Building a room temperature quantum computer

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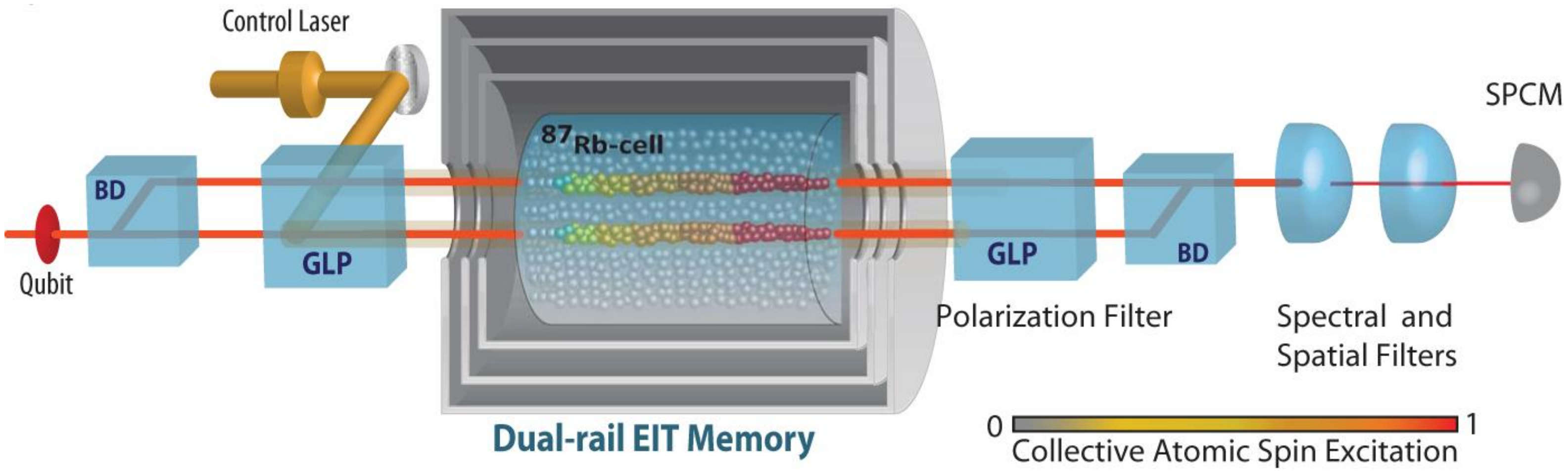
SIMONS
FOUNDATION

Outline

- Analog quantum simulators with light.
- Building a light-based quantum computer.



I. Analog quantum simulators

Feyman's quantum simulation dream

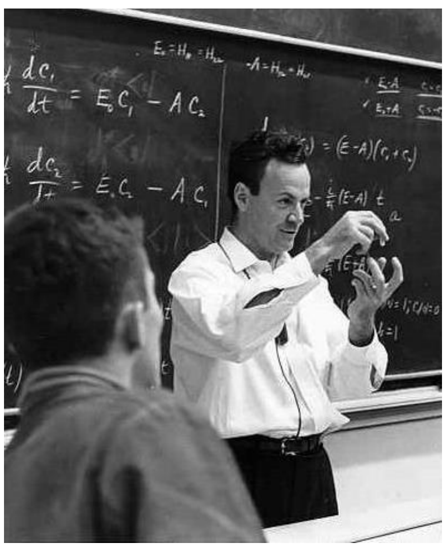
International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

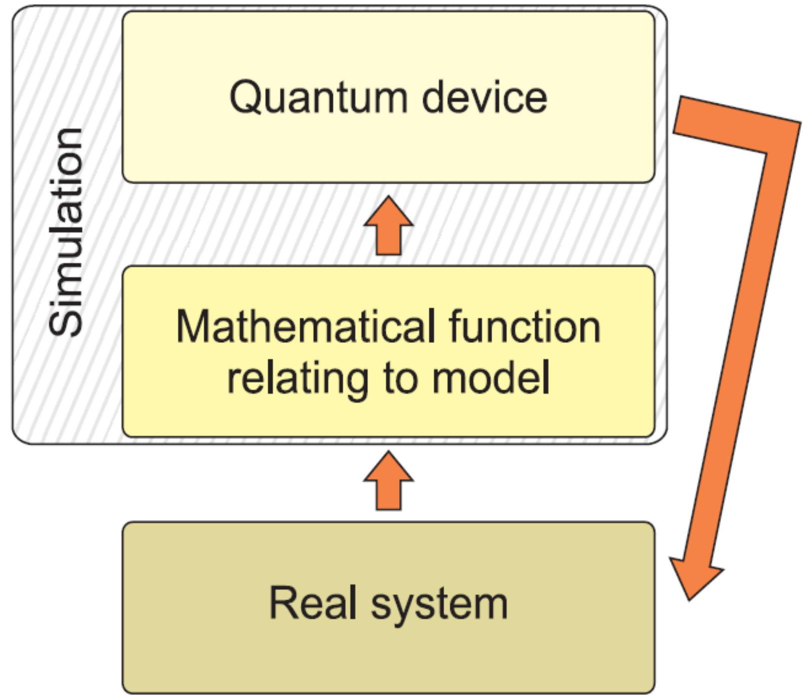
Simulating Physics with Computers

Richard P. Feynman

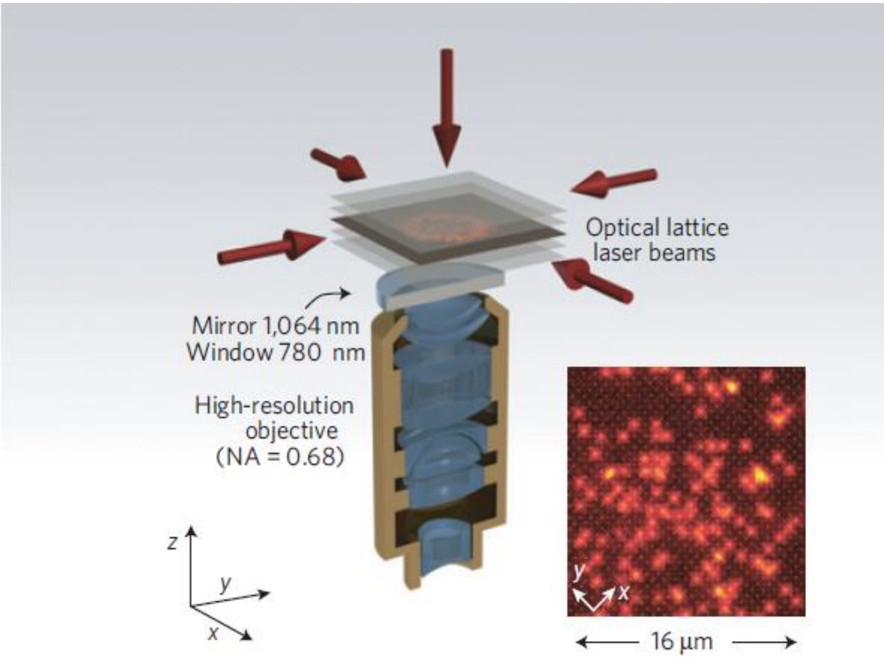
Department of Physics, California Institute of Technology, Pasadena, California 91107

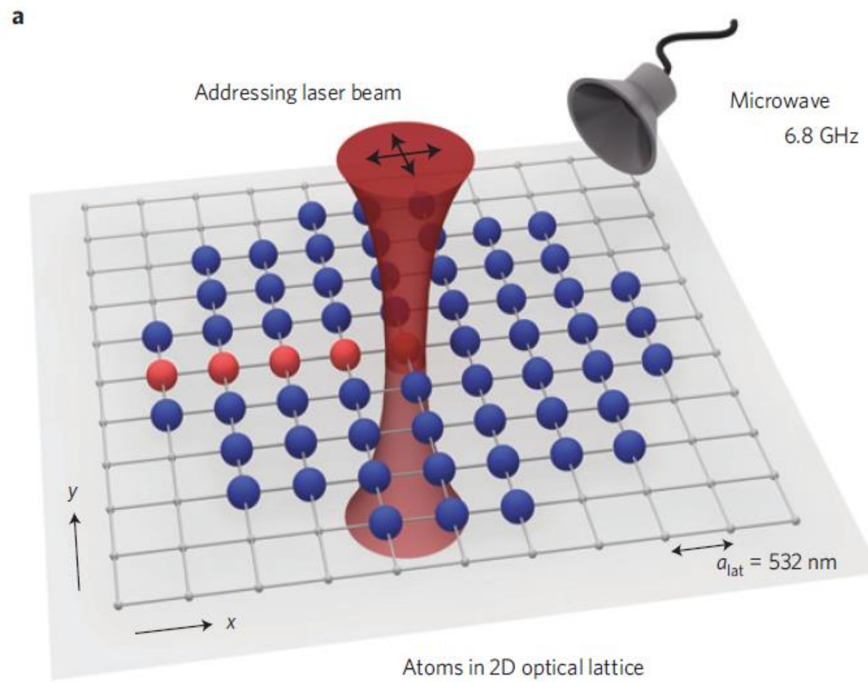
Received May 7, 1981





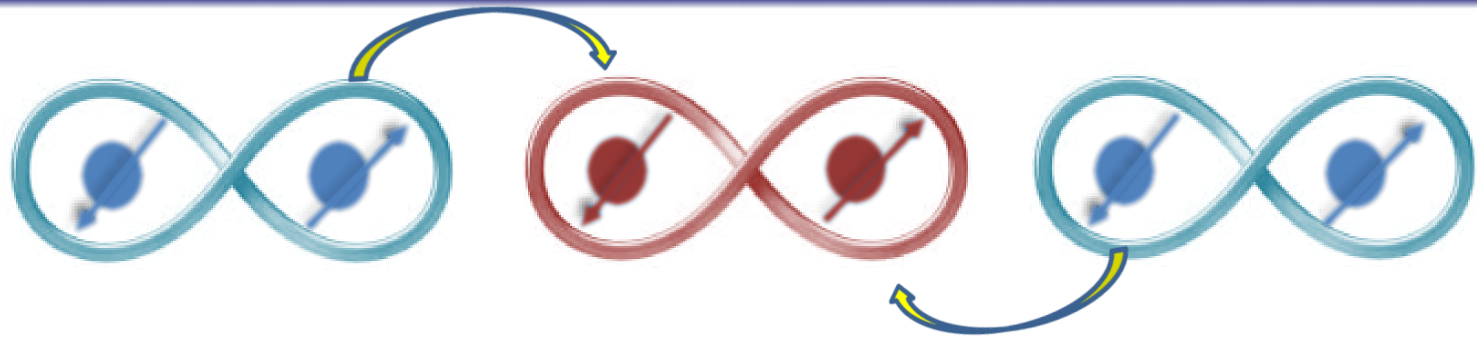
Tailoring Hamiltonians with arrays of atoms



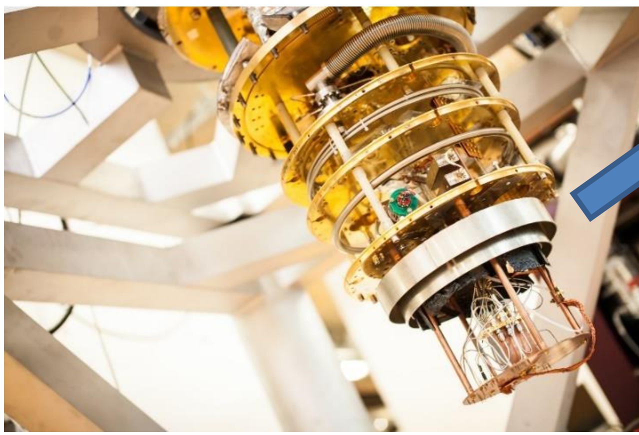


- Optimizing control of quantum matter systems to engineer their interactions to resemble different physical systems.

