Realization of a phononic network with collective modes in trapped ion system

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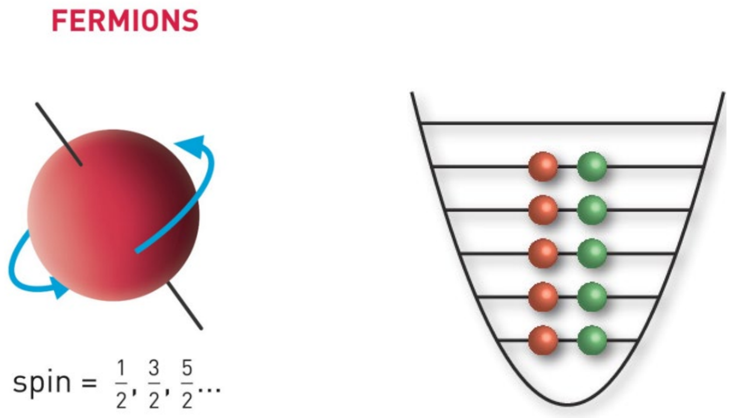
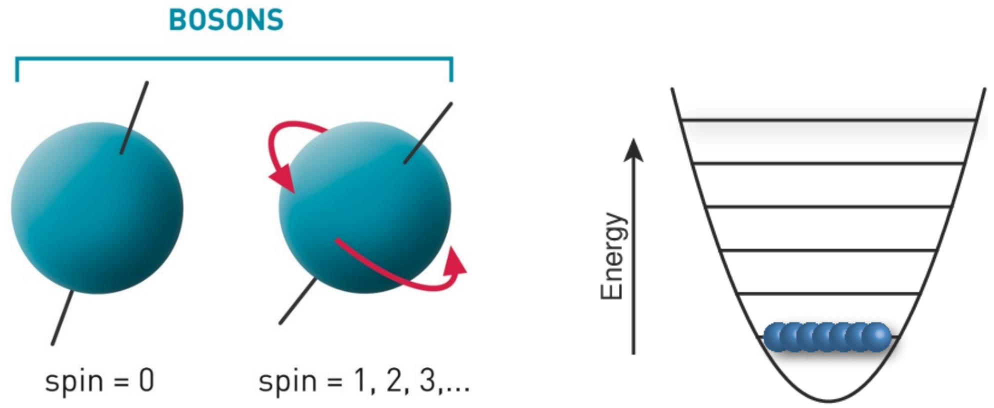
- Bosonic System: Advantage, Limitation and Application
- Phonon: A New Candidate of Realizing Bosonic System
- Trapped Ions: Programmable and Scalable Platforms
- Demonstration: Tomography with Minimum Resources
- Conclusion and Future Plans

Why we choose Bosons?





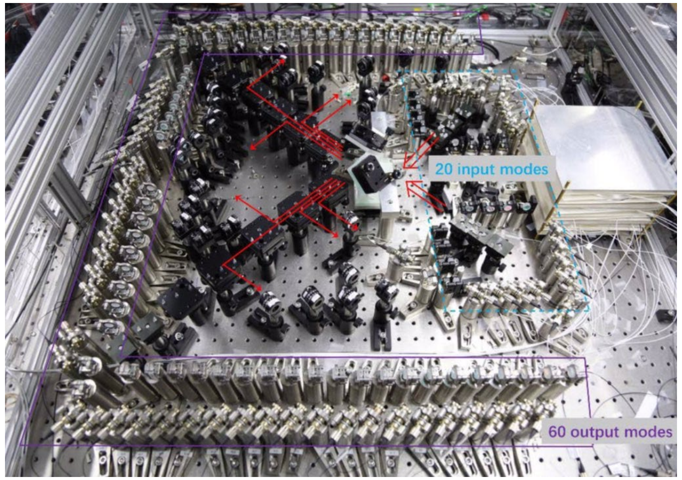
Fermionic System

- For a system with M two-level fermions(qubits), the Hilbert space of the system is 2^M
- Evolution of fermionic system follows the matrix determinants (P problem)

Bosonic System

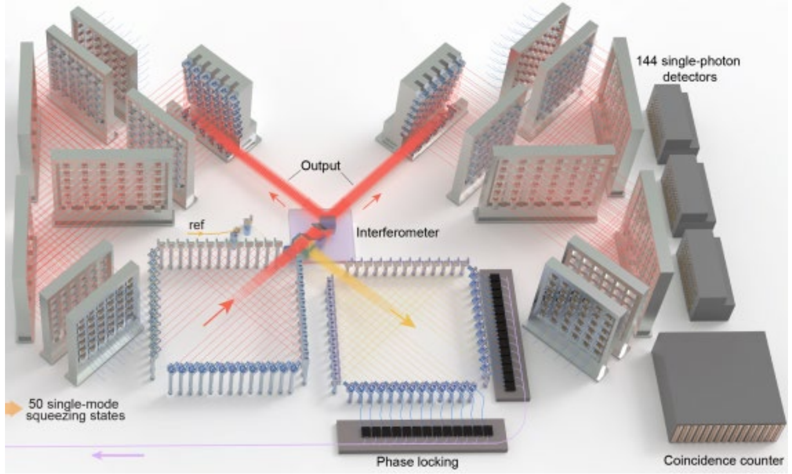
- For an N mode system with M bosons(N can be much larger than 2), the Hilbert space of the system is N^M
- Evolution of Bosonic system follow the matrix permanents (#P-hard problem)

Partially Programmable Bosonic Systems (Photonic Platforms)



Boson sampler with 60 modes[1] (2019)


Gaussian boson sampler with 100 modes[2] (2020)

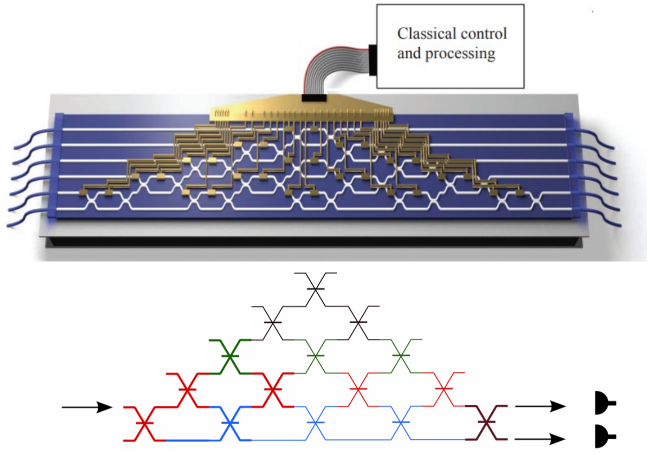


Gaussian boson sampler with 144 modes with programmable phase[3] (2021)

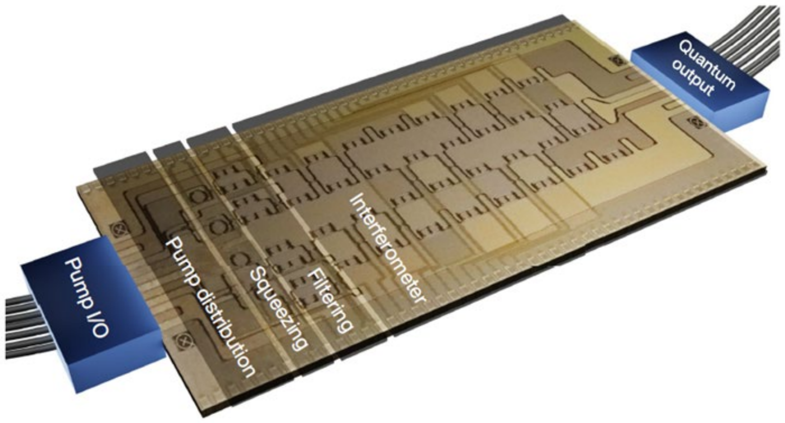
- Dimension of Hilbert space of Boson Sampler develop fast with a speed of 10^{14} per year
- Have already realized quantum advantage over the simulation capability of classical computers
- Only input states are programmable for generating different sampling tasks
- Photon loss inside interferometers and the state preparation & detection are non-deterministic

[1] Wang H, Qin J, Ding X, et al. Physical review letters, 2019, 123(25): 250503.
[2] Zhong H S, Wang H, Deng Y H, et al. Science, 2020, 370(6523): 1460-1463.
[3] Zhong H S, Deng Y H, Qin J, et al. arXiv preprint arXiv:2106.15534, 2021.

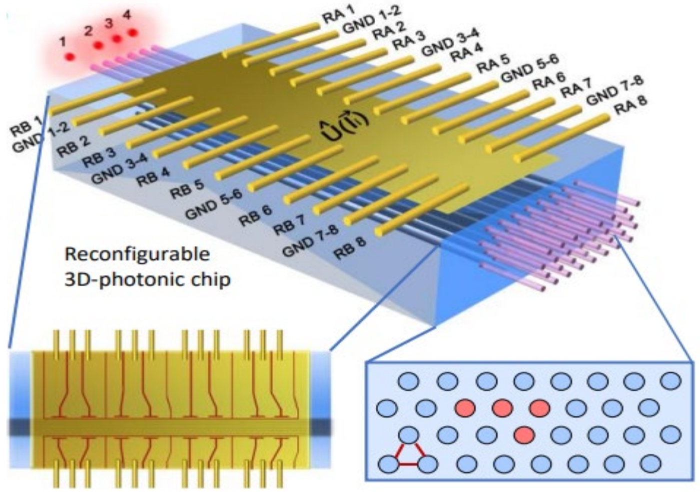
Fully Programmable Bosonic Systems (Photonic Platforms)



Universal Linear Optical Processor with 6 modes[1] (2015)



Programmable nanophotonic chip with 8 modes[2] (2020)

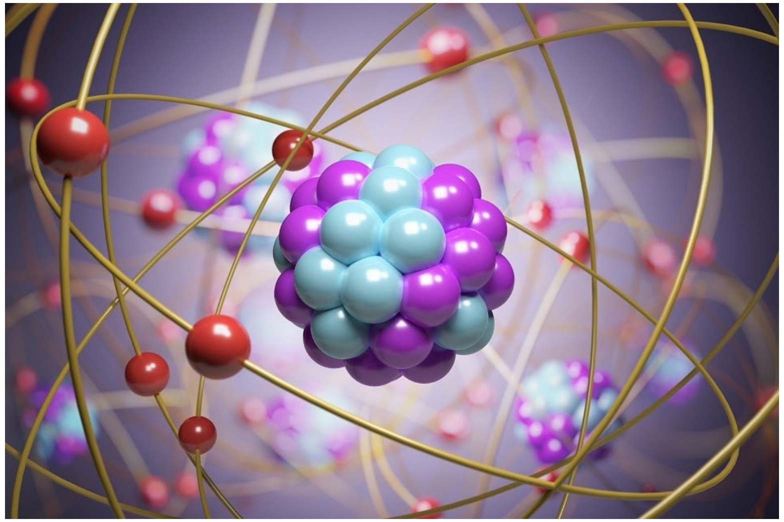


Reconfigurable 3D-photonic chip with 32 modes[3] (2021)

