Towards simulating quantum field theories with photons and atoms

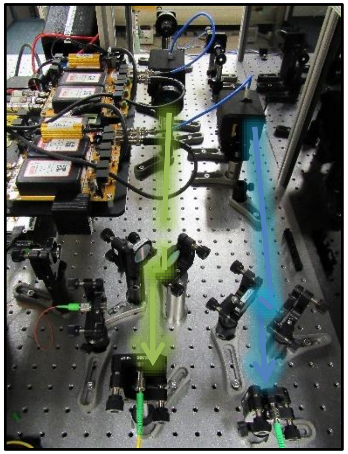
Eden Figueroa

Stony Brook room temperature quantum network

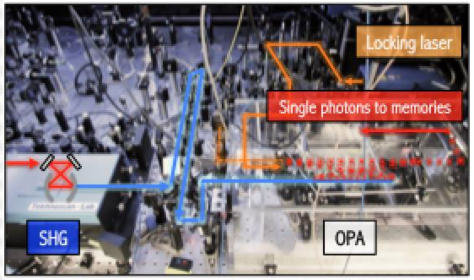
>15 interconnected quantum devices

Photon Sources

Ancilla qubits

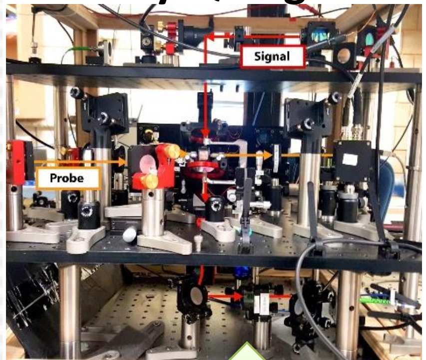


Entangled photons

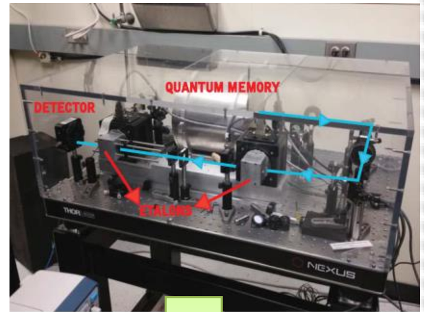


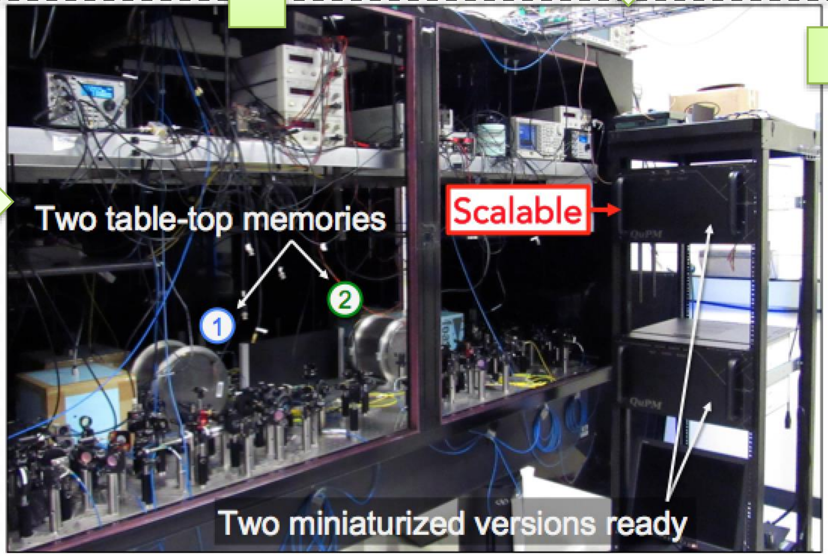
Quantum processing units

Cavity QED gate

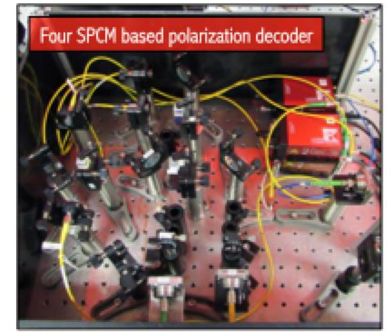


RT phase gate

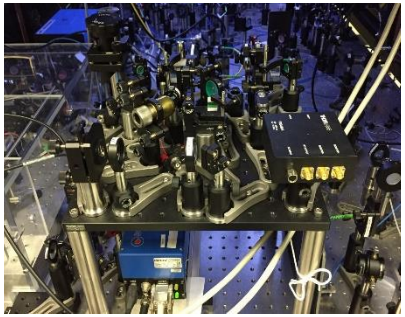




Network of quantum memories



Bell measurements



Homodyne detectors

Measurement stations

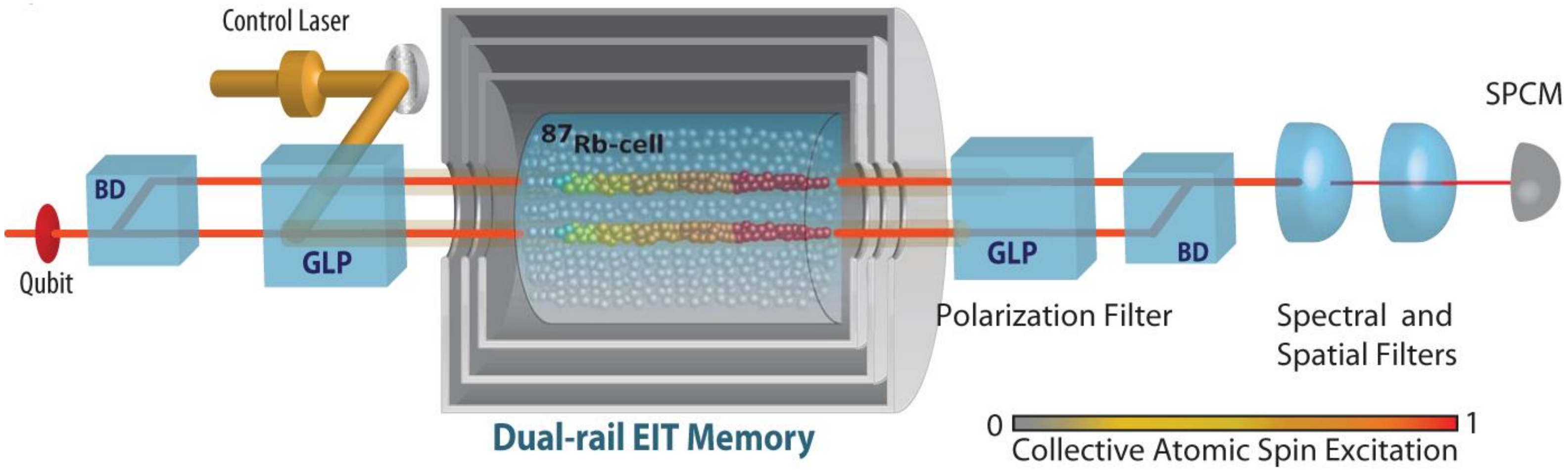
arXiv:1808.07015 (2018)

PR App. 8, 064013 (2017)

PR App. 8, 034023 (2017)

Outline

- Analog quantum simulators with light.
- Photon-photon interaction experiments.
- Scaling the size of the simulators.



I. Analog quantum simulators

Feyman's quantum simulation dream

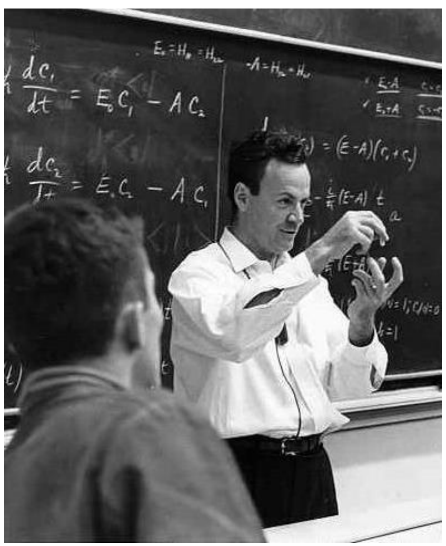
International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

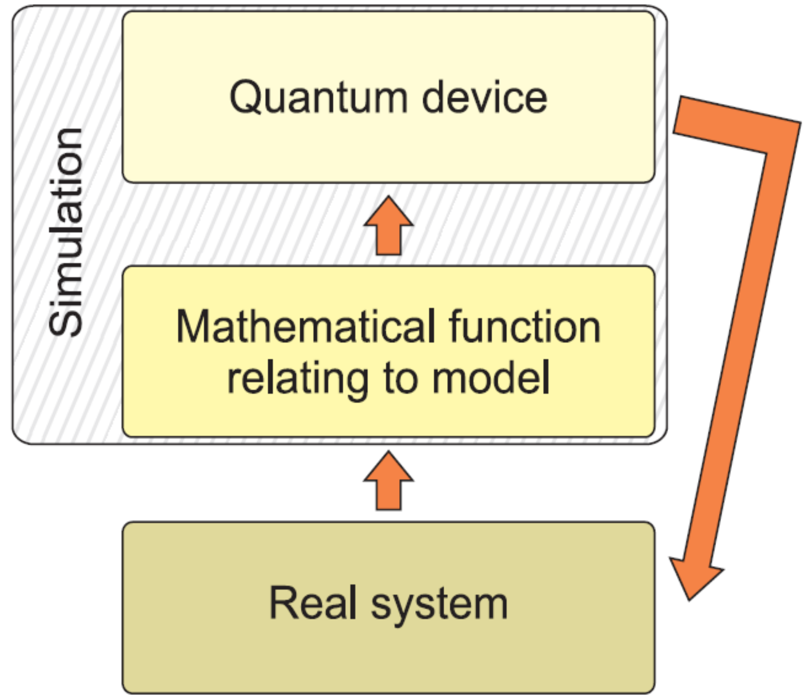
Simulating Physics with Computers

Richard P. Feynman

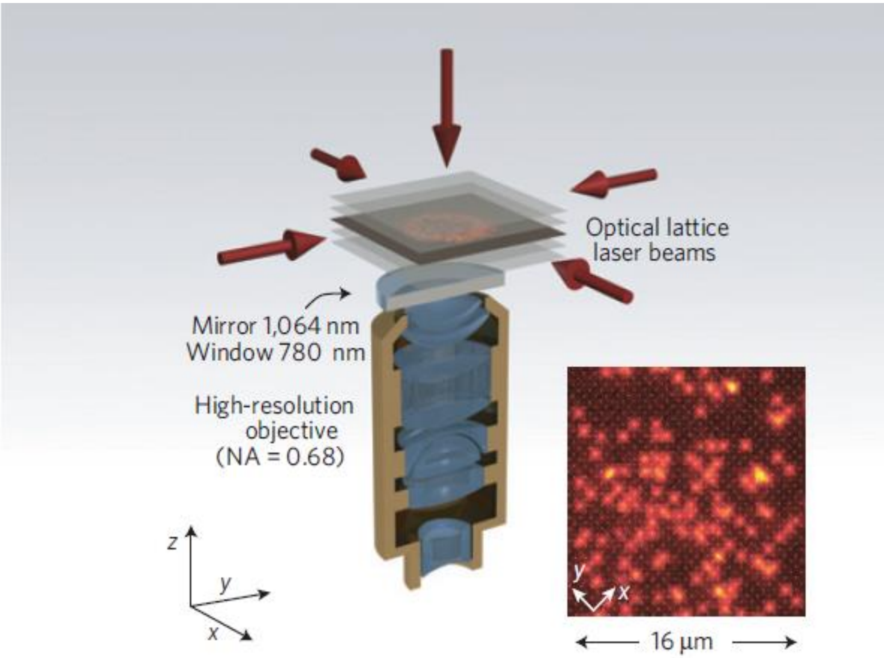
Department of Physics, California Institute of Technology, Pasadena, California 91107

