Quantum Valley Lower Saxony

Quantum computers with trapped ions

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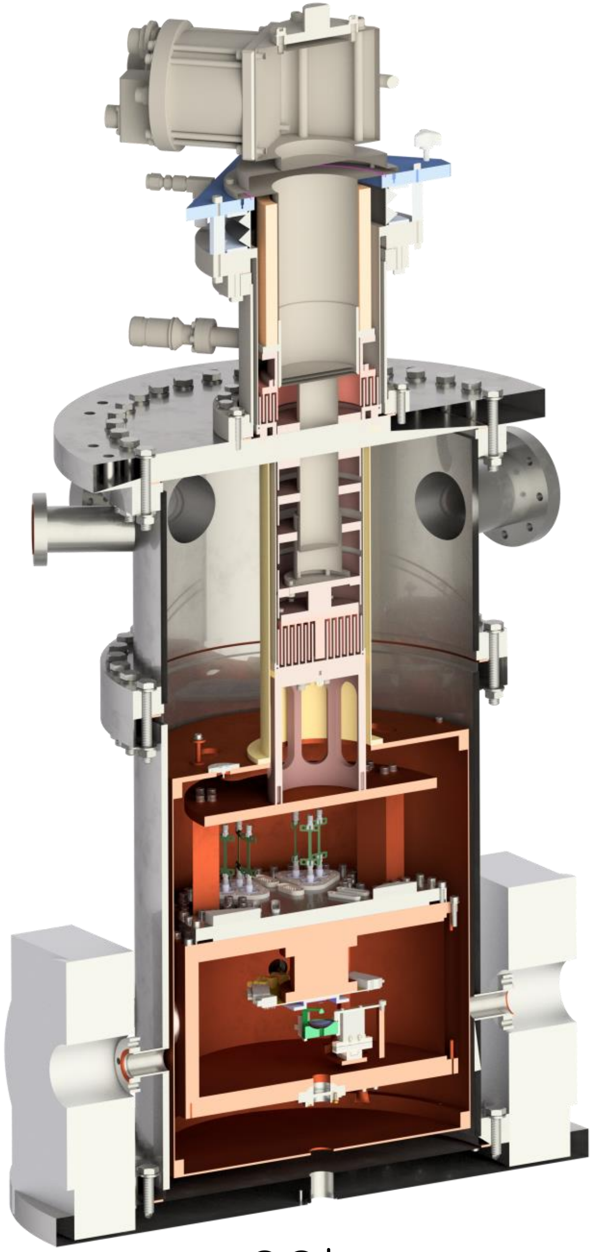
Quantum compuer demonstrators in lower saxony

- **QVLS-Q1:** 50 $^{9}Be^{+}$ qubits, trapped ion technology
- **ATIQ:** 40 $^{43}Ca^{+}$ qubits, integrated photonics
- **23 Teams**, including design, fabrication, electronics, laser, integrated optics, integrated detectors, benchmarking, error mitigation, compiler, gate mechanisms, algotithms, aplications, spill over technologies
- **Collaboration** with industry partners and other ion trap quantum computing groups in Germany



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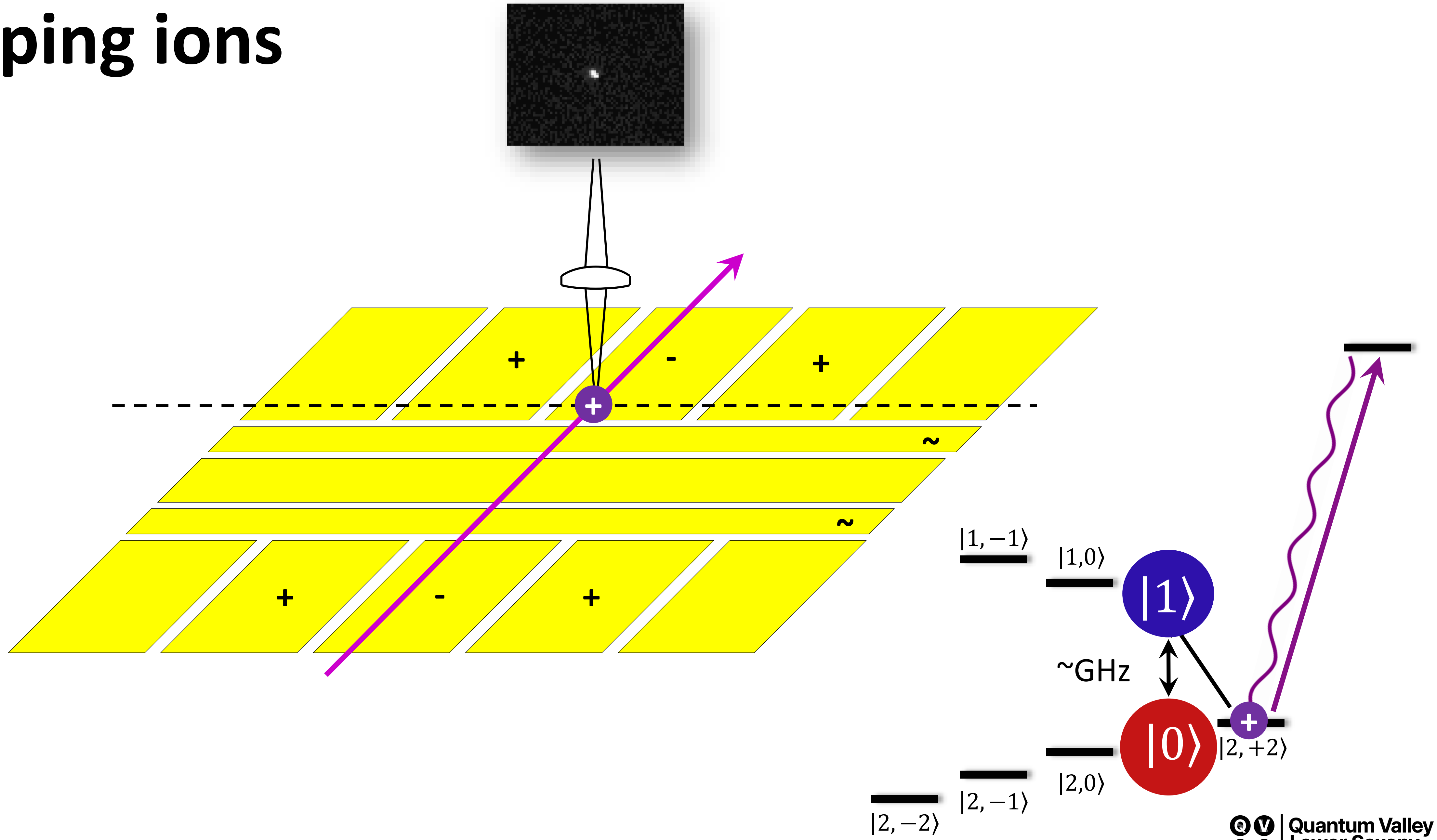
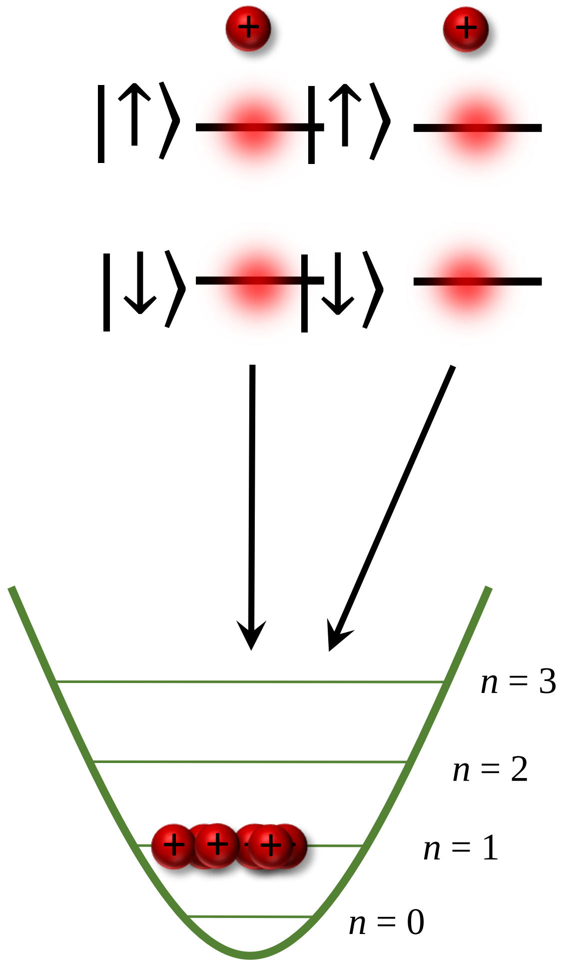
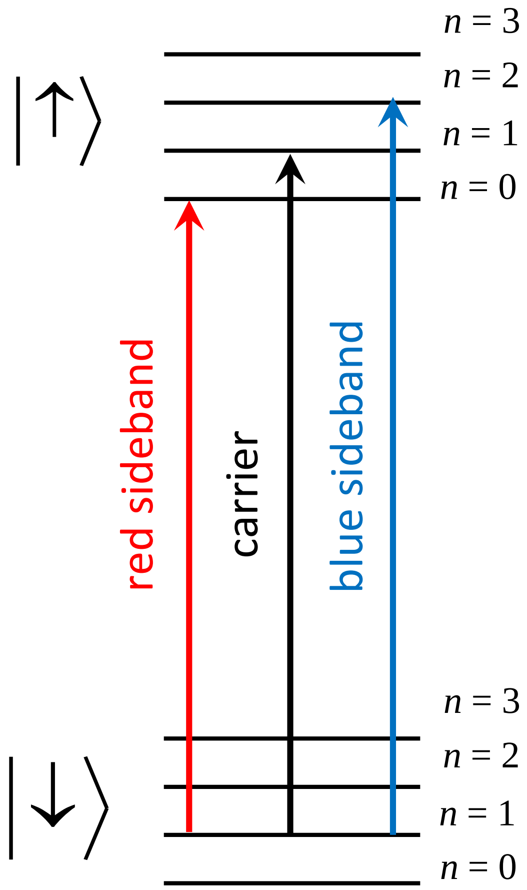
Trapping ions



