Integrated photonic quantum information processing

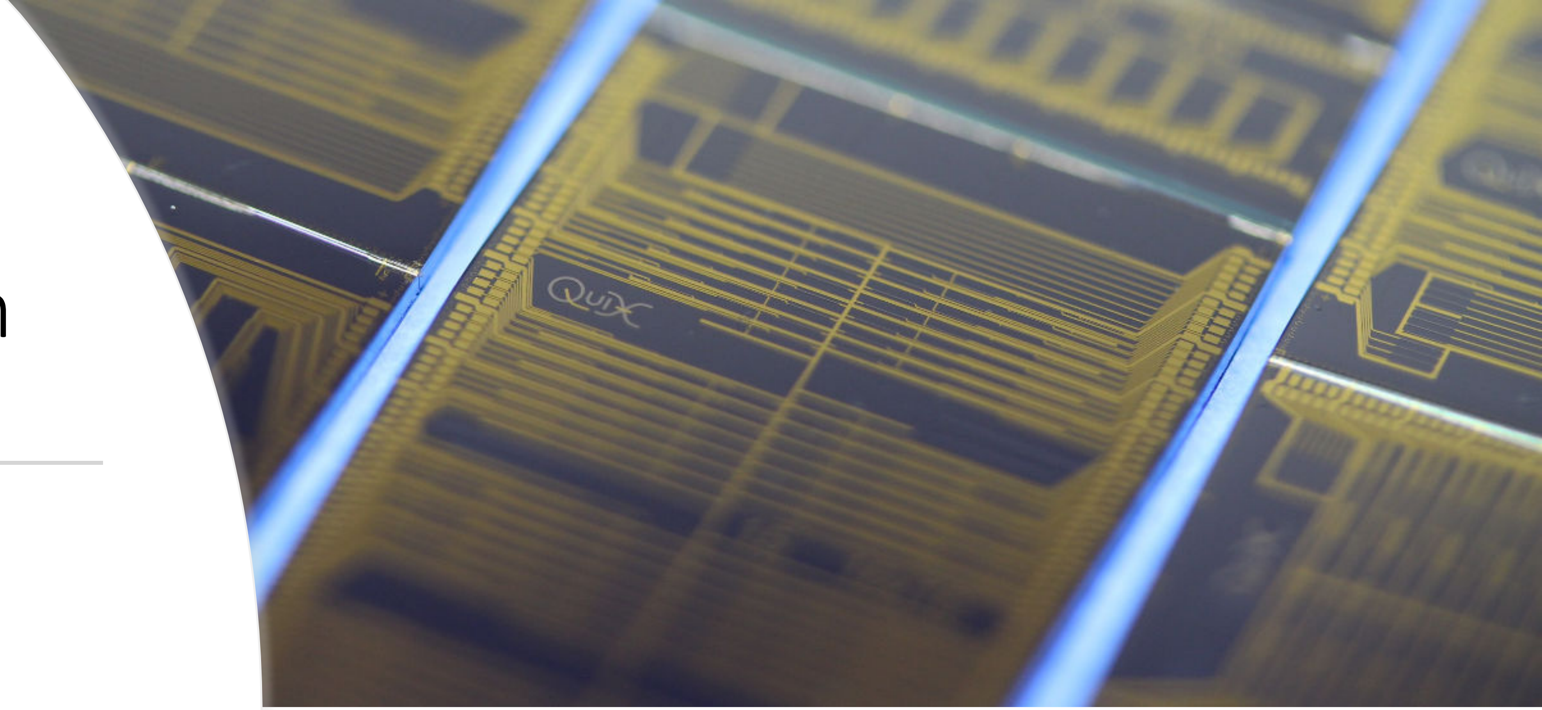
Jelmer Renema

University of Twente

j.j.renema@utwente.nl

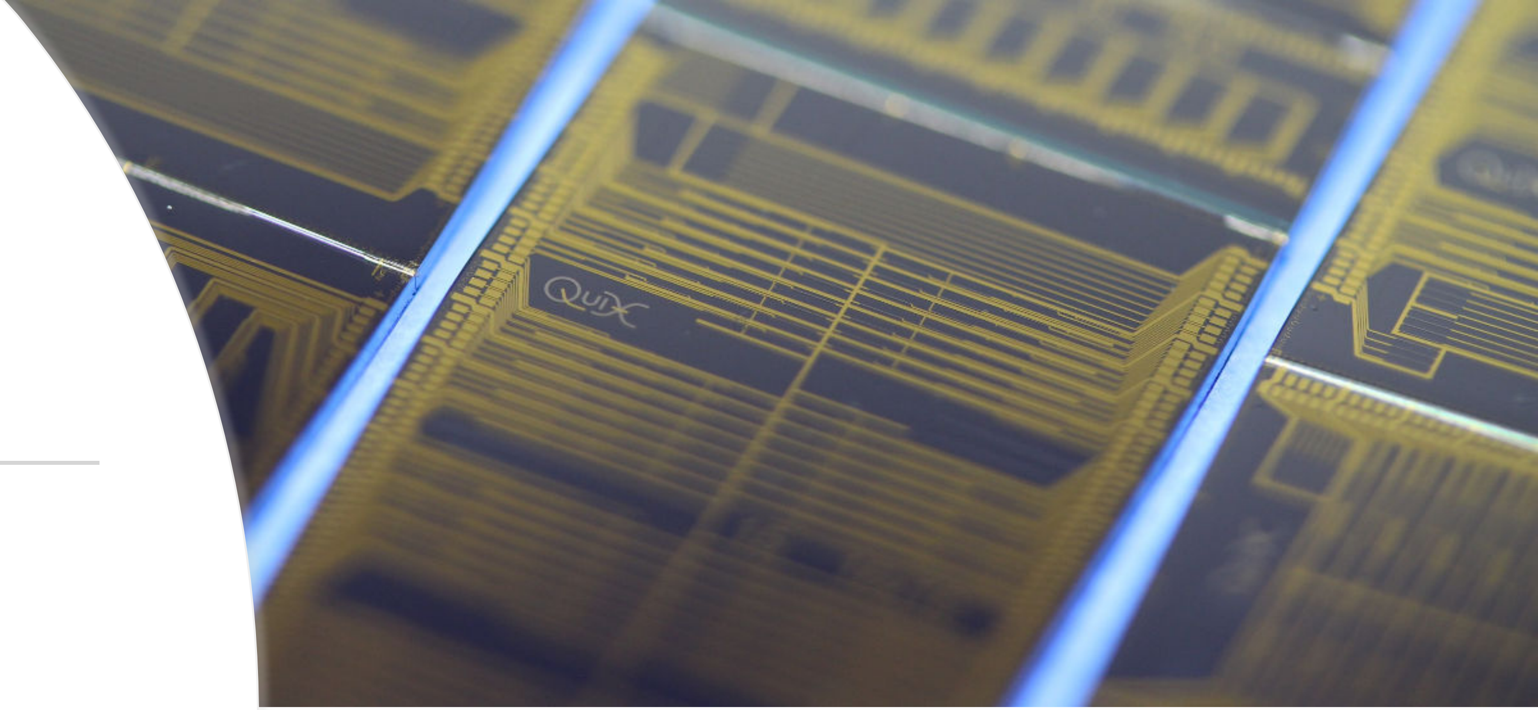
Photonics leads quantum

- Room-temperature operation
- High compatibility with telecom
- Intrinsic datacenter compatibility



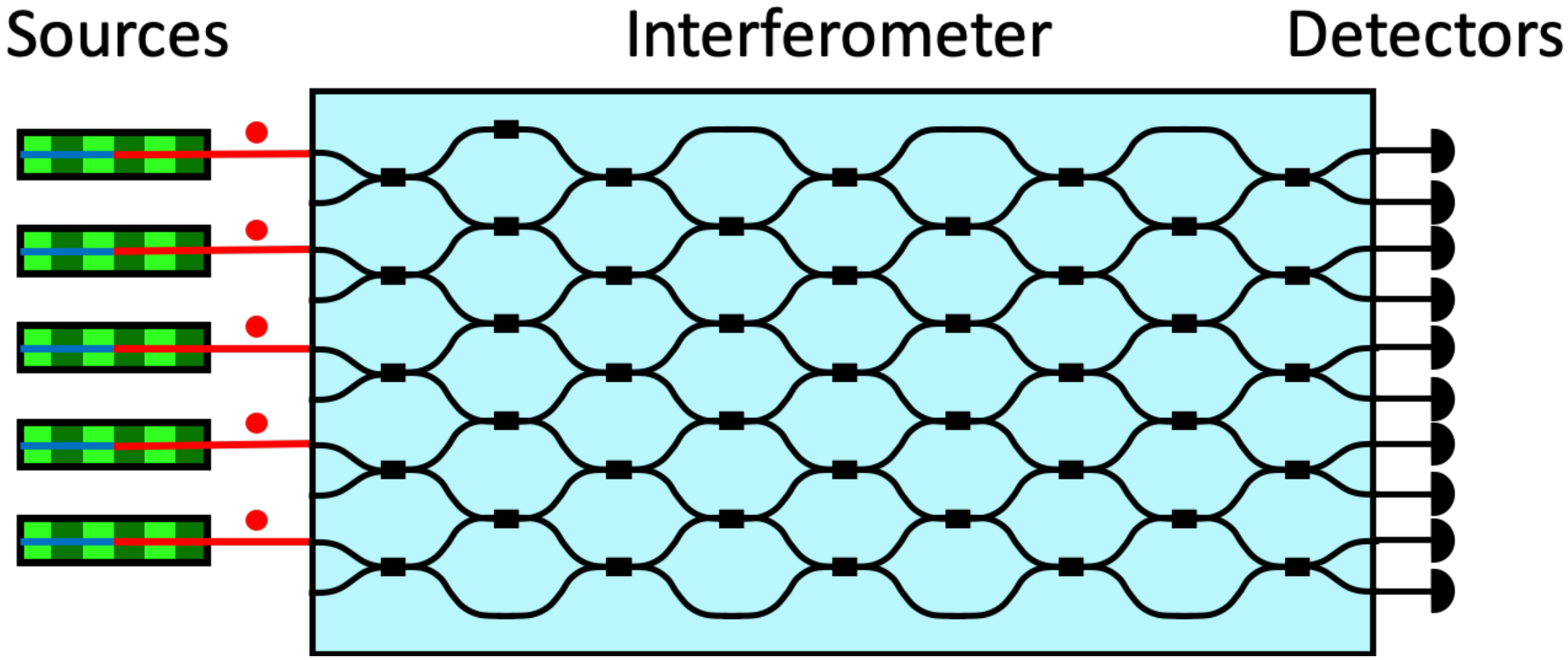
Photonic quantum computing in NL

- First sale of quantum hardware in NL
- First sale of quantum computer in NL
- Only system integrator in the quantum space
- Quantum advantage demonstration
- Today: academic efforts on quantum photonics @ U Twente