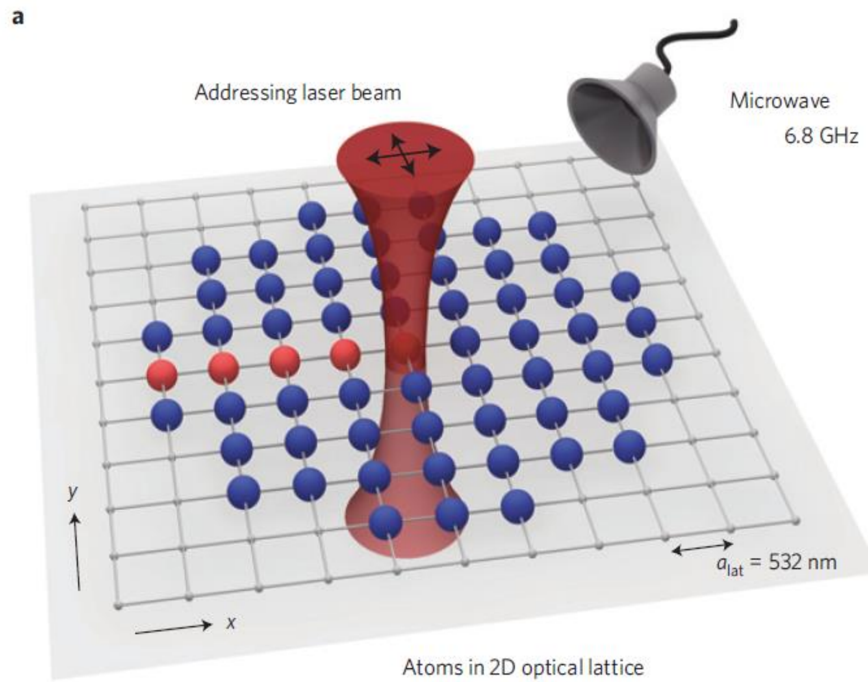
Received May 7, 1981





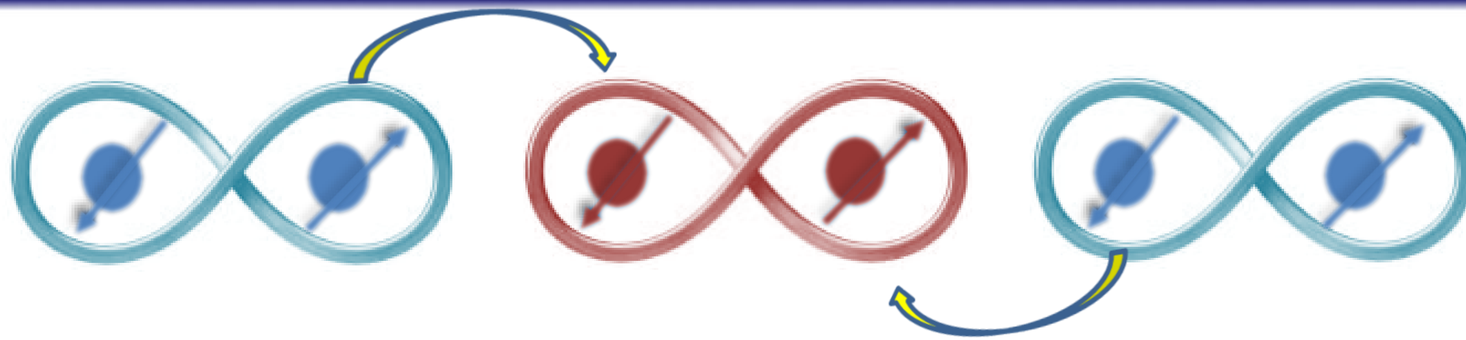
Tailoring Hamiltonians with arrays of atoms



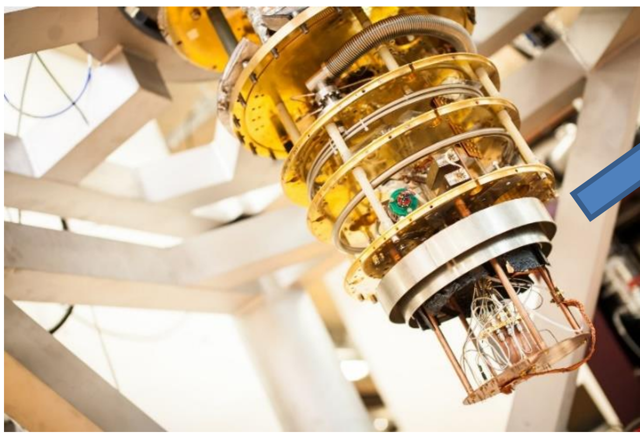


- Optimizing control of quantum matter systems to engineer their interactions to resemble different physical systems.

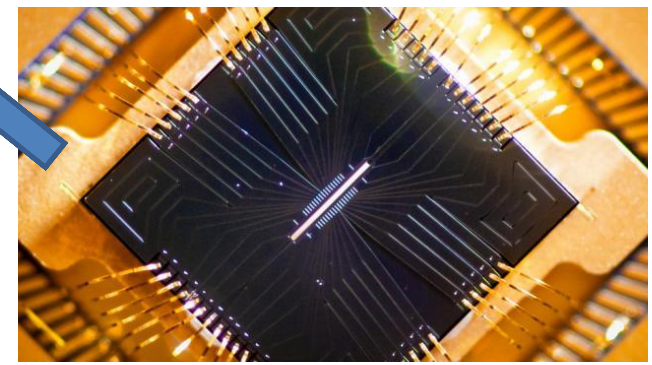
Ising Quantum simulators



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



Superconducting Quantum Simulators



Trapped Ions Quantum Simulators

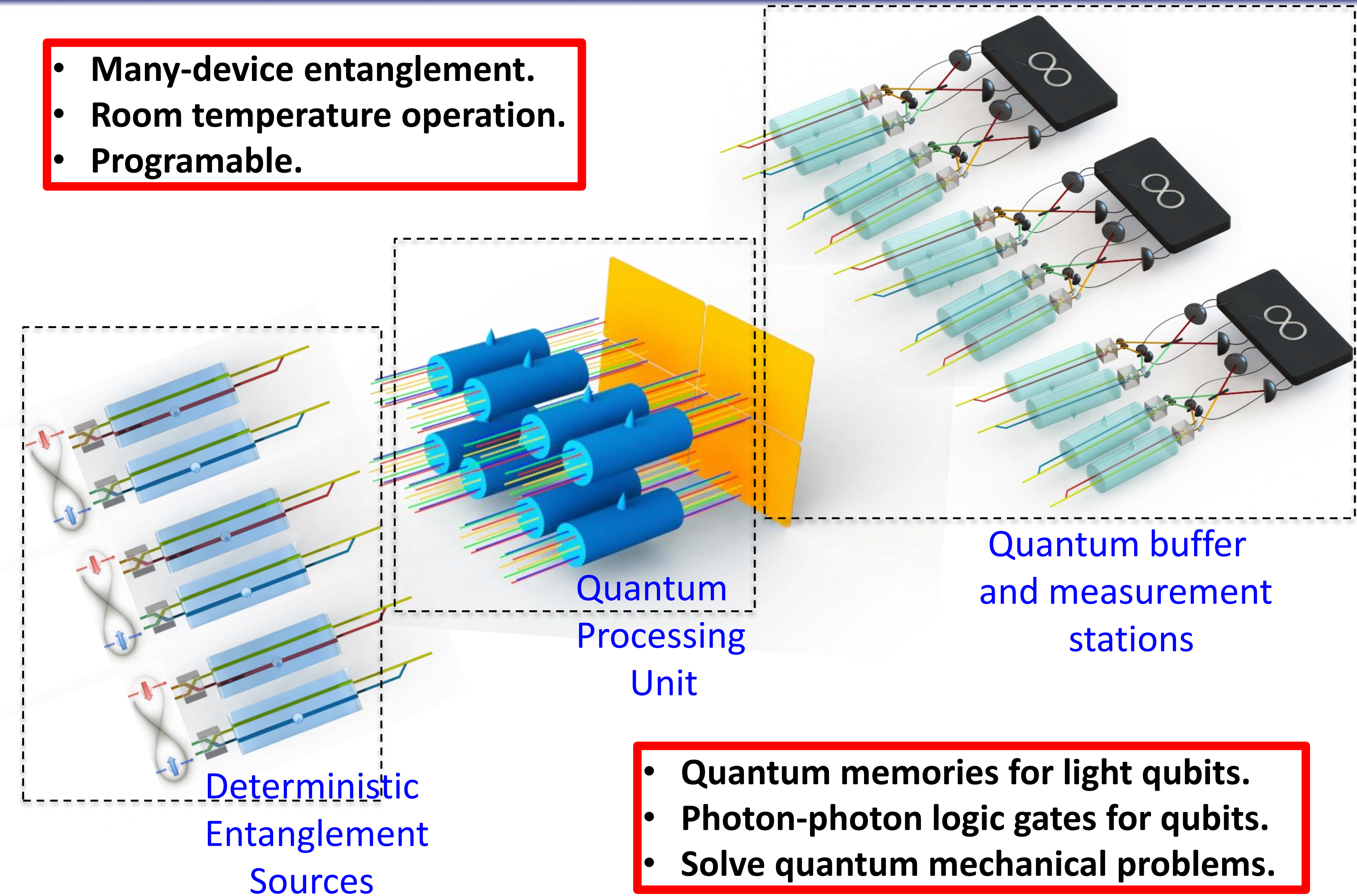
- Interactions among neighbors (NR)
- Operation at 2K
- Solves particular problems

Google rigetti CREATIVE DESTRUCTION LAB

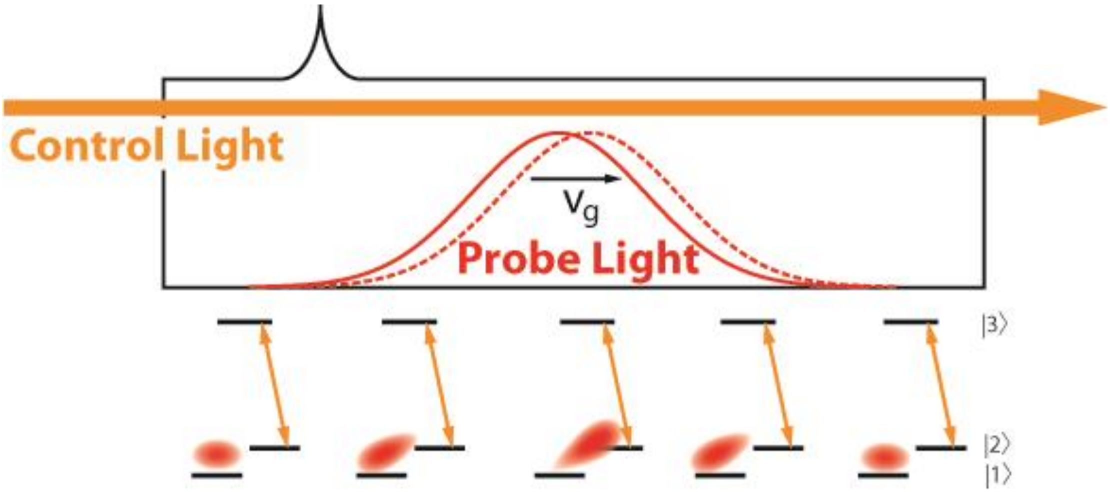
IBM D:WAVE The Quantum Computing Company™ IONQ

