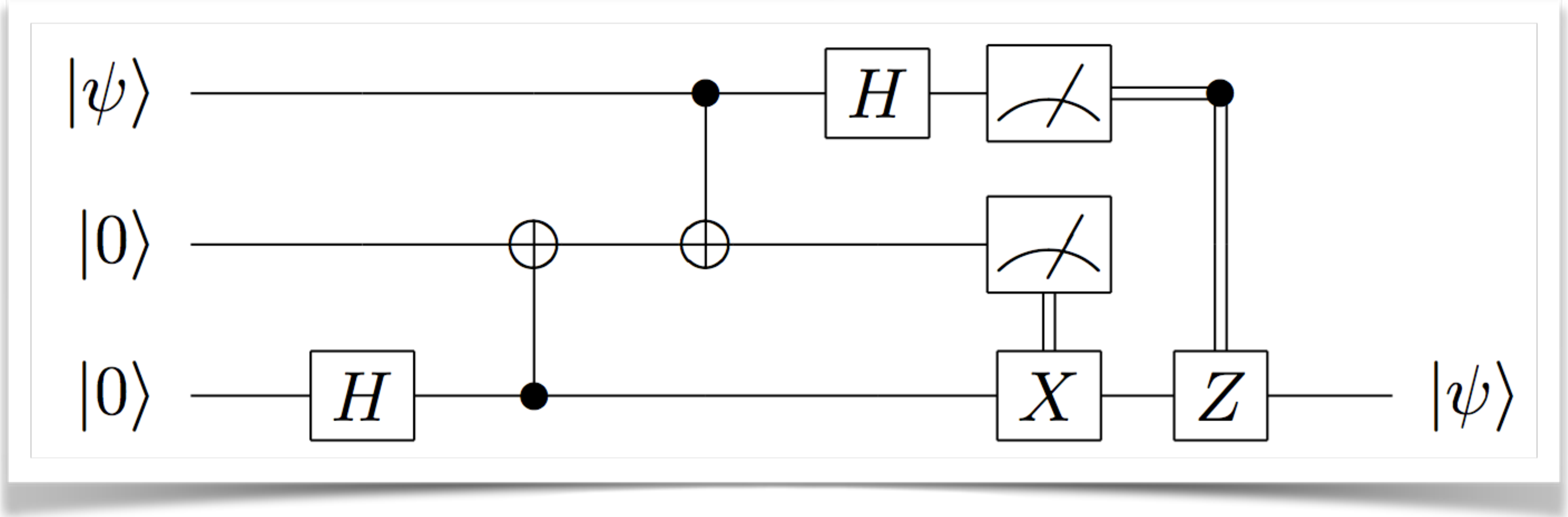

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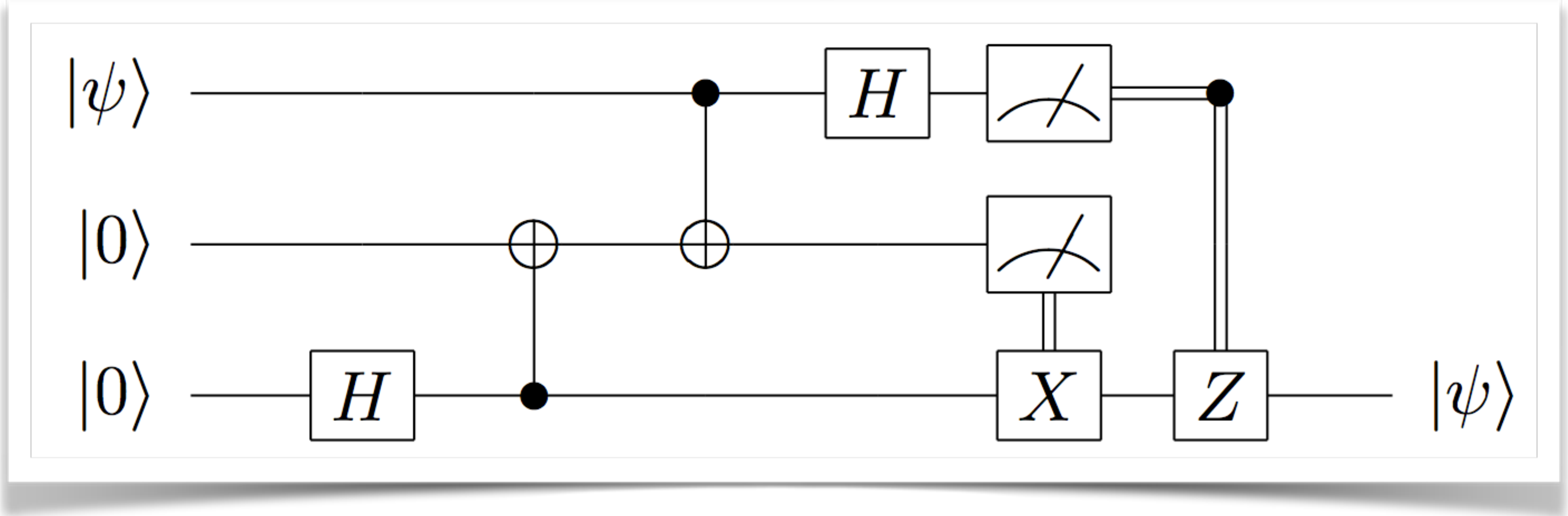

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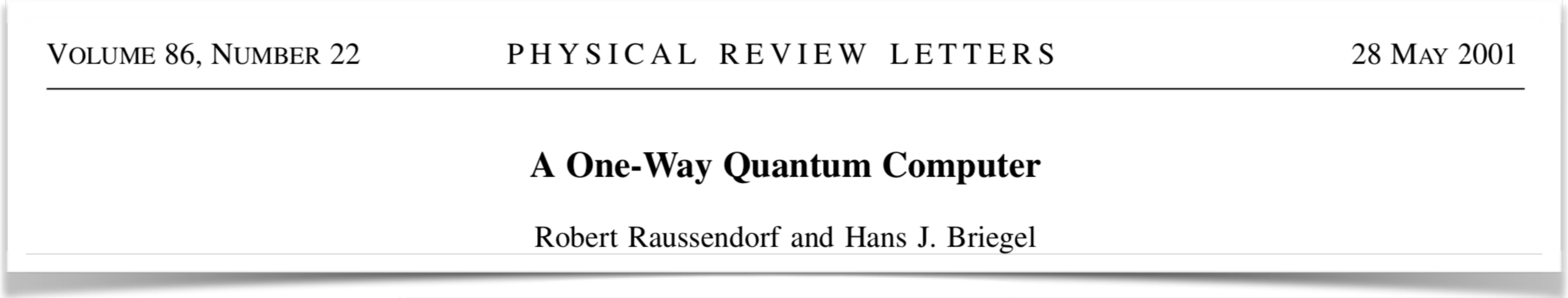
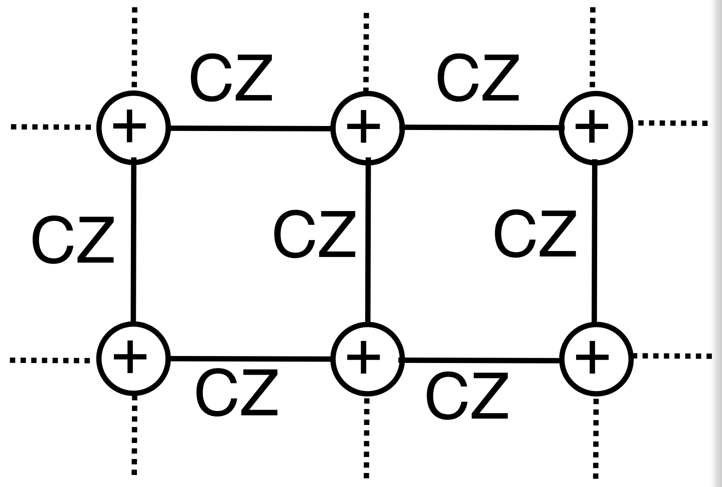


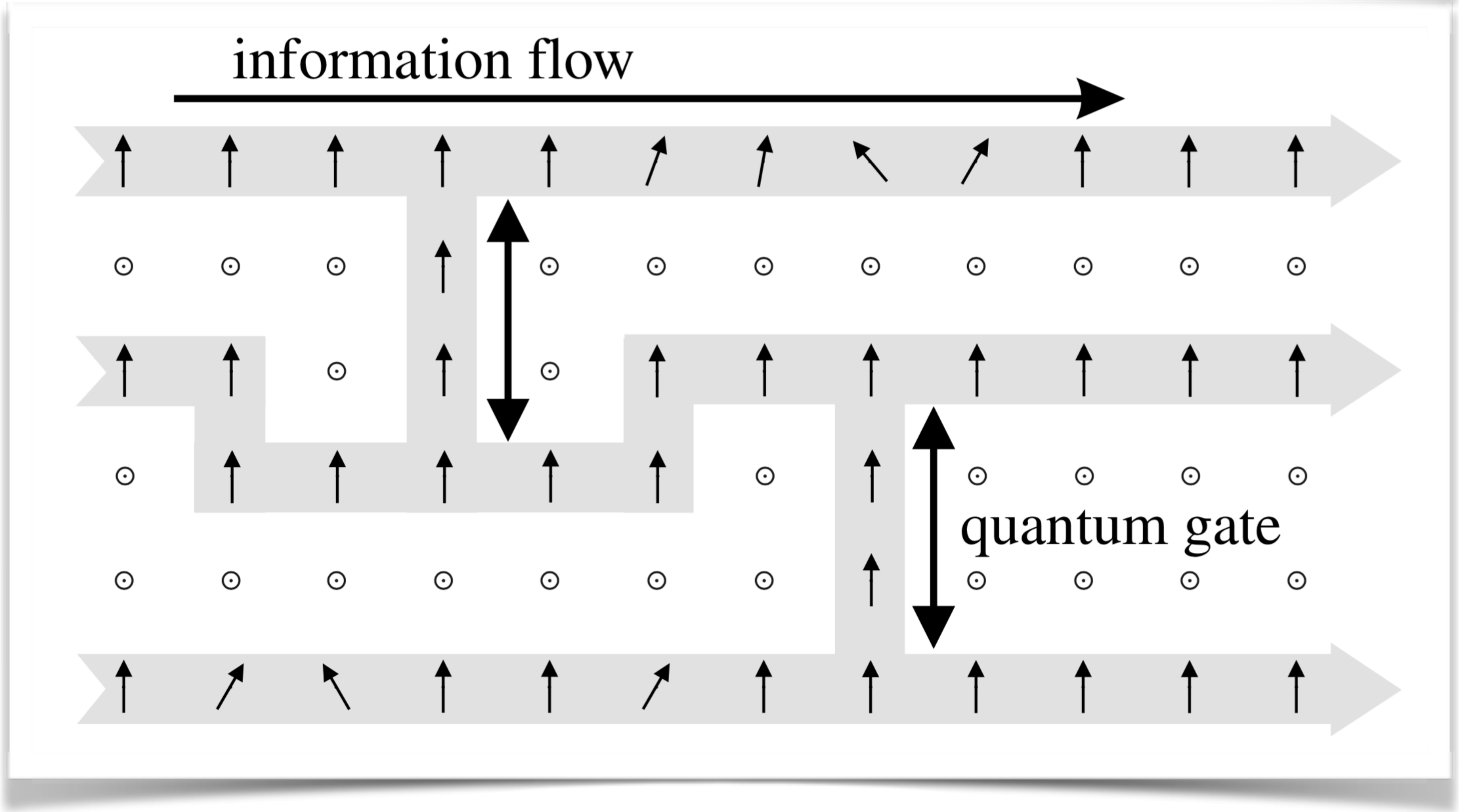
VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel



Cluster state



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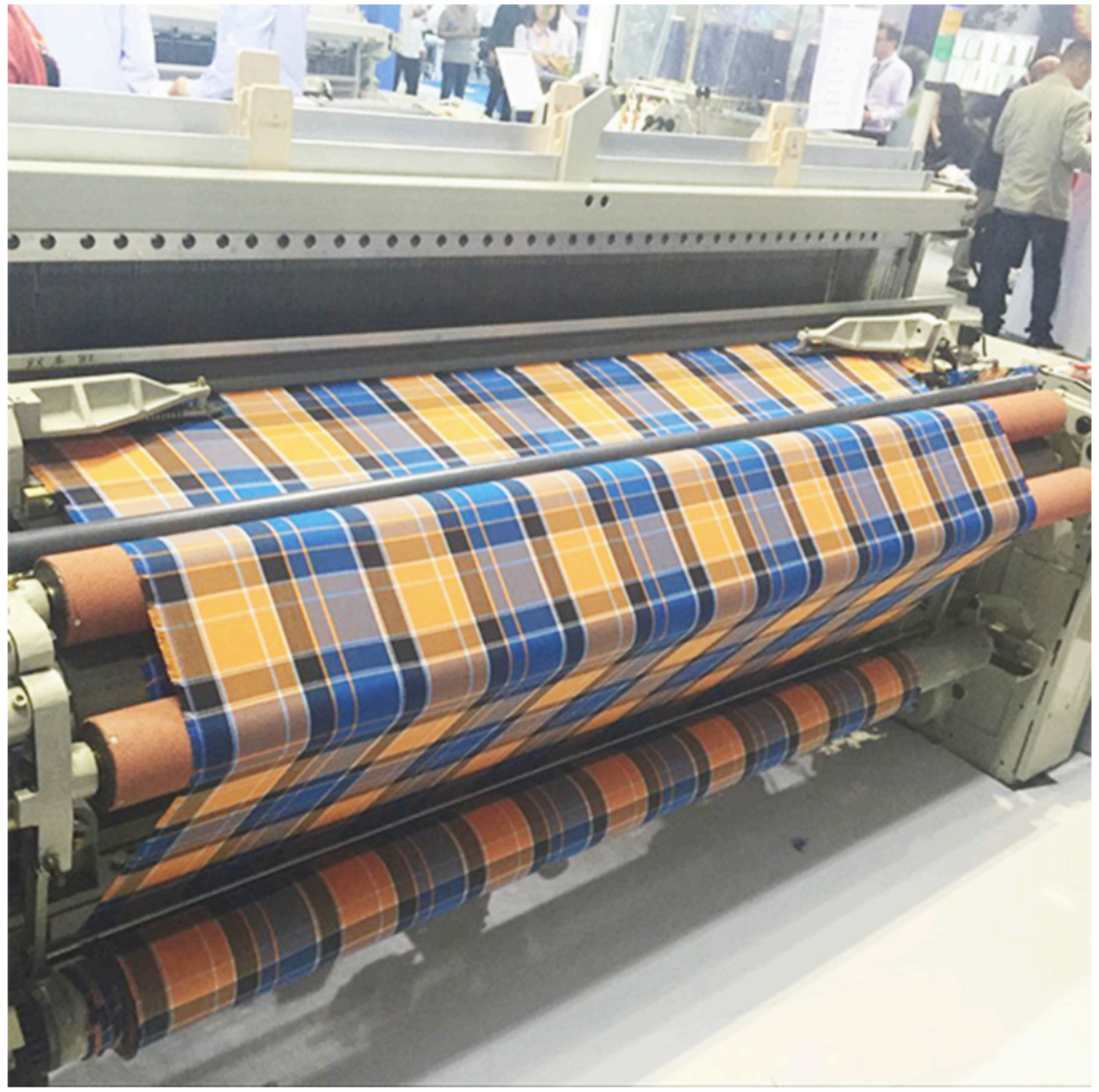
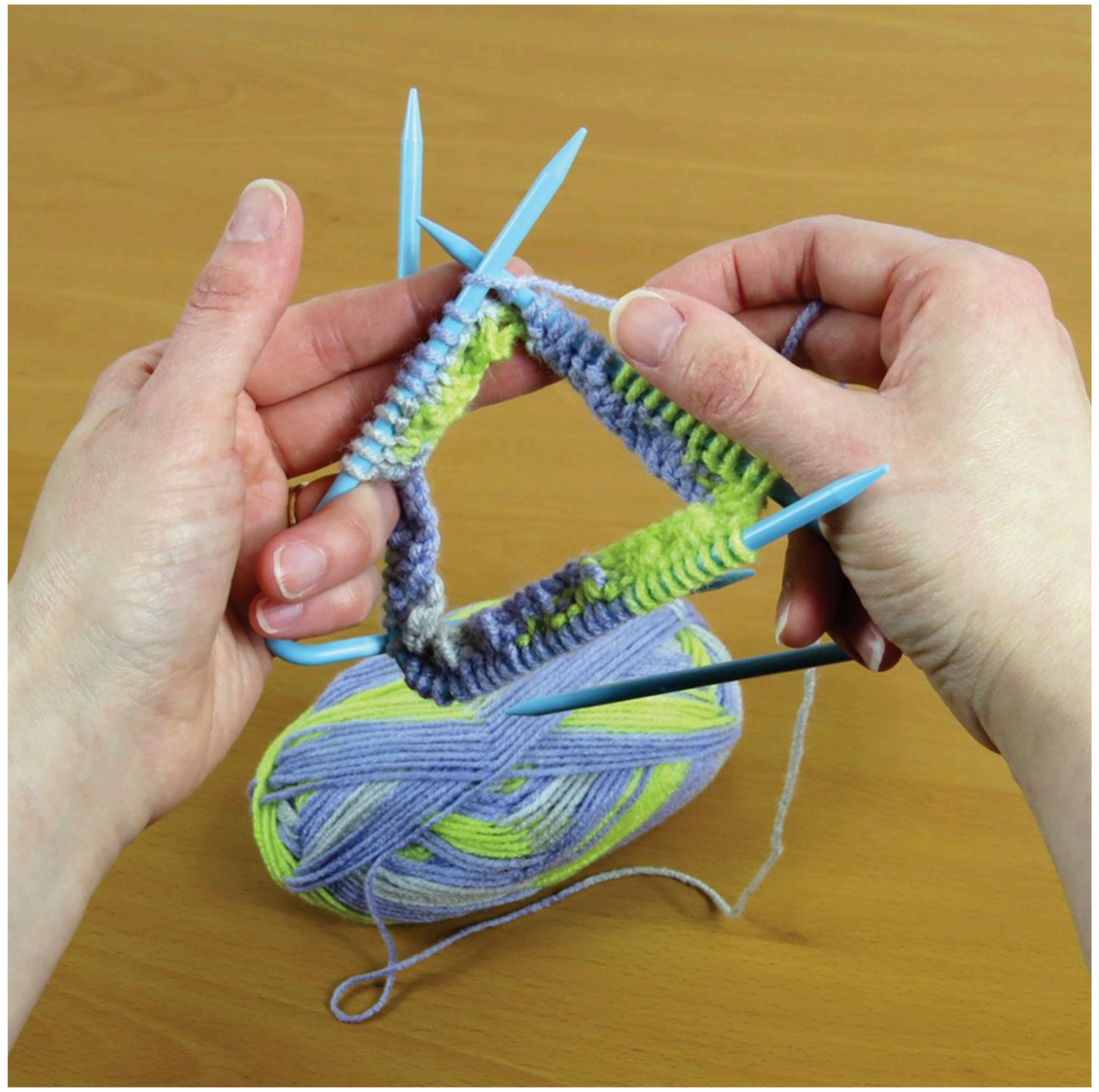
Top down

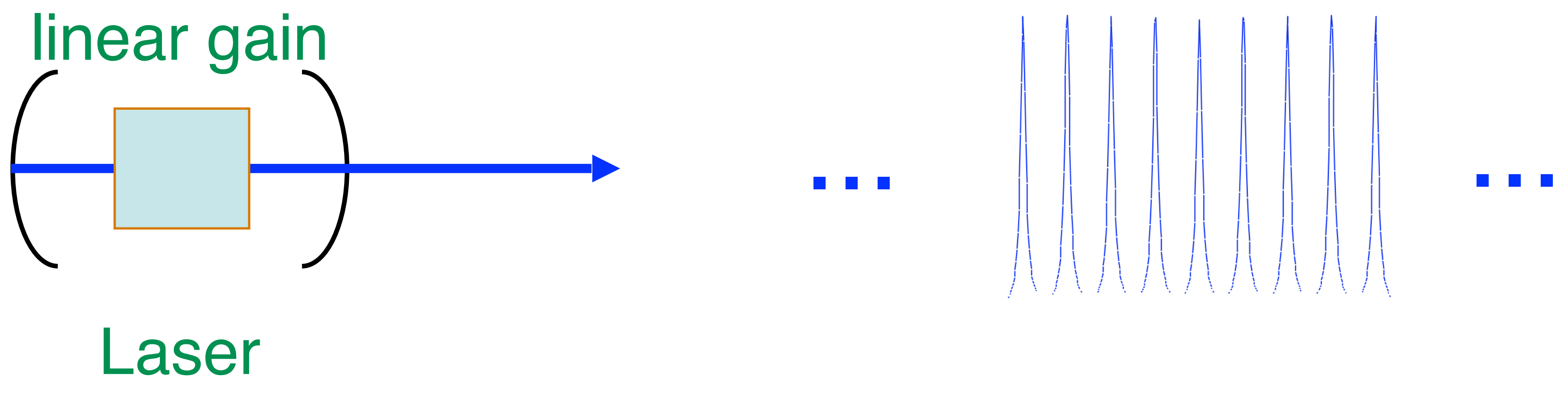


Bottom up



From the optical frequency comb (OFC)…

The eigenmodes of a cavity form a large ensemble of classically coherent modes
Carrier-envelope-phase locked mode-locked laser = **optical frequency comb**
(as many as 10^6 modes oscillating in phase)



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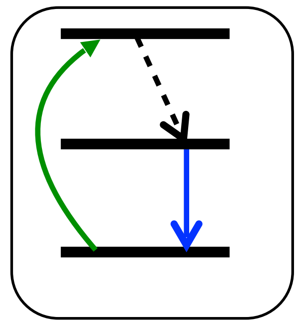

