Photonic Quantum Matter:
Mott Insulators, Landau Levels, and More

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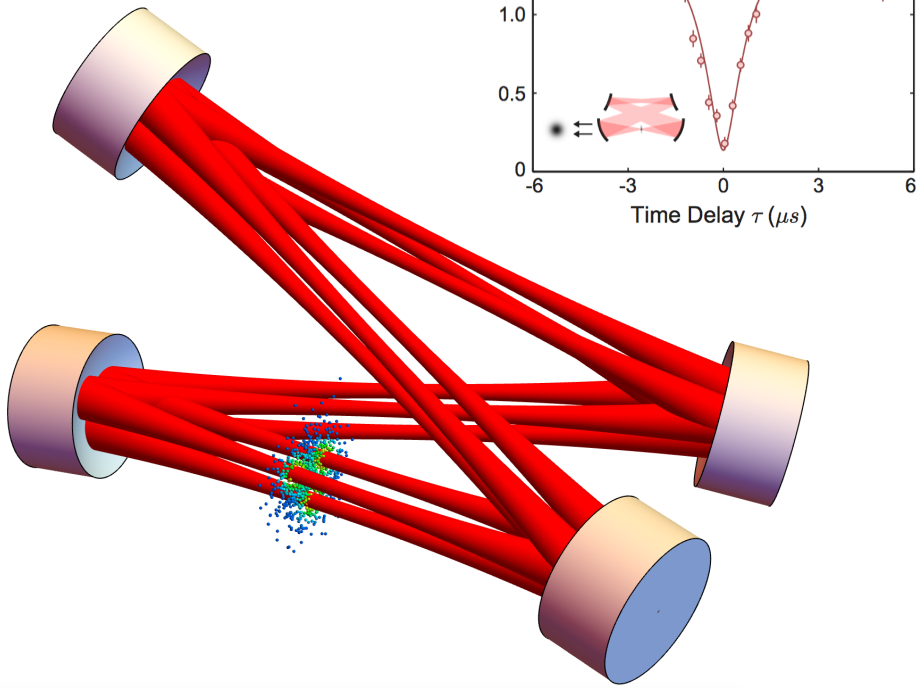
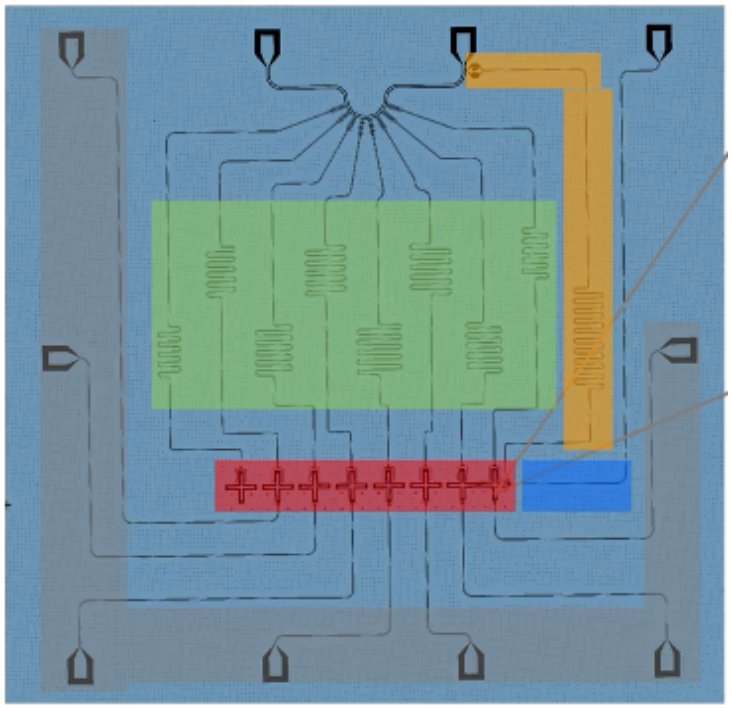
University of Chicago
Chicago, Illinois

Solvay Workshop on Quantum Simulation
Brussels, Belgium
February 19th, 2019





quantum.uchicago.edu & simonlab.uchicago.edu

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

What is a Material?

(Single Particle Control)

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

(Interaction Control)

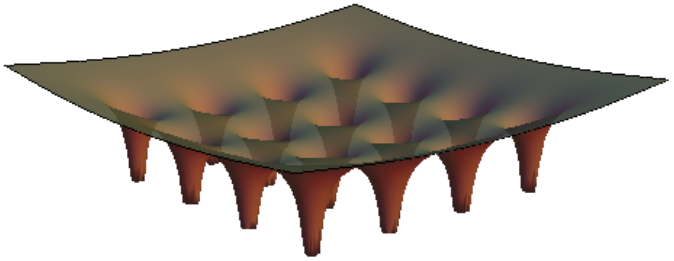
(Entropy Management)

Synthetic Quantum Materials

Solid State

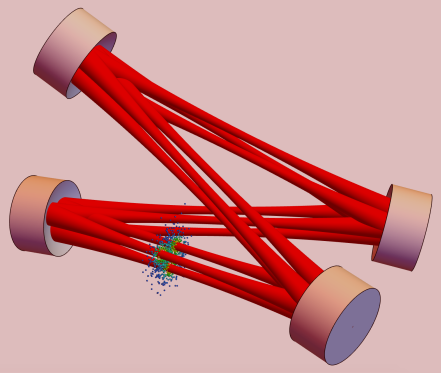
Interacting Electrons

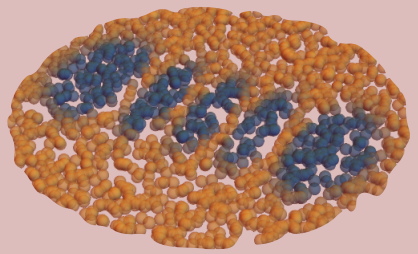
Ionic Lattice

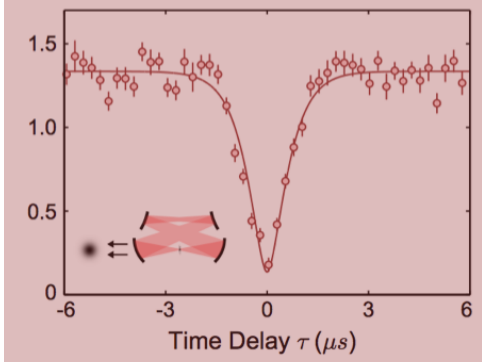


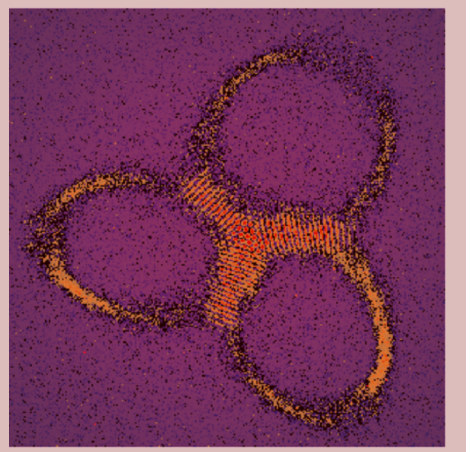
Two Platforms

Bulk Gas: *Optical Photons*

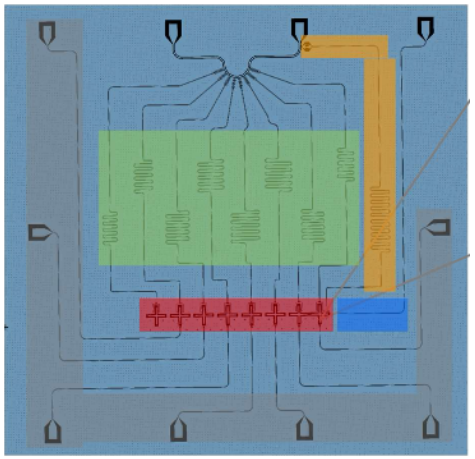


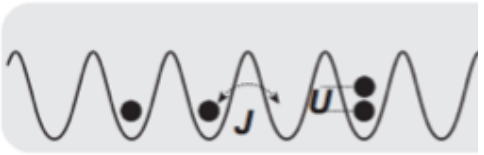


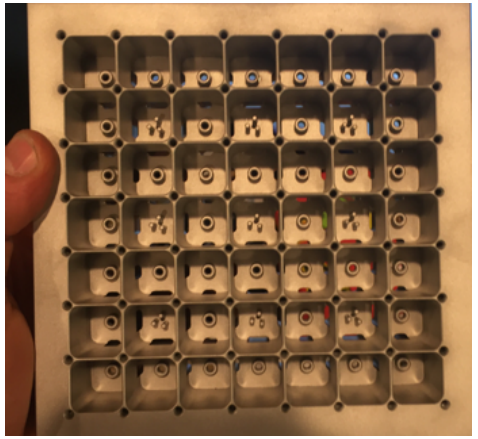


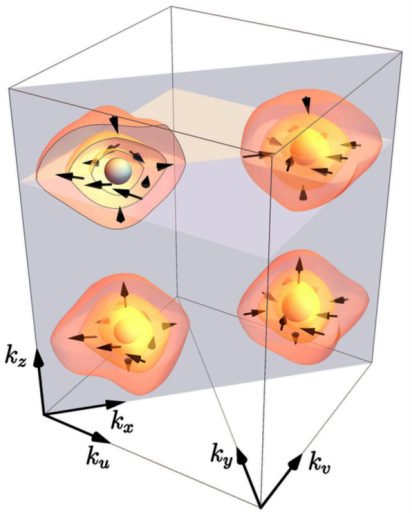


Lattice Gas: μ*W Photons*







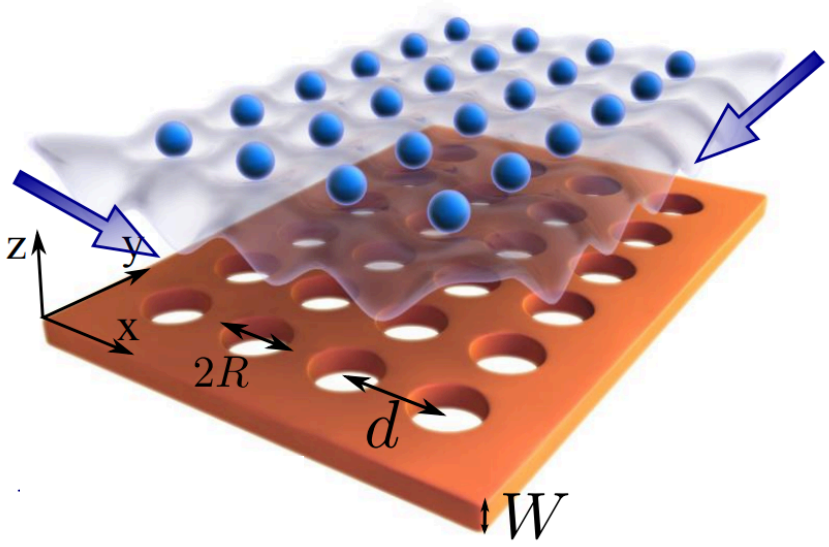


SIMON & SCHUSTER

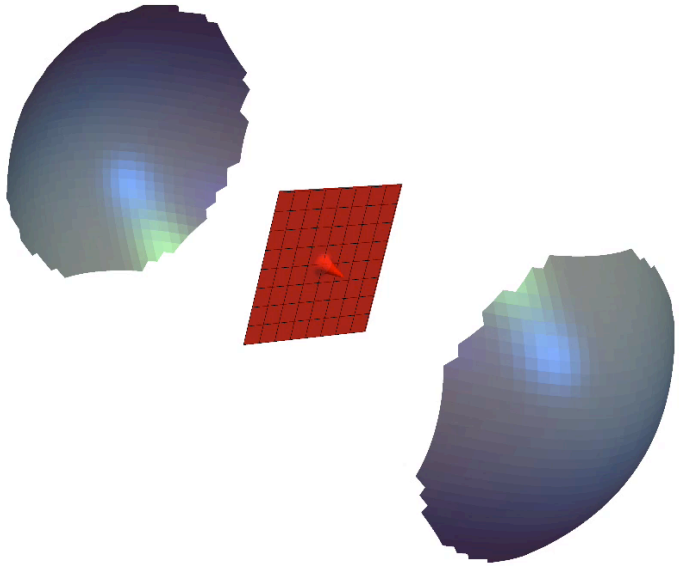
⟨Simon Lab|∂_{k_μ}|Simon Lab⟩

Lattice → Continuum

Cavity Array → *Multimode Cavity*



From: González-Tudela *et al.*, 2015



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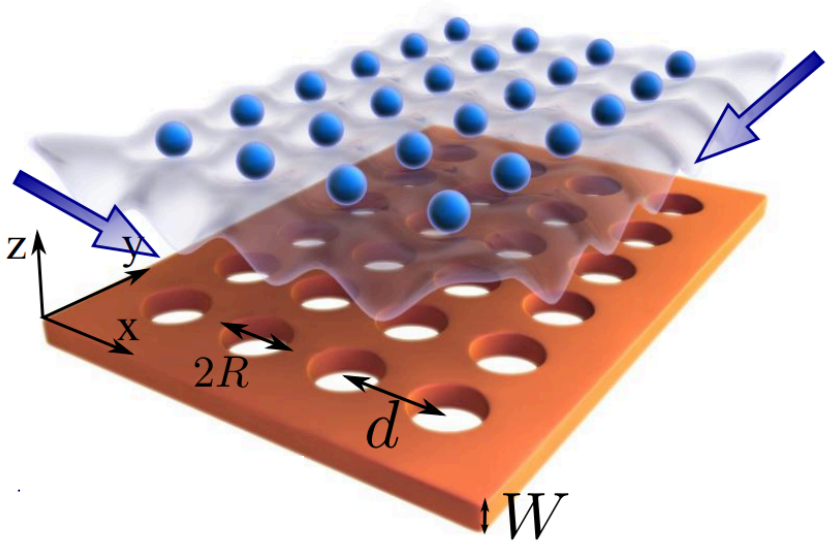

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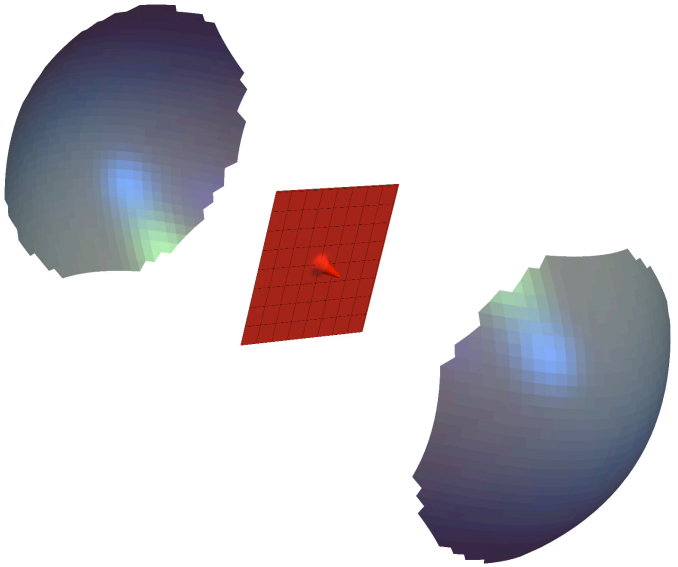
Increase Mirror Curvature



