EPFL LQG LABORATORY for QUANTUM GASES

Towards Quantum Simulation of Random Spin Models

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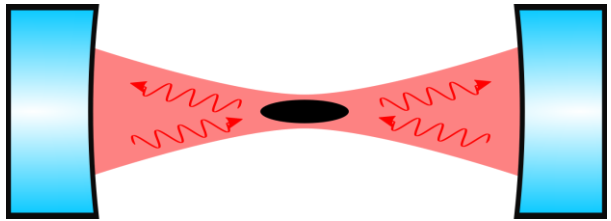
Francesca Orsi and
Jean-Philippe Brantut

20/01/2022 – Searching for New Physics at the Quantum Technology Frontier, Zürich

Laboratory for Quantum Gases

Specialty: Cold Fermions strongly interacting with light

Li^6 atoms + Photons

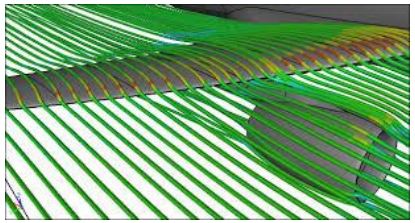


In Cavity

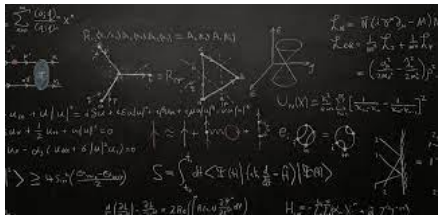
Labs:

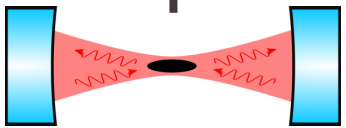
1. **Fermi Gas**: Ultra-cold Fermi gases with tuneable contact interactions
2. **Microscope**: Few Fermions with tuneable coupling to cavity

Role of Quantum Simulation in Search for New Physics



Theoretical Model | Analog Simulation | Real World





Advantages of Analog Quantum Simulation

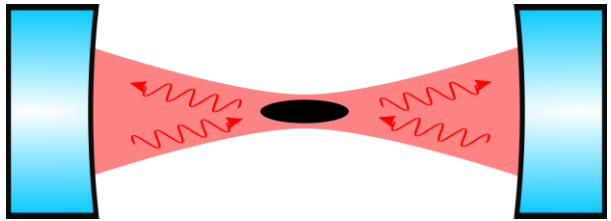
- Tunable Interaction, Temperature, Geometry, …
- Computational advantage

Atoms in Optical Resonator

Atoms:

- Internal States
- Motional degree-of-freedom

Li^6 atoms + Photons



In Cavity

Atoms in Optical Resonator

Atoms:

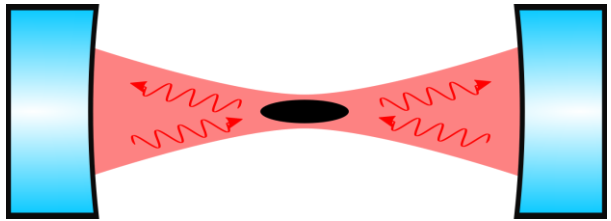
- Internal States
- Motional degree-of-freedom

Photons:

- Can mediate Flip-Flop interactions

- Can transfer momentum from one to another (Force)

Li^6 atoms + Photons



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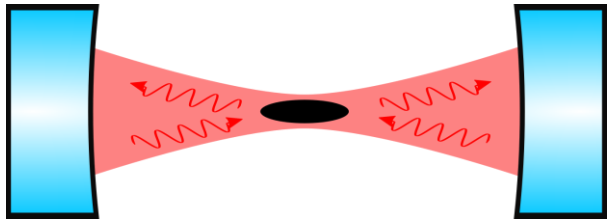


In Cavity

Cavity:

- Enhance coupling between single photon and atoms
- **non-local** all-to-all interaction

Atoms in Optical Resonator

Photons:

Q: How can we tune these interactions?