Quantum states in an ion trap



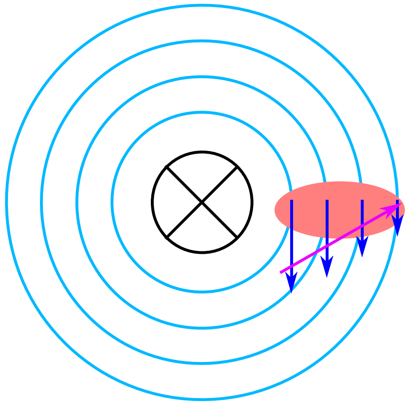


Near-field gates

Carrier transition

Interacts only with internal state

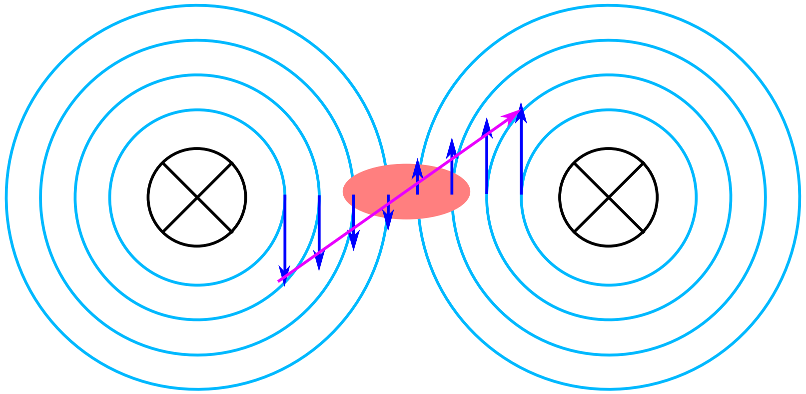
- Speed $\Omega_C \sim B$
- Scaling $B \sim d^{-1}$



