



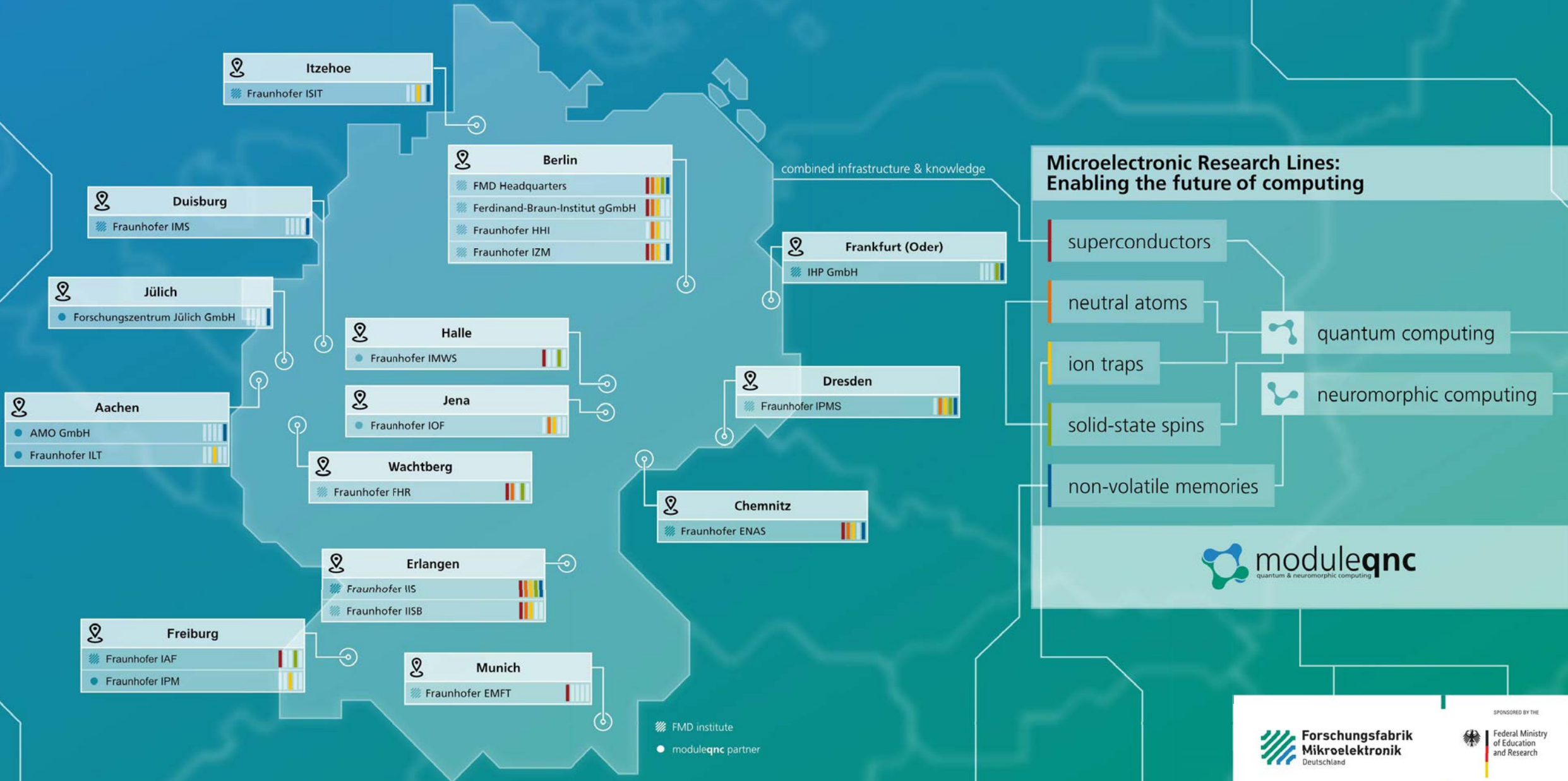


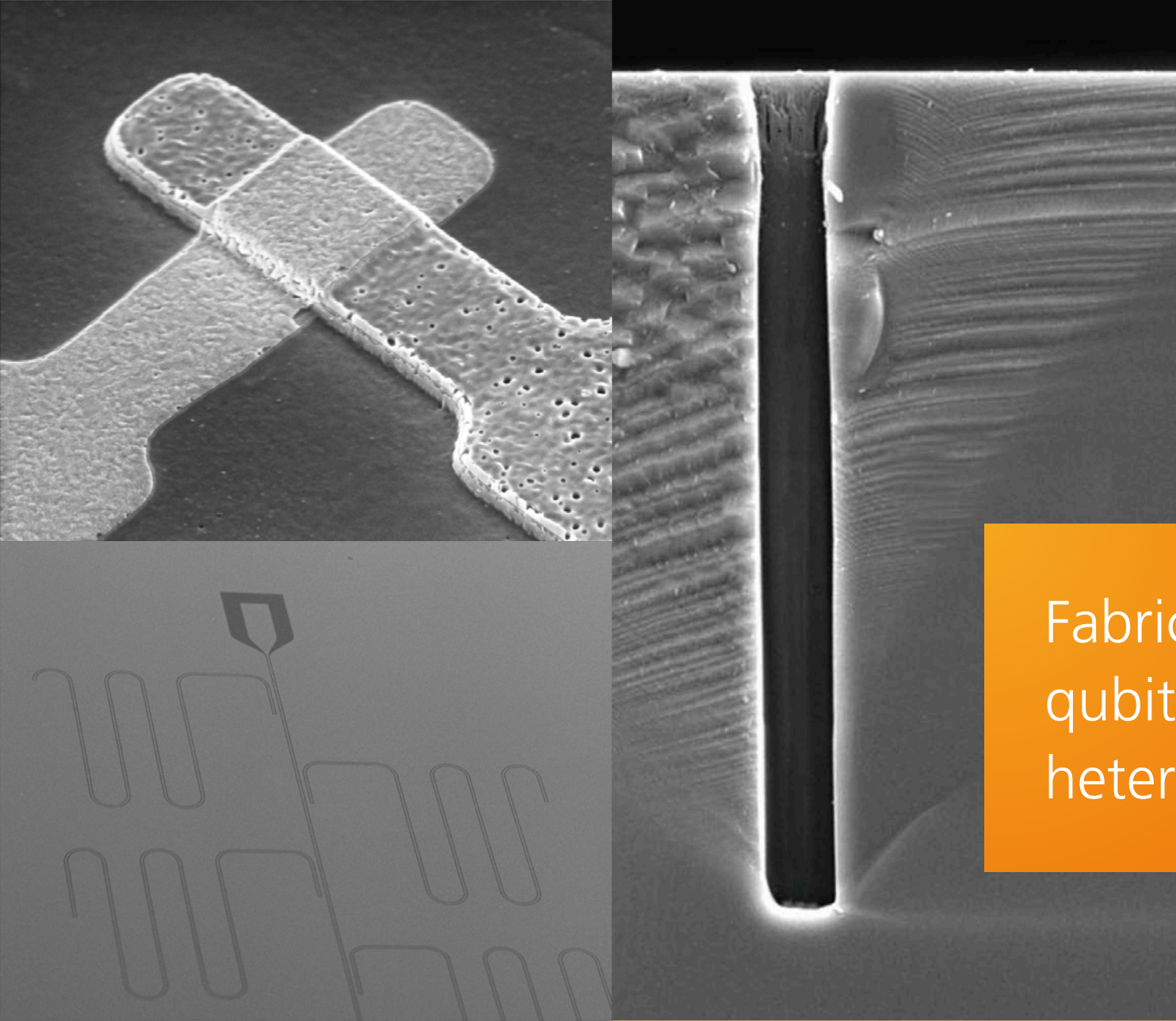
**Research Fab Microelectronics Germany (FMD)  
with extension module quantum and neuromorphic computing**



**We support research groups, start-ups and industry in the development of quantum and neuromorphic computing hardware with customized solutions from microelectronics, nanotechnology, optics and photonics.**



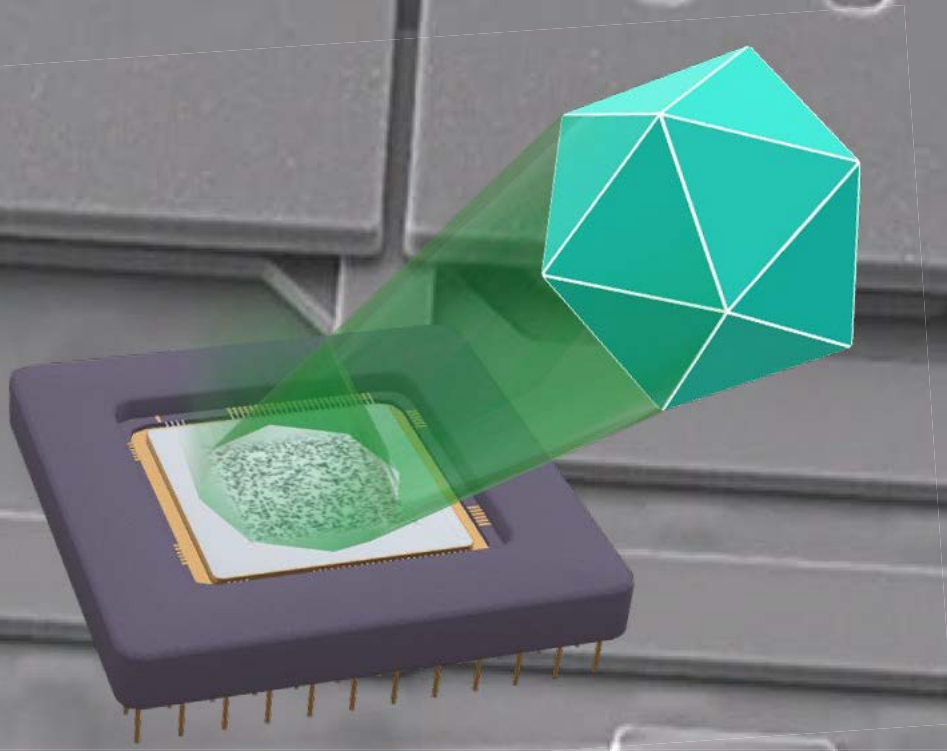





## Fabrication of superconducting qubit chips, frontend & 3D heterointegration technologies

tilt\_45°

Micromirror array allowing fast modulation of UV light in phase and intensity with high spatial resolution to address neutral atoms



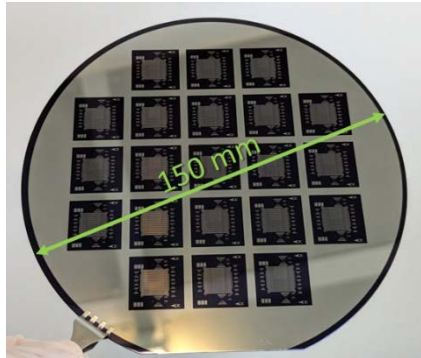


Multi-channel FPGA-based dynamical control for optical modulators (Acoustic Optical Modulators AMOs and Electro Optical Modulators EOMs)



# Novel memristor devices based on 2D-materials

AMO GmbH



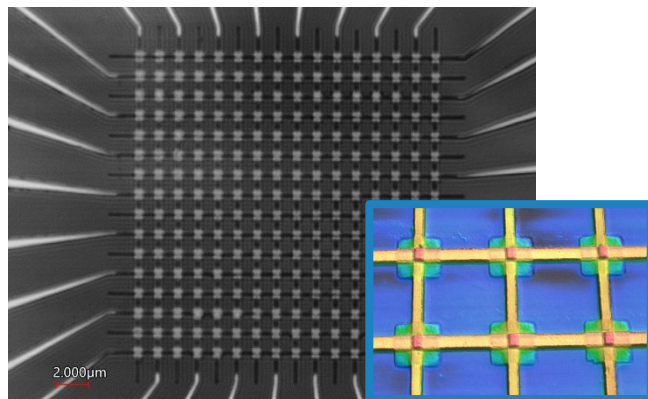
150 mm wafer with memristive devices

**Experimental pilot line for R&D and for prototype development up to small series production**

**Process technology of 2D-material memristor arrays on 150 mm wafers:**

- Metallization of bottom electrodes
- Transfer and structuring of 2D-materials on wafer-scale level (MoS<sub>2</sub>, h-BN and more)
- Metallization of top electrodes

AMO actively participates in [NeuroSys](#) and [NEUROTEC](#), two major initiatives funded by the German Federal Ministry of Education and Research (BMBF) that aim to establish a viable technology base for future European neuromorphic hardware for AI application



Microscope images of fabricated nanoscaled crossbar arrays







Forschungsfabrik  
Mikroelektronik  
Deutschland

Thank you!



# Gemeinsam disruptiv – Photonische Quantentechnologie und Neuromorphes Computing

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Prof. Dr. Carsten Schuck, Department für Quantentechnologie, Universität Münster

»QNC Summit« 06.03.2025

# Schuck-Group @ University of Münster



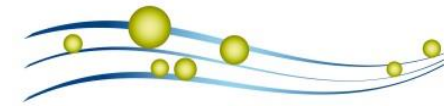
Ministry of Culture and Science  
of the State of  
North Rhine-Westphalia



Funded by

**DFG** Deutsche  
Forschungsgemeinschaft  
German Research Foundation

Funded by  
the European Union



Center for Soft Nanoscience



Bundesministerium  
für Bildung  
und Forschung

**MÜNSTER  
NANOFABRICATION  
FACILITY**



**CeNTech**  
CENTER FOR NANOTECHNOLOGY

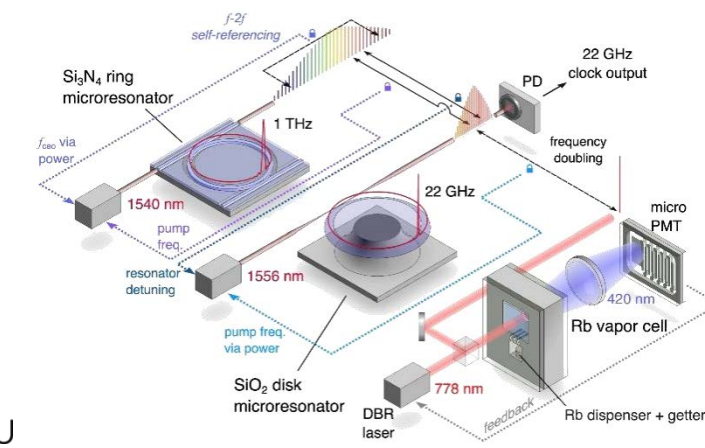
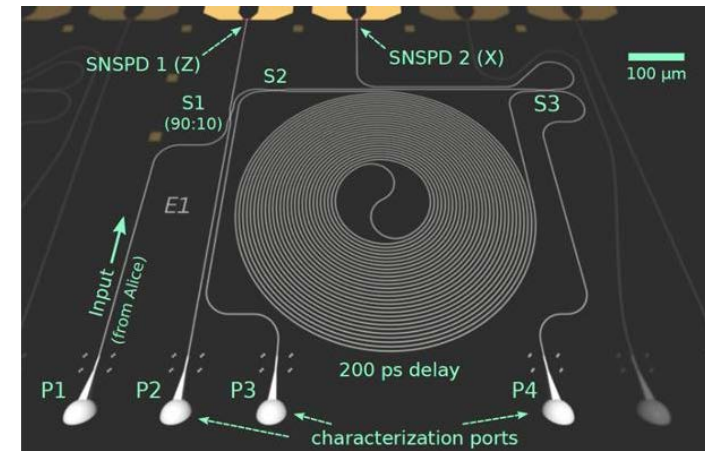
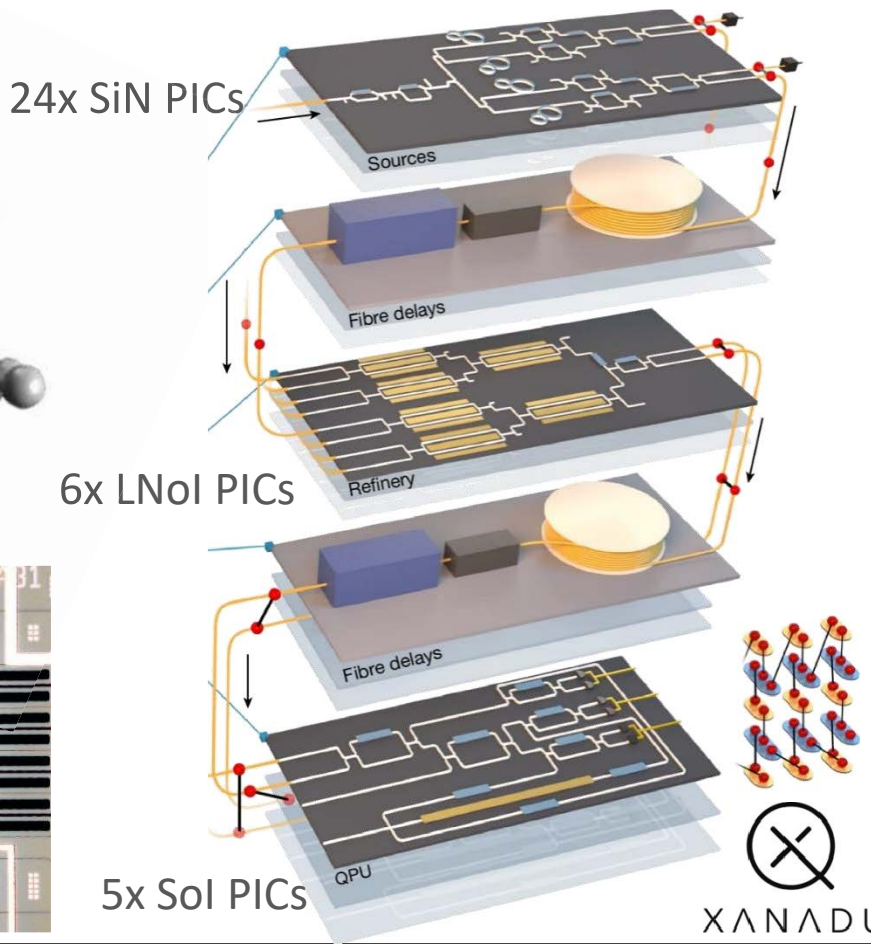
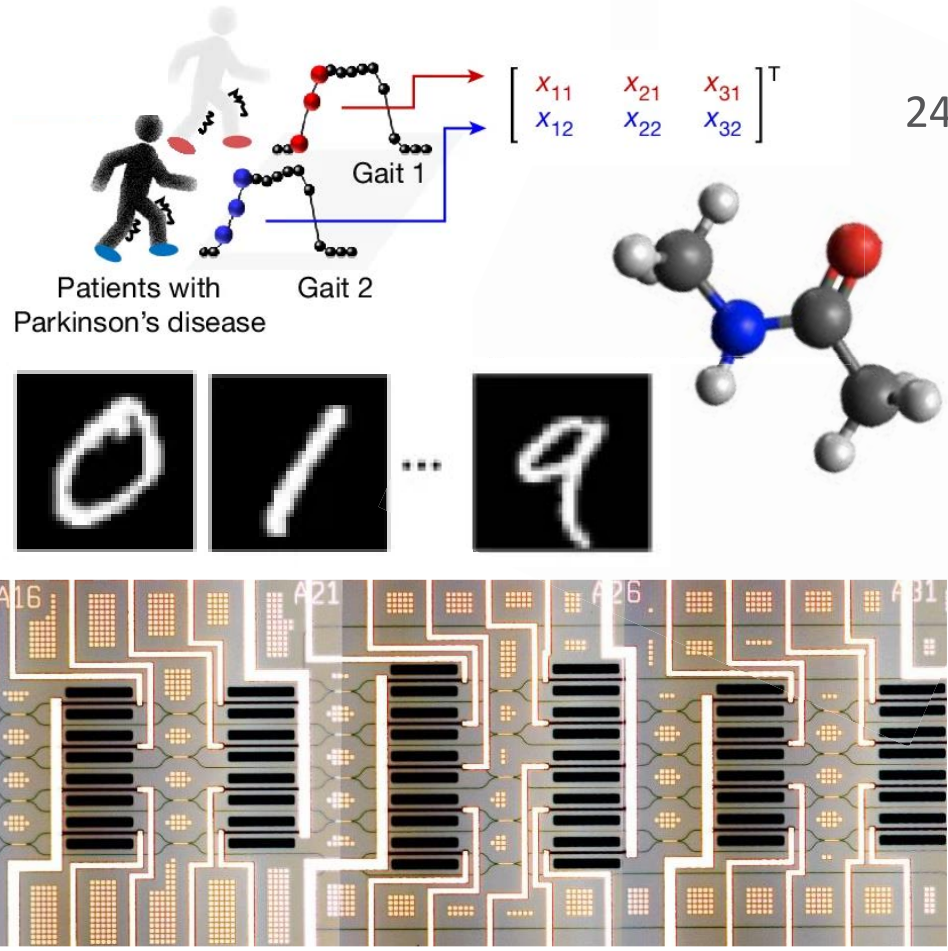
# Core Science Facilities @ University of Münster



Center for NanoTechnology (CeNTech)

Center for Soft Nanoscience (SoN)

# Neuromorphic Computing & Quantum Technology

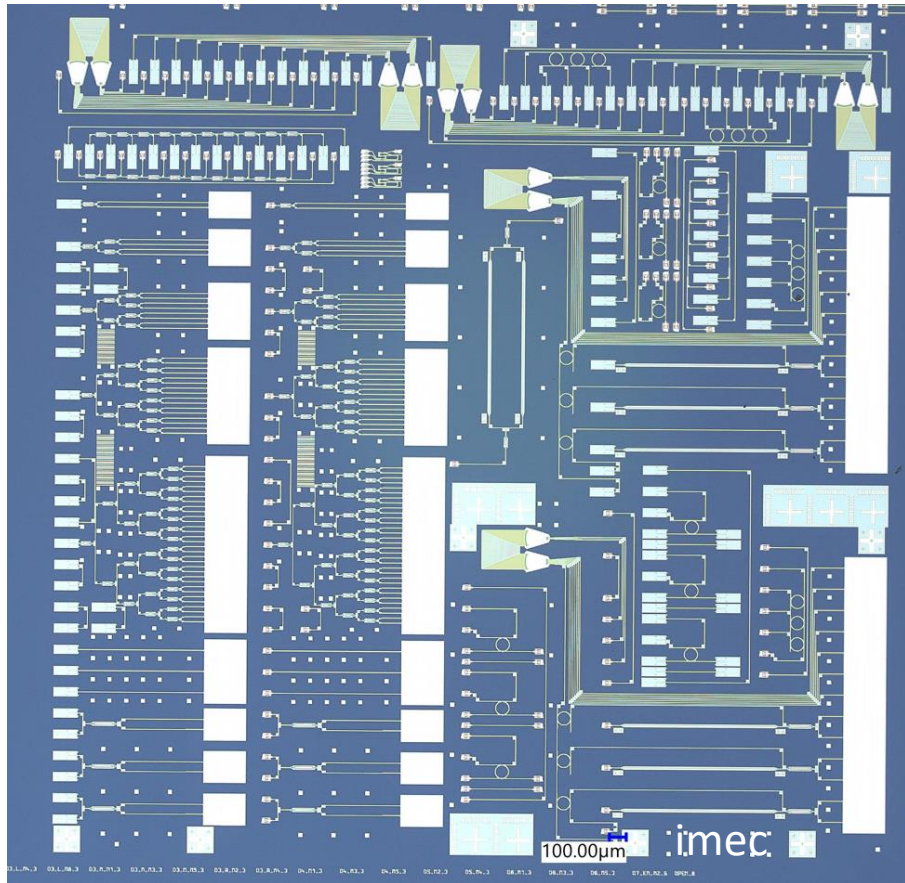


H. Zhang et al. Nat. Commun 12, 457 (2021)  
 B. Dong et al. Nature 632, 55 (2024)

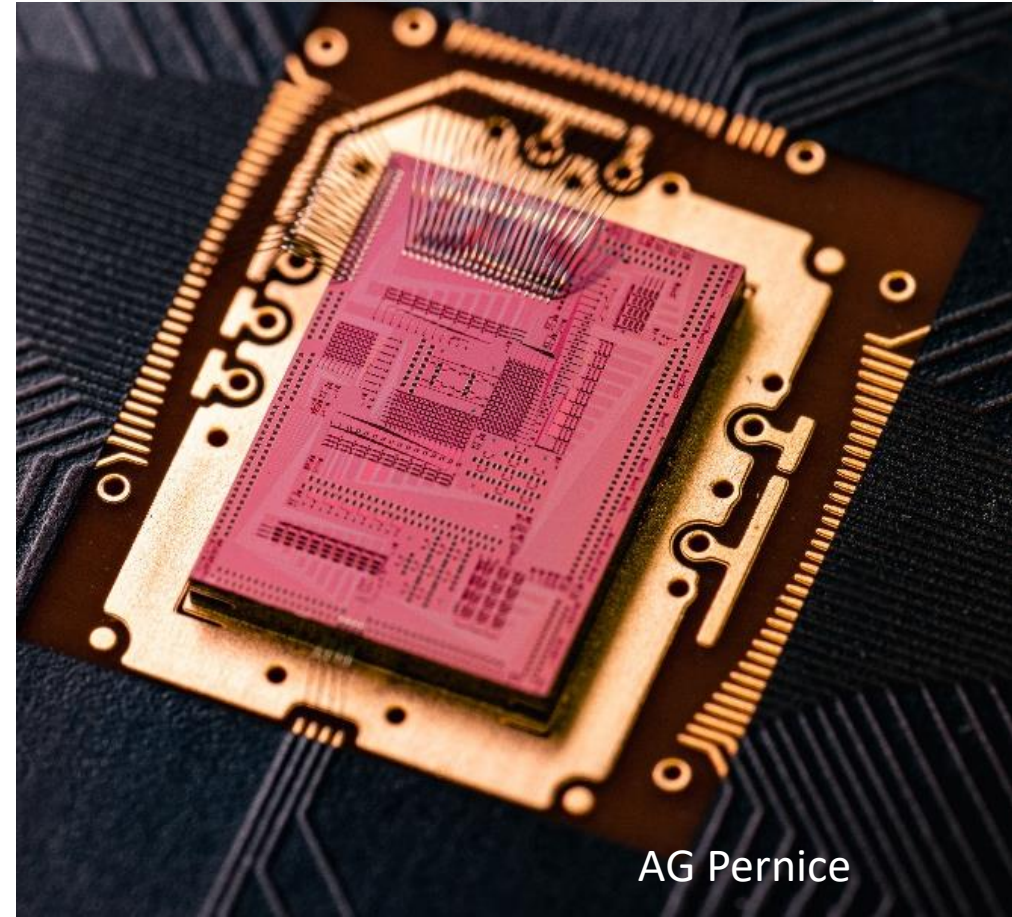
H. Aghaee Rad et al. Nature 638, 912 (2025)

F. Beutel et al., npj QI 7, 40 (2021)  
 Z. L. Newman et al. Optica 6, 680 (2019)

# Quantum Technology



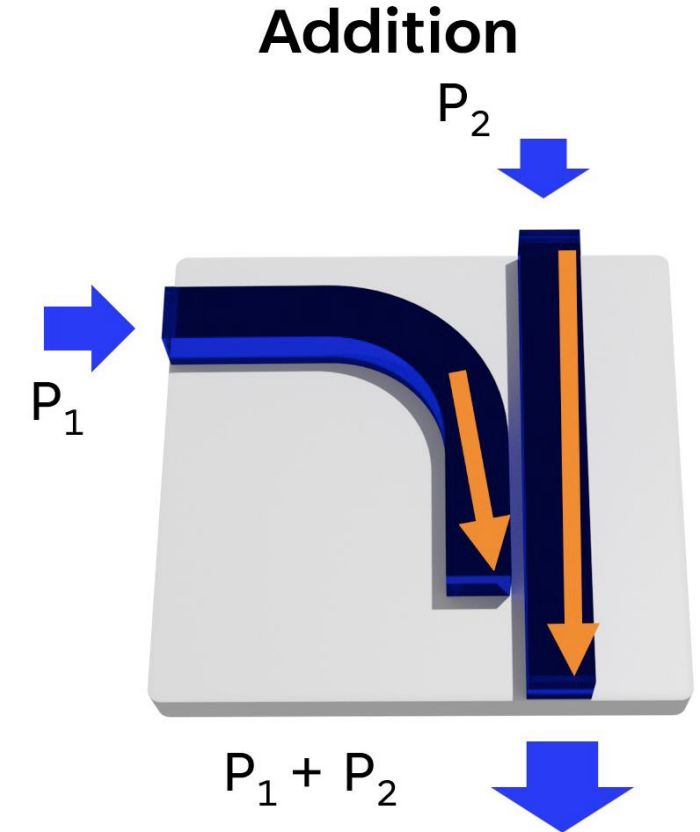
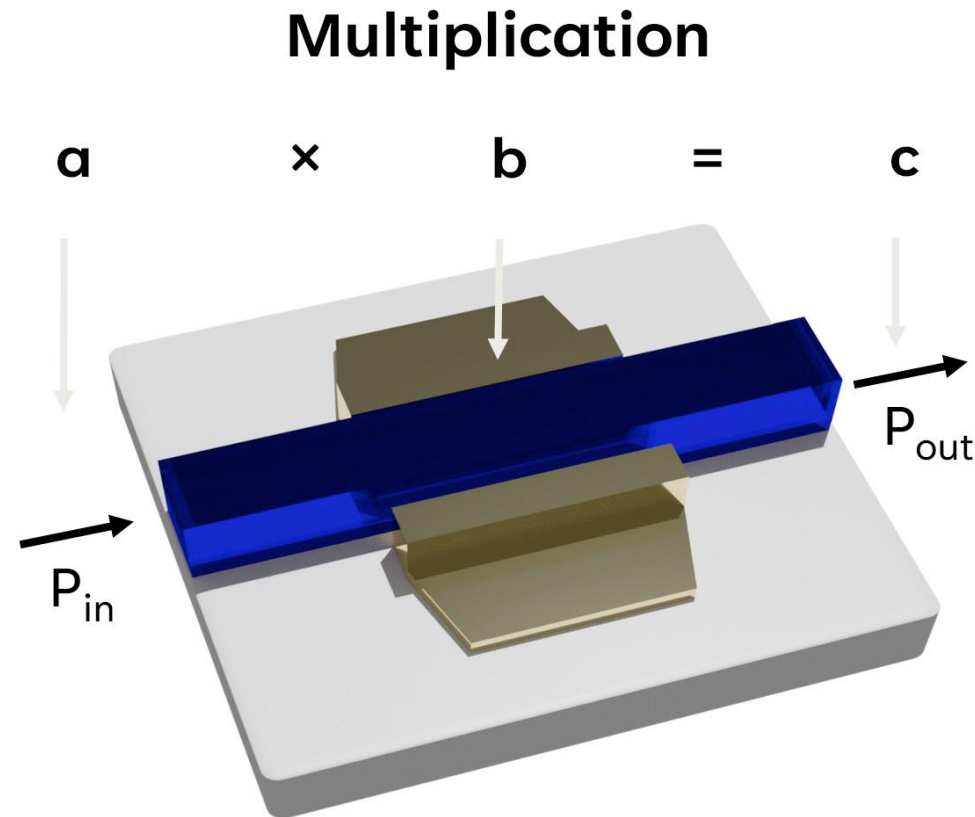
# Neuromorphic Computing





# Physical computing using photonic integrated circuits

- Model basic arithmetic with photonic building blocks
- Multiplication and addition represented with waveguides



# Photonic Crossbar Array for Matrix Vector Multiplication

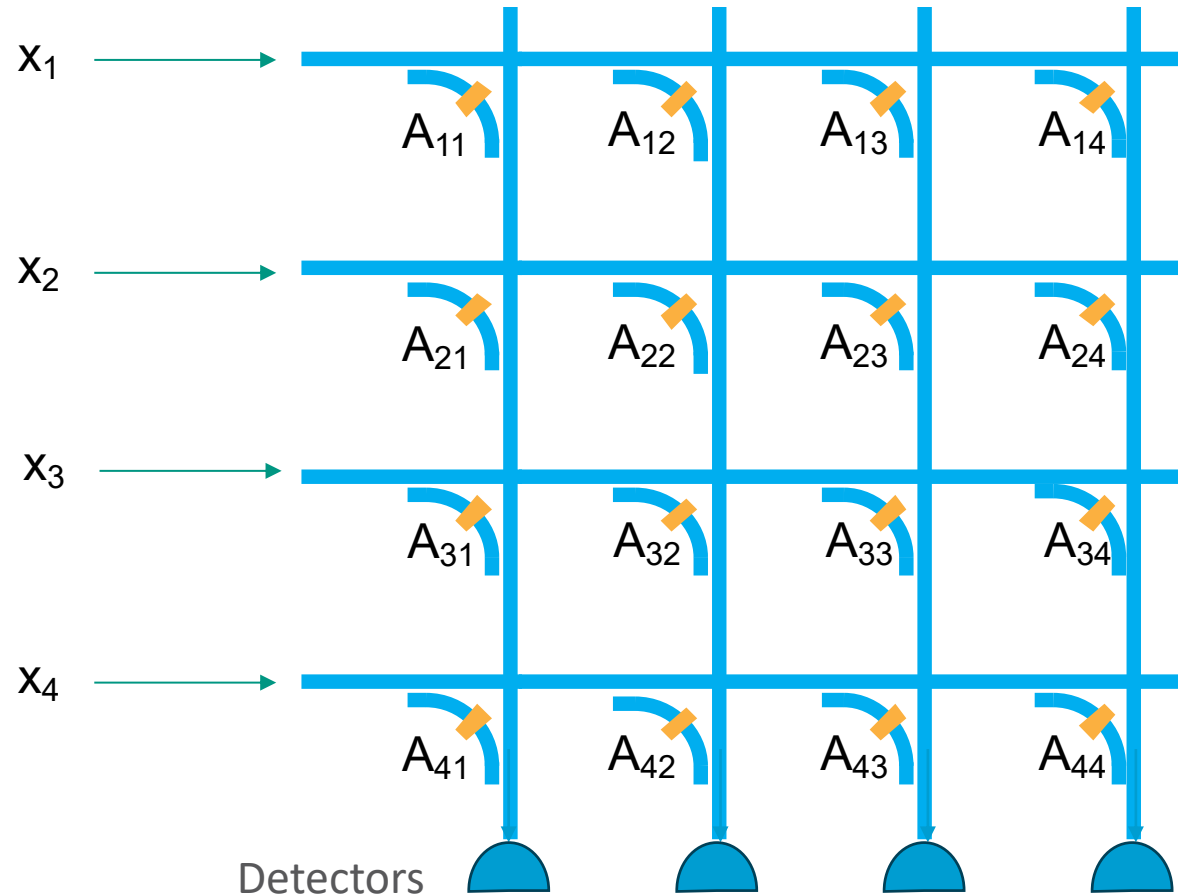
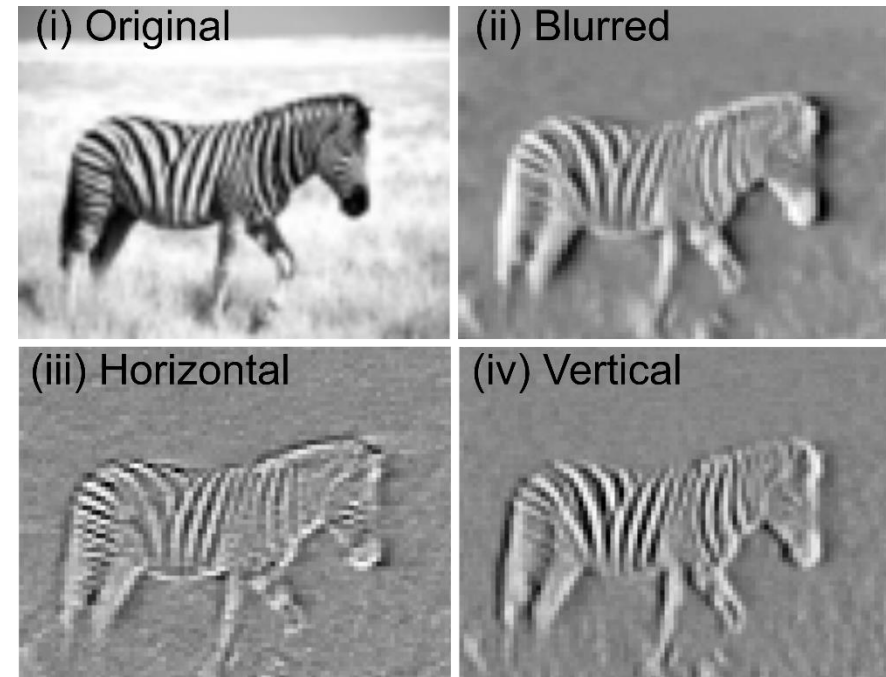


Image processing using PICs



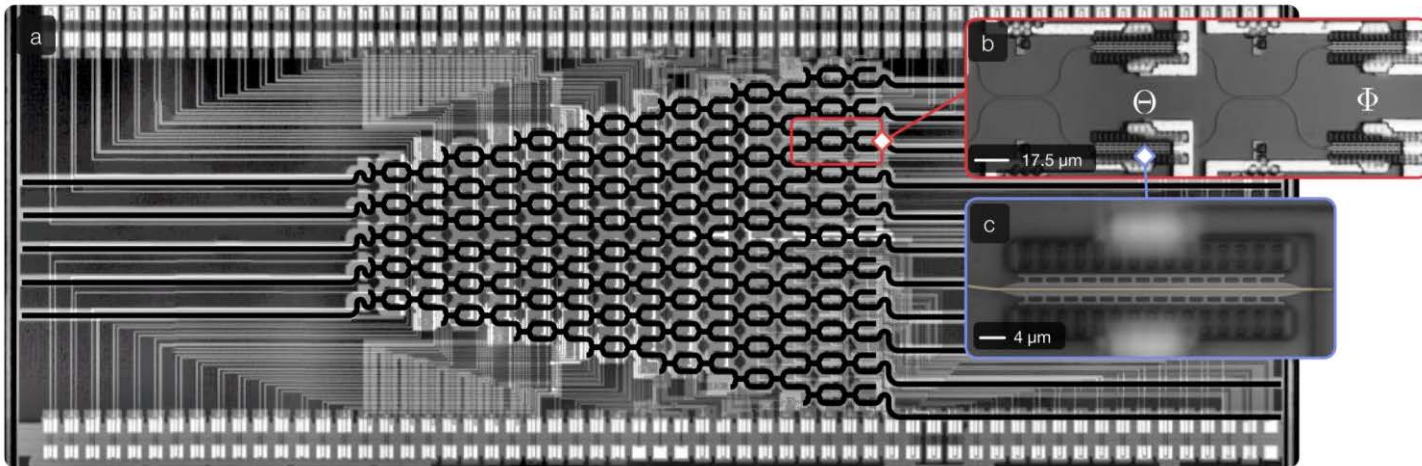
Hardware accelerators for machine learning

J. Feldmann et al. Nature 589, 52 (2021)

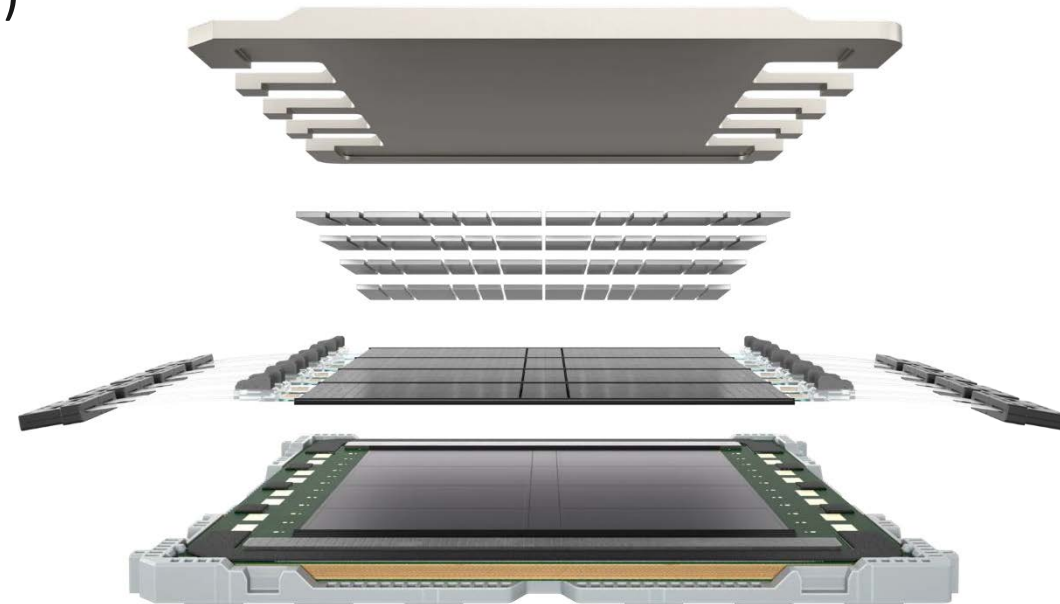
Pernice-Group (Münster, Heidelberg)

# Value creation in Quantum & Neuromorphic Computing

- academic chips produced in OPSIS foundry (2015)
- Lightmatter founded in 2017, series A in 2018 (\$11 million)
- October 2024: \$400 million Series D funding  
→ \$4.4 billion evaluation

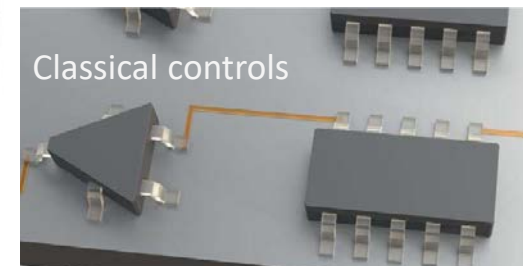
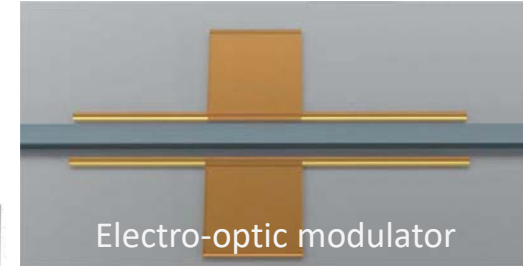
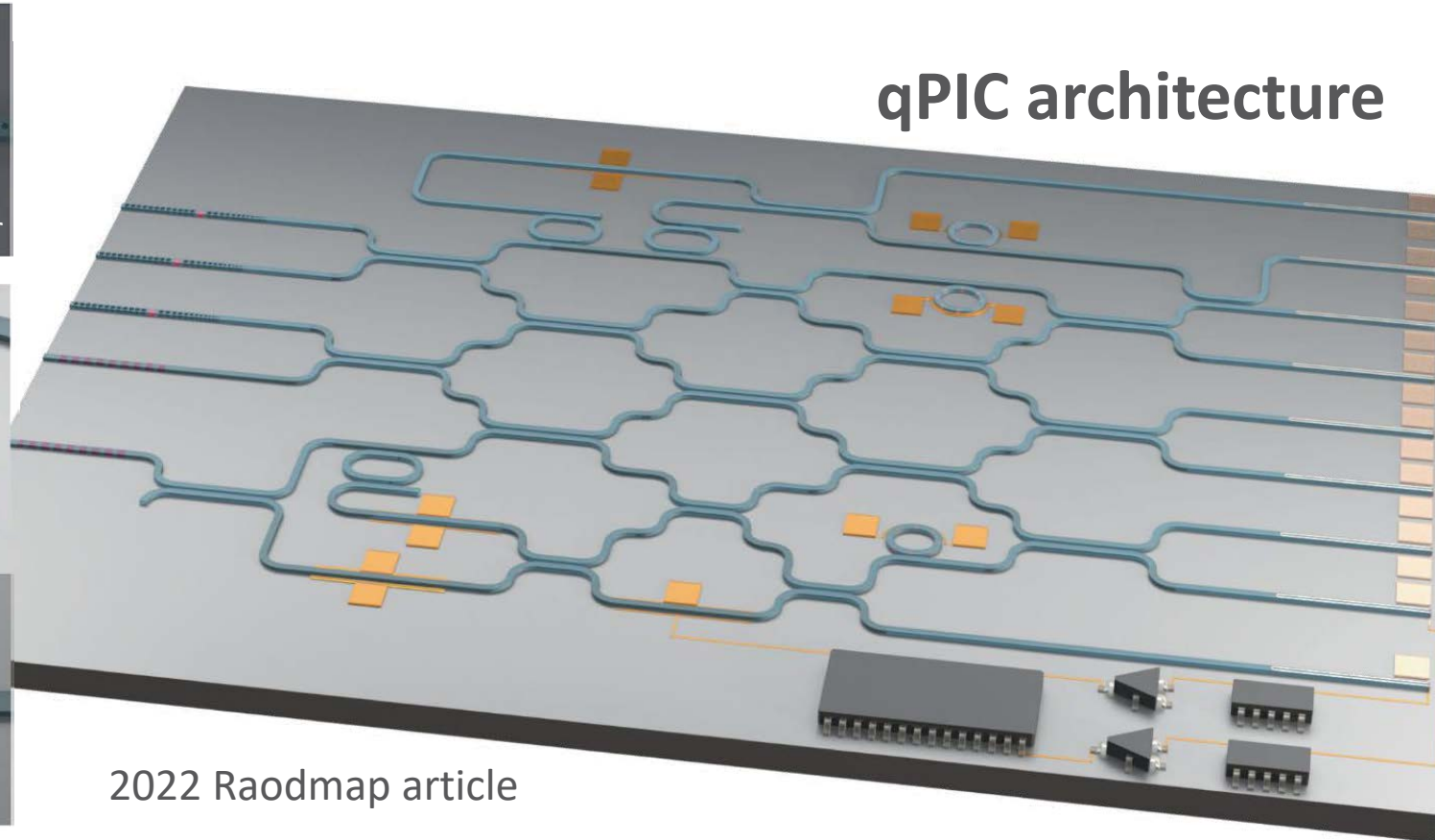
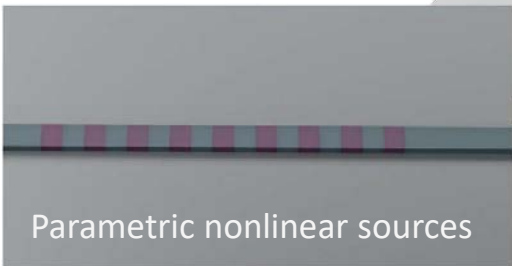
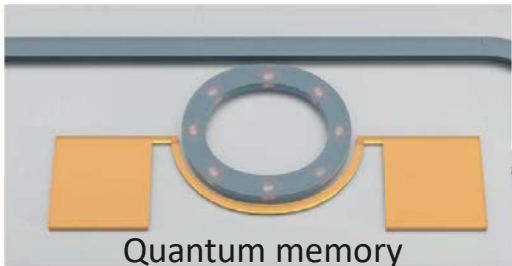
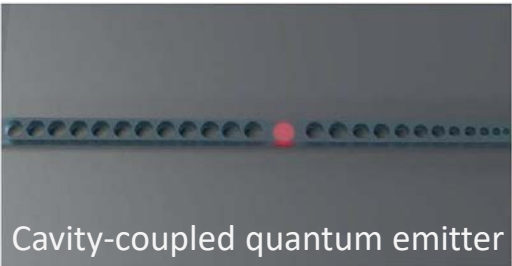


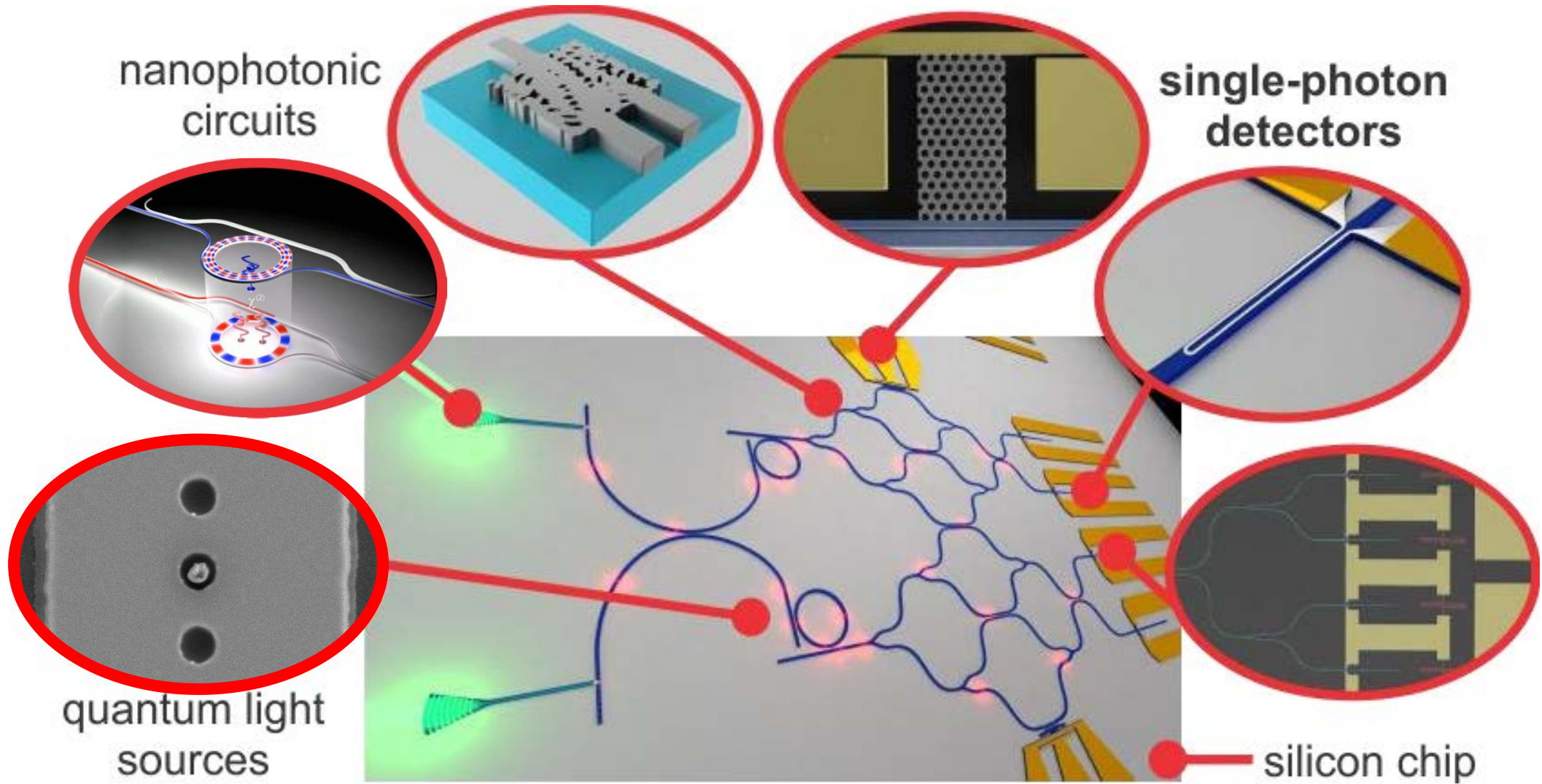
N. C. Harris et al. Quantum transport simulations in a programmable nanophotonic processor. Nature Photon 11, 447 (2017)



