Quantum-classical hybrid circuits with trapped ions

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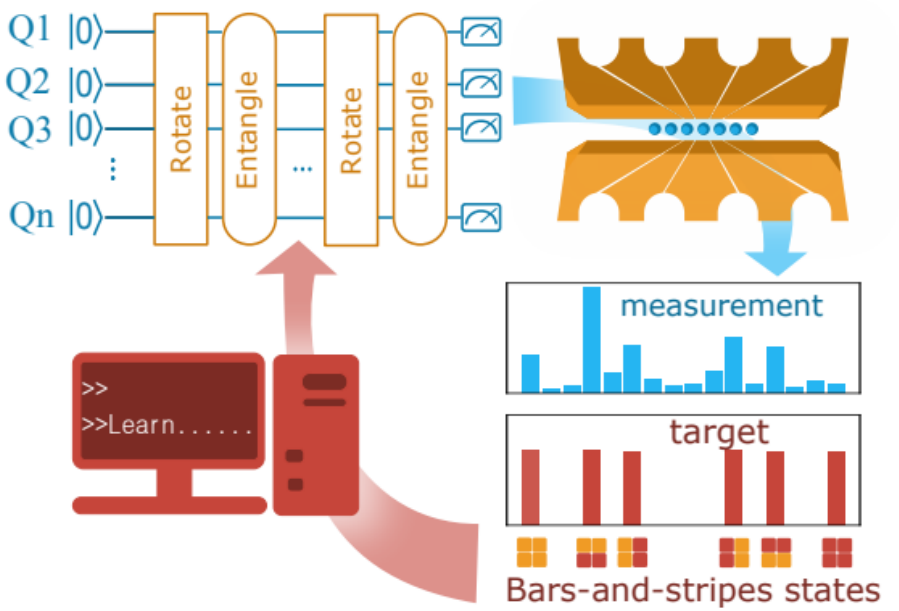


AMO Seminar, University of Virginia, Charlottesville, VA

11 November 2019

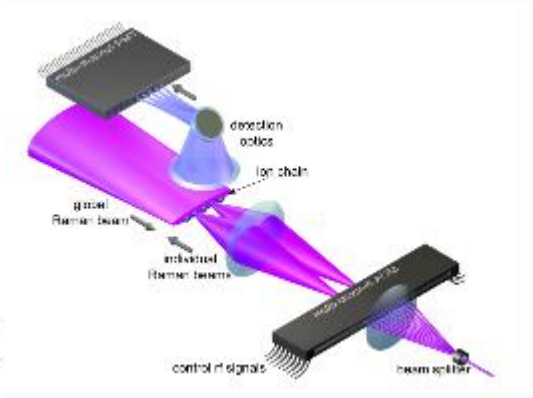
Overview

Quantum computer module

ions as qubits

hardware (5-9 qubits)

modular gates and compiler

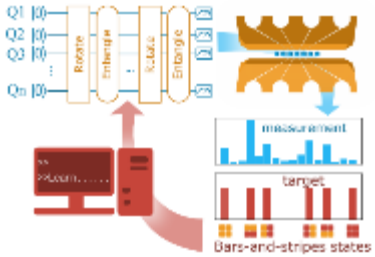


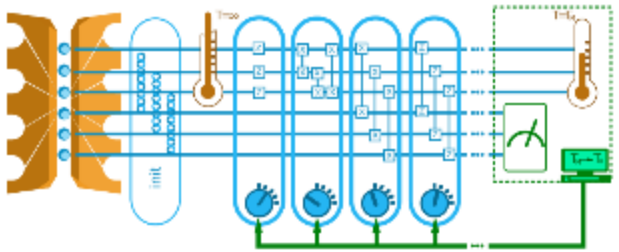
Quantum algorithms

QC comparison

Hybrid generative modelling

QAOA of thermo-field double states

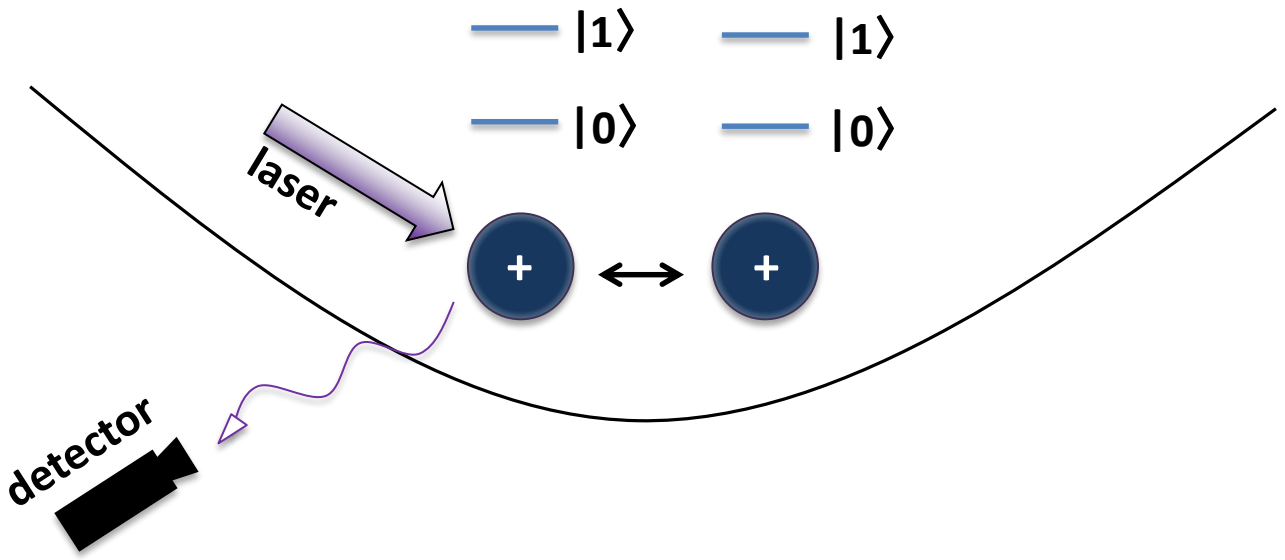




Outlook: scaling up and other plans

Trapped ions

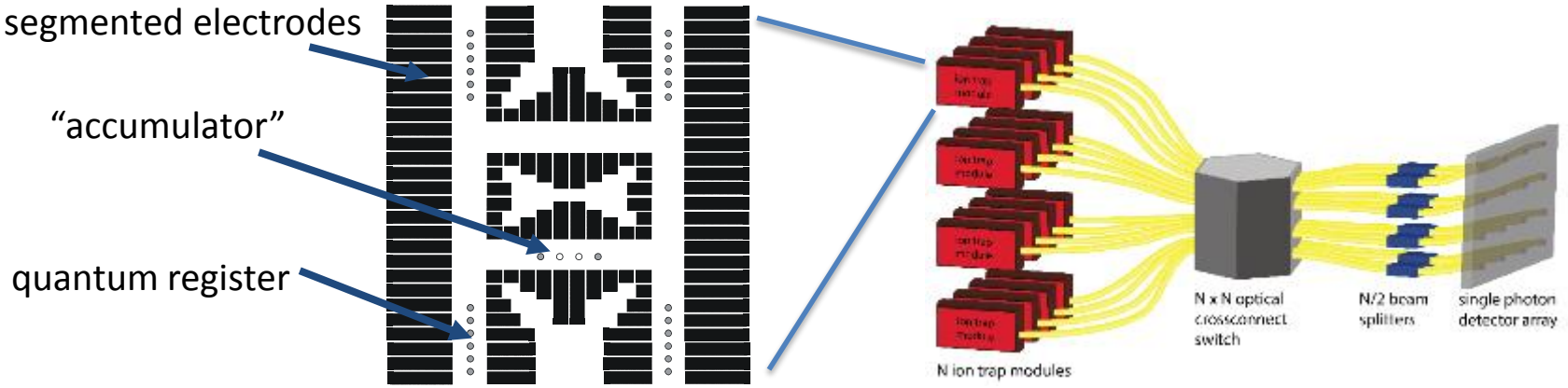
A good quantum computing candidate – why?



- Isolated quantum system, preparation and read-out with laser light
- gate operations (using lasers/microwaves)

The ion trap quantum computer (vision)

