THE UNIVERSITY OF CHICAGO

Making Topological Matter from Light

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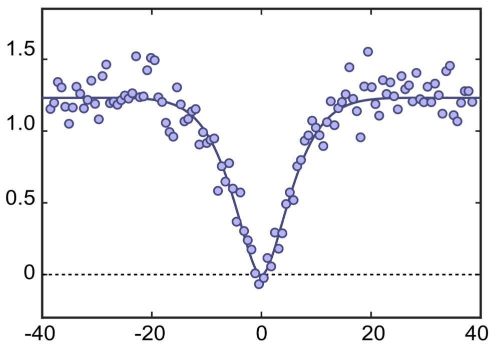
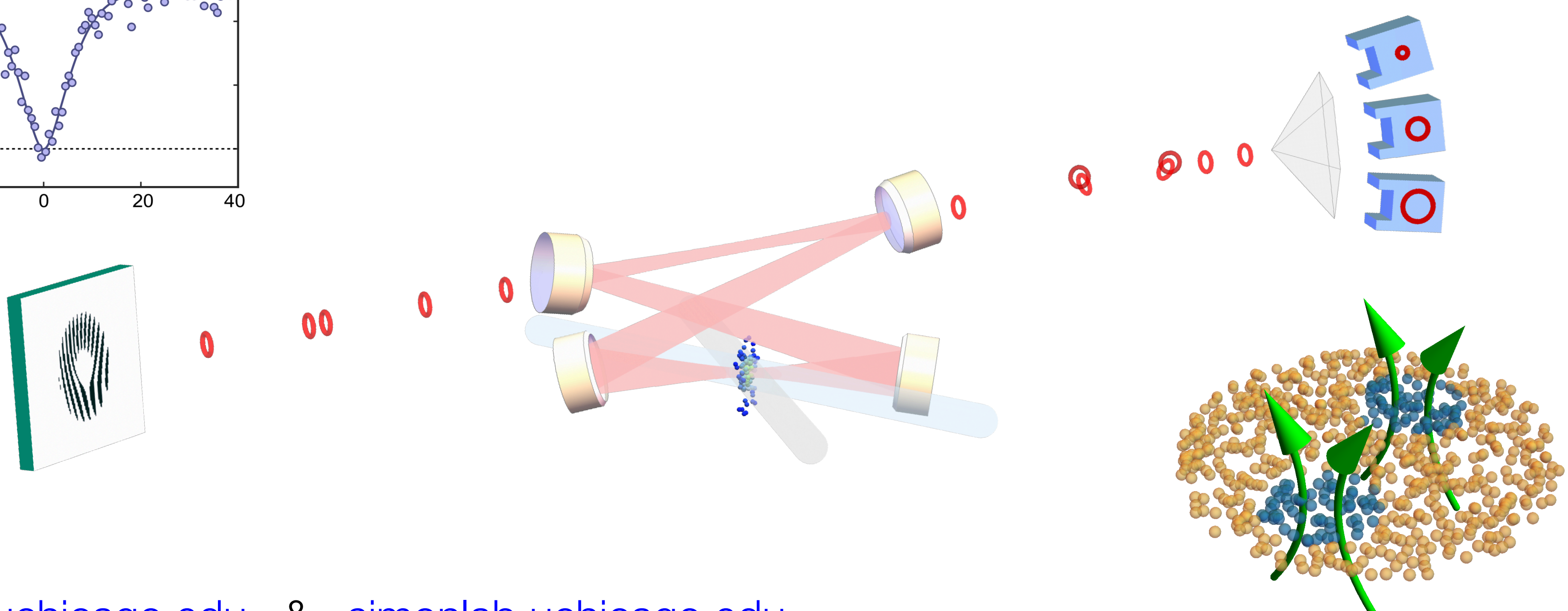
University of Chicago
Chicago, Illinois

Topological Quantum Matter: From Fantasy to Reality
KITP, Oct. 1st, 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.

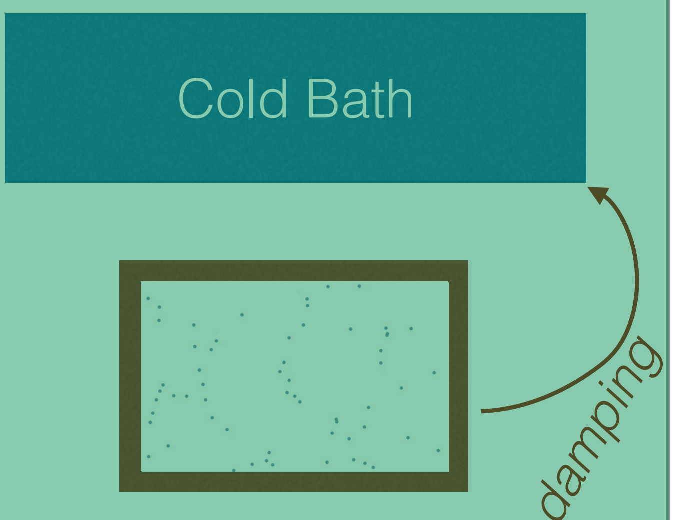
(Interaction Control)

(Entropy Management)

Ways to Order a Material

Electrons/cQED

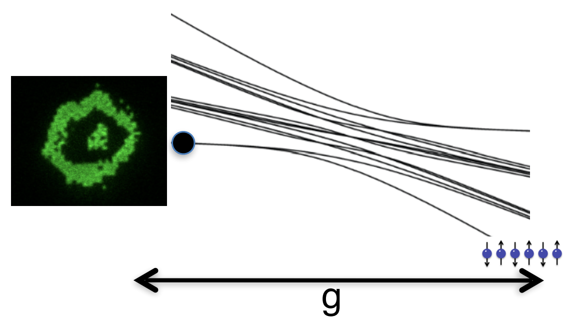
Thermalization with Reservoir



Relies upon repeated collisions with (low energy) particles in reservoir to remove energy from the system.

Ultracold Atoms

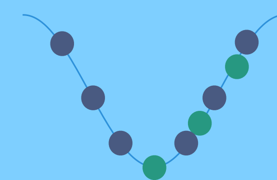
Quantum Phase Transition

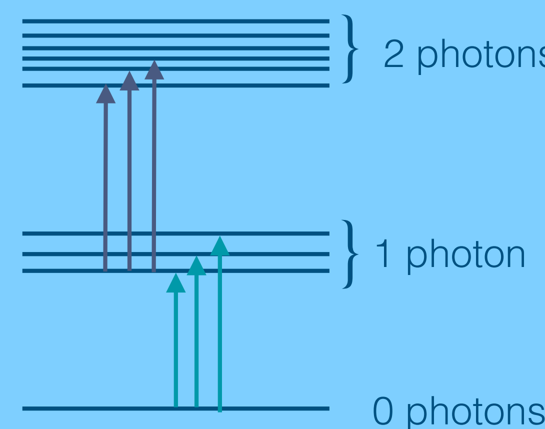


Relies on adiabatic theorem: if the Hamiltonian changes slowly enough, the system stays in the ground state

Photons

Spectroscopic Assembly





Relies upon precise knowledge of energies and wavefunction of system at each desired particle number

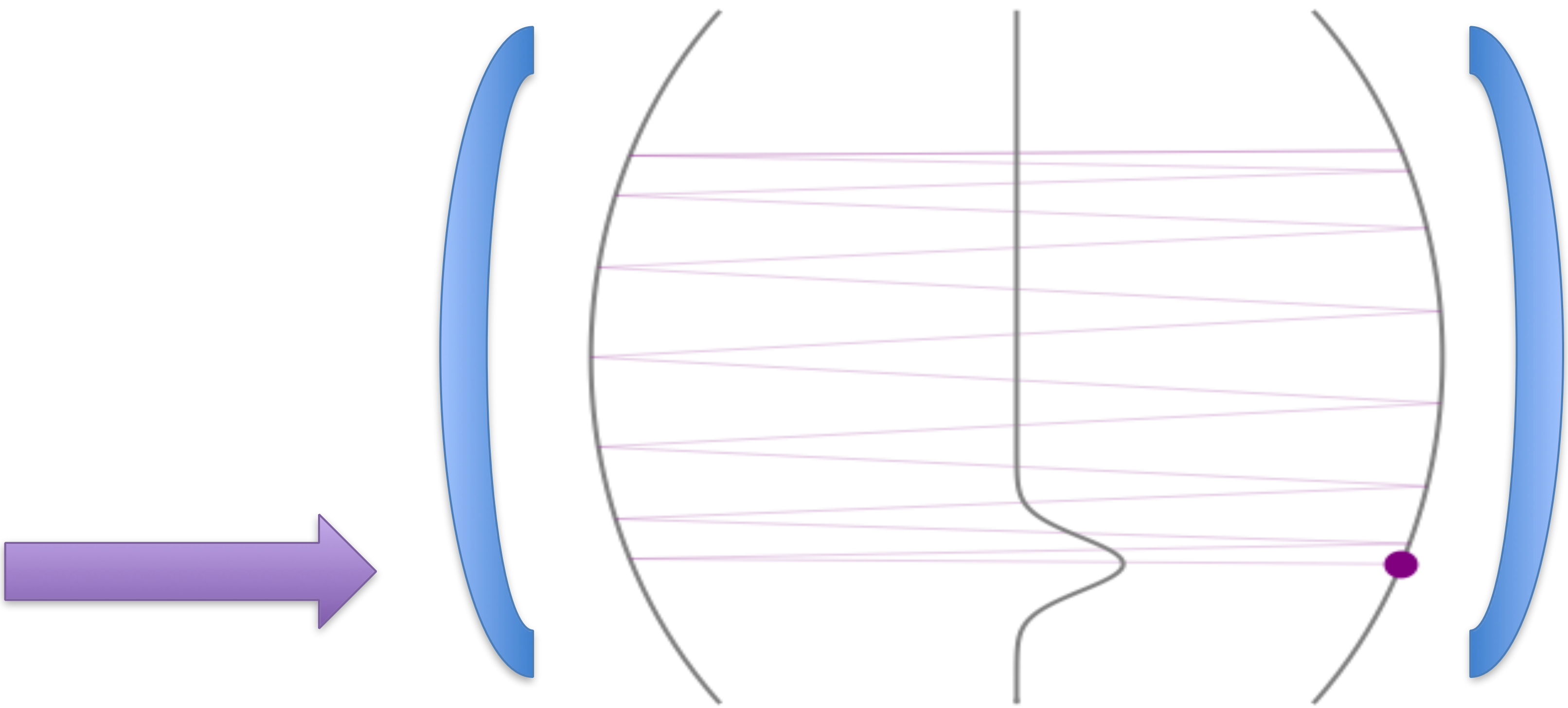
Central Premise

Photons in Multimode Resonator

↕

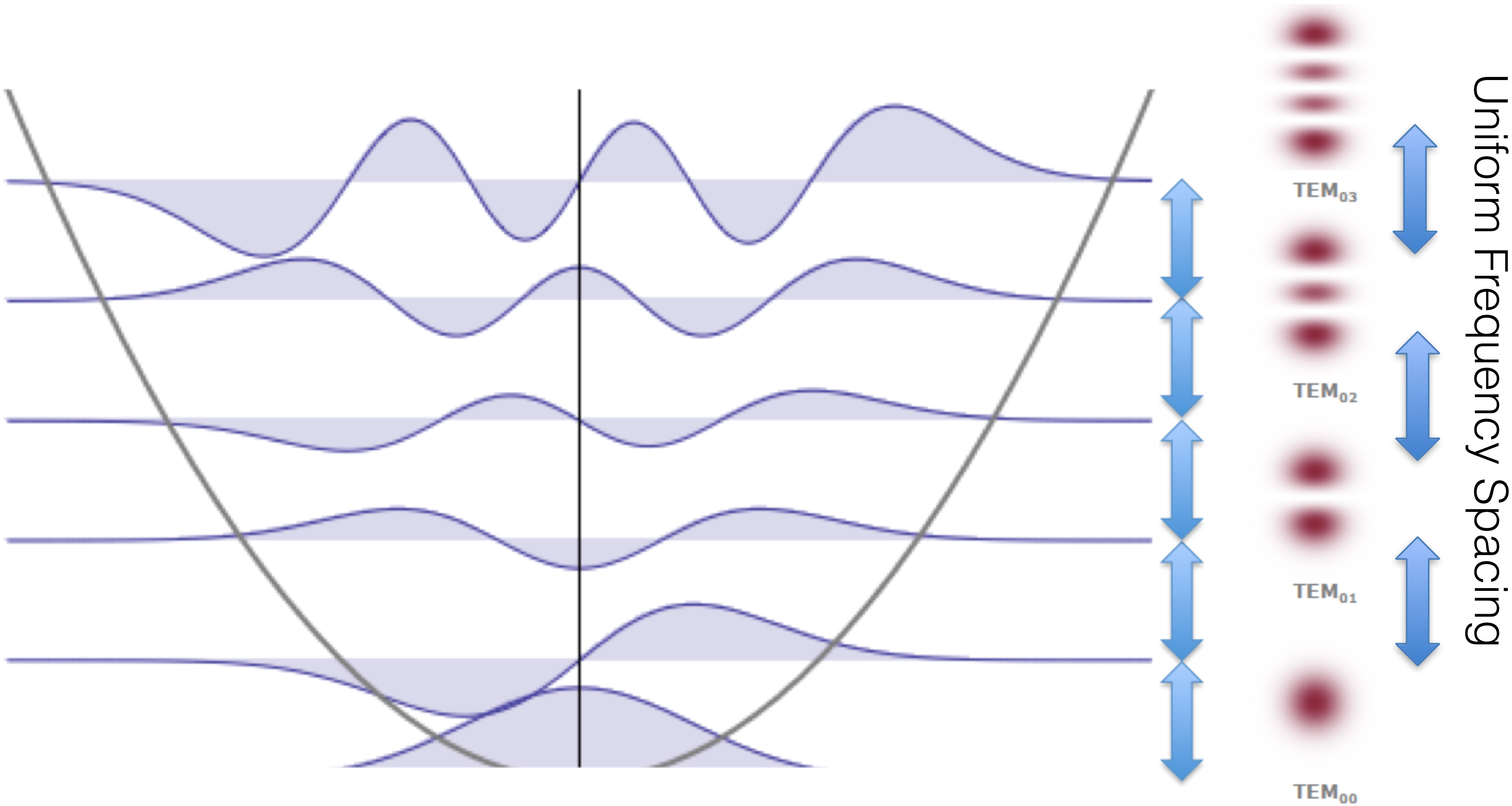
Massive Particles in Harmonic Trap

Understanding photons in optical resonators



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

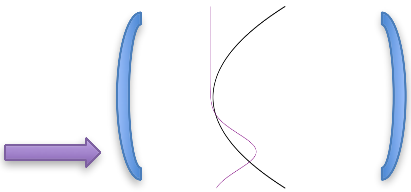
Comparing
Harmonic Oscillators & Optical Resonators

