Title: A trapped ion quantum architecture

Speakers: Norbert Matthias Linke

Series: Colloquium

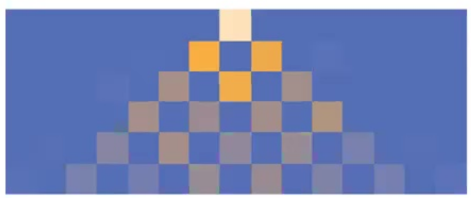
Date: October 22, 2020 - 2:00 PM

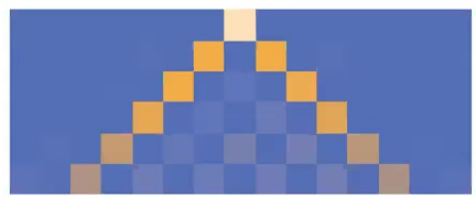
URL: http://pirsa.org/20100004

Abstract: We present a quantum architecture based on a linear chain of trapped 171Yb+ ions with individual laser beam addressing and readout. The collective modes of motion in the chain are used to efficiently produce entangling gates between any qubit pair. In combination with a classical software stack, this becomes in effect an arbitrarily programmable and fully connected quantum computer. The system compares favorably to commercially available alternatives [2].
We use this versatile setup to perform a quantum walk algorithm that realizes a simulation of the free Dirac equation where the quantum coin determines the particle mass [3]. We are also pursuing digital simulations towards models relevant in high-energy physics among other applications. Recent results from these efforts, and concepts for expanding and scaling up the architecture will be discussed.
[1] S. Debnath et al., Nature 563:63 (2016); P. Murali et al., IEEE Micro, 40:3 (2020); [3] C. Huerta Alderete et al., Nat. Communs. 11:3720 (2020).

A trapped-ion quantum architecture

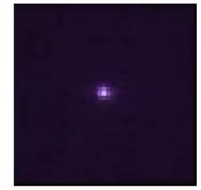
Norbert M. Linke
Joint Quantum Institute, University of Maryland
College Park, Maryland, USA





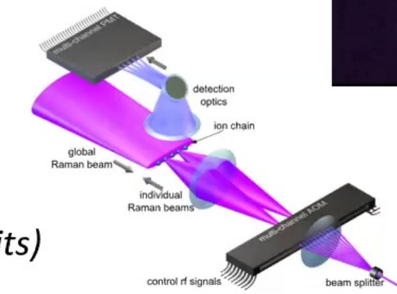
IQC Waterloo, online talk
22 October 2020

Overview



Quantum hardware

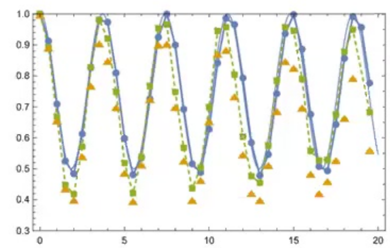
Why ions are so useful



Experimental system

Individually addressed $^{171}Yb^{+}$ ions

Modular gates and compiler (5-9 qubits)



Quantum algorithms

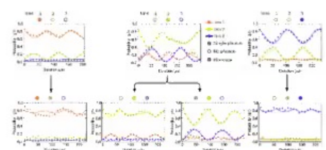
QC and compiler benchmarking

Quantum Walks and Dirac cellular automaton

Quantum field theory simulations

Quantum physics simulations

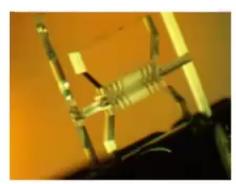
Phonon hopping

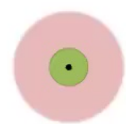


Outlook:Scaling up

New traps

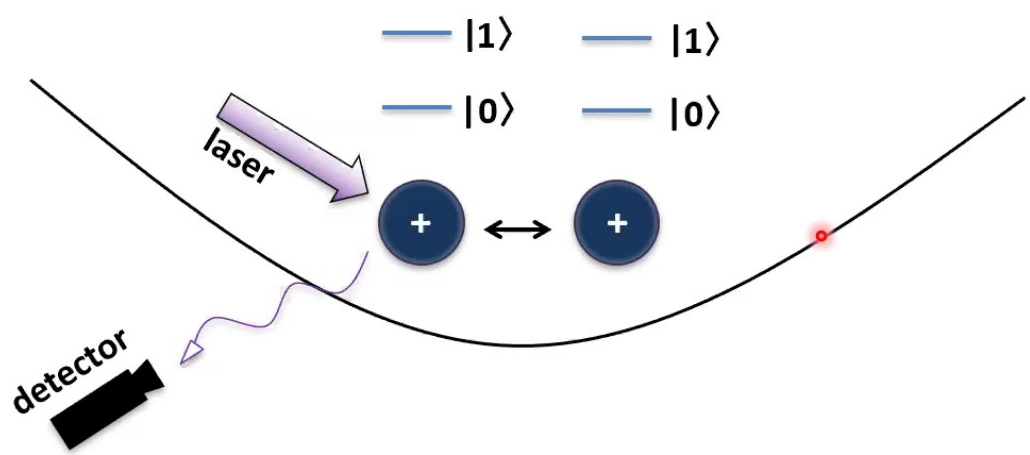
Quantum networking





Trapped ions

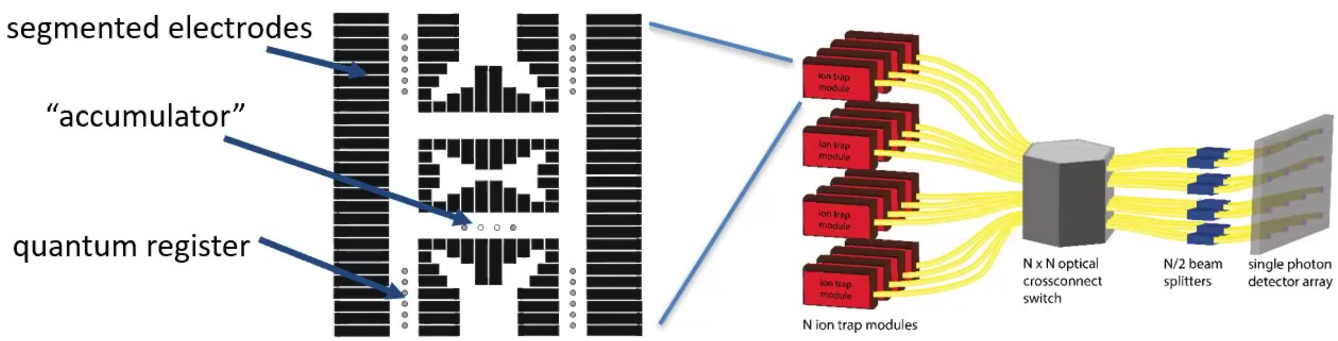
A good quantum computing and simulation candidate – why?



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

The ion trap quantum computer (vision)

Ion trap Quantum computing – the big pic

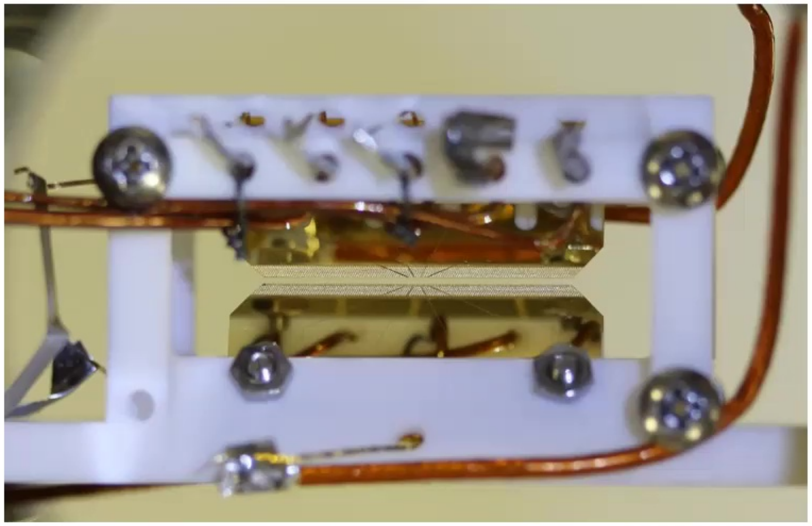


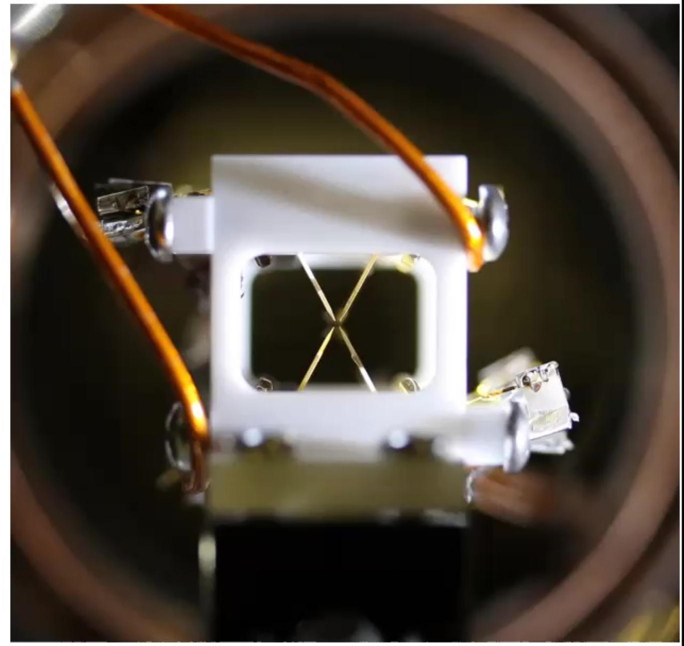
D. J. Wineland et al. 1998 **C. Monroe / J. Kim et al. 2013**

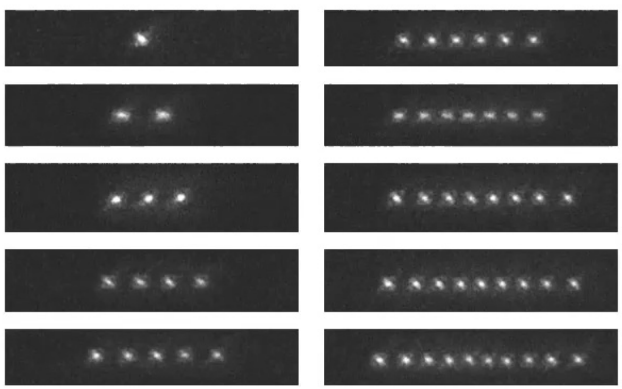
Are we there yet…? – challenges

- Higher fidelity operations
- Extend to more ions
- Classical software/control

Ion traps: hardware in current UMD module

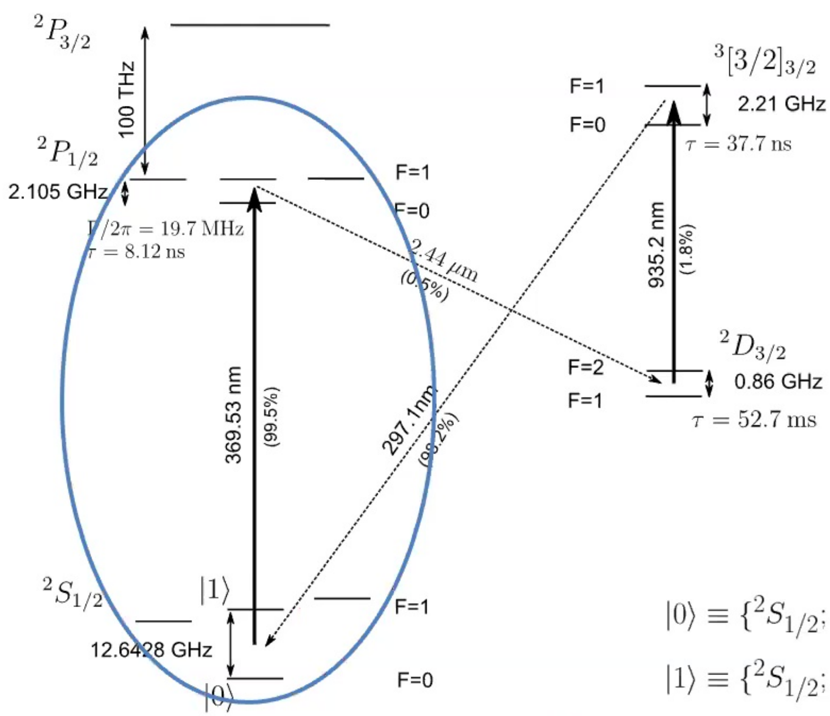






trapped ion Coulomb crystals

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



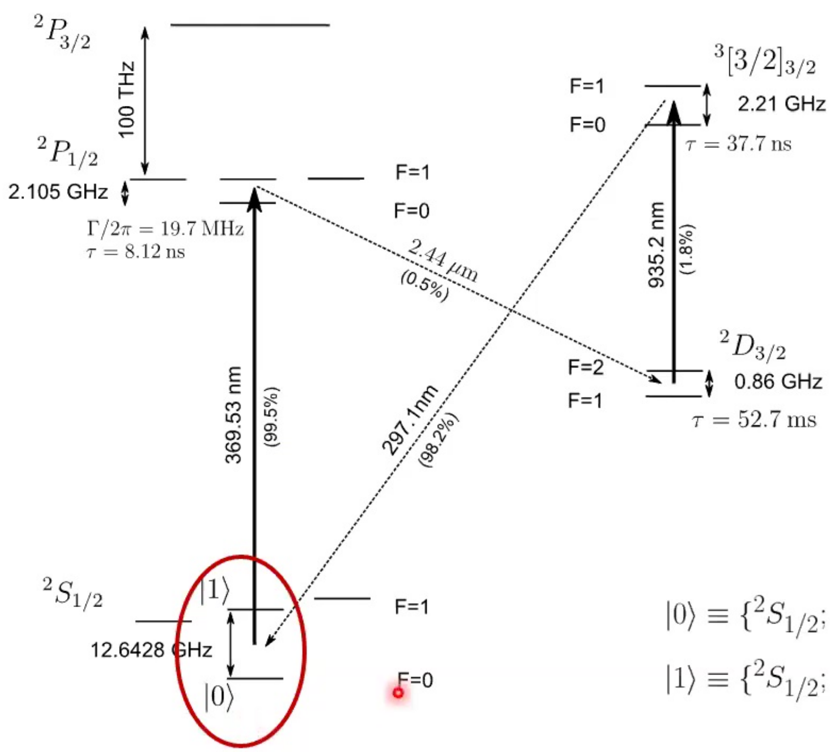
$$|0\rangle \equiv \{^2S_{1/2}; F=0, m_F=0\}$$