Ion trap Quantum computing – the big pic



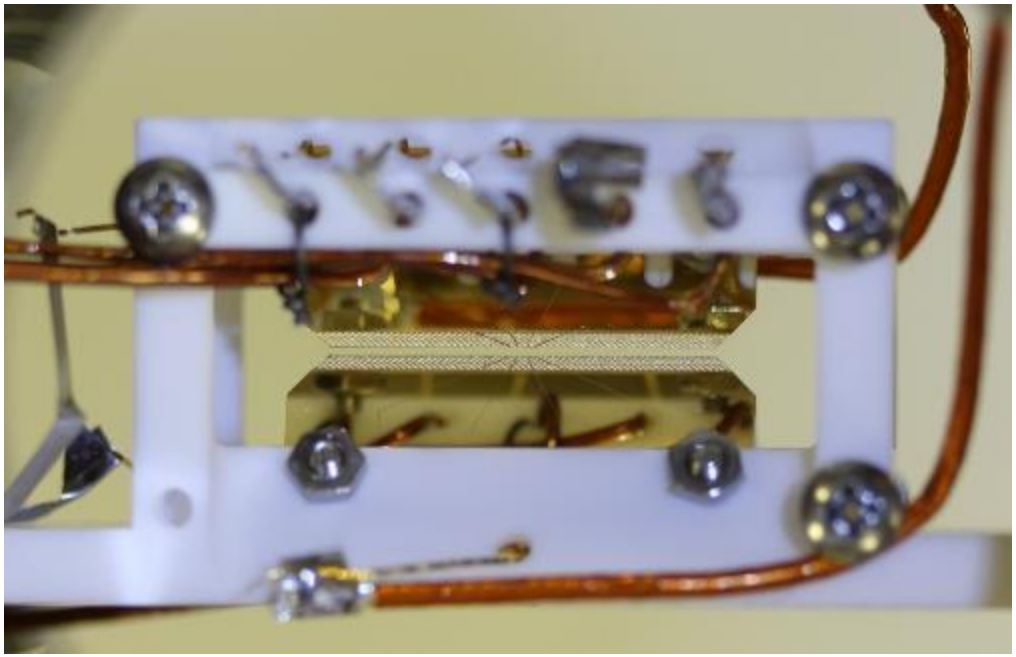
D. J. Wineland et al. 1998

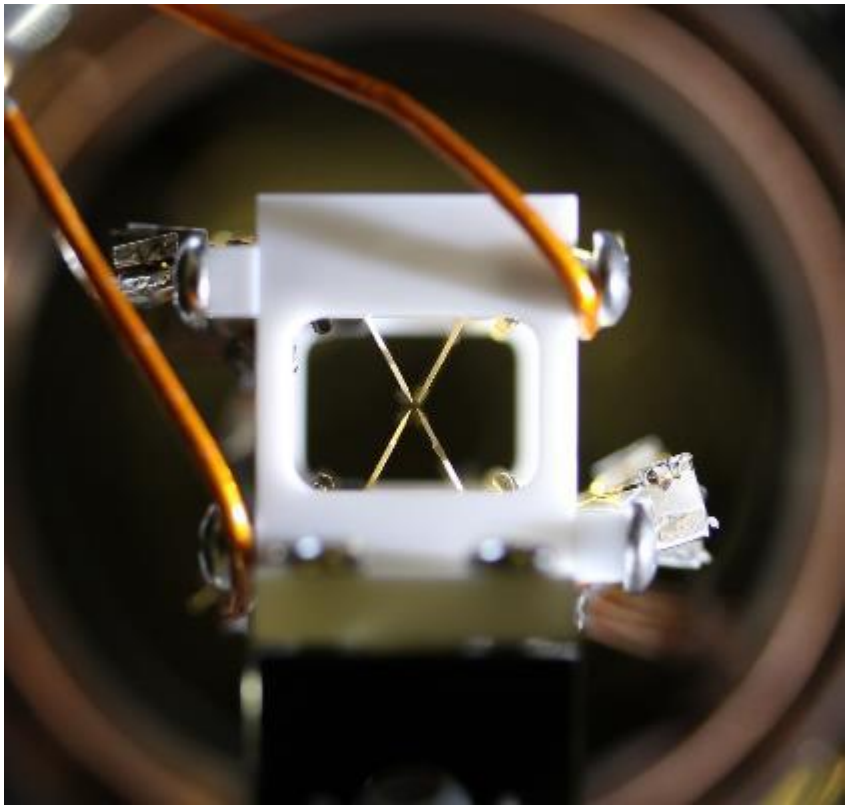
C. Monroe / J. Kim et al. 2013

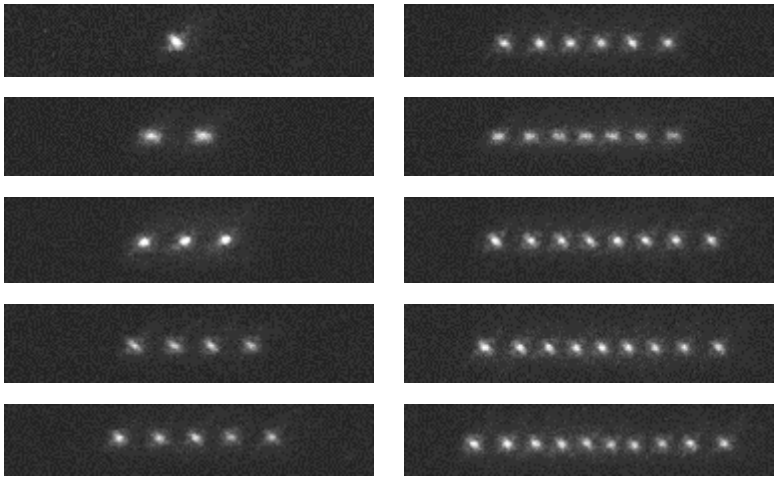
Are we there yet…? – challenges

- Higher fidelity operations
- Scalability: control over more qubits

Ion traps: hardware in current UMD module

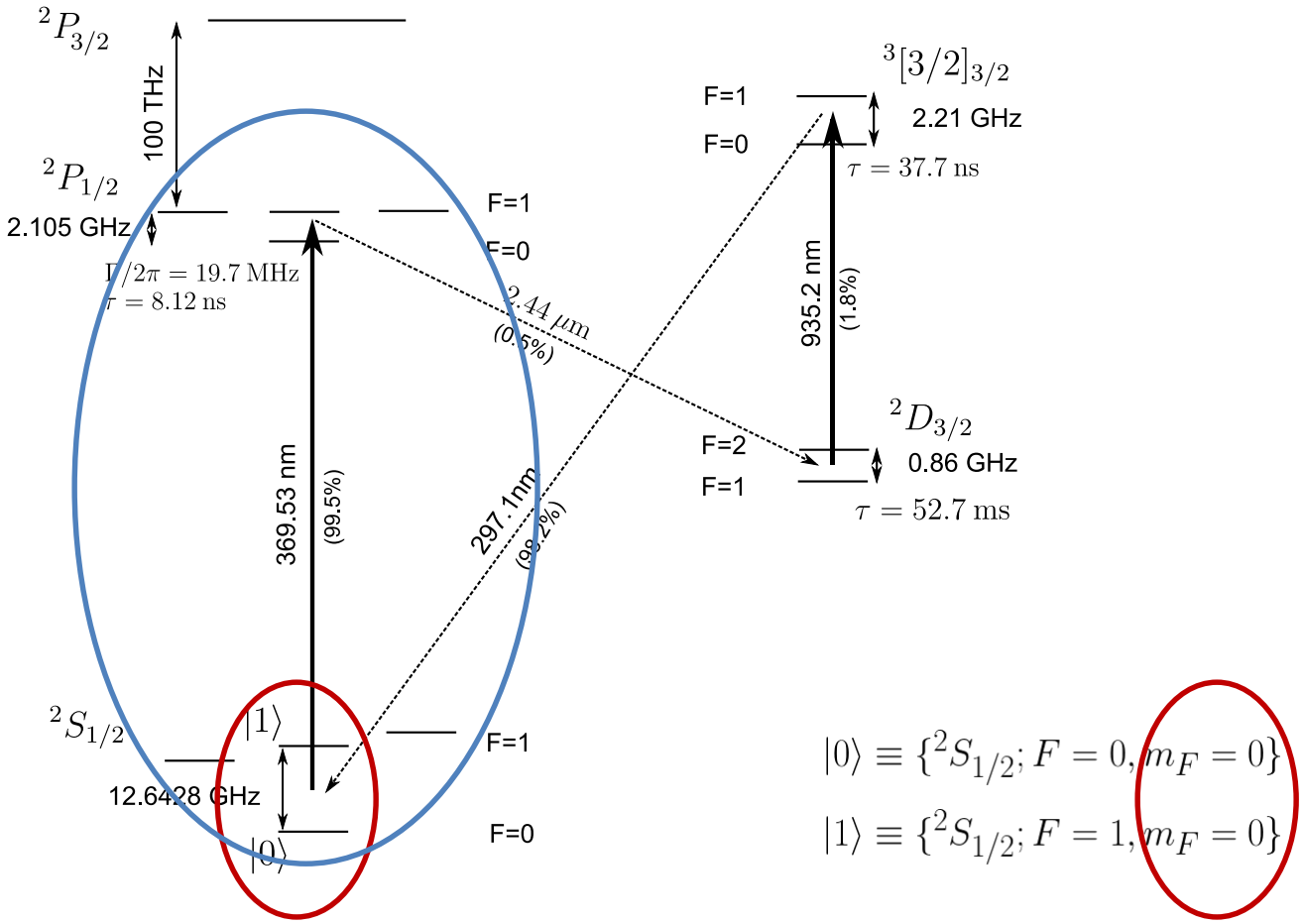






trapped ion Coulomb crystals: $^{171}Yb^{+}$

Trapped ion qubits: $^{171}Yb^{+}$ level structure



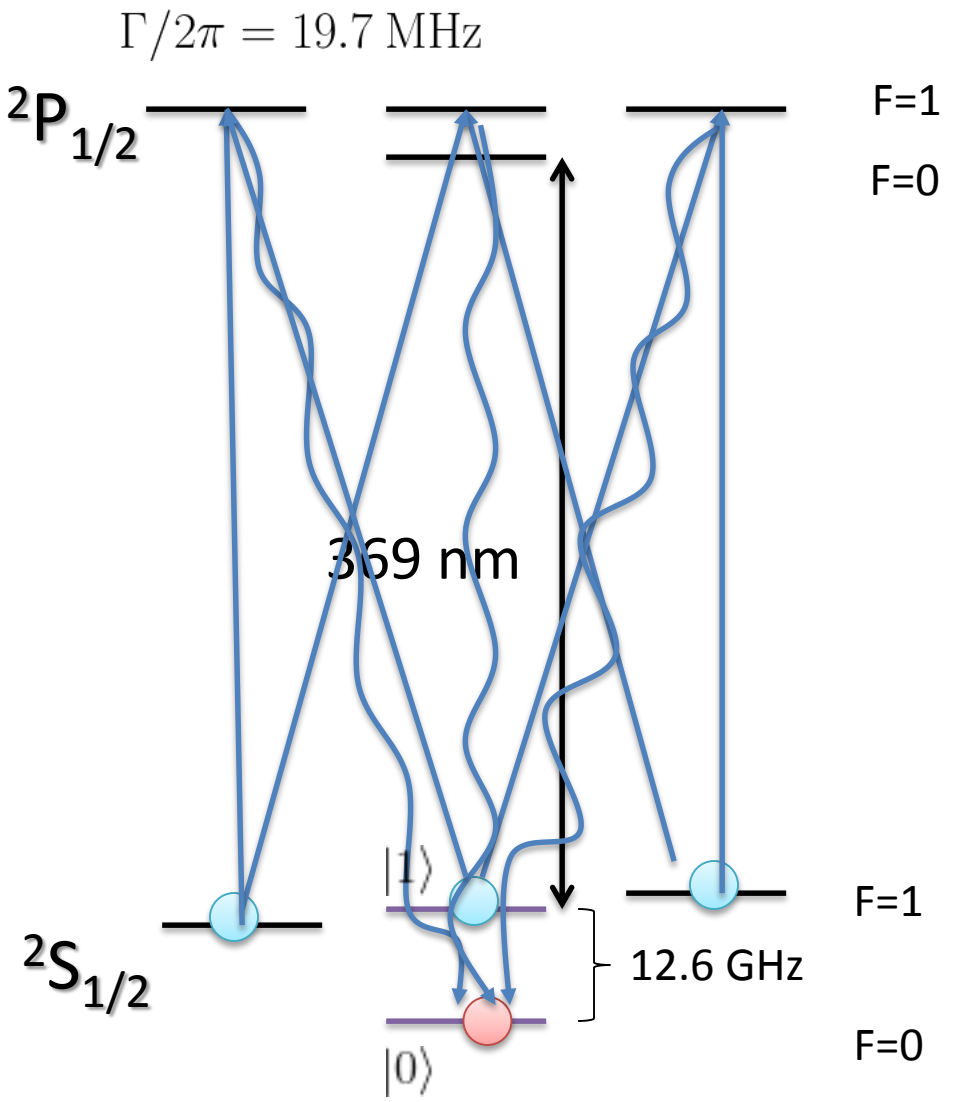
<u>compare:</u> "true" clock qubit in $^{43}Ca^{+}$ at 146G
coherence time ~1min

T.P. Harty, et al., PRL **113** (2015)

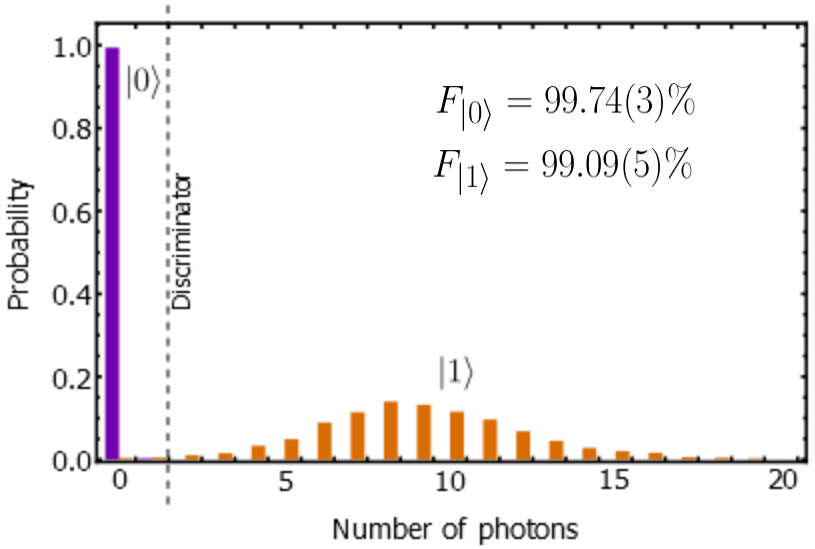
atomic clock qubit -> B-field insensitive
long coherence times: ~1s

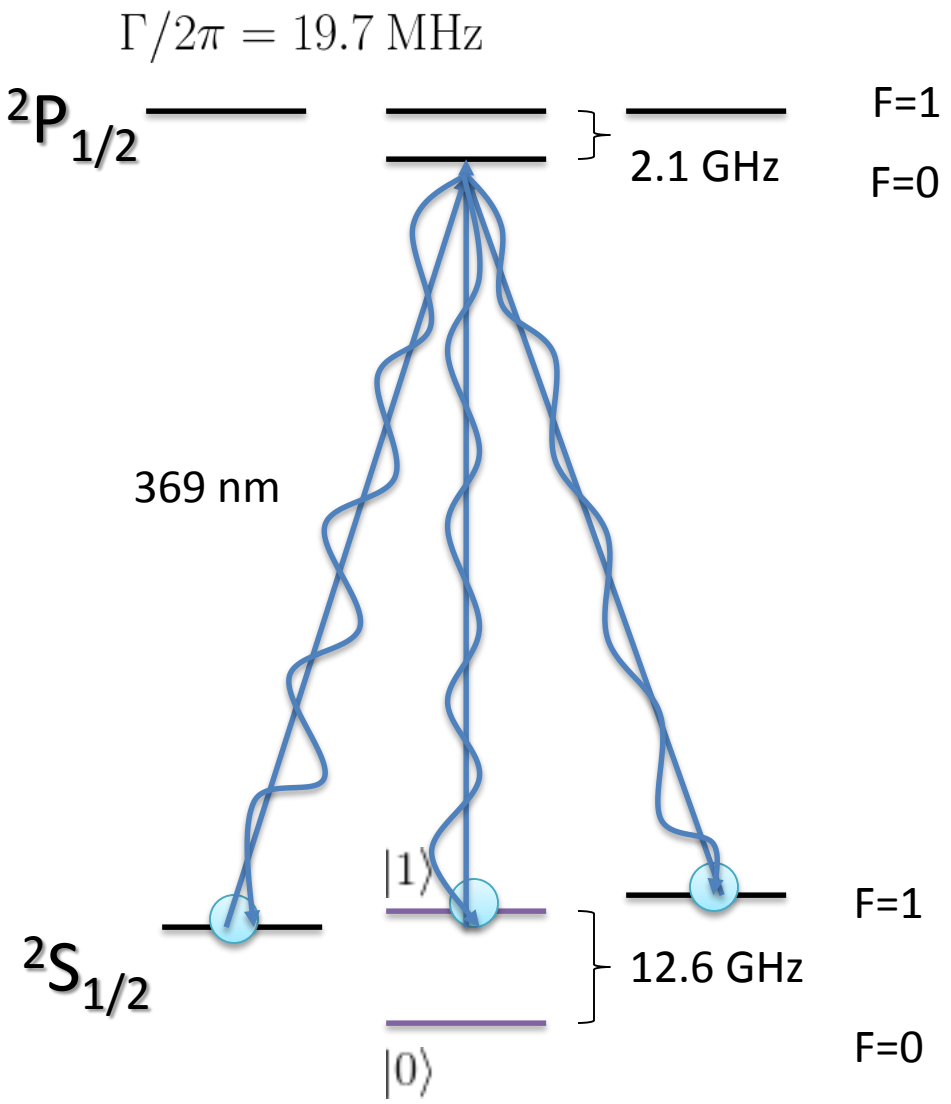
S. Olmschenk, et al., PRA **76** (2007)