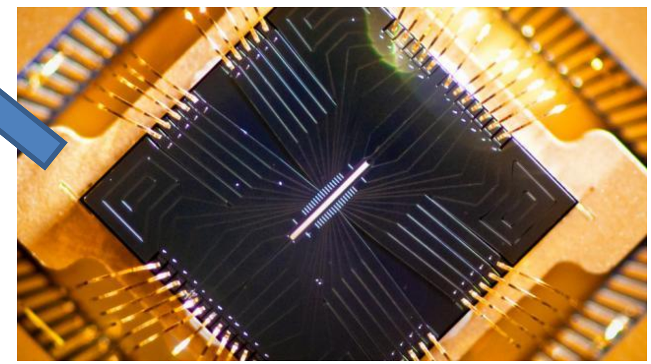
Ising Quantum simulators



$$\mathcal{H} = -J \sum_{\langle i,j \rangle} \sigma_i \sigma_j$$



Superconducting Quantum Simulators



Trapped Ions Quantum Simulators

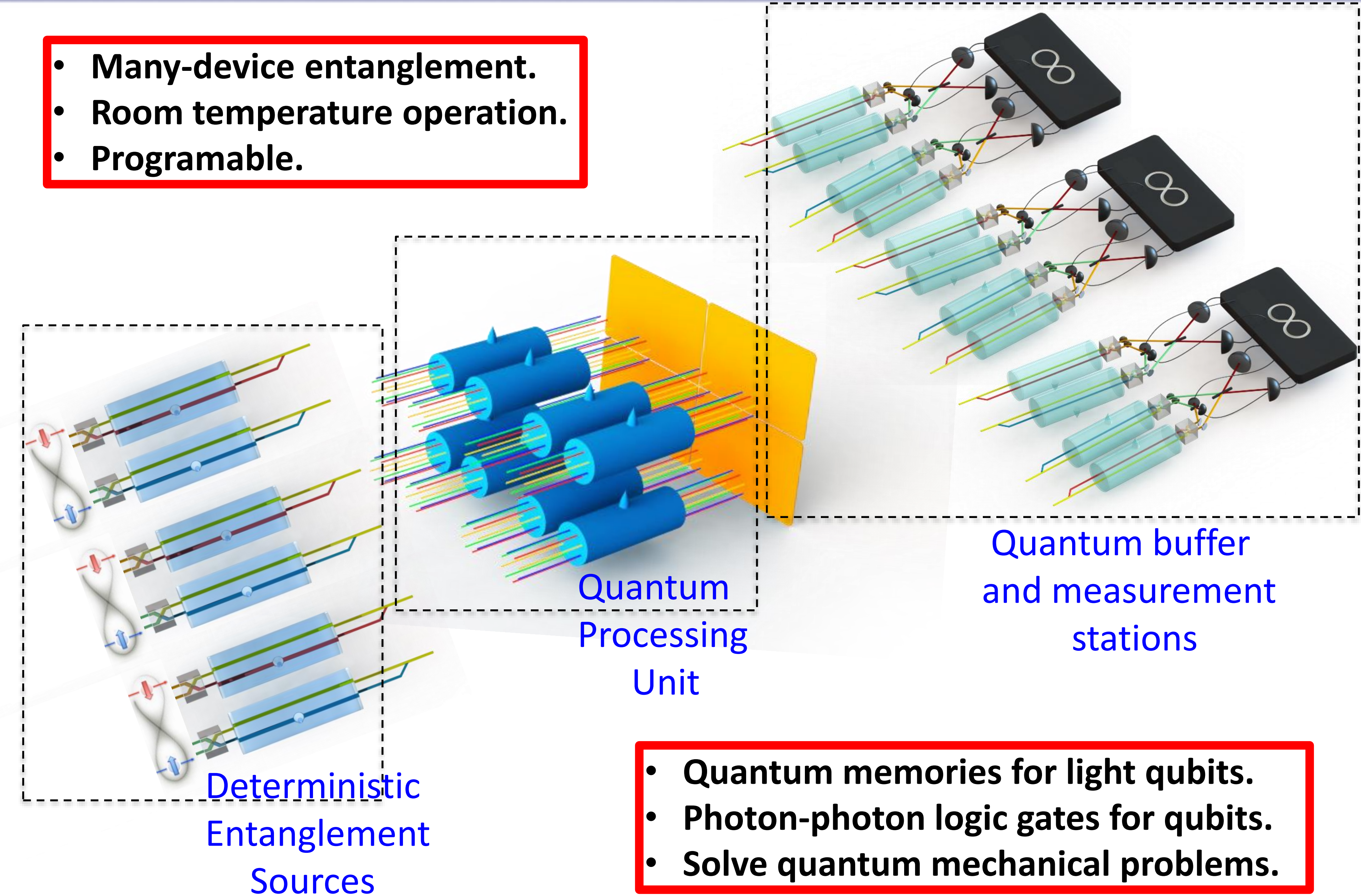
Google rigetti CREATIVE DESTRUCTION LAB

IBM D:WAVE The Quantum Computing Company™ IONQ

- Interactions among neighbors
- Operation at 2K
- Solves particular problems

Next evolution: Programable light based quantum computer

- **Many-device entanglement.**
- **Room temperature operation.**
- **Programable.**



- **Quantum memories for light qubits.**
- **Photon-photon logic gates for qubits.**
- **Solve quantum mechanical problems.**

EIT : A deeper look

With a quantized field: $\hat{E}(z,t) = \sum_k a_k(t) e^{ikz} e^{-i(\nu/c)(z-ct)}$

And the collective atomic operators: $\hat{\sigma}_{\alpha\beta}(z,t) = \frac{1}{N_z} \sum_{j=1}^{N_z} |\alpha_j\rangle\langle\beta_j| e^{-i\omega_{\alpha\beta}t}$

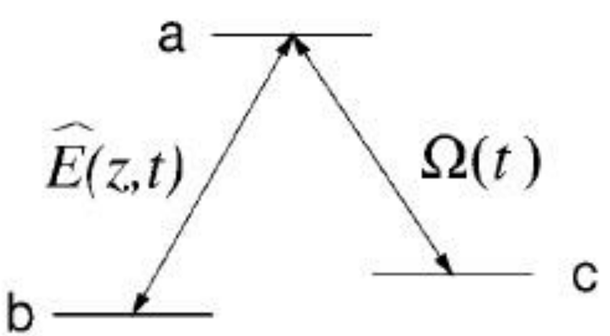
One can solve a set of Heisenberg-Lagevin equations: $\frac{\partial}{\partial t}\hat{\sigma}_{\mu\nu} = -\gamma_{\mu\nu}\sigma_{\mu\nu} + \frac{i}{\hbar}[\hat{V}, \hat{\sigma}_{\mu\nu}] + F_{\mu\nu}$

A simple solution to these equations is:

$$\boxed{\begin{aligned} \hat{\Psi}(z,t) &= \cos\theta(t)\hat{E}(z,t) - \sin\theta(t)\sqrt{N}\,\hat{\sigma}_{bc}(z,t) \\ \cos\theta(t) &= \frac{\Omega(t)}{\sqrt{\Omega^2(t) + g^2 N}}, \\ \sin\theta(t) &= \frac{g\sqrt{N}}{\sqrt{\Omega^2(t) + g^2 N}}. \end{aligned}}$$

$$\boxed{\left[\frac{\partial}{\partial t} + c\cos^2\theta(t)\frac{\partial}{\partial z}\right]\hat{\Psi}(z,t) = 0}$$

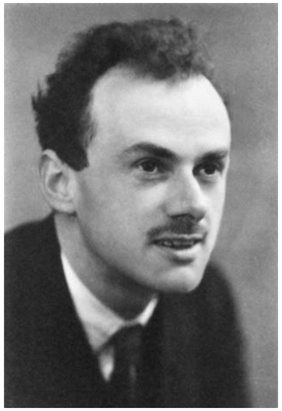
This is the Dark-State Polariton (DSP)



PRL 84, 5094 (2000)

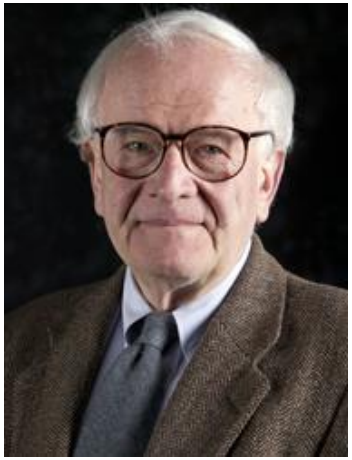
Interesting Quantum Simulation model: Dirac equation

- The Dirac equation merges quantum mechanics with special relativity.



$$\boxed{i\hbar\frac{\partial\psi}{\partial t} = H_{\mathrm{D}}\psi = (c\hat{p}\sigma_x + mc^2\sigma_z)\psi}$$

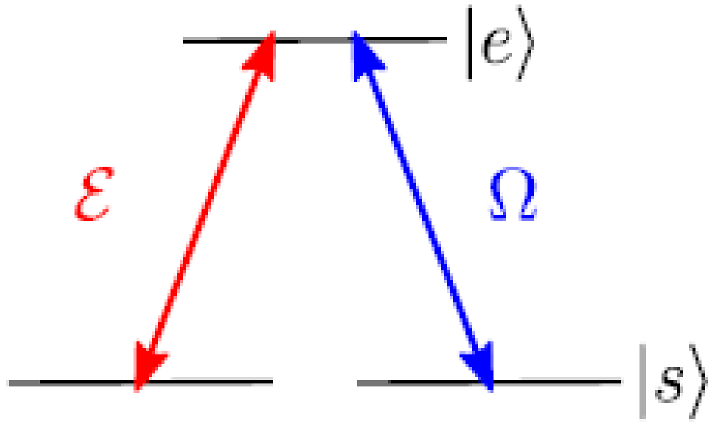
- The Jackiw-Rebbi model describes a Dirac field coupled to a soliton field.



