UNIVERSITY OF WARSAW

WYDZIAŁ MATEMATYKI, INFORMATYKI I MECHANIKI

Photonic quantum information processing

Dr. hab. Magdalena Stobińska, prof. UW | www.stobinska-group.eu

Colloquium of the Faculty of Mathematics, Informatics and Mechanics, 20 October 2022

Agenda

- My short bio
- Quantum Technologies Research Group “QCAT”
- Quantum photonic platform (short overview)
- Quantum Kravchuk Transform
- Application of Quantum Kravchuk Transform to quantum simulations
- Conclusions

My short bio

- **2007** – PhD in physics, Faculty of Physics, University of Warsaw
- **2007-2012** – Max Planck Institute for the Science of Light & Erlangen-Nuremberg University
- **2012-2016** – University of Gdańsk & Institute of Physics PAS
  FNP "Homing Plus", MSCA Career Integration Grant, NCN "Harmony", MNiSW "Iuventus Plus"
- **2015** – Habilitation in Physics
- **2017** – Visiting Professor at the University of Oxford
- **2017-2020** – Faculty of Physics, University of Warsaw
  FNP "First Team"
- **2021-now** – Faculty of Mathematics, Informatics and Mechanics, University of Warsaw
  MSCA Innovative Training Network "AppQInfo" (coordinator)
  NCN "Sonata Bis", QuantEra "PhoMemtor"

Quantum Technologies Research Group "QCAT"

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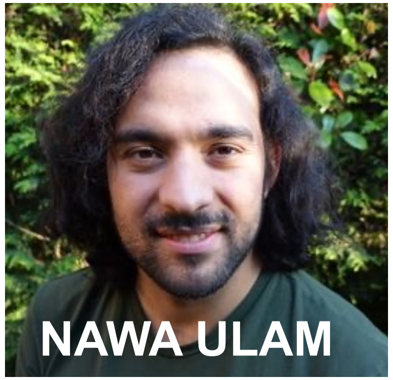

FNP

MARIE CURIE ACTIONS

Ministerstwo Edukacji i Nauki

NAWA
NARODOWA AGENCJA WYMIANY AKADEMICKIEJ

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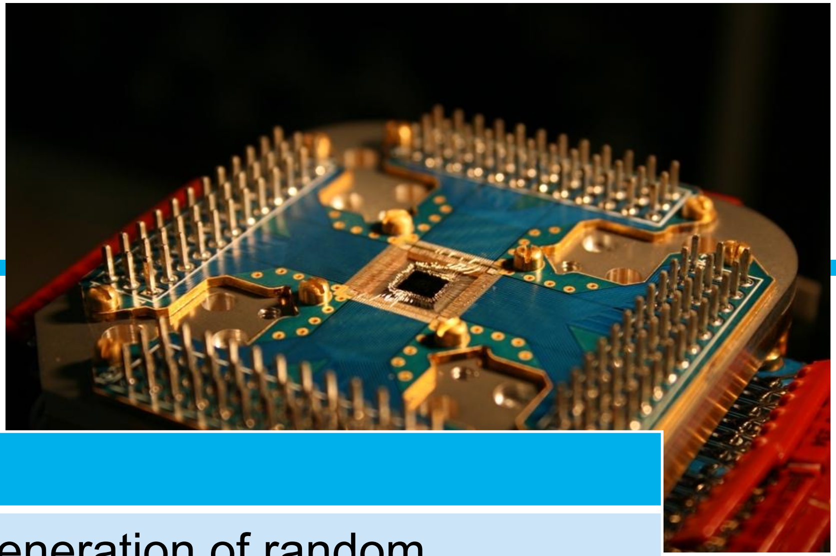
Short overview of the quantum photonic platform

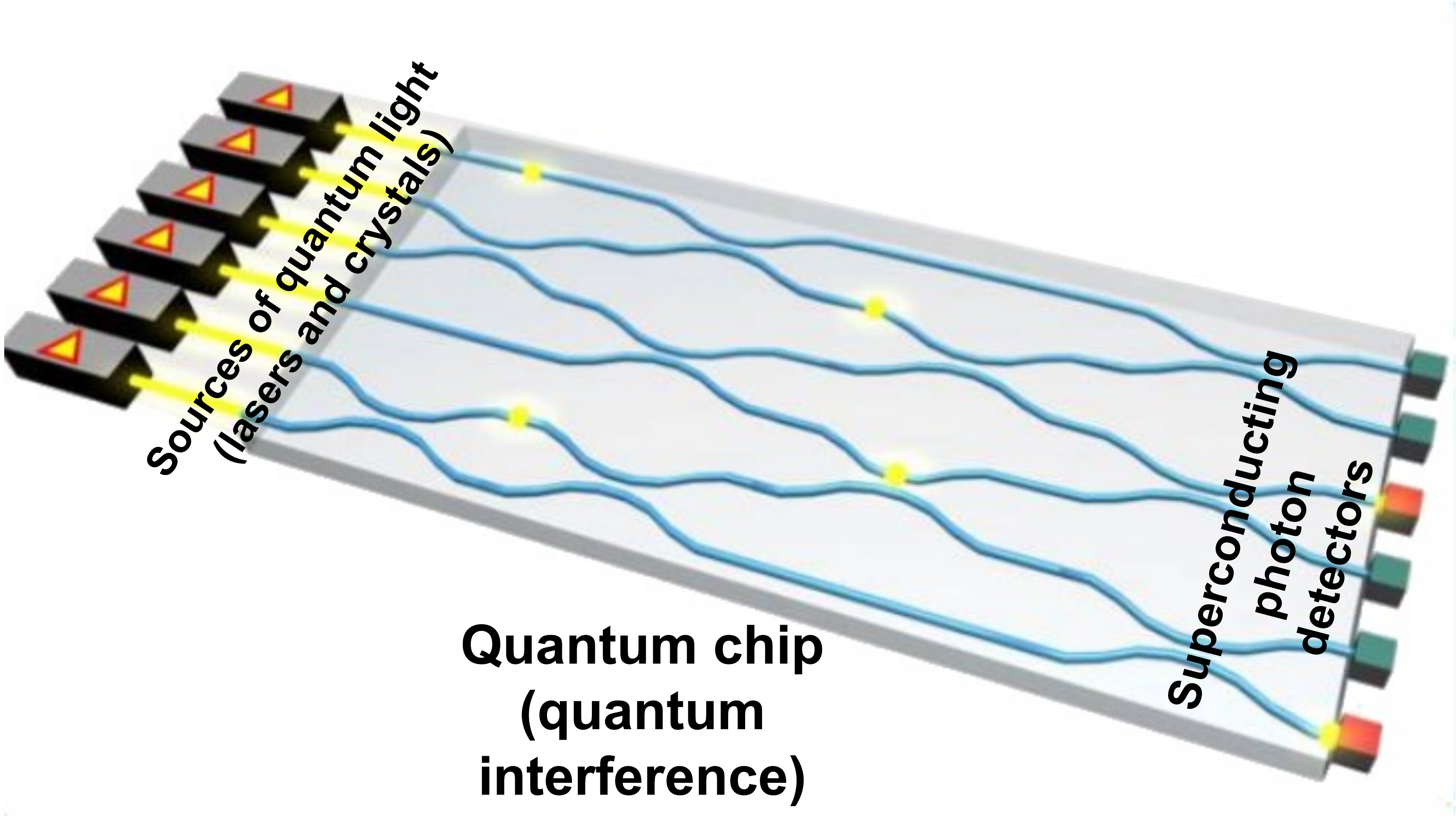
Quantum technologies



Technology	Application
Quantum Key Distribution (QKD)	Ultimately safe generation of random cryptographic keys
Quantum Metrology	Performing enhanced-precision measurements (e.g. microscopy, detection of gravitational waves)
Quantum Computing (QC)	Decreasing the complexity of computations, performing simulations of quantum materials; machine learning
Quantum Random Number Generation (QRNG)	Generating the entropy for cryptographic purposes

Second quantum revolution: utilizing quantum technologies for practical applications. **It is happening just now!**

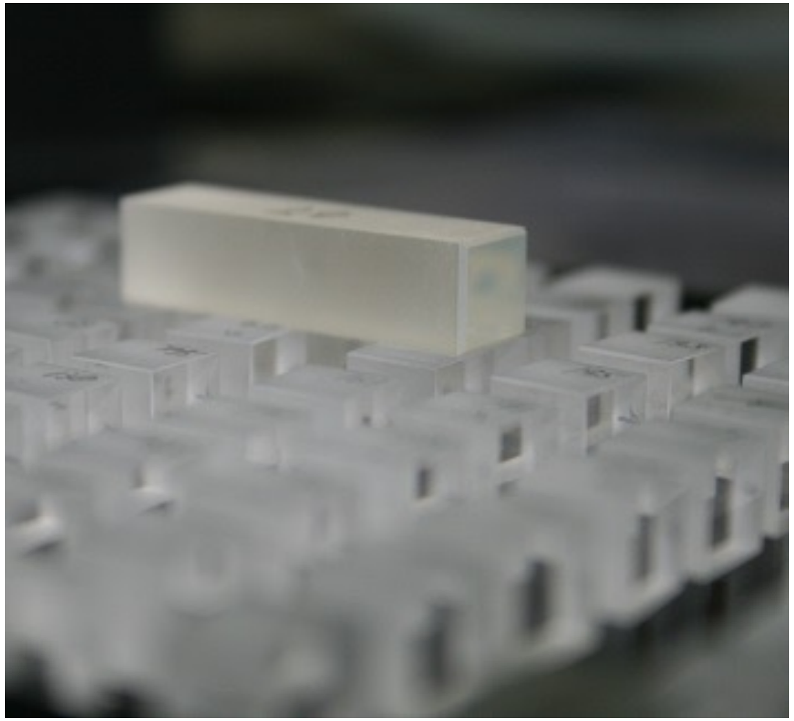
Quantum Integrated photonics



- Works in room temperature
- Small form factor
- Relatively low costs
- Photons may be transmitted in fibers or in free space

