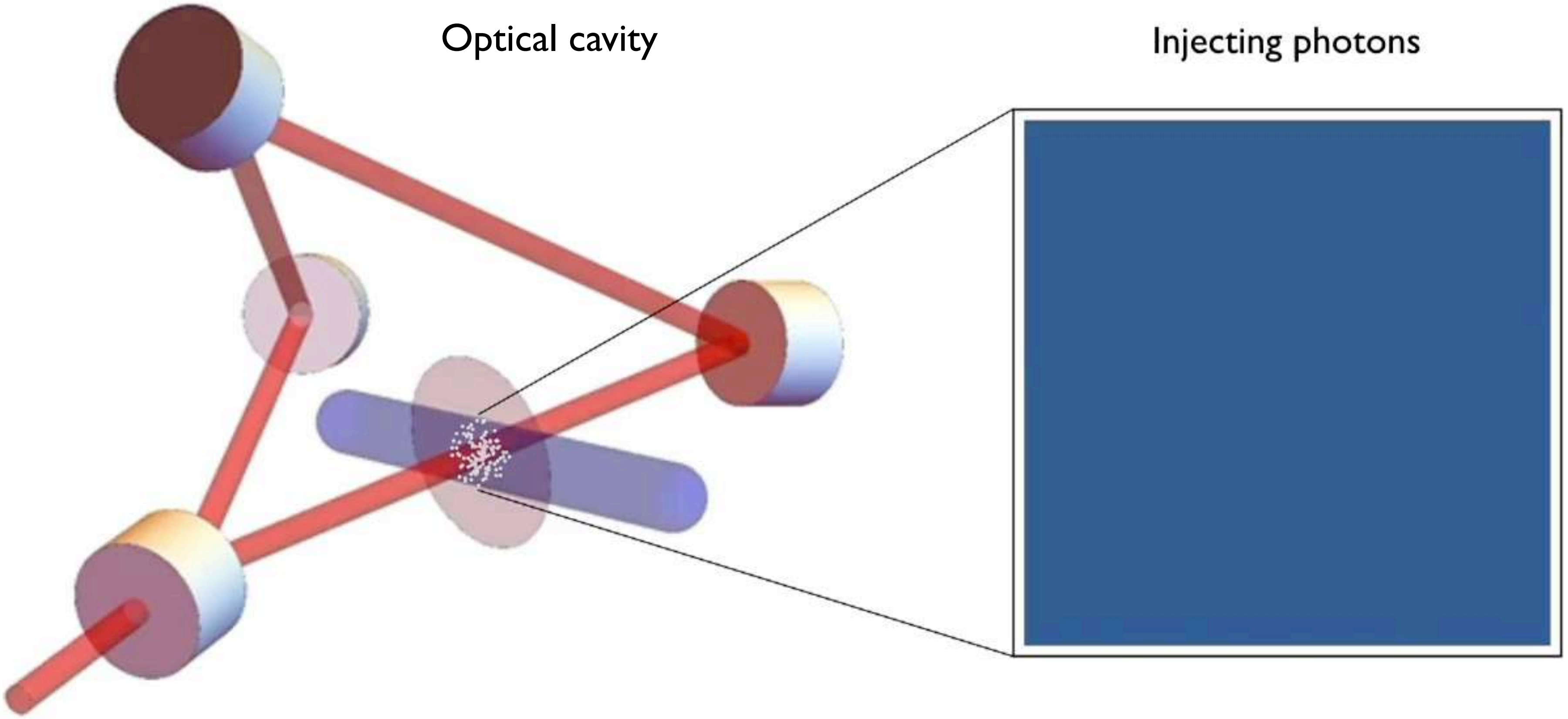
S.D. and Erich Mueller
PRA 97, 033825 (2018)

NSF
ARO - MURI

Enlightened path to anyons and quantum computation

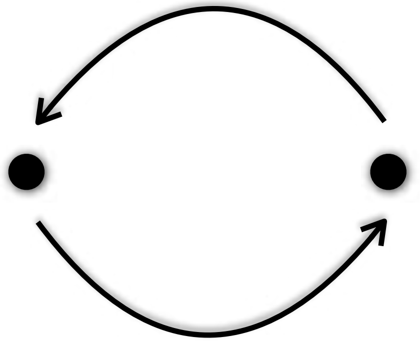
Shovan Dutta — Cavendish laboratory



Anyons

"Exchange Statistics" of identical particles:

Swap two particles — what happens to wavefunction?



Only cases in 3D

$\psi \to \psi$

Bosons

(photon, Higgs,…)

⇒ light, sound, heat…

$\psi \to -\psi$

Fermions

(electron, proton,…)

⇒ chemistry, biology…

Swap twice — same state

More possibilities in 2D!

$\psi \to e^{i\phi}\,\psi$ $\quad\quad$ $\psi \to \psi'$

Anyons

(semion, Ising, Fibonacci,…)

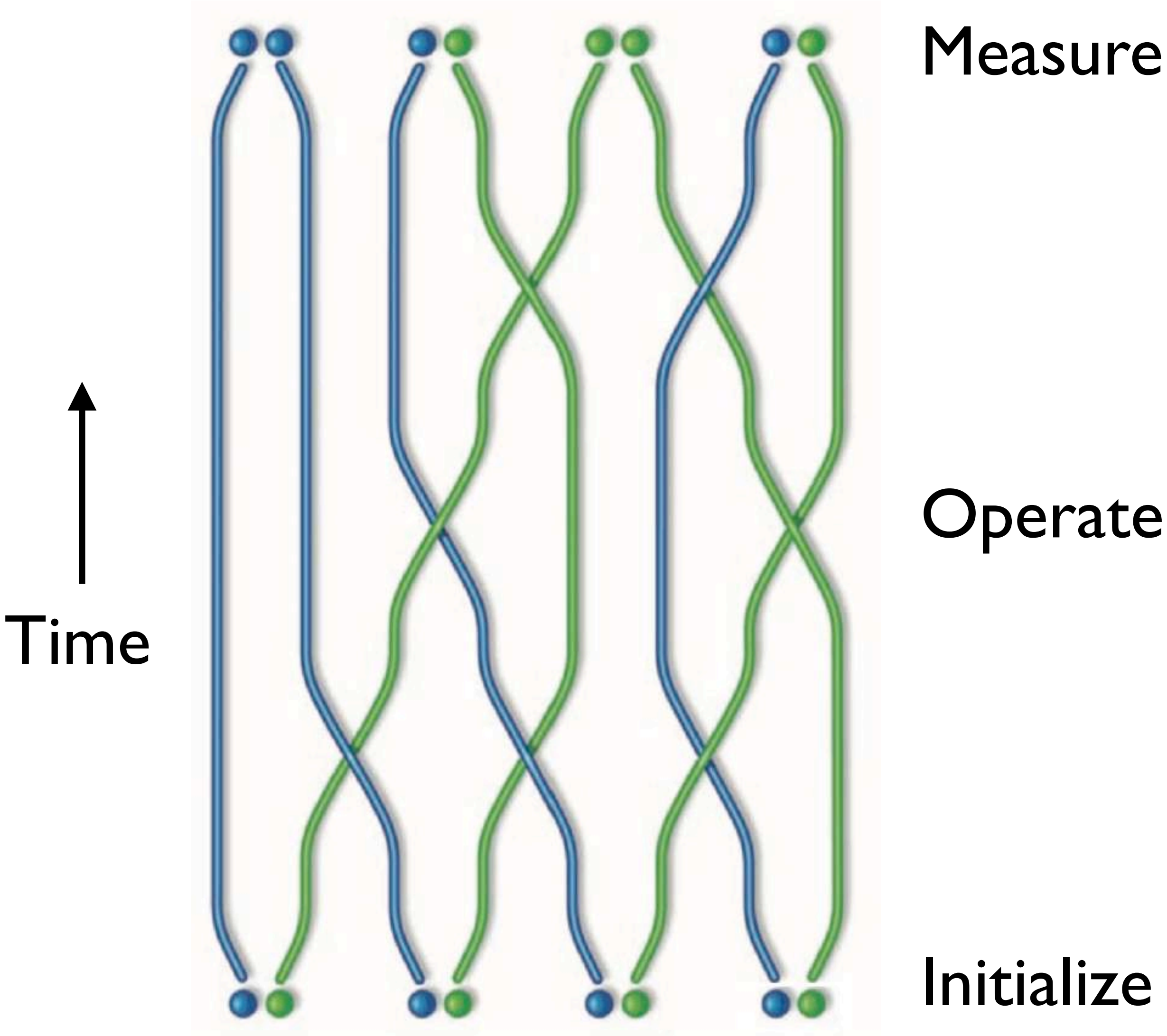
⇒ new physics, quantum computing

Swap twice — different state

⇒ Encode information in swaps

Computing with anyons

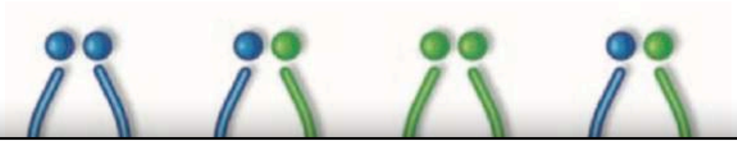
Classical computing
with beads



Quantum computing
with anyons

Computing with quantum knots
SciAm '06

Computing with anyons



NATURE | NEWS: Q&A

Inside Microsoft's quest for a topological quantum computer

Alex Bocharov explains why the company is hoping to build qubits out of particles that some scientists think might not even exist.

Elizabeth Gibney

21 October 2016

Classical computing
with beads

Quantum computing
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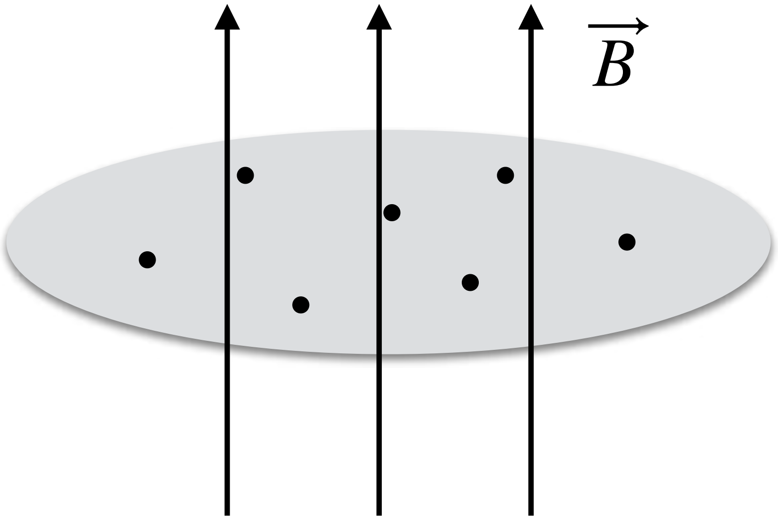
SciAm '06