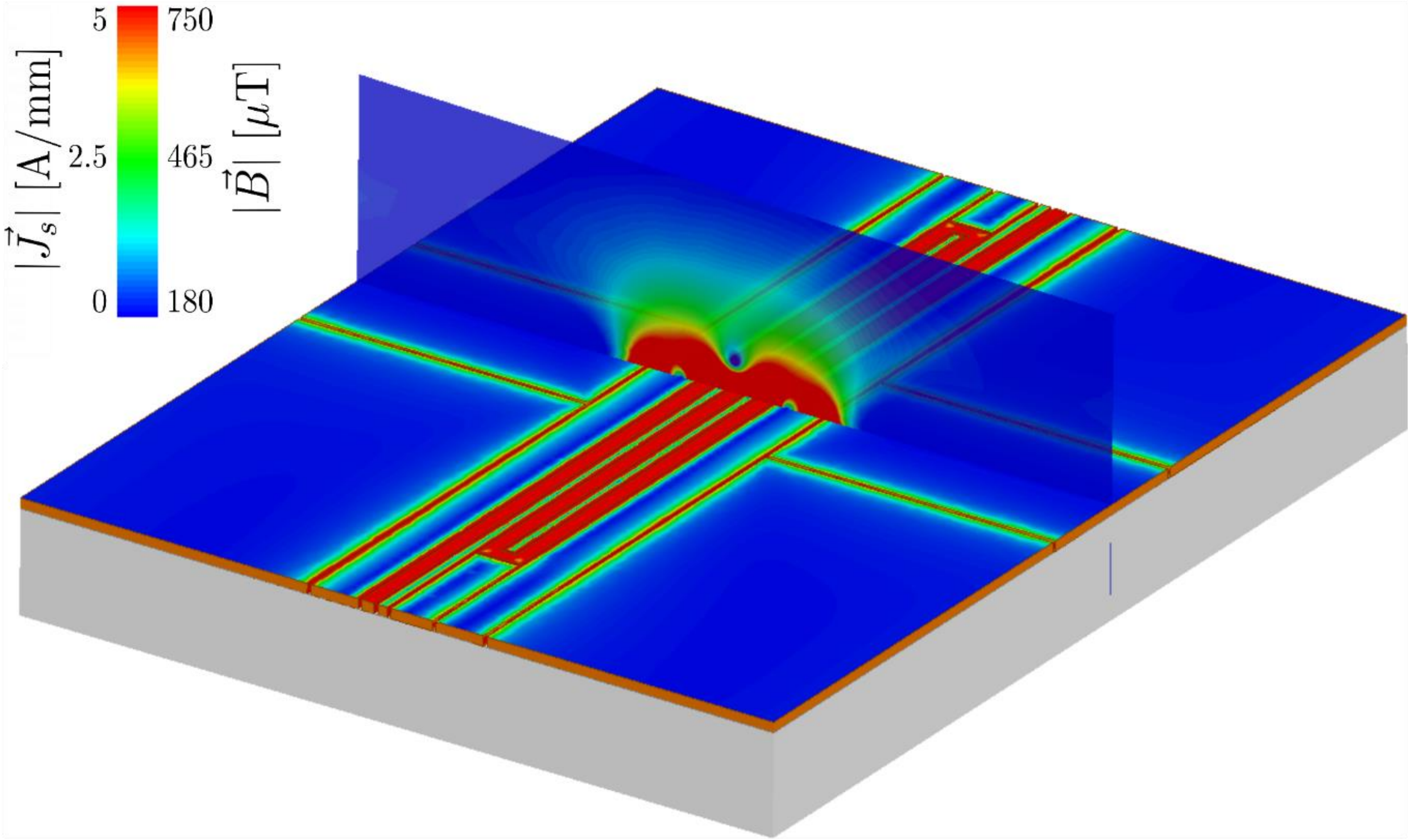
Sideband transition

Interacts with motional state

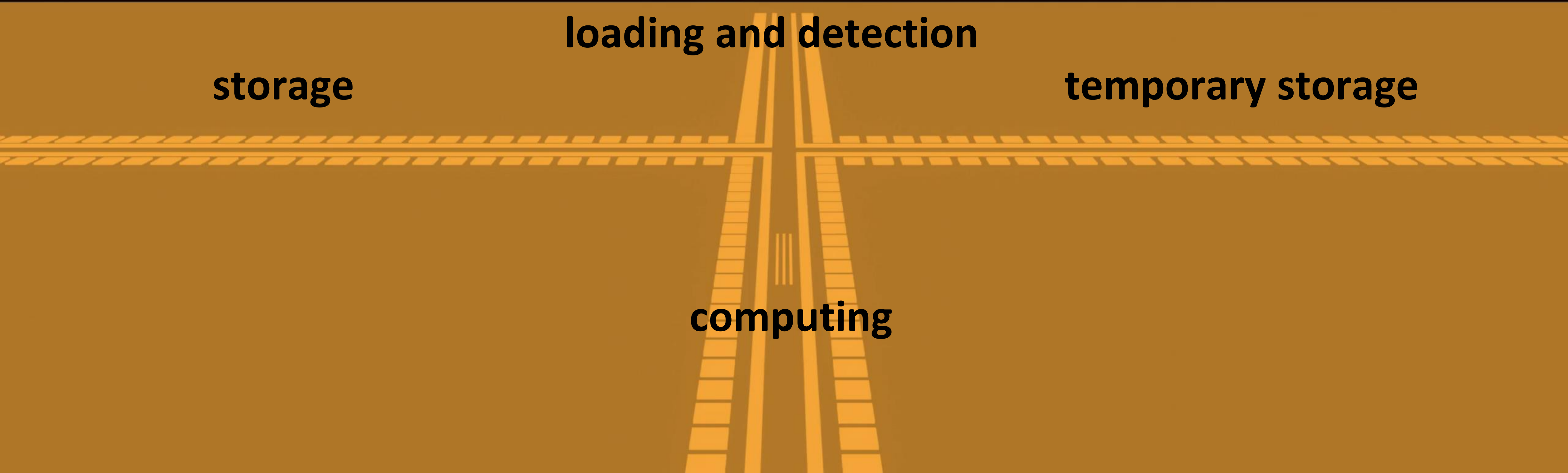
- Speed $\Omega_{SB} \sim \nabla B$
- Scaling $\nabla B \sim d^{-2}$