Lasers, crystals and detectors

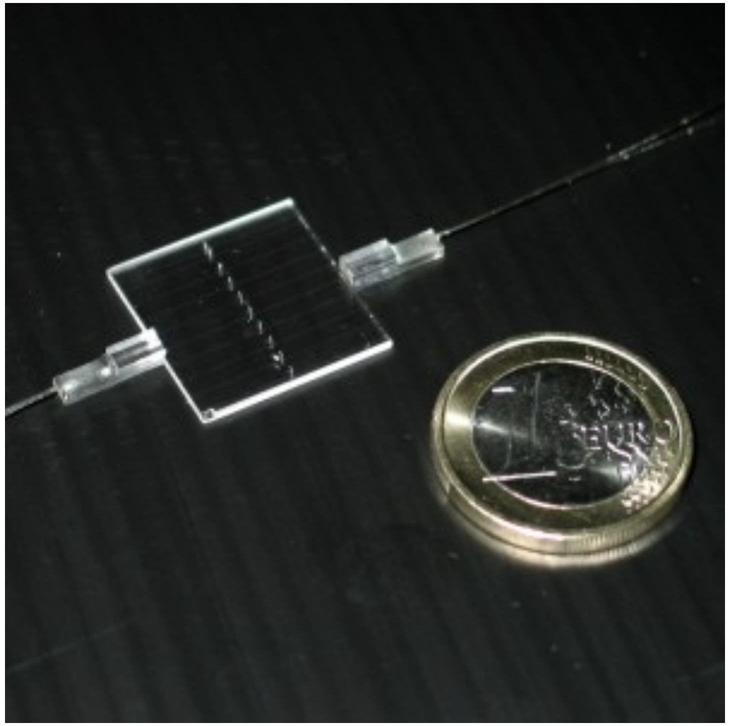
Coherent



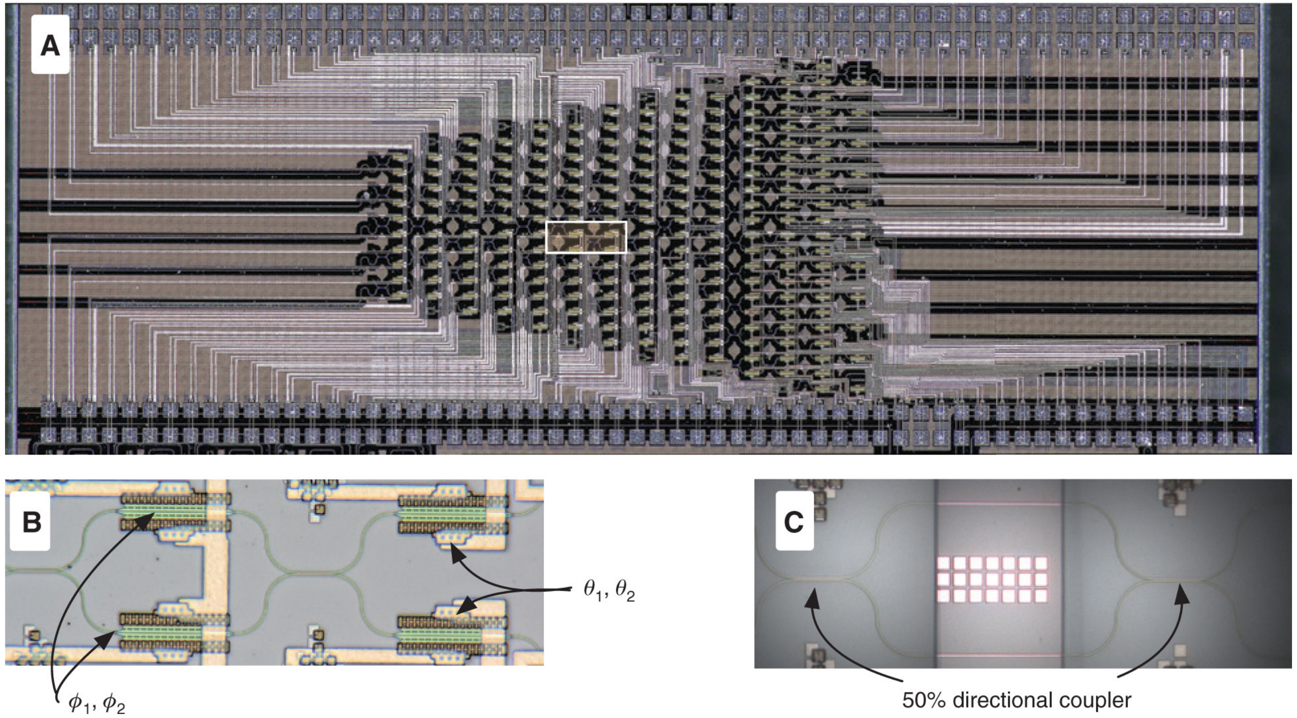
Advr

Single Quantum

Quantum photonic chips

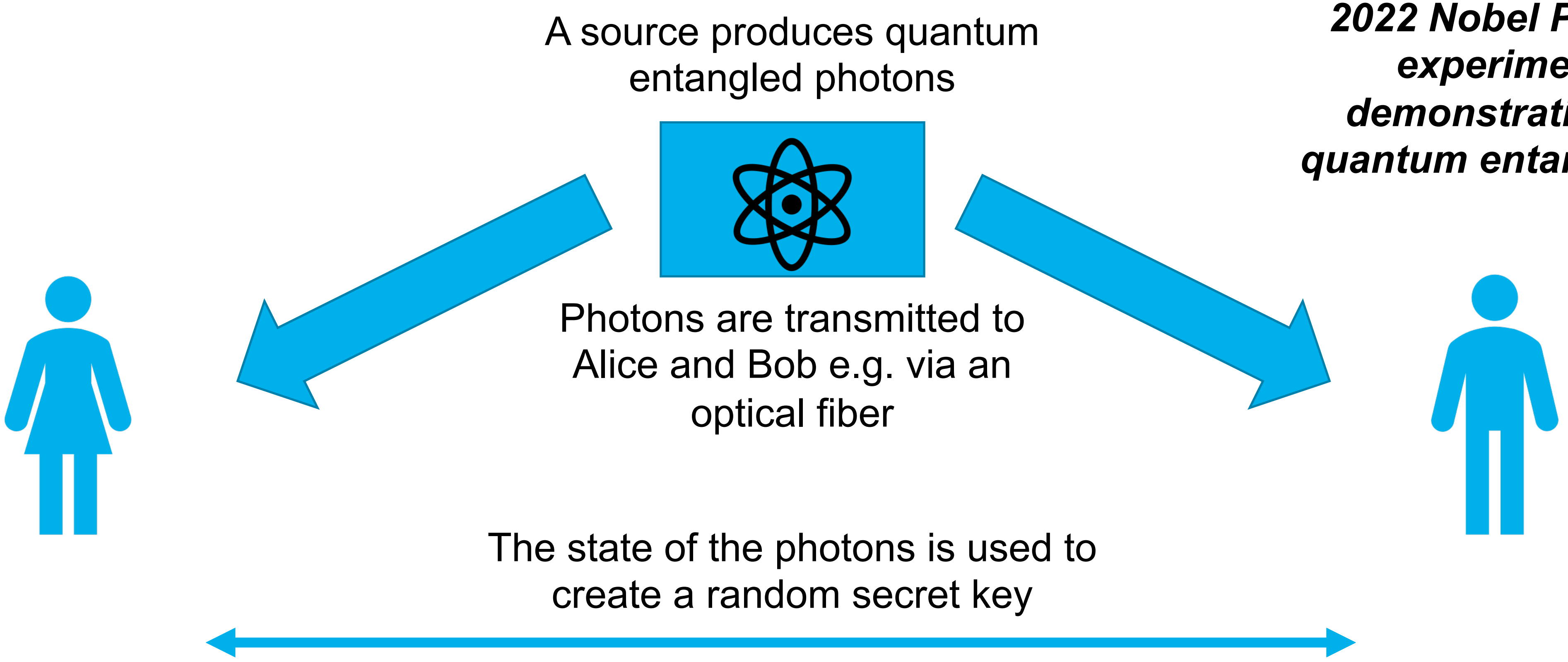


Laser micromachining



Lithography

Quantum Communication (Quantum Key Distribution)



2022 Nobel Prize for experimental demonstrations of quantum entanglement

Any „eavesdropping" of a quantum state **destroys quantum entanglement** and Alice and Bob can detect that.
For this reason, quantum key distribution is **ultimately secure**.

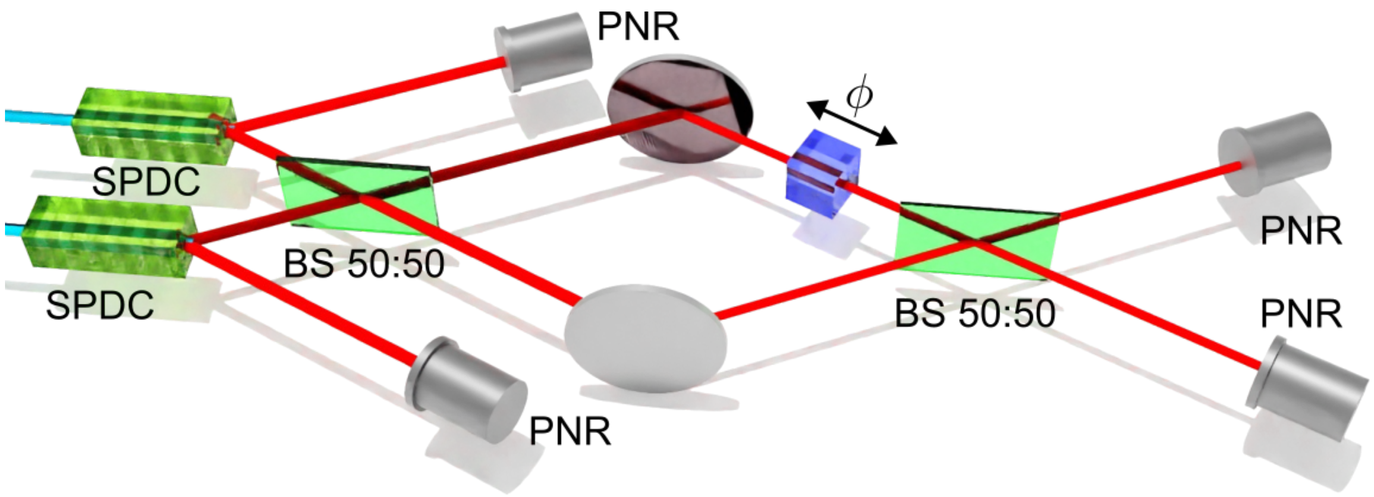
Fiber-based Quantum Communication

- Several companies have developed **quantum key distribution** systems that could enable mass manufacturing of quantum security technology
- Target audiences: governments, banking, companies
- ranges up to 800 km
- Basis of so-called “Quantum Internet”

Quantum communication in space

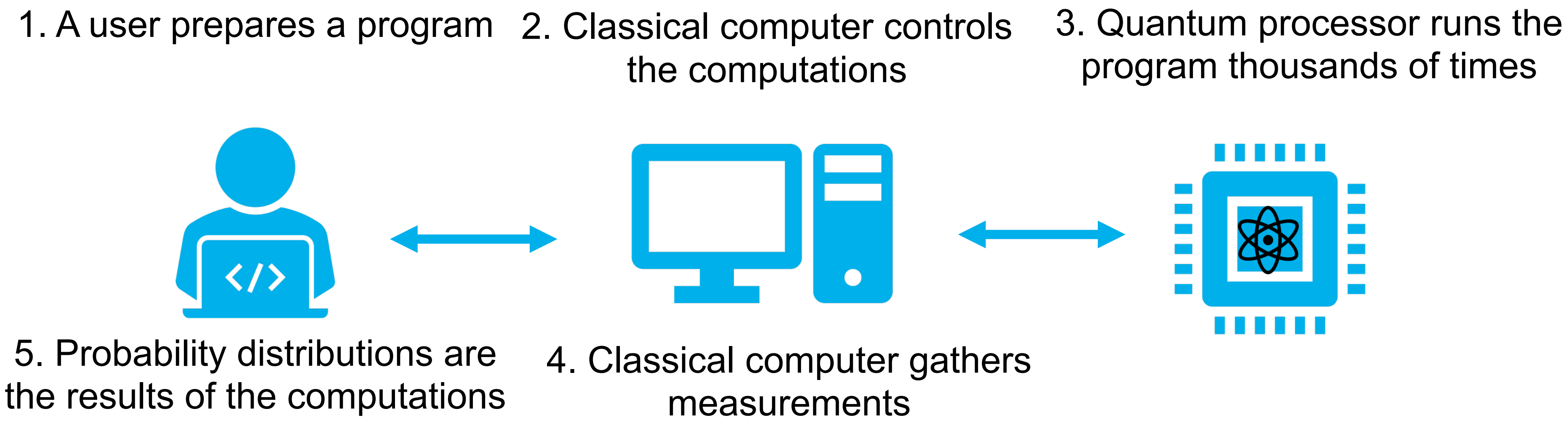
- In 2017 China built a **satellite for long-distance quantum communication**
- The distance between ground stations: between **1600 and 2400 km**
- Speed: 1 photon pair every 2 seconds
- A few new EU and non-EU projects have recently emerged, and we will see more satellite-based quantum solutions

Quantum metrology



- **Quantum metrology** allows to bypass limits of optical resolution (Standard Quantum Limit)
- **Applications:** new microscopy solutions (replacing cryogenic devices in biology and medicine), enhanced precision sensing, **observing gravitational waves**

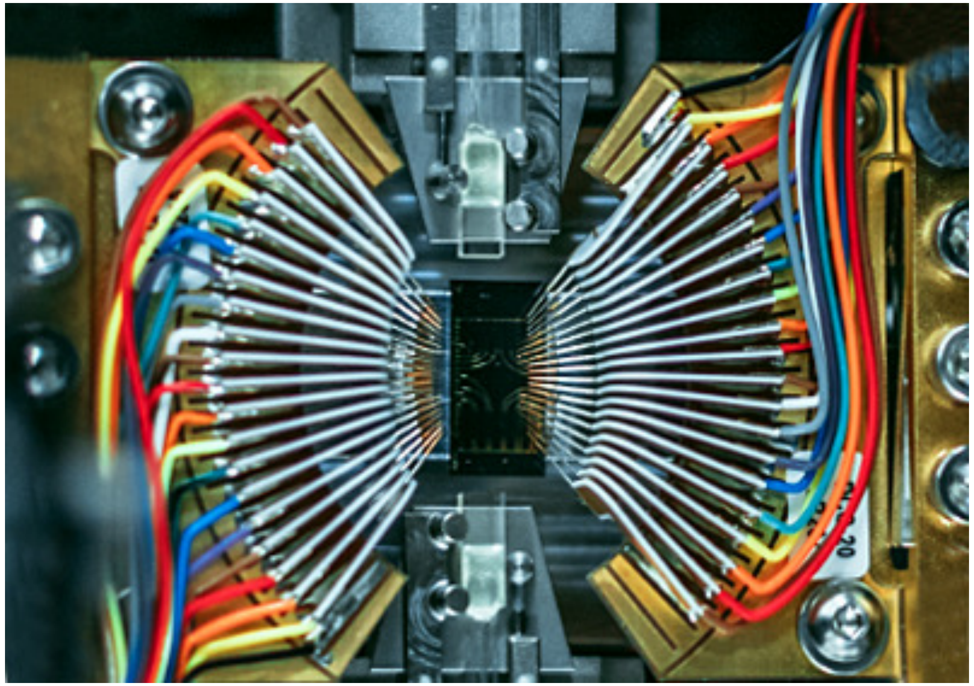
Quantum (photonic) computing



- **Quantum computing** is nothing more than gathering statistics from the measurements of the system state. Each program must be run thousands of times.

- **Quantum processor** is controlled by a classical system. At each run it starts from a ground state and applies a series of operations (described as quantum gates) which evolve it.

Photonic Quantum Machine Learning



Xanadu’s photonic processor

- **Quantum Machine Learning (QML)** merges classical and quantum computing techniques to achieve faster learning and lower energy consumption
- **Applications:** robotics, classification of data, computer vision

Quantum Kravchuk Transform and its applications

Publication: the Quantum Kravchuk Transform

Quantum interference enables constant-time quantum information processing

Science Advances ***5***, *eaau9674 (2019)*

M. Stobinska[1], A. Buraczewski[1], M. Moore[2], W. R. Clements[2], J. J. Renema[3], S. W. Nam[4], T. Gerrits[4], A. Lita[4], W. S. Kolthammer[2], A. Eckstein[2] & I. A. Walmsley[2]

[1] University of Warsaw

[2] University of Oxford (now: Imperial College), UK

[3] University of Twente, The Netherlands

[4] National Institute of Standards and Technology, Boulder, Colorado, USA

ScienceAdvances | AAAS
SIGNIFICANT RESEARCH, GLOBAL IMPACT

Publication: Quantum simulations

Quantum simulations with multiphoton Fock states

npj Quantum Information **7**, 91 (2021)

T. Sturges[1,*], T. McDermott[1,*], A. Buraczewski[1], W. R. Clements[2], J. J. Renema[3], S. W. Nam[4], T. Gerrits[4], A. Lita[4], W. S. Kolthammer[2], A. Eckstein[2], I. A. Walmsley[2], M. Stobińska[1]