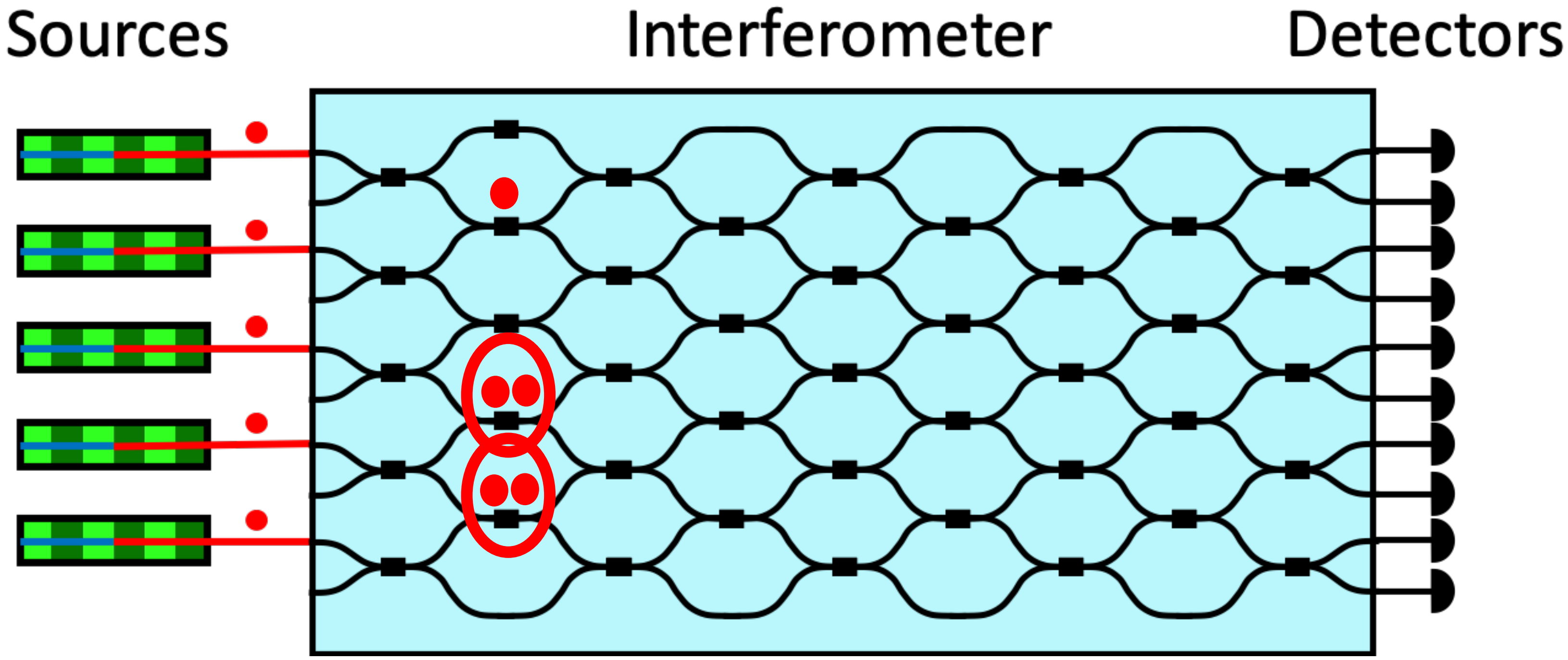


The team

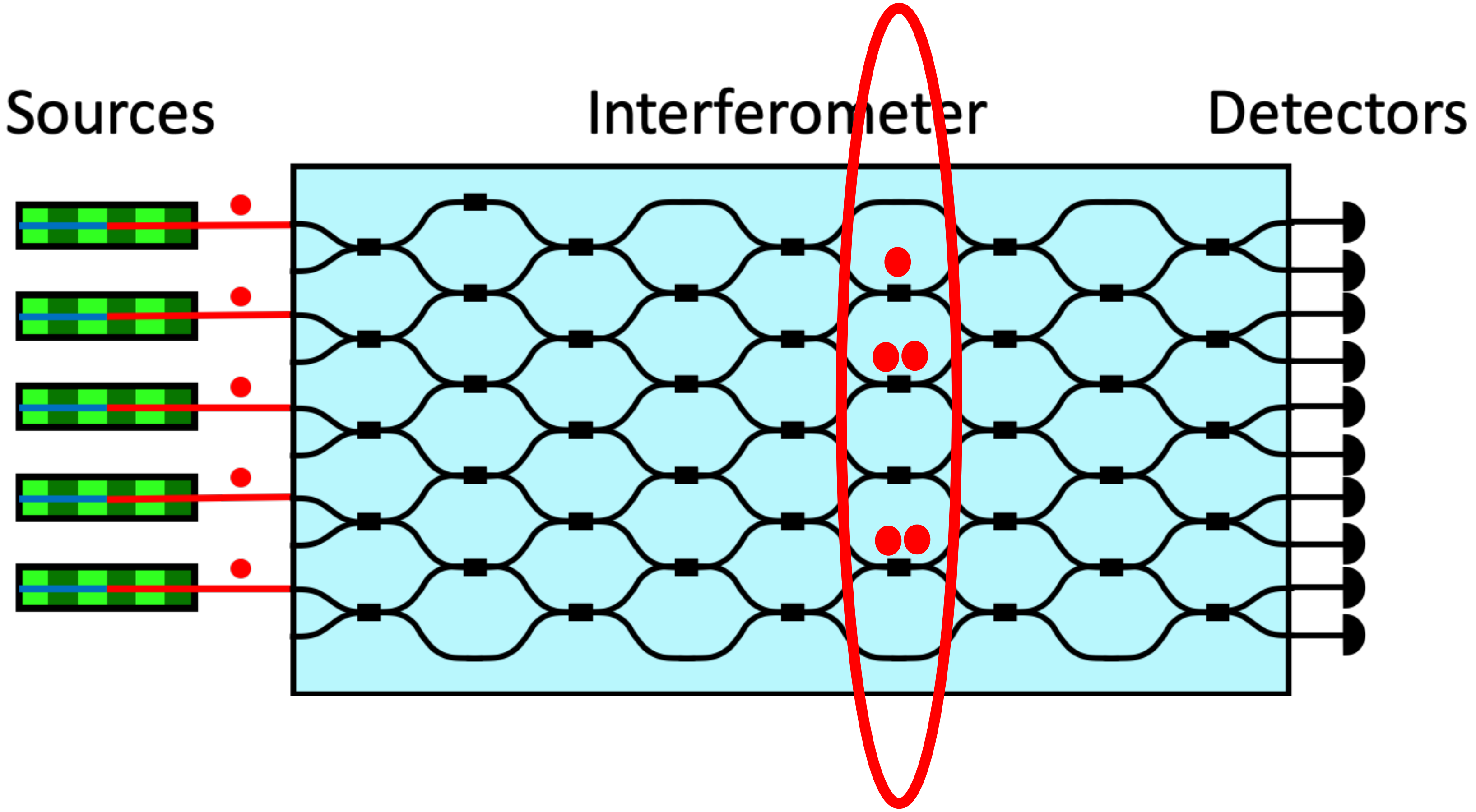
The system



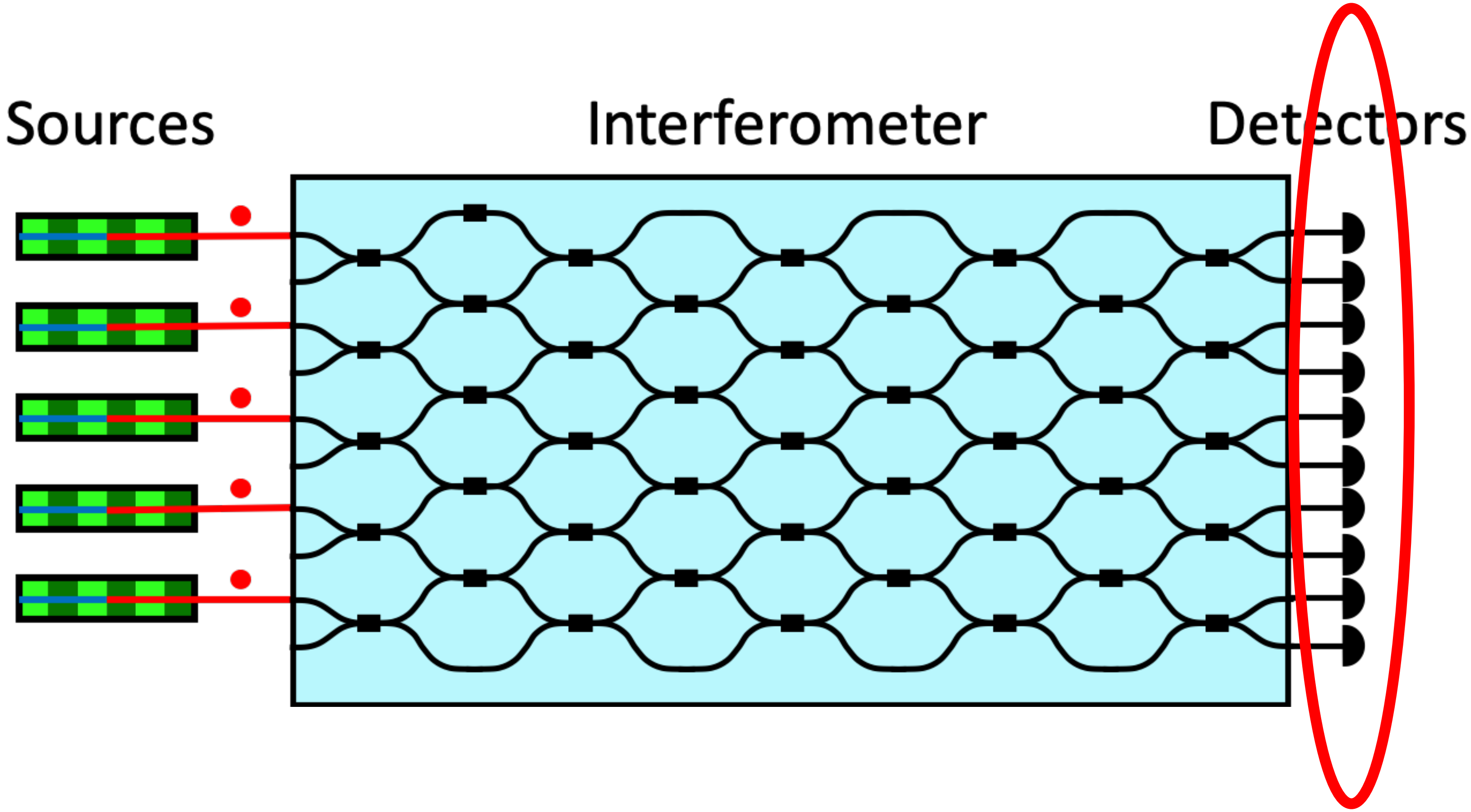
The system



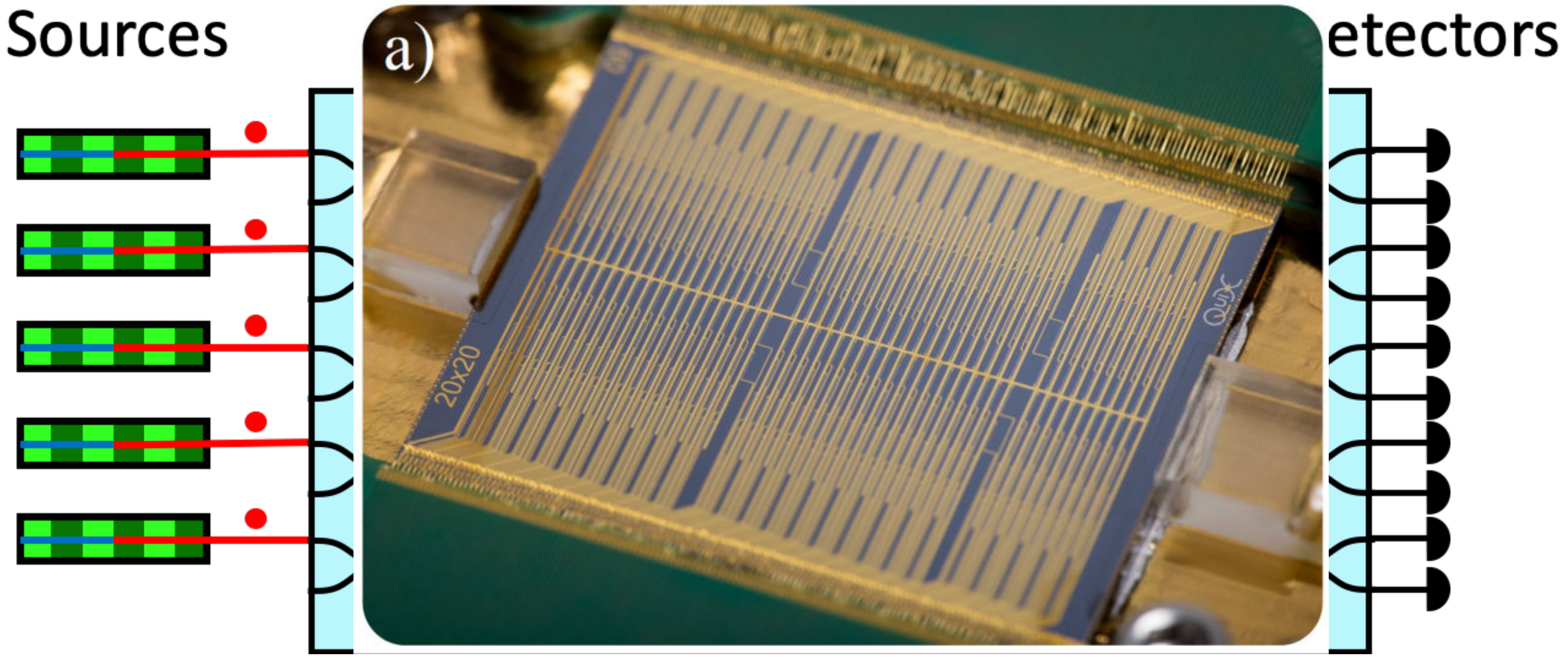
The system



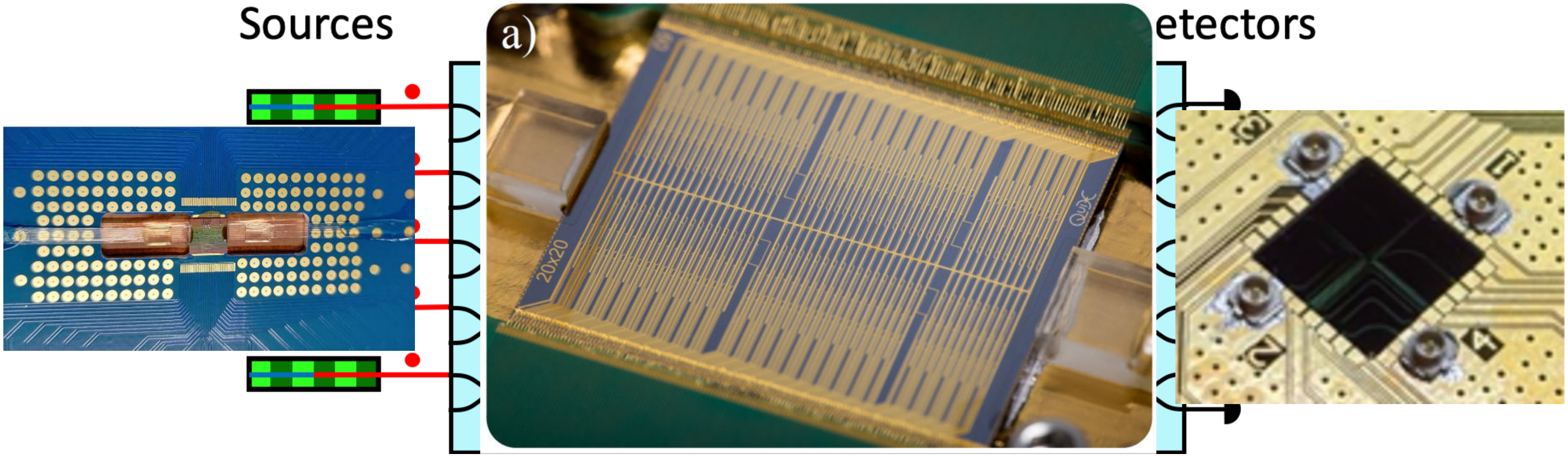
The system



The system



The system



Near-term quantum computation: Monte-Carlo integrator

M. Correa Anguita *et al*, manuscript in preparation

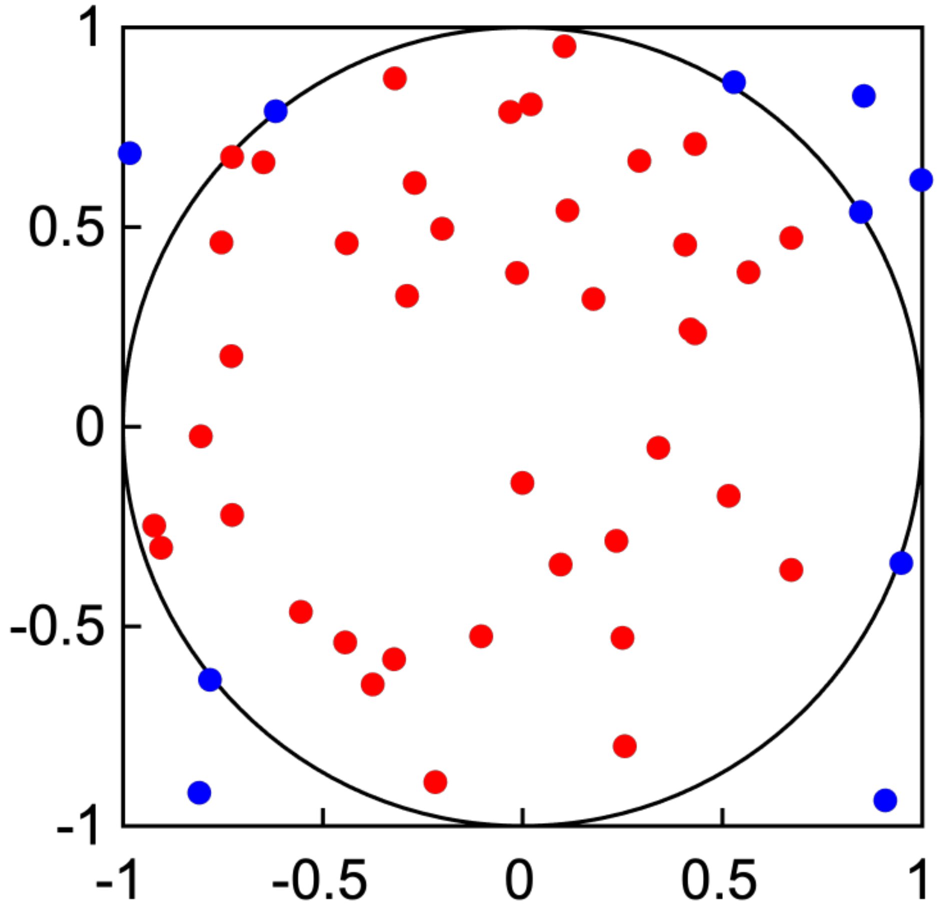
Finding useful applications for NISQ

- Many, many, false starts in finding applications for NISQ
- Big problem: NISQ only has quantum advantage for the task of drawing samples!
- Need to find situations where quantum-weighted lotteries are useful

M. Correa Anguita *et al*, manuscript in preparation

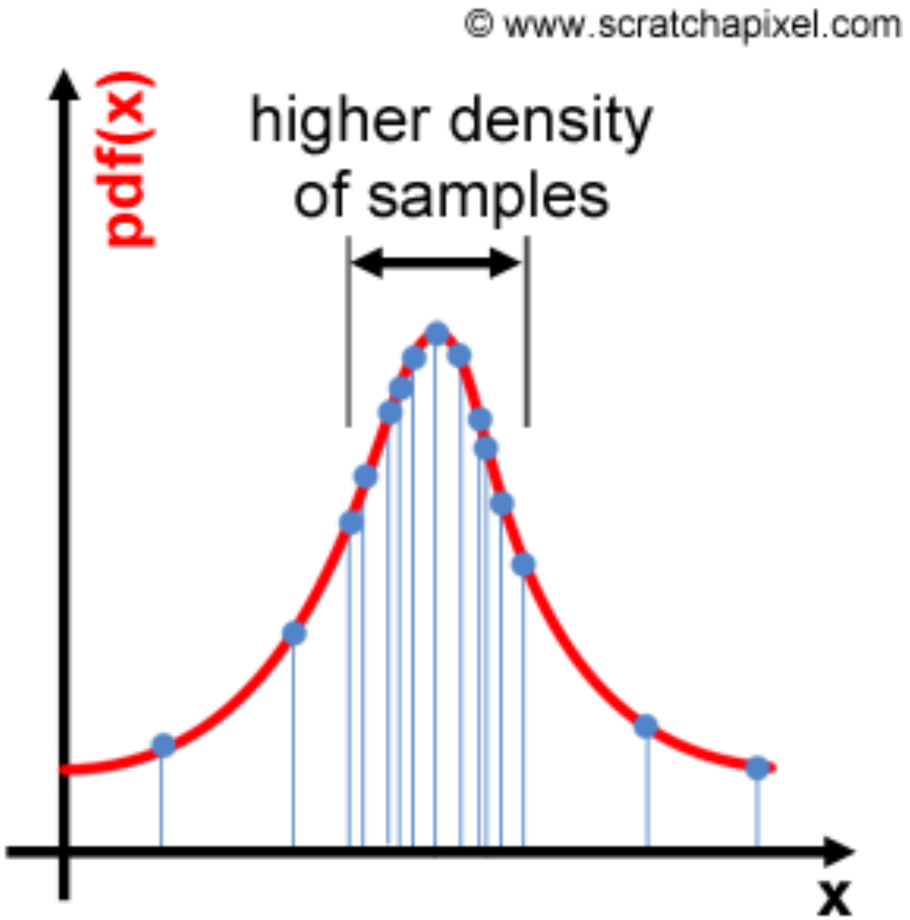
Monte carlo integration

- Compute π by uniformly throwing darts at a dart board
- $\frac{A_{circ}}{A_{sq}} = \frac{\#in}{N}$
- Error guaranteed to go as $\epsilon \propto \mathrm{C}\frac{1}{\sqrt{N}}$
- With C given by ‘how much your distribution resembles your function’