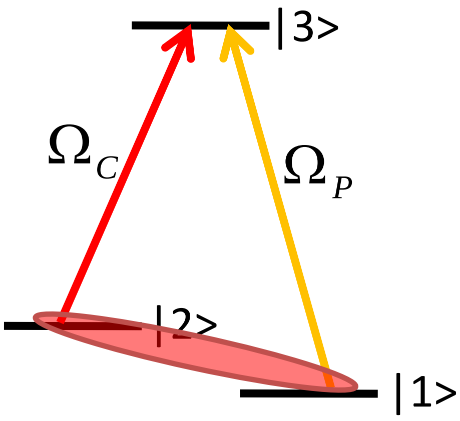
Next evolution: Programable light based quantum computer

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



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





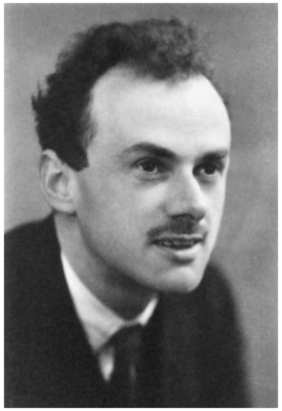
$$\hat{\Psi}(z,t) = \cos\theta(t)\hat{E}(z,t) - \sin\theta(t)\sqrt{N}\,\hat{\sigma}_{bc}(z,t)$$

$$\cos\theta(t) = \frac{\Omega(t)}{\sqrt{\Omega^2(t) + g^2 N}},$$

$$\sin\theta(t) = \frac{g\sqrt{N}}{\sqrt{\Omega^2(t) + g^2 N}}.$$

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

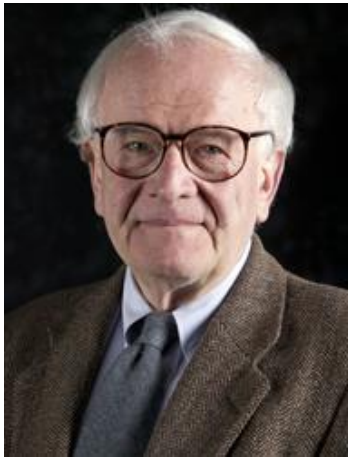
Interesting Quantum Simulation model: Dirac equation



- The Dirac equation merges quantum mechanics with special relativity.

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

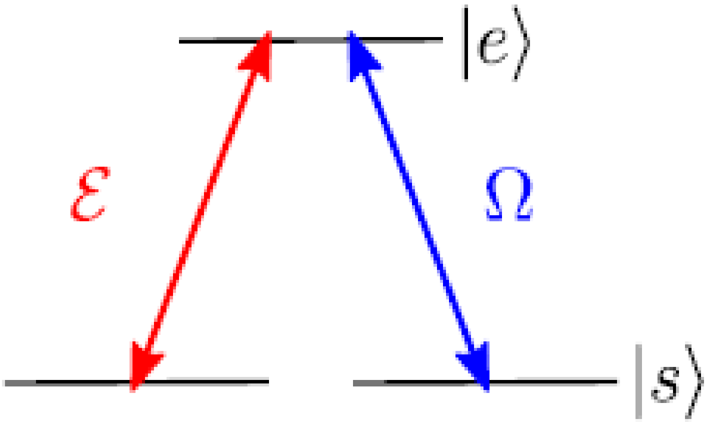
- The Jackiw-Rebbi model describes a Dirac field coupled to a soliton field.



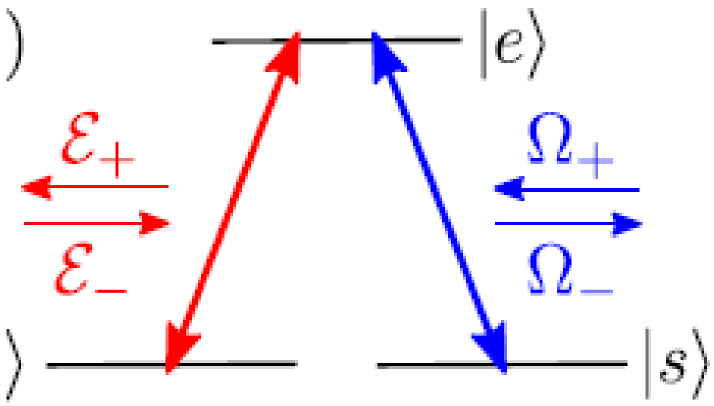
$$\boxed{i\partial_t\mathbf{\Psi}=\left(\alpha c p_z+\frac{\beta mc^2}{\kappa}\phi(z)\right)\mathbf{\Psi}}$$

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

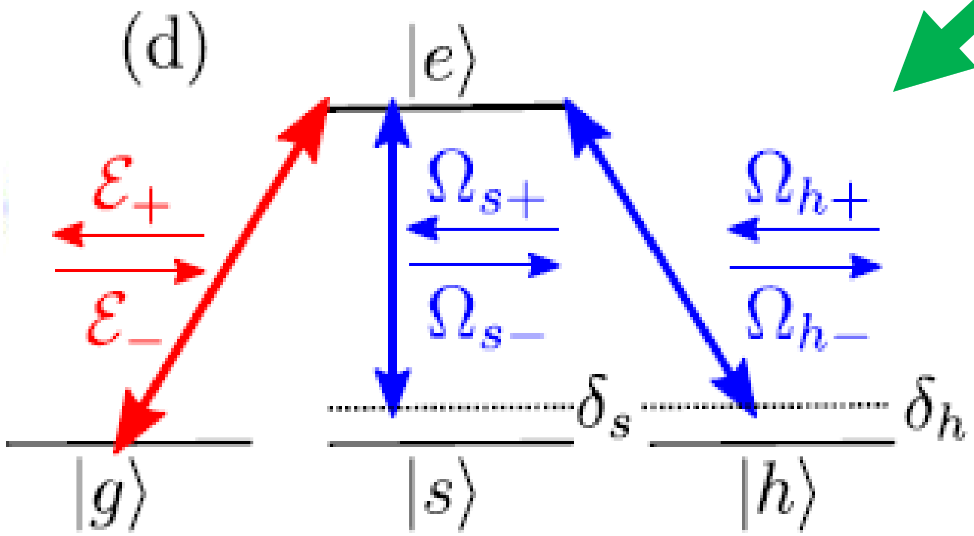
How to build a quantum simulator using dark state polaritons?



EIT setup

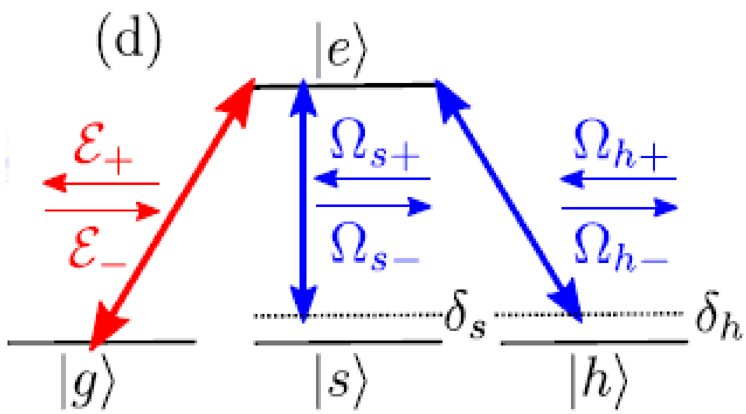


Multiple EIT systems



Spinor of light setup

PRL 105, 173603 (2010).



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

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

Spinor of light:

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

The spinor obeys a Dirac-like equation:

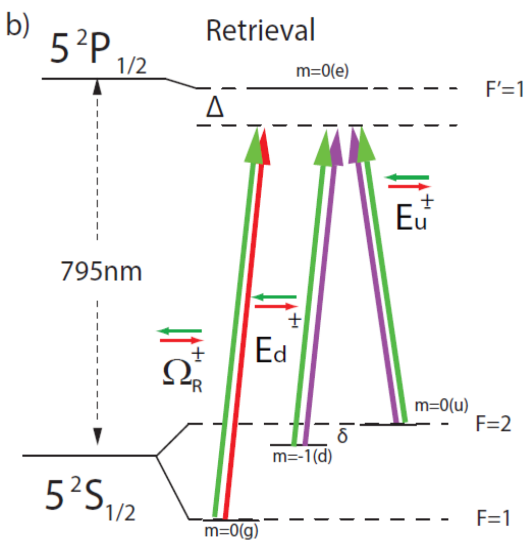
$$i\hbar\frac{\partial}{\partial t}\hat{\boldsymbol{\Psi}} = \left(i\hbar v_g\sigma_z\frac{\partial}{\partial} + \hbar\delta\sin^2\theta\sigma_y\right)\hat{\boldsymbol{\Psi}} - iL_{\text{abs}}v_g\sin^4\theta\left(\sigma_z\frac{\partial}{\partial z} - \frac{\delta}{c}\sigma_y\right)^2\hat{\boldsymbol{\Psi}}$$