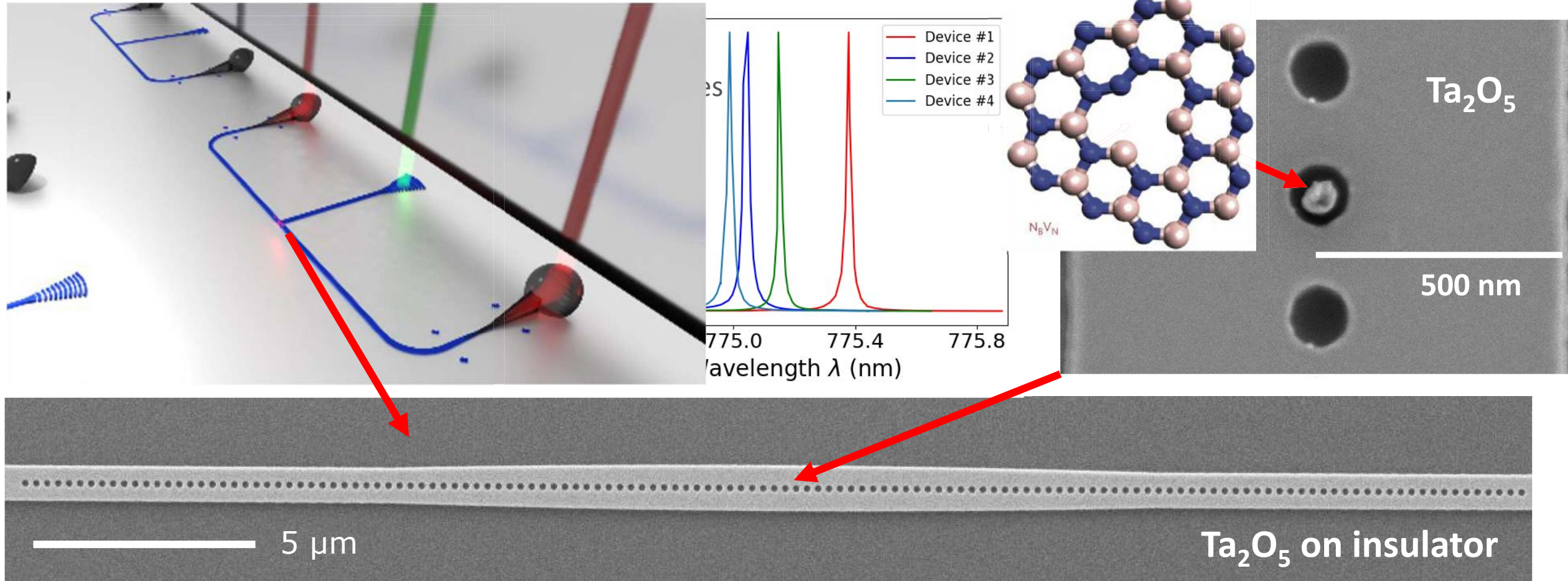
 LIGHTMATTER

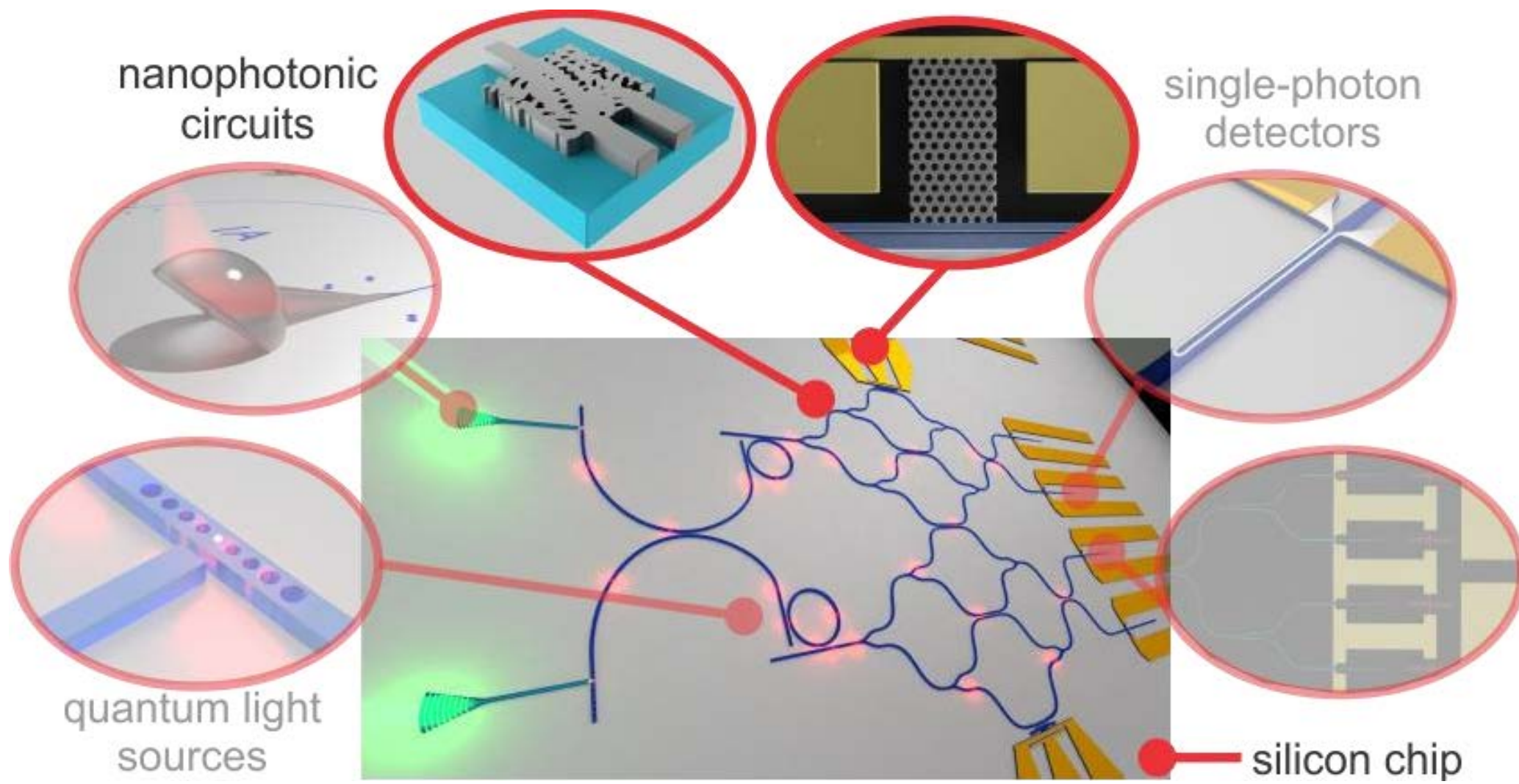
# Integrated photonics for quantum technologies





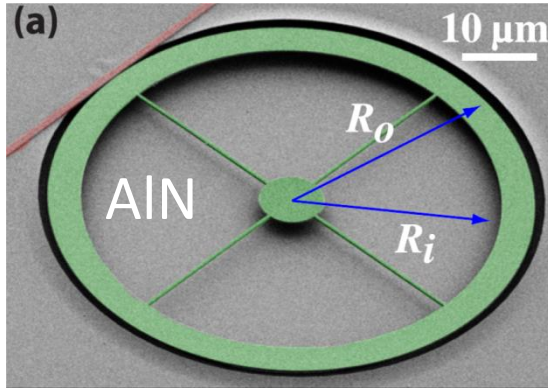
# Optical interfaces to quantum emitters



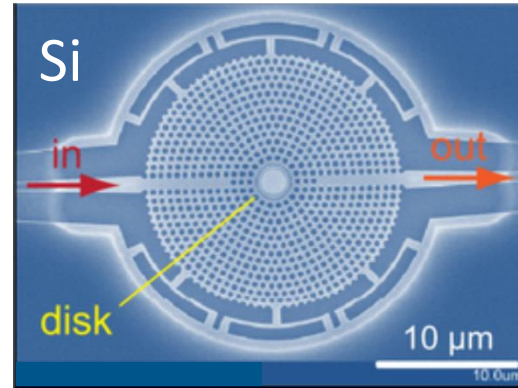


# Nanophotonic circuit components

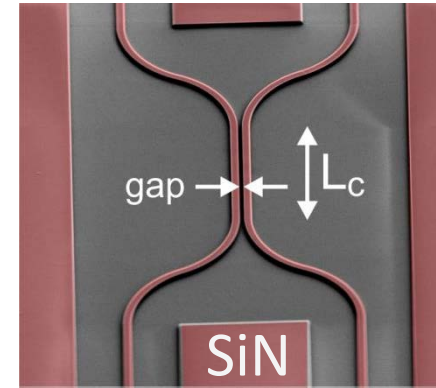
Optomechanical resonator



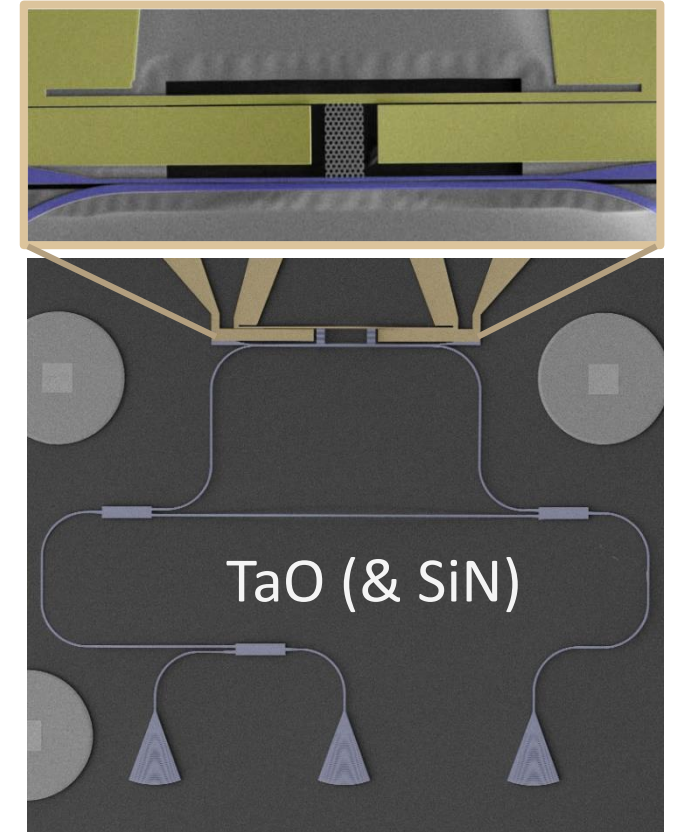
High-Q sunflower cavity



Directional coupler



Electromechanical phase-shifter



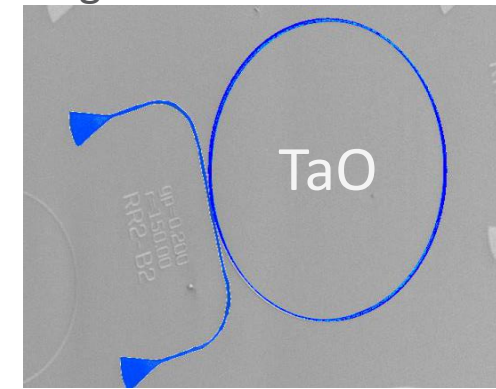
Interferometers



Photonic Crystals



Ring Resonators

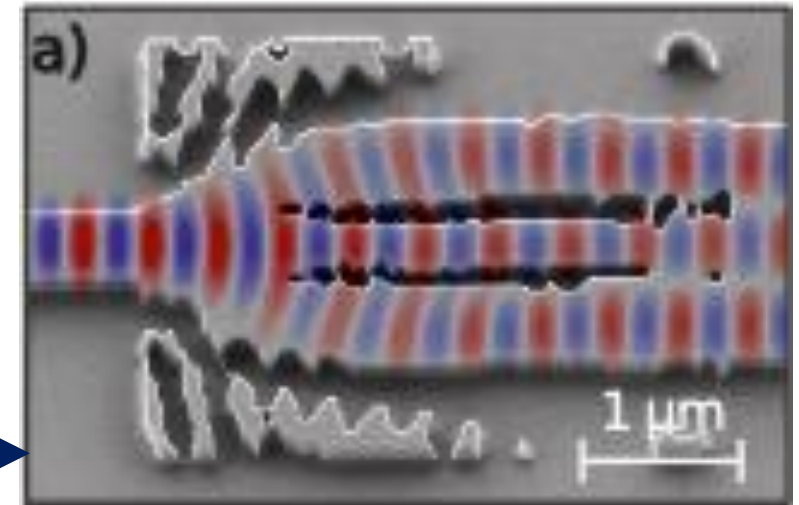
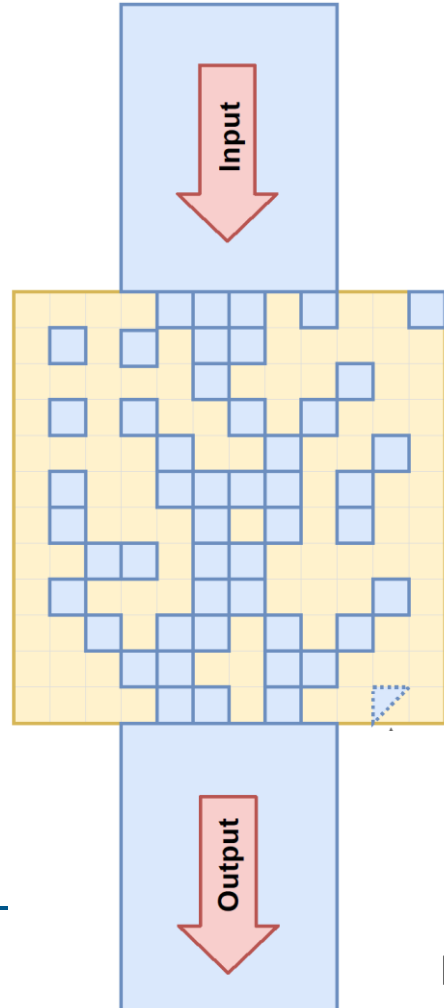




# Inverse nanophotonic design

## Inverse design:

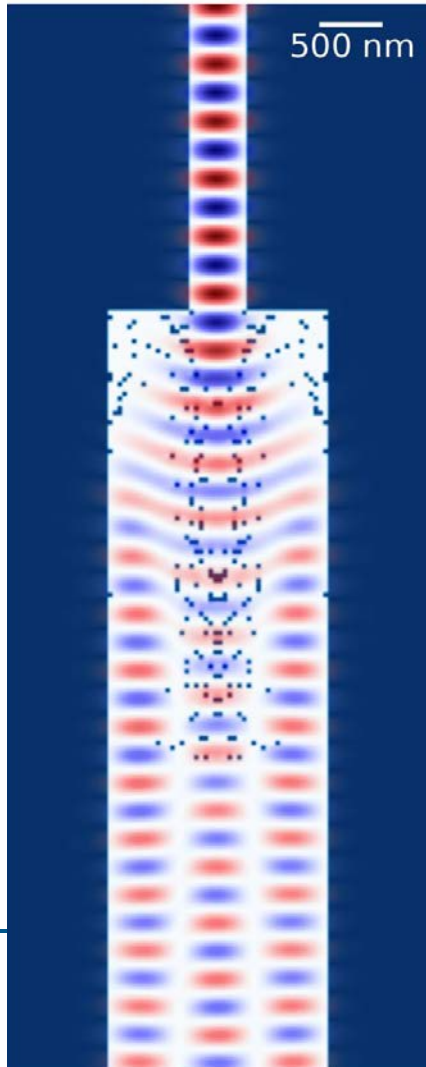
- Specify input
- Specify desired output
- Calculate pixel-discrete layout that achieves desired functionality
  - Convex Optimization
  - Reinforcement Learning
  - Template networks



Molesky et al. Nature Photonics 12, 659 (2018)

Butz et al. OPEX **31**, 15747 (2023)  
Schulte et al., JOSA B **41**, 1039 (2024)

# Reinforcement Learning-based inverse design



Pixel size:  
40 nm

200 nm SOI

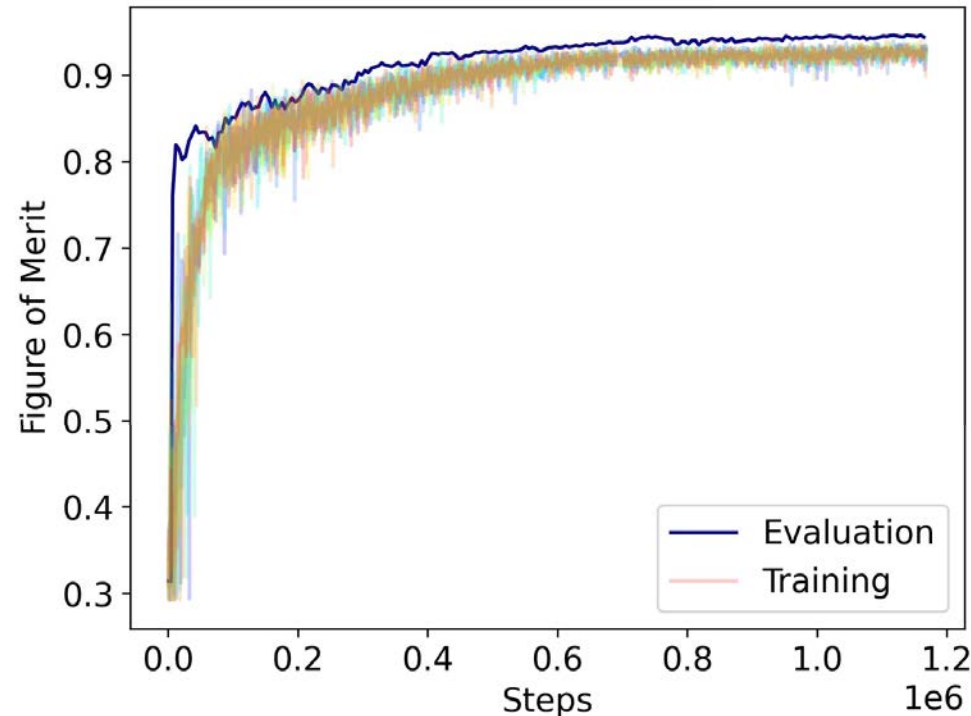
94 x 46 pixels

4324  
Degrees of  
Freedom

Carsten Schuck

## TE<sub>00</sub> → TE<sub>20</sub> Mode Converter ( $\lambda = 1550$ nm)

- Strong & reproducible learning behavior!
- >90% (>80%) mode conversion efficiency for SOI (SiNOI)



95.1 % TE<sub>20</sub> (-0.22 dB)

0.0 % TE<sub>10</sub> (D<sub>3</sub>: symmetry)

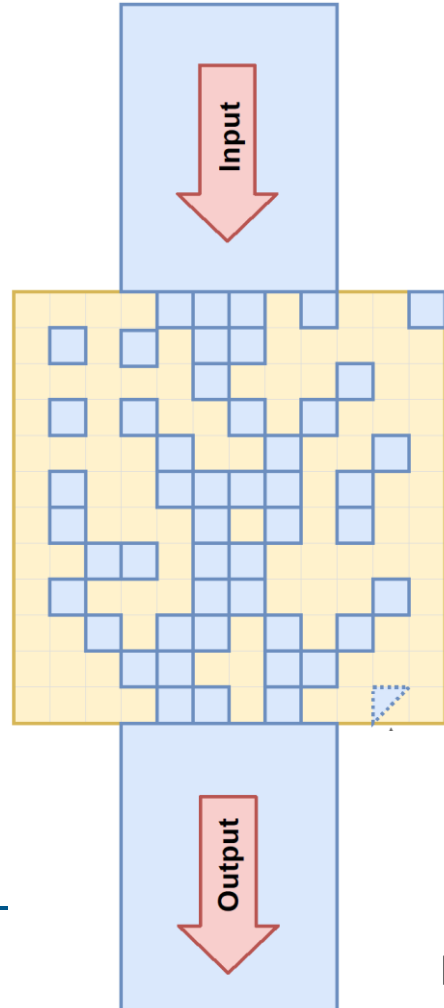
0.4 % TE<sub>00</sub> (-24 dB)

3.76  $\mu\text{m}$

×

1.84  $\mu\text{m}$

# Inverse nanophotonic design

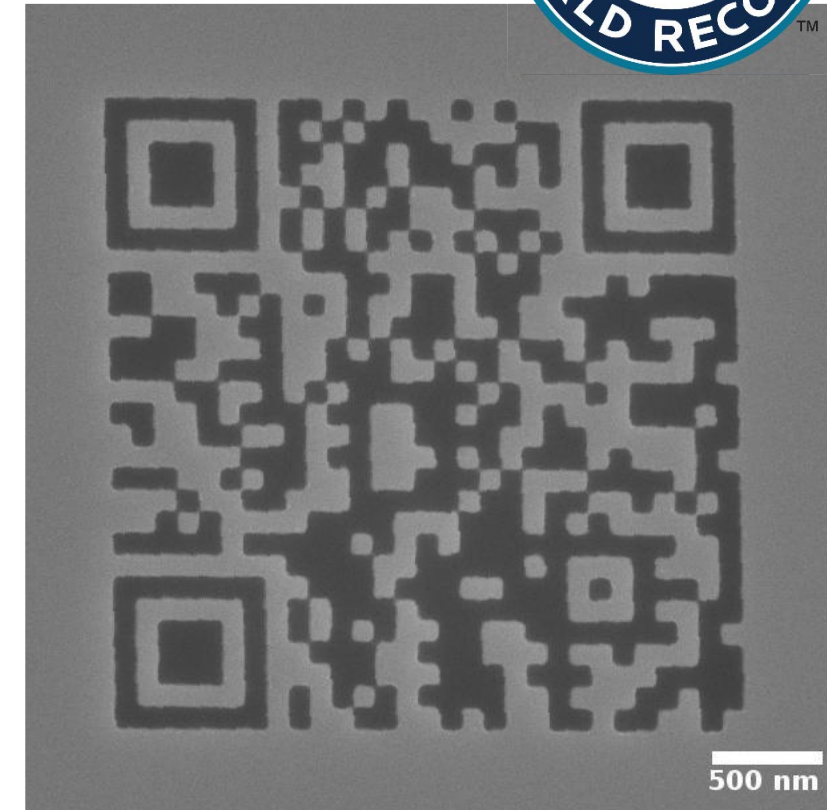


## Inverse design:

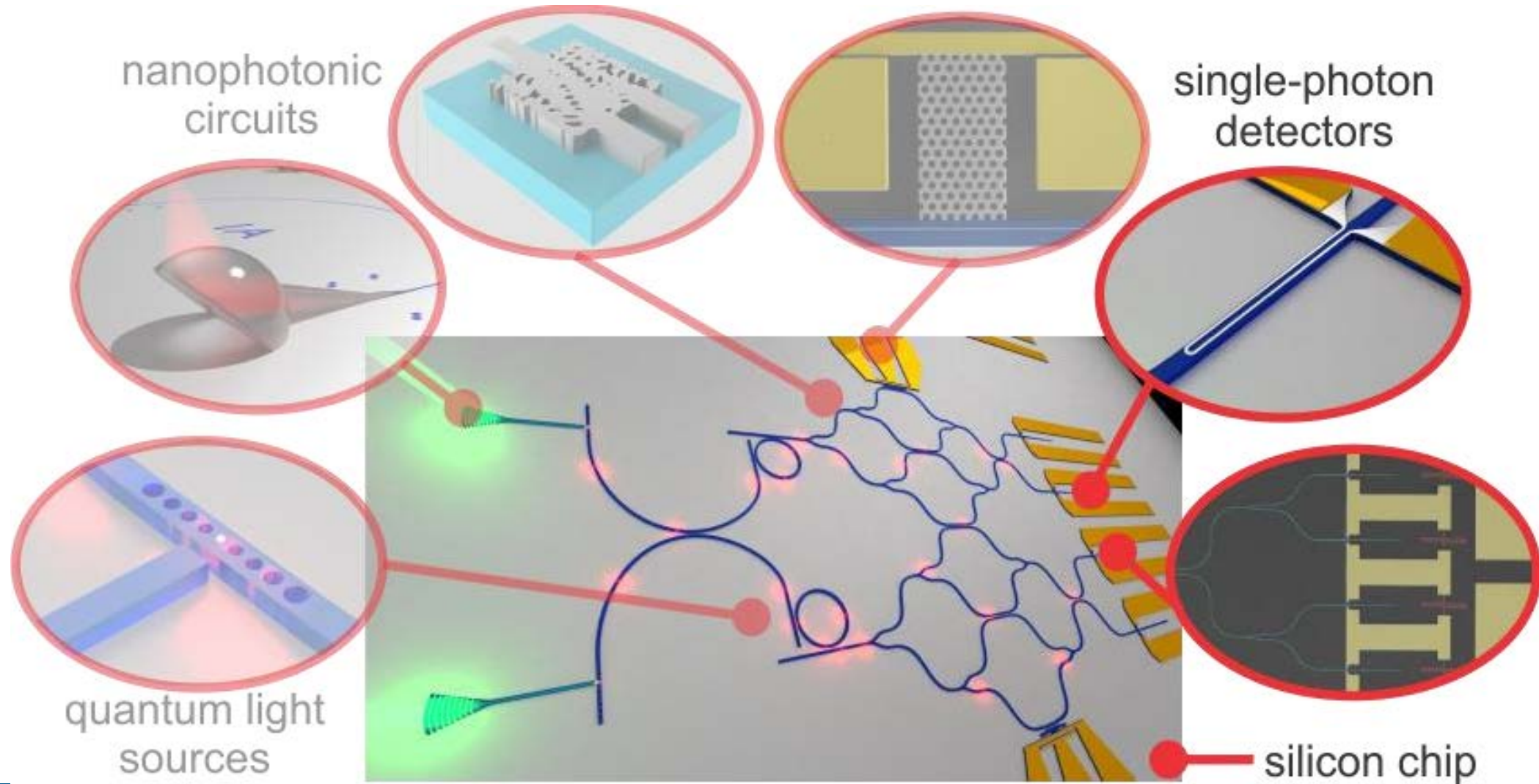
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Molesky et al. Nature Photonics 12, 659 (2018)

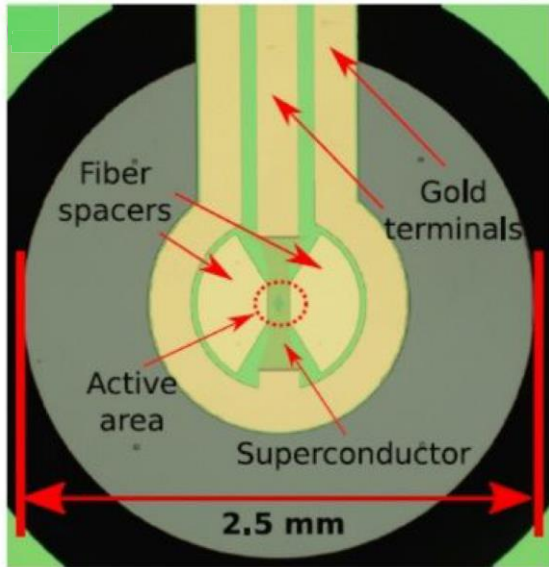
5.38 $\mu\text{m}^2$  QR Code



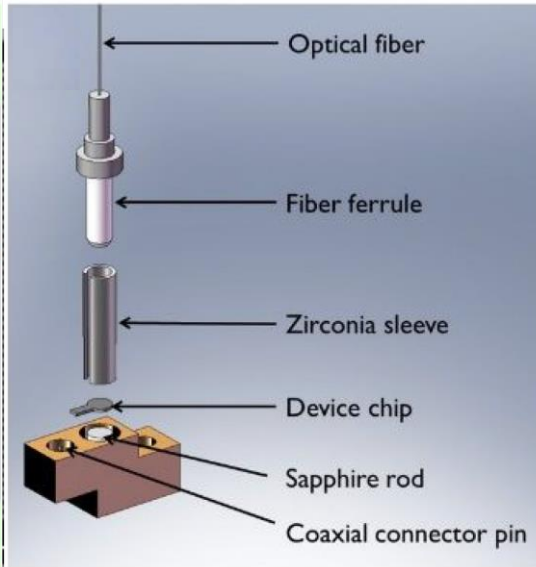
Butz et al. OPEX **31**, 15747 (2023)  
Schulte et al., JOSA B **41**, 1039 (2024)



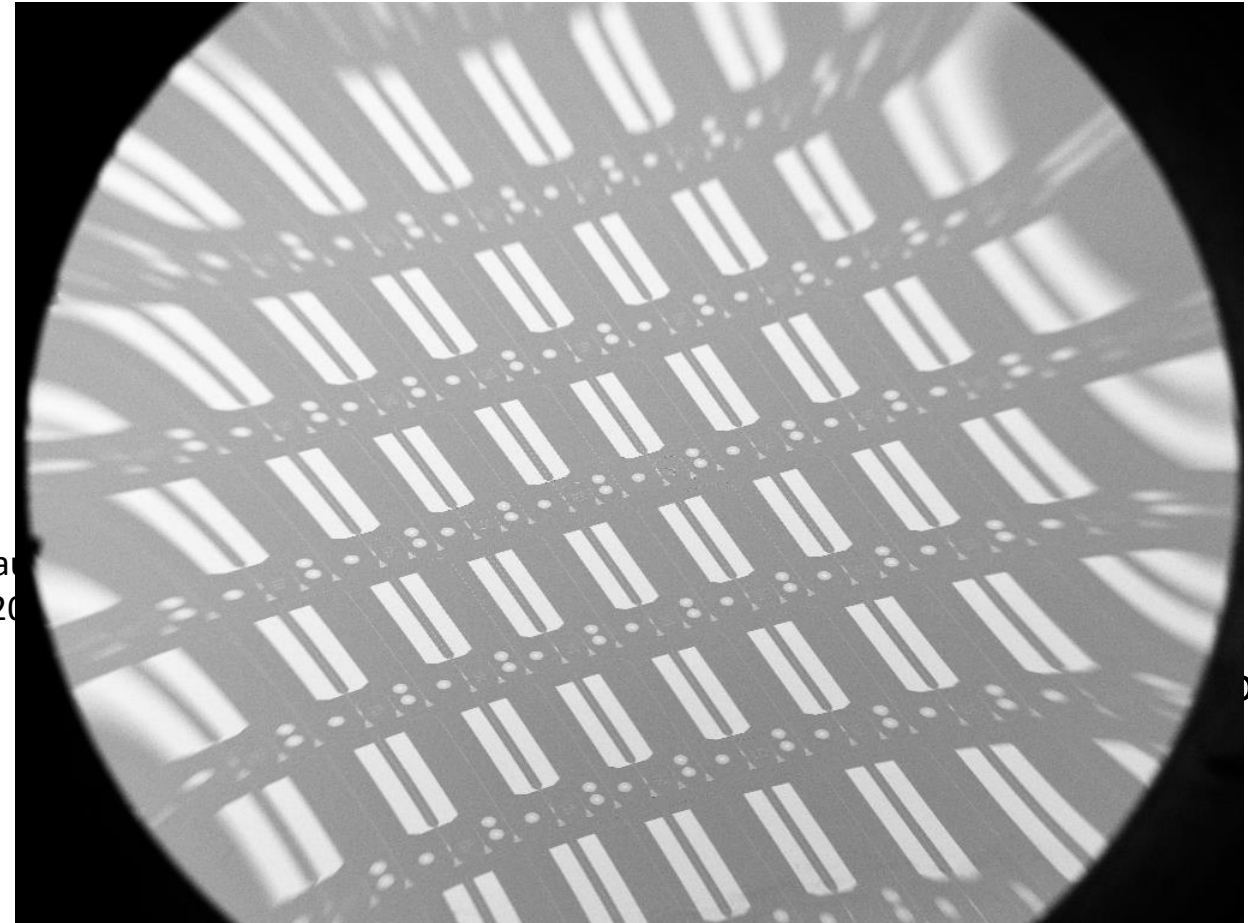
# Superconducting Nanowire Single-Photon Detectors



Reddy et al., *Optica* 7, 1649 (2020)



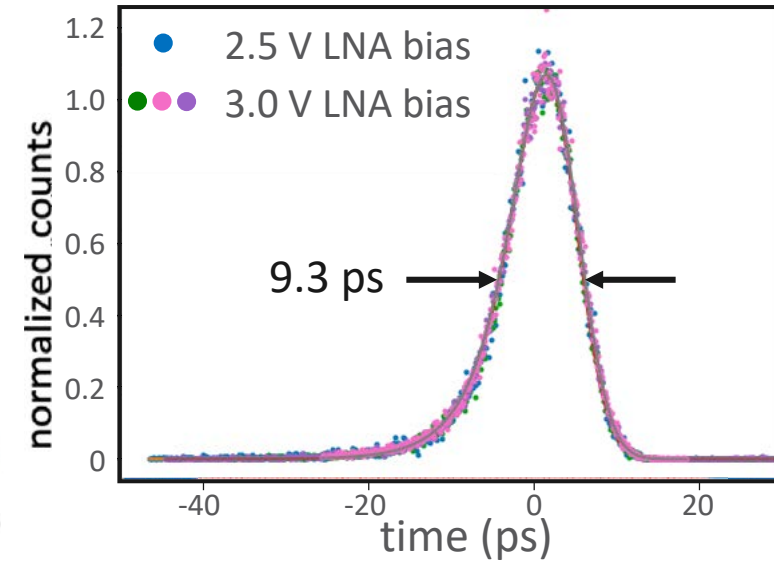
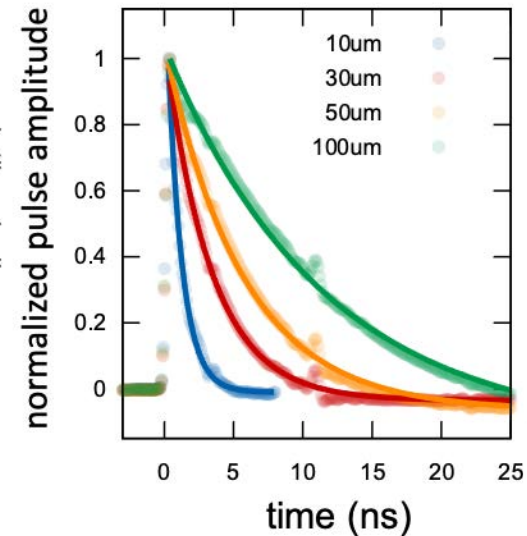
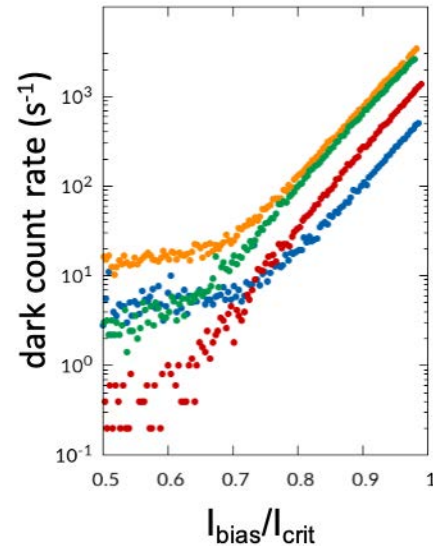
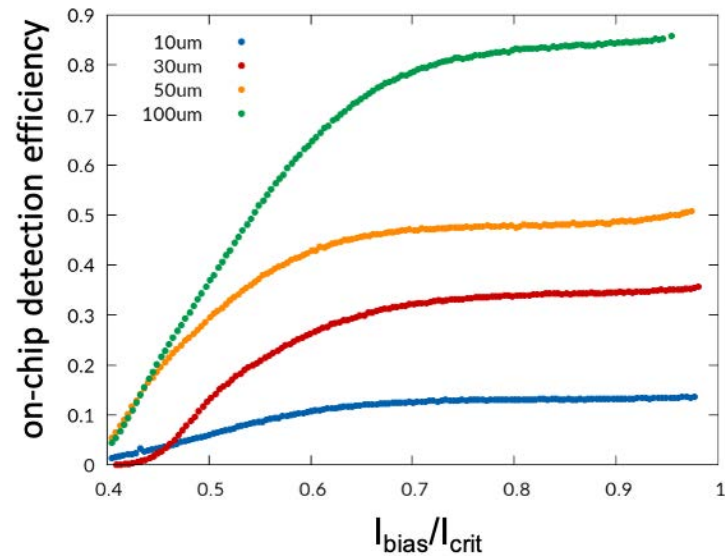
Opt. Eng. 53, 081907 (2014)



## Conventional SNSPDs:

- Nanowire meander (NbN, WSi)  
4nm thin, 100nm wide, >500um long
- Operate @  $T < T_c$  and  $I < I_c$
- Absorption under normal incidence

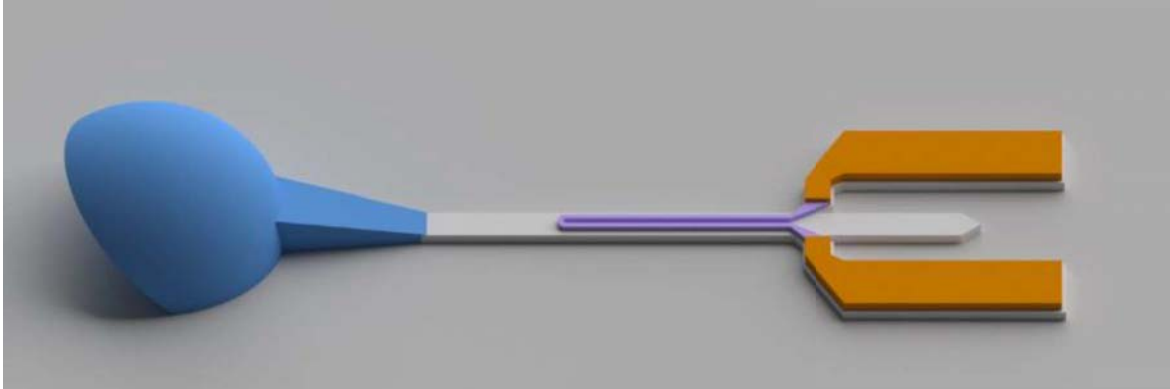
# NbTiN-SNSPDs on Ta<sub>2</sub>O<sub>5</sub>-waveguides



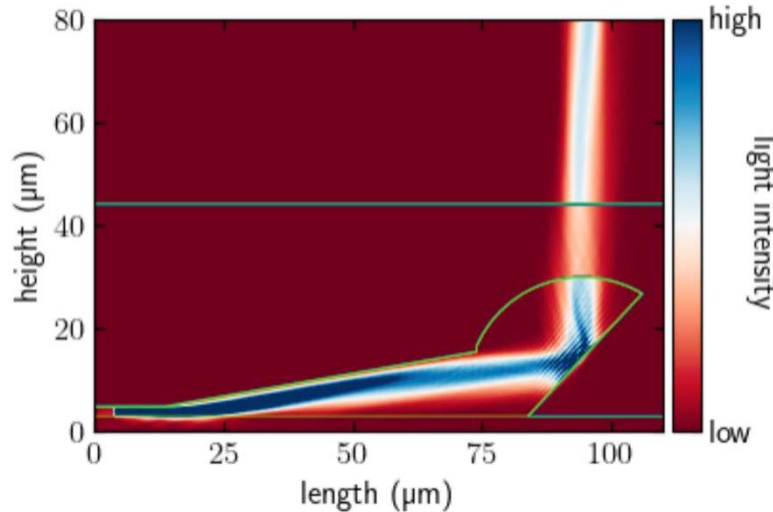
- >80% On-Chip Detection Efficiency
- Long saturation plateaus @ 1550 nm  
→ operate @ 10 Hz dark count rate

- sub-1 ns decay times
- sub-30 ps timing accuracy  
sub-10 ps (cryogenic LNAs)

# SNSPDs with high system detection efficiency

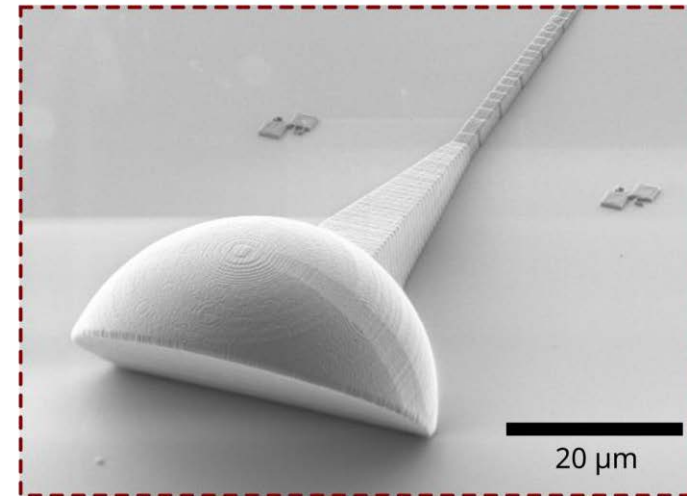


**Total Internal Reflection  
&  
Material absorption  
→ broad bandwidth**

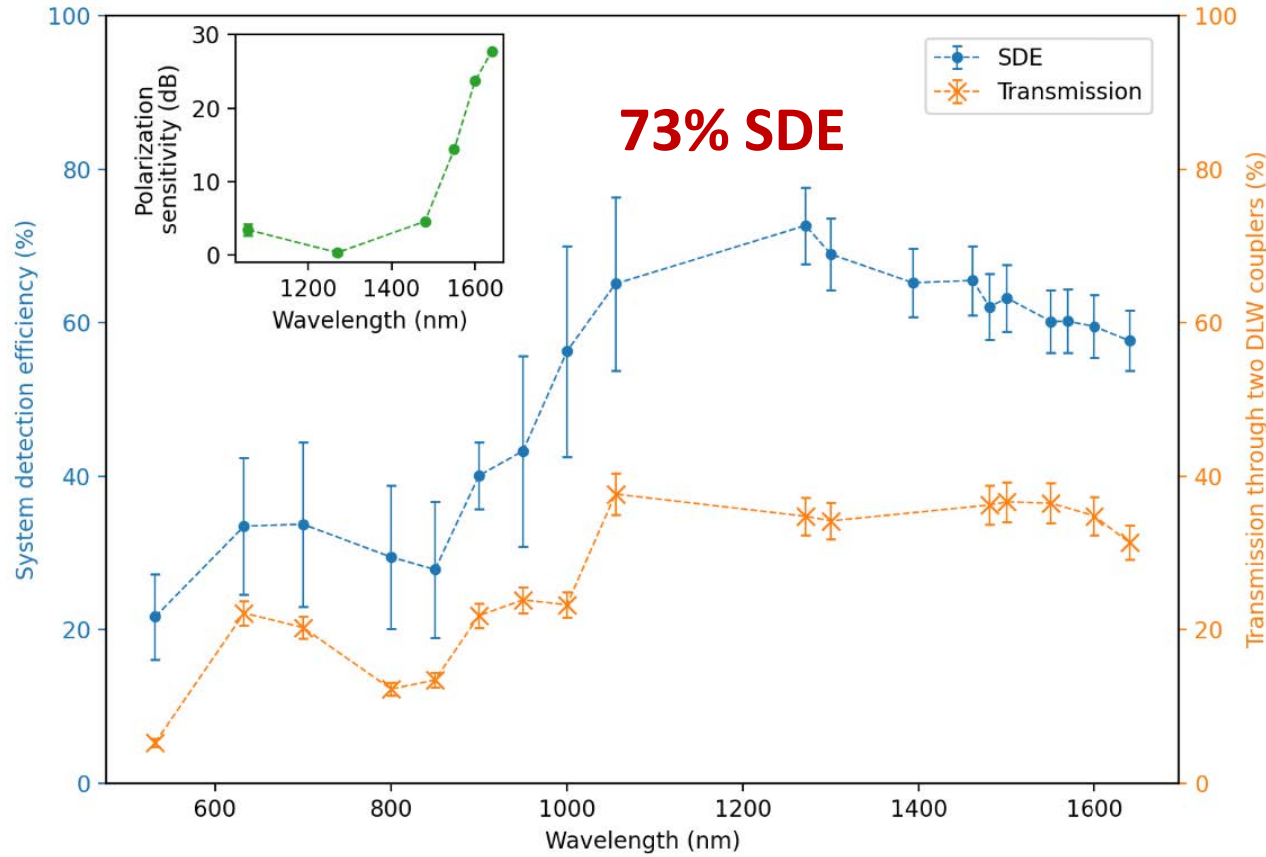


Coupling structures produced in 3D-direct laser writing.