Increase Mirror Curvature

Lattice → Continuum

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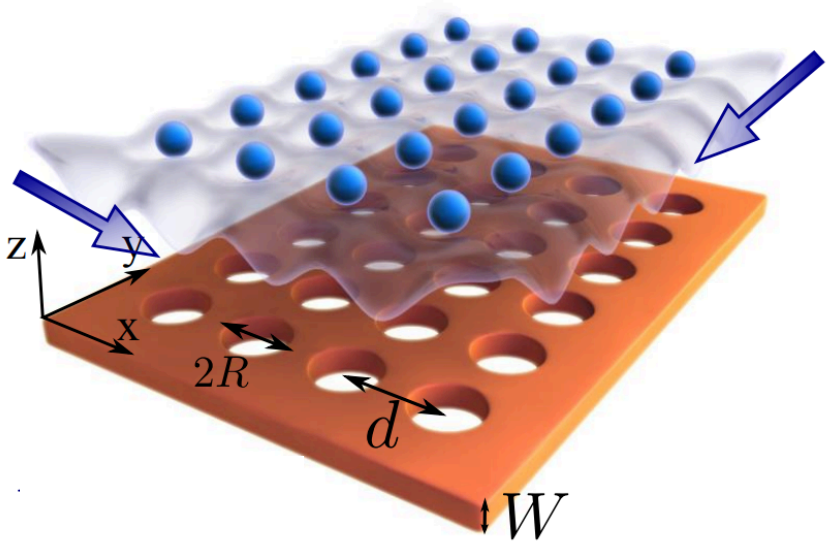
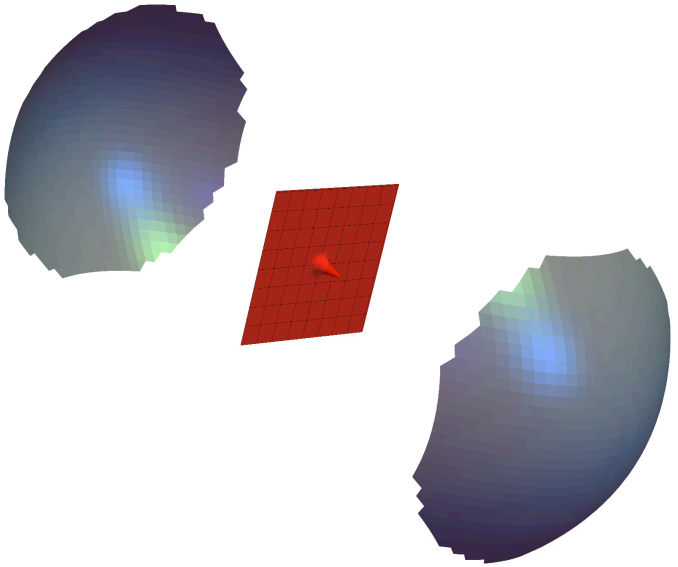


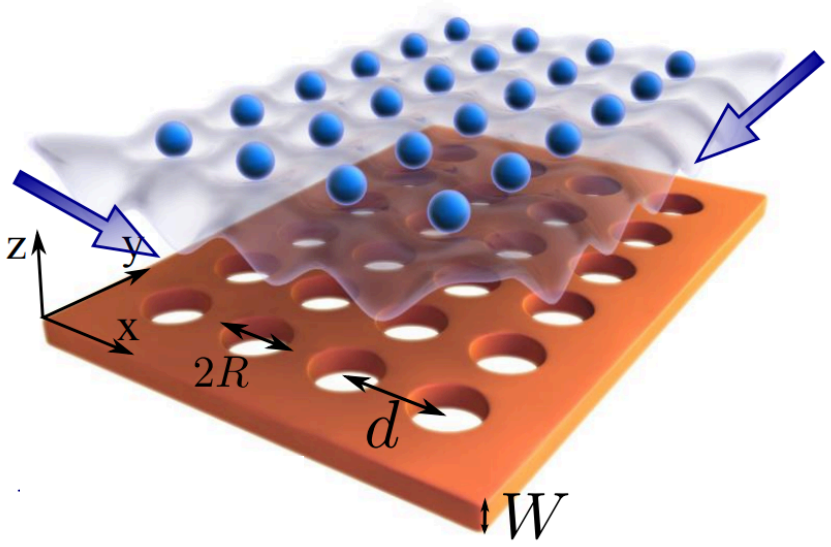
From: González-Tudela *et al.*, 2015

Stroboscopic Round-Trip Evolution



Lattice → Continuum

Cavity Array → *Multimode Cavity*



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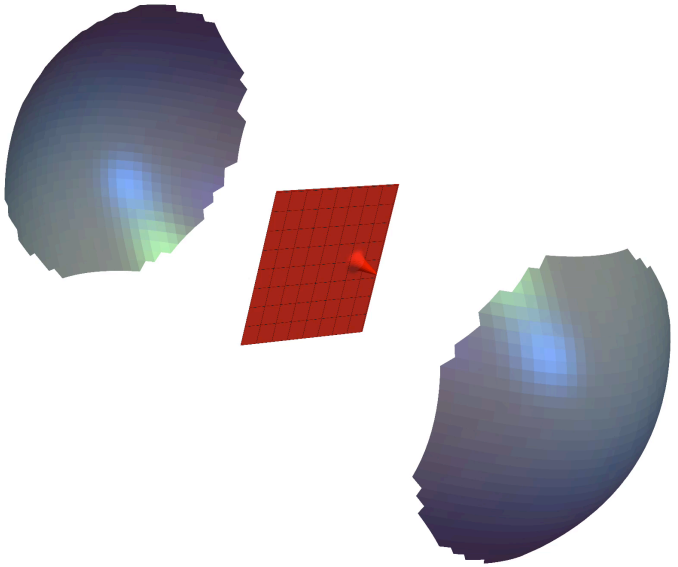
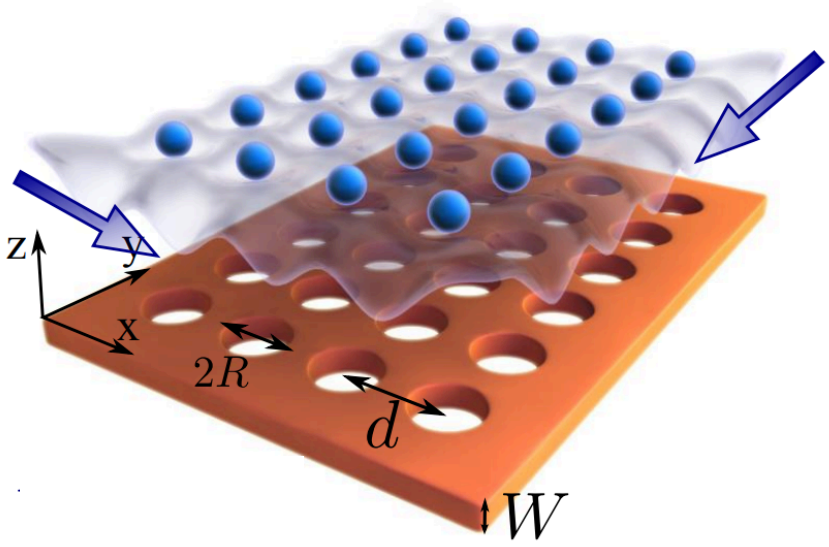


Lattice → Continuum

Cavity Array → *Multimode Cavity*



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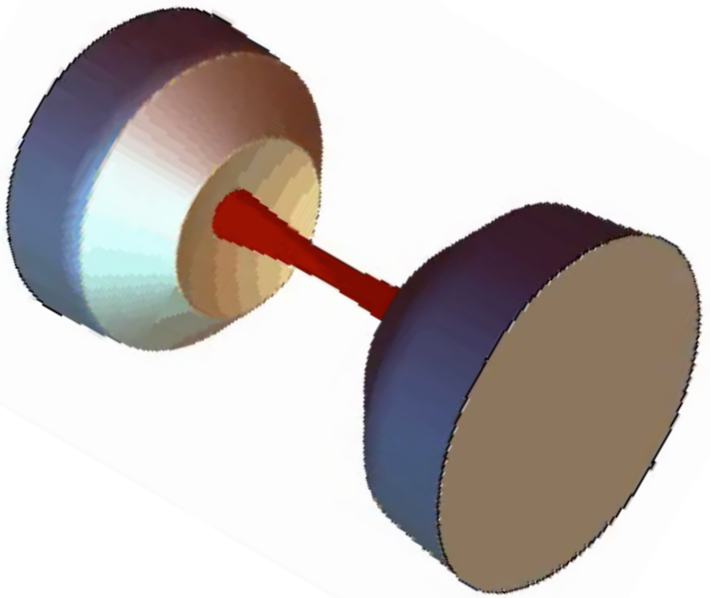
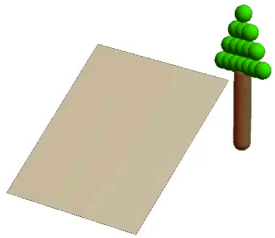
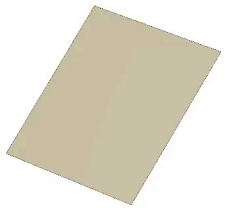


Turning the Lab Frame into a Rotating Frame

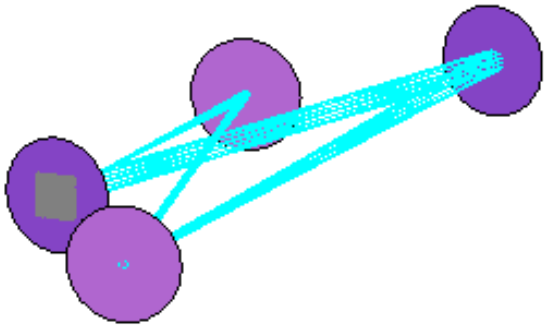
A Twisted Periscope

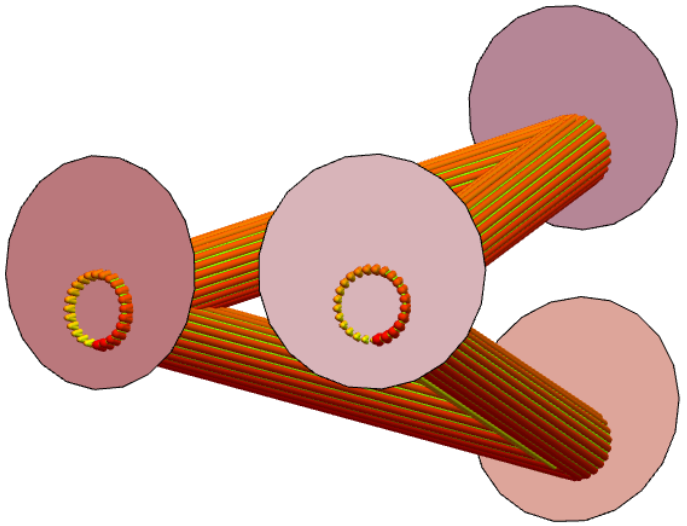
(Trees on the open sea)





Synthetic Magnetic Fields for Cavity Photons

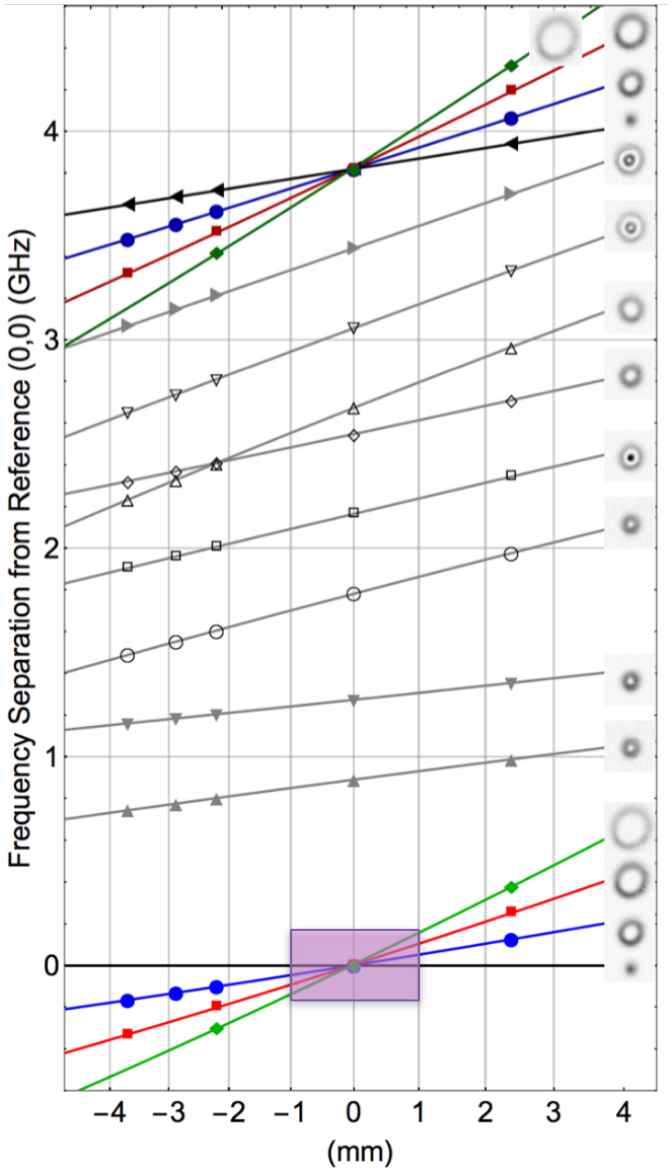


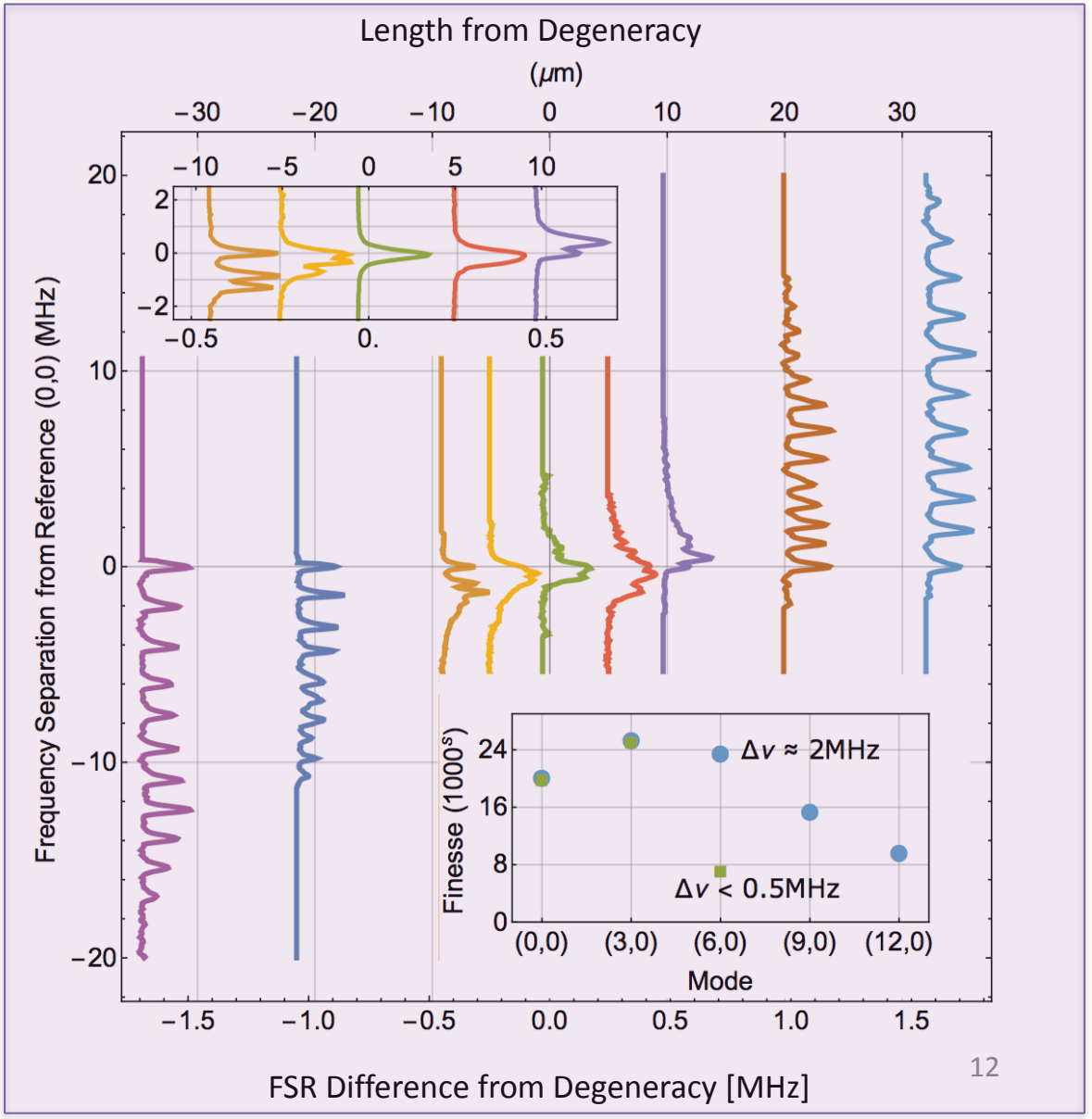


Twisting the resonator out of the plane makes the lab frame a rotating frame → Coriolis $\vec{\Omega} \times \vec{p}$ & Centrifugal Forces $\Omega^2 \vec{r}_\perp$

