Quantum Information National Laboratory Of Hungary

Peter Domokos
consortium leader

18-20 September 2023, Wigner121, Budapest

Quantum Mechanics

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Physics at the scale of atoms

- *Quantum mechanics was born in the mid 1920*
- *Many Hungarians among the great fathers of QM*

Erwin Schrödinger

Werner Heisenberg

Eugene Wigner

John von Neumann

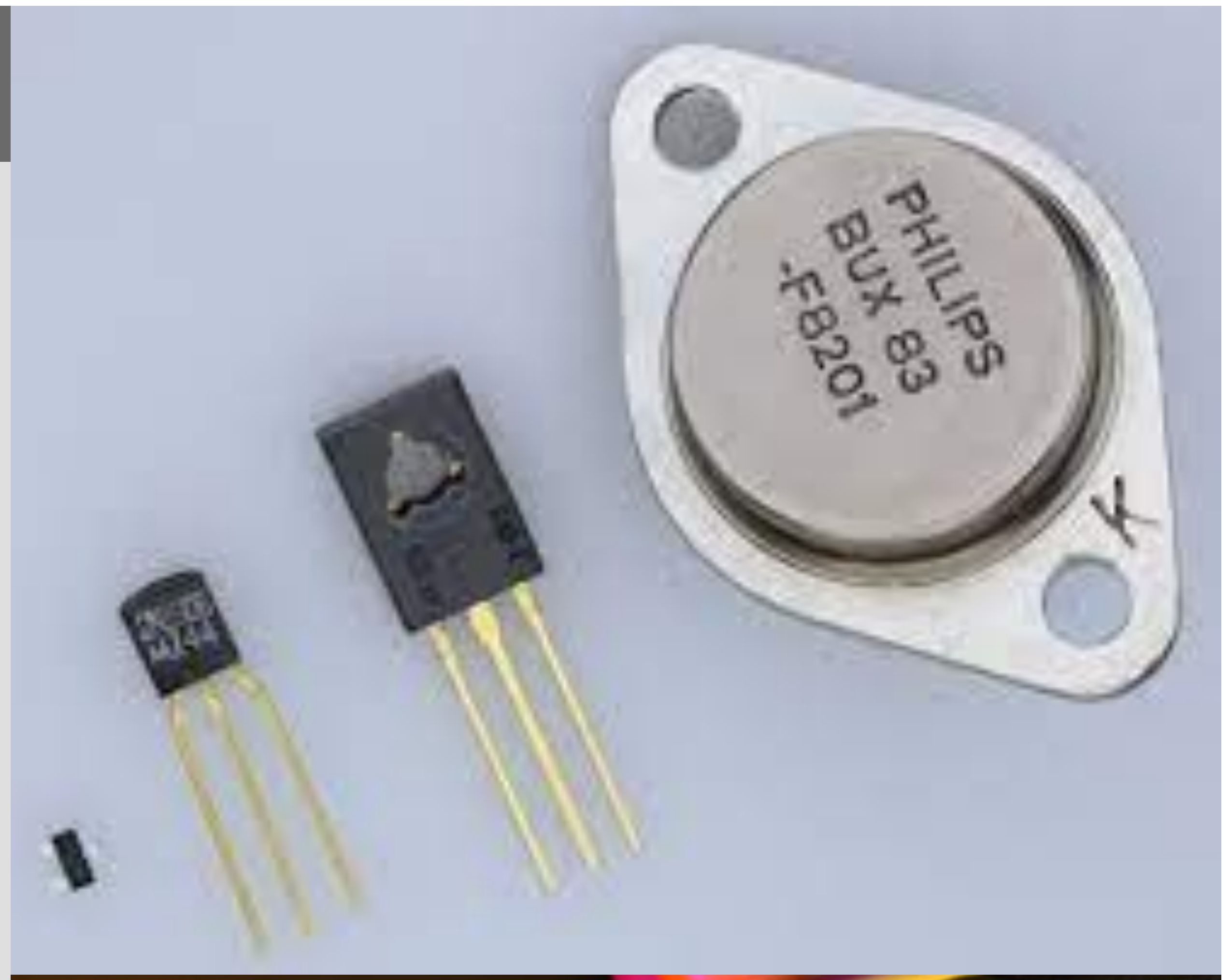
Edward Teller

Niels Bohr

First quantum revolution (20th century)

Understanding quantum mechanics

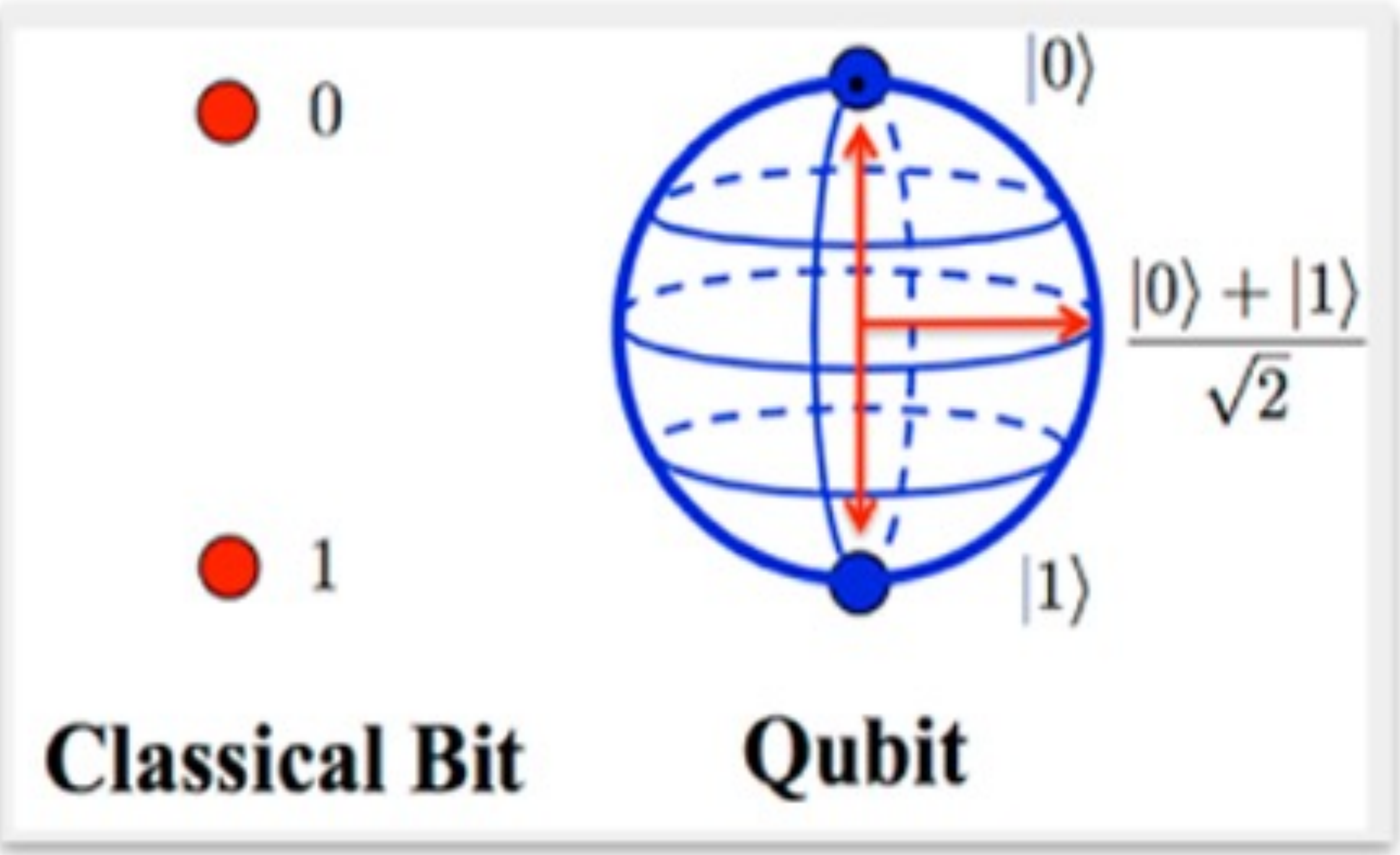
- *New devices (transistor, laser, ...)*
- *„Quantum mechanics is there, but we're not actually controlling all of the quantum systems at the individual level"*



Second quantum revolution (21th century)

Controlling individual quantum systems

- *Isolation and manipulation of single quantum systems*
- *Superposition: ability of a quantum system to be in multiple states at the same time*



Quantum technology

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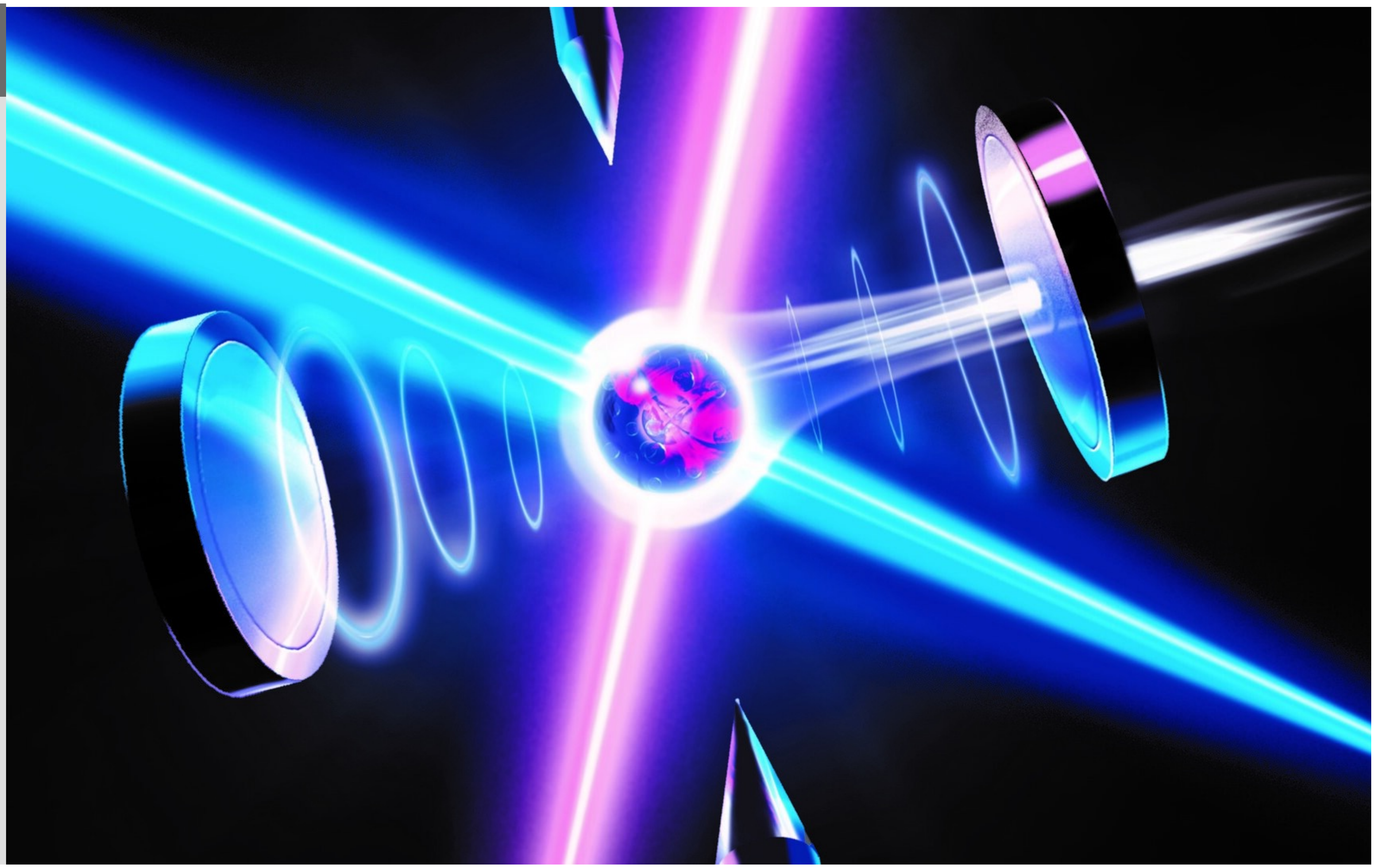
Applications

- *Quantum communication*

  Safe information channels
- *Quantum computers*

  Fast algorithms
  Simulating quantum states
- *Quantum sensing*

  Increasing measurement accuracy



Quantum Information National Laboratory of Hungary (2020)

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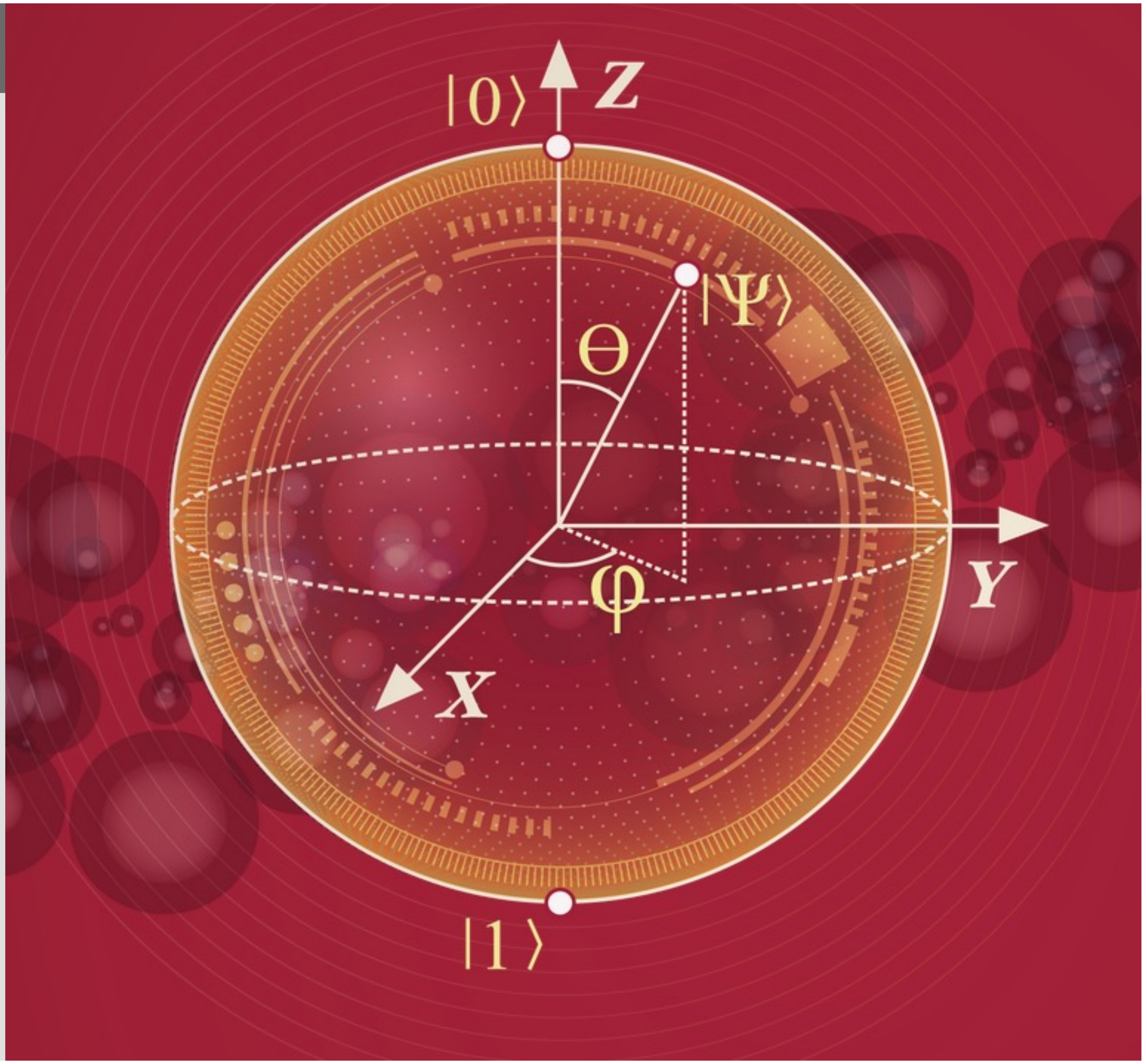
Mission

