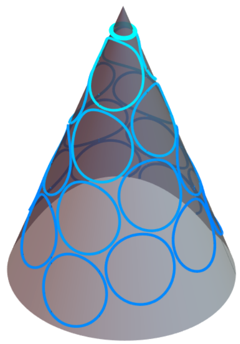
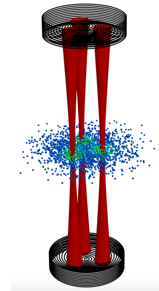


Topological Photonics

Landau Levels in Curved Space



Jon Simon

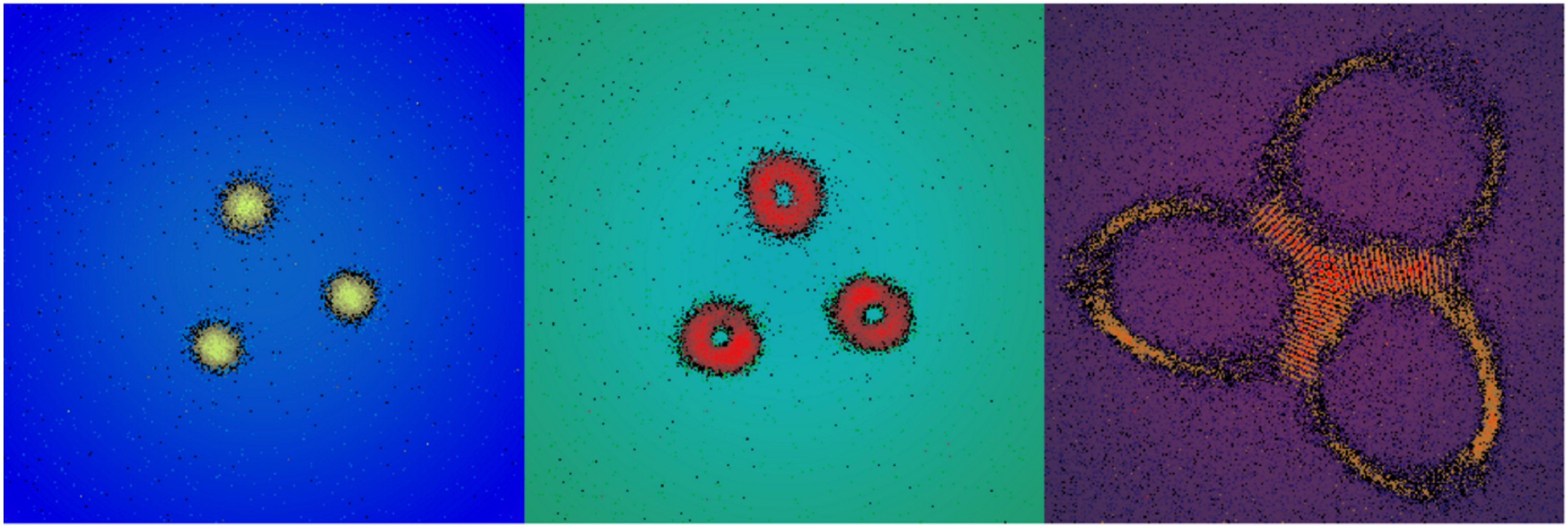
University of Chicago

Chicago, Illinois

Topological Quantum Matter

KITP @ UCSB

October 18th, 2016



quantum.uchicago.edu & simonlab.uchicago.edu

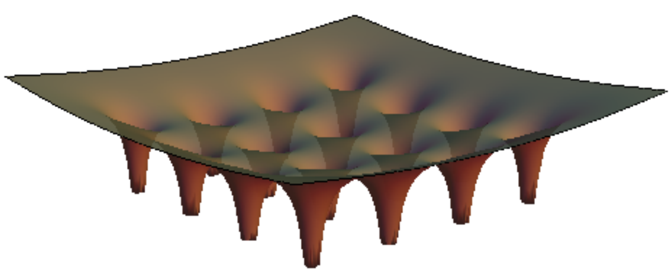
Support: AFOSR YIP, DOE YIP, DARPA YFA, DARPA FP060494, ARO MURI, AFOSR MURI, UofC MRSEC

Synthetic Material Systems

Solid State

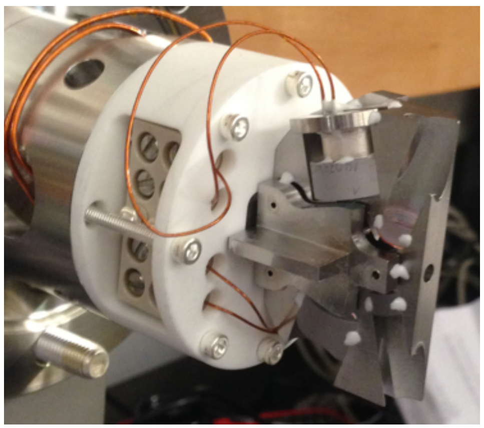
Interacting Electrons

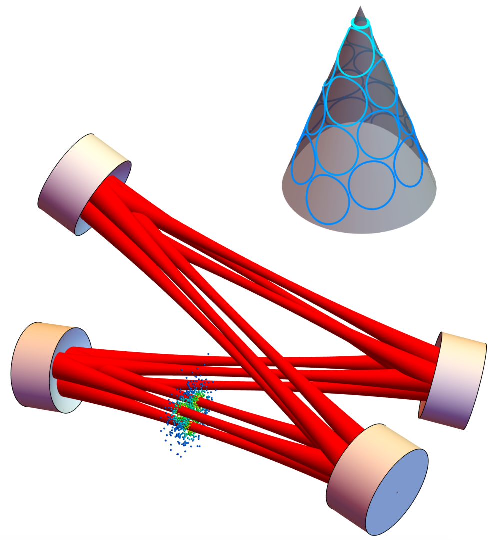
Ionic Lattice



Topological Cavity QED

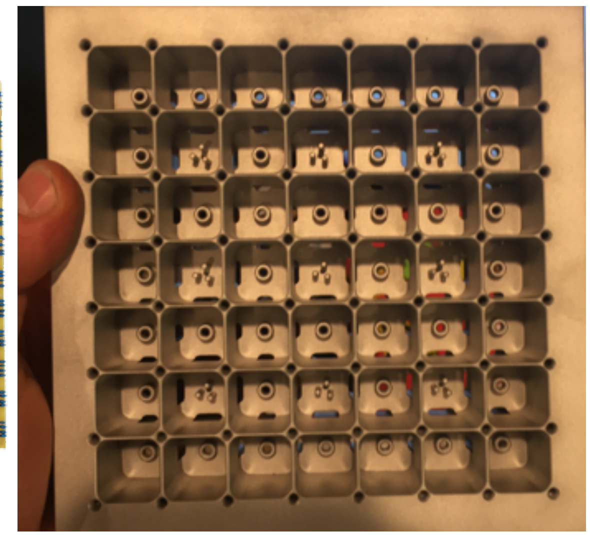
Twisted Optical Resonators





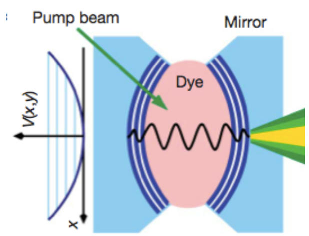
- **Bulk** Landau Levels
- **Atoms** Break T
- **Rydberg EIT** for Interactions
- **Flux threading** to build manybody states

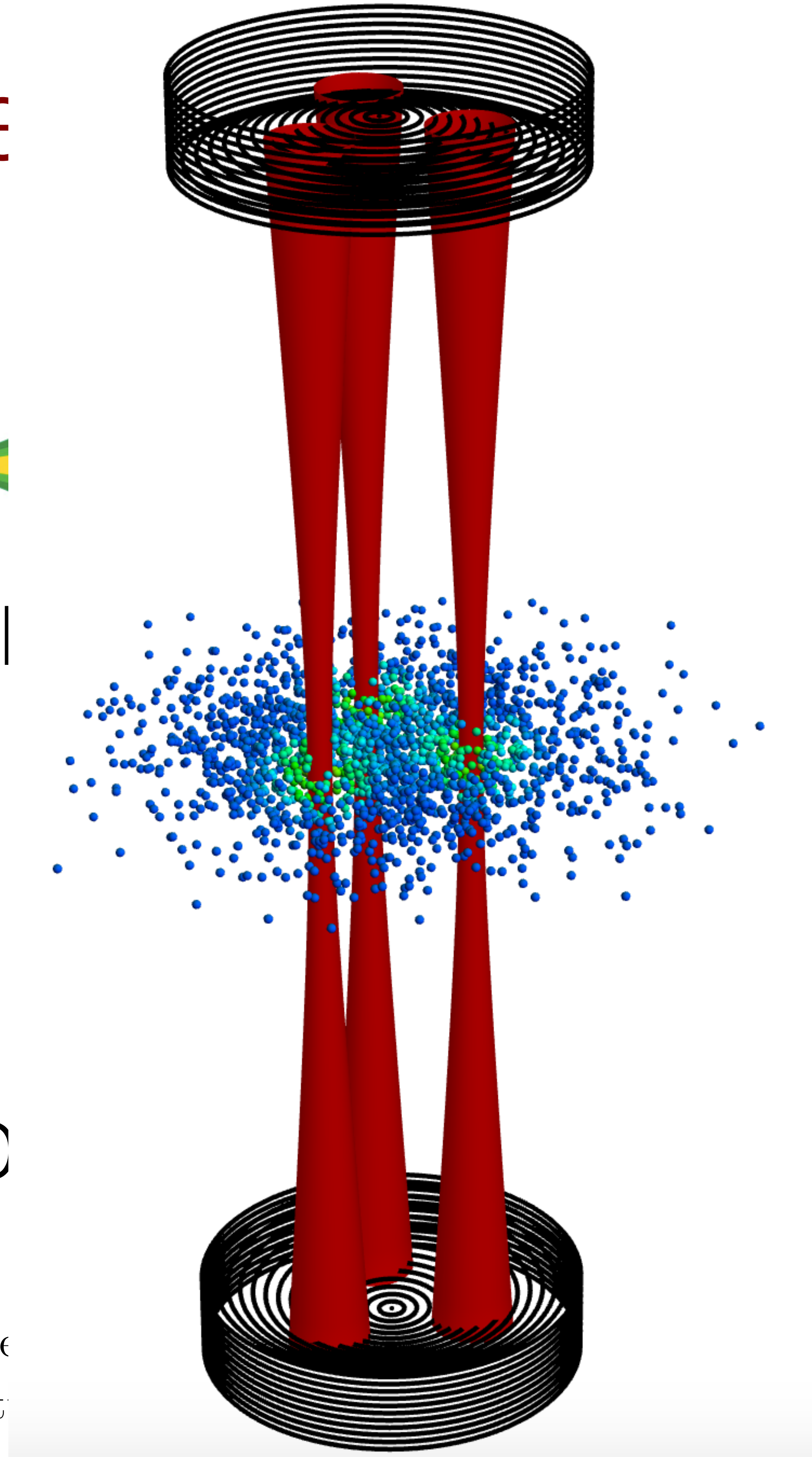
μ-wave Lattices

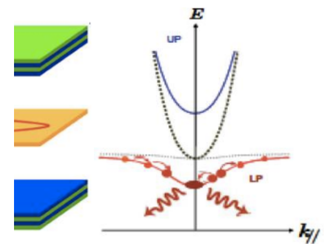


- **Lattice** Z_2 & Chern Bands
- **Ferrites** Break T
- **Transmons** for Interactions
- **Chem pot'l** to build manybody states

Synthe aterials







Photon Bl 'olaritons [2]

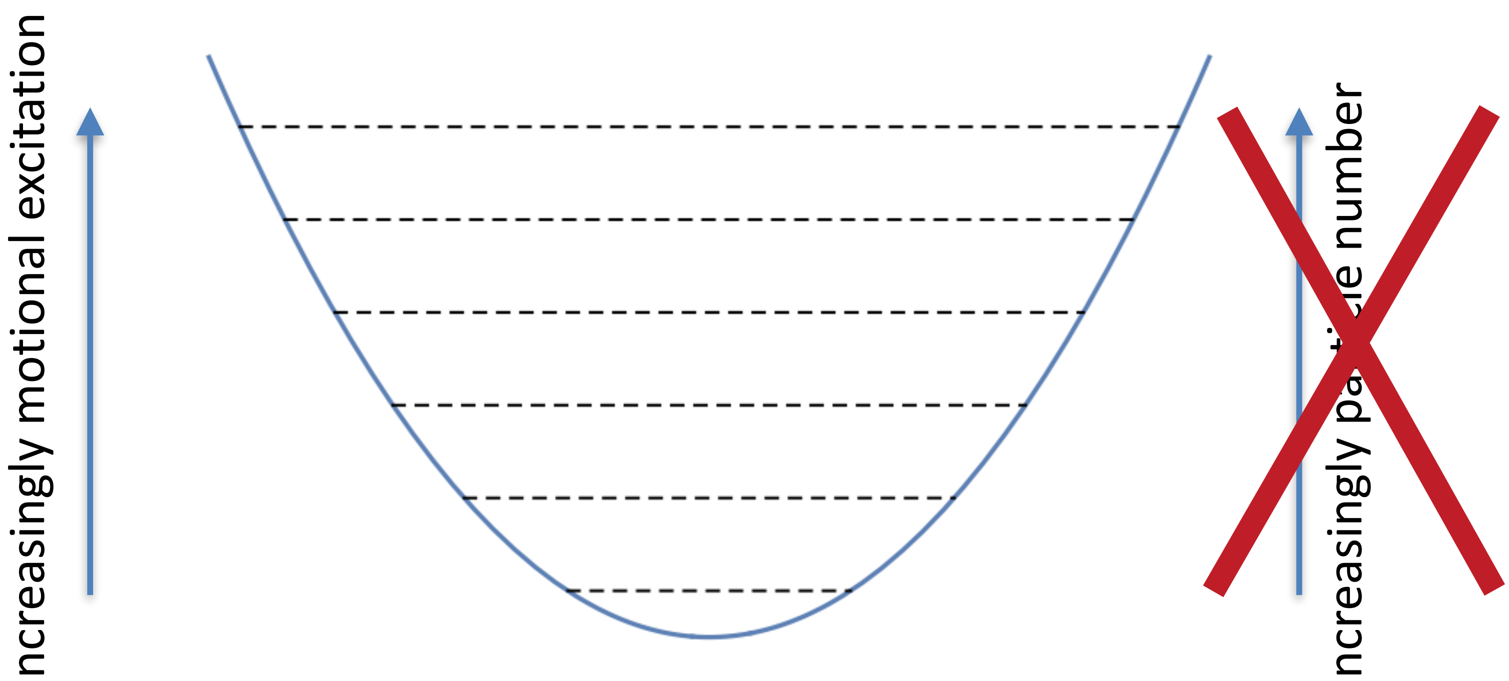
1D is [3]

[1] Klaers *et al.*, Nature ence **298**, 199 (2002)
[3] Peyronel *et al.*, Nat

Central Premise

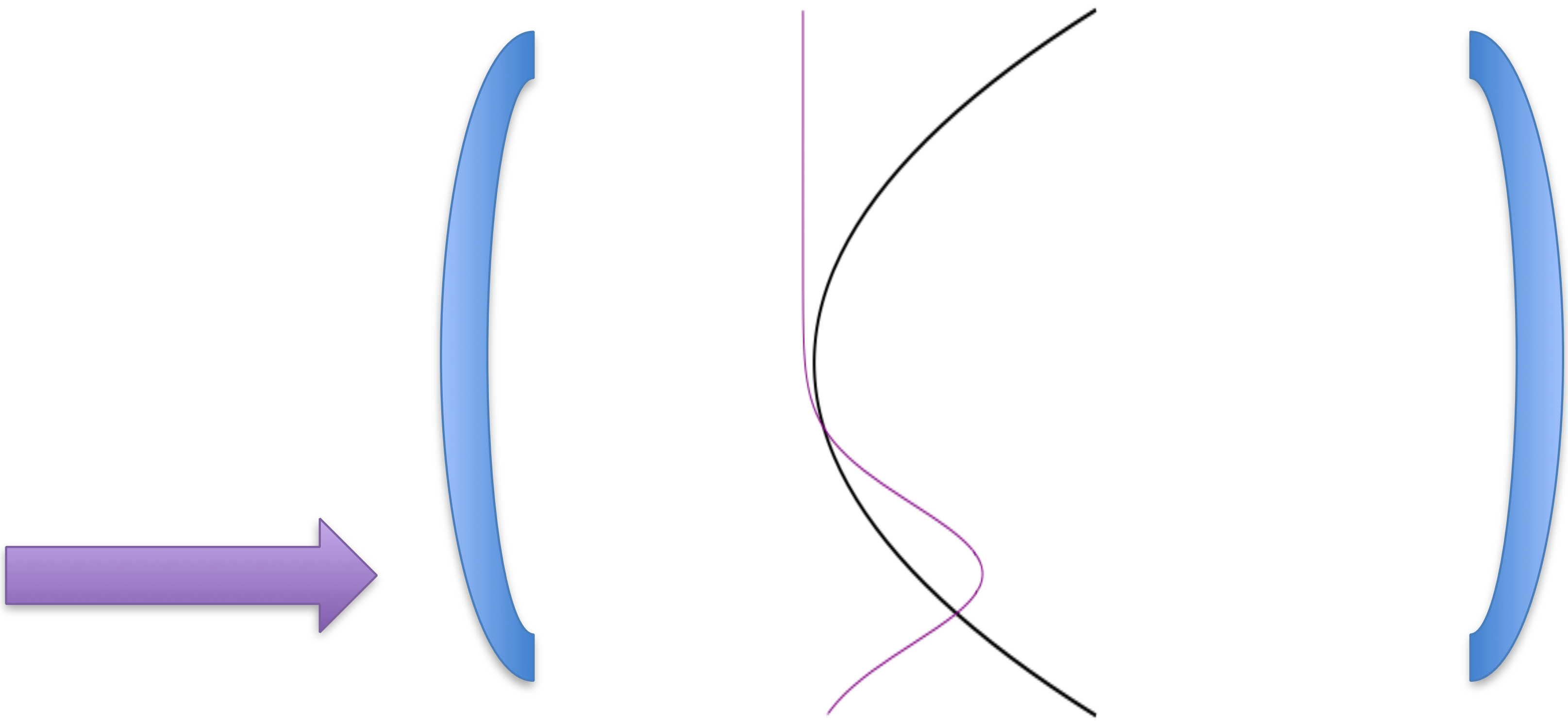
Photons in Multimode Resonator
↕
Massive Particles in Harmonic Trap

- This is a **real space-** not **Fock space-** analogy

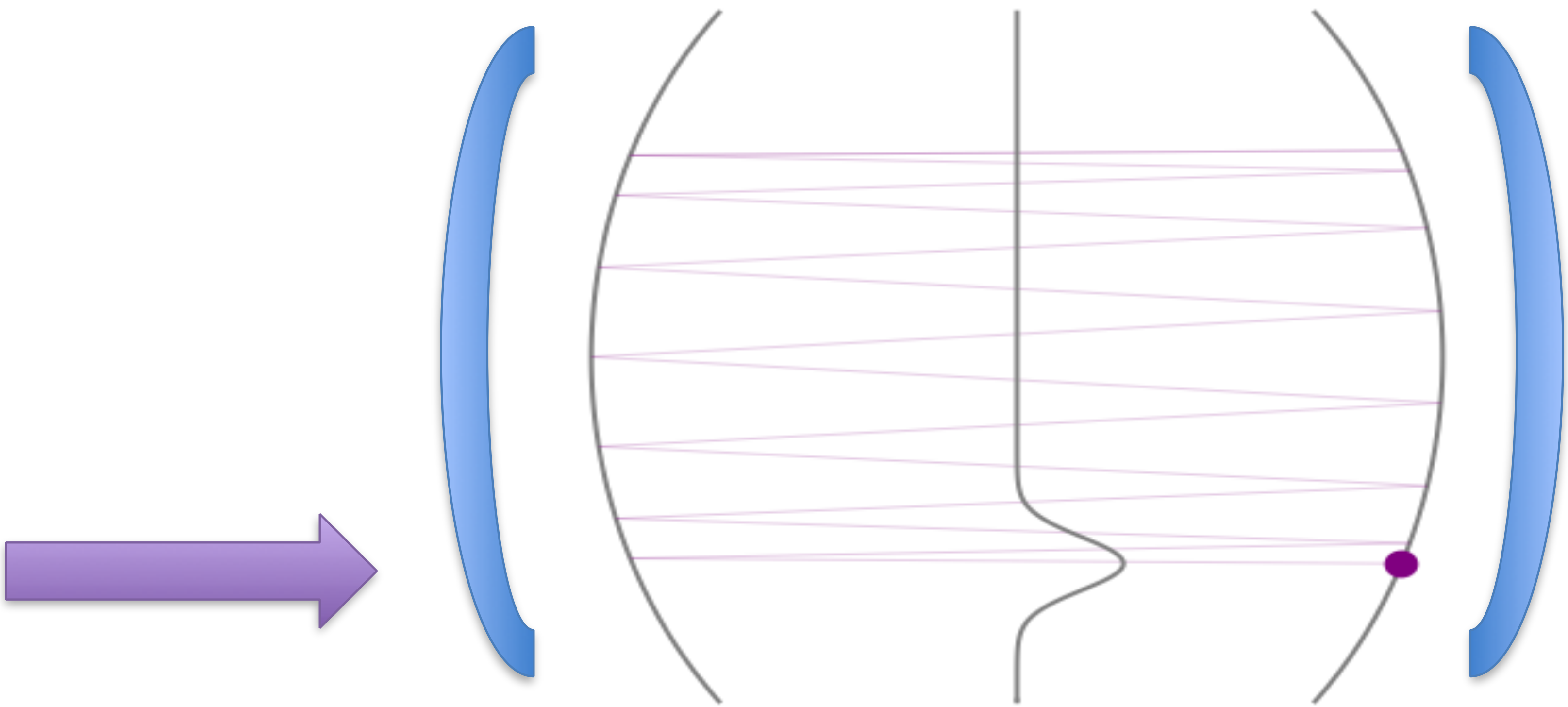


Understanding photons in optical resonators

A photon in a curved-mirror optical resonator behaves like a massive particle in a harmonic trap.

