Title: Towards large-scale quantum simulations with trapped ions - Rajibul Islam

Speakers: Kazi-Rajibul Islam

Collection/Series: Waterloo-Munich Joint Workshop

Subject: Quantum Information

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Towards large-scale quantum simulations with trapped ions

Waterloo-Munich Joint Workshop
Perimeter Institute, Waterloo
30 Sep 2024

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Quantum Information with Trapped Ions (QITI)

qiti.iqc.uwaterloo.ca

$$ University of Waterloo, NSERC, NFRF, CFREF, Ontario Early Researcher Award, US ARO

Outline

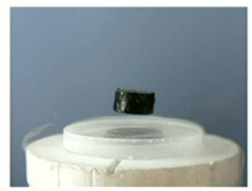
- A quick overview/refresher on trapped ion quantum simulations
- Our efforts to develop programmable and large-scale trapped-ion quantum simulators
  - Increase qubit count
  - Expand *Native* qubit interactions toolset
  - Develop high-precision coherent and incoherent control over individual ions
  - Robust and modular systems engineering
- Beyond the lab – developing open-source, full-stack quantum processors (Open Quantum Design)

Quantum Simulation

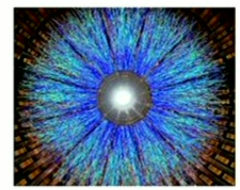
- Simulating quantum many-body system is hard, especially quantum dynamics where the quantum state has `a lot of' entanglement!
- Exponential growth of Hilbert space, 2^N for N qubits/spin-1/2 objects
- "Can Physics be simulated by a universal computer?" (Feynman, 1982)
  - "Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."

➡ Universal quantum simulator

Microscopic description?



High Temperature superconductor

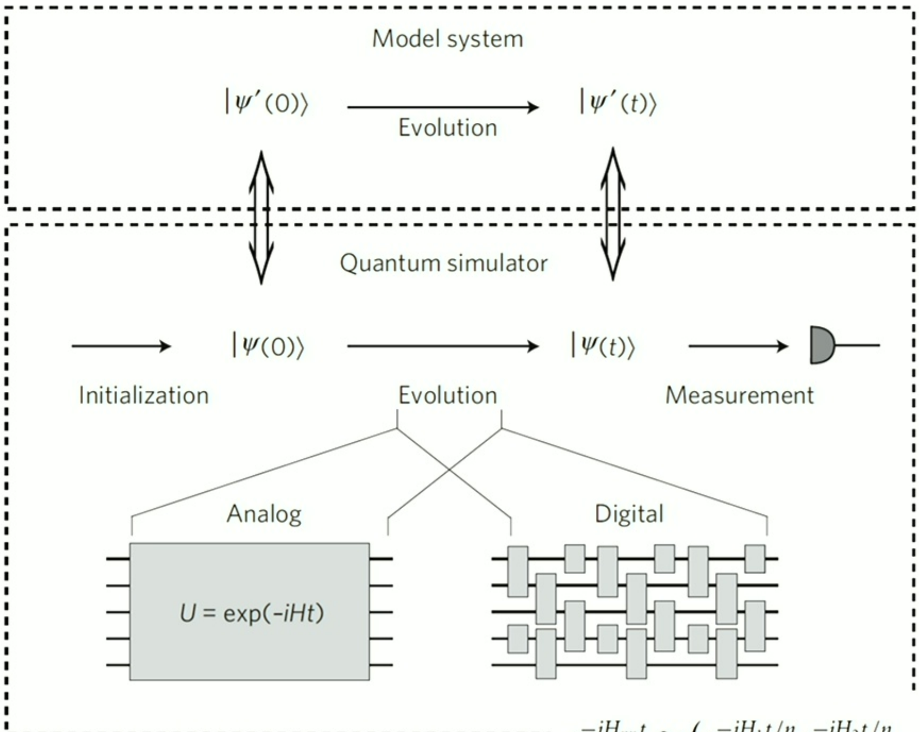


Quark Gluon 'plasma'

Potential use of quantum simulators

- Understanding/optimizing chemical reactions - Nitrogen fixation
- Phase diagram of many-body Hamiltonians
- Understanding QCD dynamics - high energy physics problems
- Predicting new materials, battery …

Analog and Digital Quantum Simulation

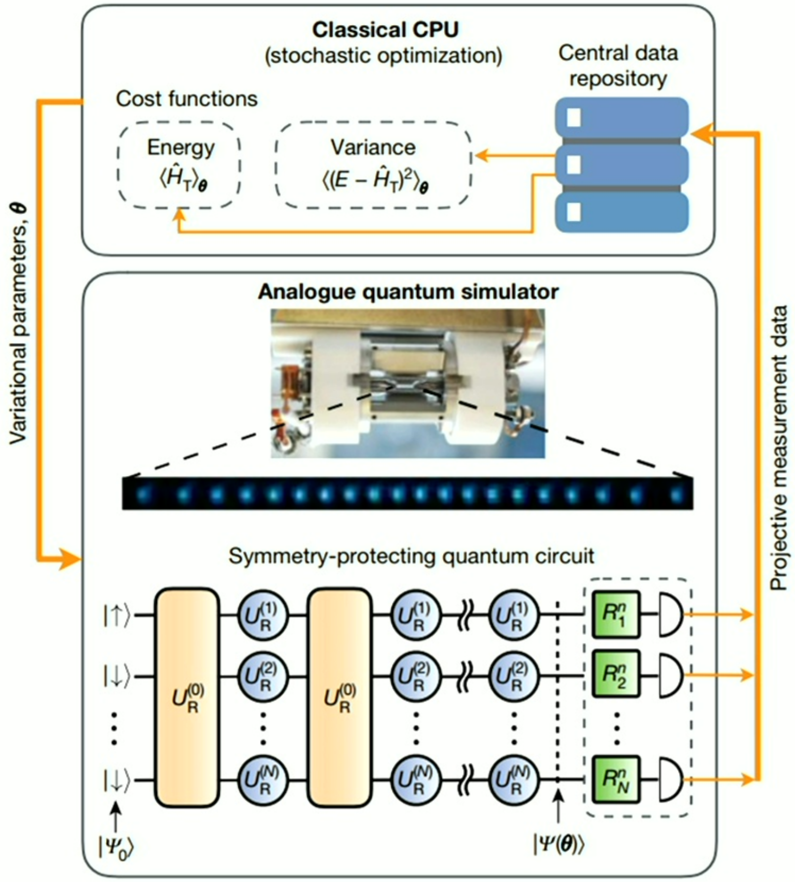


$$e^{-iH_{sys}t} \approx \left(e^{-iH_1 t/n} e^{-iH_2 t/n} \ldots e^{-iH_l t/n}\right)^n$$

Monroe et al, Rev Mod Phys (2021)

Blatt, R and Roos, C. F.,
Nature Physics **8**, 277 (2012)

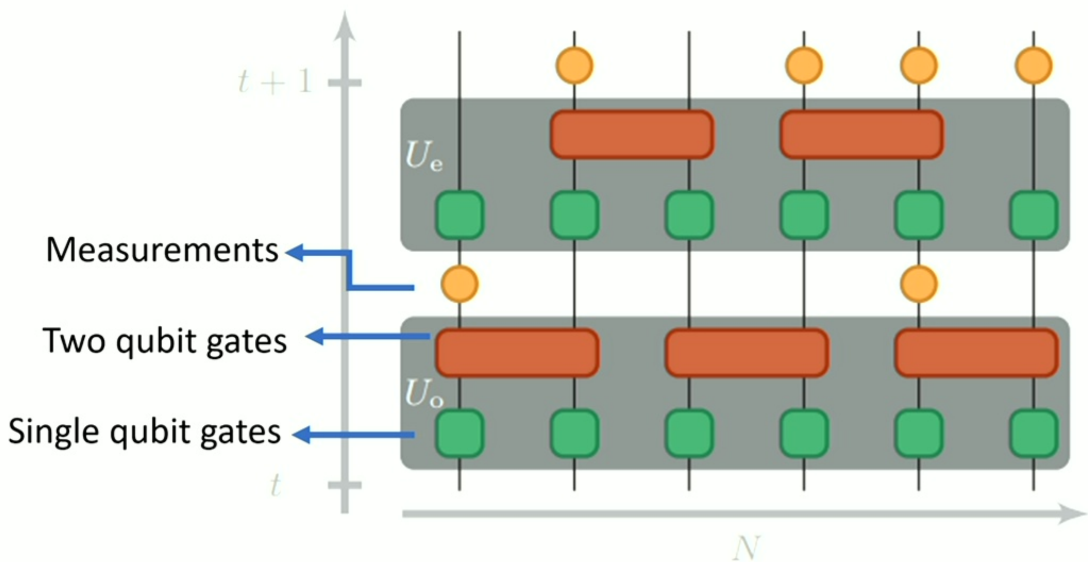
Hybrid classical-quantum simulation/computation



Hybrid computation suitable for solving problems in high-energy physics (quantum chromodynamics simulations etc.)

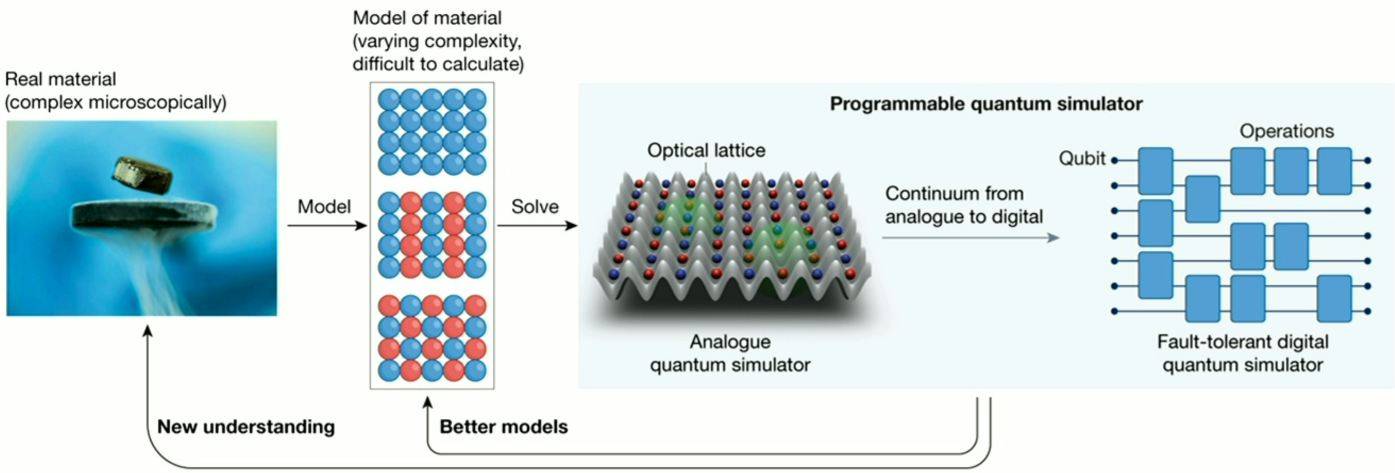
From Kokail at al. Nature 569, 355 (2019)

Quantum simulations with coherent evolution and 'mid-circuit' measurements



e.g.,
Simulating a measurement-induced phase transition for trapped-ion circuits
Stefanie Czischek et. al PRA 104, 062405 (2021)

Also check:
Measurement-induced quantum phases realized in a trapped-ion quantum computer.
Noel, C., Niroula, P., Zhu, D. *et al.* *Nat. Phys.* **18**, 760–764 (2022).



Daley, A.J., Bloch, I., Kokail, C. *et al.*
Practical quantum advantage in quantum simulation. *Nature* **607**, 667–676 (2022).

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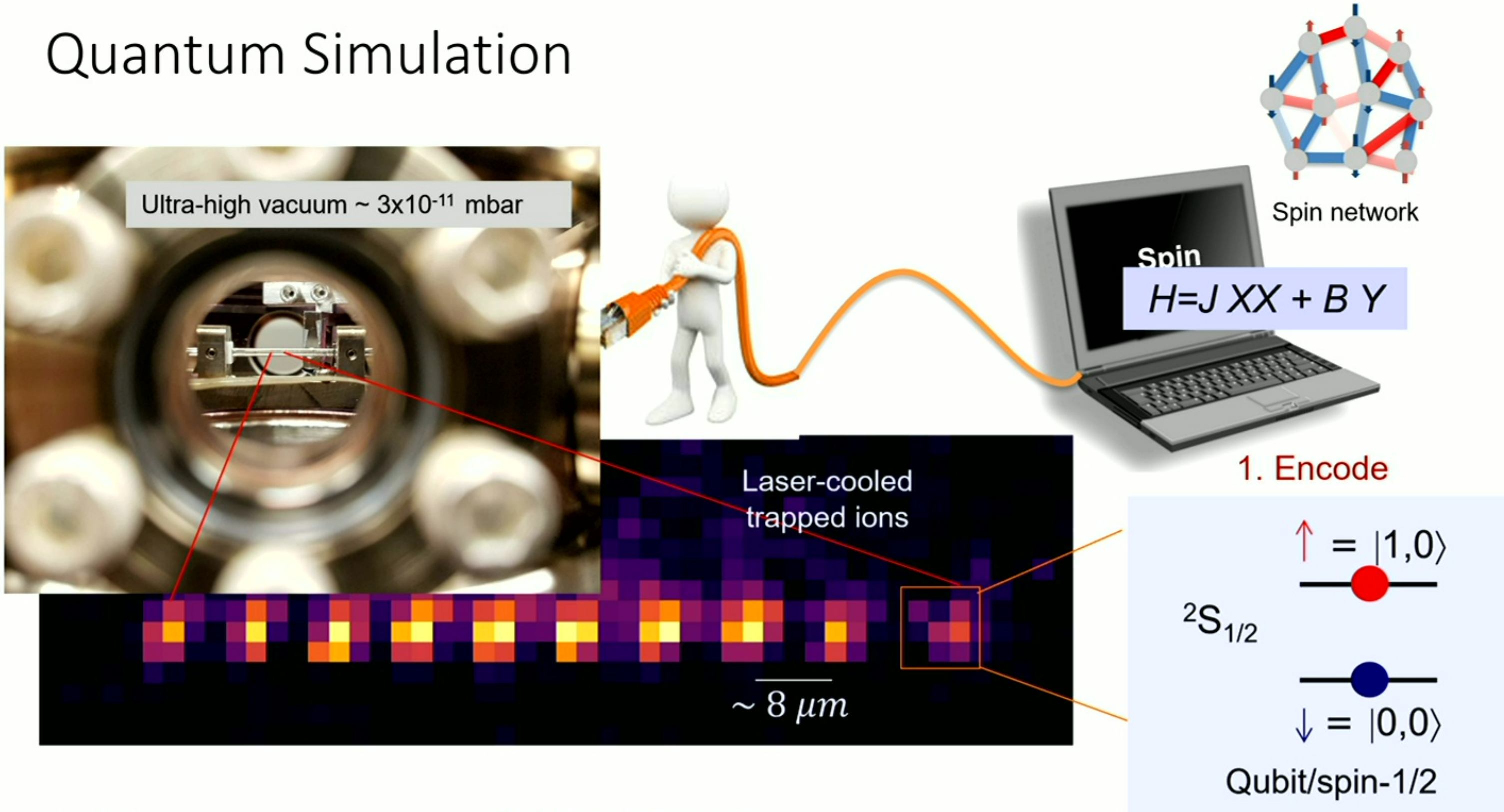
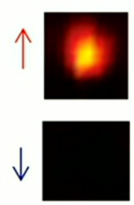
Quantum Simulation

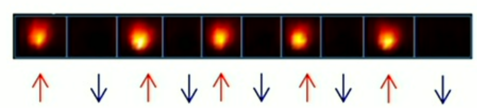


2. Time evolution requires experimental control of the Hamiltonian (and any programmed dissipation) but otherwise 'free' (we are using a real quantum system!)