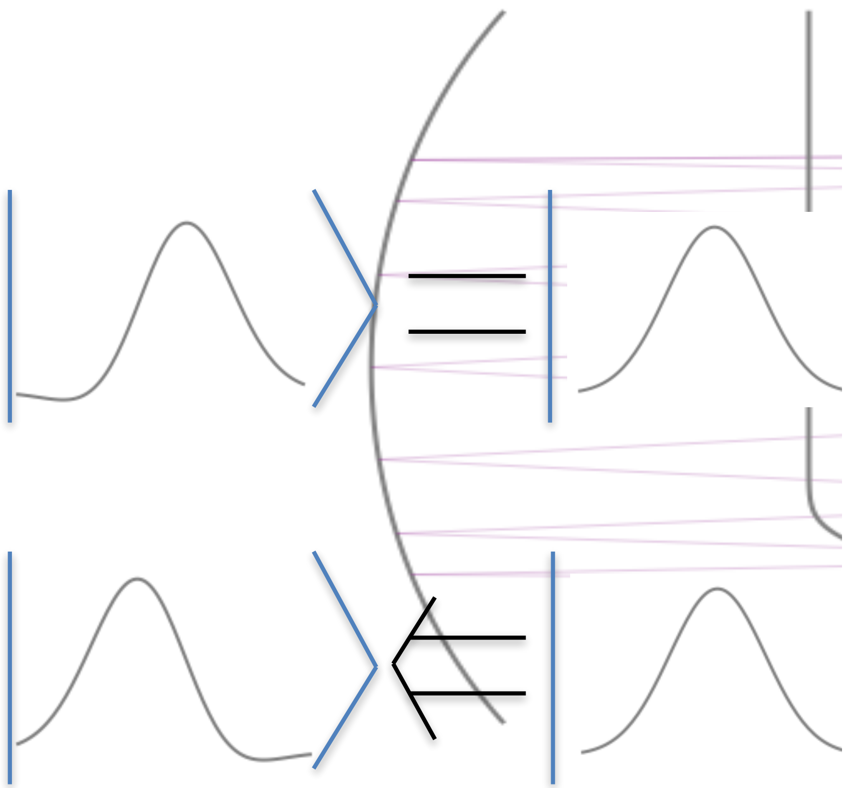


Hermite Gauss Wavefunctions

Optical Modes

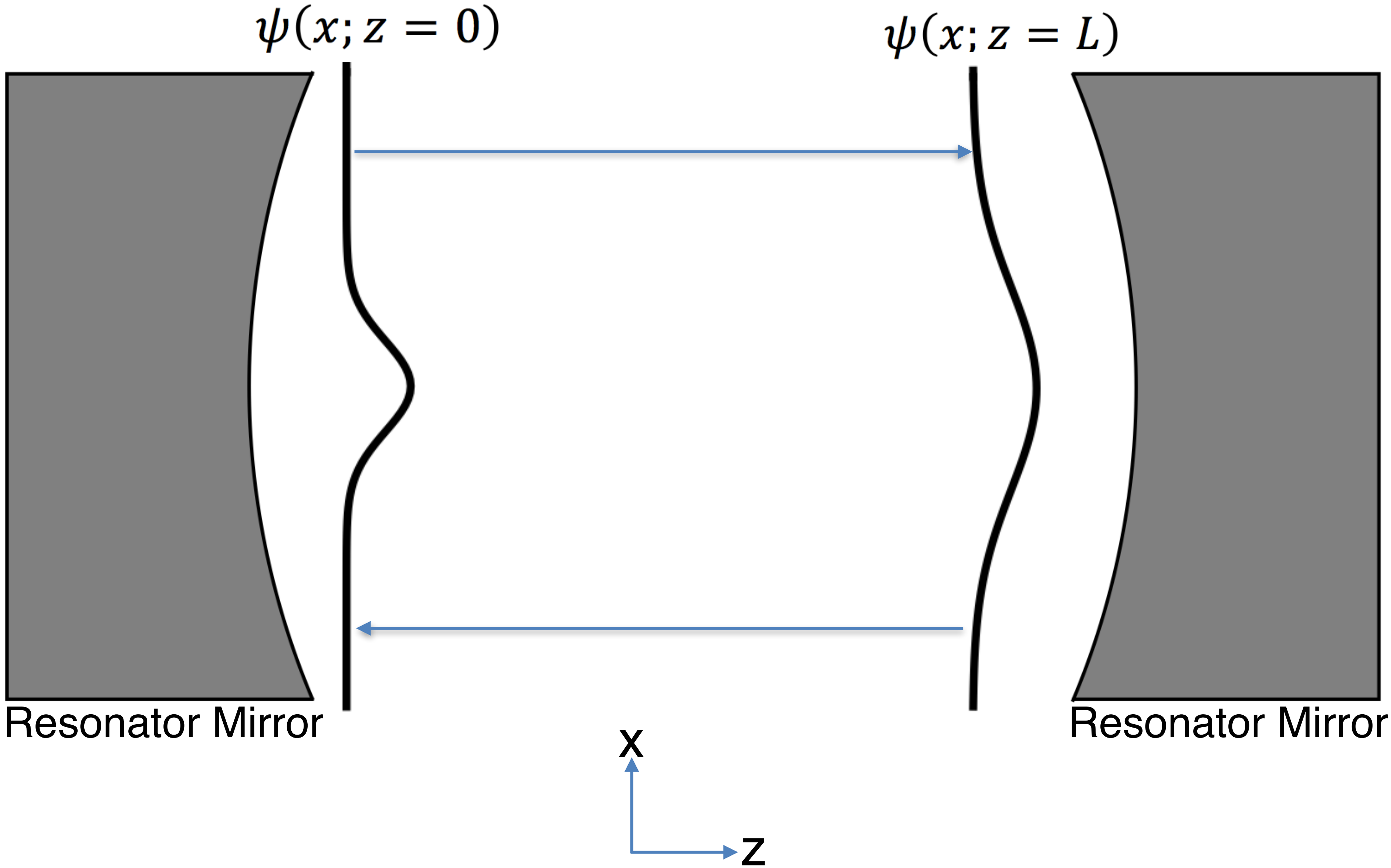
Understanding
photons in optical resonators





Formal Floquet Picture: Sommer *et al.*, **NJP** 18 (3), 035008 (2016).

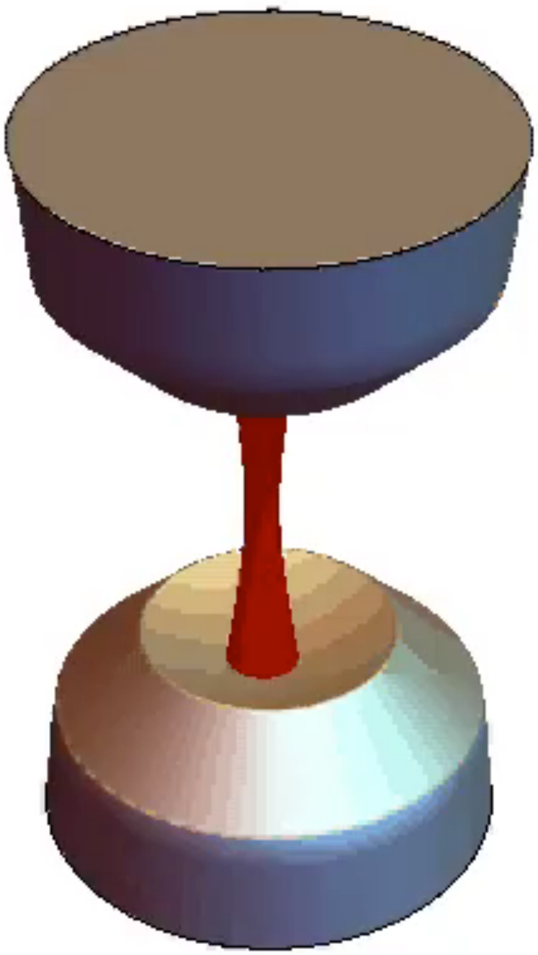
Formal Picture: *Floquet Theory*



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

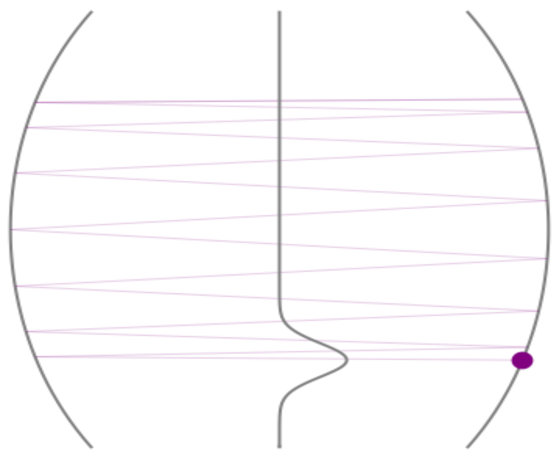
Formal Picture: *Floquet Theory*

Synthetic Magnetic Fields for Photons



Free Space Propagation → **Mass**

Mirror Curvature → **Trapping**



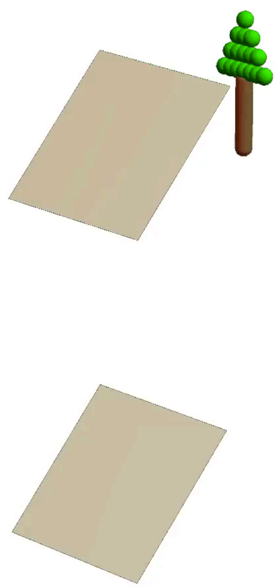
is there a (simple) way to add a synthetic magnetic field??

[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)

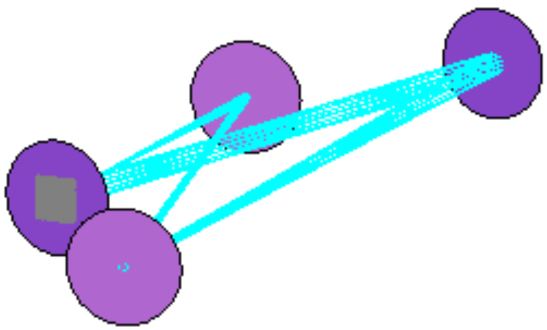
Turning the Lab Frame into a Rotating Frame

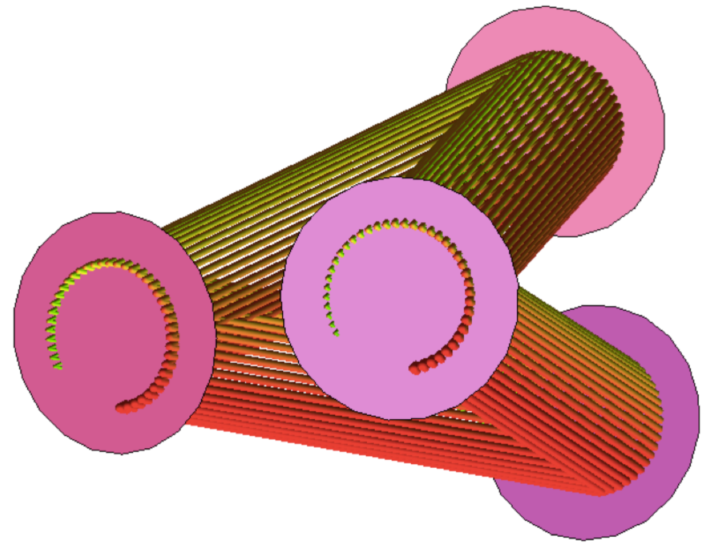
A Twisted Periscope

(Trees on the open sea)



Synthetic Magnetic Fields for Cavity Photons



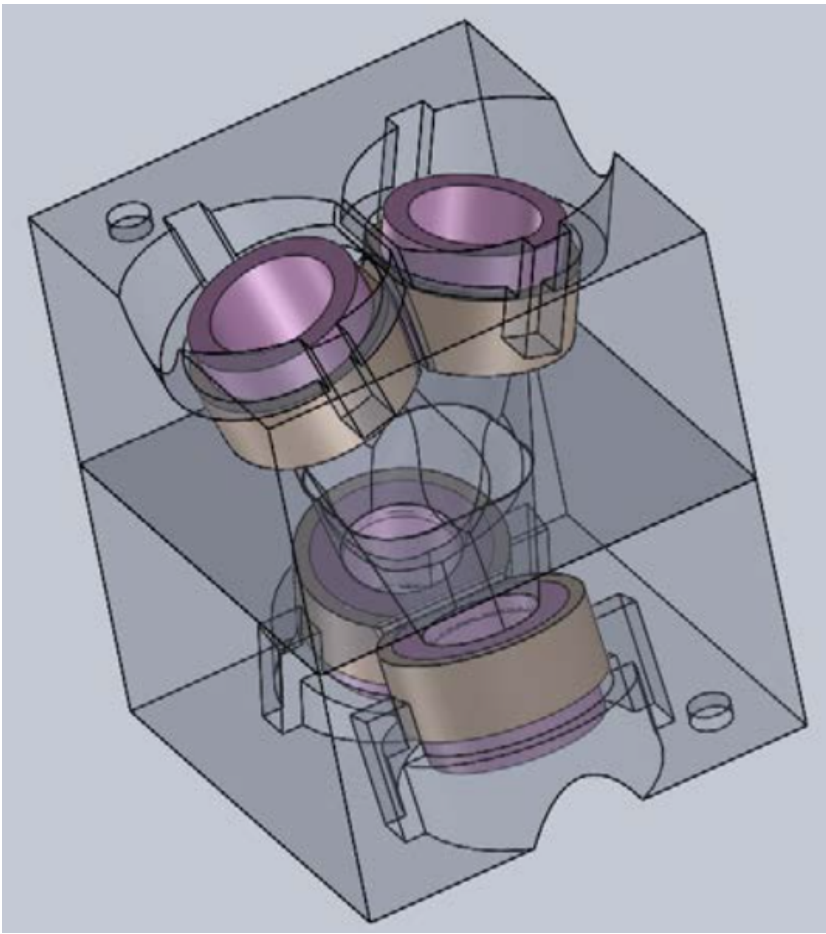


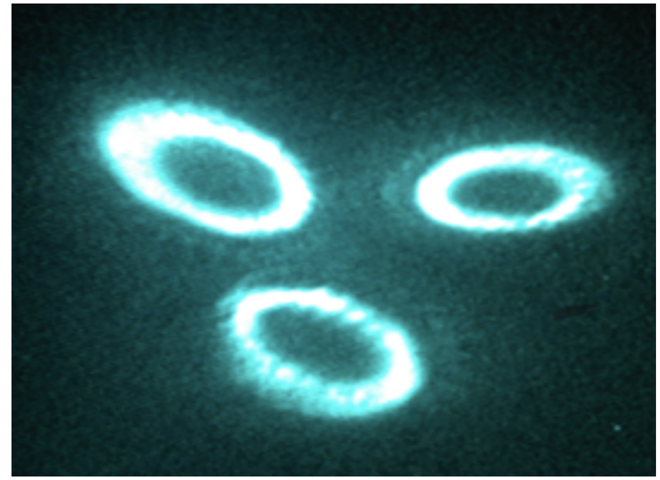
Twisting the resonator out of the plane makes the lab frame a rotating frame → Coriolis & Centrifugal Forces

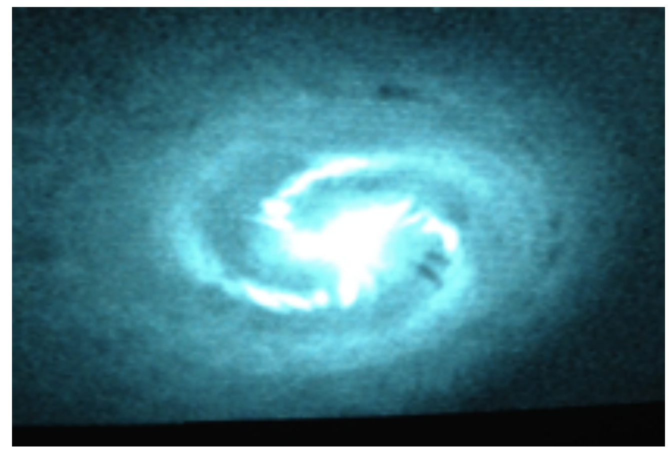
$\vec{\Omega} \times \vec{p}$ $\Omega^2 \vec{r}_\perp$

[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)

3D Print the structure
and stuff super-mirrors in!