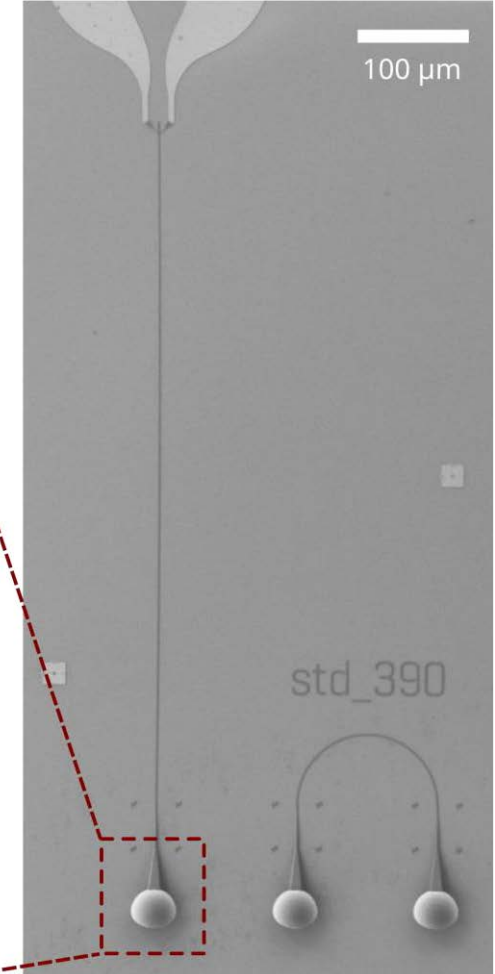
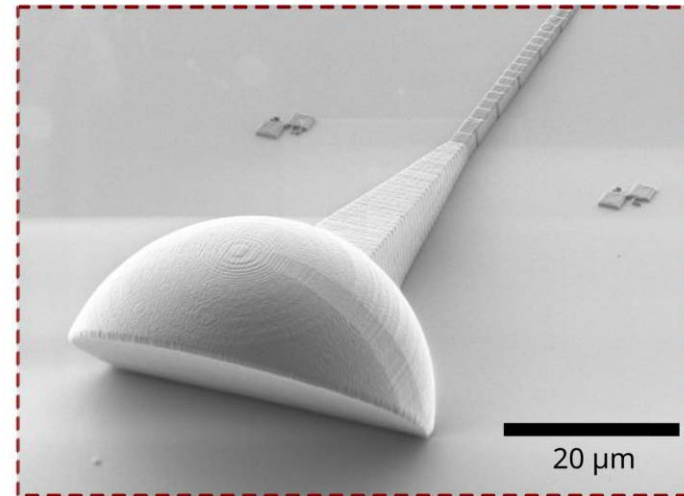
- Adiabatic mode-conversion
- total internal reflection
- Collimating lens



# SNSPDs with high system detection efficiency

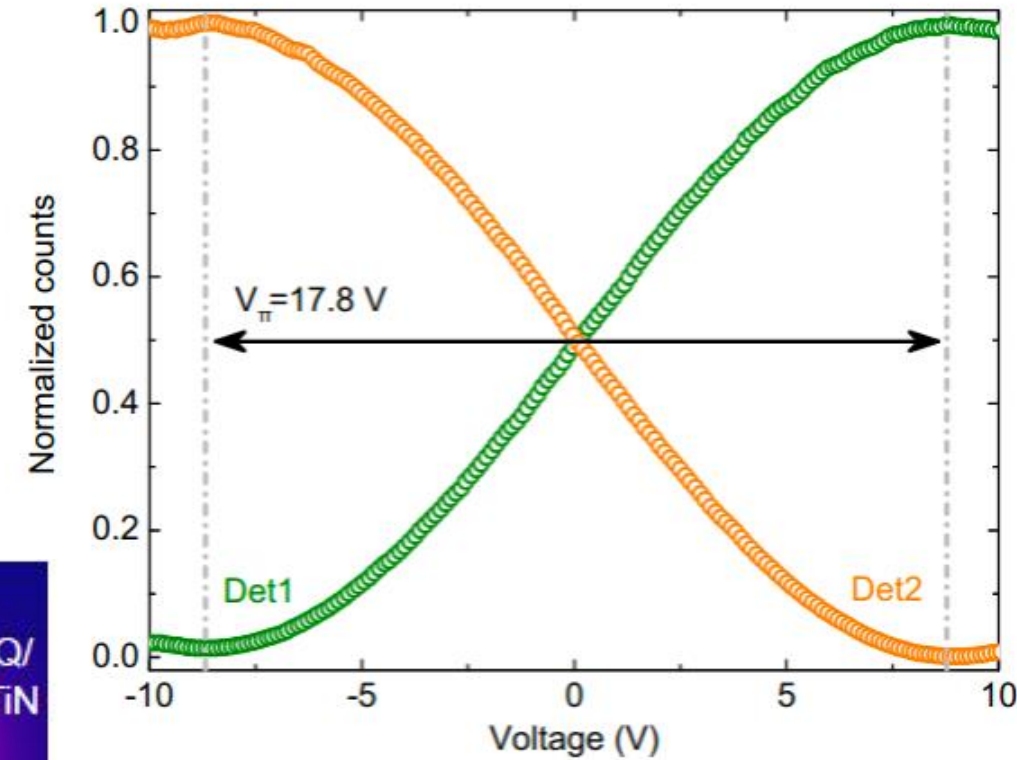
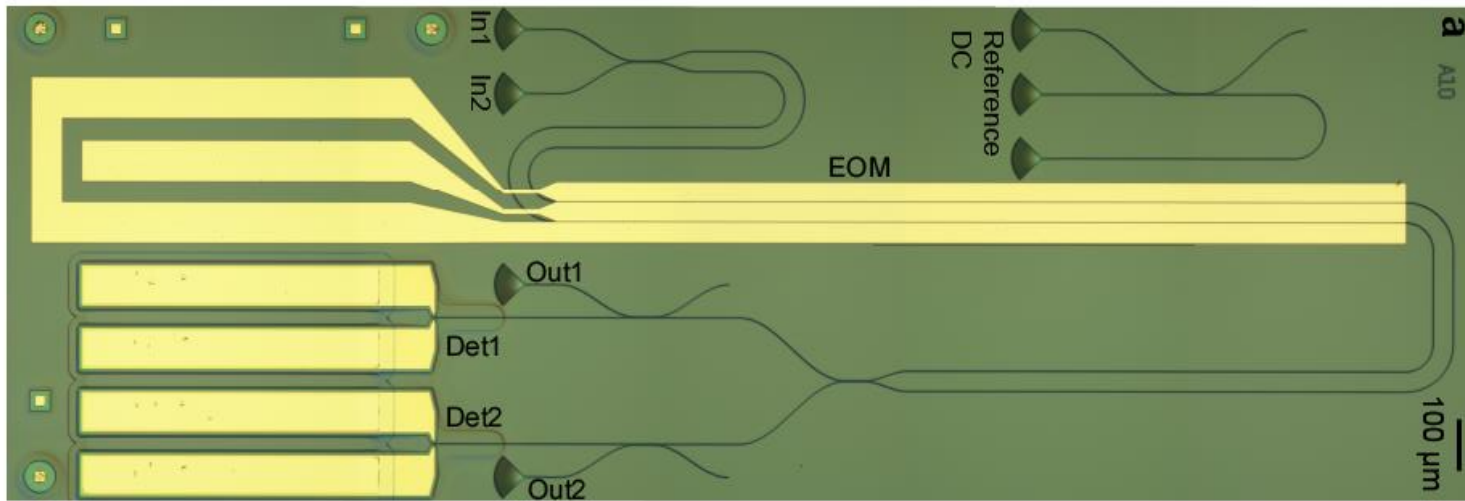


**Total Internal Reflection  
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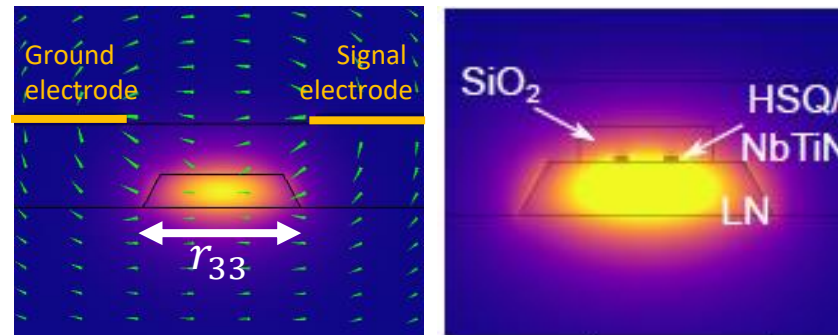




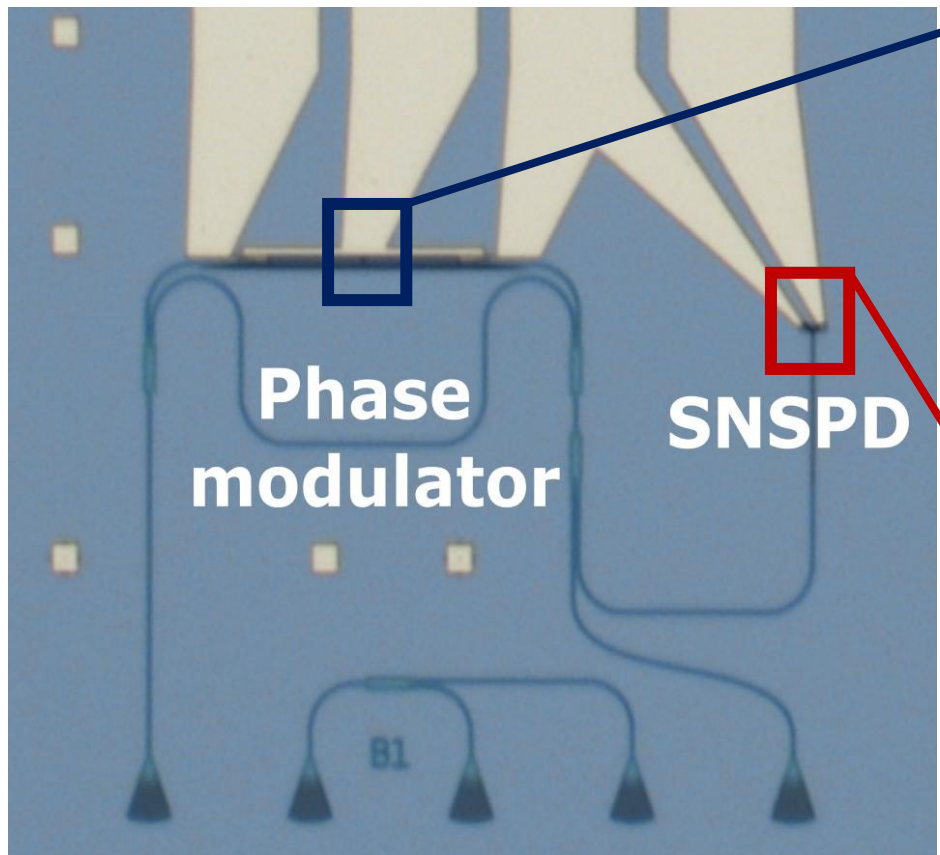
# SNSPDs integrated with thin film LNoI modulators



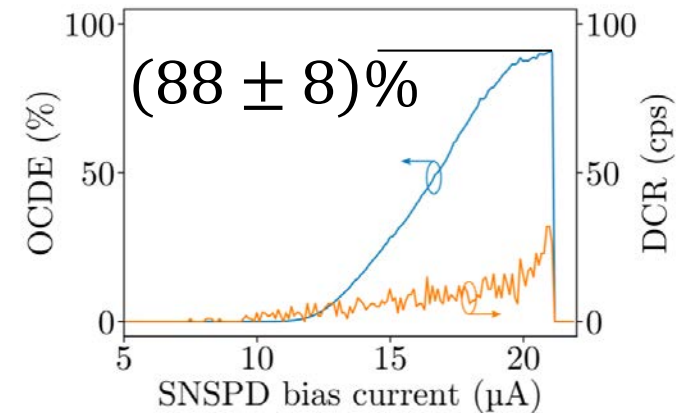
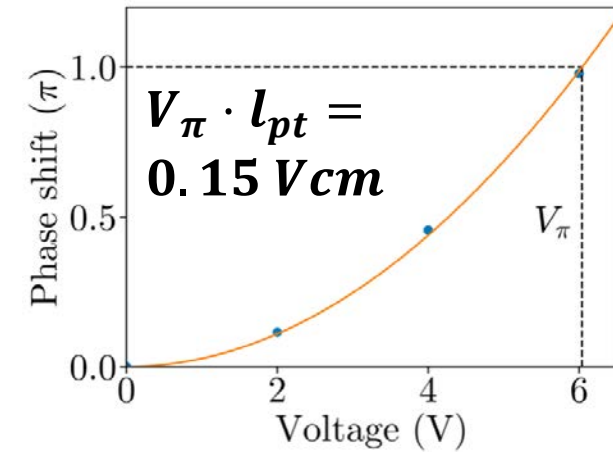
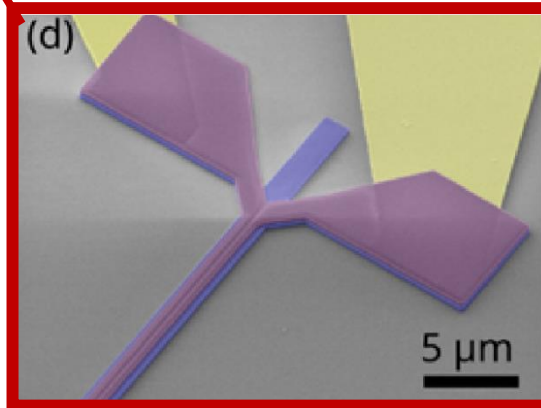
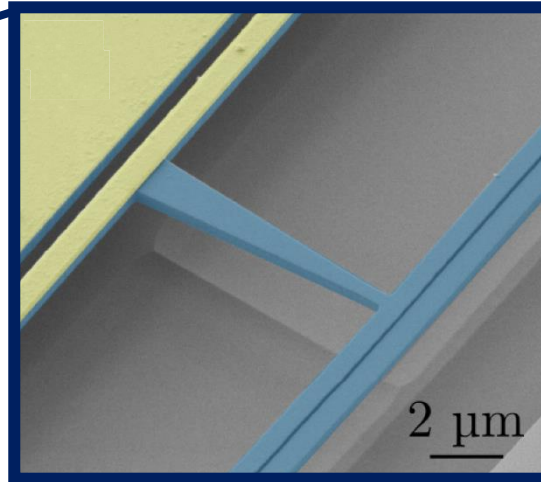
- operation of SNSPD up to 1 GHz modulation speed
- NbTiN SNSPDs: 17 ps jitter
- $V_{\pi} \cdot L = 3$  Vcm



# SNSPDs integrated with electromechanical phase shifters

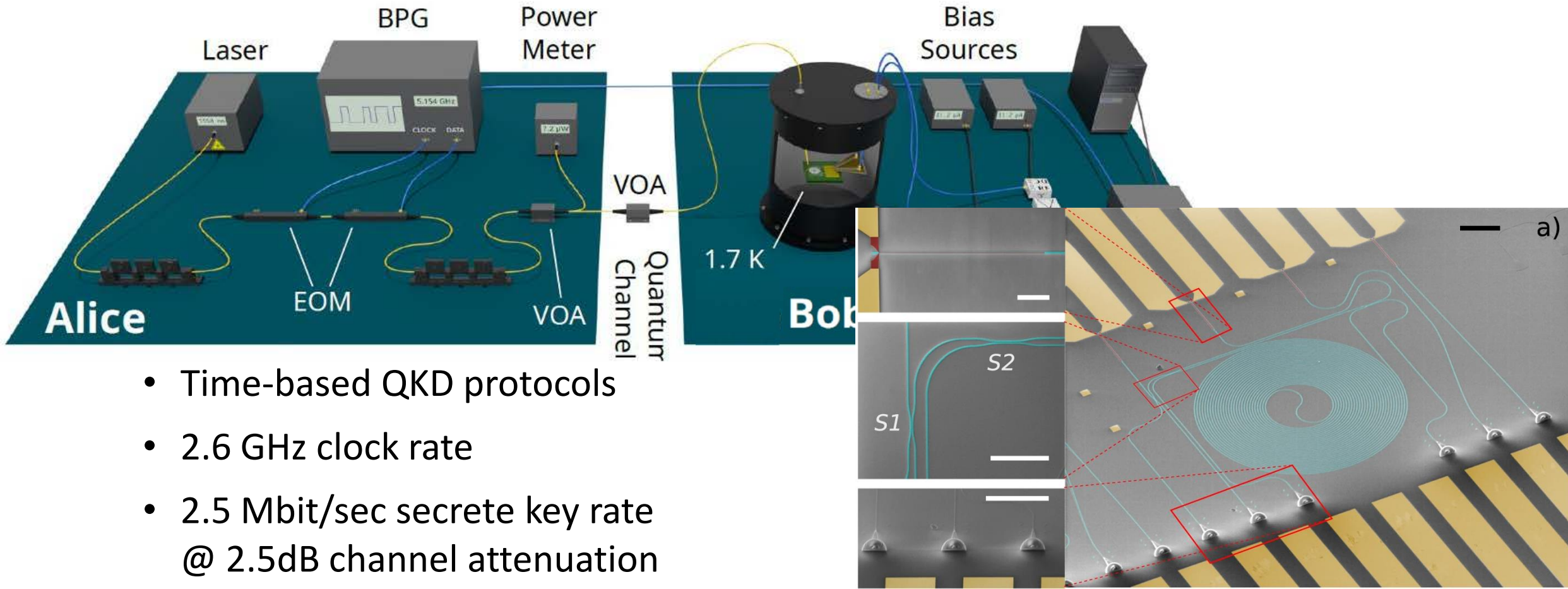


Phase-shifter insertion loss: 0.5 dB



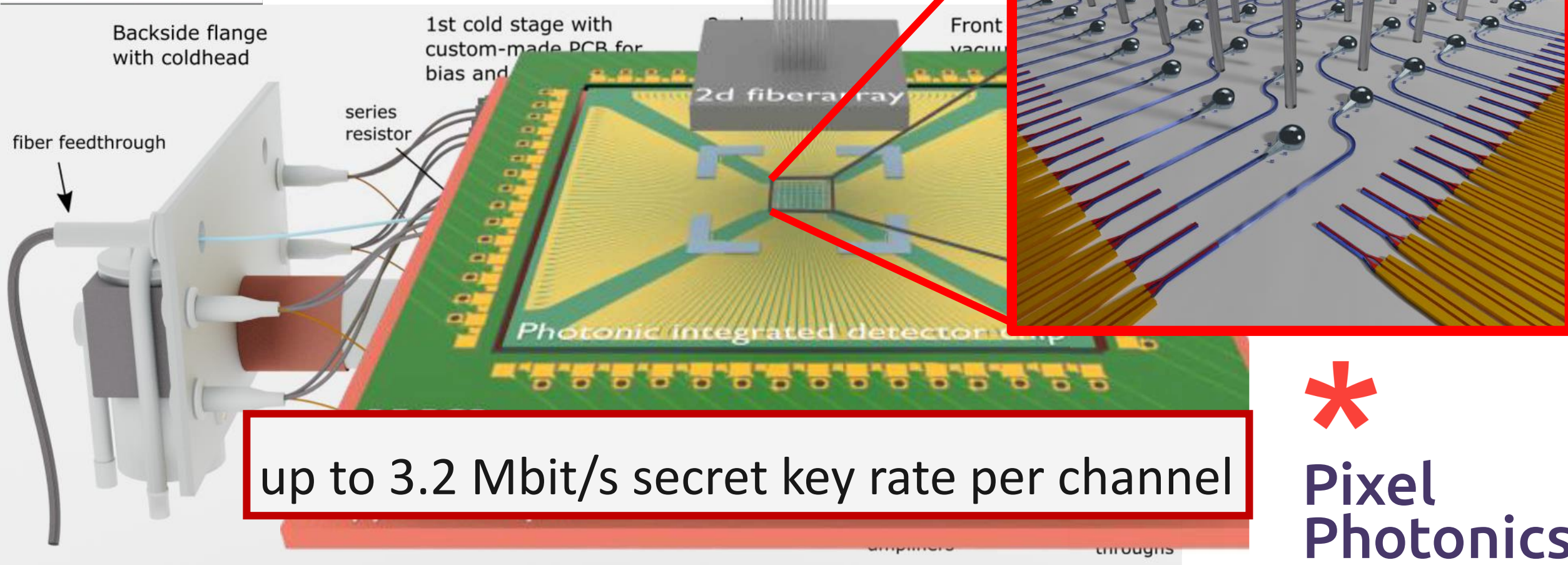
Jitter:  
12.2 ps

# Quantum Key Distribution receiver for GHz clock rates

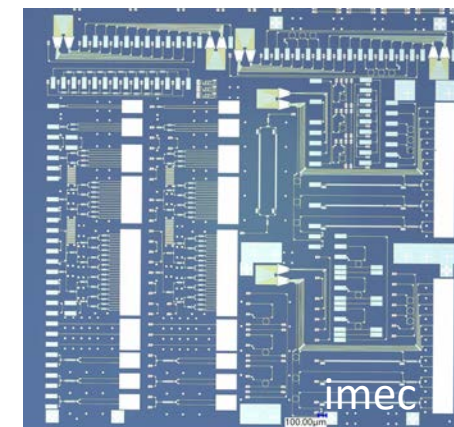
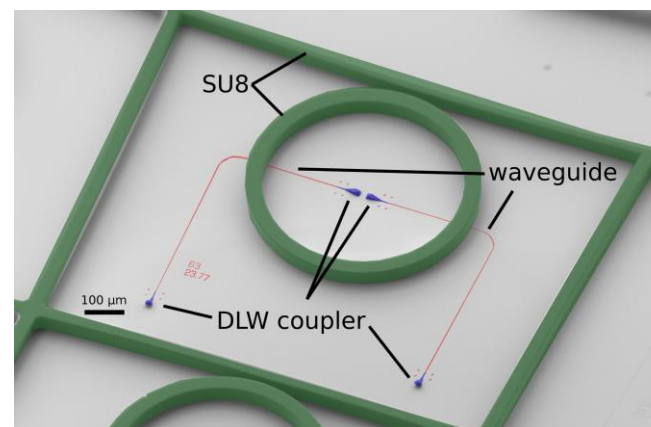
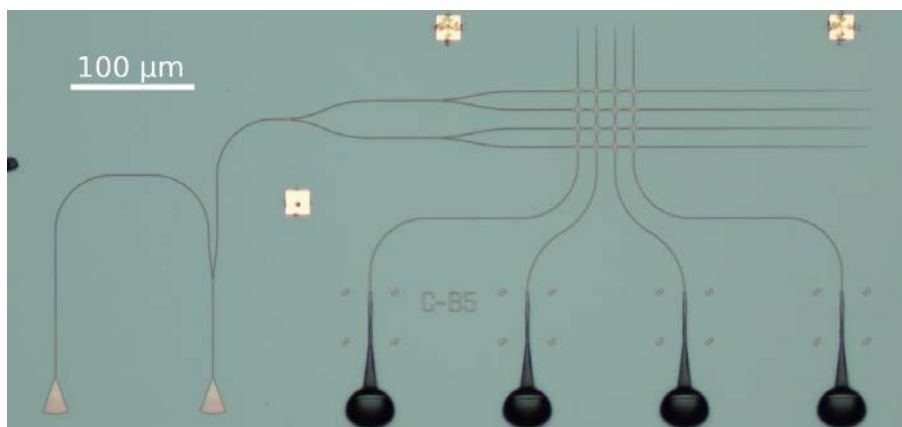
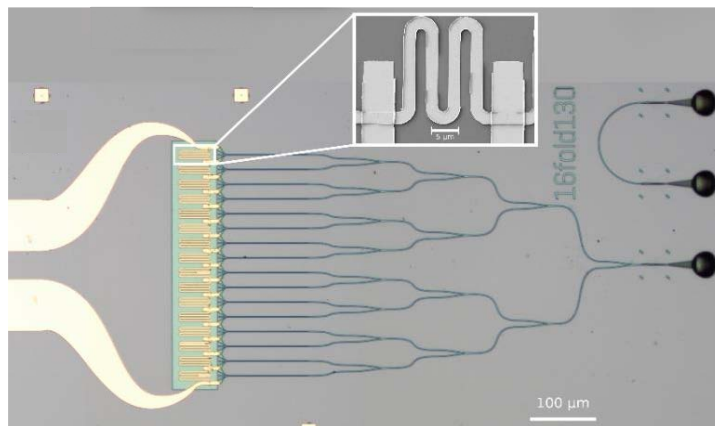
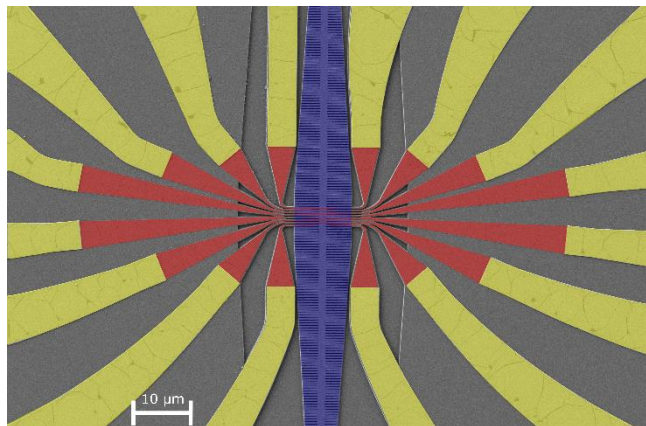


- Time-based QKD protocols
- 2.6 GHz clock rate
- 2.5 Mbit/sec secret key rate @ 2.5dB channel attenuation

# Massively parallelized receiver unit

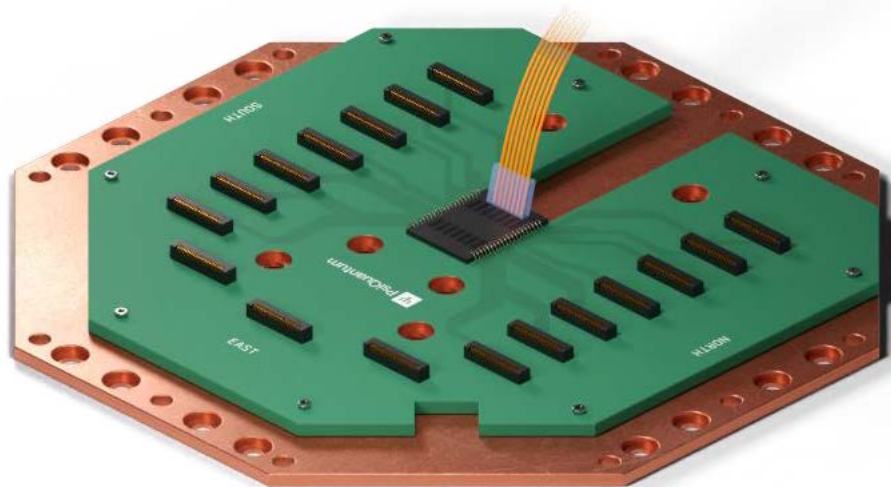


# Configure Systems for applications

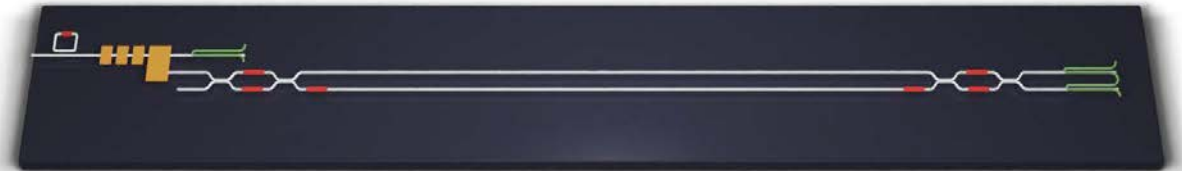


# Value creation in Photonic Quantum Computing

- academic activities in Bristol from 2006
- PSI Quantum founded in 2016, series A in 2020 (\$230 million)
- July 2021: \$450 million Series D funding  
→ \$3.15 billion evaluation



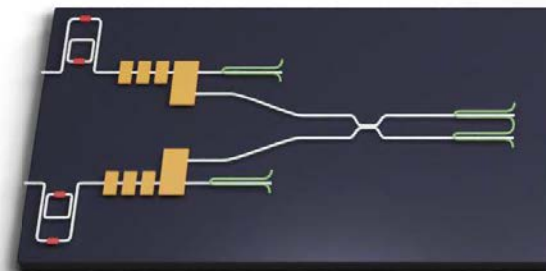
Single-qubit state preparation and measurement



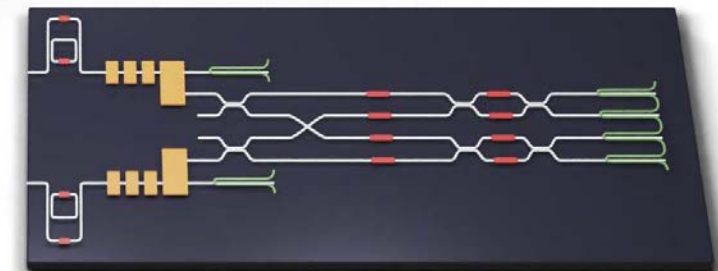
Qubit interconnect



Two-photon quantum interference



Two-qubit fusion measurement



PSI Quantum Team. Nature (Feb. 2025)

# Perspectives

- **Easy-access and transparent Foundry services for leading chip platforms**
- **Identify common primitives & interfaces for distributed architectures**
- **Services should accommodate custom designs & post-processing**
- **Open testbeds and benchmark repositories**
- **Collaborate on shared goals**

# Gemeinsam disruptiv – Photonische Quantentechnologie und Neuromorphes Computing

**Prof. Dr. Carsten Schuck**

Department for Quantum Technology, University of Münster, Germany  
Center for NanoTechnology (CeNTech)  
Center for Soft Nanoscience (SoN)





GEFÖRDERT VOM



Bundesministerium  
für Bildung  
und Forschung



qnc.summit<sup>25</sup>

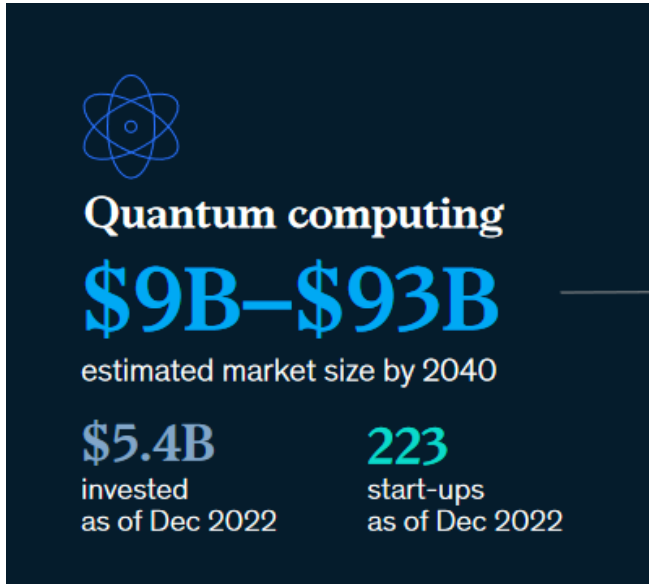
# Fortschritte von Ionenbasierten Quantencomputern und Herausforderungen bei deren Skalierung

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Dr. Björn Lekitsch, neQxt GmbH

»QNC Summit« 06.03.2025

# Quantencomputer im Jahr 2025



Quantum computing  
**\$9B–\$93B**  
estimated market size by 2040

**\$5.4B** invested as of Dec 2022  
**223** start-ups as of Dec 2022

McKinsey & Company  
Quantum Technology Monitor  
April 2023

**High-fidelity and Fault-tolerant Teleportation of a Logical Qubit using Transversal Gates and Lattice Surgery on a Trapped-ion Quantum Computer**

C. Ryan-Anderson,<sup>1,\*</sup> N. C. Brown,<sup>1,†</sup> C. H. Baldwin,<sup>1</sup> J. M. Dreiling,<sup>1</sup> C. Foltz,<sup>1</sup> J. P. Gaebler,<sup>1</sup> T. M. Gatterman,<sup>1</sup> N. Hewitt,<sup>1</sup> C. Holliman,<sup>1</sup> C. V. Horst,<sup>1</sup> J. Johansen,<sup>1</sup> D. Lucchetti,<sup>1</sup> T. Mengle,<sup>1</sup> M. Matheny,<sup>1</sup> Y. Matsuoka,<sup>1</sup> K. Mayer,<sup>1</sup> M. Mills,<sup>1</sup> S. A. Moses,<sup>1</sup> B. Neyenhuis,<sup>1</sup> J. Pino,<sup>1</sup> P. Siegfried,<sup>1</sup> R. P. Stutz,<sup>1</sup> J. Walker,<sup>1</sup> and D. Hayes<sup>1</sup>

<sup>1</sup>Quantinuum, 303 South Technology Ct., Broomfield, CO 80021, USA  
(Dated: April 26, 2024)

**Quantum computing for corrosion-resistant materials and anti-corrosive coatings design**

[Submitted on 26 Jun 2024]  
Nam Nguyen, Thomas W. Watts, Benjamin Link, Kristen S. Williams, Yuval R. Sanders, Samuel J. Elman, Maria Kieferova, Michael J. Bremne  
Obenland, Matthew Otten, Rashmi Sundareswara, Adam Holmes

> 1k to 100k logical qubits,  $10^{13}$  to  $10^{19}$  T-gates

NEWS RELEASE 14-OCT-2024

Qunova becomes first to achieve 'chemical accuracy' on commercial quantum computers with its hardware agnostic algorithm

Makes calculations 1,000 times faster on NISQ machines - brings quantum advantage one step closer

<https://www.eurekalert.org> NISQ, kein Quantenvorteil



# Qubit Technologien

## ■ Gefangene Ionen Qubits

### Demonstration of logical qubits and repeated error correction with better-than-physical error rates

M. P. da Silva (1), C. Ryan-Anderson (2), J. M. Bello-Rivas (1), A. Chernoguzov (2), J. M. Dreiling (2), C. Foltz (2), F. Frachon (1), J. P. Gaebler (2), T. M. Gatterman (2), L. Grans-Samuelsson (1), D. Hayes (2), N. Hewitt (2), J. Johansen (2), D. Lucchetti (2), M. Mills (2), S. A. Moses (2), B. Neyenhuis (2), A. Paz (1), J. Pino (2), P. Siegfried (2), J. Strabley (2), A. Sundaram (1), D. Tom (1), S. J. Wernli (1), M. Zanner (1), R. P. Stutz (2), K. M. Svore (1) ((1) Microsoft Azure Quantum, (2) Quantinuum)

arXiv:2404.02280

## ■ Supraleiter Qubits

### Willow: beating the threshold

Operating “below the threshold” has been a goal for error corrected quantum computing since its inception in the 1990s. However, after almost 30 years of advancement in device fabrication, calibration, and qubit design, quantum computers still hadn’t passed this landmark. That is, until our latest 105-qubit superconducting processor, Willow.

<https://research.google>

## ■ Neutral Atom Qubits

### Article

### Logical quantum processor based on reconfigurable atom arrays

<https://doi.org/10.1038/s41586-023-06927-3>

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Accepted: 1 December 2023

Published online: 6 December 2023

Open access

 Check for updates

Dolev Bluvstein<sup>1</sup>, Simon J. Evered<sup>1</sup>, Alexandra A. Geim<sup>1</sup>, Sophie H. Li<sup>1</sup>, Hengyun Zhou<sup>1,2</sup>, Tom Manovitz<sup>1</sup>, Sepehr Ebadi<sup>1</sup>, Madelyn Cain<sup>1</sup>, Marcin Kalinowski<sup>1</sup>, Dominik Hangleiter<sup>3</sup>, J. Pablo Bonilla Ataides<sup>1</sup>, Nishad Maskara<sup>1</sup>, Iris Cong<sup>1</sup>, Xun Gao<sup>1</sup>, Pedro Sales Rodriguez<sup>3</sup>, Thomas Karolyshyn<sup>2</sup>, Giulia Semeghini<sup>4</sup>, Michael J. Gullans<sup>3</sup>, Markus Greiner<sup>1</sup>, Vladan Vuletić<sup>5</sup> & Mikhail D. Lukin<sup>1,5</sup>

Suppressing errors is the central challenge for...  
requiring quantum error...

Nature **626**, pages 58–65 (2024)

(Quantum Error Detection)



# Qubit Technologien

## ■ Spin Qubits

### Scalable Parity Architecture With a Shuttling-Based Spin Qubit Processor

Florian Ginzl,<sup>1</sup> Michael Fellner,<sup>2,3</sup> Christian Ertler,<sup>1</sup> Lars R. Schreiber,<sup>4,5</sup> Hendrik Bluhm,<sup>4,5</sup> and Wolfgang Lechner<sup>1,2,3</sup>

<sup>1</sup>Parity Quantum Computing Germany GmbH, Schauenburgerstraße 6, 20095 Hamburg, Germany

<sup>2</sup>Parity Quantum Computing GmbH, Rennweg 1, Top 314, 6020 Innsbruck, Austria

<sup>3</sup>Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria

<sup>4</sup>JARA-FTT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Aachen, Germany

<sup>5</sup>ARQUE Systems GmbH, 52074 Aachen, Germany

(Dated: August 1, 2024)

arXiv:2403.09574

## ■ Majorana Qubits?



"The editorial team [Nature] wishes to point out that the results in this manuscript do not represent evidence for the presence of Majorana zero modes in the reported devices..."

Microsoft's Majorana 1 chip carves new path for quantum computing

<https://news.microsoft.com>

## ■ Photonen Qubits

### Scaling and networking a modular photonic quantum computer

[H. Aghaee Rad](#), [T. Ainsworth](#), [R. N. Alexander](#) , [B. Altieri](#), [M. F. Askarani](#), [R. Baby](#), [L. Banchi](#), [B. Q. Baragiola](#), [J. E. Bourassa](#), [R. S. Chadwick](#), [I. Charania](#), [H. Chen](#), [M. J. Collins](#), [P. Contu](#), [N. D'Arcy](#), [G. Dauphinais](#), [R. De Prins](#), [D. Deschenes](#), [I. Di Luch](#), [S. Duque](#), [P. Edke](#), [S. E. Fayer](#), [S. Ferracin](#), [H. Ferretti](#), ... [Y. Zhang](#)

+ Show authors

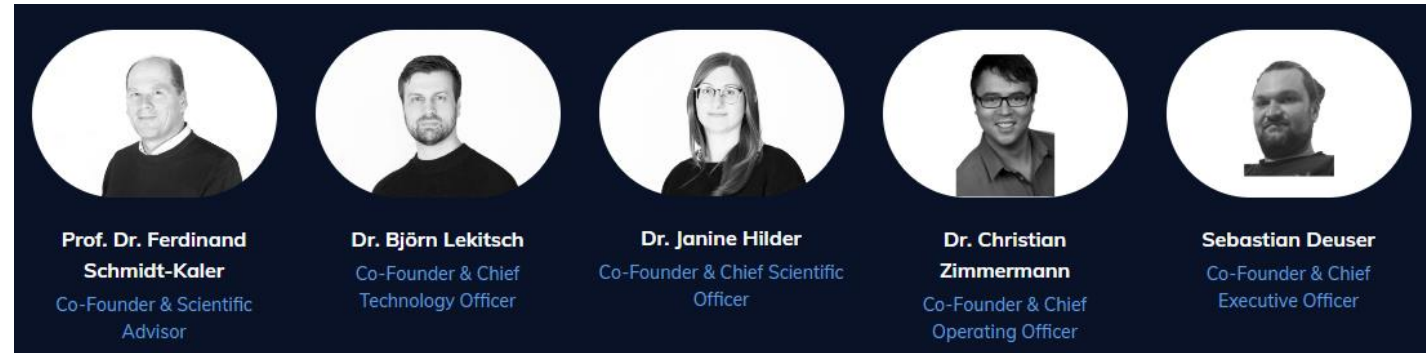
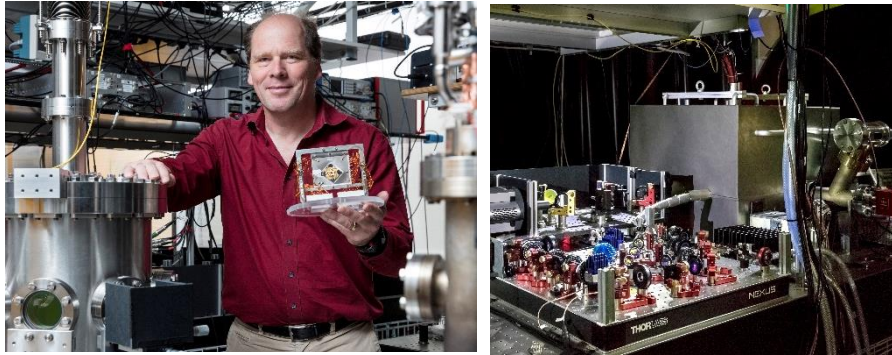
*Nature* (2025)



# neQxt – Ionen Quantencomputer



AG Quantenbit  
Prof. Dr. Ferdinand Schmidt-Kaler



- > 30 Jahre Erfahrung Quantenoptik
- Projekte US IARPA, EU Flagship, BMBF IQuAn, EVAQS, ATIQ, KonneQt
- Quantencomputer (>4 Qubits) seit 2017
- Entwicklung von Ionenfallen, Elektronik, Software (Full-Stack), Quantencomputer
- 42 Mitarbeiter (Voll- und Teilzeit)
- Standorte in Weiterstadt, Mainz, Köln und Aschaffenburg



# Stand Ionen Quantencomputer

- Quantenvolumen:

- AQT, EU-Rekord  $2^7 = 128$
- Quantinuum, Weltrekord  $2^{21} = 2.097.152$

<https://www.aqt.eu/>

<https://www.quantinuum.com>

- Fehlerraten aller Qubitoperationen

- 99,999985% ein Qubit Gatter (2024)
- 99,97% zwei Qubit Gatter (Mikrowellen, 2024)
- 99,94% zwei Qubit Gatter (Laser, 2021)

arXiv:2412.04421

arXiv:2407.07694

arXiv:2105.05828

Neutrale Atome > Qubits  
Supraleiter > Geschwindigkeit

- Kohärenzzeit

- $T_2$  bis Stunden möglich (2021)

Nat. Com. 12, 233 (2021)

- Konnektivität

- „all-to-all“ Shuttling
- „all-to-all“ optische Interconnects

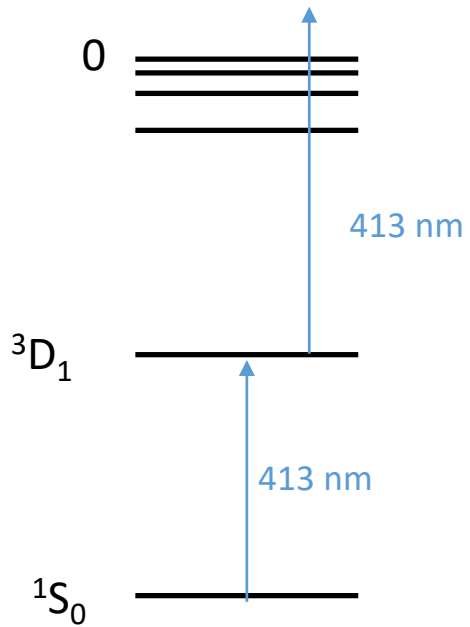
- JGUM/neQxt

- 1-Qubit Gatter  $\approx 1 \mu s$ ,  $10^{-5}$  Fehlerraten
- 2-Qubit Gatter  $\approx 50 - 100 \mu s$ ,  $10^{-3}$  Fehlerraten
- $< 10 \mu s$ ,  $10^{-5}$  Fehlerraten für alle Gatter möglich
- Kohärenzzeit  $\approx 2 s$ , Minuten möglich

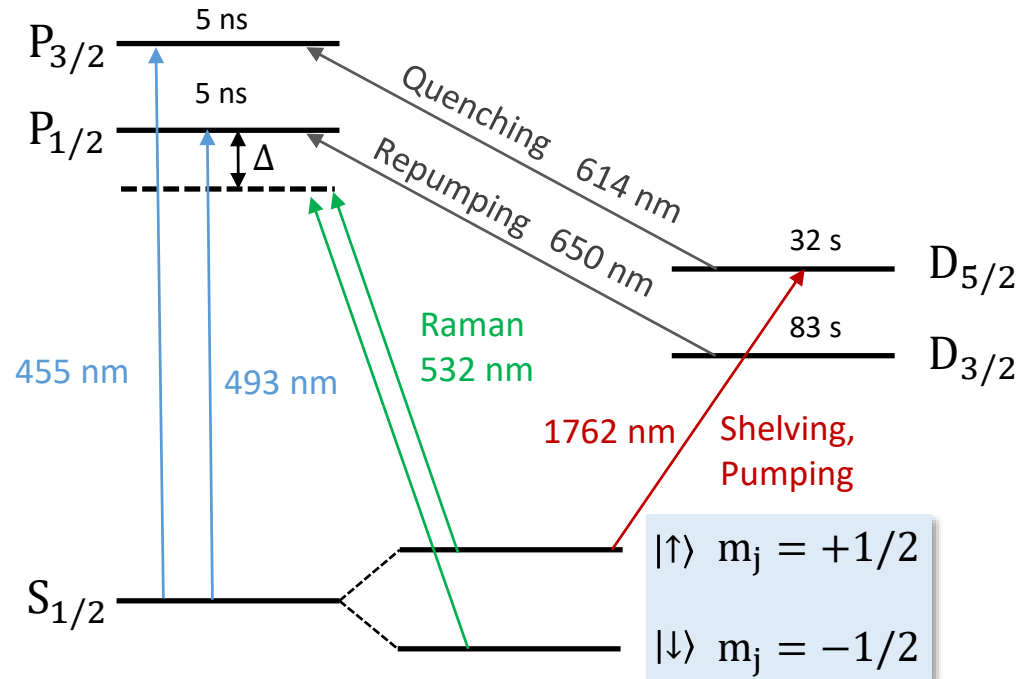


# Ionen Qubit

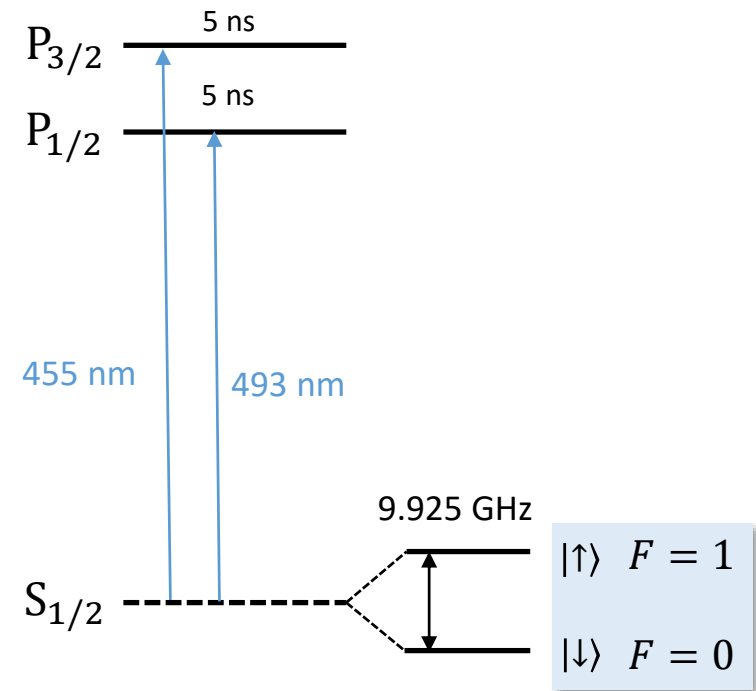
$^{138}\text{Ba}$  Neutral Atom



$^{138}\text{Ba}^+$  Spin Qubit



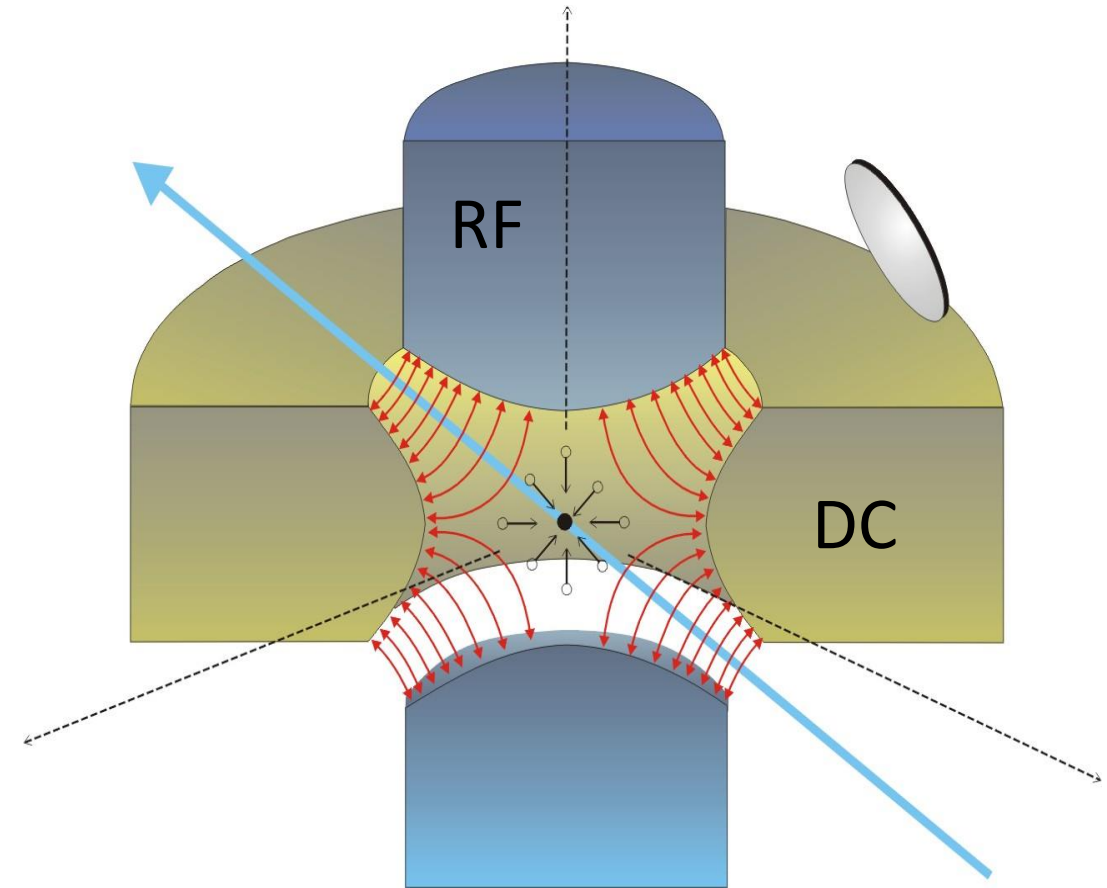
$^{133/137}\text{Ba}^+$  Hyperfine Qubit





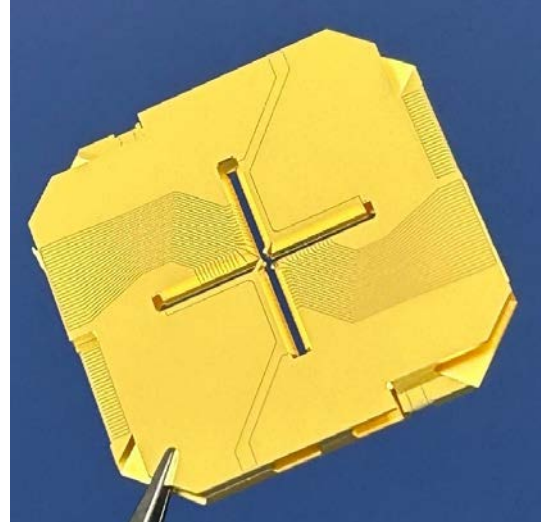
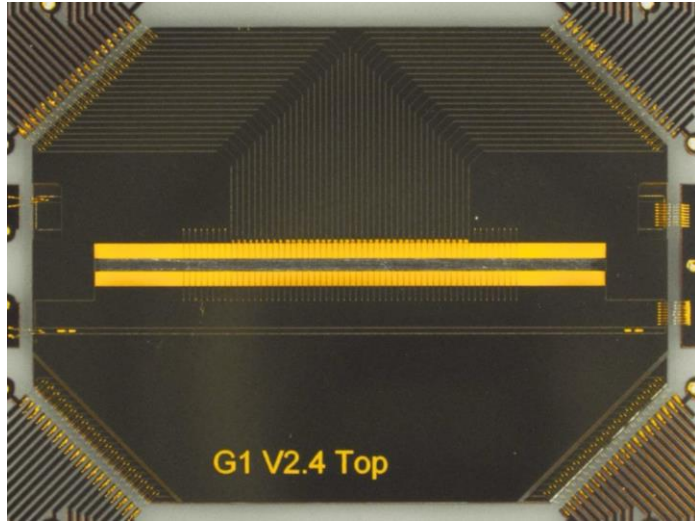
# (Wolfgang) Paul Ionenfalle

- Laplace-Gleichung verhindert das Fangen von Ionen mit statischen Feldern
- Rotierendes Sattelpotential, elektrisches Wechselfeld (AC)
- Starker Einschluss
- Linear und Junctions Fallen möglich



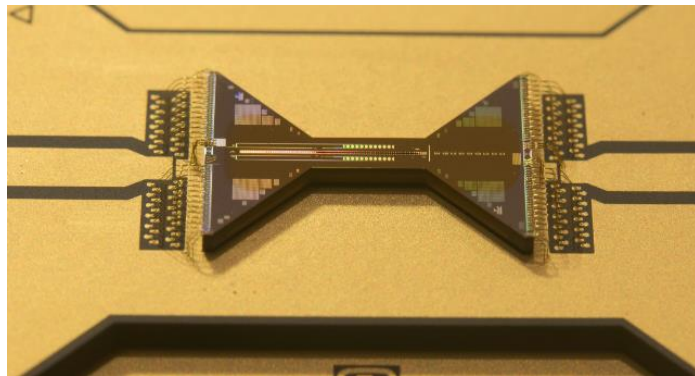
Wolfgang Paul et. al, „Ein Ionenkäfig“ (1958)

# Moderne 2D und 3D Ionenfalle



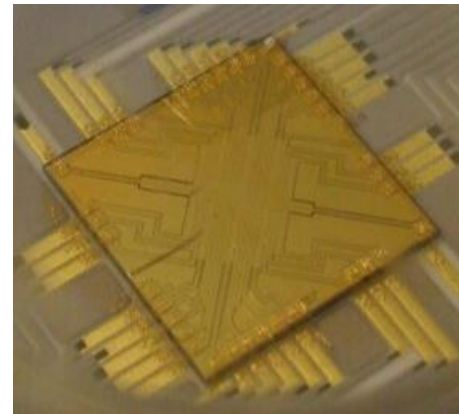
← NeQxt 3D lineare Falle

← JGU Mainz 3D X-Junction

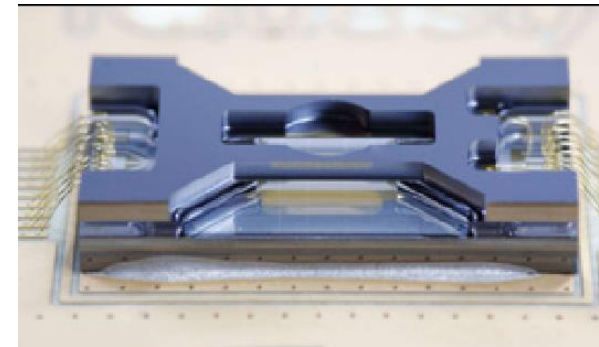


← Sandia 2D Falle

→ eleQtron 2D Falle

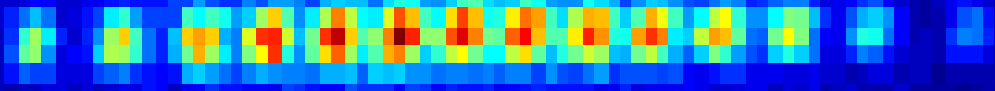


↓ Infineon 2+1D Falle

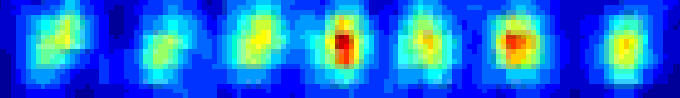


# Ionen in Paul Fallen

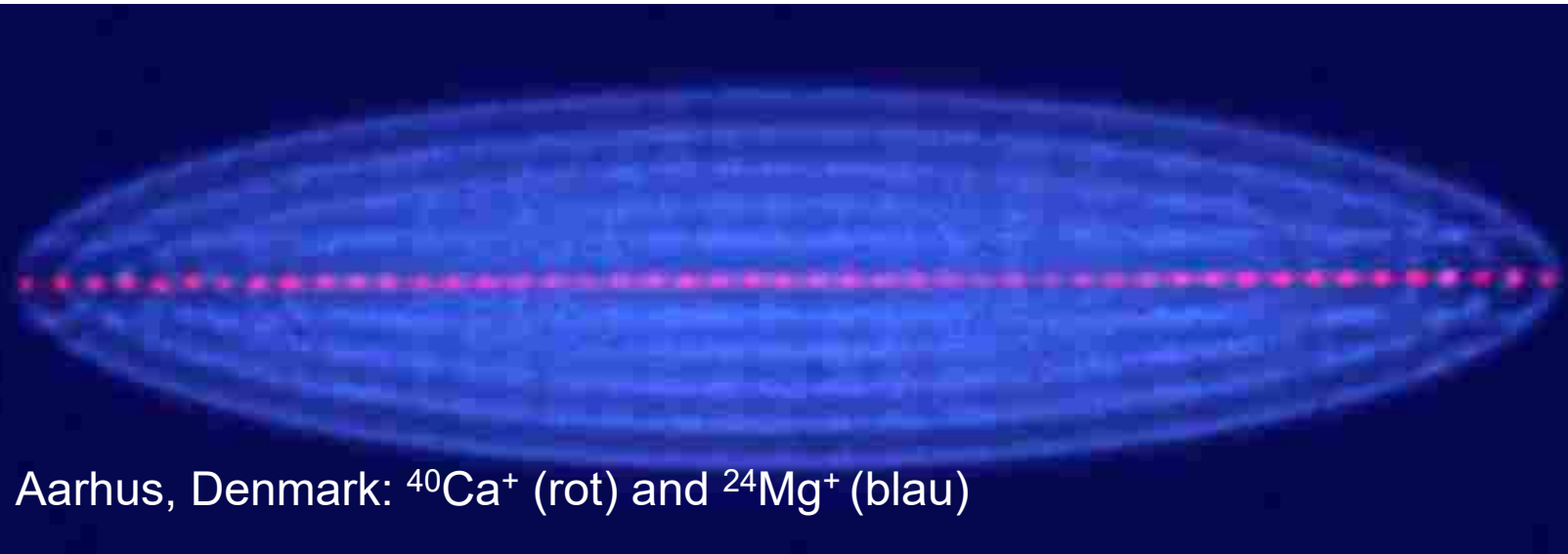
Mainz,  $^{40}\text{Ca}^+$



Innsbruck, Austria:  $^{40}\text{Ca}^+$



„atmender“ 7-Ionen Kristall



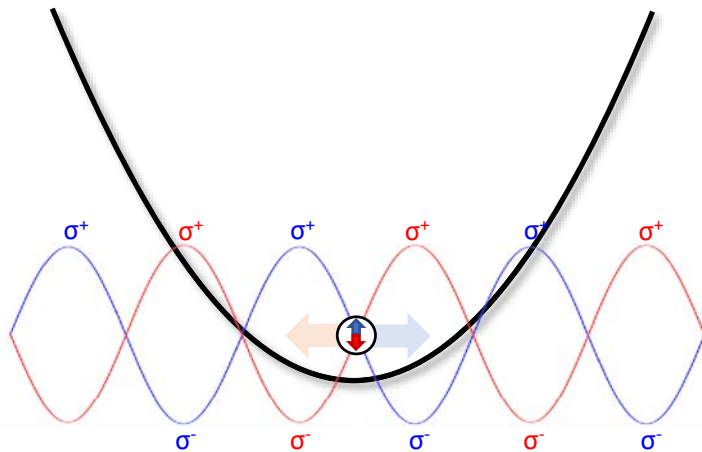
Aarhus, Denmark:  $^{40}\text{Ca}^+$  (rot) and  $^{24}\text{Mg}^+$  (blau)