3. Measurement



Single-shot detection of individual spin states, >99% fidelity per spin



Repeat for statistics and probability

Ions as a platform for quantum computation/simulation

- All qubits/spins are identical
- Long coherence time (> 1 hr demonstrated)
- Near perfect state initialization
  and detection of quantum states
- High fidelity control of individual spins/qubits and interaction between spins (entangling gates)

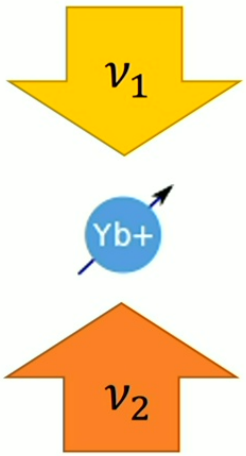
  Single spin control → simulation of external magnetic field

  single qubit fidelity 99.9999% [Lucas group, Oxford]

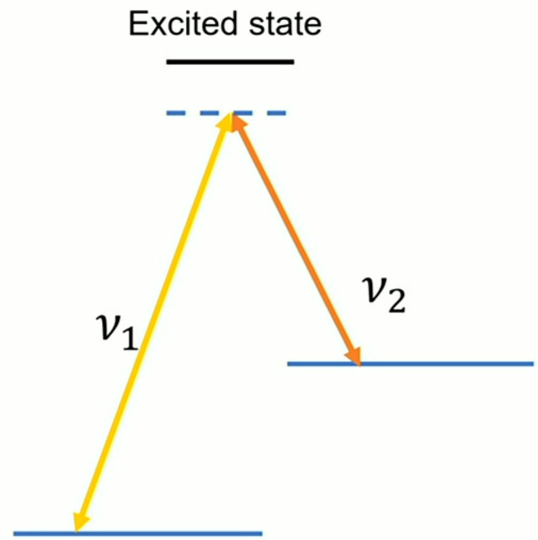
  Entangling operation / interaction between spins

  two qubit gate fidelity 99.97% [Oxford Ionics]

Coherent manipulation of single spins

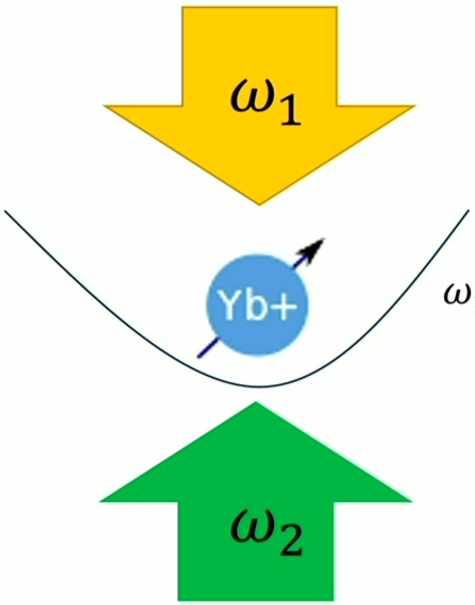


$\nu_1 - \nu_2 = \nu_{beatnote}$



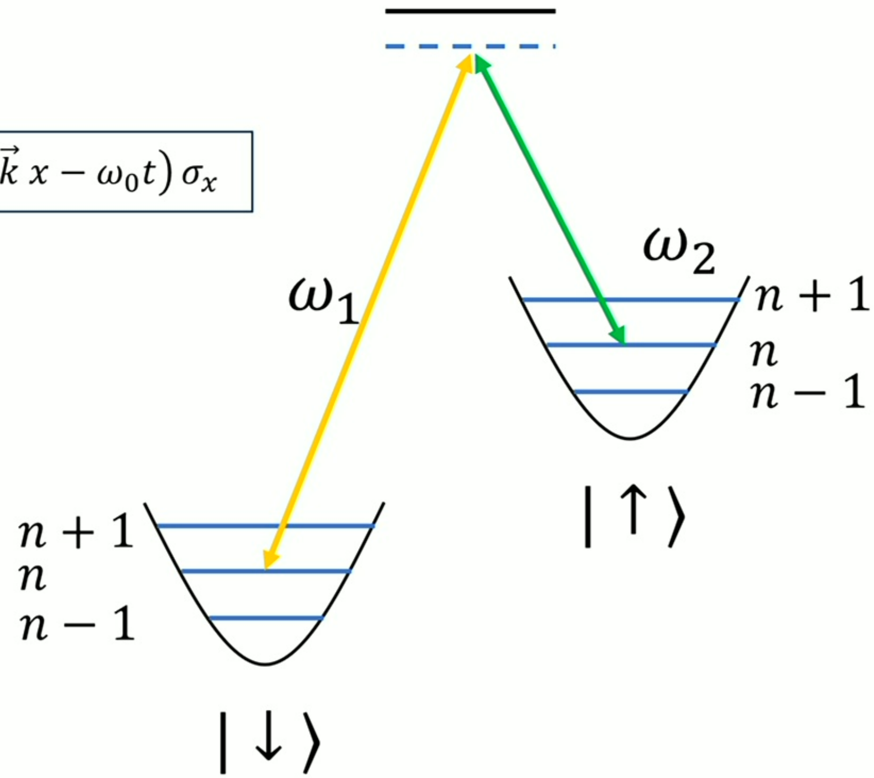
Coherent interactions: Carrier Transition

$$\mathrm{H_a} = \frac{\omega_0}{2}\sigma_z + \omega_m a^\dagger a$$



$\omega_1 - \omega_2 = \omega_0$

$$H_{\mathrm{LM}} = \Omega\cos\left(\delta\vec{k}\,x - \omega_0 t\right)\sigma_x$$



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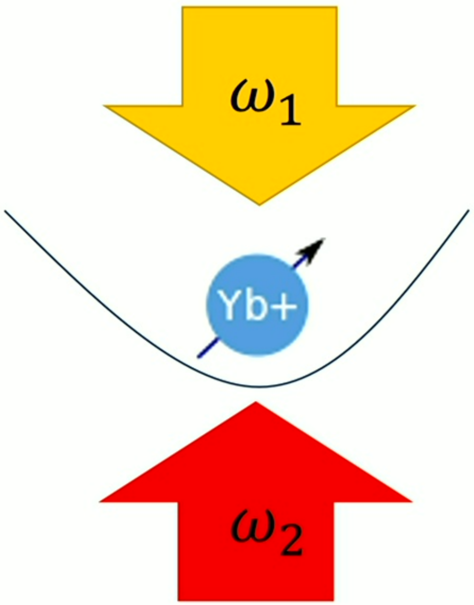
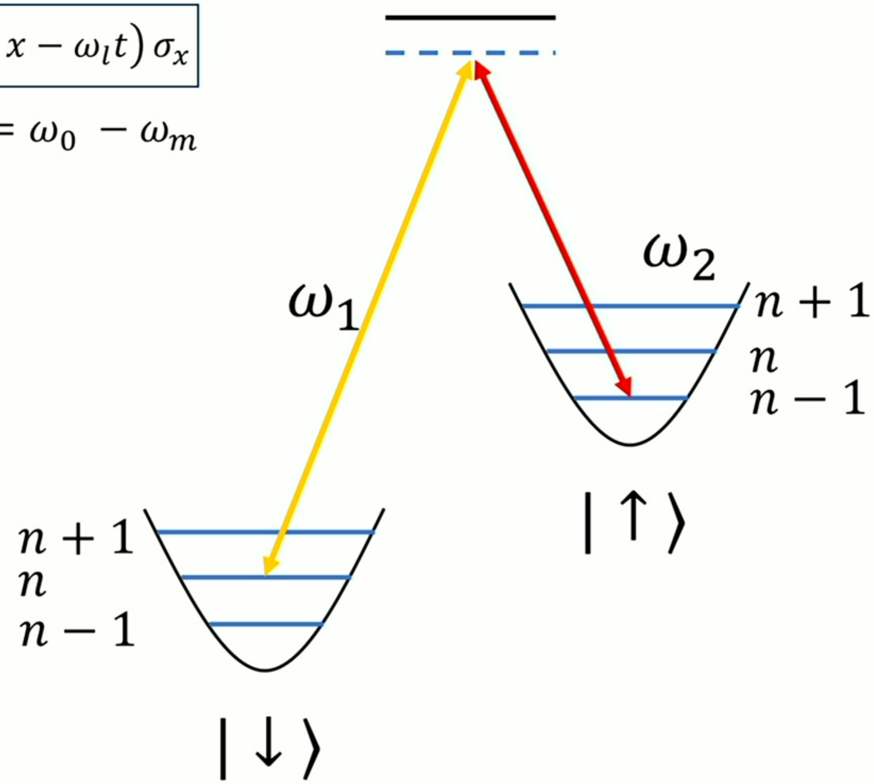
Coherent interactions: Red Sideband

$$H_a = \frac{\omega_0}{2}\sigma_z + \omega_m a^\dagger a$$



$$H_{af} = \Omega \cos(\delta\vec{k}\,x - \omega_l t)\,\sigma_x$$

$$\omega_l = \omega_1 - \omega_2 = \omega_0 - \omega_m$$

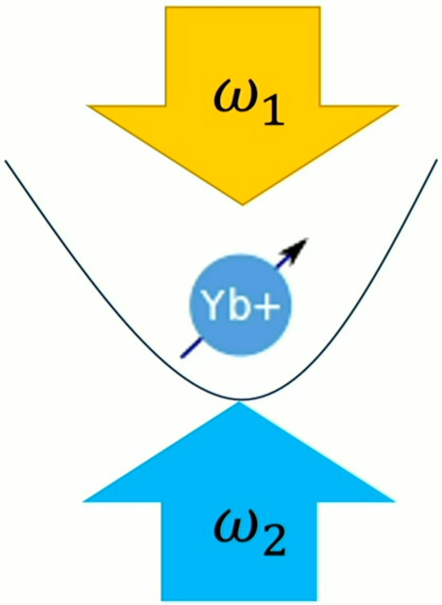


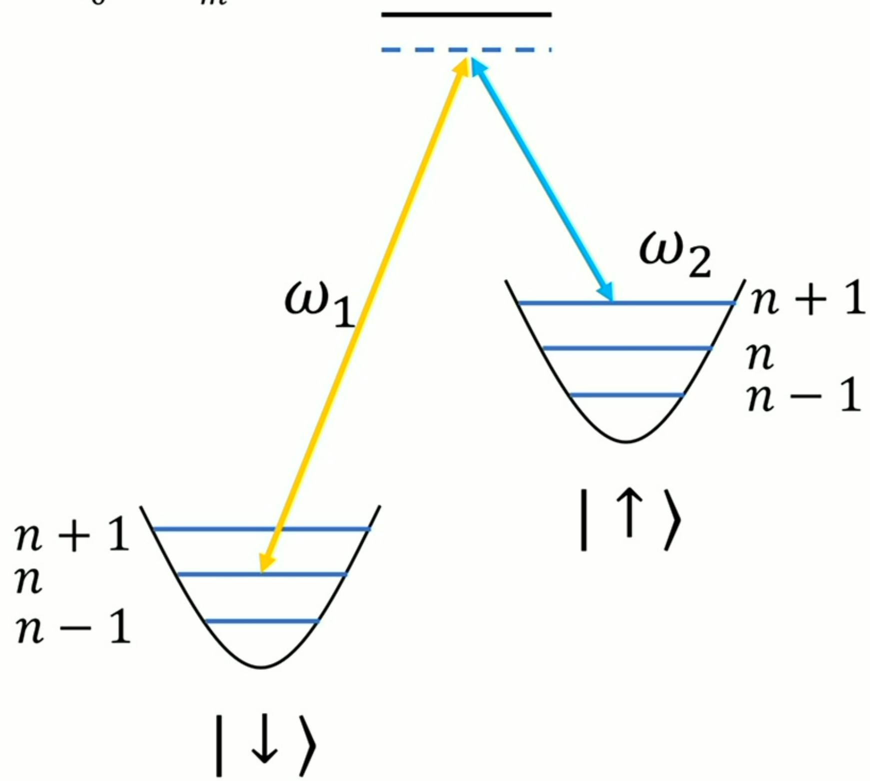
Coherent interactions: Blue Sideband

$$\mathrm{H_a} = \frac{\omega_0}{2}\sigma_z + \omega_m a^\dagger a$$

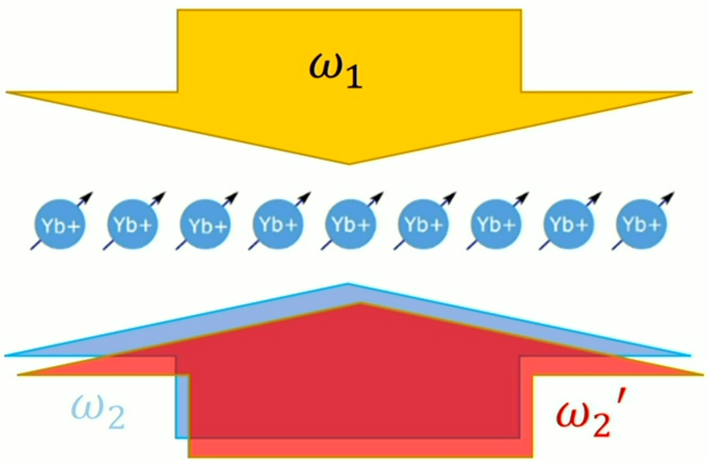
$$\mathrm{H}_{af} = \Omega\cos(\delta\vec{k}\,x - \omega_l t)\,\sigma_x$$

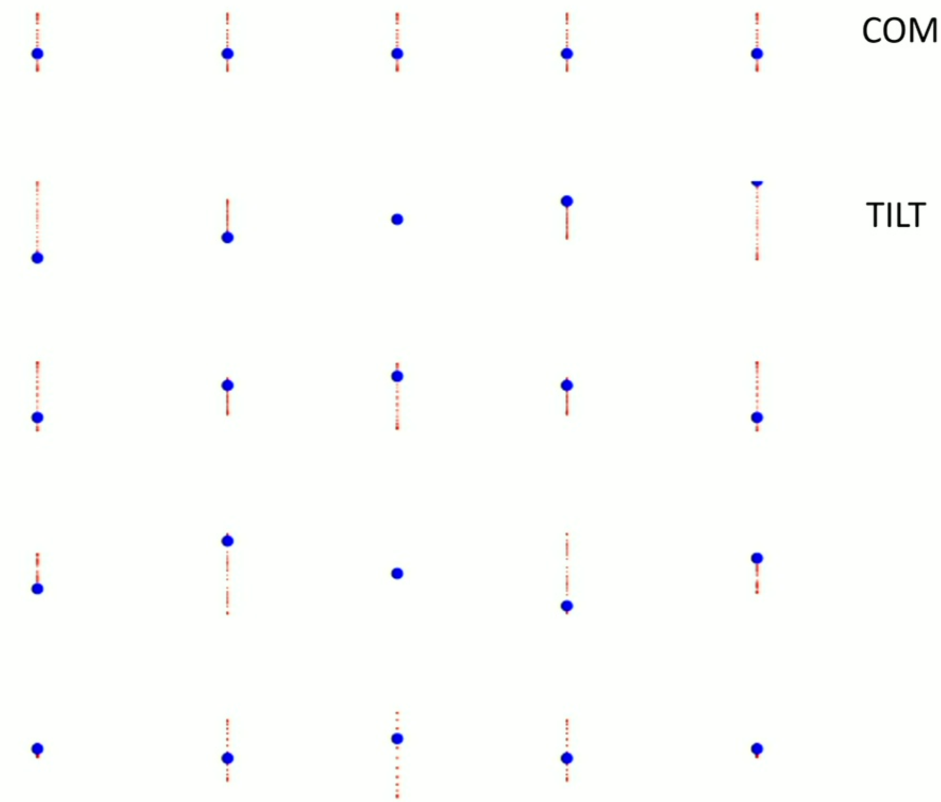
$$\omega_l = \omega_1 - \omega_2 = \omega_0 + \omega_m$$



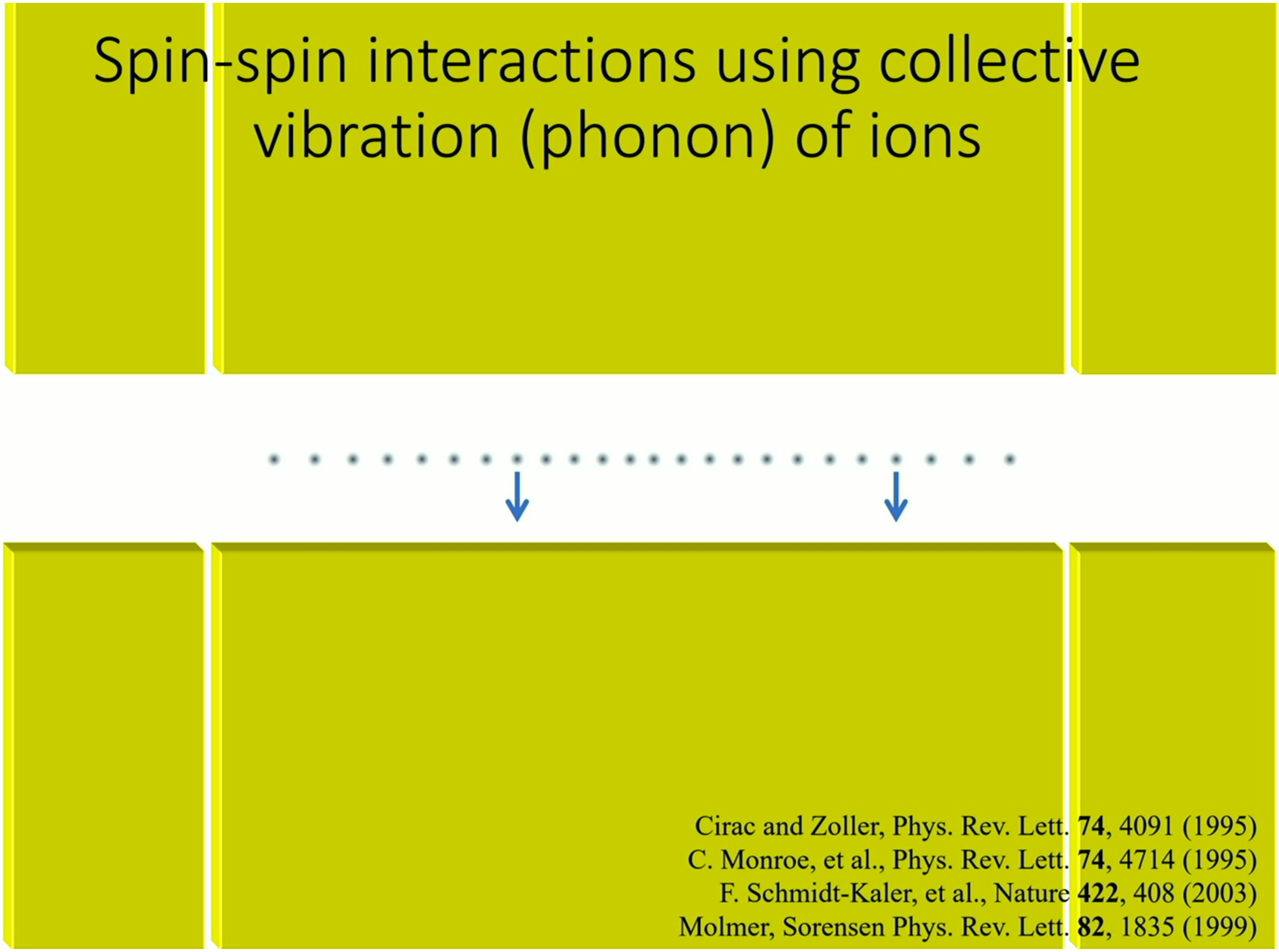


Collective Oscillation of Ions : Normal Modes





Spin-spin interactions using collective vibration (phonon) of ions



Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)