A: Tune Atomic transition

Atoms

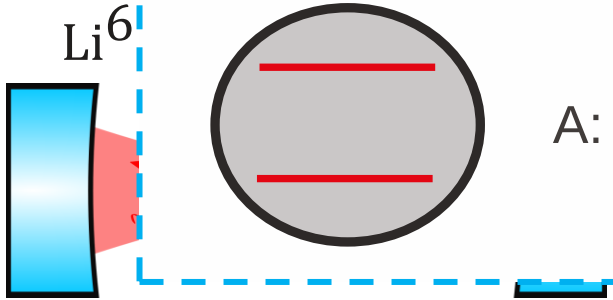
- Interr
- Motic

interactions

n from one to

v

een single photon

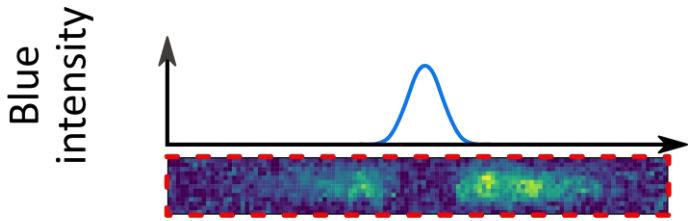


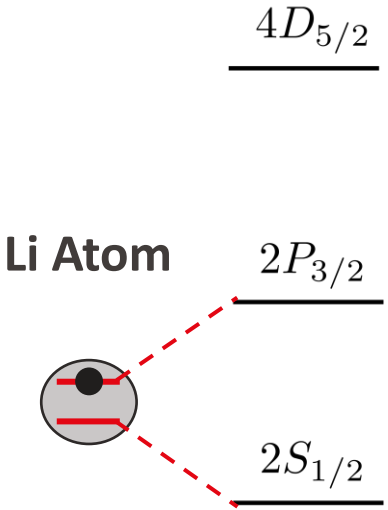
In Cavity

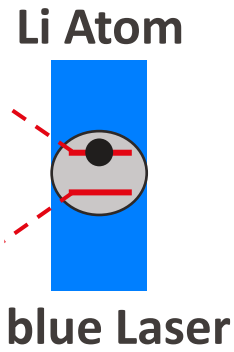
- **non-local** all-to-all interaction

Microscope experiment

Absorption spectroscopy of the cloud







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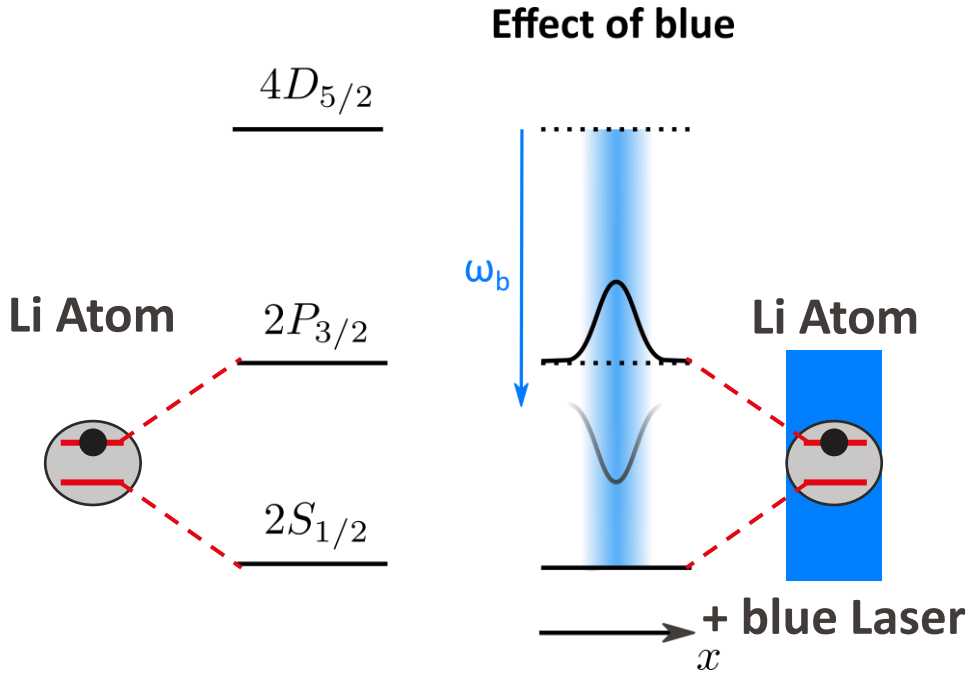
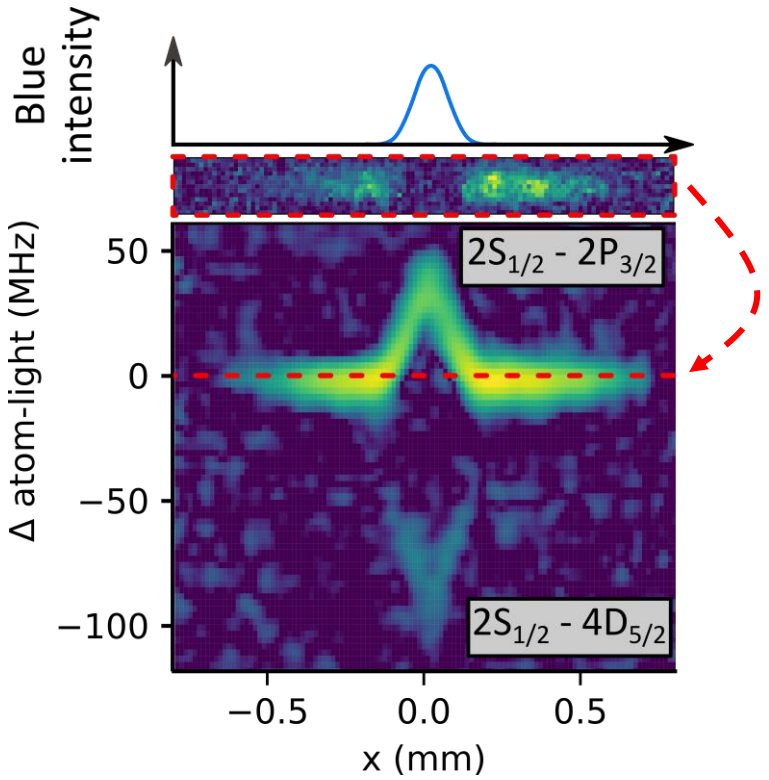
Microscope experiment