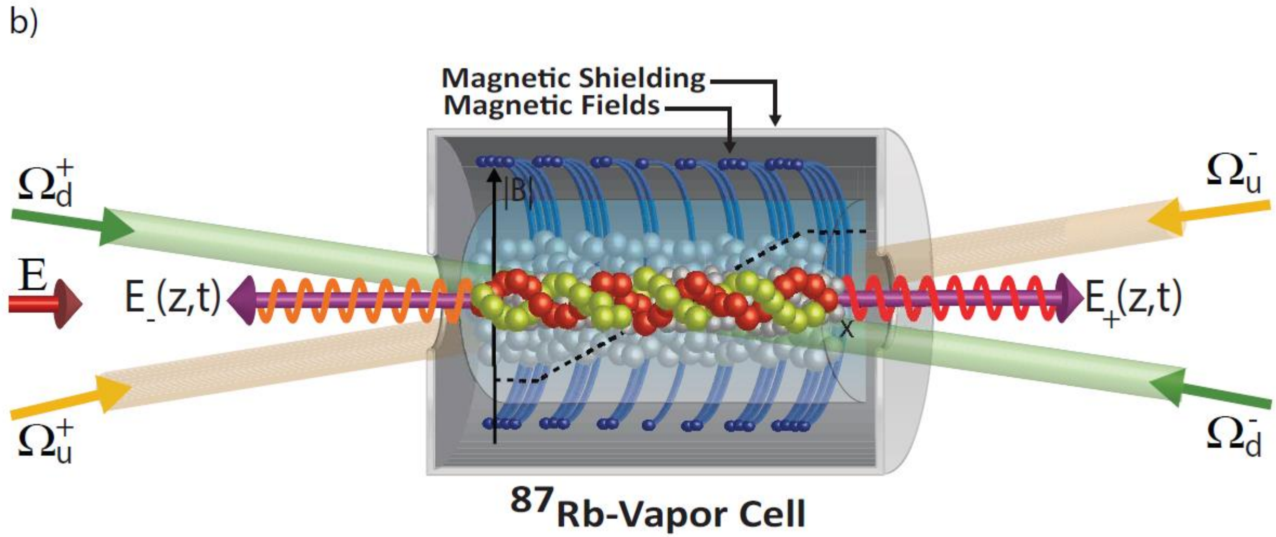
$$c^* = v_g = c\cos^2\theta$$

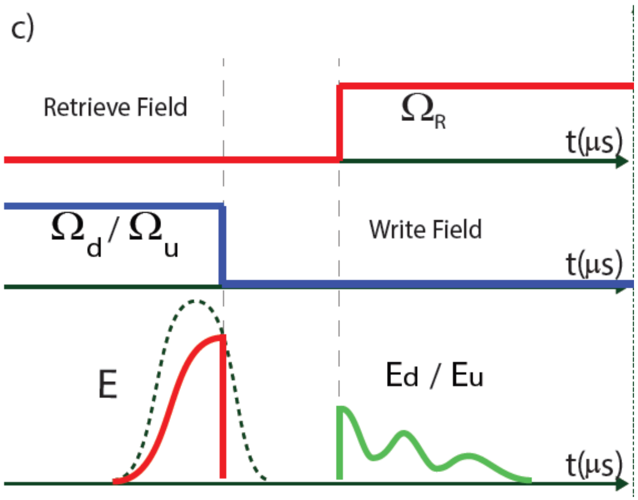
$$m^* = \hbar\delta\sin^2\theta/v_g^2$$

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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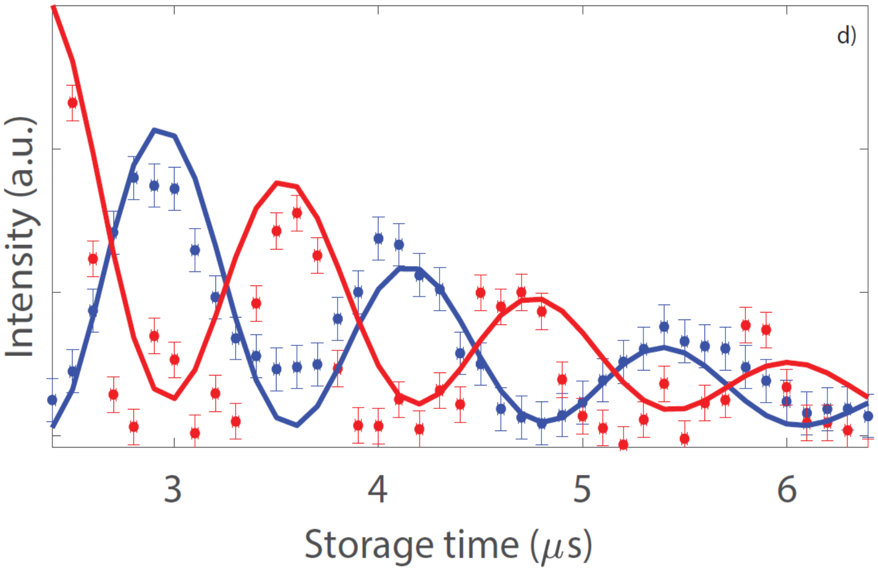
[2] *Korea Institute for Advanced Study, 85 Hoegiro, Seoul 1307*
[3] *Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 1175*

arXiv:1711.09346

Quantum simulation of Dirac spinor dynamics

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

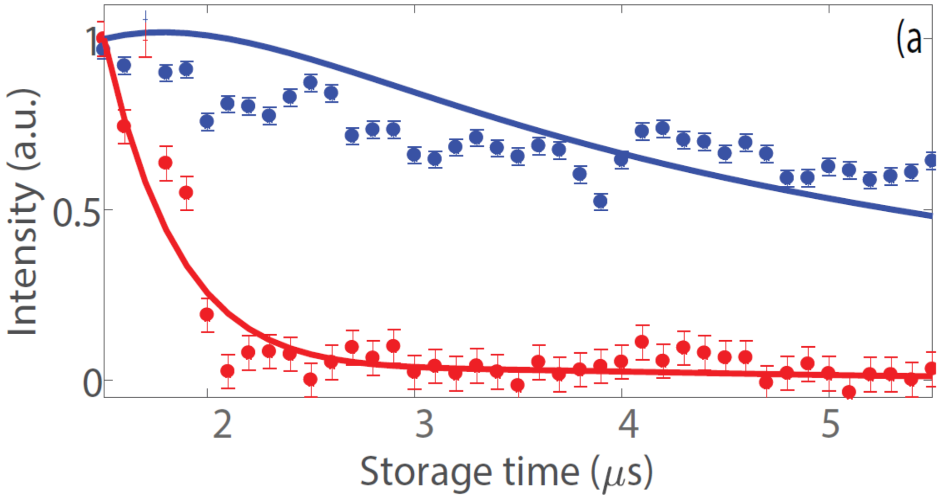
$$\boxed{\psi = (\psi_1, \psi_2)}$$



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

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

$$\boxed{\theta = \pi}$$

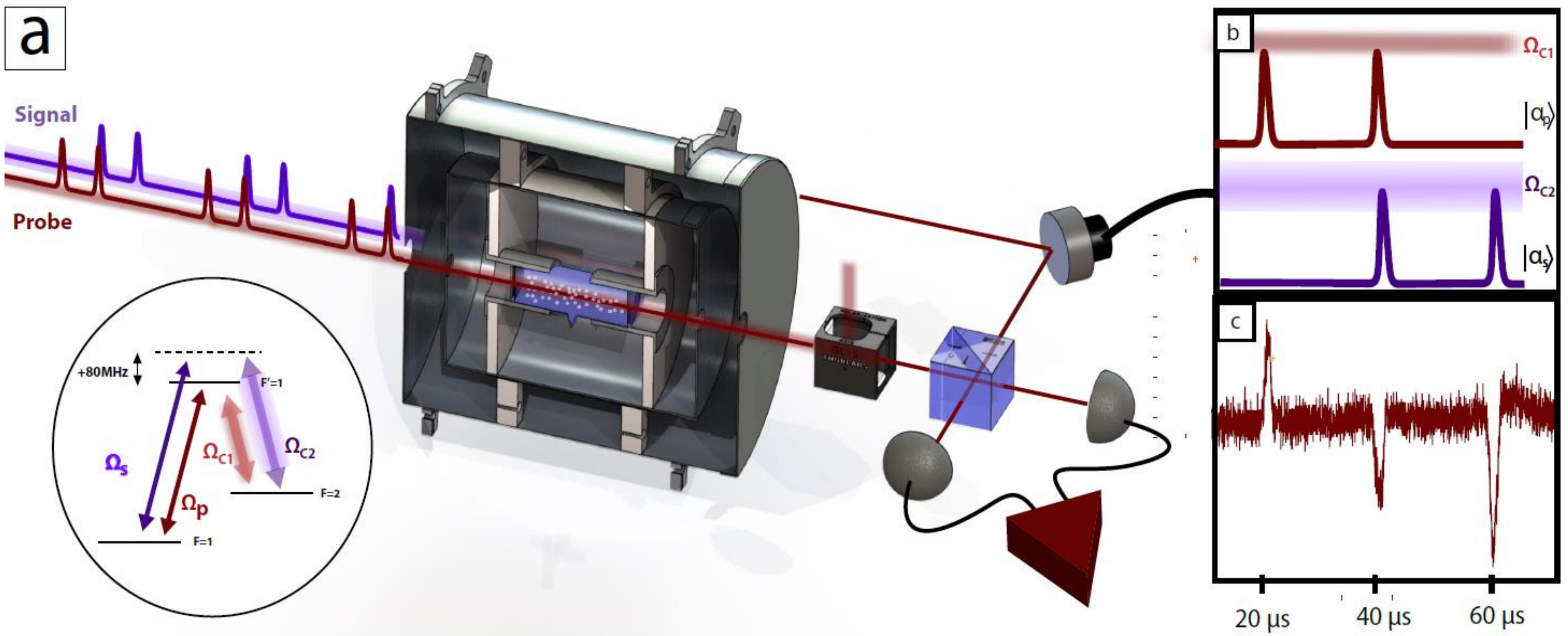


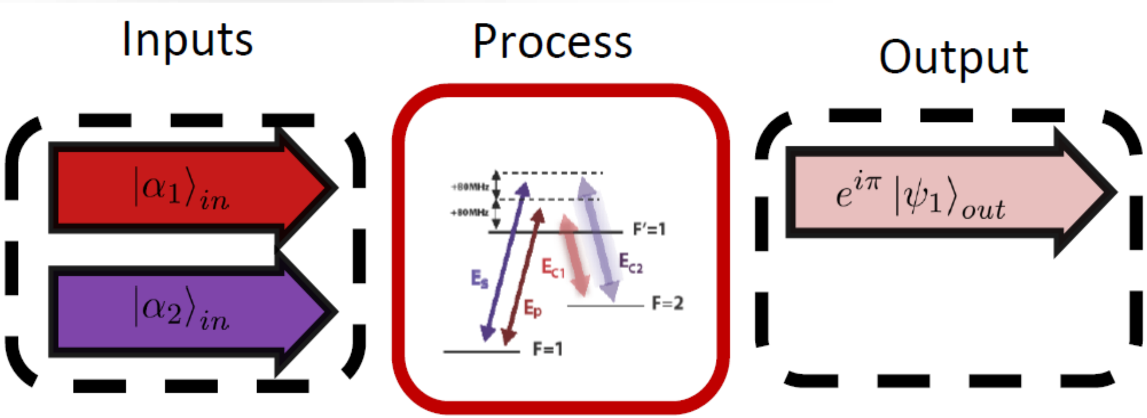
"Realizing JR would require **beams of relativistic particles interacting with Fermi quantum fields**. This realization of the **same physics requires only diode lasers and a cell of Rb atoms**."

arXiv:1711.09346

II. Photon-photon interaction experiments.

Photon-photon gate systems

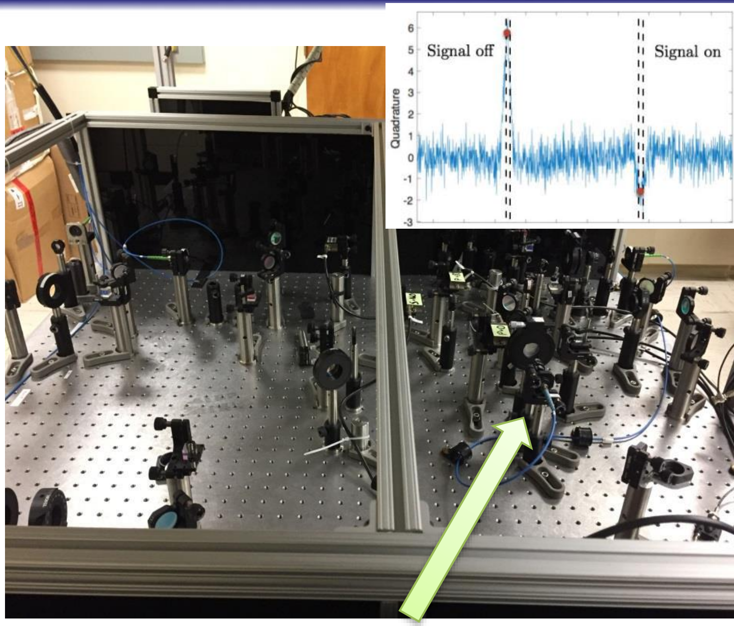




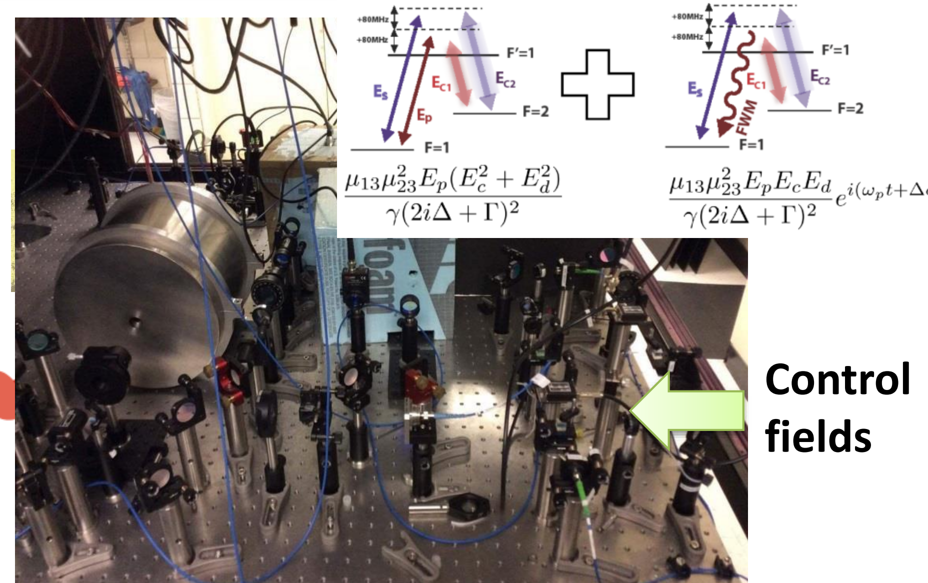
Scientific Reports 5, 16581 (2015).