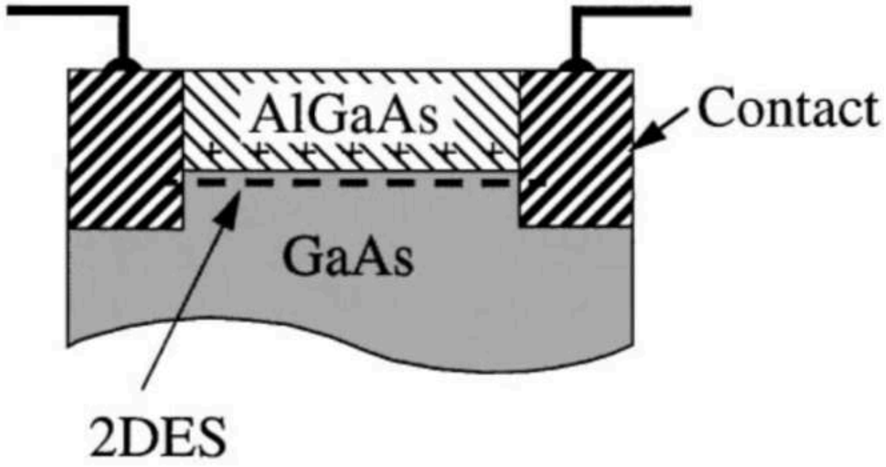
Creating anyons

As point-like excitations (“holes”) over certain 2D quantum states

— Fractional Quantum Hall (FQH) states

— formed by interacting particles in a magnetic field

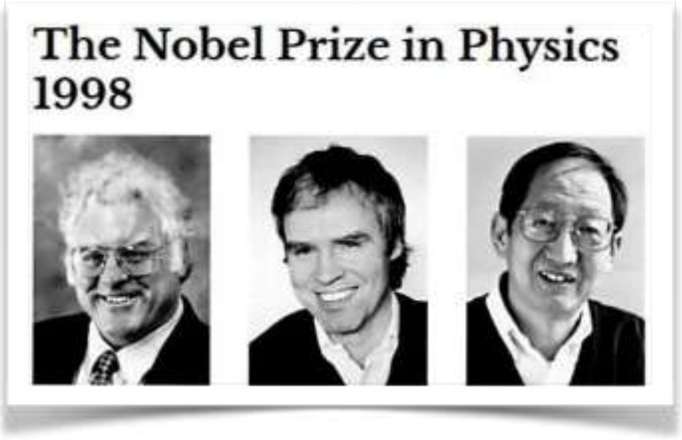




FQH states realized in semiconductor films

— anyons not observed (imperfections, low tunability)

— more promising: engineered platforms

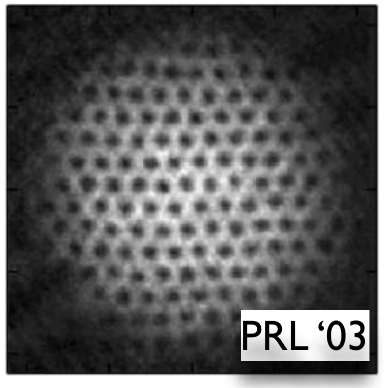


The Nobel Prize in Physics 1998

Creating anyons

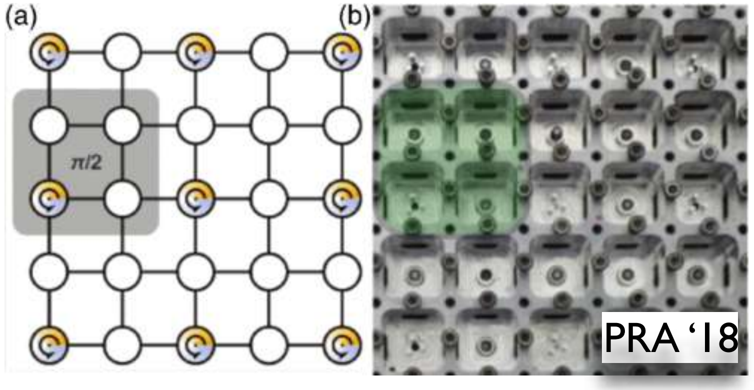
Engineered platforms:

Cold atoms



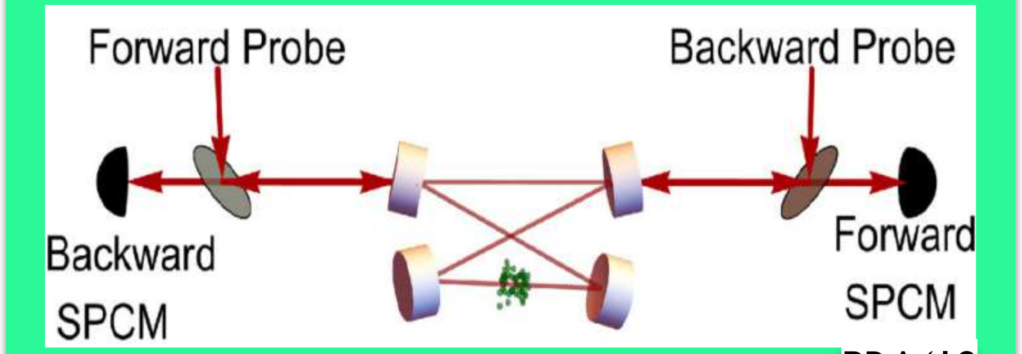
PRL '03

Microwave cavities



PRA '18

Optical cavity



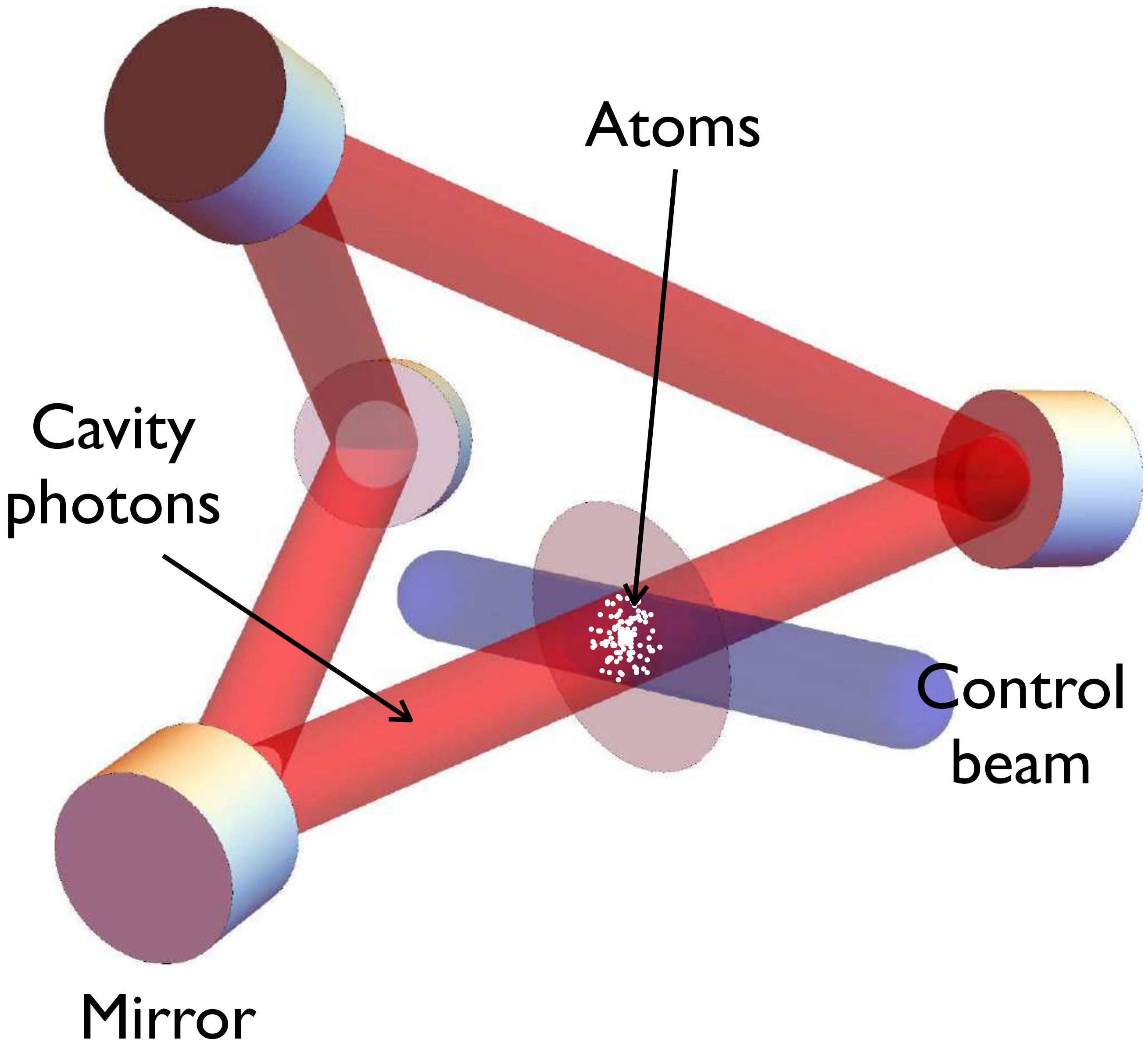
PRA '18

Programme:

1. Create FQH states ⇒ need particles in 2D, magnetic field, interactions
2. Generate anyon excitations ("holes")
3. Move them around one another
4. Measure exchange phase

Cavity setup

Simon lab — Chicago



Light bounces around fast

- stroboscopic transverse dynamics
- finite effective mass

Concave mirrors

- transverse confinement

Non-planar geometry

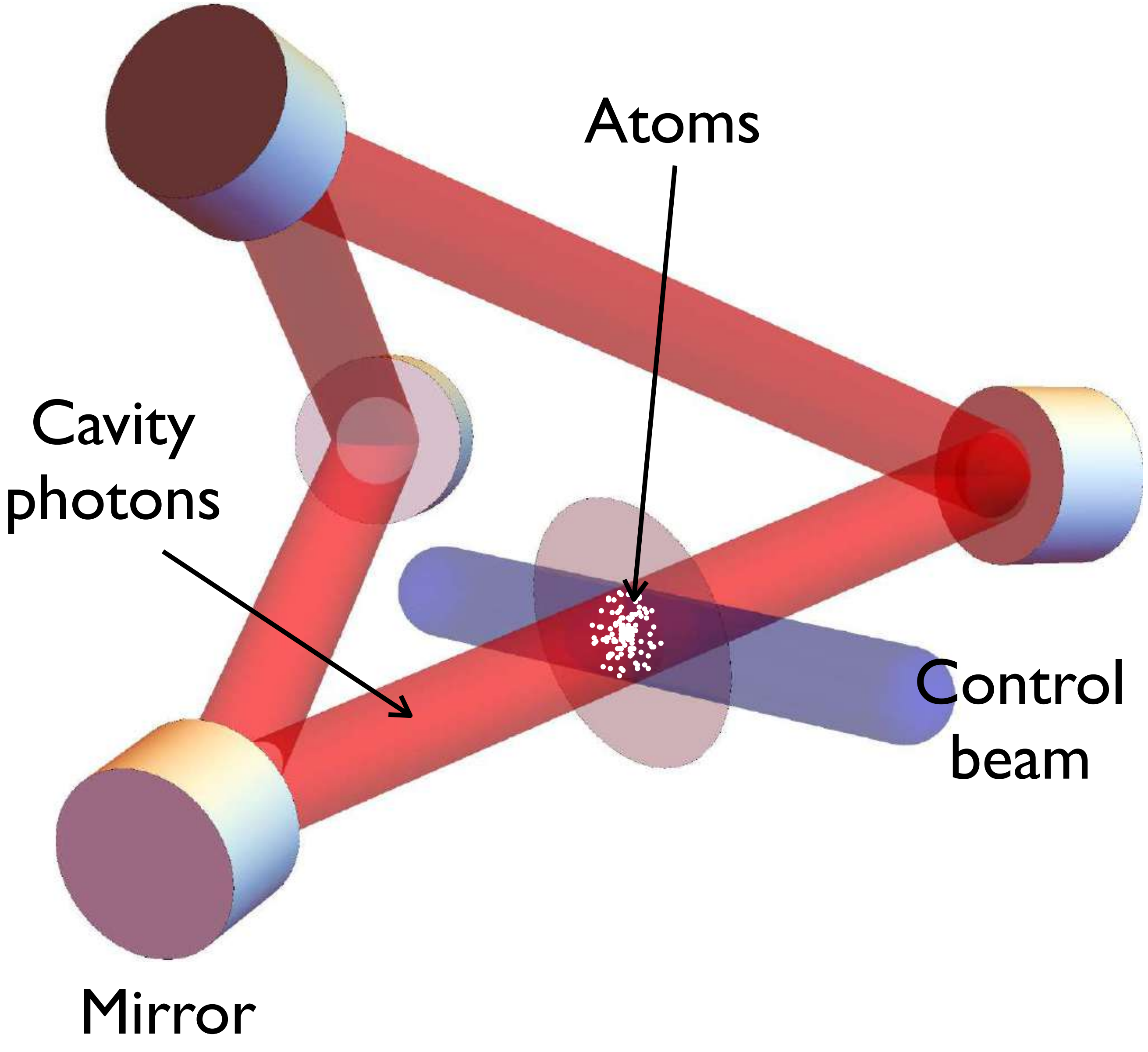
- light field rotated about axis
- effective magnetic field

Atom-photon coupling

- dressed photons
- photon dynamics + atom int.

