Title: Making Quantum Matter from Light

Speakers: Jonathan Simon

Series: Particle Physics

Date: April 21, 2020 - 2:00 PM

URL: http://pirsa.org/20040081

Abstract: In this talk I will discuss ongoing efforts at UChicago to explore matter made of light. I will begin with a broad introduction to the challenges associated with making matter from photons, focusing specifically on (1) how to trap photons and imbue them with synthetic mass and charge; (2) how to induce photons to collide with one another; and (3) how to drive photons to order, by cooling or otherwise. I will then provide as examples two state-of-the-art photonic quantum matter platforms: microwave photons coupled to superconducting resonators and transmon qubits, and optical photons trapped in multimode optical cavities and made to interact through Rydberg-dressing. In each case I will describe a synthetic material created in that platform: a Mott insulator of microwave photons, stabilized by coupling to an engineered, non-Markovian reservoir, and a Laughlin molecule of optical photons prepared by scattering photons through the optical cavity. Indeed, building materials photon-by-photon will provide us with a unique opportunity to learn what all of the above words mean, and why they are important for quantum-materials science. Finally, I will conclude with my view of the broad prospects of photonic matter in particular, and of synthetic matter more generally.

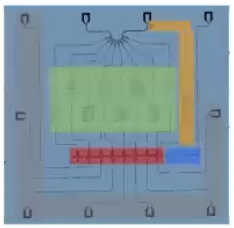
THE UNIVERSITY OF CHICAGO

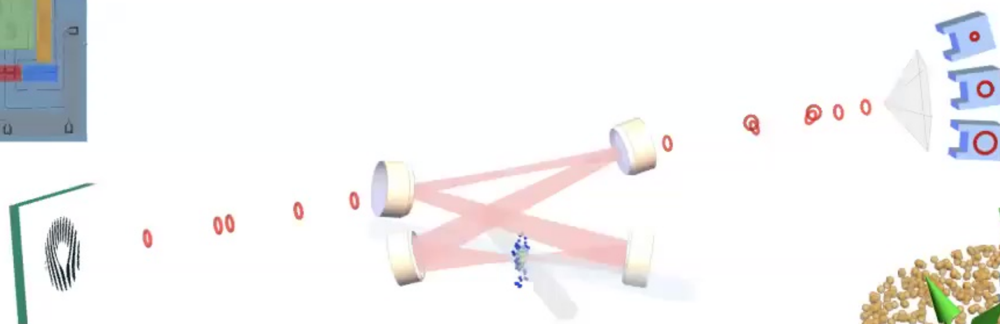
Making Quantum Matter from Light

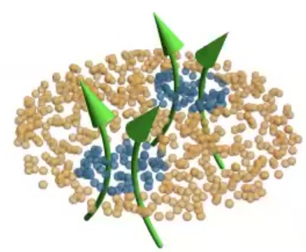
Photon Crystals & Laughlin Molecules

Jon Simon
University of Chicago
Chicago, Illinois

Perimeter Institute for Theoretical Physics
April 21st, 2020







quantum.uchicago.edu & simonlab.uchicago.edu

Support: AFOSR YIP, DOE YIP, DARPA YFA, DARPA FP060494, ARO MURI, AFOSR MURI, UofC MRSEC

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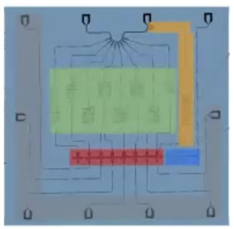

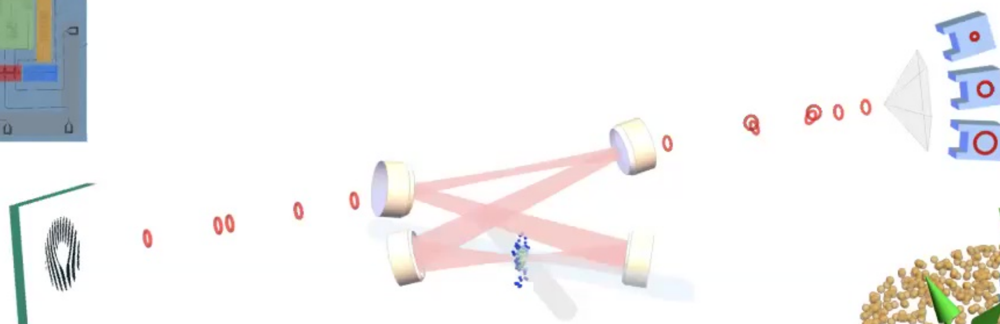

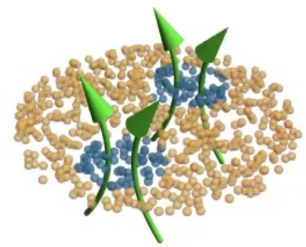

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PART I:
What are Materials?

What is a Material?

A collection of particles that interact with one another and thereby organize/order.

3

What is a Material?

(Single Particle Control)

A collection of particles that interact with one another and thereby organize/order.

3

What is a Material?

(Single Particle Control)

A collection of particles that interact with one another and thereby organize/order.

(Interaction Control)

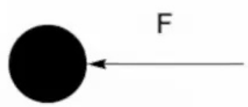
(Entropy Management)

3

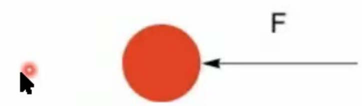
Challenge 1:

Forces do not slow photons

Massive Particle

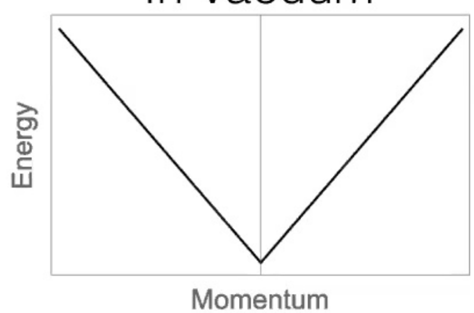


Massless Particle

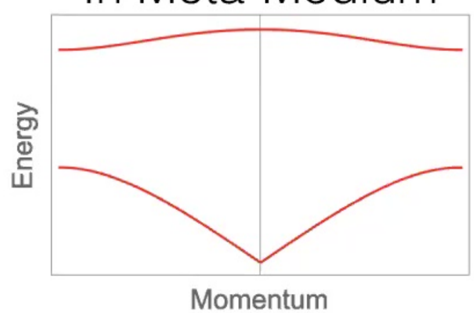


Solution: *Trap Light in a Meta-Material*

In Vacuum



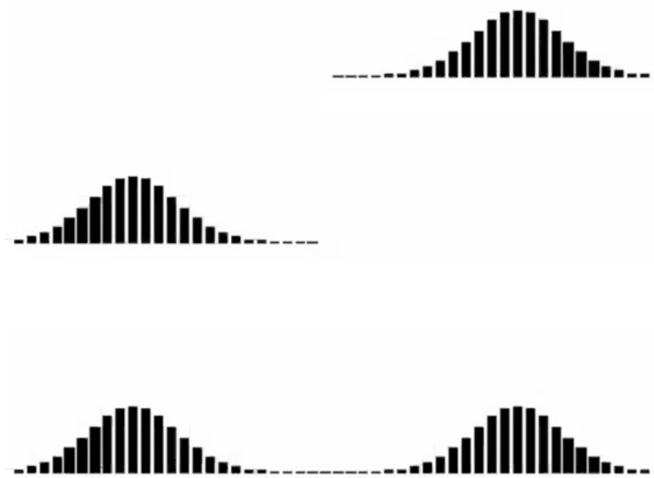
In Meta-Medium



Challenge 2: *Photons Don't Collide*

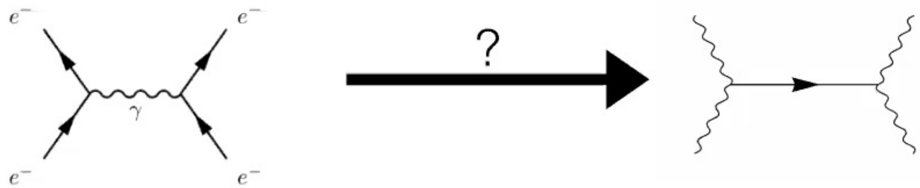
Electrons/Atoms

Photons



Challenge 2: *Photons Don't Collide*

Inspiration: *How do electrons collide?*



arXiv: 1111.6126 (2011)

Challenge 2: *Photons Don't Collide*

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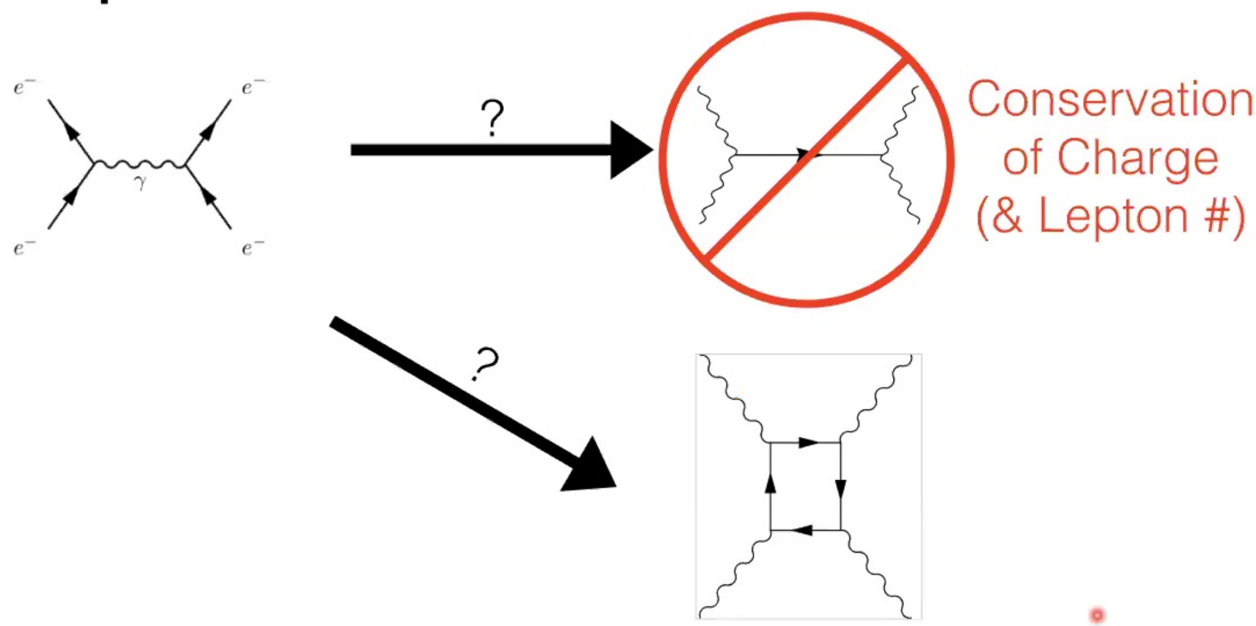

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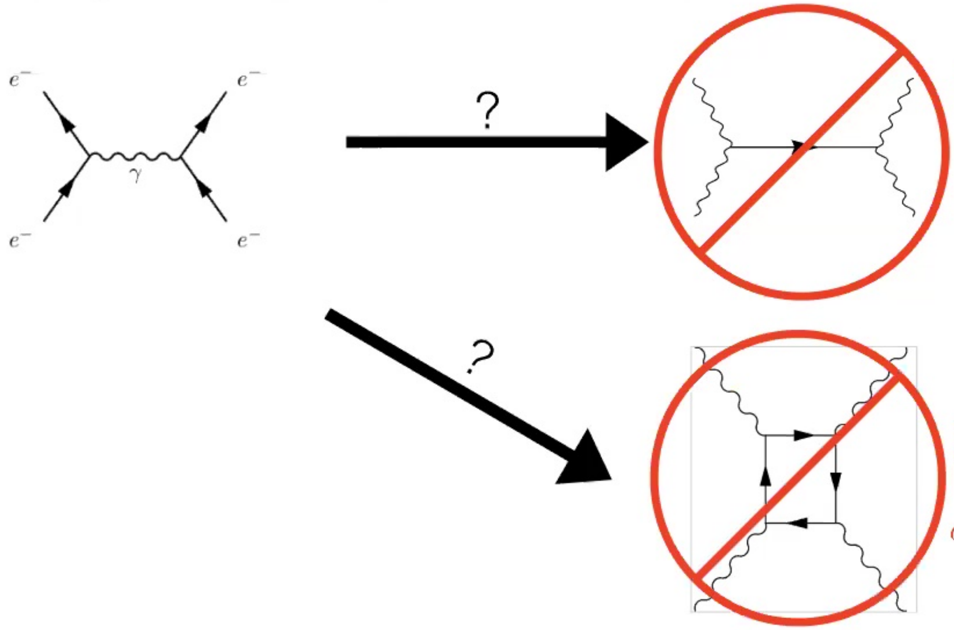


Conservation of Charge (& Lepton #)

Extremely Small

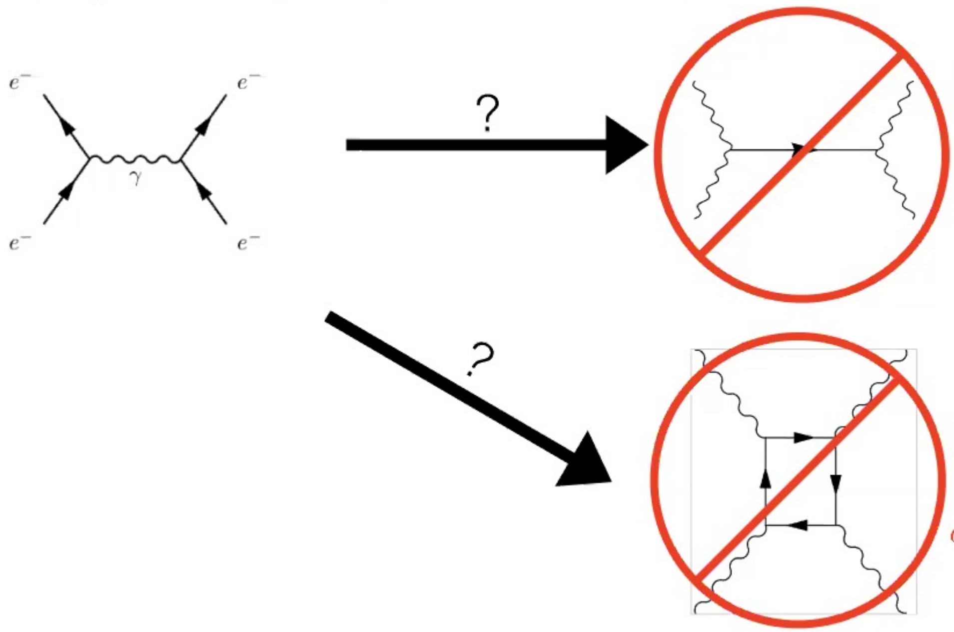
$$\sigma \approx \alpha^4 \left(\frac{\hbar}{mc}\right)^2 \left(\frac{\hbar\omega}{mc^2}\right)^6$$

$$\sim 10^{-56} \mu m^2 @ 1eV$$

arXiv: 1111.6126 (2011)

Challenge 2: *Photons Don't Collide*

Inspiration: *How do electrons collide?*



Conservation of Charge (& Lepton #)

Extremely Small

$$\sigma \approx \alpha^4 \left(\frac{\hbar}{mc}\right)^2 \left(\frac{\hbar\omega}{mc^2}\right)^6$$

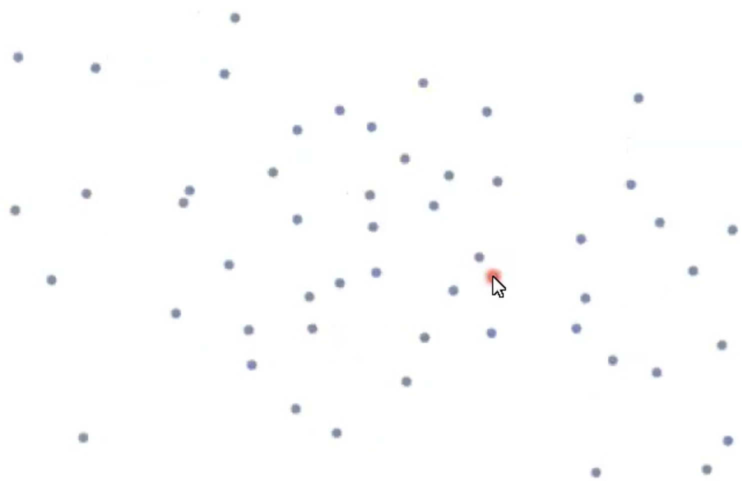
$\sim 10^{-56}\mu m^2 @1eV$

$100\mu m^2 @1eV$ ← **Right Idea... Use Atoms!**

arXiv: 1111.6126 (2011)

6

Challenge 3:
More "Quantum"→Less Cold?