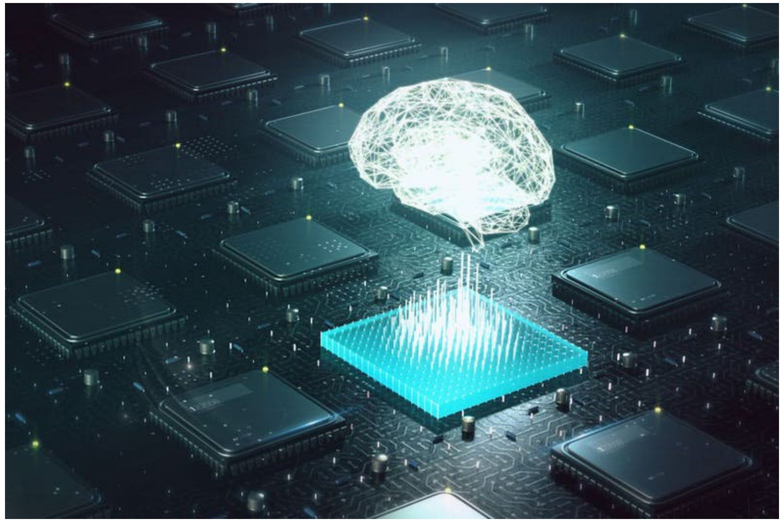
- Input states & interferometers are programmable
- Have already demonstrated some quantum algorithms with linear optics
- Still have non-deterministic state preparation & detection with a photon loss

[1] Carolan J, Harrold C, Sparrow C, et al. Science, 2015, 349(6249): 711-716.
[2] Arrazola J M, Bergholm V, Brádler K, et al. Nature, 2021, 591(7848): 54-60.
[3] Hoch F, Piacentini S, Giordani T, et al. arXiv preprint arXiv:2106.08260, 2021.

Applications



Quantum Chemistry [1] [2]



Quantum Machine Learning [3] [4]

Graph Optimization [5] [6]

- With additional squeezed input states, a Gaussian boson sampler with more applications can be realized
- **How to avoid Boson loss?**

[1] J. Huh, G. G. Guerreschi, B. Peropadre, J. R. McClean, and A. Aspuru-Guzik, Nat. Photonics 9, 615 (2015).
[2] J. Huh and M.-H. Yung, Sci. Rep. 7, 1 (2017).
[3] M. Schuld and N. Killoran, Phys. Rev. Lett. 122, 040504 (2019).
[4] U. Chabaud, D. Markham, and A. Sohbi, arXiv:2102.04579 (2021).
[5] Bromley T R, Arrazola J M, Jahangiri S, et al. Quantum Science and Technology, 2020, 5(3): 034010.
[6] Arrazola J M, Bromley T R. Physical review letters, 2018, 121(3): 030503.

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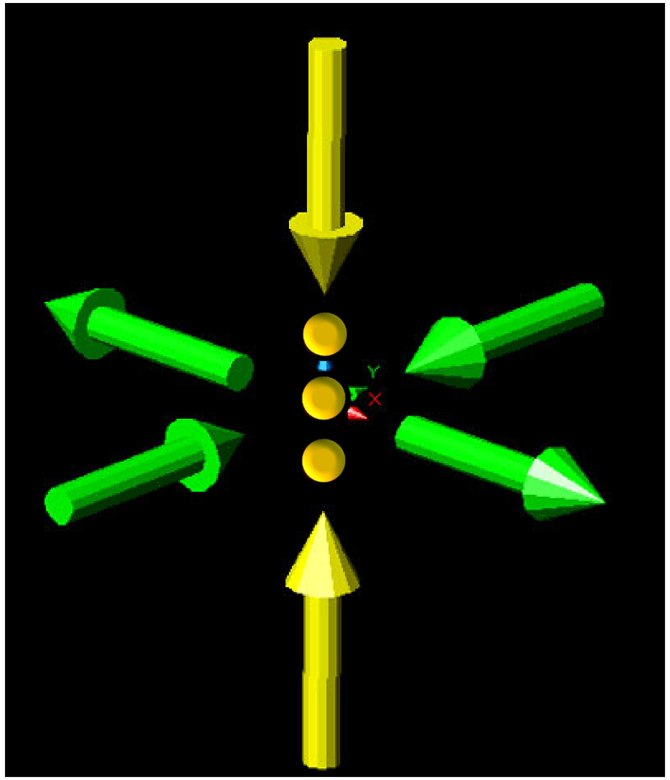
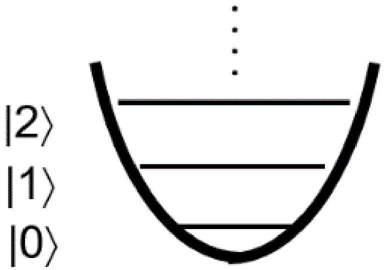
Phonon: Quantized Energy of Harmonic Oscillators



Ions trapped in an electric field

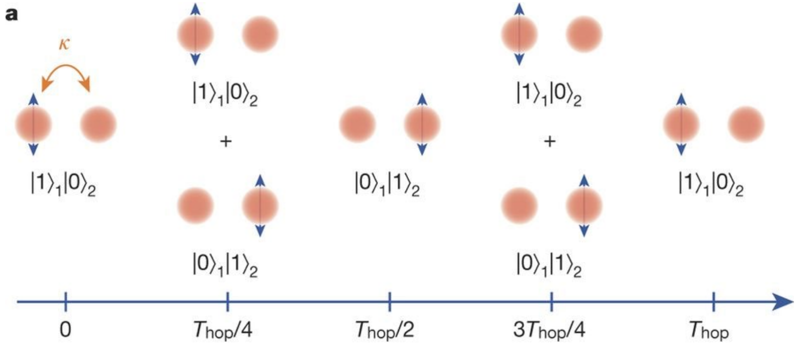
- Paul Trap: with DC electric field in z (axial) direction, and RF electric field in x and y (transverse) direction
- With transverse electric field fairly stronger than the axial field, ions will line up along z direction
- The vibration of ions in all directions can be approximately considered as harmonic oscillations[1], the quantized energy of which is phonons
- Depend on the distance between ions, the Coulomb interaction will affect the vibrational mode of the ion chain
- Local vibration (far and weak); Collective vibration (near and strong)
- **Most of the collective modes have an extremely low heating rate (<1 quanta/s) that can provide a good conservation of phonon numbers**



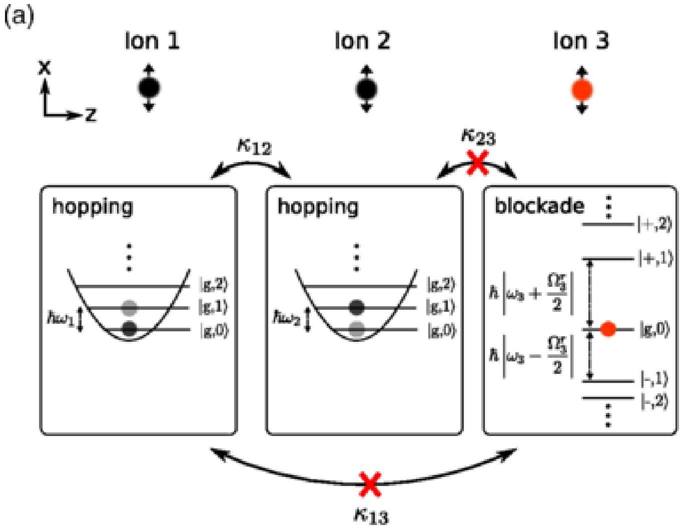
Harmonic Oscillators Energy Level

[1] Leibfried D, Blatt R, Monroe C, et al. Reviews of Modern Physics, 2003, 75(1): 281.

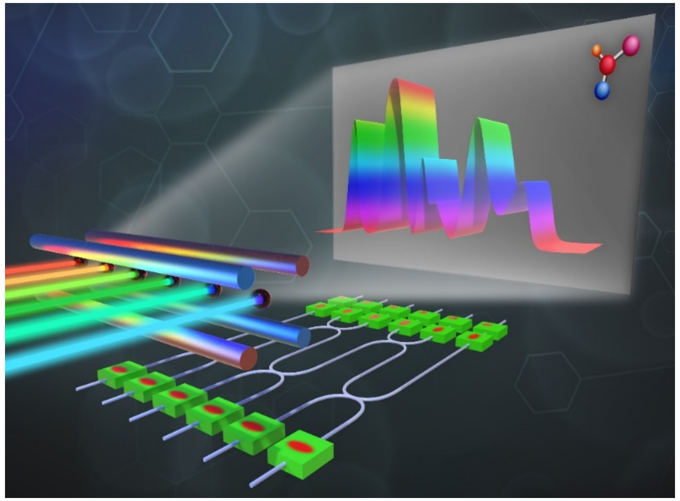
Exploring Phononic System with Local Vibrational Modes



Hong-Ou-Mandel effect with 2 local vibration[1] (2015)



Phonon hopping and blockade with 3 local vibration[2] (2018)

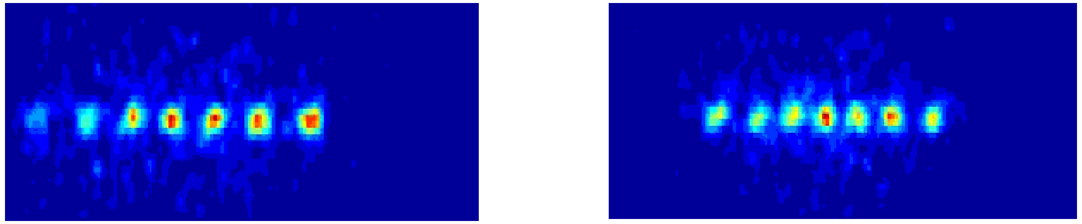


Quantum optical emulation with 2 local vibration[3] (2018)