Absorption spectroscopy of the cloud





Quantum Simulation of the following Models:

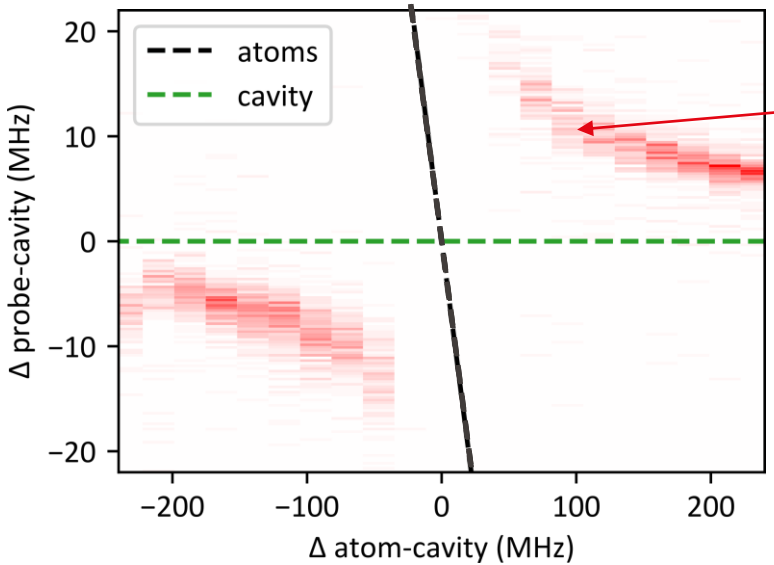
- Random Tawis-Cummings Model

- Sachdev-Ye-Kitaev Model (Outlook)

Tavis-Cummings Model

$$H = \sum_i \omega_i \sigma_i^z + \omega_c a^\dagger a + g_0 \sum_i (a\,\sigma_i^+ + a^\dagger \sigma_i^-)$$

Atoms Cavity Atoms-cavity interactions



Strong coupling of collective Dicke state

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_i \sigma_i^+ |0\rangle$$

What happens if ω_i «randomly» distributed ?