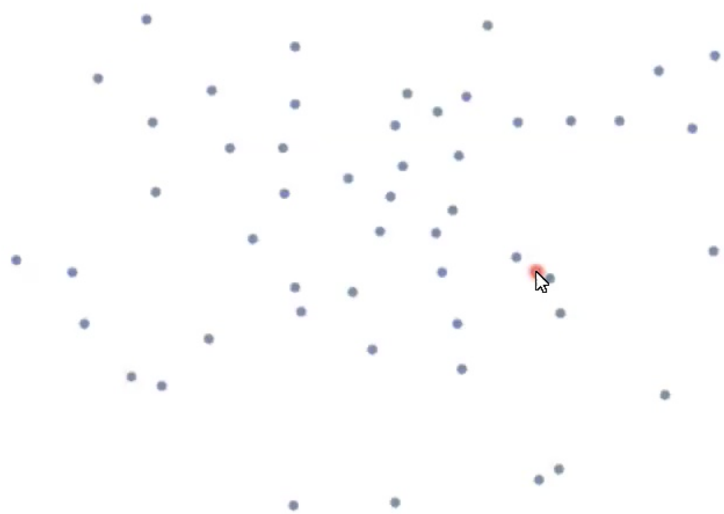


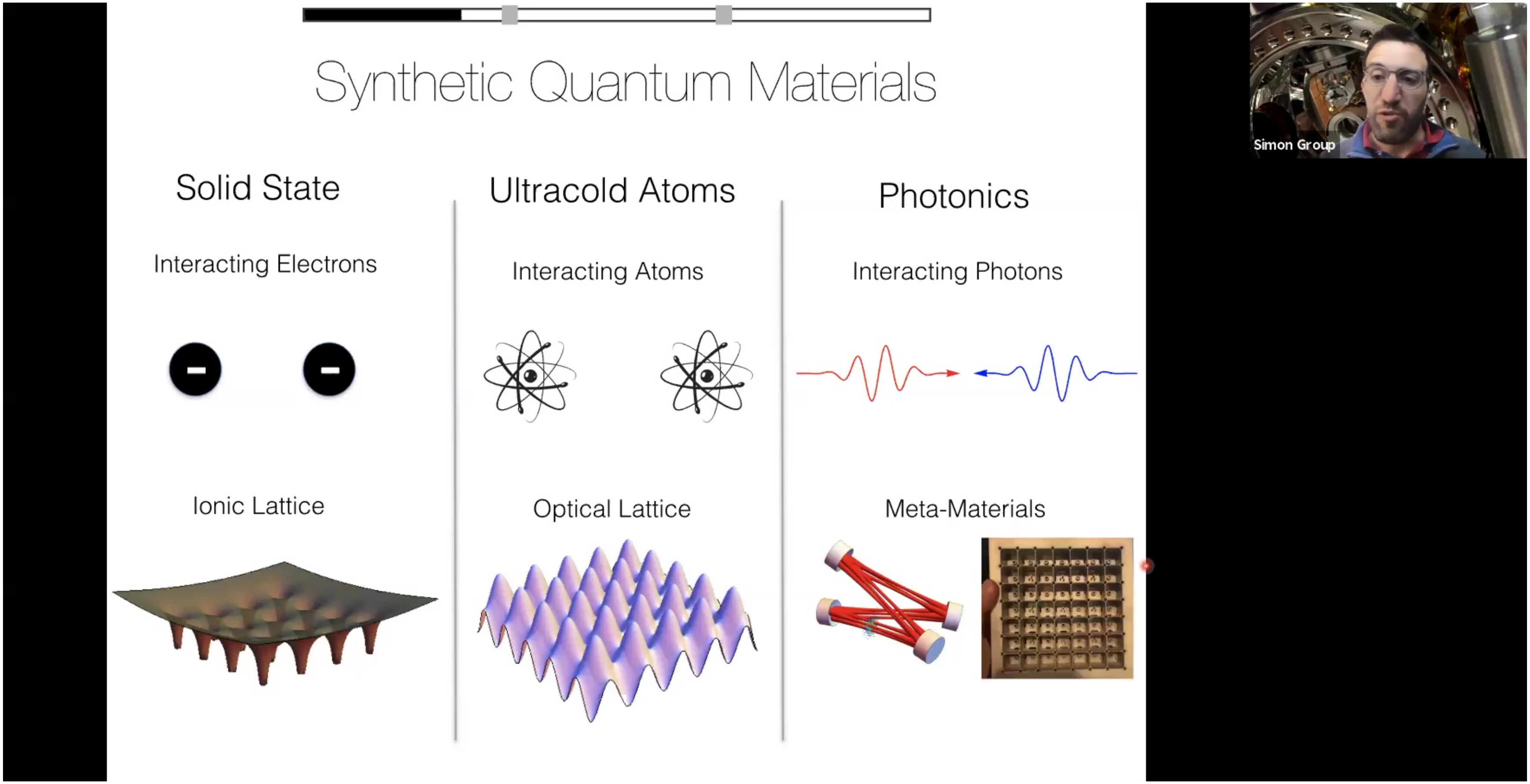
Challenge 3:

More "Quantum" → Less Cold?

Solutions:

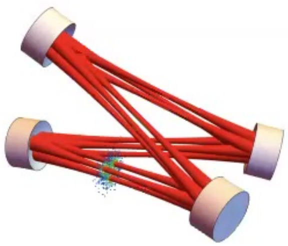
- Particle-by-particle assembly
- Local cooling

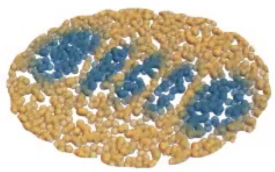


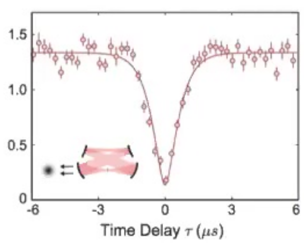

Synthetic Quantum Materials
Solid State
Interacting Electrons
Ionic Lattice
Ultracold Atoms
Interacting Atoms
Optical Lattice
Photonics
Interacting Photons
Meta-Materials
Simon Group

Two Platforms

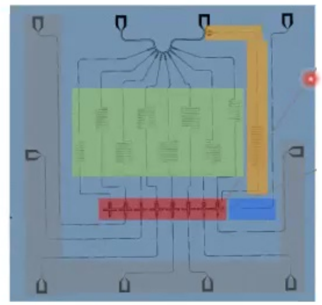
Bulk Gas: *Optical Photons*

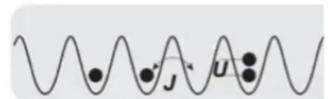


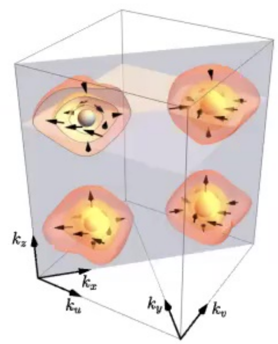


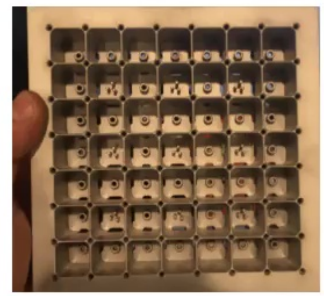


Lattice Gas: μ*W Photons*



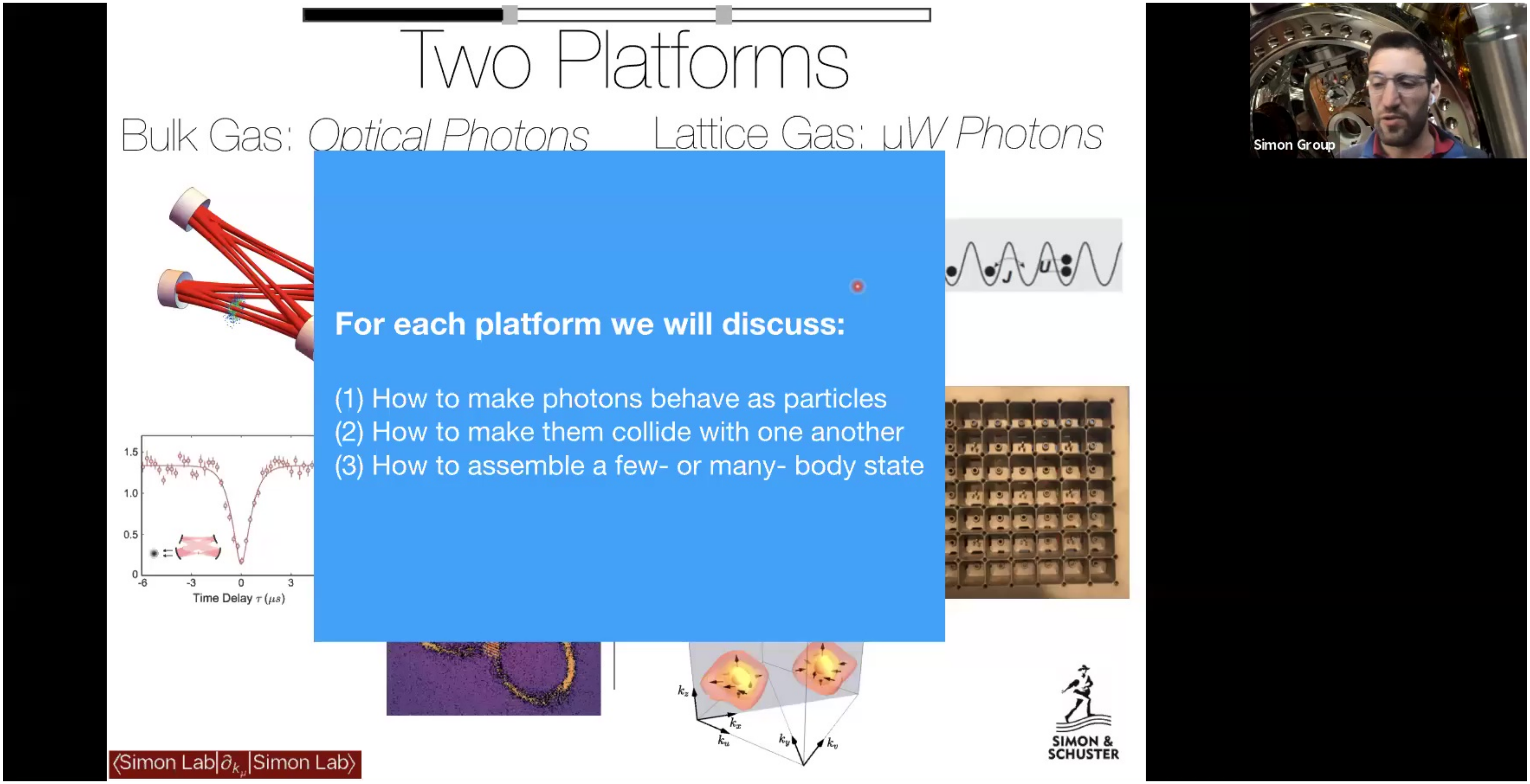


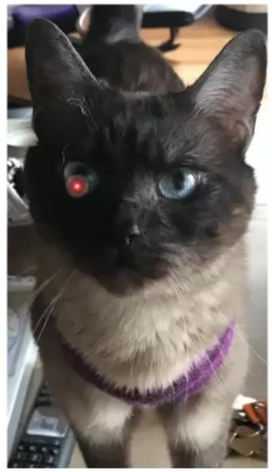




SIMON & SCHUSTER

⟨Simon Lab|∂_{k_μ}|Simon Lab⟩


Two Platforms
Bulk Gas: Optical Photons
Lattice Gas: μW Photons
For each platform we will discuss:
(1) How to make photons behave as particles
(2) How to make them collide with one another
(3) How to assemble a few- or many- body state
Time Delay τ (μs)
SIMON & SCHUSTER
⟨Simon Lab|∂$_{k_\mu}$|Simon Lab⟩
Simon Group



Emmy is *not* Schrodinger's cat;
She is 100% ALIVE

Intermission A

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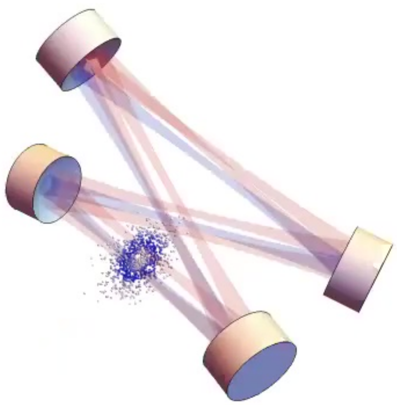
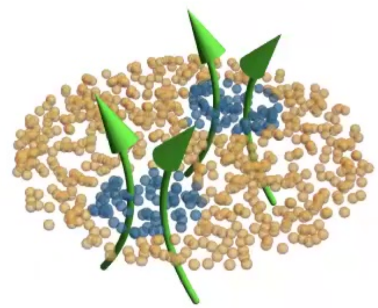
PART II:

Building Topological Materials From Optical Photons



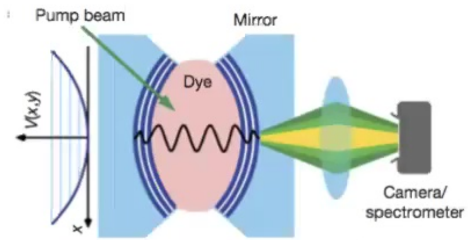


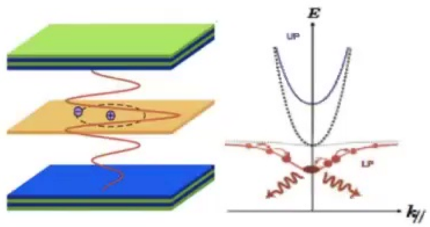
Central Premise

Photons in Multimode Resonator

↕

Massive Particles in Harmonic Trap





Klaers *et al.* Nature **468,** 545–548 (2010)   Deng *et al.,* Rev. Mod. Phys. **82**, 1489 (2010)

Central Premise

Photons in Multimode Resonator

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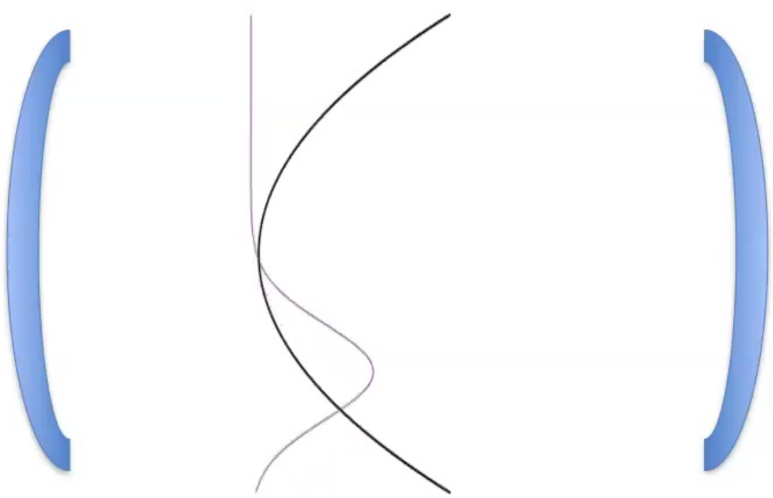
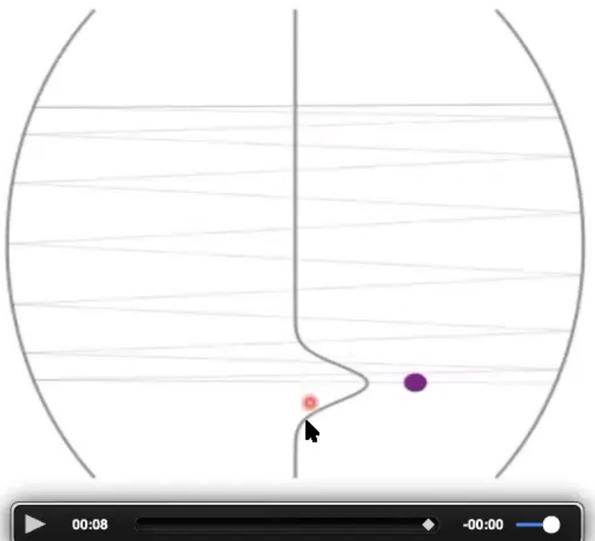
Massive Particles in Harmonic Trap