- *The Quantum Information National Laboratory boosts the research and development activity of the Hungarian scientific community within the unfolding second quantum revolution which aims at the exploitation of the enormous advancements in our ability to detect and manipulate single quanta for new kinds of applications.*



Consortium

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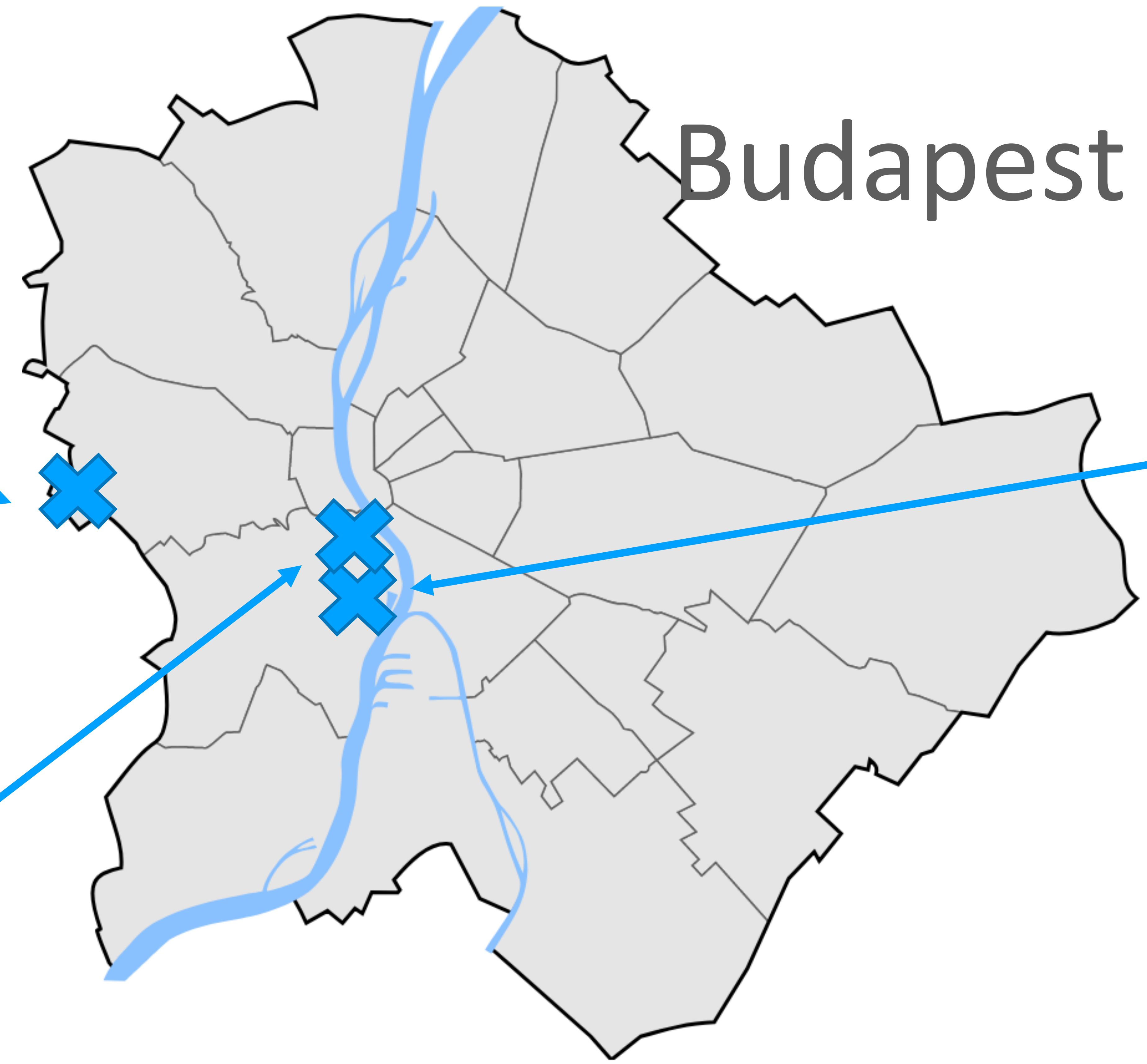

Wigner Research Centre

Eötvös Loránd University

MŰEGYETEM 1782

Budapest University of Technology and Economics

National Excellence Program, Quantum Technology	2017-2021	11 million €	Enhance research capacity
Quantum Information National Laboratory	2020-2025	14 million €	Achieve strategic goals

Wigner Research Centre for Physics

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Background

- *Quantum optics*
- *Photonics*
- *Computational material sciences*
- *Quantum information theory*
- *Nanocrystals*

Peter Domokos

COORDINATOR

Ádám Gali

LEAD RESEARCHER

Budapest University of Technology and Economics

Quantum Information National Laboratory HUNGARY

- Faculty of Electrical Engineering and Informatics
- Faculty of Natural Sciences

Background

- *Solid state physics*
- *Circuit quantum electronics*
- *Nanotechnology*
- *Telecommunication*
- *Networked systems and services*

Gergely Zaránd

LEAD RESEARCHER

Sándor Imre

LEAD RESEARCHER

Eötvös Loránd University

- Faculty of Informatics
- Faculty of Natural Sciences

Background

- *Complex systems*
- *Quantum system modeling*
- *Computing science*
- *Software technology*
- *Code analysis tools*
- *Post-quantum cryptography*

Tamás Kozsik

LEAD RESEARCHER

Gábor Vattay

LEAD RESEARCHER

Quantum communication

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Strategic goal 1

- *Realisation of a regional quantum communication network which can be joined to the pan-European quantum internet.*

Realisation of quantum bits

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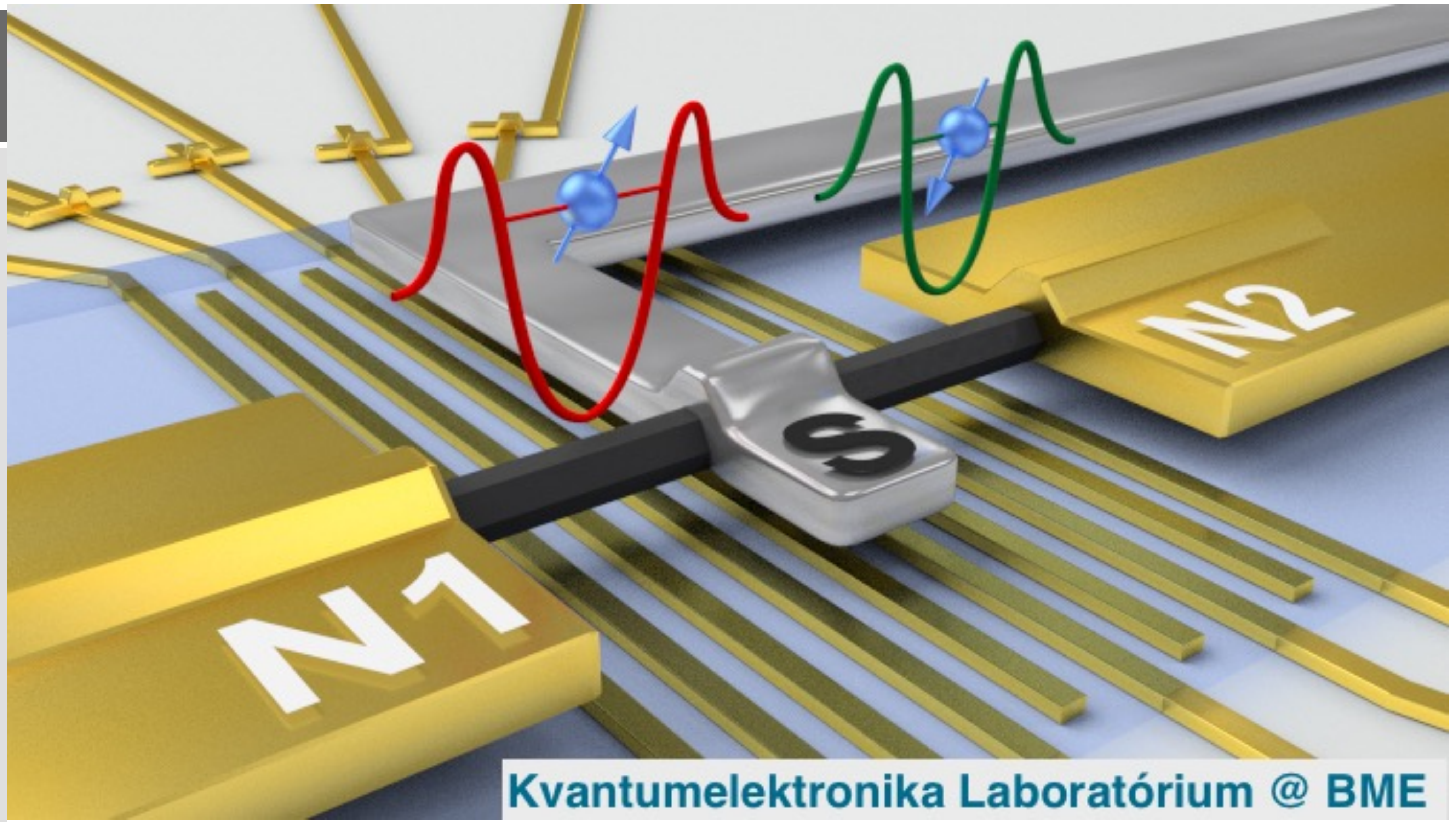
Strategic goal 2

- *Development of hardware components for quantum information processing based on atoms and artificial atoms,*
  and sustain the necessary laboratory background at the international forefront level.



Quantum computation

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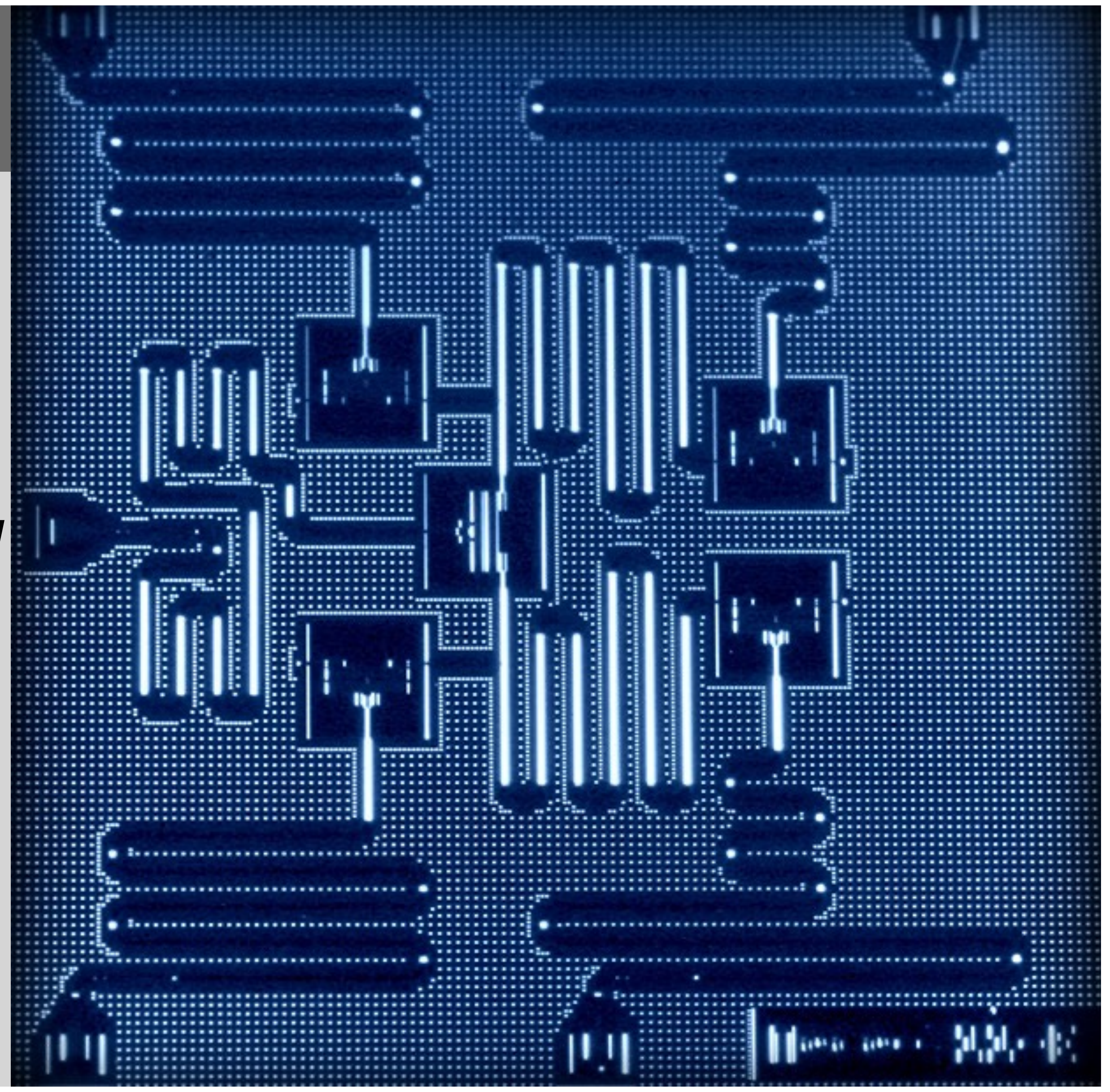
Strategic goal 3

- *Formation of the knowledge base and a pool of experts necessary to exploit the application potential of quantum computers operated as a remotely accessible large-scale infrastructure.*



Quantum communication networks

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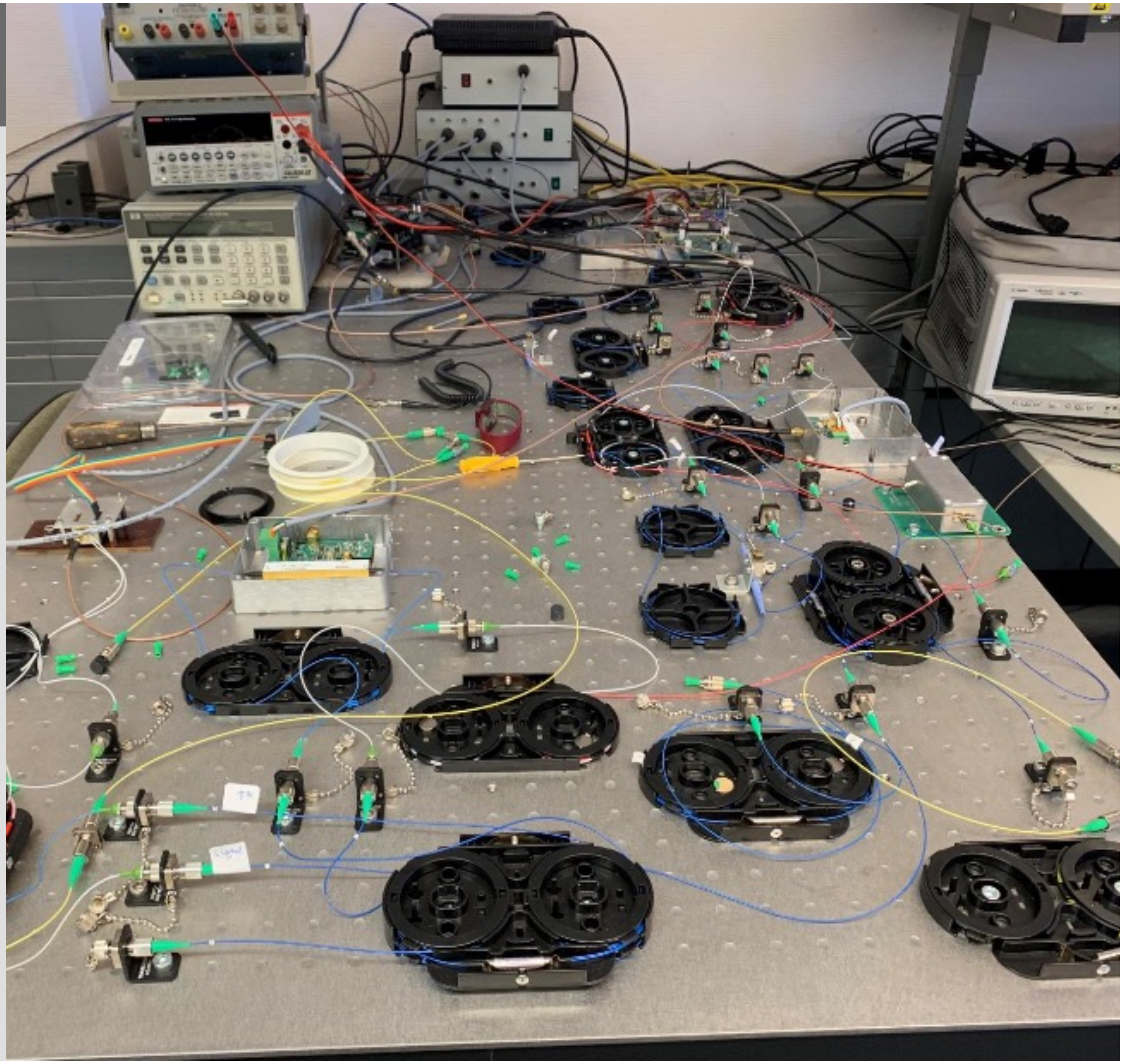
WORK PACKAGE 1