Trapped ion qubits: State initialization

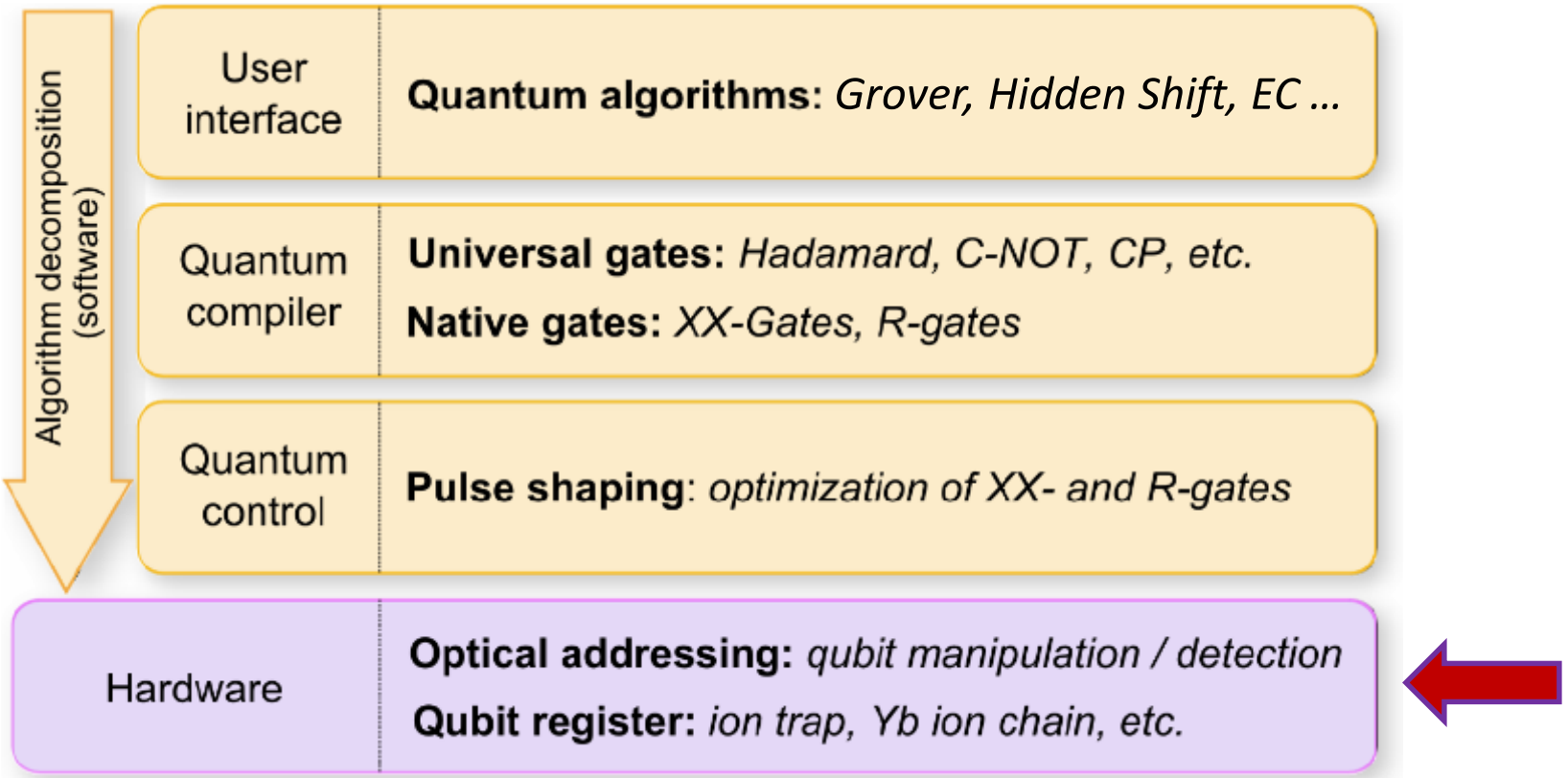


Trapped ion qubits: State detection



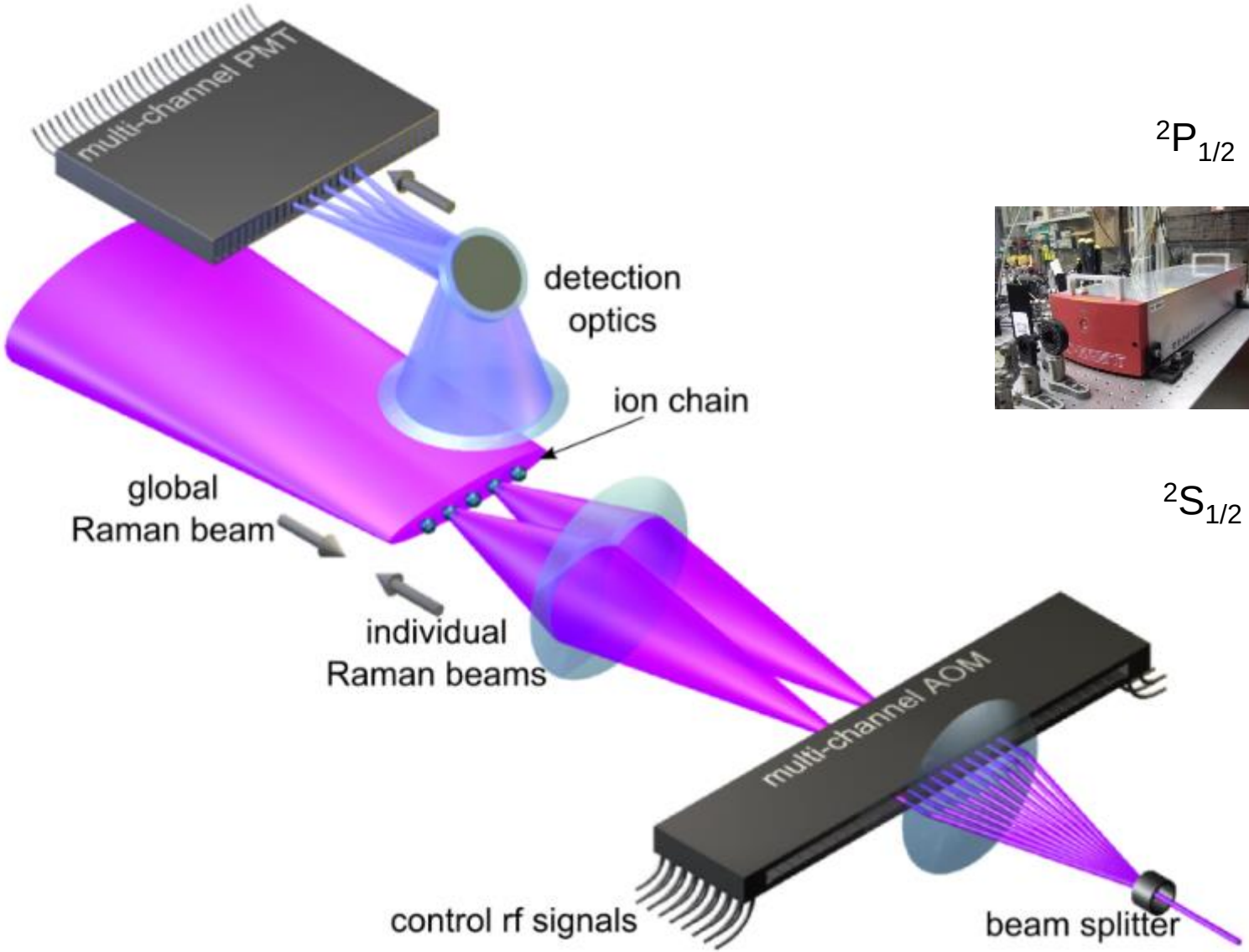


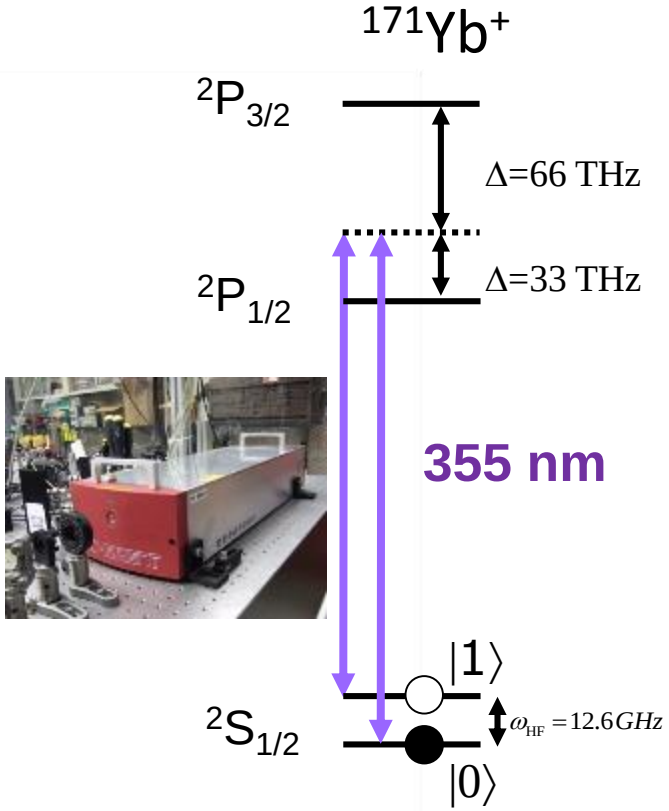
Modular architecture



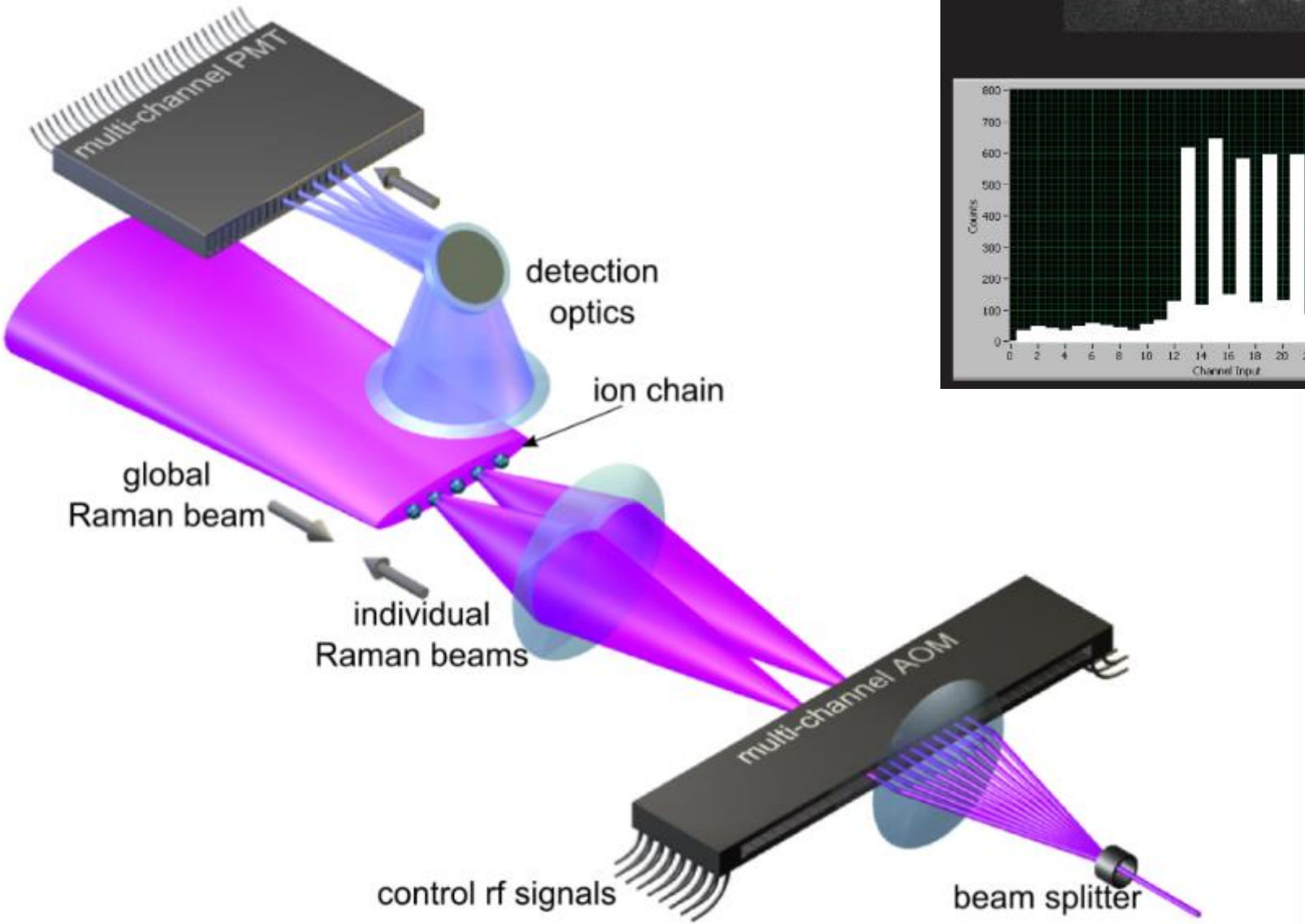
S. Debnath et al. Nature **536** (2016)

Hardware

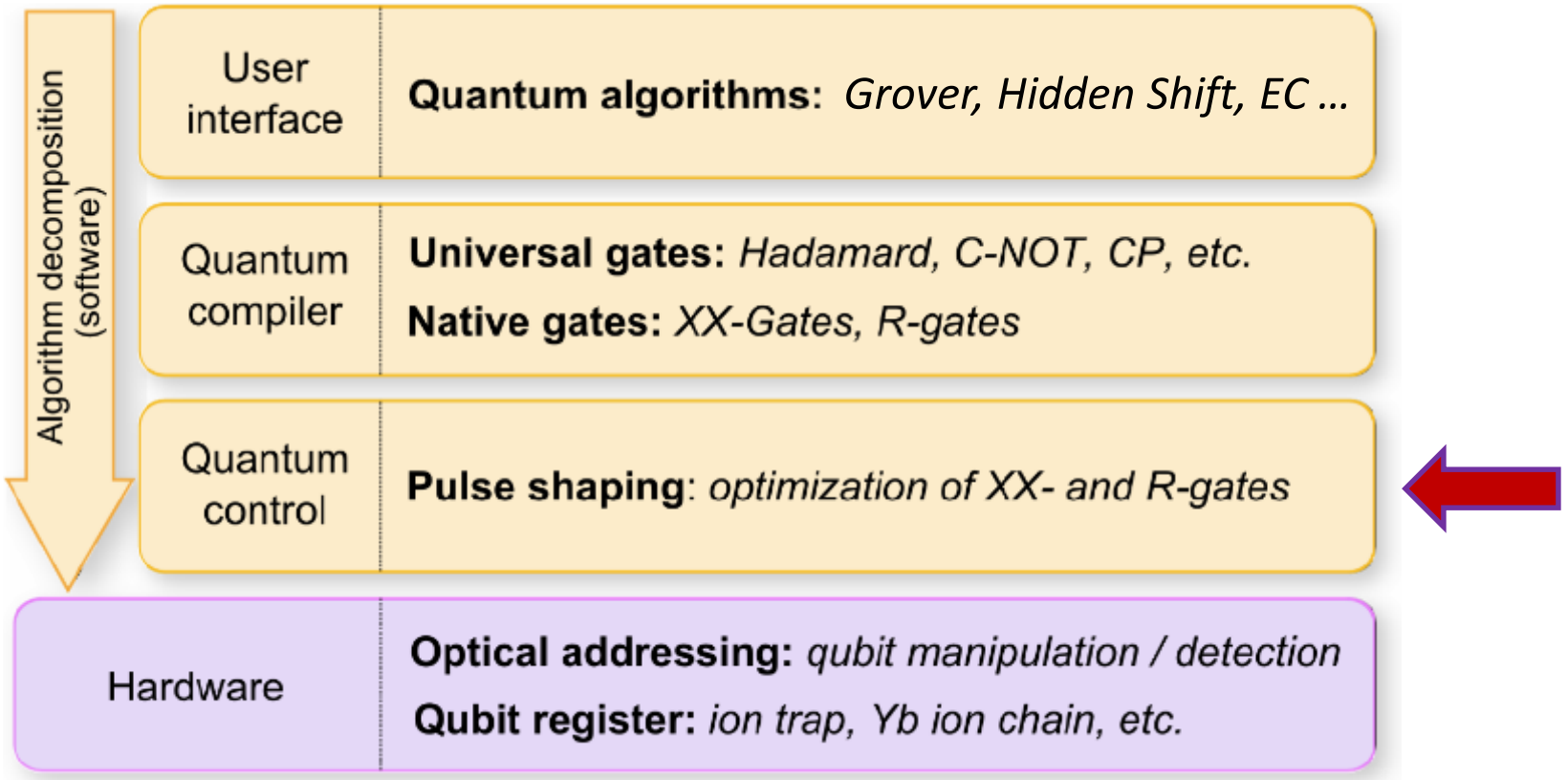

multi-channel PMT
detection optics
ion chain
global Raman beam
individual Raman beams
multi-channel AOM
control rf signals
beam splitter


$^{171}Yb^+$
$^2P_{3/2}$
Δ=66 THz
Δ=33 THz
$^2P_{1/2}$
355 nm
$|1\rangle$
$^2S_{1/2}$
$\omega_{HF} = 12.6 GHz$
$|0\rangle$

Hardware: Read-out

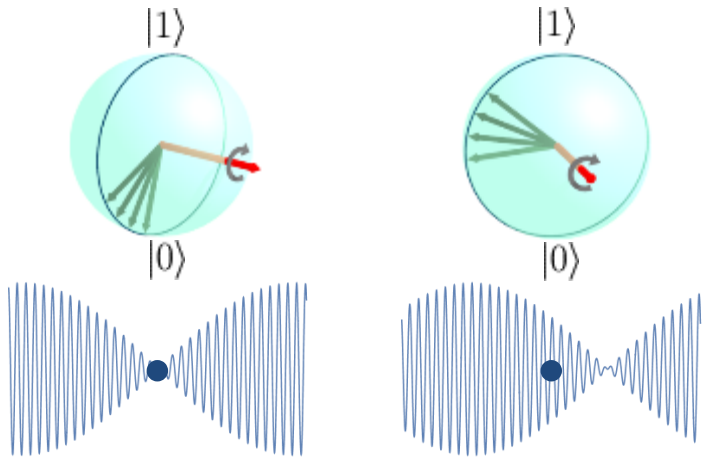


Modular architecture

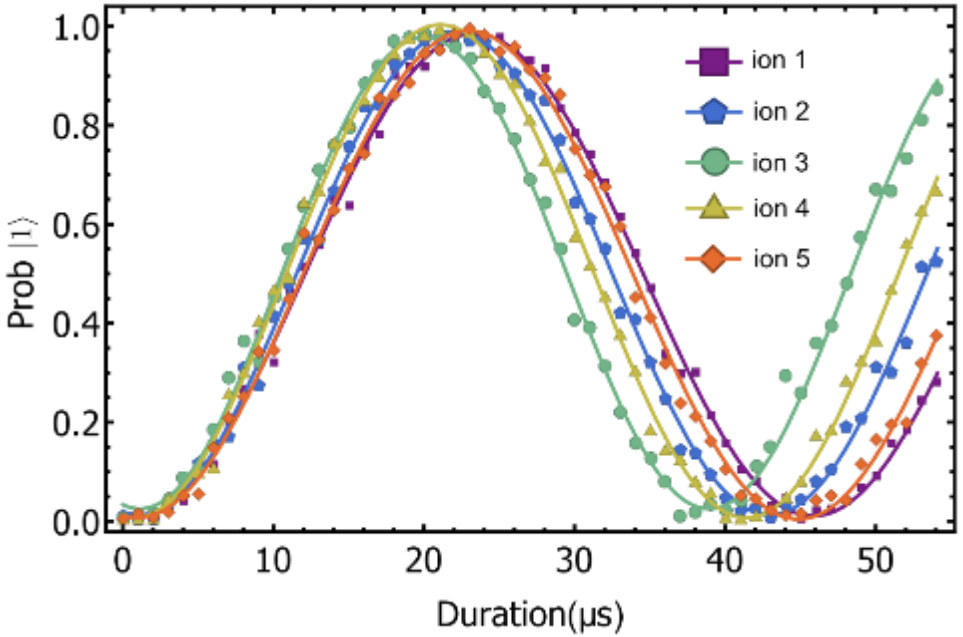


S. Debnath et al. Nature **536** (2016)

Quantum control: Single qubit rotations



Raman beat note

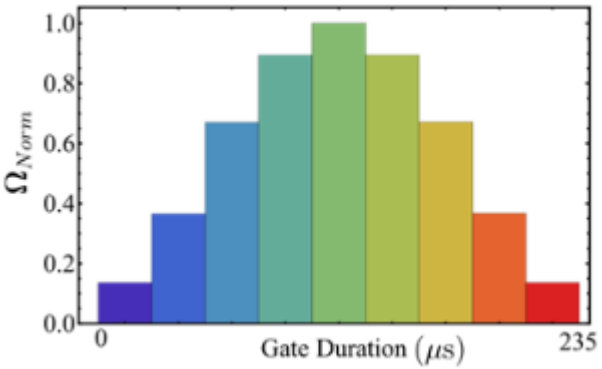


R-gate

$$R_\phi(\theta) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -i\sin(\frac{\theta}{2})e^{-i\phi} \\ -i\sin(\frac{\theta}{2})e^{i\phi} & \cos(\frac{\theta}{2}) \end{bmatrix}$$

Quantum control: Exciting the motion

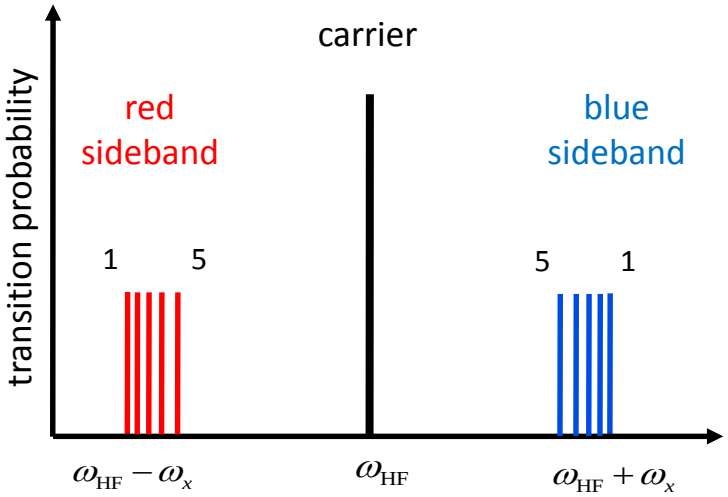
$$U(t) = \exp[-i\sum_{n,k}\hat{D}(\alpha_n^k(t))\sigma_x^n - i\sum_{i,j}\chi_{ij}(t)\sigma_x^i\sigma_x^j]$$



$$XX(\chi_{i,j}) = \begin{bmatrix} \cos(\chi_{i,j}) & 0 & 0 & -i\sin(\chi_{i,j}) \\ 0 & \cos(\chi_{i,j}) & -i\sin(\chi_{i,j}) & 0 \\ 0 & -i\sin(\chi_{i,j}) & \cos(\chi_{i,j}) & 0 \\ -i\sin(\chi_{i,j}) & 0 & 0 & \cos(\chi_{i,j}) \end{bmatrix}$$

$$\chi_{24} = -\frac{\pi}{4}$$

$$|00\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle - i|11\rangle)$$

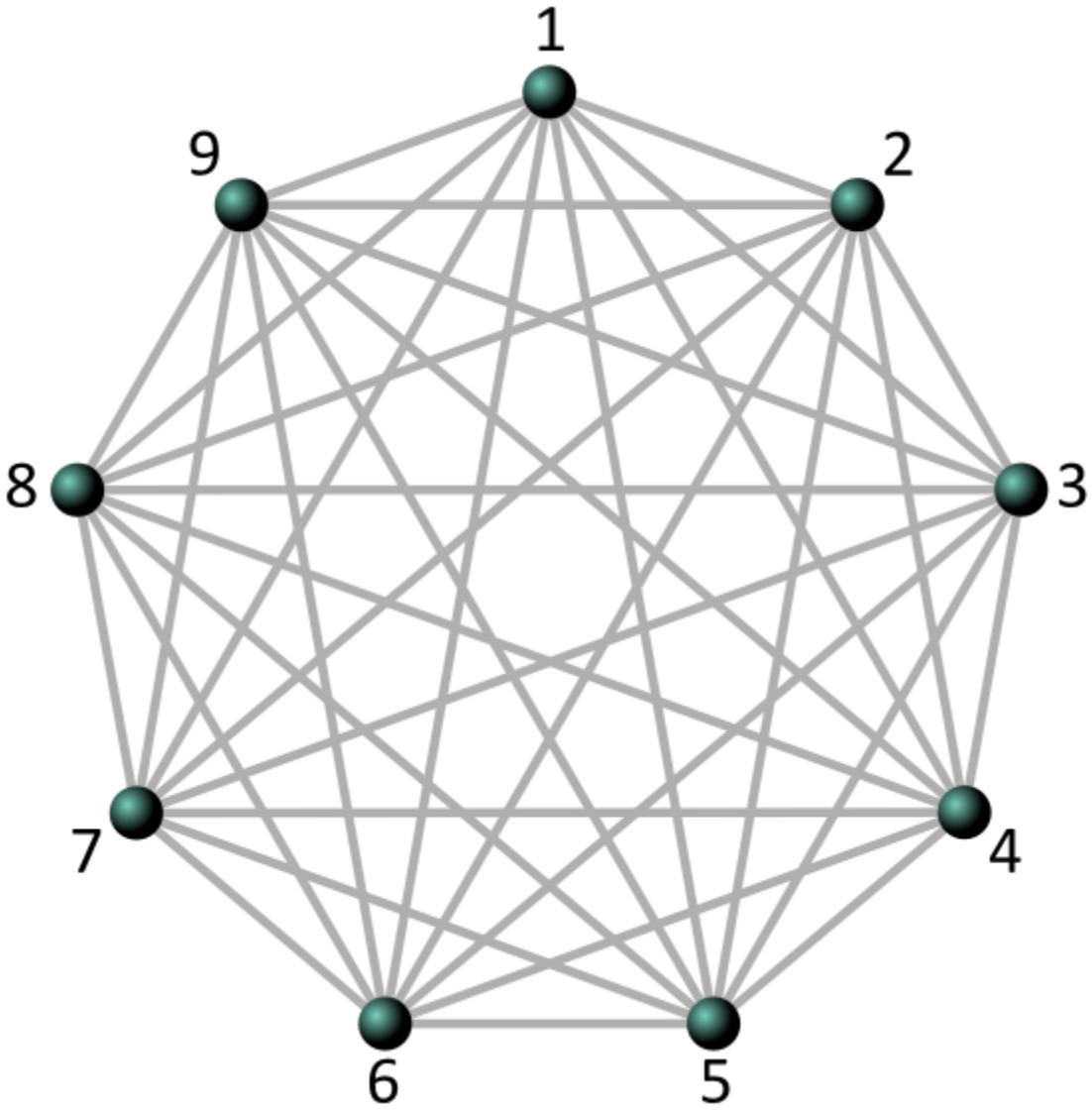


K. Mølmer and A. Sørensen, Phys. Rev. Lett. **82** (1999)

S.-L. Zhu et. al., Phys. Rev. Lett. **97** (2006)