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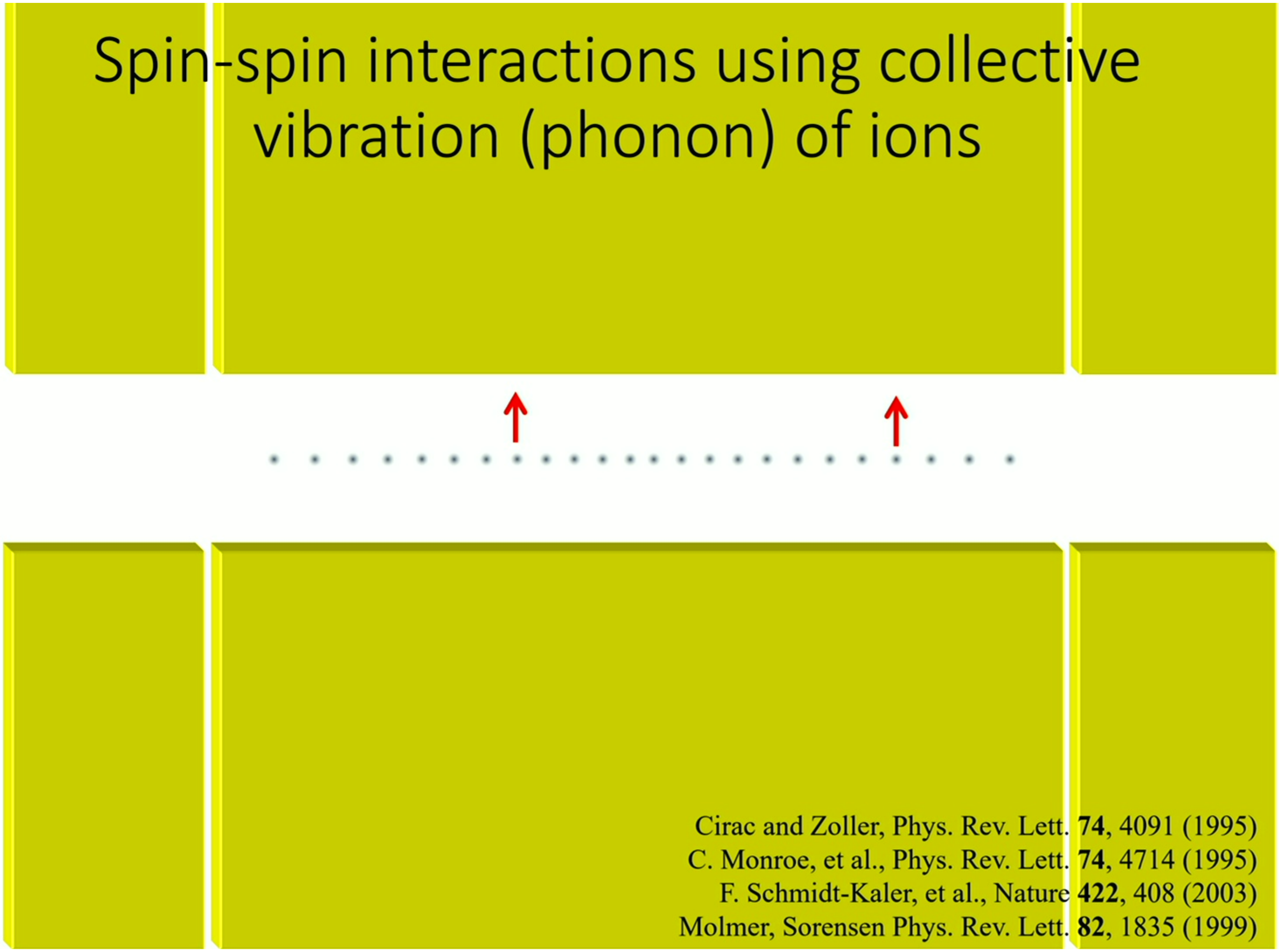

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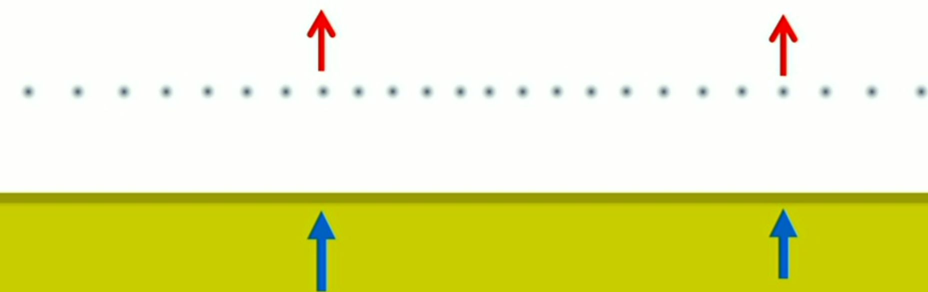

Internal states of these ions entangled

$H = \sum J_{i,j}\ \sigma_x^i \sigma_x^j$ (Ising)

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
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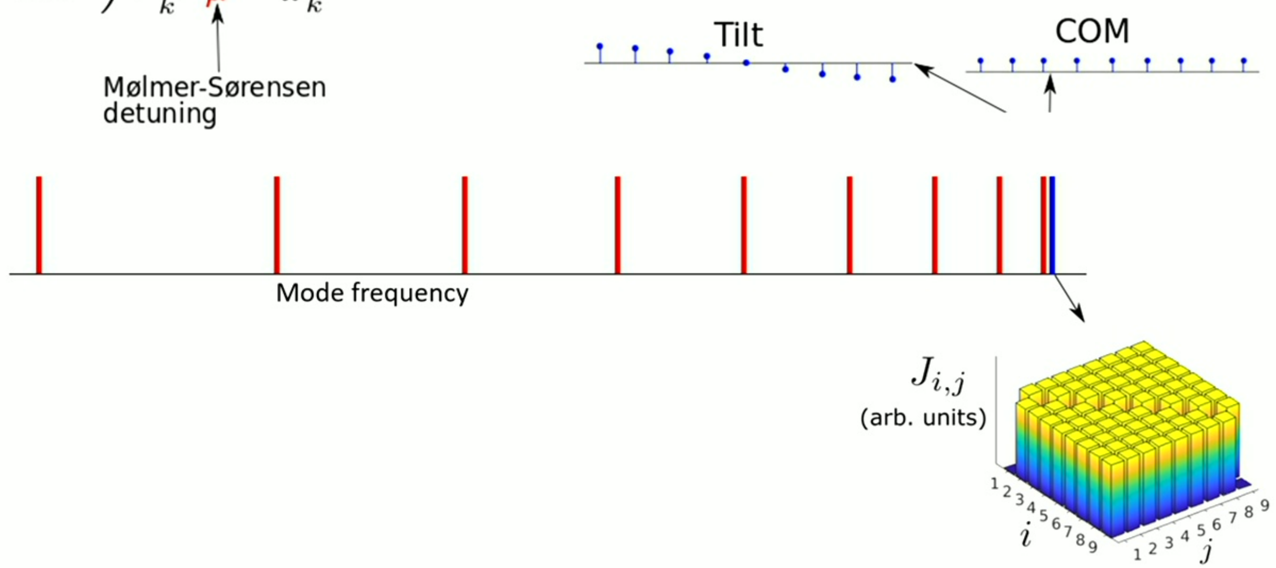
Spin dependent force = Spin-Spin Interactions

Normal mode eigenvector components

$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Laser intensity over each ion

Mølmer-Sørensen detuning



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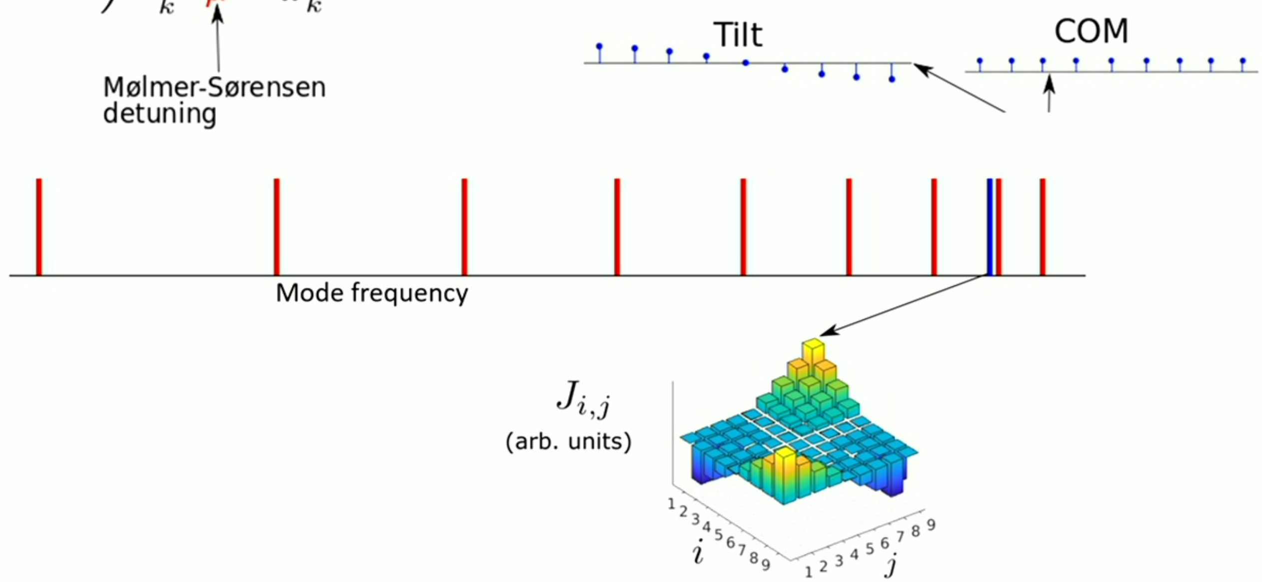

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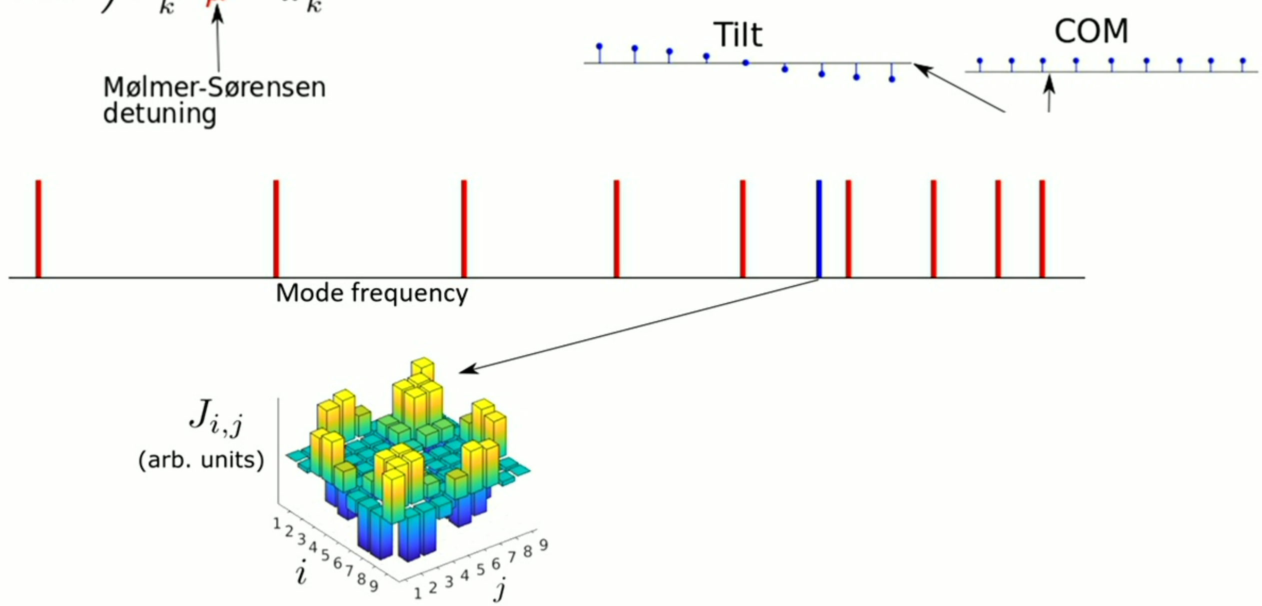


intensity and frequency are the controls for varying the interaction profile

Outline

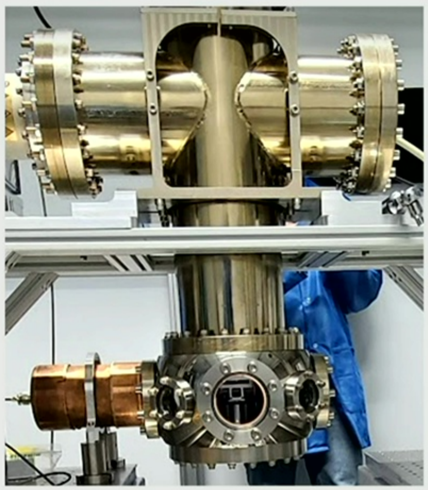
- A quick overview/refresher on trapped ion quantum simulations
- Our efforts to develop programmable and large-scale trapped-ion quantum simulators
  - Increase qubit count
  - Expand *Native* qubit interactions toolset
  - Develop high-precision coherent and incoherent control over individual ions: mid-circuit measurements
  - Robust and modular systems engineering
- Beyond the lab – developing open-source, full-stack quantum processors (Open Quantum Design)

Our Quantum Processors

Amethyst

Yb^+ ion-based quantum simulator
(< 10 qubits)

Operational

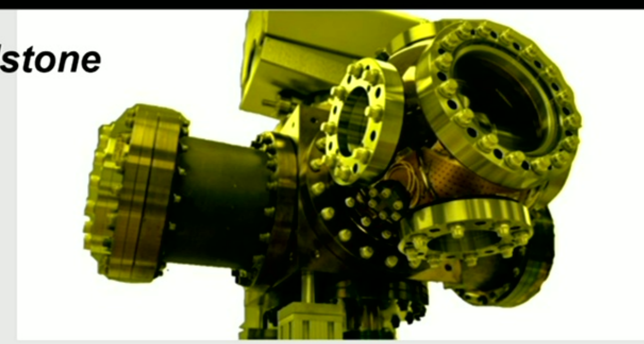


Beryl
jointly with Crystal Senko group

Ba^+ in surface trap (Sandia Nat'l Lab), up to 16 qubits/qudits with maximum individual control

final stages of construction

Bloodstone



Yb^+ ion-based quantum processor for long ion chains (> 30 qubits), programmable interactions, mid-circuit measurements

Trying to trap first ions!