$$|1\rangle \equiv \{^2S_{1/2}; F=1, m_F=0\}$$

atomic clock qubit -> B-field insensitive
long coherence times: ~1.5s

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

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



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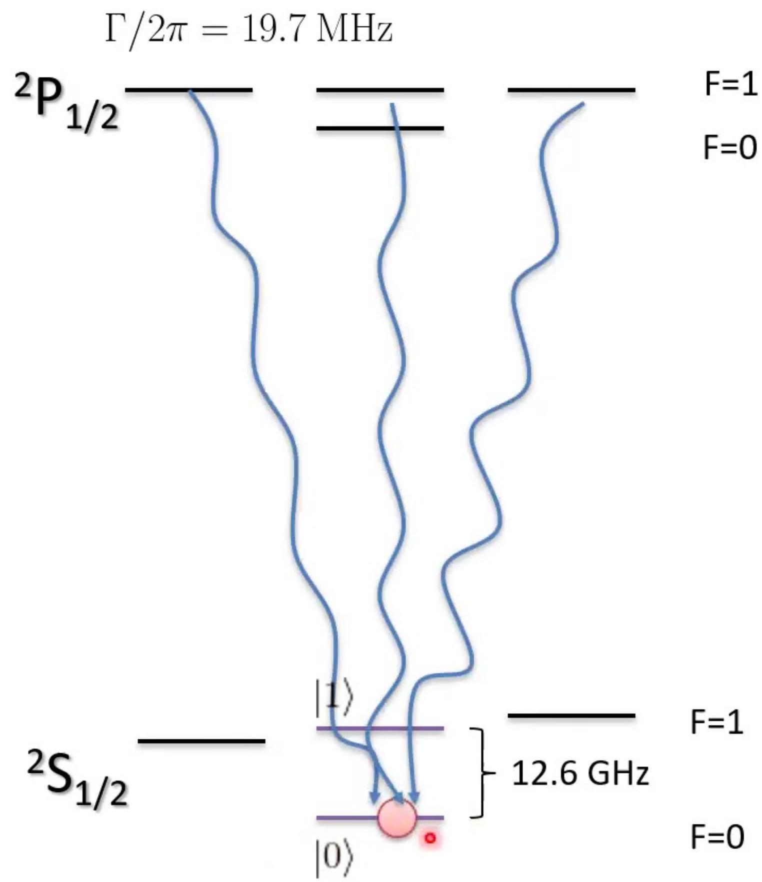
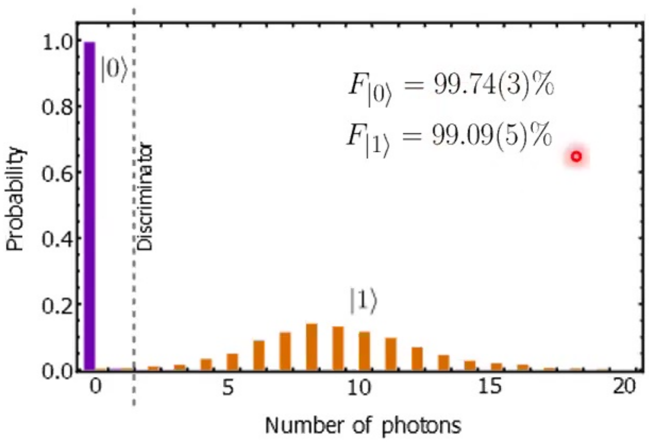
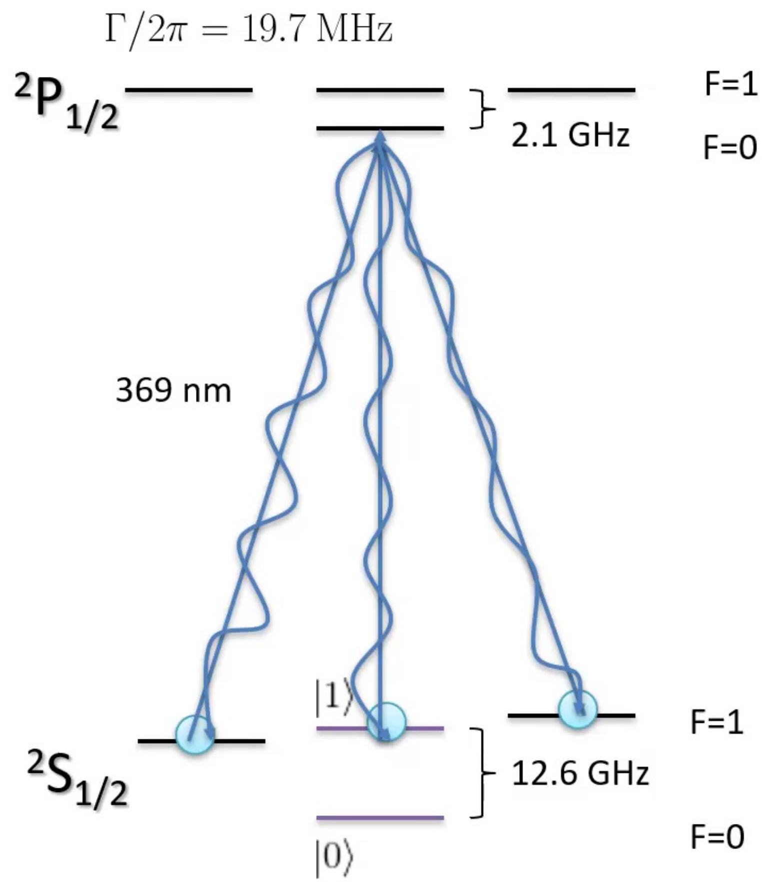
Trapped ion qubits: State initialization

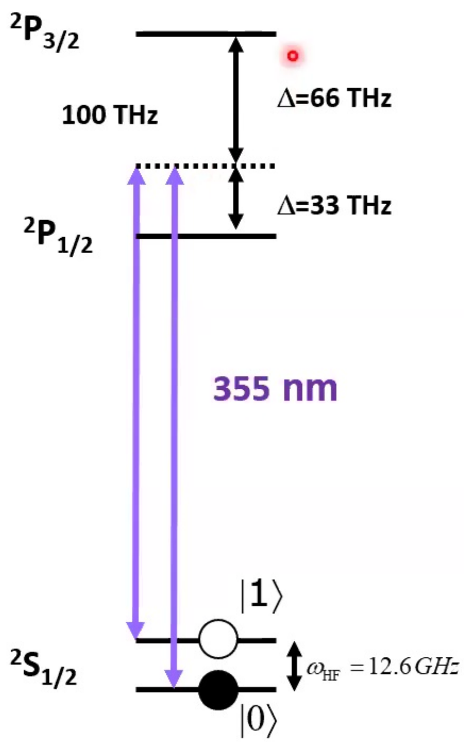


Trapped ion qubits: State detection

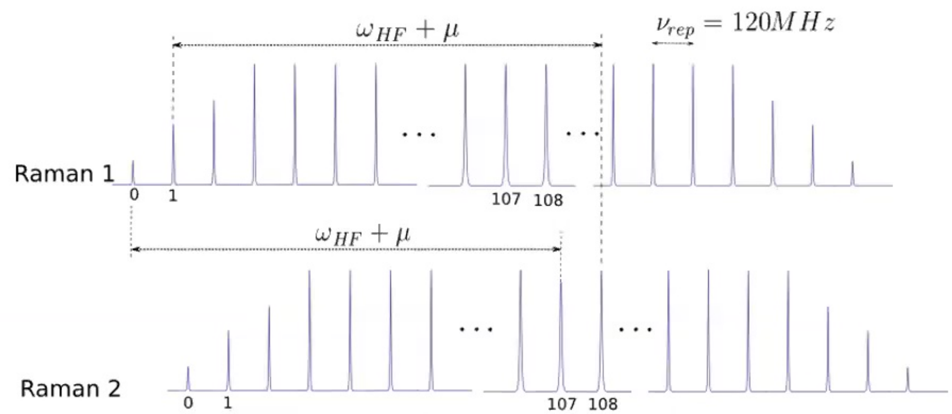




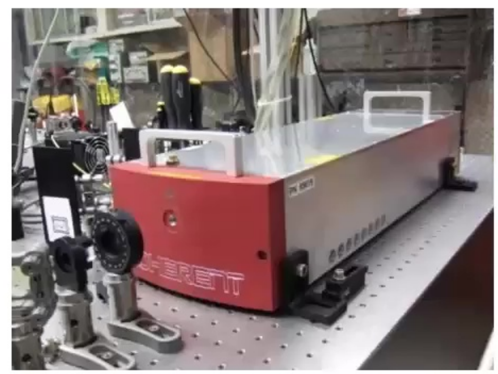
$^{171}Yb^{+}$ as a qubit: coherent manipulation



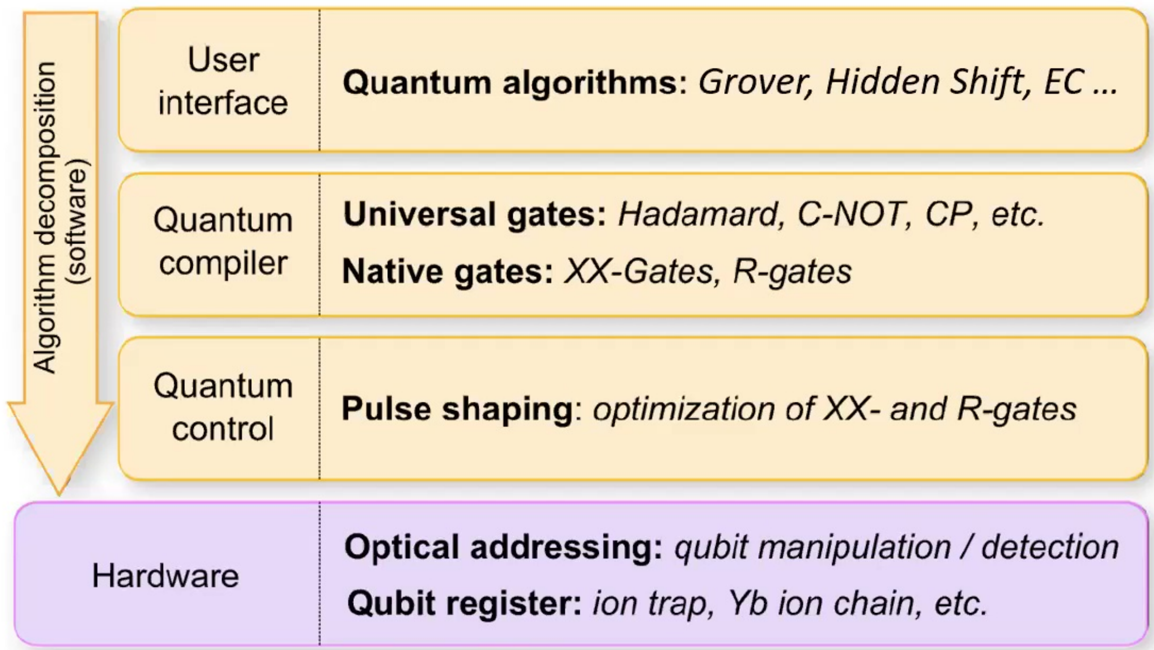
stimulated Raman transitions using pulsed 355nm



Raman beams in frequency domain

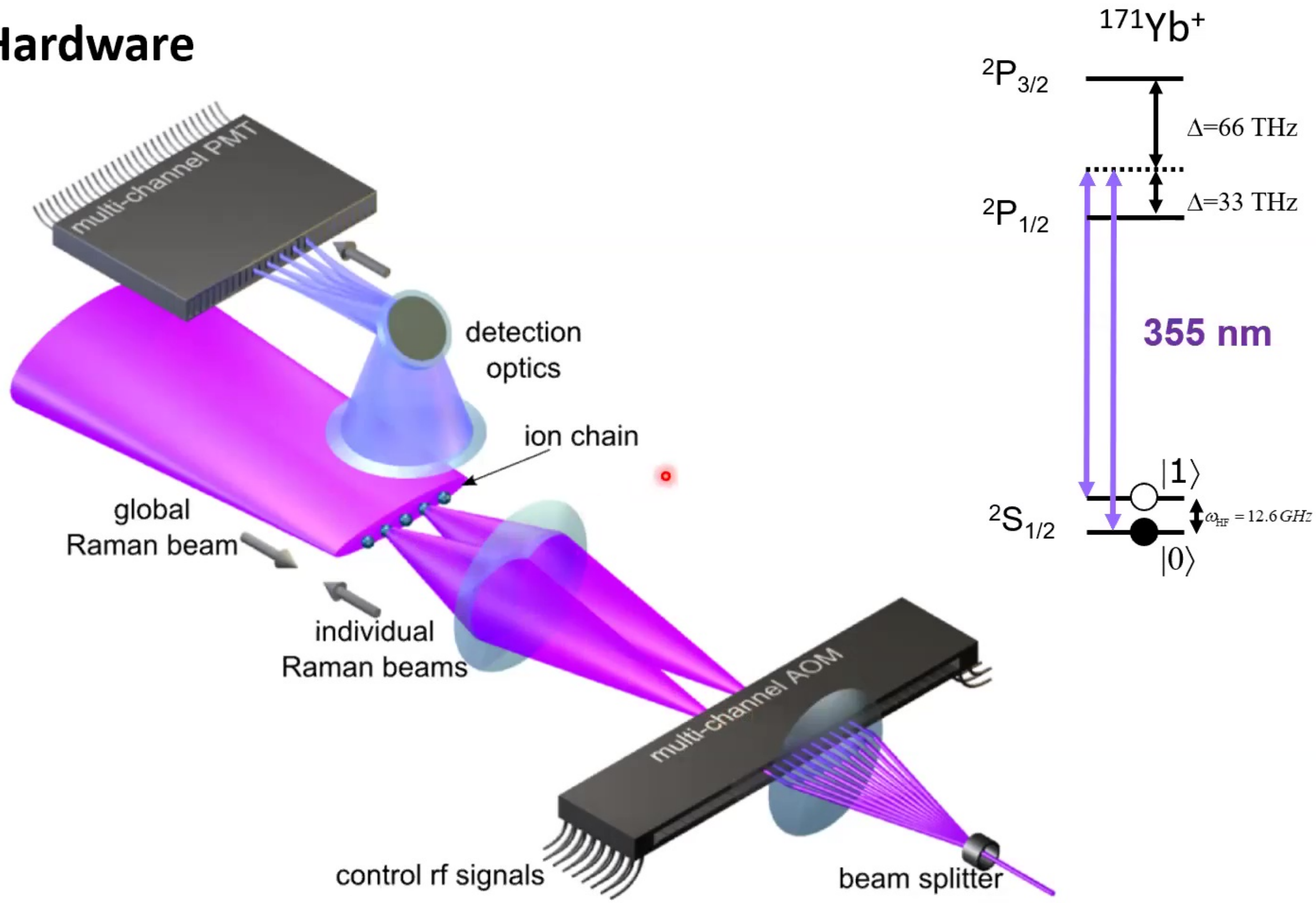


Modular architecture

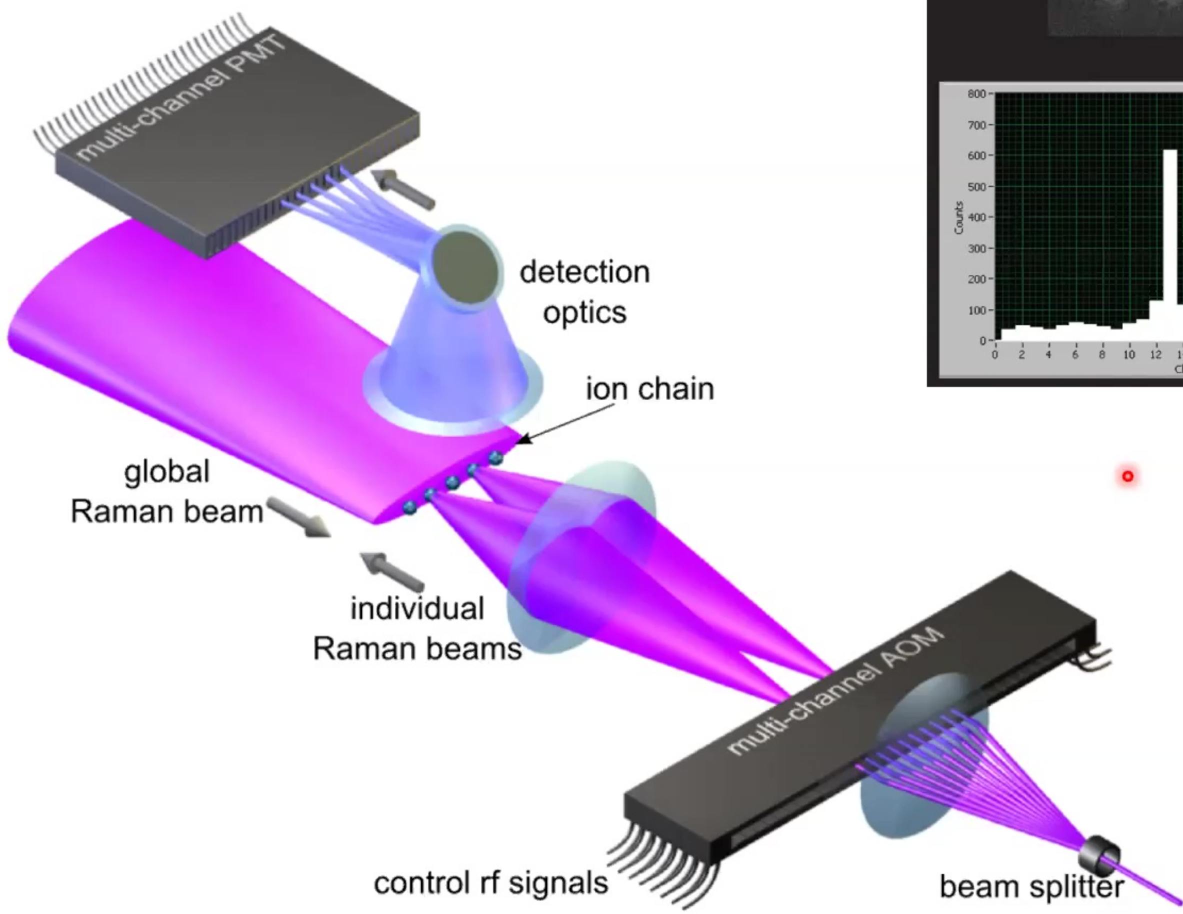


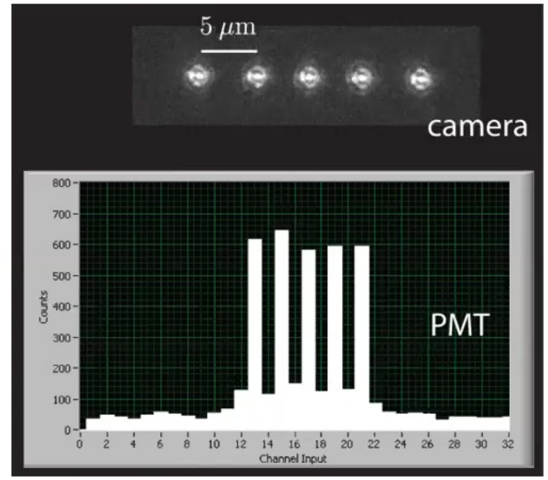
S. Debnath et al. Nature **536** (2016)