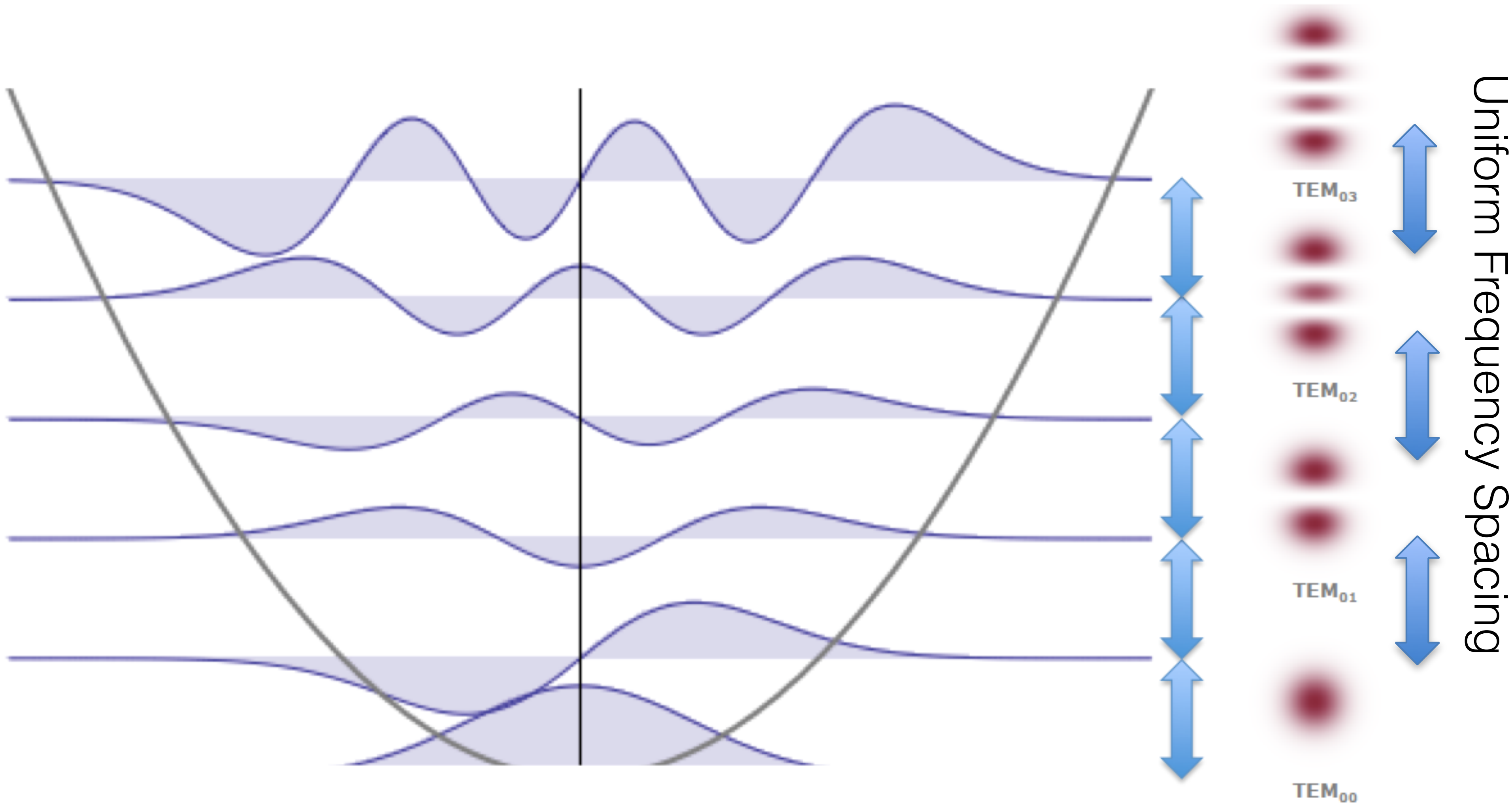


Understanding photons in optical resonators



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

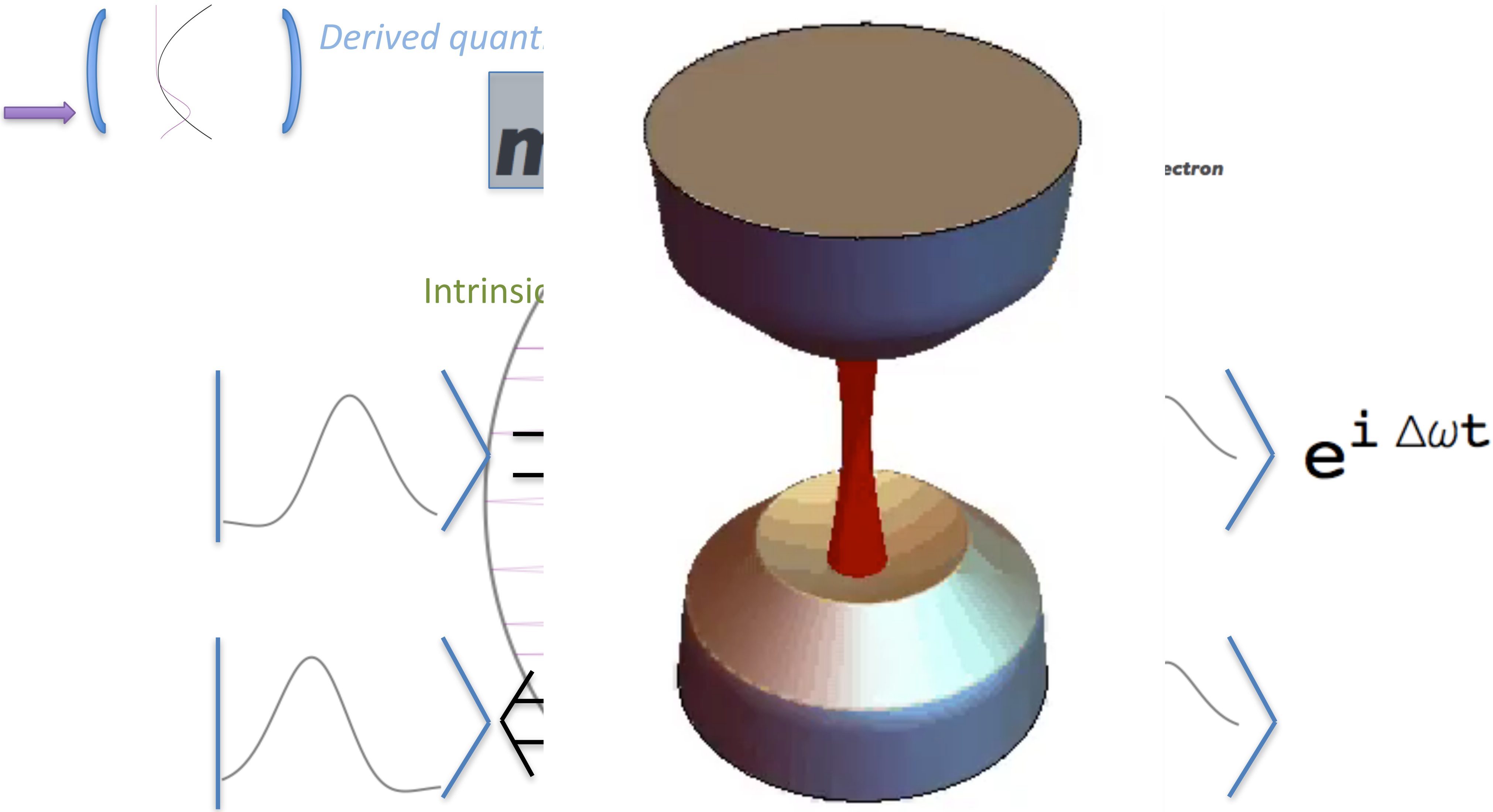
Comparing
Harmonic Oscillators & Optical Resonators



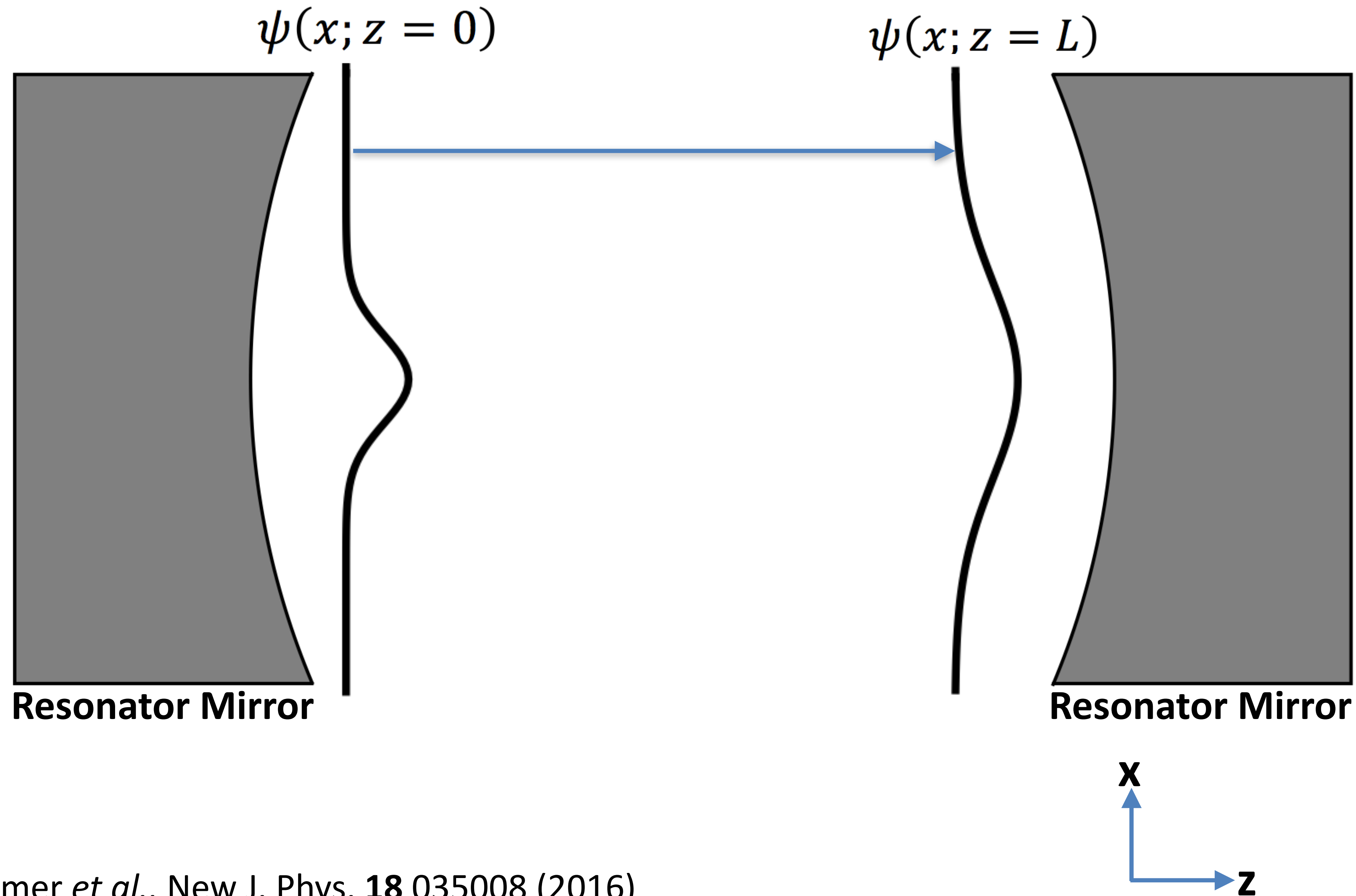
Hermite Gauss Wavefunctions

Optical Modes

Understanding
photons in optical resonators



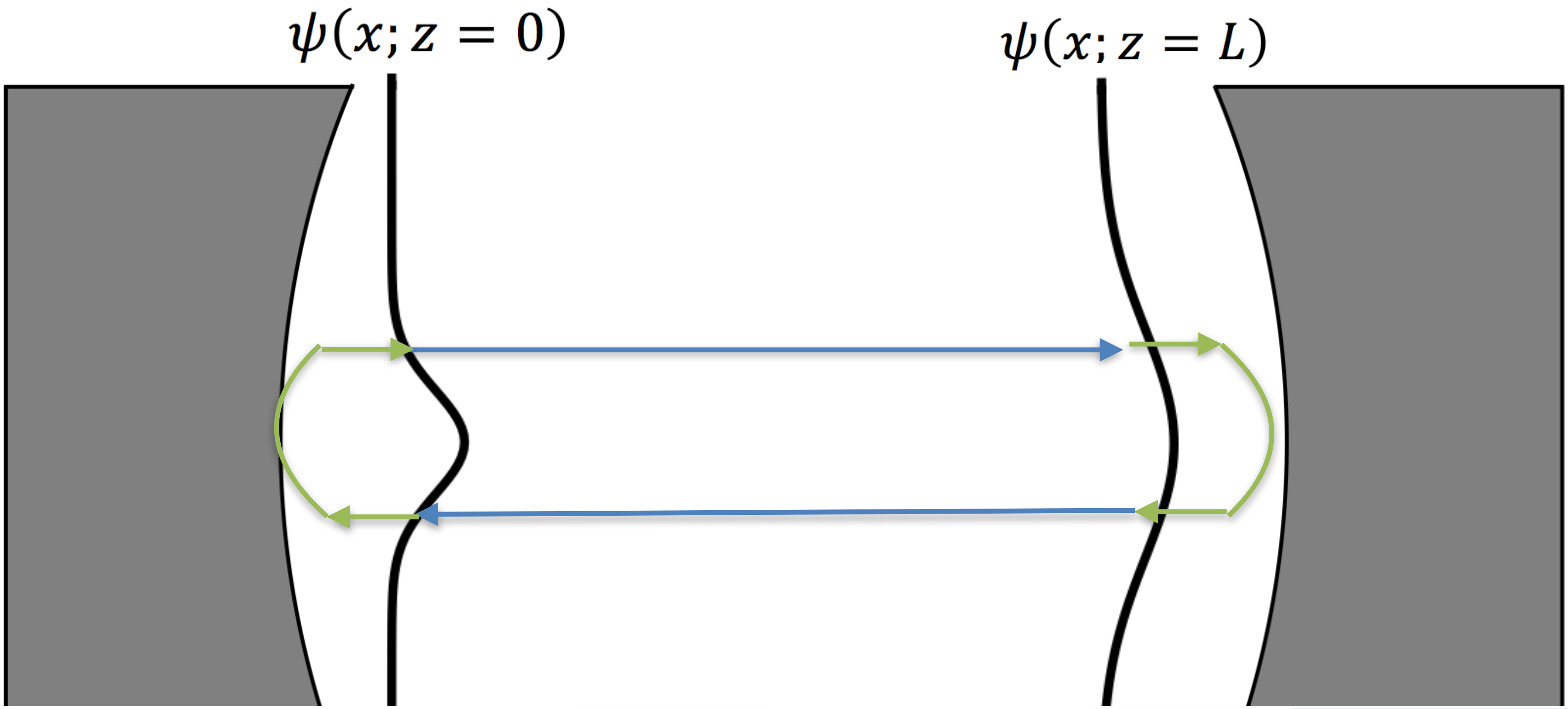
Formal Picture: **Floquet Theory**



Sommer *et al.,* New J. Phys. **18** 035008 (2016)

Formal Picture: **Floquet Theory**

Formal Picture: **Floquet Theory**



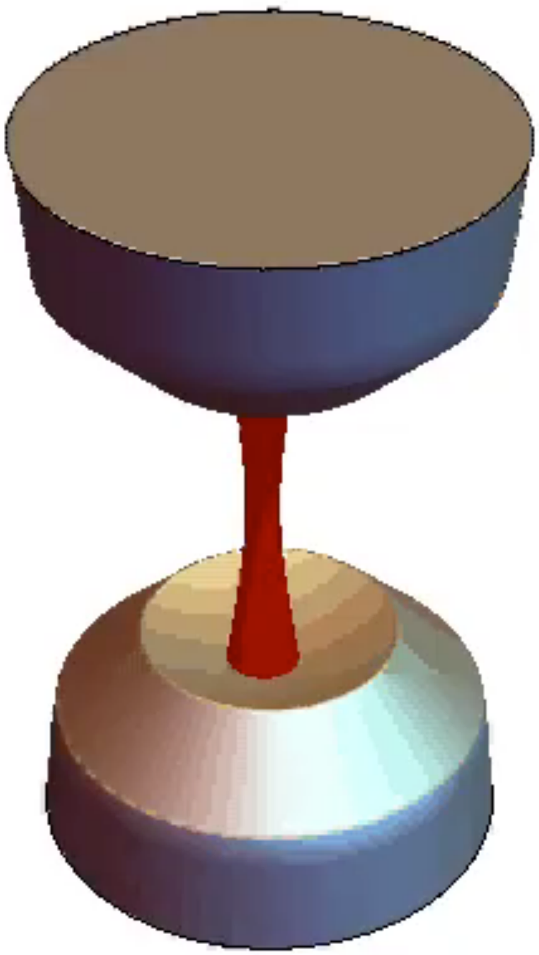
$$H_{floquet} = \frac{1}{i\,T_{RT}} Log\left[e^{-i\frac{kx^2}{2R}} e^{-i\frac{L}{2k}\left(\frac{\partial}{\partial x}\right)^2} e^{-i\frac{kx^2}{2R}} e^{-i\frac{L}{2k}\left(\frac{\partial}{\partial x}\right)^2} \right]$$

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

Rechtsman *et al.*, *Nature* **496**, 196–200 (2013)

Sommer *et al.*, New J. Phys. **18** 035008 (2016)

Synthetic Magnetic Fields for Photons



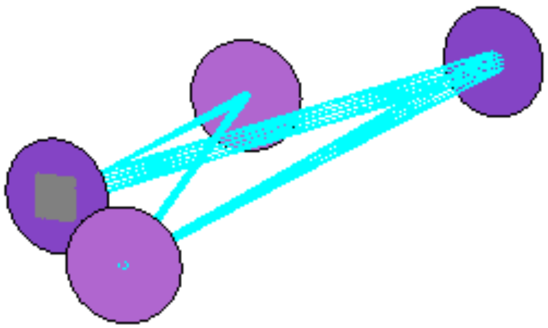
Free Space Propagation → Mass
Mirror Curvature → Trapping
Resonator Twist → B Field

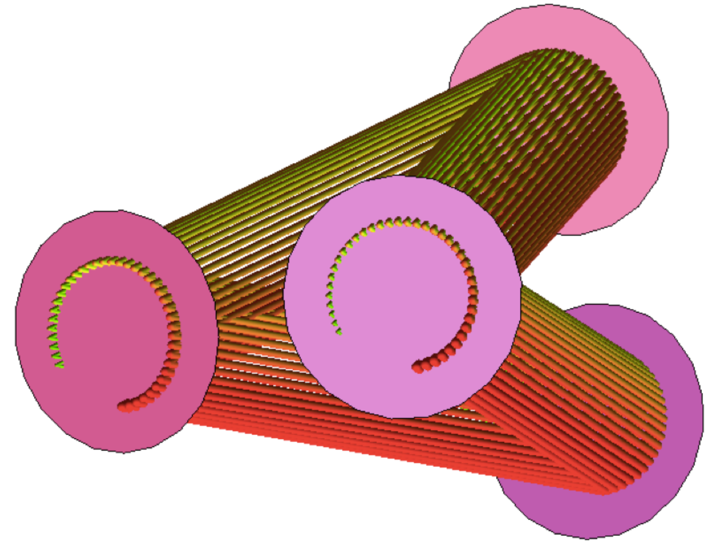
$$H_{floquet} = \frac{1}{iT_{RT}} Log\left[e^{i\theta L_z} e^{-i\frac{kx^2}{2R}} e^{i\frac{L}{2\hbar^2 k}p^2} e^{-i\frac{kx^2}{2R}} e^{i\frac{L}{2\hbar^2 k}p^2} \right]$$

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, arXiv:1411.6624 (2014)
[4] Karzig et al, arXiv: 1406.4156 (2014)

Synthetic Gauge Fields for Resonator Photons





Twisting the resonator out of the plane makes the lab frame a rotating frame!

