

SFU



# Beyond Qubit

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**CANADA  
RESEARCH CHAIRS  
CHAIRES DE  
RECHERCHE DU  
CANADA**

# Qubit

$|1\rangle$  —●—

$|0\rangle$  —●—

$$|\psi\rangle = c_0 |0\rangle + c_1 |1\rangle$$

Well developed hardware, algorithms, programming tools, ...

**Why qubit?**

# Why qubit?

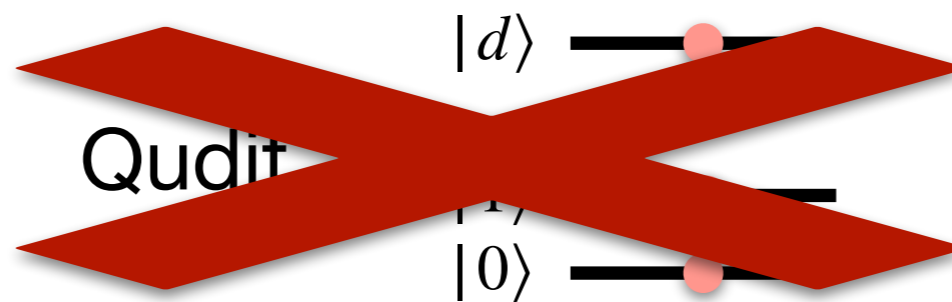


Classical (bit)

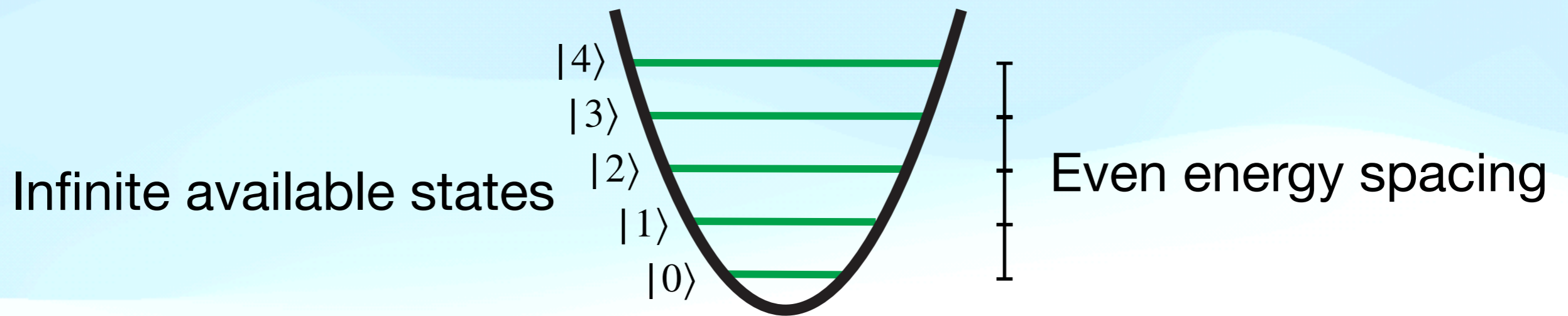


Quantum (qubit)

## What else?



# Bosonic system

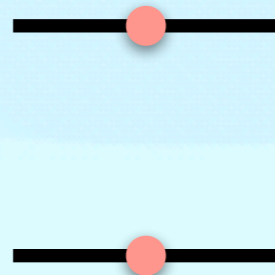


Bosonic systems = Harmonic oscillators

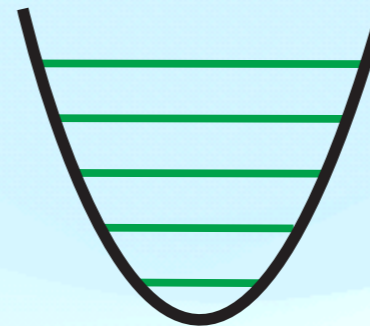
$$[\hat{Q}, \hat{P}] = i\hbar$$

# Physical Platforms

Qubit

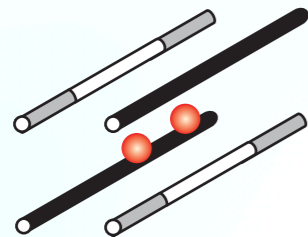
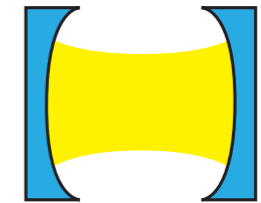


