Quantum optics and quantum simulations group

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Quantum simulations

Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

Analog QS	Digital QS
Continuous evolution	Discrete evolution
Hamiltonian engineering	Trotter expansion
No error correction	Error correction
Feynman, Int. J. Theoret. Phys. 21, 467 (1982)	Lloyd, Science 273, 1073 (1996)

Nature insight: Goals and opportunities in quantum simulation by Zoller and Cirac, Nat, Phys, April 2012

Quantum simulators

A ``working´´ definition of a quantum simulator could be:

I. Quantum simulator is an experimental system that mimics a simple model, or a family of simple models of condensed matter, high energy physics, etc.

II. The simulated models have to be of some relevance for applications and/or our understanding of challenges of condensed matter, high energy physics, or more generally quantum many body physics.

III. The simulated models should be computationally very hard for classical computers (meaning= no efficient algorithm exists, or systems are too big). Exceptions from this rule are possible for quantum simulators that exhibit novel, only theoretically predicted and not yet observed phenomena (simulating ≠ simulating and observing).

IV. Quantum simulator should allow for broad control of the parameters of the simulated model, and for control of preparation, manipulation and detection of states of the system. In particular, it should allow for validation!

Quantum simulators

What shall we simulate?

- Statics at zero temperature – ground state and its properties.
- Statics (equilibrium) at non-zero temperature
- Dynamics (Hamiltonian, but out of equilibrium)
- Dissipative dynamics

Quantum simulators objectives

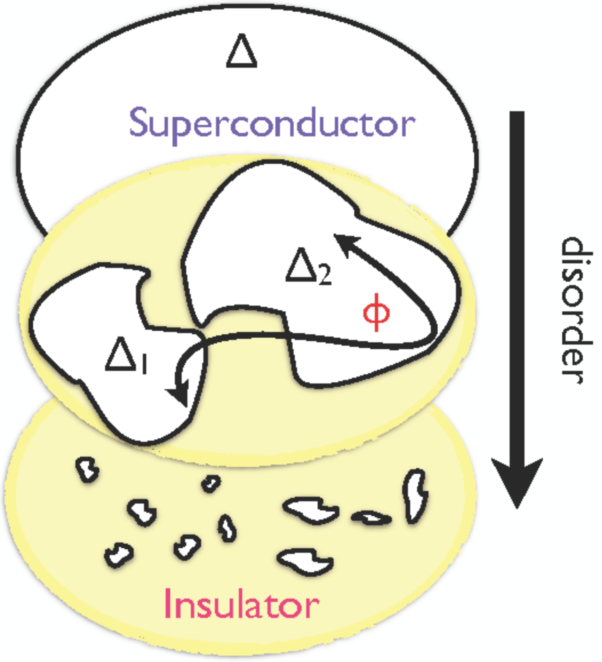
To address fundamental and debated effects such as quantum-phase transitions due to the interplay of disorder, interactions and topology.

- Metal-superfluid to insulator transitions in fermionic and bosonic systems (1D, 2D, 3D).
- Exotic lattices and disorder
- Topological insulators, also in the presence of strong interactions and disorder.
- Quantum dynamics of QMB, especially at long times
- Quantum field theories, Gravity, Strings…?
- Open systems and interaction with reservoirs, out of equilibrium phases, steady state and quenches, thermalization
- Simulation of unphysical effects/operations, forbidden with current laws such as Majorana dynamics, charge conjugation.

Understanding the behaviour of strongly-interacting particles in the presence of disorder and in different topologies is among the most challenging problems in quantum many- body physics:

- – Many degrees of freedom: NOT easy computational & theoretical schemes. Especially for fermions in more than 1D.
- – Impossible to control all the material properties at the same time.

Design theoretically and develop experimentally synthetic quantum systems where all the fundamental parameters are controllable (interactions, statistics, disorder, dimensionality and “crystalline” lattice): *quantum engineering.*



– How does disorder destroy the superconducting state?

– Fermi-Hubbard models: high-Tc superconductors (granular) simulation.

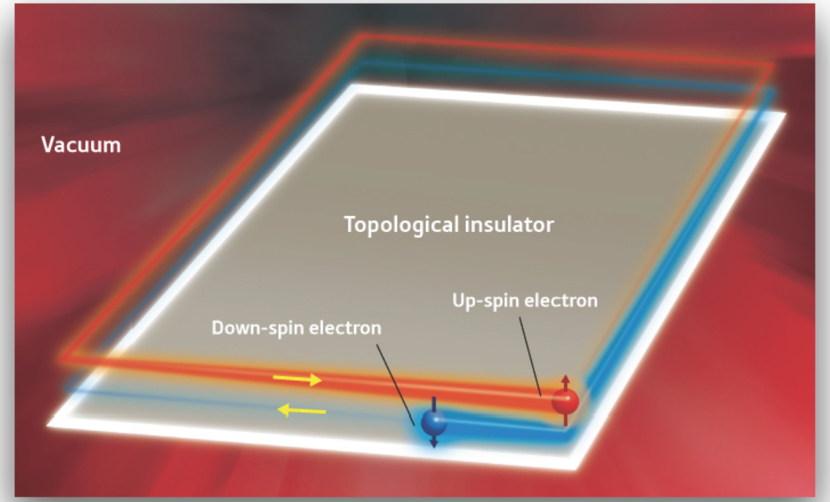
Goals: quantum simulation of granular superconductors, Fermi-Hubbard models (Holy Grail of condensed matter theories)

Topological insulators

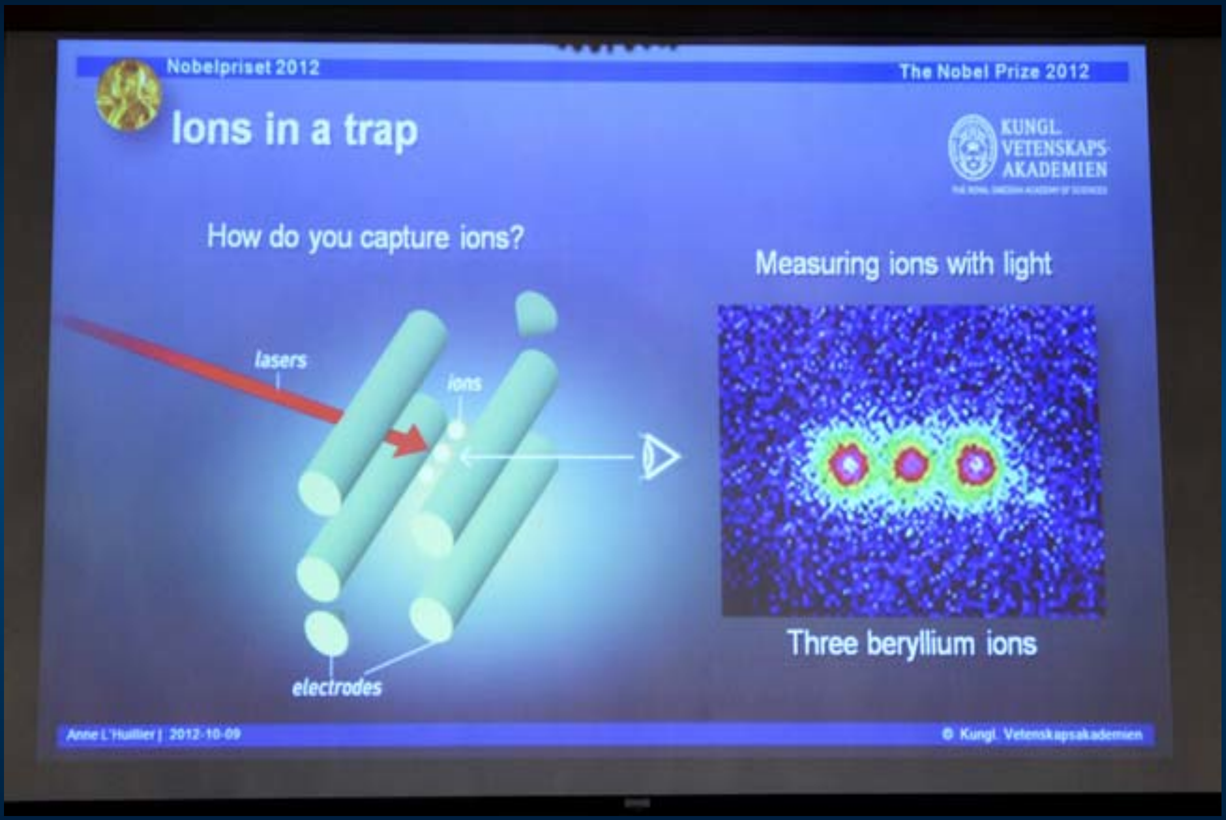
Novel materials: insulators in the bulk, but robust currents at the edges (insensitive to disorder)

Strong spin-orbit coupling: photon-atoms interactions (artificial gauge fields)

Goals: ultracold topological insulators, manipulation of edge currents, study robustness against disorder, behaviour with the interactions



Platforms for QS I: Cold ions in ions traps

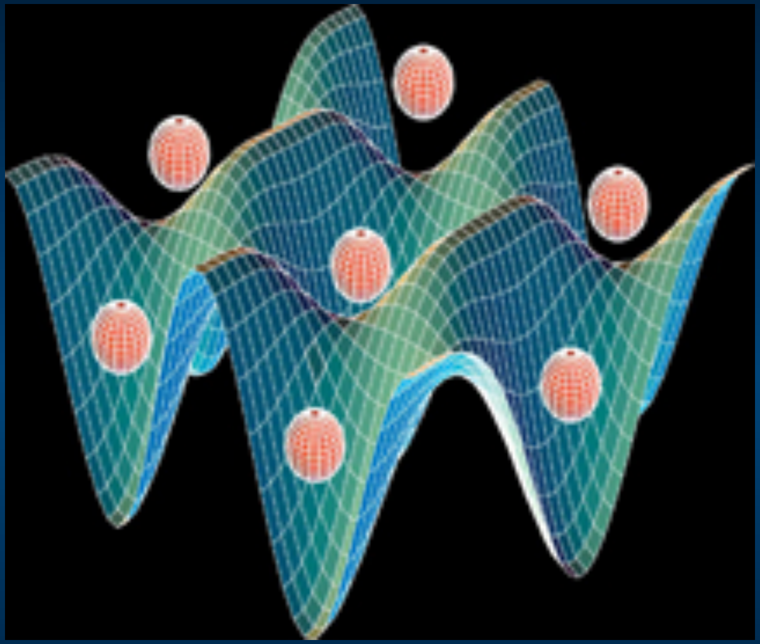


Dave Wineland, NIST

Half of the Nobel Prize of 2012 "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Cold ions in ion trap in different groups (Blatt, Monroe, Bollinger and others) have simulated a variety quantum models mainly related to quantum magnetism
 Also single particle Dirac physics analogues like Zitterbewegung.
Ions have been the best candidates for quantum computing implementations so far.