Dubail, J. et al. (2021). *arXiv preprint arXiv:2105.08444*.

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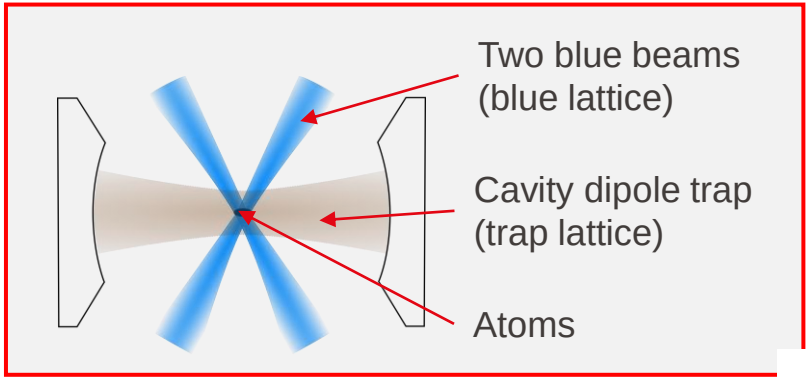
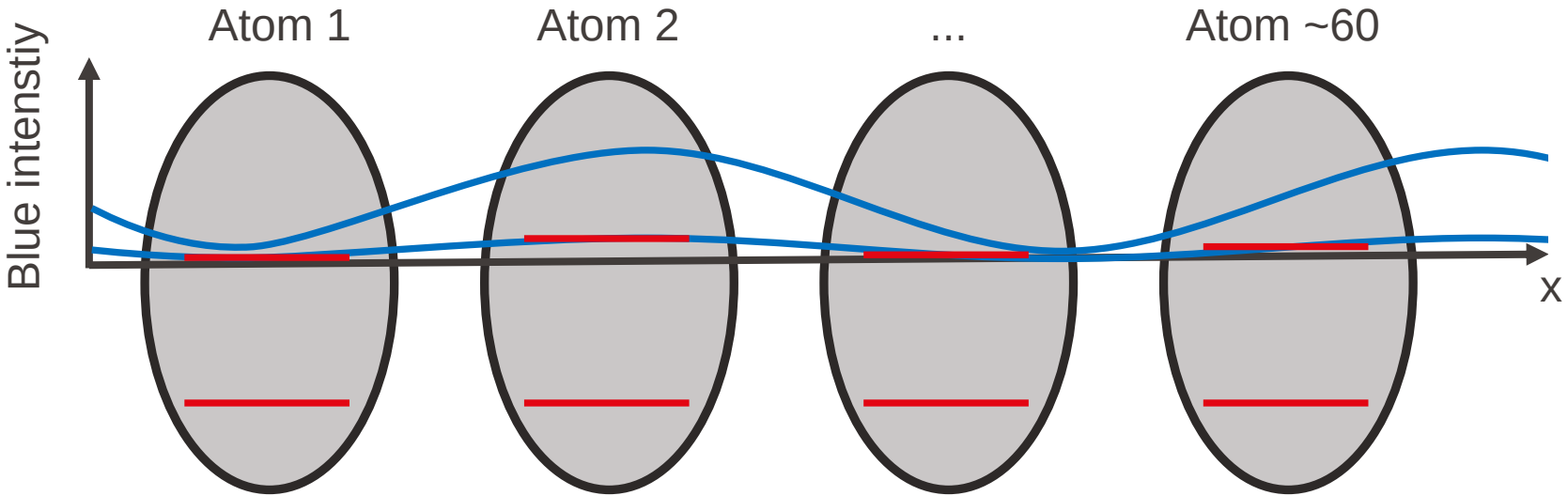
“Random” Spin Chain

$$H = \sum_i \omega_i \sigma_i^z$$

ω_i «randomly» distributed





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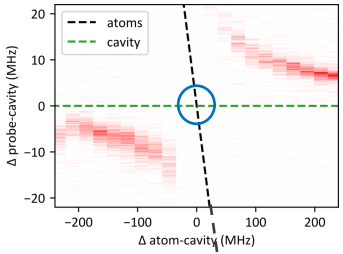
Random Tavis-Cummings Model