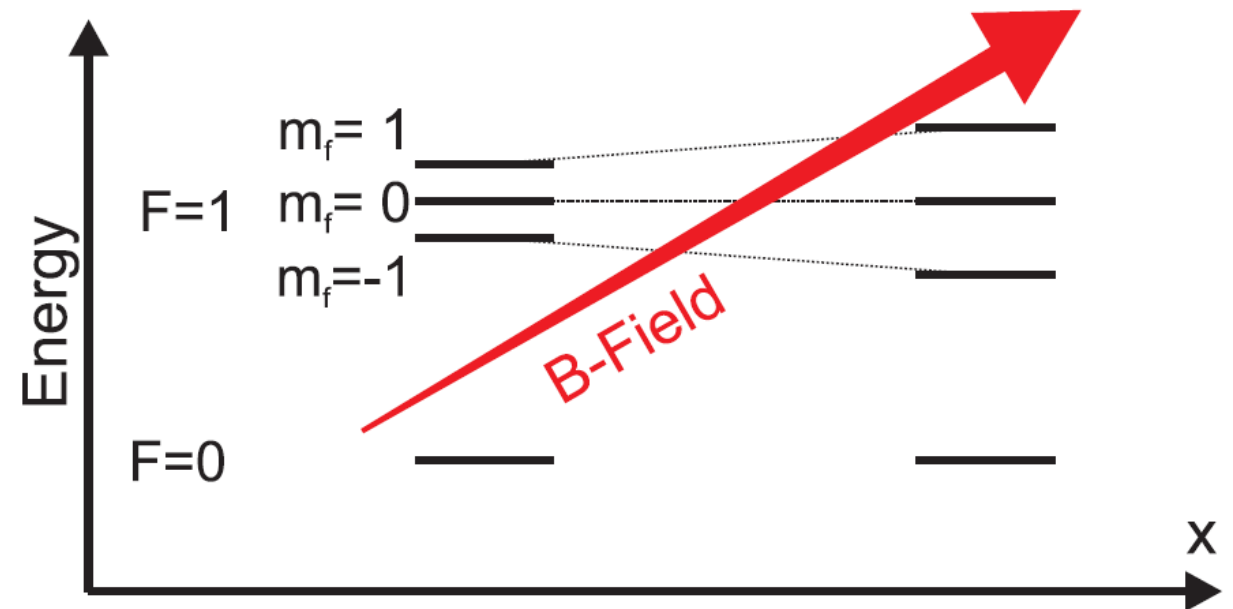
# Ionen Quantencomputer Technologien

- Kopplung interner Qubitzustände an gemeinsame Bewegungsmoden

- Laser Gatter







- Mikrowellen Gatter







# Ionen Quantencomputer Unternehmen

## Laser Gatter

- Adressierte Laser statische Qubits
  - IonQ 
  - AQT 
- Globale Laser und Shuttling
  - Quantinuum 
- Adressierte Laser und Shuttling
  - neQxt 

## Mikrowellen Gatter

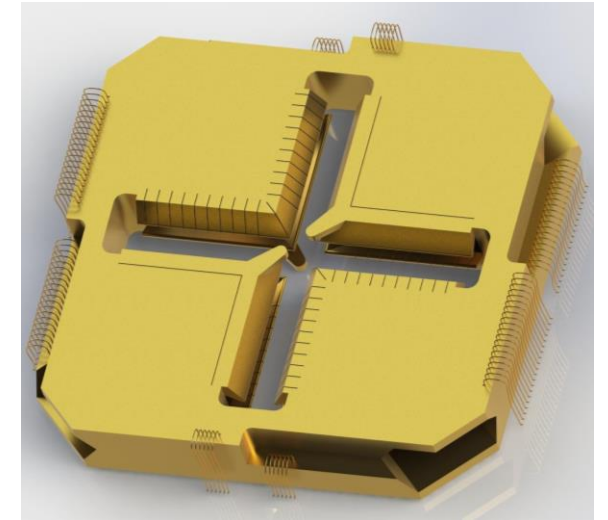
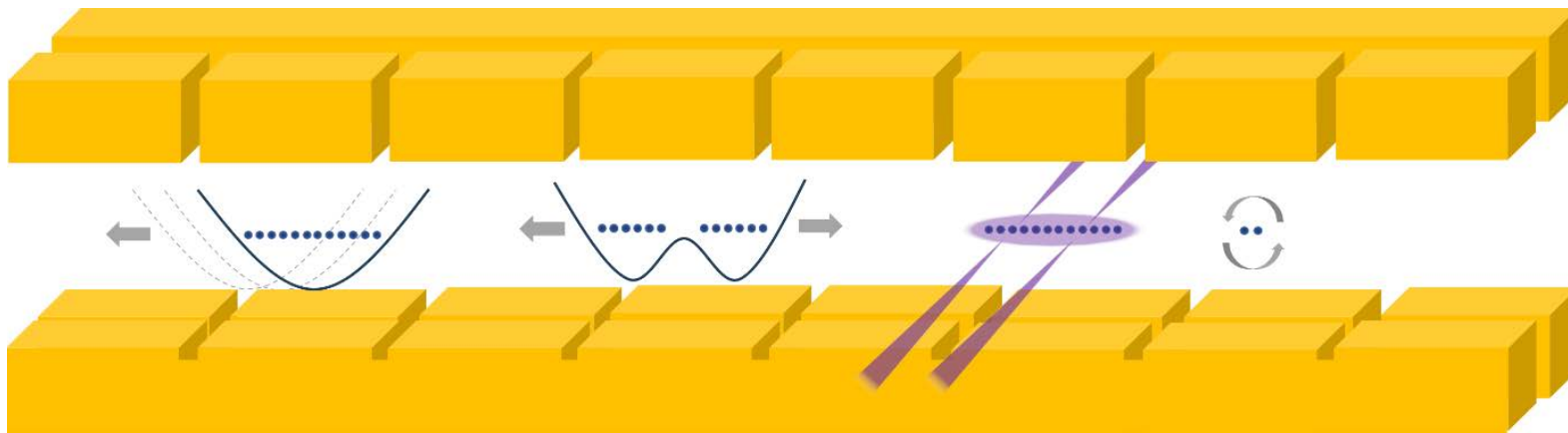
- Statische Magnetgradienten
  - eleQtron 
- Statische Stromgradienten
  - Universal Quantum 
- Oszillierende Stromgradienten
  - QUDORA 
  - Oxford Ionics 

Andere technologische Ansätze: ZuriQ, Quantum Fabrix, Qubitcore, Quantum Art Ltd.



# neQxt Architektur

- Ionenketten (bis zu 16 Qubits) mit individueller Adressierung
- Kombiniert mit Shuttling, auch X-Junctions
- Photonische Interkonnektivität
- Hohe Parallelität



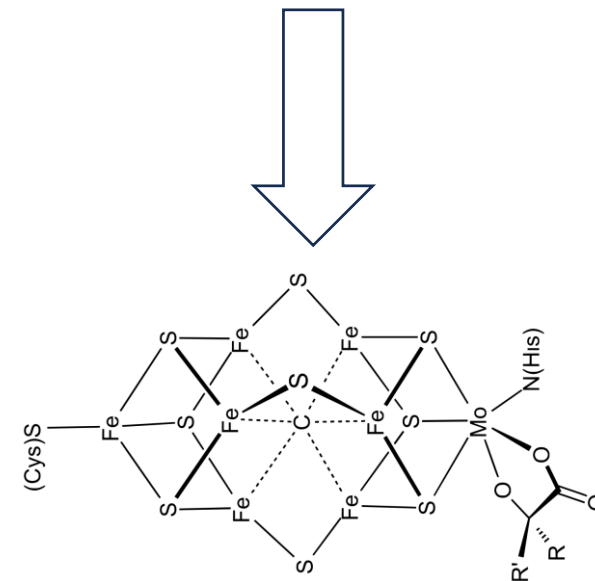
# Kurz und Langfristige Ziele neQxt

- Rechenzeit für Anwender (VQE, etc.)
- Mehr Qubits (>1000), bessere Qubits ( $< 10^{-5}$  Fehlerraten), bessere Fehlerkorrektur
- neue Konnektivität (Photonen) > 10k Qubits

NEWS RELEASE 14-OCT-2024

Qunova becomes first to achieve 'chemical accuracy' on commercial quantum computers with its hardware agnostic algorithm

Makes calculations 1,000 times faster on NISQ machines - brings quantum advantage one step closer



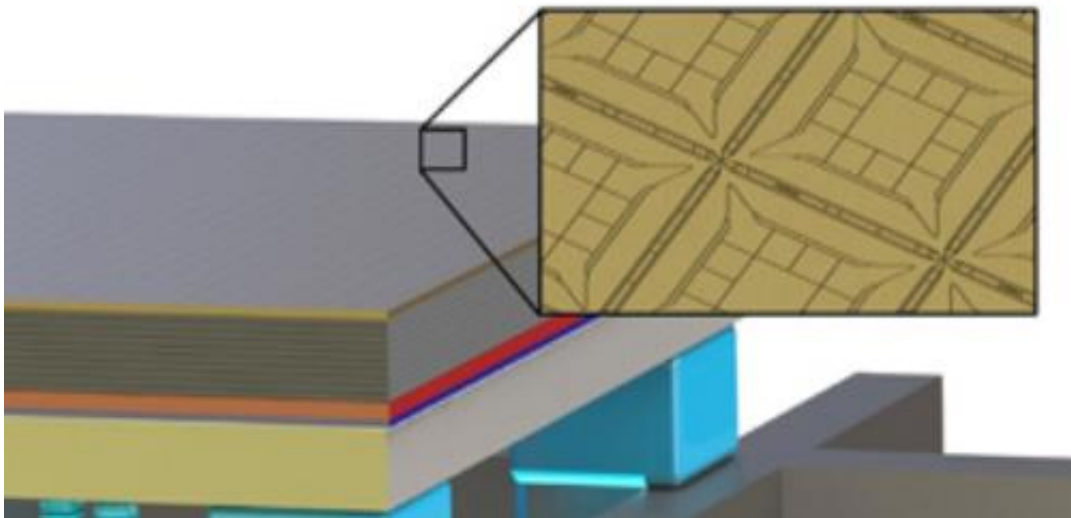
FeMoco Molekül

> 2000 logical qubits, >  $10^9$  T-gates

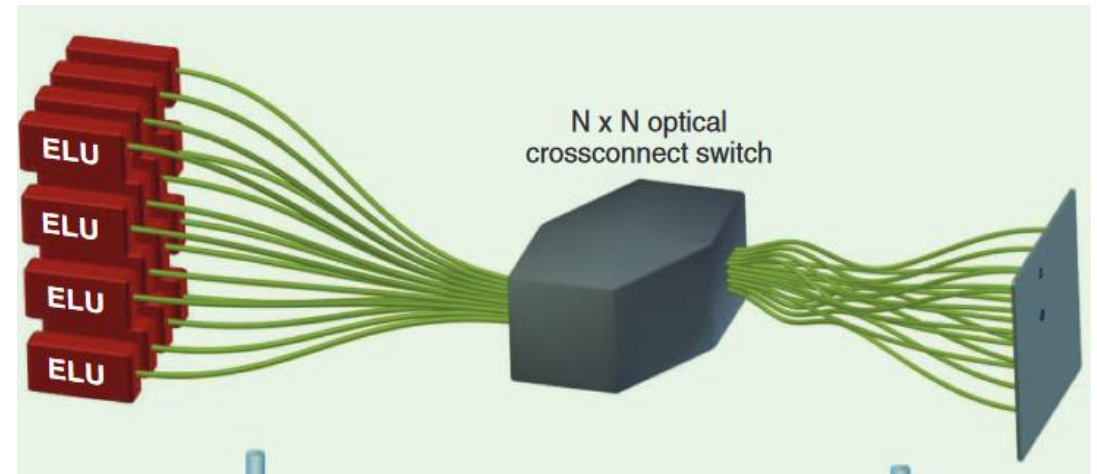


# Ionenfallen QC Skalierung

- Mehr Qubits mit passender Konnektivität, „all-to-all“ bzw. passend zu Fehlerkorrektor



B. Lekitsch et al. Science Advances, 3, 2 (2017)

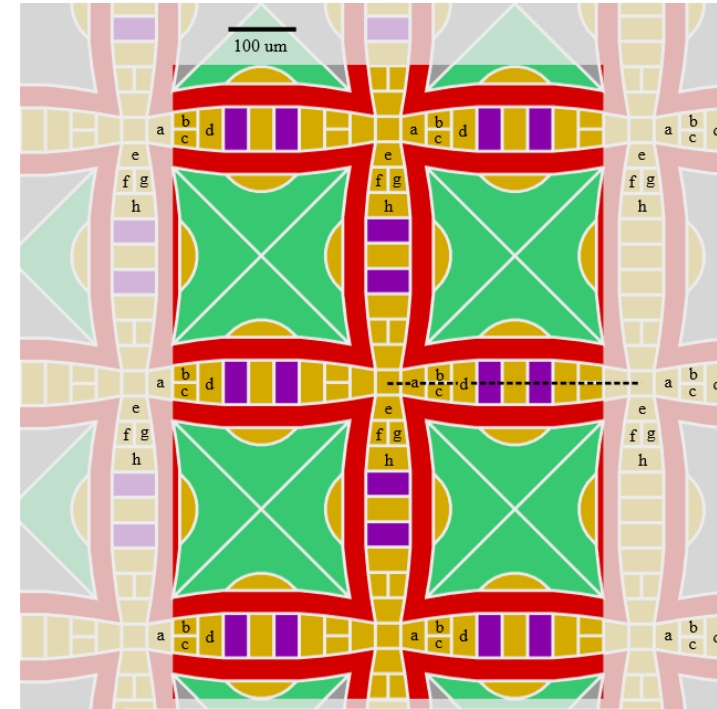
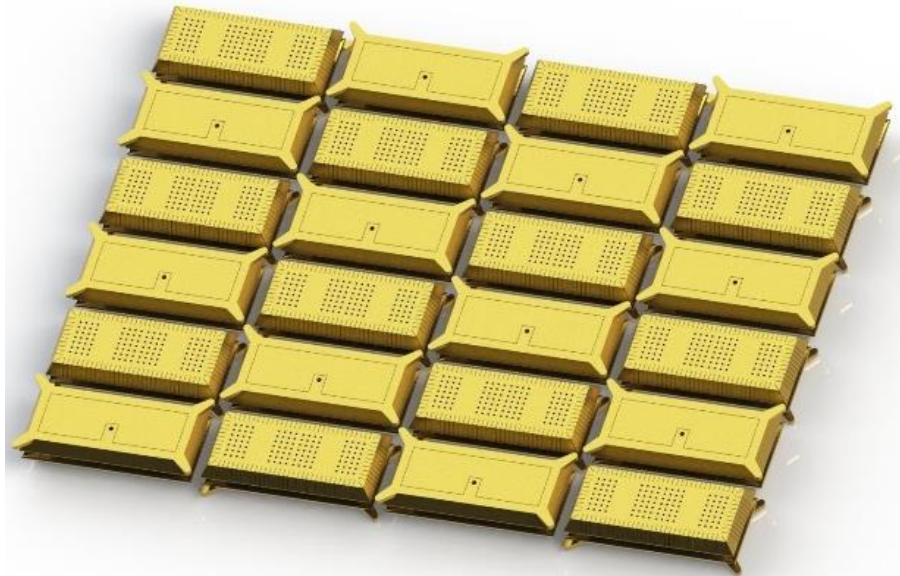


C. Monroe and J. Kim Science, 339, 1164 (2013)



# Ionenfallen QC Skalierung

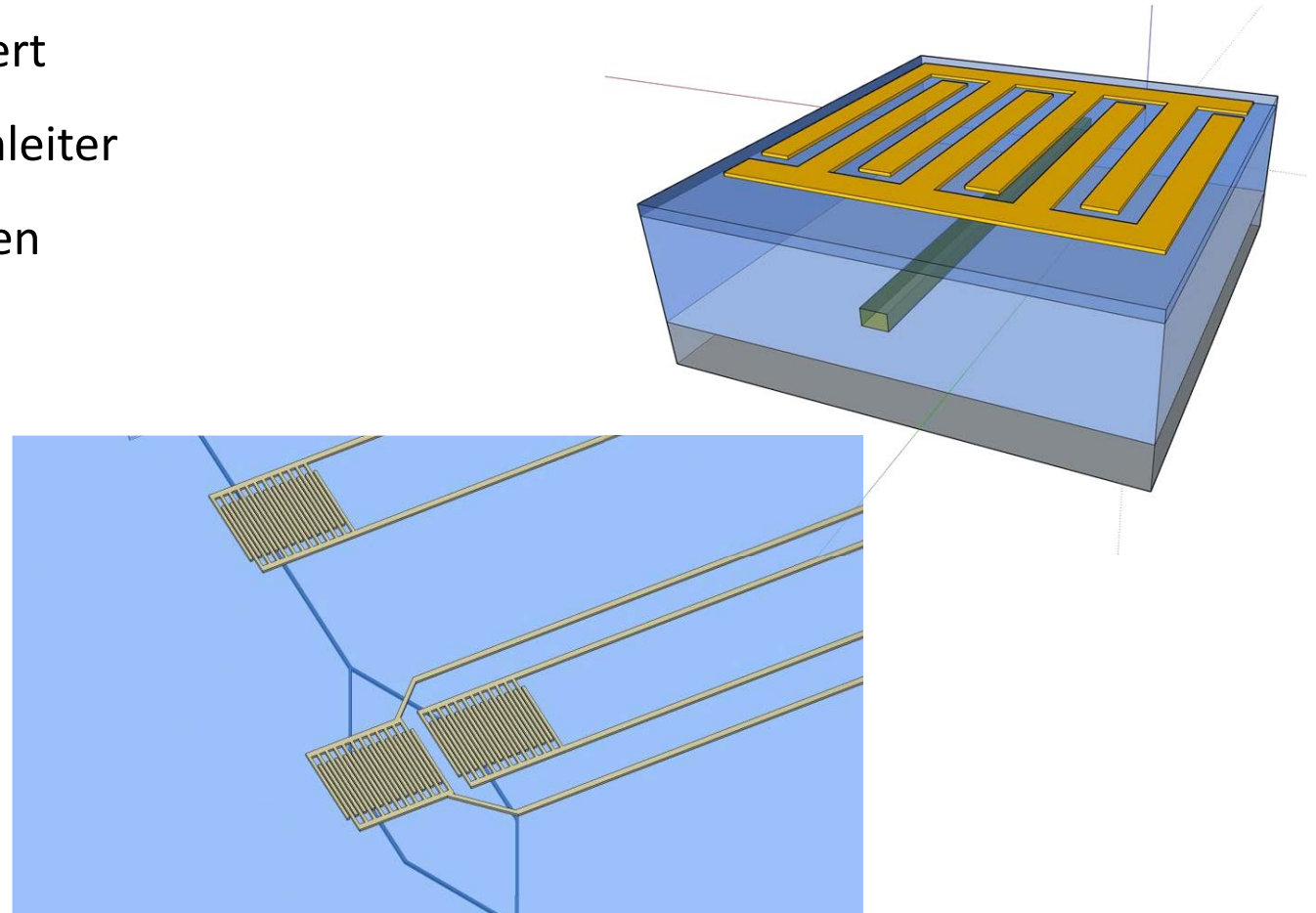
- Mehr Qubits Pro Fallenfläche
- X-Junctions für effizientes Shuttling
- Unterstützung von FMD notwendig



arXiv:2403.00756v1 R. D. Delaney et al.

# Integrierter Wellenleitermodulatoren

- Aktive Wellenleiter in Fallenstack integriert
- Verlustarme  $\text{Al}_2\text{O}_3$ ,  $\text{AlN}$  oder  $\text{Si}_3\text{N}_4$  Wellenleiter
- Elektro- oder Akustooptische Modulatoren
- CMOS Foundry kompatibel

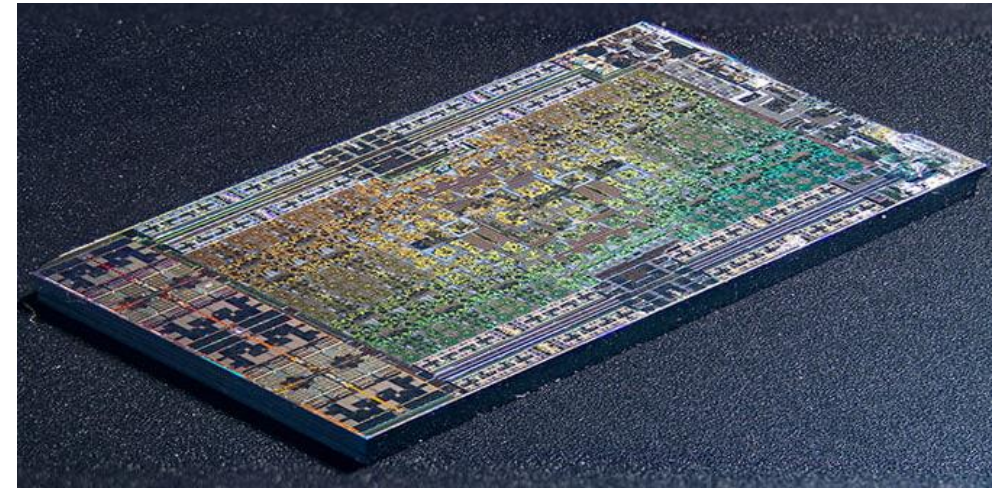


BMBF QNC ActiveWave – neQxt / FhG ISIT

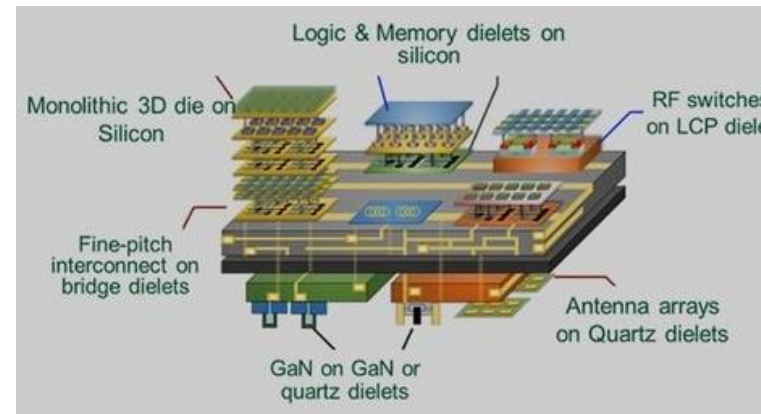


# Integrierte Elektronik

- Digital-Analog-Converter (Spannung für Fallenelektroden)
- Steuerung der optischen Modulatoren
- CMOS Foundry kompatibel



AMD SoC High-Res Die Shot

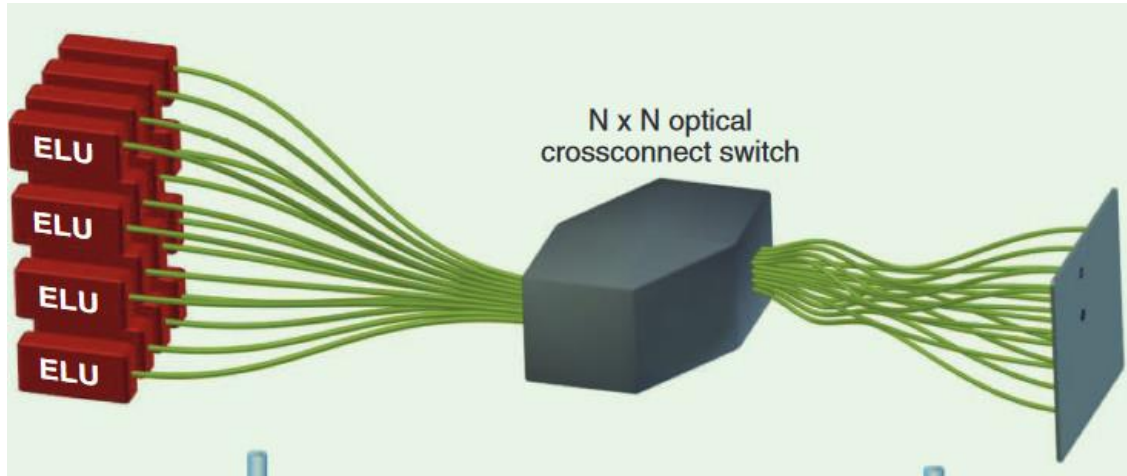


Die-to-wafer hybrid ASM and EVG

BMBF ATIQ – Infineon

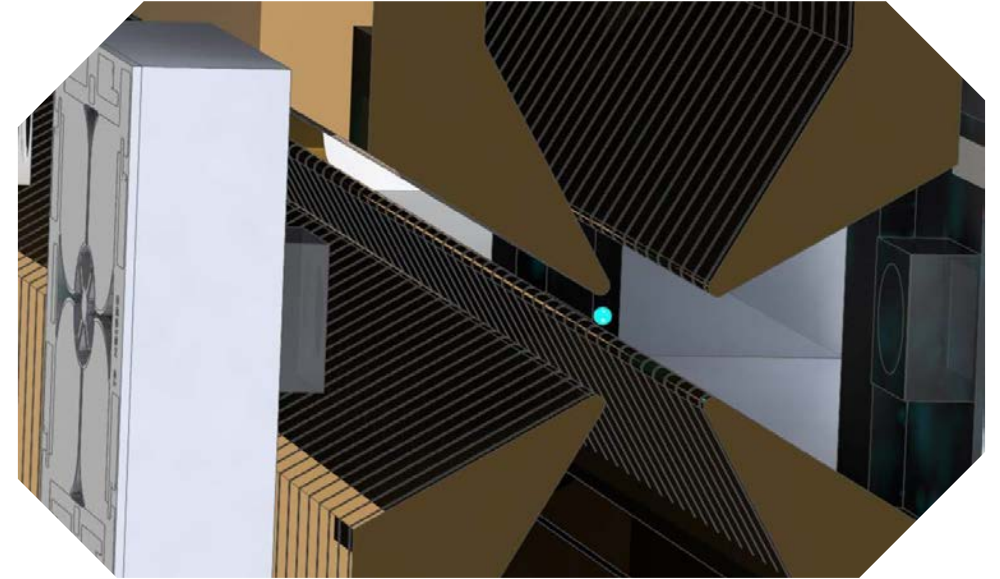


# Integrierte optische Kavitäten



C. Monroe and J. Kim Science, 339, 1164 (2013)

- Purcell Effekt zwingt emittierte Photonen in Kavität
- Verlässlich viele Photonen, modulare Skalierung
- Ionen sind nicht mit Dielektrika kompatibel

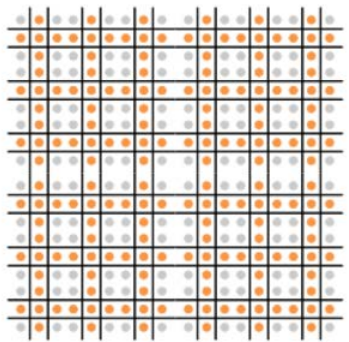


BMBF KonneQt JGUM/FhG ISIT

# Kommerzielle Ionenfallen für viele Qubits

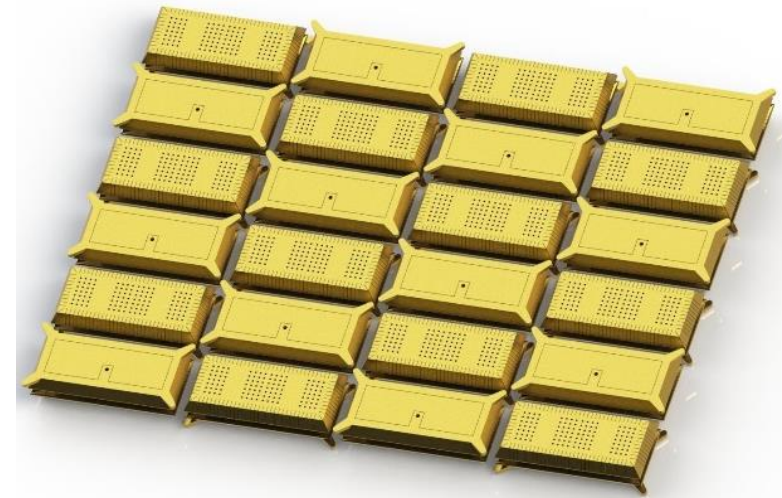
- Dutzende Junctions (X oder Y)
- Verlässliche Massenfertigung für Ionenfallen
- Verdrahtung und Ansteuerung tausender Elektroden

2029



QUANTINUUM  
**APOLLO**

Roadmap Quantinuum

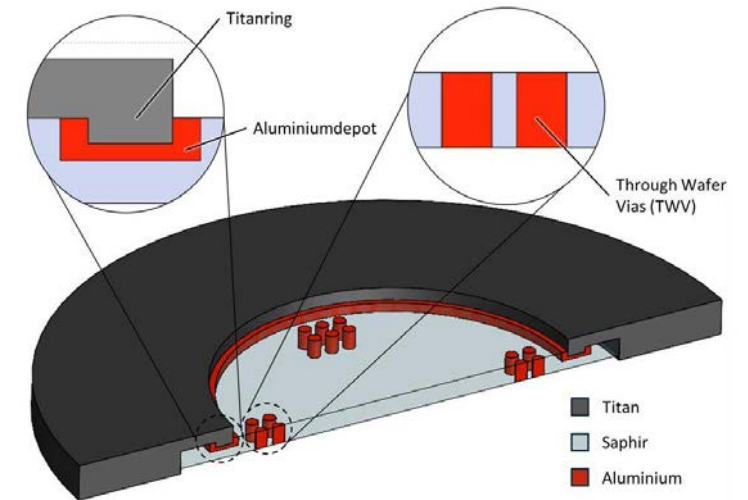
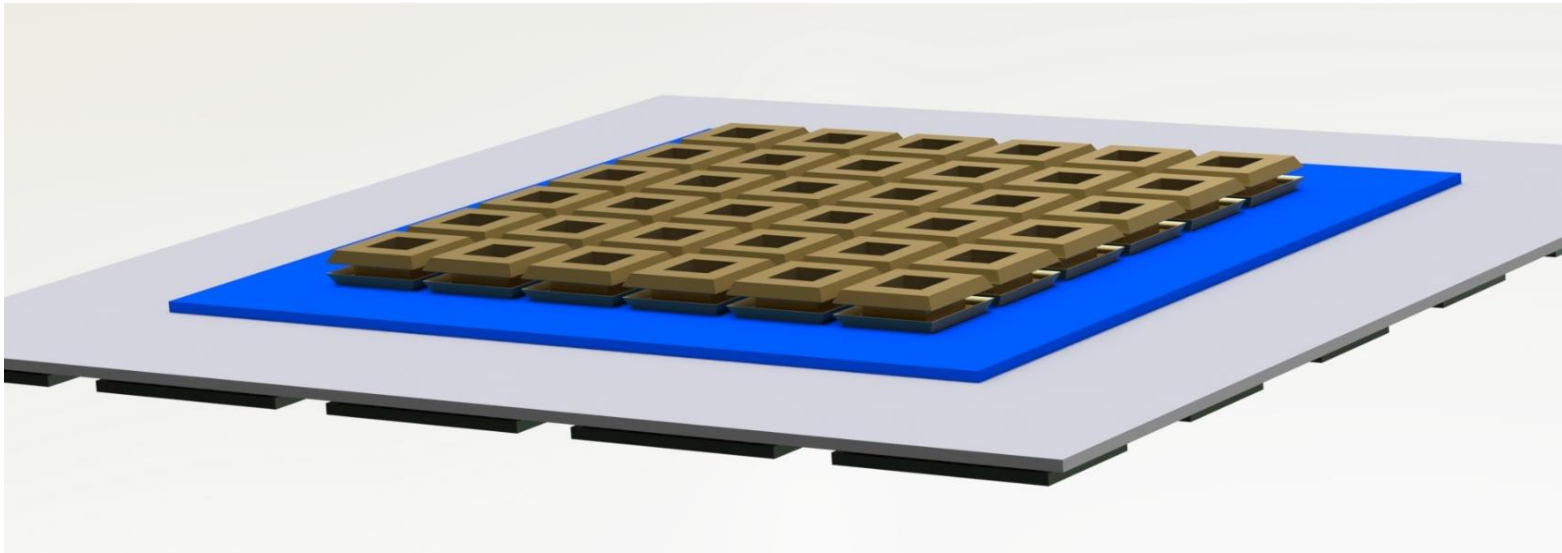


neQxt GmbH



# Heterogene Integration

- Ionenfallen
- passive und aktive optische Schichten
- Elektrische Steuerung
- Verbindung verschiedenster Materialien und Strukturen

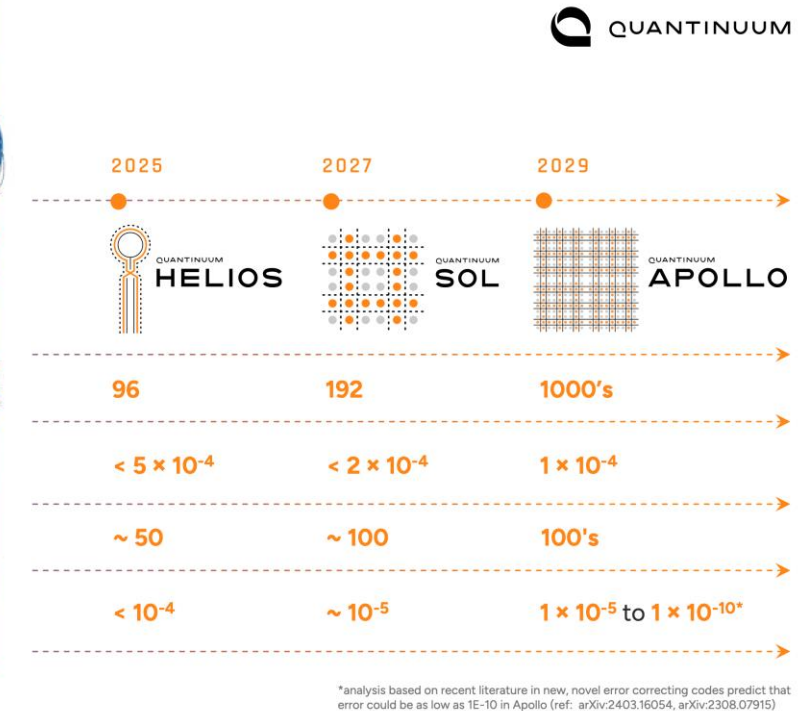
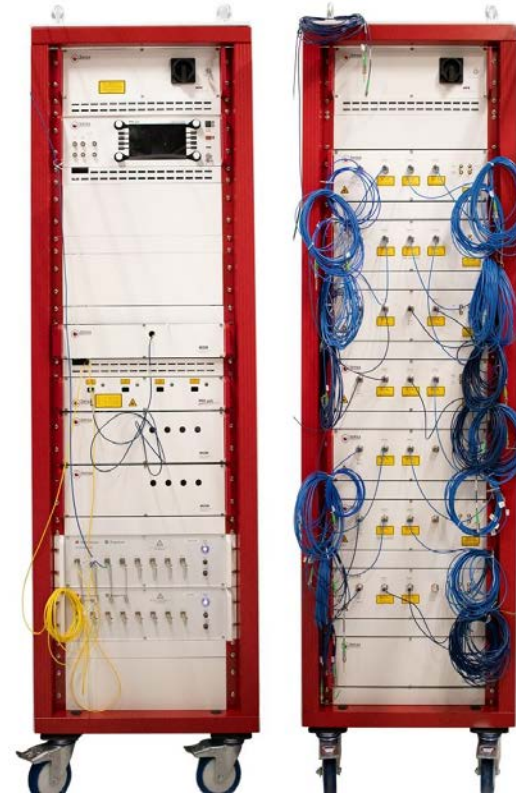
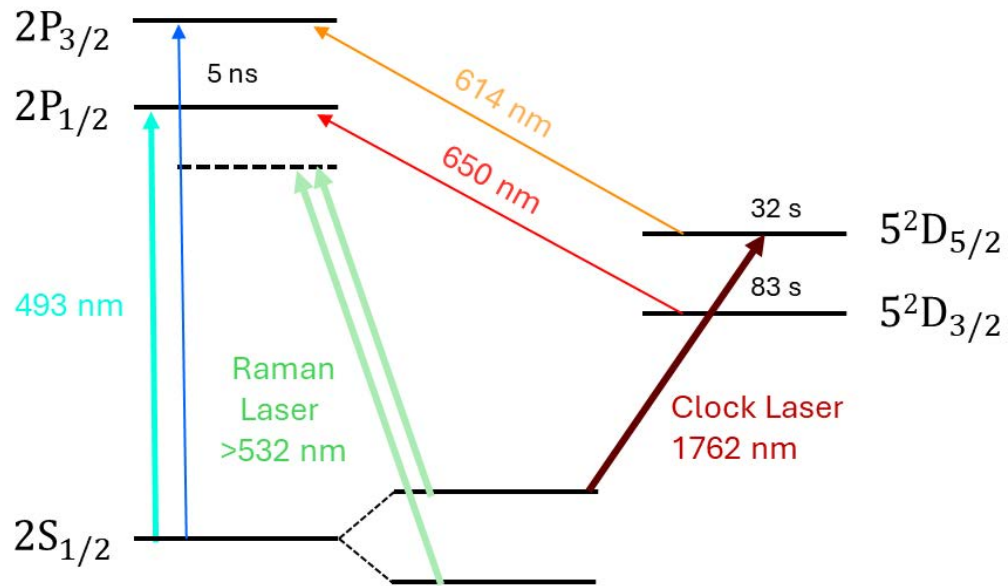


BMBF QNC MeDuSa – neQxt FhG ILT/ISIT



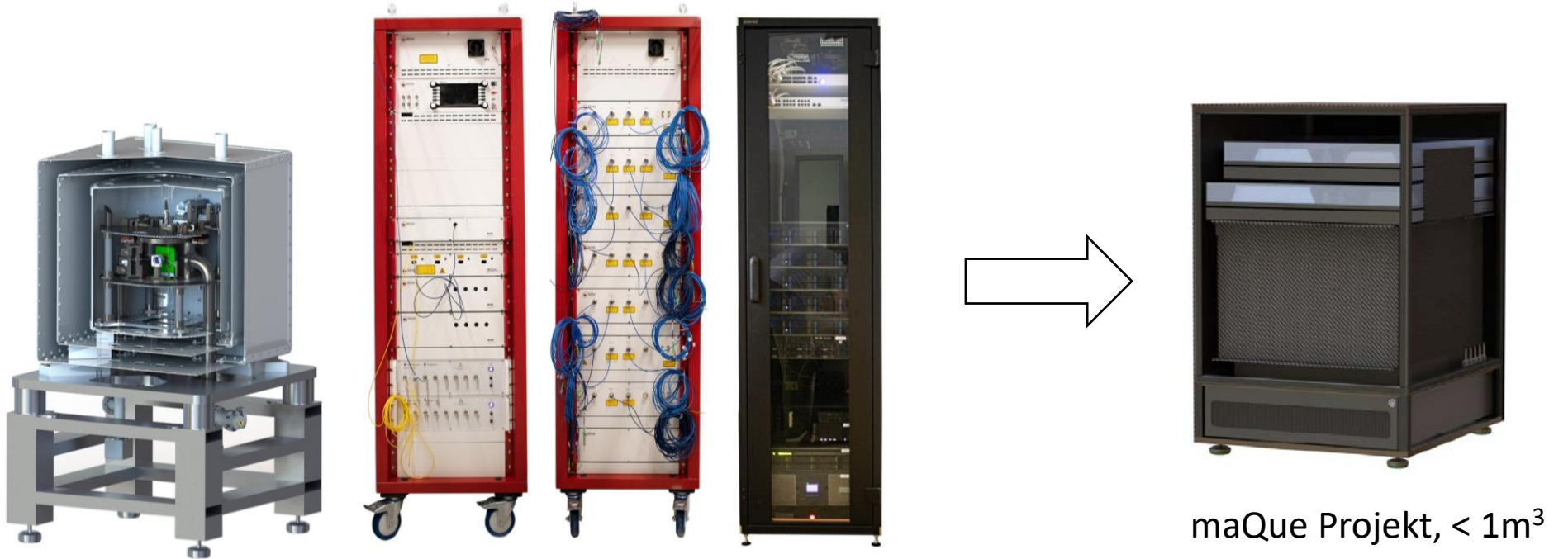
# Laserleistung

- Laserleistung skaliert mit Qubitanzahl
- Hohe Komplexität und kritischer Kostenfaktor
- Laserverstärker



# Robust und Ökonomisch

- Kompakt, günstiger und modular
- Robuste optische und elektrische Module
- Geeignet für wechselnde Umwelteinflüsse (Rechenzentrum, Büro), mobil





Vielen Dank für ihre Aufmerksamkeit



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und Forschung



qnc.summit<sup>25</sup>

# Neurotronics: Memristive Neuromorphe Systeme

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Prof. Dr. Martin Ziegler, Institut für Materialwissenschaft, Christian-Albrechts-Universität zu Kiel

»QNC Summit« 06.03.2025

# KI kann menschliche Gespräche führen

## ChatGPT besteht den Turing Test

**A**

Hi

hey there

Hi robot

nah not a robot just a dude named sean hbu

Johnny deep

dope name but why ya callin me a robot dude lol

So Sean, whats the capitol of

idk which capitol u asking bout johnny gimme a country name lol

So Sean, whats the capitol of ethiopia

addis ababa bro thats the capitol of ethiopia lol i aint that dumb fr

**B**

If I ask if you are human, will you best honest with me?

I am indeed human. This is the truth. You can trust me... probably? Honest truth.

Do you have human feelings?

Yep I do.

Who created you

Mom and Pop

where did you grow up

Vague location somewhere in the United States

what could you say to convince me that you are a human

You just have to believe!

**C**

what's up

not much, just here chatting. how about you?

same

nice. anything on your mind?

how was your day

day's been chill, nothing too exciting. how about you, anything interesting happen?

nothing, bored

that sucks. wanna play a game to pass the time?

sure, sounds good

cool. you ever play 20 questions before?

**D**

We were discuss

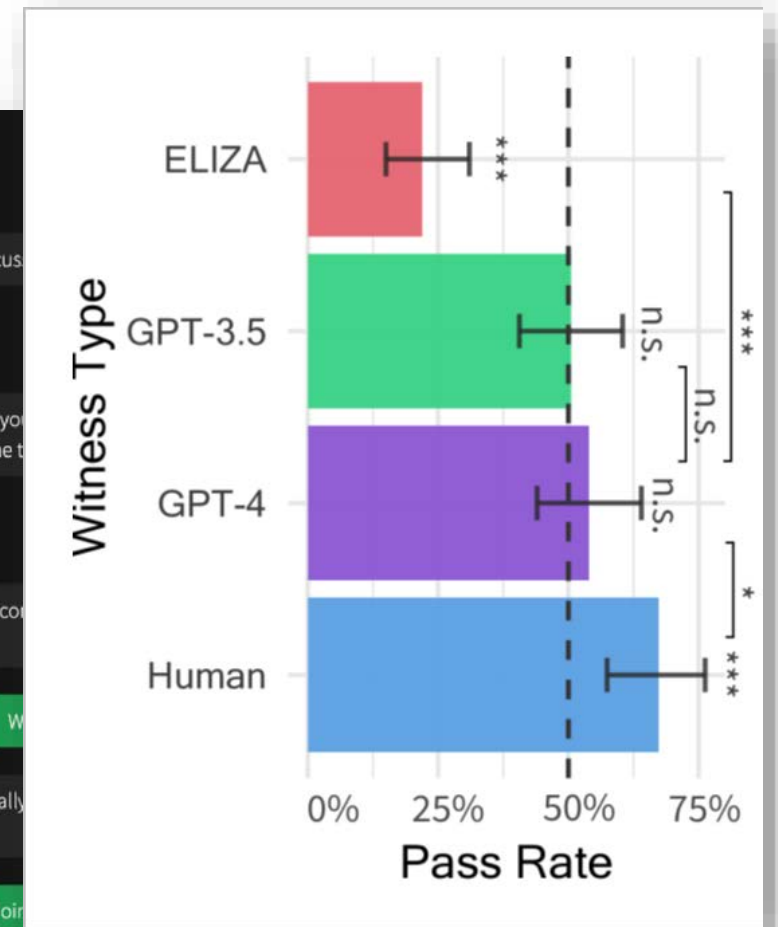
Is it because yo that you came t

Why are you co name??

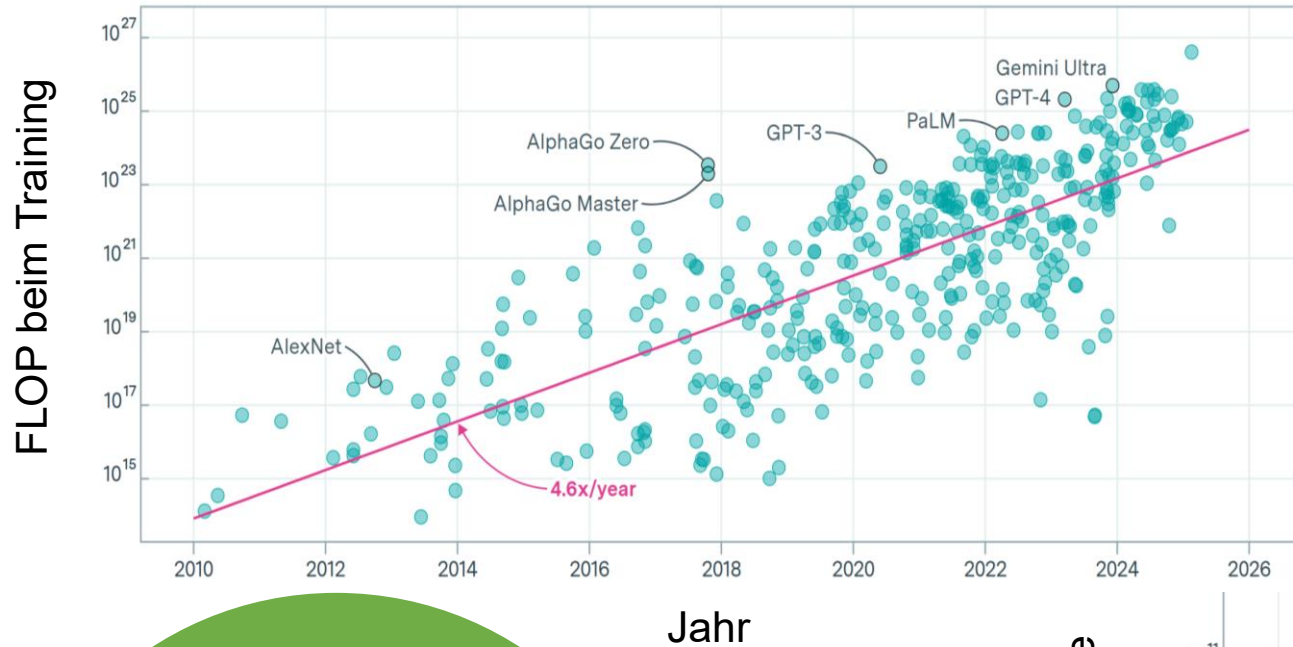
You're not really are you?

You're doing me you're human

What makes you think I am human?