T. Choi et al., Phys. Rev. Lett. **112** (2014)

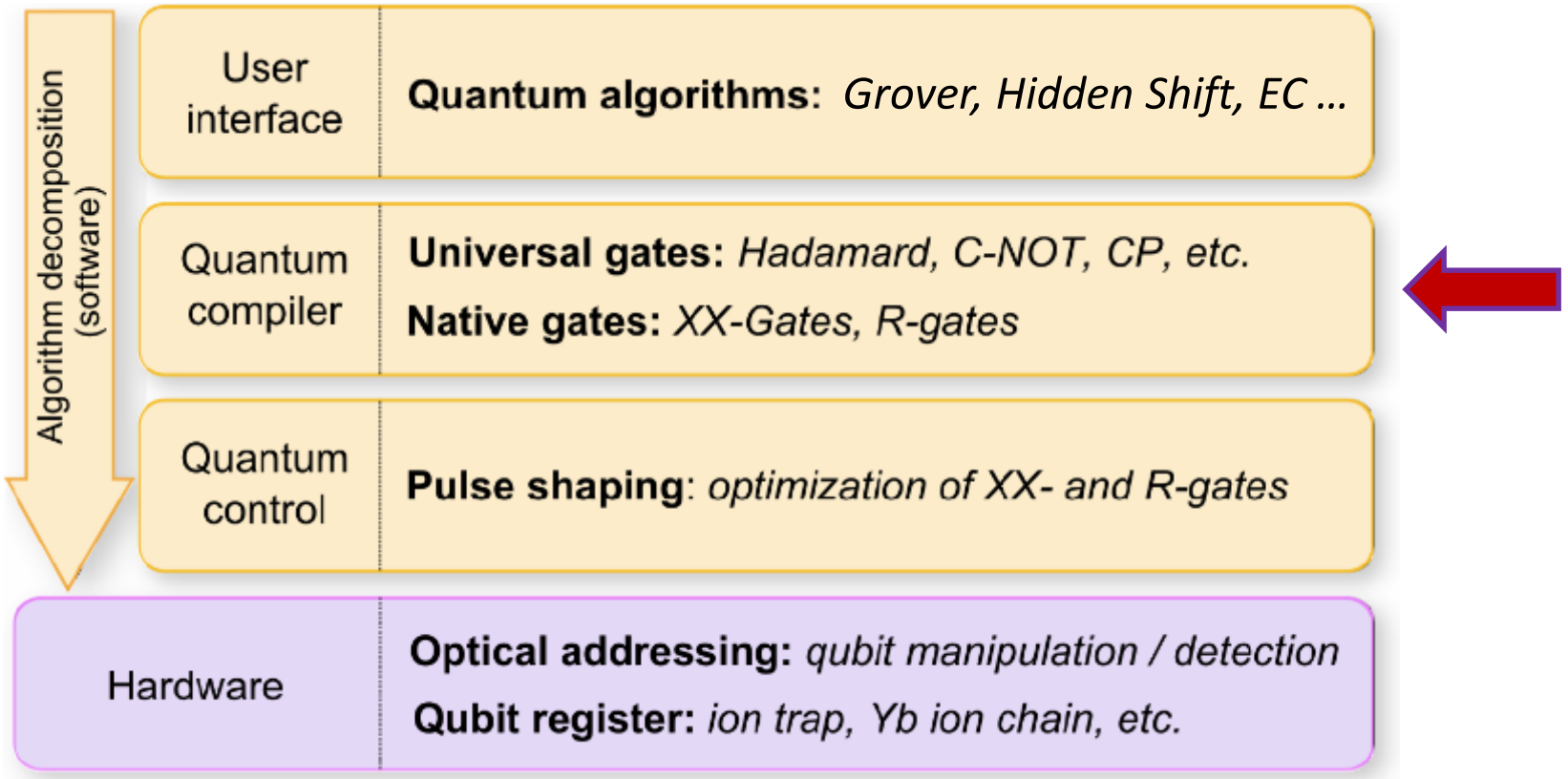
Quantum control: Full connectivity



not limited to local operations

NML et al. PNAS **114**, 13 (2017)

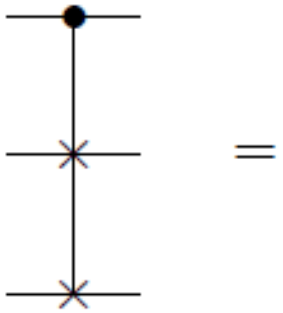
Modular architecture



S. Debnath et al. Nature **536** (2016)

Quantum compiler: Fredkin gate

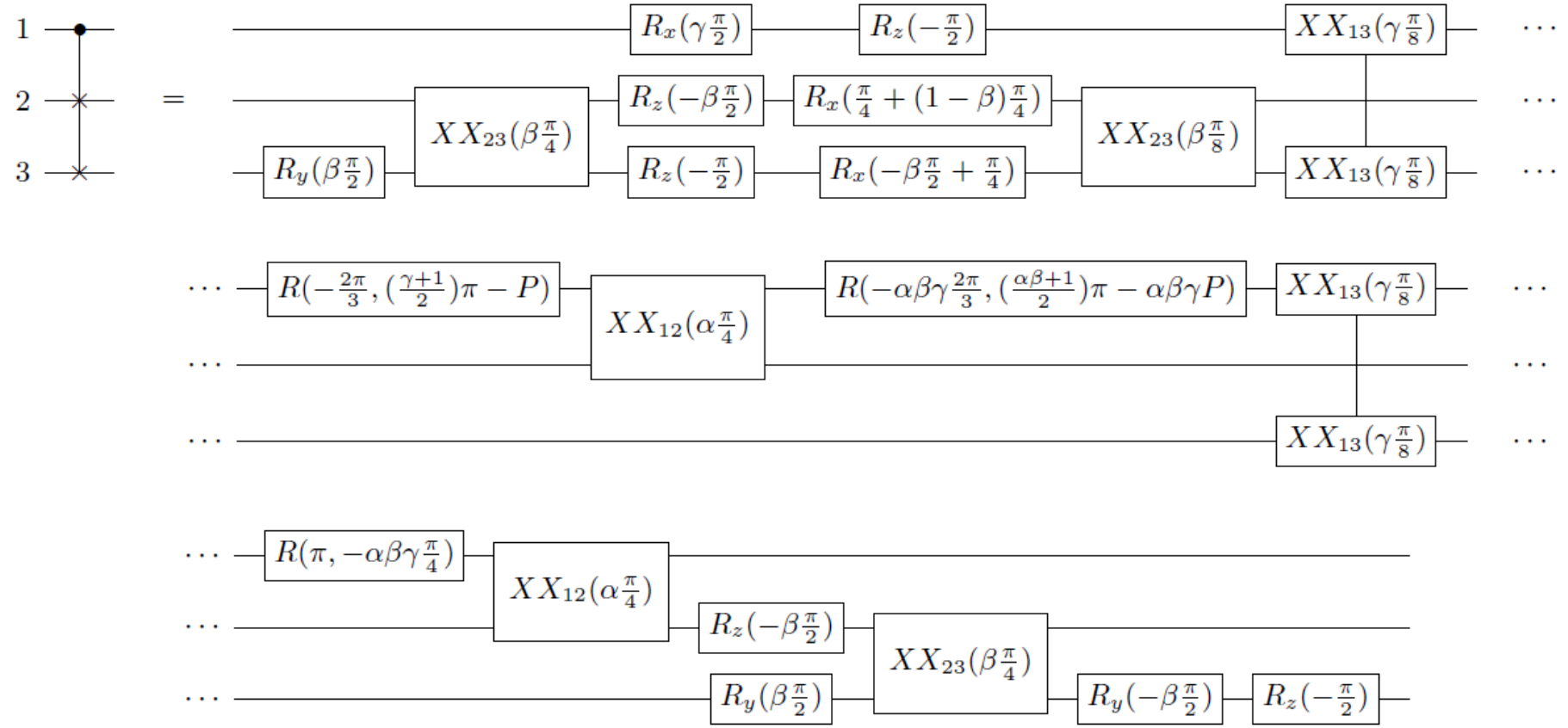
C-SWAP



$$=$$

$$\begin{pmatrix} 1 & & & & & & & \\ & 1 & & & & & & \\ & & 1 & & & & & \\ & & & 1 & & & & \\ & & & & 1 & & & \\ & & & & & 0 & 1 & \\ & & & & & 1 & 0 & \\ & & & & & & & 1 \end{pmatrix}$$

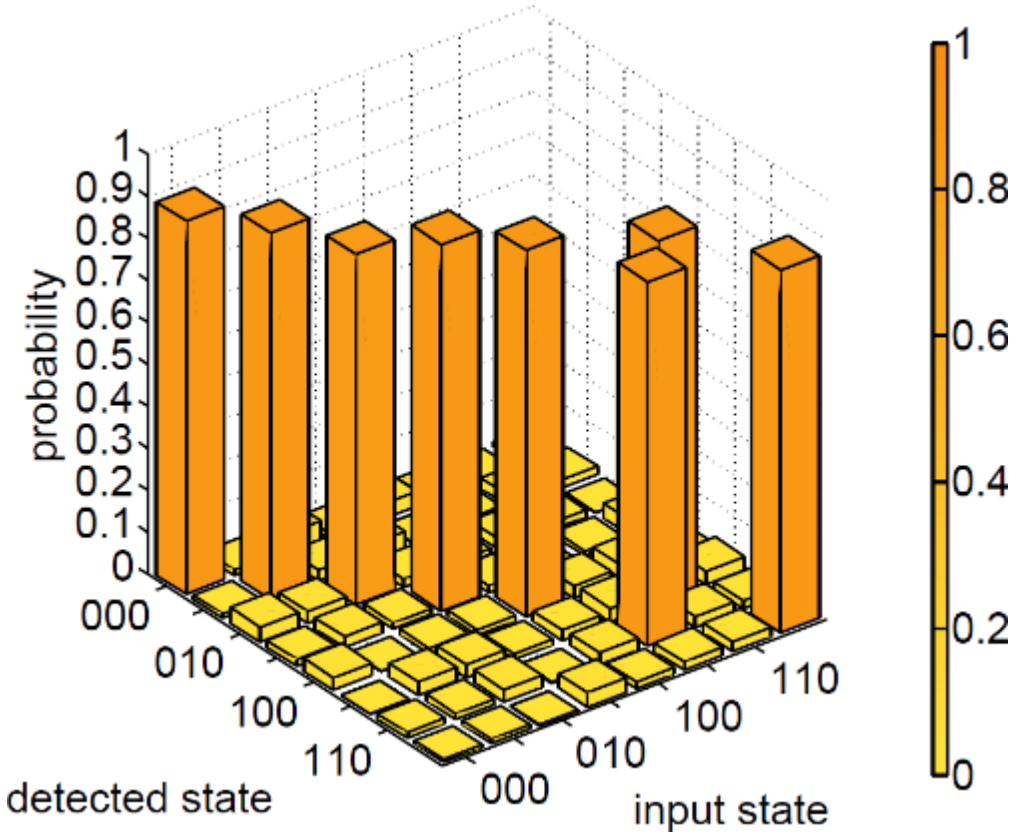
Quantum compiler: Fredkin gate circuit



$\alpha = sgn(\chi_{12})$, $\beta = sgn(\chi_{23})$, $\gamma = sgn(\chi_{13})$, and $P = \arcsin\sqrt{\frac{2}{3}}$

NML et al., PRA 98, 052334 (2018)

Quantum compiler: Fredkin gate results

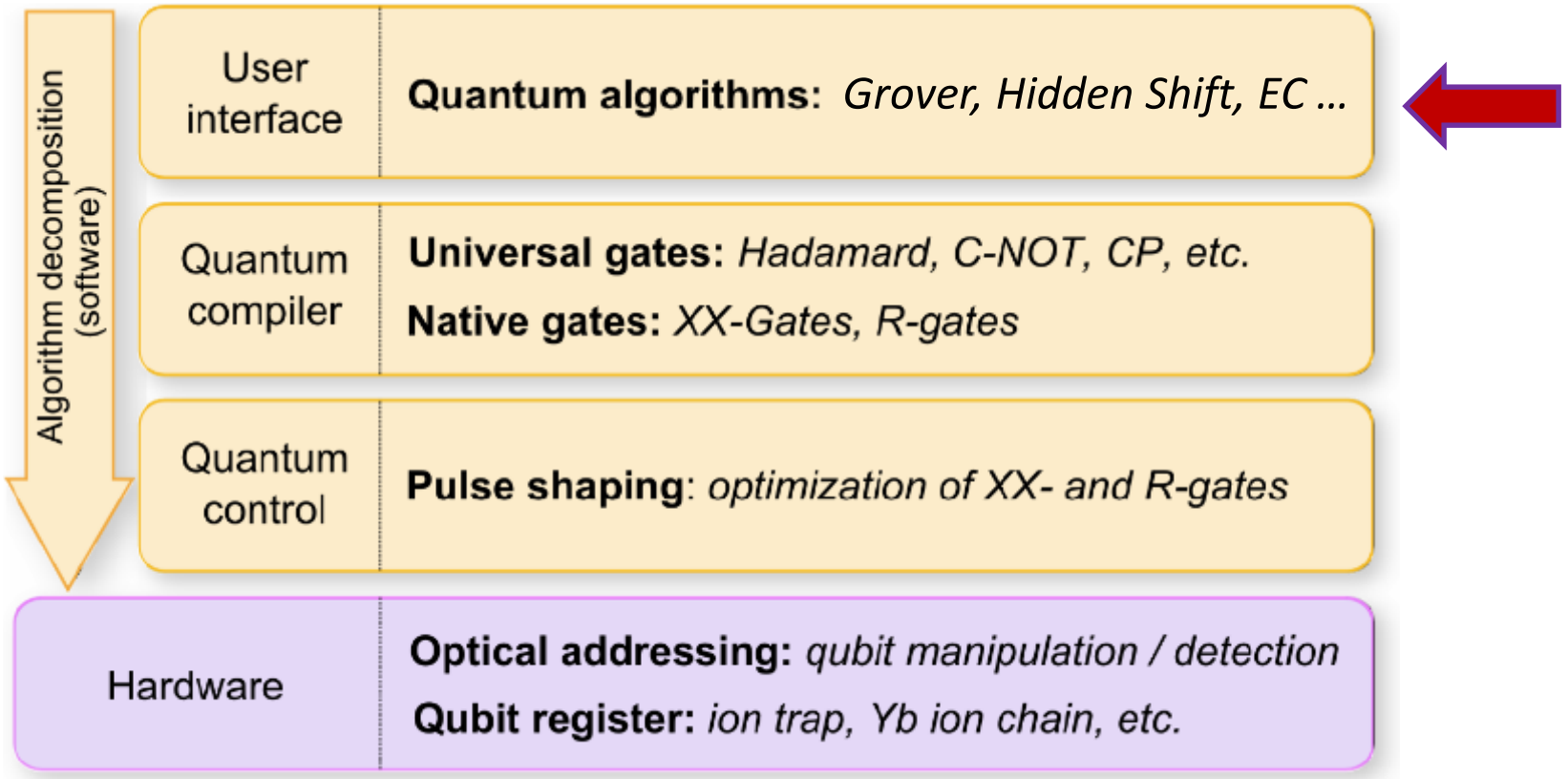


Fredkin [1,2:4], F=86.8(3)%

(corrected for 2% spam error)

NML et al., PRA 98, 052334 (2018)

Modular architecture



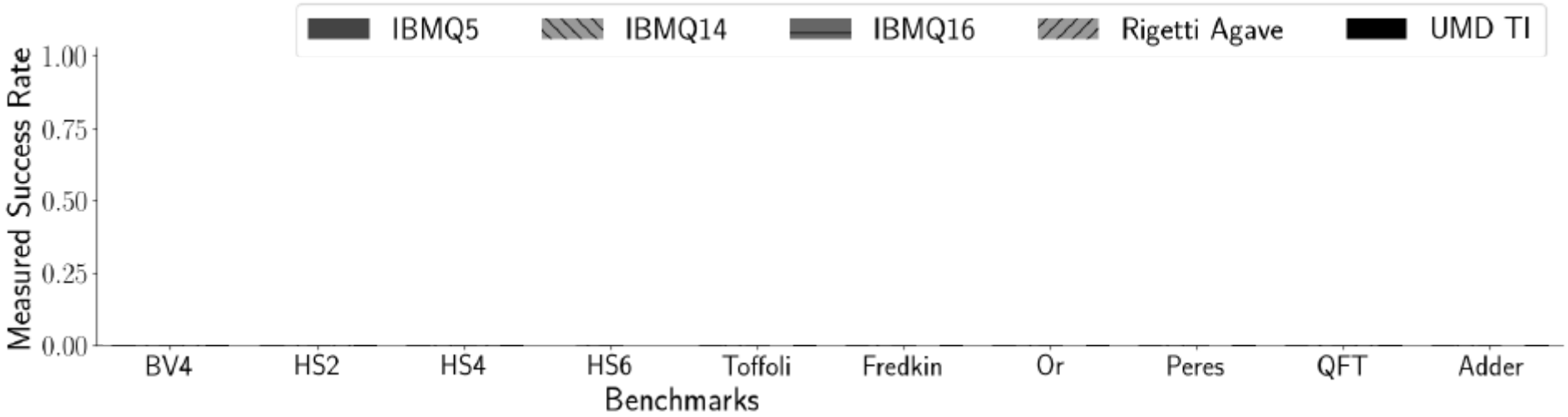
S. Debnath et al. Nature **536** (2016)