Monte carlo integration

- Compute π by uniformly throwing darts at a dart board
- $\frac{A_{circ}}{A_{sq}} = \frac{\#in}{N}$
- Error guaranteed to go as $\epsilon \propto \mathrm{C}\frac{1}{\sqrt{N}}$
- With C given by 'how much your distribution resembles your function'



The one bit of mathematics – importance sampling

Suppose we want to integrated a function of the form

$$f(x) = g(x)h(x)$$

Then $\int f(x)dx = \int g(x)h(x)$

$= \int_{g(x)} h(x)dg(x)$

$\approx \frac{1}{N}\sum_{g(x)} h(x)$

The one bit of mathematics – importance sampling

Suppose we want to integrated a function of the form

$$f(x) = g(x)h(x)$$

Then $\int f(x)dx = \int g(x)h(x)$

$= \int_{g(x)} h(x)dg(x)$

$\approx \frac{1}{N}\sum_{g(x)} h(x)$

Now suppose $g(x)$ happens to be implementable on quantum hardware...

The one bit of mathematics – importance sampling

Suppose we want to integrated a function of the form

$$f(x) = g(x)h(x)$$

Then $\int f(x)dx = \int g(x)h(x)$

$= \int_{g(x)} h(x)dg(x)$

$\approx \frac{1}{N}\sum_{g(x)} h(x)$

g(x)-weighted lottery!