Platforms for QS II: Cold atoms



Nobel 1997: Chu, Cohen-Tannoudji, Philips
“for development of methods to cool and trap atoms with laser light”

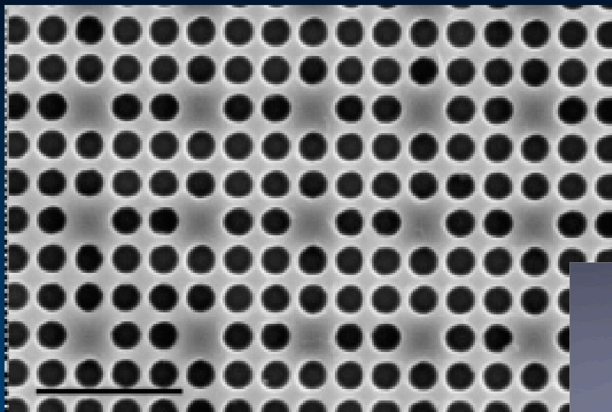
Nobel 2001: Cornel, Wieman, Ketterle
For the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of th properties of the condensates

Nobel 2005: This was divided, one half awarded to Roy J. Glauber *"for his contribution to the quantum theory of optical coherence"*, the other half jointly to John L. Hall and Theodor W. Hänsch *"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*.

Mott-Insulator-Superfluid transitions (2002 Munich) ,BEC-BCS crossovers, frustrated spin models, artificial gauge fields, 1-3 D models and many others…

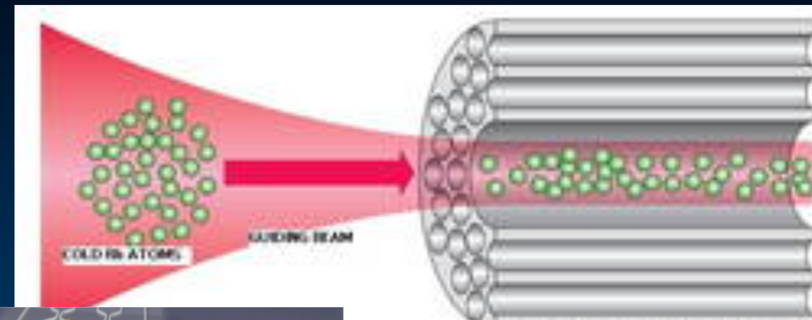
Bloch, Greiner, Hansch, Esslinger, Phillips,and many others. See reviews by Lewenstein, Dalibard,

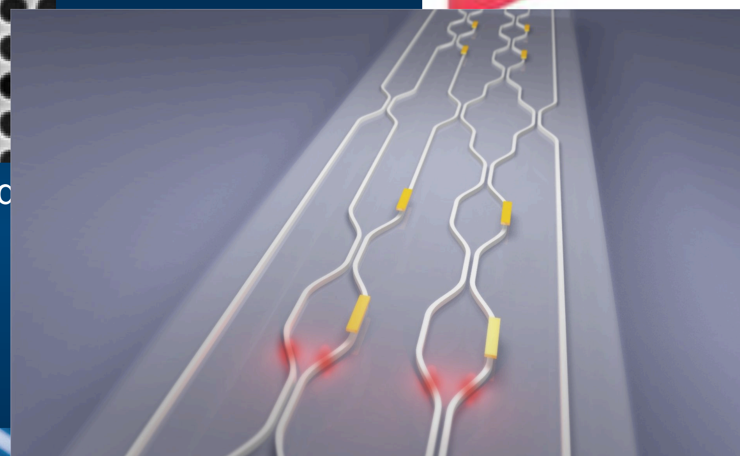
Platforms for QS III: Quantum simulations with (strong) light-matter coupling platforms

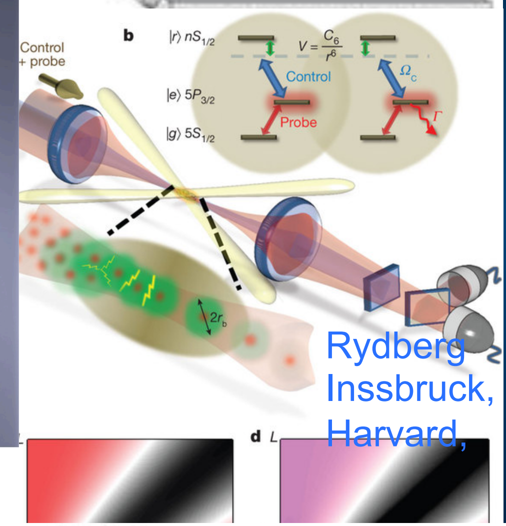


Photonic crystal structures doped atoms or q-dots. Stanford, Japan, ETH, UK and others

Holow core
Harvard,Oxford
,Darmstadt

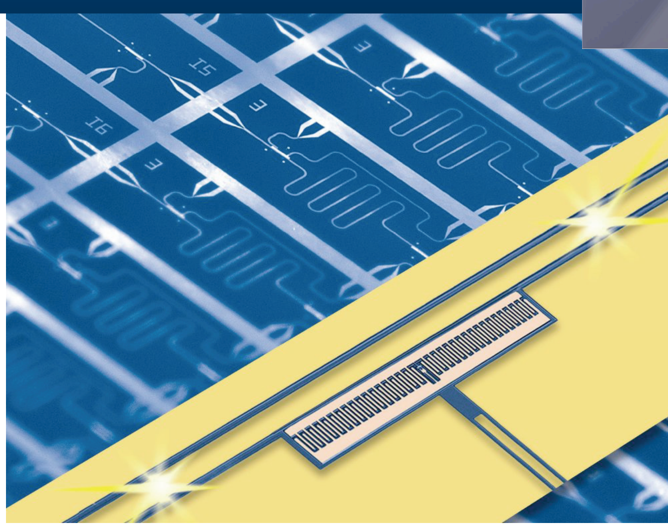




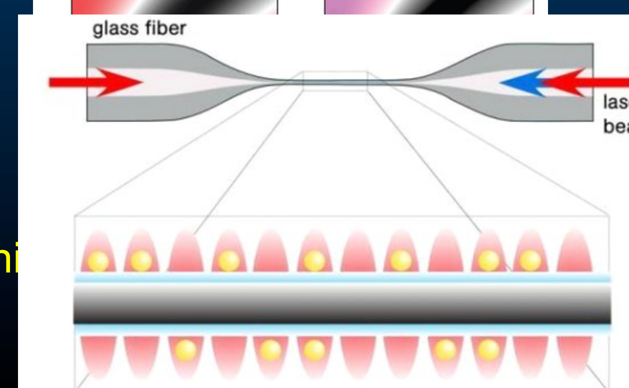


Rydberg
Inssbruck,
Harvard,

Photonic chips: Bristol,
Jena, Sydney

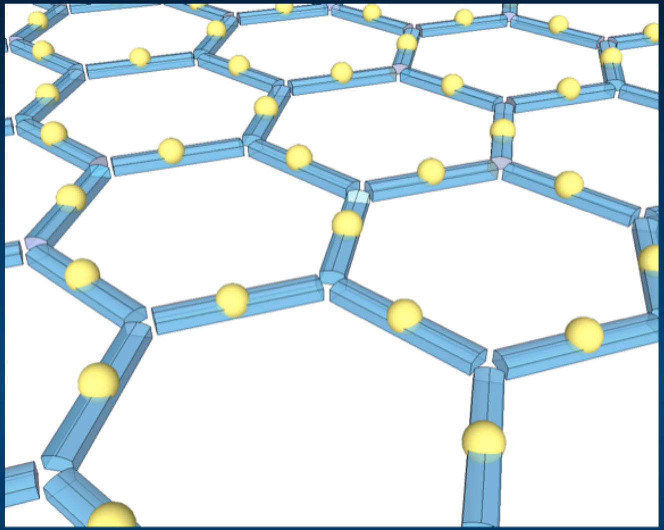


Tapered fibers
Rauschebautel,
Ritsch



Circuit QED
Wallraff, Schoelkopf,DeMartini
Girvin,Mooij, Houck,
Gross, and many others

Our work on quantum simulations of strongly correlated phenomena with Cavity QED arrays in strong coupling



Optimal implementation of JCH in Circuit QED Lattices

$$\hat{\mathcal{H}} = \sum_j \left[\left(\omega_r \hat{a}_j^\dagger \hat{a}_j + \omega_a \hat{\sigma}_j^+ \hat{\sigma}_j^- + g(\hat{a}_j^\dagger \hat{\sigma}_j^- + \hat{a}_j \hat{\sigma}_j^+)\right]\right. - J \sum_{\langle j,j' \rangle} \hat{a}_j^\dagger \hat{a}_{j'}.$$

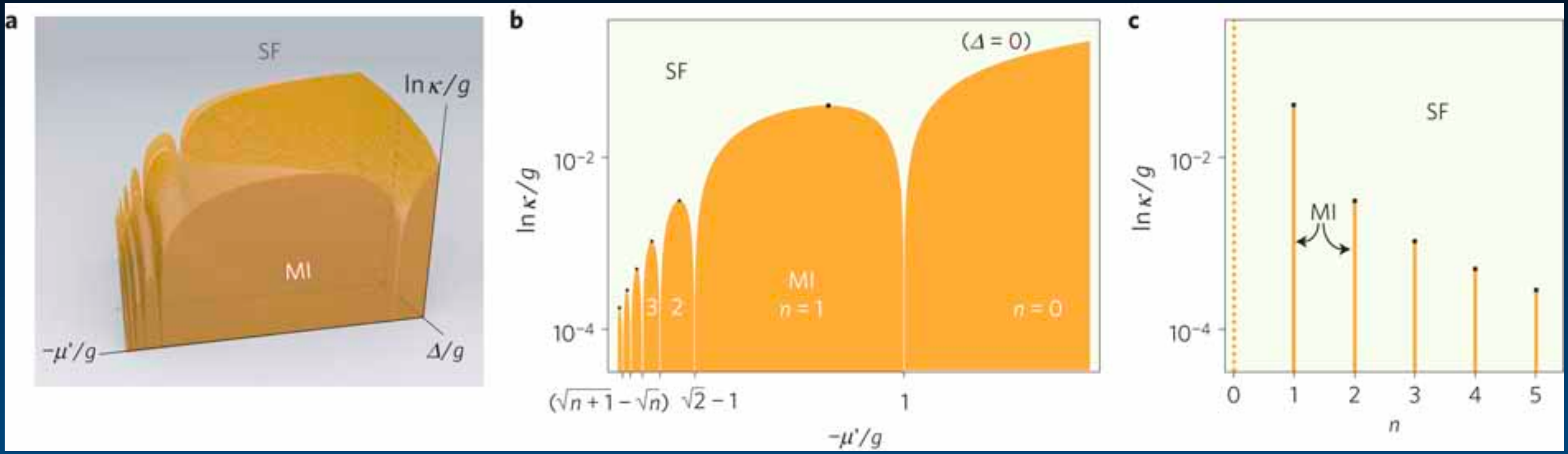
Jaynes Cummings Hubbard model

"Photon blockade induced Mott transitions and XY spin models in coupled cavity arrays Phys. Rev. A (Rap. Com.) vol. 76, 031805 (2007).