[1] University of Warsaw

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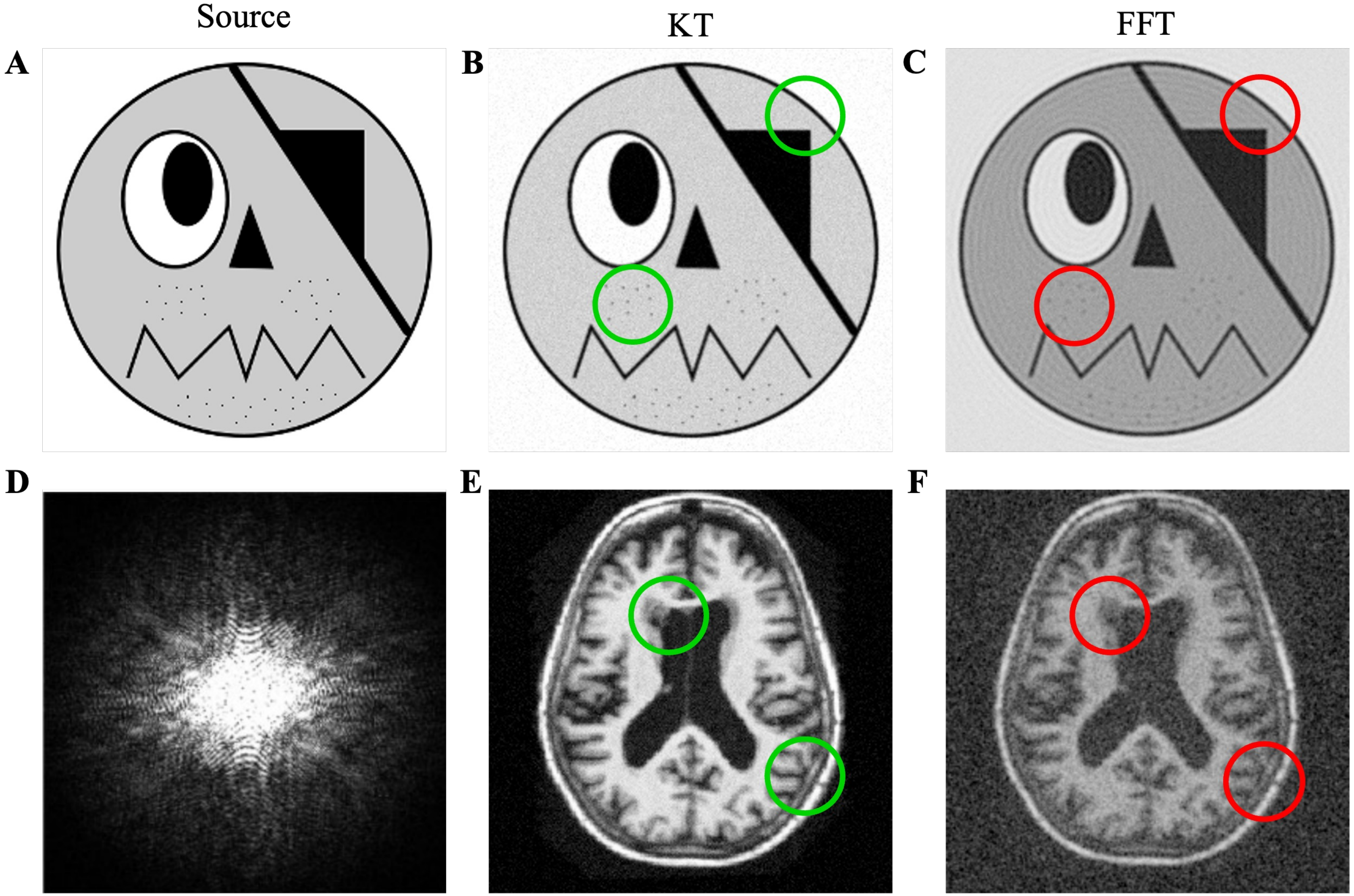
[4] National Institute of Standards and Technology, Boulder, Colorado, USA

npj | quantum information

Key motivation: help improving medical diagnostics



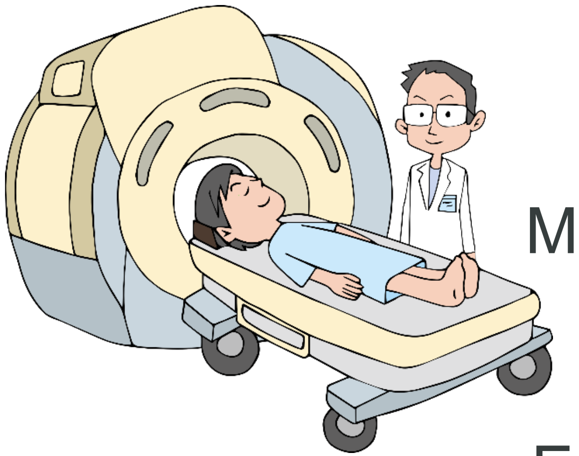
[OASIS]

- Images of 512 x 512 pixels were transformed to the frequency domain
- 1% additive Gaussian noise was added
- Inverse transforms were applied

- **Effective size of voxels is several millimetres!**
- Neuroscience requires micrometers…

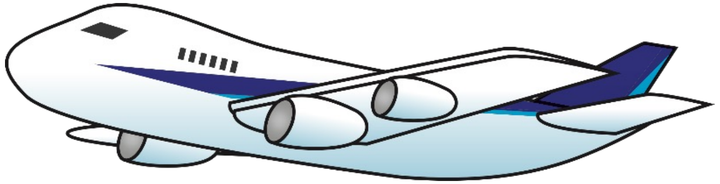
General motivation

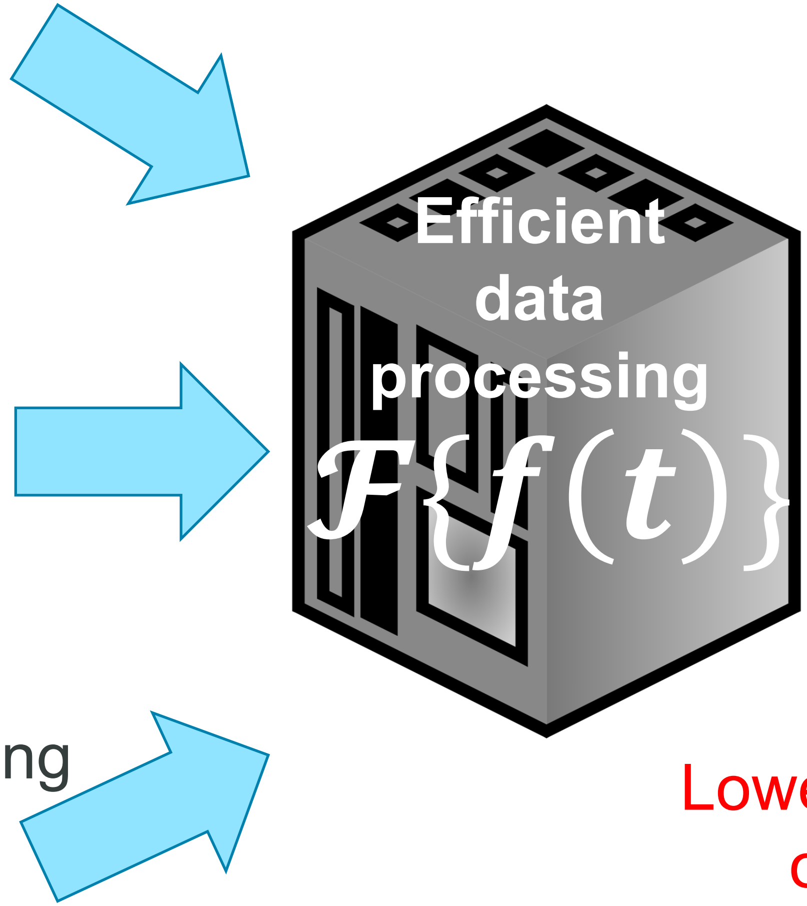
Science



Medicine

Engineering





Fourier Transform approximations

For a string of 2^n values:

DFT – $O(2^{2n})$

FFT – $O(n2^n)$

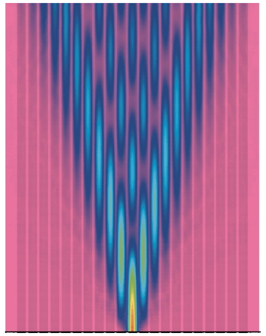
QFT – $O(n \log n)$

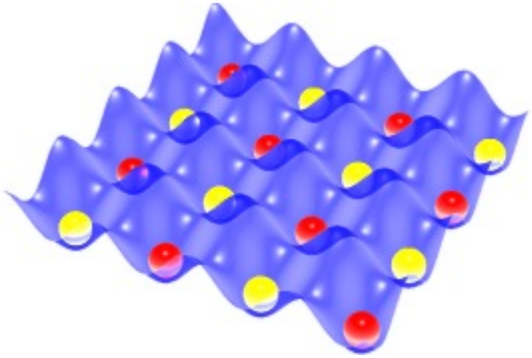
Lower bound on the complexity of the Fourier transform computation is unknown!

[openclipart.org]

Motivation for performing quantum simulations

- **Essential tool for studying complex phenomena:** quantum topology, quantum information transfer, relativistic wave equations.
- **Primary resources used so far:** collections of qubits, coherent states, multiple single-particle Fock states.
- Quantum simulations have never seriously profited from interference of multiparticle Fock states.
  [F. Flamini et al. Rep. Prog. Phys. **82**, 016001 (2019).]





Our achievements (theory + experiment)

Multiphoton Fock state interference

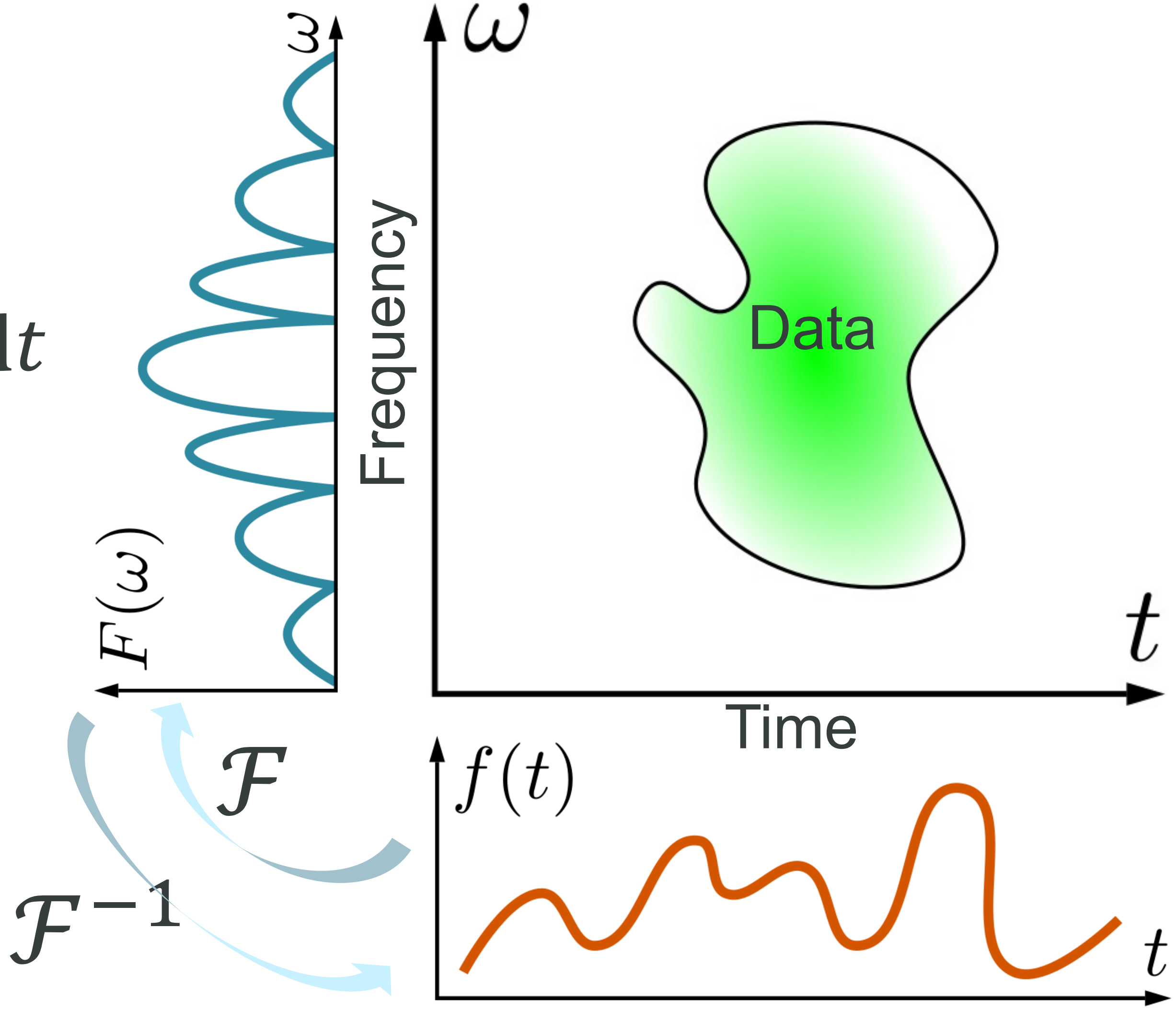
- computes the **fractional Kravchuk transform** in a single step
- has provided a **resource-efficient basic demonstration** that has revealed a topological matter not known before,
- can **simulate non-linear systems**,
- has **elucidated the perfect quantum wave packet transfer** mechanism and transport of **Majorana fermions**

We work within the quantum photonics framework,
but we **generalize our results** beyond it.