[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)

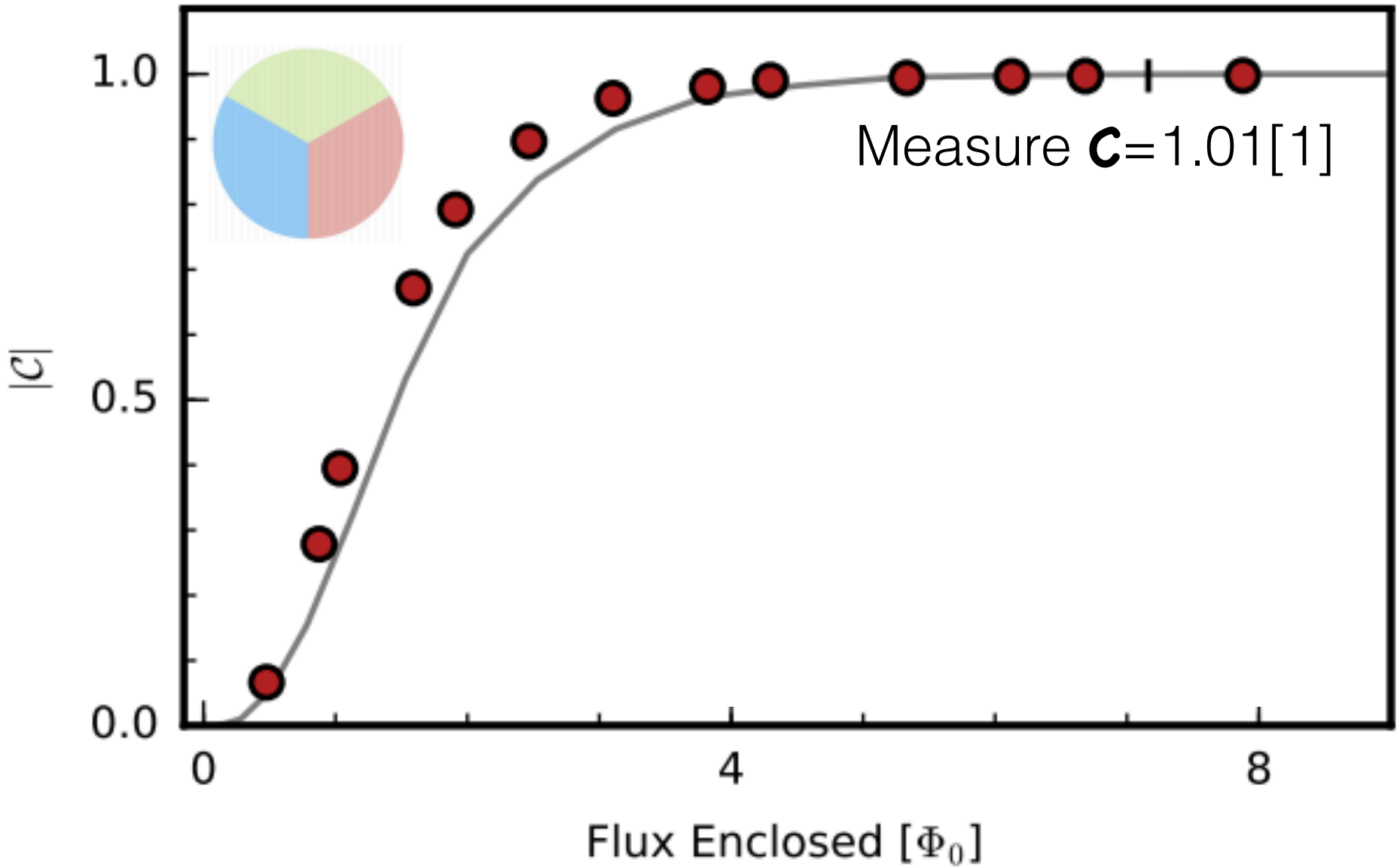
Spectroscopy of Weakly Trapped Landau Levels *(on a Cone)*





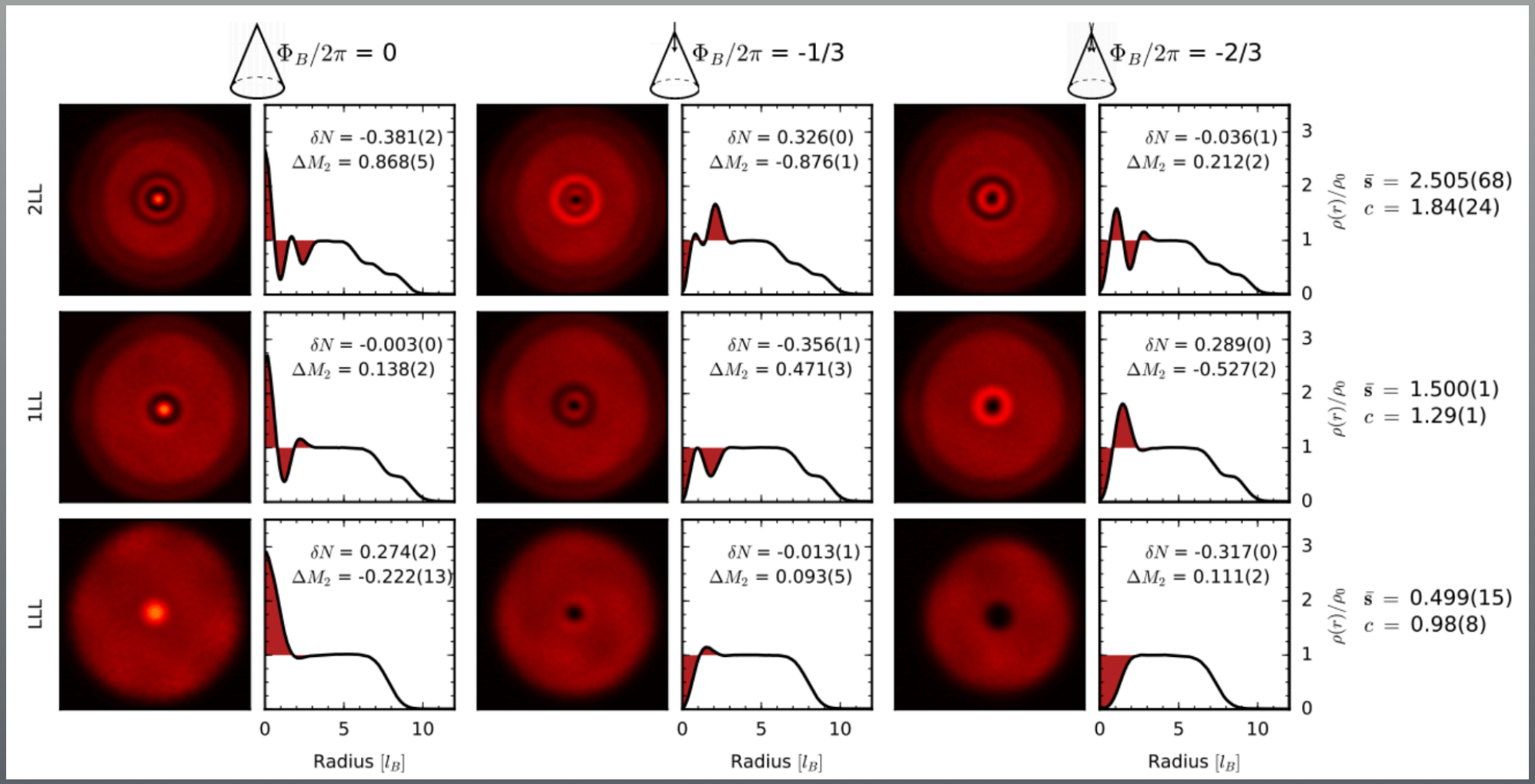
Nathan Schine *et al.*, Nature **534**, 671–675 (2016)

Measuring Topological Quantum Numbers: Kitaev's Real-Space Approach



- A. Kitaev, Ann. Phys. 321, 2 (2006)
- Ma *et al.* PRA **95**, 062120 (2017)
- Schine *et al.*, Nature **565**, 173–179 (2019)

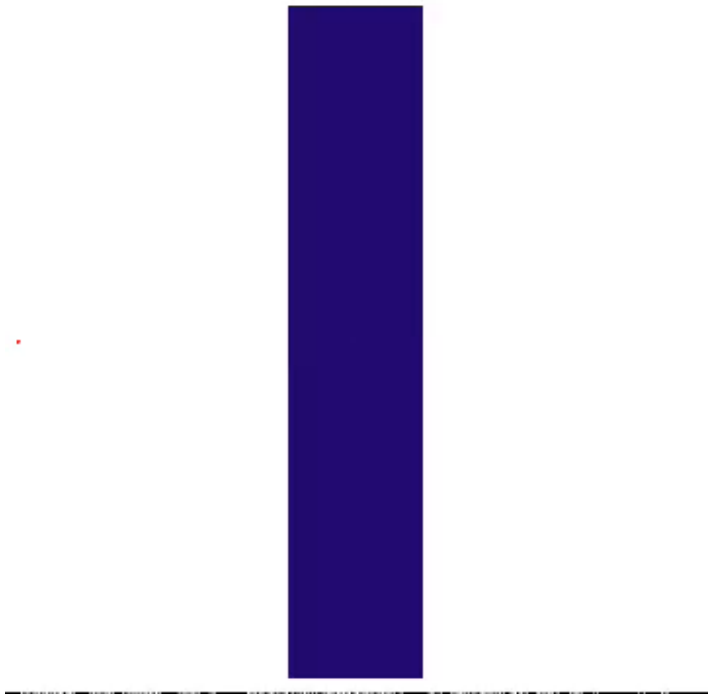
Interplay of Topology and Manifold Curvature

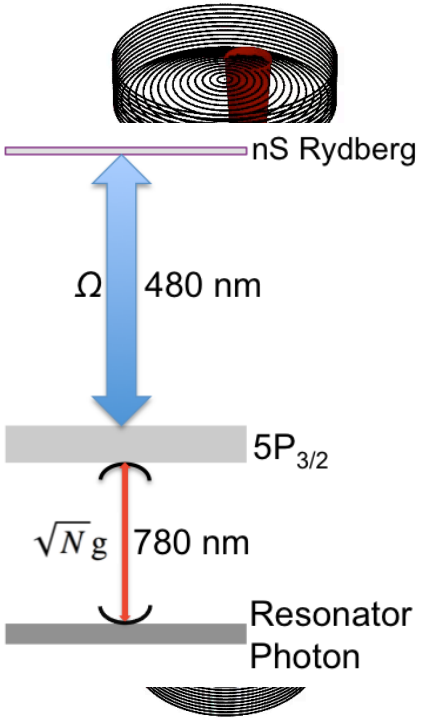


Can *et al.*, Phys. Rev. Lett. **113**, 046803 (2014), Abanov *et al.*, Phys. Rev. B **90**, 014435 (2014)

Making Cavity Photons Collide

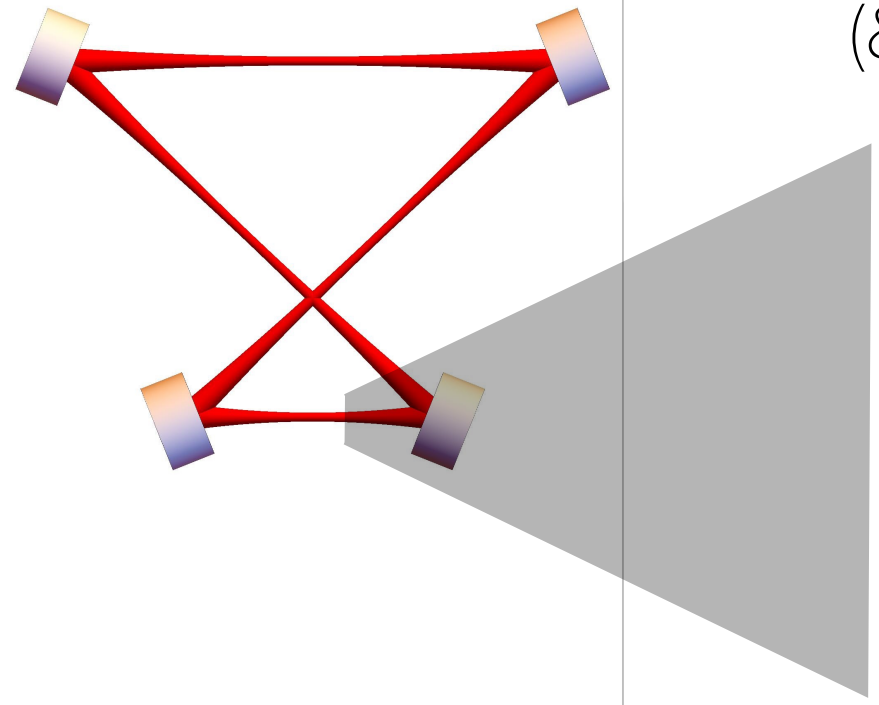
- Rydberg medium provides linear susceptibility for 1st photon
- Second photon experiences reduced susceptibility, due to Rydberg-Rydberg interaction



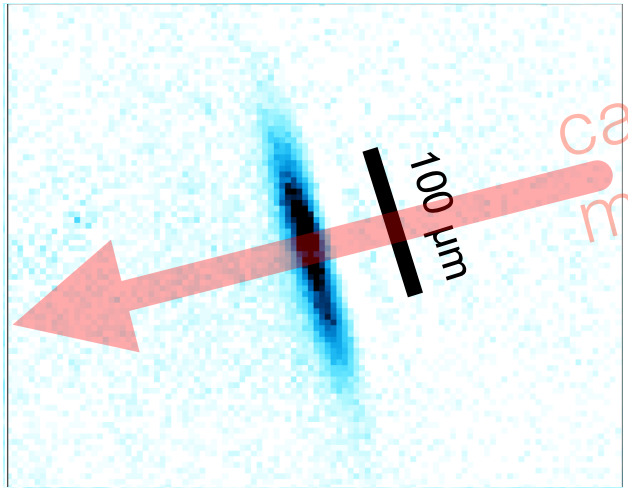


Peyronel *et al.*, Nature **488**, 57–60 (2012), Firstenberg *et al.*, Nature **502**, 71-75 (2013), Baur *et al.*, Phys. Rev. Lett. **112**, 073901 (2014), Tiarks *et al.*, Phys. Rev. Lett. **113**, 053602 (2014), Gorniaczyk *et al.*, PRL **113**, 053601 (2014)