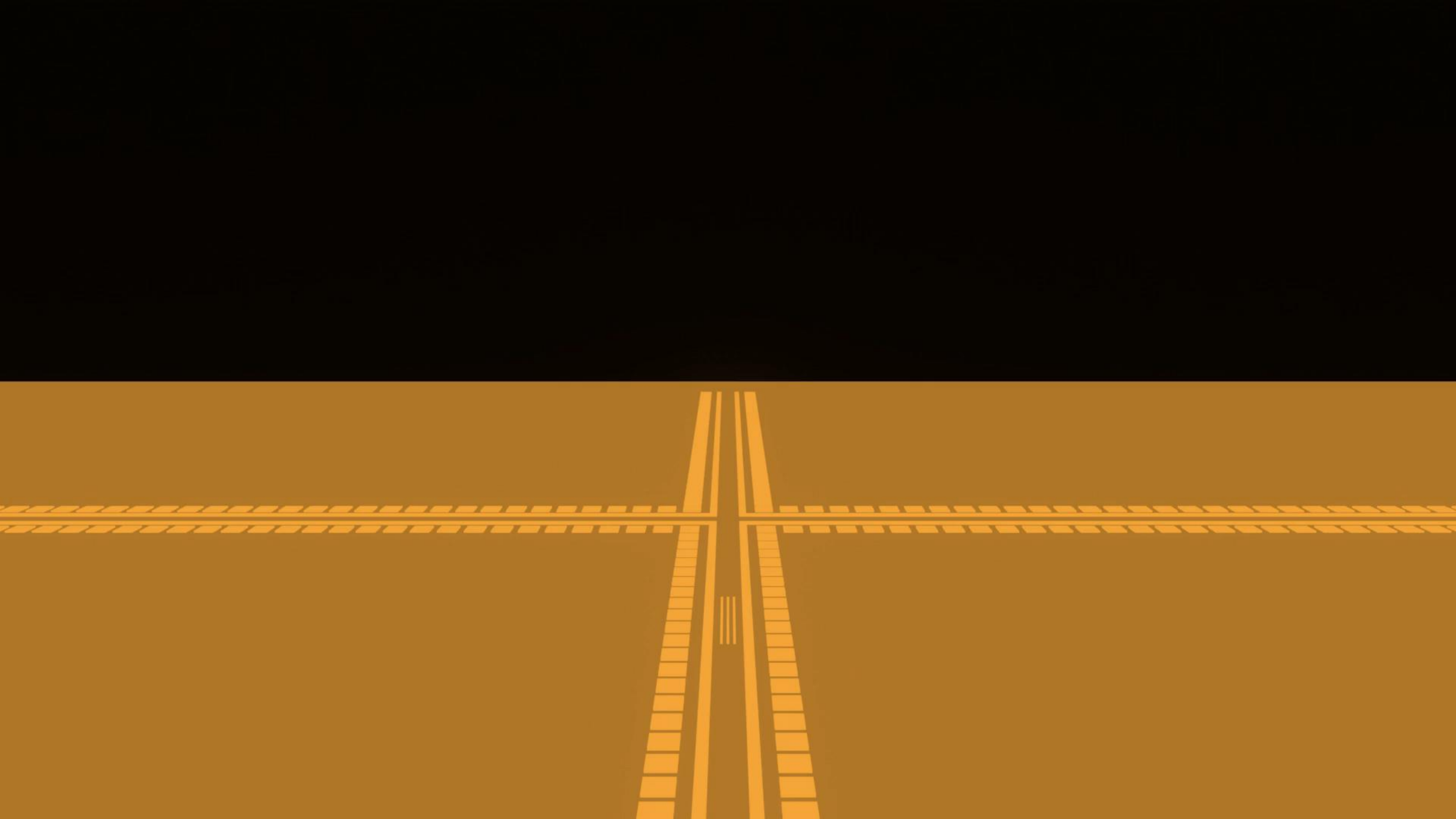


Magnetic field simulations

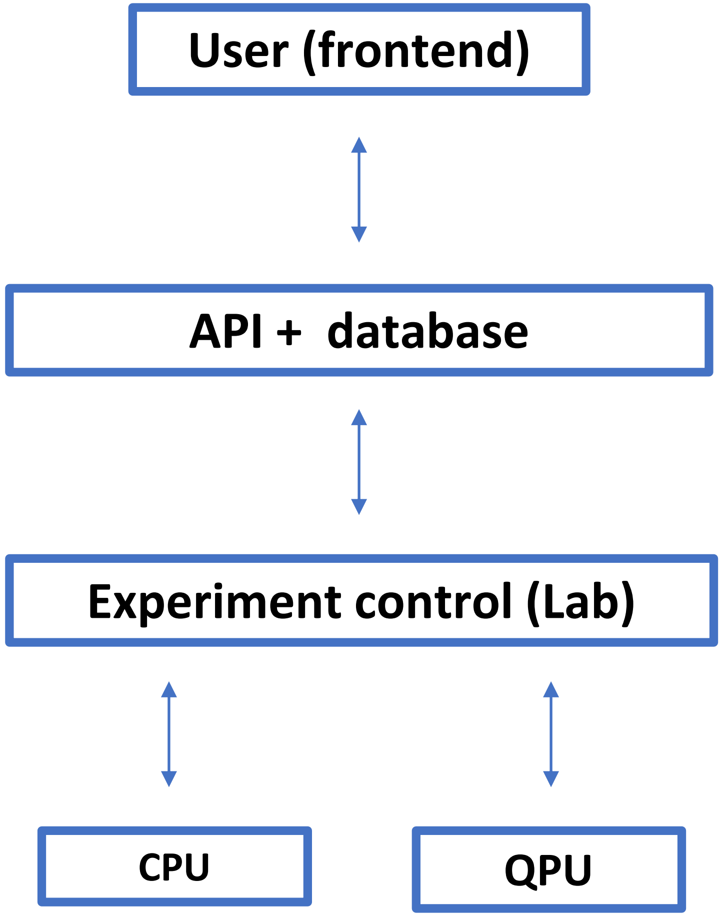


Wahnschaffe et al., Applied Physics Letters 110, 034103 (2017)


loading and detection
storage
temporary storage
computing



Qiskit to ion compiler

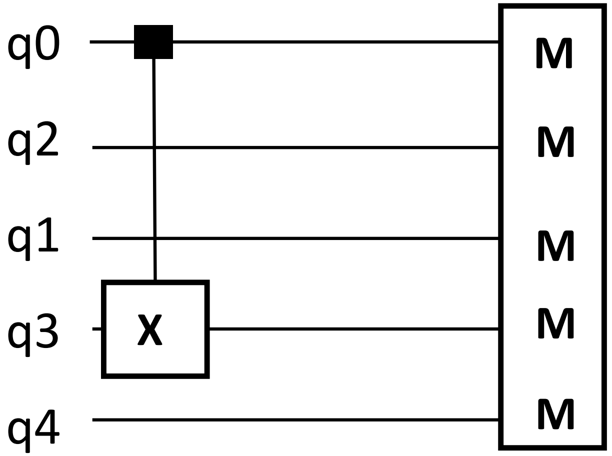


- Qiskit compatible
- Hybrid qc compatible
  - Intermediate measurements
  - Reinitialization of qubits
  - Accepts python code

Qiskit to ion compiler

Qiskit

```
qc = QuantumCircuit(5)
qc.cx(0,3)
qc.measure_all()
```



OpenQASM2

```
OPENQASM 2.0;
include "qelib1.inc";
qreg q[5];
creg meas[5];
ry(-pi/2) q[0];
rxx(-pi/2) q[0],q[3];
rx(pi/2) q[0];
ry(pi/2) q[0];
rx(-pi/2) q[3];
barrier q[0],q[1],q[2],q[3],q[4];
measure q[0] -> meas[0];
measure q[1] -> meas[1];
measure q[2] -> meas[2];
measure q[3] -> meas[3];
measure q[4] -> meas[4];
```

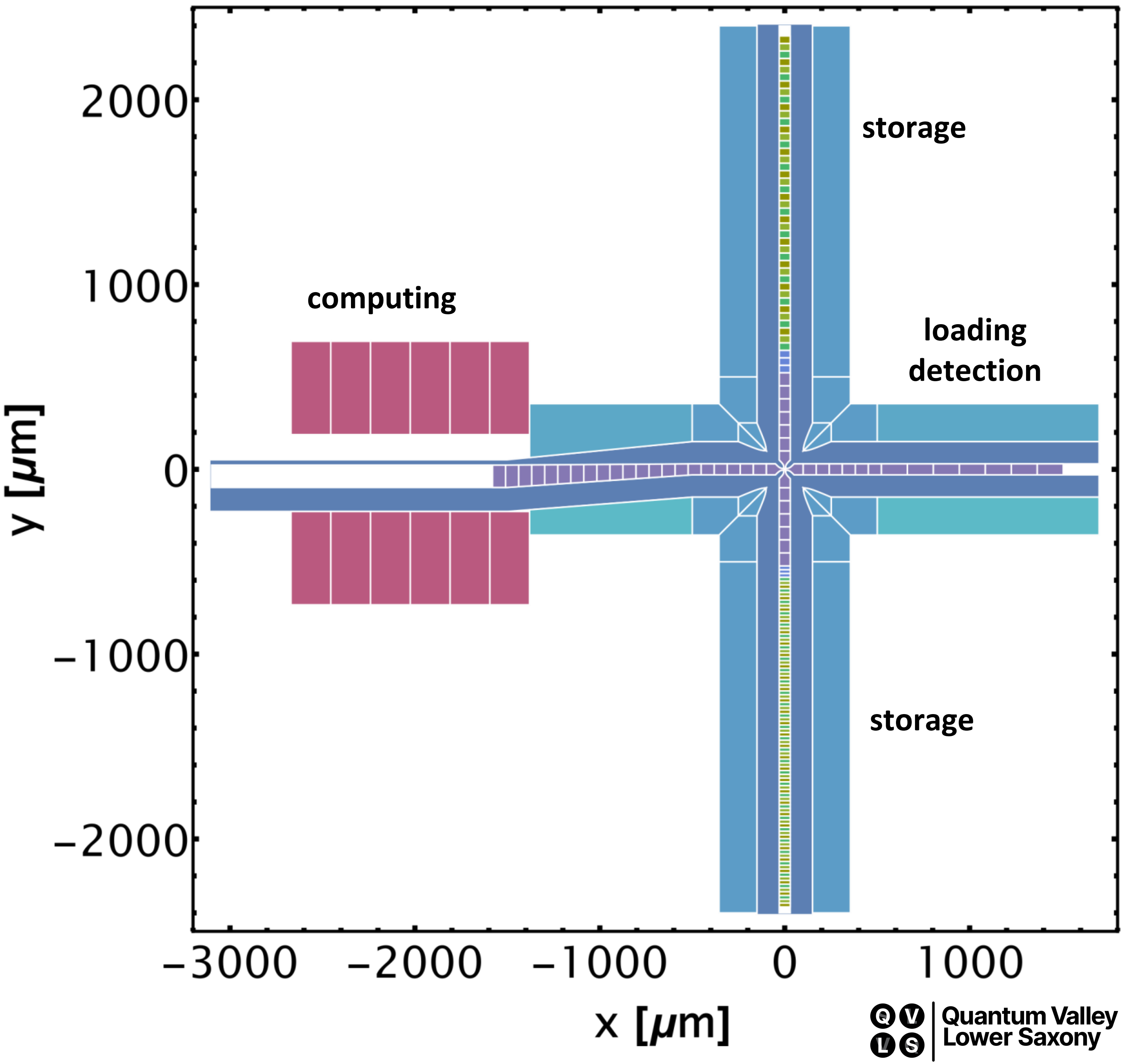
TIASM

```
TIASM 1.0;
classical_register(5);
initial_ion_order(1,2,4,0,3);
quantum_register(5);
move(storage,spam);
prepare(spam);
move(spam,compute[0]);
prepare(compute[1]);
move(compute[1],spam);
measure ->1;
move(spam,temp_storage);
move(storage,spam);
prepare(spam);
move(spam,compute[0]);
prepare(compute[1]);
move(compute[1],spam);
measure ->2;
move(spam,temp_storage);
move(storage,spam);
prepare(spam);
move(spam,compute[0]);
prepare(compute[1]);
move(compute[1],spam);
measure ->4;
move(spam,temp_storage);
move(storage,spam);
prepare(spam);
move(spam,compute[0]);
prepare(compute[1]);
ry(-1.570796);
move(storage,spam);
prepare(spam);
move(spam,compute[1]);
prepare(compute[2]);
rxx(-1.570796);
rx(1.570796);
ry(1.570796);
move(compute[2],temp_storage);
move(compute[1],spam);
measure ->0;
move(spam,compute[0]);
move(temp_storage,compute[1]);
rx(-1.570796);
move(compute[2],spam);
measure ->3;
move(spam,compute[1]);
```