Now suppose $g(x)$ happens to be implementable on quantum hardware...

M. Correa Anguita *et al*, manuscript in preparation

The one bit of mathematics – importance sampling

Suppose we want to integrated a function of the form

$$f(x) = g(x)h(x)$$

Then $\int f$

Do such cases arise in practice?

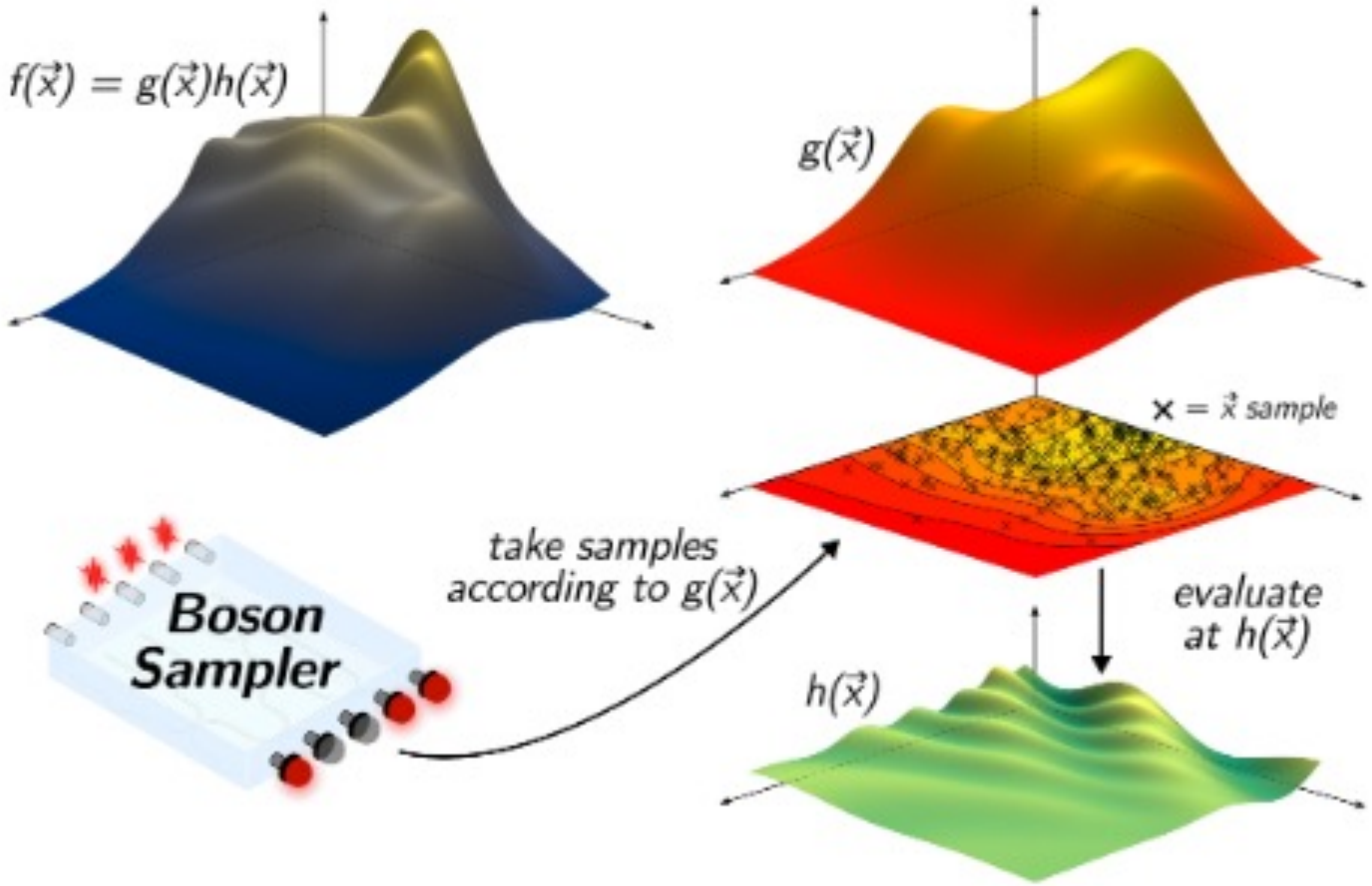
$= \int_{g(x)} h(x) dg(x)$

$\approx \frac{1}{N} \sum_{g(x)} h(x)$

g(x)-weighted lottery!

Now suppose $g(x)$ happens to be implementable on quantum hardware...

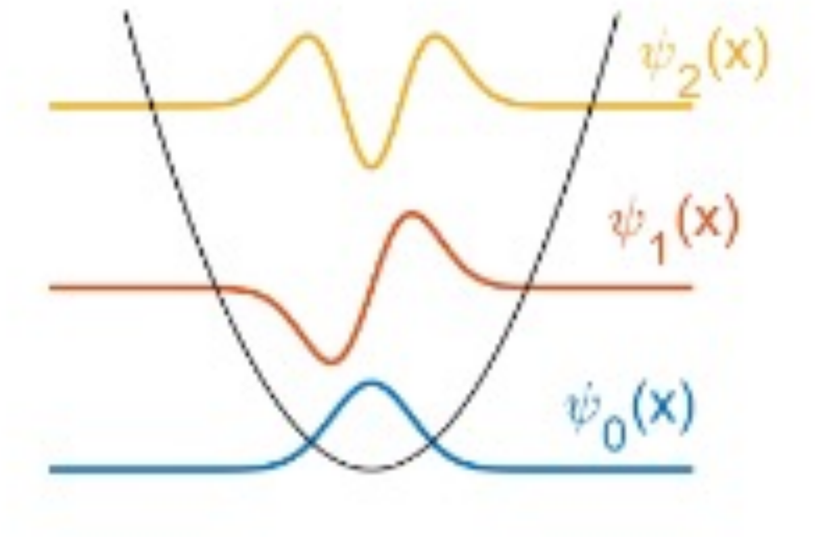
M. Correa Anguita *et al*, manuscript in preparation



$f(\vec{x}) = g(\vec{x})h(\vec{x})$
$g(\vec{x})$
$\times = \vec{x}$ sample
Boson Sampler
take samples according to $g(\vec{x})$
evaluate at $h(\vec{x})$
$h(\vec{x})$

Yes: first-order perturbation theory

$$E_1 = \langle \psi(x) | V(x) | \psi(x) \rangle = \int dx\, V(x) |\psi(x)|^2$$

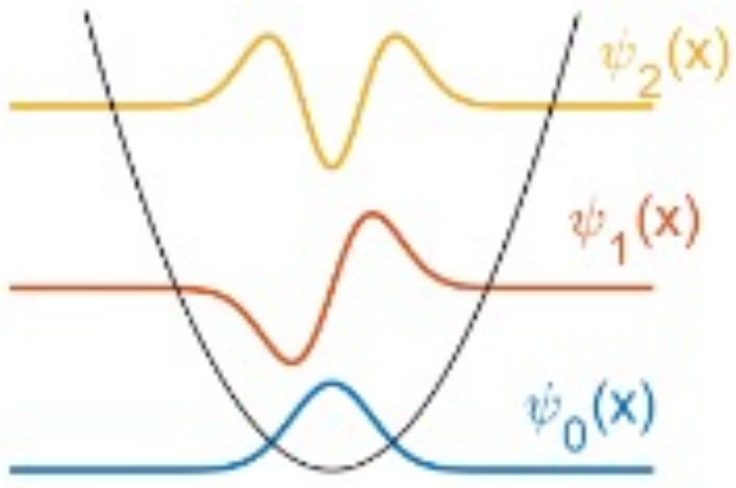


M. Correa Anguita *et al*, manuscript in preparation

Yes: first-order perturbation theory

$$E_1 = \langle \psi(x) | V(x) | \psi(x) \rangle = \int dx\, V(x) |\psi(x)|^2$$

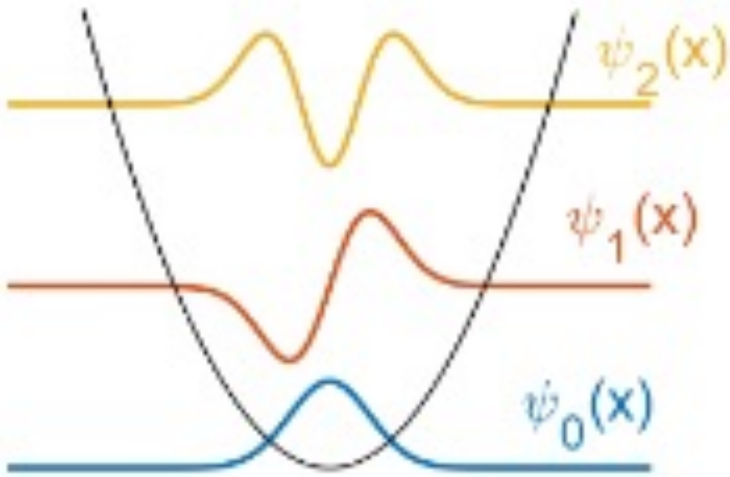
Do such cases arise in practice?