Bosonic



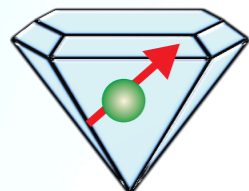
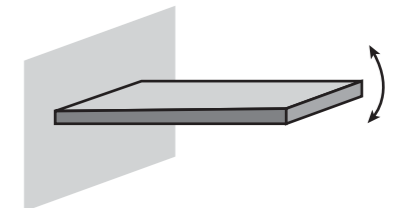
Superconductor

Microwave resonator



Trapped ion

Mechanical oscillator



Defect center

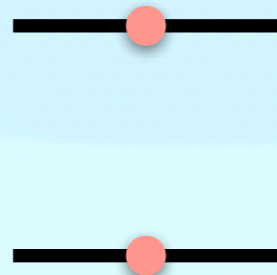
Photon



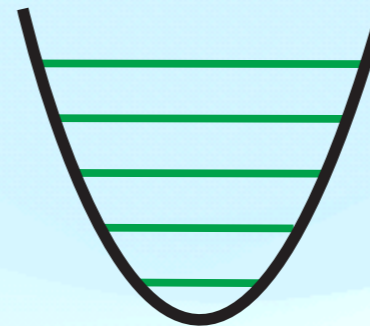
**Engineering new platforms?**

# Physical Platforms

Qubit

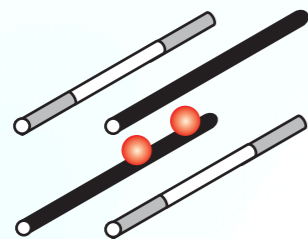
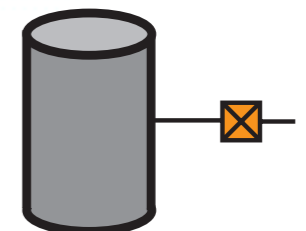


Bosonic



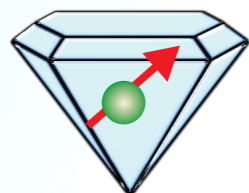
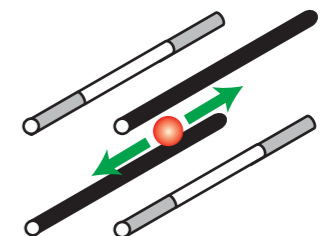
Superconductor