Hardware

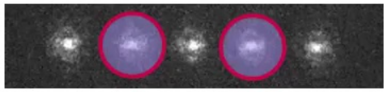

multi-channel PMT
detection optics
ion chain
global Raman beam
individual Raman beams
multi-channel AOM
control rf signals
beam splitter
$^{171}Yb^+$
$^2P_{3/2}$
Δ=66 THz
Δ=33 THz
$^2P_{1/2}$
355 nm
$|1\rangle$
$^2S_{1/2}$
$\omega_{HF} = 12.6\,GHz$
$|0\rangle$

Hardware: Read-out

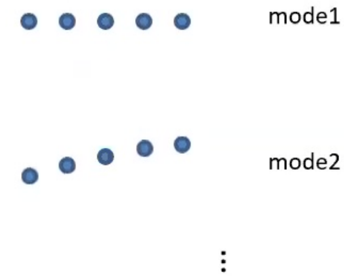


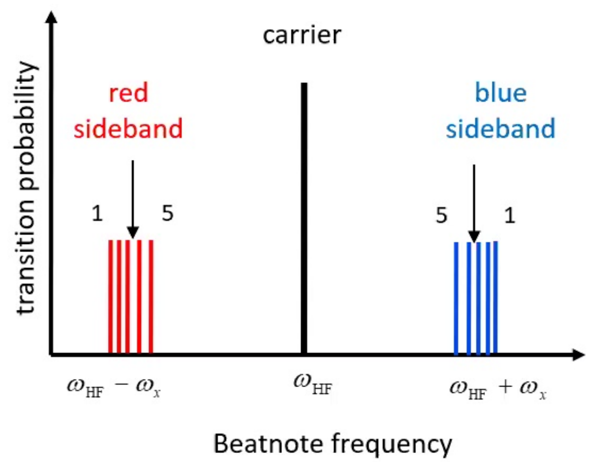


Quantum control: entangling gates (XX-gates)



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





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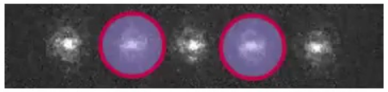
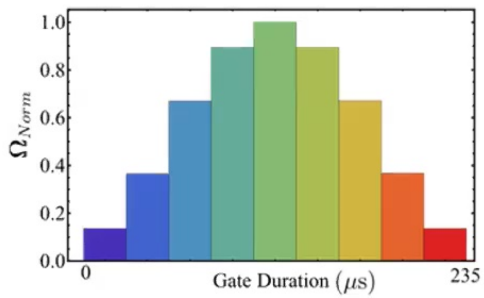
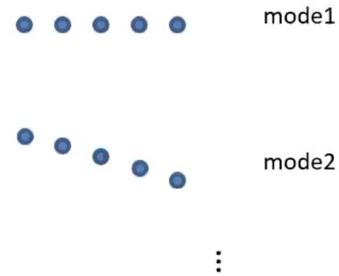


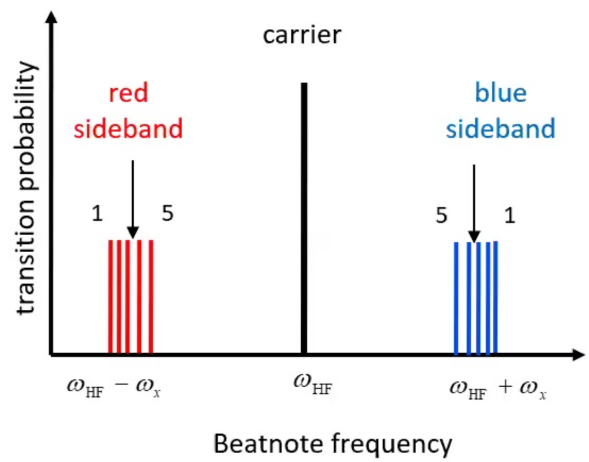
$$U(t) = \exp[-i \sum_{n,k} \hat{D}(\alpha_n^k(t))\sigma_x^n - i \sum_{i,j} \chi_{ij}(t)\sigma_x^i \sigma_x^j]$$



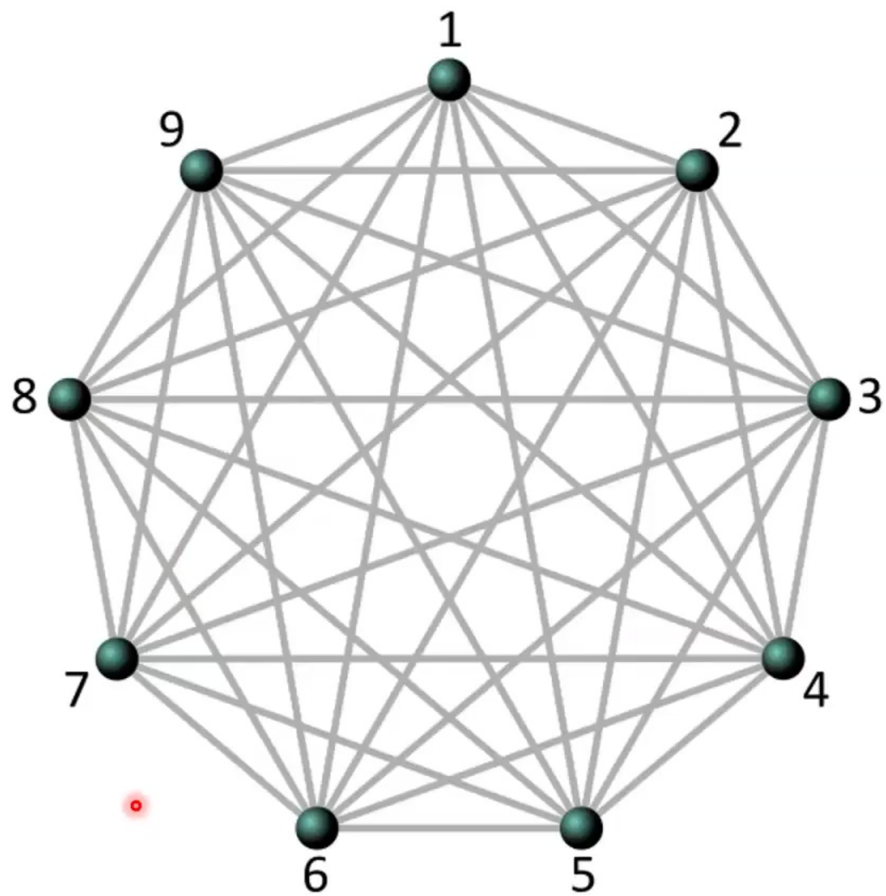
$$XX(\chi_{i,j}) = \begin{bmatrix} \cos(\chi_{i,j}) & 0 & 0 & -i\sin(\chi_{i,j}) \\ 0 & \cos(\chi_{i,j}) & -i\sin(\chi_{i,j}) & 0 \\ 0 & -i\sin(\chi_{i,j}) & \cos(\chi_{i,j}) & 0 \\ -i\sin(\chi_{i,j}) & 0 & 0 & \cos(\chi_{i,j}) \end{bmatrix}$$

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





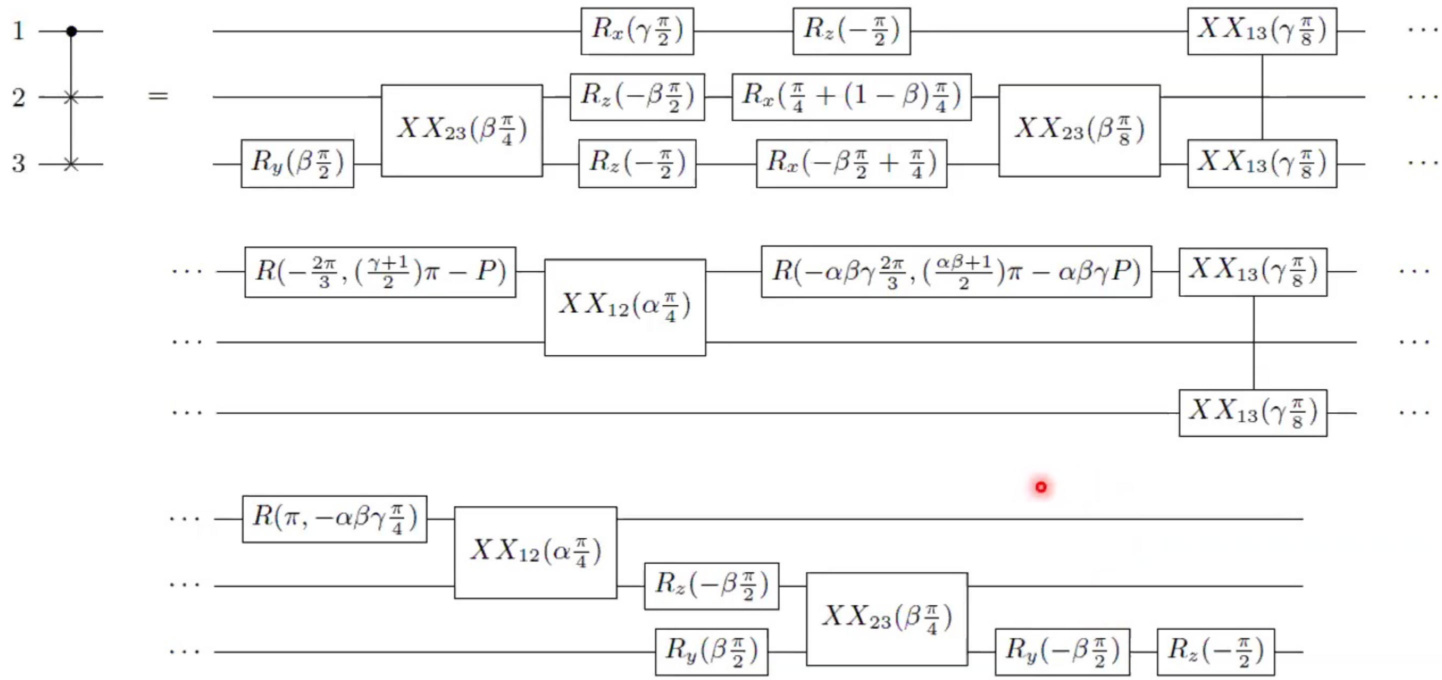
Quantum control: Full connectivity



not limited to local operations

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

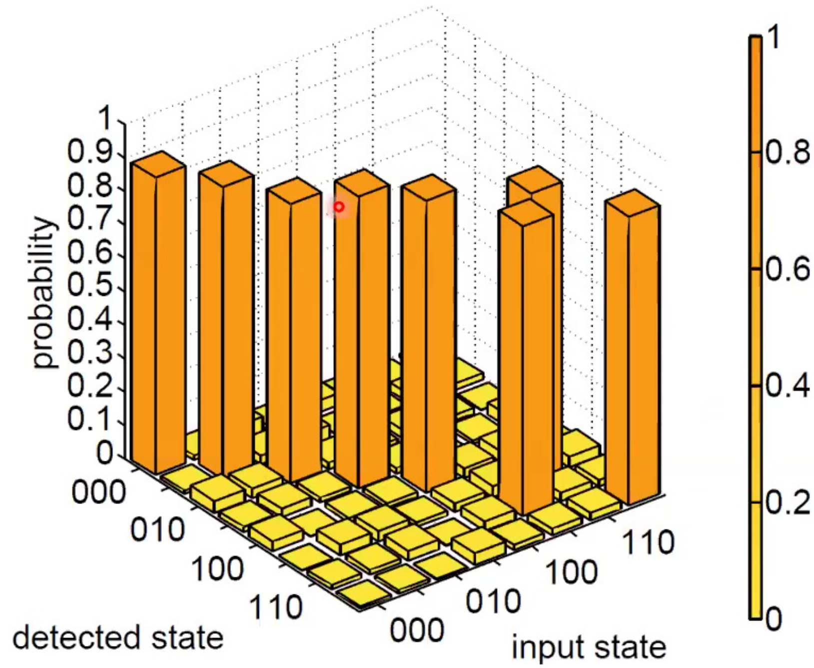
Quantum compiler: Fredkin gate circuit



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

NML et al., Phys. Rev. A **98**, 052334 (2018)

Quantum compiler: Fredkin gate results

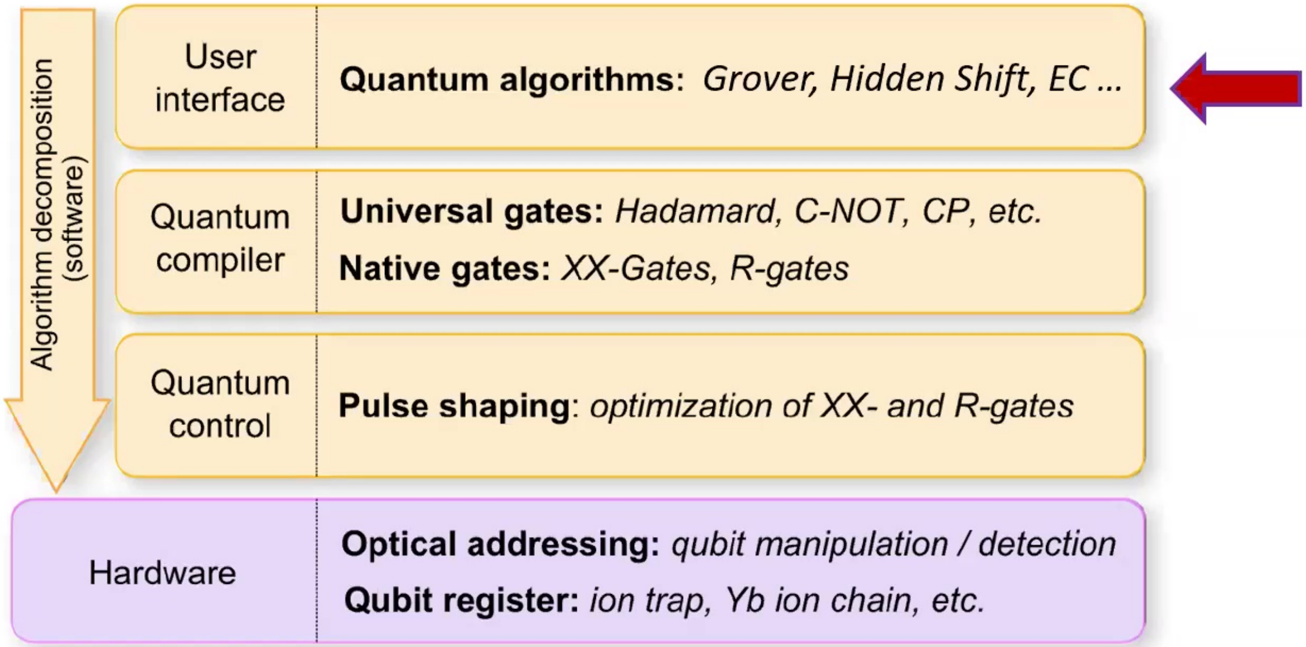


Fredkin [1,2:4], F=86.8(3)%

(corrected for 2% spam error)