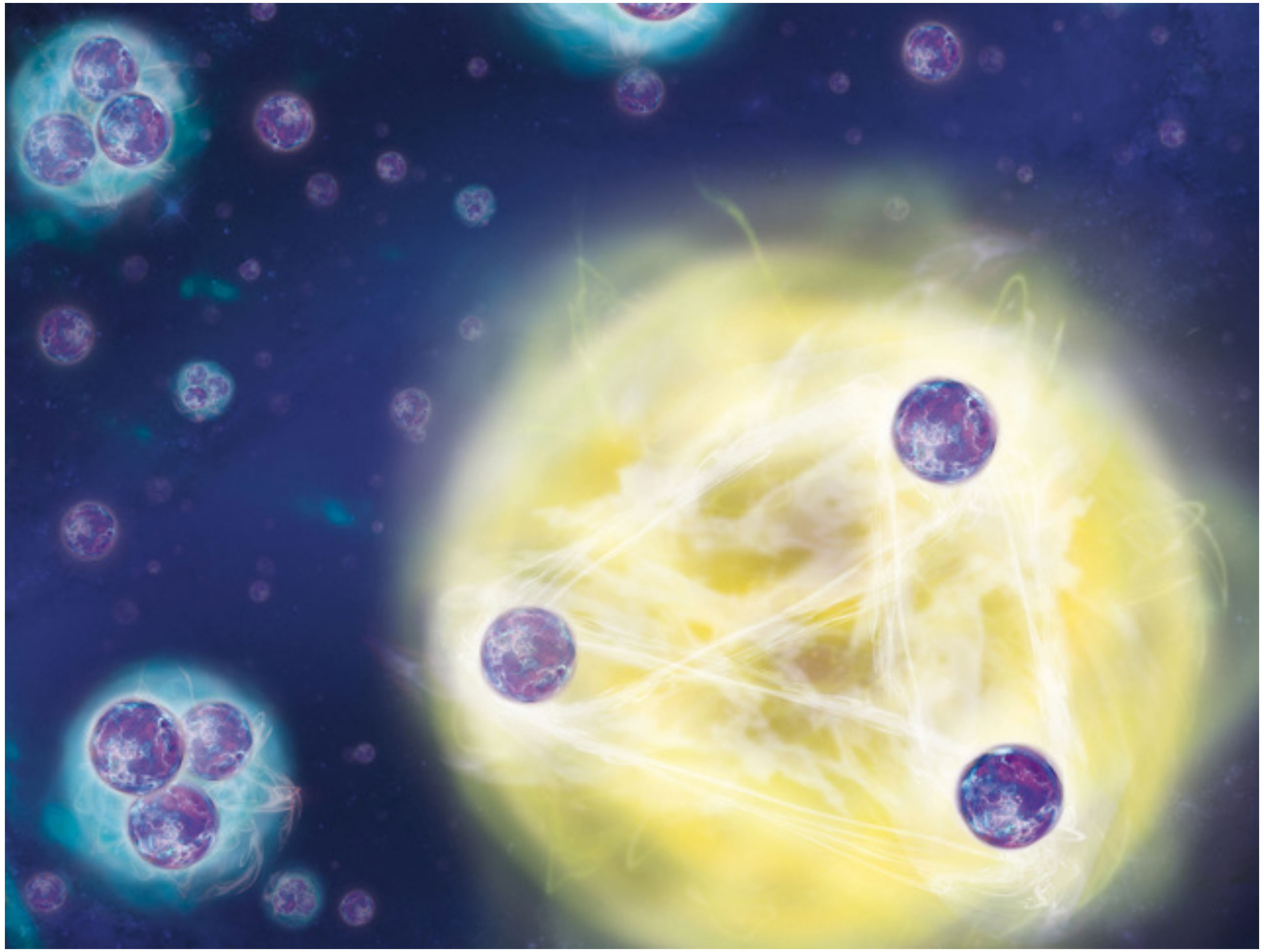


M. Correa Anguita *et al*, manuscript in preparation

Yes: Efimov physics

$$V_{\mathrm{Ef}}(\vec{x}) = -\frac{C + 1/4}{R^2}$$

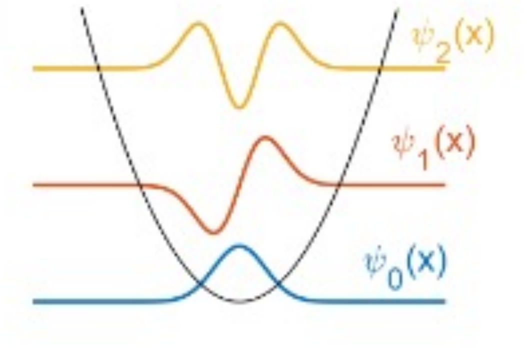




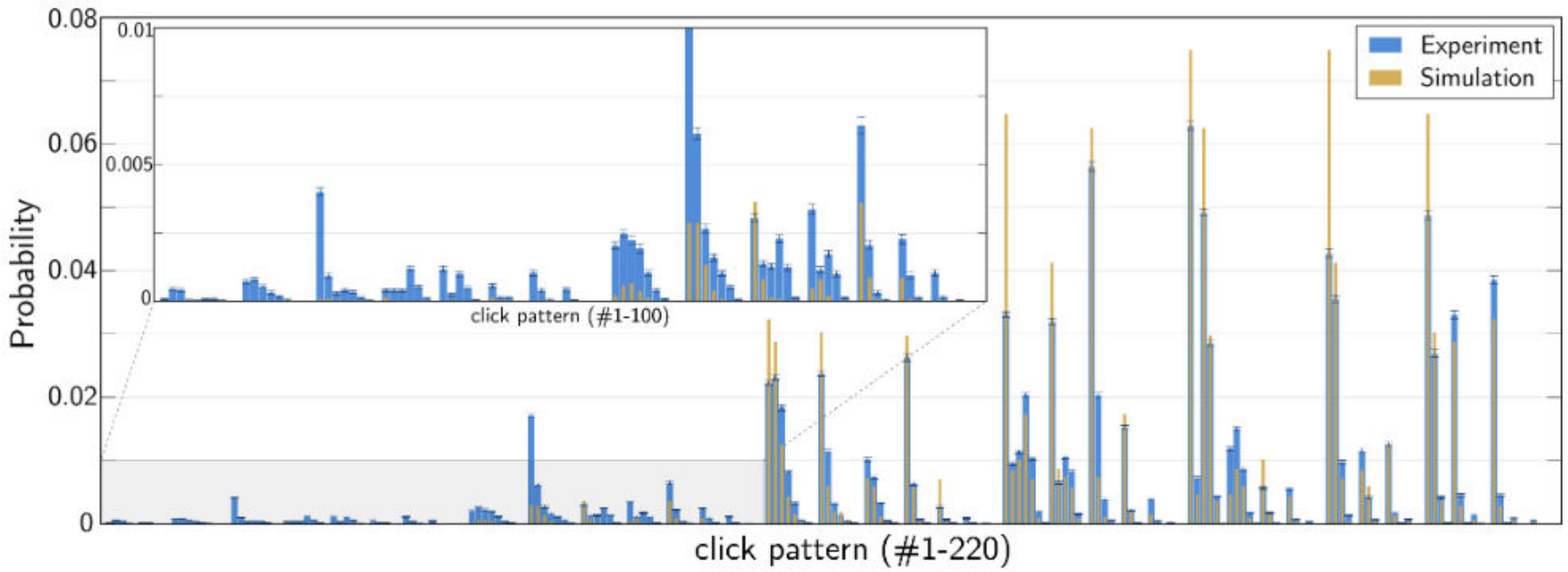
M. Correa Anguita *et al*, manuscript in preparation

Quantum-assisted Monte-Carlo integrator

Efimov potential in a harmonic trap – lowest three states



$$V_{\mathrm{Ef}}(\vec{x}) = -\frac{C + 1/4}{R^2}$$

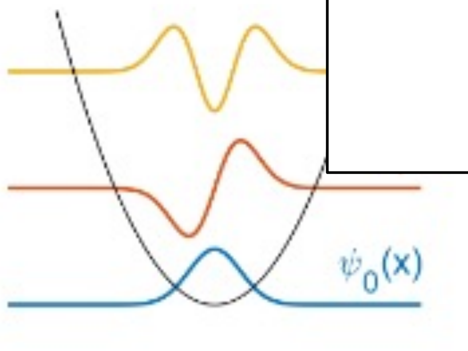


M. Correa Anguita *et al*, manuscript in preparation

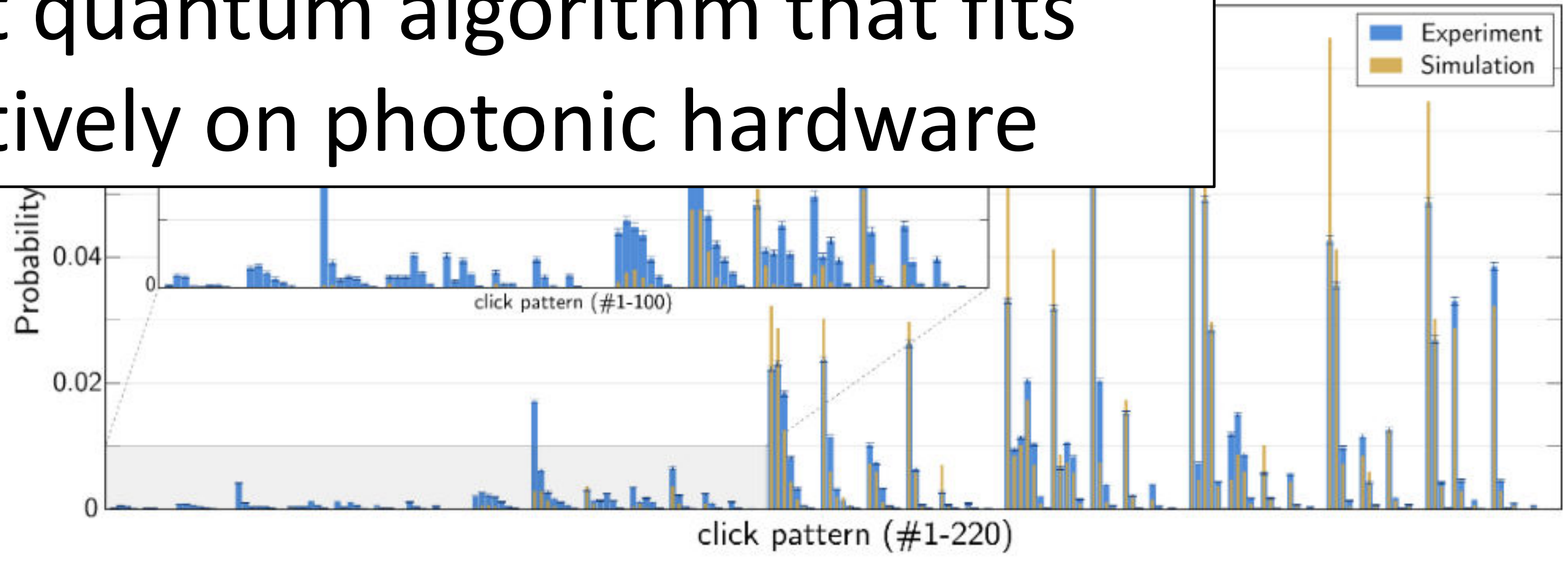
Quantum-assisted Monte-Carlo integrator

Efimov potential in a harmonic trap – lowest three states

First quantum algorithm that fits natively on photonic hardware

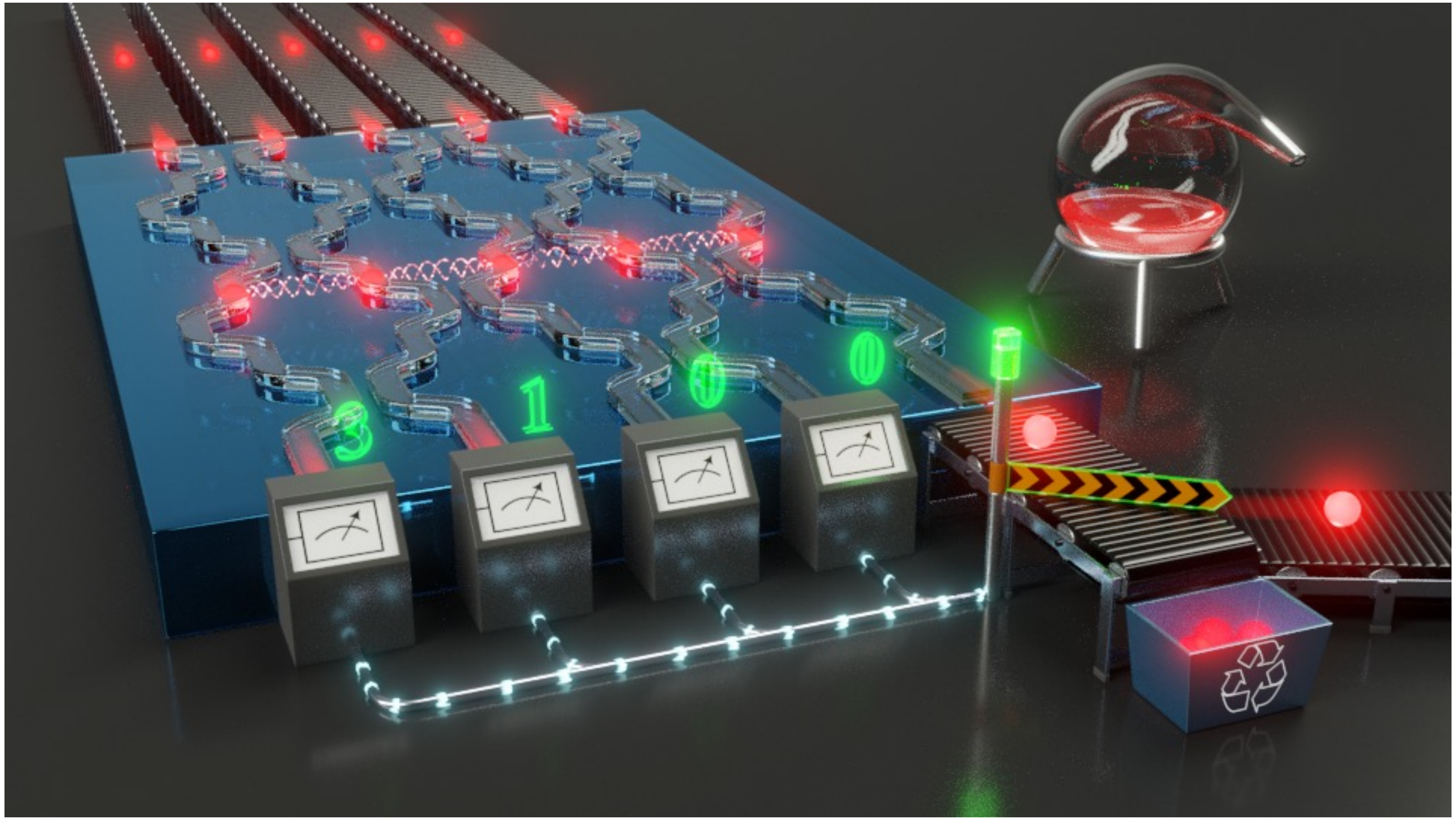


$$V_{\mathrm{Ef}}(\vec{x}) = -\frac{C + 1/4}{R^2}$$



M. Correa Anguita *et al*, manuscript in preparation

Universal quantum computation: Photon distillation



Somhorst et al, Phys. Rev. Applied 23, 044003 (2025)