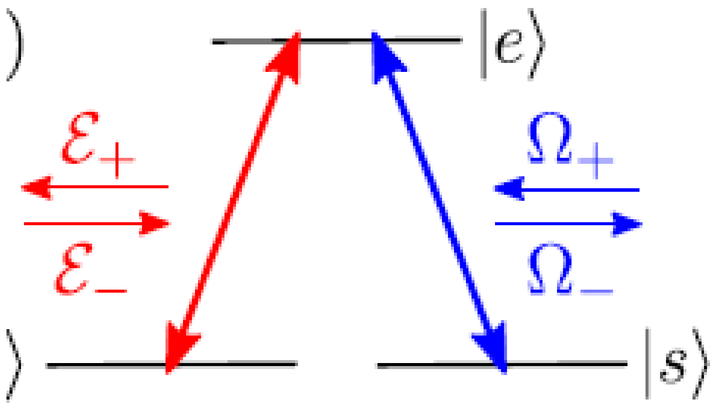
$$\boxed{i\partial_t\mathbf{\Psi} = \left(\alpha c p_z + \frac{\beta mc^2}{\kappa}\phi(z)\right)\mathbf{\Psi}}$$

- A kink in the soliton yields a topologically protected zero-energy mode.
- Leads to charge fractionalization.

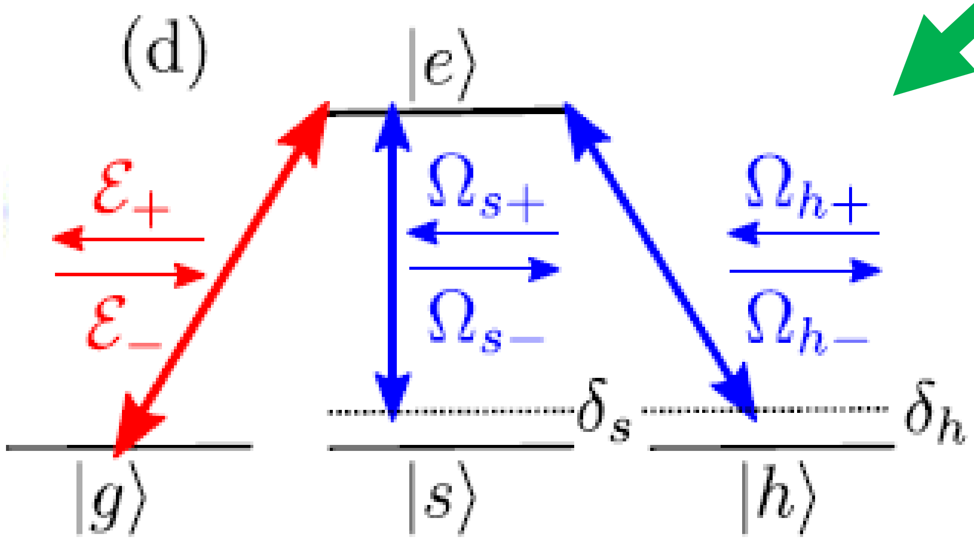
How to build a quantum simulator using dark state polaritons?



EIT setup



Multiple EIT systems

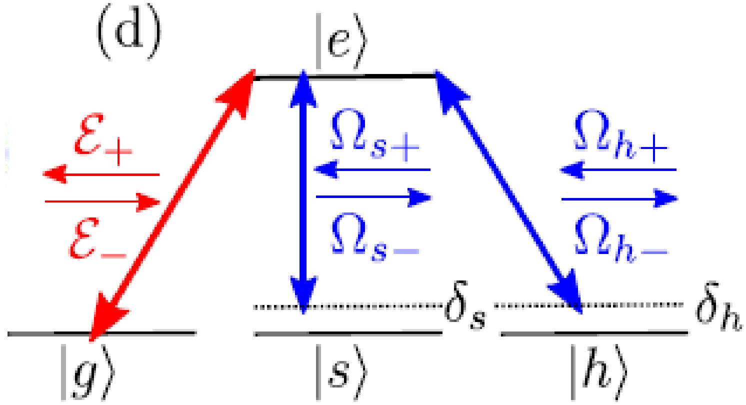


Spinor of light setup

PRL 105, 173603 (2010).

Dirac dynamics using spinor of light

(d)



$$\hat{\Psi}_+ = \cos\theta\hat{\mathcal{E}}_+ - \frac{1}{\sqrt{2}}\sin\theta(\hat{\sigma}_{gs} - i\hat{\sigma}_{gh})$$

$$\hat{\Psi}_- = \cos\theta\hat{\mathcal{E}}_- + \frac{1}{\sqrt{2}}\sin\theta(i\hat{\sigma}_{gs} - \hat{\sigma}_{gh})$$

Spinor of light:

$$\hat{\boldsymbol{\Psi}} = (\hat{\Psi}_+, \hat{\Psi}_-)^T$$

The spinor obeys a Dirac-like equation:

$$i\hbar\frac{\partial}{\partial t}\hat{\boldsymbol{\Psi}} = \left(i\hbar v_g\sigma_z\frac{\partial}{\partial} + \hbar\delta\sin^2\theta\sigma_y\right)\hat{\boldsymbol{\Psi}} - iL_{\text{abs}}v_g\sin^4\theta\left(\sigma_z\frac{\partial}{\partial z} - \frac{\delta}{c}\sigma_y\right)^2\hat{\boldsymbol{\Psi}}$$

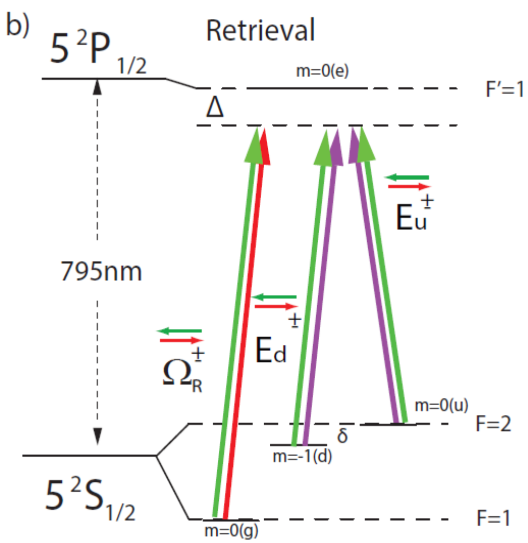
$$c^* = v_g = c\cos^2\theta$$

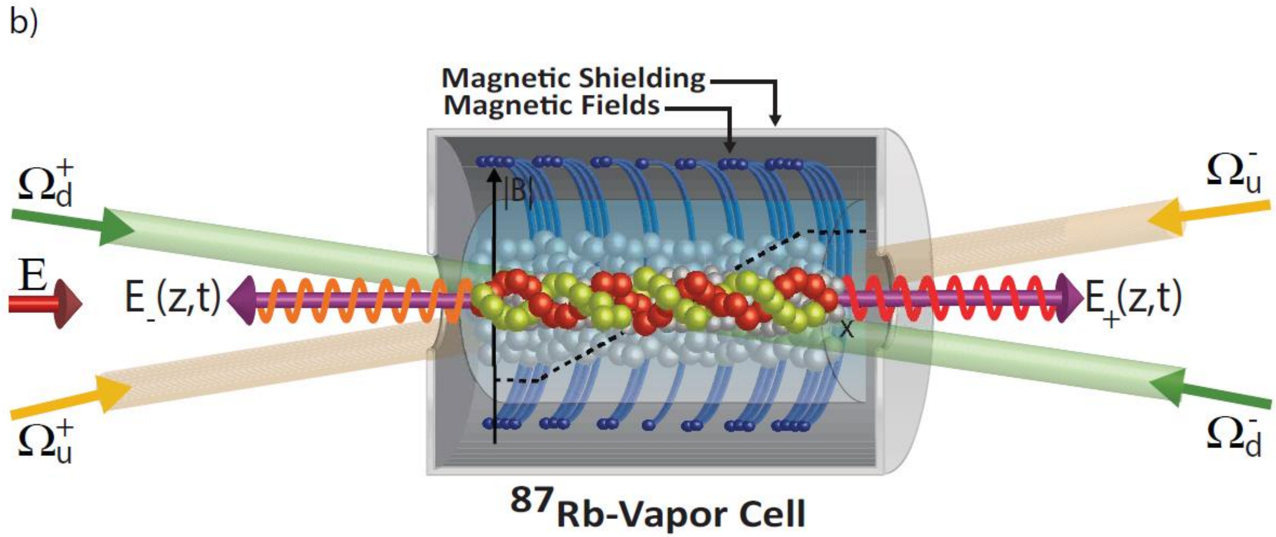
$$m^* = \hbar\delta\sin^2\theta/v_g^2$$

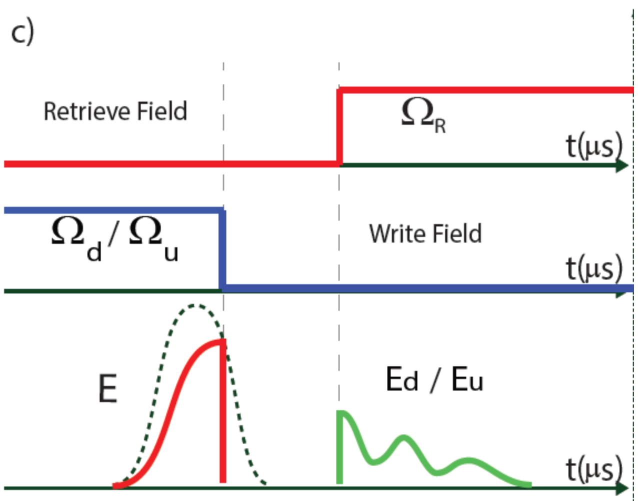
PRL 105, 173603 (2010).

Scientific Reports 4, 6110 (2014).