Cavity setup

Simon lab — Chicago



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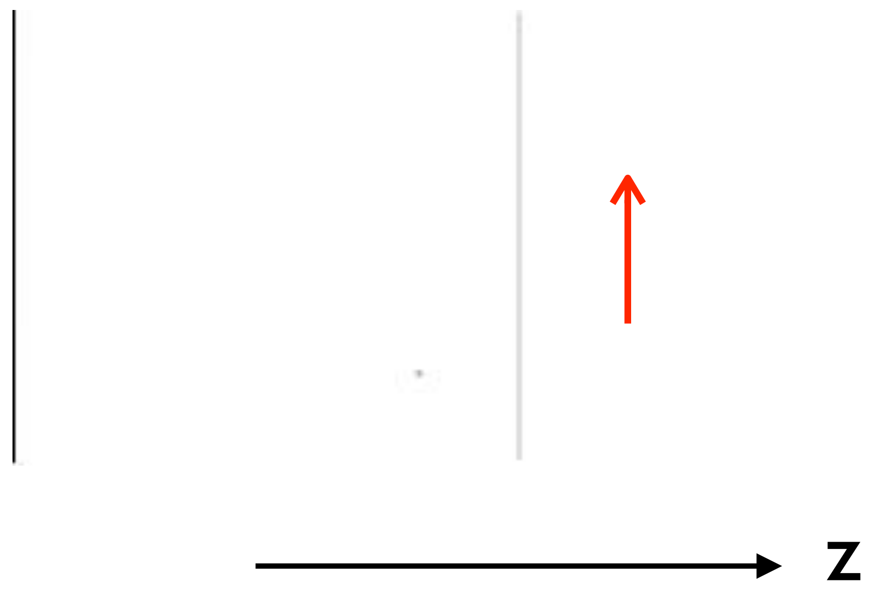
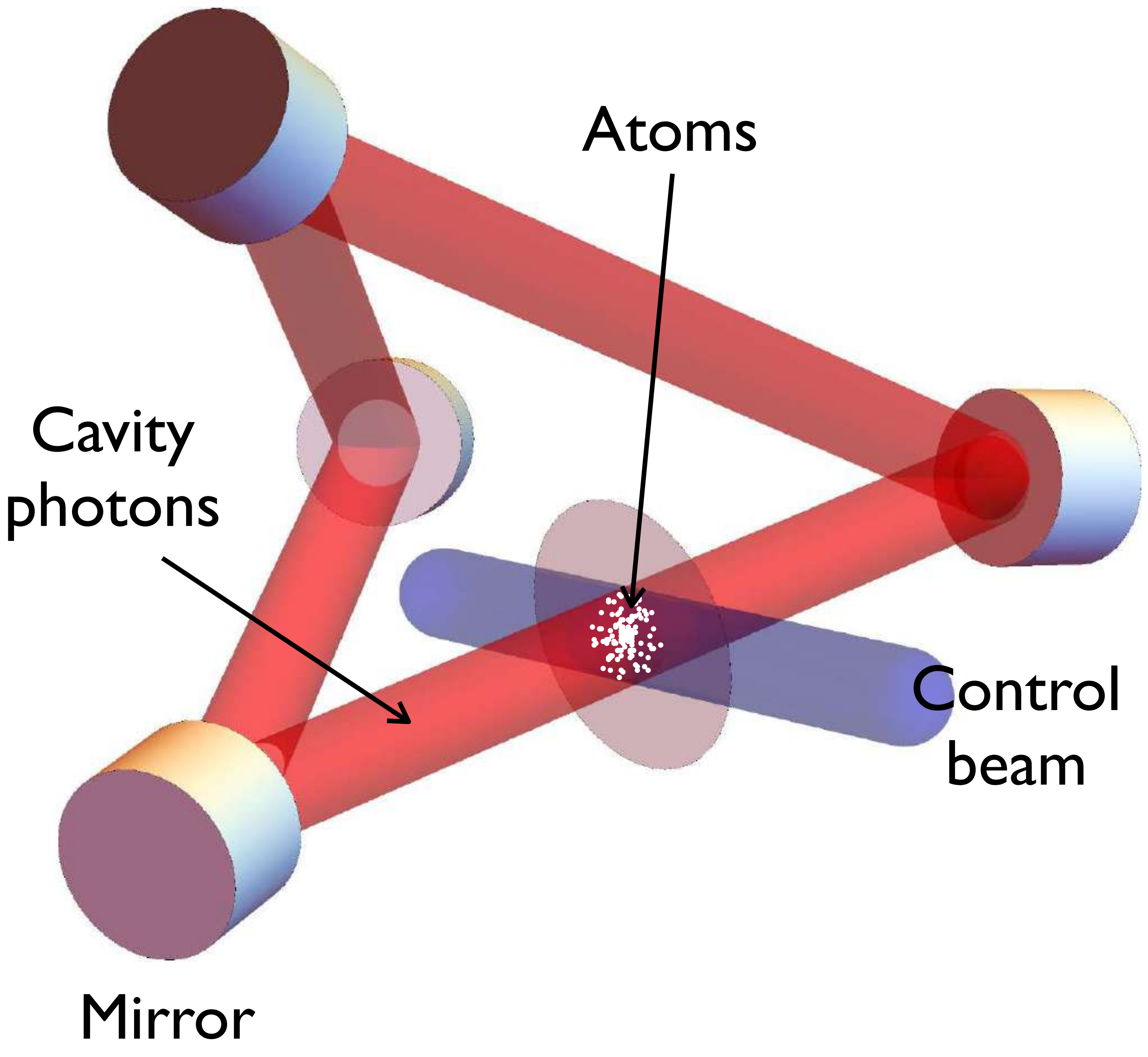
Light bounces fast — transverse dynamics



$$
\begin{aligned}
E &= \sqrt{p_z^2 + p_\perp^2}\, c \\
&\approx p_z c + \frac{p_\perp^2 c}{2 p_z} \\
&= E_z + \frac{p_\perp^2}{\underset{\overset{\uparrow}{M_\perp}}{2(E_z/c^2)}}
\end{aligned}
$$

Uniform motion along transverse direction

Cavity setup



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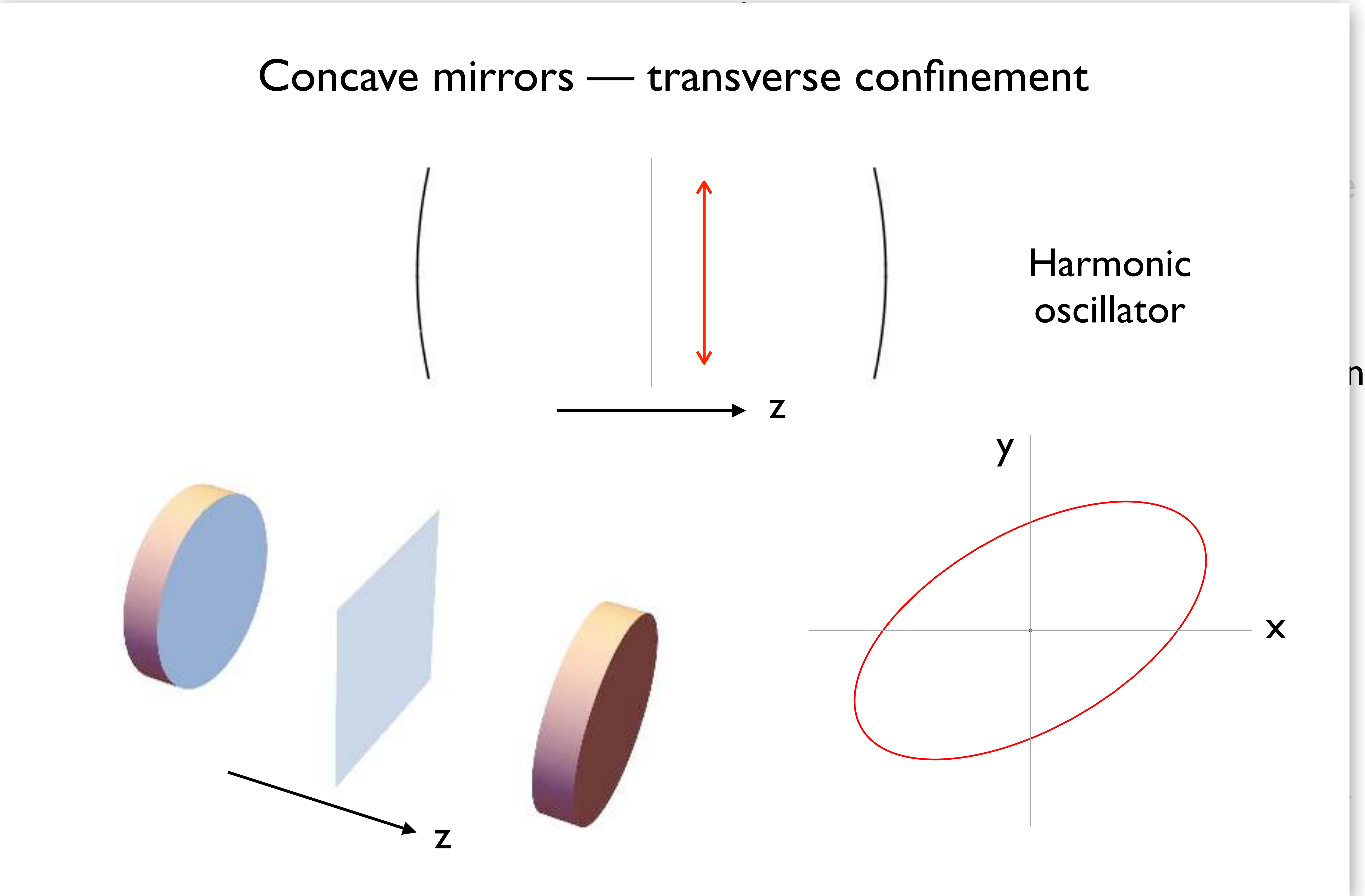
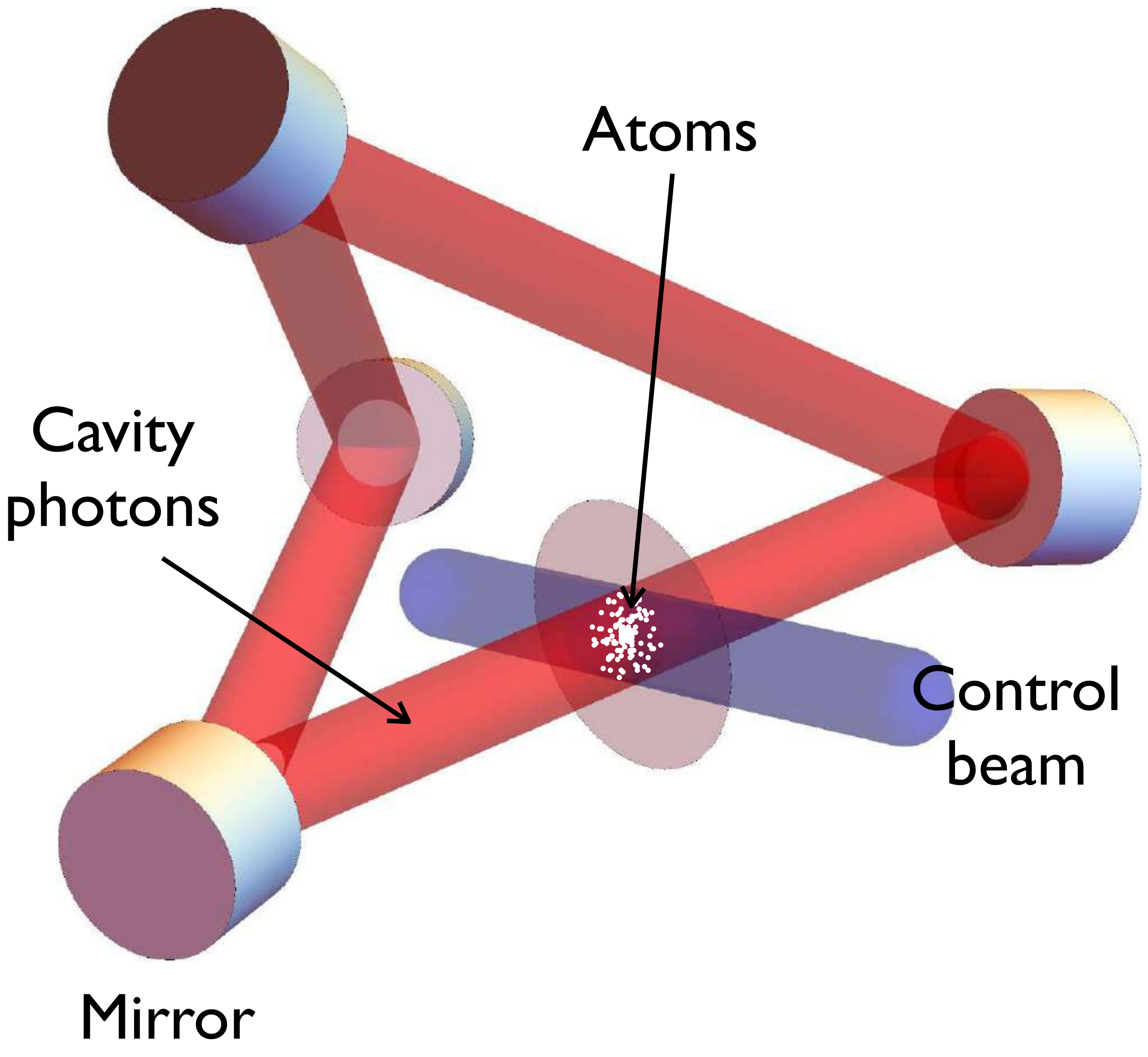