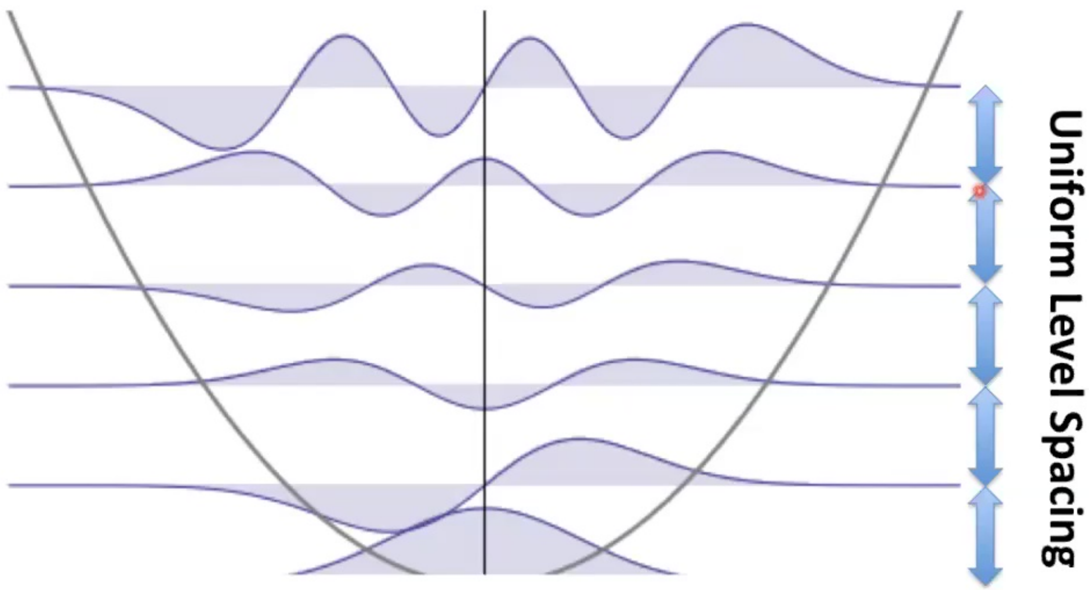


Understanding photons in optical resonators



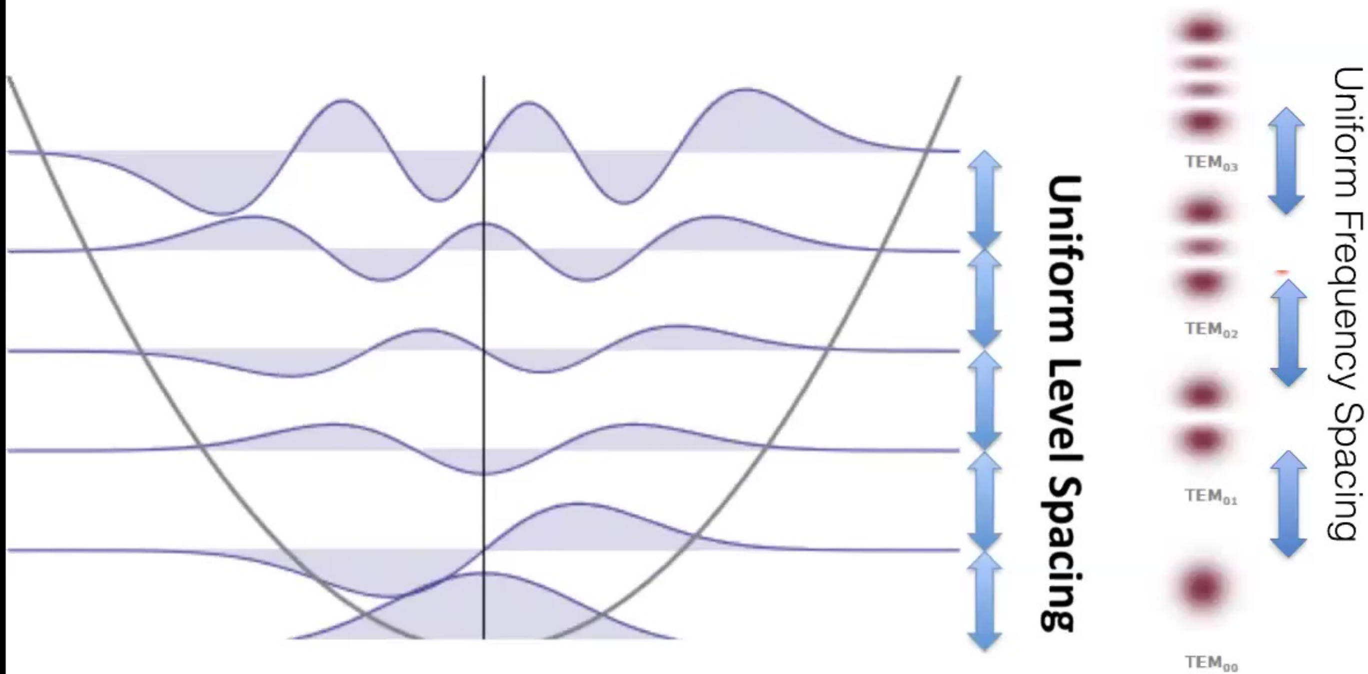
Sommer et. al., NJP 18, 035008 (2016)

Comparing
Harmonic Oscillators & Optical Resonators



Hermite Gauss Wavefunctions

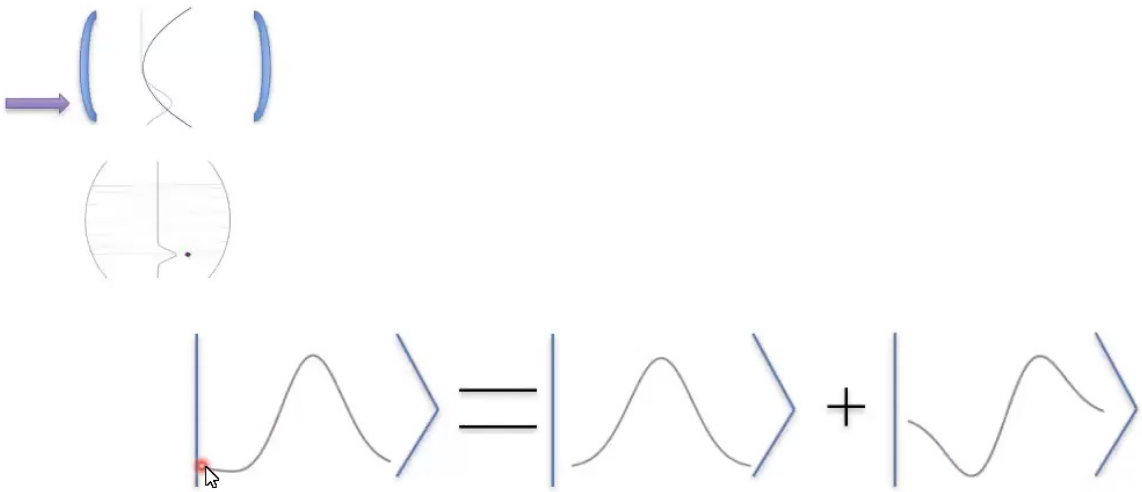
Comparing
Harmonic Oscillators & Optical Resonators



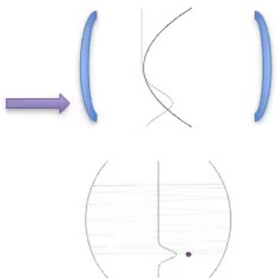
Hermite Gauss Wavefunctions

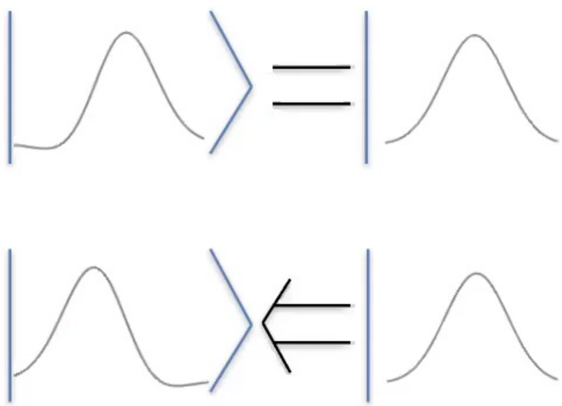
Optical Modes

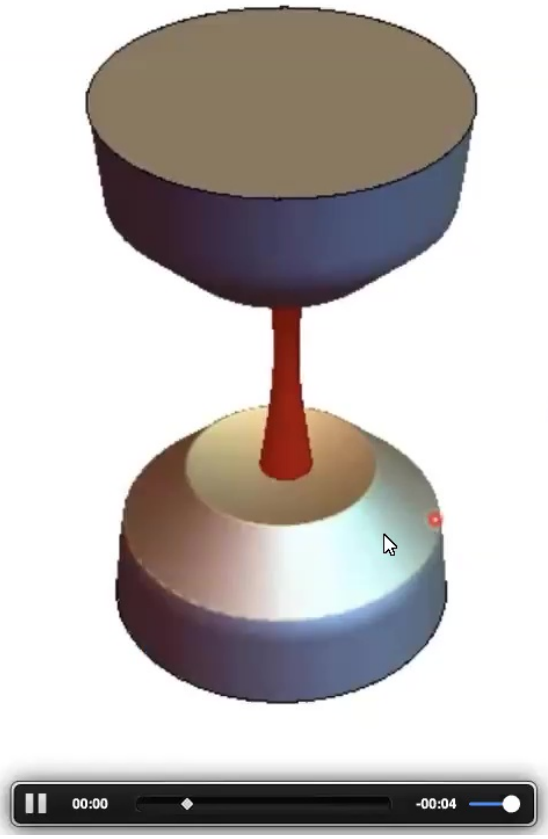
Understanding photons in optical resonators



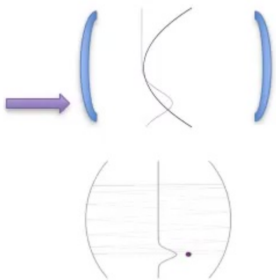
Understanding
photons in optical resonators

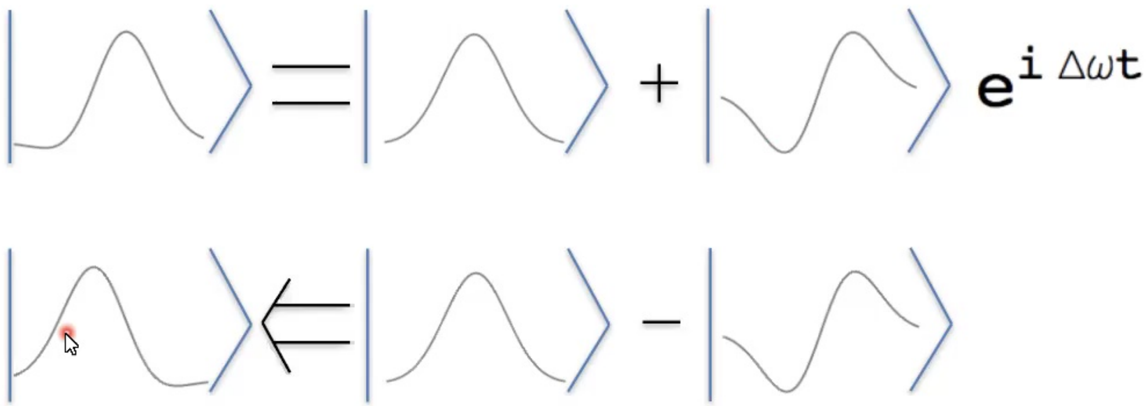


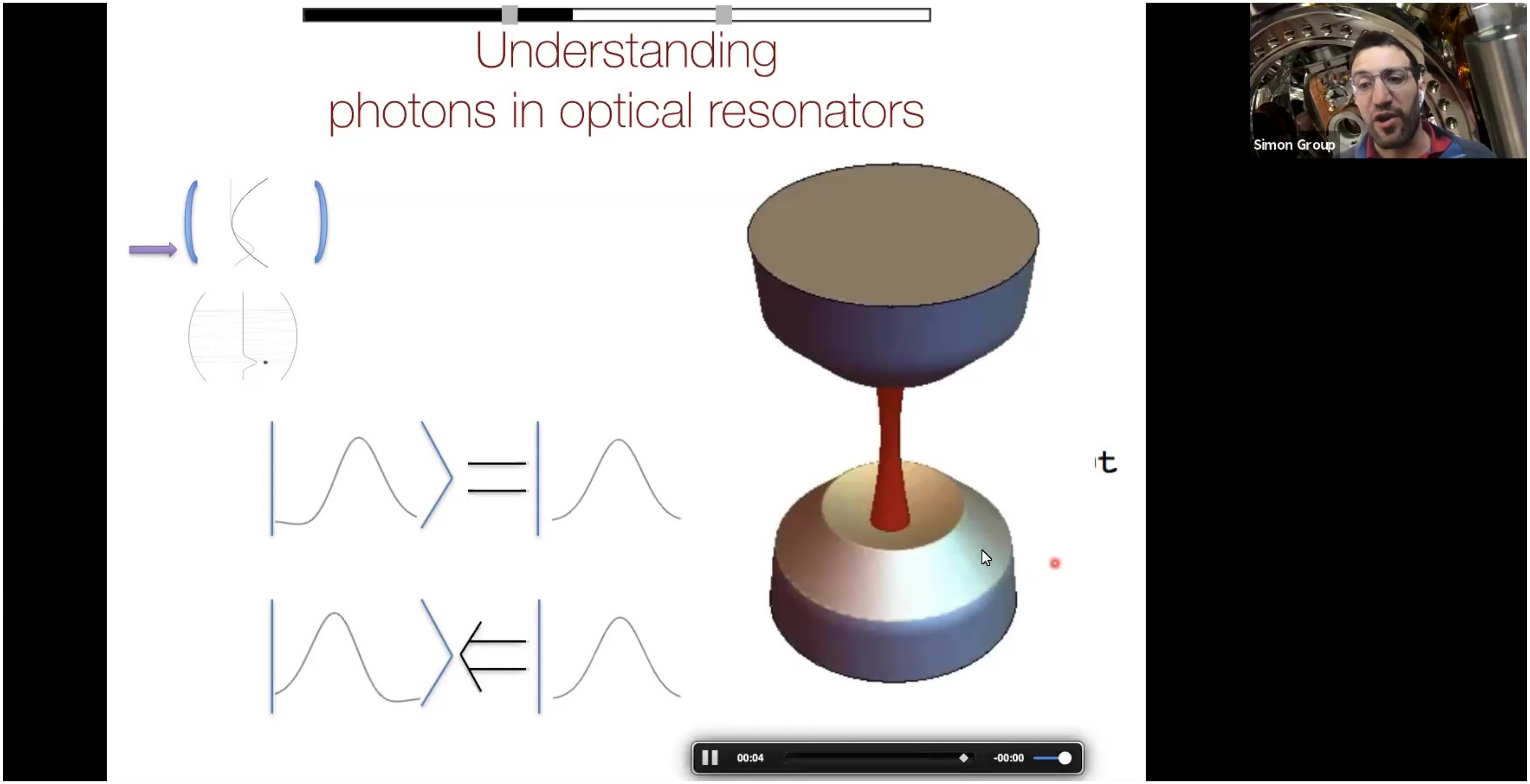




Understanding photons in optical resonators






Understanding
photons in optical resonators
Simon Group
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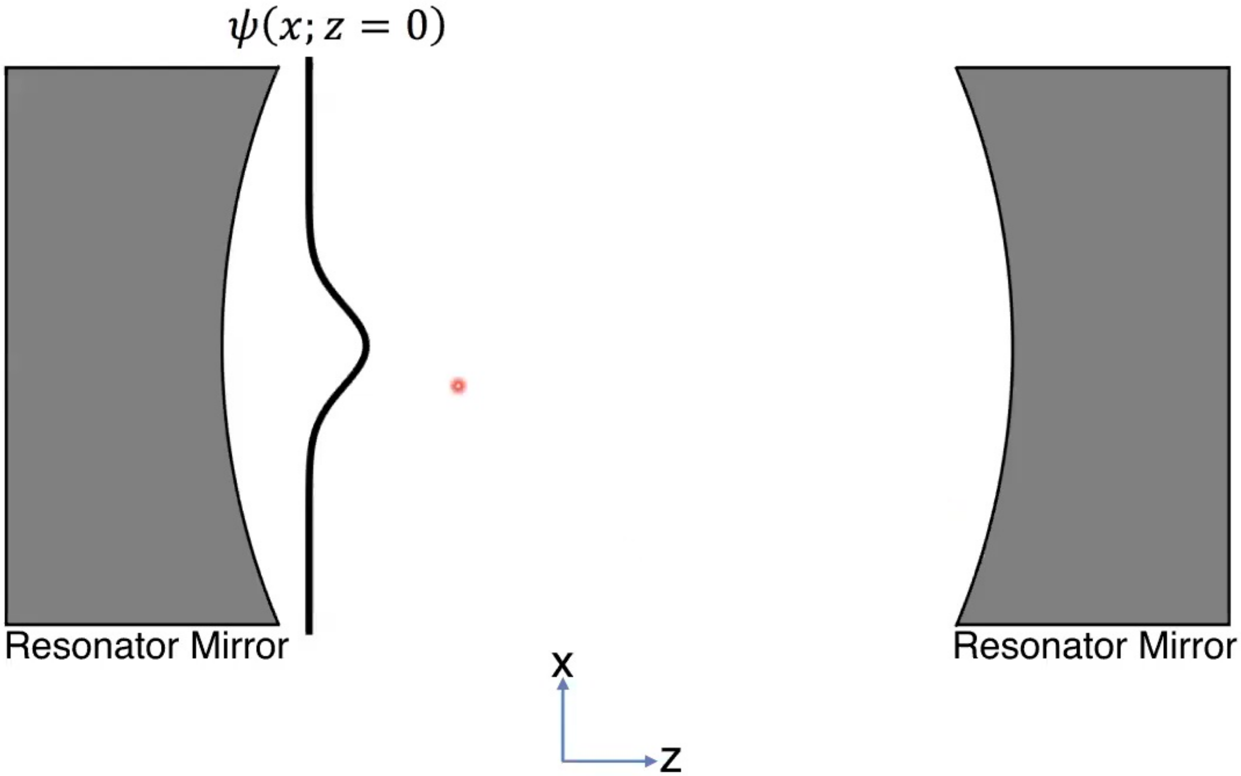
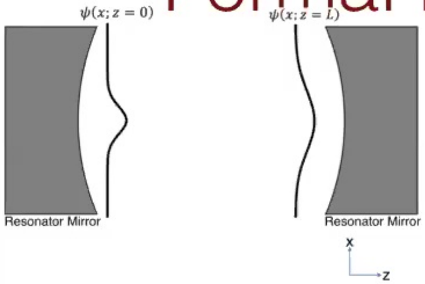
-00:00

Formal Picture: *Floquet Theory*



Sommer *et al.*, "Engineering Photonic Floquet Hamiltonians through Fabry–Pérot resonators," **NJP** 18 (3), 035008 (2016).