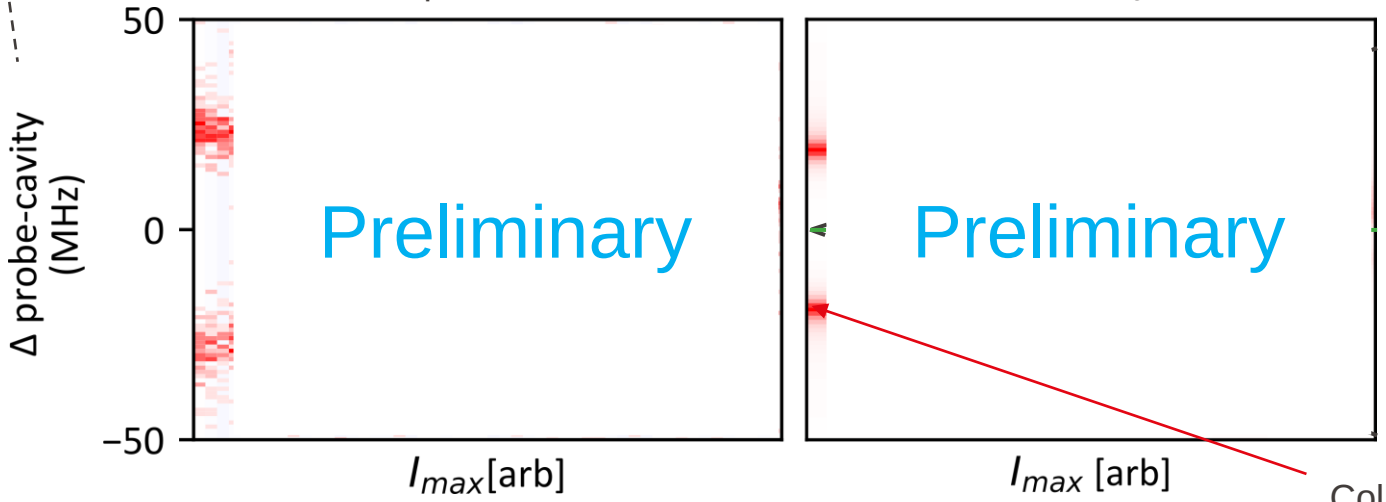
$$H = \sum_i \omega_i \sigma_i^z + \omega_c a^\dagger a + g_0 \sum_i (a\,\sigma_i^+ + a^\dagger \sigma_i^-)$$

Atoms Cavity Atoms-cavity interactions

LMG Model

Experiment

Theory



Dubail, J. et al. (2021). *arXiv preprint arXiv:2105.08444*.

Quantum Simulation of the following Models:

- Random Tawis-Cummings Model

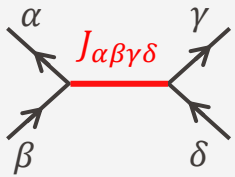
- Sachdev-Ye-Kitaev Model (Outlook)

Quantum Simulation of the SYK Model

SYK model

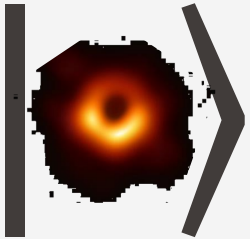
Fermions with
random all-to-all coupling

$$H = \sum_{\alpha\beta\gamma\delta} J_{\alpha\beta\gamma\delta}\, c_\alpha^\dagger c_\beta^\dagger c_\gamma c_\delta$$