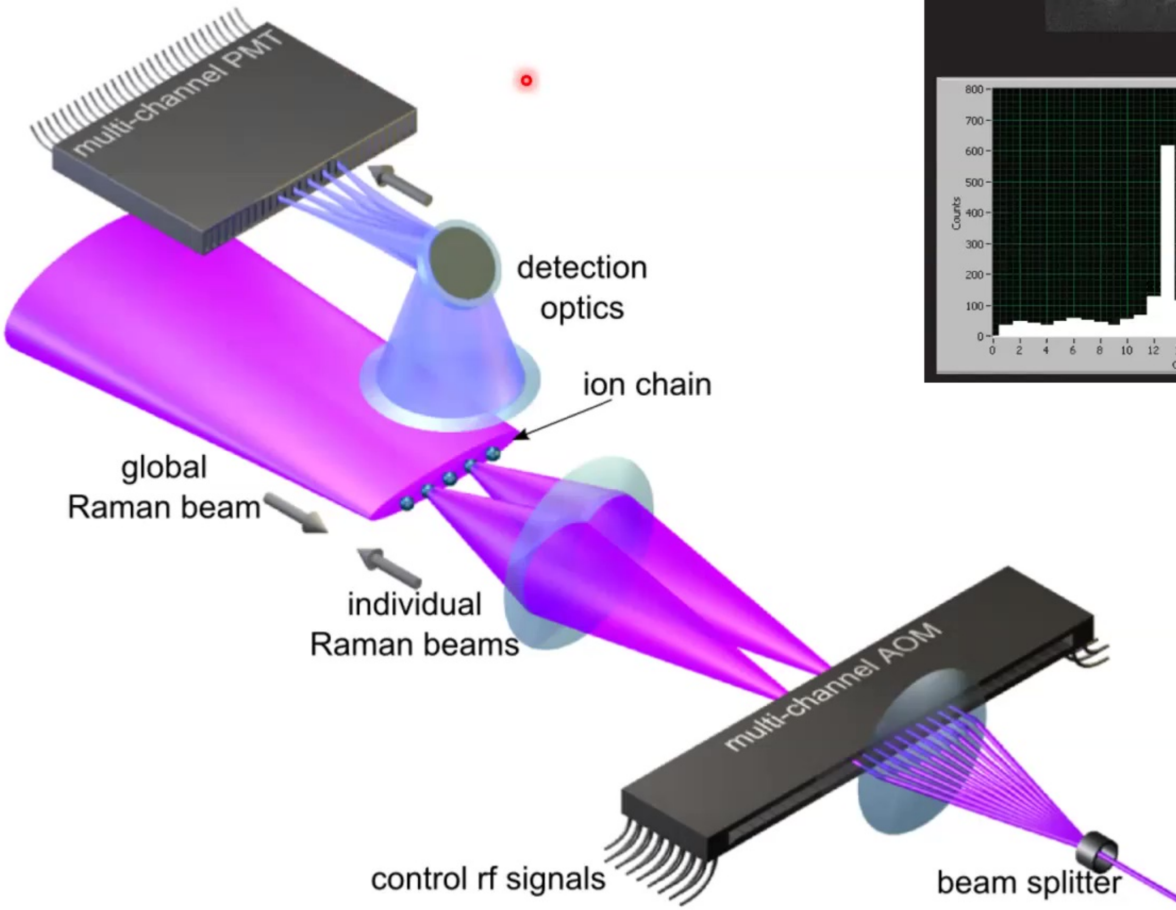
NML et al., Phys. Rev. A **98**, 052334 (2018)

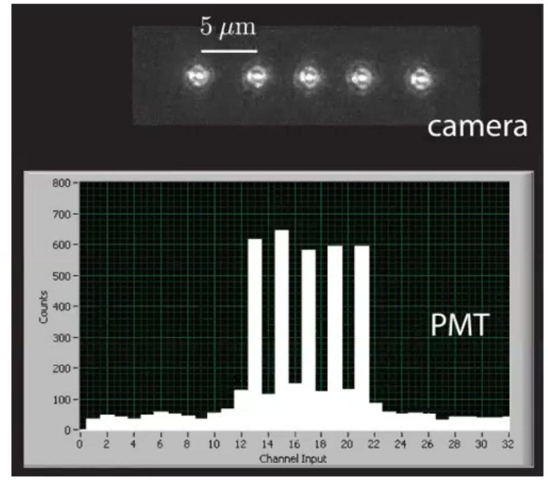
Modular architecture



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

Hardware: Read-out



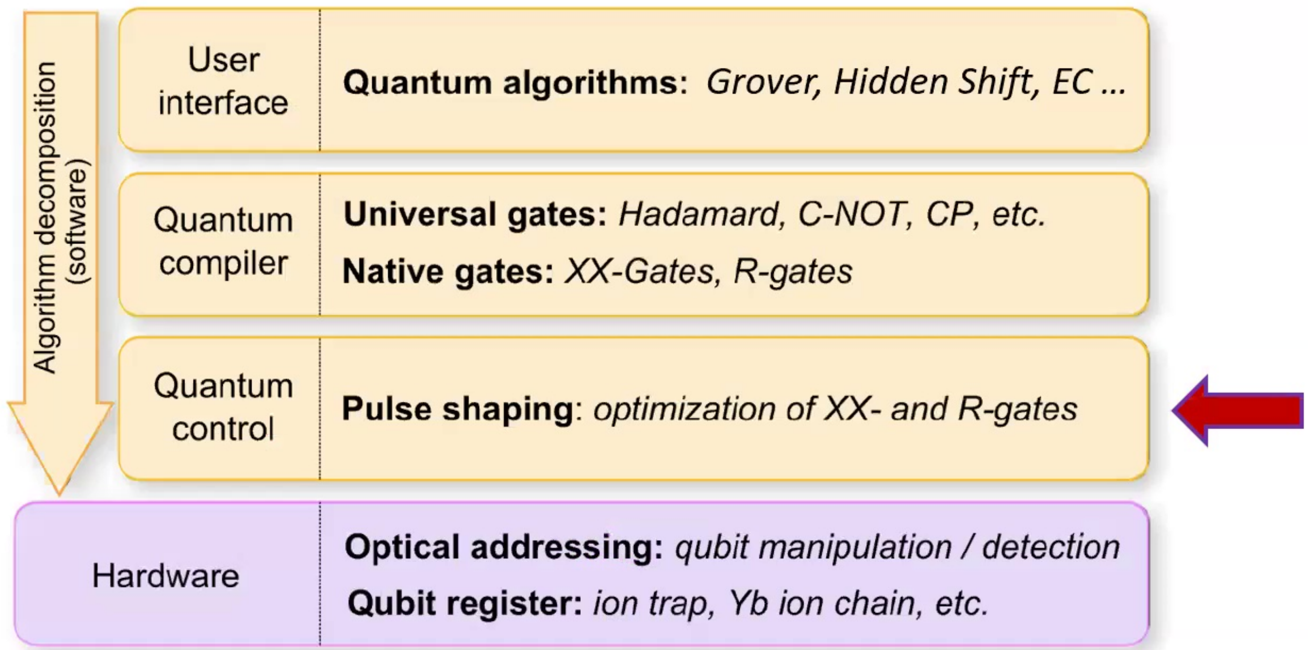


Quantum algorithms: build it …and they will come!

Quantum Fourier Transform, Bernstein-Vazirani algorithm, Deutsch-Josza algorithm[1]

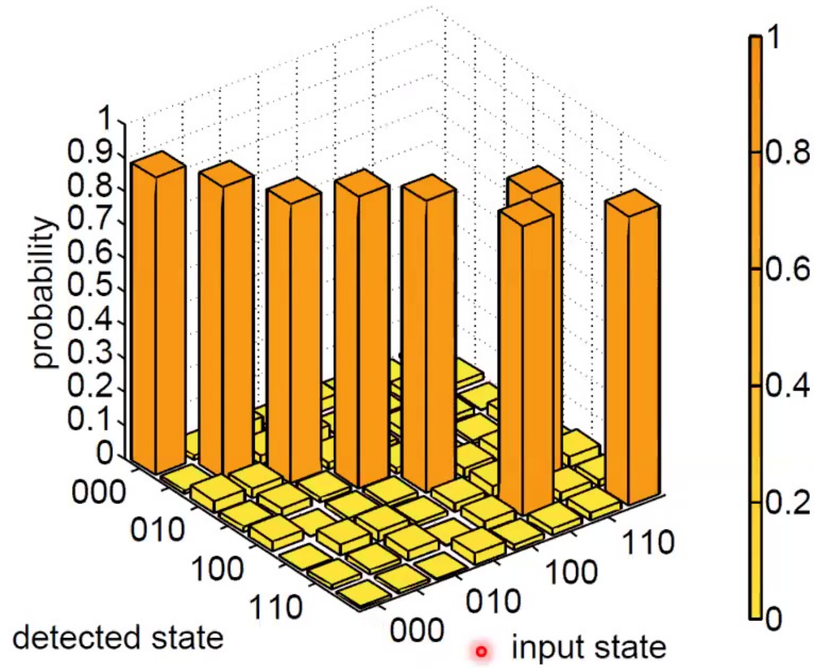
1 S. Debnath et al. Nature **536** (2016)
2 NML et al., PNAS **114**, 13 (2017)
3 NML et al., Sci Adv. **3**, 10 (2017)
4 C. Figgatt et al., Nat. Communs. **8** (2017)
5 N. Solmeyer et al., QST **3** 045002 (2018)
6 NML et al., Phys. Rev. A **98**, 052334 (2018)
7 K. A. Landsman et al., Nature **567**, 61-65 (2019)
8 M. Benedetti et al., njp QI **5**, 45 (2019)
9 D. Zhu et al., Science Advances **5**, 10 (2019)
10 A. Seif et al., J. Phys. B **51** 174006 (2018)
11 Y. Nam et al., Phys. Rev. A **100**, 062319 (2019)

Modular architecture



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

Quantum compiler: Fredkin gate results



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

(corrected for 2% spam error)

NML et al., Phys. Rev. A **98**, 052334 (2018)

…continued

CHSC games – Xingyao Wu (QuiCS)

Validation of Stabilizer States[10] – A. Kalev (QuiCS)

Lee-Yang Zeroes[17] – L. Kemper (NCSU)

Quantum hardware comparison and compiler benchmarking[11] – M. Martonosi (Princeton)

Gate learning – A. Seif and P. Titum (JQI)

Thermofield-double states[12] – T. Hsieh (Perimeter)

Compact VQE/QAOA circuits[13] – O. Shehab (IonQ)

Edge cover (QAOA) – K. Hazzard (Rice)

Dynamical mean field theory algorithm[14] – I. Rungger (NPL) / R. Duncan (CQC)

Discrete-time quantum walks[15] – R. Balu (ARL) and C. M. Chandrashekar (Chennai)

Many-body localization on a Heisenberg model[16] – S. Johri (Intel)

Scattering amplitudes[18] – Y. Meurice (UIowa)

Term ordering – M. Martonosi (Princeton)

Shadow tomography – M. Hafezi (UMD)

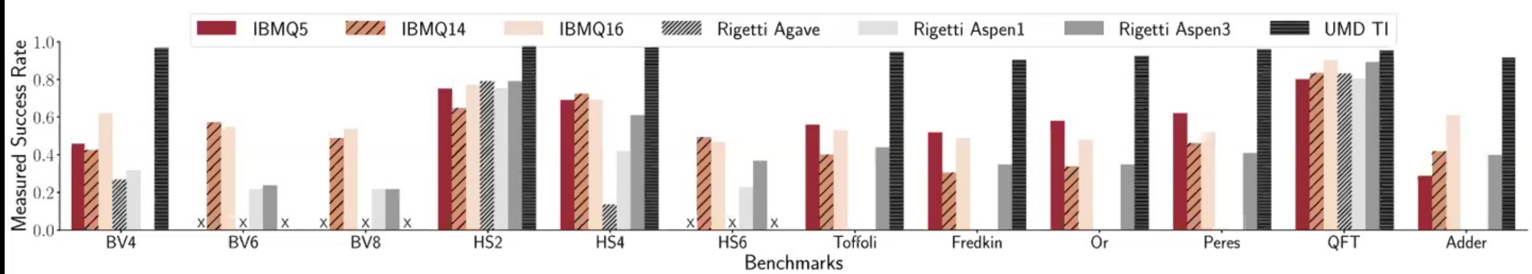
Schwinger model simulation[18] – Z. Davoudi (UMD)

⋮

10 A. Kalev et al., Phys. Rev. A 99 (2019)
11 P. Murali et al., ISCA-2019, 527-540 (2019)
12 D. Zhu et al., PNAS 117 (41) (2020)
13 O. Shehab et al., arXiv:1906.00476
14 I. Rungger et al., arXiv:1910.04735
15 C. Huerta Alderete et al., Nat. Coms. 11 (2020)
16 D. Zhu et al., arXiv:2006.12355
17 A. Francis et al., arXiv:2009.04648
18 manuscript in preparation

Quantum hardware and compiler comparison

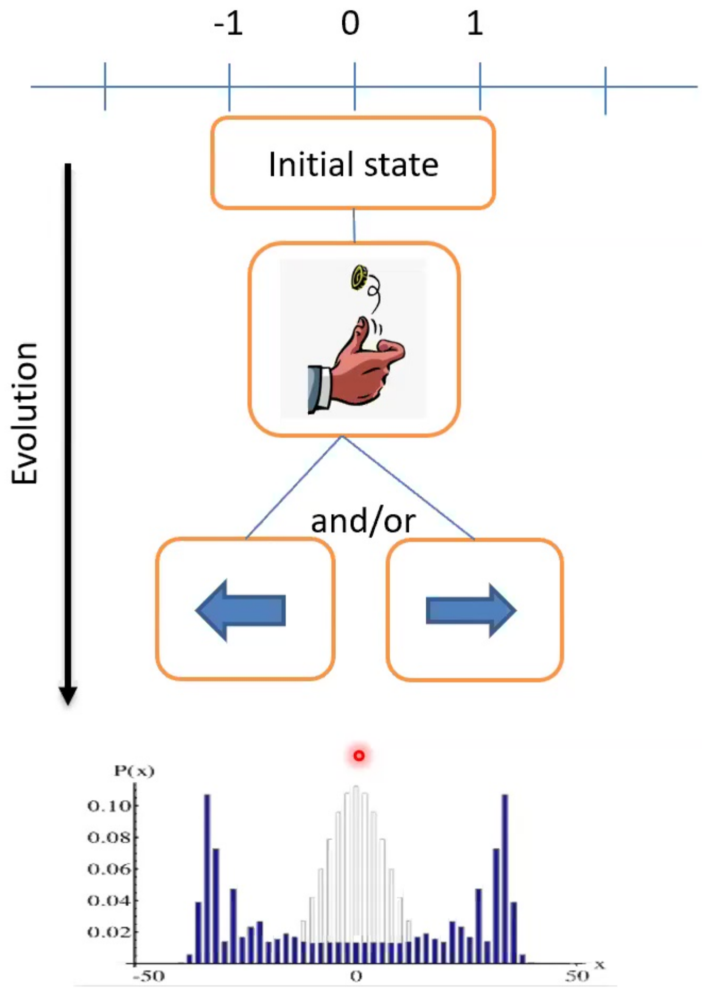
Comparison conducted by M. Martonosi (Princeton)
-> code interface



X = not done (>5 qubits)
no bar = fail

P. Murali et al., IEEE Micro, 40 (3) (2020)

Quantum Walks



see also: H. Schmitz, PRL **103,** 090504 (2009)
F. Zähringer, PRL **104**, 100503 (2010)

Quantum Walks

Initial state

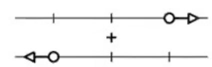
$$|\psi\rangle = |x = 0\rangle \otimes |\,?\,\rangle$$

$$\mathcal{H}_t = \mathcal{H}_p \otimes \mathcal{H}_c$$

Coin operator

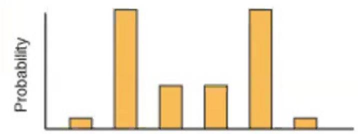
$$\hat{C}_\theta = \begin{bmatrix} \cos(\theta) & -i\sin(\theta) \\ -i\sin(\theta) & \cos(\theta) \end{bmatrix}$$

$$\left(\hat{S} \cdot (\hat{C} \otimes \hat{1}_p)\right)^t |\psi\rangle$$

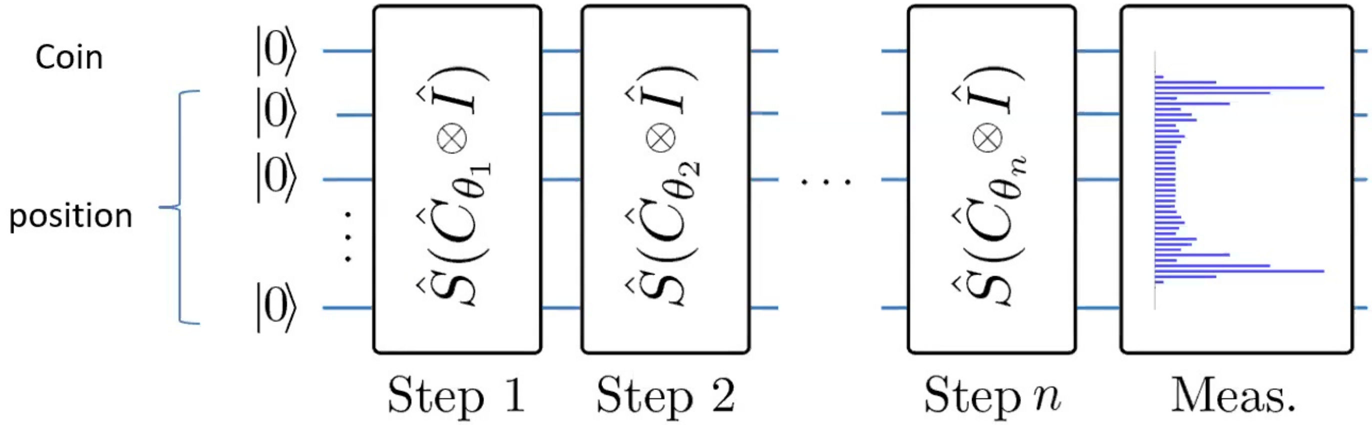


Shift operator

$$\hat{S} = |0\rangle\langle 0| \otimes \sum_{x\in\mathbb{Z}} |x-1\rangle\langle x| + |1\rangle\langle 1| \otimes \sum_{x\in\mathbb{Z}} |x+1\rangle\langle x|$$