Our Quantum Processors

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(< 10 qubits)

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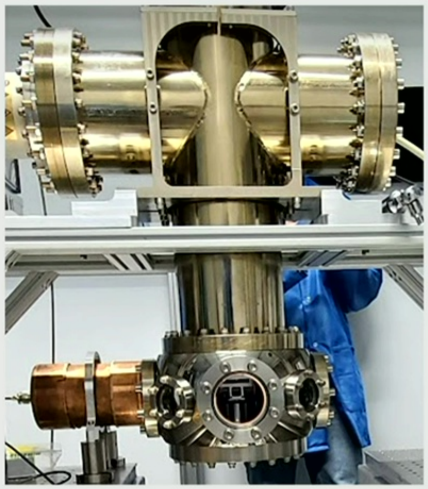

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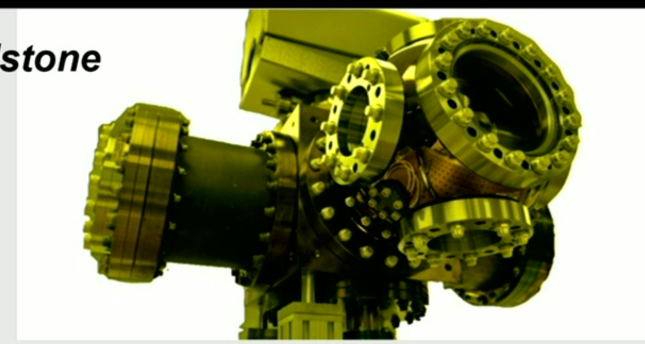


Yb^+ ion-based quantum processor for long ion chains (> 30 qubits), programmable interactions, mid-circuit measurements

Fullstack control and remote access at various levels (collaborations with Crystal Senko, Roger Melko)

Increasing qubit count

How many ions can we trap and work with (lifetime practical for performing complex quantum simulation experiments)?

- Lifetime limited by vacuum pressure and trap depth

How many qubits can we control practically?

- Typically limited by available optical controls and coherence time in presence of control fields

Requirement: Extreme High Vacuum

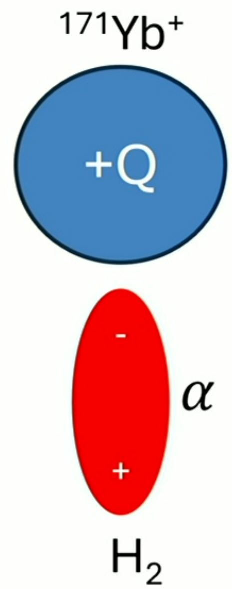
Recent 53 ion experiments observe 5-minute collision free lifetimes [1]

For observing the dynamics for 100 ms ≈ 20-30 minutes

Langevin Collision Rate

$$\gamma \approx \frac{PQ}{k_B T}\sqrt{\frac{\alpha\pi}{2m\epsilon_0}}$$

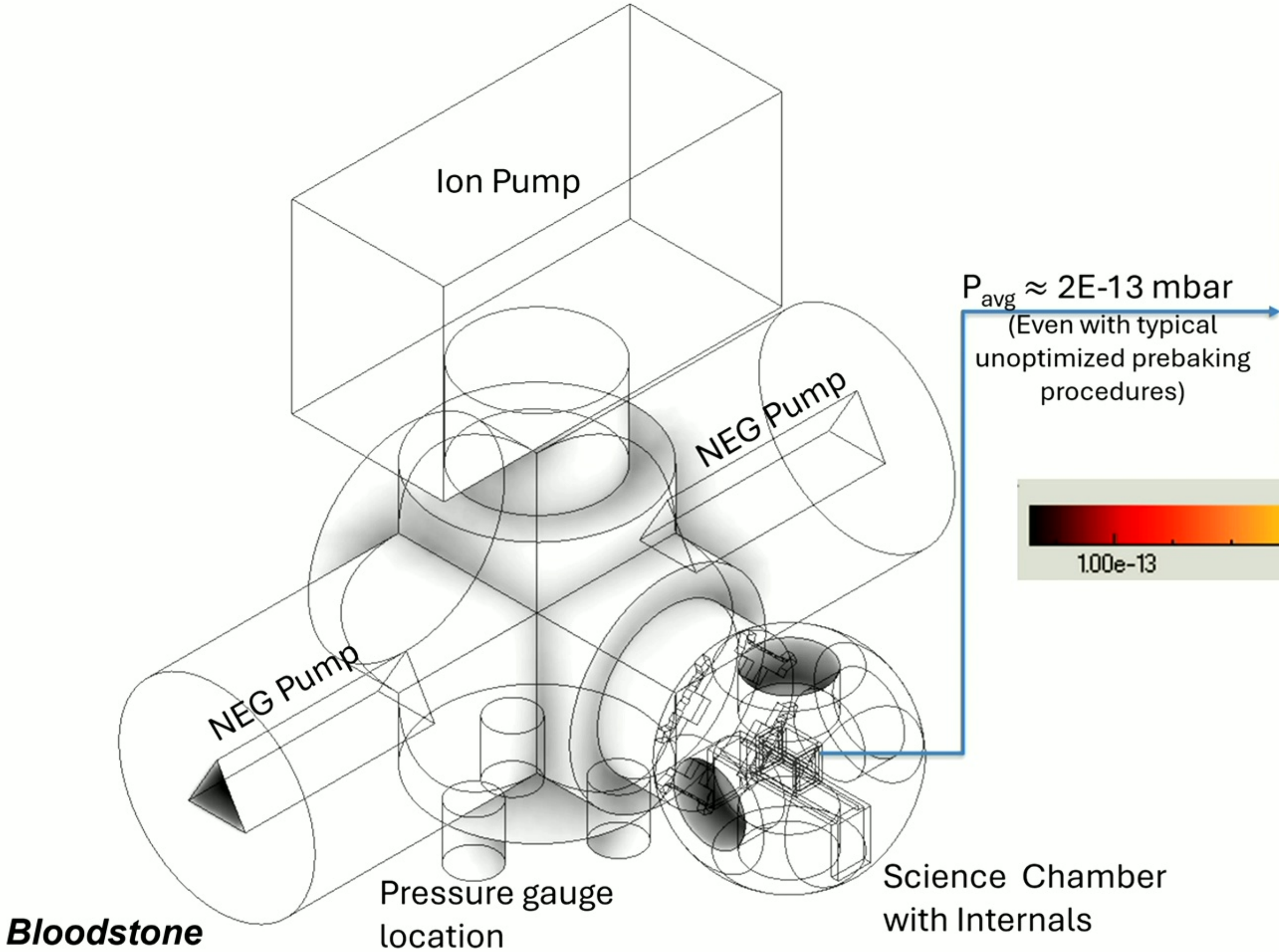
P = Pressure
Q = Ion Charge
α = Polarizability of background gas
m = Mass of gas atom



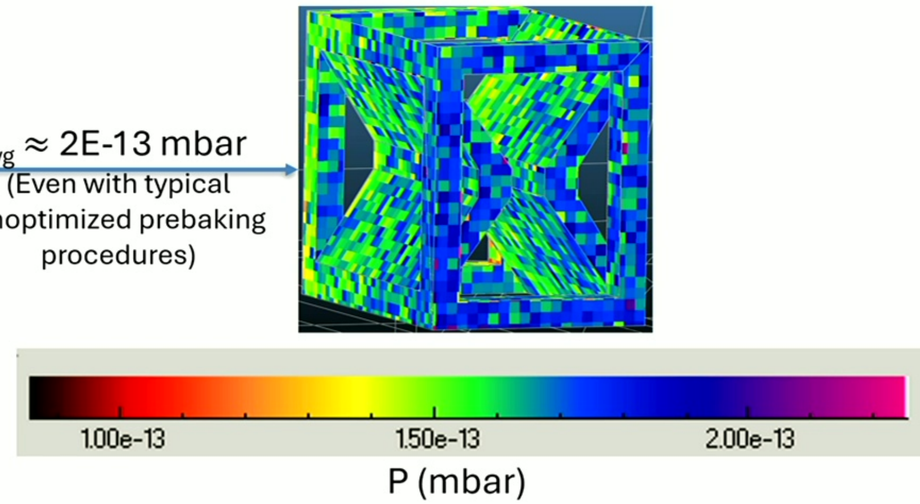
For $P = 2 \times 10^{-11}$ mbar ($\gamma \approx 5 \times 10^{-4}$) i.e. every min (30 ions)
For N ions: $P < \frac{2}{N} \times 10^{-11}$ mbar
For 50 ions: $P < 4 \times 10^{-13}$ mbar (Extreme High Vacuum, XHV)

[1] Zhang et. al Nature 551 601-604 (2017)

Room temperature XHV system possible?



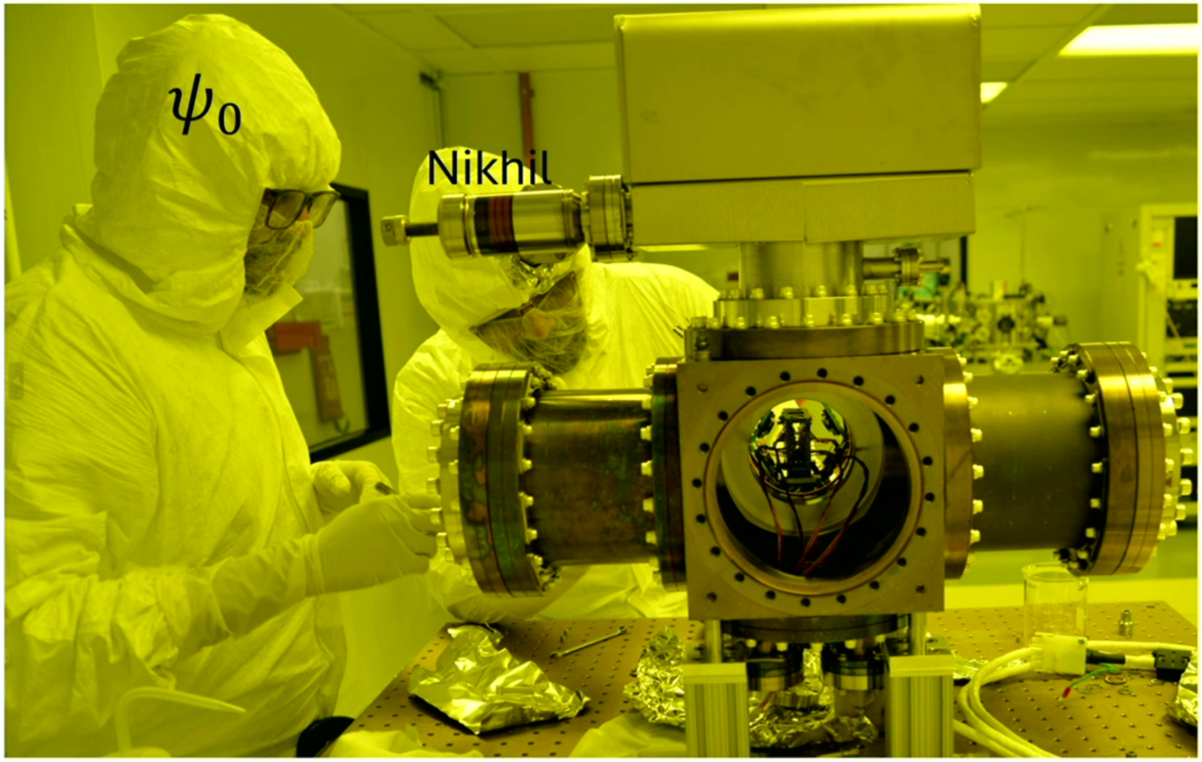
Simulation by MolFlow

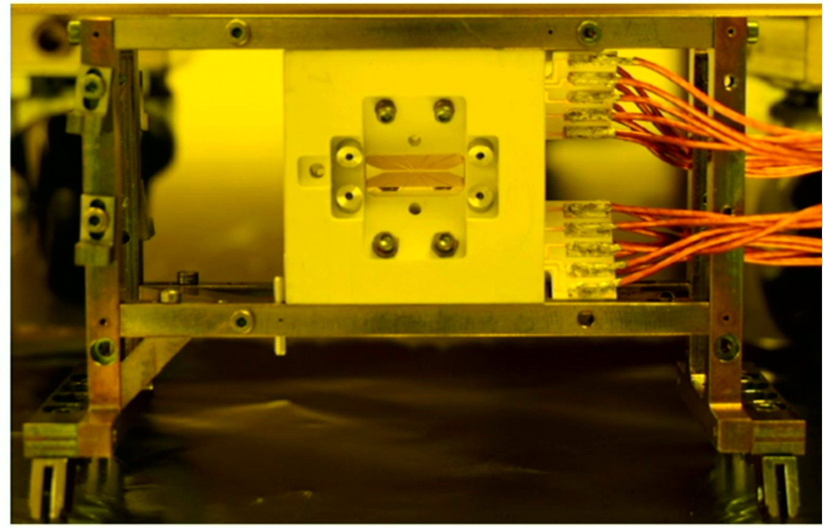


14 prospective designs were simulated.

Current design achieves < 1E-11 mbar without prebaking!

Clean Vacuum Assembly



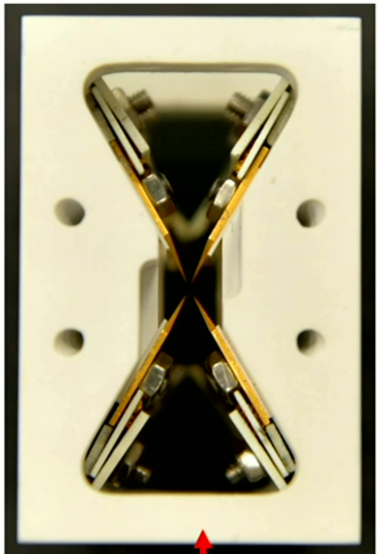


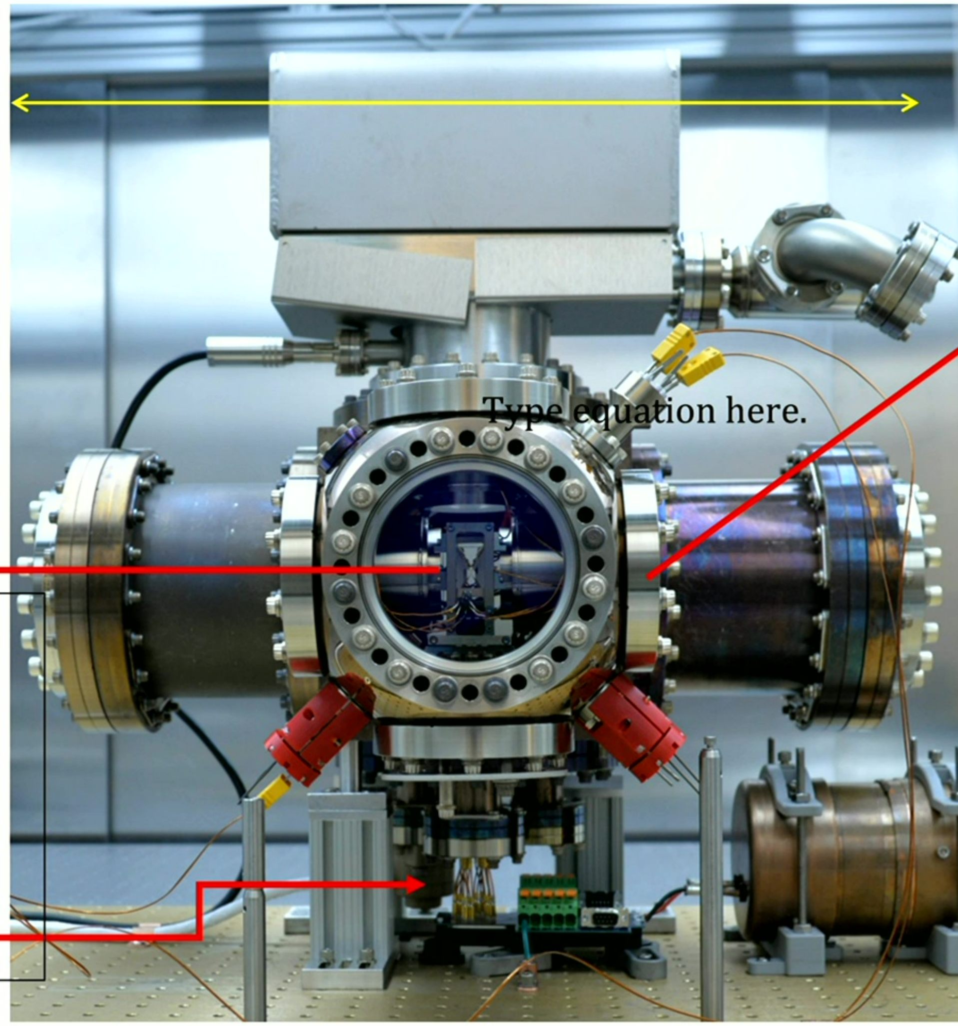
- All assembly inside cleanroom
- All metallic parts pre-treated at 400 C
- Trap ceramic mount pre-treated at 900 C
- Each internal component tested for vacuum compatibility

Bloodstone

Picture Credits: Lewis Hahn

A room temp XHV system





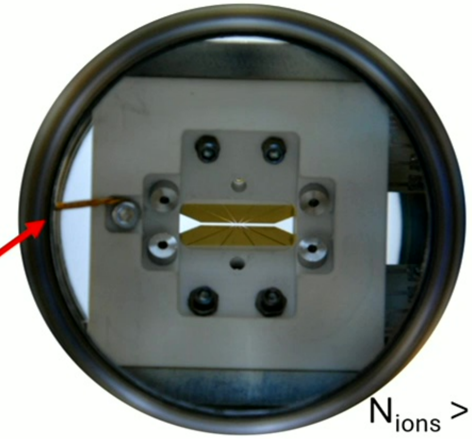
XHV

P_{meas} **< 1.7E-12 mbar**
P_{est} **< 6E-13 mbar**

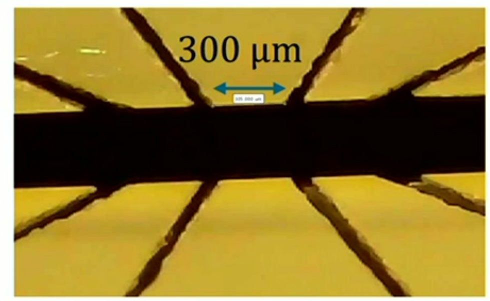
Current state of the art (room temp systems)
$P \approx$ 1E-11 mbar

Bloodstone

Side View



$N_{ions} > 50$



Segmented ‘blade style’ electrodes
Trap depth > 10^5 K

How controllable are the spin-spin interactions?

