Title: Light and matter: towards macroscopic quantum systems

Date: Nov 20, 2013 02:00 PM

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Abstract: Advances in quantum engineering and material science are enabling new approaches for building systems that behave quantum mechanically on long time scales and large length scales. I will discuss how microwave and optical technologies in particular are leading to new domains of many-body physics, both classical and quantum, using photons and phonons as the constituent particles. Furthermore, I will highlight practical consequences of these advances, including improved force and acceleration sensing, efficient signal transduction, and topologically robust photonic circuits. Finally, I will consider how such large quantum systems may help us measure and constrain theories of quantum gravity and gravity-induced decoherence.

Light and matter: towards macroscopic quantum systems

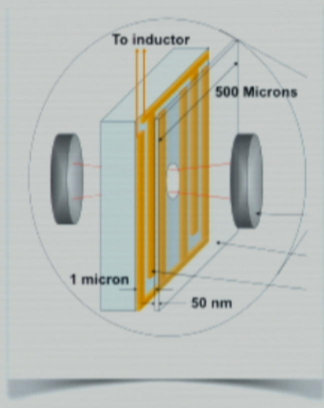
J. M. Taylor
Joint Center for Quantum Information and Computer Science
Joint Quantum Institute
National Institute of Standards and Technology

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

UNIVERSITY OF MARYLAND

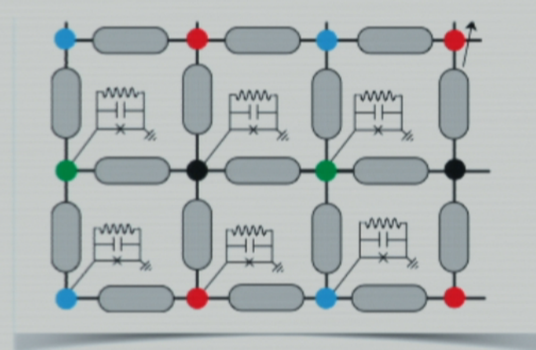
Physics Frontier Center
jqi
Joint Quantum Institute

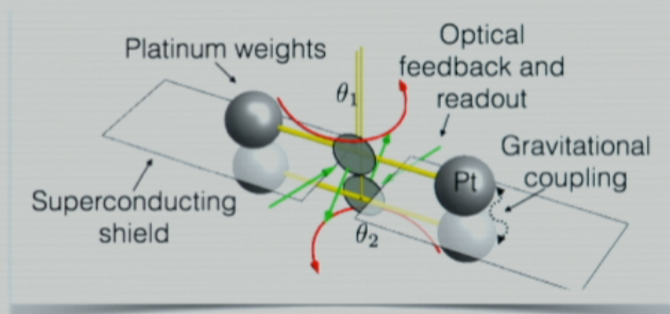
Outline



Photonics and phononics

Engineered particles:
Quantum hall with light





Noise and entanglement
with harmonic oscillators

Engineered quantum particles: photons and phonons

Consider a crystal: each atom a harmonic oscillator

Moving a neighbor: force

Engineered quantum particles: photons and phonons

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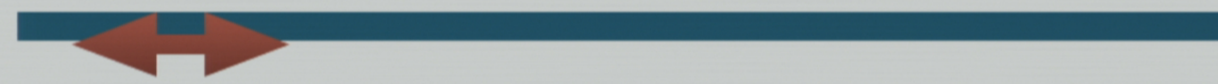
Engineered quantum particles: photons and phonons

Continuum limit? *Phonons*

A collection of harmonic oscillators described by a *wave equation*

Engineered quantum particles: photons and phonons

Continuum limit? *Phonons*

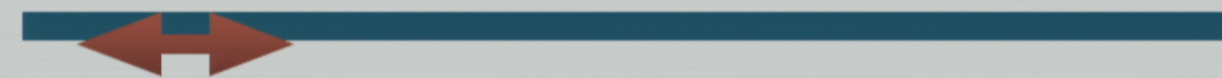


A collection of harmonic oscillators described by a *wave equation*

New *normal modes*: harmonic oscillators for each solution of the wave equation with appropriate boundaries

Engineered quantum particles: photons and phonons

Continuum limit? *Phonons*



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New *normal modes*: harmonic oscillators for each solution of the wave equation with appropriate boundaries

By engineering propagation properties (material, dielectric) and boundary conditions… We control the nature of excitations in the system

Engineered quantum particles: photons and phonons

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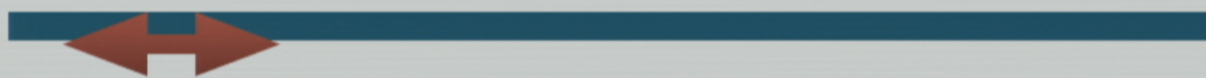

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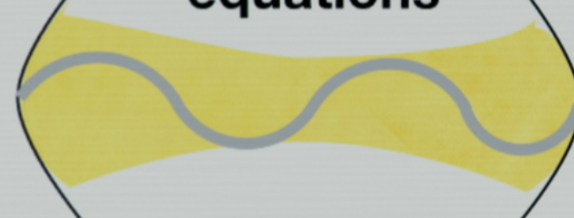
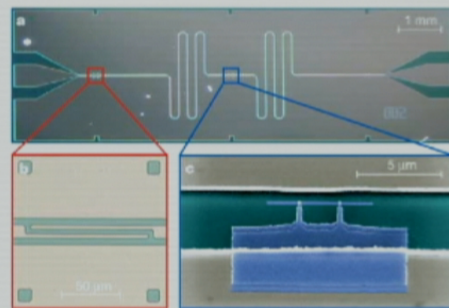
Photons: repeat, using Maxwell's equations

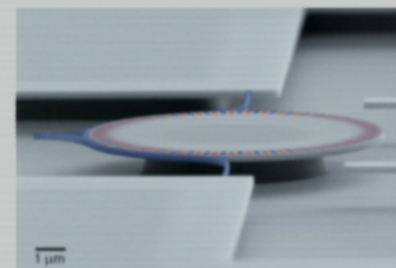


Recent examples of phononic and photonic systems

Silicon nitride membranes
Harris, Regal, Polzik, …

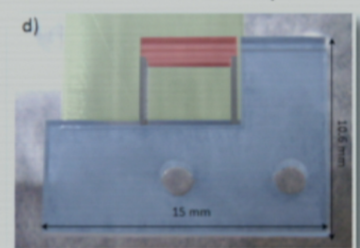


Superconducting strip line resonators
Haroche, Schoelkopf, …

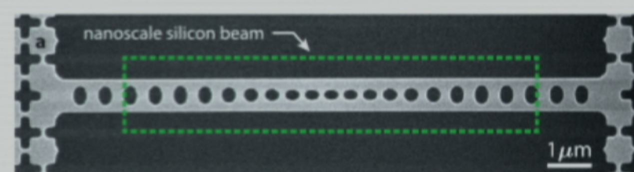


Whispering-galley mode optical resonators
Vahala, Kimbel, Srinivasan …

Glass flexures
Pratt, Shaw, …



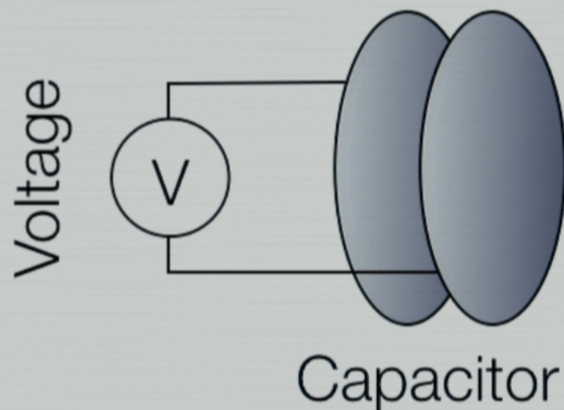
Photonic-phononic crystals
Painter, Cleland, Tang, …



A familiar electromechanical system

Microphones and loudspeakers

Electrical signal <=> mechanical motion



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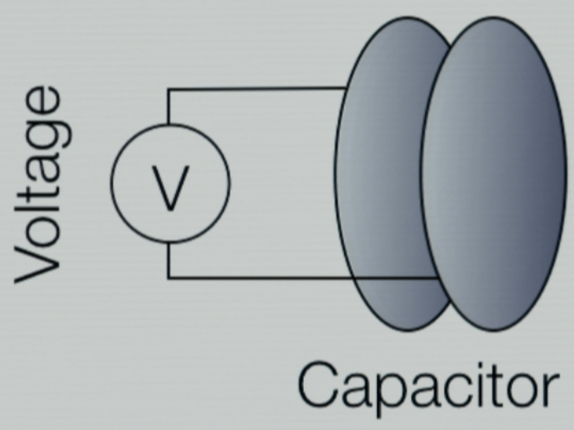
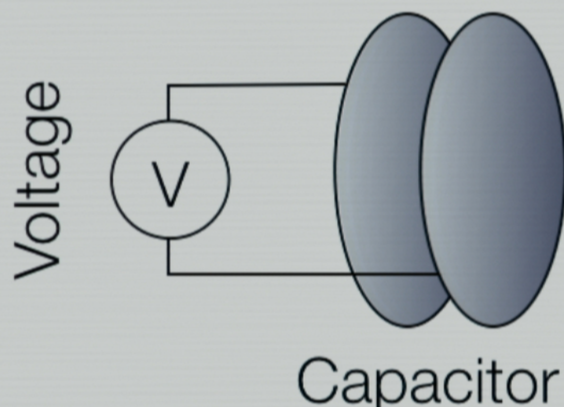


Change in V <=> change in C <=> change in x

A familiar electromechanical system

Microphones and loudsp

Electrical signal <=> r



Example: Theramin's Thing

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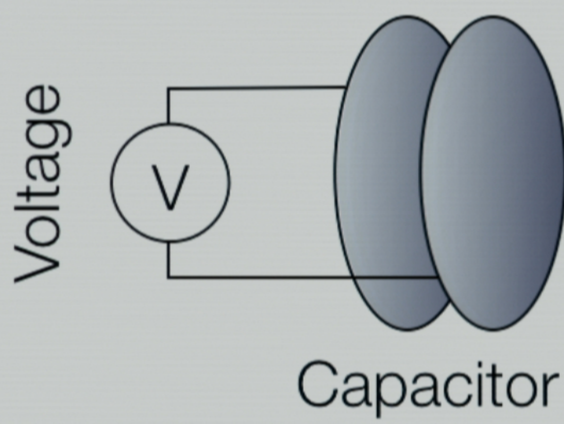

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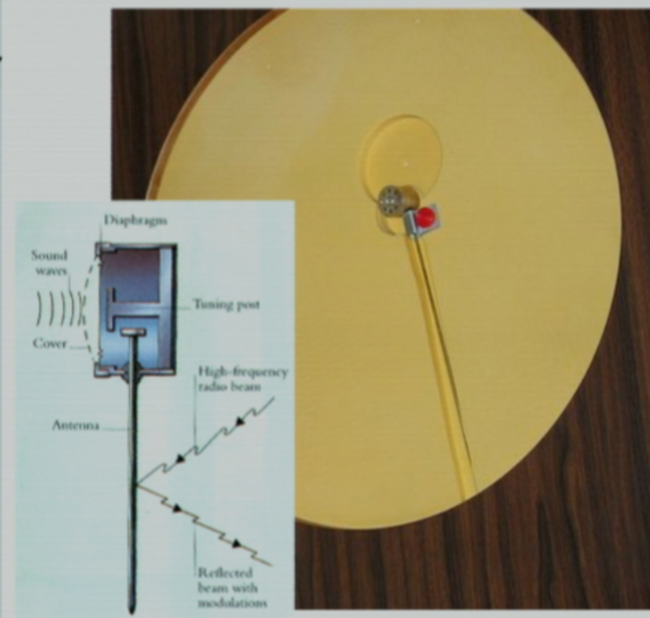