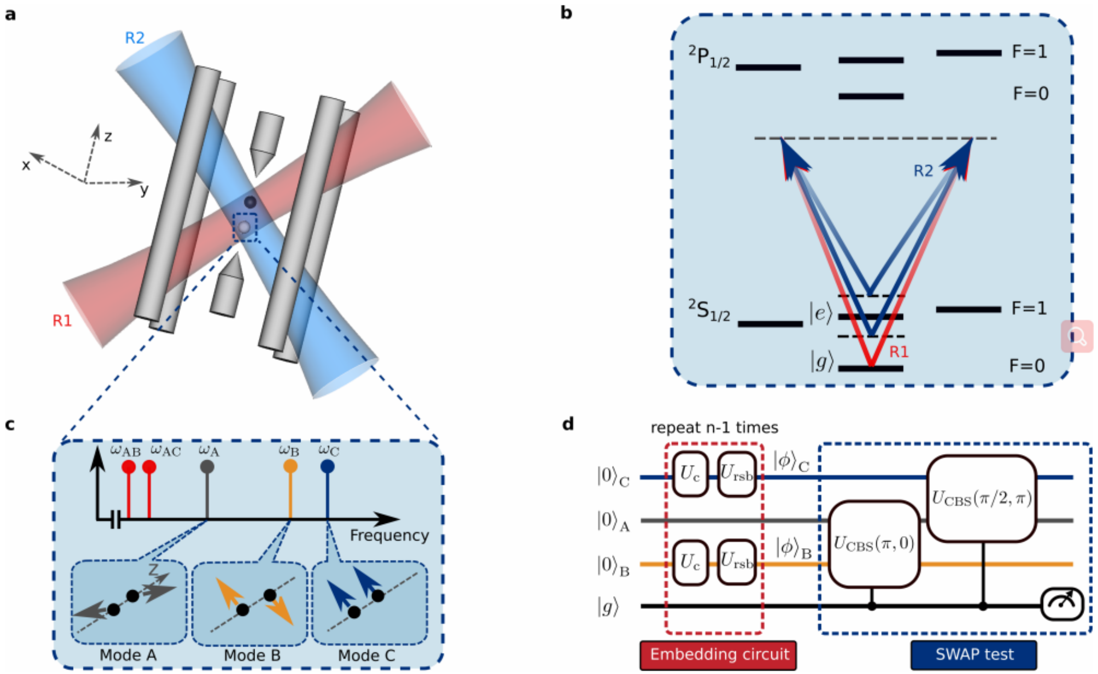
- **Phonons in trapped ion system are indistinguishable, the interference between phonons is a purely quantum effect, the initial state can be deterministically prepared and detected through a sideband transition**
- With Coulomb interaction (far and weak) and phonon blockade, we can control the naturally hopping of phonons between two nearest neighbor local vibrational modes
- Limited by nearest neighbor interaction, it takes much longer time to build a fully connected phononic network with local vibrational modes

[1] Toyoda K, Hiji R, Noguchi A, et al. Nature, 2015, 527(7576): 74-77.
[2] Debnath S, Linke N M, Wang S T, et al. Physical review letters, 2018, 120(7): 073001.
[3] Shen Y, Lu Y, Zhang K, et al. Chemical science, 2018, 9(4): 836-840.

Building Phononic System with Collective Vibrational Modes



Collective vibrational modes in axial direction (From Univ. Innsbruck)



Phonon SWAP gate between 2 collective vibrational modes[1] (2021)

- Two Raman beams (blue and red) are used to control the state of ions
- By preparing one ion in an uncontrollable initial state, only the other ion can be addressed by Raman beams to realize a SWAP gate between collective vibrational modes
- Through a full connection between all the ions and modes, a more efficient phonon network is possible
- When the number of ions increase, it's not easy to prepare such an initial state
- **How to construct a scalable and programmable system with collective vibrational modes?**

[1] Nguyen C H, Tseng K W, Maslennikov G, et al. arXiv preprint arXiv:2104.04168, 2021.

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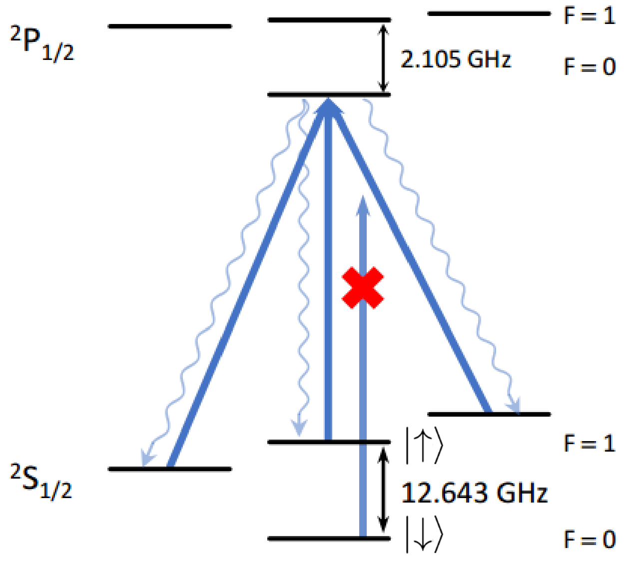
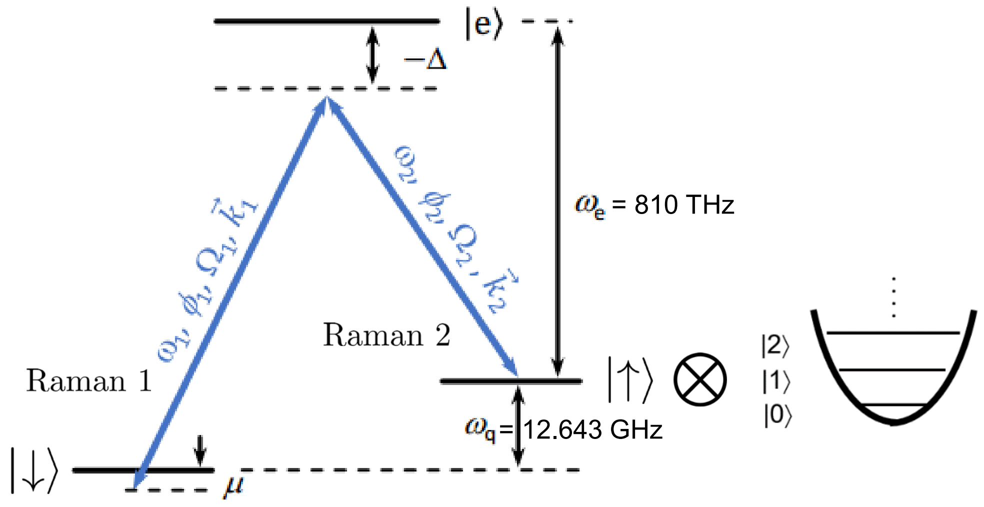
Control Yb⁺ Ions with Lasers



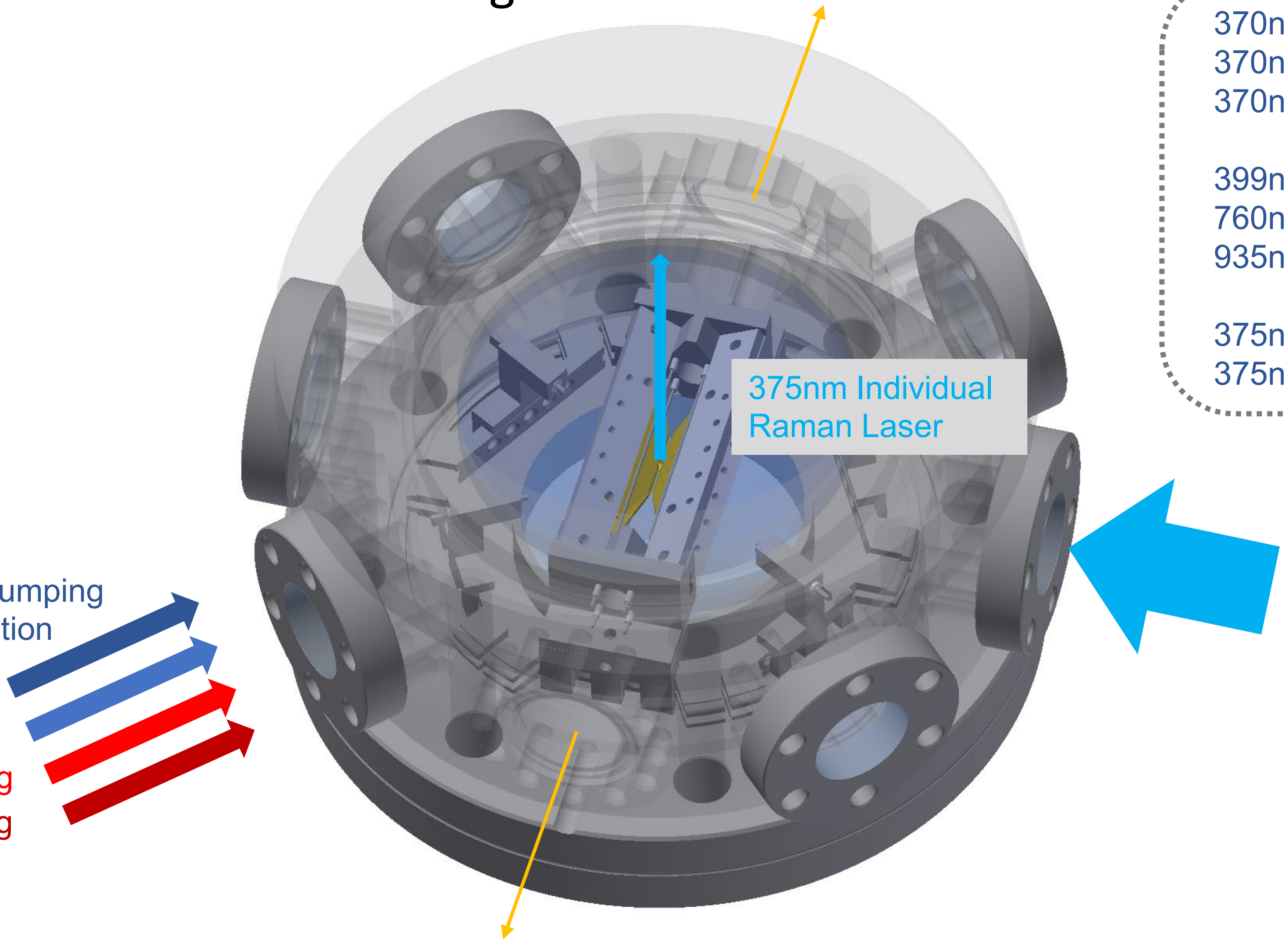
State Detection of Yb Ions



Λ-type two photon Raman transition

- Our qubit states are encoded in $S_{1/2}$ level with an energy splitting of 12.6GHz
- A 369nm CW laser is used for state detection to get fluorescence from spin up state
- Two 375nm pulsed lasers from different directions are used to realized a two photon Raman transition to drive our qubits.
- The vibrational modes of the ions can be driven in the Raman process with a coupling to our qubits (Jaynes-Cumming model)

Vacuum chamber and laser arrangement

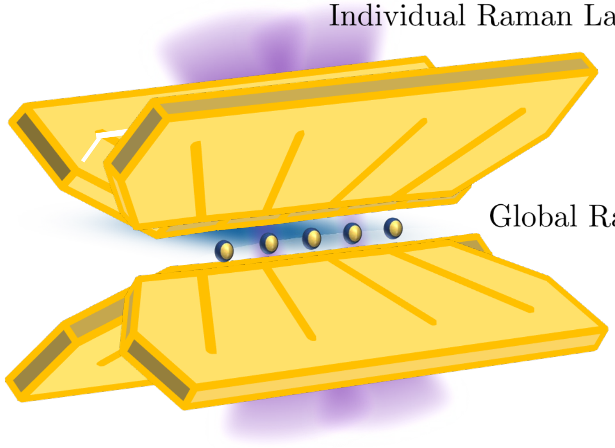


370nm Cooling: $\approx 10\ \mu W$
370nm Detection: $\approx 5\ \mu W$
370nm Pumping: $\approx 2\ \mu W$