Experiments: Princeton, Yale, ETH, Aalto, Meissner..,

Reviews: Rossini and Fazio JOSA B, hartmann et al., Laser Phys., Koch, Schmidt, Tureci Nature Physis 2012, Schmidt-Koch JOSA
Angelakis,Noh, "From Mott to interacting theories with photons and polaritons" Reports in Progress in Physics 2014,
Angelakis (editor) "Quantum simulations with strongly correlated photons" Volume in Springer 2014

Jaynes-Cummings-Hubbard phases of light



$$\hat{\mathcal{H}} = \sum_j \left[\left(\omega_r \hat{a}_j^\dagger \hat{a}_j + \omega_a \hat{\sigma}_j^+ \hat{\sigma}_j^- + g(\hat{a}_j^\dagger \hat{\sigma}_j^- + \hat{a}_j \hat{\sigma}_j^+) \right) \right] - J \sum_{\langle j, j' \rangle} \hat{a}_j^\dagger \hat{a}_{j'}. \qquad (1)$$

Tough problem numerically, as you have more degrees of freedom atom+field in each site, but also more interesting. Possible exotic phases for light like supesolidity, crystallization etc, even out of equilibrium

Reviews: Rossini and Fazio JOSA B, hartmann et al., Laser Phys., Koch, Schmidt, Tureci Nature Physis 2012, Schmidt-Koch JOSA
Angelakis,Noh, "From Mott to interacting theories with photons and polaritons" Reports in Progress in Physics 2014,
Angelakis (editor) "Quantum simulations with strongly correlated photons" Volume in Springer 2014

Out of-equilibrium simulations in driven JCH arrays

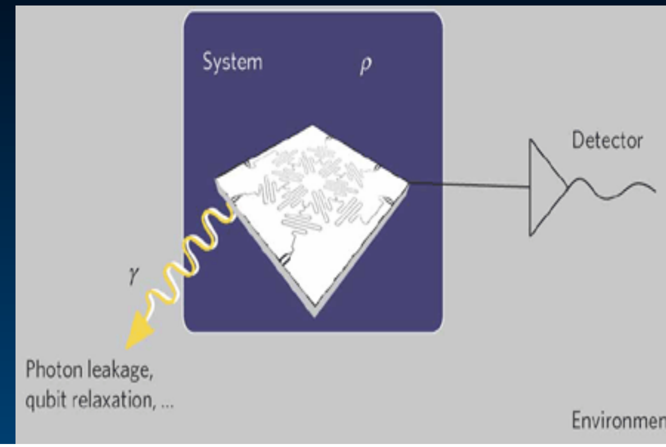
Taking into account losses, the ground state of JCH is the vacuum! Boring by any aspect…

There is no grand canonical ensemble for photons. Just by coupling them to a heat bath introduces excitations to the system.

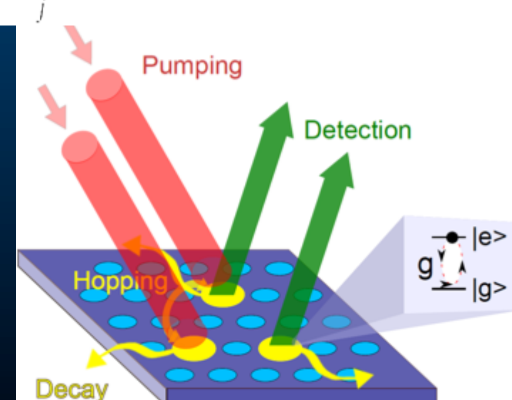
Can look at quasi-equilibrium assuming the time to get there is smaller dissipation time? Hmm…

Driven systems is one way to go. Need methods from open systems to treat the system. Novel phases possible?

Cavity arrays Ideal for simulating open QMB systems

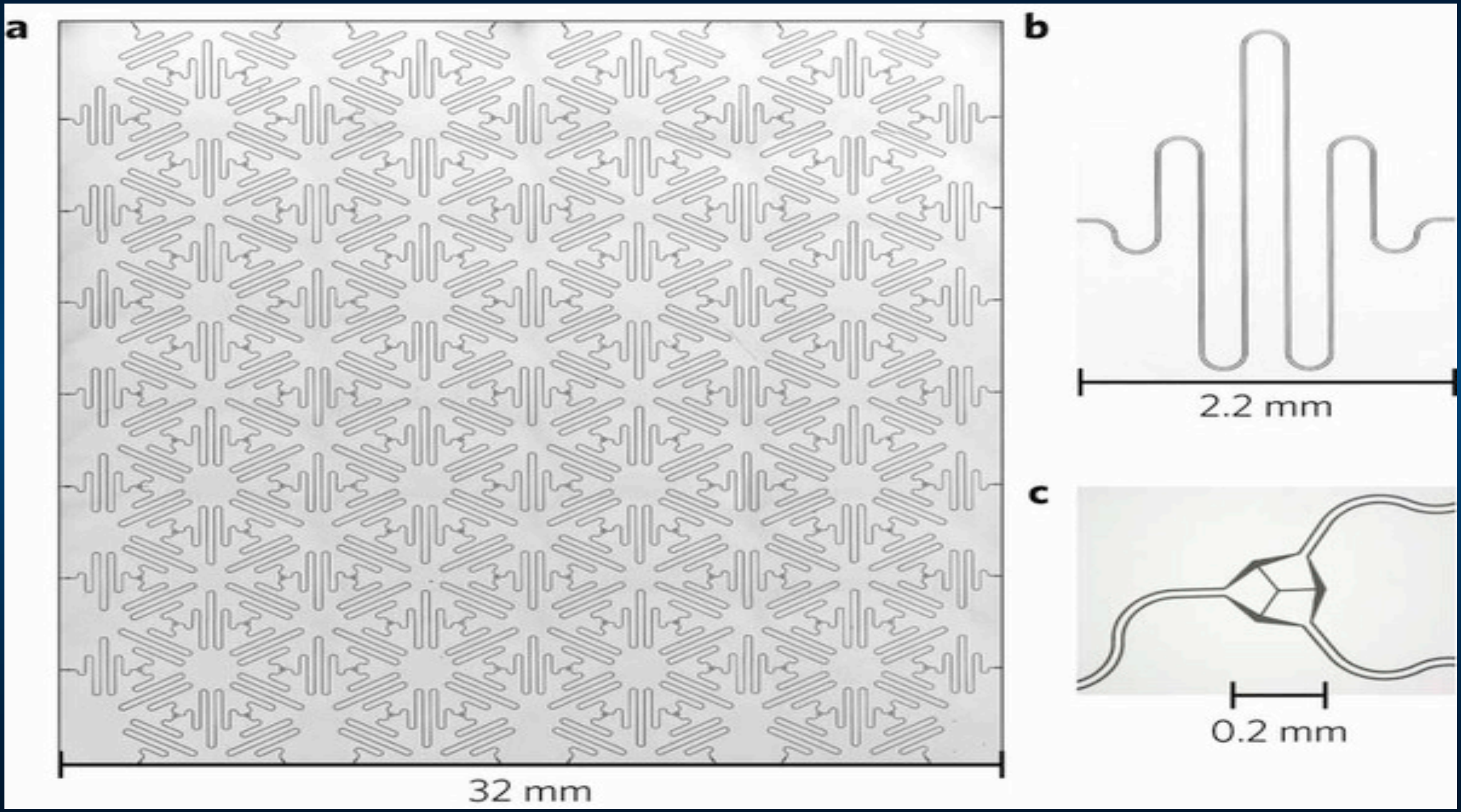


$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\mathrm{i}[H,\rho] + \gamma\sum_j (2\sigma_j^- \rho\sigma_j^+ - \sigma_j^+\sigma_j^-\rho - \rho\sigma_j^+\sigma_j^-) + \tilde{\kappa}\sum_j (2a_j\rho a_j^\dagger - a_j^\dagger a_j\rho - \rho a_j^\dagger a_j), \qquad (20)$$



Gruzic Clark, Jacksh, Angelakis, *Many body effects beyond the Bose-Hubbard model in non-equilibrium resonator arrays, New Journ Phys. 2012*

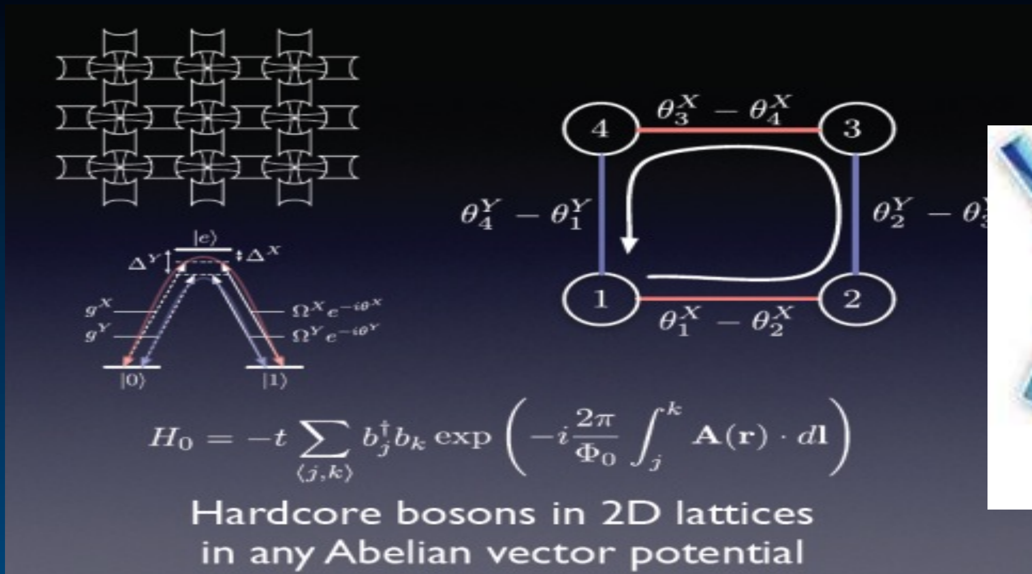
Circuit QED technology today…



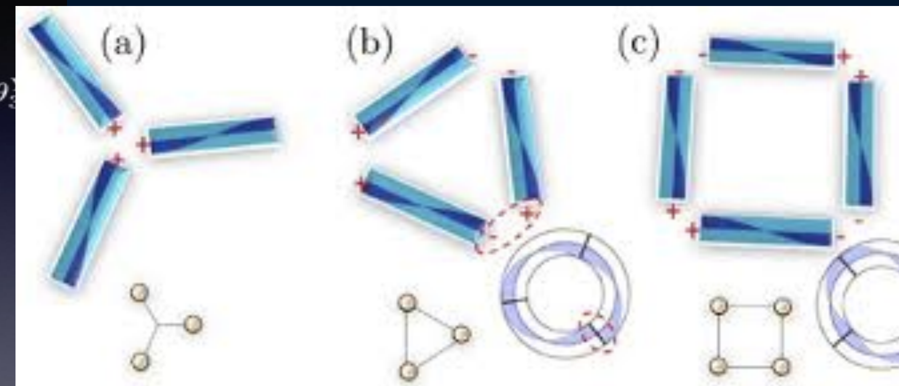
More than 200 microwave cavities coupled in a Kagome lattice!

Houck and Underwood lab, Princeton Univ. No atoms added (yet…)

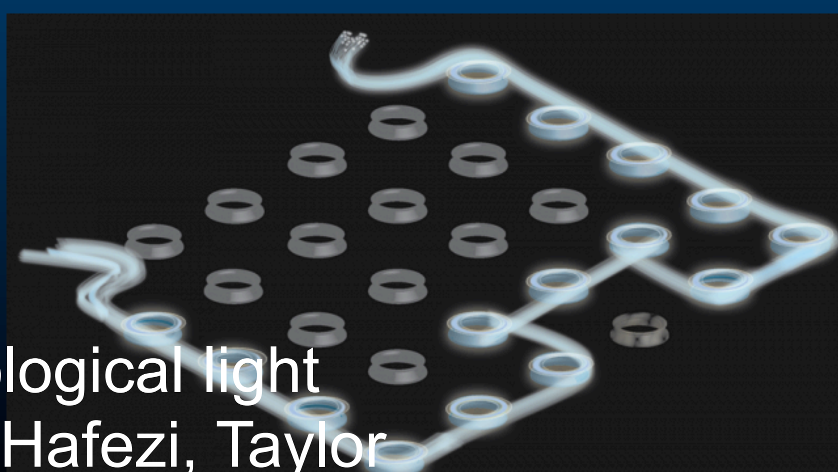
Gauge fields with photons and polaritons



Gauge fields and FQH with cavity arrays Angelakis, Cho.