Fourier Transform (FT)

$\mathcal{F}\{f(t)\}$:

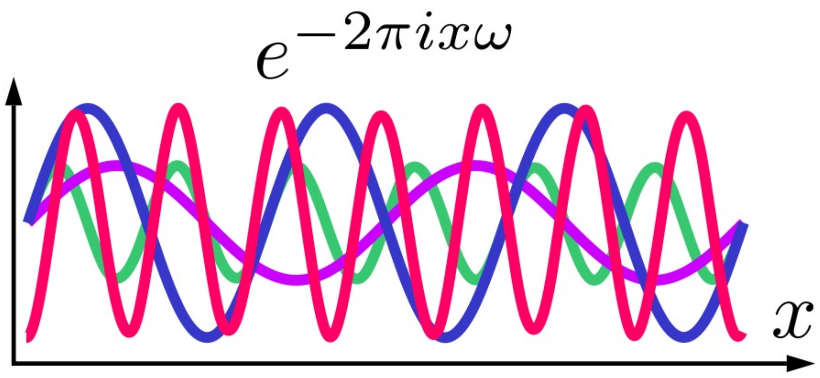
$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-it\omega}\, f(t)\, \mathrm{d}t$$



Discrete Fourier Transform (DFT)

A discrete approximation of the FT (discretization):

$$X_k = \frac{1}{\sqrt{S+1}} \sum_{l=0}^{S} e^{-2\pi i \cdot \frac{kl}{S+1}} \cdot x_l$$



Plane waves

$$(x_0, x_1, \ldots, x_S) \to (X_0, X_1, \ldots, X_S)$$

- DFT $\longrightarrow$ FT for large S
- Number of operations: $O(n^2)$, $n = S + 1$
- Fractional DFT do not reproduce fractional FT
- FFT computes DFT in $O(n \log n)$ for periodic data with period $n = 2^m$

Fast Fourier Transform (FFT)

$$X_k = \sum_{m=0}^{S/2} e^{-2\pi i \cdot \frac{km}{S/2+1}} \cdot x_{2m} + e^{-2\pi i \cdot \frac{k}{S+1}} \sum_{m=0}^{S/2} e^{-2\pi i \cdot \frac{km}{S/2+1}} \cdot x_{2m+1}$$

- Computes the DFT with a “divide & conquer” method
- Operates on sequences of $S = 2^n$ length (zero padding introduces errors)
- Lowers the number of operations from $O(2^{2n})$ to $O(n2^n)$

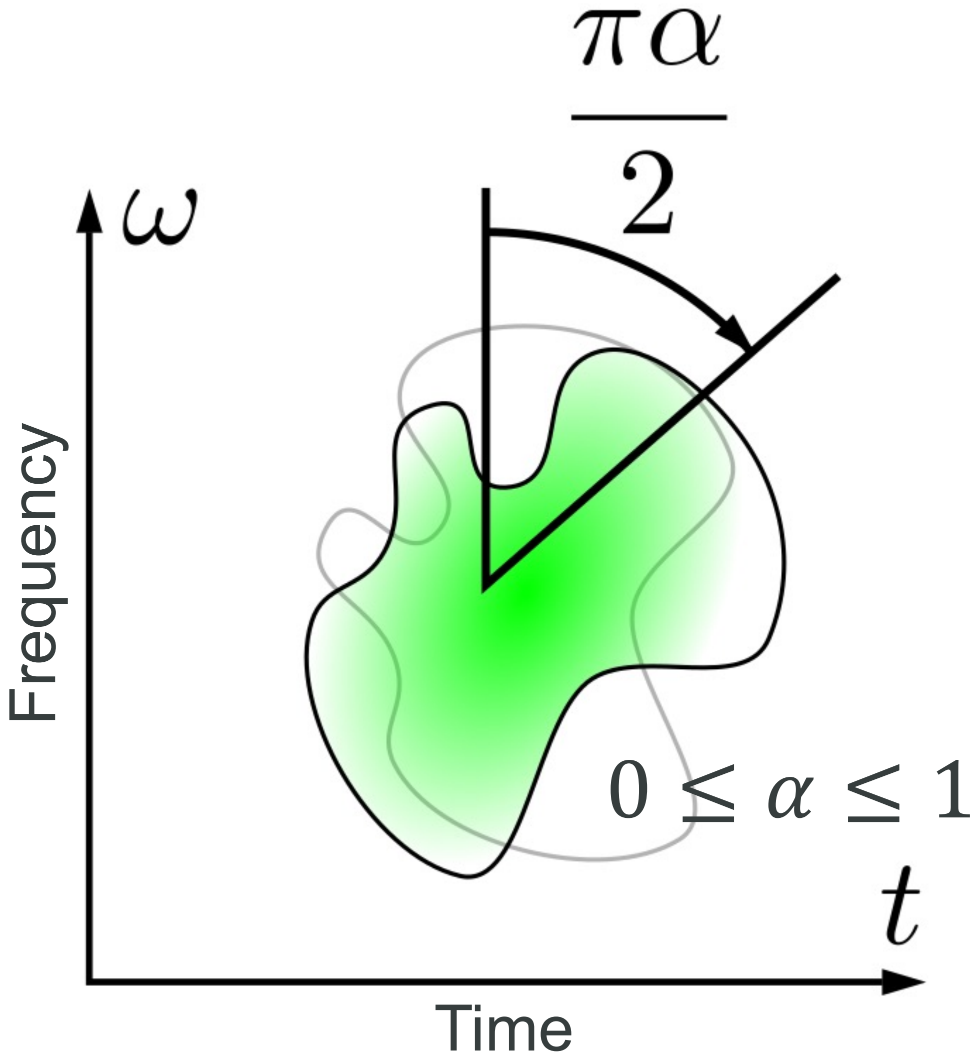
[J. W. Cooley et al., IEEE Trans. on Audio and Electroacoustics **15,** 76 (1967)]

Fractional FT

α-power of FT, $\mathcal{F}^{\alpha}\{f(t)\}$, corresponds to a rotation by $\frac{\pi\alpha}{2}$ in the phase space

$$\mathcal{F}^{0}\{f(t)\} = f(t) \qquad \mathcal{F}^{1}\{f(t)\} = F(\omega)$$

$$\mathcal{F}^{2}\{f(t)\} = f(-t) \qquad \mathcal{F}^{3} = \mathcal{F}^{-1}$$



Tomography of quantum states: fractional FT is the Radon transform of the Wigner distribution

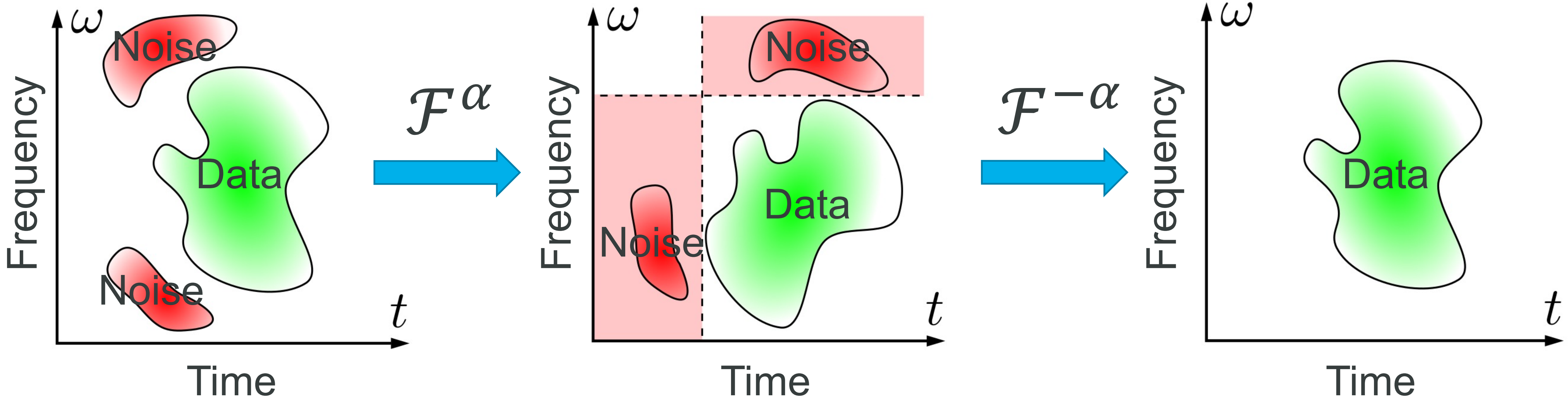
$$\mathcal{R}_{\alpha\pi/2}\{W\} = |\mathcal{F}^{\alpha}\{\psi(t)\}|^2$$

[P.-Y. Lin, *The Fractional Fourier Transform and Its Applications,* National Taiwan University, Taipei, Taiwan (1999)]

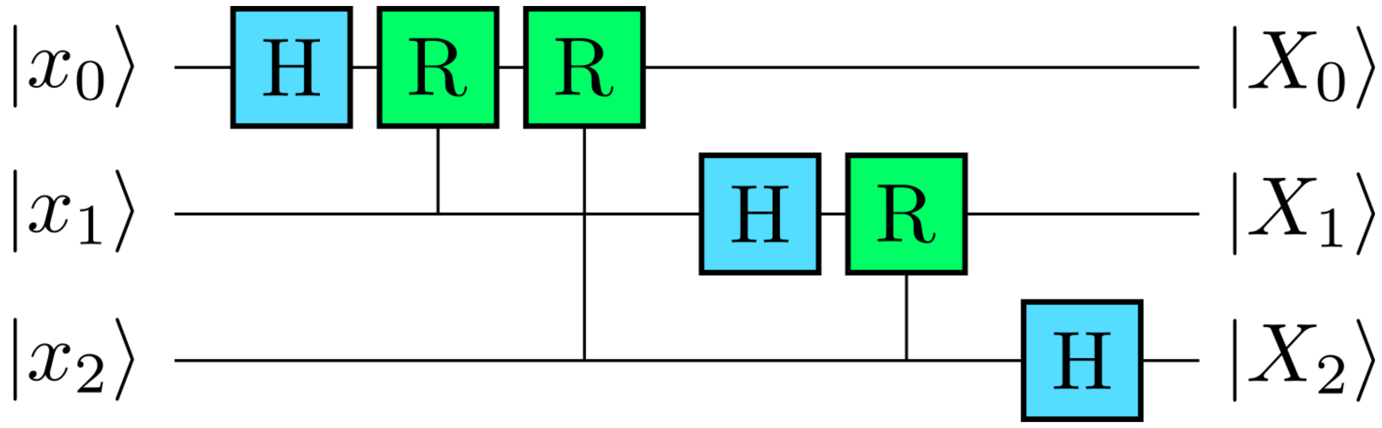
Fractional FT – the main applications

- Processing of noisy data
- Exploring a specific region of interest
- Optical signal processing
- Phase retrieval
- Tomography
- Data compression

[A. Camara et al., J. Opt. Soc. Am. A **26**, 1301 (2009)]



Quantum Fourier Transform (QFT)



H – Hadamard gate

R – controlled phase gate

- Performs the **DFT on quantum amplitudes** with quantum gates

$$|X_k\rangle = \frac{1}{\sqrt{S+1}} \sum_{l=0}^{S} e^{2\pi i \cdot \frac{kl}{S+1}} |x_l\rangle$$

- **Lowers the number of operations** from $O(n2^n)$ to $O(n \log n)$

Kravchuk Transform (KT)

Alternative discrete approximation of the FT

$$X_k = \sum_{l=0}^{S} e^{i\vartheta_{kl}} \cdot \phi_k^{(p)}(l - Sp, S) \cdot x_l$$

$$p = \sin^2 \frac{\pi\alpha}{4}$$

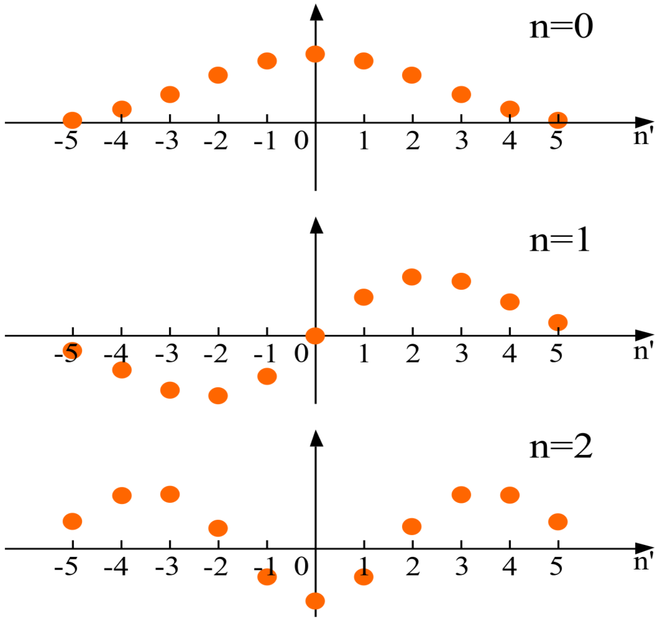
$$\vartheta_{kl} = -\frac{\pi\alpha}{2}\frac{S}{2} + \frac{\pi}{2}(l-k)$$

- Works for **non-periodic data** of arbitrary length
- Utilizes Kravchuk functions $\phi_k^{(p)}(l', S)$ instead of plane waves
- DFT $\longrightarrow$ FT for large S & computes α-power of the FT
- Number of operations:: $O(n^2)$, $n = S + 1$
- Can be viewed as an overlap of two spin $S/2$ states

$$e^{i\frac{\pi}{2}(l-k)}\phi_k^{(p)}(l - Sp, S) = \left\langle \frac{S}{2}, \frac{S}{2} - k \right| \exp\left(i\frac{\pi\alpha}{2}\, S_x\right) \left| \frac{S}{2}, \frac{S}{2} - l \right\rangle$$

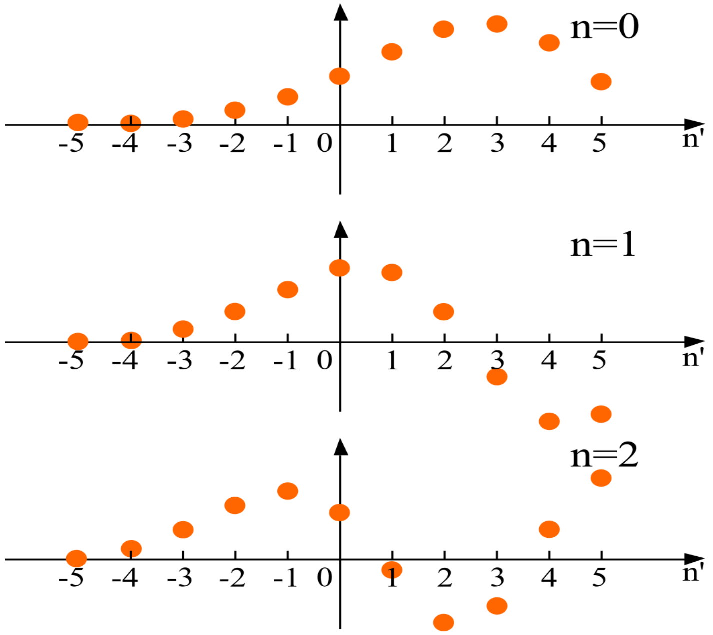
Kravchuk functions $\phi_n^{(p)}(n', N)$