Creating spinors of light experimentally







Realizing topological relativistic dynamics with slow light polaritons at room temperature

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[1] *Department of Physics and Astronomy, Stony Brook University, New York 11794-3800, USA*
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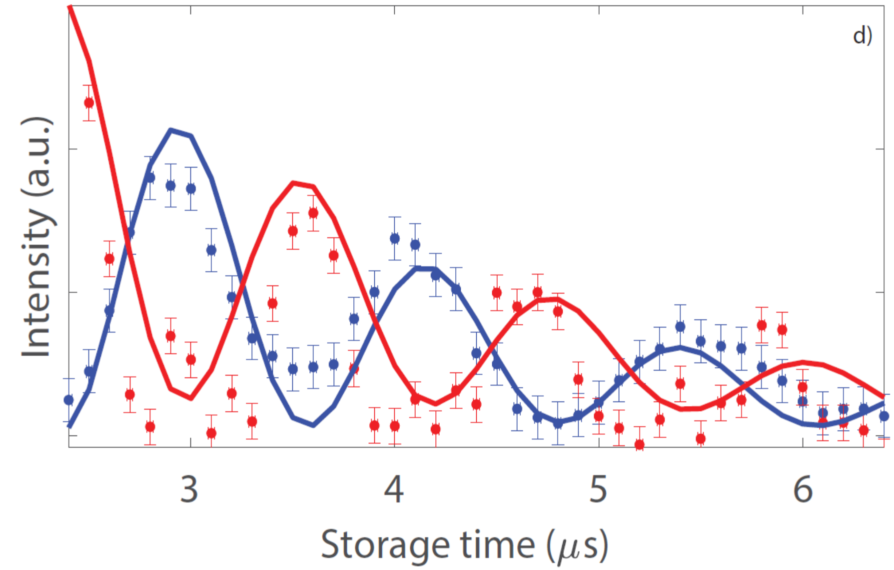
[3] *Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 1175*

arXiv:1711.09346

Quantum simulation of Dirac spinor dynamics

$$i\partial_t \psi = \left(i v_g \sigma_z \partial_z + m_{eff} v_g^2 \sigma_y - \gamma\right) \psi$$

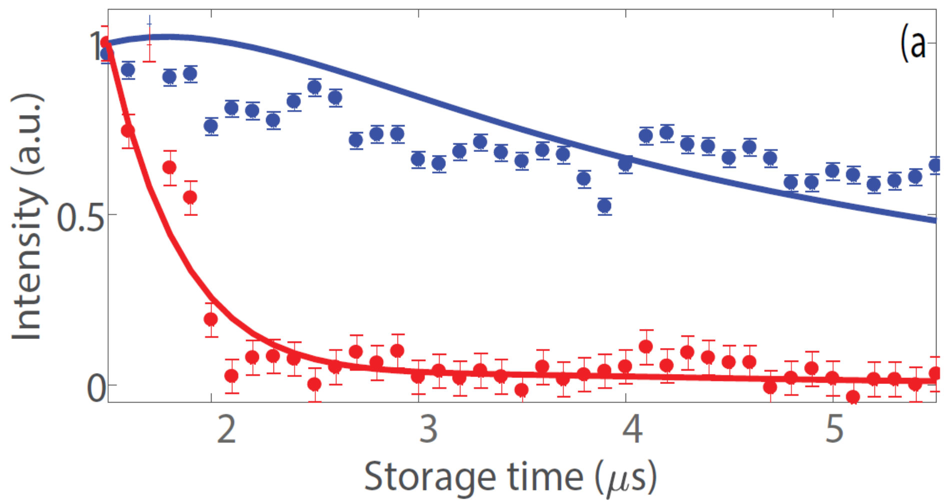
$$\psi = (\psi_1, \psi_2)$$



$$i\partial_t \psi = \left(i v_g \sigma_z \partial_z + m_{eff}(z) v_g^2 \sigma_y - \gamma\right) \psi$$

$$\psi_k(x) \; = \; e^{i\theta_k(x)} |\psi_k(x)|$$

$$\theta = \pi$$



"Realizing JR would require **beams of relativistic particles interacting with Fermi quantum fields**. This realization of the **same physics requires only diode lasers and a cell of Rb atoms**."

arXiv:1711.09346

Road map for a DSP-based quantum simulator

Fundamental tools

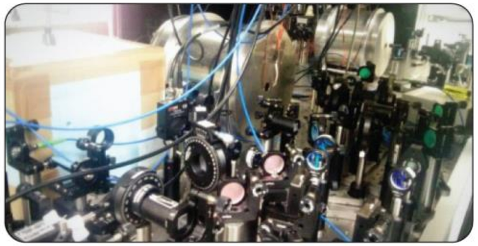
- Quantum light matter interfaces

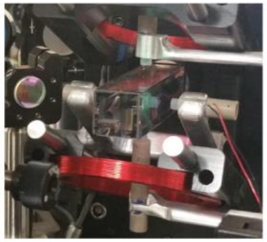
→ To realize the creation of spinor slow-light polaritons (SSP) obeying an effective 1D Dirac equation

- Optical Kerr non-linearities

→ To add interactios, in order to achieve relativistic many-body models such as the Thirring model.

PRL 105, 173603 (2010).





$$i\hbar\partial_t\Psi_s = -\frac{\hbar^2}{2m_{\mathrm{nr},s}}\partial_z^2\Psi_s + i\hbar\eta_s\partial_z\Psi_s + \hbar\Omega_0\Psi_{\bar{s}} + \chi_{ss}\Psi_s^\dagger\Psi_s^2 + \chi_{s\bar{s}}\Psi_{\bar{s}}^\dagger\Psi_{\bar{s}}\Psi_s$$

Bosonic Thirring Model, PRL 110, 100502 (2013).

$$i\partial_t\Psi_j = -\frac{1}{2m_j}\nabla^2\Psi_j + V_j\Psi_j + 2\chi_j\Psi_j^\dagger\Psi_j^2 + \chi_{12}\Psi_j\Psi_{\bar{j}}^\dagger\Psi_{\bar{j}}$$

Cooper pairing Model, PRA 86, 043840 (2012).

- EIT in atomic ensembles
- EIT Kerr non-linearities
- Cavity EIT

$$i\partial_t\mathbf{\Psi} = \left(\alpha c p_z + \frac{\beta m c^2}{\kappa}\phi(z)\right)\mathbf{\Psi}$$

Jackiw-Rebbi Model, Scient. Rep. 4, 6110 (2014).

$$H = -t\sum_{p,q}[\sigma^+_{p+1,q}\sigma^-_{p,q}e^{i(\theta^X_{p+1,q}-\theta^X_{p,q})} + \sigma^+_{p,q+1}\sigma^-_{p,q}e^{i(\theta^Y_{p,q+1}-\theta^Y_{p,q})} + \mathrm{H.c.}]$$

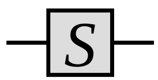
Quantum Hall effect Model, PRL 101, 246809 (2008).

$$-\partial_{\bar{z}}^2\psi + \frac{m}{m_R}\left[\bar{V} - \bar{\epsilon} + \bar{V}\cos(2\bar{z}) + 2\bar{\chi}\psi^\dagger\psi\right]\psi = 0$$

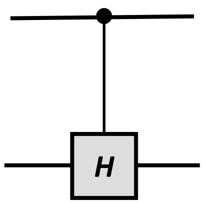
Non-linear Schroedinger Model, EPL, 103 (2013) 34001 (2011).

II. Light-based digital quantum computers

Common Quantum Gates (fundamental building blocks):

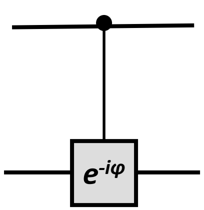


Phase gate: $S(\varphi) = \begin{pmatrix} 1 & 0 \\ 0 & e^{-i\varphi} \end{pmatrix}$



Hadamard $H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$

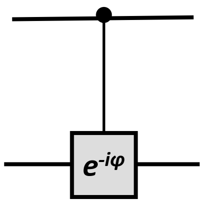
Controlled Phase gate:



$$\phi = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{-i\phi} \end{pmatrix}$$

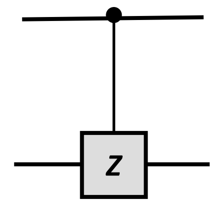
Construction of the CNOT Gate:

By adjusting the Controlled Phase gate one may build many uses two qubit gates:



$$\phi = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{-i\phi} \end{pmatrix}$$

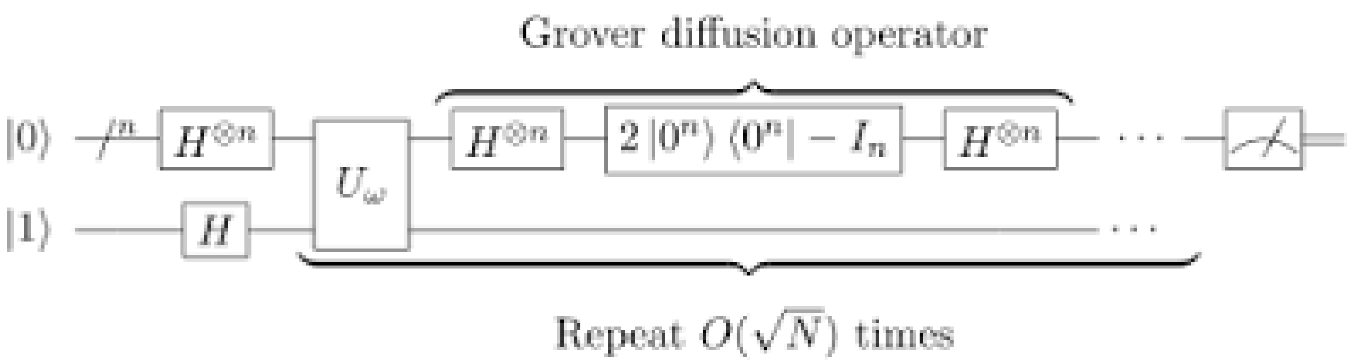
Φ=π



$$CZ = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Hadamard: $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$

This form allows the construction of many useful gates/algorithms:

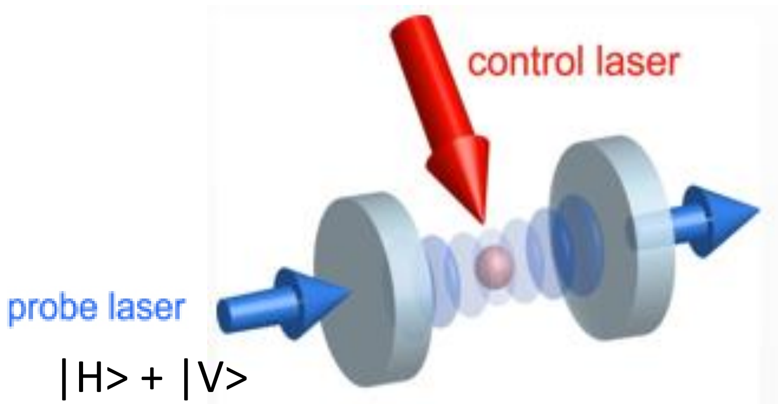


Quantum Gates

- Logic gates are a fundamental in classical computing

NOT AND OR

- Quantum gates work similarly on qubits



|H> - |V>

|H> + |V>

How to build a qubit gate?