arXiv:1803.07012

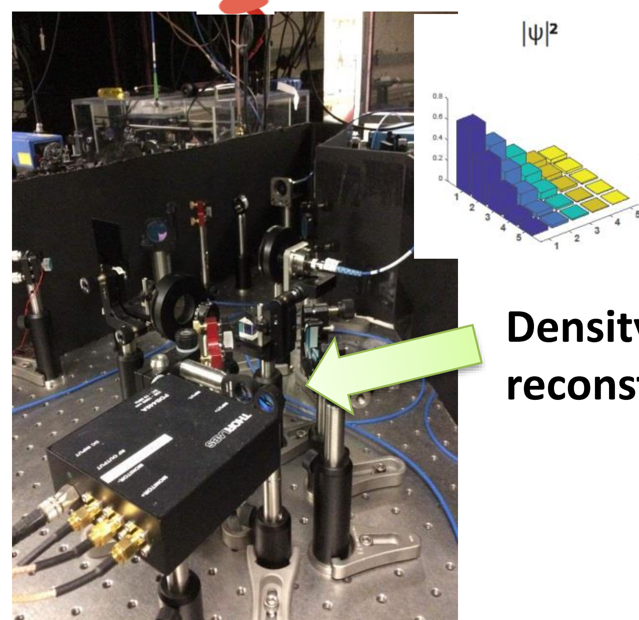
Reconstruction of wave-functions



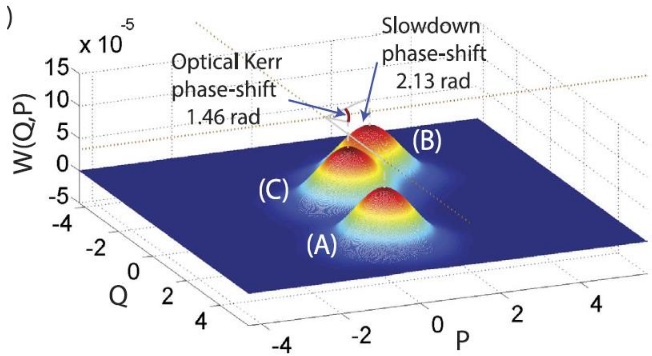
Single- photon level pulses for probe and signal



Control fields



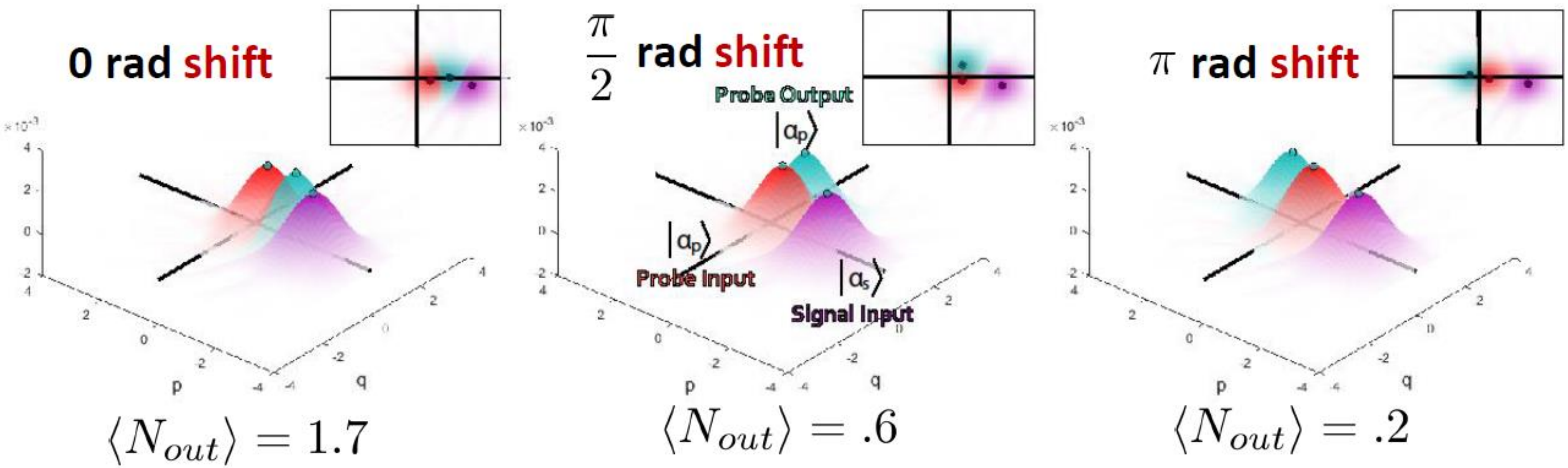
Density matrix reconstruction



Wave function characterization

arXiv:1803.07012

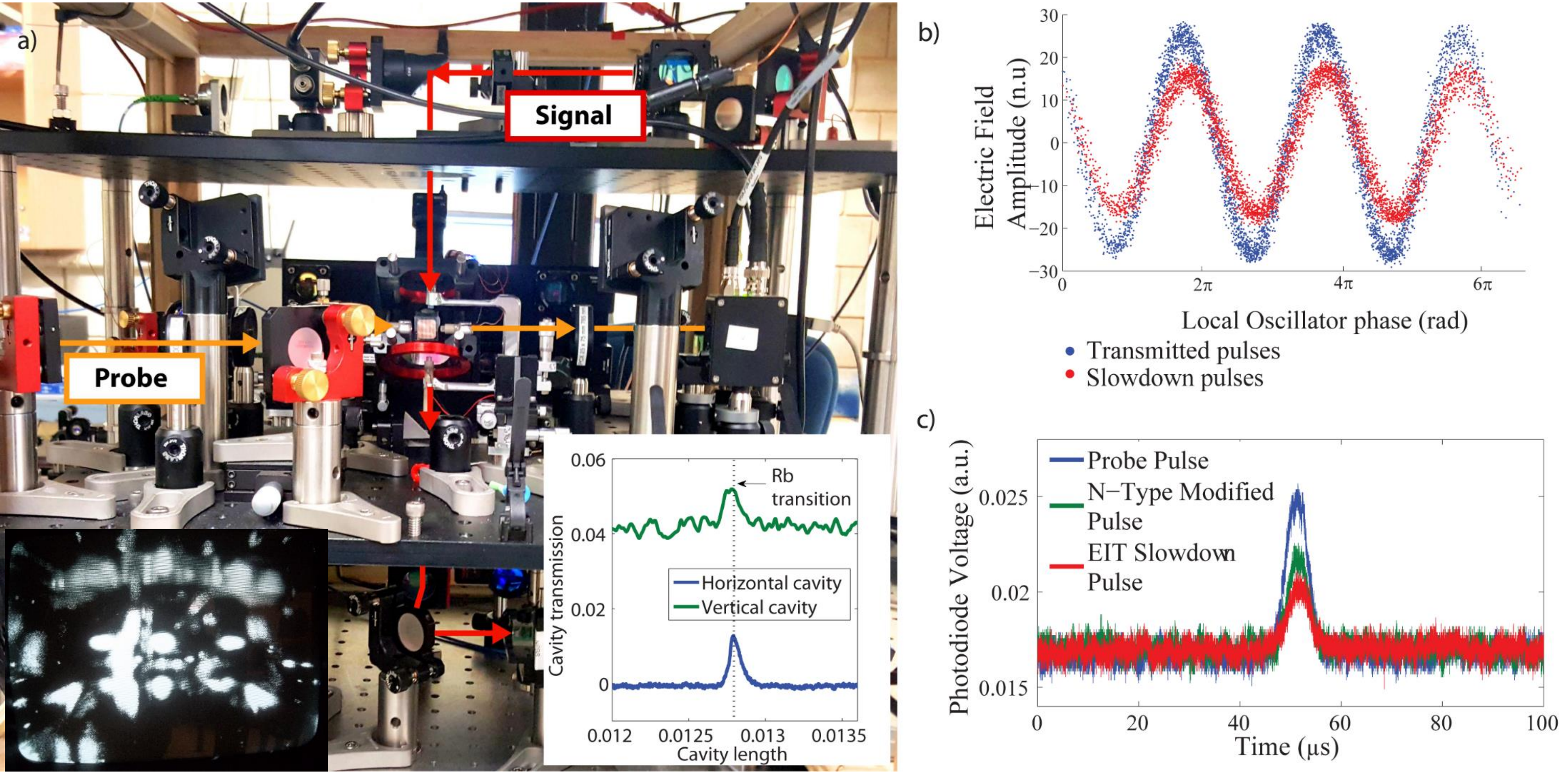
Pi-phase shifts in single photon fields mediated by few-photons