$$H_{floquet} = \frac{1}{iT_{RT}} Log \left[e^{i\theta L_z} e^{-i\frac{kx^2}{2R}} e^{i\frac{L}{2\hbar^2 k}p^2} e^{-i\frac{kx^2}{2R}} e^{i\frac{L}{2\hbar^2 k}p^2} \right]$$

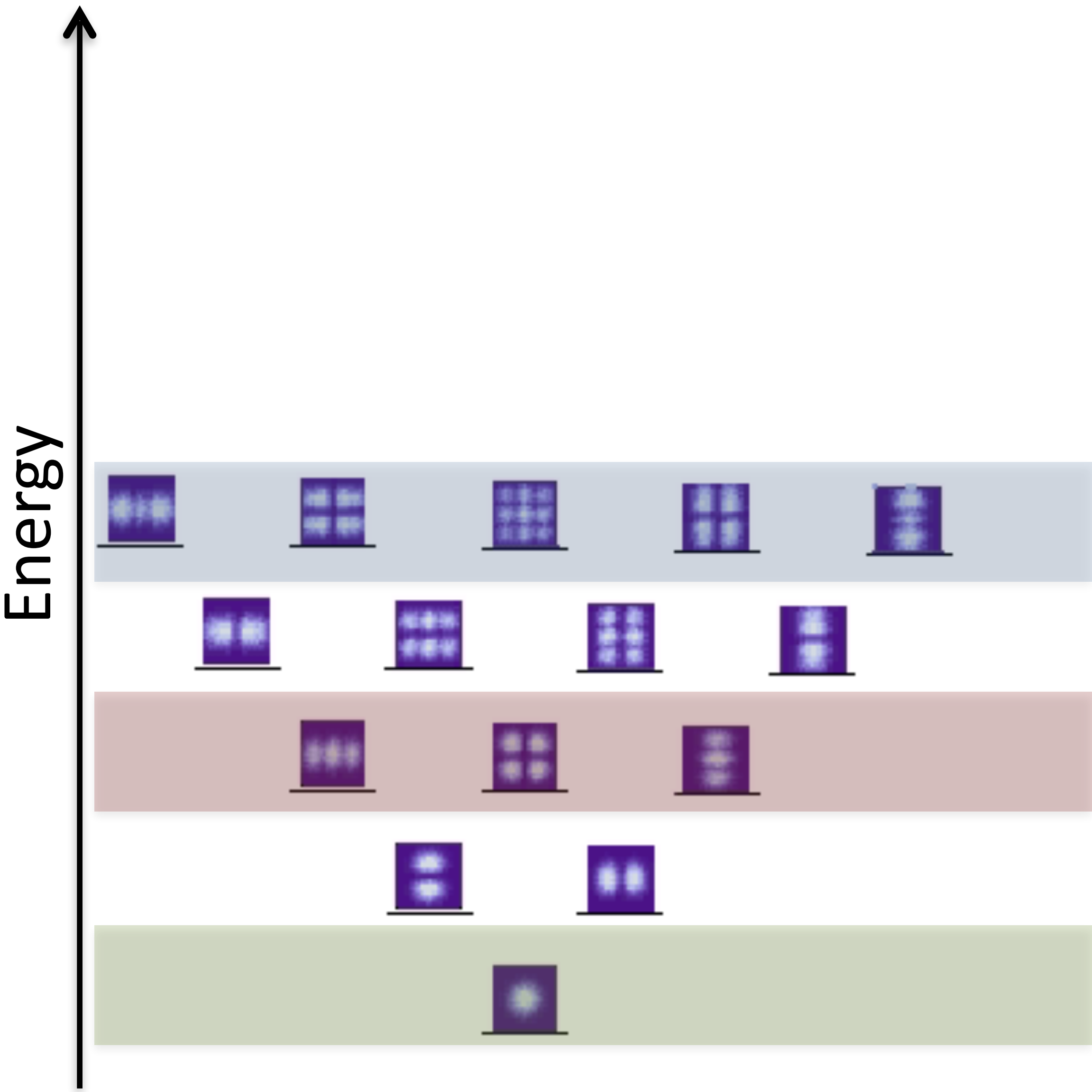
[1] Cooper, Phys. Rev. Lett. **106**, 175301 (2011)

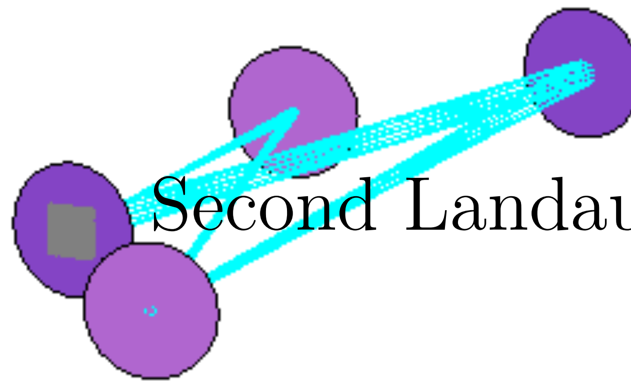
[2] Otterbach, Phys. Rev. Lett. **104**, 033903 (2010)

[3] Maghrebi et al, arXiv:1411.6624 (2014)

[4] Karzig et al, arXiv: 1406.4156 (2014)

Flattening Photonic Landau-Levels





Second Landau Level

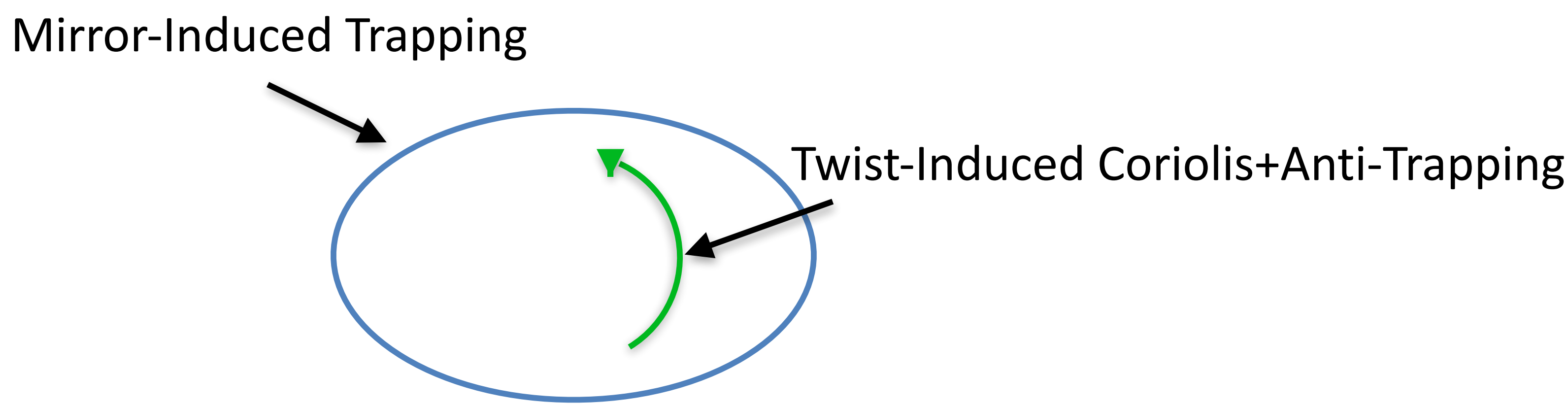
First Landau Level

Lowest Landau Level

$$\Psi_L(z \equiv x + iy) = \frac{z^L}{\sqrt{\pi L!}} e^{-z\,\bar{z}}$$

Photonic Centrifugal Barrier

- Twisted Cavity → Lab Frame Coriolis Force + Anti-Trapping
- Slightly Astigmatic Harmonic Confinement (**drives Δ*l* = ±2 transitions**)



[1] Fetter, Rev. Mod. Phys. **81**, 647 (2009)
[2] Cooper, Adv. in Phys., **57**, 539 (2008)

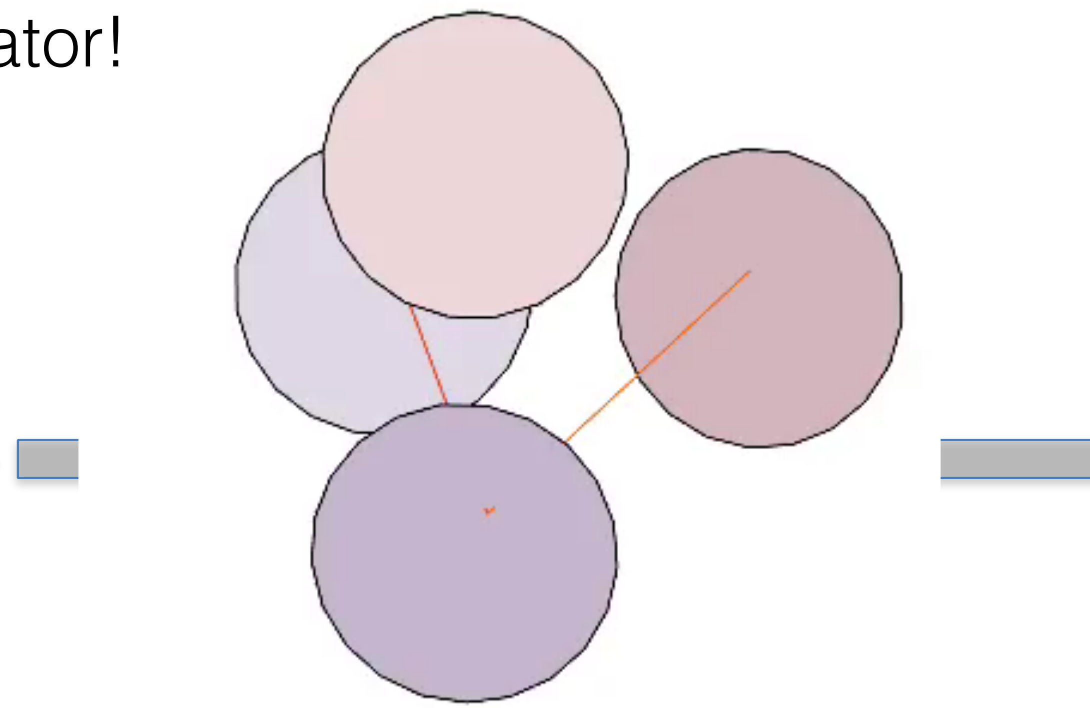
Stabilizing the System

- Floquet instability at degeneracy due to Δl = ±2 transitions
- Modify LLL to include only l=0,3,6,9… removes instability

$$\Psi_M(z \equiv x + iy) = \frac{z^{3M}}{\sqrt{3\pi M!}} e^{-z\bar{z}}$$

- How? Keep twisting resonator!

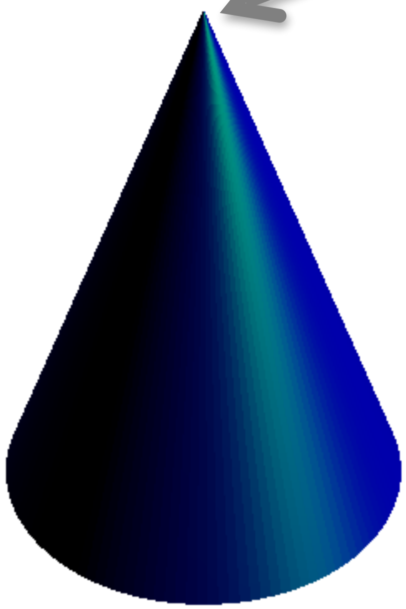
LLL for different
Floquet manifolds
(longitudinal modes)

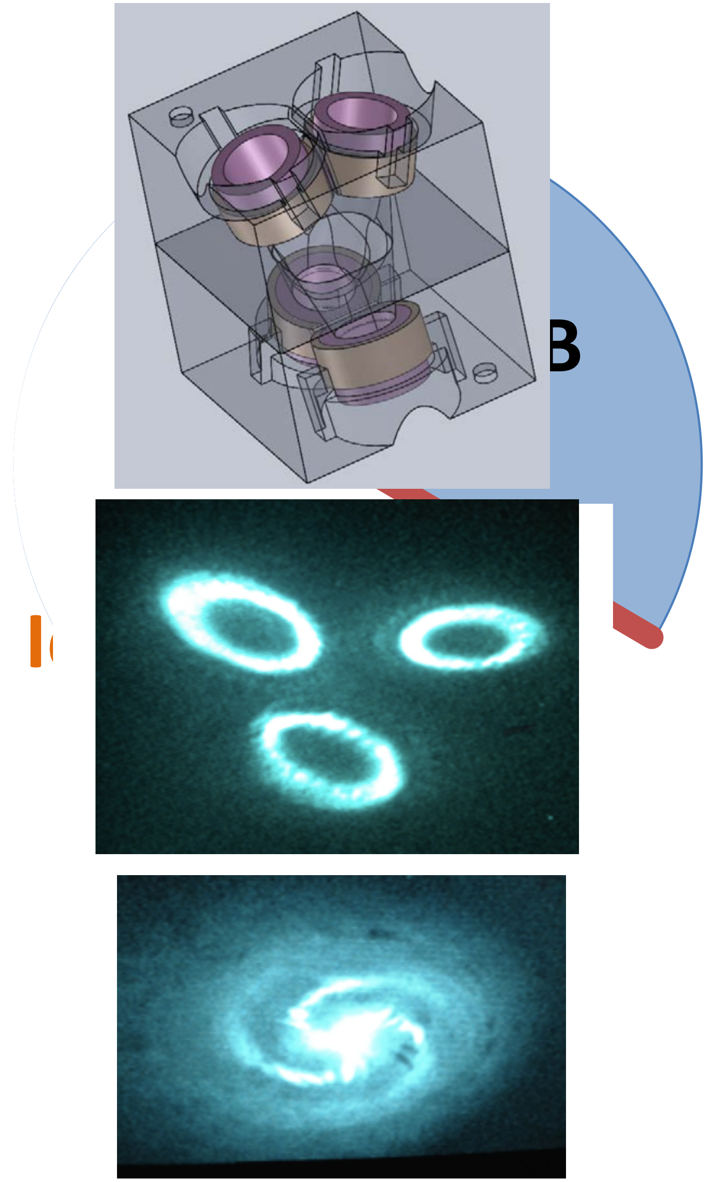


What is this new, stable "LLL," **physically**?

Landau Levels on a Cone

All Gaussian Curvature
Concentrated Here

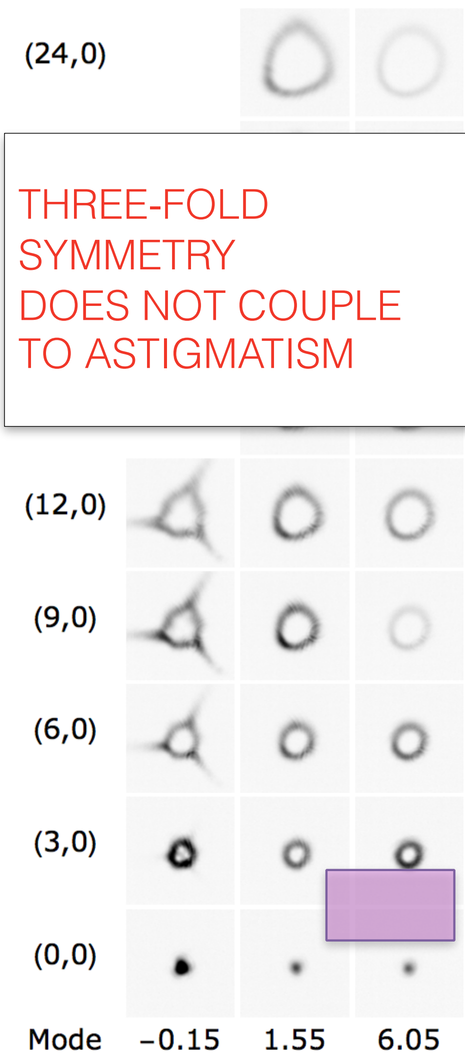




Schine *et al.*, **Nature** doi:10.1038/nature17943 (2016)

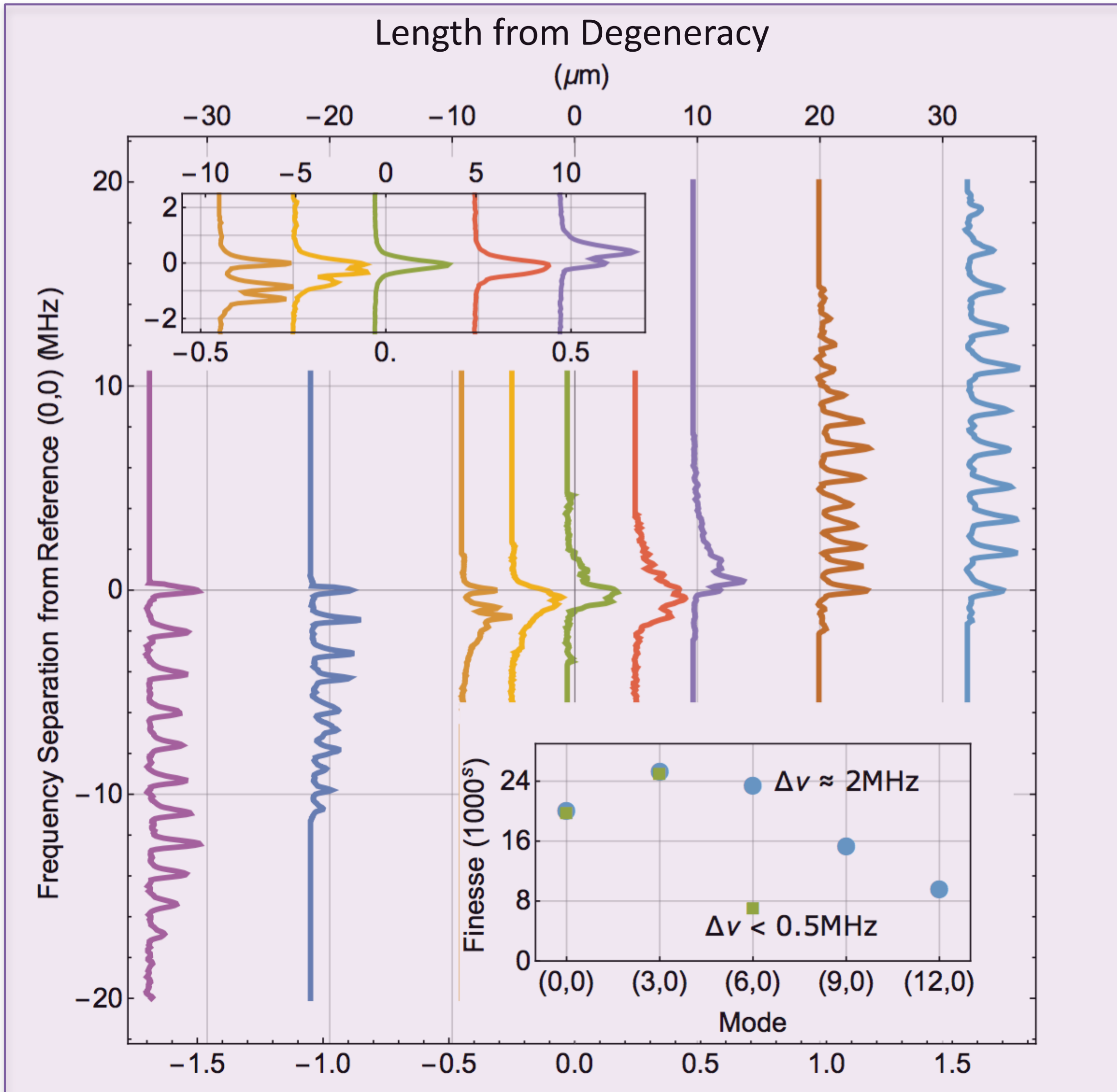
Spectroscopy of Weakly Trapped Landau Levels on a Cone

No Centrifugal Barrier!