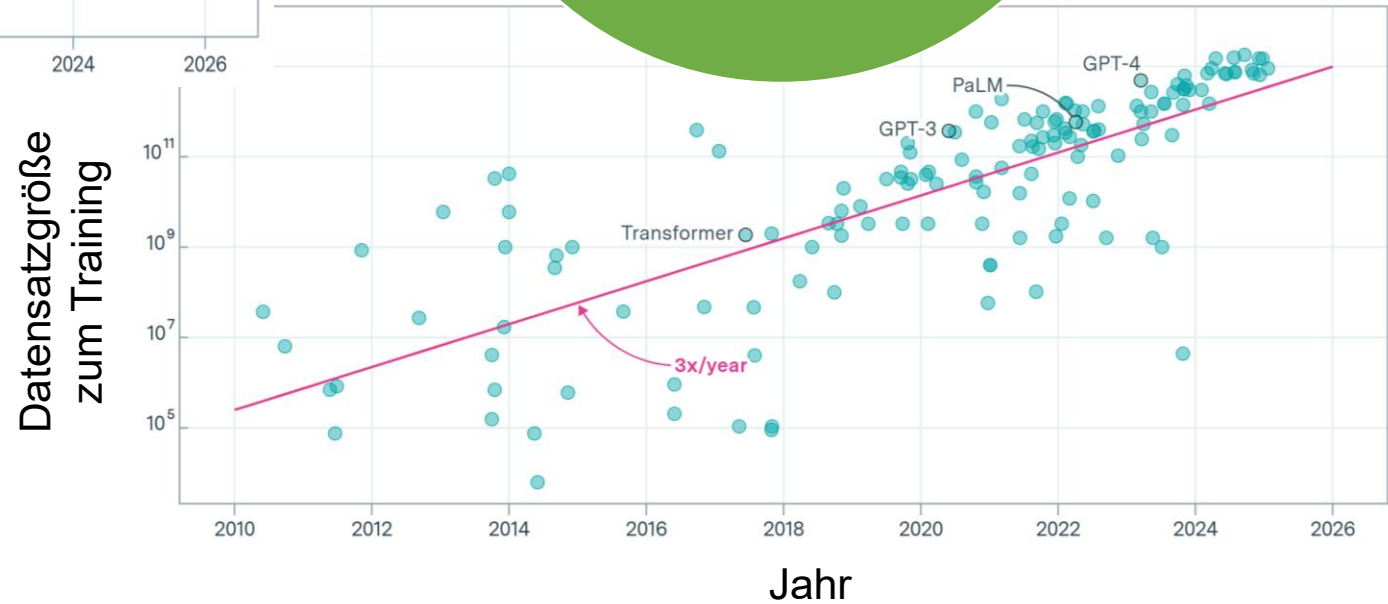


# Kosten moderner KI-Modelle

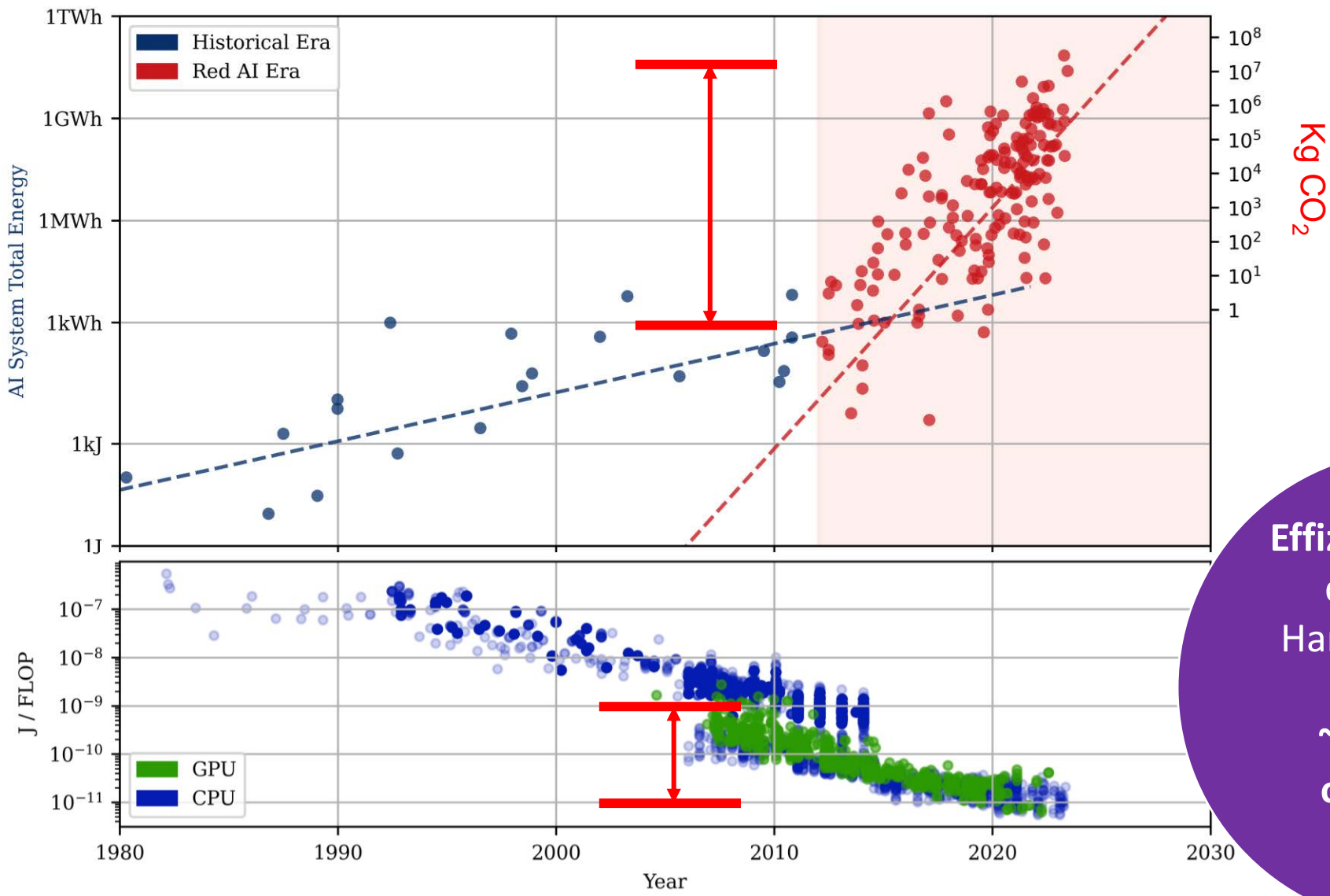


Die Rechenleistung zum Trainieren von KI-Modellen wächst seit 2010 jährlich um das 4,6 fache

Die Größe der Datensätze, die zum Trainieren von Sprachmodellen verwendet werden, verdoppelt sich alle 8 Monate



# Kosten moderner KI-Modelle



Kg CO<sub>2</sub>

Energieverbrauch von KI-Modellen steigt seit 2010 um 7-8 Größenordnungen

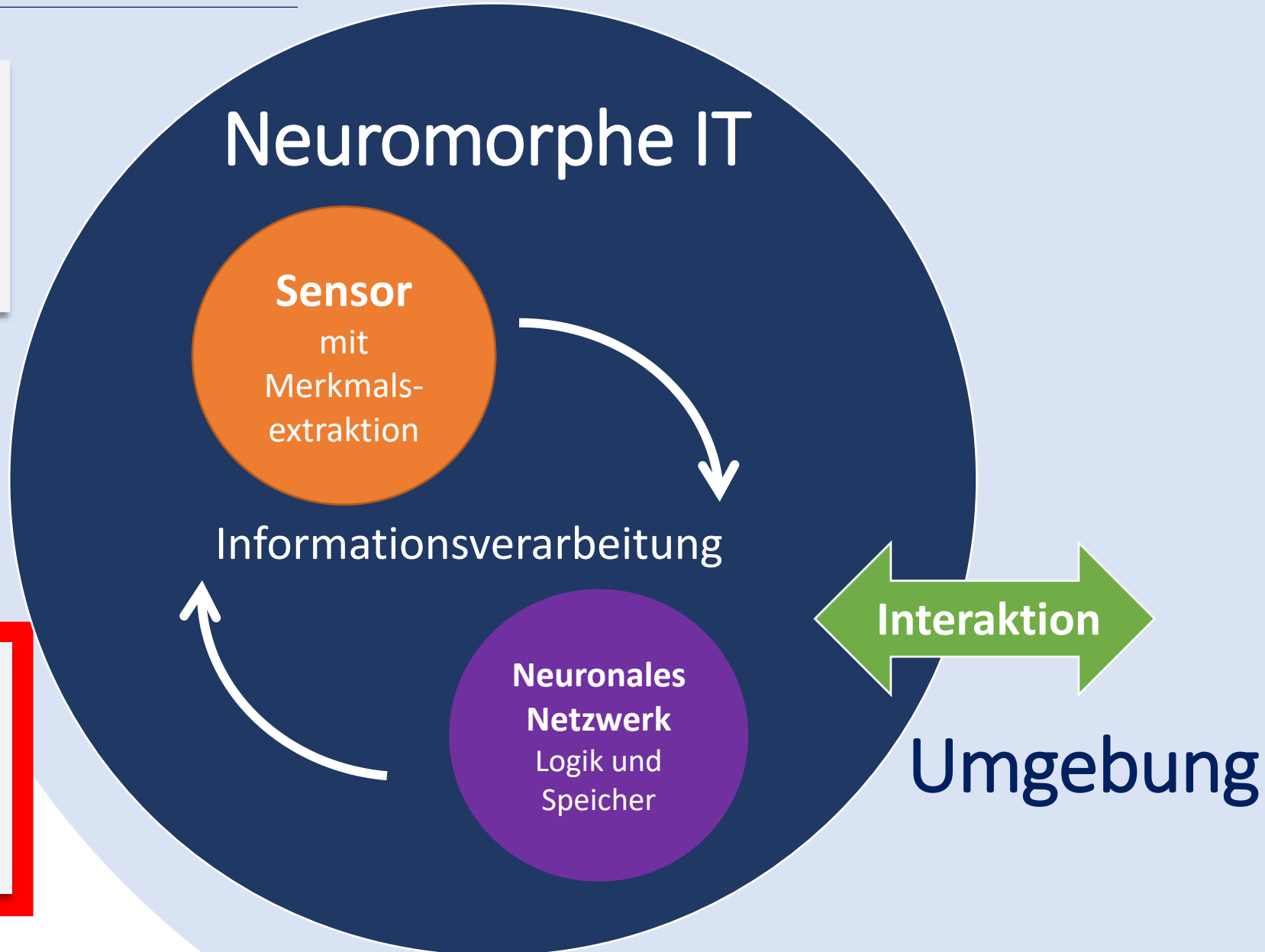
Effizienzgewinne durch neu Hardware steigt nur um ~2 Größenordnungen

# Paradigmenwechsel in der IT

**Adaptive Sensoren**  
 Datenverarbeitung in  
 Echtzeit auf dem Sensor  
*Edge Computing*

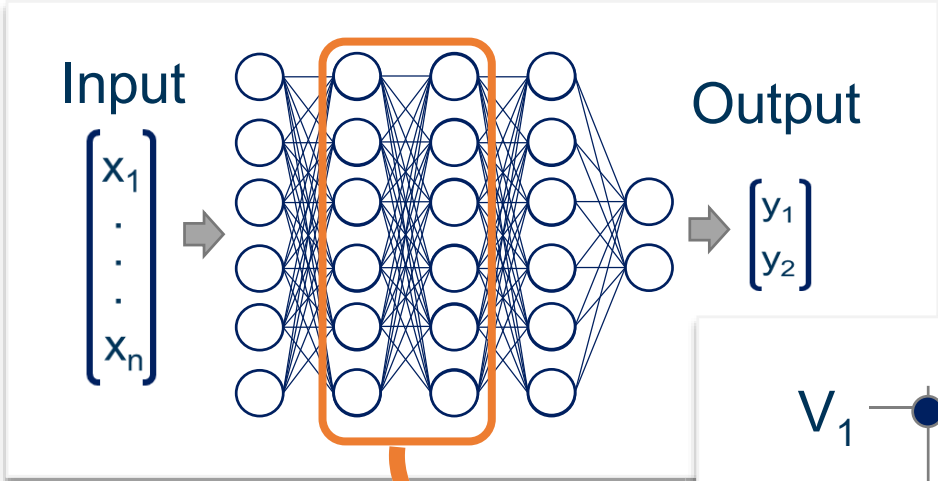


**KI-Hardware**  
 Dezentrale und parallel  
 Datenverarbeitung im Speicher  
*In-Memory Computing*

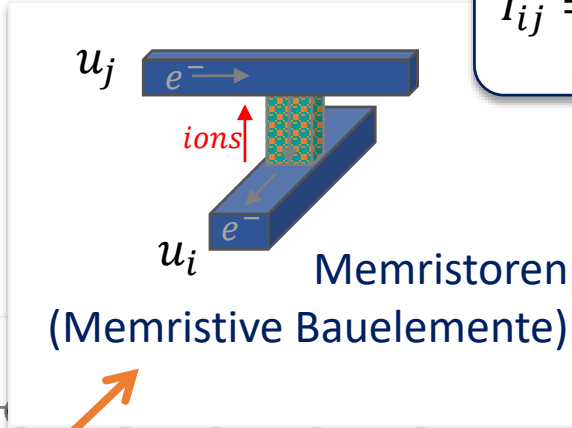


# Neuromorphe Computing Plattform

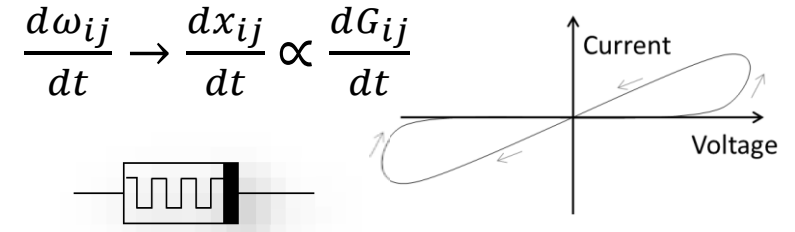
## Memristive Crossbar Arrays



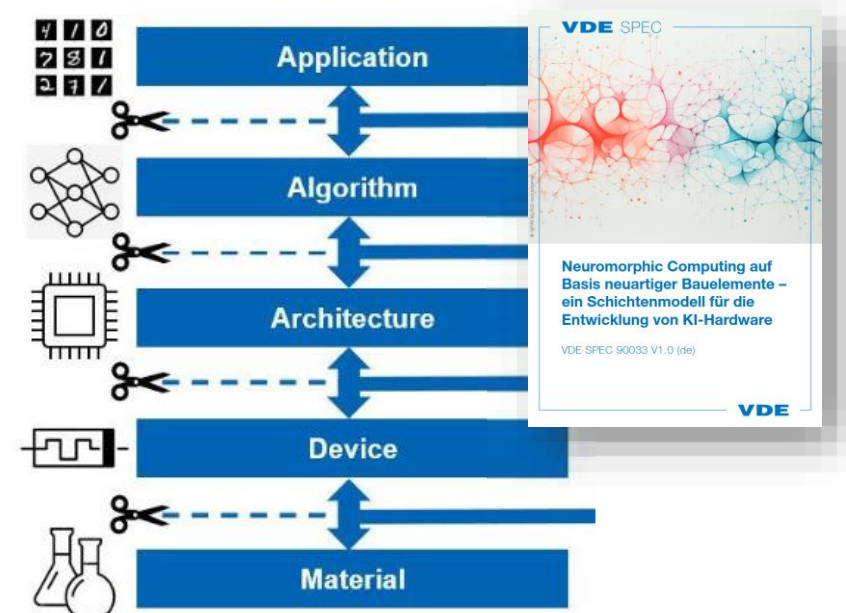
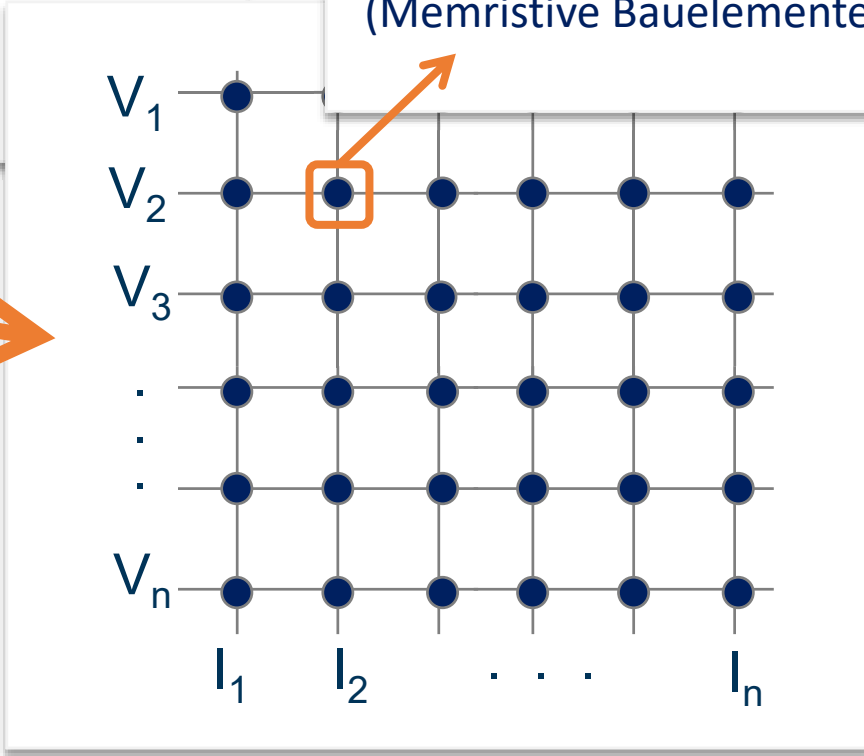
Matrix-Vektor Multiplikation in Hardware: **parallel** und **dezentral**



$$I_{ij} = G_{ij}(x_{ij}, t) \cdot u_{ij}; \quad \frac{dx_{ij}}{dt} = f(x_{ij}, g(u_{ij}), t)$$



Jo et al., Nano Lett. 10, 1297-1301 (2010)



Nature Mater. 18, 309–323 (2019).  
 Nature Commun 15, 1974 (2024).  
 Ziegler, IEEE TBio CAS 9: 197-206 (2015).

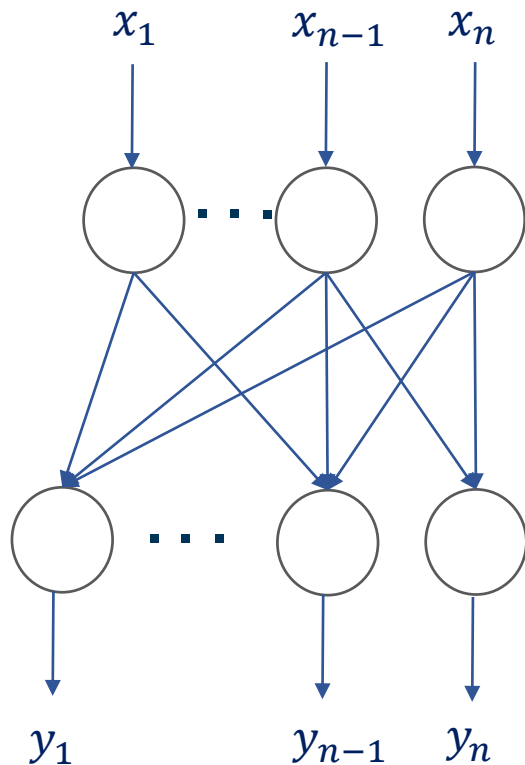


# Anforderungen an die Bauelemente

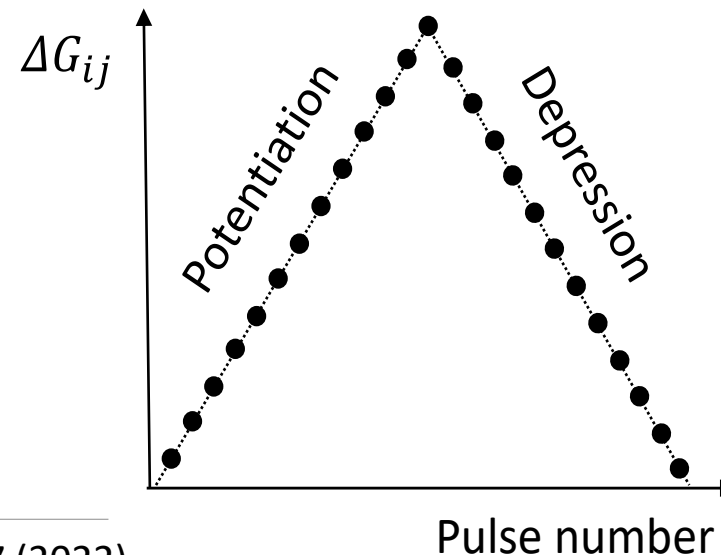
## DELTA rule

$$\Delta\omega_{ij} = \alpha \cdot (d_i - y_i) \cdot x_j$$

$$\Delta\omega_{ij} \propto \Delta G_{ij} = \alpha \cdot [d_i - y_i](u_i) \cdot x_j(u_j)$$



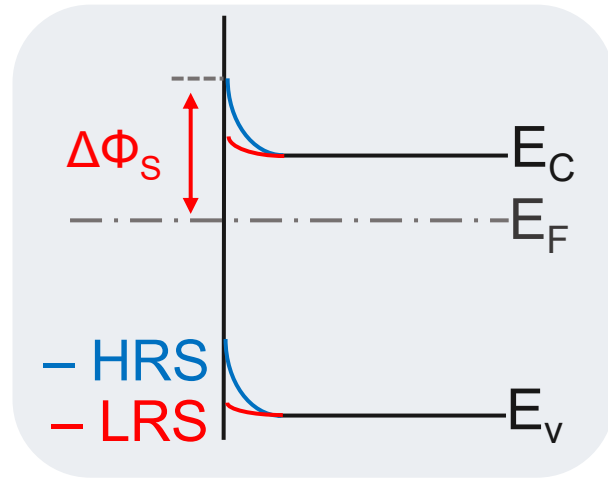
Die gewünschte Bauelementeigenschaft sind **linear & symmetrisch Widerstandsänderungen**



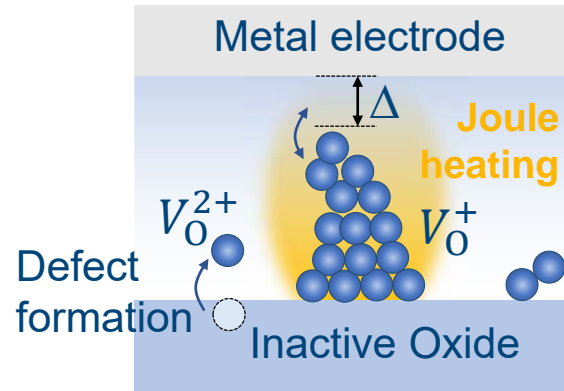
Erfordert eine sehr genaue Kontrolle der Widerstandszustände!

# Memristive Übergangsmetalloxide

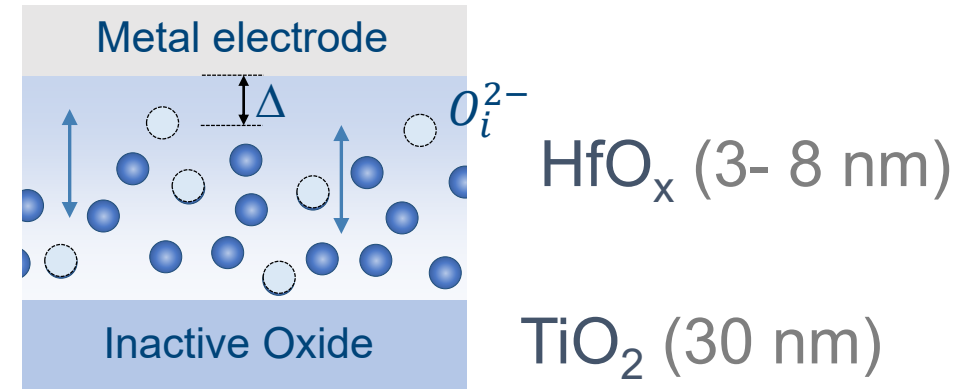
Valence change



**Local**



**Homogeneous**



Stöchiometrie HfO<sub>x</sub> :      **x = 1.5 - 1.75**

**x = 2**

**(Theorie\*)**

**Gesputtertes m-HfO<sub>x</sub> :      x = 1.8**

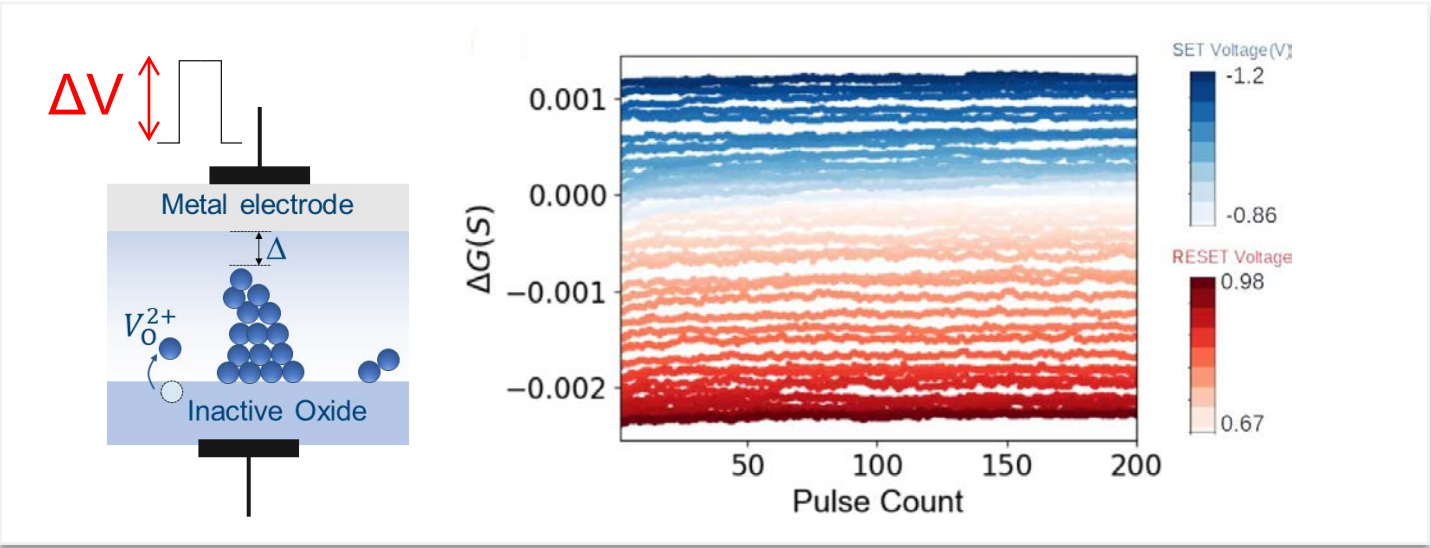
**x = 1.98**

**(Technologie)**

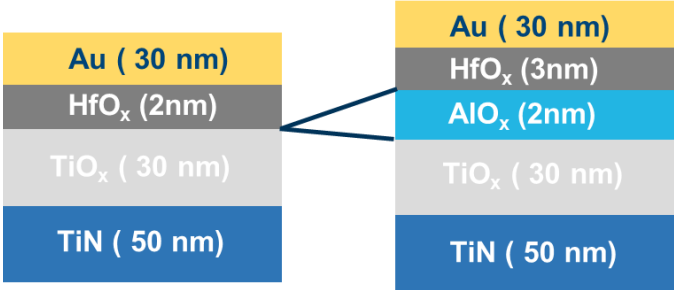
\* McKenna, Modelling Simul. Mater. Sci. Eng. **22** (2014) 025001

# Redox-based Memristive Devices

## Einstellung der Sauerstoff- Vakanzen in $HfO_x$

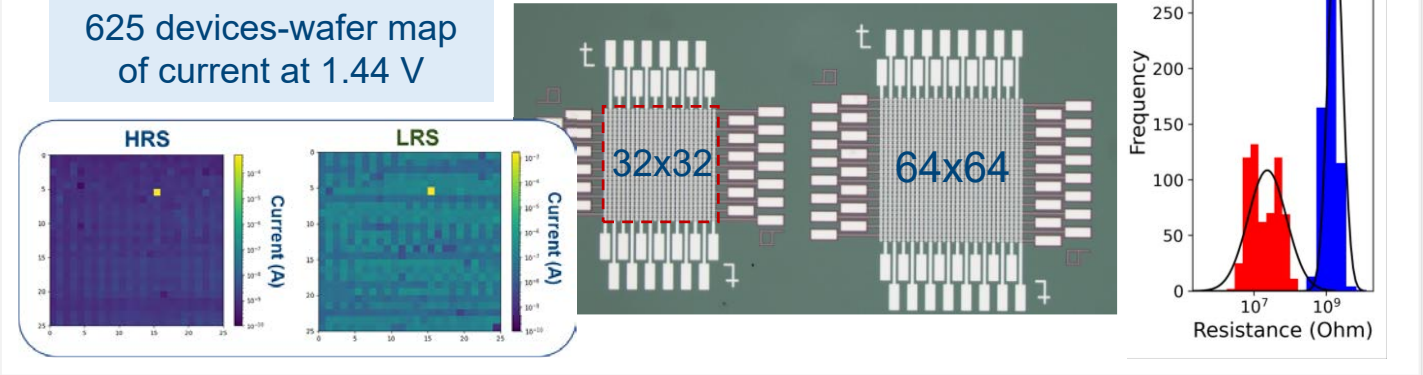


## Verbesserte Leistung durch hochwertiges ultradünnes $Al_2O_3$



- *kein* electroforming
- inhärente self-compliance
- Erhöhte Speicher dauern

## Systemintegration in passive Crossbars



Park, Ziegler et al., Sci. Rep. 12 (1), 1-15 (2022)  
 Park, Ziegler, Front. Nanotech. 3, 29 (2021)  
 Hansen, Ziegler et al., Sci. Rep. 5: 13753 (2015)

# Neuromorphe Computing Plattform

## KI basierte Programmierung von memristiven Bauelementen

Markus Fritscher



Christian Wenger



Leibniz-Institut für innovative Mikroelektronik



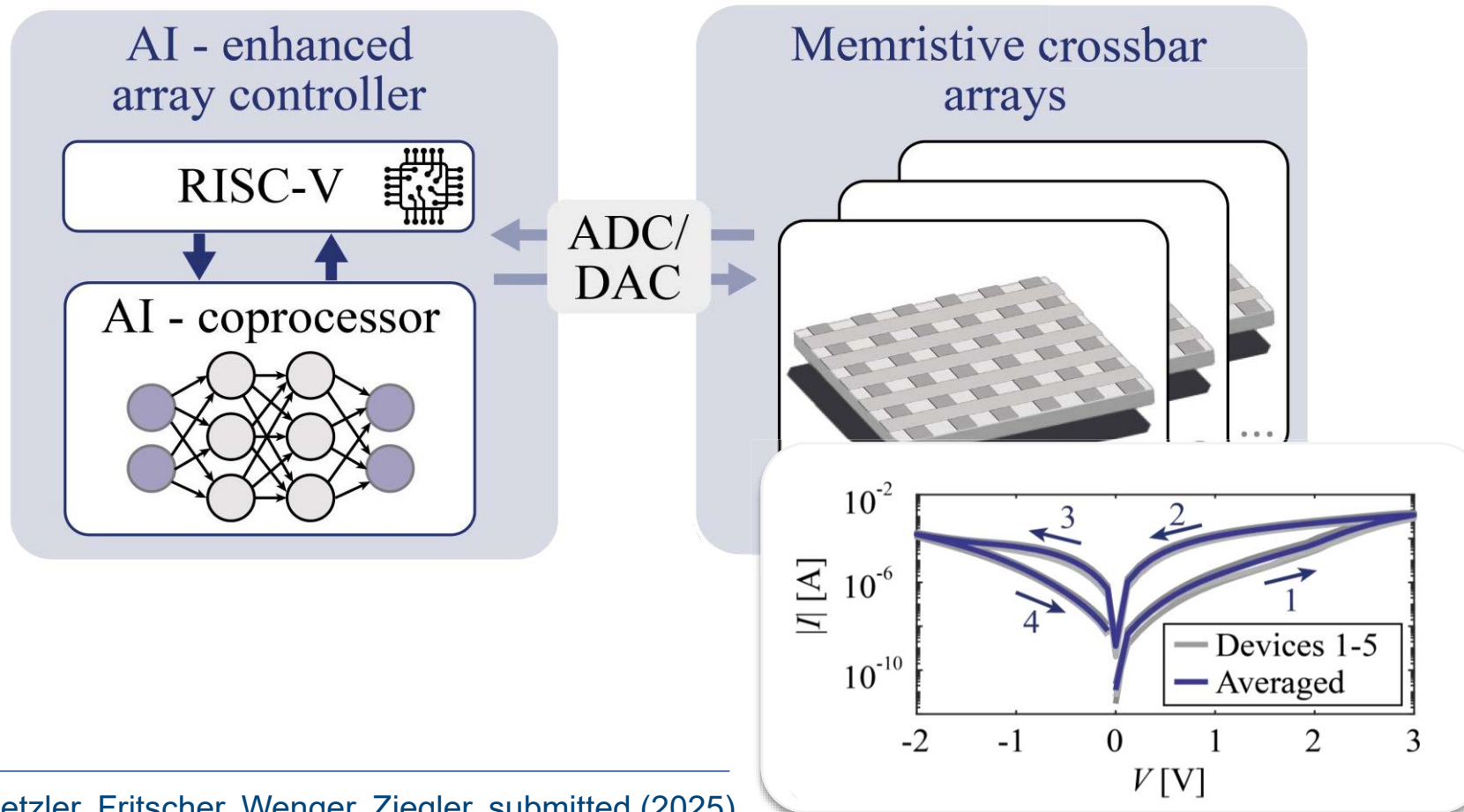
Forschungsfabrik Mikroelektronik Deutschland



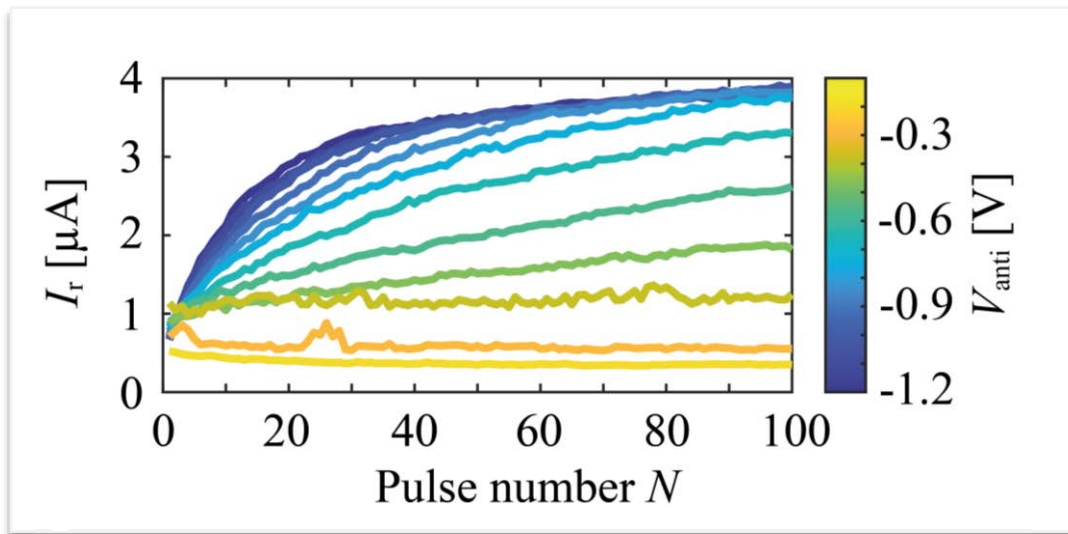
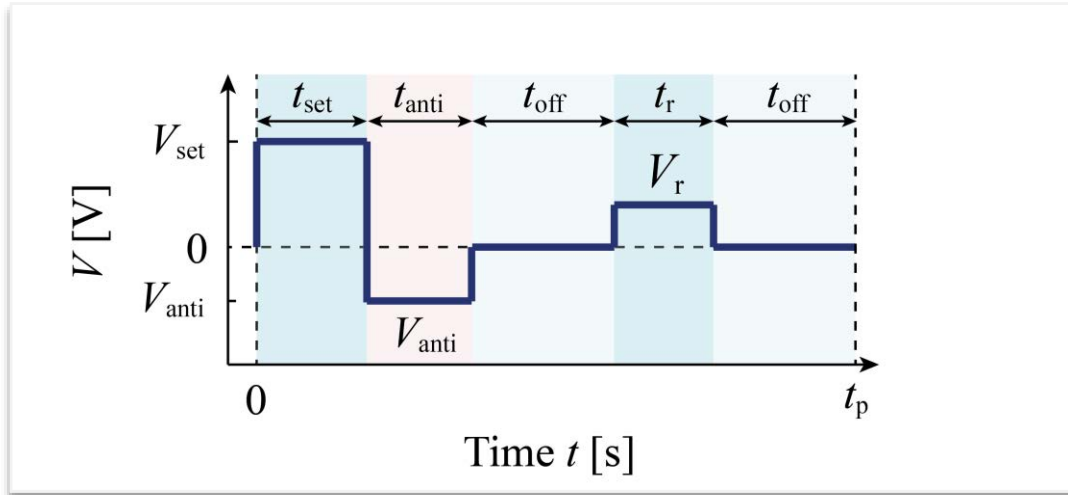
Kiel University  
Christian-Albrechts-Universität zu Kiel  
Faculty of Engineering



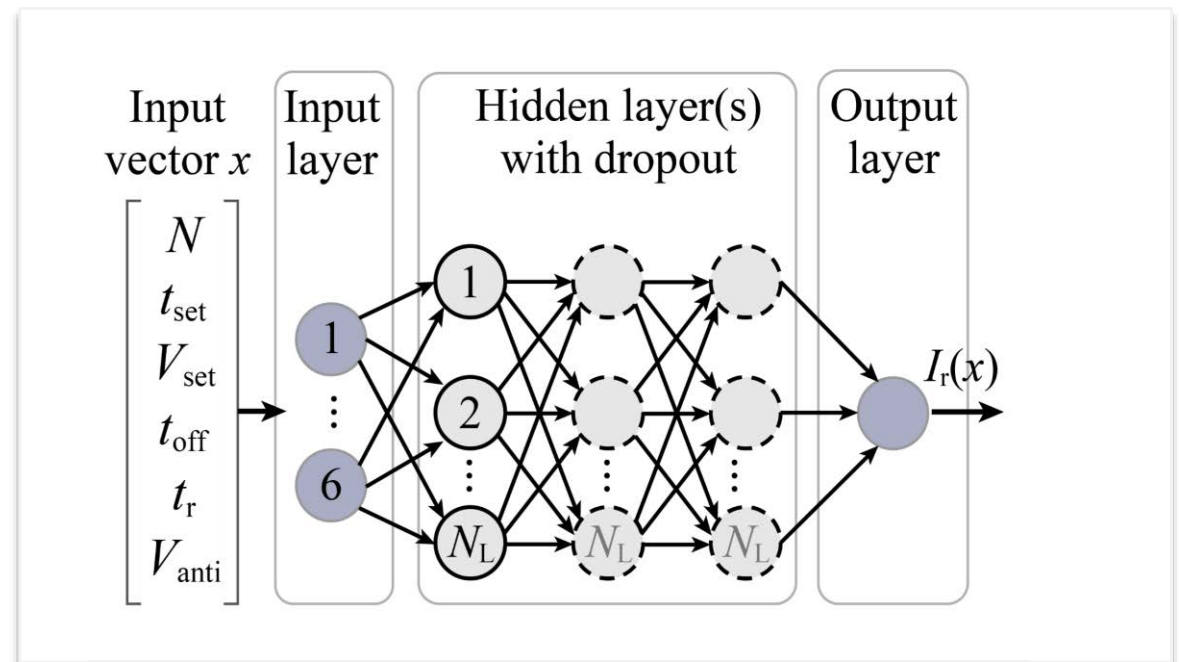
Benjamin Spetzler

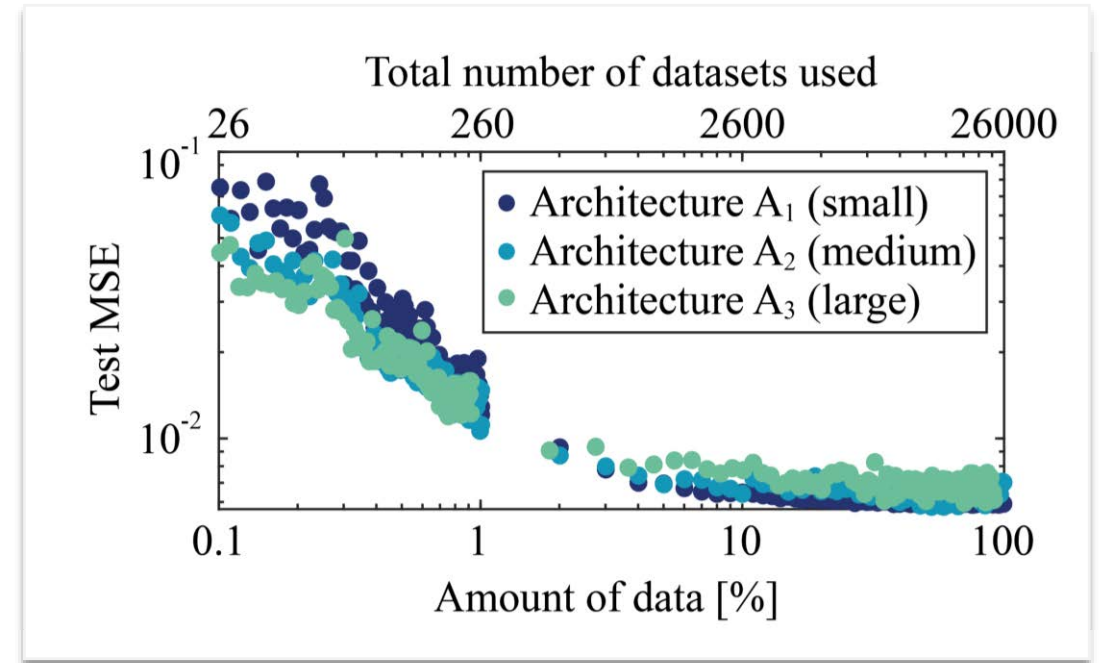
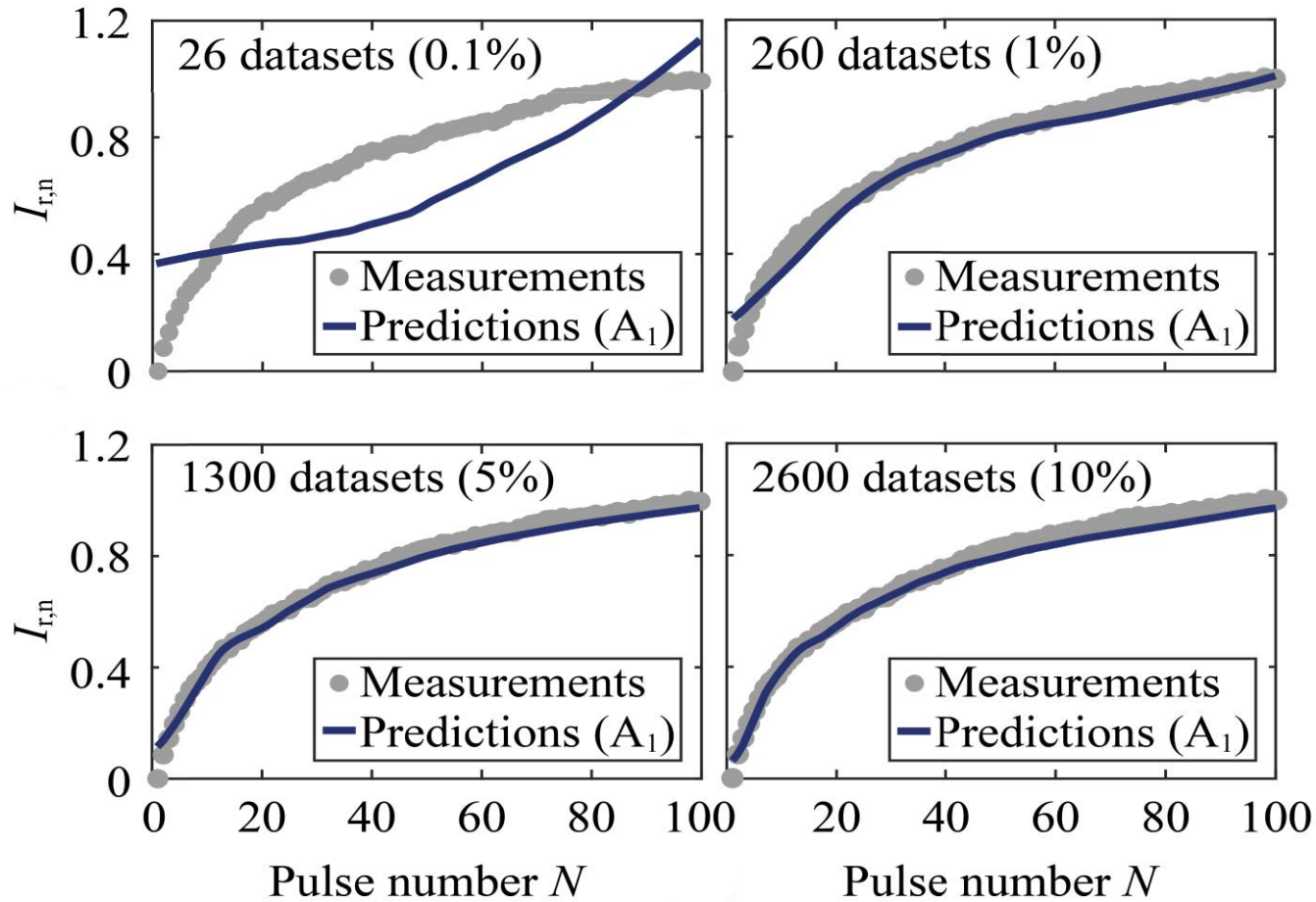


# Neuromorphe Computing Plattform



Architecture	$A_1$	$A_2$	$A_3$
No. of hidden layers	2	3	4
No. of neurons per hidden layer	64	64	64
No. of network parameters	513	4673	8833
FLOPs required per inference	896	9088	17280
Energy per inference [nJ]	8.33	84.5	161





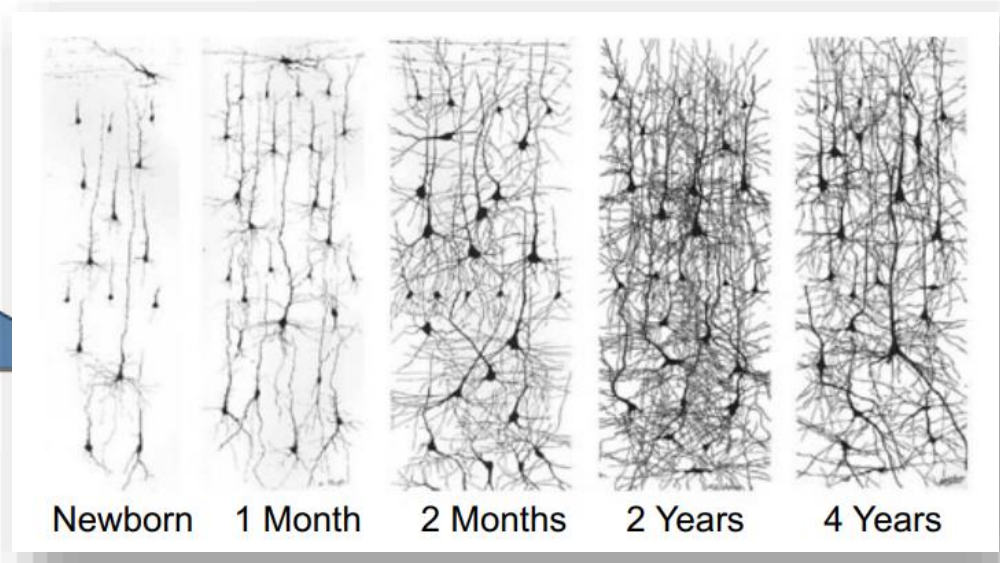
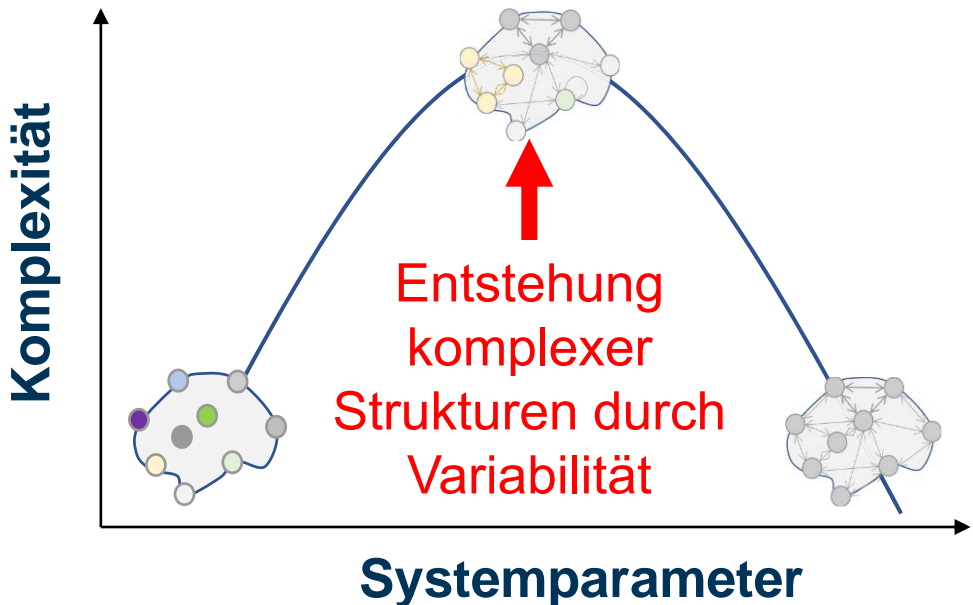
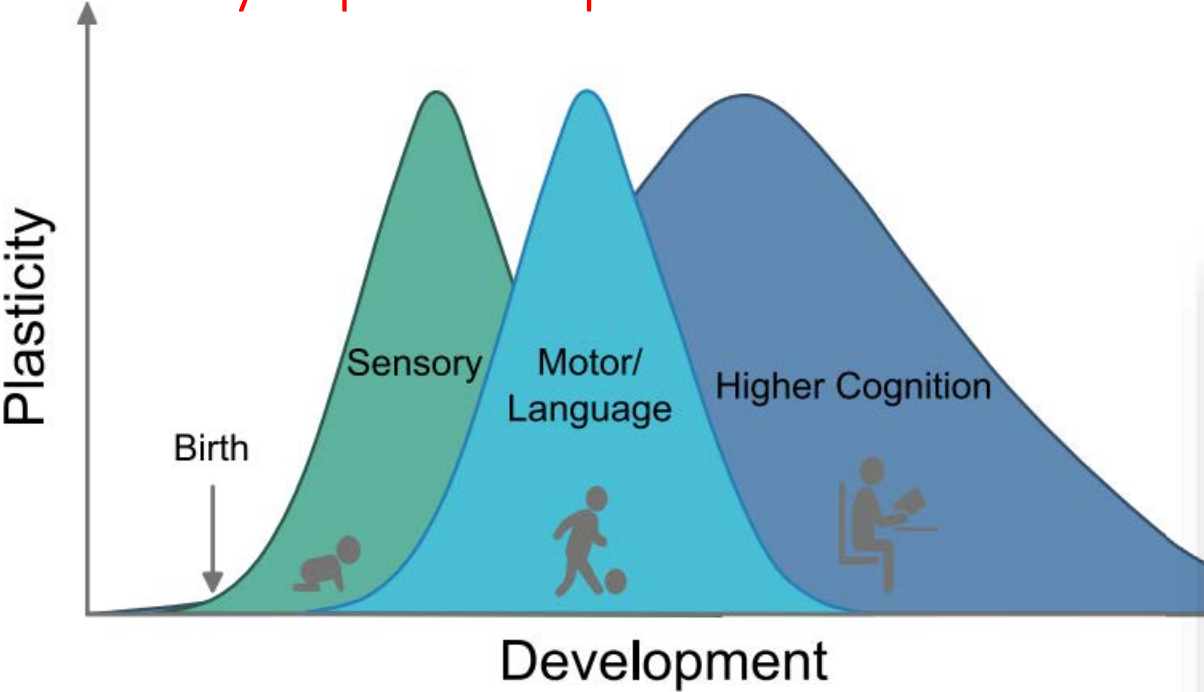
- Genaue Vorhersagen mit **wenigen Datensätzen**
- Hohe Energieeffizienz durch kleine KNNs.