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

arXiv:1803.07012

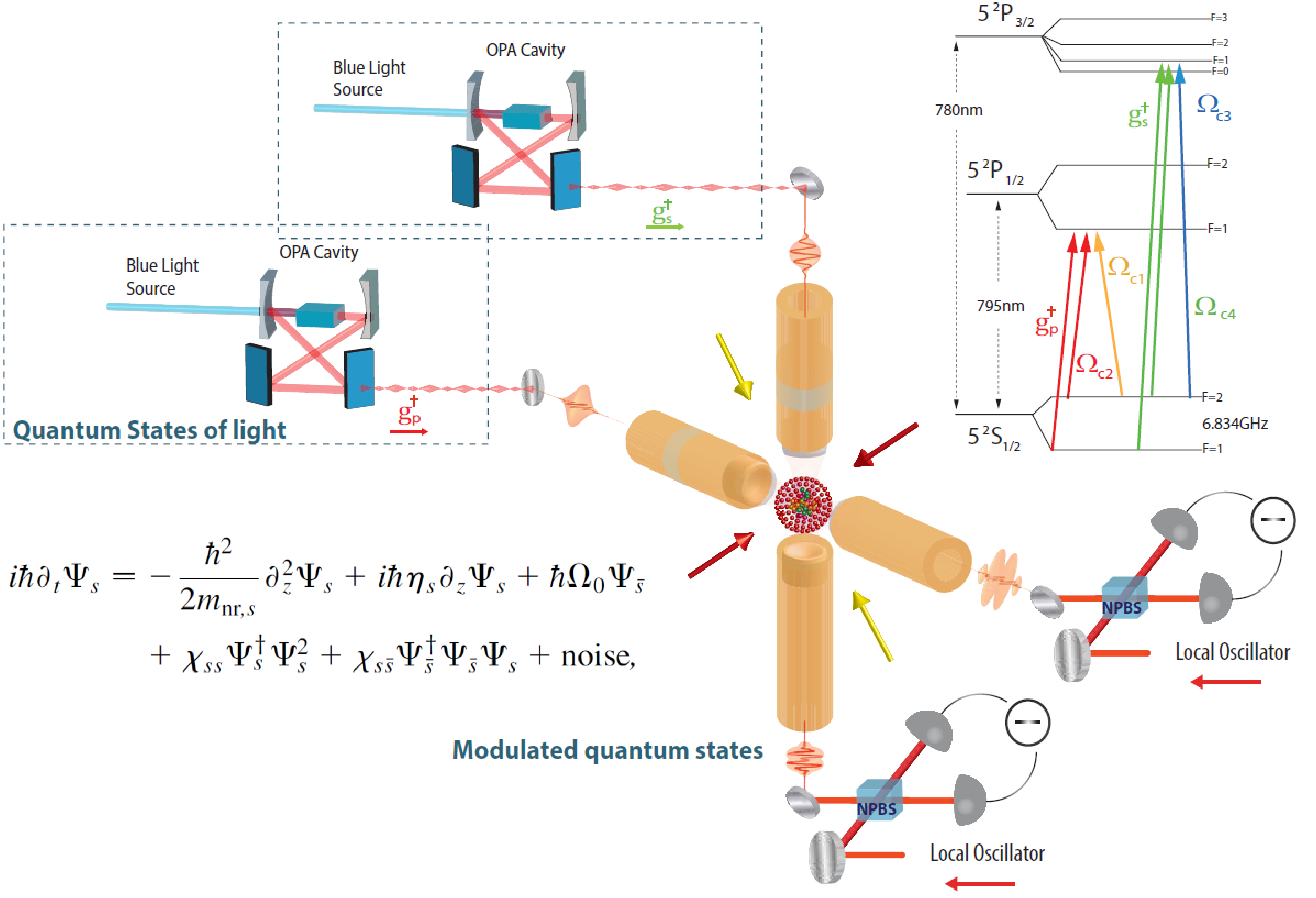
Implementation of a crossed cavity QED/EIT system



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



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

Road map for a DSP-based quantum simulator

Fundamental tools

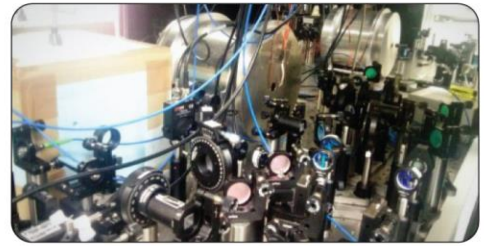
- Quantum light matter interfaces

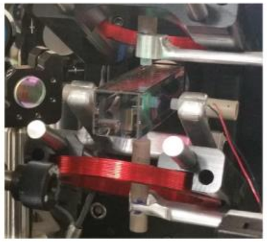
  → To realize the creation of spinor slow-light polaritons (SSP) obeying an effective 1D Dirac equation

- 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).

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

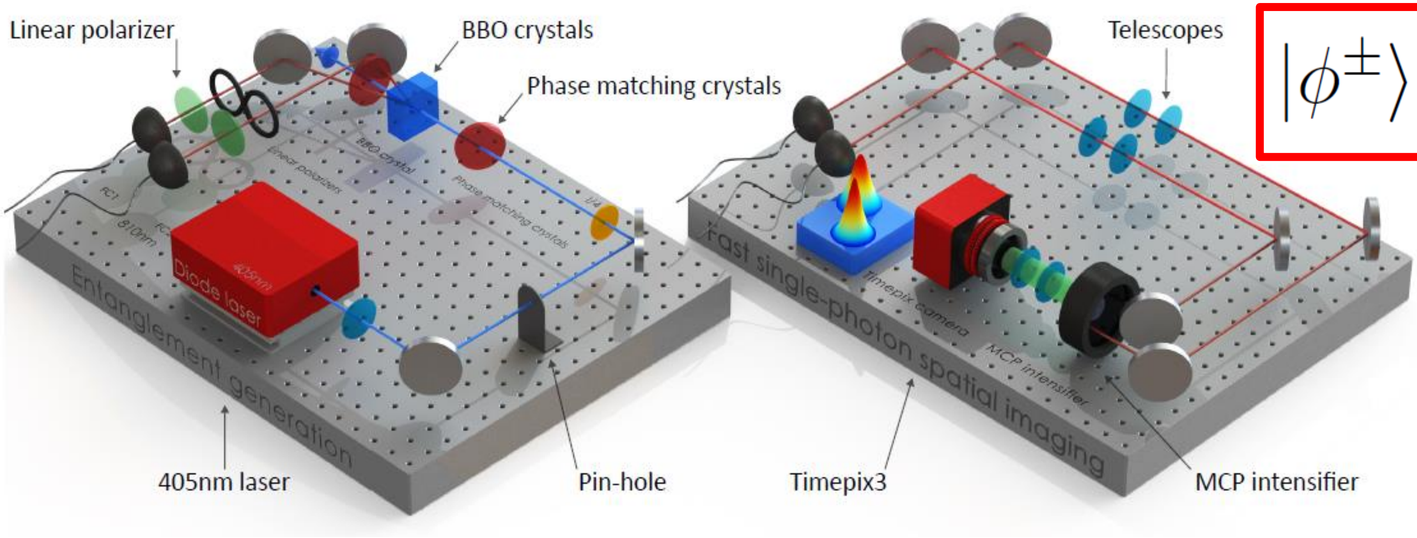
Quantum Hall effect Model, PRL 101, 246809 (2008).

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

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

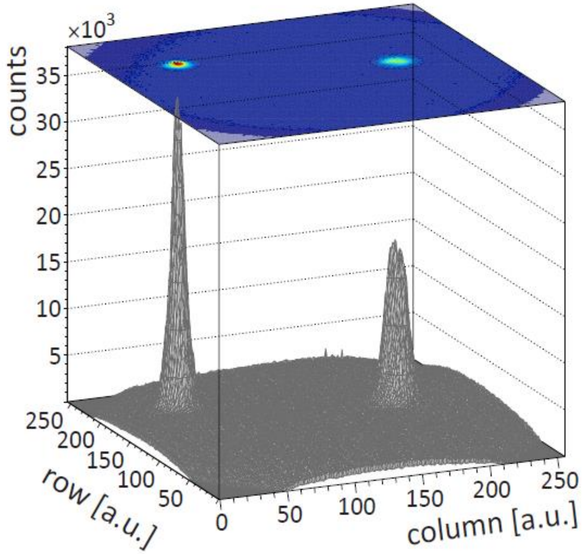
III. Scaling the number of qubits

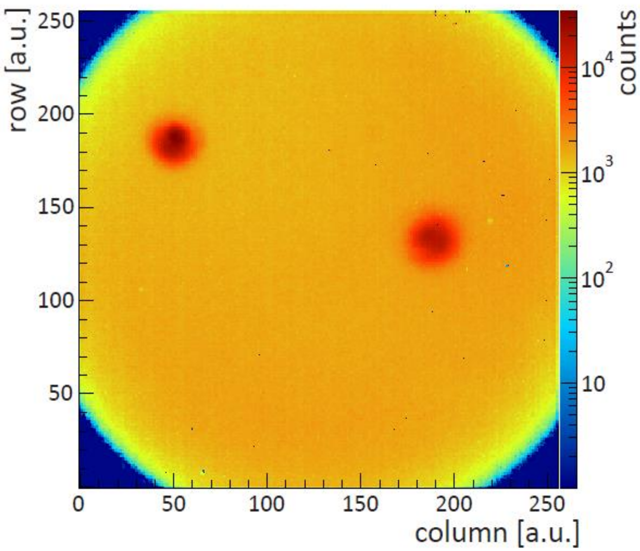
Entanglement imaging (SBU/BNL)



$$|\phi^{\pm}\rangle = \frac{(|HH\rangle \pm |VV\rangle)}{\sqrt{2}}$$

- TimePix camera with intensifier.
- Single photon level detection in time and space.
- Entanglement pictures.



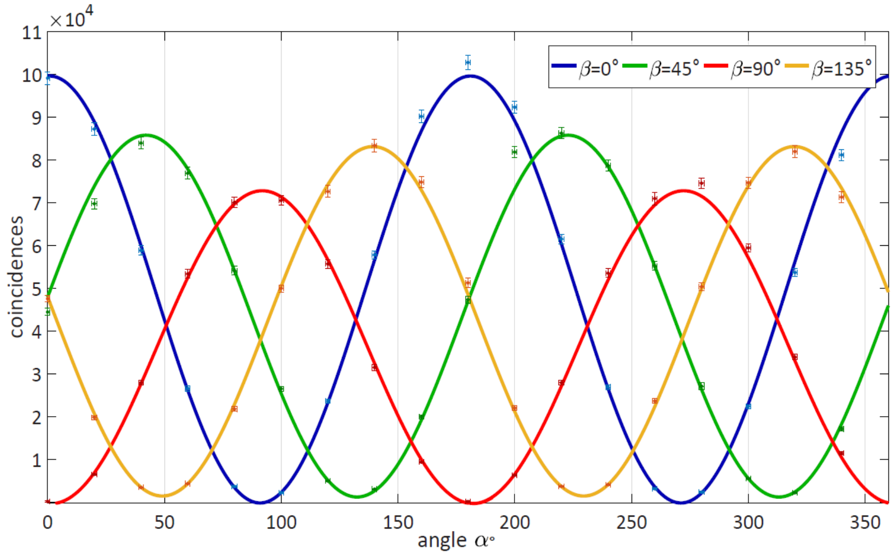


arXiv:1808.06720 (2018).

Entanglement characterization (SBU/BNL)

$$S = E(\alpha,\beta) + E(\alpha',\beta) - E(\alpha,\beta') + E(\alpha',\beta') \leq 2$$

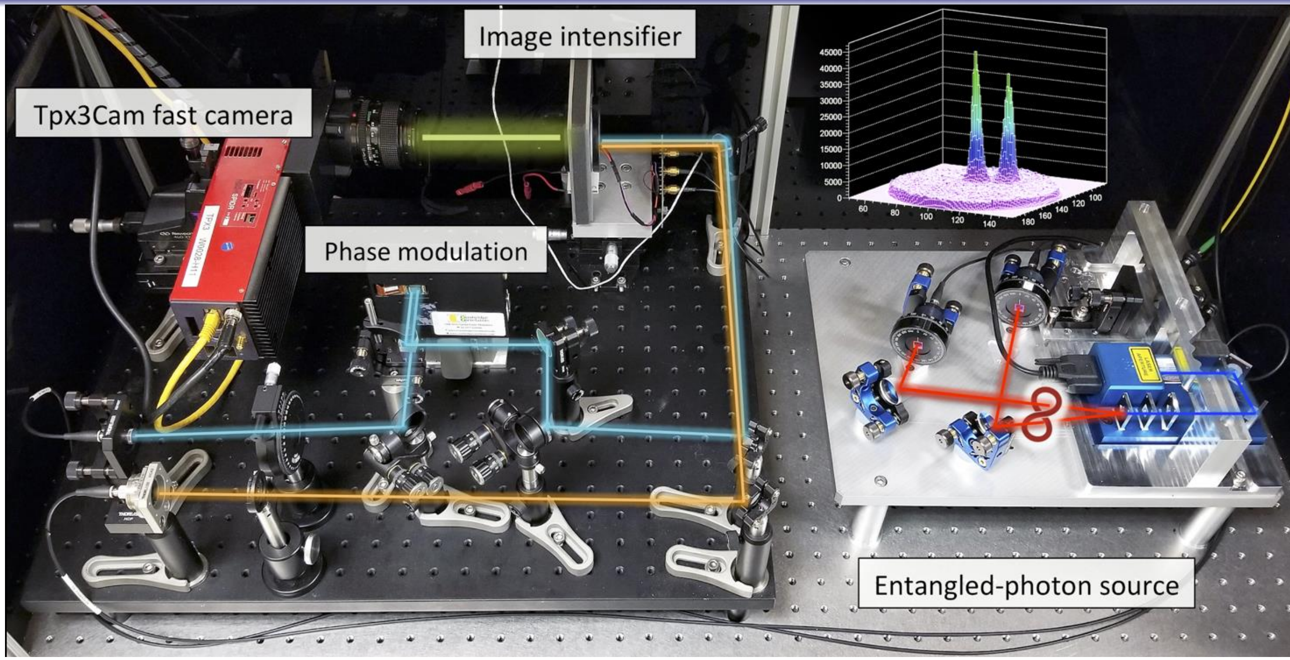
$$E(\alpha,\beta) = \frac{N_{VV}(\alpha,\beta)+N_{HH}(\alpha,\beta)-N_{VH}(\alpha,\beta)-N_{HV}(\alpha,\beta)}{N_{VV}(\alpha,\beta)+N_{HH}(\alpha,\beta)+N_{VH}(\alpha,\beta)+N_{HV}(\alpha,\beta)}$$