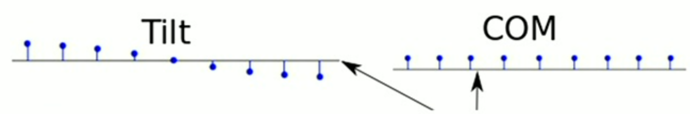
Spin-Spin Interactions

Normal mode eigenvector components

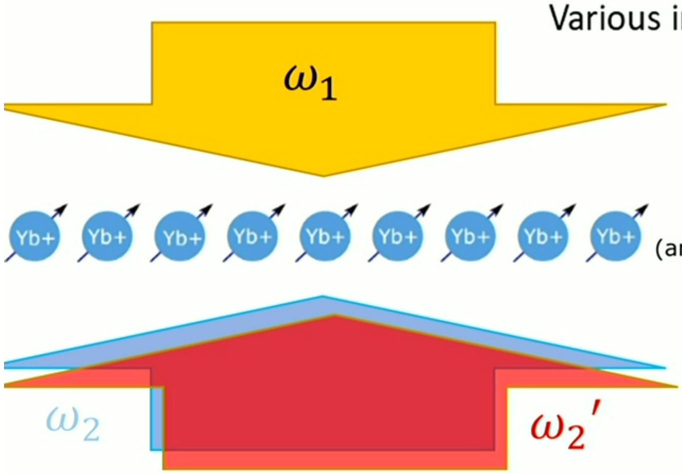
$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m}\right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Laser intensity over each ion

Mølmer-Sørensen detuning



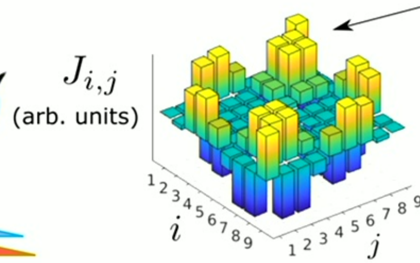
Various interaction profiles accessible by changing the detuning μ



$\omega_1 - \omega_2 = \omega_0 + \mu$

$\omega_1 - \omega_2' = \omega_0 - \mu$

Mode frequency



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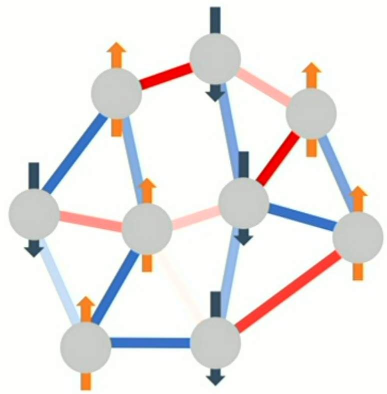
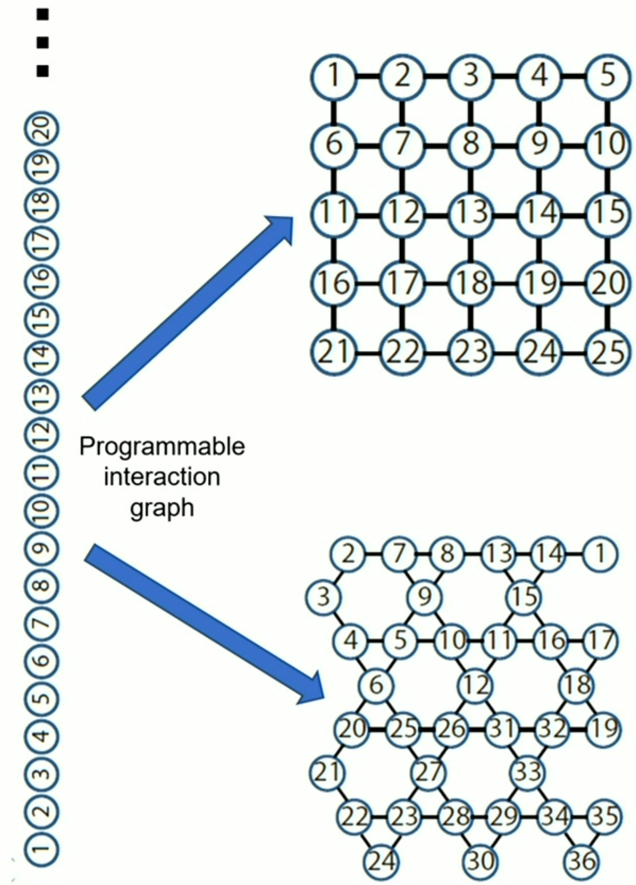


Fully-connected spin system



Also see:

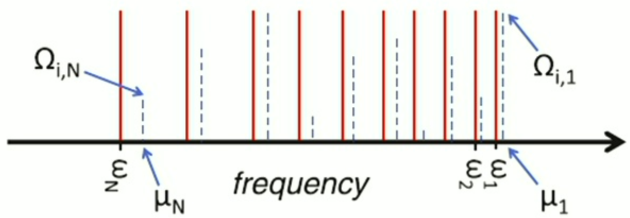
- Efforts to build 2D traps (Phil Richerme, Kihwan Kim, NIST …)
- Dynamical Hamiltonian engineering:
  F. Rajabi, S. Motlakunta, C. Shih, N. Kotibhaskar, Q. Quraishi, A. Ajoy, R. Islam
  npj Quantum Information **5**:32 (2019)

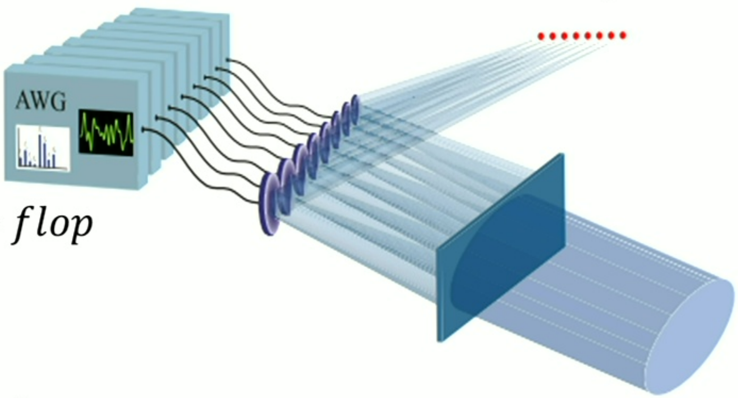
Arbitrary interaction graph between spins

S Korenblit et al 2012 New J. Phys. 14 095024.

$H = \sum J_{i,j}\, \sigma_x^i \sigma_x^j$ (Ising)

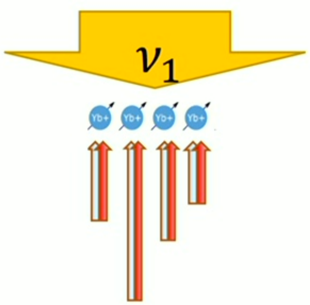
$H_{XY} = \sum J_{i,j} \left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j\right)$ $Flip - flop$





$$\eta_{i,m} = b_{i,m}\delta k \sqrt{\frac{\hbar}{2M\omega_m^{(x)}}}$$

$$J_{i,j} = \sum_n \Omega_{i,n}\Omega_{j,n} \sum_m^N \frac{\eta_{i,m}\eta_{j,m}\omega_m^{(x)}}{\mu_n^2 - \left(\omega_m^{(x)}\right)^2}$$



Laser power (Rabi frequency)

Individual addressing

~ laser detuning

Excite multiple modes selectively

$O(N^2)$ controls required.

Finding the N^2 Rabi frequencies is a hard problem involving non-linear optimization

$$\eta_{i,m} = b_{i,m}\delta k \sqrt{\frac{\hbar}{2M\omega_m^{(x)}}}$$

Lamb-Dicke parameter

EASY ←

$$J_{i,j} = \sum_n \Omega_{i,n}\Omega_{j,n} \sum_m^N \frac{\eta_{i,m}\eta_{j,m}\omega_m^{(x)}}{\mu_n^2 - \left(\omega_m^{(x)}\right)^2}$$

Rabi Frequencies (laser powers), N^2 parameters

Raman Beatnote Detunings (laser frequencies), N parameters

→ HARD

S Korenblit et al 2012 New J. Phys. 14 095024

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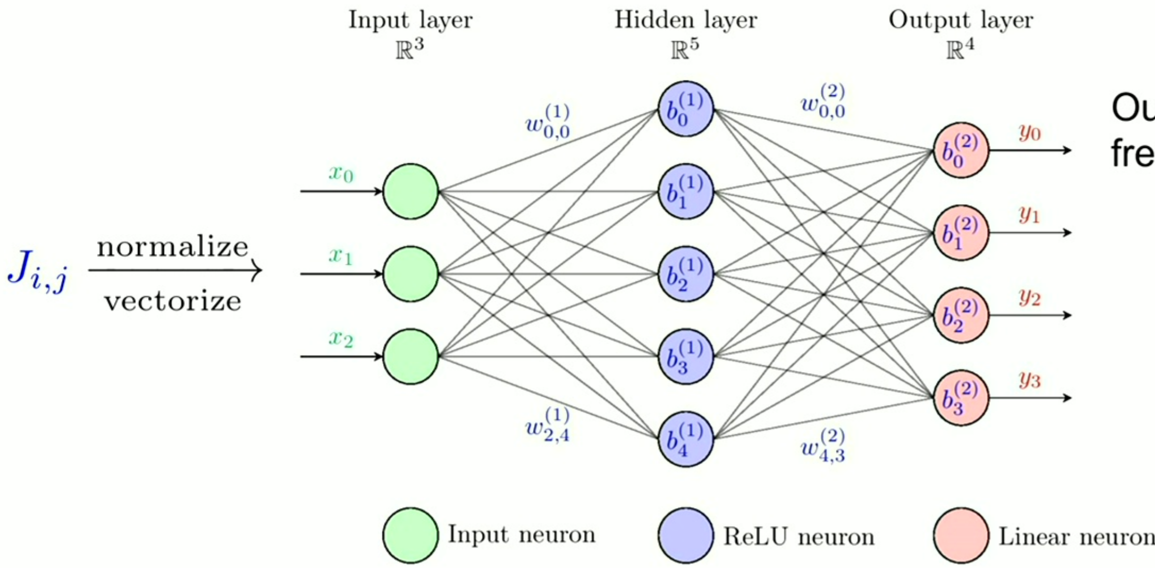
APPROACH: Use machine learning to find the Rabi frequencies, $\Omega_{i,n}$, given an arbitrary $J_{i,j}$.

Feed Forward Neural Network

To tune an analog quantum simulator



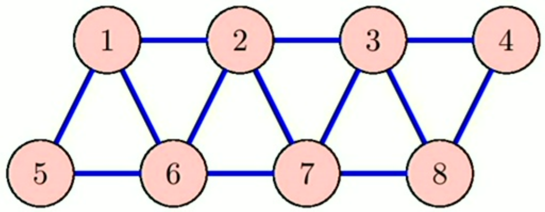
Output →Rabi frequencies

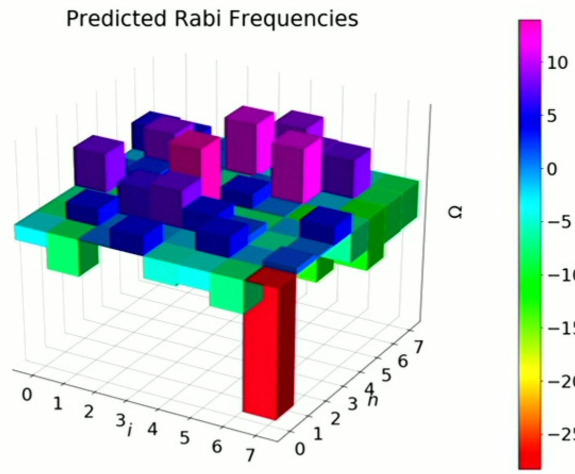
Collaboration with Roger Melko

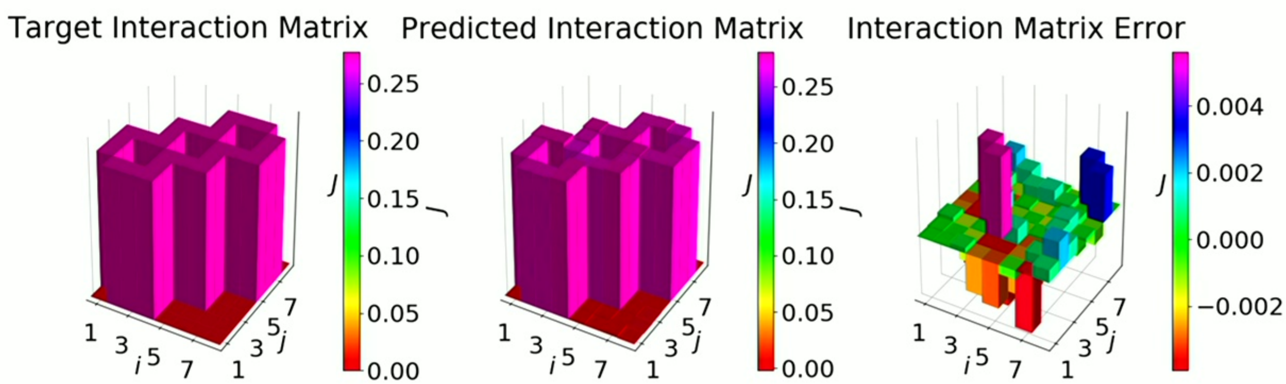
Yi Hong Teoh, Marina Drygala, Roger Melko, Rajibul Islam
Quantum Science and Technology, 5 (2020) 024001

Test Cases

Two-Dimensional Triangular Lattice





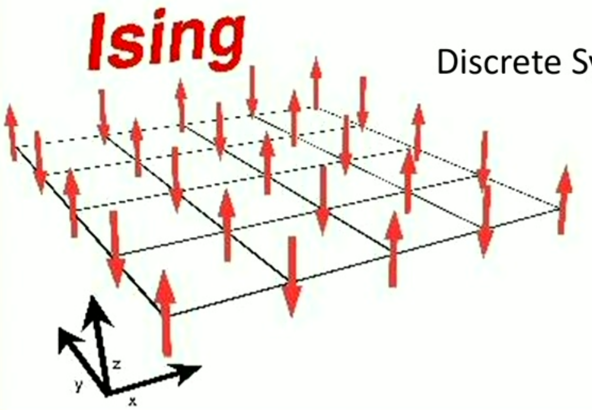


Error:
0.74%

Yi Hong Teoh, Marina Drygala, Roger Melko, Rajibul Islam
Quantum Science and Technology, 5 (2020) 024001

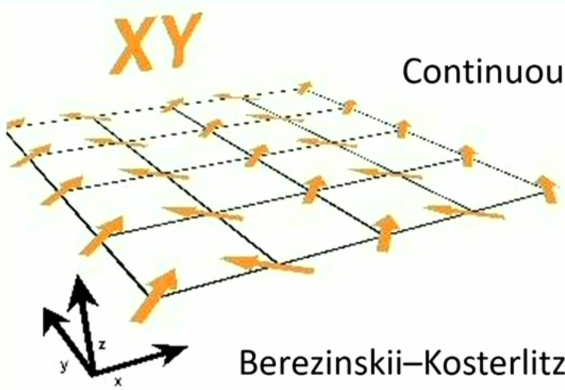
Beyond Ising-type interactions

Can we create $\sum_{i>j} J_{ij}^{x}\sigma_x^i\sigma_x^j + J_{ij}^{y}\sigma_y^i\sigma_y^j$?