399nm Ionization: $\approx 5\ \mathrm{m}W$
760nm Repumping: $\approx 10\ \mathrm{m}W$
935nm Repumping: $\approx 20\ \mathrm{m}W$

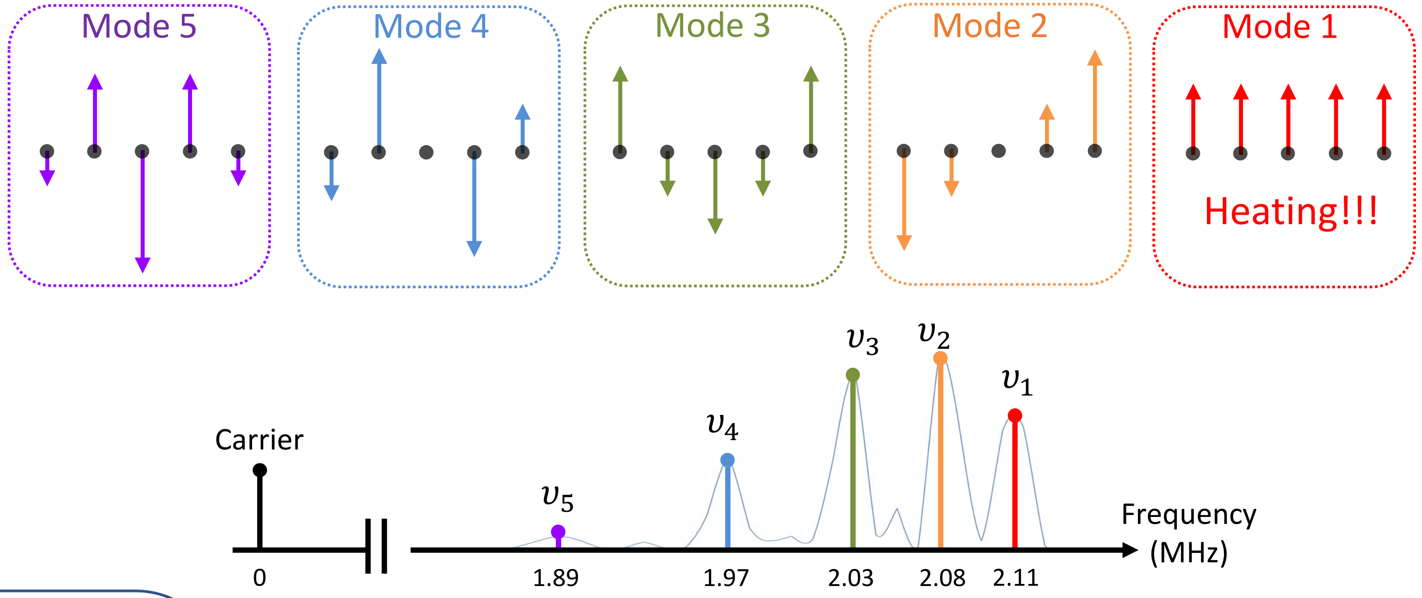
375nm Individual Raman: $\approx 1\ \mathrm{m}W \times 5$
375nm Global Raman: $\approx 100\ \mathrm{m}W$

Individual Laser System for Raman Transition



Zhang, S., Lu, Y., Zhang, K. et al. Nat Commun 11, 587 (2020).

Collective Vibrational Modes in Transevers Direction



- Our Jaynes-Cummings Hamiltonian for interactions between ions and Raman Lasers takes the form:

$$H_I \approx \frac{\Omega}{2}\left[\sigma_+\left(1 + i\eta a e^{-i\nu t} + i\eta a^\dagger e^{i\nu t}\right) e^{-i\mu t + i\phi} + \text{h.c.}\right]$$

- Which can be divided into three parts:

$$H_{car} = \frac{\Omega}{2}(\sigma_+ e^{i\phi} + \text{h.c.}),$$ Carrier: Rotate qubit states

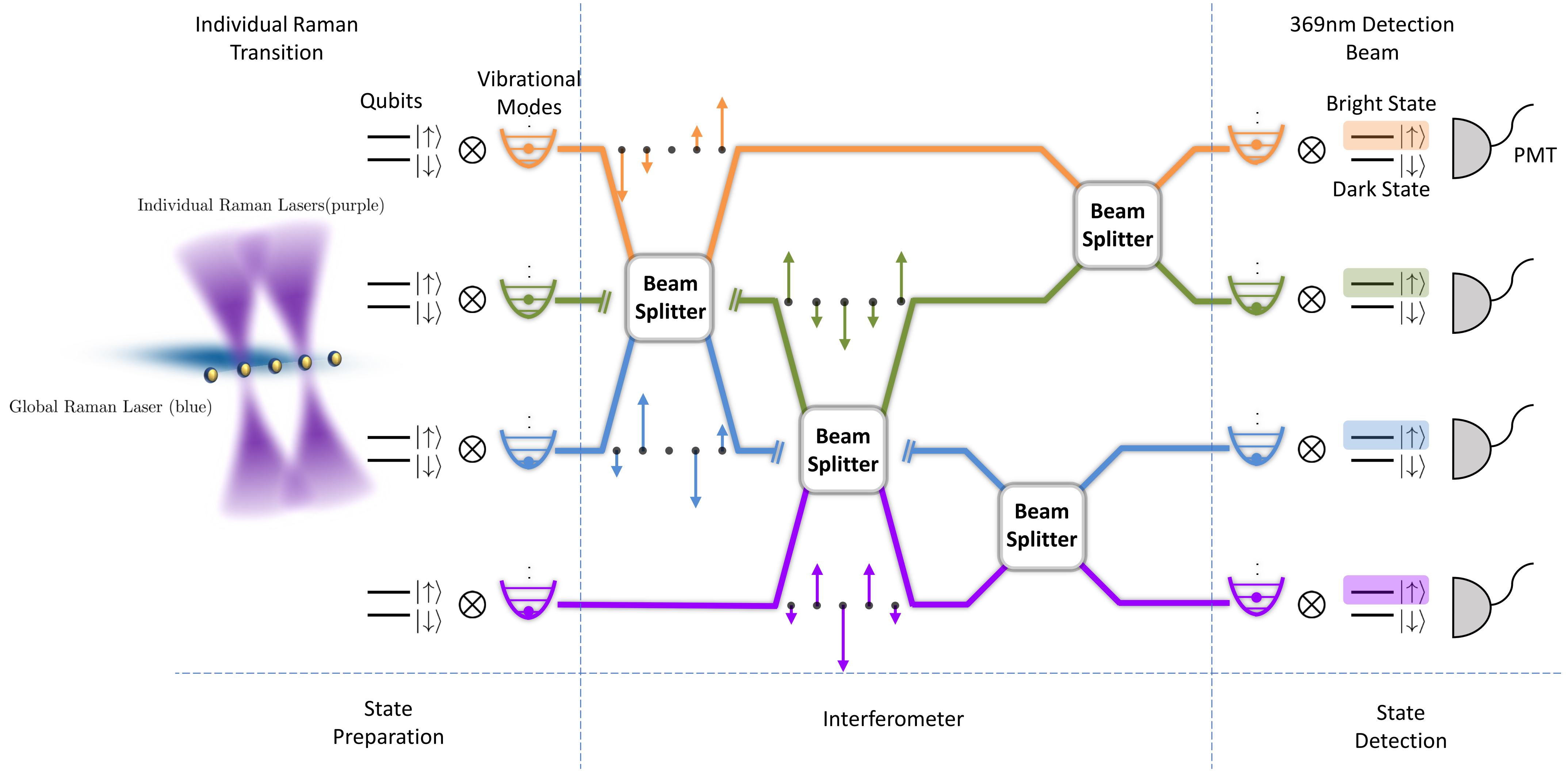
$$H_{rsb} = \frac{i\eta\Omega}{2}(\sigma_+ a e^{i\phi} - \text{h.c.}),$$ Red Sideband: Rotate qubit with phonons(-1)

$$H_{bsb} = \frac{i\eta\Omega}{2}(\sigma_+ a^\dagger e^{i\phi} - \text{h.c.}),$$ Blue Sideband: Rotate qubit with phonons(+1)

- By adjusting the detuning of Raman lasers, different transitions will be resonantly driven with different frequency

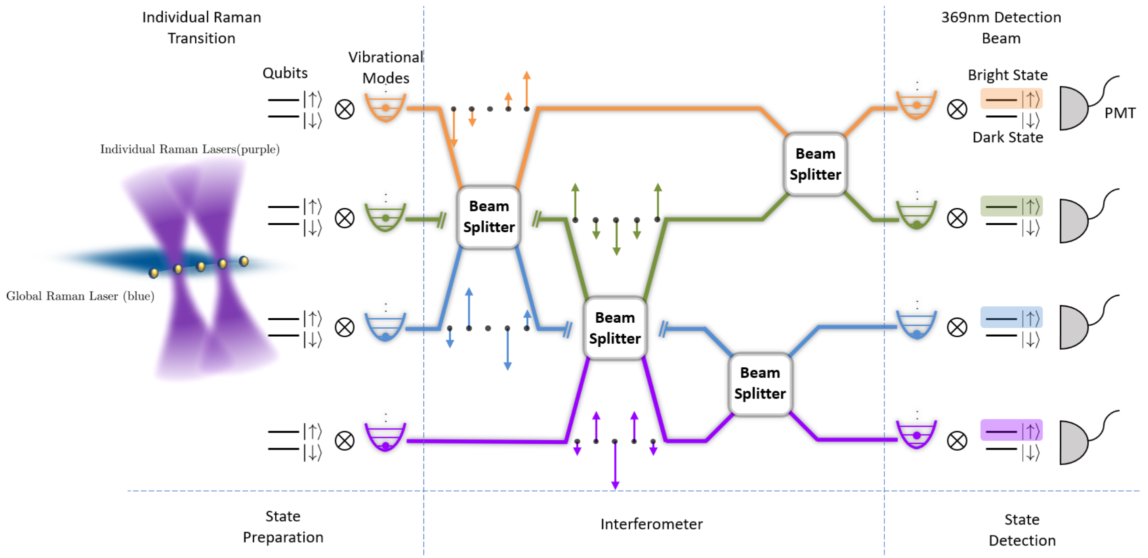
- Collective vibrational modes offer a full connection between almost all the modes and ions, principally, we can choose one ion to drive almost all the modes

Realizing a Scalable and Programmable Phononic Network



[1] W Chen, et al. Nature Physics, 2023, 19(6): 877-883.