- **Physically meaningful:** they describe eigenstates of a finite harmonic oscillator



$p = \frac{1}{2}$

$N = 10$



$p = \frac{1}{4}$

$N = 10$

- For $N \to \infty$ they tend to Hermite-Gauss polynomials (quantum harmonic oscillator)
- They are **discrete orthogonal polynomials** associated with the binomial distribution

[N. M. Atakishiev, K. B. Wolf, J. Opt. Soc. Am. A **7**, 1467 (1997)]

Kravchuk functions $\phi_n^{(p)}(n', N)$ (cont'd)

Kravchuk functions obey the following **difference equation**

$$\left(\frac{1}{2}N - n\right)\phi_n^{(1/2)}(n', N) = \frac{1}{2}\left[\alpha(n')\phi_n^{(1/2)}(n'-1, N) + \alpha(n'+1)\phi_n^{(1/2)}(n'+1, N)\right]$$

$$\alpha(n') = \left[\left(\frac{1}{2}N + n'\right)\left(\frac{1}{2}N - n' + 1\right)\right]^{\frac{1}{2}},$$

which can be written in a form of an **eigenvalue equation**

$$\left\{-\frac{1}{2}\left[\alpha(n')\exp(-\partial_{n'}) + \alpha(n'+1)\exp(\partial_{n'})\right] + \frac{1}{2}(N+1)\right\}\phi_n^{(1/2)}(n', N) = \left(n + \frac{1}{2}\right)\phi_n^{(1/2)}(n', N)$$

$\exp(x\partial_{n'})f(n') = f(n'+x)$ – a finite-shift operator

[N. M. Atakishiev, K. B. Wolf, J. Opt. Soc. Am. A **7**, 1467 (1997)]

Kravchuk functions $\boldsymbol{\phi_n^{(p)}(n', N)}$ (cont'd)

The eigenequation possesses a real, equally-spaced spectrum characteristics of the **harmonic oscillator**

$$\boldsymbol{H}^{(N)}(s)\,\phi_n^{(1/2)}(s,N) = \left(n + \frac{1}{2}\right)\phi_n^{(1/2)}(s,N), \qquad n = 0,1,\dots,N$$

where

$$\boldsymbol{H}^{(N)}(s) = -\frac{1}{2}\left[\alpha(s)\exp(-\partial_s) + \alpha(-s)\exp(\partial_s)\right] + \frac{1}{2}(N+1).$$

One may identify $\boldsymbol{H}^{(N)}(s)$ as the **Hamiltonian of a finite quantum harmonic oscillator.**

This Hamiltonian is related to the **Lie algebra of the rotation group SO(3).**

[N. M. Atakishiev, K. B. Wolf, J. Opt. Soc. Am. A **7**, 1467 (1997)]

Fractional Fourier-Kravchuk Transformations

We define the αth power of the one-dimensional finite Fourier–Kravchuk transform $\widehat{\boldsymbol{F}}$ by a linear operator that maps the Kravchuk basis functions onto themselves:

$$\widehat{\boldsymbol{F}}^{\alpha}\,\phi_n(s,N) = \exp\left(\frac{i\alpha\pi}{4}\right)\exp\left[-\frac{i\pi}{2}\,\alpha\,\boldsymbol{H}^{(N)}(s)\right]\phi_n(s,N)$$
$$= \exp\left(-\frac{i\alpha\pi n}{2}\right)\phi_n(s,N)$$

Properties:

- $\boldsymbol{F}^0 = \mathbf{1}$,
- $\boldsymbol{F}^4 = \mathbf{1}$,
- its square is the inversion matrix: $\boldsymbol{F}^2 = \boldsymbol{I}$,
- $\boldsymbol{F}^{\alpha}$ are unitary: $(\boldsymbol{F}^{\alpha})^{\dagger} = \boldsymbol{F}^{-\alpha}$.

[N. M. Atakishiev, K. B. Wolf, J. Opt. Soc. Am. A **7**, 1467 (1997)]

The Fourier-Kravchuk Rotations

$$[J_1, J_2] = iJ_3, \qquad [J_2, J_3] = iJ_1, \qquad [J_3, J_1] = iJ_2$$

where

$$J_1 = s\,\cdot,$$

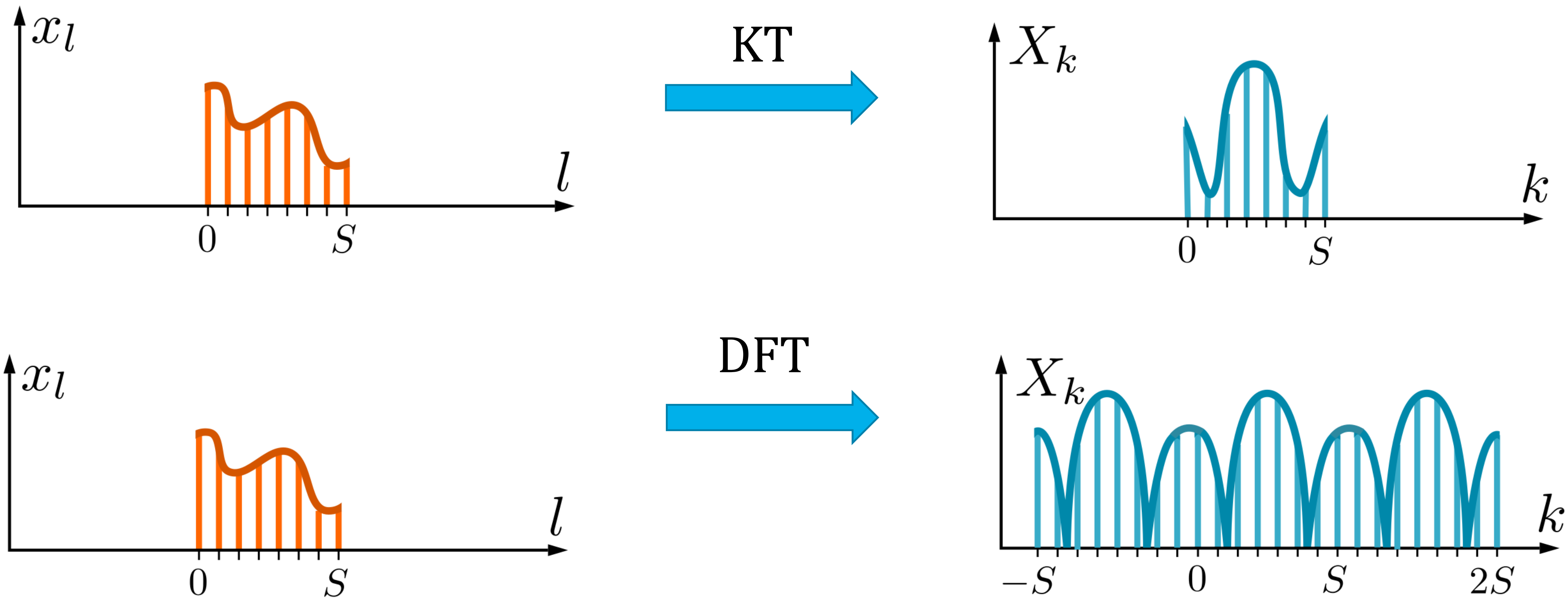
$$J_2 = -P_s^{(N)}, \qquad \left[s, \boldsymbol{H}^{(N)}(s)\right] = \frac{1}{2}\left[\alpha(-s)\exp(\partial_s) - \alpha(s)\exp(-\partial_s)\right] = iP_s^{(N)}$$

$$J_3 = \boldsymbol{H}^{(N)}(s) - \frac{1}{2}(N+1).$$

.

[N. M. Atakishiev, K. B. Wolf, J. Opt. Soc. Am. A **7**, 1467 (1997)]

Finite signal processing – DFT vs. KT



KT – exemplary applications

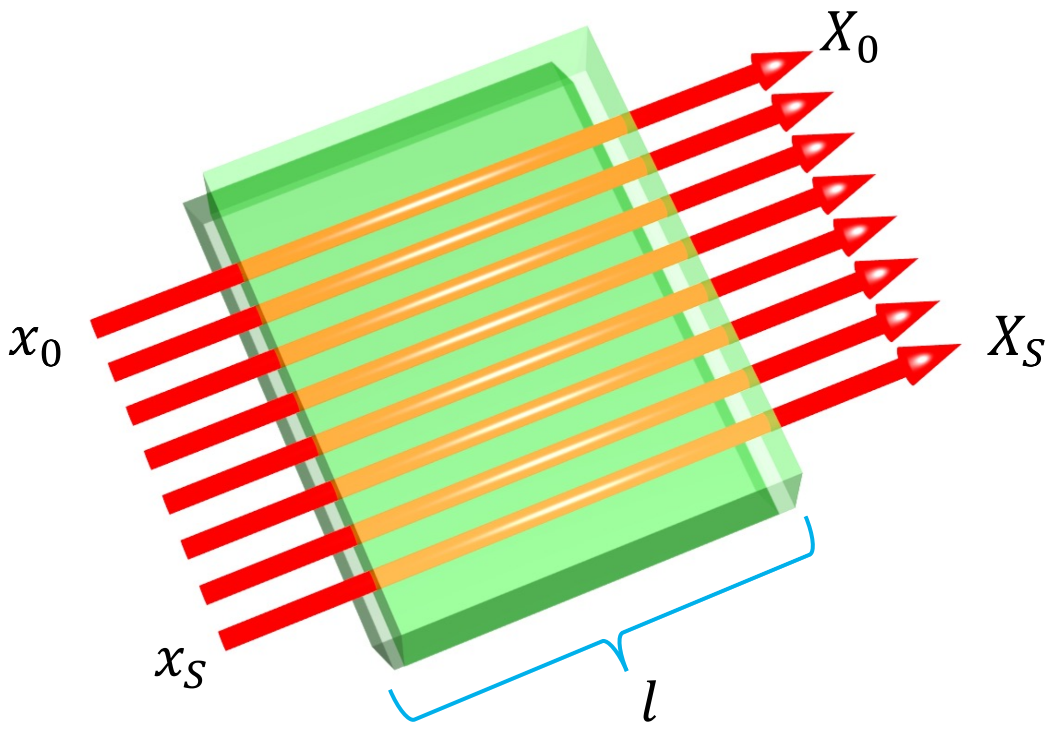
- Image analysis with the Kravchuk moments – transform coefficients are used as data vectors for shape recognition

  [P. T. Yap et al., IEEE Transactions on image processing **12**, 1367 (2003)]

- Reconstruction of medical images (MRI, ultrasound), especially for high resolution data
- Automatic identification of tumors in computer tomography scans
- Character recognition (e.g. Chinese)
- Error-correcting codes
- Digital watermarking, anti-fraud techniques (fractional KT)

KT features a prohibitive runtime

Photonic waveguide realization of the QKT

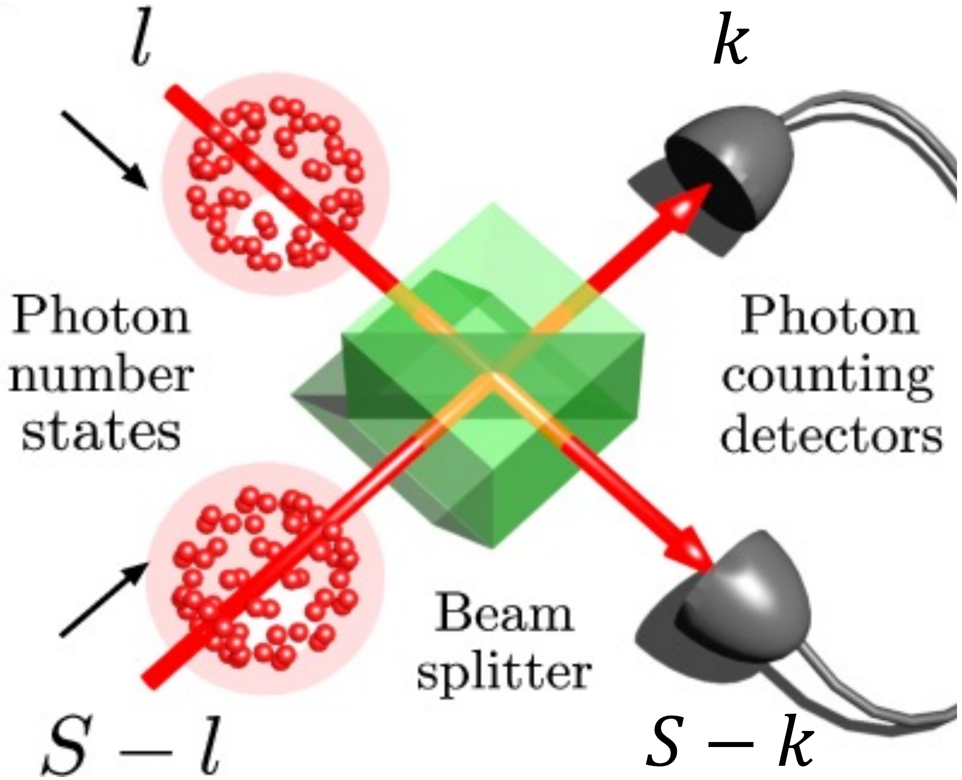


- Optical chip with parallel planar waveguides
- The fractionality is set by the chip length
- The input and output sequence length is limited by the number of waveguides
- Requires S photon sources and detectors

[N. M. Atakishiev, K. B. Wolf, J. Opt. Soc. Am. A **7**, 1467 (1997),
S. Weimann et al., Nature Commun. **7**, 11027 (2016),
A. Crespi et al., Nature Commun. **7**, 10469 (2016)]

Our result: QKT in a single step

Multiphoton Hong-Ou-Mandel interference computes the QKT in O(1)



$$\mathcal{A}_S^{(r)}(k,l) = e^{-i\theta\frac{S}{2}}\langle k, S-k|U_{BS}|l, S-l\rangle$$
$$= e^{-i\theta\frac{S}{2}} e^{i\frac{\pi}{2}(k-l)} \phi_k^{(r)}(l-Sr, S)$$