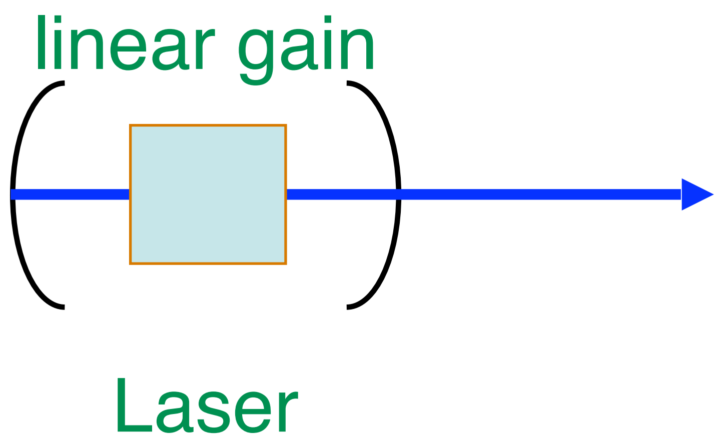

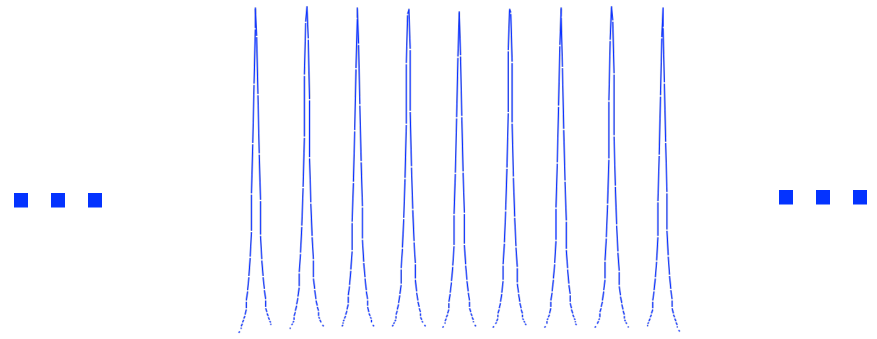


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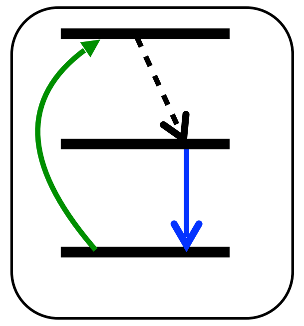

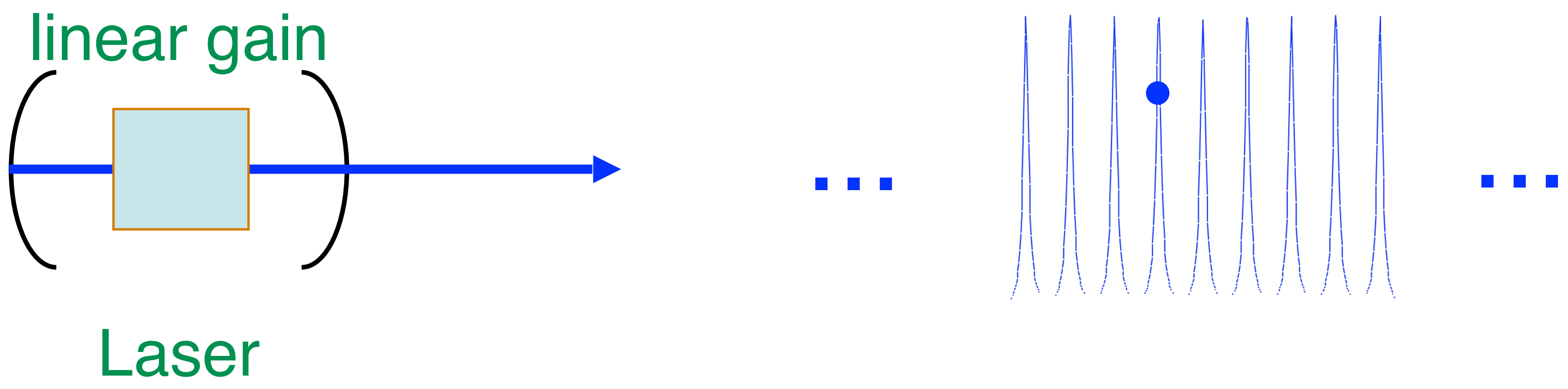

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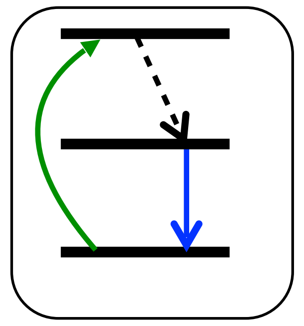

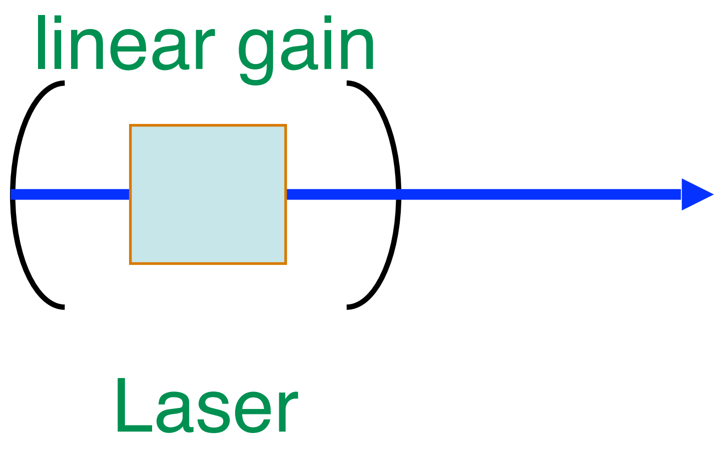

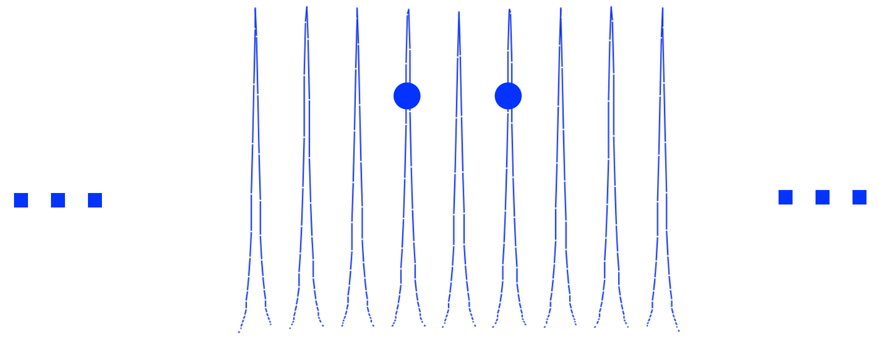

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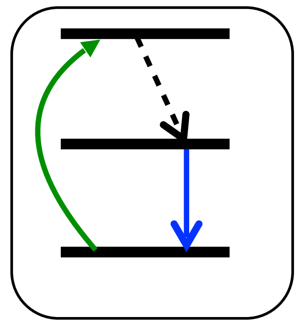

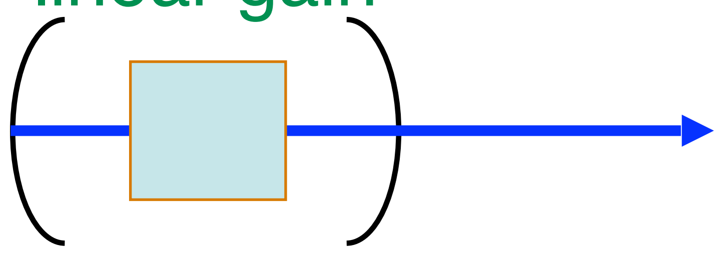

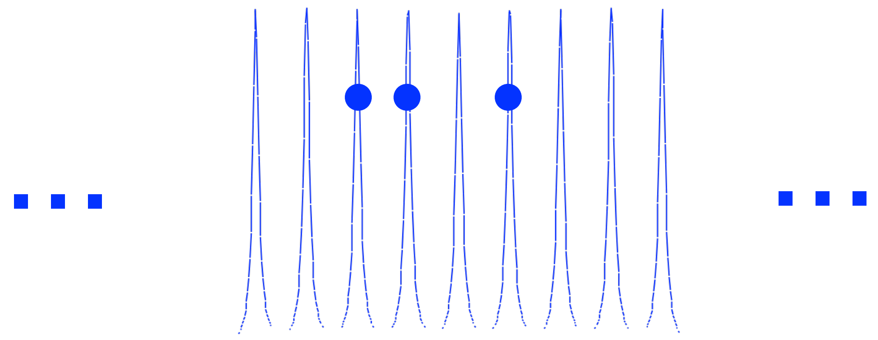

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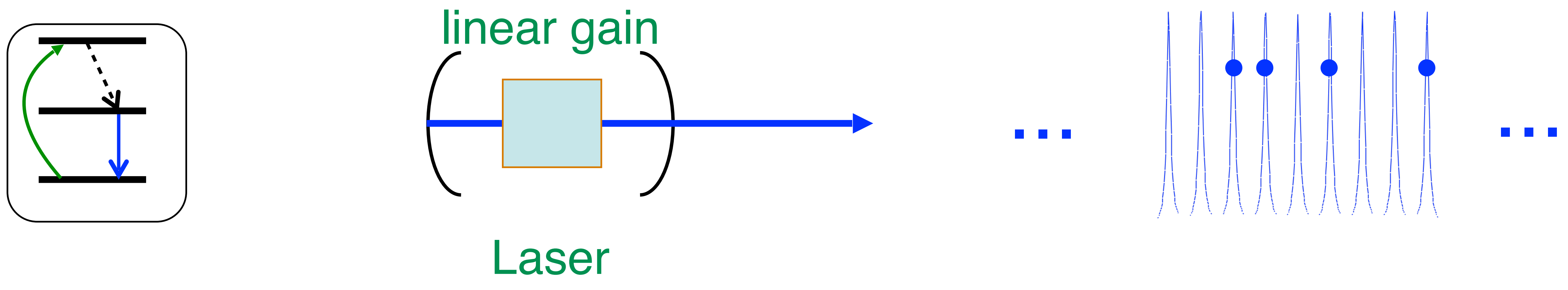

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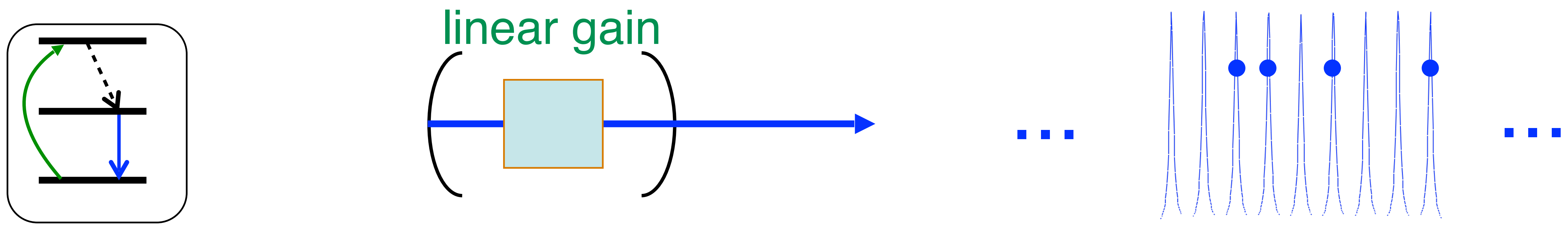

Laser


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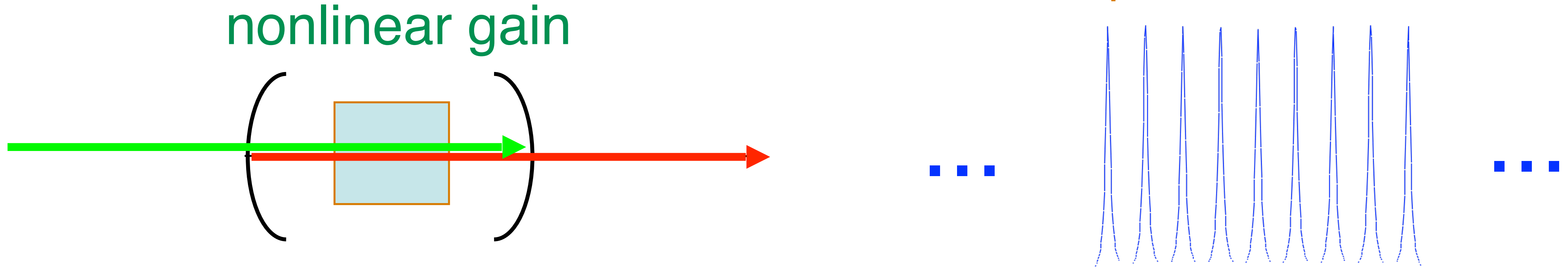
… to the *entangled* OFC: a quantum computer?



Optical Parametric Oscillator
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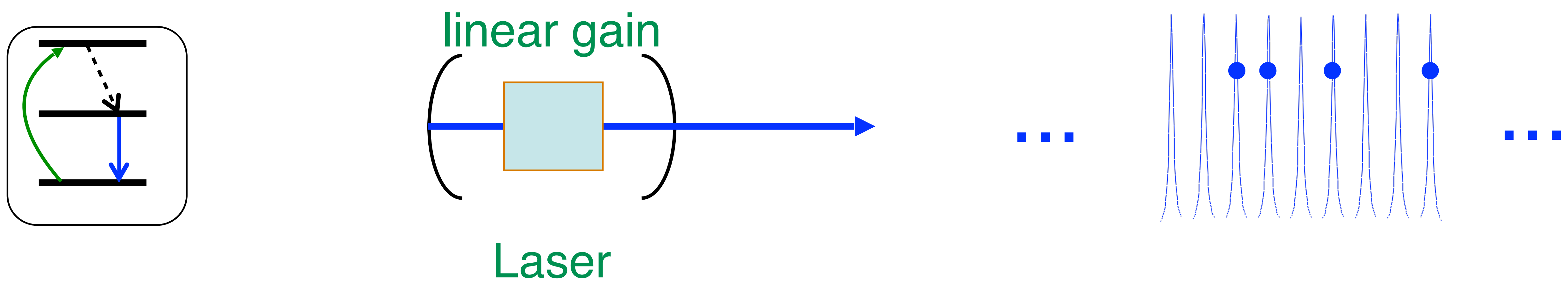

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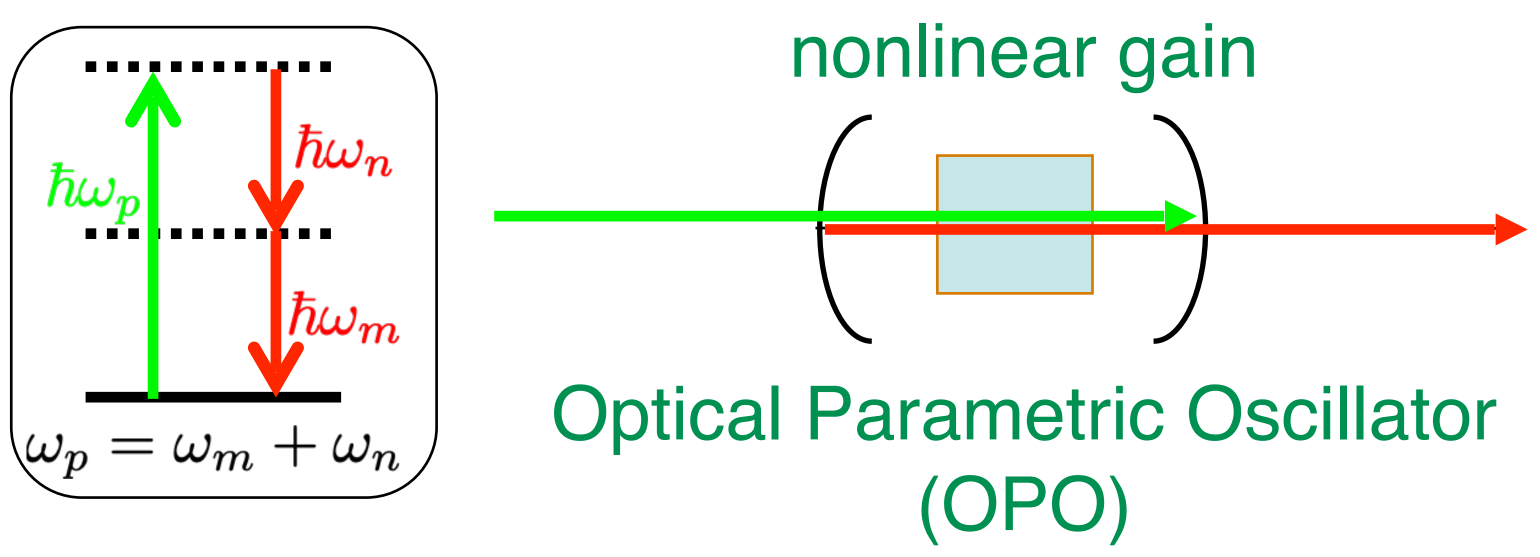

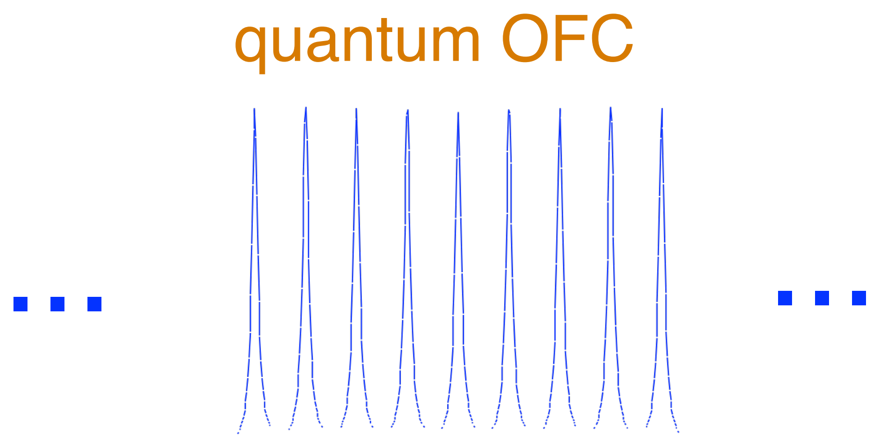

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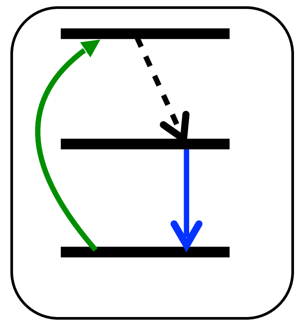
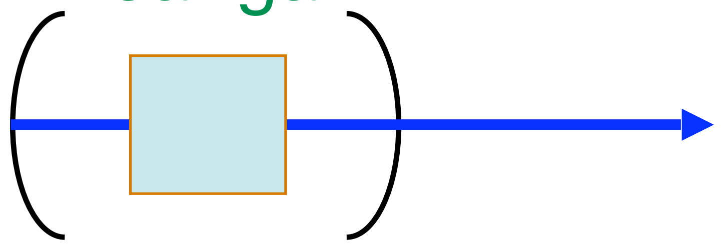


linear gain



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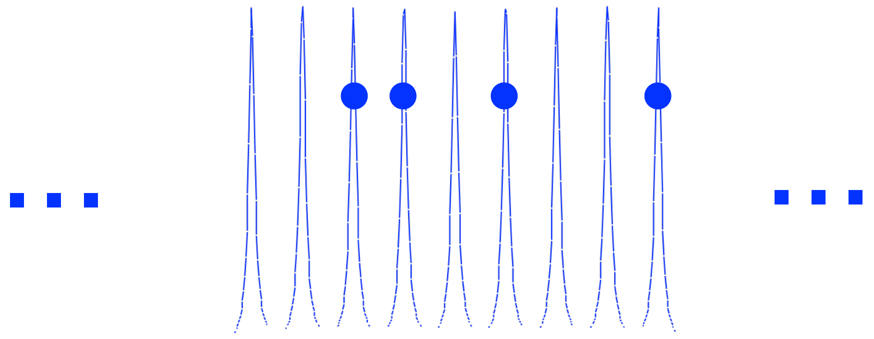

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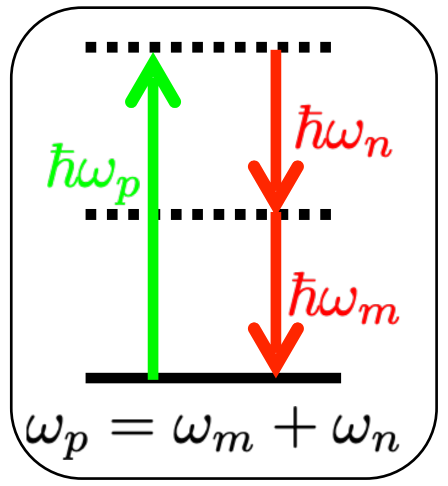

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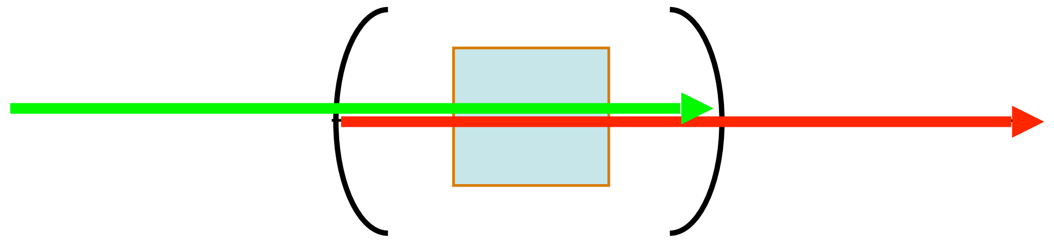

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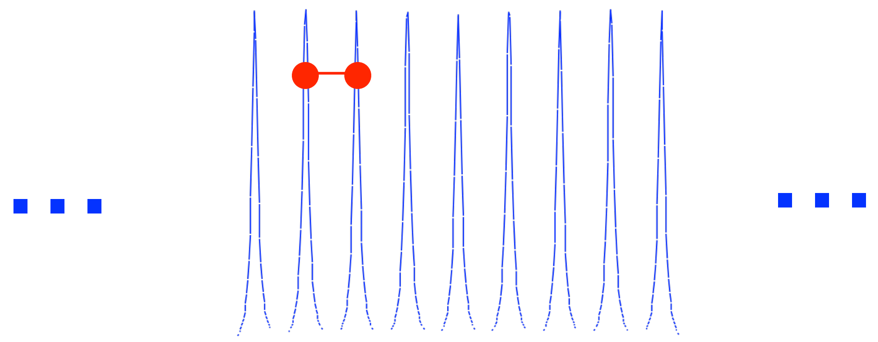
quantum OFC