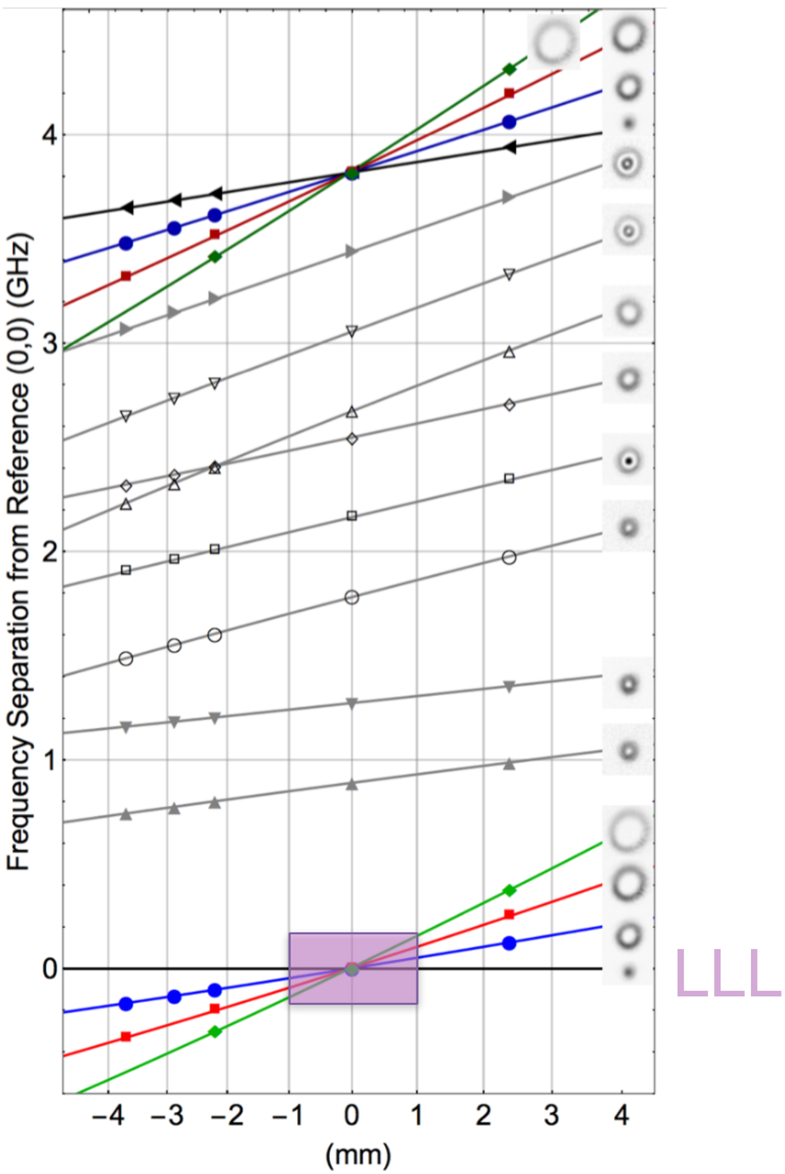


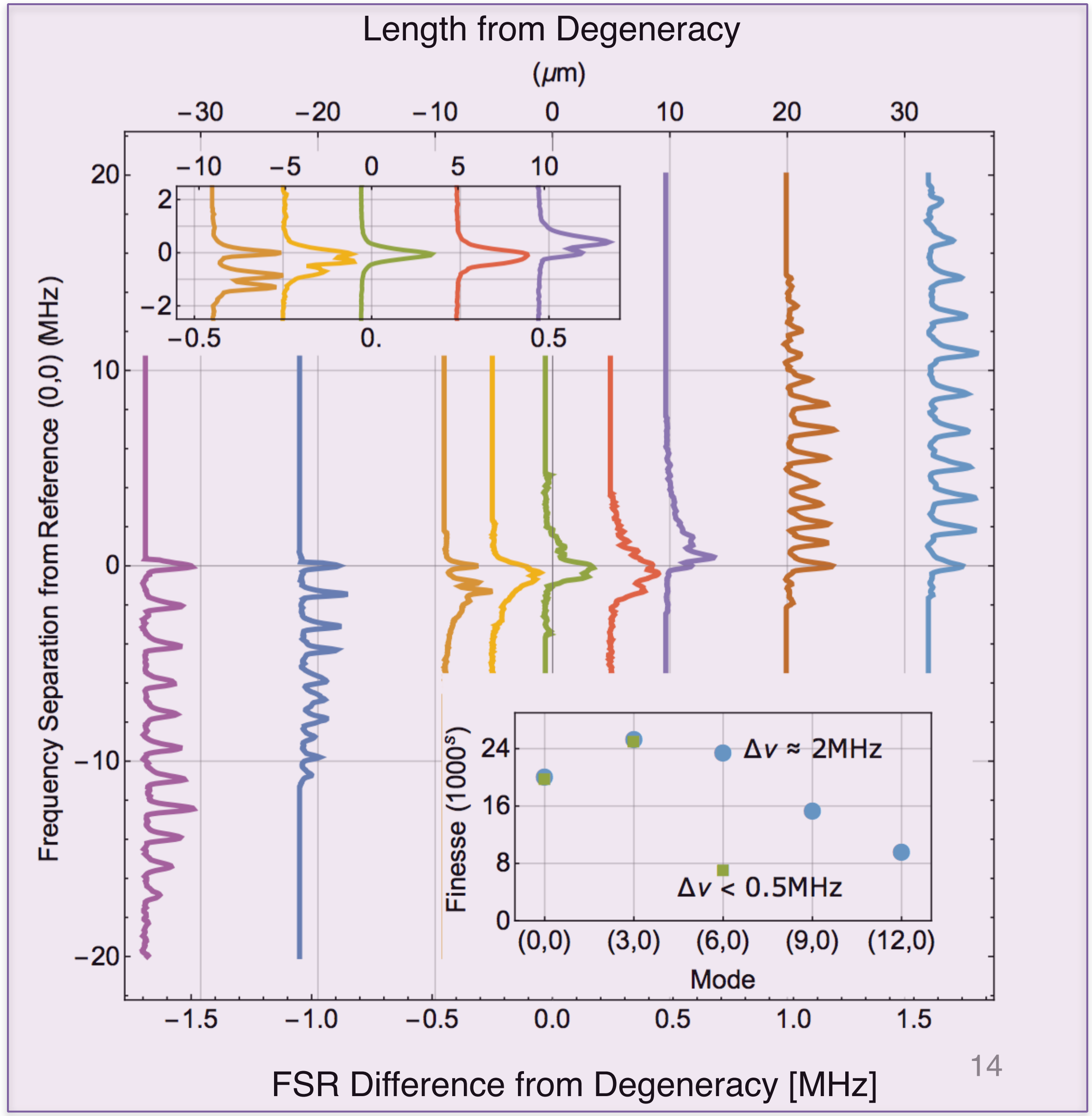




$$\Psi_L(z \equiv x + iy) = \frac{z}{\sqrt{\pi L!}} e^{-z\,\bar{z}}$$

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



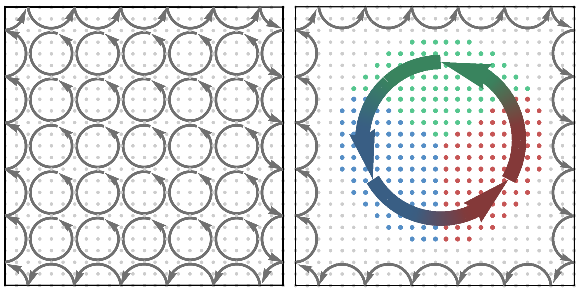


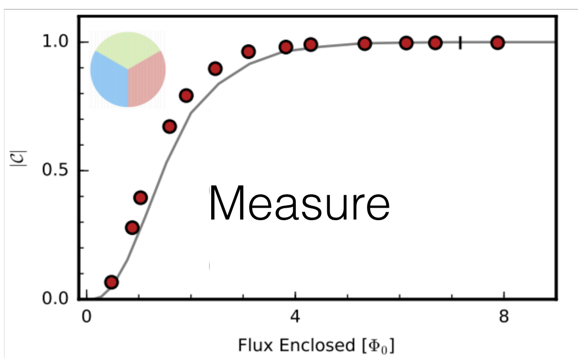
Schine et al., Nature, 534, 671 (2016)

Single-Particle Topology Smorgasbord

Kitaev's Chern Marker

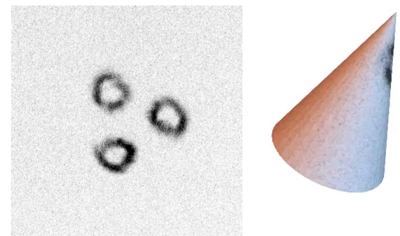
$$\mathcal{C} = 12\pi i \times Tr\left[PAPBPC - PCPBPA\right]$$



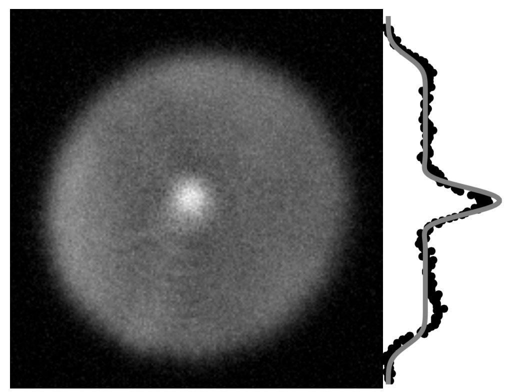


Schine *et al.* Nature **565** (2019)
Ma *et al.* PRA **95**, 062120 (2017)
A. Kitaev, Ann. Phys. **321**, 2 (2006)

Mean Orbital Spin



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

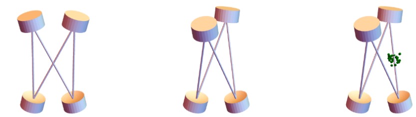


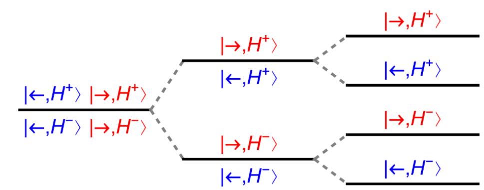
0.31[2] states

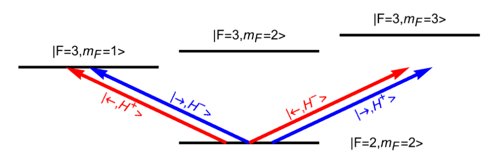
$$\bar{s} = 0.47(1).$$

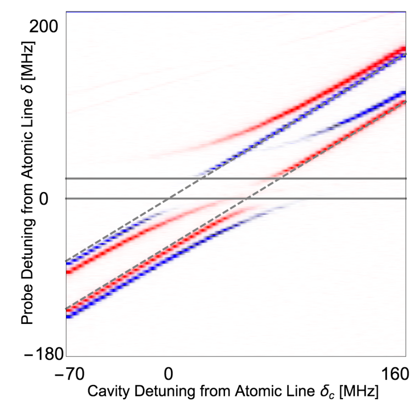
Can *et al.*, PRL **113**, 046803 (2014),
Abanov *et al.*, PRB **90**, 014435 (2014)

Breaking T in a Cavity





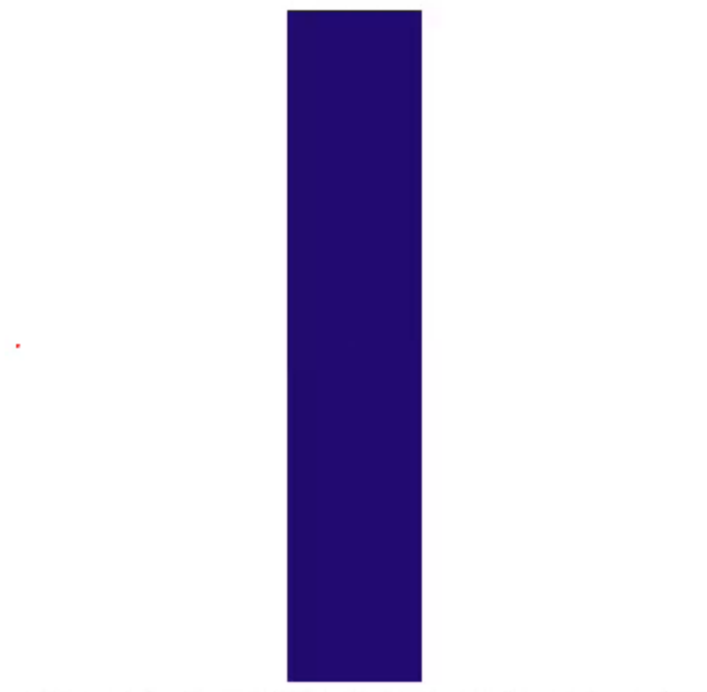


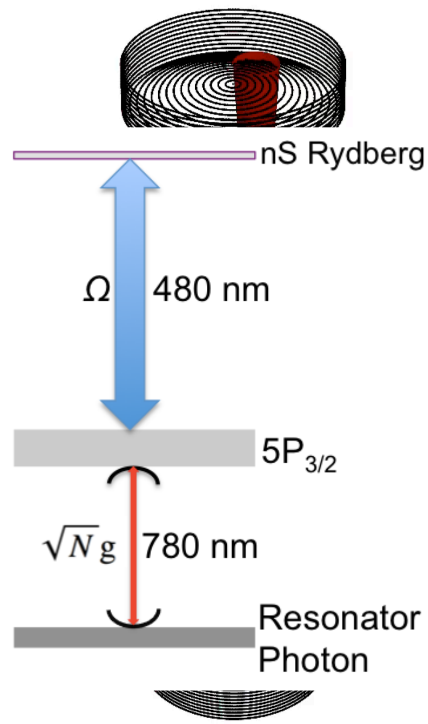


Jia *et al.*, Phys. Rev. A **97**, 013802 (2018)

Making Cavity Photons Collide

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

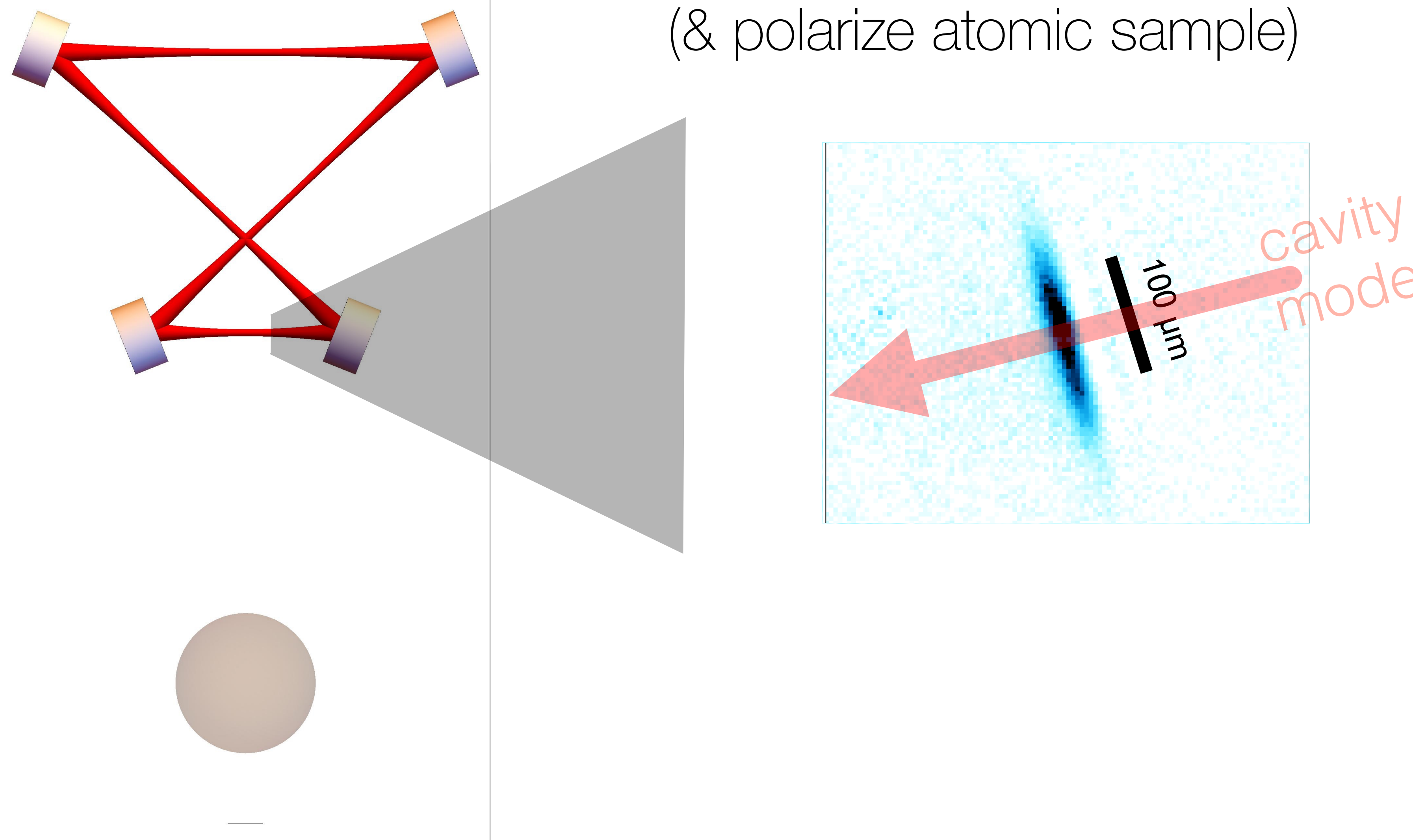




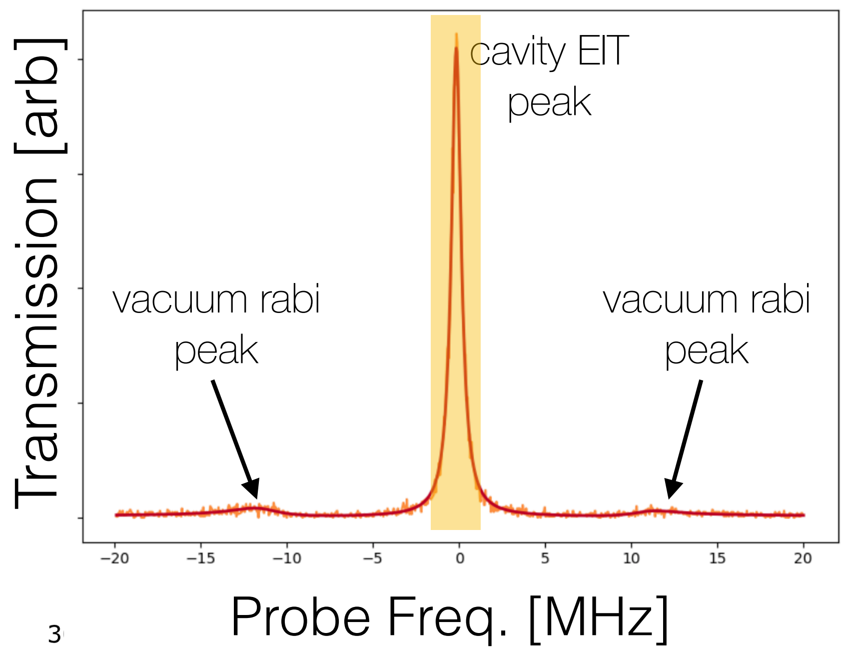
Peyronel *et al.*, Nature **488**, 57–60 (2012), Firstenberg *et al.*, Nature **502**, 71-75 (2013), Baur *et al.*, Phys. Rev. Lett. **112**, 073901 (2014), Tiarks *et al.*, Phys. Rev. Lett. **113**, 053602 (2014), Gorniaczyk *et al.*, PRL **113**, 053601 (2014)

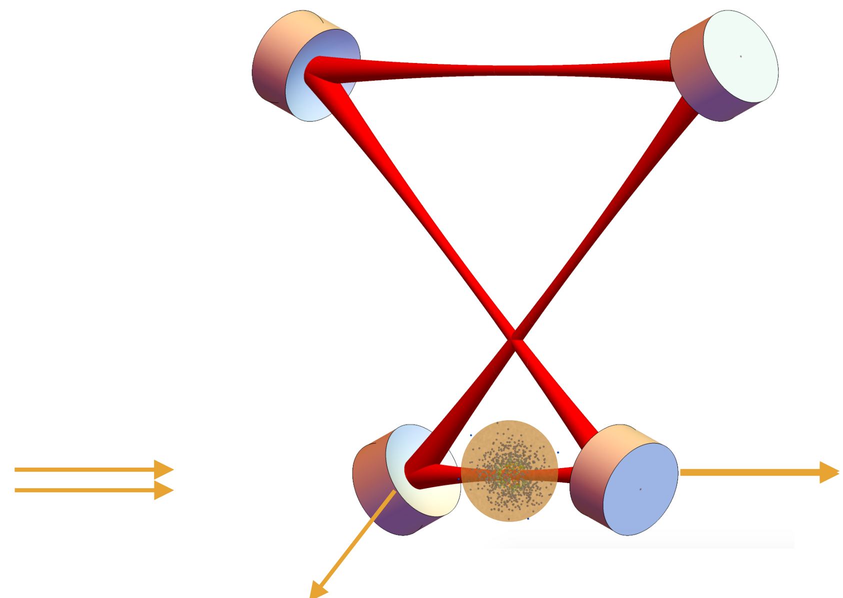
The Apparatus
Combining Rydbergs and Optical Cavities

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

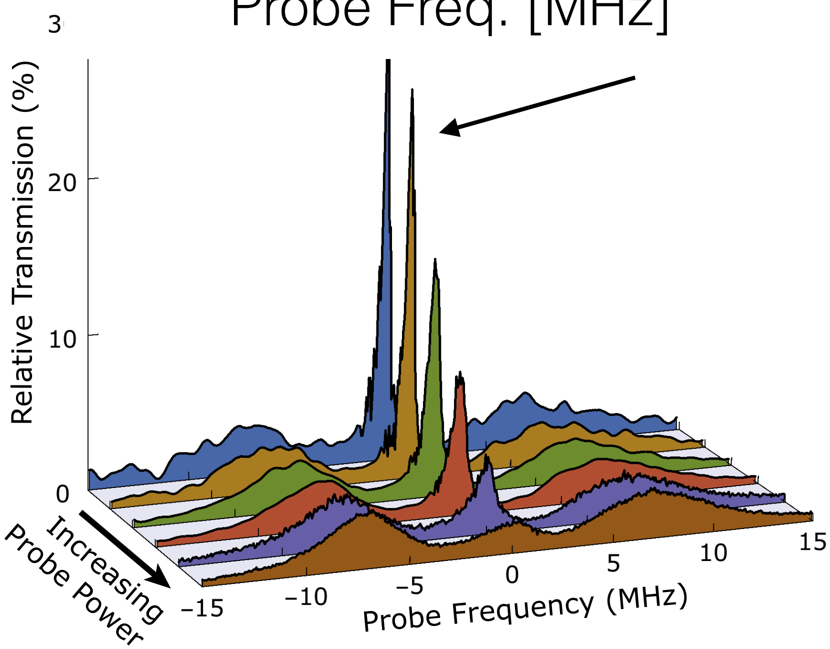


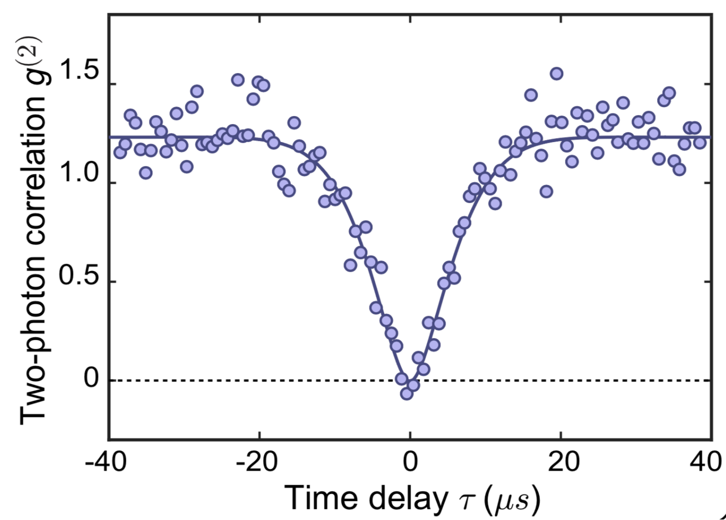
Observation of Cavity Polariton Blockade
in a 0-dimensional quantum dot