Quantum Walks

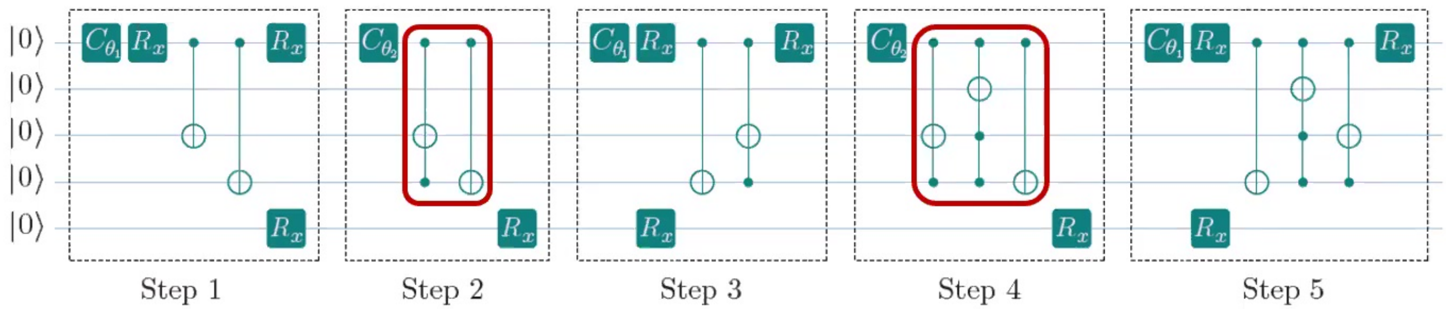


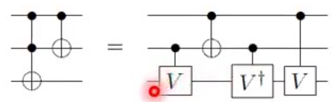
Mapping position space to qubit state

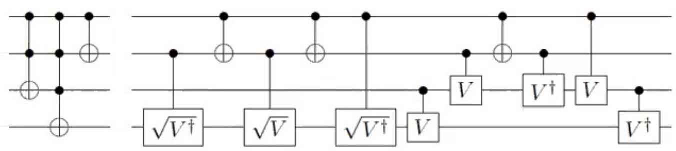
-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
1001	1010	1011	0100	0101	0110	0111	0000	0001	0010	0011	1100	1101	1110	1111

Quantum Walks

Circuits

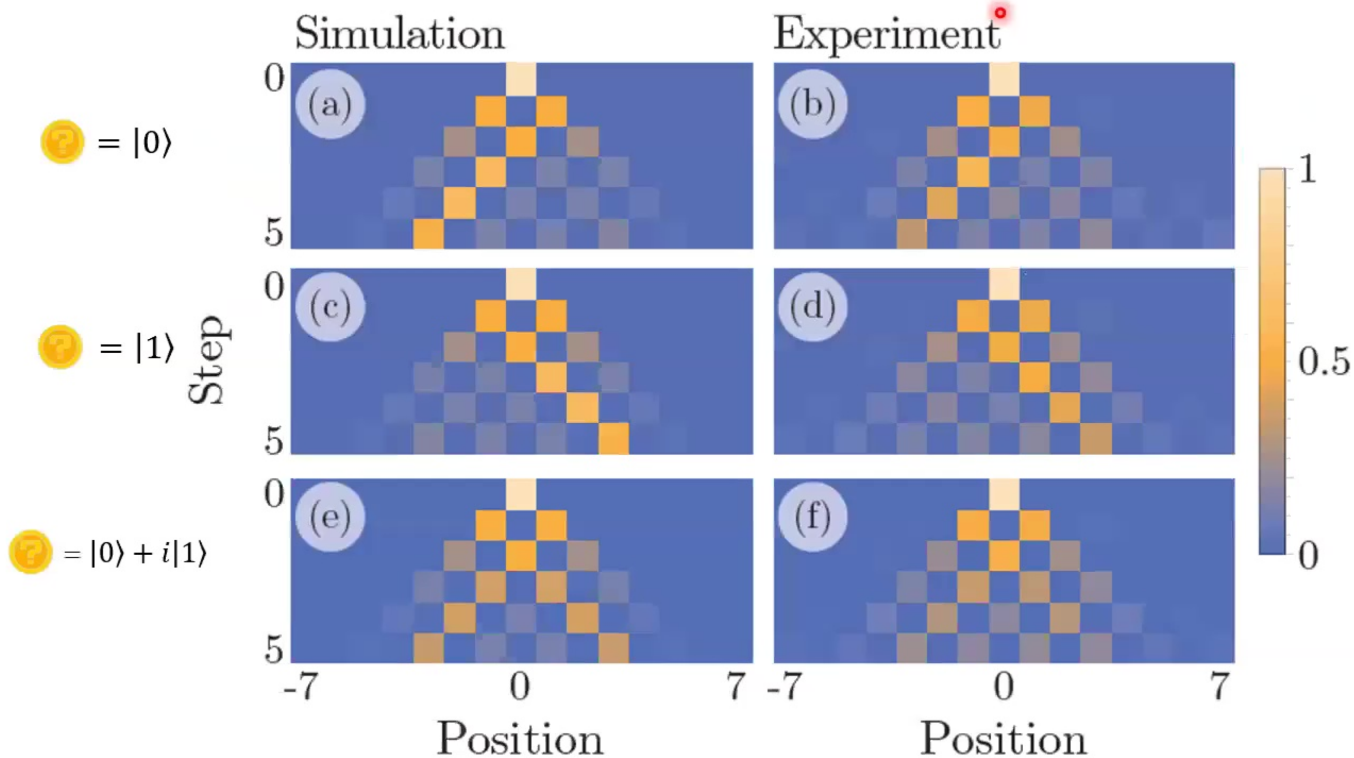






Quantum Walks

$|\psi\rangle = |x=0\rangle \otimes |$ 🪙 $\rangle$



C. Huerta Alderete, Nature Communications 11, 3720 (2020)

Quantum Walks and Dirac cellular automaton

$$\hat{W}_{ss} = \hat{S}_+(\hat{C}(\theta_2) \otimes I)\hat{S}_-(\hat{C}(\theta_1) \otimes I)$$

$$\hat{S}_- = |0\rangle\langle 0| \otimes \sum_{i\in\mathbb{Z}} |i-1\rangle\langle i| + |1\rangle\langle 1| \otimes \sum_{i\in\mathbb{Z}} |i\rangle\langle i| \qquad \text{(Left)}$$

$$\hat{S}_+ = |0\rangle\langle 0| \otimes \sum_{i\in\mathbb{Z}} |i\rangle\langle i| + |1\rangle\langle 1| \otimes \sum_{i\in\mathbb{Z}} |i+1\rangle\langle i| \qquad \text{(Right)}$$

$$\frac{\partial}{\partial t}\begin{bmatrix}\psi^0_{x,t}\\ \psi^1_{x,t}\end{bmatrix} = \cos(\theta_2)\begin{bmatrix}\cos(\theta_1) & -i\sin(\theta_1)\\ i\sin(\theta_1) & -\cos(\theta_1)\end{bmatrix}\begin{bmatrix}\frac{\partial\psi^0_{x,t}}{\partial x}\\ \frac{\partial\psi^1_{x,t}}{\partial x}\end{bmatrix} + \begin{bmatrix}\cos(\theta_1+\theta_2)-1 & -i\sin(\theta_1+\theta_2)\\ -i\sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2)-1\end{bmatrix}\begin{bmatrix}\psi^0_{x,t}\\ \psi^1_{x,t}\end{bmatrix}$$

details: N. P. Kumar et al., Phys. Rev. A 97, 012116 (2018)

Quantum Walks and Dirac cellular automaton

$$\hat{W}_{ss} = \hat{S}_+(\hat{C}(\theta_2) \otimes I)\hat{S}_-(\hat{C}(\theta_1) \otimes I)$$

$$\hat{S}_- = |0\rangle\langle 0| \otimes \sum_{i\in\mathbb{Z}} |i-1\rangle\langle i| + |1\rangle\langle 1| \otimes \sum_{i\in\mathbb{Z}} |i\rangle\langle i|$$ (Left)

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(Left) → $\psi^0_{x,t}$, (Right) → $\psi^1_{x,t}$

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If $\cos(\theta_1+\theta_2) = 1$

$$i\hbar\left[\partial_t - \cos\theta_2\left(\cos\theta_1\sigma_z - i\sin\theta_1\sigma_x\right)\partial_x\right]\Psi(x,t) = 0$$

Massless Dirac Eq.

details: N. P. Kumar et al., Phys. Rev. A 97, 012116 (2018)

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If $\cos(\theta_1+\theta_2) = 1$ $\quad i\hbar\left[\partial_t - \cos\theta_2\left(\cos\theta_1\sigma_z - i\sin\theta_1\sigma_x\right)\partial_x\right]\Psi(x,t) = 0$ Massless Dirac Eq.

If $\theta_1 = 0$ and very small θ_2 $\quad i\hbar\left[\partial_t\ (1-\theta_2^2/2)\sigma_z\partial_x + i\theta_2\sigma_x\right]\Psi(x,t) \approx 0$ Massive Dirac Eq.

details: N. P. Kumar et al., Phys. Rev. A 97, 012116 (2018)

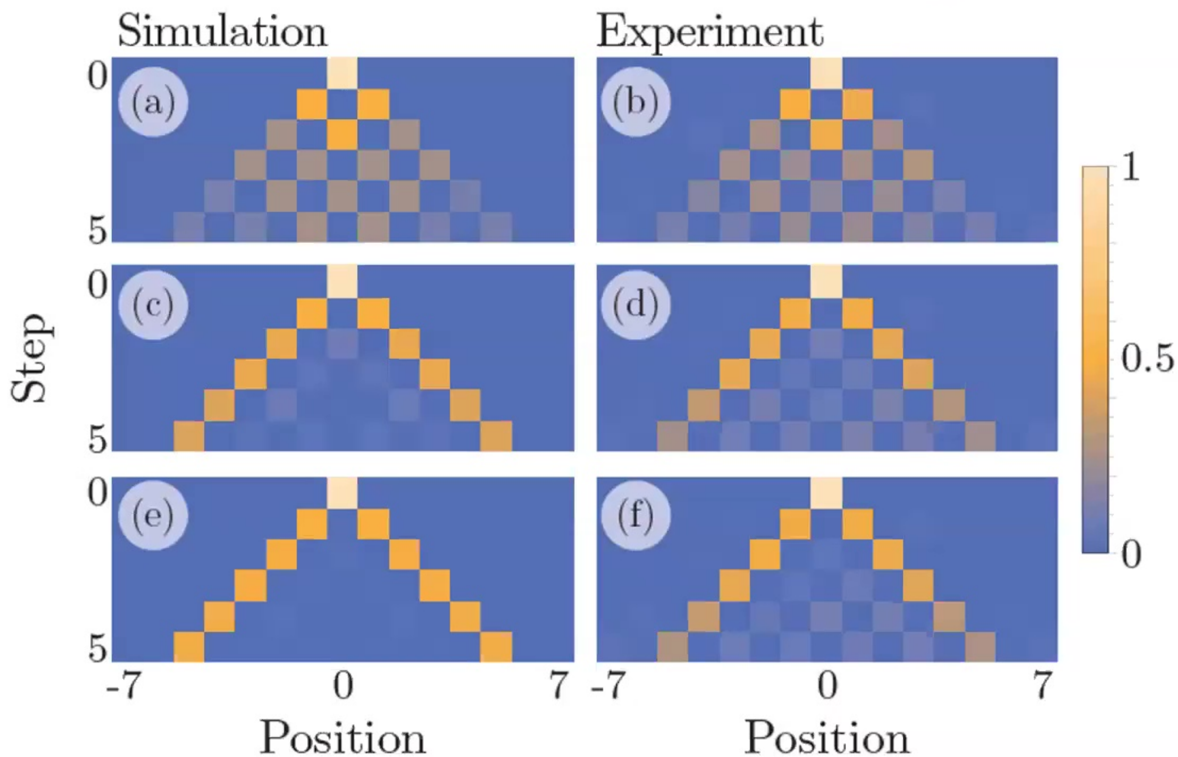
Quantum Walks and the Dirac equation

$|\psi\rangle = |x = 0\rangle \otimes (|0\rangle + i|1\rangle)$

$\theta_1 = 0, \theta_2 = \pi/4$

$\theta_1 = 0, \theta_2 = \pi/10$

$\theta_1 = 0, \theta_2 = \pi/20$

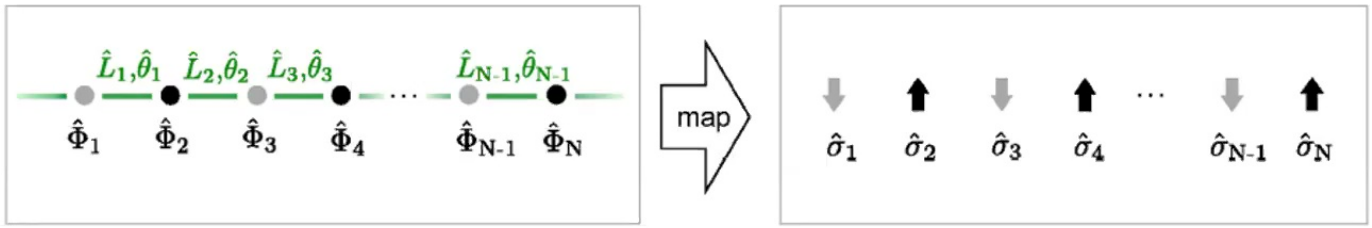


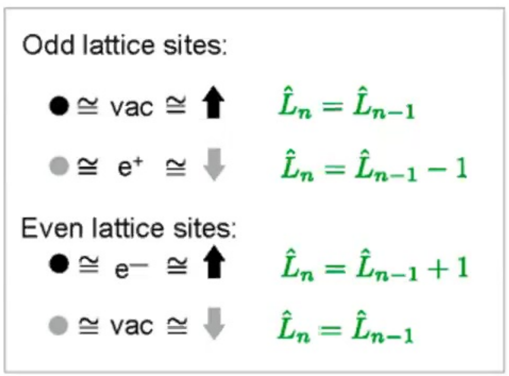
C. Huerta Alderete, Nature Communications 11, 3720 (2020)

Schwinger model – digital simulation

Lattice Schwinger model (spinless 1+1D QFT, discretized space, normalize)

$$\hat{H}_{\mathrm{lat}} = -\mathrm{i}w \sum_{n=1}^{N-1} [\hat{\Phi}_n^{\dagger} e^{\mathrm{i}\hat{\theta}_n} \hat{\Phi}_{n+1} - \mathrm{H.C.}] + m \sum_{n=1}^{N} (-1)^n \hat{\Phi}_n^{\dagger} \hat{\Phi}_n + J \sum_{n=1}^{N-1} \hat{L}_n^2,$$





C. Muschik et al 2017 New J. Phys. 19 103020 (2018)

Schwinger model – digital simulation

-> spin/qubit basis (Jordan-Wigner transformation) $\hat{\Phi}_n = \prod_{l<n} [\mathrm{i}\hat{\sigma}_l^z]\hat{\sigma}_n^-$

Invariance to local gauge, make choice: $\hat{\sigma}_n^- \rightarrow \left[\prod_{l<n} \mathrm{e}^{-\mathrm{i}\hat{\theta}_l}\right]\hat{\sigma}_n^-$

$$\hat{H}'_{\mathrm{lat}} = w\sum_{n=1}^{N-1}[\hat{\sigma}_n^+\hat{\sigma}_{n+1}^- + \mathrm{H.C.}] + \frac{m}{2}\sum_{n=1}^{N}(-1)^n\hat{\sigma}_n^z + J\sum_{n=1}^{N-1}\hat{L}_n^2$$

Gauss' law requires for photon link:

$$\hat{L}_n = \epsilon_0 + \tfrac{1}{2}\textstyle\sum_{l=1}^{n}(\hat{\sigma}_l^z + (-1)^l)$$

-> number of spin-up qubits conserved

C. J. Hamer et al. Phys. Rev. D 56 (1997)

Schwinger model – digital simulation

Final qubit Hamiltonian

$$\hat{H}_s = \frac{\mu}{2}\sum_{n=1}^{N}(-1)^n\sigma_n^z + x\sum_{n=1}^{N-1}\{\sigma_n^+\sigma_{n+1}^- + \text{h.c.}\} + \frac{1}{4}\sum_{n=1}^{N-1}\left\{\sum_{m=1}^{n}\left[\sigma_m^z + (-1)^m\right]\right\}^2$$