Concave mirrors — transverse confinement

Harmonic oscillator

Cavity setup



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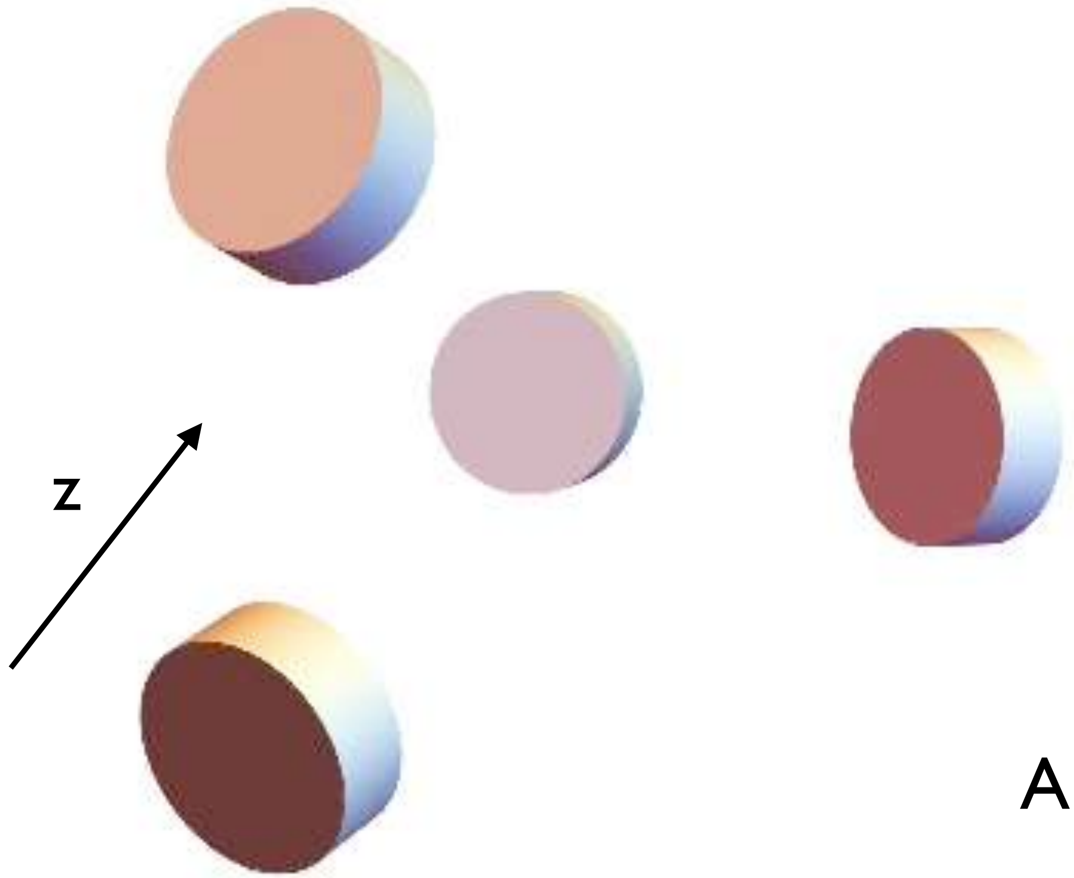
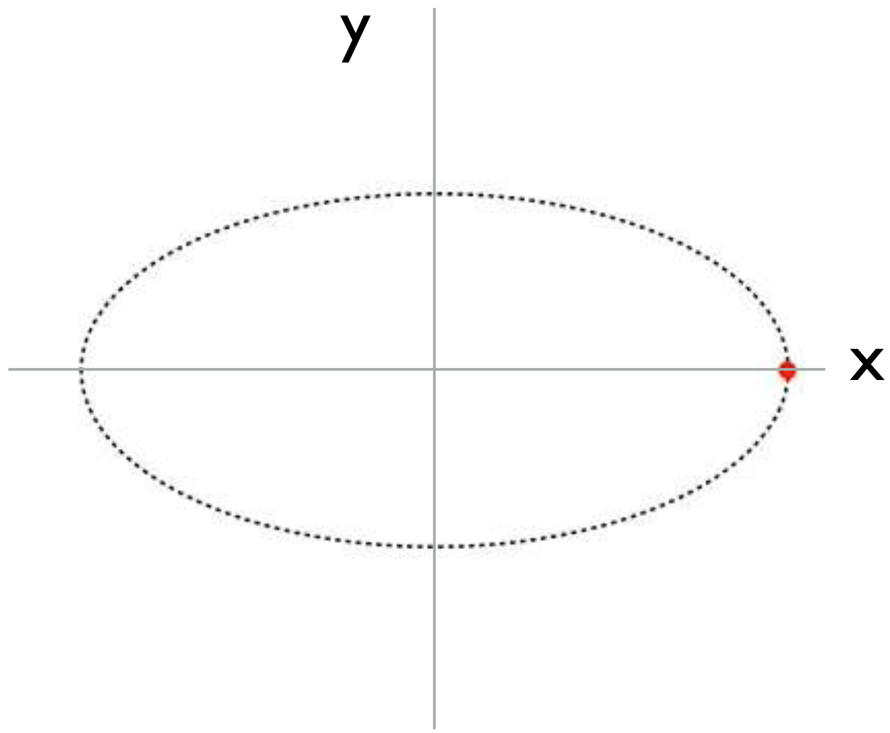
Cavity setup

Non-planar geometry — effective magnetic field





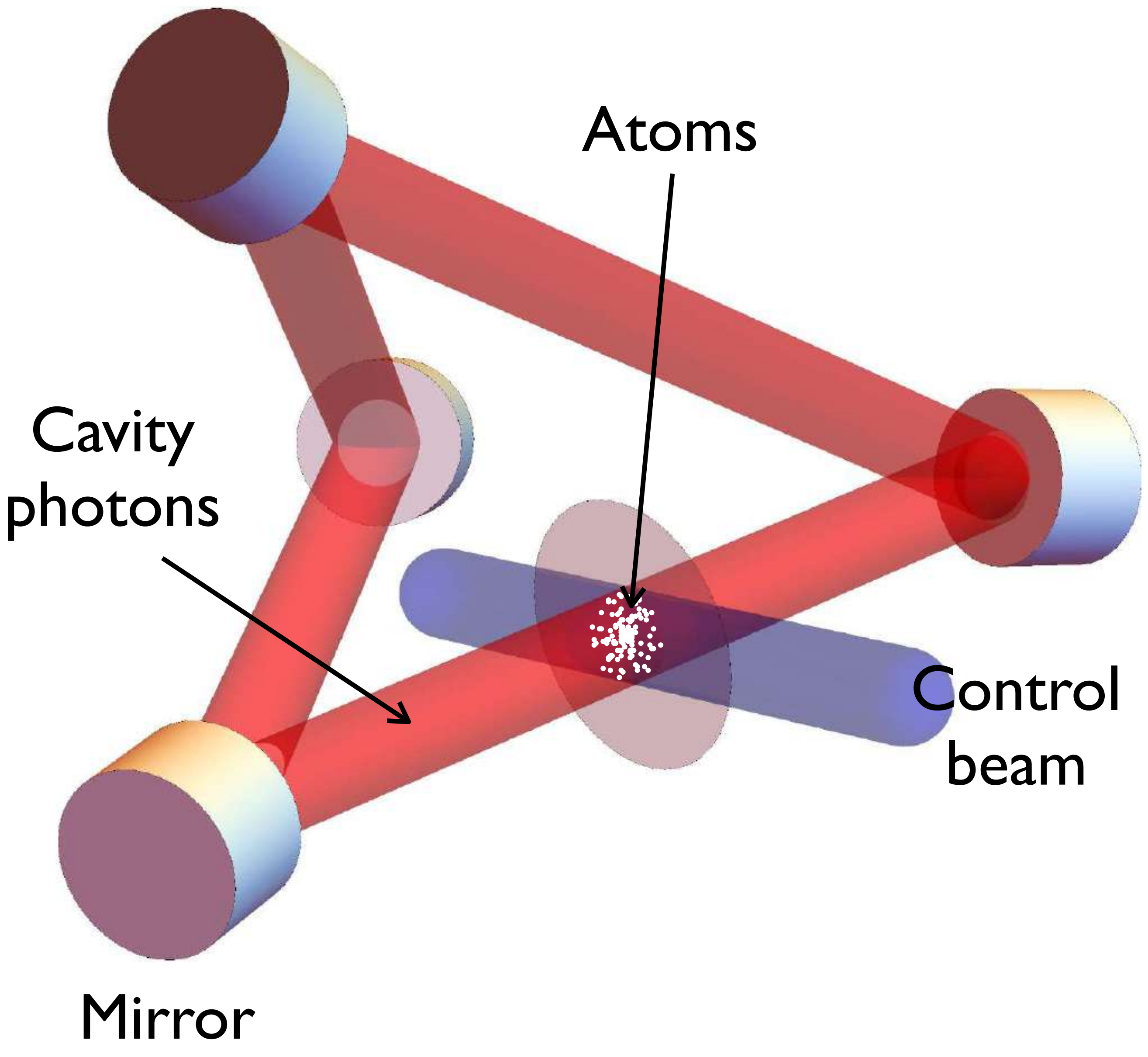
Magnetic field for photons
Nature '16

Analogous to seeing a harmonic oscillator from a uniformly rotating frame

$$\vec{F}_{\text{Coriolis}} = \vec{v}_\perp \times (2M_\perp \vec{\omega}_{\text{rot}}) \equiv \vec{v}_\perp \times (q\vec{B}_{\text{eff}})$$