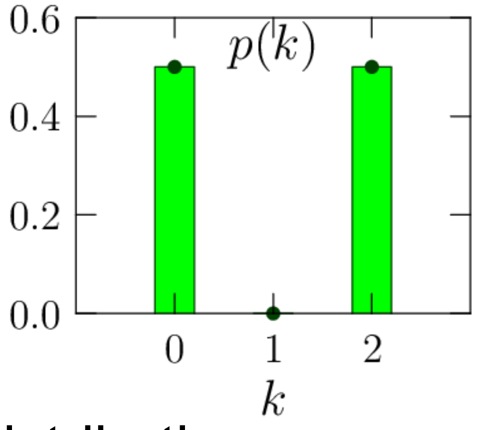
Two-photon HOM effect

[C.-K. Hong, Z.-Y. Ou, L. Mandel. PRL 59, 2044 (1987)]

- Two-photon bunching

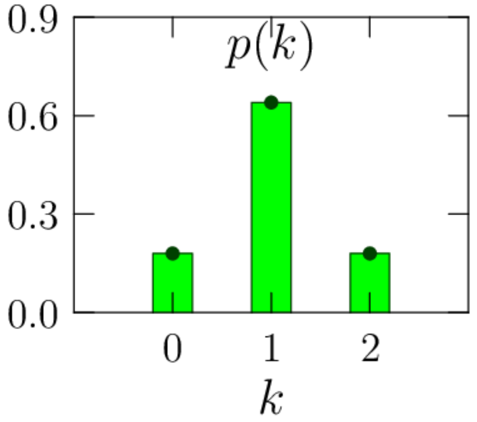
$r = 0.5$

$|\psi_{in}\rangle = |1{,}1\rangle$

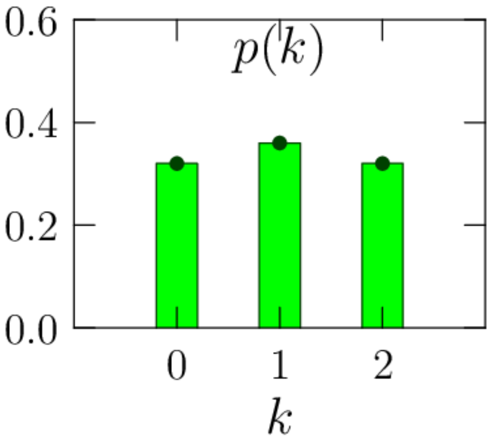


- Changing the BS reflectivity alters the output distribution

$r = 0.1$

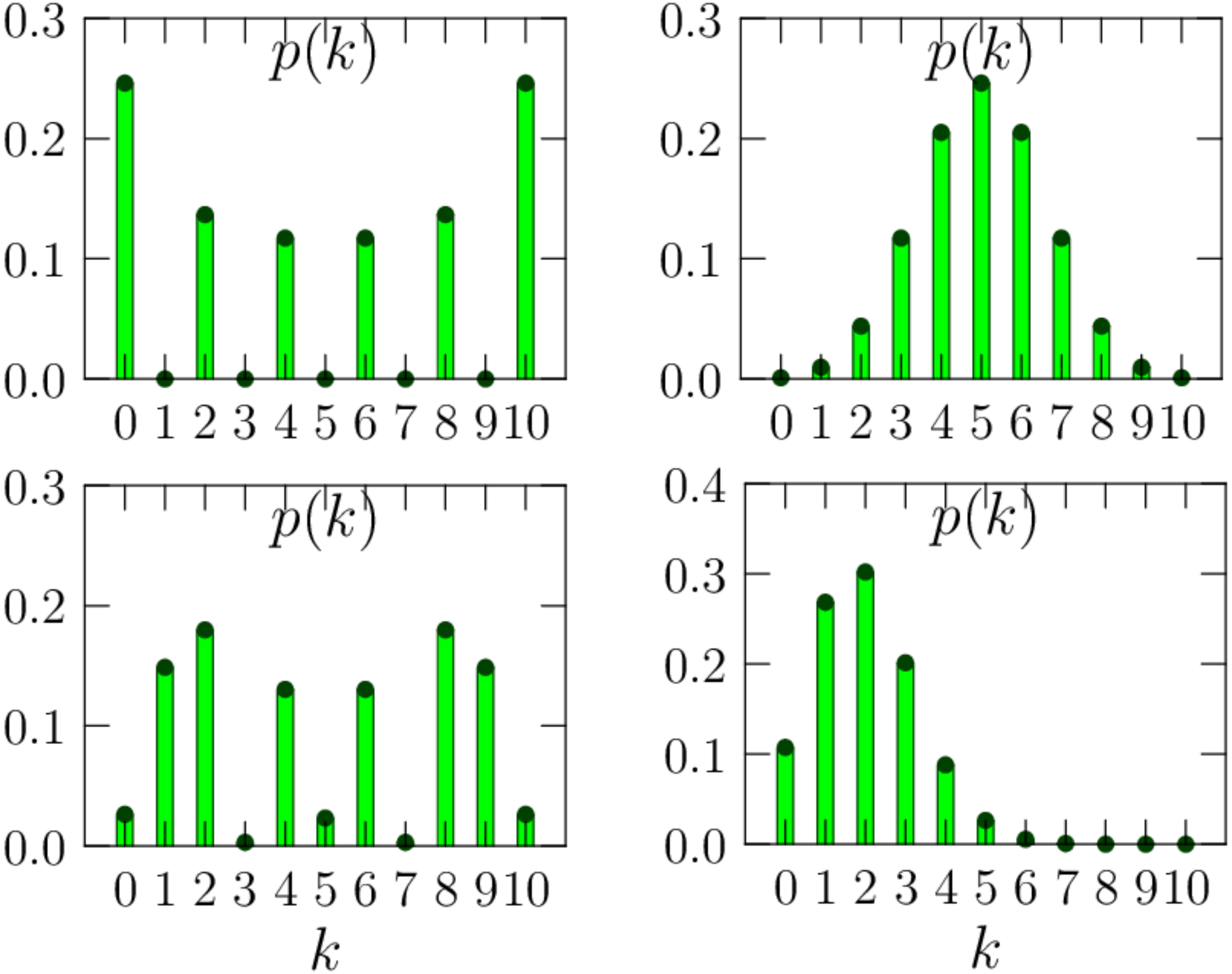


$r = 0.2$



Multiphoton generalized HOM effect

$|\psi_{in}\rangle = |5,5\rangle$ $\quad$ $|\psi_{in}\rangle = |0,10\rangle$



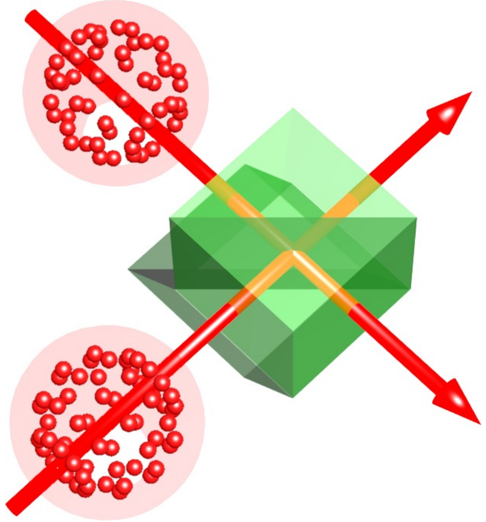
$r = 0.5$

$r = 0.2$

- Photon number (Fock) states:

$$|l\rangle = \frac{(a^\dagger)^l}{\sqrt{l!}}|0\rangle$$

$$|S-l\rangle = \frac{(b^\dagger)^{S-l}}{\sqrt{(S-l)!}}|0\rangle$$



Practical steps 1

Let's send a superposition to a BS

$$|\psi\rangle = \sum_{l=0}^{S} x_l |l, S-l\rangle$$

BS interaction is photon number conserving

$$U_{BS}(\theta, \varphi) = \exp\left\{\frac{\theta}{2}\left(a^\dagger b e^{-i\varphi} - a b^\dagger e^{i\varphi}\right)\right\}$$

$r = \sin^2 \frac{\theta}{2}$ is the BS reflectivity (we take $\varphi = \frac{\pi}{2}$).

Let's use photon-number-resolved measurements (TESs) – projective measurement

$$|k\rangle\langle k| \; \& \; |S-k\rangle\langle S-k|$$

Practical steps 2

Probability of measuring k and $S-k$ at outputs is equal to

$$\left|\langle k, S-k|U_{BS}\left(\theta, \frac{\pi}{2}\right)|\psi\rangle\right|^2 = \left|\sum_{l=0}^{S} x_l \langle k, S-k|U_{BS}\left(\theta, \frac{\pi}{2}\right)|l, S-l\rangle\right|^2$$

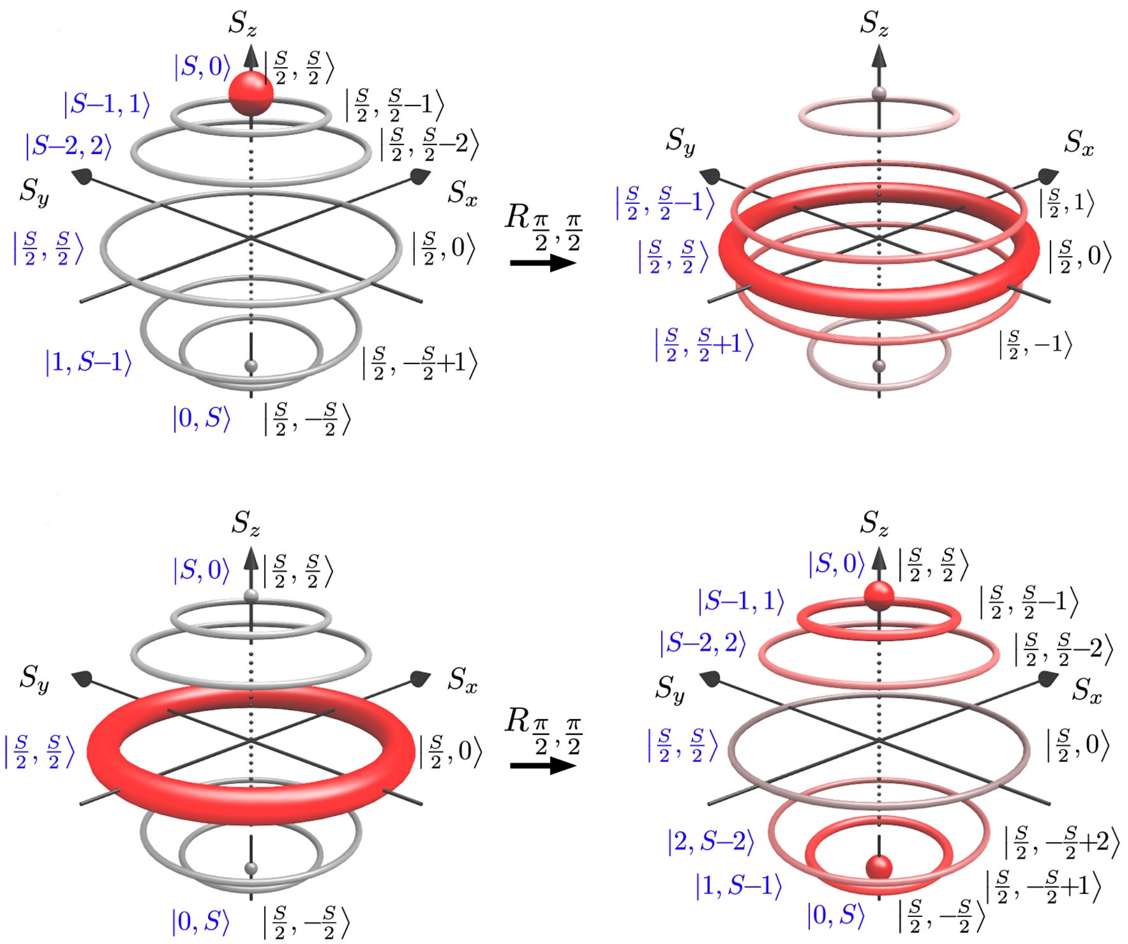
gives the **absolute square of the QKT of input probability amplitudes**

$$|X_k|^2 = \left|\sum_{l=0}^{S} \mathcal{A}_S^{(r)}(k,l)\, x_l\right|^2$$

QKT fractionality is set by the reflectivity $\alpha = \frac{2\theta}{\pi} = \frac{4}{\pi}\arcsin\sqrt{r}$.