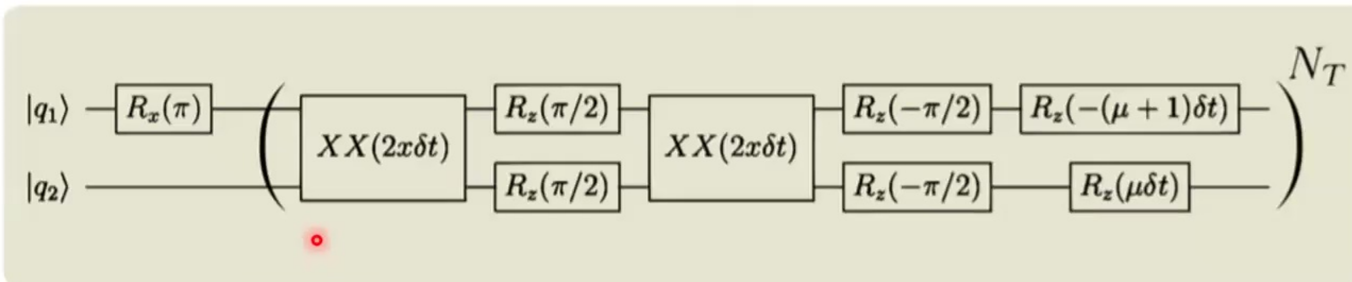
Fermion mass, hopping on lattice, E-field interaction

Trotterize, choose parameters

$$x = 0.6, \quad \mu = 0.1, \quad \delta t = 0.5, \quad N_t = 20.$$

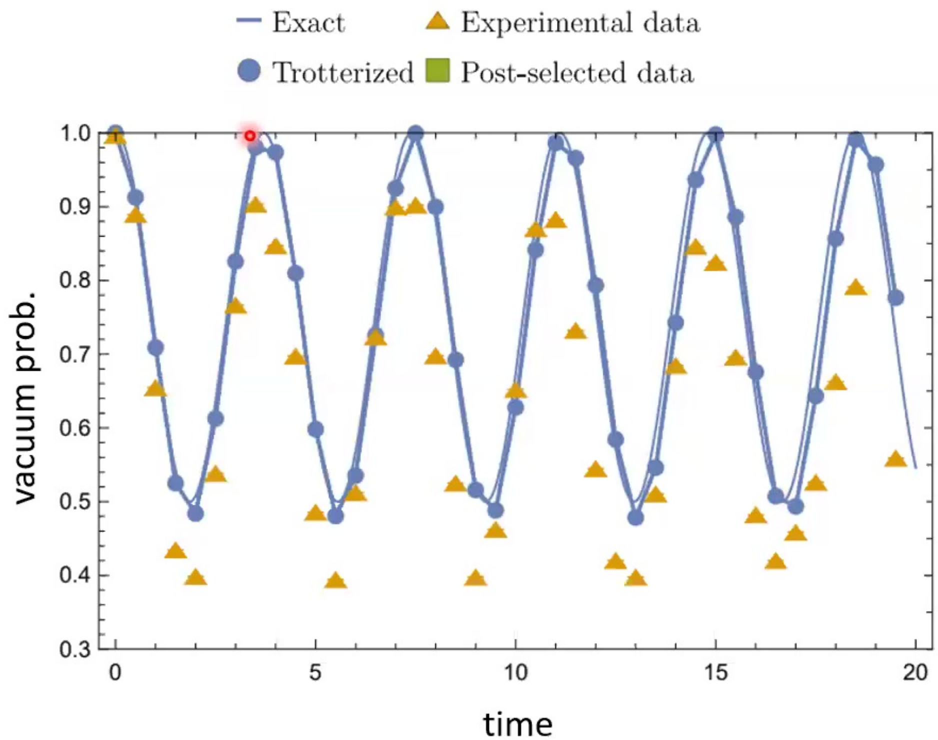
Schwinger model – digital simulation

1-site model circuit (for each time step)



Schwinger model – digital simulation

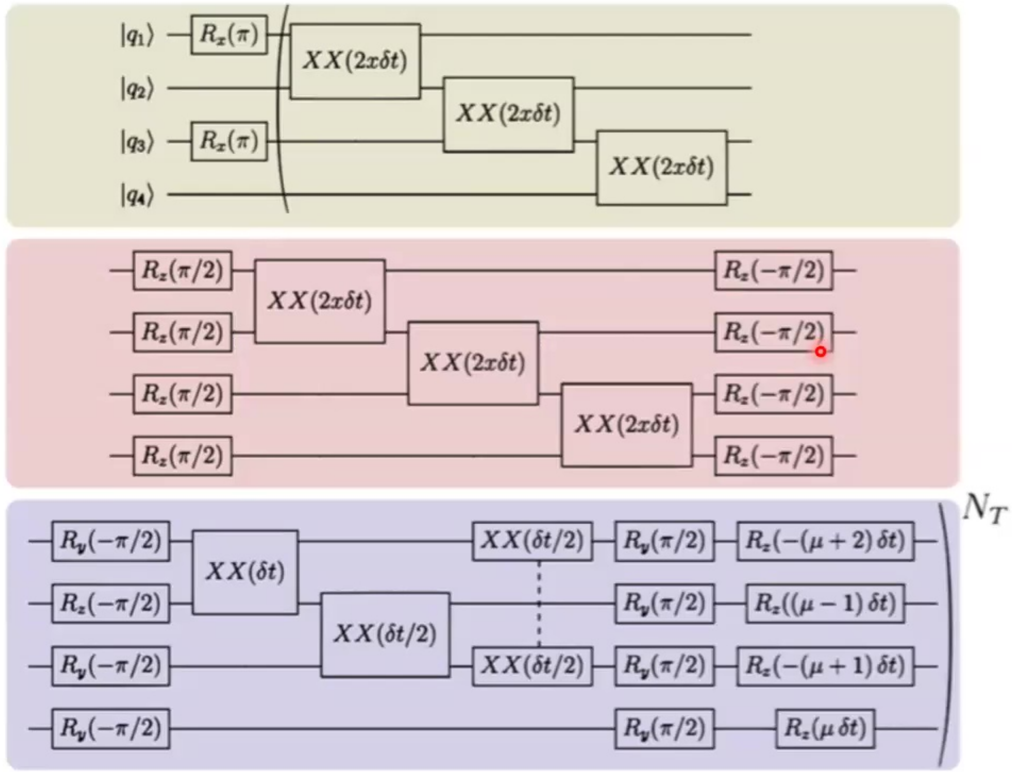
results



See also Innsbruck group: E. Martinez, Nature 516, 534 (2016)

Schwinger model – digital simulation

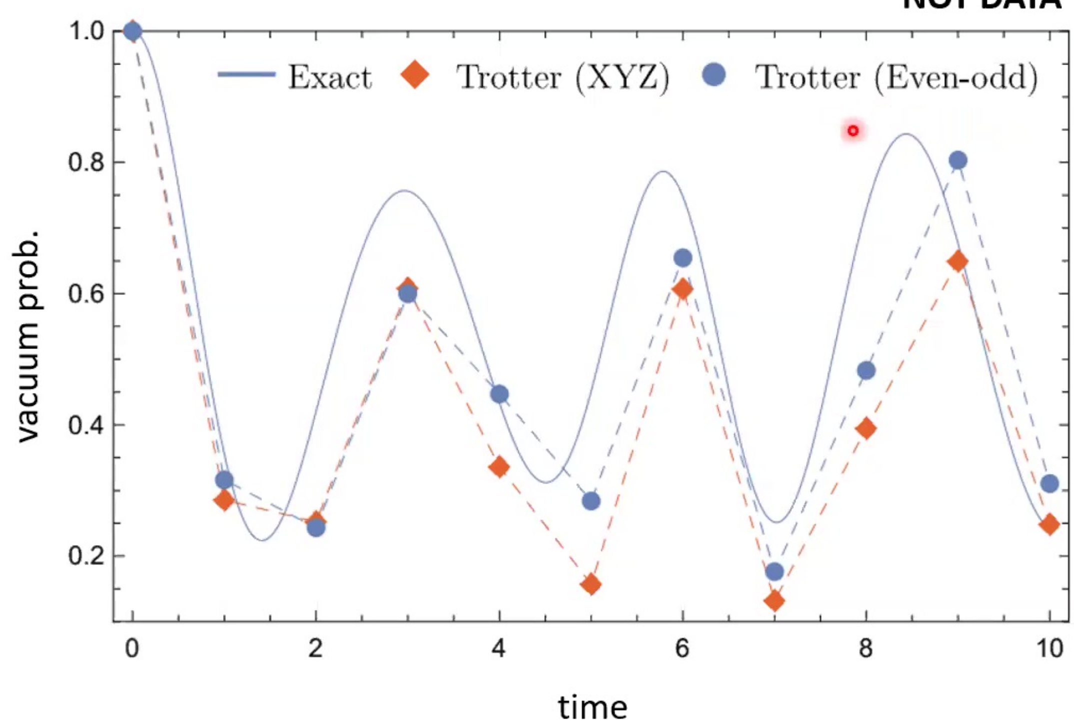
2-site model circuit



Schwinger model – digital simulation

Different term ordering choices

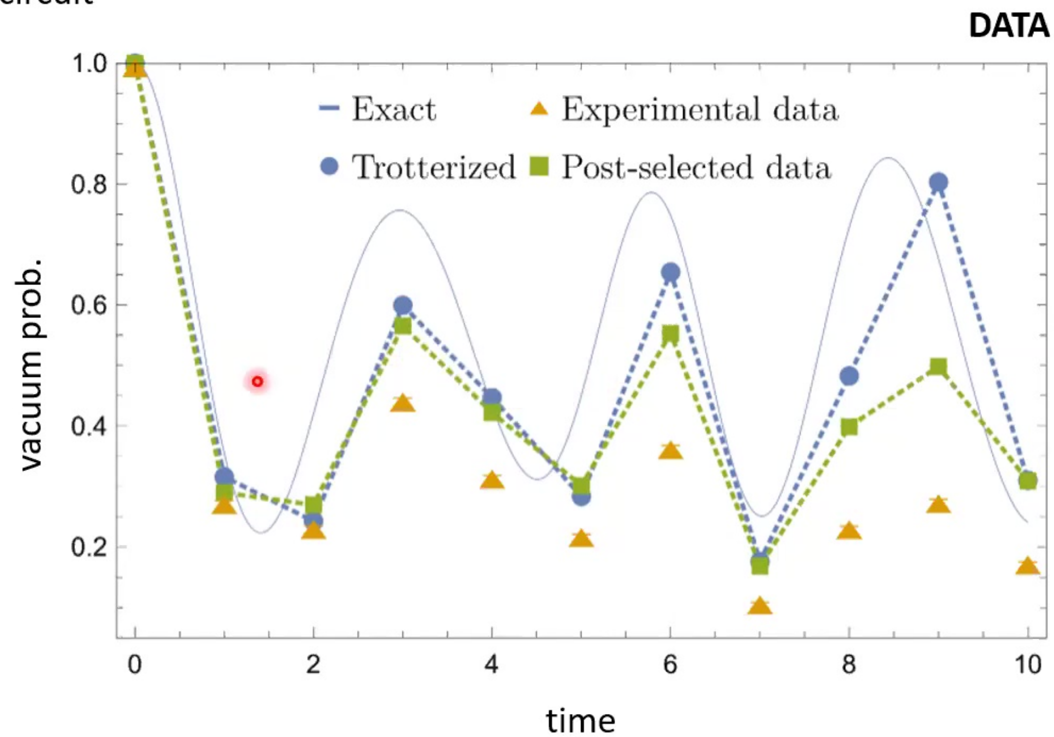
NOT DATA



A. Childs et al., Phys. Rev. Lett. 123, 050503 (2019)

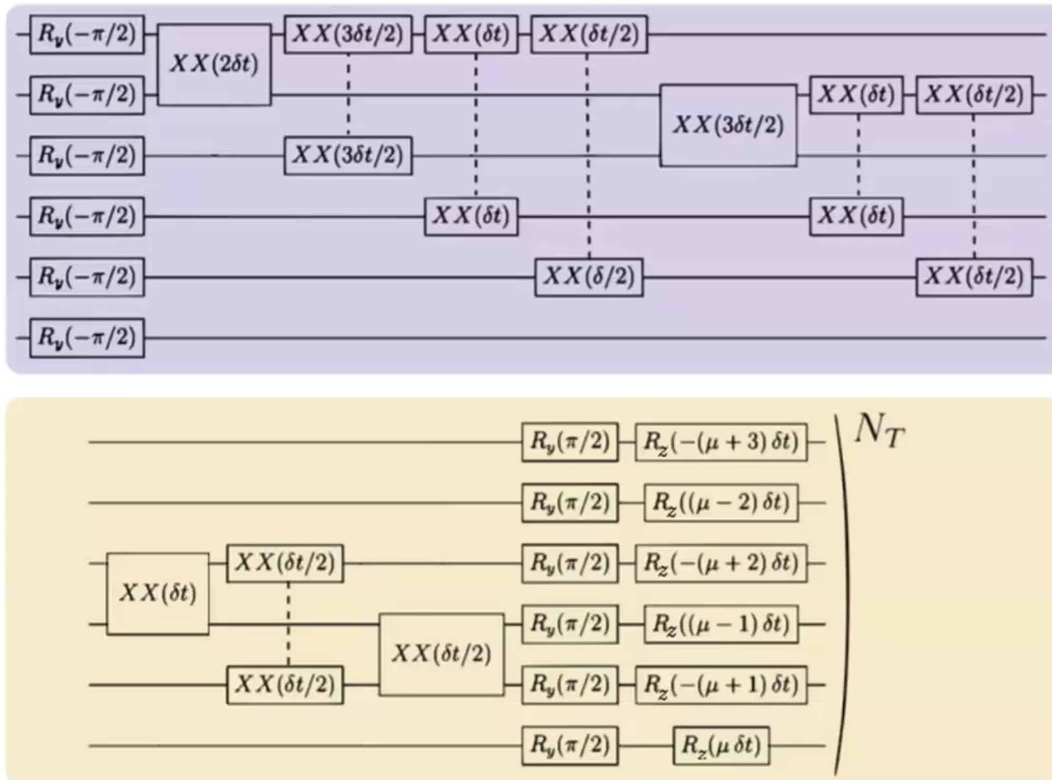
Schwinger model – digital simulation

2-site model circuit



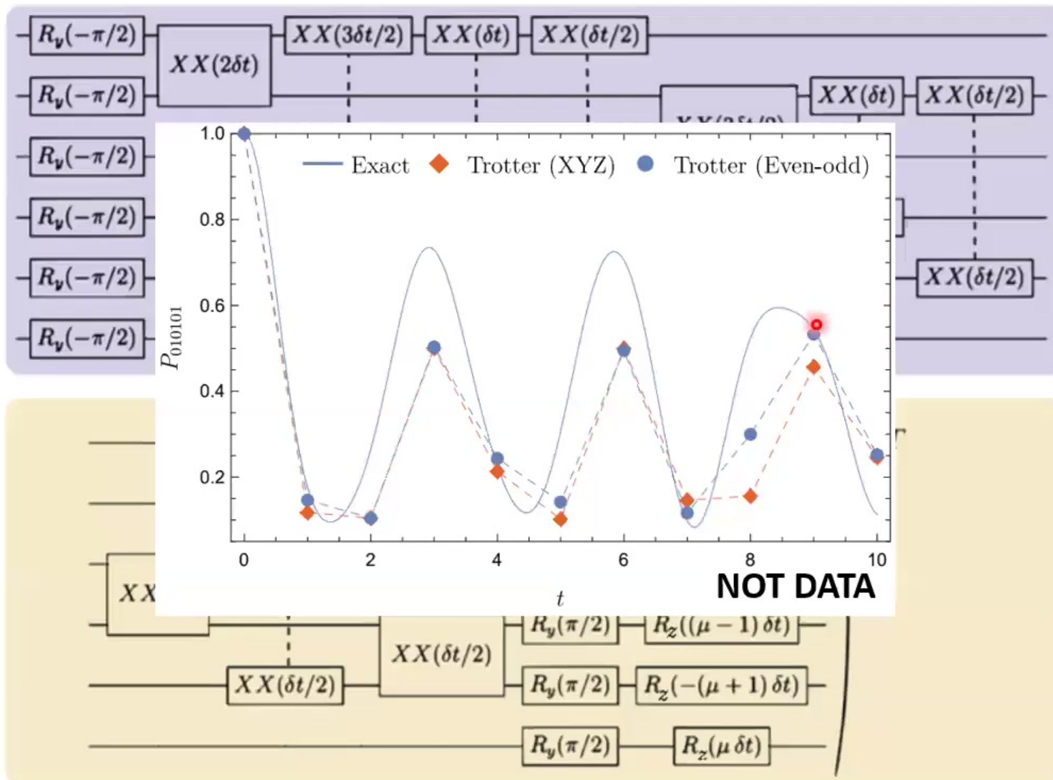
Schwinger model – digital simulation

…continued



Schwinger model – digital simulation

...continued



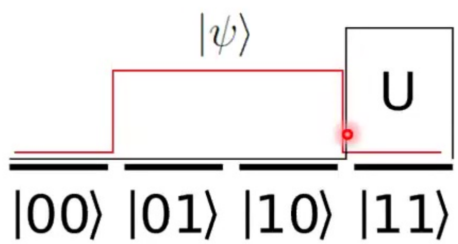
Scattering in a quantum Ising model

Ising Hamiltonian
$$\hat{H} = -J\sum_{i=1}^{N}\hat{\sigma}_i^x\hat{\sigma}_{i+1}^x - h_T\sum_{i=1}^{N}\sigma_i^z$$