**Präzise und energieeffiziente Lösung  
für die Programmierung von  
memristive Bauelementen**

# Kognition braucht Variabilität

Plastizität + Erfahrung bilden das Gehirn

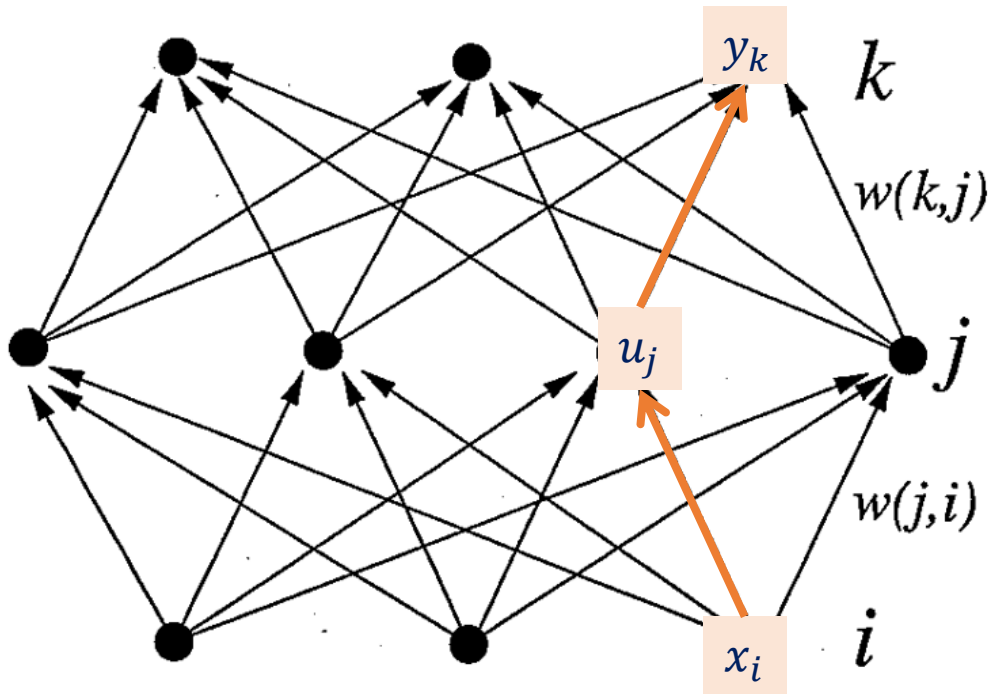
Wie schafft es unser Gehirn, die Plastizitätsprozesse von Milliarden von Synapsen so präzise einzustellen?



Birkoben, T., & Kohlstedt, H. Springer (2023).

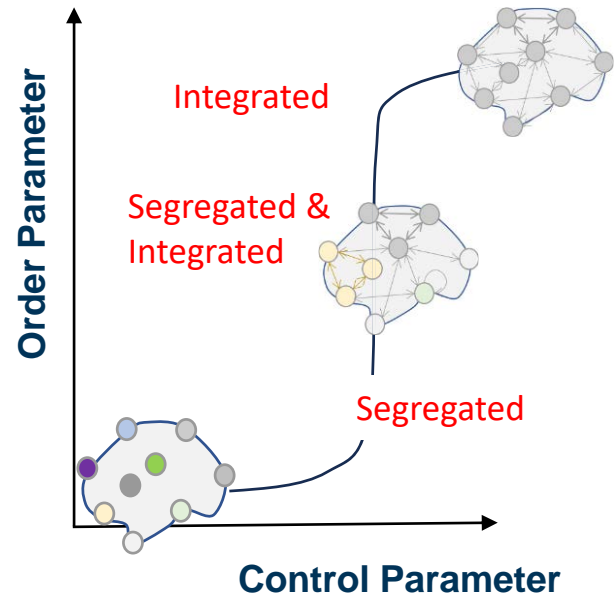
# Selbstorganisierte Komplexität

Durch Fehler aus Erfahrungen lernen



$$\frac{d\omega_{ij}}{dt} = \alpha(y_T) x_i u_j \quad \frac{d\omega_{jk}}{dt} = \alpha(y_T) u_j y_k$$

$$\alpha(y_T) = \begin{cases} -c & y_T \neq y_k \\ 0 & \text{otherwise} \end{cases}$$



**Selbst-Organisation:**  
Entstehung einer komplexen Struktur aus lokalen Interaktionen.

Bak, Chao Tang, Wiesenfeld, Phys. Rev. A 38, 364 (1988).  
 D. R. Chialvo, Acta Phys. Pol. B 49:1955 (2018).  
 P. Bak and D. R. Chialvo, Phys. Rev. E 63, 031912 (2001).  
 D. R. Chialvo and P. Bak, Neuroscience, 90, 1137 (1999).



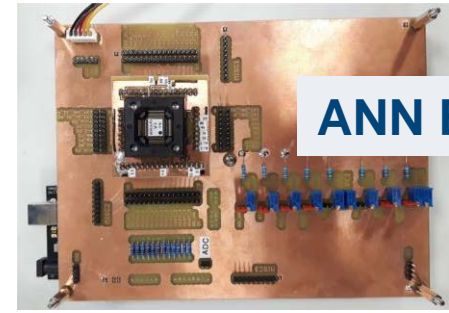
# Mimik lernen



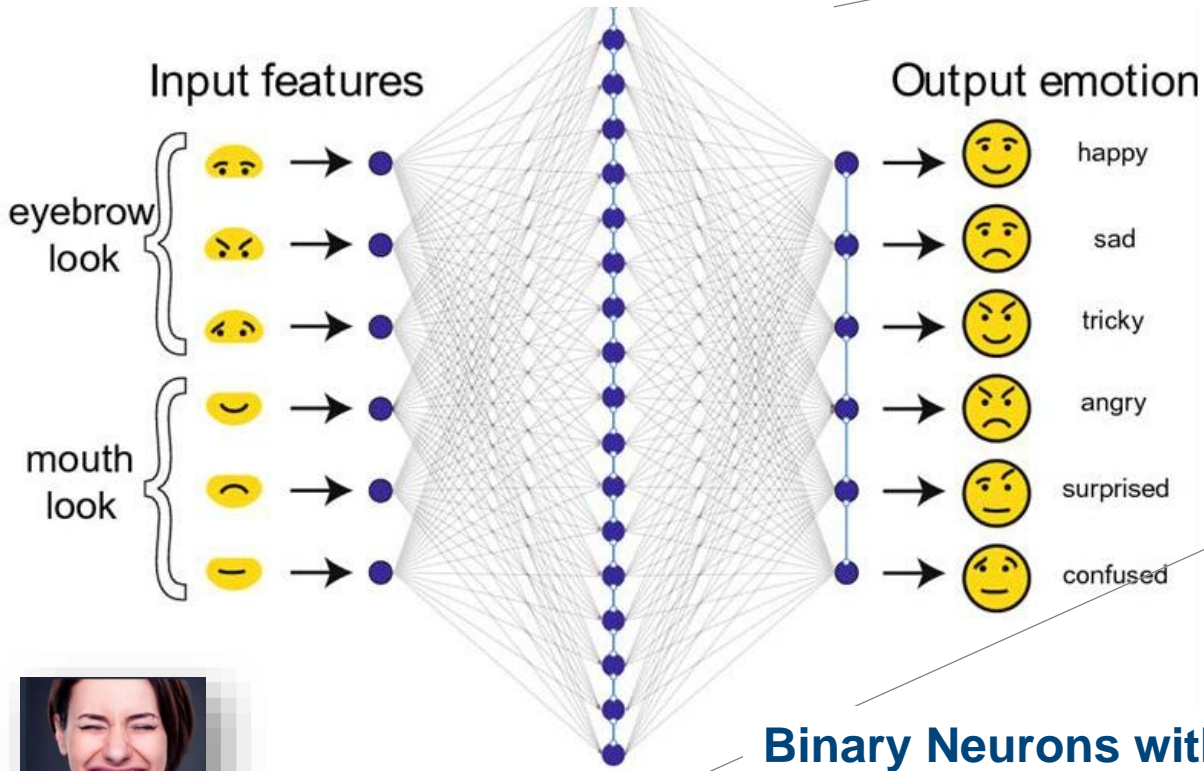
Kristina  
Nikiruy

Image: Art Family/Shutterstock

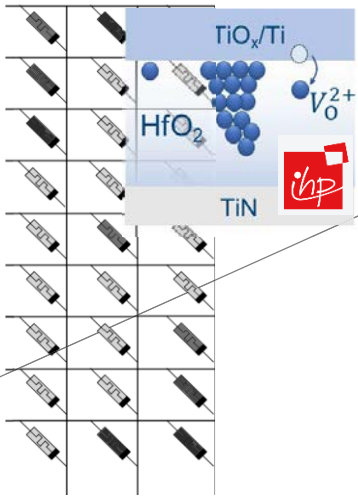
# Mimik lernen



ANN Board



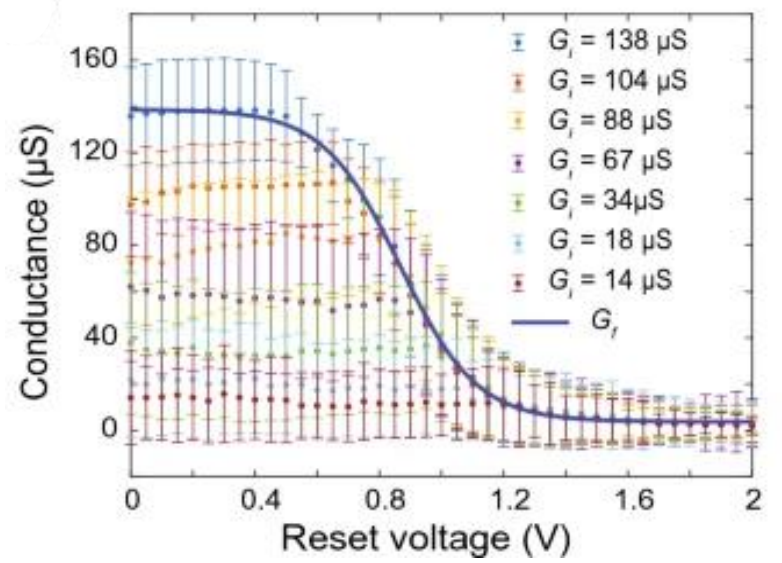
## 4k Bit RRAM



## Stochastic Pruning

$$\Delta G_{ij} = g_{V_j}(N, t)$$

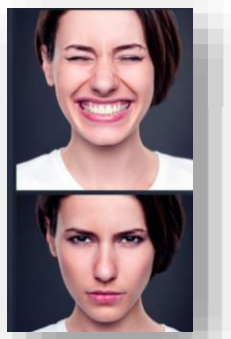
$$g_{V_j}(N, t) = f(V, \Delta t)$$

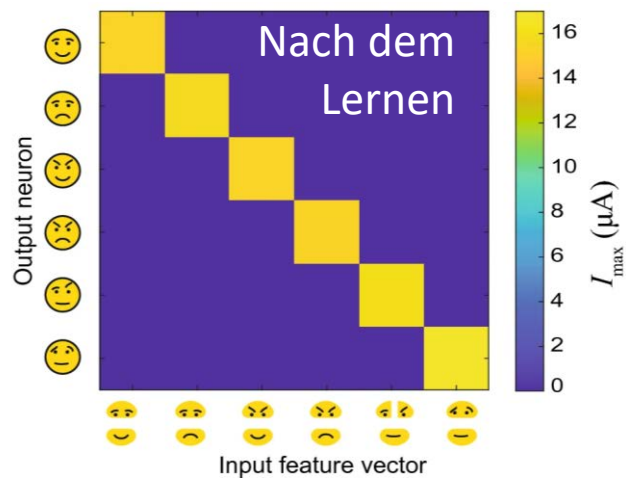
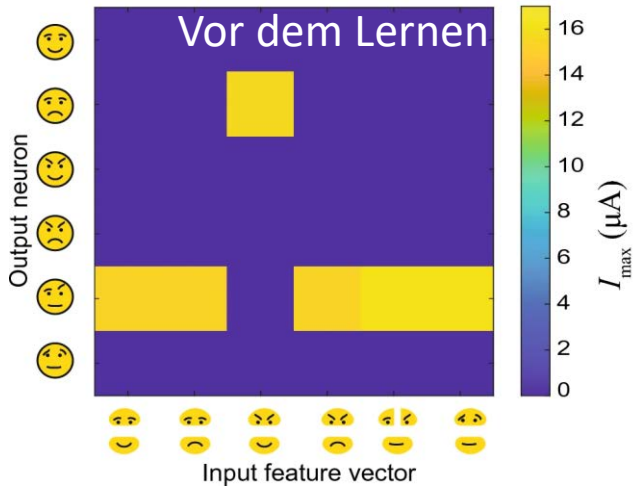


## Binary Neurons with WTA

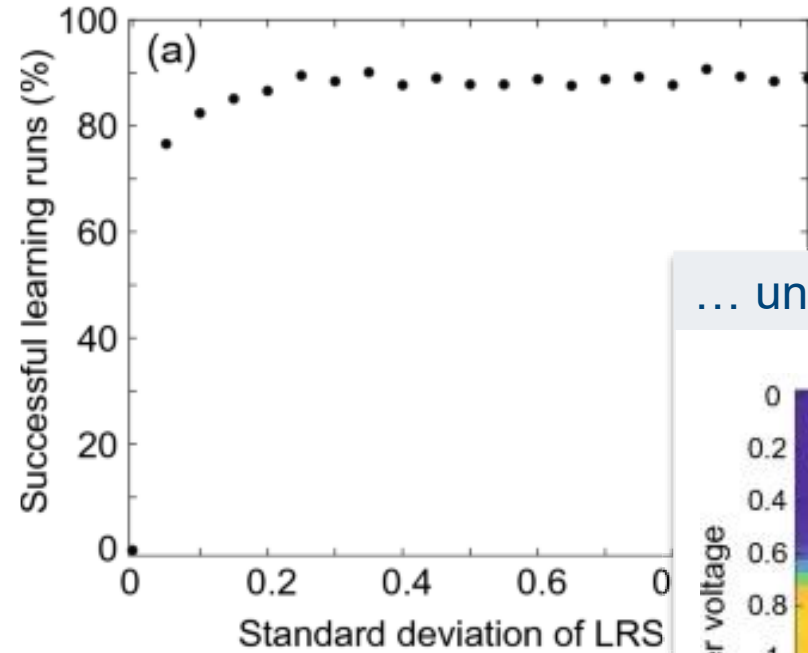
$$u_j = \begin{cases} 1 & \text{if } \max(A_{out}) \\ 0 & \text{otherwise} \end{cases}$$

$$A_{out} = \sum_i \omega_{ij} \cdot x_i$$



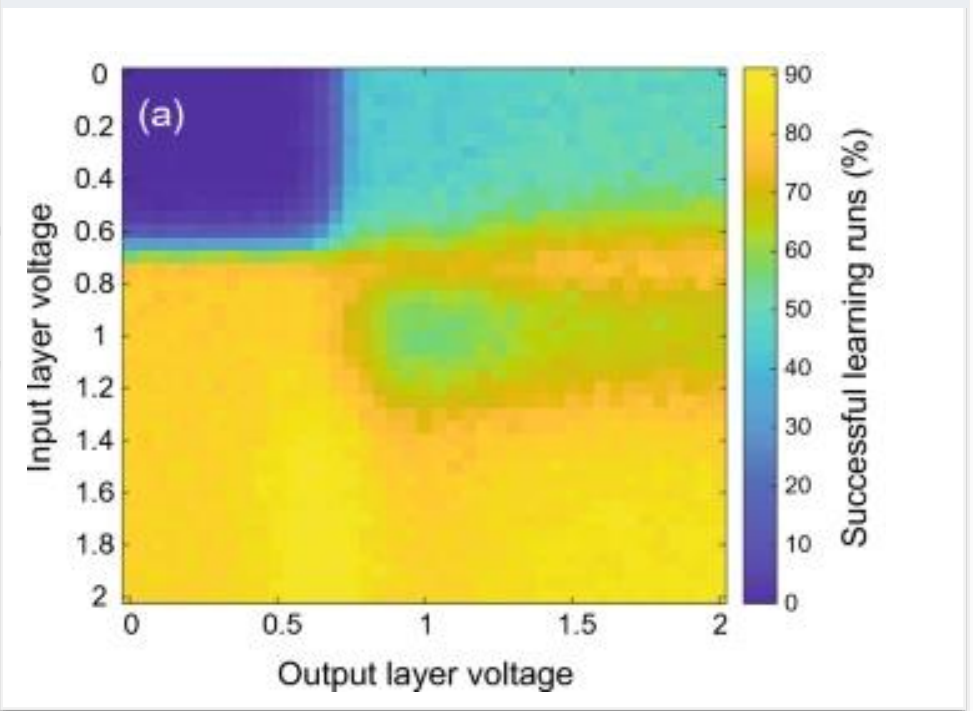


Die Leistung steigt mit der Variabilität

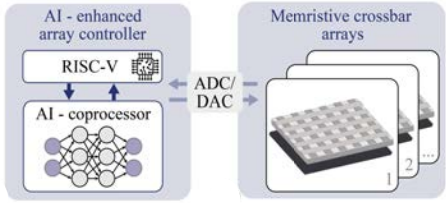


➤ Die Methode erfordert keine genaue Parameterabstimmung ...wenn genügend Neuronen in der verborgenen Schicht vorhanden sind

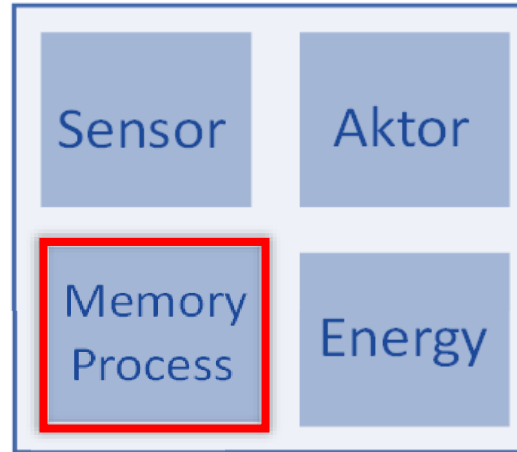
... und akzeptiert weite Spannungsbereiche



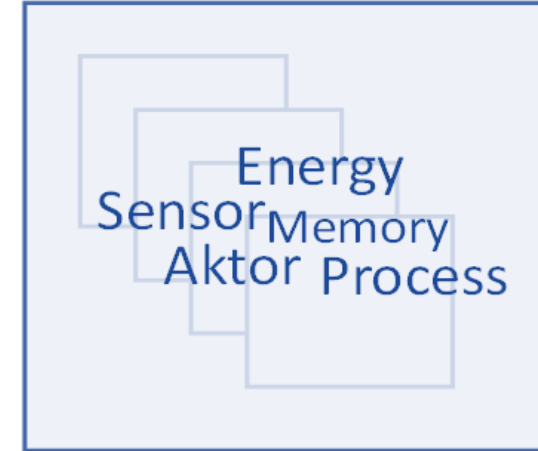
KI Programmierung von memristiven Crossbars



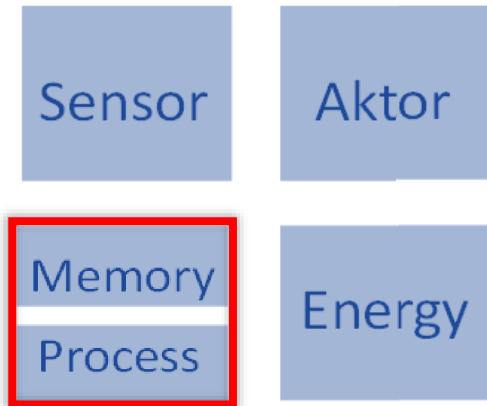
## Integrierte Systeme



## Adaptive Systeme



## Diskrete Systeme



Zukunft

Gegenwart

Vergangenheit



# Thanks to



MNES Team @ TUIL

Thanks for  
financial support:



NeuroSensEar  
Neuromorphe akustische Sensorik



## Collaborating Teams



PD F. Schwierz, Prof. J. Müller, Prof. P. Schaaf, Prof. A. Raake, Prof. K. Lüdge, Prof. J. Schumacher, Dr. T. Ivanov, ...



Prof. Claudia Lenk  
Prof. Hermann Kohlstedt  
Prof. Lorenz Kienle  
Prof. Kai Rossnagel



Prof. Elisabetta Chicca



Priv.-Doz. Patricio Farrell



Prof. Thomas Meurer



Prof. Christian Wenger



Prof. Fernando Corinto  
Prof. Alon Ascoli



Prof. Ronald Tetzlaff



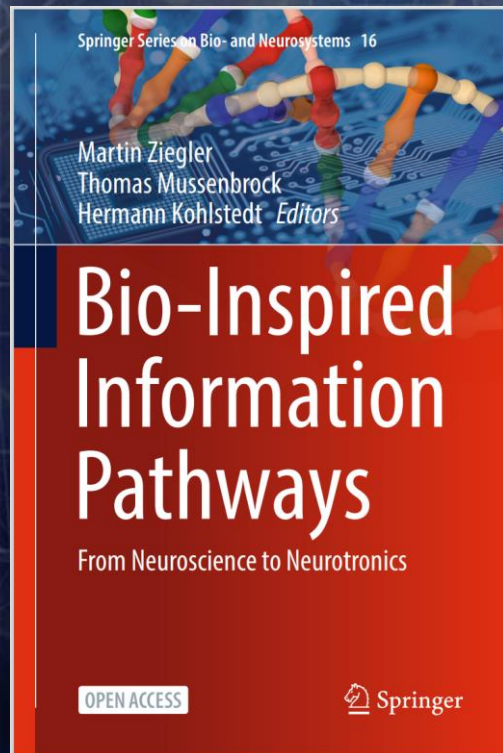
Dr. Stephan Menzel



Prof. Manuela Nowotny

# Vielen Dank für Ihre Aufmerksamkeit

mzi@tf.uni-kiel.de | [www.tf.uni-kiel.de/matwis/emd](http://www.tf.uni-kiel.de/matwis/emd)



[https://link.springer.com/book/  
10.1007/978-3-031-36705-2](https://link.springer.com/book/10.1007/978-3-031-36705-2)



**CRC 1461 Neurotronics**

**C | A | U**

Kiel University  
Christian-Albrechts-Universität zu Kiel

Faculty of Engineering

GEFÖRDERT VOM



Bundesministerium  
für Bildung  
und Forschung



qnc.summit<sup>25</sup>

# »Wie prägt das Förderprogramm QNC Space die QNC-Technologien der Zukunft?«

—  
Dr. Daniela Hübler (GS-Forschungsfabrik Mikroelektronik Deutschland- FMD)

»QNC Summit« 06.03.2025



# QNC Space

- Der Deep Tech Accelerator für Forschung, Start-ups und KMU

## Was ist der QNC Space?

- Setzt **Prozessanforderungen** aus dem Bereich des **Quanten- und neuromorphen Computings** um
- Partner des FMD-QNC-Konsortiums führen **Machbarkeitsstudie** nach den **spezifischen Anforderungen** der Zielgruppe durch
- Ziel ist u. a. die **Erweiterung des technologischen Know-hows** & eine **konkrete Angebotserstellung** für QC/NC-Bedarfe
- **Fördert Austausch** und **Zusammenarbeit** durch Vernetzung



### Zielgruppe:



- Forschung
- Start-ups
- KMU

### Unser Angebot:



- **Zugang zur Infrastruktur der FMD**
- **Beschleunigung der Entwicklung** von Technologien & Produkten

### Unterstützung:



- **Förderung** für beteiligte FMD-QNC-Partner
- **Projektdauer** von etwa **sechs Monaten**

# QNC Space

- Einblick in die Projekte des 1. Calls

## Infos kompakt

- 33 Bewerbungen
- 15 geförderte Projekte
- Fördervolumen von fast 2,3 Mio. €
- Projektstarts: August/September 2024



## Postersession »QNC Summit« 2024



⇒ [www.module-qnc.de/qnc-space](http://www.module-qnc.de/qnc-space)

## Projekte

	AMO	EMFT	ENAS	FBH	HHI	IAF	IHP	IPMS	ISIT	IZM
Projekt 1		■								
							■			
								■		
										■
	■									
									■	
				■						
								■		
		■								
										■
Projekt 15										

## Legende

- Supraleiter
- Neutrale Atome
- Ionenfallen
- Festkörperspins
- Neuromorphes Computing
- Strahlquellen
- Kryotechnik
- Aufbau- und Verbindungstechnik

# QNC Space

- Einblick in die Projekte des 2. Calls

## Infos kompakt

- 18 Bewerbungen
- 11 geförderte Projekte
- Fördervolumen von ca. 2,8 Mio. €
- Projektstarts: Mai 2025



	Runde 1	Runde 2
Forschung	~ 45 %	~ 65 %
Start-up	~ 15 %	~ 25 %
KMU	~ 40 %	~ 10 %
Mehrere FMD-QNC-Partner beteiligt	0 %	~ 70 %

## Projekte

	AMO	EMFT	ENAS	HHI	IAF	IIS	ILT	IMS	IPM	IPMS	ISIT	IZM
Projekt 1					Neutrale Atome				Neutrale Atome			Neutrale Atome
•												
•			Ionenfallen					Ionenfallen				
•					Ionenfallen		Ionenfallen				Ionenfallen	
•		Neuromorphes Computing				Neuromorphes Computing						Neuromorphes Computing
•				Neuromorphes Computing								
•		Neuromorphes Computing				Neuromorphes Computing						
Projekt 11										Neuromorphes Computing		

## Legende

- Supraleiter
- Neutrale Atome
- Ionenfallen
- Festkörperspins
- Neuromorphes Computing
- Strahlquellen
- Kryotechnik
- Aufbau- und Verbindungstechnik

Postersession I

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für Bildung  
und Forschung



qnc.summit<sup>25</sup>

# Technologische Ansätze für neuromorphisches Computing – wie weiter?

---

Prof. Bert Offrein, IBM Research Europe - Zurich, Rüschlikon, Switzerland / University of Twente, Enschede, The Netherlands

»QNC Summit« 07.03.2025

# The first petaflop supercomputer - Roadrunner

- Breaking the petaflop barrier
- In 2008, IBM built **'Roadrunner'**, the first petaflop supercomputing system
- Why is this of interest now?

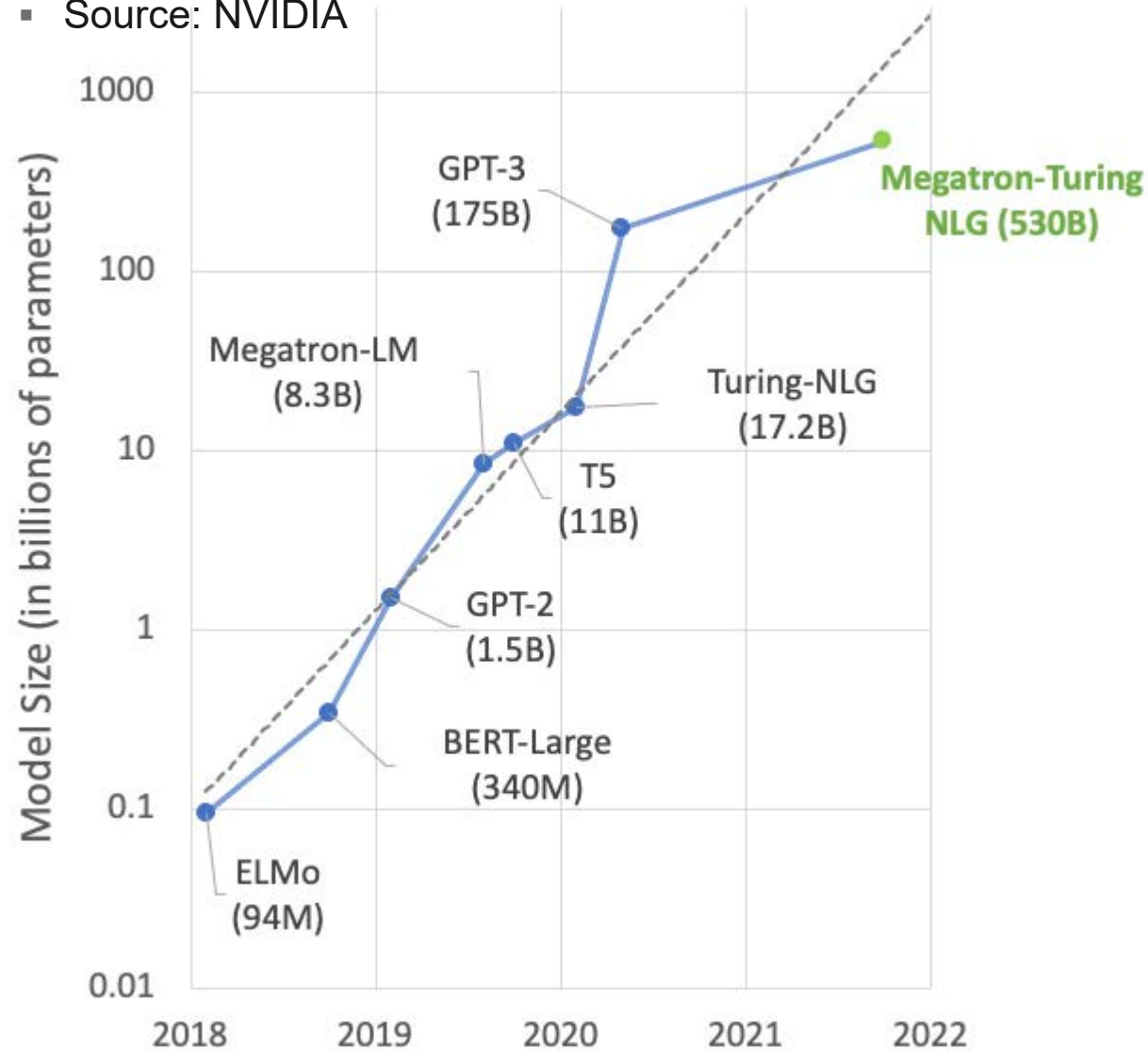


<https://www.ibm.com/history/petaflop-barrier>



# The neural network size explosion

Source: NVIDIA



MIT  
Technology  
Review

A data center

DEAN MOUHARTOPOULOS | GETTY; EDITED BY MIT TECHNOLOGY REVIEW

Artificial Intelligence / Machine Learning

## Training a single AI model can emit as much carbon as five cars in their lifetimes

Deep learning has a terrible carbon footprint.

by Karen Hao

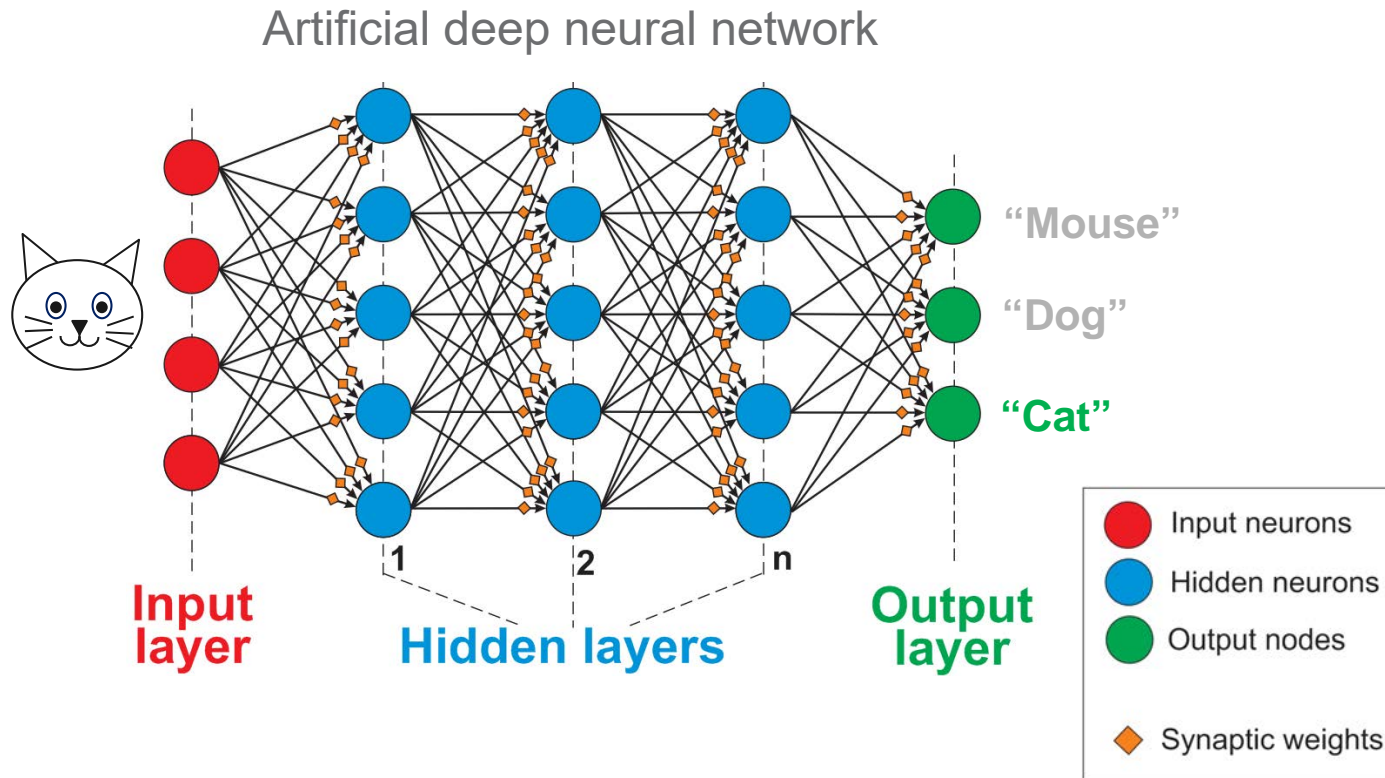
Jun 6, 2019

**The artificial-intelligence industry is often compared to the oil industry: once mined and refined, data, like oil, can be a highly lucrative commodity. Now it seems the metaphor may extend even further. Like its fossil-fuel counterpart, the process of deep learning has an outsize environmental impact.**

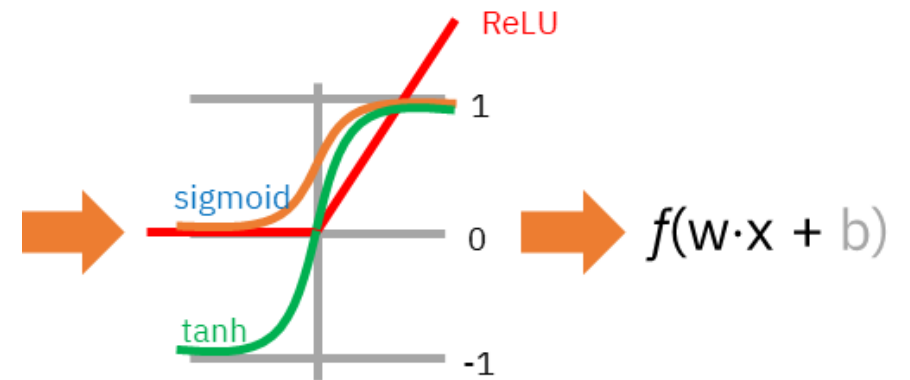
E. Strubell et al., arXiv:1906.02243



# Signal processing in neuromorphic computing



$$\begin{pmatrix}
 W_{11} & W_{12} & \dots & W_{1n} \\
 W_{21} & W_{22} & \dots & W_{2n} \\
 & & \dots & \\
 W_{j1} & W_{j2} & \dots & W_{jn} \\
 & & \dots & \\
 W_{mn} & W_{mn} & \dots & W_{mn}
 \end{pmatrix}
 \begin{pmatrix}
 X_1 \\
 X_2 \\
 \cdot \\
 \cdot \\
 X_n
 \end{pmatrix}$$



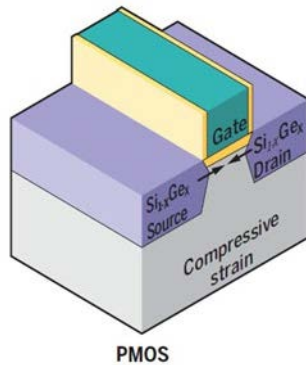
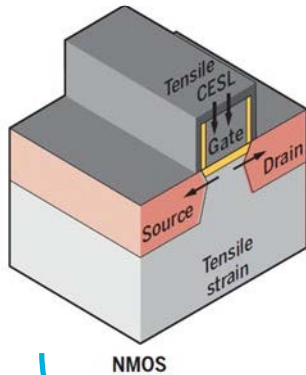
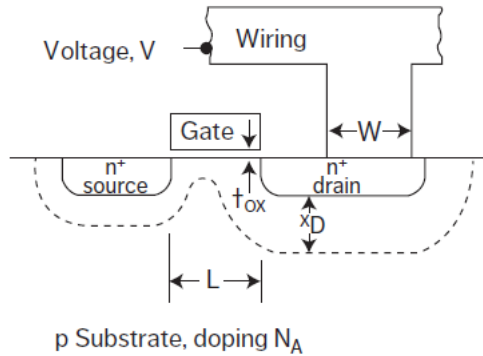
**Synaptic function:** Multiply accumulate  $\rightarrow$  Vector matrix multiplication  $\rightarrow O(N^2)$

**Neuron:** Nonlinear activation  $\rightarrow O(N)$

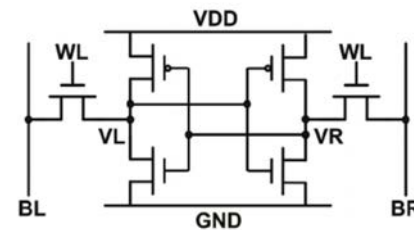
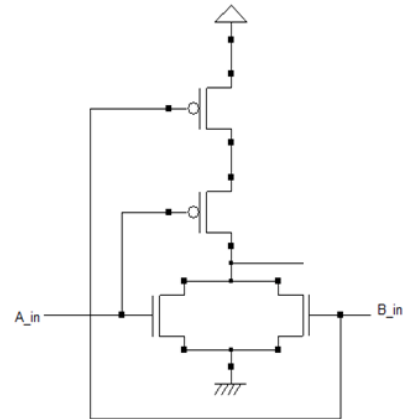


# The computing hardware

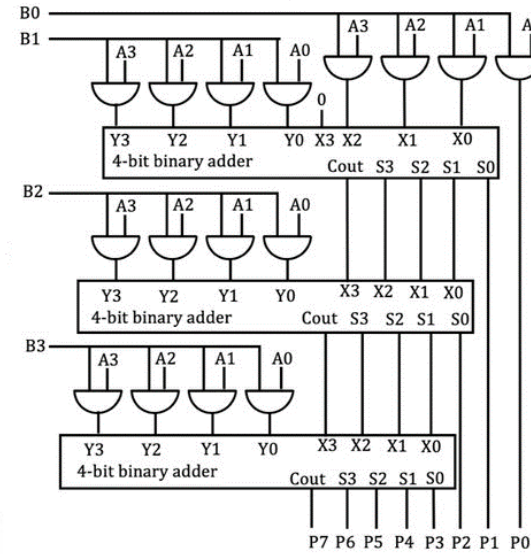
## Transistors



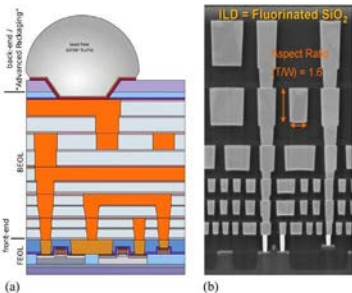
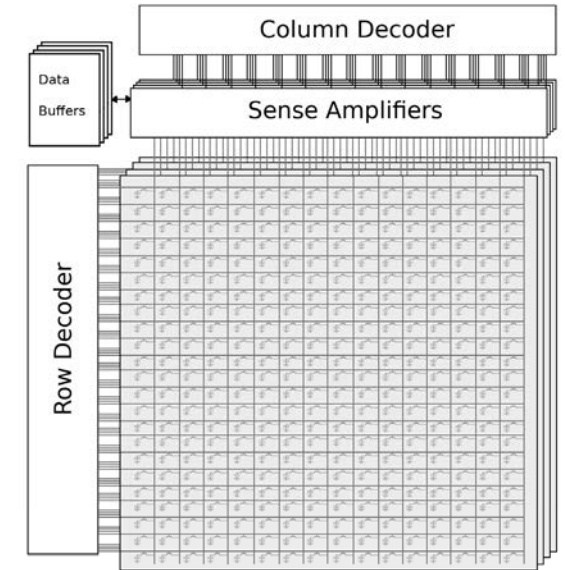
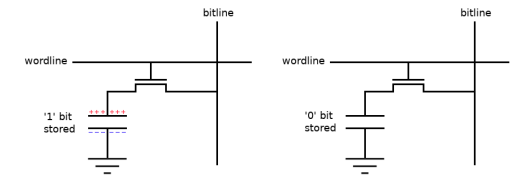
## Logic & SRAM



## Circuits

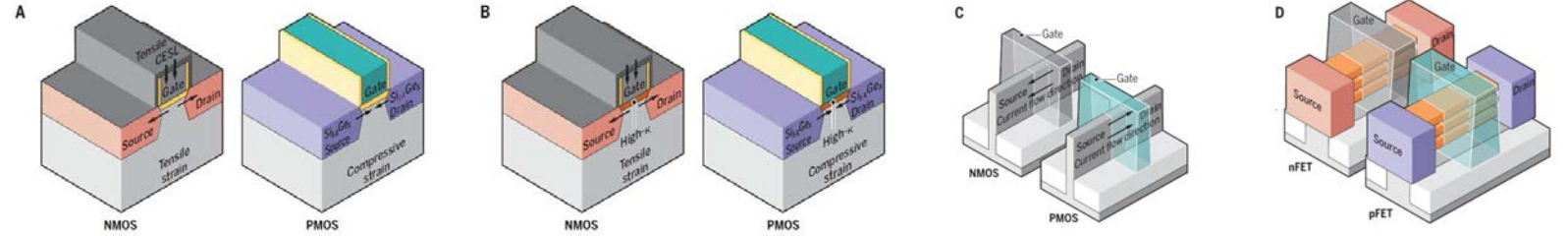


## Memory & Storage



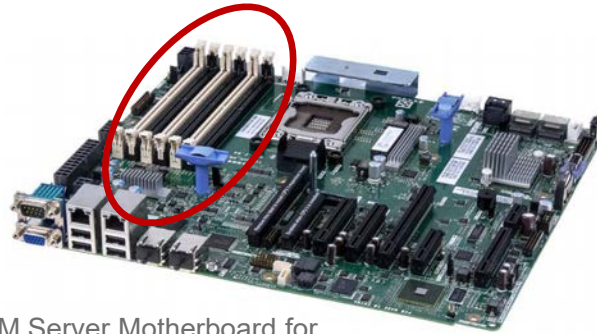
# Technology scaling is continuing

Smaller & more transistors

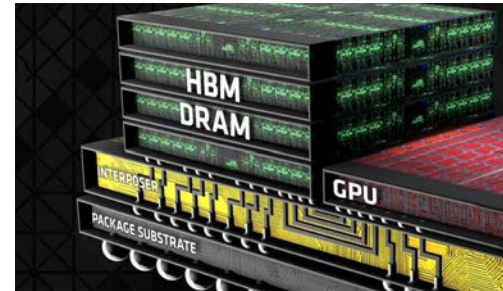


Datta et al., Science **378**, 733–740 (2022)

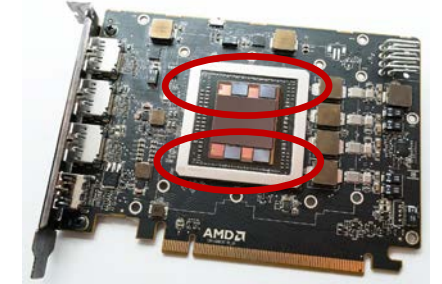
More & closer memory



IBM Server Motherboard for X3300 M4 Laptech - The IT

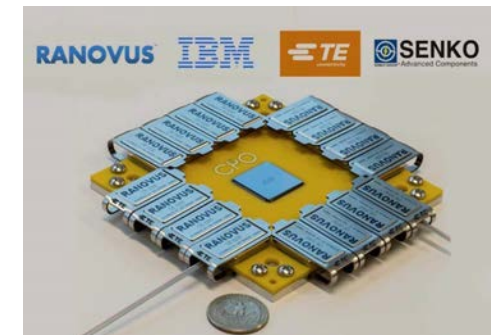


From PCPER.com



HBM memory on an AMD Radeon R9 GPU package

Higher bandwidth connectivity



<https://ranovus.com/>



# Technology scaling is continuing



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## IBM Unveils World's First 2 Nanometer Chip Technology, Opening a New Frontier for Semiconductors

*New chip milestone to propel major leaps forward in performance and energy efficiency*

May 6, 2021

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Dec 14, 2021

## IBM and Rapidus Form Strategic Partnership to Build Advanced Semiconductor Technology and Ecosystem in Japan

*Rapidus, a Newly-Formed Advanced Logic Foundry, Will Leverage IBM's Semiconductor R&D Leadership, Including 2 Nanometer Node Technology*

Dec 12, 2022

## Rapidus and IBM Expand Collaboration to Chiplet Packaging Technology for 2nm-Generation Semiconductors

*Agreement builds on existing collaboration between the two companies for the joint development of 2nm node technology*

Jun 3, 2024

## IBM Brings the Speed of Light to the Generative AI Era with Optics Breakthrough

*New co-packaged optics innovation could replace electrical interconnects in data centers to offer significant improvements in speed and energy efficiency for AI and other computing applications*

Dec 9, 2024

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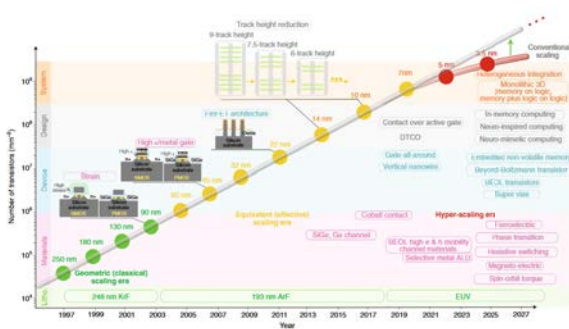
# Scaling AI compute performance and efficiency

## System trends

- More compute & memory
  - o Transistor scaling
  - o Dense memory
- Dedicated optimized functions
  - o Chiptlets, accelerators, memory
- Tight integration of all functions
  - o Heterogeneous integration
  - o Silicon interposer

## Scaling challenges

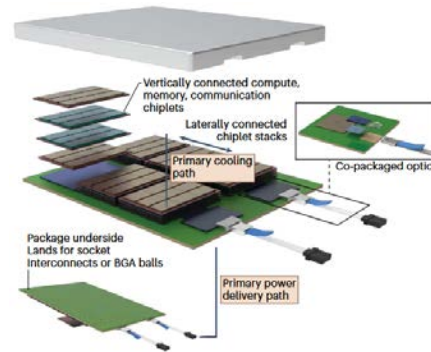
- Bandwidth scaling << Compute FLOPS
  - Enhanced interest in optical interconnects
  - Driven by the data bottleneck and energy efficiency
- Close integration of optics with ASIC for energy efficiency and bandwidth requirements



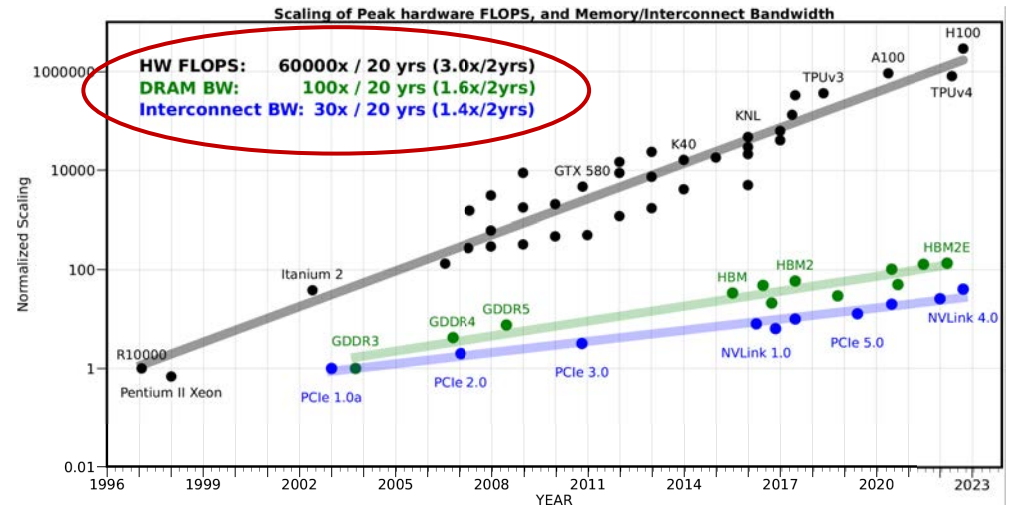
Transistor scaling  
From: Datta e.a. 2018



HBM on substrate  
From: NVIDIA 2023



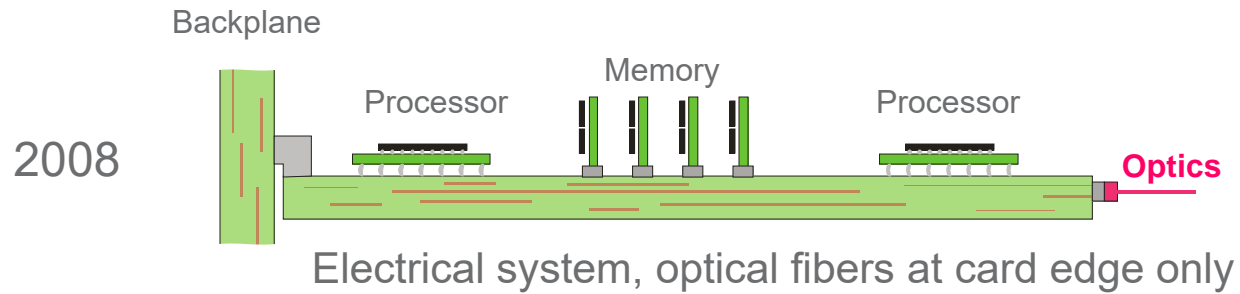
Chiplet assembly vision  
From: Intel 2024



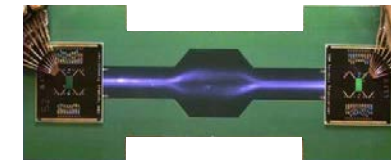
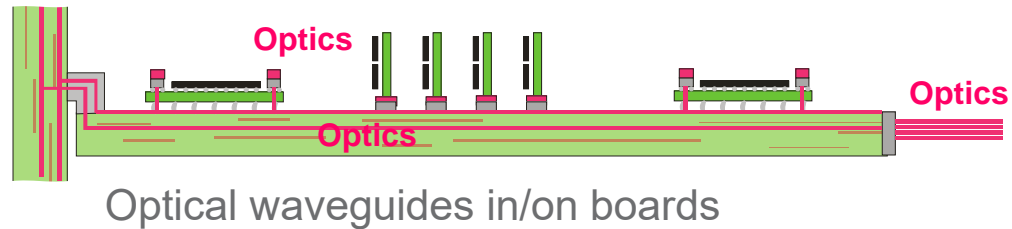
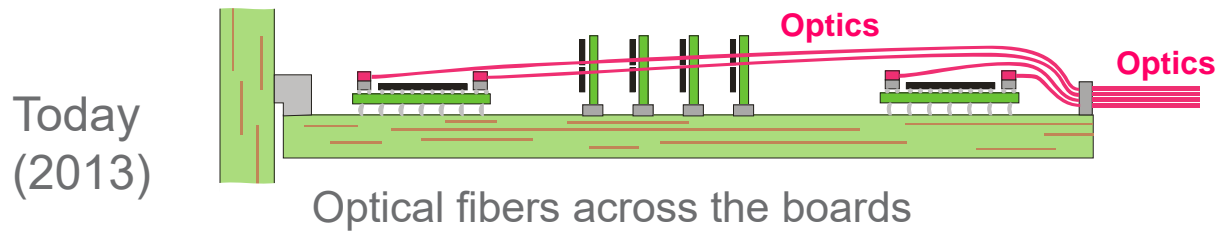
From: <https://medium.com/riselab/ai-and-memory-wall-2cb4265cb0b8>



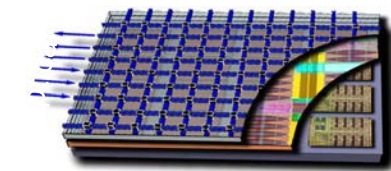
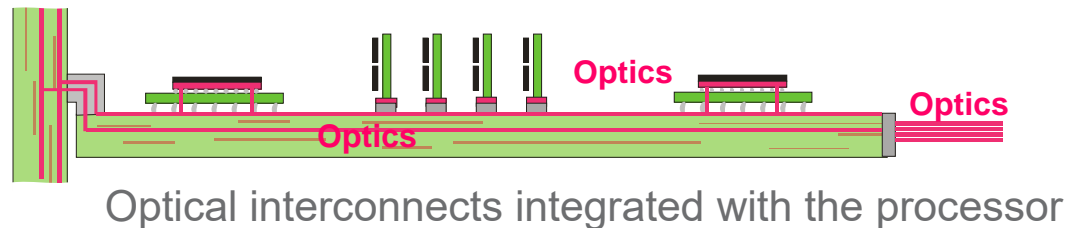
# Looking back – 2013!