Change in V <=> change in C <=> change in x

Optomechanics: photons coupled to phonons

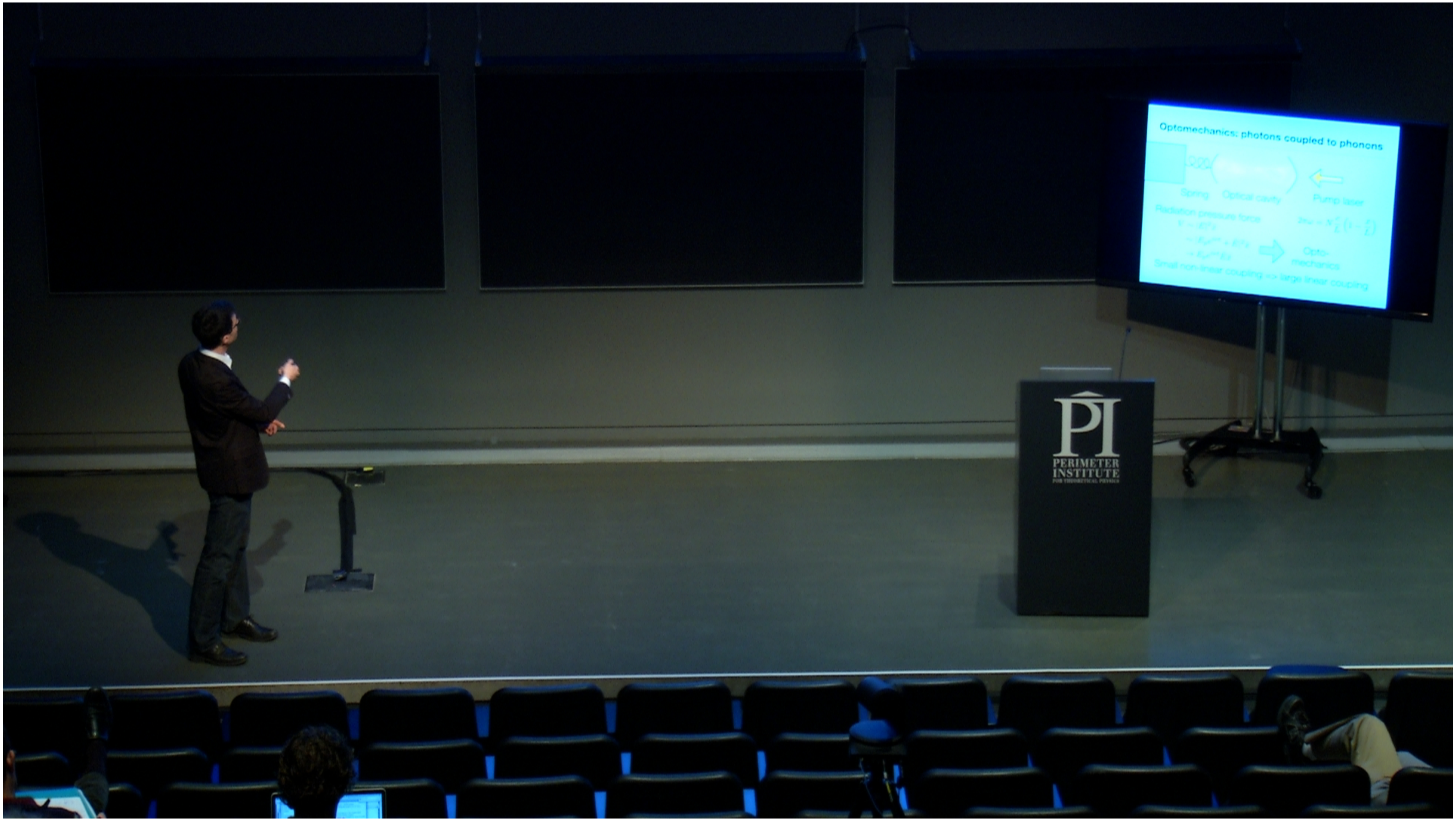
$$2\pi\omega = N\frac{c}{L}\left(1 - \frac{x}{L}\right)$$

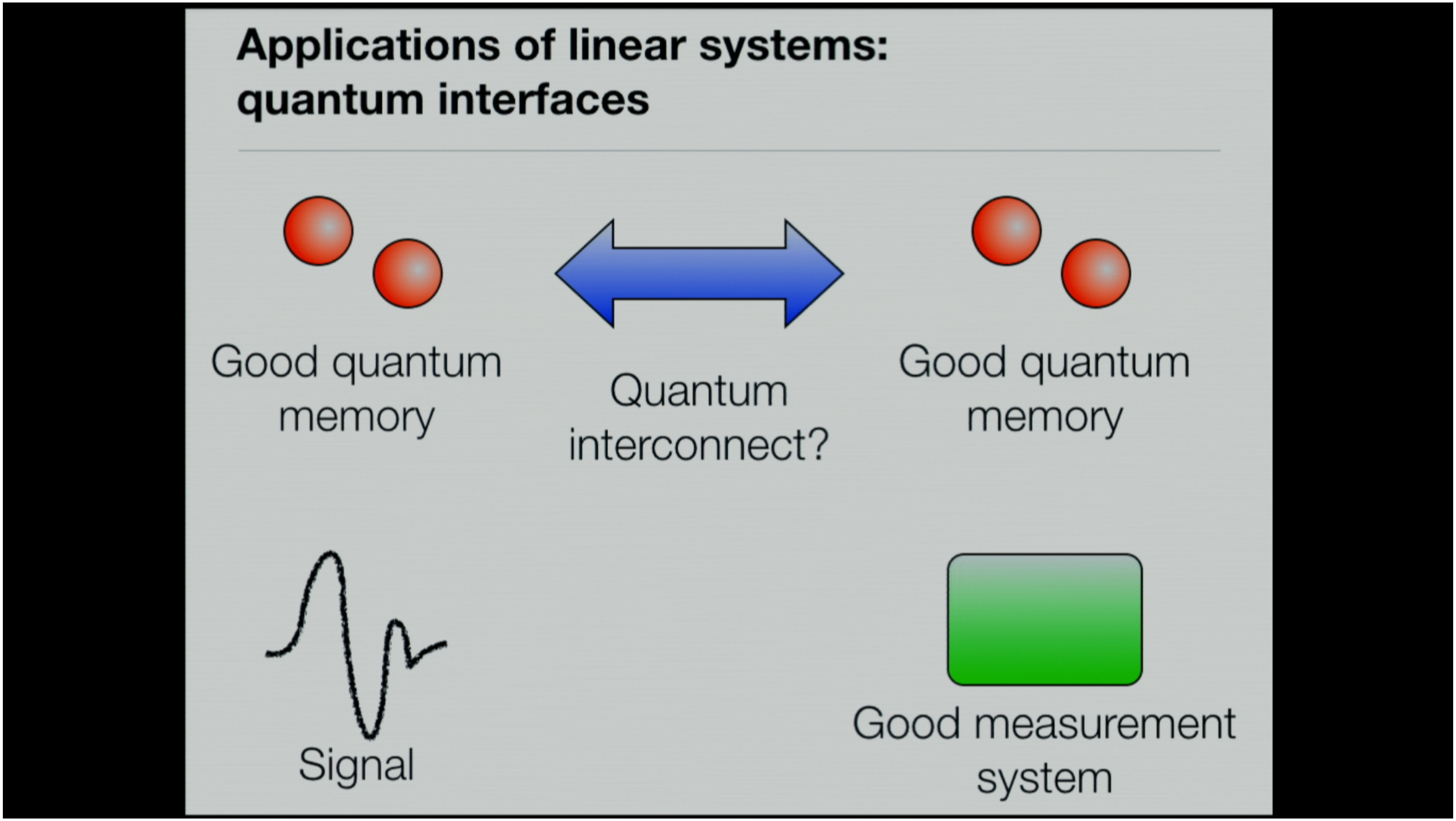
Radiation pressure force

$$V \sim |E|^2 \hat{x}$$
$$\sim |E_p e^{i\nu t} + \hat{E}|^2 \hat{x}$$
$$\to E_p e^{i\nu t} \hat{E} \hat{x}$$

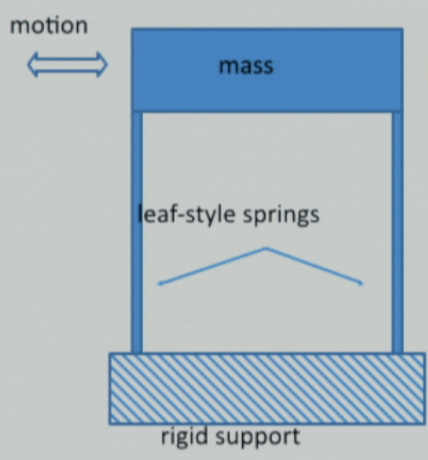
Opto-mechanics

Small non-linear coupling => large linear coupling


Optomechanics: photons coupled to phonons
PERIMETER
INSTITUTE


Applications of linear systems:
quantum interfaces
Good quantum
memory
Quantum
interconnect?
Good quantum
memory
Signal
Good measurement
system

Acceleration sensing via a mechanical oscillator at NIST



Motion changes cavity resonance → Detect position

[Kumanchik, Guzman-Cervantes, Pratt, JMT]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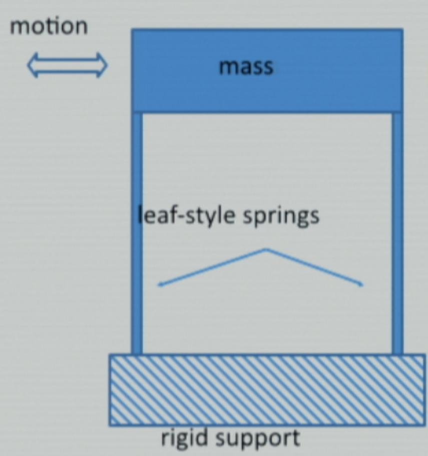
Acceleration sensing via a mechanical oscillator at NIST



Motion changes cavity resonance → Detect position

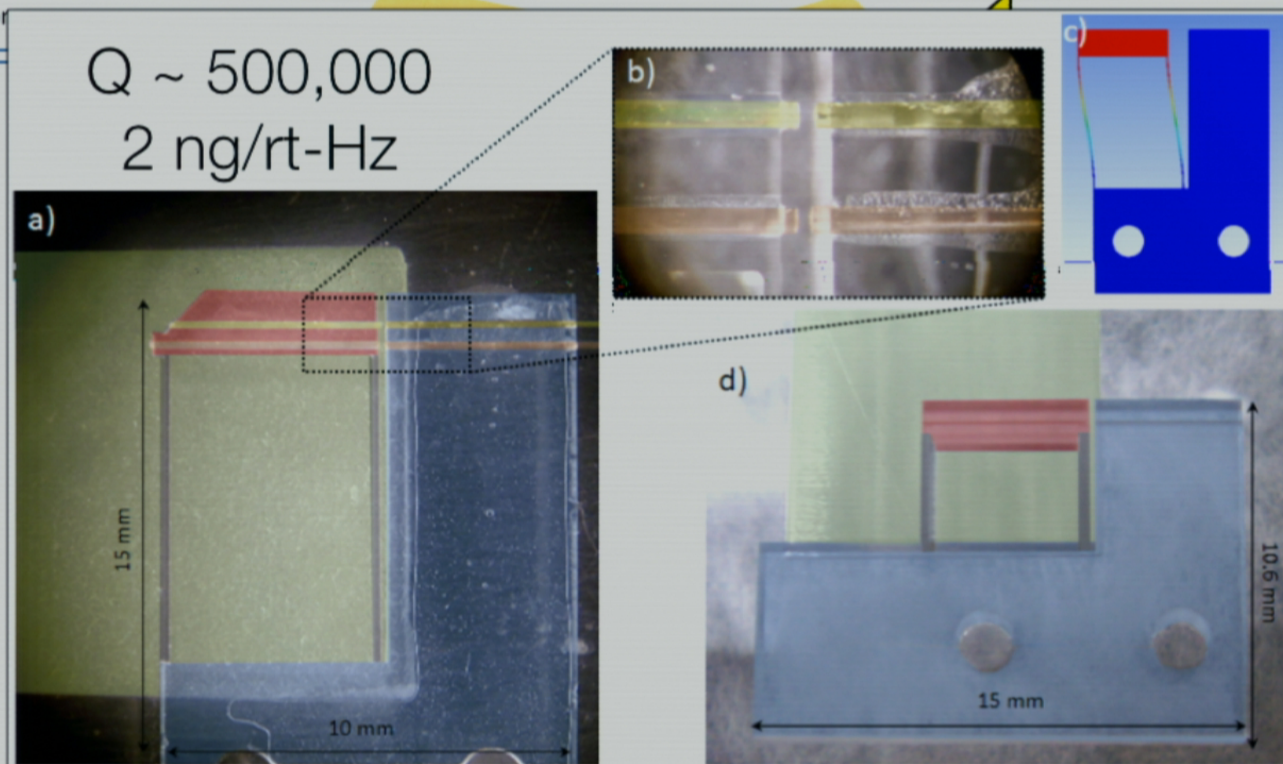
Self-calibration to the SI via optomechanics

$$\delta x = \frac{a}{\omega^2}$$

[Kumanchik, Guzman-Cervantes, Pratt, JMT]