Holographic ⟷ **Duality**

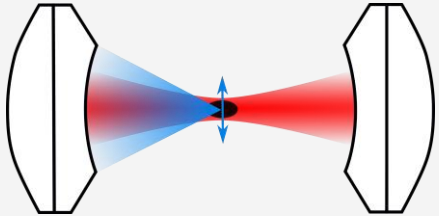
Quantum Gravity

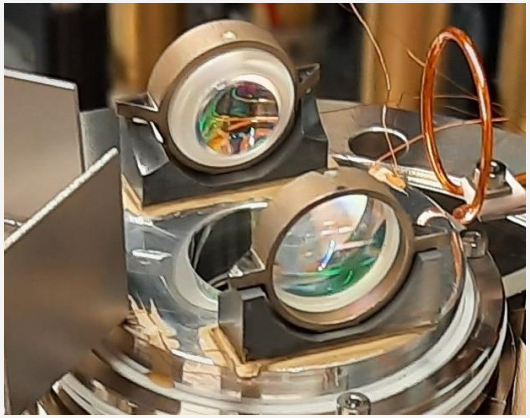


Quantum ⟷ **Simulation**

Optomechanics Experiment

Temporally and spatially tunable cavity-mediated long-range interactions





Liu, Hong, and Julian Sonner. *Nature Reviews Physics* 2.11 (2020): 615-633.

EPFL LQG

Theory collaborations:

Hauke Group

UNIVERSITÀ DI TRENTO
Dipartimento di Fisica

Synthetic Quantum Systems

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Soumik Bandyopadhyay

Philipp Uhrich

Université de Strasbourg

Guido Pupillo

Alumni:
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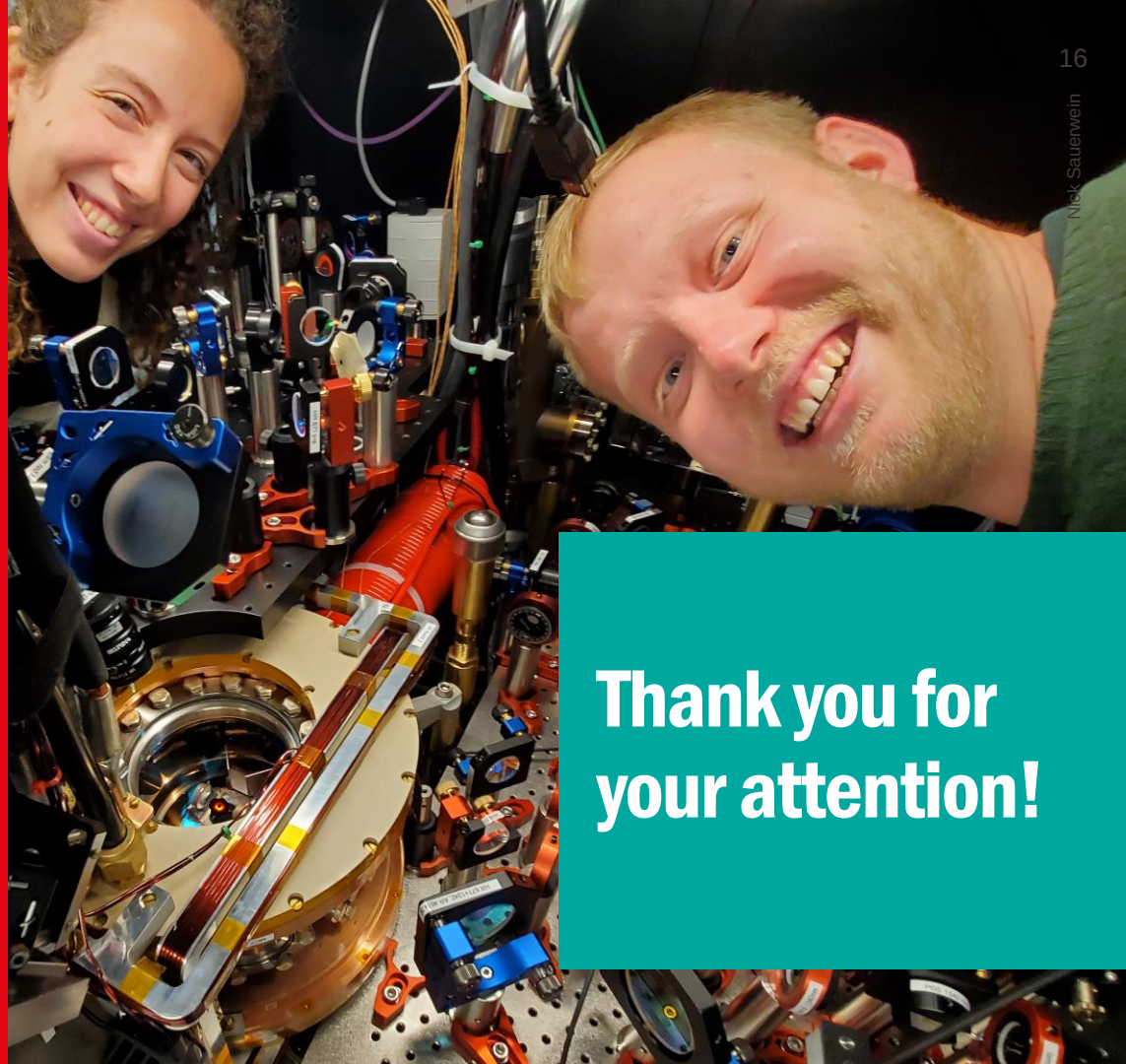
- Tigrane Cantat-Moltrecht