Suppose you want to build a photonic QC

You need lots and lots of single photons

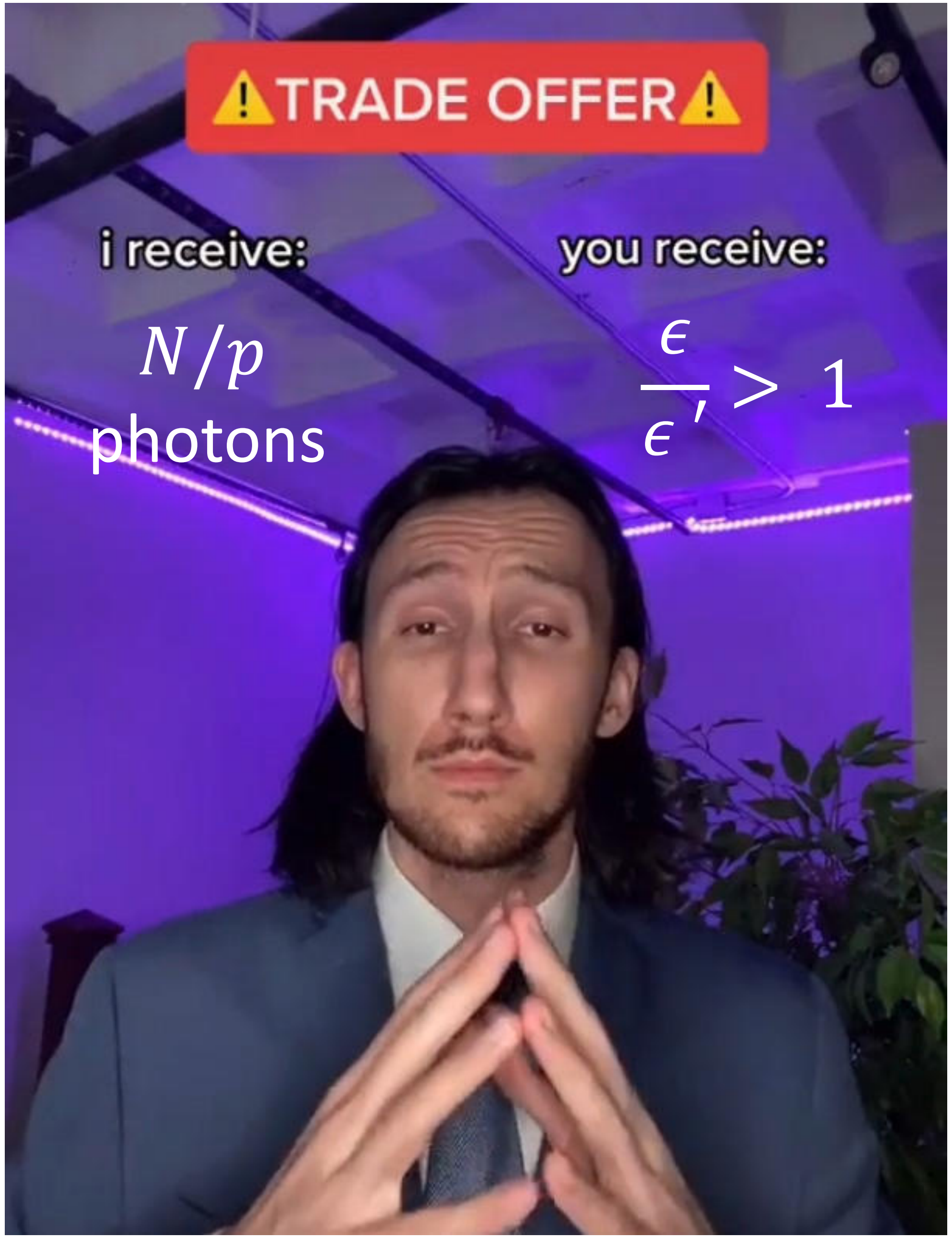
So, lots and lots of shots from a single photon source

OOM estimate: 10^6 qubits,
10^1 photons per qubit,
10^2 multiplexing per photon

Regime where tuning up a single source doesn't make sense anymore

Photon distillation

Probabilistically trade N “bad” photons with error ϵ for *one* “better” photon $\epsilon' < \epsilon$ with probability p.



Setting up the problem

Orthogonal bad bit model

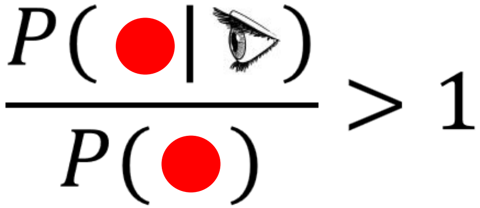
- Indistinguishable $P(\bullet) = (1 - \epsilon)$
- Distinguishable $P(\blacklozenge) = \epsilon$
- $\rho_T = \rho^{\otimes N}$ with $\rho = (1-\epsilon)|1_g\rangle\langle 1_g| + \epsilon|1\rangle_b\langle 1|_b$
- Circuit U
- Compute $\rho_{out}(M)$ using standard techniques

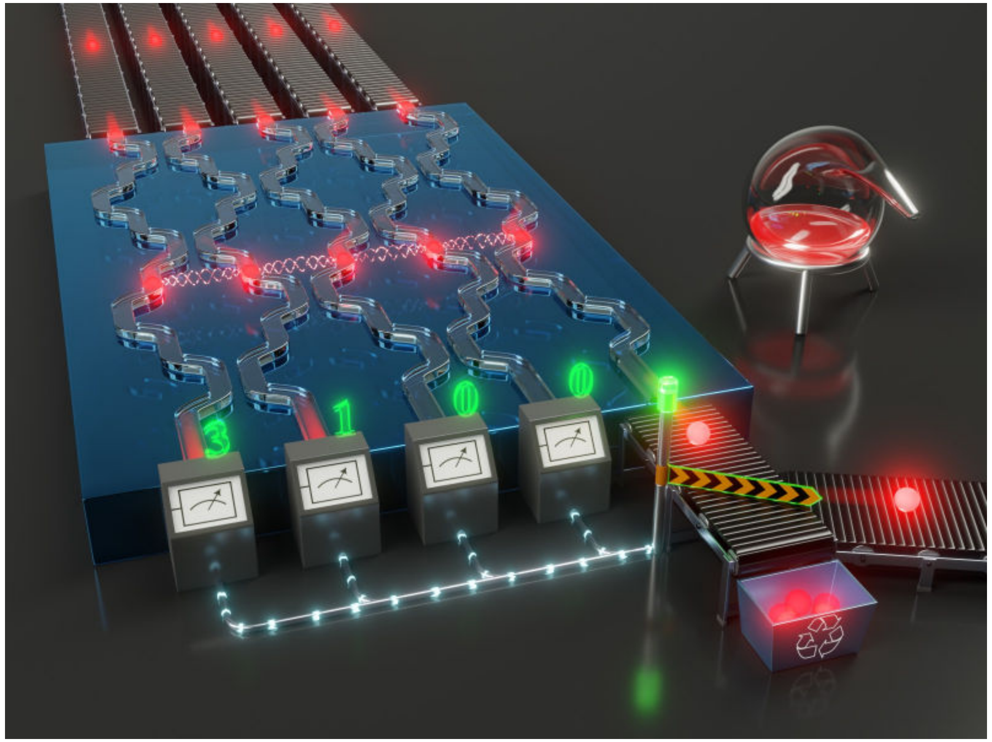
Moylett, Alexandra E., *et al*. *Quantum Science and Technology* 5.1 (2019): 015001.

Photon distillation

How to decrease ϵ?

→ Find  and U such that

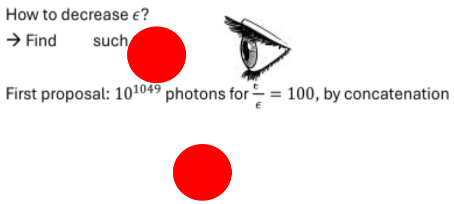




Photon distillation

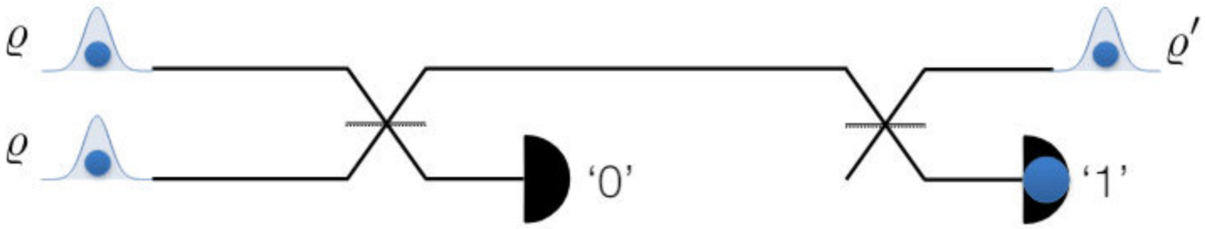
How to decrease ϵ?

→ Find  such that



First proposal: 10^{1049} photons for $\frac{\epsilon'}{\epsilon} = 100$, by concatenation

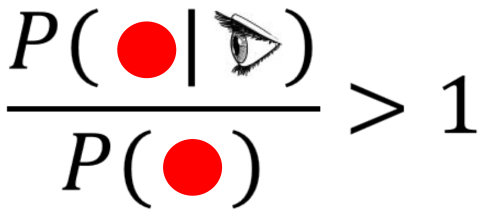
$$\epsilon' = \frac{\epsilon}{N}$$



Sparrow, Christopher. *Quantum interference in universal linear optical devices for quantum computation and simulation*. Diss. Imperial College London, 2018.