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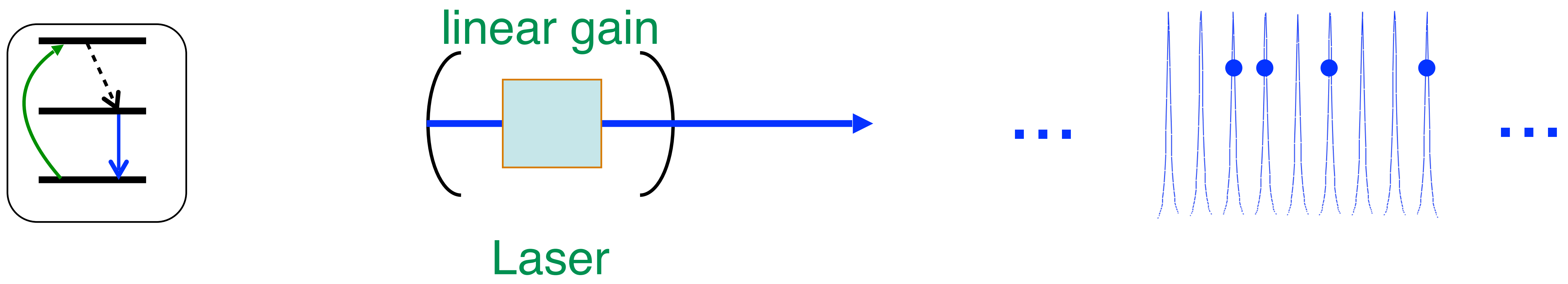
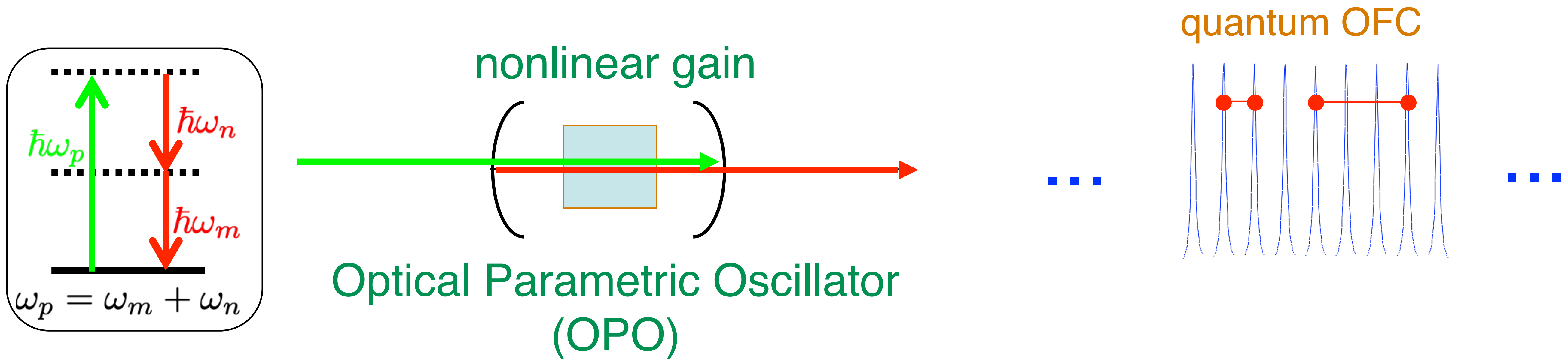


John L. Hall

Theodor W. Hänsch

... to the *entangled* OFC: a quantum computer?



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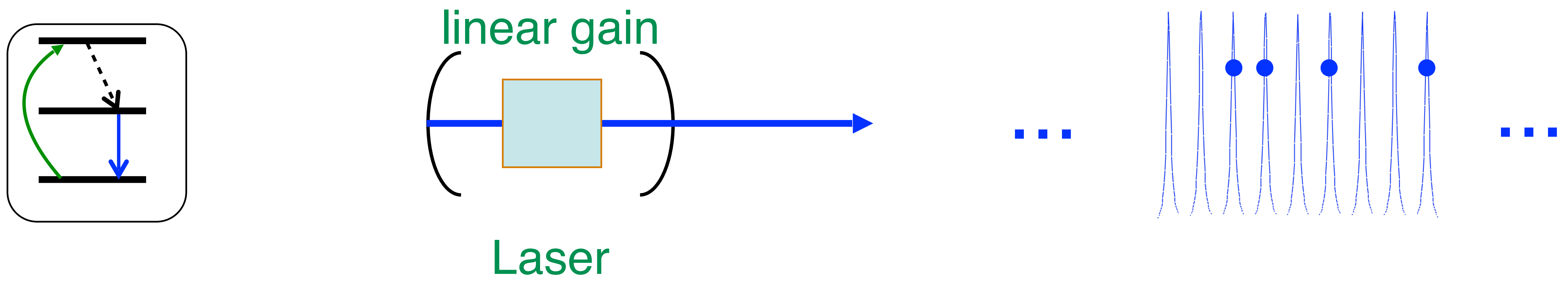


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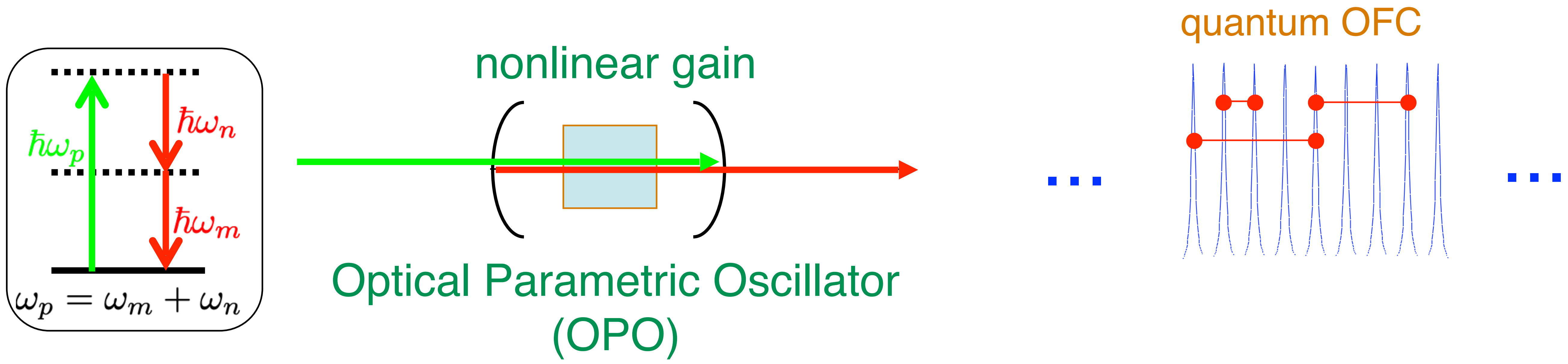

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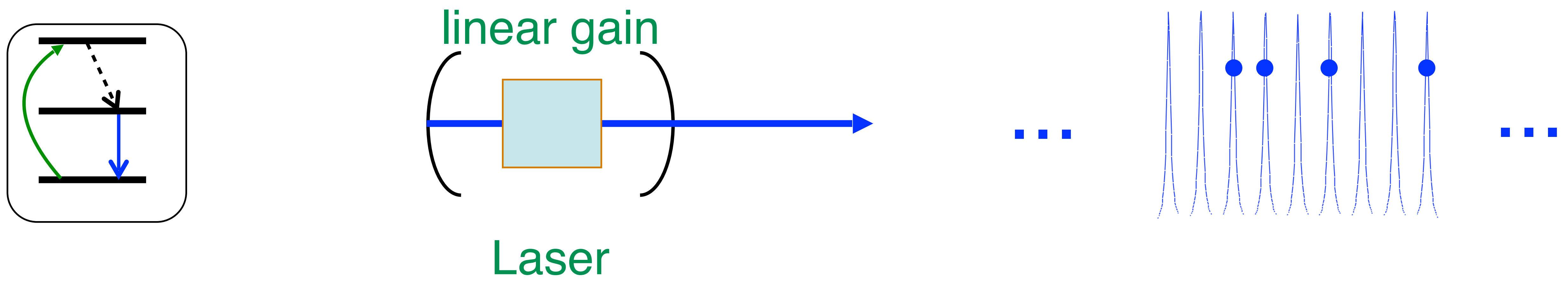


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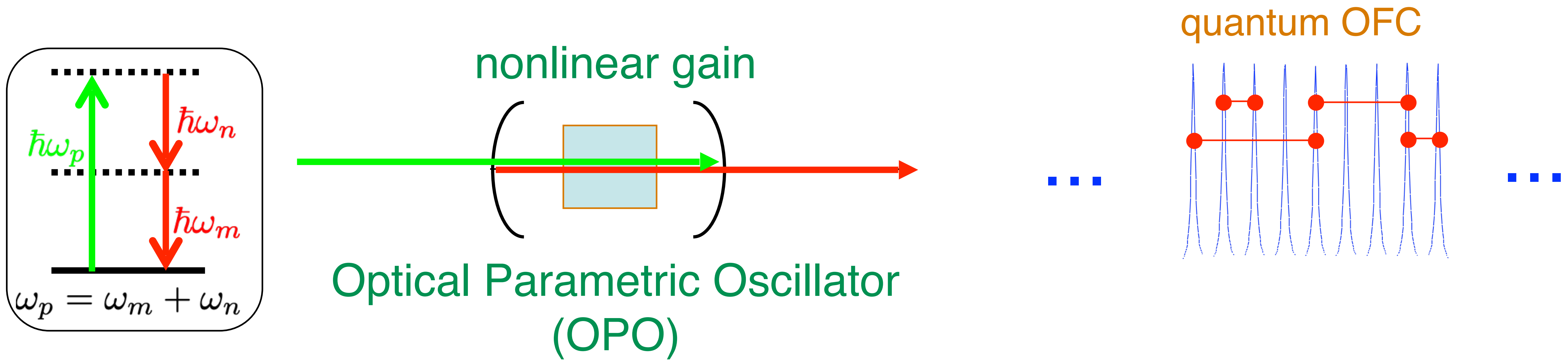

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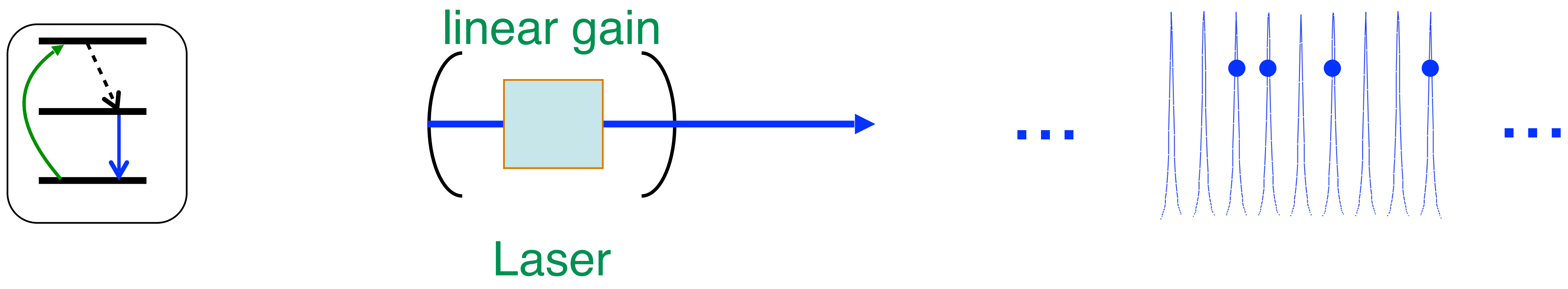

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Theodor W. Hänsch

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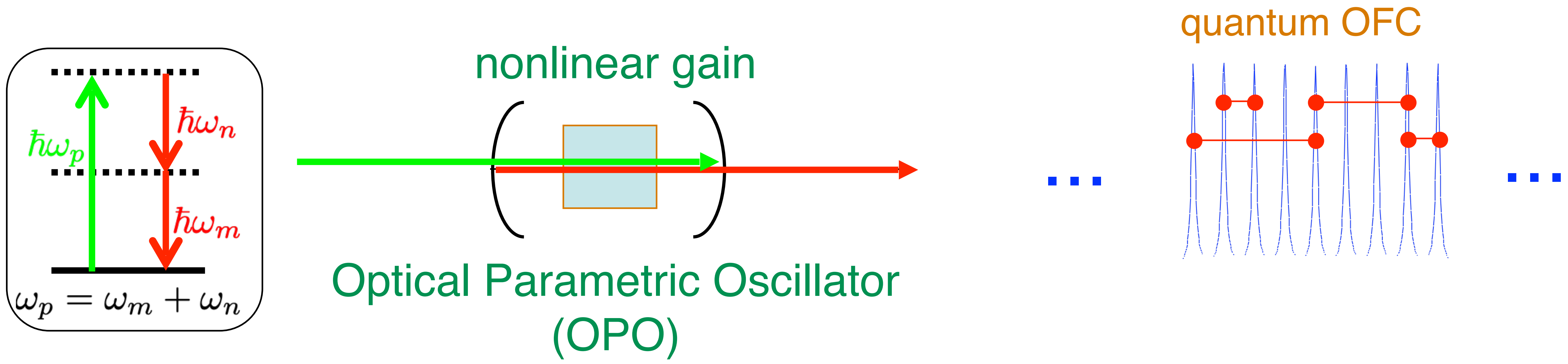
- **Cluster-state** entanglement in one fell swoop



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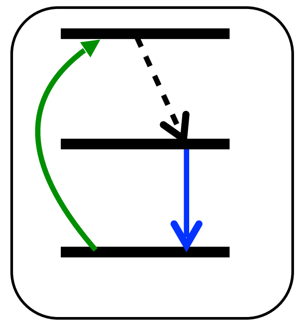

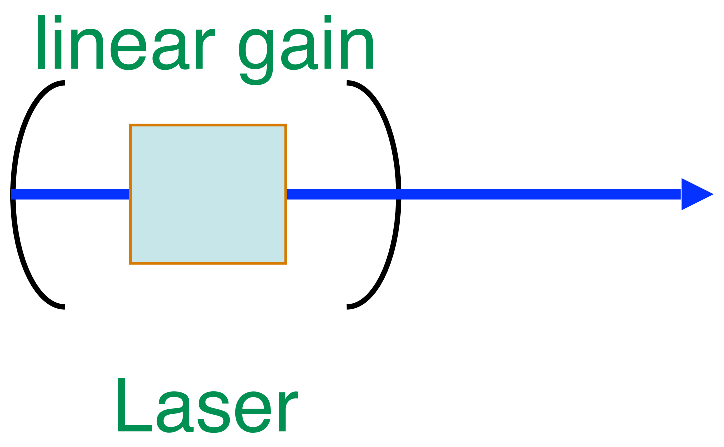

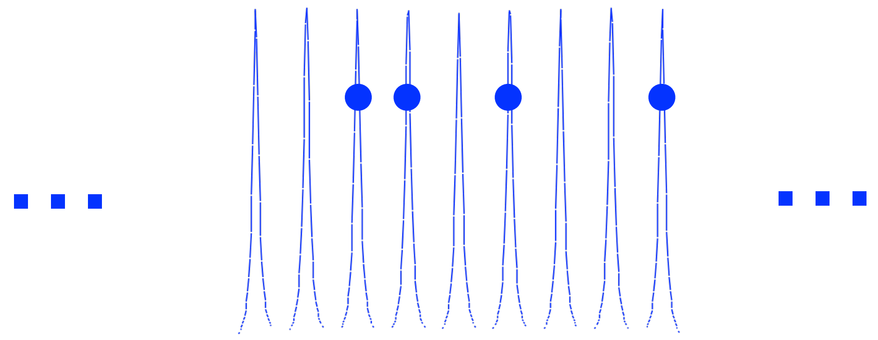


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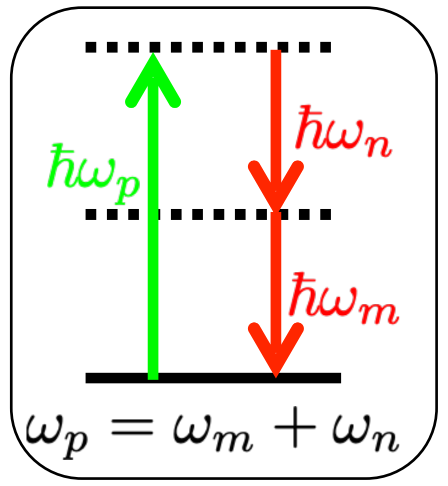
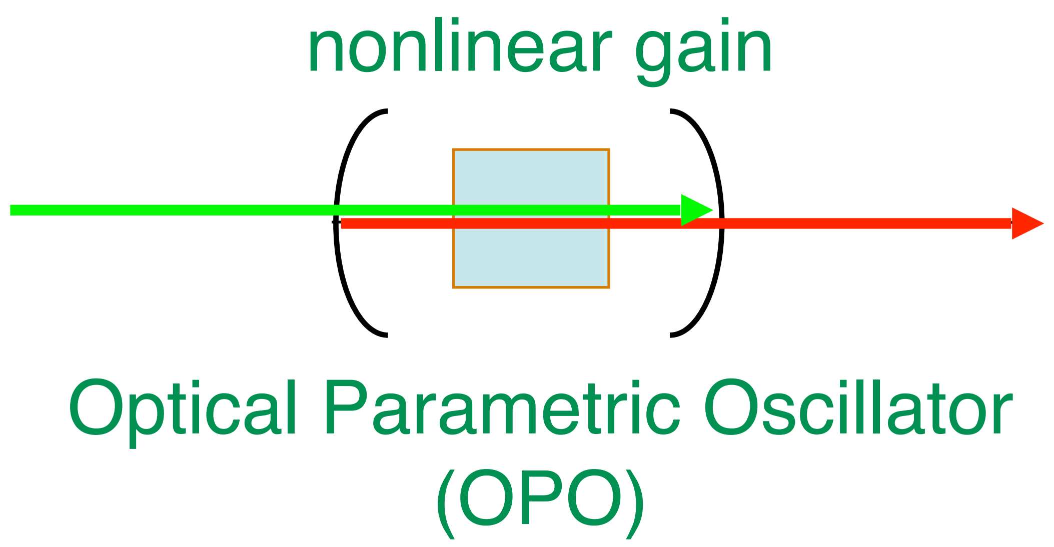
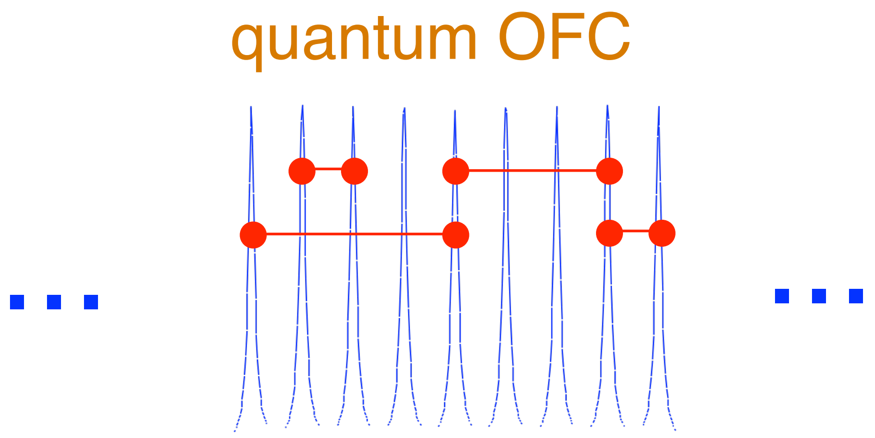
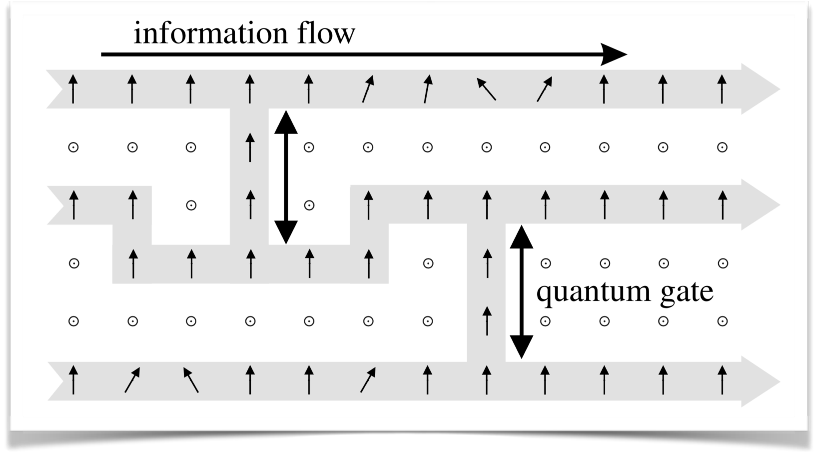
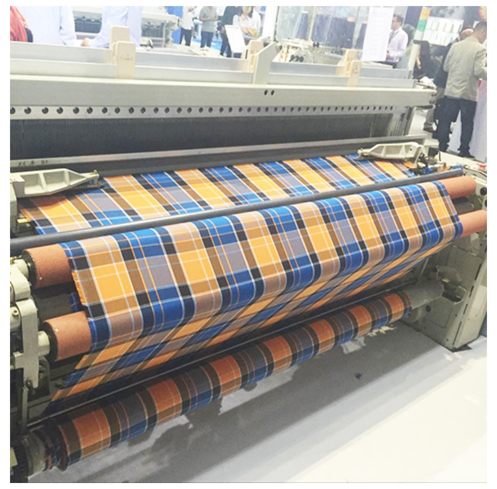




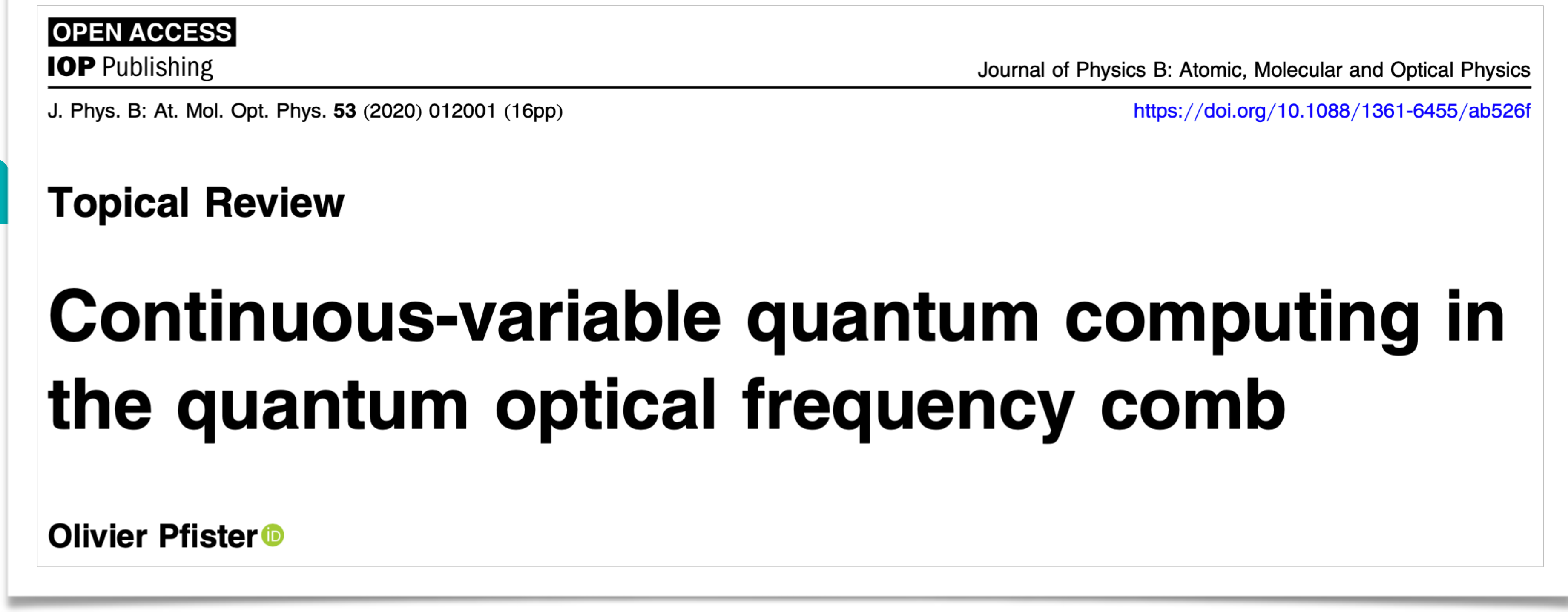


- **Cluster-state** entanglement in one fell swoop
- A top-down, large-scale quantum register of ENTANGLED QUANTUM FIELDS ("QUMODES") rather than qubits.