- **The basic operation to perform is:**

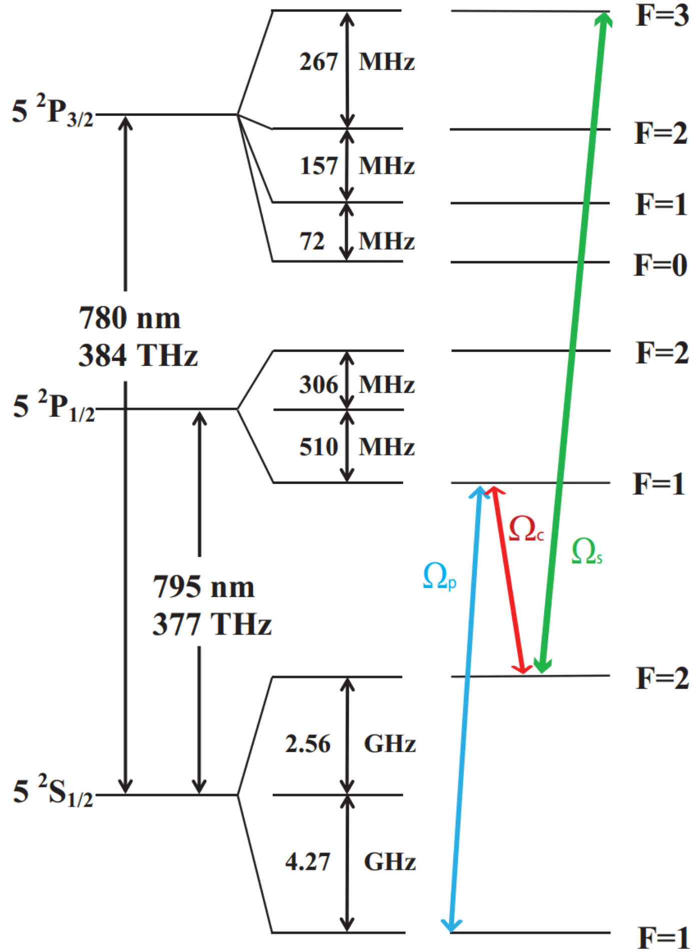
$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)|1\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + e^{-i\phi}|1\rangle)|1\rangle$$

- **The "phase shift" is given by:** $\phi = \kappa n_1 n_2$

- **Single photon operation requires a medium with large non-linearities and low absorption.**

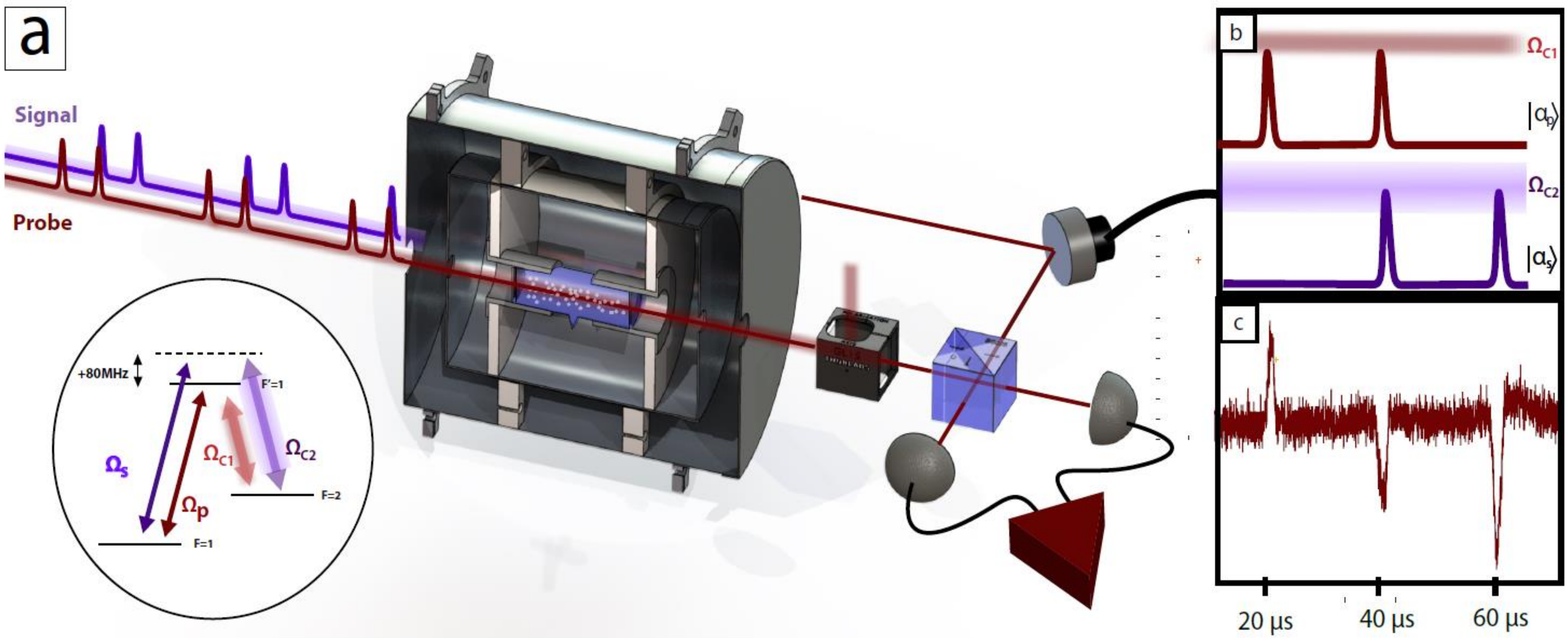
- **Possible answer: a combination of EIT and Kerr-non-linearities.**

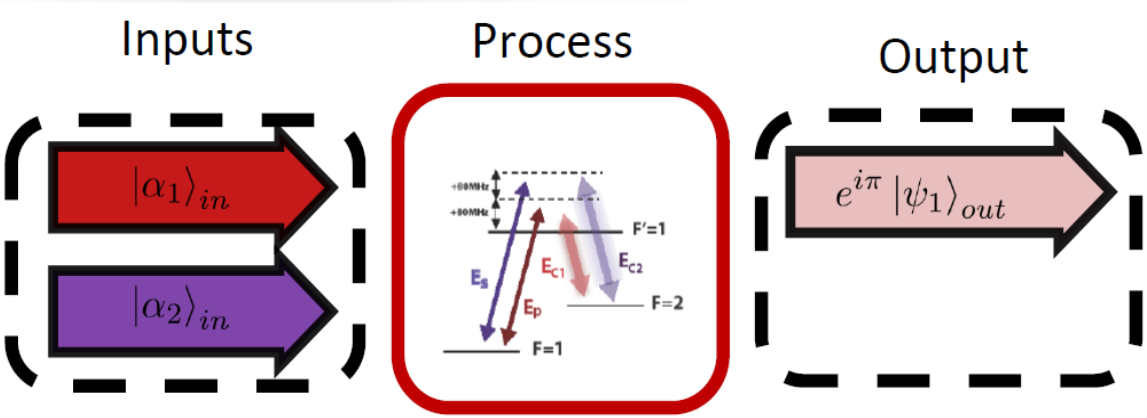
Engineering a N-type schemes in Rubidium 87



PRL 106, 193006 (2011).
PRA 83, 041804 (2011).

Photon-photon gate systems

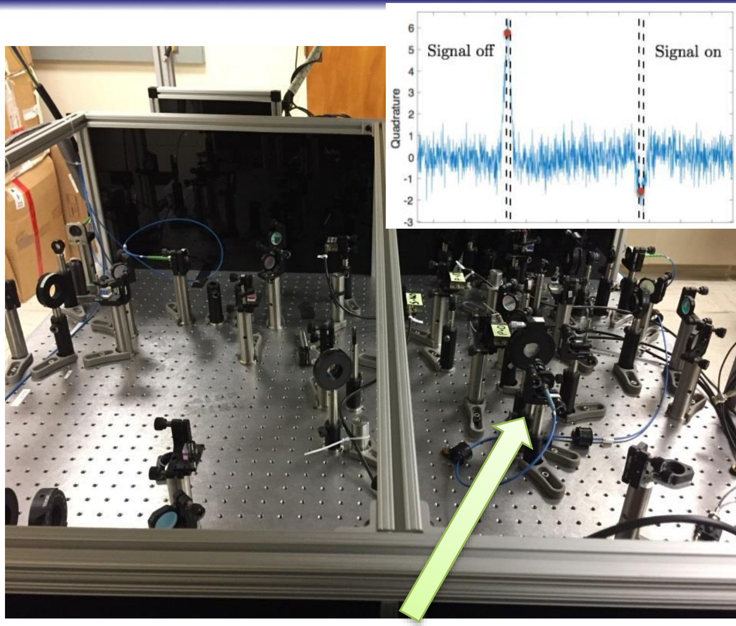




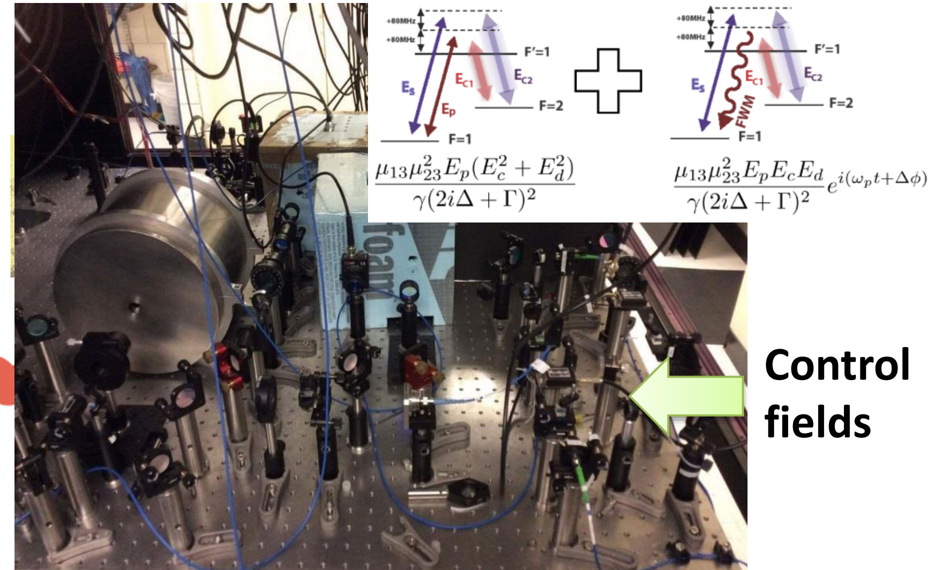
Scientific Reports 5, 16581 (2015).