Photon distillation

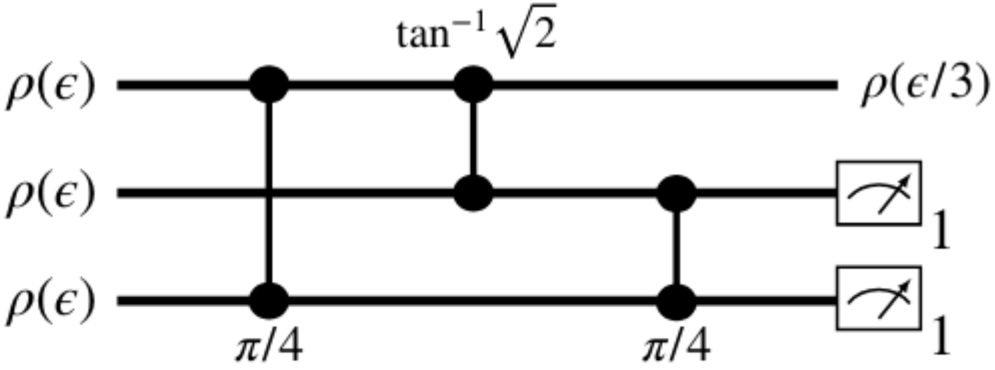
How to decrease ϵ?

→ Find  such that 

Second proposal: 59000 photons for $\frac{\epsilon'}{\epsilon} = 100$, by concatenation

$$\epsilon' = \frac{\epsilon}{3}$$

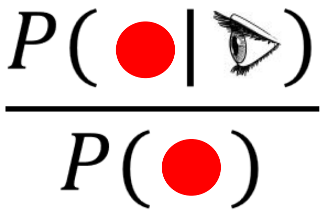
$$p = \frac{1}{3}$$



Marshall, Jeffrey. "Distillation of indistinguishable photons." *Physical Review Letters* 129.21 (2022): 213601.

Photon distillation

How to decrease ϵ?

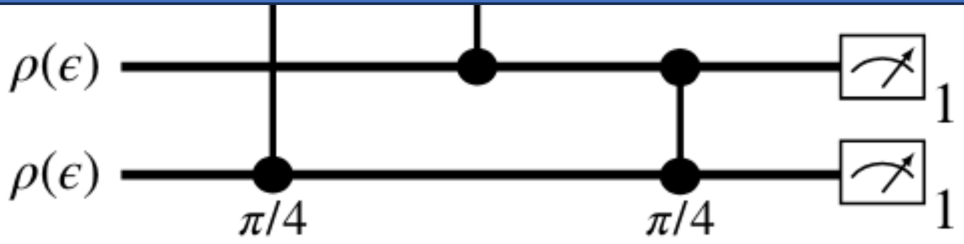
→ Find  such that 

Second p … tion

Can we do better?

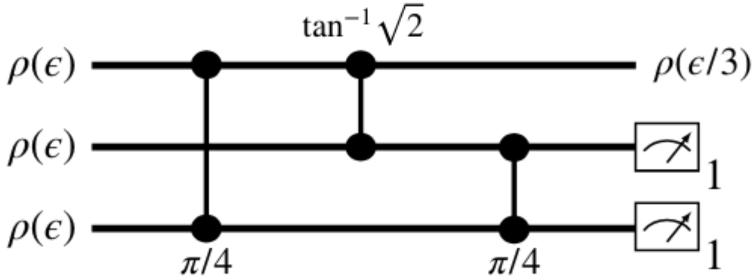
$$\epsilon' = \frac{\epsilon}{3}$$

$$p = \frac{1}{3}$$



Realization

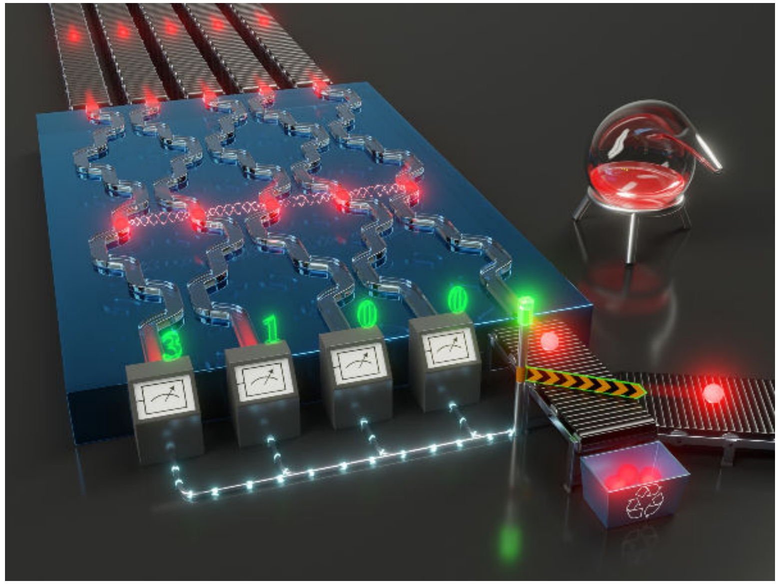
Scheme of [1] = 3-mode Fourier transform!



That gives a way to generalize: N photons in N modes

$\rightarrow \epsilon' = \frac{\epsilon}{N}?$

$\rightarrow p = \frac{1}{N}?$



Marshall, Jeffrey. "Distillation of indistinguishable photons." *Physical Review Letters* 129.21 (2022): 213601.

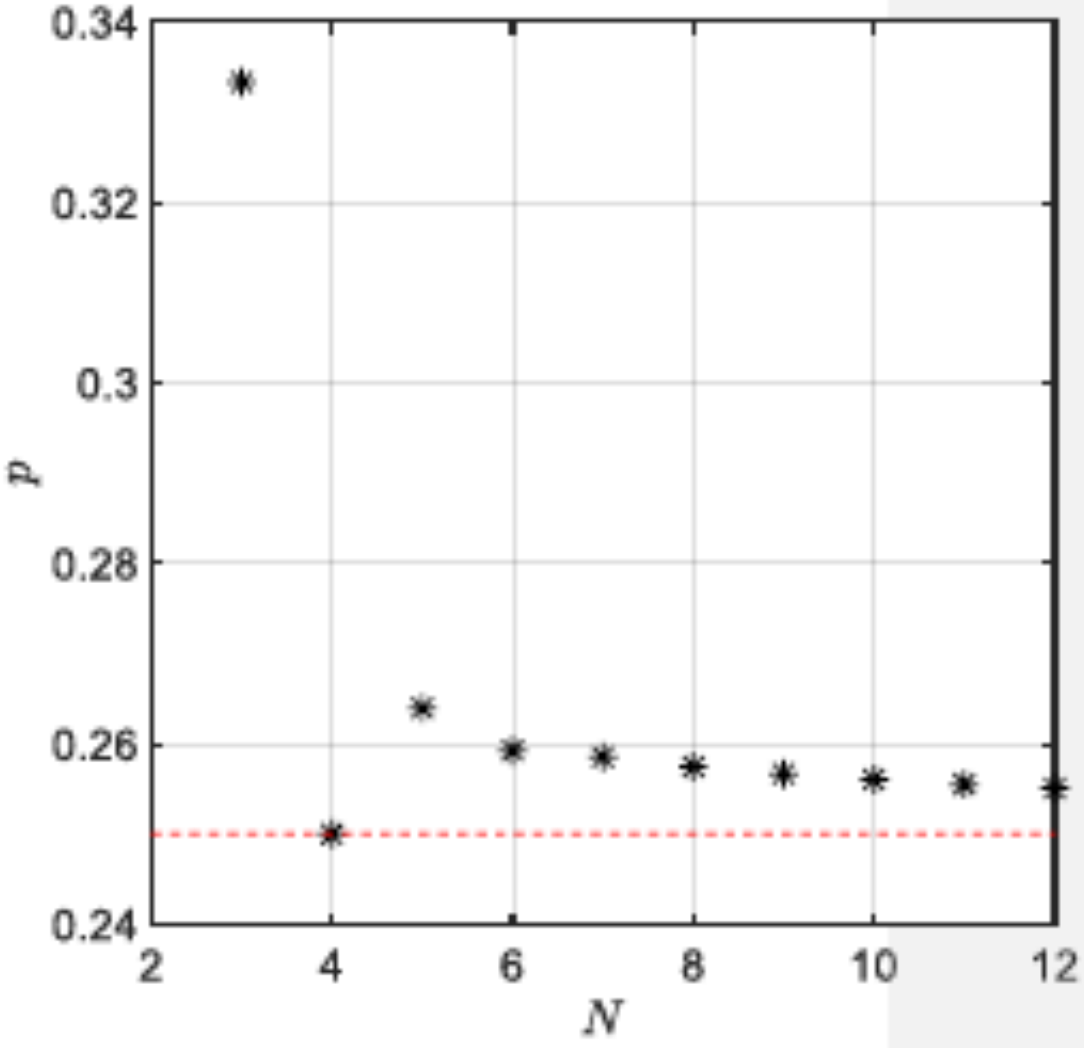
N-photon distillation

Simulations on *N*-mode Fourier transform

$$p = \sum_{j=0}^{N} (-1)^j (j+1) \prod_{i=1}^{j} (1 - \frac{i}{N})$$

$p \to \frac{1}{4}$ (proof by NASA Ames)

$\epsilon' = \epsilon / N$



Somhorst et al, Phys. Rev. Applied 23, 044003 (2025)

N-photon distillation

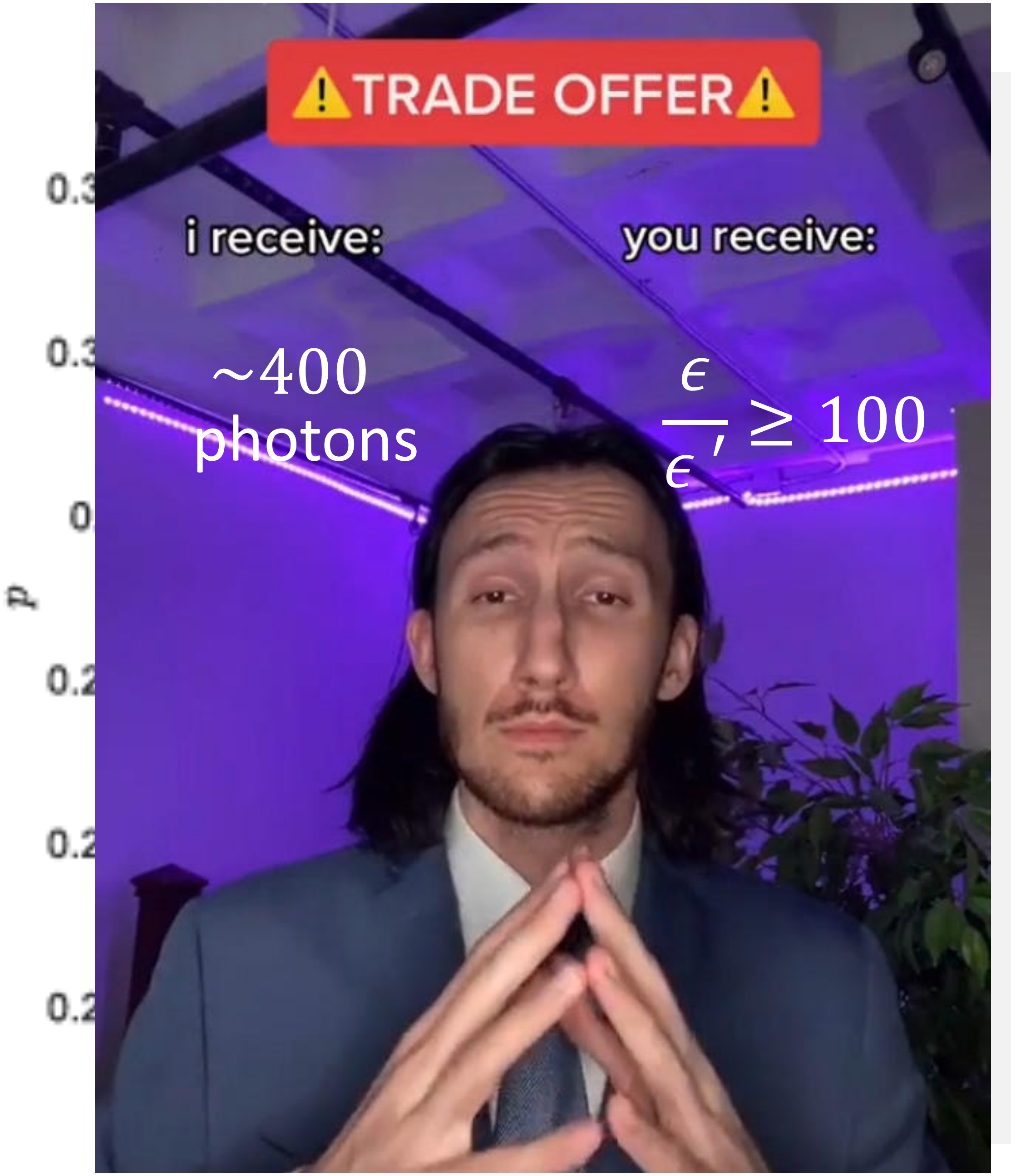
Simulations on *N*-mode Fourier transform

$$p = \sum_{j=0}^{N} (-1)^j (j+1) \prod_{i=1}^{j} \left(1 - \frac{i}{N}\right)$$

$p \to \frac{1}{4}$ (proof by NASA Ames)