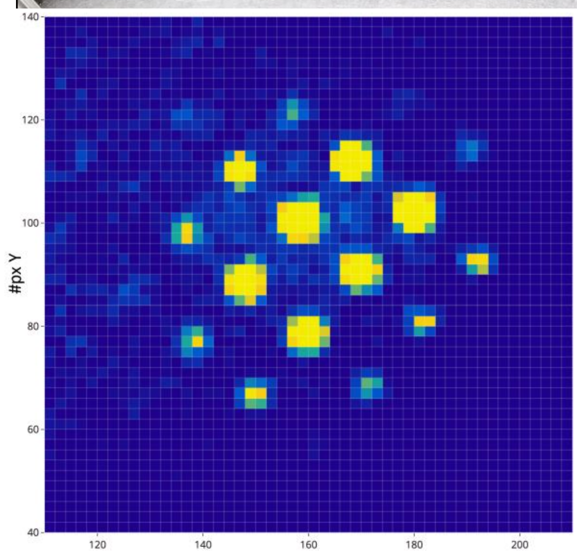
- **Entanglement characterization.**
- **Bell inequality violation.**
- **81 simultaneous entanglement measurements.**

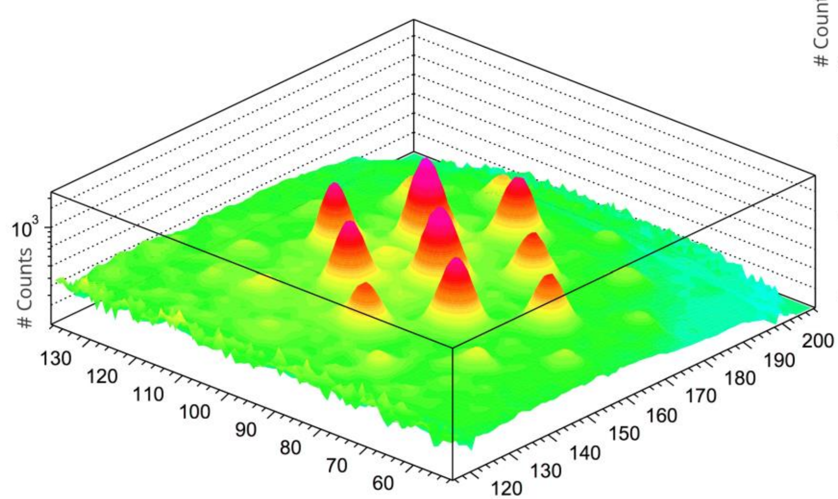
arXiv:1808.06720 (2018).

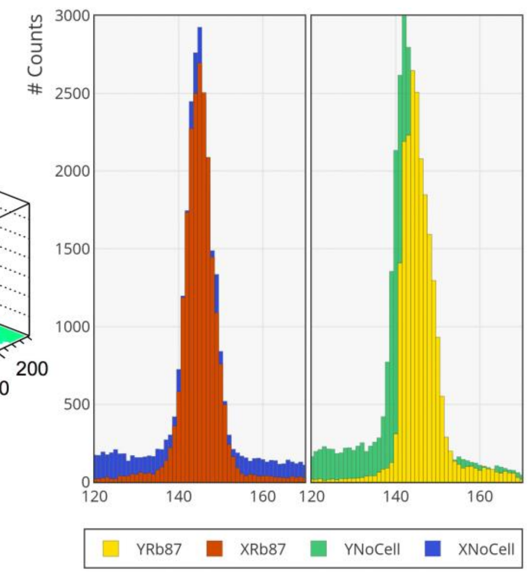
Scaling and multiplexing: a quantum grid (SBU/BNL)



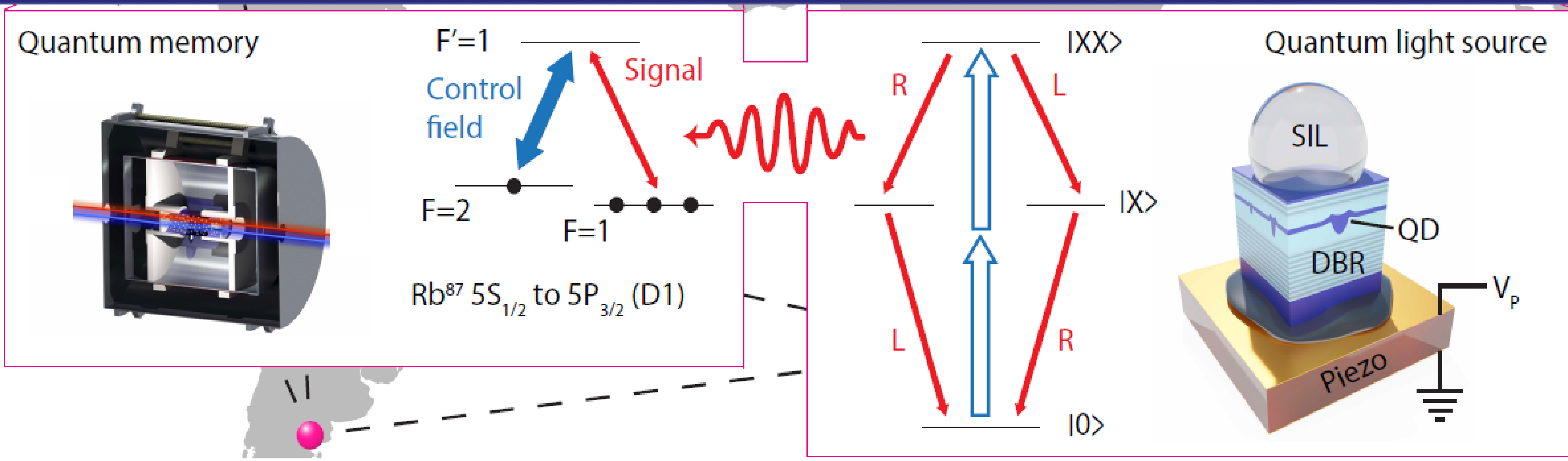
- TimePix camera with intensifier.
- Single photon level detection in time and space.
- 16-rail system created.
- Rubidium interaction.

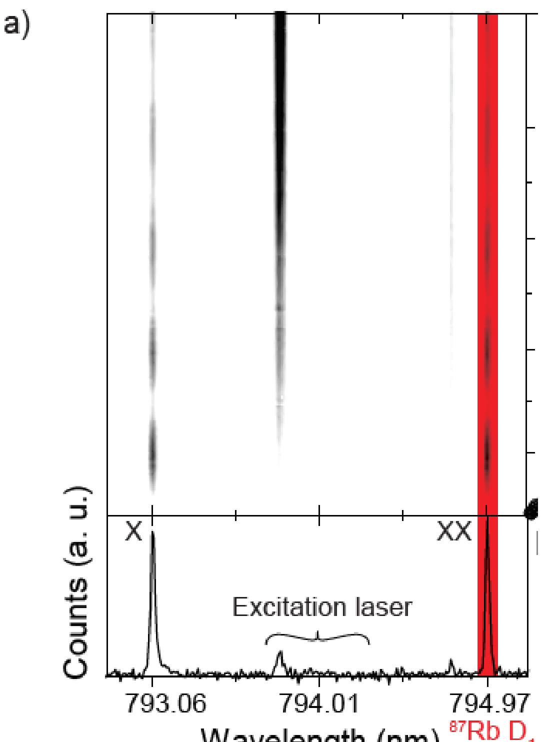


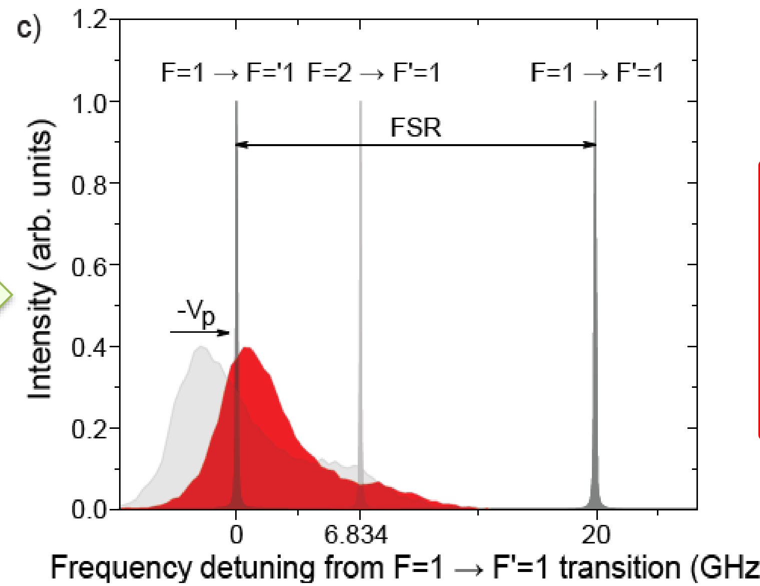




Interaction with entangled photons from quantum dots (SBU/KTH)