Microwave resonator



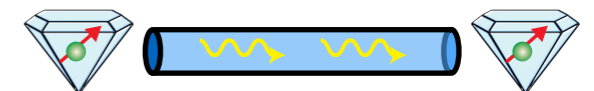
Trapped ion

Mechanical oscillator



Defect center

Photon

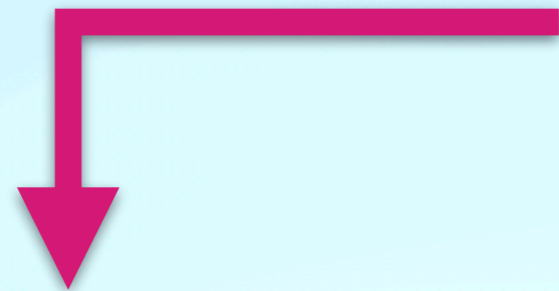


**Bosonic system is already there!**

**Why boson?**

# More (degree of) freedom

Bosonic code



$$|\psi_L\rangle = c_0 |0_L\rangle + c_1 |1_L\rangle$$

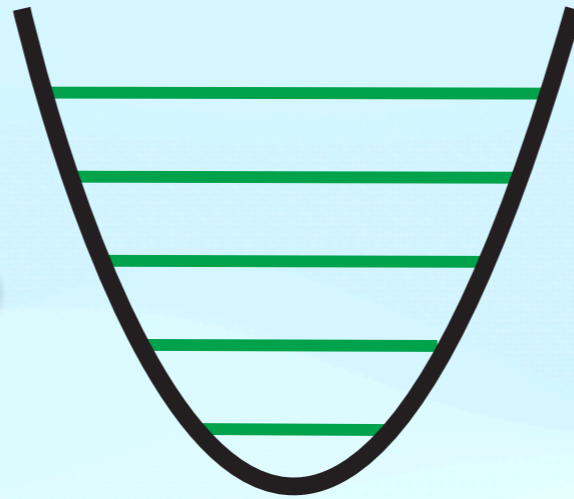
$$|\Psi_0\rangle \equiv |0_L\rangle$$