arXiv:1803.07012

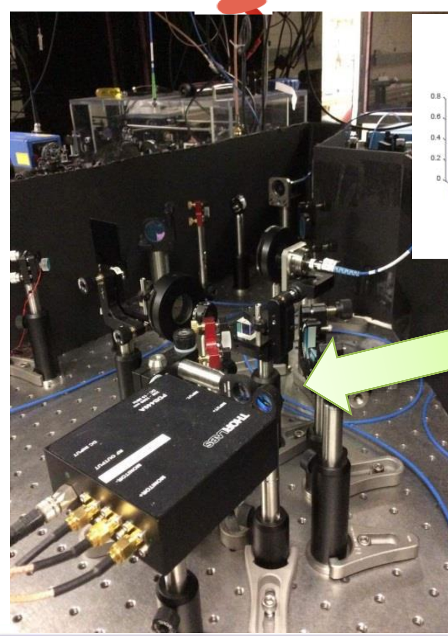
Reconstruction of wave-functions

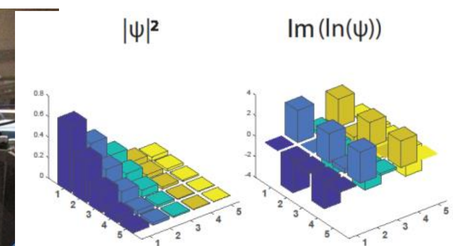


Single- photon level pulses for probe and signal

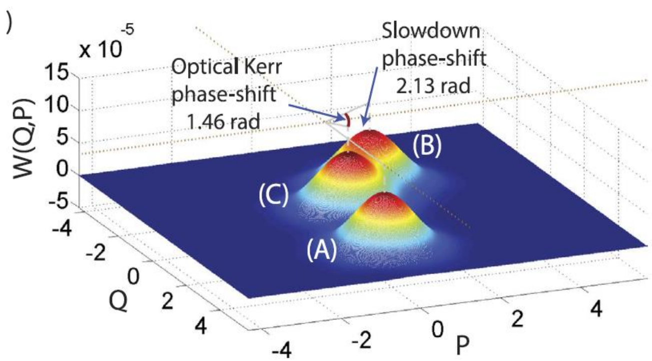


Control fields





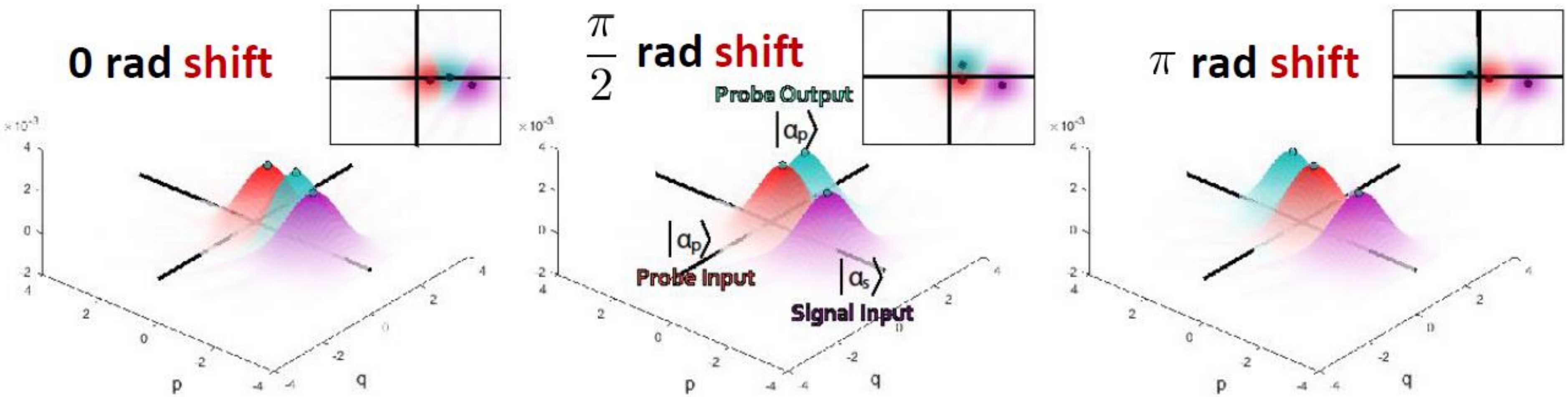
Density matrix reconstruction



Wave function characterization

arXiv:1803.07012

Pi-phase shifts in single photon fields mediated by few-photons



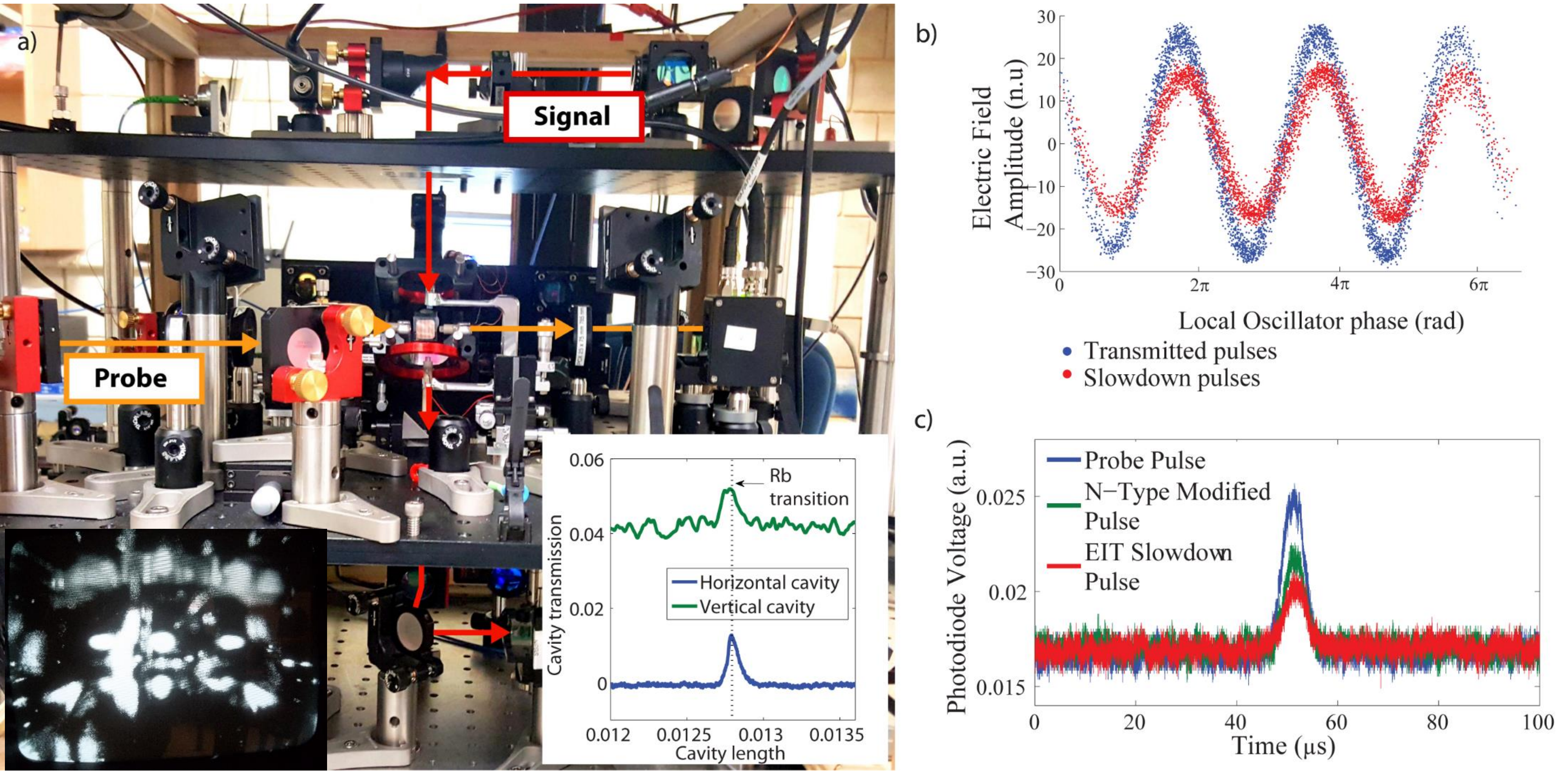
$\langle N_{out} \rangle = 1.7$ $\langle N_{out} \rangle = .6$ $\langle N_{out} \rangle = .2$

- Triggered pi phase shifts
- High transmission (~80%)
- High-Fidelity (~90%)
- Room-Temperature

arXiv:1803.07012

III. Enhancing photon-photon interaction

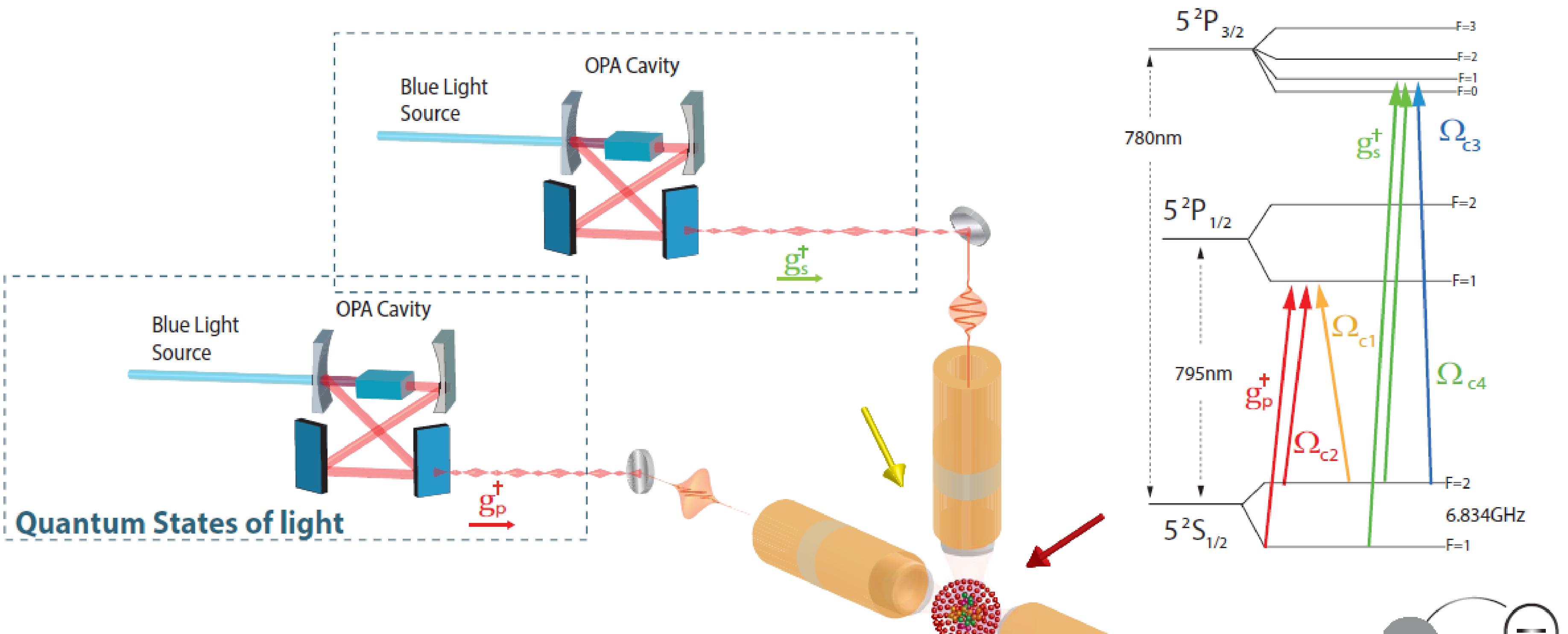
Implementation of a crossed cavity QED/EIT system