$\epsilon' = \epsilon / N$

<u>No concatenation required!!</u>



Somhorst et al, Phys. Rev. Applied 23, 044003 (2025)

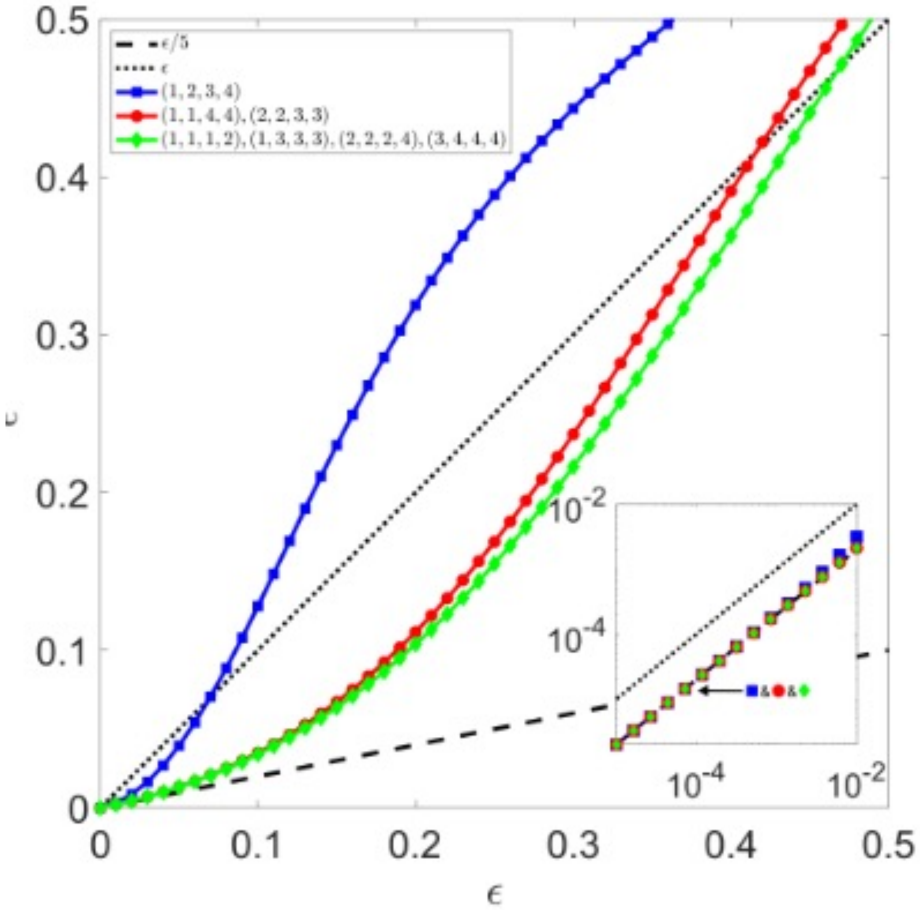
Photon distillation vs error correction

- Photon distillation has a higher threshold for photon distinguishability than error correction w/ surface code
- Photon distillation + error correction is a more efficient use of resources (as measured in photon sources) than just error correction

Somhorst et al, Phys. Rev. Applied 23, 044003 (2025)

Behaviour above threshold

- For the surface code: error threshold is about 0.6% to 1%
- For photon distillation: error threshold is at least 10%, probably more
- Moreover, there's also photon loss!



Somhorst et al, Phys. Rev. Applied 23, 044003 (2025)

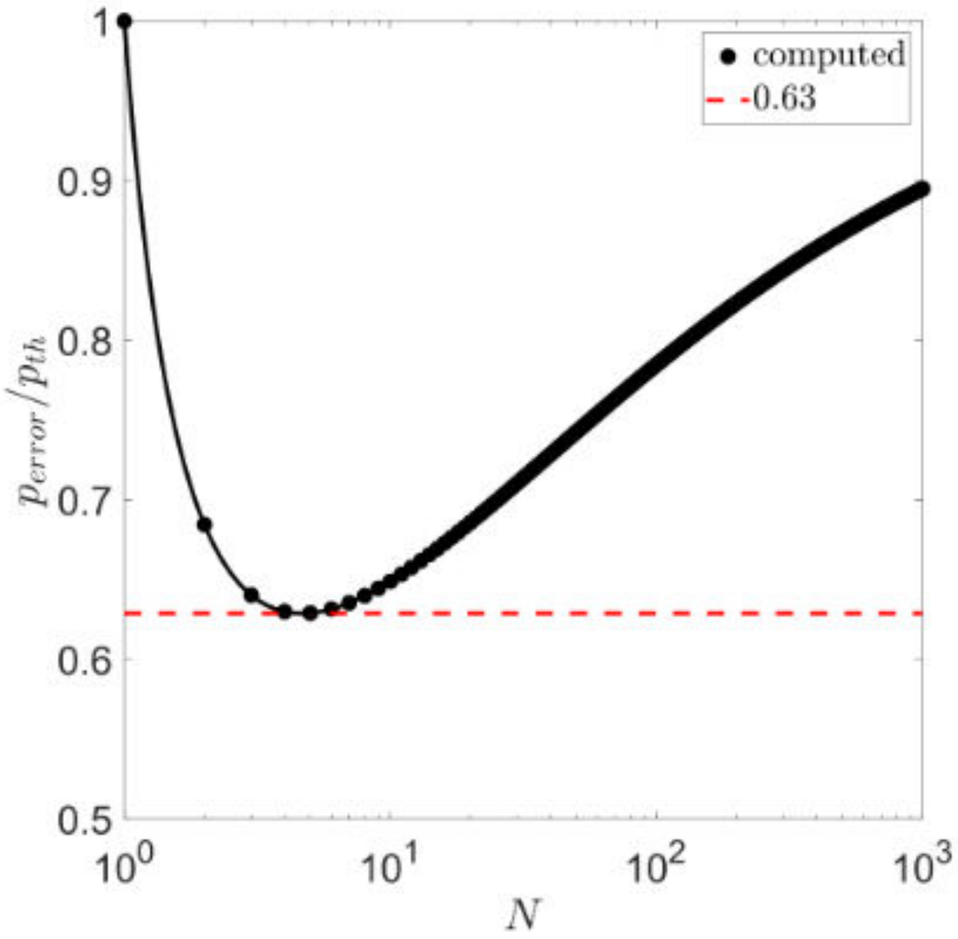
Behaviour below threshold

- Assume linear interchange between Pauli errors and photon errors

$$p_{error} = \alpha\, \epsilon$$

$$C_{\mathrm{L}}^{\mathrm{dist.}} = C_{\mathrm{L}} \cdot \left(\frac{2\sqrt{N}\log(\frac{p_{\mathrm{error}}}{p_{\mathrm{th}}})}{\log(\frac{p_{\mathrm{error}}}{p_{\mathrm{th}}}) - \log(N)} \right)^2 .$$

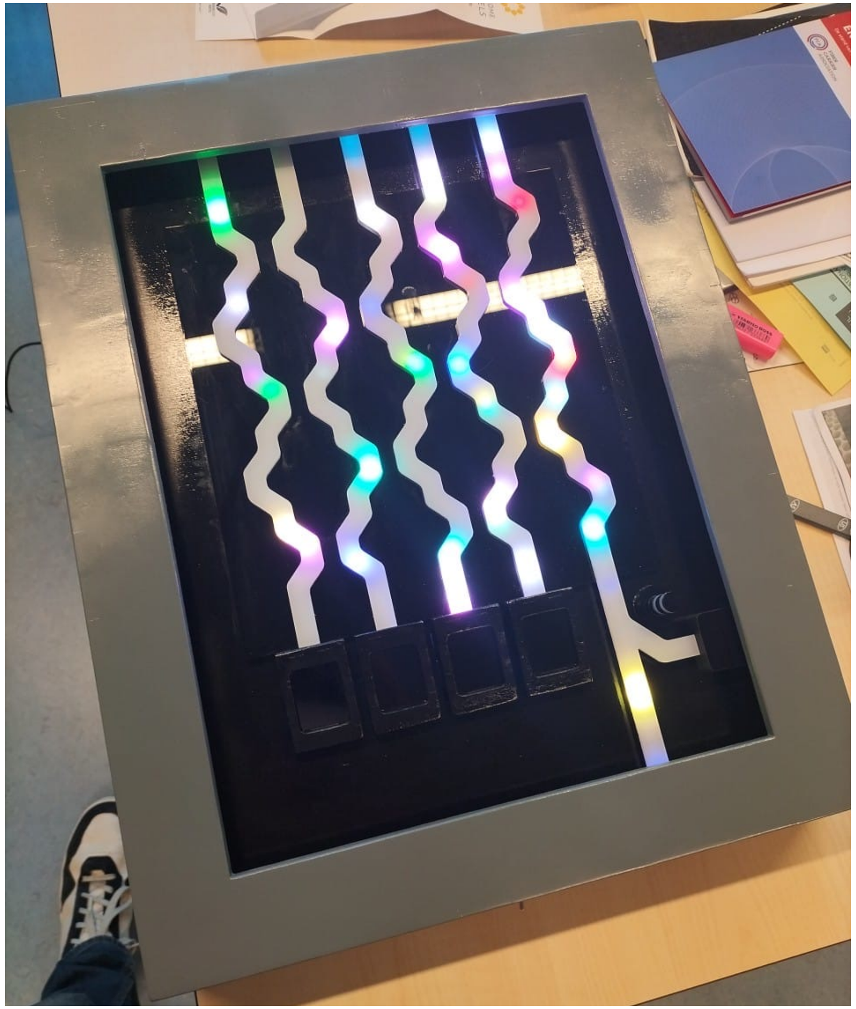
- Also turns out: nonlinear relation helps us



Somhorst et al, Phys. Rev. Applied 23, 044003 (2025)

Conclusion

- Indistinguishability errors can be reduced by photon distillation.
- Lowest resource costs scaling to date: $\epsilon' = \frac{\epsilon}{N}$ requires $\sim 4N$ photons.
- This component will turn up in real photonic quantum computers!



Somhorst et al, Phys. Rev. Applied 23, 044003 (2025)