From the optical frequency con


OPEN ACCESS
IOP Publishing
Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. **53** (2020) 012001 (16pp)
https://doi.org/10.1088/1361-6455/ab526f

Topical Review

Continuous-variable quantum computing in the quantum optical frequency comb

Olivier Pfister

The eigenmodes of a cavity form a large ensemble of classically coherent modes

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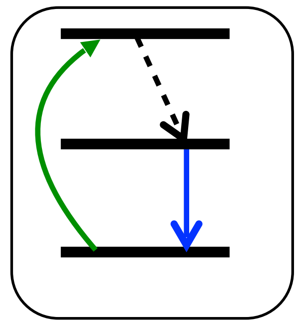

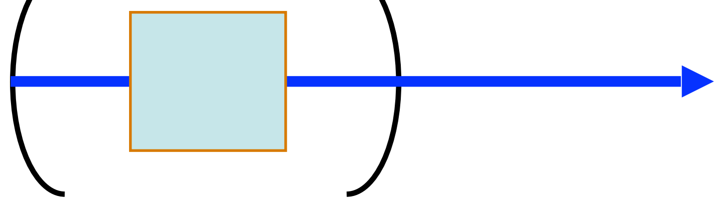

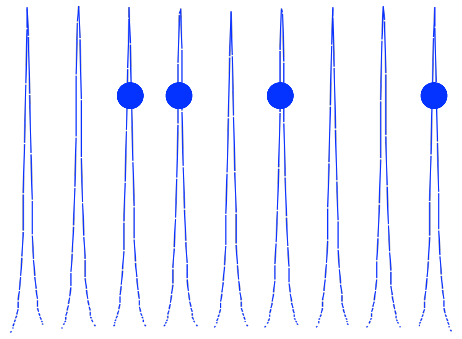

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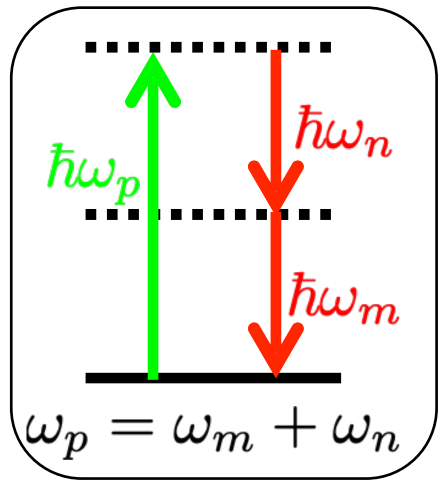

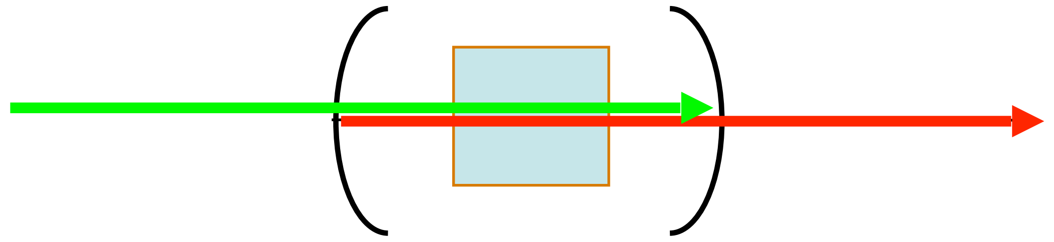

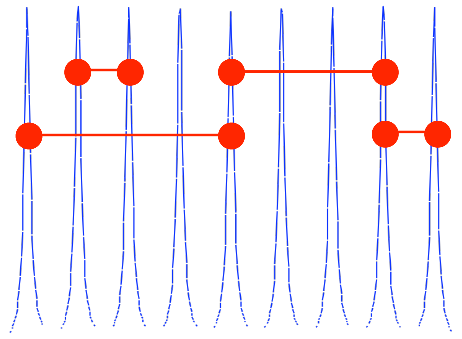

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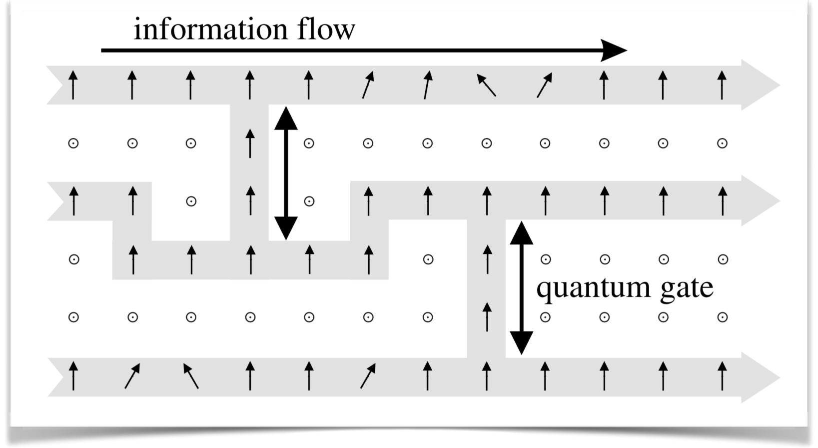
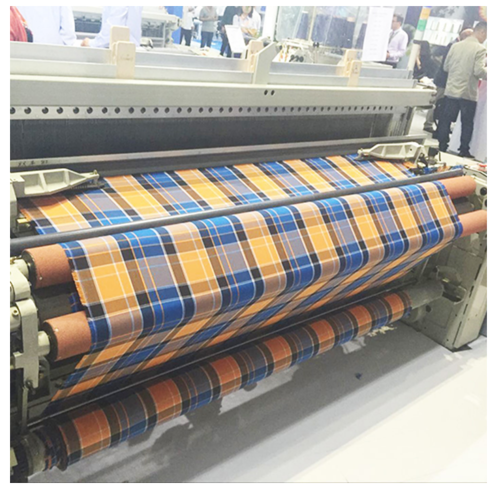
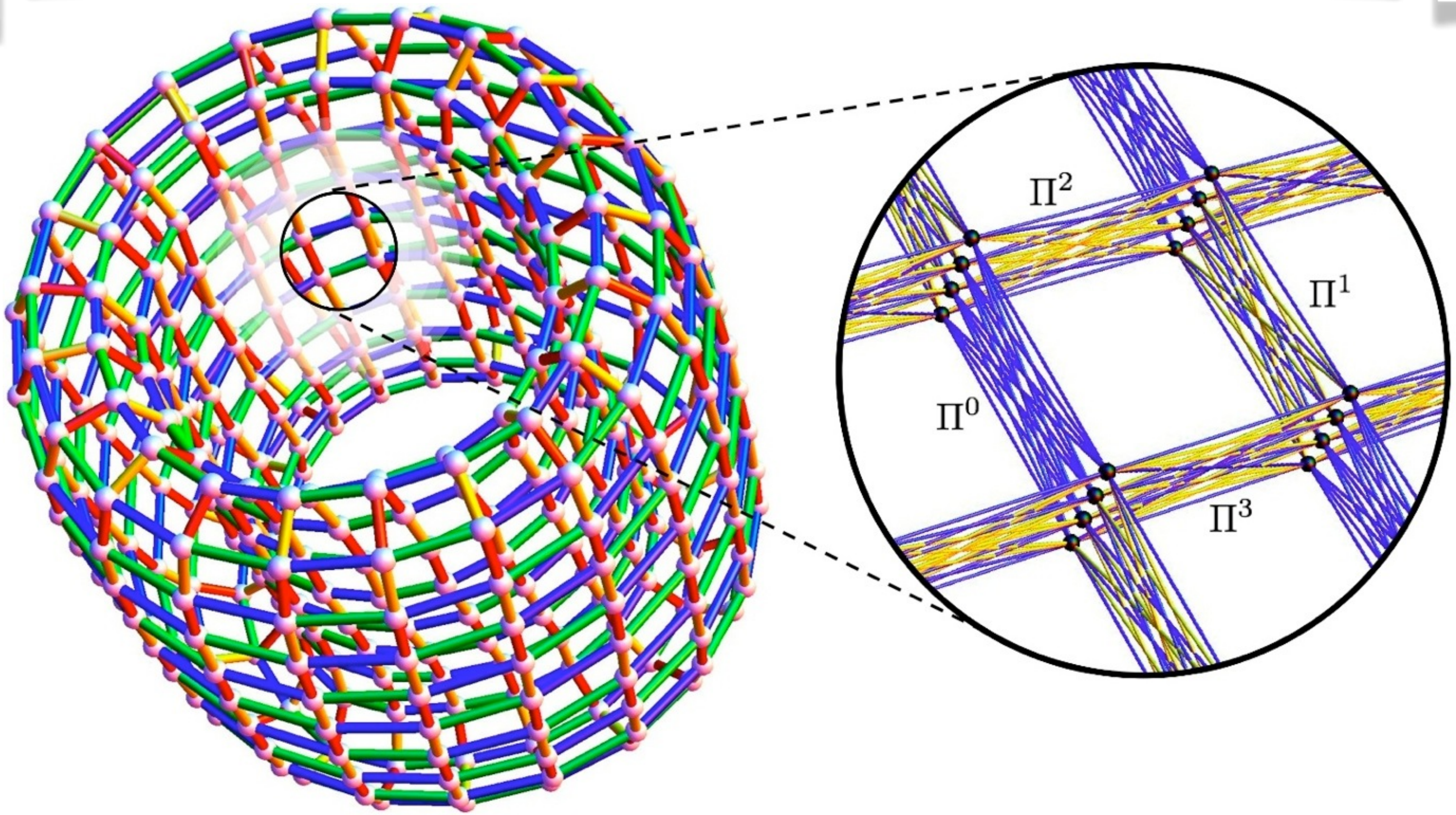




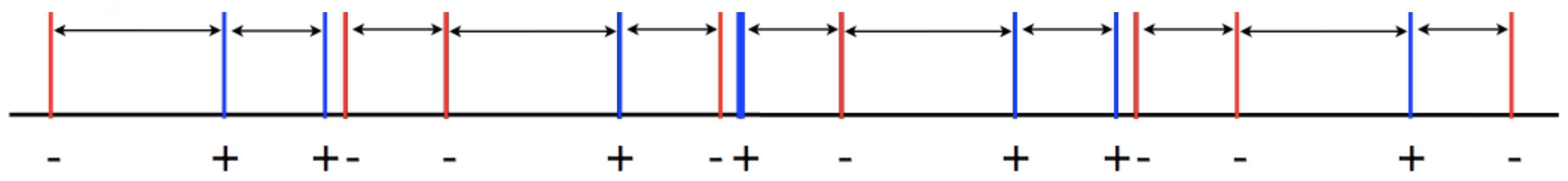
Selected for a Viewpoint in *Physics*
PRL **101,** 130501 (2008) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2008

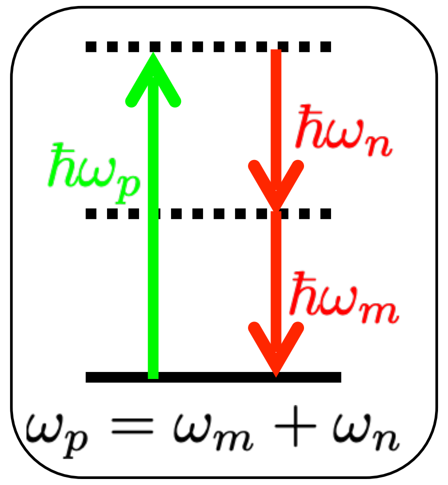
One-Way Quantum Computing in the Optical Frequency Comb

Nicolas C. Menicucci,[1,2] Steven T. Flammia,[3] and Olivier Pfister[4]



15 pump modes into YZY, ZZZ, ZYY

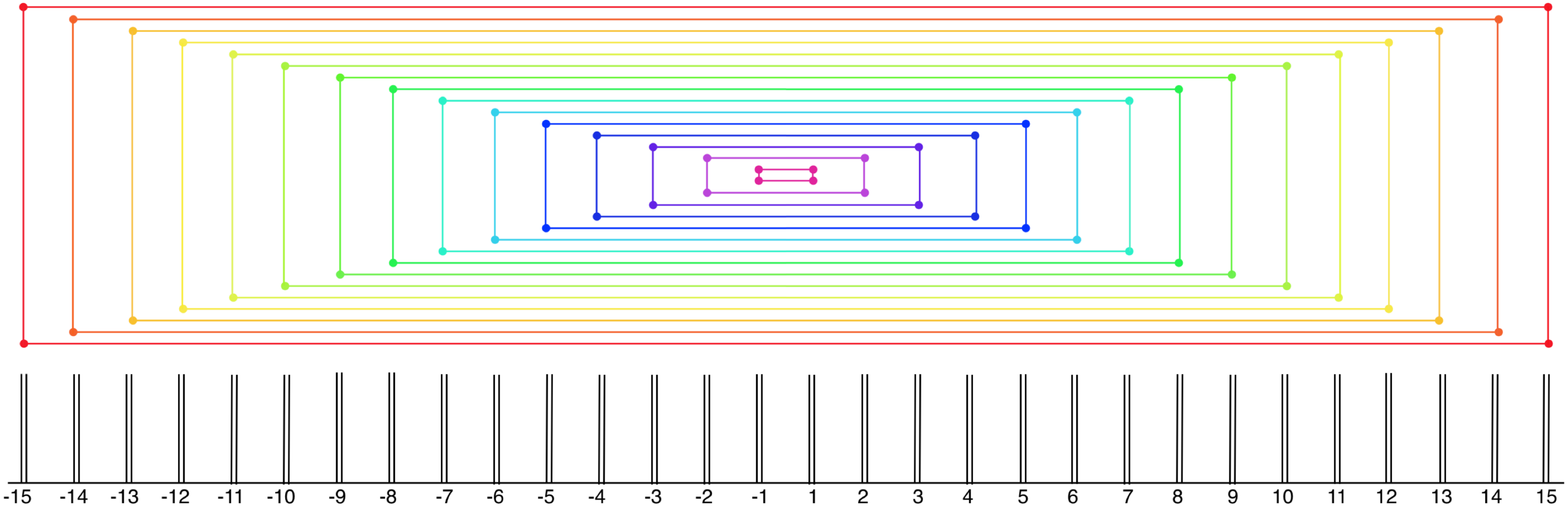




PRL 107, 030505 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Parallel Generation of Quadripartite Cluster Entanglement in the Optical Frequency Comb

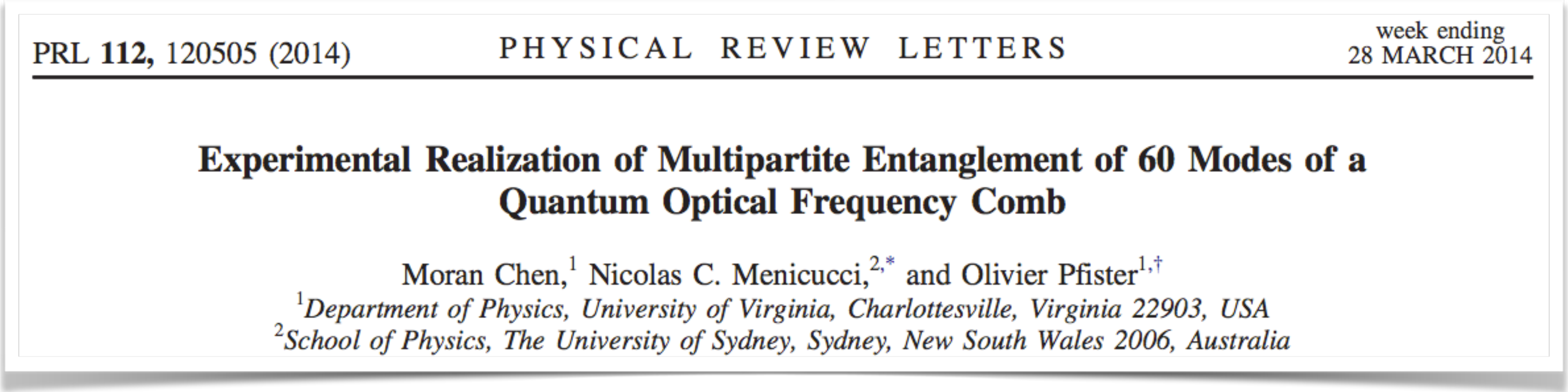
Matthew Pysher,[1] Yoshichika Miwa,[2] Reihaneh Shahrokhshahi,[1] Russell Bloomer,[1] and Olivier Pfister[1,*]



Entanglement gets scaled up in an optical frequency comb

Using a single nonlinear optical element, researchers have entangled dozens of the comb's optical modes.