Formal Picture: *Floquet Theory*



$$\psi(x', z = L) = e^{i\,k_z L} \quad \psi(x; z = 0)$$

$$\psi(x', z = L) = e^{i\left(k\,L - \frac{k_x^2}{2k}\right)L} \psi(x; z = 0)$$

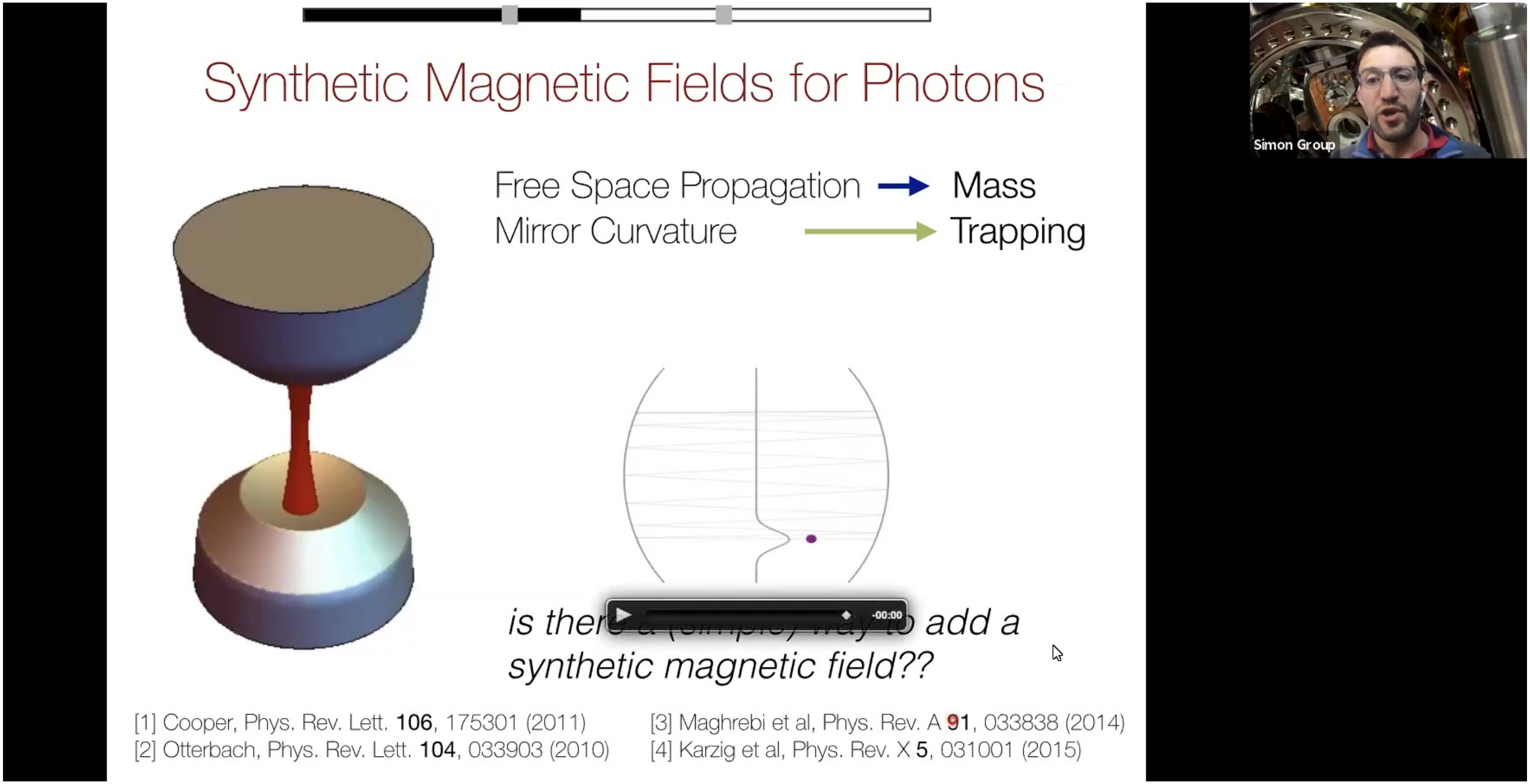
$$\psi(x', z = L) \propto e^{-i\frac{L}{2k}\left(\frac{\partial}{\partial x}\right)^2} \psi(x; z = 0)$$

$$\psi_{RT} \propto e^{-i\frac{kx^2}{2R}} e^{-i\frac{L}{2k}\left(\frac{\partial}{\partial x}\right)^2} e^{-i\frac{kx^2}{2R}} e^{-i\frac{L}{2k}\left(\frac{\partial}{\partial x}\right)^2} \psi$$

$$\psi_{RT} \propto e^{i\,H_{floquet} T_{RT}} \psi$$

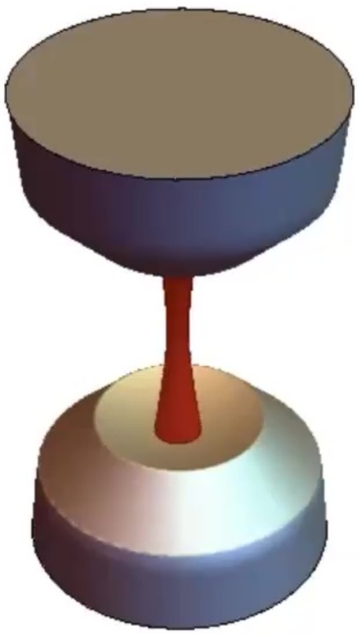
$$H_{floquet} = \frac{1}{i\,T_{RT}} Log\left[e^{-i\frac{kx^2}{2R}} e^{-i\frac{L}{2k}\left(\frac{\partial}{\partial x}\right)^2} e^{-i\frac{kx^2}{2R}} e^{-i\frac{L}{2k}\left(\frac{\partial}{\partial x}\right)^2}\right]$$

Sommer et. al., **NJP** 18, 035008 (2016)

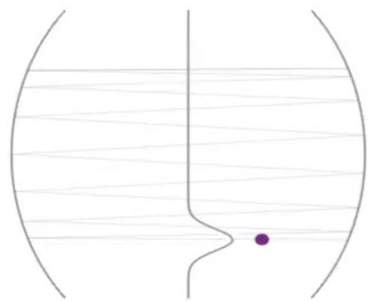


Synthetic Magnetic Fields for Photons
Free Space Propagation → Mass
Mirror Curvature → Trapping
Simon Group
-00:00
is ther
add a
synthetic magnetic field??
[1] Cooper, Phys. Rev. Lett. 106, 175301 (2011)
[2] Otterbach, Phys. Rev. Lett. 104, 033903 (2010)
[3] Maghrebi et al, Phys. Rev. A 91, 033838 (2014)
[4] Karzig et al, Phys. Rev. X 5, 031001 (2015)

Synthetic Magnetic Fields for Photons



Free Space Propagation → Mass
Mirror Curvature → Trapping
Resonator Twist → B Field



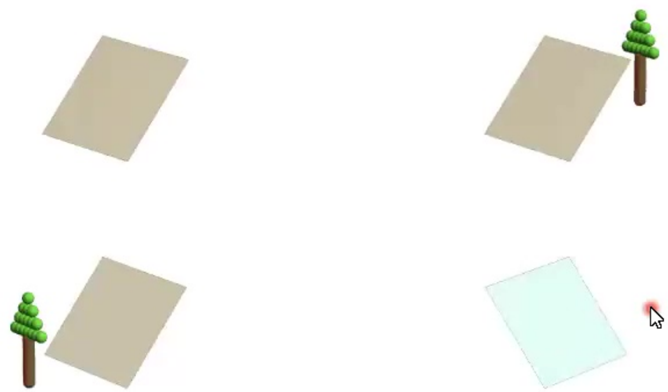
is there a (simple) way to add a synthetic magnetic field??

[1] Cooper, Phys. Rev. Lett. **106**, 175301 (2011)
[2] Otterbach, Phys. Rev. Lett. **104**, 033903 (2010)
[3] Maghrebi et al, Phys. Rev. A **91**, 033838 (2014)
[4] Karzig et al, Phys. Rev. X **5**, 031001 (2015)

Turning the Lab Frame into a Rotating Frame

A Twisted Periscope

(Trees on the open sea)

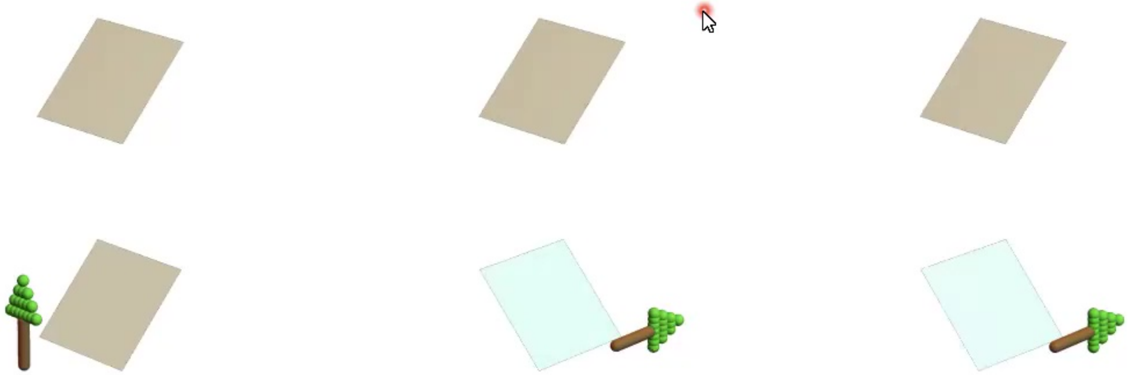


20

Turning the Lab Frame into a Rotating Frame

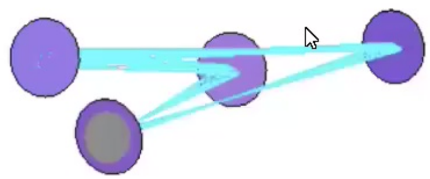
A Twisted Periscope

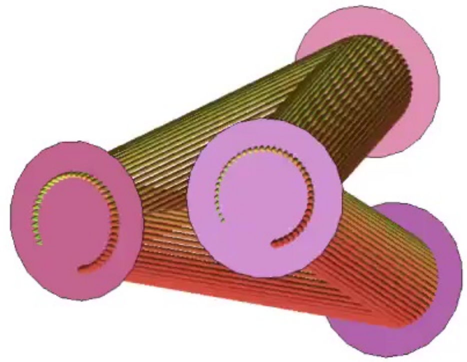
(Trees on the open sea)



20

Synthetic Magnetic Fields for Cavity Photons





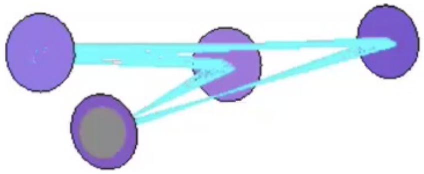
Twisting the resonator out of the plane makes the lab frame a rotating frame → Coriolis & Centrifugal Forces

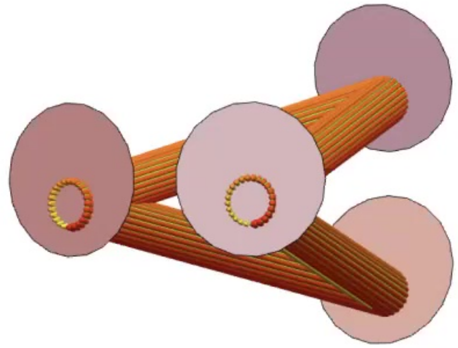
Coriolis: $\vec{\Omega} \times \vec{p}$ → $\vec{v} \times \vec{B}$

Centrifugal Forces: $\Omega^2 \vec{r}_\perp$ → *Cancel with Mirror Curvature*

[1] Cooper, Phys. Rev. Lett. **106**, 175301 (2011)
[2] Otterbach *et al.*, Phys. Rev. Lett. **104**, 033903 (2010)
[3] Maghrebi *et al.*, Phys. Rev. A **91**, 033838 (2015)
[4] Karzig *et al.*, Phys. Rev. X **5**, 031001 (2015)

Synthetic Magnetic Fields for Cavity Photons





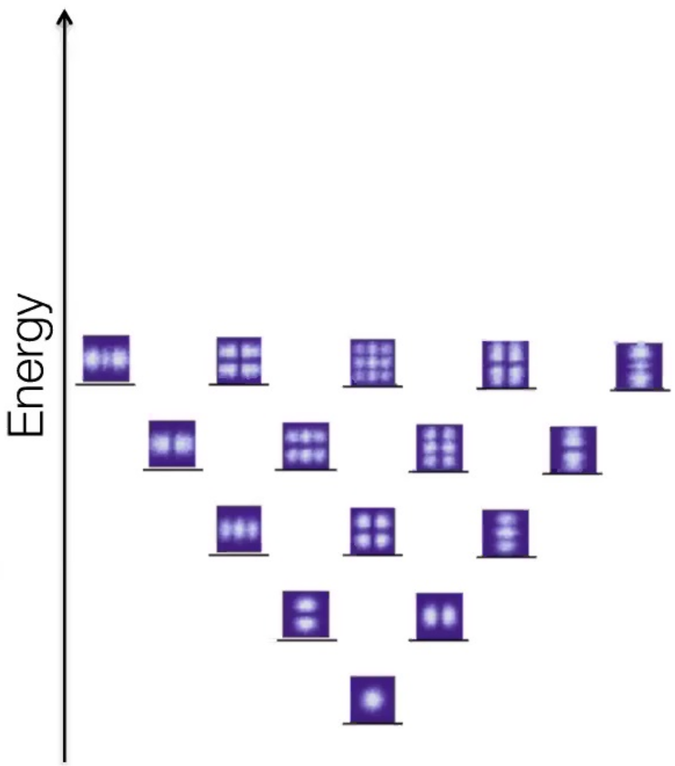
Twisting the resonator out of the plane makes the lab frame a rotating frame → Coriolis & Centrifugal Forces

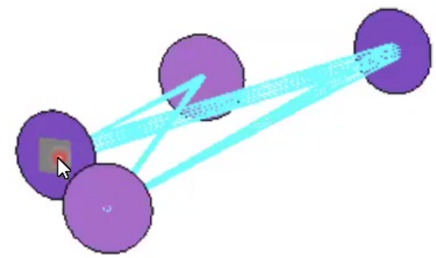
Coriolis: $\vec{\Omega} \times \vec{p}$ → $\vec{v} \times \vec{B}$

Centrifugal Forces: $\Omega^2 \vec{r}_\perp$ → *Cancel with Mirror Curvature*

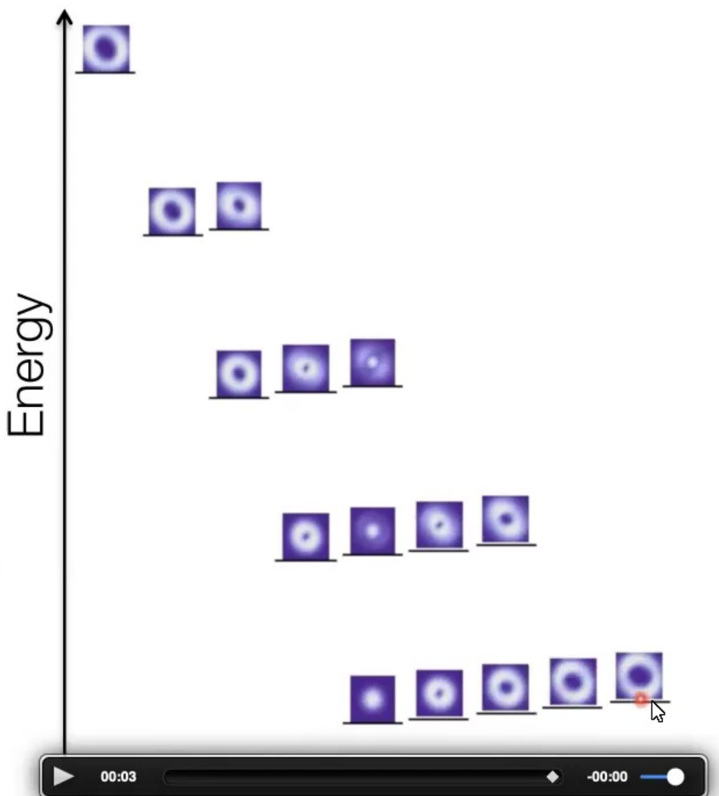
[1] Cooper, Phys. Rev. Lett. **106**, 175301 (2011)
[2] Otterbach *et al.*, Phys. Rev. Lett. **104**, 033903 (2010)
[3] Maghrebi *et al.*, Phys. Rev. A **91**, 033838 (2015)
[4] Karzig *et al.*, Phys. Rev. X **5**, 031001 (2015)