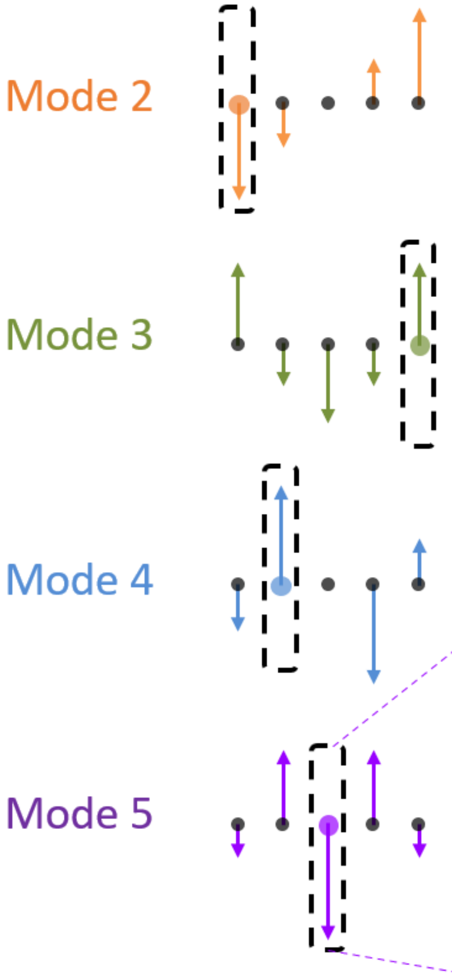
Realizing a Scalable and Programmable Phononic Network

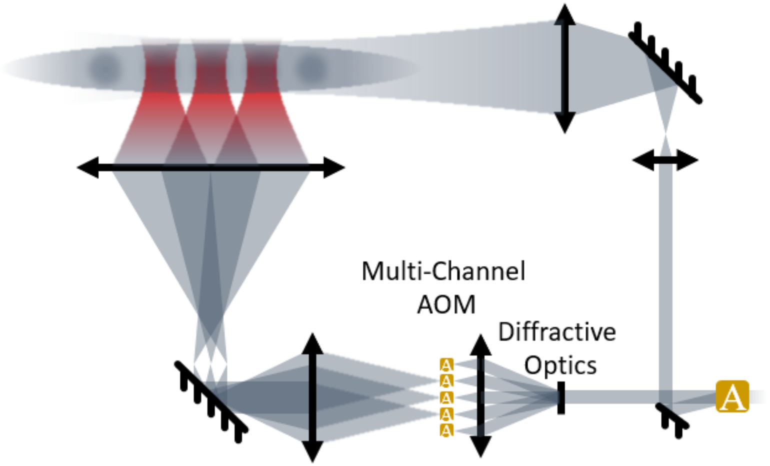


- In this network, phonons (energy) will evolving through different vibrational modes, in fact, it is an energy exchange between modes driven by laser-ion interactions
- **All the parts can be programmed including initial state and interferometer through coupling between qubits and modes**
- Beam splitters between every two modes can be realized regardless of orders, which means the circuit can be much simpler
- **The number of modes increasing with the number of ions, the only thing is to keep the frequency distance between vibrational modes (> 0.05MHz) to reduce off-resonant coupling**
- Both Squeezing and Displacement operations can be added to any part of this system[1], performing a more advanced system such as a Gaussian Boson Sampler

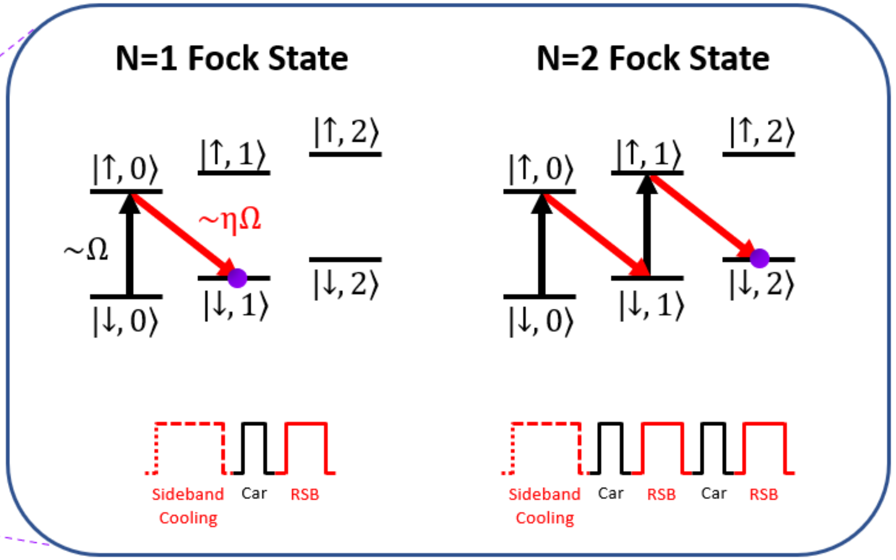
[1] Shen Y, Lu Y, Zhang K, et al. Chemical science, 2018, 9(4): 836-840.

Phonon State Preparation with Mode-Ion Coupling



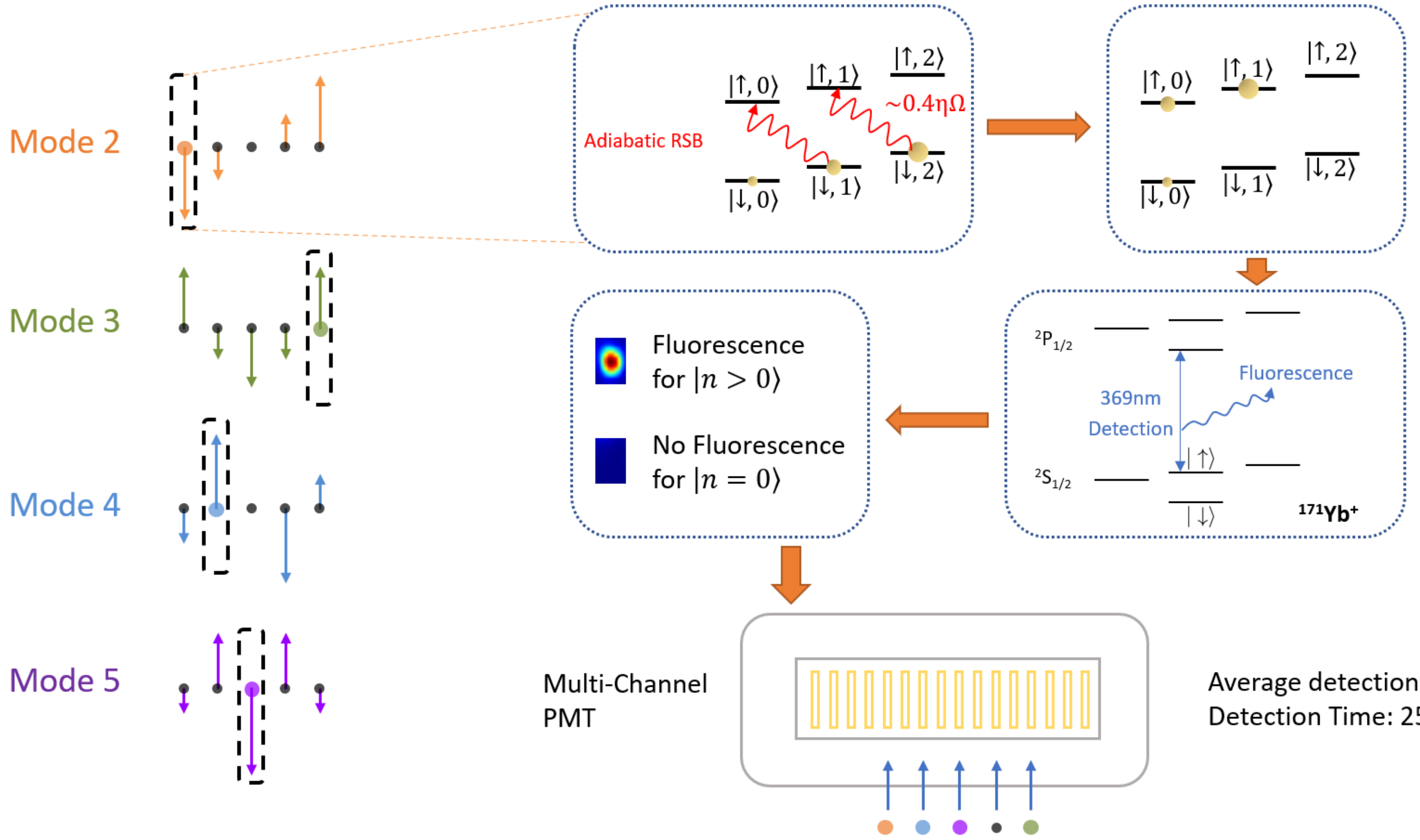


Yao Lu, Shuaining Zhang, Kuan Zhang, et al., Nature **572**, 363 (2019)



- Modes & ions are mapped by choosing the largest coupling strength (Lamb-Dicke Parameter)
- Individual sideband operations generated from diffractive optics element (DOE) and multi-channel AOM are used to control different modes separately
- With a combination of carrier and sideband operations, preparation of any Fock States can be realized

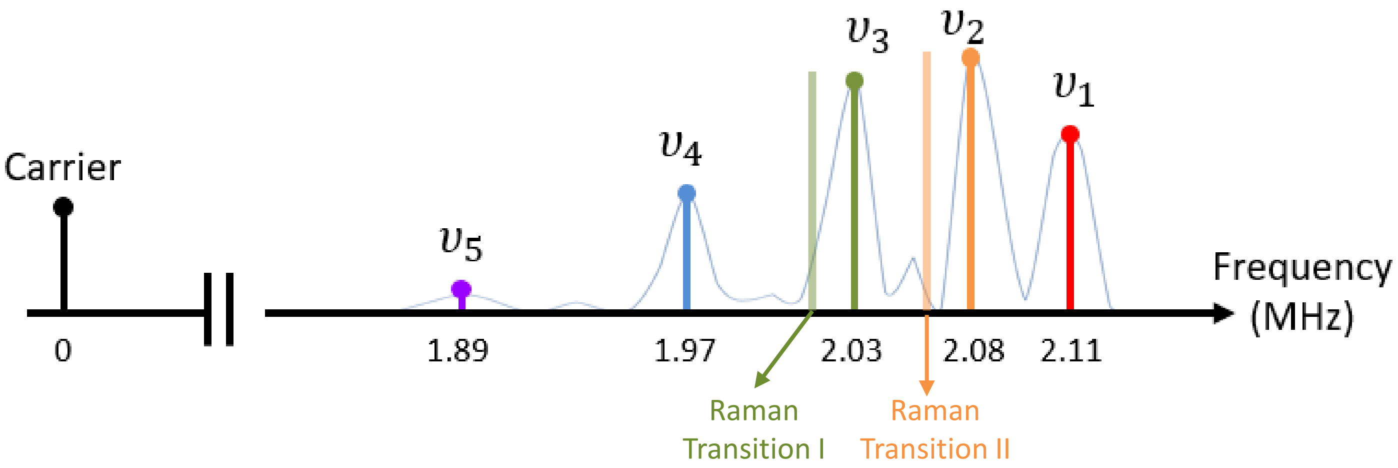
Phonon State Detection with Mode-Ion Coupling