Acceleration sensing via a mechanical oscillator at NIST

motion



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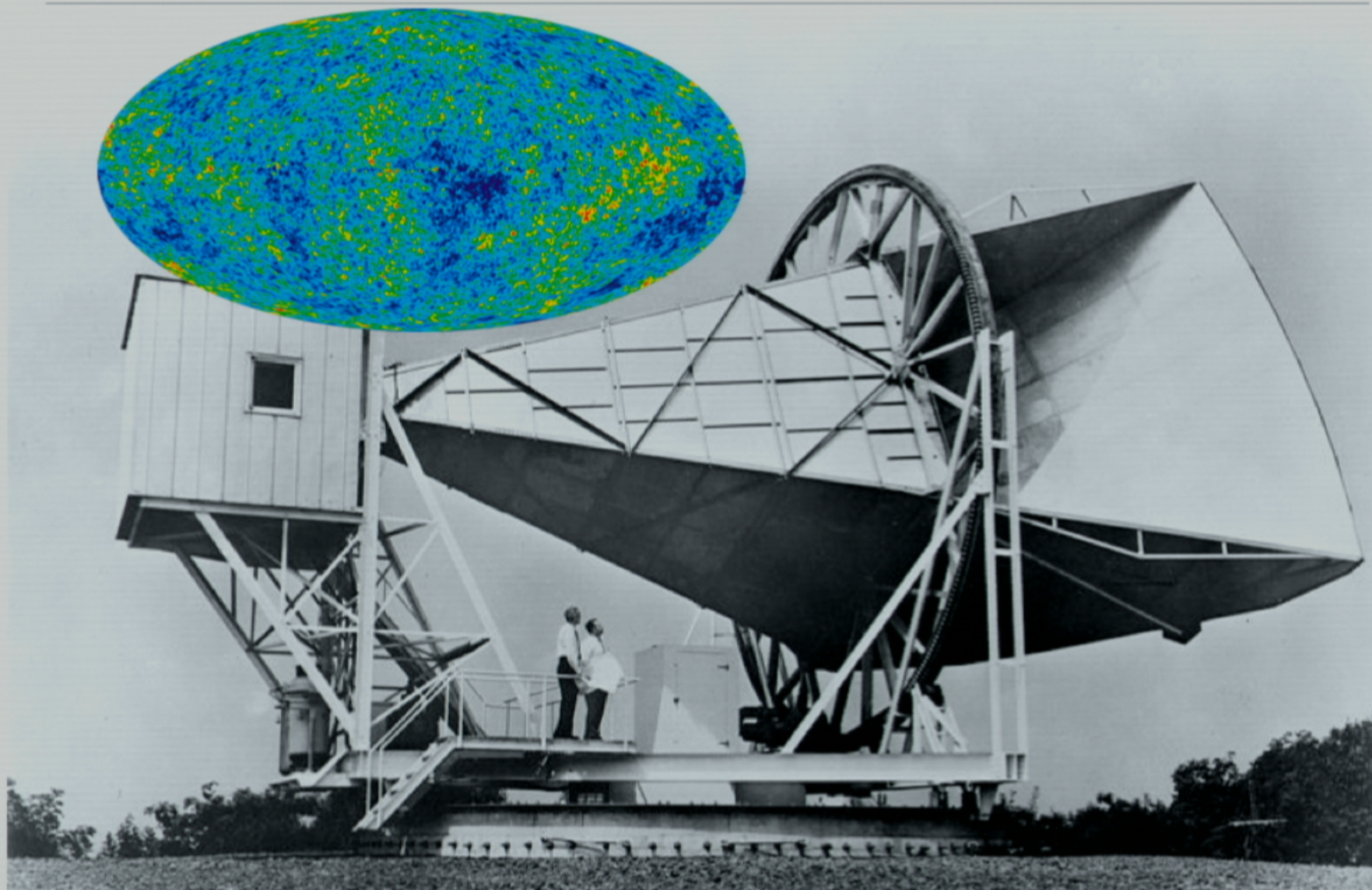
Change in wavelength of light

[Kumanchik, Guzman-Cervantes, Pratt, JMT]

Efficient detection of astrophysical rf photons



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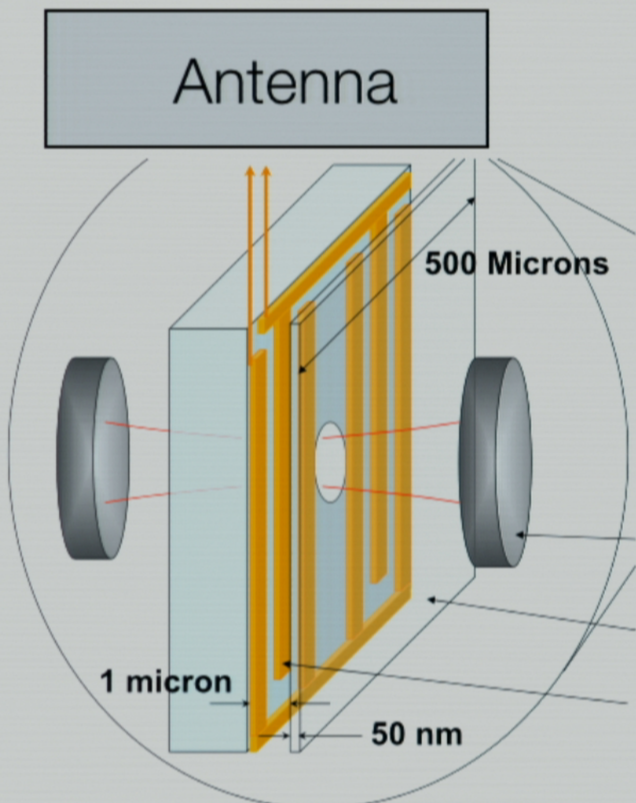
Efficient detection of astrophysical rf photons

[R. Curley, JMT]



Consider case of a 'high-Q'antenna pointing at sky

$T_{ant} << 300$ K

Can we measure this without inducing additional noise from room temperature circuits?

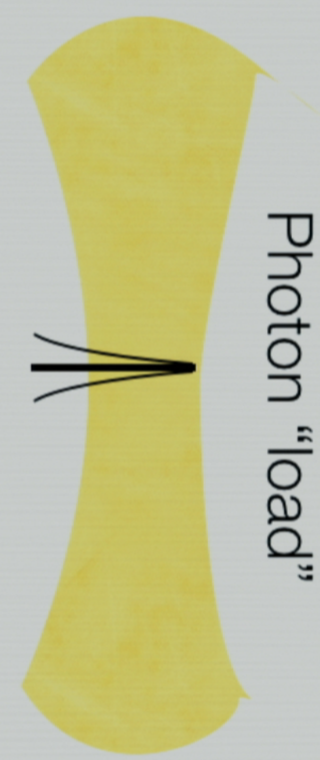
A universal interface?

[JMT, Sorensen, Marcus, Polzik, PRL (2011)]

Opto-
mechanics

$$V \propto |E|^2 x$$

$$\rightarrow |E_{\mathrm{p}}| e^{i\nu t} \hat{E} \hat{x}$$



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Electro-
mechanics

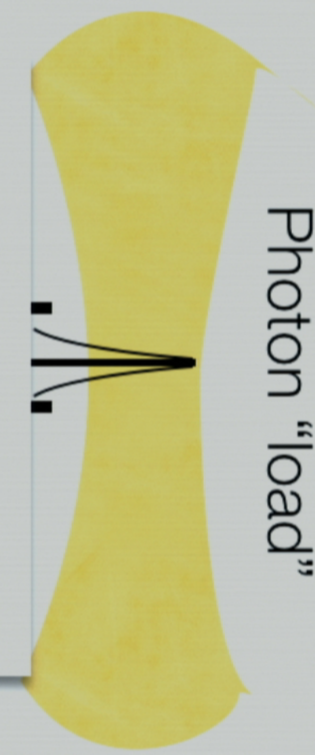
$$V = \frac{q^2}{2C}(1 + \frac{x}{C}\frac{dC}{dx}$$

Quantum regime?

Can transduce a cold source when dephasing slow:

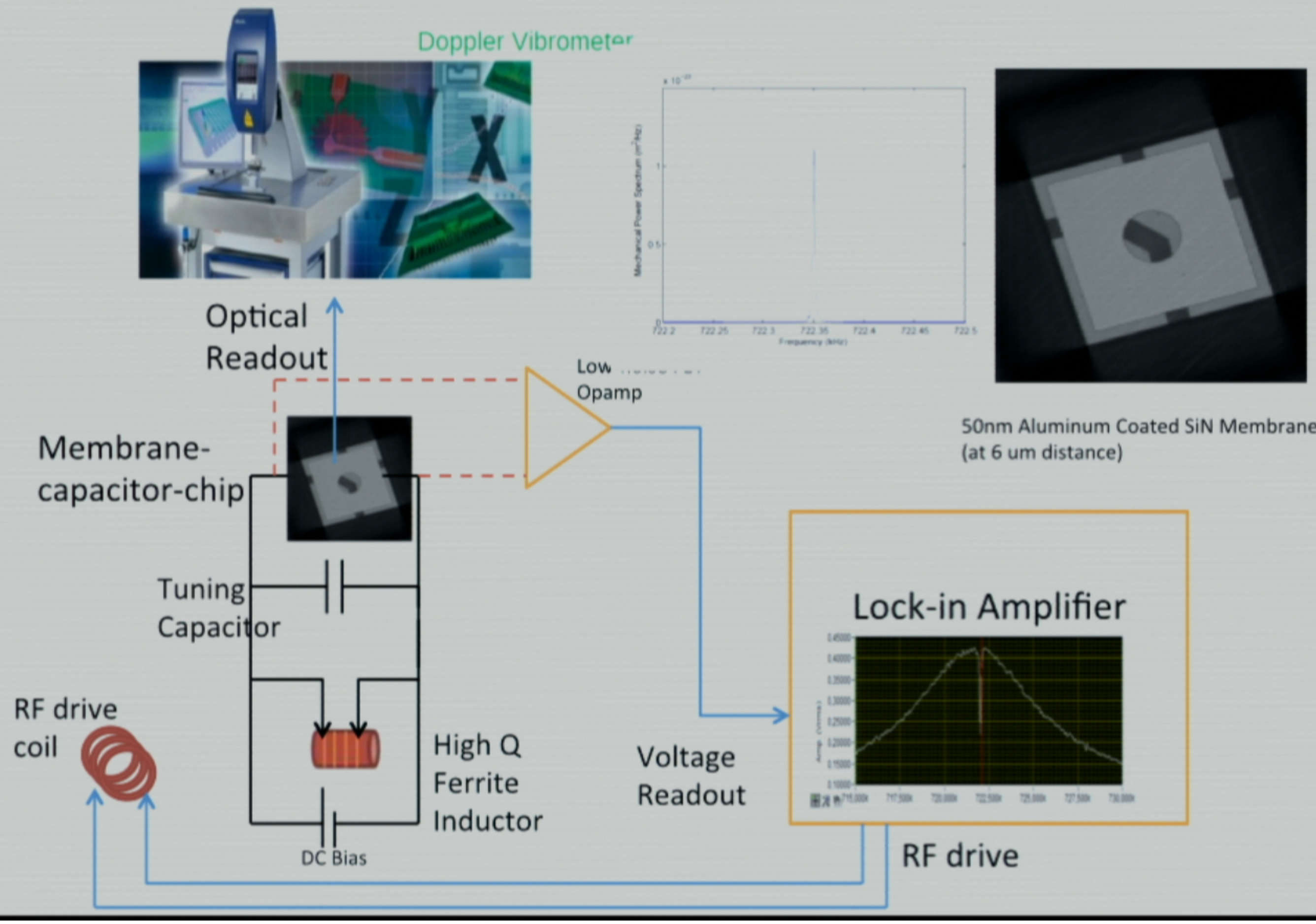
$$\omega > \gamma(n_\mathrm{th} + 1/2)$$

or $$\frac{\omega}{\gamma}\omega \gg \frac{k_b T}{\hbar}$$



Versatile optical interface

Experimental evidence: mechanically-induced transparency



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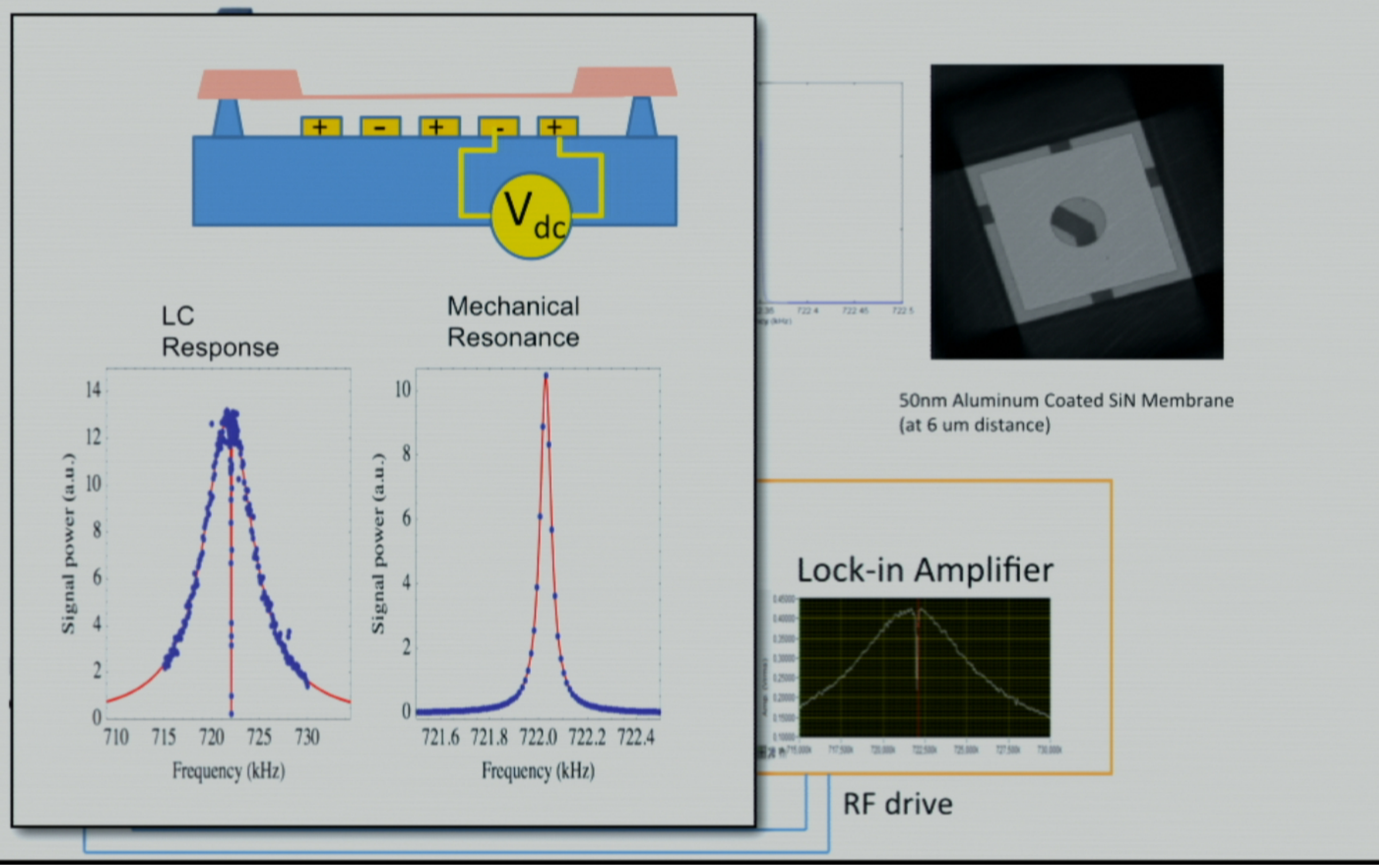

Linear and non-linear systems

When is quantum mechanics necessary to describe your system?