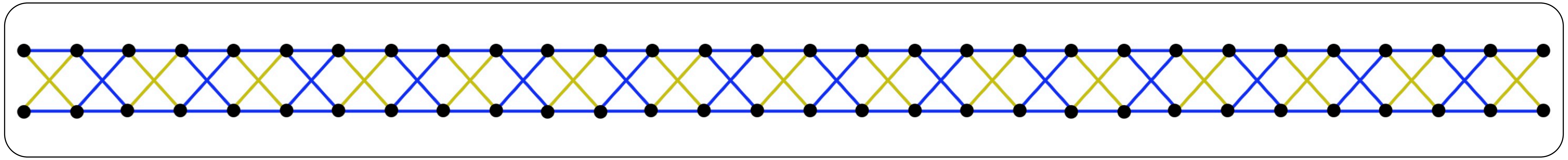
www.physicstoday.org September 2011 Physics Today 21

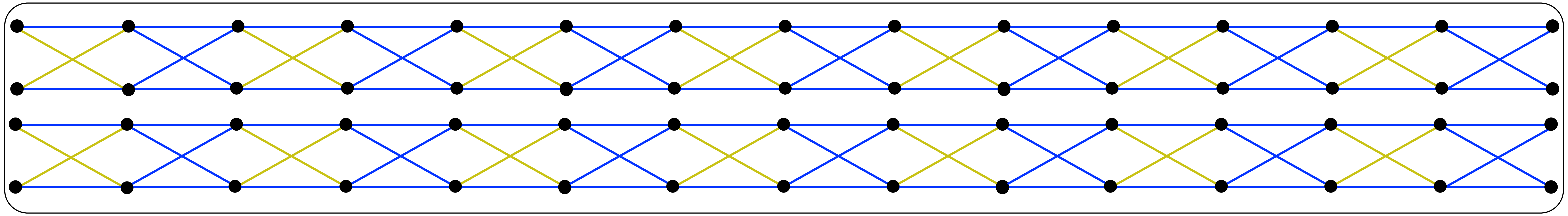


PRL **112,** 120505 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Experimental Realization of Multipartite Entanglement of 60 Modes of a Quantum Optical Frequency Comb

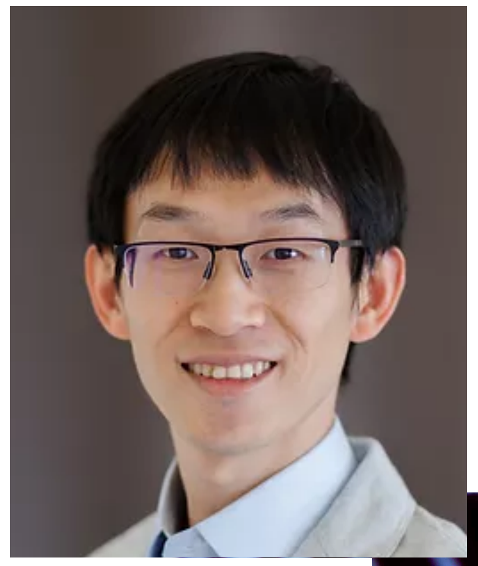
Moran Chen,[1] Nicolas C. Menicucci,[2,*] and Olivier Pfister[1,†]
[1]*Department of Physics, University of Virginia, Charlottesville, Virginia 22903, USA*
[2]*School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*



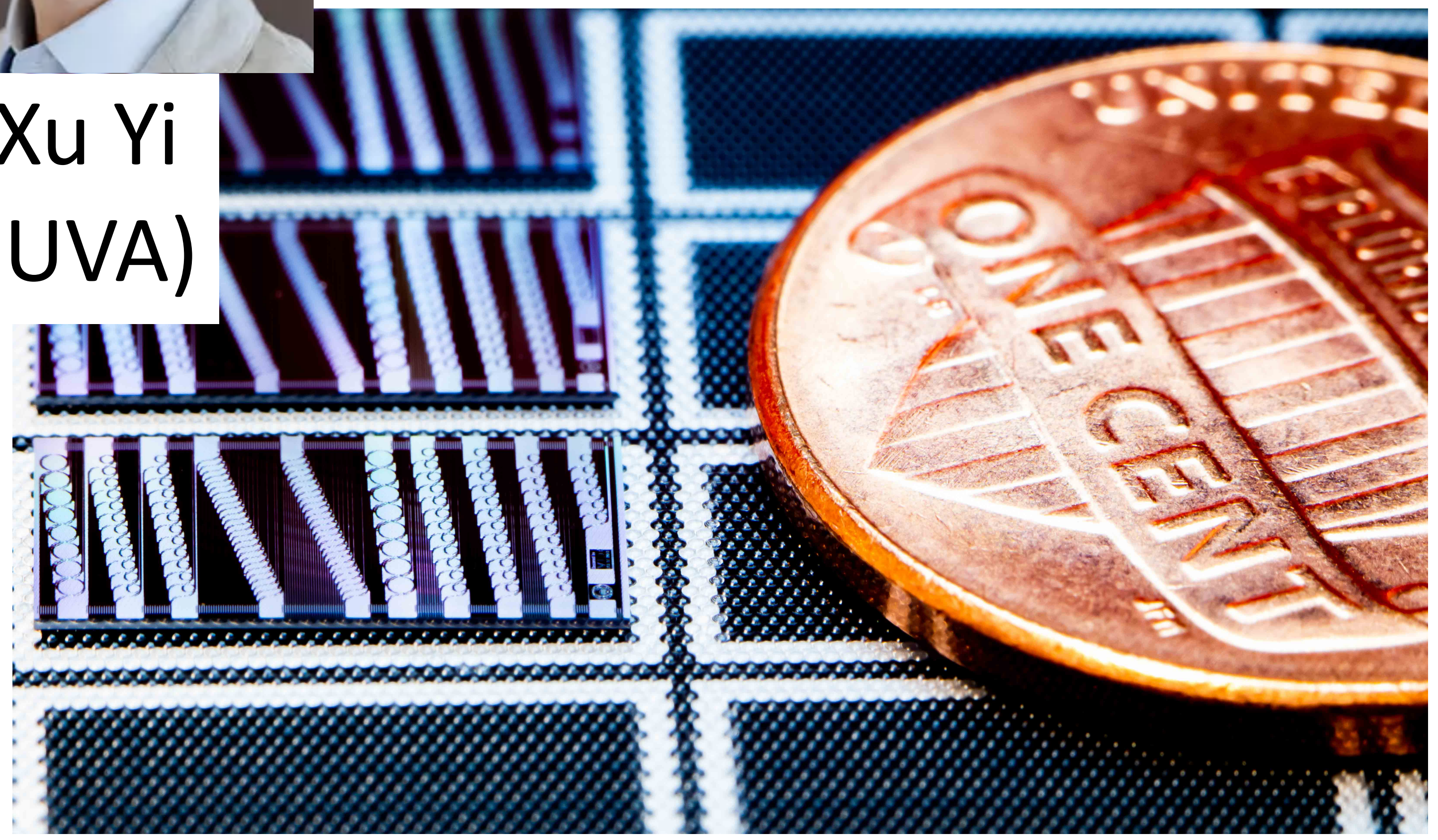


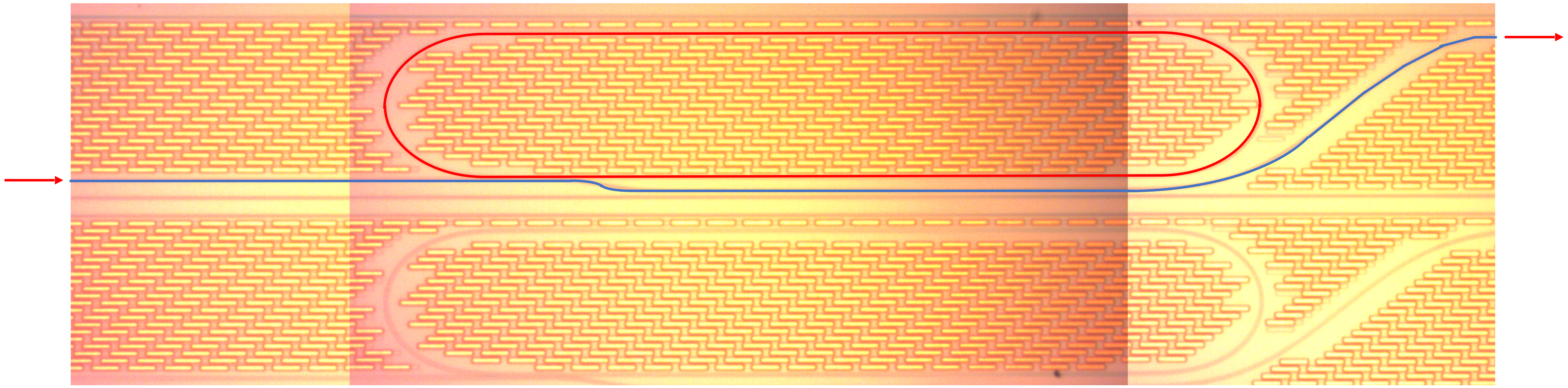
We measured flat-gain emission of OPO over **6000** modes

Squeezed microcombs with integrated SiN photonic circuits



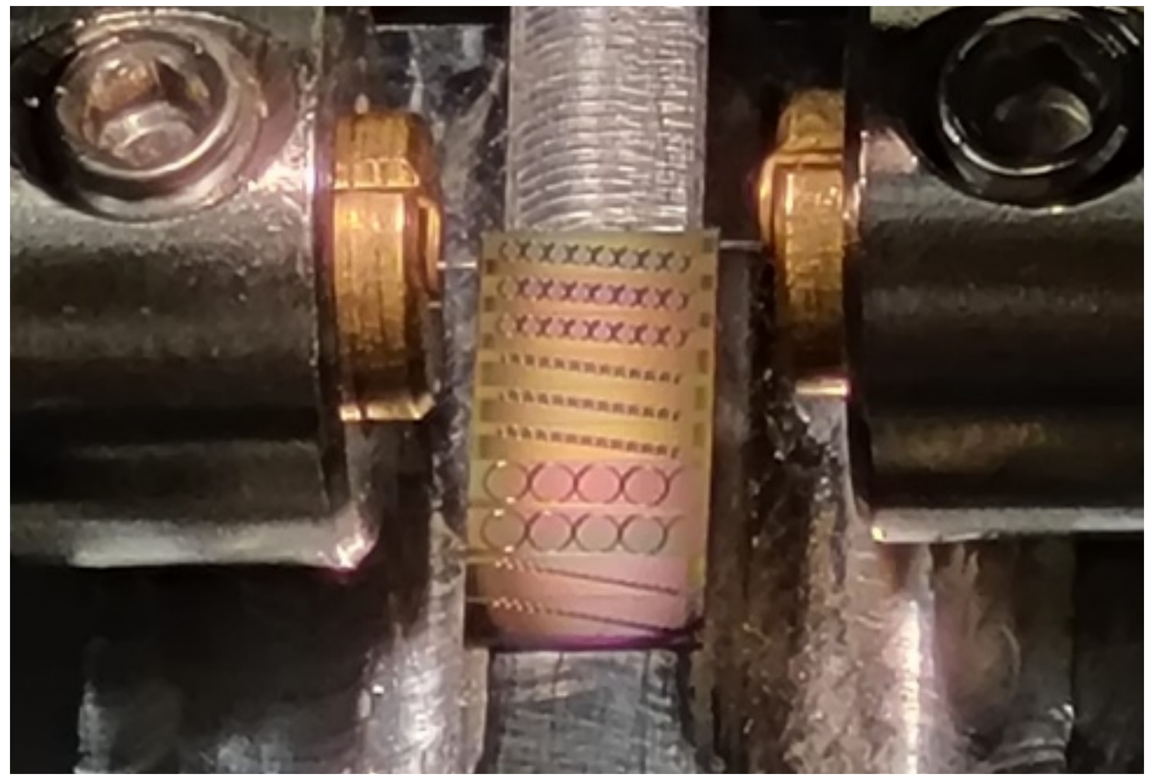
Xu Yi
(UVA)

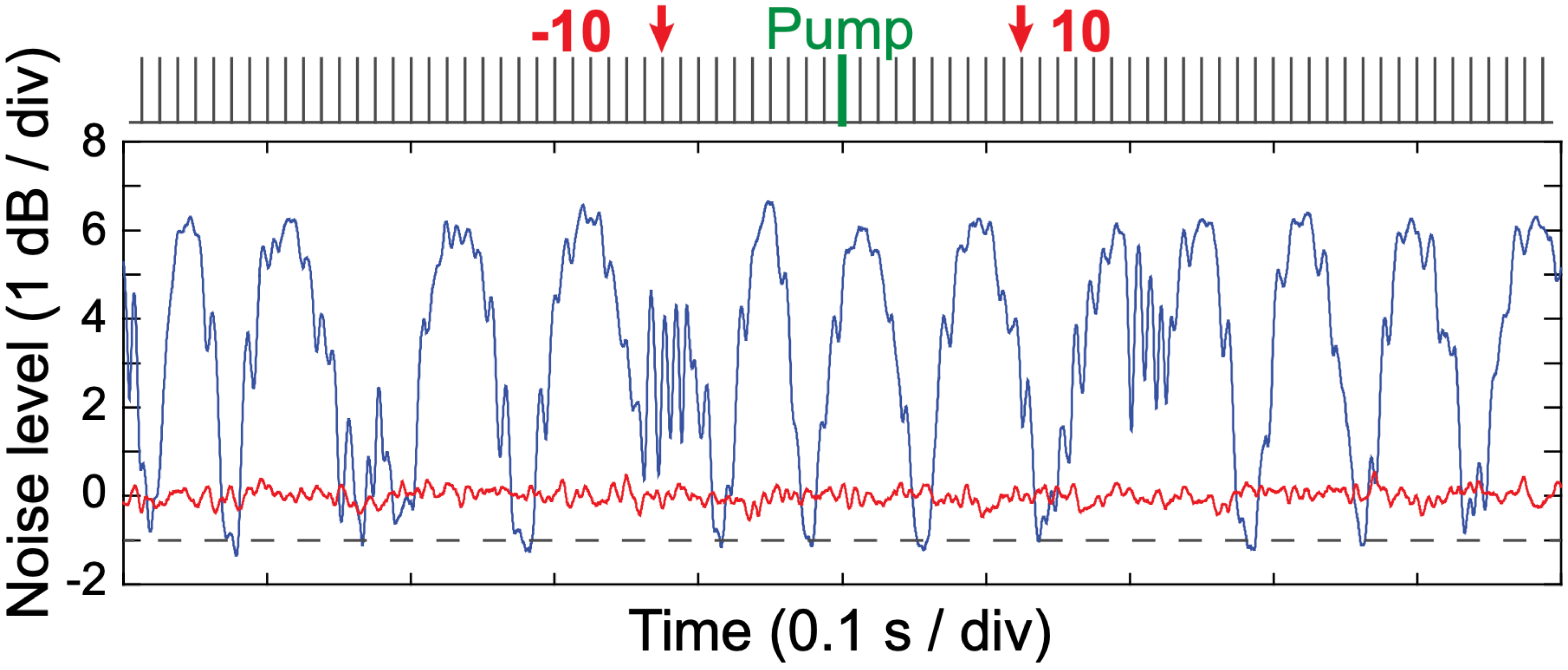




SiN squeezing quantum microcomb:

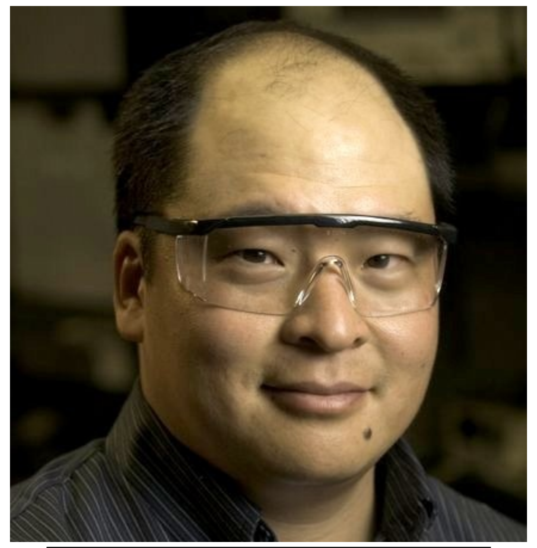
- Foundry fabricated.
- > 1 dB raw squeezing (loss dominated)
- > 50 quantum modes confirmed.





Jahanbozorgi et al., Optica **10**, 1100 (2023)

Non-Gaussian quantum optics: PHOTONS



Sae Woo Nam
(NIST)

Thomas Gerrits
(NIST)

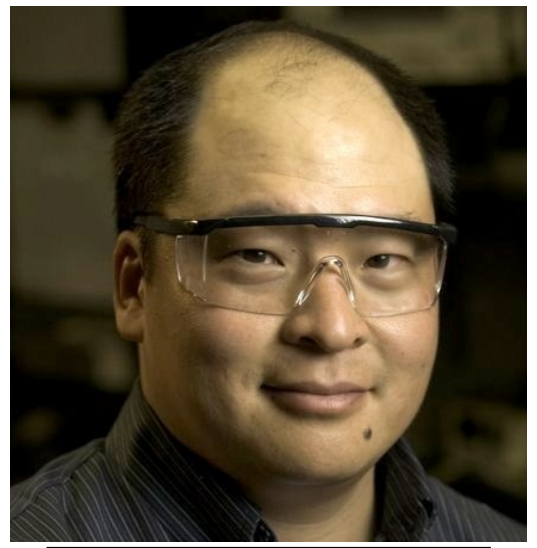
Experimentally accessible non-Gaussian resource: photon-number detection

Aaron Miller
(Quantum Opus)

Ideal POVM set ≡

Fock states have non-positive Wigner functions.

Superconducting transition-edge sensor:



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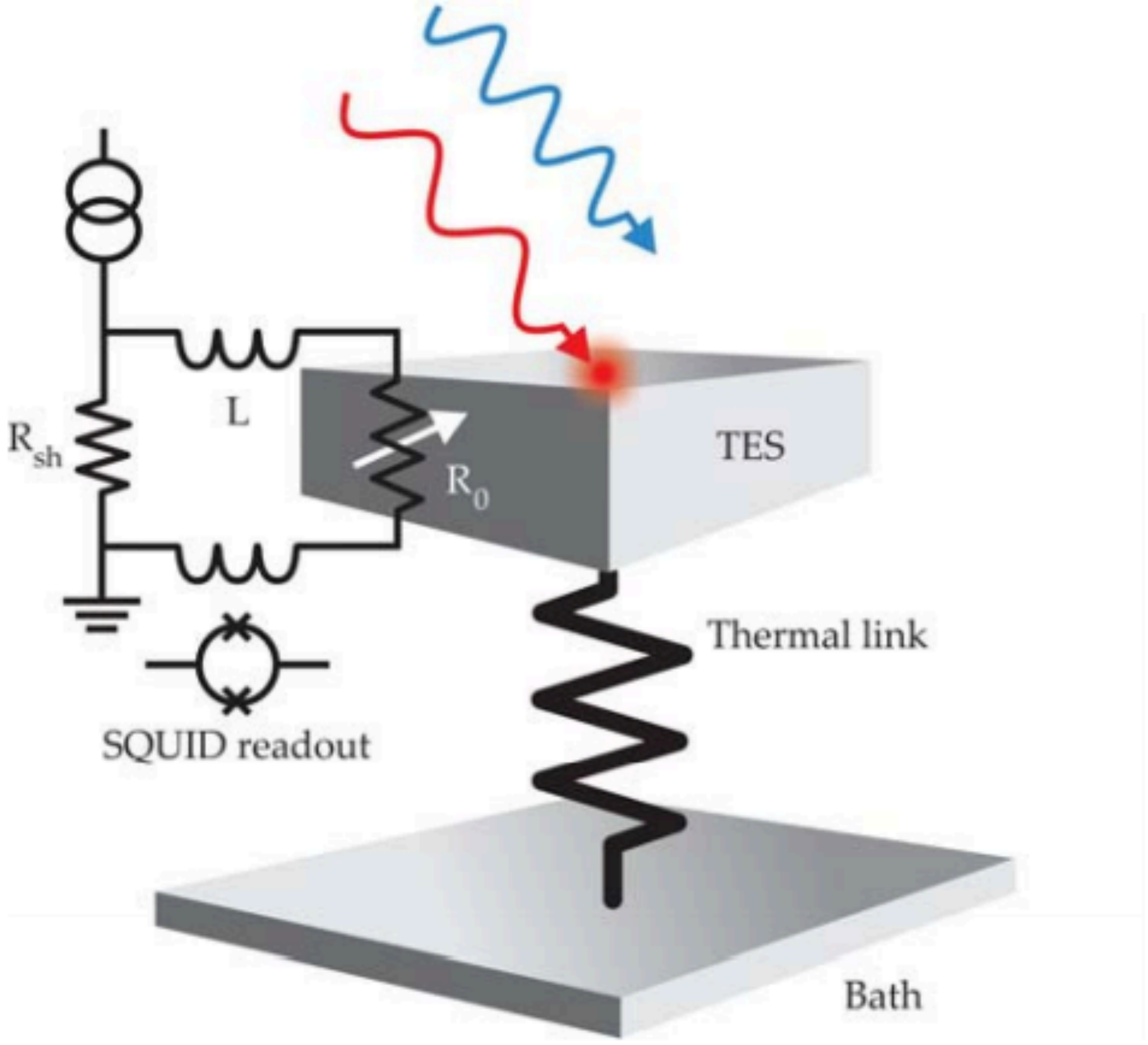
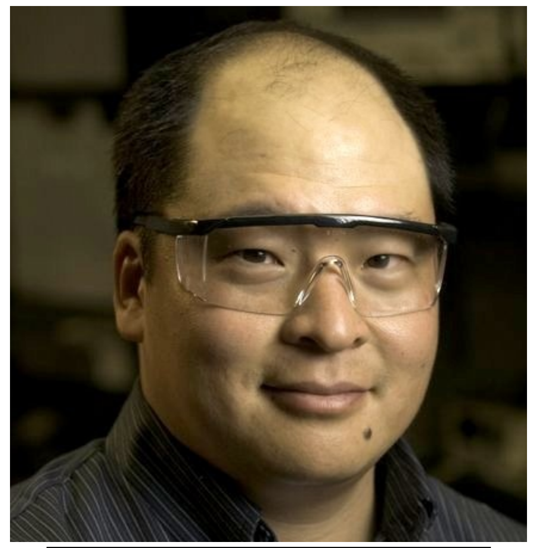


Physics Today **71**, 8, 28 (2018)



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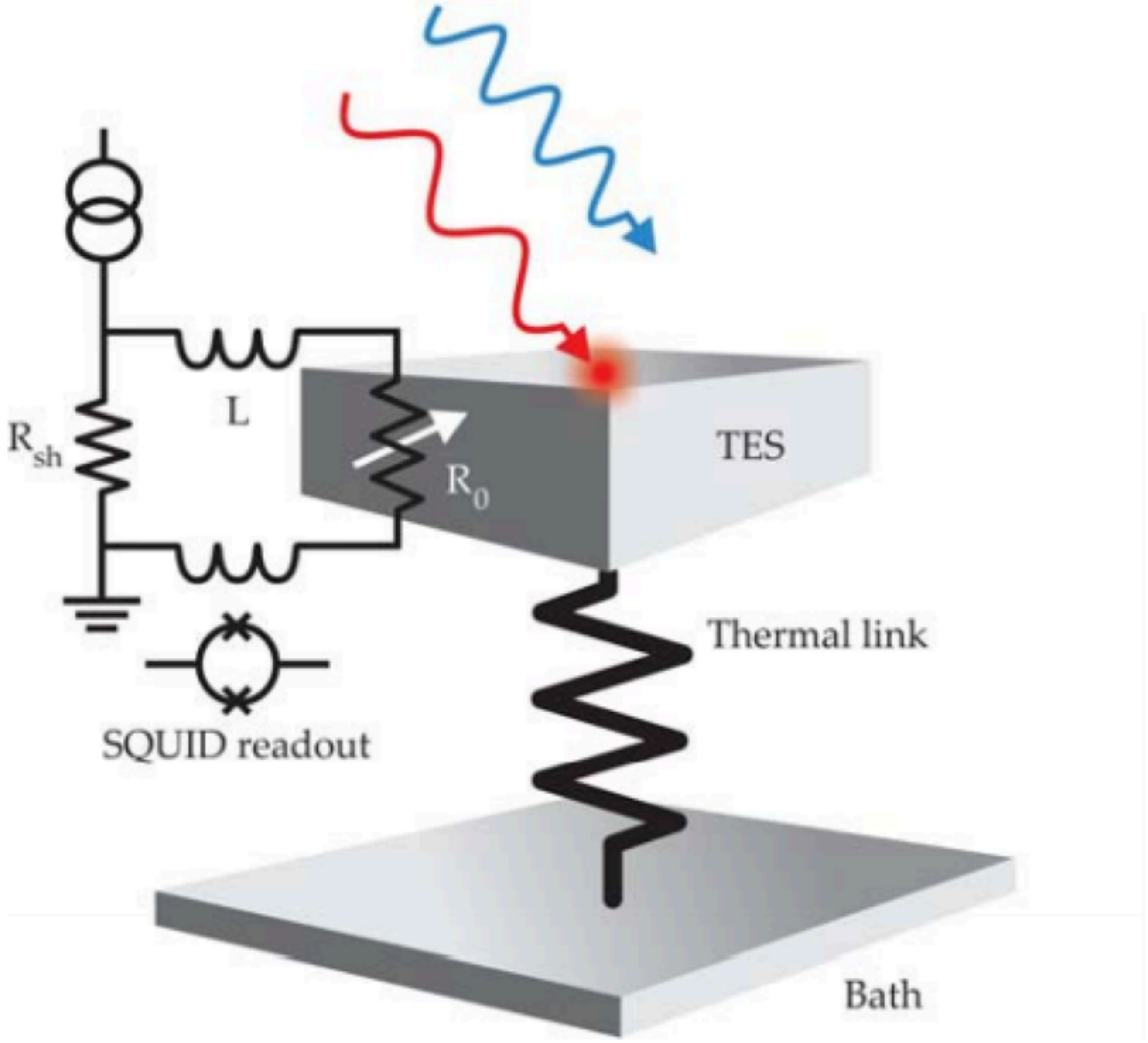