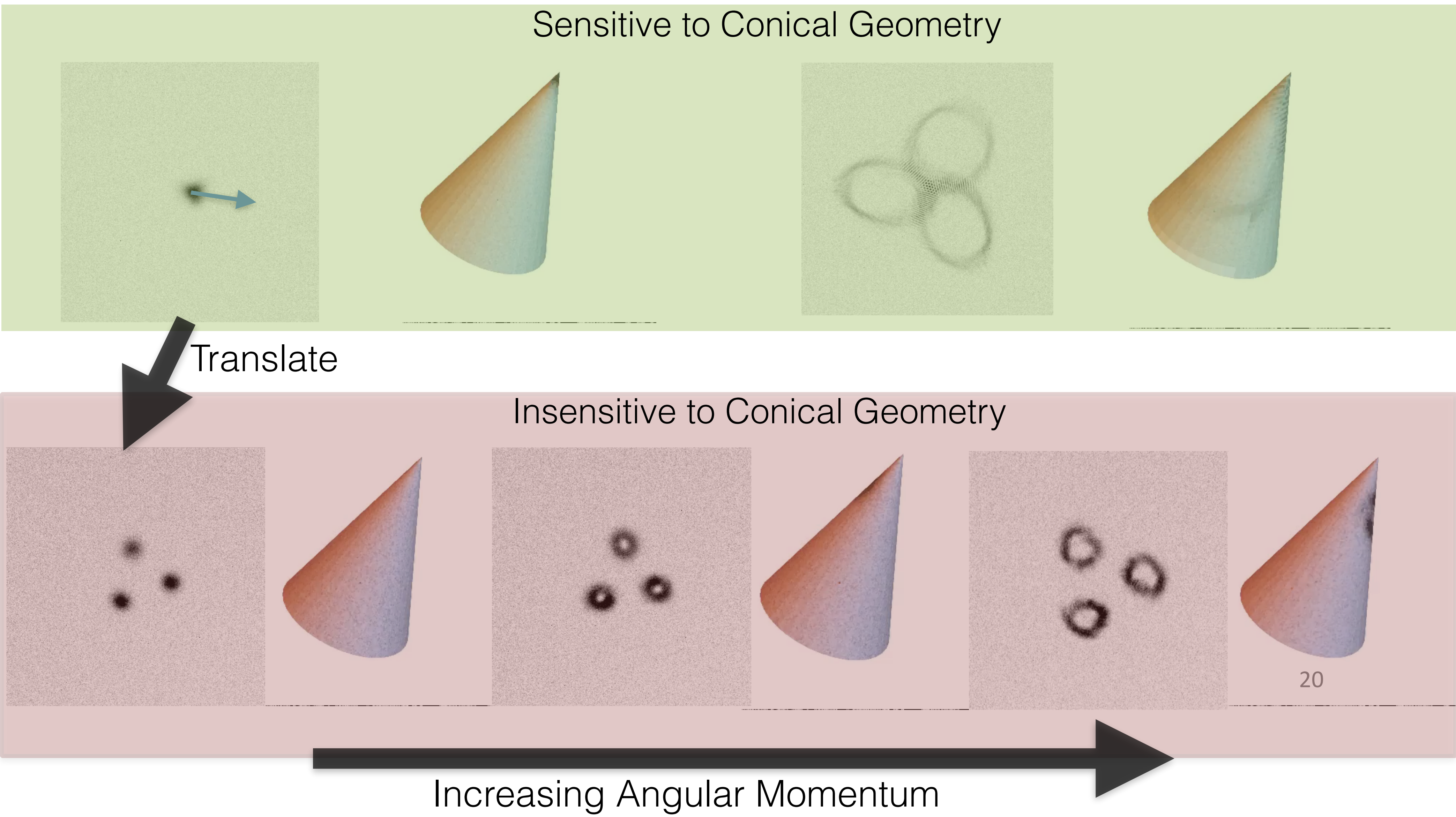
THREE-FOLD SYMMETRY DOES NOT COUPLE TO ASTIGMATISM

LLL

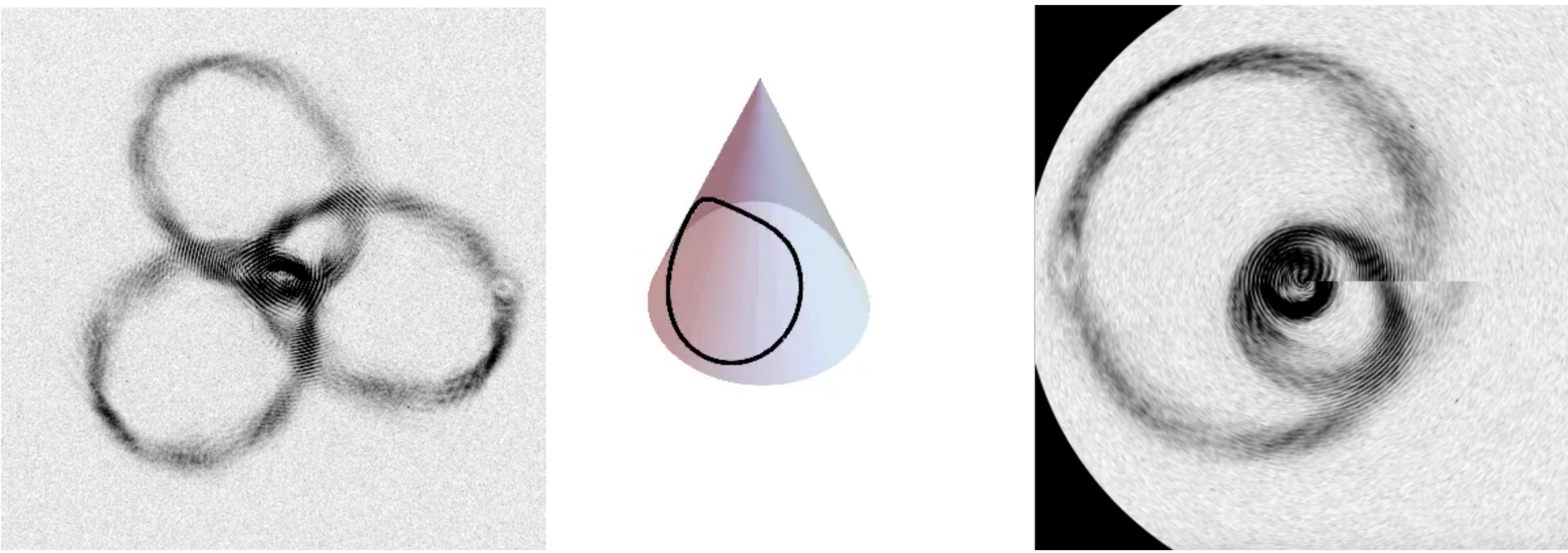


Schine *et al.*, **Nature** doi:10.1038/nature17943 (2016)

Exploring the Lowest Landau Level (on a Cone)

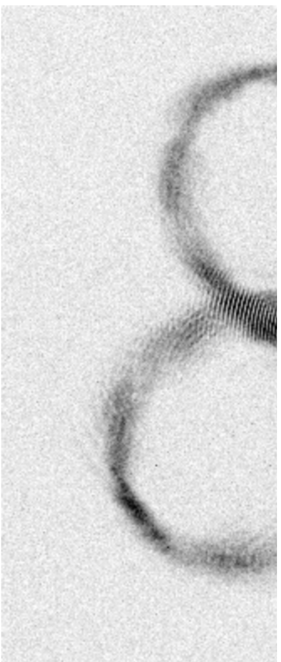


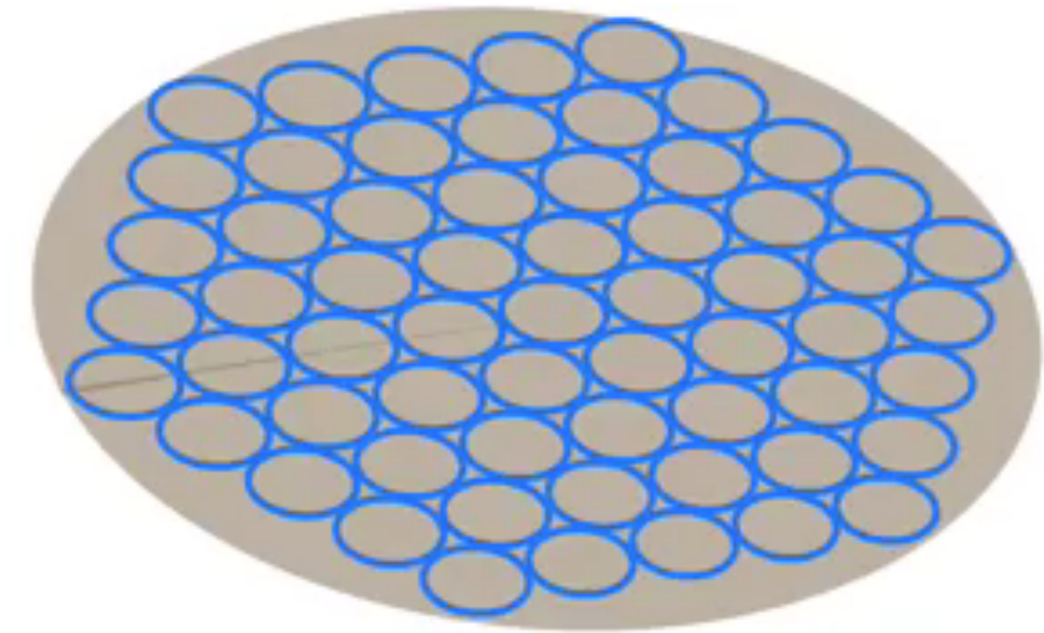
Orbiting the Cone Tip

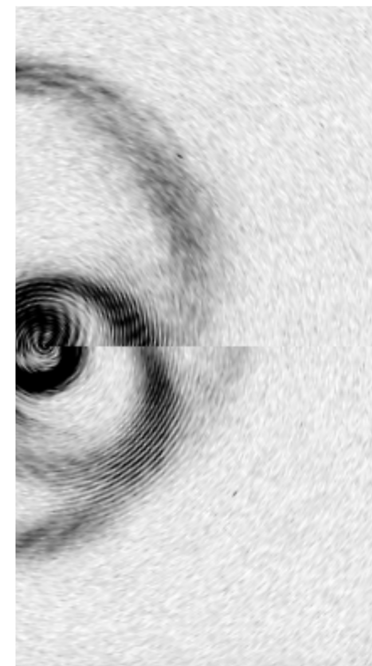


Biswas *et al., arXiv 1412.3809 (2014)*

Orbiting the Cone Tip







Biswas *et a*

Interplay of Topology and Manifold Curvature

Prediction (Wen-Zee

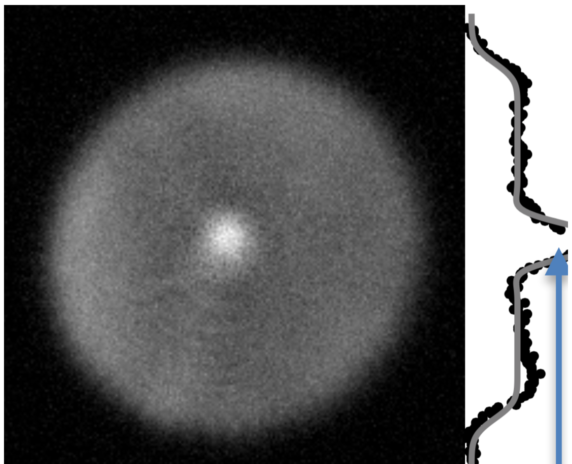
Mean orbital spin $\overline{s}$

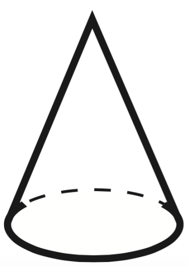
$$+\frac{1}{2}\frac{R(x)}{4\pi}$$

Cone Tip

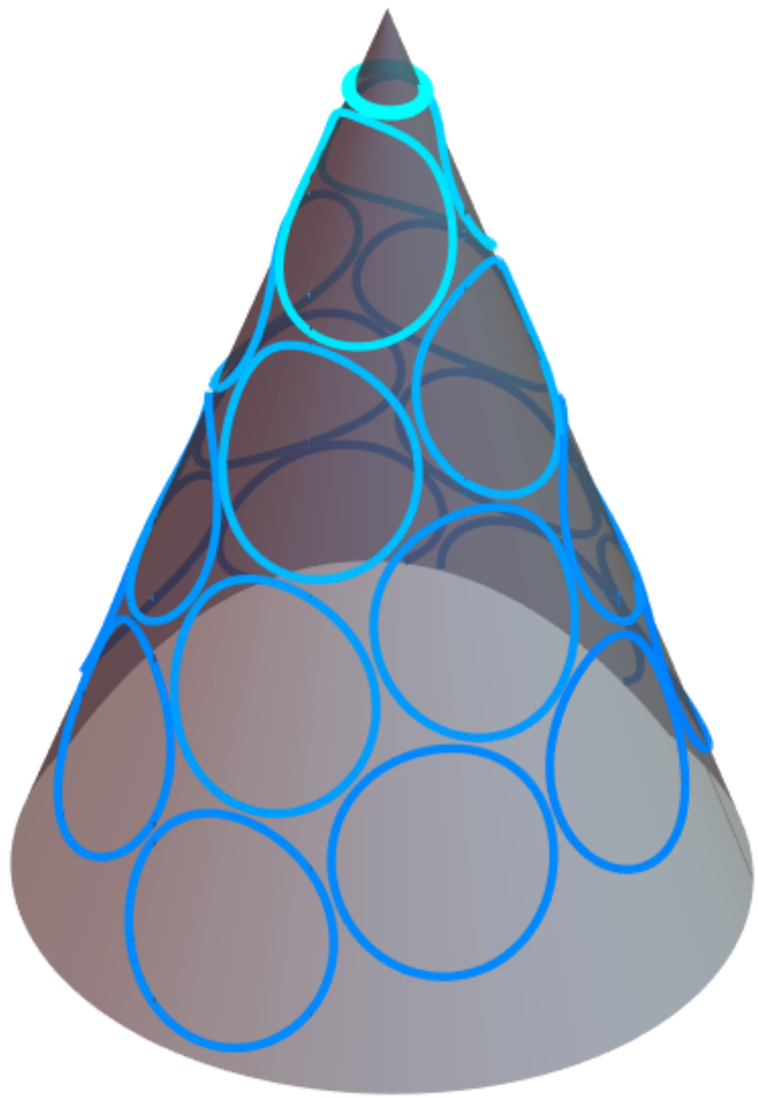
$$\frac{1}{2}\frac{R(x)}{4\pi}+\frac{e\,\delta B(x)}{h}$$

l=0,3,6,9…

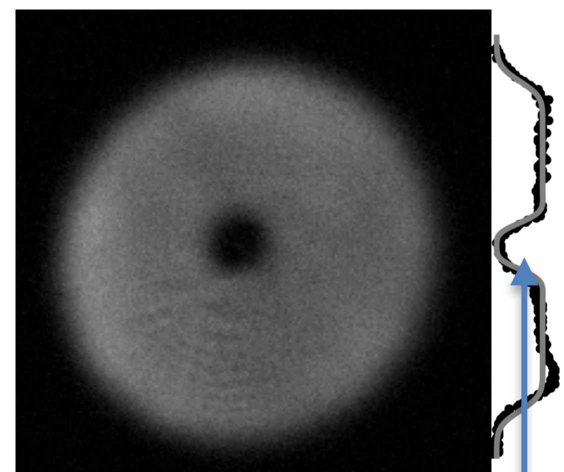


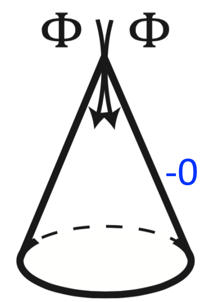


0.31[2]



l=2,5,8,11…



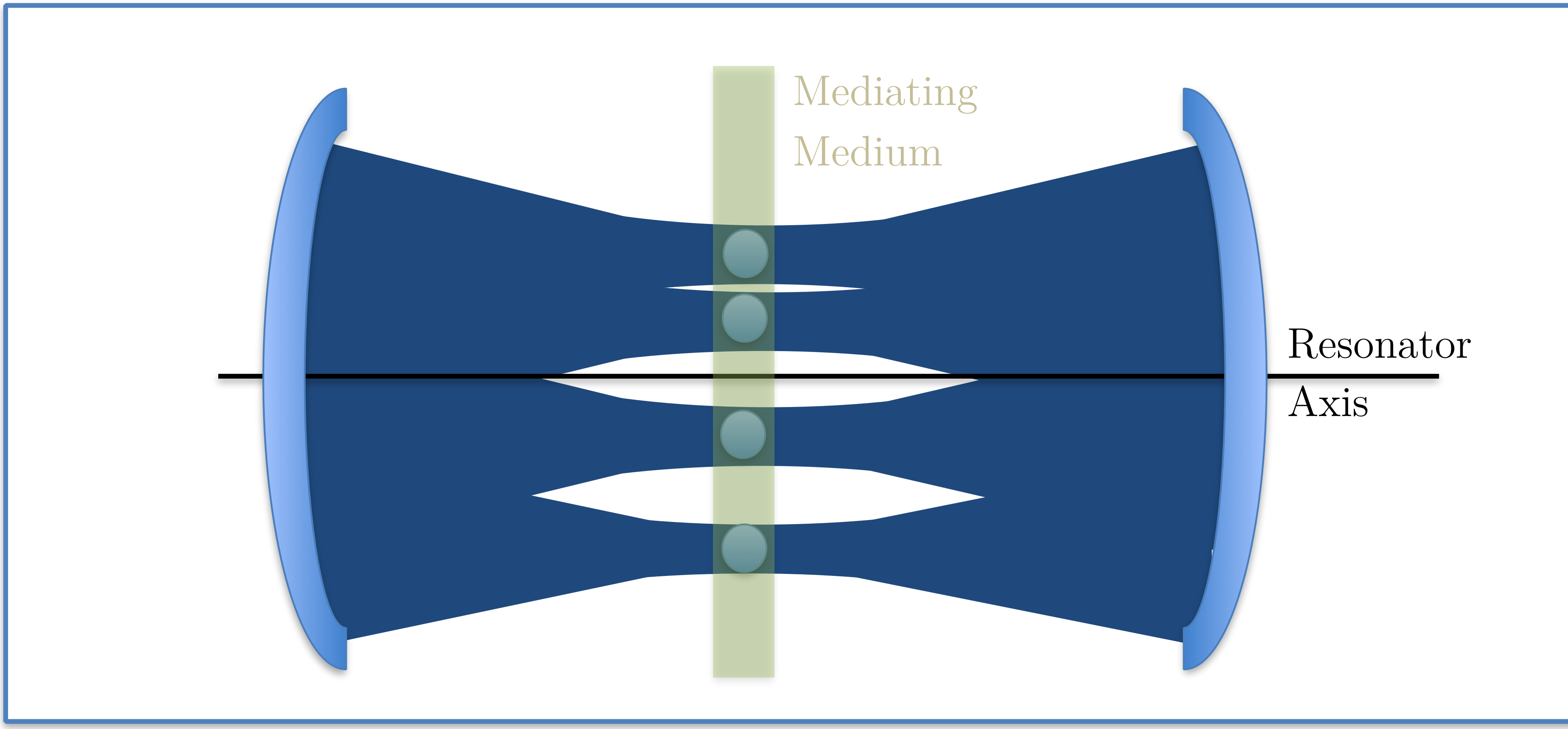


-0.35[2] states

Can *et al.*, Phys. Rev. Lett

ev. B **90**, 014435 (2014)

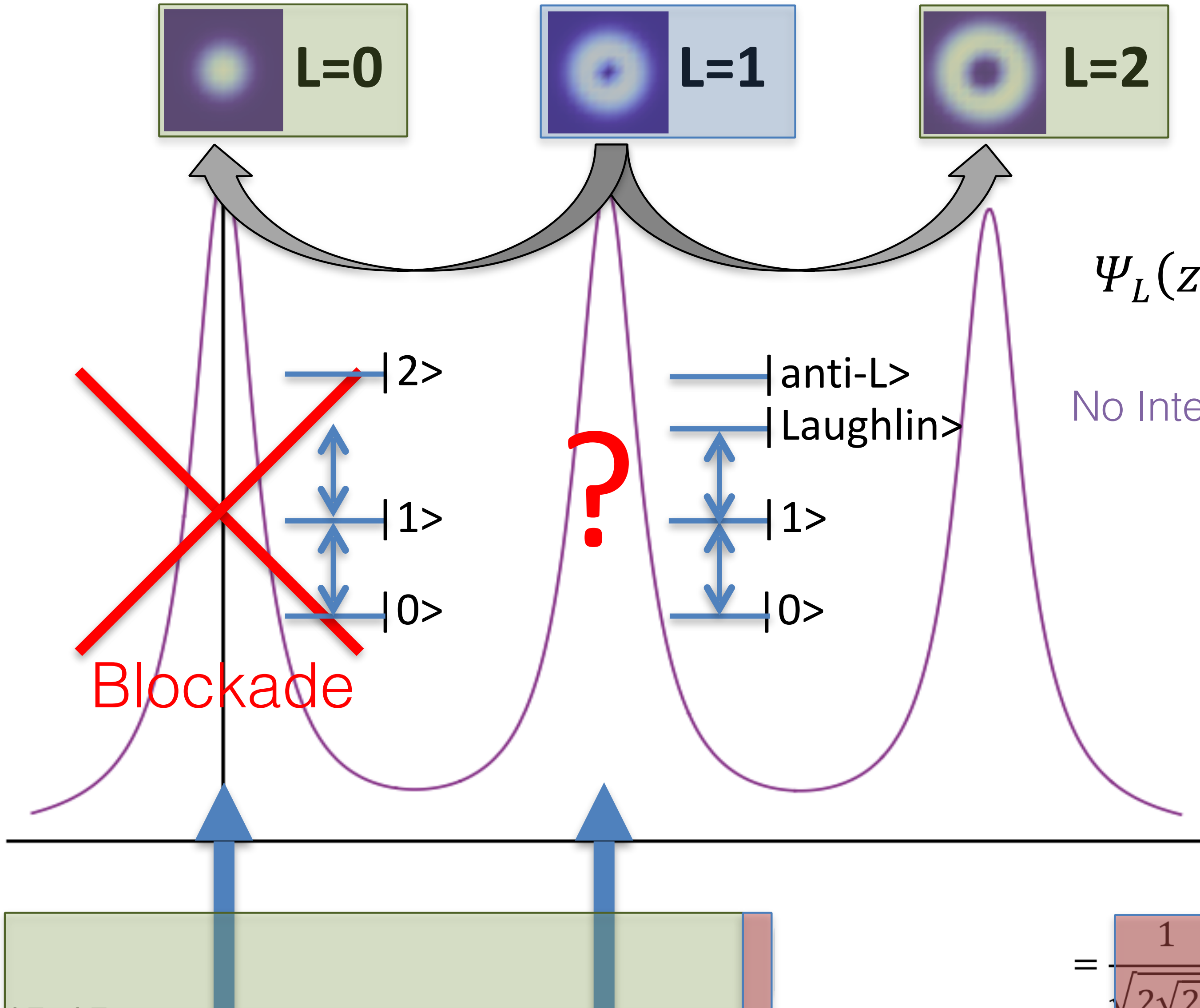
Adding Photon-Photon Interactions



- Rydberg atoms interact → photons interact…
- *Now what? How do we make manybody ground states?*