4-site single particle
$$\hat{H} = h_t + J\sigma_1^x + \frac{J}{2}\left(\sigma_1^x\sigma_2^x - \sigma_1^y\sigma_2^y\right)$$

potential barrier
$$\hat{V} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & U \end{pmatrix}$$

mapping to 2 qubits

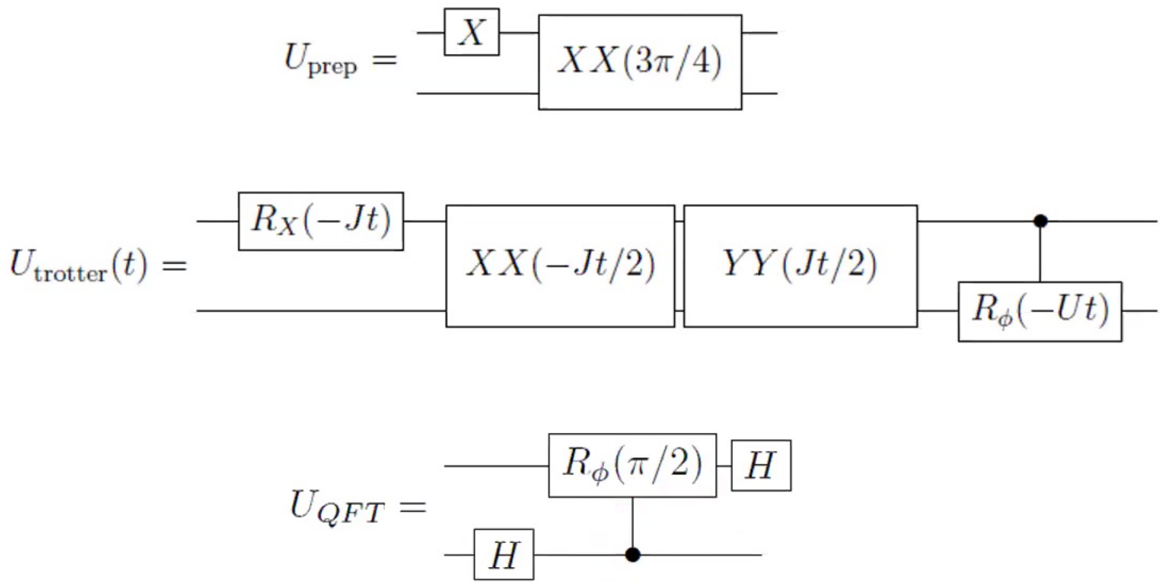


initial state
$$|\psi\rangle = \frac{-1}{\sqrt{2}}\left(|01\rangle + i|10\rangle\right)$$

Goal: measure phase shift of scattered wavefunction

Scattering in a quantum Ising model

Real time scattering



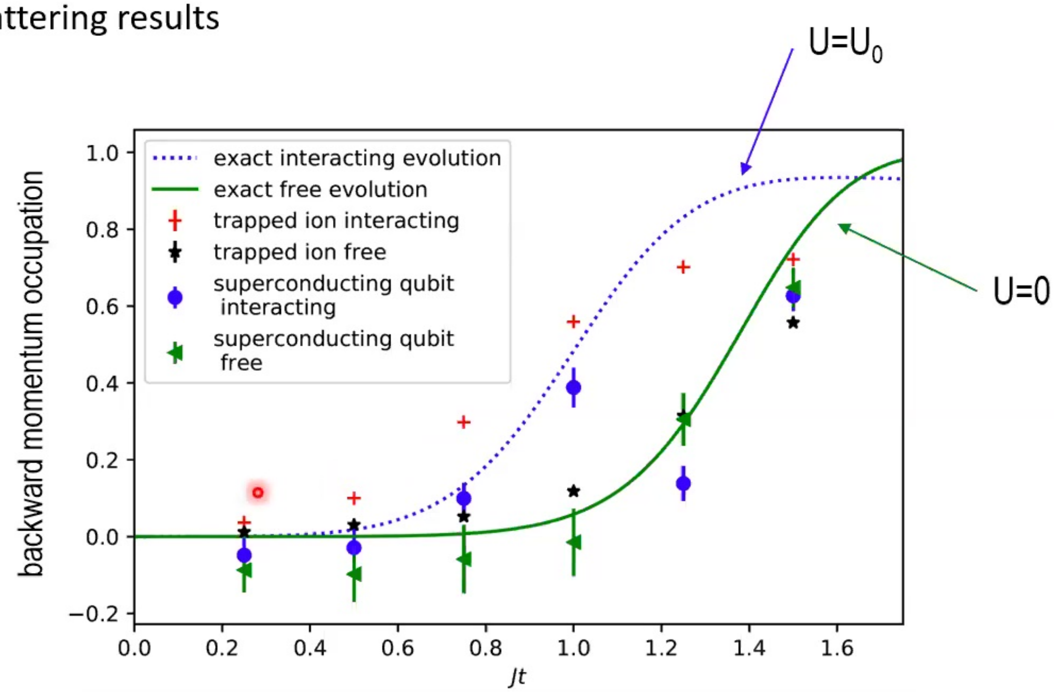
Measure momentum population

$|10\rangle$ forward

$|11\rangle$ backward

Scattering in a quantum Ising model

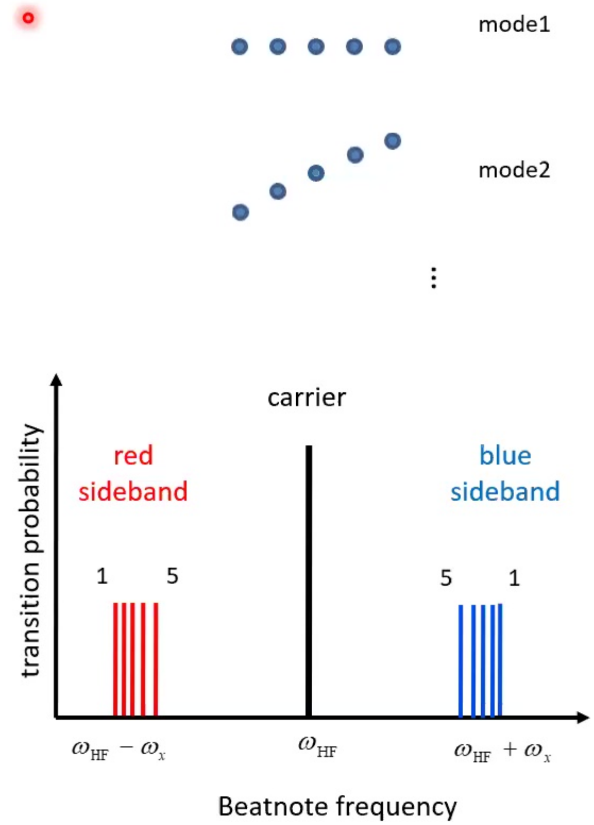
Real time scattering results



parameters: h_T=1, J=0.02, U_0=0.03

E. Gustafson, Y. Zhu et al. in prep.

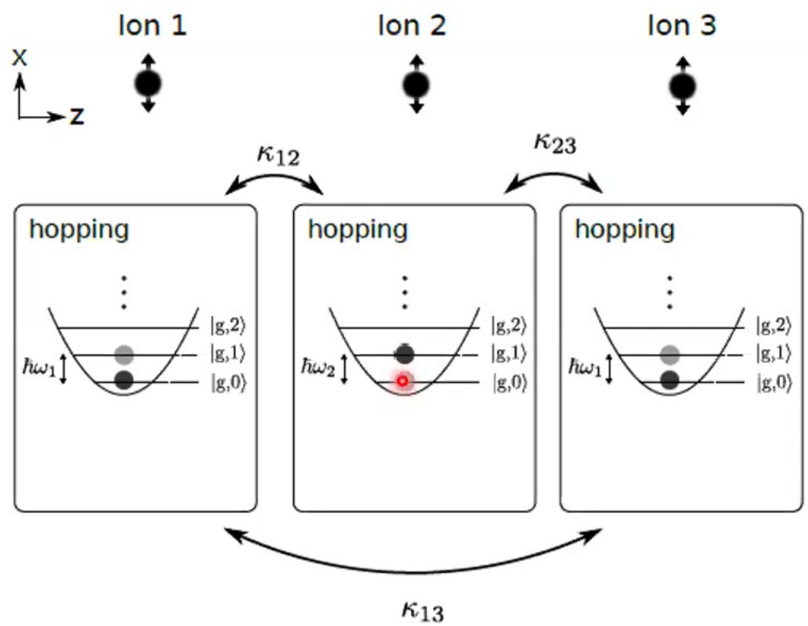
Exciting the motion: Normal mode picture



Exciting the motion: Local mode picture

Single phonons –> coupled quantum harmonic oscillators -> hopping!

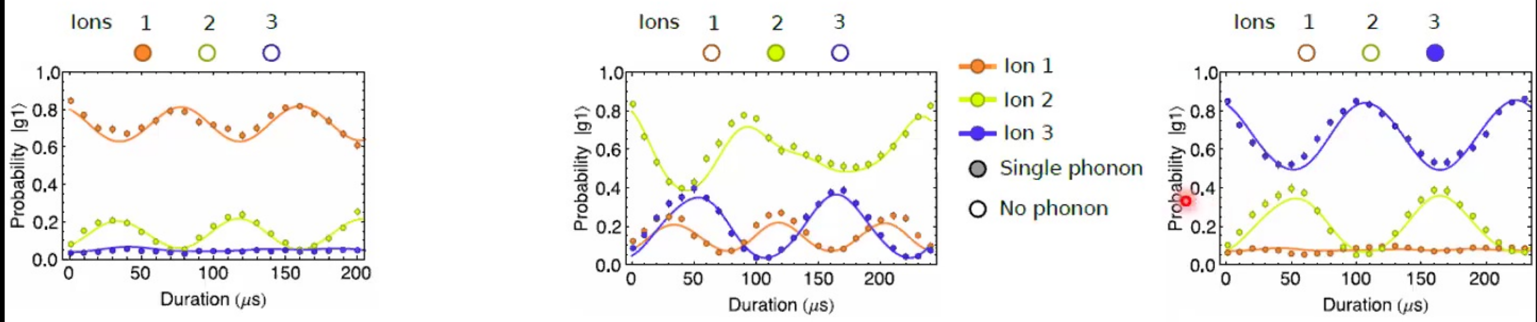
Phonon hopping



$$H_p = \sum_j (\omega_x + \omega_j) a_j^\dagger a_j + \sum_{j<k} \kappa_{jk} (a_j^\dagger a_k + a_j a_k^\dagger)$$

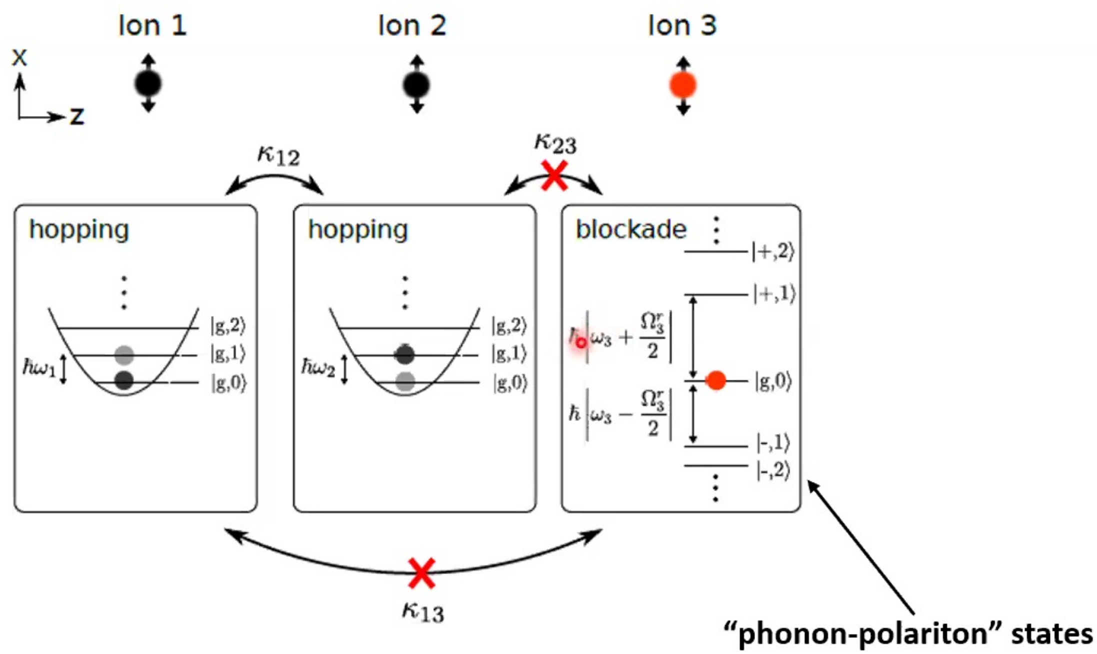
$$\kappa_{jk} = e^2/(2M\omega_x d_{jk}^3)$$

Results: Phonon hopping



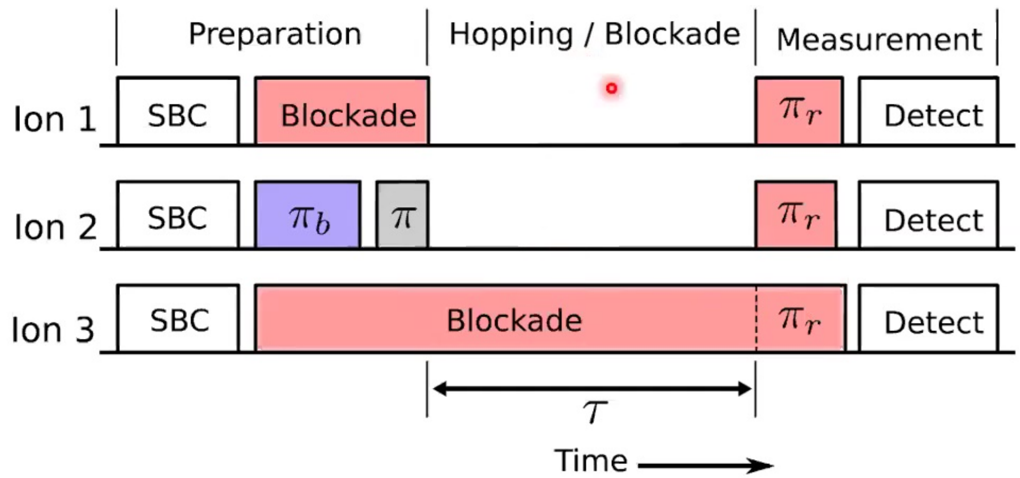
S. Debnath, et al. PRL 120 (2018)