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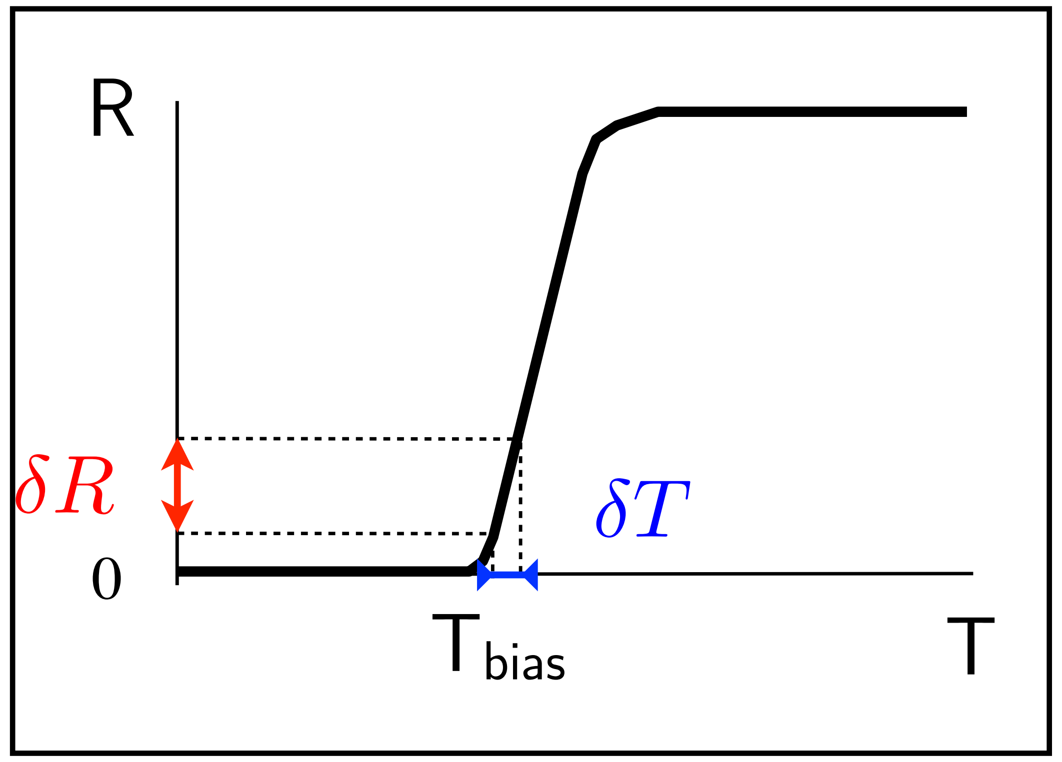

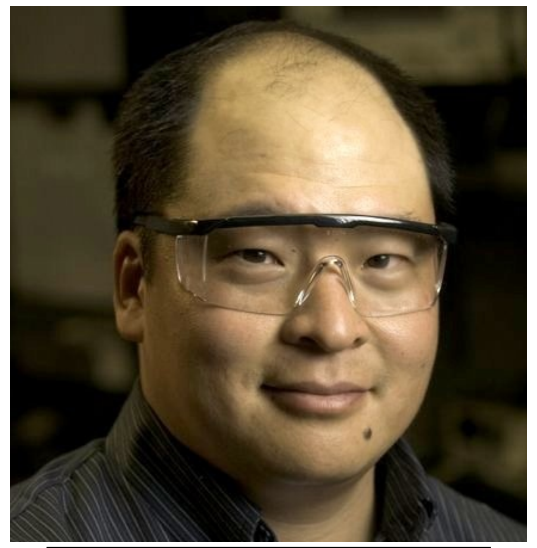

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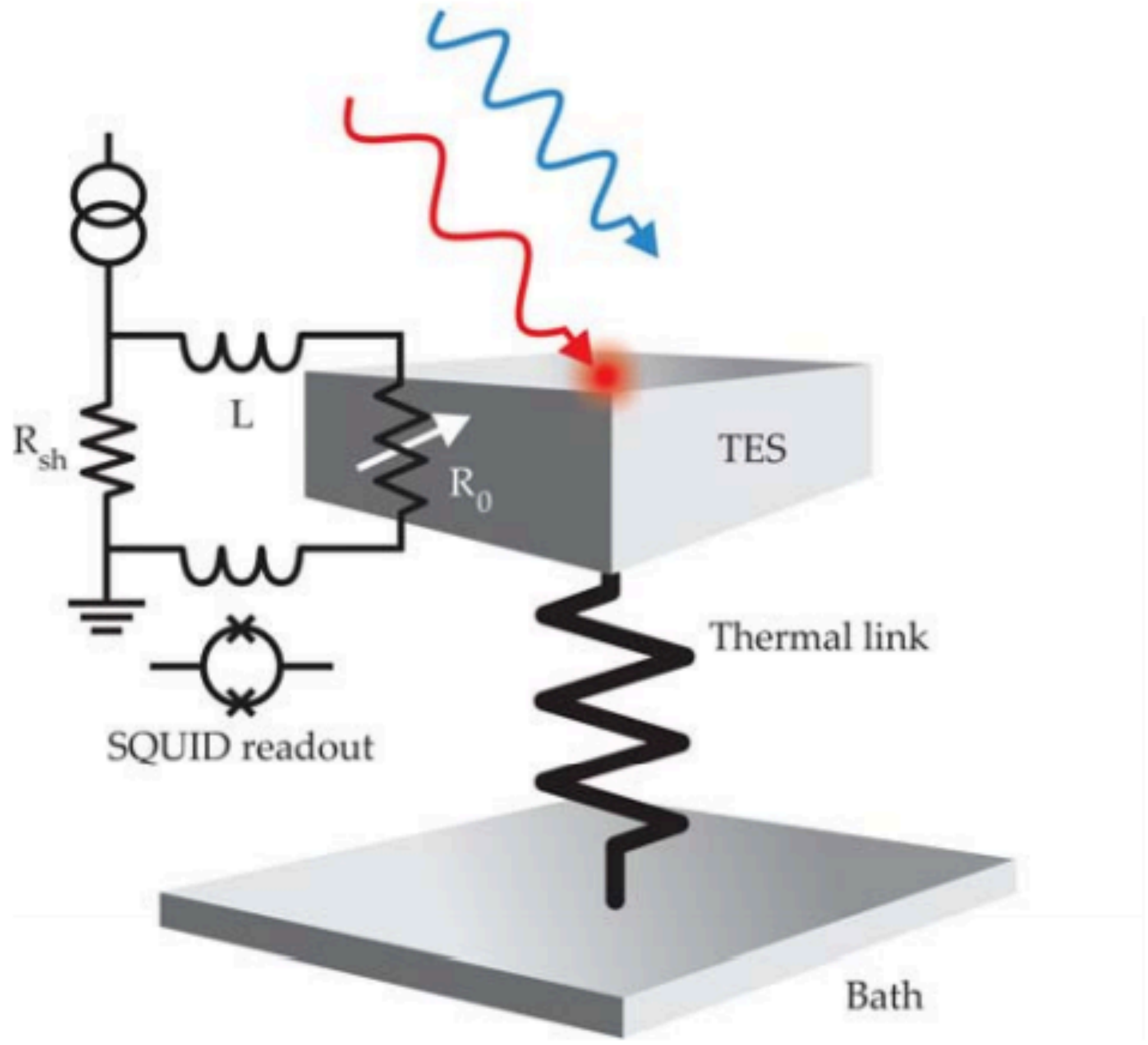

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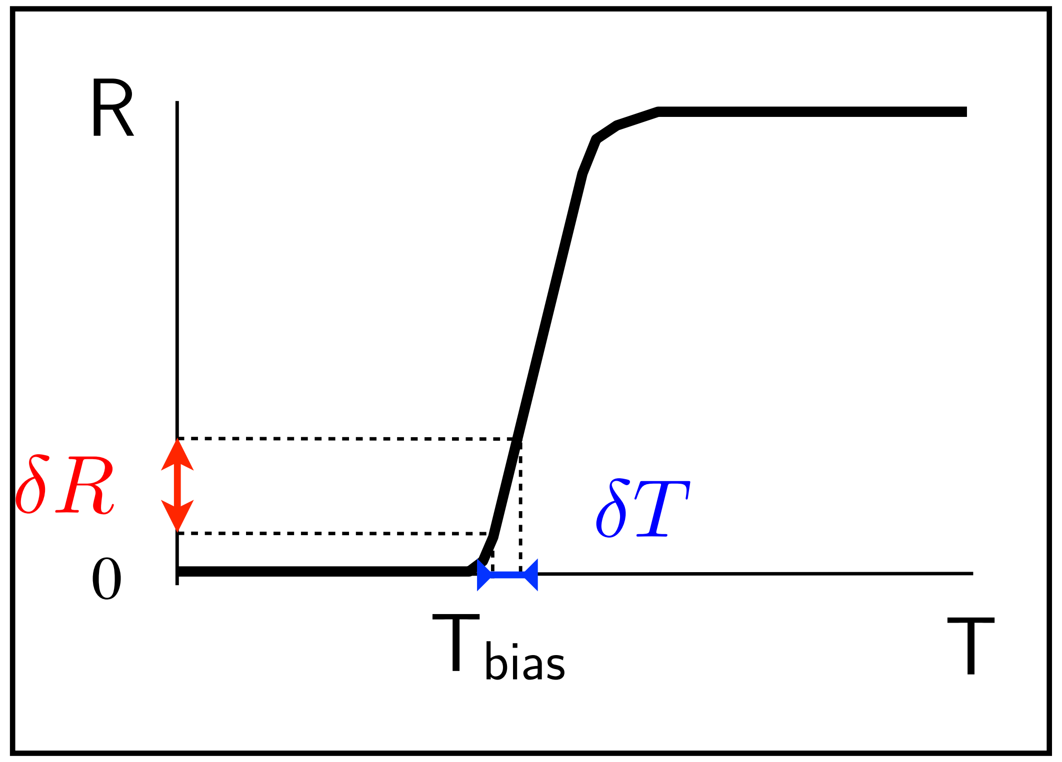

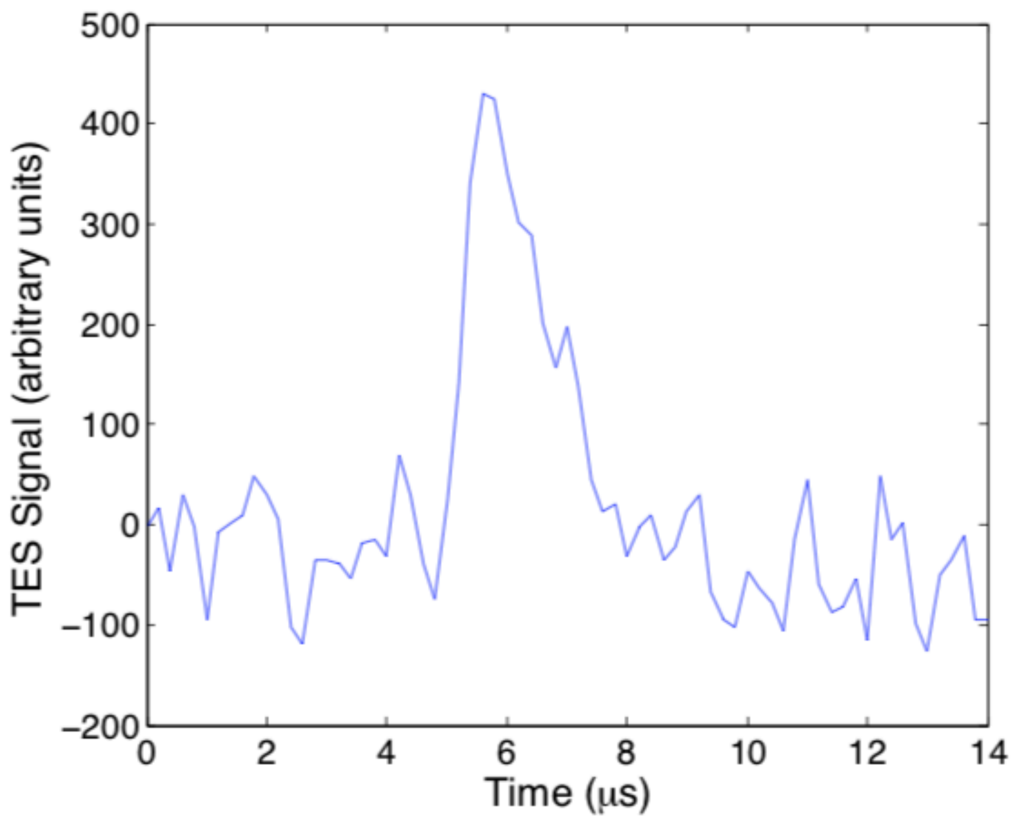

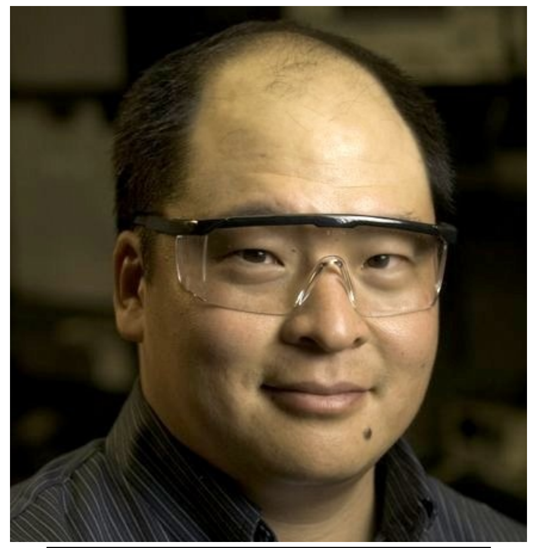

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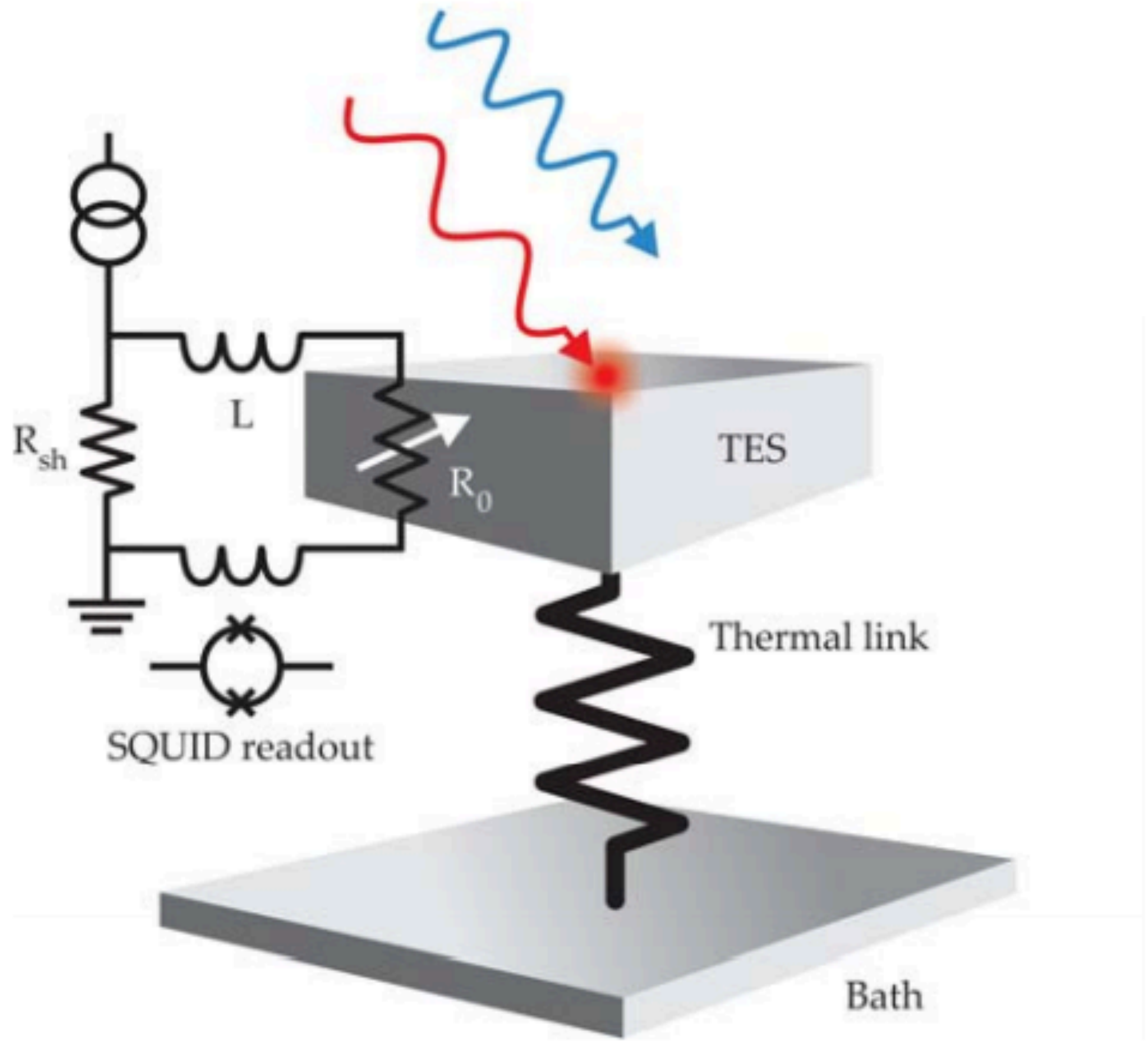