A matrix of numbers

Operators

Linear case $H = \sum_{ij} (a_i^\dagger \ a_i) \mathbb{M}_{ij} \begin{pmatrix} a_j \\ a_j^\dagger \end{pmatrix}$

Exactly solvable $\dot{a}_i = i[H, a_i] = i \left(\mathbb{F}_{ij} a_j^\dagger + \mathbb{G}_{ij} a_j \right)$

Ehrenfest's theorem exact $\langle \dot{a}_i \rangle = i \left(\mathbb{F}_{ij} \langle a_j^\dagger \rangle + \mathbb{G}_{ij} \langle a_j \rangle \right)$


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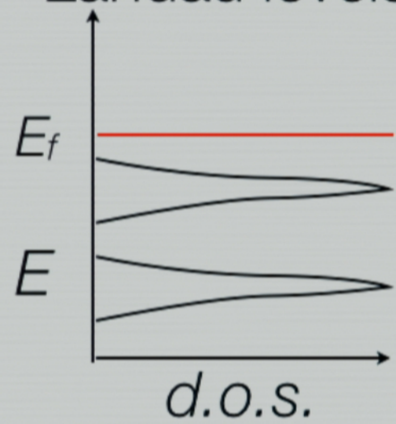
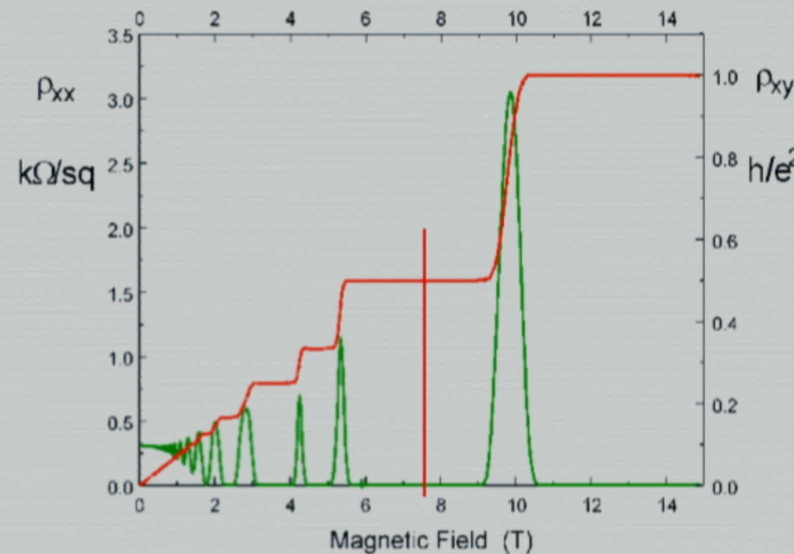
Quantum hall: a review

Magnetic field induces Landau levels





At a band insulator-topological insulator boundary, transport occurs on the edge (Laughlin; Halperin)

[Klitzing, Tsui, ...]

Building a topological system: Synthetic gauge fields

Generator of (magnetic) translation:

$$\exp[-i(\hat{p} - \vec{A})a]$$

[Photons: Haldane, Soljacic, Girvin;
Atoms: Cooper, Spielman, Bloch, Dalibard, ...]

Building a topological system: Synthetic gauge fields

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Translation over a closed path (on a lattice)

$$\oint_C \vec{A} \cdot d\vec{l} \rightarrow \exp(-i \sum_{<>} A \cdot dl)$$

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Addition of momentum term equivalent...

$$H = \frac{p^2}{2m} + V(x) + \vec{p} \cdot \vec{\alpha}$$

On a lattice

$$H_{\mathrm{lat}} = -t \sum_{<ij>} a_i^\dagger a_j e^{iA_{ij}l}$$

[Photons: Haldane, Soljacic, Girvin;
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Synthetic gaug

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$\exp[-i(\hat{p} - \vec{A})$

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Addition of mon

H

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Example on a lattice: Hofstadter butterfly

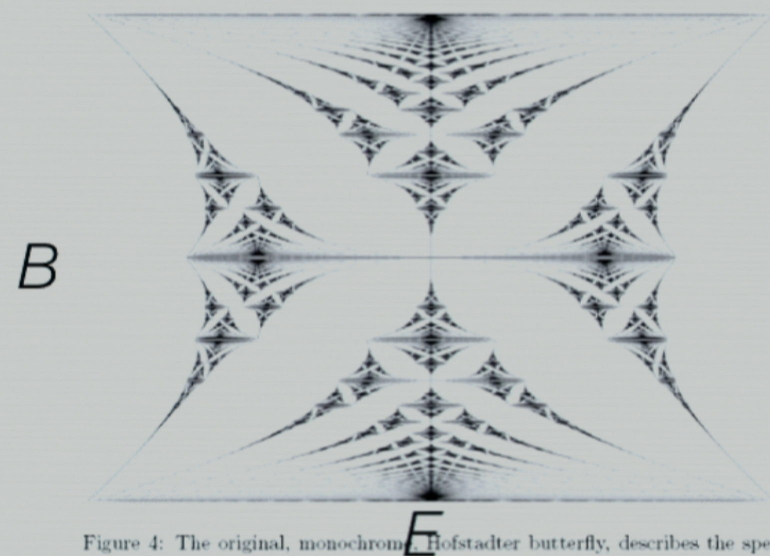
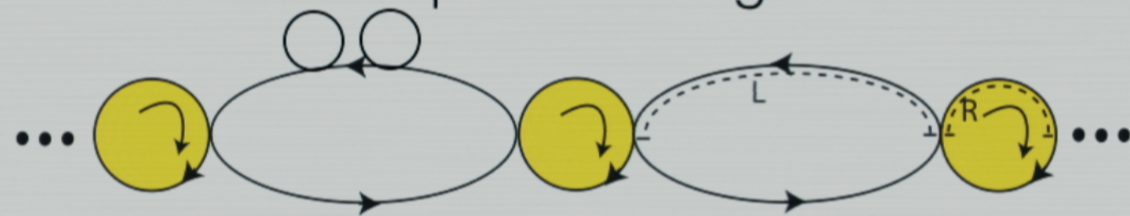


Figure 4: The original, monochrome Hofstadter butterfly, describes the spectrum of a quantum particle in a magnetic field and periodic potential. The vertical axis is related to the magnetic field, and the horizontal axis is the energy axis.

Synthetic magnetic fields with optical resonators

Coupled resonator optical waveguide



Tight-binding Hamiltonian for photons

[M. Hafezi et al, Nature Phys (2011)]

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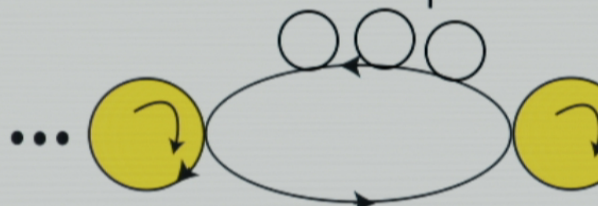
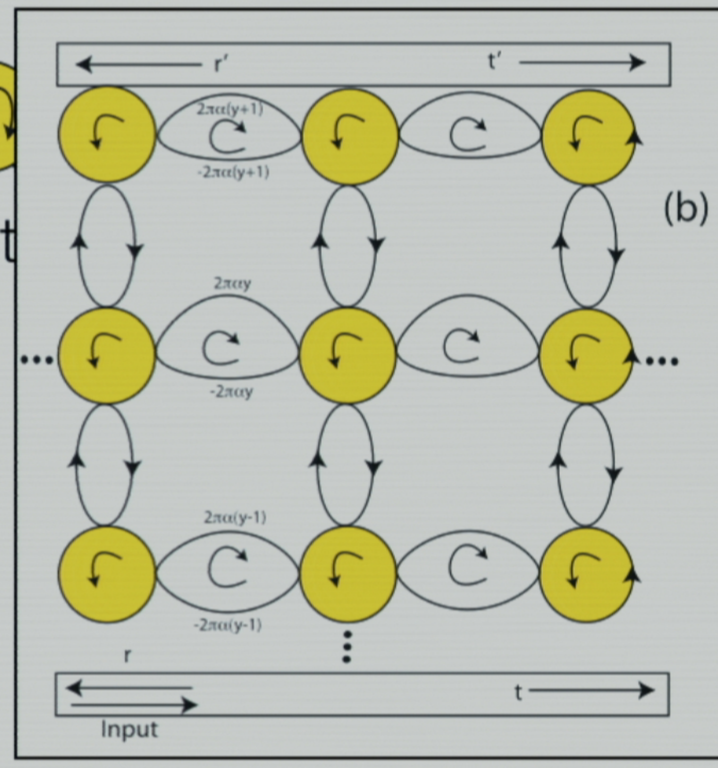


Tight-binding Hamilt

$$H_0 = J \sum_{x,y} \hat{a}^\dagger_{x+1,y} \hat{a}_{x,y} e^{i2\pi\alpha y} + \hat{a}^\dagger_{x,y+1} \hat{a}_{x,y}$$



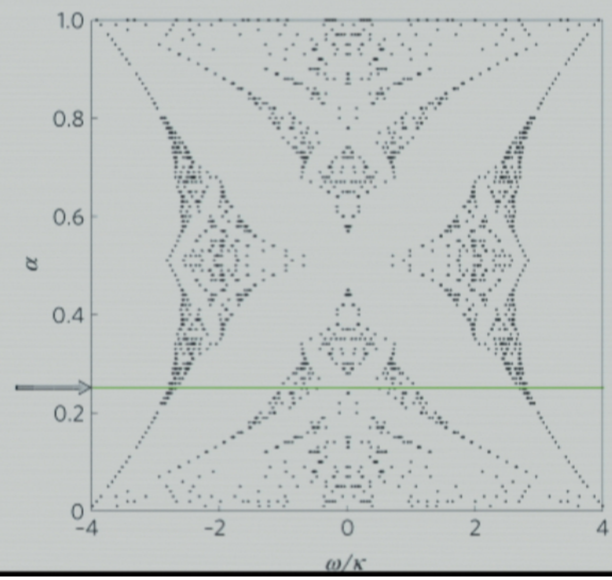
[M. Hafezi et al, Nature Phys (2011)]

Hofstader butterfly and edge states

Probe transmission/ reflection

$$r'(\omega) = -i\nu \sum_{i \in in, j \in out} \left[\frac{1}{\omega - H_{s-wg}} \right]_{i,j}$$