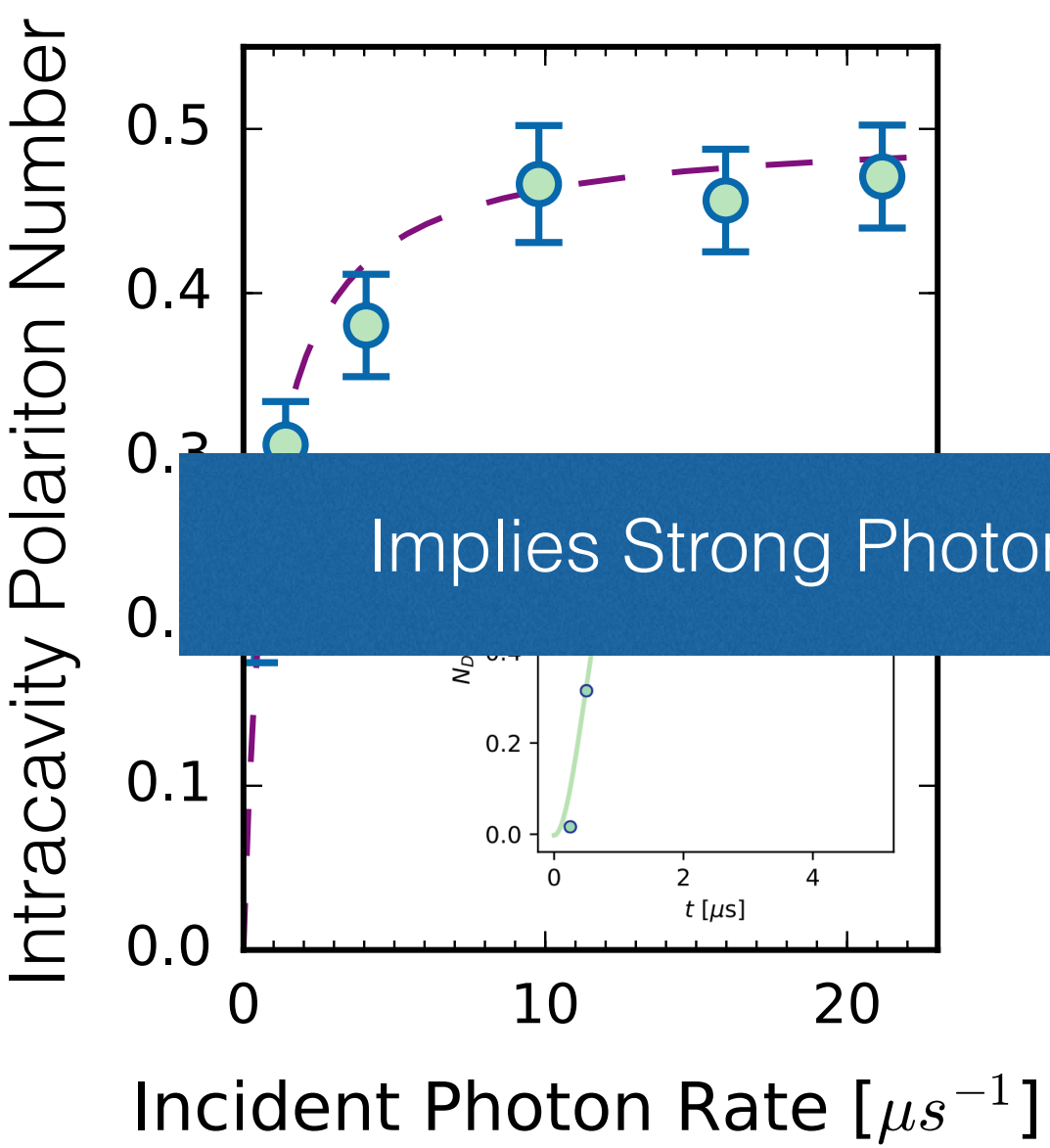
The Apparatus
A 0-dimensional polaritonic quantum dot

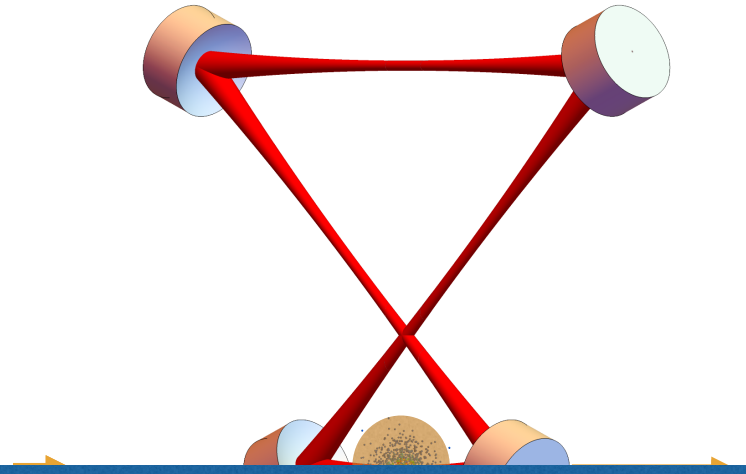


dRSC cooling to 10 μm, 0.5μK
(& polarize atomic sample)

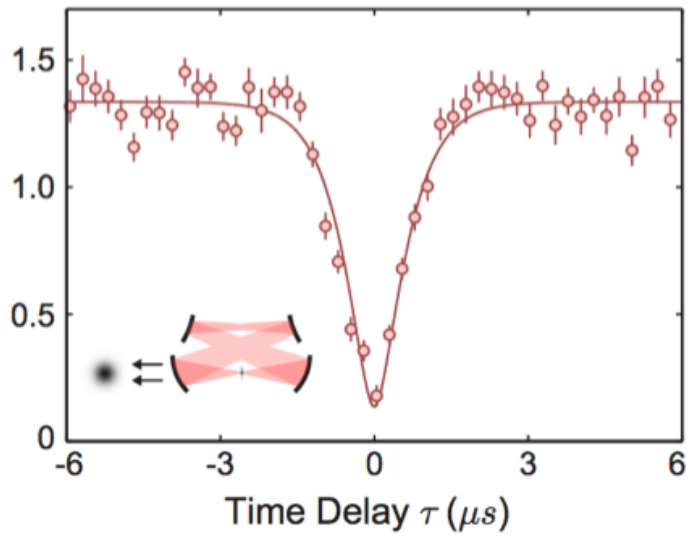


Observation of Cavity Polariton Blockade
in a 0-dimensional quantum dot





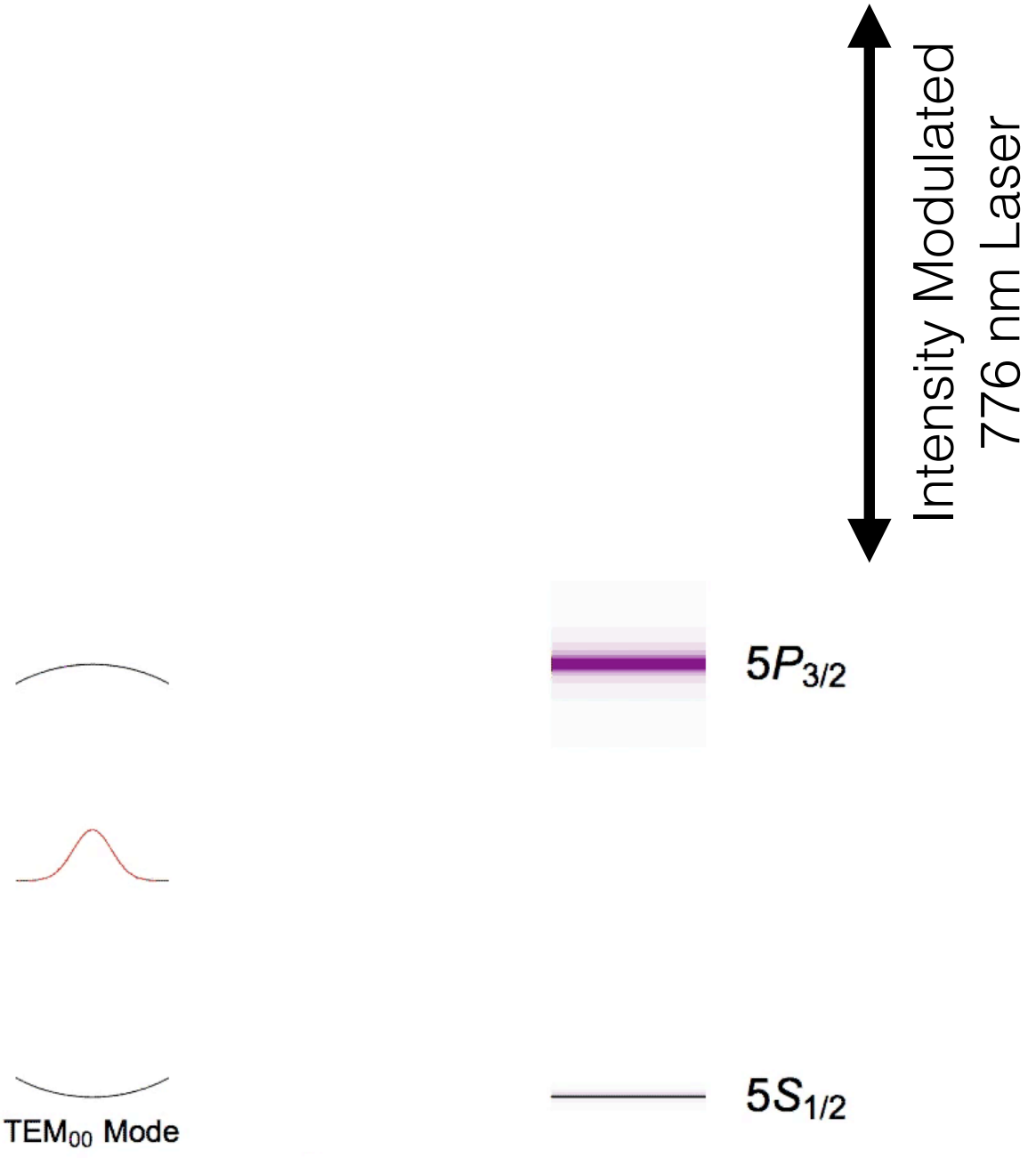
Implies Strong Photon-Photon Interactions



[1] Ningyuan *et al.*, Nature Physics **14**, 550–554 (2018).

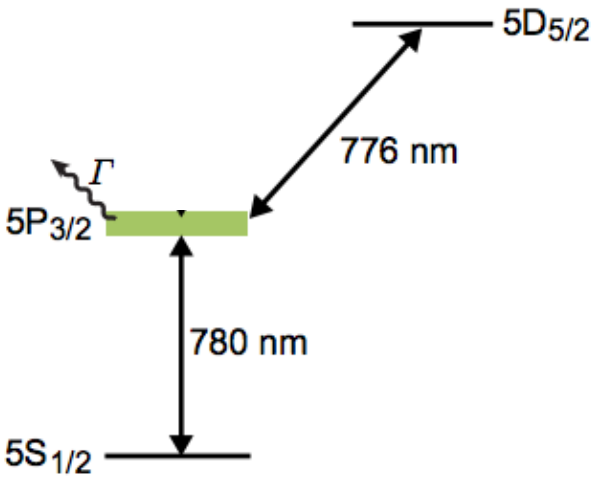
[2] Guerlin *et al.*, Phys. Rev. A **82**, 053832

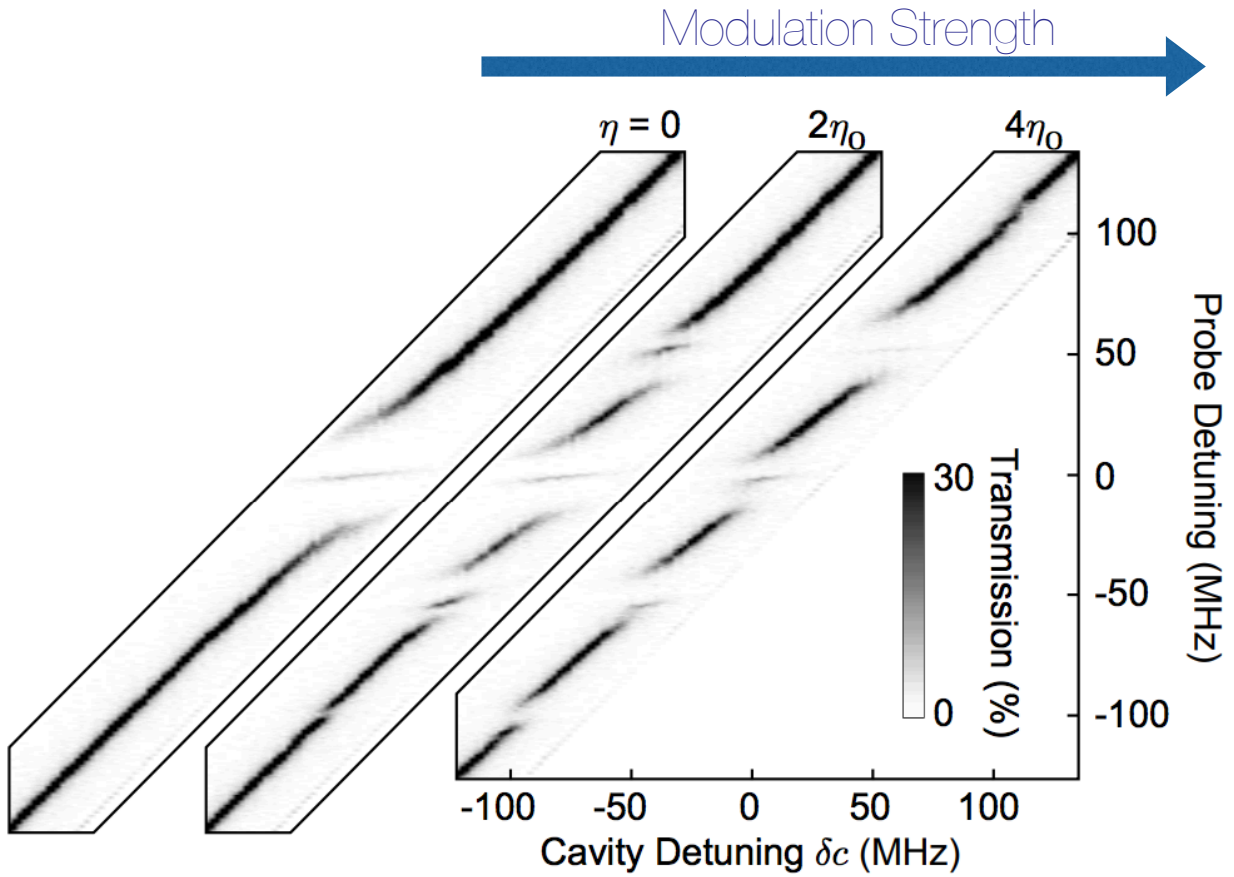
A Multimode Collider:
Sculpting the Atomic Density of States



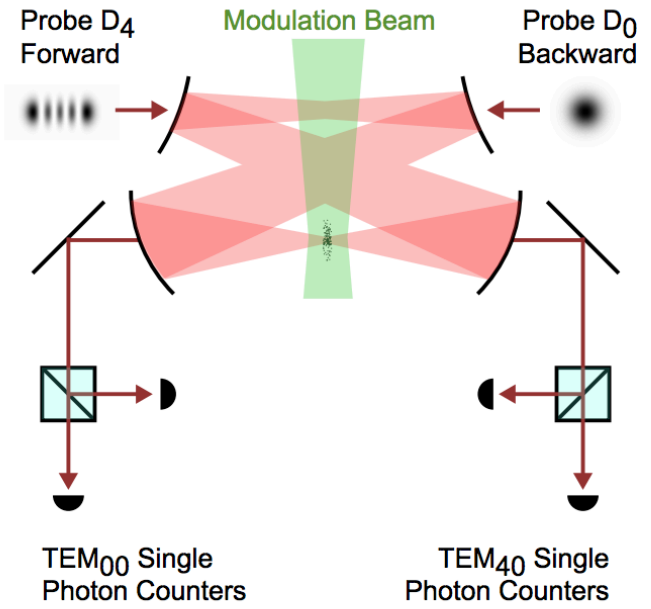
Floquet Polaritons to Floquet Rydberg Polaritons

in a single-mode cavity





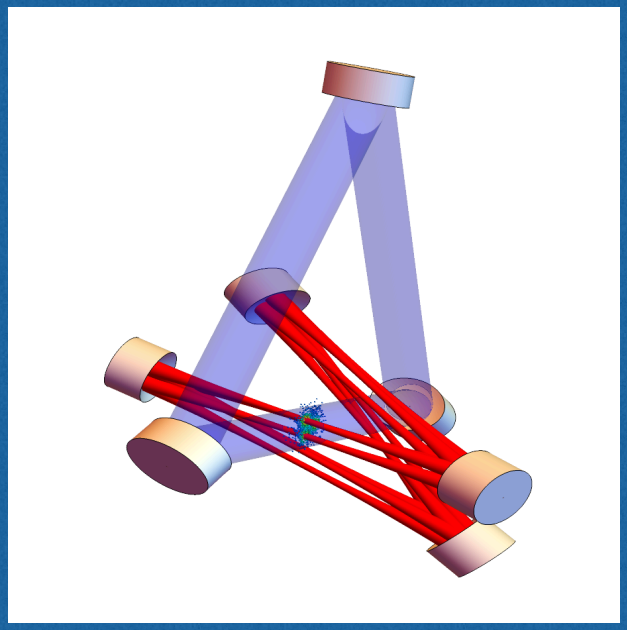
A Multimode Polariton Collider



Multimode Photon-by-Photon Switching!