$$|\Psi_1\rangle \equiv |1_L\rangle$$

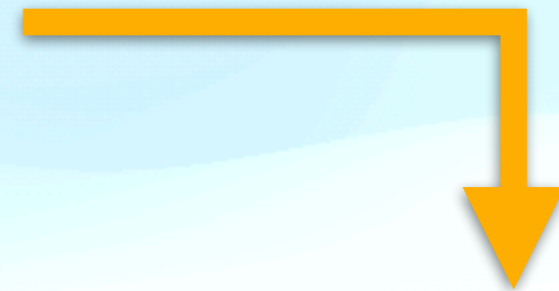
$$|\Psi_2\rangle$$

$$|\Psi_3\rangle$$

$$|\Psi_4\rangle$$

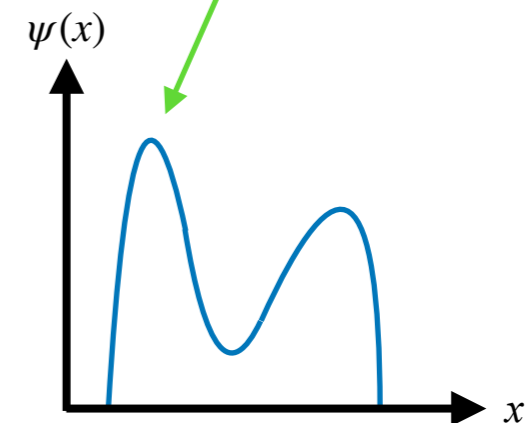


Continuous-Variable  
Quantum information



$$|\psi\rangle = \int \psi(x) |x\rangle dx$$

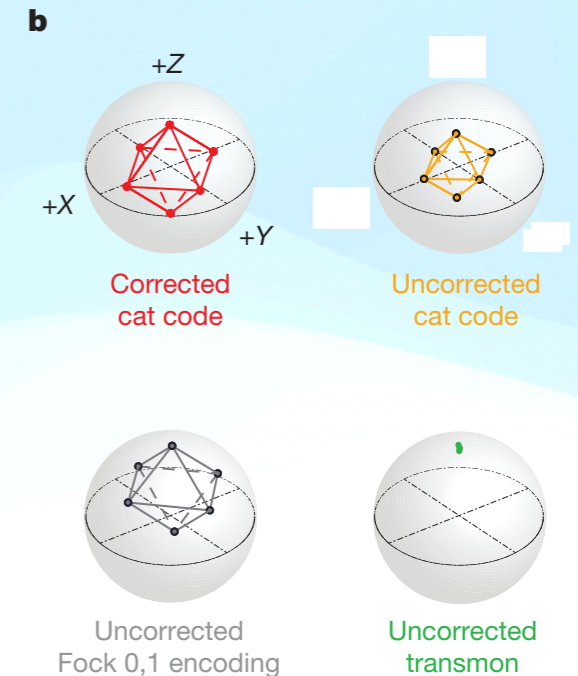
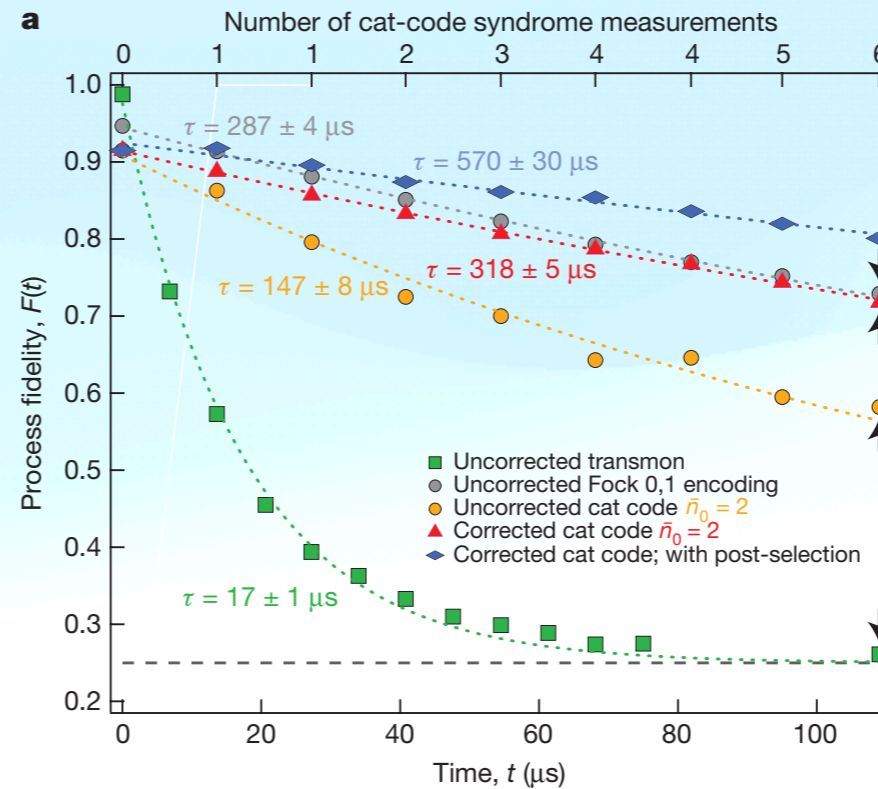
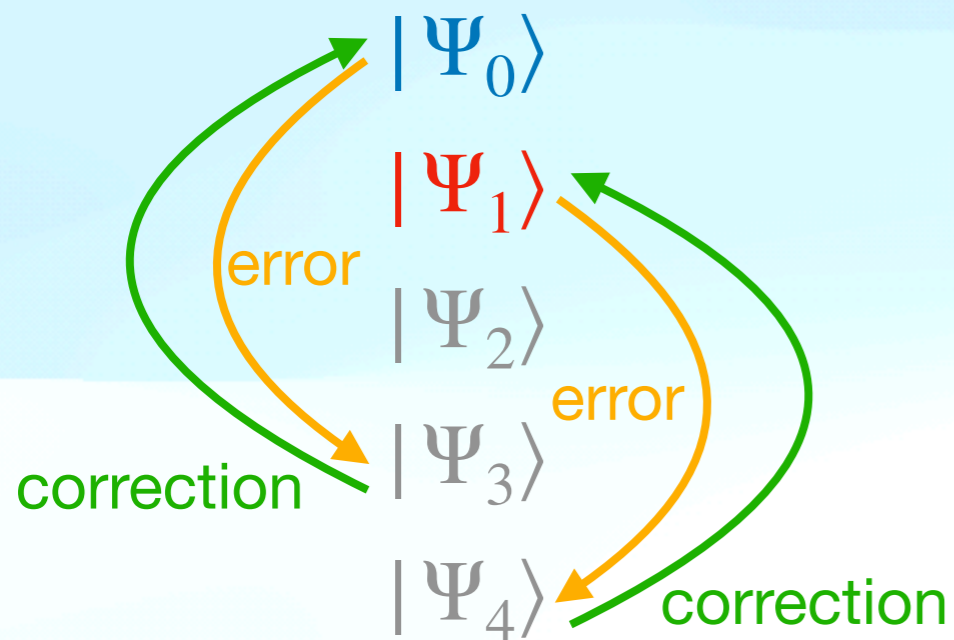
Continuous  
wavefunction