Regional quantum network

- *Quantum communication networks offer superior security compared to encryption algorithms we use to protect communication lines today.*
- *Free-space quantum network*
- *Optical-fibre quantum network*

  intra-city quantum link
  Hungary – Croatia (BB-84)
  Budapest – Bratislava – Vienna (entanglement based)
- *Quantum Random Number Generator*

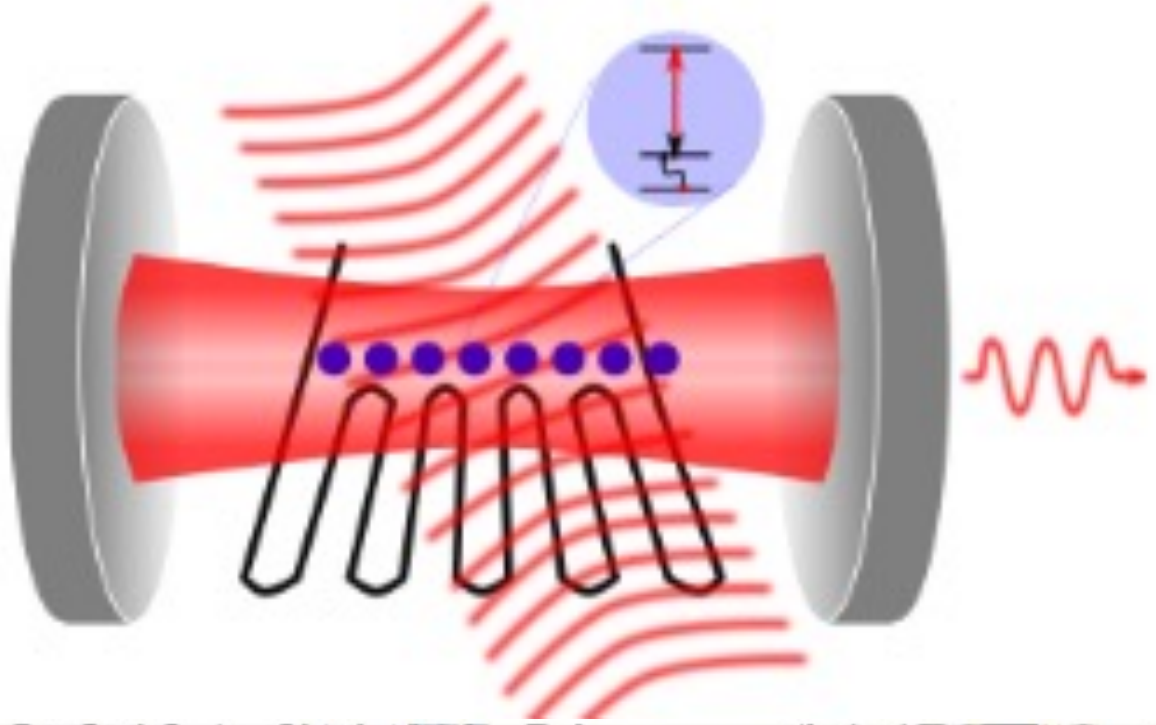


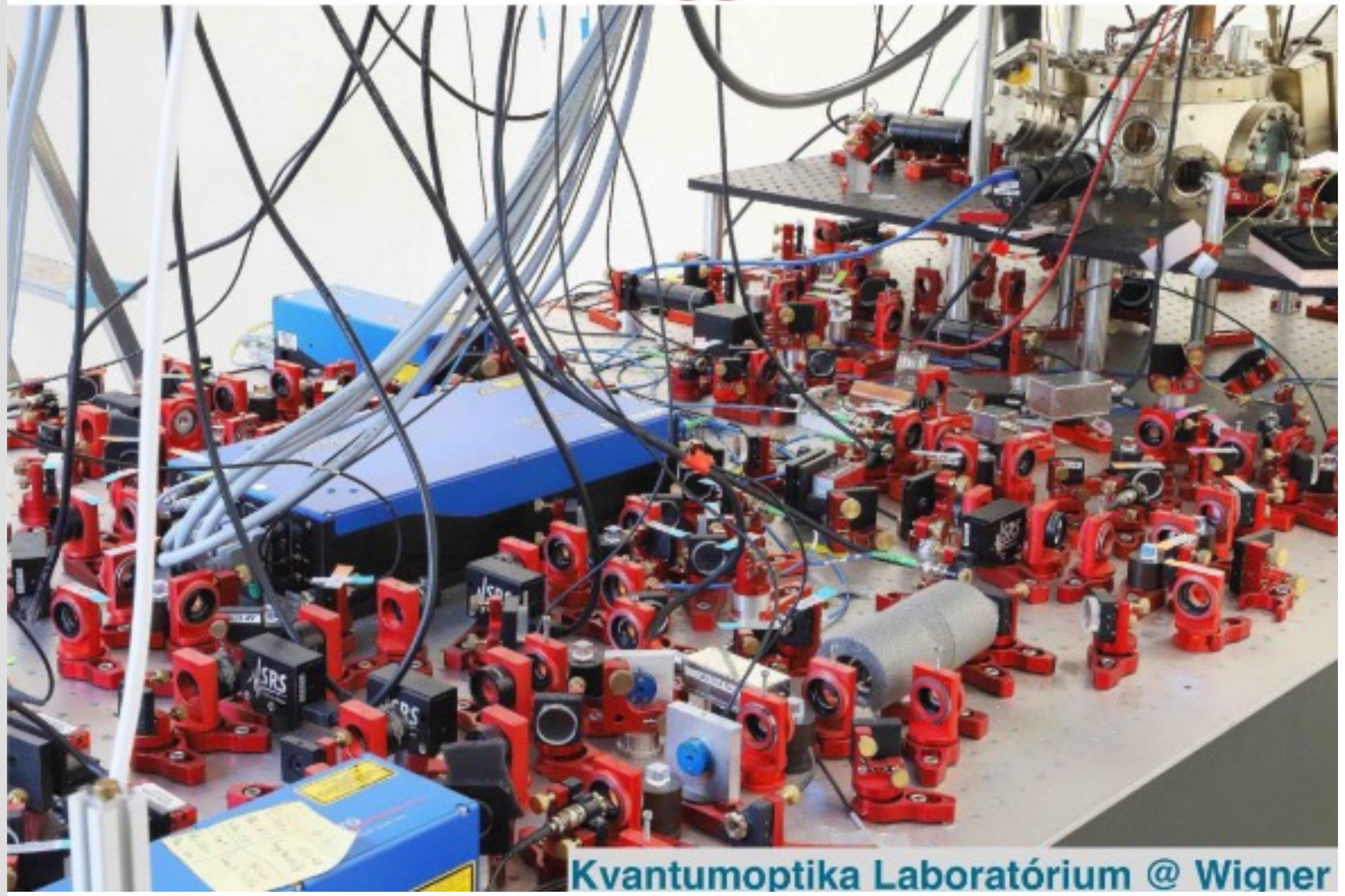
Quantum interfaces

WORK PACKAGE 2

Hybrid quantum systems

- *Atom-photon interface: mixing optical and microwave radiation using the quantum resonances of rubidium atoms*
- *Spin-photon interface: manipulate the electron spin states in artificial atoms (point defects in diamond or silicon carbide) by laser beams and microwave field*





Solid-state quantum memories

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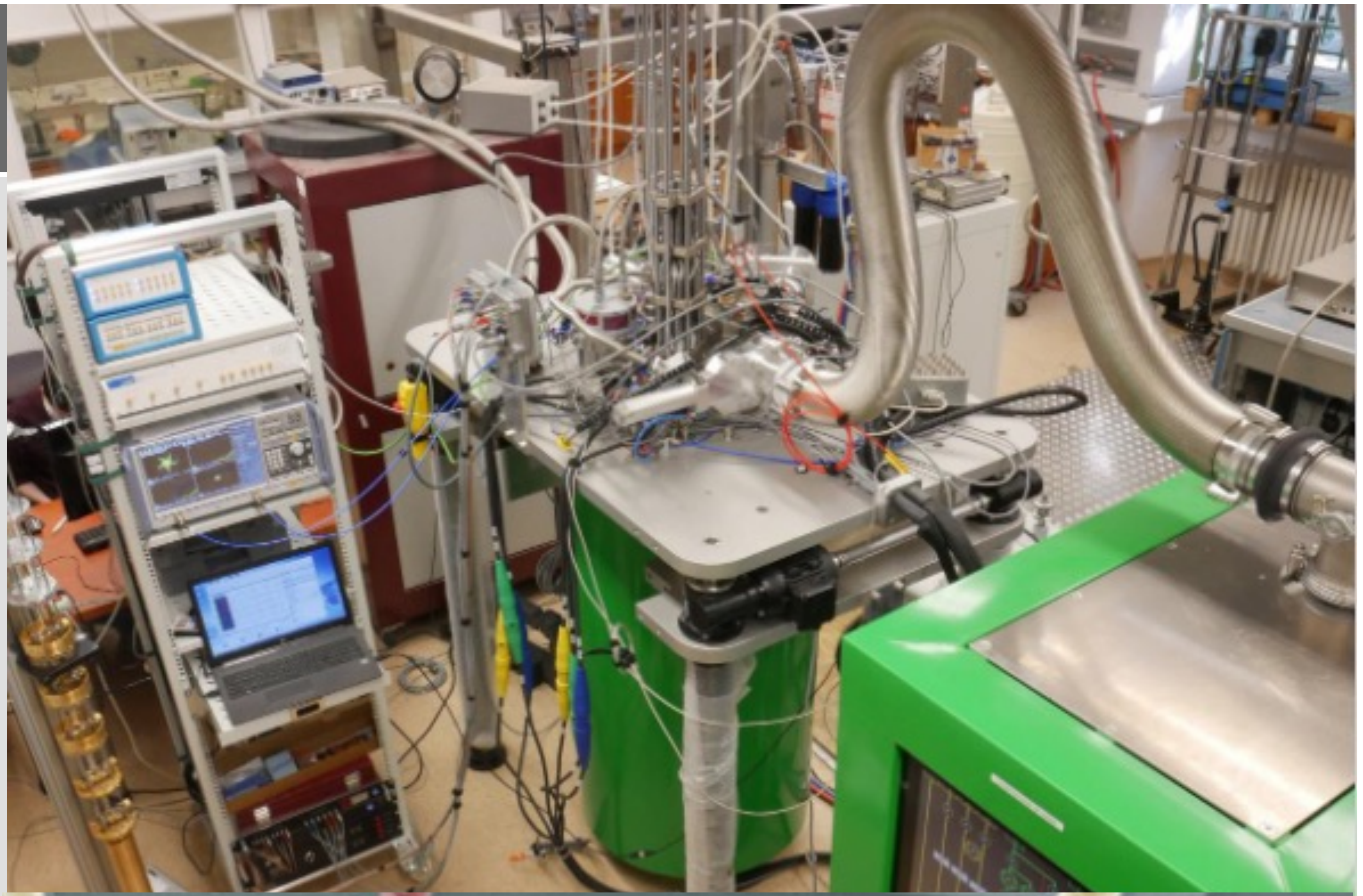
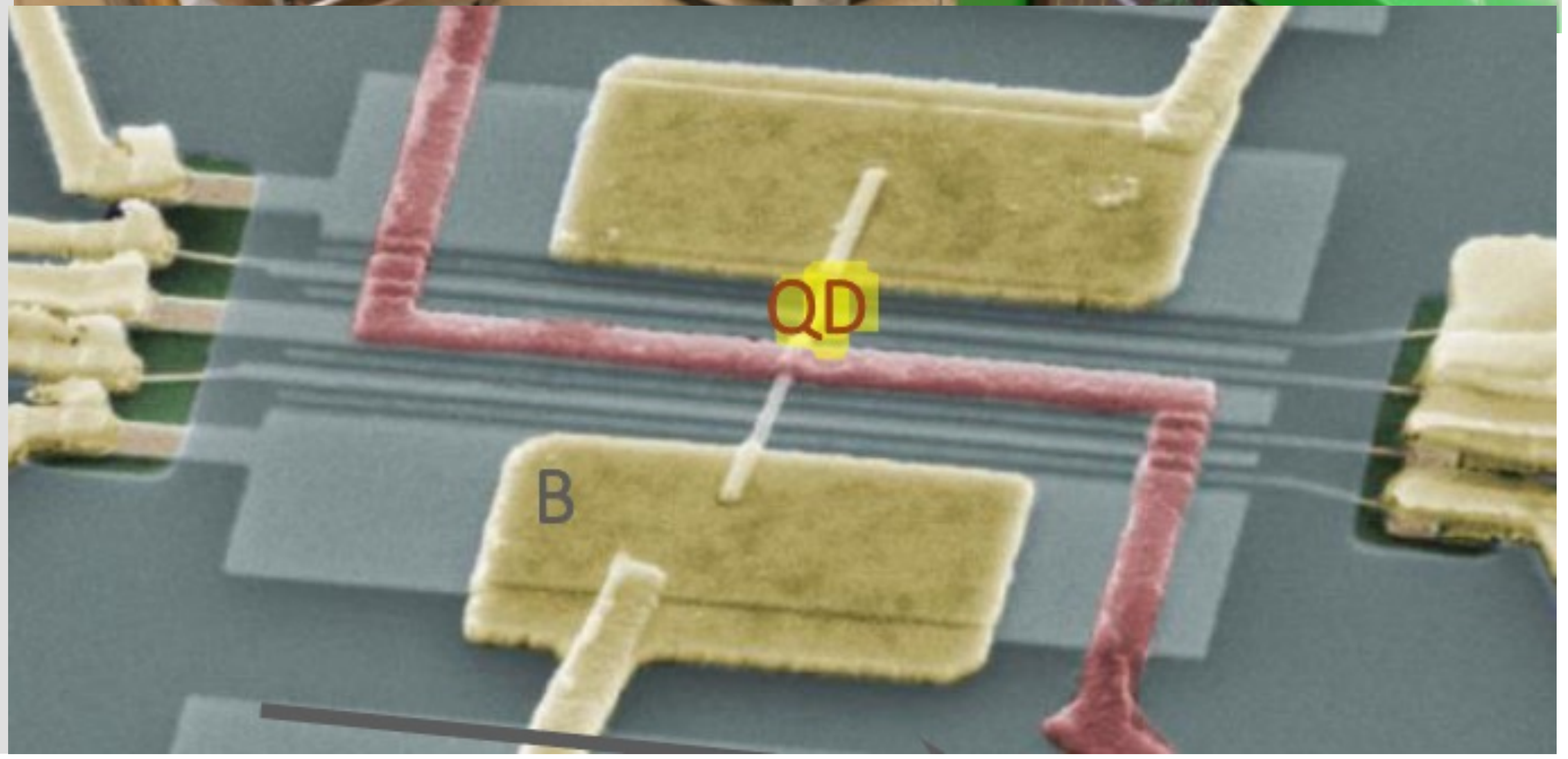
WORK PACKAGE 3