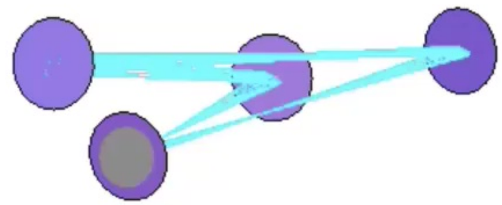
Flattening Photonic Landau-Levels

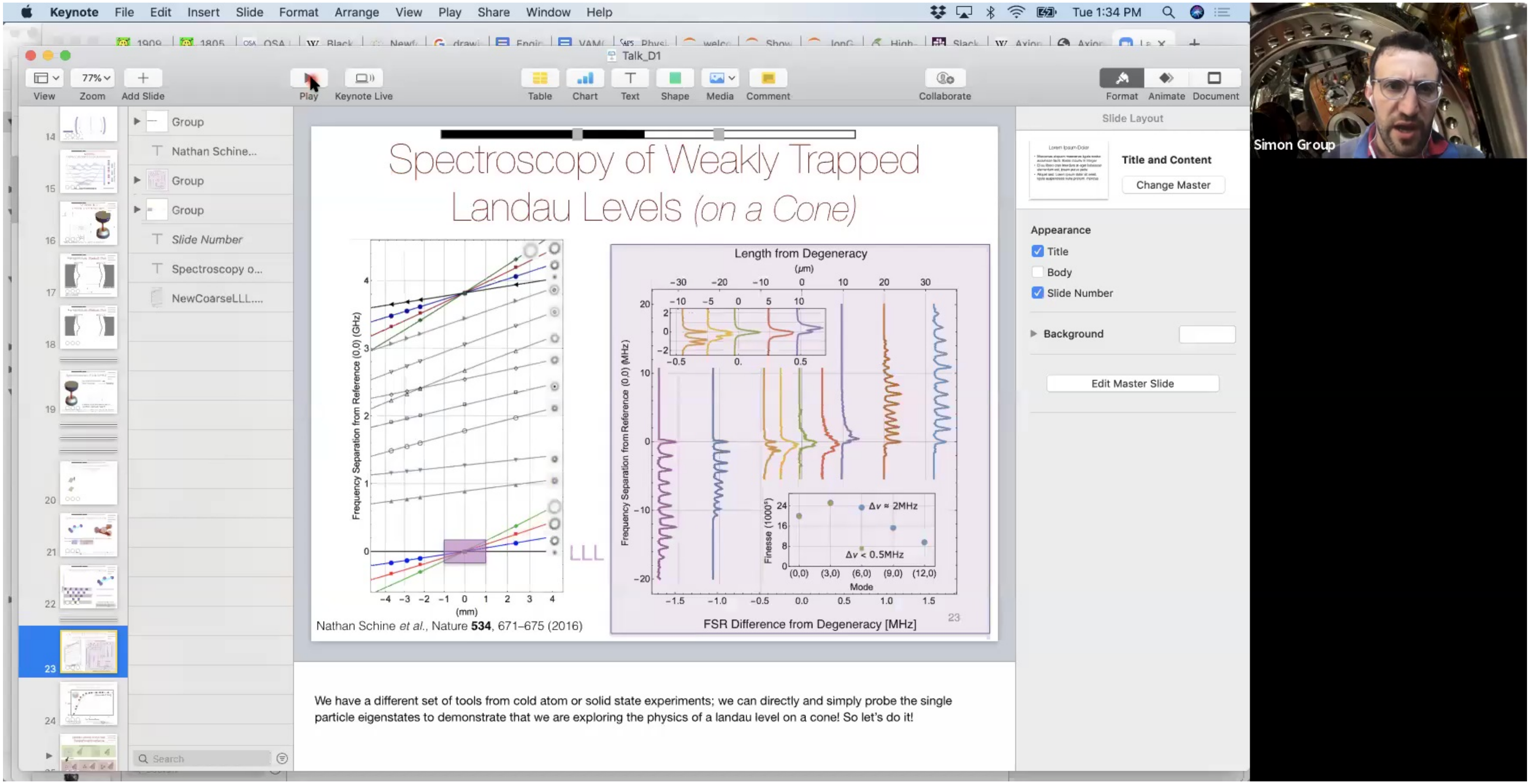




Flattening Photonic Landau-Levels

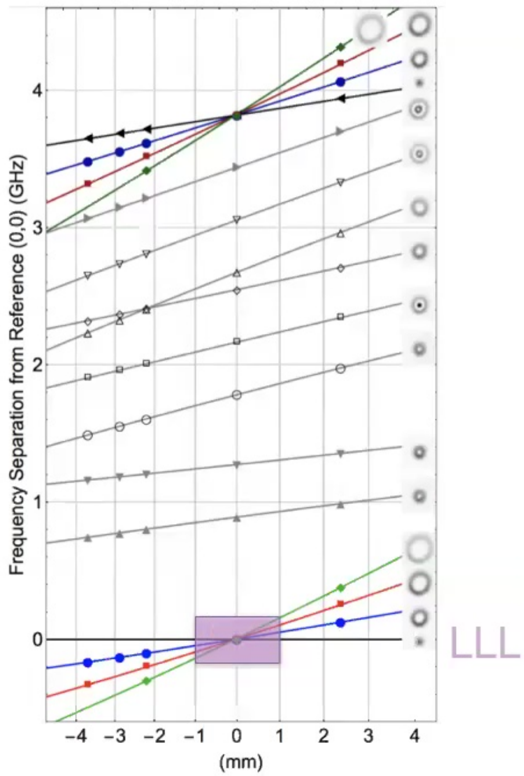




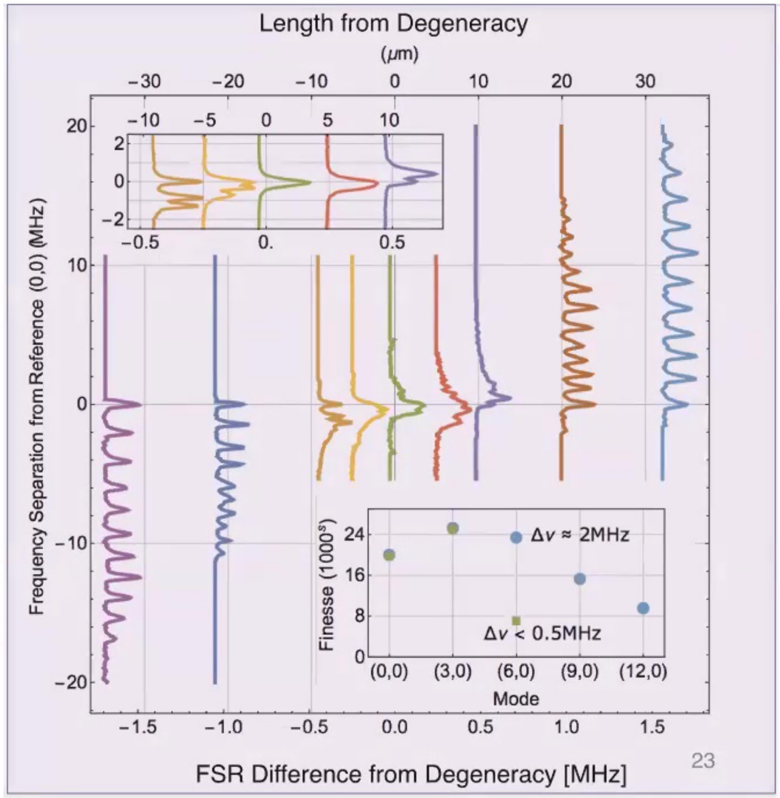


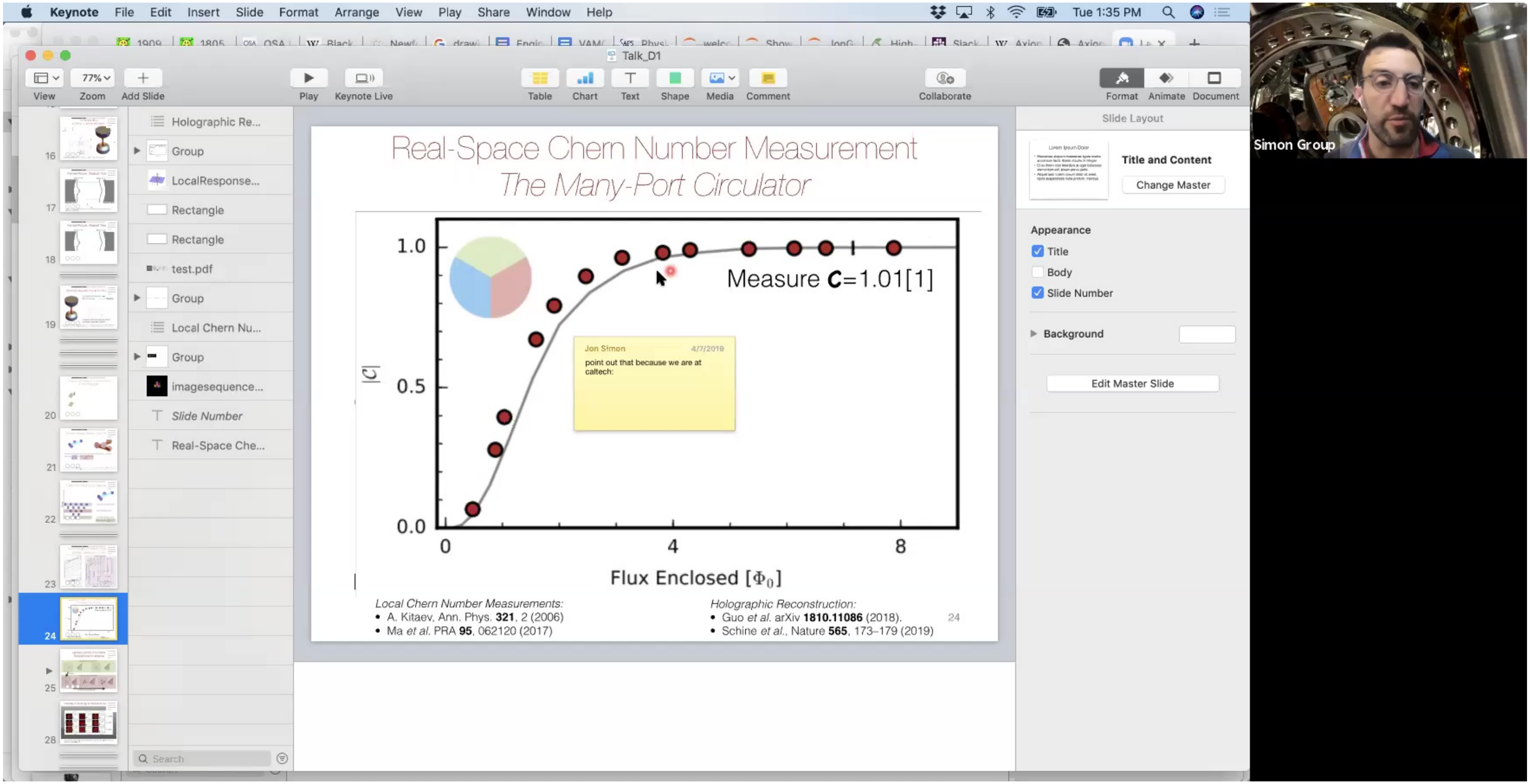
Spectroscopy of Weakly Trapped Landau Levels (on a Cone)
LLL
(mm)
Frequency Separation from Reference (0,0) (GHz)
Nathan Schine et al., Nature 534, 671–675 (2016)
Length from Degeneracy
(μm)
Frequency Separation from Reference (0,0) (MHz)
Finesse (1000s)
Δν ≈ 2MHz
Δν < 0.5MHz
Mode
FSR Difference from Degeneracy [MHz]
23
We have a different set of tools from cold atom or solid state experiments; we can directly and simply probe the single particle eigenstates to demonstrate that we are exploring the physics of a landau level on a cone! So let's do it!
Simon Group

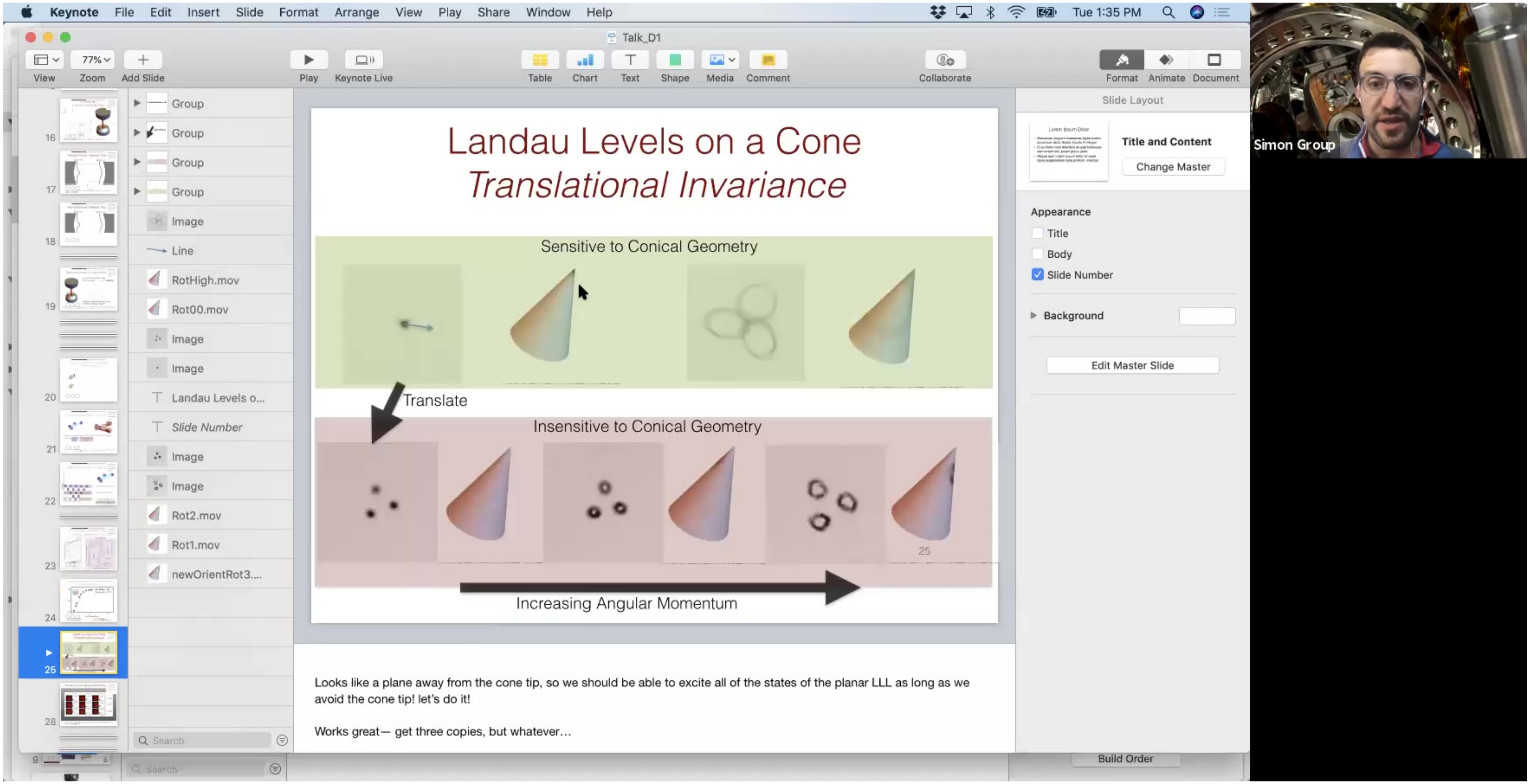
Spectroscopy of Weakly Trapped Landau Levels *(on a Cone)*