Calculated transmission coefficient



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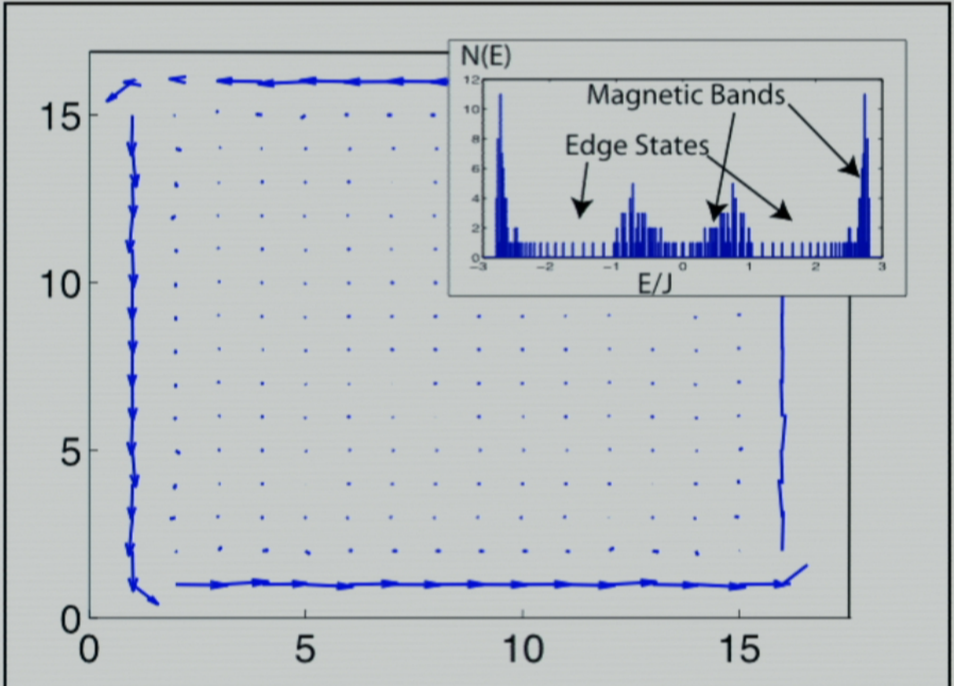
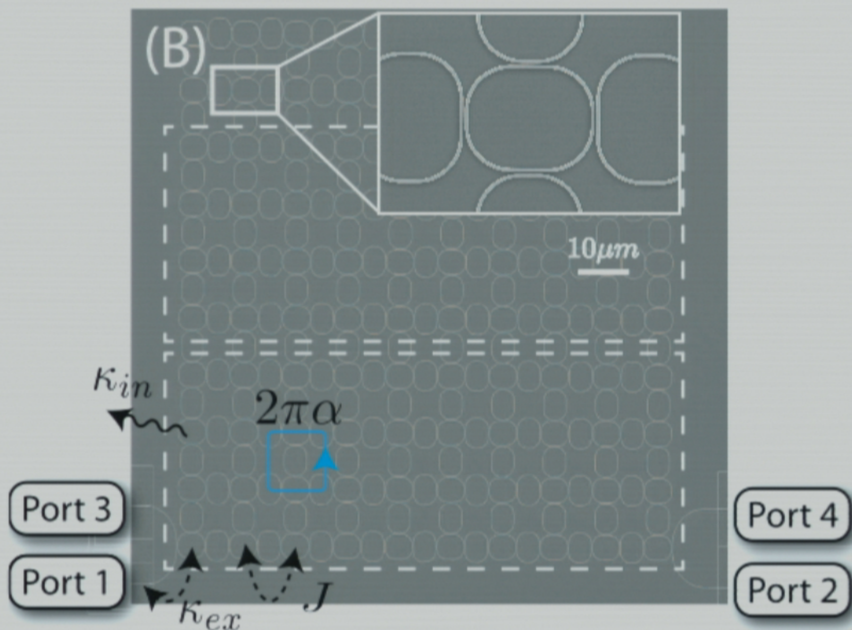
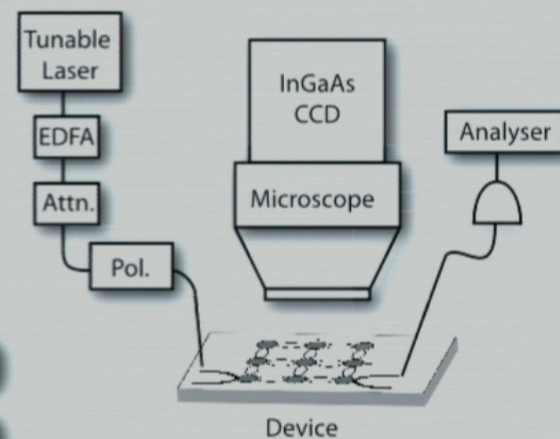


Realization using Silicon-on-Insulator





[M. Hafezi, S. Mittal, J. Fan, A. Migdall, JMT, Nat. Phot. (2013)]

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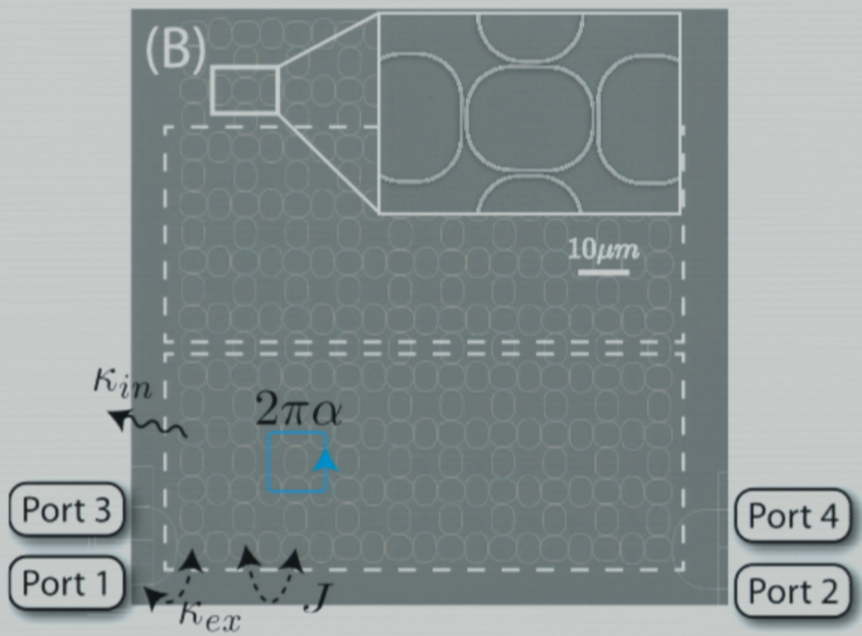

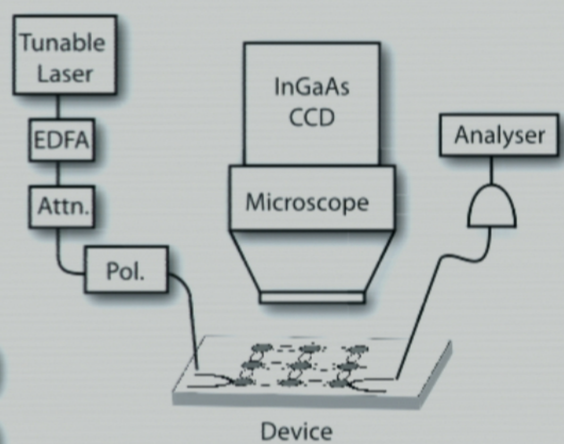

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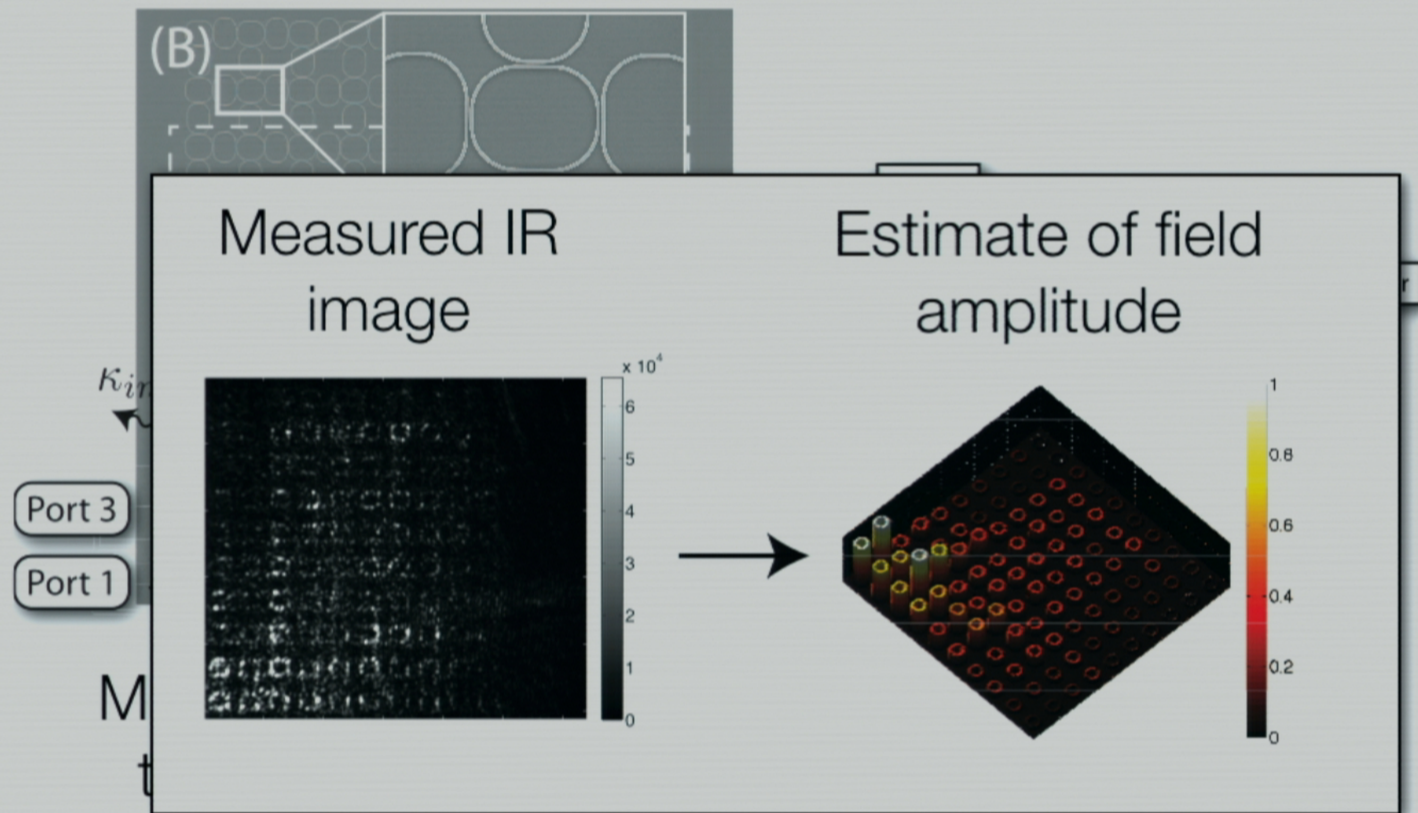

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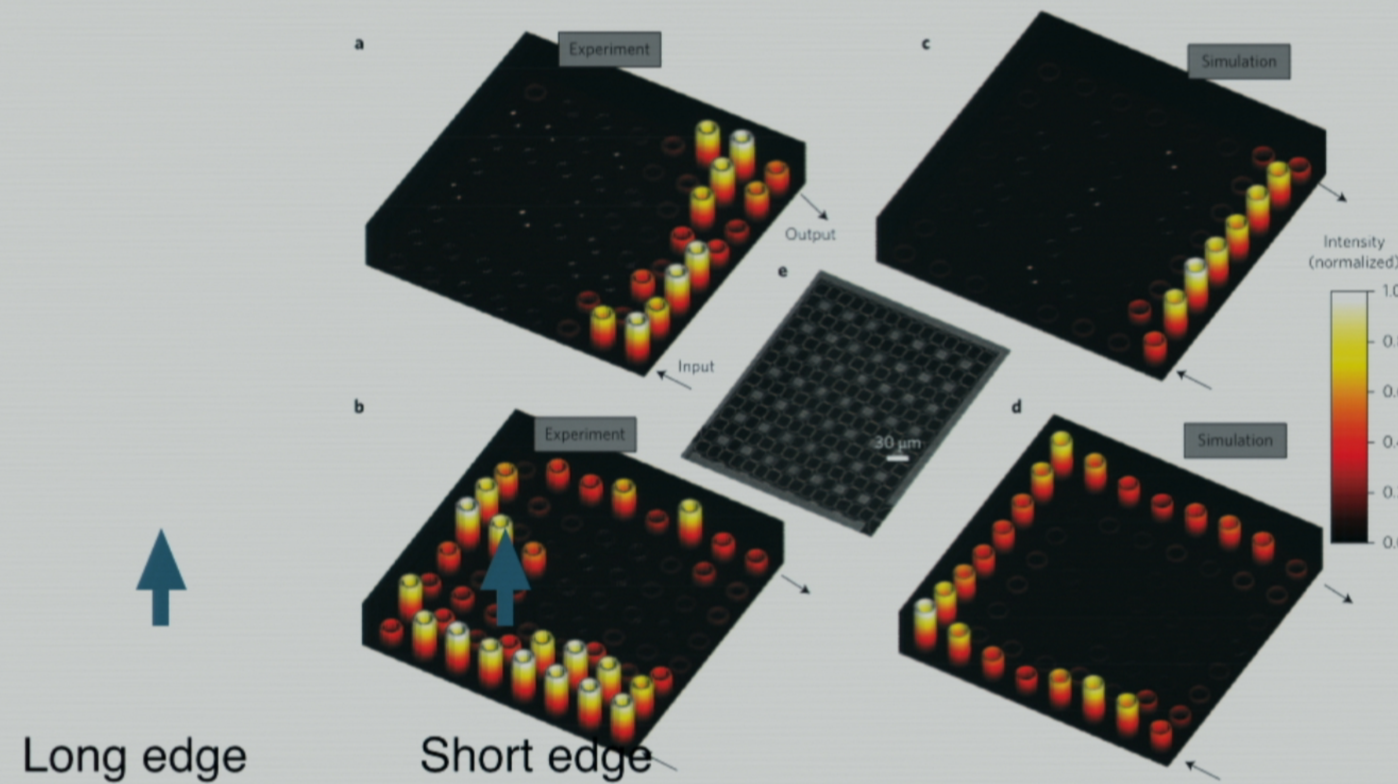
Clockwise versus counterclockwise