What's going on now:
Photonic Laughlin States

Topological
Manybody States



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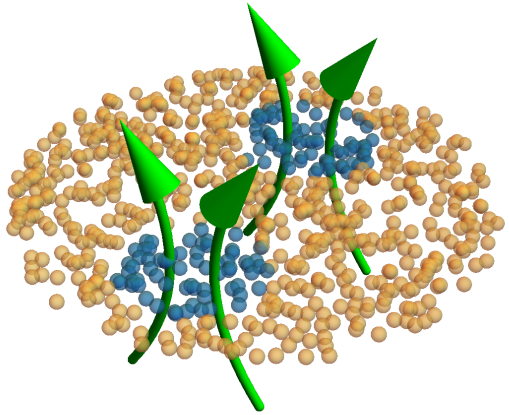
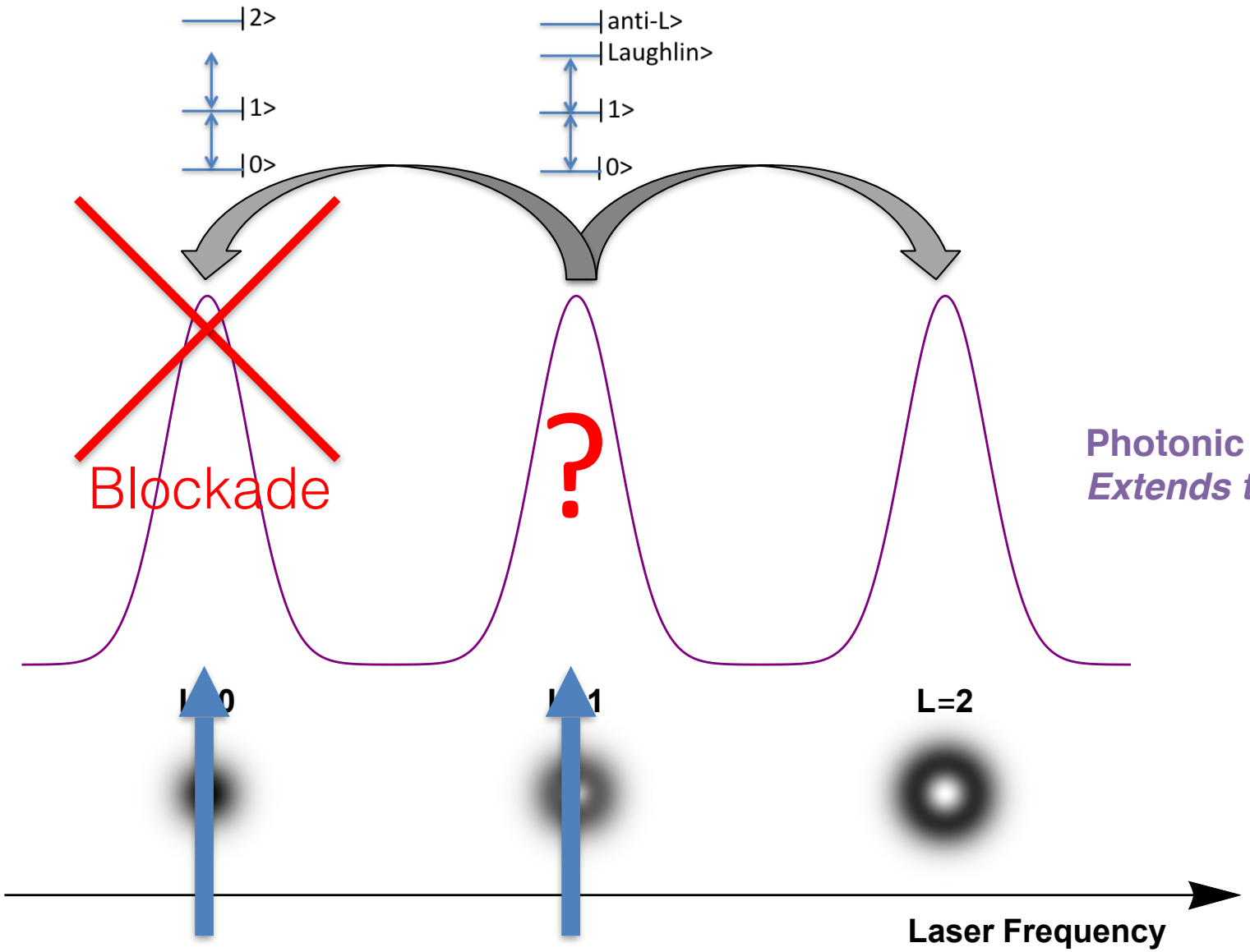


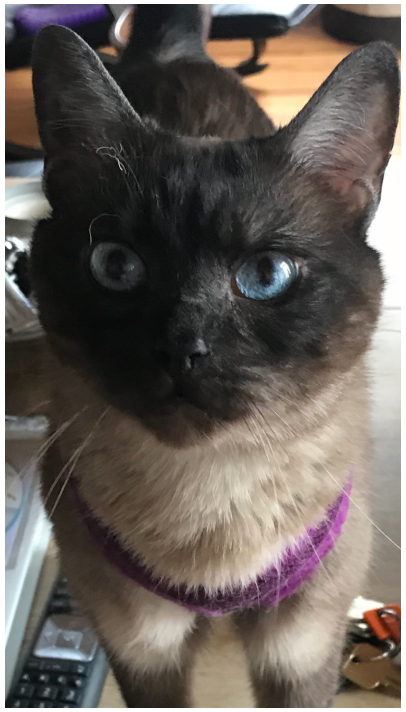
Now under vacuum

Ongoing: Blockade Assembly of a (Floquet) Laughlin State



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)



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

Intermission

What is a Material?

(Single Particle Control)

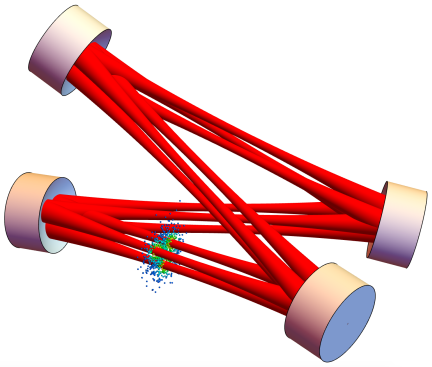
A collection of particles that interact with one another and thereby organize/order.

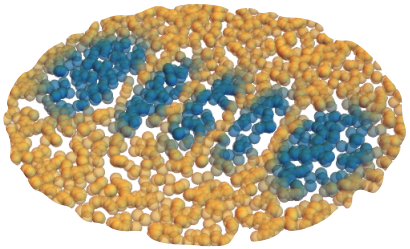
(Interaction Control)

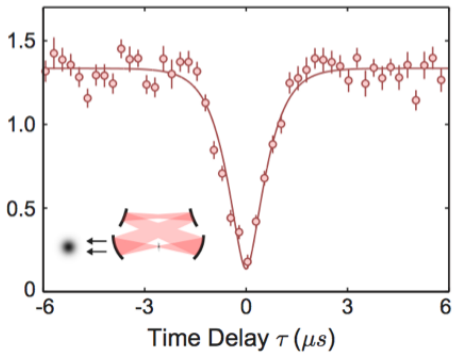
(Entropy Management)

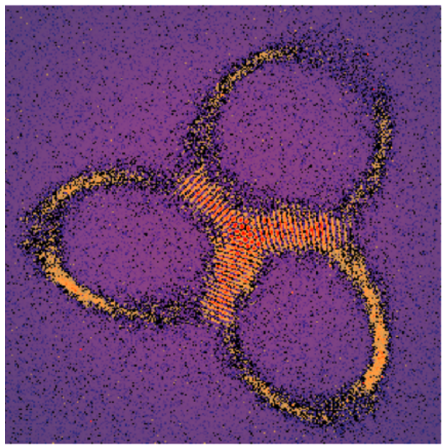
Two Platforms

Bulk Gas: *Optical Photons*

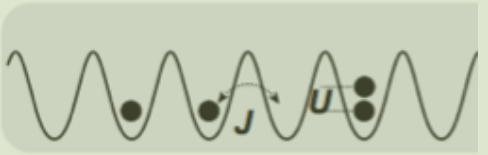


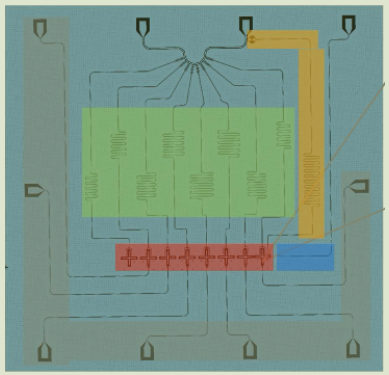


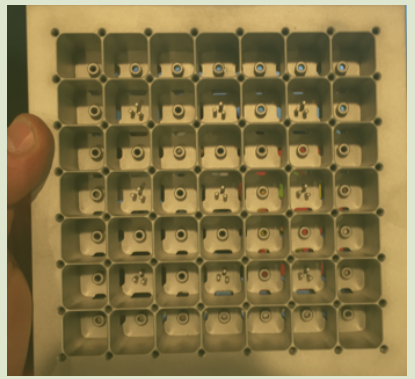


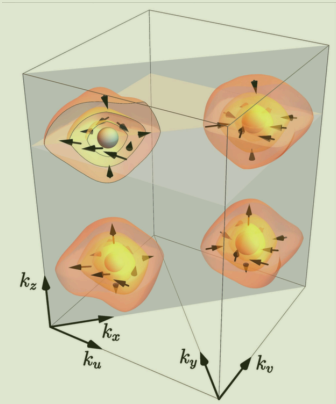


Lattice Gas: μ*W Photons*





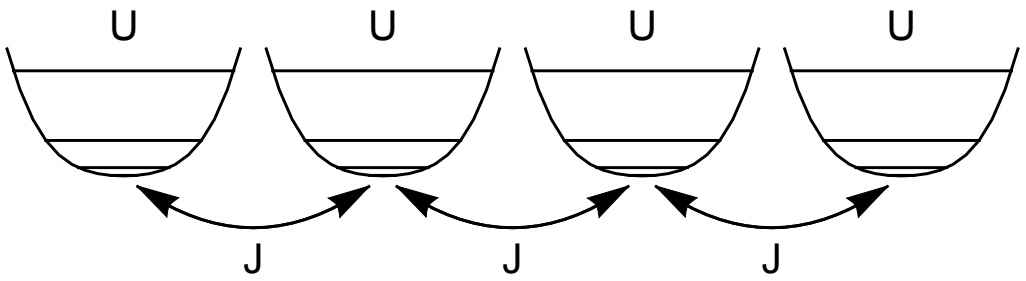




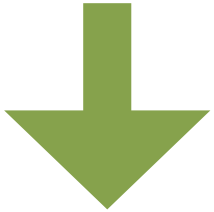
SIMON & SCHUSTER

⟨Simon Lab|∂_{k_μ}|Simon Lab⟩

Stabilizing Incompressible Fluid

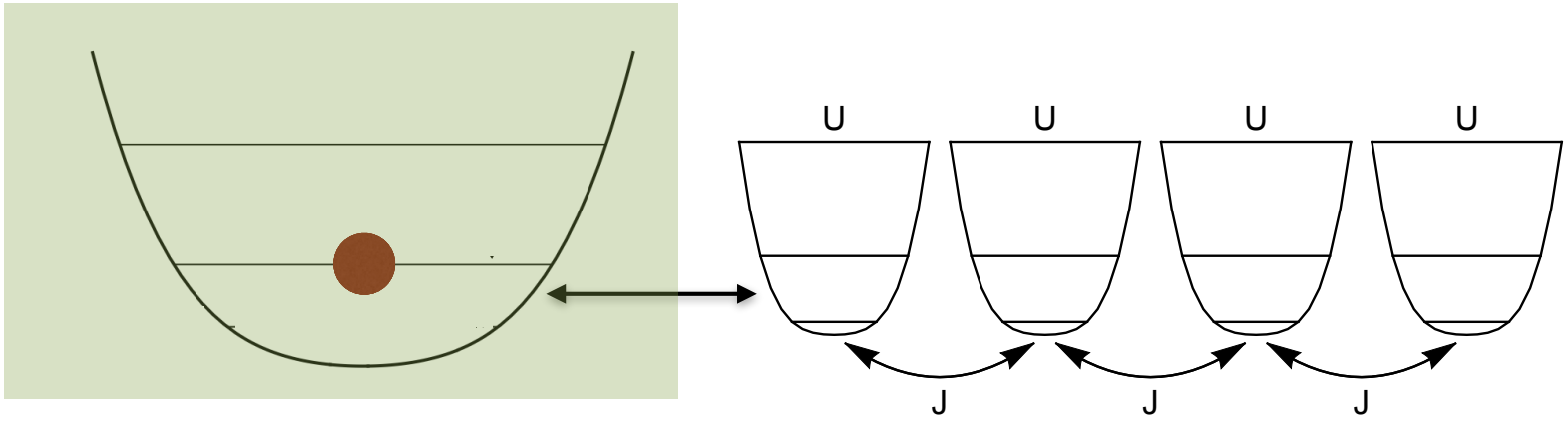


Engineered Dissipation



- Autonomous stabilizer for incompressible photon fluids and solids. Ma *et al.*, PRA **95**, 043811 (2017)
- Engineering Topological Many-Body Materials in Microwave Cavity Arrays. Anderson *et al.*, PRX **6**, 041043 (2016)