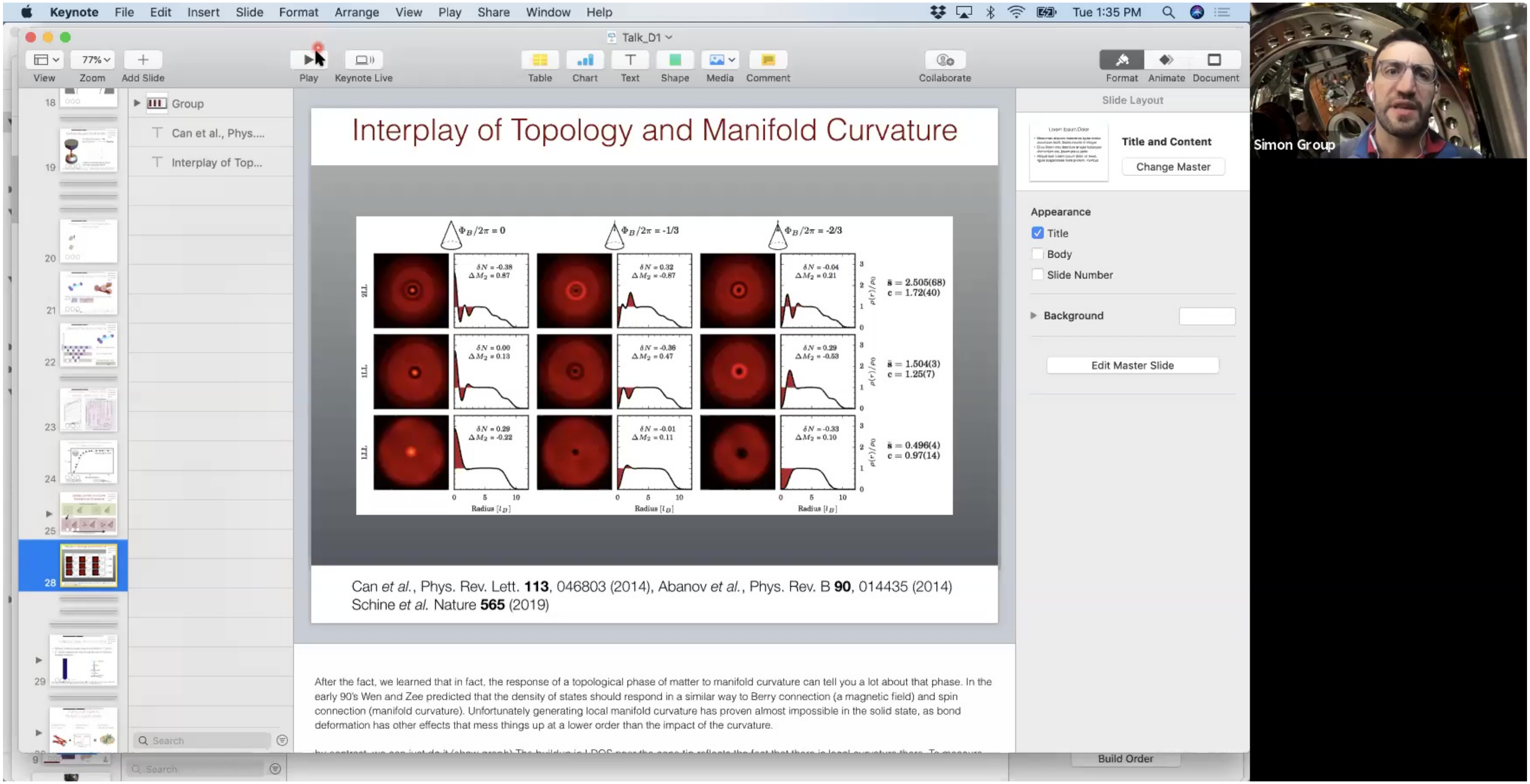


Nathan Schine *et al.*, Nature **534**, 671–675 (2016)



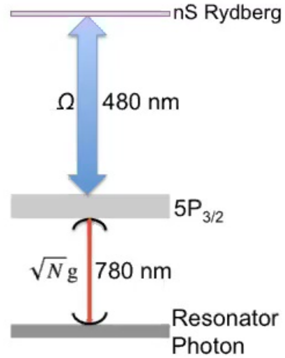

Real-Space Chern Number Measurement
The Many-Port Circulator
Measure C=1.01[1]
1.0
0.5
0.0
0
4
8
Flux Enclosed [Φ0]
Jon Simon
4/7/2019
point out that because we are at caltech:
Local Chern Number Measurements:
• A. Kitaev, Ann. Phys. 321, 2 (2006)
• Ma et al. PRA 95, 062120 (2017)
Holographic Reconstruction:
• Guo et al. arXiv 1810.11086 (2018).
• Schine et al., Nature 565, 173–179 (2019)
24
Simon Group


Landau Levels on a Cone
Translational Invariance
Sensitive to Conical Geometry
Translate
Insensitive to Conical Geometry
25
Increasing Angular Momentum
Looks like a plane away from the cone tip, so we should be able to excite all of the states of the planar LLL as long as we avoid the cone tip! let's do it!
Works great— get three copies, but whatever…
Simon Group


Interplay of Topology and Manifold Curvature
Can et al., Phys. Rev. Lett. 113, 046803 (2014), Abanov et al., Phys. Rev. B 90, 014435 (2014)
Schine et al. Nature 565 (2019)
After the fact, we learned that in fact, the response of a topological phase of matter to manifold curvature can tell you a lot about that phase. In the early 90's Wen and Zee predicted that the density of states should respond in a similar way to Berry connection (a magnetic field) and spin connection (manifold curvature). Unfortunately generating local manifold curvature has proven almost impossible in the solid state, as bond deformation has other effects that mess things up at a lower order than the impact of the curvature.
Simon Group

Making Cavity Photons Collide

- Rydberg medium provides linear susceptibility for 1st photon
- 2nd photon experiences reduced susceptibility via Rydberg-Rydberg interaction



Peyronel *et al.*, Nature **488**, 57–60 (2012), Firstenberg *et al.*, Nature **502**, 71-75 (2013), Baur *et al.*, Phys. Rev. Lett. **112**, 073901 (2014), Tiarks *et al.*, Phys. Rev. Lett. **113**, 053602 (2014), Gorniaczyk *et al.*, PRL **113**, 053601 (2014)

29

Making Cavity Photons Collide

- Rydberg medium provides linear susceptibility for 1st photon
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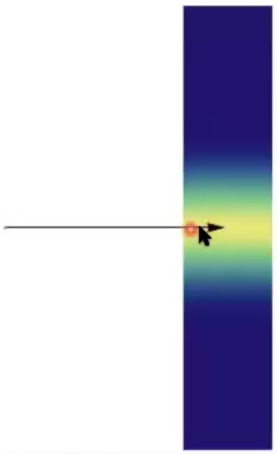

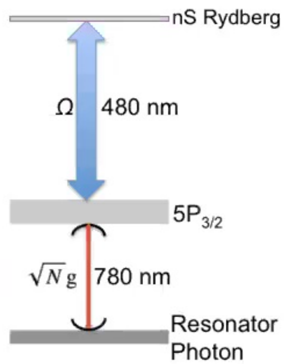

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Peyron… …berg *et al.*, Nature **502**, 71-75 (2013), Baur *et al.*, Phys. Rev. Lett. **112**, 073901 (2014), Tiarks *et al.*, Phys. Rev. Lett. **113**, 053602 (2014), Gorniaczyk *et al.*, PRL **113**, 053601 (2014)

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Making Cavity Photons Collide

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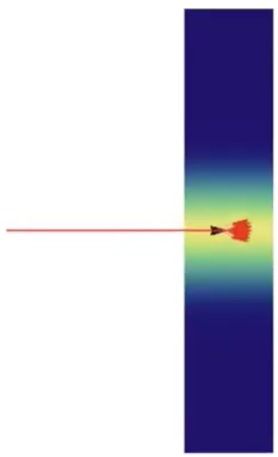
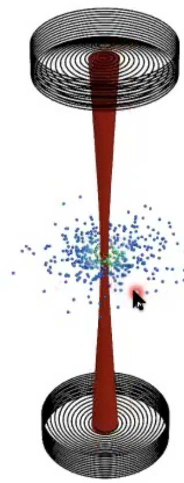
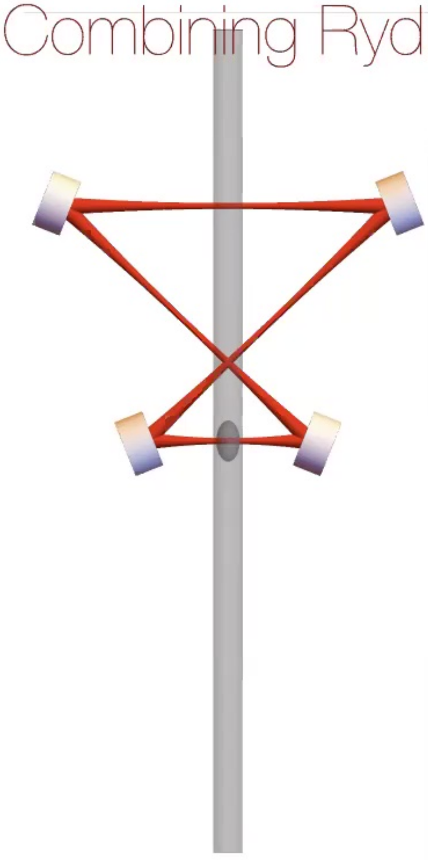


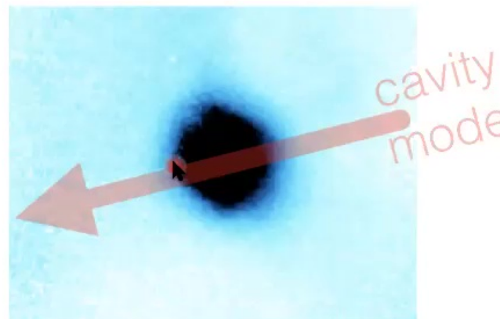


Peyronel *et al.*, Nature **488**, 57–60 (2012), Firstenberg *et al.*, Nature **502**, … ett. **112**, 073901 (2014), Tiarks *et al.*, Phys. Rev. Lett. **113**, 053602 (2014), Gorniaczyk *et a*…

The Apparatus

Combining Rydbergs and Optical Cavities

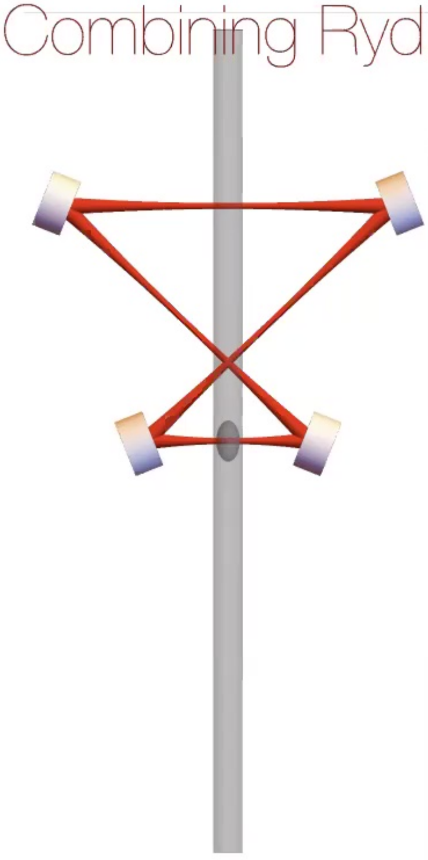




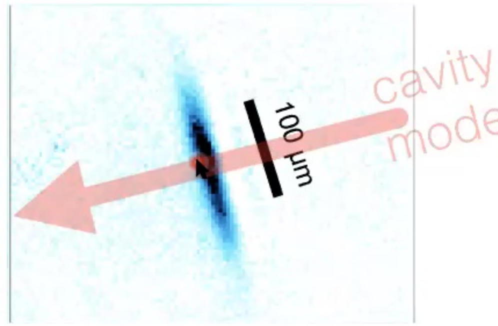
31

The Apparatus

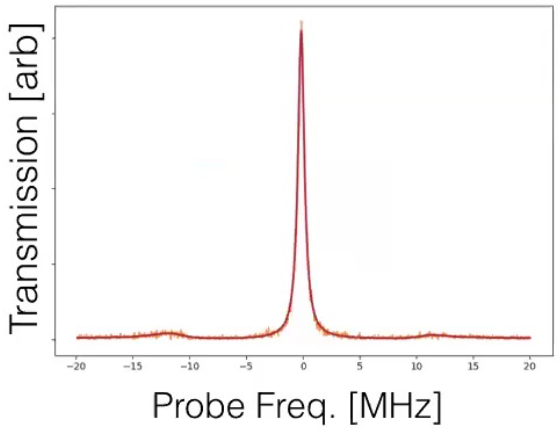
Combining Rydbergs and Optical Cavities

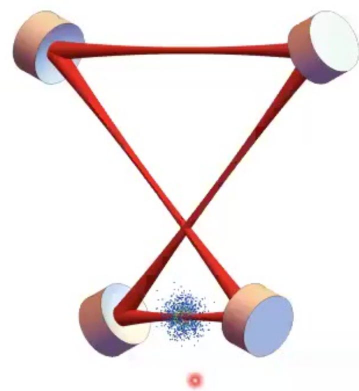


dRSC cooling to 10 μm, 0.5μK
(& polarize atomic sample)



Observation of Cavity Polariton Blockade
in a 0-dimensional quantum dot





[1] Ningyuan *et al.*, Nature Physics **14**, 550–554 (2018). [2] Guerlin *et al.*, Phys. Rev. A **82**, 053832

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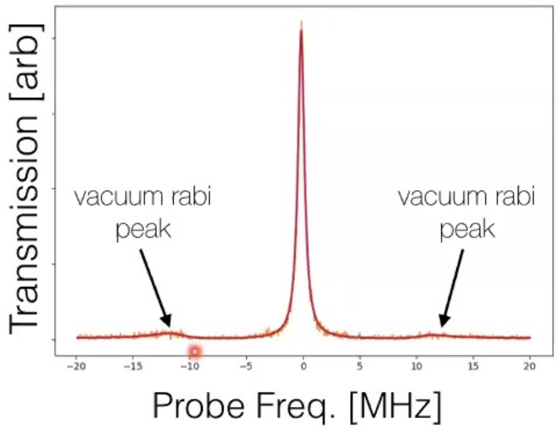

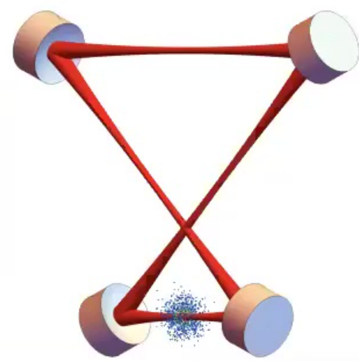

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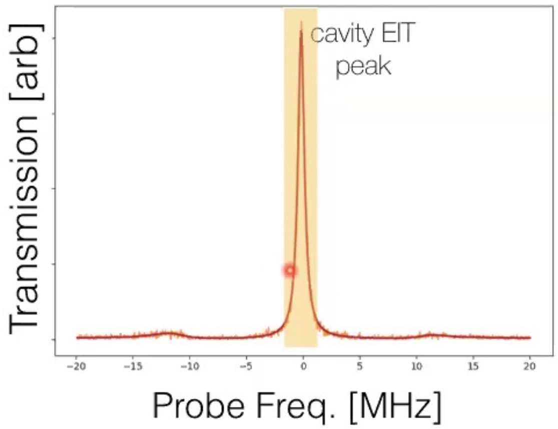

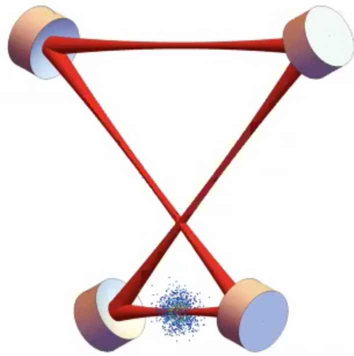

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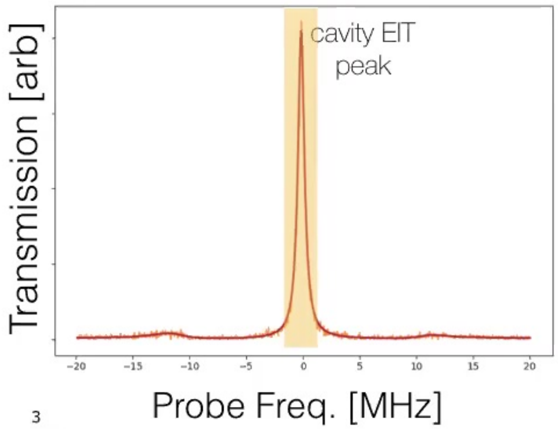
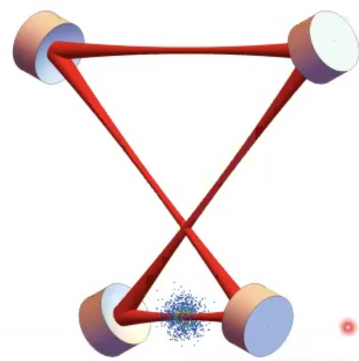
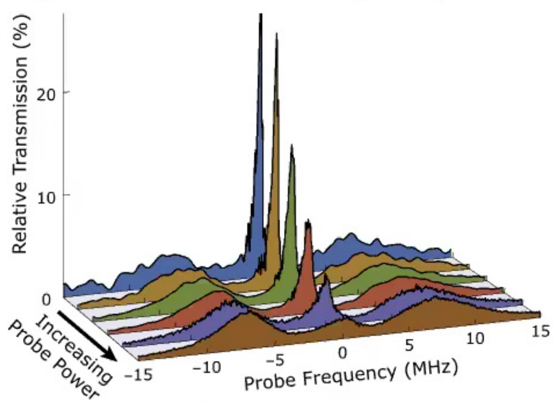
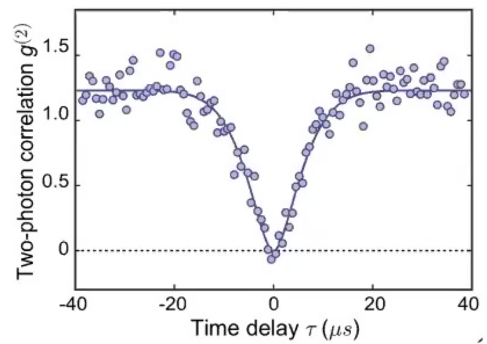