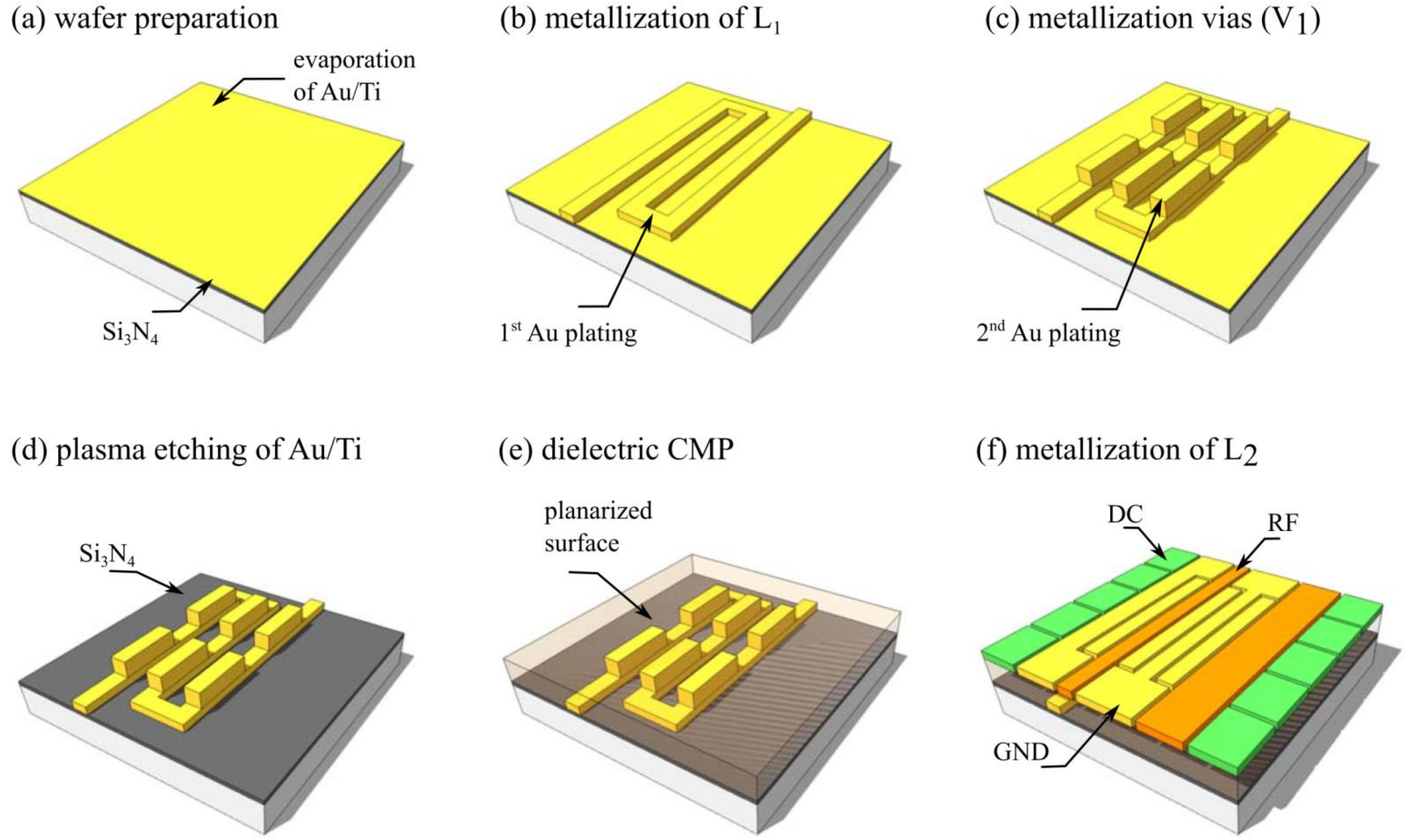
Schmale et al., IEEE procedings QSW 2022, p. 32-37

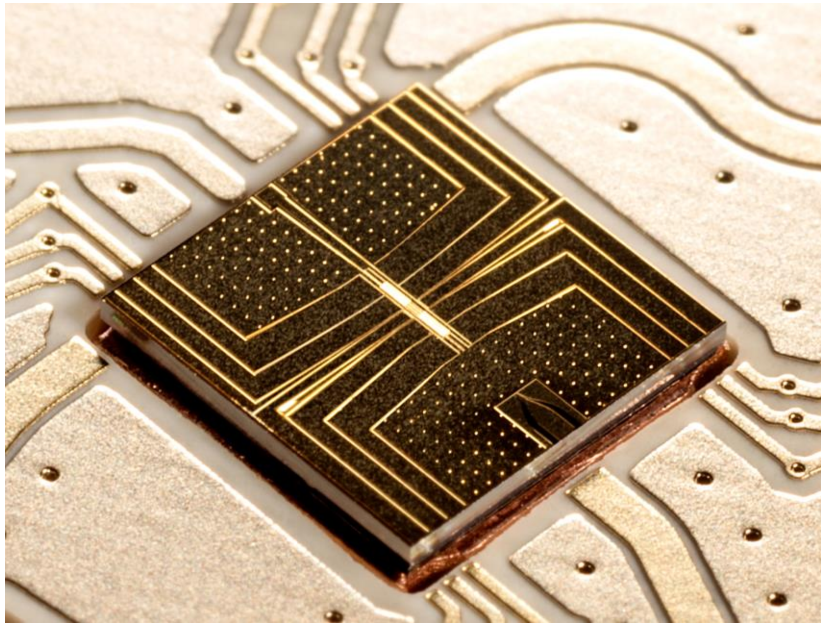
Test chip design

- 222 Electrodes
- 1 RF
- 221 DC:
- 50 inner DCs
- 12 outer DCs
- 24 shim DCs
- 45 upper storage DCs (40µm)
- 90 lower storage DCs (20µm)
- (3+3 indiv. per register)