Quantum bit architerctures

- *Semiconductor-superconductor hybrid qubits*
- *Topological spin structures in magnetic data storage*
- *Quantum-domain intelligent memory networks*
- *Implementing and manipulating telecom-wavelength-compatible quantum storage*





Optical quantum information

WORK PACKAGE 4

Quantum optical processor

- *First optical chip in Central and Eastern Europe*
- *QuiX Quantum*
- *Goal: carry out boson sampling experiments*

Quantum computation and simulation of quantum systems

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WORK PACKAGE 5

Benchmarking NISQ quantum computers

- *Optimalization problems (DWave)*
- *Non-linear protocols (IBM, Rigetti)*
- *Quantum approximate optimization algorithms (IBM, Rigetti)*
- *Validation of quantum superiority*

Amazon Braket

aws

D:Wave The Quantum Computing Company™

IBM

rigetti

NISQ: Noisy Intermediate Scale Quantum Computers

Software technology for quantum computing

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WORK PACKAGE 6

Software technology

- *Quantum computer emulator*
  - high-performance target hardware (FPGA)
  - quantum Fourier transformation realized
- *Fast simulator of Photonic Quantum Computers*
  - PIQUASSO
  - open source Python package
  - https://piquasso.com/
- *Post-quantum cryptography*
  - resistant protocols for different cryptography problems

PIQUASSO

Quantum communication network

RESULTS

Quantum Key Distribution

- *Fiber-based QKD demonstrated (BME – Wigner)*
- *Entanglement-based free-space QKD*
- *Entangled photon source developed, Bell-test*
- *Clock Transmission System developed (ESA, Relcom Ltd)*
- *Symmetric keys generated QBER = 7 %*
  at very low SNR
- *Actual quantum channel distance = 14 m*
  16 dB channel attenuation can be withstood
- *Successful sync tests over the Danube*
  ~ 700 m of clock transfer (BME - Vodafone)

Quantum communication tools

RESULTS

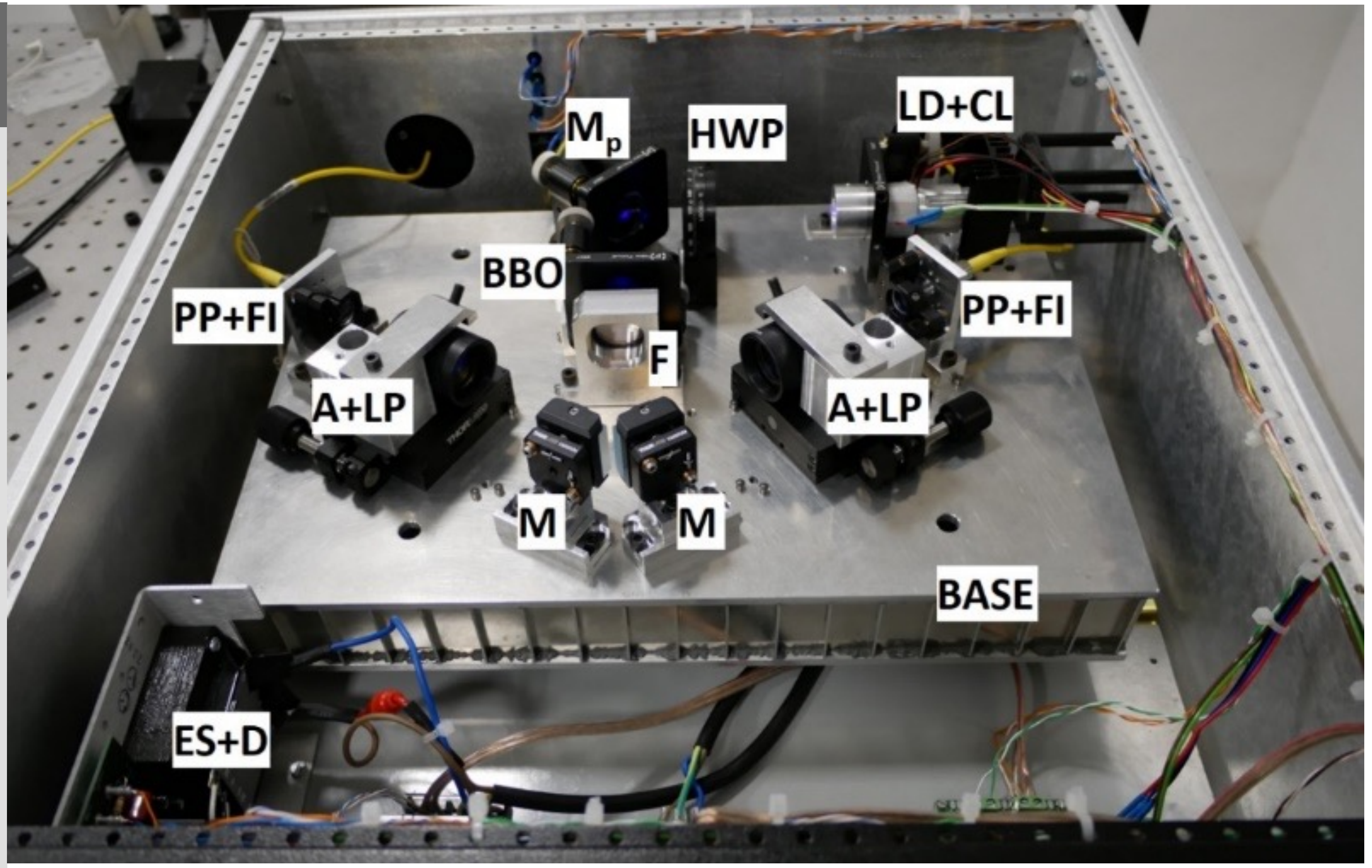
Entangled photon pair source

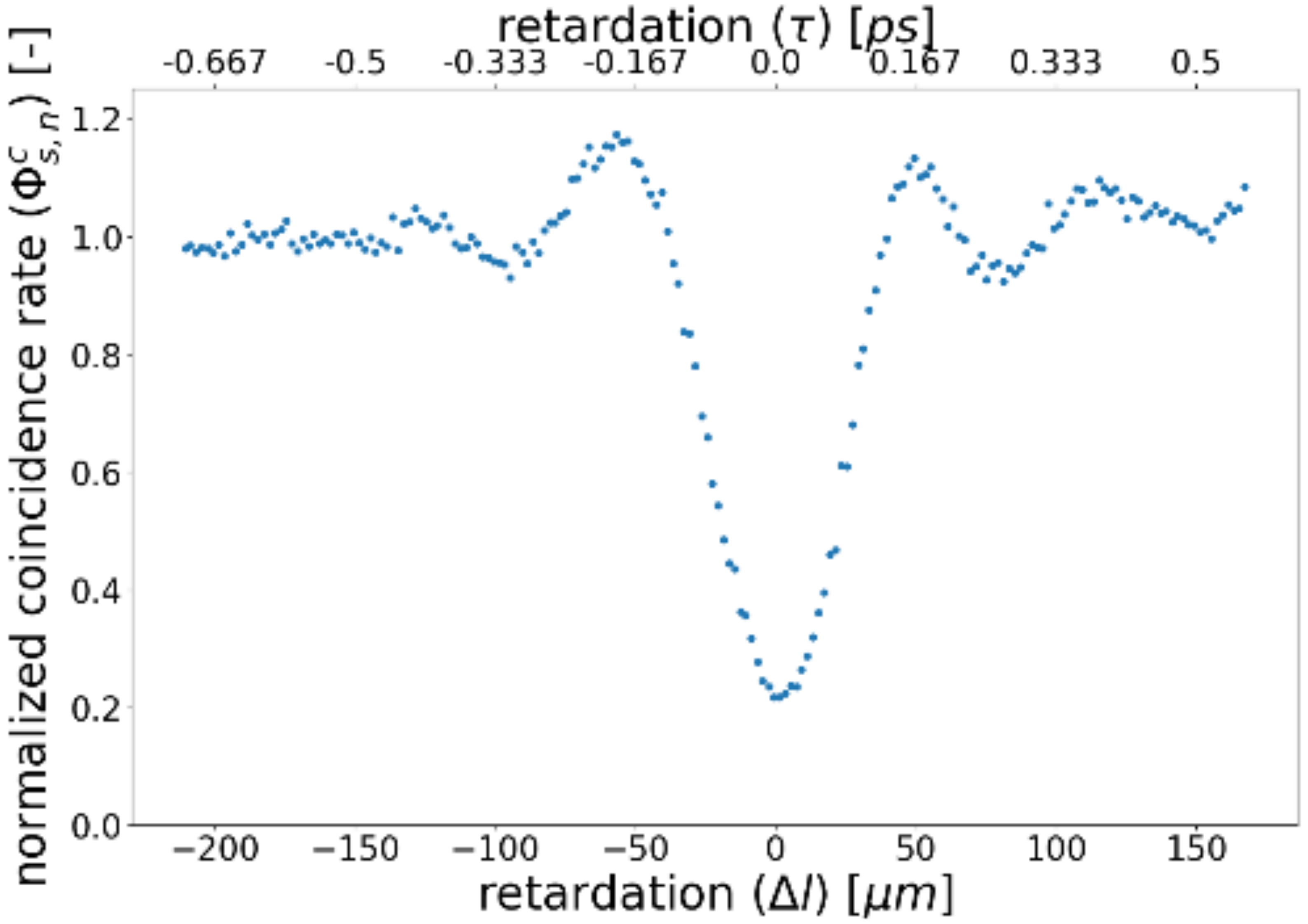
- *Stabilized compact source @ 810 nm*
- *Optical parametric down-conversion*

Filter configuration		Long-pass from 600 nm	Band-pass at 810 nm
Signal flux	Φ_s	636 $\pm$ 95 kcps/mW	17.3 $\pm$ 2.6 kcps/mW
Coincidence flux	Φ_s^c	130 $\pm$ 39 kcps/mW	6.8 $\pm$ 1.1 kcps/mW
Heralding ratio	$\mathbb{P}_h$	20 $\pm$ 3 %	39 $\pm$ 6 %
Bandwidth (FWHM)	-	202 nm	10 nm

- *Single photon source operation: Hong-Ou-Mandel interference*

Cs. T. Holló et al, Optical Engineering (2022)



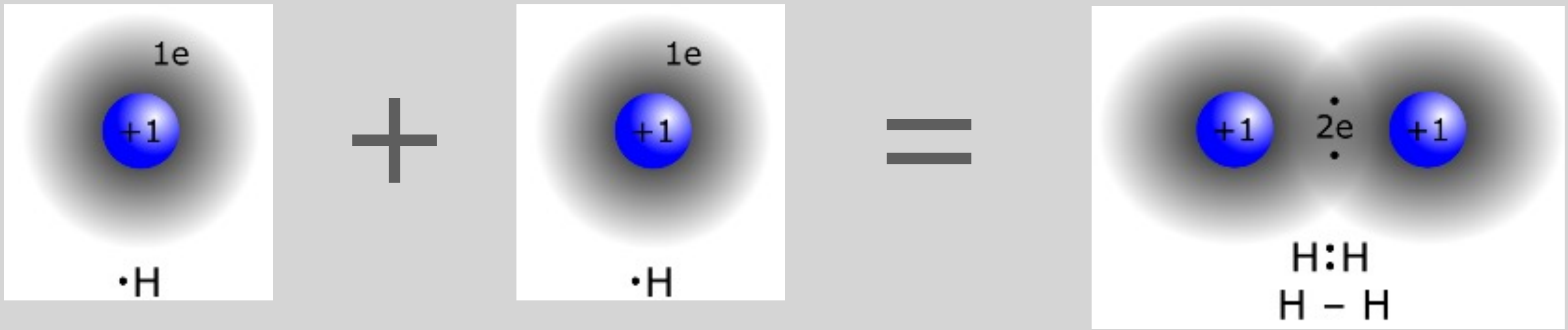


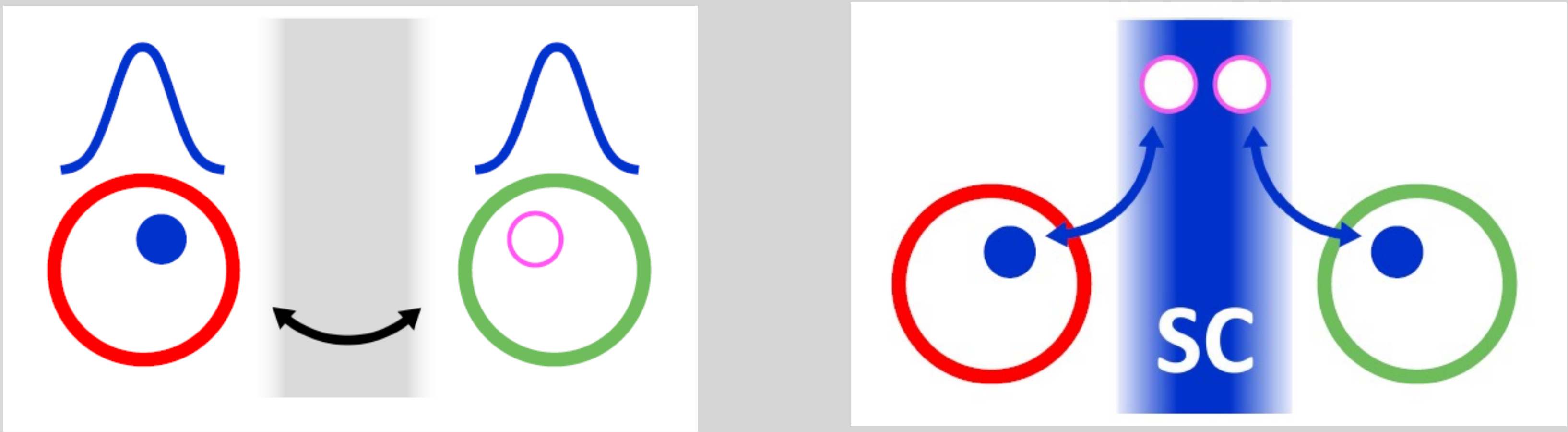
Towards topological quantum bits

RESULTS

Realisation of Andreev molecules

- *Large spatial extension of the zero-energy states in a magnetic field* Scherübl et al, Nature Communications (2020)
- *Interacting quantum bits*





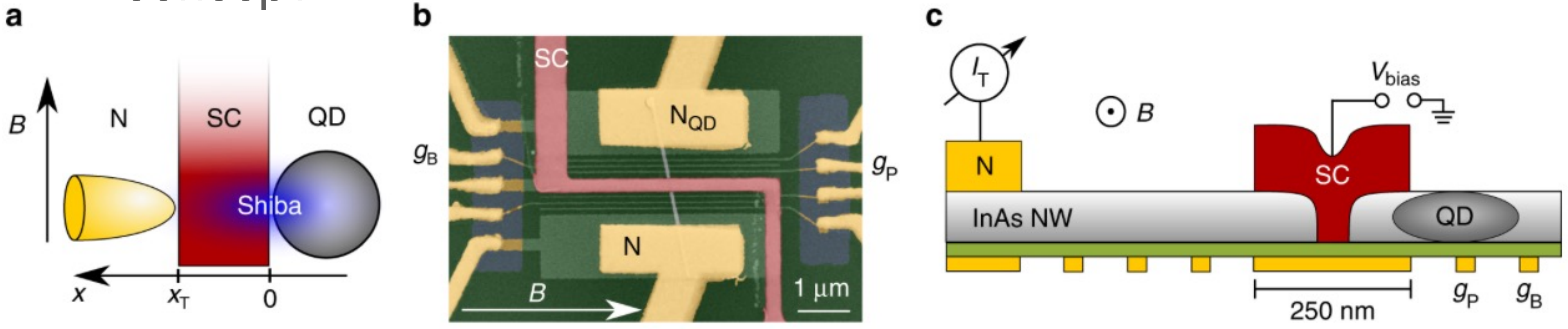
Kürtössy et al, Nanoletters (2021)