Ningyuan *et al.*, PRA **93**, 041802 (2016), Parigi *et al.*, PRL **109**, 233602 (2016)
Peyronel *et al.*, Nature **488**, 57-60 (2012)

Blockade-Assembly of Small Laughlin States
the "Quantum Optics" way



$$\Psi_L(z \equiv x + iy) = \frac{z^L}{\sqrt{\pi L!}} e^{-z\,\bar{z}}$$

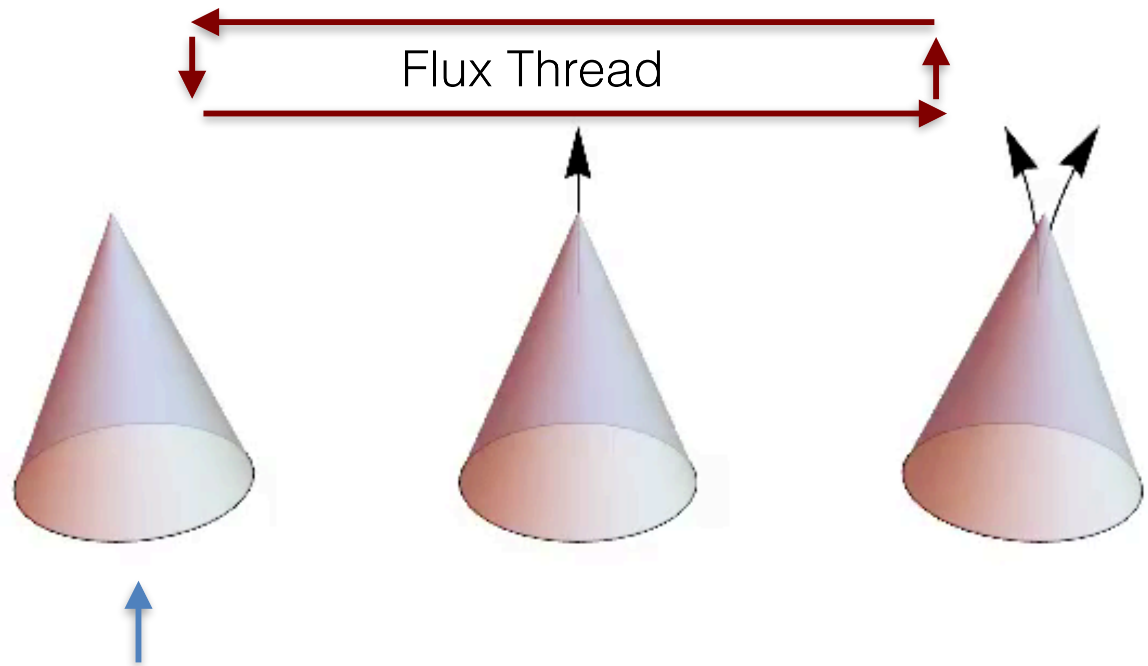
No Interactions➔2 photon transmission

LAUGHLIN FILTER

$$= \frac{1}{\sqrt{2\sqrt{2}\pi}} (z_1 - z_2)^2 e^{-(z_1\bar{z}_1 + z_2\bar{z}_2)}$$

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

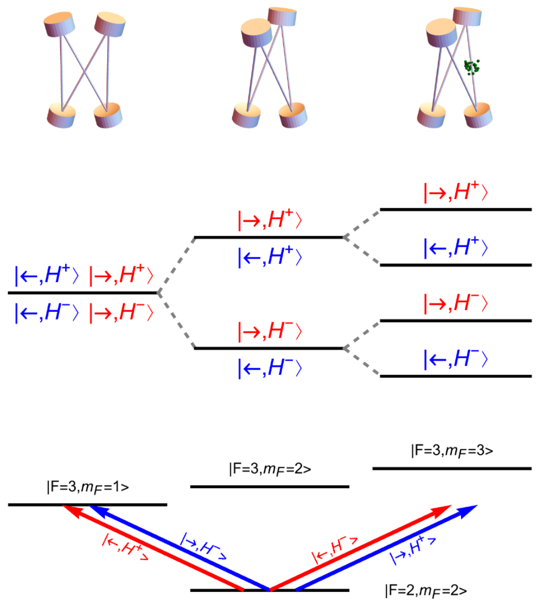
Thouless-Pumping to Laughlin States
the "Quantum Optics" way

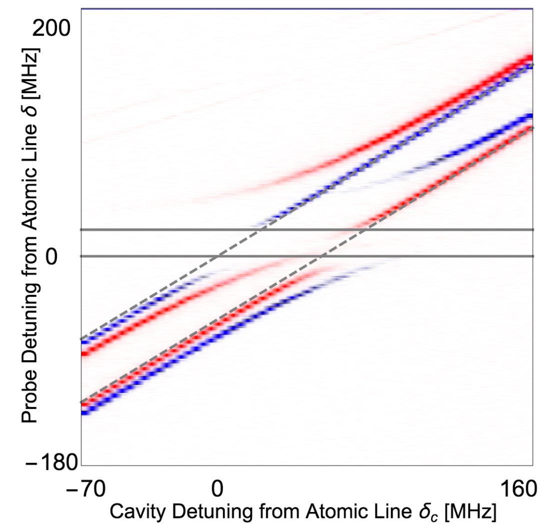


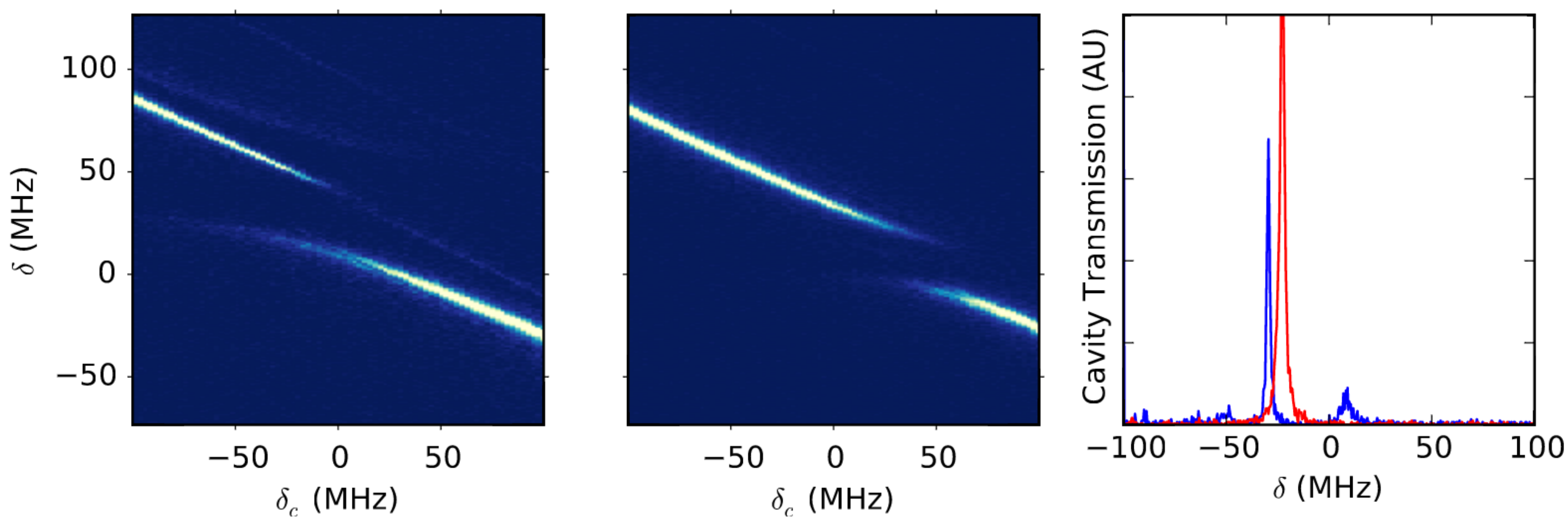
Blockaded
injection of a
single particle at
the cone tip

Grudst *et al.,* Phys. Rev. Lett. **113**, 155301 (2014)
Lohse *et al.*, Nat. Phys. 3584, (2016)

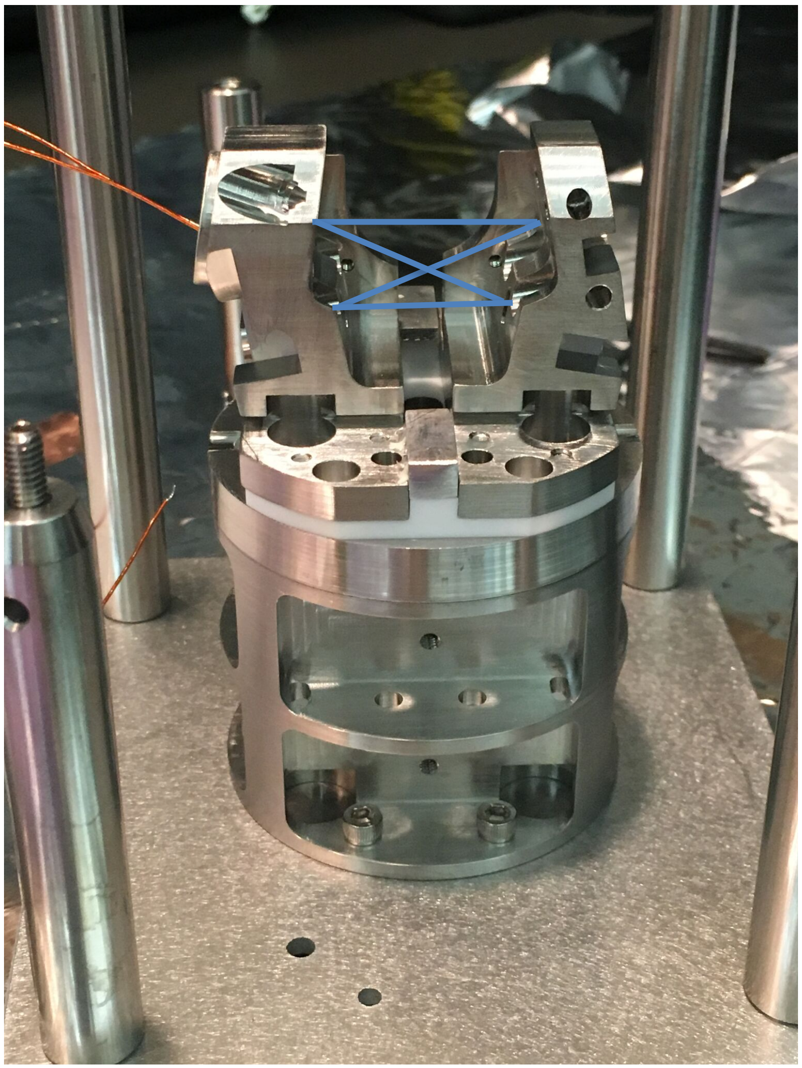
T-Breaking in Twisted Optical Cavities

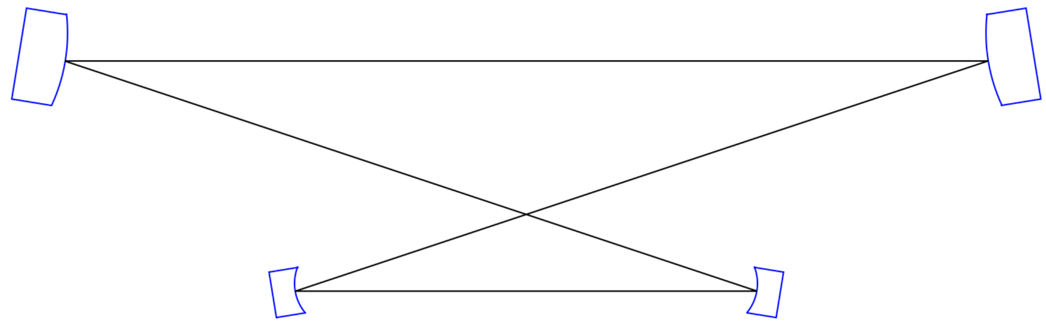






Next-Generation Resonator
Ostracizing the Rydbergs



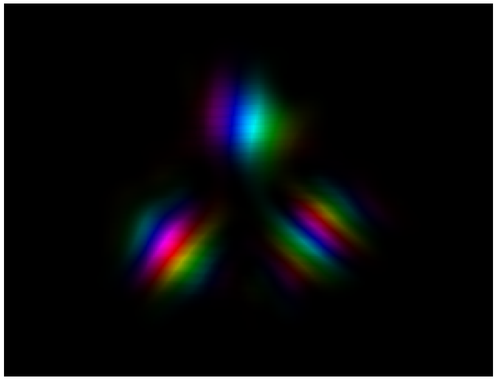


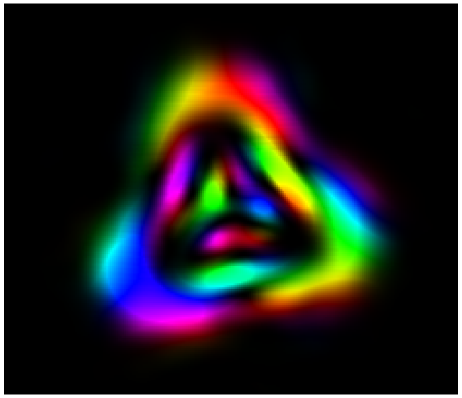
Convex Mirrors → Smaller Waist (12 microns) @ 1cm to atoms stable (confocal)

Outlook

- Chern Number (Kitaev's Real-Space Formalism):

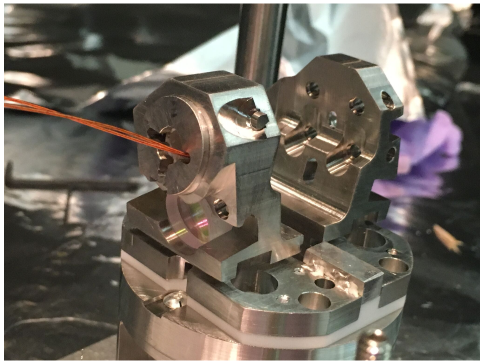
Holographic Reconstruction of Band Projectors

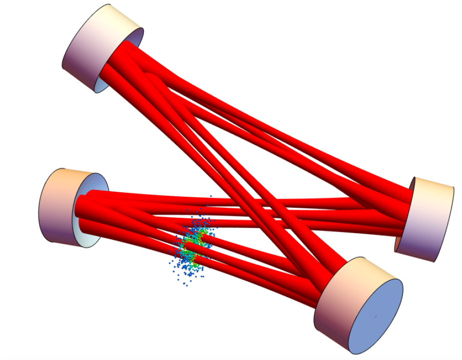




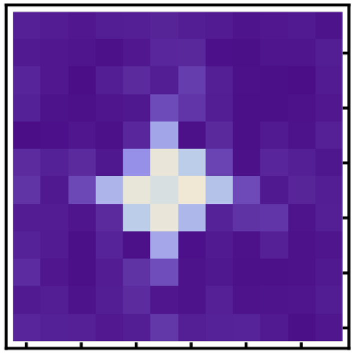
- Strong Interactions:

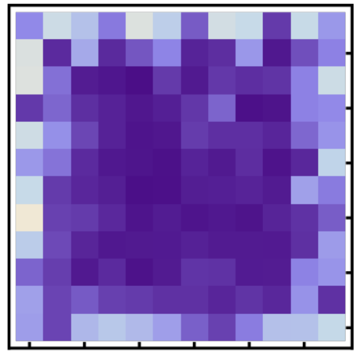
(0-d) Polariton Quantum Dots to (2-d) Laughlin Puddles

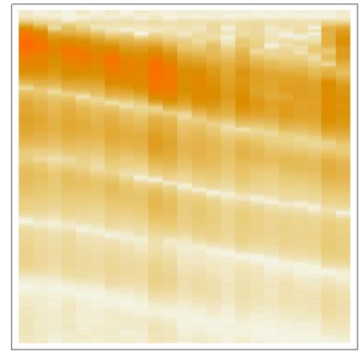




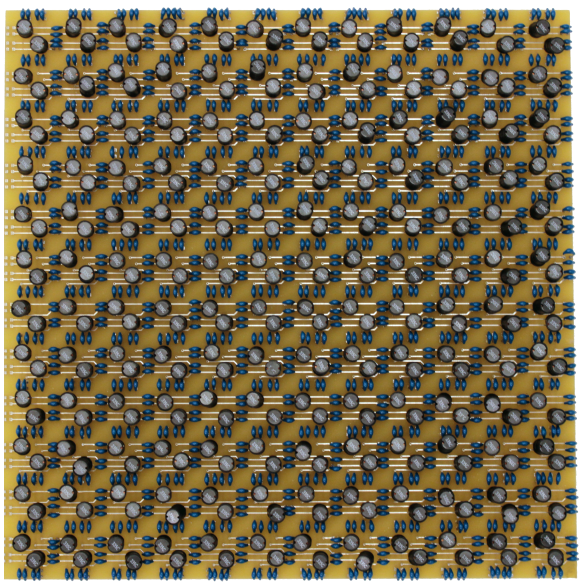
Engineering μWave Quantum Materials



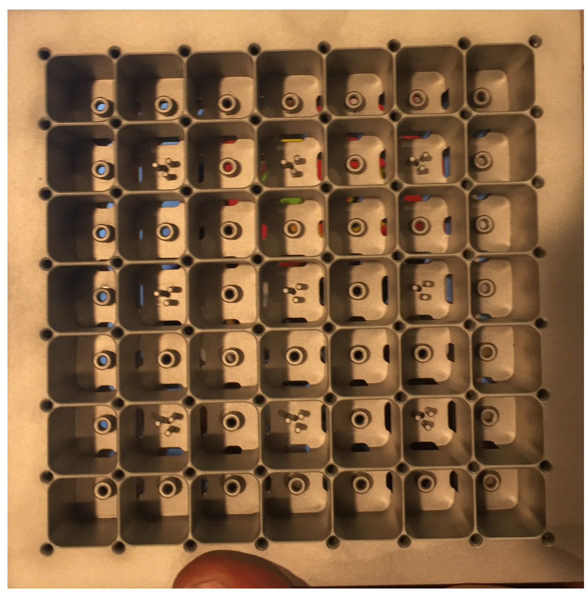




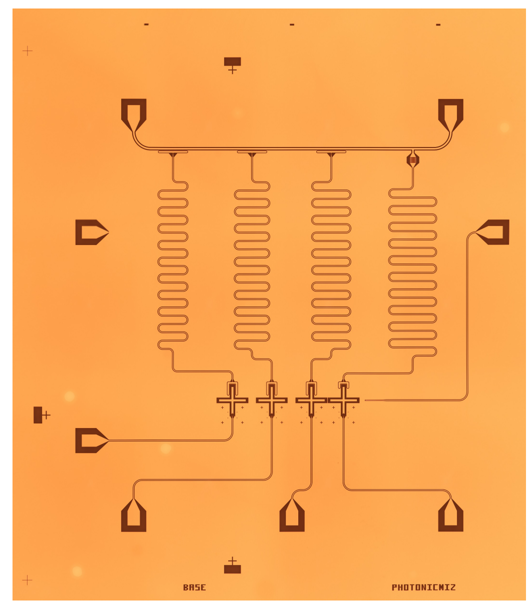
Z_2 TI (QSH)