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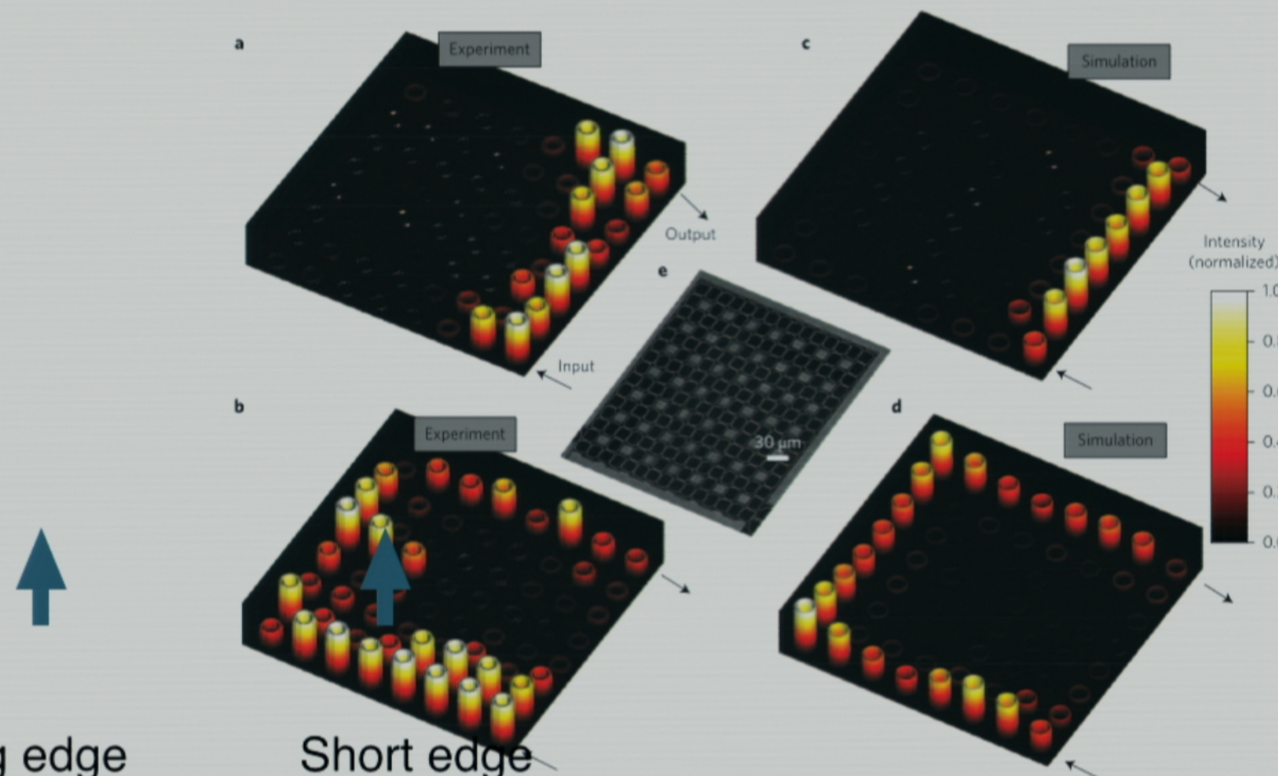


Long edge

Short edge

Fractional quantum Hall:
the Pfaffian state as quantum memory

A topological phase of matter with anyonic excitations sufficient for quantum memory...

VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

Paired Hall State at Half Filling

Martin Greiter,[a] Xiao-Gang Wen, and Frank Wilczek

School of Natural Sciences, Institute for Advanced Study, Olden Lane, Princeton, New Jersey 08540

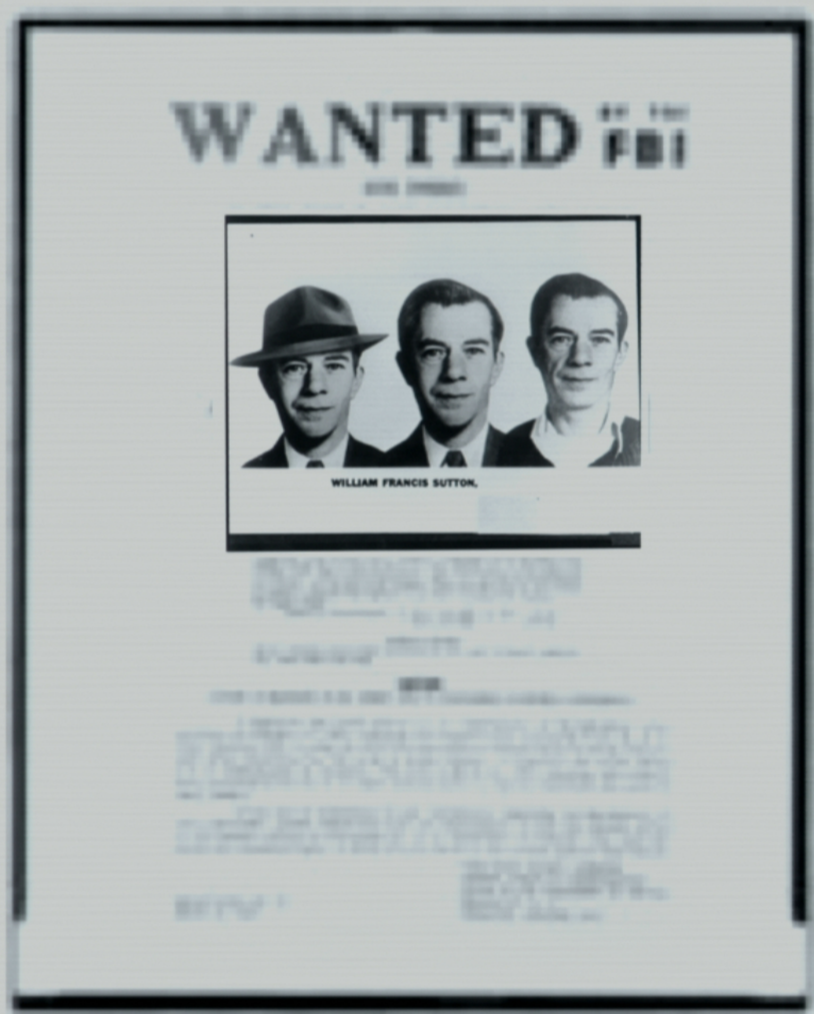
(Received 4 April 1991)

The existence of a novel incompressible quantum liquid for spinless fermions at $\nu = \frac{1}{2}$ in the Ha
effect is suggested. This state is plausibly related by smooth extrapolation in quantum statistics to
strong p-wave pairing state of fermions in zero magnetic field, and reduces to a state previously propos
by Halperin in the (unrealistic) limit of tightly bound pairs. It supports unusual excitations, includi
neutral fermions and charge-$e/4$ anyons with statistical parameter $\theta = \pi/8$. Numerical experiments a
presented, which provide evidence for several aspects of our theory.

Exact ground state

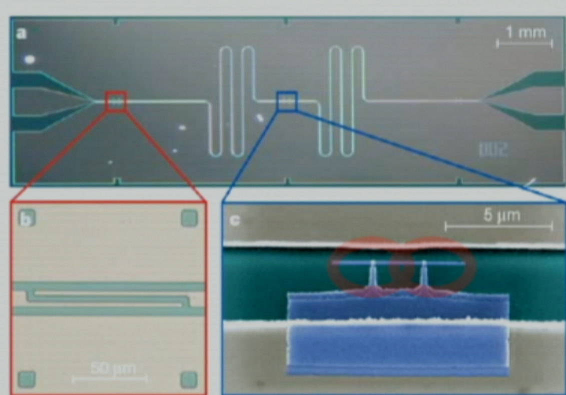
$(\nu = 1)$

$$V_{i;jk} = \sum_{\text{triples}} \delta^{(2)}(z_i - z_j)\,\delta^{(2)}(z_i - z_k)$$



"Why do you rob banks, Mr. Sutton?"
"Because that's where the money is."

Microwave nonlinear optics



[Schoelkopf group]

Small mode volume =>
large electric field per photon

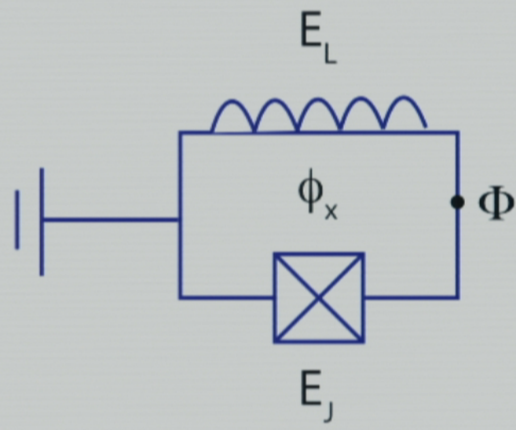
Superconducting material:
low loss per photon

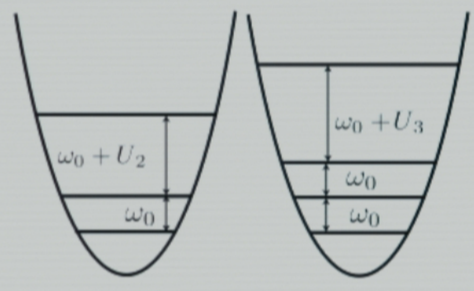
Josephson junction:
large nonlinearity available

Microwave domain: 3-body interaction

[M. Hafezi, P. Adhikari, JMT, arxiv:1308.0225]
[P. Adhikari, M. Hafezi, JMT, PRL 2013]

Start with a ‘fluxonium’ qubit

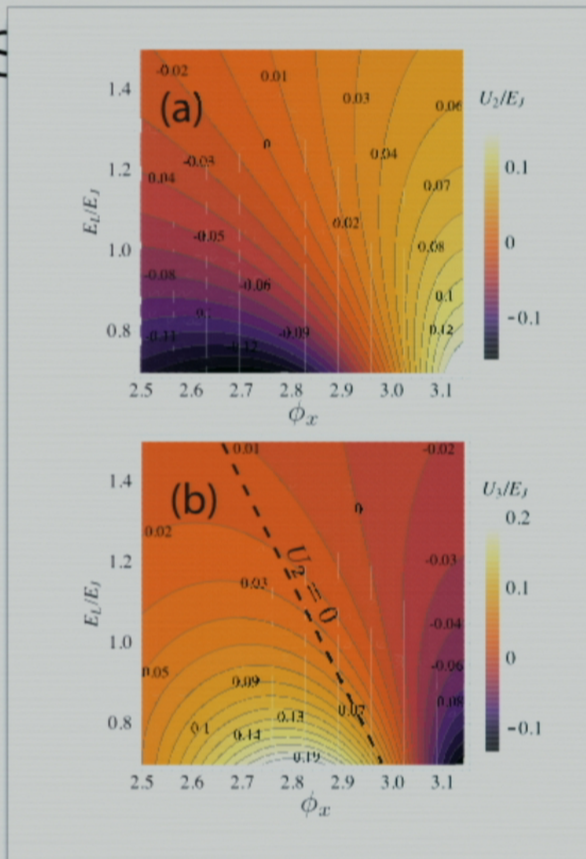




Microwave domain: 3-body interaction

[M. Hafezi, P. Adhikari, JMT, arxiv:1308.0225]
[P. Adhikari, M. Hafezi, JMT, PRL 2013]

S ’ qubit



Excitation spectrum nearly linear: analogous to LC resonator

$$H \approx \omega a^\dagger a + U_2 {a^\dagger}^2 a^2 + U_3 {a^\dagger}^3 a^3$$

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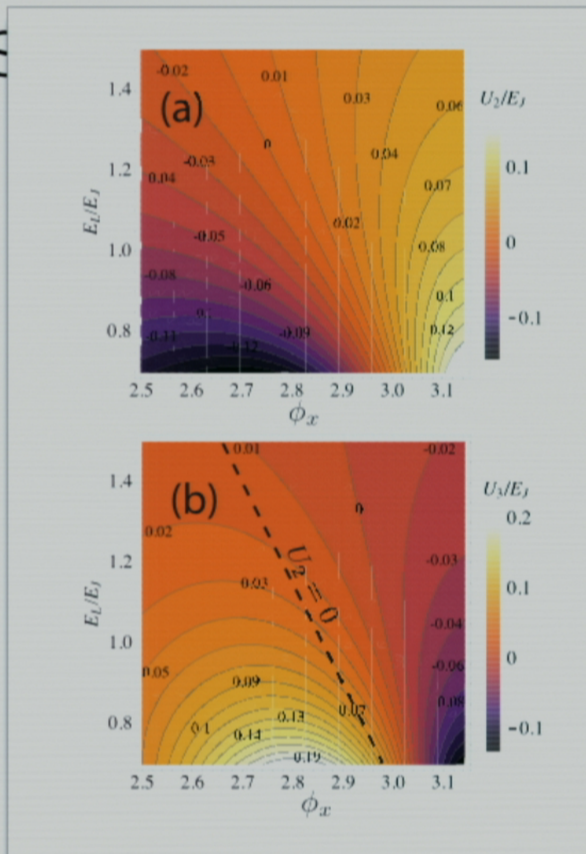