1 photon/polariton lifetime (μs)

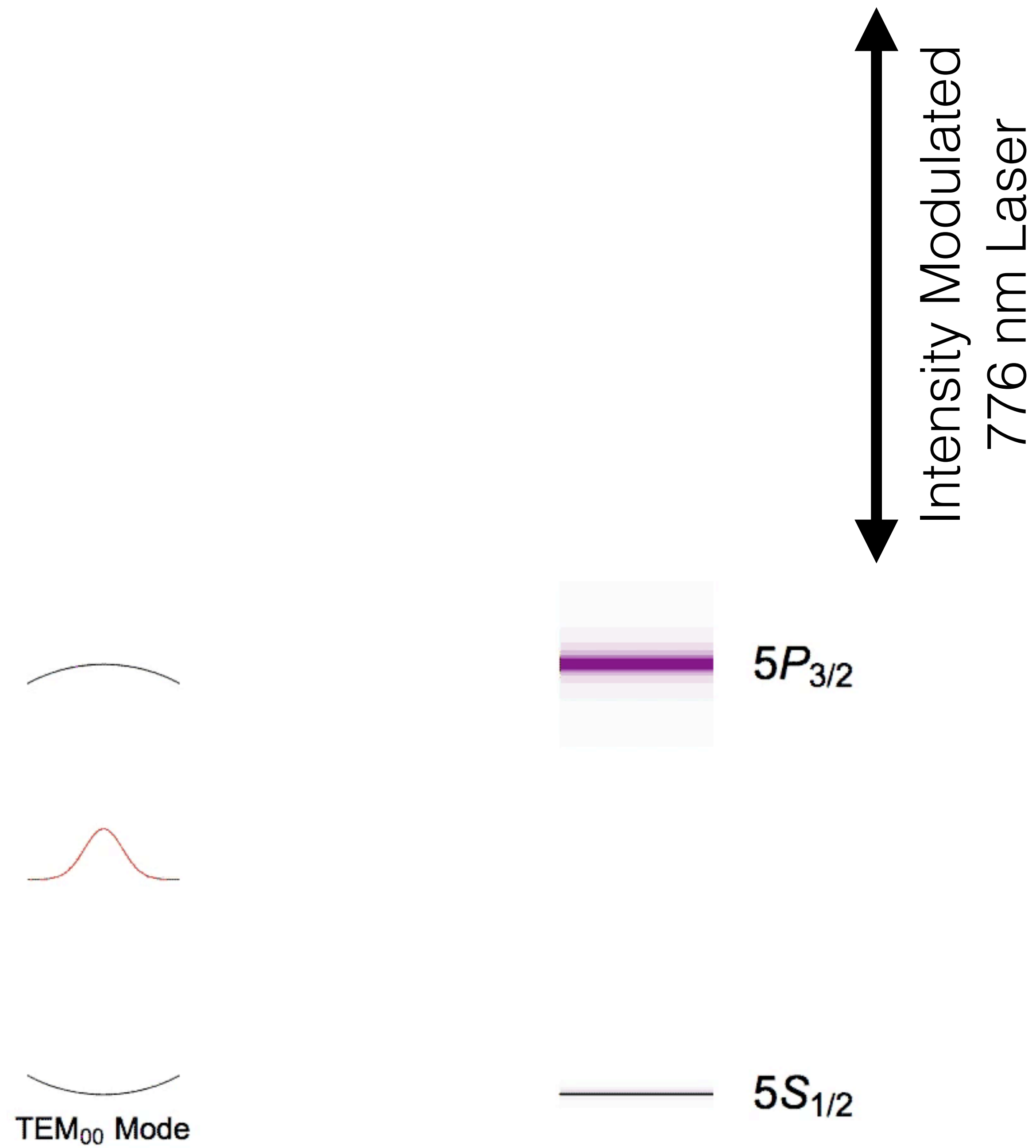




[1] Ningyuan *et al.*, Nature Physics **14**, 550–554 (2018).

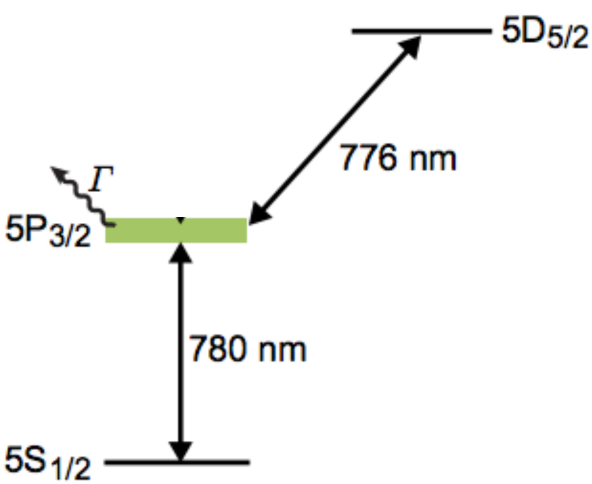
[2] Guerlin *et al.*, Phys. Rev. A **82**, 053832

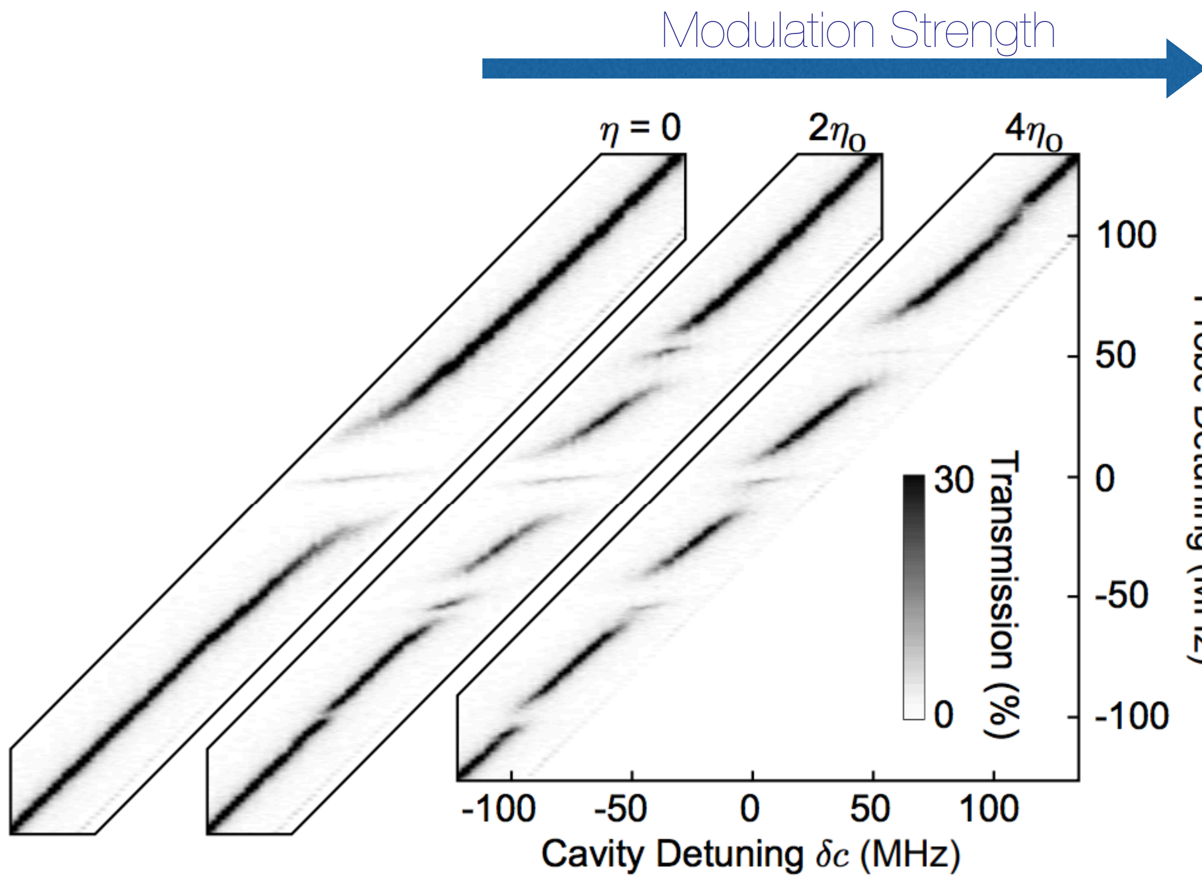
A Multimode Collider:
Sculpting the Atomic Density of States



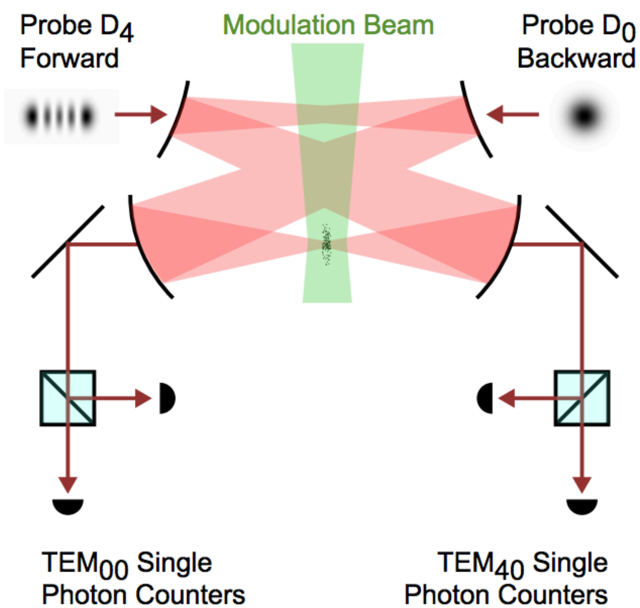
Floquet Polaritons to Floquet Rydberg Polaritons

in a single-mode cavity





A Multimode Polariton Collider



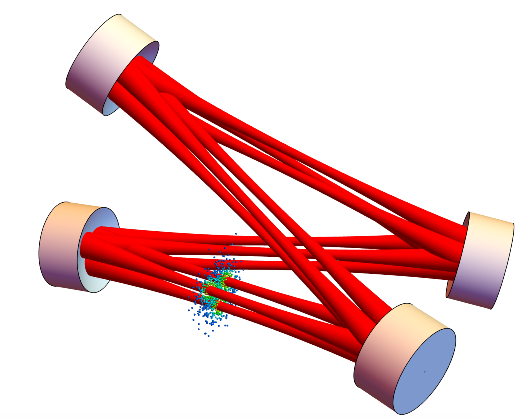
Multimode Photon-by-Photon Switching!

Putting it all Together
Photonic Laughlin States

Magnetic Fields for Photons

Photon-Photon Scattering

Topological Manybody States



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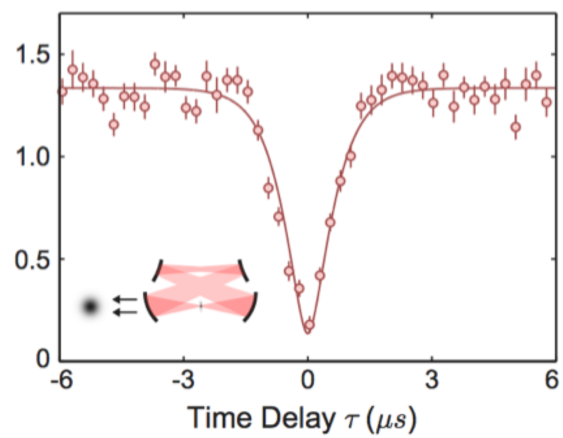

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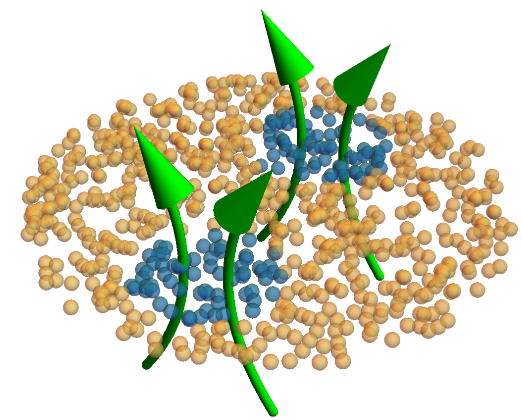
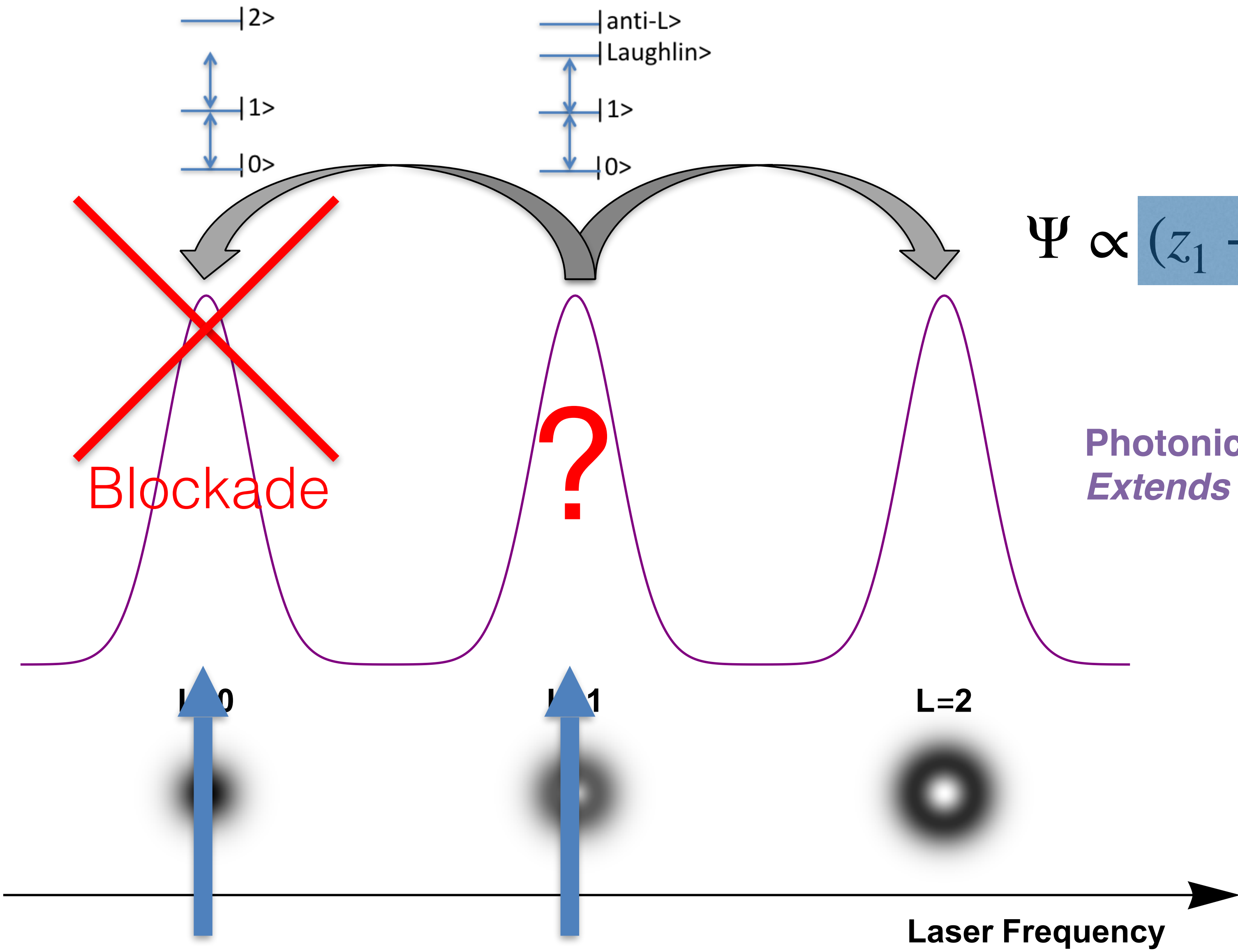


Clark *et al.*, arXiv: 1907.05872 (2019)

Assembling a Laughlin Molecule
the concept



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

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)