Generalization to qudits

Multiphoton HOM interference **realizes a single-qudit rotation**

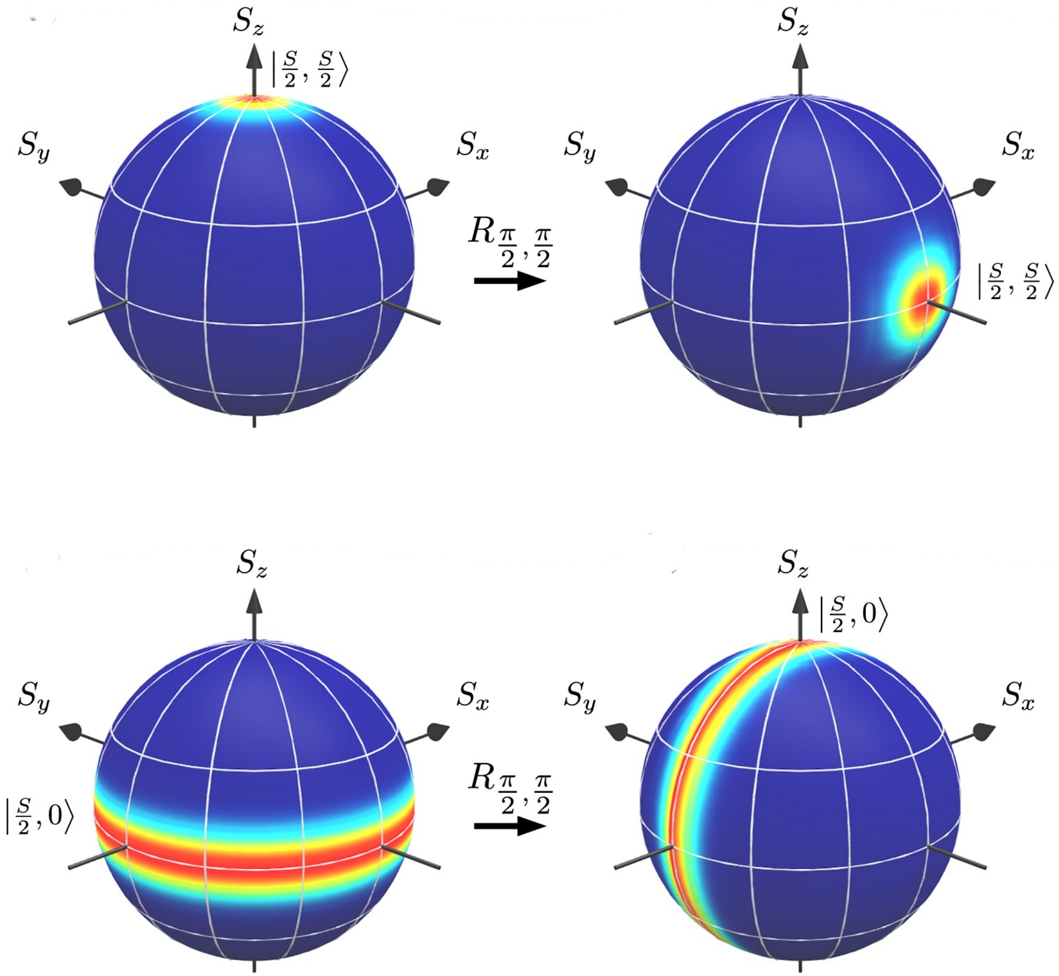


- Dual Fock states with S photons (blue) map onto spin-S/2 Dicke states (black) – qudit encoding
- BS interaction models exchange interaction
- This coincides with a qudit rotation

$$R_{\theta,\varphi=\pi/2} = \exp\{-i\theta S_x\} = U_{BS}\left(\theta, \varphi = \frac{\pi}{2}\right)$$

in the Dicke state basis

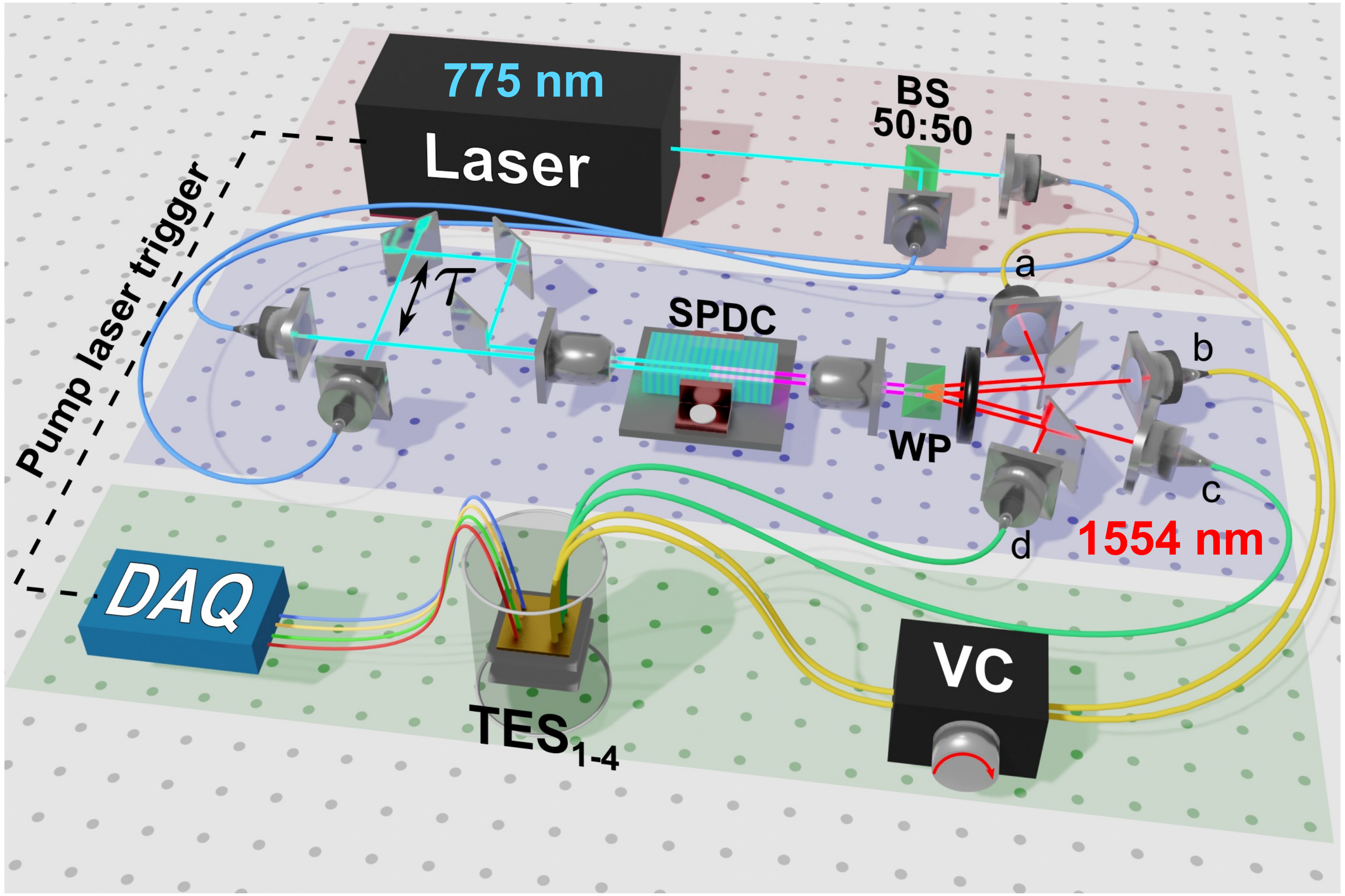
QKT as a single-qudit rotation



Bloch sphere:

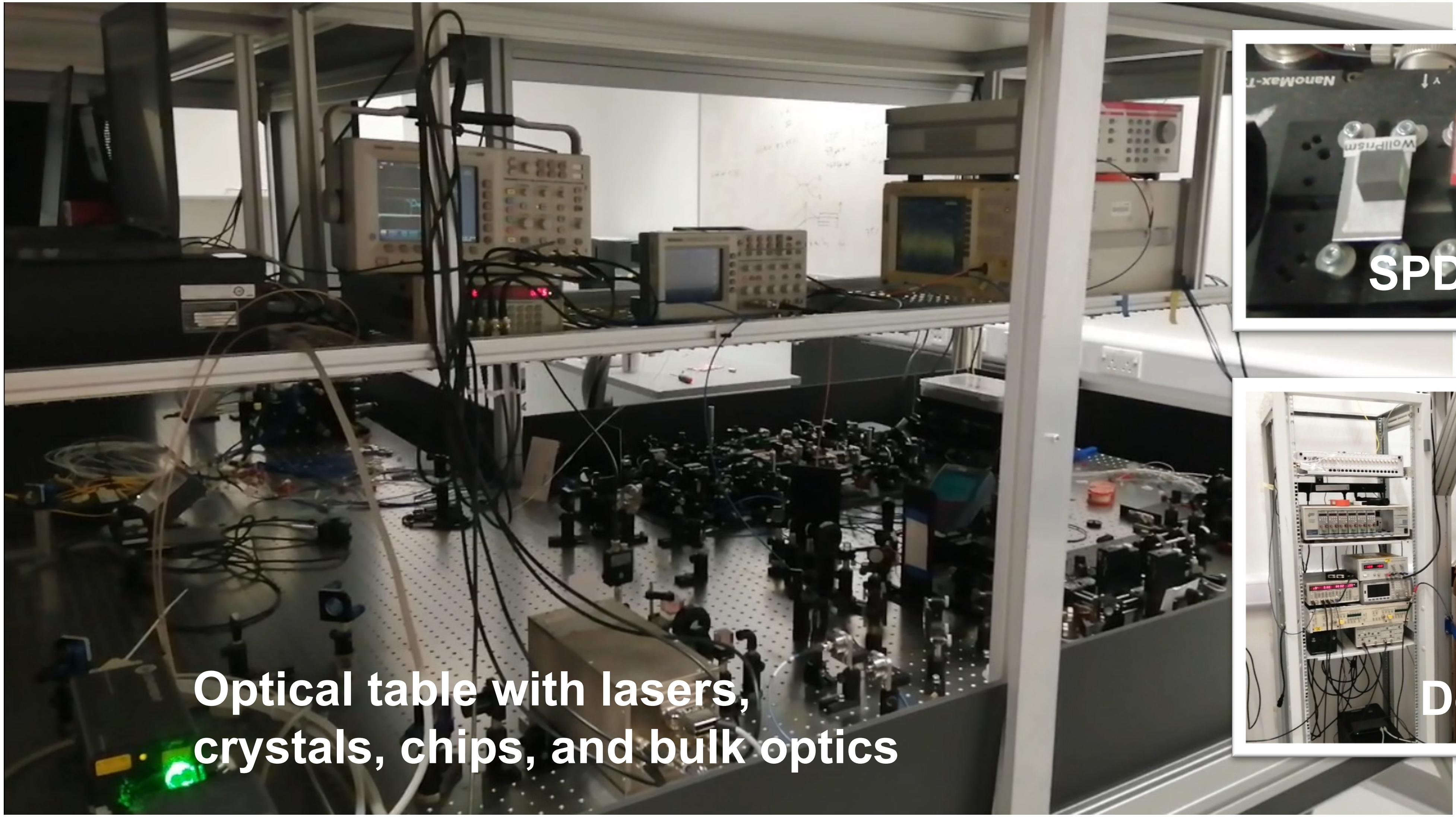
the QKT transfers the input – a position eigenstate – into the same state but in S_y basis – a momentum eigenstate

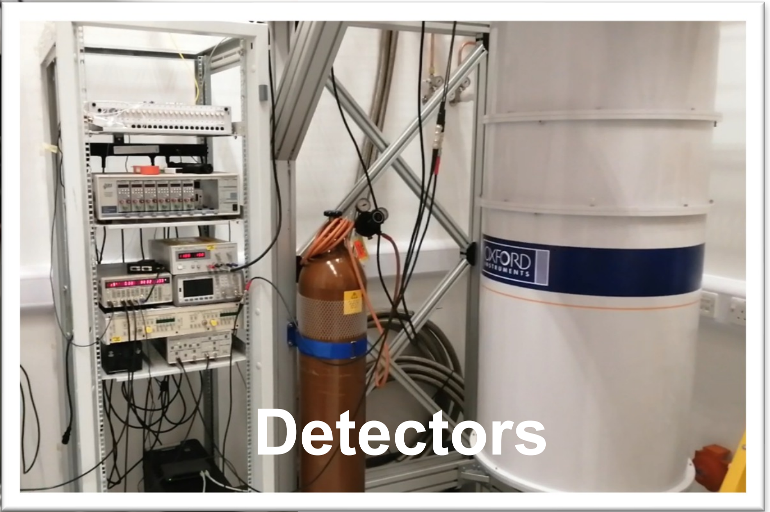
Experimental setup (University of Oxford)



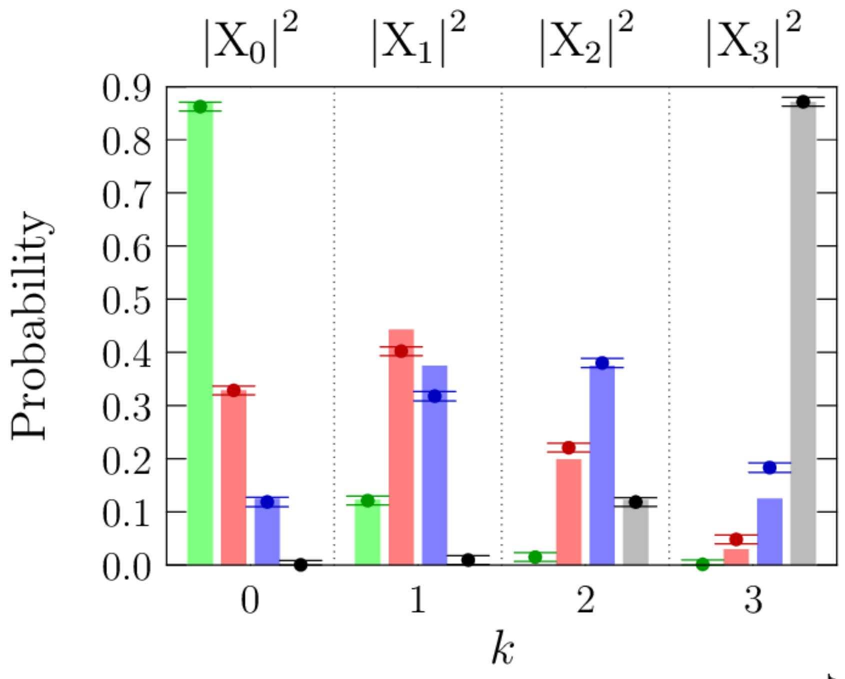
- **SPDC** – spontaneous parametric down-conversion waveguides in PP-KTP crystal.
- **WP** – Wollaston prism.
- **VC** – variable-ratio fiber coupler.
- **TES** – transition-edge sensors with efficiency exceeding 90% → photon-number resolved measurement.
- **DAQ** – data acquisition unit.