Lattice QH



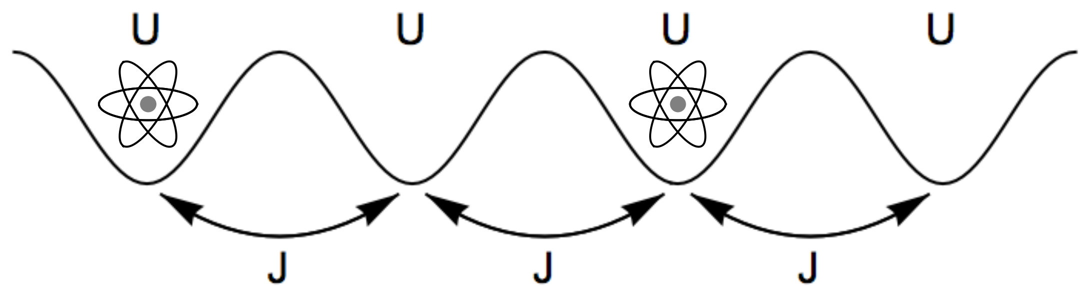
Chemical Potential



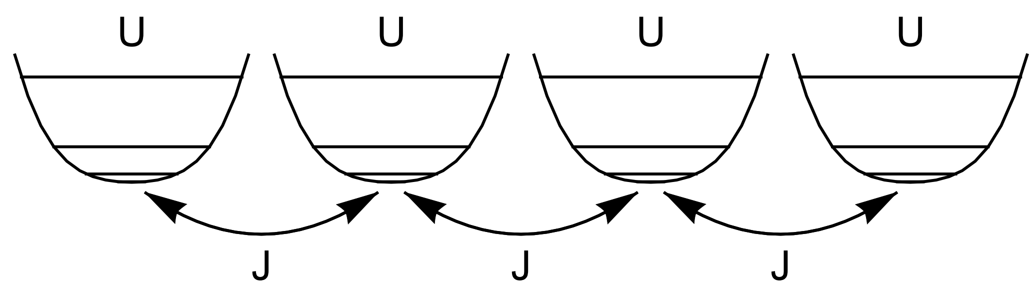
schuster.lab

The Analogy

Cold Atoms
-*Hopping* in an optical lattice
-S-wave contact *interactions*

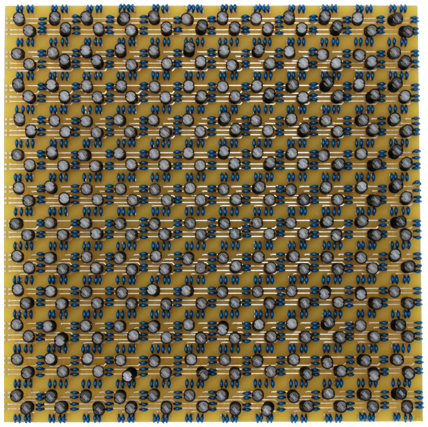


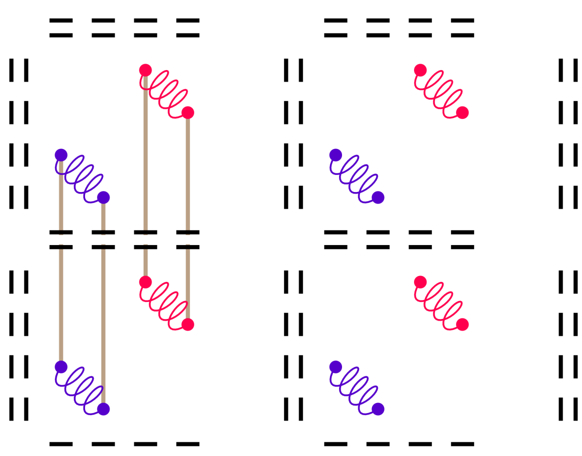
Microwave photons
-*Hopping* btwn cap.-coupled SC resonators
-Qubit-mediated *interactions*



Two Approaches to Synthetic Magnetic Flux in Circuits

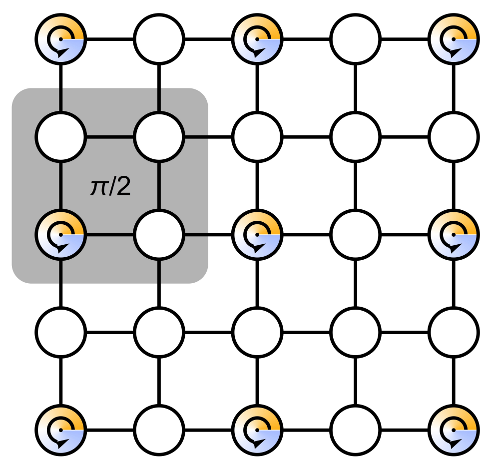
Weave Tunnel Couplers to Create Peierls Phase





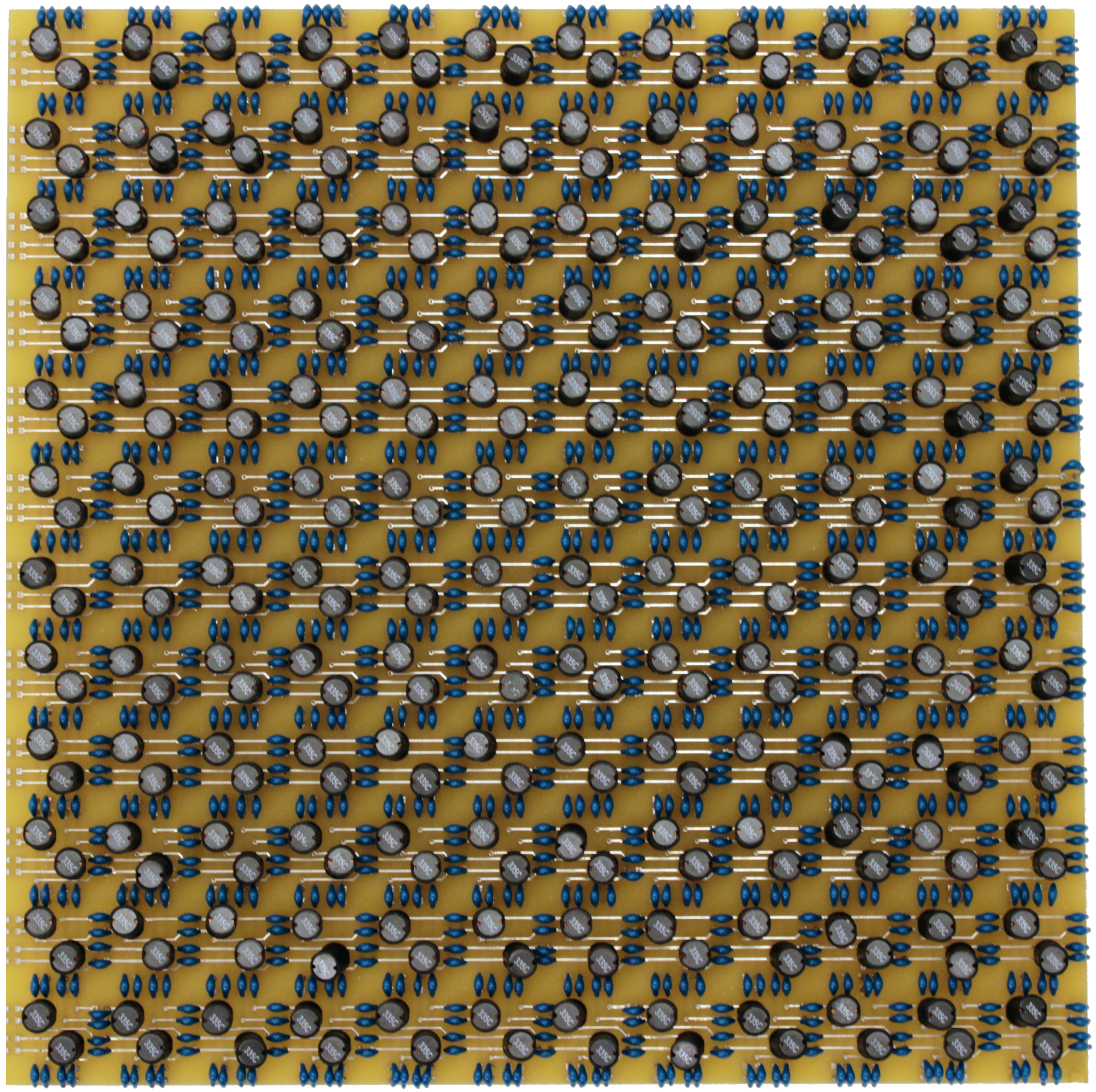
Ningyuan *et al.*, **PRX** 5 (2), 021031

Employ Chiral Orbitals to Create Peierls Phase

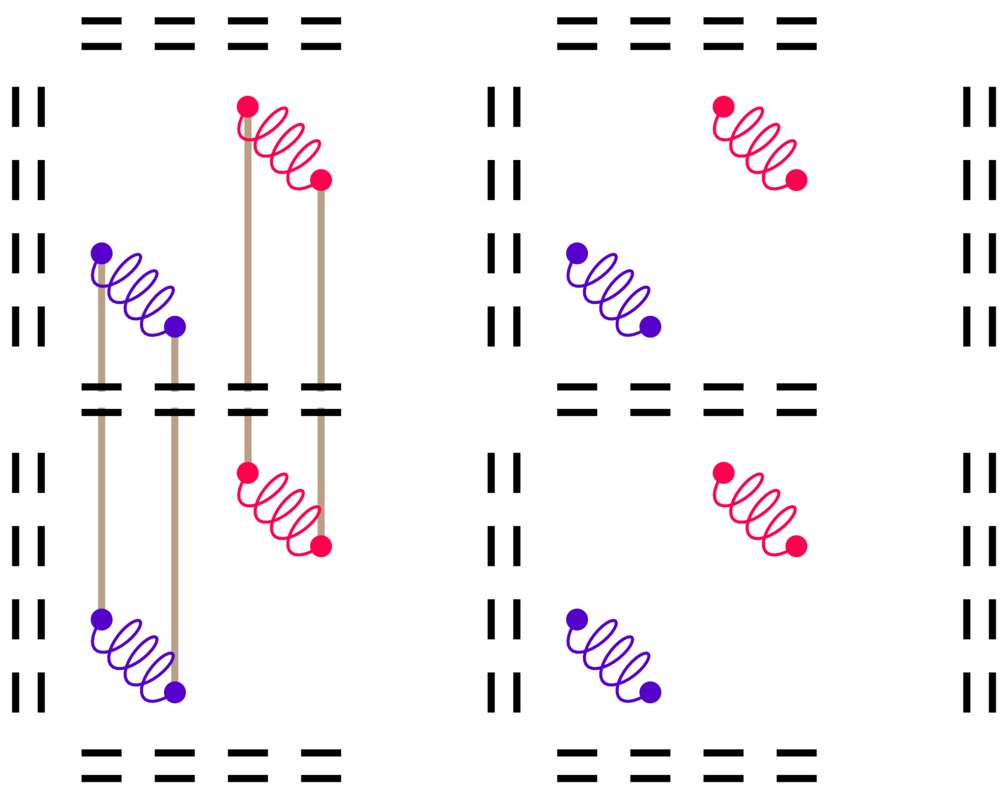


Anderson *et al.*, **arXiv**: 1605.03177, in press **PRX**

(Braided) Topological Circuits



"Braiding" the Planes @ $\alpha=\pi/2$



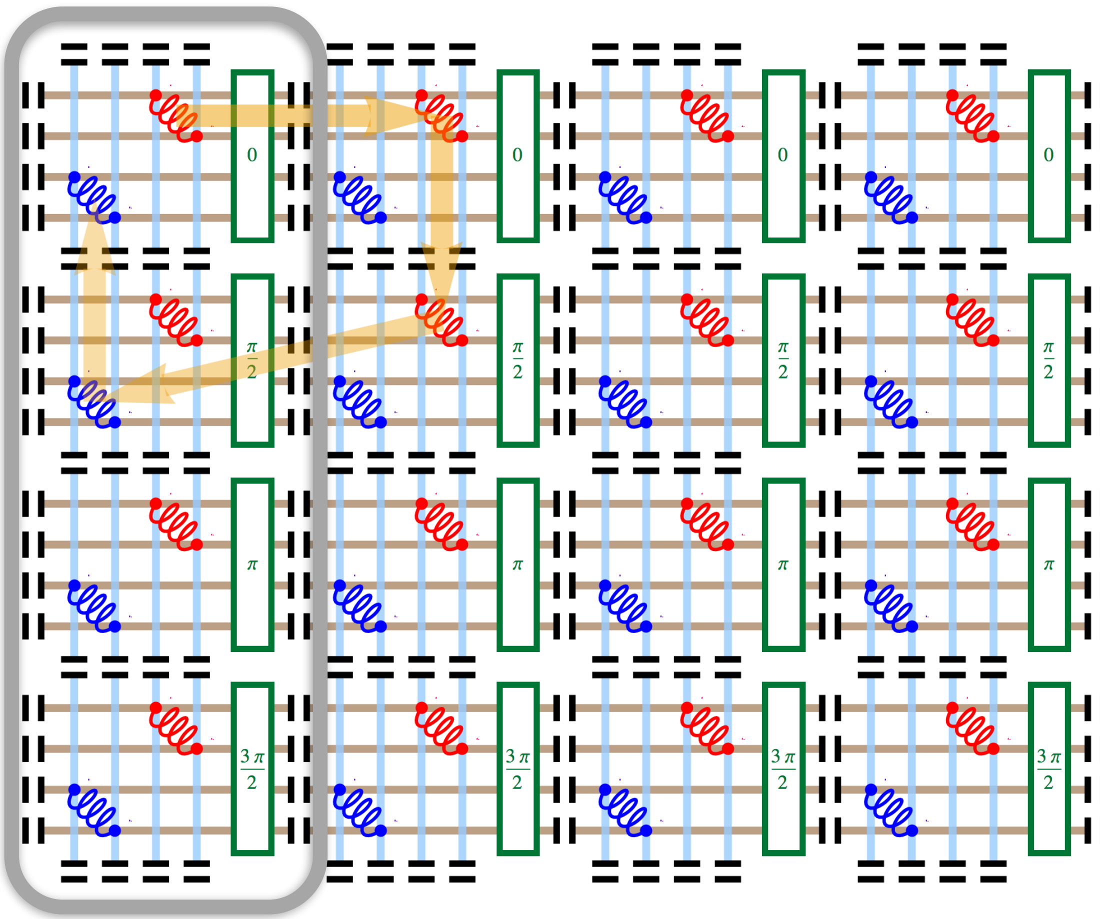
$(V_1, V_2) \rightarrow (V_1, V_2)$

$(V_1, V_2) \rightarrow (V_1, V_2)$

$(V_1, V_2) \rightarrow (-V_2, V_1)$

$(-V_2, V_1) \rightarrow (-V_2, V_1)$

"Braiding" the Planes



Unit Cell

$$|\uparrow\rangle = \mathbf{A} + i\mathbf{B}$$

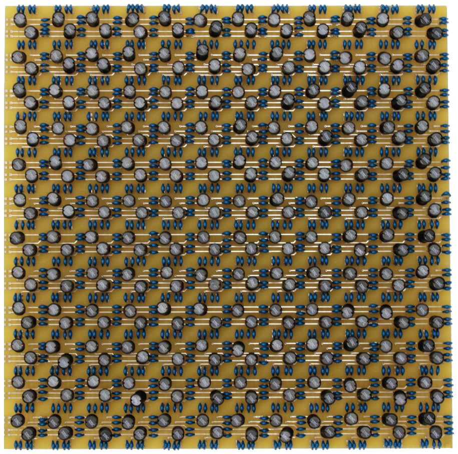
$$|\downarrow\rangle = \mathbf{A} - i\mathbf{B}$$

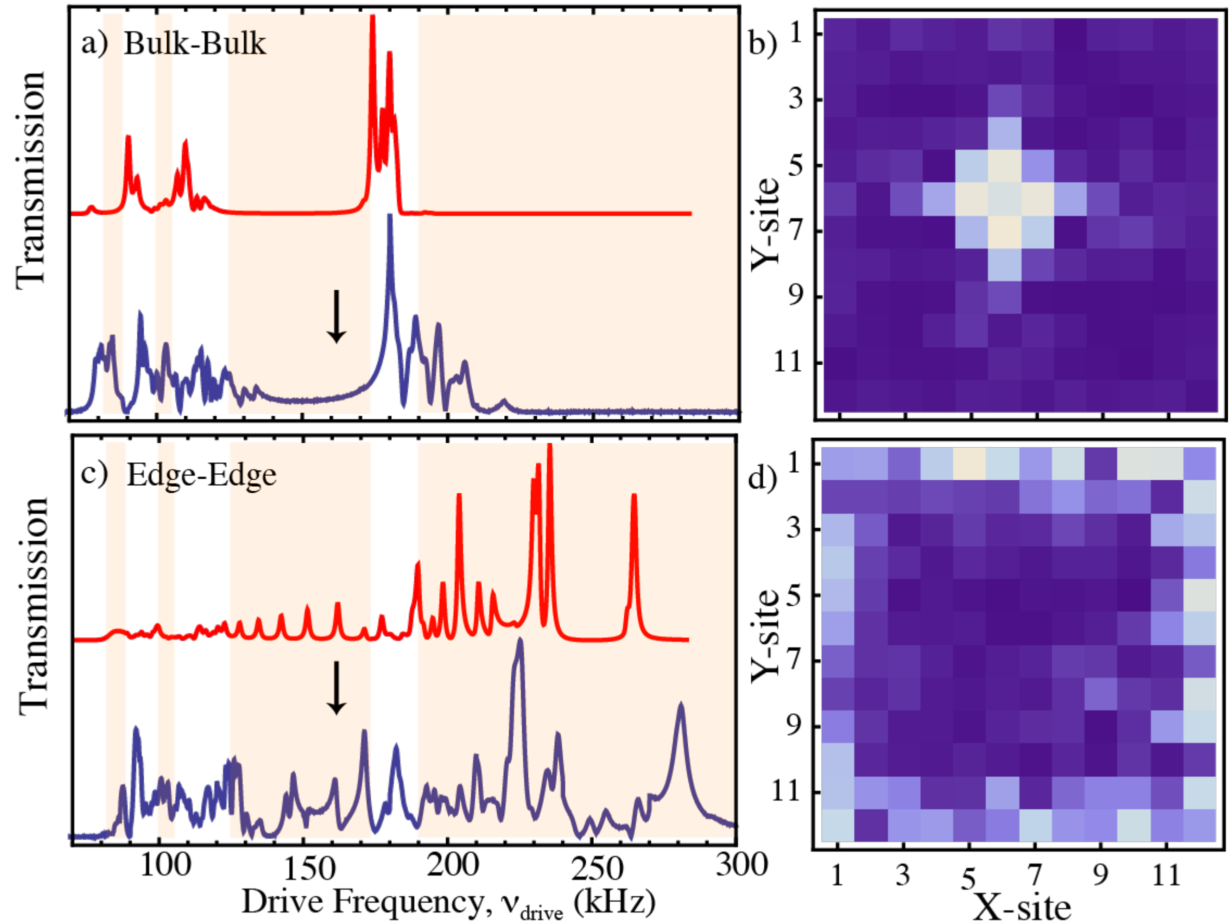
$$|\uparrow\rangle \rightarrow -i\,|\uparrow\rangle = e^{i\pi/2}|\uparrow\rangle$$

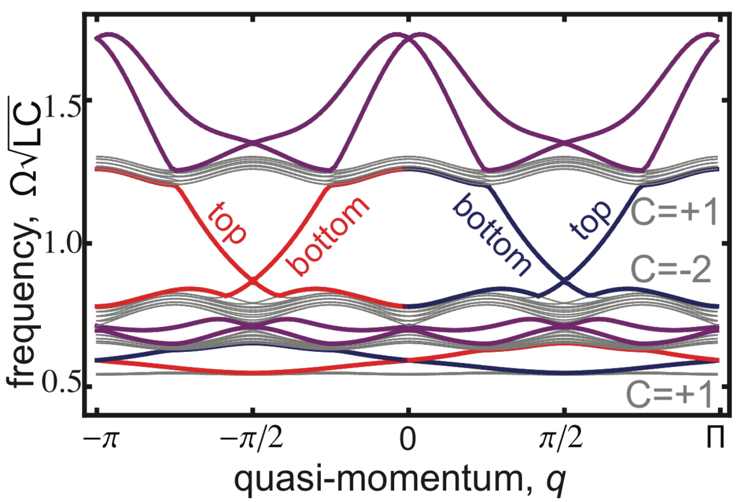
$$|\downarrow\rangle \rightarrow -i\,|\downarrow\rangle = e^{-i\pi/2}|\downarrow\rangle$$