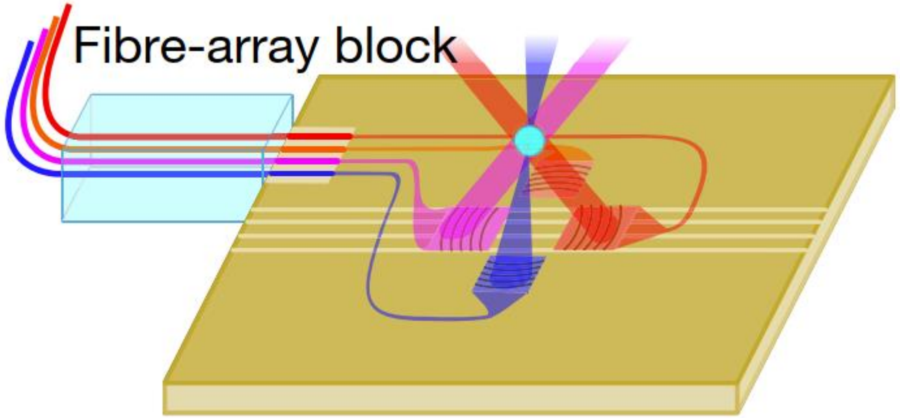
Multi layer trap fabrication



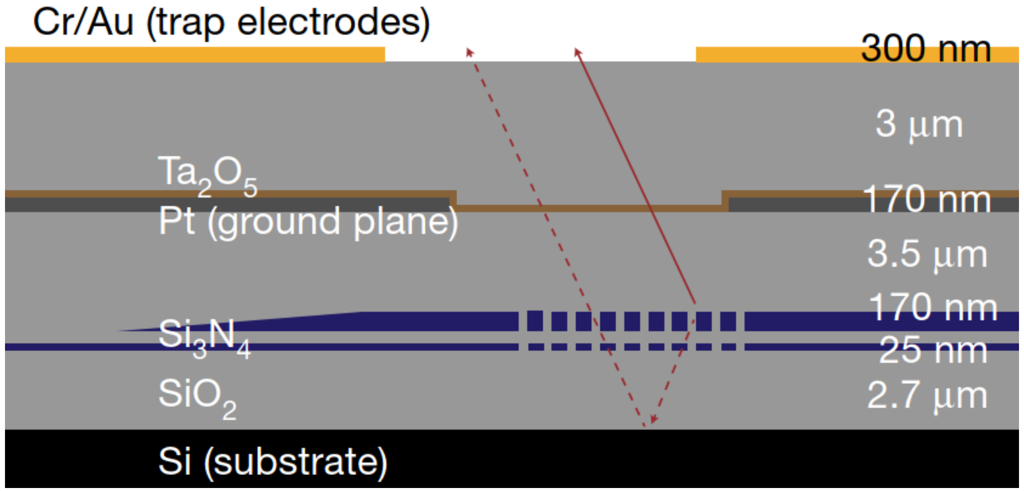


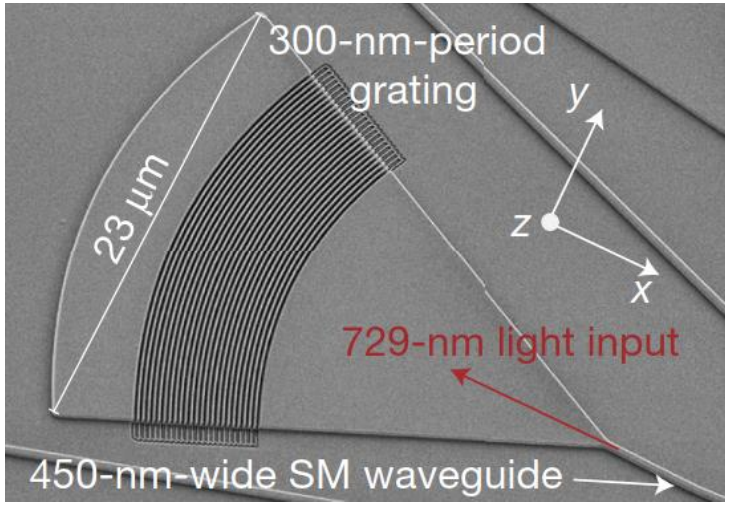
A Bautista-Salvador et al 2019 New J. Phys. 21 043011

Integrated waveguides



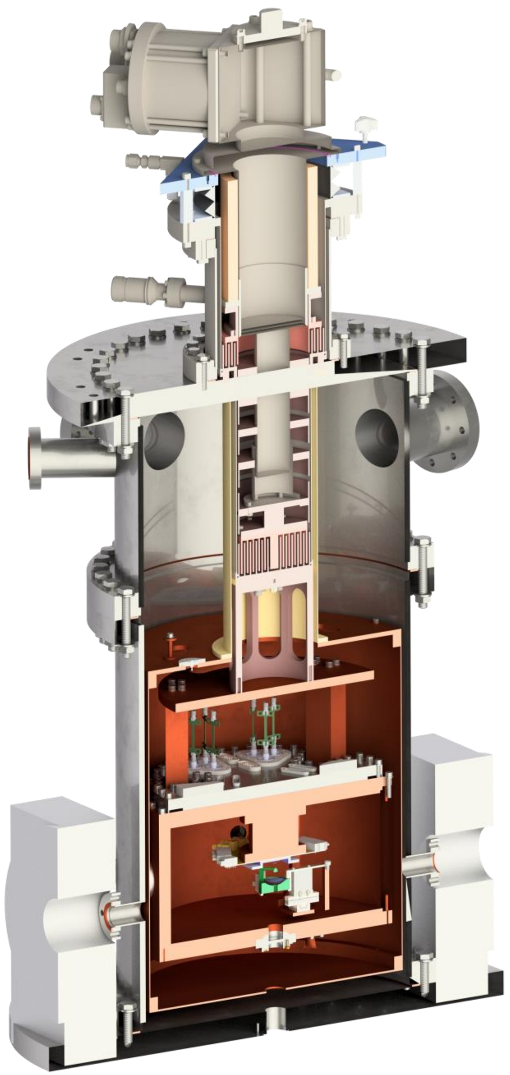
R. J. Niffenegger et al., Nature 586, 538–542 (2020)