- *Kitaev chain → Majorana fermions*

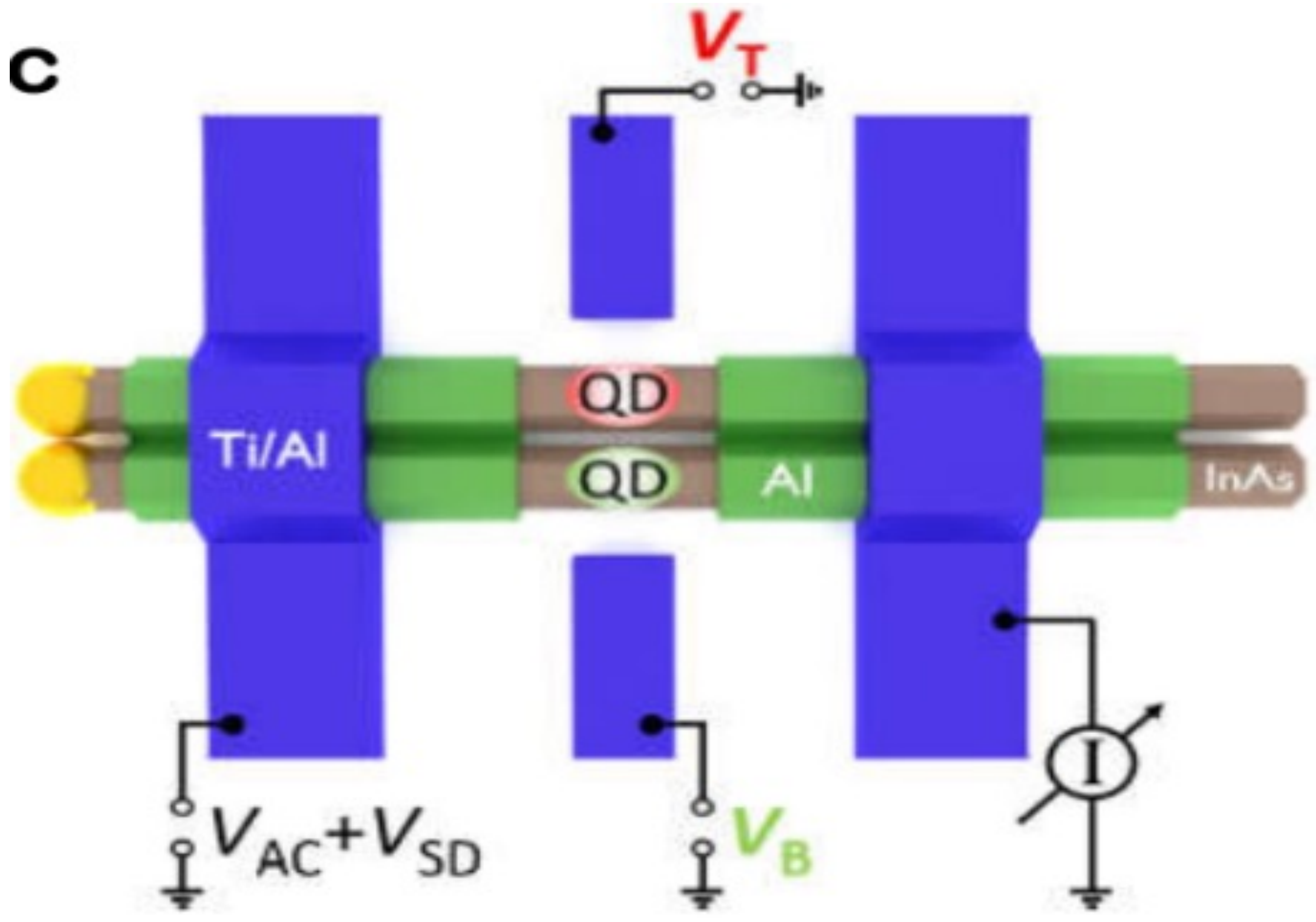
Andreev qubit concept

real image

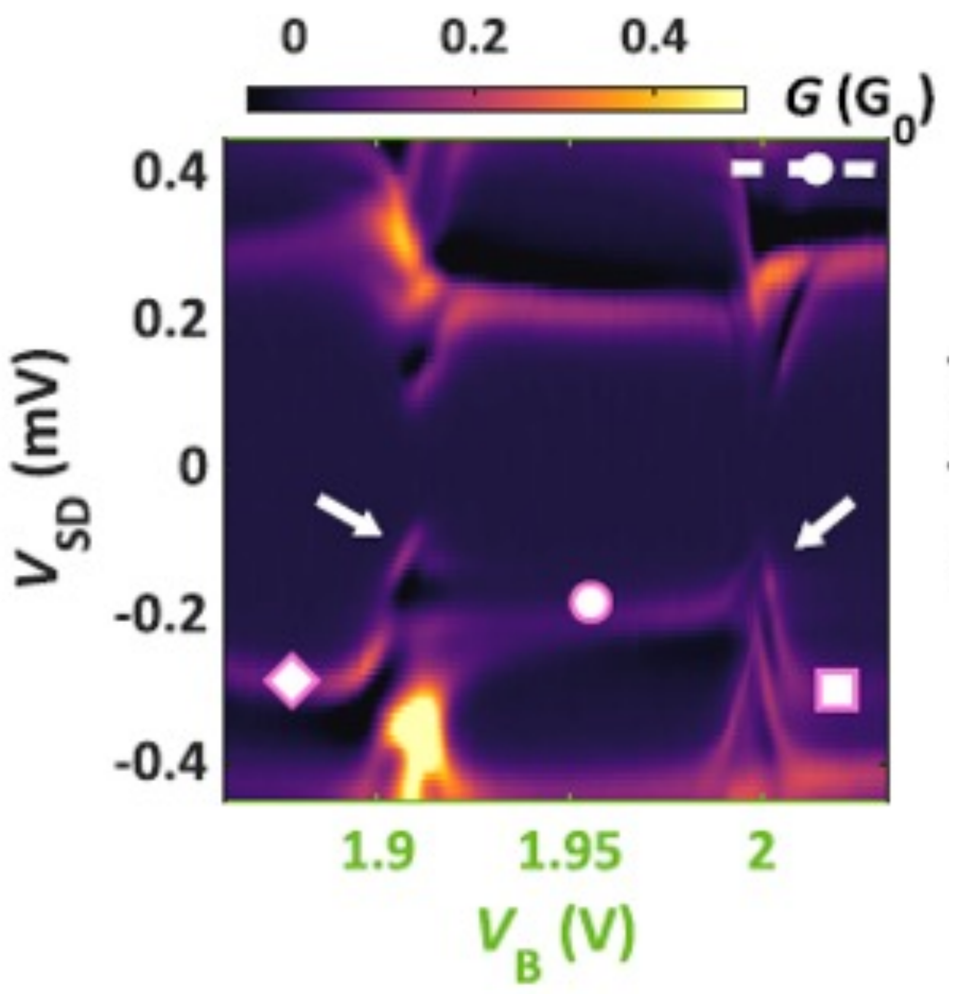
scheme



coupling of qubits



spectrum with bond states



Novel states of matter for data storage

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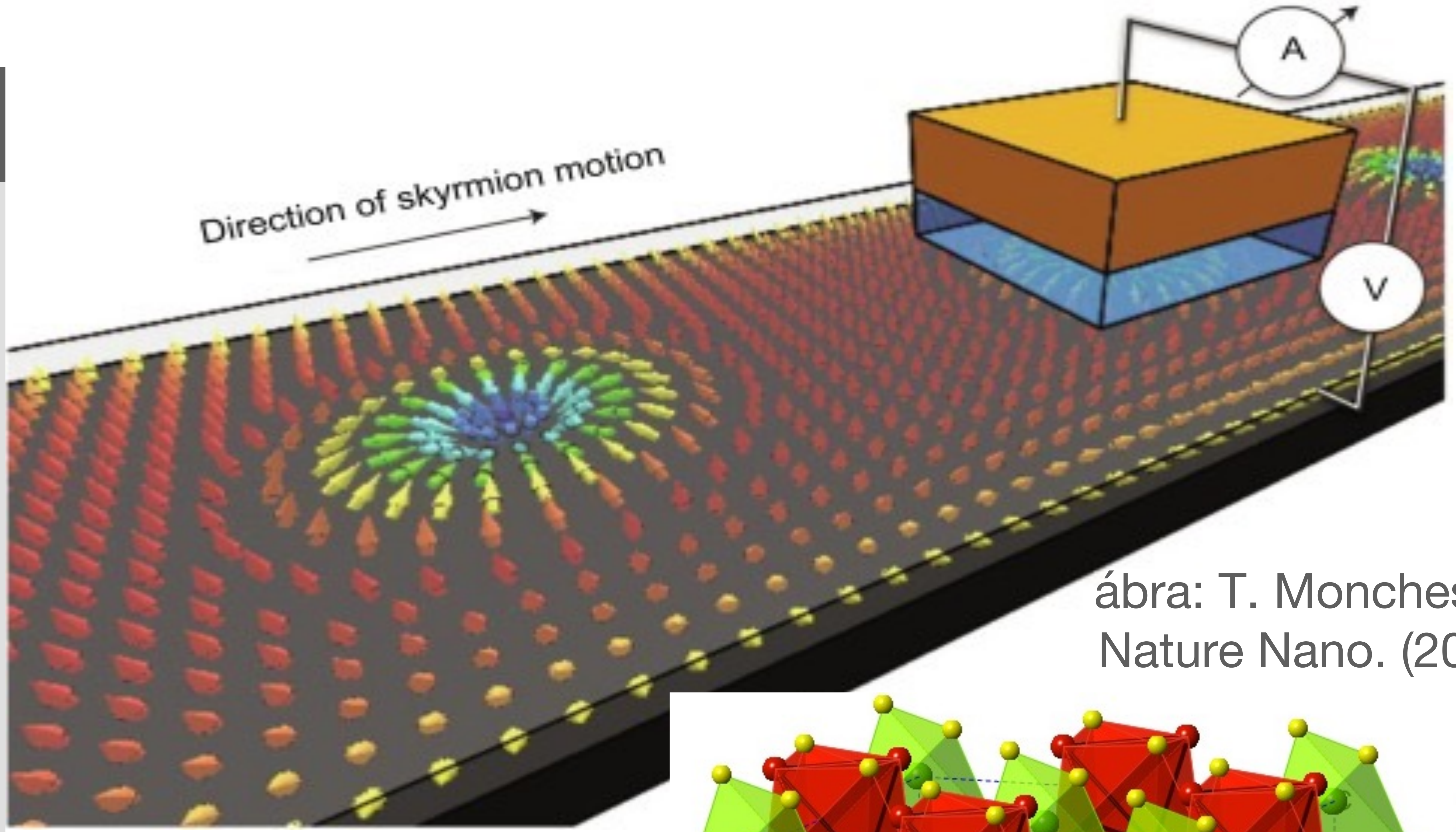
RESULTS

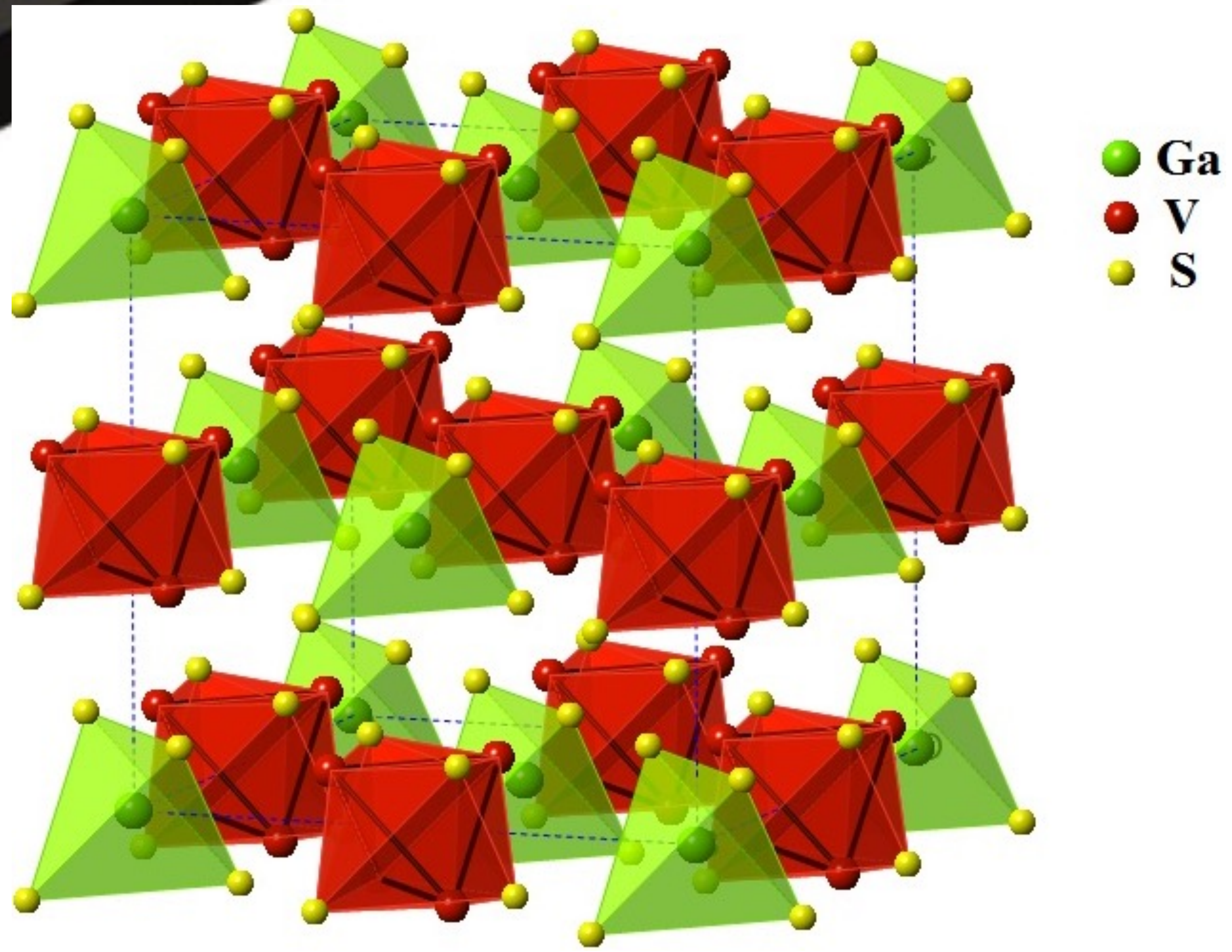
Magnetic skyrmions

- *Stable, localised, topologically protected spin patterns*
- *Mobility due to current drive*
- *Ga**V**$_4$S$_8$ → Ga**Mo**$_4$S$_8$*
- *Size: 18 nm → 9.8 nm*
- *Electric polarization accompanies the skyrmions*
- *Manipulation of skyrmions by electric field*

Á. Butykai, et al., npj Quantum Materials **7**, 26 (2022)



ábra: T. Monchesky, Nature Nano. (2015).