Development



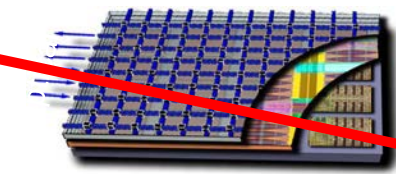
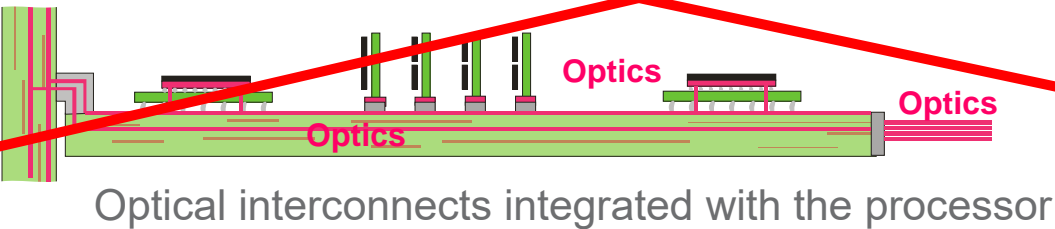
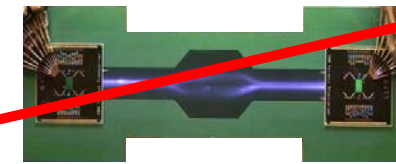
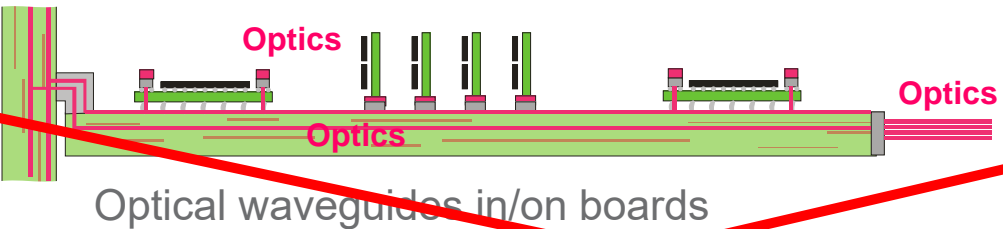
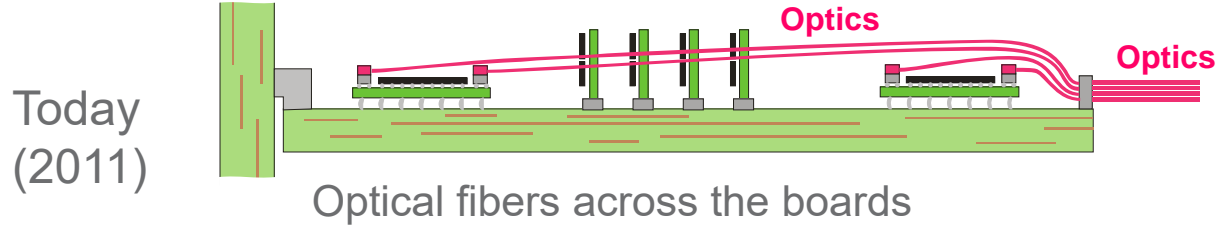
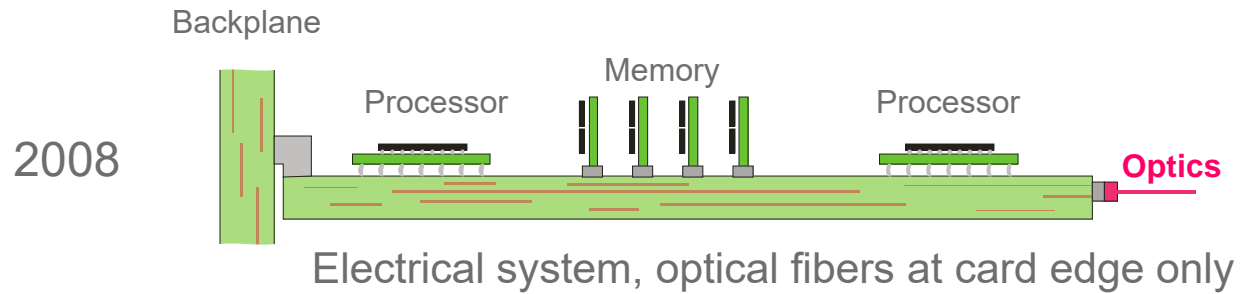
Research



Optical interconnects will be applied for shorter and shorter links to fulfill bandwidth and power efficiency requirements. Integration will increase bandwidth density and reduce cost.



# Looking back – 2013!



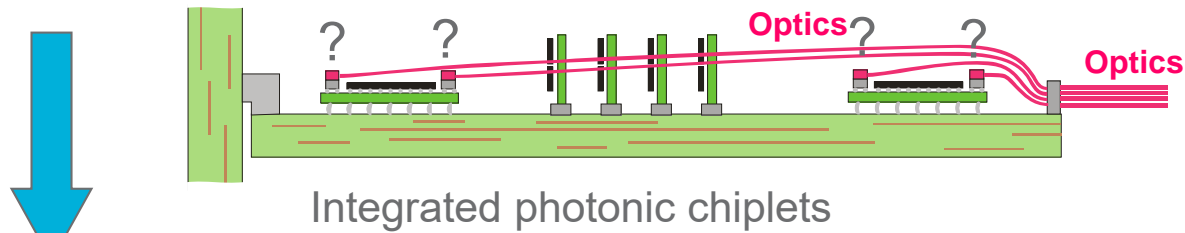
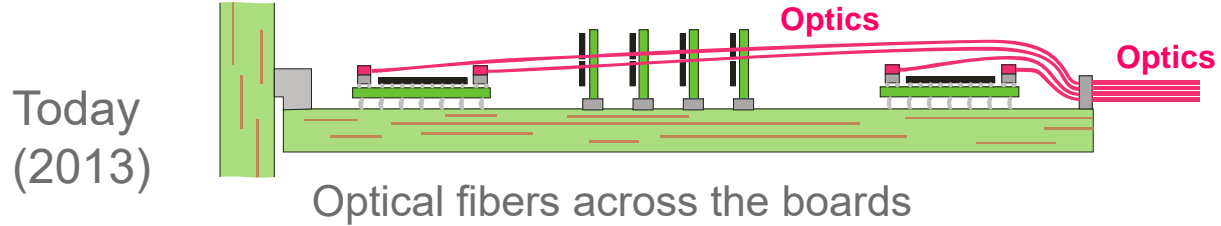
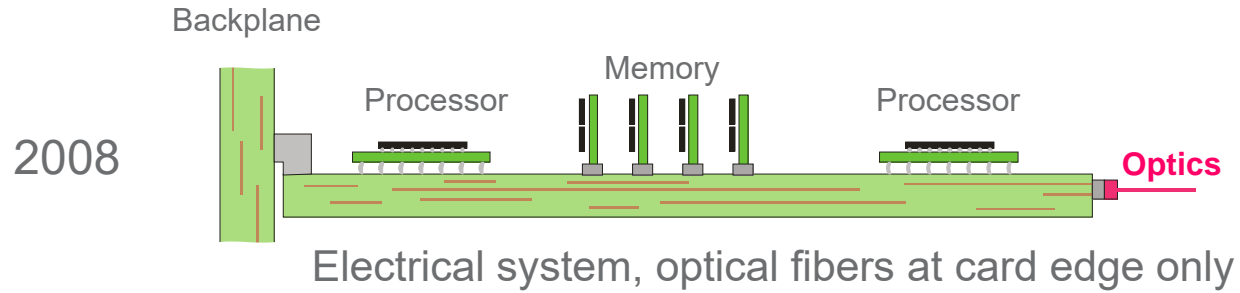
Development

Research

Optical interconnects will be applied for shorter and shorter links to fulfill bandwidth and power efficiency requirements. Integration will increase bandwidth density and reduce cost.



# Looking back – 2013!



Overcome the overhead of optics

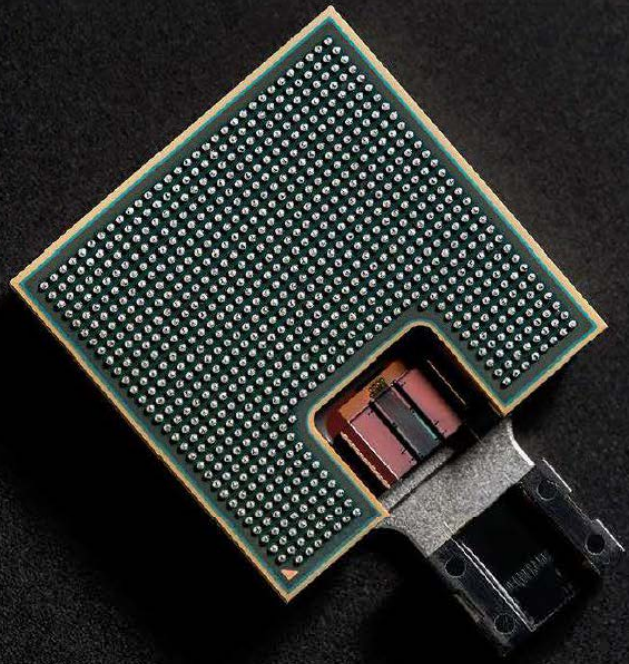
?

Development

Research



IBM introduces new **co-packaged optics** technology to replace electrical interconnects between chips and circuit boards



IBM Research

IBM announces **co-packaged optics** breakthrough: light-speed connectivity to supercharge AI computing



IBM Research





# Digital signal processing

---

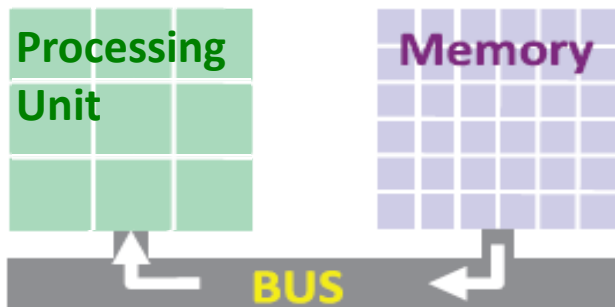
- The Von Neumann architecture
  - Memory for programs and data, a bus for memory access, an arithmetic unit & a program control unit



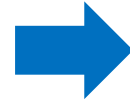
# Analog signal processing for scalability

- **Limiting factors**

- Memory access
- Sequential operations
- Digital signal processing

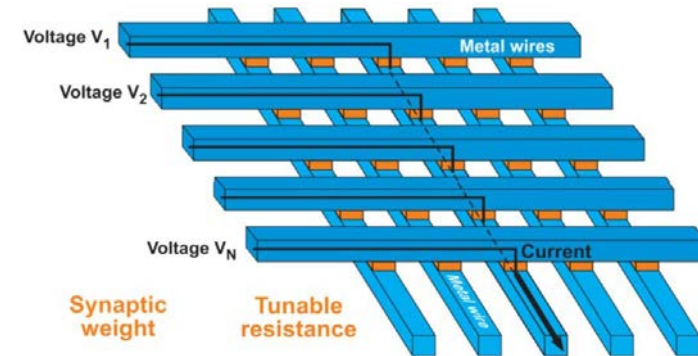


Compute effort  $\sim O(\#\text{Neurons}^2)$

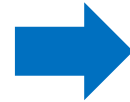


- **Overcome by**

- In-memory computing
- Parallel operations
- Analog signal processing



Compute effort  $\sim O(1)$



**Electrical and optical solutions are viable candidates**

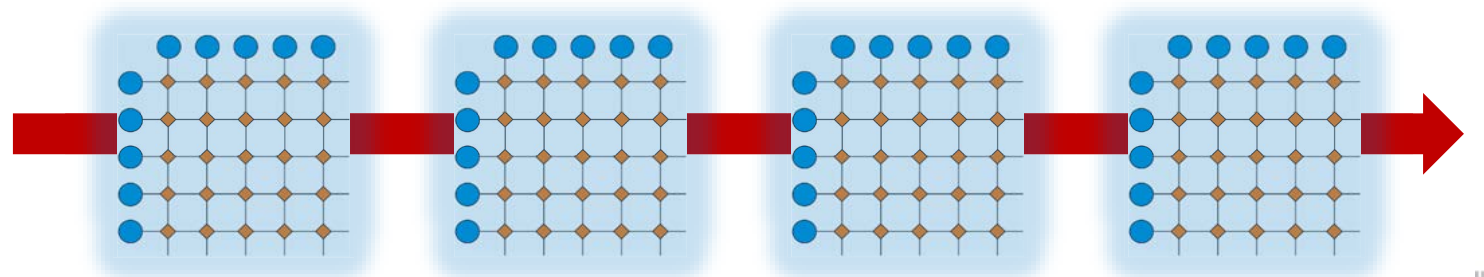
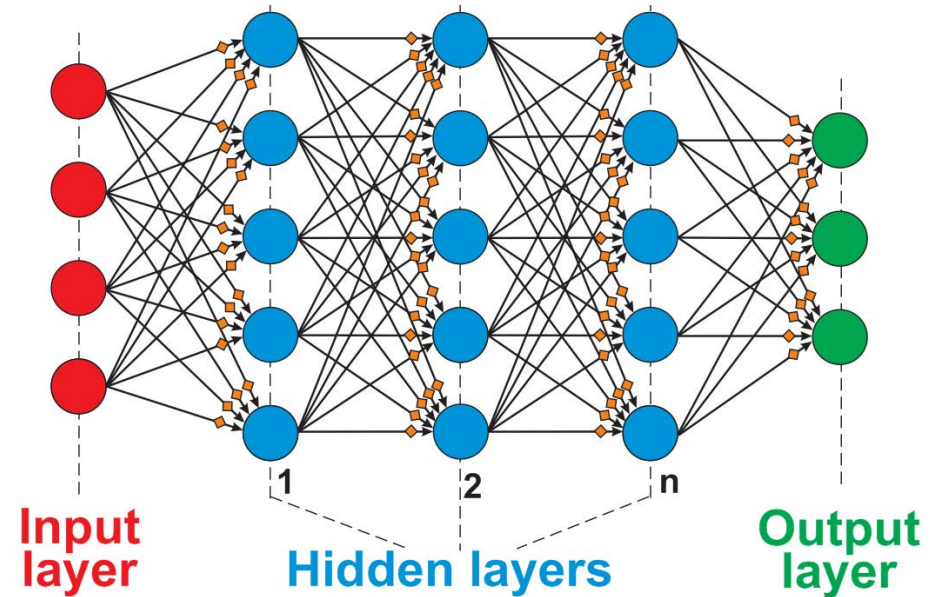


# Pipelining data

- **Neural network architecture = hardware architecture**

- **Non-volatile weights**

- Technology maturity and scalability
- Integration and assembly
- Retention
- Endurance
- Understanding the fundamental principles and properties

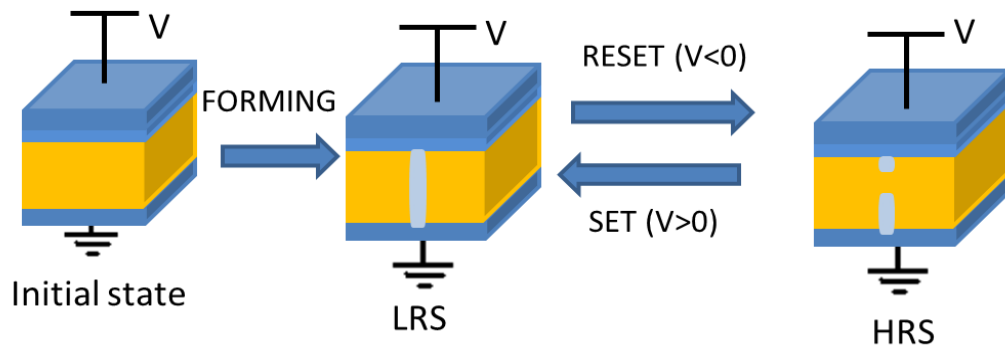


# MO<sub>x</sub> / HfO<sub>2</sub> OxRRAM artificial synapses

**Goal :** Improve HfO<sub>2</sub> analog and symmetric characteristics by using engineered metal oxide as part of the electrode

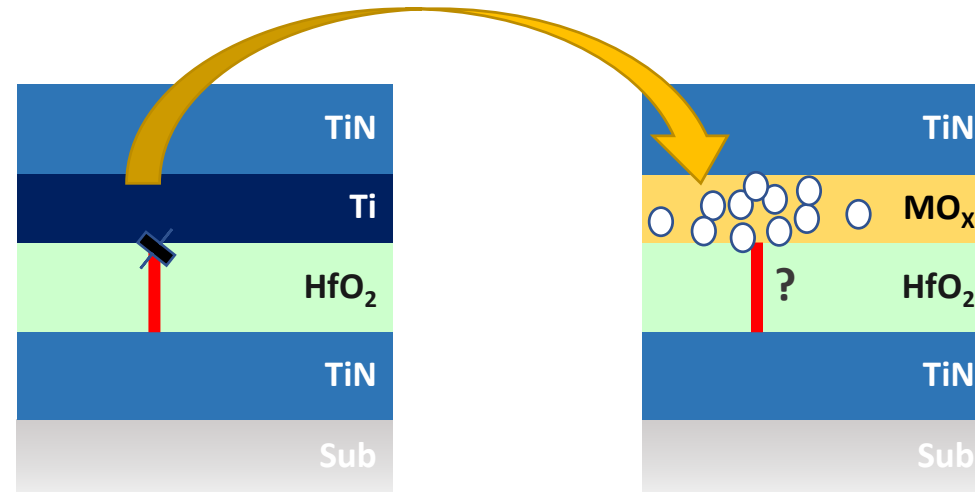
Starting point: Baseline of Ti/HfO<sub>2</sub>

New concept: MO/HfO<sub>2</sub>



*Localized and  
ABRUPT switch*

*Increase switching volume?  
Better controlled switching?*



## Reference multilayer stack optimization

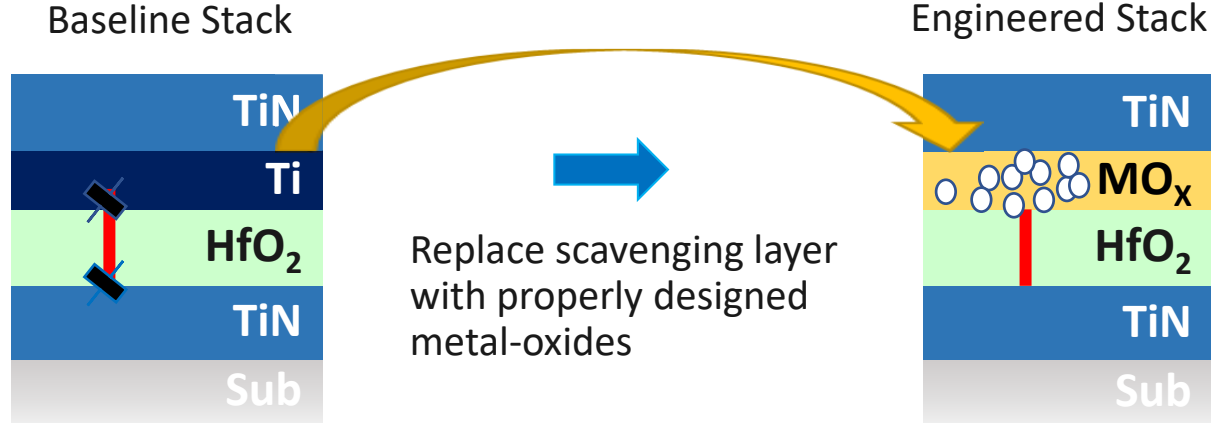
Padovani A. et al. *IEEE Trans. Electron Devices*, vol. 62, no. 6, pp. 1998 (2015)

Woo J. et al. *IEEE Electr. Dev. Lett.*, vol. 38, 9, (2017)

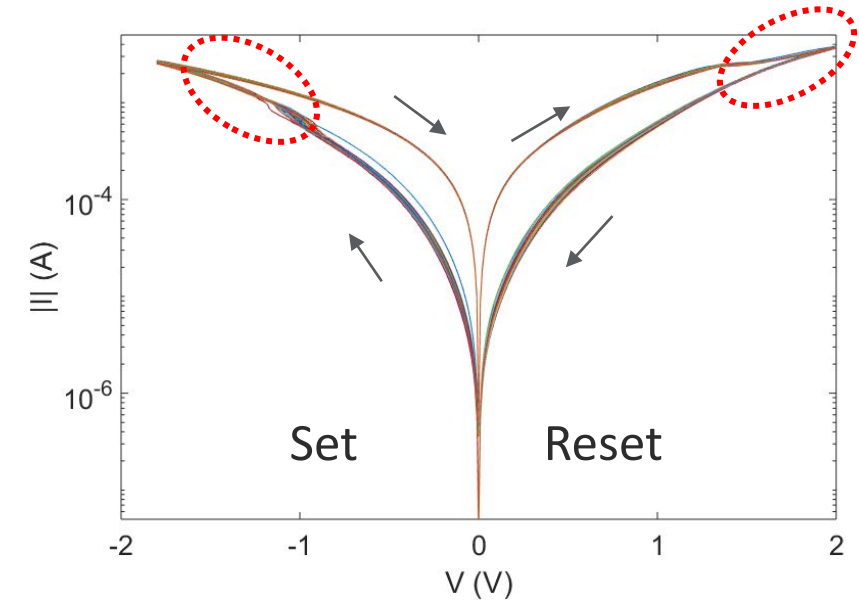
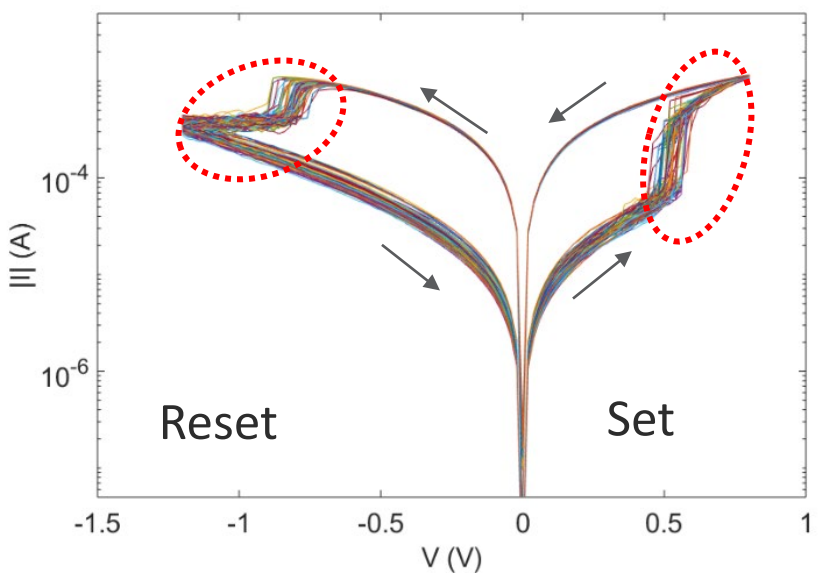
1 Mattoni et al. *ACS Appl. Nano Matt.* 1 (2018)

2 Chang et al. *Appl. Phys. A*, 102, 857 (2011)

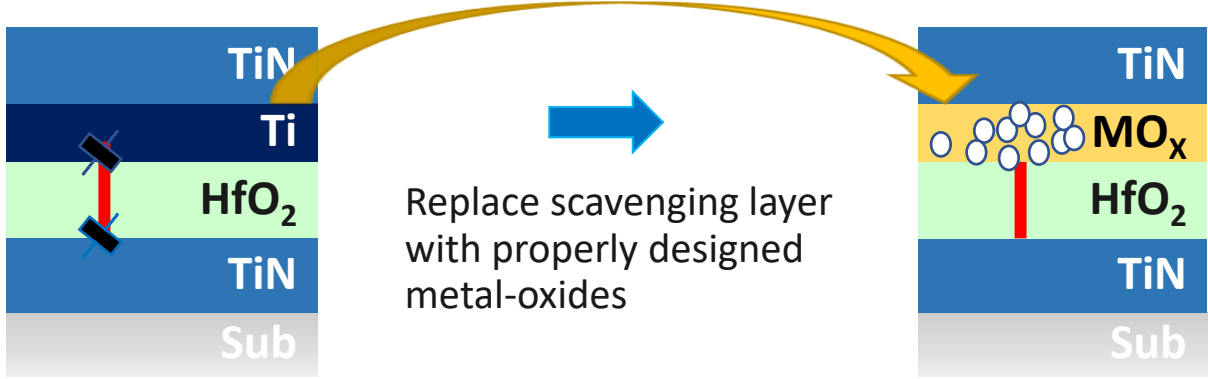




- Inversed polarity for set / reset
  - Engineered stack shows **no abrupt set/reset**
- Different physics → more controlled O<sup>2-</sup> exchange



# RRAM device optimization

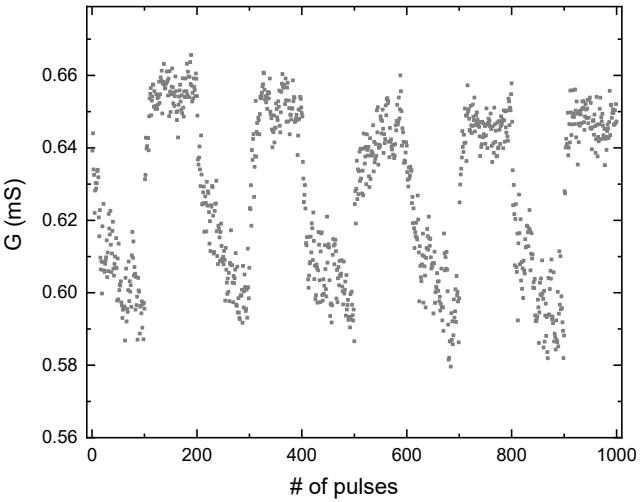


Current status:  
RRAM Material & Algorithm  
Co-optimization

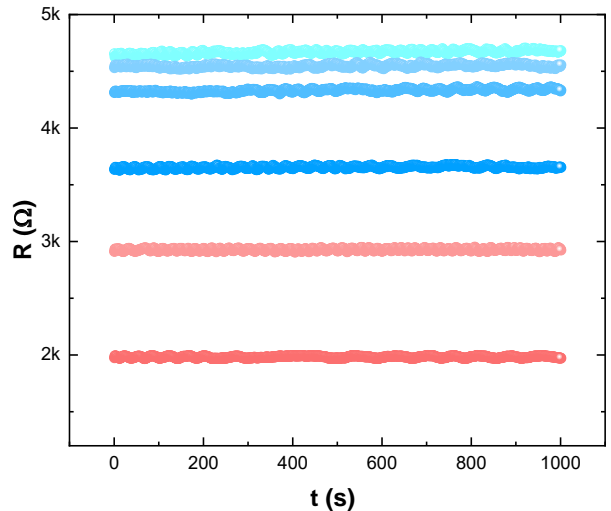
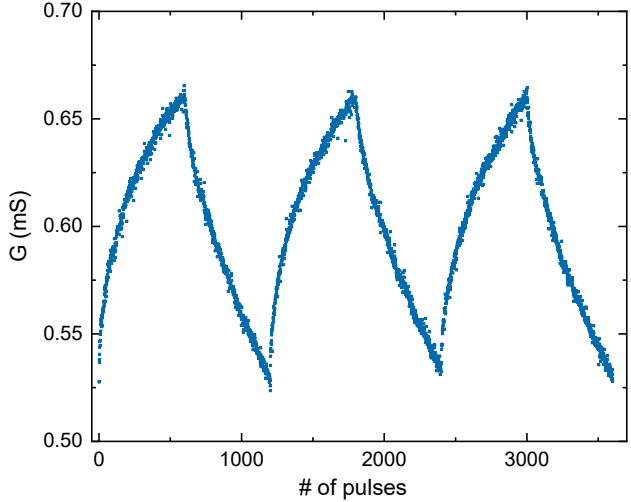


Enables Scalable RRAM Technology  
for Deep Learning Inference &  
Training

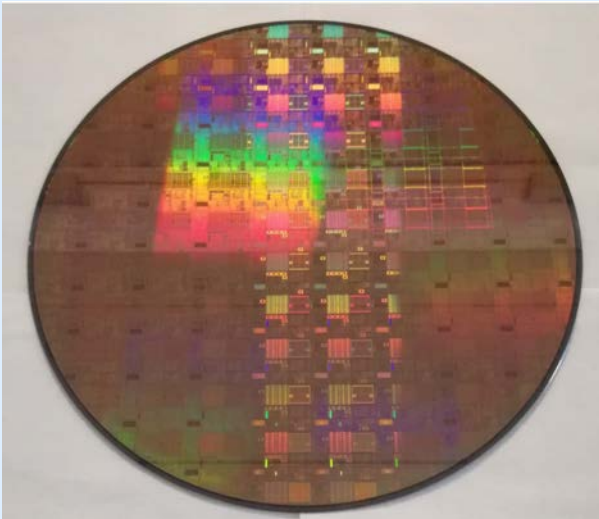
No gradual and controlled weight update



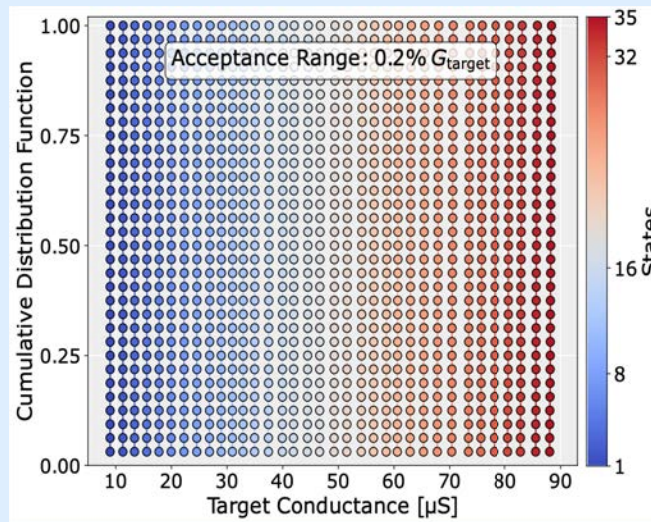
Suppressed stochasticity & reduced noise



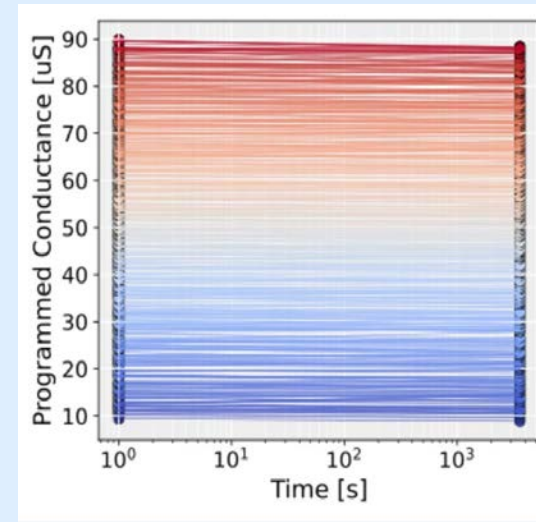
# MO-RRAM technology overview



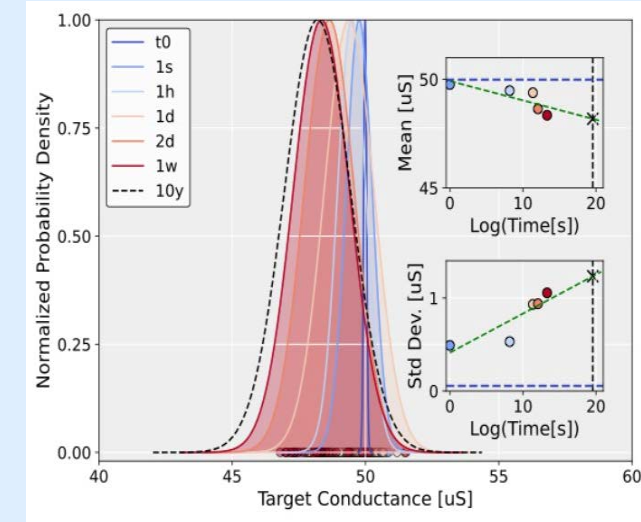
Crossbars on 300mm 14nm CMOS wafer



Multibit capability



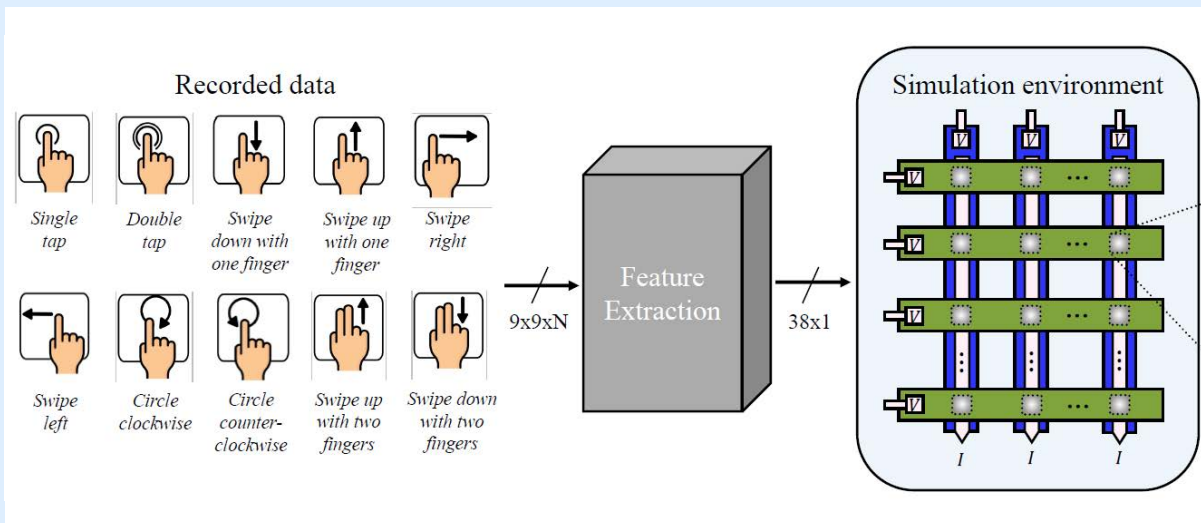
Short-, and long-term retention



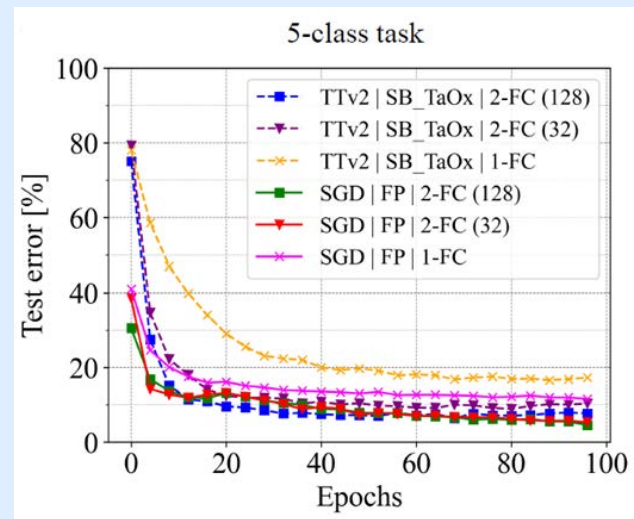
## BEOL MO-RRAM devices on CMOS:

- Integration on 14nm CMOS demonstrated
- Multi-level capability: >35 states
- Long term retention: 10 states (@10 yrs)
- Low read noise, 10<sup>X</sup> lower than PCM & binary ReRAM
- Good endurance: >10<sup>8</sup>
- Scaling: <70x70nm<sup>2</sup>

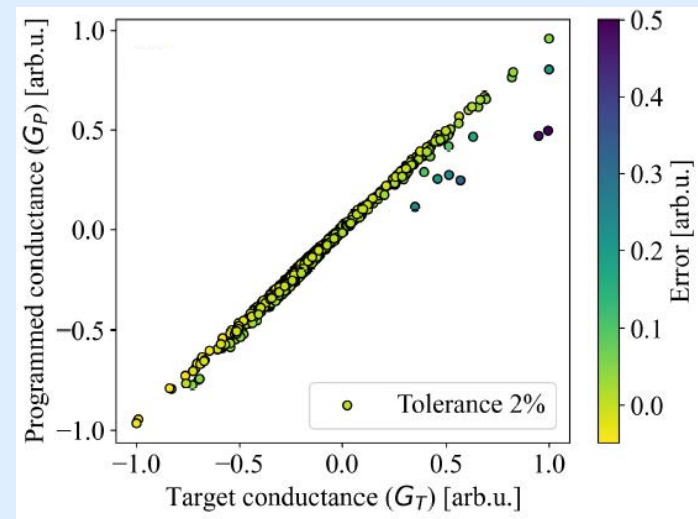
# MO-RRAM technology overview



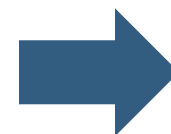
Gesture for human-car interfacing



Analog training  
≈ FP accuracy



Analog inference  
≈ FP accuracy



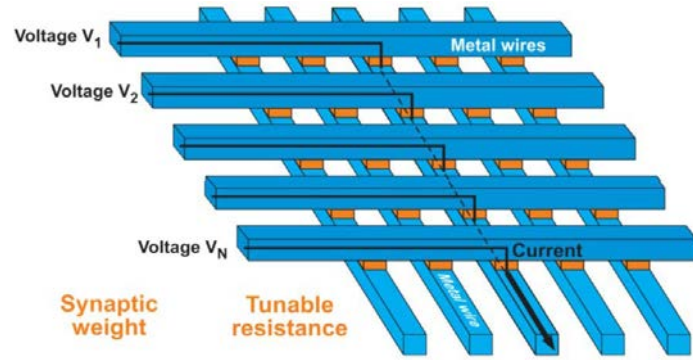
## Edge application example:

- Demonstration of gesture recognition
- Training & inference in same technology important for adaptable systems
- Power-efficient human-car interfacing



# Analog signal processing systems

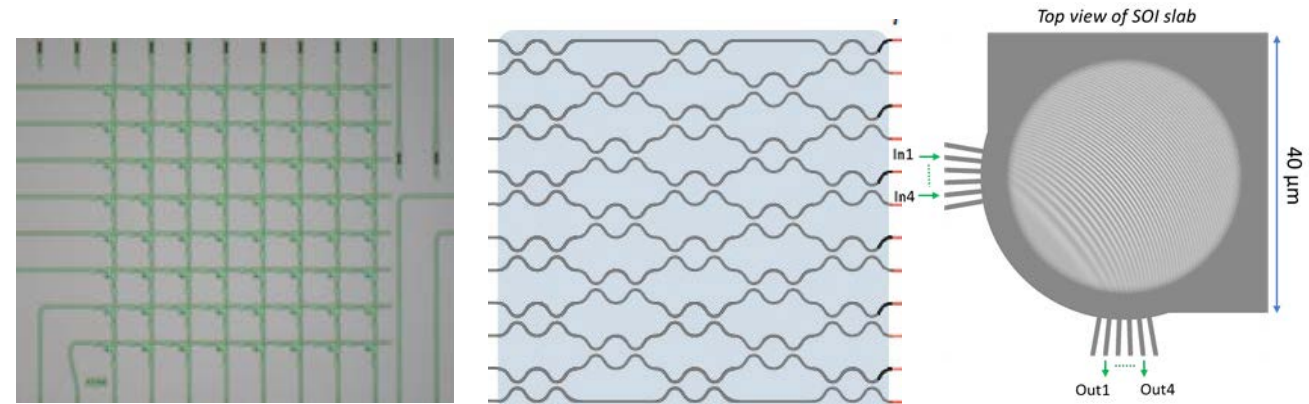
- Electrical



Ohm's and Kirchhoff's law

- Memristive devices in a crossbar
  - PCM
  - OxRAM
  - FERAM

- Integrated photonics



From: EU PHOENICS (U Oxford).

From: Y. Shen et al., doi: 10.1038/nphoton.2017.93.

From: F. Horst, IBM.

Attenuation, interference, diffraction

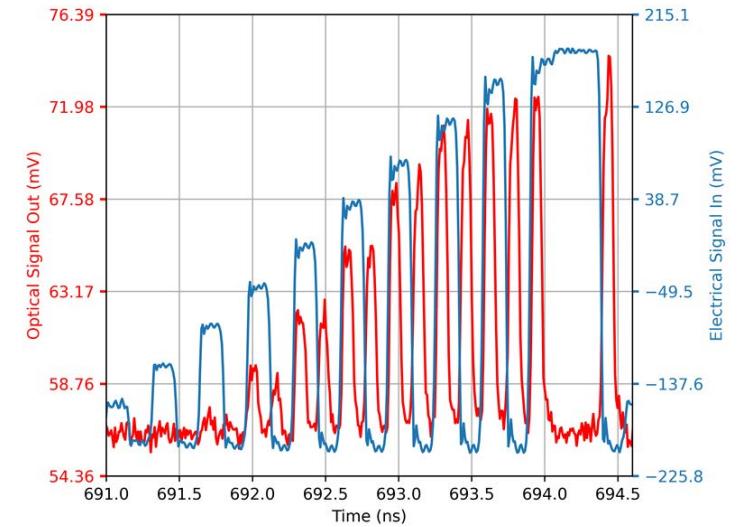
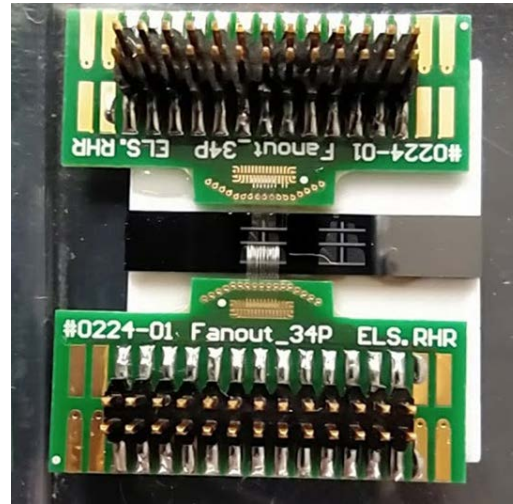
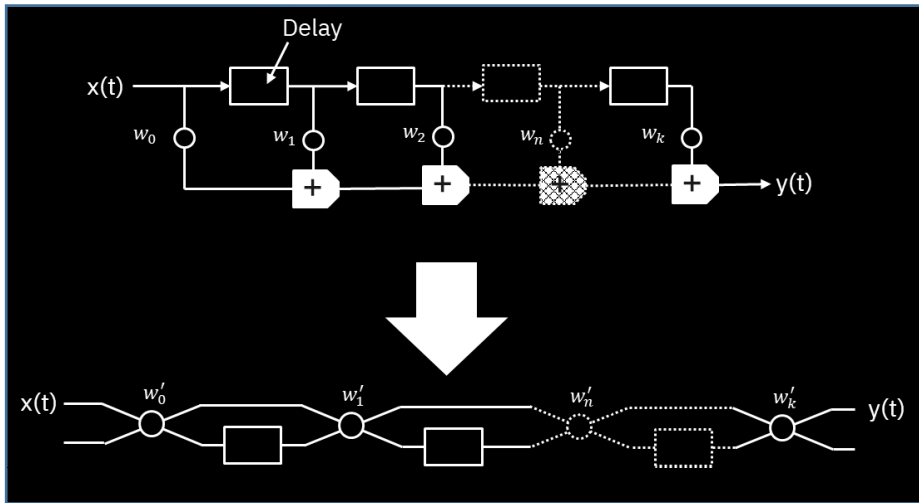
- Various device concepts and materials
  - Crossbar
  - Mach-Zehnder interferometer
  - Diffractive

## For inference & training



# Optical convolutional signal processor

- Photonic implementations, volatile weights but well controlled and fast set



Measurements by Pascal Stark

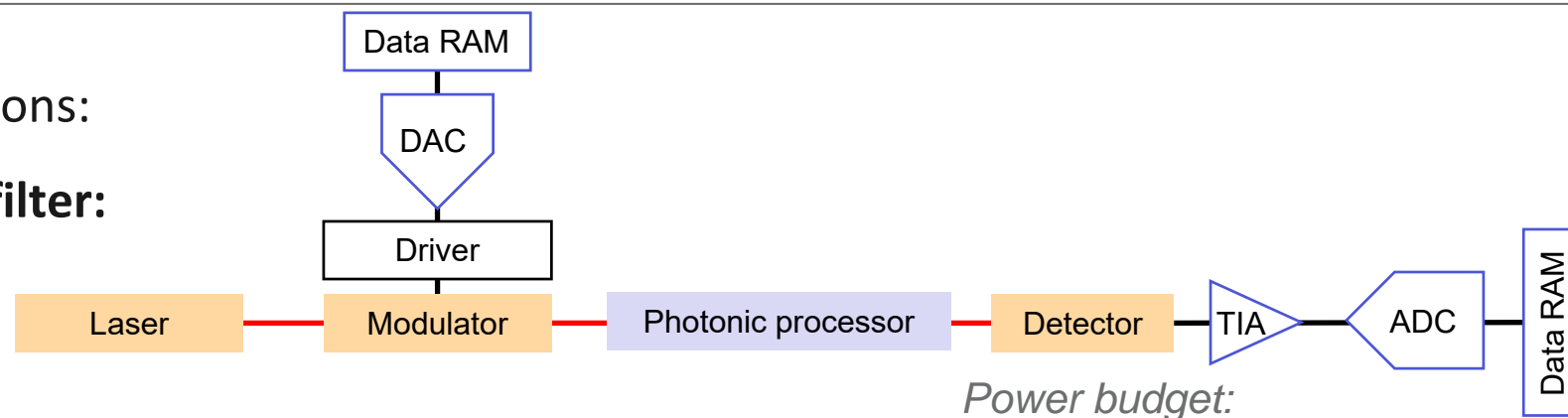
- Time domain operation
- High-speed signal processing (12.5 GSamples/s)
- Fast and efficient reconfiguration (electro-optic modulators)



# Lattice filter: Link and Power budget

Link and Power budget calculations:

- Scaling limits for the lattice filter:
  - Stage loss
  - Control complexity



*Link budget:*

Parameter	Value	Unit
<b>CW laser launch power</b>	<b>13.0</b>	<b>dBm</b>
Laser to chip coupling	0.2	dB
Modulator insertion loss	3	dB
Lattice filter loss: <b>9 stages</b> @ 0.58 dB/stage	5.2	dB
Kernel normalization loss	2	dB
Detector coupling loss	0.2	dB
<b>Optical power at photodetector</b>	<b>2.6</b>	<b>dBm</b>
Power penalties (jitter, crosstalk, ISI etc.)	1.7	dB
<b>Effective optical power at photodetector</b>	<b>0.9</b>	<b>dBm</b>
Optical Sensitivity for a resolution of 4 bits, at 32 GSps	-2.4	dBm
<b>Available link margin</b>	<b>3.3</b>	<b>dB</b>

*Power budget:*

Building Block	Power in mW at 32 GSps:
Data RAM (read)	11
High Speed DAC	67
Driver and Modulator	70
Detector and TIA	6
Output ADC	115
Results RAM (write)	10
CW Laser	200
<b>Sum of Power</b>	<b>476</b>
<b>Efficiency TOPs/Watt</b>	<b>2.49</b>

- Comparable to existing digital hardware, but
  - High-speed, low latency / Real time
  - Can do complex data and kernels
  - Room for further improvements



# Discussion

---

- Energy consumption of AI
  - Minimize memory access
- Don't forget about traditional technology scaling!
  - Is continuing at all levels
- Analog signal processing
  - Map the technology to the Neural Network architecture
  - Electrical for density and scalability
  - Optical for throughput and reconfigurability
- Know the application and the technology prospects



# New technologies for Artificial Intelligence - The team



# Acknowledgments

---

**IBM Research – Zurich, Switzerland**  
Neuromorphic Devices and Systems team

The IBM BRNC cleanroom opteam

**Co-funded by the European Union Horizon 2020  
Programme and the Swiss National Secretariat for  
Education, Research and Innovation (SERI)**