A Mott Insulator of Photons



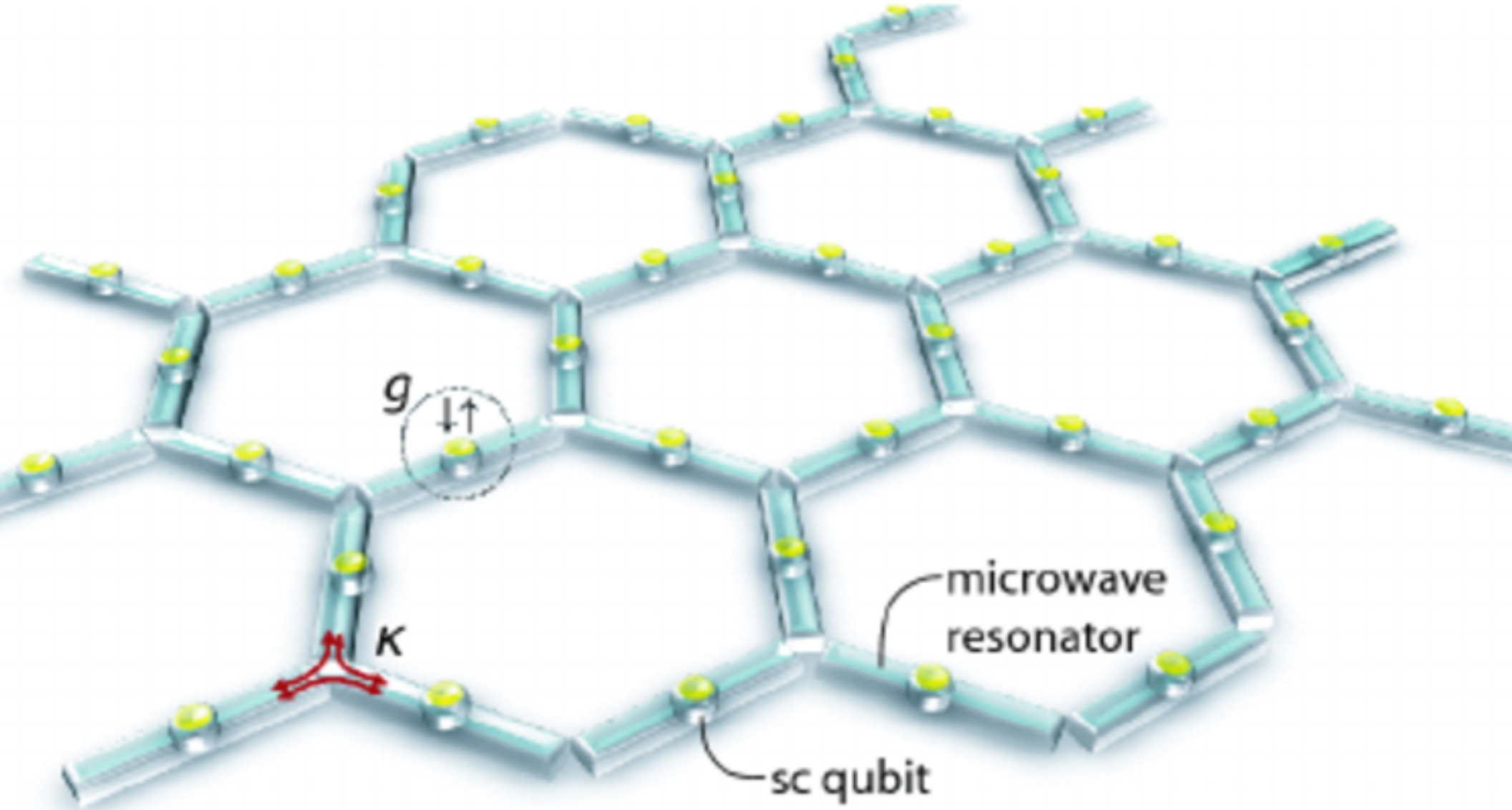
How do we realize the ingredients of this system??

Kap
92,

Strongly-Correlated Phases of Light

- Biella, Storme, Lebreuilly, Davide Rossini, Fazio, Carusotto, & Ciuti, Phase diagram of incoherently driven strongly correlated photonic lattices
- Hartmann, Quantum simulation with interacting photons (2016)
- Noh & Angelakis, Quantum simulations and many-body physics with light (2016)
- Schiro, Bordyuh, Oztop, & Tureci, On the phase transition of light in cavity QED lattices (2012)
- Houck, Türeci & Koch, On-chip quantum simulation with superconducting circuits (2012)
- Grujic, Clark, Jaksch & Angelakis, Non-equilibrium many-body effects in driven nonlinear resonator arrays (2012)
- Hayward, Martin & Greentree, Fractional Quantum Hall Physics in Jaynes-Cummings-Hubbard Lattices (2012)
- Leib & Hartmann, Bose–Hubbard dynamics of polaritons in a chain of circuit quantum electrodynamics cavities (2010)
- Koch & Le Hur: Superfluid–Mott-insulator transition of light in the Jaynes-Cummings lattice (2009)
- Schmidt & Blatter, Strong coupling theory for the Jaynes-Cummings-Hubbard model (2009)
- Cho, Angelakis, & Bose, Fractional Quantum Hall State in Coupled Cavities (2008)
- Hartmann. Brandao & Plenio, Quantum Many-Body Phenomena in Coupled Cavity Arrays
- Rossini & Fazio, Mott insulating and glassy phases of polaritons in 1D arrays of coupled cavities (2007)
- Chang, Gritsev, Morigi, Vuletic, Lukin & Demler, Crystallization of strongly interacting photons in a nonlinear optical fiber (2007)
- Na, Utsunomiya,Tian, & Yamamoto, Strongly Correlated Polaritons in a Two-Dimensional Array of Photonic Crystal Microcavities (2007)
- Hartmann & Plenio, Strong photon non-linearities and photonic Mott insulators
- Angelakis, Santos, & Bose, Photon blockade induced Mott transitions and XY spin models in coupled cavity arrays (2007)
- Hartmann, Brandao, & Plenio, Strongly Interacting Polaritons in Coupled Arrays of Cavities (2006)

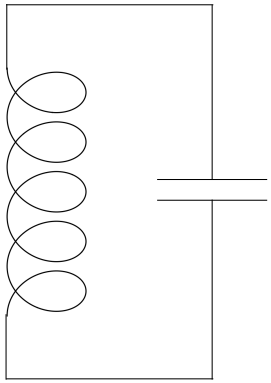
Strongly-Correlated Phases of Light



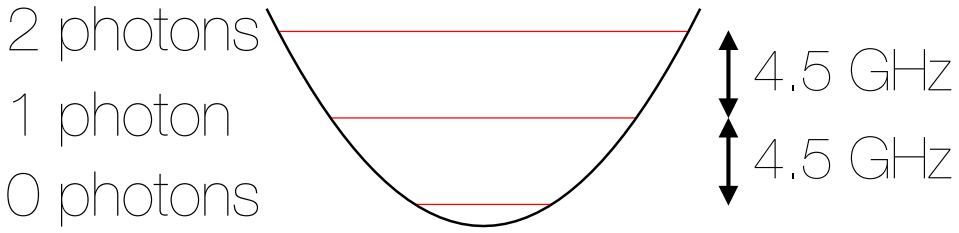
Houck Group

Making a Lattice Site

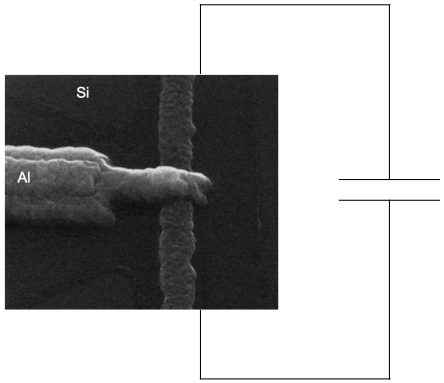
Linear L-C Resonator



L=constant

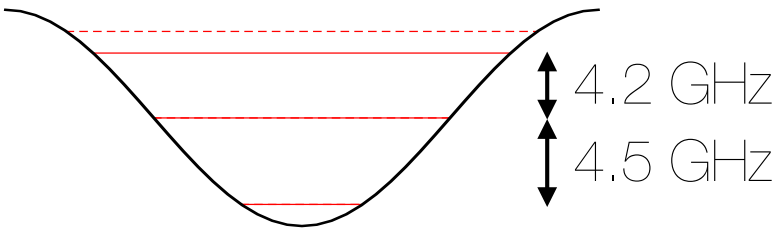


Non-Linear L-C Resonator



L=*L*(*I*)