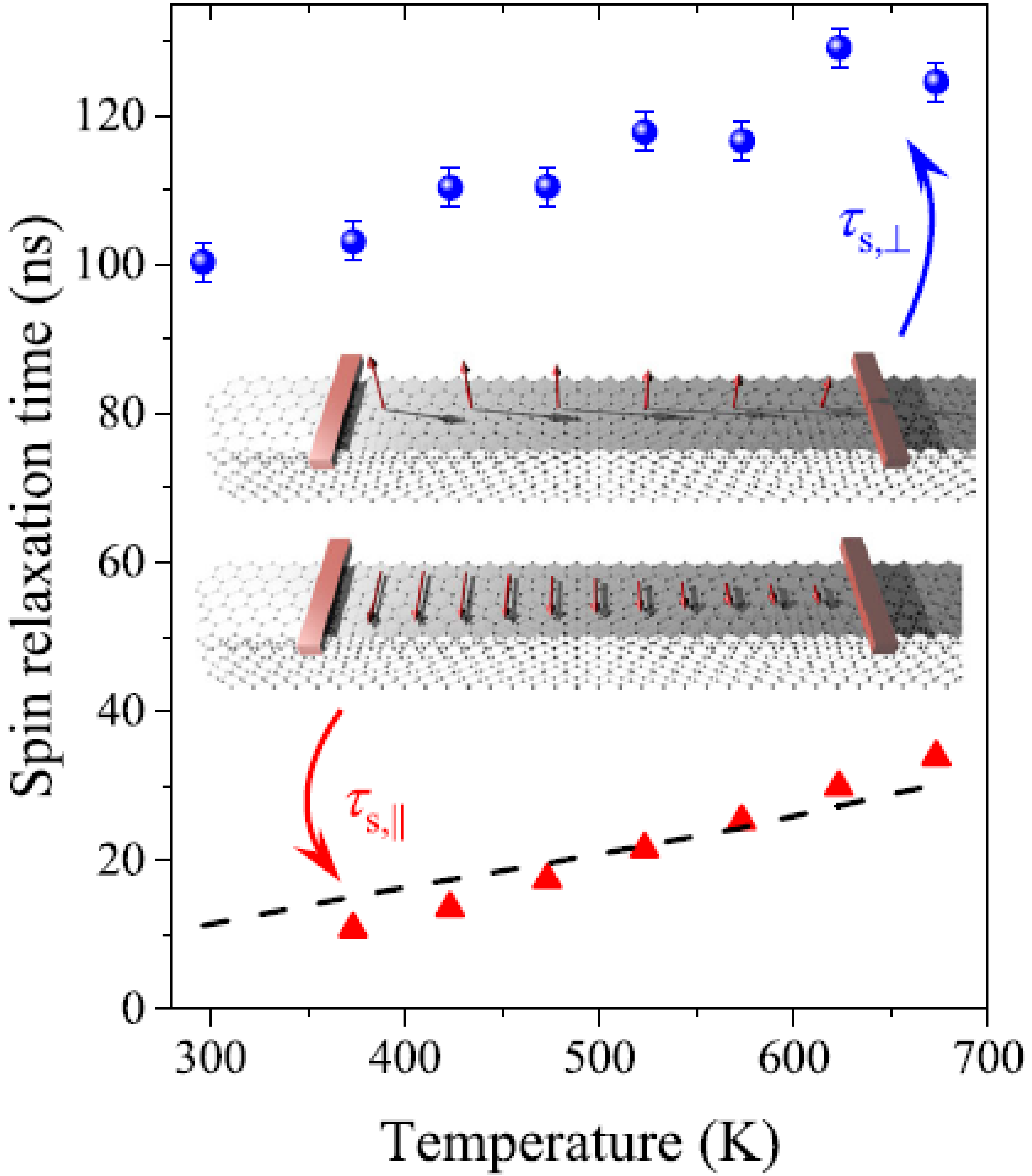
Ultralong spin-lifetime in graphite

RESULTS

Spintronics

- *Graphene is conventionally thought to revolutionize spintronics, however, it has too many adatoms, impurities, surface area*
- *Graphite: an old material, archetype of semimetals*
- *Spins injected with perpendicular/paralel polarization to the plane*
- *Spin relaxation lifetime can be as long as 100 ns*

B. Márkus *et al.*, Nat. Comm. **14**, 2831 (2023).



Atom-photon interface

RESULTS

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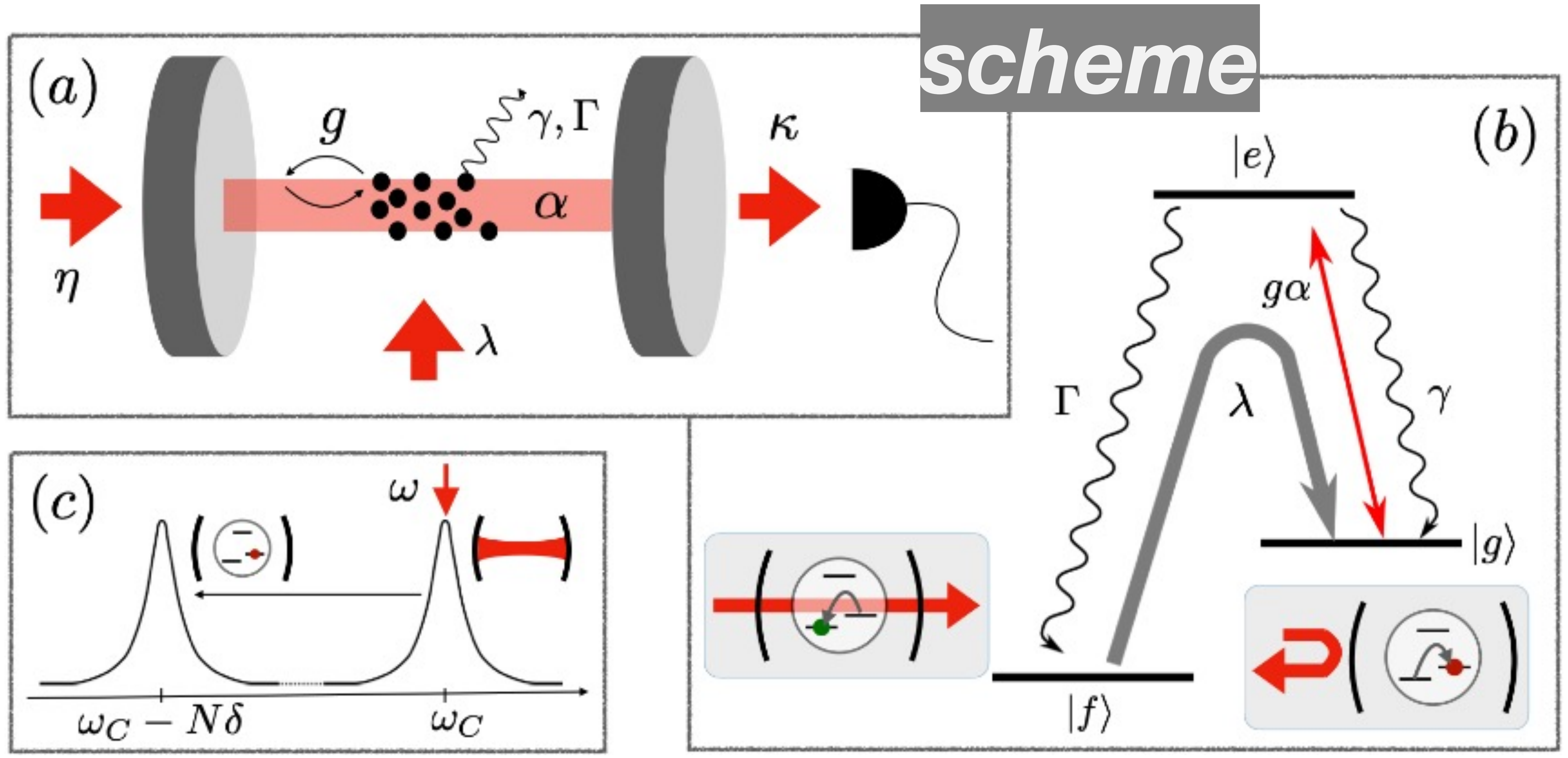
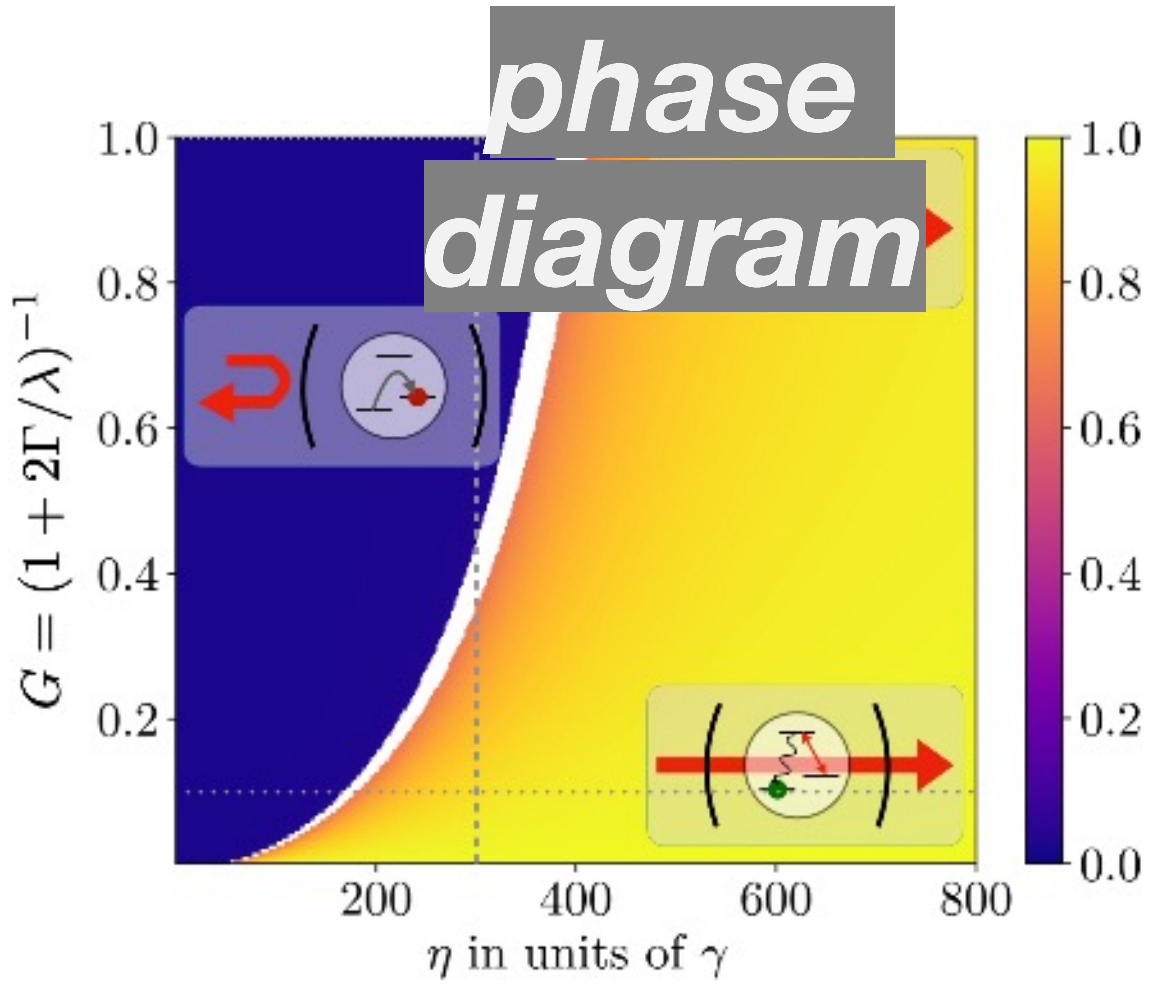
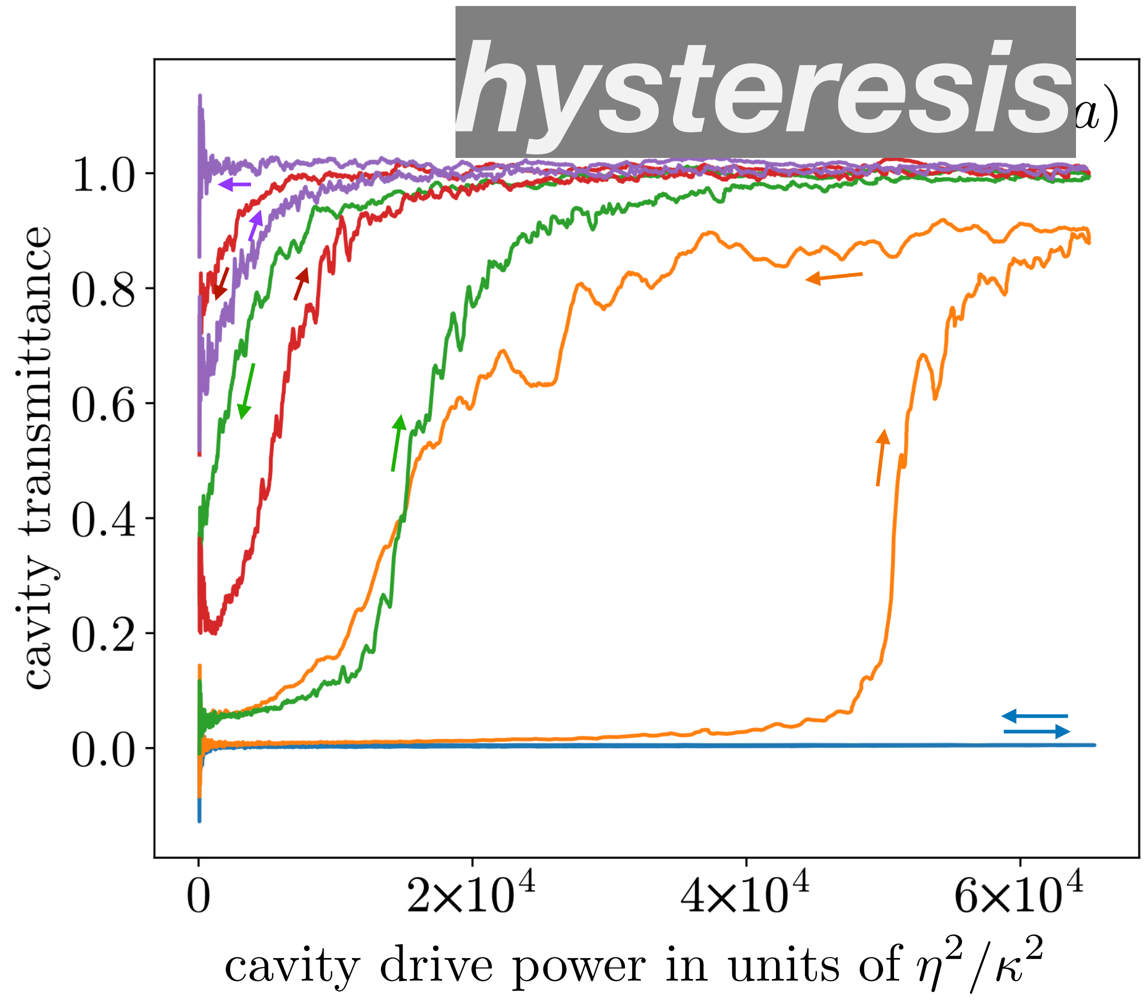
Ground state bistability

- *Trapped cloud of cold atoms strongly coupled to a single mode of a cavity*
- *Hyperfine ground states of Rb represent long-lived quantum memory*
- *Two laser drives acting on the memory states: pump λ and probe η*
- *Cavity transmittance recorded: order parameter of the memory state*
- *Bistable switching generated*