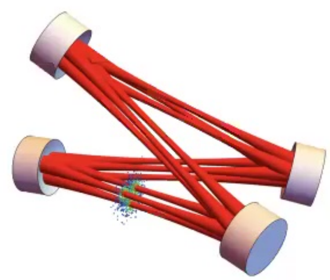
[1] Ningyuan *et al.*, Nature Physics **14**, 550–554 (2018). [2] Guerlin *et al.*, Phys. Rev. A **82**, 053832

Putting it all Together
Photonic Laughlin States

Magnetic Fields for Photons

Photon-Photon Scattering

Topological Manybody States



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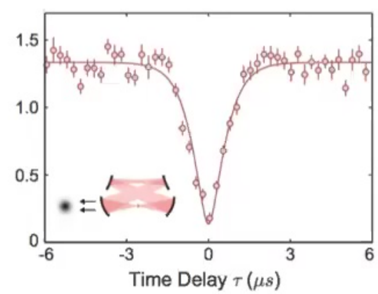

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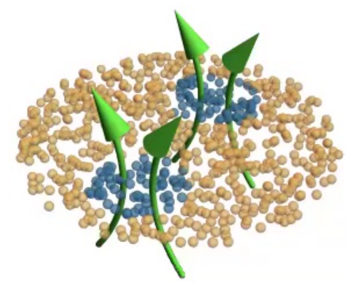
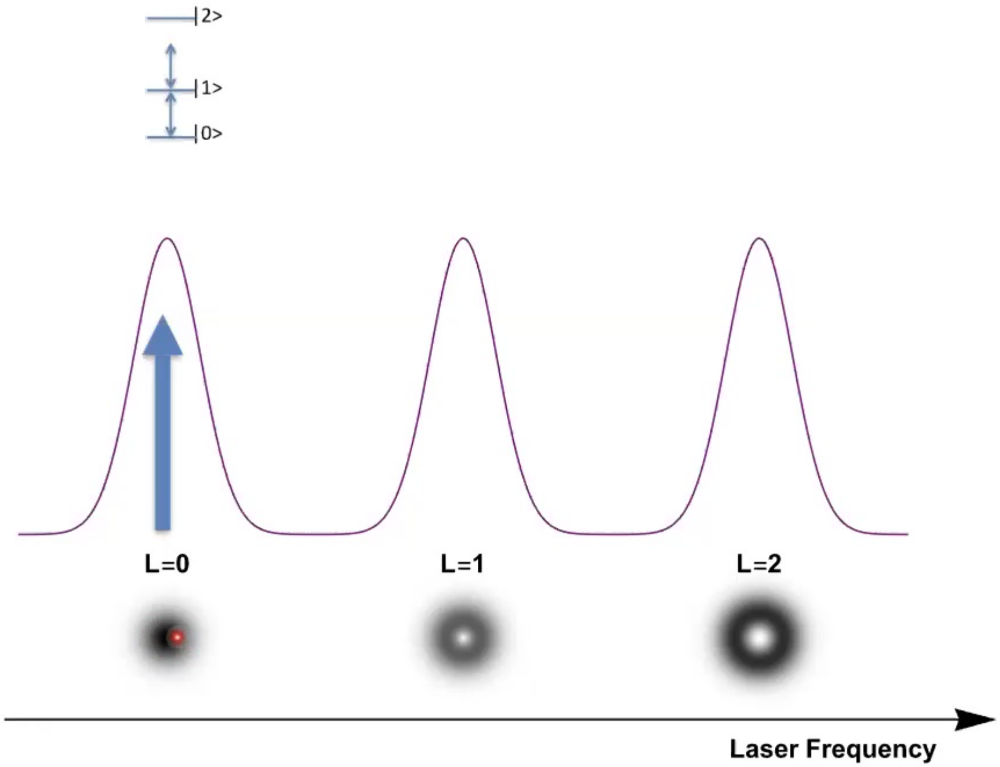


Clark *et al.,* arXiv: 1907.05872 (2019), **Nature**, in Press

Assembling a Laughlin Molecule

Gedanken Experiment



[1] Gemelke et al., arXiv: 1007.2677 (2010), [2] Umucalilar et al., PRL **108**, 206809 (2012) [3] Baur et al., PRA **78**, 061608 (2008)
[4] Hafezi et al., NJP **15**, 063001 (2013), [5] Schauß et al., Nature **491**, 87-91 (2012)

Assembling a Laughlin Molecule

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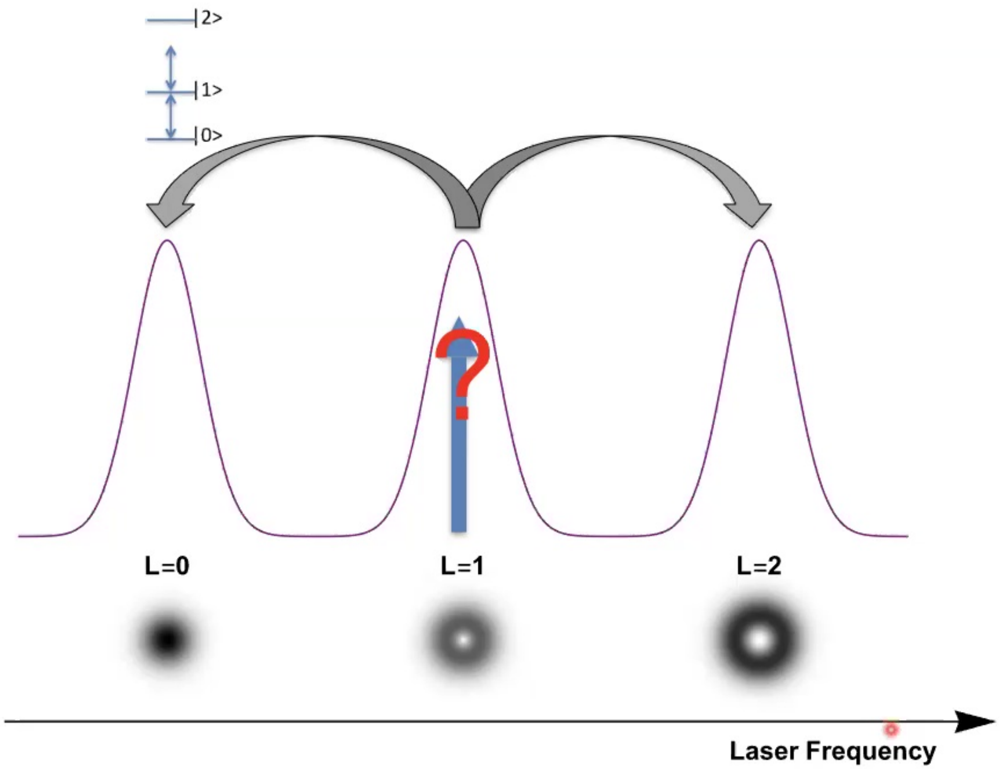

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Assembling a Laughlin Molecule

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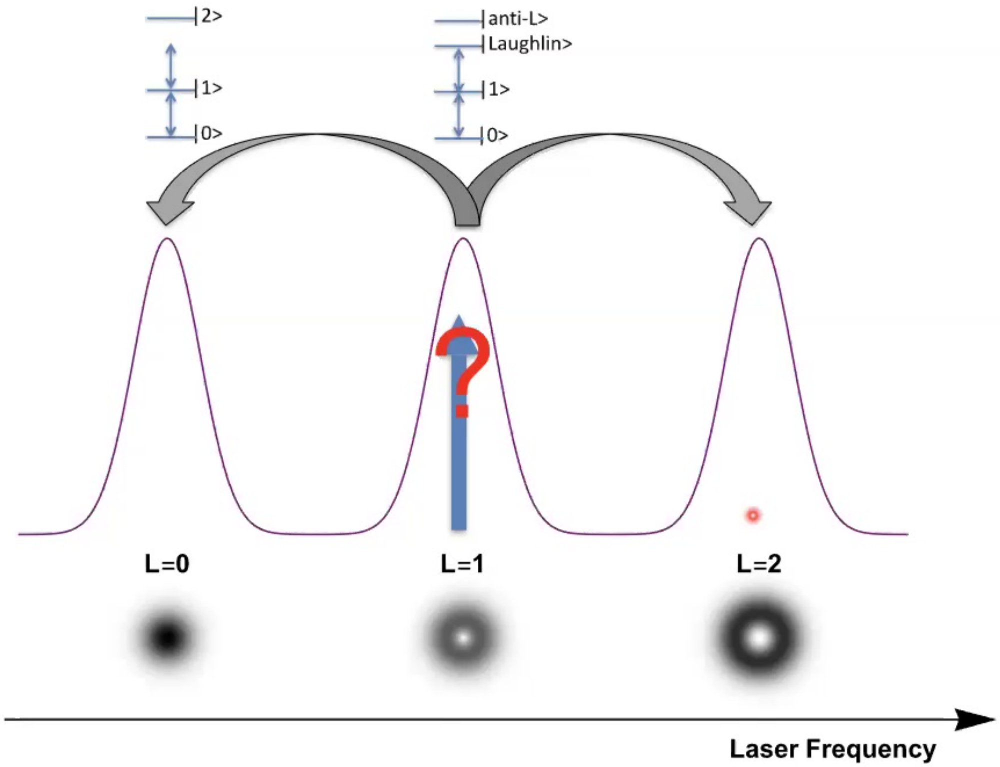

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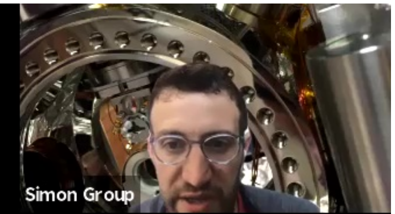

Assembling a Laughlin Molecule

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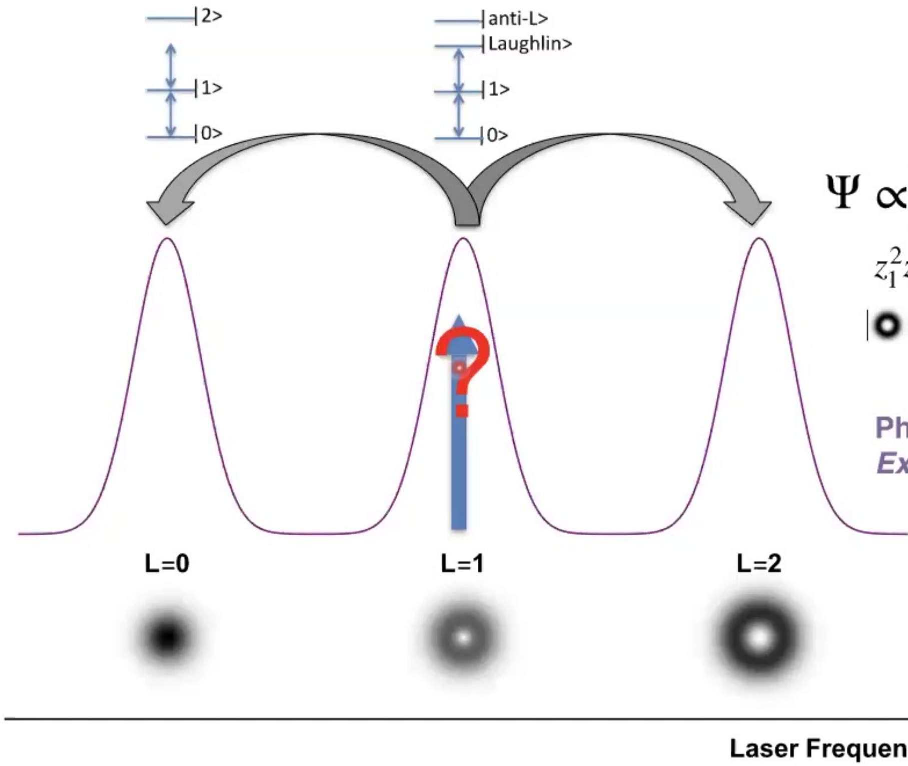
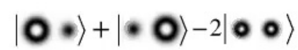


$$\Psi \propto (z_1 - z_2)^2 e^{-\left(|z_1|^2 + |z_2|^2\right)}$$

$$z_1^2 z_2^0 + z_1^0 z_2^2 - 2 z_1 z_2$$



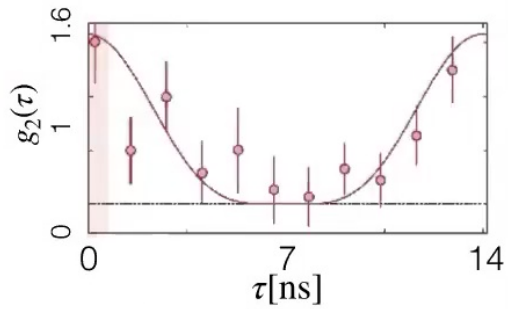
Photonic LAUGHLIN FILTER

Extends to higher photon number

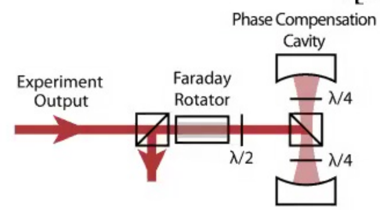
[1] Gemelke et al., arXiv: 1007.2677 (2010), [2] Umucalilar et al., PRL **108**, 206809 (2012) [3] Baur et al., PRA **78**, 061608 (2008)
[4] Hafezi et al., NJP **15**, 063001 (2013), [5] Schauß et al., Nature **491**, 87-91 (2012)

Do the photons avoid one another?

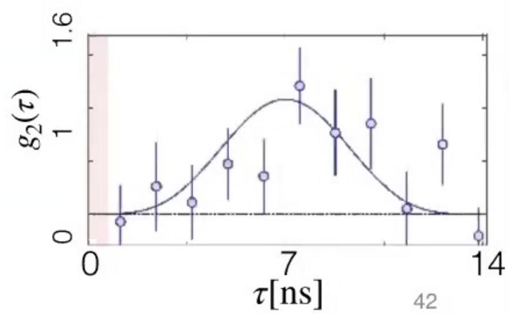
Photon-Bunched Molecule
(due to Floquet coupling phase)



Floquet Compensation Cavity



Anti-Bunched Molecule



Clark *et al.,* arXiv: 1907.05872 (2019)