So α=±π/2: Spin-Hall

A Topologically Insulating Circuit

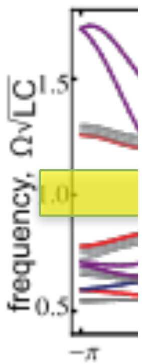


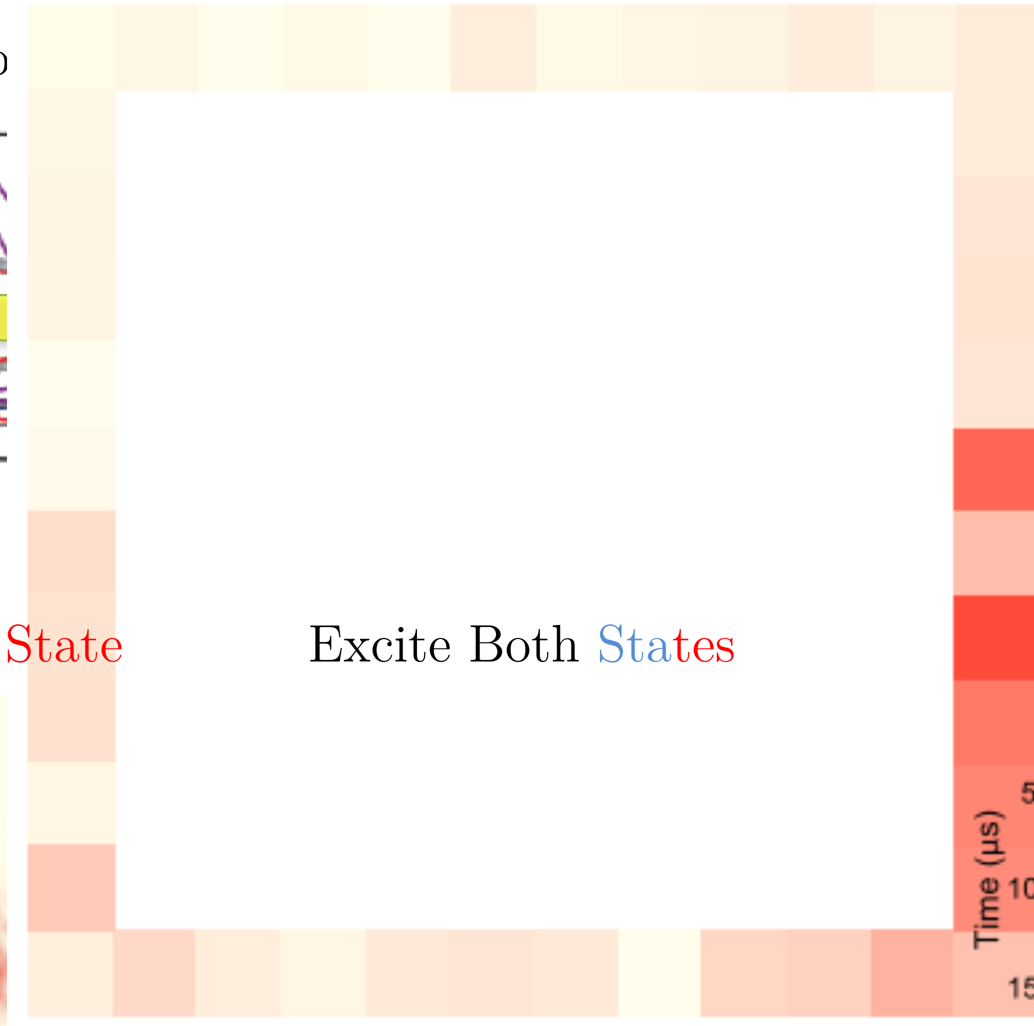




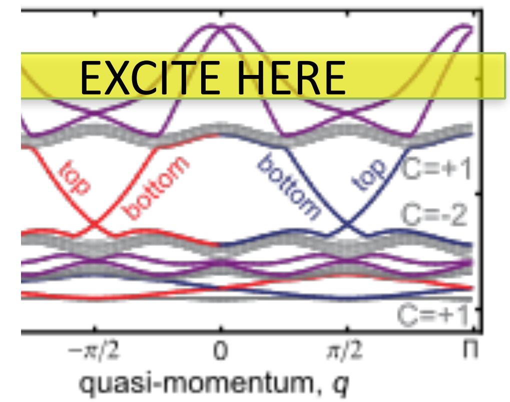
Spin- and Time- Resolved Dynamics

Topolo

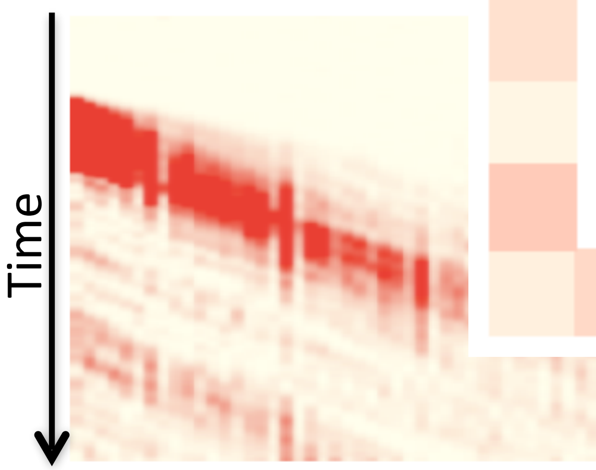




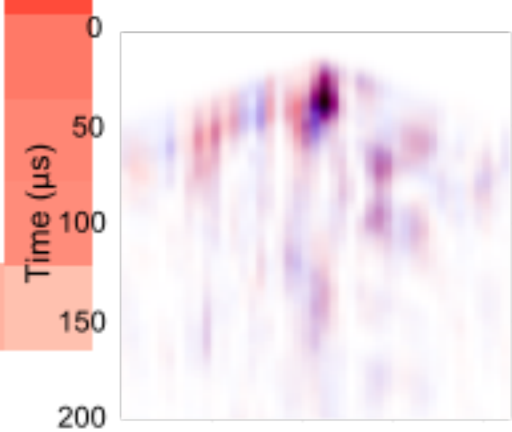
Unprotected Gap



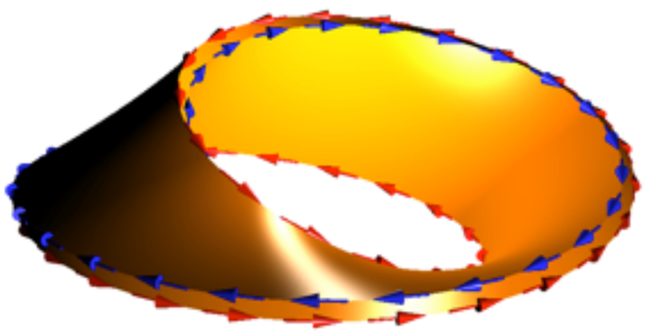
Excite One Spin State

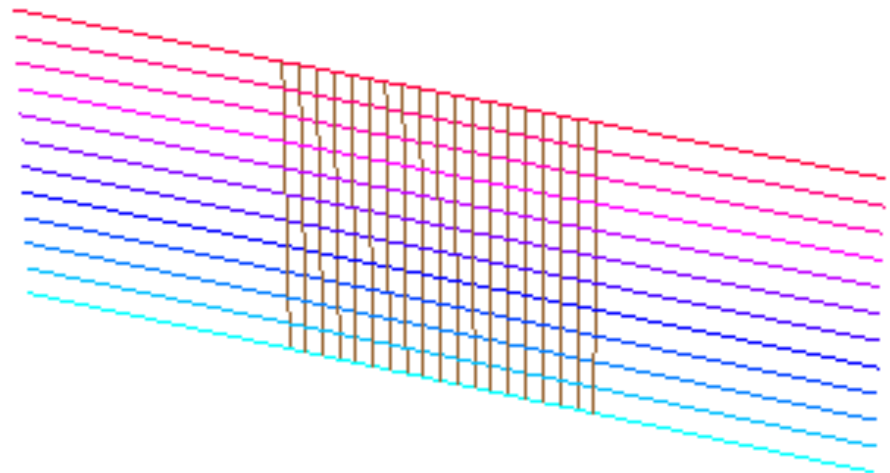


Excite Both States



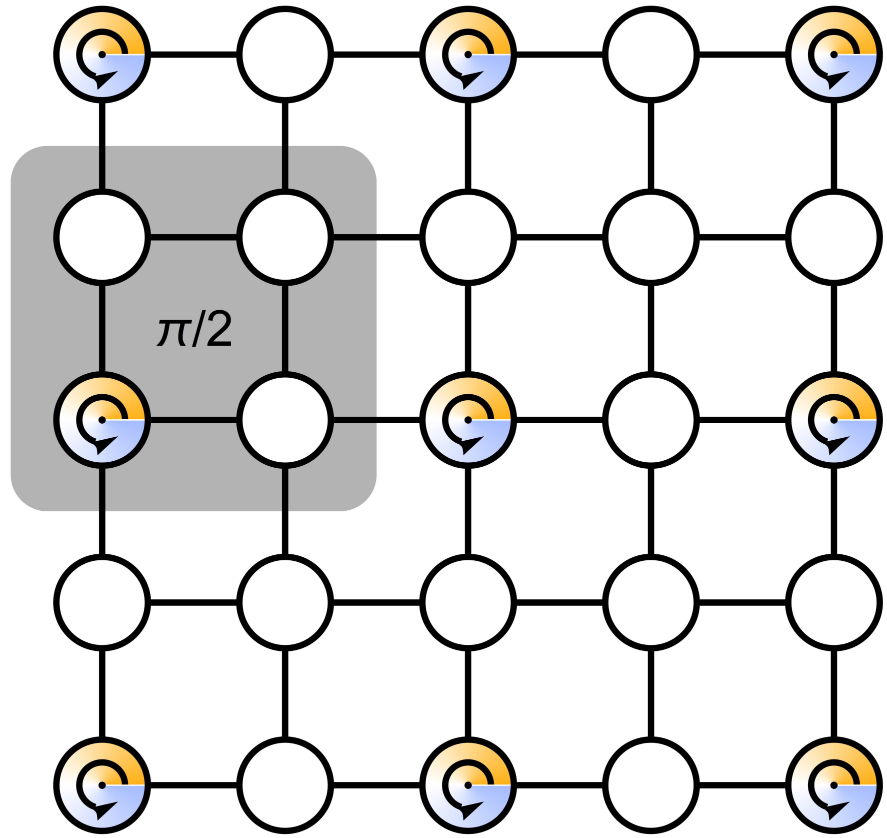
Exotic Global Topologies: Möbius TI





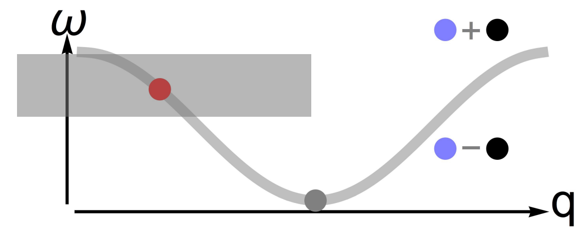
- Large wavelength compared to material size
- Useful for making tori, cylinders, etc.. for FQH physics

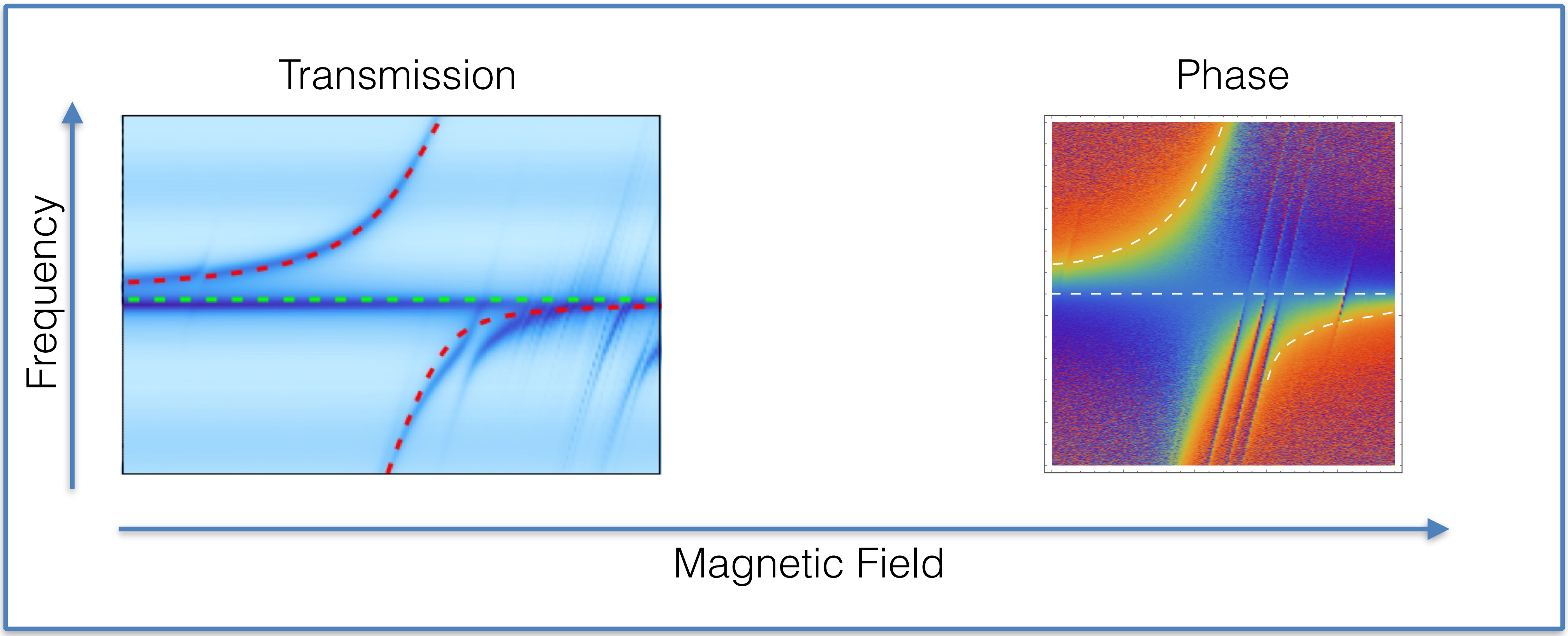
Breaking T Symmetry
Microwave Chern Insulators



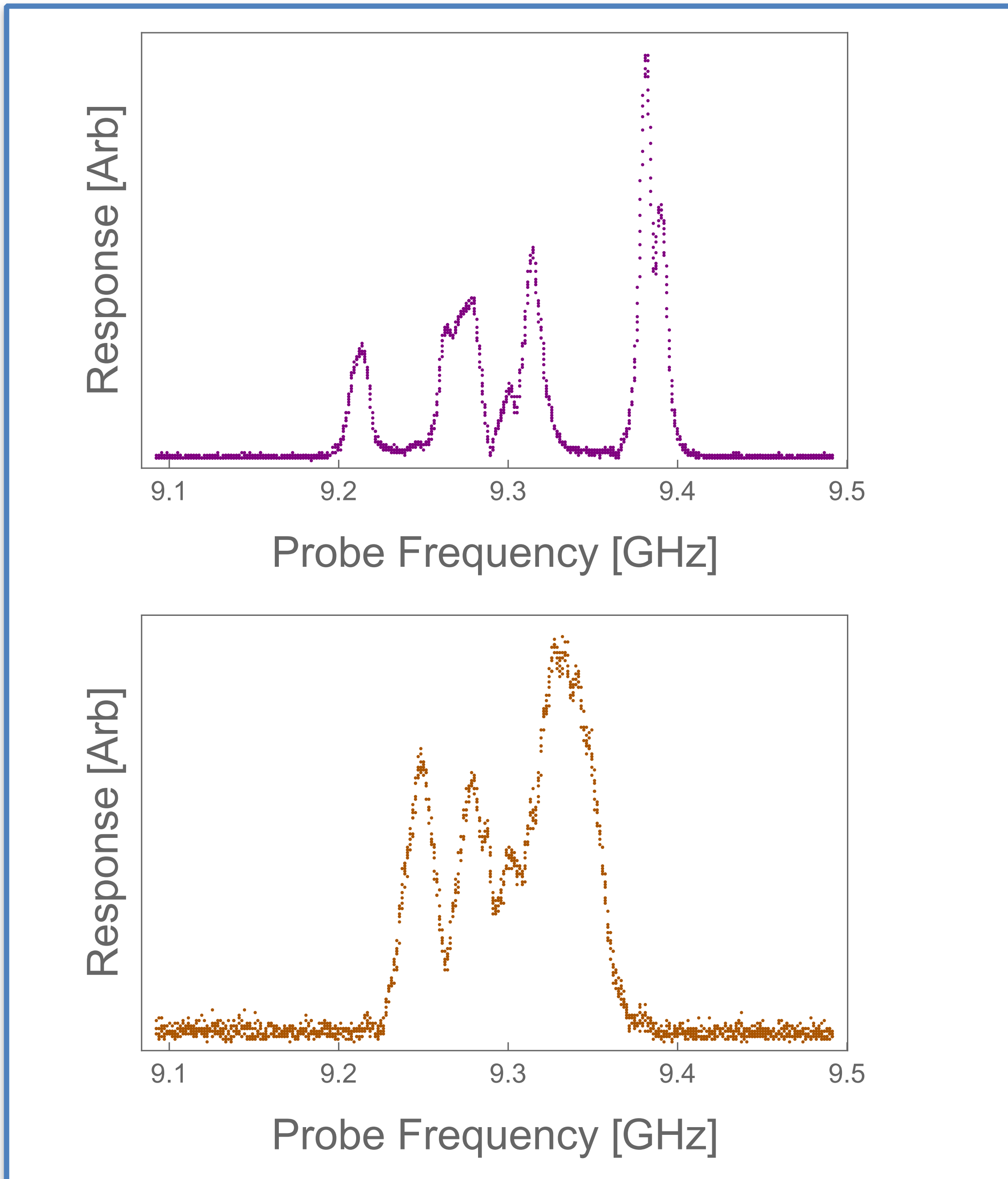
Building a Superconducting Photonic Lattice: A Chiral (p_x+ip_y) Site

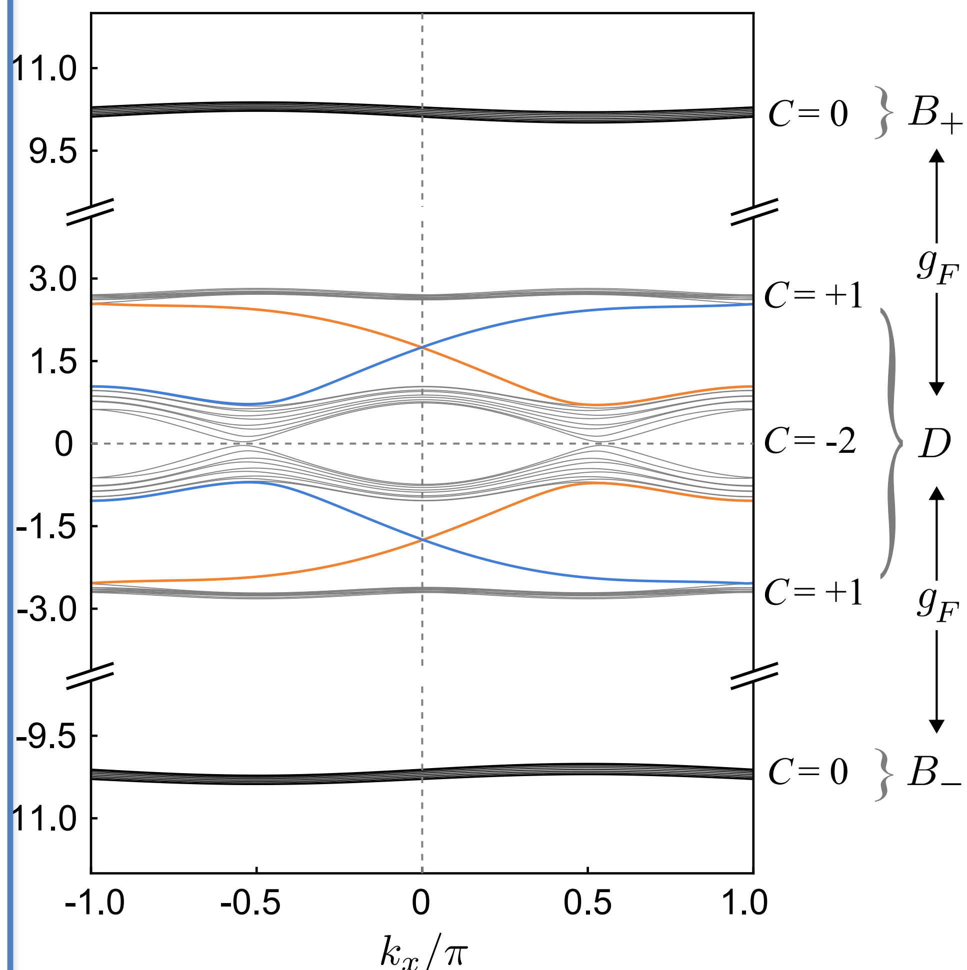
Isolated Chiral Mode
(unspoiled by YIG)