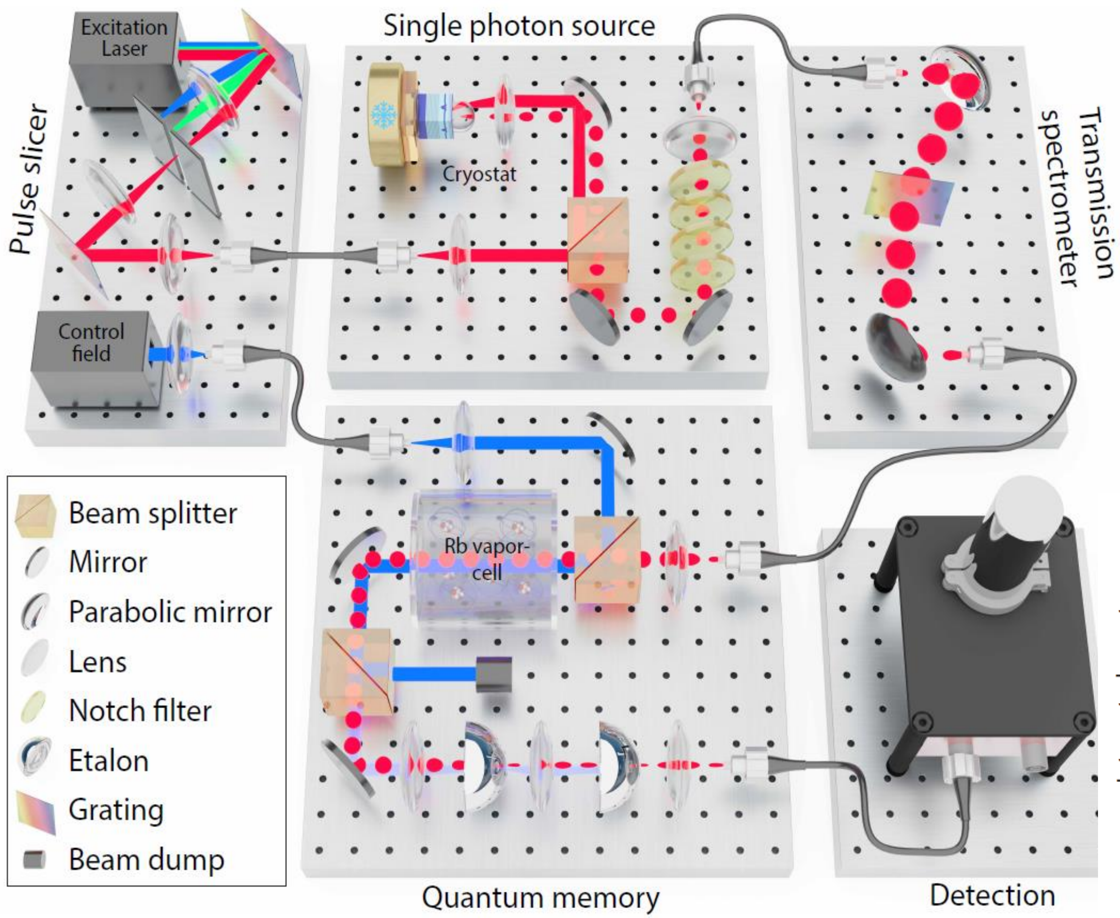


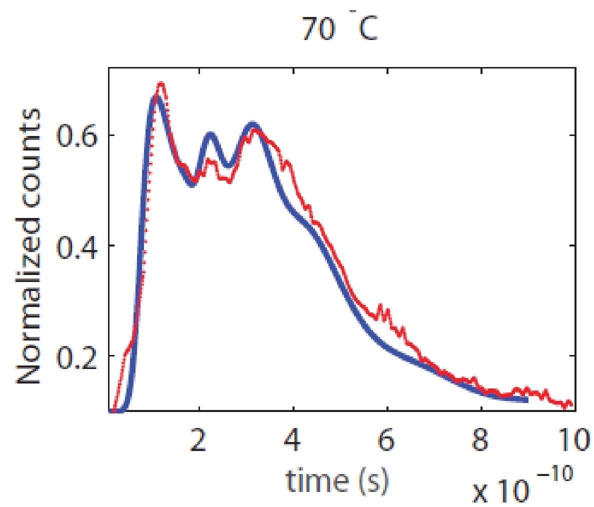


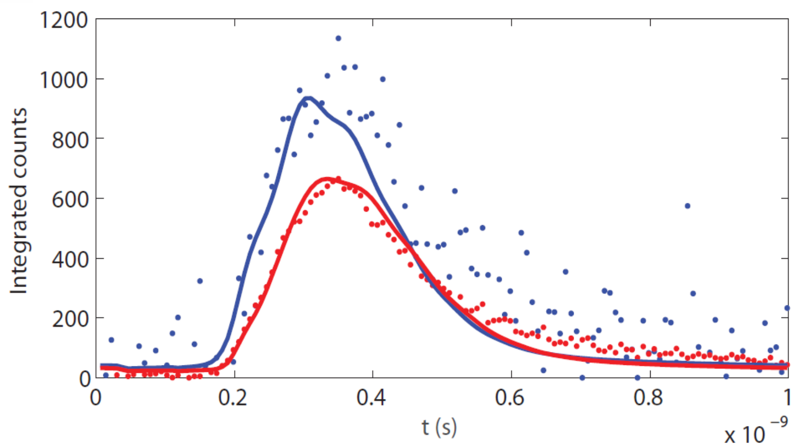
- Quantum dot photons tuned to the Rubidium D1 line (795nm)

arXiv:1808.05921 (2018).

Electromagnetically Induced Transparency with quantum dot photons (SBU/KTH)





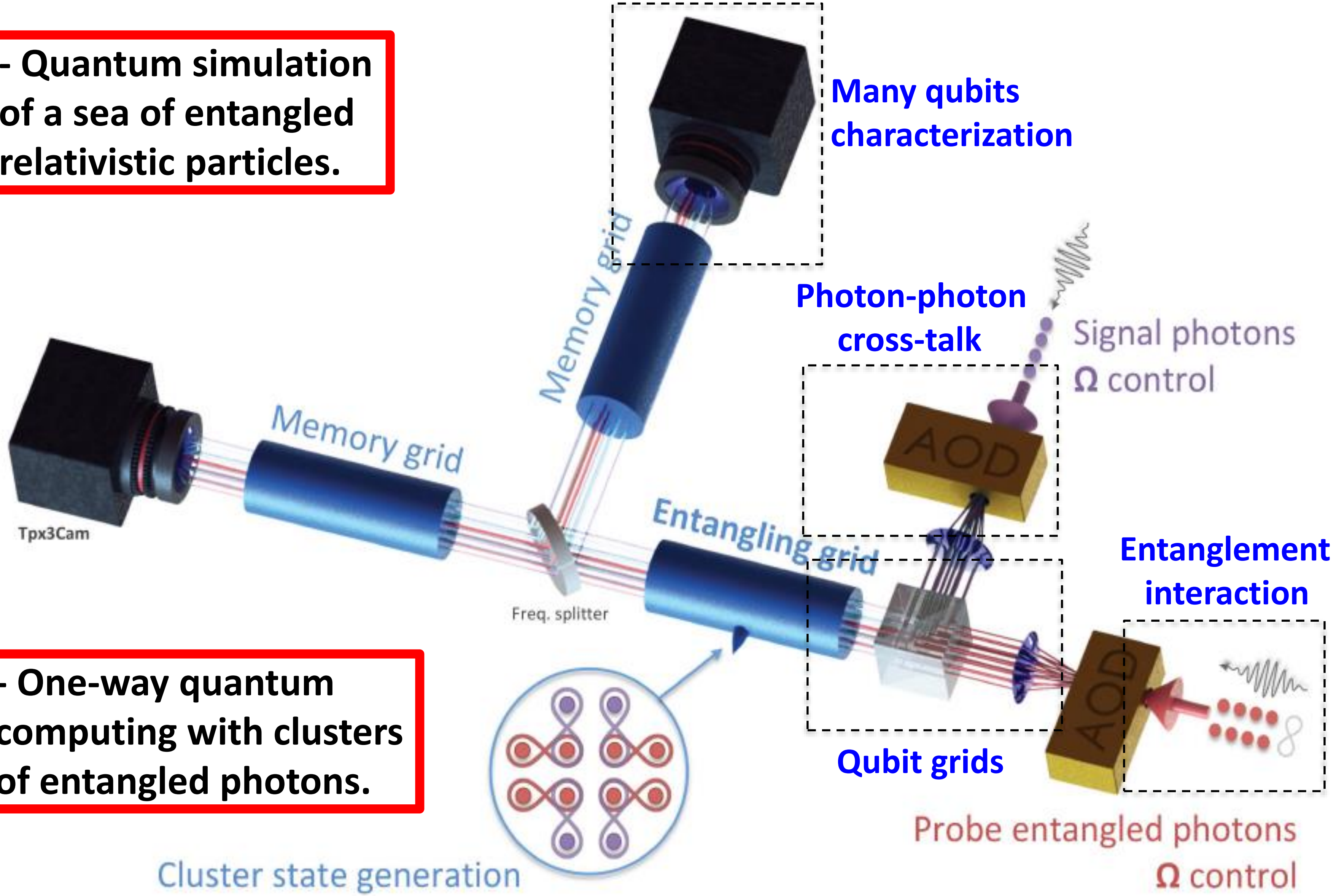


- **New dynamics of fast photons interacting with atoms on resonance.**
- **Control-field-induced transparency for fast photons.**

arXiv:1808.05921 (2018).

Outlook: A light-based quantum computer

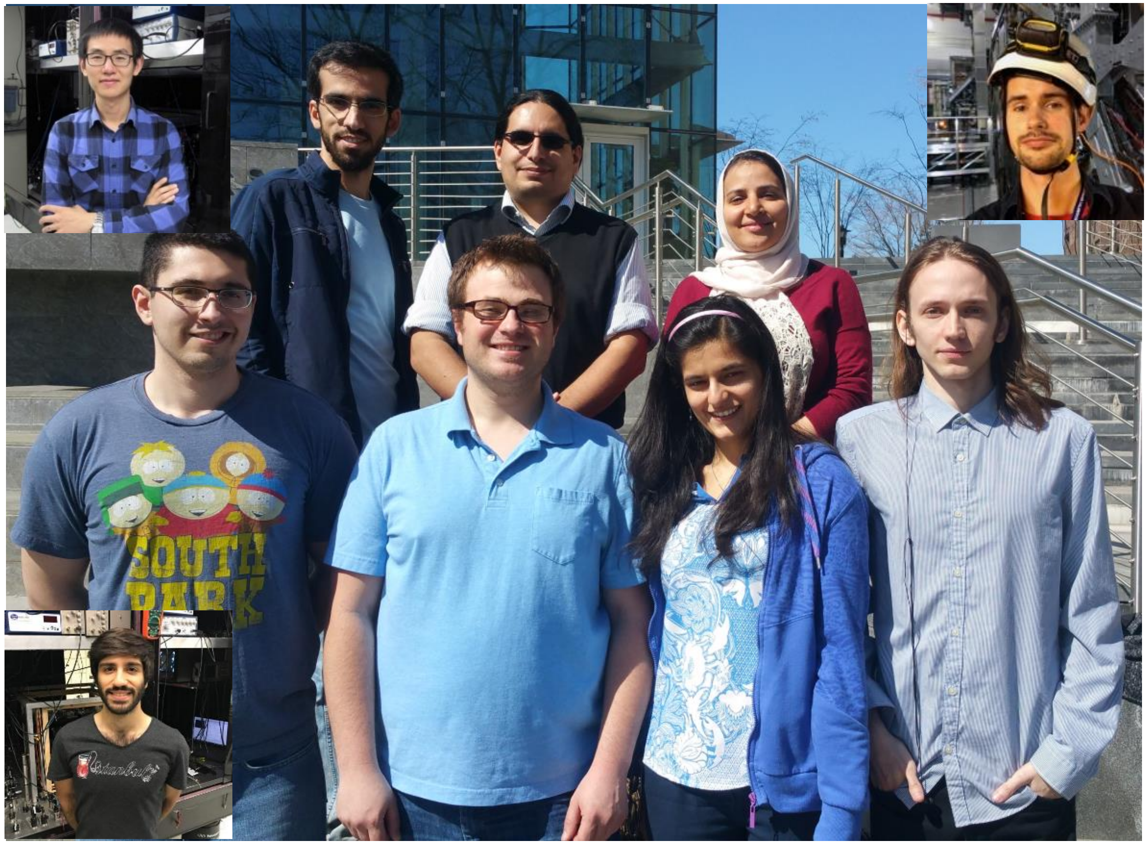
- Quantum simulation of a sea of entangled relativistic particles.



- One-way quantum computing with clusters of entangled photons.

Take-home ideas

- Small summary.
  - Quantum simulation with light and atoms.
  - Phase switching operations triggered by a few photons.
  - Interaction with entangled photons.
  - Grids with many light-qubits coming soon.



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