Discrete Symmetry

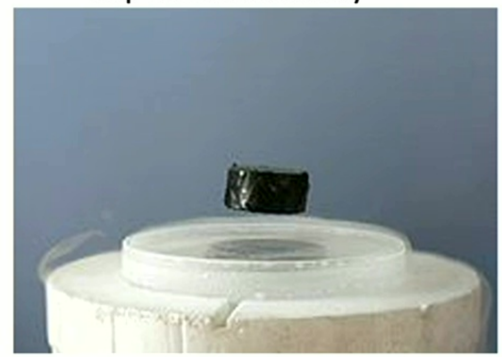
Image courtesy: physics.org



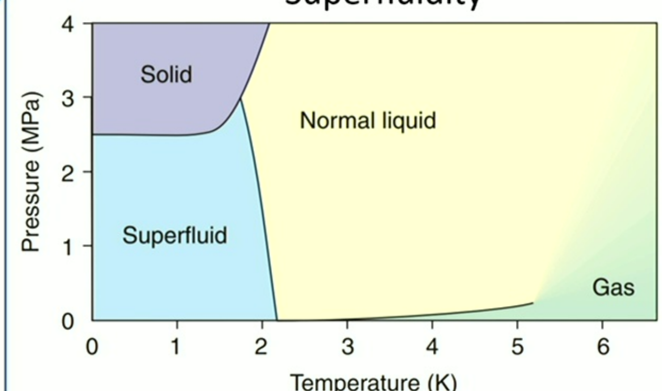
Continuous Symmetry

Berezinskii–Kosterlitz–Thouless transition (BKT transition) : 2016 Nobel prize

Superconductivity



Superfluidity



Phase diagram of ^4He at low temperatures

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Can we create $\sum_{i>j} J_{ij}^{x}\sigma_x^i\sigma_x^j + J_{ij}^{y}\sigma_y^i\sigma_y^j$?

Approach 1

$$\sum_{i>j} J_{ij}\sigma_i^x\sigma_j^x + \sum_i B_i\,\sigma_i^z$$

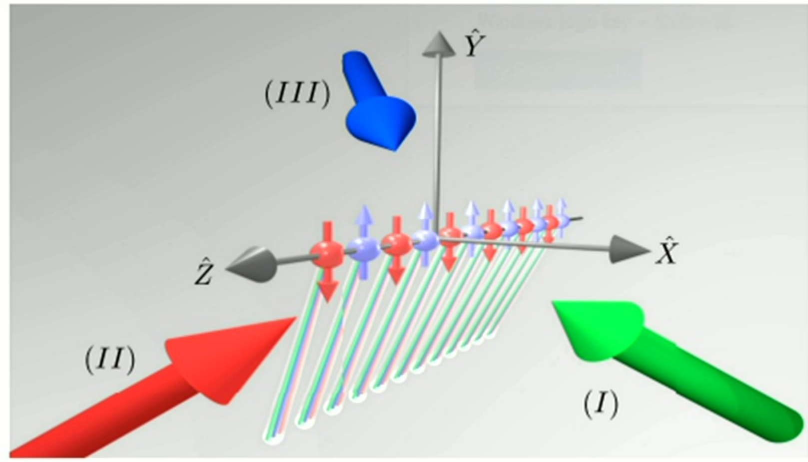
RWA $B_i \gg J_{ij}$

$$\mathcal{H}_{XY} = \frac{1}{2}\sum_{i<j} J_{ij}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y)$$

Richerme et al. *Nature* 511, 198–201 (2014).
Jurcevic et al, *Nature* 511, 202 (2014)

Issues with this approach:
Thomas G. Kiely and J. K. Freericks
Phys. Rev. A **97**, 023611

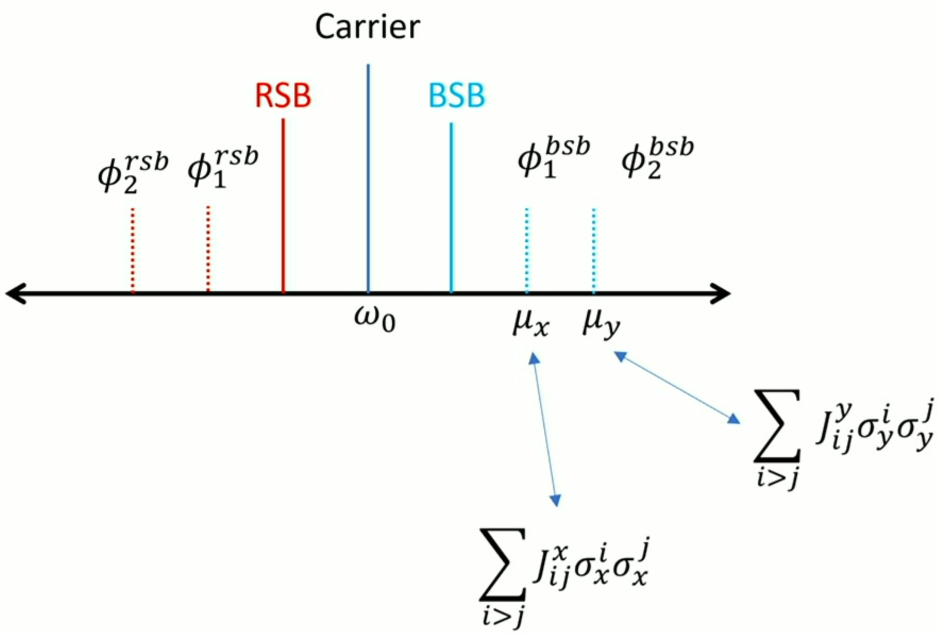
Approach 2 (Proposal)



Davoudi et al. Phys. Rev. Research 2, 023015

Approach 3 (Floquet) – Periodic drive of XX and YY terms, fast enough to reduce Trotter errors

How much can a single motional mode do ?



$$H = \sum_{i>j} J_{ij}^x \sigma_x^i \sigma_x^j + J_{ij}^y \sigma_y^i \sigma_y^j$$

If we drive a dual-tone Molmer-Sorensen scheme, can we get the anisotropic XY model?

Turns out, **Yes!**

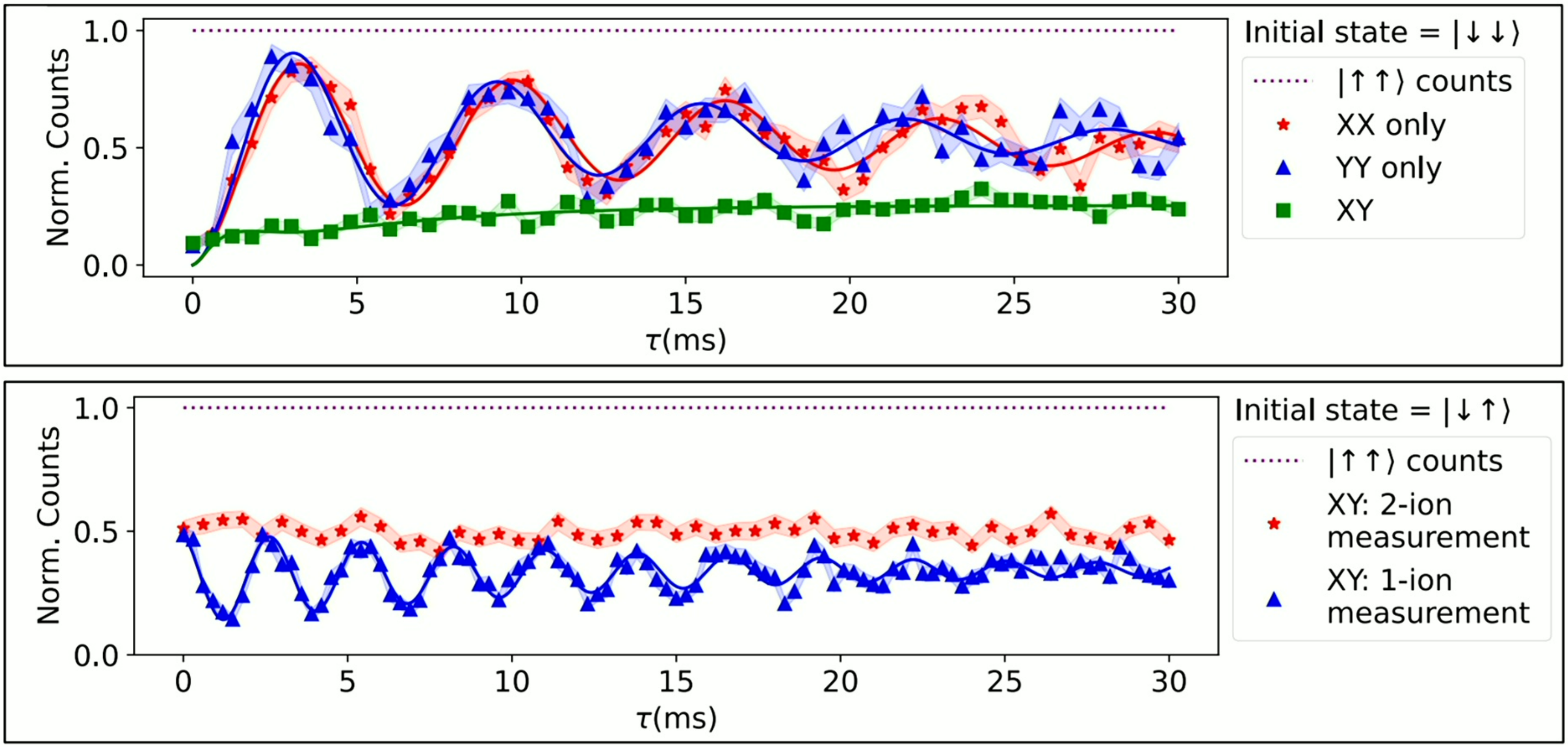
Provided,

$$|\mu_x - \mu_y| \gg \max\left(\left|J_{ij}^{x,y}\right|\right)$$

(easy constraint to satisfy experimentally!)

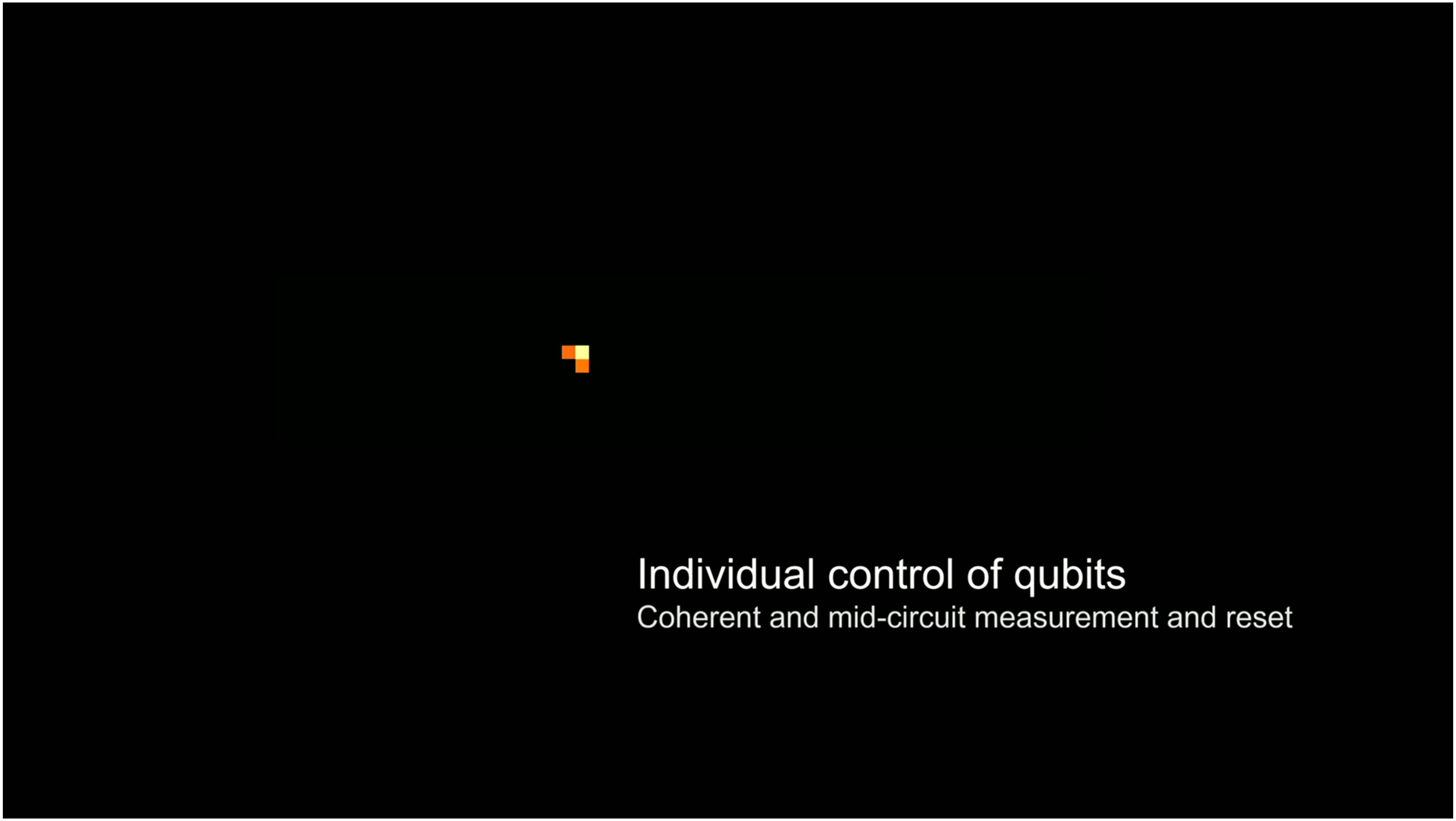
Kotibhaskar et al. *Phys. Rev. Research* **6**, 033038 (2024)

Experimental XY data



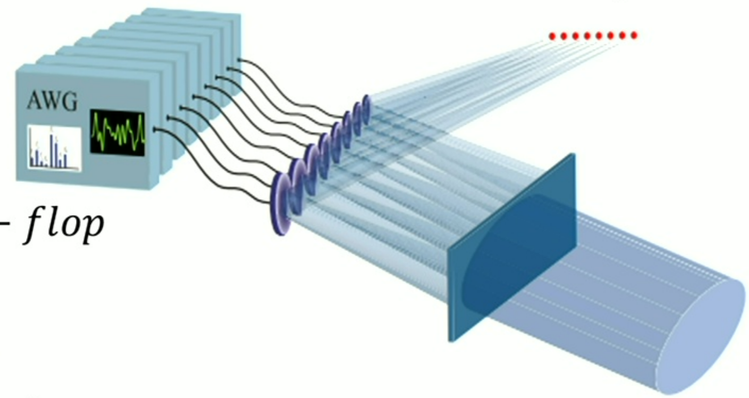
Amethyst

Kotibhaskar et al. *Phys. Rev. Research* **6**, 033038 (2024)


Individual control of qubits
Coherent and mid-circuit measurement and reset

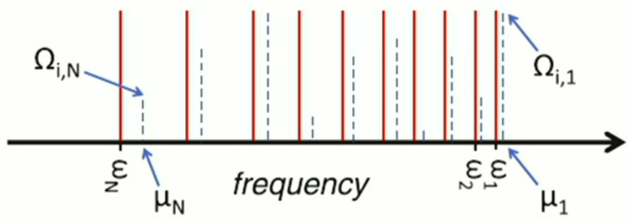
Arbitrary interaction graph
between spins

S Korenblit et al 2012 New J. Phys. 14 095024.