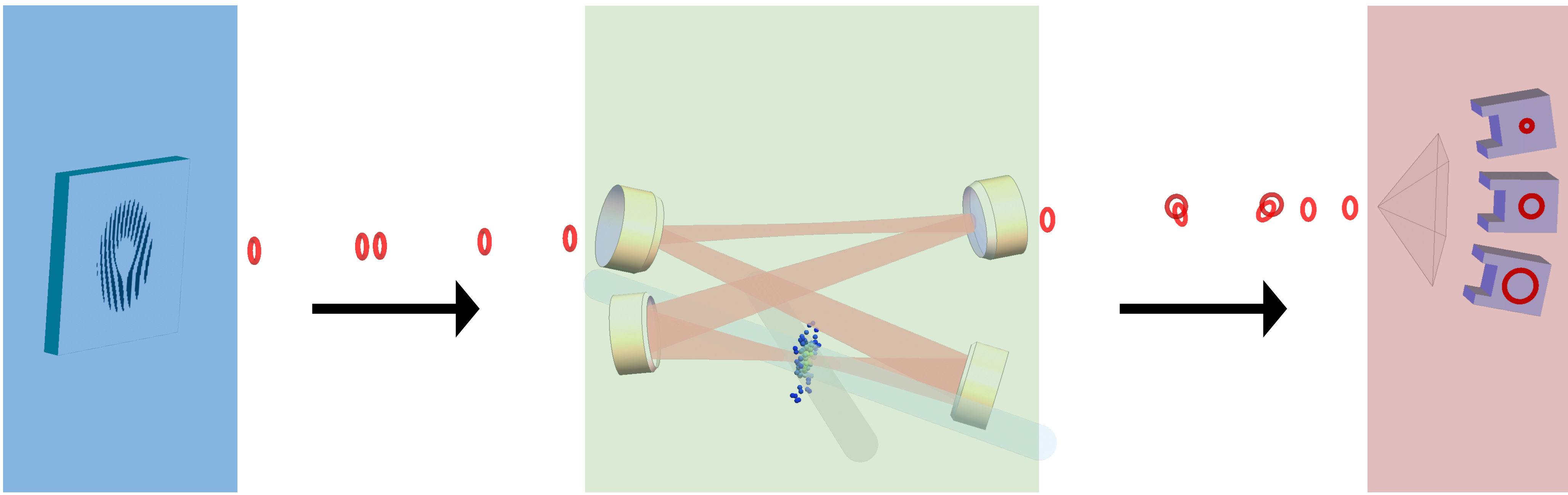
Making a Topological Molecule

the experiment

DMD

Twisted Cavity
+
Rydbergs

Sequential
Cavities
+
SPCMs



OAM
Generation

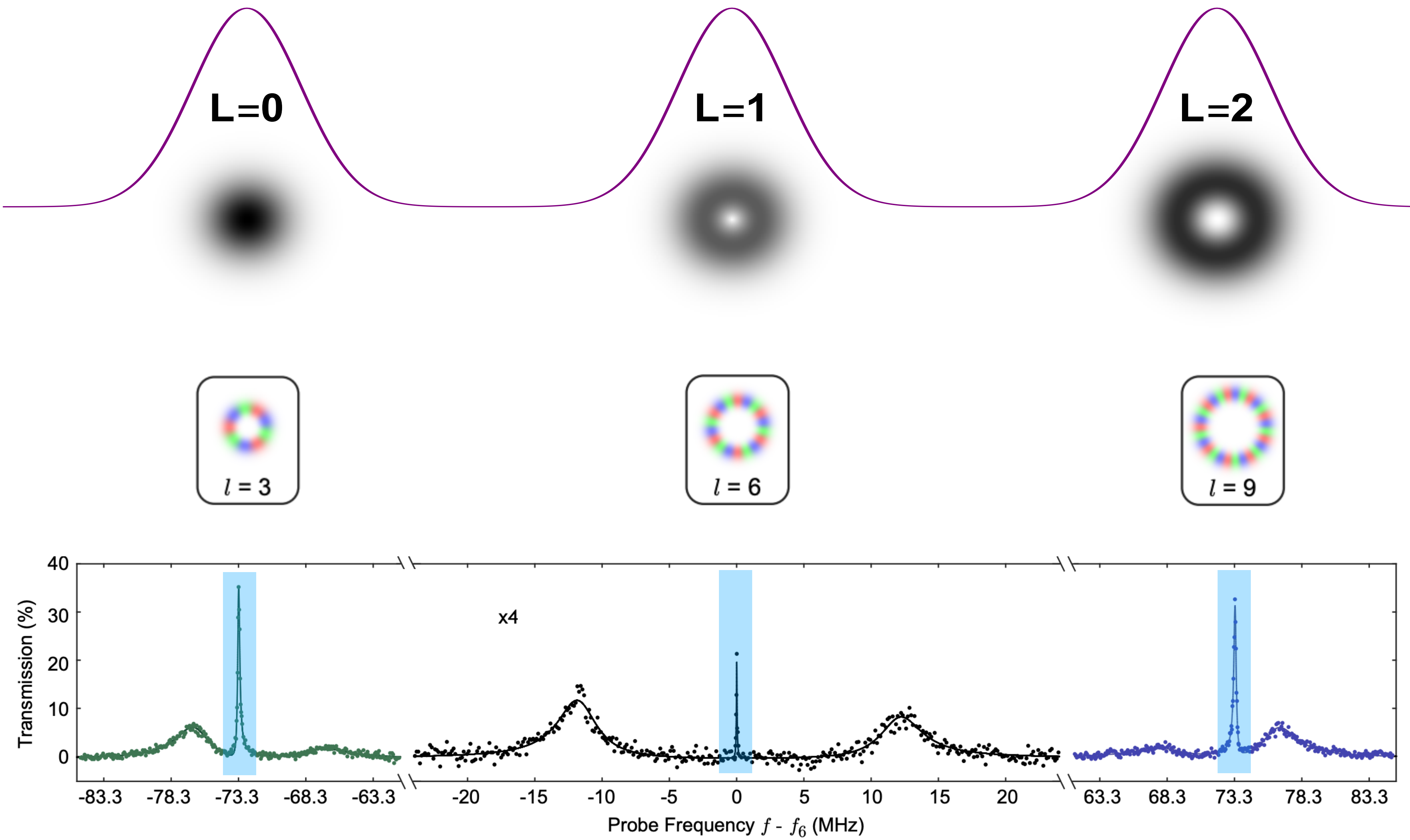
Interacting LLL
Polaritons

OAM-Sorted
Detection

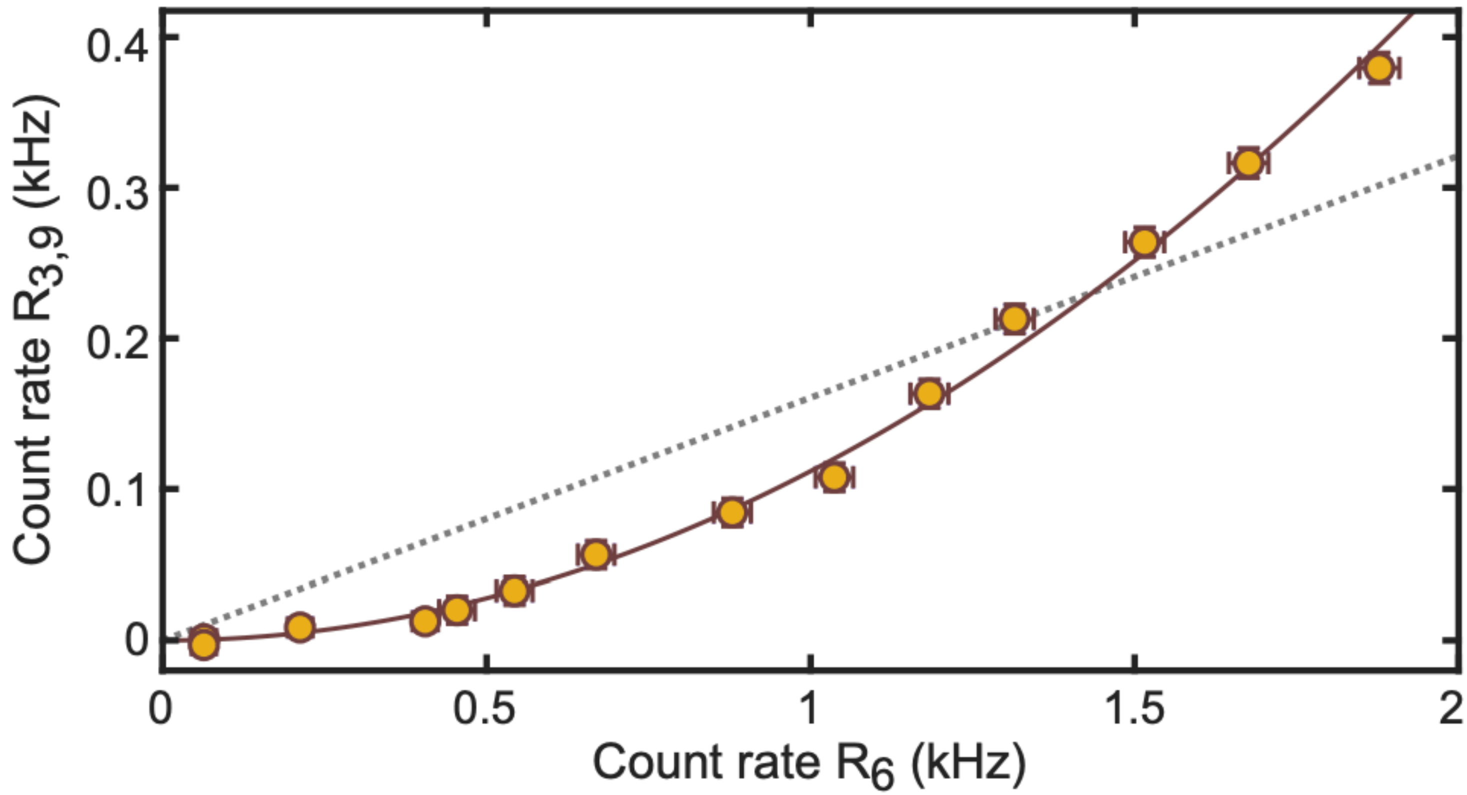
Inspiration: Umucalilar et al., PRL **108**, 206809 (2012)

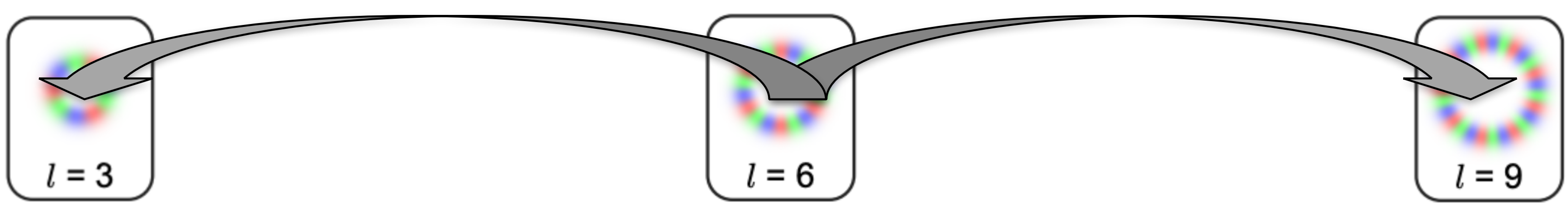
Making a Topological Molecule

Single-Particle Orbital Spectroscopy

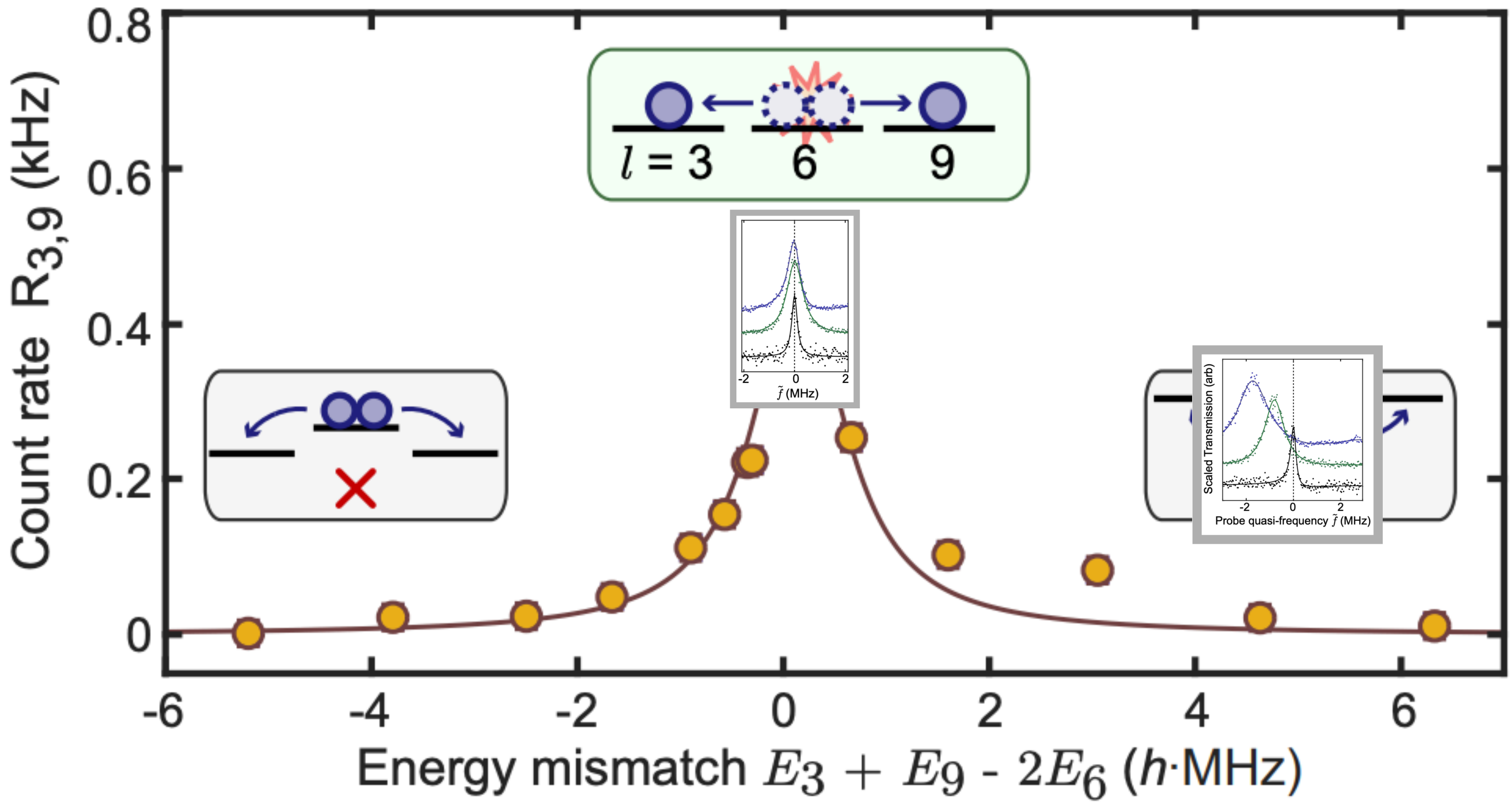


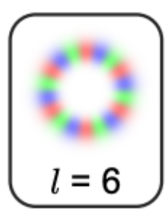
Assembling a Topological Molecule
LLL Orbital-Changing Collisions