B. Gábor et al, Phys. Rev. A 107, 023713 (2023)







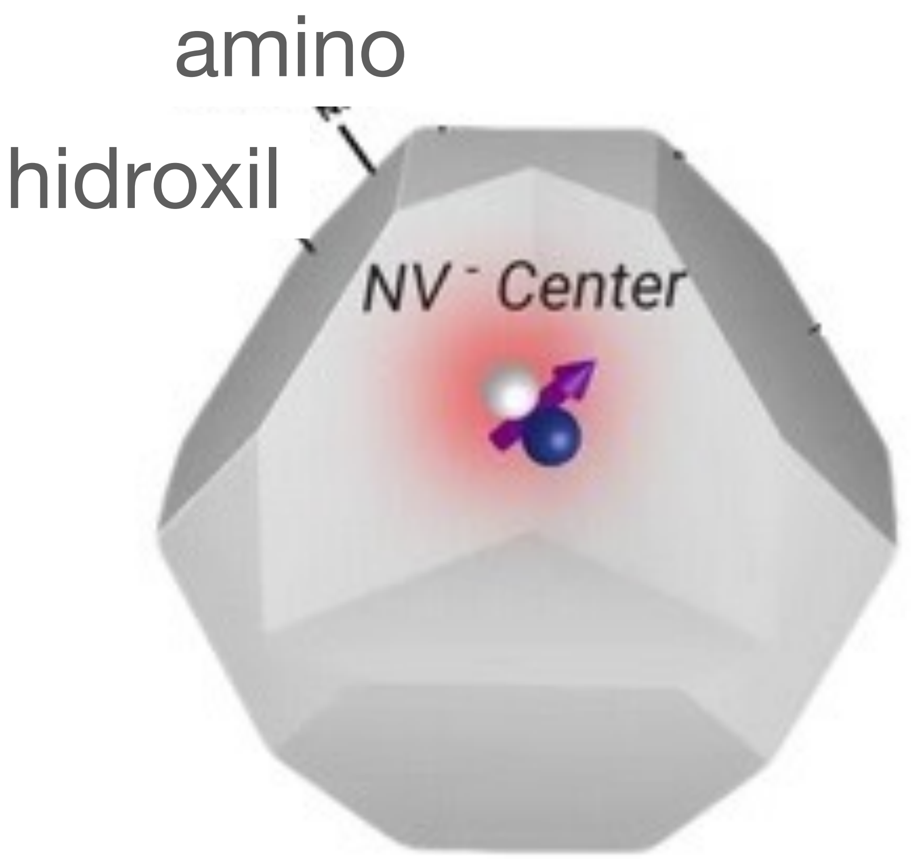
Spin-photon interface

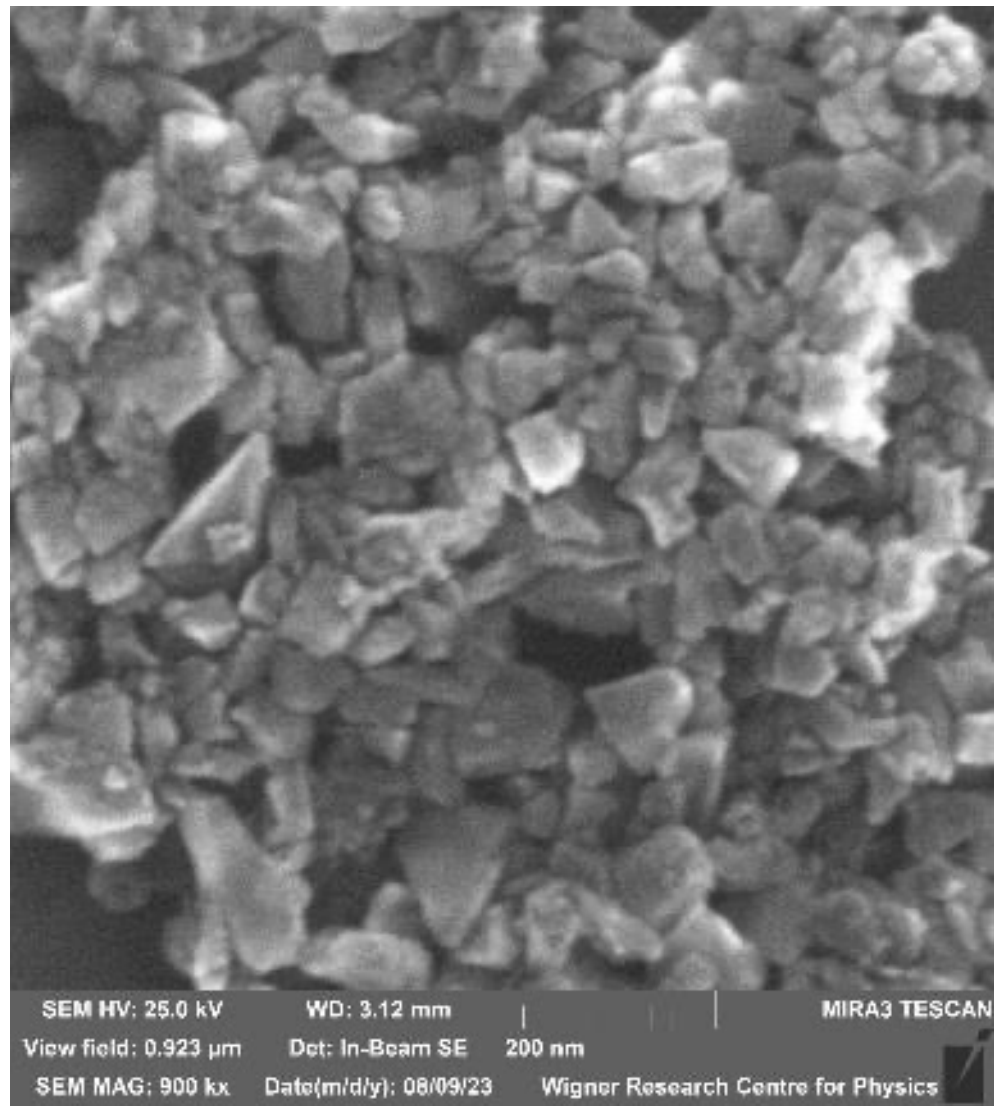
RESULTS

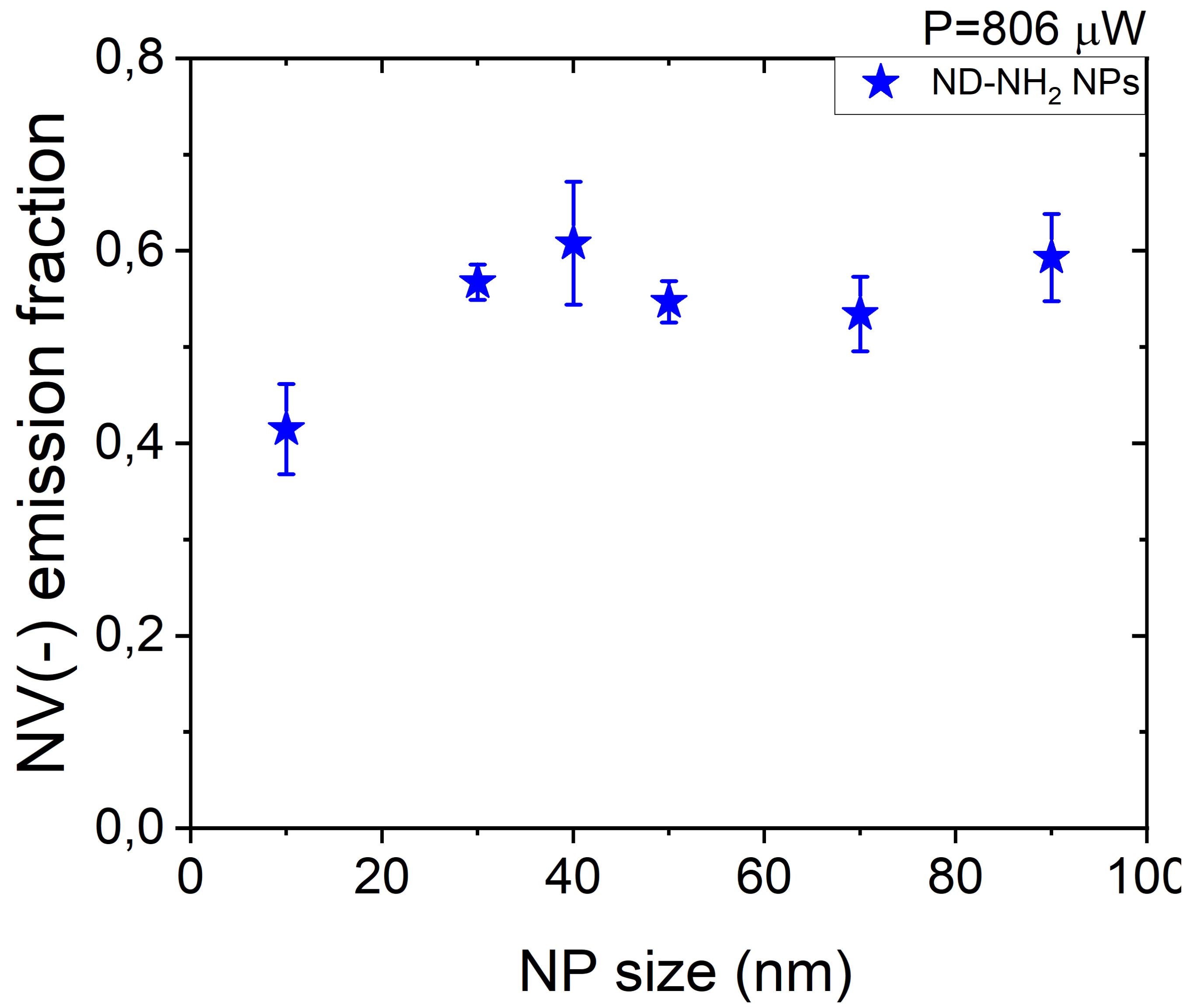
NV centre in nanodiamond

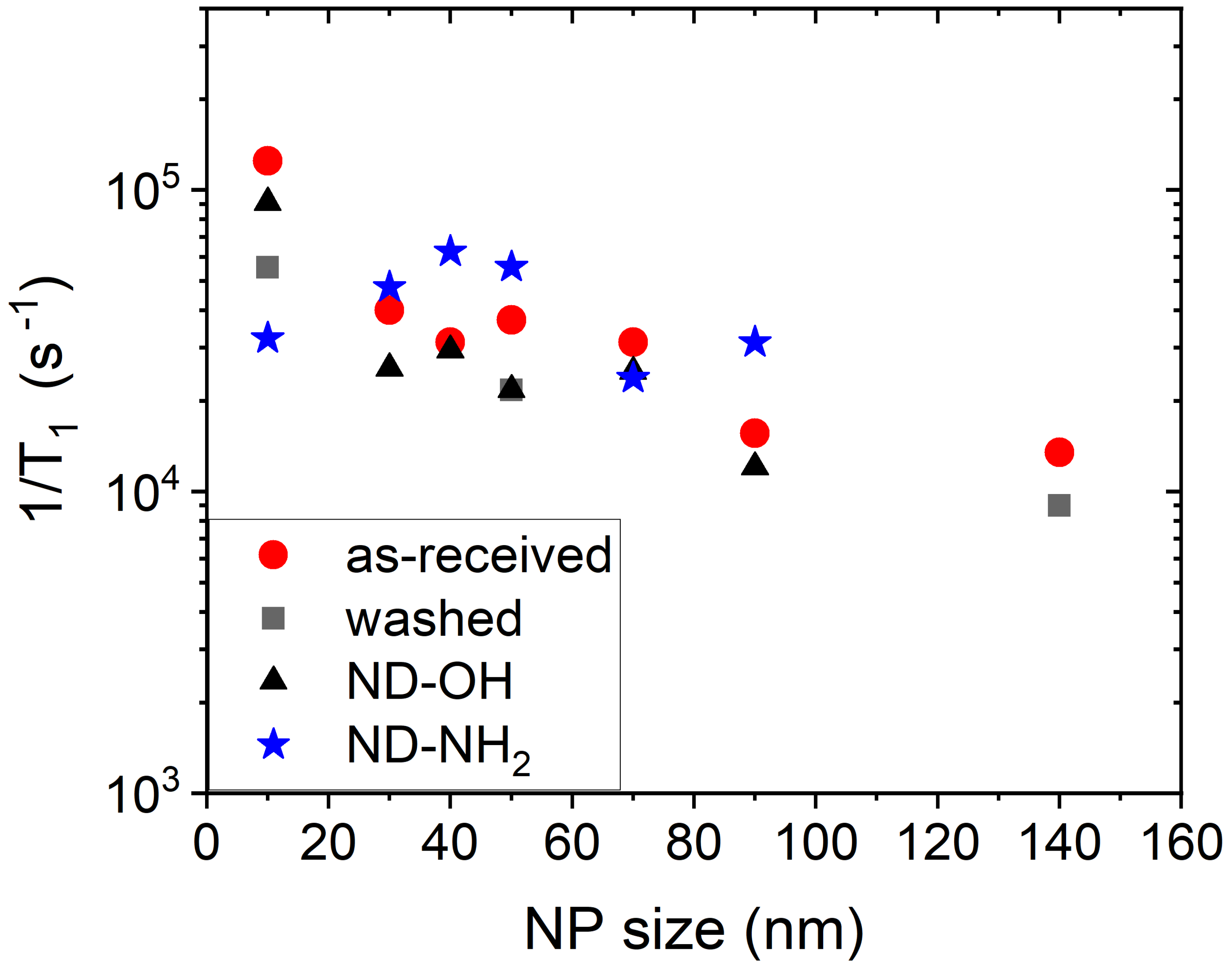
- *The fluorescence nanodiamond (FND) is a highly stable photon source that does not photo-bleach*
- *The spin of the negatively charged Nitrogen-vacancy (NV) center can be read out optically*
- *Manipulation of NV- center population by the termination of the FND, the laser power, and the size of FND*
- *Stabilisation of NV qubit state by using NH_2 termination*
- *Manipulation of the relaxation time by surface termination*

N. Jegenyes, V. Verkhovlyuk et al., to be submitted









Sequential Quantum Gate Decomposer (SQUANDER)

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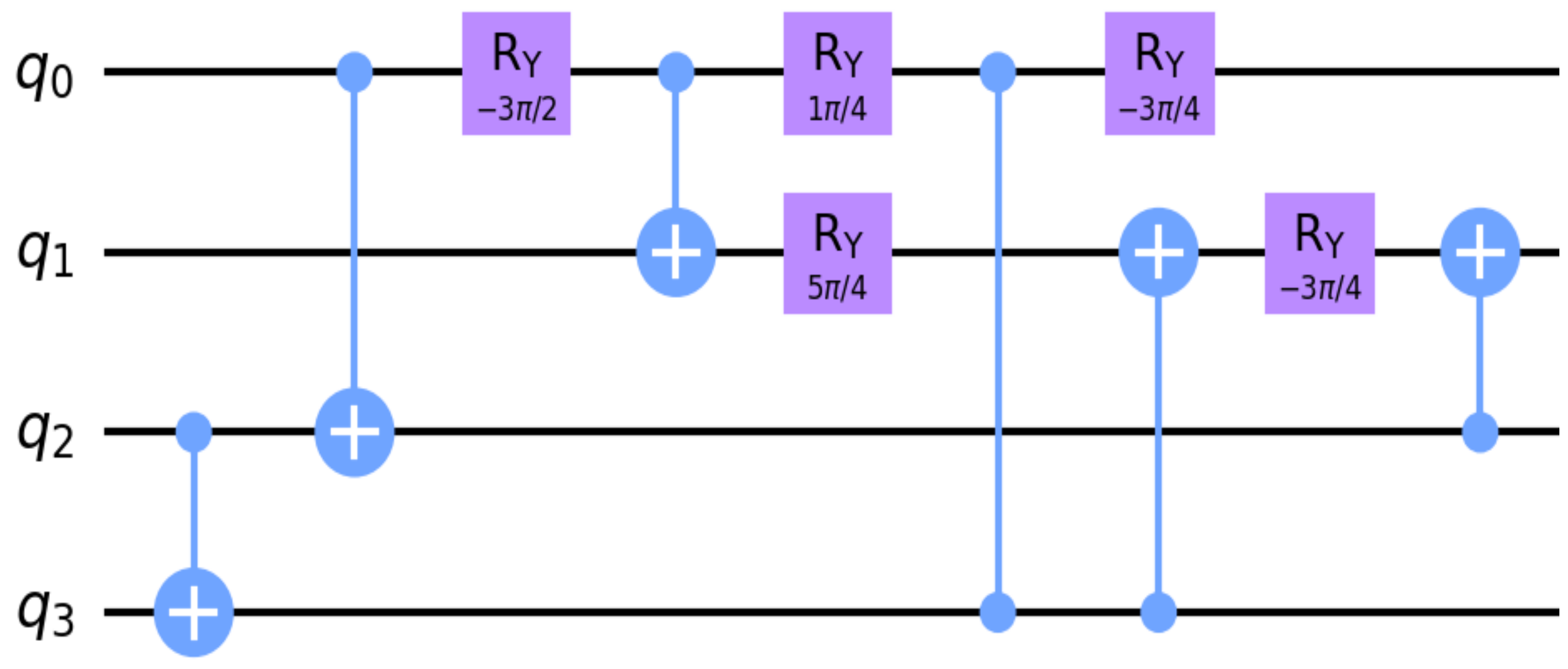
RESULTS