Excitation spectrum nearly linear:
analogous to LC resonator

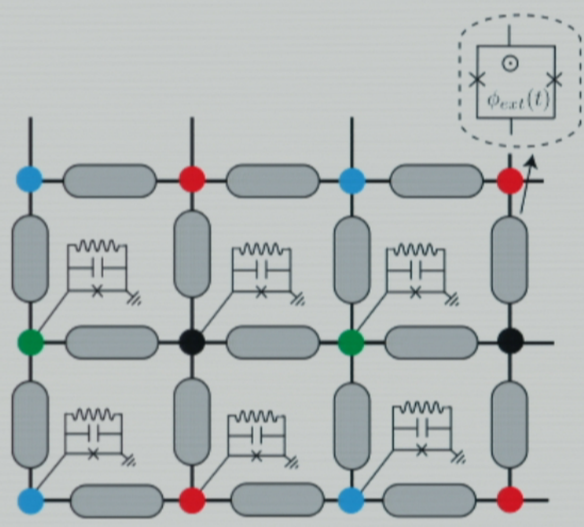
$$H \approx \omega a^\dagger a + U_2 {a^\dagger}^2 a^2 + U_3 {a^\dagger}^3 a^3$$

Extending this to fractional quantum Hall

$$H = -J \sum_{x,y} \hat{a}^{\dagger}_{x+1,y} \hat{a}_{x,y} e^{-i2\pi\alpha y} + \hat{a}^{\dagger}_{x,y} \hat{a}_{x+1,y} e^{+i2\pi\alpha y}$$
$$+ \hat{a}^{\dagger}_{x,y+1} \hat{a}_{x,y} + \hat{a}^{\dagger}_{x,y} \hat{a}_{x,y+1} + \frac{1}{6} U_3 \hat{a}^{\dagger 3}_{x,y} \hat{a}^{3}_{x,y}$$

Produce magnetic field?

- tunneling phase



PHYSICAL REVIEW A **82**, 043811 (2010)

Time-reversal-symmetry breaking in circuit-QED-based photon lattices

Jens Koch,[1] Andrew A. Houck,[2] Karyn Le Hur,[1] and S. M. Girvin[1]
[1]*Departments of Physics and Applied Physics, Yale University, P.O. Box 208120, New Haven, Connecticut 06520, USA*
[2]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*
(Received 11 June 2010; published 11 October 2010)

Breaking time-reversal symmetry is a prerequisite for accessing certain interesting many-body states such as fractional quantum Hall states. For polaritons, charge neutrality prevents magnetic fields from providing a direct symmetry-breaking mechanism and, similar to the situation in ultracold atomic gases, an effective magnetic field has to be synthesized. We show that in the circuit-QED architecture, this can be achieved by inserting simple superconducting circuits into the resonator junctions. In the presence of such coupling elements, constant parallel magnetic and electric fields suffice to break time-reversal symmetry. We support these theoretical predictions with numerical simulations for realistic sample parameters, specify general conditions under which time reversal is broken, and discuss the application to chiral Fock-state transfer, an on-chip circulator, and tunable band structure for the Kagome lattice.

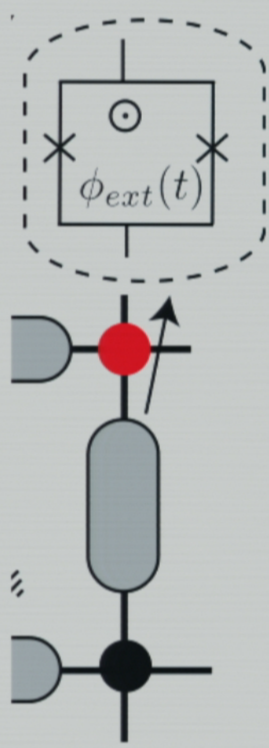
ARTICLES
PUBLISHED ONLINE: 7 OCTOBER 2012 | DOI: 10.1038/NPHOTON.2012.236
nature photonics

Realizing effective magnetic field for photons by controlling the phase of dynamic modulation

Kejie Fang[1], Zongfu Yu[2] and Shanhui Fan[2]*

The goal to achieve arbitrary control of photon flow has motivated much of the recent research on photonic crystals and metamaterials. As a new mechanism for controlling photon flow, we introduce a scheme that generates an effective magnetic field for photons. We consider a resonator lattice in which the coupling constants between the resonators are harmonically modulated in time. With appropriate choice of the spatial distribution of the modulation phases, an effective magnetic field for photons can be created, leading to a Lorentz force for photons and the emergence of topologically protected one-way photon edge states that are robust against disorders—without the use of magneto-optical effects.

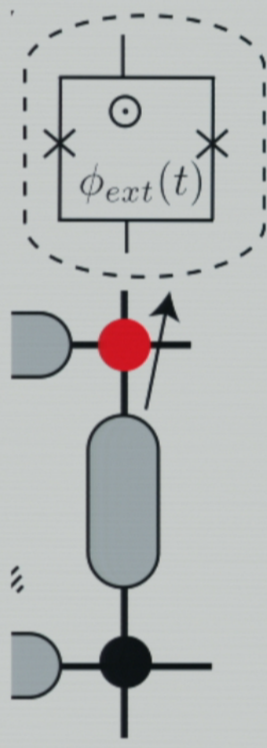
Synthetic field via frequency conversion



Start with a multi-color (nonlinear) lattice

$$H \approx \omega a_i^\dagger a_i + (\omega + \nu) a_j^\dagger a_j + H_{\rm nl} + V$$

Synthetic field via frequency conversion



Start with a multi-color (nonlinear) lattice

$$H \approx \omega a_i^\dagger a_i + (\omega + \nu) a_j^\dagger a_j + H_{\mathrm{nl}} + V$$

Turn on coupling (e.g., flux-flux) via modulated DC squid

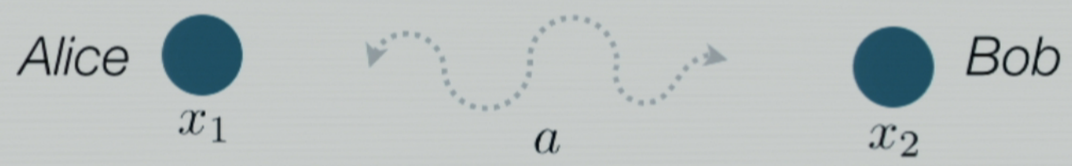
$$V \sim \phi_i \phi_j \cos(\nu t + \theta) \rightarrow a_i^\dagger a_j e^{i\theta} + \mathrm{H.c.}$$

Make rotating wave approximation — get nontrivial hopping phase!

Practical benefit: frequency fixed, only need control of relative phase of converters to produce desired magnetic field (no fine-tuning)

Force laws as a communication channel

Back to basics: Lorentz invariance => local theory



Non-local force 'law'? Integrate out force carriers

$$\omega a^\dagger a + \lambda(a + a^\dagger)(x_1 + x_2)$$

Force laws as a communication channel

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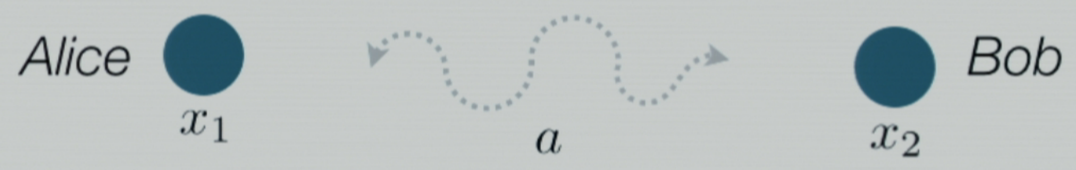


Non-local force 'law'? Integrate out force carriers

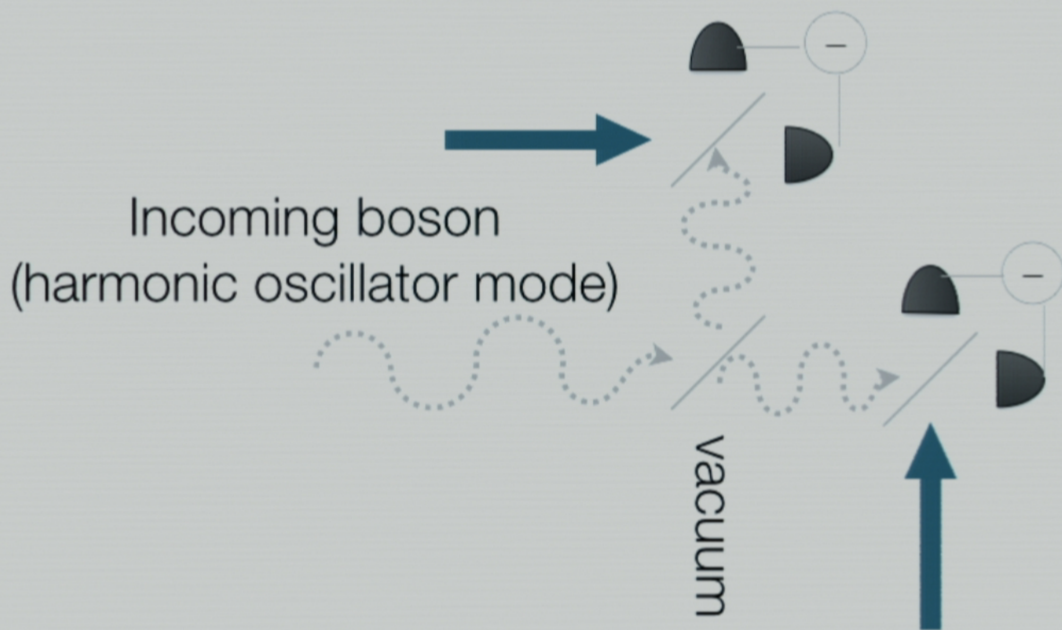
$$\omega a^\dagger a + \lambda(a + a^\dagger)(x_1 + x_2)$$

$$U = \exp\left(ip\frac{\lambda}{\omega}(x_1 + x_2) \right)$$

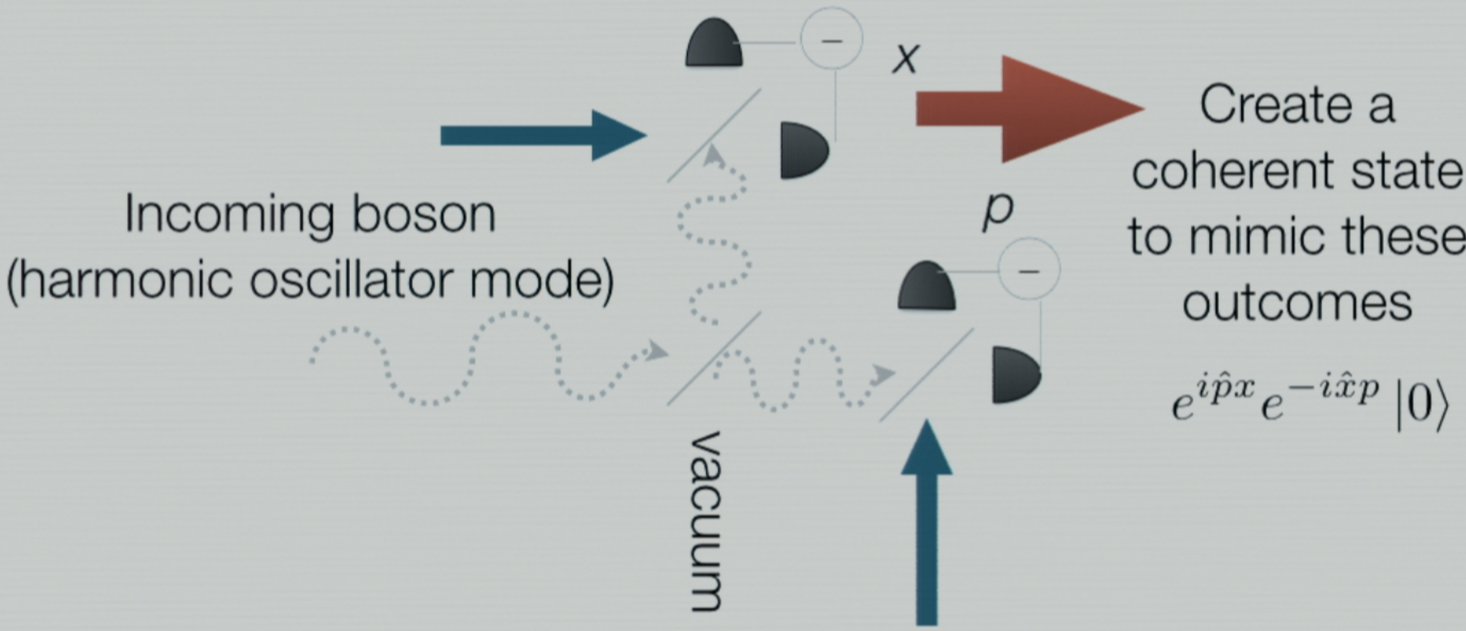
$$a \to a - \frac{\lambda}{\omega}(x_1 + x_2)$$