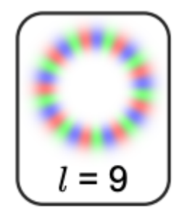




Assembling a Topological Molecule
Energy Conservation of LLL Collisions





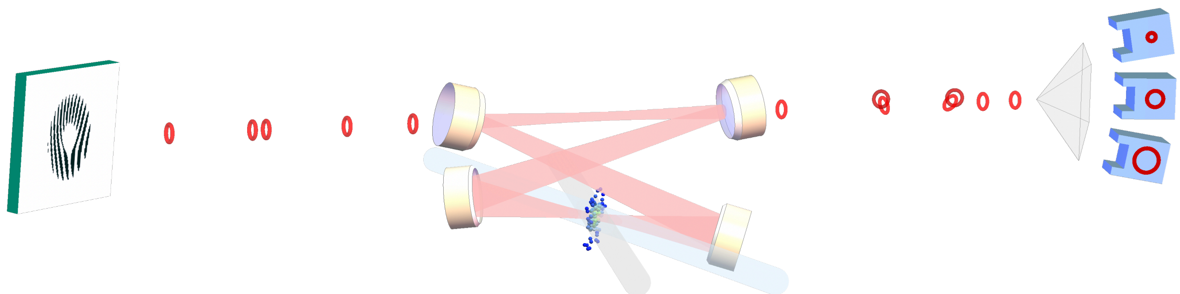


Characterizing the Topological Molecule

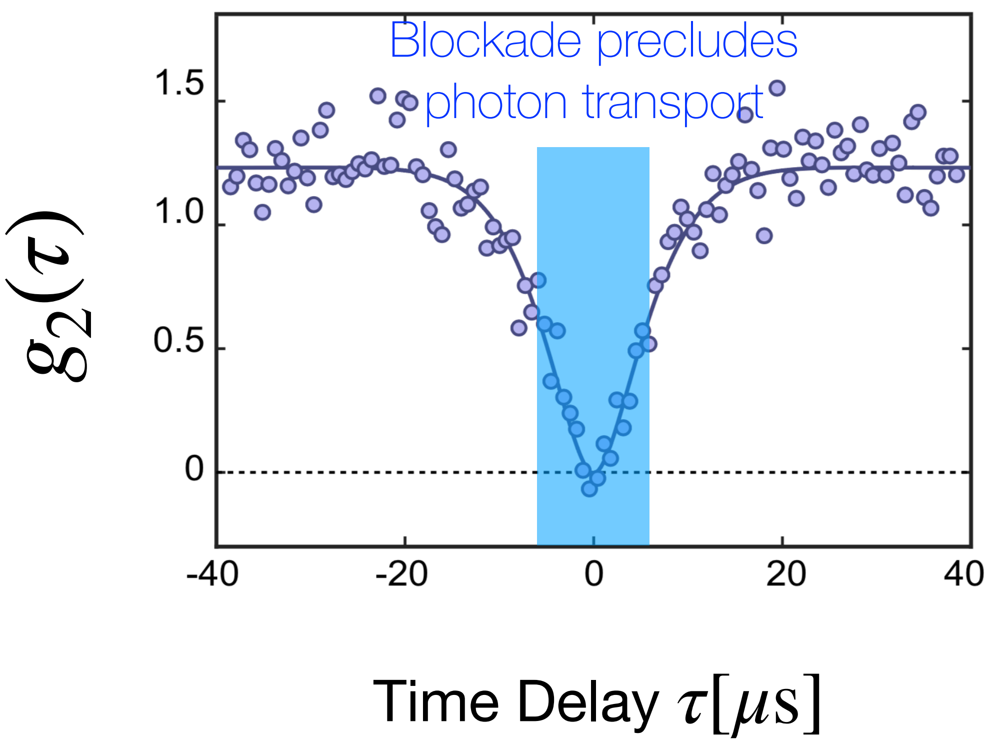
Temporal Correlations

Input Classical Laser Light

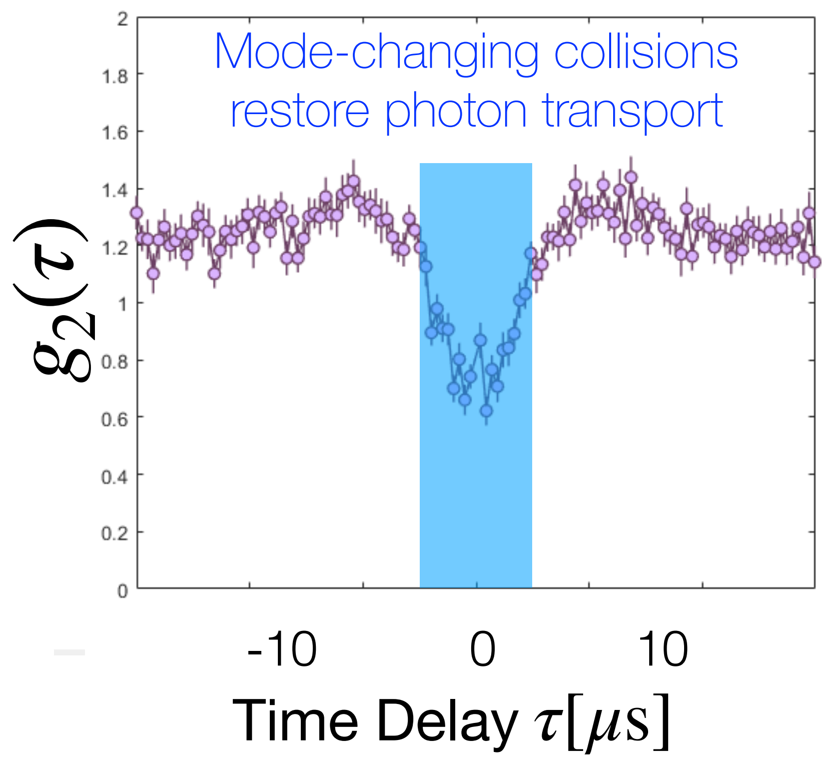
Output “Quantum” Light



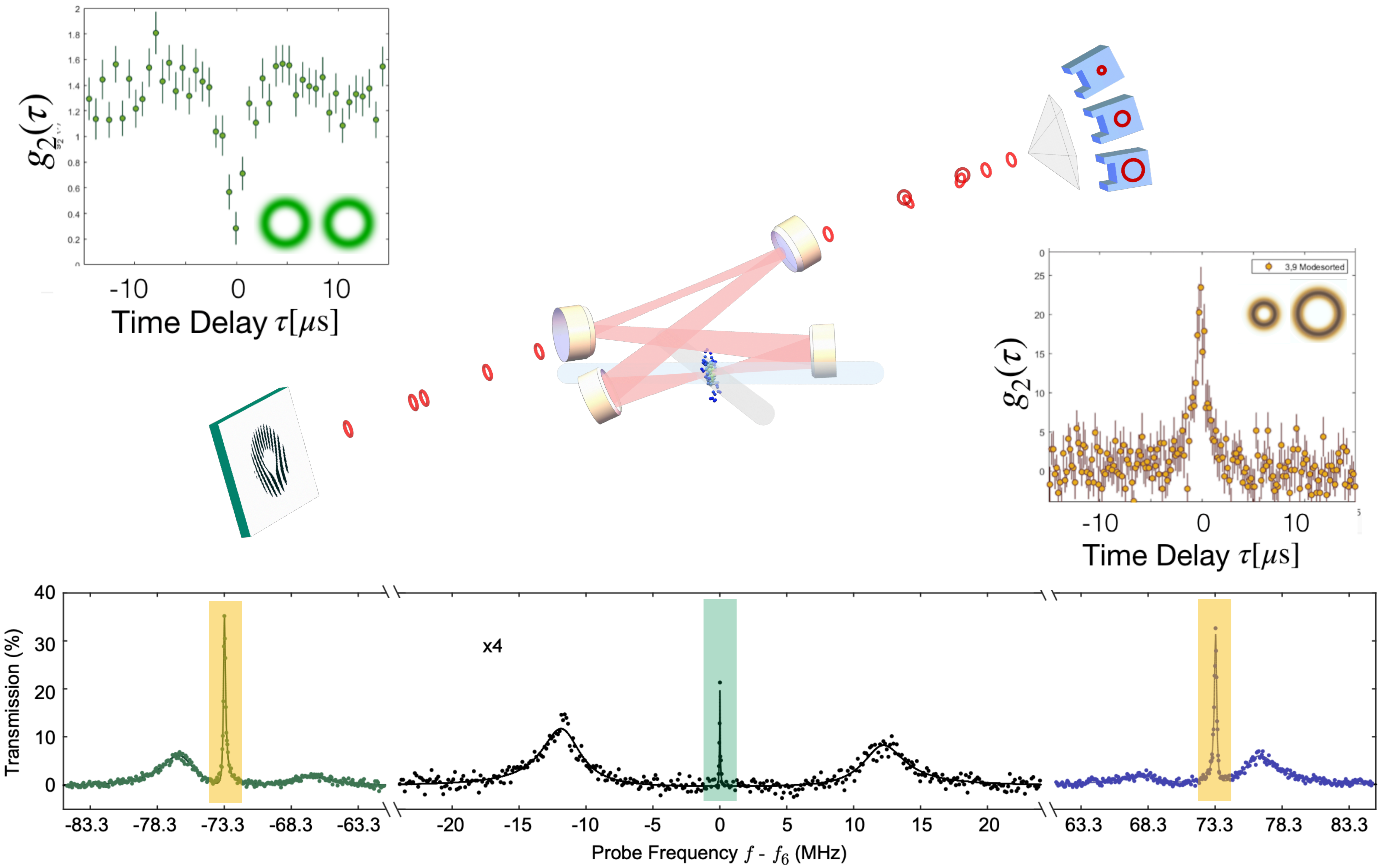
Prior Single Mode Quantum Dot, **l=0**



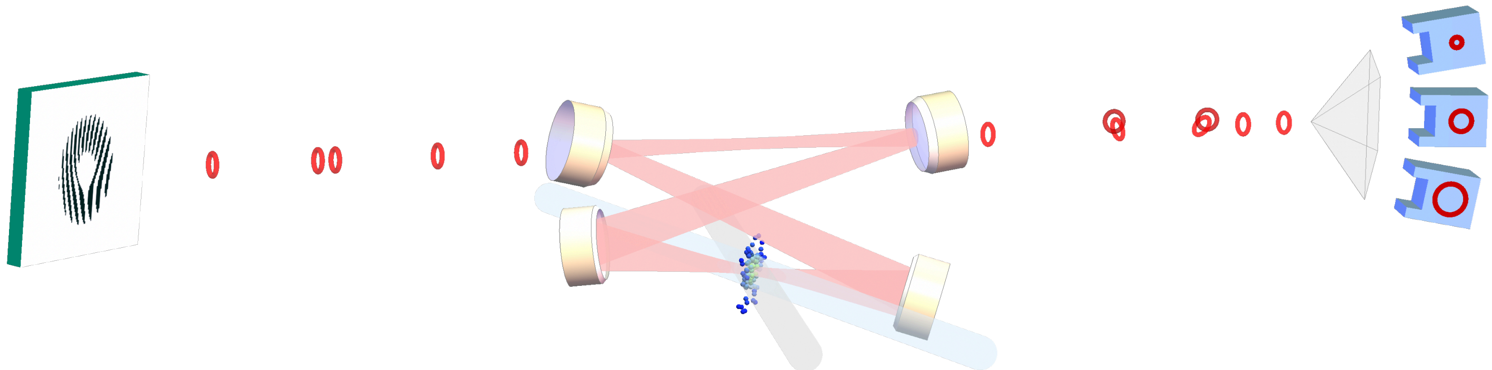
Landau Level, **all modes**



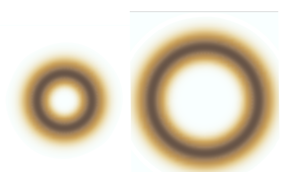
Characterizing the Topological Molecule
Orbital Angular Momentum Conservation



So are we making Laughlin Molecules?!



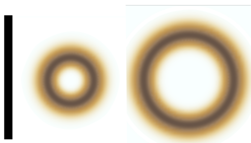
From measured correlations, two-photon "molecules" leaking from the cavity have the approximate form:

$|\Psi_{phot}\rangle \approx 0.8|$  $\rangle + e^{i\phi}\, 0.6\,|$  $\rangle$

The photons are only entangled (and hence potentially in a Laughlin state) if ϕ is well-defined. *How do we measure it?!*

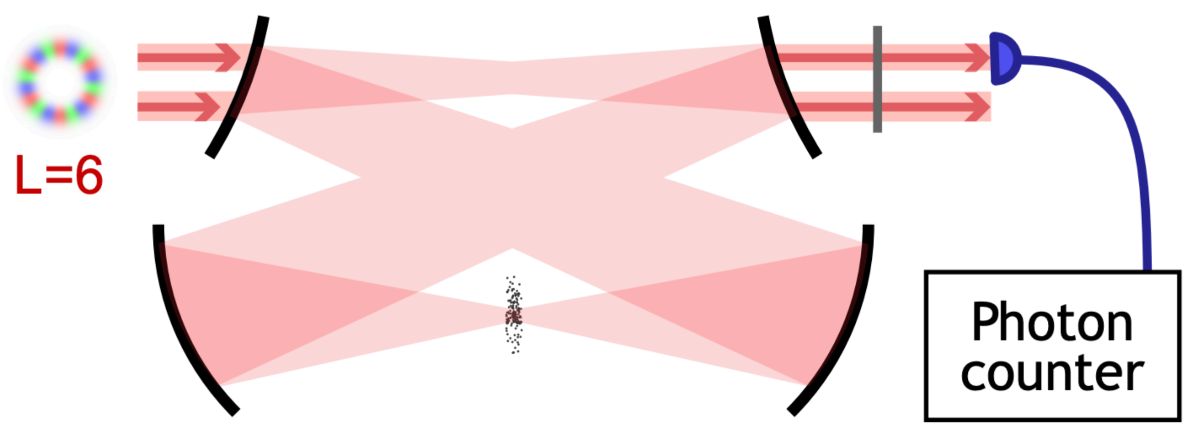
Characterizing the Topological Molecule

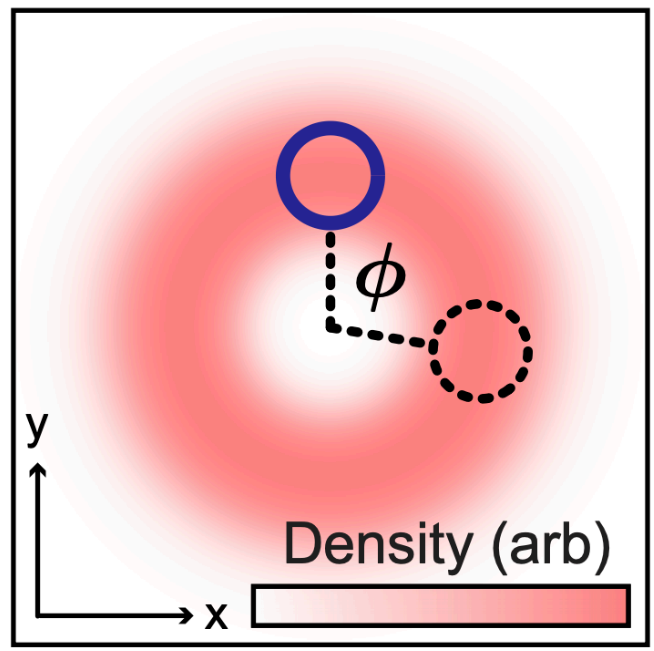
Bunching/Antibunching in Space

$|\Psi_{phot}\rangle \approx 0.8|$  $\rangle + e^{i\phi}\, 0.6\, |$  $\rangle$

Keeps the photons: apart if $\phi=\pi$ (***Laughlin***),
together if $\phi=0$ ("***Anti-Laughlin***"),
uncorrelated if ϕ undefined/random

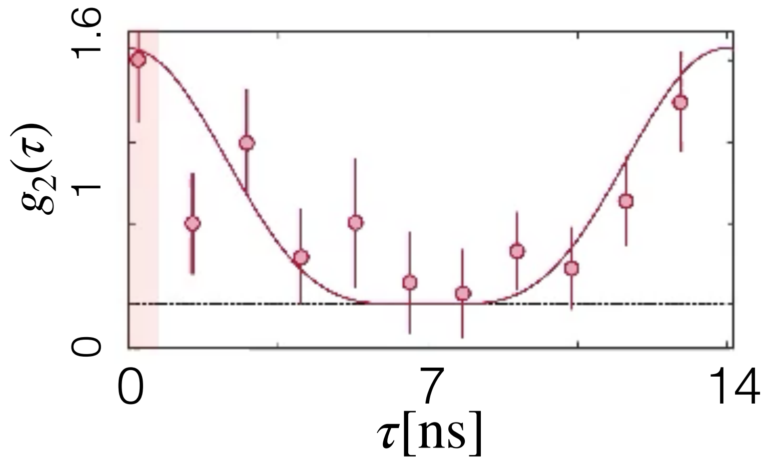
→ *measure in a* conjugate basis!
(*real space correlations instead of orbital-space!*)





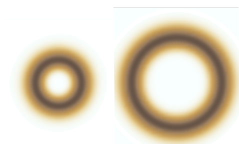
Characterizing the Topological Molecule
Real Space

Photon-Bunched Molecule
(due to Floquet coupling phase)



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

A Laughlin State of Light!

$|\Psi_{phot}\rangle \approx 0.8|$  $\rangle - 0.6|$  $\rangle$

- Photons inhabit in the Lowest Landau Level
- Photons avoid one-another in real-space
- Photons are correlated in orbital angular momentum

$$\Psi_{phot} = z_1^3 z_2^3 (z_1^3 - z_2^3)^2 e^{-\left[|z_1|^2 + |z_2|^2\right]}$$

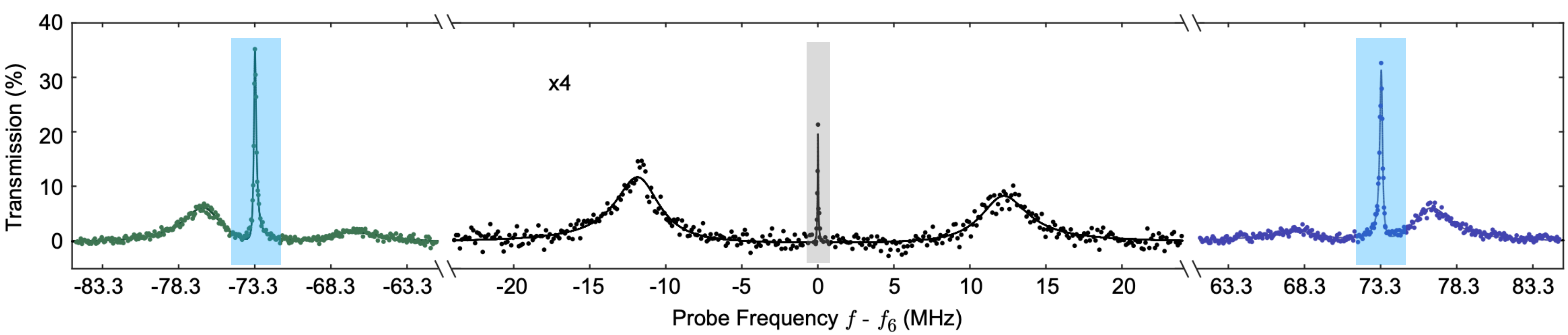
Clark *et al.*, arXiv: 1907.05872 (2019)

For the experts:
What *Precisely* is our Laughlin State?

$$\Psi = z_1^3 z_2^3 (z_1^3 - z_2^3)^2 e^{-\left[|z_1|^2 + |z_2|^2\right]}$$

Two-*photon* (Bosonic) Laughlin state on a cone with a quasi-hole @ the origin

This is a Laughlin state of *photons* outside the cavity, **not yet** *polaritons* inside the cavity — we presently use mode-dependent dark-state rotation angles to compensate for slightly-too-short-lived polaritons



Wider → faster decay → enhanced photon population compared with polariton population