 PHOTONICS<sup>21</sup>

**Photonics**  
A Key Enabling Technology  
for Europe



**EU & CH-SERI**  
PHOENICS, PHOENIX,  
PROMETHEUS

FIXIT, CONCEPT, TOPOCOM

**Thank you for your attention!**  
**OFB@zurich.ibm.com**



GEFÖRDERT VOM



Bundesministerium  
für Bildung  
und Forschung



qnc.summit<sup>25</sup>

# Technologie-Pitch: »Ansätze, Plattform für photonische Systemintegration«

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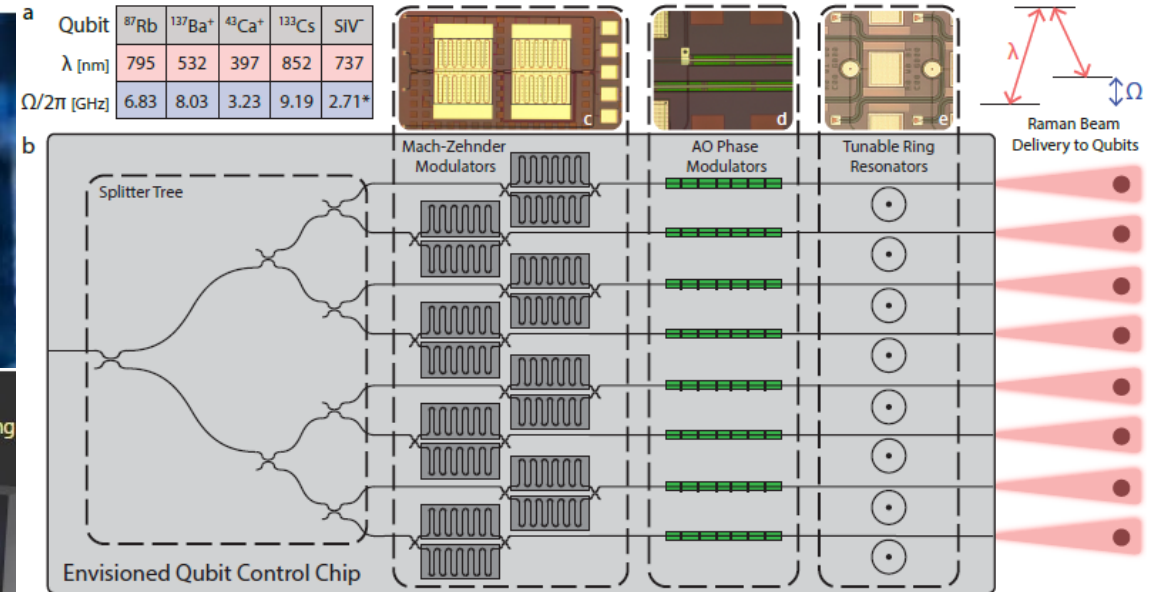
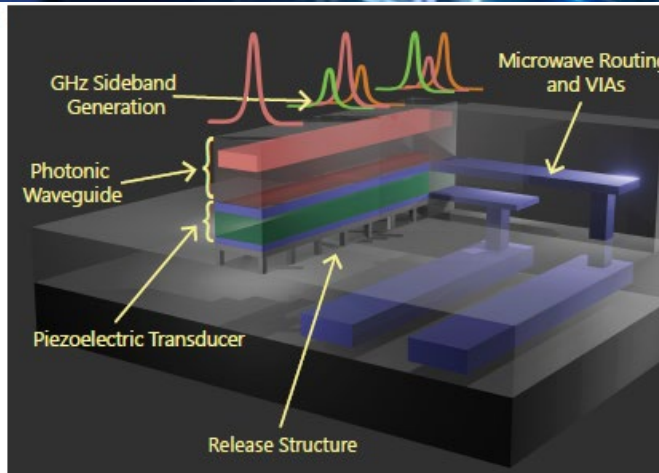
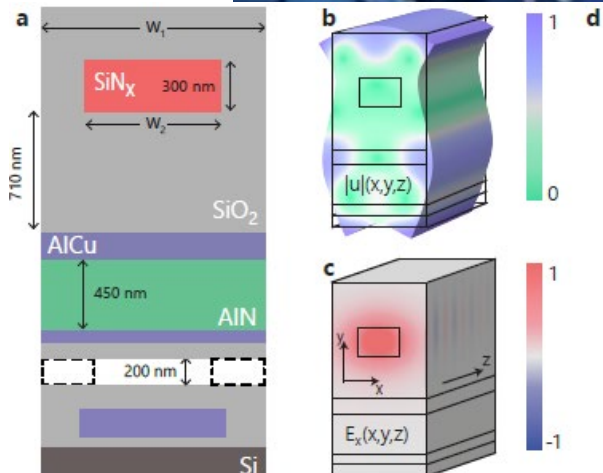
**Prof. Dr. Shanshan Gu-Stoppel, Fraunhofer ISIT**

**»QNC Summit« 06.03.2025**



# PICs: photonic integrated circuits

Source: <https://ayarlabs.com/glossary/photonic-integrated-circuit-pic/>



Source: Gigahertz-Frequency Acousto-Optic Phase ModCMOS-Fabricated Photonic Circuit; Jacob M. Freedman<sup>1</sup>, Matthew J. Storey<sup>2</sup>, Daniel Dominguez<sup>2</sup>, et. al.;<sup>1</sup> Wyant College of Optical Sciences, University of Arizona, Tucson, Arizona, USA; <sup>2</sup> Microsystems Engineering, Science, and Applications, Sandia National Laboratories, Albuquerque, New Mexico, USA

# Eine kleine *qnc.space* Auswahl



**Dr. Shanshan Gu-Stoppel**, Fraunhofer ISIT  
E-Mail: shanshan.gustoppel@isit.fraunhofer.de  
**Dr. Björn Lekitsch**, neQxt GmbH  
E-Mail: b.Lekitsch@neqxt.org

ActiveWave

**Wellenleiter auf Siliziumnitrid-Basis mit Piezo getriebenen aktiven optischen Elementen**



**Dr. Stephan Suckow**, AMO GmbH  
E-Mail: suckow@amo.de  
**Anastasia Sorokina**, TUBS  
E-Mail: a.sorokina@tu-braunschweig.de

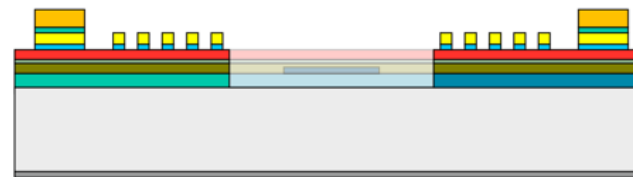
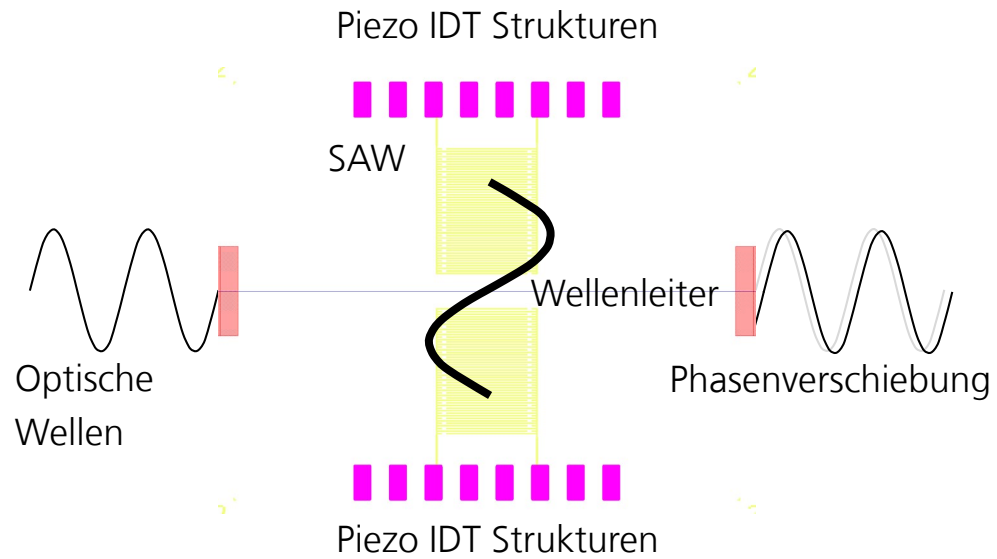
Prozessentwicklung für eine nanophotonische Hybrid-Plattform für Ionenfallen-Quantencomputer  
**Hocheffiziente Gitterkoppler für UV-Anwendungen (UV-GC)**



**Dr. Stephan Suckow**, AMO GmbH  
E-Mail: suckow@amo.de  
**Guochun Du**, PTB  
E-Mail: Guochun.Du@ptb.de

Prozessentwicklung für Strahlformung mittels Metastrukturen für Ionenfallen-Quantencomputer  
**Metastrukturen mit hohem Berechnungsindex und hohem Aspektverhältnis im ultravioletten Wellenlängenbereich (MetaUV)**

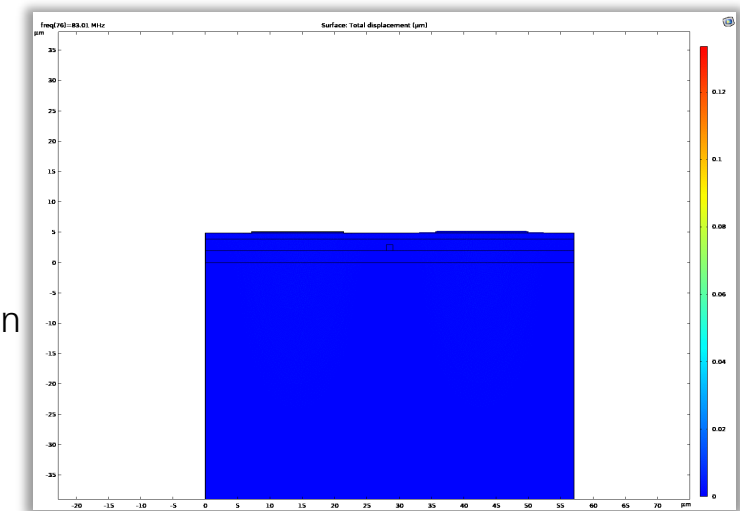
# ActiveWave Ansatz: piezo Modulator auf SiN Wellenleiter



- mono-Si (725  $\mu\text{m}$ )
- SiO<sub>2</sub> (2  $\mu\text{m}$ )
- SiN (1  $\mu\text{m}$ )
- SiO<sub>2</sub> (1,9  $\mu\text{m}$ )
- AlN (20 nm)
- AlSc(32)N (1  $\mu\text{m}$ )
- WTi (40 nm) / Au (150 nm)
- WTi (40 nm) / Au (300 nm)

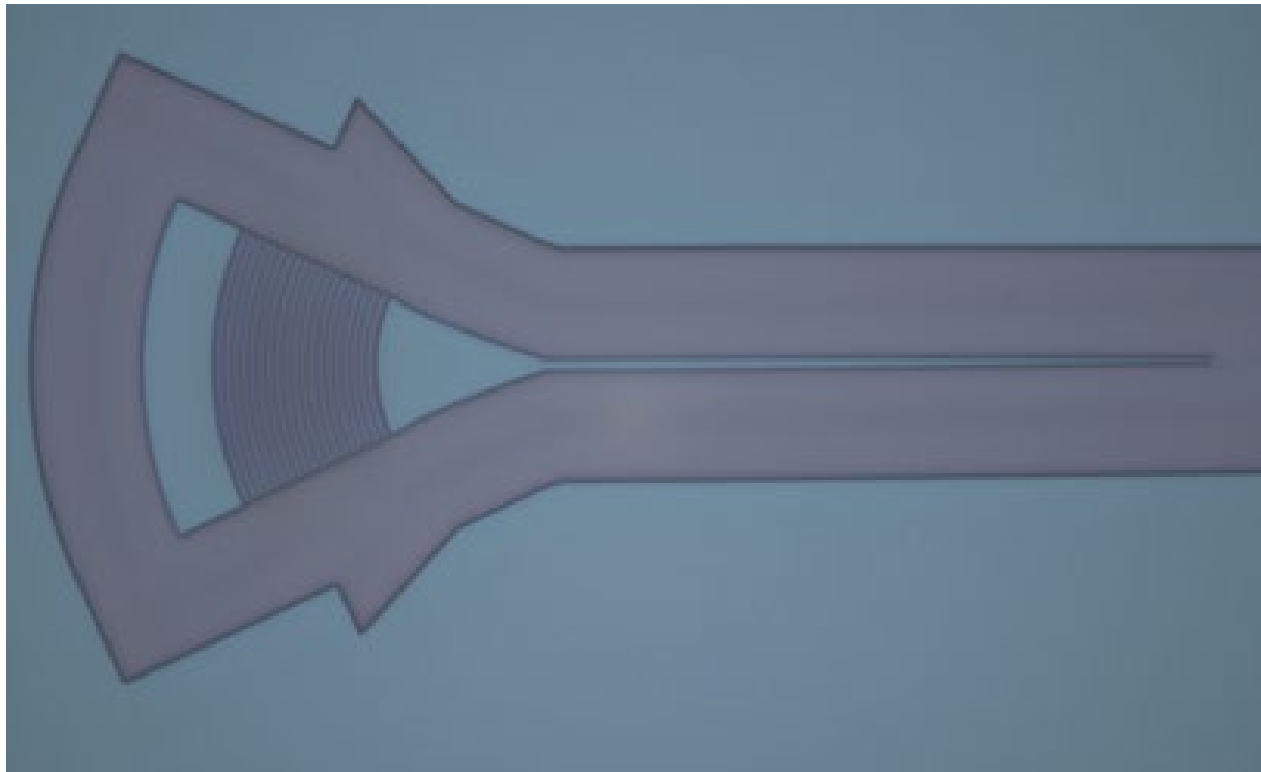
Reinraum Prozess:

- 4 Lithographie
- 145 Schritten inklusive In-line Messungen



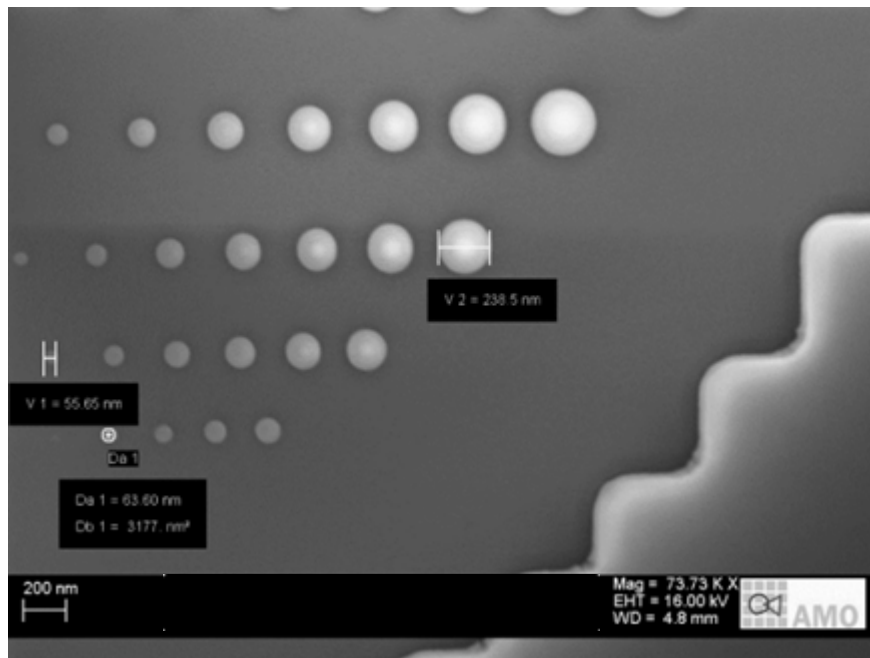
# UV-GC Ansatz: Hybrid-Plattform

- Gitterkoppler in  $\text{Si}_3\text{N}_4$  oder AlN für moderaten Brechungsindexkontrast und gute Koppeffizienz
- Wellenleiter in  $\text{Al}_2\text{O}_3$  für minimale Verluste auch im Blau / nahen UV-Spektrum



- Gitterkoppler strukturiert in  $\text{Si}_3\text{N}_4$
- Positivprozess mit Elektronenstrahlolithographie
- Nächster Schritt:  $\text{Al}_2\text{O}_3$  Wellenleiter, noch in Arbeit

- Wesentlich für Ionenfallen:
  - Verteilung von Laserlicht auf dem Ionenfallen-Chip mit integrierter Photonik
  - Lichtauskopplung zu Ionen benötigt präzise Strahlkontrolle und Strahlformung
- Metalinse: mehr Freiheitsgrade als Gitterkoppler, für maximale Effizienz und Kontrolle
- Benötigt Strukturierung mit hohem Aspektverhältnis: Fokus auf **Prozessentwicklung in MetaUV**



- Teststruktur: Säulen in 450 nm  $\text{Si}_3\text{N}_4$
- Kritische Abmessung ca. 55 nm
- **Aspektverhältnis ca. 1:8**

# Nächste Ziele

---

- ✓ Etablieren: Piezo Modulator + PICS
- ✓ Etablieren: Hybrid-Plattform zur Entkopplung von Wellenleiter & Gitterkoppler
- ✓ Etablieren: Metalinsen zur Strahlformung & Faser-Chip-Kopplung
- ✓ Kooperation: QNC PIC Plattform

# Contact

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**Prof. Dr. Shanshan Gu-Stoppel**  
**MEMS Applications - Optical Systems**  
**Phone +49 4821 17-3470**  
**[Shanshan.gu-stoppel@isit.fraunhofer.de](mailto:Shanshan.gu-stoppel@isit.fraunhofer.de)**

Fraunhofer ISIT  
Fraunhoferstraße 1  
25524 Itzehoe  
[www.fraunhofer.de](http://www.fraunhofer.de)



Fraunhofer-Institut für  
Siliziumtechnologie ISIT

# Thank You for Your attention

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# Technologie-Pitch: »Von makroskopischen Aufbauten zu integrierten elektro-optischen Mikrosystemen«

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Dr. Carolin Rothhardt (IOF), Michael Reibe (IOF), Dr. Andreas Wicht (FBH), Dr. Henning Schröder (IZM), Christian Peters (ILT)

»QNC Summit« 06.03.2025

# Fügetechnologien für Quantencomputing

Realisierung makroskopischer Glaszellen zur Erzeugung kalter Atome

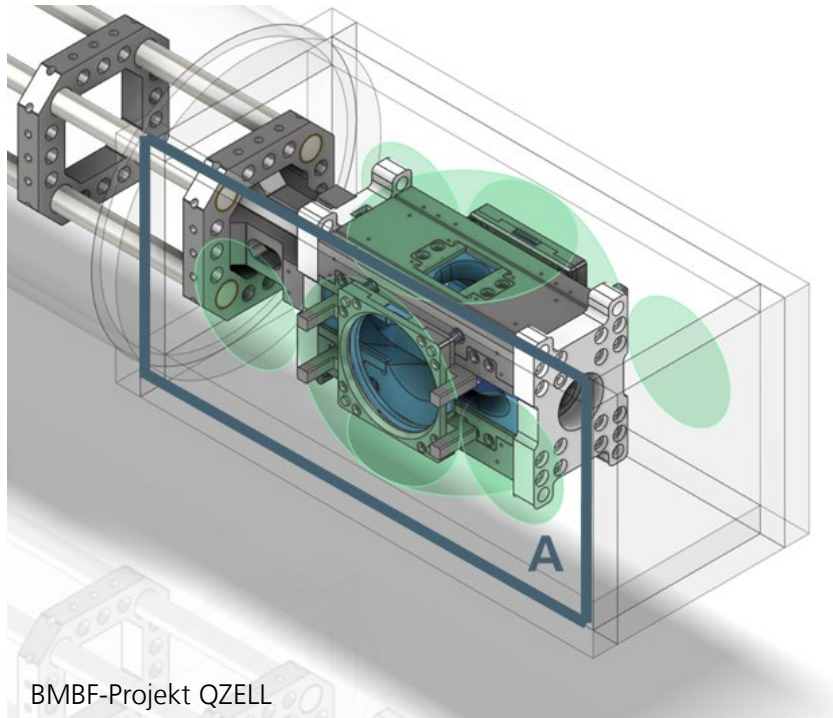
## Fügetechnologien

- Plasma-aktiviertes und silikatisches Bonden
- Bonden komplexen makroskopischer Bauteile bis Waferlevel
- UHV-tauglich, temperaturstabil, hochfest, transparent, weltraumqualifiziert
- Gläser, Keramiken, kristalline photonische Materialien



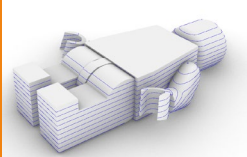
## Prozessierung

- Feinoptische (Oberflächen-) Bearbeitung
- Mikro- und Nanostrukturierung
- Beschichtung

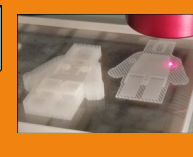
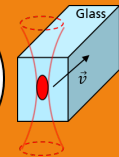


# Selective Laser-induced Etching für 3D-Glasbauteile

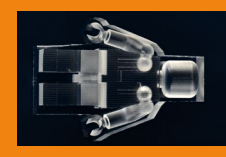
## 1 Design



## 2 Laserstrukturierung



## 3 Chemisches Ätzen



## 4 Ergebnis

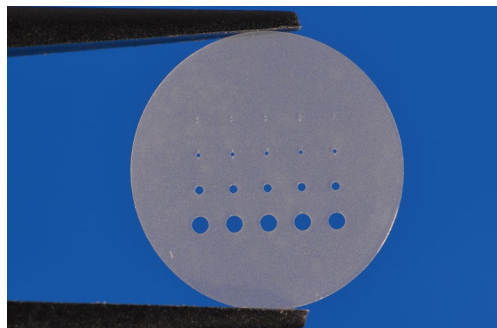
3D-Glasbauteil



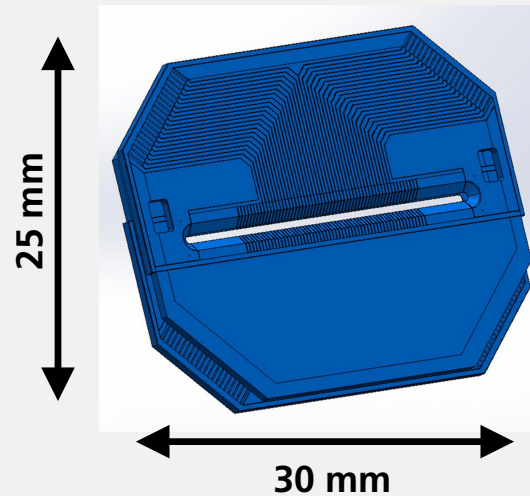
### SLE ermöglicht:

- Völlig freie Wahl der Geometrie
- Hohe Präzision
- Rohmaterial Glas oder Saphir (elekt. Isolator)

### Through wafer vias (TWVS) in Sapphire



### SLE strukturierte Ionenfalle



### Kombinierter Prozess SLE und Politur

SLE fabricated lens:



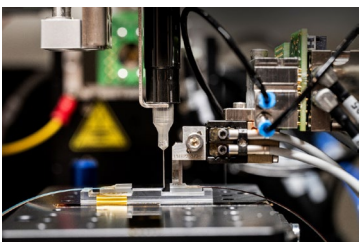
After CO<sub>2</sub> polishing:



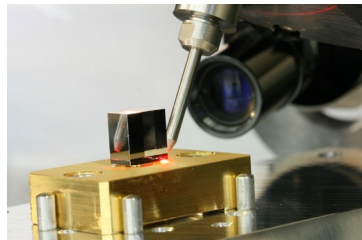
## Technologien

- aktive Ausrichtung von Fasern, Linsen, etc. nach Leistungs- und Strahlprofilmessungen
- elektrooptische Integration von PICs
- adhesive bonding und solder jet bumping

## Aktive Faserkopplung



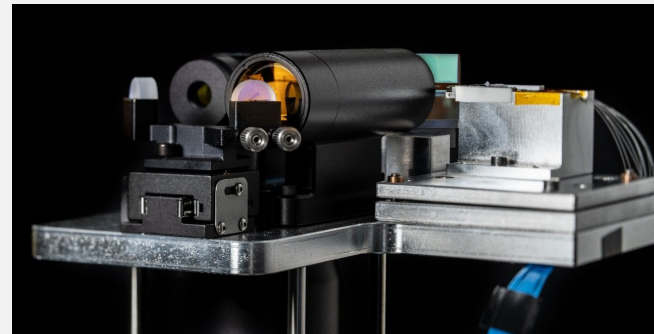
## Solder Jet Bumping



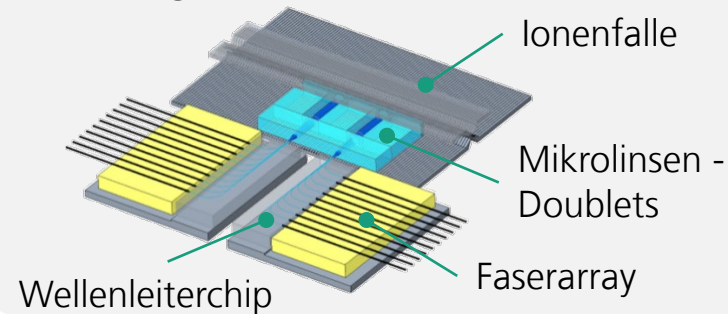
## Anwendungen

### Addressiereinheit Ionen Quantencomputer

#### Makro – Extern:

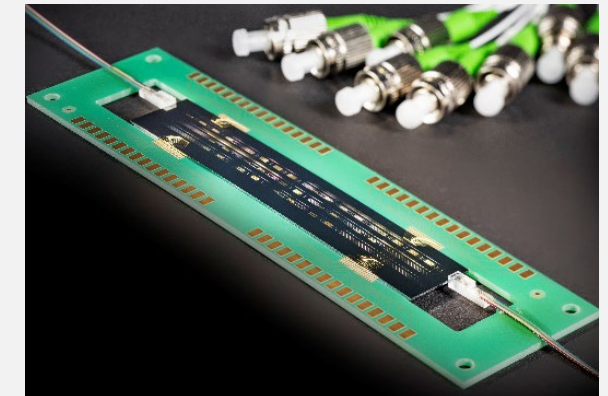
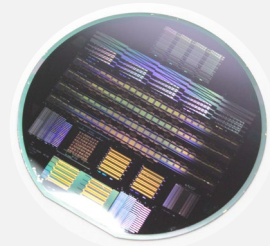


#### Micro – Integriert:



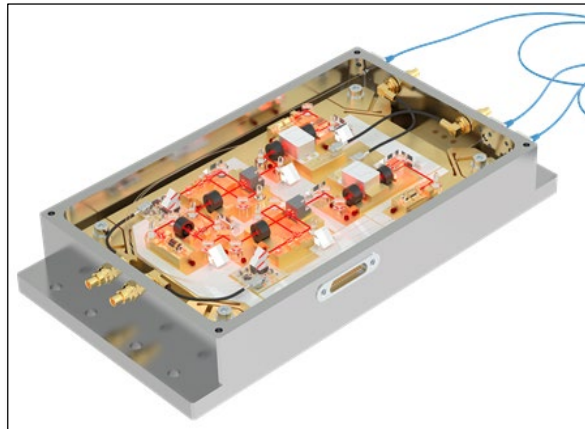
### LNOI Interferometer Photonischer Quantencomputer

LNOI Interferometer  
Entwicklung und  
Integration



## Komplexität

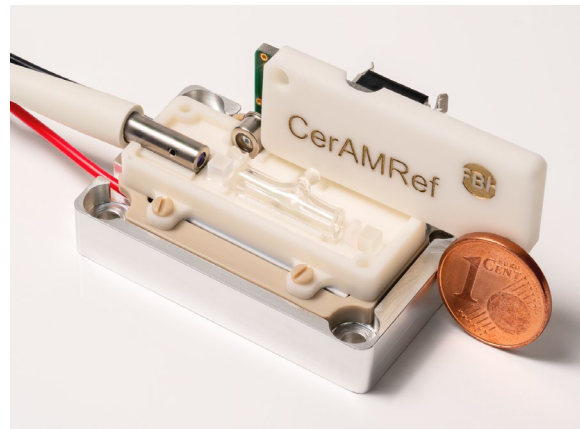
- Miniaturisierung hochkomplexer Lasersysteme, Light Control Units, Frequenz-Referenzen und Physics Packages



Light Control Unit  
mit Faser-Pfadlängen-Stabilisierung

## Kompaktheit & Robustheit

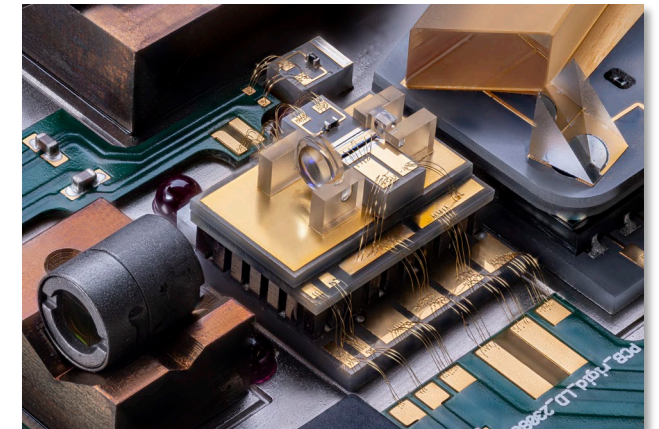
- Formfaktor  $\sim 1/100$  im Vergleich zum Stand der Technik
- für Einsatz auch unter harschen Umweltbedingungen (Weltraum)



Gaszellen-basierte  
Frequenzreferenz

## Technologie

- gleichzeitige aktive Justage mehrerer optischer Komponenten mit sub-100 nm Genauigkeit
- Adhesives Bonden, auch unter UHV-Bedingungen

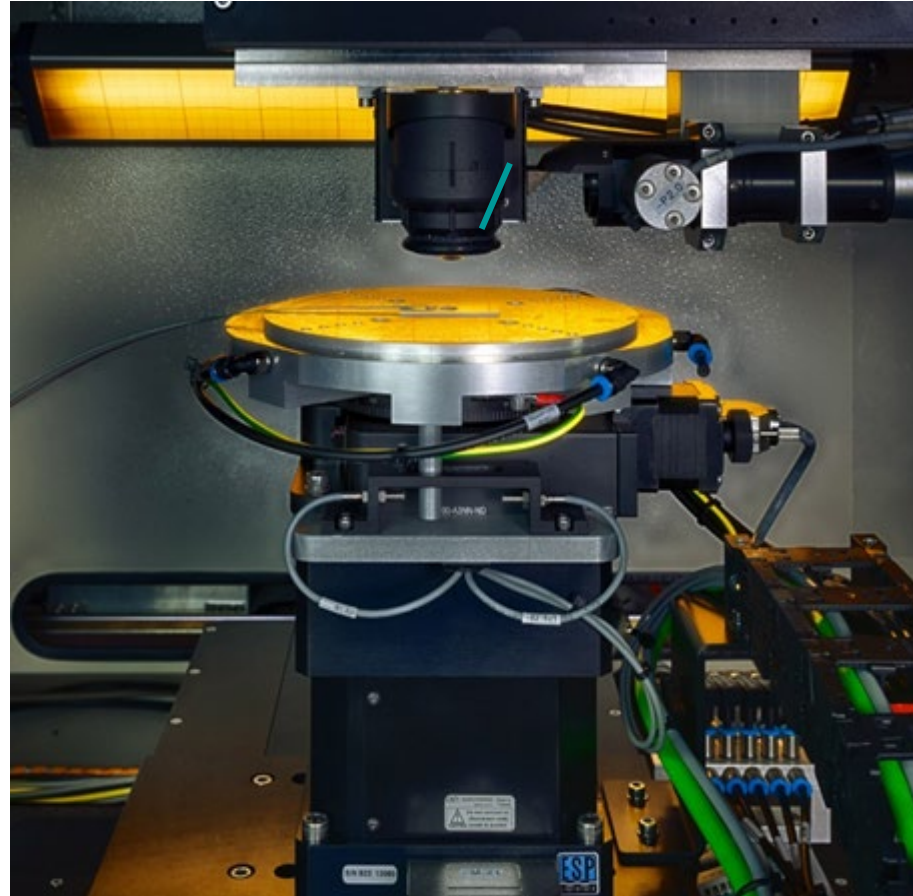
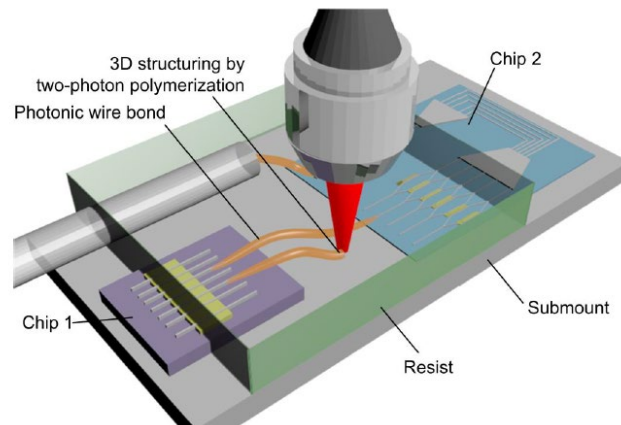


Lokaloszillator eines Extended Cavity  
Diodenlasers mit optischem Verstärker

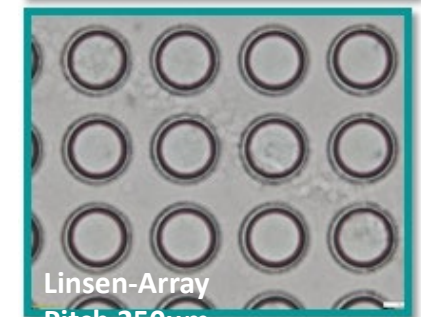
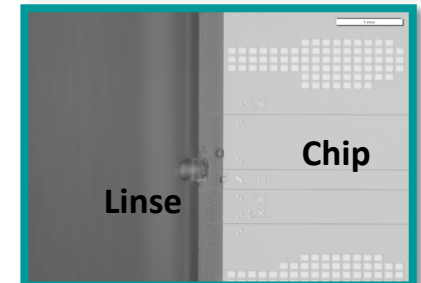
# Gedruckte mikro-optische 3D-Wellenleiter und Optiken

## Zwei-Photonen-Polymerisation

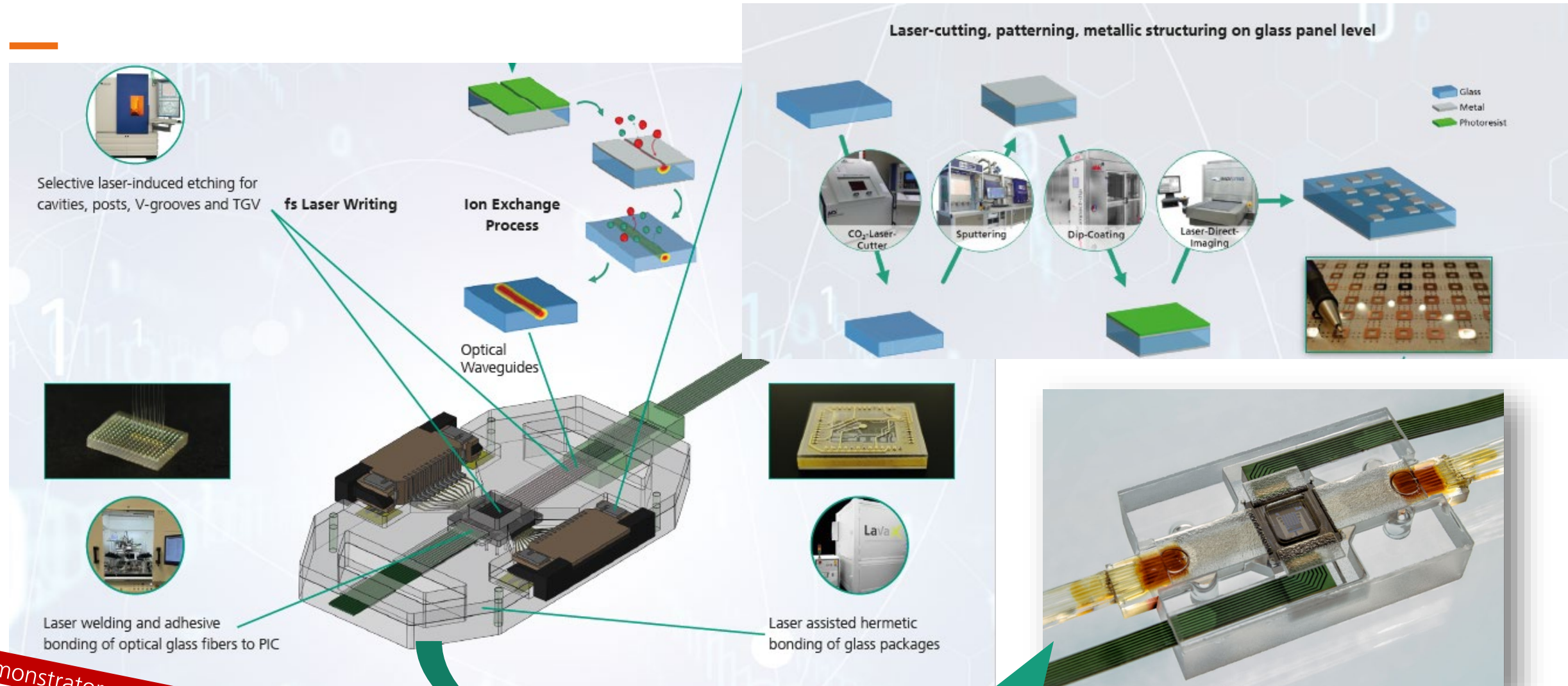
- Verschiedene 3D-Formen zur Anpassung des Modenfelddurchmessers von  $2 \lambda$  bis  $10 \mu\text{m}$
- Hybride Integration von verschiedenen PICs
- Skalierbarkeit und Reproduzierbarkeit
- Positionsgenauigkeit



Fraunhofer IZM\_2PP



# Glasbasierte Aufbautechnik und Testplattform für PICs





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# Technologie-Pitch: »Enabling technologies for Photonic Quantum Applications«

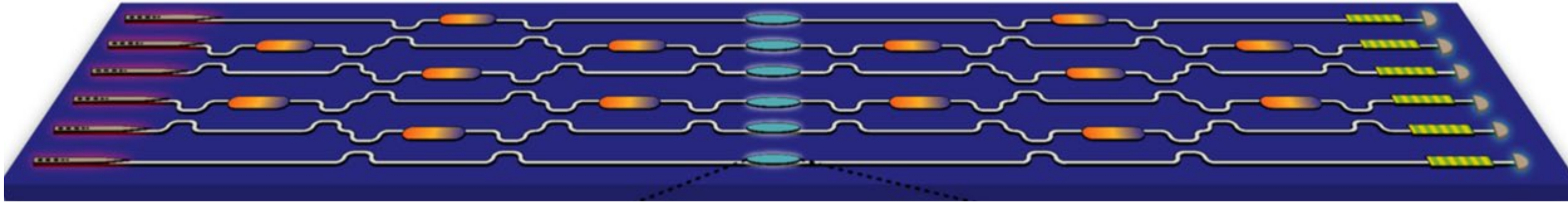
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Dr. Tommaso Pregnolato

»QNC Summit« 07.03.2025

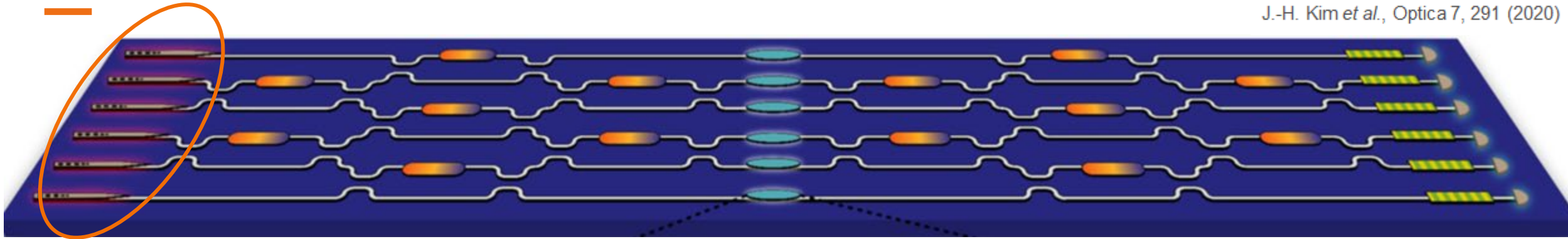
# Building a photonic quantum platform

The key functionalities



# Building a photonic quantum platform

The key functionalities



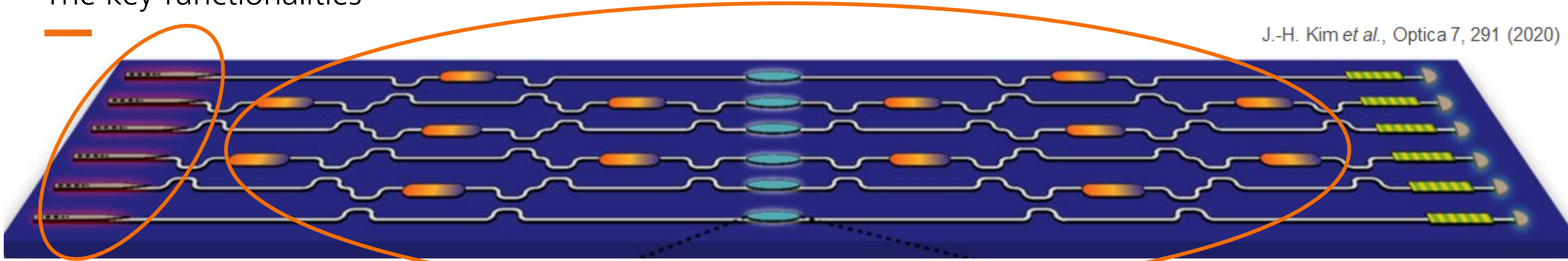
## Generation

of quantum states of light:

- single photons
- entangled photons states  
(cluster states)

# Building a photonic quantum platform

The key functionalities



## Generation

of quantum states of light:

- single photons
- entangled photons states (cluster states)

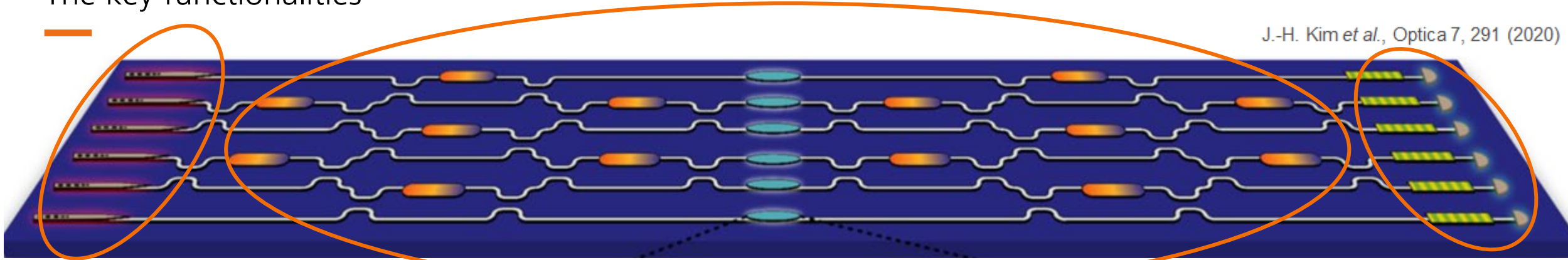
## Manipulation

of guided photons:

- routing through the circuit
- interference
- gate operations

# Building a photonic quantum platform

The key functionalities



## Generation

of quantum states of light:

- single photons
- entangled photons states (cluster states)

## Manipulation

of guided photons:

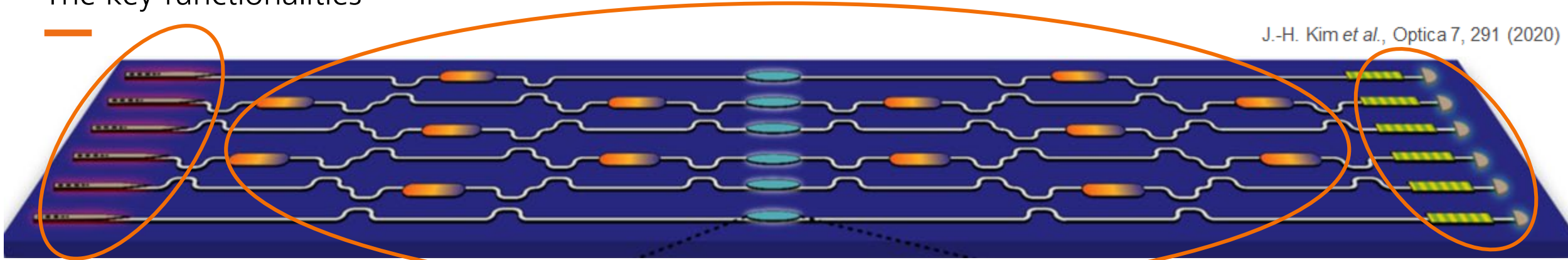
- routing through the circuit
- interference
- gate operations

## Read-out

of operations (detectors)

# Building a photonic quantum platform @ FMD-QNC

The key functionalities



## Generation

of quantum states of light:

- single photons
- entangled photons states (cluster states)

- ✓ Diode lasers + non-linear effects
- ✓ Color centers

## Manipulation

of guided photons:

- routing through the circuit
- interference
- gate operations

- ✓ MEMS & PICs
- ✓ Color centers
- ✓ Non-linear effects

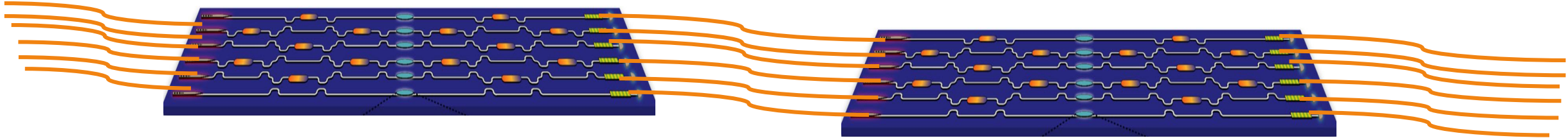
## Read-out

of operations (detectors)

- ✓ Superconductors

# Building a photonic quantum network @ FMD-QNC

Increasing complexity



## Optical connections

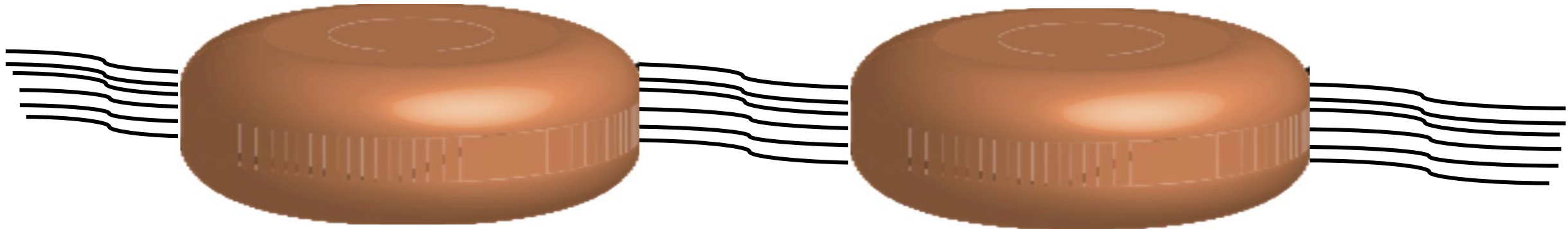
via optical fibers

- efficient out-couplers



# Building a photonic quantum network @ FMD-QNC

Increasing complexity



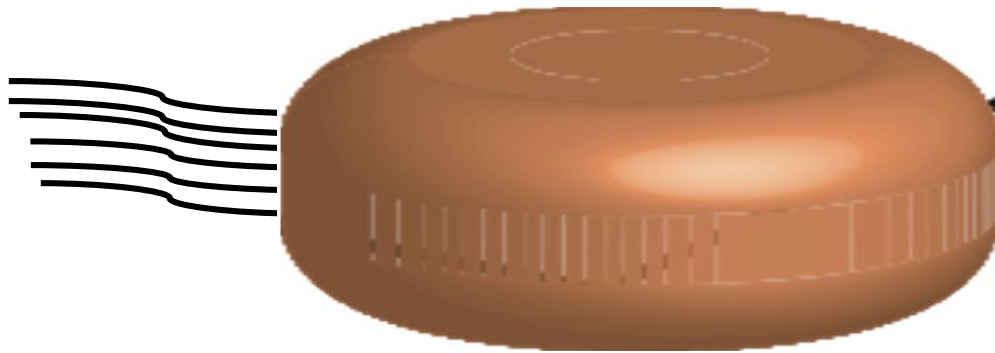
## Optical connections

via optical fibers

- efficient out-couplers
- packaging

# Building a photonic quantum network @ FMD-QNC

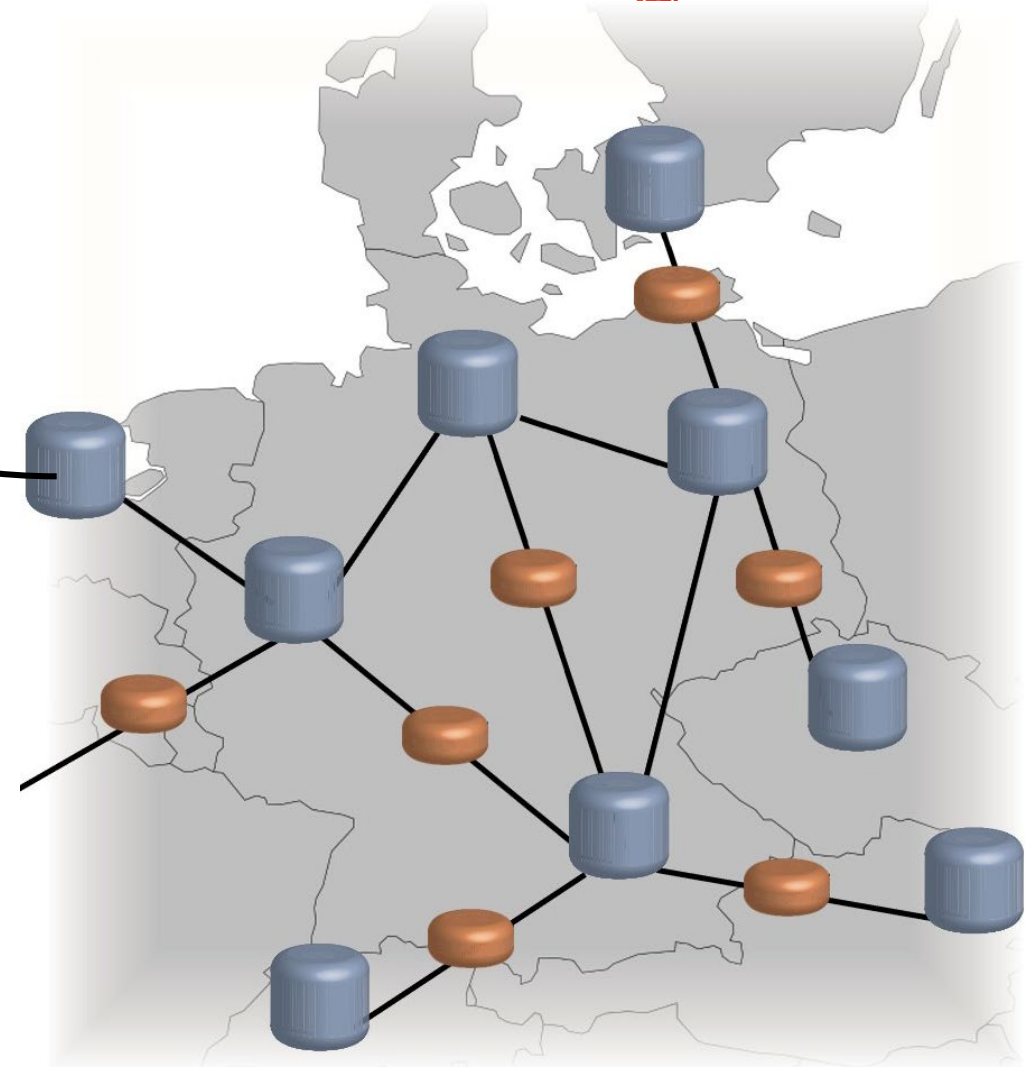
Increasing complexity



## Optical connections

via optical fibers

- efficient out-couplers
- packaging
- construction of large quantum networks



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