Quantum hardware and compiler comparison

P. Murali, M. Martonosi (Princeton), A. J. Abhari (IBM), NML (UMD) et al. ISCA-2019 527-540

Quantum hardware and compiler comparison

Comparison conducted by M. Martonosi (Princeton)
-> code interface

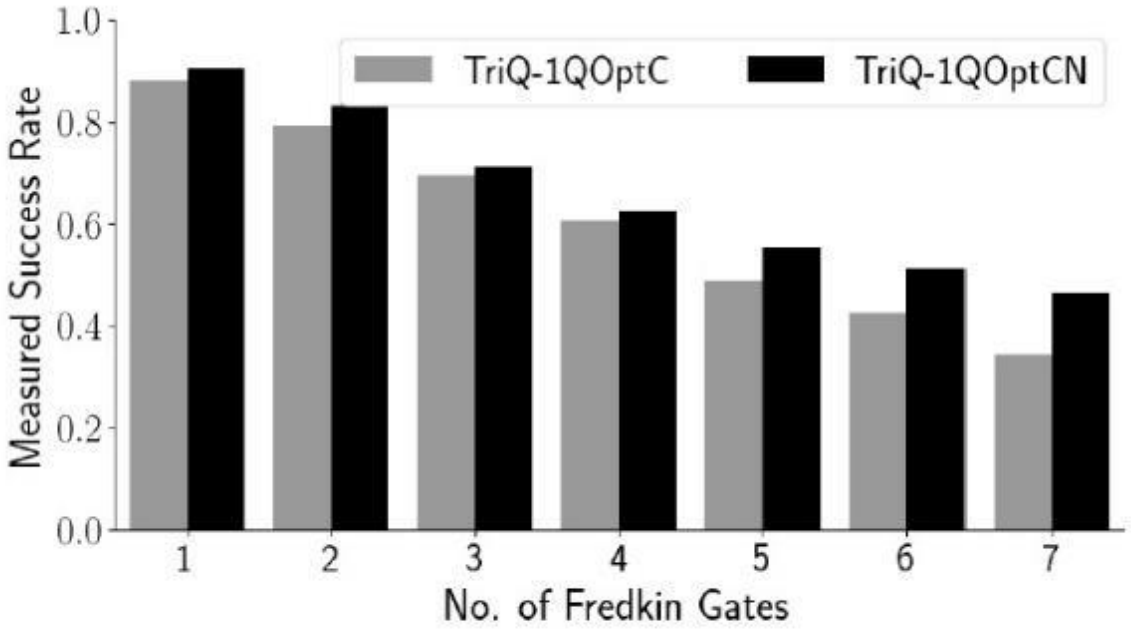


F = fail, **S** = not done (>5 qubits)

P. Murali, M. Martonosi (Princeton), A. J. Abhari (IBM), NML (UMD) et al. ISCA-2019 527-540

Example algorithms on multiple platforms (Princeton)

Compiler optimizes qubit mapping



Gate	$F_{estimate}$
XX[4:5]	0.980
XX[2:5]	0.991
XX[1:4]	0.970
XX[1:2]	0.985
XX[3:5]	0.998
XX[1:3]	0.995
XX[2:3]	0.994
XX[2:4]	0.996
XX[3:4]	0.994

P. Murali, M. Martonosi (Princeton), A. J. Abhari (IBM), NML (UMD) et al. ISCA-2019 527-540

Quantum-classical hybrid computing

Classical optimizer

- Gradient descent
- Bayesian optimization
- …

FEEDBACK

Quantum computer

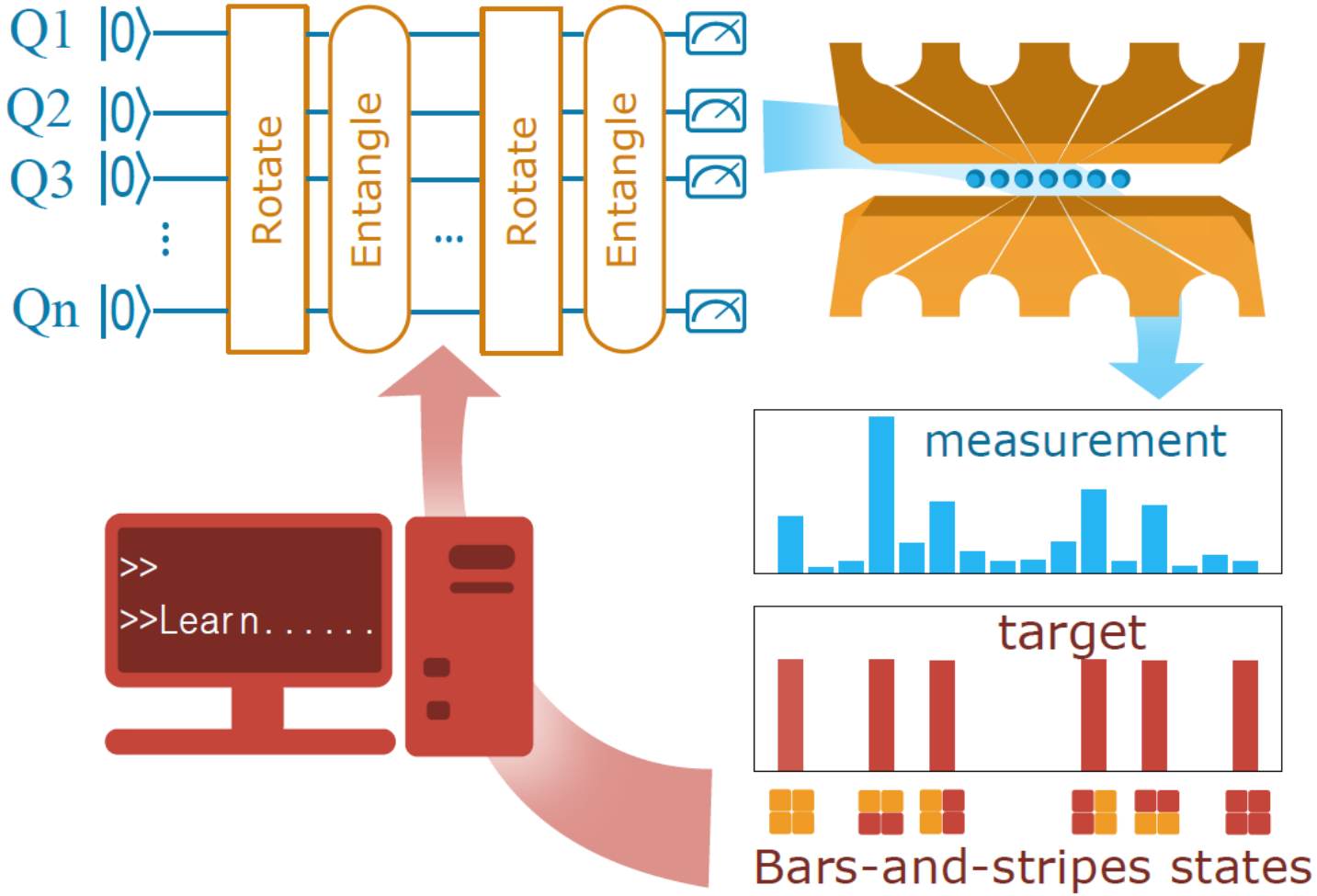
Algorithm decomposition (software)

User interface	**Quantum algorithms:** *e.g. QAOA circuits*
Quantum compiler	**Universal gates:** *Hadamard, C-NOT, CP, etc.* **Native gates:** *XX-Gates, R-gates*
Quantum control	**Pulse shaping**: *optimization of XX- and R-gates*
Hardware	**Optical addressing:** *qubit manipulation / detection* **Qubit register:** *ion trap, Yb ion chain, etc.*

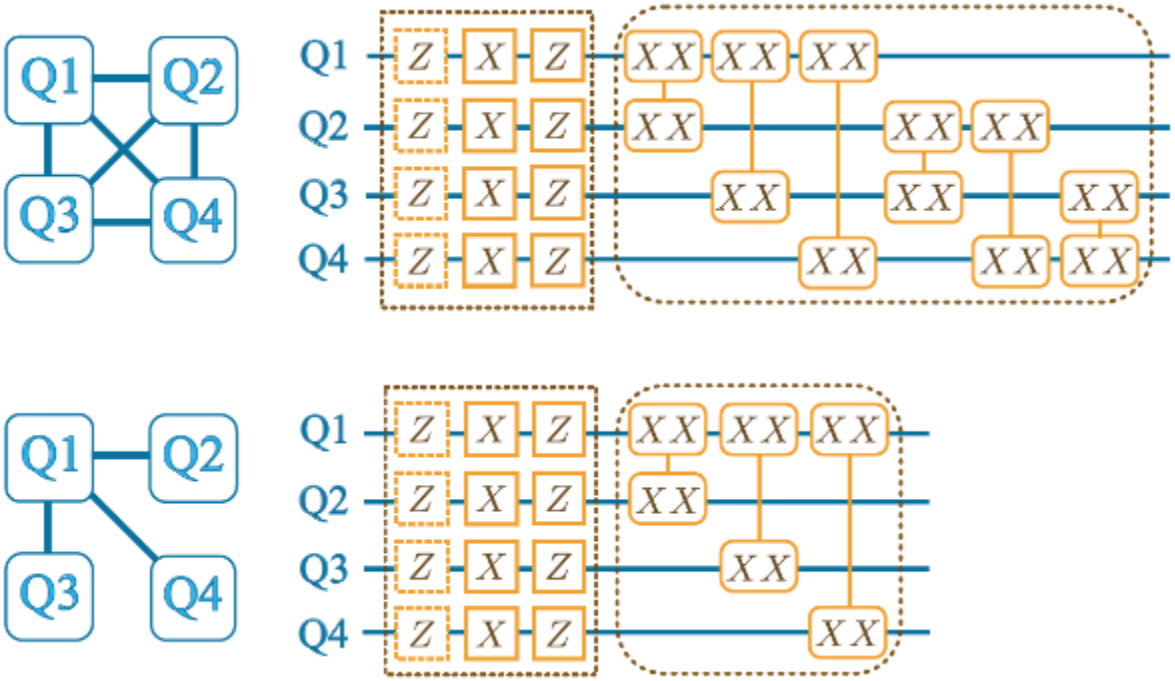
see also Innsbruck hybrid-AQS:
Kokail et al., Nature 569 (2019)

Hybrid machine learning: Bars and Stripes

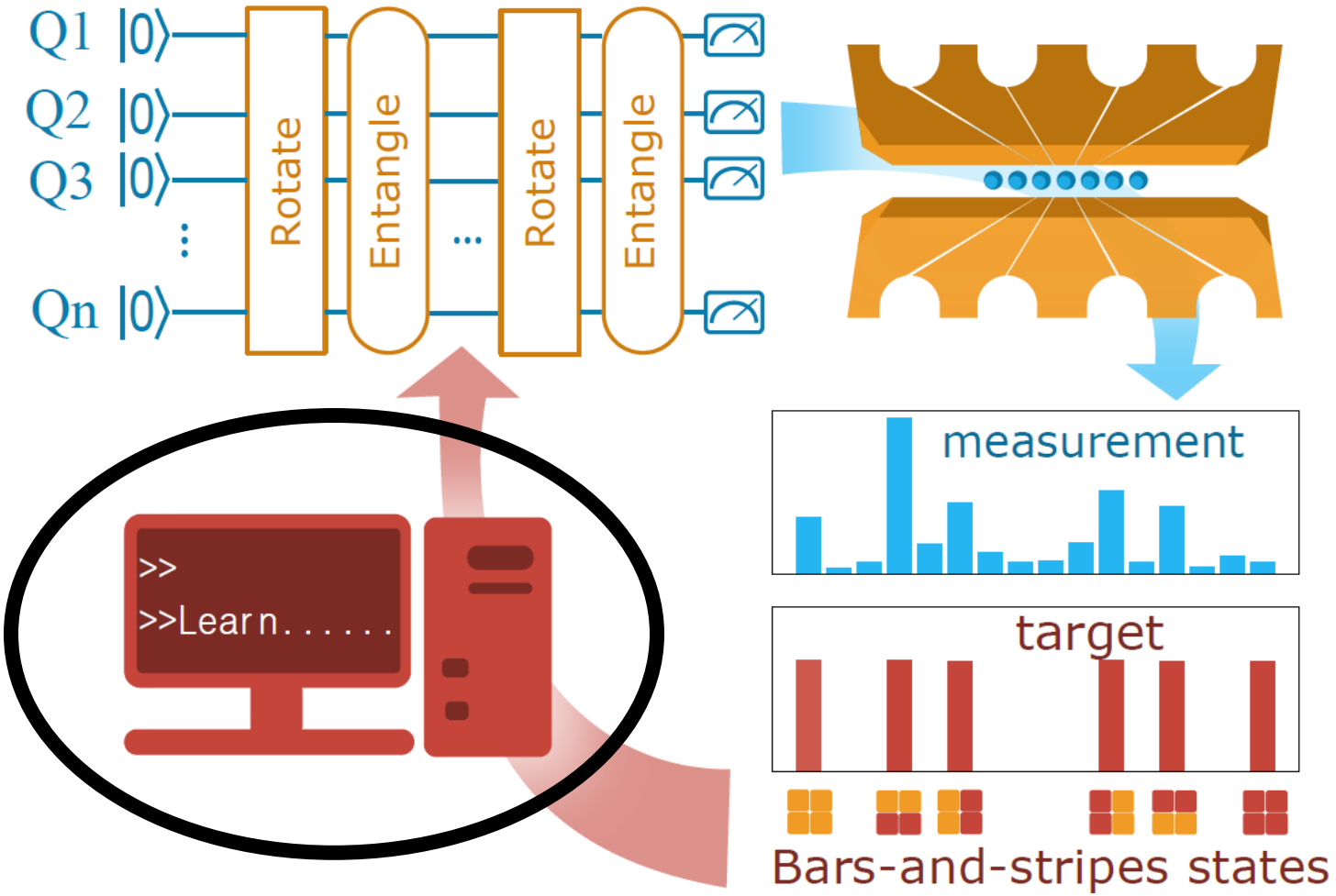
Hybrid machine learning: Bars and Stripes



Hybrid machine learning: Bars and Stripes

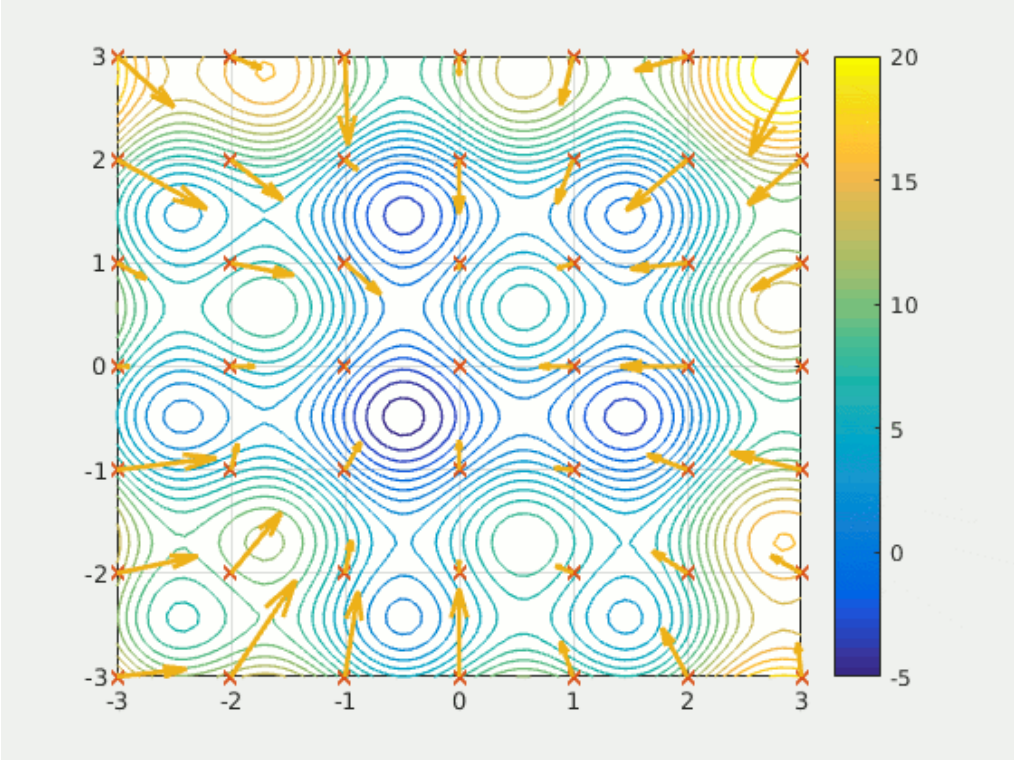


Hybrid machine learning: Bars and Stripes



Hybrid machine learning: Bars and Stripes

Classical Leaner 1: Particle Swarm Optimization (PSO)



Animation from Wikipedia by Ephramac

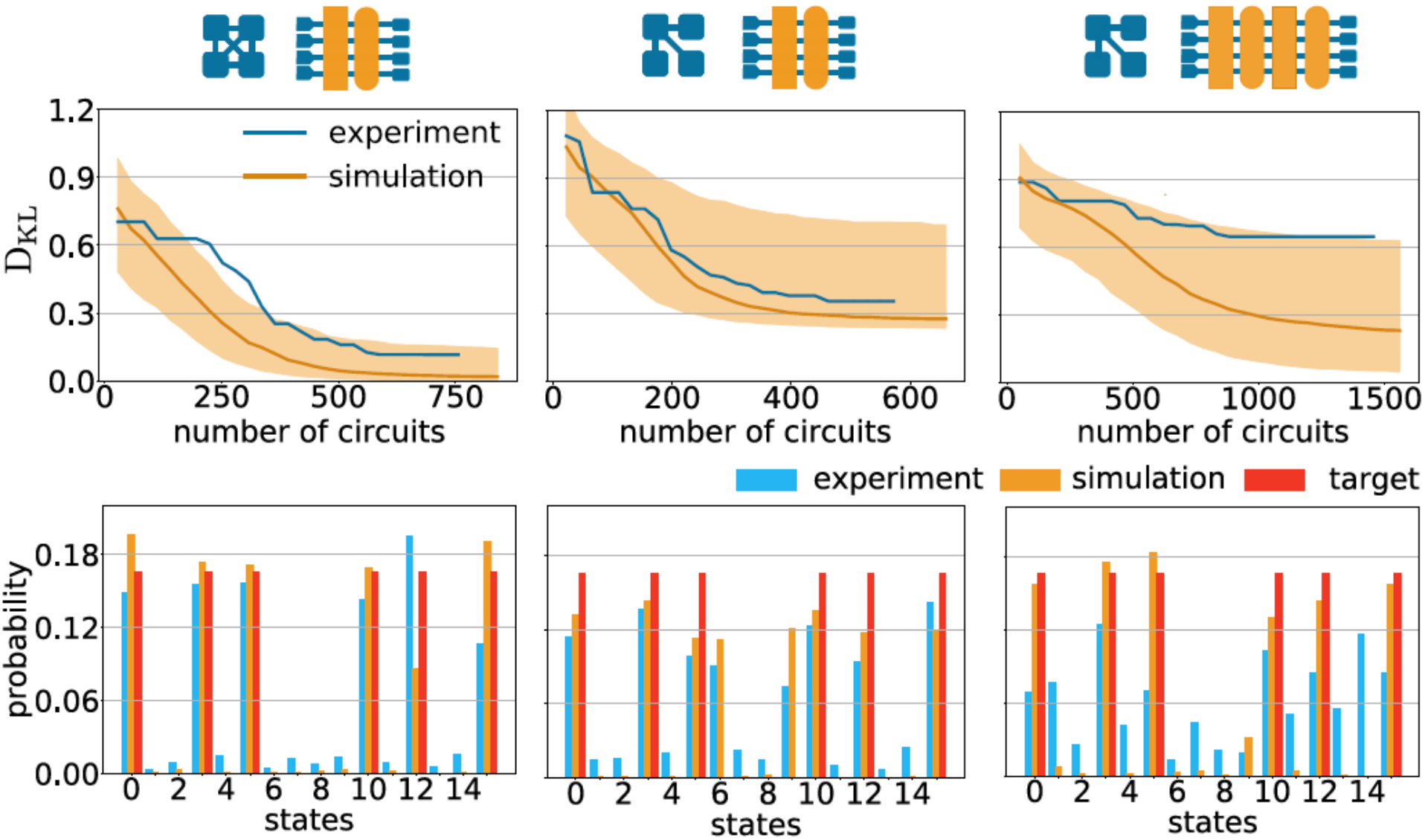
Classical Leaner 2: Bayesian Optimization (BO)

surrogate model

Using “Optaas” package by Mindfoundry (Oxford, UK)