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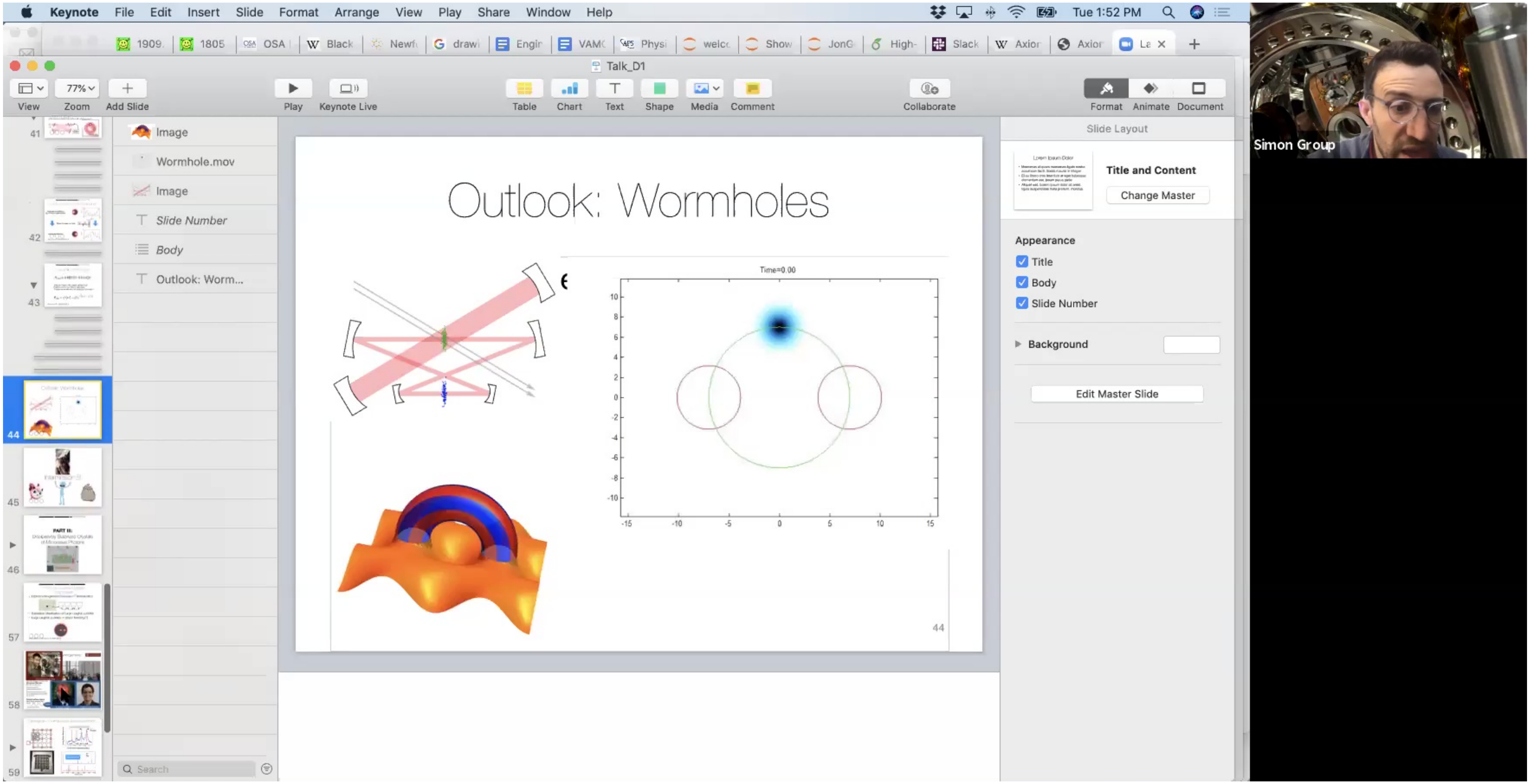
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Simon Group
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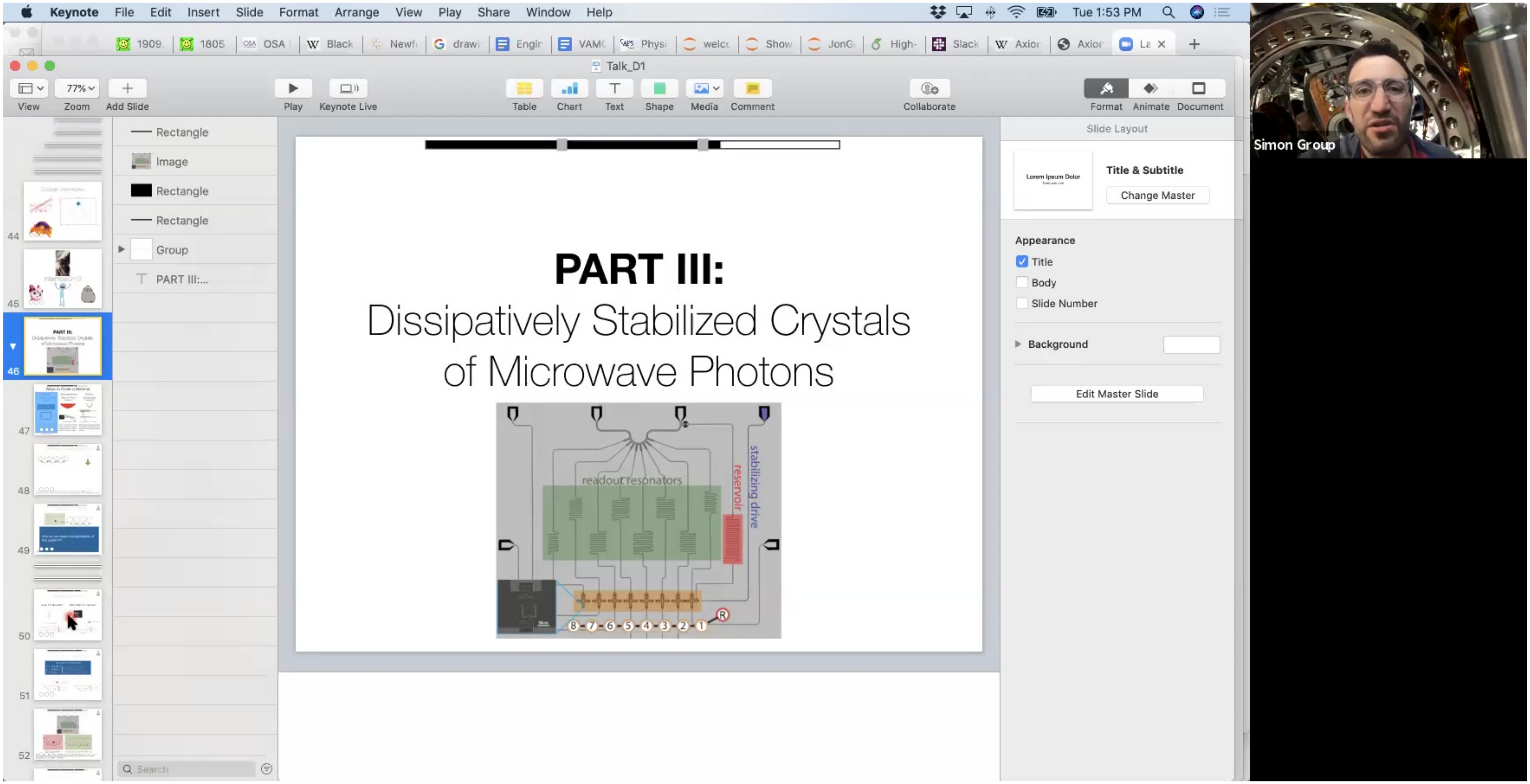
Edit Master Slide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Tue 1:53 PM
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PART III:
Dissipatively Stabilized Crystals
of Microwave Photons
readout resonators
reservoir
stabilizing drive
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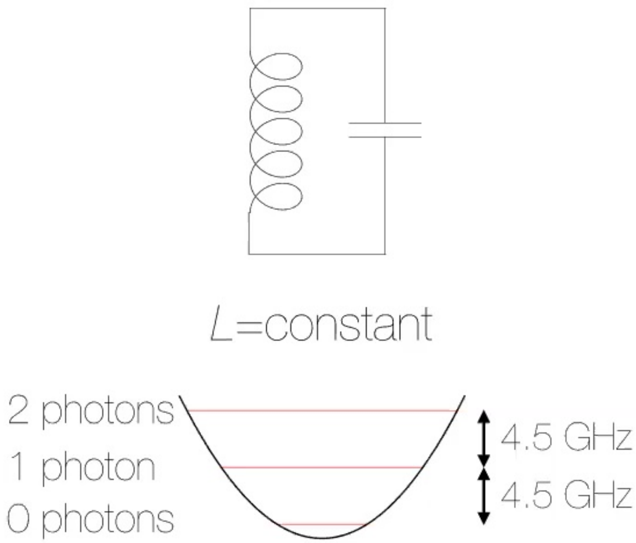
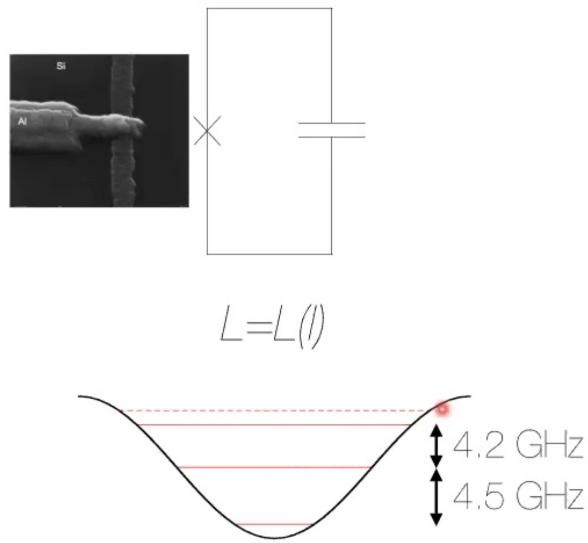
Making a Lattice Site

Linear L-C Resonator

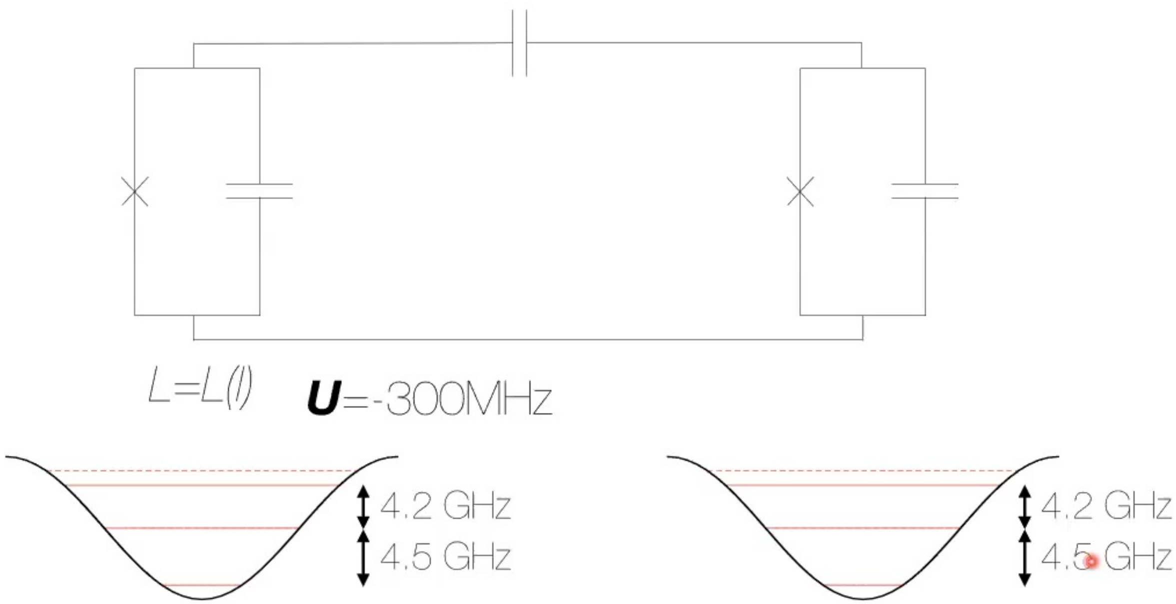


Non-Linear L-C Resonator



SIMON & SCHUSTER

Coupling the Lattice Sites



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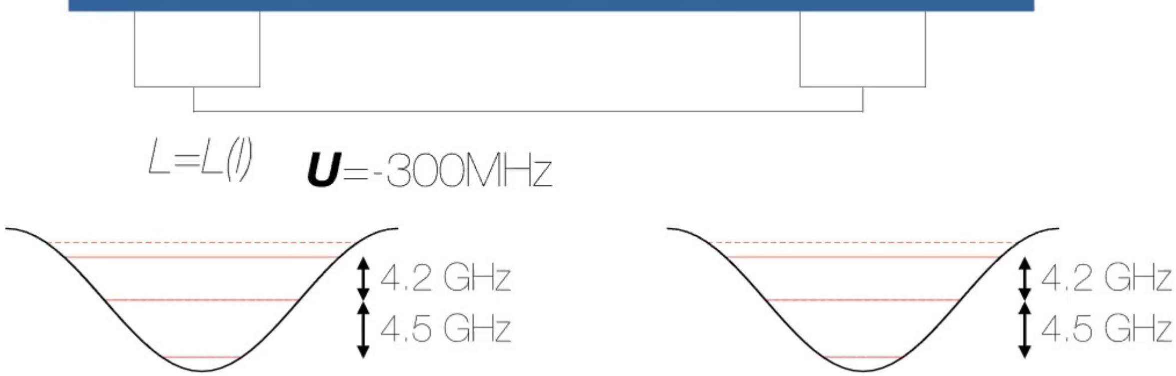
Coupling the Lattice Sites

SIMON & SCHUSTER

Summary of Parameters

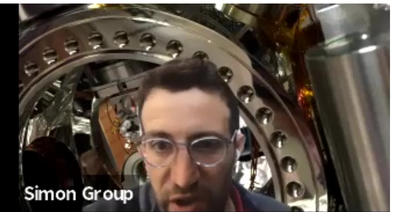
$U = -300$ MHz
$J = 10$ MHz
$T_1 = 40$ μs

Collide 12000 times
or Tunnel 400 sites,
within single-particle lifetime



Dave Schuster
Andrey Gromov
Brandon Anderson

Acknowledgements



Optical Materials
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Logan Clark (PD)

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Claire Baum (PhD)
Alex Georgakopolous (Former PhD)
Jia Ningyuan (Former PhD)
Tianxing Zhang (Former PhD)
Albert Ryou (Former PhD)

Carl Padgett (Former UG)
Michelle Chalupnik (Former UG)

Microwave Materials
Alex Ma (Former PD)

Clai Owens (PhD)
Brendan Saxberg (PhD)

Sarayu Narayan (Former UG)
Aman LaChapelle (Former UG)
Lin Su (UG)

Optical/mmWave Hybrid
Aziza Suleymanzade (PhD)
Mark Stone (PhD)

Jasmine Kalia (UG)

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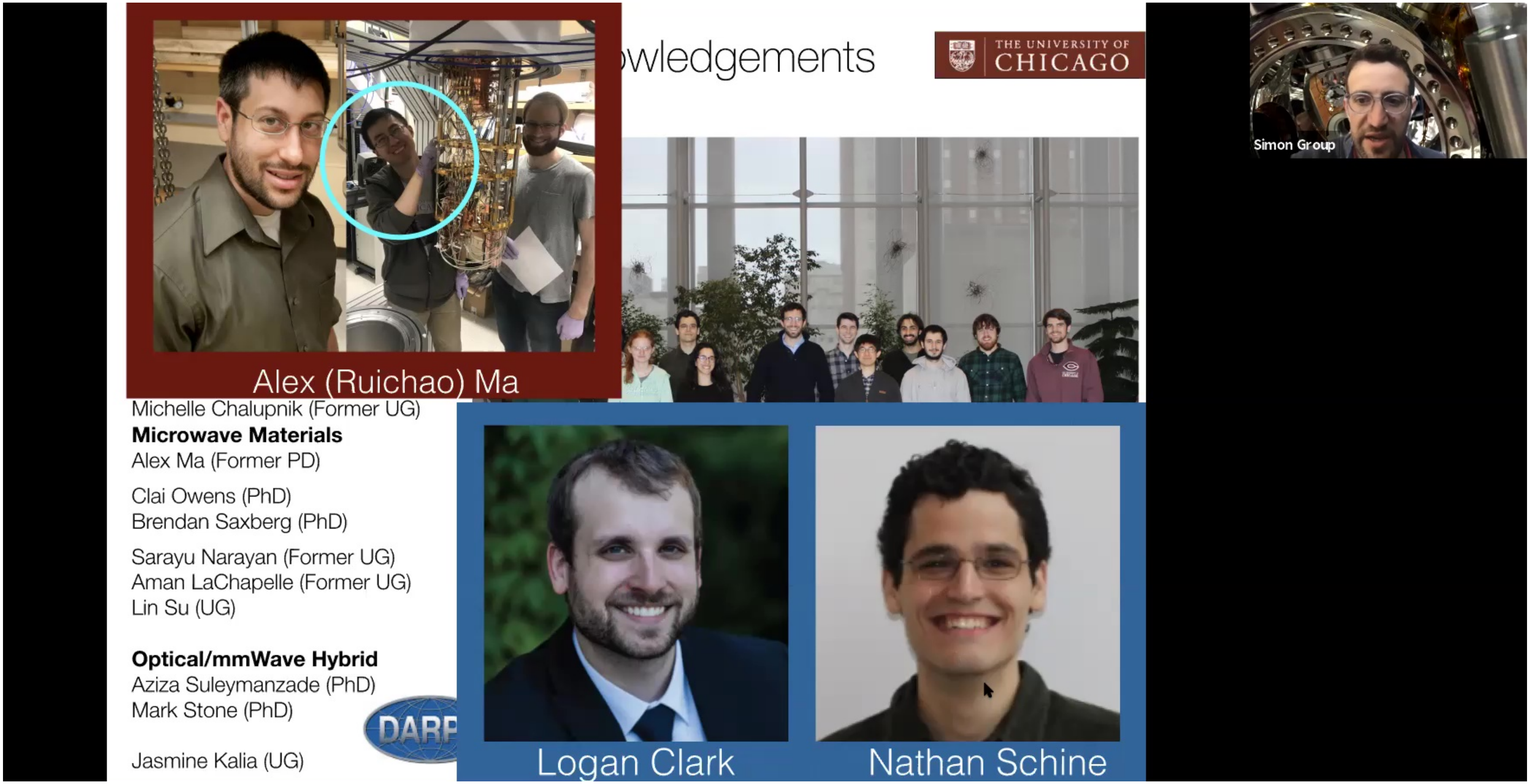
wledgements
THE UNIVERSITY OF CHICAGO
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Alex (Ruichao) Ma
Michelle Chalupnik (Former UG)
Microwave Materials
Alex Ma (Former PD)
Clai Owens (PhD)
Brendan Saxberg (PhD)
Sarayu Narayan (Former UG)
Aman LaChapelle (Former UG)
Lin Su (UG)
Optical/mmWave Hybrid
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Mark Stone (PhD)
Jasmine Kalia (UG)
Logan Clark
Nathan Schine