$$\omega a^\dagger a - \frac{\lambda^2}{\omega}(x_1^2 + x_2^2 + 2x_1 x_2)$$

An example screen: measure both quadratures



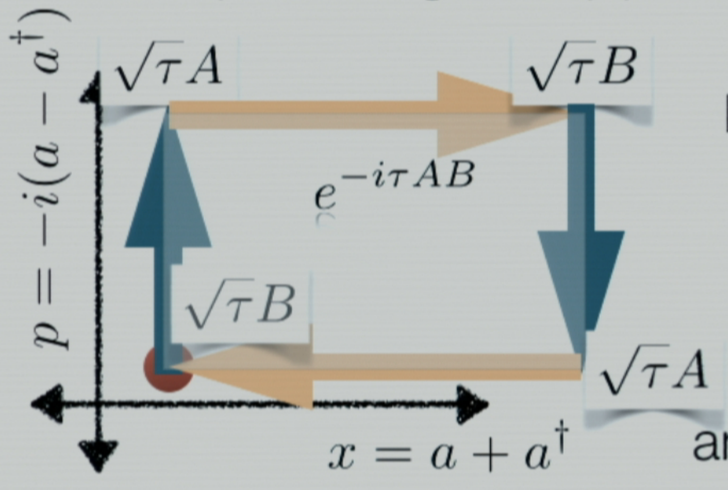
An example screen: measure both quadratures



This procedure *unavoidably* adds noise
[x,p] ≠ 0 => 'amplifier' noise

A circuit model for force laws

Geometric 'phase' gate approach from ion trappers



Want an interaction between *A*lice and *B*ob

$$V = AB$$

Consider a set of interactions with an ancillary harmonic oscillator

$\exp(-i\sqrt{\tau}xA)$ 'copy' A information

$\exp(-i\sqrt{\tau}pB)$ 'copy' B information

$\exp(i\sqrt{\tau}xA)$ Remove 'A' information

$\exp(i\sqrt{\tau}pB)$ Remove 'B' information

Noise for classical (non-entangling) forces

[Kafri & Taylor, arXiv:1311.4558]

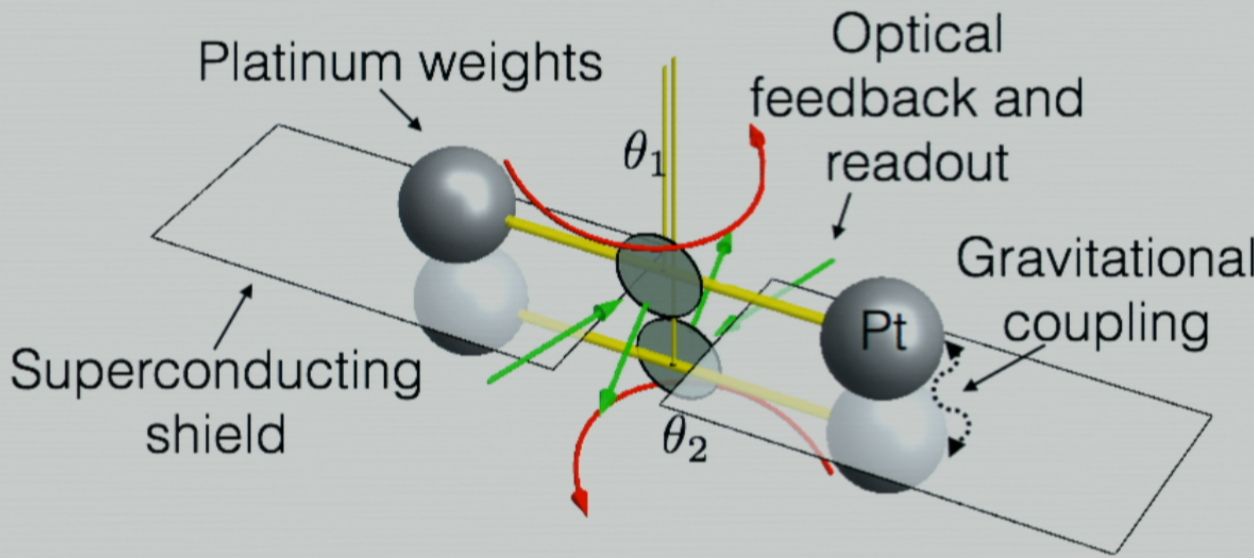
A few (non-essential) points:

- Let Alice and Bob be harmonic oscillators (mass *m*, frequency)
- They interact via $gx_a x_b$
- They have conjugate momentum p_a, p_b

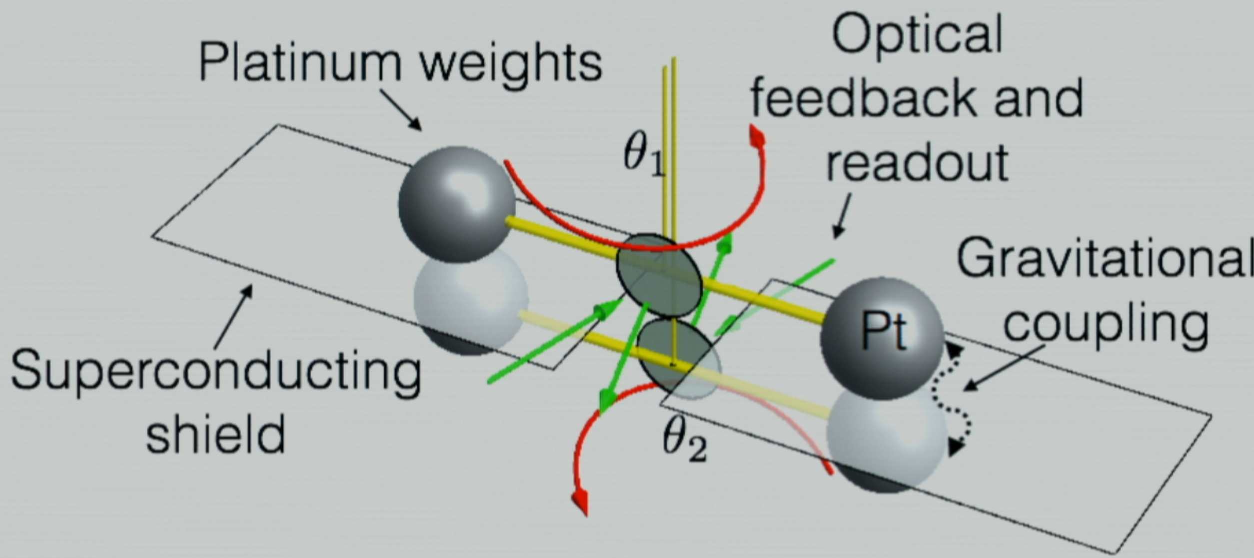
Then: Alice and Bob interacting 'classically'
(over all possible non-entangling channels) =>

$$\partial_t \left(\mathrm{Var}^{(e)}(p_a) + \mathrm{Var}^{(e)}(p_b) \right) \geq 2|g|\hbar m \omega$$

Testing entanglement generation via gravity: coupled Cavendish-style torsional oscillators

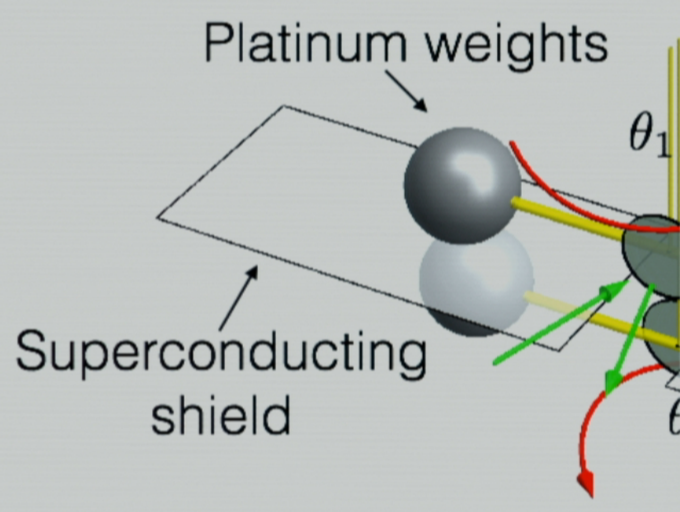


Testing entanglement generation via gravity: coupled Cavendish-style torsional oscillators



$g \leq Gn/\omega \sim \dfrac{10^{-6}\mathrm{Hz}^2}{\omega}$ => one phonon every 3,000 s

Testing entanglement generation via gravity: coupled Cavendish-style torsional oscillators



Procedure

(1) Verify g is due to gravity

(2) Estimate heating rate over 3000 s

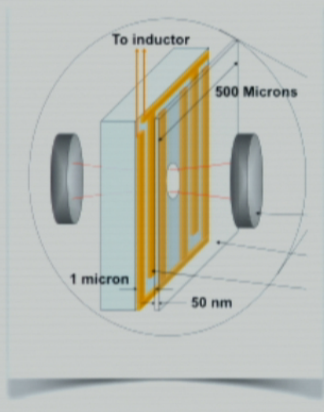
(3) Repeat 10^7 times

Hard experiment *but* embarrassingly parallel

$$g \leq Gn/\omega \sim \frac{10^{-6}\mathrm{Hz}^2}{\omega}$$ => one phonon every 3,000 s

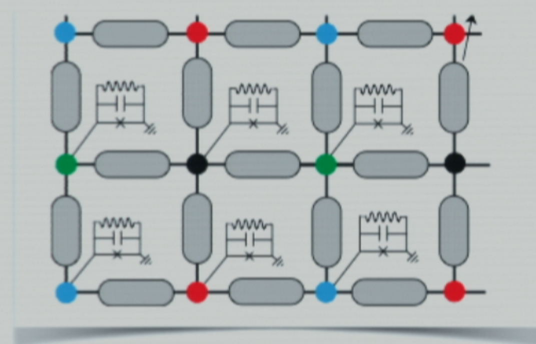
Thermal background at 10 mK ~ one phonon every 10 s

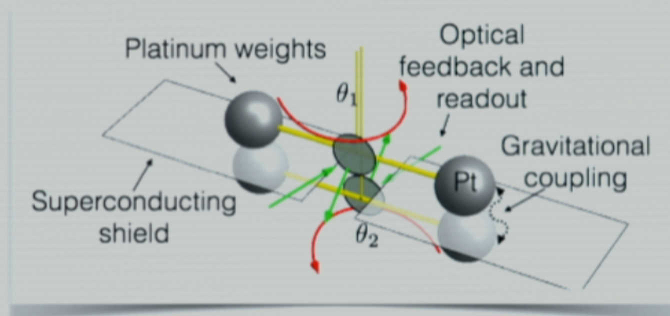
Outlook



Better mechanics and optics for a room temperature *quantum* interface; SI-calibrated detectors

Circuit QED simulation of fractional quantum Hall, lattice gauge theories, and beyond

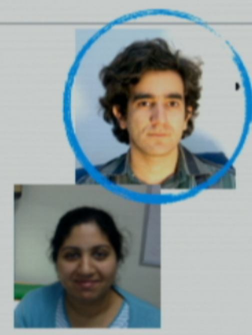




Noise-based entanglement tests: tool for quantum information, testing the quantum nature of gravity

Quantum information group @ JQI

- Postdocs
  - **Mohammad Hafezi**
  - Vanita Srinivasa
  - **F. Guzman-Cervantes**
  - Utku Kemiktarak
  - Michael Gullans



- Students
  - **Prabin Adhikari**
  - **Dvir Kafri**
  - Haitan Xu
  - **Xunnong Xu**
  - **Sunil Mitall**
  - Chiao-Hsuan Wang
  - Steven Ragole
  - Zachary Epstein

@quantum_jake
http://groups.jqi.umd.edu/taylor

NIST National Institute of Standards and Technology U.S. Department of Commerce

UNIVERSITY OF MARYLAND

Physics Frontier Center jqi Joint Quantum Institute

JQI: C. Lobb, S. Rolston, L. Orozco, F. Wellstood, **A. Migdall**, **J. Fan,** G. Solomon, E. Waks, C. Monroe
NIST: G. Strouse, **J. Pratt, G. Shaw**, K. Srinivasan
Harvard: **M. D. Lukin**, **E. Demler**
Copenhagen/NBI: **E. Polzik, A. Sørensen, C. Marcus**