Experimental setup (University of Oxford)





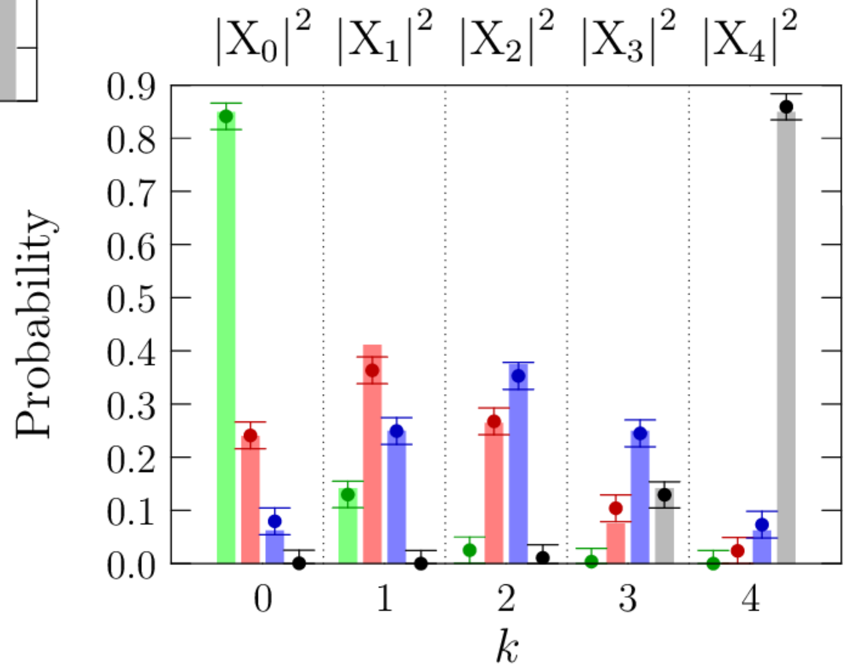
$|0, S\rangle$ interference – $(x_0 = 1, x_2 = 0, \ldots, x_S = 0)$

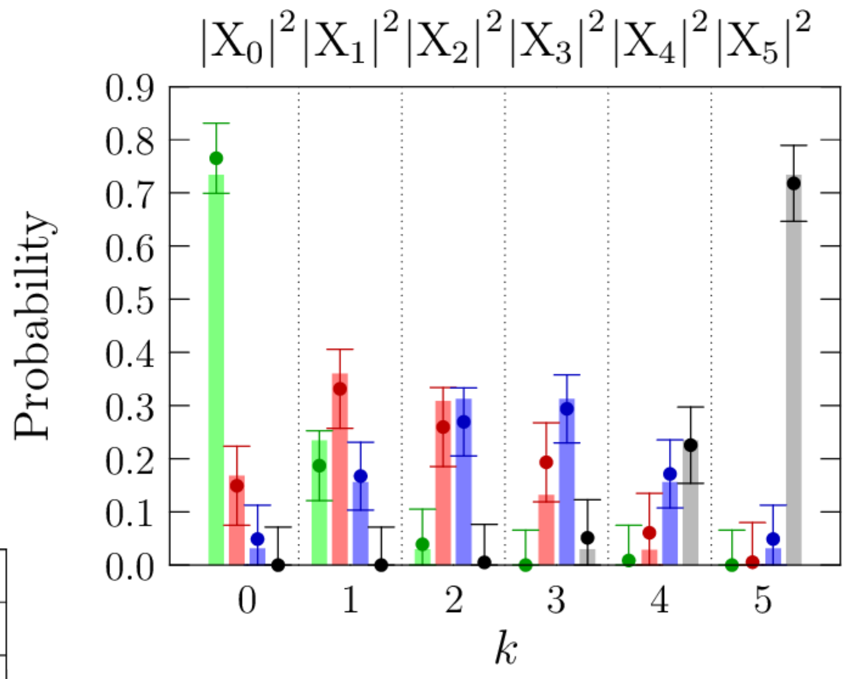


$|\psi_{in}\rangle = |0,3\rangle$
(1,0,0,0)

$$|X_k|^2 = \left|\sum_{l=0}^{S} \mathcal{A}_S^{(r)}(k,0)\right|^2$$

$|\psi_{in}\rangle = |0,4\rangle$
(1,0,0,0,0)

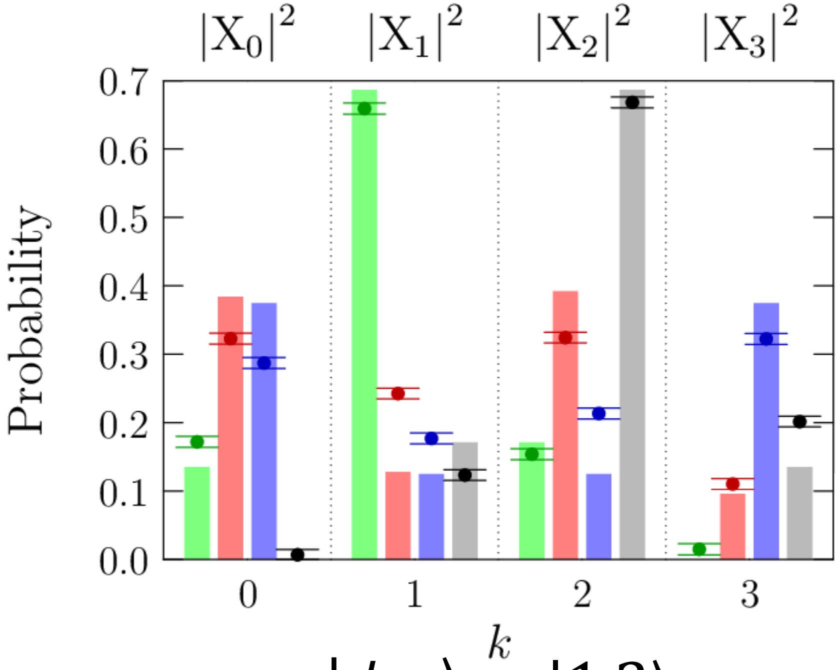




$|\psi_{in}\rangle = |0,5\rangle$
(1,0,0,0,0,0)

$r = 0.05, \alpha = 0.28$
$r = 0.20, \alpha = 0.60$
$r = 0.50, \alpha = 1.00$
$r = 0.95, \alpha = 1.72$

$|l, S-l\rangle$ interference – $(x_0 = 0, \ldots, x_l = 1, \ldots, x_S = 0)$



$|\psi_{in}\rangle = |1,2\rangle$

(0,1,0,0) $$|X_k|^2 = \left|\sum_{l=0}^{S} \mathcal{A}_3^{(r)}(k,1)\right|^2$$

$r = 0.05, \alpha = 0.28$

$r = 0.20, \alpha = 0.60$

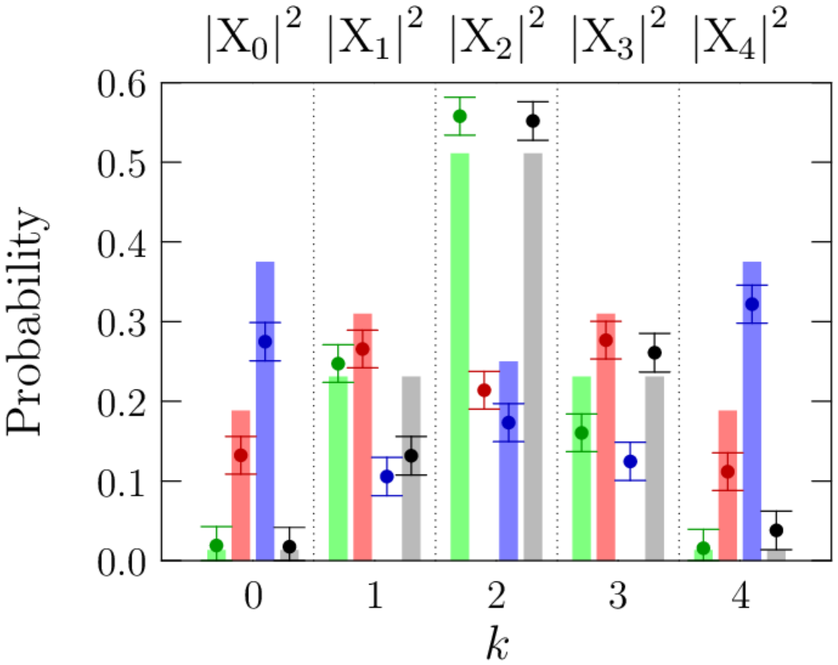
$r = 0.50, \alpha = 1.00$

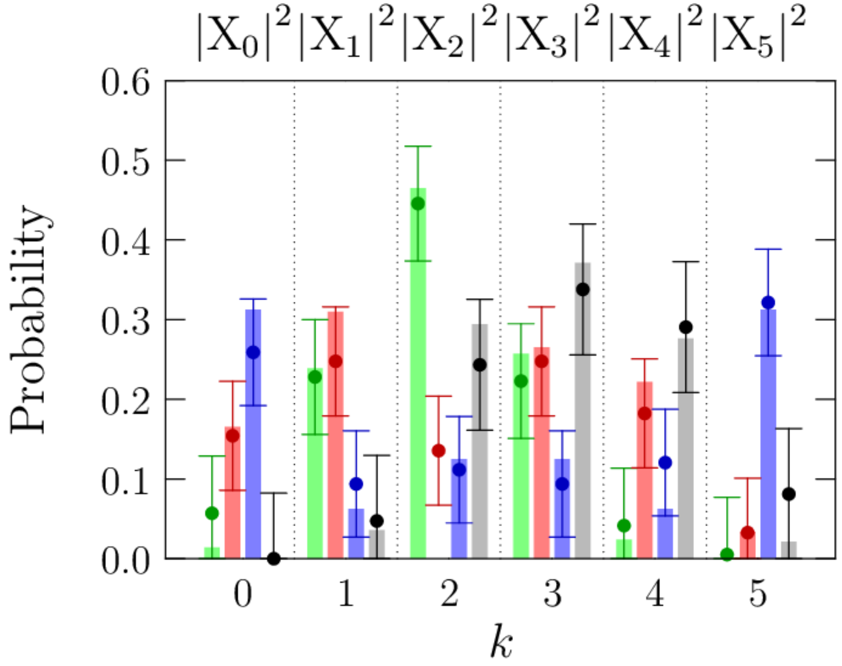
$r = 0.95, \alpha = 1.72$

$|\psi_{in}\rangle = |2,2\rangle$

(0,0,1,0,0)

$$|X_k|^2 = \left|\sum_{l=0}^{S} \mathcal{A}_4^{(r)}(k,2)\right|^2$$





$|\psi_{in}\rangle = |2,3\rangle$

(0,0,1,0,0,0)

$$|X_k|^2 = \left|\sum_{l=0}^{S} \mathcal{A}_5^{(r)}(k,2)\right|^2$$

Conclusions

- Realization of the fractional QKT with qudit systems shows that transformation of large data sequences in $O(1)$ is possible
- Since a BS sees orthogonal spectral or polarization modes independently, one can extend the transform to higher dimensions
- The photonic proof of concept is currently limited by the range of input states that can be prepared
- New applications: studying non-crystalline topological materials, beyond the recently challenged bulk-edge correspondence theorem. [C. Downing et al., Phys. Rev. Lett. **123**, 217401 (2019)].
- Qudit-based algorithms exhibit significantly lower complexity than qubit-based ones

Patent

A Method of Performing Quantum Fourier-Kravchuk Transform (QKT) and a Device Configured to Implement Said Method

URZĄD PATENTOWY
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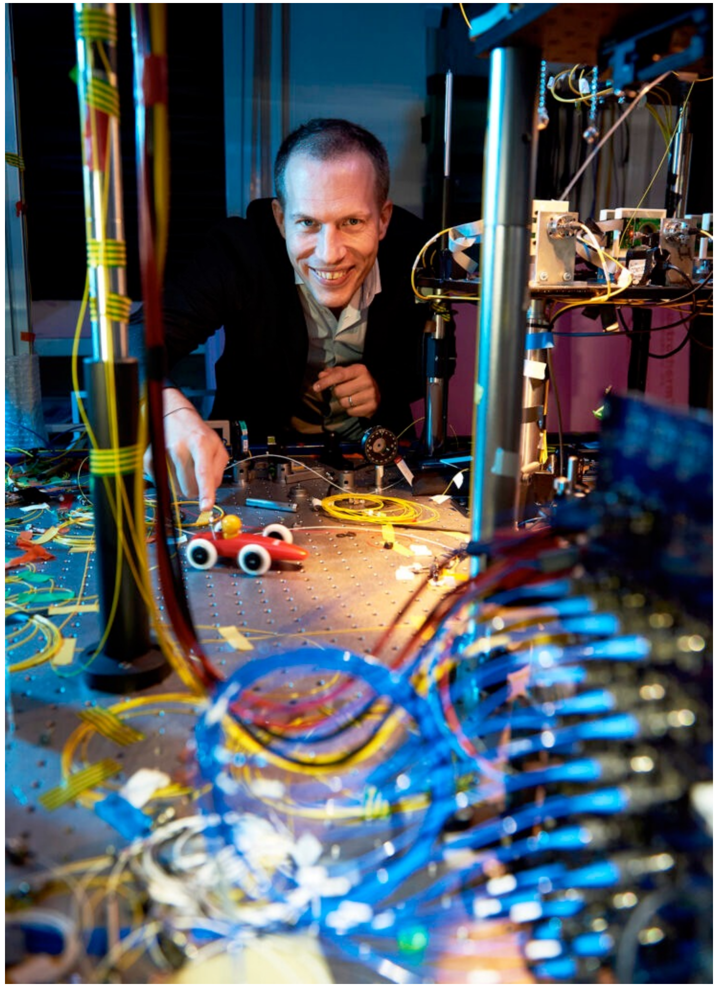
WIPO | PCT
The International
Patent System

- Patent Office of the Republic of Poland (2018) - PL426228
- World Intellectual Property Organization (WIPO) (2019) - WO/2020/008409
- US Patent Office (2021) - US20210271731
- China Patent Office (2021) - CN113692593

Lecture of Prof. Philip Walther

- All interested in the topic are kindly invited to a seminar, which will be given by Prof. Philip Walther – a renowned quantum physicist from the University of Vienna.
- **Title:** Quantum Photonics – from quantum computing to quantum foundations exploring the quantum-gravity interface
- **Place:** Room 2180, MIM UW building (Banacha 2)
- **Date/time:** Thursday, 3 November 2022, 14:30 hours



Thank you!

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