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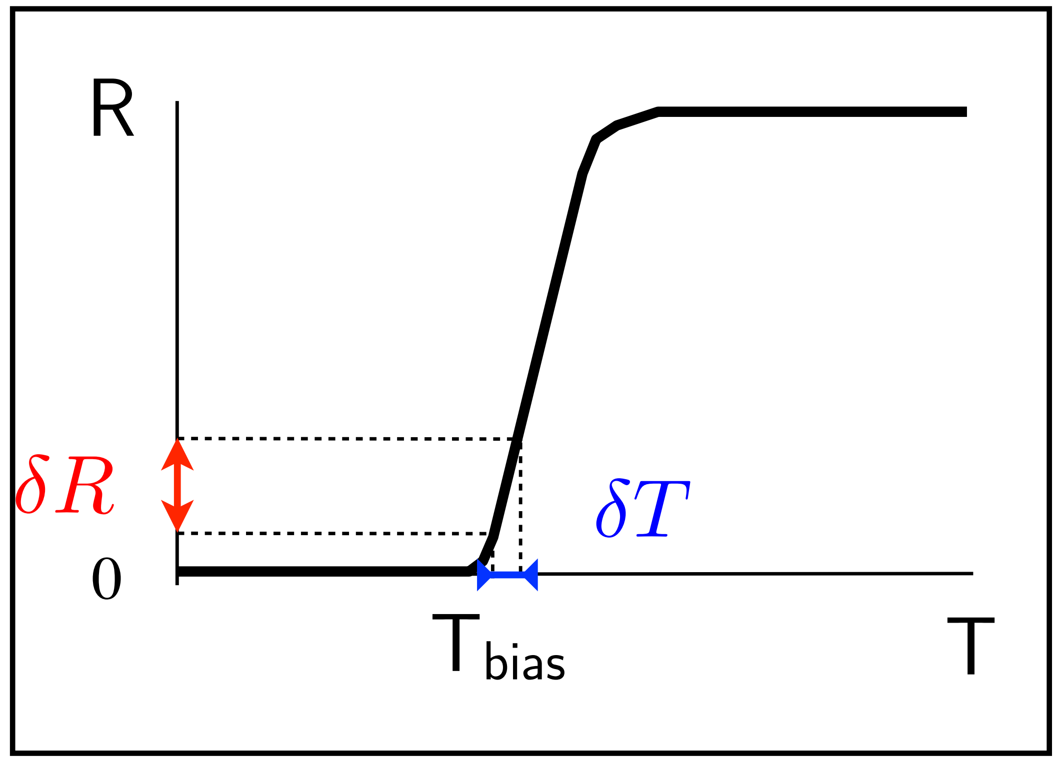
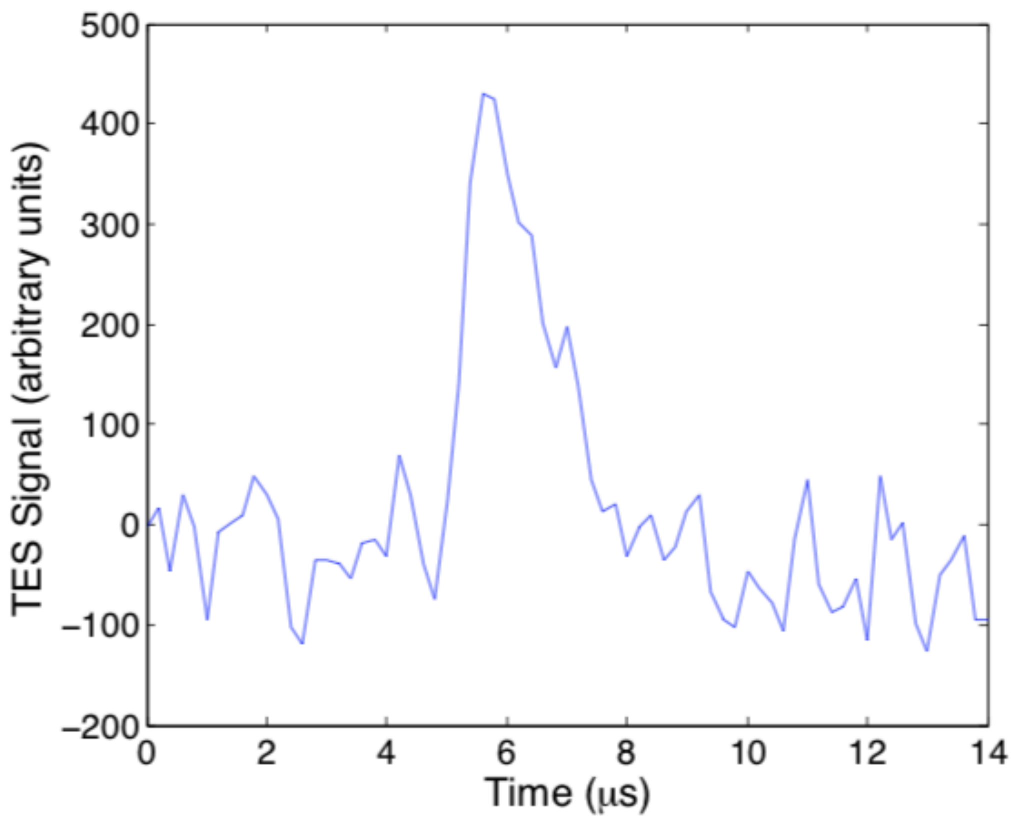
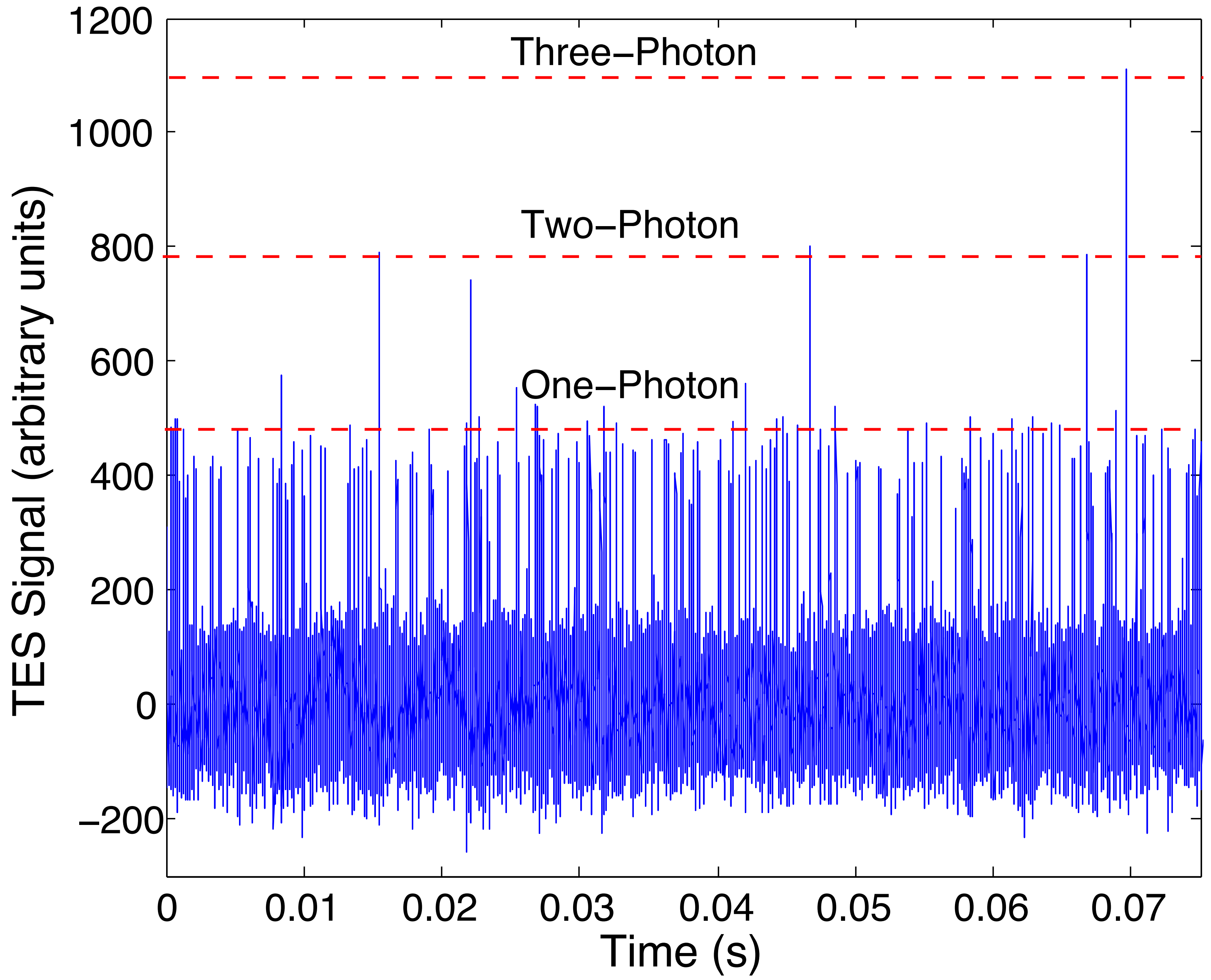
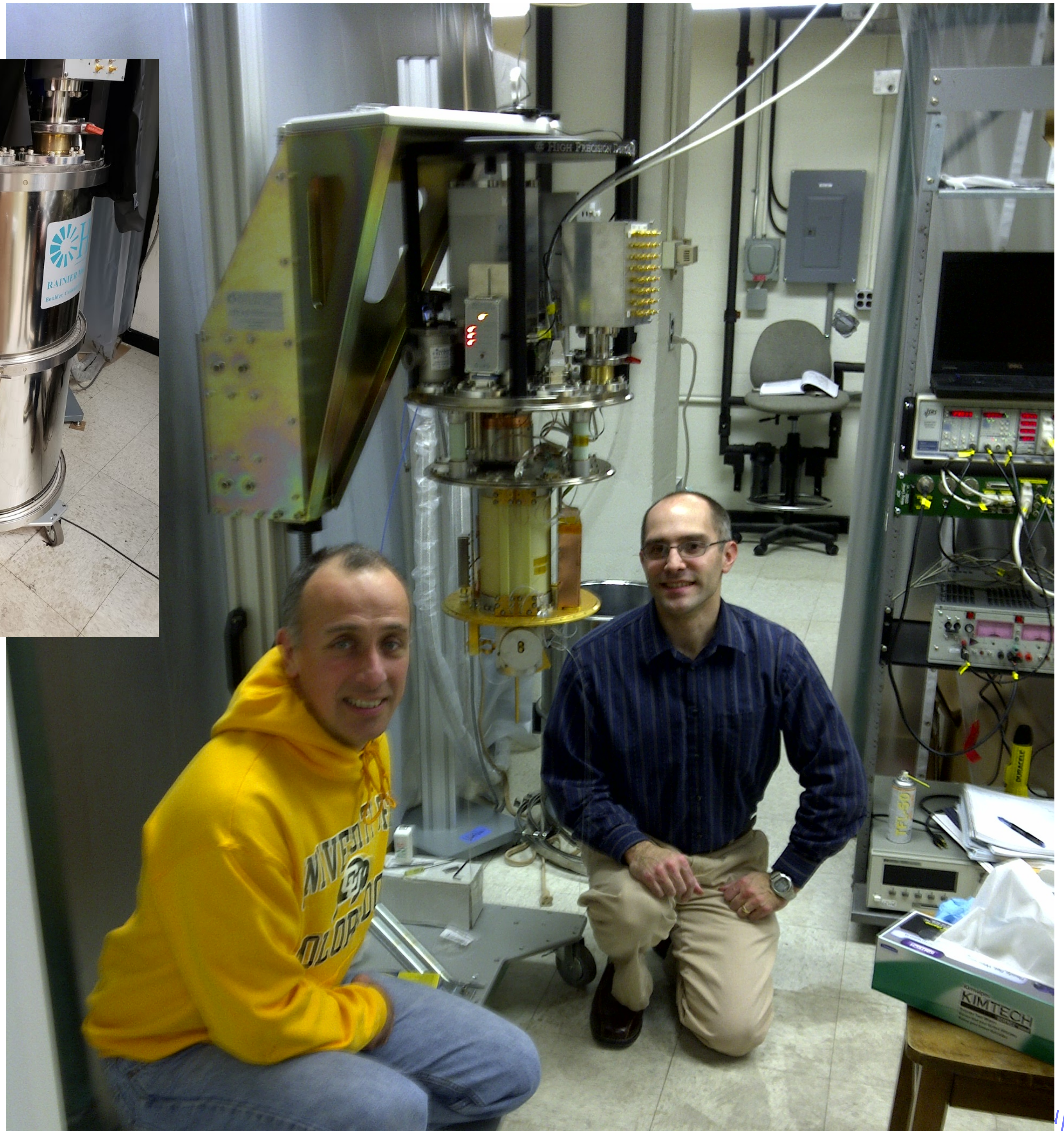
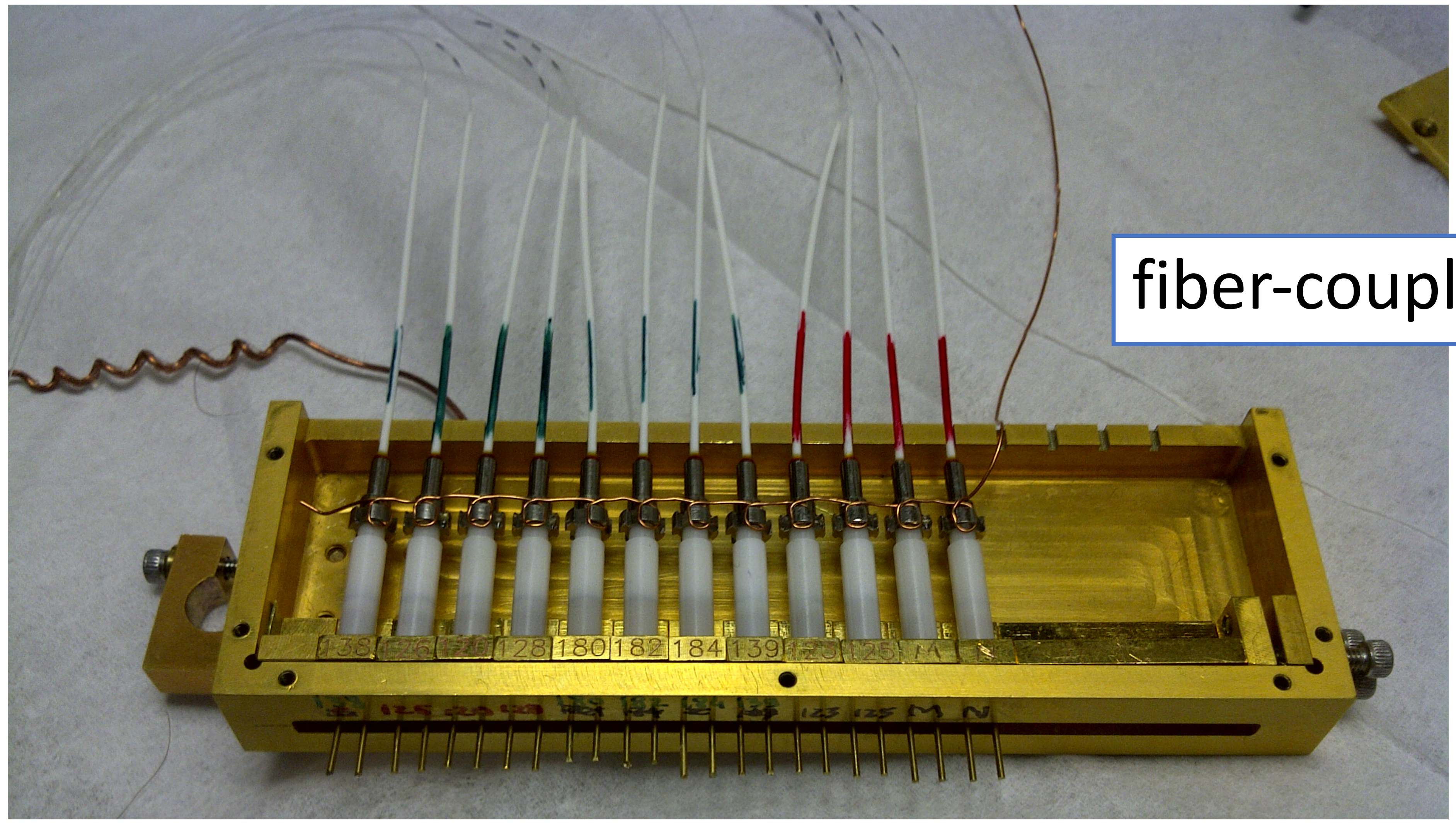