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Thank you for your attention!

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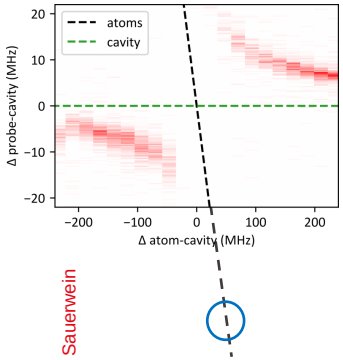
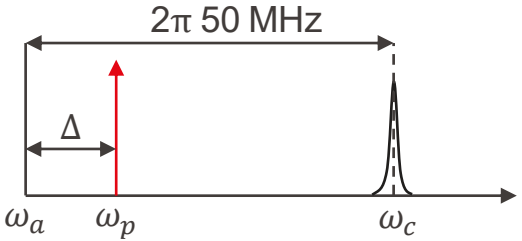
Random Lipkin-Meshkov-Glick Model



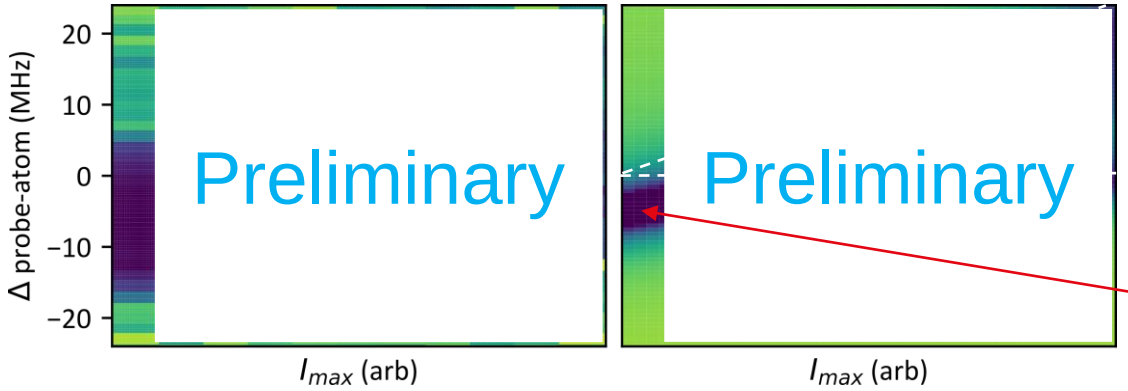


Lipkin-Meshkov-Glick (LMG) model

$$H = \chi \sum_j \sigma_j^+ \sum_i \sigma_i^- + \sum_i \omega_i \sigma_i^z$$

Cavity interactions — Spin energy

Measurement of $\langle \sum_i \sigma_i^z \rangle$



Collectively-coupled Dicke state

- Muniz, Juan A., et al. *Nature* 580.7805 (2020): 602-607.
- Lewis-Swan, Robert J., et al. *Physical Review Letters* 126.17 (2021): 173601.