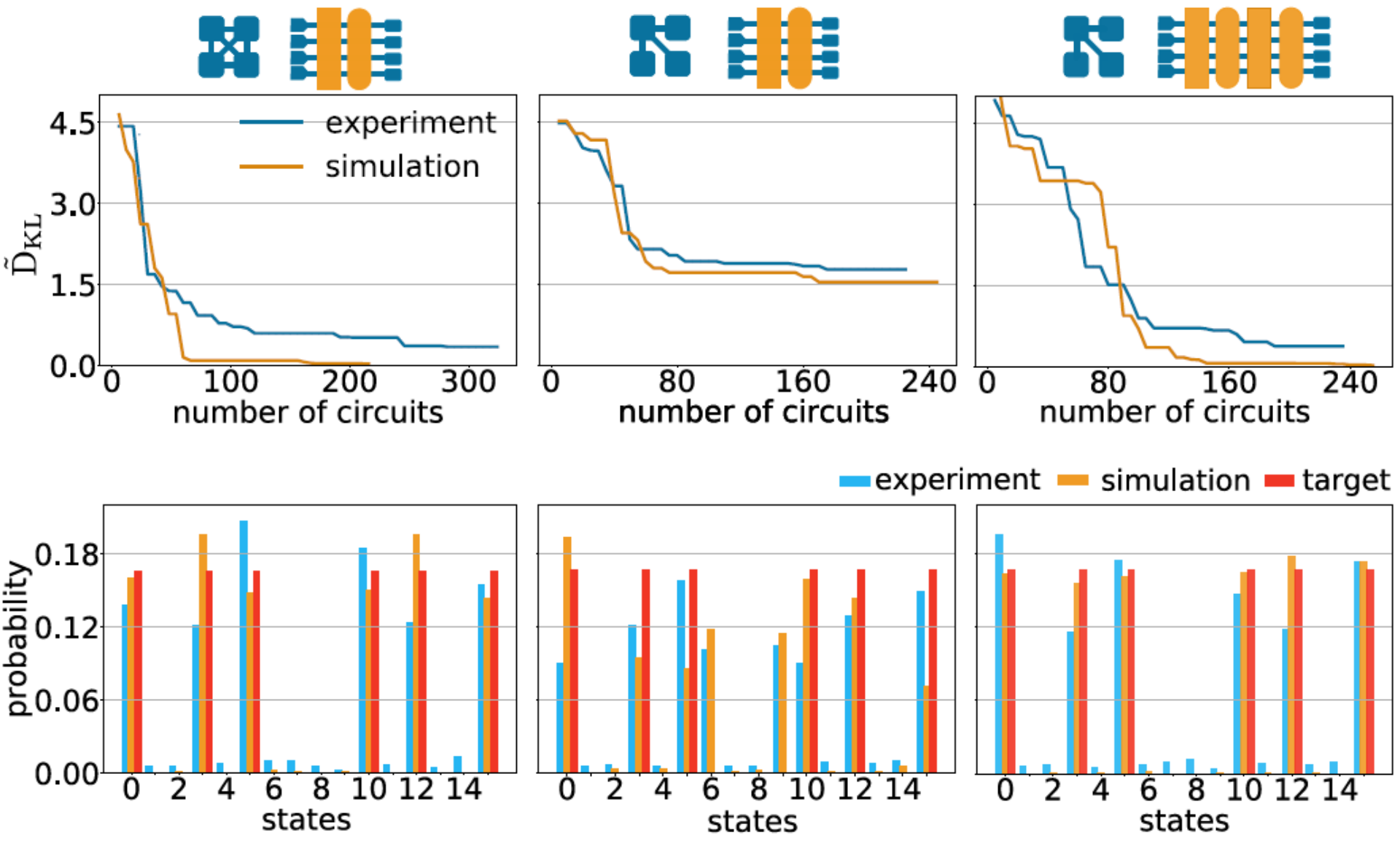
MIND FOUNDRY

Hybrid machine learning: Particle Swarm Results



D. Zhu et al., Science Advances 5, 10 (2019)

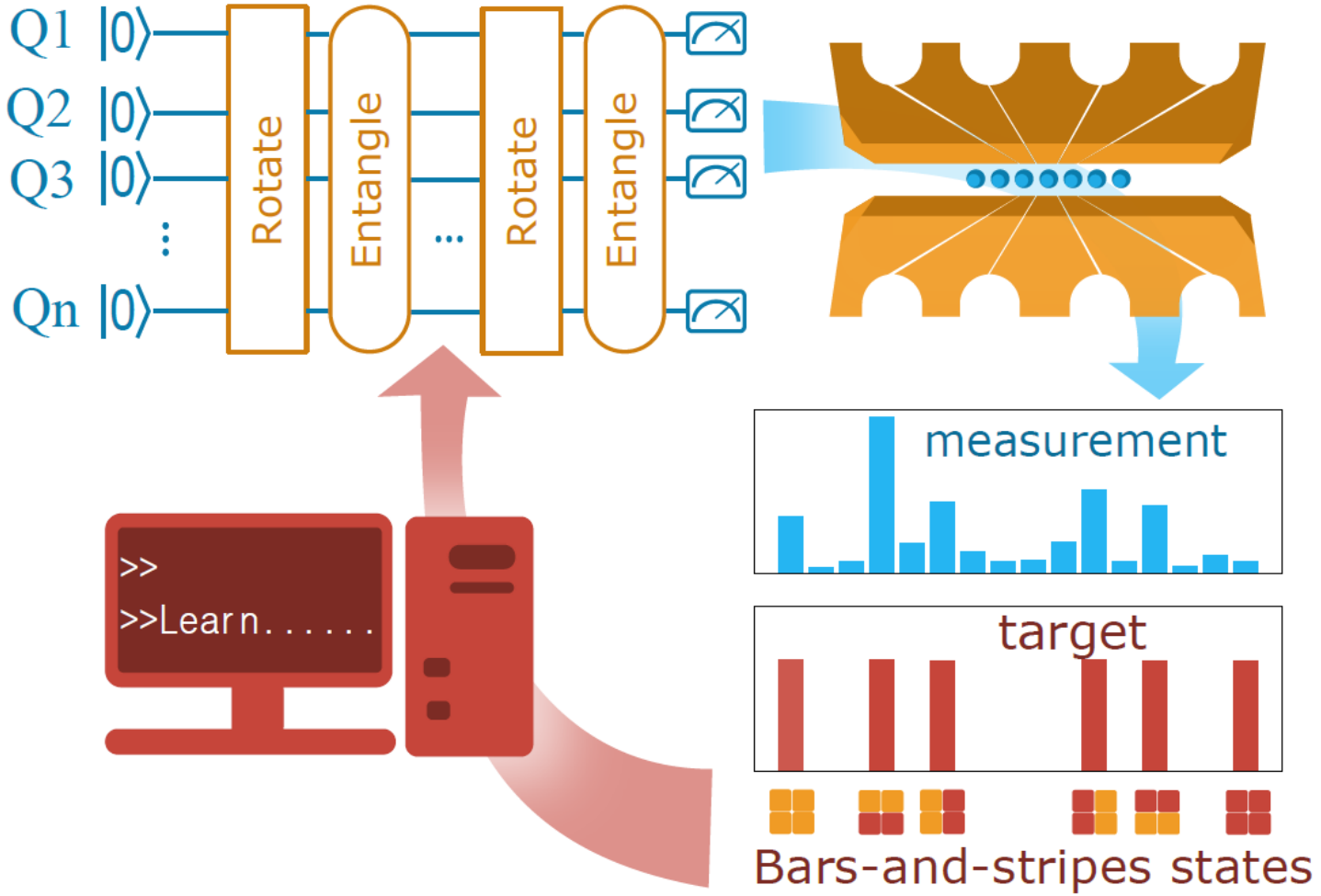
Hybrid machine learning: Bayesian Optimization Results



successful 26-parameter optimization

D. Zhu et al., Science Advances 5, 10 (2019)

Hybrid machine learning …thoughts

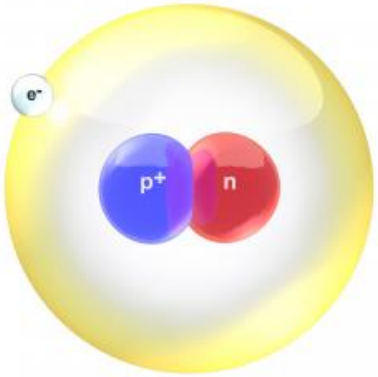


D. Zhu et al., Science Advances 5, 10 (2019)

Hybrid machine learning …applications

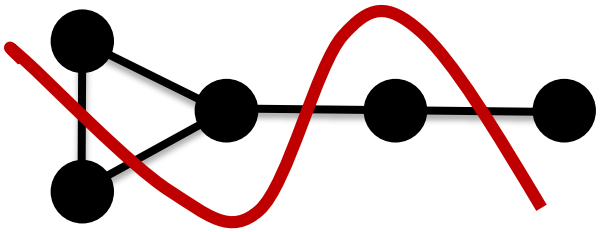
Ground state binding energy of the Deuteron nucleus (VQE)

O. Shehab et al., arXiv:1904.04338 (2019)



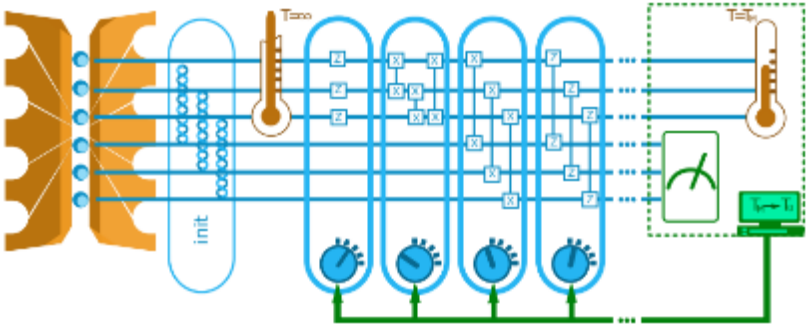
Solving the Max-Cut problem (QAOA)

O. Shehab et al., arXiv:1906.00476 (2019)



Creation of thermo-field double states (QAOA)

D. Zhu et al., arXiv:1906.02699 (2019)



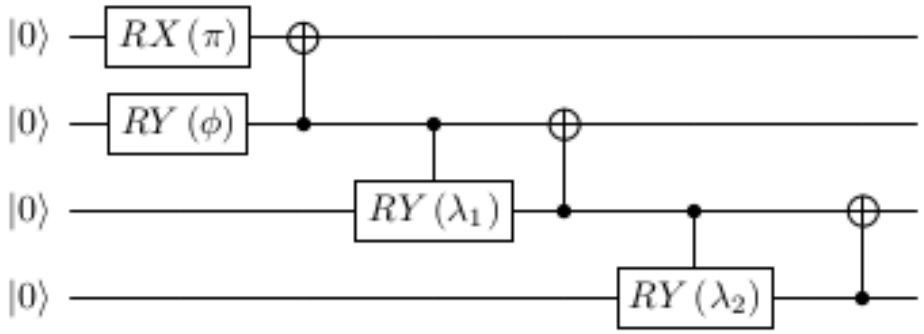
Noise reduction by past-light cone method

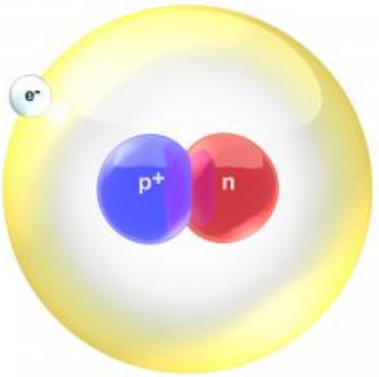
Noise reduction by past-light cone method

4-qubit Hamiltonian (EFT), -2.14MeV for p=1 (exact is -2.2MeV):

```
H4 = 28.656709445 * I + (-2.143303525)*X0*X1 + (-3.91311896)*X1*X2 +
(-5.67064811)*X2*X3 + (-2.143303525)*Y0*Y1 + (-3.91311896)*Y1*Y2 +
(-5.67064811)*Y2*Y3 + (0.218290555)*Z0 + (-6.125)*Z1 + (-9.625)*Z2 +
(-13.125)*Z3
```

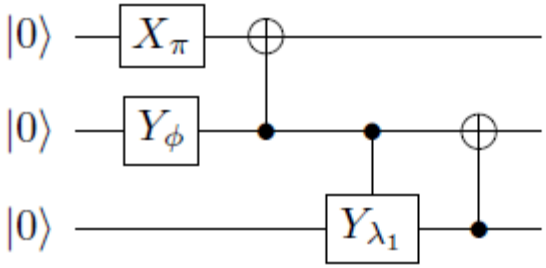
Canonical 4-qubit UCC ansatz



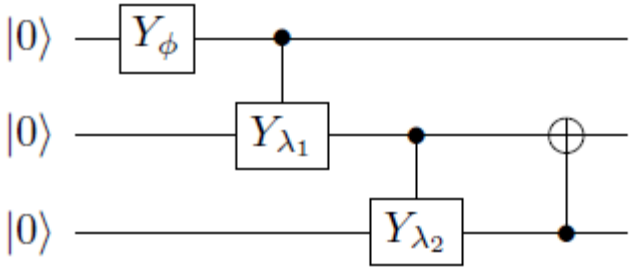


Shehab, O., et al. arxiv:1904.04338

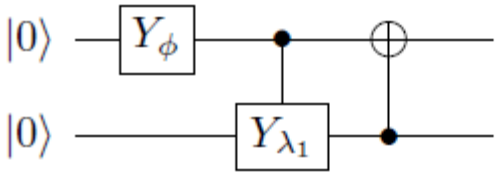
Noise reduction by past-light cone method