Outlook

- Technical Advance: Increased OD/reduce disorder

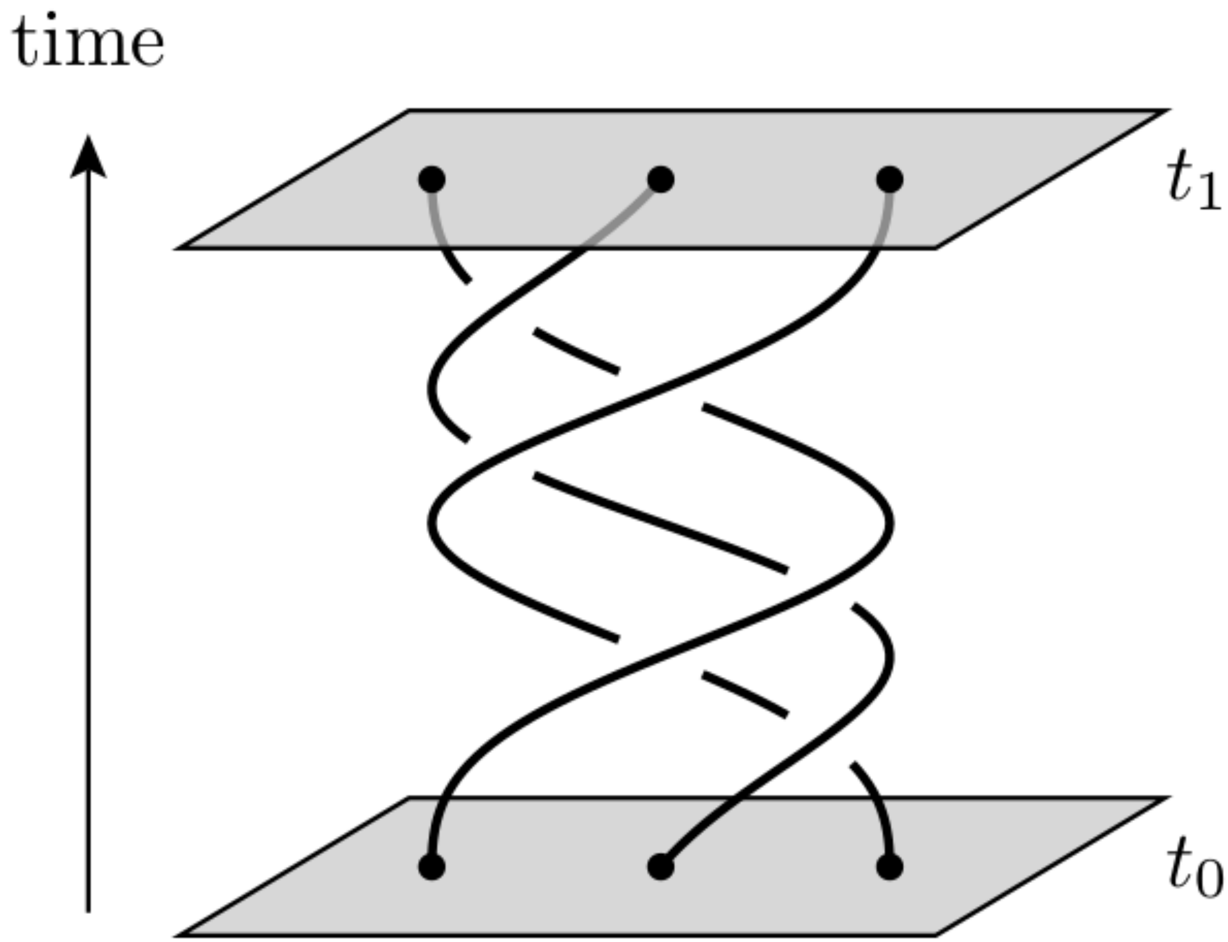
→ Polaritonic Laughlin States

→ Dissipative Stabilization of larger states [1]

→ Anyon Braiding [2]

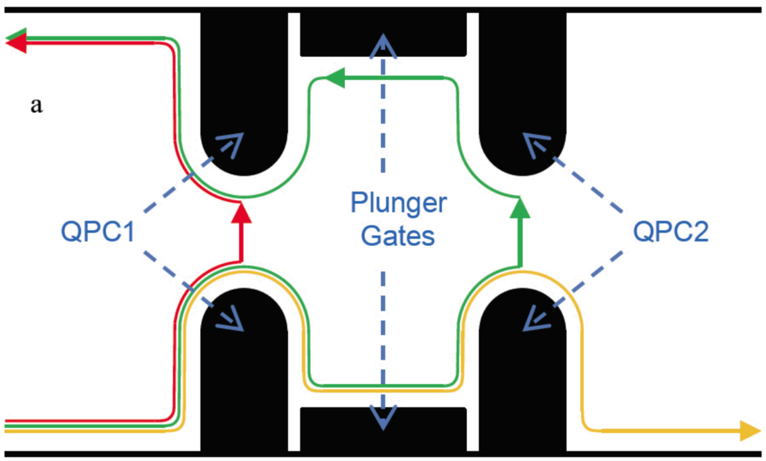
[1] Ruichao Ma *et al.* "A dissipatively stabilized Mott insulator of photons." *Nature* **566,** 51-56 (2019)
[2] Grudst *et al.* “Interferometric measurements of many-body topological invariants using mobile impurities” *Nature Communications* **7**, 11994 (2016)

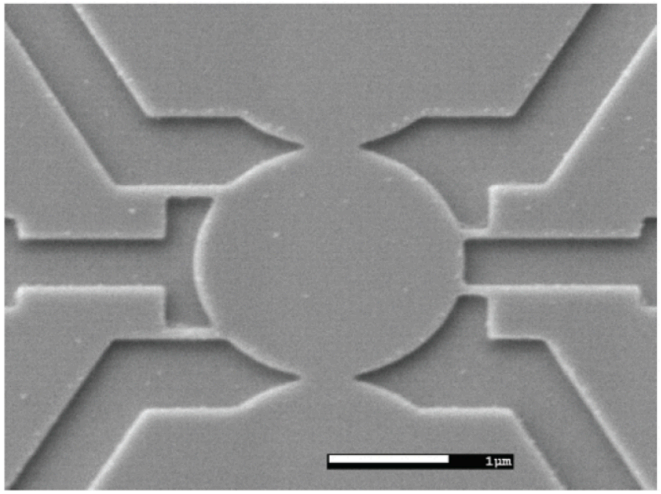
Outlook: Anyon Braiding

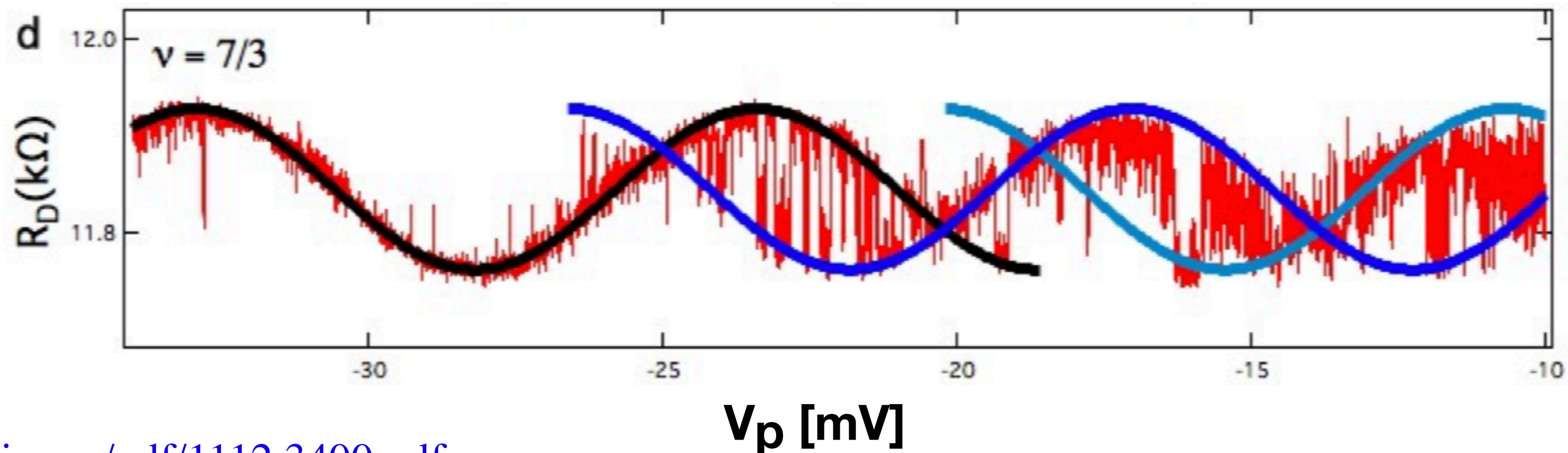


Taken from https://quantumcomputing.stackexchange.com/questions/2030/what-exactly-are-anyons-and-how-are-they-relevant-to-topological-quantum-computi

How Anyons are Braided in Solid State 2DEGs





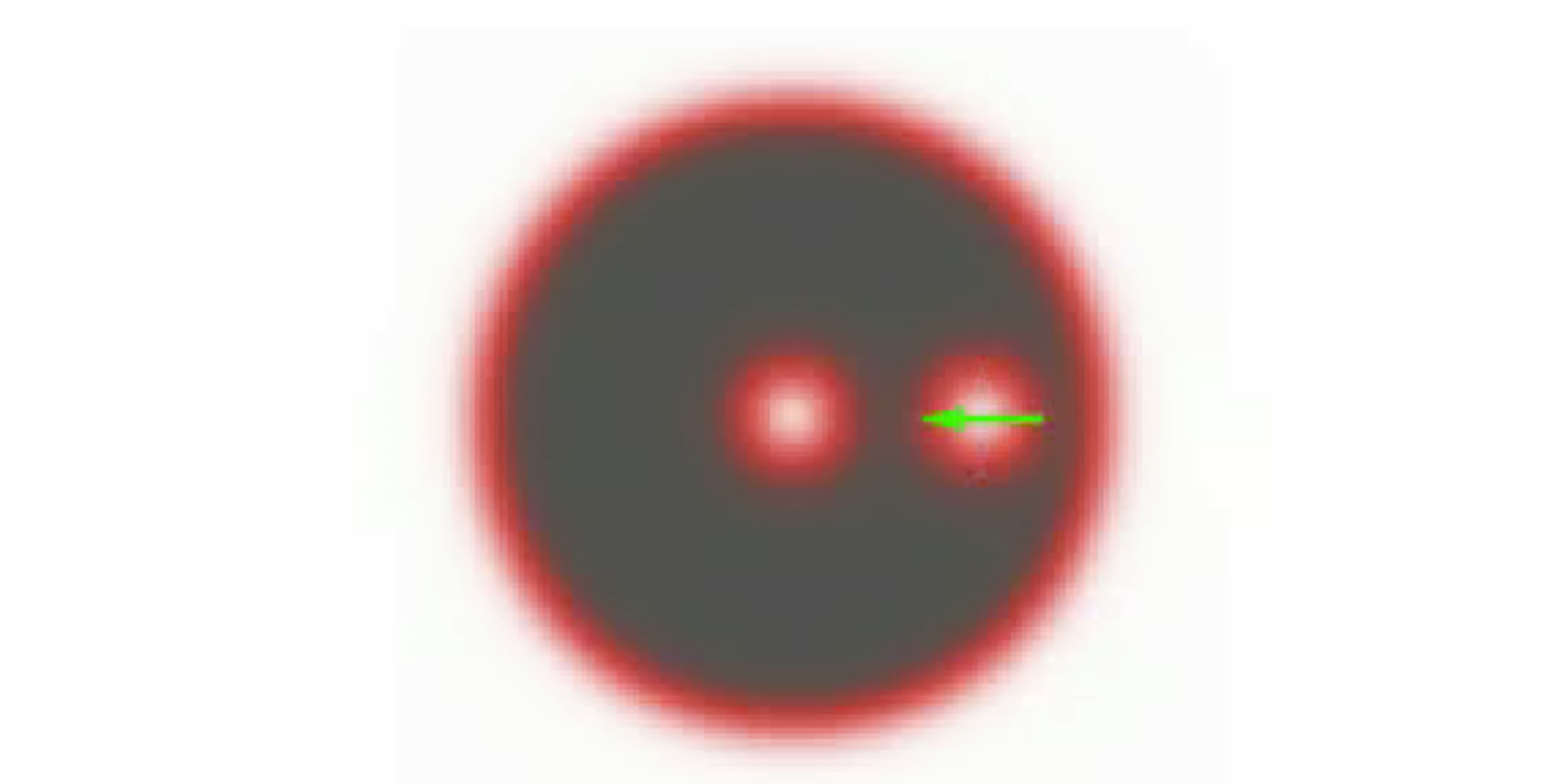


https://arxiv.org/pdf/1112.3400.pdf
https://arxiv.org/abs/1401.1897

Detecting Braiding Phases via Impurity Interferometry

Grudst *et al.* "Interferometric measurements of many-body topological invariants using mobile impurities" Nature Communications **7**, 11994 (2016) https://www.nature.com/articles/ncomms11994

Detecting Braiding Phases via Impurity Interferometry



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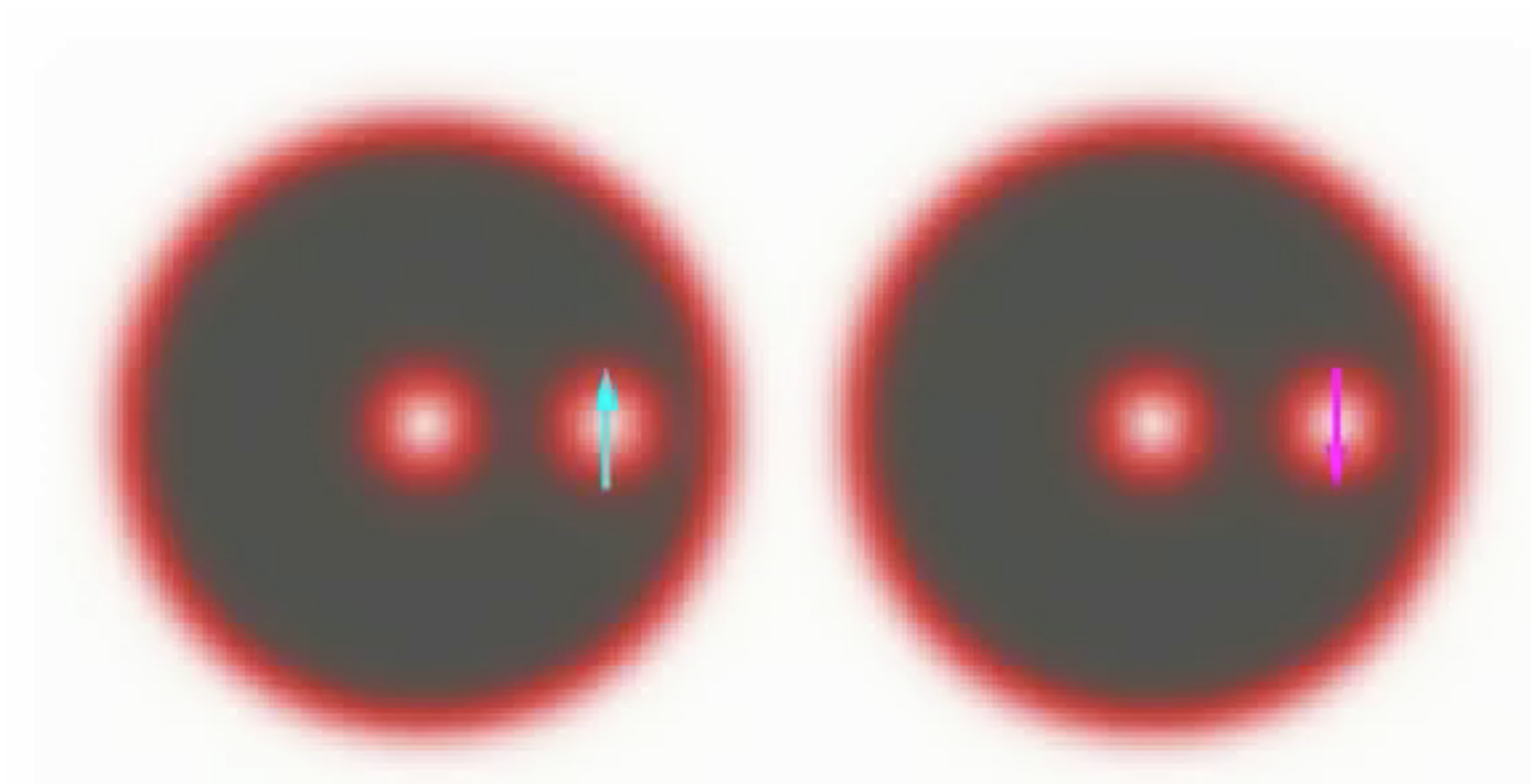
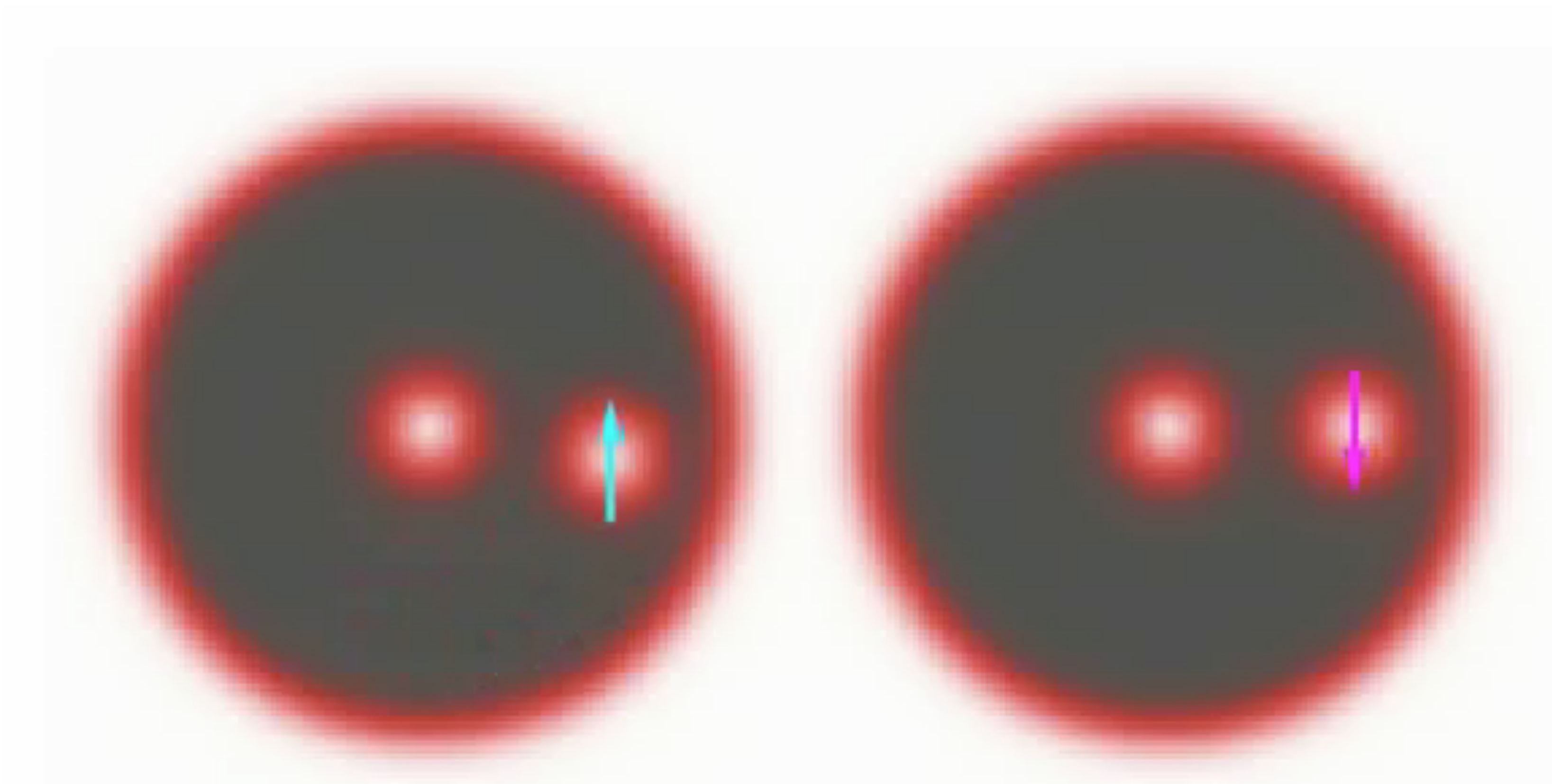
Detecting Braiding Phases via Impurity Interferometry