$\vec{F}_{\text{Centrifugal}} = M_\perp \omega_{\text{rot}}^2 \vec{r}_\perp$ (anti-trap)

Cavity setup



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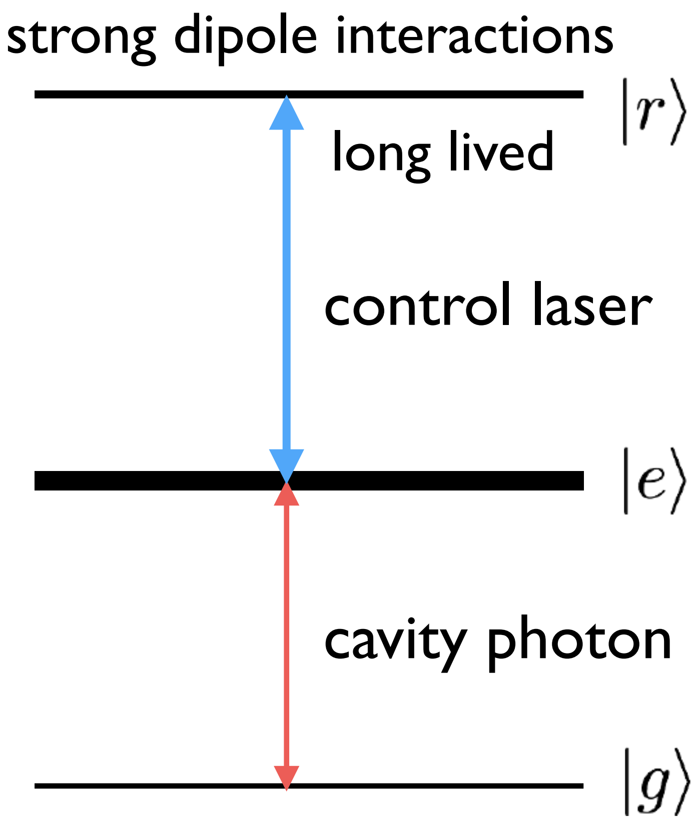
Cavity setup

Atom-photon coupling — interactions



Atomic energy levels

$\Longrightarrow$

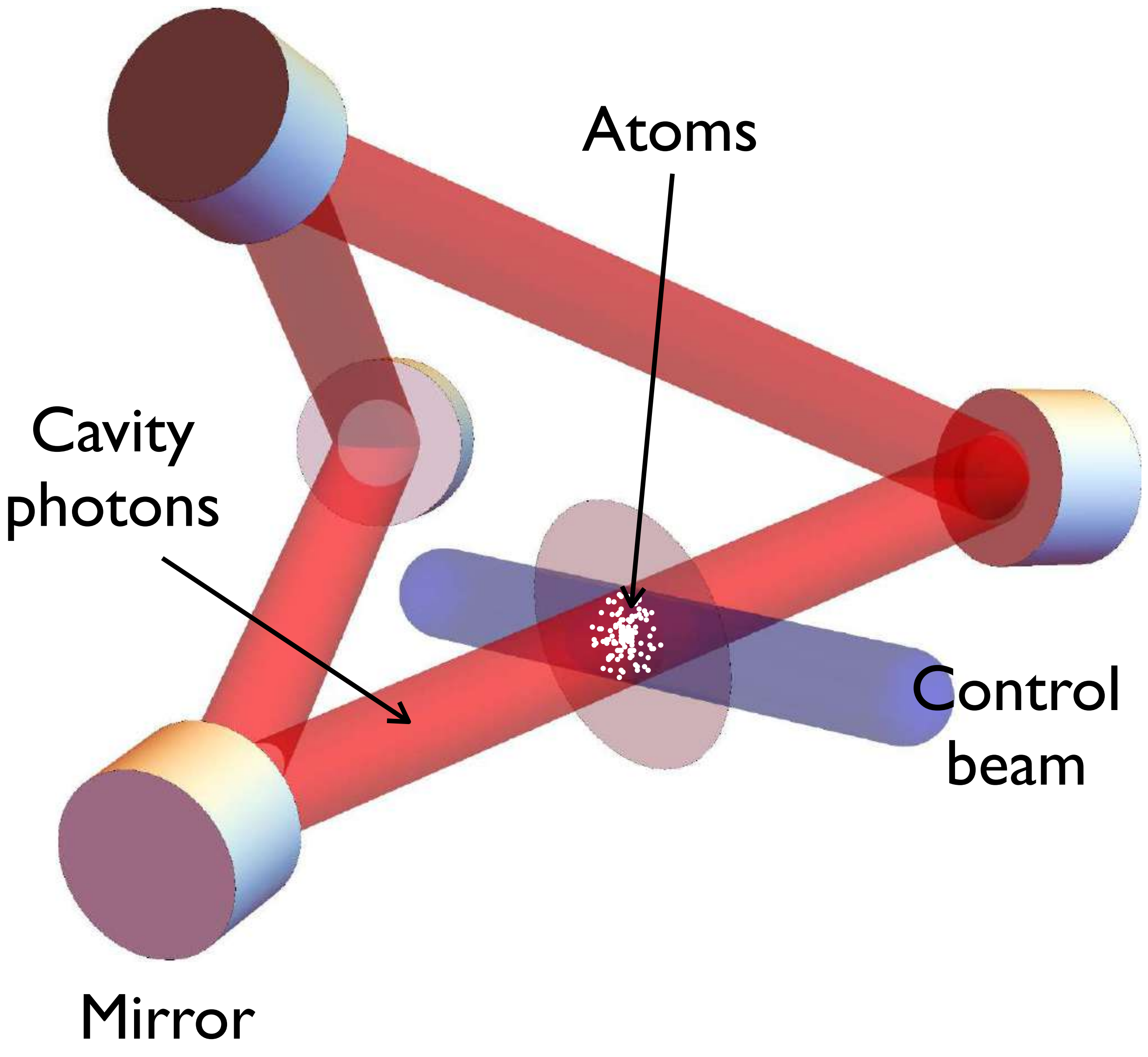
“Dressed” photons
(atom-photon hybrid)

Dynamics
of photons

Interactions
of atoms

Cavity setup

Simon lab — Chicago



Light bounces around fast

- stroboscopic transverse dynamics

2D trapped
interacting photons
in a magnetic field

Atom-photon coupling

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Cavity setup

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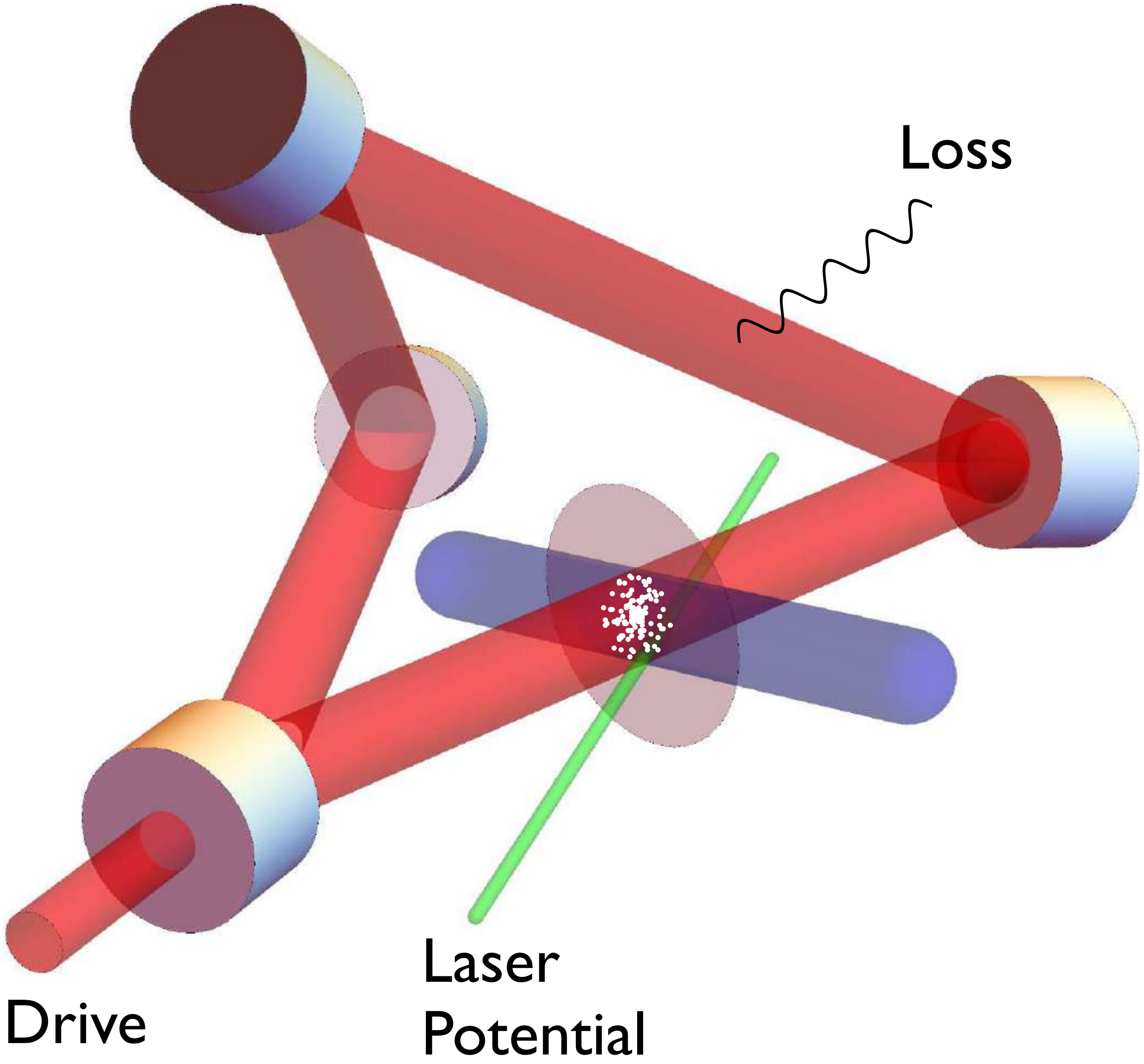


2D trapped
interacting photons
in a magnetic field

+

Drive, Potential, Loss

Creating FQH state

N-photon ground state is an FQH state:

$$\Phi_N(z_1, z_2, \ldots, z_N) \propto \prod_{j<k}(z_j - z_k)^2 \, e^{-\sum_i |z_i|^2/2}$$

Laughlin

How do you inject photons to create this state?