U=-300MHz

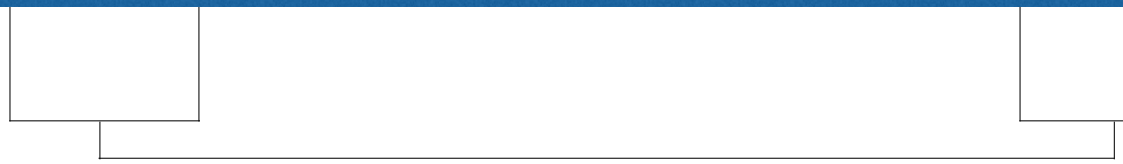


Coupling the Lattice Sites

Summary of Parameters

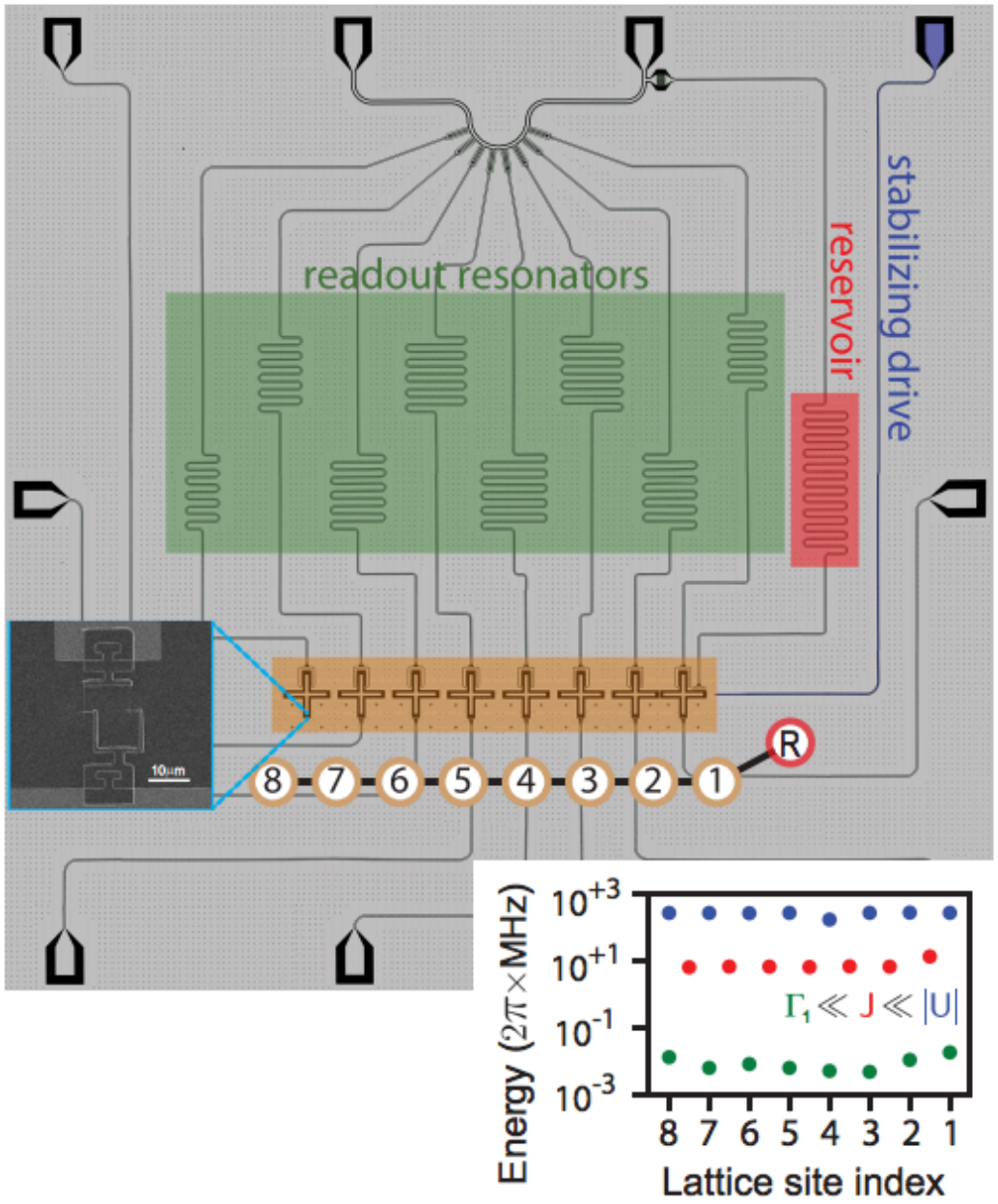
U = -300 MHz
J = 10 MHz
T_1 = 40 µs

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



L=L(l) ***U***=-300MHz

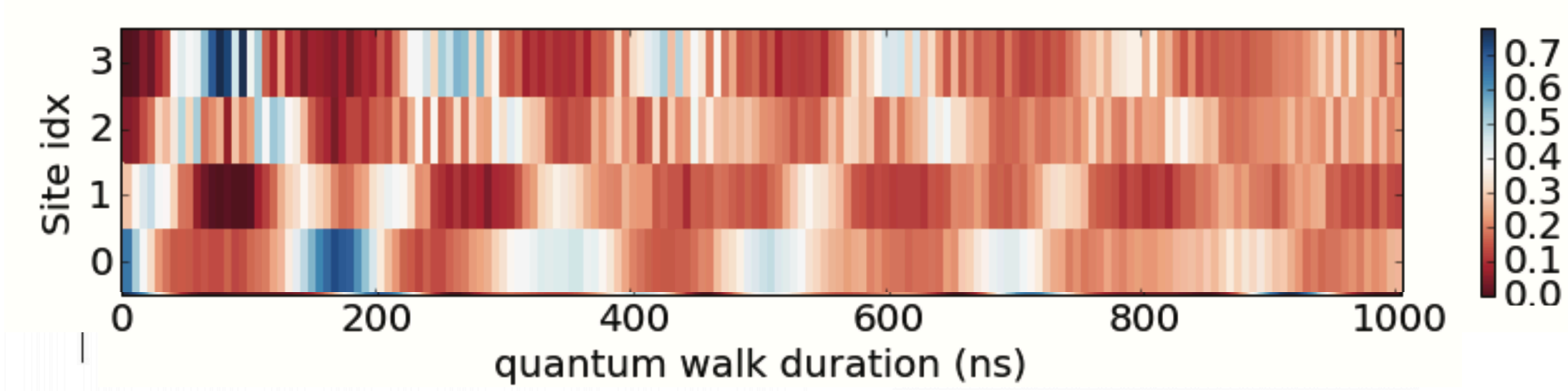
The Actual Lattice

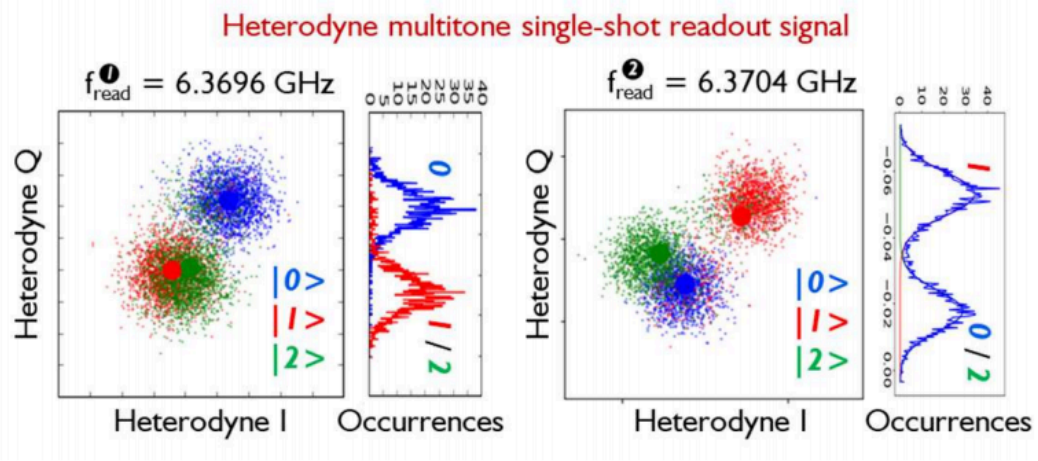


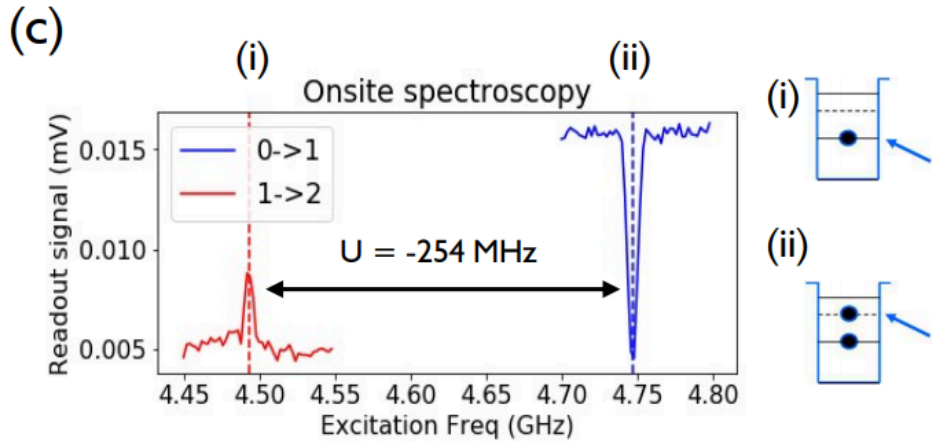
Ruichao Ma *et al.*, Nature **566**, 51–57 (2019)

Microscopy Tools in the Circuit Lattice

Measured

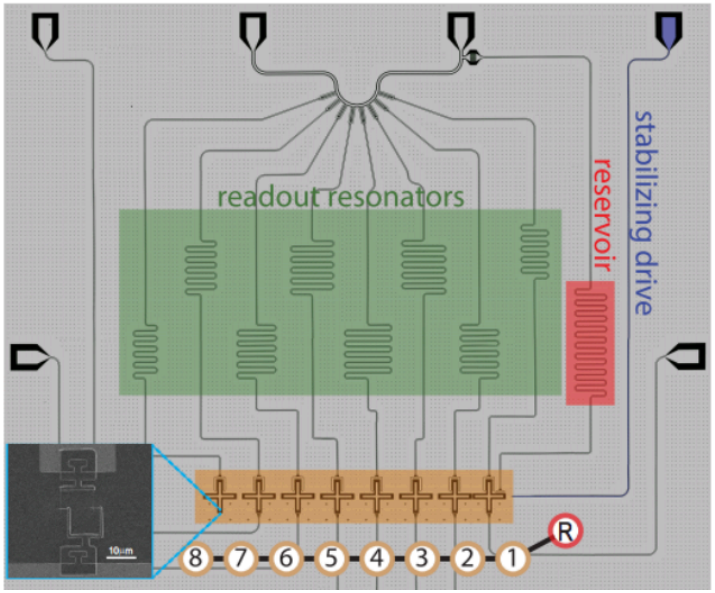


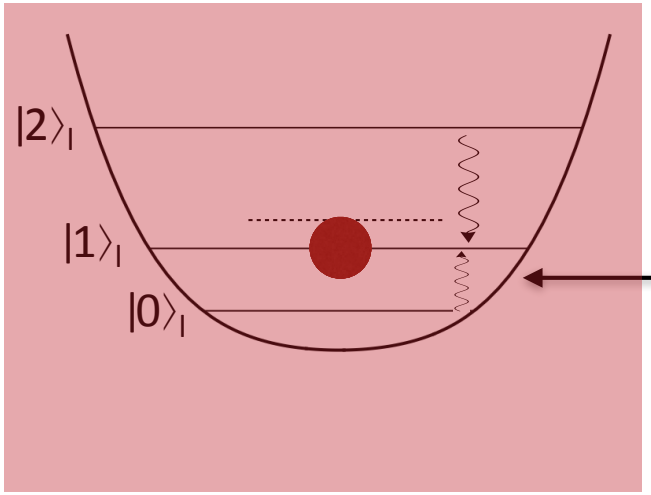


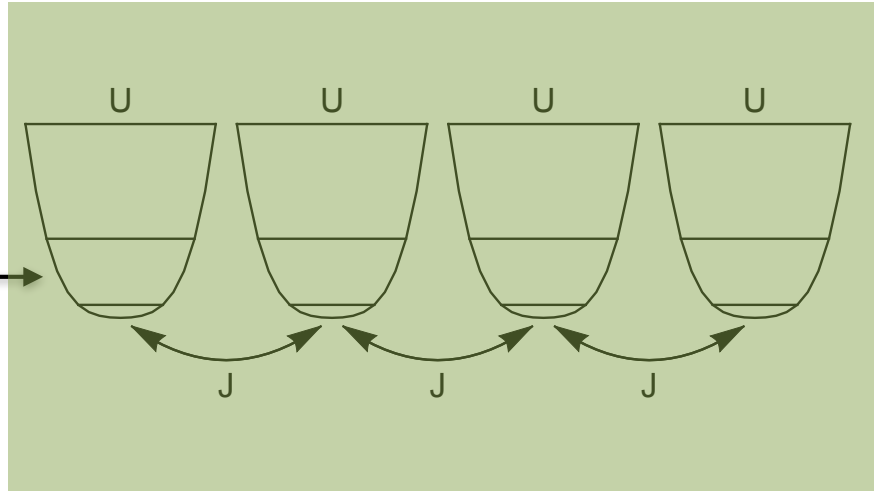


Ruichao Ma et al. arXiv: 1807.11342 (2018)

A Mott Insulator of Photons





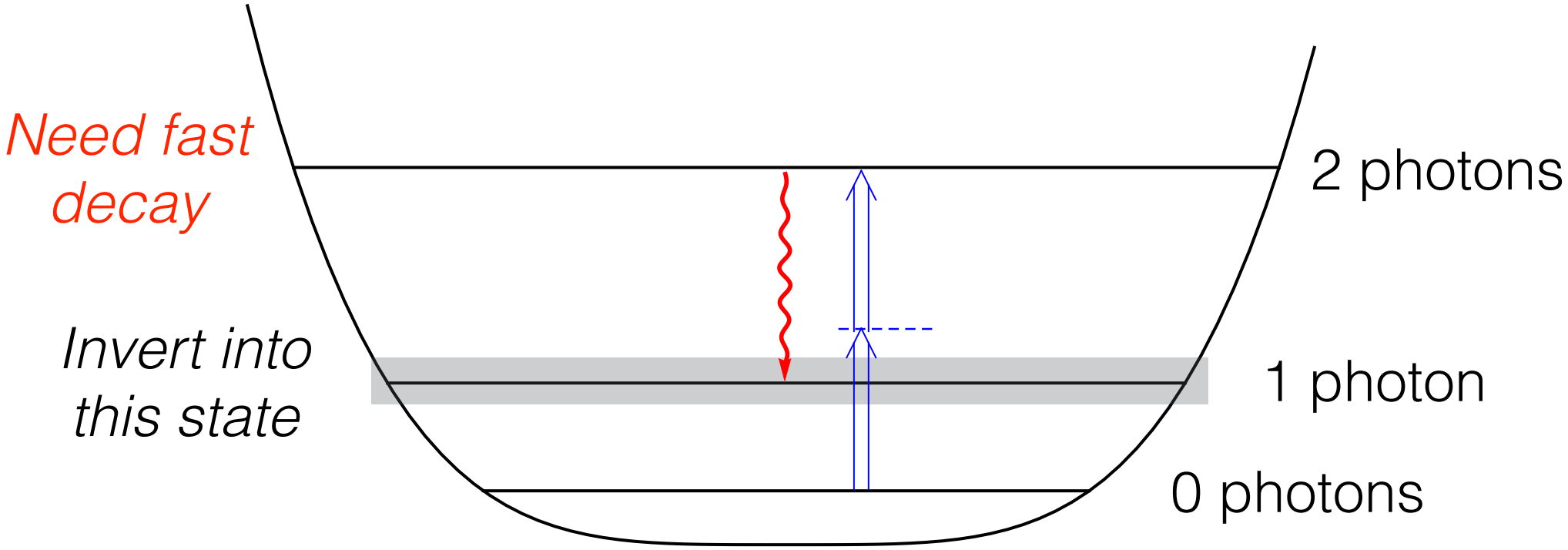


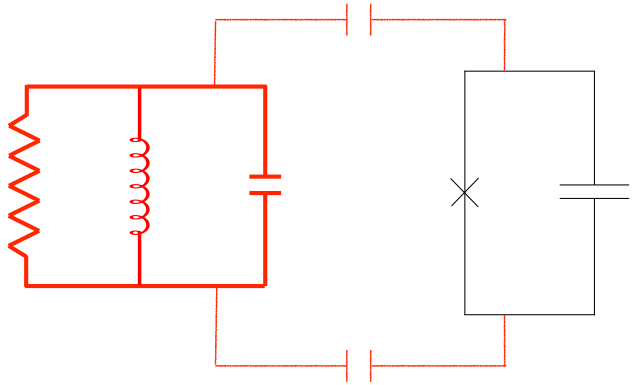
But not (yet) this!

I've told you how to make this

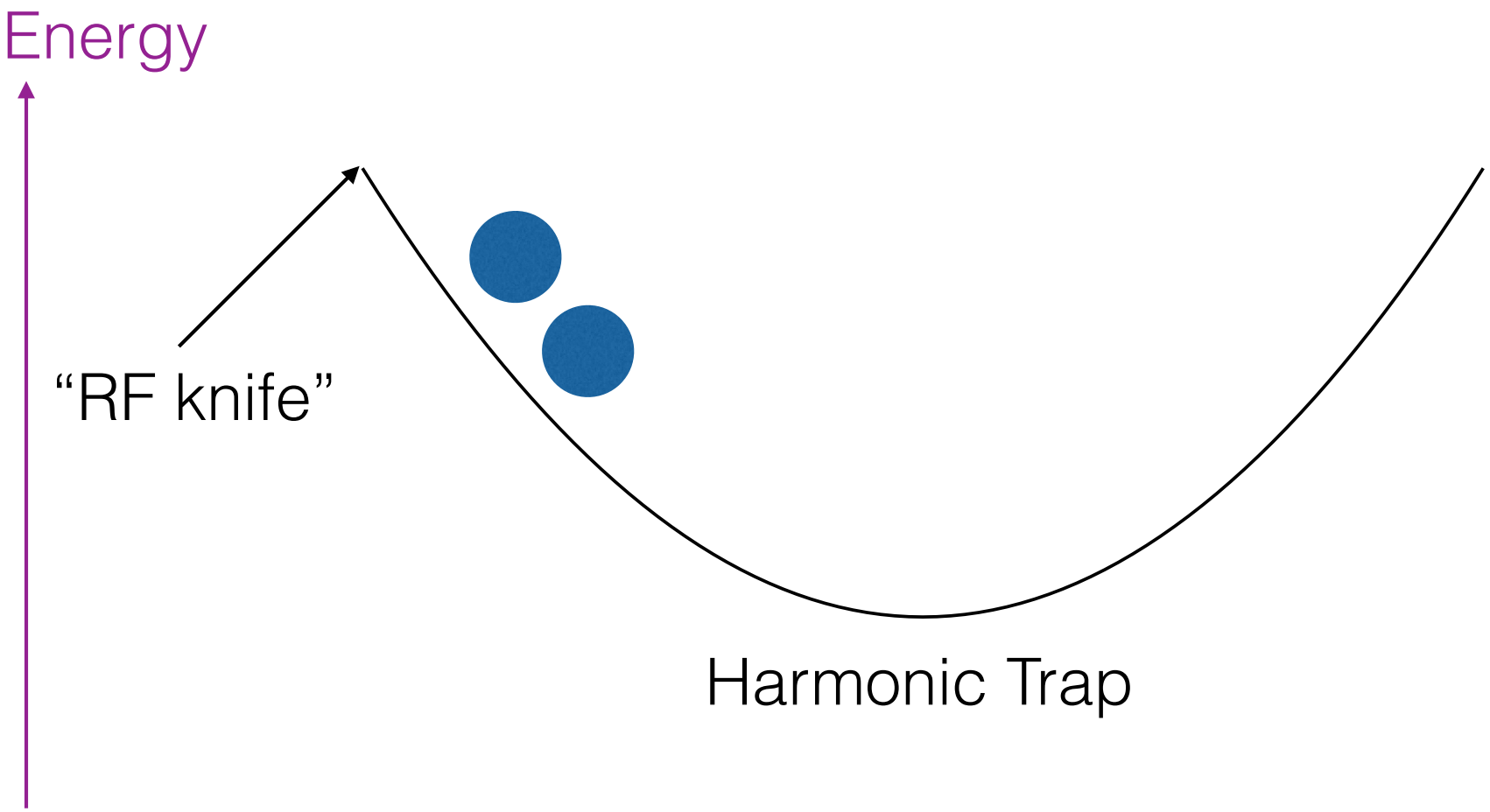
Kapit *et al.,* PRX **4**, 031039 (2014) ; Hacohen-Gourgy et al, PRL **115** 240501 (2015); Hafezi *et al.* PRB **92**, 174305 (2015); Biella *et al.* PRA **96**, 023839 (2017) (2017); Ma *et al.* PRA **95**, 043811, (2017)