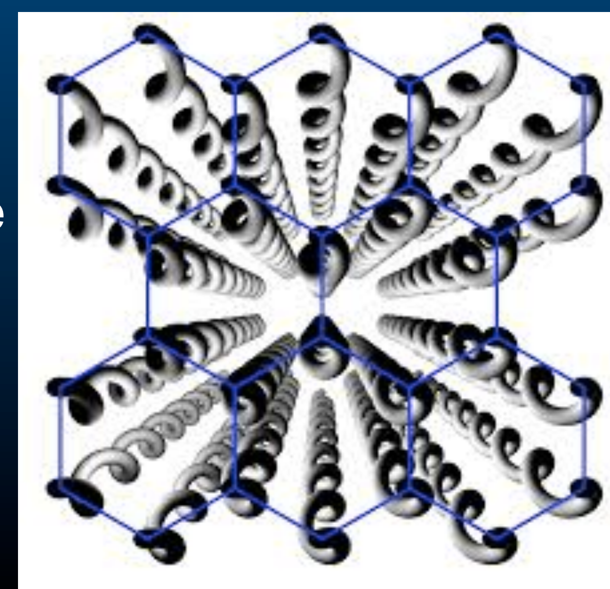


Gauge fields in Circuit QED
Yale Girvin and others

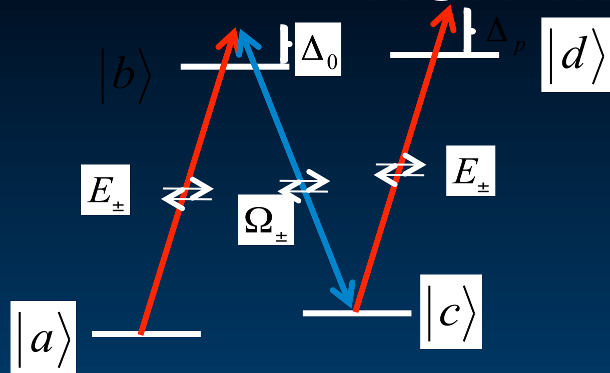


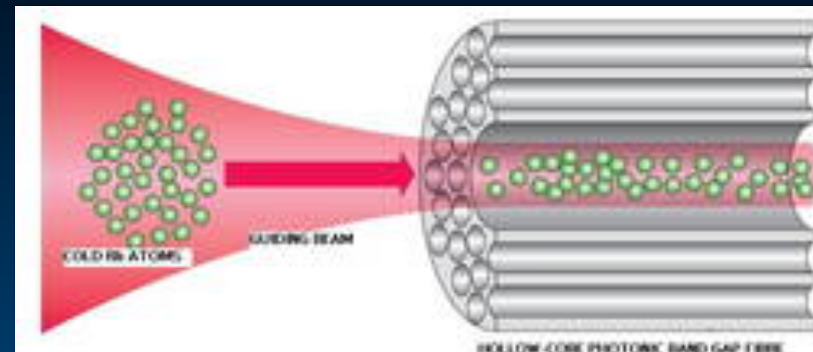
Topological light
JQI, Hafezi, Taylor

Photonic graphene
Szameit, Jena



Strongly correlated models in quantum nonlinear set ups -theory





The 4th level |d> allows for strong Interaction of the Kerr type allowing for the creation of a Tonks gas of polaritons/photons

$$H = \hbar \int dz \left[\frac{1}{2m_{eff}} \partial_z \Psi^+(z) \partial_z \Psi(z) + \tilde{g} \Psi^+(z) \Psi^+(z) \Psi(z) \Psi(z) \right]$$

Chang et al. Nature Physics **4**, 884 (200

$$\Psi = \frac{(\Psi_+ + \Psi_-)}{2}$$

$$\Psi_\pm = g\sqrt{2\pi n_z}\,\hat{E}_\pm / \Omega_\pm$$

$$m_{eff} = -\frac{\Gamma_{1D} n_z}{4\Delta_0 v_g}$$

$$2\tilde{g} = \frac{\Gamma_{1D} v_g}{\Delta_p}$$

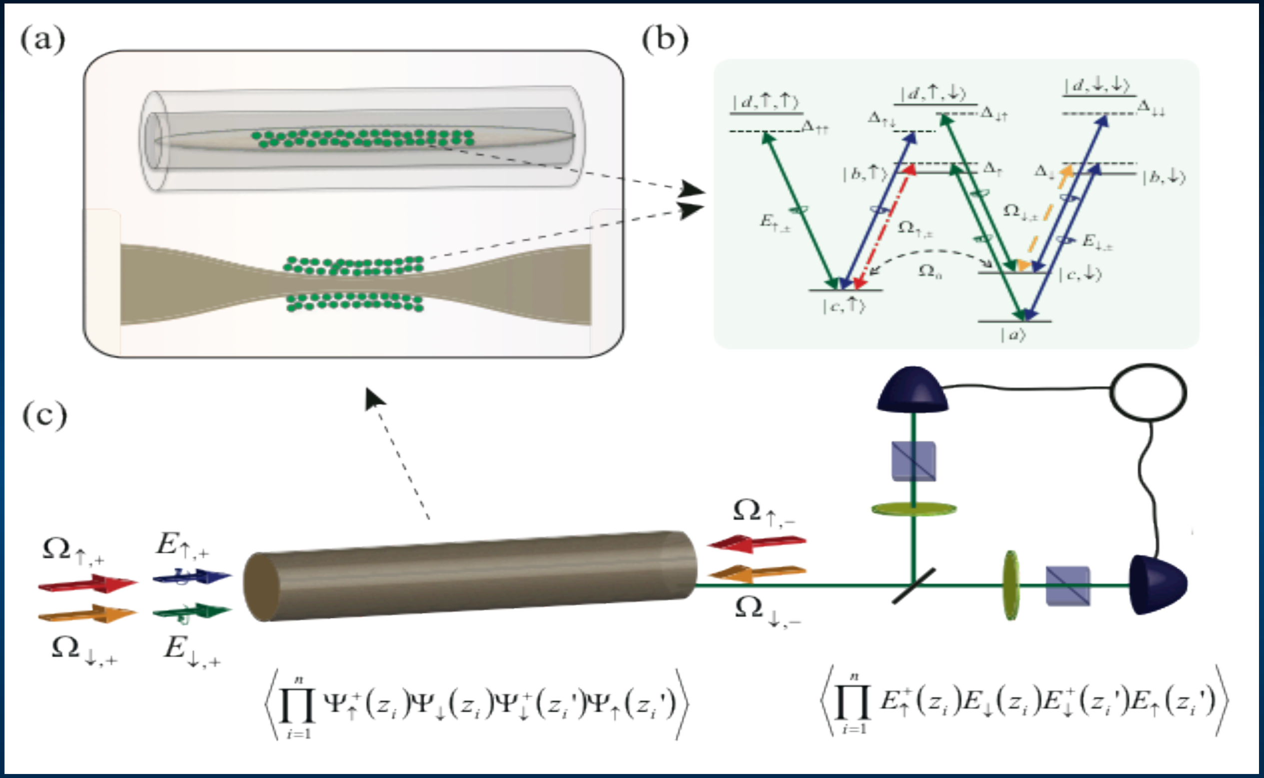
$$\Omega_\pm(t) = \Omega(t)$$

$$\Gamma_{1D} = 4\pi g^2 / v$$

$$v_g \approx v\Omega^2 / (\pi g^2 n_z)$$

$$g \propto 1/\sqrt{A_{eff}}$$

Photons as interacting fermions: Luttinger and Thirring models (theory)



1) Two, oppositely polarized photon pulses, enter the EIT medium and transform into two types of stationary dark state polaritons that will mimick the fermions
2) Interactions are adiabatically turned on and **controlled optically** by tuning the relevant detunings and control field strengths

Angelakis, Huo, Kyoseva, Kwek,, " Luttinger liquid and spin charge separation with light" PRL 2011; Highlight Nature 472, 272 (2011)

Angelakis, Huo, Chang, Kwek, Korepin, "Mimicking interacting relativistic theories with light" PRL 2013

The Thirring model with quantum nonlinear optics

$$H=\int dz[\bar{\Psi}(-i\hbar\,|\eta|\,\gamma_1\partial_z+m_0\eta^2)\mathbf{\Psi}+\frac{\chi}{2}\bar{\mathbf{\Psi}}\gamma^{\mu}\mathbf{\Psi}\bar{\mathbf{\Psi}}\gamma_{\mu}\mathbf{\Psi}],$$

$$\gamma_0=\sigma_x,\ \gamma_1=i\sigma_y$$

TM describes interacting Dirac fermions in 1+1D. Exciting physics due to the changing of mass due to interactions!

*Behaviour of correlation functions figured out conclusively only for the massless fermionic case (*in the sense that a formula for the n-points field correlation is known)

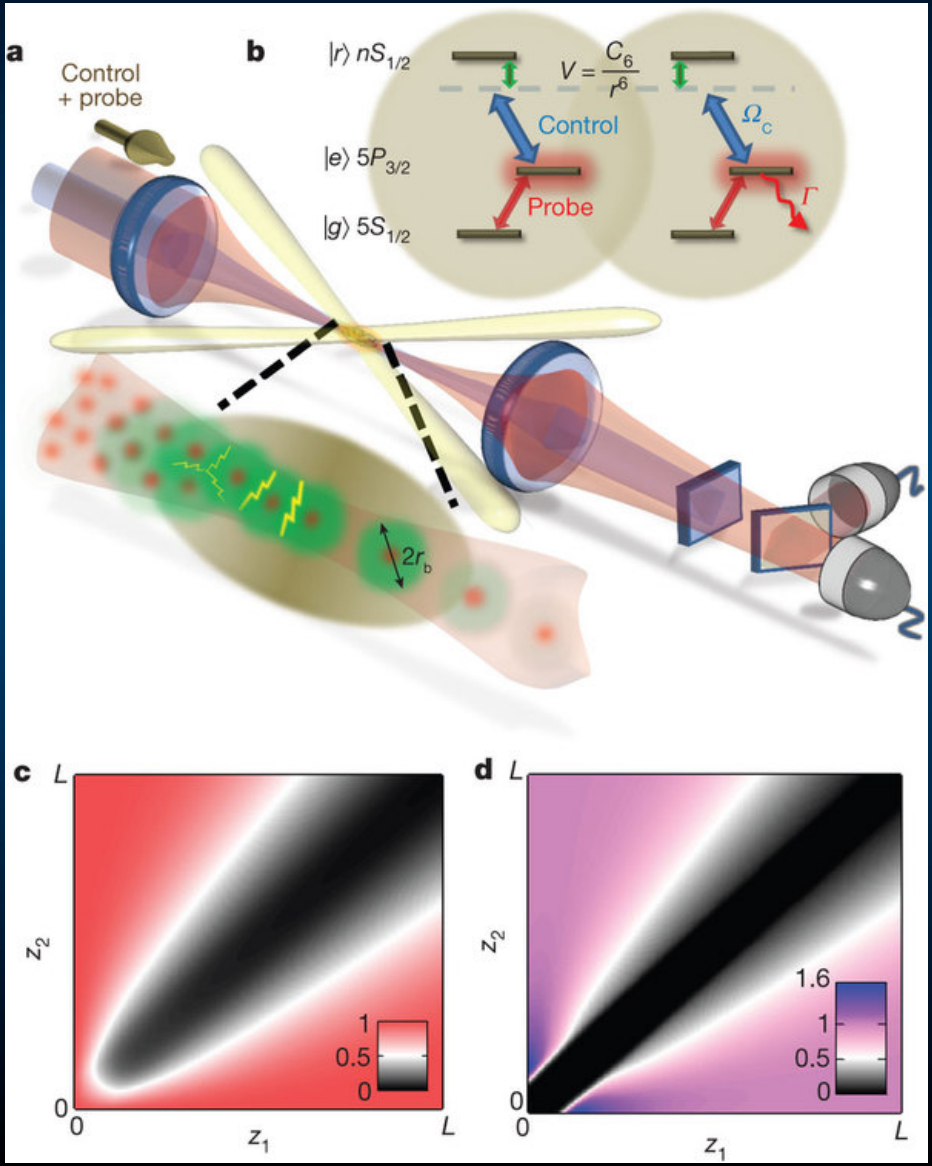
In the massive case, the *mass spectrum* of the model and the *scattering matrix* was explicitly evaluated by Bethe Ansatz though an explicit formula for the correlation is not know despite efforts from various seminal theorists*(Smirnov, Zamolodchikov, Fring, Korepin).*