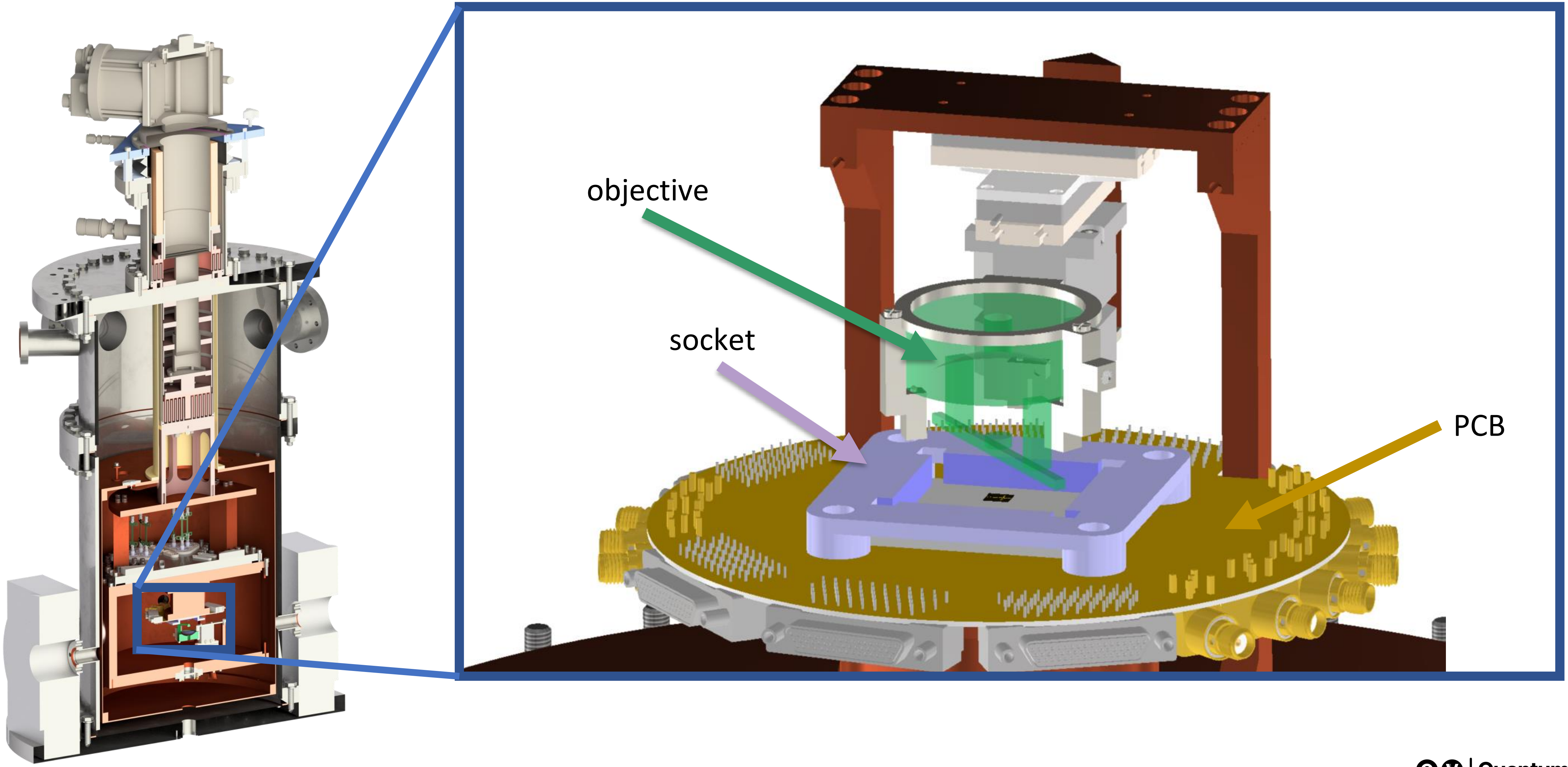
K. Mehta et al., Nature 586, 533–537 (2020)

Demonstrator apparatus



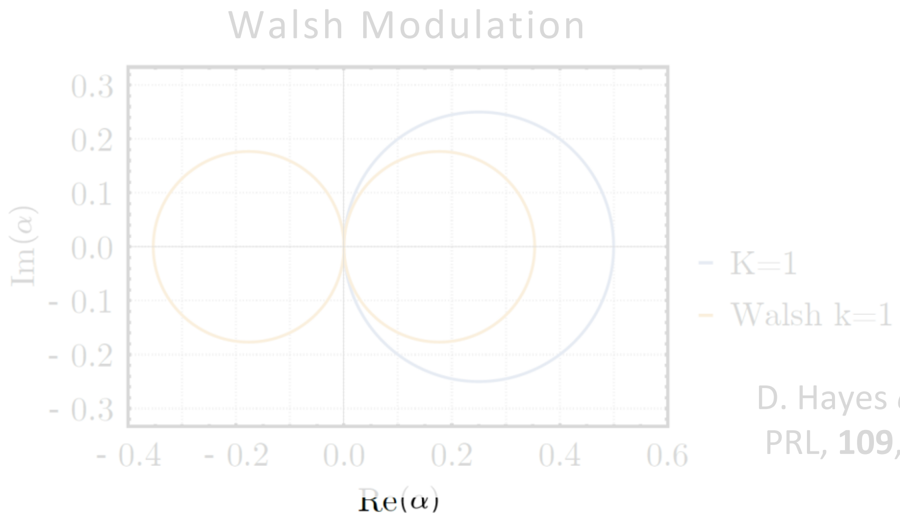
- 300 DC lines for trap operation
- 30 auxilliary DC lines
- 9 HF lines
- 30 optical fiber connections
- Highly versatile
  - Applicable to other projects and demonstrators

Inner chamber

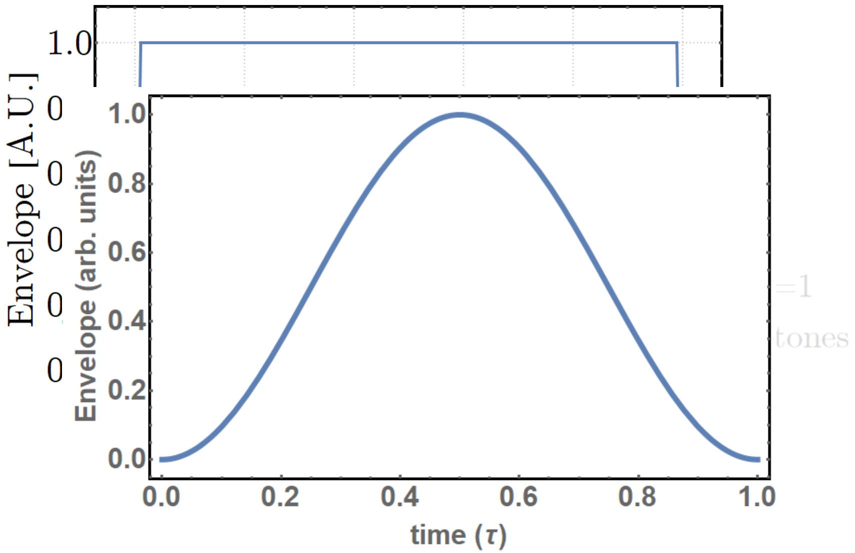


Quantum control

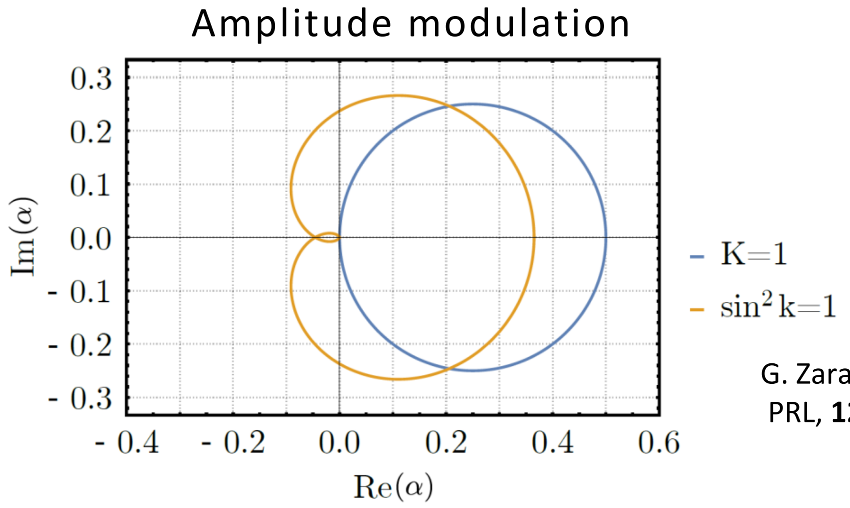
K. Mølmer *et al.*,
PRL. **82** (1999);