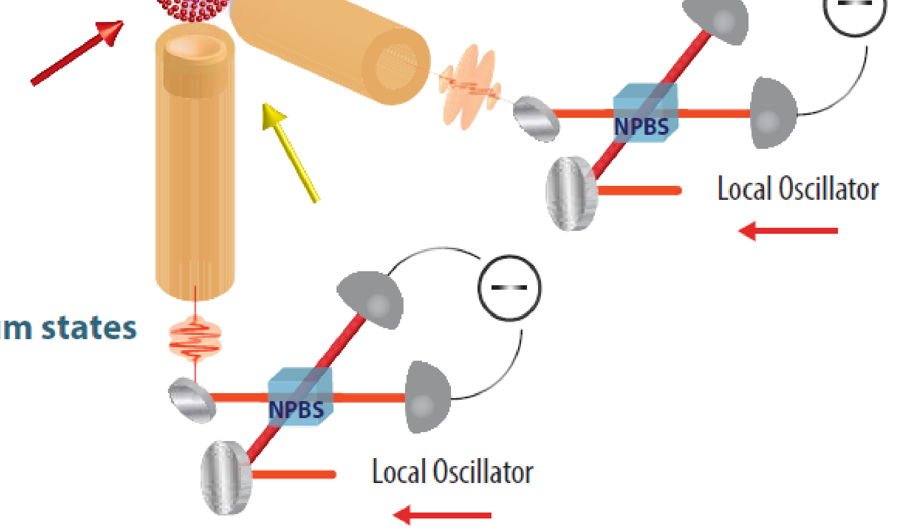
Current Status:

- Construction of cavities in a multi-layer system
- Observation of magneto-optical trapping and characterization of atomic cloud
- Observation of coupling between atoms and the two cavities.

Outlook: Quantum simulation with quantized light fields



$$i\hbar\partial_t\Psi_s = -\frac{\hbar^2}{2m_{\mathrm{nr},s}}\partial_z^2\Psi_s + i\hbar\eta_s\partial_z\Psi_s + \hbar\Omega_0\Psi_{\bar{s}} + \chi_{ss}\Psi_s^\dagger\Psi_s^2 + \chi_{s\bar{s}}\Psi_{\bar{s}}^\dagger\Psi_{\bar{s}}\Psi_s + \text{noise},$$