For the Bosonic TM, things are more unclear…

A tunable quantum simulator of the TM could be first tested against the known results (massless case) and then used to probe the unknown regime!

Angelakis, Huo, Chang, Kwek, Korepin, "Mimicking interacting relativistic theories with light" PRL 110 100502 (March 2013)

Strongly correlated models in quantum nonlinear set ups-experiment

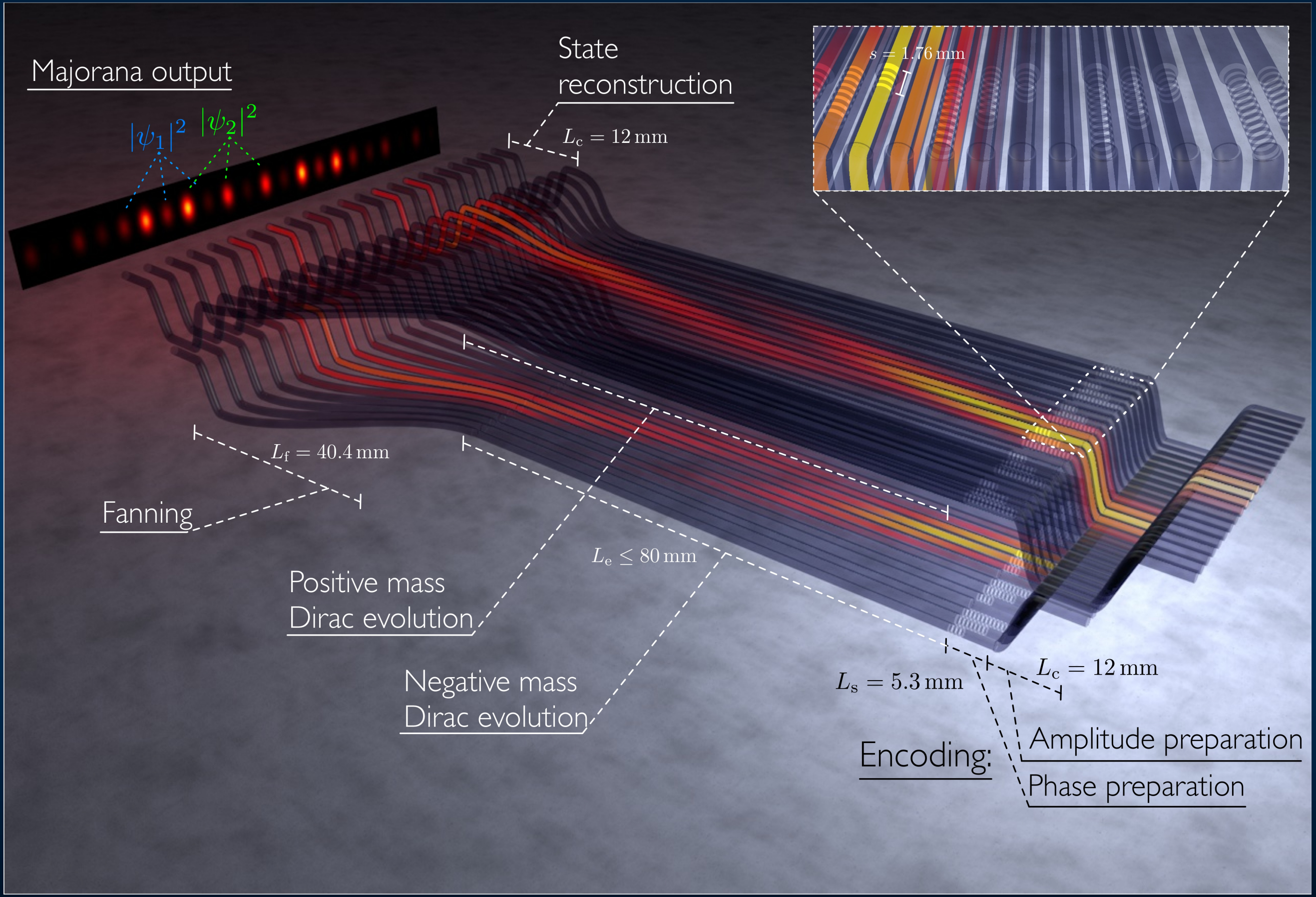


Rydberg-blockade-mediated interaction between slow photons.
Peyronel et al.,

Attractive photons in a quantum nonlinear medium
Firstenberg el al

Vuletic, Lukin groups

Simulating unphysical effects: Majorana dynamics in photonic lattices (the first experimental simulation of unphysical dynamics)



Collaboration with Jena

"Experimental simulation of charge conservation violation and Majorana dynamics"
Keil, Noh, Rai, Stutzer, Angelakis, Szameit, arXiv:1404.5444

Majorana equation

General Lorentz covariant equation

$$i\hbar\gamma^{\mu}\partial_{\mu}\psi = m\psi_c$$

Obeyed by the hypothetical "Majoranons"

The difference with the Dirac equation is that Majorana contains the operation of charge conjugation leading to dynamics violating charge conservation. Thus the Majoranon is unphysical!

We will show here how to effectively simulate Majoranon dynamics with photons!

Majorana fermions are neutral and their own antiparticles. Neutrino?

$$\psi = \psi_c$$

A range of theories beyond the standard model exist, which connect the violation of charge conservation with the existence of higher dimensions of spacetime or describe alternative models where the photon acquires a non-zero photon mass.

E. Majorana, Nuovo Cim. 9, 335 (1932); ibid 14, 171(1937) F. Wilczek, Nat. Phys. 5, 614 (2009)

Majorana equation – Quantum simulation

Observation: Majoranon can be decomposed as superposition of Majorana fermions with opposite masses

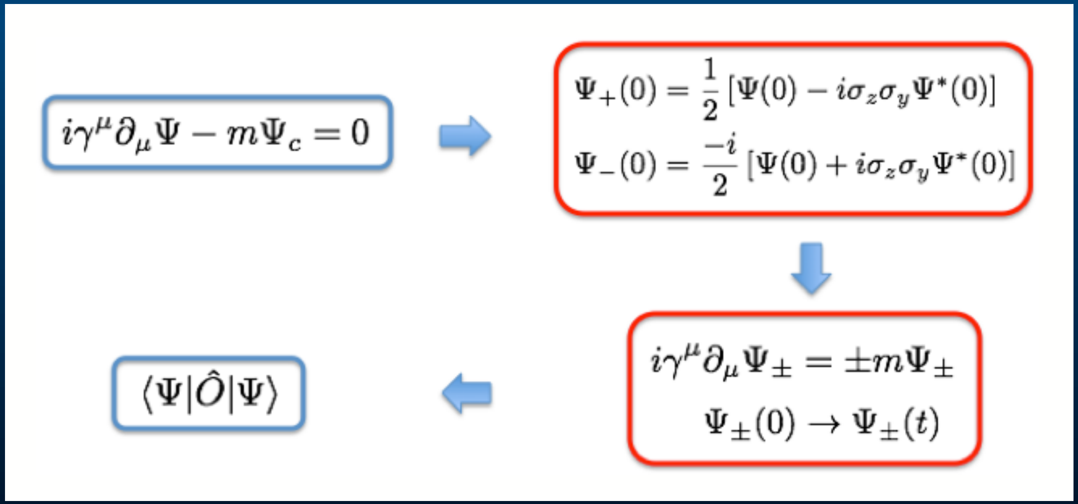
$$\Psi = \Psi_{+m} + i\Psi_{-m}$$

↓ Majorana field

$$i\partial_t\psi_\pm - \sigma_x p_x \psi_\pm \mp m\sigma_z\psi_\pm = 0 .$$

↘ Dirac fields

Steps for Quantum simulation

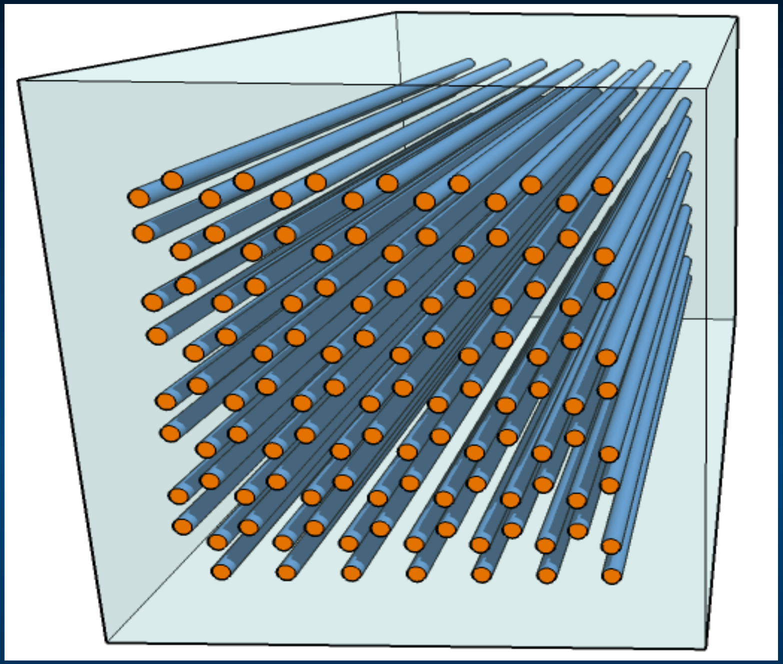


Can be done with single ion, No spin-spin interaction

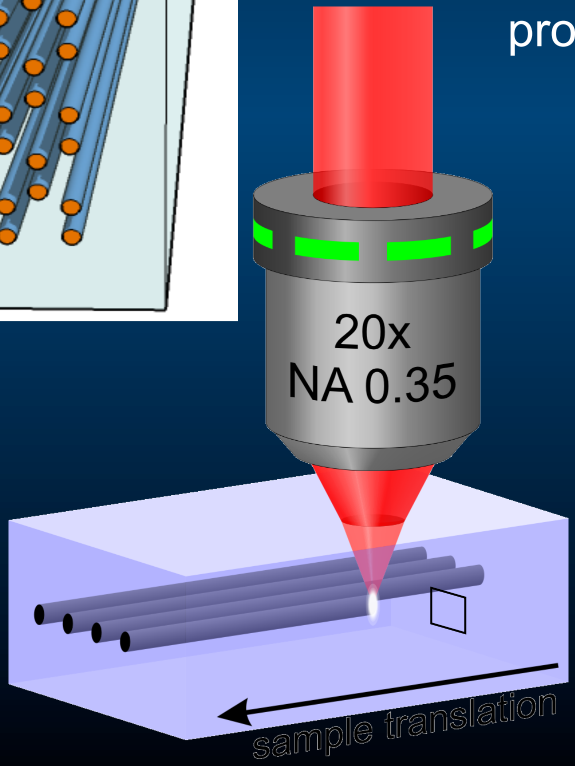
Full tomography including the phonons-Possible with photons?