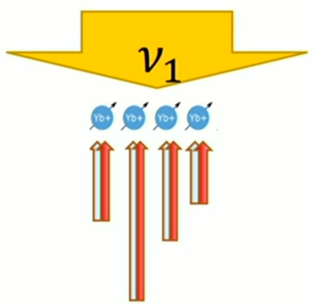
$H = \sum J_{i,j}\, \sigma_x^i \sigma_x^j$ (Ising)

$H_{XY} = \sum J_{i,j} \left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j\right)$ $Flip - flop$



$$\eta_{i,m} = b_{i,m}\delta k \sqrt{\frac{\hbar}{2M\omega_m^{(x)}}}$$

$$J_{i,j} = \sum_n \Omega_{i,n}\Omega_{j,n} \sum_m^N \frac{\eta_{i,m}\eta_{j,m}\omega_m^{(x)}}{\mu_n^2 - \left(\omega_m^{(x)}\right)^2}$$



Laser power
(Rabi frequency)

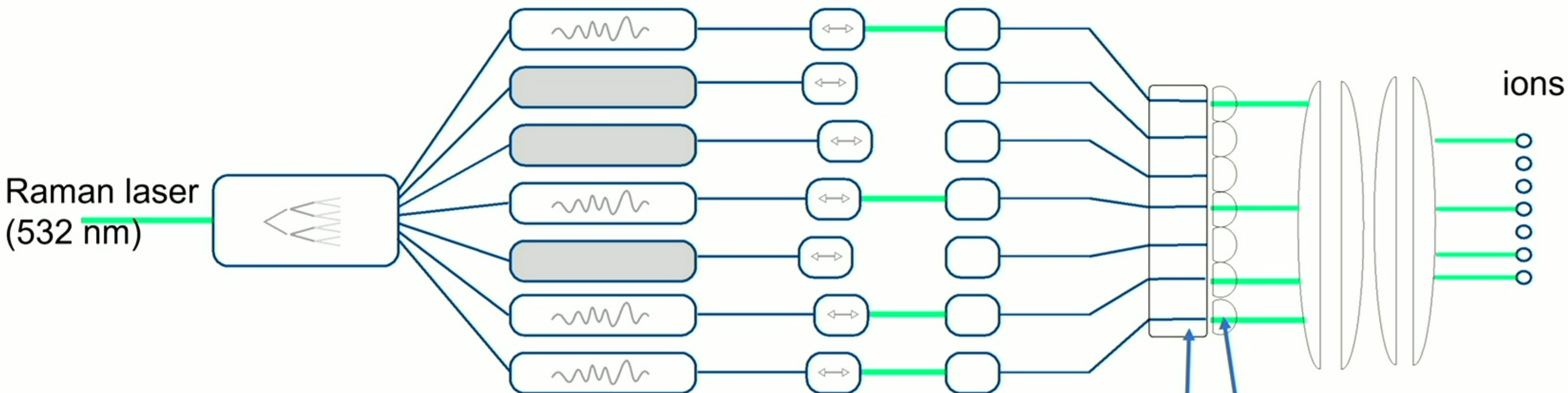
Individual addressing

~ laser detuning

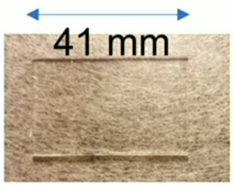
Excite multiple
modes selectively

$\boldsymbol{O}(\boldsymbol{N}^2)$ controls required.

Raman transitions in Ba^{+} with individual addressing



Split



Create individual beams for each ion

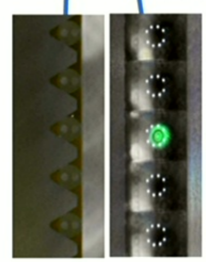
Modulate
With AOM

Allows for full coherent control of ion-phonon couplings

Path length
match

Expand
Beam size

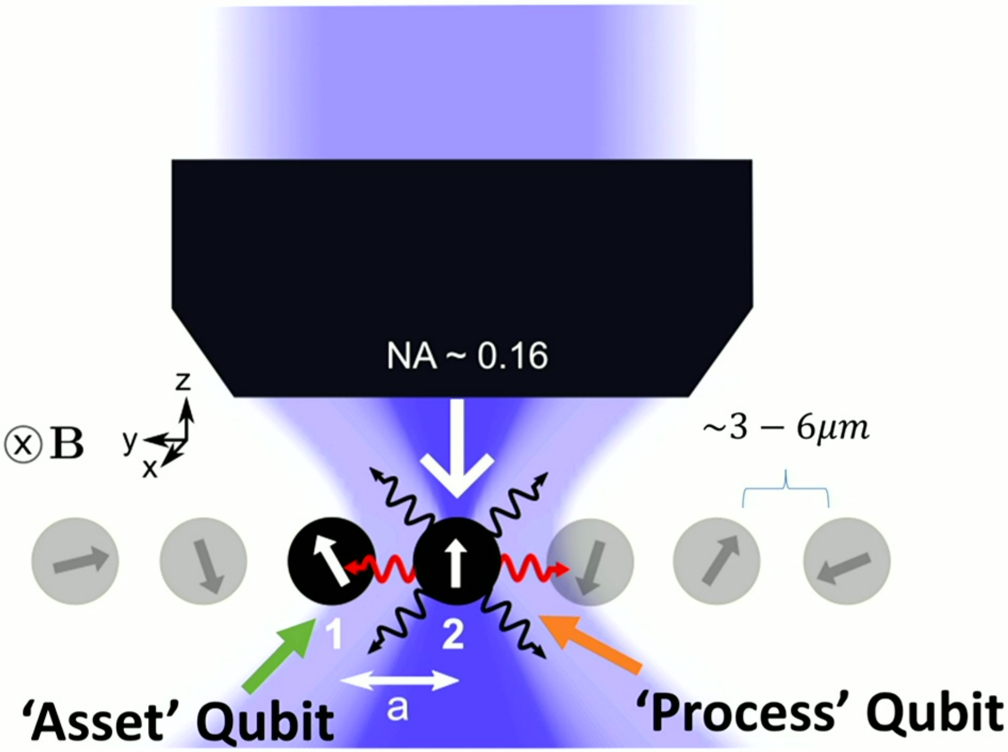
Shrink
Pitch+ Beam
size



Beryl

Binai-Motlagh et al., Quantum Sci. Technol. **8** (2023) 045012

Mid-circuit measurement and reset:
Accidental quantum measurements (AQM)



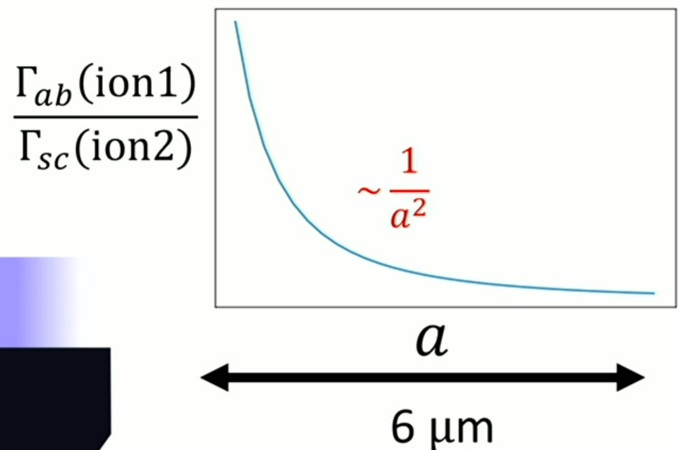
ion-1: qubit to be preserved
ion-2: qubit to be measured/reset

Sainath Motlakunta et al., *Nature Communications* 15:6575 (2024)

Fundamental limit of decoherence
Absorption of scattered photon from ion 2

$$\frac{\Gamma_{ab}(\text{ion1})}{\Gamma_{sc}(\text{ion2})} \leq \text{5E-6}$$

(for $^{171}\text{Yb}^{+}$ Ions placed 6 μm away)



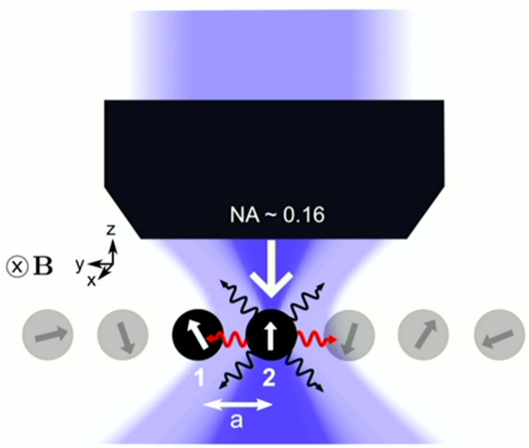
Corresponds to

$F_{2|1} \approx$ 99.996% for optical pumping

$F_{2|1} \approx$ 99.96% for state detection

(11μs detection time)

Can be further improved with magnetic field orientation



ion-1: qubit to be preserved
ion-2: qubit to be measured/reset

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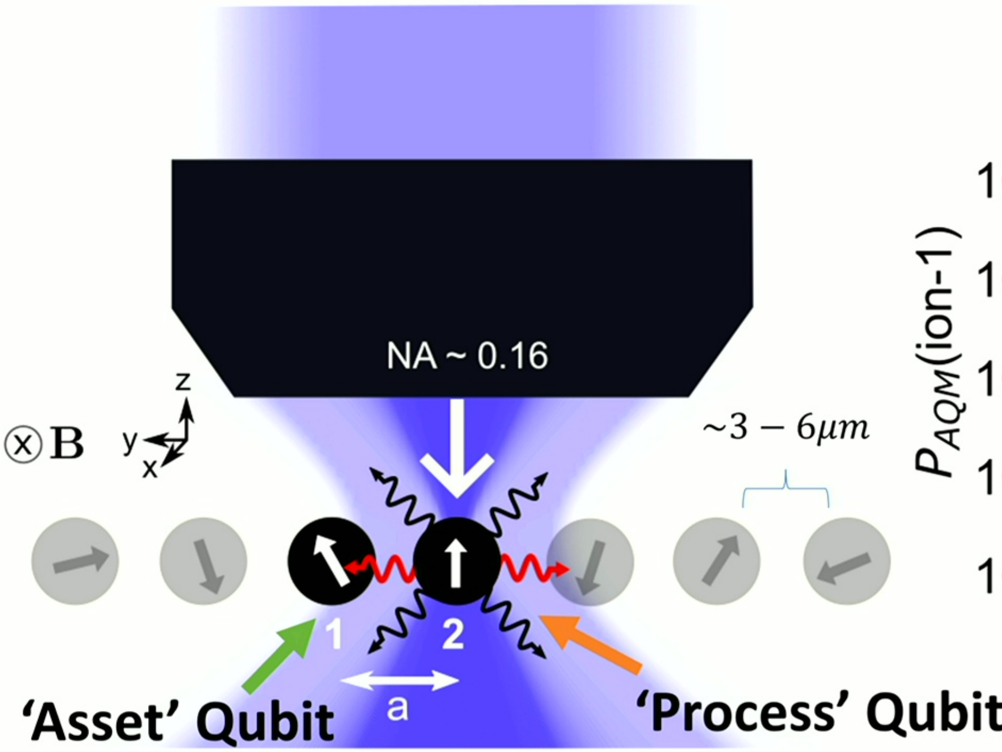
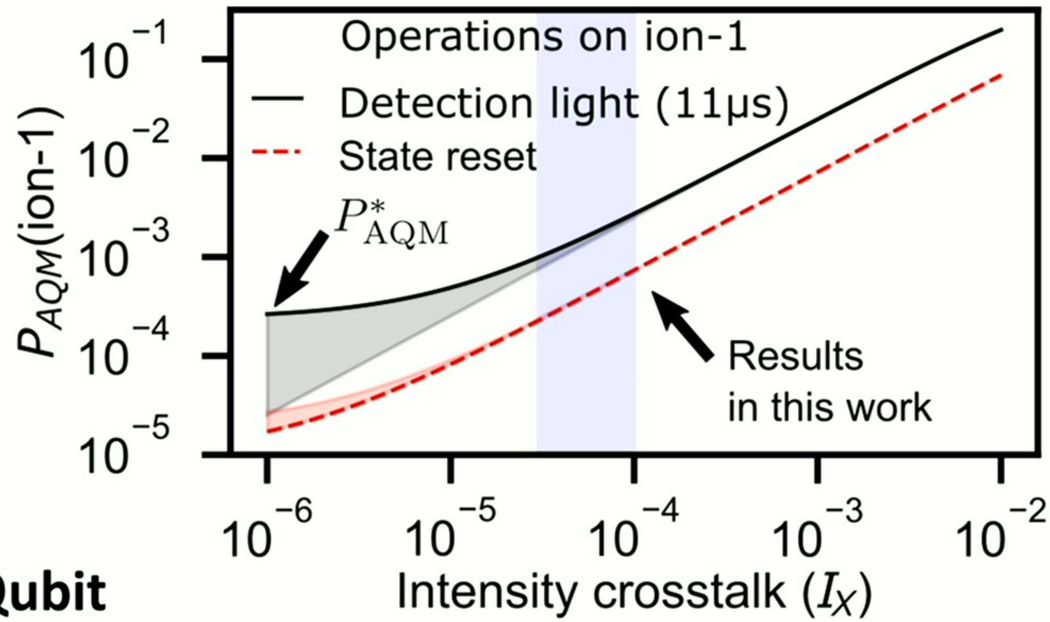
Mid-circuit measurement and reset: Accidental quantum measurements (AQM)





ion-1: qubit to be preserved
ion-2: qubit to be measured/reset

Sainath Motlakunta et al., *Nature Communications* 15:6575 (2024)

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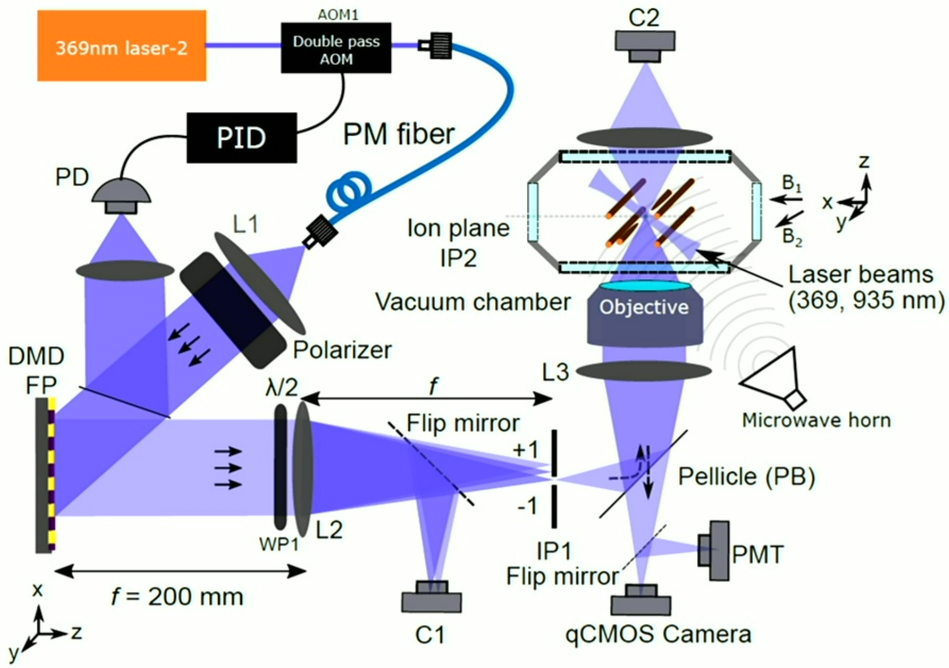
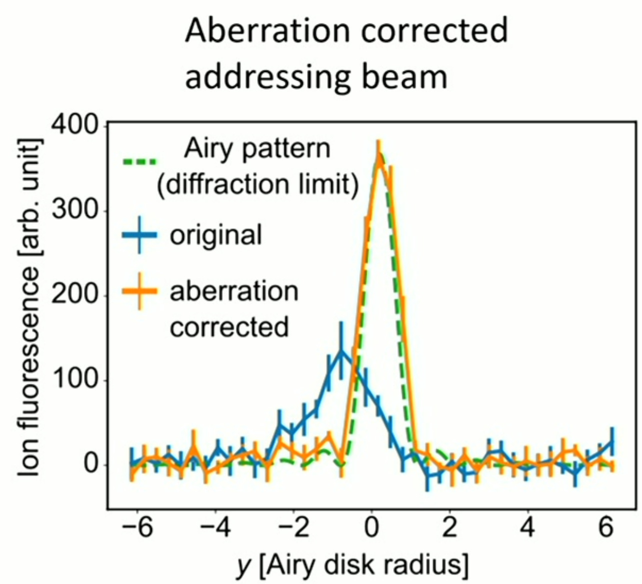
Minimal intensity crosstalk – Aberration corrected addressing



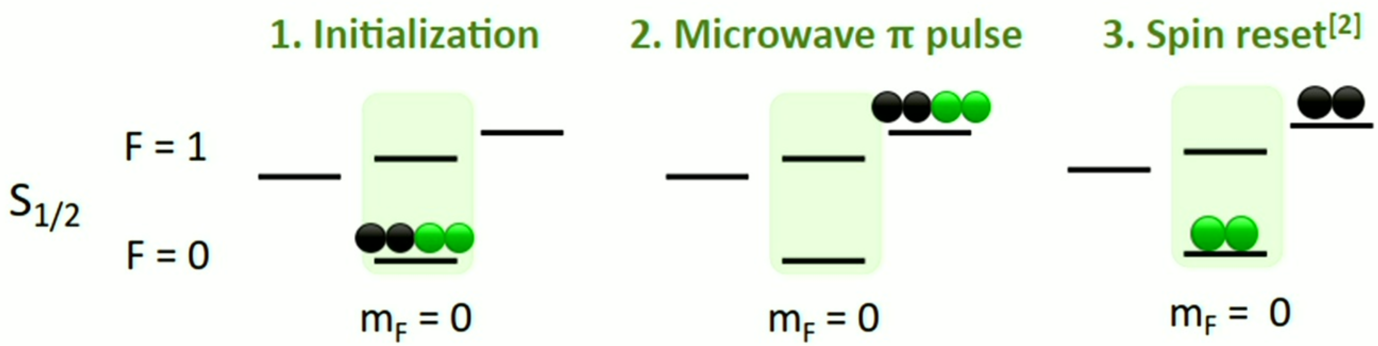
Chung-You Shih et. al
npj Quantum Information **7: 57 (2021)**