Properties:

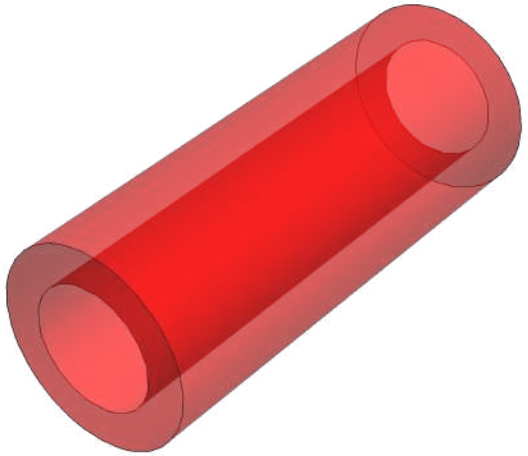
Angular momentum $L_N = N(N-1)\hbar$ Energy $E_N \approx N\hbar\omega_B$

Idea: transition from $|\Phi_n\rangle$ to $|\Phi_{n+1}\rangle$ by

(i) pumping photons with angular momentum $L_{n+1} - L_n = 2n\hbar$

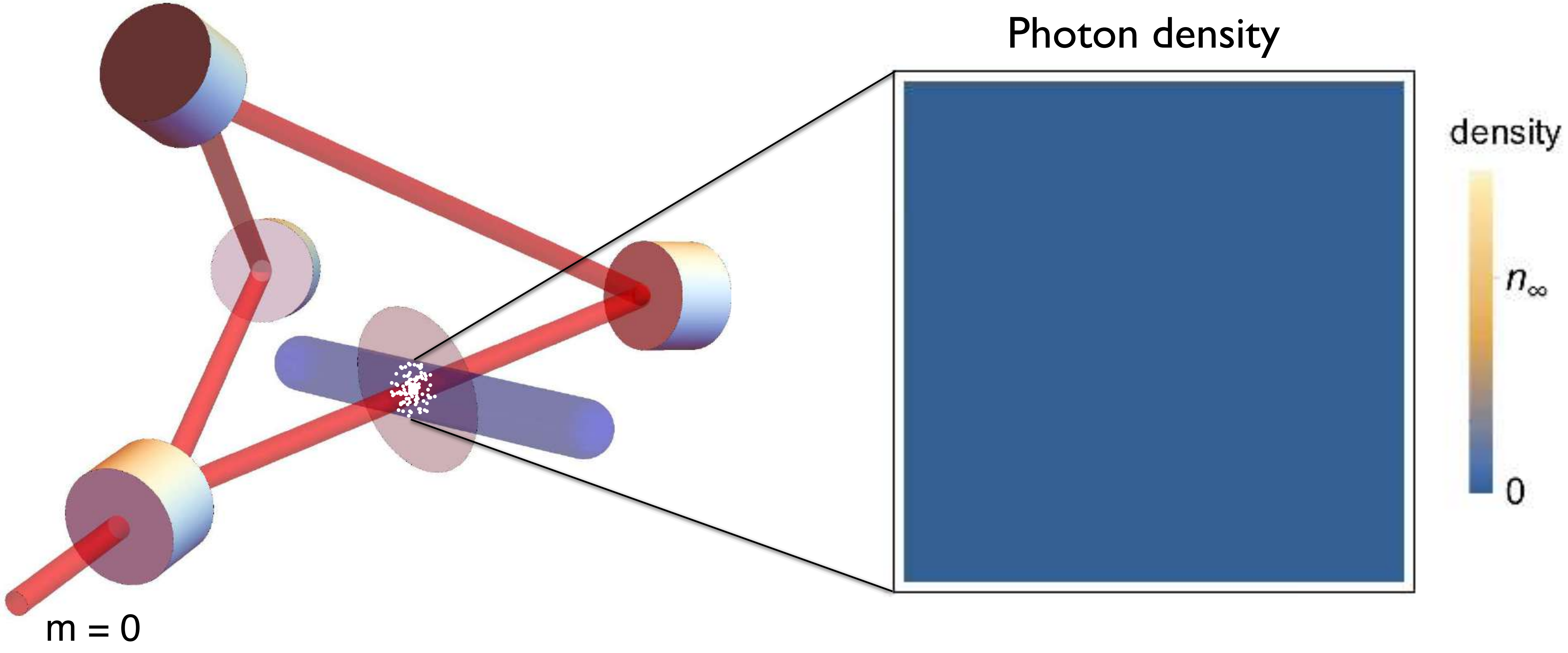
(ii) sweeping frequency thru resonance, $\omega \approx \omega_B$