$\times e^{i\phi_{braid}}$ $\qquad$ $\times 1$

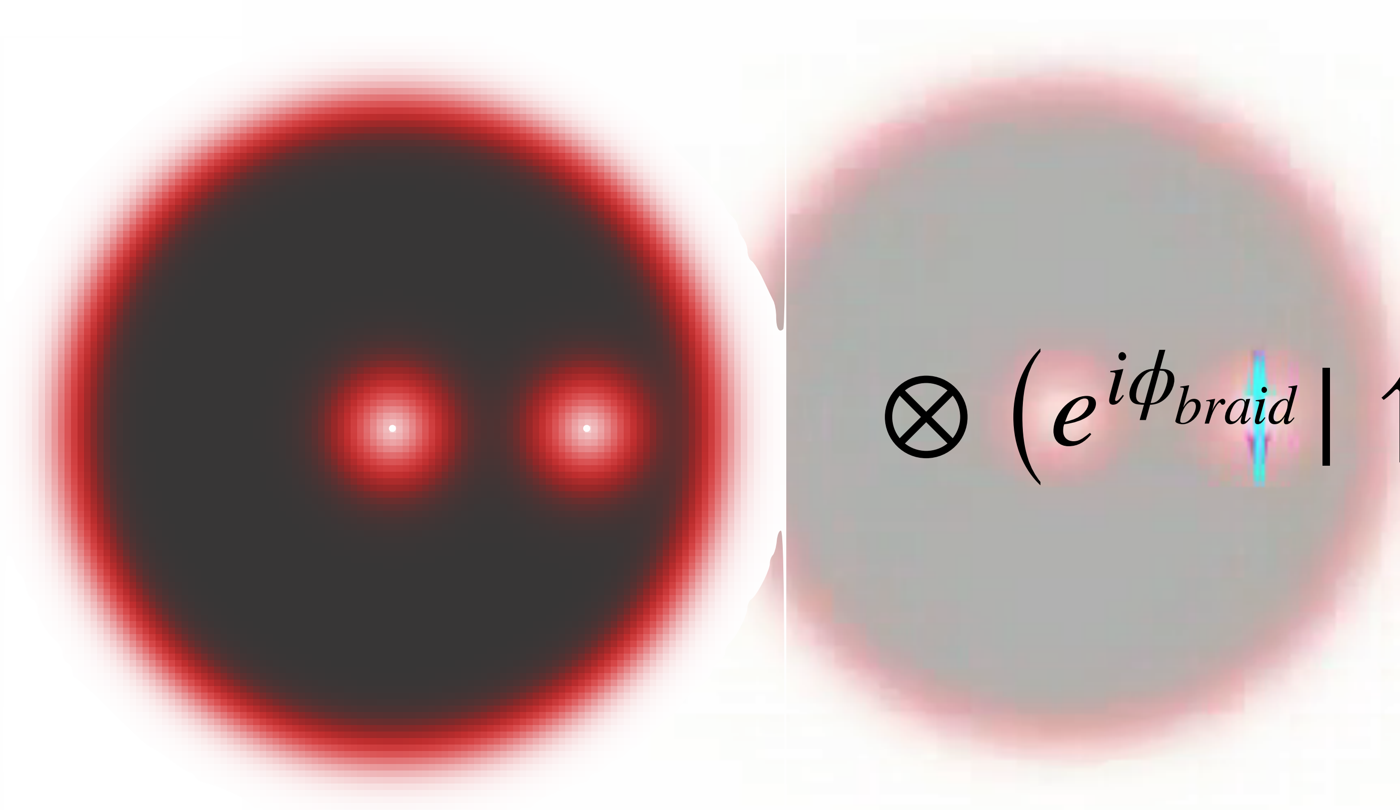
Grudst *et al.* "Interferometric measurements of many-body topological invariants using mobile impurities" Nature Communications **7**, 11994 (2016) https://www.nature.com/articles/ncomms11994

Detecting Braiding Phases via Impurity Interferometry



Grudst *et al.* "Interferometric measurements of many-body topological invariants using mobile impurities" Nature Communications **7**, 11994 (2016) https://www.nature.com/articles/ncomms11994

Detecting Braiding Phases via Impurity Interferometry



$$\otimes \left(e^{i\phi_{braid}} | \uparrow \rangle + | \downarrow \rangle \right)$$

Grudst *et al.* “Interferometric measurements of many-body topological invariants using mobile impurities” Nature Communications **7**, 11994 (2016) https://www.nature.com/articles/ncomms11994

Detecting Braiding Phases via Impurity Interferometry

$$\otimes \, | \nearrow \rangle$$

Grudst *et al.* “Interferometric measurements of many-body topological invariants using mobile impurities” Nature Communications **7**, 11994 (2016) https://www.nature.com/articles/ncomms11994

Acknowledgements

Dave Schuster
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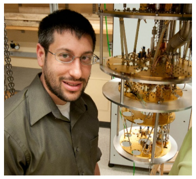

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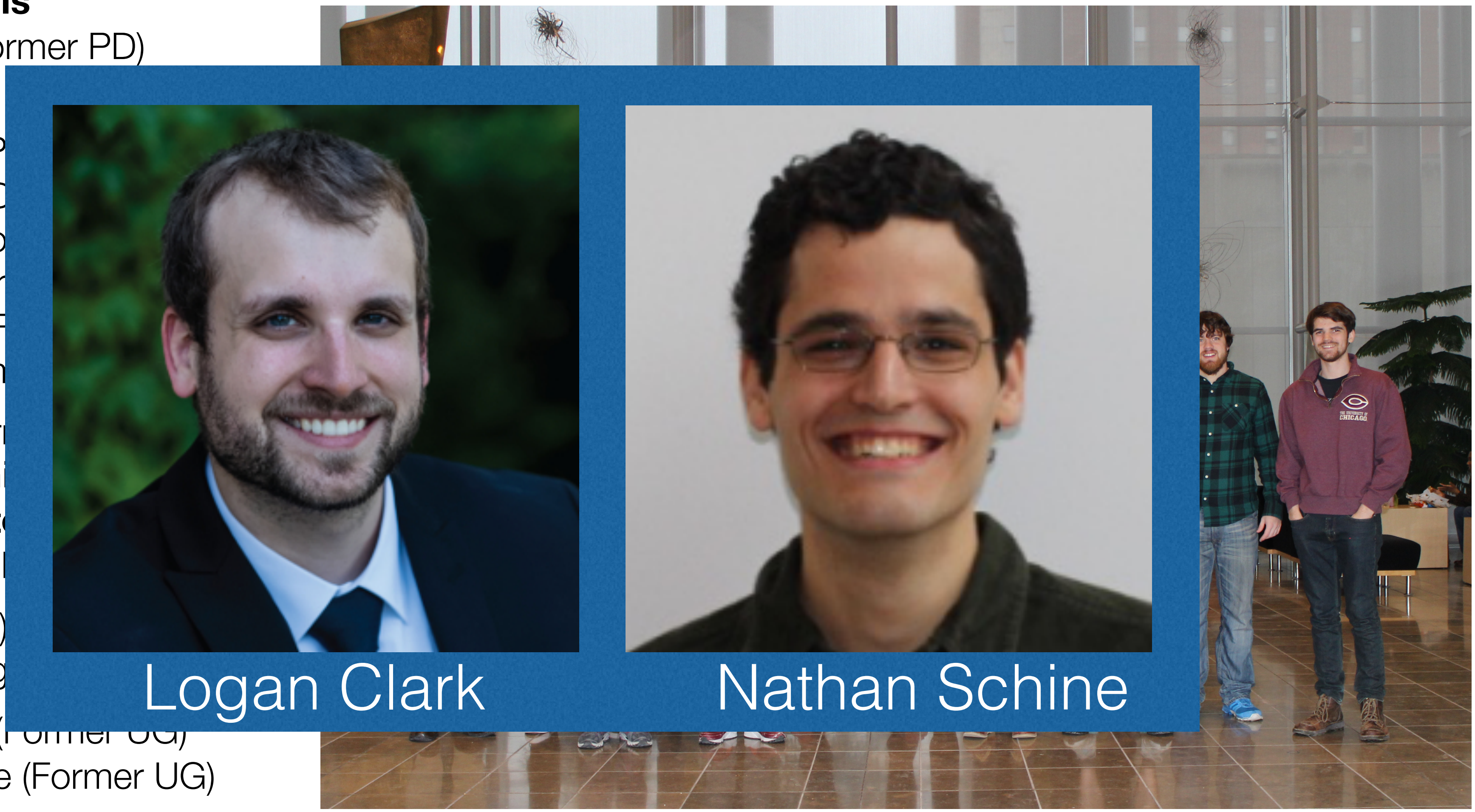

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Nathan Schine

quantum.uchicago.edu & simonlab.uchicago.edu

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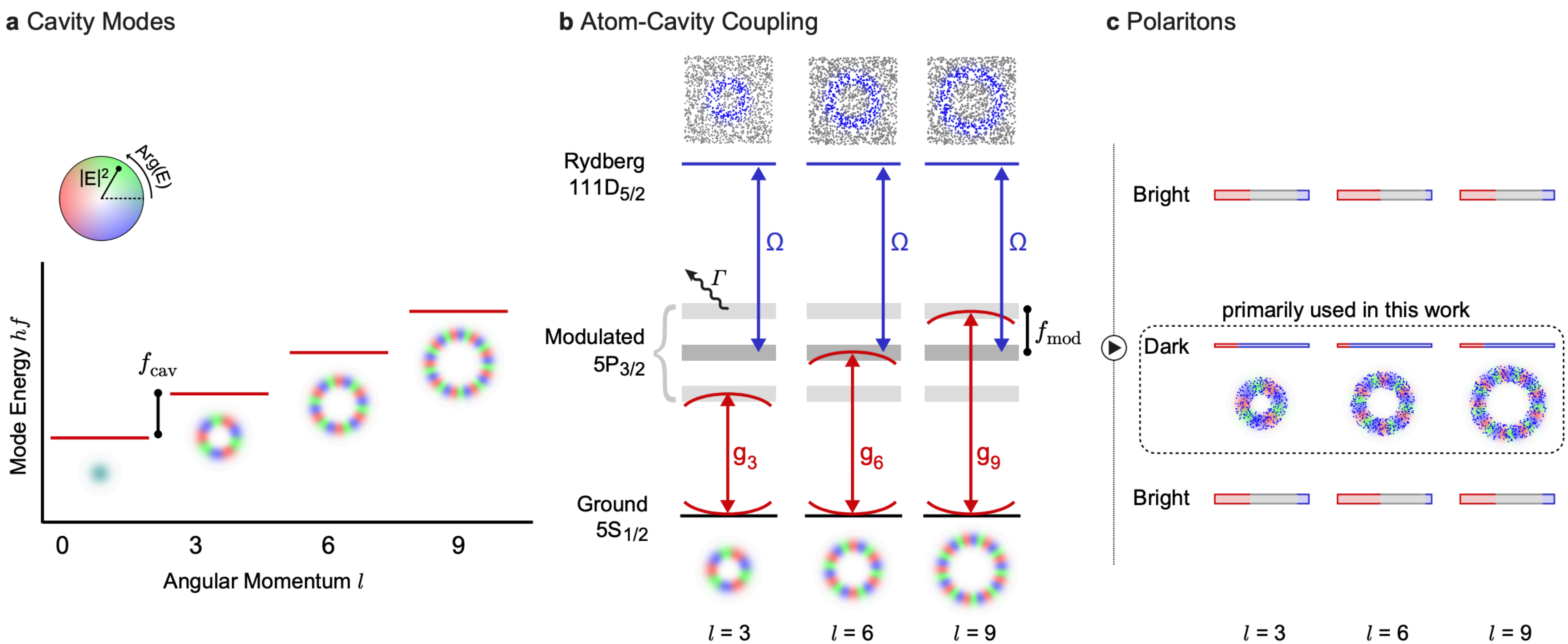
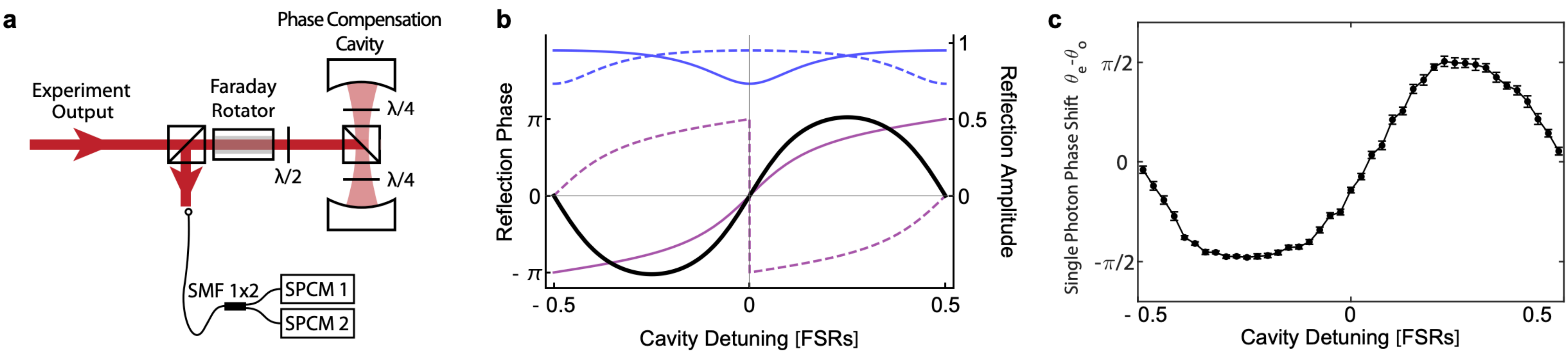
Laughlin Atomic/Optical Level Structure (Excluding Floquet)



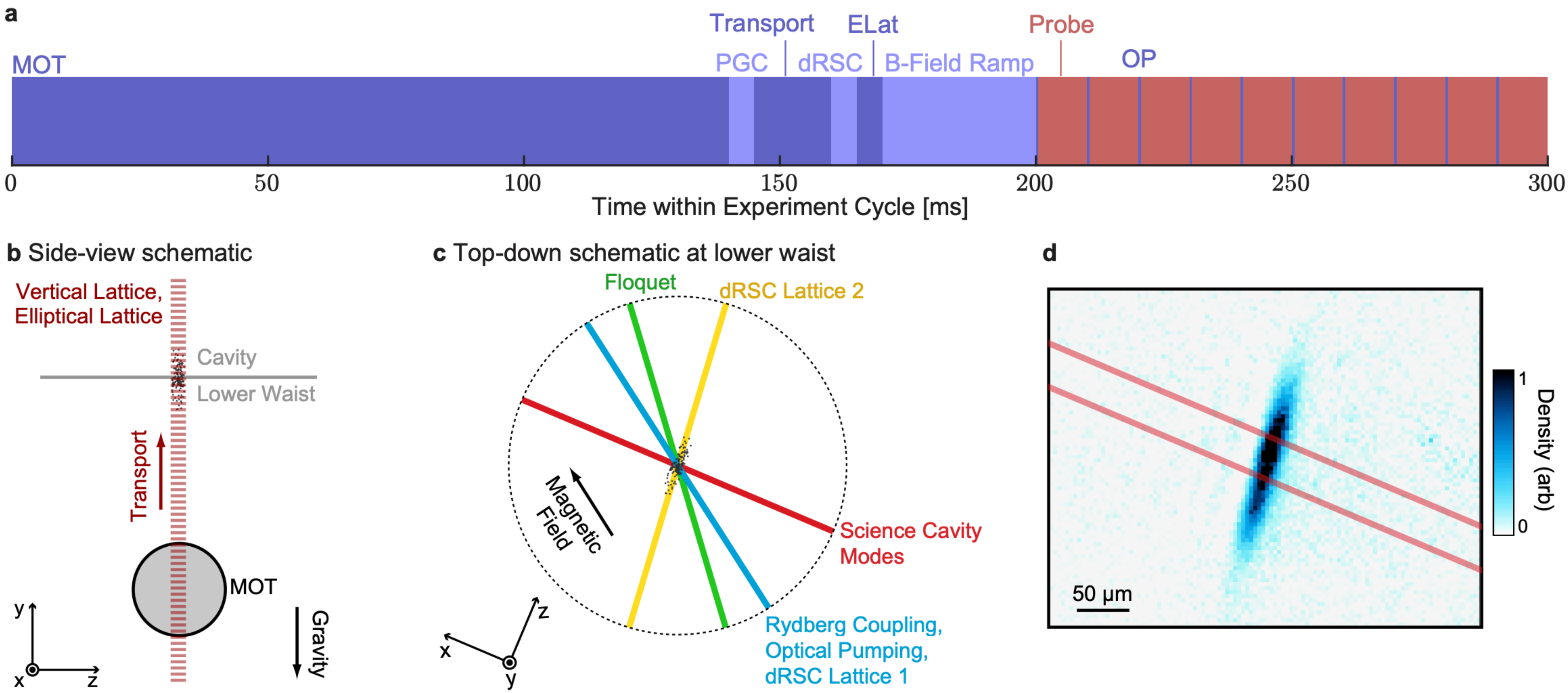
Mode-Dependent Phase Shifting Cavity (“Phase Compensation Cavity”)



Compensation cavity finesse ≈ 3

Single-ended, overcoupled, confocal cavity

Experimental Sequence



Cavity Mode Waist vs Length, and Position along Cavity