C.Noh, B. M. Rodriguez-Lara, and D. G. Angelakis, PRA 2012

Photonic waveguide arrays



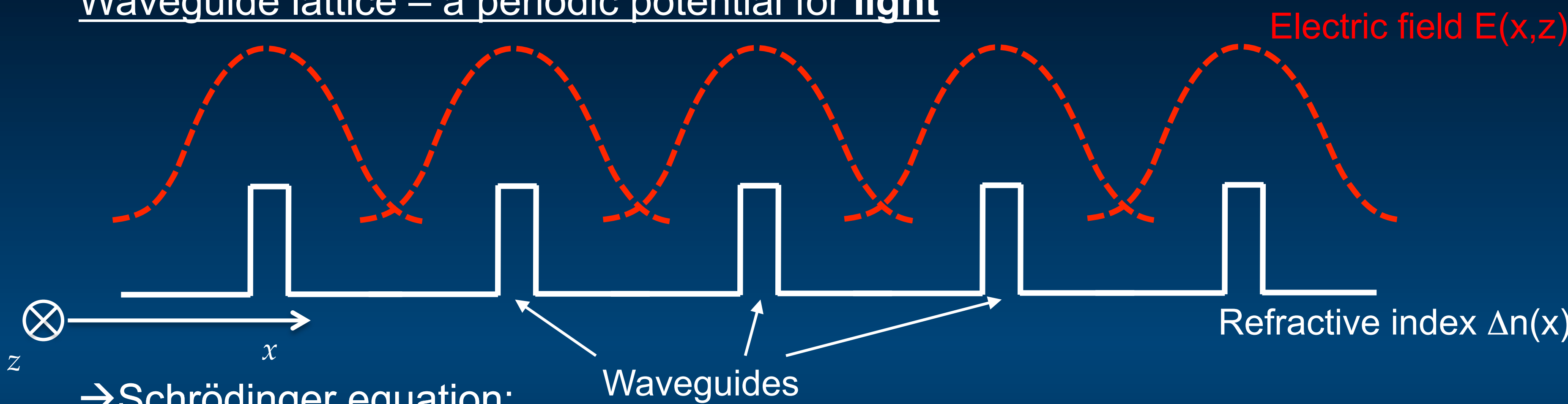
- **Direct waveguide inscription** by ultrashort laser pulses
- Permanent refractive index increase
- Waveguide separation → κ
- Power/Translation velocity → on-site propagation constant σ



Szameit & Nolte, *J. Phys. B* **43,** 163001 (2010)

Optics as quantum-mechanical analogue

<u>Waveguide lattice – a periodic potential for **light**</u>



→Schrödinger equation:

$$i\hbar\partial_t\Psi + \frac{\hbar^2}{2m}\partial_x^2\Psi - V(x)\Psi = 0$$

→Paraxial **Helmholtz** equation:

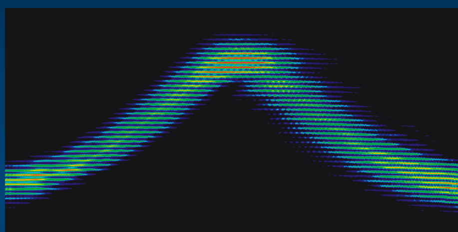
$$i\frac{\lambda}{2\pi}\partial_z E + \frac{\lambda^2}{8\pi^2 n_0}\partial_x^2 E + \Delta n(x)E = 0$$

$$V(x) \leftrightarrow -\Delta n(x)$$
$$\Psi(x,t) \leftrightarrow E(x,z)$$
$$t \leftrightarrow z$$
$$m \leftrightarrow n_0$$
$$h \leftrightarrow \lambda$$

Optical analogues to the Schrödinger equation

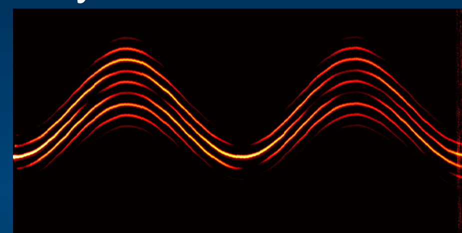
$$i\hbar\frac{\partial\Psi}{\partial t}+\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2}+V(x)\Psi=0$$

Bloch oscillations



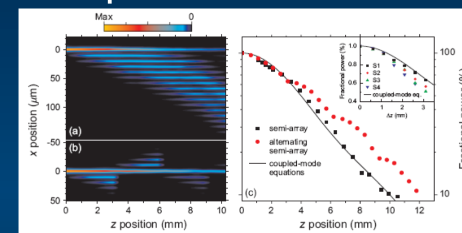
Phys. Rev. Lett. **83**, 4752–4755 (1999).
Phys. Rev. Lett. **83**, 4756–4759 (1999).

Dynamic Localization



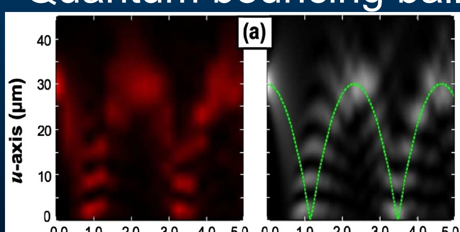
Phys. Rev. Letters **96**, 243901 (2006).
Nature Physics **5**, 271-275 (2009).

Optical Zeno effect



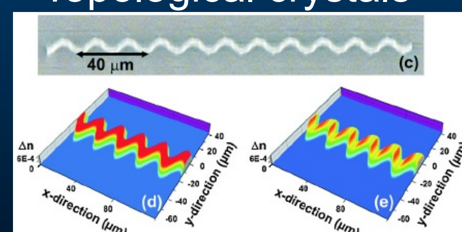
Optics Express **16**, 3762-3767 (2008).
Phys. Rev. Lett. **101**, 143602 (2008).

Quantum bouncing ball



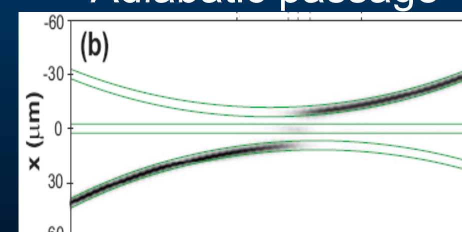
Phys. Rev. Lett. **102**, 180402 (2009).

Topological crystals



Phys. Rev. Lett. **104**, 150403 (2010).

Adiabatic passage



Phys. Rev. B **76**, 201101(R) (2007).
Phys. Rev. Lett. **101**, 193901 (2008).

1D-Dirac equation in photonic lattices

- Optical emulator of 1D-Dirac equation:

$$i\partial_t \mathbf{\Psi} + ic\boldsymbol{\sigma}_1 \partial_x \mathbf{\Psi} - \frac{c^2 m(x)}{\hbar}\boldsymbol{\sigma}_3 \mathbf{\Psi} = 0$$

- Time t = longitudinal coordinate z
- Waveguides →Discretisation in x:

$$m(x) \to m_n,\ \mathbf{\Psi} \to \mathbf{\Psi}_n,\ \partial_x \mathbf{\Psi} \to \begin{pmatrix} \Psi_{n+1}^1 - \Psi_n^1 \\ \Psi_n^2 - \Psi_{n-1}^2 \end{pmatrix}$$

$$i\partial_z \mathbf{\Psi}_n + ic\begin{pmatrix} \Psi_n^2 - \Psi_{n-1}^2 \\ \Psi_{n+1}^1 - \Psi_n^1 \end{pmatrix} + \frac{c^2 m_n}{\hbar}\begin{pmatrix} -\Psi_n^1 \\ \Psi_n^2 \end{pmatrix} = 0$$

- Substitute: $\delta_n \equiv \dfrac{c^2 m_n}{\hbar},\ \kappa \equiv c,\ a_n \equiv -i(-1)^n \Psi_n^1,\ b_n \equiv (-1)^n \Psi_n^2$

$$i\partial_z \begin{pmatrix} a_n \\ b_n \end{pmatrix} + \kappa\begin{pmatrix} b_n + b_{n-1} \\ a_{n+1} + a_n \end{pmatrix} + \delta_n \begin{pmatrix} -a_n \\ b_n \end{pmatrix} = 0$$

→ Coupled mode equation for binary waveguide superlattice (sublattices a, b)

Nearest neighbour coupling $\kappa \leftrightarrow c$

On-site modulation $\delta_n \propto m_n$

Longhi, *Opt. Lett.* **35,** 235 (2010)

Majorana dynamics in photonic waveguide arrays

- We start from the two-component Dirac

$$i\partial_t \mathbf{\Phi}^{\pm} + i\boldsymbol{\sigma}_1 \partial_x \mathbf{\Phi}^{\pm} \mp m\boldsymbol{\sigma}_3 \mathbf{\Phi}^{\pm} = 0 \quad \text{with} \quad \mathbf{\Phi}^{\pm} \equiv \begin{pmatrix} \Phi^{\pm,1} \\ \Phi^{\pm,2} \end{pmatrix}$$

- Time t → normalised longitudinal coordinate Z
- Waveguides →Discretisation in x:

$$\mathbf{\Phi}^{\pm} \rightarrow \mathbf{\Phi}_n^{\pm},\ \partial_{\mathbf{x}} \mathbf{\Phi}^{\pm} \rightarrow \begin{pmatrix} \Phi_{n+1}^{\pm,1} - \Phi_n^{\pm,1} \\ \Phi_n^{\pm,2} - \Phi_{n-1}^{\pm,2} \end{pmatrix}$$

$$i\partial_Z \mathbf{\Phi}_{\mathbf{n}}^{\pm} + i\begin{pmatrix} \Phi_n^{\pm,2} - \Phi_{n-1}^{\pm,2} \\ \Phi_{n+1}^{\pm,1} - \Phi_n^{\pm,1} \end{pmatrix} \pm m\begin{pmatrix} -\Phi_n^{\pm,1} \\ \Phi_n^{\pm,2} \end{pmatrix} = 0$$

This approximation requires smooth spinors, hence the input state profile should extend over several sites

- Substitute:

$$a_n^{\pm} \equiv -i(-1)^n \Phi_n^{\pm,1},\ b_n^{\pm} \equiv (-1)^n \Phi_n^{\pm,2}$$

$$i\partial_Z \begin{pmatrix} a_n^{\pm} \\ b_n^{\pm} \end{pmatrix} + \begin{pmatrix} b_n^{\pm} + b_{n-1}^{\pm} \\ a_{n+1}^{\pm} + a_n^{\pm} \end{pmatrix} \pm m\begin{pmatrix} -a_n^{\pm} \\ b_n^{\pm} \end{pmatrix} = 0$$