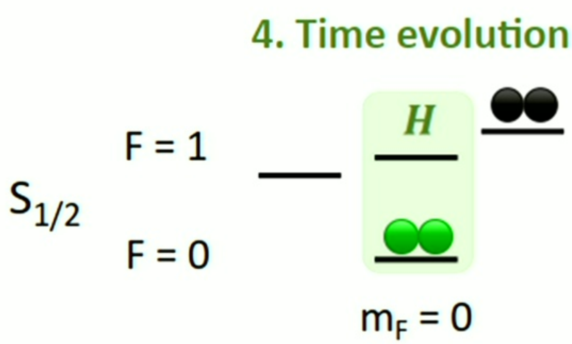


- Use a single ion as sensor for aberration at a single point
- Use DMD to create a Fourier hologram
- Compensate for the aberrations
- Used IFTA(iterative Fourier transform) to create diffraction limited beam profiles

Sainath Motlakunta et al., *Nature Communications* 15:6575 (2024)

Hamiltonian verification through shelving

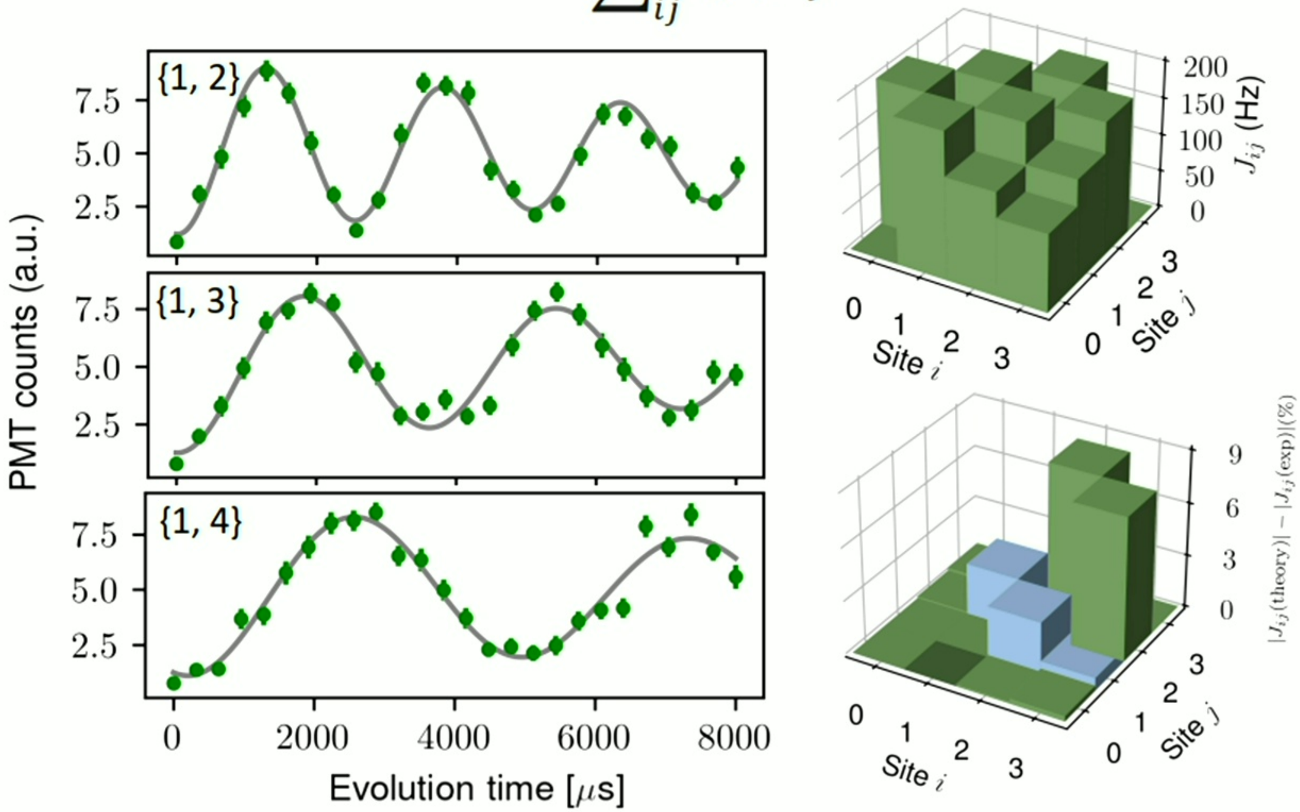




Shelved ions
- Lie outside the qubit subspace
- Contribute to the motional coupling

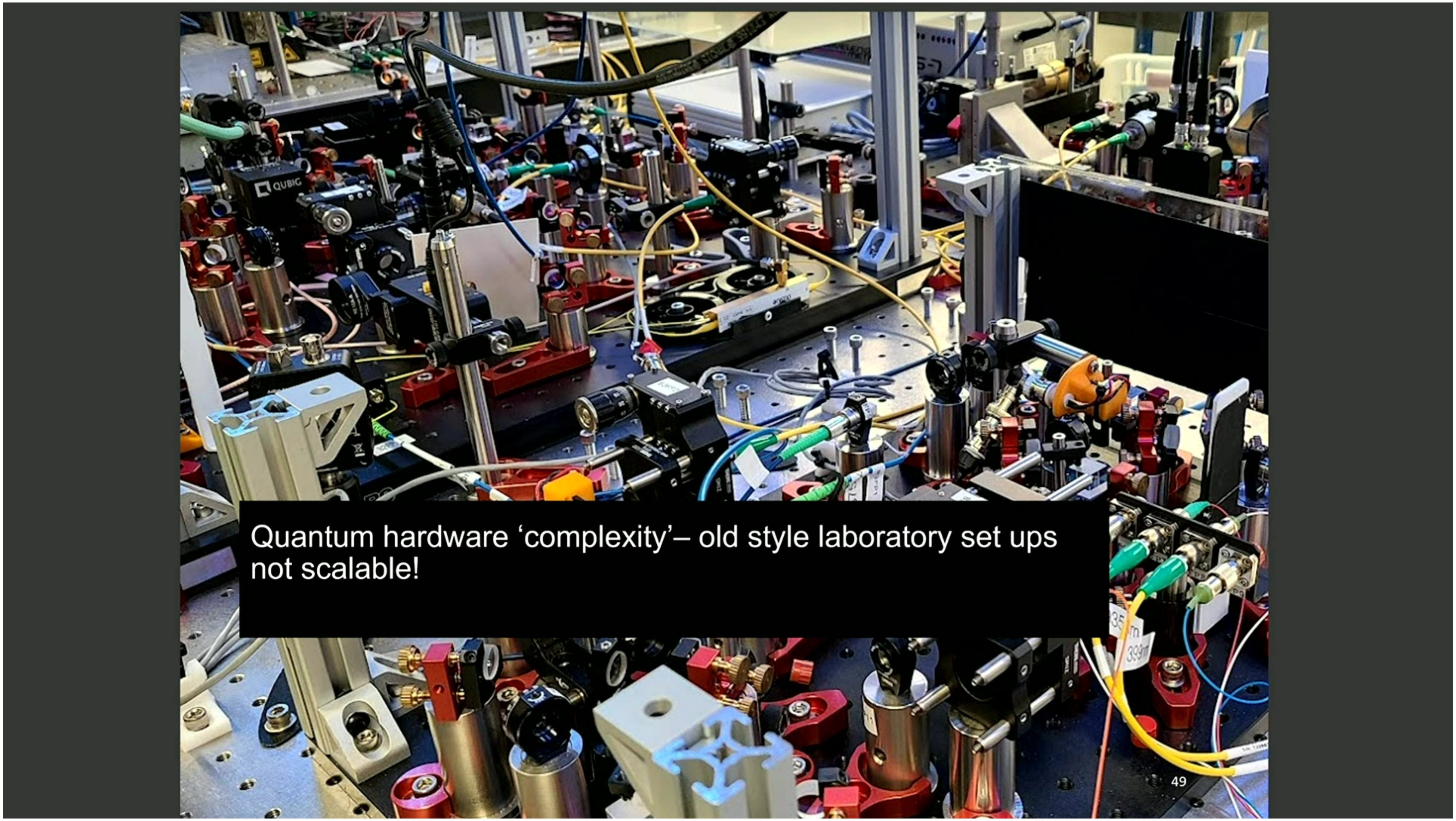
The pair of ions evolve under H.

$$H = \hbar \sum_{ij} J_{ij} \sigma_i^x \sigma_j^x$$



Ongoing collaboration with Tim Hsieh, Liujun Zou on Hamiltonian benchmarking

Preliminary Data


Quantum hardware 'complexity'– old style laboratory set ups not scalable!
49

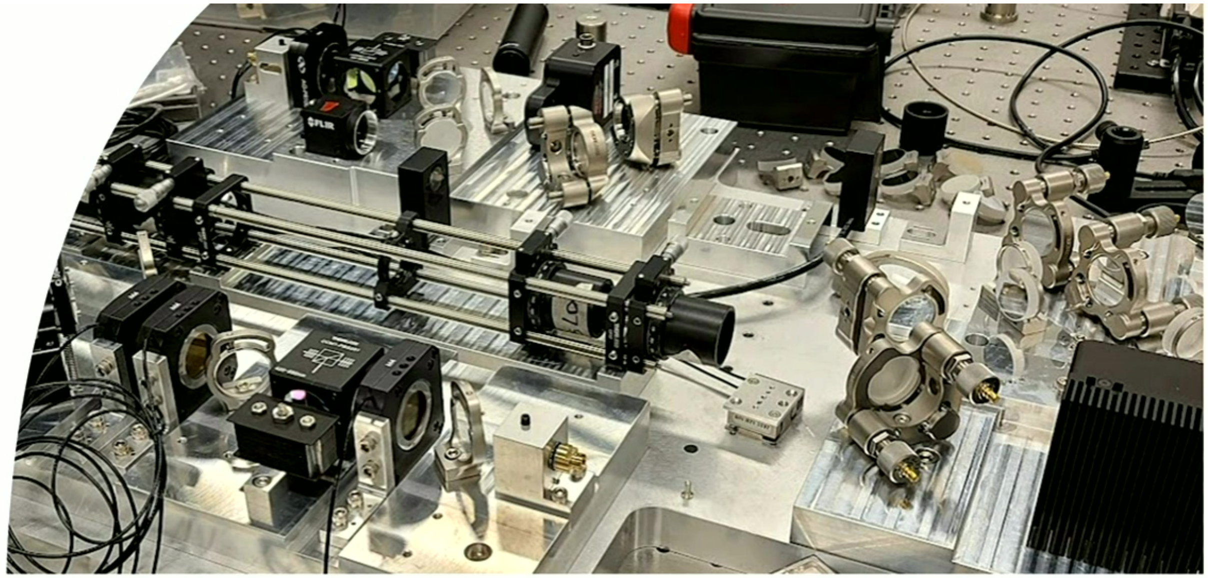
Systems engineering approach

CAD optimization and Custom CNC-milled optics ‘pegboards’ for stability and compactness!

Start up from the lab →
Lightflow Optics Inc.

LightFlow

Optimal design flow for optical circuits



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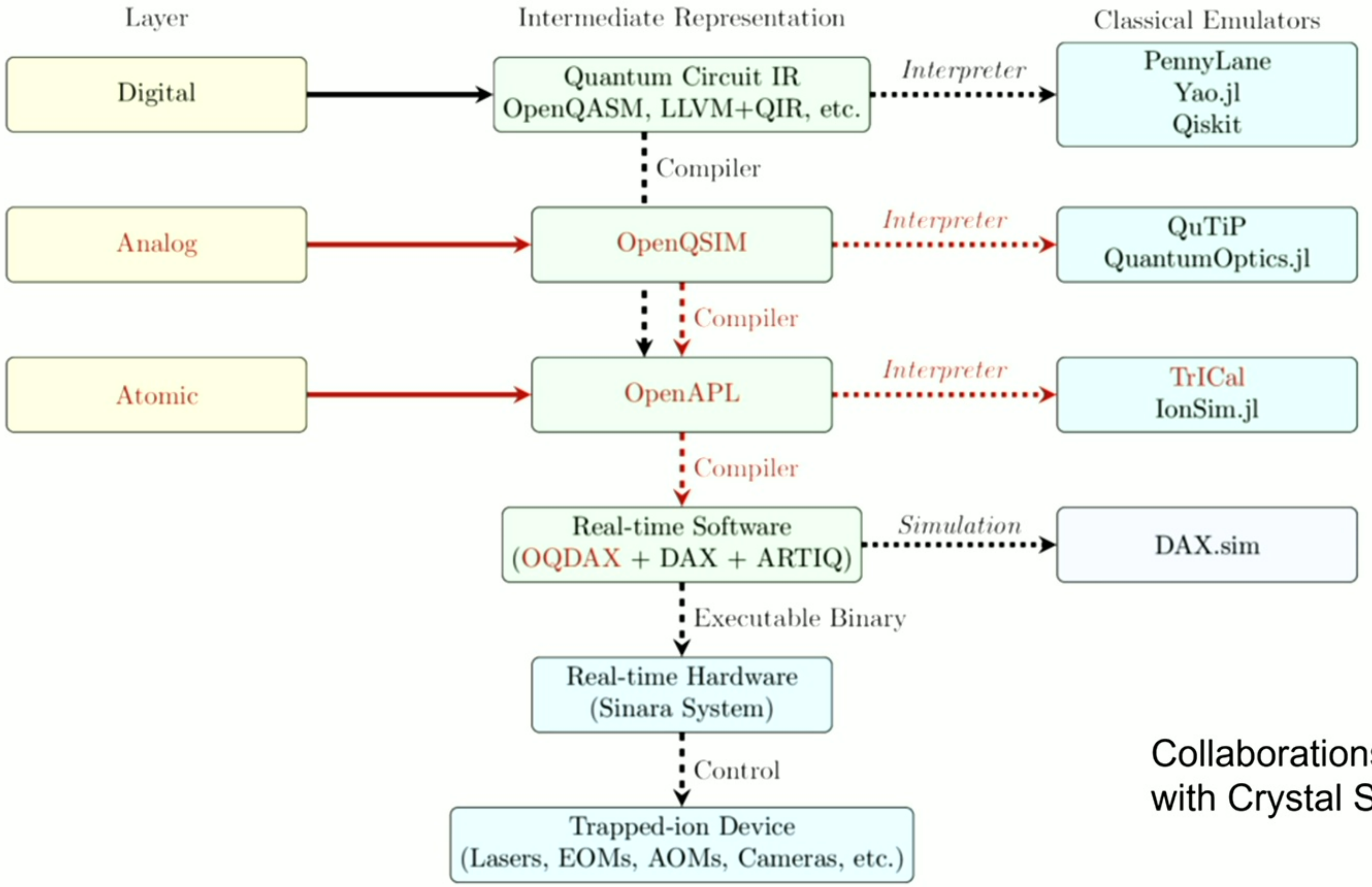
Development of fullstack quantum operating systems!



Collaborations
with Crystal Senko, Roger Melko

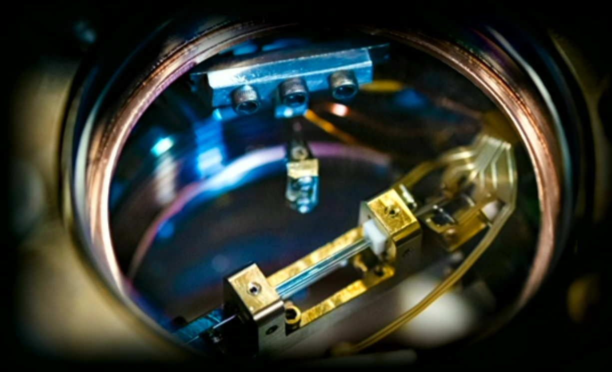
Crystal Senko

Roger Melko

Greg Dick (CEO)

Rajibul Islam

An Accessible Quantum Platform



Open Quantum Design

OpenQuantumDesign.org

Open Source
Non-profit organization to foster collaborations and build strong research ecosystems.

Full Stack
Open hardware and software at all levels, providing flexibility and intuitive tools.

Quantum Computing
Robustly engineered trapped-ion hardware for tackling difficult problems.

Summary

- Trapped ions – a versatile platform for quantum simulation. Strength – versatility of interactions including arbitrarily programmable all-to-all couplings, long coherence time (compared to gate and measurement time)
- We are developing trapped-ion programmable quantum simulators
  - ***Amethyst*** – Our first gen quantum simulation testbed that demonstrated native anisotropic XY interactions, feasibility of in-situ mid-circuit reset and measurement
  - ***Bloodstone*** – Arbitrary single and two-qubit gates on >30 Yb+ ions, mid-circuit measurement and reset (arguably the lowest vacuum pressure of any room temp ion system achieved)
  - **Beryl** – Fully-connected spin system with up to 16 Ba+ ions (qubits and possibility of extending to qudit operations), shuttling operations.
- Development of open-source full-stack control with Open Quantum Design!