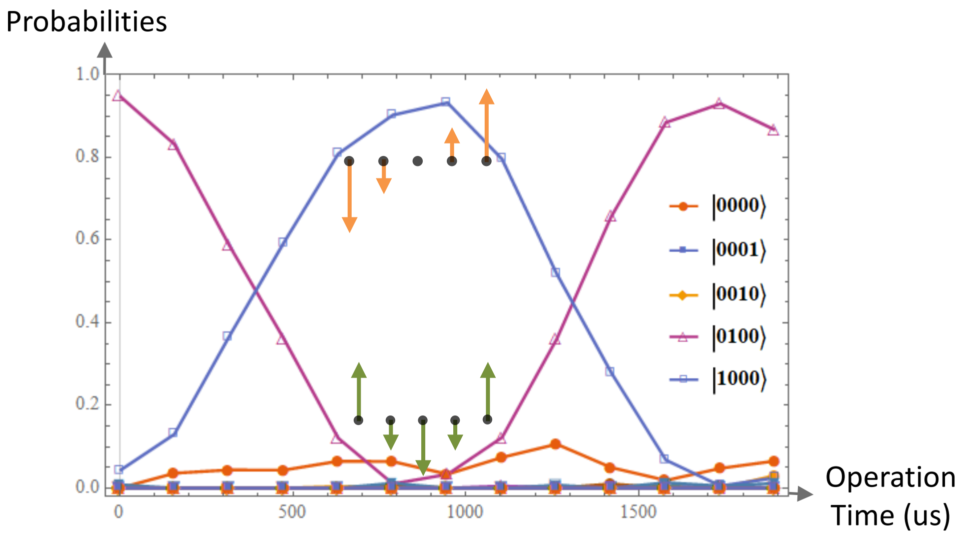


- The mapping between modes & ions keeps the same with state preparation part
- Adiabatic red sideband transition is used to project different phonon states into each ions' bright or dark state
- With detection beam, different phonon states can be distinguished through ions' fluorescence
- A multi-channel PMT is used to individually collect each ions' fluorescence

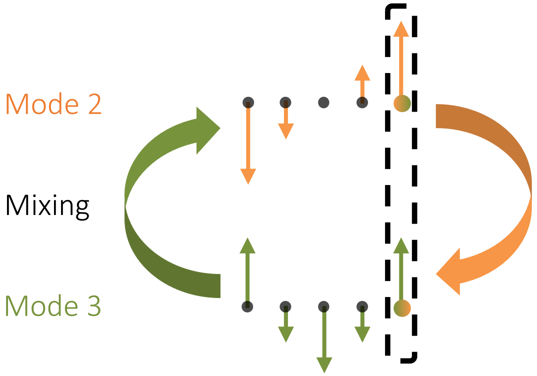
Average detection fidelity: 98.2%
Detection Time: 250 us

Phonon Beam Splitter with Mode-Ion Coupling





Beam splitter between two vibrational modes



- By applying two Raman Transitions at the same time, we realize a spin-dependent[1] beam splitting operation

$$U = e^{i\frac{\eta_2\eta_3\Omega^2}{4\Delta}t\sigma_z(a_2 a_3^\dagger e^{-i\Delta\phi}+a_2^\dagger a_3 e^{i\Delta\phi})}$$

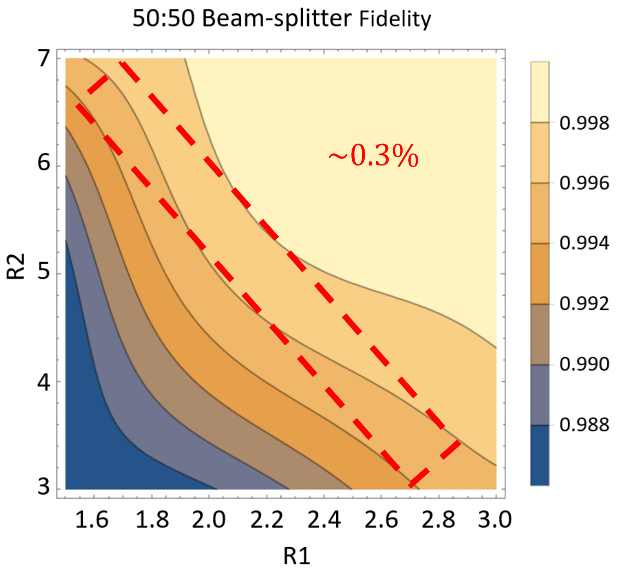
- The rotating angle and phase are controllable by changing Raman lasers' power and phase

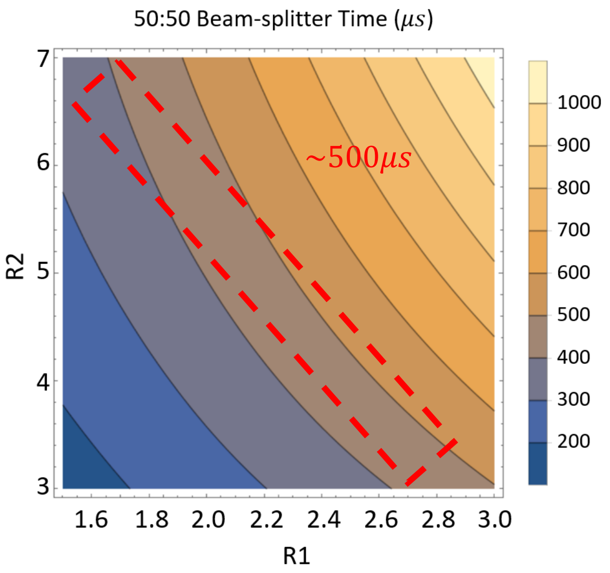
$$\theta(t) = \frac{\eta_2\eta_3\Omega^2}{4\Delta}t$$

$$\Delta\phi = \phi_2 - \phi_3$$

- By changing the frequencies of two Raman transitions, any ion can drive the beam splitting operation between two chosen vibrational modes
- The frequency distance between vibrational modes should be large enough (> 0.05MHz) to avoid off-resonant coupling

Numerical Simulation of the Influence of Off-resonant Coupling Error





The off-resonant coupling errors and the speed of beam-splitter mainly depends on:

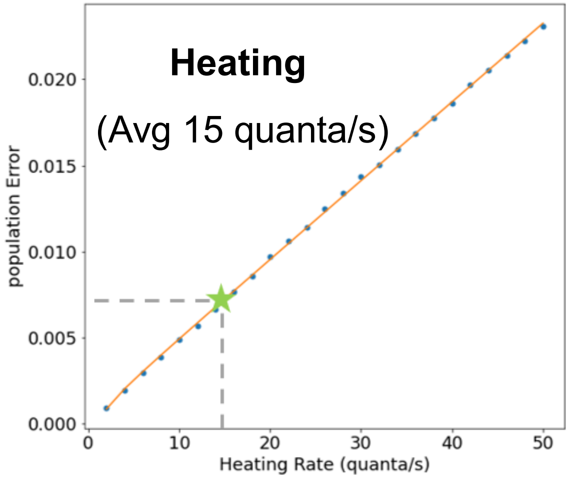
$$R_1 = \Delta_{\mathrm{bs}}/\sqrt{\eta_{j,m}\Omega_{j,m}\eta_{j,n}\Omega_{j,n}} \qquad R_2 = \delta\bar{\nu}_{\mathrm{M}}/\Delta_{\mathrm{bs}}$$

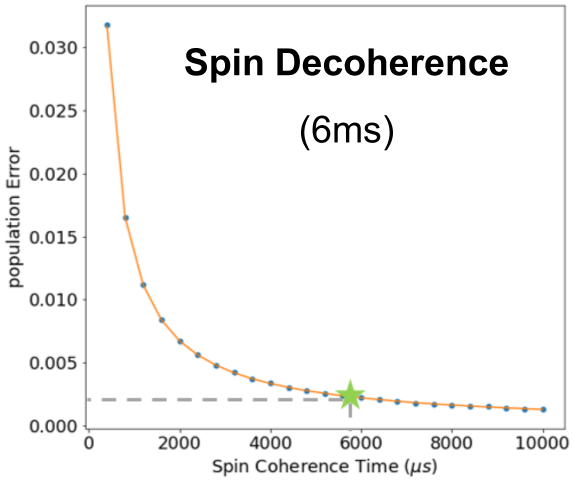
Detuning

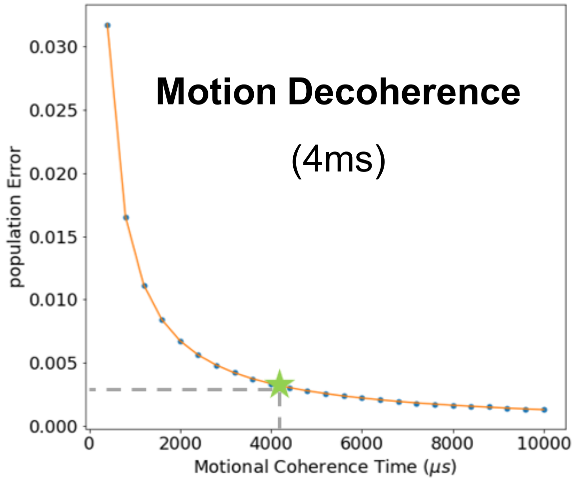
Coupling Strength between laser and modes

Average mode distance (Under equal spacing assumption)

Numerical Simulation of the Influence of Systematic Induced Error







Simulated error rates:

Heating: 0.7%

Spin Decoherence: 0.2%

Motion Decoherence: 0.3%

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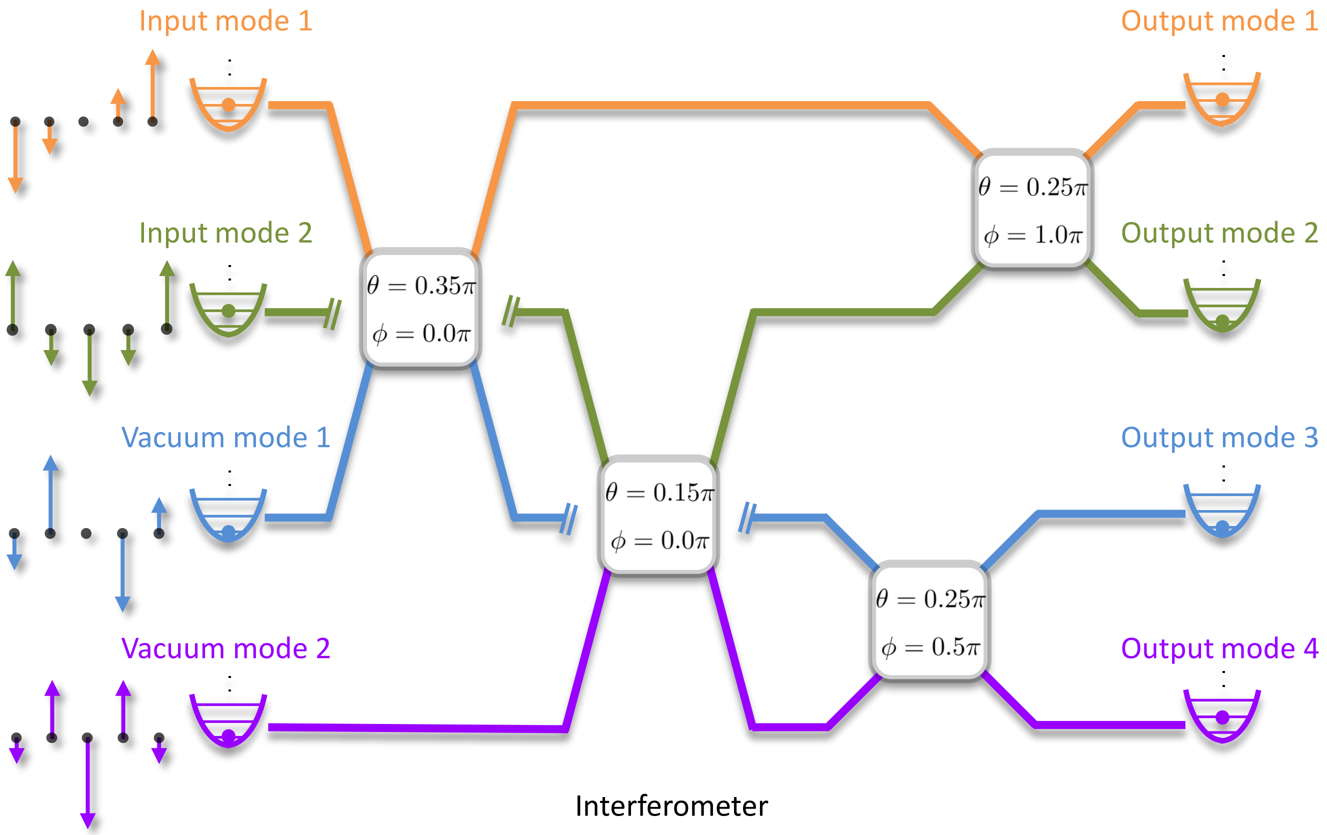
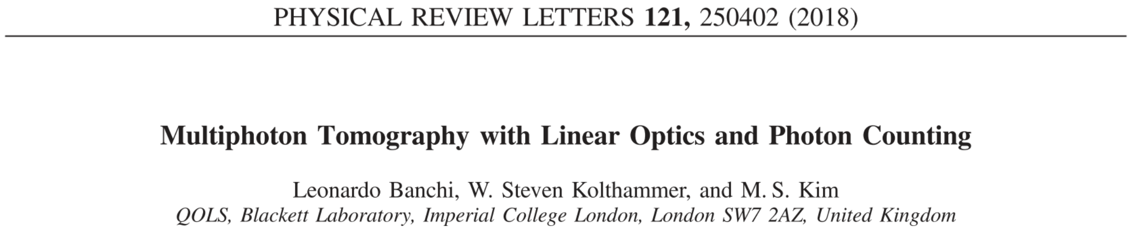
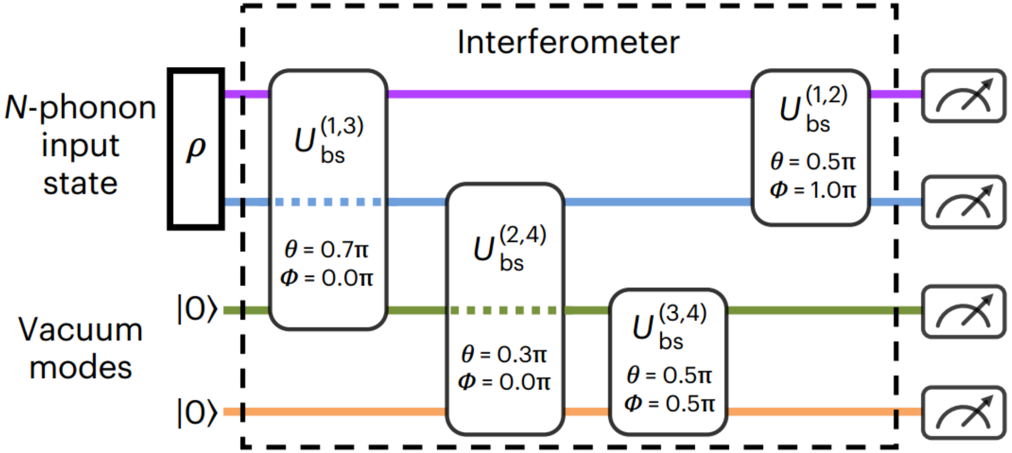
Phonon State Tomography with Ancillary Modes

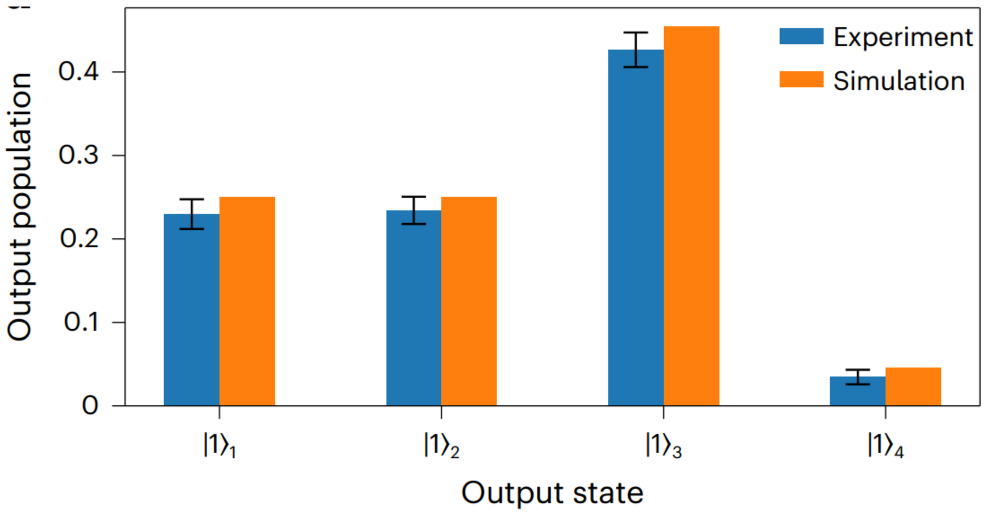


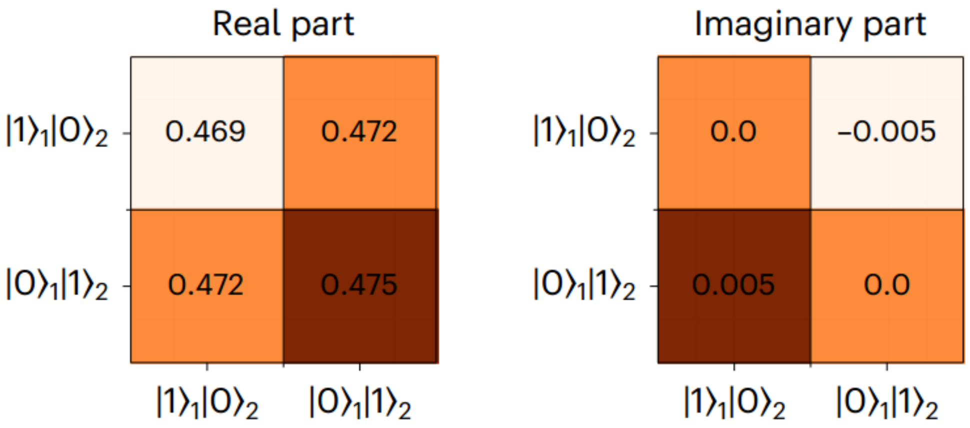


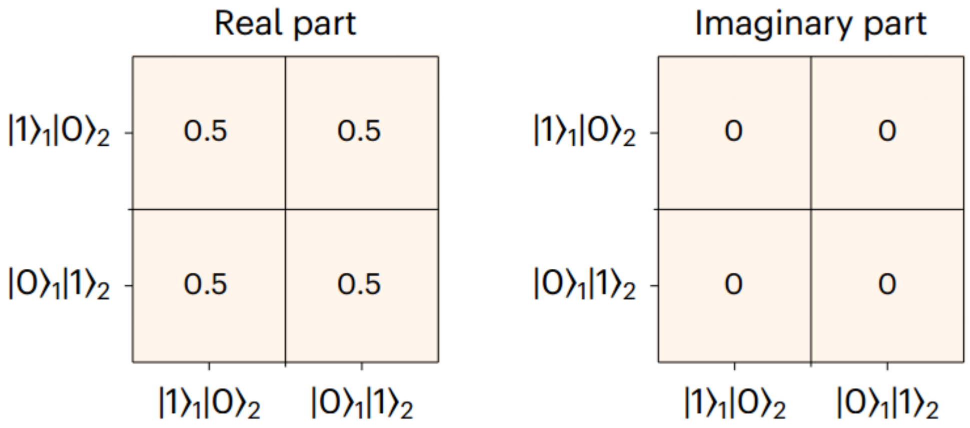
- With 2 vacuum modes used as ancillary modes, for a 2-mode input system, we can realize a one-time reconstruction of the input state from output probabilities regardless of phonon numbers
- The Hilbert space of the system can be easily extended with the same interferometer without any change, which reduce the need of quantum resources to a minimum level
- Based on the pre-knowledge of total input phonon number, only possible output state will be considered
- Phononic system can provide a good conservation of total phonon number