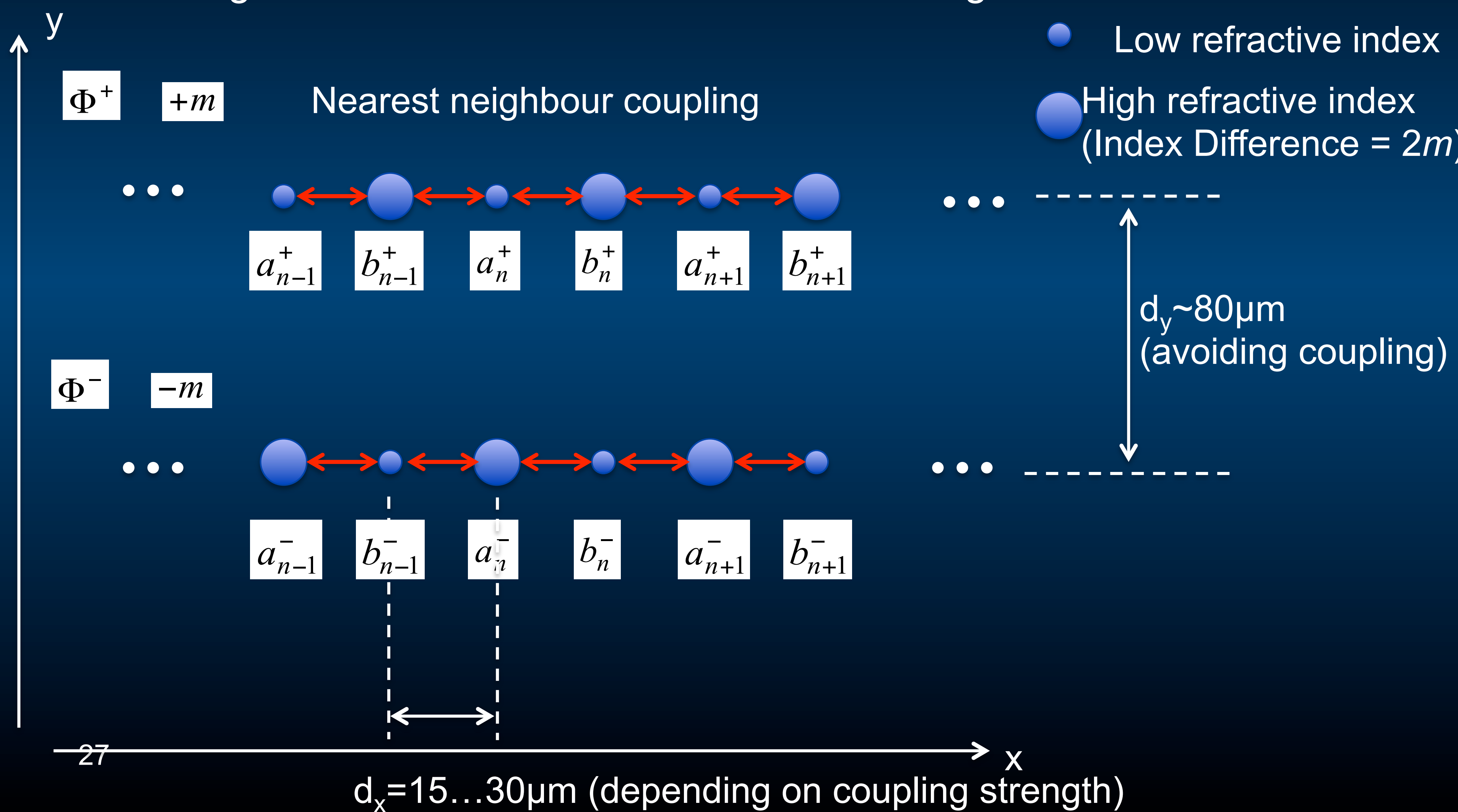
→ Coupled mode equation for two binary waveguide superlattices (electric field amplitude on the sublattices a^+, b^+, a^-, b^-)

Nearest neighbour coupling

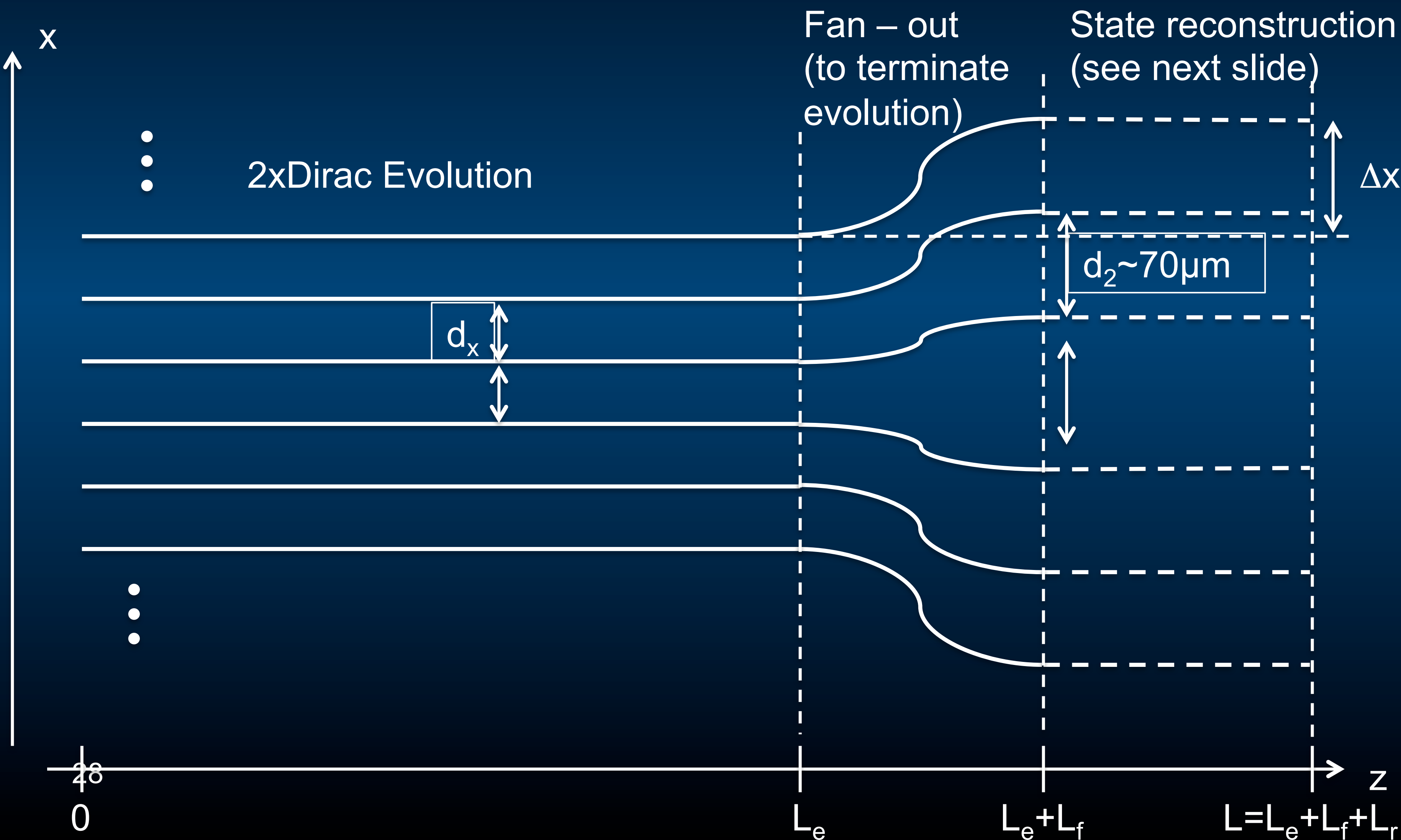
On-site modulation $\propto \pm m$

Majorana dynamics in photonic lattices

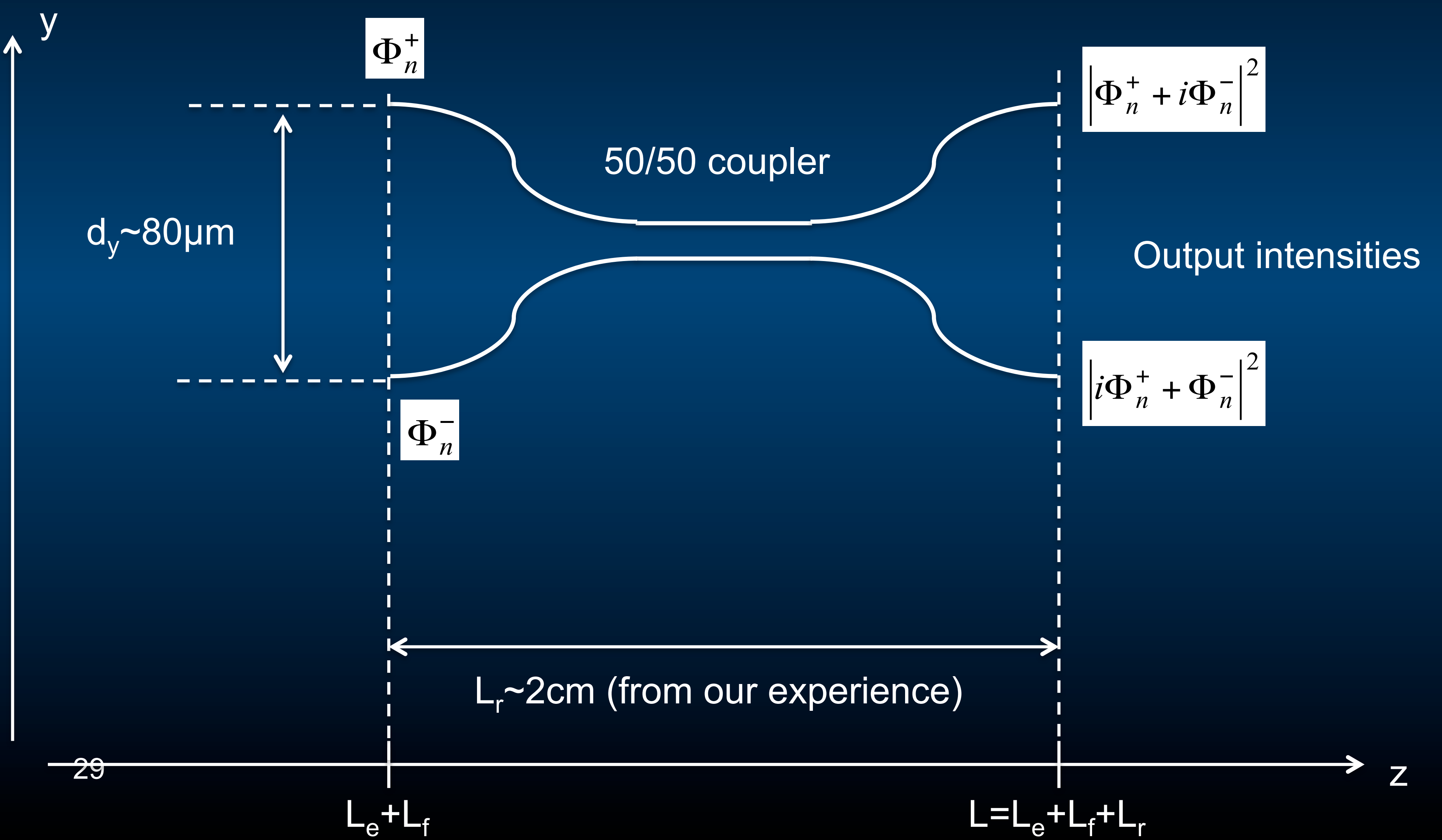
- The 2 Dirac components can be emulated in two separate waveguide lattices as illustrated in the following cross – section:



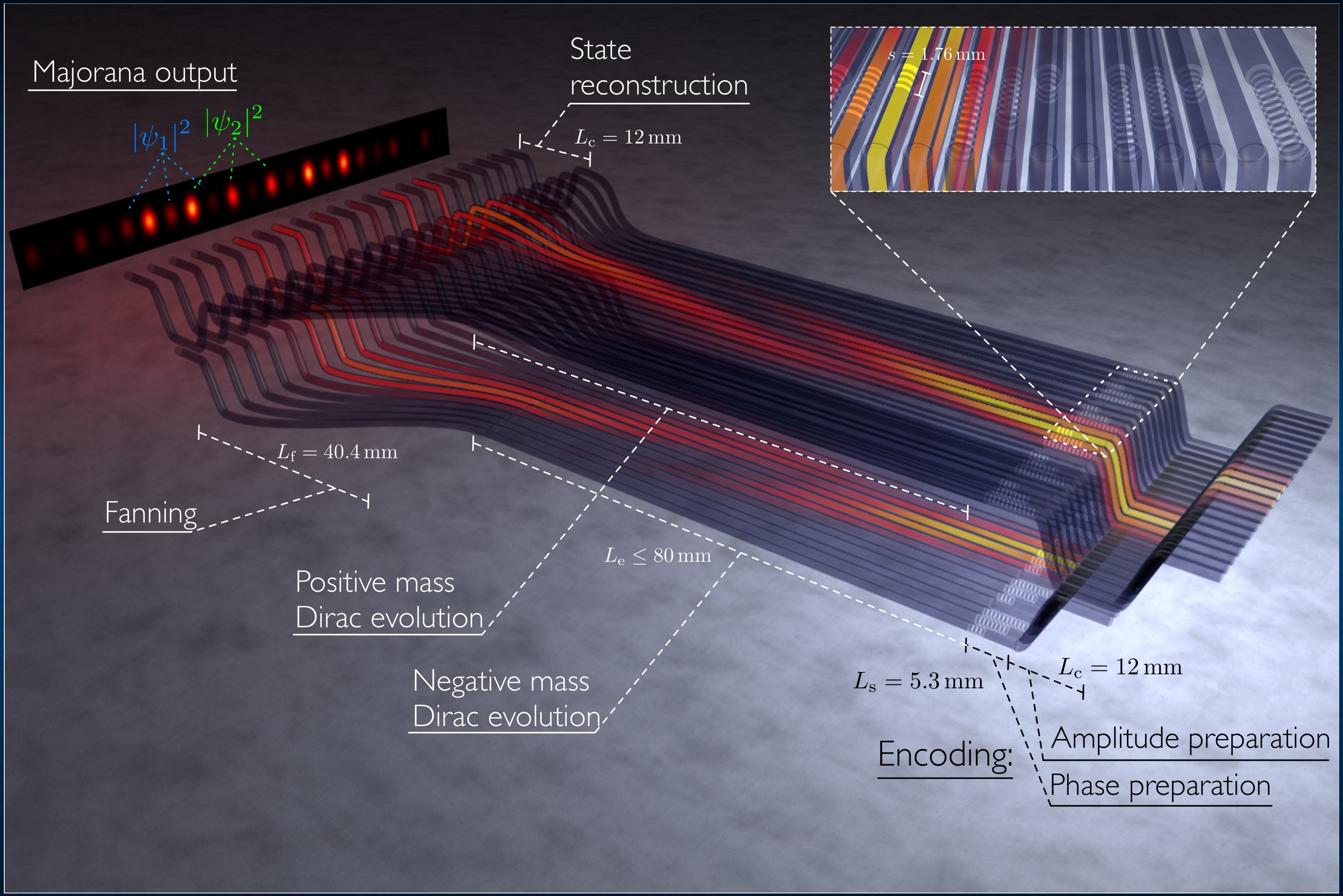
Top-view of the system



Side view of state reconstruction

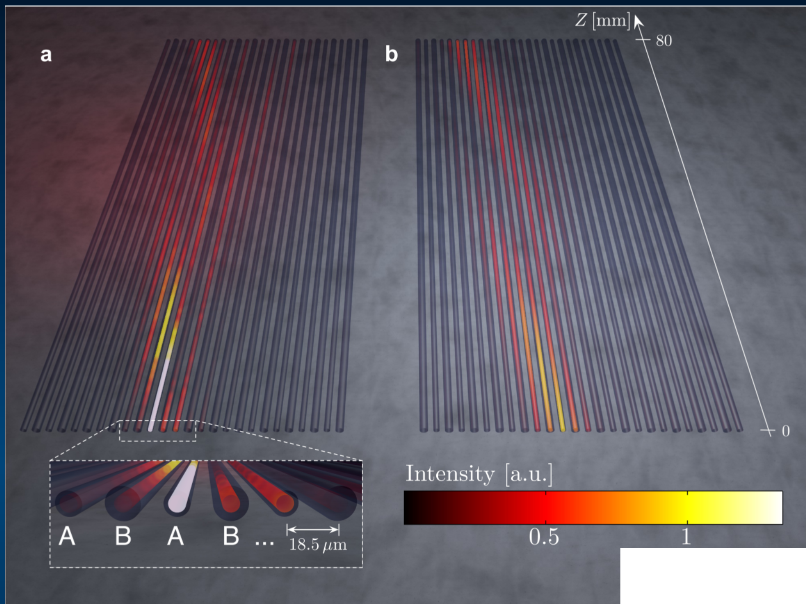


Results



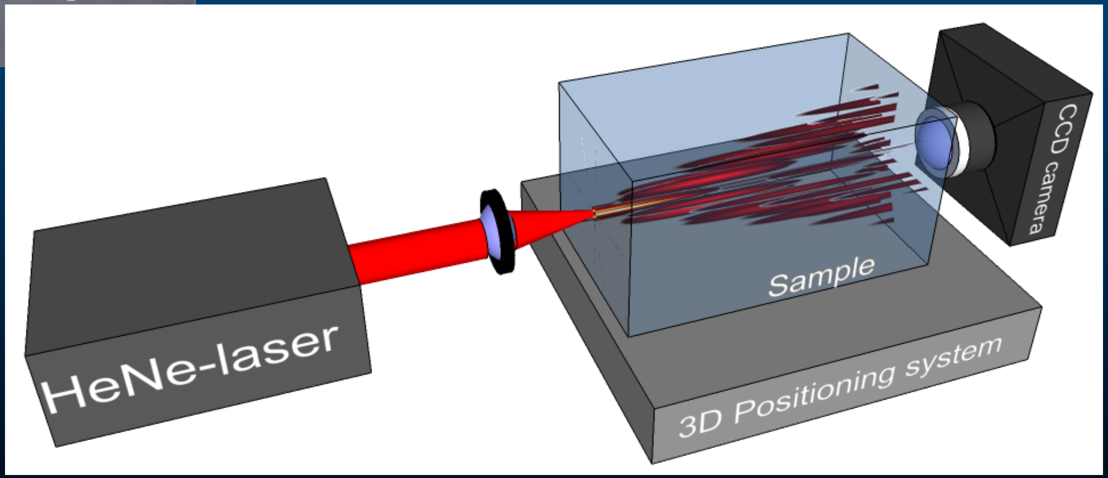
The waveguide sample, where two Dirac equations with opposite masses are simulated in two parallel planar lattices.

Results



View from above and observation of photonic Zitterbewegung.

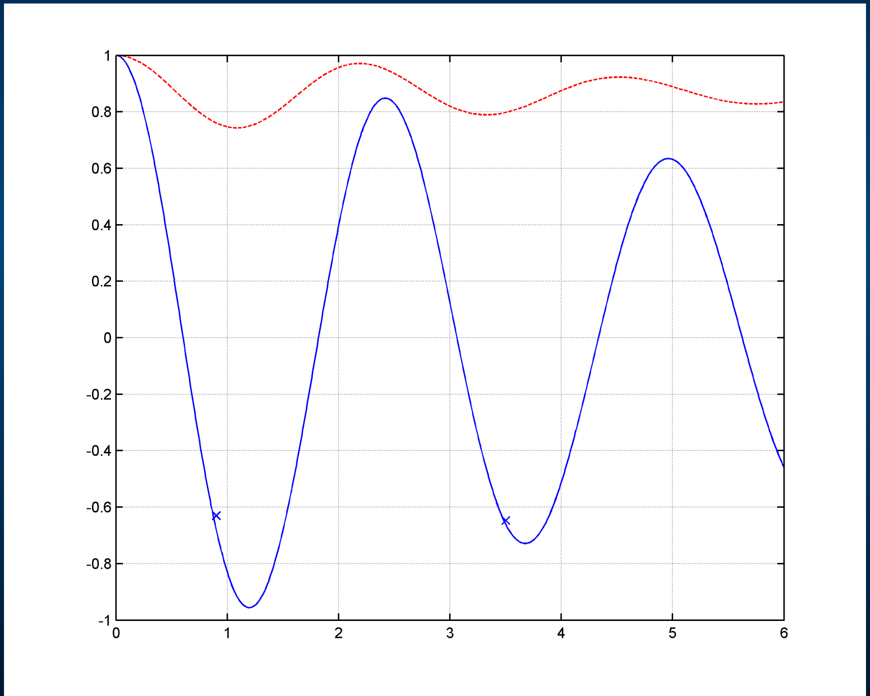
Left is theory and right is the experiment



3D positioning and measuring

Results

$$\langle \sigma_z \rangle = \sum_n |\psi_{1,n}|^2 - |\psi_{2,n}|^2$$



Measures the population difference between the positive and negative energy branches.

For a Dirac particle at rest or equivalently of very large mass is a conserved quantity(finite non-zero momentum components cause small oscillation)

For the same initial conditions, the Majoranon oscillates wildly!

The Dirac particle oscillated due to finite non-zero momentum components in the initial wave packet, while the oscillation for the Majoranon is mainly due to the unphysical mass term!

Quantum simulations platforms / Effects to be simulated	COLD ATOMS	COLD IONS	COLD RYDBERG ATOMS	PHOTONS (linear systems, integrated chips)	STRONG LIGHT COUPLING PLATFORMS (Circuit QED arrays, slow light polaritons, quantum nonlinear optics…)
Quantum phase transitions in 1D, 2D, 3D (bosons and fermions, with and without disorder)					
Effective Gauge fields (Hall and Spin Hall) , Topological insulators (without interactions). Single particle but exotic physics Boson sampling type of problems,					
Gauge fields and Topological insulators WITH interactions Fractional Hall effect, etc..					
Open QMB systems Out of equilibrium effects Quenches and thermalization					
Quantum Field Theories Gravity, Higgs Exotic models					
Unphysical effects/operations (Complex conjugation, Majorana, Entanglement monotones)					
Digital QS, Applications in Quantum Computing, QS and new quantum algorithms?					

Thank you for your attention!

PhD and Postdoc positions available

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