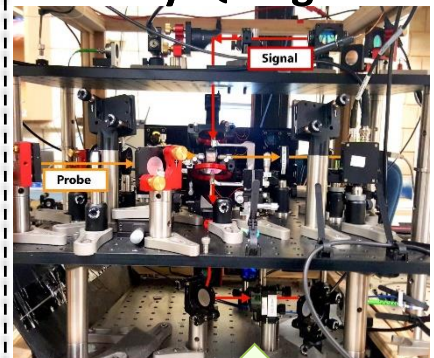
Modulated quantum states

Quantum computing network

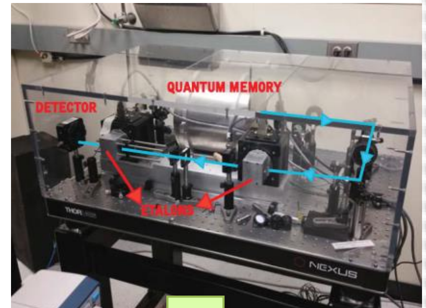
- ~20 interconnected quantum devices

Quantum processing units

Cavity QED gate

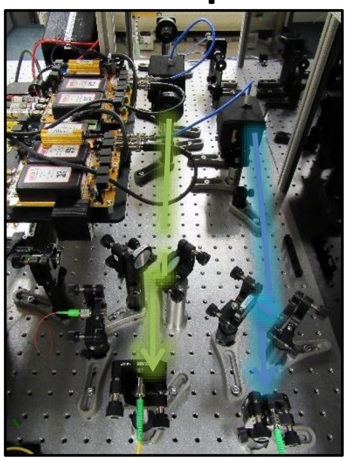


RT phase gate

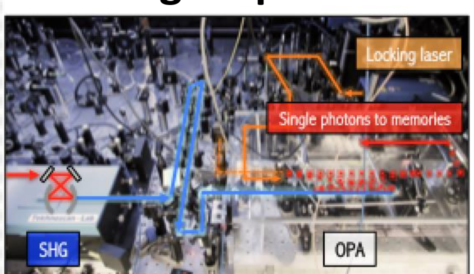


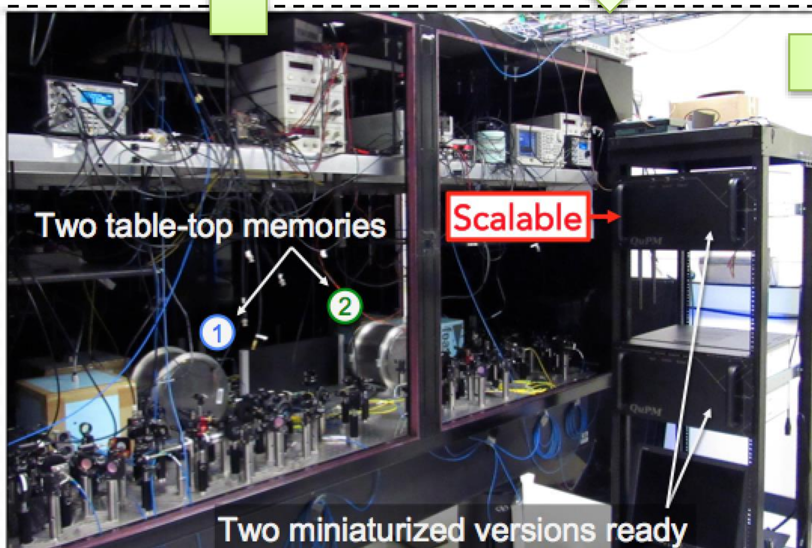
Photon Sources

Ancilla qubits

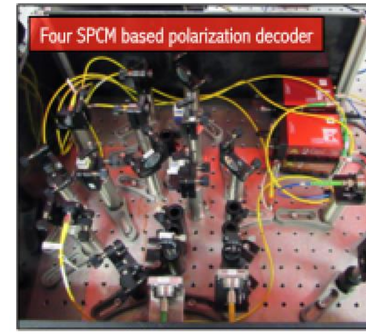


Entangled photons

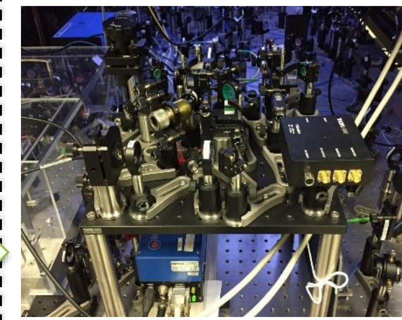




Network of quantum memories



Bell measurements

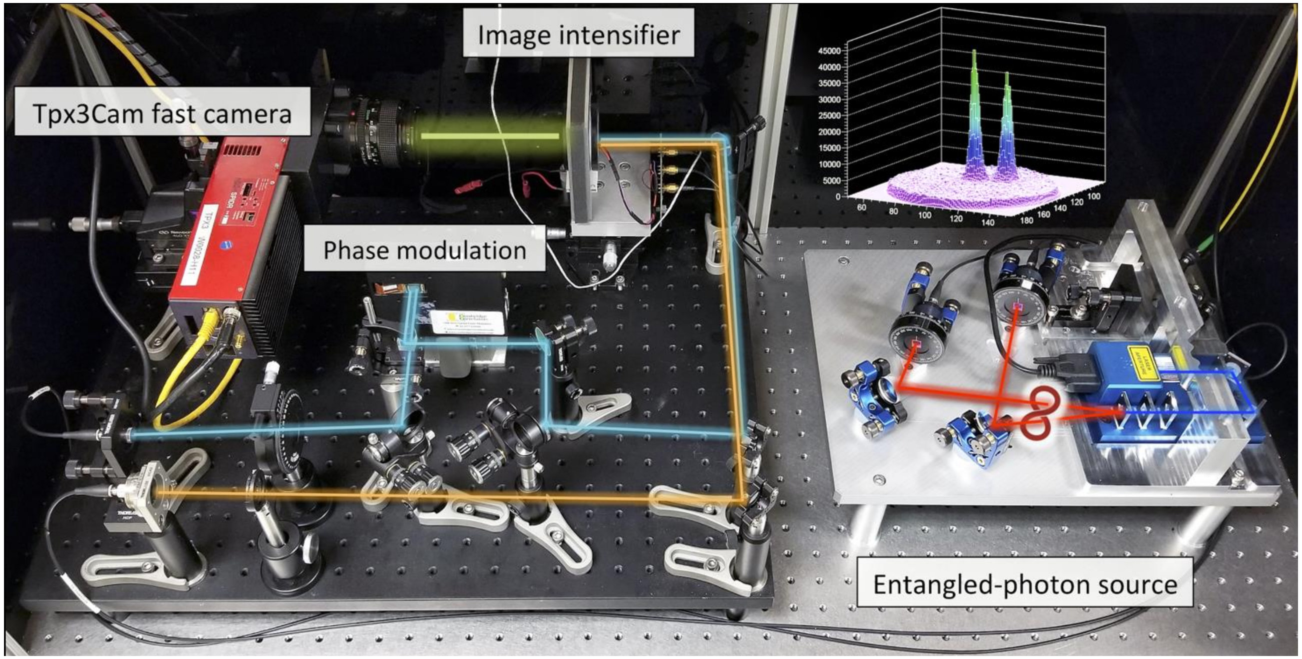


Homodyne detectors

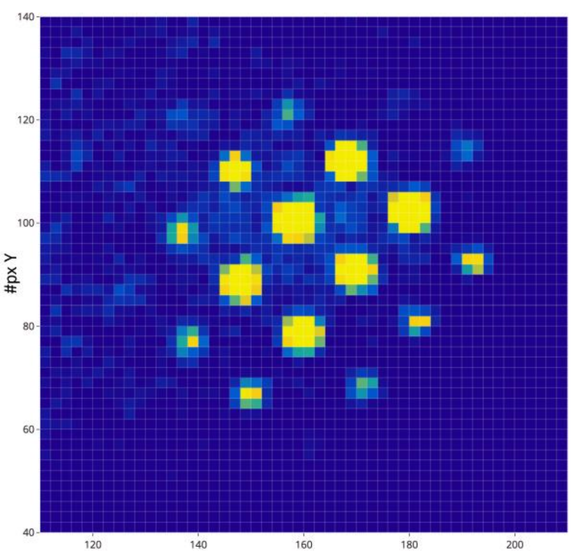
Measurement stations

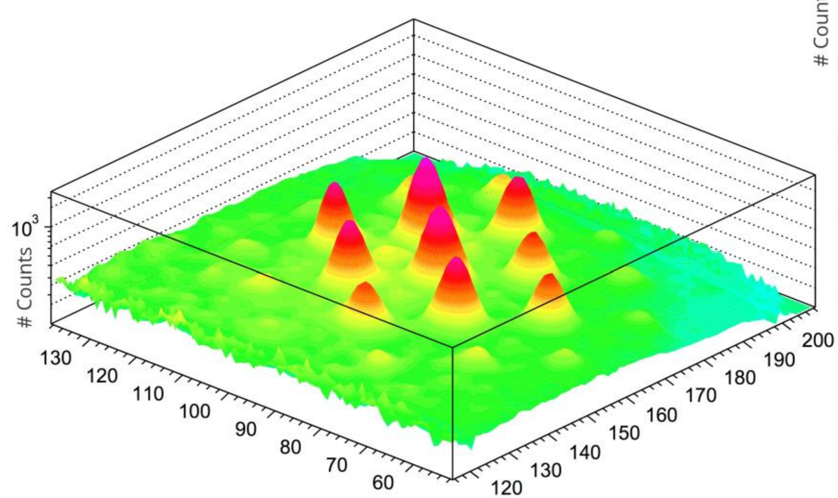
- Largest quantum processing network of its kind.

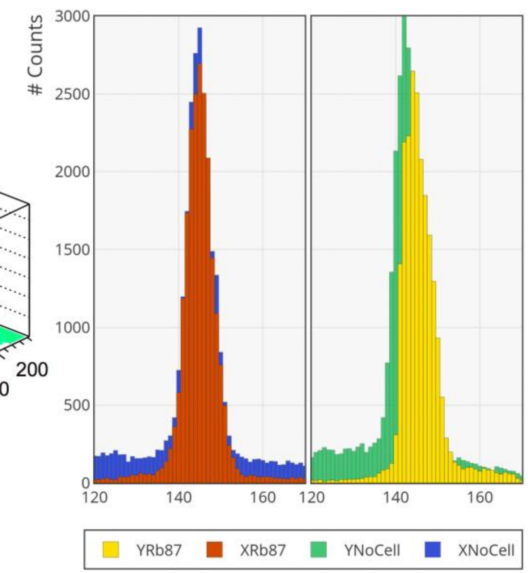
Scaling and multiplexing: a quantum grid



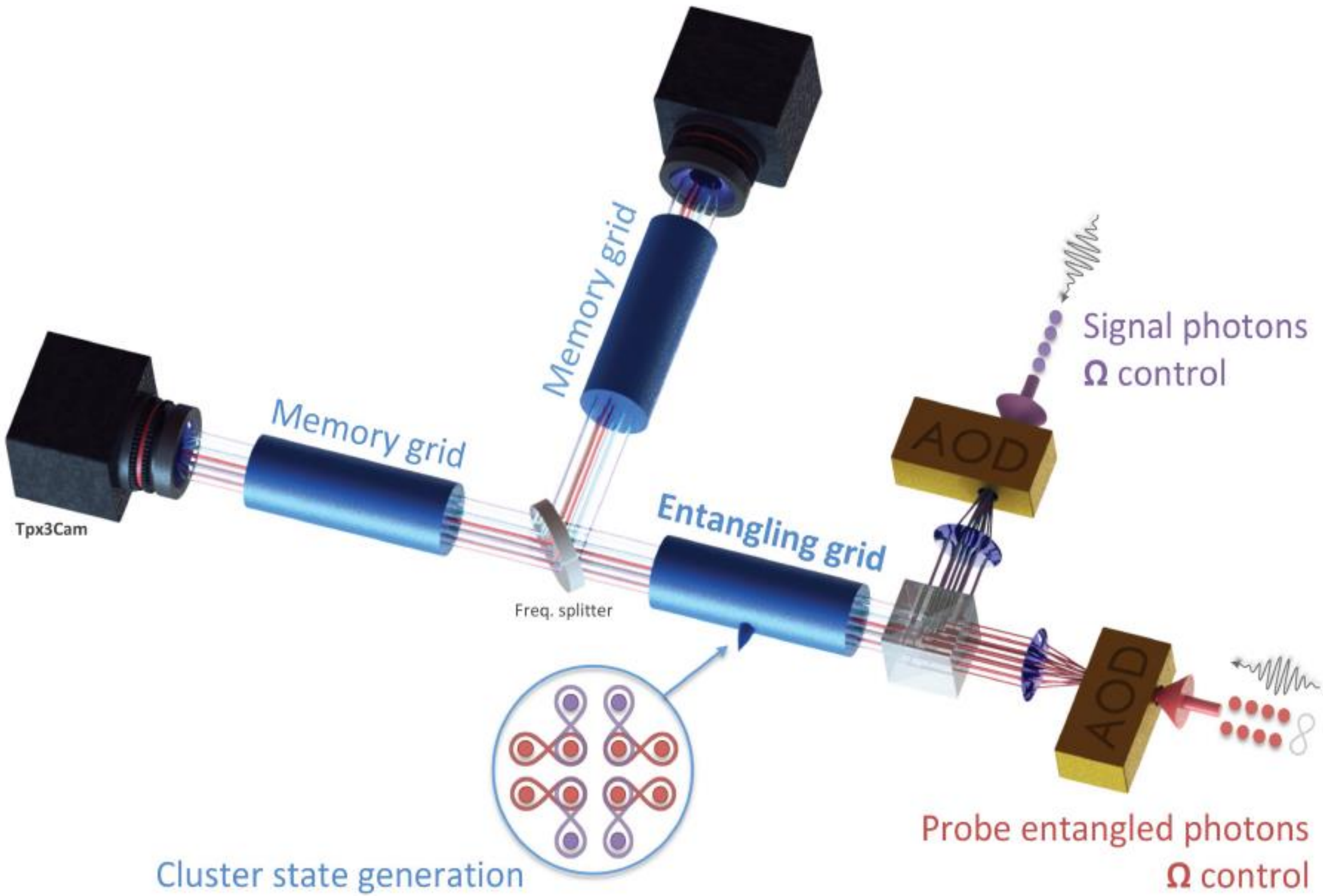
- TimePix camera with intensifier.
- Single photon level detection in time and space.
- 16-rail system created.
- Rubidium interaction.



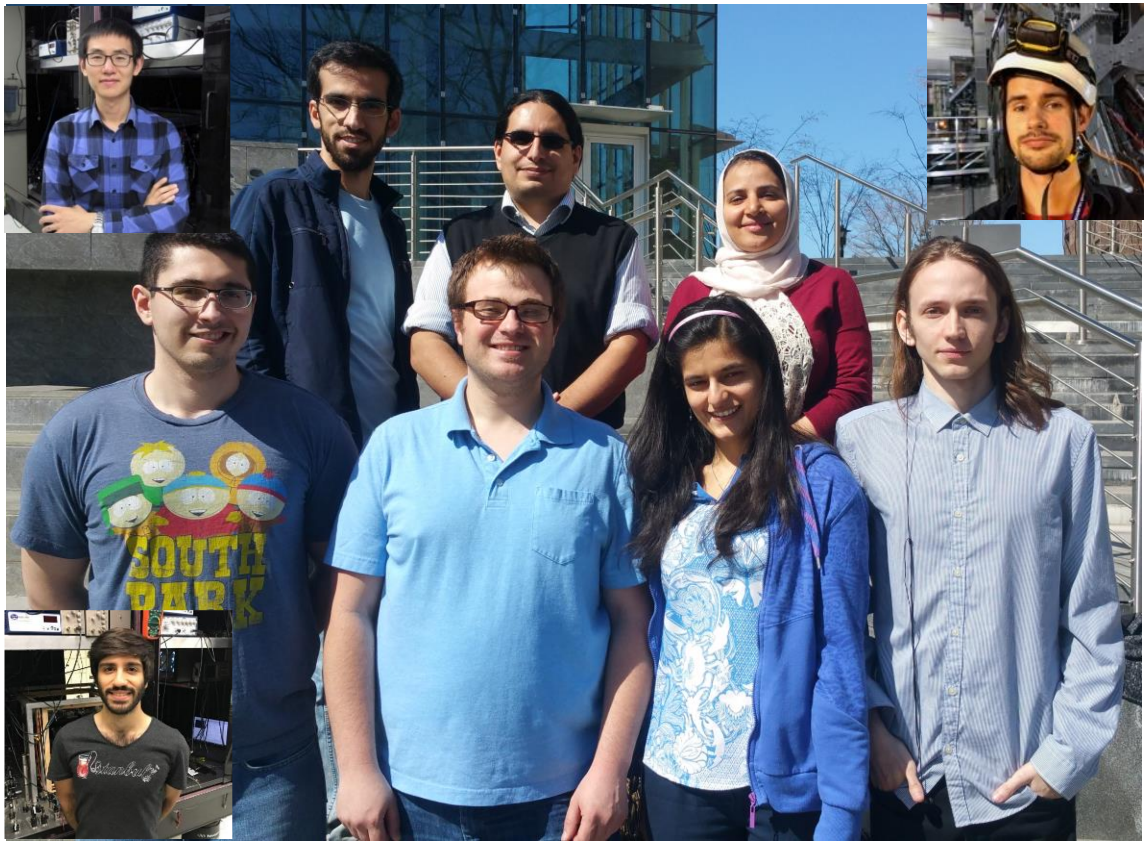




Vision: A quantum grid for photonic quantum simulation and computing.



- Small summary.
  - Room temperature quantum networks already available.
  - Phase switching operations triggered by a few photons.
  - Quantum simulation with light and atoms.
  - Small light-based RT quantum computer within reach.



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