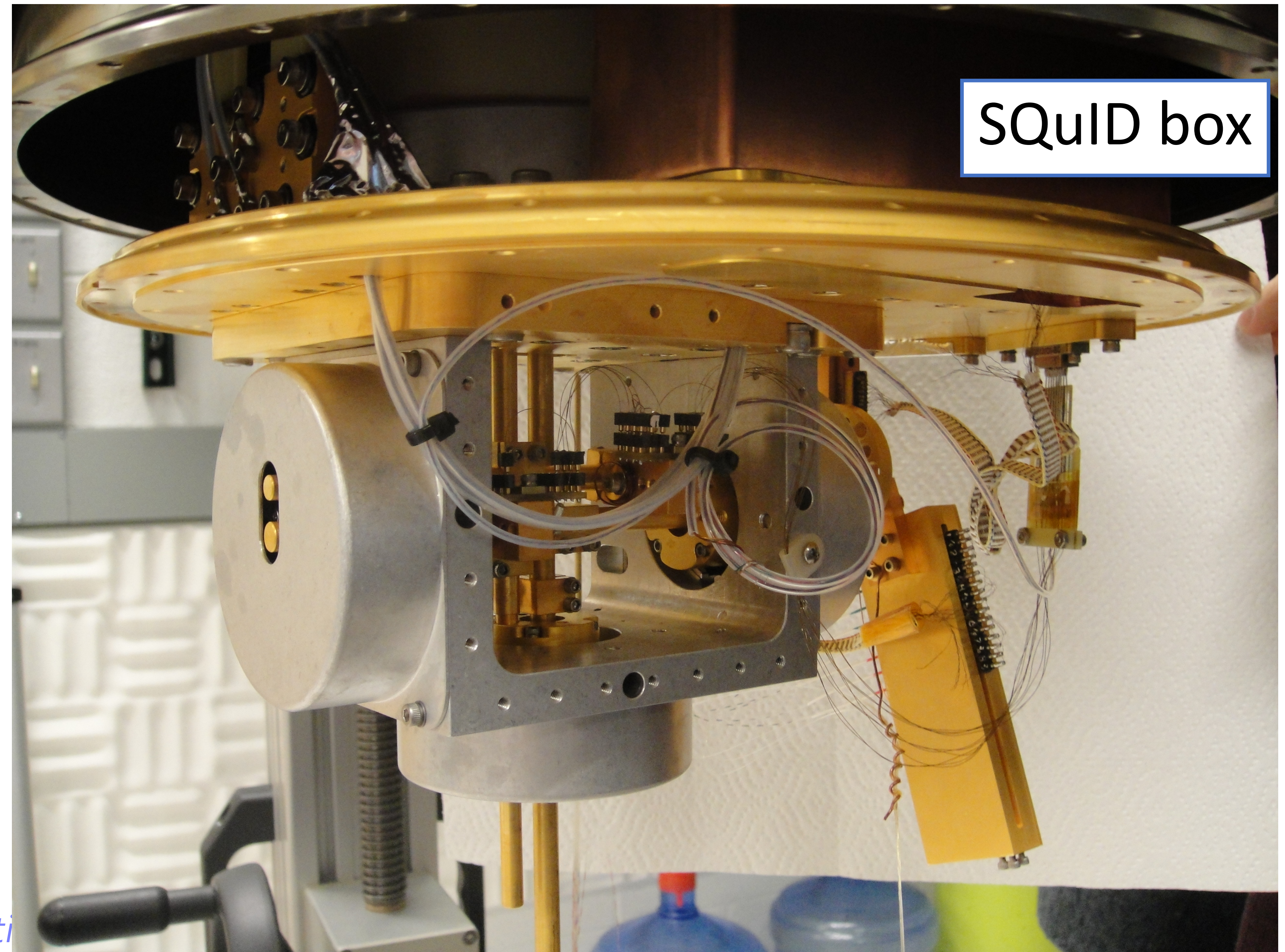




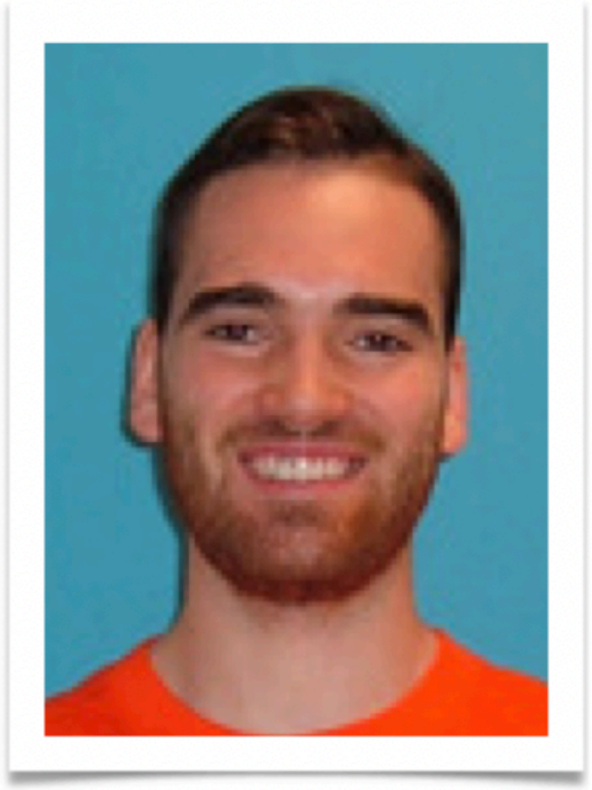
Superconducting TES system @ 100 mK



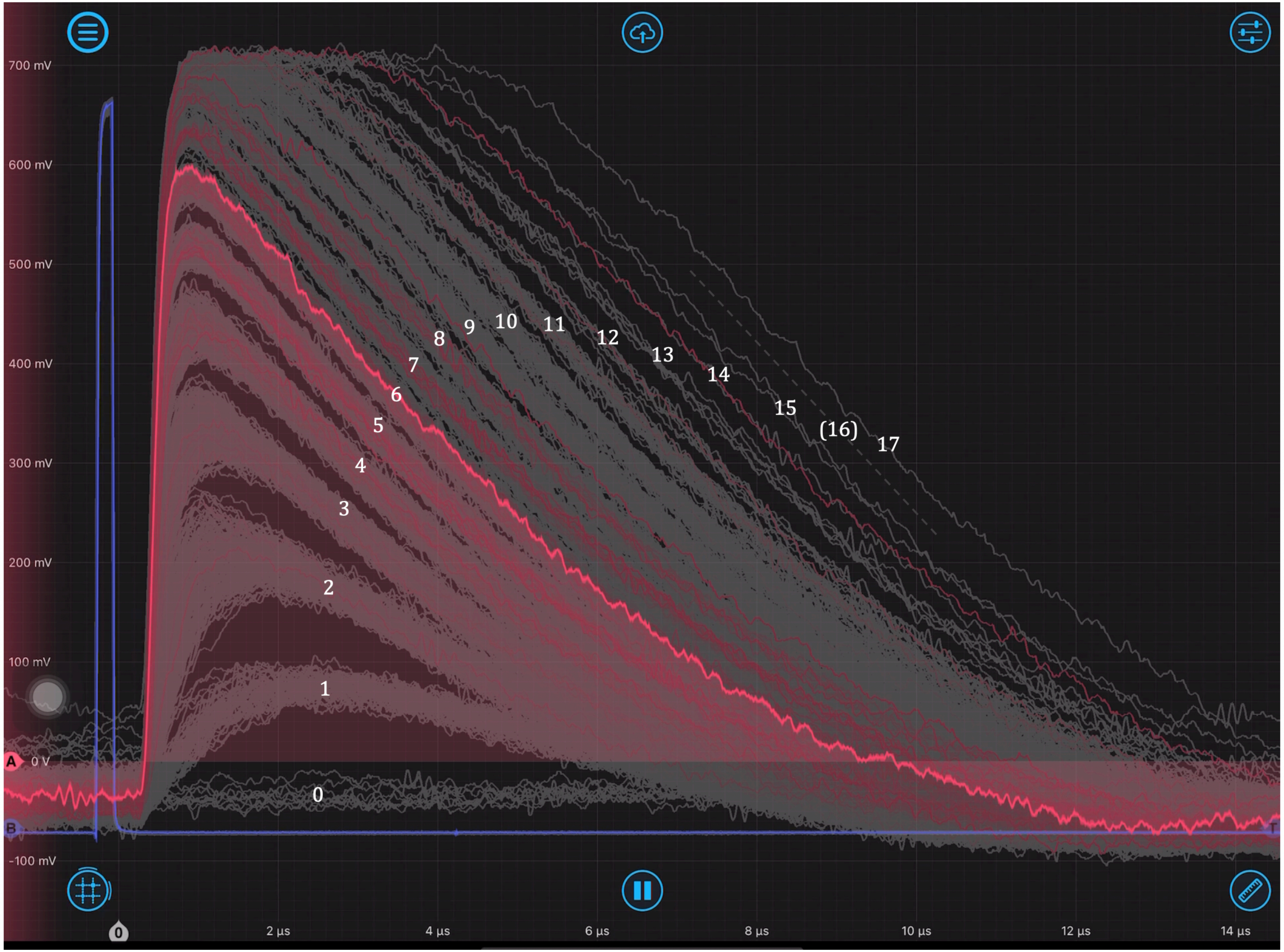




Laser pulses into one TES channel



Miller Eaton



nature photonics

Article

https://doi.org/10.1038/s41566-022-01105-9

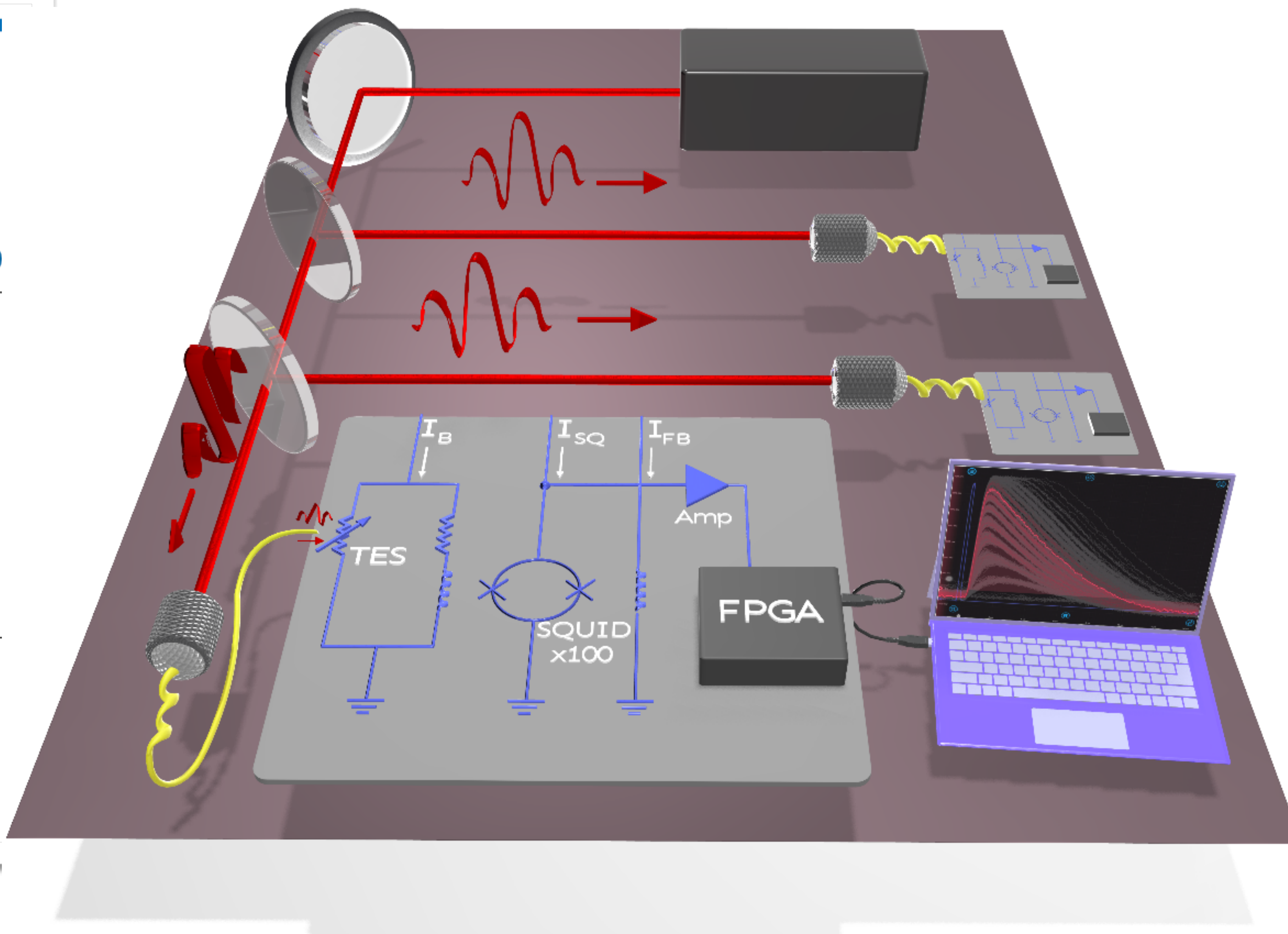
Resolution of 100 photons and quantum generation of unbiased random numbers

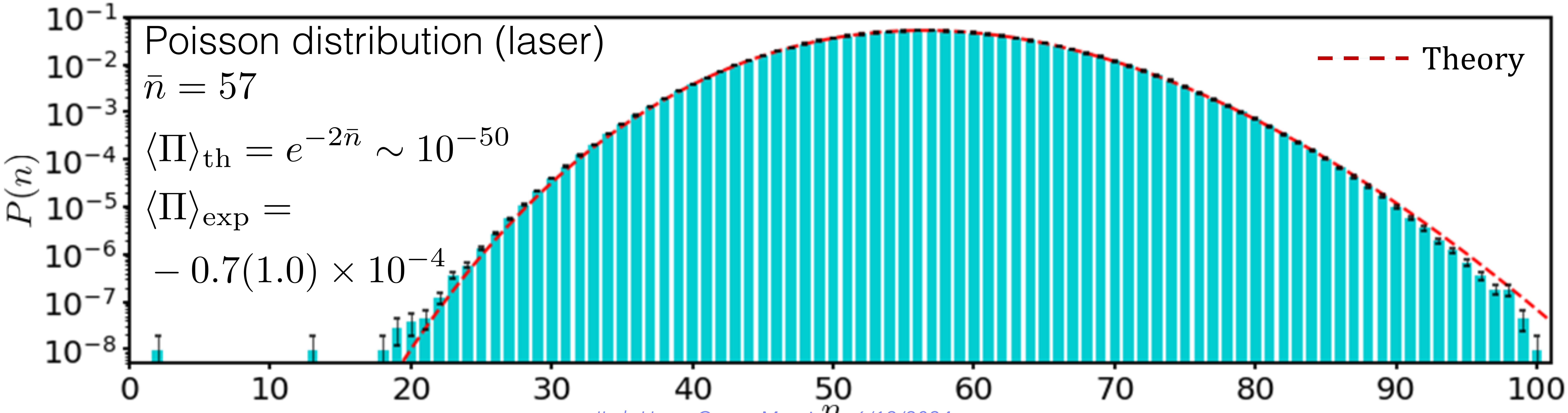
Received: 27 May 2022

Accepted: 11 October 2022

Published online: 19 December 2022

Miller Eaton[1,6], Amr Hossameldin[1,6], Richard J. Birrittella[2,3], Paul M. Alsing[2], Christopher C. Gerry[4], Hai Dong[5], Chris Cuevas[5] & Olivier Pfister[1]





Quantum simulation of quantum field theory

$$\langle \psi_{\rm out} | \mathcal{T}\{ e^{-\frac{i}{\hbar} t H} \} | \psi_{\rm in} \rangle$$

Quantum simulation of quantum field theory

- Now we can address our simulation goal which is to evaluate the scattering amplitude

$$\langle\psi_{\rm out}|\mathcal{T}\{e^{-\frac{i}{\hbar}tH}\}|\psi_{\rm in}\rangle$$

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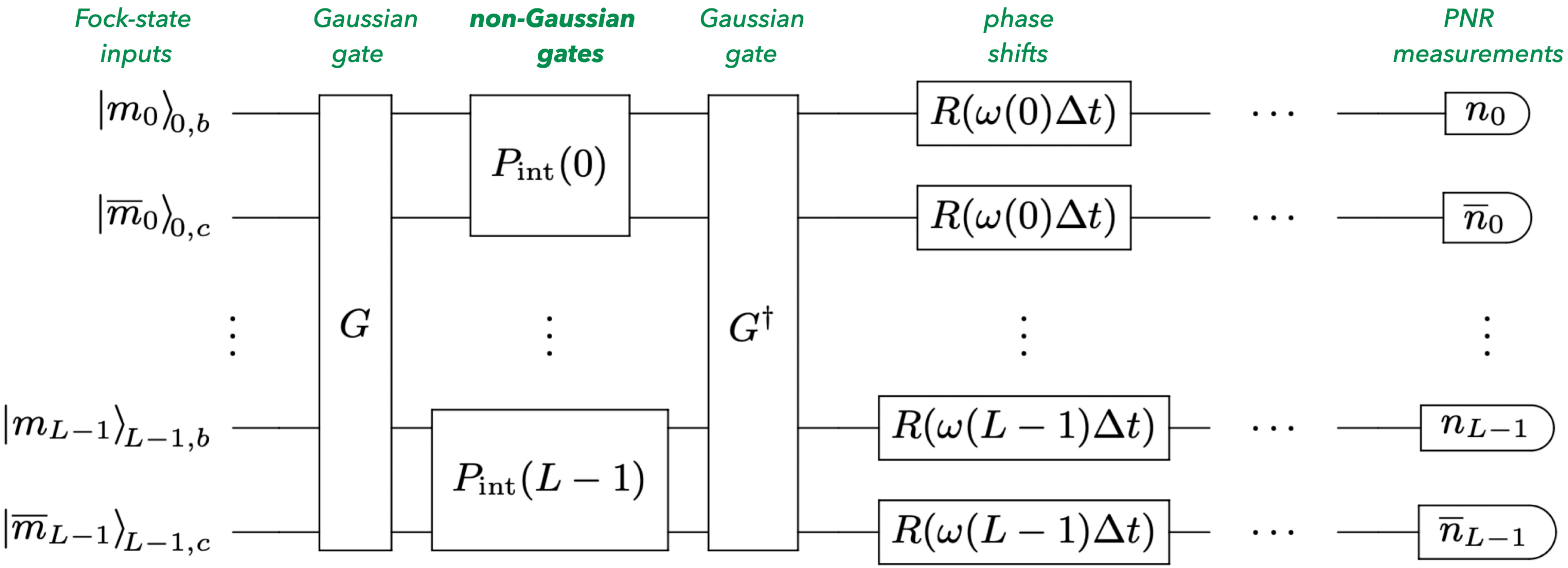
- Project into an arbitrary (random) quantum state: measure photon numbers

- Repeat process until **statistically significant** sampling yields probability distribution

$$\left| \langle \psi_{\text{out}} | \mathcal{T}\{ e^{-\frac{i}{\hbar} tH} \} | \psi_{\text{in}} \rangle \right|^2$$

Quantum optical simulation of quantum field theory



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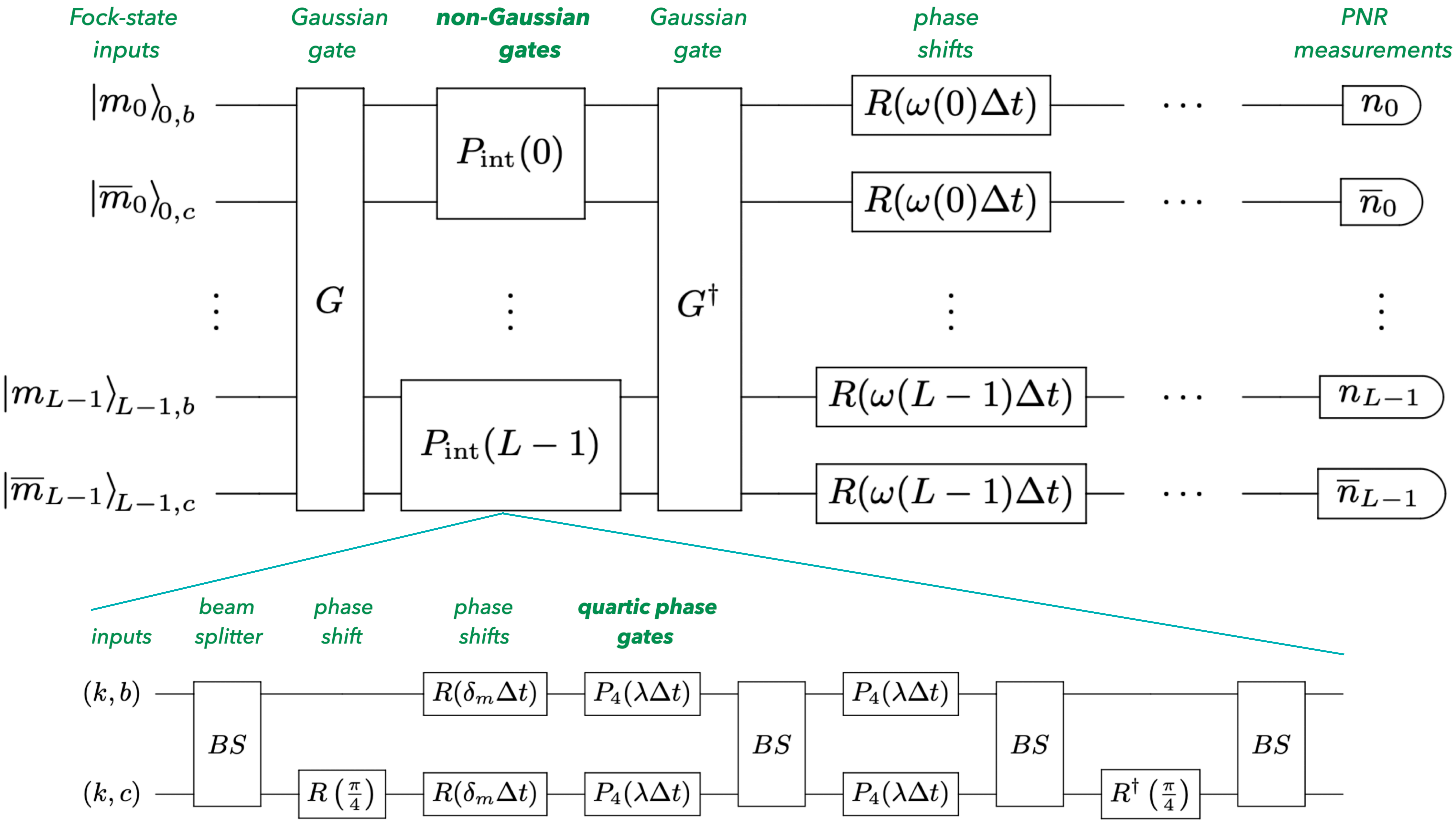

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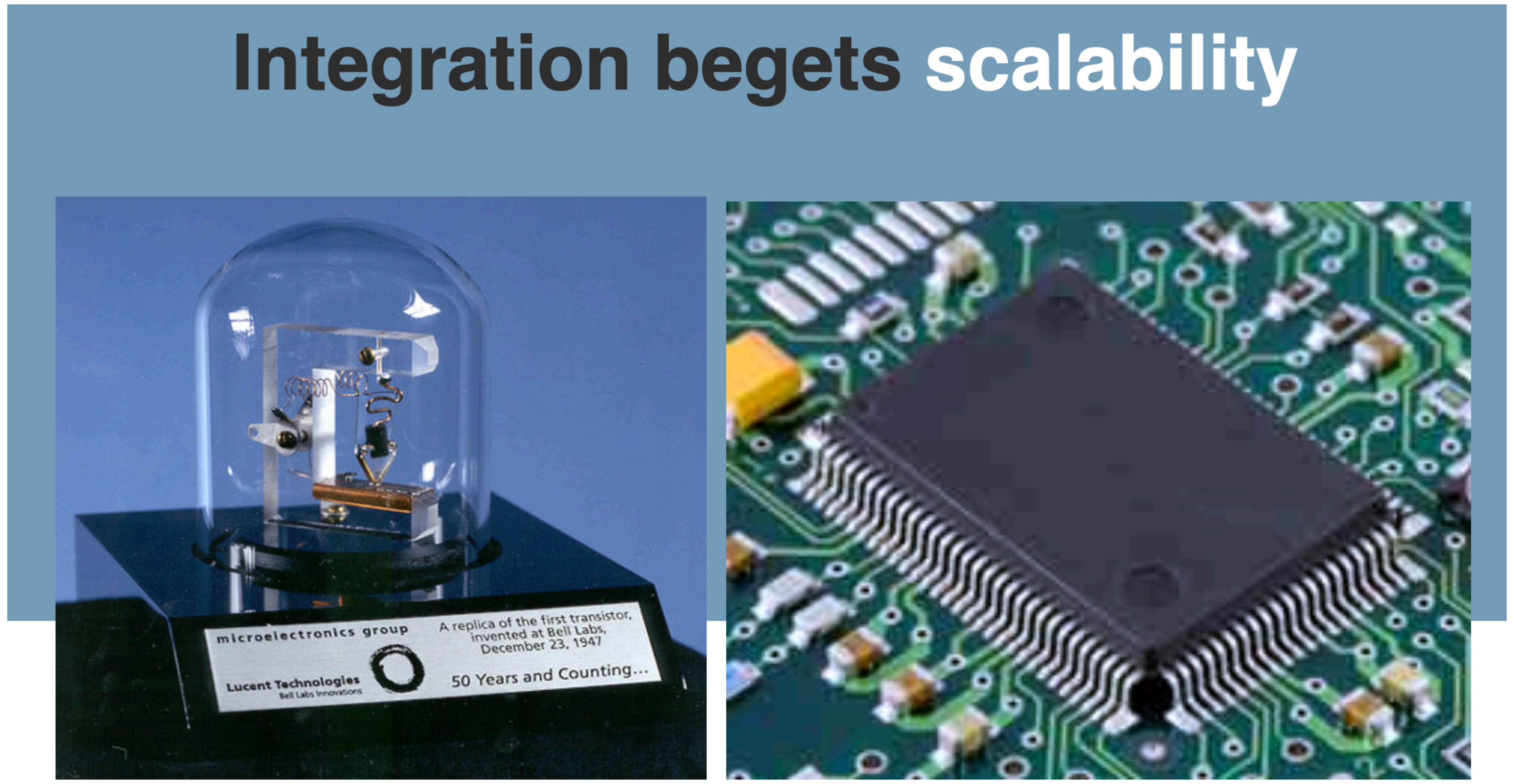

1956 Nobel Prize

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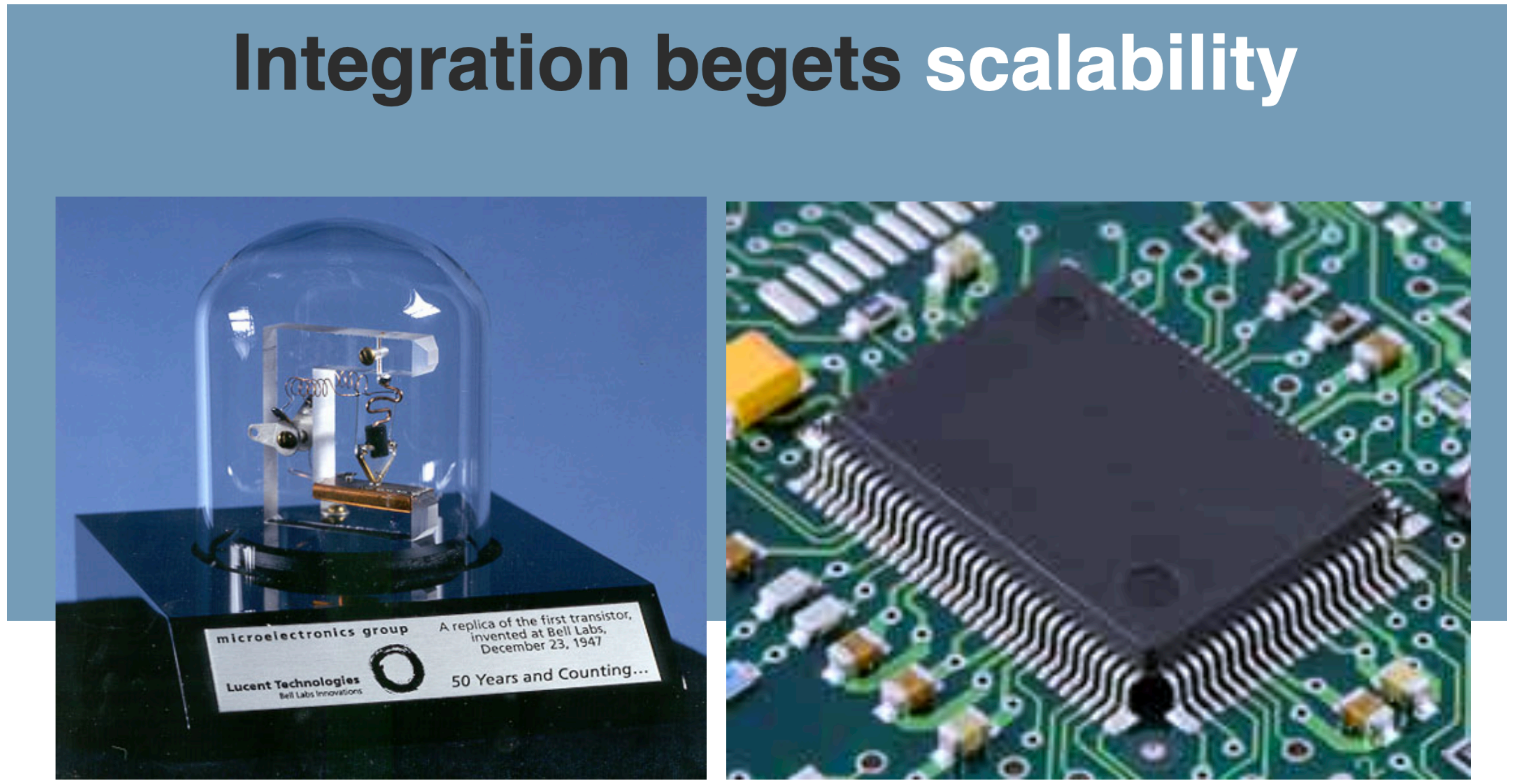

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