# Bosonic code

## Break-even point for Error Correction



LETTER

Nature 536, 441 (2016)

doi:10.1038/nature18949

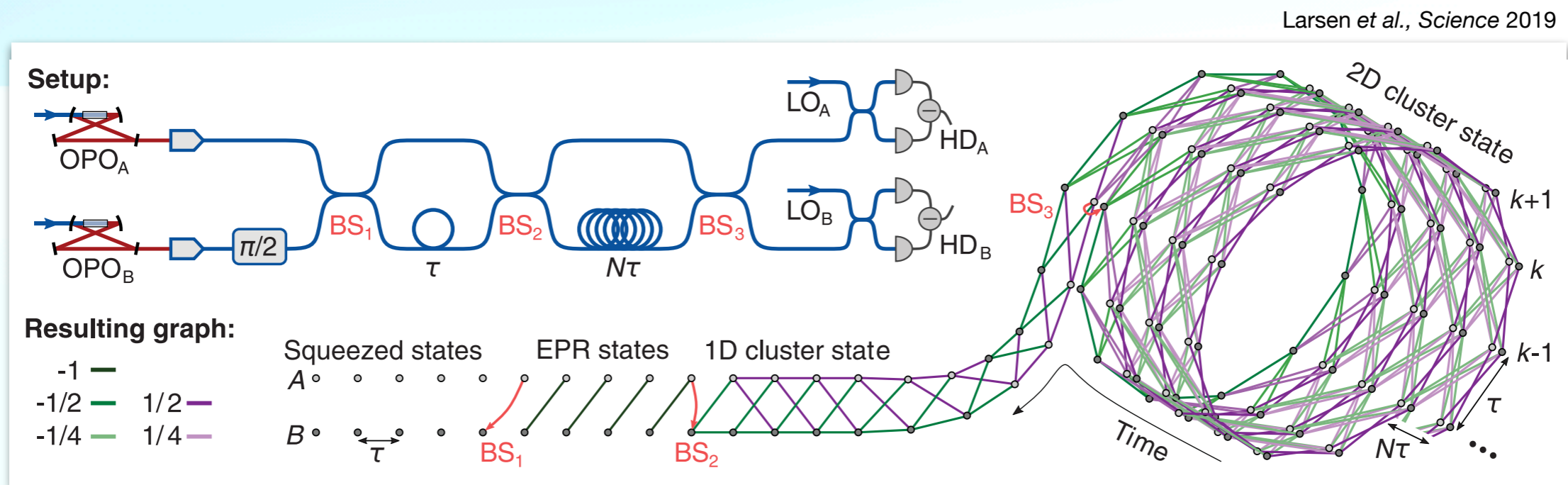
## Extending the lifetime of a quantum bit with error correction in superconducting circuits

Nissim Ofek<sup>1\*</sup>, Andrei Petrenko<sup>1\*</sup>, Reinier Heeres<sup>1</sup>, Philip Reinhold<sup>1</sup>, Zaki Leghtas<sup>1,†</sup>, Brian Vlastakis<sup>1</sup>, Yehan Liu<sup>1</sup>, Luigi Frunzio<sup>1</sup>, S. M. Girvin<sup>1</sup>, L. Jiang<sup>1</sup>, Mazyar Mirrahimi<sup>1,2</sup>, M. H. Devoret<sup>1</sup> & R. J. Schoelkopf<sup>1</sup>