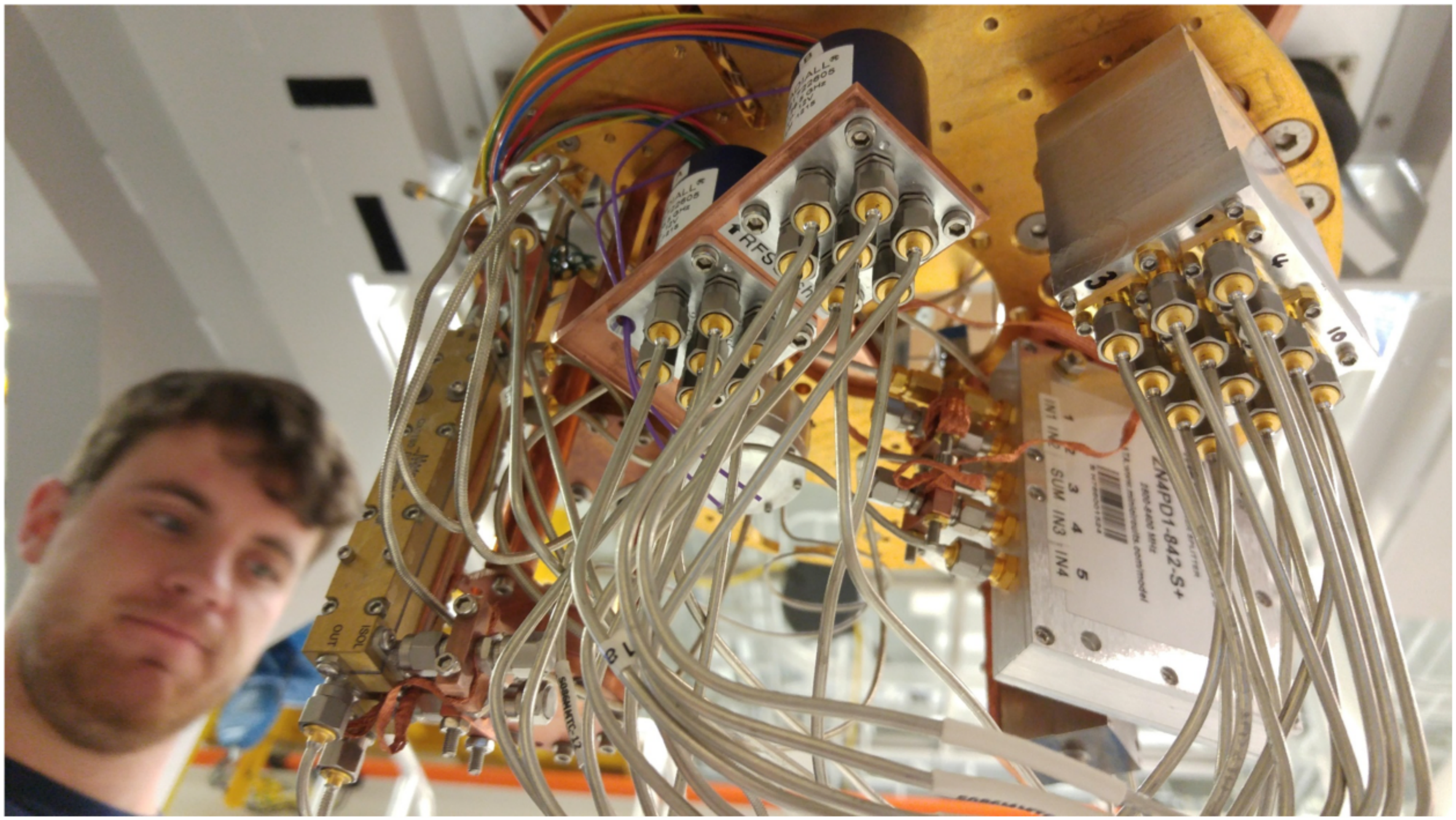
A 7x7 α=¼ Harper-Hofstadter Lattice





Temporal Dynamics in an α=¼ Hofstadter Lattice

Time

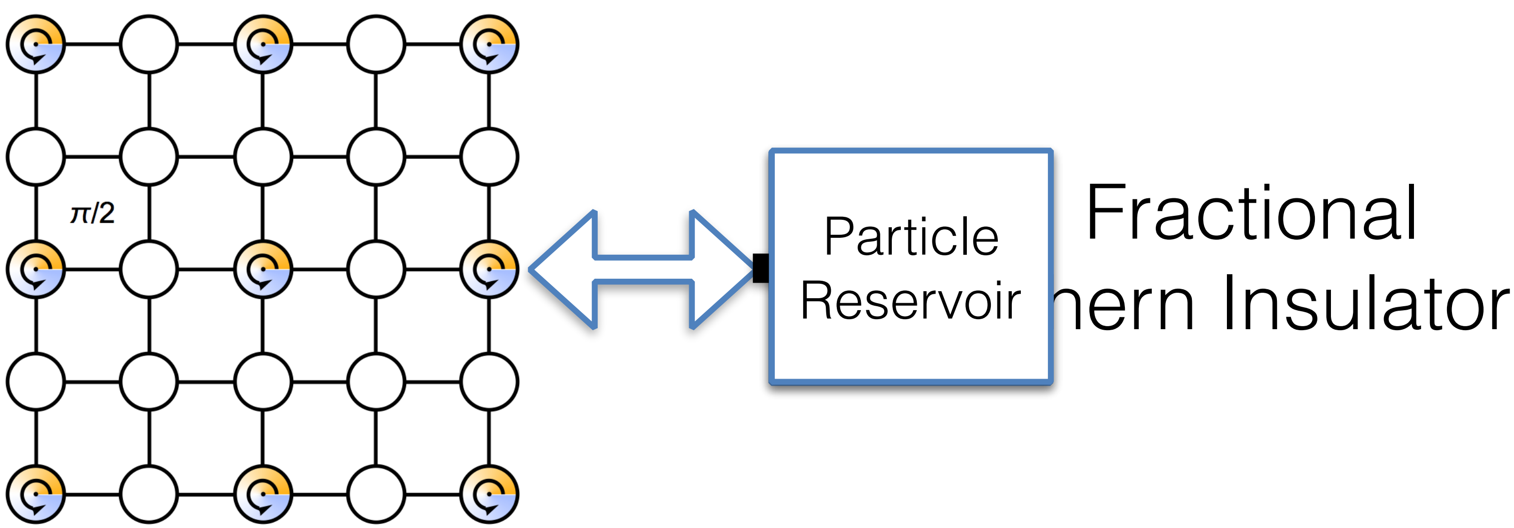


How do we build manybody states?

- Add interactions via J-J qubits on each site

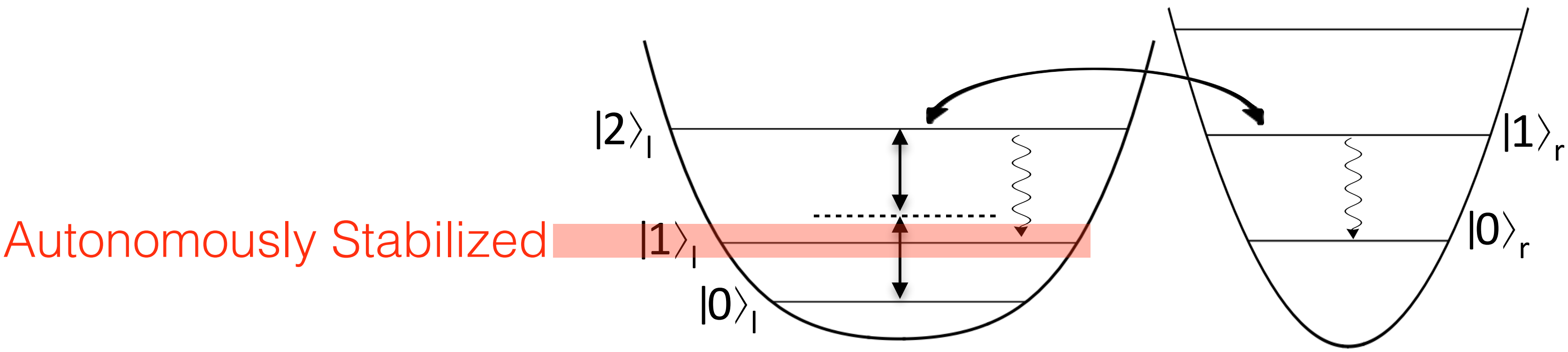
… but how do we create correlated, interacting phases?

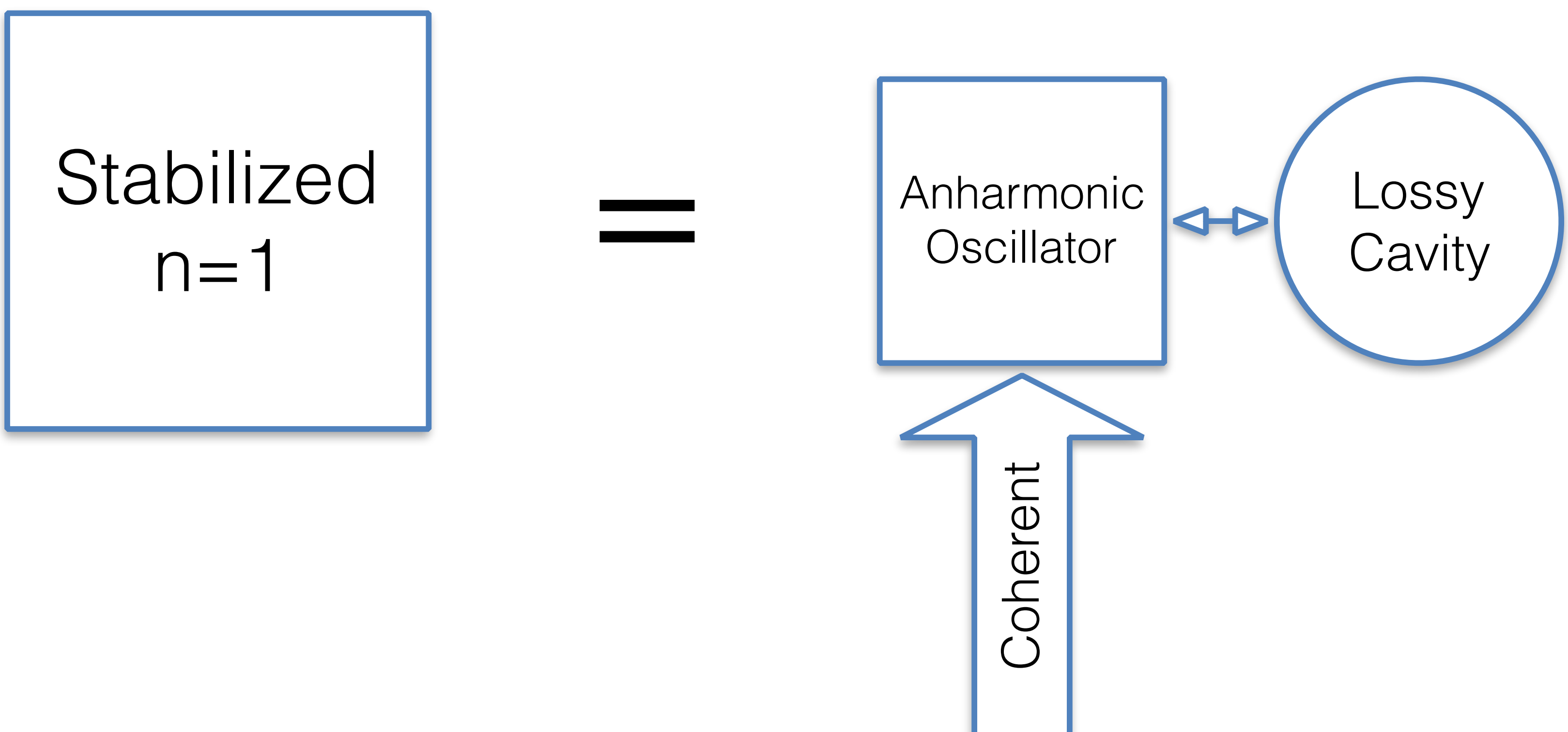
- Connect the lattice to a T=0 chemical potential—populates the system with particles!

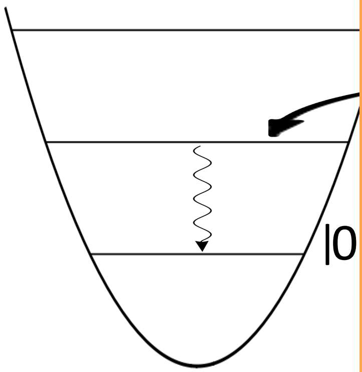


Hafezi *et al.*, PRB **92**, 174305 (2015)
Kapit *et al.*, PRX **4**, 031039 (2016)

Building a Particle Reservoir



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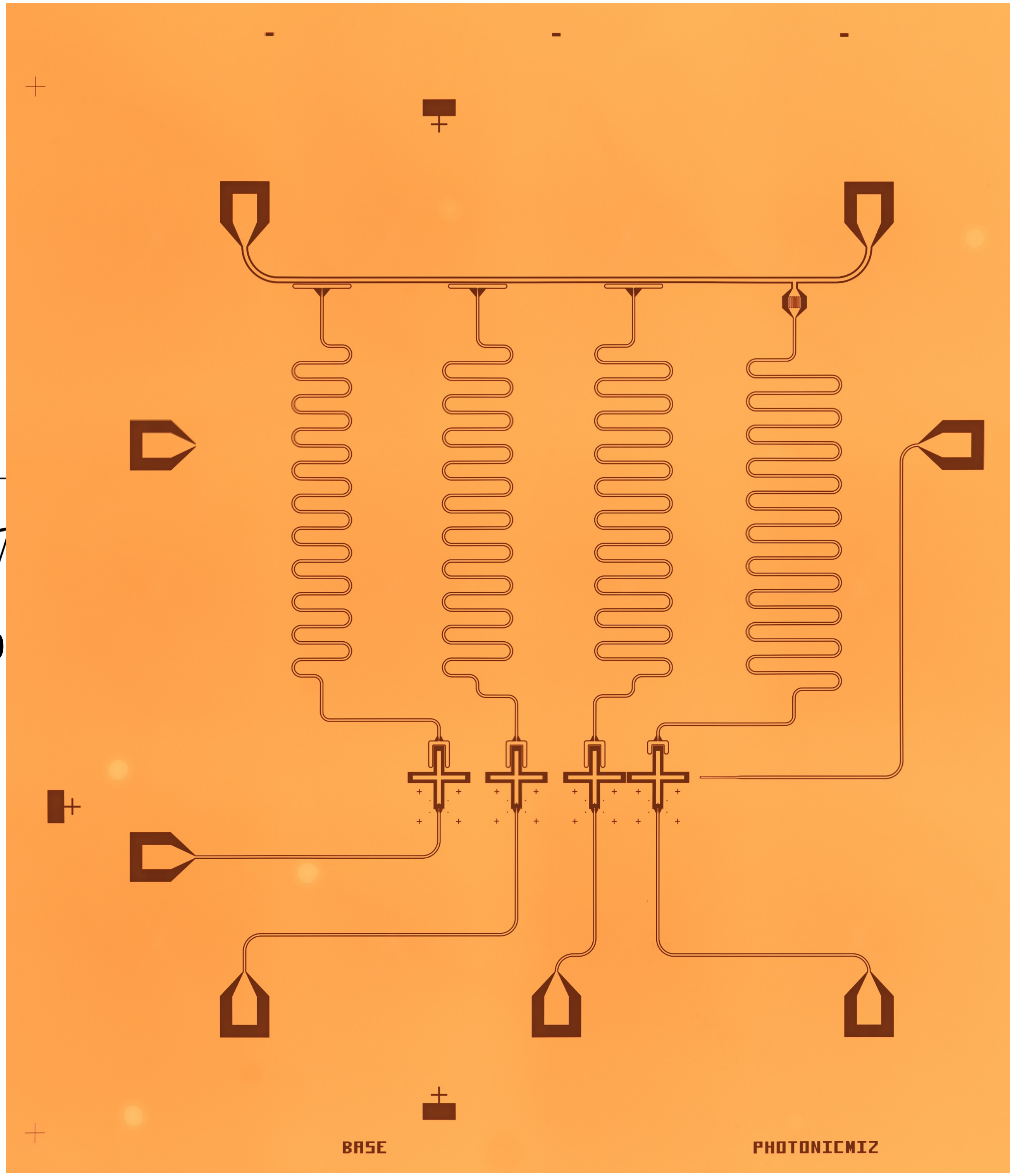
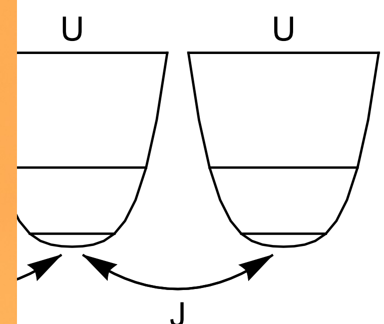

BASE
PHOTONICMIZ


U
U
J

Towards Photonic Materials

Experiment

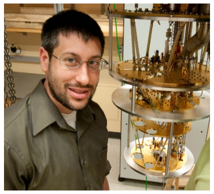
- Schine *et al.*, "Synthetic Landau levels for photons," **Nature** 534, 671–675 (2016).
- Ningyuan *et al.*, "Observation and characterization of cavity Rydberg polaritons," **PRA** 93 (4), 041802 (2016).
- Ningyuan *et al.*, "Time-and site-resolved dynamics in a topological circuit," **PRX** 5 (2), 021031 (2015).
- Ryou *et al.*, "Active Cancellation of Acoustical Resonances with an FPGA FIR Filter," **arXiv**: 1604.04668 (2016).
- Sommer *et al., "*Time-Reversal Symmetry Breaking in a High-Finesse Non-Planar Cavity,*" In Preparation.*

Theory

- Sommer *et al., "*Engineering Photonic Floquet Hamiltonians through Fabry–Pérot resonators," **NJP** 18 (3), 035008 (2016).
- Anderson *et al.*, "Engineering topological materials in microwave cavity arrays," accepted to **PRX**.
- Ma *et al.*, "Hamiltonian Tomography of Photonic Lattices," **arXiv**:1607.05180 (2016).
- Sommer *et al.*, "Quantum Crystals and Laughlin Droplets of Cavity Rydberg Polaritons," **arXiv**: 1506.00341 (2015).
- Ma *et al.,* "A Simple Chemical Potential for Photons," *In Preparation.*

Thanks!

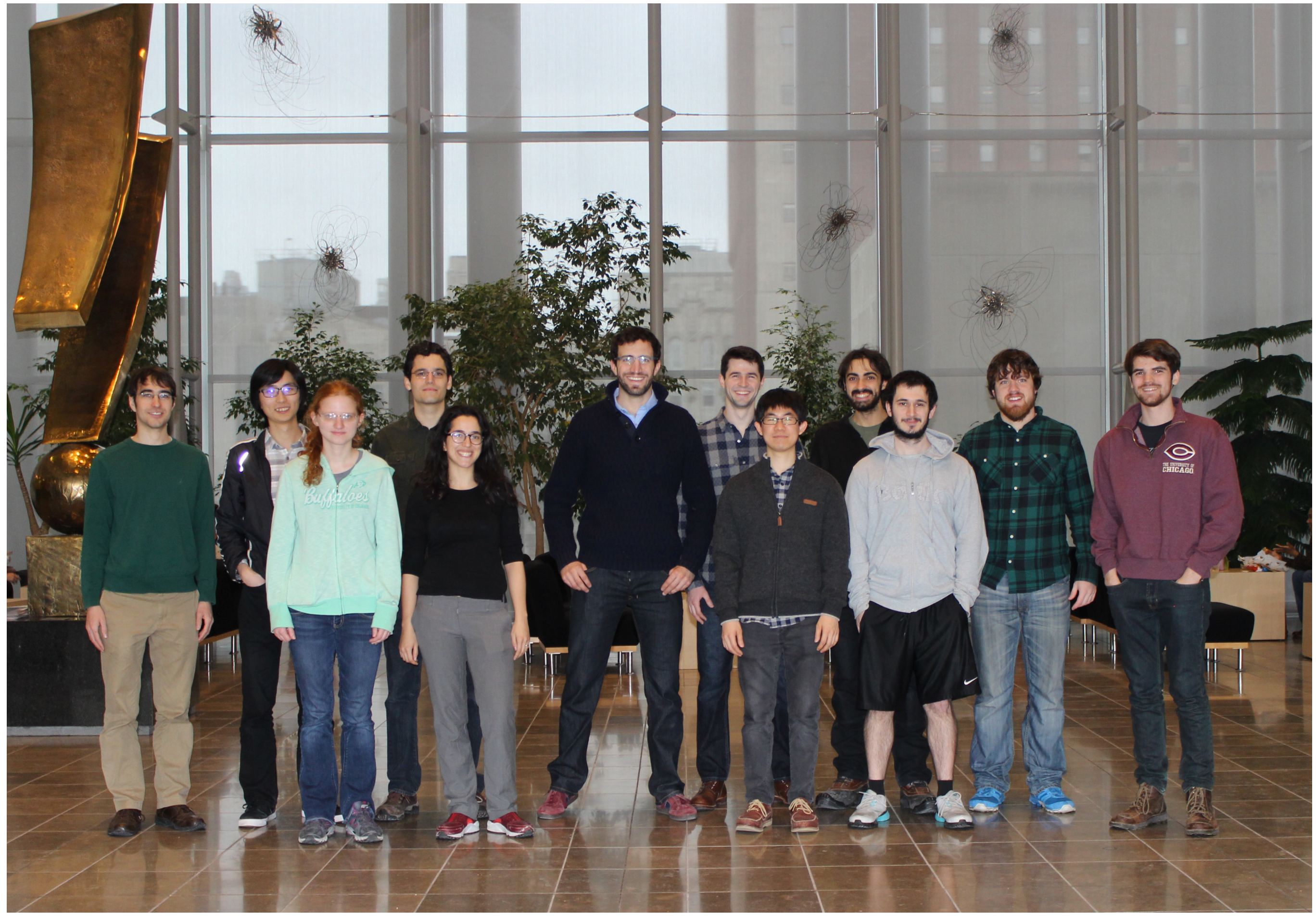
Dave Schuster
Andrey Gromov
Brandon Anderson



Bulk Polaritonic Materials
Ariel Sommer (PD)
Nathan Schine (PhD)
Alex Georgakopolous (PhD)
Jia Ningyuan (PhD)
Albert Ryou (PhD)
Michelle Chalupnik (UG)

Lattice Microwave Materials
Alex Ma (PD)
Clai Owens (PhD)
Brendan Saxberg (PhD)
Aman LaChapelle (UG)

Optical/mmWave Hybrid
Aziza Suleymanzade (PhD)
Mark Stone (PhD)
Scott Eustice (UG)



quantum.uchicago.edu & simonlab.uchicago.edu