D. Hayes *et al.* ,
PRL, **109**, 2012



Haddadfarshi *et al.*,
NJP, **18** (2016)

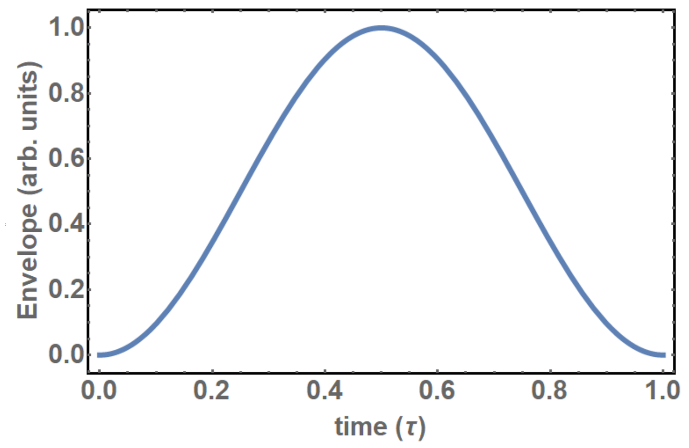


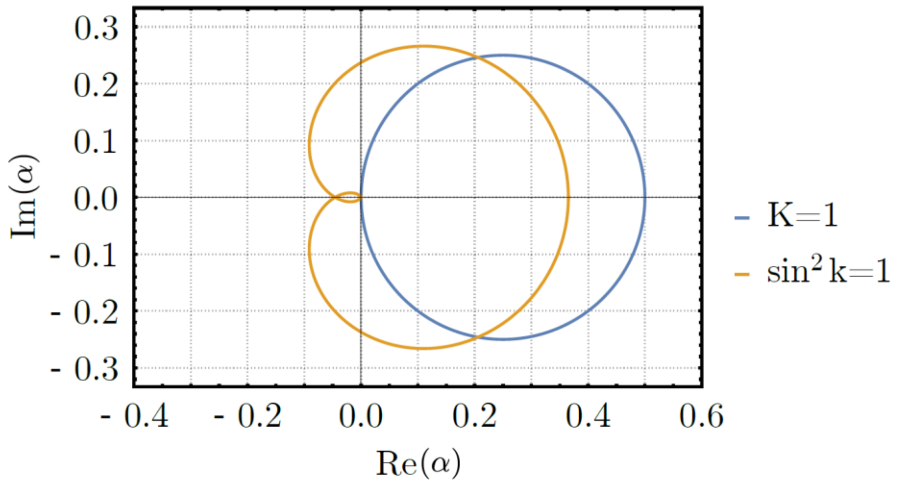
G. Zarantonello *et al.*,
PRL, **123**, 2019

High-fidelity shaped pulses

- Robust against heating
- Robust against mode-drift
- Robust against mode-noise
- Reduced impact of spectator motional modes

$\Rightarrow$ $\mathcal{F} \simeq 99.5(2)\%$





G. Zarantonello et al., Phys. Rev. Lett. **123**, 260503

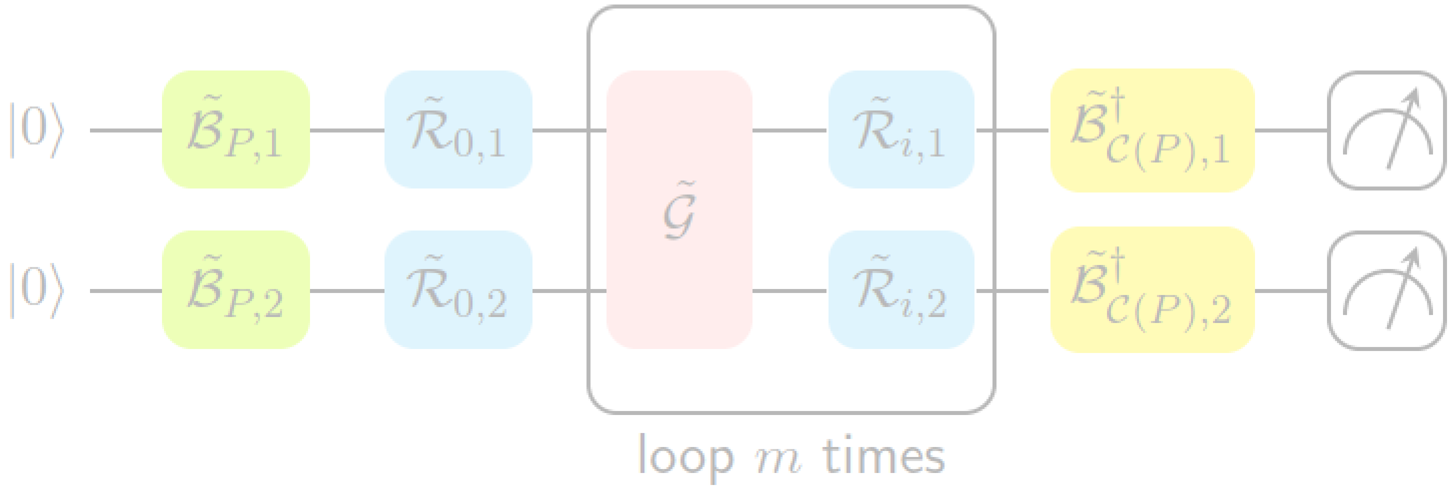
Preliminary Error Budget: The remaining big ticket items

Error source	Error for short gate	Error for long gate	Proposed solution
Spectator mode initial temperture	$6 \cdot 10^{-4}$	$3 \cdot 10^{-3}$	Sympathetic cooling and cryogenic environment
Heating of entangling mode	$2 \cdot 10^{-3}$	$7 \cdot 10^{-4}$	Cryogenic environment
Common AC Zeman shift of both ions	$3 \cdot 10^{-4}$	$3 \cdot 10^{-3}$	Better microwave field engineering
Motional mode instability	$3 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	More stable RF resonator Better thermal control of trap

Cycle benchmarking: Simple algorithms

Computational gate:	$\tilde{\mathcal{B}}$	single qubit $\pi/2$ rotation	x, y, z deterministic
Pauli gate:	$\tilde{\mathcal{R}}$	single qubit π rotation	x, y, z random
Entangling g…			…ce
Calculated gate:	$\tilde{\mathcal{B}}$	π or $\frac{\pi}{2}$	$\lvert 00\rangle$ or $\lvert 11\rangle$ randomly

$$\mathcal{F} = 96.6\,\%$$



Last slide

Quantum Valley Lower Saxony

QVLS Scientists (November 2022)

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QUANTUM FLAGSHIP

microQC

Bundesministerium für Bildung und Forschung

Niedersächsisches Ministerium für Wissenschaft und Kultur

VolkswagenStiftung