Phonon blockade

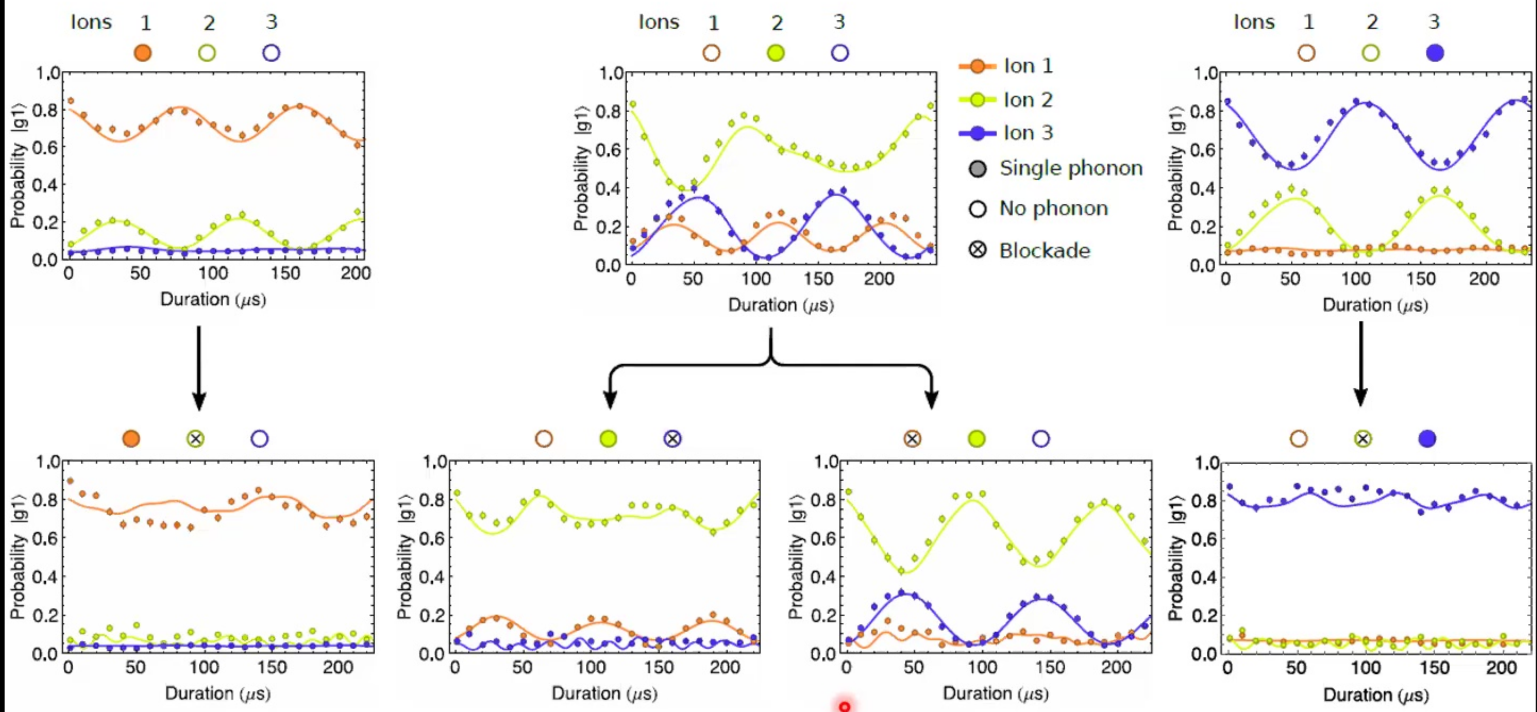


$$H_b = \sum_j \Delta_j |e\rangle_j \langle e|_j + \sum_j \frac{\Omega_j^r}{2}(\sigma_j^+ a_j + \sigma_j^- a_j^\dagger)$$

Phonon blockade



Results: phonon blockade



S. Debnath, et al. PRL 120 (2018)

Scaling up

no system will be fully connected for large N

the compilation challenge

D. Kielpinski et al., Nature **417** (2002)

C. Monroe et al., Phys. Rev. A **89** (2014)

A. Bermudez et al., Phys. Rev. X **7** (2017)

D. Hucul, et al., Nature Phys. **11** (2015)

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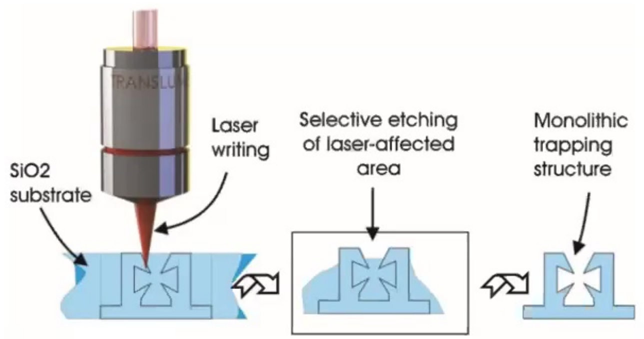
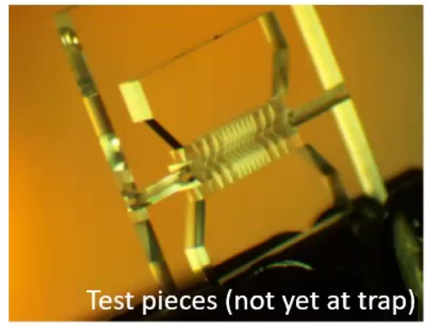
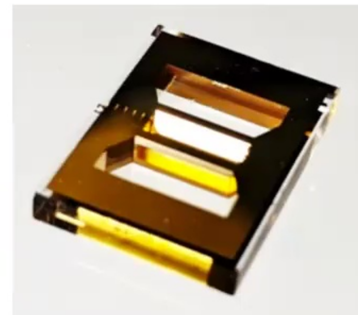
D. Hucul, et al., Nature Phys. **11** (2015)

Outlook 1: a new trap platform

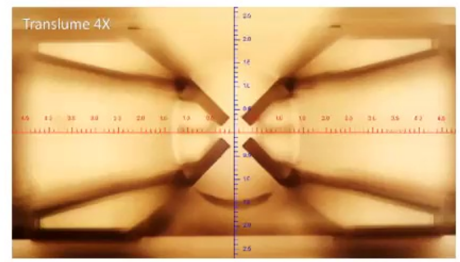
Monolithic 3D trap made of Fused Silica by Translume Inc. ("perfect engineering")

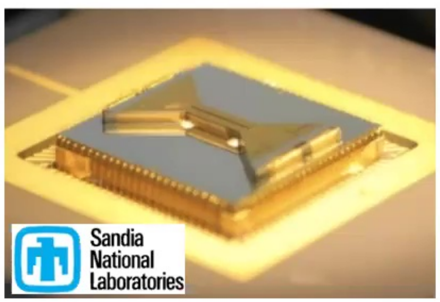






collaboration with G. Pagano (Rice)



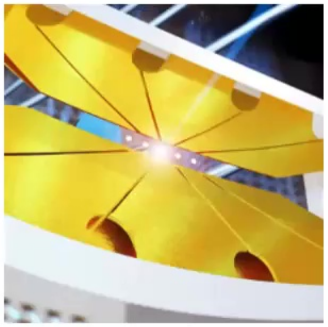


2D surface traps:
C. Monroe group, PTB, Honeywell, NIST and others

A direct-transmission networking node

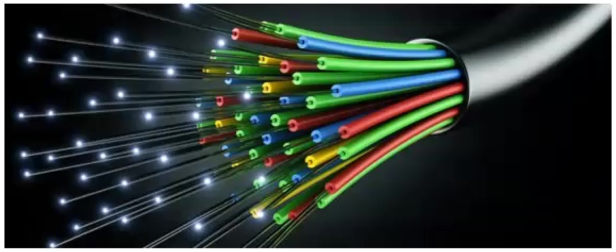
good memories / processor nodes

ions
neutral atoms
NV centers
quantum dots



good flyers with fiber infrastructure

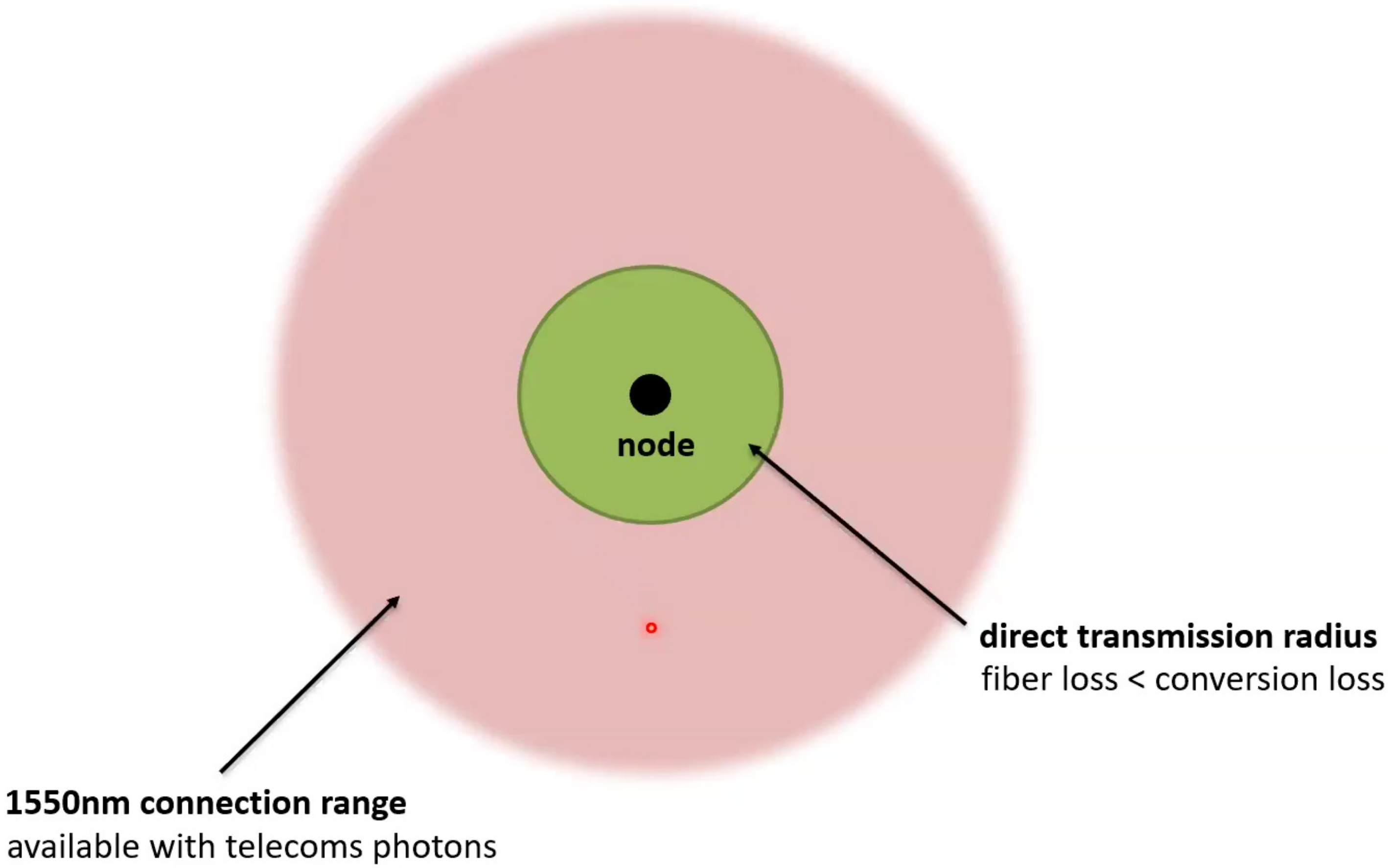
photons



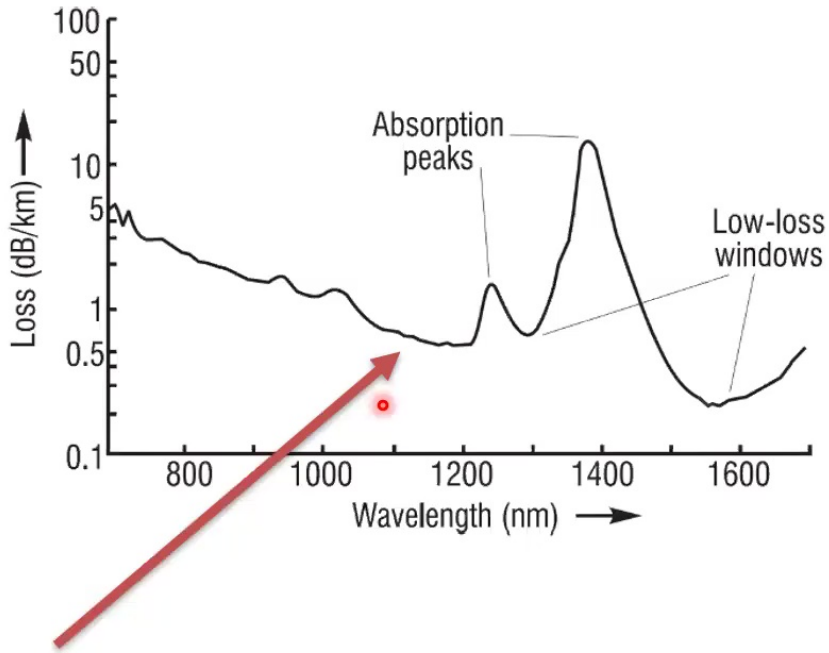
UV / visible → telecoms 1550nm

frequency conversion (?)

A direct-transmission networking node

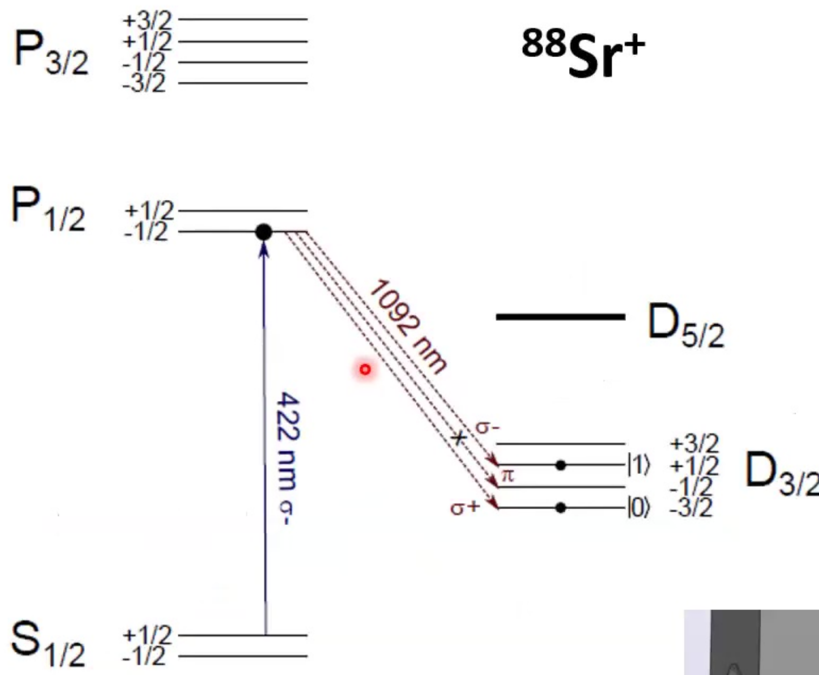


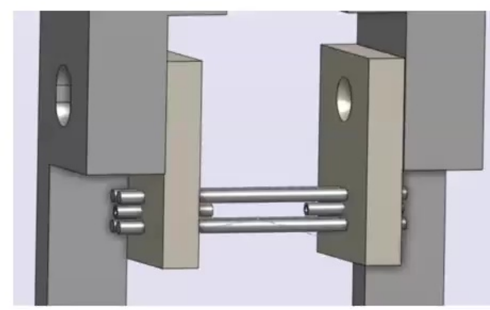
A direct-transmission networking node



smallest-wavelength minimum (Telecom O-band)

A direct-transmission networking node





Chris Monroe
(->Duke)

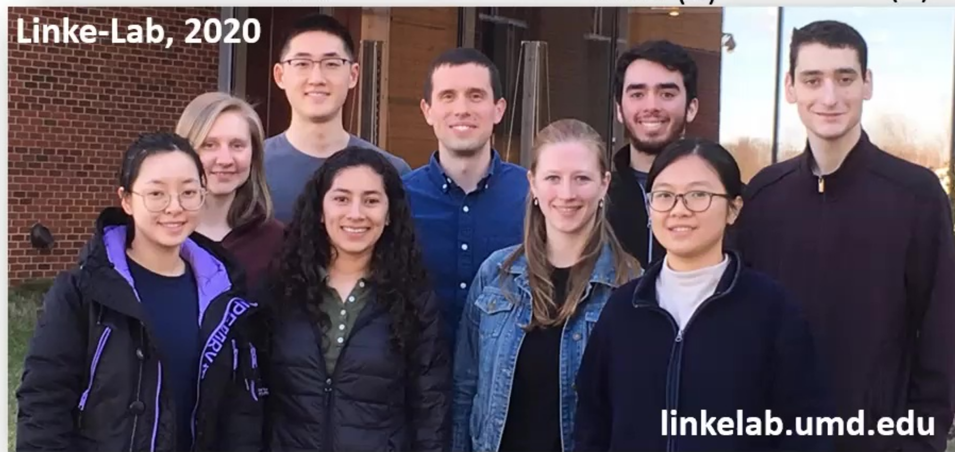
DEPARTMENT OF
PHYSICS

Convergence
Accelerator

ARL

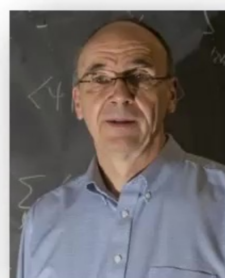
PHYSICS
FRONTIER
CENTER
JOINT QUANTUM INSTITUTE

Denton Wu | NML | Raphael J. Metz (u) | Noah J. Cubert (u)



Yingyue Zhu | Alaina Green | **Cinthia H. Alderete** | Mika A. Chmielewski | Nhung H. Nguyen

Zohreh Davoudi
(UMD)



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Guido Pagano
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