$$|\Phi_0\rangle \to |\Phi_1\rangle \to \ldots |\Phi_N\rangle$$

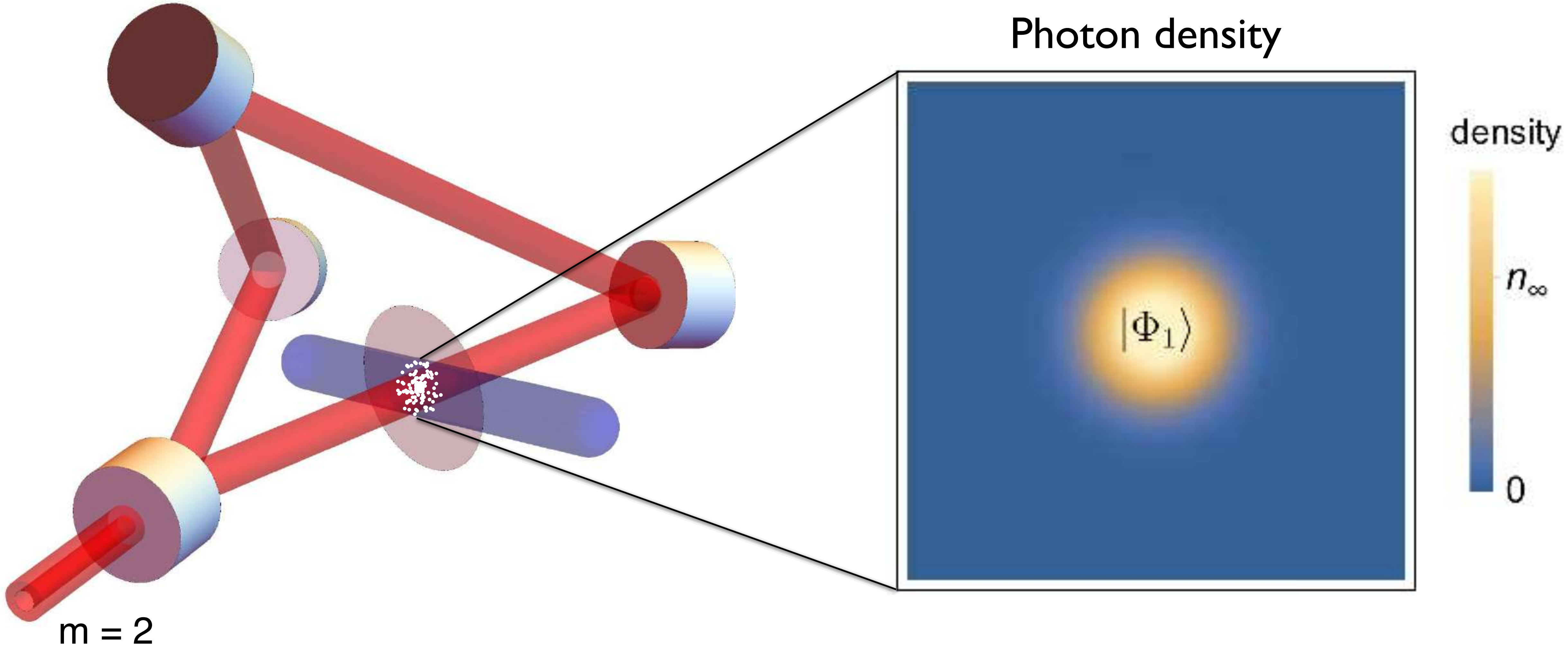


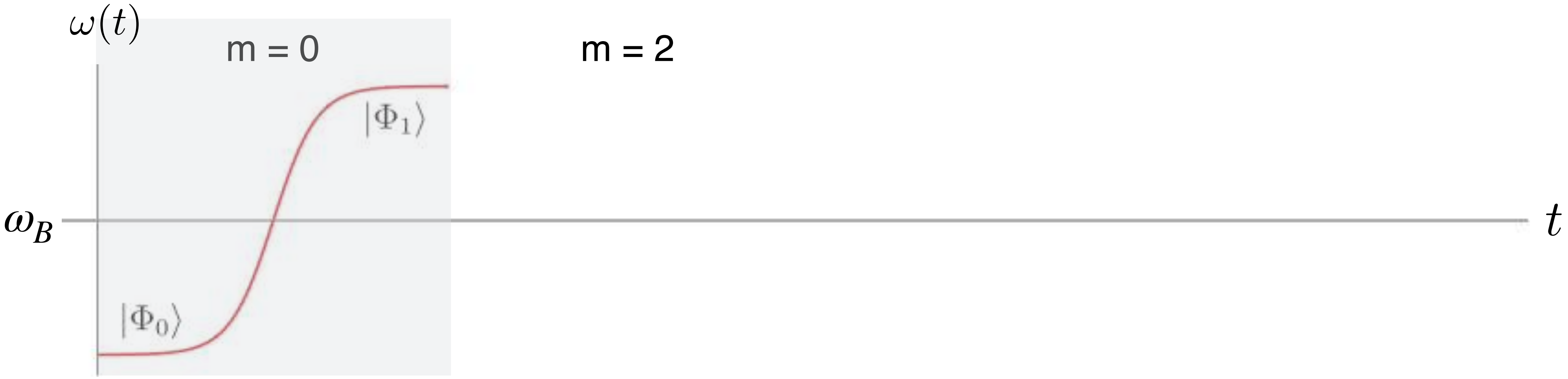
Lagurre-Gauss
laser beams

Creating FQH state

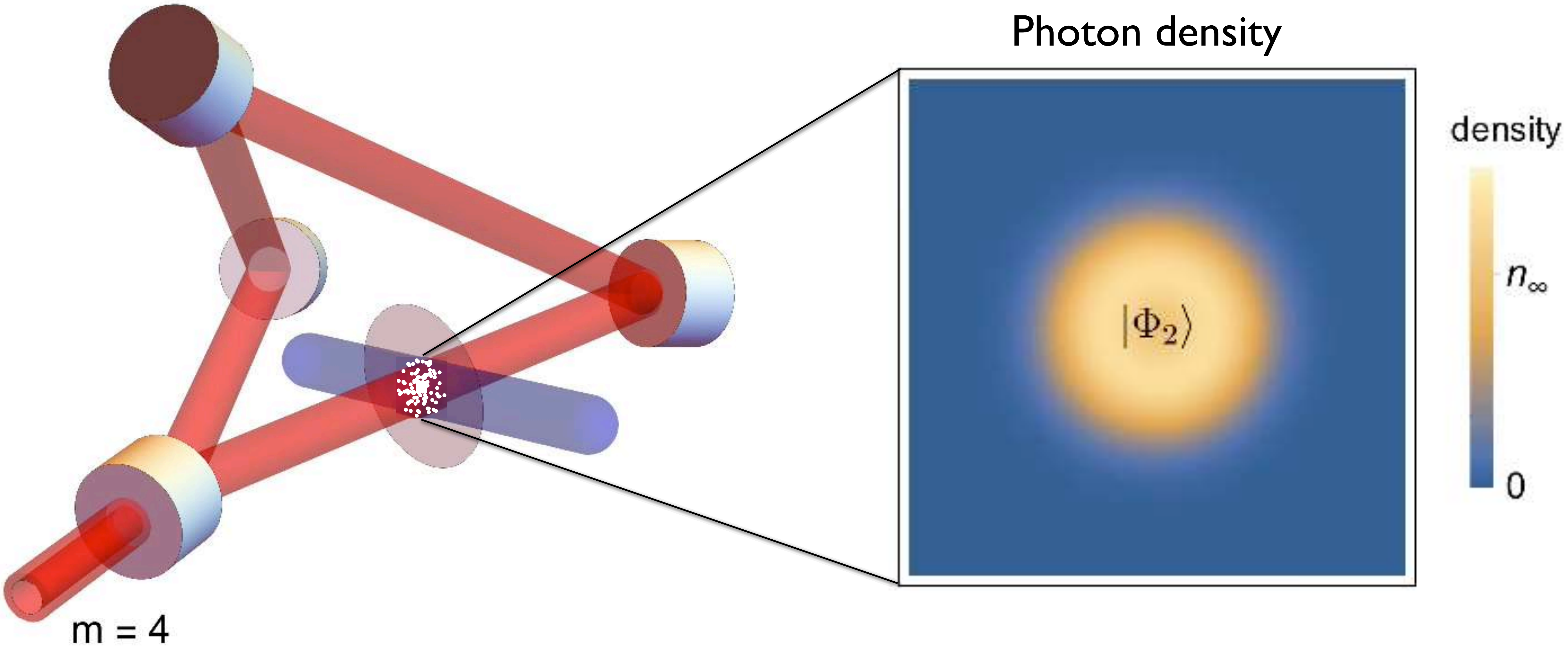


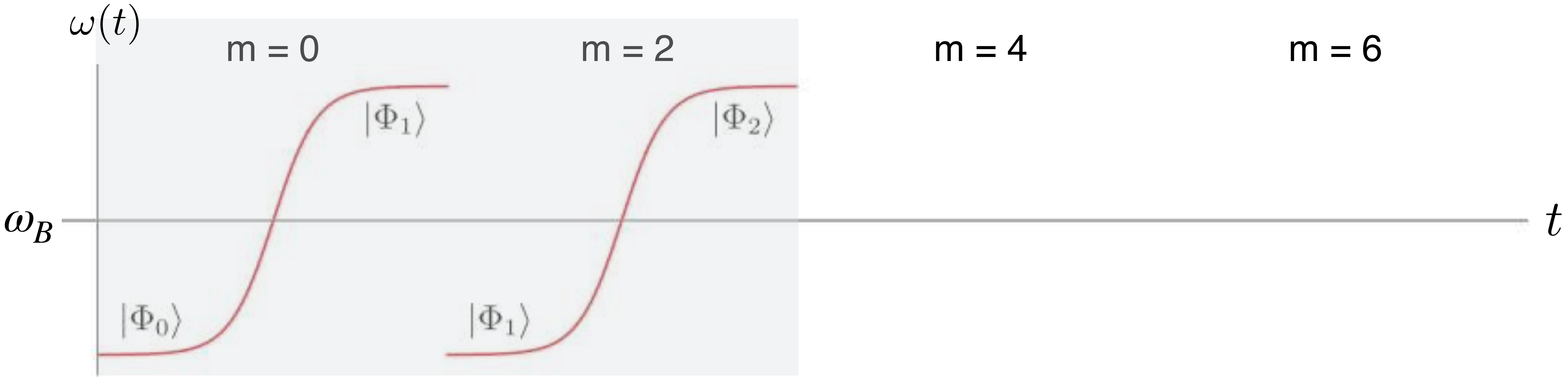
Creating FQH state





Creating FQH state





Creating anyons ("holes")

Holes should act like anyons with exchange phase $\phi = \pi/2$

Exchange: $\psi \to e^{i\pi/2}\psi$

Wilczek

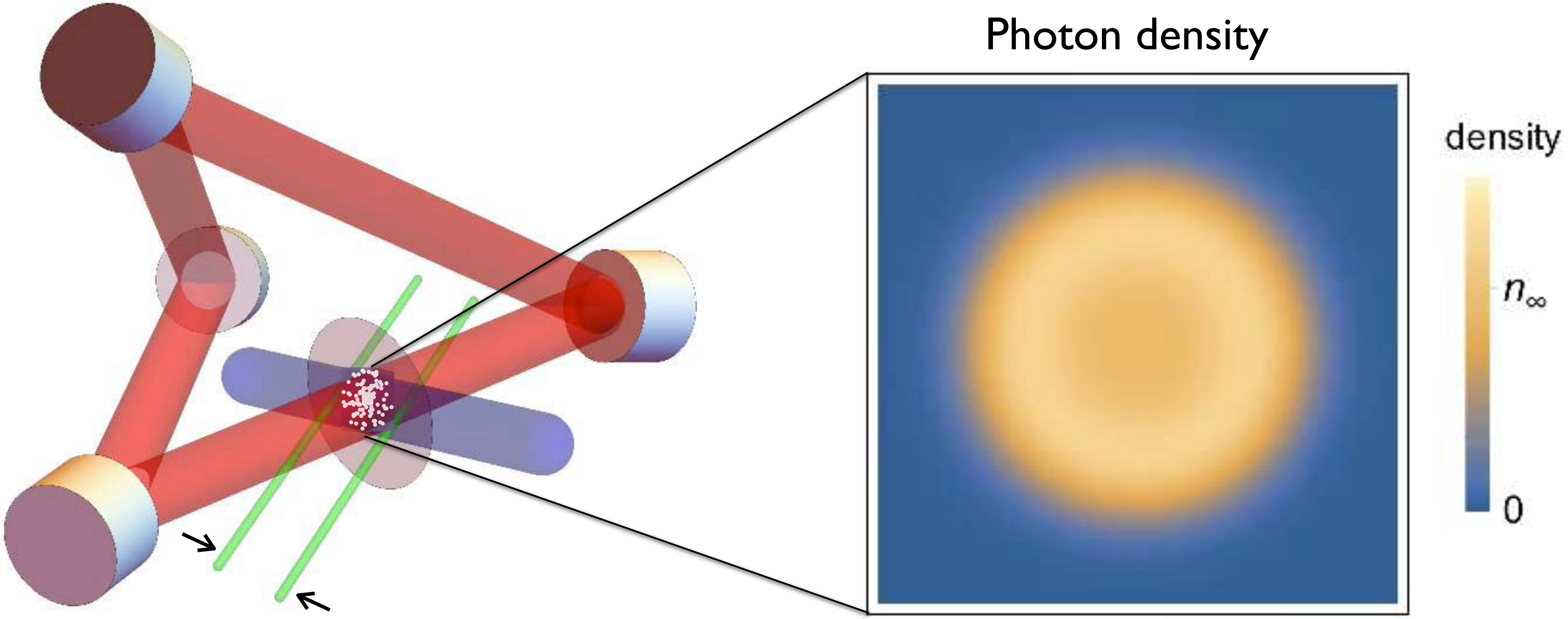
Creating anyons (“holes”)

Holes should act like anyons with exchange phase $\phi = \pi/2$

Exchange: $\psi \to e^{i\pi/2}\psi$

Wilczek

Idea: insert strong localized off-resonant lasers to pierce holes



Photon density

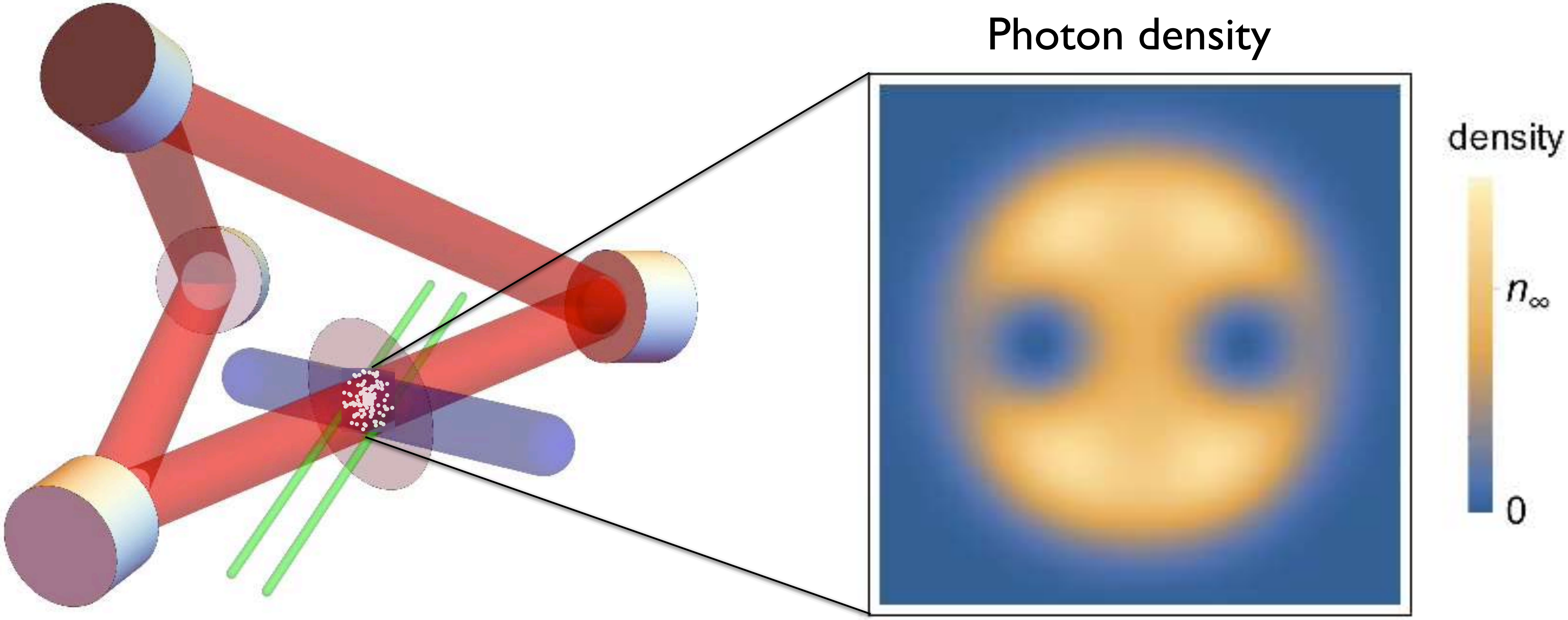
Braiding anyons (“holes”)

Wilczek

Holes should act like anyons with exchange phase $\phi = \pi/2$

Exchange: $\psi \to e^{i\pi/2}\psi$

Idea: rotate pinning lasers to drag anyons around each other

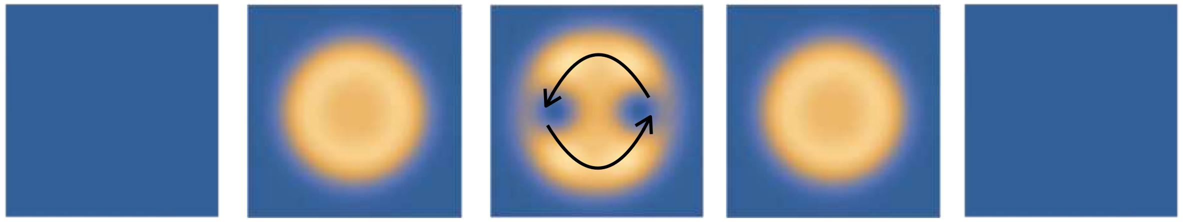


Measuring exchange phase

Idea: compare with a reference $|R\rangle$ which is unaffected by drives

(e.g., using Rydberg blockade)