Measurement of Atomic Excitation

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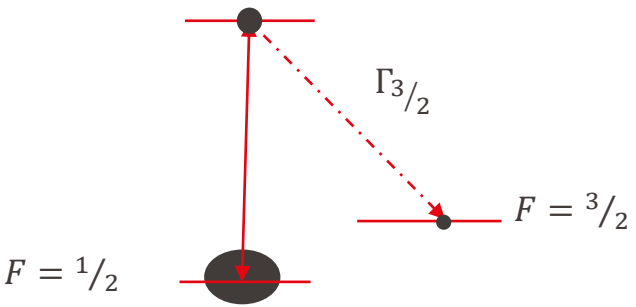
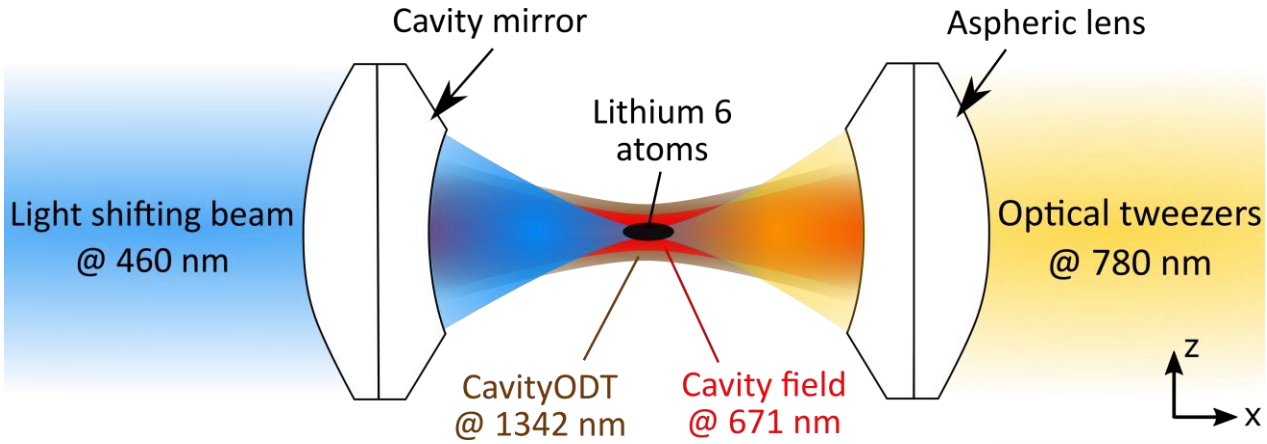
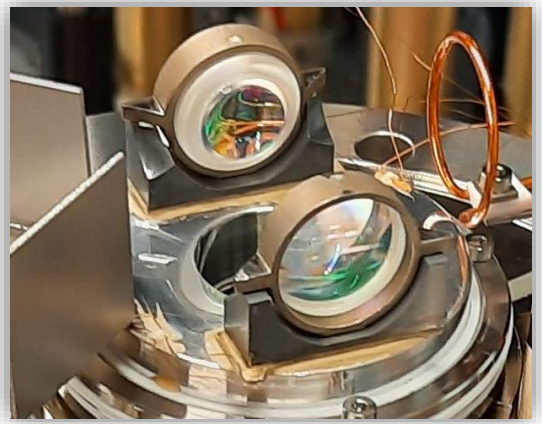
Measurement of $\langle J_z \rangle$ by depumping



Microscope experiment



- High-finesse cavity
- High atom-cavity cooperativity
- Time and space tunability of trapping potentials
- Time and space tunability of atom-cavity coupling



Effect of Blue on Cavity Transmission

- Blue shifts the 2S-2P transition
- Two photon transition coupling couples strongly to the cavity

$$\Omega_{blue} = 40\ MHz\ * 2\ \pi$$