The Stabilizer:
"Optically Pumping" a Qubit

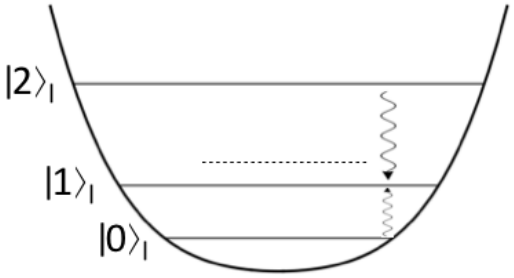


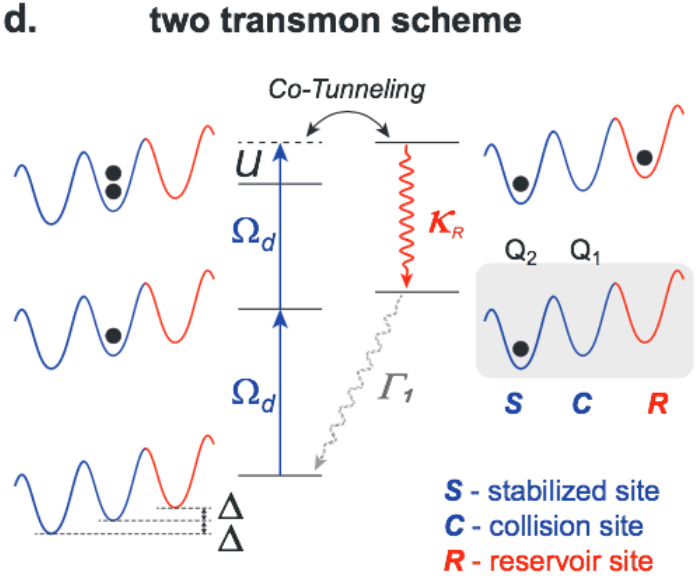


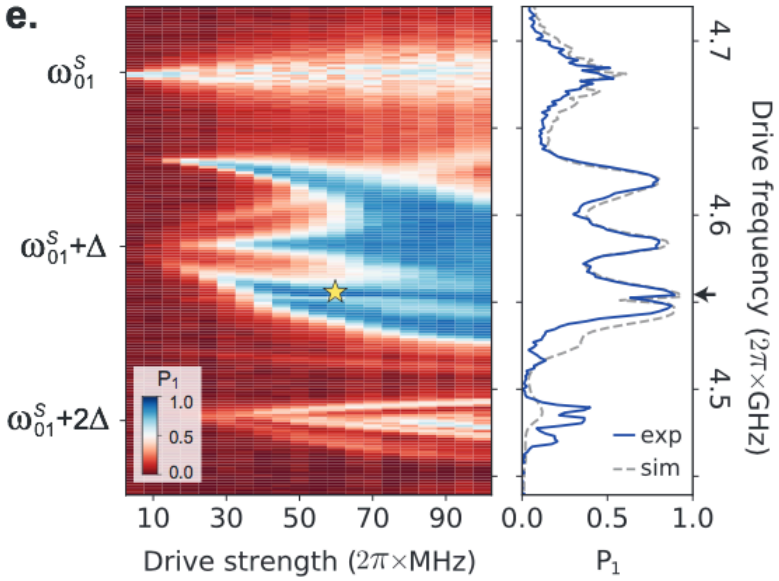
The Stabilizer: Analogy To Evaporation to BEC

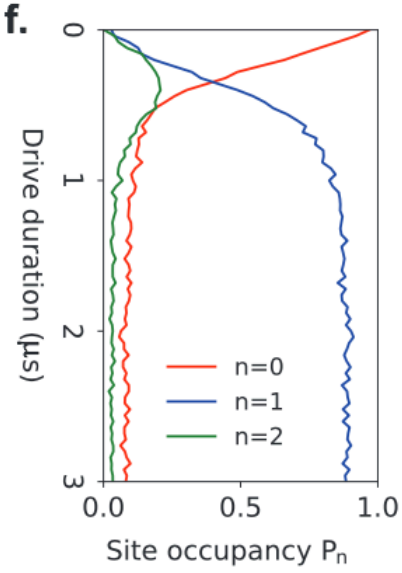


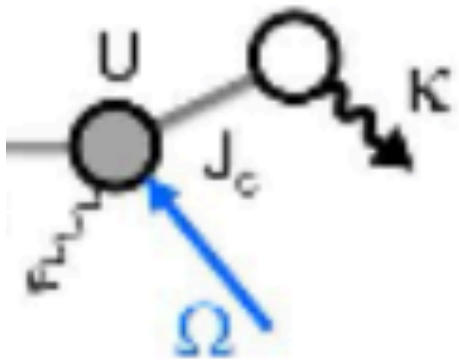
The Stabilizer





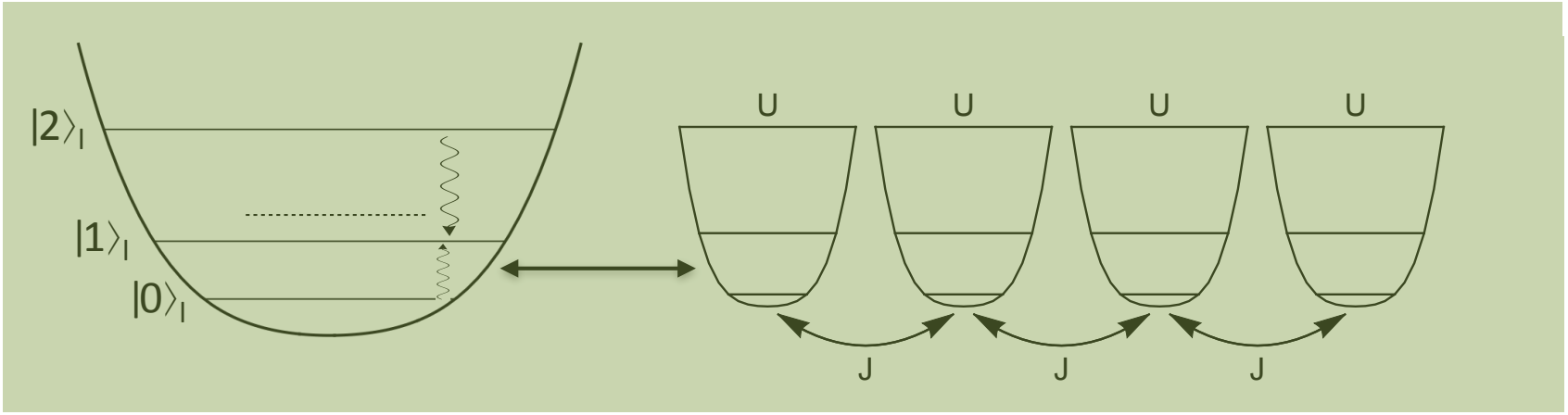






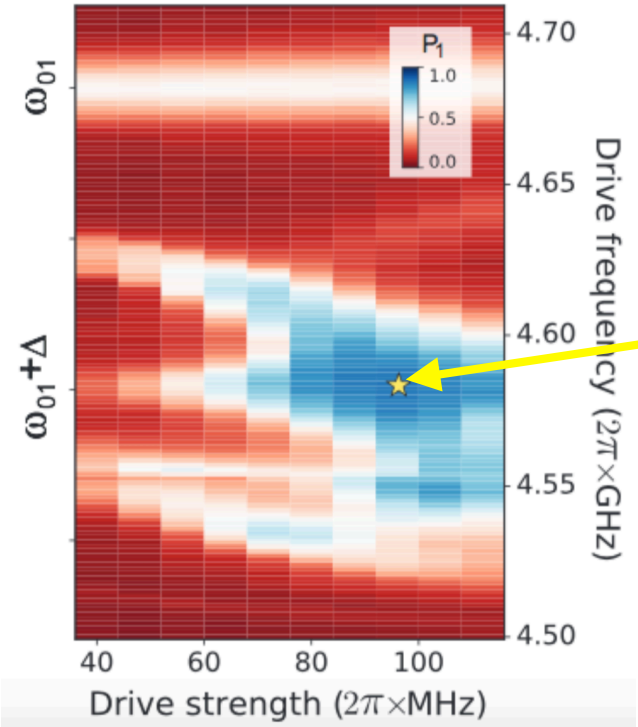
Ruichao Ma et al. PRA **95**, 043811 (2018)

The Photon Mott Insulator



We now know how to make all the pieces!

Chain Fidelity vs Drive Parameters

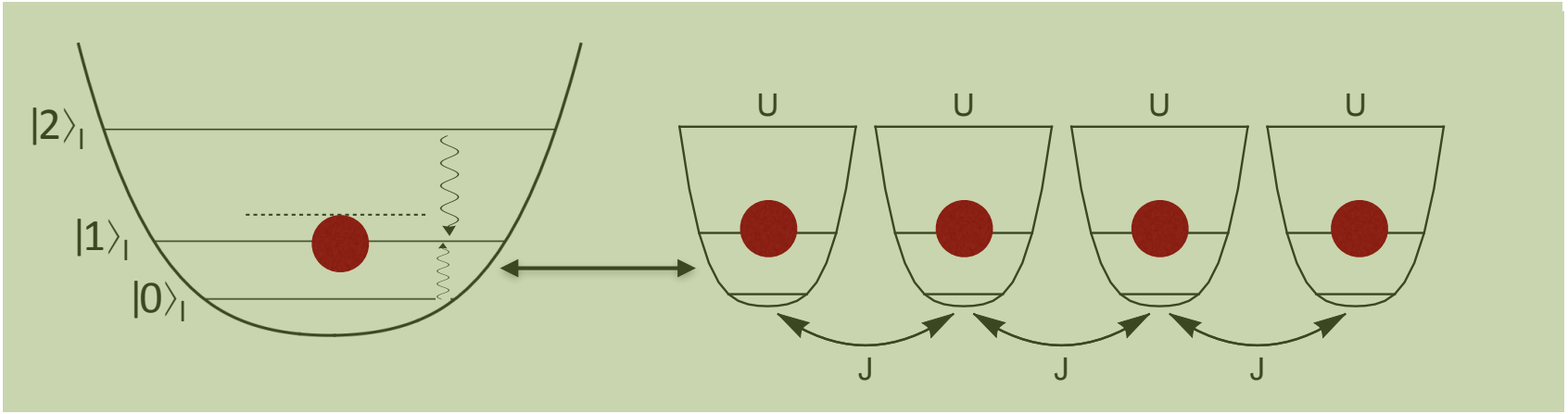


This is our Mott Insulator!

Temporal Filling Dynamics

Ruichao Ma et al. arXiv: 1807.11342 (2018)

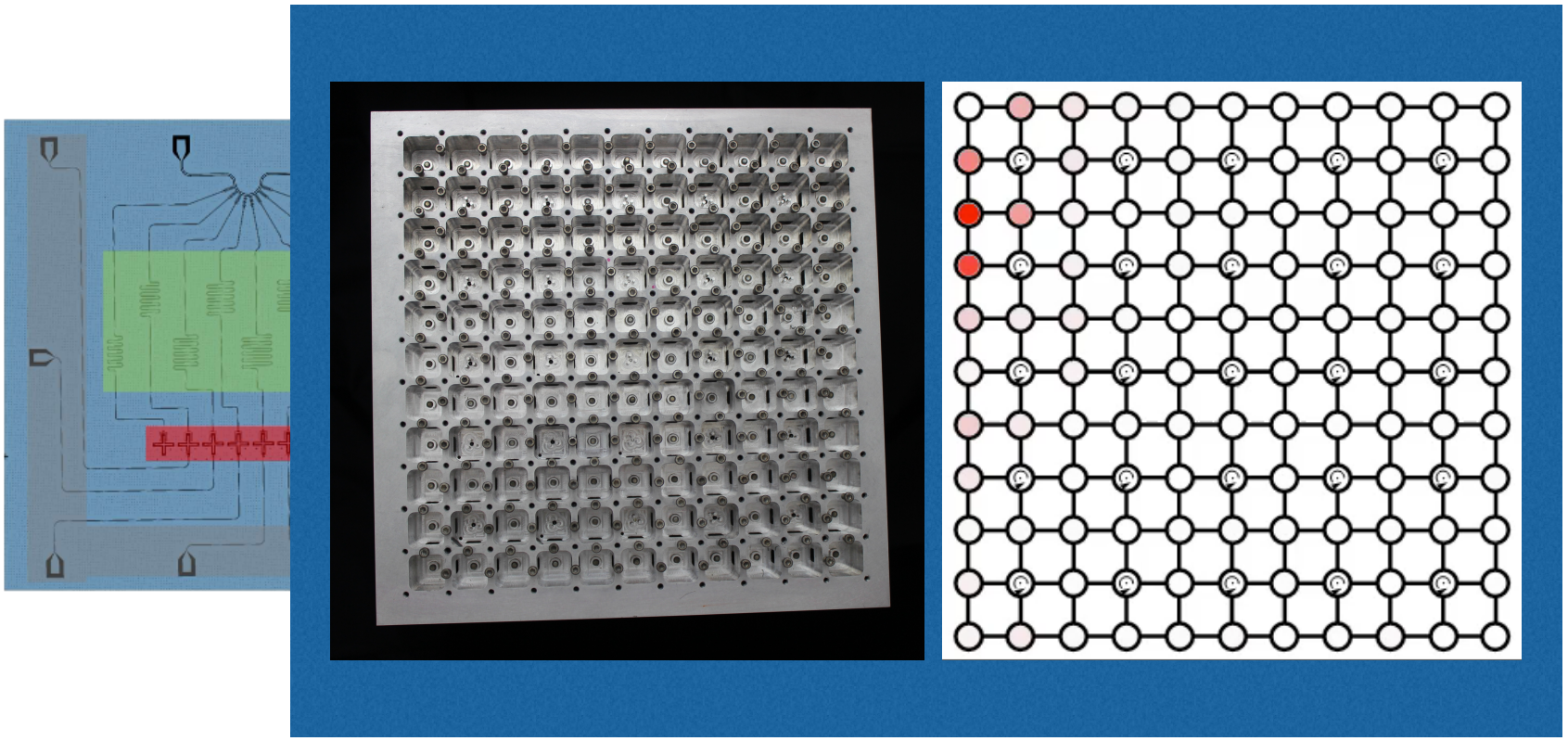
Hole Refilling Dynamics



What Happens Next?!

Ruichao Ma *et al.* Nature **566**, 51–57 (2019)

Outlook: Fractional Chern Circuit



?

Owens *et al.*, PRA **97**, 013818 (2018)

Anderson *et al.*, PRX **4**, 041043 (2016)

Outlook: Non-Equilibrium Thermodynamics

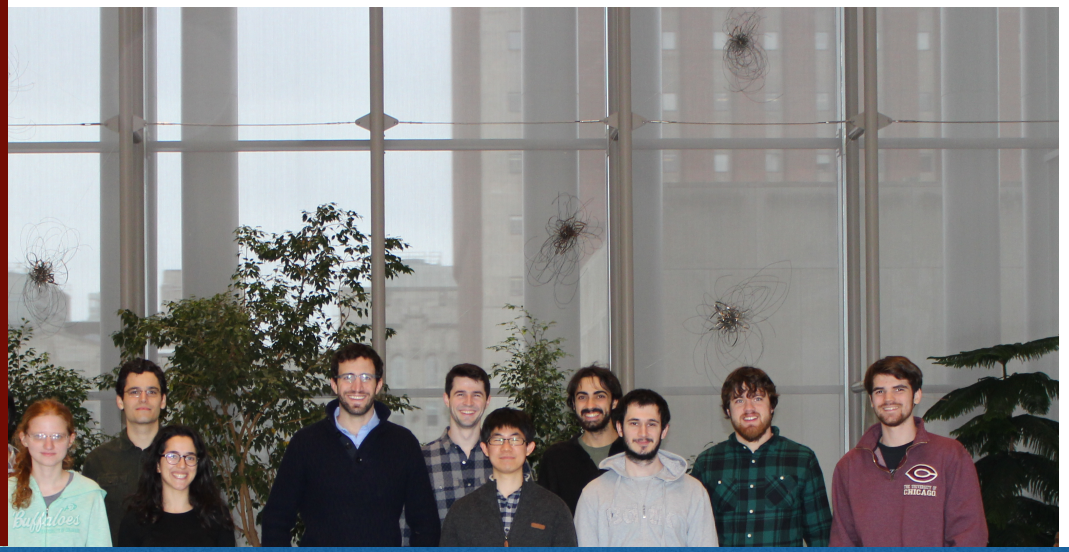
Open questions:

- Non-eq. thermodynamic theory of stabilization
- Therm. rate of density vs therm rates of correlators— string order?
- How much does stabilization perturb equilibrium phases?
- Optimal stabilizer? Model dependence…

Endres *et al.*, Science **14**, 334, 6053 (2011)

owledgements

Alex (Ruichao) Ma



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Brendan Saxberg (PhD)

Sarayu Narayan (UG)

Aman LaChapelle (Former UG)

Optical/mmWave Hybrid

Aziza Suleymanzade (PhD)

Mark Stone (PhD)

Lin Su (UG)

... and Many More!

Logan Clark

Nathan Schine