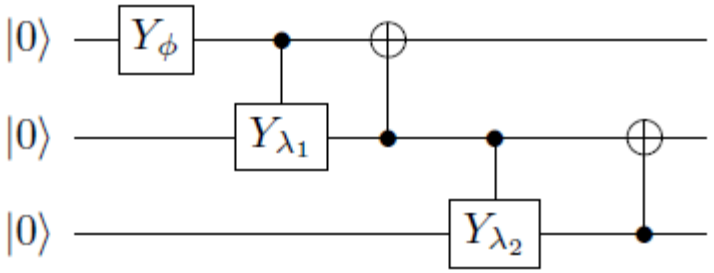
(a) X_1X_2 or Y_1Y_2



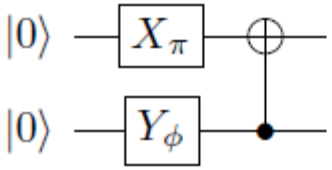
(c) X_3X_4, Y_3Y_4 or Z_3



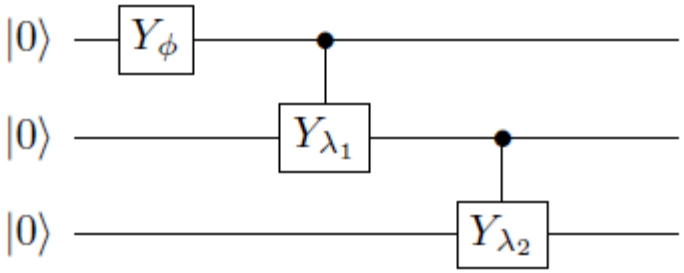
(e) Z_2



(b) X_2X_3 or Y_2Y_3

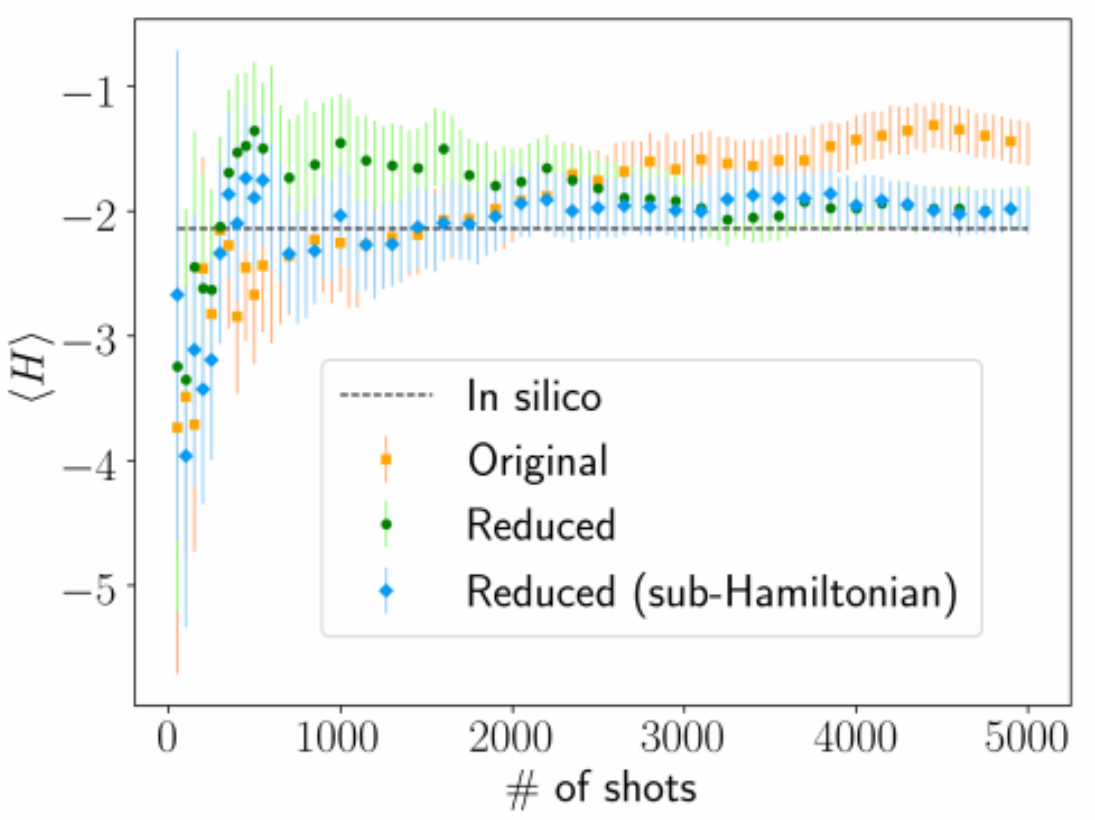


(d) Z_1



(f) Z_4

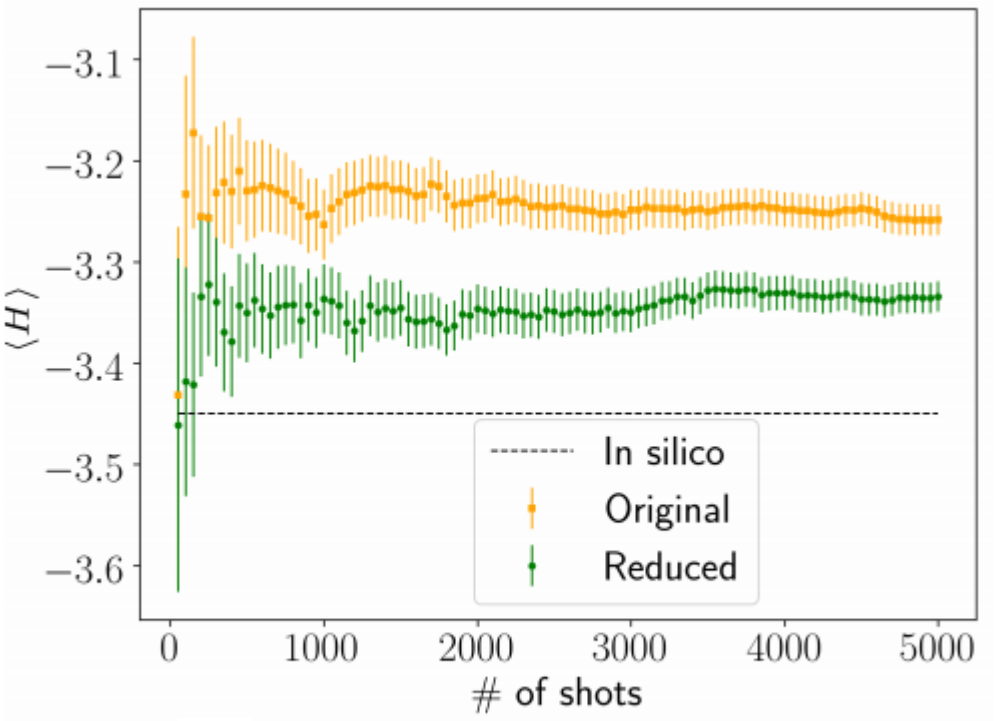
Noise reduction by past-light cone method



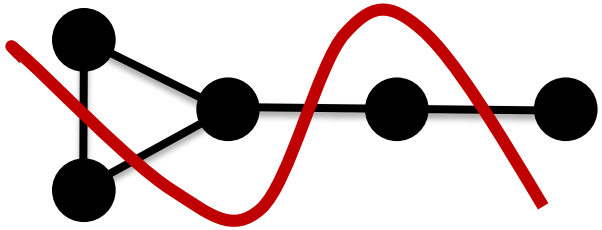
Binding energy vs. # of measurements

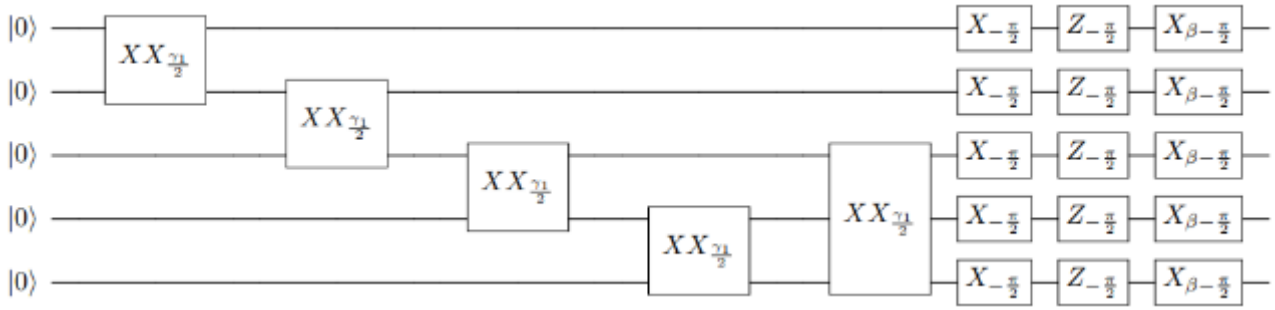
O. Shehab et al., arXiv:1906.00476 (2019)

Max-Cut and past light cones (p=1)



MAXCUT vs. # of measurements



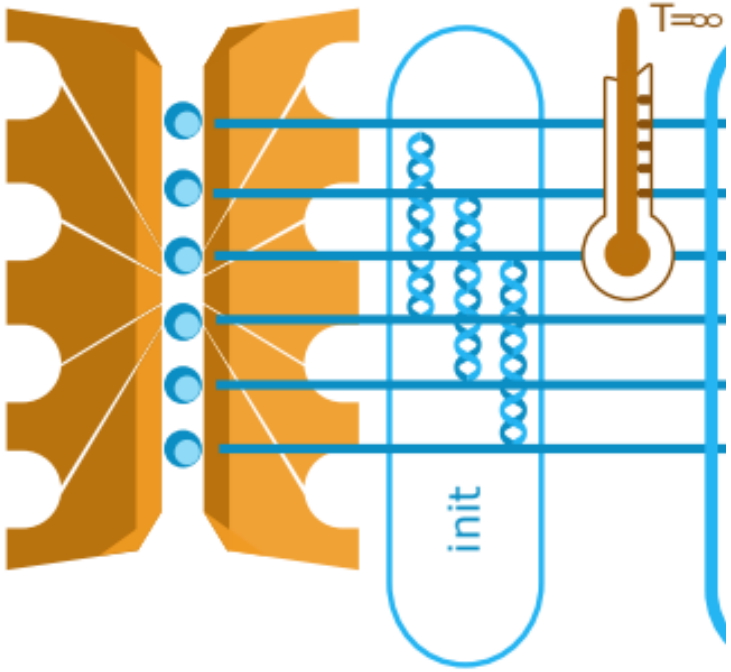


O. Shehab et al., arXiv:1906.00476 (2019)

Creation of thermo-field double states (QAOA)

QAOA – Quantum Approximate Optimization Algorithm [E. Farhi et al., MIT-CTP/4610 (2014)]

$$|TFD\rangle = \sum_n |n\rangle_A |n'\rangle_B$$



Y. Takahashi, H. Umezawa, Int. Jour. Mod. Phys. B 10, 1755 (1996)

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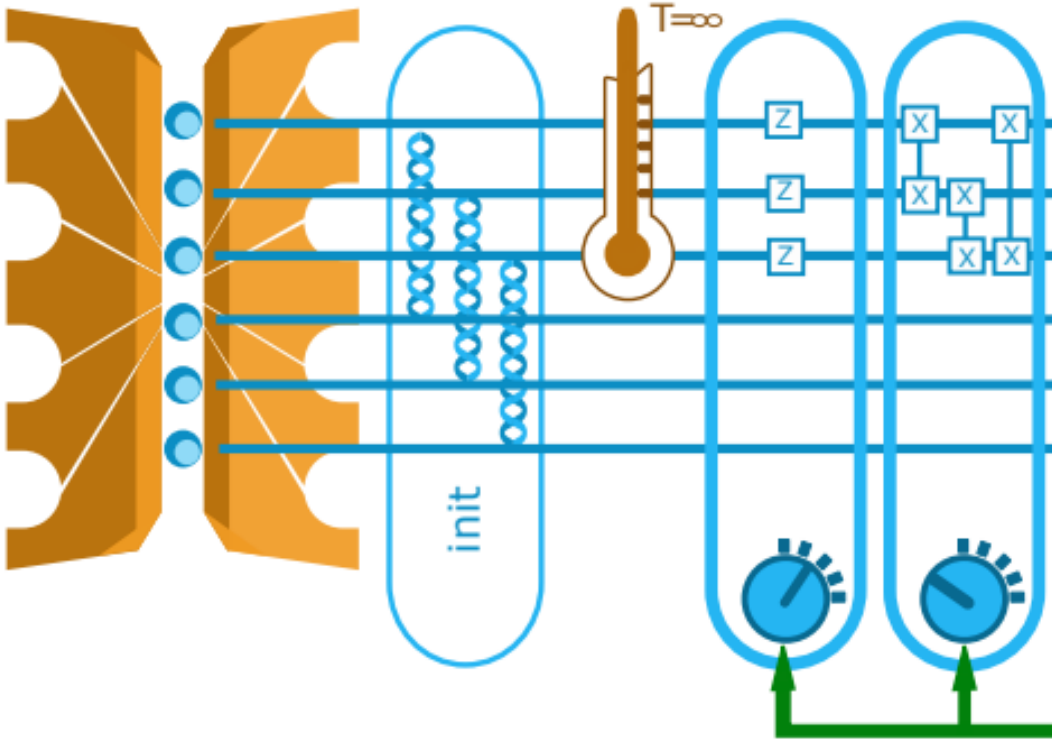
Transverse-field
Ising Hamitonian

$$gH_Z + H_{XX}$$



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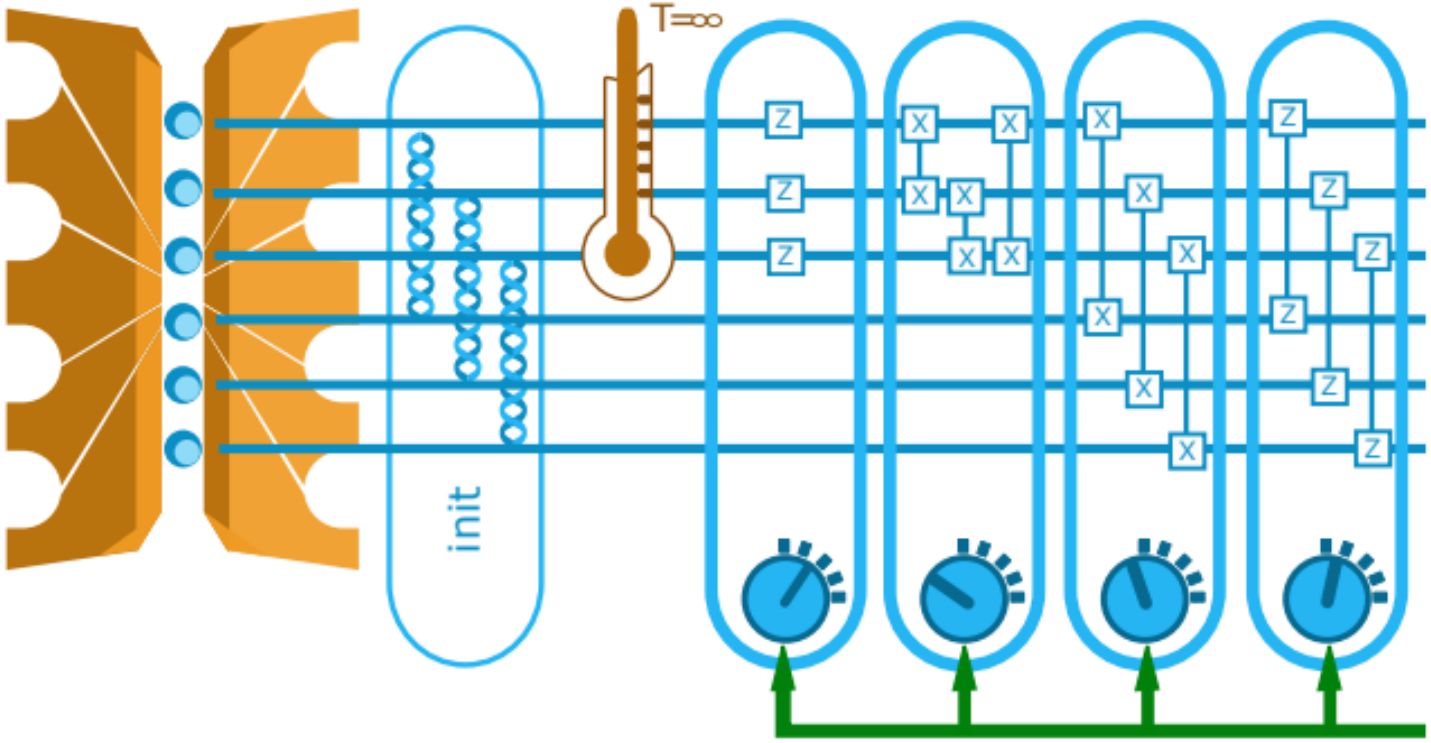

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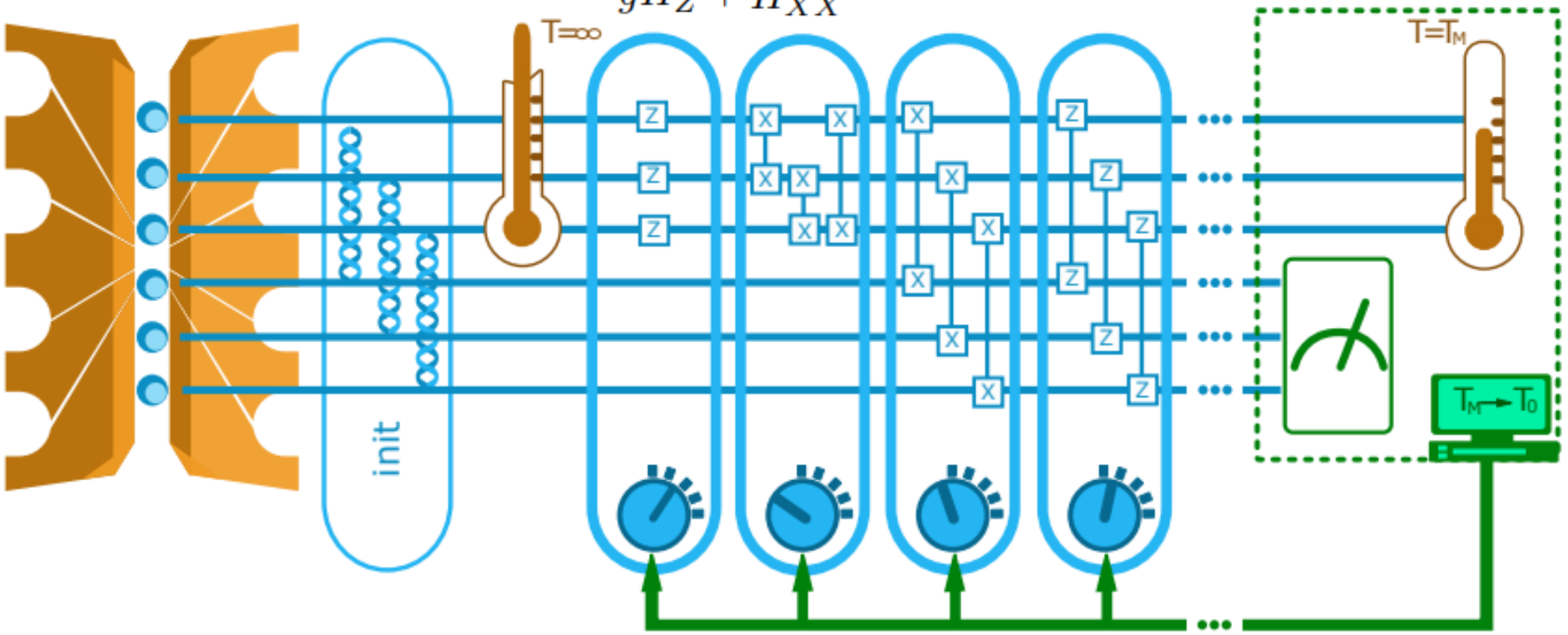
Transverse-field
Ising Hamitonian