Demonstration: Tomography with Minimum Resources





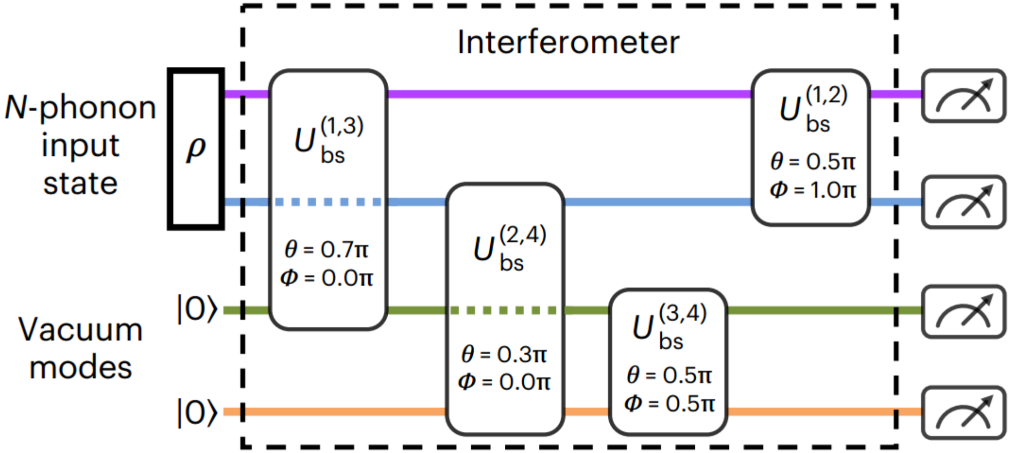


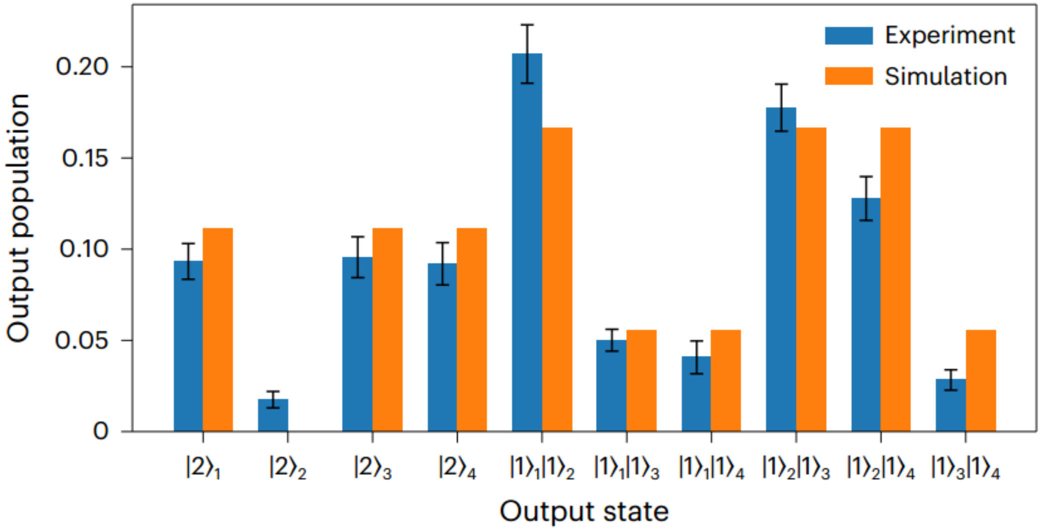


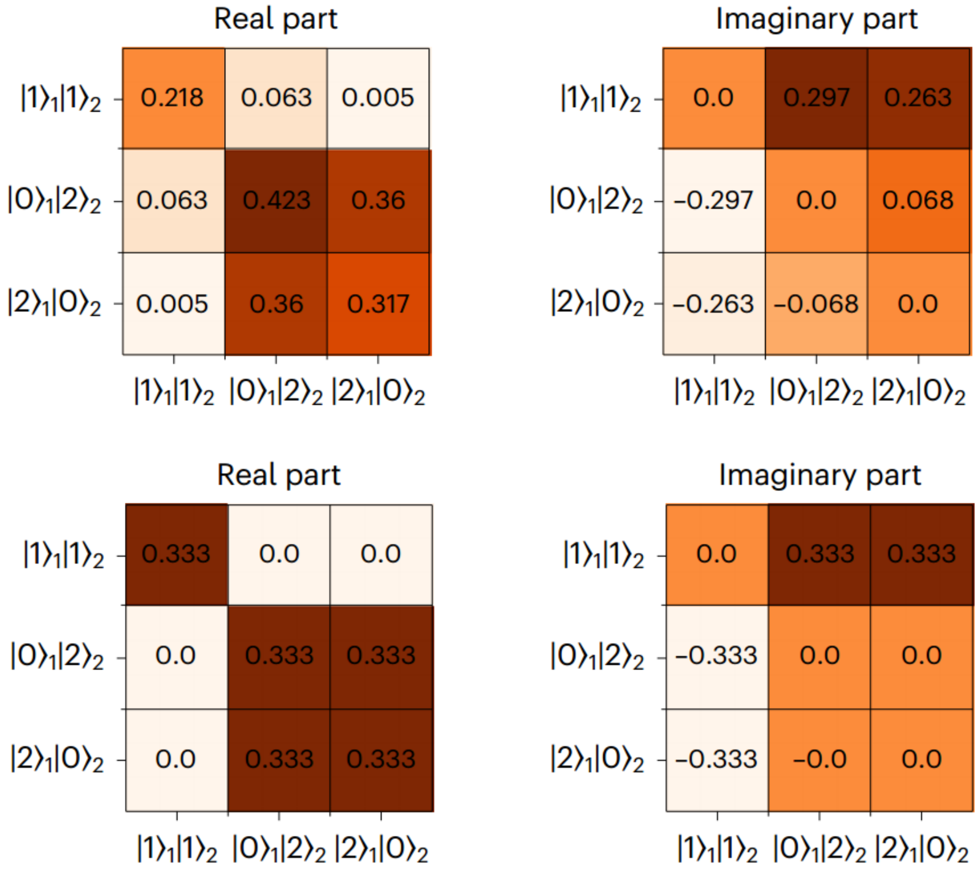
$$|\psi_{in}\rangle = \frac{1}{\sqrt{2}}|1000\rangle + \frac{1}{\sqrt{2}}|0100\rangle$$

Reconstruction Fidelity: 94.5%

[1] W Chen, et al. Nature Physics, 2023, 19(6): 877-883.







$$|\psi_{in}\rangle = \frac{1}{\sqrt{3}}|1,1,0,0\rangle + \frac{i}{\sqrt{3}}|2,0,0,0\rangle + \frac{i}{\sqrt{3}}|0,2,0,0\rangle$$

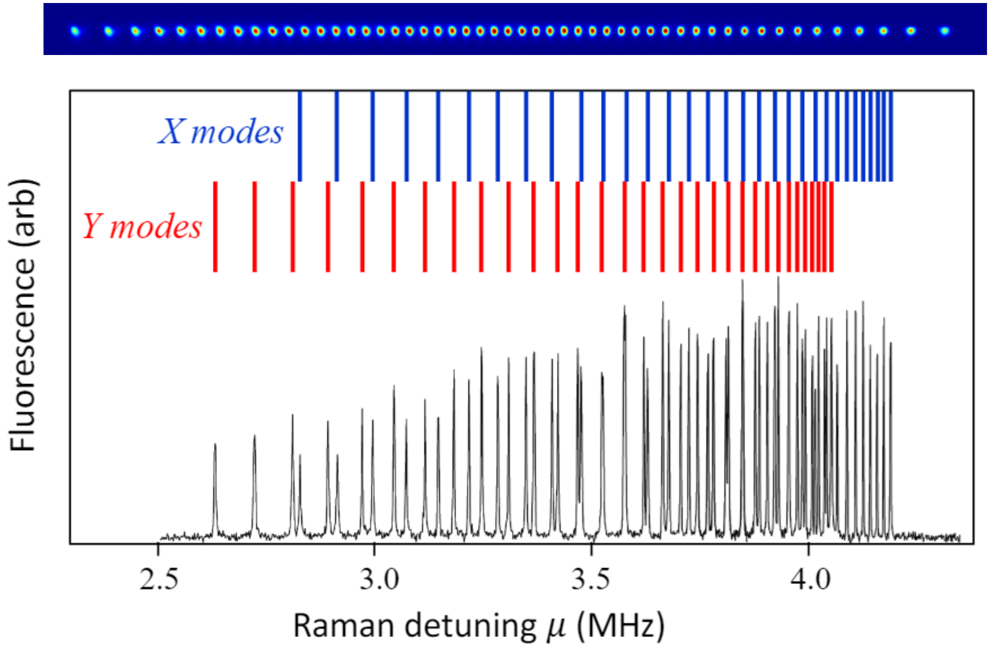
Reconstruction Fidelity: 93.7%

[1] W Chen, et al. Nature Physics, 2023, 19(6): 877-883.

- Bosonic System : Advantage, Limitation and Application
- Phonon: A New Candidate of Realizing Bosonic System
- Trapped Ions: Programmable and Scalable Platforms
- Demonstration: Tomography with Minimum Resources
- Conclusion and Future Plans

Conclusion and Future Plans

Frequency Spectrum of 32 ions in a linear chain[1]



- Using phonons which provide a good total number conservation for a bosonic system
- Our sideband transition provides a deterministic state preparation and detection of phonon states
- Realized a scalable and programmable phononic network to demonstrate a tomography experiment
- We can Further Scaling up the network by increasing number of ions, now the most advanced system of trapped ion can have a 32 linear ion chain (IonQ)
- Our system also have capability of performing Gaussian Boson Sampling[2] with Phonon-number-resolving detection[3] for more applications

[1] Rev. Mod. Phys. 93, 025001 (2021)
[2] Huh J., et al., Nature Photon 9, 615–620 (2015).
[3] S. An, et al., Nature Phys. 11, 193 (2015).

Acknowledgement

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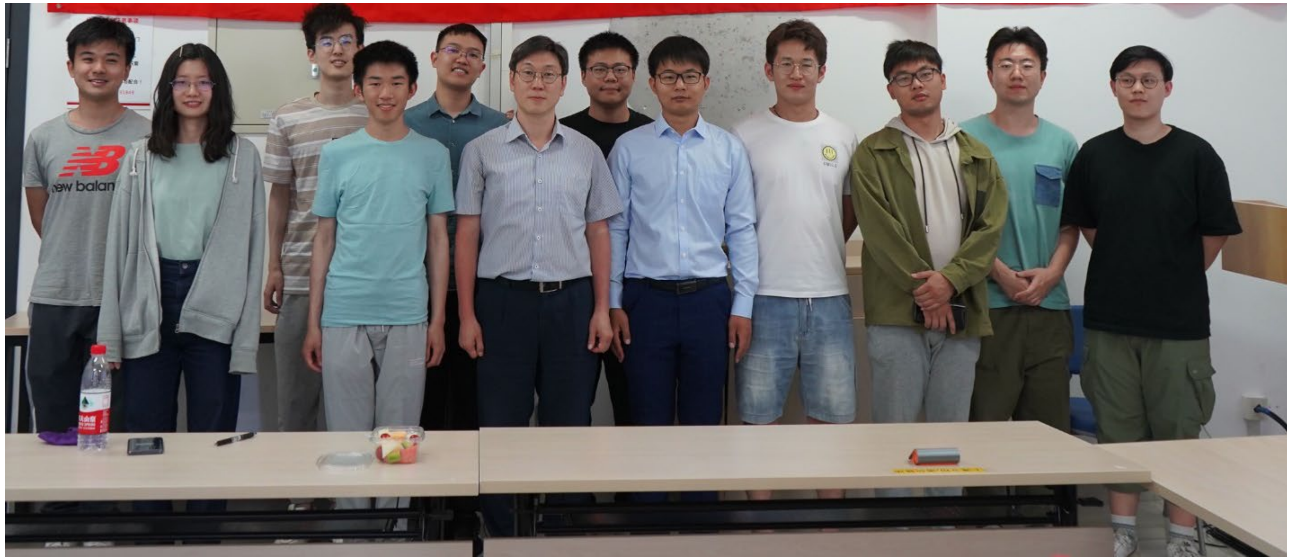

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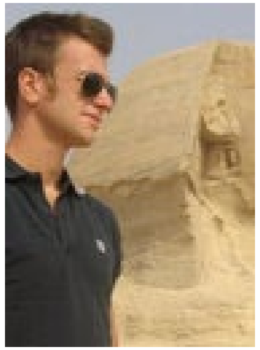

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Thank You

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