Optimization based quantum gate synthesis

- *Quantum circuit optimization through iterations of adaptive compression*
- *FPGA based data-flow engines speed up the optimization process by (10-100)x*
- *(7-220)x less gates compared to QISKIT*

Zimborás et al, Quantum 6, 710 (2022)



CNOT gate counts in several quantum circuits:

Circuit name	Qubits	QISKIT *CNOT*	SQUANDER *CNOT*
ex2_227	7	2852	133
majority_239	7	4024	143
rd53_131	7	6538	93
cm82a_208	8	11246	51

Photonic Quantum Computer Simulation

RESULTS

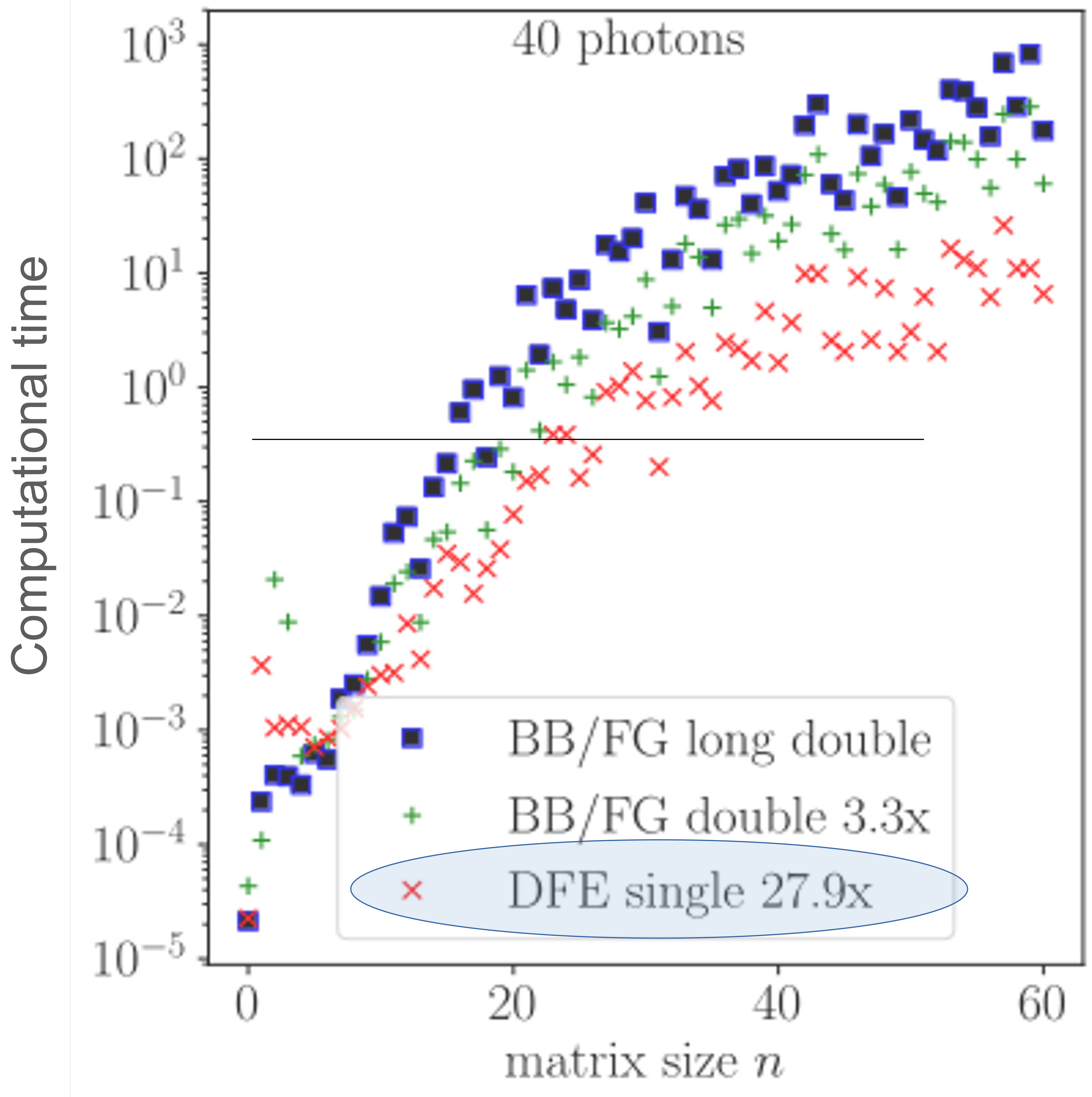
Simulation speedup by FPGA

- *Exact boson sampling simulation up to 48 photons with single FPGA chip*

20 photons: ~0.01 sec/sample
30 photons: ~1 sec/sample
40 photons: ~40 sec/sample

- *Approximate boson sampling simulation up to 80 photons with single FPGA chip*
- *ERCIM News 128*

Permanent computation benchmarks



number of modes

Traveling salesman problem

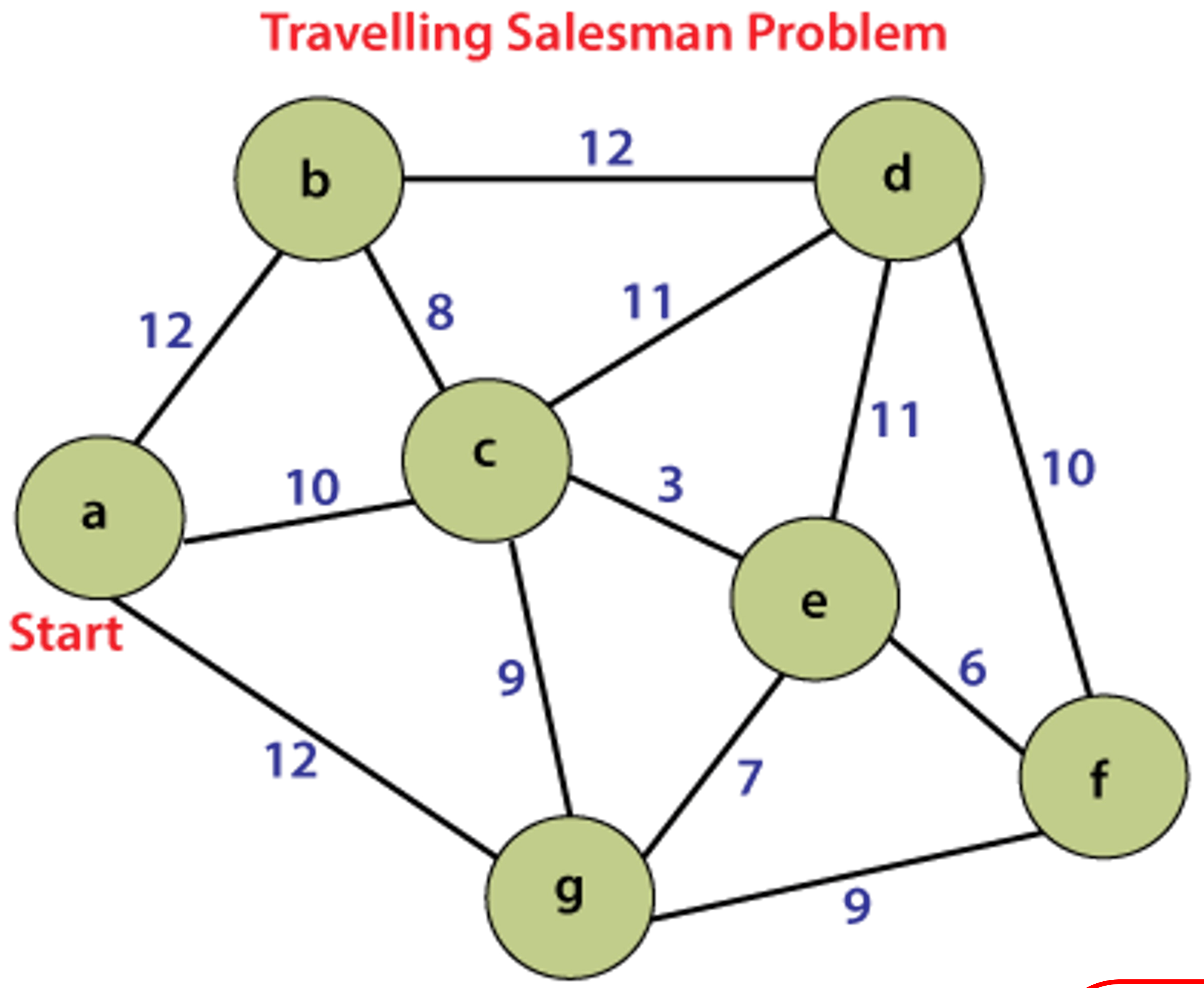
RESULTS

Optimal Quantum Circuit Design

- *Combinatorial optimization problems*
- *Task: Find the shortest path that goes through all the cities and returns to the start*
- *HOBO technique ⟶ variational quantum circuit (FUNC-QAOA) that surpasses all the other prior circuit designs in all the circuits metrics simultaneously and matches (up to log corrections) the theoretical optima*

npj Quantum Information 8, 39 (2022)
arXiv:2209.03386

2 talks @ QIP 2022 & 2023



	optimal	X-QAOA	XY-QAOA	MTZ ILP	HOBO	FUNC-QAOA
qubits	$n \log n$	n^2	n^2	$n^2 \log n$	$n \log n$	$n \log n$
gates	n^2	n^3	n^3	n^3	n^3	n^2
depth	n	n	n	$n \log n$	n^2	$n \log n$
depth (LNN)	n	n^2	n^2	$n^2 \log n$	$n^2 \log n$	$n \log n$
energy span	n	n^3	n^2	n^4	n^2	n
param.gates	n^2	n^3	n^3	n^3	n^3	n^2
eff.space	$n \log n$	n^2	$n \log n$	$n^2 \log n$	$n \log n$	$n \log n$

Post-quantum cryptography

RESULTS

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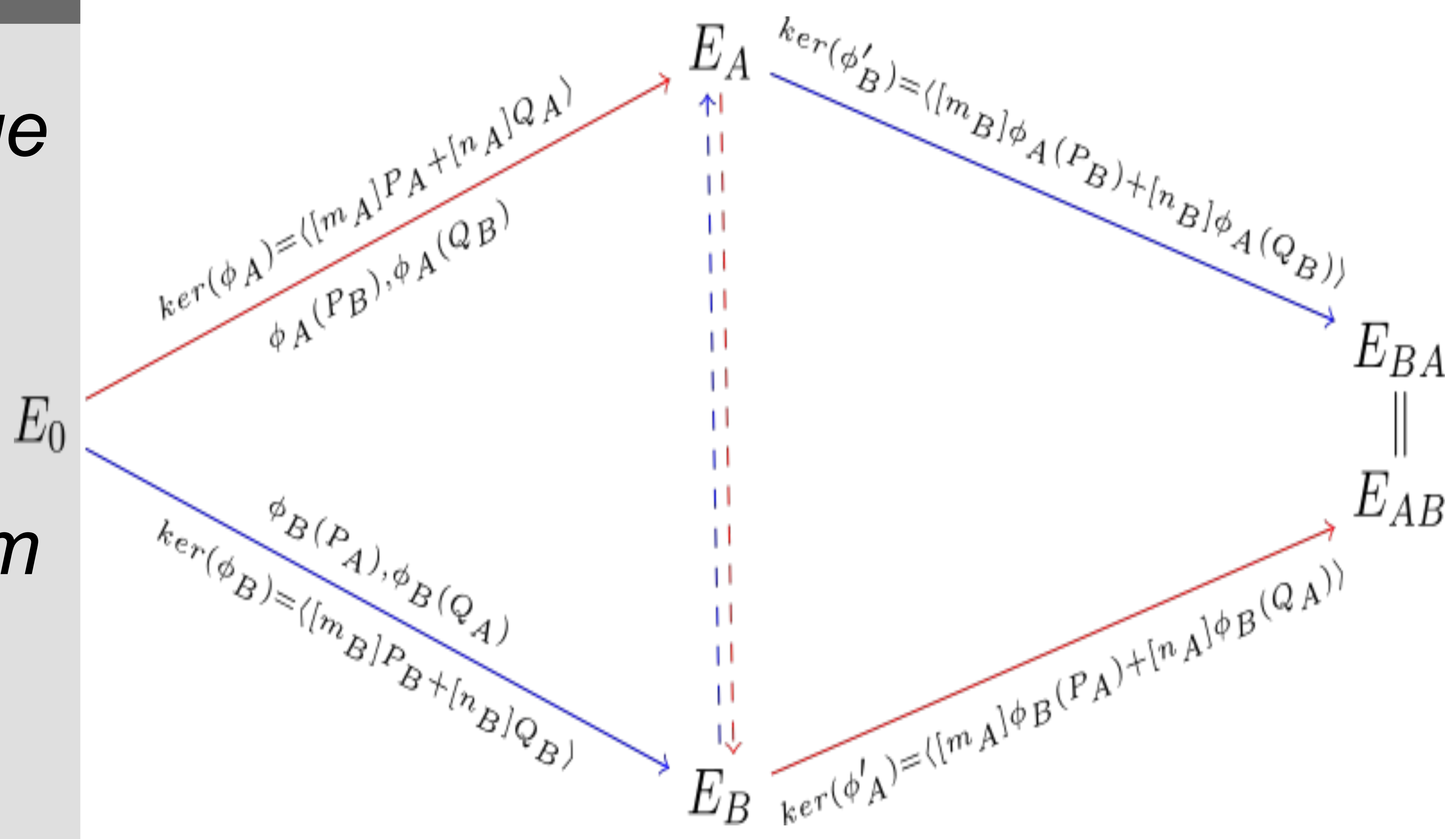
Cryptanalysis of pSIDH

- *pSIDH is a recently proposed key exchange supposedly resistant to quantum attacks*
- *Hardness relies on the so-called IsERP problem for prime degree isogenies*
- *We showed how to break it with a quantum computer*
- *First application of non-abelian hidden subgroup problems to completely break a cryptosystem*

Mingjie Chen, Muhammad Imran, Gábor Ivanyos, Péter Kutas, Antonin Leroux, Christophe Petit, *Accepted to Asiacrypt 2023 (one of the three top cryptography venues)*



Asiacrypt 2023
December 4-8, 2023
Guangzhou, China

Research and development

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QNL

- *1 mission*
- *3 strategic goals*
- *6 work packages*
- *18 projects*
- *15 research groups*
- *82 PhD student*
- *35 young researchers*

Figures of merits

- *50 Q1 publication / year*
- *90 conference talks / year*
- *15 domestic industrial partners*
- *8 international industrial partners*
- *90 international academic partners*
- *12 EU-s consortial projects*
- *4.5 billion HUF grant*

Industrial cooperations

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Thank you for your attention!