$$gH_Z + H_{XX}$$

$$|TFD(\beta)\rangle = \sum_n e^{-\beta E_n/2} |n\rangle_A |n'\rangle_B$$



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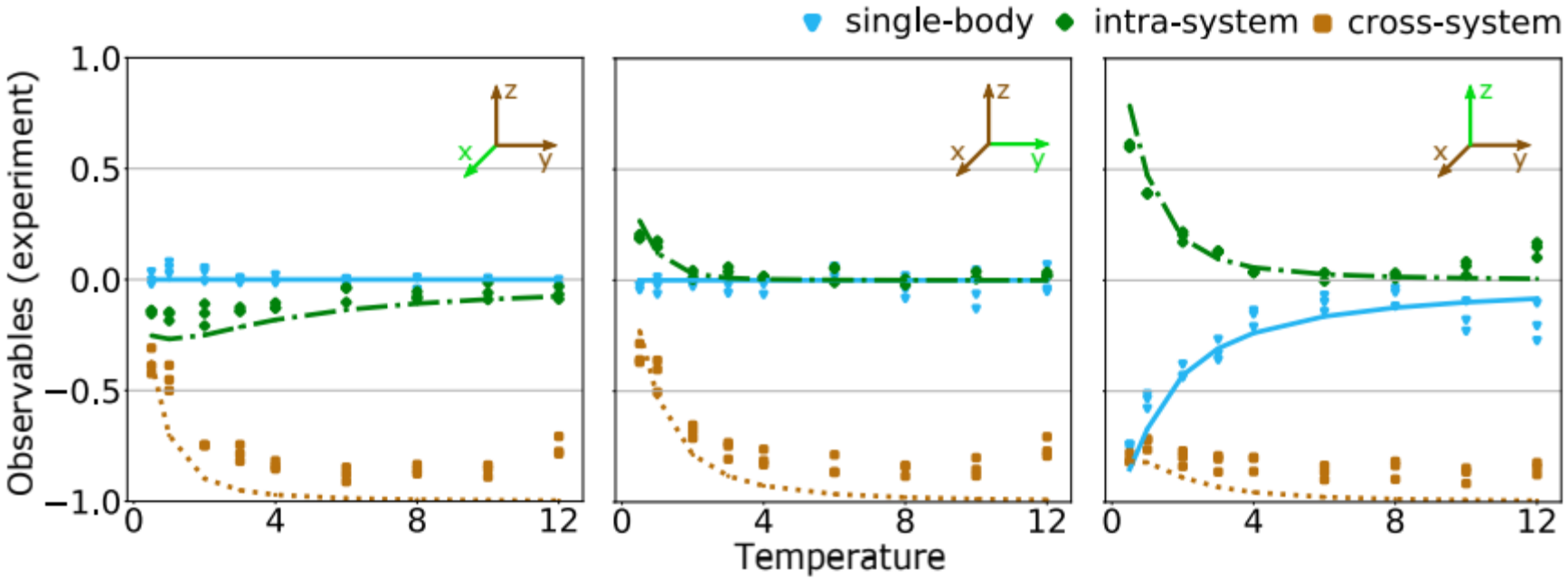
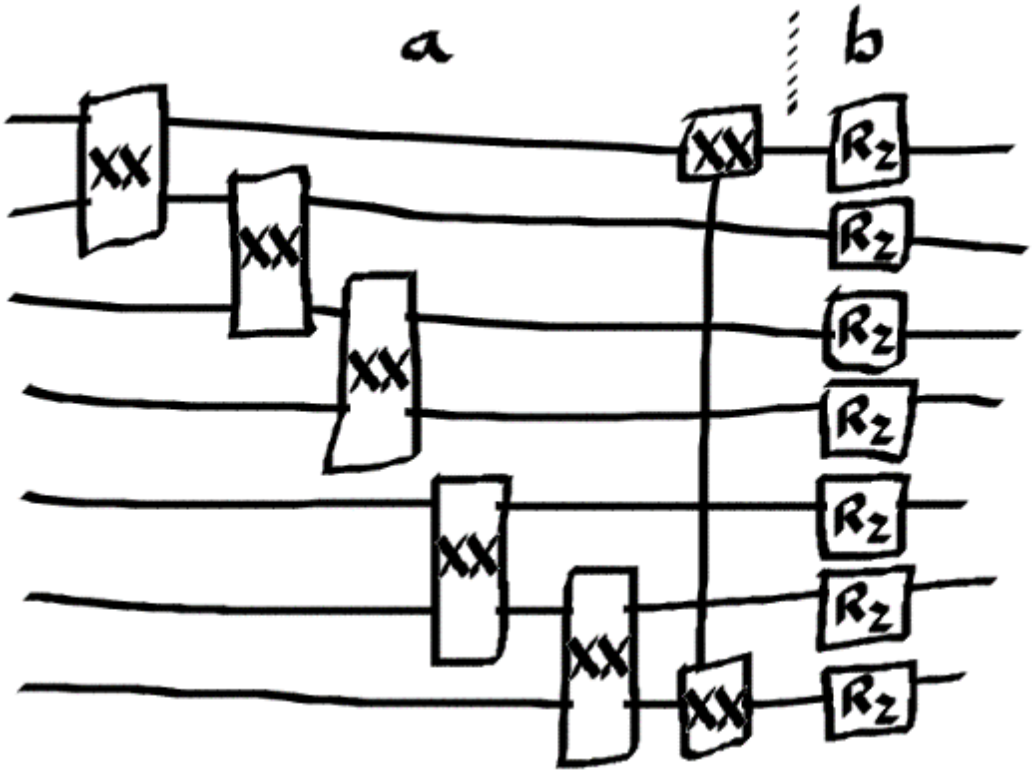


D. Zhu et al., arXiv:1906.02699 (2019)

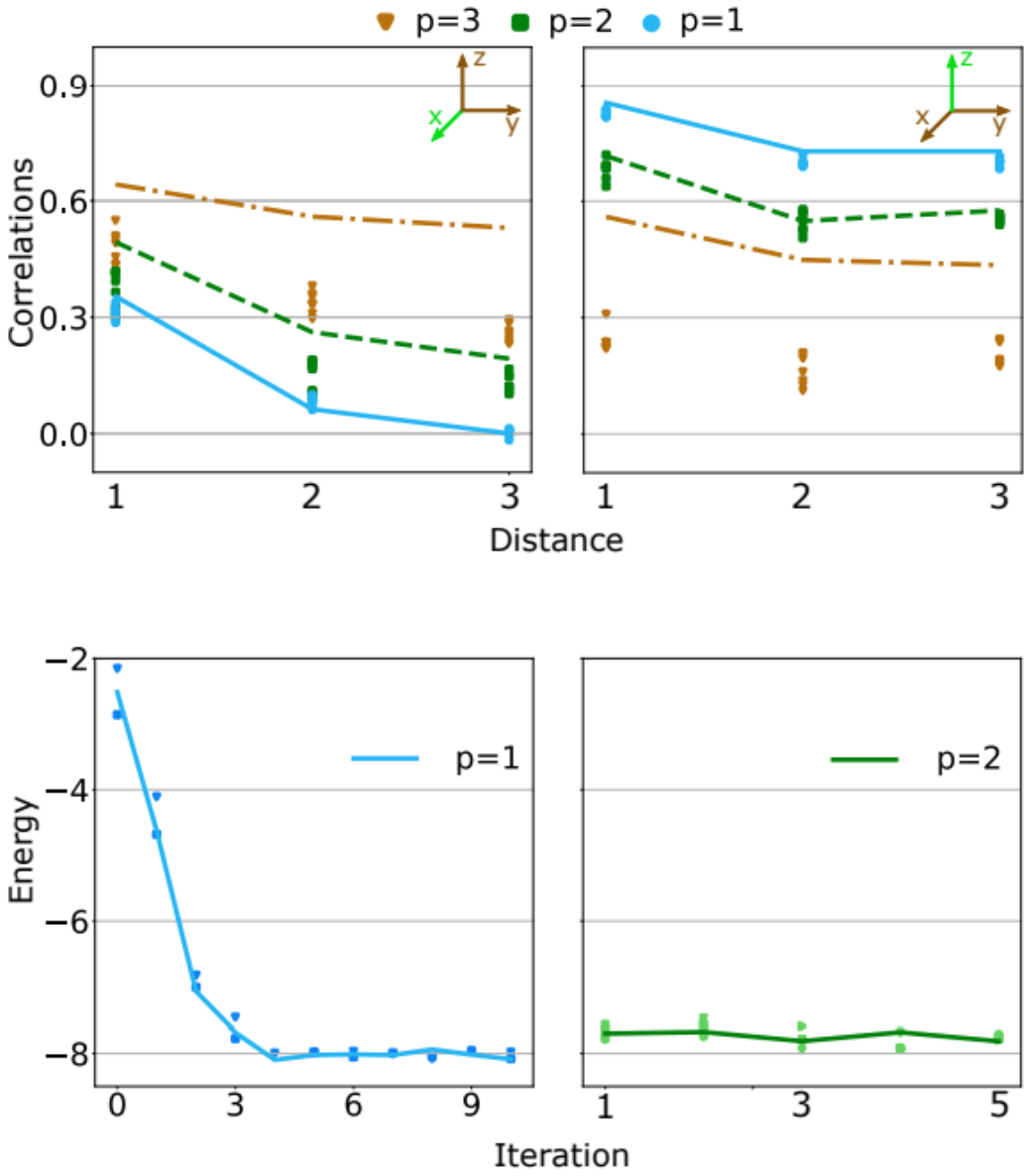
Prepare ground state for 7 qubits (zero temp.)

Transverse-field Ising model – prepare the (quantum critical) ground state

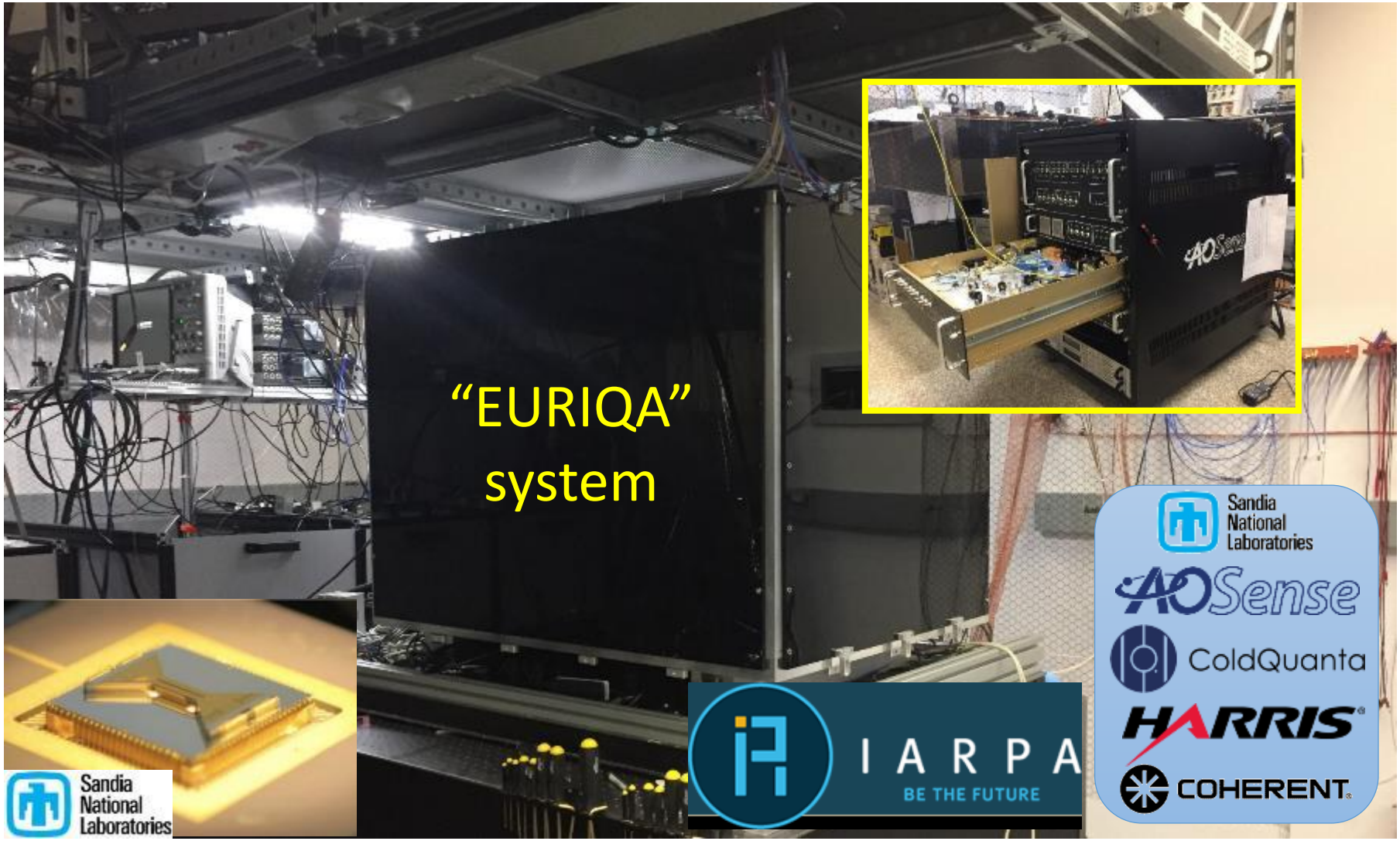
QAOA– circuit block on 7 qubits, can reach exact value (-8.8) with p=3



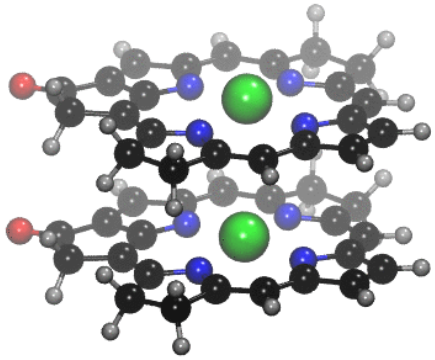
QAOA on a digital quantum computer



Outlook: the future - scaling up

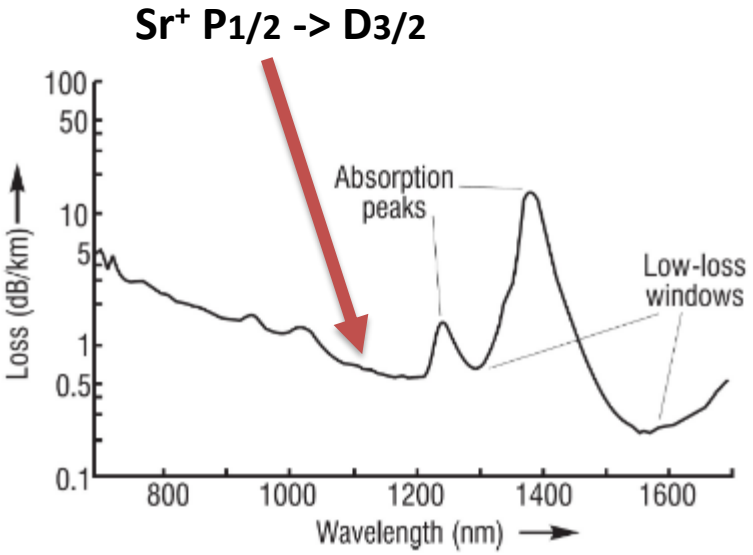


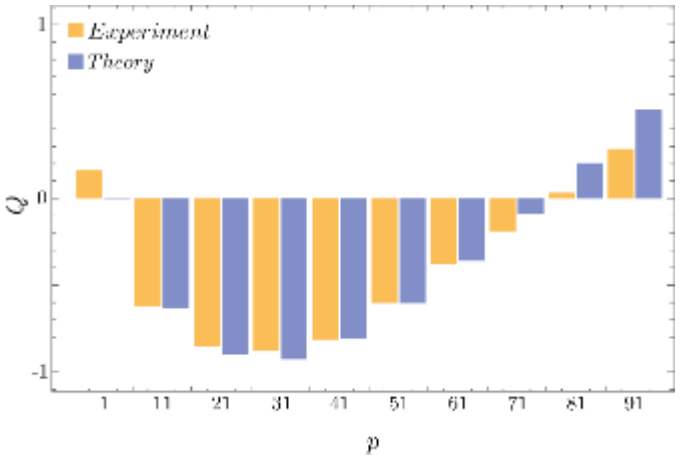
Outlook: Other projects



- More quantum algorithms / machine-learning-enhanced quantum operations / chemistry simulations

- Quantum networking with Strontium ions (telecom-ready entangled photons)





- Simulating exotic quantum phenomena (para-particles, phonon-dynamics)

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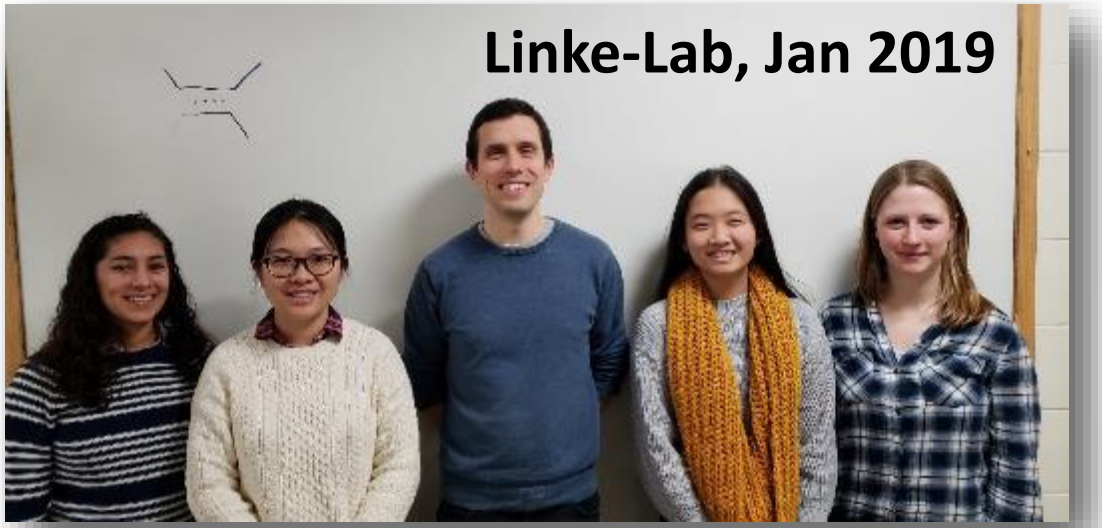
Chris Monroe



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