# Continuous Variable

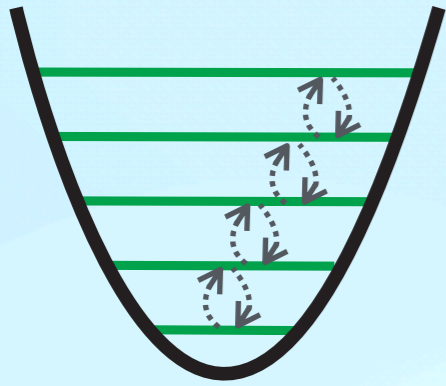
$$|0\rangle|0\rangle + |1\rangle|1\rangle \quad \longrightarrow \quad \int |x\rangle|x\rangle dx$$

Bell state  
1 e-bit
EPR state  
 $\approx (\log \bar{n} + 1)$  e-bit

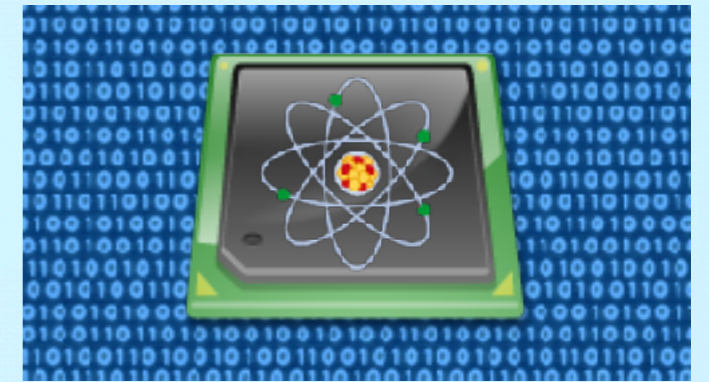


CV entanglement between 1 million mode

# Challenges (yet)



Optimal control and implementation?



Programming CV or qubit-bosonic systems?



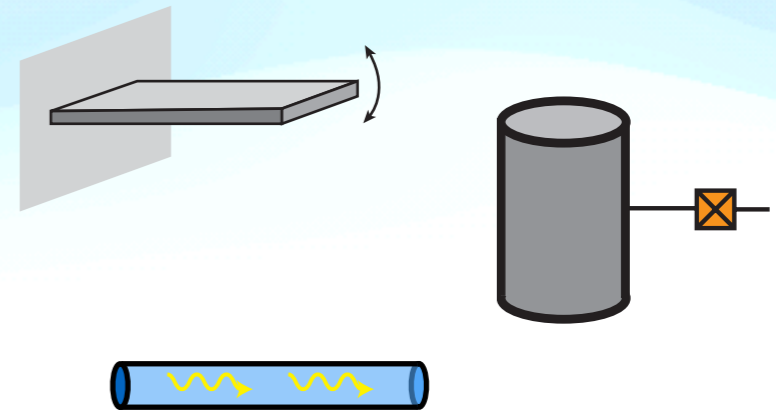
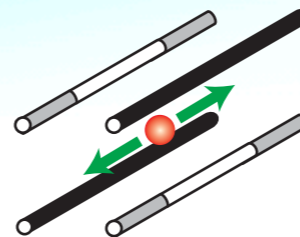
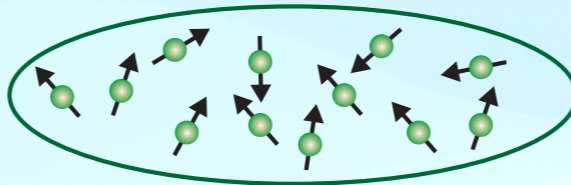
Translating algorithms from qubit to CV?



# Beyond Qubit

## Bosonic systems:

- Everywhere
- More freedom
- More entanglement
- Platform advantages



Should we give them more attention?