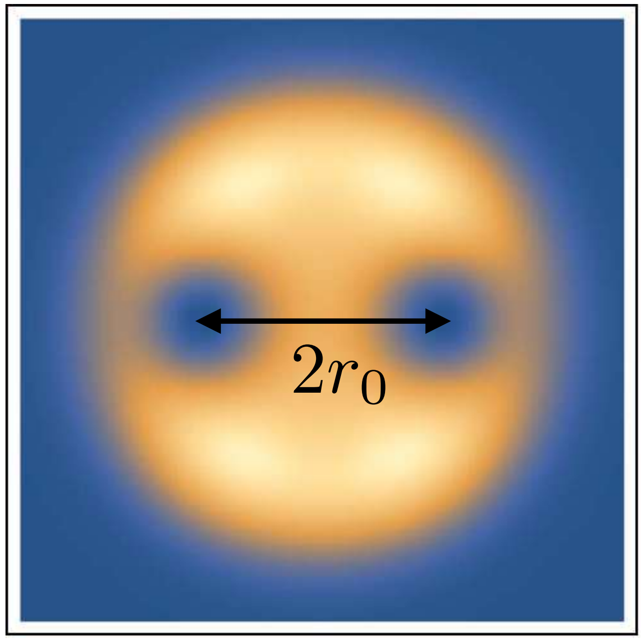
$|0\rangle$ → RF pulse → $|0\rangle + |R\rangle$ → Create FQH, create holes, braid, remove holes, remove photons → $e^{i\phi}|0\rangle + |R\rangle$

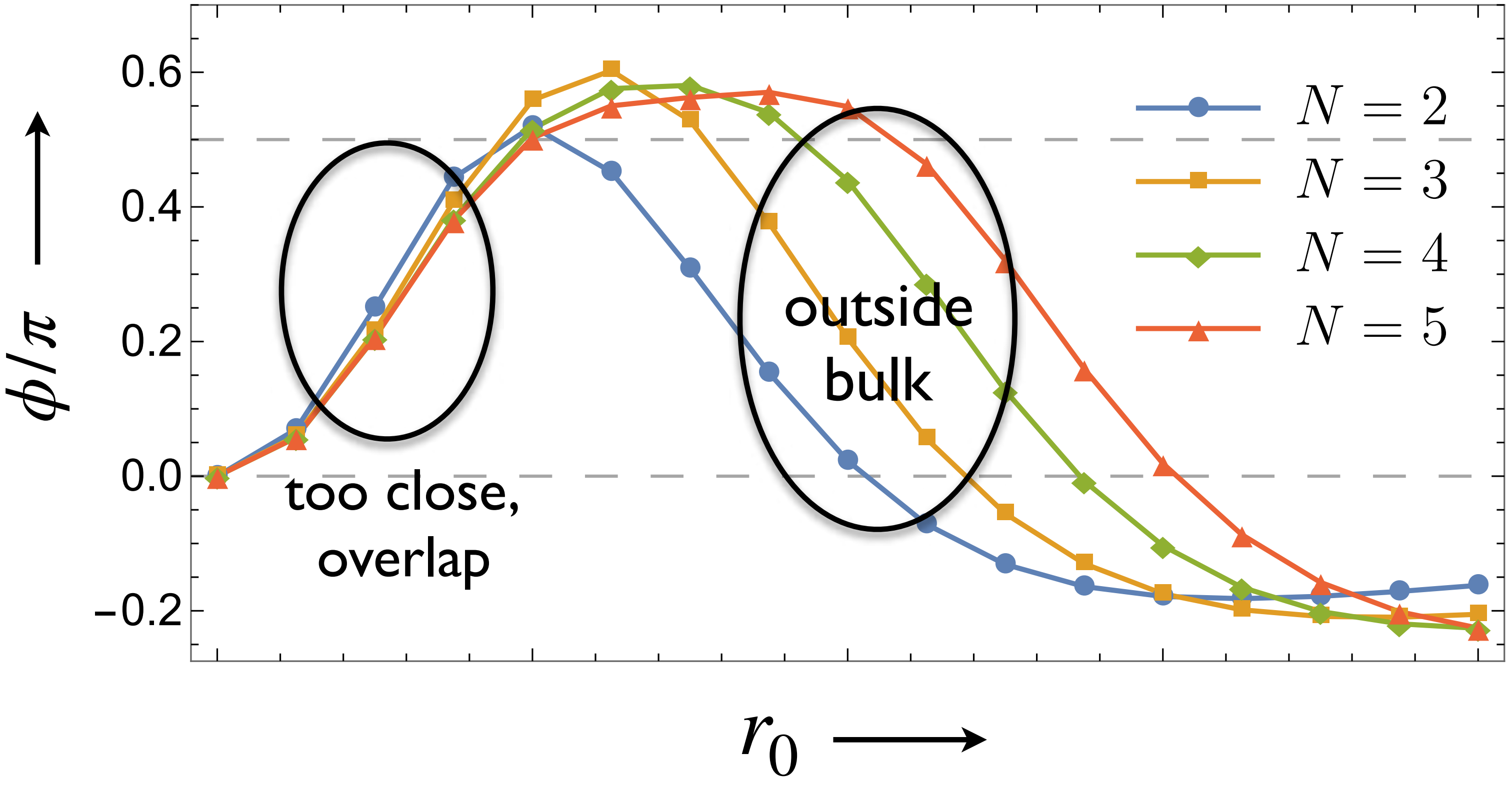


$e^{i\phi}|0\rangle + |R\rangle$ → RF pulse → $(1 - e^{i\phi})|0\rangle + (1 + e^{i\phi})|R\rangle$ → Measure $|R\rangle$ population → $\cos^2(\phi/2)$

Measuring exchange phase

Expected phase ($\pi/2$) emerges for larger photon numbers (N)

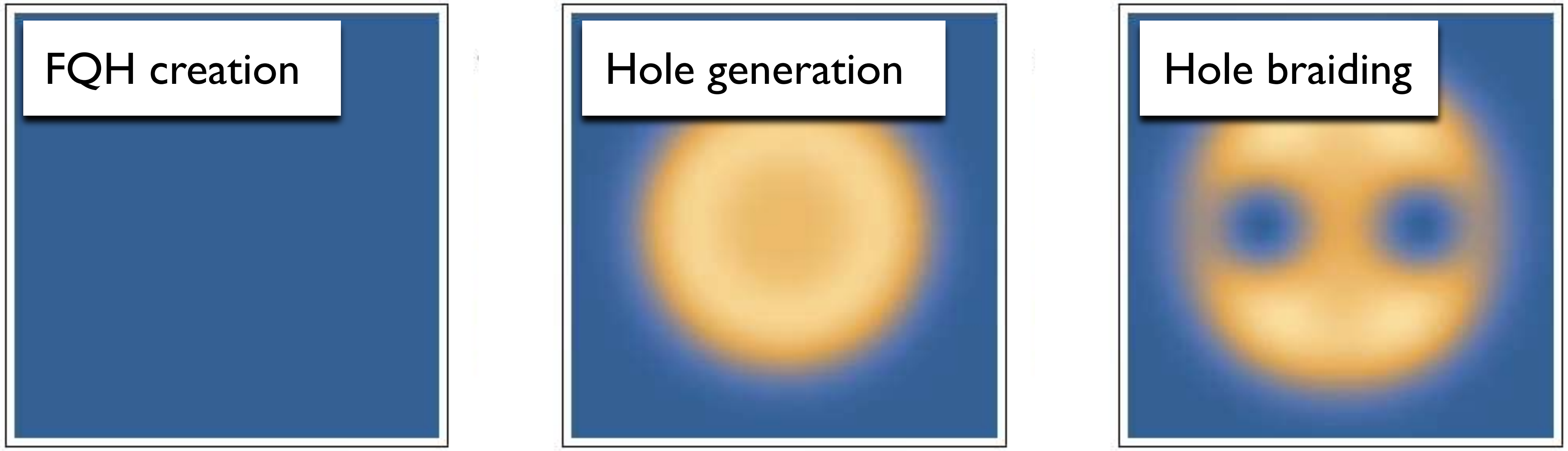




Constraints

I. Sweeps must be slow enough to prevent unwanted excitations

- Rates limited by interaction strength V
- Fast sweeps:



II. Sweeps must be fast compared to photon loss rate γ

$$\Longrightarrow \quad V/\gamma \gtrsim 10\, N^2 \ln N$$

Big improvement over existing protocols (less demanding, high fidelity)

Still hard to achieve (current experiments have $V/\gamma \sim 50$)

Summary

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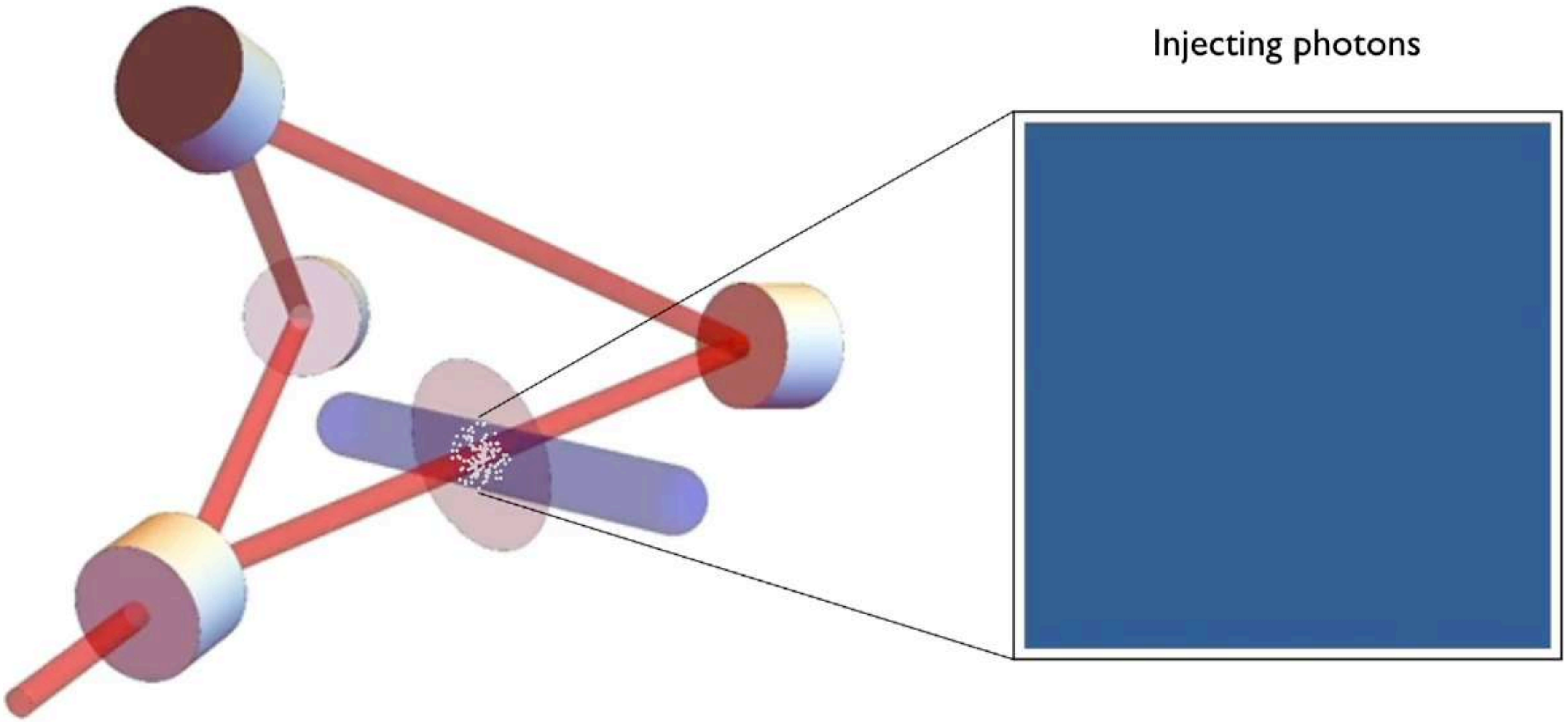
- Inject photons one-by-one to create Laughlin state
- Move pinning lasers to create and braid anyons (holes)
- Interferometrically measure exchange statistics



- Realize few-particle FQH states and perform externally controlled anyon braiding